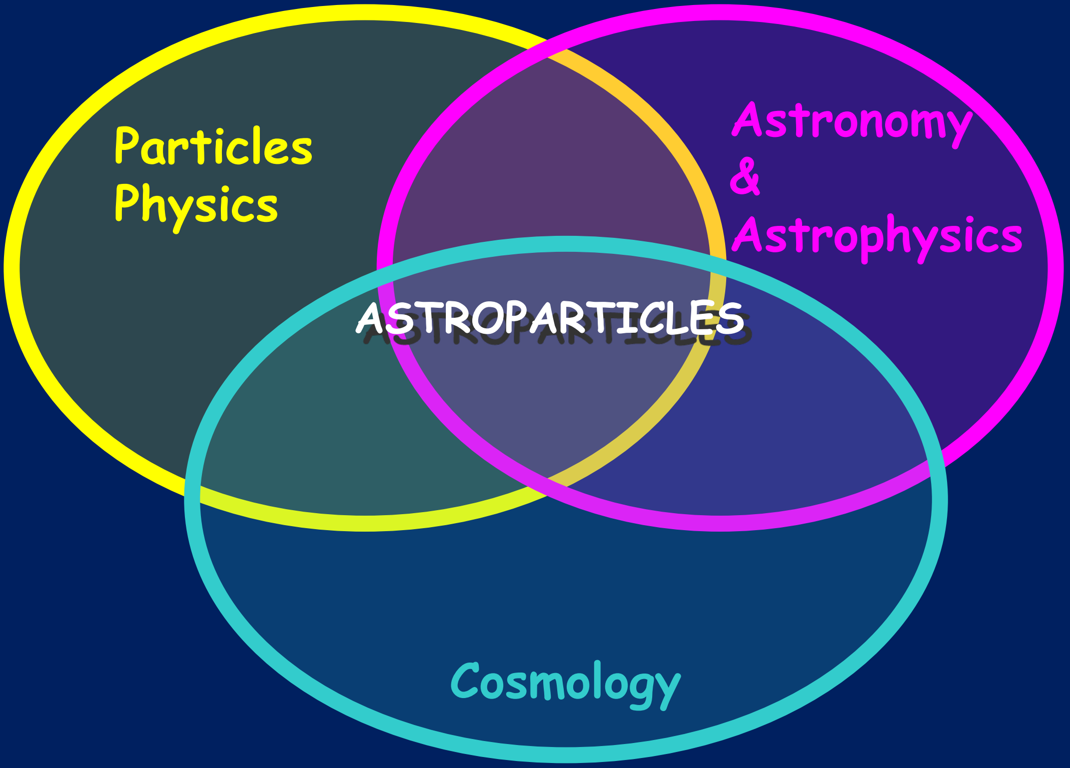
ASTROPARTICLES

ESIPAP– 2022

"still@home"

François Montanet



Forewords

This is the first of a series of videos covering two related courses: an Introduction to Astroparticles Physics (1st week) and a course devoted to Cherenkov and Imaging Detectors (3rd week) mostly applied to astroparticles detection. The two courses are strongly related and are both given by myself.

The videos will be posted well in advance before the first week, so that you can organize your viewing at your own pace.

For the 1st course, we will have a live "Questions & Answers" session on Thursday 20 afternoon, followed by a live Tutorial session.

If you have any urgent questions or would like to chat or talk with me, you can do it on the relevant Slack channel.

Bias and choices for this course

All aspects of Astroparticle physics, phenomenology, instrumental technics etc… cannot be covered in just a few hours of lectures, so I will certainly present an incomplete and biased view of the domain. I apology in advance.

I will thus concentrate manly on the high energy aspects of cosmic rays for the phenomenology and on instruments and observations that use either imaging technics or Cherenkov light.

Plan of the course

and partitioning into < 20' videos

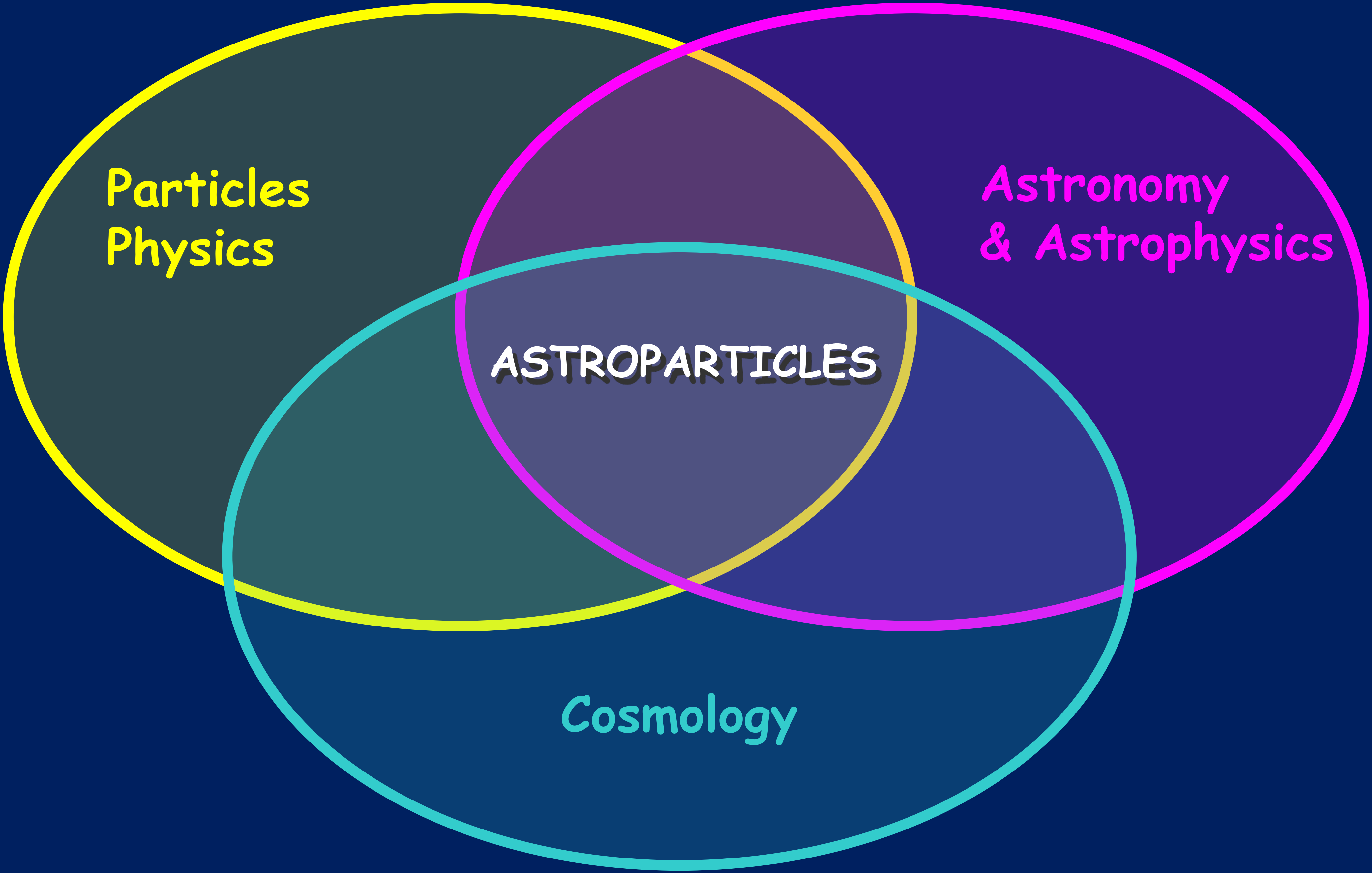
- Introduction (20')
  - The bias and choices for this course
  - What are astroparticles ?
  - Why studying them ?
  - Links to astrophysics particle physics and cosmology
  - A quick zoology of instruments and detectors
- Nature and properties of Astroparticles (20')
  - Composition
  - Spectrum
  - Anisotropies
- Propagation medium (10')
  - Intergalactic medium
  - Galactic medium
  - Atmosphere

Nota Bene: Most of Observables, Instrumentations and Observations will be postponed to my lecture on Cherenkov and Imaging detectors (3rd week).

- Astrophysical Sources Models (20')
  - Astrophysical shocks
  - Fermi acceleration
  - Standard Model for the production of galactic CR, SNR
- Other sources (20')
  - Gamma-ray sources, pulsars
  - AGN, SBG and other extragalactic sources
  - Neutrinos sources
  - "top-down" type of sources at UHE
- Propagation (20')
  - CR propagation in the Galaxy: The Leaky box model
  - VHE γ-rays propagation
  - UHECR propagation
- Air Showers (20')
  - Air Showers Physics
  - Observables

Introducing Astroparticles

1st Video (20')



Particles Physics

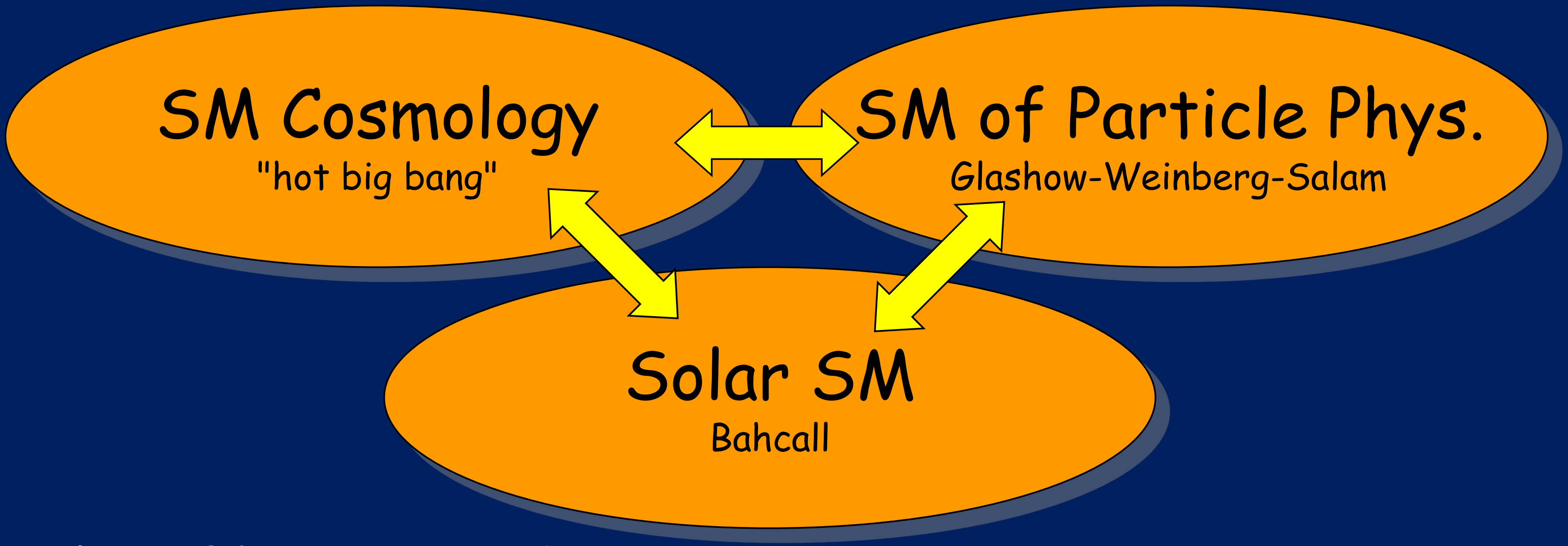
Astronomy & Astrophysics

ASTROPARTICLES

Cosmology

What can we learn from Astroparticles

Matching "standard models"… or not



SM Cosmology
"hot big bang"

SM of Particle Phys.
Glashow-Weinberg-Salam

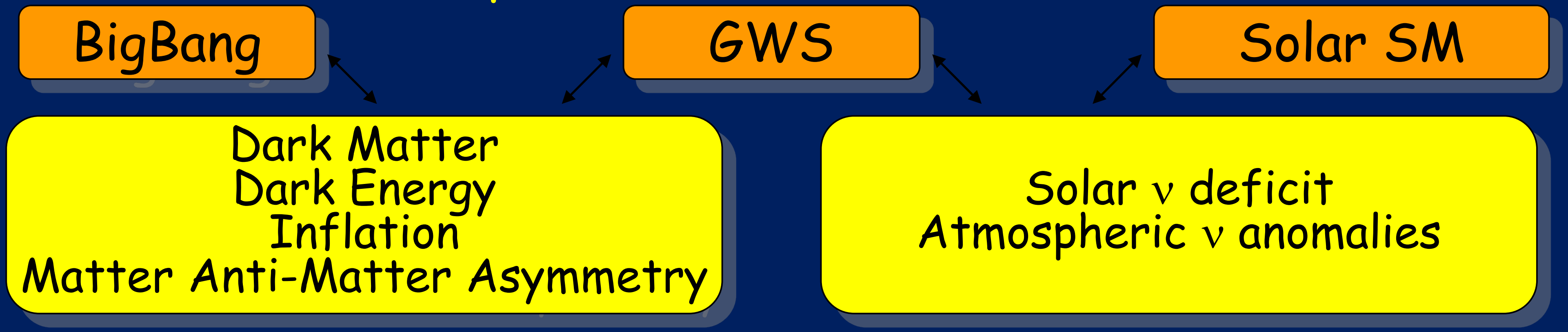
Solar SM
Bahcall

Examples of happy breeding…

Nucleosynthesis $\Rightarrow N_\nu$

$\Omega h^2, LSS... \Rightarrow \sum m_\nu < ...$

… as well as some disputes…



BigBang

GWS

Solar SM

Dark Matter
Dark Energy
Inflation
Matter Anti-Matter Asymmetry

Solar ν deficit
Atmospheric ν anomalies

Direct searches

↓

new particles production-observations

(Tevatron, LHC)

New Physics

Indirect searches

$FCNC$, CP

$FV \to \mu \to e\gamma$

d_n^e

B physics

Progress in Theory

Supergravity

→ Superstrings, M-Theory

Cosmology

Measure the parameters

of the Univers

and their evolution

Astroparticle Physics

Neutrino Physics

Cosmic Rays

γ Astronomy

Gravitationnal Waves

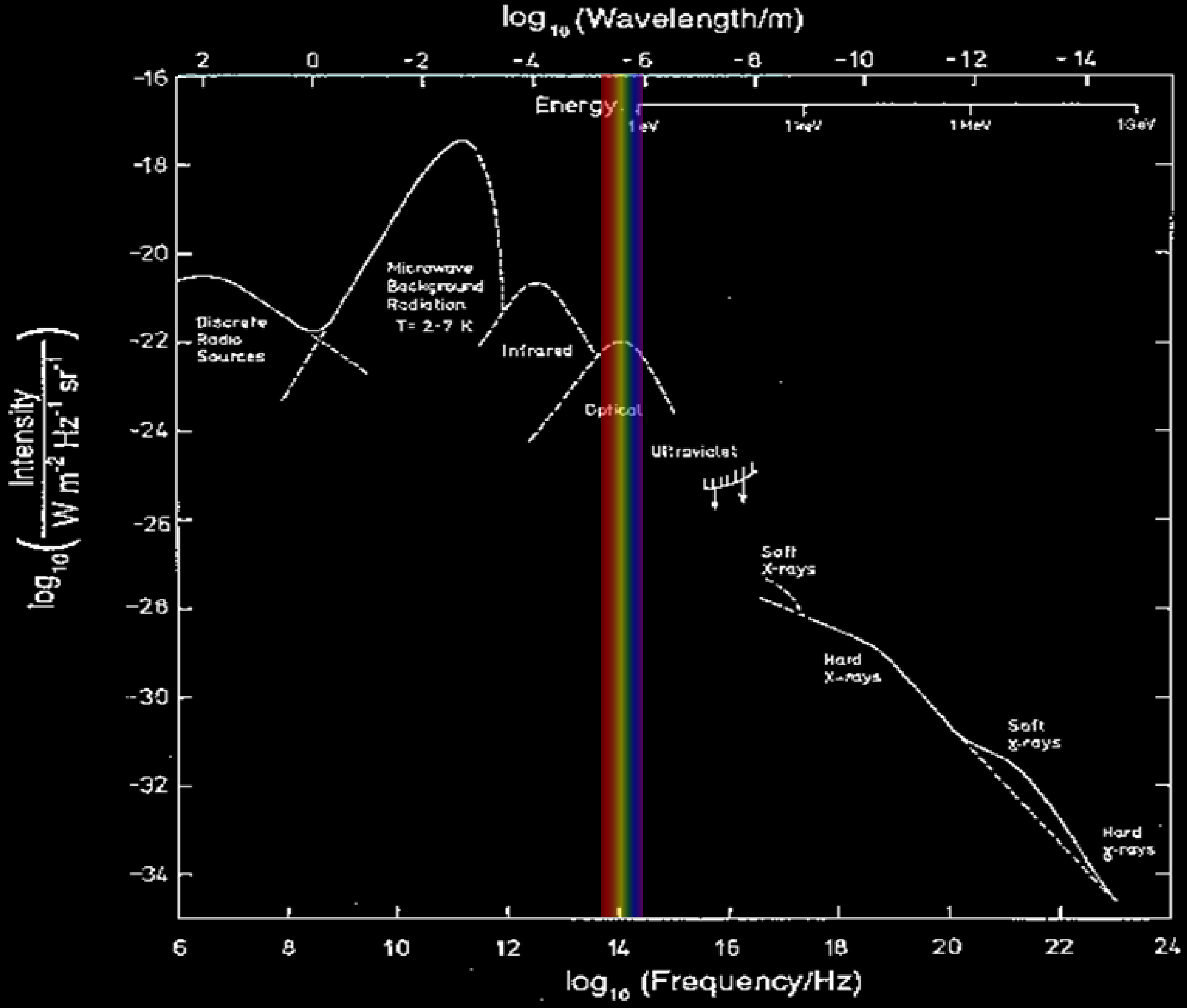
↓

New Physics probes

What are "Astroparticles"

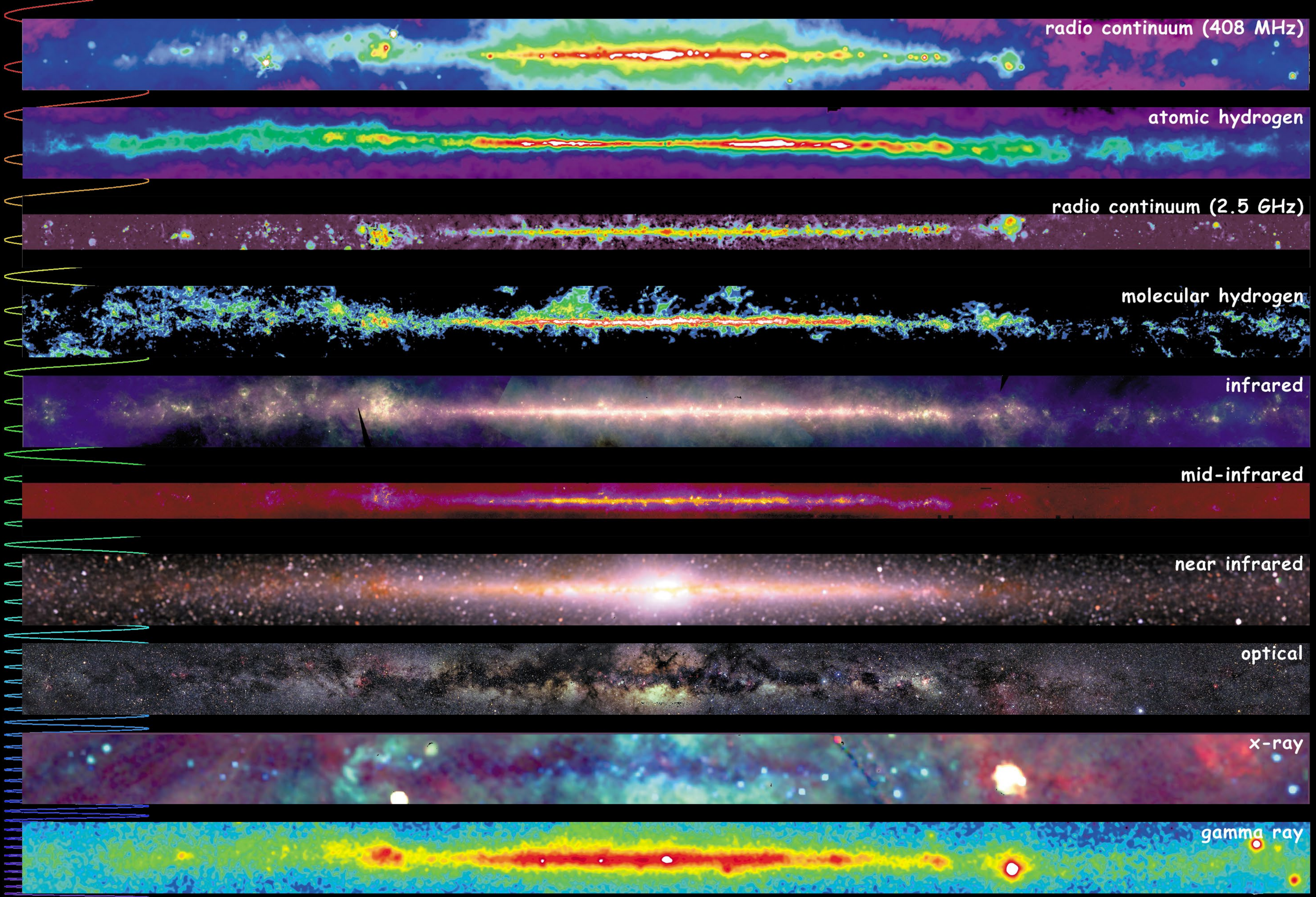
What we know… roughly.

A multi-wavelength sky



Our Galaxy

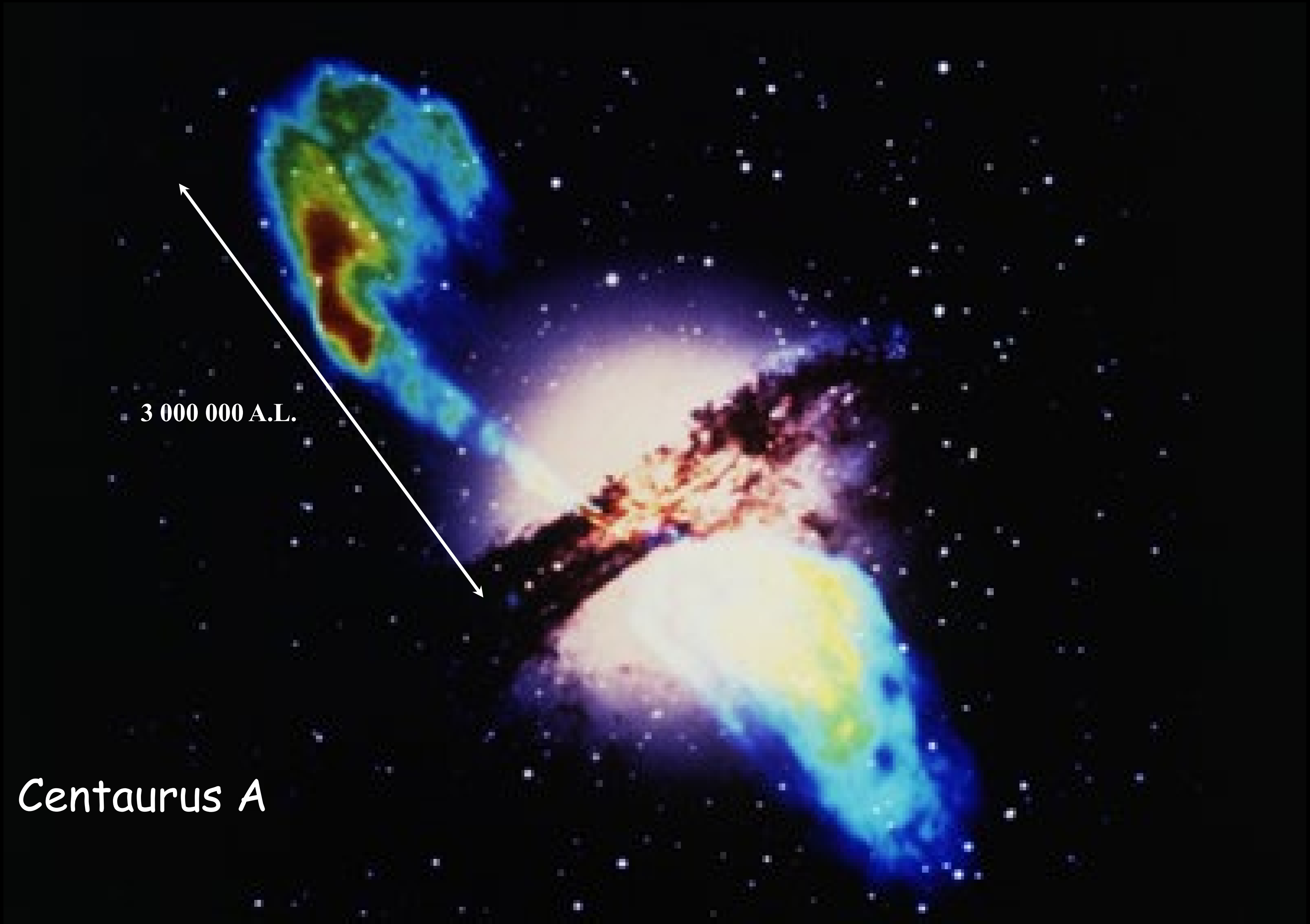
The optical Milky Way



http://adc.gsfc.nasa.gov/mw

Multiwavelength Milky Way

Radio Galaxy



Let there be light !

All what we know is Astrophysics is thanks to 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…

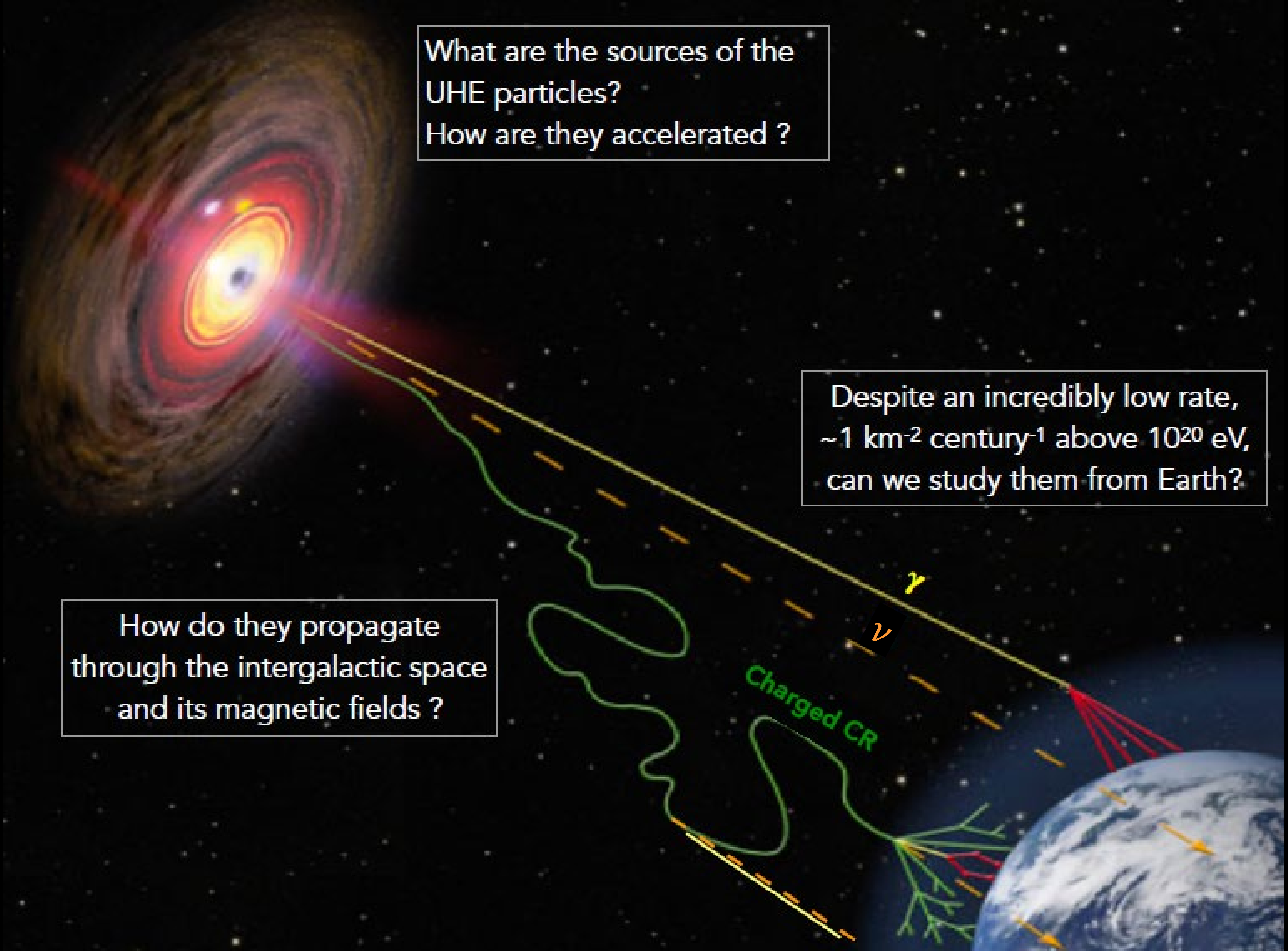
- ∃ on-luminous messengers :
  cosmic rays (charged), neutrinos and Gravitational Waves !
- Rare but precious : ~ 4 CR/cm²/s

CR astronomy is impossible...

- Directions randomized by magnetic fields (except at UHE)
- What we would know if it was the same for photons

but not astrophysics !

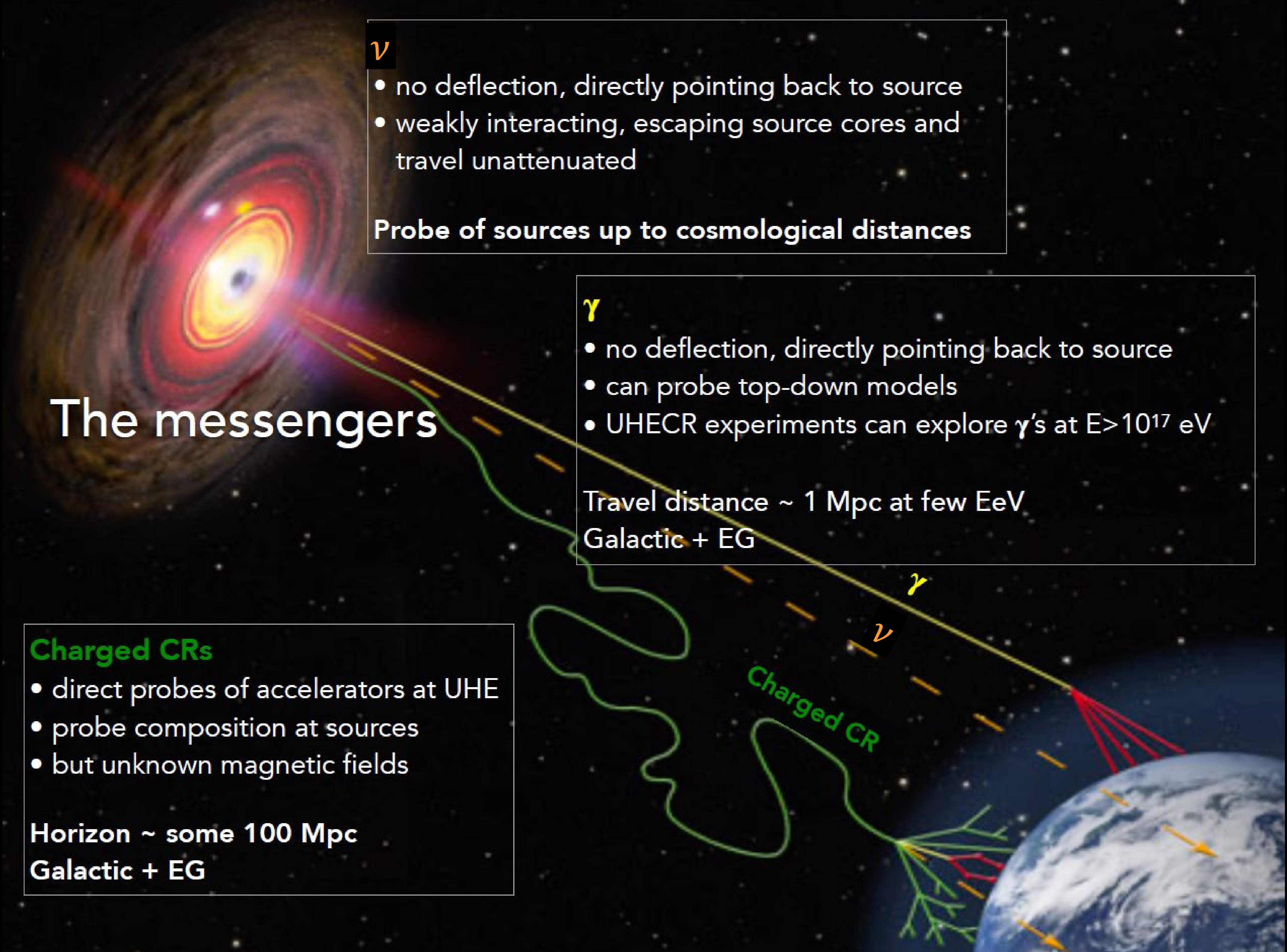
- Energy spectra and chemical composition tells us a lot…



What are the sources of the UHE particles?
How are they accelerated ?

Despite an incredibly low rate, ~1 km^{-2} century^{-1} above 10^{20} eV, can we study them from Earth?

How do they propagate through the intergalactic space and its magnetic fields ?



The messengers

ν

- no deflection, directly pointing back to source
- weakly interacting, escaping source cores and travel unattenuated

Probe of sources up to cosmological distances

γ

- no deflection, directly pointing back to source
- can probe top-down models
- UHECR experiments can explore γ's at $E>10^{17}$ eV

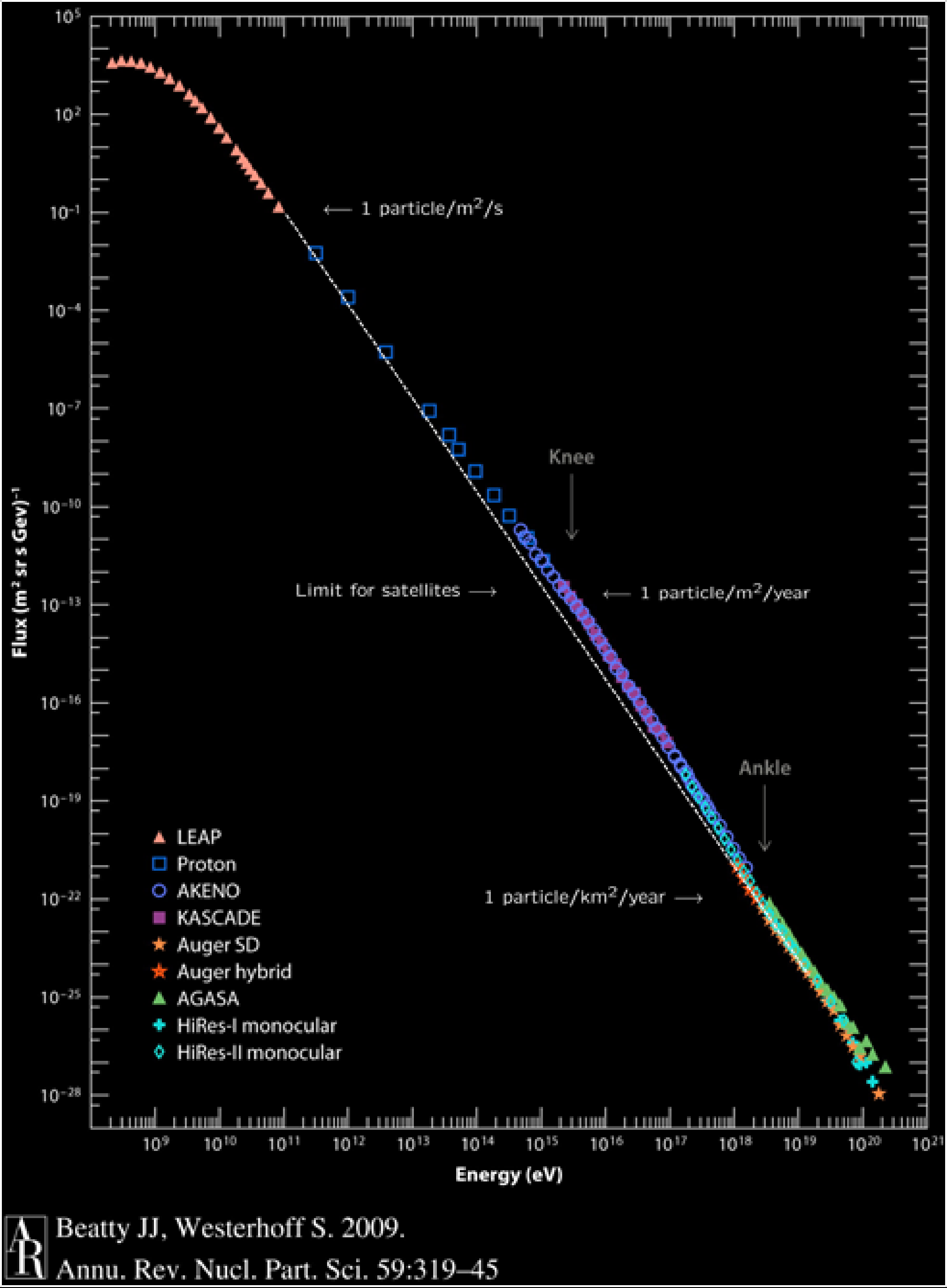
Travel distance ~ 1 Mpc at few EeV
Galactic + EG

Charged CRs

- direct probes of accelerators at UHE
- probe composition at sources
- but unknown magnetic fields

Horizon ~ some 100 Mpc
Galactic + EG

The "all particles" spectrum

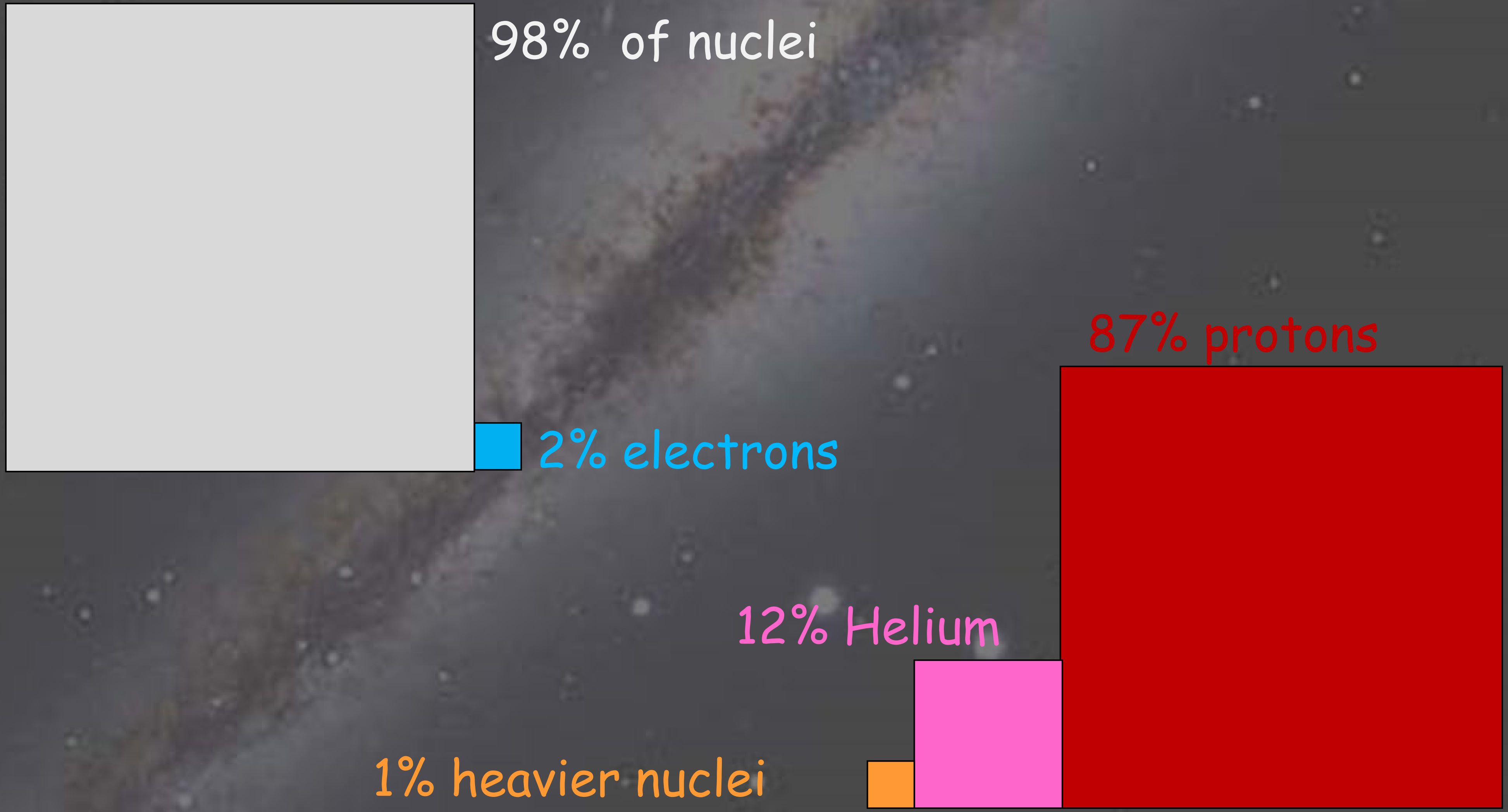


AR Beatty JJ, Westerhoff S. 2009.
Annu. Rev. Nucl. Part. Sci. 59:319–45

- Regular spectrum over 12 decades in energy, and 32 decades in flux
- Small break near 3×10^{15} eV: the "knee"
- An other one near 10^{18} eV: the "ankle"
- More details seen now including more inflections
- Spectrum badly known at the two extremities
  - Geomagnetic "shield" + Solar modulation
  - Extreme rareness…

Charge cosmic rays composition

(at low energy)



98% of nuclei

2% electrons

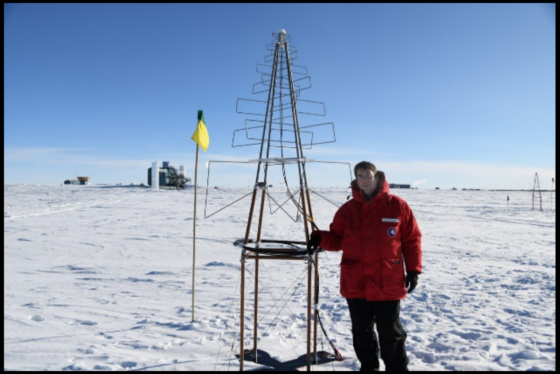
87% protons

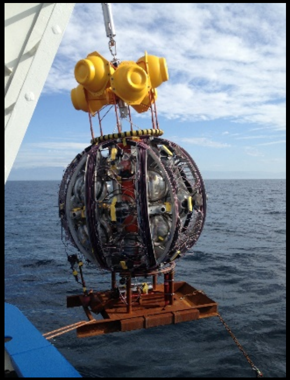
12% Helium

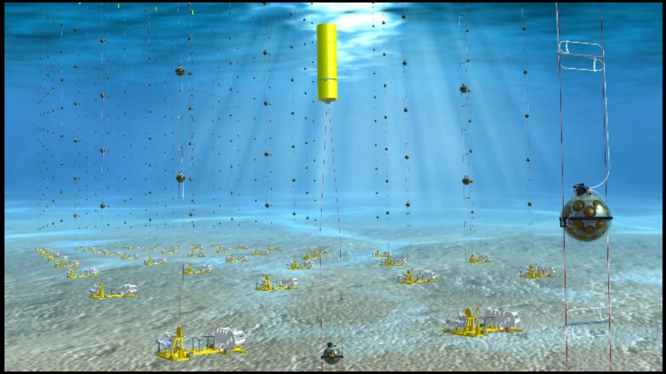
1% heavier nuclei

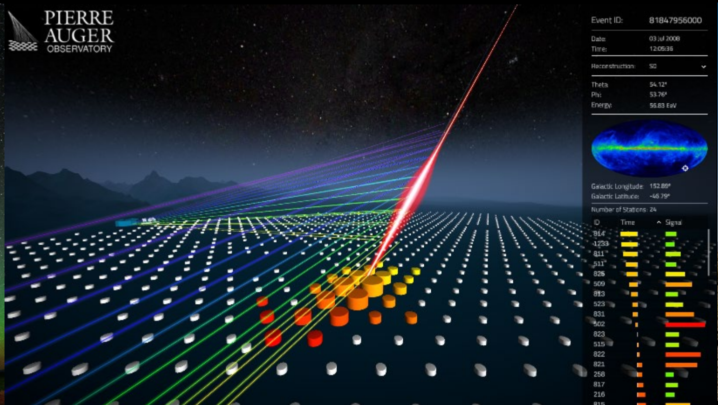
Total Flux : 4 RC/cm^2/s

A quick glimpse on some of the tools









Event ID: 81847956000

Date: 03 Jul 2008
Time: 12:05:36

Reconstruction: SD

Theta: 54.12°
Phi: 53.76°
Energy: 56.83 EeV

Galactic Longitude: 152.89°
Galactic Latitude: -46.79°

Number of Stations: 24

Nature and properties of Astroparticles

Composition
Spectrum
Anisotropies

2nd video (20')

Data on composition charged cosmic rays

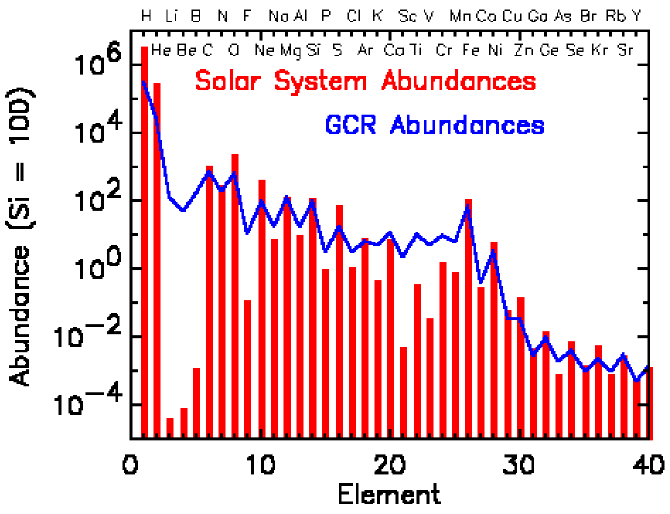
- Chemical composition
  - Nuclei = 98% (H = 87%, He = 12%, heavier than He = 1%)
  - Electrons = 2%
  - More or less standard composition (i.e. solar system) except for fewer H and He and presence of secondary nuclei + a few "anomalies"

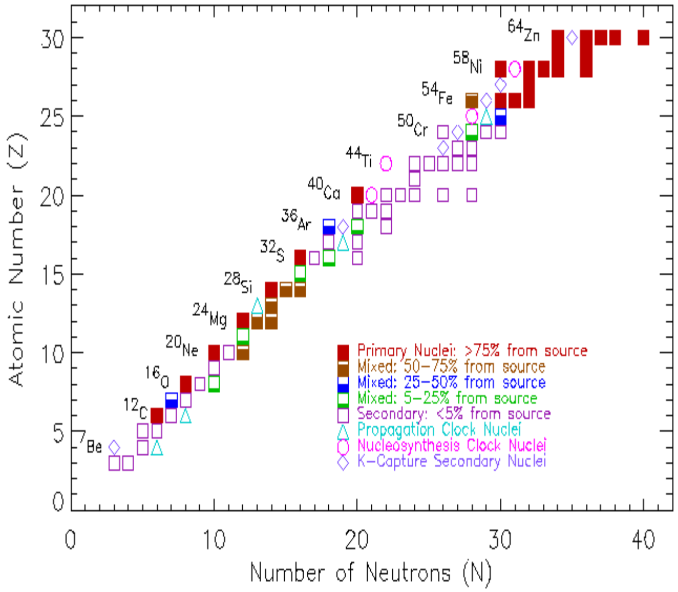
- Secondary atoms
  - Li, Be, B : spallation of C, N, O (+ nuclei below the Fe peak)
  - Nuclear thicknesses traversed by CR : X_{CR} = 6 to 10 g/cm²

- Isotopic anomalies
  - $^{22}N \rightarrow$ link to 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)
  - Lifetime of CR in the Galaxy $\tau_{CR} \approx 2 \times 10^7$ years

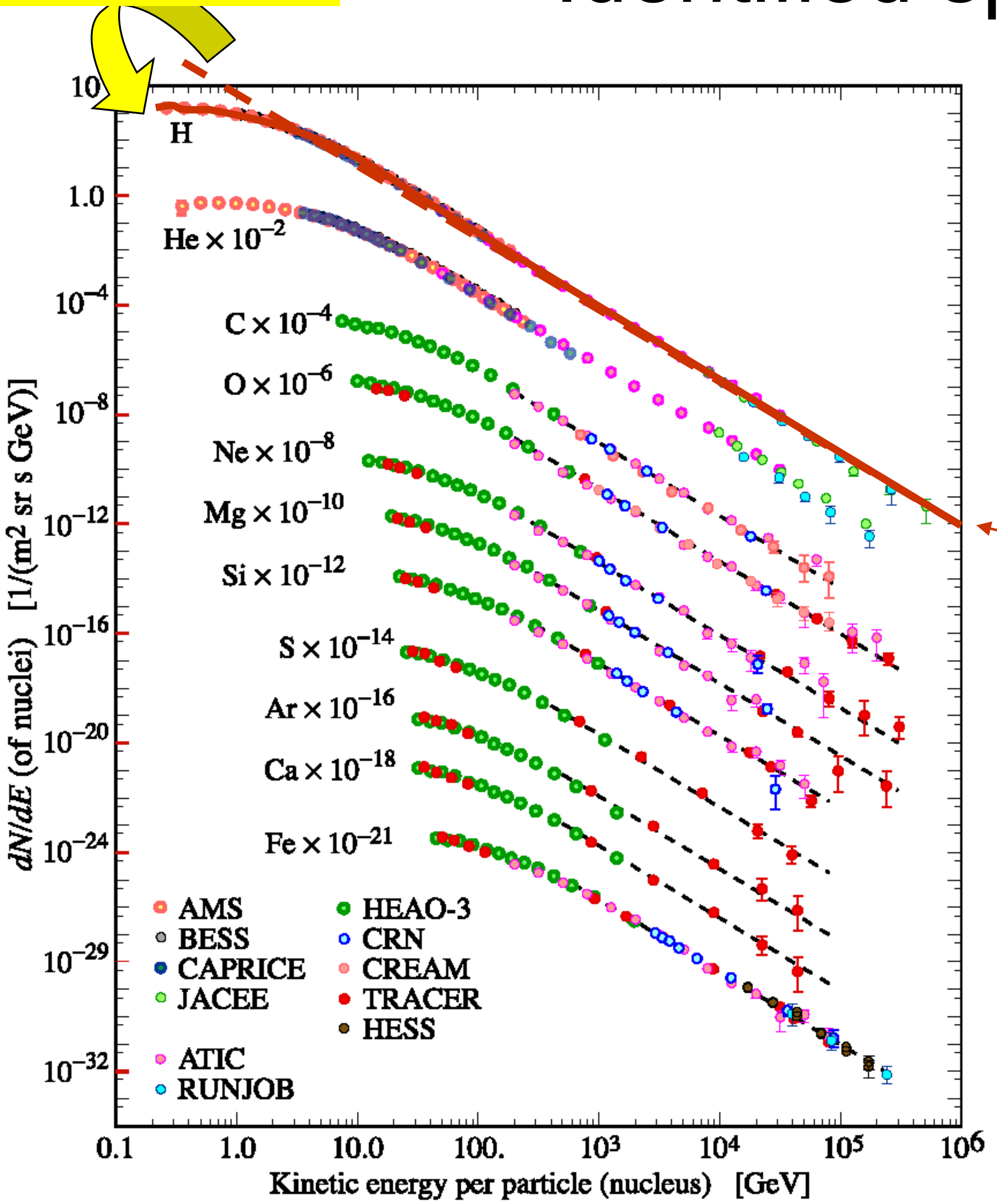
- Using both $\rightarrow \frac{X_{CR}}{c\, \tau_{CR}} \approx 0.2 \frac{p}{cm^3} \Rightarrow$ CR halo extension $\approx 3 - 7$ kpc





Geomagnetic cutoff
+
Solar modulation

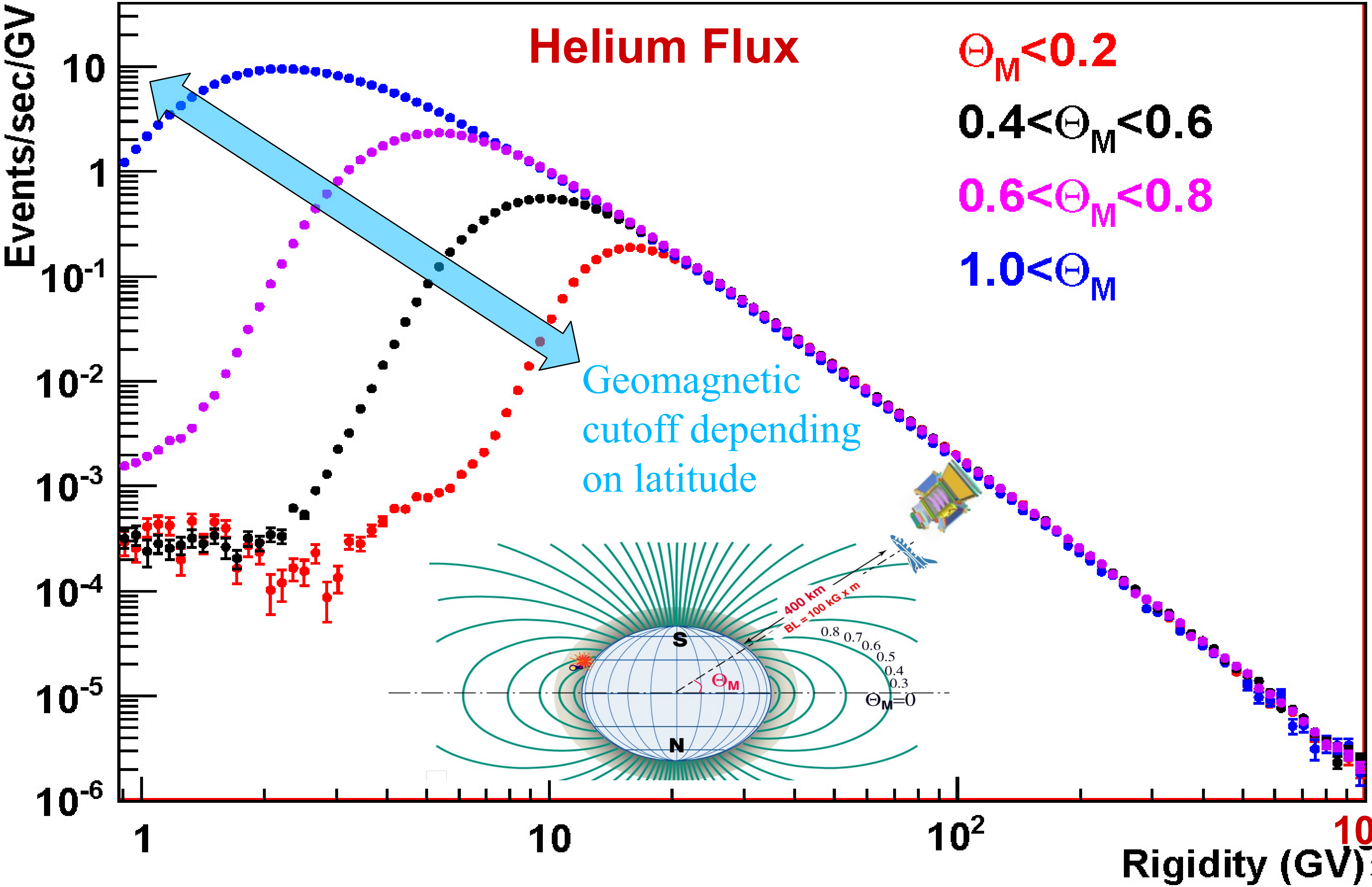
Identified spectra



Parallel power-laws up to 10^{14} eV/nucleon : impressively quasi-universal spectral indices.

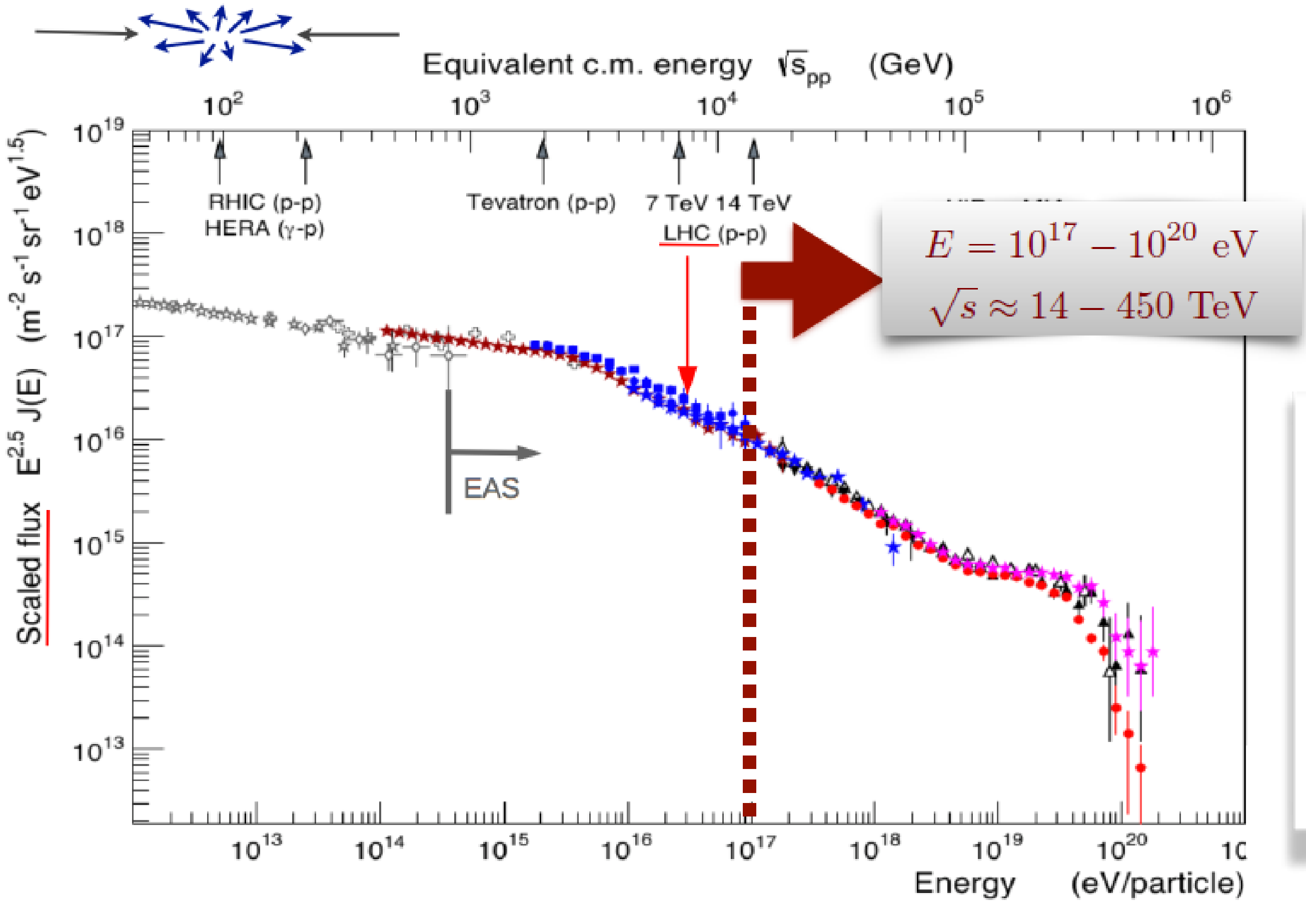
$$\frac{dN}{dE} \propto E^{-\alpha}$$

Data from AMS on ISS



Geomagnetic cutoff depending on latitude

CR spectrum above 1 TeV up to UHE



$$E = 10^{17} - 10^{20}\ \mathrm{eV}$$

$$\sqrt{s} \approx 14 - 450\ \mathrm{TeV}$$

UHECRs

ASTROPHYSICS

- ✓ where is the transition between a Galactic and an extra-Galactic origin of UHECRs?
- ✓ what is causing the suppression of the flux at the highest energies?
- ✓ can we perform UHECRs astronomy?

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets

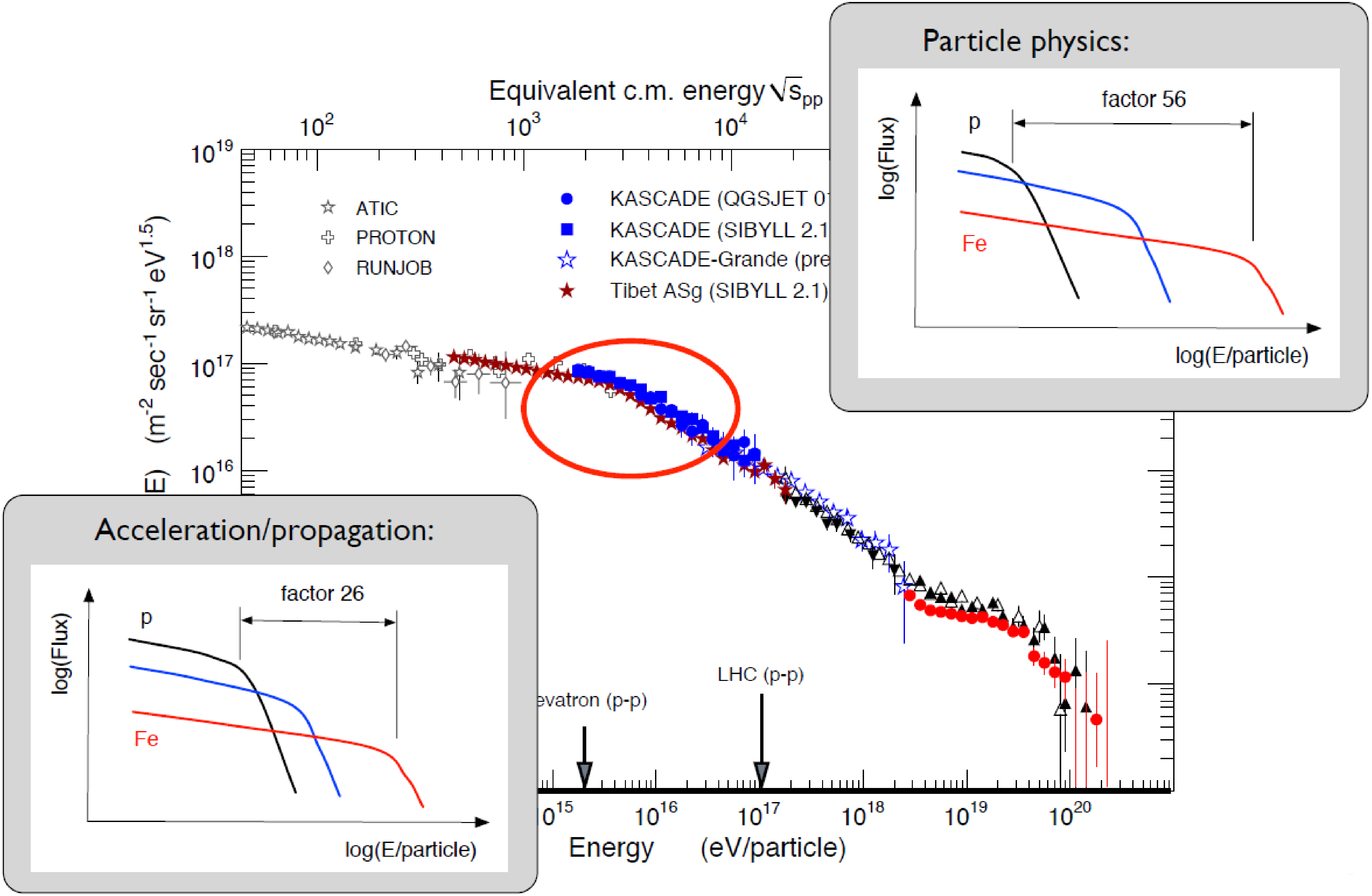
Need accelerator of size of Mecury's orbit to reach 10^{20} eV with current technology

(M. Unger, 2006)

PARTICLE PHYSICS

- ➡ very different energetic and kinematic phase space, for targets with <A>~14
- ➡ LHC tuning of hadronic interaction models employed in UHECR
- ➡ + constrain or find hints of new phenomena (e.g. Lorentz invariance violation)

Origin and physics of the knee



Particle physics:

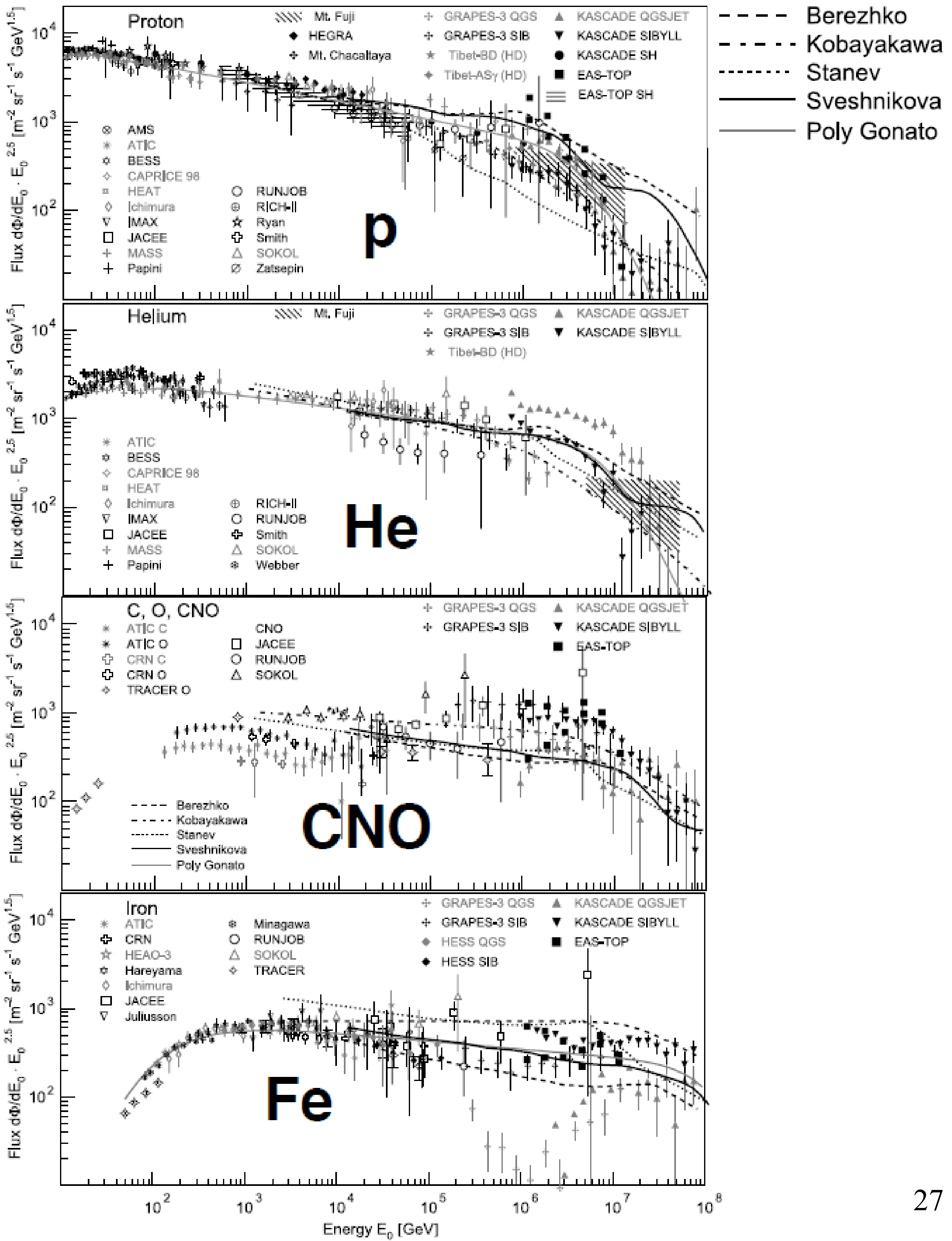
Acceleration/propagation:

Z dependent cutoff at the knee ?

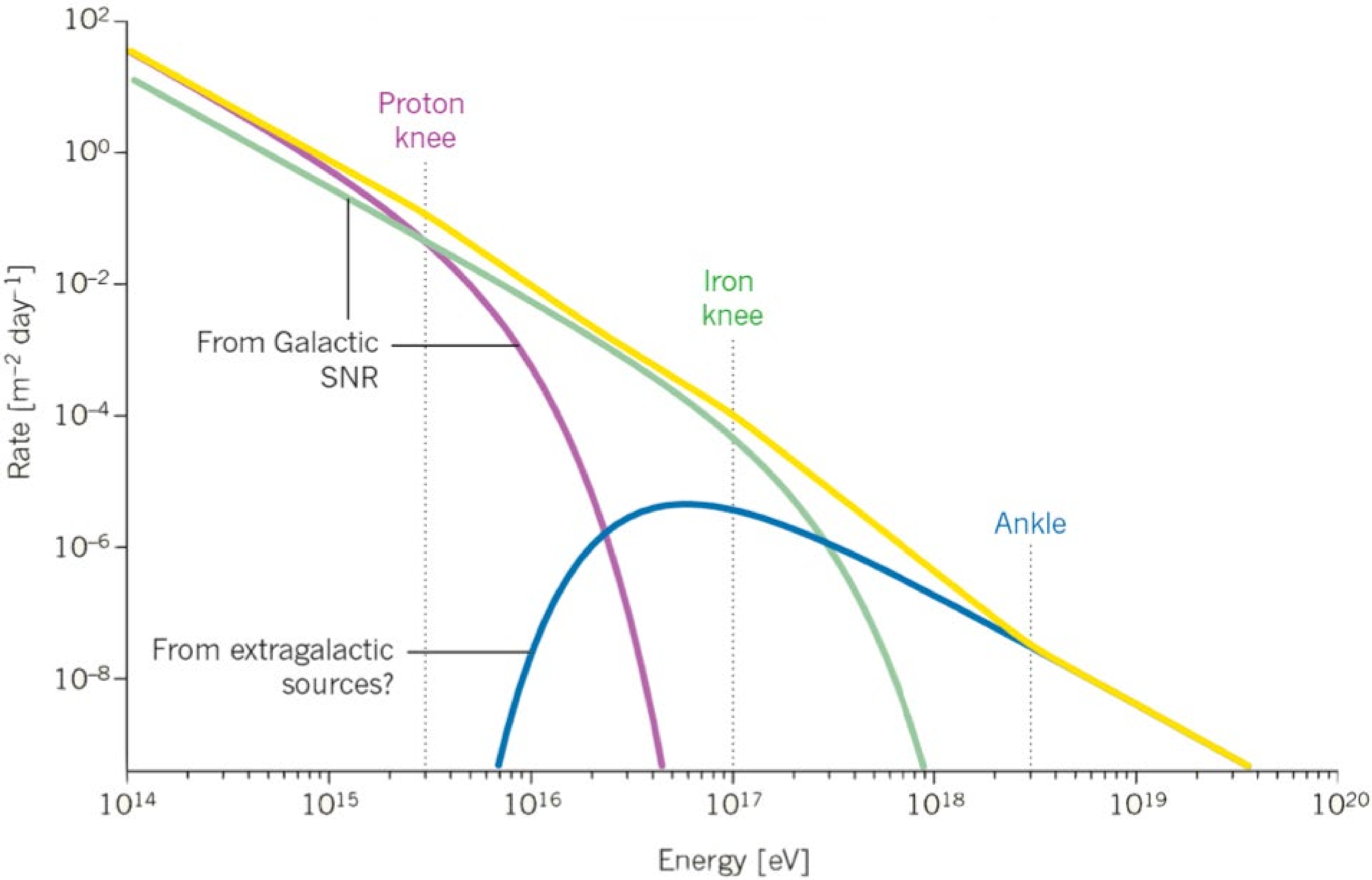
No obvious conclusions yet as above the knee implies indirect composition measurements inferred from ground based detectors using hadronic models thus model dependent conclusions.

Second knee at 10^{17}eV ?

J.R. Hörandel / Advances in Space Research 41 (2008) 442–463



Toward a global spectral picture



Transition GCR to EGCR ?

all-particle spectra including 2nd galactic component

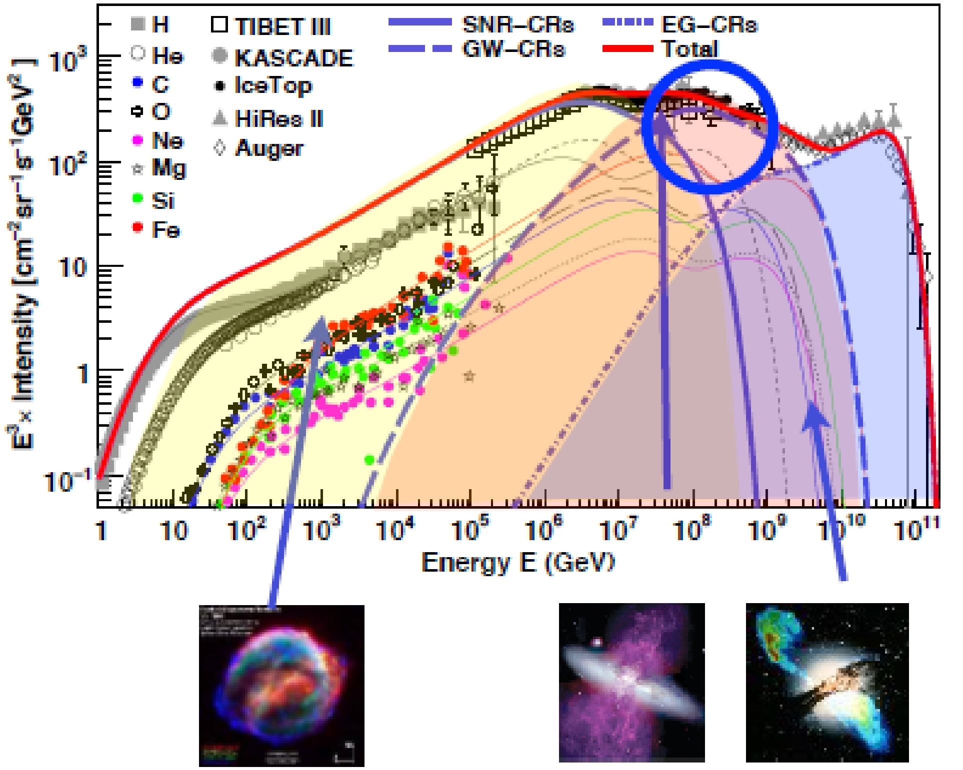
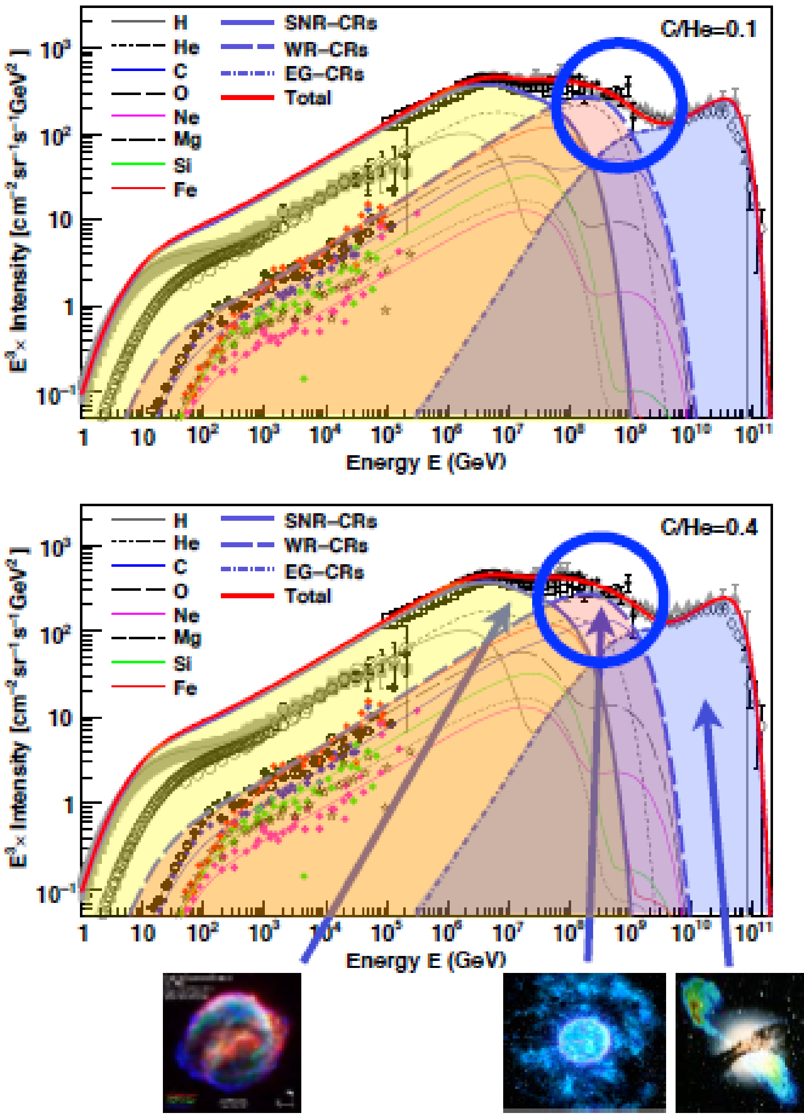


Table 3. Injection energy of SNR-CRs used in the calculation of all-particle spectrum in the WR-CR model (Figure 6).

Particle type	C/He = 0.1 $f(\times 10^{49}$ ergs)	C/He = 0.4 $f(\times 10^{49}$ ergs)
Proton	8.11	8.11
Helium	0.67	0.78
Carbon	2.11×10^{-2}	0.73×10^{-2}
Oxygen	2.94×10^{-2}	2.94×10^{-2}
Neon	4.41×10^{-3}	4.41×10^{-3}
Magnesium	6.03×10^{-3}	6.03×10^{-3}
Silicon	5.84×10^{-3}	5.84×10^{-3}
Iron	5.77×10^{-3}	5.77×10^{-3}

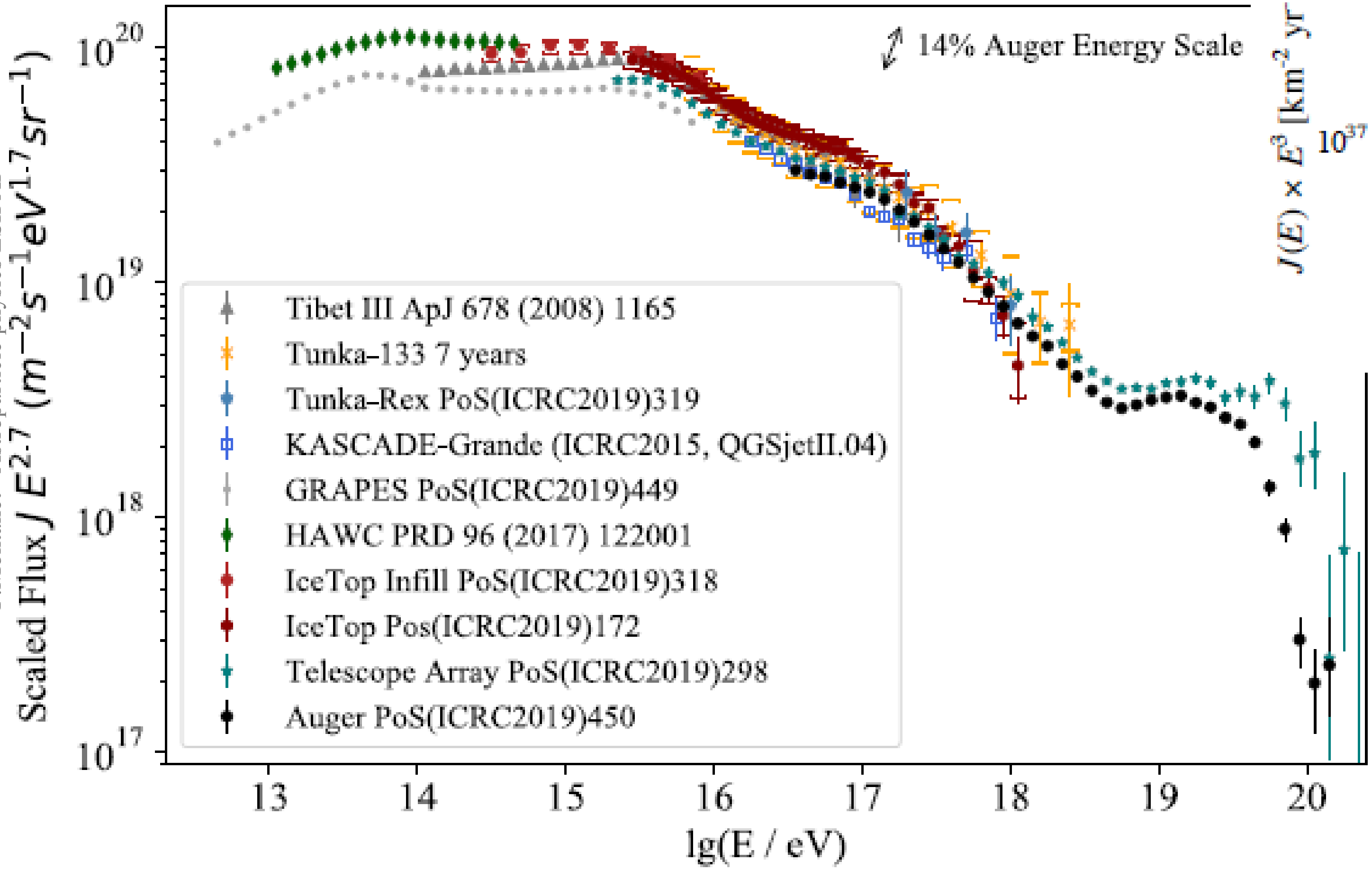


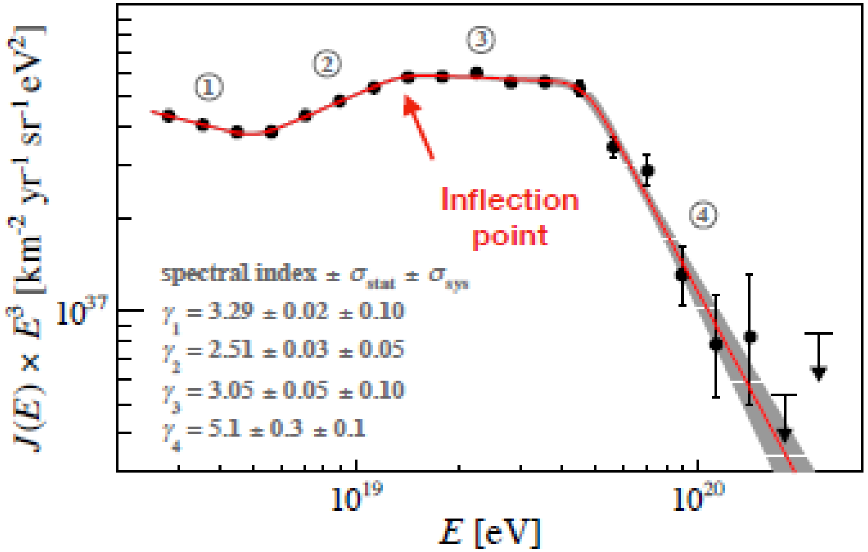
S. Thoudam et al., A&A 595 (2016) A33

Spectum @ UHE

1. Energy spectrum – status today

(Schröder, rapporteur talk, ICRC 2019)



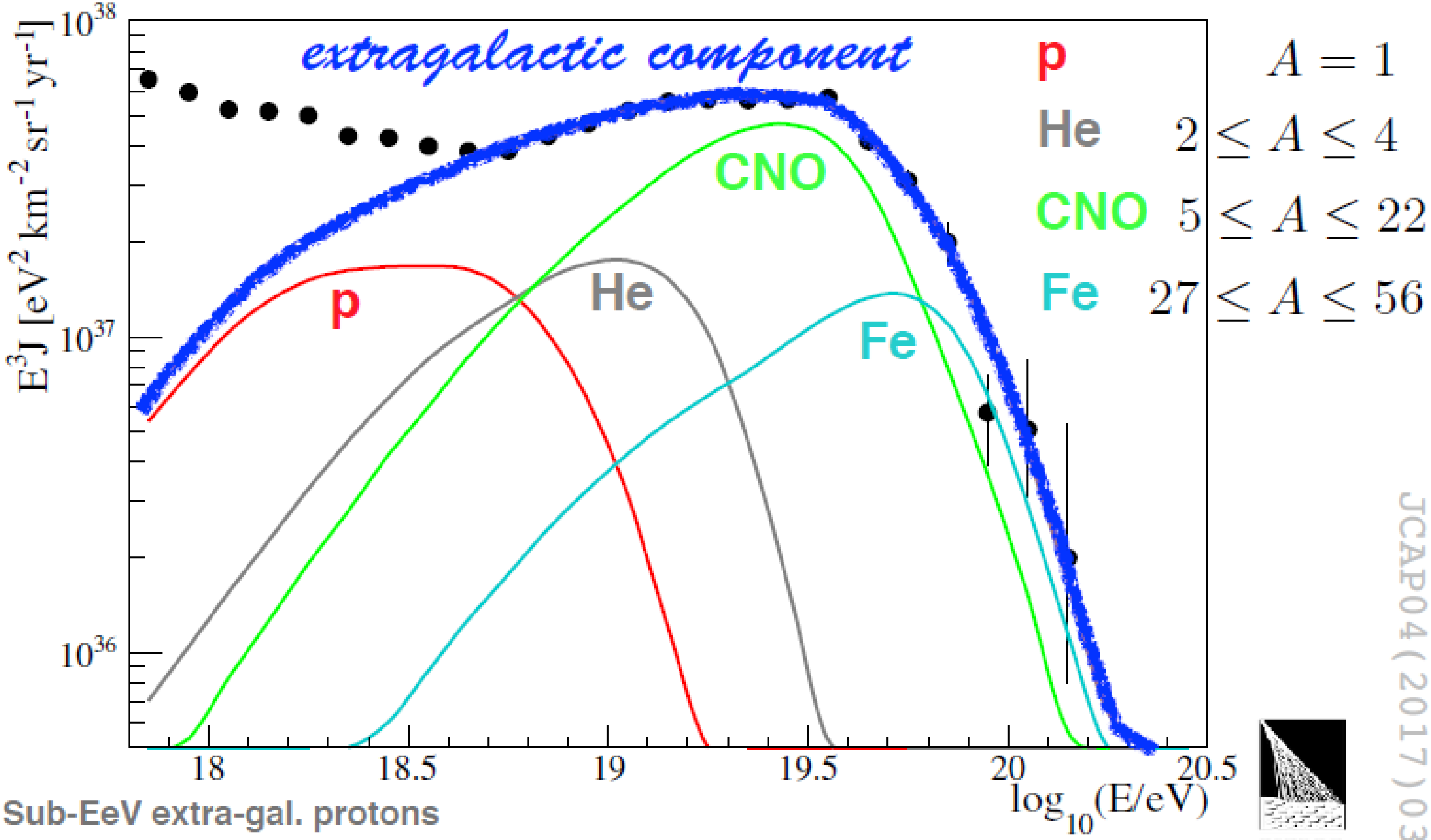


(Auger, Phys. Rev. Lett. & Phys. Rev. D 2020)

- **Many new structures established**
- **Discrepancy at highest energies?**
- **Flux suppression due to GZK effect or max. particle injection energy?**

Transition GCR to EGCR ?

Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory



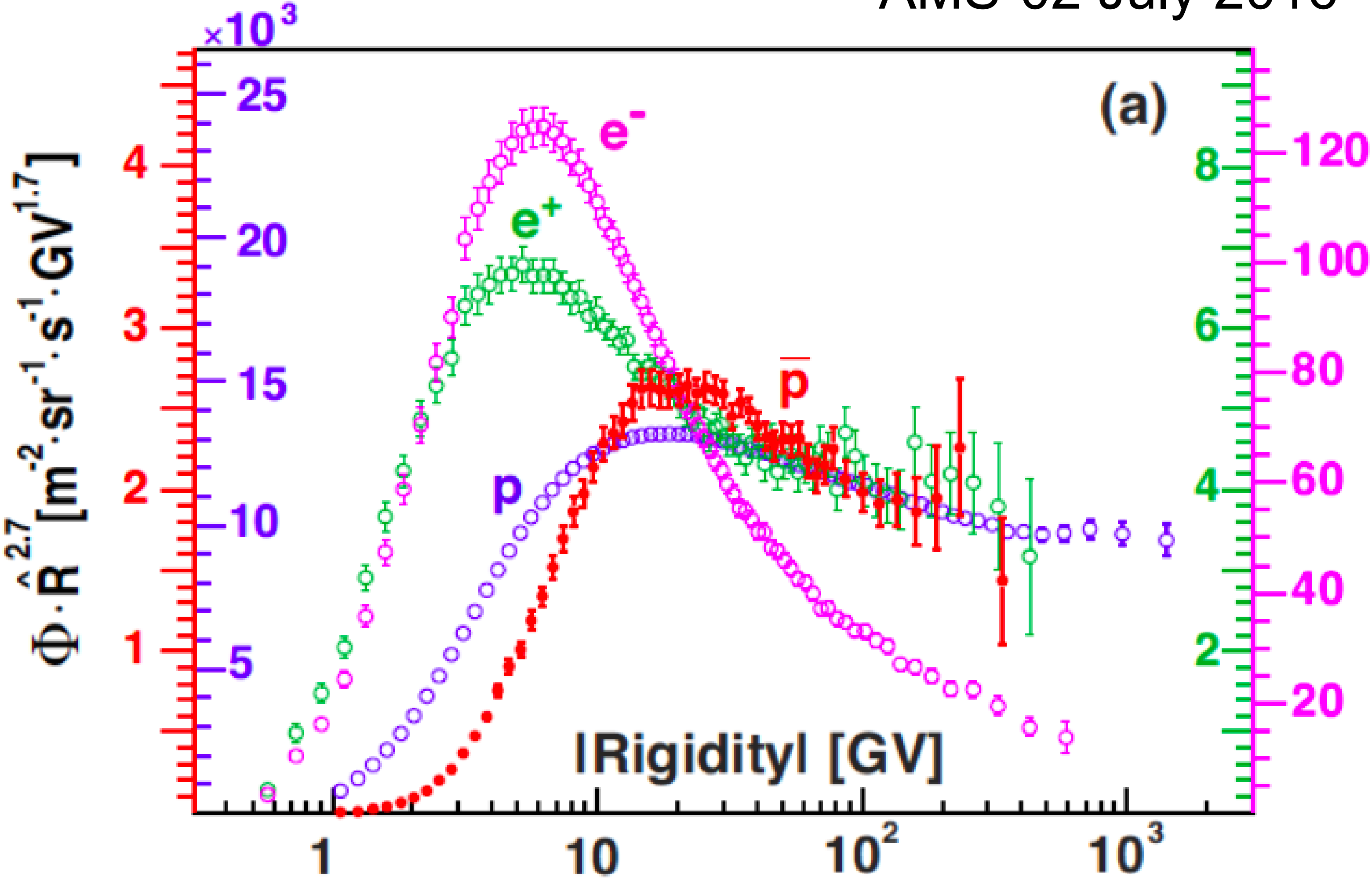
JCAP04(2017)038

Sub-EeV extra-gal. protons from interactions of heavier nuclei

Other mysteries at lower energy

Fluxes of e$^+$, e$^-$, p and anti-p

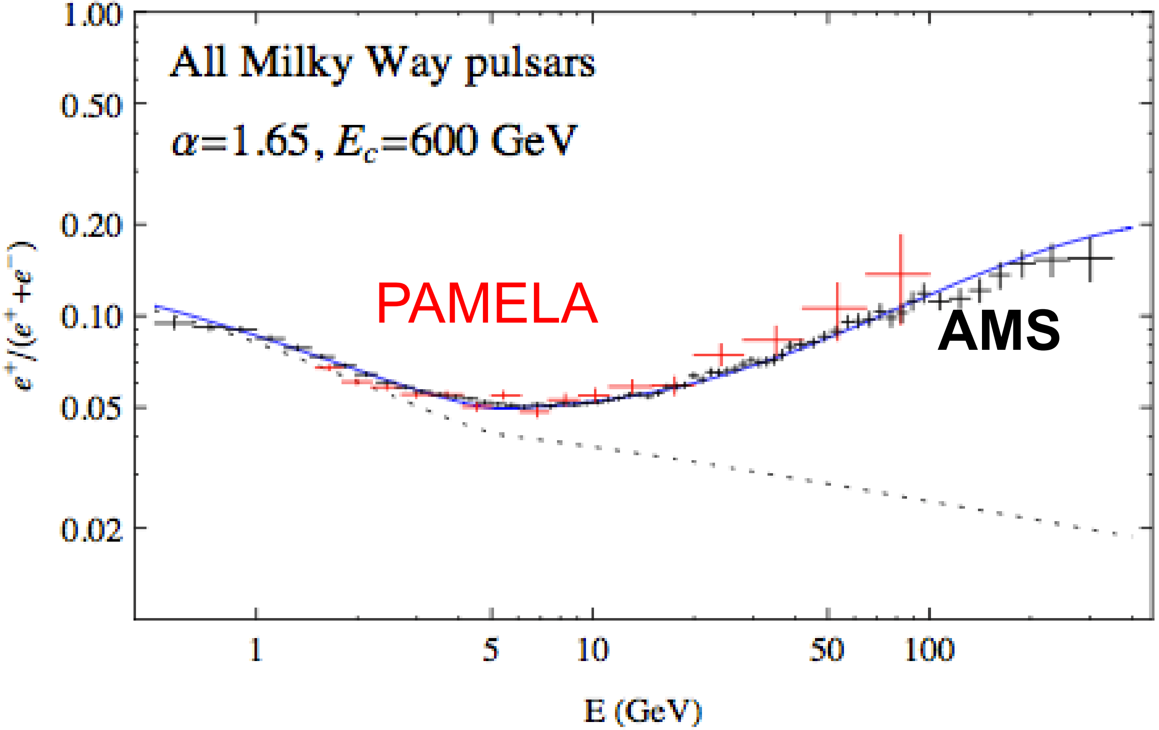
AMS-02 July 2016



Origin of the positron excess

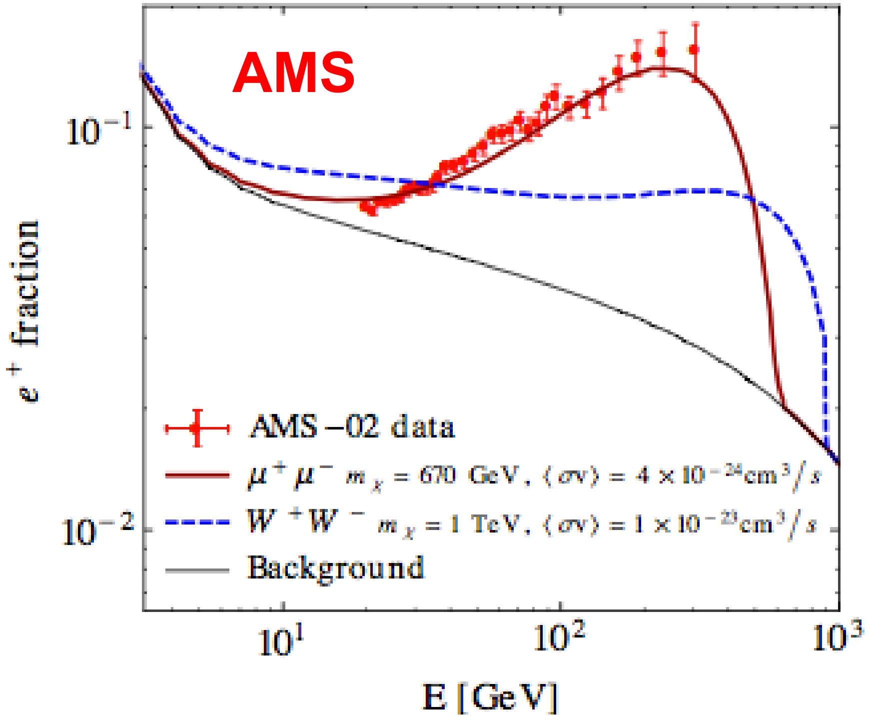
Astrophysical objects

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**

Gamma rays

- Gamma-rays observed → few TeV
- Spectrum ± understood up to MeV.
- Above, the diffuse spectrum and that of sources are very "hard", in $1/E^2$ revealing acceleration processes.

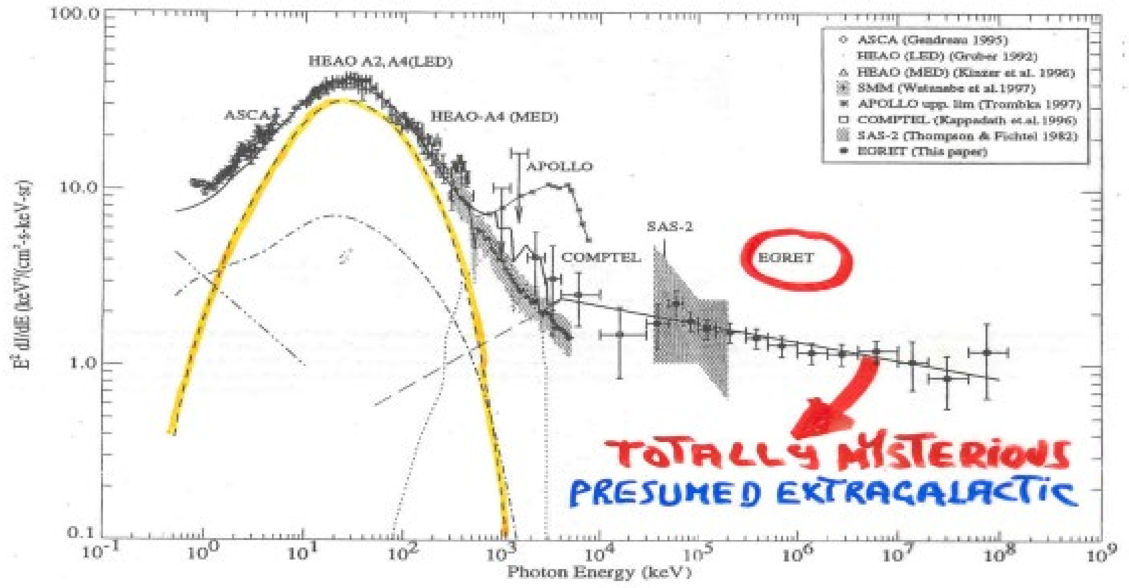
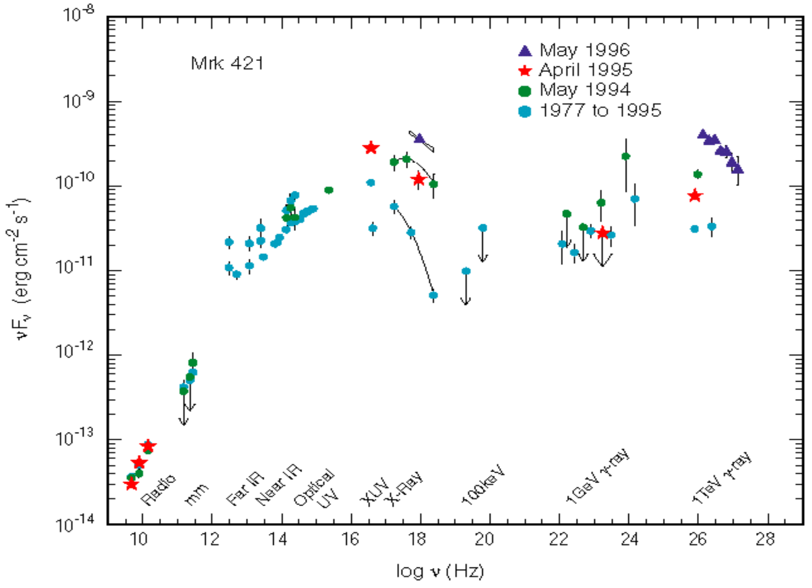


FIG. 10.—Multiwavelength spectrum of the extragalactic gamma-ray spectrum from X-rays to high-energy gamma rays. The estimated contribution from Seyfert I (*dot-dashed line*), and Seyfert II (*dashed*) are from the model of Zdziarski (1996); steep-spectrum quasar contribution (*triple-dot–dashed line*) is taken from Chen, Fabian, & Gendreau (1997); Type Ia supernovae (*dotted line*) is from The et al. (1993). The blazar contribution below 4 MeV (*long-dashed line*) is derived assuming the average blazar spectrum breaks around 4 MeV (McNaron-Brown et al. 1995) to a power law with an index of ∼ −1.7. The thick solid line indicates the sum of all the components.



How is this non thermal equilibrium radiation produced?

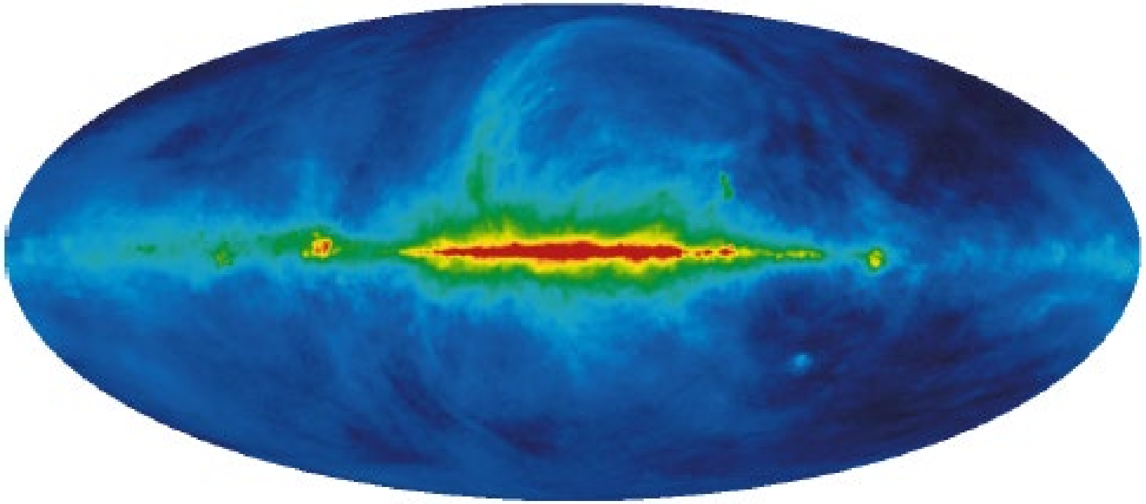
Gamma, diffuse emission

Emission due to:

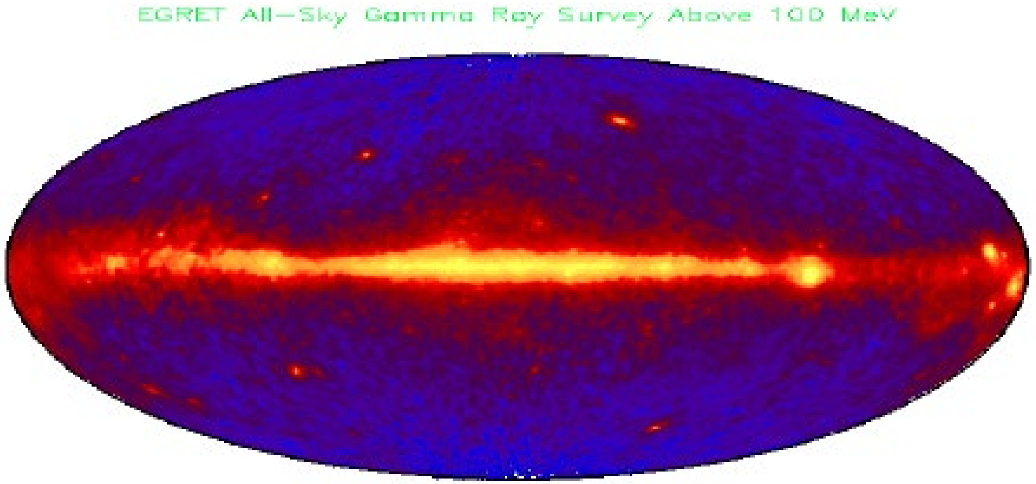
- the interactions of cosmic electrons with:
  - the magnetic fields (synchrotron radiation dominates the radio emission of the Galaxy up to a few GHz)
  - interstellar Matter (ISM); bremsstrahlung important bellow 100 MeV
  - Interstellar photon: Inverse Compton above GeV
- the decay of π^0 produced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

Gamma, diffuse emission

408 MHz



100 MeV



Galactic or Extragalactic CR ?

At moderate energy (γ-rays ~ 1 GeV), a strong answer from EGRET, already in 1993 !

Hypothesis: if most CR are extra or metagalactic, the density of CR should be identical in our Galaxy and in its satellites, then,

- Radio observations radio give the mass of gas M_H in the SMC
- M_H implies a measurable flux for SMC of: $2.5 \times 10^{-7} cm^{-2}.s^{-1}$

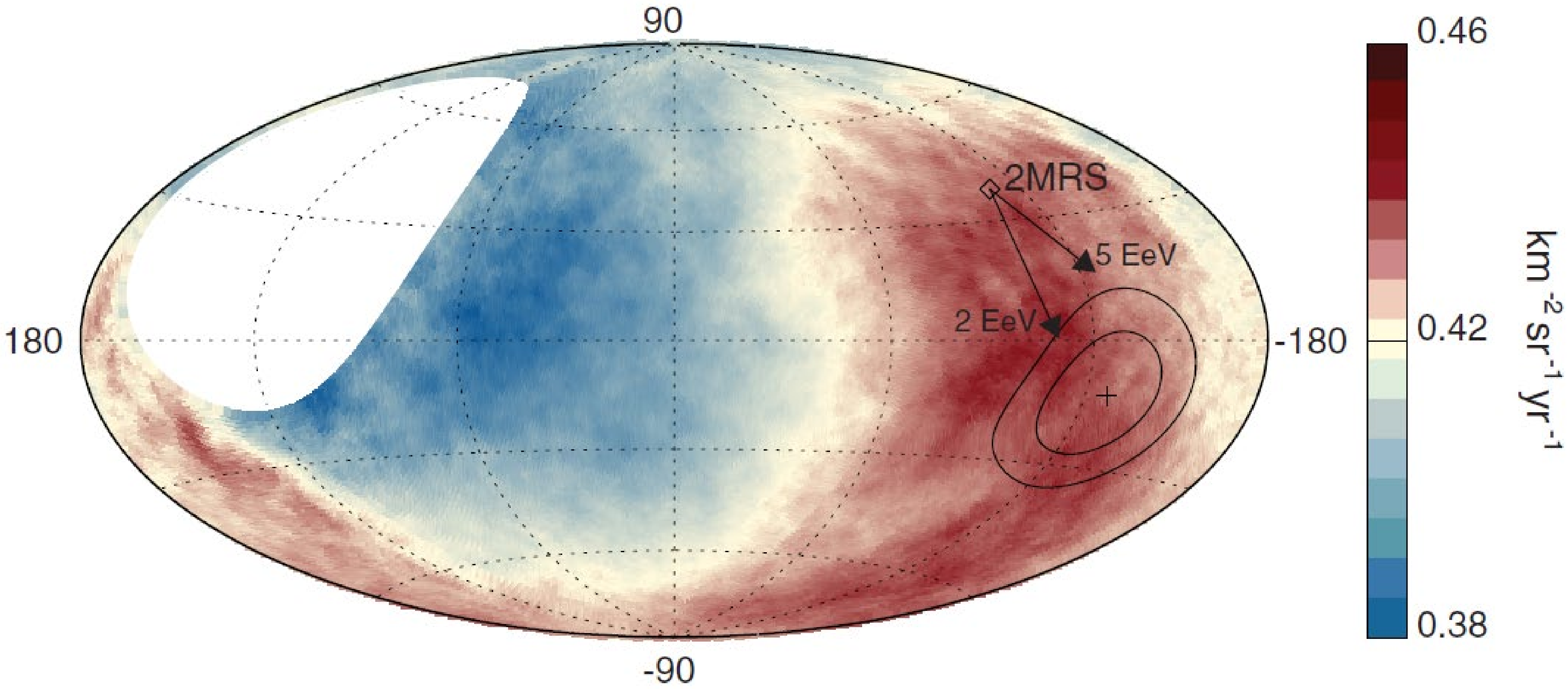
$$F_\gamma \propto M_H N_{CR} R_q$$

- EGRET gaves an upper limit (at 95%CL): $< 0.5 \times 10^{-7} cm^{-2}.s^{-1}$
- The CR density is 5 times smaller within SMC

Cosmic rays are indeed mostly produced by and confined within the Milky-Way!

Extragalactic UHECR ?

Definite answer from AUGER, only in 2017!



- Dipolar distribution of CR with energy above 8×10^{18}eV
- The excess is ~12%
- The pole of this excess is 120° away from the galactic center and matches with local extragalactic matter distribution.

⇒ UHECR are from extra-galactic origin !

The general problematic

- From thermal speeds to UHE (few 10^{20} eV)

Produce them

- From top to down (decay…)
- From bottom to up (acceleration)

Preserve them

- Energy losses (Synch., IC, π, 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

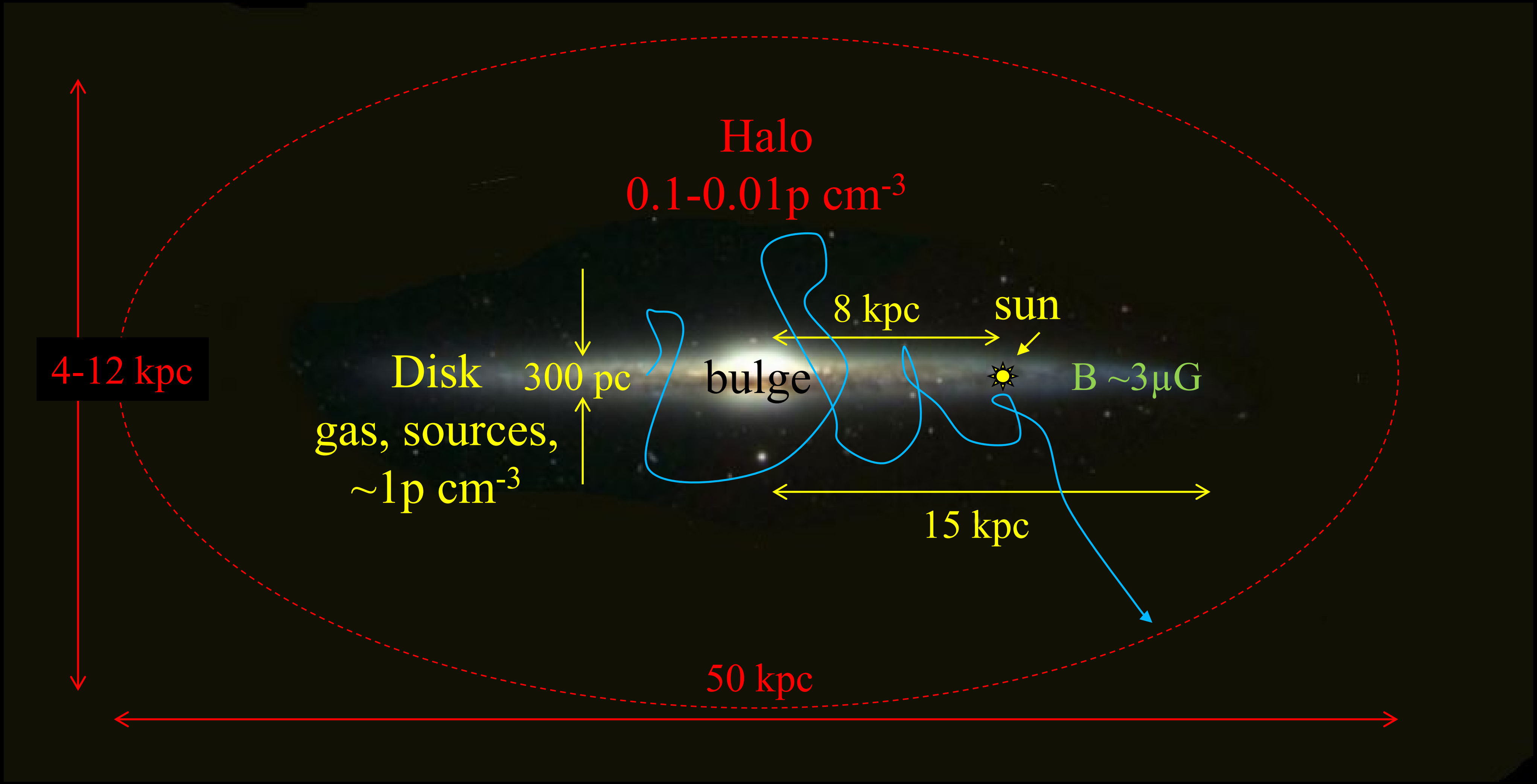
Propagation medium

IGM, ISM and atmosphere

3rd video (< 20')

Dimensions of the Milky Way

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

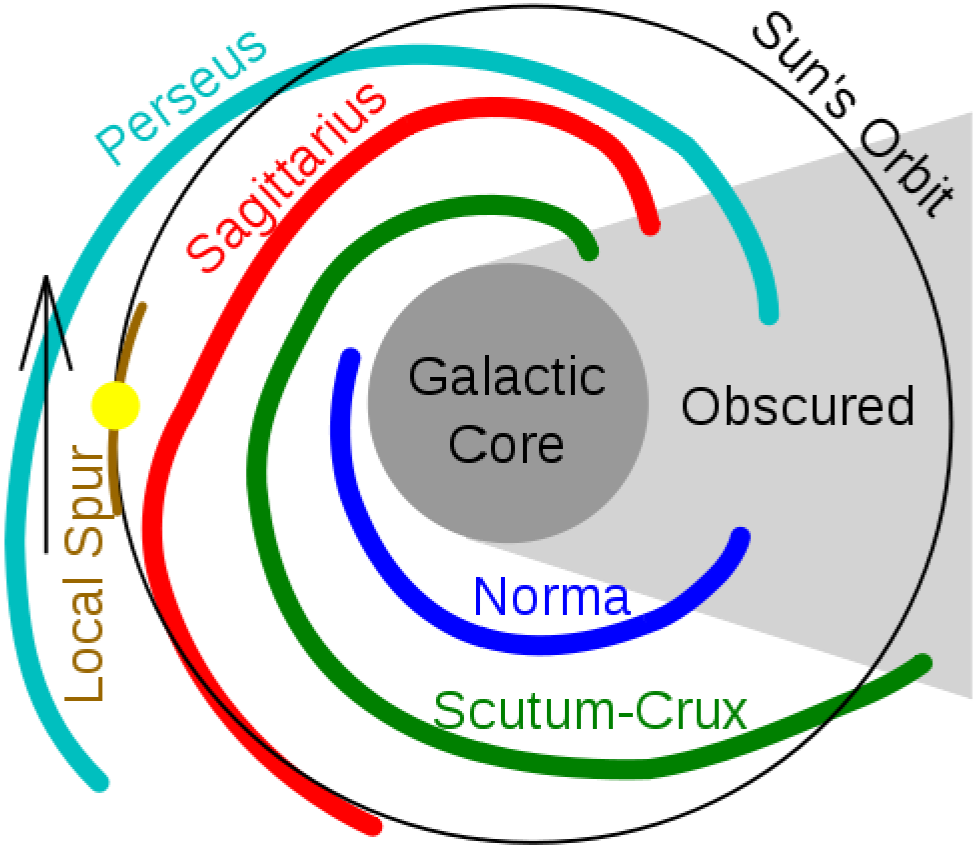


Milky Way, a spiral galaxy

Milky Way, a spiral galaxy

Local spur and neighboring arms
local matter and B field
inhomogeneity.

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

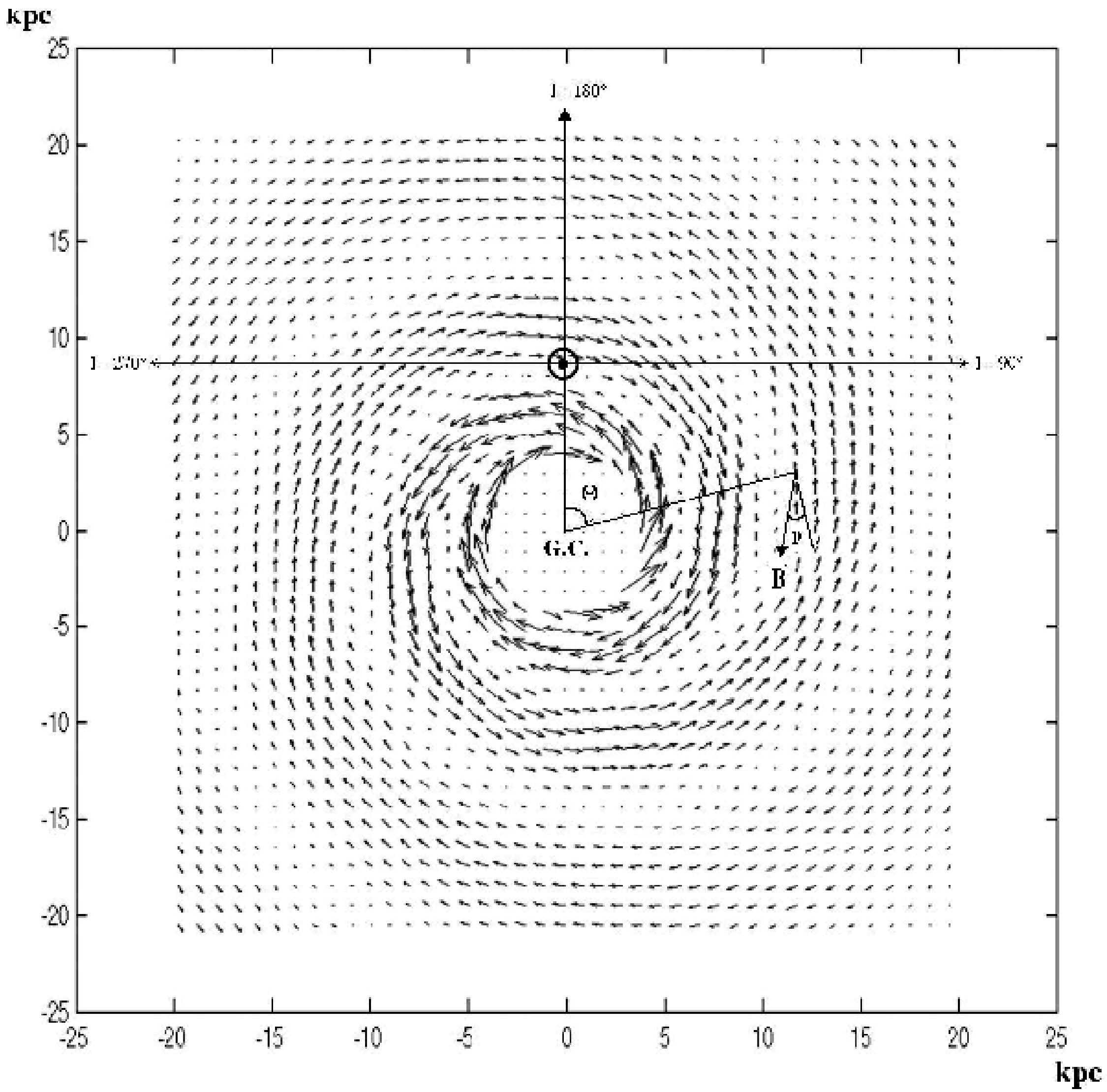


Milky Way, a spiral galaxy

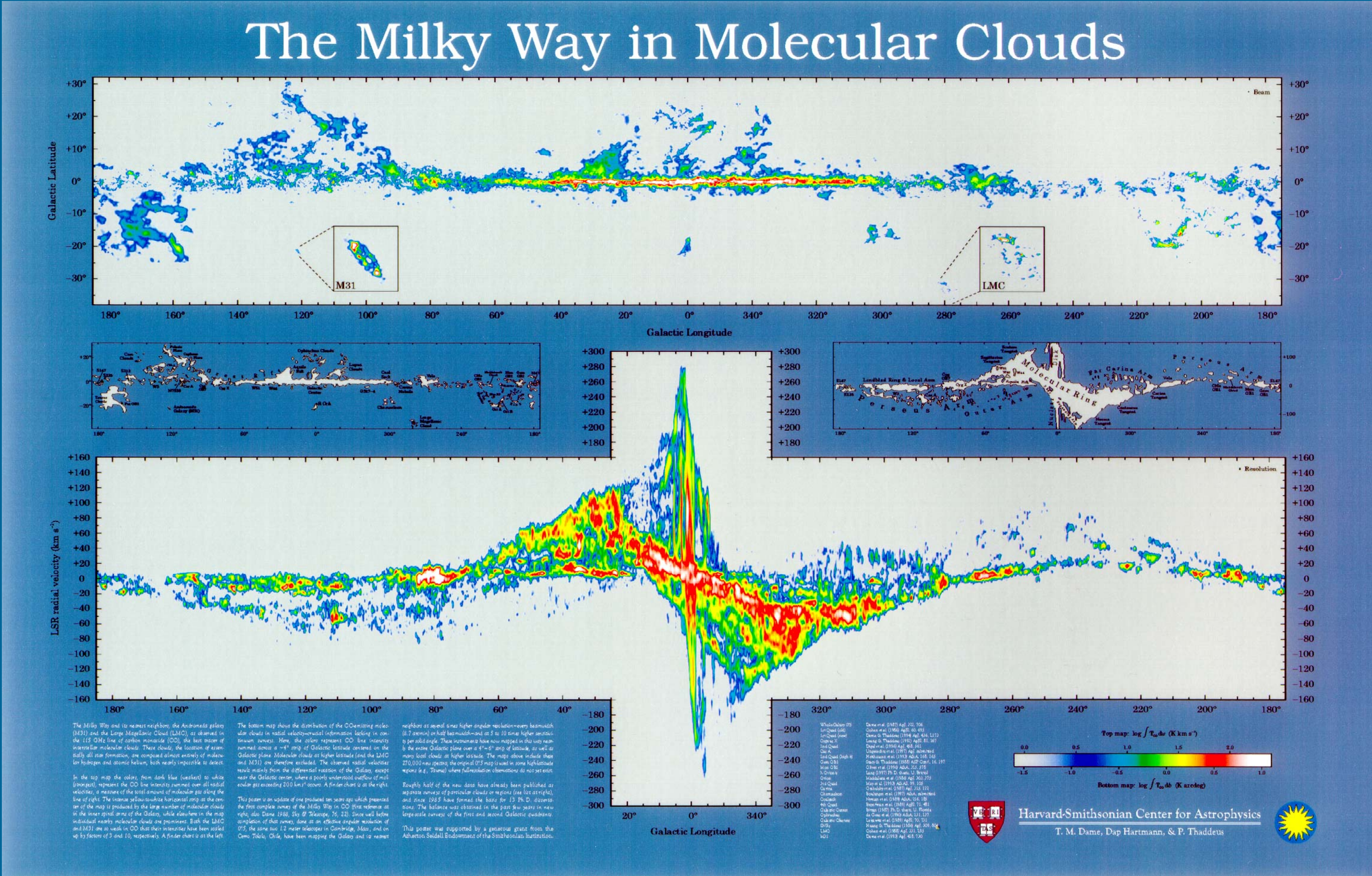
Local spur and neighboring arms local matter and B field inhomogeneity.

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

Known from measured from Faraday rotation of the polarized emission and dispersion measurements on pulses from radio pulsars.



A thick target…



The Milky Way in Molecular Clouds

The Milky Way and its nearest neighbors, the Andromeda galaxy (M31) and the Large Magellanic Cloud (LMC), as observed in the 115 GHz line of carbon monoxide (CO), the best tracer of interstellar molecular clouds. These clouds, the location of essentially all star formation, are composed almost entirely of molecular hydrogen and atomic helium, both nearly impossible to detect.

In the top map the colors, from dark blue (weakest) to white (strongest), represent the CO line intensity summed over all radial velocities, a measure of the total amount of molecular gas along the line of sight. The intense yellow-to-white horizontal strip at the center of the map is produced by the large number of molecular clouds in the inner spiral arms of the Galaxy, while elsewhere in the map individual nearby molecular clouds are prominent. Both the LMC and M31 are so weak in CO that their intensities have been scaled up by factors of 3 and 10, respectively. A finder chart is at the left.

The bottom map shows the distribution of the CO-emitting molecular clouds in radial velocity—crucial information lacking in continuum surveys. Here, the colors represent CO line intensity summed across a ~4° strip of Galactic latitude centered on the Galactic plane. Molecular clouds at higher latitude (and the LMC and M31) are therefore excluded. The observed radial velocities result mainly from the differential rotation of the Galaxy, except near the Galactic center, where a poorly understood outflow of molecular gas exceeding 200 km s⁻¹ occurs. A finder chart is at the right.

This poster is an update of one produced ten years ago which presented the first complete survey of the Milky Way in CO (first reference at right; also Dame 1988, Sky & Telescope, 76, 22). Since well before completion of that survey, done at an effective angular resolution of 0°.5, the same two 1.2 meter telescopes in Cambridge, Mass., and on Cerro Tololo, Chile, have been mapping the Galaxy and its nearest neighbors at several times higher angular resolution—every beamwidth (8.7 arcmin) or half beamwidth—and at 5 to 10 times higher sensitivity per solid angle. These instruments have now mapped in this way nearly the entire Galactic plane over a 4°–6° strip of latitude, as well as many local clouds at higher latitude. The maps above include these 270,000 new spectra; the original 0°.5 map is used in some high-latitude regions (e.g., Taurus) where full-resolution observations do not yet exist.

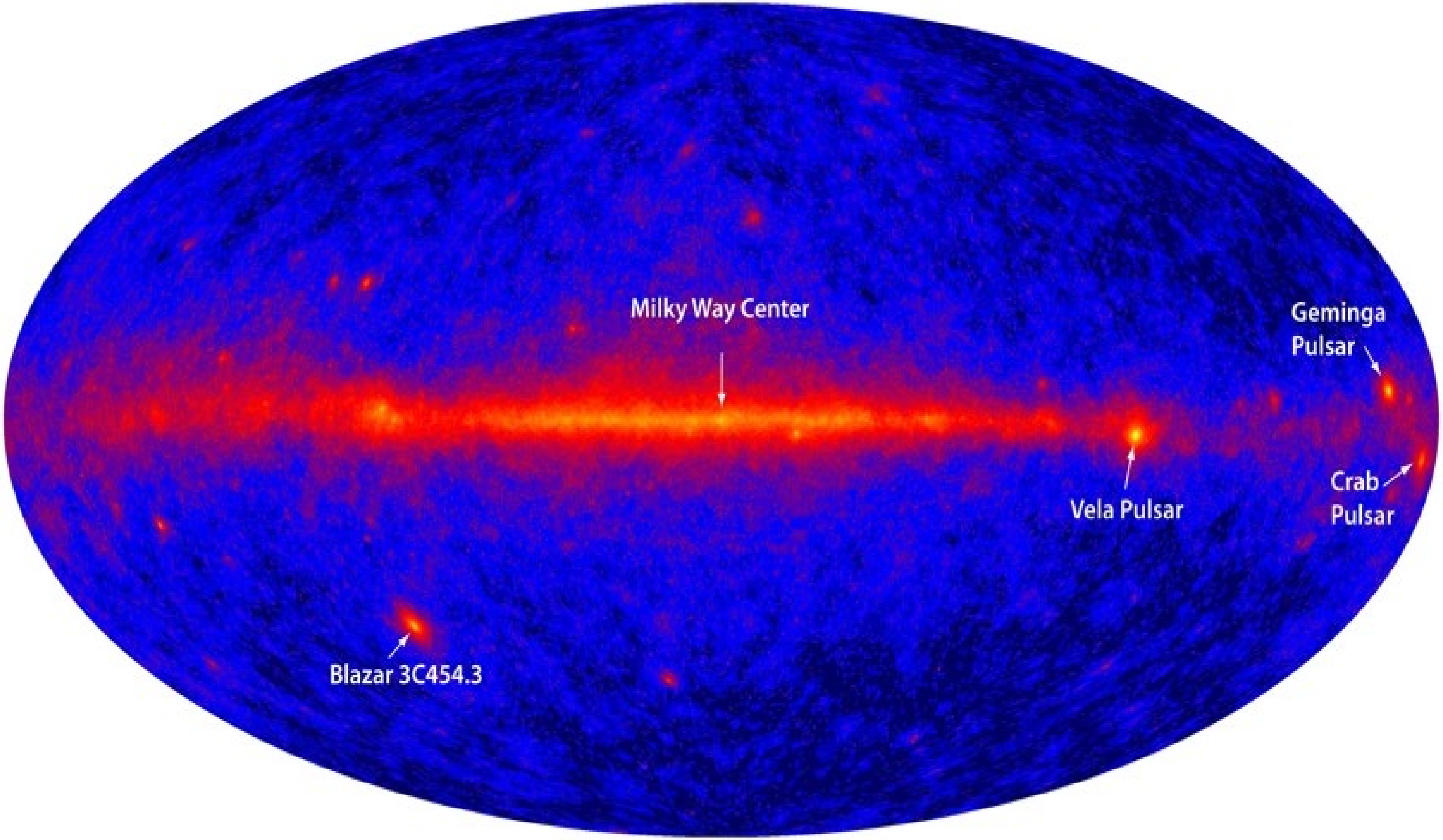
Roughly half of the new data have already been published as separate surveys of particular clouds or regions (see list at right), and since 1985 have formed the basis for 13 Ph.D. dissertations. The balance was obtained in the past few years in new large-scale surveys of the first and second Galactic quadrants.

This poster was supported by a generous grant from the Atherton Seidell Endowment of the Smithsonian Institution.

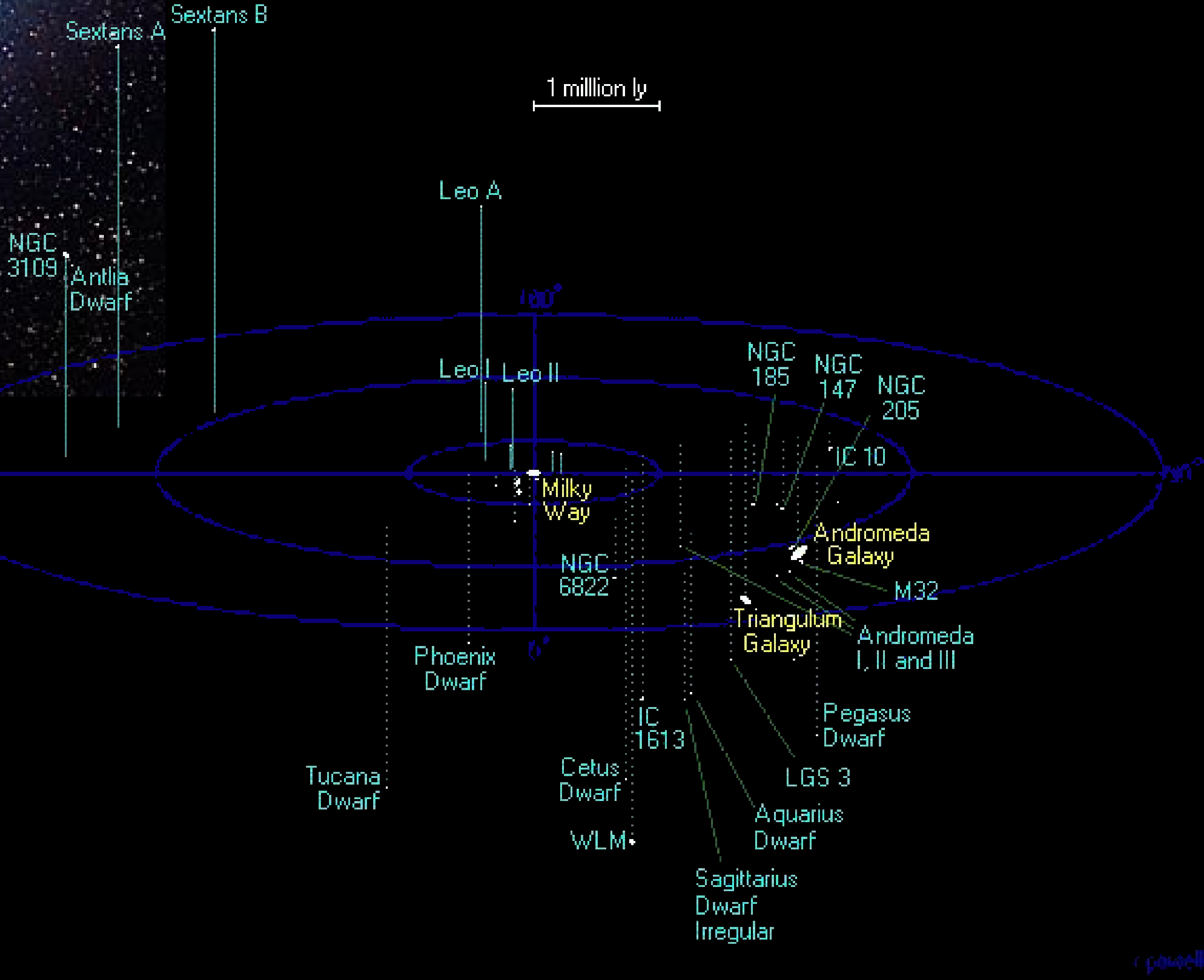
Harvard-Smithsonian Center for Astrophysics
T. M. Dame, Dap Hartmann, & P. Thaddeus

A thick target

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



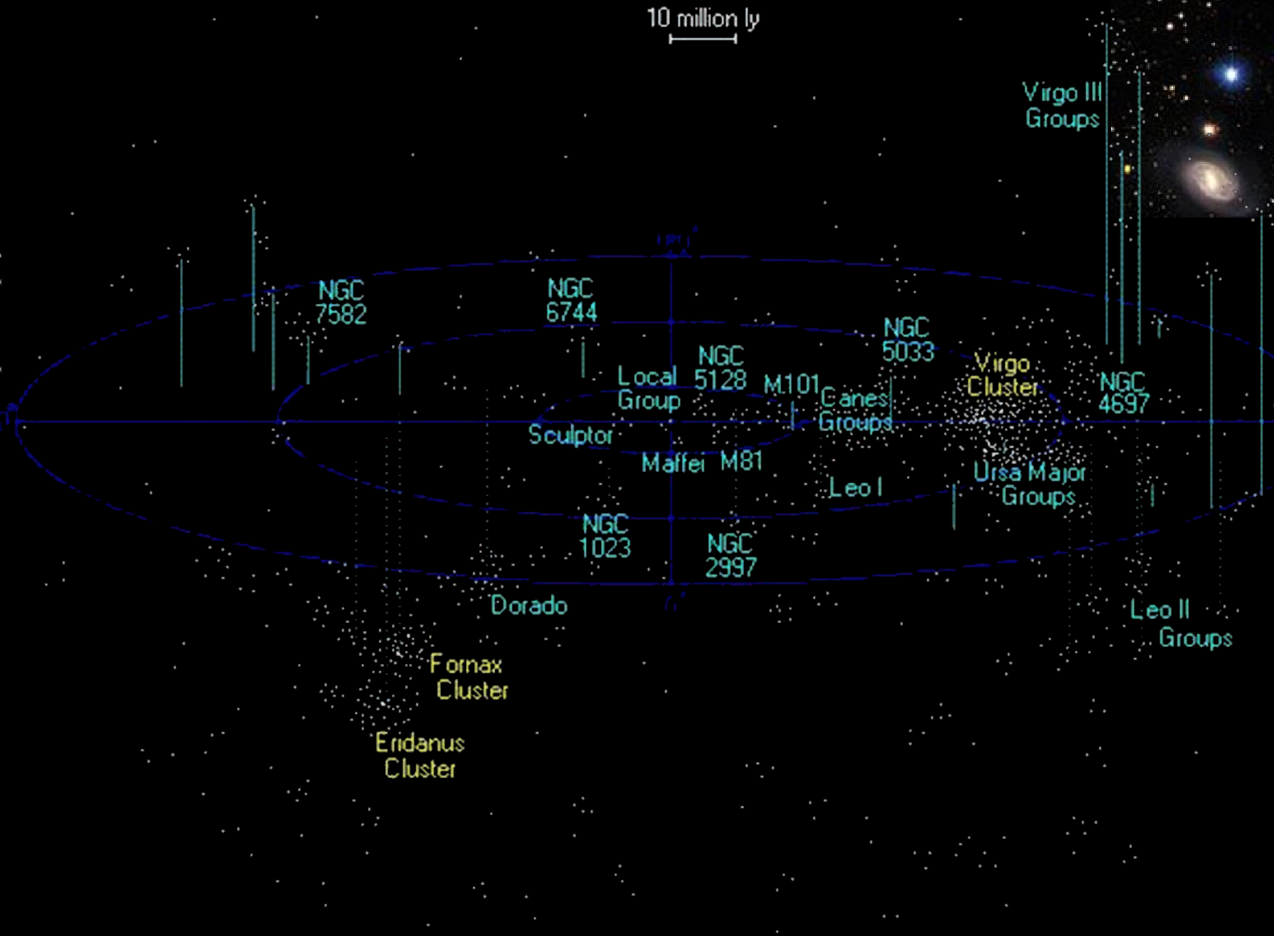
The nearby islands…



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

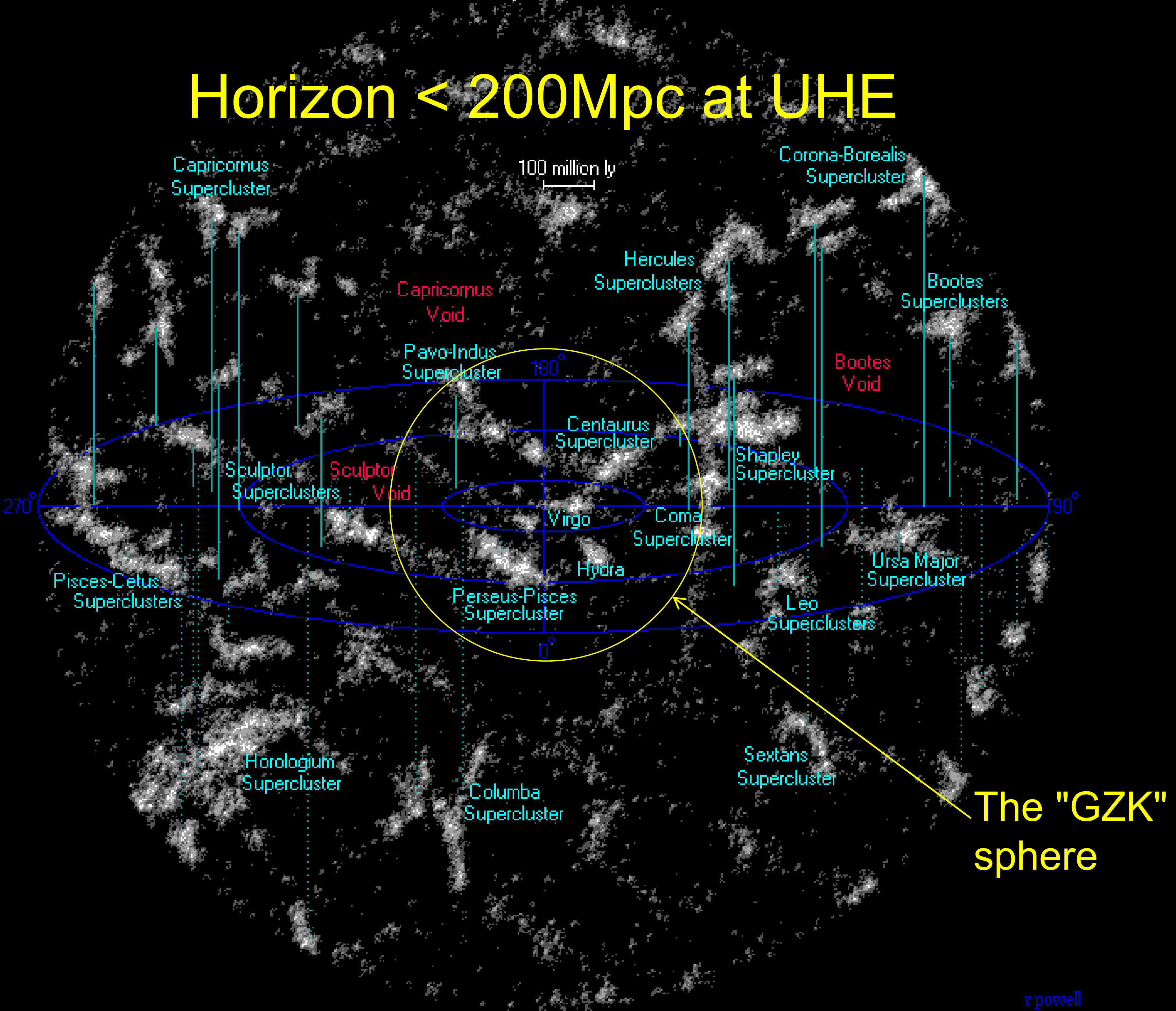
The local group and the Virgo cluster

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



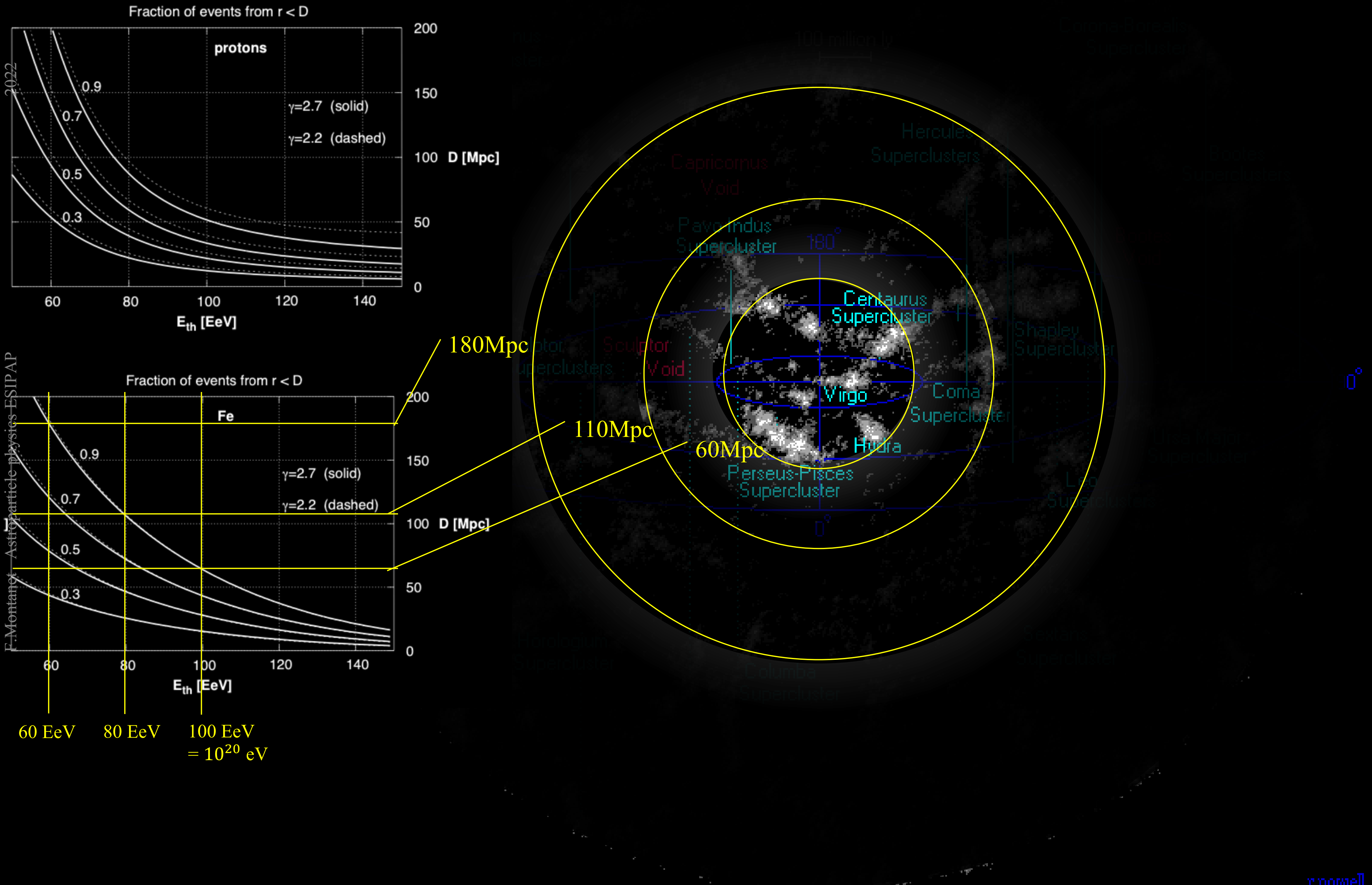
Another super cluster: Abel 1689

Horizon < 200Mpc at UHE



The "GZK" sphere

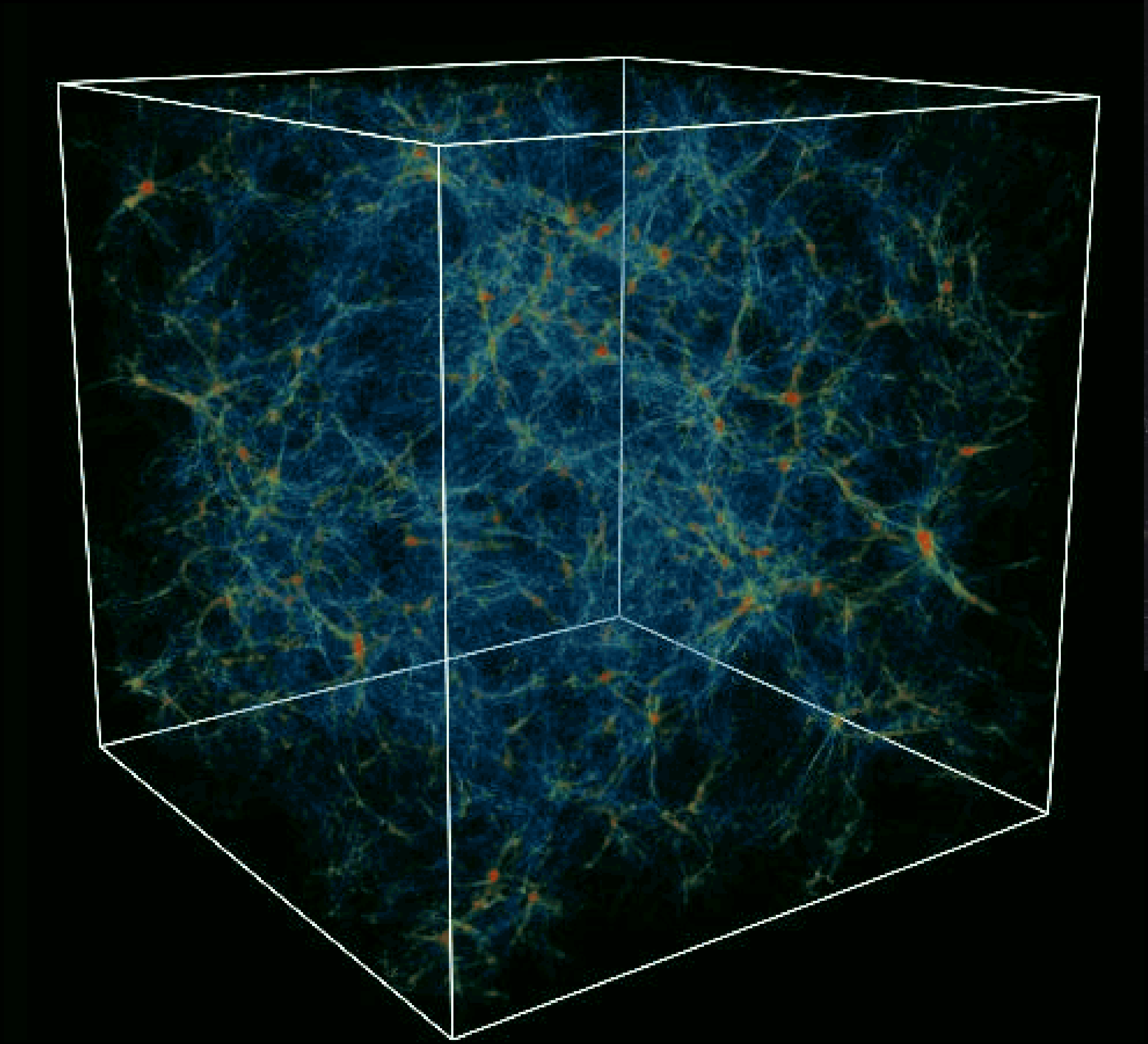
Horizon < 200Mpc at UHE



F.Montanet – Astroparticle physics ESIP AP 2022

r.powell

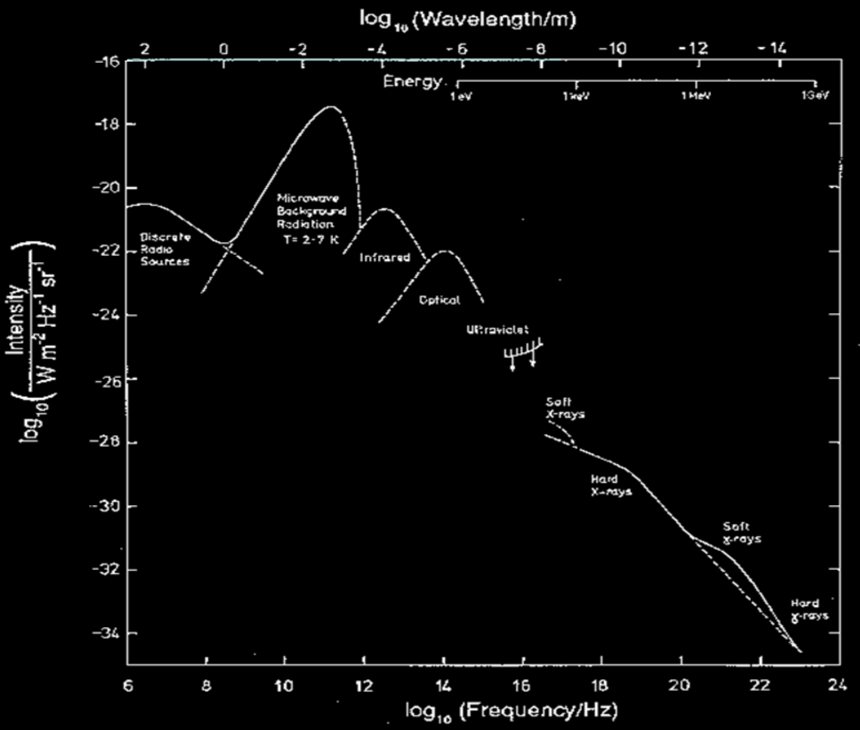
Large scale filamentary structures

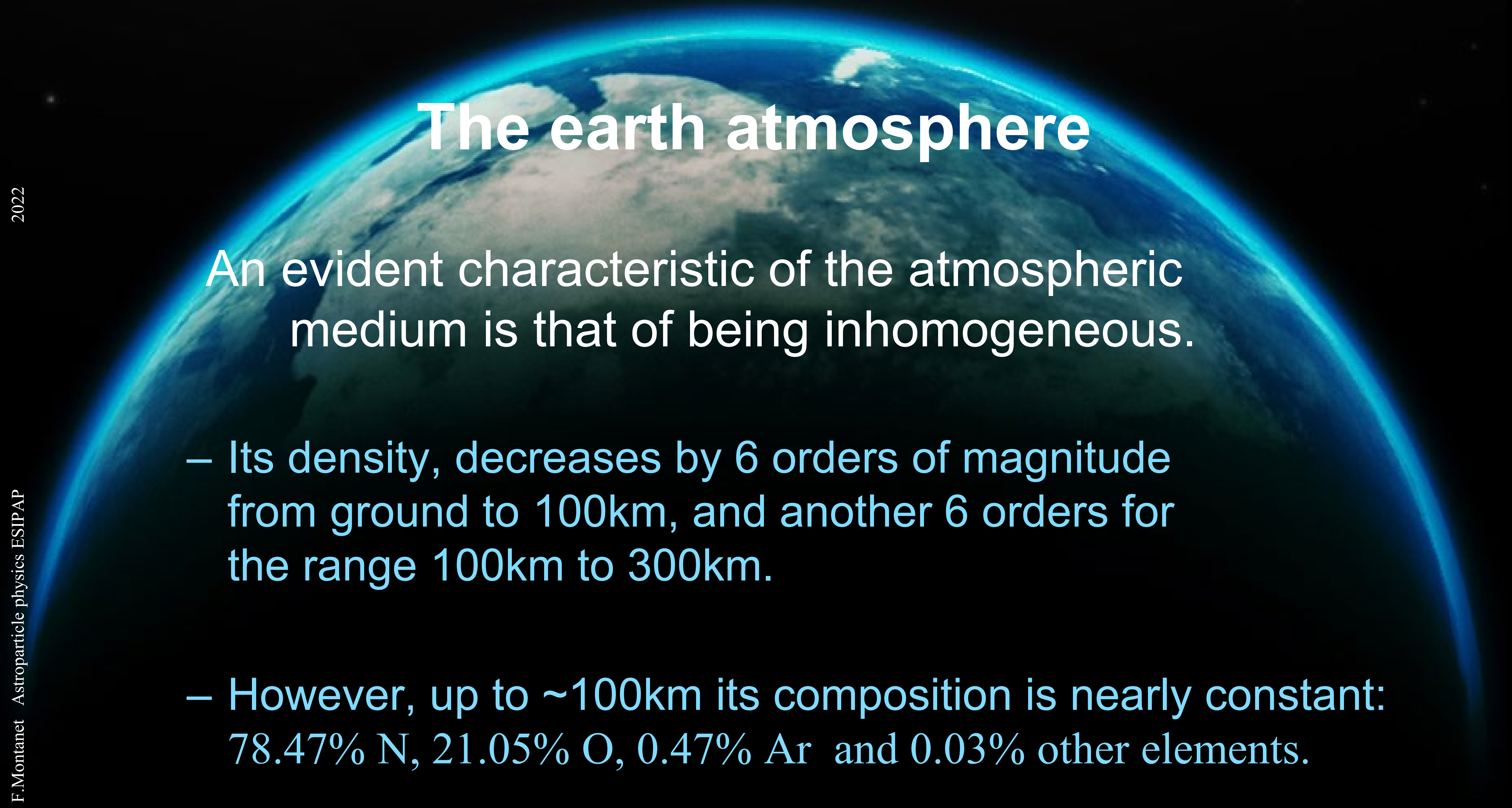


Vacuum is not emptiness !

- Inter Galactic Medium (vacuum) contains:
  - Magnetic fields (regular + random) are highly speculative and range from 2×10^{-6} nT (20 pG) to 10^{-4} nT (1 nG).
  - Very little matter (p, He, and a few electrons): ~ 0.25 baryon / m^3
  - Electromagnetic radiations:
    - 413 CMB photons per cm^3
    - Also IR, radio photons…
  - Neutrinos:
    - Mostly CνB neutrinos (decoupled when universe was only 2" old!)
    - Today 1.95K i.e. 1.7×10^{-3} eV
    - 336 ν (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, decreases by 6 orders of magnitude from ground to 100km, and another 6 orders for the range 100km to 300km.
- However, up to ~100km its 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 temperature is not quite constant!)

The earth atmosphere

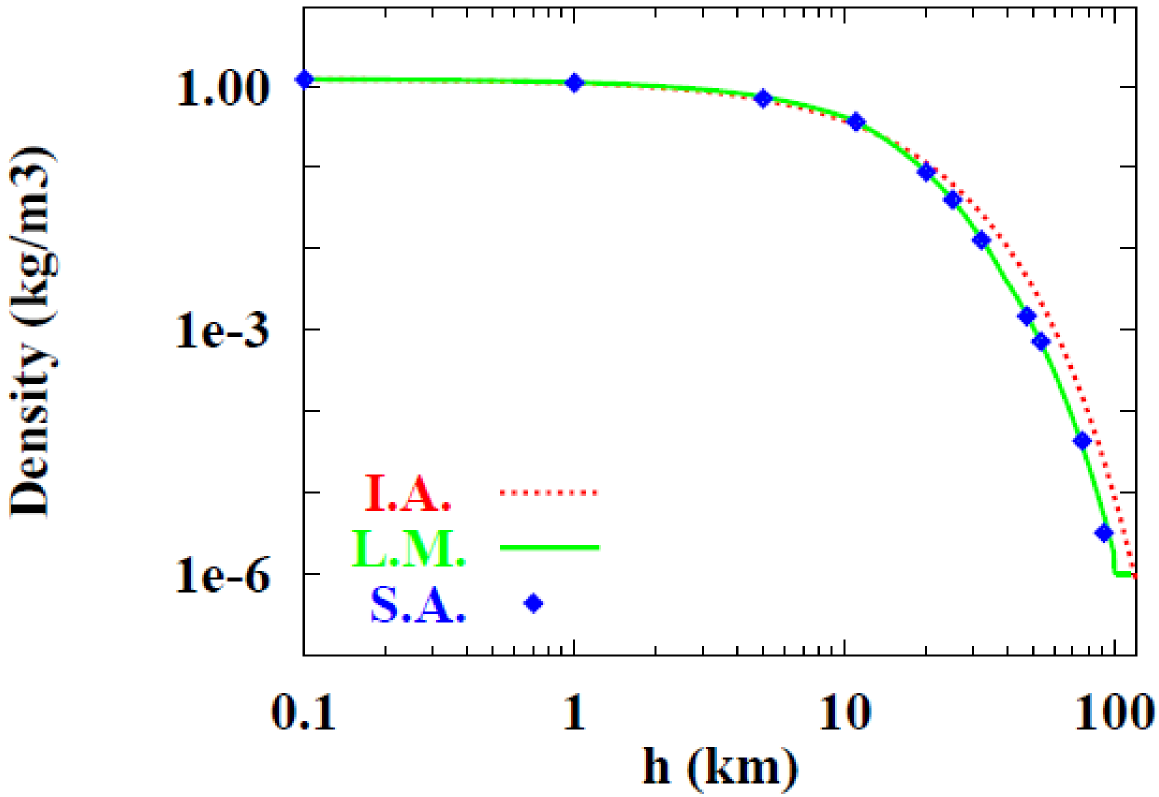


Figure 2.3. Density of the air as a function of the vertical altitude. The dots represent the US standard atmosphere data [14], while the full green line corresponds to Linsley's model [16] and the dashed red one to the isothermal atmosphere

$$
\begin{aligned}
\rho(h) &= \rho_0 e^{-gMh/RT} \\
&= \rho_0 e^{-gh/rT} \\
&= \rho_0 e^{-h/h_0}
\end{aligned}
$$

$$
\begin{array}{rcll}
\text{with } \rho_0 &=& 1.225\ \mathrm{kg\cdot m^{-3}} & \text{air density at sea level (average hygrometry)} \\
g &=& 9.81\ \mathrm{m\cdot s^{-2}} & \\
T &\approx& 288\ \mathrm{K} & \\
R &=& N_A \cdot k_B = 8.314\ \mathrm{J\cdot K^{-1}\cdot mol^{-1}} & \text{perfect gaz universal constant} \\
M &=& 28.965\times 10^{-3}\ \mathrm{kg\cdot mol^{-1}} & \text{molar mass of air} \\
r &=& \dfrac{R}{M} \approx 287\ \mathrm{J\cdot K^{-1}\cdot kg^{-1}} &
\end{array}
$$

$$\Rightarrow \text{scale height } h_0 = r \cdot T/g \approx 8.4\ \text{km}$$

The earth atmosphere

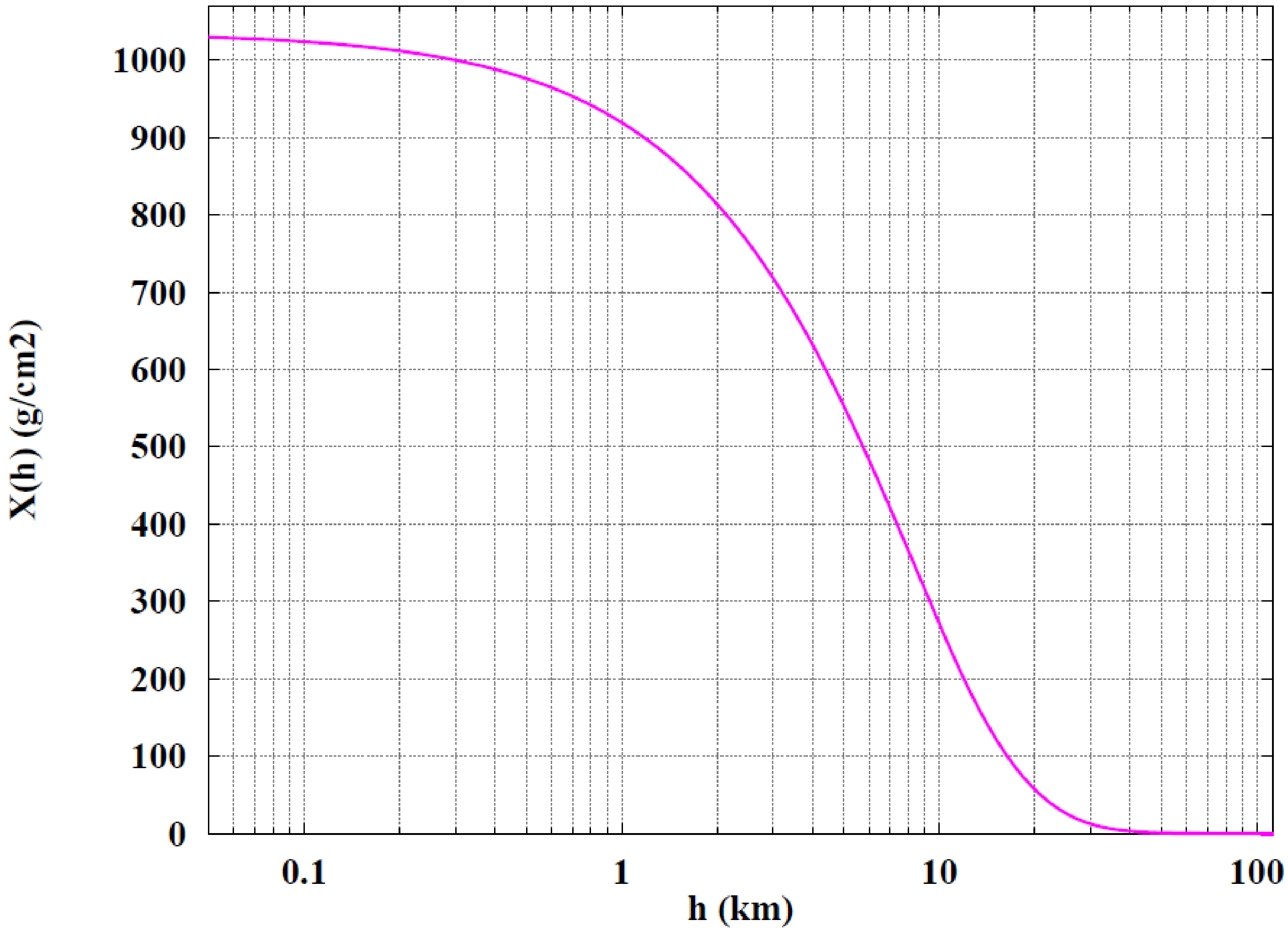


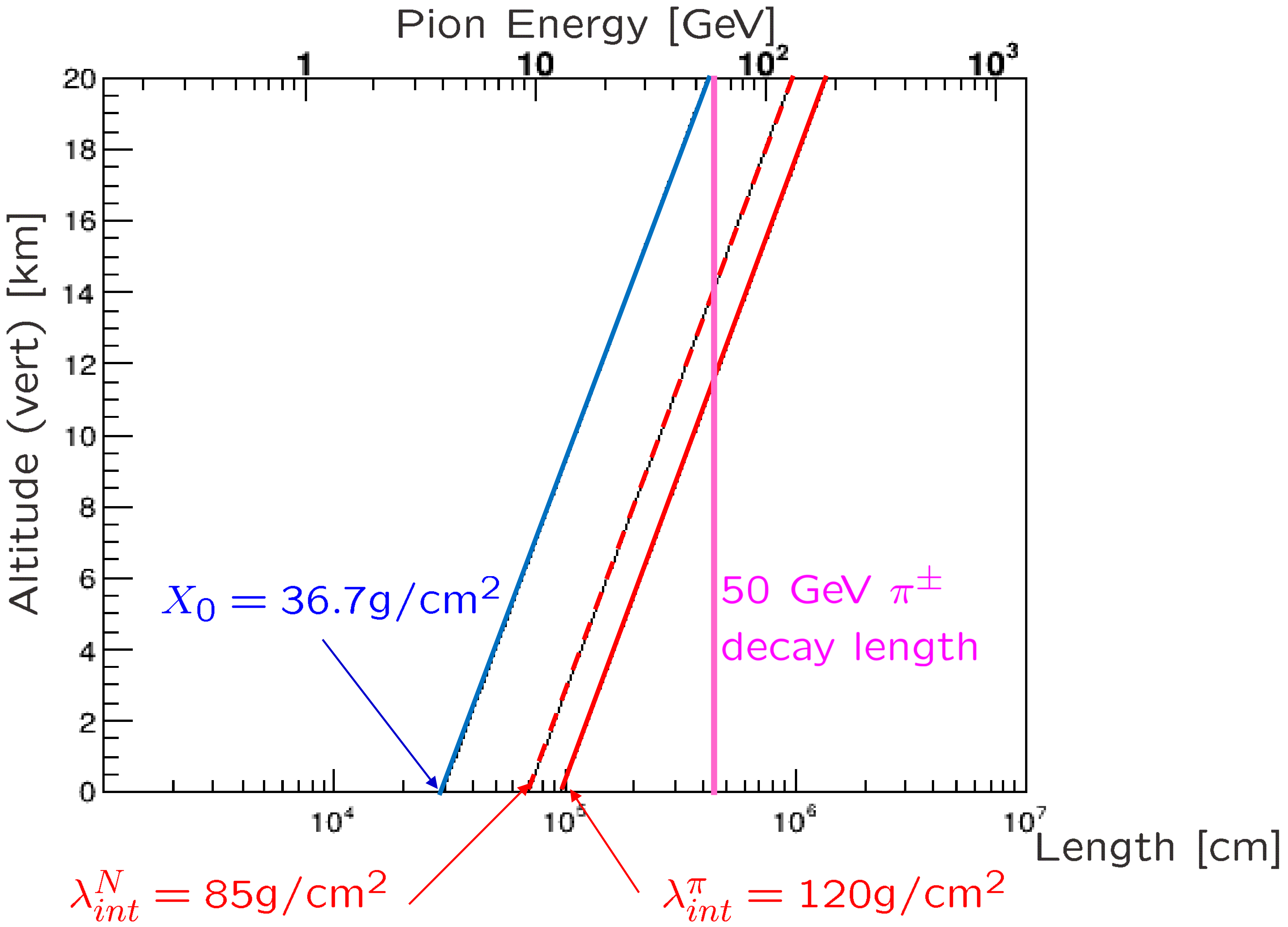
Figure 2.4. *Vertical atmospheric depth, X_v, versus vertical altitude over sea level, h, accordingly with Linsley's model [16].*

The earth atmosphere

In terms of particle/radiation interaction with matter, the atmosphere is:

- A total of $\approx$ 1000 g/cm^2 at sea level.
- So 1 atm $\approx$ 12 interaction lengths ($\lambda_N \approx$ 85 g/cm^2).
- A vertical proton first interacts at $h \approx$ 15 km
- One radiation length (at 1 atm) is $X_0 =$ 36.6 g/cm^2 $\approx$ 300 m.
- One Moliere radius (at 1 atm) is $\rho_M \approx$ 78 m.
- The Lorentz factor for a muon produced at $h =$ 10 km to reach ground before decaying is $\Gamma >$ 15 (i.e. $E >$ 1.6 GeV).
- The critical energy (EM) is $Ec =$ 84.2 MeV.

Interaction and radiation lengths in atmosphere

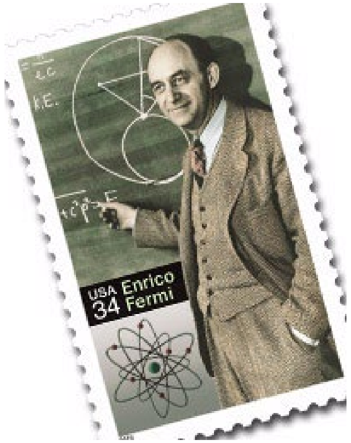


The atmosphere: a huge calorimeter to observe high-energy cosmic-rays.

Astrophysical Sources
Cosmic Accelerators

4th video (20')

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 $|E| \approx 0$
  $\Rightarrow$ 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 turbulences or Alfven waves act as massive scattering centers (recoilless).

Fermi 1949 :

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

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:

Assume:

- Initial energy: E_0
- Constant energy gain at each cycle: $\Delta E = \varepsilon E$
- Constant escape probability: P_{esc}

thus:

- Particle energy after n iterations: $E_n = E_0(1+\varepsilon)^n$
- 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 un 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 and reshuffling the above:

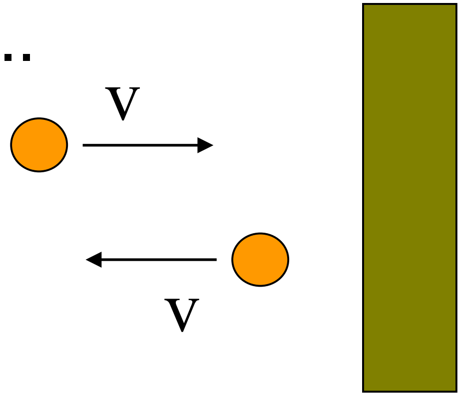
$$N(\geq E) \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

➡ Power laws are natural !

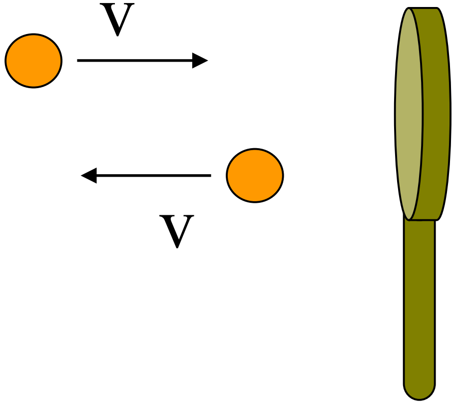
with $$\gamma = -\frac{\ln(1-P_{esc})}{\ln(1+\varepsilon)} \approx \frac{P_{esc}}{\varepsilon} = \frac{1}{\varepsilon} \times \frac{T_{cycle}}{T_{esc}}$$

A small analogy…

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



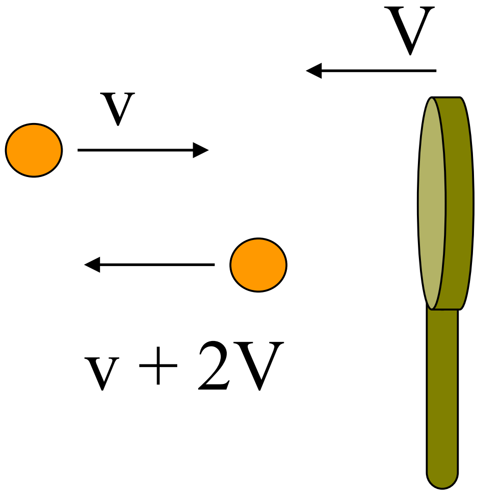
bounce = speed unchanged



Same thing with
a motionless racquet...

Then how does one accelerate a tennis ball ?!

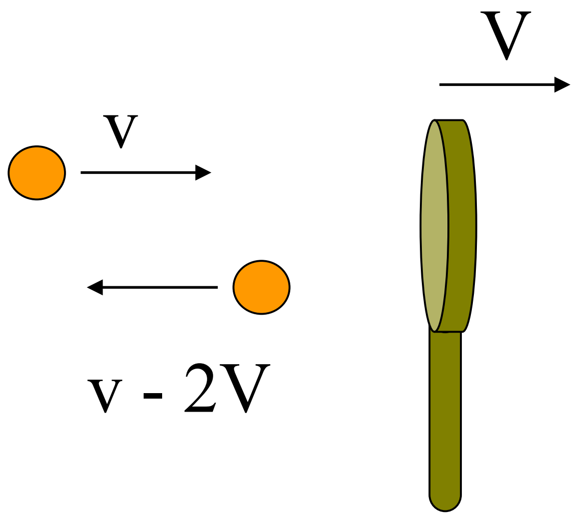
- Moving racquet !
  - Neither gain nor loss of energy… in the racquet reference frame !



Speed unchanged with respect to the racquet

→ acceleration through a change of reference frame

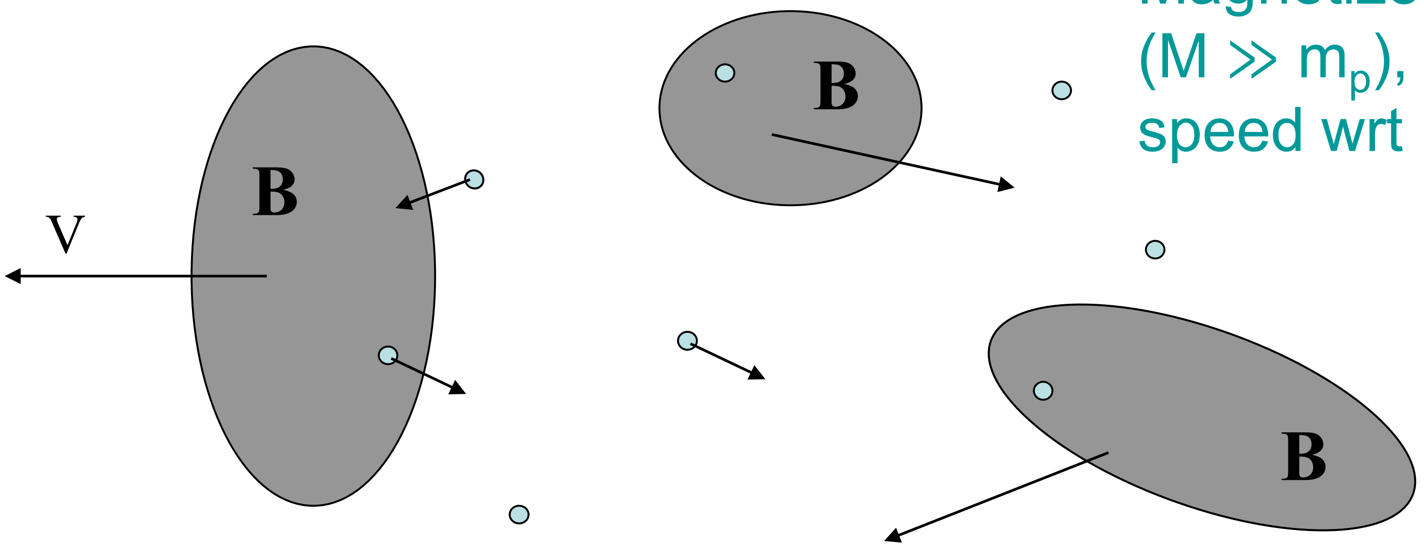
- But this can also decelerate
  A drop shot:



Particle deceleration !

Fermi Acceleration

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



Magnetized clouds ($M \gg m_p$), with a typical speed wrt ISM ~10km/s

- Magnetic inhomogeneities or plasma waves also work...

The essence of stochastic Fermi acceleration

1. When a particle bounces on an **incoming** magnetic mirror, in a **head-on** collision, it **gains** energy.

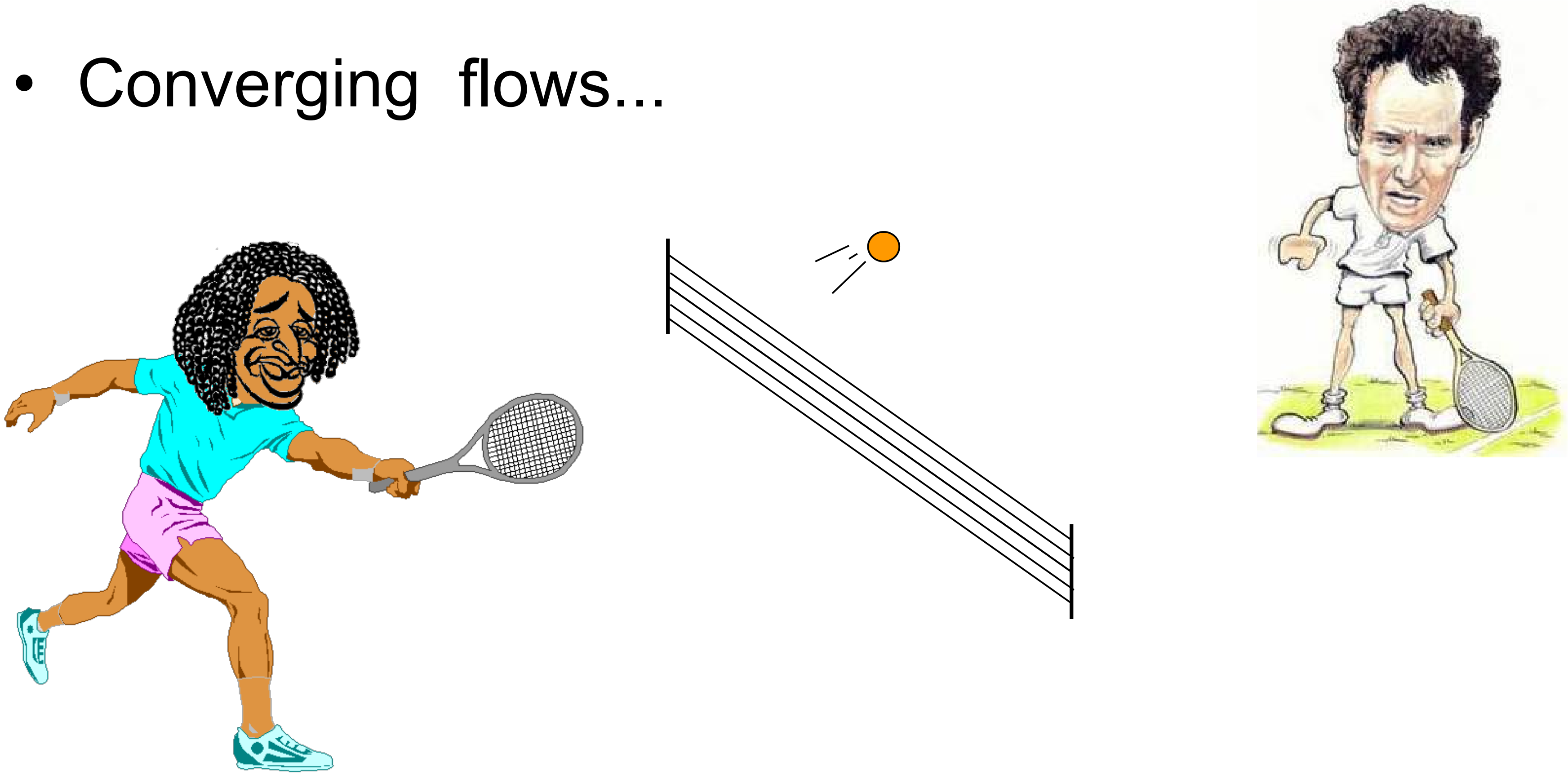
2. When a particle bounces on a **receding** magnetic mirror that it catches back, it **loses** energy.

3. Head-on collisions are **more frequent** than receding collisions.

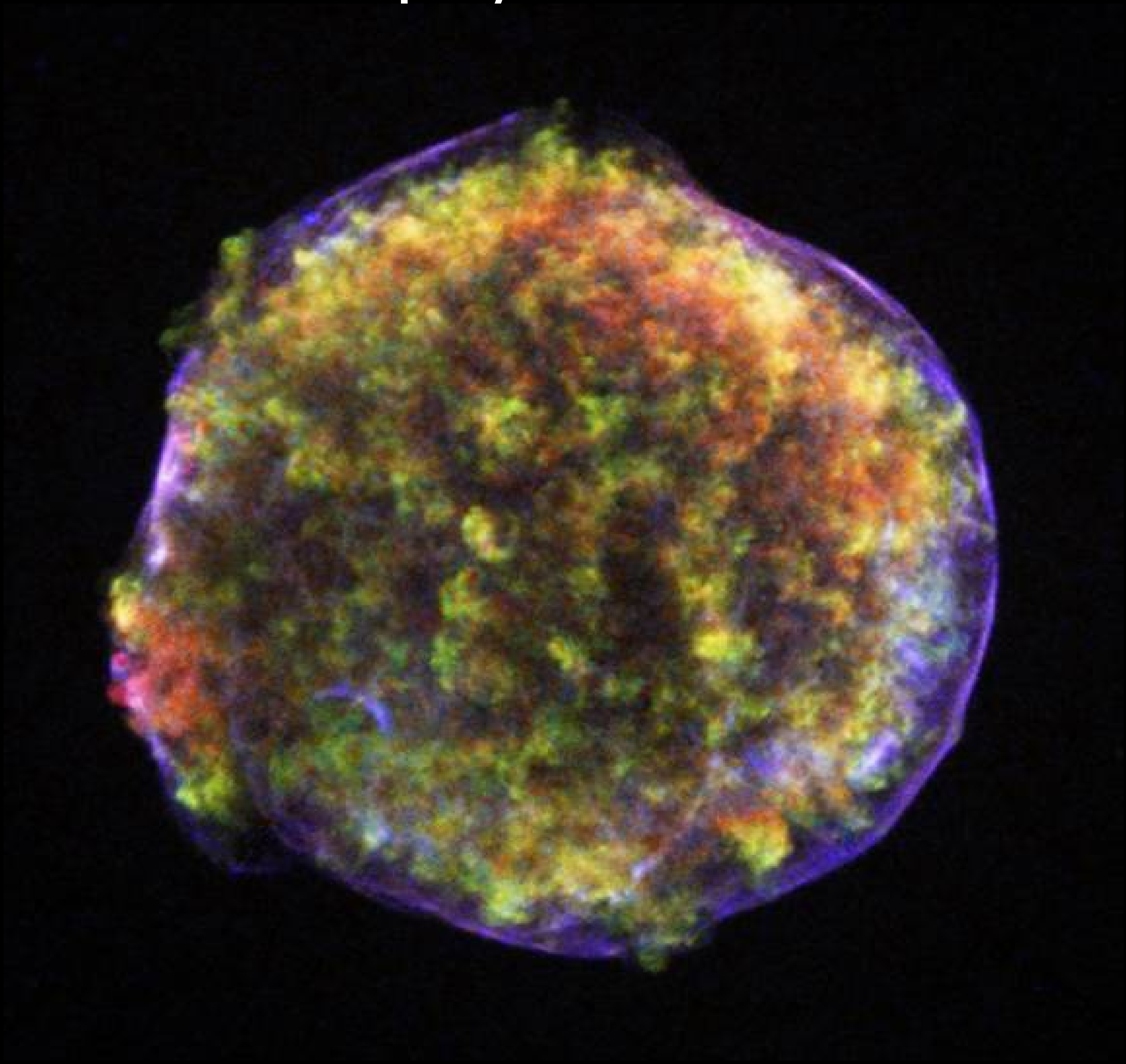
⇒ Net energy gain in average (stochastic process)

Add a second player...

- Converging flows...

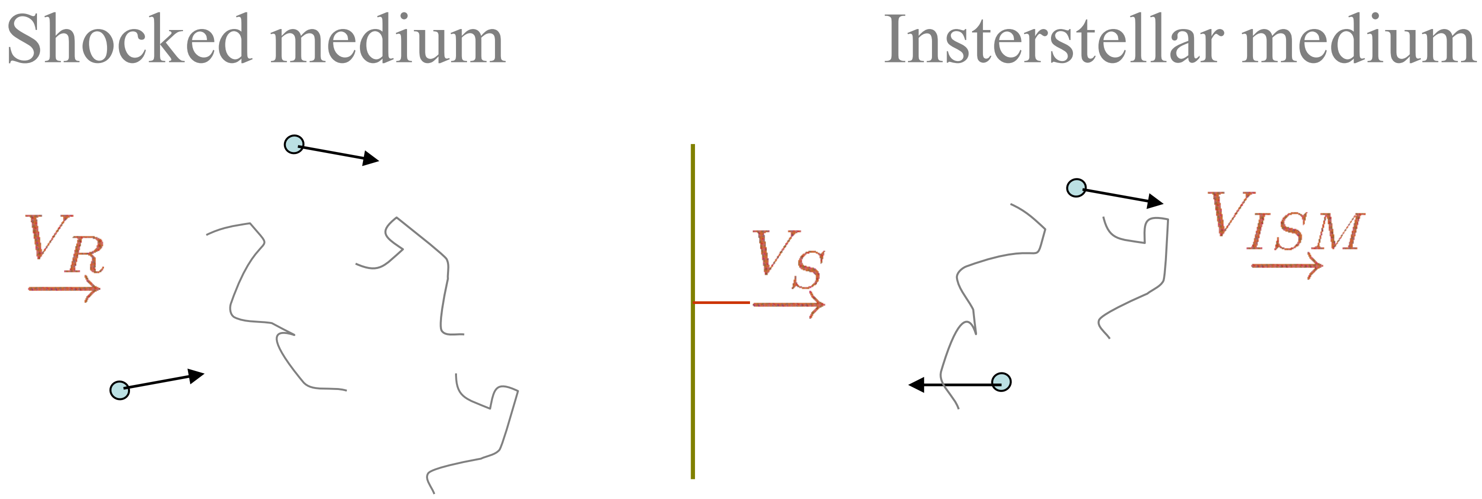


Astrophysical shocks



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).

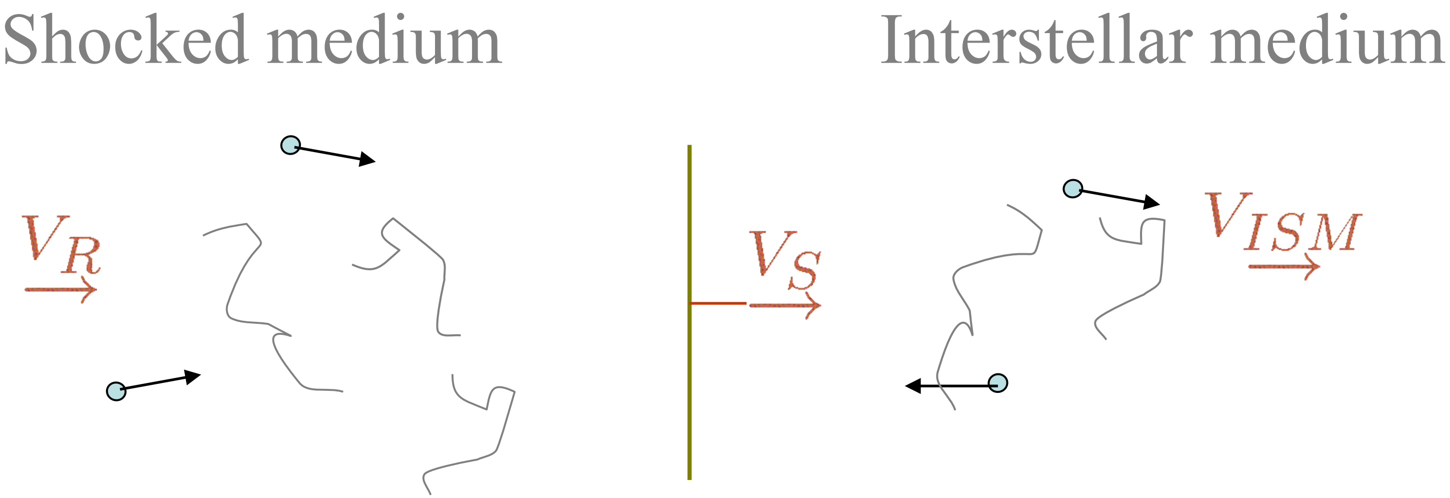


Shocked medium

Insterstellar medium

Shocks hydrodynamics

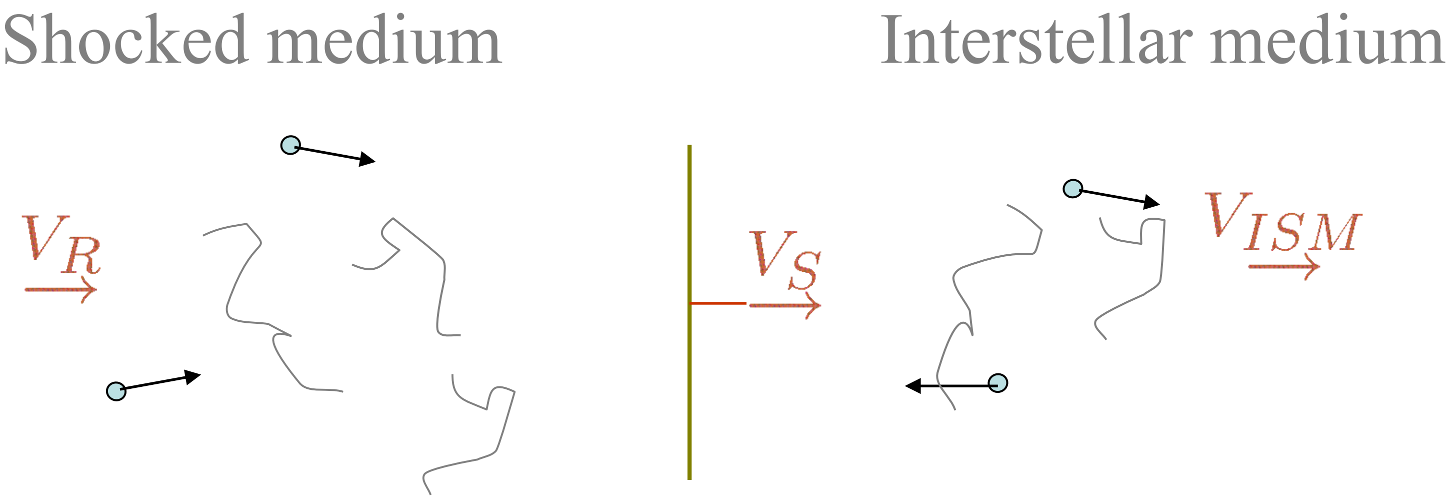
- Shock wave:



- The shock moves at a speed V_S which depends on V_R and the specific heat of both media.
- For an ionized ISM: $V_S \approx \frac{4}{3} V_R$

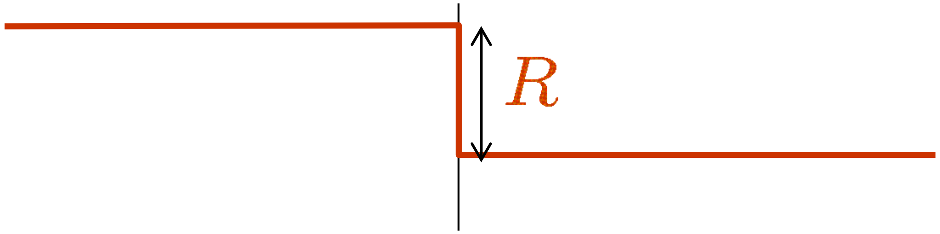
Shocks hydrodynamics

- Shock wave:



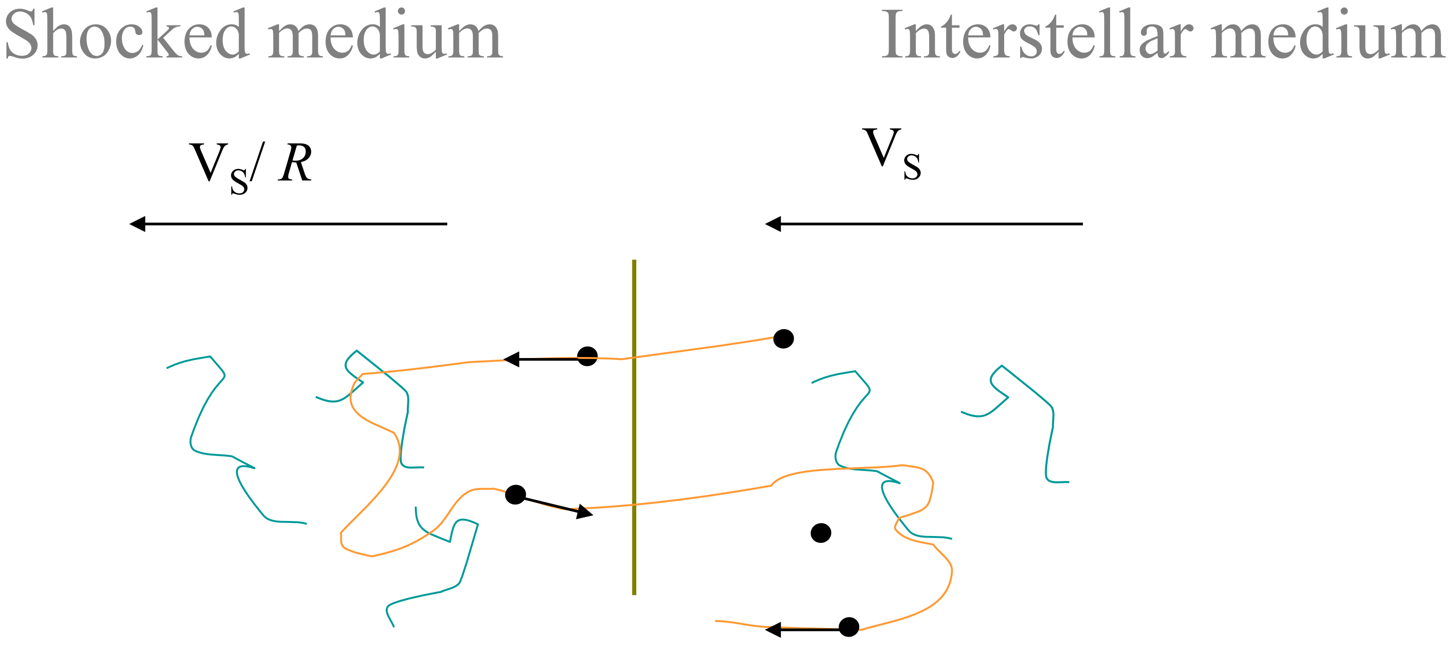
- The shock intensity is characterized by the compression factor:

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



Shocks hydrodynamics

In the shock frame

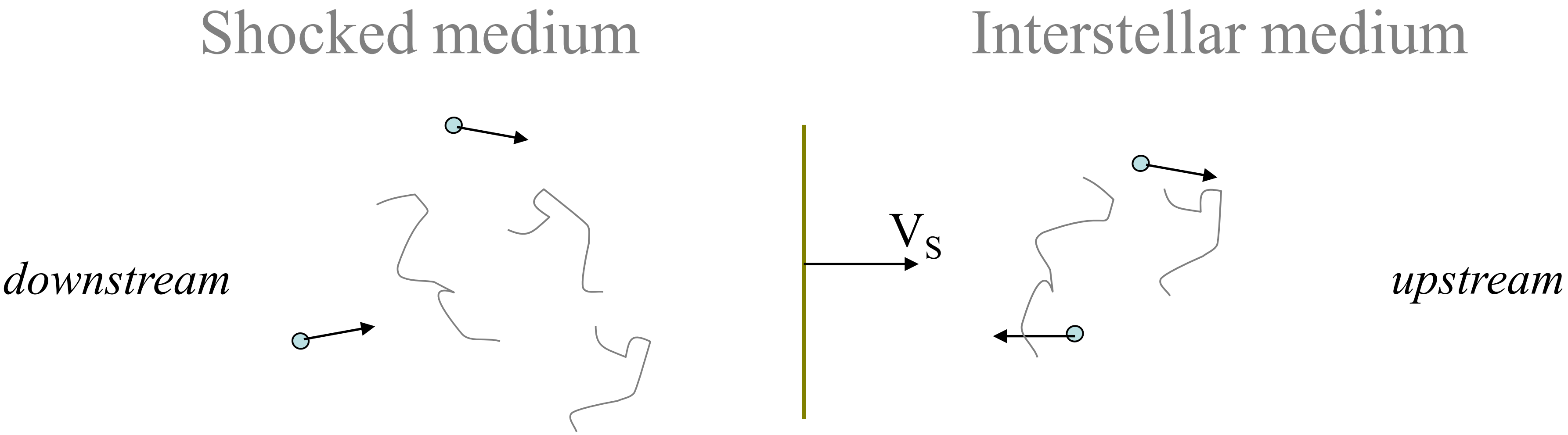


- In the shock frame, the upstream (non-shocked) medium flows toward the shock at a speed V_S and the downstream (shocked) medium flows away with a speed reduced by the compression factor (mass flow conservation) :

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

Shock wave diffusive acceleration

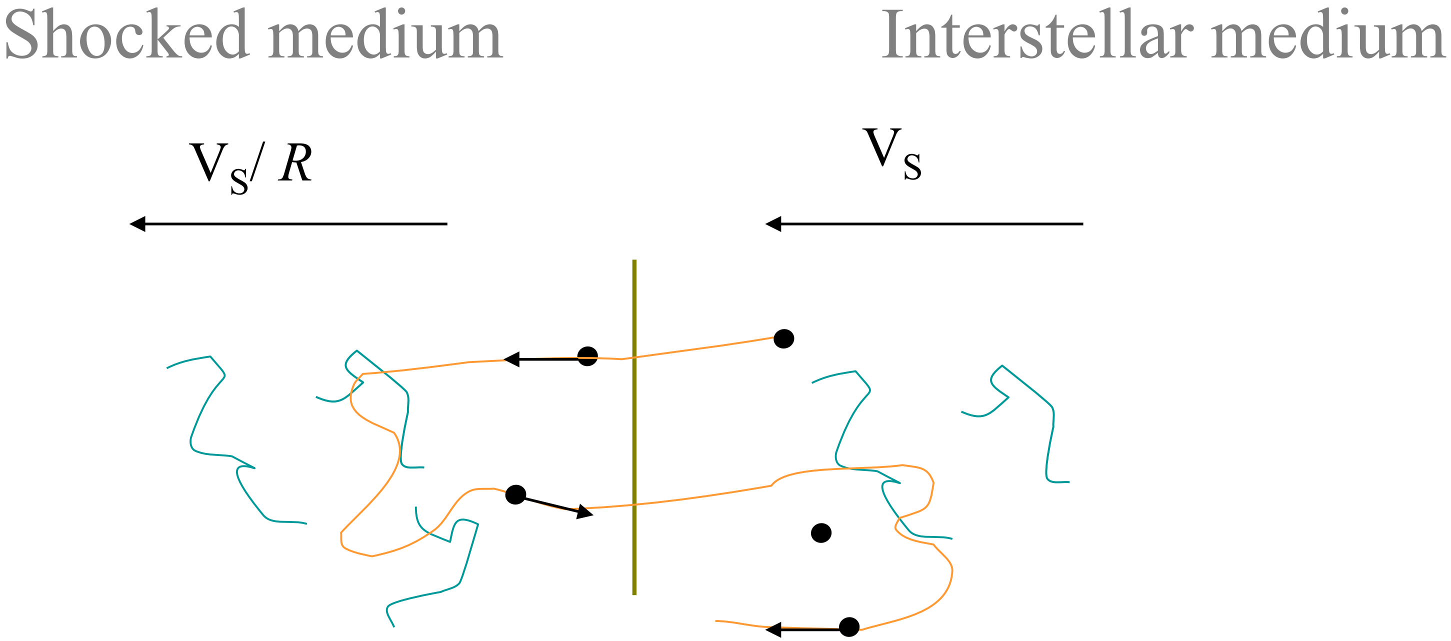
- Shock wave (e.g. supernova explosion)



- Magnetic wave generation:
  - **Downstream** : by the shock (compression, turbulence, hydro and MHD instabilities, shear, etc.)
  - **Upstream** : by the accelareted cosmic rays themselves !

→ ‘isotropization’ of the distribution
(in the local frame)

A win-win process !



Shocked medium

Interstellar medium

V_S / R

V_S

In the shock frame

- At each shock crossing, one way or the other, the particle hits a "magnetic wall" with a relative speed:

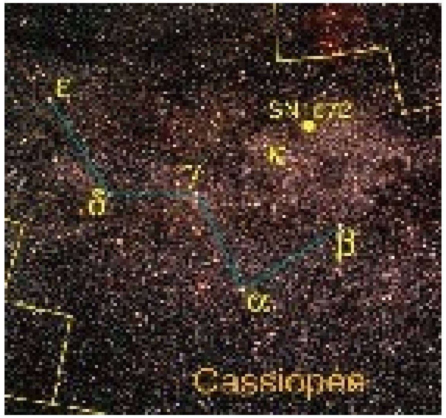
$$V = (1 - 1/R)V_S$$

→ only head-on collisions…

Summary on acceleration

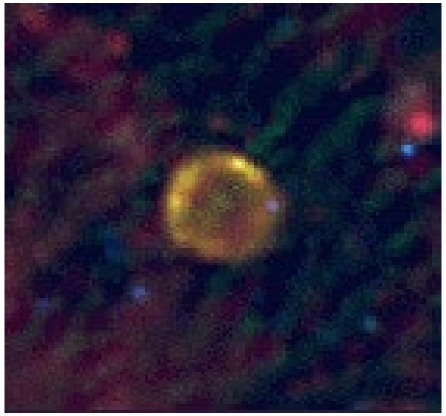
- Acceleration from interaction with fields
  - **E** field: e.g. induced by spinning magnets such as neutron stars (pulsars) or black holes…
  - **B** field: inhomogeneous moving fields
  - MHD waves
- Acceleration by reference frame transformation
  - Fermi stochastic acceleration (2nd order)
  - Diffusive shock acceleration (1st 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, $\mathbf{E_{max} \approx 10^{14}}$ eV hardly $\mathbf{10^{15}}$ eV

Tycho, 11 November 1572...

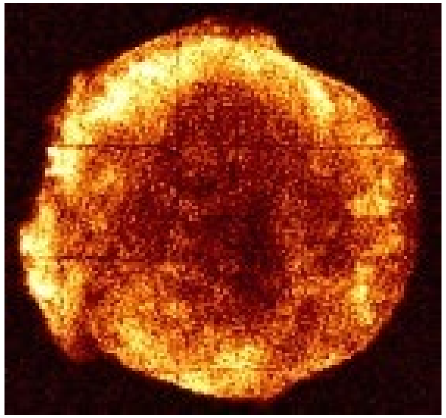


position

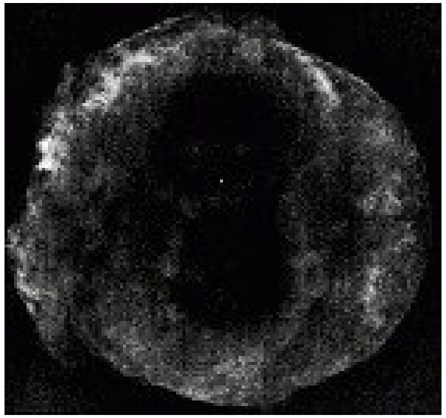
visible



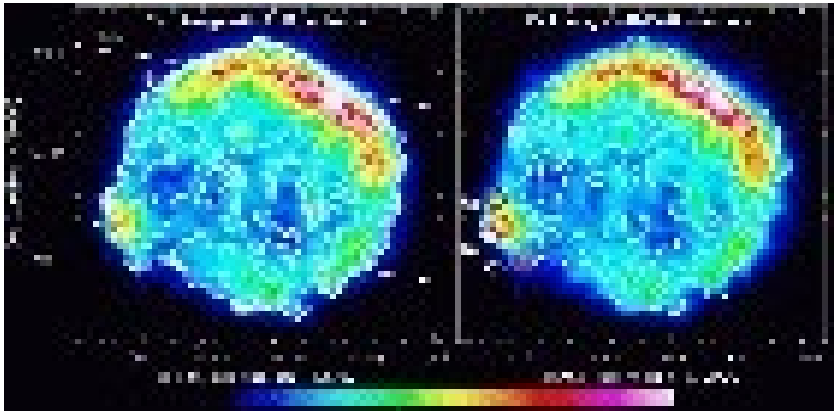
IRAS



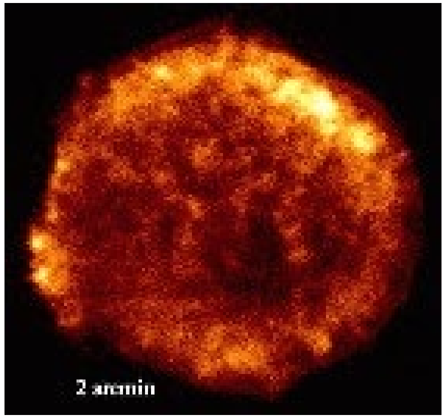
Km (VLA)



6 cm (VLA)



Si K (XMM) Fe K



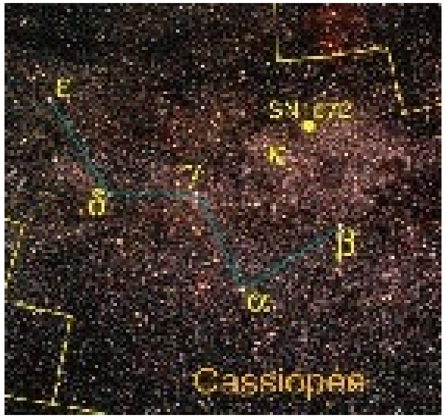
X (ROSAT)

Astrophysical Sources zoology

5th video (15')

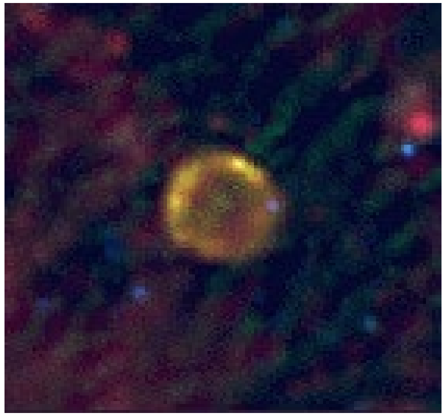
Tycho, 11 November 1572...

A typical SNR

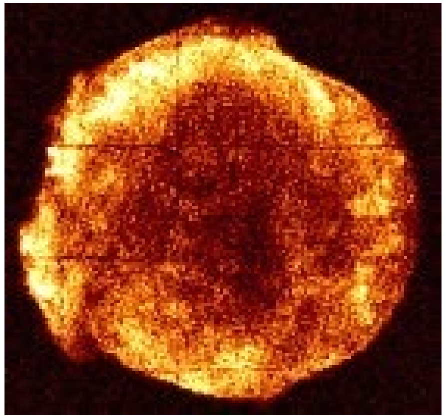


position

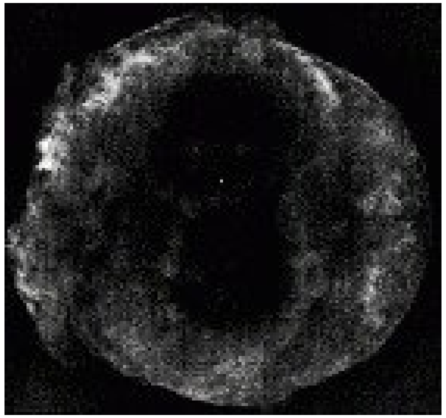
visible



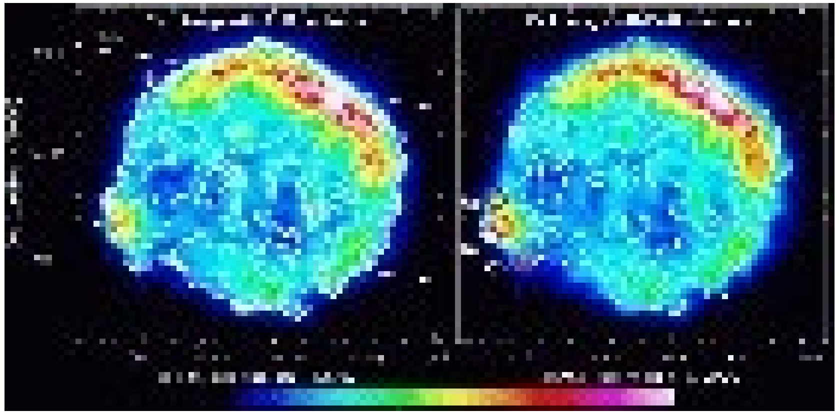
IRAS



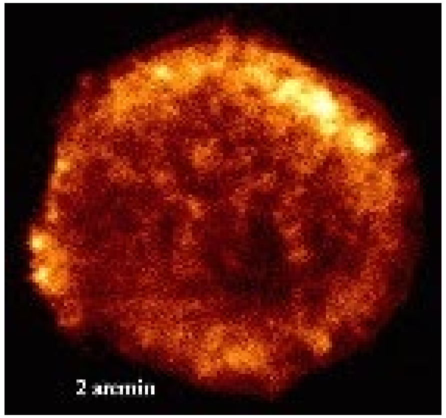
Km (VLA)



6 cm (VLA)



Si K (XMM) Fe K



X (ROSAT)

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: …… $\varepsilon_{CR}\times V_{conf}/\tau_{conf}$ $\sim 10^{41}\mathrm{erg/s}$!
  - Power injected by SN in the Galaxy: ………………… $10^{42}\mathrm{erg/s}$!

→ Enough power for Galactic CR

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 expending 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 wavelength.
  - SNe explosion is essential to the Galaxy chemical content: heavy elements enrichment.

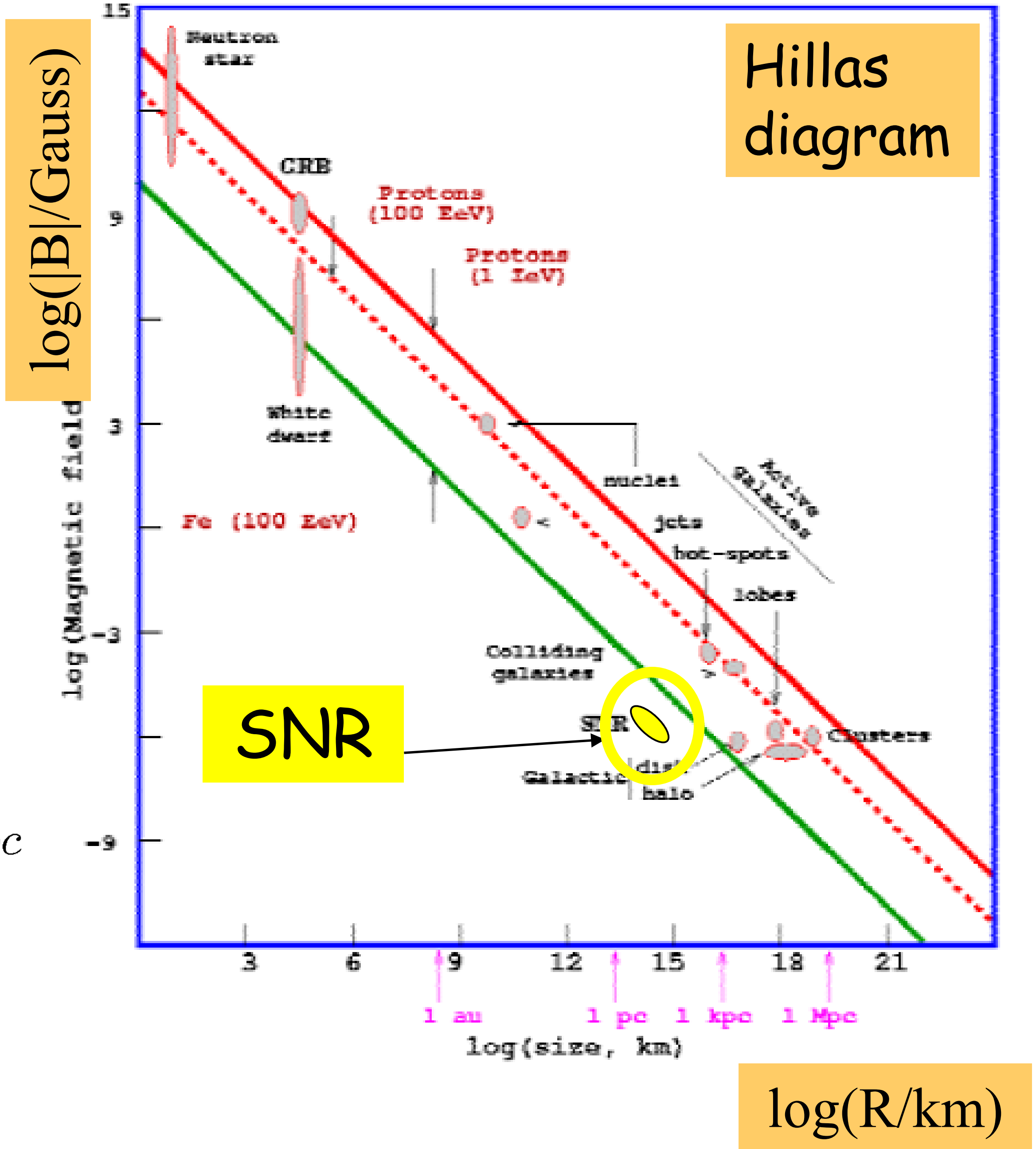
Finite size

Finite size of magnetic field confinement region

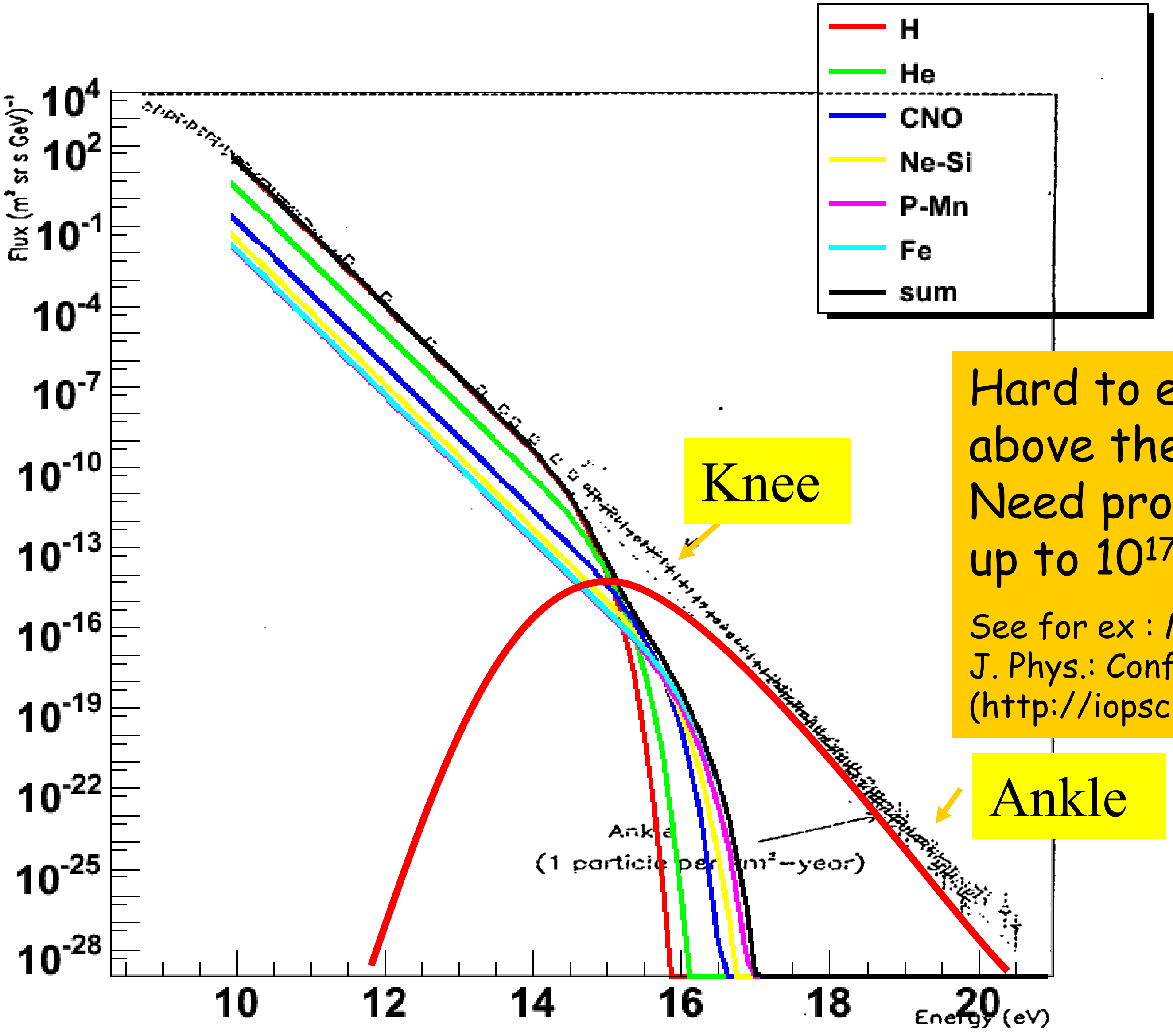
⇕

Larmor radius

$$r_g \leq R$$
$$\Leftrightarrow \quad \frac{p}{ZeB} \leq R$$
$$\Leftrightarrow \quad E \leq Ze \times B \times R$$
$$\Leftrightarrow \quad E \leq (10^{17} eV) Z B_{\mu G} R_{pc}$$



CR SM with Emax / Z



Hard to explain a single power law above the knee.
Need probably another component up to 10^{17}eV or more.

See for ex : M. Hillas
J. Phys.: Conf. Ser. 47 (2006) 168
(http://iopscience.iop.org/1742 6596/47/1/021)

Other sources…

- Galactic sources:
  - Compact objects, neutron stars and pulsars…
    - Unipolar induction, very high E fields but also strong magnetic fields => synchrotron losses => mostly radiation (X, gamma-rays).
  - Collective effects in super-bubbles (vast regions with multiple SNR)

- Extragalactic sources:
  - AGN's: massive BH accreting matter => most luminous objects in universe,
    - disk and jets, hot spots. Good candidate up to UHE
  - Starburst galaxies: high star formation periods often consequence of fusion of galaxies
    - Collective effects expected. Good candidate up to UHE, hint by Auger
  - GRB's: transient one-shot sources, hyper-Novae, beamed emission
    - Good candidate up to UHE, but no evidence from neutral transient studies so far.

Hillas diagram

Standard estimates for E_{max} :

- Confinement :

  $r_g = E/ZeB < R \Rightarrow E < ZeBR$

- Unipolar inductor (pulsar):

  $E < ZeBR(\Omega R/c) \approx \beta_s \, ZeBR$

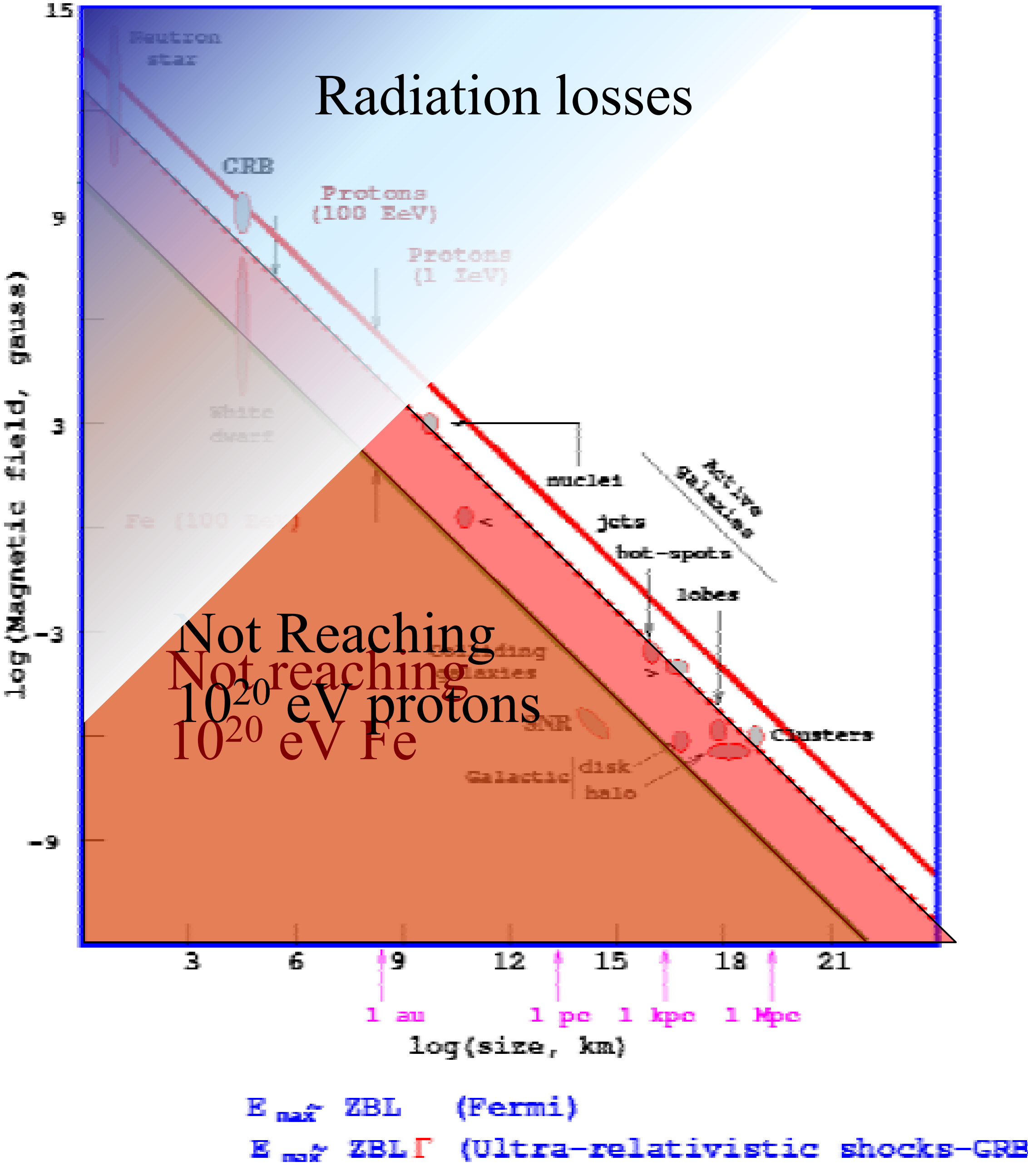
- Diffusive acceleration by no relativistic shocks:

  $\tau_{acc} \approx 10\,\kappa/V_S^2 < R/V_S$

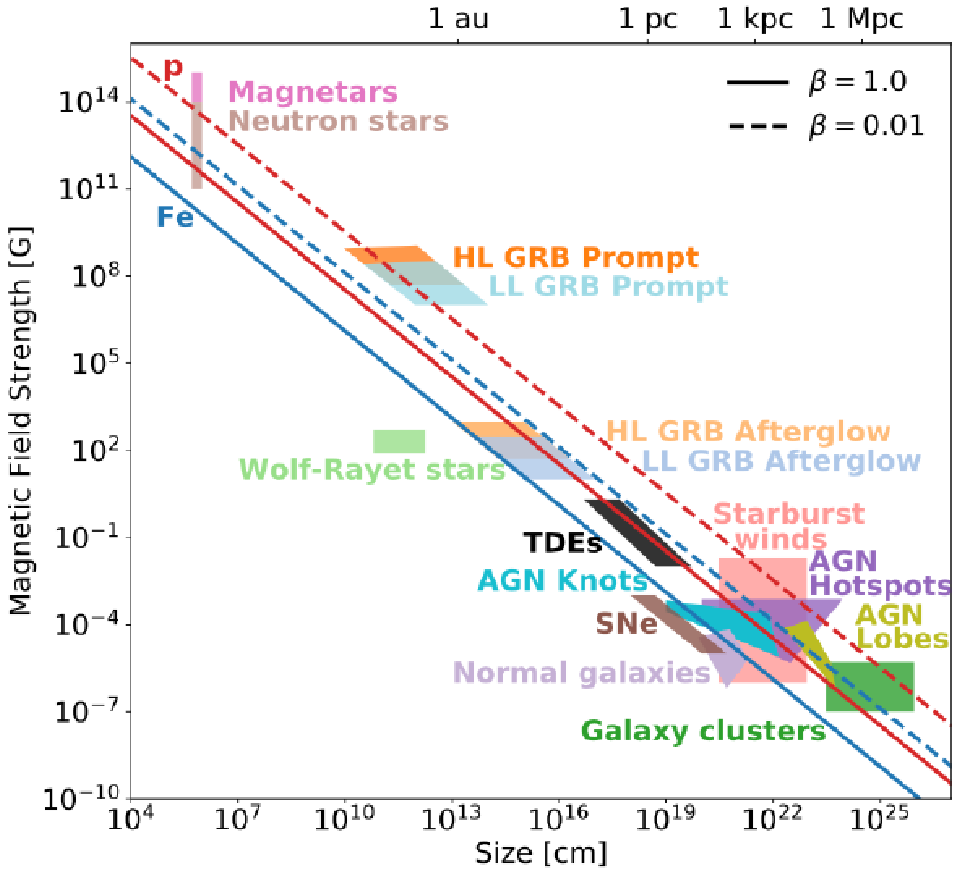
  with $\kappa > r_g c \Rightarrow E < \beta_s ZeBR$

- General Hillas condition:

  $E_{ZeV} < 0.9\,\beta_s \Gamma_s ZeB_{Gauss} R_{pc}$



Constraints on source candidates



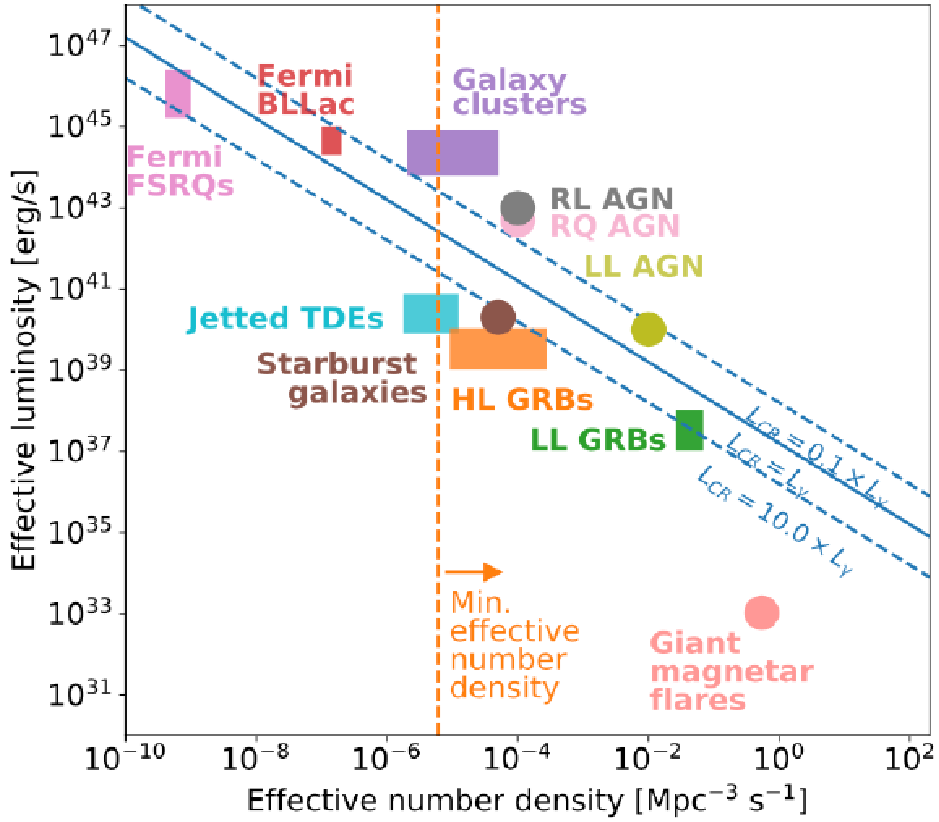
↳ $L_{pc} >> r_L$ d

↳ ρ_{rad} and ρ_{mat} low

↳ $B_{\mu G}$ → fast t_{acc}

→ small energy losses

$$E_{\max} = \beta_{\text{sh}} e B R \Gamma$$



$$L_\gamma > 3 \times 10^{44}\ \text{erg s}^{-1} \times \left(\frac{E/Z}{10^{18.5}\ \text{eV}}\right)^2 \times \left(\frac{\Gamma^2/\beta}{100}\right)$$

Relativistic shocks

- Acceleration / Γ^2 works fine for a couple of cycle
- After that it fails for mere kinematical reasons
- But this is still very efficient (>> 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

Extra-galactic radio galaxy lobes

AGNs, StarBurst galaxies

Gamma Ray Bursts

Protons, Iron, Nuclei?

Spectral index

Explaining isotropy is not trivial

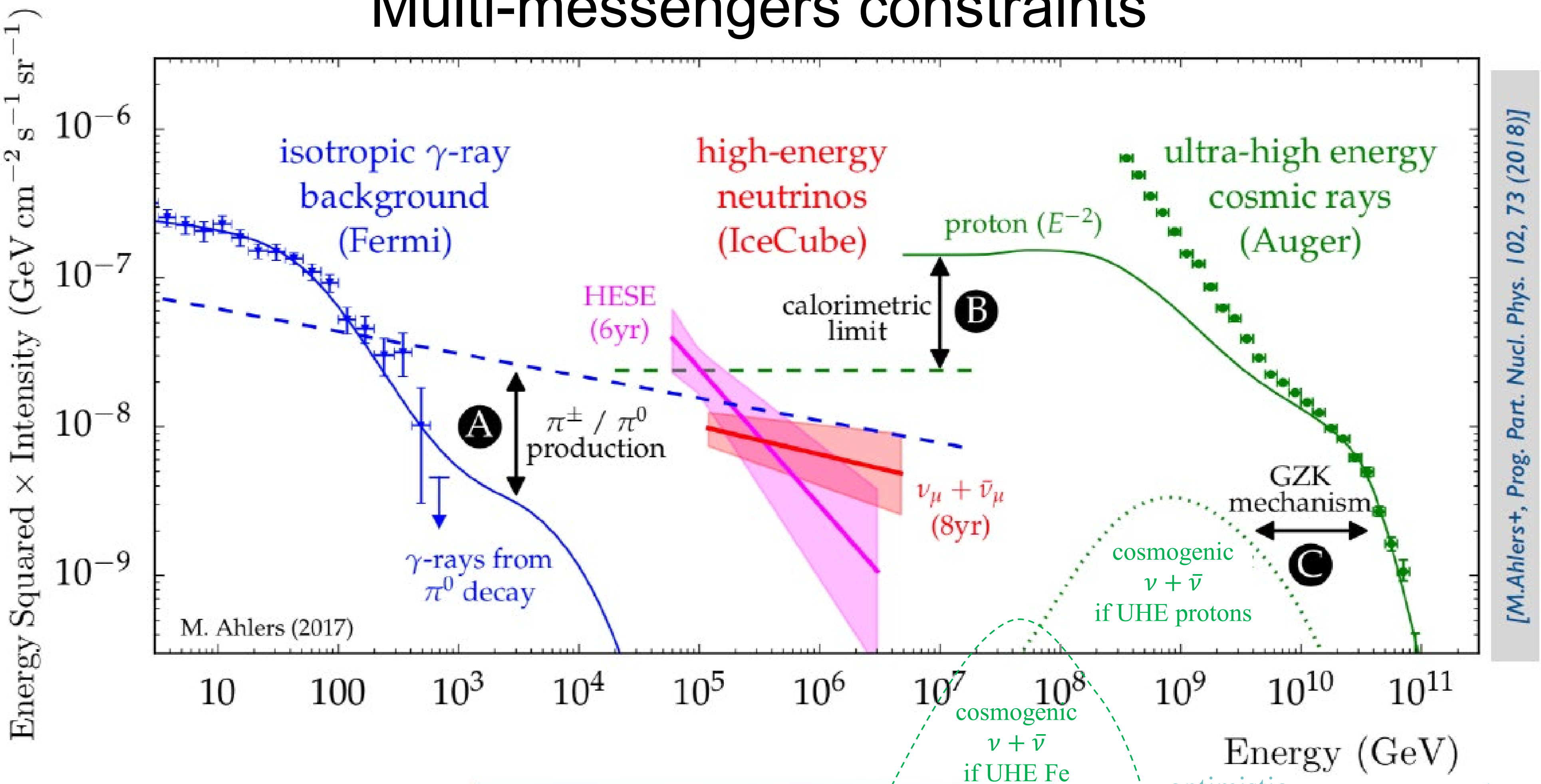
Angular coincidences to be confirmed…

Top-Down

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

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

Multi-messengers constraints



[M.Ahlers+, Prog. Part. Nucl. Phys. 102, 73 (2018)]

Top-Down Signatures

Composition:
Photons & Neutrinos fluxes => 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!! (local SHRs or TDs)
or ~ Homogeneous

and even more exotic stuff…

Strongly interacting neutrinos

Lorentz Invariance Violation

Special Relativity Violation

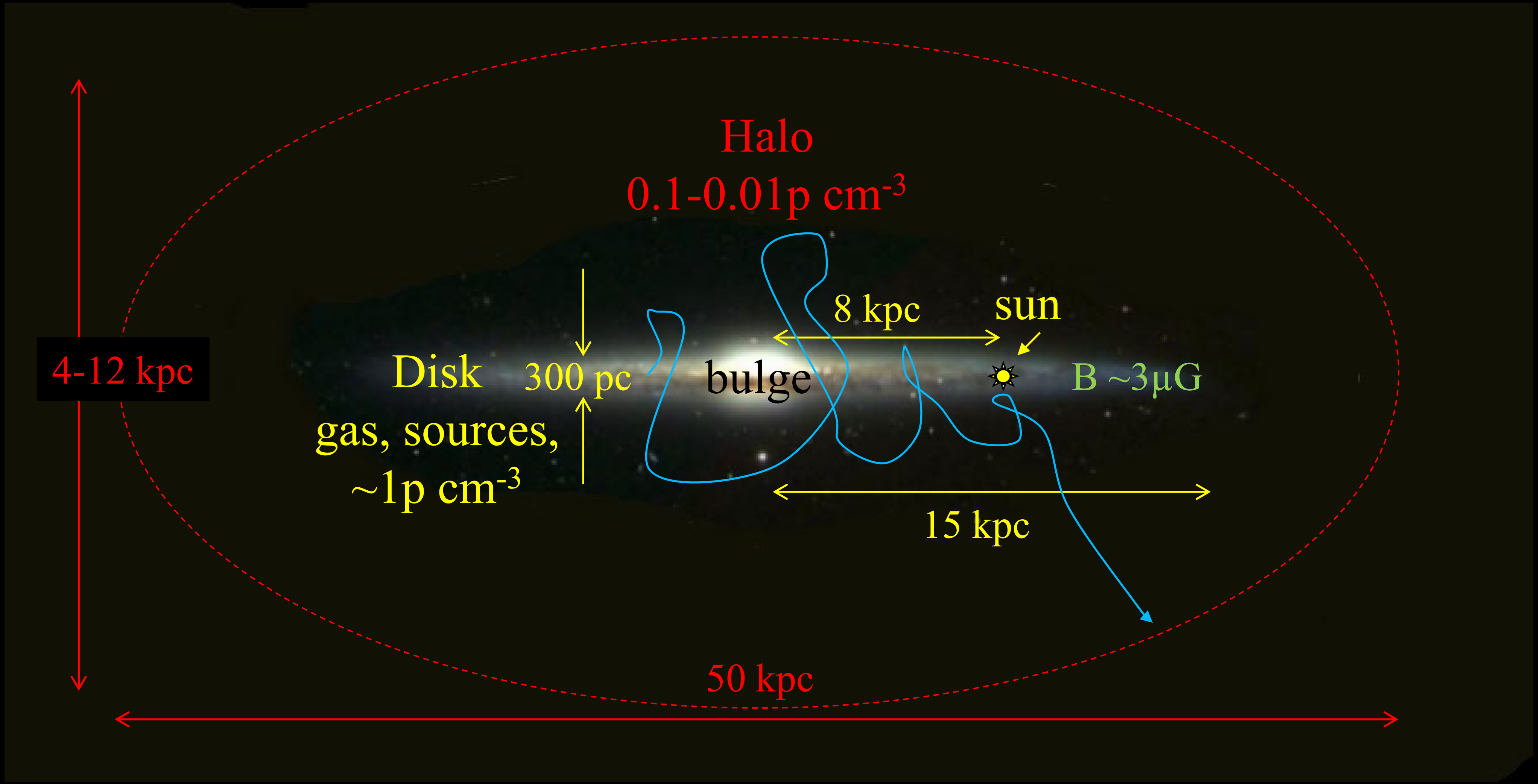
etc…

Propagation

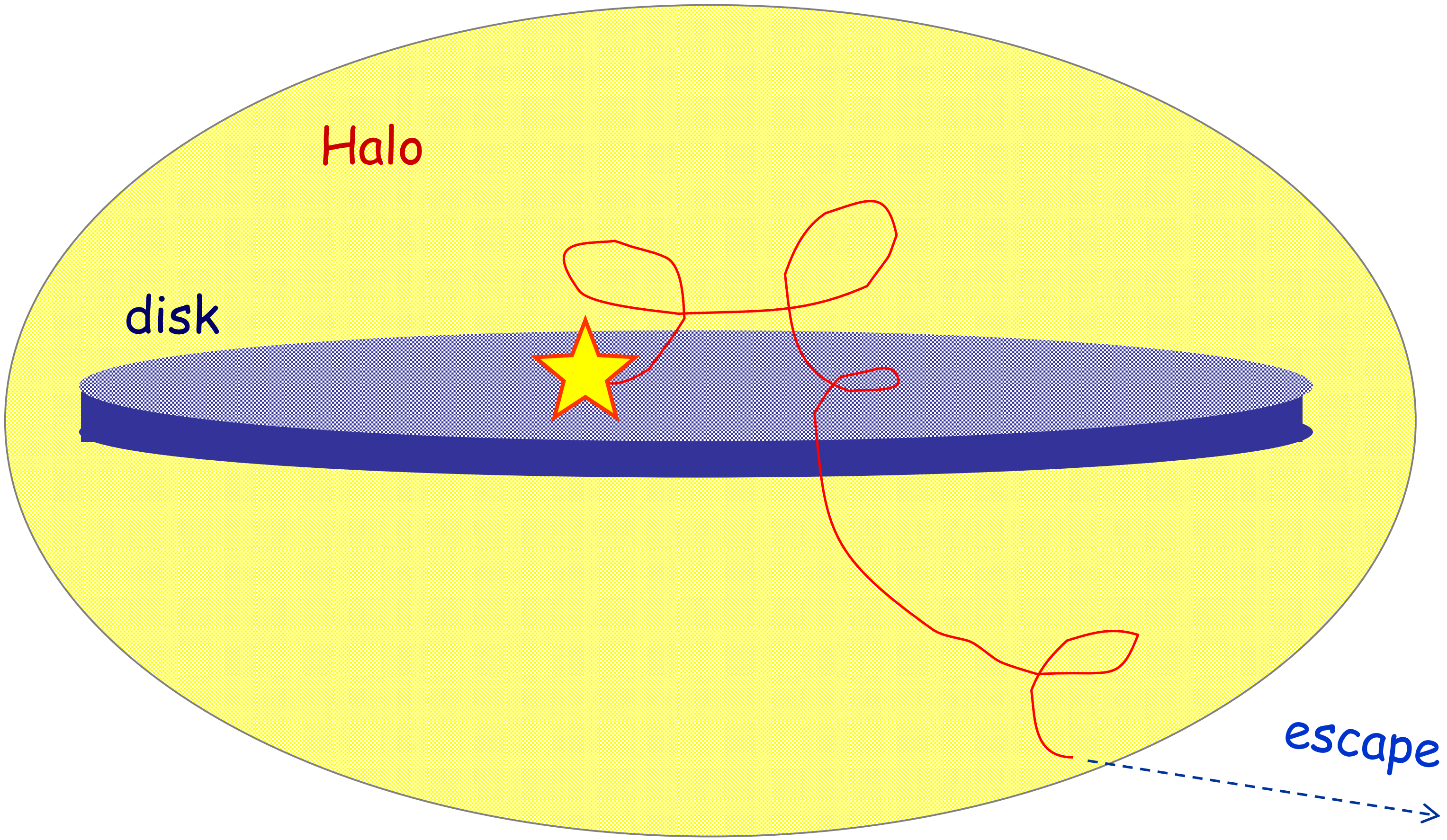
6th video (20')

Dimensions of the Milky Way

1 pc ≈ 3 l.y. ≈ 3×10^{16} m

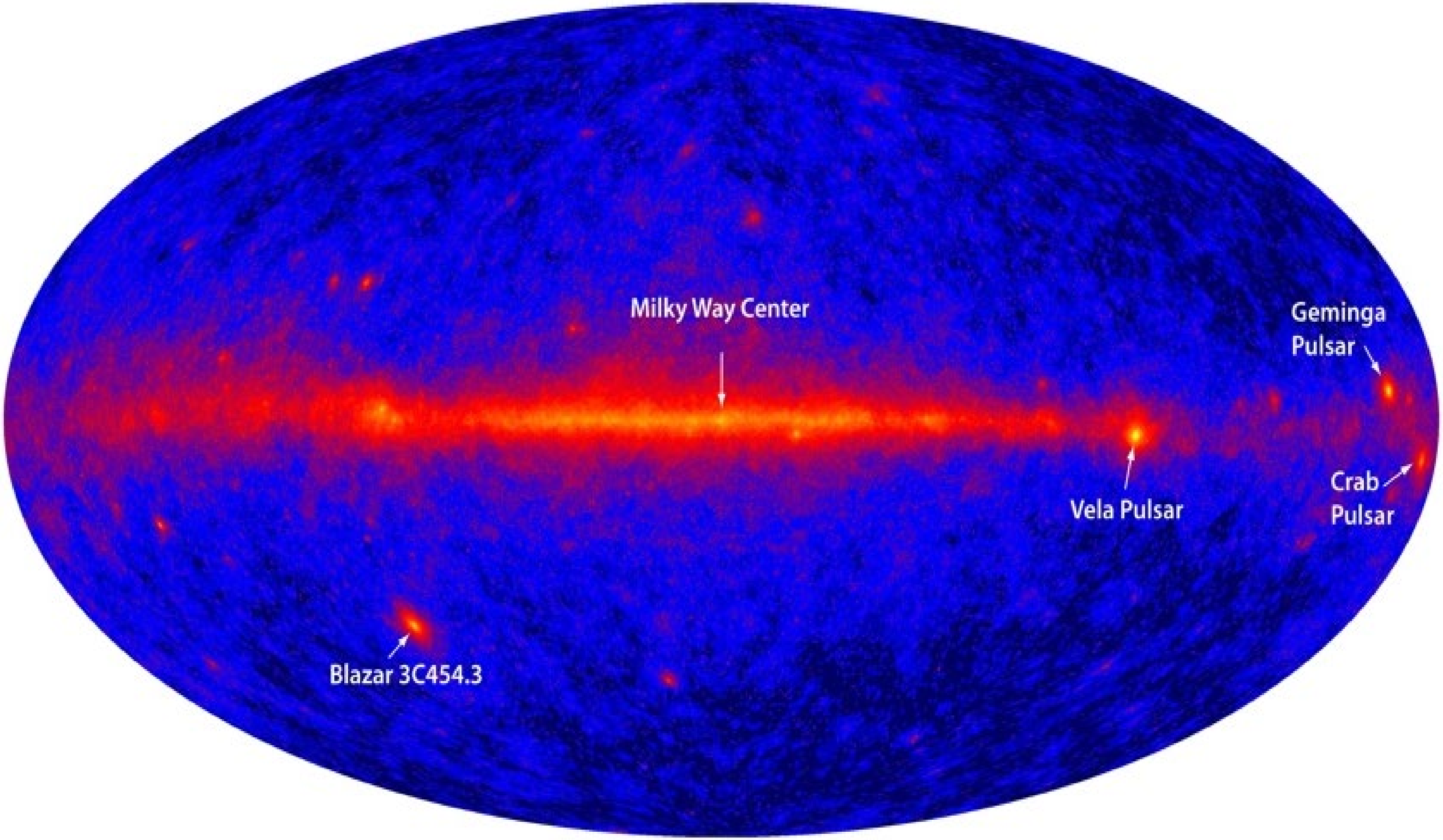


RC propagation in the Galaxy : the Leaky Box Model



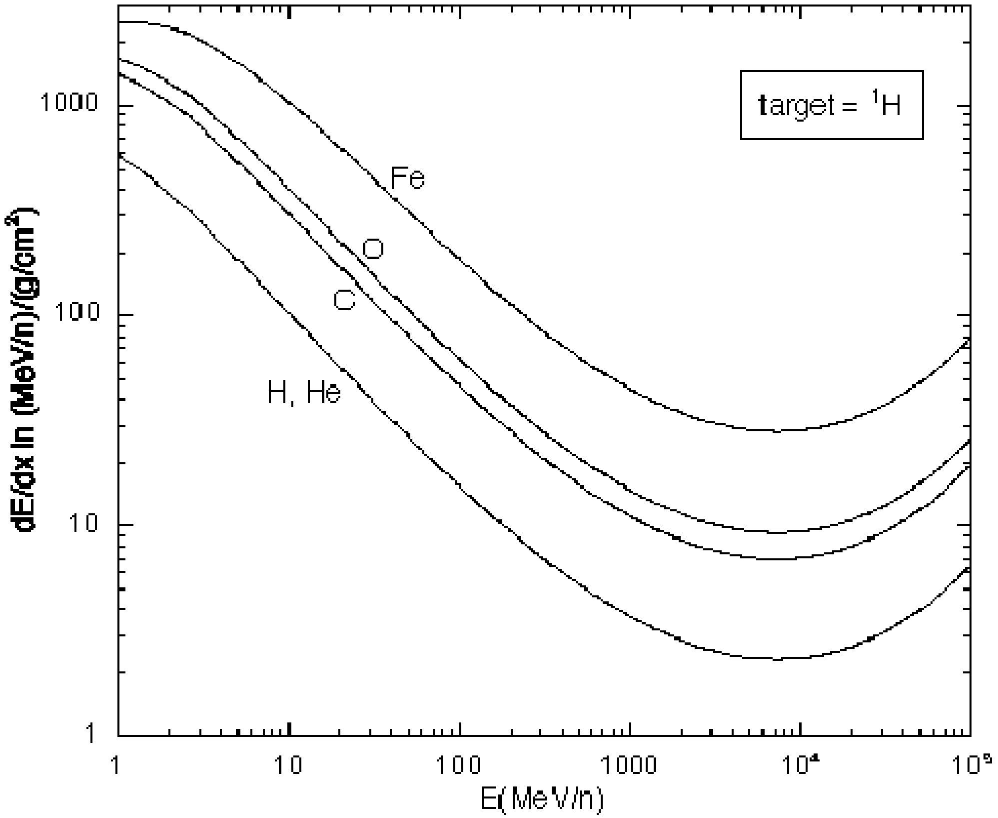
A thick target

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

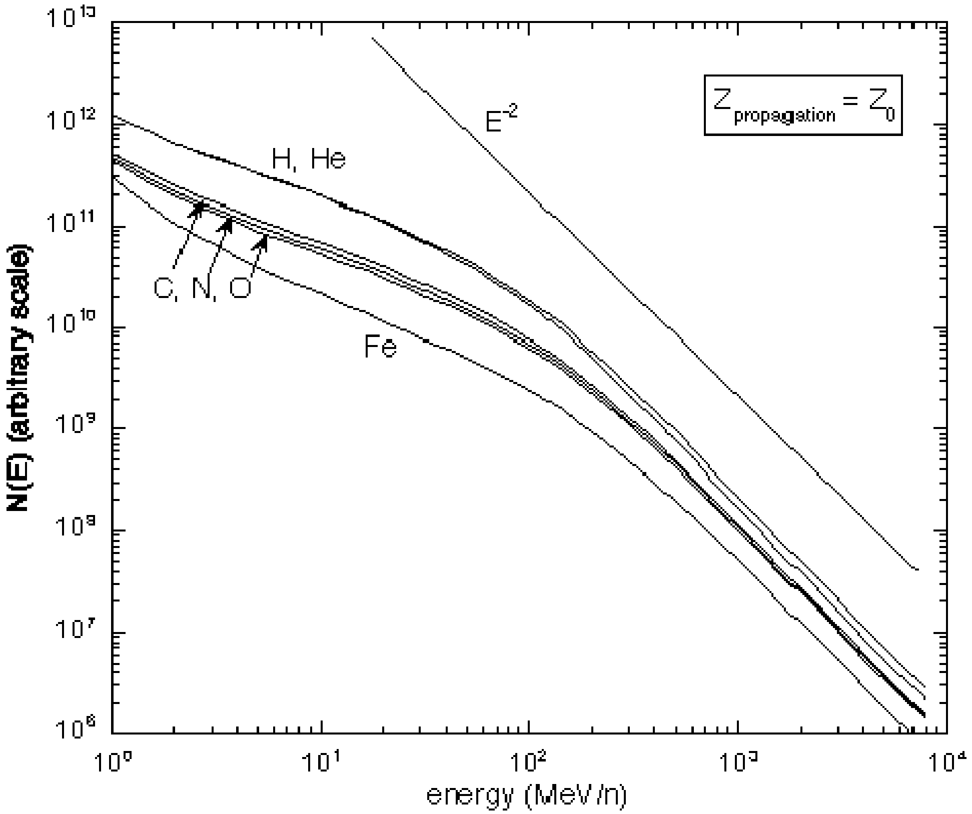


Cosmic rays transport

- Propagation in the interstellar medium



Energy loss: ionization, Coulombian interactions



Propagated spectra ionization losses only (thick target)

Grammage

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

$$\begin{aligned} \frac{dN_S}{dx} &= -\frac{\sigma_P}{m} N_P \\ \text{thus} \quad N_S &= N_P e^{-\frac{\sigma_P}{m} x} \\ \text{and} \quad x &= -\frac{m}{\sigma_P} \log(N_S/N_P) \end{aligned}$$

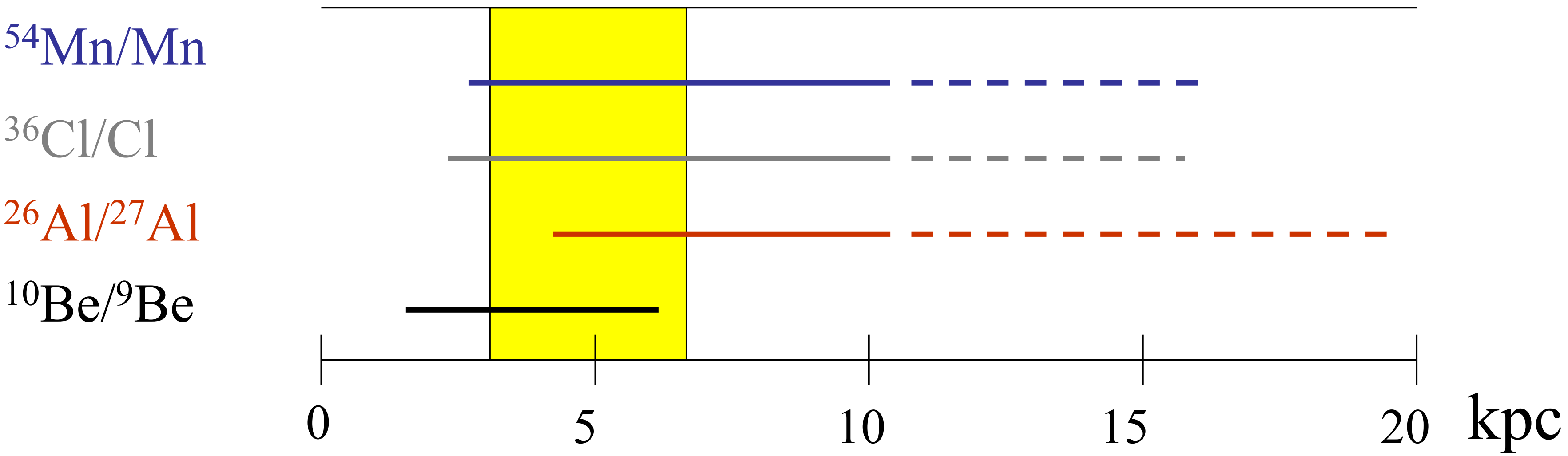
$$\mathrm{B/C} \approx 35\% \Rightarrow x = -\frac{m}{\sigma_P} \log(B/C) \approx 60 kg.m^{-2}$$

$$\text{if} \quad Br(C + P \to B + X) \approx 100\%$$

Cosmic clocks and halo size

- $^{12}C + H \rightarrow\ ^{9}Be$ (stable secondary nucleus)
  $^{12}C + H \rightarrow\ ^{10}Be$ (unstable secondary nucleus: ~ 4×10^{8} years)
- The ratio $^{10}Be\ /\ ^{9}Be$ 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)

  ⇒ determination of the CR confinement zone



Confinement and escape

- The average measured grammage is $x \approx 50 kg.m^{-2}$
- Associated lengths:

$$\begin{aligned} \lambda_{esc} &= x/\rho \approx 750 kpc, \\ \text{with} \quad \rho &= 1.4\, n_H\, m_p \approx 2.2 \times 10^{-21} kg.m^{-3} \end{aligned}$$

- $\lambda_{esc} \gg R_{gal} = 20 kpc$ ⇒ CR are confined
- $\lambda_{esc} \ll \lambda_{pp} = (n_H\, \sigma)^{-1} \approx 6 Mpc$ ⇒ CR can escape
- Long lived radioactive secondaries (cosmic clocks) indicate $\tau_{esc} \approx 20 Myr$
- Average density scanned by CR:

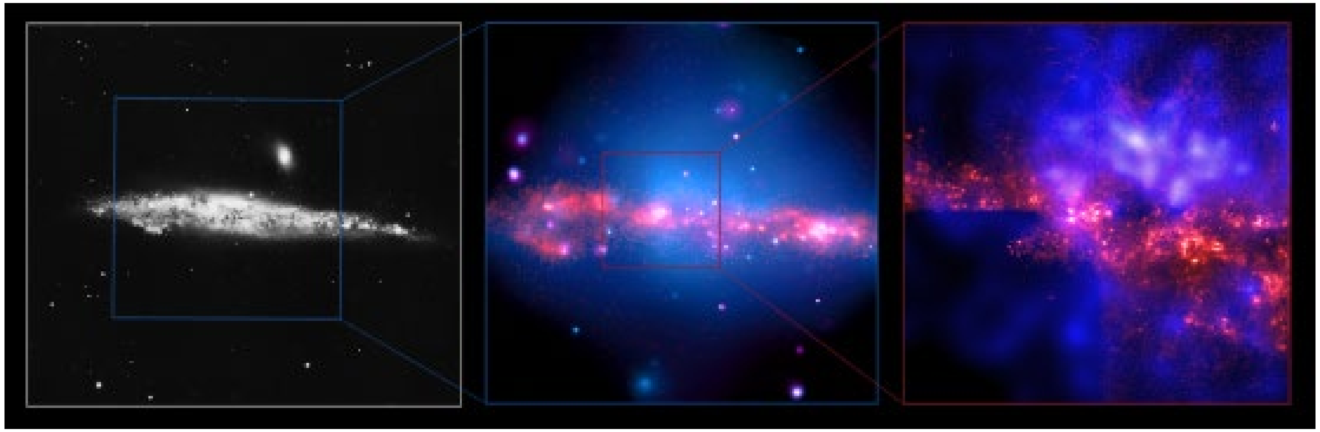
$$n_H = \lambda_{esc}/c\, \tau_{esc}\, m_p \approx 0.3 cm^{-3} < n_{disk} = 1 cm^{-3}$$

⇒ 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

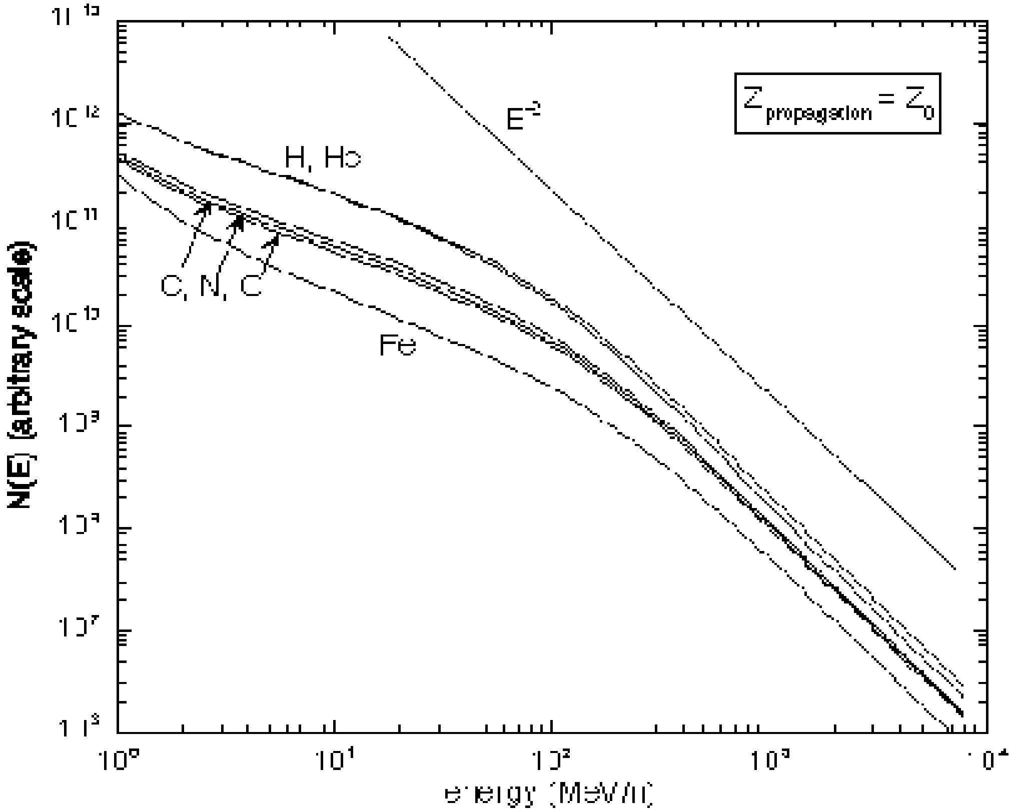
$$T = 10^6\ K \quad \text{et}\ n = 10^{-3} cm^{-3}$$



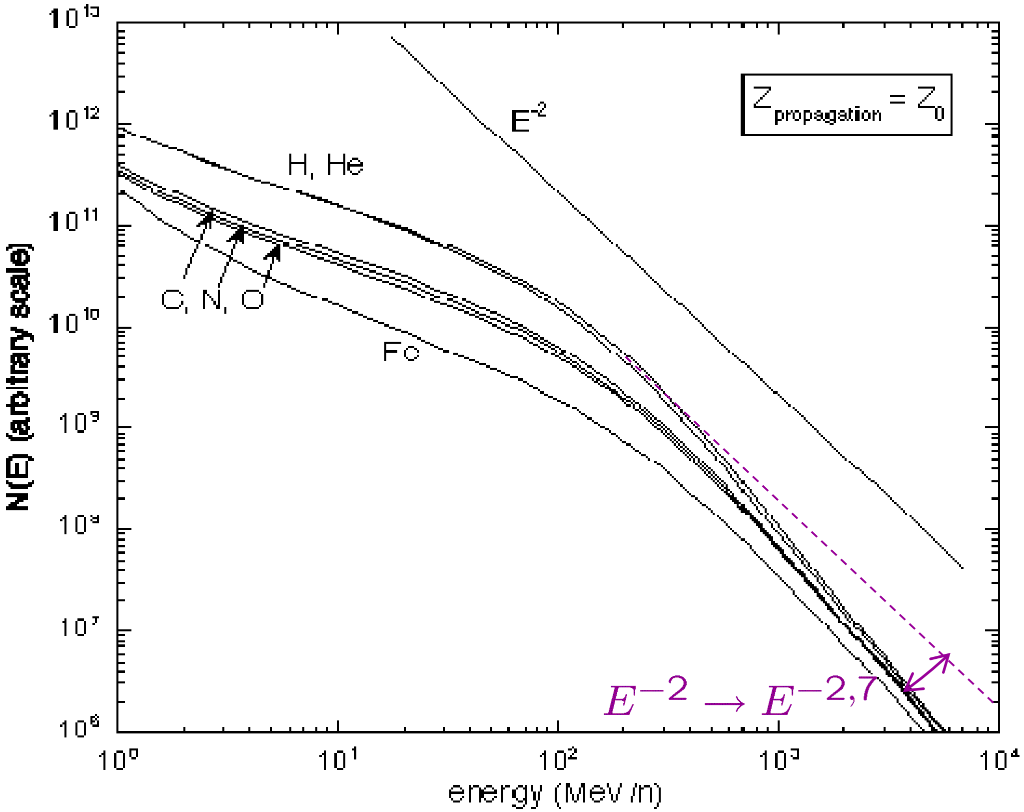
- NGC 4631 galaxy and its halo of hot ionized matter emitting X-rays as seen by Chandra

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

Full transport equation

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

diffusion $+ \vec{\nabla}.\left[D_{\chi\chi}\vec{\nabla}\psi - \vec{V}\psi\right]$ convection

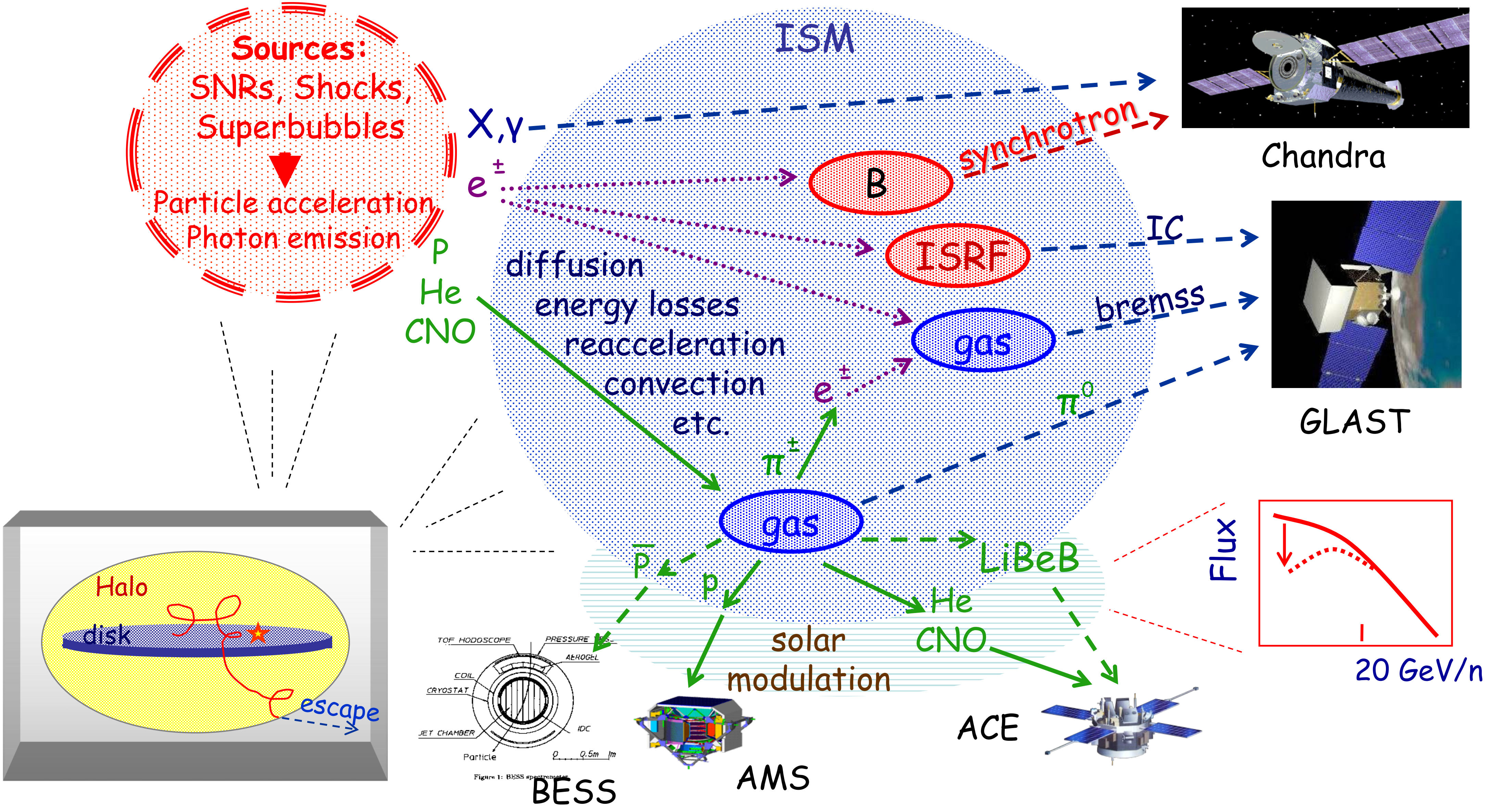
diffusive reacceleration $+ \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right]$

E-loss $- \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}.\vec{V}\psi\right]$ convection

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

*ψ(**r**,p,t) – momentum density*

Propagation in the ISM
et observational contrains



Sources:
SNRs, Shocks,
Superbubbles
Particle acceleration
Photon emission

ISM

X,γ

$e^{\pm}$

B

synchrotron

Chandra

ISRF

IC

gas

bremss

GLAST

p
He
CNO

diffusion
energy losses
reacceleration
convection
etc.

$e^{\pm}$

$\pi^{\pm}$

π^{0}

gas

$\bar{p}$

p

LiBeB

He
CNO

solar
modulation

Halo

disk

escape

BESS

AMS

ACE

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 for too naive acceleration models!

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

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

- Cut off energy, knee, non-linearities, γ-ray emission by SNR, source distribution...

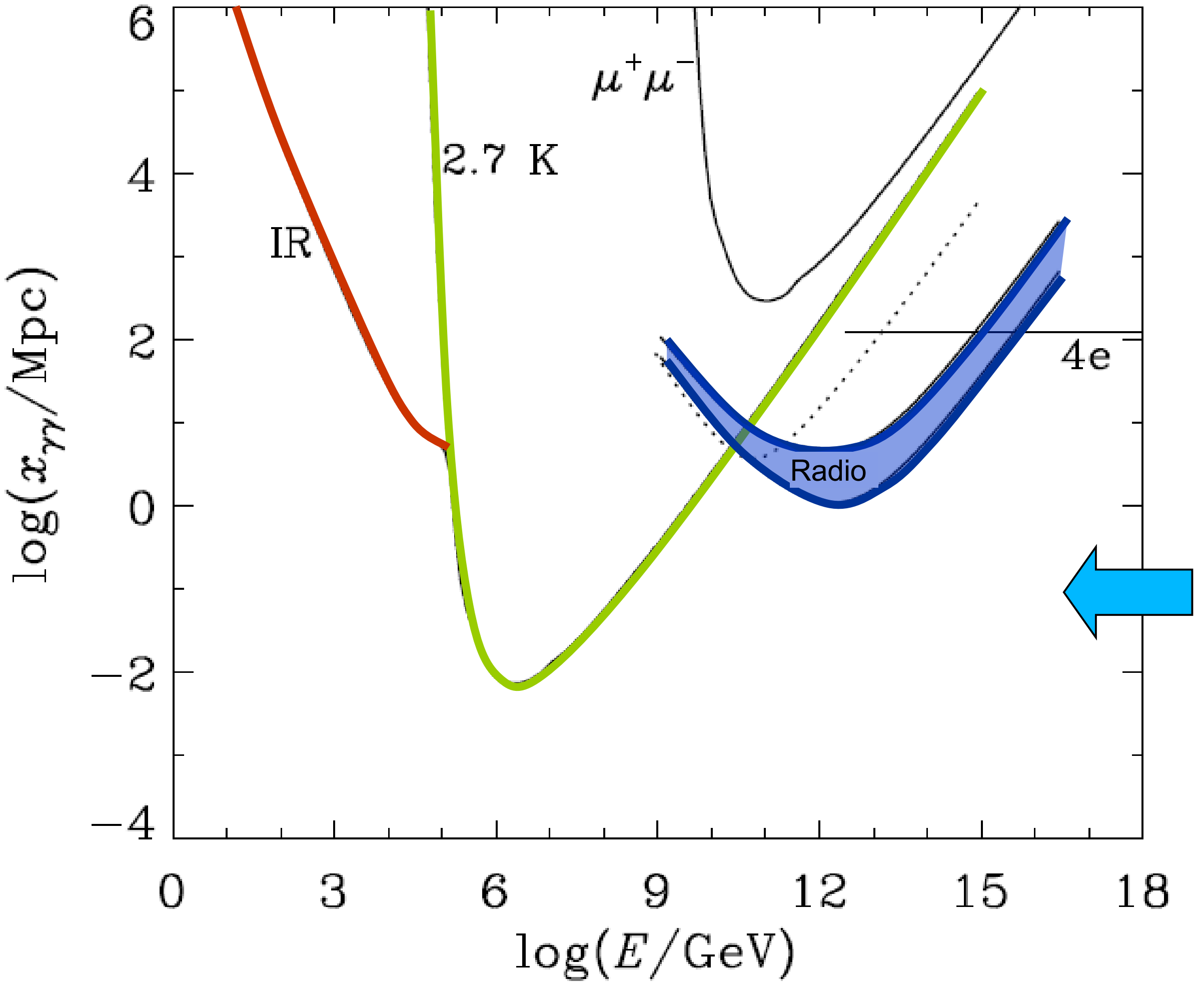
Many parameters ⇒ need many observational constrains.

V(U)HE GAMMA-RAY PROPAGATION

Photon attenuation at VHE by intergalactic photon backgrounds

$\gamma + \gamma_{\mathrm{BG}} \rightarrow e^{+} + e^{-}$ ⇨

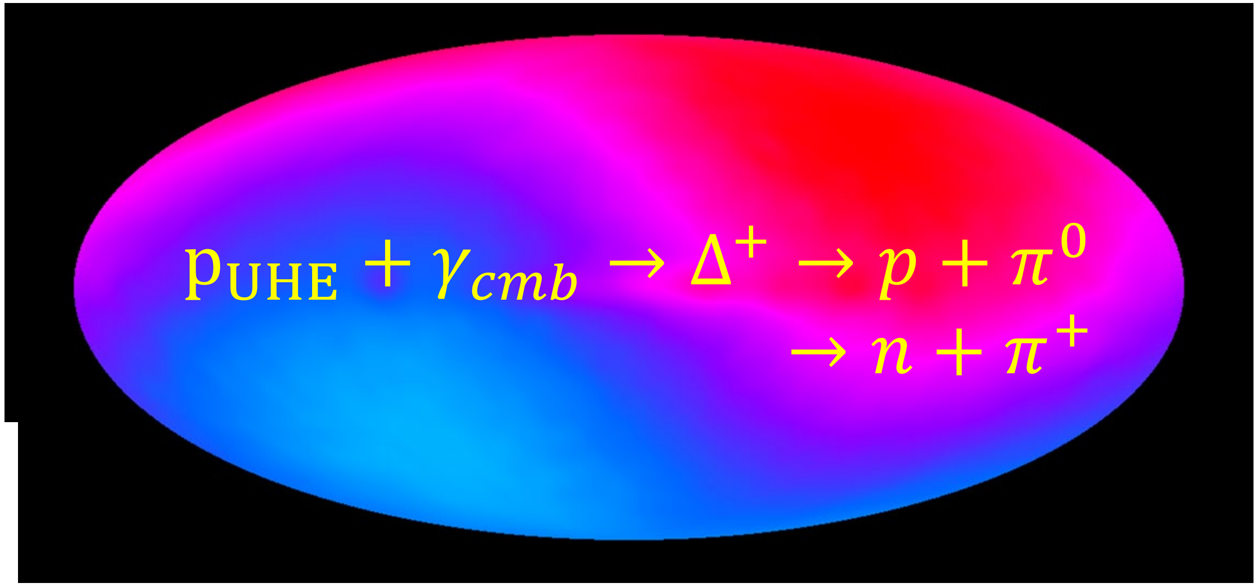
Initiates a showering process
⇒ Low energy(GeV) diffuse flux γ-rays



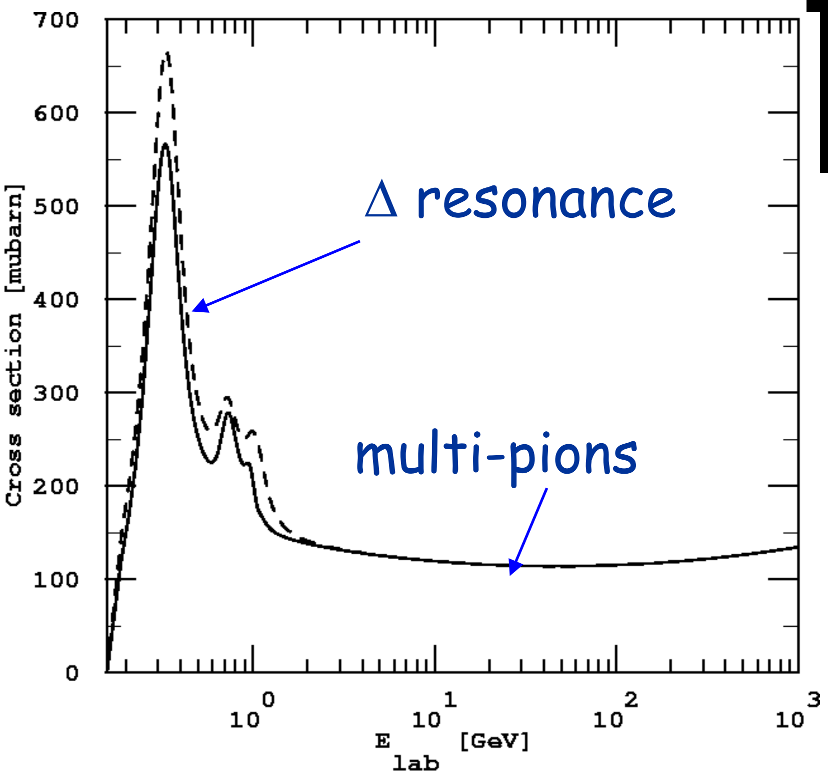
⇦ Effective γ-rays horizon:
100Mpc at 1TeV
1Mpc at >10 TeV

UHECR PROPAGATION

An extreme case of relativistic kinematics !!!



$$p_{UHE} + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

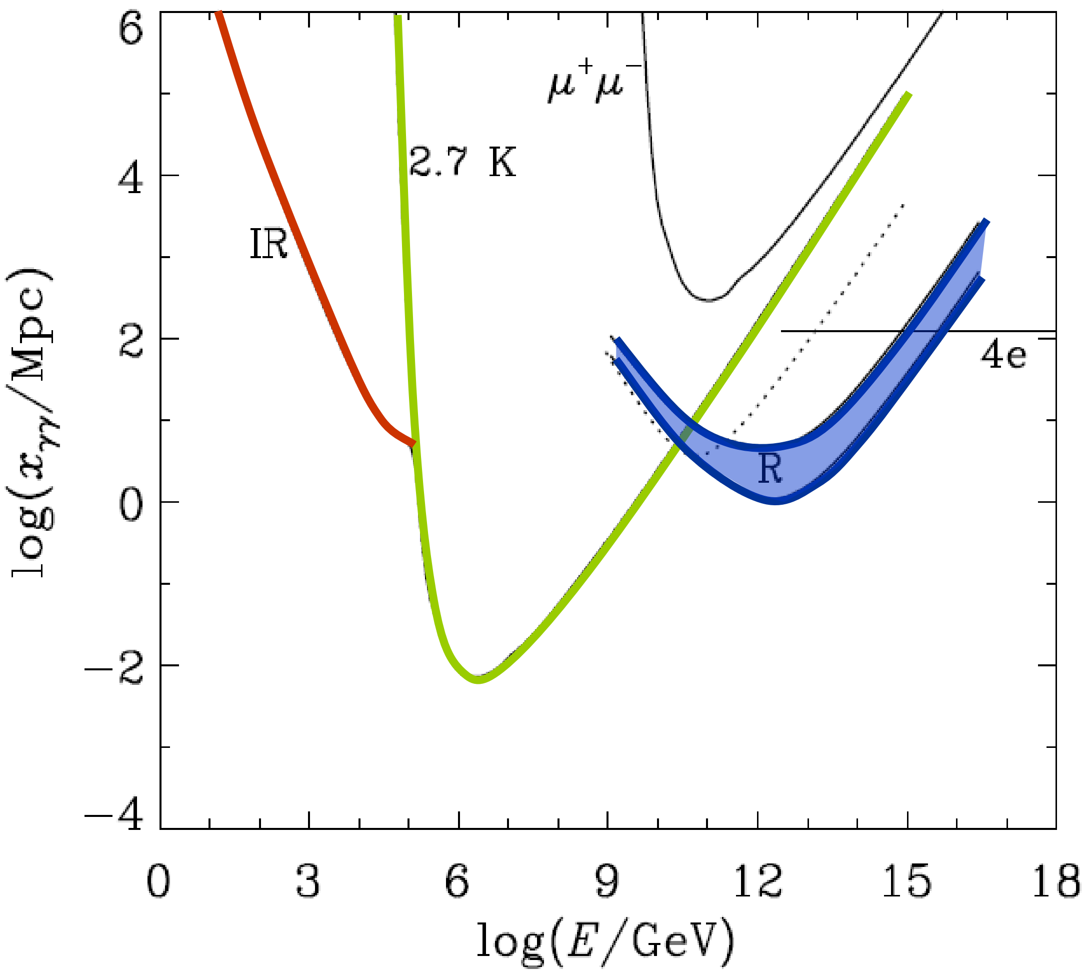


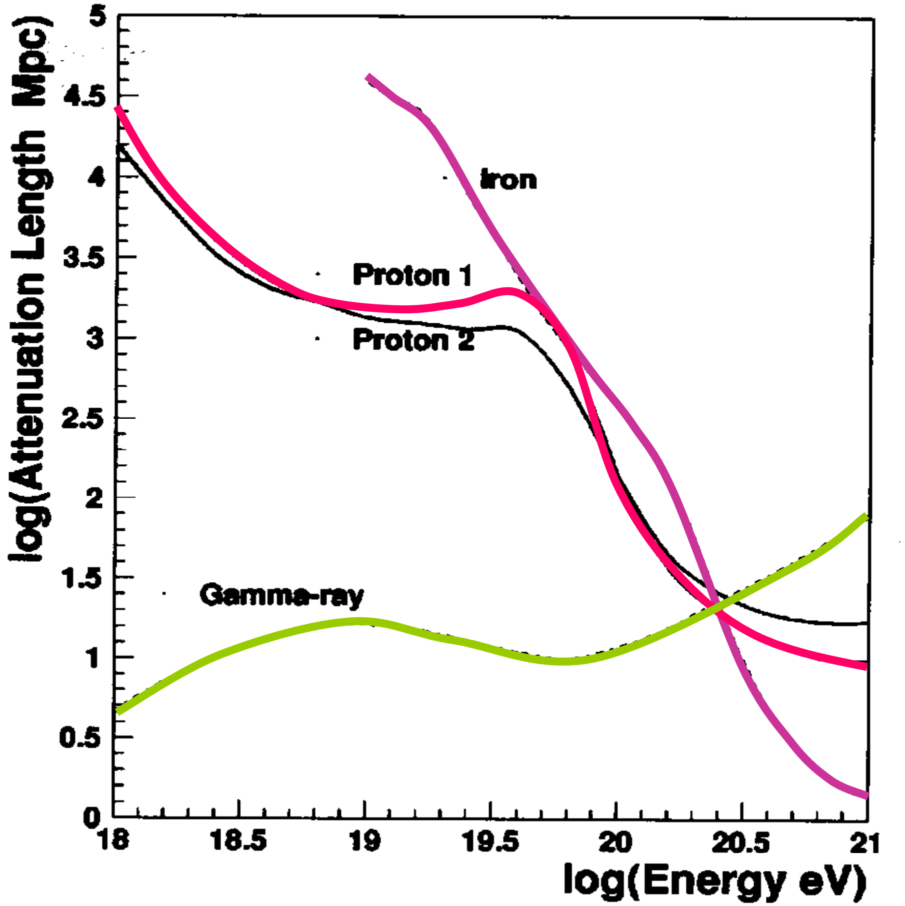
GZK
"cutoff"

Greisen ‘66, Zatsepin & Kuzmin ‘66

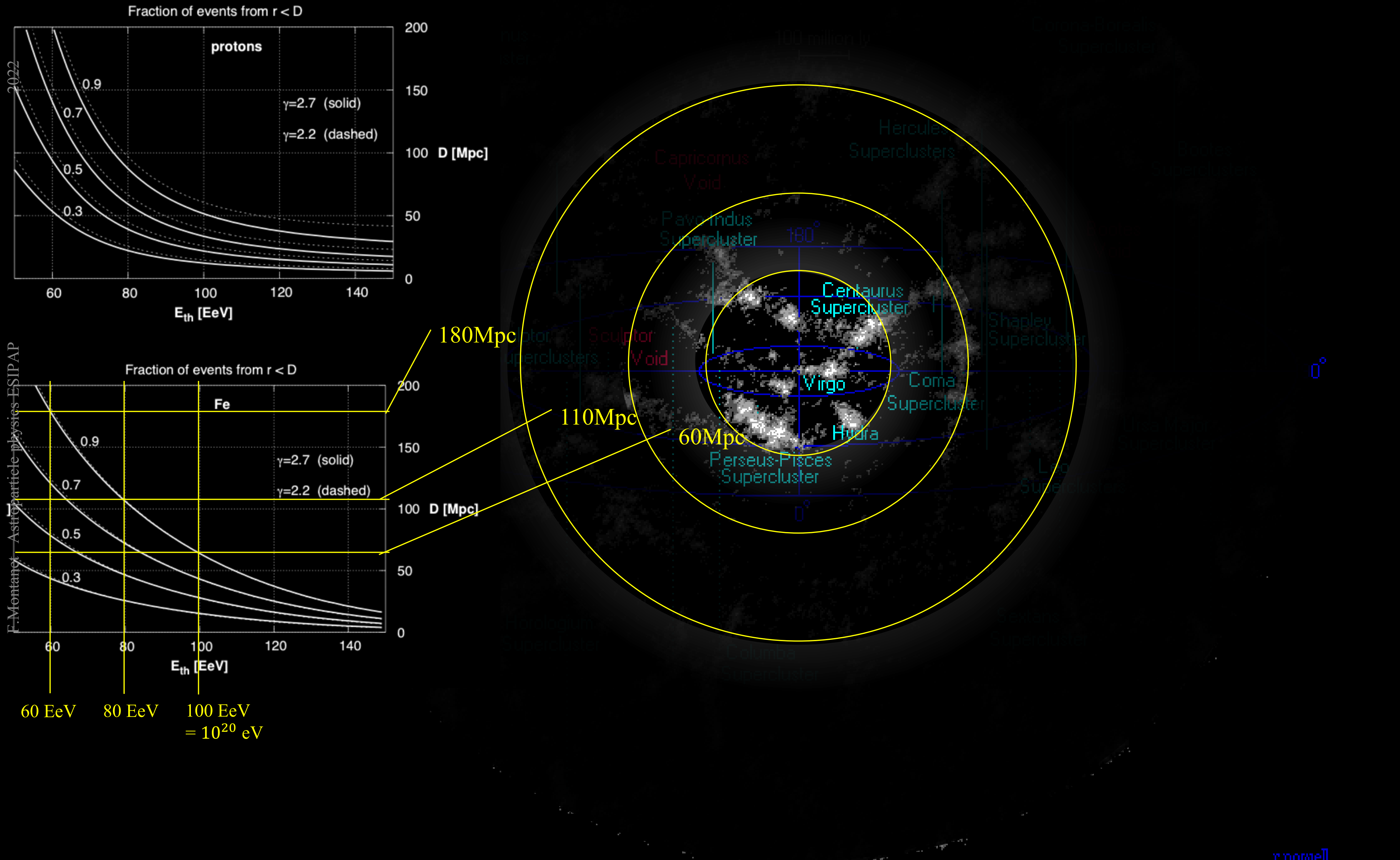
Energy losses

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



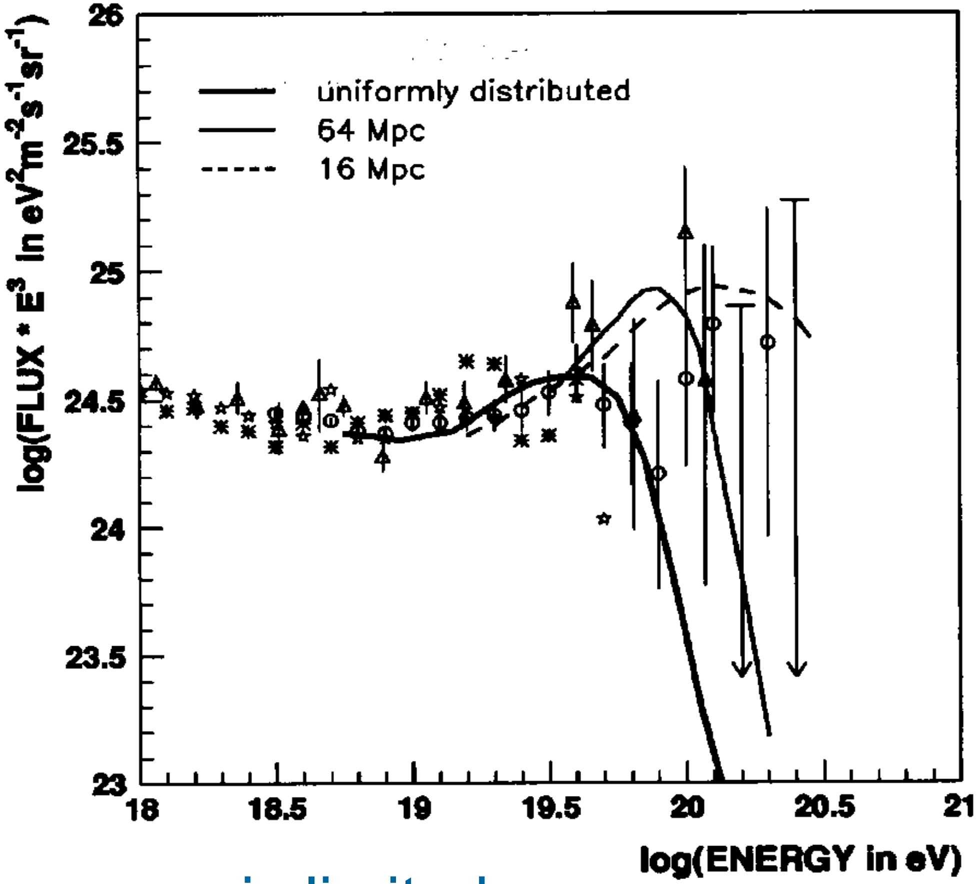


Horizon < 200Mpc at UHE



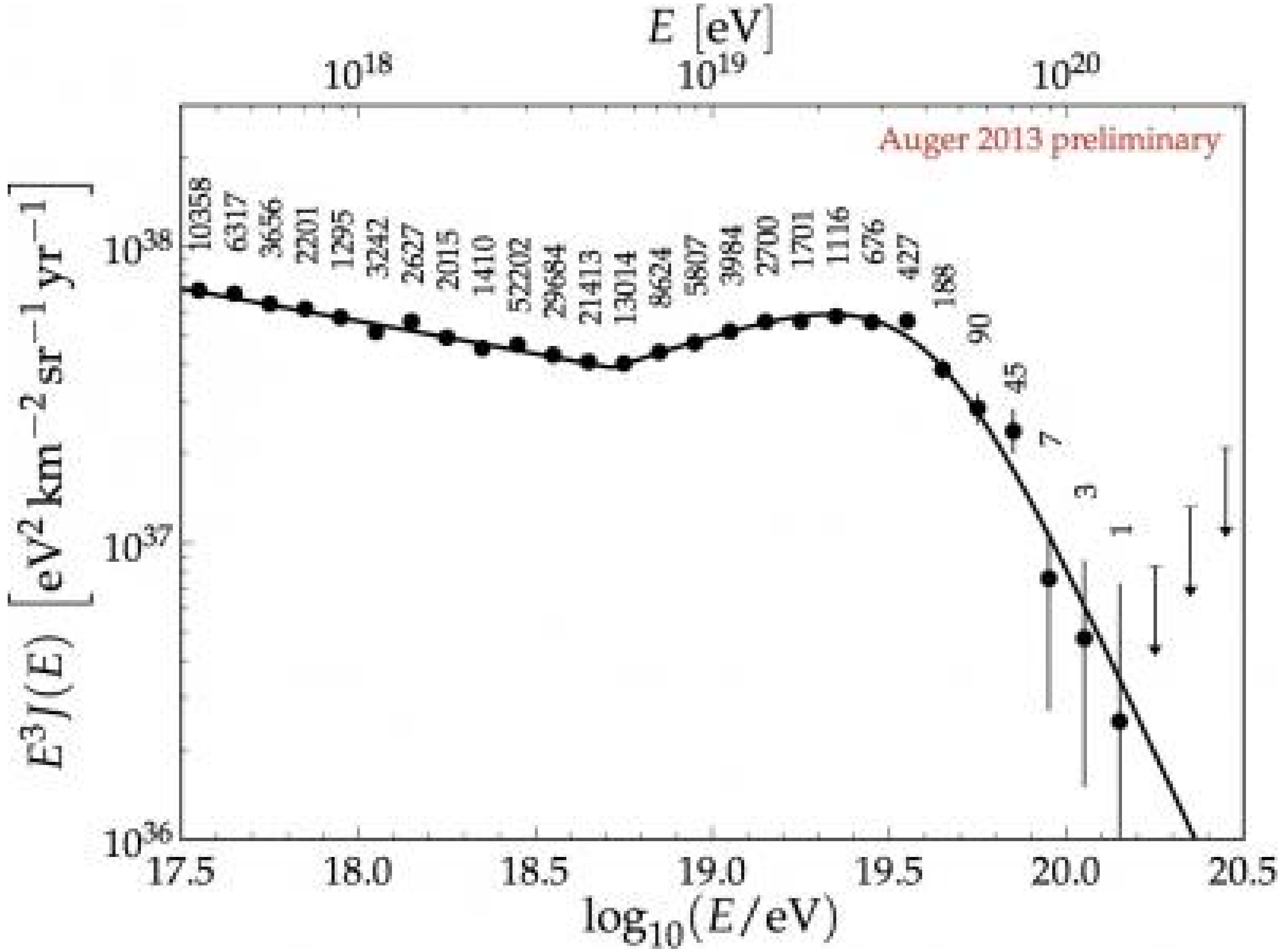
GZK suppression

- Greisen-Zatsepin-Kuz'min

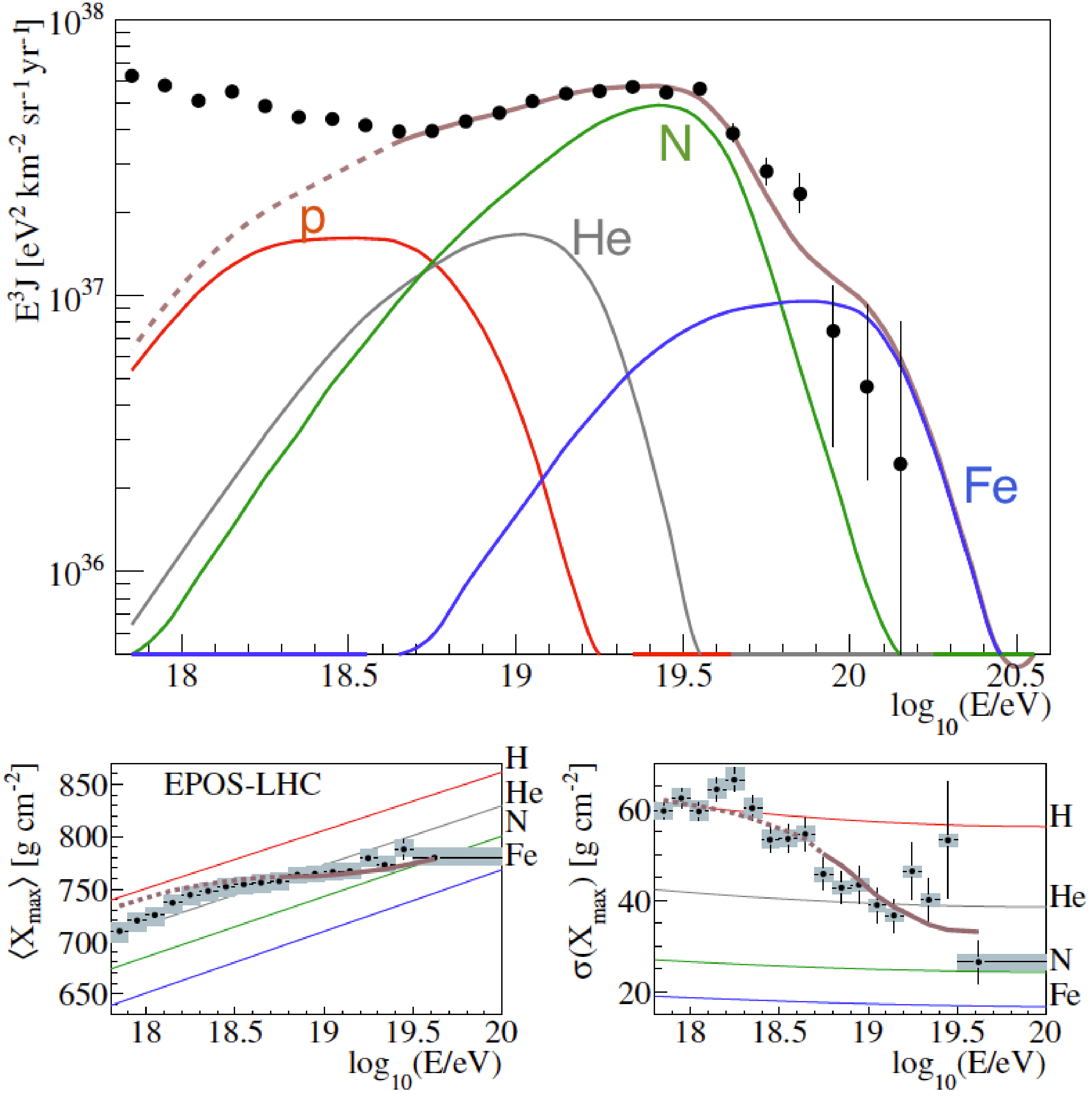


- Distance to the source is limited to 100 Mpc for 10^{20} eV protons, and 15 Mpc for 3×10^{20} !
- Actually even less if particles are deflected ($D_{effectif} > D_{linear}$)

GZK like suppression (Auger)



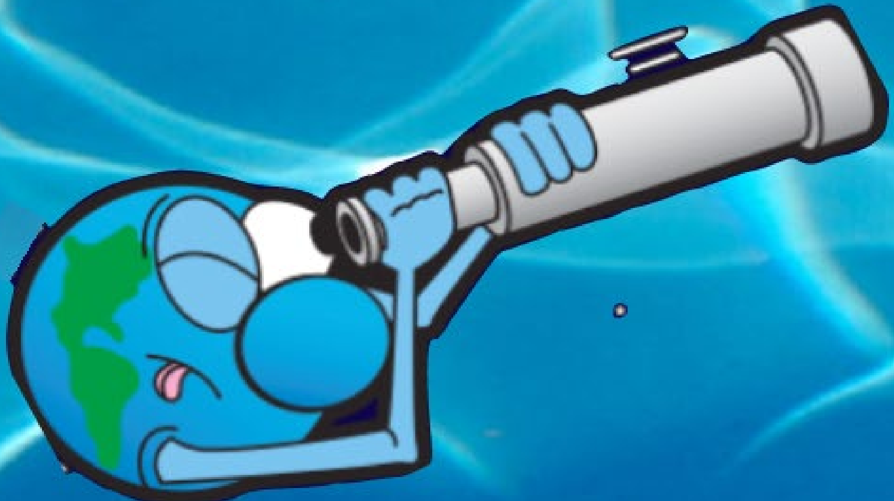
Flux suppression (Auger)



The spectrum is best fitted by a succession of cutoffs of the different groups of elements, with $R_{cut} = 10^{18.67\pm0.03} V$, thus pointing to the flux at Earth being partly limited by the maximum energy at the source. The best fit returns $\gamma = 0.94^{+0.09}_{-0.10}$, suggesting a very hard source spectrum, and an injection of mostly intermediate mass nuclei, with very few protons or iron nuclei.

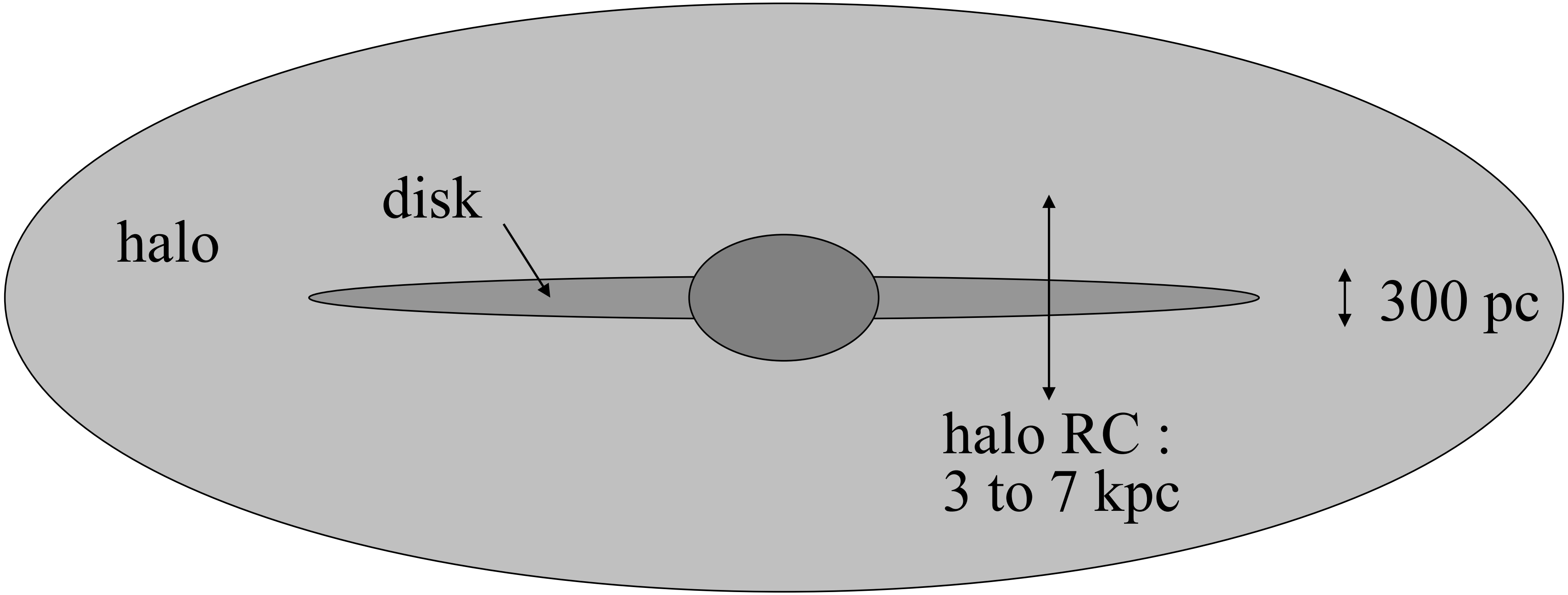
It has to be noted that the fit also finds a second local minimum, with $\gamma = 2$ and a larger maximum rigidity, more in line with standard models of cosmic-ray acceleration. While the spectrum is fitted well in this case too, wider distributions of UHECR masses than observed in the data are in turn predicted at each energy, showing how crucial the measures of mass composition are to resolve the origin of the observed flux suppression.

MAGNETIC DEFLECTIONS



Galactic magnetic deflection

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

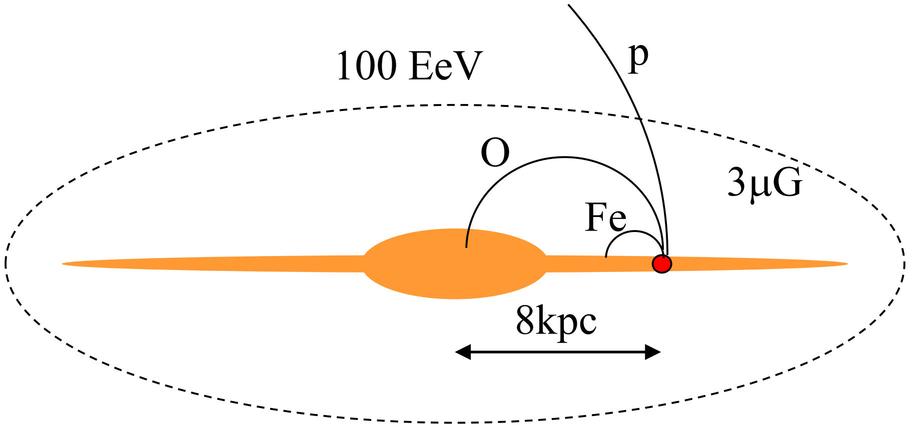


- 2×10^{19} eV **proton in** $B = 3\ \mu G$ $\Rightarrow$ $r_g \sim 7$ kpc
- 5×10^{20} eV **Fe in** $B = 3\ \mu G$ $\Rightarrow$ $r_g \sim 7$ kpc

Propagation in the Galaxy

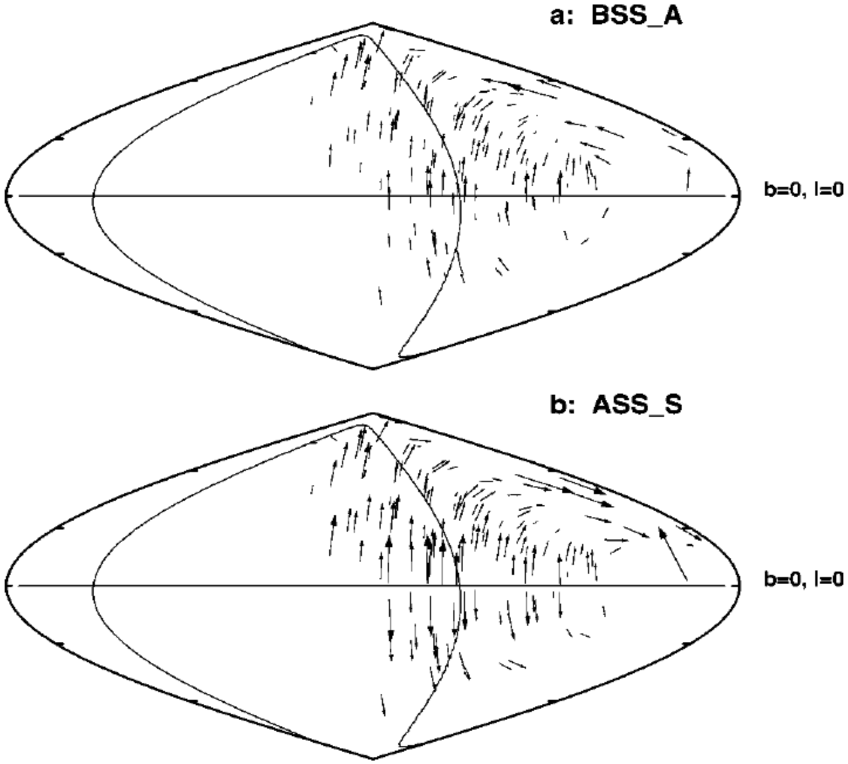
- Galactic magnetic field model, given that:

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



- Possible galactic confinement of 10^{20}eV nuclei

- 10^{18}eV neutrons decay length
  $\beta\gamma c\tau \approx$ 10kpc ⇒ galactic distances



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

Pointing at UHECR sources?

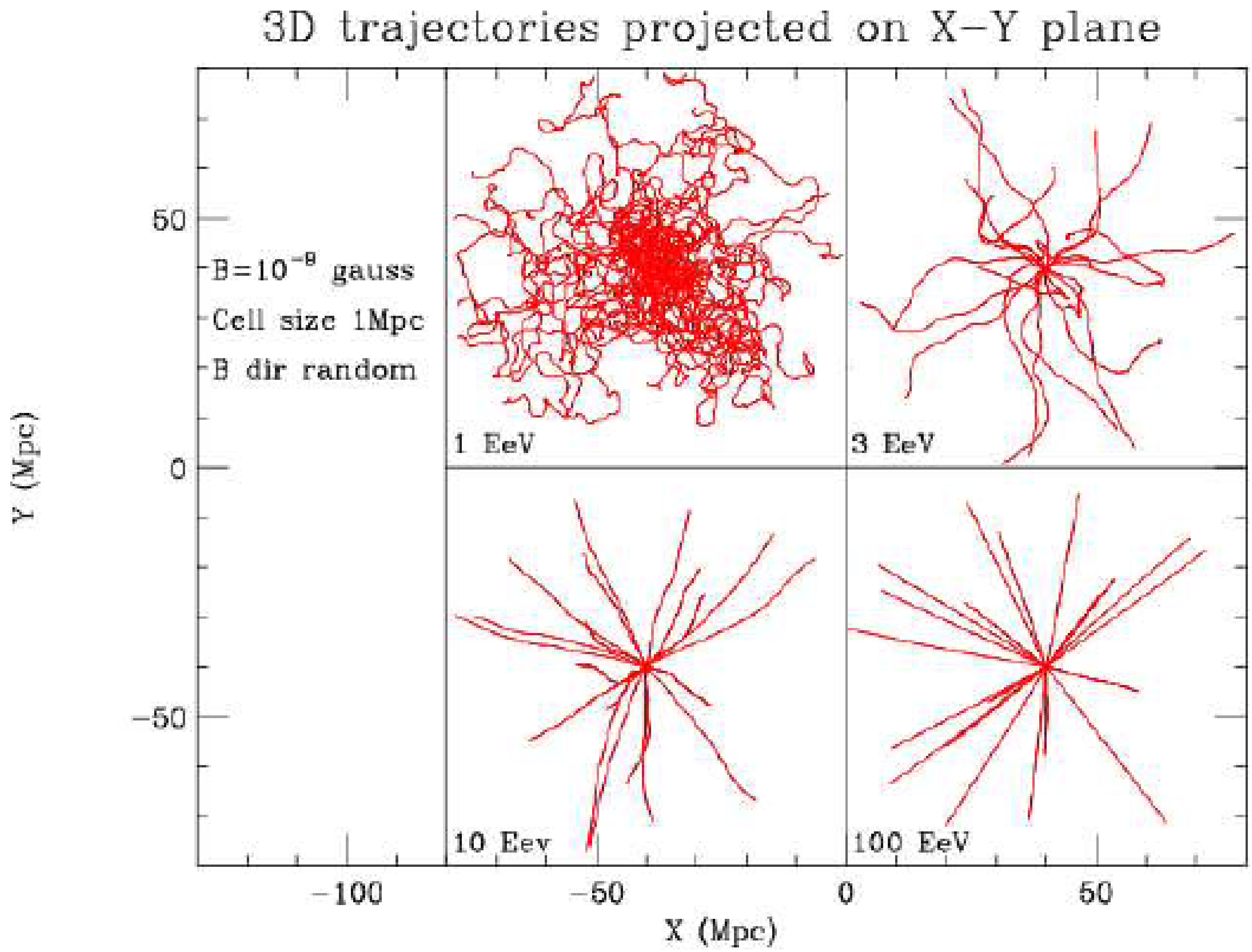
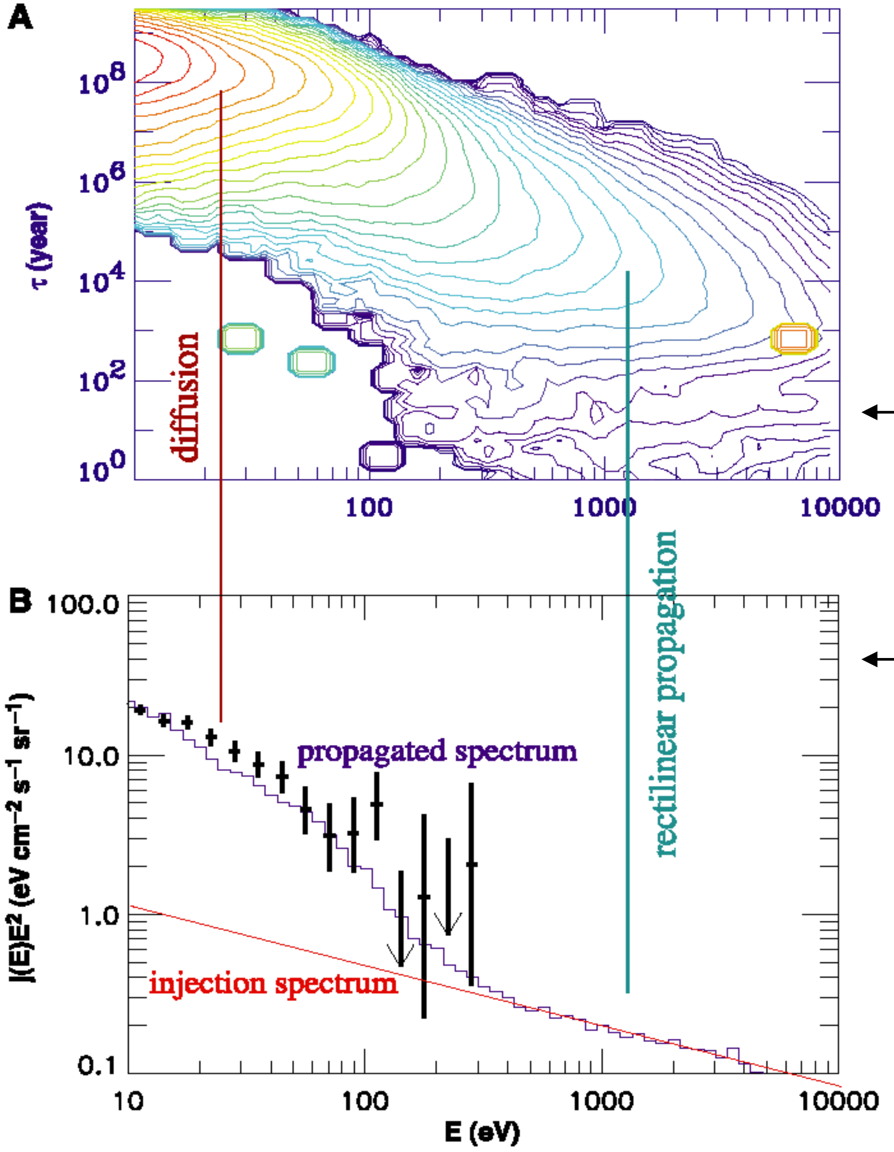


Figure 7: Projected view of 20 trajectories of proton primaries emanating from a point source for several energies. Trajectories are plotted until they reach a physical distance from the source of 40Mpc. See text for details.

Extra-galactic UHECR propagation



From diffusive regime to rectilinear propagation [Sigl]

Time-Energy correlation

Average spectrum

Depends on the strength and coherence length of EG magnetic fields

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

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

Mapping IG fields with UHECR?

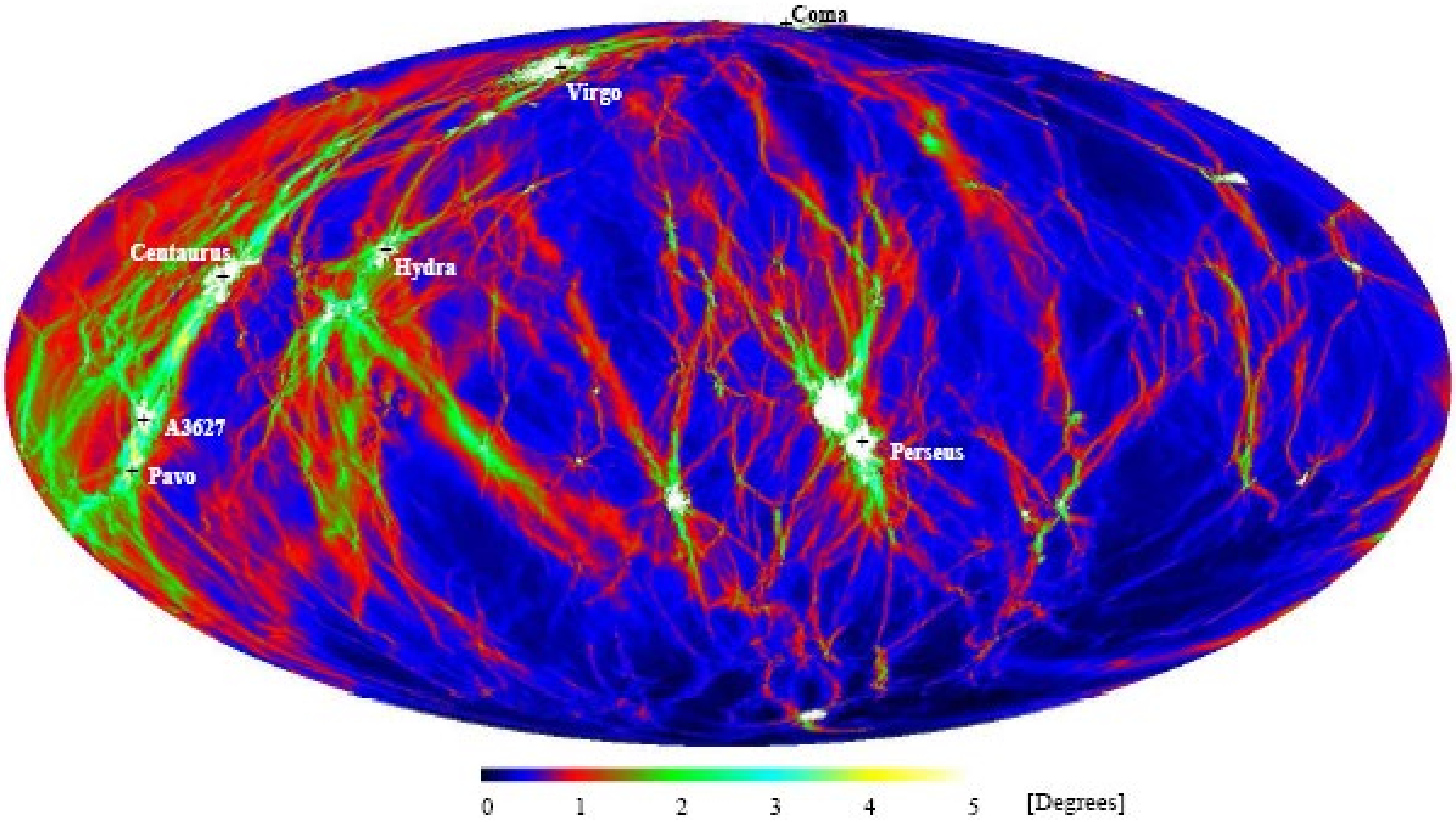


FIG. 1. Full sky map (area preserving projection) of deflection angles for UHECRs with energy 4×10^{19} eV using a linear color scale. All structure within a radius of 107 Mpc around the position of the Galaxy was used. The coordinate system is galactic, with the galactic anti-center in the middle of 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.

Air Shower Physics

7th & 8th videos (2x20')

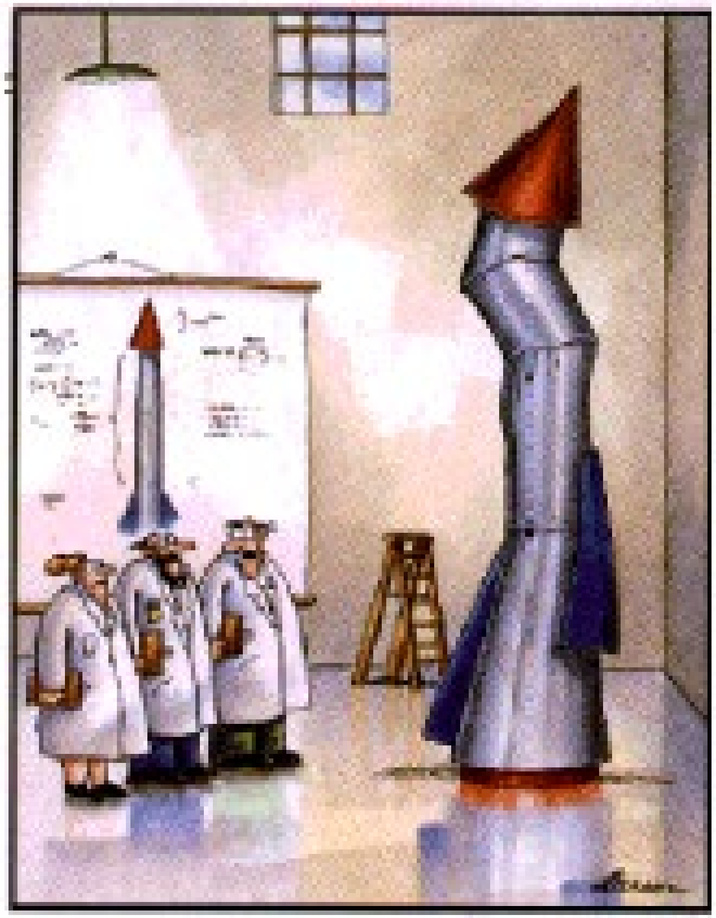
A peek above the knee !

To measure the inclusive spectrum at the knee, one needs a 10m² exposed during 10 years !

The realistic experimental limits are:

- For satellites ~ 1m² (sr) during ~few years
- For balloons, ~ 10m²(sr) during n×30 days

→ E < few TeV



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

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 ≥ 10TeV

- Atmosphere used as a calorimeter
  (~1000 g 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 light nuclei (p, He) - heavy nuclei(Fe)
  - distinction photon-hadron
  - distinction neutrino-hadron

The earth atmosphere

In terms of particle/radiation interaction with matter, the atmosphere is:

- A total of ≈ 1000 g/cm^2 at sea level.
- So 1 atm ≈ 12 interaction lengths ($\lambda_N \approx 85$ g/cm^2).
- A vertical proton first interacts at $h \approx 15$ km
- One radiation length (at 1 atm) is $X_0 = 36.6$ g/cm^2 ≈ 300 m.
- One Moliere radius (at 1 atm) is $\rho_M \approx 78$ m.
- The Lorentz factor for a muon produced at $h = 10$ km to reach ground before decaying is $\Gamma > 15$ (i.e. $E > 1.6$ GeV).
- The critical energy (EM) is $Ec = 84.2$ MeV.

The shower development

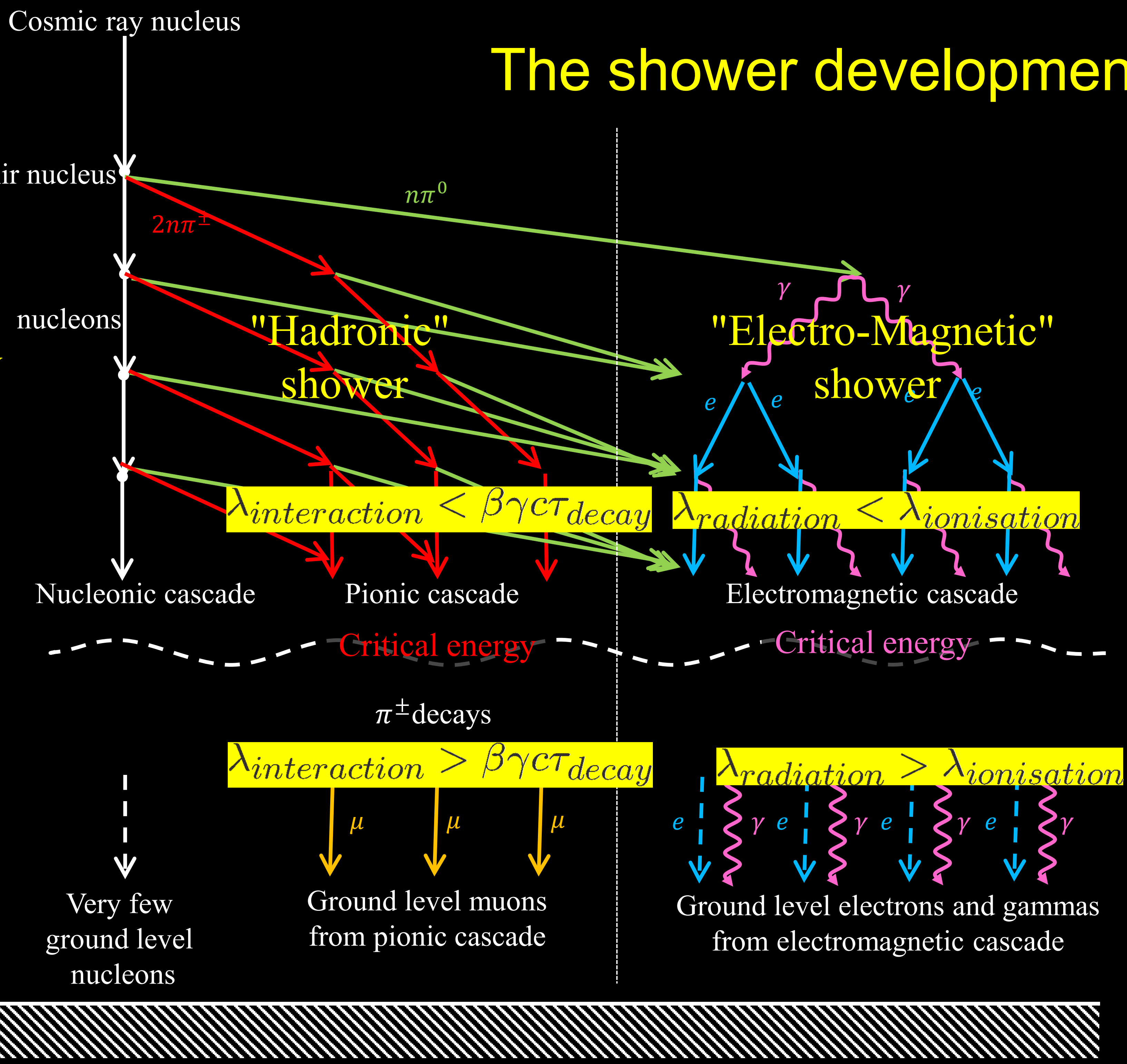
Physics well out of reach of colliders !

At each step energy is shared by more numerous particles

Maximum of development

No more multiplication, decrease by decay and energy loss

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



Cosmic ray nucleus

Air nucleus

nucleons

$n\pi^0$

$2n\pi^{\pm}$

"Hadronic" shower

"Electro-Magnetic" shower

γ γ

e e e e

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

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

Nucleonic cascade

Pionic cascade

Electromagnetic cascade

Critical energy

Critical energy

$\pi^{\pm}$decays

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

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

μ μ μ

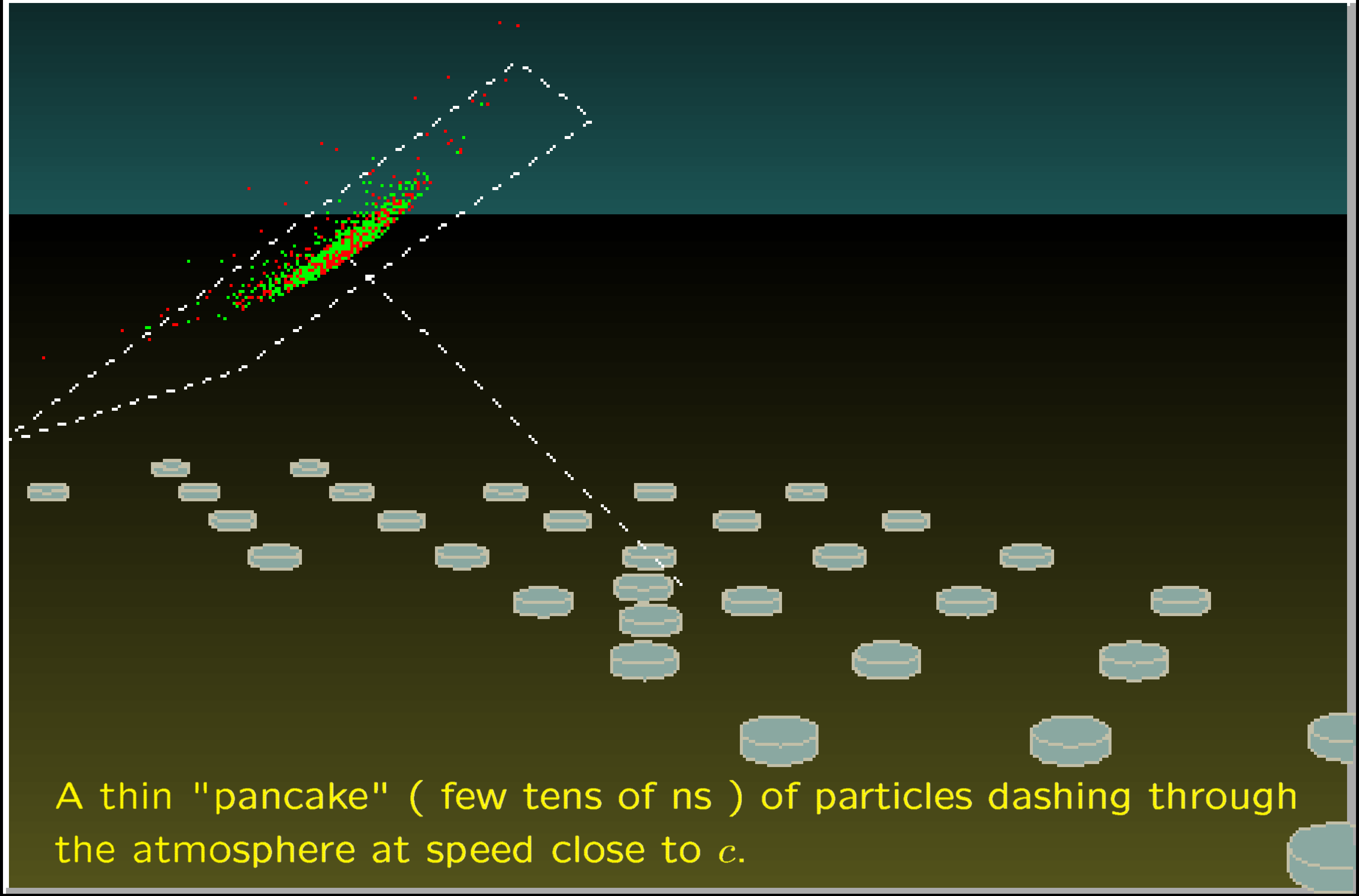
e γ e γ e γ e γ

Very few ground level nucleons

Ground level muons from pionic cascade

Ground level electrons and gammas from electromagnetic cascade

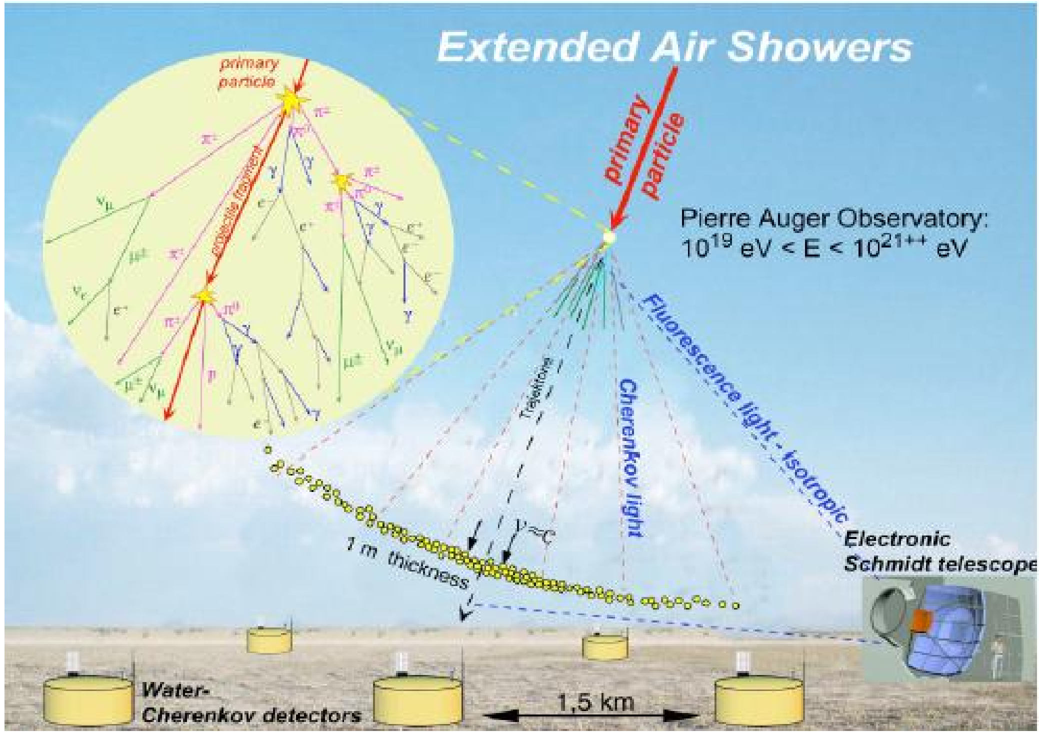
Time structure



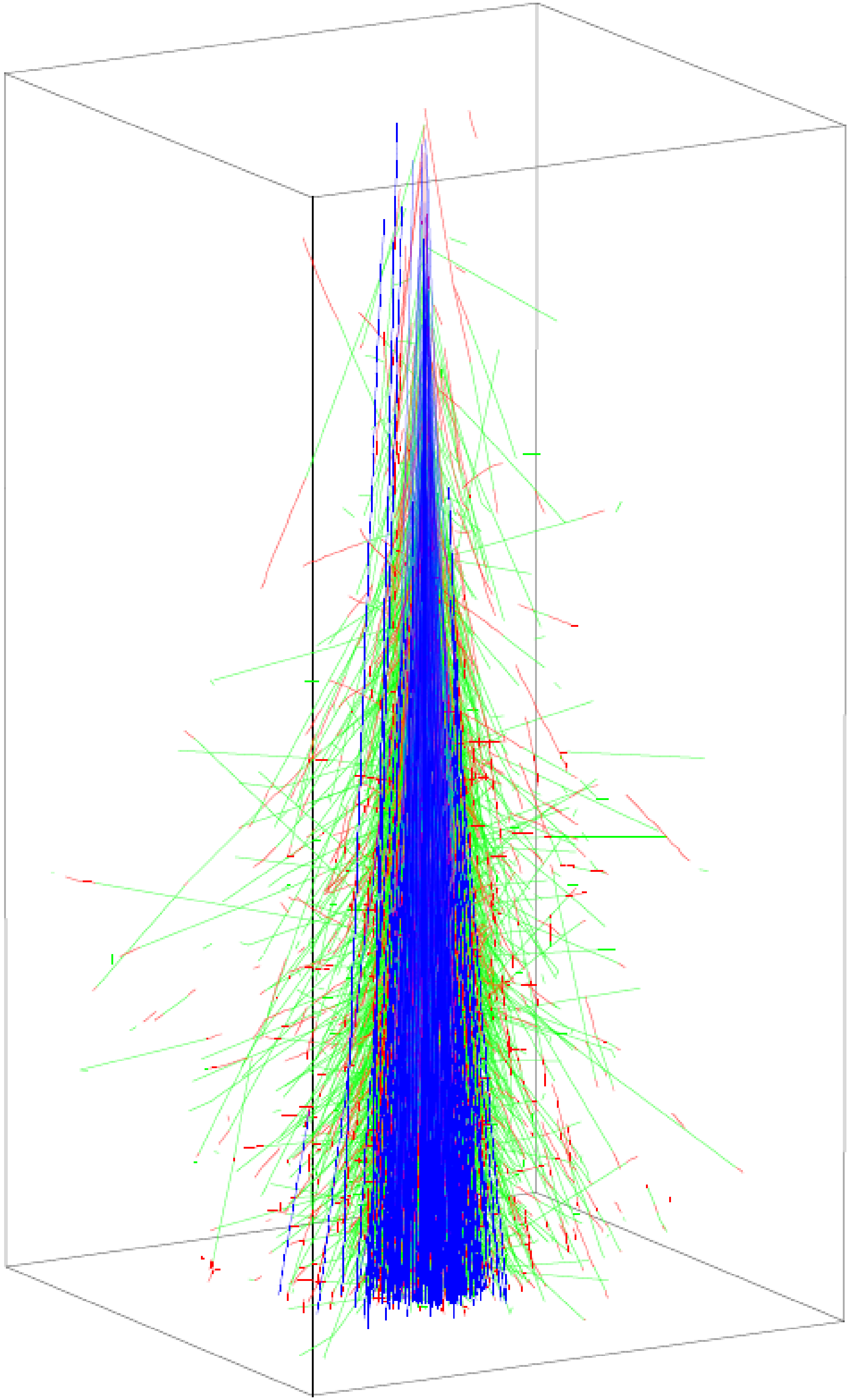
A thin "pancake" (few tens of ns) of particles dashing through the atmosphere at speed close to c.

p or nucleus + N or O nucleus → hadronic cascade

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



Primary electrons and photons induce an electromagnetic shower consisting mainly of secondary e^-, e^+ and γ (muon poor shower)



Shower development

« des giboulées d'électrons »

Rayons cosmiques
par Pierre Auger
1941 PUF

At 10^{19} eV, a shower is:

10^{11} particles
at sea level

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

Ground observables

- Secondary particles reaching ground

As a function of the primary energy and of the altitude:

  - Residual Hadrons (nuclear fragments): not numerous (>11λ_{int}).
  - $e^{\pm}$: the more numerous at shower development maximum.
  - $\mu^{\pm}$: most reach ground and may penetrate deep underground.
  - γ : may be detected at ground level via $e^{+}e^{-}$ pair conversion.

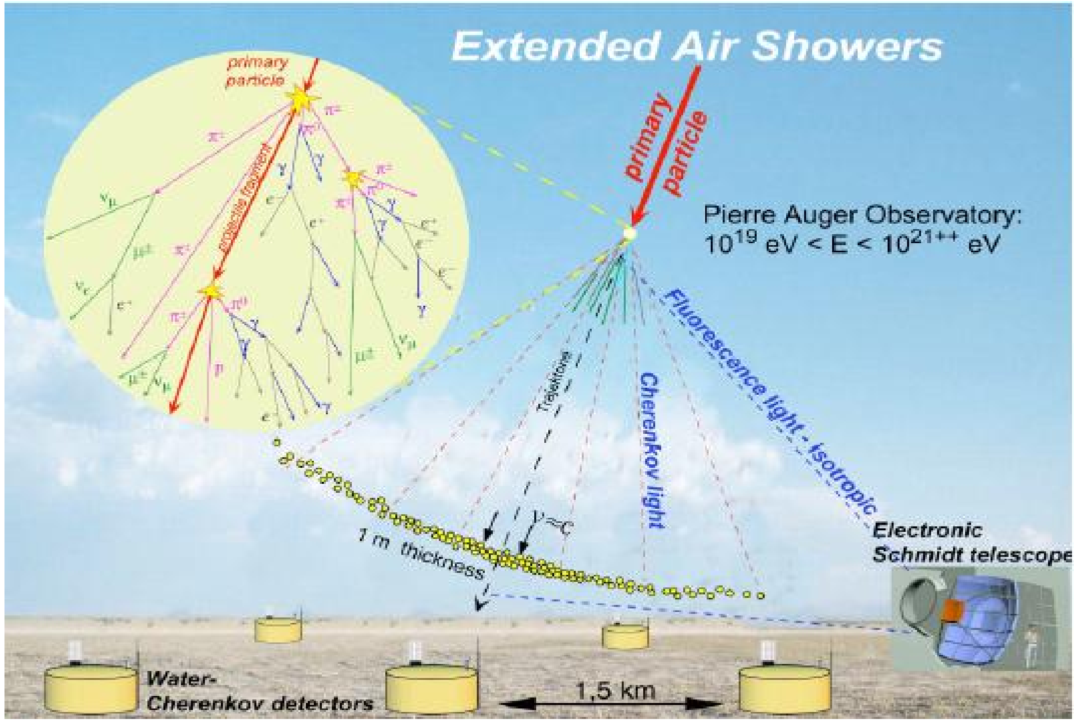
- Photons (visible, UV) emitted along the trajectories of charged particles (Cherenkov effect, N_2 fluorescence) during the shower development

→ Calorimetric 3D information !

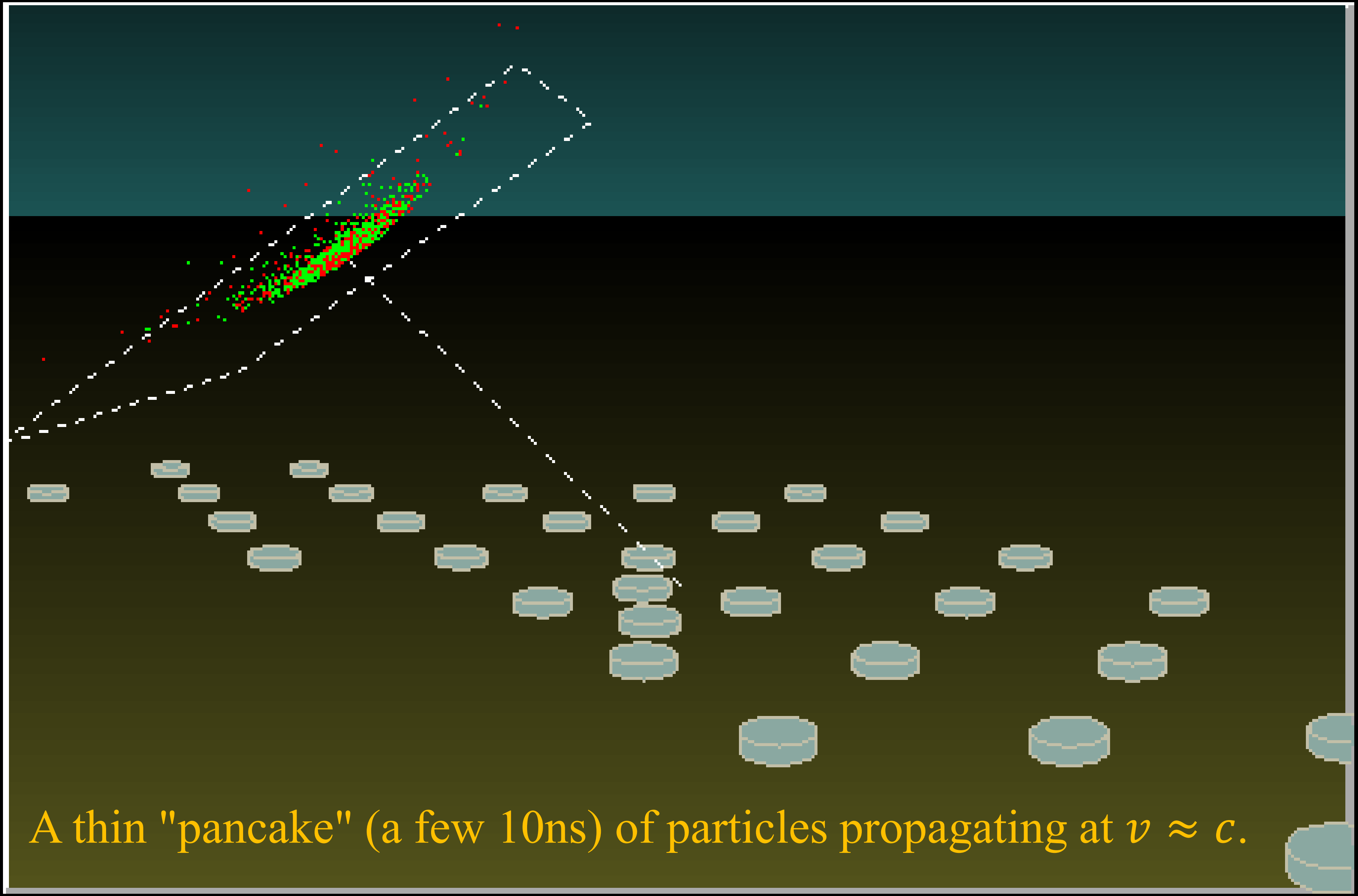
- Radio emission by the shower particles in the geomagnetic field, charge excess or by the induced plasma.

Temporal aspects

- A light speed moving "pancake" of charged particles.
- This front is more or less curved depending at which stage of the shower development the particles are produced.
- The front thickness (~ 10 m) induce as signal time spread in each detector.
- The arrival time differences at ground on the sampling detectors
  → arrival direction (Δθ ≈ 1°).
- The Cherenkov light front (forward emission) is thinner (~m) than the charged particle front
  → well defined timing.



Time structure



A thin "pancake" (a few 10ns) of particles propagating at $v \approx c$.

Models for the development of EM shower

- Let study the mean number of particles $(e^+, e^- \text{ or } \gamma)$ crossing a plan $\perp$ to the shower axis after a slant depth t (in units of X_0).

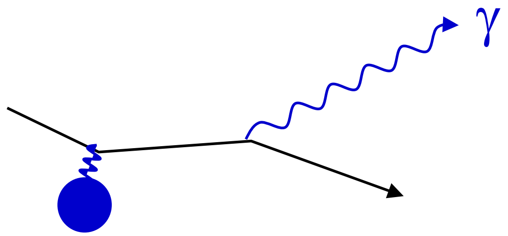
- As long as the ionization losses are small wrt radiation losses (bremsstrahlung and pair prod) the number of particle increase exponentially.

- 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).

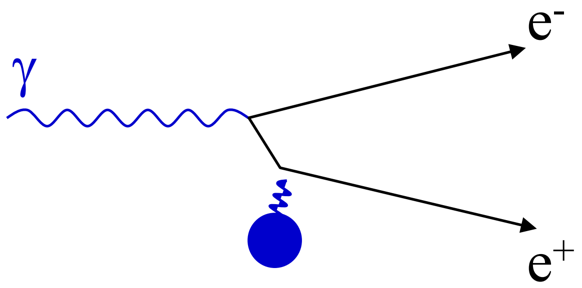
- At the transition between the two phases, (maximal development), the mean energy is equal to the critical energy.

Radiative processes (E > E_c)

Bremsstrahlung :



Pairs production :

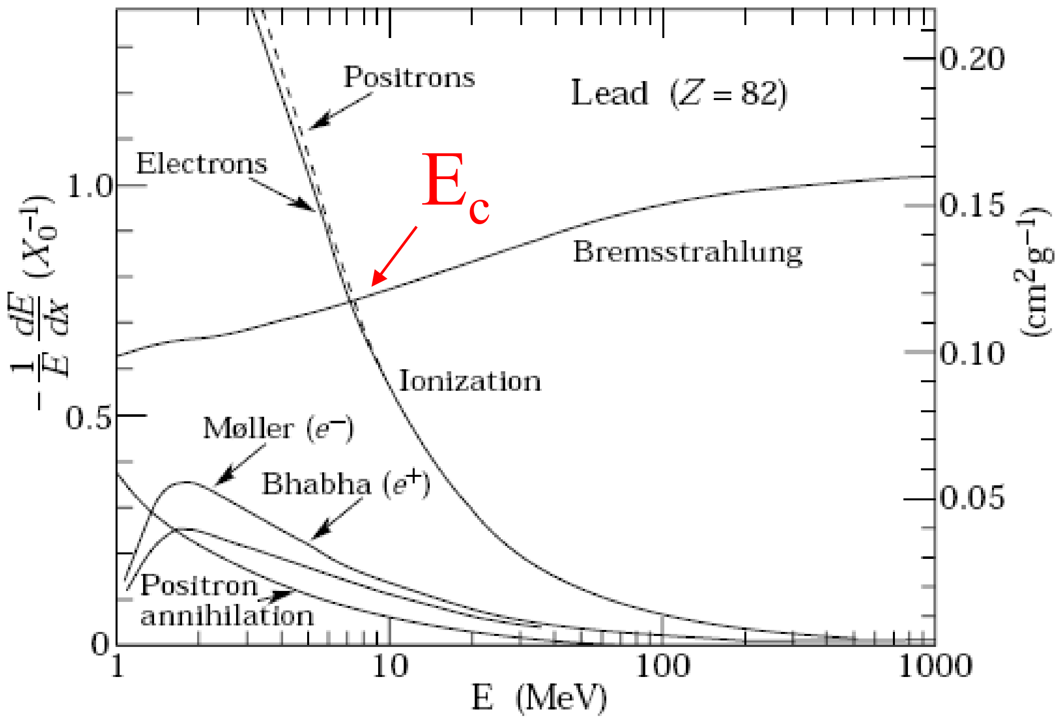


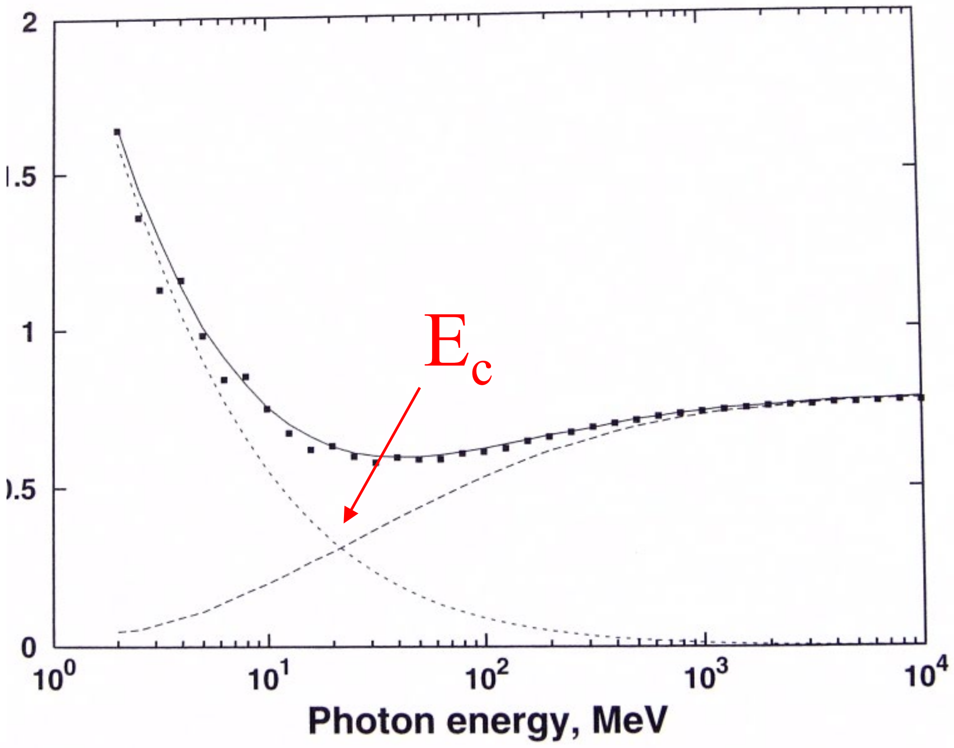
Radiation length X_0 :

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

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

EM cascades (Rossi & Greisen)

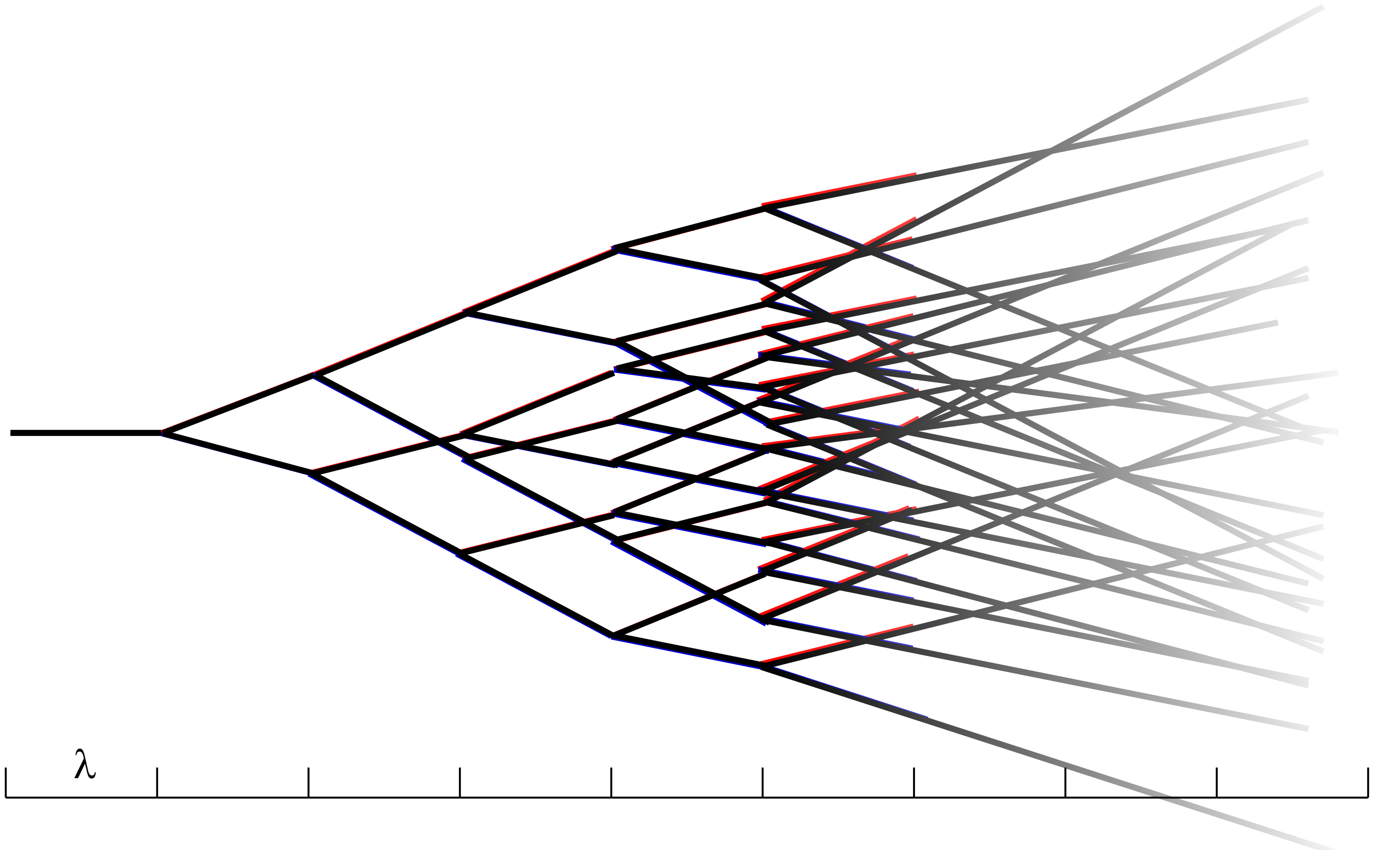




Critical energy: below this energy, ionization losses dominate.

Simplified development model (Heitler)

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



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

Heitler model of EM showers

- After t radiation length, there are 2^t particles with energy $E = E_0/2^t$ thus

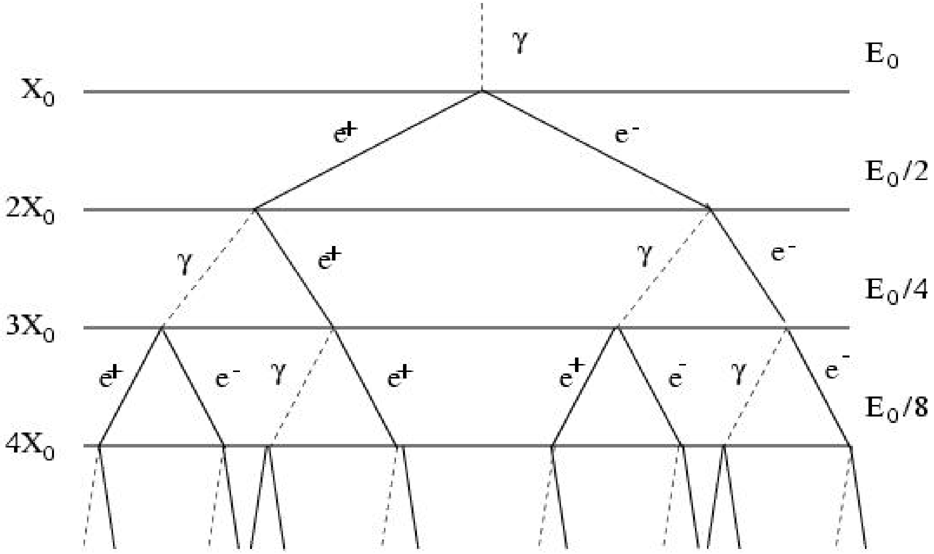
$$t \log 2 = \log\left(\frac{E_0}{E}\right)$$

- The particles of energy E are produced at thickness: $t(E) \approx \log(E_0/E)$

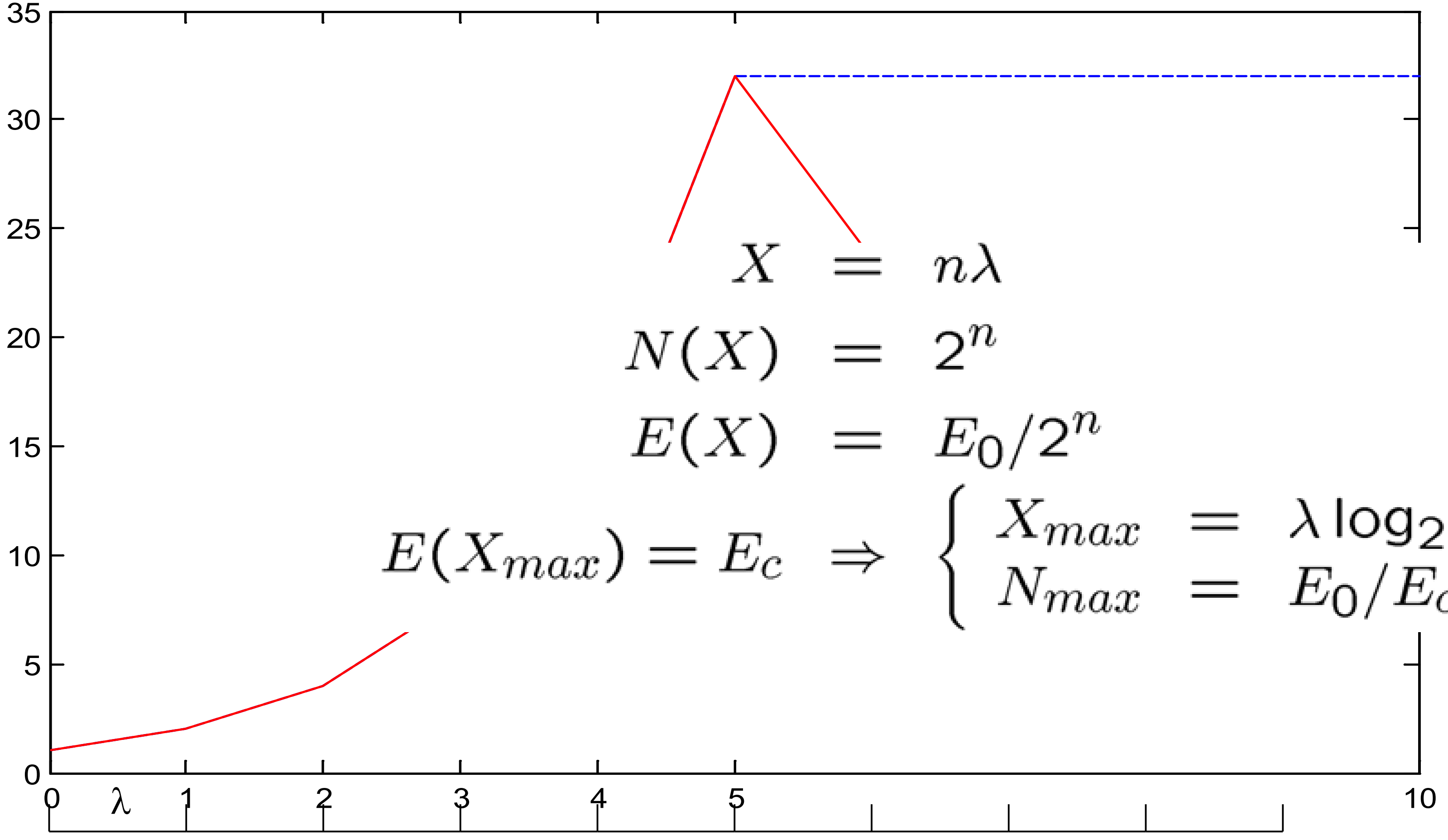
- The maximal development of the shower is reach for a thickness:

$$t_{max}(E_0) \approx \log_2\left(\frac{E_0}{E_c}\right)$$

- 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 integral-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 γ with energy $\in [W, W+dW]$, at tX_0 depth

- The simplifying factor is the absence of any energy scale.

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 γ with energy $\in [W, W+dW]$, at tX_0 depth

- Initial conditions:
  - 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:
  - $\Gamma(W,t) = f(t)/W^{s+1}$ and $\Pi(E,t) = g(t)/E^{s+1}$ (absence of energy scale)

…but they don't satisfy the initial conditions!

Approximation A (cont)

- 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 (this is called Mellin transformation, analogue to Fourier or Laplace transforms but with power law as function base).

- 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 $y = \log(E_0/E)$ following:

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

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

Taking into account ionization energy losses:

the "age" parameter

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

- One can modify the above results:

$$y = \log\left(\frac{E_0}{E_c}\right) \qquad \text{and} \qquad s = \frac{3t}{t+2y}.$$

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

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

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

- s is called the shower "age".

EM showers : some orders of magnitude

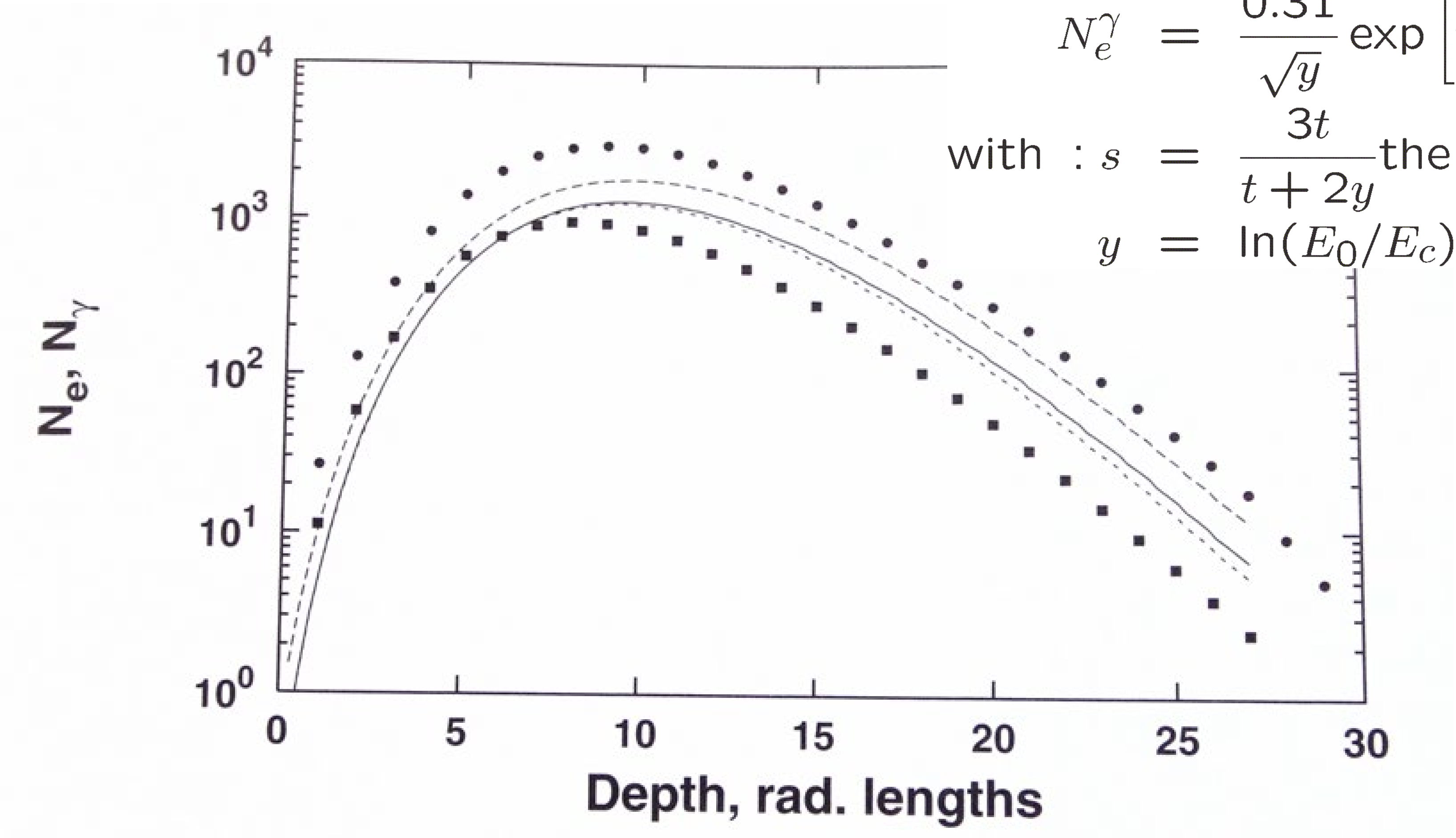
Primary γ energy E_0	Thickness traverse $t_{max}\,X_0$ (g cm^{-2})	Altitude (m)	$N_e(t_{max})$
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	$0,9 \times 10^6$
10^{19} eV	936	1200	$7,4 \times 10^9$
10^{20} eV	1021	0	$7,0 \times 10^{10}$

EM cascades (Rossi & Greisen)

$$N_e^{\gamma} = \frac{0.31}{\sqrt{y}} \exp\left[t\left(1 - \frac{3}{2}\ln s\right)\right]$$

$$\text{with } : s = \frac{3t}{t+2y} \text{ the shower age}$$

$$y = \ln(E_0/E_c)$$



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

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

- At maximal development level, the mean number of electrons is proportional to the primary energy $y = \log\left(\frac{E_0}{E_c}\right)$.

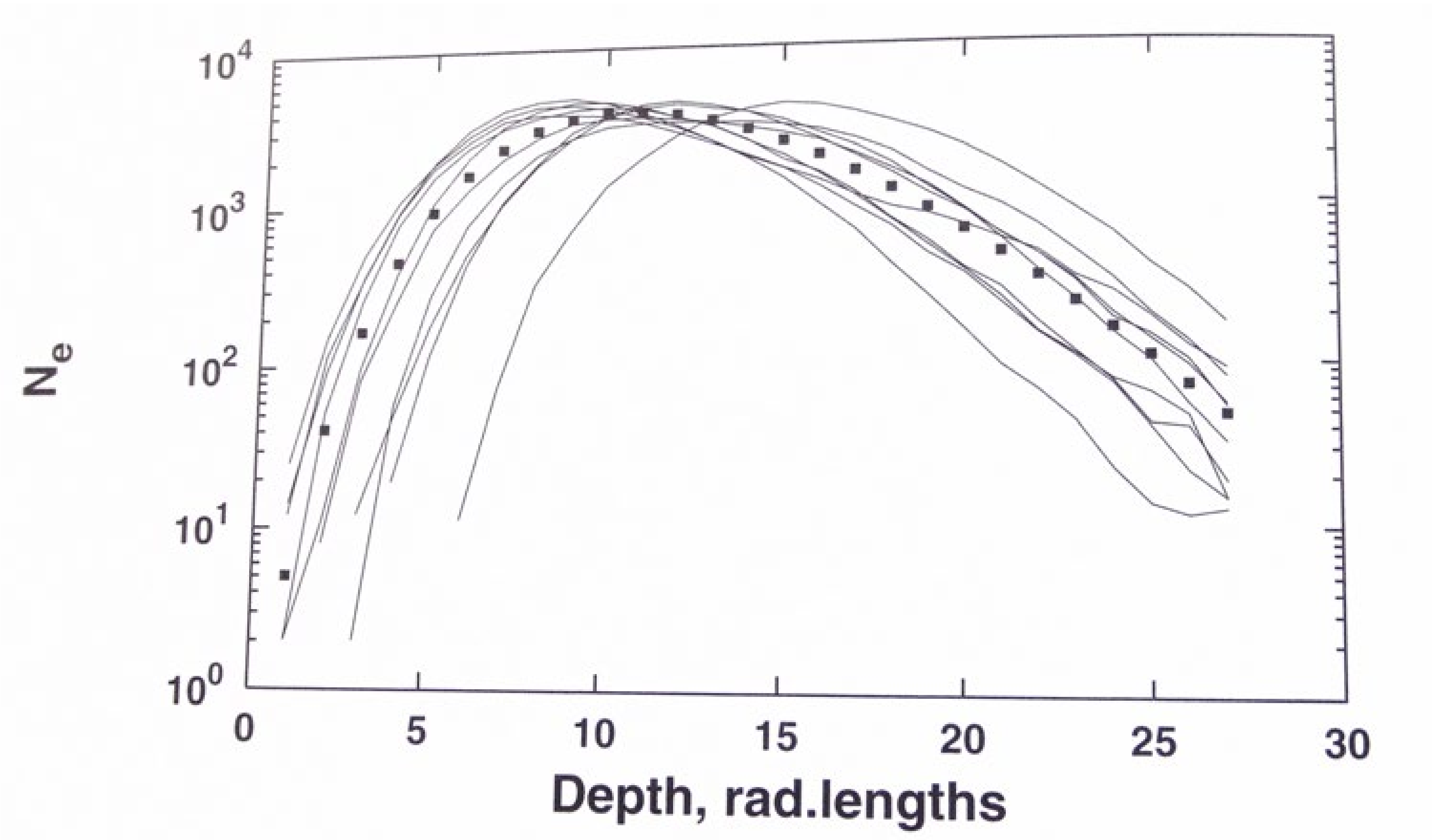
- Fluctuations on N_e:
  - Fluctuations on the depth of first interaction (exponential law)
  - Fluctuations in the shower development (approximately log-normal because of the multiplicative behavior)
  - Sampling fluctuations (depends on the type of detectors, their arrangement on the ground etc.)

- 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.

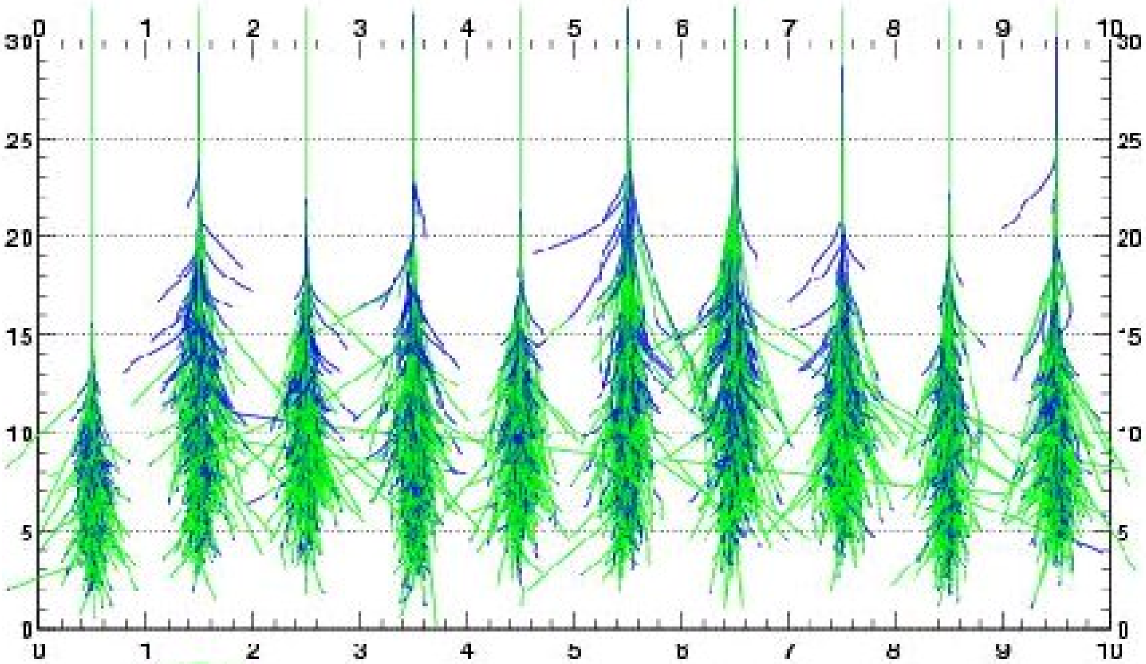
Cascades EM (Rossi & Greisen)



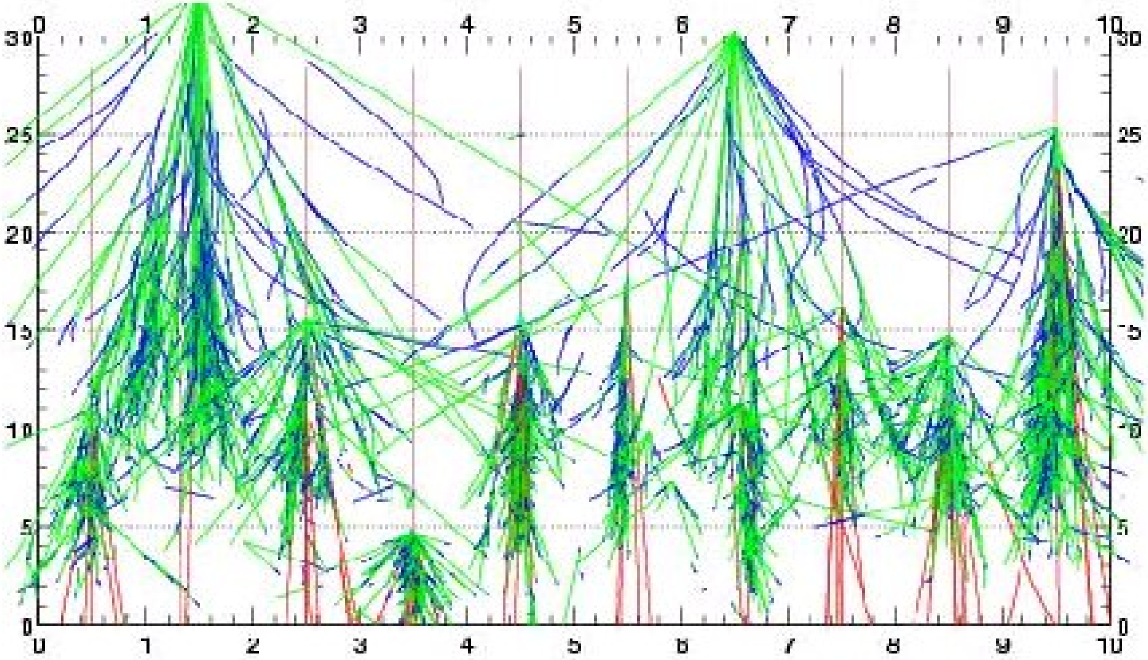
Shower to shower fluctuations
10 showers at 10^{14}eV compared to the average of 100 showers.

GAMMA-RAY (EM) INDUCED SHOWERS

10 γ
300 GeV



10 protons
300 GeV



Simulations de
M. de Naurois

γ induced shower 300 GeV

Roughly symmetric around the axis

Small transverse dispersion (multiple scattering)

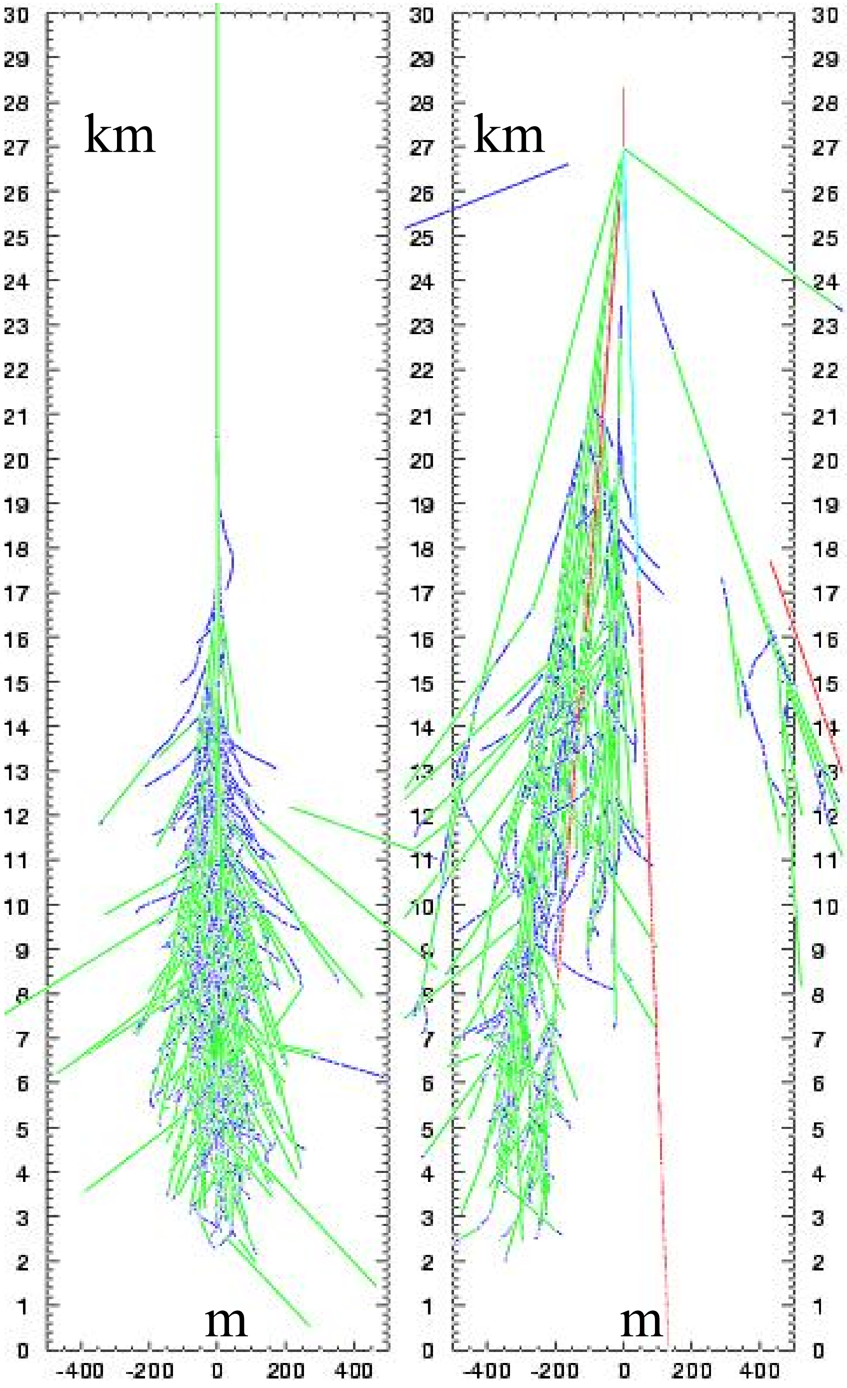
(almost) no muons

…

(unless E_0>1 PeV)

Essentially

e+ e- and γ 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

- Shower's charged particles emit light:
  - Cherenkov light : very collimated along the shower axis (Cherenkov angle at 1 Atm. ≈ 1°) threshold depending on the altitude : at ground 22 MeV for $e^{\pm}$ et 4.5 GeV for $\mu^{\pm}$

    (20 photons/m at $\beta \approx 1$ and 1 atm)

    Essentially used for gamma-ray astronomy
  - Nitrogen fluorescence: isotropic emission

    (≈ 4 photons per electron per m)

    Essentially used at UHE ≥ 10^{18}eV.
- This light detected by ground telescopes provides 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 (≈ 10% duty cycle).

Lecture on Imaging & Cherenkov Detectors

HADRONIC SHOWERS MODELS AND DETECTION

The shower development

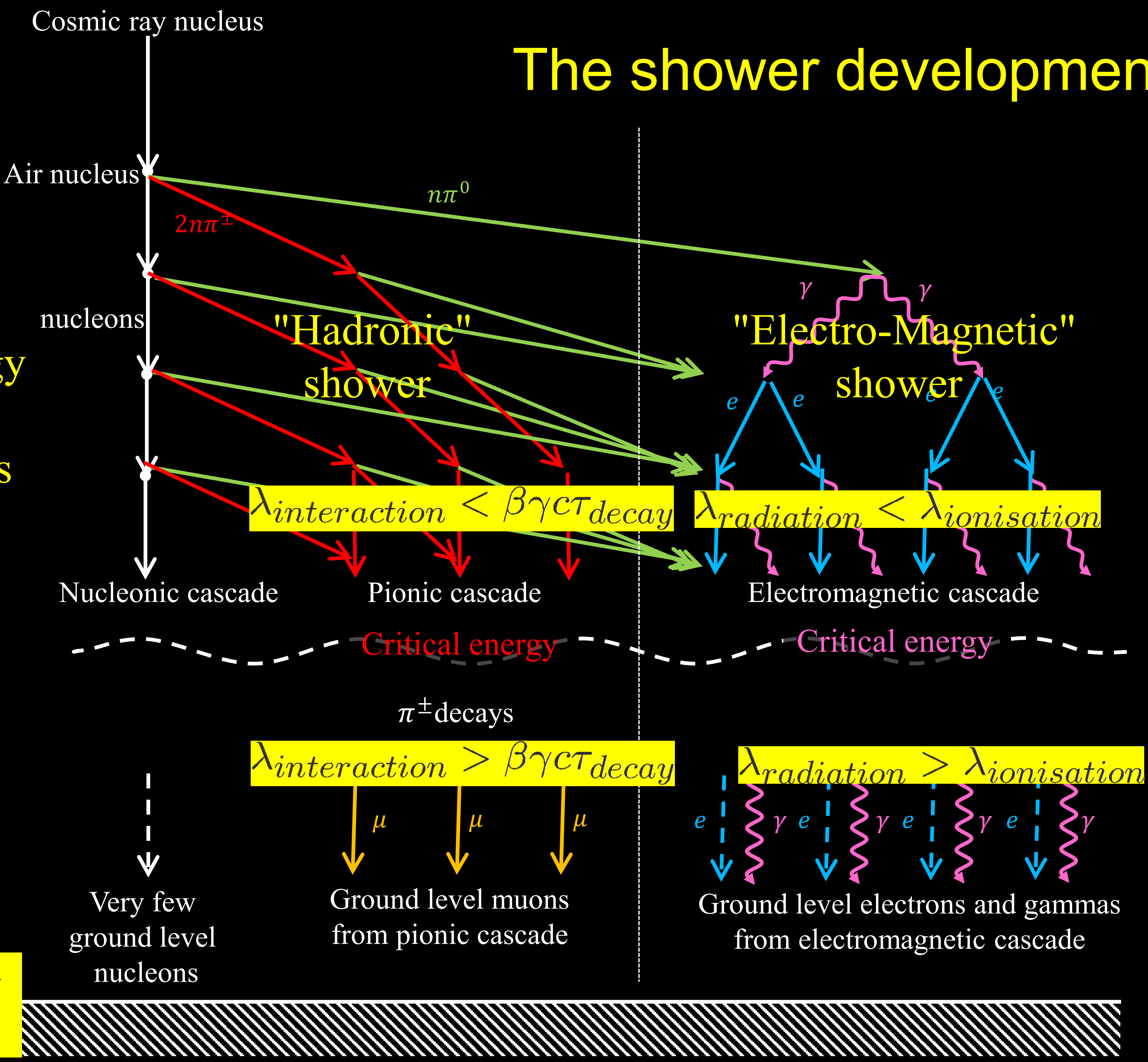
Physics well out of reach of colliders !

At each step energy is shared by more numerous particles

Maximum of development

No more multiplication, decrease by decay and energy loss

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



Cosmic ray nucleus

Air nucleus

nucleons

$n\pi^0$

$2n\pi^{\pm}$

"Hadronic" shower

"Electro-Magnetic" shower

γ γ

e e e e

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

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

Nucleonic cascade

Pionic cascade

Electromagnetic cascade

Critical energy

Critical energy

$\pi^{\pm}$decays

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

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

μ μ μ

e γ e γ e γ e γ

Very few ground level nucleons

Ground level muons from pionic cascade

Ground level electrons and gammas from electromagnetic cascade

"Hadronic" showers (protons or nuclei primaries)

- 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 π^0 decay to $\gamma\gamma$).
  - 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 fixed target experiment (even worse at colliders).

Still, the main behavior observed on EM showers remains valid.

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 a 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)*

Gaisser longitudinal Parametrization

Gaiser Hillas formulae:

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

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

Averaging on X_1 depth of 1^{st} 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 : $\approx 36.7 \mathrm{g/cm^2}$

Cricital energy : $\epsilon_0 \approx 74 \mathrm{GeV}$

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

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

Longitudinal development

Xmax and energy :

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

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

Nuclei :

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

Thus :

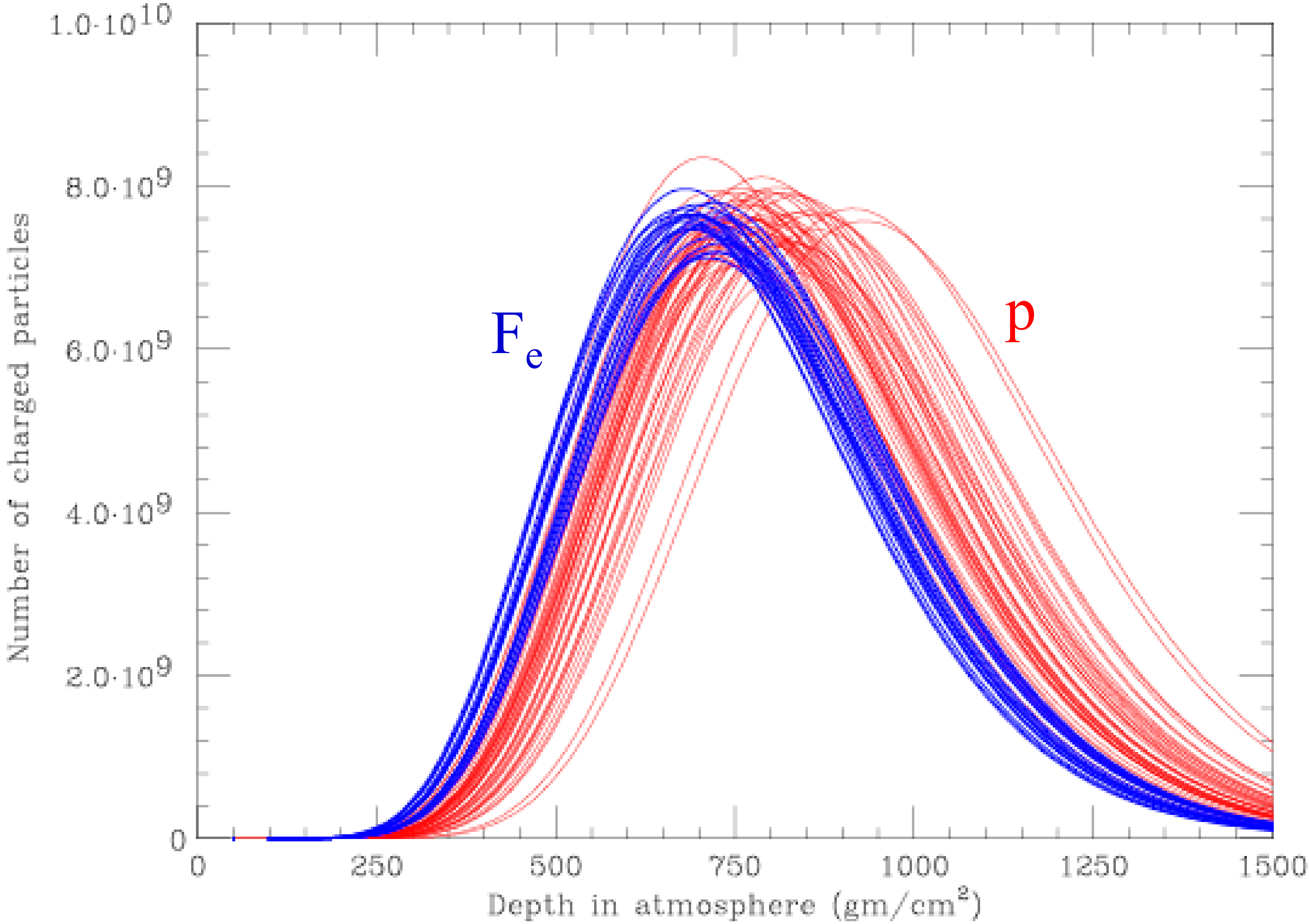
$$\begin{aligned} X_A^{max} &= X_0 \log\left(\frac{E_0}{A\epsilon_0}\right) \\ &= X_p^{max} - X_0 \log(A) \end{aligned}$$

For example iron/proton $A = 56$:

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

Structure in space

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

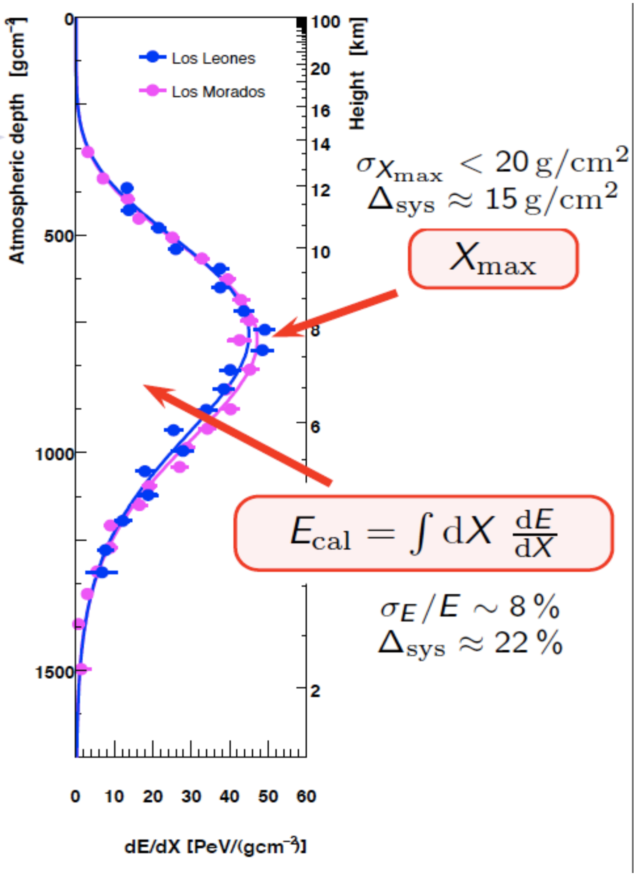


From EAS longitudinal profile to primary CR mass composition

Average depth of shower maximum $\langle X_{max} \rangle$;

Width of distribution RMS(X_{max}) at a certain E

sensitive to <u>primary composition</u>

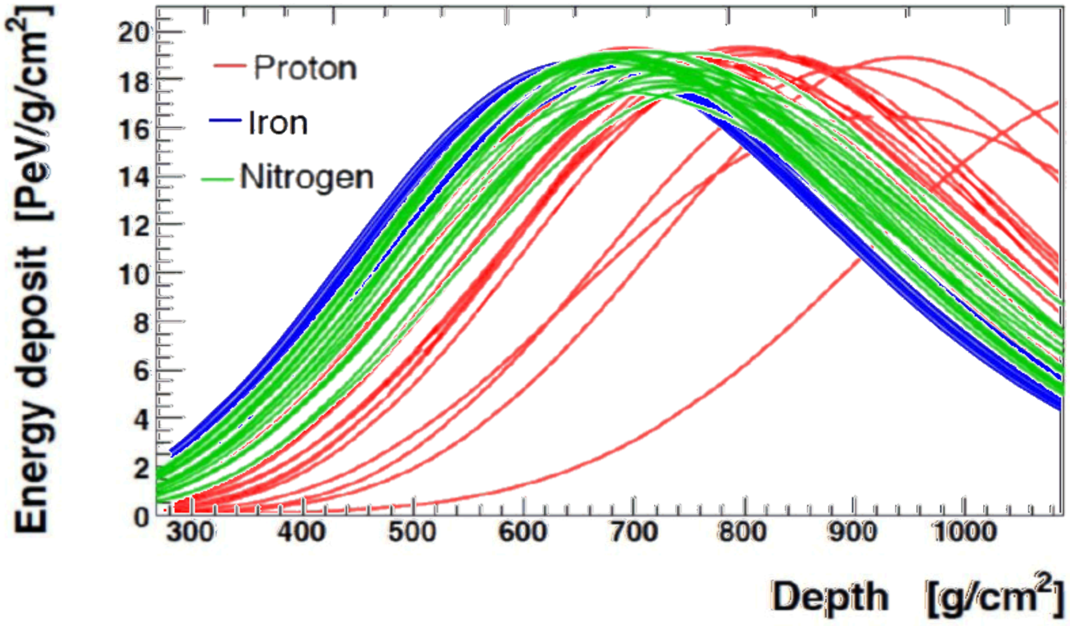


$\sigma_{X_{\rm max}} < 20\,{\rm g/cm^2}$
$\Delta_{\rm sys} \approx 15\,{\rm g/cm^2}$

$X_{\rm max}$

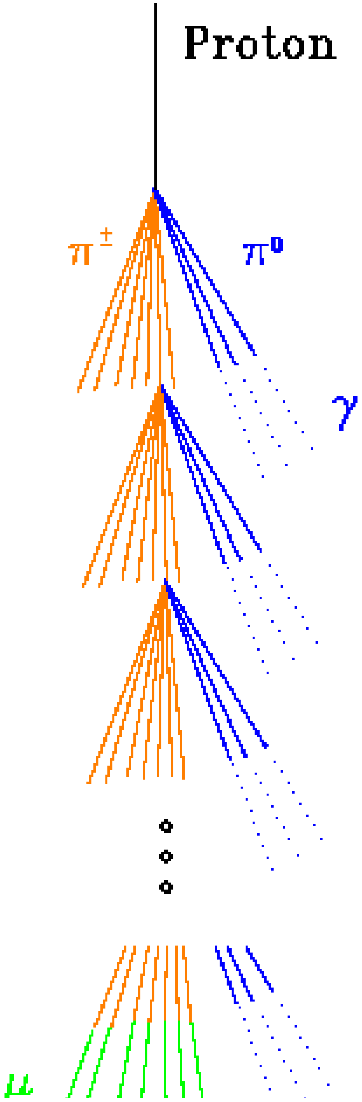
$E_{\rm cal} = \int {\rm d}X\, \frac{{\rm d}E}{{\rm d}X}$

$\sigma_E/E \sim 8\,\%$
$\Delta_{\rm sys} \approx 22\,\%$



$$X_{max} \propto \log(E_0) \boxed{- \log(A)}\ (\text{MC Sim.})$$

A simplified development model



Energy per pion	$N_{\pi^{\pm}}$
$E_0/10$	$\frac{2}{3}10$
$E_0/100$	$(\frac{2}{3}10)^2$
$E_0/1000$	$(\frac{2}{3}10)^3$
⋮	⋮
$E_c = E_0/10^{n_c}$	$(\frac{2}{3}10)^{n_c}$

⇒ tutorials

A simplified development model

The size (number of electrons at max) is proportional to the primary energy:

$$N_e^{max} \approx S_0 E_0/\epsilon_0 = E_0/(1.7\mathrm{GeV})$$

The depth of max is proportional to the log of the energy:

$$X_{max} \approx X_0 \log(E_0/\epsilon_0) \Rightarrow 80\mathrm{g/cm^2\ per\ decade}$$

Showers from heavier nuclei produce more muons than lighter ones.

$$N_\mu^{Fe} \approx 2 \times N_\mu^p(E)$$

Shower from heavier nuclei start higher up and reach max higher up too.

$$X_{max}^{Fe} < X_{max}^p$$

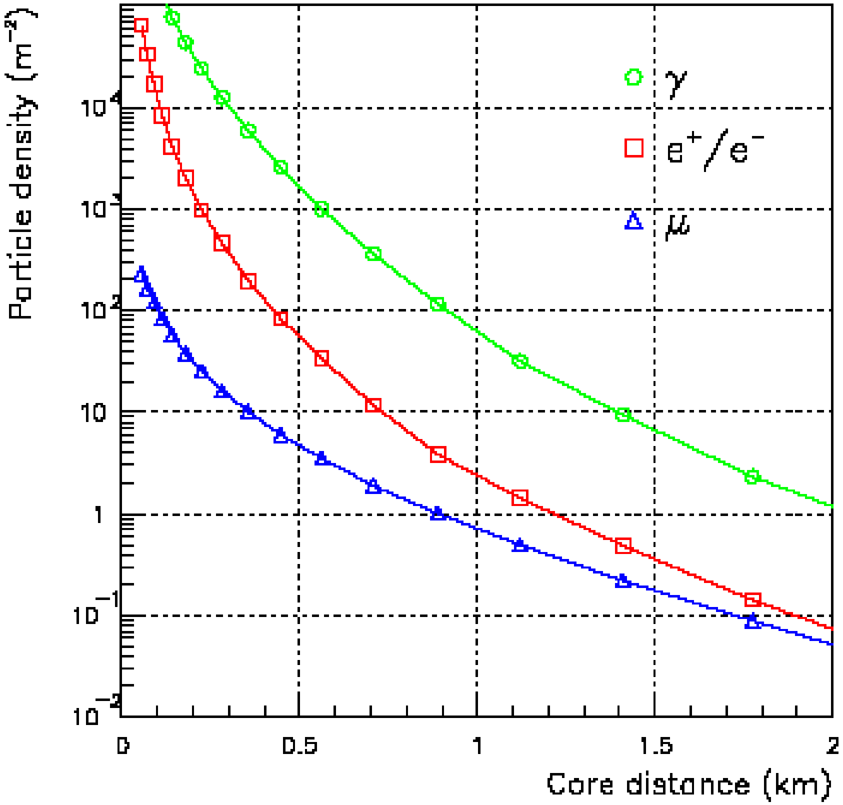
Lateral evolution

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 the detectors used where η depends on the incident angle of the shower and the primary energy.

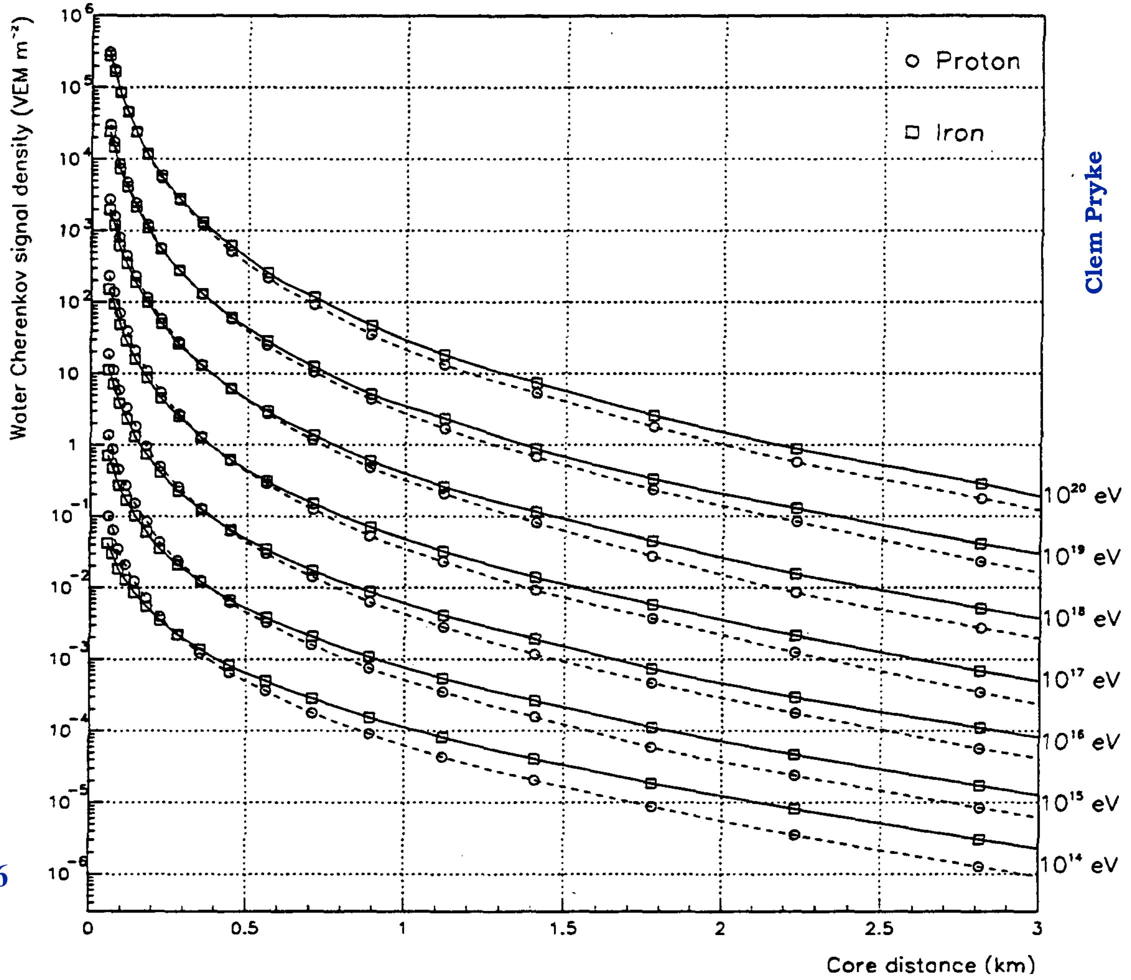
For $r > 800$m this (empirical) expression must be modify as $(r/800)^{1.03}$



Shower Density Lateral Distribution
(simulation)

Detector Signal Density

(equiv.muons/m^2)



1

10^{-6}

Clem Pryke

10^{20} eV

10^{15} eV

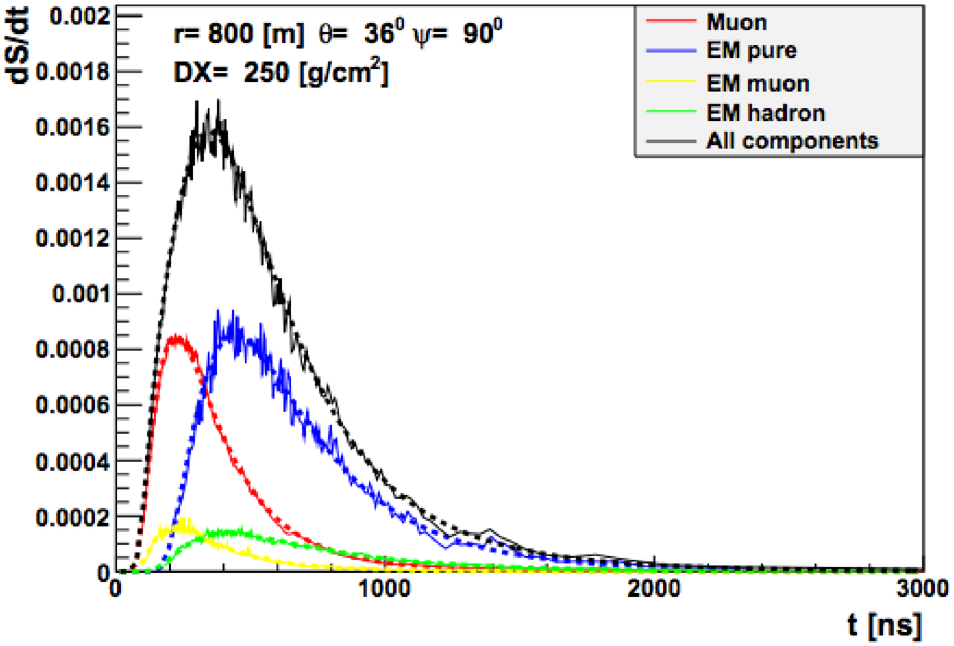
3km

Core Distance (km)

Shower universality

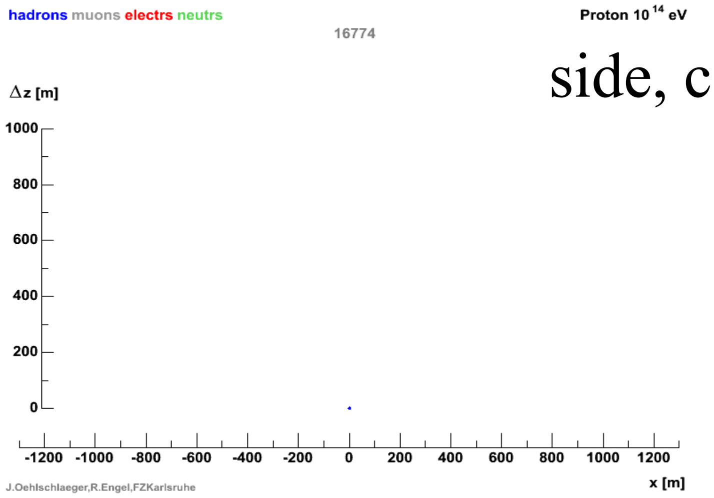
- Owing to the extremely large number interactions involved in the EM component of the showers, its development can be described in a universal way from only a few macroscopic parameters (similarly to a black body spectrum that can be described knowing the temperature only).

- The hadronic/muonic part of the shower is a priori not as universal but simulation studies for energies above $E > 10^{17.5}\ \mathrm{eV}$ show that a universal description of the shower profiles (longitudinal, lateral and timewise) can be achieved knowing only a reduced set of macroscopic variables E, X_{max}, N_{μ}

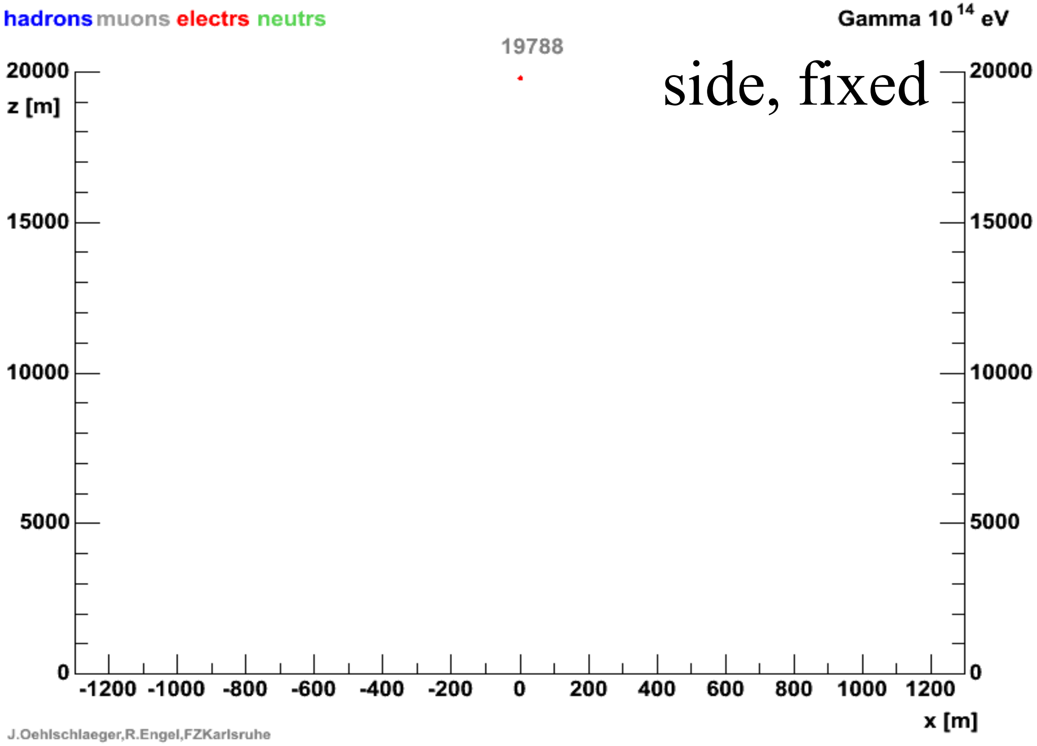


List of CORSIKA shower movies

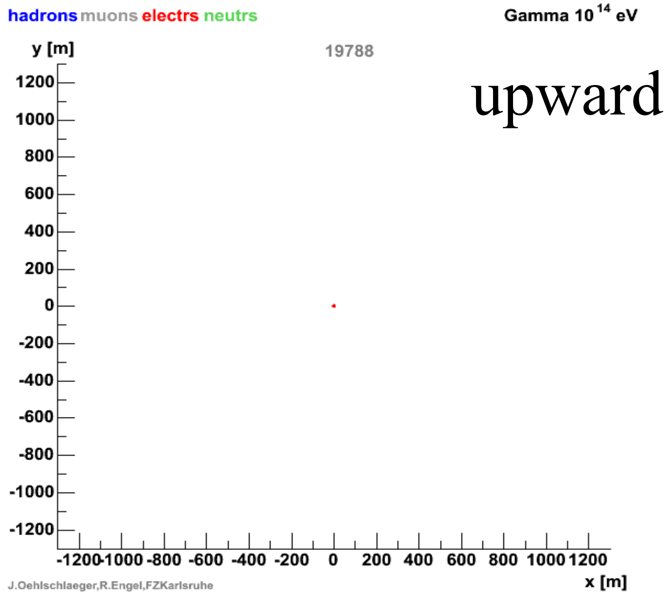
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sanga14zx13.gif sanga14xz13.gif sanga14yx13.gif	gamma 100 TeV, vertical	side, co-moving side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed



side, co-moving



side, fixed

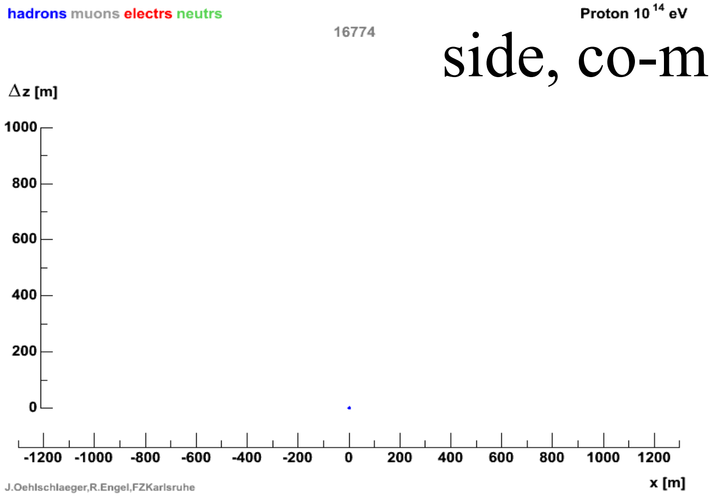


upwards, co-moving

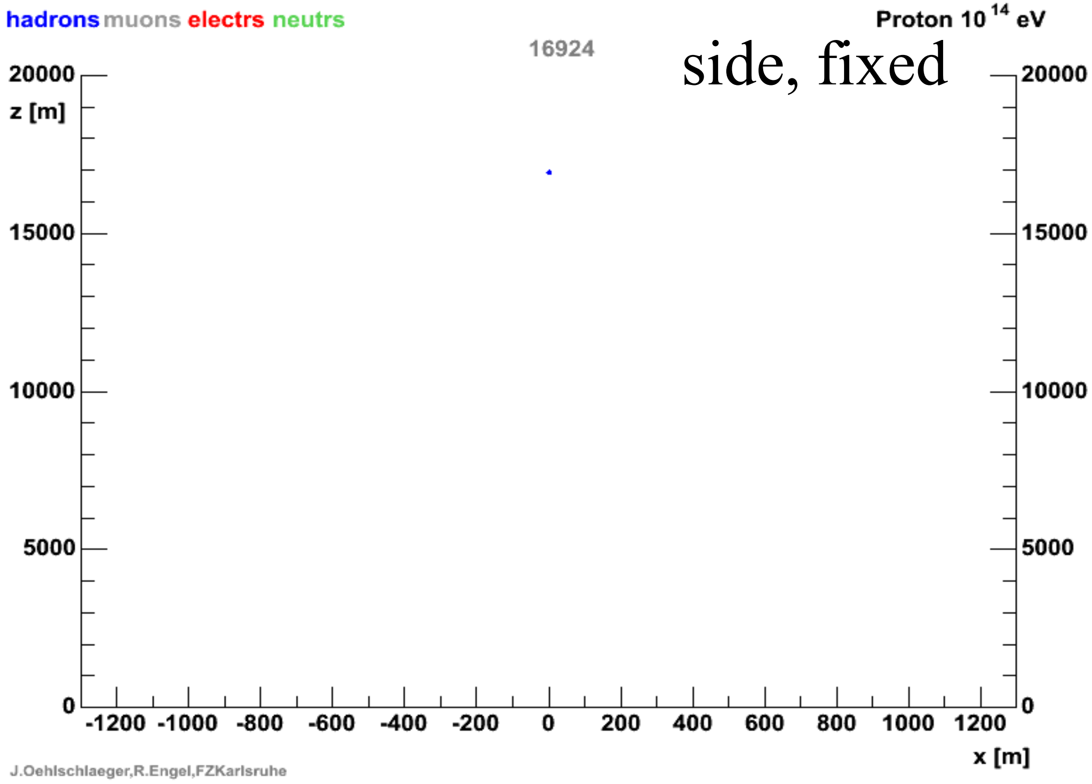
gamma, 100 TeV, vertical

List of CORSIKA shower movies

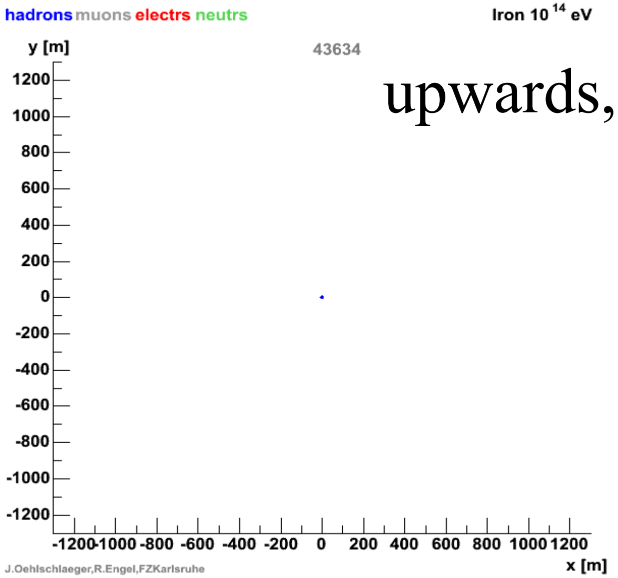
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sanpr14zx13.gif sanpr14xz13.gif sanpr14yx13.gif	proton 100 TeV, vertical	side, co-moving side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed



side, co-moving



side, fixed

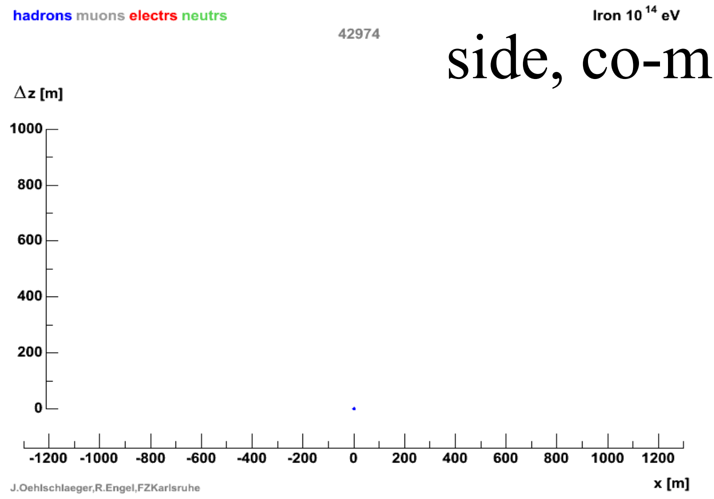


upwards, co-moving

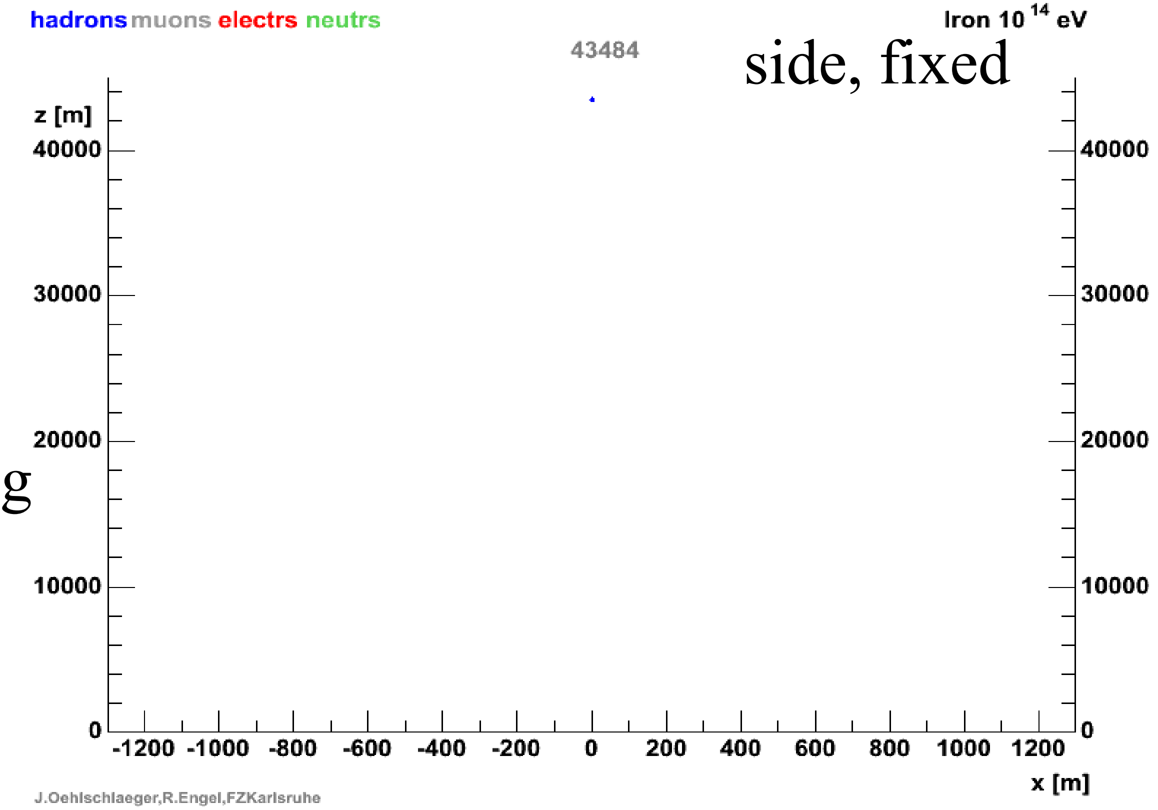
Proton, 100 TeV, vertical

List of CORSIKA shower movies

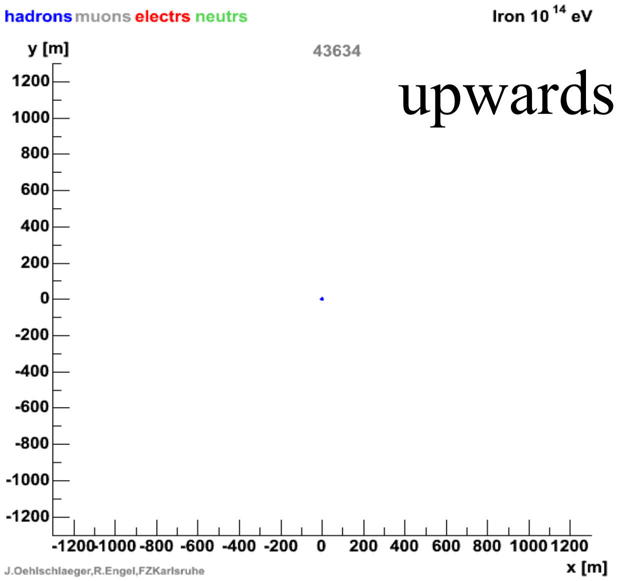
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sanfe14zx13.gif sanfe14xz13.gif sanfe14yx13.gif	iron 100 TeV, vertical	side, co-moving side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed



side, co-moving



side, fixed

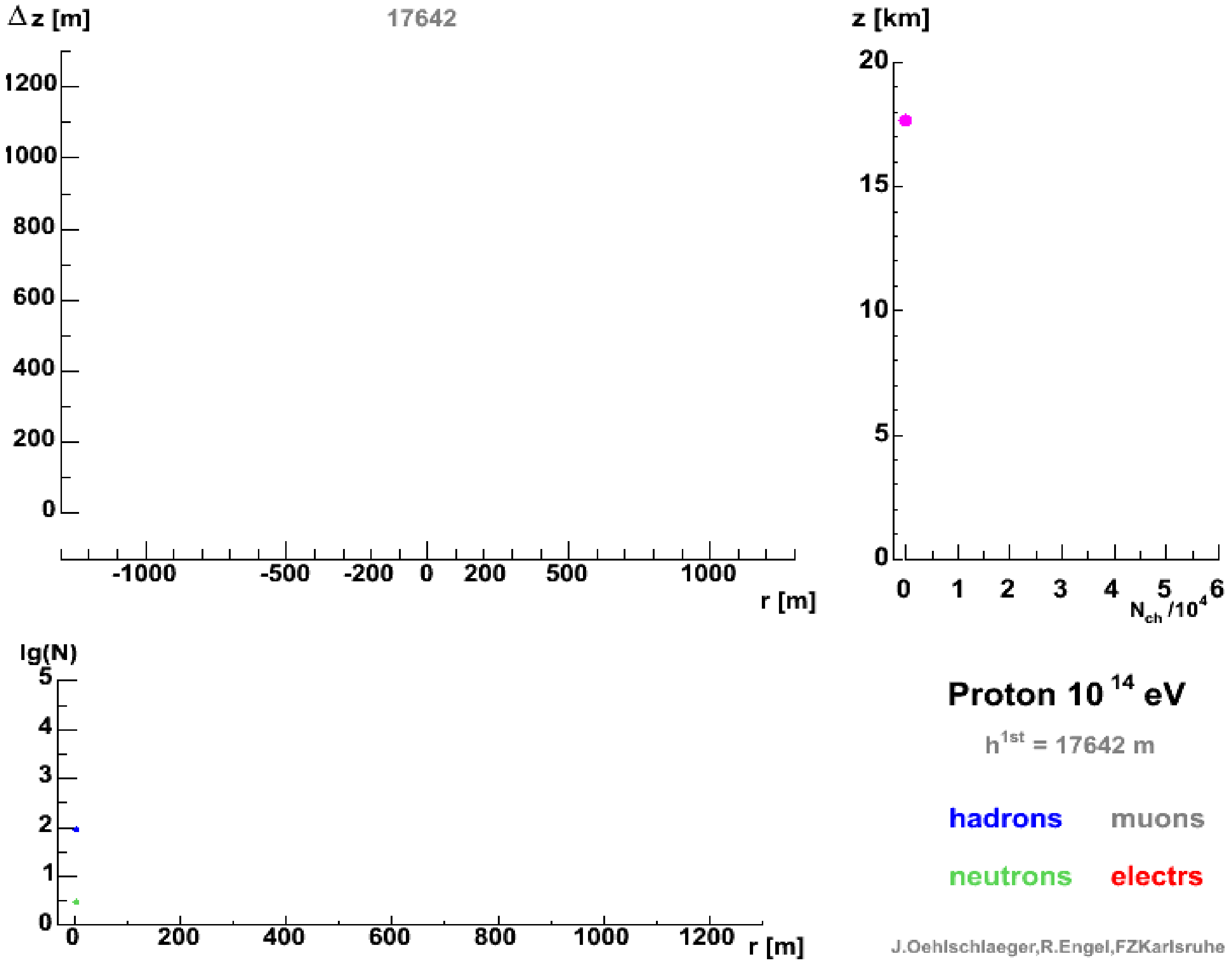


upwards, co-moving

Iron, 100 TeV, vertical

List of CORSIKA shower movies

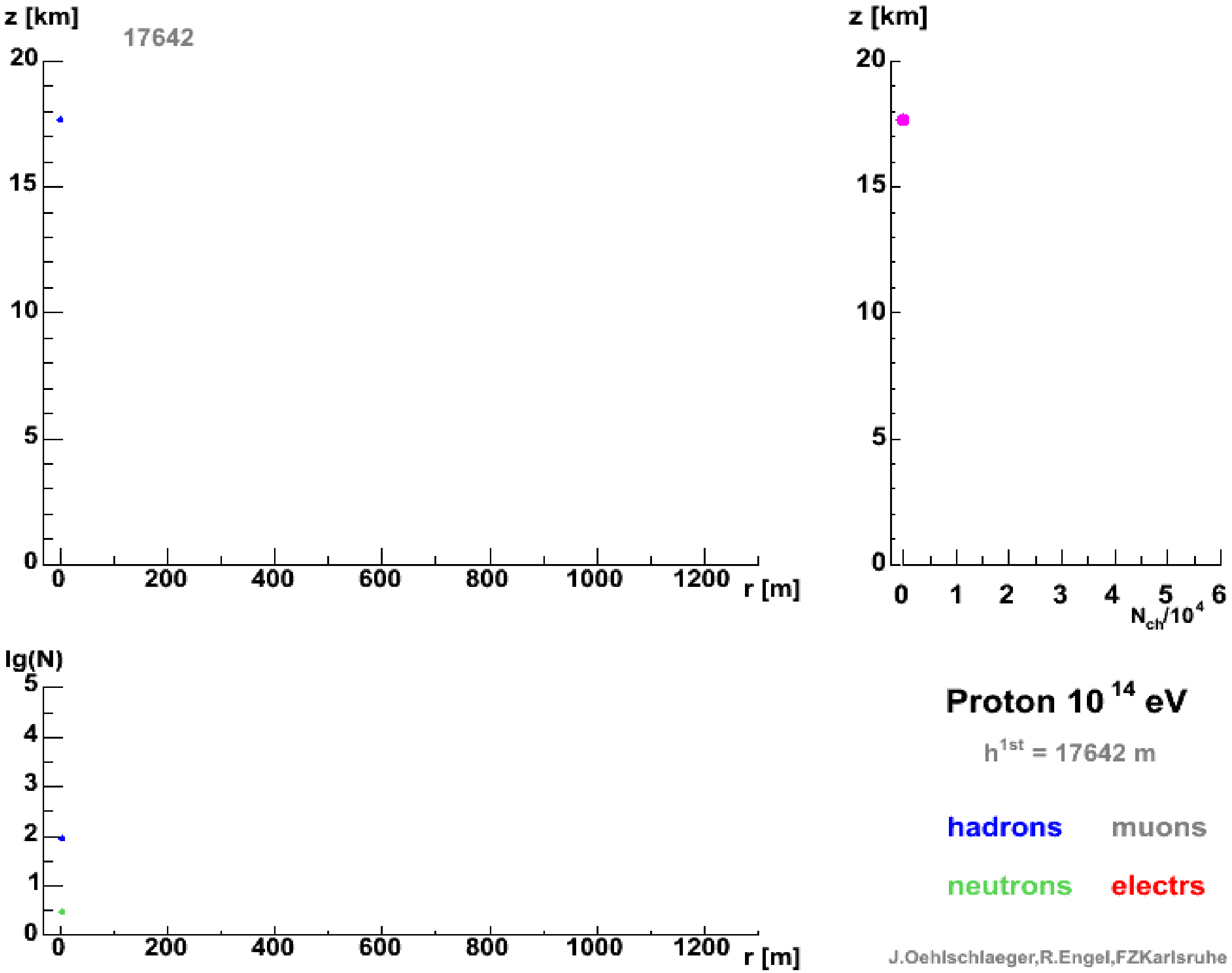
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif nchargedrz03.gif nchargedxz03.gif nchargedyx03.gif	proton 100 TeV, vertical	side, co-moving side, fixed side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution



Proton, 100 TeV, vertical

List of CORSIKA shower movies

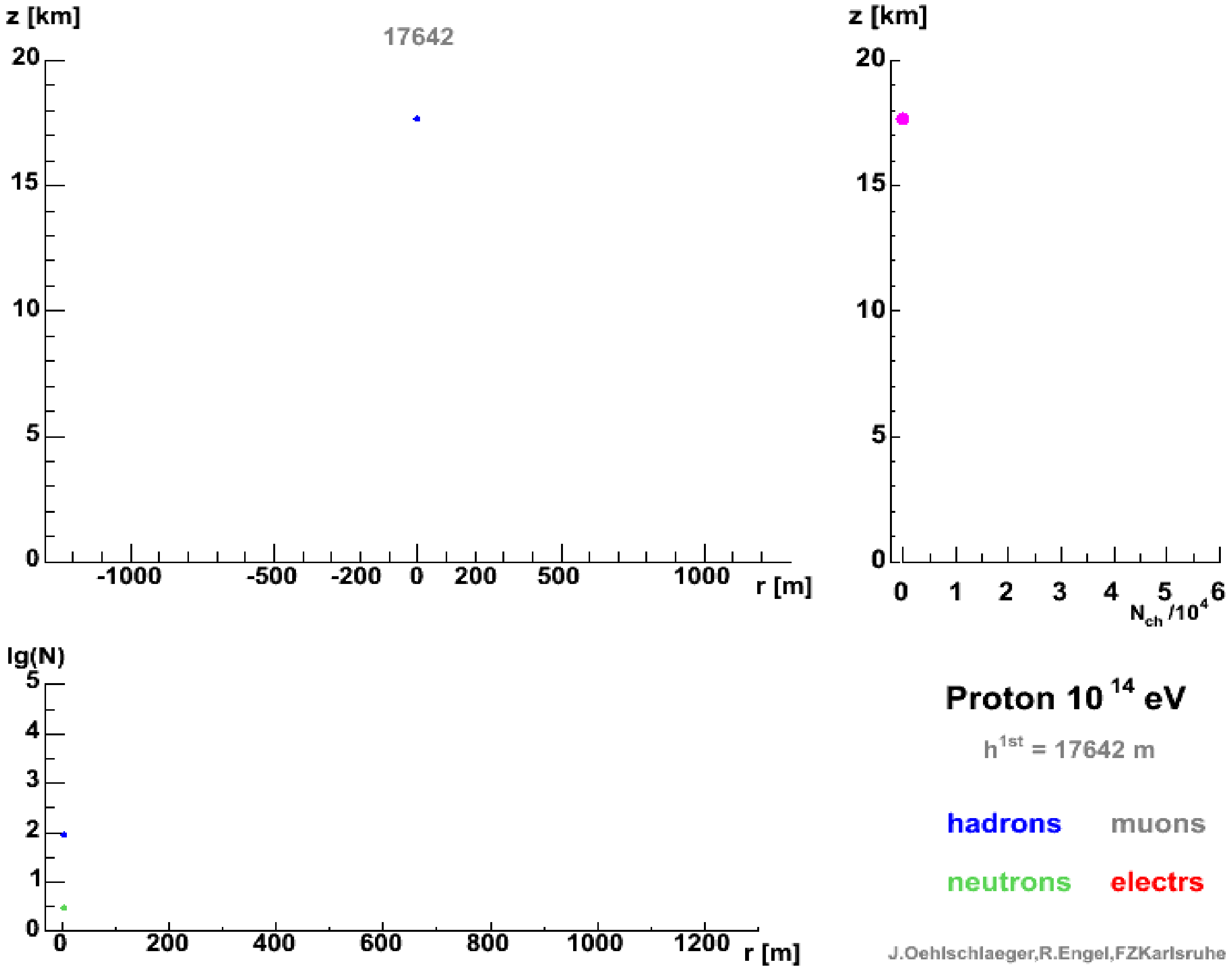
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif	proton 100 TeV, vertical	side, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution
nchargedrz03.gif		side, fixed		
nchargedxz03.gif		side, fixed		
nchargedyx03.gif		upwards, co-moving		



Proton, 100 TeV, vertical

List of CORSIKA shower movies

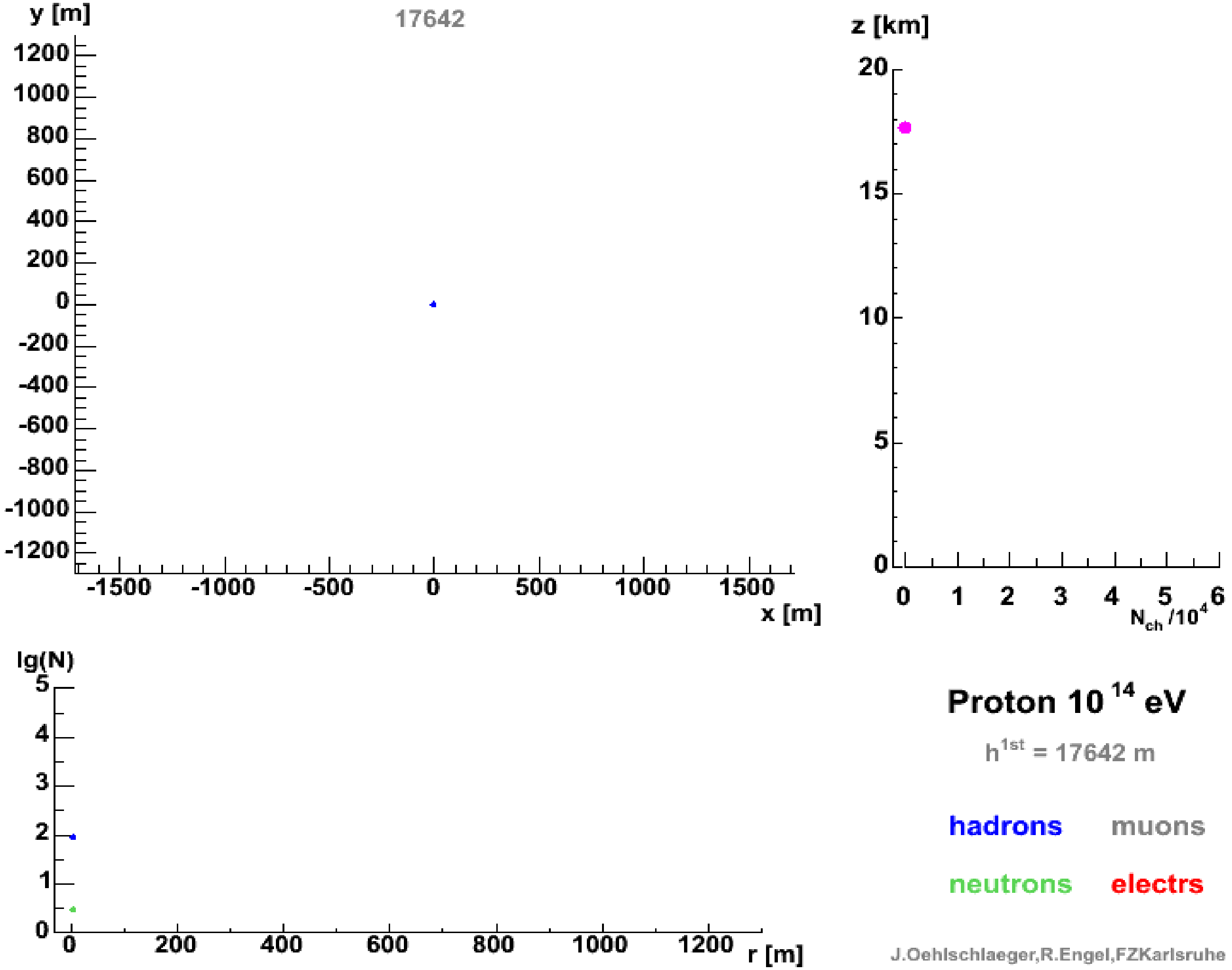
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif nchargedrz03.gif nchargedxz03.gif nchargedyx03.gif	proton 100 TeV, vertical	side, co-moving side, fixed side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution



Proton,
100 TeV,
vertical

List of CORSIKA shower movies

Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif nchargedrz03.gif nchargedxz03.gif nchargedyx03.gif	proton 100 TeV, vertical	side, co-moving side, fixed side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution



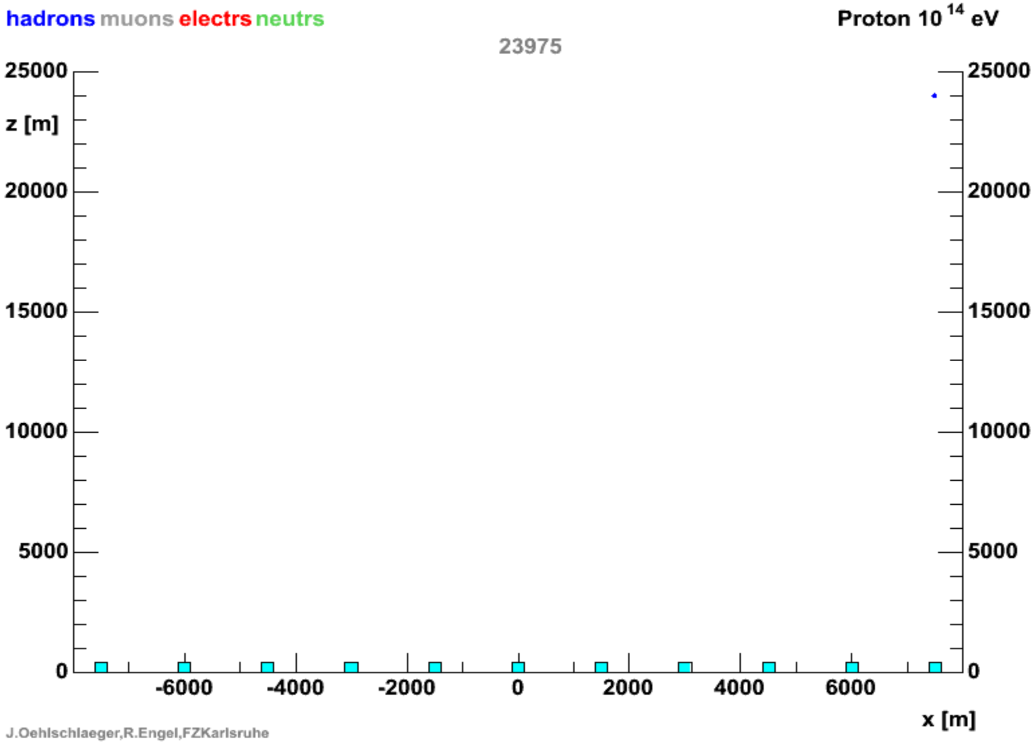
Proton, 100 TeV, vertical

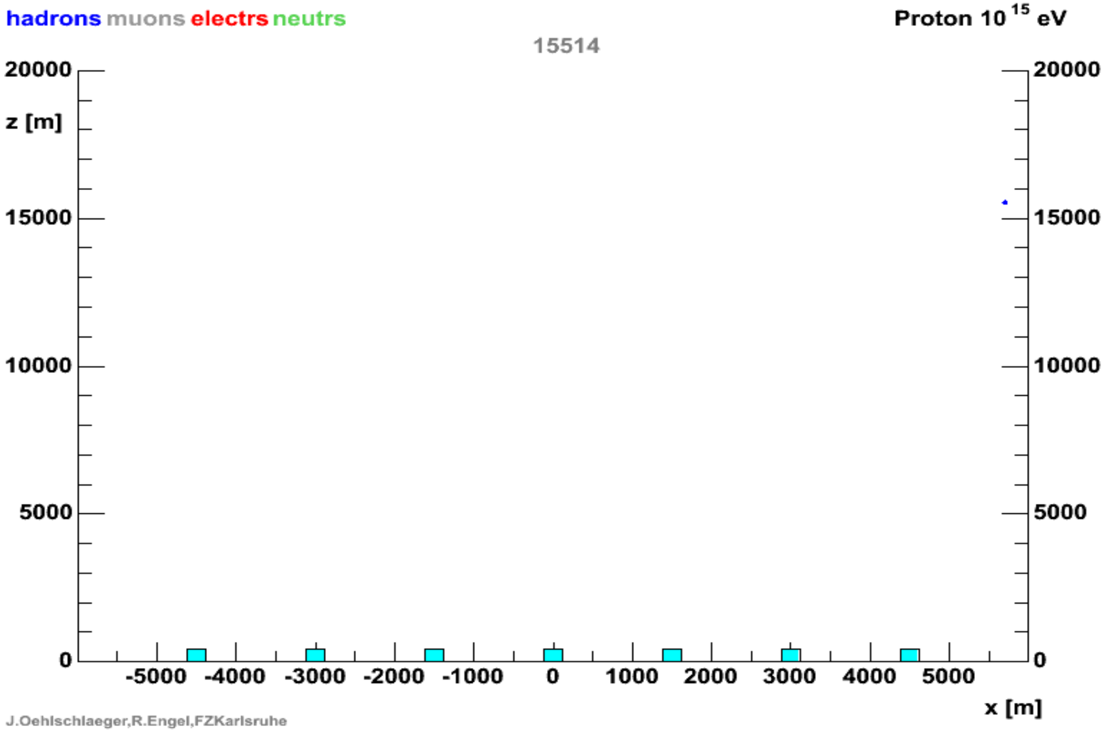
List of CORSIKA shower movies

Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sincpr14xz03.gif sincpr15xz03.gif	proton, 100 TeV, 30 deg proton, 1 PeV, 30 deg	side, fixed	0.1 GeV 1 GeV	coloured particle types, actual altitude [m] displayed, hit detectors flashing

Proton, 100 TeV, 30 deg

Proton, 1 PeV, 30 deg



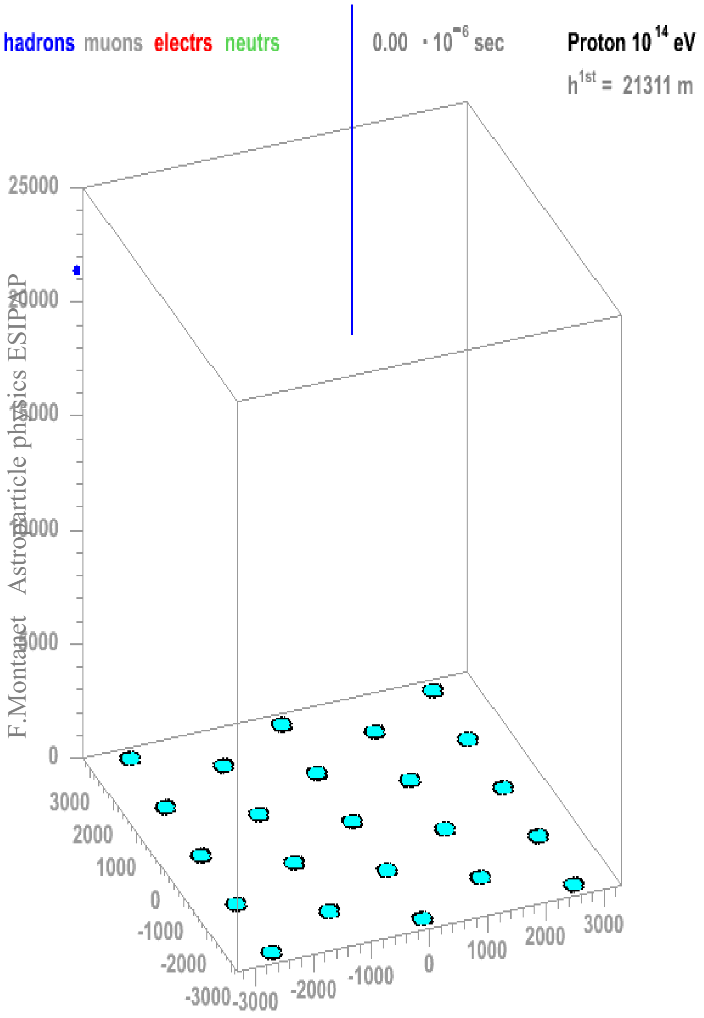


Beware ! not at same vertical scale

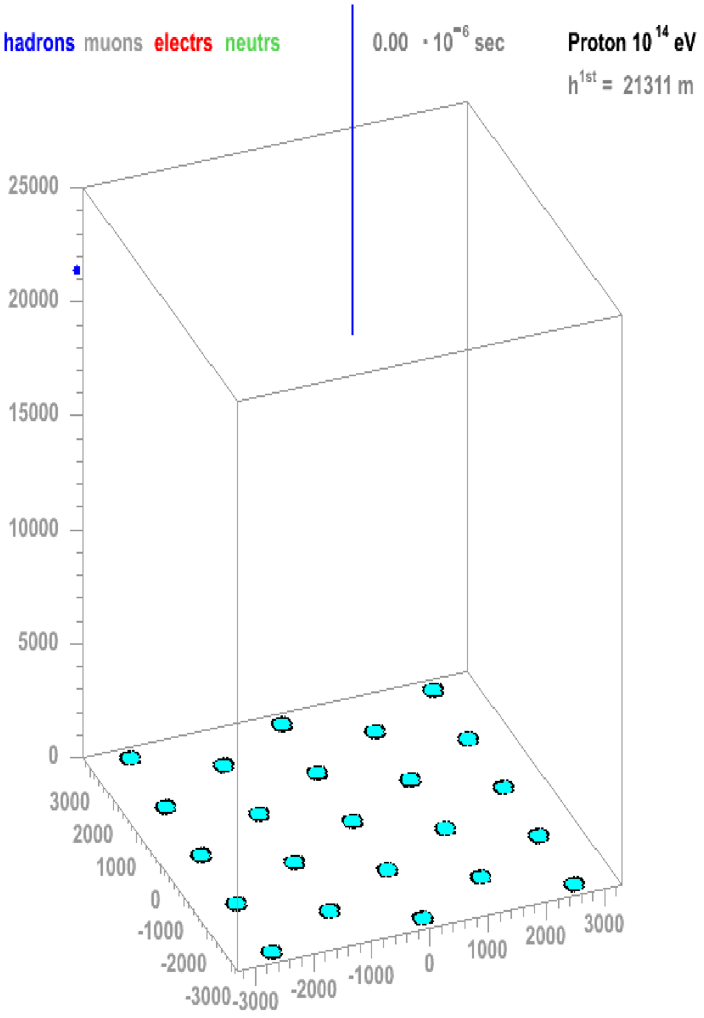
List of CORSIKA shower movies

Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
trafix14prh.gif trafix14prhm.gif trafix14prhme.gif	proton, 100 TeV, vertical	perspective, fixed	0.1 GeV	traces of hadrons traces of hadrons & muons traces of hadrons & muons & electrons

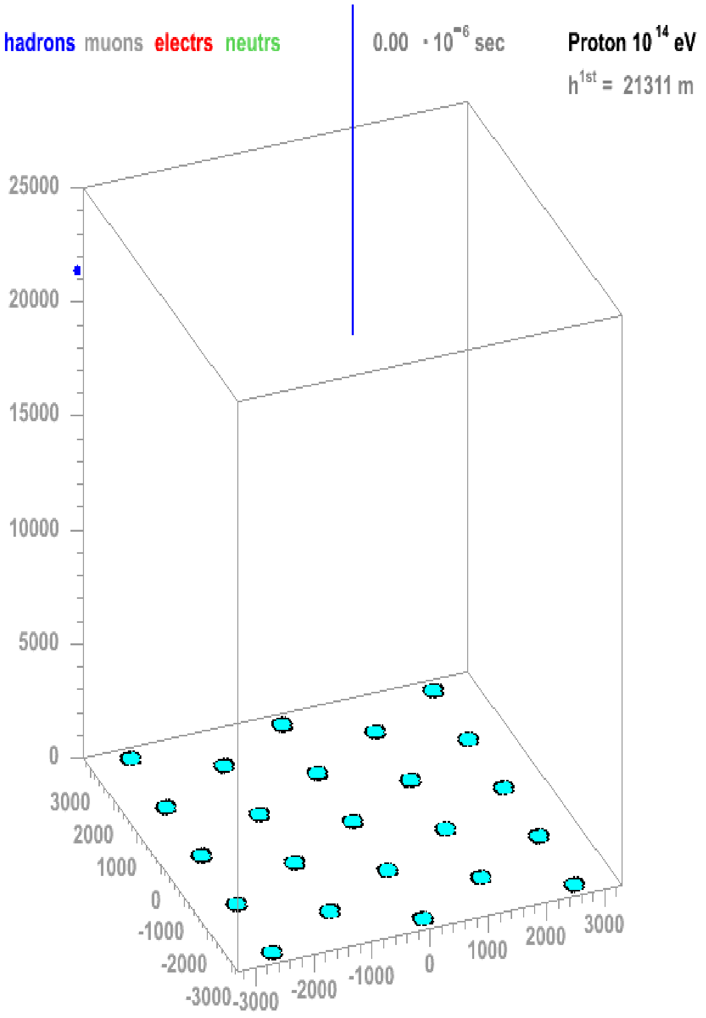
Proton, 100 TeV, vertical



J.Oehlschlaeger,R.Engel,FZKarlsruhe



J.Oehlschlaeger,R.Engel,FZKarlsruhe



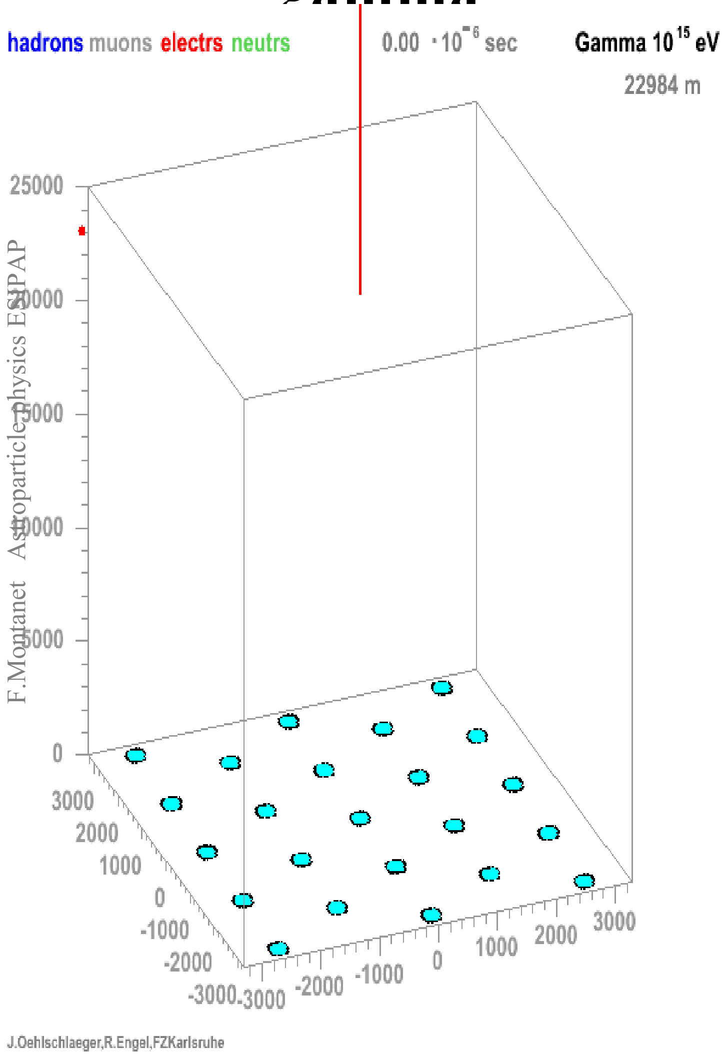
J.Oehlschlaeger,R.Engel,FZKarlsruhe

List of CORSIKA shower movies

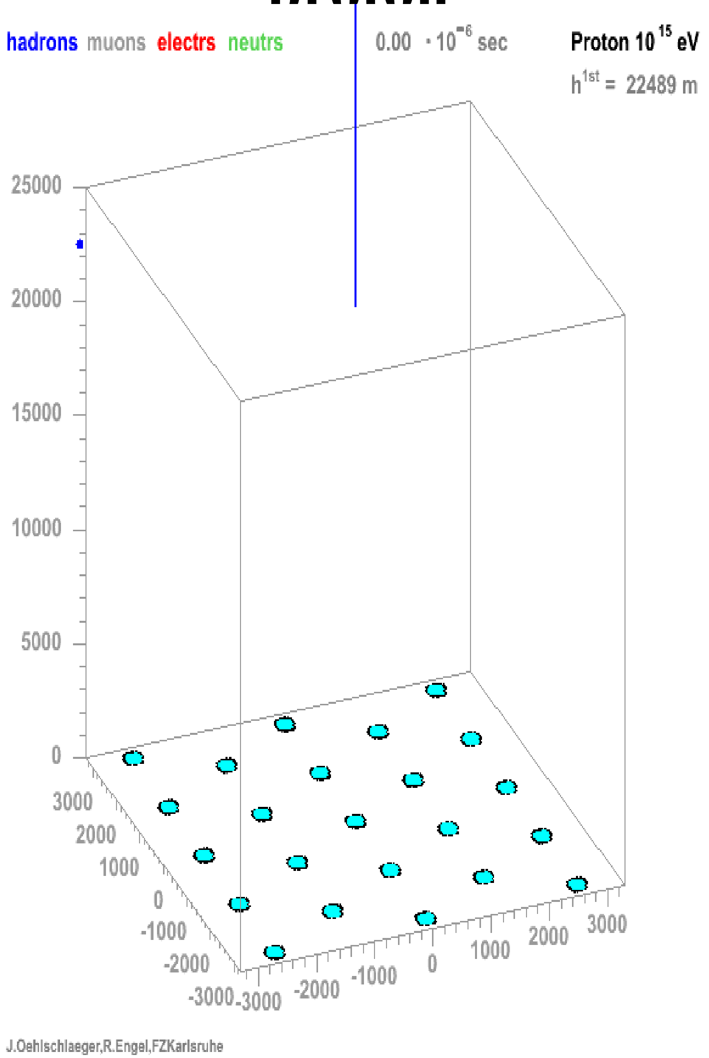
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
trafix15ga05.gif trafix15pr05.gif trafix15fe05.gif	gamma, 1 PeV, vertical proton, 1 PeV, vertical iron, 1 PeV, vertical	perspective, fixed	1 GeV	traces of hadrons & muons & electrons

1 PeV, vertical

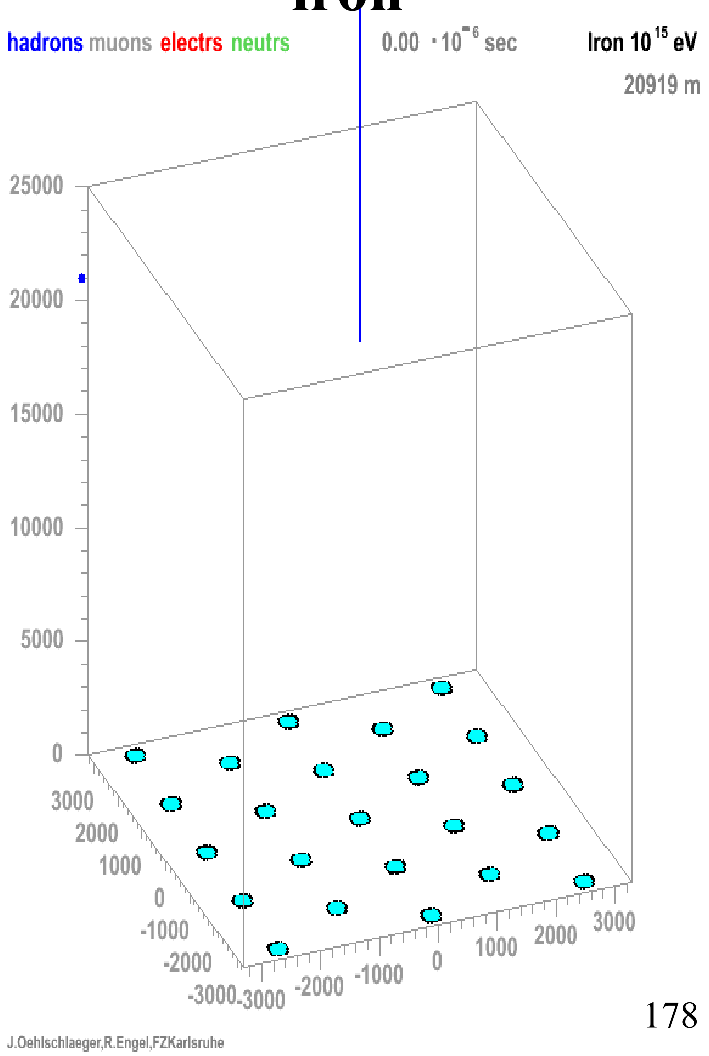
gamma



proton



iron



Thank you
for your attention

See you soon in live (Q&A +tutorial)