

# ASTROPARTICLES

ESIPAP - 2015  
François Montanet



## Plan of the course

- Introduction + very brief History
- Nature and properties of Astroparticles
- Propagation medium, IGM, ISM and atmosphere
- Astrophysical Sources
  - Astrophysical shocks
  - Fermi acceleration
  - Standard Model for the production of galactic CR, SNR
  - Gamma-ray sources, pulsars
  - AGN and other extragalactic sources
  - Neutrinos sources
- Cosmological Sources
  - Cosmological implications
  - Dark Matter as a source of CR
  - "top-down" type of sources at UHE
- Propagation
  - CR propagation in the Galaxy: The Leaky box model
  - VHE  $\gamma$ -rays propagation
  - UHECR propagation
  - Air Showers Development
- Observables & Observations
  - Primary CR detection (on top of atmosphere)
  - Gamma-ray (EM) induced showers detection => my lecture on Cherenkov det.
  - Hadronic Showers Models and Detection
  - UHECR detection => my lecture on Cherenkov det
- Dark matter search (very briefly on this, done by J. Macias)
- Neutrino Physics with astroparticles (briefly on this, overlaps with other lecturers & detection discussed in my lecture on Cherenkov det)
- Gravitational waves (not covered, very specific)

2015  
F. Montanet - Astroparticle physics ESIPAP

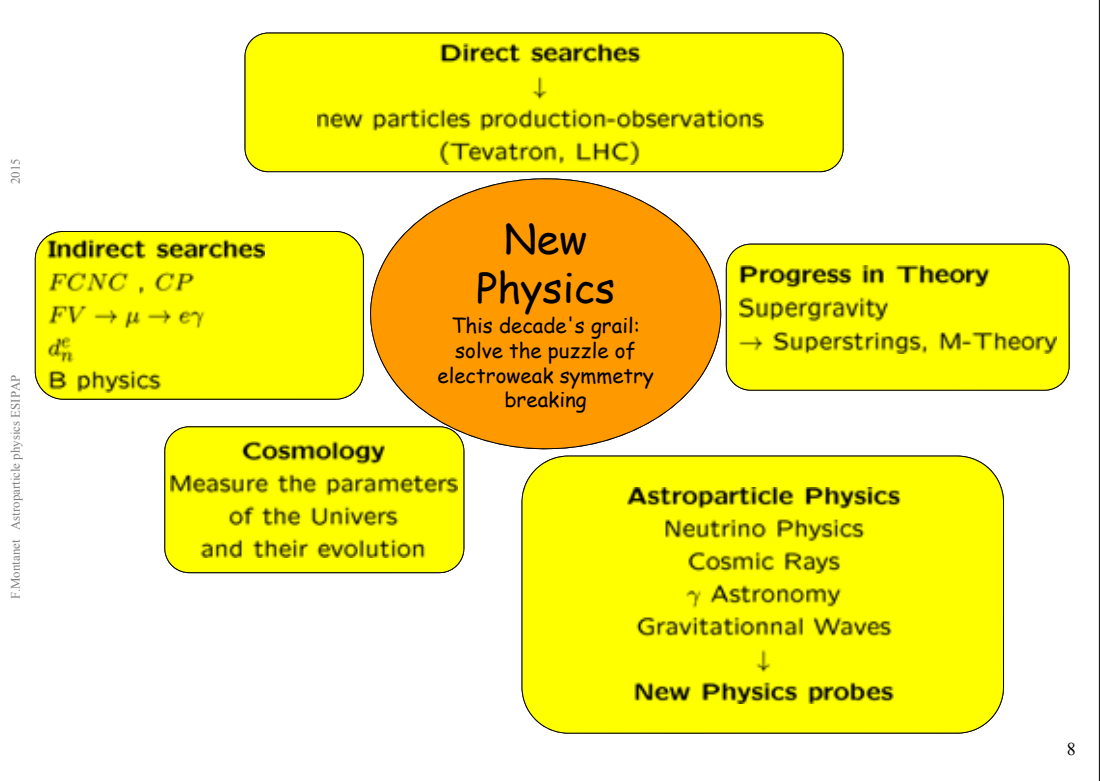
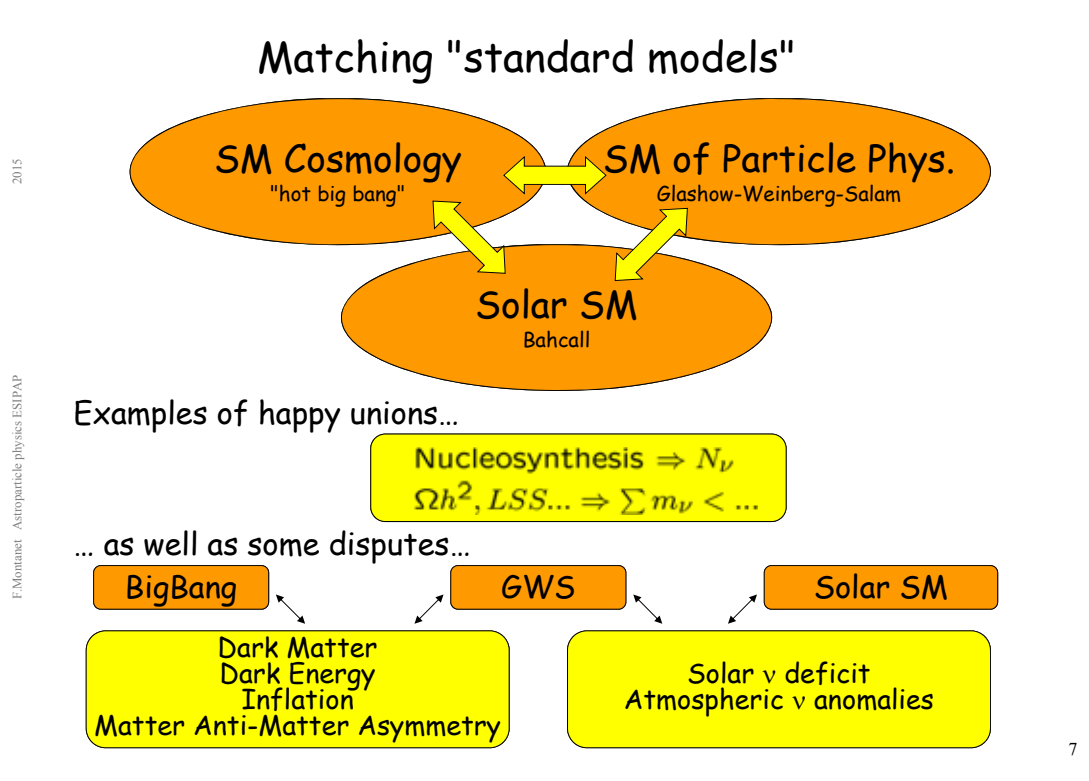
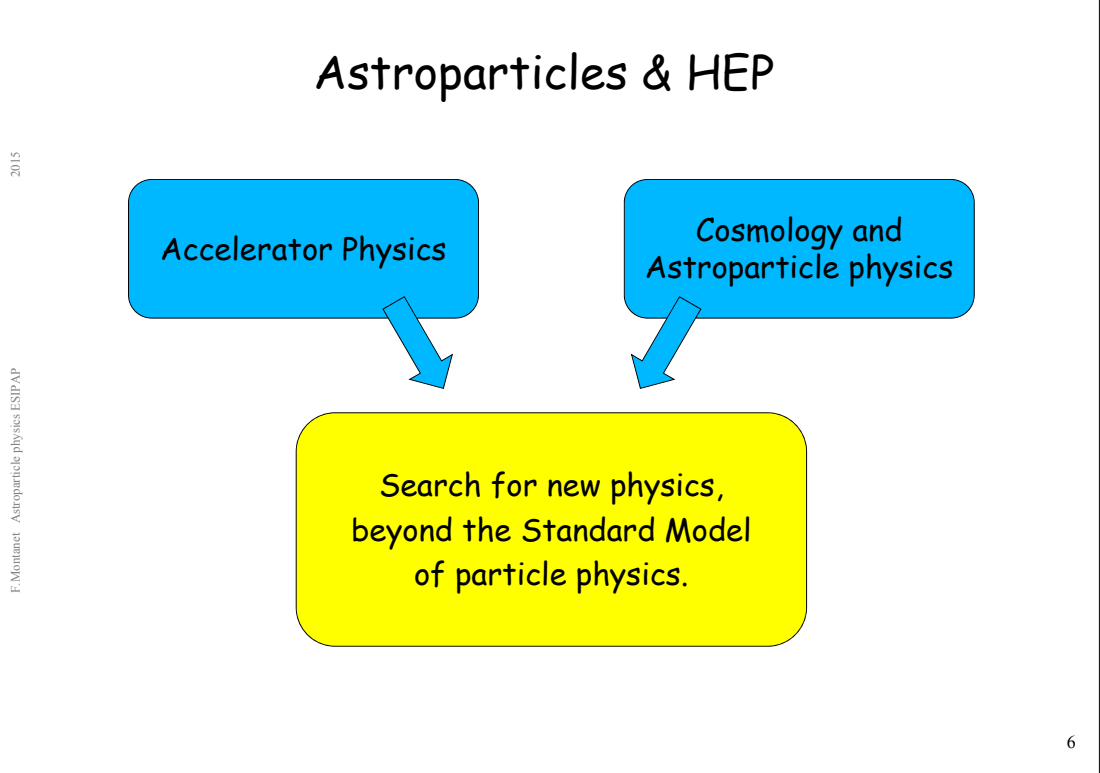
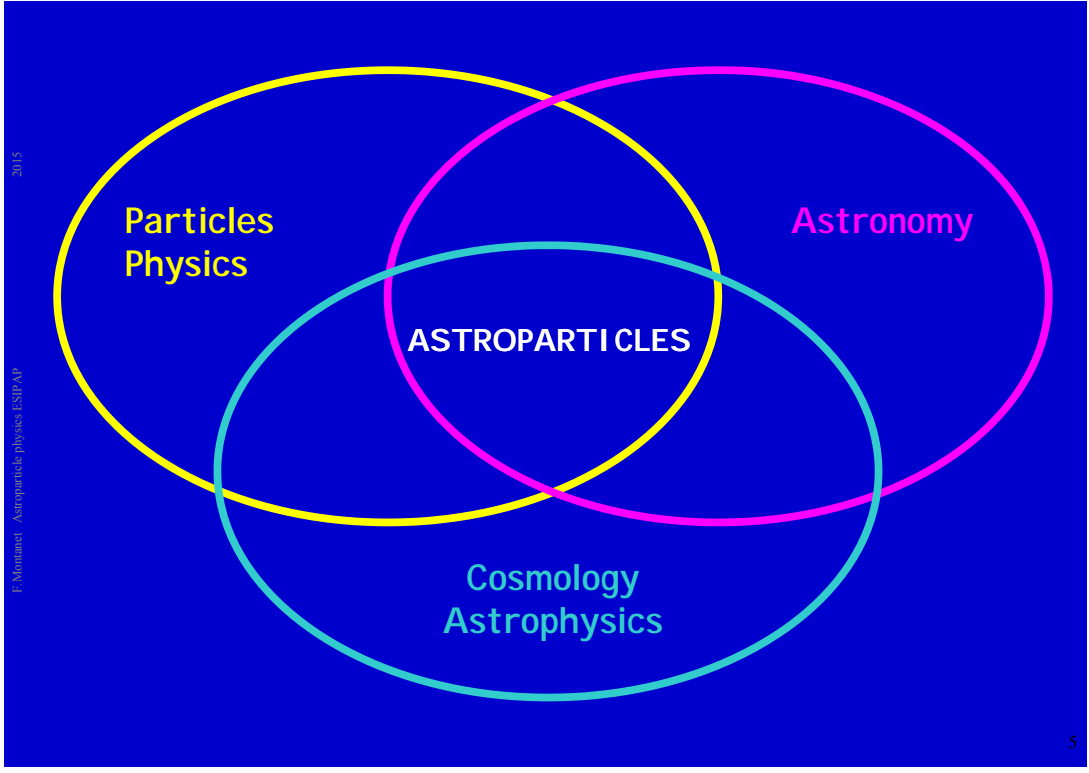
## Why studying Astroparticles

### Open questions

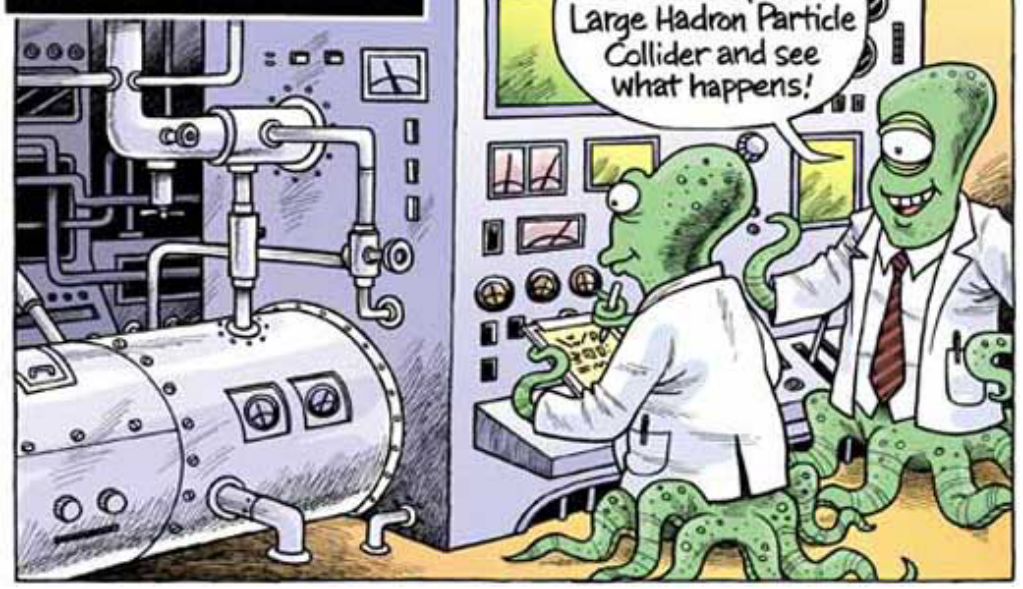
#### Understand our Universe at extreme scales

- The Higgs boson or the origin of mass
- Nature and mass of Neutrinos
- Fundamental symmetries: CP, supersymmetry
- New dimensions in physical space?
- What is our Universe made of?
- Sources and propagation of cosmic rays?
- New Physics at  $E \gg E(\text{LHC})$ ?

2015  
F. Montanet - Astroparticle physics ESIPAP



13,8 BILLION YEARS AGO,  
A FEW SECONDS BEFORE THE  
CREATION OF OUR UNIVERSE...



# What are "Astroparticles"

What we know

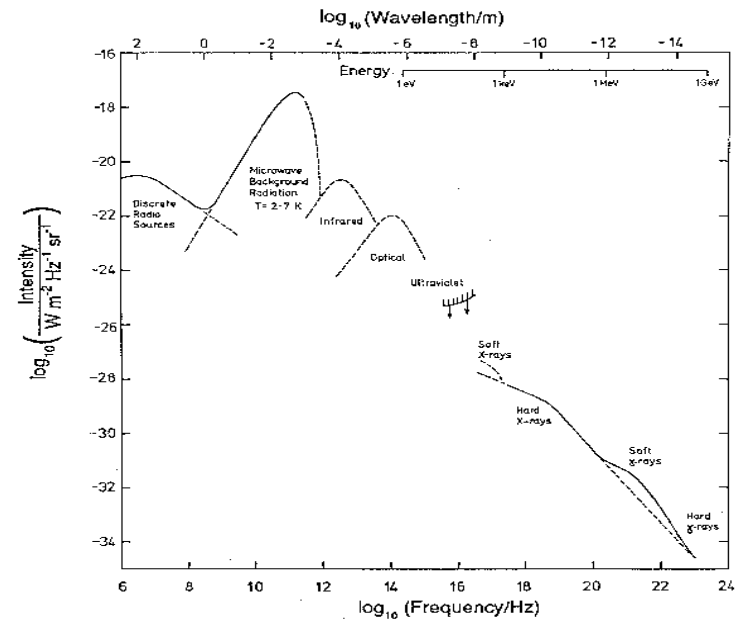
Let there be light !

**All what we know in astrophysics is thanks to the light !**

- Temperatures, stars masses, galaxies, magnetic fields, chemical composition, age of stars and structures...
- Nuclear reactions, galactic and extragalactic hydrodynamics, MHD, explosions, nucleosynthesis, past, future... EVERYTHING !

Well, almost everything...

## A multi-wavelength sky



## Our Galaxy

The optical Milky Way



## Our Galaxy

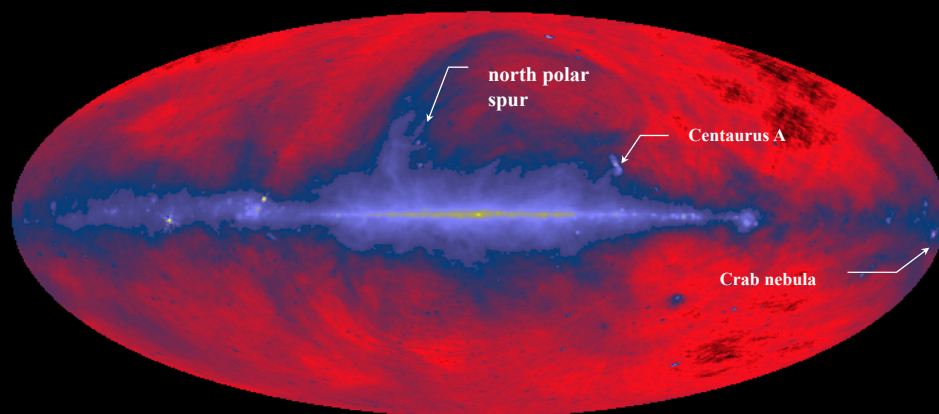
The optical Milky Way



## Our Galaxy

The Milky Way : Radio at 73cm

408 MHz / 73.5 cm /  $1.6 \cdot 10^{-6}$  eV

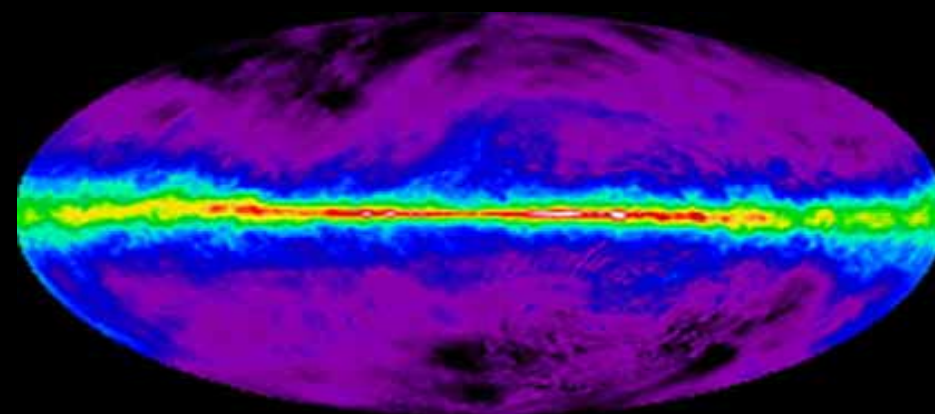


Essentially from the movement of ultra relativistic electrons probably issue from supernovae remnants in the galactic magnetic field.

## Our Galaxy

The Milky Way : Radio at 21 cm

( $\sim 1.42$  GHz / 21.1 cm /  $5.9 \cdot 10^{-6}$  eV)

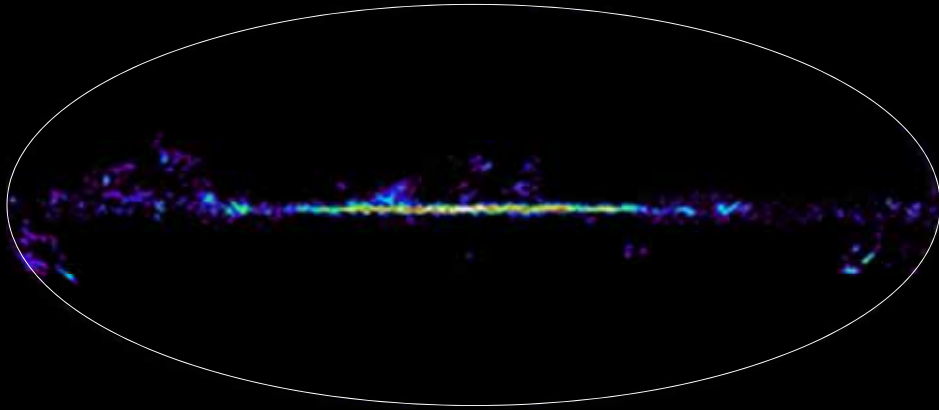


Hyperfine transition of hydrogen. Structures are due to the column density of atomic hydrogen clouds along the line of sight.

## Our Galaxy

The Milky Way : Radio at 2,6mm

*Millimetric waves (115 GHz / 2.6 mm /  $4.7 \cdot 10^{-4}$  eV)*

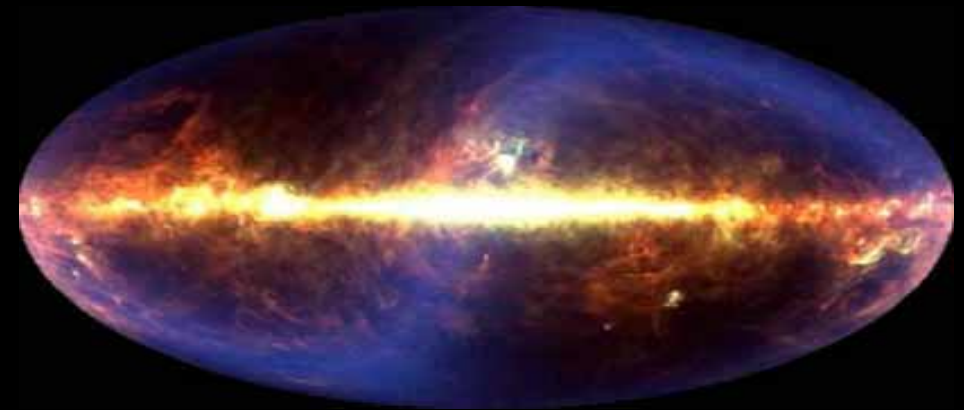


Rotation mode ray of carbon monoxide. One assumes that CO abundance is proportional to that of cold molecular hydrogen (directly undetectable).

## Our Galaxy

Infra red

*Infrared (3  $10^3$  to 25  $10^3$  GHz / 100 to 12  $\mu$ m / 0.01 to 0.1 eV)*



Thermal emission, due to interstellar dust heated by starlight.

## Our Galaxy

It structure is clearly visible in IR (COBE satellite).

*Near Infrared (86  $10^3$  à 240  $10^3$  GHz / 1.25 à 3.5  $\mu$ m / 0.35 à 1 eV).*



Giant stars emission in the disk and in the bulb

## Our Galaxy

Optical

*Visible (460  $10^3$  GHz / 0.65  $\mu$ m / 2 eV – red)*

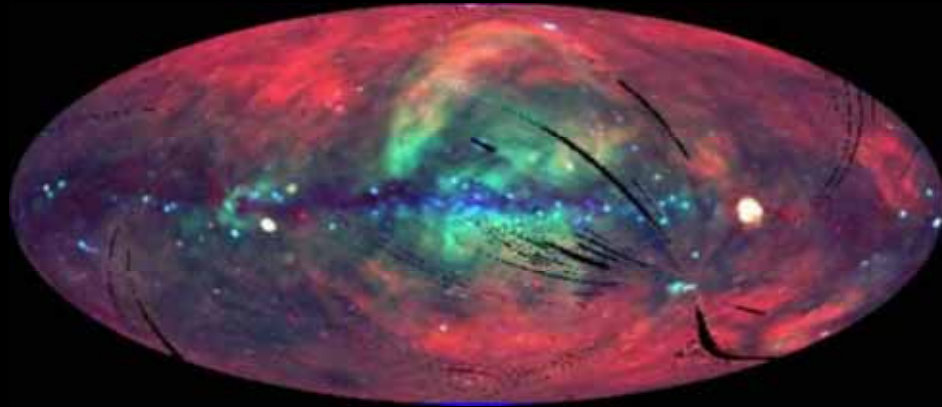


Visible light is absorbed by interstellar dust clouds. Only stars close enough to the solar system (few parsec) are seen.

## Our Galaxy

### X-rays

X-rays ( $60 \cdot 10^6$  to  $360 \cdot 10^6$  GHz /  $5$  to  $8.3$  nm /  $0.25$  to  $1.5$  keV).

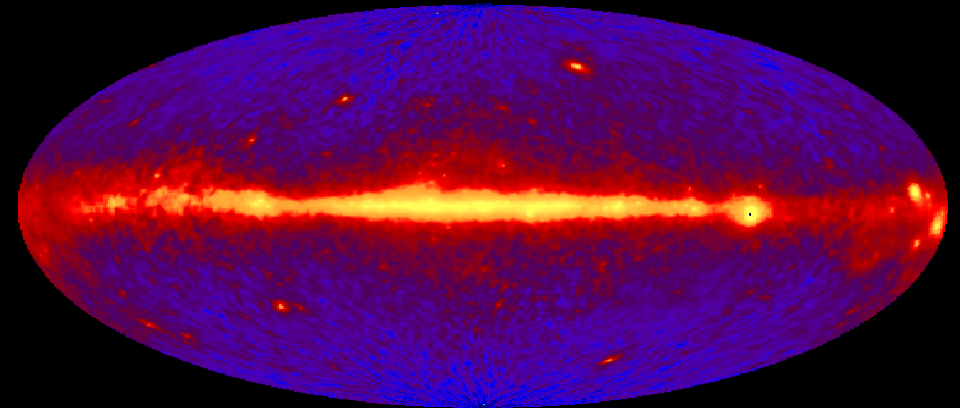


Diffuse X-ray emission from overheated and shocked gas.

## Our Galaxy

### Gamma-rays

Gamma-rays ( $> 2.4 \cdot 10^{13}$  GHz /  $< 12.5$  fm /  $> 100$  MeV).



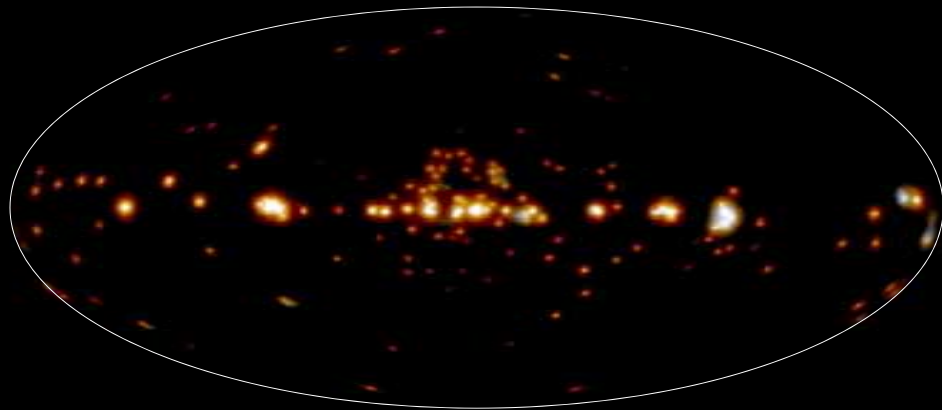
Photons (gammas) from the decay of neutral pions produced in the interaction of CR with interstellar matter, from the Bremsstrahlung of CR and from the inverse Compton of relativistic electrons with ambient photons.

## Our Galaxy

HE gamma-rays ( $> 100$  MeV EGRET satellite)

Resolved point-like sources:

Binary systems, pulsars, SN remnants...

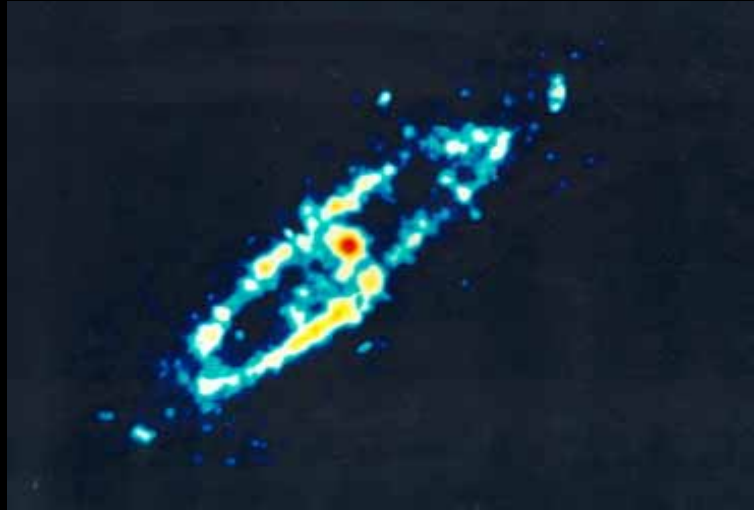


2015

F.Morinnet - Astroparticule physique ESPAP



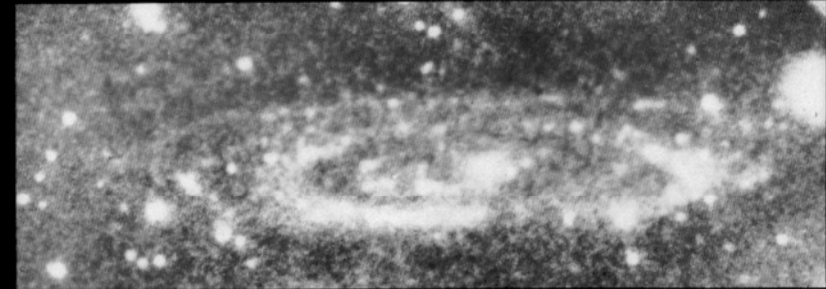
## Andromeda (M31): IR



Star forming  
regions in  
spiral arms

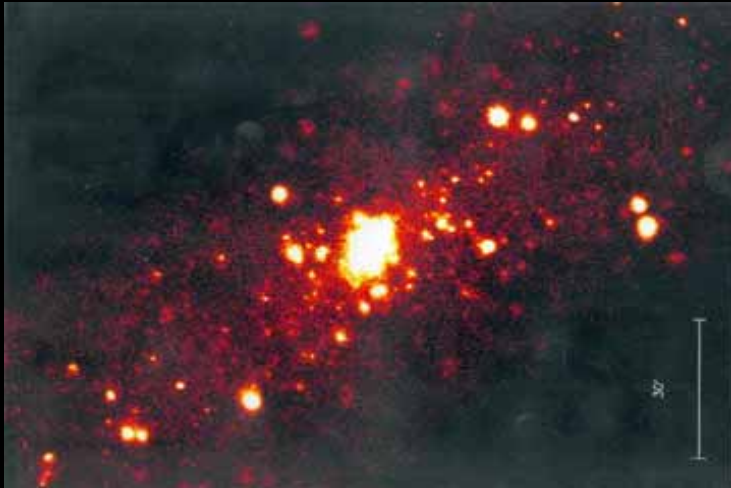
## Andromeda (M31): UV

*This photograph of the galaxy M31 reveals the prominence at ultraviolet wavelengths (2000 Å) of young stars in the spiral arms over the older population in the central bulge.*  
(B. Milliard/Laboratoire d'Astronomie Spatiale).



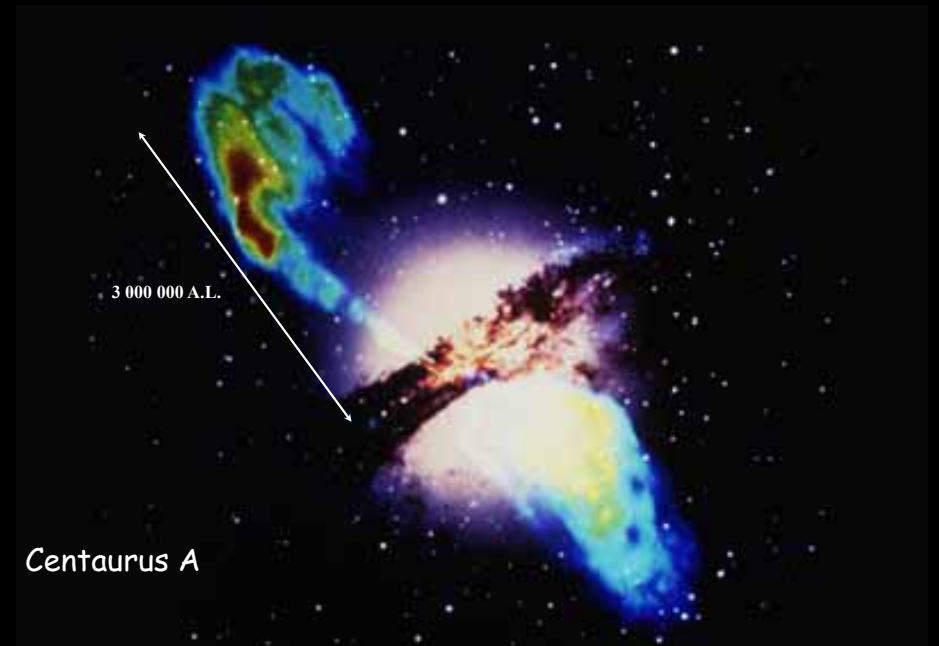
Young,  
hot stars  
in spiral  
arms

## Andromeda (M31): Xray



Xray binaries,  
supernova  
remnants, hot gas

## Radio Galaxy



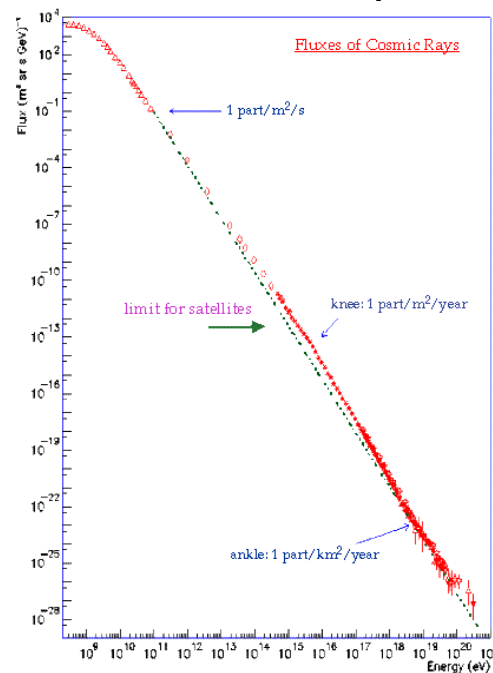
Centaurus A

# Let there be light !

## All what we know in astrophysics is thanks to the light !

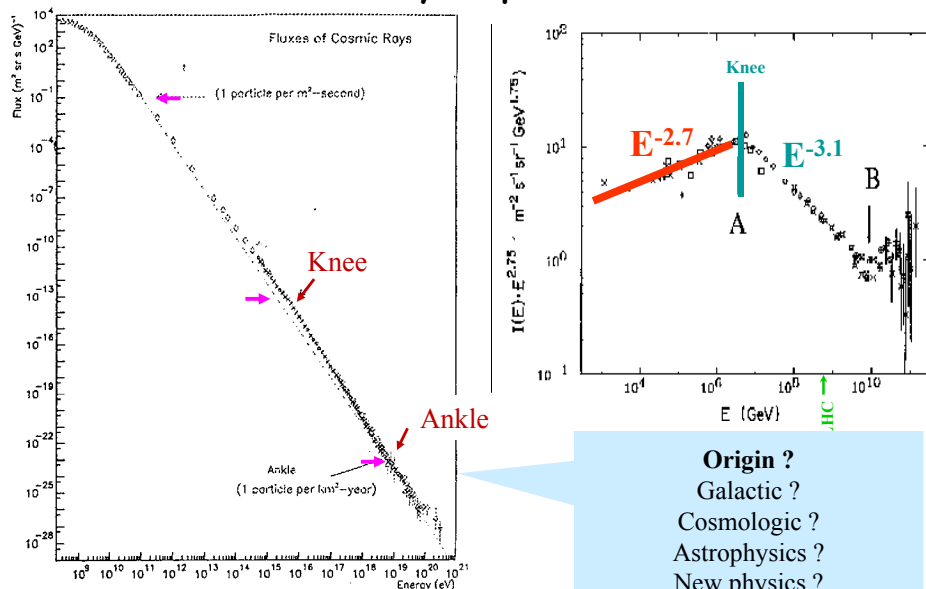
- Temperatures, stars masses, galaxies, magnetic fields, chemical composition, age of stars and structures...
- Nuclear reactions, galactic and extragalactic hydrodynamics, MHD, explosions, nucleosynthesis, past, future... EVERYTHING !
- Well, almost everything...
  - Non-luminous messengers : CR !
  - Rare but precious :  $\sim 4 \text{ CR/cm}^2/\text{s}$   
 $\sim 30 \mu\text{g/s}$  on entire earth ( 1kg per year !)
- CR astronomy is impossible...
  - Directions randomized by magnetic fields
  - What we would know if it was the same for photons !
- ...but not astrophysics !
  - Energy spectra and chemical composition tells us a lot...

# The "all particles" spectrum



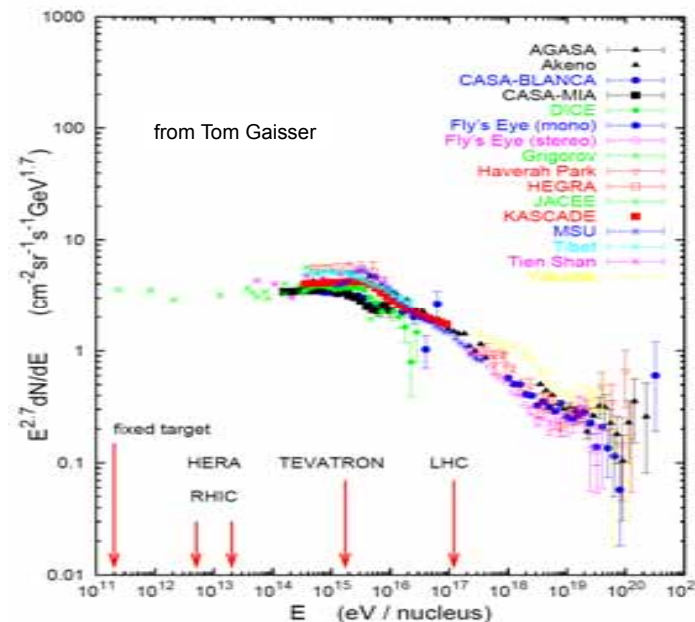
- Regular spectrum over 12 decades in energy, and 32 decades in flux !!!
- Small break near  $3 \times 10^{15} \text{ eV}$  : the "knee"
- An other one near  $10^{18} \text{ eV}$  : the "ankle"
- Spectrum badly known at the two extremities
  - Geomagnetic "shield" + Solar modulation
  - Extreme rareness...

# Cosmic-rays spectrum



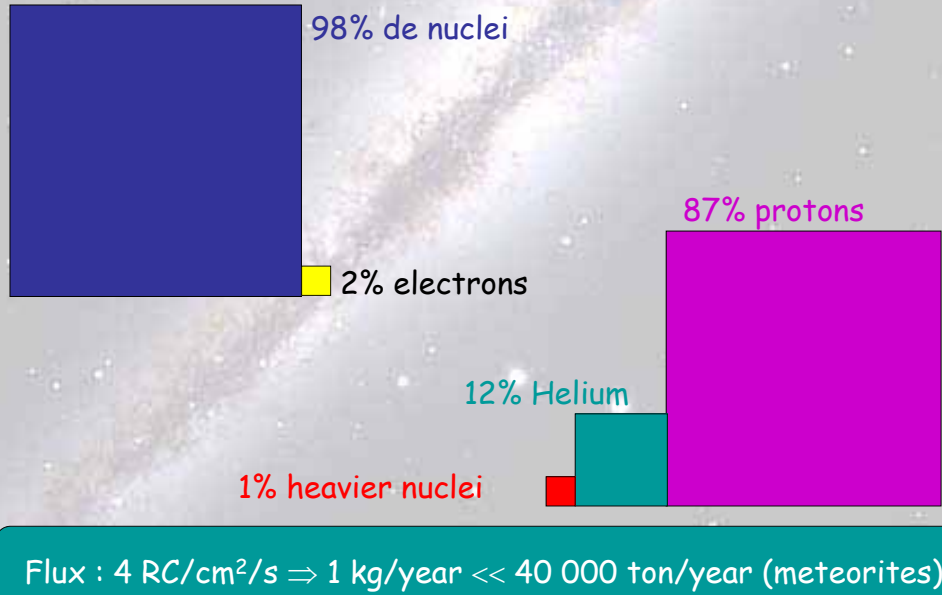
Origin ?  
Galactic ?  
Cosmologic ?  
Astrophysics ?  
New physics ?

# CR Spectrum above a TeV



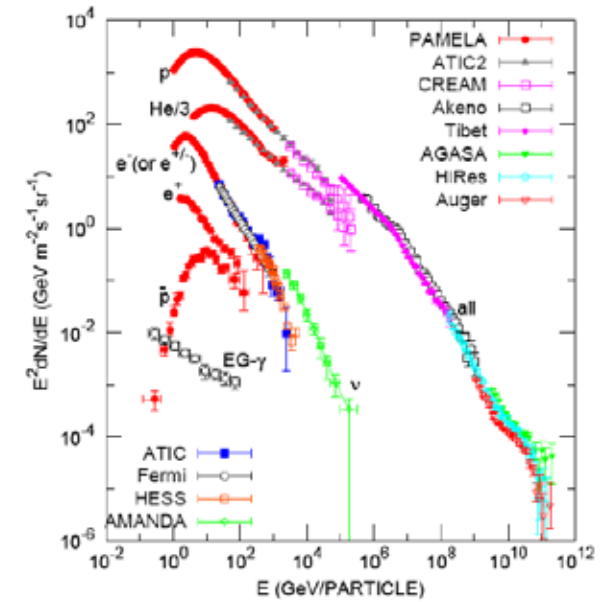


# Charge cosmic rays composition



2015  
F.Montanet - Astroparticule physics ESPAP

# Identified spectra

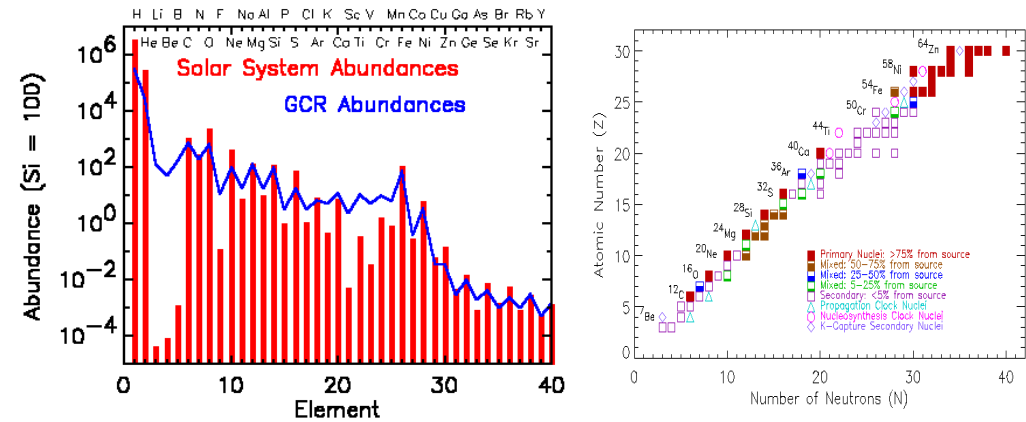


# Overview of CR data on composition

- **Chemical composition**
  - Nuclei = 98% (H = 87%, He = 12%, "metals" = 1%)
  - Electrons = 2%
  - More or less standard composition (i.e. solar system) except for fewer H and He, presence of secondary nuclei, and a few "anomalies"...
- **Secondary atoms**
  - Li, Be, B : spallation of C, N, O (+ nuclei below the Fe peak)
  - Nuclear thicknesses traversed by CR :  $X_{CR} = 6$  to  $10$  g/cm<sup>2</sup>
- **Isotopic anomalies**
  - $^{22}Ne \rightarrow$  link with massive stars
- **Cosmic clocks**
  - $^{10}Be \rightarrow ^{10}B$ ,  $\tau \approx 4 \times 10^6$  years (as well as  $^{26}Al$ ,  $^{36}Cl$ ,  $^{53}Mn$ ,  $^{54}Mn$ ,  $^{59}Ni$ )
  - $\tau_{RC} \approx 2 \times 10^7$  years
  - $\frac{X_{RC}}{c\tau_{RC}} \approx 0.2$ part/cm<sup>3</sup> ⇒ CR halo extention (≈ 3-7 kpc)

2015  
F.Montanet - Astroparticule physics ESPAP

# Nature of cosmic rays



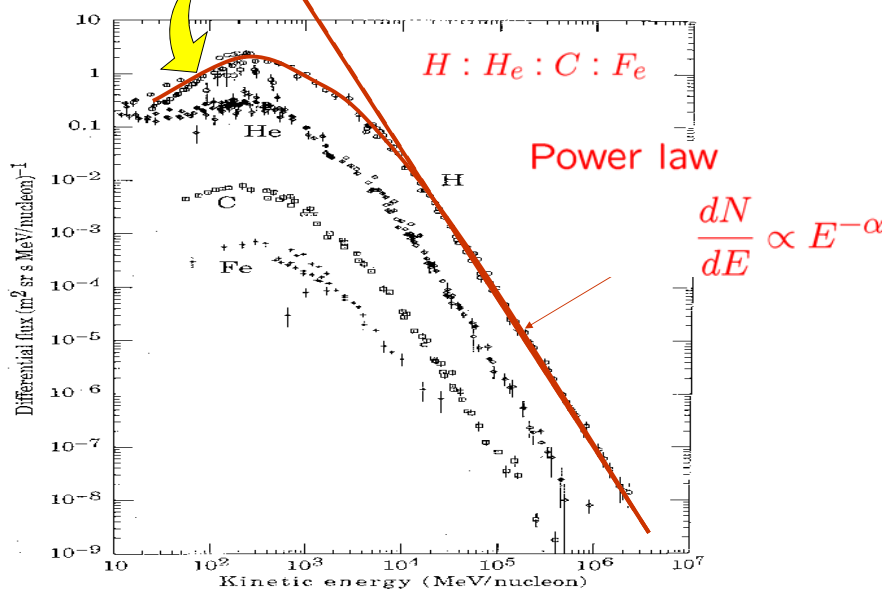
2015  
F.Montanet - Astroparticule physics ESPAP

Abundances different in CR and local measurements (Li Be B and Sub-Fe)

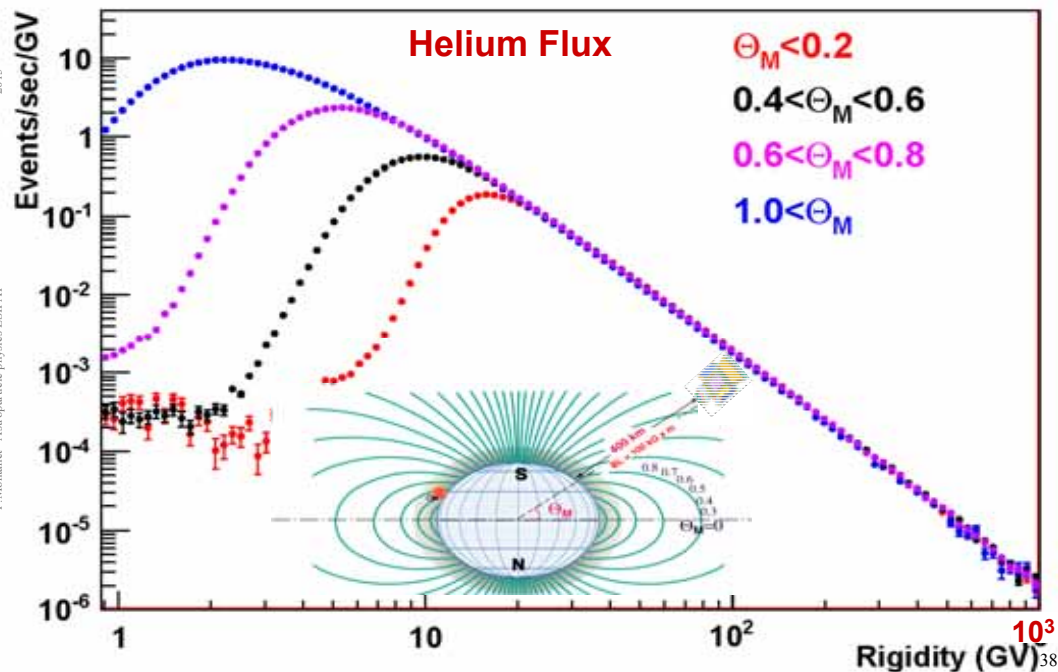
CR undergo spallations and produce secondary CR

# Nature of primary cosmic rays

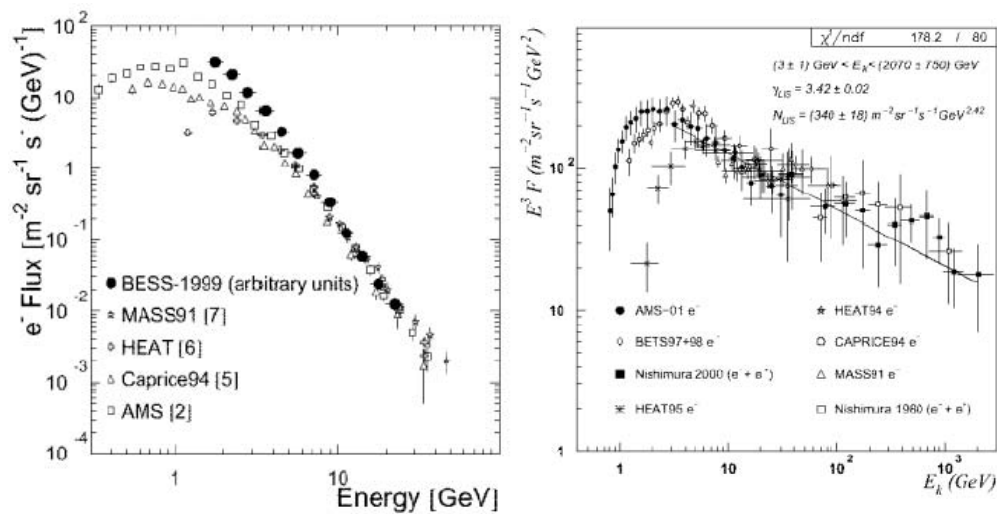
Solar modulation



# Data from AMS on ISS

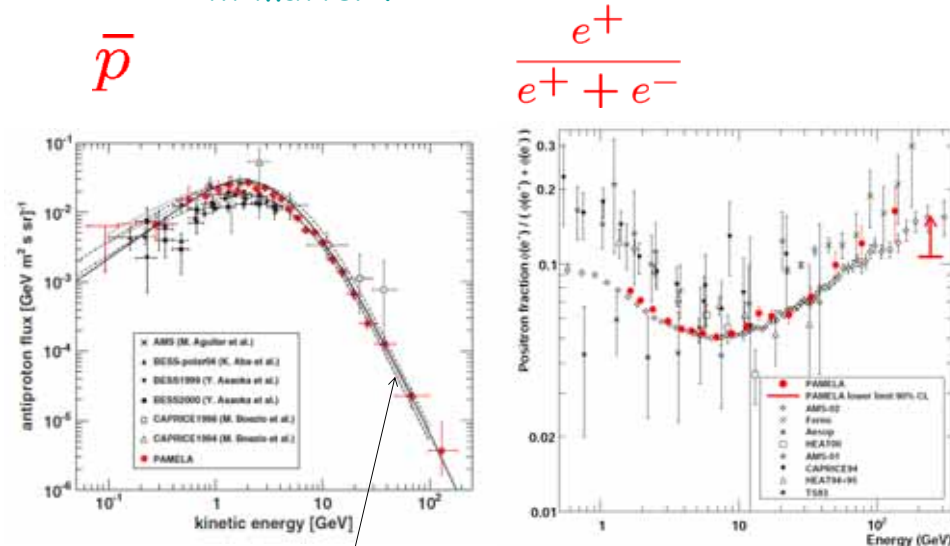


# Electron primary flux



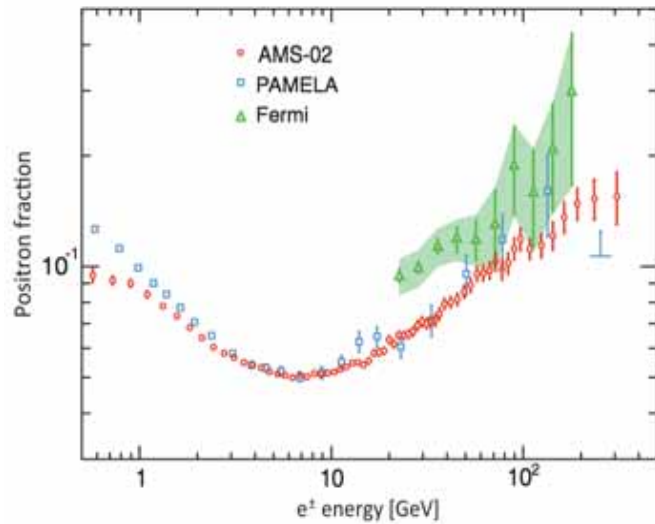
# Nature of primary cosmic rays

Antimatter ?

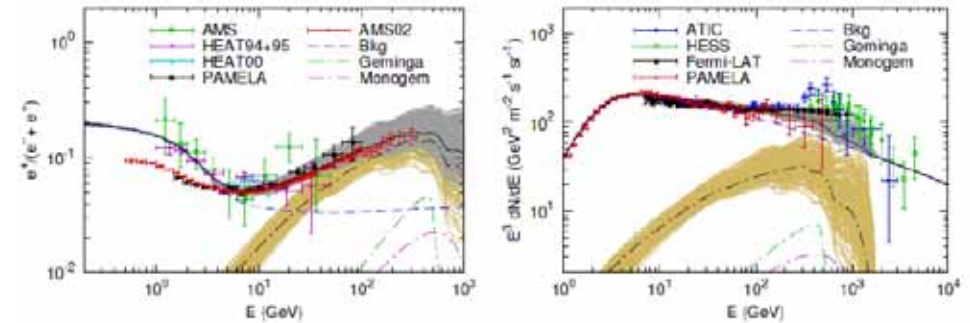


Pure secondary (standard) propagation

# Positron fraction in primary flux



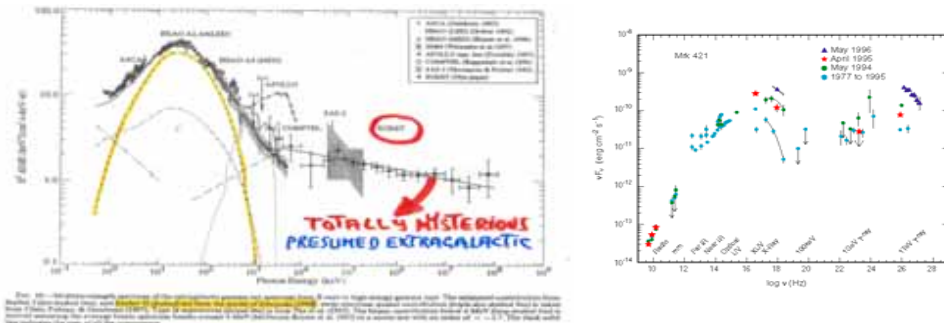
# Antimatter search (Dark Matter ?)



... or rather a boring "local" pulsar spoiling physicists dreams !

# Gamma rays

- Gamma-rays observed  $\rightarrow$  TeV
- Spectrum  $\pm$  understood un to MeV.
- Above, the diffuse spectrum and that of sources are very "hard", in  $1/E^2$  and of still unclear origin...



Why all this non thermal equilibrium radiation?

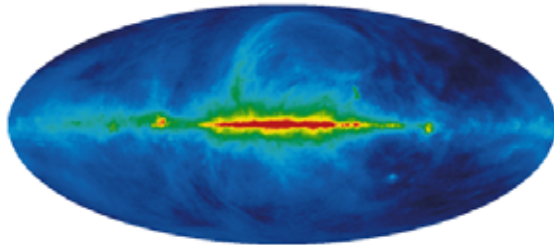
# Gamma, diffuse emission

Emission due to:

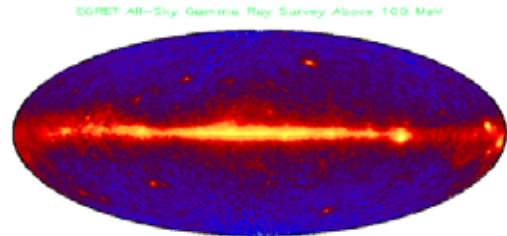
- the interactions of cosmic electrons with:
  - the magnetic fields (synchrotron radiation dominates the radio emission of the Galaxy up to a few GHz)
  - interstellar Matter (ISM); bremsstrahlung important below 100 MeV
  - Interstellar photon: Inverse Compton above GeV
- the decay of  $\pi^0$  produced when CR interact with protons and nuclei
  - $\pi^0 \rightarrow \gamma\gamma$  above 100 MeV
  - Concomitant emission of  $\nu$  in the decay of  $\pi^\pm$

## Gamma, diffuse emission

408 MHz



100 MeV



## Galactic or Extragalactic CR ?

Definite answer from EGRET in 1993 !

Hypothesis: if CR are extra or metagalactic, the density of CR is identical in our Galaxy and in its satellites

- Radio observations give the mass of gas  $M_H$  in the SMC
- $M_H$  implies a measurable flux for SMC of:  $2.5 \times 10^{-7} \text{ cm}^{-2} \cdot \text{s}^{-1}$   
 $F_\gamma \propto M_H N_{CR} R_q$
- EGRET gives an upper limit (at 95%CL):  $< 0.5 \times 10^{-7} \text{ cm}^{-2} \cdot \text{s}^{-1}$
- The CR density is 5 times smaller within SMC

Cosmic rays are indeed Galactic !

## The general problematic

- Thermal speeds  $\rightarrow$  RCUHE (few  $10^{20}$  eV)

Produce them

- From top to bottom (decay...)
- From bottom to top (acceleration)

Preserve them

- Energy losses (Synch., IC,  $\pi$ , pairs...)
- Destruction (photo-dissociation...)
- Escape probabilities

Propagate them

- Propagation in ISM and IGM (mag fields: deflection, confinement...)
- Re-acceleration

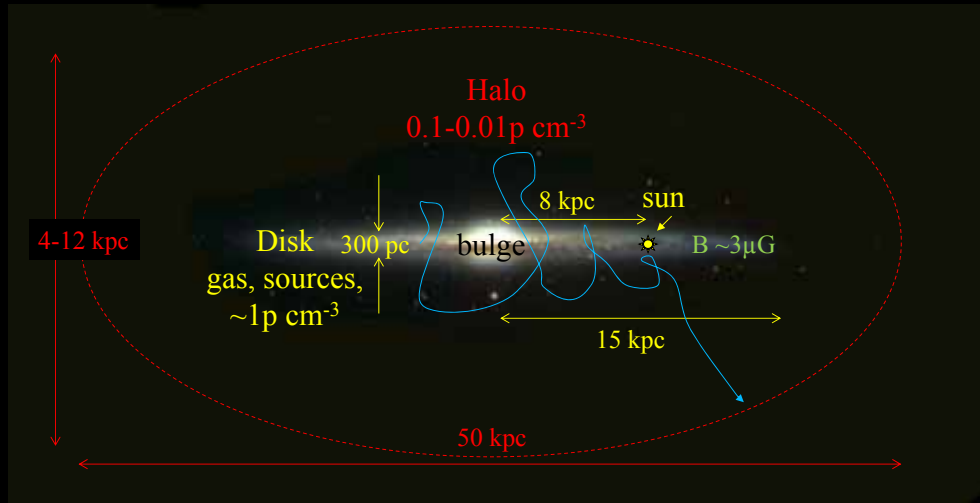
Detect them

- Balloons, satellites...
- Air showers...
  - Cherenkov telescopes
  - Surface & Fluorescence Detectors

Propagation medium,  
IGM, ISM and  
atmosphere

# Dimensions of the Milky Way

$1 \text{ pc} \approx 3 \text{ l.y.} \approx 3 \times 10^{16} \text{ m}$



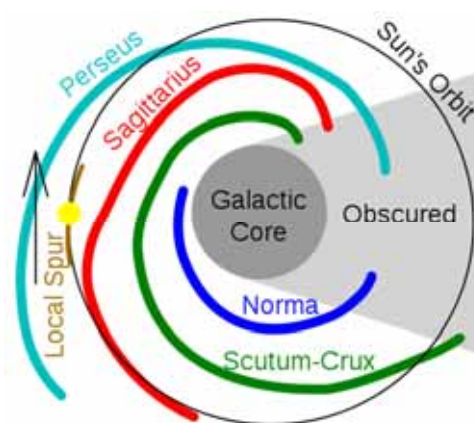
# Milky Way, a spiral galaxy



# Milky Way, a spiral galaxy

Local spur and neighboring arms  $\Rightarrow$  local matter and B field inhomogeneity.

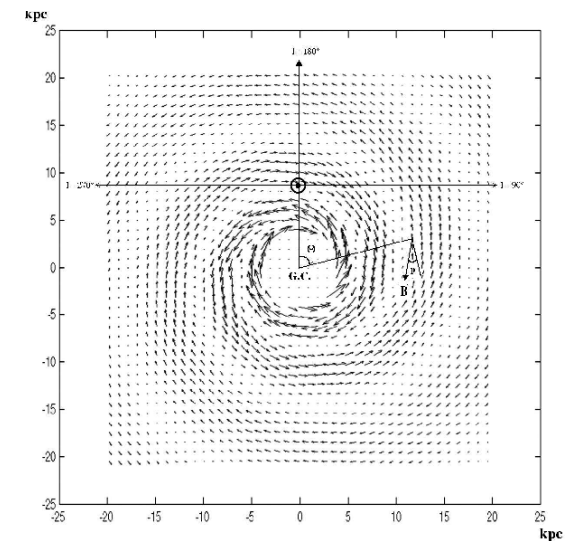
Mean "regular" B field  $\sim 3 \mu\text{G}$  roughly parallel to spiral arms, more intense in between arms.



# Milky Way, a spiral galaxy

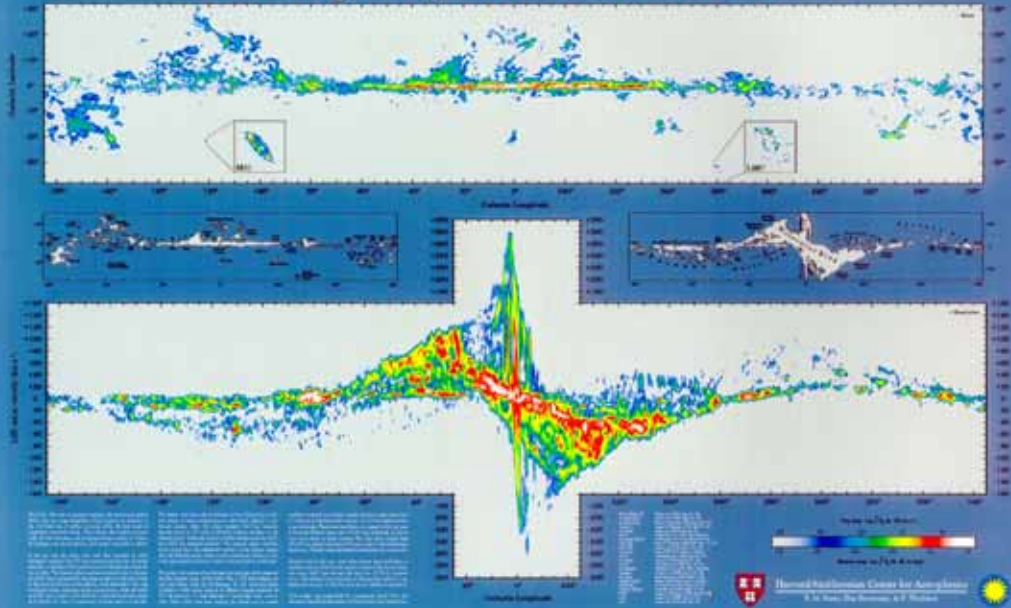
Local spur and neighboring arms  $\Rightarrow$  local matter and B field inhomogeneity.

Mean "regular" B field  $\sim 3 \mu\text{G}$  roughly parallel to spiral arms, more intense in between arms.



## A thick target...

### The Milky Way in Molecular Clouds

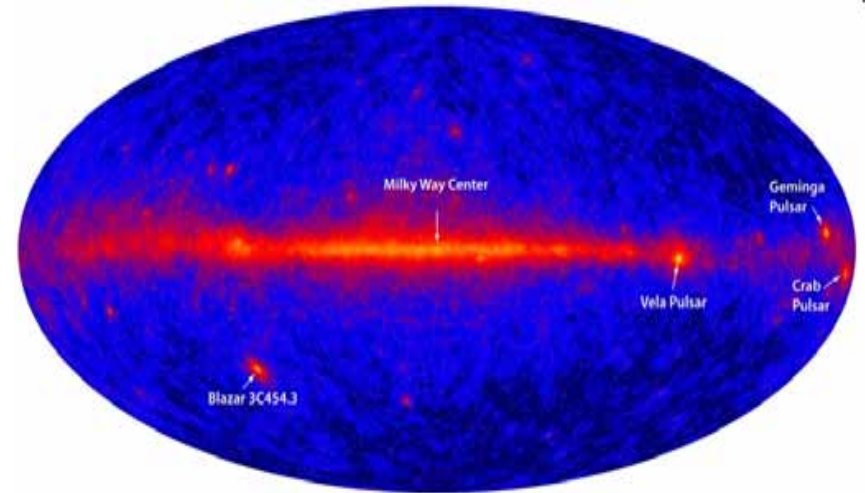


2015

F. Montanet - Astroparticle physics ESPAP

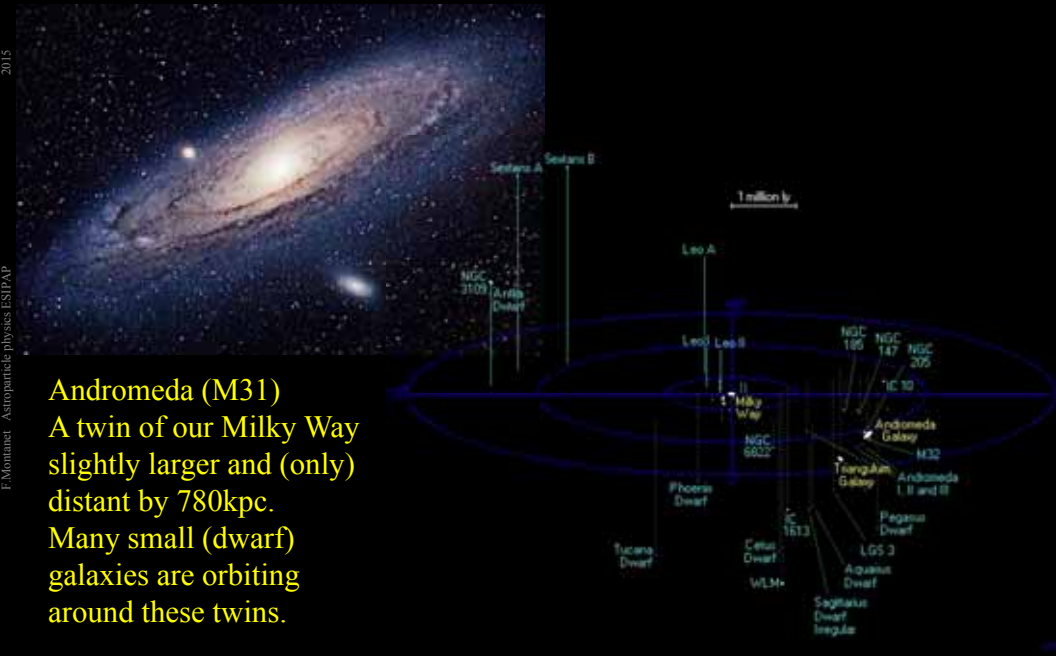
## A thick target

- Diffuse gamma-ray emission from galactic CR interaction with matter (mostly molecular H clouds).



54

## The nearby islands...



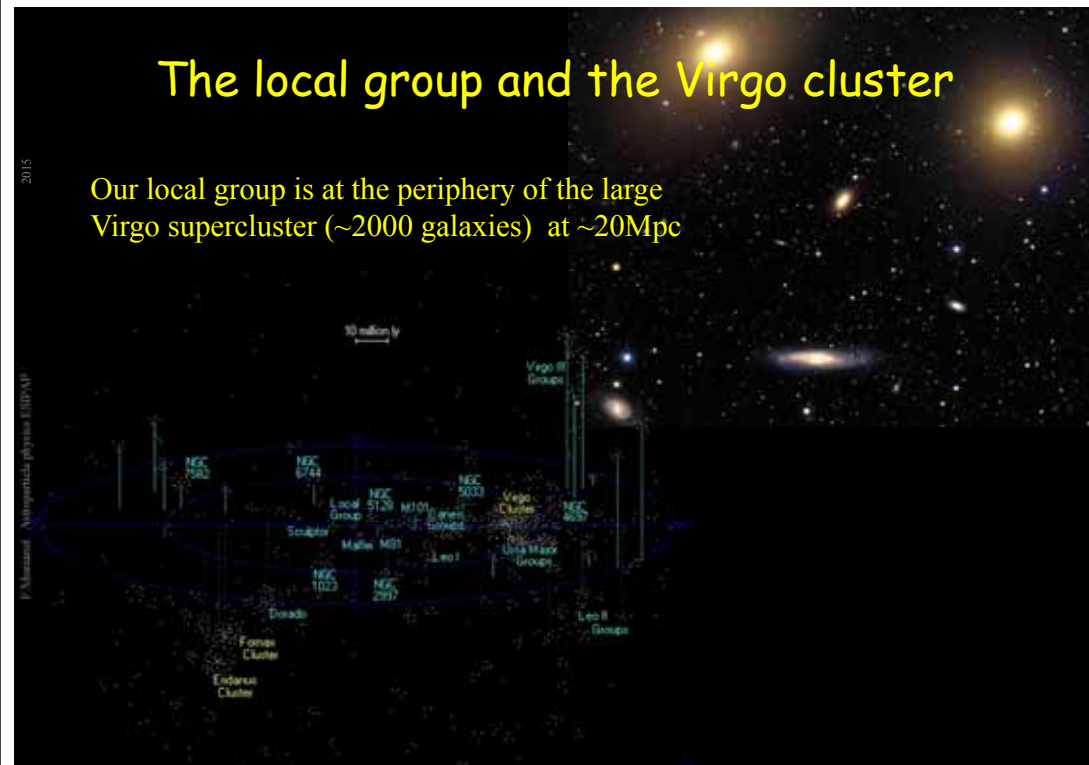
Andromeda (M31)  
A twin of our Milky Way slightly larger and (only) distant by 780kpc.  
Many small (dwarf) galaxies are orbiting around these twins.

2015

F. Montanet - Astroparticle physics ESPAP

## The local group and the Virgo cluster

Our local group is at the periphery of the large Virgo supercluster (~2000 galaxies) at ~20Mpc



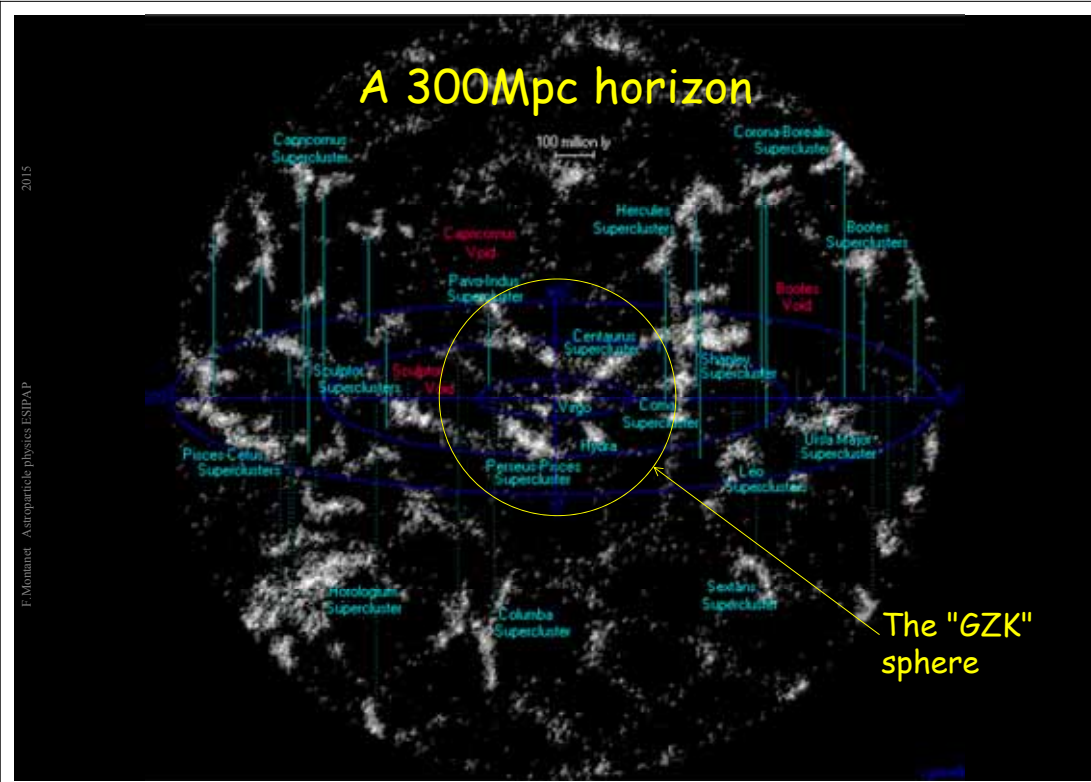
2015

F. Montanet - Astroparticle physics ESPAP

## Another super cluster: Abel 1689

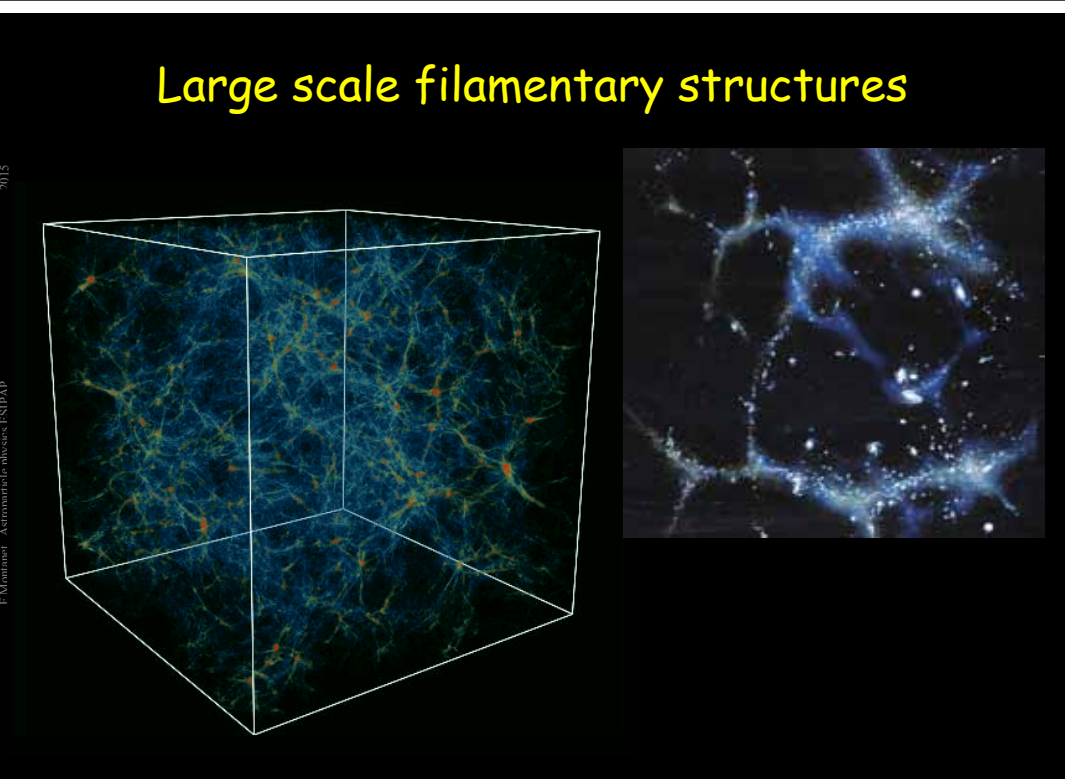


## A 300Mpc horizon



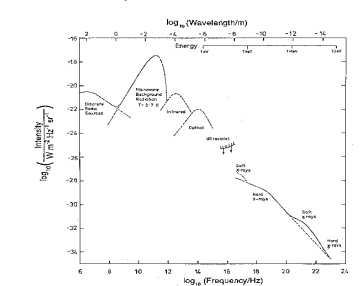
The "GZK" sphere

## Large scale filamentary structures



## Vacuum is not emptiness !

- Inter Galactic Medium contains:
  - Magnetic fields (regular + random) are highly speculative and range from  $2 \cdot 10^{-6}$  nT (20pG) to  $10^{-4}$  nT (1nG).
  - Very little matter (p, He, and a few electrons):  $\leq 1$  proton /  $m^3$
  - Electromagnetic radiations:
    - 413 CMB photons per  $cm^3$
    - Also IR, radio photons...
  - Neutrinos:
    - Mostly  $C\nu B$  neutrinos (decoupled when universe was only 2" old!)
    - Today 1.95°K i.e.  $1.7 \cdot 10^{-3}$  eV
    - 336  $\nu$  (all species) per  $cm^3$
- + Many mysterious dark matter WIMPs ...

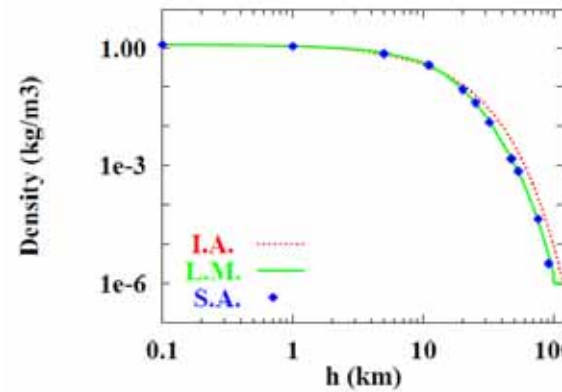


# The earth atmosphere

- An evident characteristic of the atmospheric medium is that of being inhomogeneous.
  - Its density, diminishes six orders of magnitude when the altitude above sea level passes from zero to 100km, and another additional six orders for the range 100km to 300km.
  - Although up to ~100km, the composition is nearly constant: 78.47% N, 21.05% O, 0.47% Ar and 0.03% other elements.
  - It follows a quasi exponential profile ("quasi" because T is not quite constant!)

$$\rho(h) = \rho_0 e^{-gMh/RT}$$

# The earth atmosphere

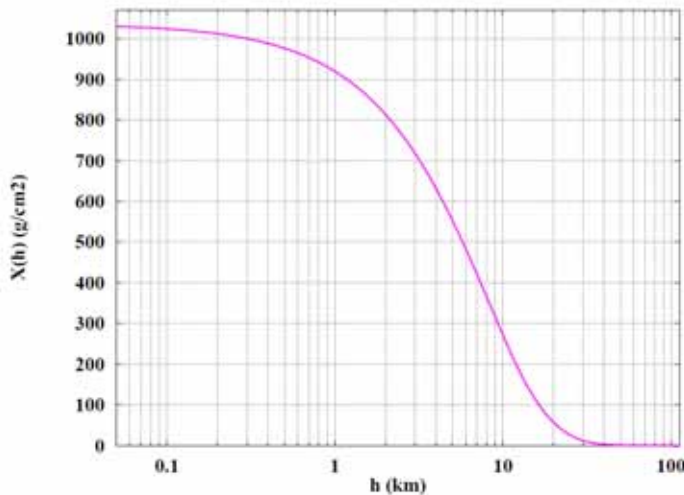


**Figure 2.3.** Density of the air as a function of the vertical altitude. The dots represent the US standard atmosphere data [14], while the full green line corresponds to Linsley's model [16] and the dashed red one to the isothermal atmosphere  $\rho(h) = \rho_0 e^{-gMh/RT}$  with  $\rho_0 = 1.225 \text{ kg/m}^3$ ,  $M = 28.966$  and  $T = 288 \text{ K}$ .

$$\rho(h) = \rho_0 e^{-gMh/RT}$$

Scale height  $gM/RT \approx 9 \text{ km}$

# The earth atmosphere



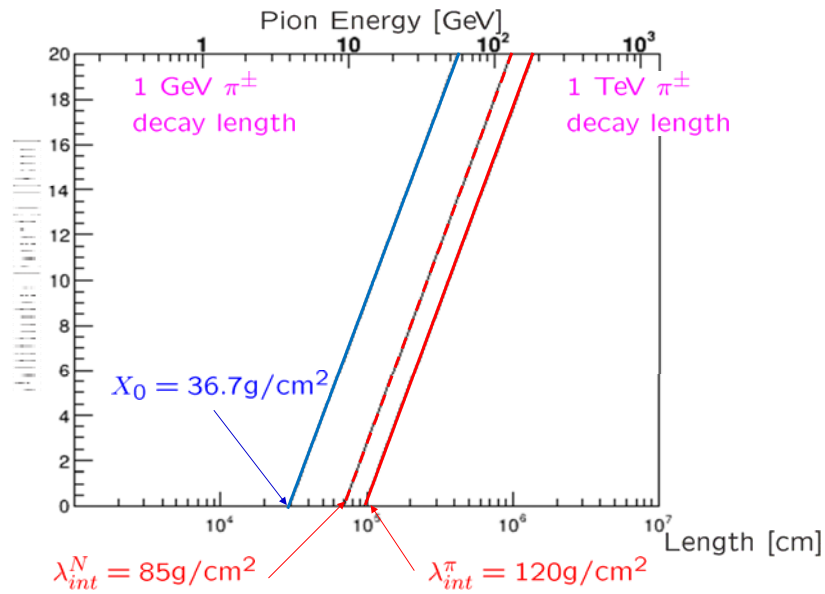
**Figure 2.4.** Vertical atmospheric depth,  $X_v$ , versus vertical altitude over sea level,  $h$ , accordingly with Linsley's model [16].

# The earth atmosphere

- In terms of particle/radiation interaction with matter, the atmosphere is:
  - A total of  $\approx 1000 \text{ g/cm}^2$  at sea level
  - So 1 atm  $\sim 12$  interaction lengths ( $\lambda_N \approx 85 \text{ g/cm}^2$ )
  - A vertical proton first interacts at  $h \sim 15 \text{ km}$
  - One radiation length (at 1 atm)  $X_0 = 36.6 \text{ g/cm}^2 \approx 300 \text{ m}$
  - One Moliere radius (at 1 atm) is  $\rho_M \approx 78 \text{ m}$
  - The Lorentz factor for a muon produced at  $h = 10 \text{ km}$  to reach ground before decaying is  $\Gamma > 15$  ( $> 1.6 \text{ GeV}$ )
  - Critical energy (EM)  $E_c = 84,2 \text{ MeV}$



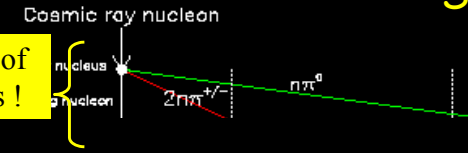
# Interaction and radiation lengths in atmosphere



65

# Shower development

Physics well out of reach of colliders !



At each step energy is shared by more numerous particles

$\lambda_{interaction} < \beta \gamma c \tau_{decay}$

"Hadronique" shower

"Electro-Magnétique" shower

$\lambda_{radiation} < \lambda_{ionisation}$

Maximum of développement

Critical Energy  $E_c$

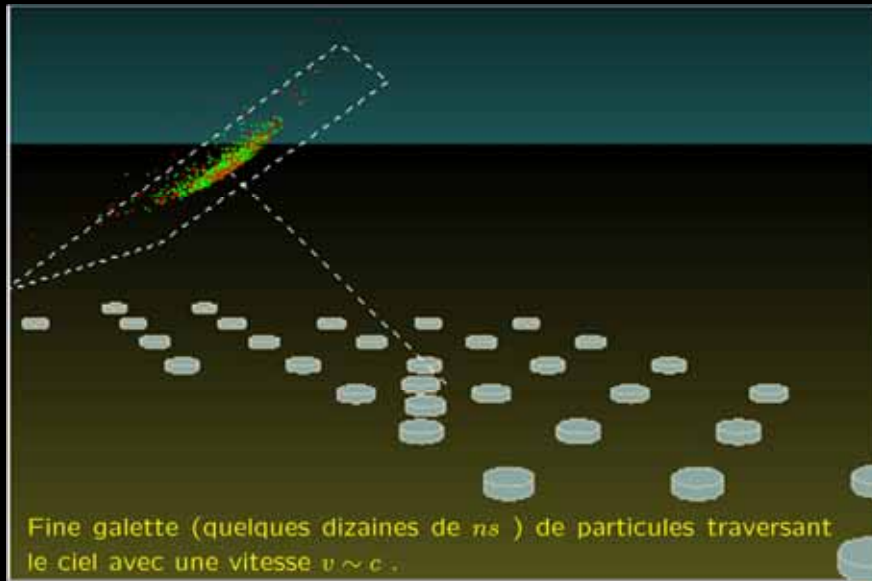
No more multiplication, decrease by decay and energy loss

$\lambda_{interaction} > \beta \gamma c \tau_{decay}$

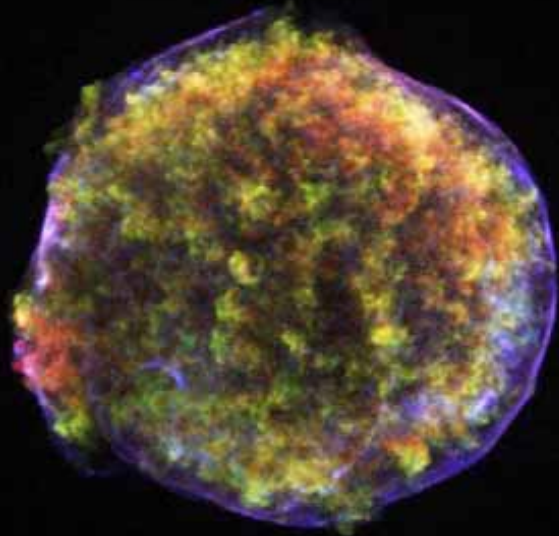
$\lambda_{radiation} > \lambda_{ionisation}$

At ground, essentially  $\mu^\pm \gamma e^\pm$

# Time structure



# Astrophysical Sources Cosmic Accelerators

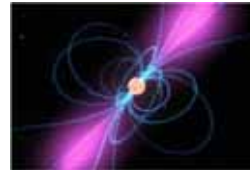
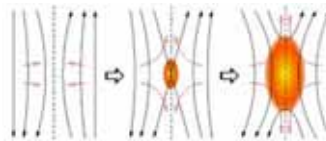


## General ideas on acceleration

- Take the necessary energy somewhere...
  - Kinetic energy:
    - Translation: shock waves, moving clouds...  
→ Fermi acceleration
    - Rotation : pulsars, black holes, neutron stars
  - Gravitational energy
    - via accretion (→ jets...): accretion disks (divers)
  - Electromagnetic (EM)
    - From turbulence, from compression, or from rotating magnets...
- In fine, charged particles interact with EM fields:  $f = q(E + v \times B)$
- Remember:  
Astrophysical shocks are collisionless.  
→ Energy transfert through EM fields !

## E and B fields in Universe

- \* In ISM as on earth,  $\langle E \rangle \approx 0$ 
  - ISM is neutral or conducting
- \* Transient electric fields:
  - Magnetic re-connections (e.g. solar flares...)
  - EM waves
- \* Producing  $E$  fields in EM "engines"
  - Astrophysical dynamos, induction machines
- \* Magnetic fields :
  - $\varepsilon_B \approx 1\text{eV}/\text{cm}^3 \approx \varepsilon_{\text{optique}} \approx \varepsilon_{\text{CMB}} \approx \varepsilon_{\text{CR}} !!!$
  - Astrophysical plasmas :  
ISM, stars, accretion disks, IGM, jets, etc...



## Magnetic field production

- Large scale movements of ionized media  
→ generating magnetic fields, magnetized clouds...
- Turbulence in interstellar medium  
→ Magnetic turbulence, inhomogeneous B fields, plasma waves...
- Hydro and MHD instabilities
  - e.g. Rayleigh-Taylor in supernova remnants
- "Streaming" instabilities
  - CR generates waves in a magneto-actif plasma  
→ creating the conditions for their own diffusion

# Magnetic field production

In many cases, equipartition can be reached

- for ex: behind a shock wave :  
thermal en.  $\sim$  kinetic en.  $\sim$  magnetic en.

⇒ Energy exchange between macroscopic structures and individual particles

⇒ individual particles may reach very high energies!

# Magnetic fields and acceleration !

• How is it possible at all?

magnetic fields don't work ! ( $\vec{F} \perp \vec{B}$ )

• Well, variable  $\vec{B}(t)$  fields do ! (example: *Betatron*)

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

• In a different reference frame, a pur  $\vec{B}$  field is feeled as a  $\vec{E}$  field...

$$\vec{E}' = \vec{v} \times \vec{B} \text{ (for } v \ll c\text{)}$$

• In principle, one can always identified an effective  $\vec{E}$  field that works, but the description in terms of  $\vec{B}$  fields is often simpler (and more physical !)

→ Acceleration by "change of reference frame"

# Principle of Fermi acceleration

## The Ingredients :

- **A magnetic field  $\vec{B}$**   
= with a regular component  $\vec{B}_0$   
+ and irregular component  $\delta\vec{B}$
- **A plasma** i.e. a good electrical conductor :  
 $\vec{E} + \vec{u} \times \vec{B} = 0$  and  $|E| \approx 0$   
⇒ the magnetic field is "frozen" and moves with the plasma (Alfven).
- **A CR population** coupled to the medium via the magnetic field  $\vec{B}$ . They scatter on the field irregularities. This diffusion processes are **collisionless** i.e. they conserve the particle energy. The MHD or Alfven waves act as massive scattering centers (recoilless).



## Fermi 1949 :

- first hypothesis of converging movements of MHD perturbations  
⇒ "first order" acceleration, but where ?
- second more realistic hypothesis at that time: random mouvement of interstellar gas clouds (observed) or MHD perturbations  
⇒ "second order acceleration.

# Where to accelerate

• **At creation :**

- For example:  $e^-$  extracted from the surface of a neutron star by an intense E field.

• **Within the source neighborhood :**

- For example: Fermi acceleration in plasma shocks in a SNR.

• **During transport:**

- "reacceleration" by shock waves and excitation of Alfven waves during diffusive transport in the Galaxy.

# Power laws and stochastic processes

The power laws observed in differential energy spectra follow naturally from cyclic acceleration mechanisms with constant energy gain and constant escape probabilities:

- Initial energy:  $E_0$
- Energy gain at each cycle:  $\Delta E = \varepsilon E$
- Particle energy after  $n$  iterations:  $E_n = E_0(1 + \varepsilon)^n$
- Escape probability from the acceleration zone:  $P_{esc}$
- Probability to remain in the acceleration zone:  $(1 - P_{esc})^n$

# Power laws and stochastic processes

- Particle energy after  $n$  iterations:  $E_n = E_0(1 + \varepsilon)^n$
- Probability to remain in the acceleration zone:  $(1 - P_{esc})^n$

Number of iterations to reach an energy  $E$ :

$$n = \frac{\ln(E/E_0)}{\ln(1 + \varepsilon)}$$

Proportion of particles accelerated up to an energy equal or greater than  $E$  :

$$N(\geq E) = N_0 \sum_{m=n}^{\infty} (1 - P_{esc})^m = N_0 \frac{(1 - P_{esc})^n}{P_{esc}}$$

thus : 
$$\frac{\ln(P_{esc}N/N_0)}{\ln(1 - P_{esc})} = n = \frac{\ln(E/E_0)}{\ln(1 + \varepsilon)}$$

eliminating  $n$ :

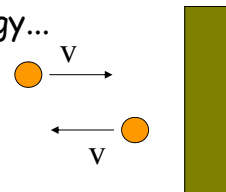
$$N(\geq E) \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

with  $\gamma = \frac{-\ln(1 - P_{esc})}{\ln(1 + \varepsilon)} \approx \frac{P_{esc}}{\varepsilon} = \frac{1 T_{cycle}}{\varepsilon T_{esc}}$

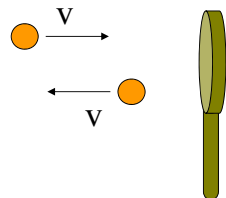
➔ Power laws are natural !

## A small analogy...

- A tennis ball bouncing on a wall  
- neither gain nor loss of energy...



bounce = speed unchanged

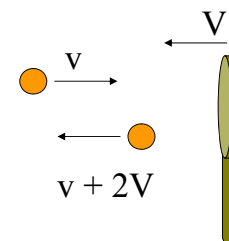


Same thing with a motionless racquet...

Then how does one accelerate a tennis ball ?!

- Moving racquet

- Neither gain nor loss of energy... in the racquet reference frame !

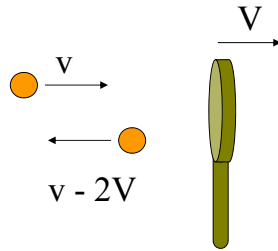


Speed unchanged with respect to the racquet



➔ acceleration through a change of reference frame

- A drop shot:

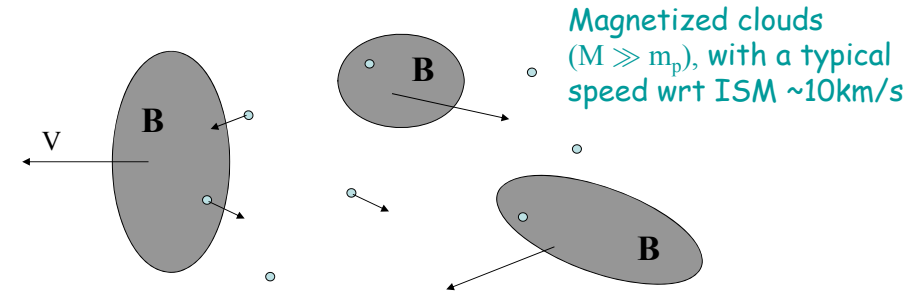


Particle deceleration !

81

## Fermi Acceleration

- Ball → charged particle
- Racquet → "magnetic mirrors"



- Magnetic inhomogeneities or plasma waves also work...

82

## The essence of stochastic de Fermi acceleration

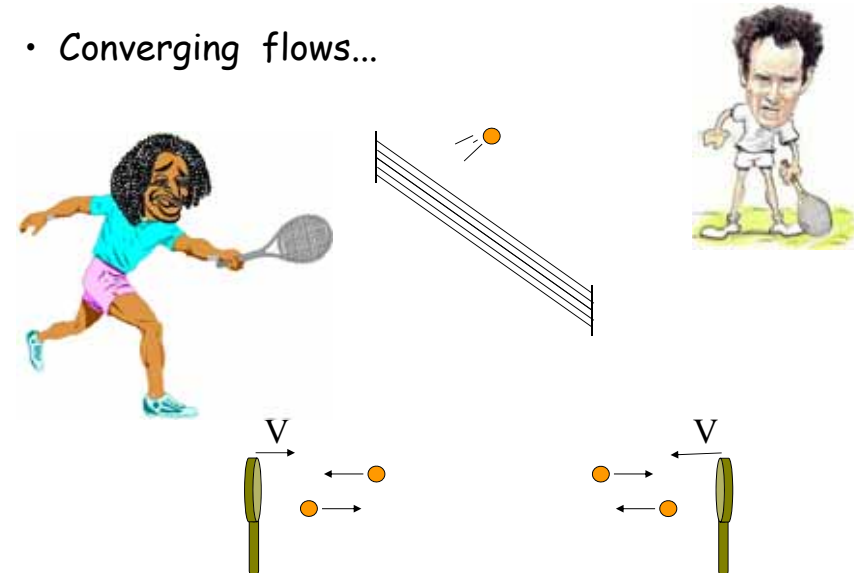
- 1 When a particle bounces on an incoming magnetic mirror, in a head-on collision, it gains energy.
- 2 When a particle bounces on a receding magnetic mirror that it catches back, it loses energy.
- 3 Head-on collisions are more frequent than receding collisions.

⇒ Net energy gain in average (stochastic process )

83

## Add a second player...

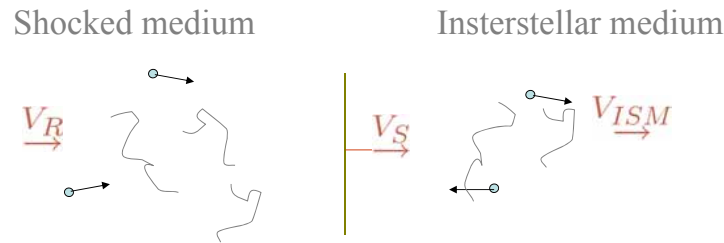
- Converging flows...



84

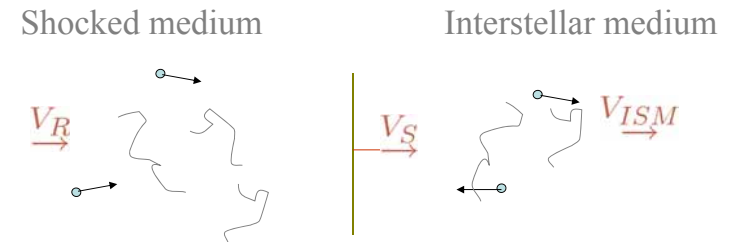
# Shocks hydrodynamics

- Shock waves (e.g. supernova explosion) : expending plasma flow with a speed  $V_R$  much larger than the sound speed in the interstellar medium (ISM).



# Shocks hydrodynamics

- Shock wave:

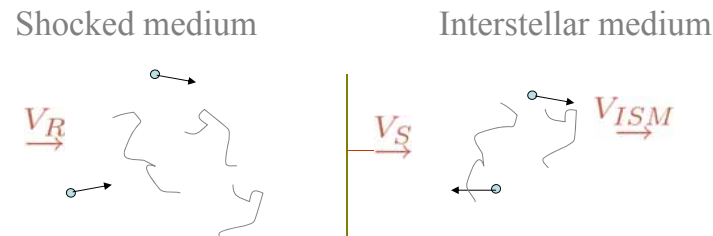


- The shock moves at a speed  $V_S$  which depends on  $V_R$  and the specific heat of both media.

- For an ionized ISM:  $V_S \approx \frac{4}{3} V_R$

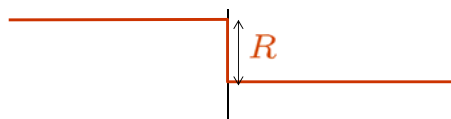
# Shocks hydrodynamics

- Onde de choc :



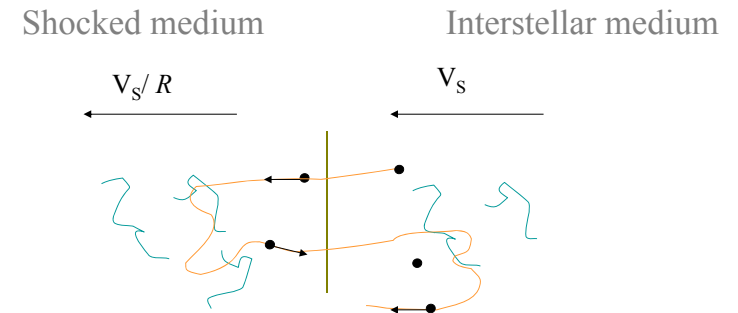
- The shock intensity is characterized by the compression factor:

$$R = \frac{V_S/V_R}{V_S/V_R - 1} \approx 4$$



# Shocks hydrodynamics

*In the shock frame*

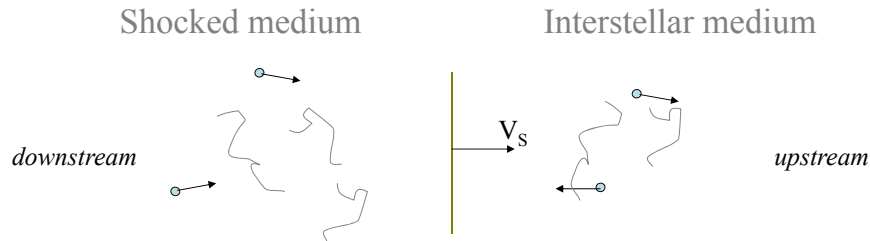


- In the shock frame, the upstream (non-shocked) medium flows toward the shock at a speed  $V_S$  and the downstream (shocked) medium flows away with a speed reduced by the compression factor (mass flow conservation) :

$$V_S/V_d = R \approx 4$$

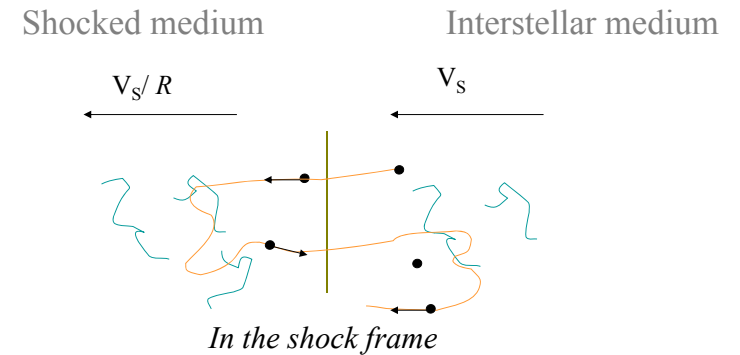
# Shock wave diffusive acceleration

- Shock wave (e.g. supernova explosion)



- Magnetic wave generation:**
  - Downstream : by the shock (compression, turbulence, hydro and MHD instabilities, shear, etc.)
  - Upstream : by the accelerated cosmic rays themselves !
- 'isotropization' of the distribution (in the local frame)

# A win-win process !



- At each shock crossing, one way or the other, the particle hits a "magnetic wall" with a relative speed:
 
$$V = (1 - 1/R)V_s$$
 → only head-on collisions...

# Summary on acceleration

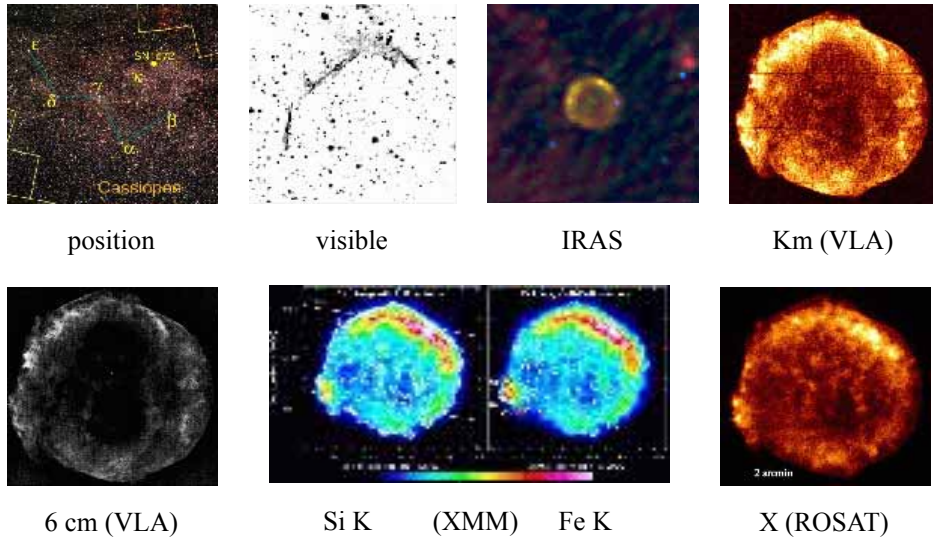
- Acceleration from interaction with fields**
  - E field:** e.g. induced by spinning magnets such as neutron stars (pulsars) or black holes...
  - B field:** inhomogeneous moving fields
  - MHD waves**
- Acceleration by reference frame transformation**
  - Fermi stochastic acceleration (2<sup>nd</sup> order)
  - Diffusive shock acceleration diffusive (1<sup>st</sup> order)
- Power law are natural**
  - Fermi type process ( $\Delta E \propto E, P_{ech}$ )
  - Universal power law for non relativistic shocks ( $N(E) \propto E^{-2}$ )
- Cosmic rays up to the knee**
  - CR power = power of SNe,  $E_{max} \approx 10^{14} \text{ eV}$  hardly  $10^{15} \text{ eV}$

# The CR standard model

- Analytic calculations, simulations and observations show that diffusive shock acceleration works !
- Supernovae and GCRs
  - Estimated efficiency of shock acceleration :... 10 – 50%
  - Power required to sustain CR energy density: .....  $\epsilon_{CR} \times V_{conf} / \tau_{conf} \sim 10^{41} \text{ erg/s} !$
  - Power injected by SN power in the Galaxy: .....  $10^{42} \text{ erg/s} !$

→ Enough power for Galactic CR

# Tycho, 11 November 1572...



# The CR standard model

- Proposed acceleration site, **isolated SNR**
  - Supernovæ : ejection of many solar masses of nuclear matter at supersonic speeds (~ 10 000 km/s) following massive star explosion.
  - Formation of a quasi spherical expanding shock wave that wipes out the interstellar medium (ionized beforehand by the progenitor's radiation).
  - Total kinetic energy injected by the explosion:  $10^{51}$  erg (=  $10^{44}$  J).
  - Roughly 3 SNe per century within our Galaxy, which corresponds to an averaged power of  $10^{42}$  erg/s ( $10^{35}$ W)
  - SNR are observed at all wavelengths.
  - SNe explosion is essential to the Galaxy chemical content: heavy elements enrichment.

# The CR standard model

- Shock waves in isolated SNe (SNR)
  - Source composition source ~ interstellar medium + modifications (ionizability, volatility, Z/A effects,  $^{22}\text{Ne}$ ...)
  - Source spectrum:  $E^{-2}$  power law
  - Maximal energy reached:  $E_{\text{max}} \sim 10^{14}$  eV
- Energetics :
  - Measured flux / speed = CR density
  - CR density  $\times$  mean energy = energy density
  - Energy density  $\times$  confinement volume = total energy
  - Total energy / confinement time = necessary injected power
  - $P_{\text{CR}} \sim 1.5 \times 10^{41}$  erg/s
- Required efficiency ~ 10-30%...

# Finite size

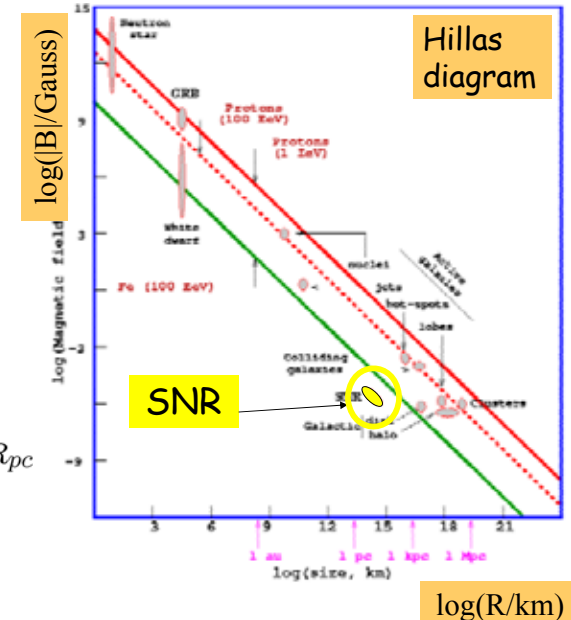
Finite size of confinement magnetic field  
 $\updownarrow$   
 Larmor radius

$$r_g \leq R$$

$$\Leftrightarrow \frac{p}{ZeB} \leq R$$

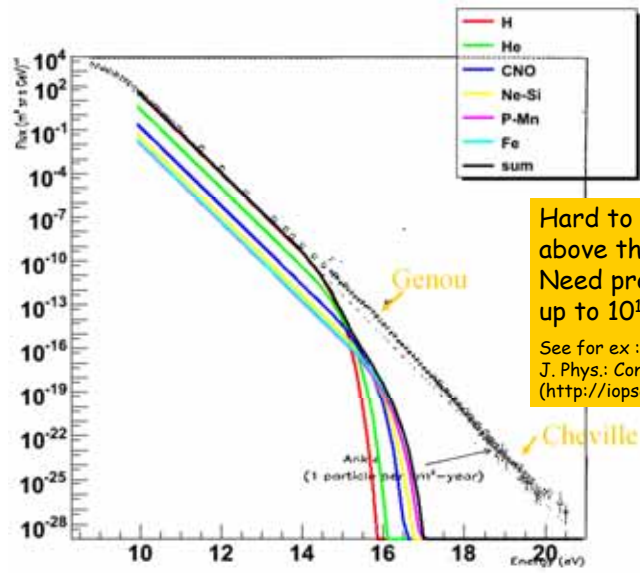
$$\Leftrightarrow E \leq Ze \times B \times R$$

$$\Leftrightarrow E \leq (10^{17} \text{ eV}) Z B_{\mu G} R_{pc}$$



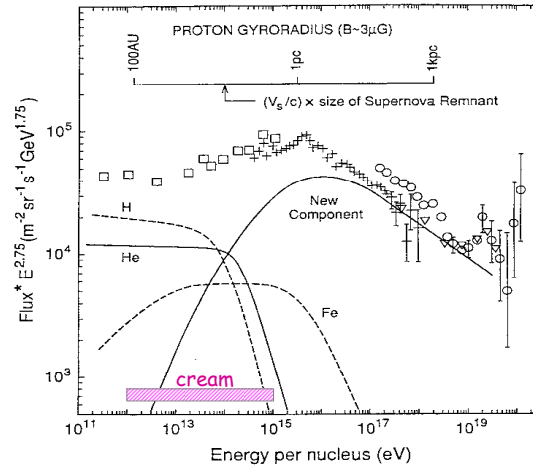


# CR SM with $E_{max} \propto Z$



Hard to explain a single power law above the knee.  
Need probably another component up to  $10^{17}$  eV  
See for ex : M. Hillas  
J. Phys.: Conf. Ser. 47 (2006 ) 168  
(<http://iopscience.iop.org/1742-6596/47/1/021>)

# The knee



- Is the knee simply the consequence of an energy cut-off of accelerators (SNR) or is it due to :
  - a propagation effect ?
  - different CR sources ?
  - a physics threshold at  $\sim E_{LHC}$  ?

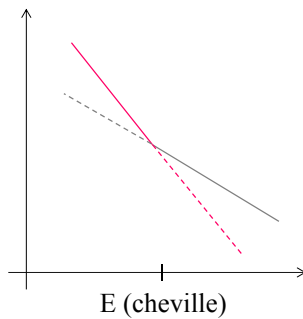
⇒ The CR SM implies a change in composition at the knee energy.

**SNR energy limit :  $E_{max} \sim Z \cdot 10^{15}$  eV**

- Data:
- Proton4 sat
  - Akeno
  - Yakutsk
  - Haverah Pk

# Explaining the ankle is much easier...

- Two components with two different slopes...



- For exemple, galactic and extragalactic...

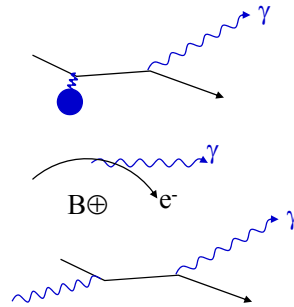
# DIFFUSE GAMMA-RAY SOURCE

# VHE gamma-rays sources

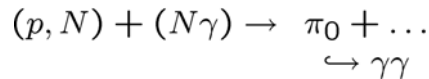
## γ-rays production processes:

- Electro-Magnetic processes :

- Bremsstrahlung
- Synchrotron radiation
- Inverse Compton



- Hadronics processes:



# Hadronic production of gamma-rays

Source function [TK Gaisser]

$$q_k(E_k, r) = \int \frac{d\sigma_{i \rightarrow k}(E_k, E_i)}{dE_k} \left( \frac{c\rho(r)}{m} \right) \left( \frac{4\pi}{c} \phi(E_i) \right) dE_i$$

Fluxes on earth (neutrals)

$$\phi_{k=\gamma} = \frac{dN_k}{dAdE_k d\Omega} = \int \frac{q_k(E_k, r)}{4\pi r^2} d^3r = \int_0^{r_{max}} \frac{q_k(E_k, r)}{4\pi} dr d\Omega$$

Scale invariance :  $E_\gamma/E_i = Z$  ( $Z$  indep. of  $E$ )  
(for  $E_k \gg m_i/2 = m_\pi/2 \approx 70MeV$ )  
(system mass scale).

$$\left. \begin{array}{l} \text{Scale invariance} \\ \text{(for } E_k \gg m_i/2 = m_\pi/2 \approx 70MeV) \\ \text{(system mass scale).} \end{array} \right\} \Rightarrow \phi_k \propto \phi_i$$

Parent spectral density power law  $\phi_i \propto E_i^{-\alpha}$   
[Gaisser, Helsen, Berezhinsky, Stanev]

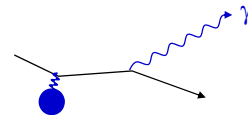
$$\phi_\gamma = 4\pi\rho \left[ \frac{\sigma_{inel}}{m_N} \right] \left[ \frac{2Z_{N \rightarrow \pi^0 \rightarrow \gamma}}{\alpha} \right] \phi_{CR}(E)$$

$$\frac{\phi_\gamma}{\phi_{CR}} \approx 6 \times 10^{-4} \times \left( \frac{\rho R}{[g.cm^{-2}]} \right) \rho R = \text{target column density}$$

# Bremsstrahlung

$$\frac{d\sigma_{e \rightarrow \gamma}(E_\gamma, E_e)}{dE_\gamma} = \frac{1}{E_e N_A X_0} \phi(z)$$

where  $\phi(z)$  is a function of  $z = E_\gamma/E_e$



For energies  $> 70MeV/c^2$ , there is a scaling relation between the  $\gamma$  energy and that of the parent electron. (the only mass scale in the problem is the electron mass, much lower than 70 MeV).

$\Rightarrow$  the differential spectrum of the progenitor electrons ( $\phi_e(E_e) \propto E_e^{-\alpha}$ ) is transmitted to the  $\gamma$  differential spectrum:

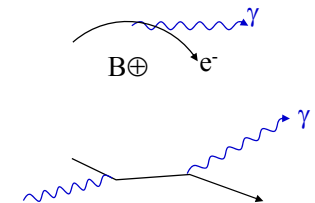
$$\phi_\gamma(E_\gamma) \propto E_\gamma^{-\alpha}$$

For  $dN/dE_e = a_e E_e^{-\alpha}$  and  $\alpha = 2.7$

$$q_{br} \approx 1.2 \times 10^{-25} a_e n E_\gamma^{-2.7} \text{ photons GeV}^{-1} \text{ s}^{-1} \text{ cm}^{-3}$$

# VHE Gamma sources

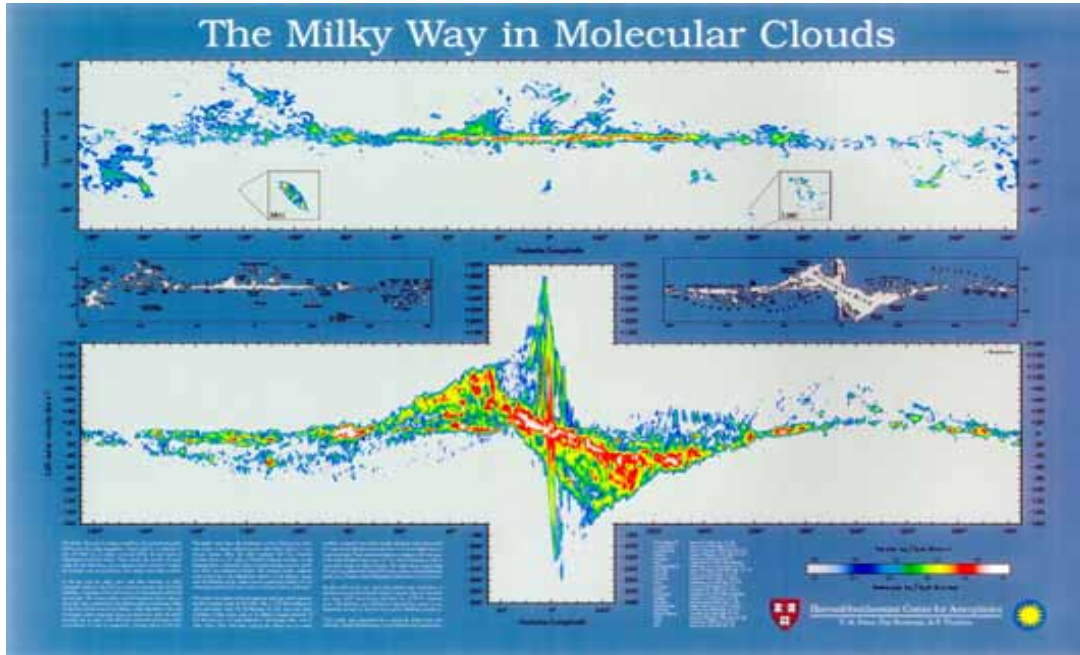
- Productions of  $\gamma > 10 \text{ MeV}$
- Synchrotron radiation negligible.
- Inverse Compton



For  $\phi_e \propto E^{-\alpha}$   
the IC spectrum is much flatter  
 $\propto E^{-(\alpha+1)/2}$

but  $N_e \ll N_p$  and the electron spectrum drops  $\searrow$  above a few GeV (synchrotron radiation energy losses)

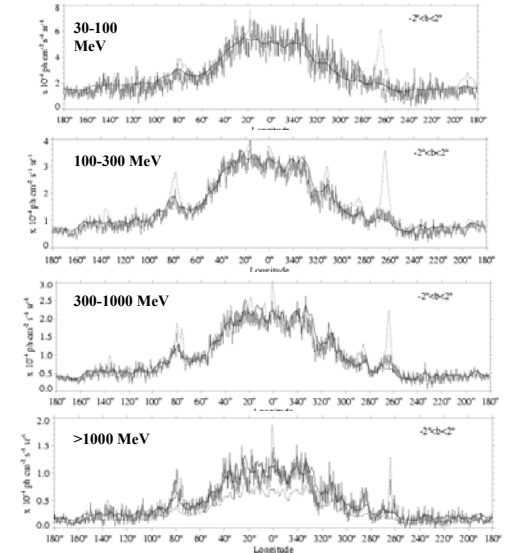
# The target...



# Tracking back the CR flux elsewhere in the Galaxy

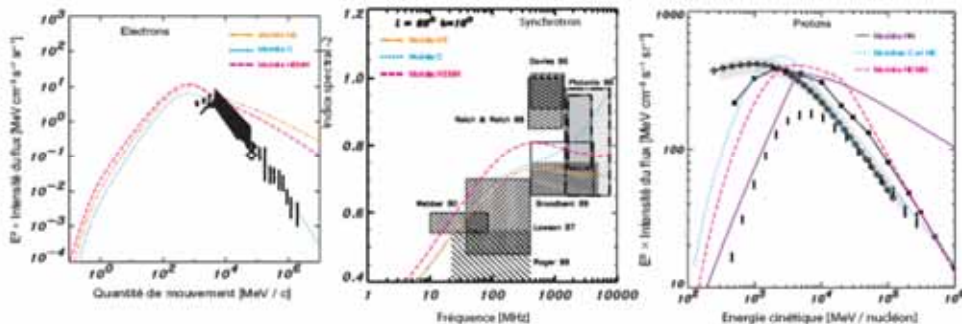
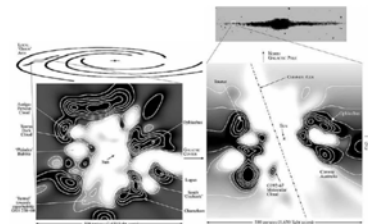
- Knowing the target column density from radio 21cm measurements and fitting the diffuse  $\gamma$  flux, one can map the density, spectrum and composition of CR elsewhere in the galaxy.

- S.D.Hunter et al, ApJ 481 (1997) 205
- M.Pohl and J.A.Esposito ApJ, 507 (1998) 327
- S.LeBohec et al, astro-ph/0003265
- Strong, A.W., Moskalenko, I.V., ApJ 509:213-228, 1998



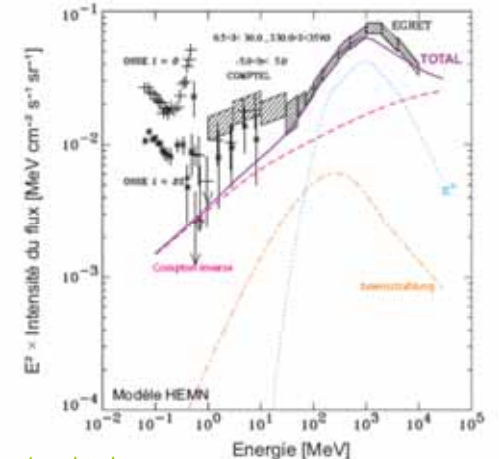
# Tracking back the CR flux elsewhere in the Galaxy

- Other constrains
  - Protons local spectrum and flux (altered <10GeV solar magnetic field)
  - Electrons local spectrum and flux (influenced by the local bubble of matter under-density)
  - Radio measurements of the synchrotron emission



# Tracking back the CR flux elsewhere in the Galaxy

- Refined predictions based on detailed simulations (magnetic model of the galaxy, CR diffusion equation, matter density maps...):  
for ex: GALPROP program

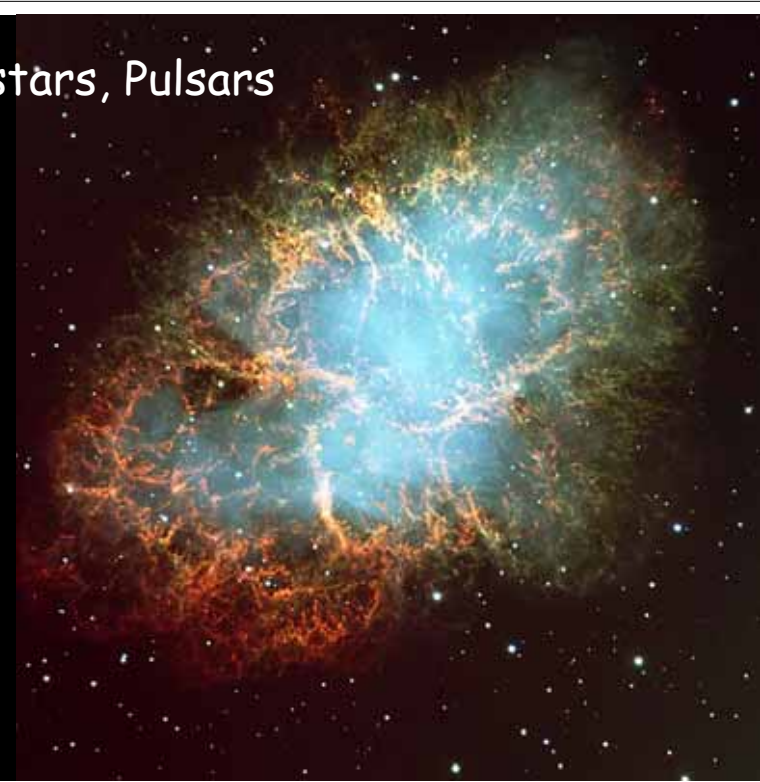


<http://www.gamma.mpe-garching.mpg.de/~aws/aws.html>

# COMPACT OBJECT ENVIRONMENT : NEUTRON STARS AND PULSARS BLACK HOLES

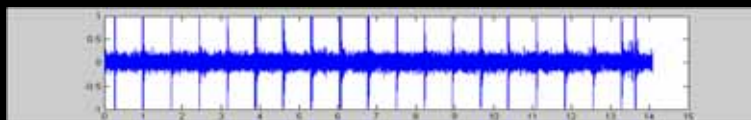
## Neutron stars, Pulsars

Journey into the  
Crab nebula.

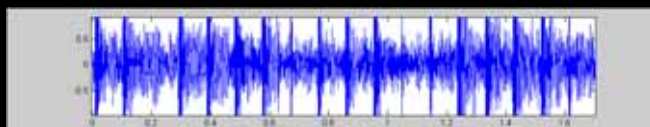


### Here is radio pulsar...

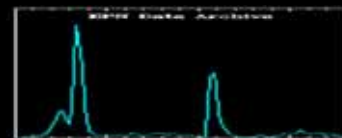
PSR0329+54  
~1,40 Hz



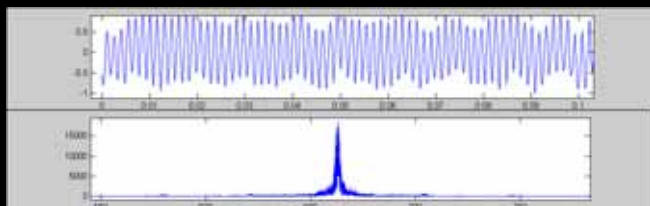
Vela  
PSR0833-45  
~11Hz



Crabe  
PSR0531+21  
~30 Hz



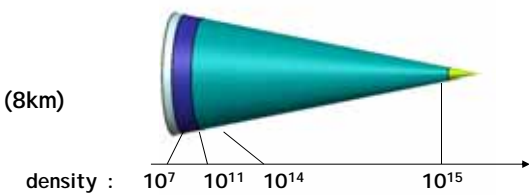
PSR1937+21  
~641 Hz



## Neutron stars

- Ultra compact objects:
  - Density ~ nuclear matter ( $10^{13} \times$  water !)
  - sphere ~ 10 km radius
  - gravitation at surface ~  $5 \times 10^{10} \times$  gravitation on earth
- Density and structure varies with :

- Iron core (0,3km)
- Neutrons and Nuclei (0,6km)
- Neutrons forming an superfluid ocean (8km)
- Unknown (1km)



# Magnetic field of a neutron star

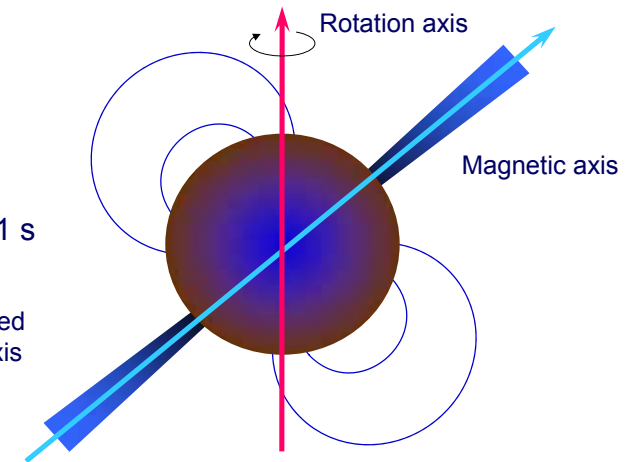
- Most celestial bodies bear a magnetic field (i.e. the sun:  $10^{-3}$  Tesla)
- At the surface of a neutron star, it is  $\approx 10$  million Tesla
- This value is intrinsically linked to the rapid rotation (conservation of rotation kinetic energy and magnetic energy  $\rightarrow$  concentration)
- A kind of giant **COSMIC DYNAMO** : rotation of  $\vec{B} \Rightarrow \vec{E} \Rightarrow 10^{18}V$  !!
- The electric force at the surface is  $\gg$  gravitational force !  
 $\rightarrow$  charged particles are **expelled** and **accelerated**  
 $\Rightarrow 10^{38} e^-$  per second radiating synchrotron light.
- The strong anisotropy of the radiation is badly understood but probably due to the intense  $\vec{E}$  and  $\vec{B}$  fields near the "polar caps".

# Unipolar Induction

- Neutron star :  
a rotating magnet with a magnetosphere

Neutron star  
 Mass =  $1.4 M_{\odot}$   
 Radius = 10 km  
 Rotation period = 1 s

Radio beam emitted along magnetic axis



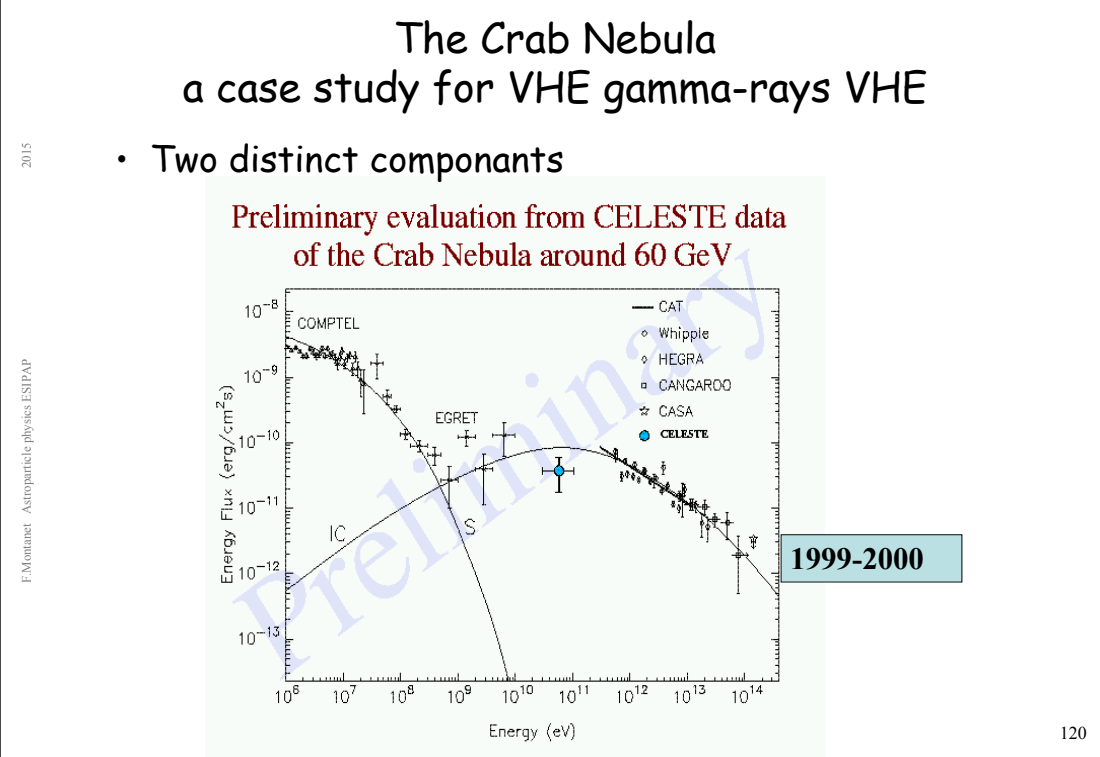
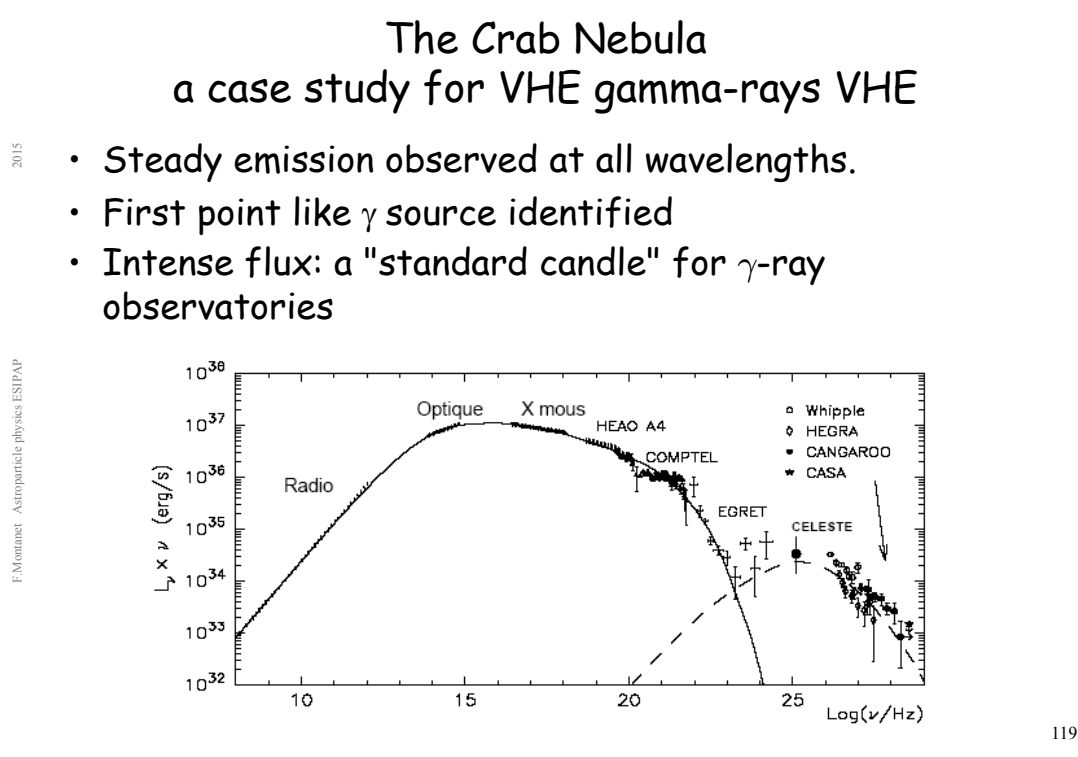
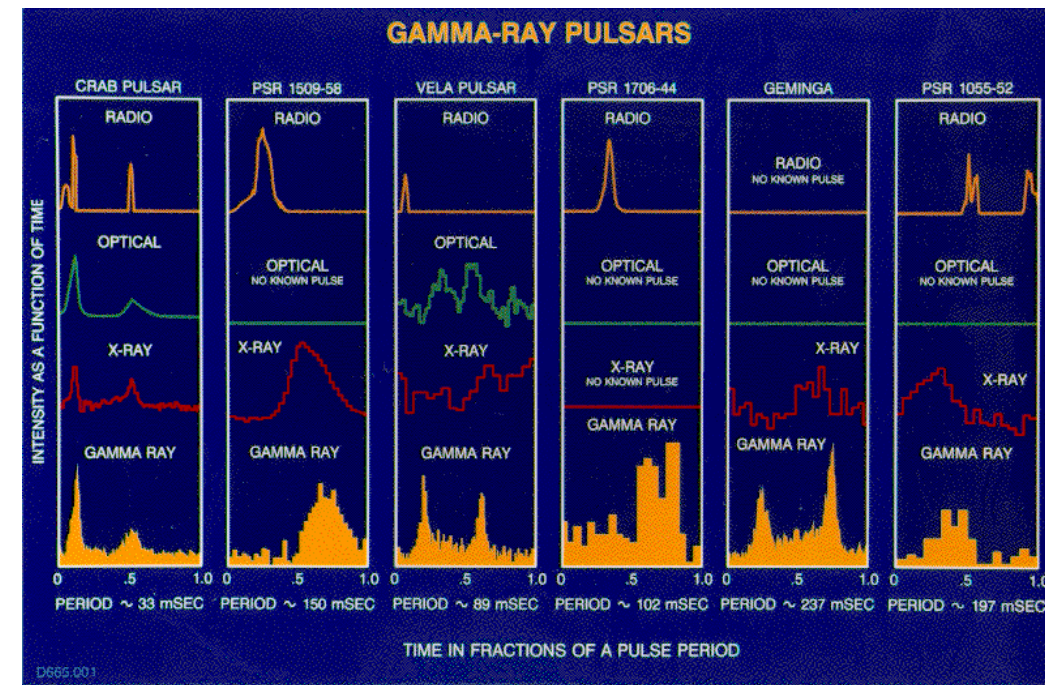
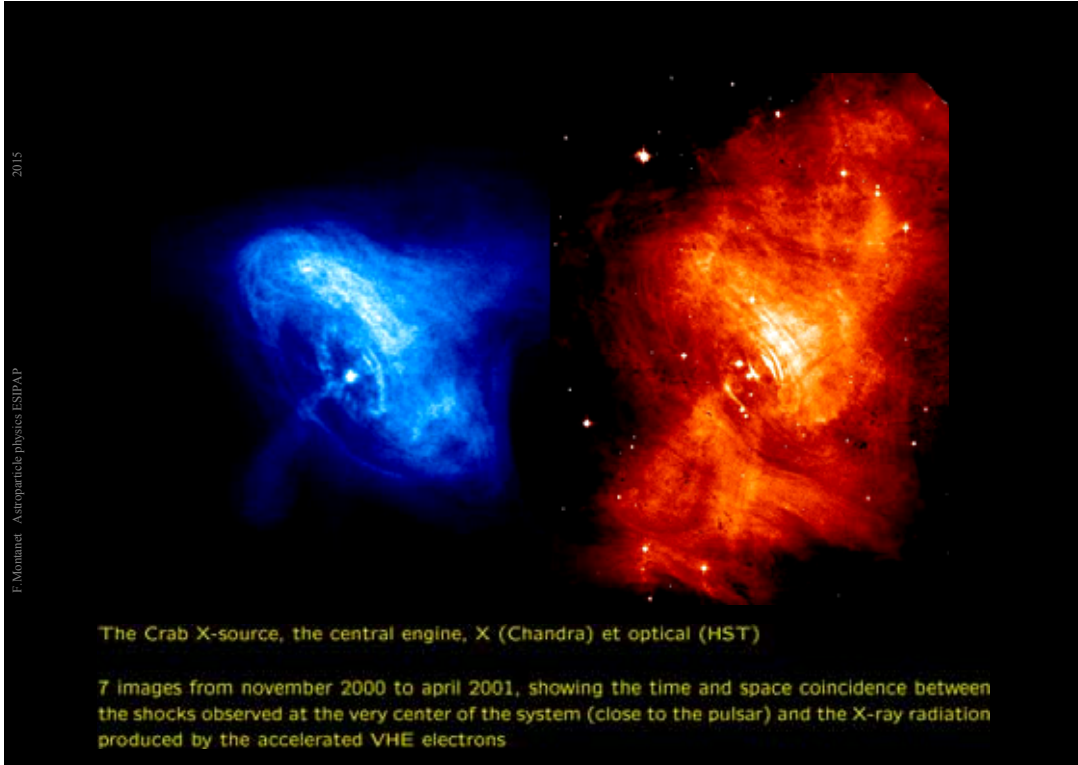
# Unipolar induction

- Neutron star :  
a rotating magnet with a magnetosphere

$$\rho_0 = \vec{\nabla} \cdot \left( \frac{(\vec{\Omega} \times \vec{r}) \times \vec{B}}{4\pi c} \right) = \frac{\vec{\Omega} \cdot \vec{B}}{2\pi c \left( 1 - |\vec{\Omega} \times \vec{r}/c|^2 \right)}$$

$$\Delta V \approx \frac{\Omega^2 B_s R^3}{c^2} = 3 \times 10^{16} \Omega_2^2 B_{13} R_6^3 \text{ Volts}$$

The top part of the image shows the Crab Nebula in optical light (top) and X-rays (bottom). The bottom right part contains a diagram titled 'Pulsar Geometry' which shows a rotating magnetized neutron star with magnetic field lines, corotating plasma on closed field lines, and a light cylinder. It also illustrates the 'Retardation Outflow of Charged Particles on Open Field Lines' and 'Pulsed X-Rays from Neutron Star in Crab Nebula (30 pulses per second)' with 'Off Pulse' and 'On Pulse' images.



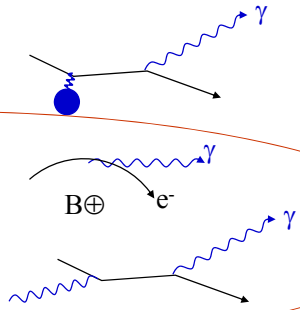
# VHE photons sources

- $\gamma$ -ray production:
  - Electro-magnetic processes :

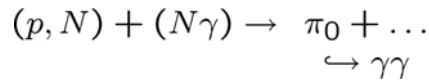
- Bremsstrahlung

- Synchrotron radiation

- Inverse Compton scattering



- Hadronic processes :

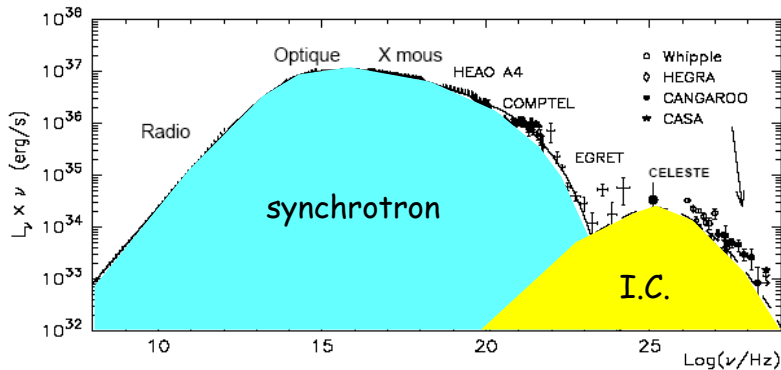


# The Crab Nebula a case study for VHE gamma-rays VHE

- TeV emission is based on **Inverse Compton** scattering
- The  $e^-$  producing **synchrotron radiation** can interact with these synchrotron photons.
- If  $\lambda_{\text{photon cible}} \ll \lambda_{\text{compton}} = \frac{h}{m_e c}$  it is possible to transfer most of the incident  $e^-$  energy to the photon.  
ex: A  $10^{13} eV$   $e^-$  can boost an I.R. photon I.R. into a VHE gamma-ray.
- These "Self Synchrotron Compton" models reproduce both GeV and TeV spectra.

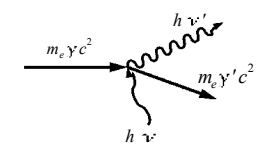
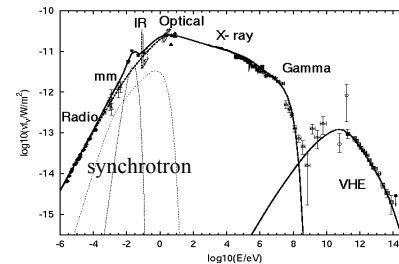
# The Crab Nebula a case study for VHE gamma-rays

Model SSC : Synchrotron Self Compton



# PWN emission mechanisms: the Crab Nebula

- Assume leptonic model: synchrotron and Inverse Compton emission
- Relativistic electrons and positrons created and accelerated by the pulsar

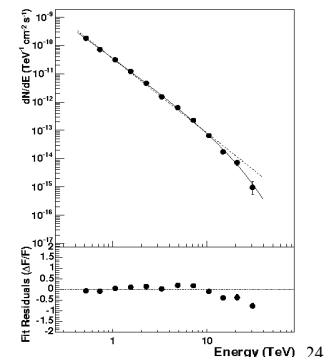


Target photons : CMB, interstellar IR, stellar photons, synchrotron (SSC)...

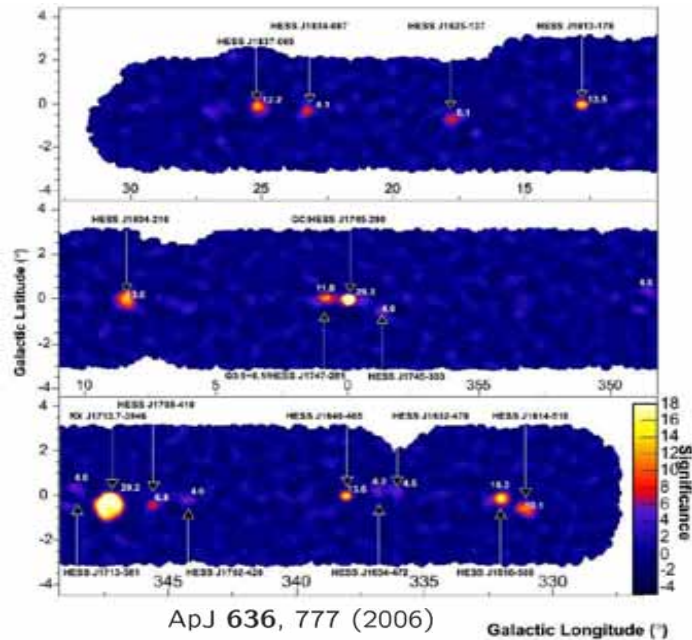


Radio, optical, X-rays

H.E.S.S. spectrum (A&A 2006 in press, astro-ph/0607333): Spectral curvature, Consistent with IC expectations

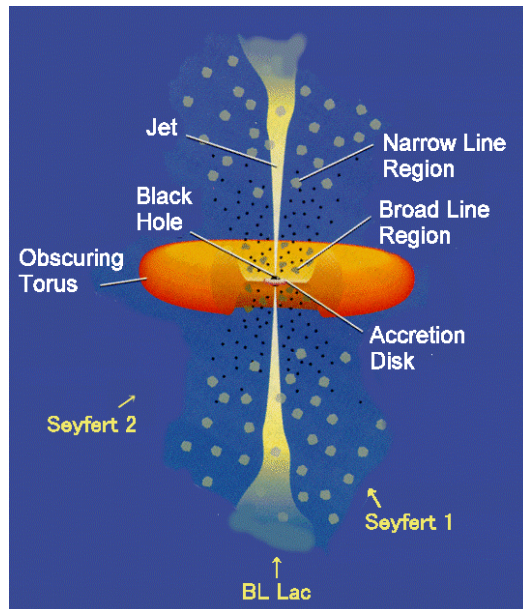


Many recently discovered sources in the Galactic plan by HESS, MAGIC and VERITAS large angle surveys



## THE ENVIRONMENT OF SUPERMASSIVE BLACK HOLES: ACTIVE GALACTIC NUCLEI

### AGN: a unified scheme



### Active Galactic Nuclei

- Galaxies with an important activity of its nucleus
- Numerous classes of objects:
  - Radio-galaxies
  - Radio-quasars
  - BL Lac objects
  - Violently Variables objects (VVO)
  - Radio Quiet Quasars
  - Seyfert Galaxies of type 1
  - Seyfert Galaxies of type 2
  - Low Ionization Nuclear Emission-Line Regions (LINERs)
  - Nuclear HII Regions
  - "Star Burst" Galaxies
- Arbitrary categories et badly mal defined.

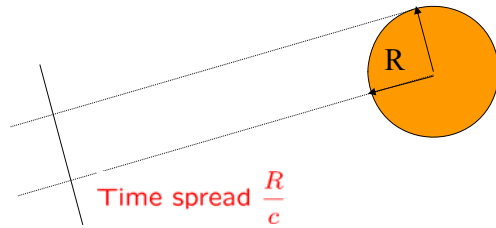


# What is an AGN

## • Elementary AGN model:

Discovered in the early 60ties when trying to identify the sources in the 3<sup>rd</sup> Cambridge Catalogue.

- Superluminous objects
  - Spectral redshift → cosmological distances
  - For 3C273 →  $P \approx 10^{40}$  Watts  $\approx 10000$  the Milky Way  $\approx 1000$  SN/year
- Very small objects
  - Variability criteria →  $d \approx$  solar system size !!



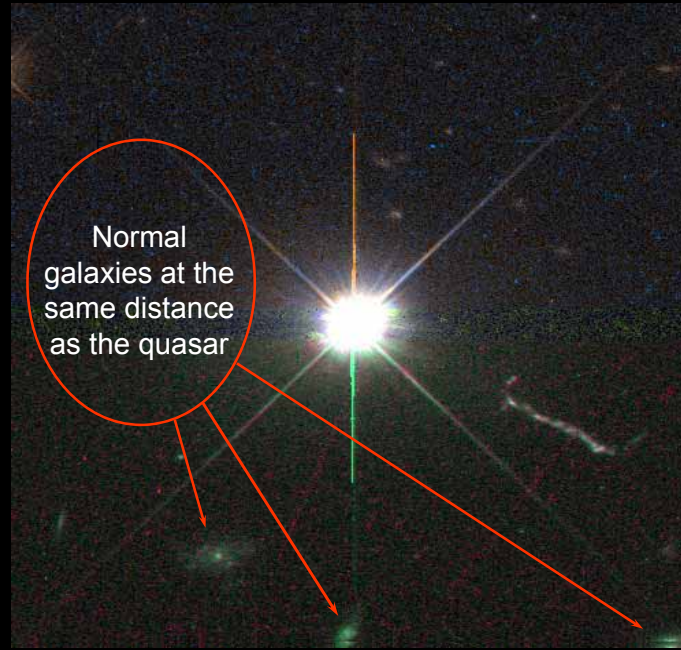
# What is an AGN

## • Elementary AGN model:

Discovered in the early 60ties when trying to identify the sources in the 3<sup>rd</sup> Cambridge Catalogue.

- Objects from the past
  - The most distance quasars observed ( $z \approx 5$ ) are at distances of the order of the radius of the **observable universe!**
  - No such objects in our close environment → must be linked to a phase of the galaxy evolution.

# The Quasar 3C 273



In 1963, 3C 273, the first quasar, was discovered. They can be up to **1000 more luminous** than the massive host galaxy. The emission originates in the **active nucleus** of the galaxy.

# What is an AGN

## • Necessarily a gravitational engine

Thermonuclear falls short by a factor 10 to 100 !

Form of energy release	Efficiency of energy production (wrt $mc^2$ )
• Chemical energy .....	$10^{-9}$
• Nuclear energy .....	$10^{-2}$
• Accretion of mass onto non-rotating black holes .....	$6 \times 10^{-2}$
• Accretion onto maximally rotating Kerr black holes .....	0.42
• Rotational energy of maximally rotating Kerr black holes .....	0.29

## What is an AGN

- Necessarily a gravitational engine

$$E_{tot} = 0 \Rightarrow E_{cin} = \frac{GmM}{R} \Rightarrow R \text{ must be small}$$

Huge mass, small volume  $\Rightarrow$  BLACK HOLE !!!

$$\text{With } R_S = \frac{2GM}{c^2} \Rightarrow E_{rad.max} \approx \frac{GM R_S}{R_S R} m = \frac{1 R_S}{2 R} mc^2$$

Accounting for relativistic corrections and ergosphere rotation  
 $\rightarrow$  conversion efficiency  $m \rightarrow E$  few 10%

133

## What is an AGN

- Necessarily a gravitational engine

One gets  $10^{40}$  Watts with  $15M_{\odot}$ /year.

Over  $10^8$  years (age measured from radio lobes)  $\Rightarrow 10^9 M_{\odot}$   
 $\Rightarrow R_S \approx 10^{13} m$  compatible with variability.

More over, one is below **Eddington** luminosity  
(radiation pressure = gravitational forces)

$$\left( L \approx \frac{4\pi c}{\sigma_T} GMm_H \right) \text{ de } \left( \frac{\sigma_T L}{4\pi R^2} = \frac{GMm_H}{R^2} \right)$$

$\Rightarrow$  PLAUSIBLE.

134

## What is an AGN

- Accretion of matter:

- In absence of angular momentum:

$$\vec{v}_{\infty} \text{ directed toward the BH: } \frac{GMm_H}{R} = kT$$

$\Rightarrow$  almost all is radiated in  $X$  or  $\gamma$  rays

INCOMPATIBLE with MEASUREMENTS

- With angular momentum:

Intense radiation in the UV : OBSERVED

$\Rightarrow$  **Anisotropic Accretion**

**in the shape of an ACCRESTION DISK**

135

## What is an AGN

- Jets:

Relativistic particles constituting the jets are accelerated when reflecting on the boundaries of a magnetic "tunnel" induced by the rotating plasmas near the BH.

- Hot spots

Terminal shocks (jet-IGM): large size moderate field regions  
 $\Rightarrow$  plausible place for UHECR production.

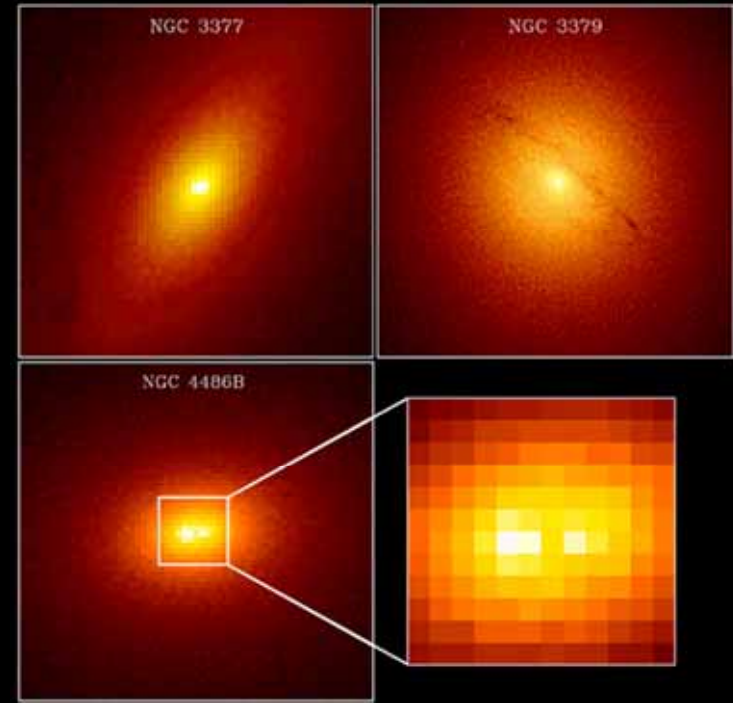
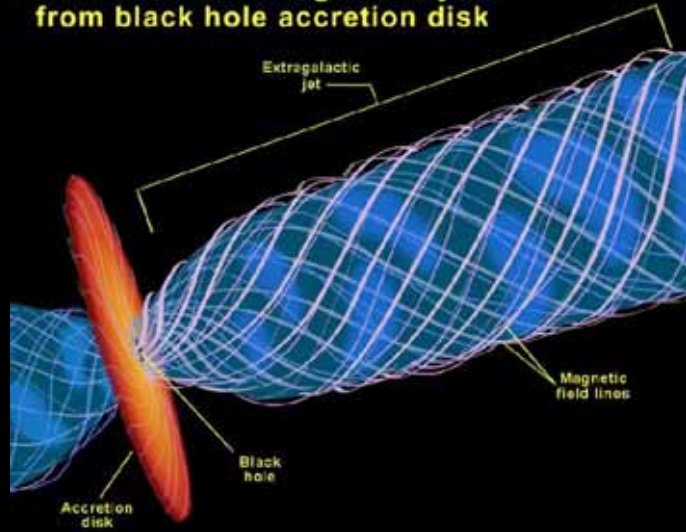
$\rightarrow$  explains many observed phenomena with both leptonic and hadronic models.

136

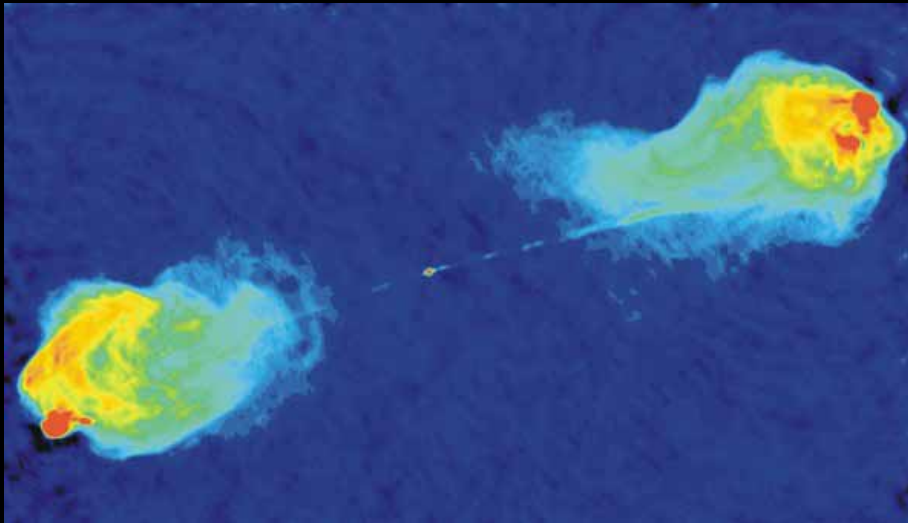
# What is an AGN

- Jets:

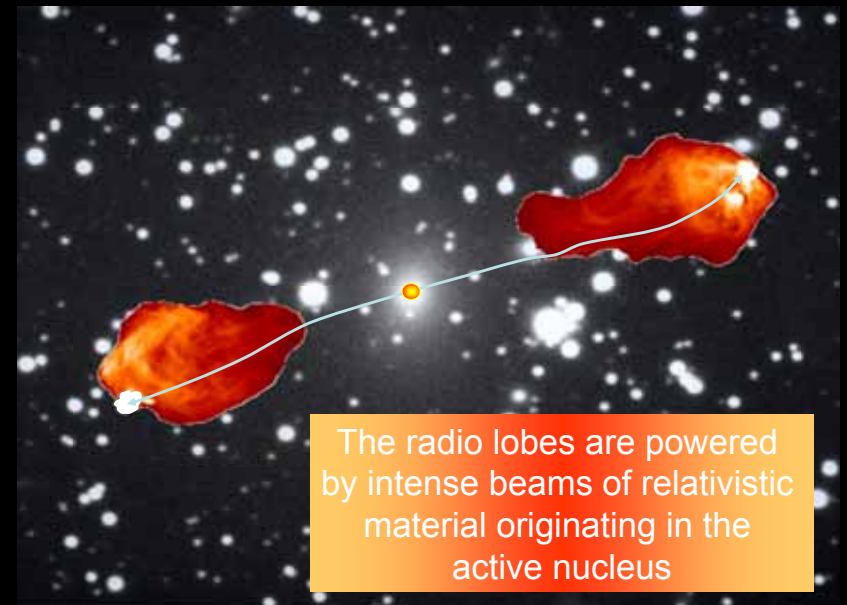
Formation of extragalactic jets from black hole accretion disk



# Cygnus A



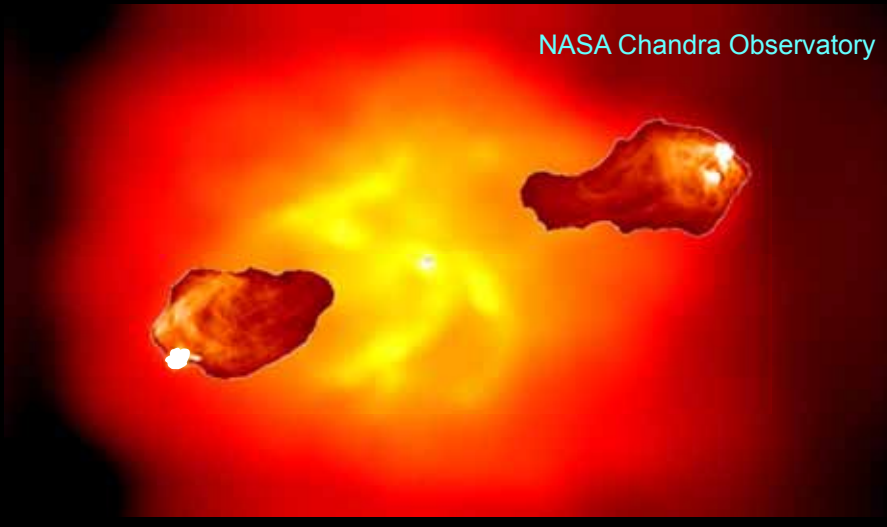
# The Radio Galaxy Cygnus A



The radio lobes are powered by intense beams of relativistic material originating in the active nucleus

# Cygnus A - X-ray image

The image shows the distribution of hot intergalactic gas surrounding the radio source.



2015

F.Montanet - Astroparticelle physics ESPAP



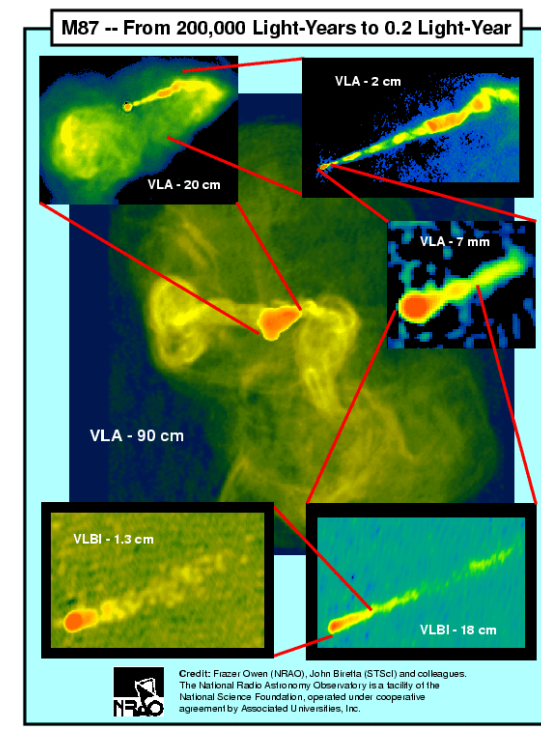
2015

F.Montanet - Astroparticelle physics ESPAP



2015

F.Montanet - Astroparticelle physics ESPAP

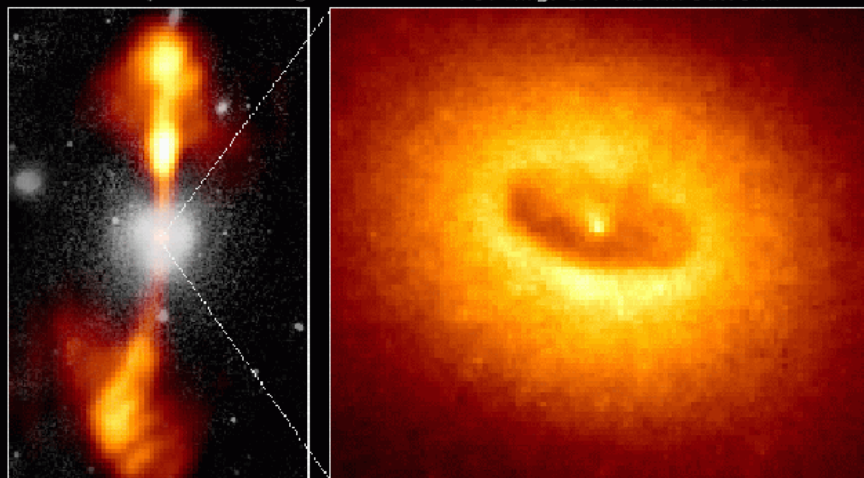


# Core of Galaxy NGC 4261

Hubble Space Telescope  
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

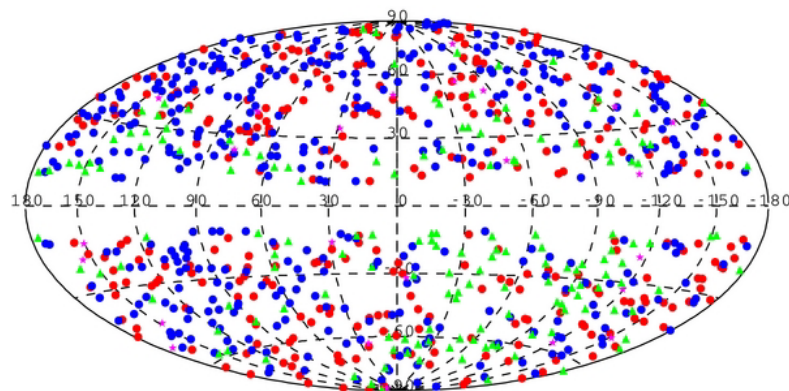
HST Image of a Gas and Dust Disk



380 Arc Seconds  
88,000 LIGHTYEARS

17 Arc Seconds  
400 LIGHTYEARS

# FERMI 2<sup>nd</sup> LAC catalogue

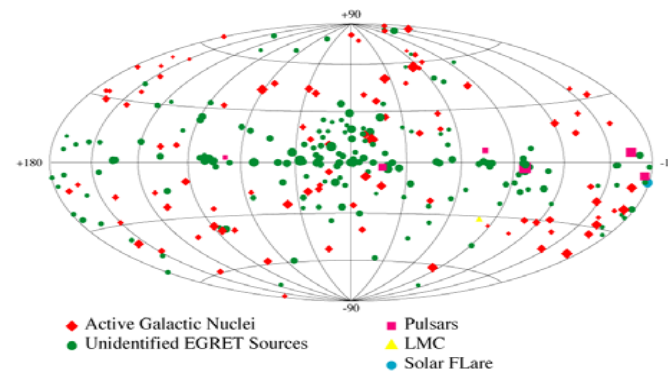


886 AGN with a clear GeV gamma-ray signal, identified with comprising 395 BL Lacertae objects (BL Lac objects), 310 flat-spectrum radio quasars (FSRQs), 157 candidate blazars of unknown type (i.e., with broadband blazar characteristics but with no optical spectral measurement yet), 8 misaligned AGNs, 4 narrow-line Seyfert 1 (NLS1s), 10 AGNs of other types, and 2 starburst galaxies

# EGRET

- Before EGRET : 3C273
- After EGRET : 33 AGN a more than  $5\sigma$  all Blazars

Third EGRET Catalog  
E > 100 MeV



# EGRET

- AGN basic results :
  - The  $\gamma$ -ray energy flux is often dominant
  - A naive estimate  $(4\pi d^2 L) \approx 10^{47} \rightarrow 10^{49} \text{ ergs.s}^{-1}$
  - $0,03 \leq z \leq 2,28$
  - $(30 \text{ MeV} - 30 \text{ GeV})$  spectrum  $\sim$  a power law:  
 $\frac{dN}{dE} \propto e^{-\alpha}$  with  $1,3 \leq \alpha \leq 3,0$
  - Many sources are strongly and rapidly variables on time scales  $\sim 1$  month.
  - Many known AGN are not detected in  $\gamma$ -rays.

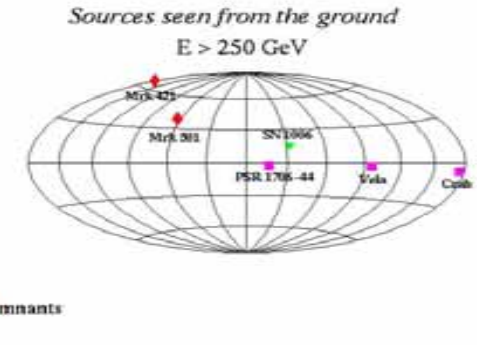
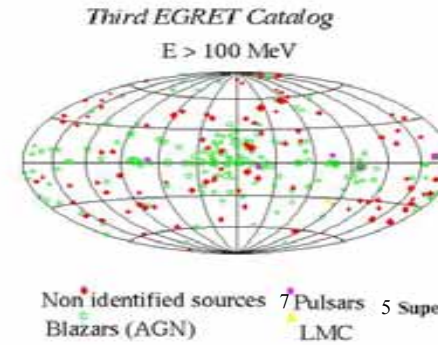
# EGRET

## Variability:

- Most EGRET Blazars are variable on time scales  $\sim$ days or months.

Source	$T_{\text{var}}$ (jours)	$T_{\text{var AGN}}$ (jours)
0208-512	8	4
0235+164	<90	<46
0446+112	15	...
0528+134	2	0,65
1253-55	2	1,3
1406-076	6	2,4
1633+382	2	0,7
2251+158	4	2,2

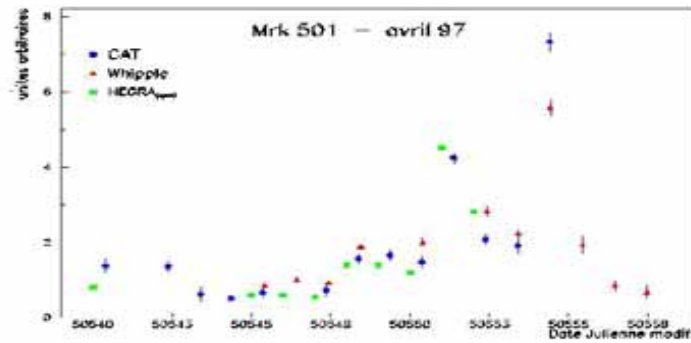
- Short time scales are **constraining the source size**:  
1 day  $\Rightarrow$  Scharzchild radius of a  $10^{10} M_{\odot}$  black hole.



After COS-B, the great success of EGRET has been the rather unexpected discovery that  $\approx 100$  blazars are brilliant in the GeV energy range *with no turn-over at maximum energies*

During about the same decade the TeV observations broke through, with no pre-notice. The a posteriori surprise is the scarcity of sources

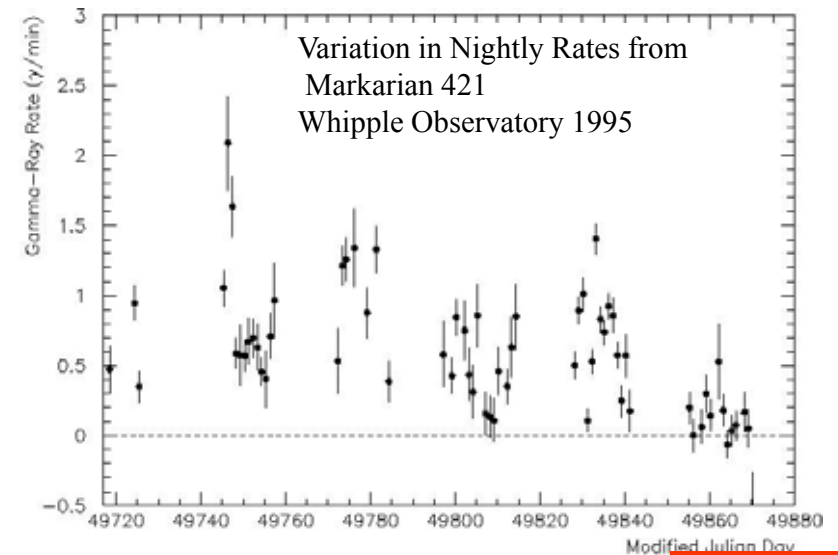
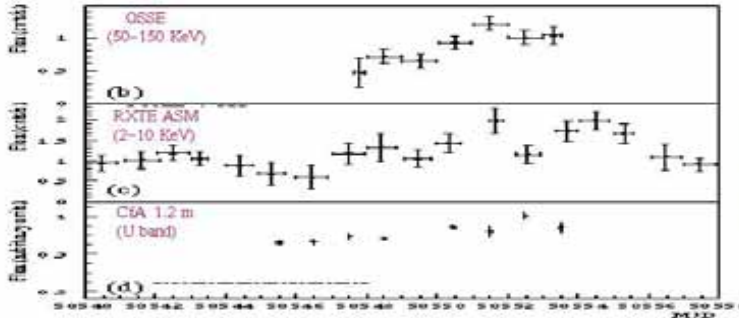
- the intermediate region, from 30 to 300 GeV, remains unexplored
- the (few) TeV blazars are weak EGRET sources
- the absorption ( $\gamma \gamma \rightarrow e^+e^-$ ) obscures the far Universe for TeV  $\gamma$ 's



Mrk 501 flares of April 1997 showing variability on a day scale

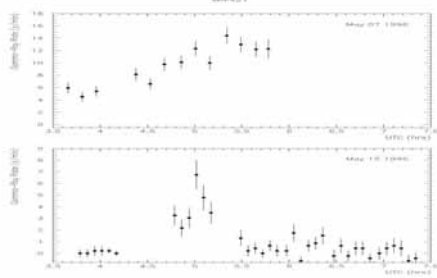
Even faster (<hr) variations have been evidenced by the Whipple on Mrk 421

Flux sensitivity on the scale of the hour is needed



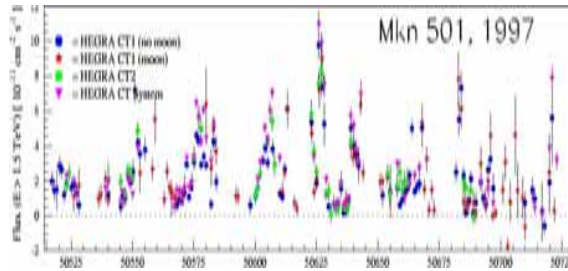
Variation in Nightly Rates from Markarian 421 Whipple Observatory 1995

Buckley et al. 1996

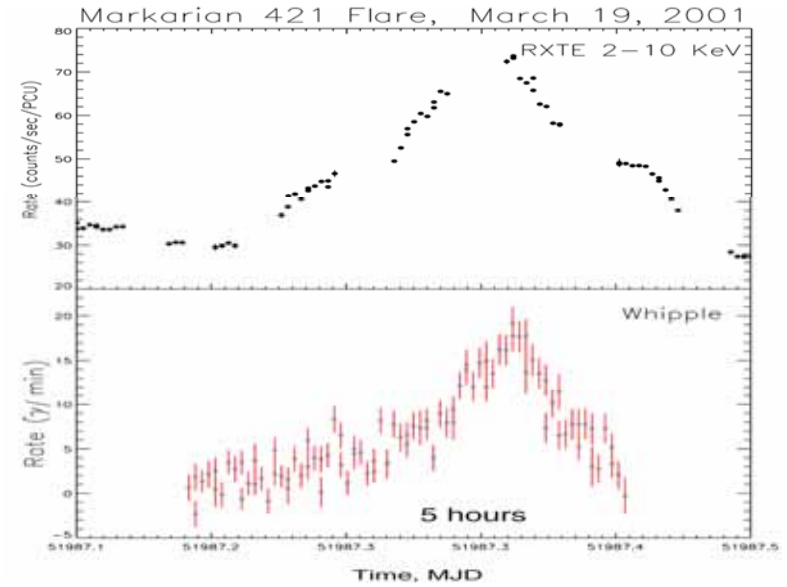


Markarian 421  
Whipple Observatory  
Hours - minutes

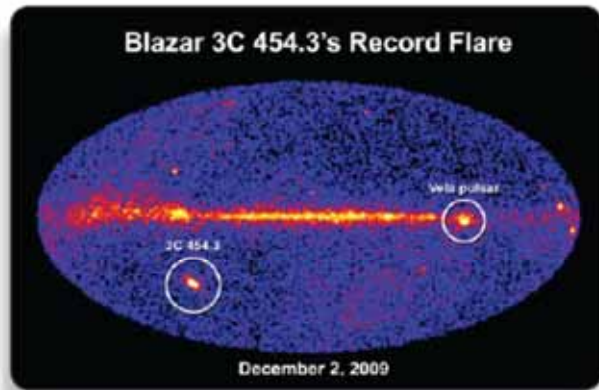
Markarian 501  
HEGRA  
Days-months



## Time coincidence $X$ and TeV $\gamma$

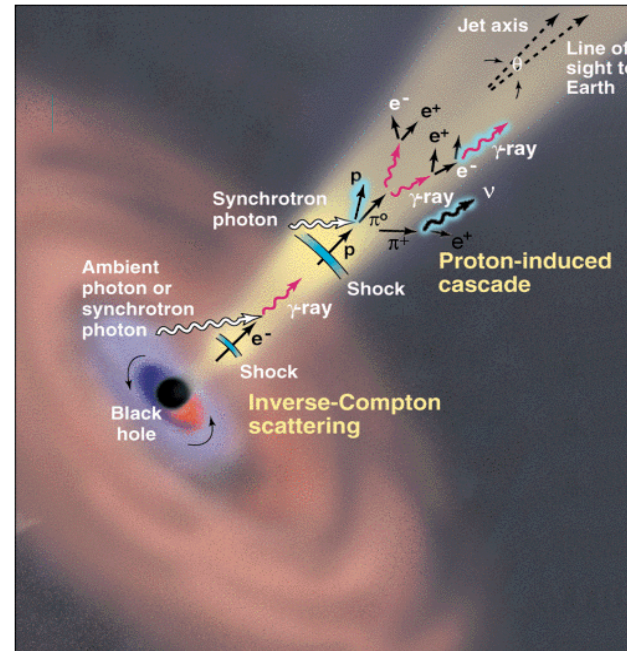


Flare de 3C454.3 : 2 x luminous than Vela  
although  $10^6$  x distant !



Unprecedented flares from the blazar 3C 454.3 in the constellation Pegasus now make it the brightest persistent gamma-ray source in the sky. That title usually goes to the Vela pulsar in our galaxy, which is millions of times closer (Credit: NASA/DOE/Fermi LAT Collaboration).

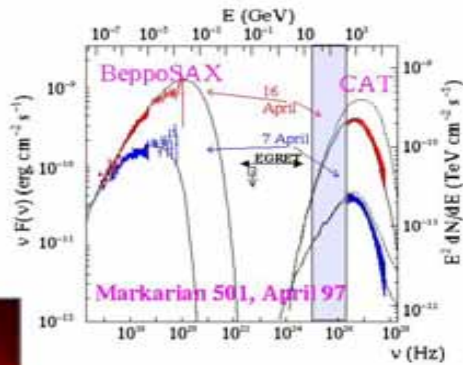
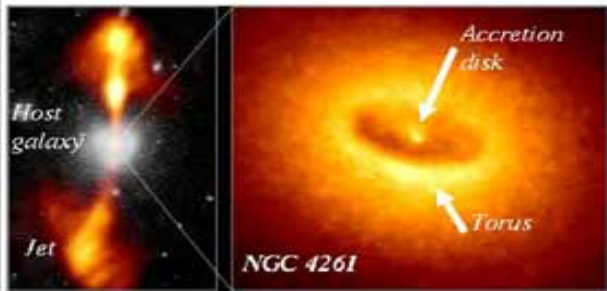
## AGN Jet Emission Mechanisms



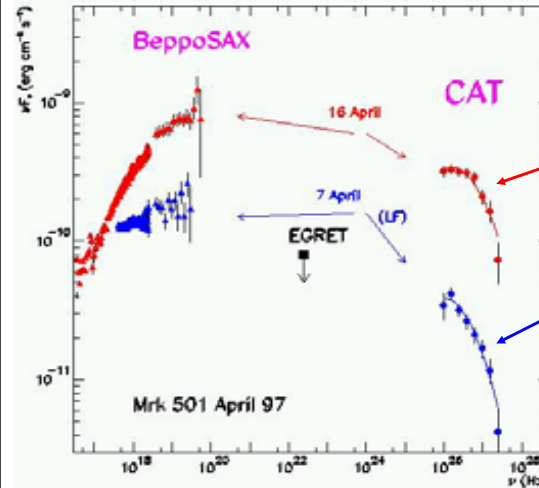
**Cosmic Cannon:**  
Looking down the  
Barrel of the Cannon

**Electron Progenitors:**  
Synchrotron Self Compton  
External Compton  
**Proton Progenitors:**  
Proton Cascades  
Proton Synchrotron

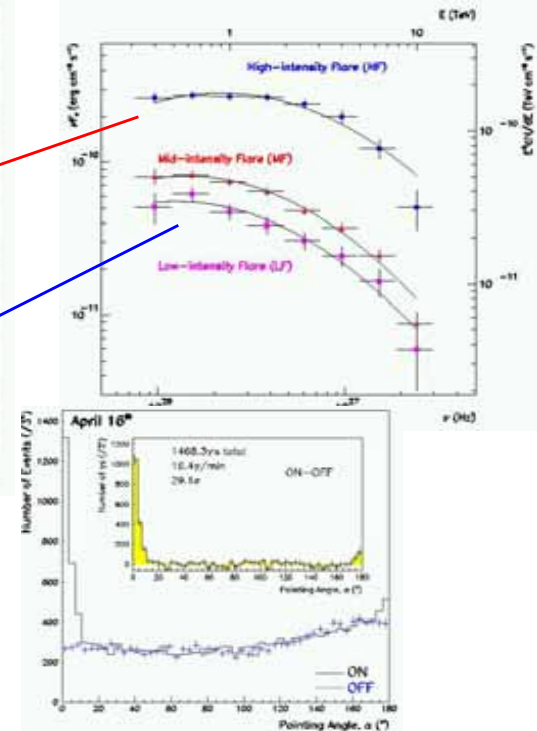
- AGN / Blazar : Markarian 501
- Supermassive Black Hole ( $M > 10^6 M_{\odot}$ )
- With an accretion disk ( 1 pc )
- Surrounded by a torus of dust ( 100 pc )
- Radio loud: Two jets ( <100 kpc )



- Blazars
- Near jet axis :  $\theta \leq 1/\gamma$  -> High energy emission
- Strong variability on time scale of a *day* or even less



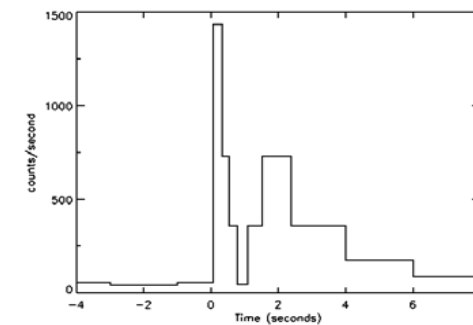
Markarian 501  
Flare of April 1997



# GAMMA RAY BURSTS



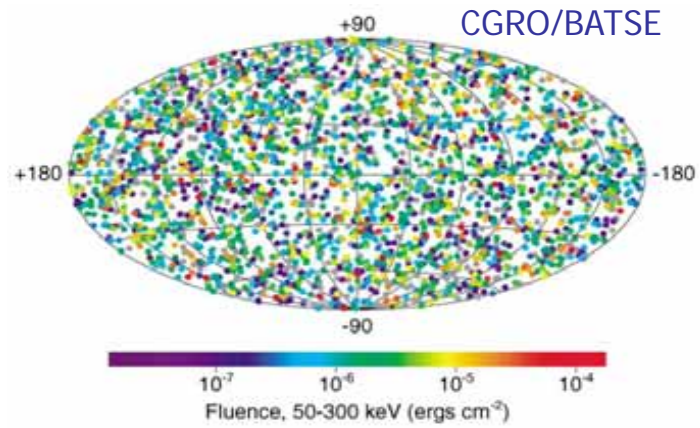
## Vela Program (1969-1979)



- Discovered in 1967 when spying thermonuclear bomb tests.
- A 30+ years old mystery unraveled in the 90ties !

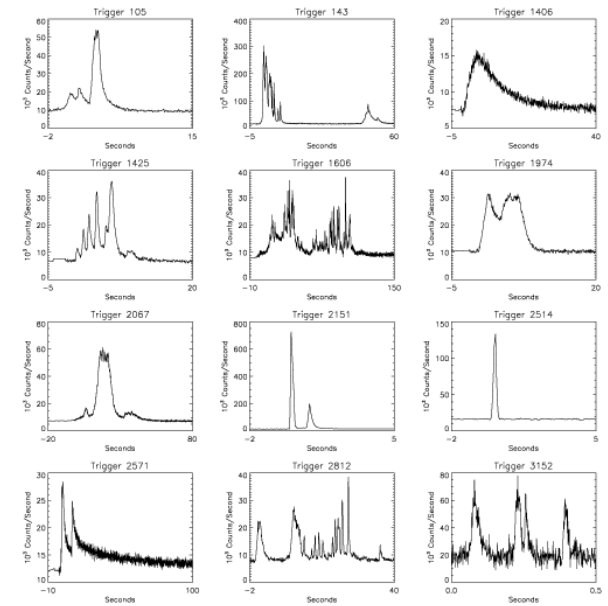


# Gamma-ray Burst Sky



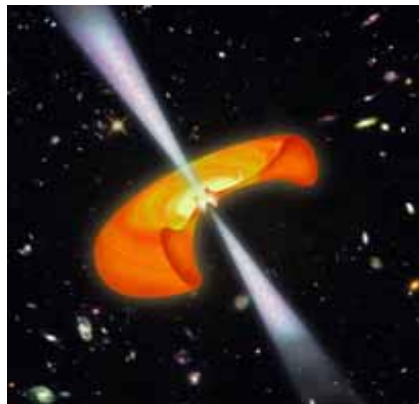
~ Once a day, anywhere in the universe !

# GRB



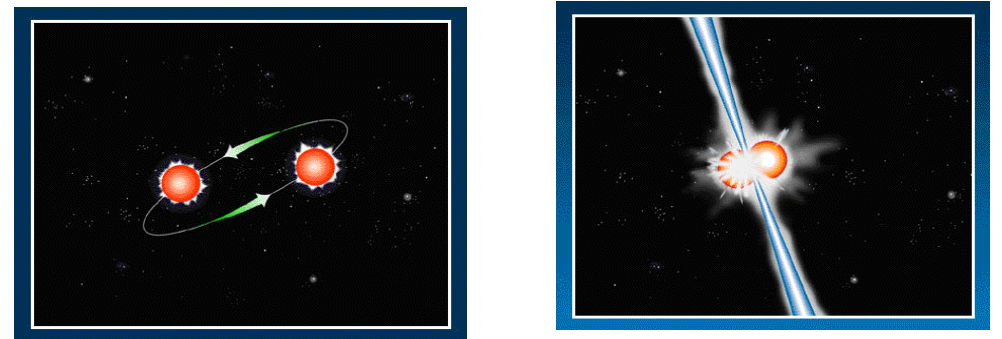
# Hypernova

Death of a massive star ?



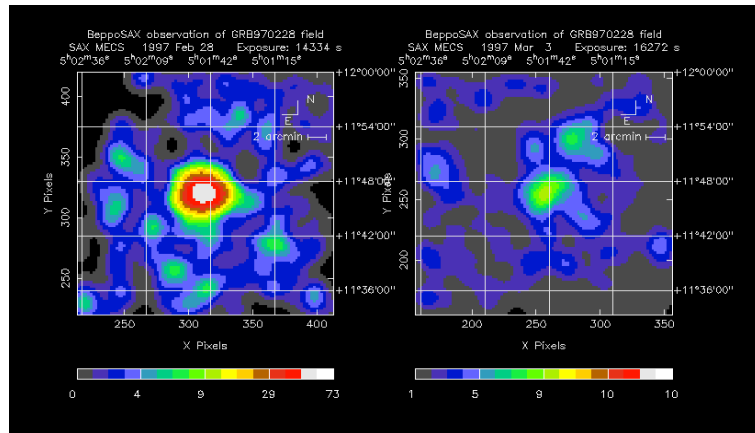
- A billion trillion times the power from the Sun

# Catastrophic Mergers



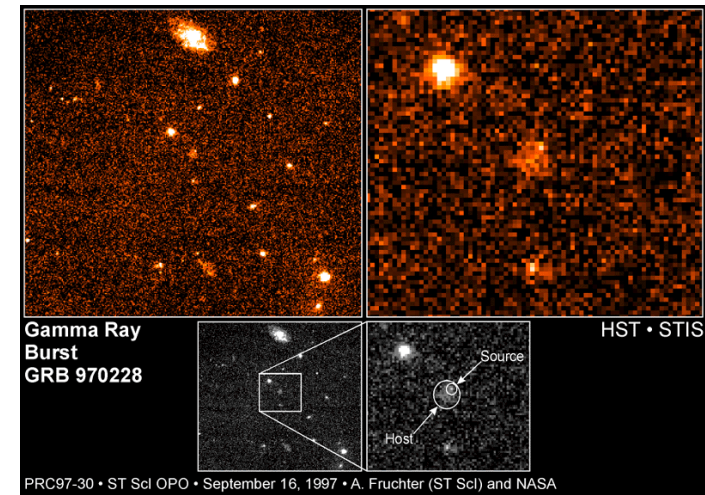
- Spiral death of 2 neutron stars or black holes

# Afterglow



- Discovered in 1997 by BeppoSAX satellite

# GRB afterglow en optique



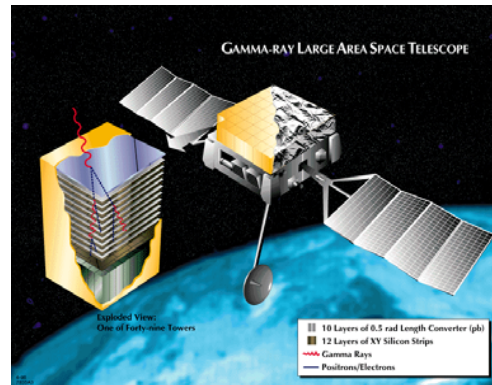
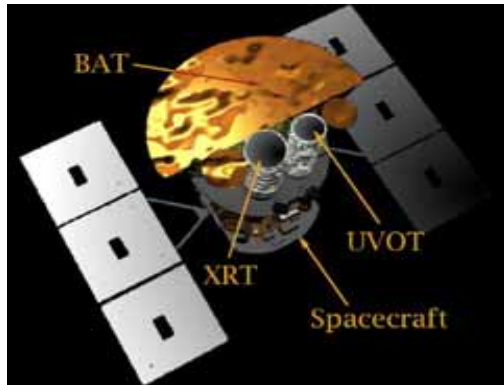
# New Missions = Better Data

HETE II (launched 10/9/00)

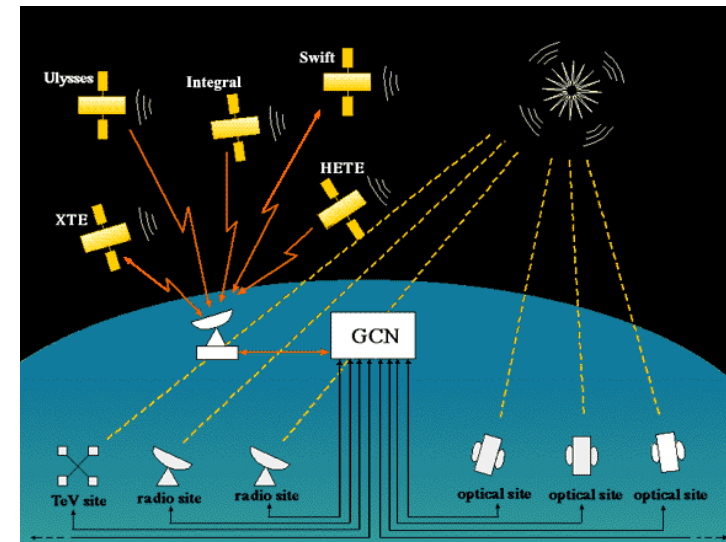
INTEGRAL (launched 17/10/2002)

Swift (launched 20/11/2004)

FERMI (launched 16/5/2008)



# The Gamma ray bursts Coordinates Network



# GRB's

- **Gamma-Ray Bursts : intense gamma-ray flux**
  - 0.1 to 1 MeV, and up to 100 MeV
  - Emitted on a short time scale (~ 1 second !)
  - Observed ~once per day, with an isotropic distribution
  - Source at cosmological distances (most distant is  $z = 9.4$  !!)
- **$\gamma$ -ray luminosity:  $\sim 10^{52}$  erg/s ( $10 \times \text{SNe}$  !)**
- **Extreme variability in intensity and spectrum**
  - Time scales from 10 ms to 10 s
  - Some very short 1 ms variabilities  $\rightarrow$  internal shocks
- **Clear bimodality suggesting the existence of two separate populations:**
  - a "short" population with an average duration of about 0.3 seconds
  - a "long" population with an average duration of about 30 seconds.

169

# UHE SOURCES

170

## General limits on models

### Shock waves

- **Acceleration site confinement:  $r_g = E/ZcB < L$** 
  - Depends in fact on  $V_{\text{shock}} = \beta c$  :
$$E_{\text{max}} \approx \beta \times Ze \times Bc \times L$$

### Unipolar induction

- **Accelerate in one step (  $E$  field,  $f_{\text{Lorentz}} \approx V_{\text{rot}} \times B \times R$  )**
  - $\rightarrow$  No confinement necessary

### Top-Down Models

- **No acceleration at all !**
  - Decay products of exotic physics states, supermassive particles at  $E_{\text{GUT}}$ , Topological Defects...

171

## Bottom-Up

### ZeVatrons

*Astrophysical Accelerators reaching ZeV*  
 Acceleration = Fermi-like diffuse acceleration.  
 First challenge,  $E_{\text{max}}$  : Reach  $\geq 10^{20}$  eV  
 (if 1 TeV is hard, guess for  $10^9$  TeV !!)  
 Second challenge, Propagation :  $B_{\text{igm}}$   
 (determine the spectrum and the arrival)

### Hillas criterion:

Magnetic confinement in the shock zone i.e.  
 $1 R_{\text{gyr}} < \text{accelerator size}$

### Not many candidates survive!

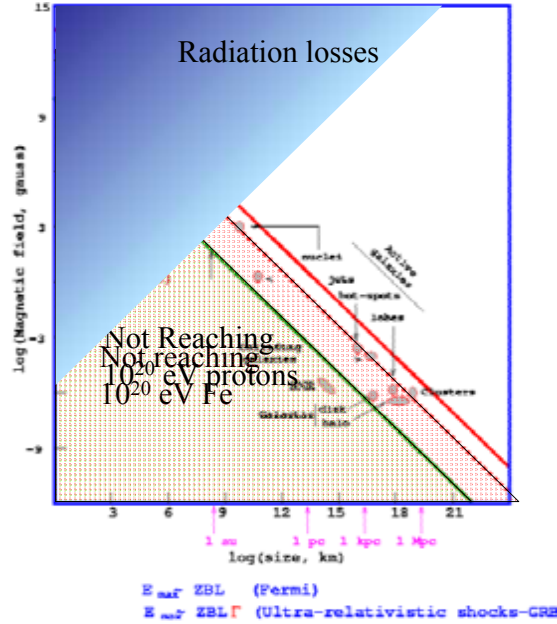
*Neutron stars (pulsars)*  
*AGNs*  
*Radio lobes*  
*Clusters*  
*Colliding Galaxies/Clusters*  
*Gamma Ray Bursts*

172

# Hillas diagram

Standard estimates for  $E_{max}$  :

- Confinement :  
 $r_g = E/(ZeB) < R \Rightarrow E < ZeBR$
- Unipolar inductor (pulsar)  
 $E < ZeBR(\Omega R/c) \approx \beta_s ZeBR$
- Diffusive acceleration by non relativistic shocks:  
 $\tau_{acc} \approx 10\kappa/u_s^2 < R/u_s$  avec  $\kappa > r_g c$   
 $\Rightarrow E < \beta_s ZeBR$
- Diffusive acceleration by relativistic shocks:  
 $E < \Gamma_s ZeBR$
- General Hillas condition:  
 $E < 0.9\beta\Gamma ZeB_{Gauss} R_{pc} ZeV$



# Relativistic shocks

- Acceleration  $\propto \Gamma^2$  works fine for a couple of cycle
- After that it fails for mere kinematical reasons
- But this is still very efficient ( $\gg$  standard shocks)
- Confinement is easier

A weak deflexion is enough :  $\delta\theta \approx 1/\Gamma_s \Rightarrow r_g < R_s/\Gamma_s$   
 $\Rightarrow E_{max} \approx \Gamma_s \times$  larger  
 $\Rightarrow$  one can reach the limits induced by energy losses

# BOTTOM -UP

Galactic pulsars  
 Extragalactic radio galaxy lobes  
 Gamma Ray Bursts

Protons, Iron, Nuclei?

Spectral index

Explaining isotropy is not trivial

Angular coincidences to be confirmed...

# Top-Down

Topological defects, superheavy relics  
 with  $M \sim$  GUT scale that is  $\sim 10^{16}$ GeV

- Energy  $\gg 10^{20}$  eV easy!  
 (QCD fragmentation spectrum QCD with  $M \sim 10^{24}$  eV!!)
- Explaining the flux is not trivial !!  
 (natural density scale is  $\sim H_0^{-1}$ )
- Composition of UHECR is the clue (photons + neutrinos) !!

# Low energy gamma-rays constraint

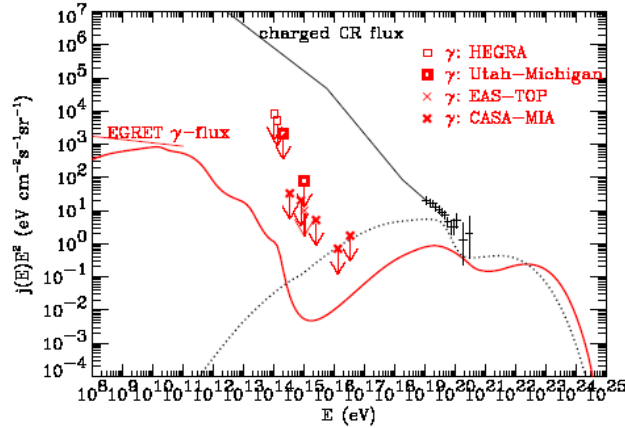


Figure 28: Predictions for the differential fluxes of  $\gamma$ -rays (solid line) and protons and neutrons (dotted line) in a TD model characterized by  $p = 1$ ,  $m_X = 10^{16}$  GeV, and the decay mode  $X \rightarrow q + q$ , assuming the supersymmetric modification of the fragmentation function, Eq. (57), with a fraction of about 10% nucleons. The calculation used the code described in Ref. [206] and assumed the strongest URB version shown in Fig. 10 and an EGMF  $\leq 10^{-11}$  G. 1 sigma error bars are the combined data from the Haverah Park [3], the Fly's Eye [7], and the AGASA [8] experiments above  $10^{19}$  eV. Also shown are piecewise power law fits to the observed charged CR flux (thick solid line) and the EGRET measurement of the diffuse  $\gamma$ -ray flux between 30 MeV and 100 GeV [185] (solid line on left margin). Points with arrows represent upper limits on the  $\gamma$ -ray flux from the HEGRA [257], the Utah-Michigan [510], the EAS-TOP [511], and the CASA-MIA [258] experiments, as indicated.

# Top-Down Signatures

## Composition:

Flux de Photons, Neutrinos  $\gg$  Protons

The current (AUGER) limits on UHE neutrino and photon flux already kill most Top-Down models !!

## Spectrum:

QCD-like fragmentation spectrum quite "hard"

## Cosmography:

Halo distribution!! (SHRs & TDs locales)  
or ~ Homogeneous

# and even more exotic stuff...

*Strongly interacting neutrinos*

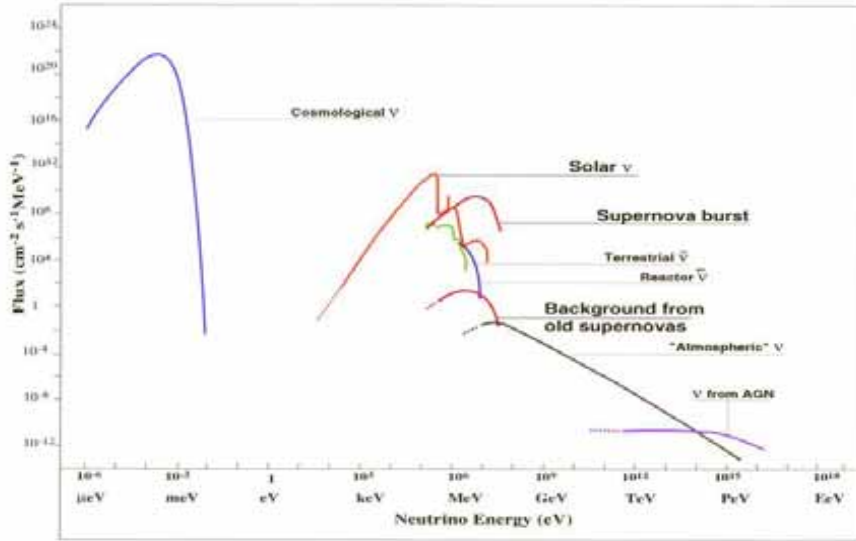
*Lorentz Invariance Violation*

*Special Relativity Violation*

*etc...*

# NEUTRINOS SOURCES

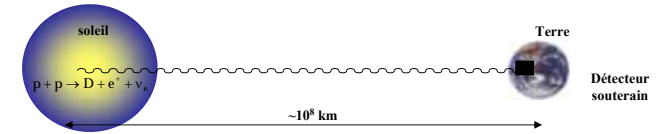
# The overall neutrino spectrum



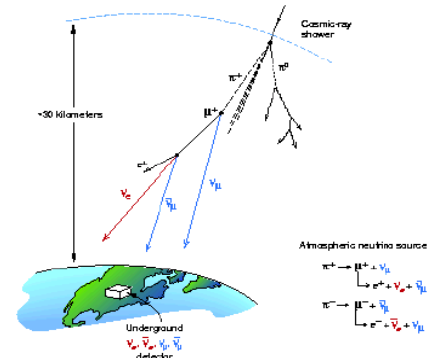
2015 F. Monjanet - Astroparticule physique ESPAP

# Natural Neutrinos Sources

Solar Neutrinos



Atmospheric Neutrinos

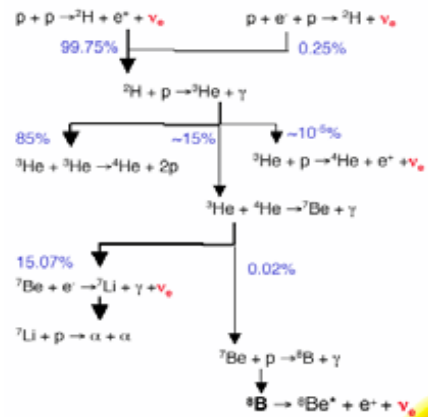


Also, Super Novae (SN1987A), Neutrinos de beam-dump cosmiques (AGN, GRB...), Neutrinos cosmogéniques, Neutrinos reliques du BigBang...

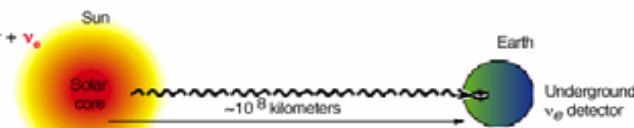
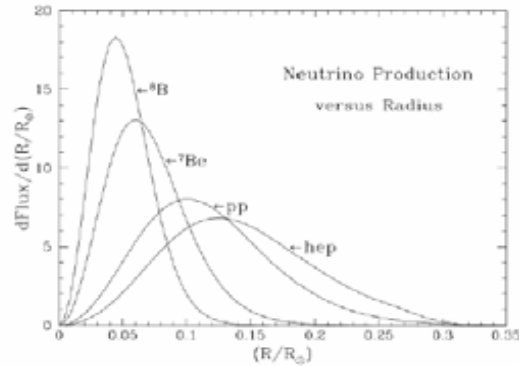
2015 F. Monjanet - Astroparticule physique ESPAP

# Neutrino Production in the Sun

## Light Element Fusion Reactions



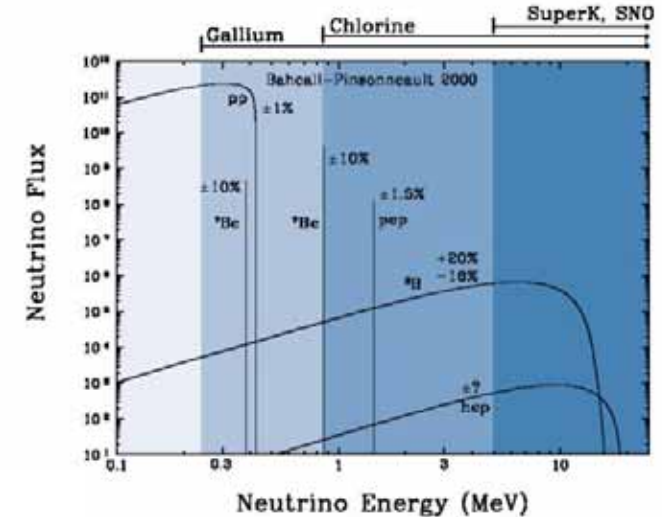
## Neutrino Production Radius



Primary neutrino source  
 $p + p \rightarrow D + e^+ + \nu_e$

Karsten Heeger, LBNL

2015 F. Monjanet - Astroparticule physique ESPAP



2015 F. Monjanet - Astroparticule physique ESPAP

Solar neutrino flux from p-p chain reactions based on the standard solar model (Bahcall and Pena-Garay, 2004). Flux units are  $\text{cm}^{-2} \text{sec}^{-1} \text{MeV}^{-1}$  for continuum sources and  $\text{cm}^{-2} \text{sec}^{-1}$  for line sources.

# Solar Standard Model

- \*NEW\* 39 experts agree on cross secs & systematics!

Rev. Mod. Physics, Oct 1998, astro-ph/9805121



- How well do we know  $T$ ?  
 $\phi(pp) \sim T^{-1.2}$ ,  $\phi(Be) \sim T^8$ ,  $\phi(B) \sim T^{18}$   
 → Helioseismology as a test...
  - The sun is a resonant cavity  
 frequencies depend on  $U = P/\rho$ .
  - The SSM predicts  $U$   
 Measured/SSM  $U(r)$  agree < 1%!
  - Temperature Uncertainty:  
 SSM alone:  $\Delta T/T = \pm 2.7\%$   
 SSM + Helio:  $\Delta T/T = \pm 1.4\%$

# SNe neutrinos

Normal stellar situation: the fusion thermal and radiation pressure compensate the gravitation pressure.

During the collapse, the gravitation binding energy ( $\approx 3 \times 10^{53}$  erg) cannot escape in an other form than neutrino-antineutrino pairs.

99% of the energy in the form of neutrinos  
 1% in the form of kinetic energy  
 0.01% of the energy in optical photons.

The neutron star is opaque to neutrinos. The diffusion and escape time is of the order of 1 second.

$$\langle E \nu_e \rangle \approx 11 \text{ MeV}$$

$$\langle E \bar{\nu}_e \rangle \approx 16 \text{ MeV}$$

# SN1987a

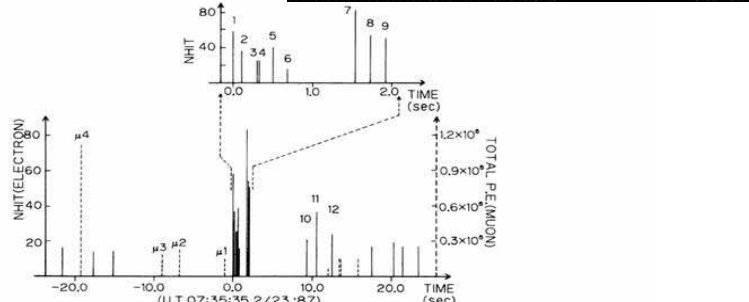
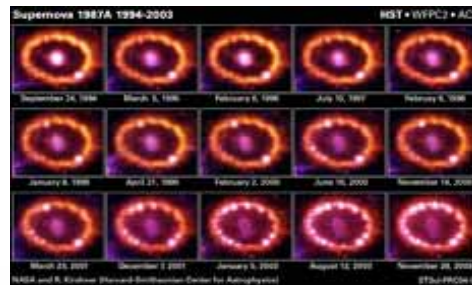
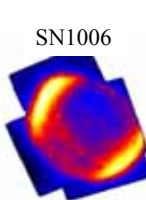
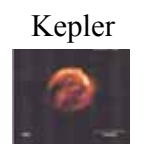
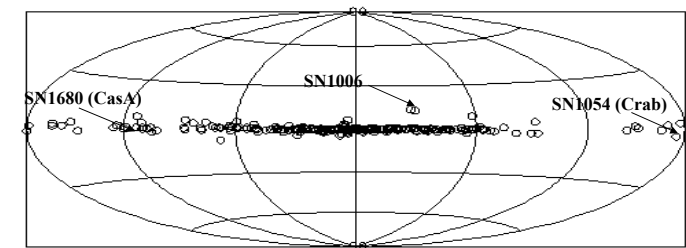
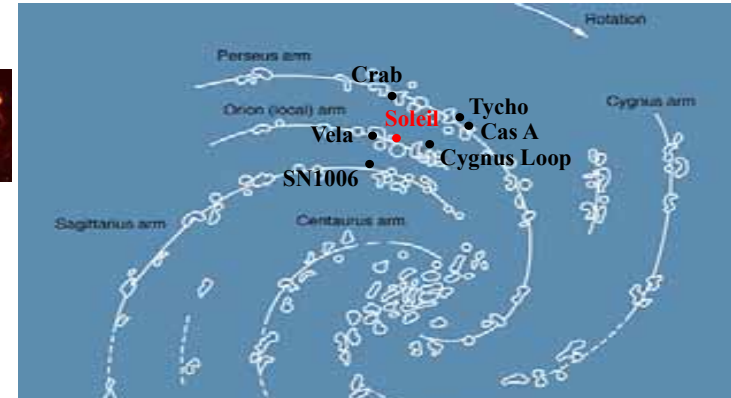
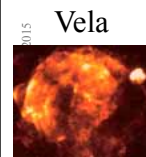
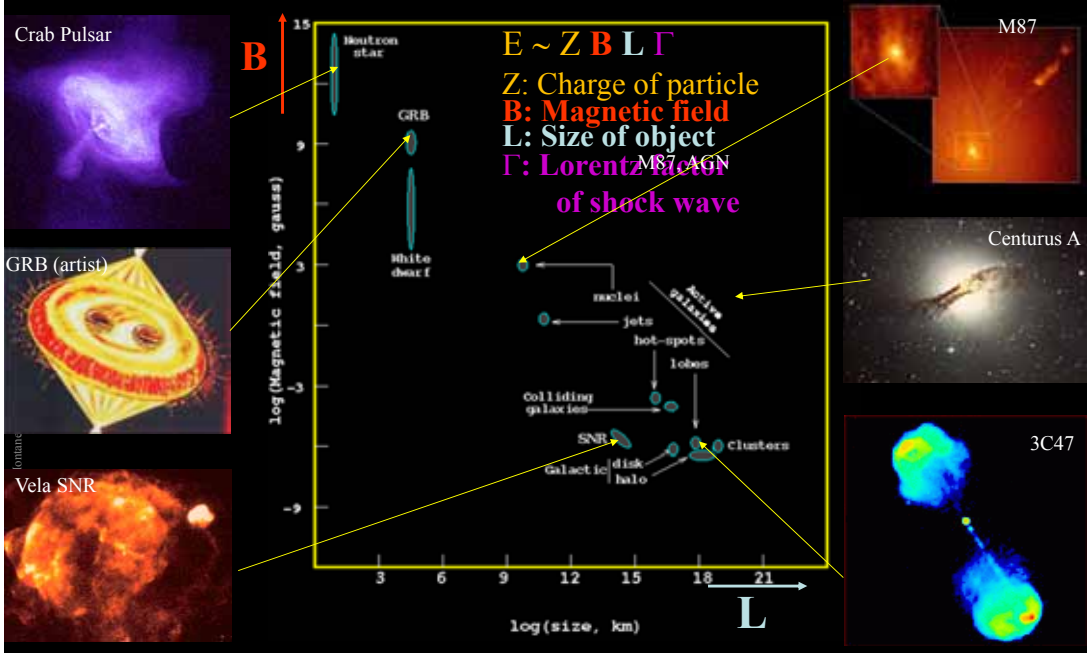


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMTs,  $N_{hit}$  (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events  $\mu 1 - \mu 4$  are muon events which precede the electron burst at time zero. The upper right figure is the 0-2-sec time interval on an expanded scale.

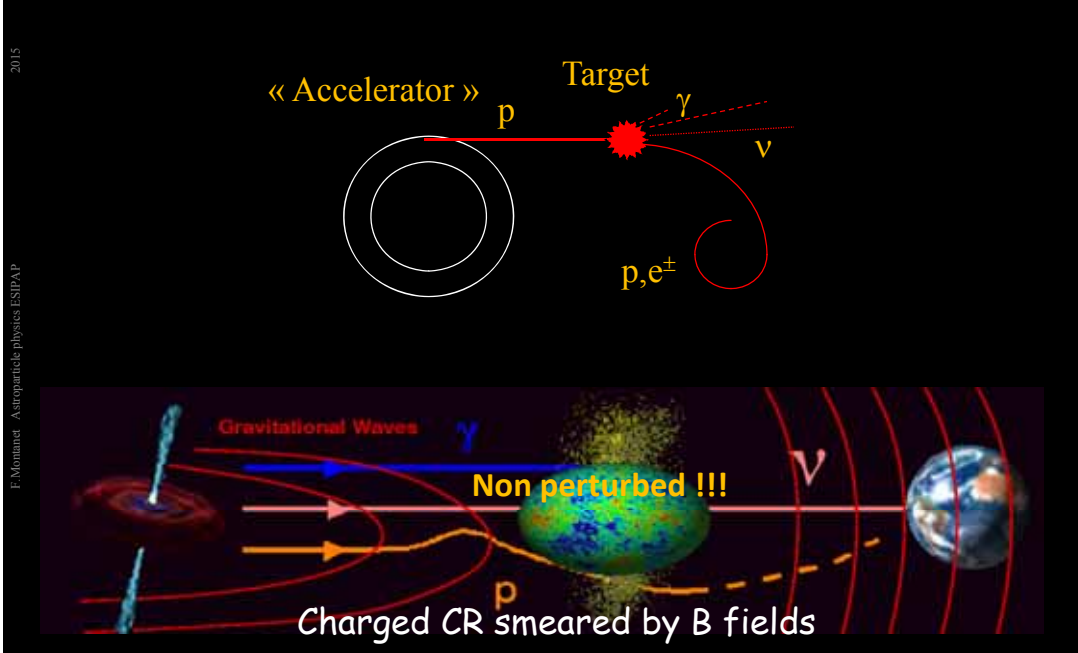
# SuperNovae Remnants



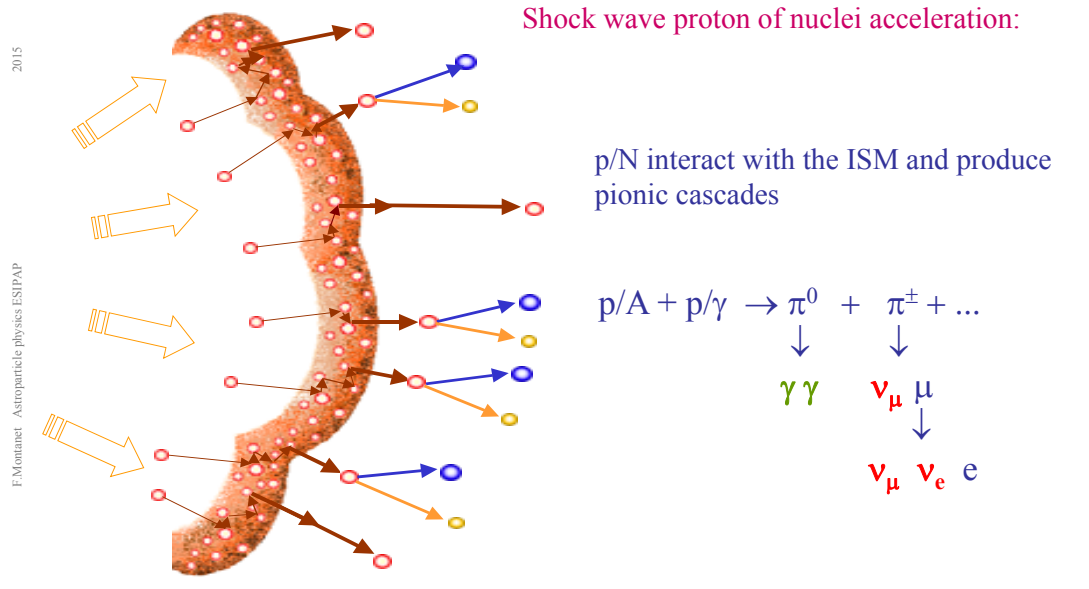
# Cosmic Accelerators: ( Hillas Plot)



# Cosmic Neutrino Beam



# Fermi acceleration and UHE neutrino production

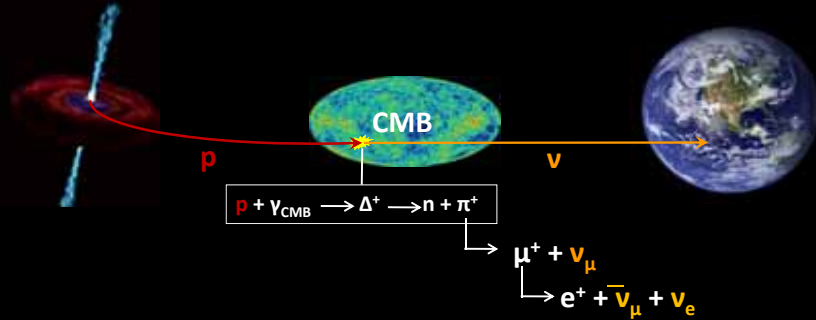


# COSMOLOGICAL SOURCES

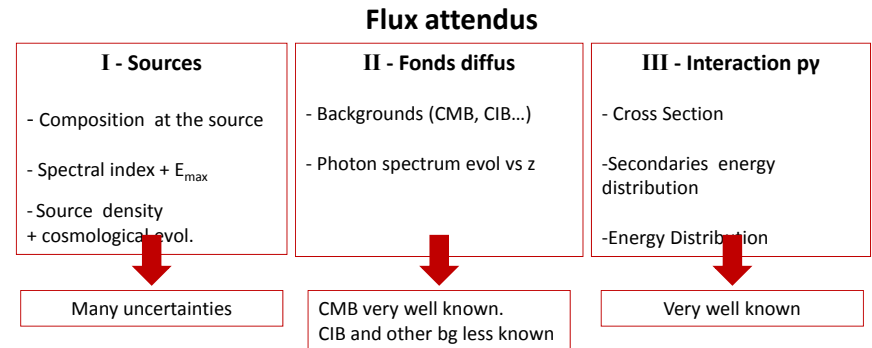


# "Cosmogenic" or "GZK" Neutrinos

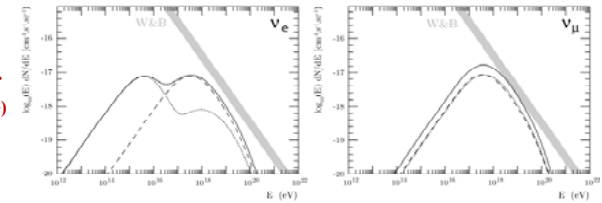
- Produced by the propagation of UHECR in the IGM.
- Main assumptions:
  - UHECR are protons or nuclei (makes a big difference)
  - The sources distribution is following a given redshift distribution
  - Spectra are known and flux are generic
  - The target density is well known (CMB photons)
- This flux can be predicted in a relatively robust manner.



# Cosmogenic or "GZK" Neutrinos



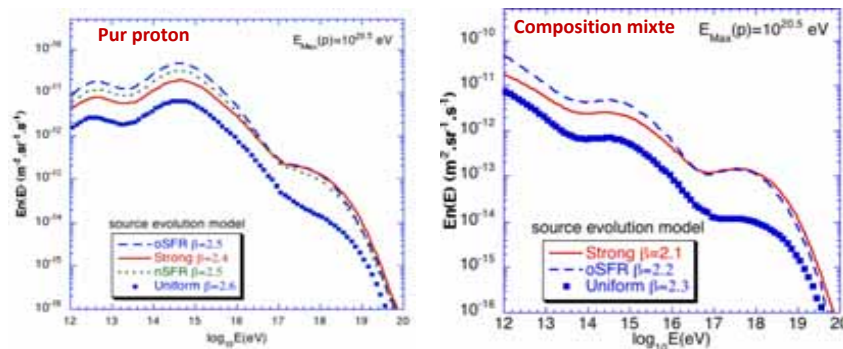
**I + II + III** →  
 $\nu_{\mu} : \nu_e : \nu_{\tau} = 2:1:0$  (source)  
 oscillations  
 $1:1:1$  (earth)



# Flux of "GZK" neutrinos

Influence of

- Composition of UHECR,
- Sources distribution and evolution.

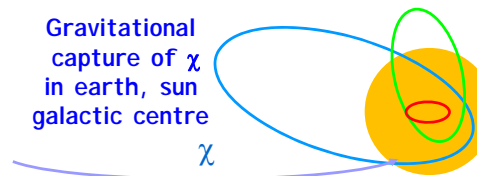


# Dark Matter as a source of neutrinos

Annihilation in Halo, Earth, Sun or Galactic Centre

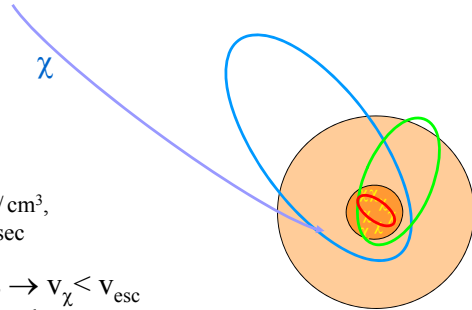
Signature	Experiment
<b>Halo</b> Positron, Antiproton Gamma rays $\chi \chi \rightarrow Z \gamma, \gamma \gamma$	BESS, CAPRICE, AMS, ... HESS, GLAST, MILAGRO, ...
<b>Earth, Sun, GC</b> Neutrino $\chi \chi \rightarrow WW, ff$ $W, f \rightarrow \nu X$	SuperK, Baksan, IMB, MACRO AMANDA, ANTARES, Baikal, ...

Gravitational capture of  $\chi$  in earth, sun galactic centre



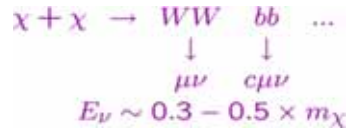
WIMP loses energy by elastic interaction  
 $\Rightarrow$  if  $v < v_{\text{escape}}$ , capture  
 capture + annihilation balance  
 $\Rightarrow$  constant density in core

# Dark Matter as a source of neutrinos



DM halo  
 $\rho_\chi \sim 0.3 \text{ GeV/cm}^3$ ,  
 $v_\chi \sim 300 \text{ km/sec}$

Collisions  $\rightarrow v_\chi < v_{\text{esc}}$   
 Gravitational capture  
 in the center  
 gravitational wells



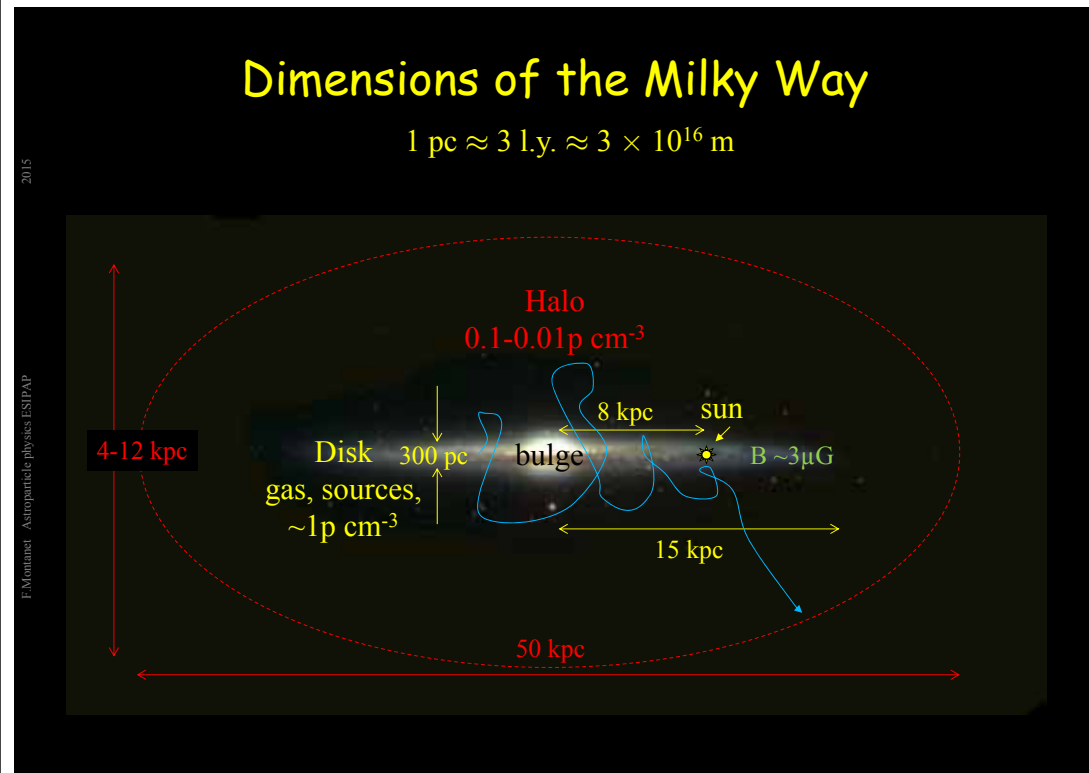
$\Rightarrow$  Indirect search for Neutralinos  
 by neutrino telescopes

# Propagation

## The general problematic

- Thermal speeds  $\rightarrow$  RCUHE (few  $10^{20}$  eV)

Produce them	<ul style="list-style-type: none"> <li>• From top to bottom (decay...)</li> <li>• From bottom to top (acceleration)</li> </ul>
Preserve them	<ul style="list-style-type: none"> <li>• Energy losses (Synch., IC, <math>\pi</math>, pairs...)</li> <li>• Destruction (photo-dissociation...)</li> <li>• Escape probabilities</li> </ul>
Propagate them	<ul style="list-style-type: none"> <li>• Propagation in ISM and IGM (mag fields: deflection, confinement...)</li> <li>• Re-acceleration</li> </ul>
Detect them	<ul style="list-style-type: none"> <li>• Balloons, satellites...</li> <li>• Air showers...                             <ul style="list-style-type: none"> <li>- Cherenkov telescopes</li> <li>- Surface &amp; Fluorescence Detectors</li> </ul> </li> </ul>



# Propagation des RC dans la Galaxie : Leaky box model

2015

F.Montanet - Astroparticle physics ESPAP

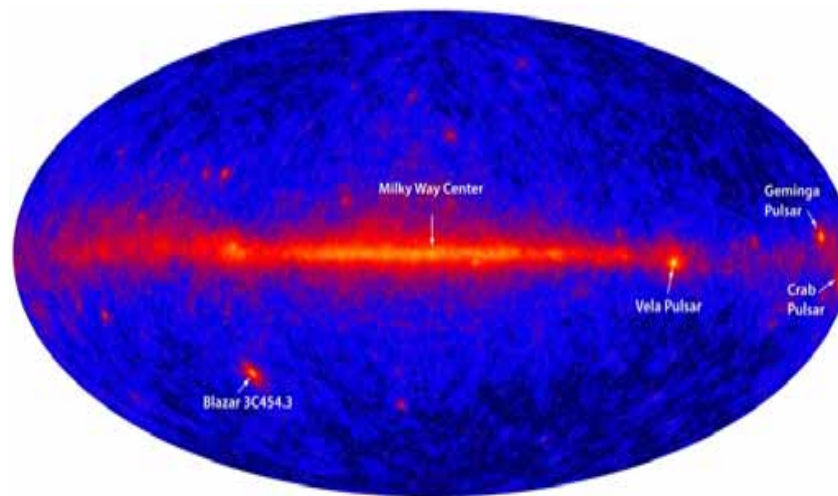
201

# A thick target

2015

F.Montanet - Astroparticle physics ESPAP

- Diffuse gamma-ray emission from galactic CR interaction with matter (mostly molecular H clouds).



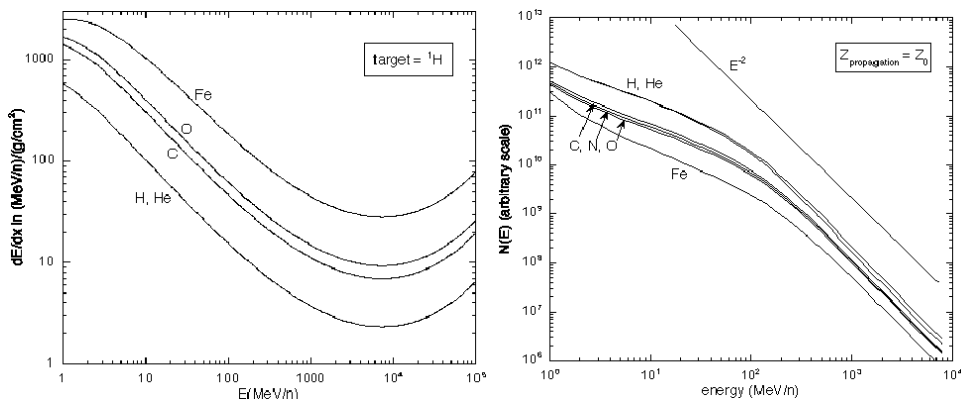
202

# Cosmic rays transport

2015

F.Montanet - Astroparticle physics ESPAP

- Propagation in the interstellar medium



Energy loss: ionization, Coulombian interactions

Propagated spectra ionization losses only (thick target)

203

# Grammage

2015

F.Montanet - Astroparticle physics ESPAP

- Column density or quantity of matter traversed by the CR from its production site to earth (in  $\text{kg} \cdot \text{m}^{-2}$  or  $\text{g} \cdot \text{cm}^{-2}$ )
- Given the diffusion time (known from cosmic clocks see below) the measurement of grammage allows the understanding of the diffusion extension zone.
- The ratio secondary/primary allows estimating the grammage traversed:

$$\frac{dN_S}{dx} = -\frac{\sigma_P}{m} N_P$$

donc  $N_S = N_P \exp\left(-\frac{\sigma_P}{m} x\right)$

et  $x = -\frac{m}{\sigma_P} \log(S/P)$

$$B/C \approx 35\% \Rightarrow x = -\frac{m}{\sigma_P} \log(B/C) \approx 60 \text{kg} \cdot \text{m}^{-2}$$

if  $Br(C + P \rightarrow B + X) \approx 100\%$

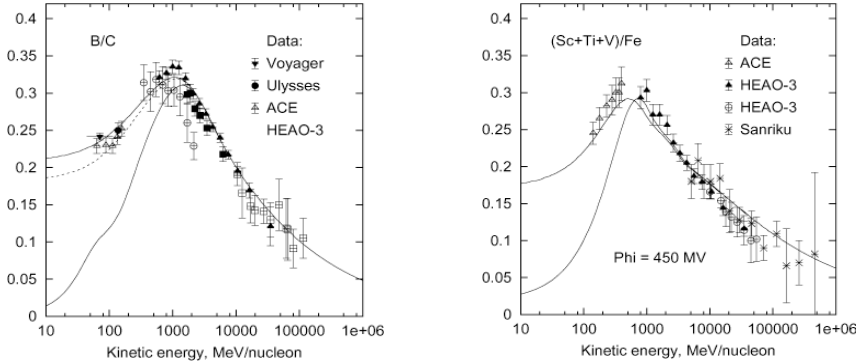
204

# Secondary / Primary ratio

The grammage depend on the parent nucleus:

- (Li+Be+B) / (C+N+O) ⇒ mean grammage of 50 kg.m<sup>-2</sup>
- (Sc+Ti+V)/Fe ⇒ mean grammage of 20 kg.m<sup>-2</sup>

and Primary/Secondary ratio (thus grammage) depends on the energy as well:



# Secondary / Primary ratio

- A complete CR transport model

– The secondary to primary ratio can be expressed by:

$$\frac{N_S}{\tau_{esc}} + \frac{N_S}{\tau_{spallation}} = \frac{N_P}{\tau_{P \rightarrow S}}$$

$$\Rightarrow \frac{N_S}{\tau_{esc}} + n\beta c\sigma_S N_S = n\beta c\sigma_{P \rightarrow S} N_P$$



$$\frac{N_S}{N_P} = \frac{\sigma_{P \rightarrow S}}{\sigma_S + 1/\lambda_{esc}}$$

with  $\lambda_{esc} = n\beta c\tau_{esc}$

# Cosmic clocks

Unstable nuclei with lifetimes comparable to the escape time  $T_{1/2} \approx \tau^{esc}$  can be used as cosmic clocks.

The ratio unstable/stable isotope helps desantangling density and escape time.

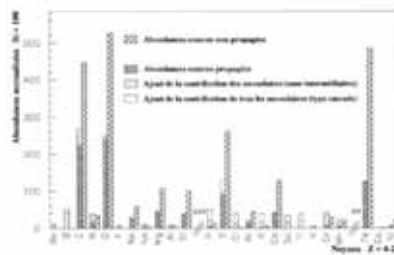
- $^{10}\text{Be} \rightarrow \tau = 2.17\text{Myr}$
- $^{26}\text{Al} \rightarrow \tau = 1.31\text{Myr}$
- $^{36}\text{Cr} \rightarrow \tau = 0.44\text{Myr}$

$$\frac{N_j}{\tau_{esc}} + \frac{N_j}{\tau_{rad}} + \frac{N_j}{\tau_{spallation}} = Q_j + \sum_{k>j} \frac{N_j}{\tau_{k \rightarrow j}}$$

Si  $\tau_{rad} \ll \tau_e$  et  $\tau_{rad} \ll \tau_{spallation}$  :

Measure isotopic ratio  $\rightarrow \frac{N_{rad}}{N_{stable}} = \frac{\tau_{rad}}{\tau_{esc}} + \frac{\tau_{rad}}{\tau_{spallation}}$   $\rightarrow$  Estimate escape time.

On gets  $\tau_e \approx 20\text{Myr}$



# Cosmic clocks and halo size

- Radioactive decay:

$$\frac{N_j}{\tau_{esc}} + \frac{N_j}{\tau_{rad}} + \frac{N_j}{\tau_{spallation}} = Q_j + \sum_{k>j} \frac{N_j}{\tau_{k \rightarrow j}}$$

Measure isotopic ratios  $\rightarrow$

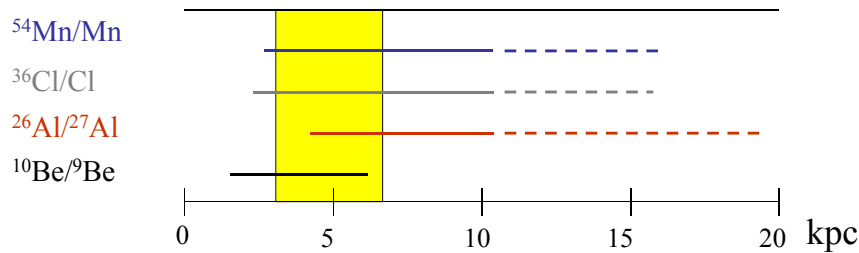
$$\frac{N_{rad}}{N_{stable}} = \frac{\tau_{rad}}{\tau_{esc}} + \frac{\tau_{rad}}{\tau_{spallation}}$$

$\rightarrow$  Estimate escape time

- $^{12}\text{C} + \text{H} \rightarrow ^9\text{Be}$  (stable secondary nucleus)
- $^{12}\text{C} + \text{H} \rightarrow ^{10}\text{Be}$  (unstable secondary nucleus:  $\sim 4 \times 10^8$  years)
- The ratio  $^{10}\text{Be} / ^9\text{Be}$  depends on secondaries history (and on cross sections).
  - Link between quantity of matter traversed and diffusion time.

# Cosmic clocks and halo size

- $^{12}\text{C} + \text{H} \rightarrow ^9\text{Be}$  (stable secondary nucleus)
- $^{12}\text{C} + \text{H} \rightarrow ^{10}\text{Be}$  (unstable secondary nucleus:  $\sim 4 \times 10^8$  years)
- The ratio  $^{10}\text{Be} / ^9\text{Be}$  depends on secondaries history (and on cross sections).
  - Link between quantity of matter traversed and diffusion time.
- Diffusion parameters adjustments (excursion in the less dense galactic halo)
  - $\Rightarrow$  determination of the CR confinement zone



# Confinement and escape

- The average measured grammage is  $x = 50 \text{ kg} \cdot \text{m}^{-2}$
- Associated lengths:
 
$$\lambda_{esc} = x/\rho \approx 750 \text{ kpc},$$
 with  $\rho = 1.4 n_H m_p \approx 2.2 \times 10^{-21} \text{ kg} \cdot \text{m}^{-3}$
- $\lambda_{esc} \gg R = 20 \text{ kpc} \Rightarrow$  CR are confined
- $\lambda_{esc} \ll \lambda_{pp} = (n_H \sigma)^{-1} \approx 6 \text{ Mpc} \Rightarrow$  CR can escape
- Long lived radioactive secondaries (cosmic clocks) indicate  $\tau_{esc} \approx 20 \text{ Myr}$
- Average density scanned by CR:

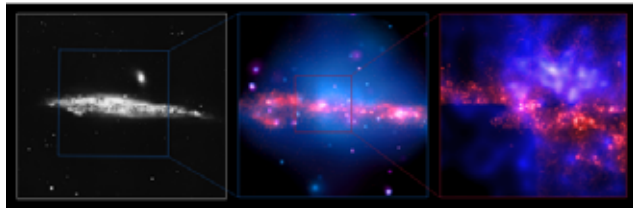
$$n_H = \lambda_{esc}/c \tau_{esc} m_p \approx 0.3 \text{ cm}^{-3} < n_{disk} = 1 \text{ cm}^{-3}$$

$\Rightarrow$  CR diffuse in a thinner region: the Halo

# Disk & Halo

- CR can wander out of the disk in a magnetized halo of hot ionized matter

$$T = 10^6 \text{ K} \quad \text{et} \quad n = 10^{-3} \text{ cm}^{-3}$$



- NGC 4631 galaxy and its halo of hot ionized matter emitting X-rays as seen by Chandra

# The « leaky box » model

- Diffusive approximation...

$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial E} [b(\vec{r}, E) N_i(\vec{r}, E, t)] = Q_i(\vec{r}, E) - \frac{N_i}{\tau_{tot}(\vec{r}, E)} + D(\vec{r}, E) \nabla^2 N_i$$

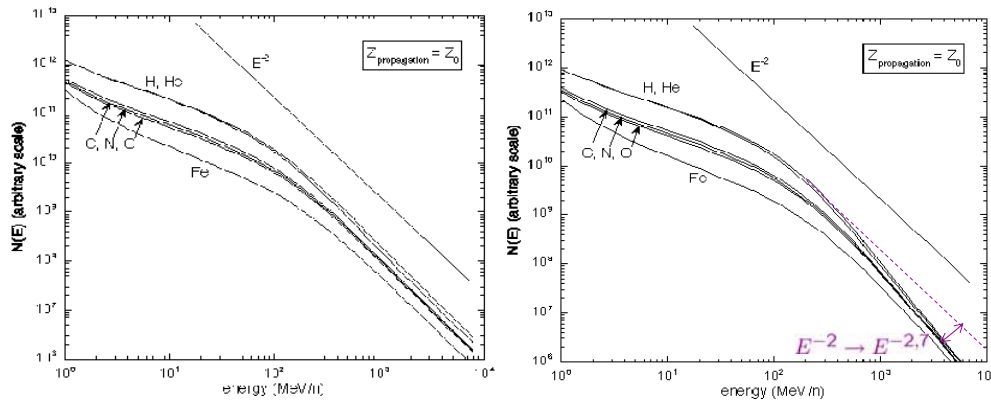
$\uparrow$  flux in energy space (losses + acceleration)    
  $\uparrow$  injection, "in flight" production    
  $\uparrow$  destruction, decay, escape    
  $\uparrow$  diffusion

- Re-acceleration...

$$+ \frac{1}{2} \frac{\partial^2}{\partial E^2} [c(\vec{r}, E) N_i(\vec{r}, E, t)]$$

# Slope of the propagated spectrum

- Escape out of the confinement zone
  - Confinement (escape probability) decrease with E



Without escape  
(thick target)

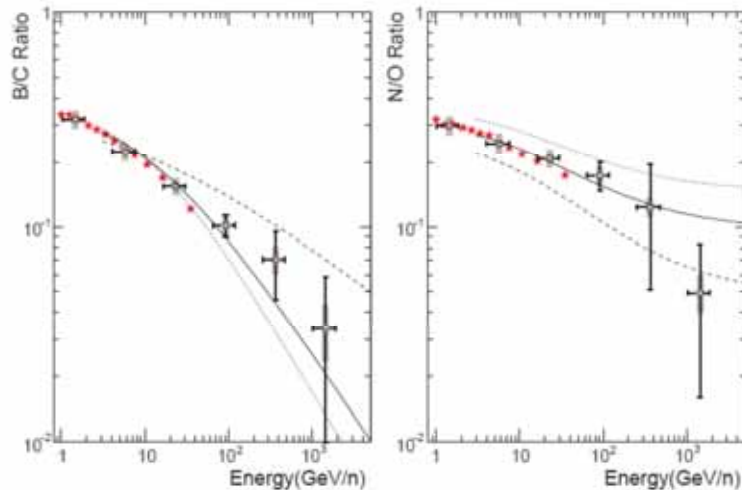
$\tau_{conf} \propto E^{-0.7}$   
 $\rightarrow E^{-2.7}$  spectrum

# CR confinement

- Escape depends on E
  - Diffusion on magnetic inhomogeneities
  - When  $E \nearrow, r_g \nearrow$  thus interaction with inhomogeneities with larger wavelengths.
- $D(E)$  is an increasing function
  - $D = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^x$  where  $\rho$  is the particle rigidity
  - $\rightarrow \tau_{conf}(E) \propto E^{-x}$
- Kolmogorov spectrum  $\rightarrow \tau_{conf}(E) \propto E^{-1/3}$ 
  - $x - 2 = 1/3 < 0,7$  ... clearly not enough but...
  - ISM perturbations ? Diffusion-convection, MHD ?
- Determination of  $\tau_{conf}(E)$  a posteriori :
  - $2,7 - 2 = 0,7$  !!!

# The CREAM results

## Secondary/Primary ratio



Compatible with propagation models with escape terms in  $E^{0.6}$

# CR anisotropy

- Very weak observed anisotropy (first angular harmonic)
  - $\delta \sim (0,5 - 1)10^{-3}$  de  $10^{12}$  à  $10^{14}$ eV
  - $\delta \sim 1$  à 2% à  $10^{17}$ eV
  - Upper limit : 5% à  $10^{18}$ eV, 10% à  $10^{18,5}$ eV, 30% à  $10^{19}$ eV
- Constraints on  $D(E)$ 
  - In the diffusive approximation, one can compute  $\delta$  taking into account the position of the solar system wrt the Galaxy.
- Observed anisotropy incompatible with sources distributed like SNR and a diffusion term  $D(E) \propto E^{0.6}$  below 10 GeV...
  - ... but compatible with  $D(E) \propto E^{1/3}$  !

# Sources Distribution

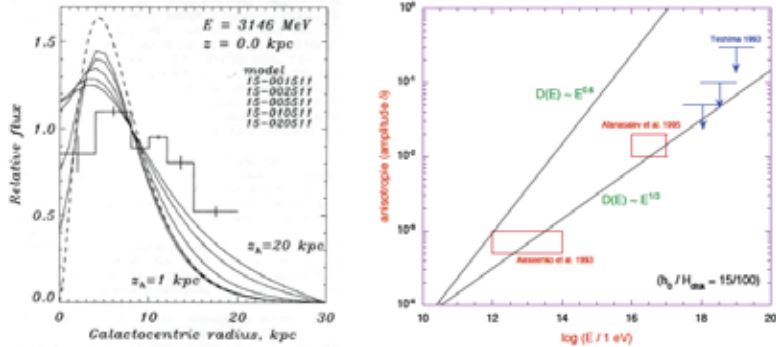


FIG. 5.1 - À gauche : distribution galactocentrique des flux de rayons cosmiques prédits par les modèles de propagations pour différentes tailles du halo de confinement (courbes en trait continu), comparée à la distribution déduite des observations d'EGRET. La courbe en pointillé montre la distribution source supposée, conforme à la distribution des SNRs, piquée sur l'anneau moléculaire à 4 kpc. À droite : évolution de l'anisotropie du rayonnement cosmique prédite pour un coefficient de diffusion en  $E^{0.6}$  (hypothèse SNR) ou en  $E^{1/3}$  (comme attendu théoriquement et suggéré par les rapports d'abondance du rayonnement cosmique), comparée aux contraintes observationnelles. La seconde solution est seule en accord avec les données.

→ Source distribution is more uniform...

# Full transport equation

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p) \text{ sources (SNR, nuclear reactions...)}$$

diffusion +  $\vec{\nabla} \cdot (D_{\chi\chi} \vec{\nabla} \psi - \vec{V} \psi)$  convection

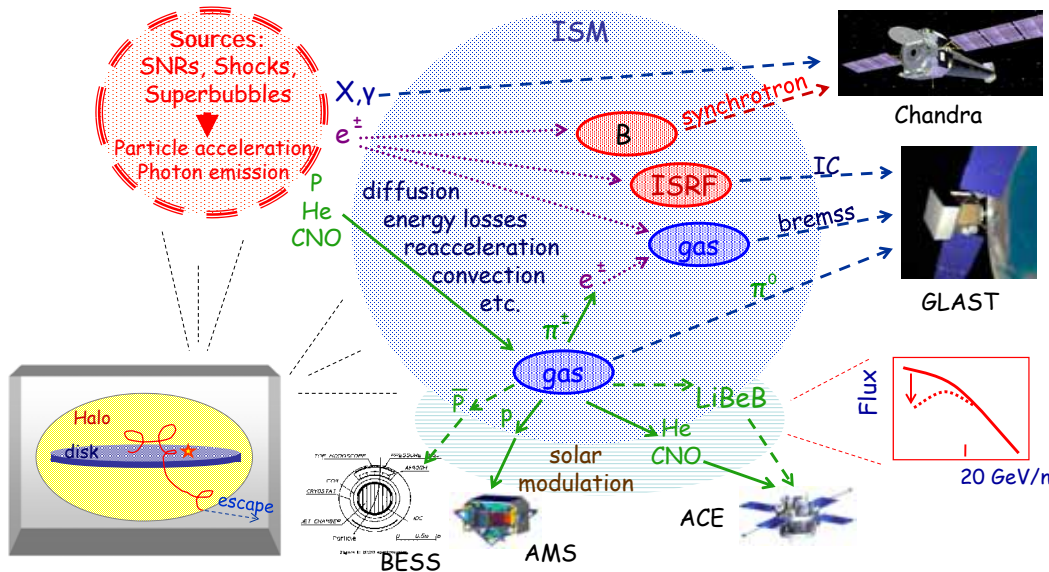
diffusive reacceleration +  $\frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \left( \frac{\psi}{p^2} \right) \right]$

E-loss -  $\frac{\partial}{\partial p} \left( \frac{dp}{dt} \psi \right) - \frac{1}{3} p \vec{\nabla} \cdot \vec{V} \psi$  convection

fragmentation -  $\frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$  Radioactive decay

$\psi(\vec{r}, p, t)$  - momentum density

# Propagation in the ISM et observational constrains



# Summary for galactic CR

Everything works fairly well...

- Propagation in the ISM:
  - Complete theory with energy losses, diffusion, in flight nuclear reactions, CR escape, reacceleration, ... impressive results. (see for example GLAPROP model, A. Strong et I Moskalenko)

- Secondaries / Primaries
- Cosmic clock
- Anisotropies
- Theoretical expectations (~ Kolmogorov spectrum :  $D(E) \propto E^{0.36}$ )

...except naive acceleration models!

- Observation + models require source spectra  $\propto E^{-2.35}$  (high energy spectral shape and  $I_{\text{aires}}/I_{\text{aires}}$  ratio "best fit")
- "Softer" (steeper) than standard spectra for strong shocks  $f(E^{-2})$

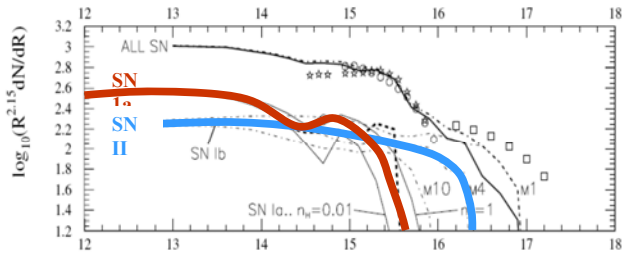
It is possible to find an agreement between diffusive propagation models and standard SNR models,

- Cut off energy, knee, non-linearities,  $\gamma$ -ray emission by SNR, source distribution...

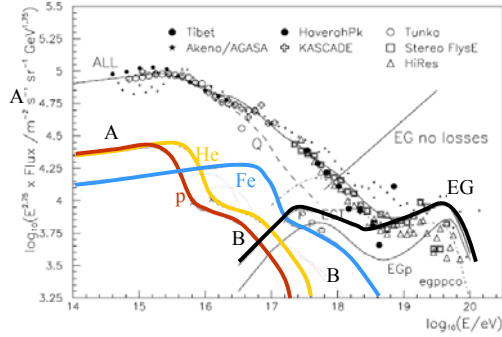
Many parameters  $\Rightarrow$  need many observational constrains.

# A conciliation exemple CR SM & diffusion

M.Hillas J. Phys., Conf. Ser. 47 (2006) 168 (<http://iopscience.iop.org/1742-6596/47/1/021>)

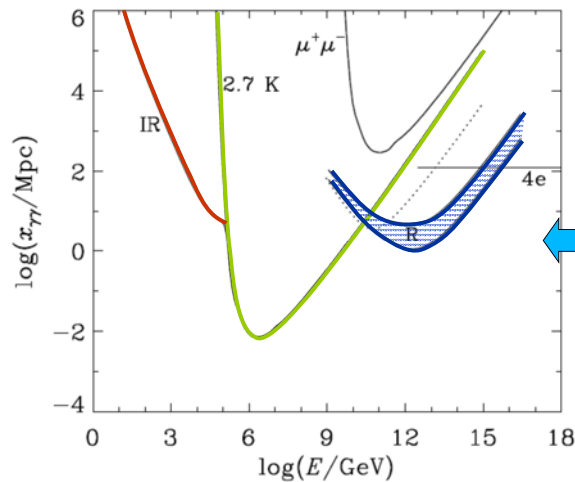


Based on former work by Bell et Lucek on amplification and self-production of Bfield perturbations by CR.



# GAMMA-RAY PROPAGATION

# Photon attenuation at VHE by intergalactic photon backgrounds

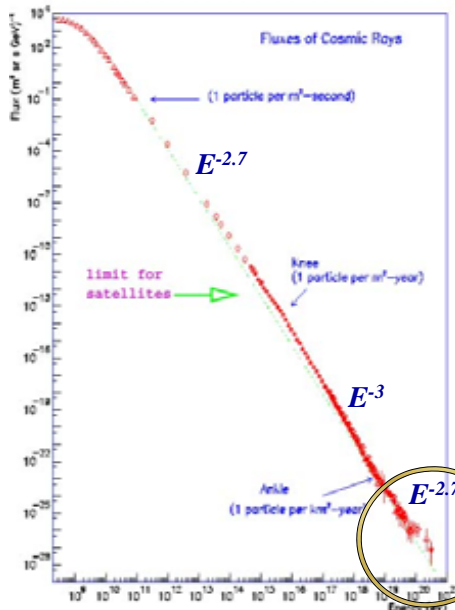


Effective  $\gamma$  horizon:  
100Mpc at 1TeV  
1Mpc at 10 TeV  
and above

# UHECR PROPAGATION



# The CR spectrum



Galactic CR :  
Supernovae, MIS,  
but no source pointing!

Galactic ?  
SuperNovae? Superbubbles?  
reacceleration?  
Heavier nuclei → protons ?

Extragalactic ?  
source ?, composition ?

**UHECR, terra incognita**

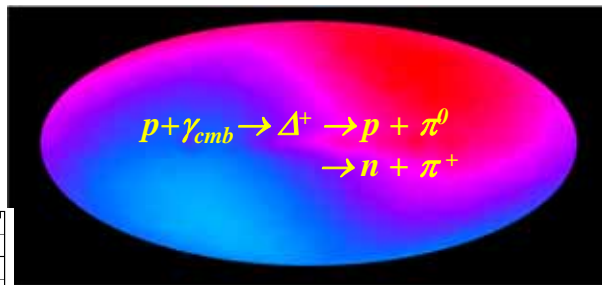
**AUGER**

# UHECR propagation

3 essential effects :

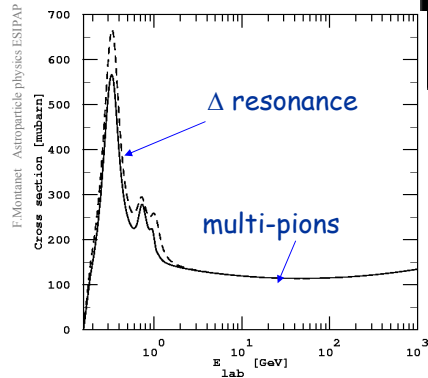
- Energy losses: modify the spectral shape
- Particle confinement (escape depending on energy)
- Spatial and angular diffusion due to magnetic fields. (regular or fluctuating, inhomogeneities, waves)

# An extrem case of relativistic kinematics !!!



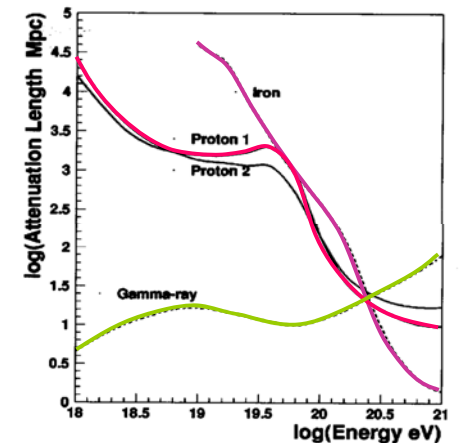
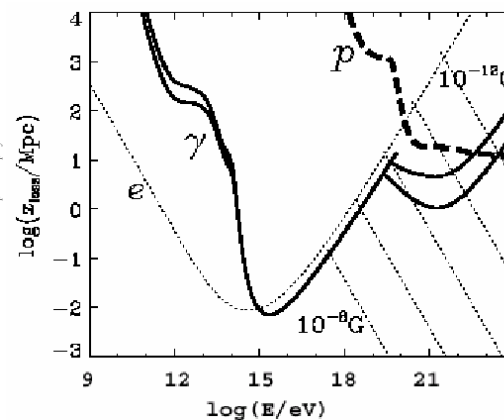
**GZK**  
**"cutoff"**

Greisen '66, Zatsepin & Kuzmin '66



# Energy losses

- $p + \gamma_{2.7K} \rightarrow n + \pi^+; p + \pi^0; p + e^+ + e^-$
- $A + \gamma_{2.7K} \rightarrow (A-1) + N; (A-2) + 2N; A + e^+ + e^-$
- $\gamma + \gamma_{2.7K} \rightarrow e^+ + e^-$

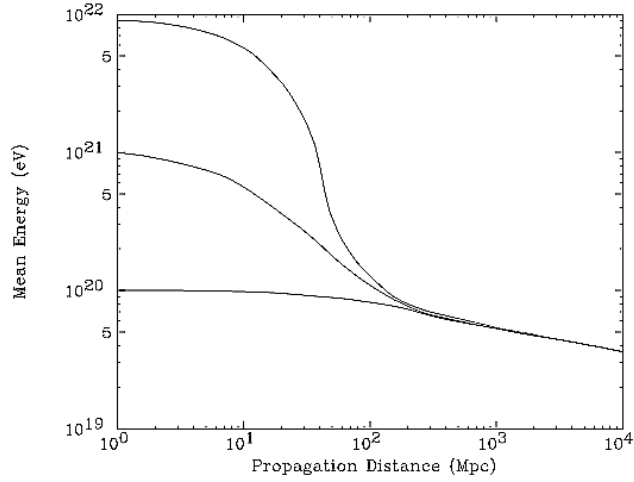


# Consequences on spectral shape

Protons:  
 Photo Pion production  
 CMB photons  
 $p + \gamma_{\text{cmb}} \rightarrow \Delta \rightarrow p/n + \pi$

Fe:  
 photo-dissociation  
 on IR bg and CMB

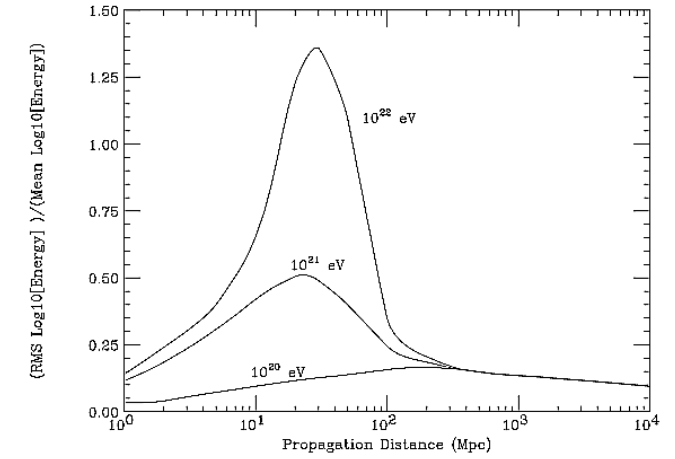
Photons: paires  $e^+e^-$   
 on radio bg



Protons energy vs. distance (J. Cronin)  
 Energy loss on CMB

# UHE Extragalactic Particles

Fluctuation dues to multiple scattering



Protons energy vs. distance (J. Cronin)  
 Energy loss on CMB

# UHE Extragalactic Particles

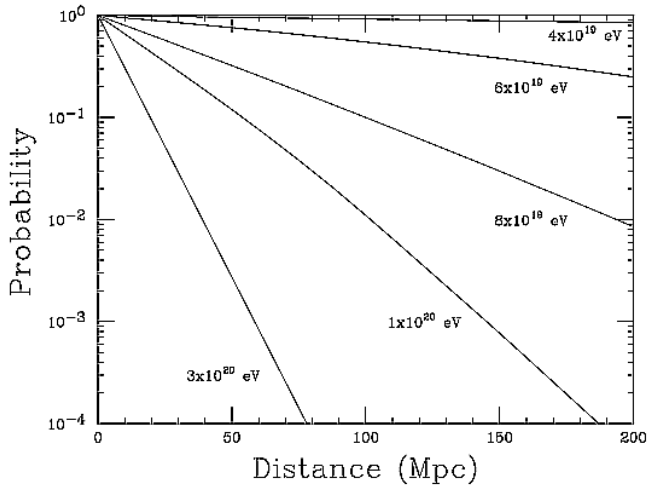
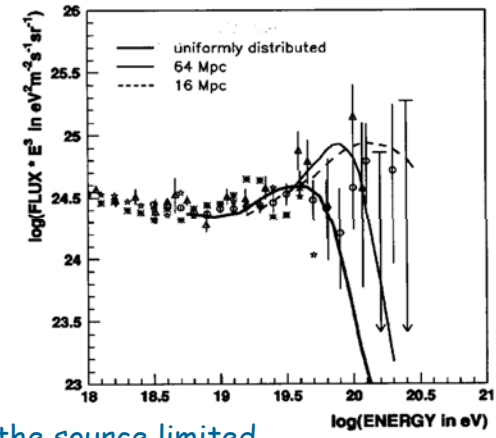


Figure 6: Probability that an observed event at a given energy has its source at a distance greater than the indicated distance. A source spectrum proportional to  $E^{-2.5}$  is assumed. Figure provided Paul Sommers, University of Utah.

# GZK suppression

• Greisen-Zatsepin-Kuz'min

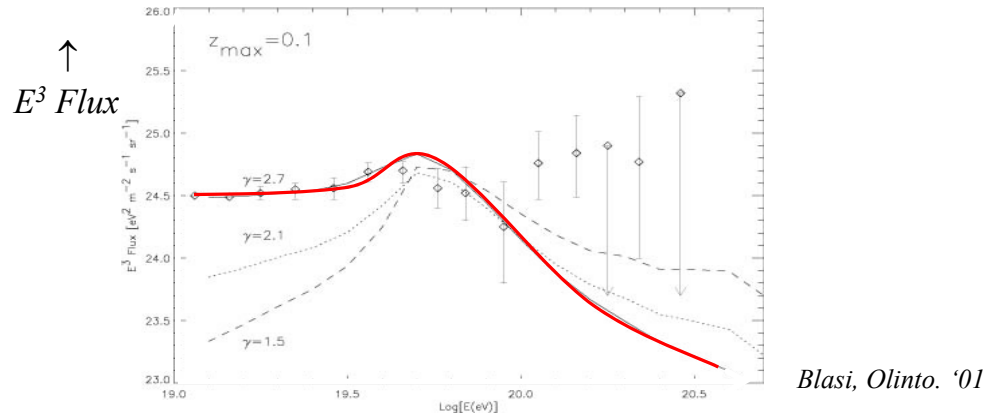


- Distance to the source limited to 100 Mpc for  $10^{20}$  eV protons, and 15 Mpc for  $3 \times 10^{20}$  !
- Actually even worse if particles are deflected ( $D_{\text{effectif}} > D_{\text{linear}}$ )

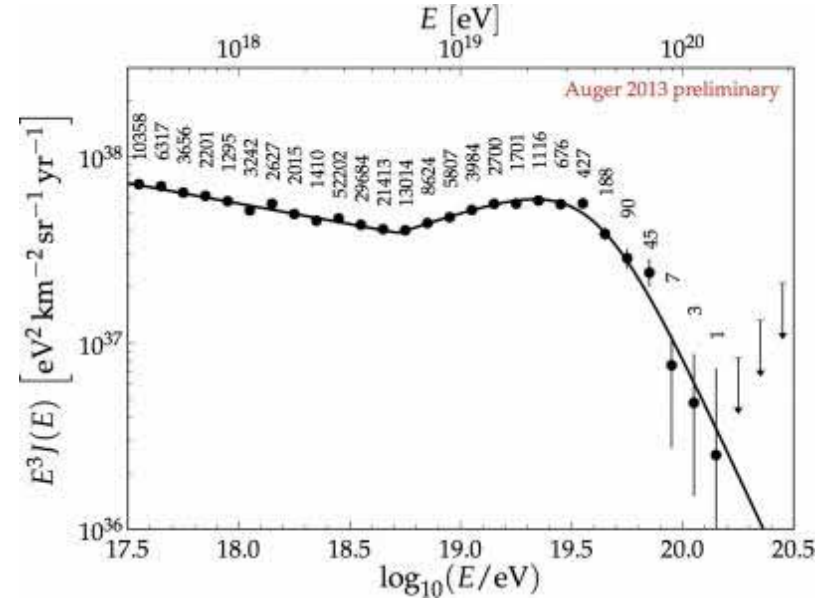
# Spectrum above GZK cutoff

Depends among other things:

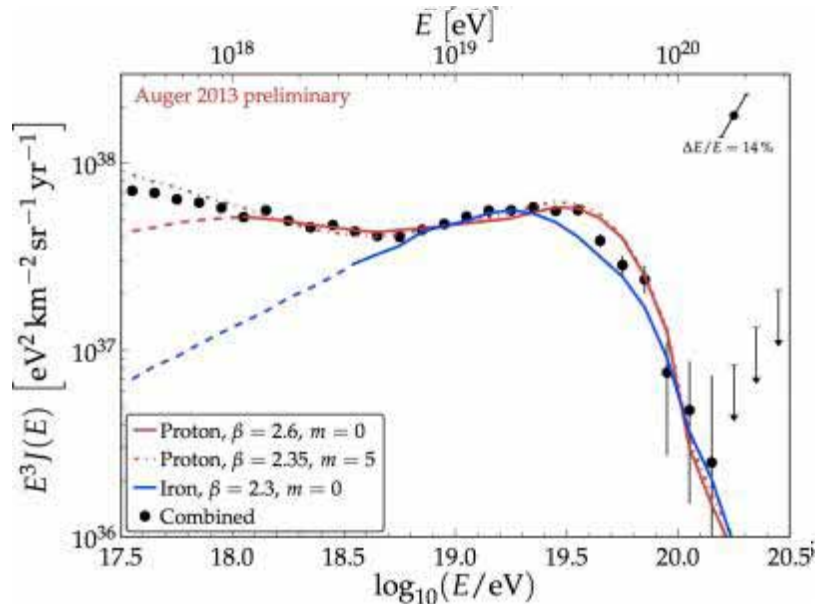
- ☞ From the injection spectrum
- ☞ From the sources cosmological distribution (evolution)
- ☞ From IG magnetic fields



# GZK like suppression (Auger)



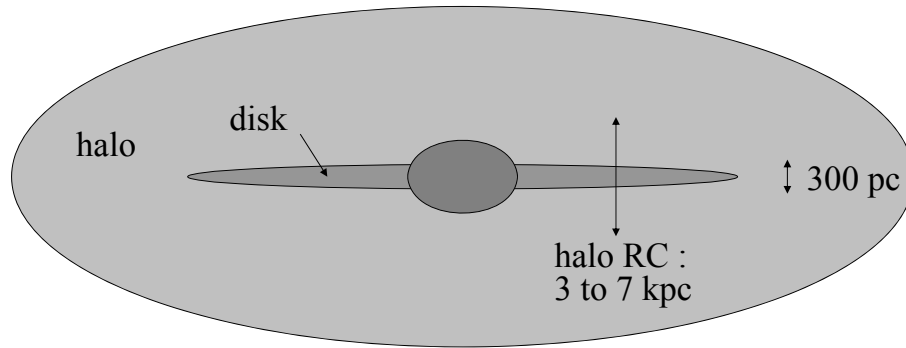
# GZK like suppression (Auger)



# MAGNETIC DEFLECTIONS

# Galactic magnetic deflection

- $10^{18}$  eV proton in a  $B = 3 \mu\text{G}$  field  $\Rightarrow r_g \sim 370$  pc

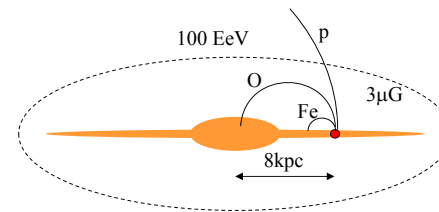


- $2 \times 10^{19}$  eV proton in  $B = 3 \mu\text{G}$   $\Rightarrow r_g \sim 7$  kpc
- $5 \times 10^{20}$  eV Fe in  $B = 3 \mu\text{G}$   $\Rightarrow r_g \sim 7$  kpc

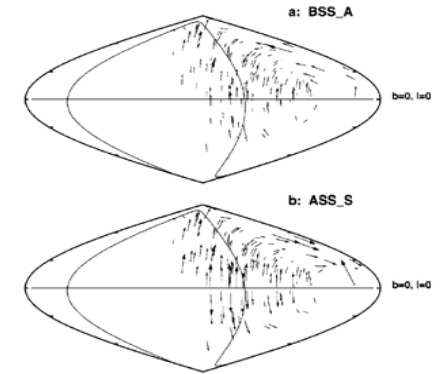
# Propagation the Galaxy

- Galactic magnetic field model

$$\left( \frac{R_{Larmor}}{kpc} \right) = \left( \frac{1}{Z} \right) \cdot \left( \frac{E}{1 EeV} \right) \cdot \left( \frac{ZB}{\mu G} \right)$$



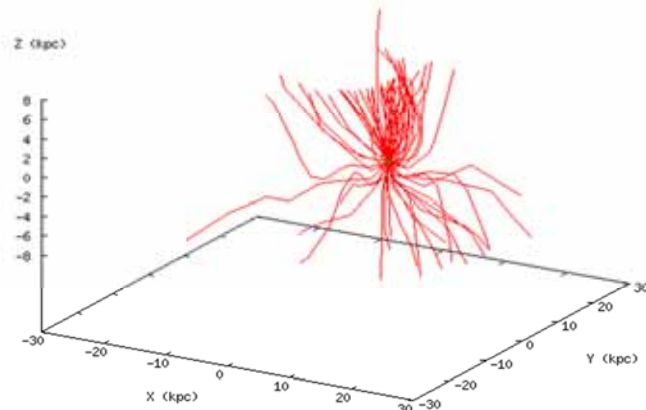
- Possible galactic confinement of  $10^{20}$ eV nuclei
- $10^{18}$ eV neutrons decay length  $\beta\gamma c\tau \approx 10\text{kpc} \Rightarrow$  galactic distances



Tracking back direction of proton events  $>4 \cdot 10^{19}$  out of the Galaxy, two different field hypothesis [Stanev97]

# Pointing at UHECR sources?

100 EeV Iron Nucleus Distribution Under the Influence of Regular Galactic Field and Galactic Wind Field



O'Neil, Olinto, Blasi '01

# Pointing at UHECR sources?

3D trajectories projected on X-Y plane

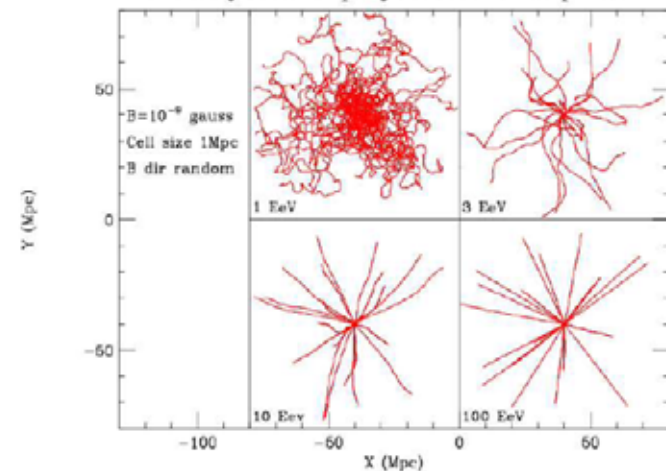
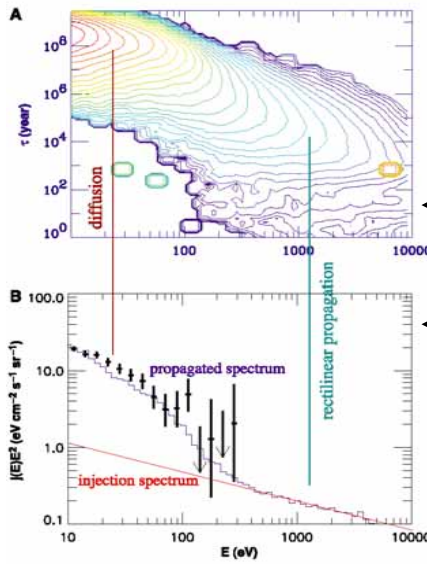


Figure 7: Projected view of 20 trajectories of proton primaries emanating from a point source for several energies. Trajectories are plotted until they reach a physical distance from the source of 40Mpc. See text for details.

# Extra-galactic UHECR propagation

2015 F. Montanet - Astroparticle physics ESPAP



From diffusive regime to rectilinear propagation [Sigl]

Time-Energy correlation

Average spectrum

Depends on the strength and coherence length of EG magnetic fields

$$\theta(E) \approx 0.025^\circ \sqrt{\frac{d}{\lambda}} \left( \frac{\lambda}{10 \text{ Mpc}} \right) \left( \frac{B}{10^{-11} \text{ G}} \right) \left( \frac{E}{10^{20} \text{ eV}} \right)^{-1}$$

$$\tau(E) \approx 200 \text{ yr} \left( \frac{d}{100 \text{ Mpc}} \right)^2 \left( \frac{\lambda}{10 \text{ Mpc}} \right) \left( \frac{B}{10^{-11} \text{ G}} \right)^2 \left( \frac{E}{10^{20} \text{ eV}} \right)^{-2}$$

# Mapping IG fields with UHECR?

2015 F. Montanet - Astroparticle physics ESPAP

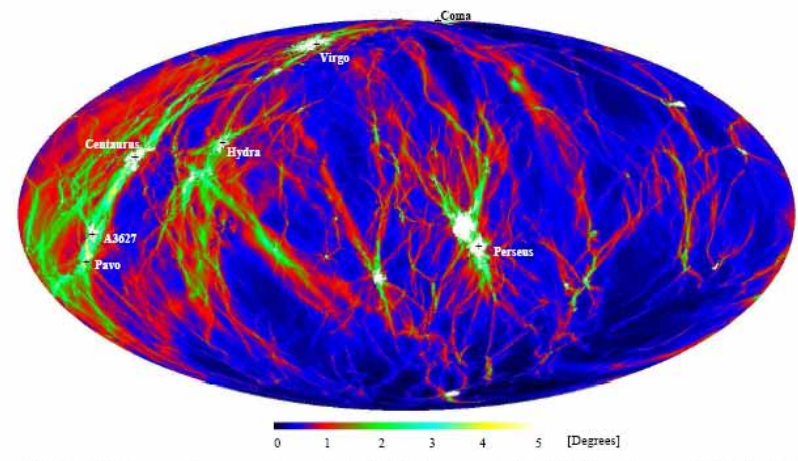


FIG. 1. Full sky map (area preserving projection) of deflection angles for UHECRs with energy  $4 \times 10^{19}$  eV using a linear color scale. All structure within a radius of 107 Mpc around the position of the Galaxy was used. The coordinate system is galactic, with the galactic anti-center in the middle of the map. Positions of identified clusters are marked using the locations of the corresponding halos in the simulation. Note that deflections internal to the Milky Way have not been included.

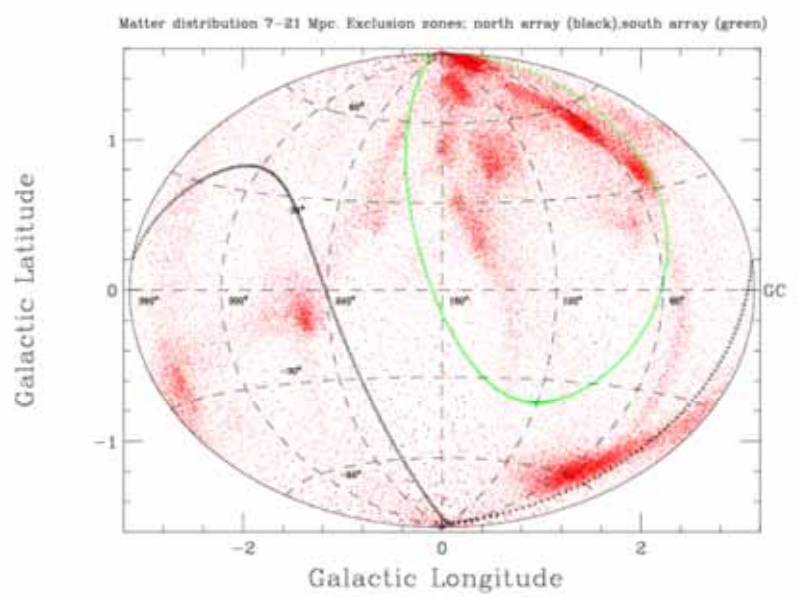
# Diffusion in the Universe

2015 F. Montanet - Astroparticle physics ESPAP

- If they are protons, arrival direction  $\approx$  source direction
    - $r_L \approx 100 \text{ kpc} \times Z \times (E/10^{20} \text{ eV}) \times (B/10^{-6} \text{ G})^{-1}$
    - $\delta\theta \sim \lambda_B/r_L$  deviation per field correlation length  $\Rightarrow \Delta\theta \sim \sqrt{D\lambda_B}/r_L$
    - $\rightarrow$  Proton astronomy!
  - Correlations between arrival directions and sources: UHECR distribution is NOT ISOTROPIC!!! (AUGER 2007)
    - Confirmation of a GZK limited horizon
    - Few sources in the GZK sphere  $\rightarrow$  anisotropic
    - Astrophysical origine is confirmed!
  - Arrival time delay
    - $\Delta t \sim \Delta\theta^2 d/c \sim D^2 \lambda_B / r_L^2 c$
    - If eruptive or transient sources (GRBs, TDs), they must overlap in time (otherwise E(t)!)
      - Multiplets of events from same direction observed but no significant ordering in E or deviation.
- $\rightarrow$  Correlation must be confirmed! (statistics...)

# Matter distribution in the GZK sphere

2015 F. Montanet - Astroparticle physics ESPAP



# Observables & Observations

2015

F.Montanet - Astroparticle physics ESIPAP

## PRIMARY RC DETECTION (ON TOP OF ATMOSPHERE)

246

### How to characterize the primary particle?

- Mass  $m$
- Electric charge  $Ze$
- Velocity  $v = \beta c$
- Lorentz Facteur  $\gamma = E/mc^2$
- Momentum  $p = mc\beta\gamma$
- Kinetic energy  $T = mc^2(\gamma - 1)$

2015

F.Montanet - Astroparticle physics ESIPAP

247

### How to characterize the primary particle?

Detector	Observable	Link with the particule
Magnetic spectrometer	Rigidity & Sign of Z	$pc/Ze$
Time of flight	Velocity/c	$\beta$
Proportionnal counters Scintillators Ionisation chamber	Ionisation	$dE/dx = Z^2 f(\beta)$
Čerenkov effect	Č photons density	$dN/dx = Z^2 g(\beta)$
Transition radiation	Number of photons X	$N = Z^2 h(\gamma)$
Calorimeter	Deposited energie	$mc^2(\gamma - 1)$

2015

F.Montanet - Astroparticle physics ESIPAP

248

## Two important radiations for particle identification

Two effects of the **polarization** induced by charged particles in dielectric medium

Proportionnal to  $Z^2$

- Čerenkov radiation : si  $v > c/n$   
Sensitive to  $\beta = v/c$
- Transition radiation : at the interface of  $\neq$  dielectric media  
Sensitive to  $\gamma = E/(mc^2)$

249

## Cherenkov Radiation

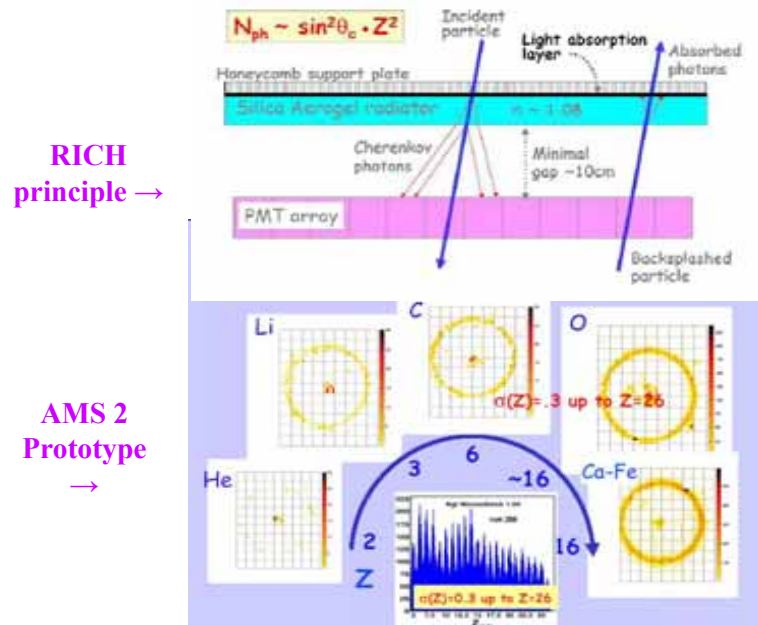
- Emitted on a cone whose axis is along the particle trajectory and of half opening angle  $\theta_C$  tel que  $\cos\theta_C = 1/(\beta n(\omega))$
- Threshold defined by the condition  $\cos\theta_C < 1$
- Emission at all frequencies with  $n(\omega) > 1$  (from UV to radio), flat in  $h\nu$  in photon yield Generally detected from near UV to visible light.

$$\frac{dN^2}{dx d\omega} = \frac{\alpha}{c} Z^2 \sin^2 \theta_C$$

- Allow discrimination between particles with same momentum and  $\neq$  masses. (électrons / protons / noyaux) up to energies of the order of 10 GeV/nucleon if  $\Delta\beta/\beta \approx 10^{-3}$
- Allow determining the orientation of the particle direction.
- "Ring Imaging Cherenkov" detector or RICH : allow a precise measurement of the charge.

250

## Cherenkov imaging (RICH) and charge measurement



251

## Transition radiation

- Origine : if a particle traverse the boundary between 2  $\neq$  dielectric media, the solution corresponding to each medium do not satisfy the conditions at the boundary.  
→ nécessité d'une onde « libre » supplémentaire.
- A dielectric medium is characterised by its "plasma" frequency  $\omega_p$  (oscillation frequency of free-like electrons)  
$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$
 or  $\hbar\omega_p = 2E_R \sqrt{4\pi n_e a_B^3} \approx 20\text{eV}$   
 $n_e$  = electron density ;  
 $E_R$  = Rydberg energy = 13.6eV ;  
 $a_B$  = Bohr radius
- Roughly half of the energy is emitted in the frequency domaine  $0.1\gamma\omega_p < \omega < \gamma\omega_p$  for a Lorentz factor  $\gamma \approx 1000$ , This is the X-ray domaine (2 to 20 keV)
- Energy emitted by the interface if  $I = \alpha z^2 \gamma \hbar\omega_p / 3$

252

## Transition radiation (cont)

- Angular distribution peaked at small angles around particle direction:  
 $\theta \approx 1/\gamma$
- Small yield of X-photons per interface :  $N \approx \alpha Z^2 \approx 10^{-2} Z^2$   
→ multiply the number of interfaces  
→ stack plastic sheets or fibers
- X-ray detection by photo-electric effect: proportional tubes
- Discriminates between particles with same energy and  $\neq$  masses at high energies (100 GeV to 1 TeV) (instrumental detection threshold for X-rays).
- Can measure the Lorentz factor  $\gamma$  up to  $10^5$ . In this case, choose material adequately to have a progressive threshold.

253

## Charge particles and cosmic antimatter

### Satellite born experiment : AMS-1, PAMELA, AMS-2

- **First satellite based experiments** on cosmic rays : **HEAO-C, Ariel-VI (1979)** → relatively low energy (up to a few 10 GeV/nucleon)
- **First satellite based magnetic spectrometer** en satellite : **AMS-1** on the space shuttle « Discovery » (1998)
- **New generation of experiments:**  
**PAMELA** (since Juin 2006)  
**AMS-2** (since May 2011)  
on the International Space Station → **data up to ~TeV**  
and precise measurements of flux of cosmic antiparticles

254

## AMS-2 On Board ISS

**Mission Number:** STS-134  
**Launch:** May 19, 2011  
**Orbiter:** Endeavour



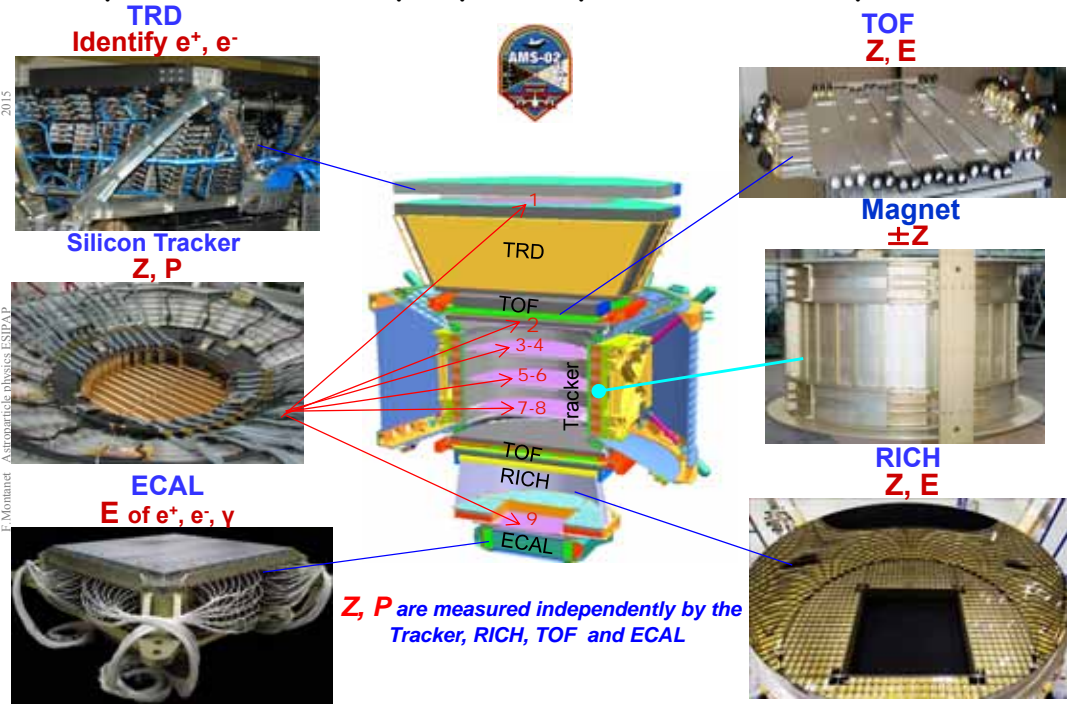
## Space spectrometers

	AMS-1 (June 1998)	PAMELA (June 2006 - ...)	AMS-2 (May 2011 - ...)
Spectrometer Acceptance	0.82 m <sup>2</sup> sr	20.5 cm <sup>2</sup> sr	0.82 m <sup>2</sup> sr
Spectrometer	Permanent magnet Nd Fe B 0.15 T BL <sup>2</sup> = 0,15 T m <sup>2</sup> 6 plans (Si)	Permanent magnet Nd Fe B 0.48 T BL <sup>2</sup> = 0,10 T m <sup>2</sup> 6 plans (Si)	Permanent magnet Nd Fe B 0.15 T BL <sup>2</sup> = 0,15 T m <sup>2</sup> 6 plans (Si)
Time of Flight	yes	yes	yes
Cherenkov	Aerogel (threshold)	-	Ring Imaging Ch.
Transition rad	-	yes	yes
Neutrons det.	-	<sup>3</sup> He	-
Anticoincidence	-	yes	yes
Calorimeter	-	16,3 X <sub>0</sub> W+22 plans (Si)	16 X <sub>0</sub> Pb+fibers sc.

256



# A precision, multipurpose spectrometer up to TeV



**TRD**  
Identify  $e^+$ ,  $e^-$

**TOF**  
 $Z, E$

**Magnet**  
 $\pm Z$

**RICH**  
 $Z, E$

**Silicon Tracker**  
 $Z, P$

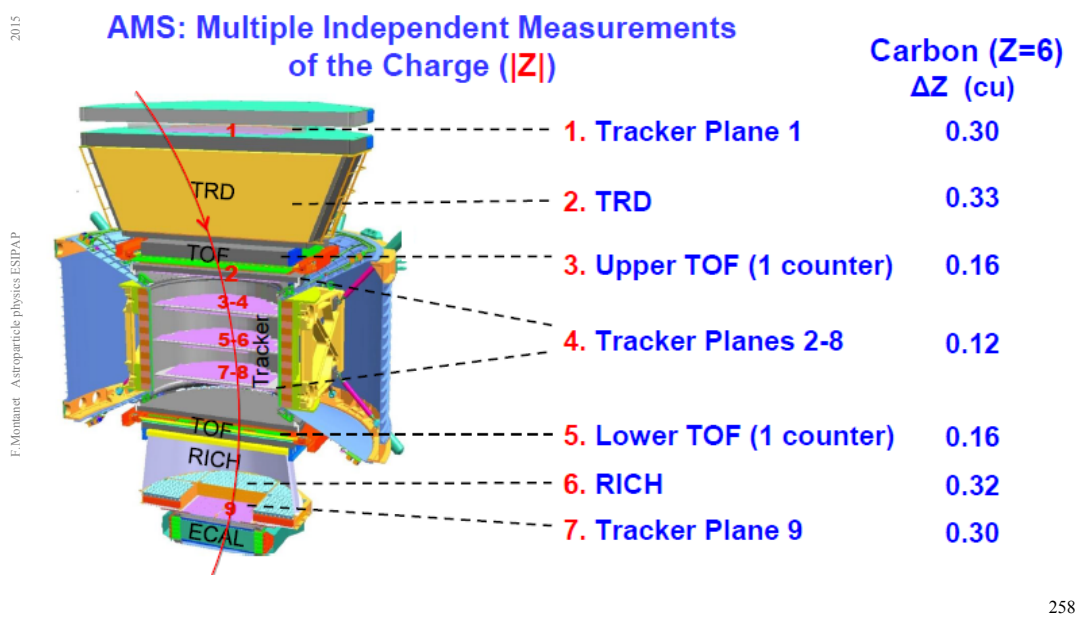
**ECAL**  
 $E$  of  $e^+$ ,  $e^-$ ,  $\gamma$

$Z, P$  are measured independently by the Tracker, RICH, TOF and ECAL



# AMS charge identification

**AMS: Multiple Independent Measurements of the Charge ( $|Z|$ )**



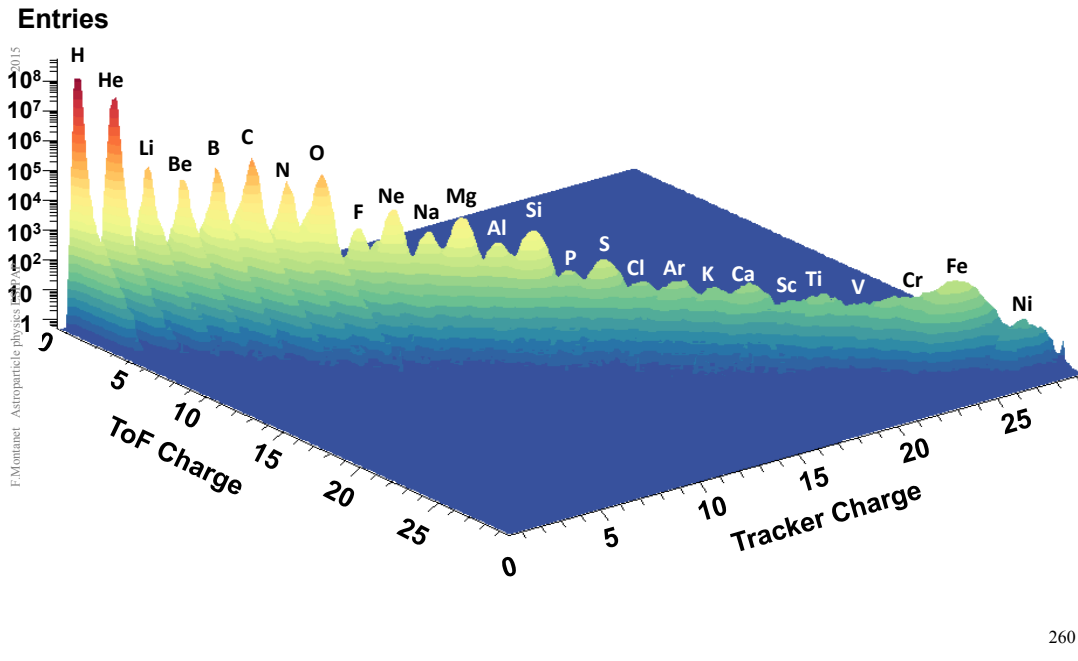
	Carbon ( $Z=6$ ) $\Delta Z$ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30



# Full coverage of anti-matter & CR physics

	$e^-$	$P$	He, Li, Be, ... Fe	$\gamma$	$e^+$	$\bar{P}, \bar{D}$	$\bar{He}, \bar{C}$
TRD							
TOF							
Tracker							
RICH							
ECAL							
Physics example	Cosmic Ray Physics				Dark matter		Antimatter

# AMS Nuclei Measurement on ISS

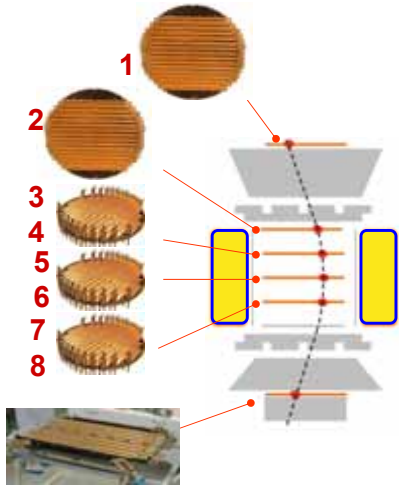


# Silicon Tracker

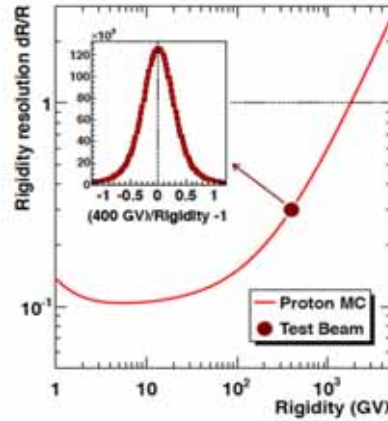
Coordinate resolution 10  $\mu\text{m}$

→ 20-UV Lasers to monitor inner tracker alignment

→ Cosmic rays to monitor outer tracker alignment

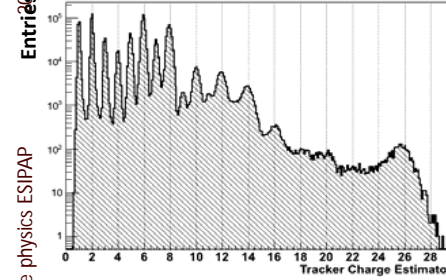


9 layers of double sided silicon microstrip detectors  
192 ladders / 2598 sensors/ 200k readout channels



# Silicon Tracker charge resolution

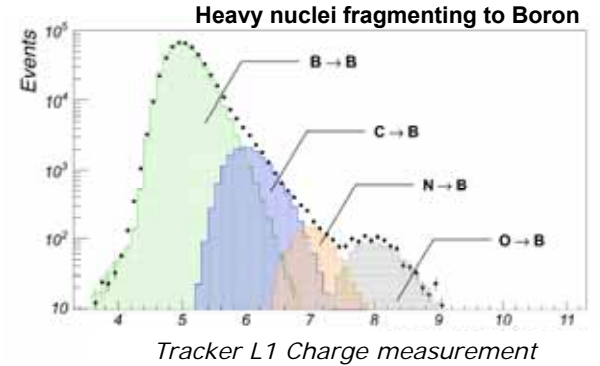
Abundances not corrected for detector efficiencies  
H and He prescaled



The first layer (L1), used as a standalone charge detector has a charge resolution ( $\sim 0.3$  c.u.) that allows the identification of the fragmentations, being at the top of the instrument (TOI)

Thanks to several energy deposits in silicon and the High Dynamic Range of the Front End electronics, the Silicon Tracker has a very accurate charge resolution

→  $\sim 0.1$  c.u.

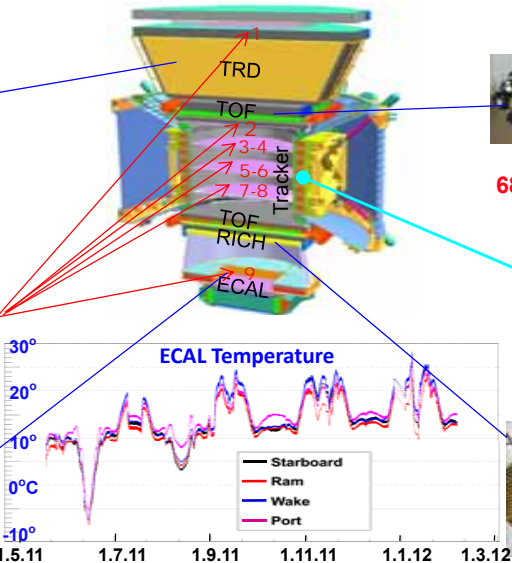


# Flight electronics for thermal control

TRD  
24 Heaters  
8 Pressure Sensors  
482 Temperature Sensors

Silicon Tracker  
4 Pressure Sensors  
32 Heaters  
142 Temperature Sensors

ECAL  
80 Temperature Sensors

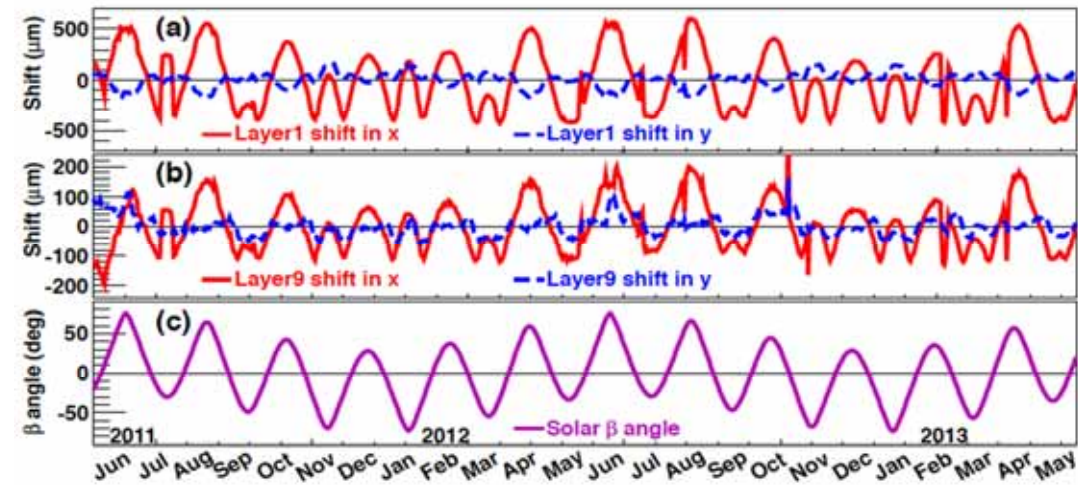


TOF & ACC  
64 Temperature Sensors

Magnet  
68 Temperature Sensors

RICH  
96 Temperature Sensors

# Seasonal effects on Tracker

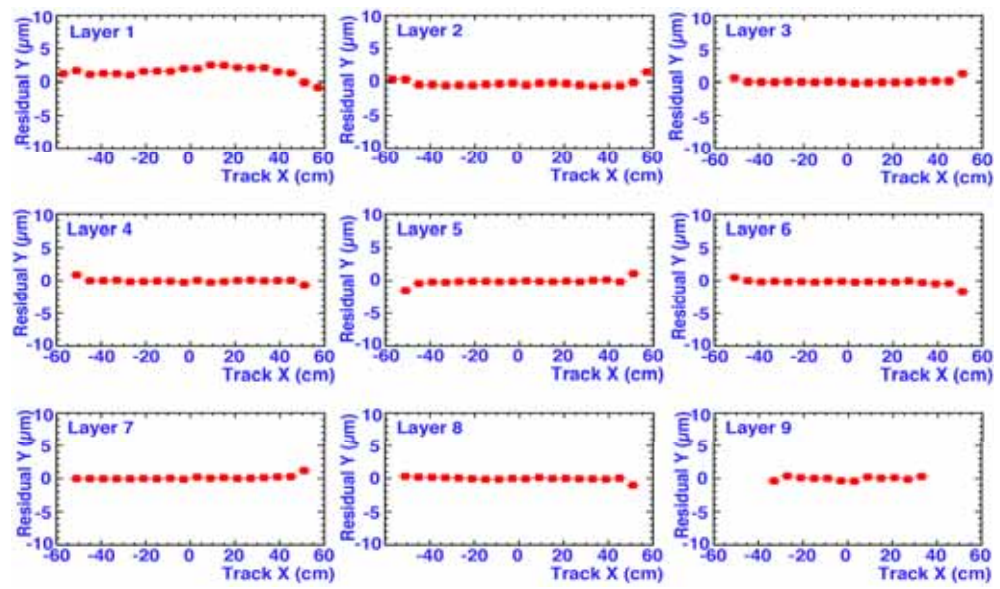




# Tracker layers alignment accuracy

2015

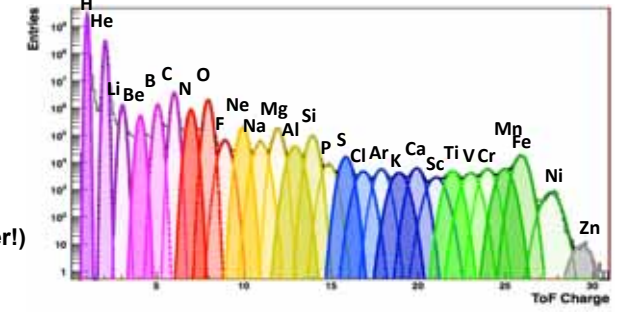
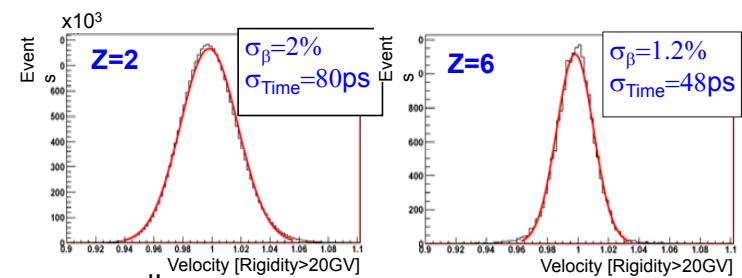
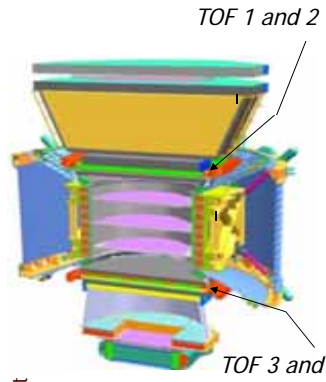
FMontanet Astroparticle physics ESIPAP



# Time of Flight (TOF)

2015

FMontanet



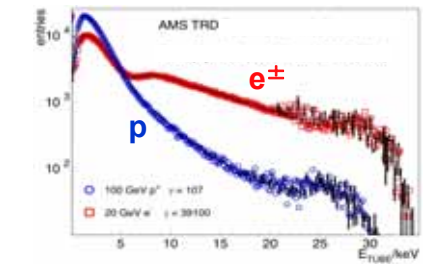
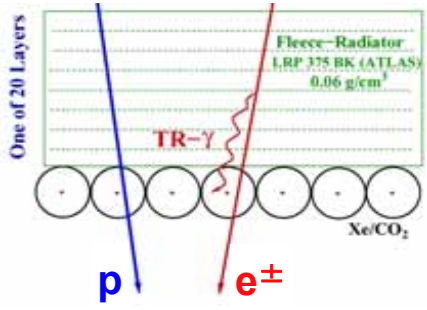
Up-going particles (fake anti-matter!) rejection up to 10<sup>9</sup>



# Transition Radiation Detector (TRD)

2015

FMontanet Astroparticle physics ESIPAP



$$P_e = \sqrt[n]{\prod_i P_e^{(i)}(A)}$$

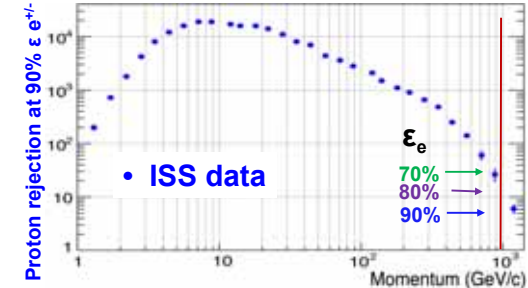
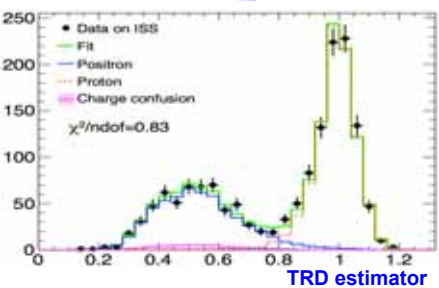
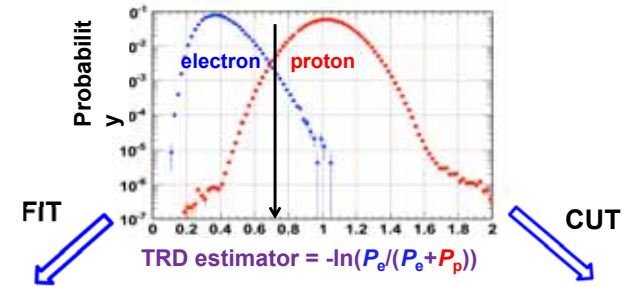
$$P_p = \sqrt[n]{\prod_i P_p^{(i)}(A)}$$



# TRD e/p separation

2015

FMontanet Astroparticle physics ESIPAP

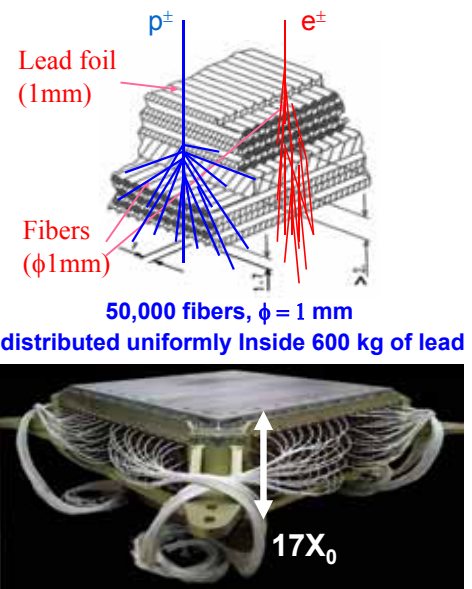




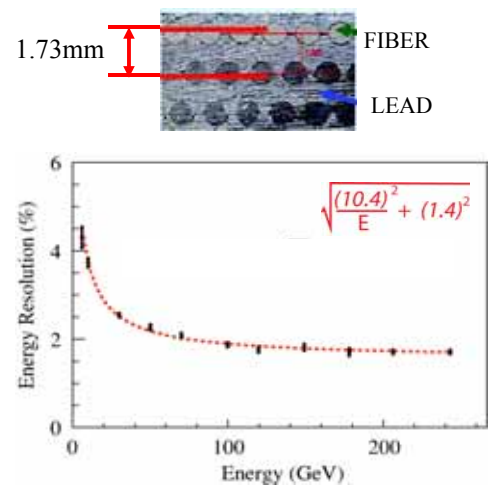
# Electromagnetic Calorimeter (ECAL)

2015

F.Montanet Astroparticle physics ESIPAP



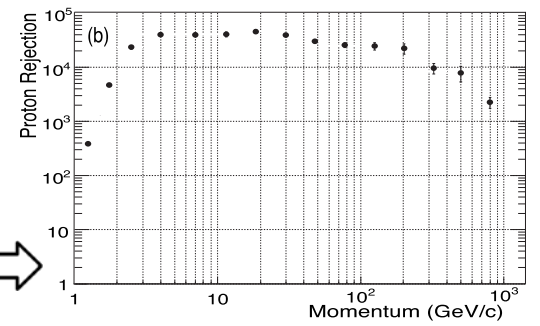
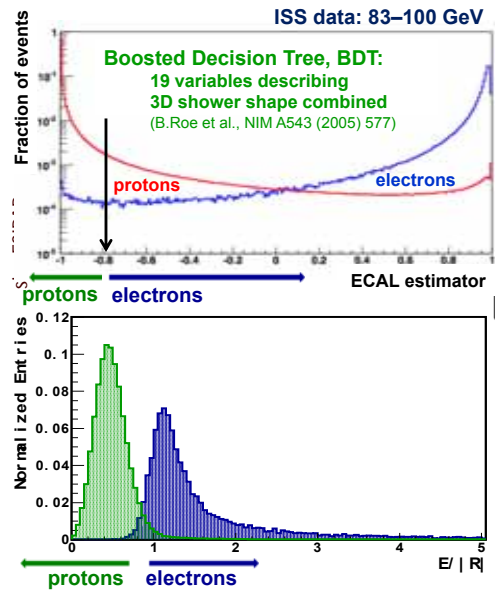
A precision, 3-D measurement of the directions and energies of gammas and electrons up to 1 TeV



269



# ECAL e/p rejection



The Calorimeter thanks to its shower shape imaging capabilities can discriminate very sensibly electromagnetic from hadronic showers

Combining the ECAL energy information with the Tracker Rigidity (E/R) the e/p rejection can be furtherly increased

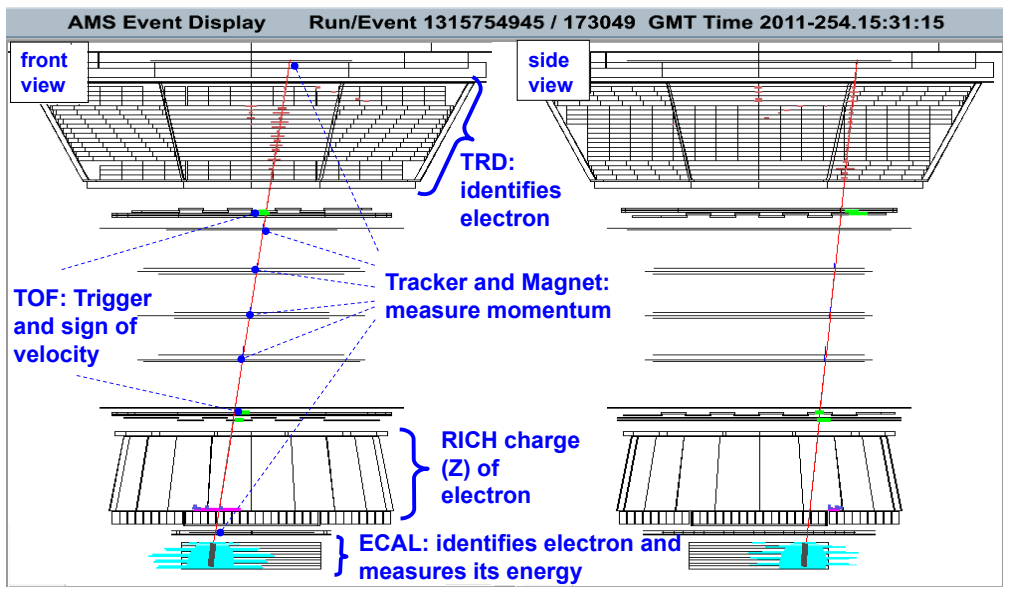
270



# AMS data on ISS - 1.03 TeV electron

2015

F.Montanet Astroparticle physics ESIPAP



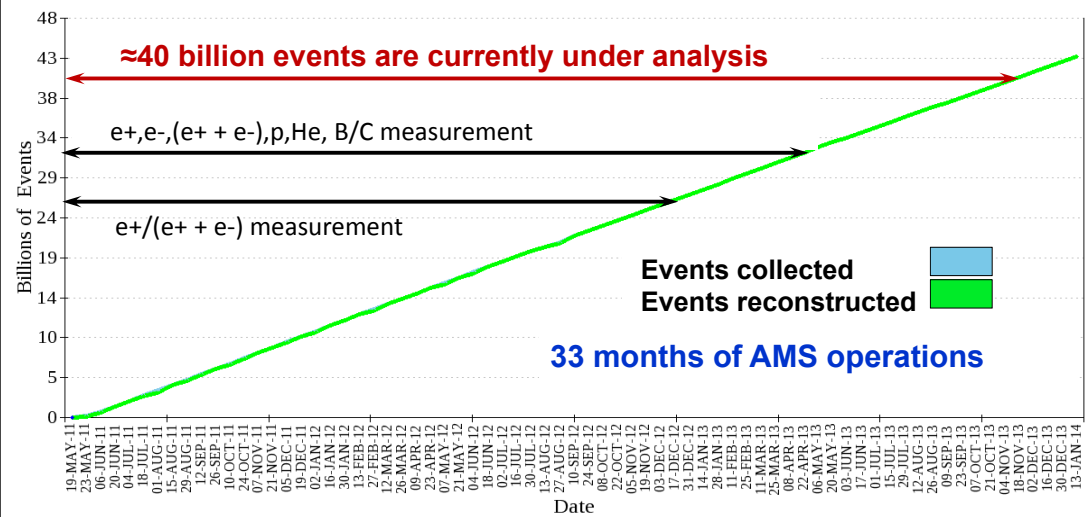
271



# High statistics

2015

To date AMS collected  $\approx 45$  billion events



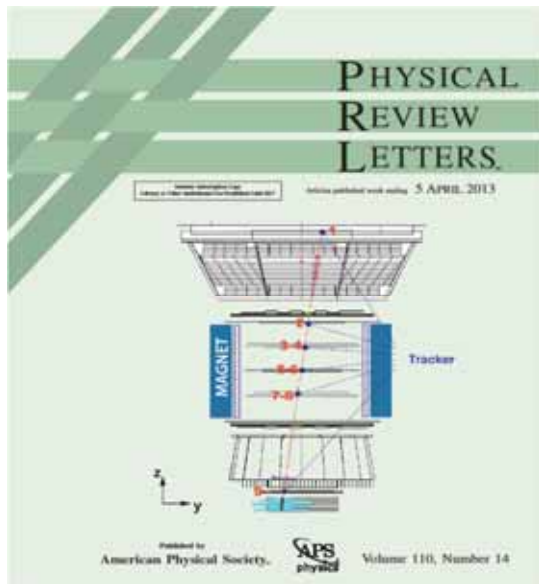
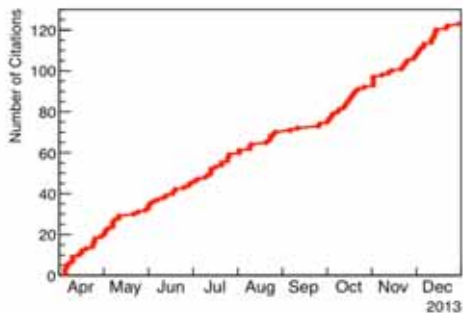
272



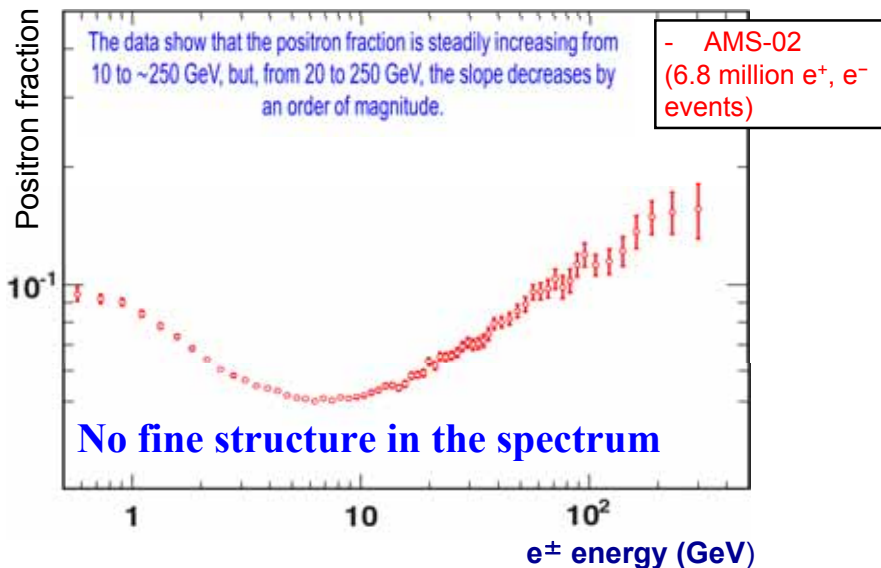
# AMS-02 First Published Result

“First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV”

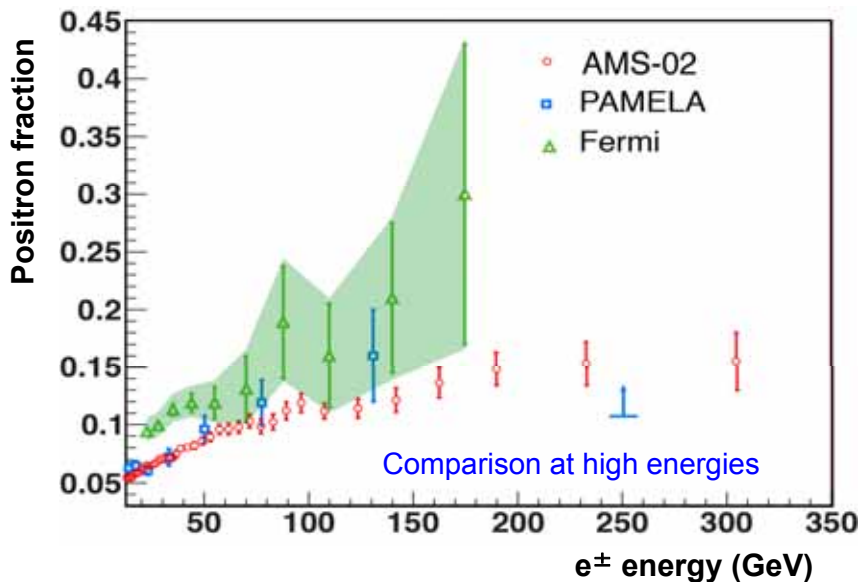
Selected as a “Viewpoint” by APS



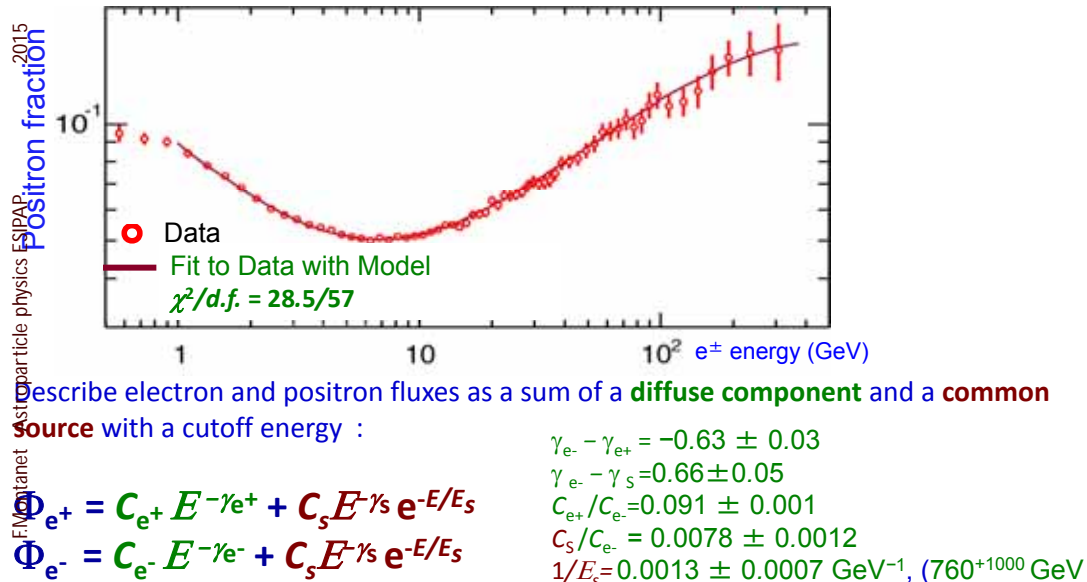
# Positron fraction (0.5 - 350 GeV)



# Positron fraction @ high energies



# Minimal empirical model



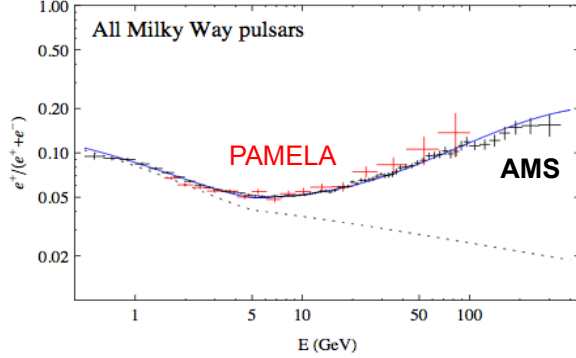


# Origin of the excess

15

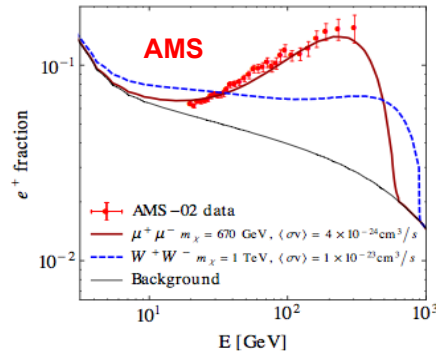
## Astrophysical objects

Cholis arXiv: astro-ph/1304.1840



## Dark Matter

Kopp hep-ph/1304.1184



Different energy behavior of the positron fraction:

- **Pulsars predictions:**
  - slow fall at high energies
  - anisotropic positron flux
- **Dark Matter prediction:**
  - steeper fall at high energies
  - isotropic positron flux

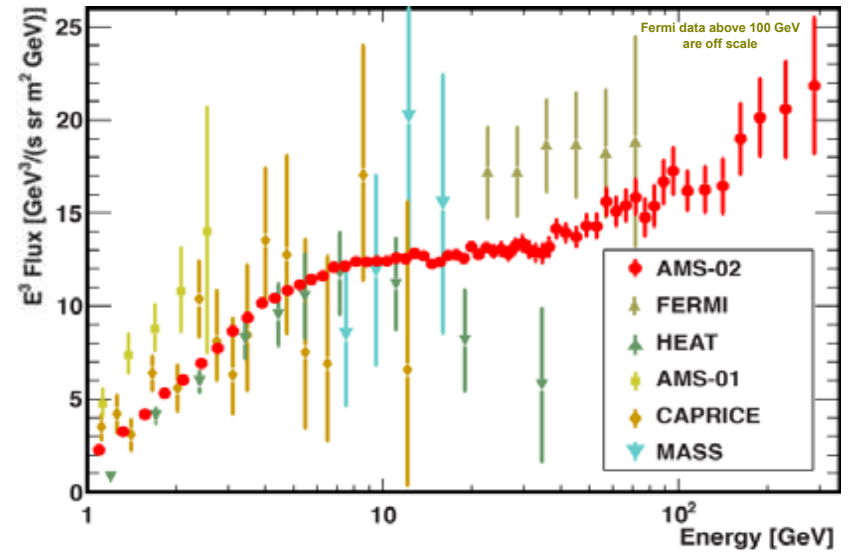
F.Montanet /

2015

F.Montanet Astroparticle physics ESIPAP

277

# Positron (e+) flux

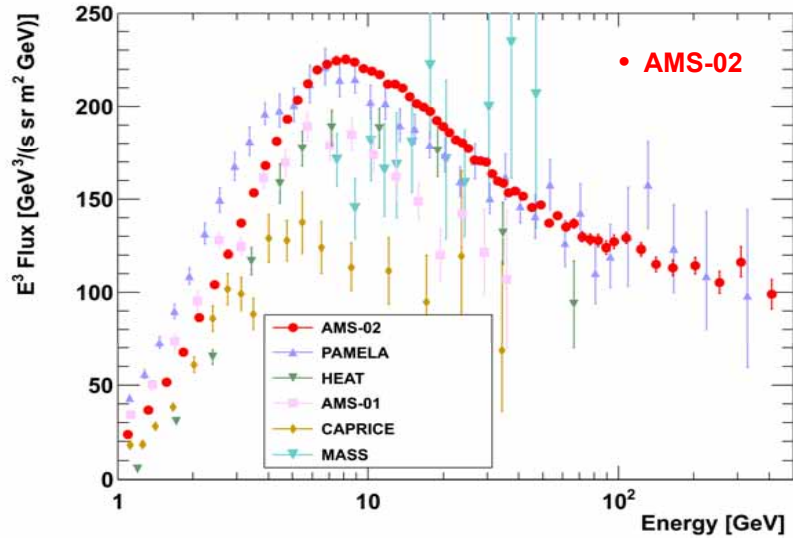


278

# Electron (e-) flux

2015

F.Montanet Astroparticle physics ESIPAP

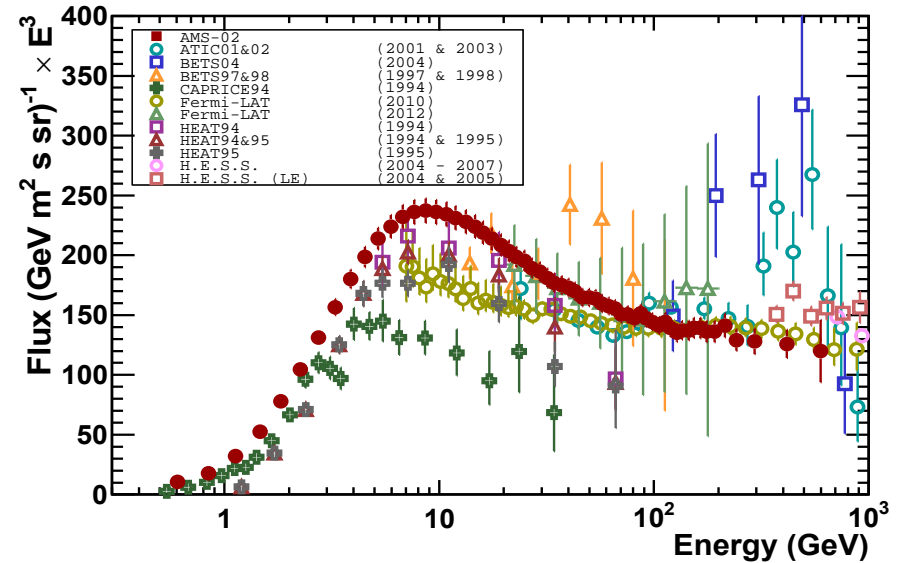


279

# All-electron (e+e-) flux

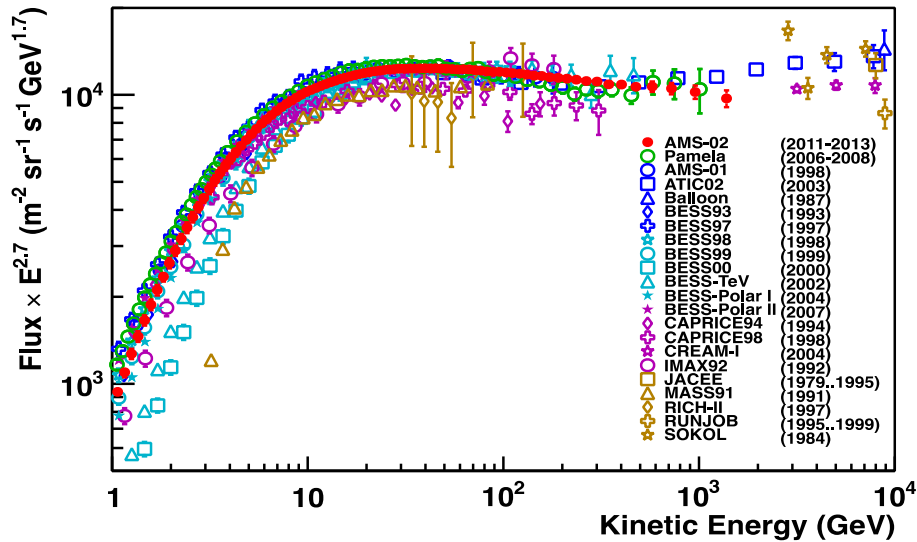
2015

F.Montanet Astroparticle physics ESIPAP



280

# Proton flux



# A nearby Pulsar ?

Mature pulsars: (0.01 < T < 1 Myr)

$e^\pm$  are confined to the pulsar wind nebula until it merges with the ISM. Merger process is fast so that pulsars can be treated as burst-like sources of  $e^\pm$

Contribution could be from a few local pulsars

- Geminga: d = 160 pc, T = 0.37 Myr

- Monogem: d = 290 pc, T = 0.11 Myr

but pair conversion efficiency needs to be high (30 - 40%)

Contribution could be from a large number of pulsars, distant and local, with an assumed continuum distribution and injection spectrum

$$\frac{dN_{e^\pm}}{dE} \propto E^{-1.5} e^{-E/E_p}$$

# Charged particles (1 TeV → few 100 TeV)

## Balloon Experiments

- Very high altitude flights: 40 km  $\equiv$  3,9 g cm<sup>-2</sup>
- Load: up to  $\approx$  270 kg and 10 m<sup>3</sup>
- Many former flights: JACEE (USA + Japon) ; RUNJOB (Russie + Japon) etc. using emulsion chambers !
- Recently: Ultra Long Duration Balloon (ULDB) Flights 60-100 jours (NASA, Antarctic) → the CREAM experiment (Cosmic Ray Energetics and Mass)



# CREAM

## Ultra Long Duration Balloon

ULDB Proj., Adv.Sp.Res33,1633(2004) : NASA project to develop

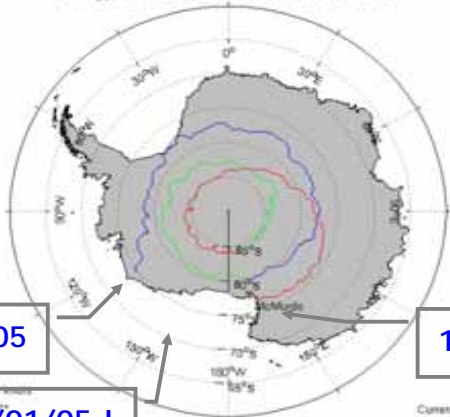
- Flight of < 100 days
- Payload  $\leq$  2 tons
- Alt 33000 meter
- CREAM n° 1 : 2006 (2005/LDB)



# CREAM 2004

2015

CREAM Flight Data: Trajectory  
Covering period from: 2004-12-15 23:22:56 to 2005-01-21 13:19:47



CREAM I:  
16/12/04 - \*\*/01/05  
>39 days flight  
World Record

21/01/05

16/12/04

24/01/05 !

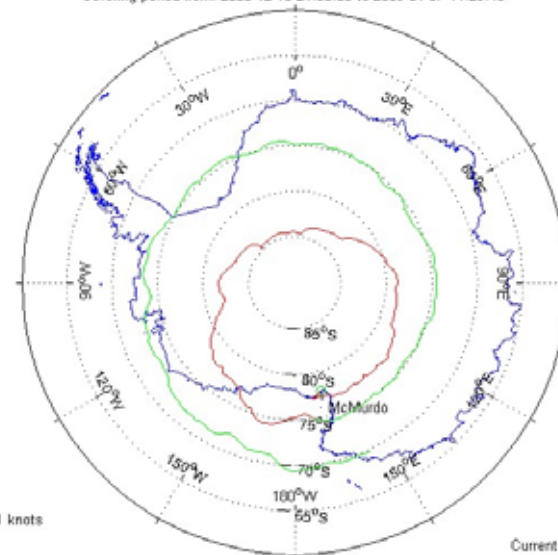
Current Speed: 16.16 knots  
Current Course: 319.2°  
Current Lat: -74°41'  
Current Lon: -124°40'24"  
Current MET: 36 days 0 hrs 50 mins 46.893 sec since launch  
Current Time: 2005-01-21 13:19:47 UTC  
Current Altitude: 124500 feet

285

# CREAM 2008

2015

CREAM Flight Data: Trajectory  
Covering period from: 2008-12-16 21:08:56 to 2009-01-07 11:29:46



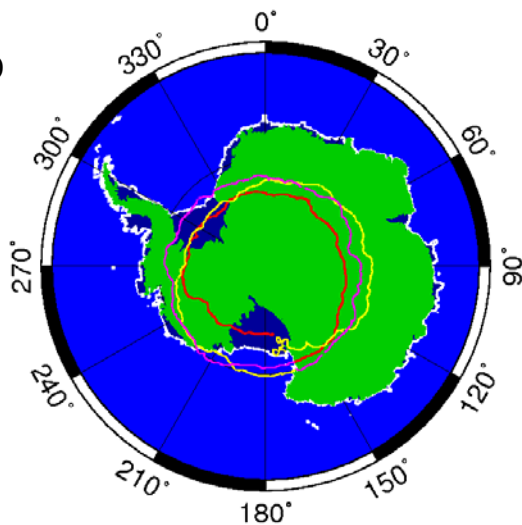
Current Speed: 0.01 knots  
Current Course: 0°  
Current Lat: -69°48'13.2"  
Current Lon: 155°51'54"  
Current MET: 19 days 13 hrs 35 mins 0.65 sec since launch  
Current Time: 2009-01-07 11:29:46 UTC  
Current Altitude: 4720.1444 feet

286

# CREAM 2009

2015

1 décembre 2009  
au 8 janvier 2010



GM 2010 Jan 08 17:01:00 CREAM\_Antarctica\_2009-2010

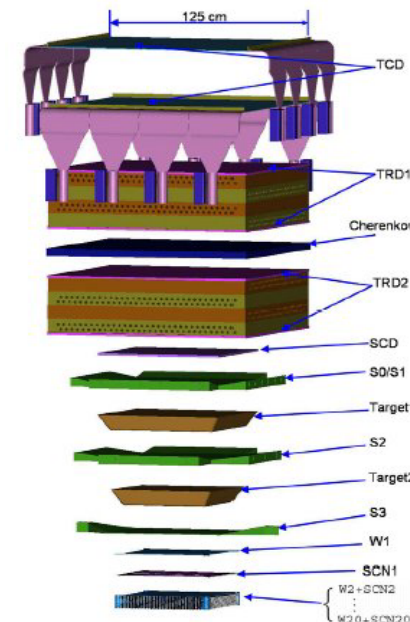
287

# CREAM

Cosmic Ray Energetics and Mass

2015

- **Objectives :**  
CR composition and spectrum of the different elements (from TeV to ~500 TeV)
- **Acceptance :** 2,2 m<sup>2</sup> sr
- **Energy measurement:**
  - Calorimeter 20 X<sub>0</sub> (W + scint. fibres)
  - Transition Radiation Detector
- **Identification :**
  - TRD
  - Cherenkov detector "CHERCAM" similar to AMS-2



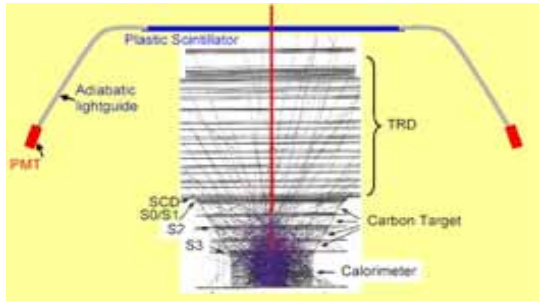
F.Montanet - Astroparticule physique ESPAP

F.Montanet - Astroparticule physique ESPAP

288

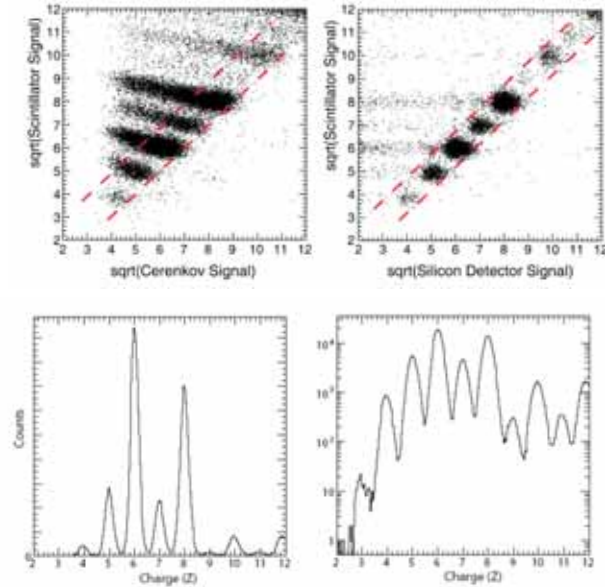


# CREAM experiment

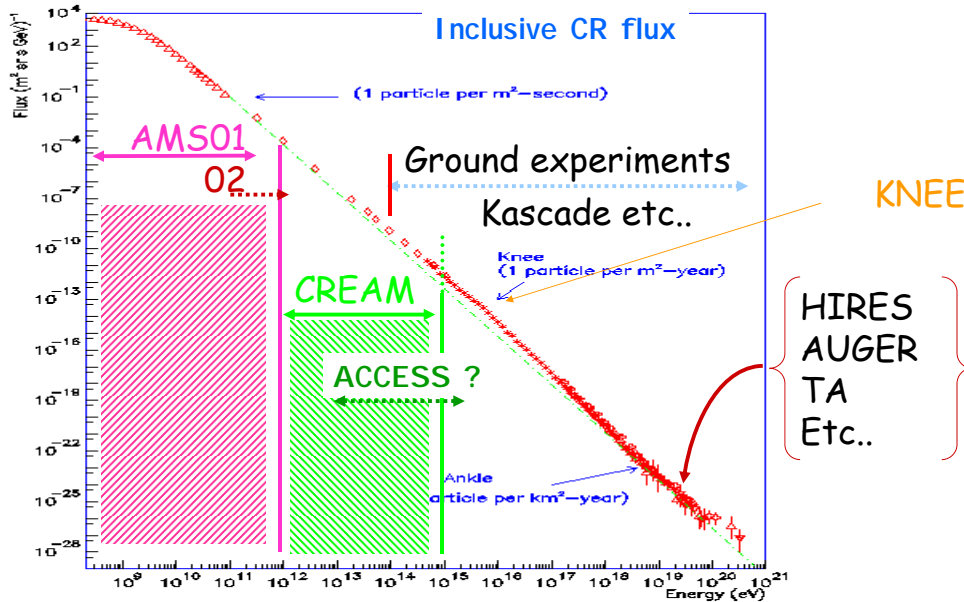


- At TeV energies, the interaction of CR in the calorimeter induces many backscattered secondary particles that one have to veto.
- The "CHERCAM" cherenkov solves this problem by measuring accurately the time of any through going particle as well as achieving a precise charge measurement ( $\pm 0,3 e$ )

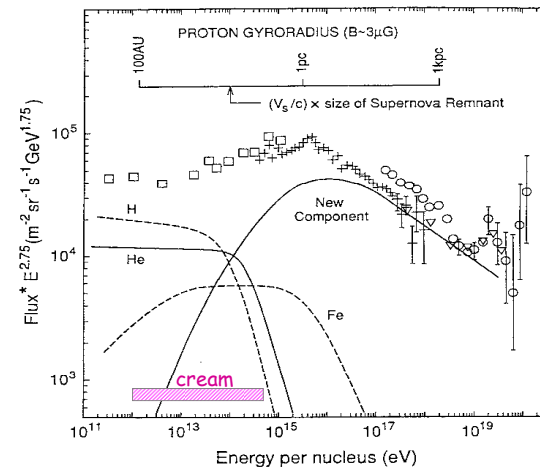
# CREAM experiment



# Contexte expérimental



# The knee

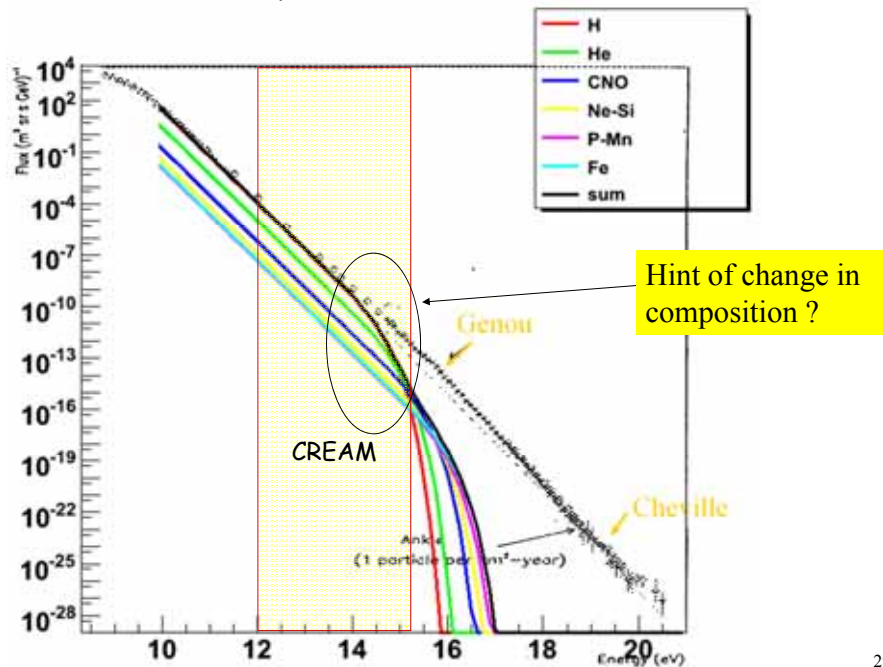


- Is the knee due to:
  - Acceleration mechanisms
  - or to changes :
    - in propagation?
    - in CR sources?
    - in interaction properties (threshold)?

⇒ A diffuse SNR shock acceleration with  $E_{max}$  implies a change in composition around  $\sim 10^{14}$  eV.

**SNR energy limit:  $E_{max} \sim Z \cdot 10^{14}$  eV**

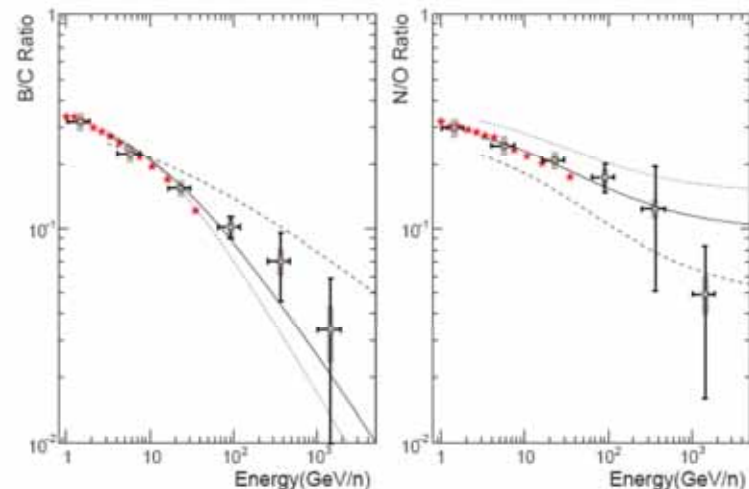
## CR SM with $E_{max} \propto Z$



293

## Galactic CR propagation with CREAM

Secondary/Primary ratio



Compatible with propagation models with escape term in  $E^{0.6}$

294

## AIR SHOWERS DEVELOPMENT MODELS

## A peek above the knee !

To measure the inclusive spectrum at the knee, one needs a  $10\text{m}^2$  exposed during 10 years !

The realistic experimental limits are:

- For satellites  $\sim 1\text{m}^2$  (sr) during  $\sim$ few years
- For balloons,  $\sim 10\text{m}^2$  (sr) during  $n \times 30$  jours

$\rightarrow E < 10^{15}$  eV



It's time we face reality my friends, we should keep to ground detectors !

295

296

## Extensive Air Showers: the phenomenon and the observables

- **The large shower of secondary particles** induced by the interaction of a primary CR in the upper atmosphere can be detected on an extensive area → large effective surfaces to fight against low flux at  $E \geq 1000$  TeV
- **Atmosphere used as an calorimeter** ( $\sim 1000$  g  $\text{cm}^{-2}$  at sea level for a vertical shower)
- From the observables, one aims at measuring:
  - Incident direction;
  - Primary energy  $E_0$  ;
 and if possible, get access to the **nature of the primary particle** :
  - distinction  $\gamma$ -hadron ;
  - distinction **light nuclei** (p, He) - **heavy nuclei**(Fe)

297

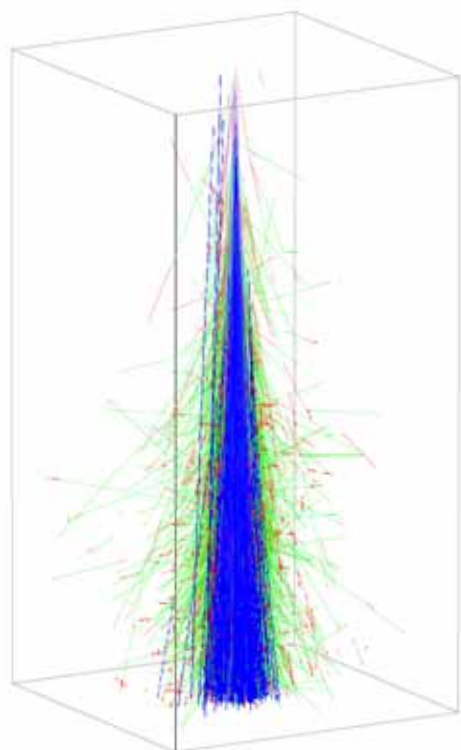
## p or nucleus + N or O nucleus → hadronic cascade

- **Hadronic component:** nuclear fragments, nucleons, mesons  $\pi$ , K, etc.
- **Electromagnetic component:** induced by  $\pi^0 \rightarrow \gamma\gamma$  and other radiative decays
- **Muonic component:** induced by decays of  $\pi^\pm$  and  $K^\pm$
- **Atmospheric Neutrinos** issued from  $s$   $\pi^\pm$   $K^\pm$  and  $\mu^\pm$  decays



Primary electrons and  $\gamma$  induce an **electromagnetic shower** consisting mainly of secondary electrons, positrons and  $\gamma$  (muon poor)

298



## Shower development

« des giboulées d'électrons »

Rayon cosmiques  
par Pierre Auger  
1941 PUF

A  $10^{19}$  eV shower

$10^{11}$  particles  
at sea level

Photons + electrons (99%),  
muons (1%)

299

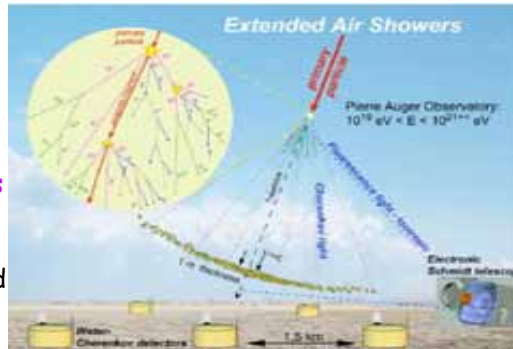
## Ground observables

- **Secondary particles reaching ground**  
As a function of the primary energy and of the altitude:
  - Residual Hadrons (nuclear fragments): not numerous ( $> 11 \lambda_{int}$ ).
  - $e^\pm$ : the more numerous at shower development maximum.
  - $\mu^\pm$ : most reach ground and may penetrate deep underground.
  - $\gamma$  secondaries: may be detected at ground level via  $e^+e^-$  pair conversion (e.g. Cherenkov effect in water).
- **Photons (visible, UV) emitted along the trajectories of charged particles (Cherenkov effect,  $N_2$  fluorescence) during the shower development**  
→ **Calorimetric 3D information!**
- **Radio emission by the shower particles in the geomagnetic field or by the induced plasma.**

300

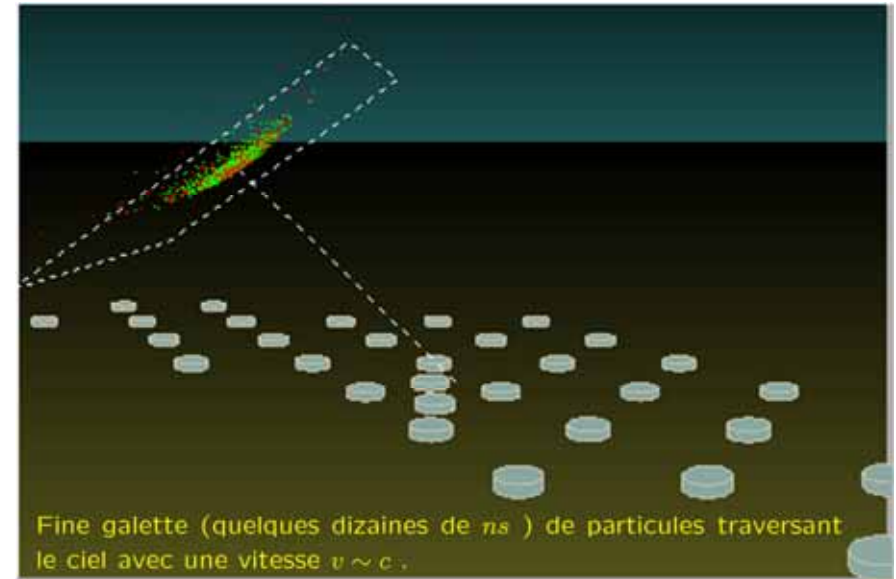
## Temporal aspects

- A light speed moving "pancake" of charged particles.
- This front is more or less curved depending on the shower development stage.
- The front thickness ( $\sim 10$  m) induce as signal time spread in each detector.
- The arrival time differences at ground on the sampling detectors  $\rightarrow$  arrival direction ( $\Delta\theta \approx 1^\circ$ ).
- The Cherenkov light front (forward emission) is thinner ( $\sim m$ ) than the charged particle front  $\rightarrow$  well defined timing.



301

## Time structure



302

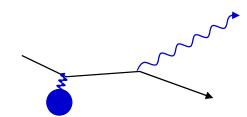
## EM shower Longitudinal development

- Mean number of particles ( $e^+, e^-$  or  $\gamma$ ) crossing a plan  $\perp$  to the shower axis after a slant depth  $t$  (in units of  $X_0$ ).
- As long as the ionization losses are small wrt radiation losses (bremsstrahlung and pair prod) the number of particle increase exponentially.
- When the mean energy per particle decreases below the critical energy ( $E_c \approx 84,2$  MeV in air), the number of particle decreases (shower extinction phase).
- At the transition between the two phases, (maximal development), the mean energy is equal to the critical energy.

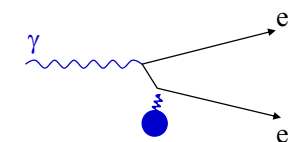
303

## Radiative processes ( $E > E_c$ )

Bremsstrahlung :



Pairs production :



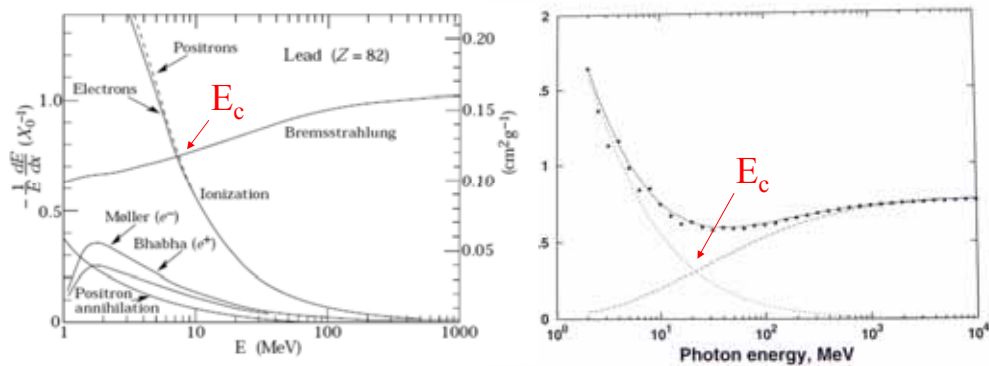
Radiation length  $X_0$  :

- energy loss =  $1/e$  due to bremsstrahlung
- $7/9$  of the range of a  $\gamma$  due to pair production.

In air :  $X_0 = 36.7 \text{g/cm}^2$

304

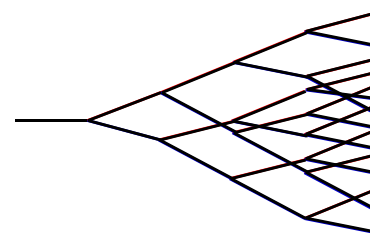
# EM cascades (Rossi & Greisen)



Critical energy: below this energy, ionization losses dominate.

# Simplified development model (Heitler)

- Cascade consisting of only one type of particles having an interaction length  $\lambda$ .
- At each interaction, 2 particles of same type are emitted sharing the energy exactly in 2.



$\lambda$								
X =	1	2	3	4	5			
N =	2	4	8	16	32			
E =	1/2	1/4	1/8	1/16	1/32			$E_c = E_0/32$

# Longitudinal development

- After  $t$  radiation length, there are  $2^t$  particles with energy

$$E = E_0/2^t$$

soit :  $t \ln 2 = \ln(E_0/E)$

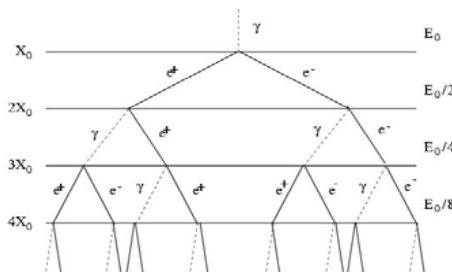
- The particles of energy  $E$  are produced at thickness:

$$t(E) \approx \ln(E_0/E)$$

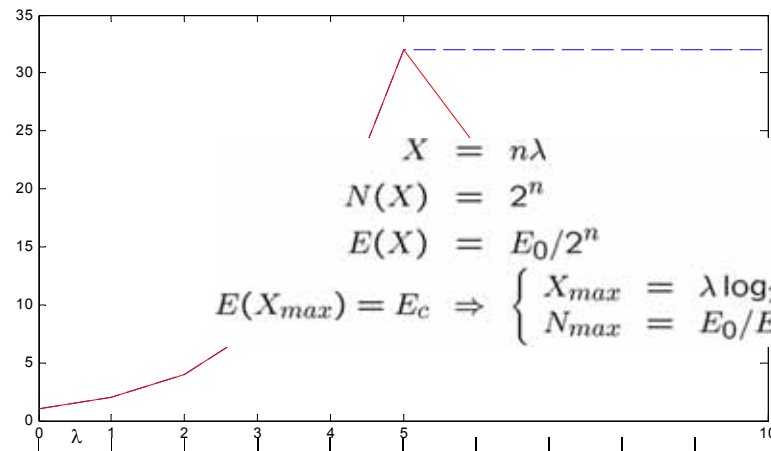
- The maximal development of the shower is reach for a thickness:

$$t_{max}(E_0) \approx \ln(E_0/E_c)$$

- More realistic models agree with this rough estimate.



# Simplified development model (Heitler)



$$X = n\lambda$$

$$N(X) = 2^n$$

$$E(X) = E_0/2^n$$

$$E(X_{max}) = E_c \Rightarrow \begin{cases} X_{max} = \lambda \log_2(E_0/E_c) \\ N_{max} = E_0/E_c \end{cases}$$

X =	1	2	3	4	5			
N =	2	4	8	16	32			
E =	1/2	1/4	1/8	1/16	1/32			$E_c = E_0/32$

## Longitudinal development: Approximation "A" (B. Rossi, K. Greisen)

- Approximation "A" describes the shower development phase where only bremsstrahlung and pair creation are in action.
- From Bethe-Heitler theory, one obtains des integro-differential linear and coupled equations leading to:
  - $\Pi(E, t)dE$  = average number of  $e^\pm$  with energy  $\in [E, E + dE]$ , at  $tX_0$  depth
  - $\Gamma(W, t)dW$  = average number of  $\gamma$  with energy  $\in [W, W + dW]$ , at  $tX_0$  depth
- The simplifying factor is the absence of any energy scale.

309

## Approximation A (cont)

- $\Pi(E, t)dE$  = average number of  $e^\pm$  with energy  $\in [E, E + dE]$ , at  $tX_0$  depth
- $\Gamma(W, t)dW$  = average number of  $\gamma$  with energy  $\in [W, W + dW]$ , at  $tX_0$  depth
- Initial condition :
  - If the primary particle is a  $\gamma$  :  $\Gamma(W, 0) = \delta(E - E_0)$
  - If the primary particle is an  $e^\pm$  :  $\Pi(E, 0) = \delta(E - E_0)$
- Obvious special solutions:  
 $\Gamma(W, t) = f(t)/W^{s+1}$  et  $\Pi(E, t) = g(t)/E^{s+1}$   
 (absence of energy scale)

... but they dont satisfy the initial conditions!

310

## Approximation A (suite)

- The obvious solutions (power-law spectra, therefore scale invariant) correspond to an initial condition interesting in itself: an incident beam with a power law spectrum with an integral spectral index  $s$ .
- These special solutions form a base and a solution that fulfills the initial condition (photon or electron with an energy  $E_0$ ) is obtained from a superposition of  $1/E^{s+1}$  spectra (Mellin transformation, analogue to Fourier or Laplace transforms).
- Result : for a given value of  $t$ , the particle spectrum is very close to a power law  $1/E^{s+1}$  with a value of  $s$  that varies with  $t$  and  $y = \ln(E_0/E)$  following:

$$s = \frac{3t - 1}{t + 2y}$$

- The number of particle with energy  $E$  is maximal for  $s = 1$

311

## Taking into account ionization energy losses: the "age" parameter

- Approximation A is not valid anymore when the electron mean energy  $E_e$  is close to the critical energy  $E_c$ .

- One can modify the above results:

$$y = \ln\left(\frac{E_0}{E_c}\right) \quad \text{et} \quad s = \frac{3t}{t + 2y}$$

- Semi empirical formula given by Greisen for an incident  $\gamma$ , for the mean number of electrons after traversing  $t$  radiation length:

$$\bar{N}_t = \frac{0.31}{\sqrt{y}} \exp\left[t\left(1 - \frac{3}{2} \ln s\right)\right]$$

- The parameter  $s$  increase with  $t$ . It is  $< 1$  during the development phase, reaches 1 at the maximal development stage for  $t_{max} = y = \ln(E_0/E_c)$  and is  $> 1$  during the extinction phase.
- $s$  is called the "age".

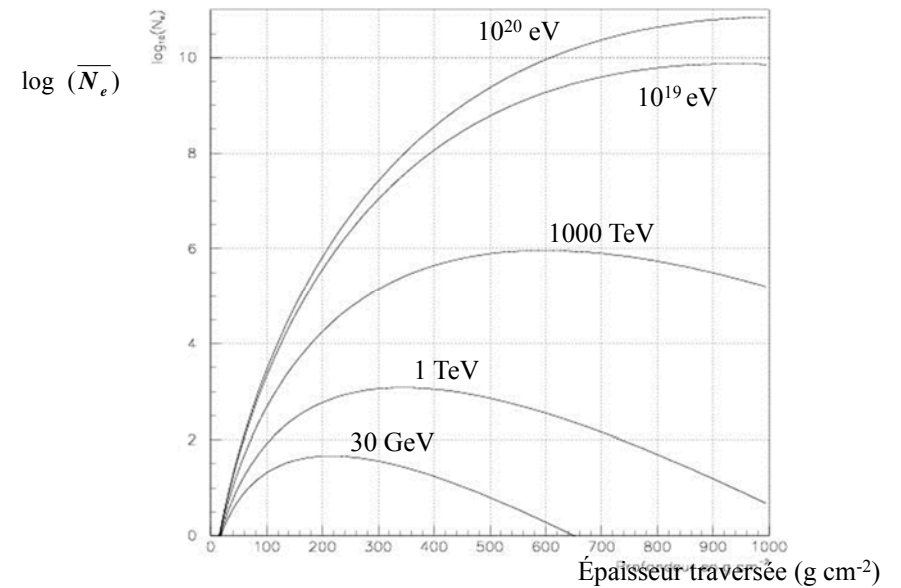
312

## EM showers : some orders of magnitude

Primary $\gamma$ energy $E_0$	Thickness traverse $t_{\max} X_0$ ( $g\ cm^{-2}$ )	Altitude (m)	$N_e(t_{\max})$
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	$0,9 \times 10^6$
$10^{19}$ eV	936	1200	$7,4 \times 10^9$
$10^{20}$ eV	1021	0	$7,0 \times 10^{10}$

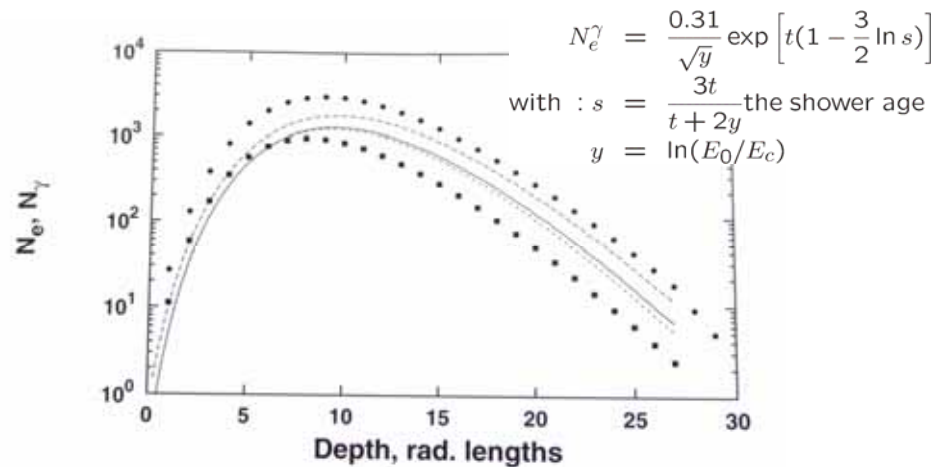
313

## EM shower average profiles



314

## EM cascades (Rossi & Greisen)



Parametrisation (Greisen) and Monte Carlo (EGS4)  
photons 1TeV,  $E_c=10MeV$

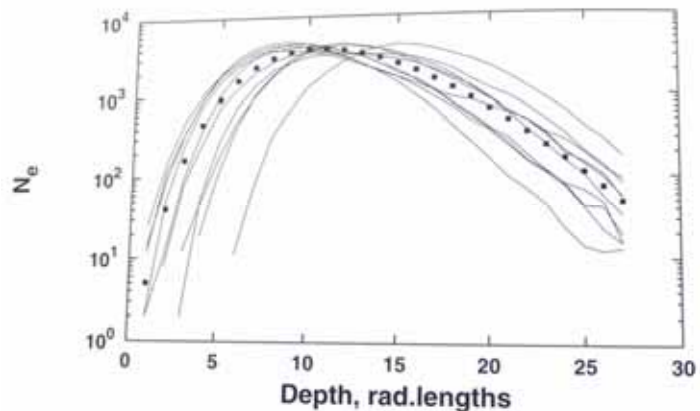
315

## Shower size i.e. number of electrons at ground level as an energy estimator

- At maximal development level, the mean number of electrons quasi proportional to the primary energy ( $y = \ln(E_0/E_c)$ ).
- Fluctuations on  $N_e$ :
  - Fluctuations on the depth of first interaction (exponential law)
  - Fluctuations in the shower development (approximately log-normal because of the multiplicative behaviour)
  - Sampling fluctuations (depends on the type of detectors, their arrangement on the ground etc.)
- If the altitude of the maximal development is known (direct optical measurement), or if one can estimate the age independently (from lateral distribution of the electrons) one can avoid the first kind of fluctuations.
- Fluctuations are minimal at the maximum of development.

316

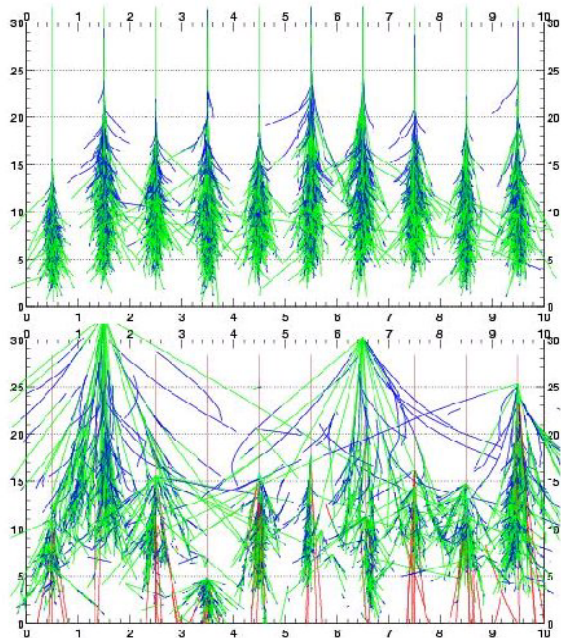
# Cascades EM (Rossi & Greisen)



Shower to shower fluctuations  
 10 showers at  $10^{14}$ eV compared to the average of 100 showers.

# GAMMA-RAY (EM) INDUCED SHOWERS

10  $\gamma$   
 300 GeV



10 protons  
 300 GeV

Simulations de  
 M. de Naurois

# Electromagnetic showers ( $e^\pm$ or $\gamma$ primary)

## Dominating phenomena

- Radiation processes:
  - Bremsstrahlung of  $e^\pm$
  - Pair production ( $>MeV$ )  $e^+e^-$  pairs
- Multiple scattering (small angular deflections) of  $e^\pm$
- Energy losses by  $e^\pm$ 
  - par ionization
  - atomic excitation

In the Coulomb field of nuclei



$\gamma$  induced shower 300 GeV

Roughly symmetric around the axis

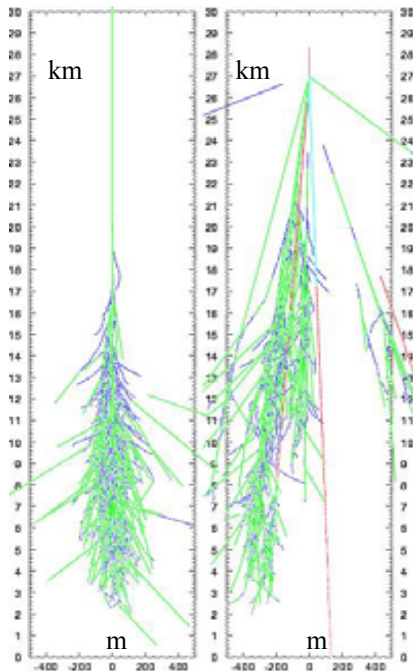
Small transverse dispersion (multiple scattering)

(almost) no muons

...

(unless  $E_0 > 1$  PeV)

Essentially  $e^+ e^-$  and  $\gamma$  secondaries



proton induced shower 300 GeV

Large transverse momentum

Muon component (from mesons decays)

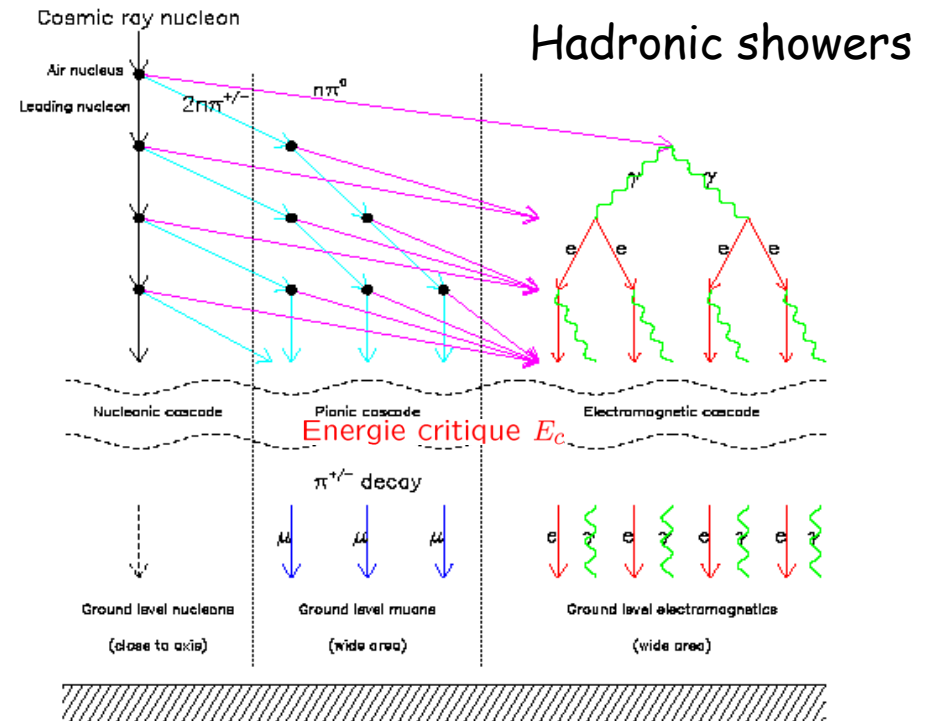
A hadronic shower does contain EM sub-showers

# Optical photon emission by showers

- Showers charged particles emit light:
  - **Cherenkov light** : very collimated along the shower axis (Cherenkov angle at 1 Atm.  $\approx 1^\circ$ ) threshold depending on the altitude : at ground 22 MeV for  $e^\pm$  et 4.5 GeV for  $\mu^\pm$  (20 photons per m per  $\beta \approx 1$  charged particle at 1 atm) Essentially used for gamma-ray astronomy
  - **Nitrogen fluorescence**: isotropic emission ( $\approx 4$  photons per electron per m) Essentially used at UHE  $\geq 10^{18}$ eV.
- This light detected by ground telescopes gives us very rich information on the 3D development of the showers. It give a quasi calorimetric reliable measurement of the energy.
- ... but optical detectors can only work during moonless clear sky nights ( $\approx 10\%$  duty cycle).

Lecture on Imaging & Cherenkov Detectors

# HADRONIC SHOWERS MODELS AND DETECTION



# "Hadronic" showers (proton ou noyau primaire)

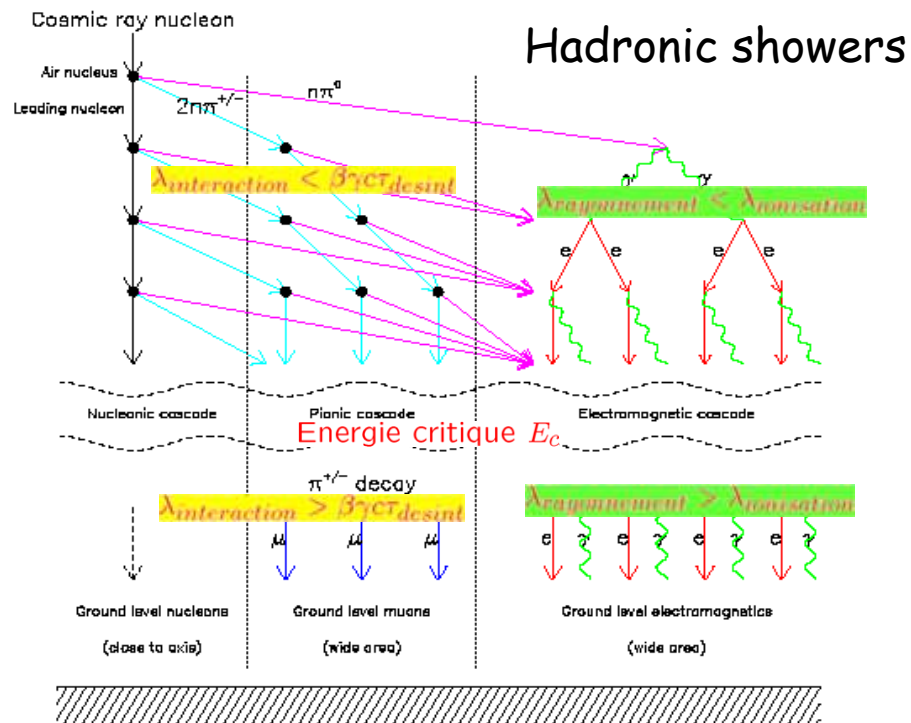
- Great complexity implying the use of numerical simulations:
  - Many length scales : nucleon interaction length, pion interaction length, EM radiation length, atmosphere density height scale...
  - Superposition of a nuclear cascade, a pionic cascade and an electromagnetic cascade (the later from  $\pi^0$  decay  $\gamma$ ).
  - Large fluctuations in the multiplicity of secondaries.
- But simulations are subject to many uncertainties:
  - p+N or N+N interactions: sensitivity to nuclear models.
  - Energy range unexplored by accelerators and colliders : sensitivity to nucleon structure functions (parton distributions) and fragmentation functions extrapolated far from the measured regions.
  - The inelasticity and in general the very forward diffractive physics is not well measured in fixe target experiment (even worse at colliders). Still, the main behavior observed on EM showers remains valid.

325

# From EM to Hadronic showers

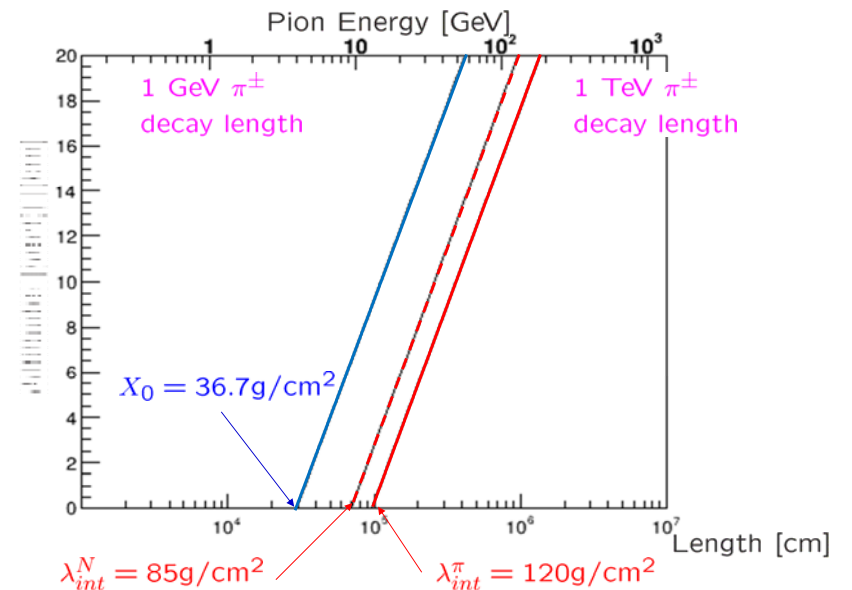
- The main observables are the same:
  - Number of electrons, gamma but also muons at ground and their lateral distributions.
  - Longitudinal profile and maximal dev. altitude (optical detectors).
  - Number of muons at ground level and lateral distribution of muons.
- Feynman scaling is rather well verified in the fragmentation: it plays an role analogue to that of Bethe-Bloch formulae for EM showers (absence of mass/energy scale).
- Simulations have allowed to establish empirical formulae inspired by EM showers useful for quick estimates (T.K. Gaisser, A.M. Hillas)

326



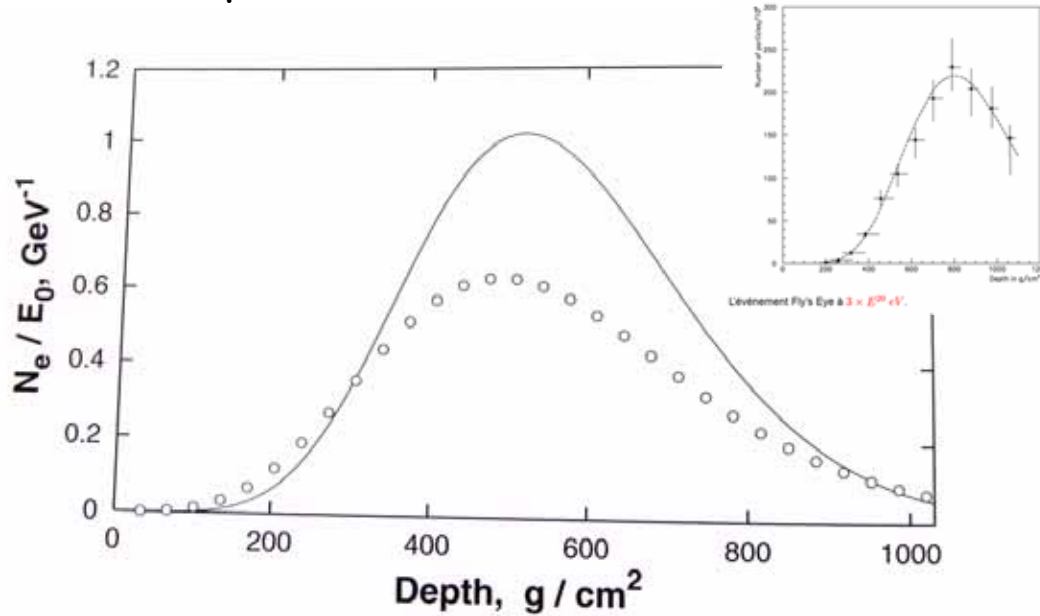
327

# Interaction and radiation lengths in atmosphere



328

## Development of Hadronic vs EM showers



329

2015

F. Montanet - Astroparticule physics ESPAP

## Gaisser longitudinal Parametrization

Gaisser Hillas formulae :

$$N_e(X - X_1) = N_e^{max} e^p \left( \frac{X - X_1}{X_{max} - \lambda} \right)^p \exp - \left( \frac{X - X_1}{\lambda} \right)$$

$$\text{avec } p = \frac{X_{max} - \lambda}{\lambda}$$

Averaging on  $X_1$  depth of 1<sup>st</sup> interaction :

$$\bar{N}_e(X) = N_e^{max} \frac{p}{p+1} e^p \left( \frac{X}{X_{max} - \lambda} \right)^{p+1} \exp - \left( \frac{X}{\lambda} \right)$$

$$X_{max} = X_0 \log \left( \frac{E_0}{\epsilon_0} \right)$$

$$N_e^{max} = \frac{E_0}{\omega}$$

Radiation length :  $\approx 36.7 \text{g/cm}^2$

Critical energy :  $\epsilon_0 \approx 74 \text{eV}$

Empirical relation between size and energy:  $\omega \approx 1.7 \text{GeV}$

Incident nucleus interaction length (of energy  $E_0$ )  $\lambda_N \approx 70 \text{g/cm}^2$

330

2015

F. Montanet - Astroparticule physics ESPAP

## Longitudinal developpment

**Xmax and energy :**

$$X_{max} \approx X_0 \log \left( \frac{E_0}{\epsilon_0} \right)$$

$$\Rightarrow 80 \text{g/cm}^2 \text{ per energie decade}$$

**Nuclei :**

Superposition principle : a nucleus  $^A N$  is equivalent to  $A$  protons.

Thus :

$$X_A^{max} = X_0 \log \left( \frac{E_0}{A \epsilon_0} \right)$$

$$= X_p^{max} - X_0 \log(A)$$

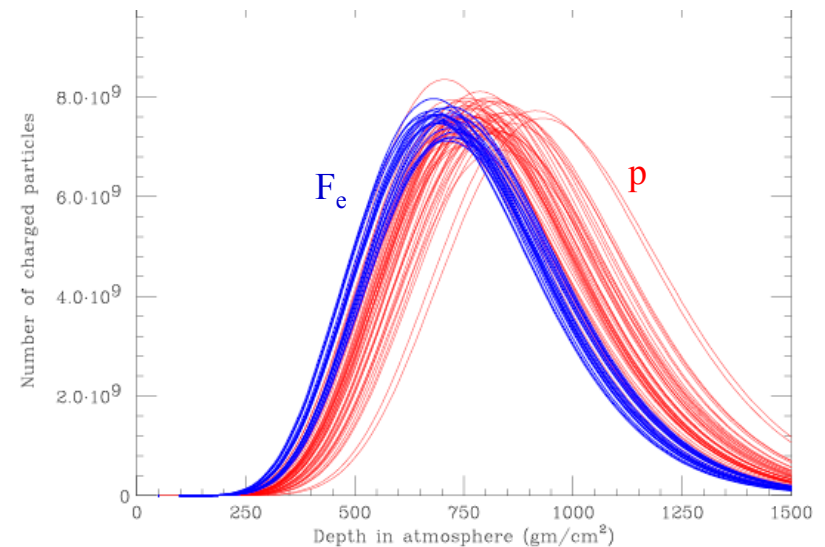
For example iron/proton  $A = 56$  :

$$X_0 \log(A) = 36.7 \log(56) = 148 \text{g/cm}^2$$

331

## Structure in space

Shower to shower fluctuations largely due to the depth of the first interaction.



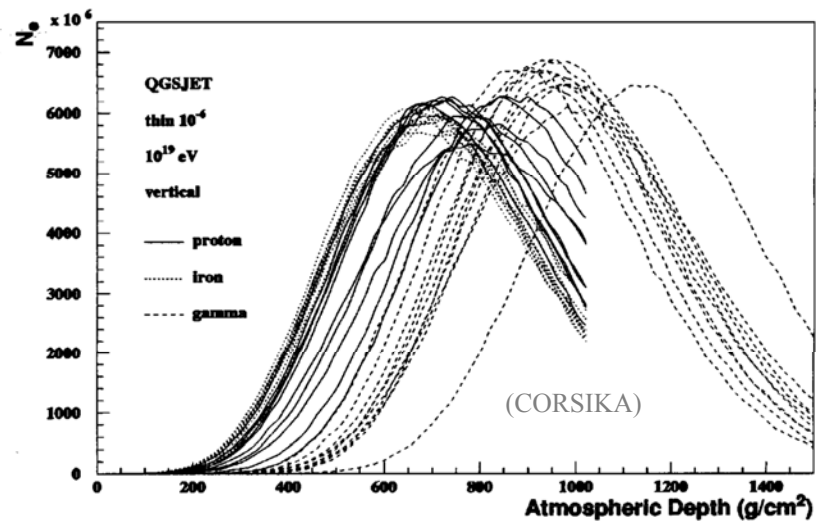
332

2015

F. Montanet - Astroparticule physics ESPAP

## Primary identification

- Requires a good statistics and a good knowledge of the initial energy, the shower angle (+ systematic corrections because of atmospheric attenuation)



333

## Radial extension

The radial distribution is determined by **the mean transverse momentum ( $P_T$ )** from hadronic interactions and by **multiple scattering**. In air, the Molière radius is  $\approx 75\text{m}$ .

Molière radius ( $\sim 1/4$  of the radiation length) :

$$\langle \delta\theta^2 \rangle = \left( \frac{21\text{MeV}}{E} \right) \delta X$$

$$r_1 = \left( \frac{E_s}{E_c} \right) X \approx 9.3 \text{ g}/\text{cm}^2$$

Nishimura, Kamata, Greisen :  
multiple scattering + transverse momentum

$$xf(x) = C(s)x^{(s-1)}(1+x)^{(s-4.5)}$$

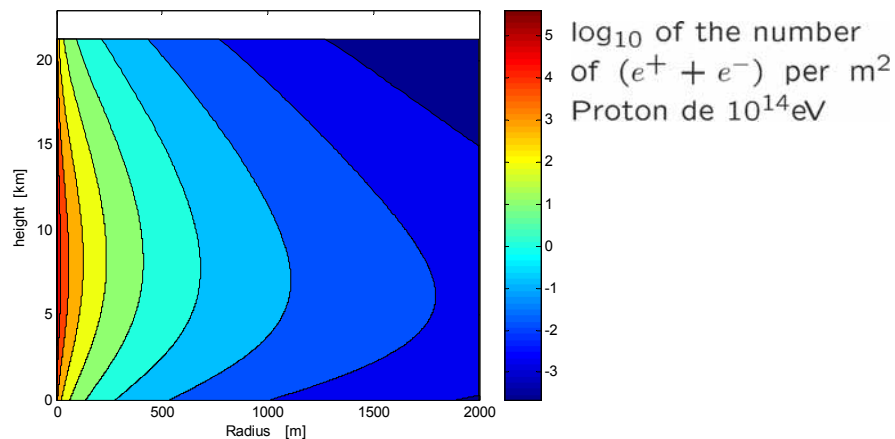
$$\text{with : } x = \frac{r}{r_1}$$

normalization tel que :

$$2\pi \int_0^\infty xf(x)dx = 1$$

338

## $e^+ + e^-$ lateral density



339

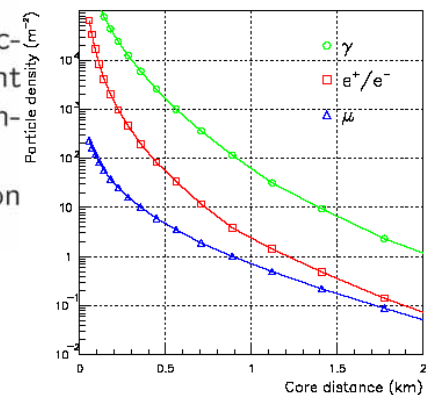
## Lateral evolution

The density as a function of the distance to the center of the shower is characterized by a **lateral density function (LDF)**

$$\rho(r) \propto k \times r^{-[\eta+f(r)]}$$

where  $f$  et  $k$  depends on the type of detectors used where  $\eta$  depends on the incident angle of the shower and the primary energy.

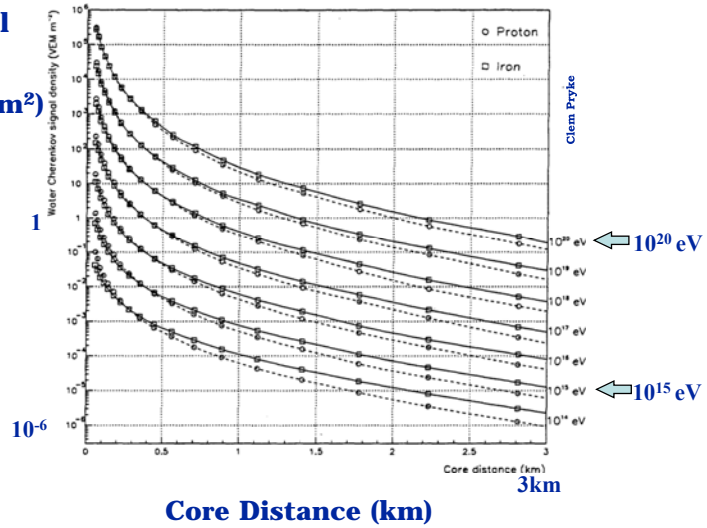
For  $r > 800\text{m}$  this (empirical) expression must be modify as  $(r/800)^{1.03}$



340

## Shower Density Lateral Distribution (simulation)

**Detector Signal Density**  
(equiv. muons/m<sup>2</sup>)



## Particle energy distribution

Rossi Greisen :

$$\frac{dN}{d(\log E)} \approx \frac{1}{E^{s+1}}$$

E. Nerling (thesis) :

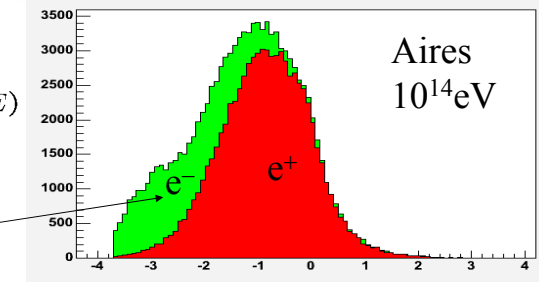
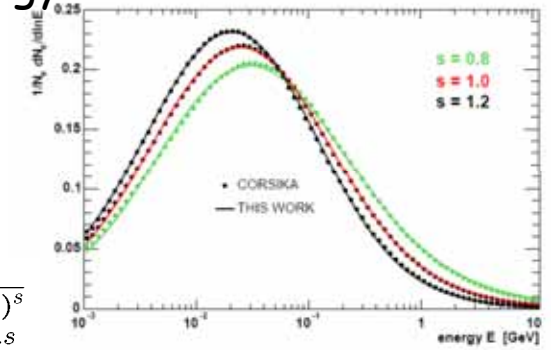
$$f_e(E, s) = a_0 \frac{E}{(E + a_1)(E + a_2)^s}$$

$$a_1 = 6.42522 - 1.53183.s$$

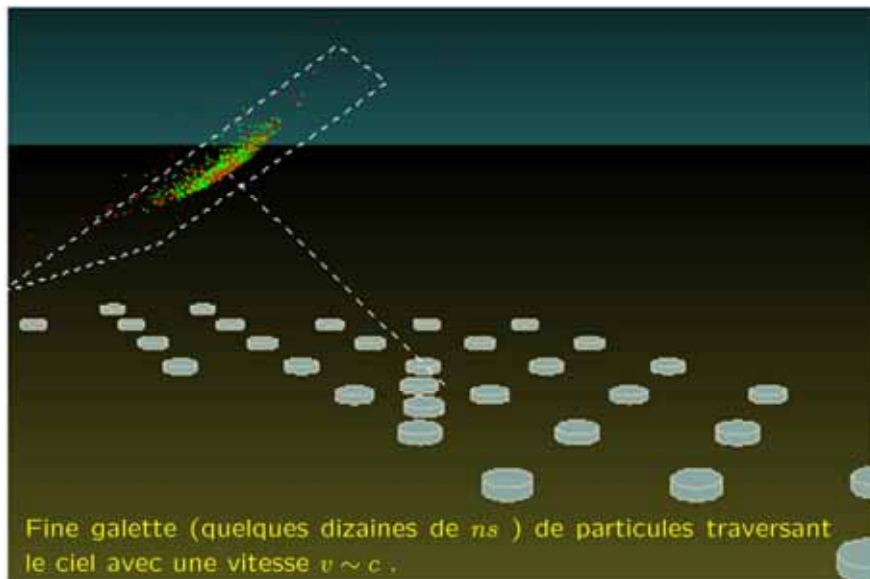
$$a_2 = 168.168 - 42.1368.s$$

E en MeV

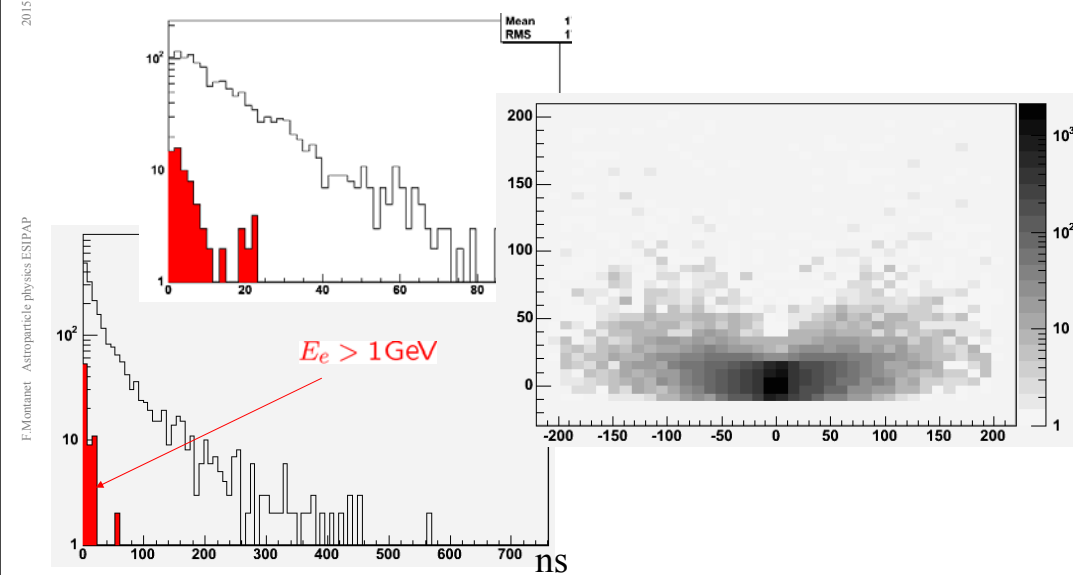
$$a_0^{-1} = \int_{\log E_{cut}} f(E, s) d(\log E)$$



## Time structure



## Time structure



# UHECR detection

2015

F. Montanet - Astroparticle physics ESIPAP


 Lecture on  
Imaging & Cherenkov  
Detectors

345

# Neutrino Physics with astroparticules

2015

F. Montanet - Astroparticle physics ESIPAP

 Lecture on  
Imaging & Cherenkov  
Detectors

346