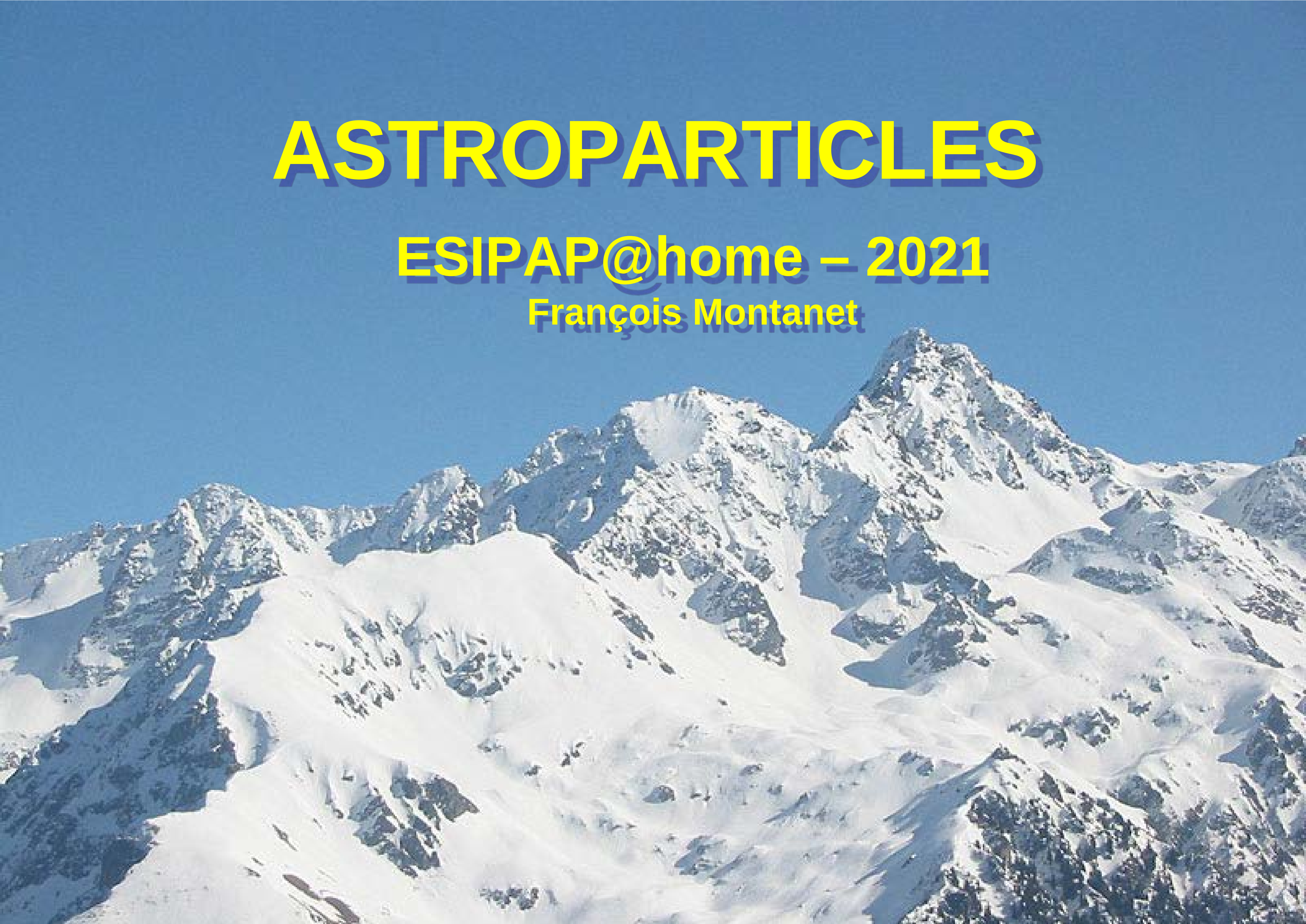
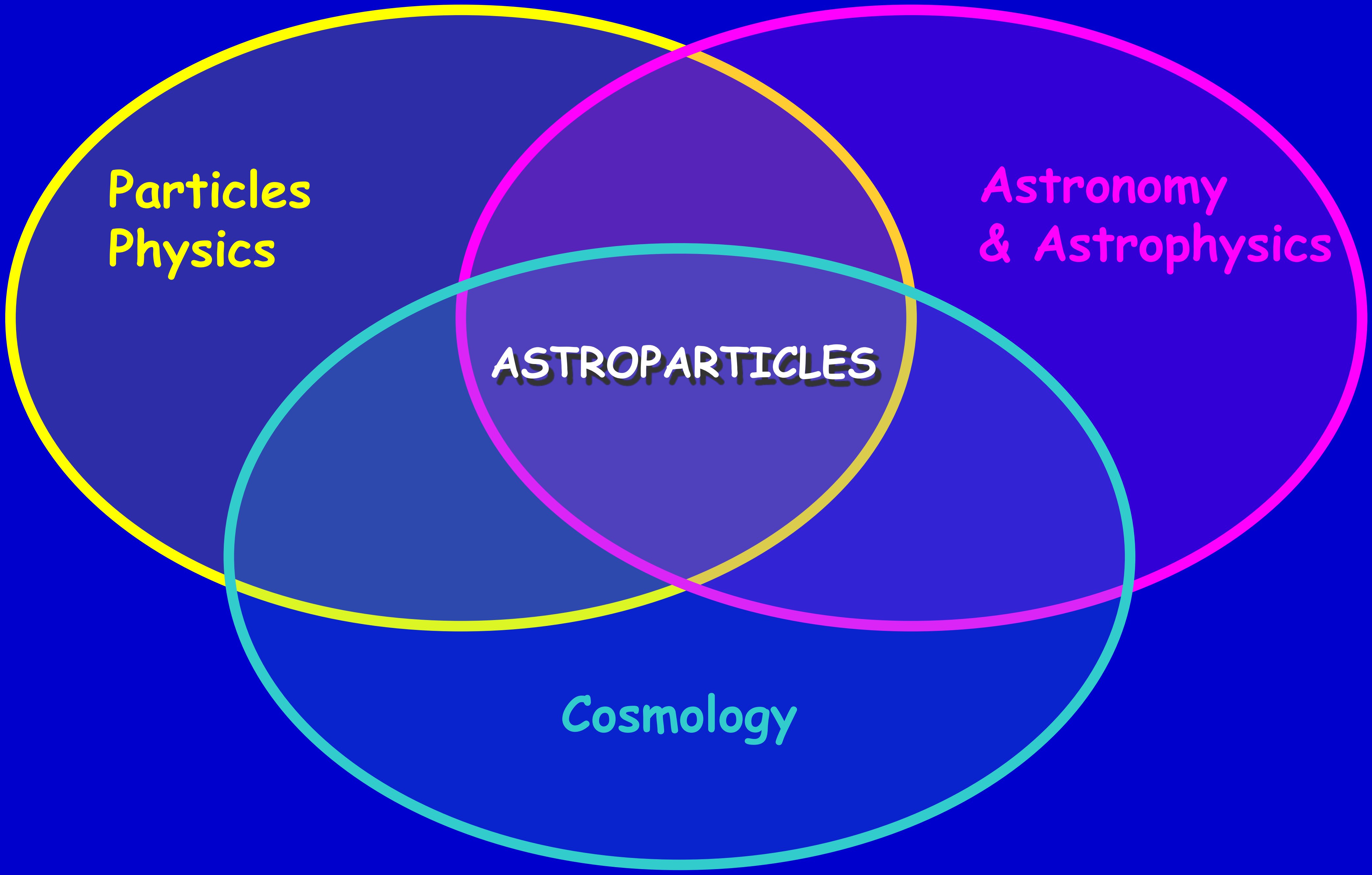
ASTROPARTICLES

ESIPAP@home – 2021

François Montanet




Particles
Physics
Astronomy
& Astrophysics
ASTROPARTICLES
Cosmology

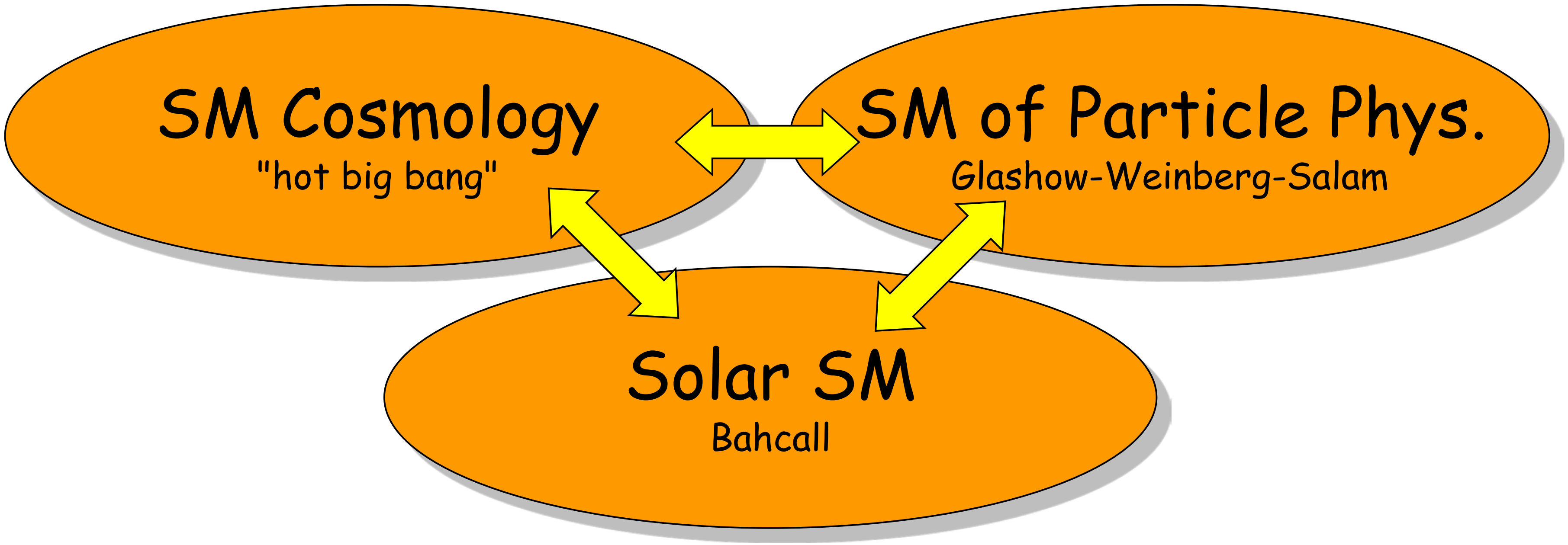
Plan of the course

- Motivations, Introduction
- Nature and properties of Astroparticles
  - Composition
  - Spectrum
  - Anisotropies
- Propagation medium
  - Intergalactic medium
  - Galactic medium
  - Atmosphere
- Astrophysical Sources
  - Astrophysical shocks
  - Fermi acceleration
  - Standard Model for the production of galactic CR, SNR
  - Gamma-ray sources, pulsars
  - AGN and other extragalactic sources
  - Neutrinos sources
  - "top-down" type of sources at UHE
- Propagation
  - CR propagation in the Galaxy: The Leaky box model
  - VHE γ-rays propagation
  - UHECR propagation
  - Air Showers Development

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

What can we learn from Astroparticles

Matching "standard models"



SM Cosmology

"hot big bang"

SM of Particle Phys.

Glashow-Weinberg-Salam

Solar SM

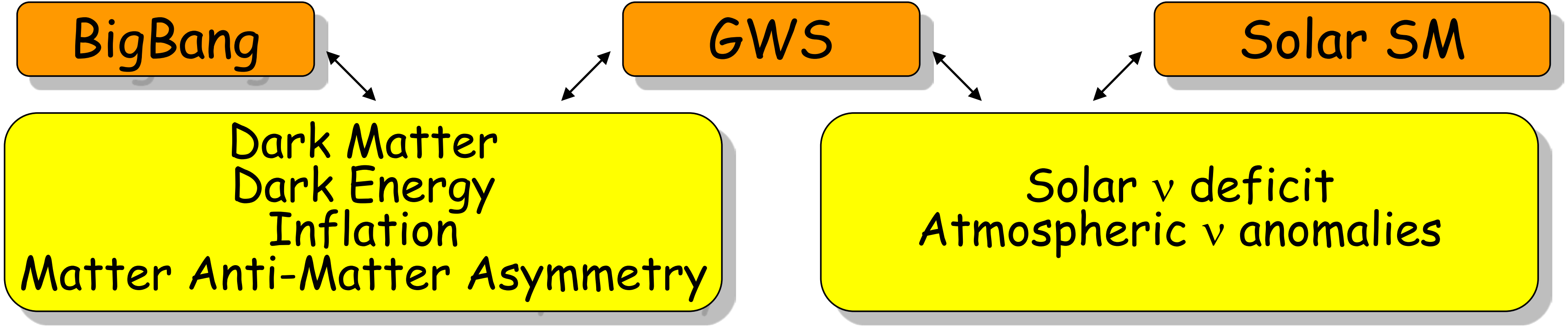
Bahcall

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)

Indirect searches

$FCNC$, CP

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

d_n^e

B physics

New Physics

This decade's grail:
solve the puzzle of
electroweak symmetry
breaking

Progress in Theory

Supergravity

→ Superstrings, M-Theory

Cosmology

Measure the parameters
of the Univers
and their evolution

Astroparticle Physics

Neutrino Physics

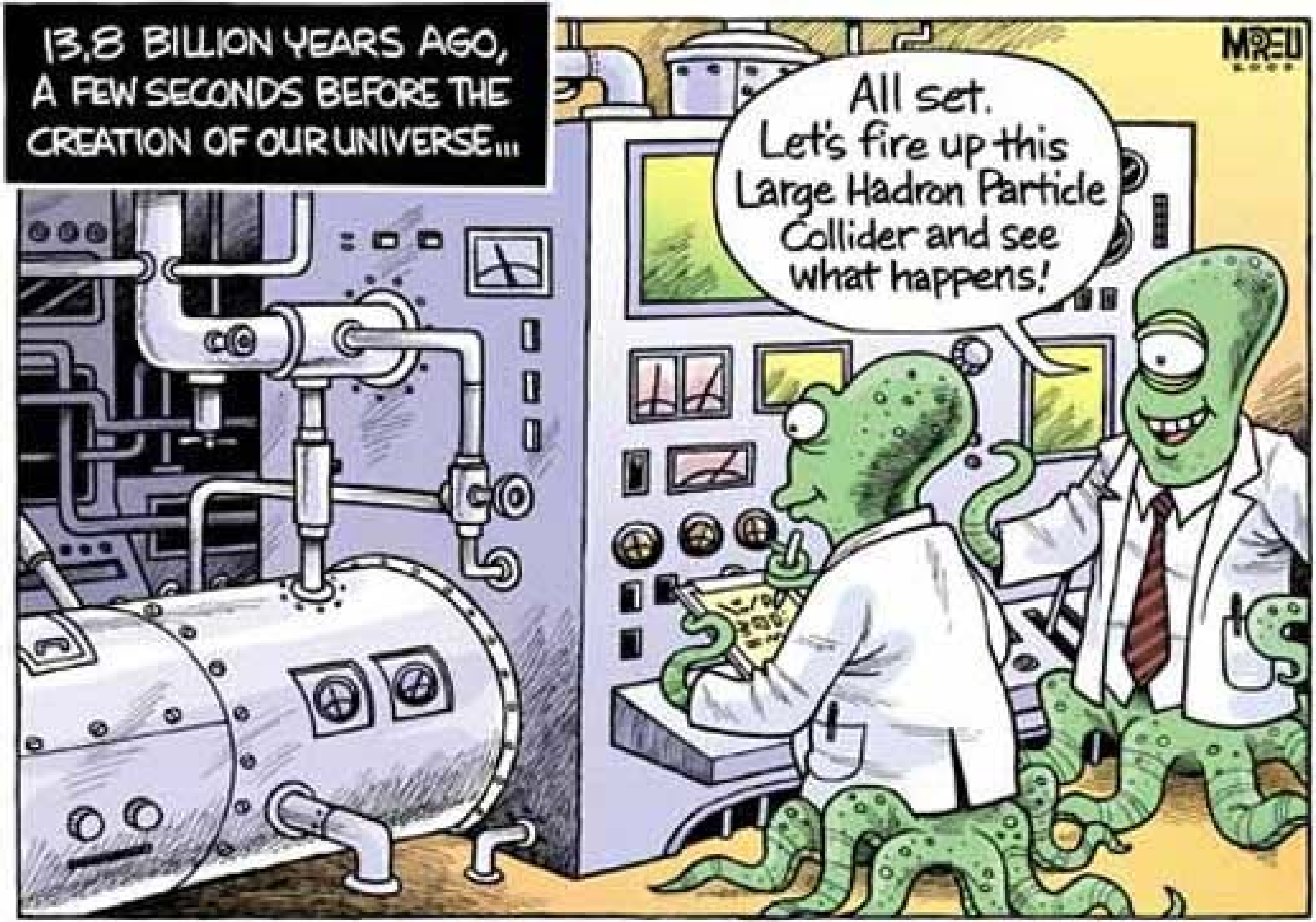
Cosmic Rays

γ Astronomy

Gravitationnal Waves

↓

New Physics probes


13,8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
MREU
All set. Let's fire up this Large Hadron Particle Collider and see what happens!

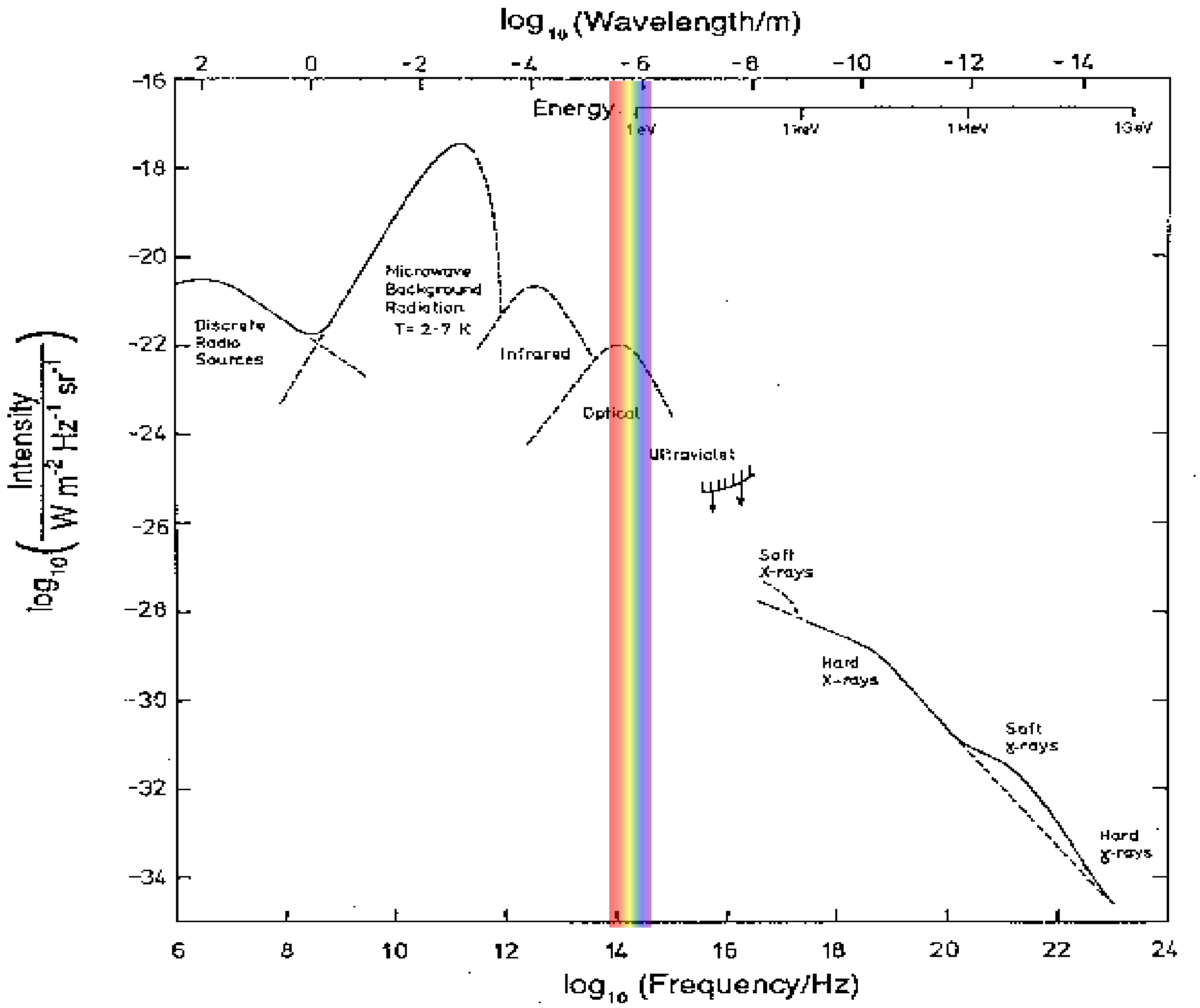
What are "Astroparticles"

What we know… roughly.

Let there be light !

All what we know in astrophycics is thanks to the light !

- A multi-wavelength sky



Our Galaxy

The optical Milky Way

Our Galaxy

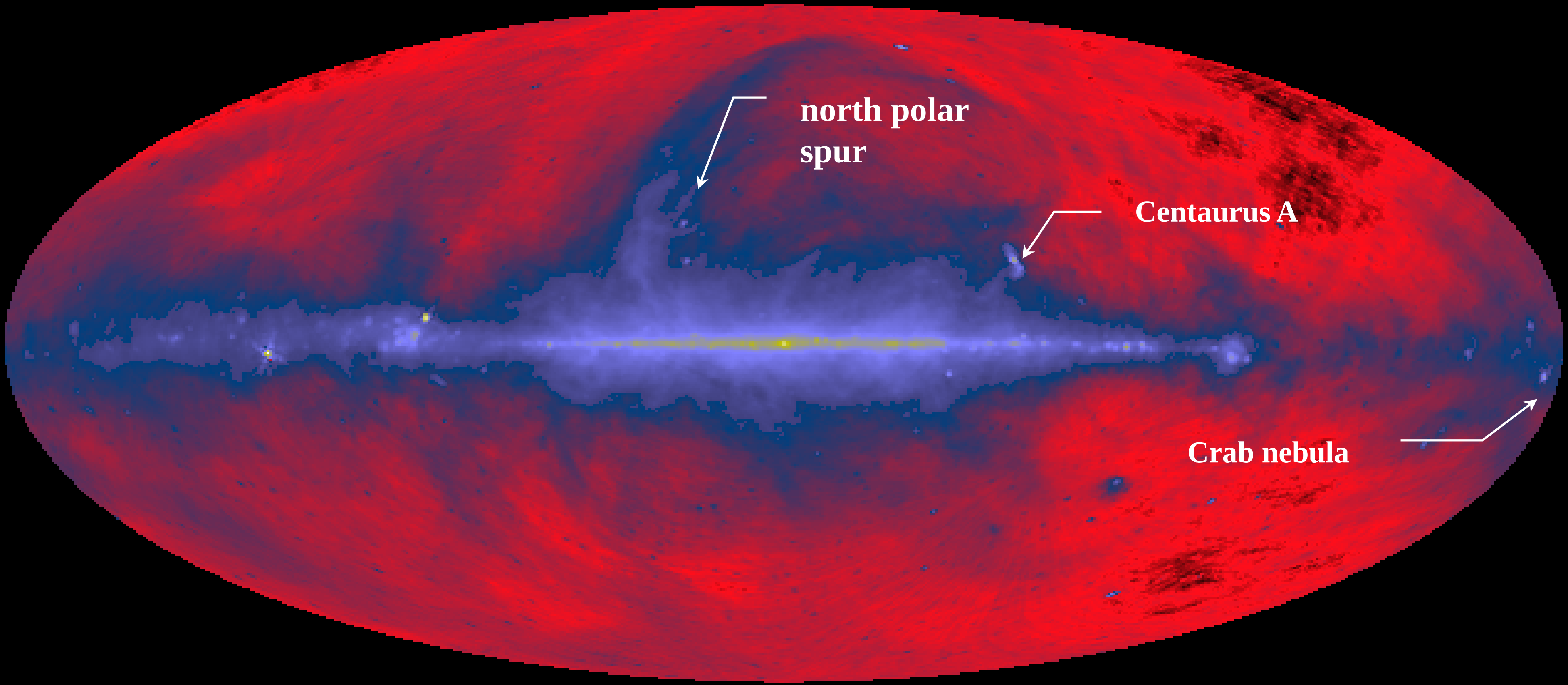
The optical Milky Way

Lund Observatory

Our Galaxy

The Milky Way : Radio at 73cm

408 MHz / 73.5 cm / 1.6 10^{-6} *eV)*

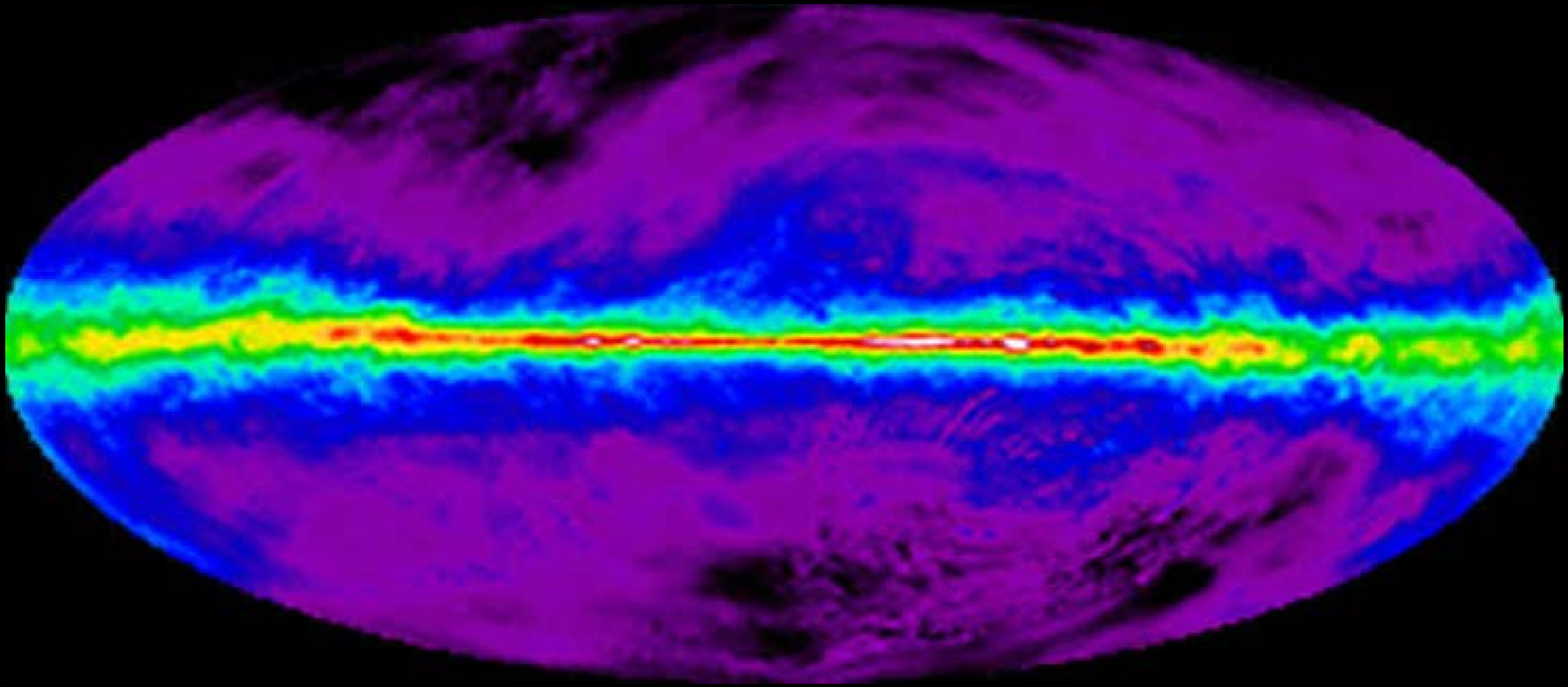


Essentially from the movement of ultra relativistic electrons probably issue from supernovae remnants in the galactic magnetic field.

Our Galaxy

The Milky Way : Radio at 21 cm

(~1.42 GHz / 21.1 cm / 5.9 10^{-6} eV)

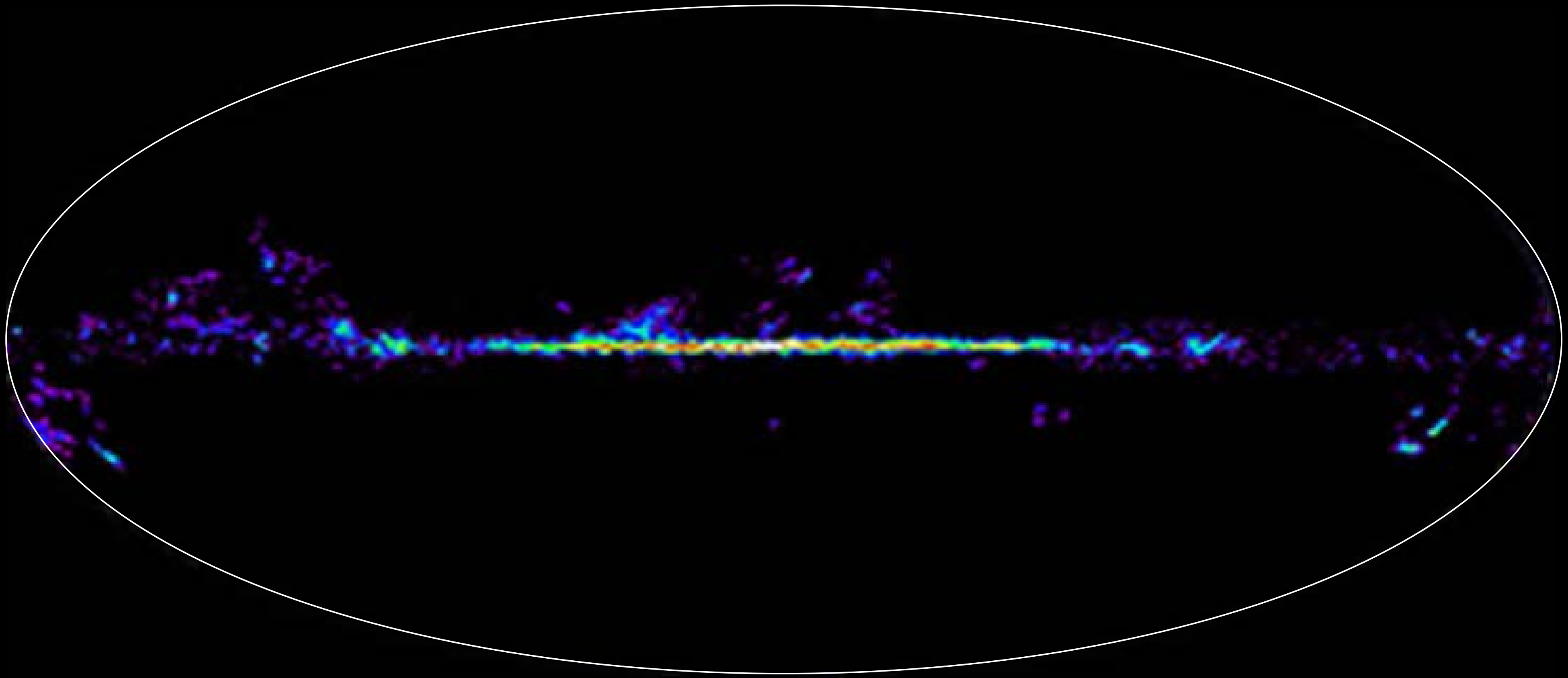


Hyperfine transition of hydrogen. Structures are due to the column density of atomic hydrogen clouds along the line of sight.

Our Galaxy

The Milky Way : Radio at 2,6mm

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

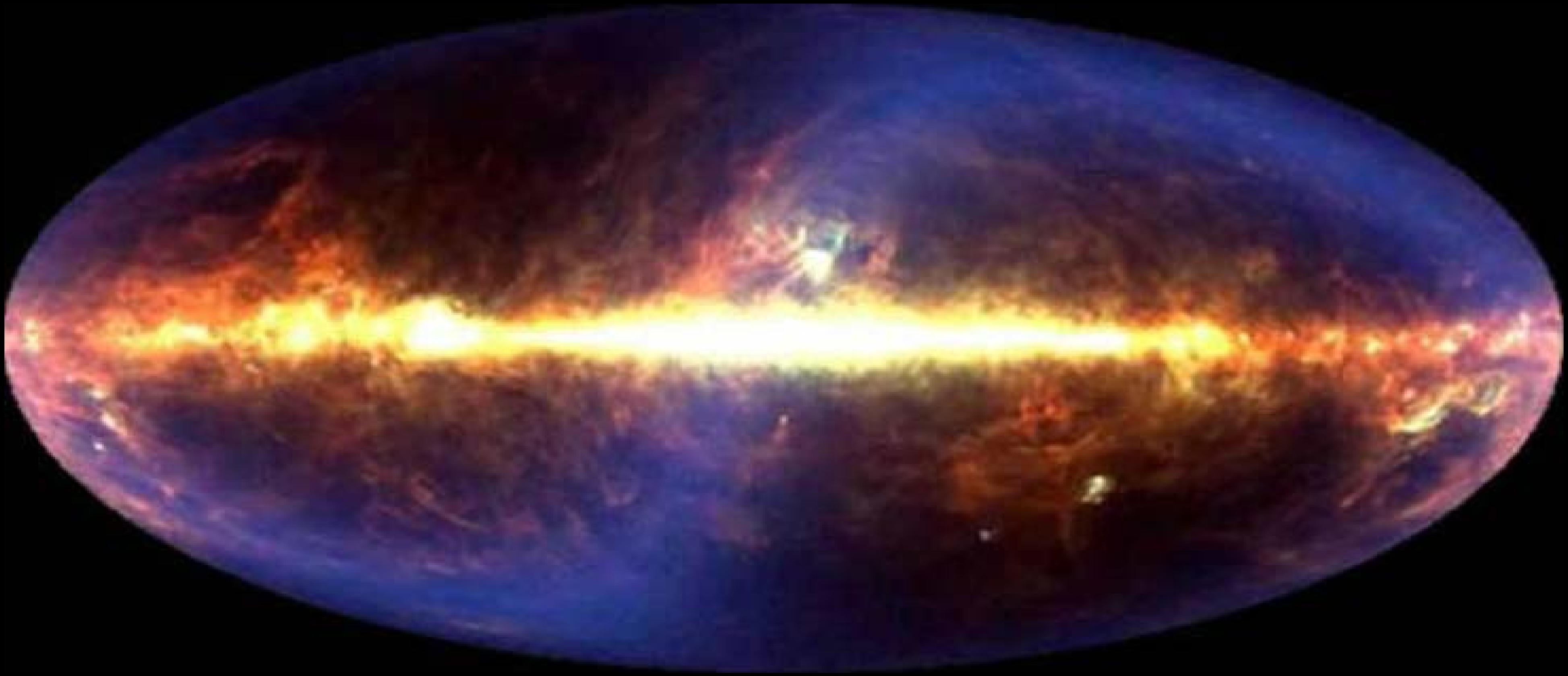


Rotation mode ray of carbon monoxide. One assumes that CO abundance is proportional to that of cold molecular hydrogen (directly undetectable).

Our Galaxy

Infra red

Infrared (3 10^3 to 25 10^3 GHz / 100 to 12 μm / 0.01 to 0.1 eV)

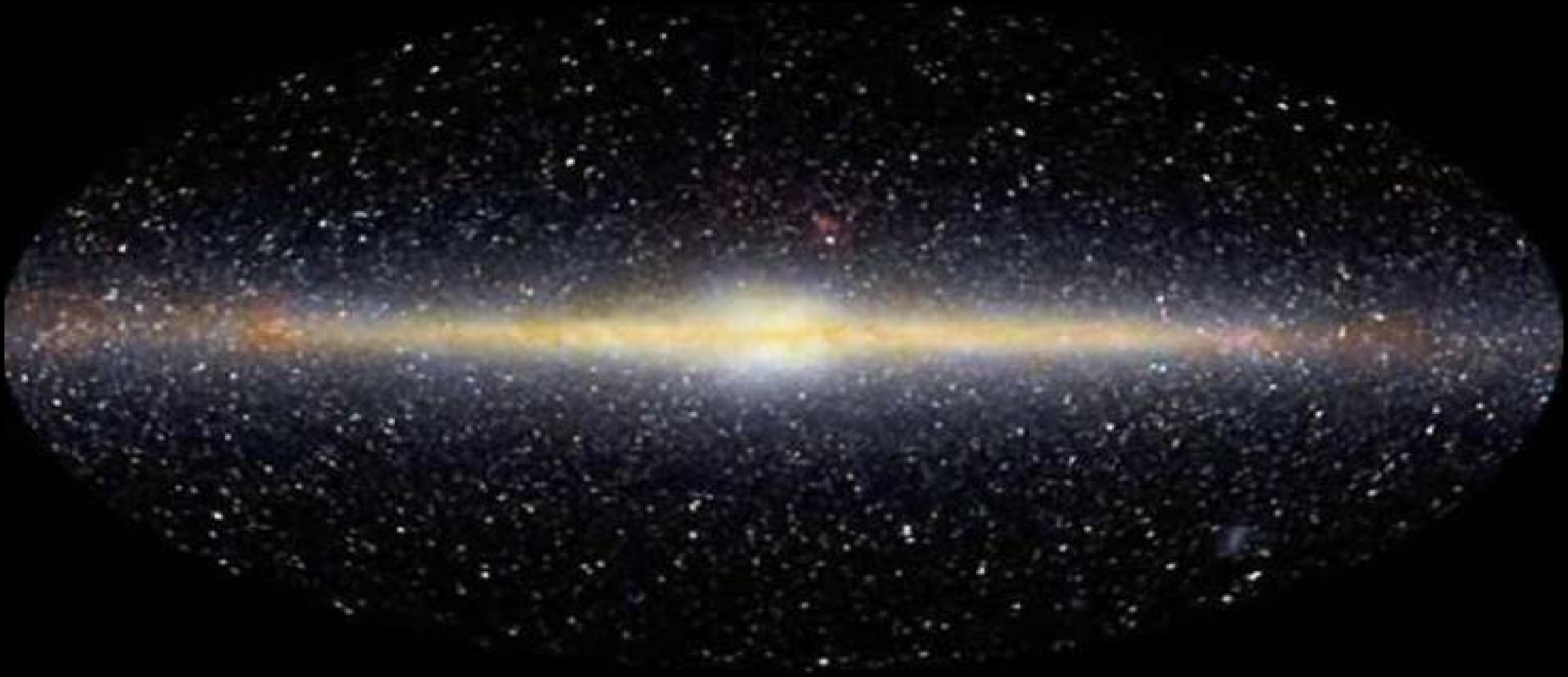


Thermal emission, due to interstellar dust heated by starlight.

Our Galaxy

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

Near Infrared (86 10^3 à 240 10^3 GHz / 1.25 à 3.5 μm / 0.35 à 1 eV).



Giant stars emission in the disk and in the bulb

Our Galaxy

Optical

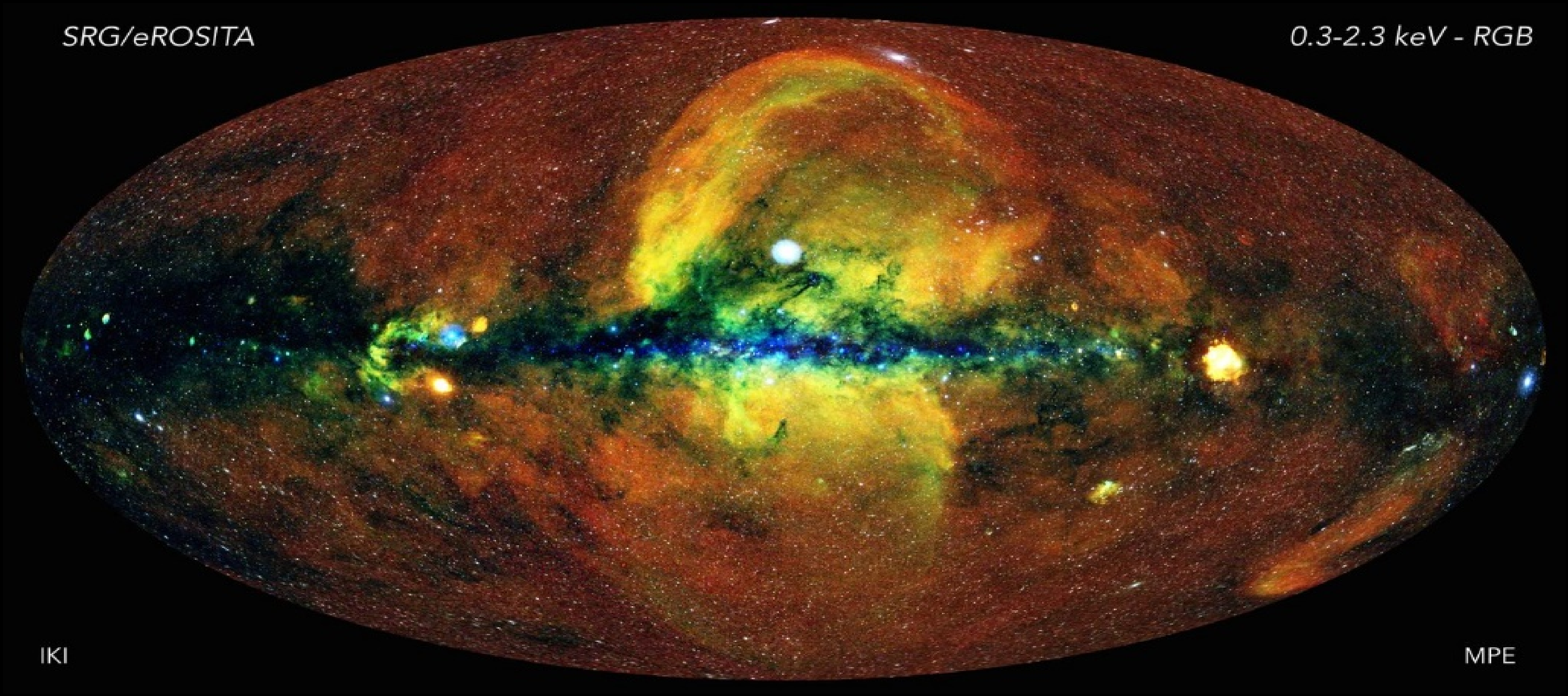
Visible (460 10^3 GHz / 0.65 μm / 2 eV – red)

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

Our Galaxy

X-rays

X -rays (60.10^6 to 360.10^6 GHz / 5 to 8.3 nm / 0.25 to 1.5 keV).

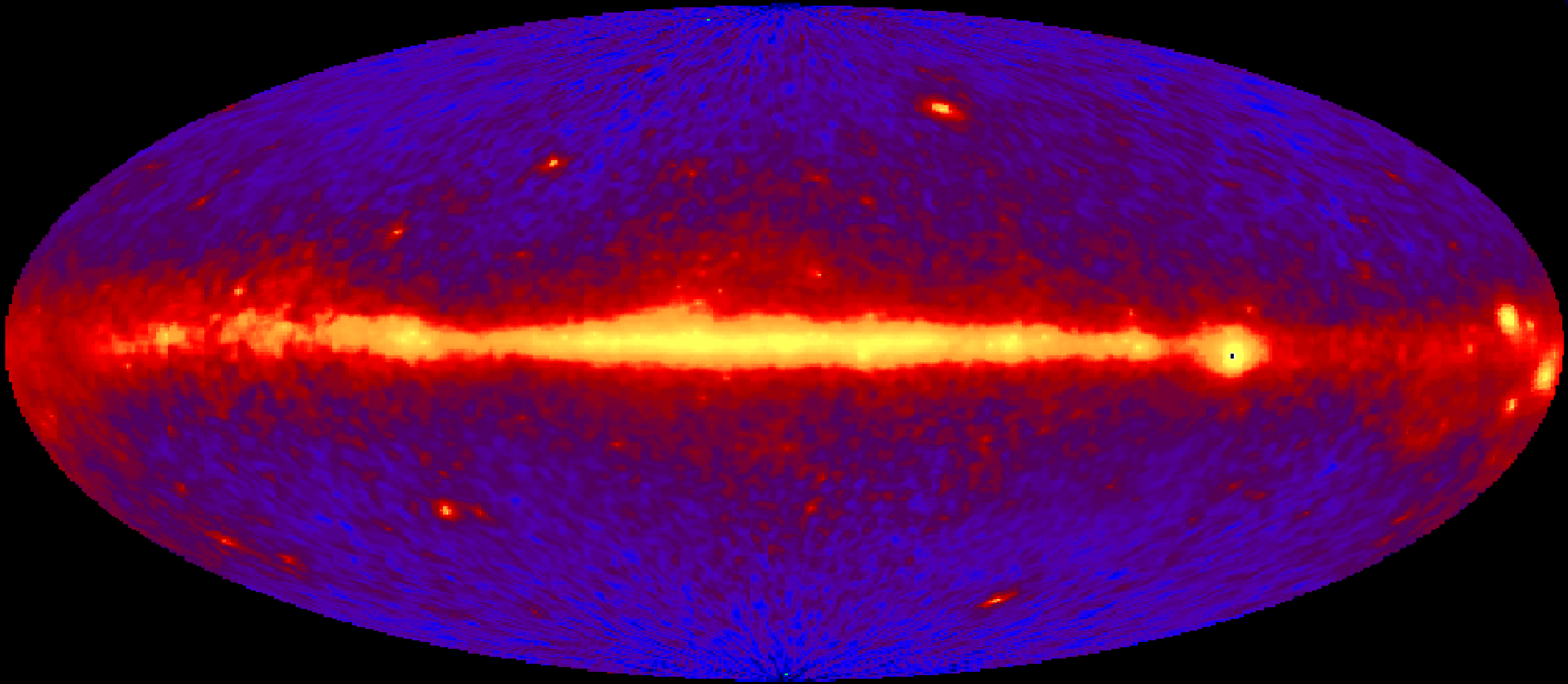


Diffuse X-ray emission from overheated and shocked gas.

Our Galaxy

Gamma-rays

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

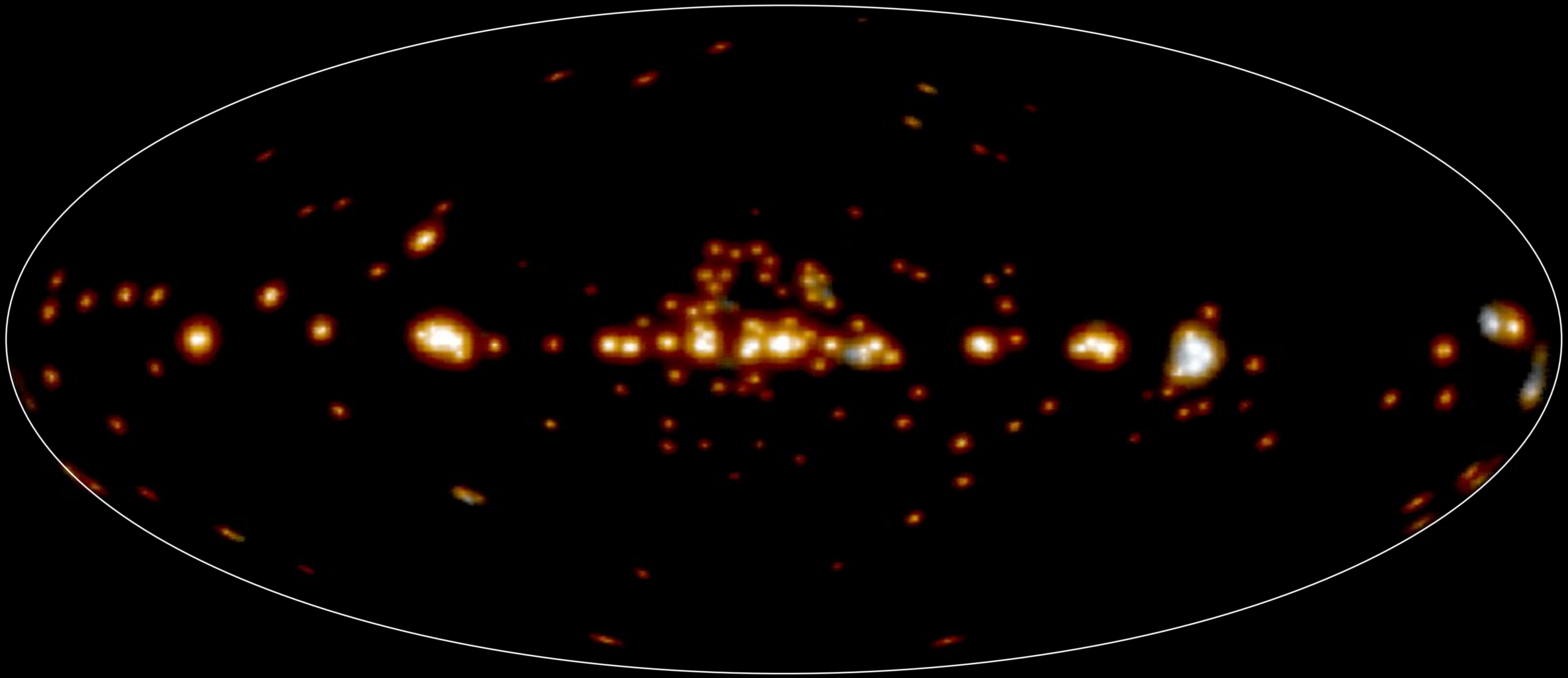


Photons (gammas) from the decay of neutral pions produced in the interaction of CR with interstellar matter, from the Bremsstrahlung of CR and from the inverse Compton of relativistic electrons with ambient photons.

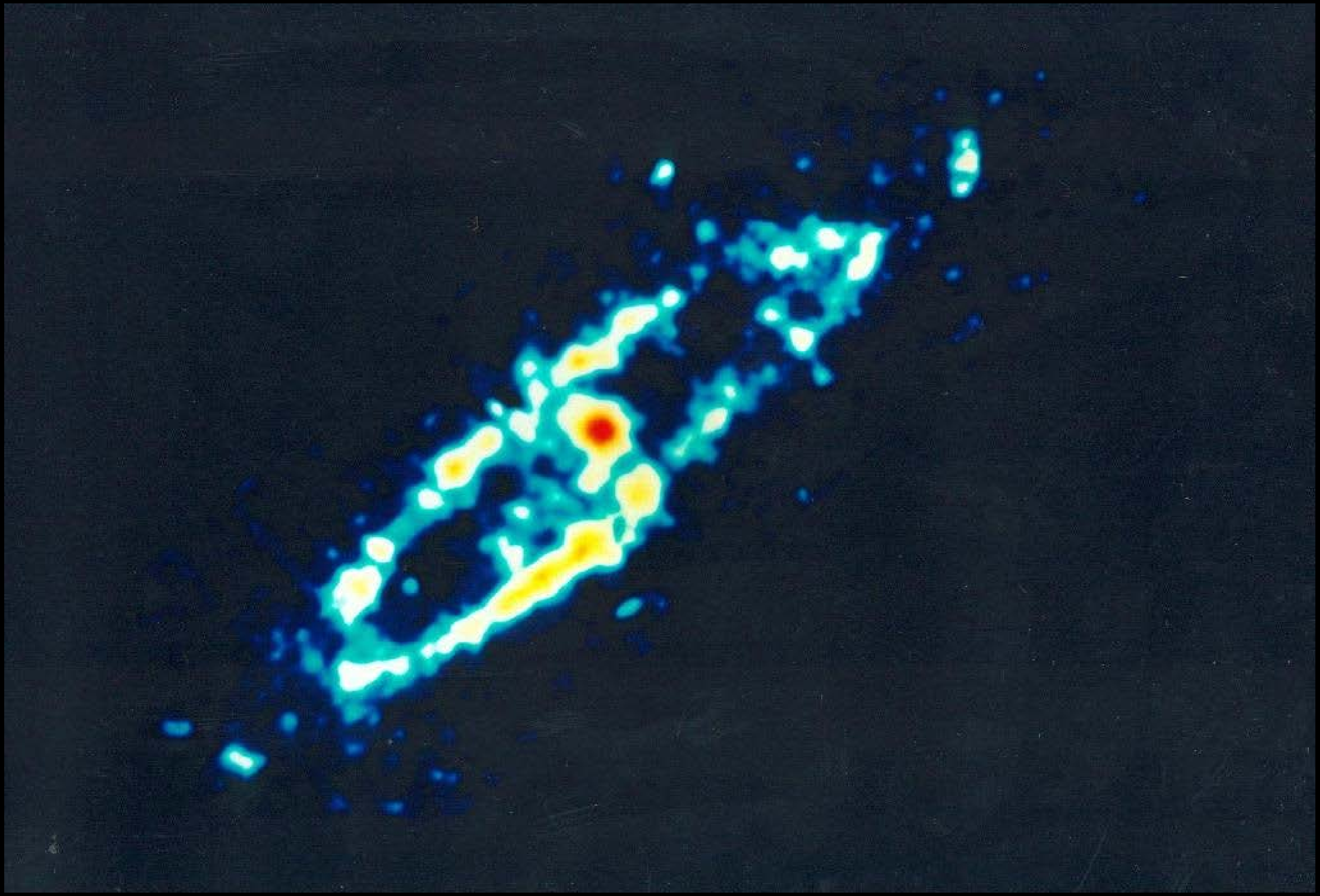
Our Galaxy

HE gamma-rays (>100MeV EGRET satellite)

Resolved point-like sources:
Binary systems, pulsars, SN remnants…



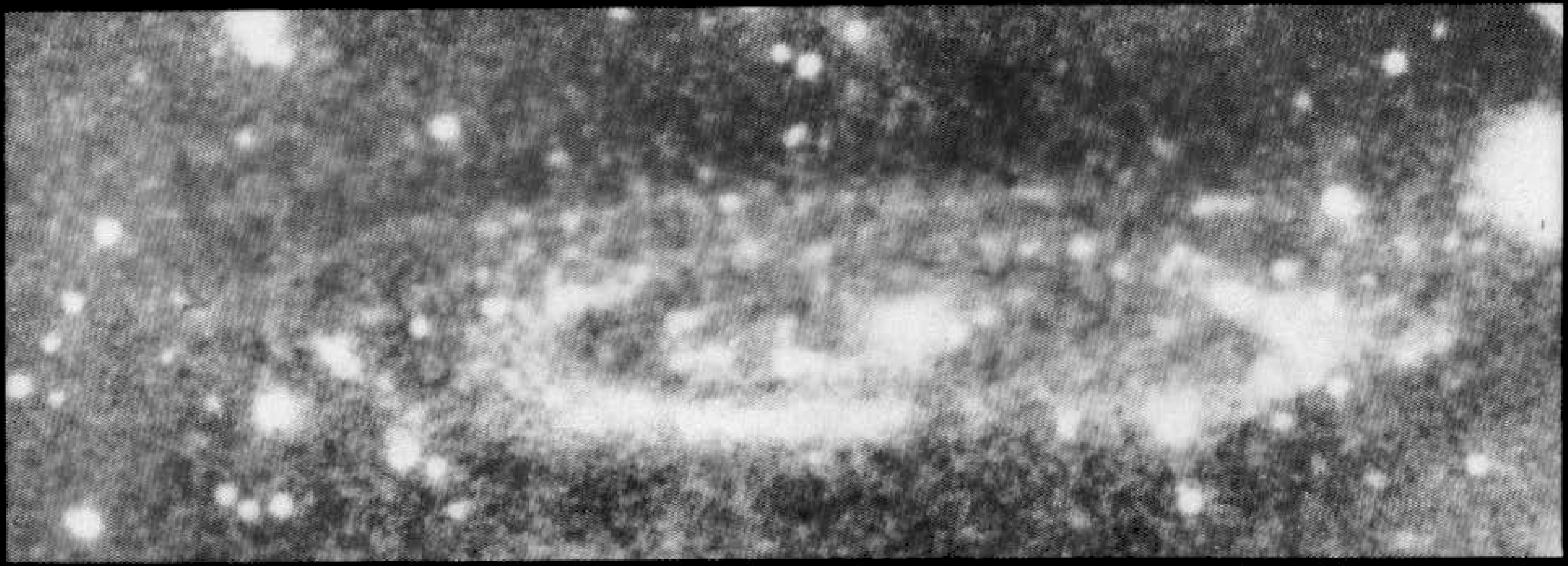
Andromeda (M31): IR



Star forming regions in spiral arms

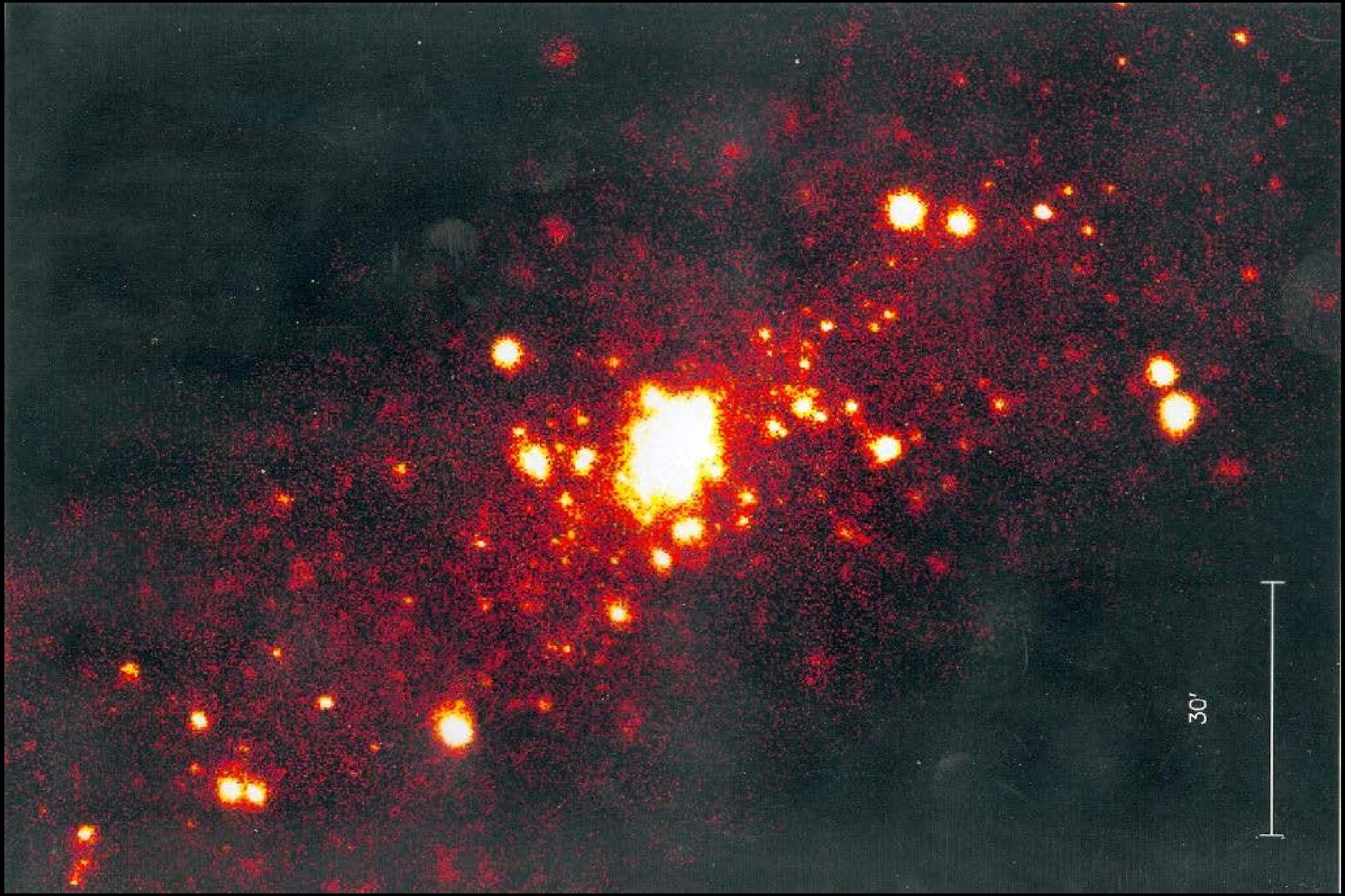
Andromeda (M31): UV

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



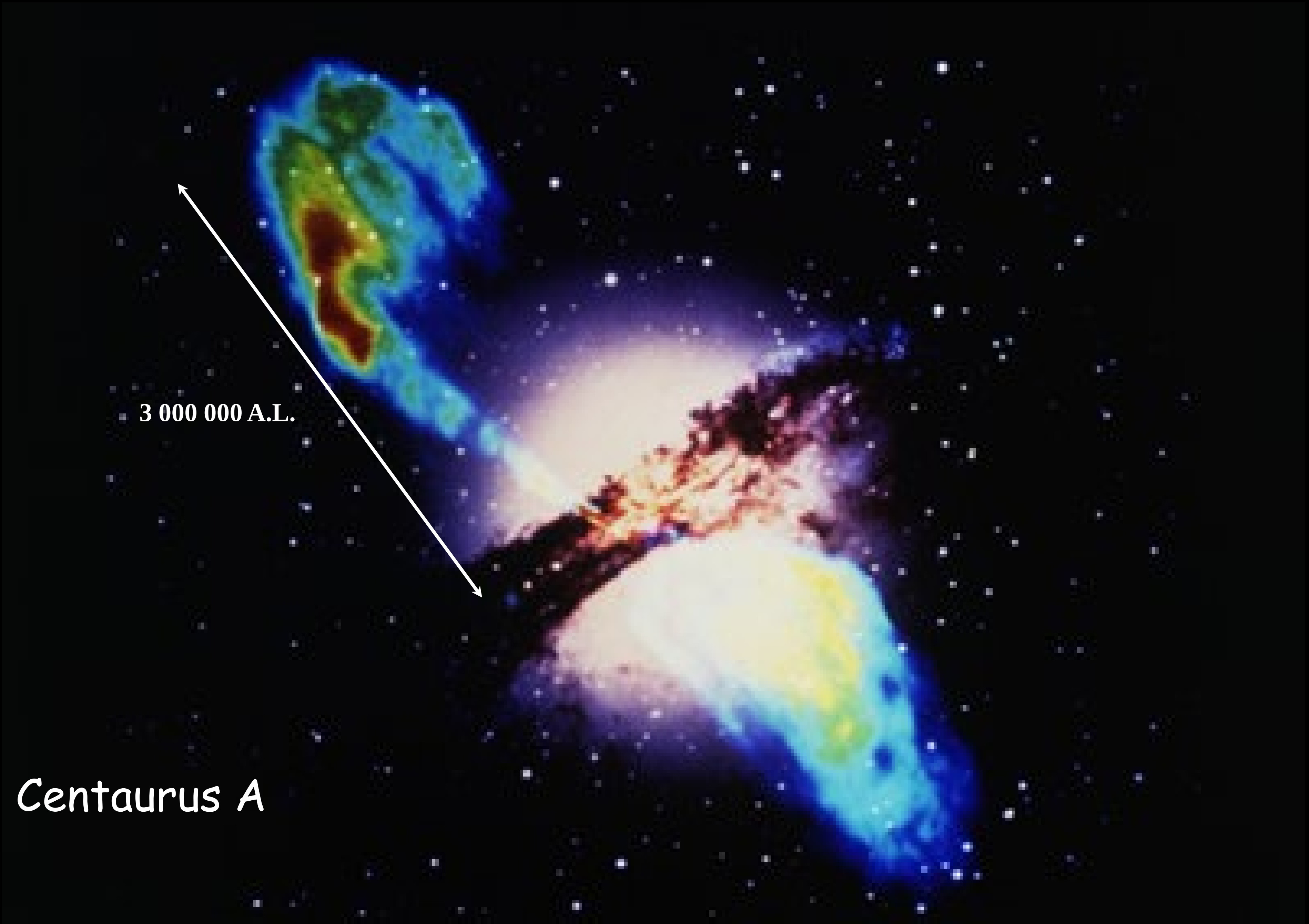
Young,
hot stars
in spiral
arms

Andromeda (M31): Xray



Xray binaries, supernova remnants, hot gas

Radio Galaxy



Let there be light !

All what we know in astrophycics is thanks to the light !

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

Well, almost everything…

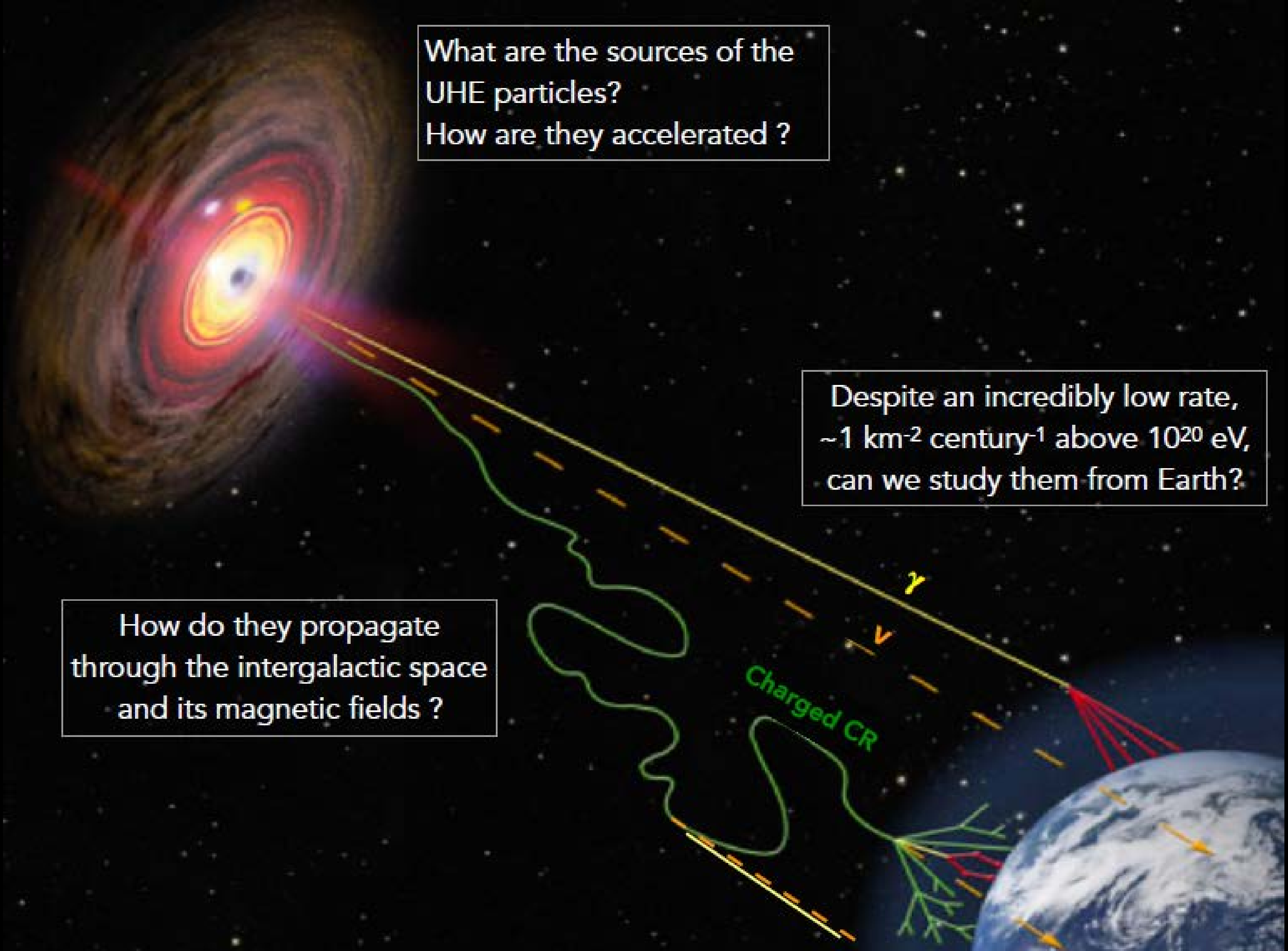
- ∃ on-luminous messengers :
  cosmic rays (charged), neutrinos and Gravitational Waves !
- Rare but precious : ~ 4 CR/cm²/s
  ~30 µg/s on entire earth (1kg per year !)

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…

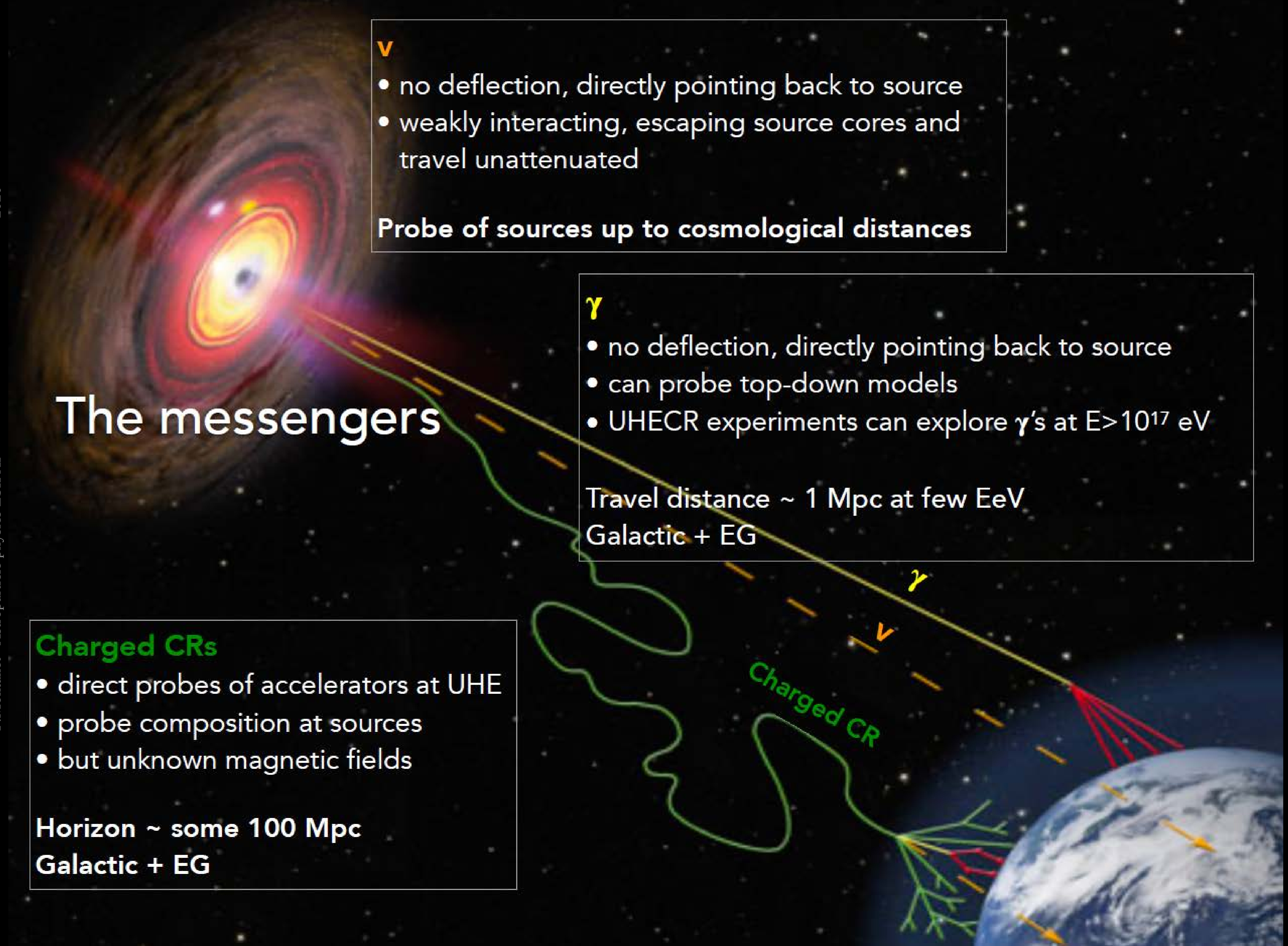


What are the sources of the UHE particles?
How are they accelerated ?

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

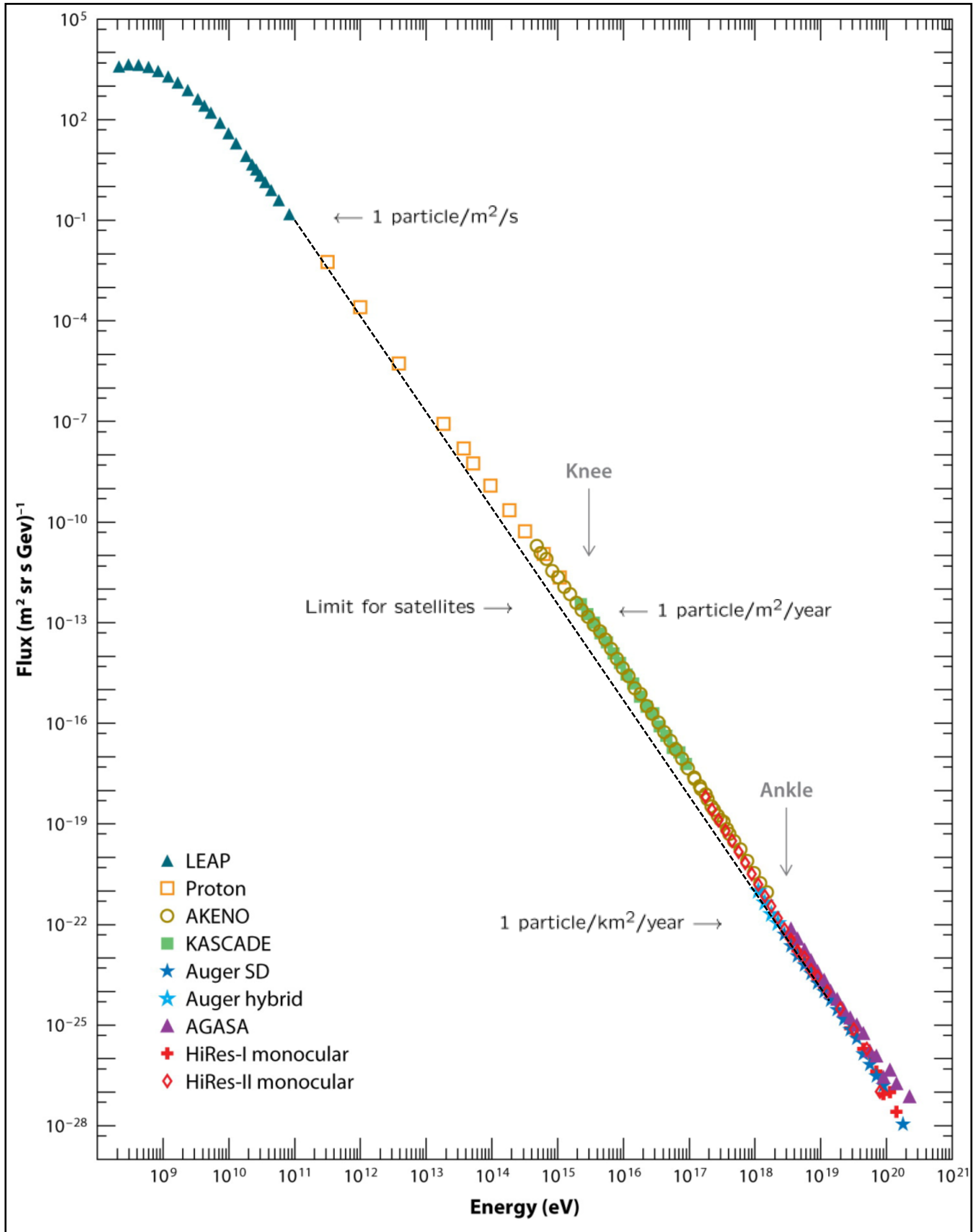
Travel distance ~ 1 Mpc at few EeV
Galactic + EG

Charged CRs

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

Horizon ~ some 100 Mpc
Galactic + EG

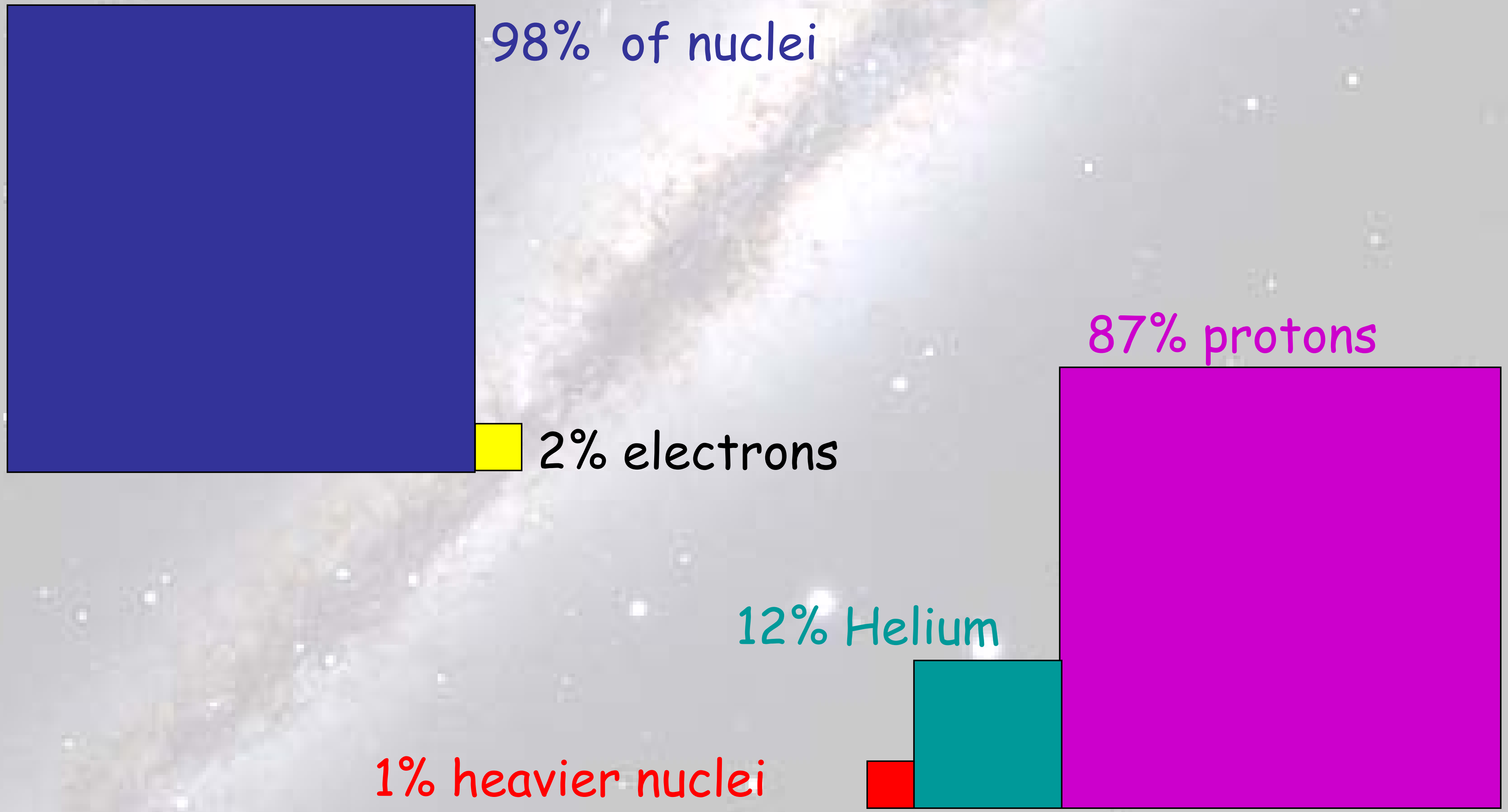
The "all particles" spectrum



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"
- Spectrum badly known at the two extremities
  - Geomagnetic "shield" + Solar modulation
  - Extreme rareness…

Charge cosmic rays composition



98% of nuclei

2% electrons

87% protons

12% Helium

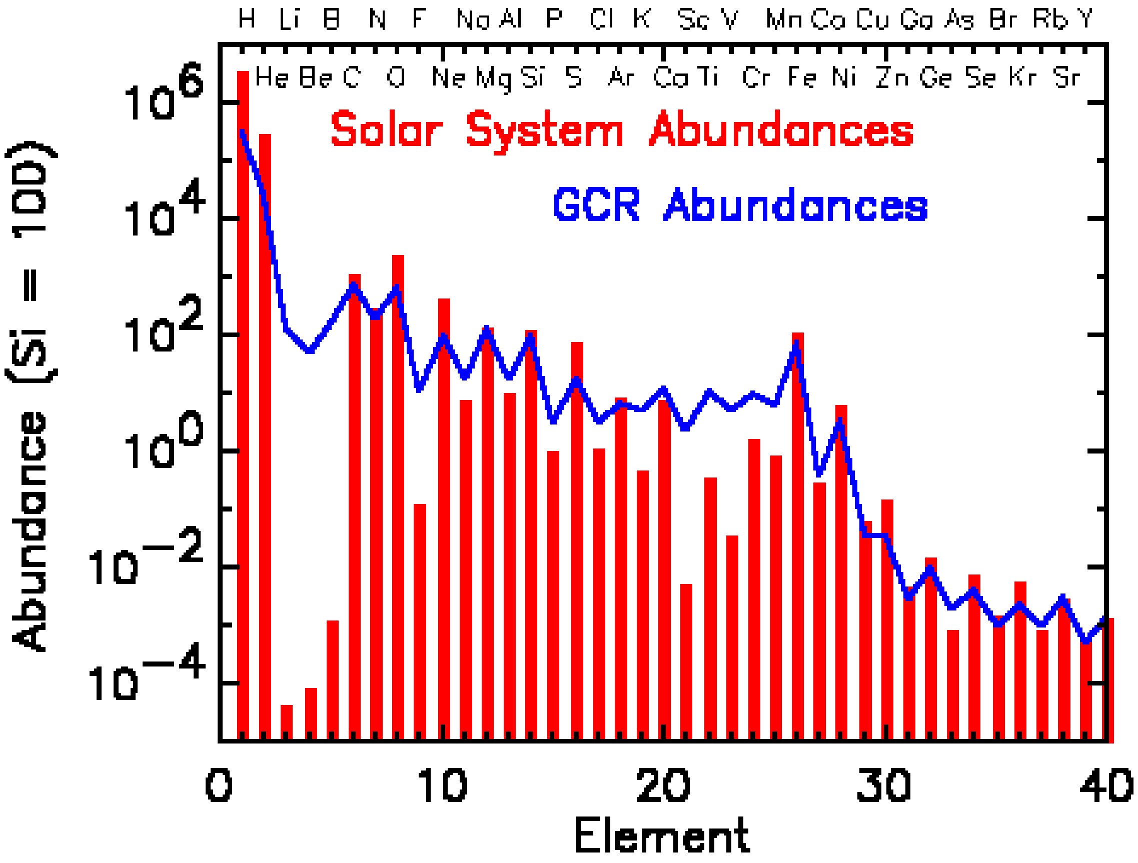
1% heavier nuclei

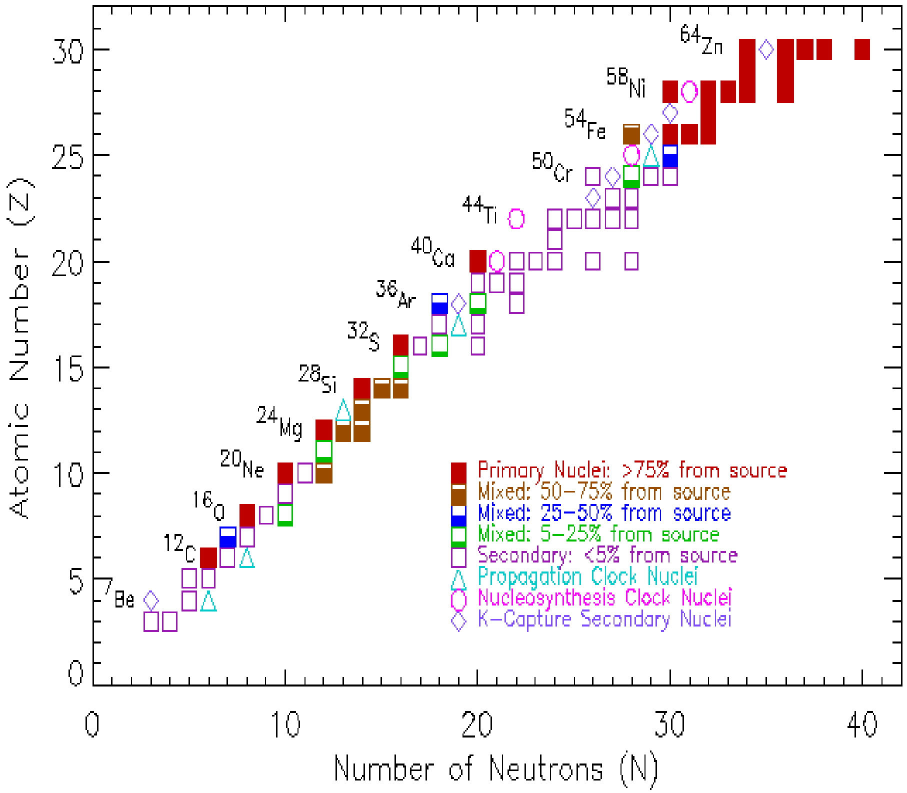
Flux : 4 RC/cm^2/s $\Rightarrow$ 1 kg/year $\ll$ 40 000 ton/year (meteorites)

Overview of CR data on composition

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

Nature of cosmic rays



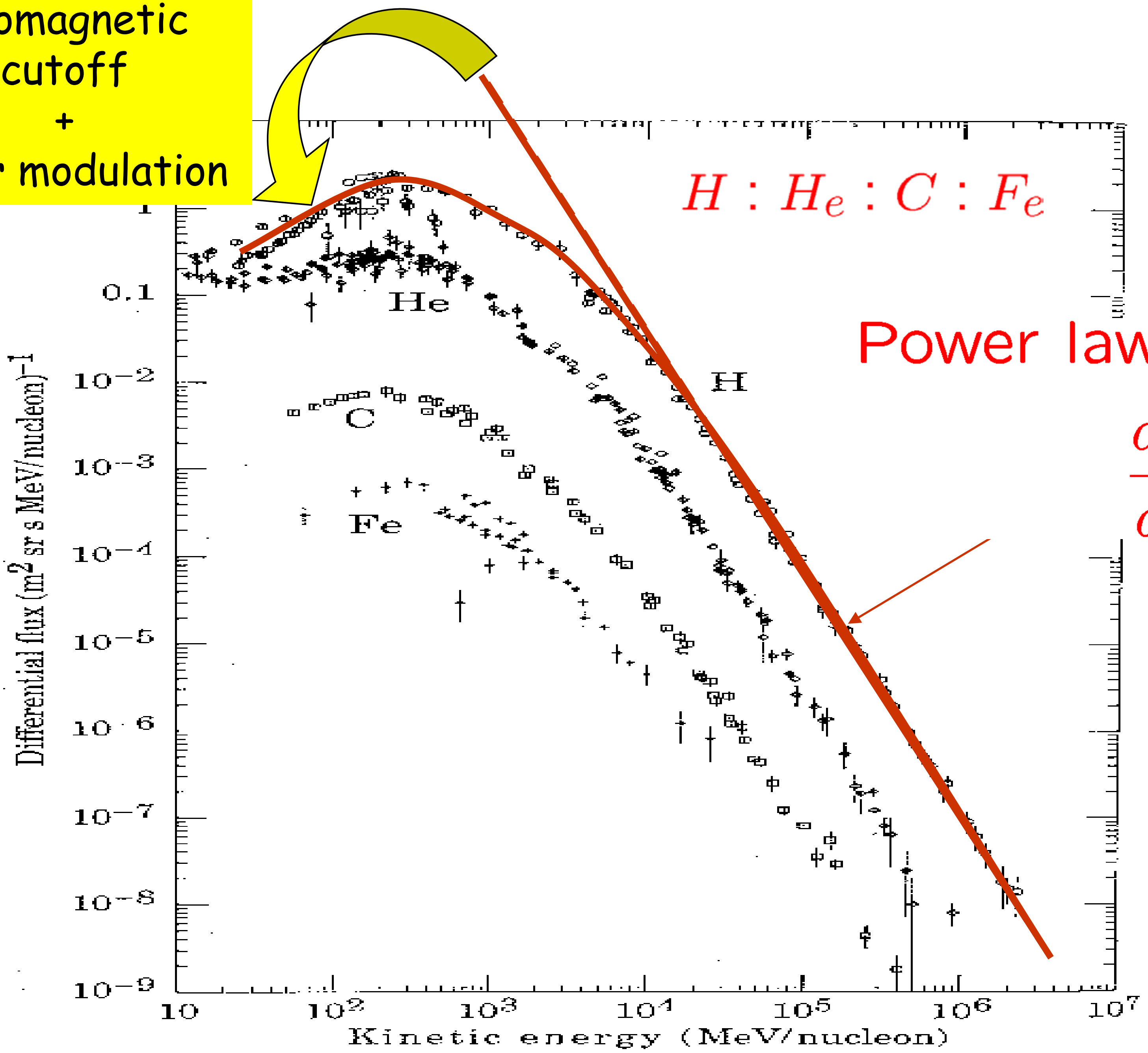


Abundances different in CR and local measurements
(Li Be B and Sub-Fe)

CR undergo spallations and produce secondary CR

Nature of primary cosmic rays

Geomagnetic cutoff
+
Solar modulation

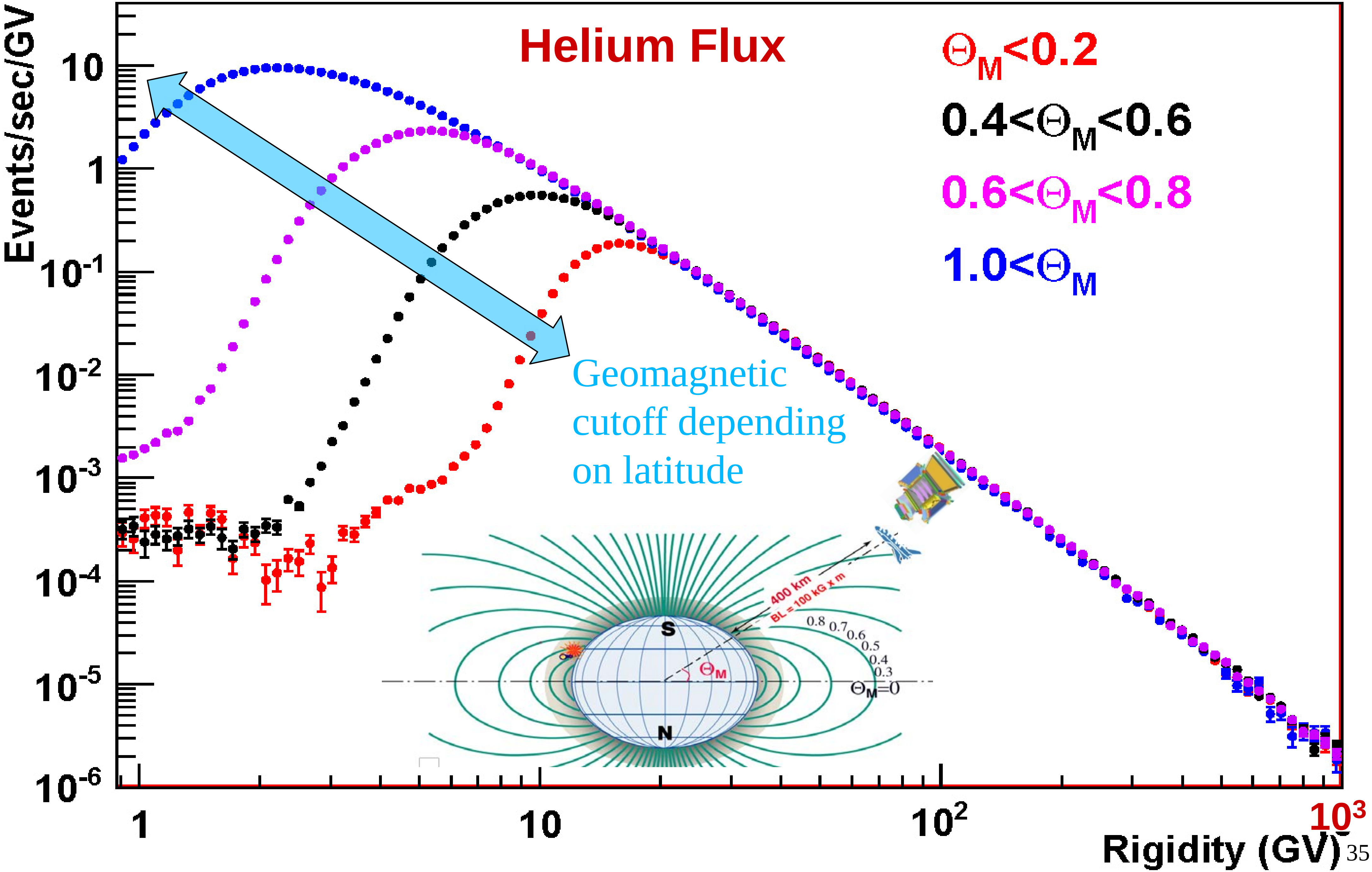


$H : He : C : Fe$

Power law

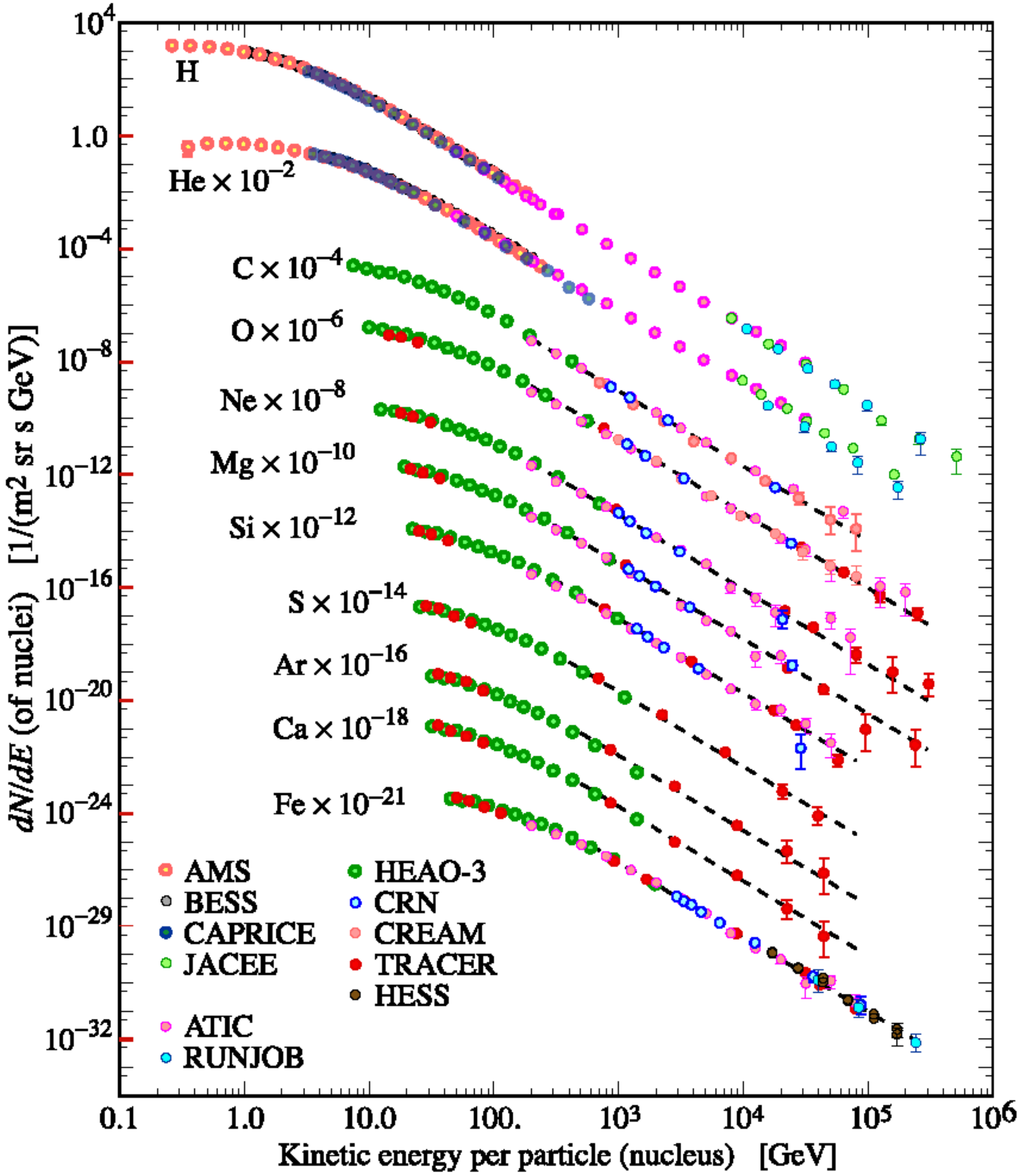
$$\frac{dN}{dE} \propto E^{-\alpha}$$

Data from AMS on ISS



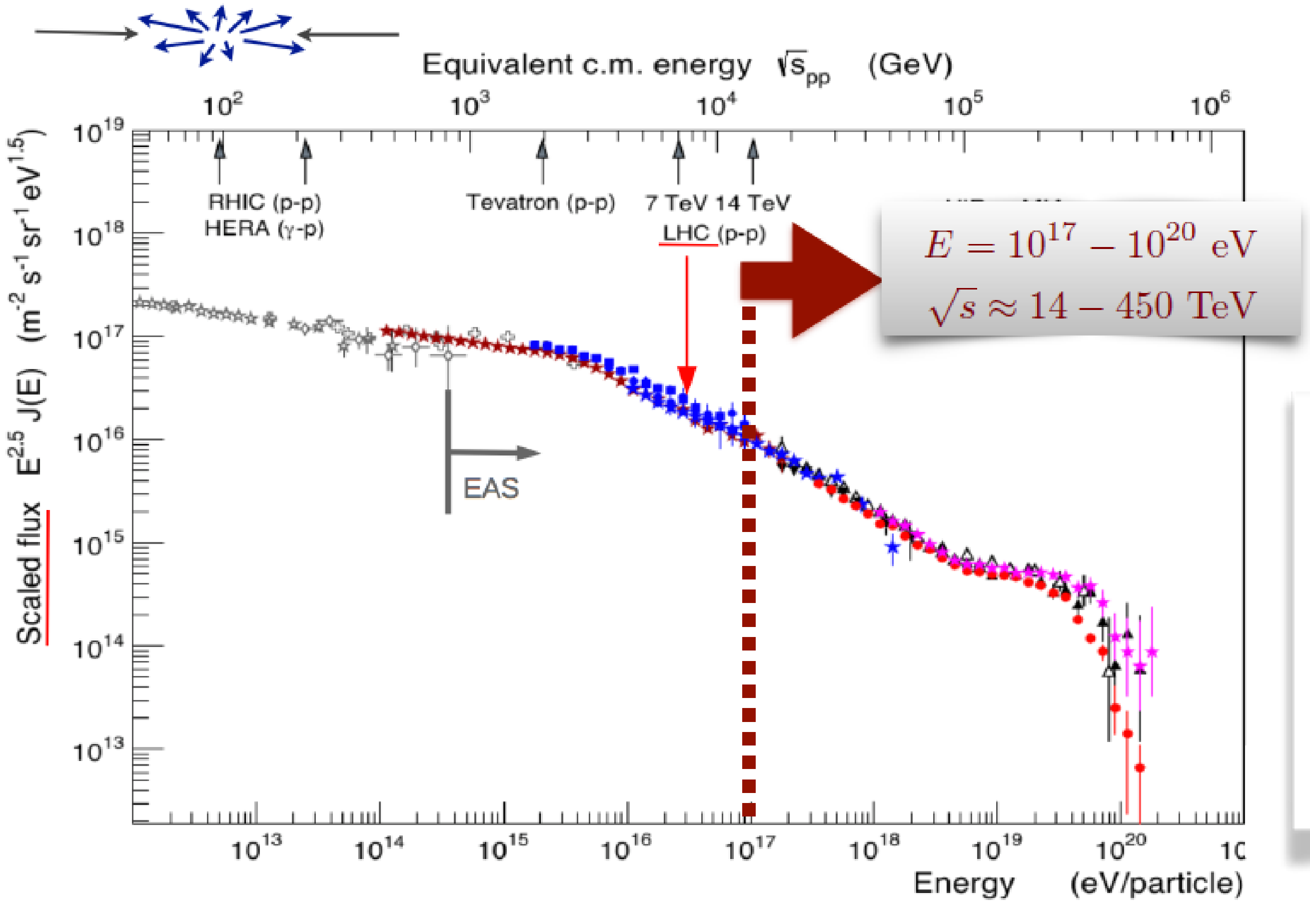
Geomagnetic cutoff depending on latitude

Identified spectra



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

CR spectrum above 1 TeV up to UHE



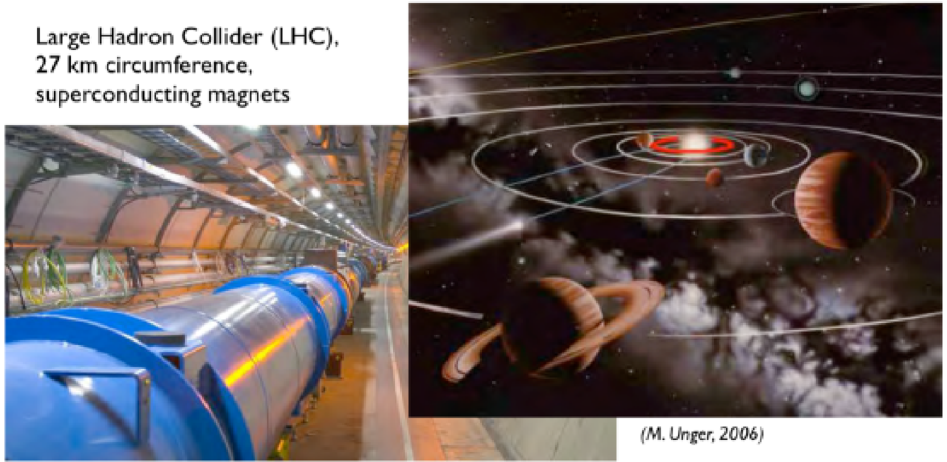
$$E = 10^{17} - 10^{20} \text{ eV}$$

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

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

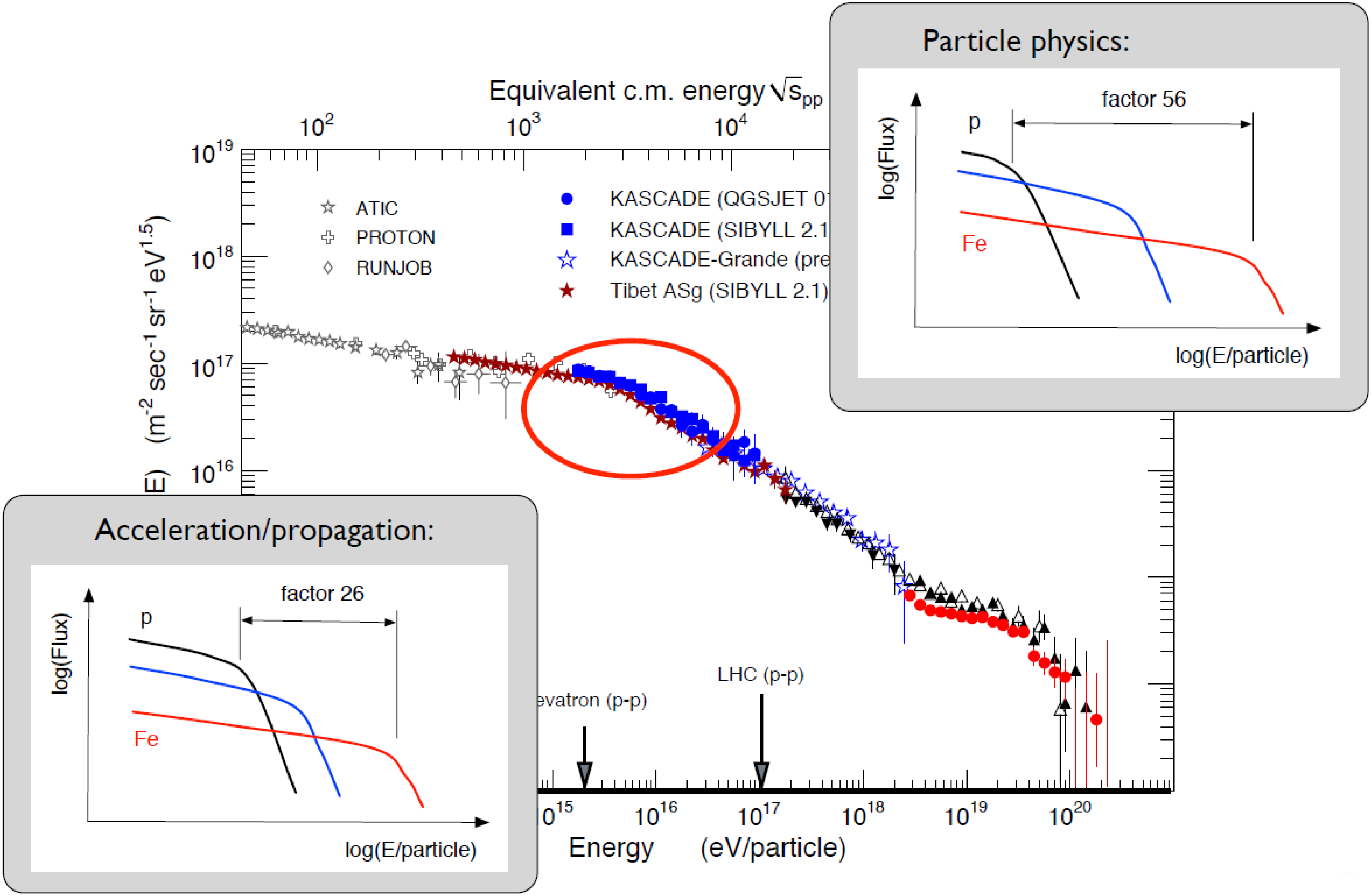
Need accelerator of size of Mecury's orbit to reach 10^{20} eV with current technology

(M. Unger, 2006)

PARTICLE PHYSICS

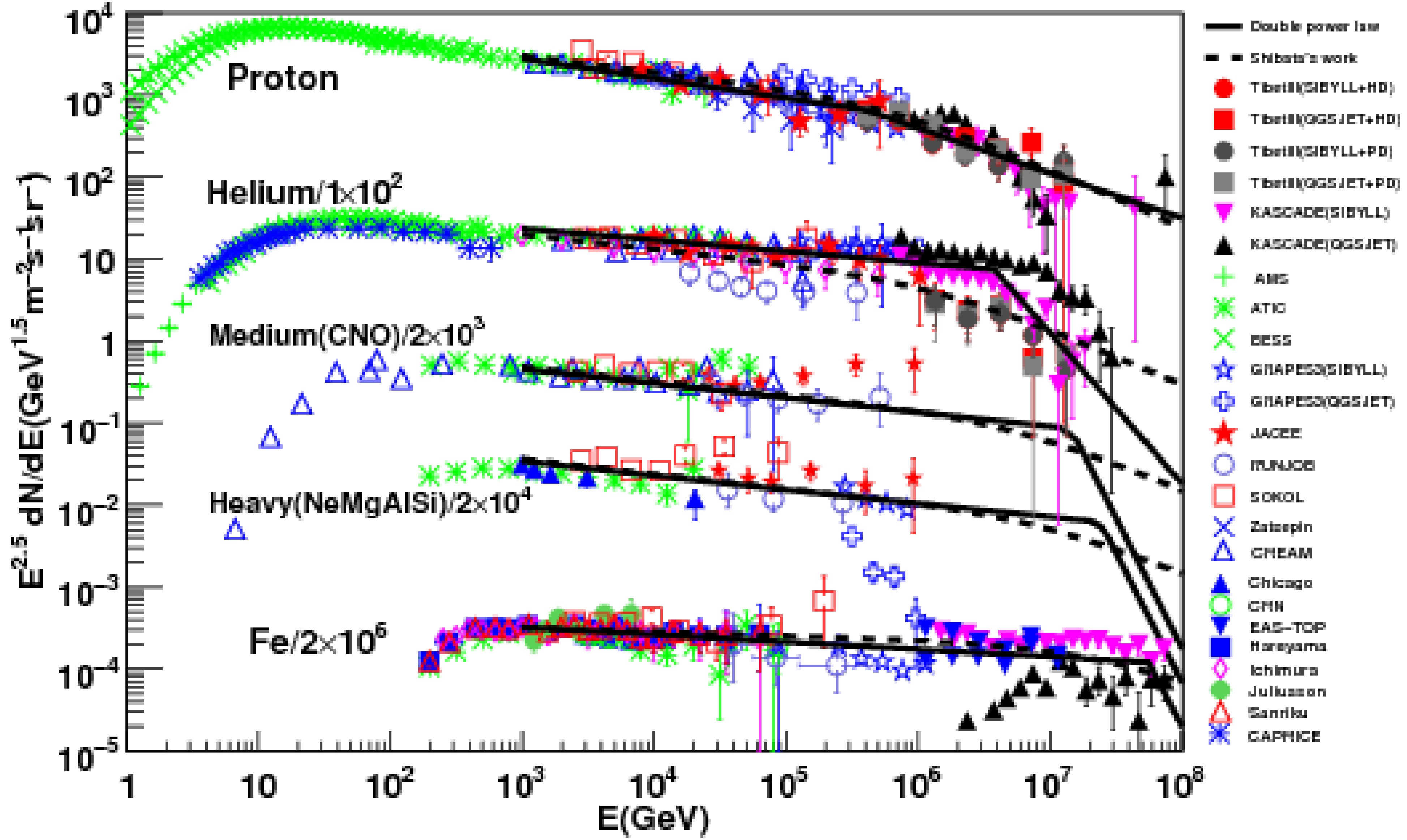
- ➡ very different energetic and kinematic phase space, for targets with <A>~14
- ➡ LHC tuning of hadronic interaction models employed in UHECR
- ➡ + constrain or find hints of new phenomena (e.g. Lorentz invariance violation)

Origin and physics of the knee


Particle physics:

Acceleration/propagation:

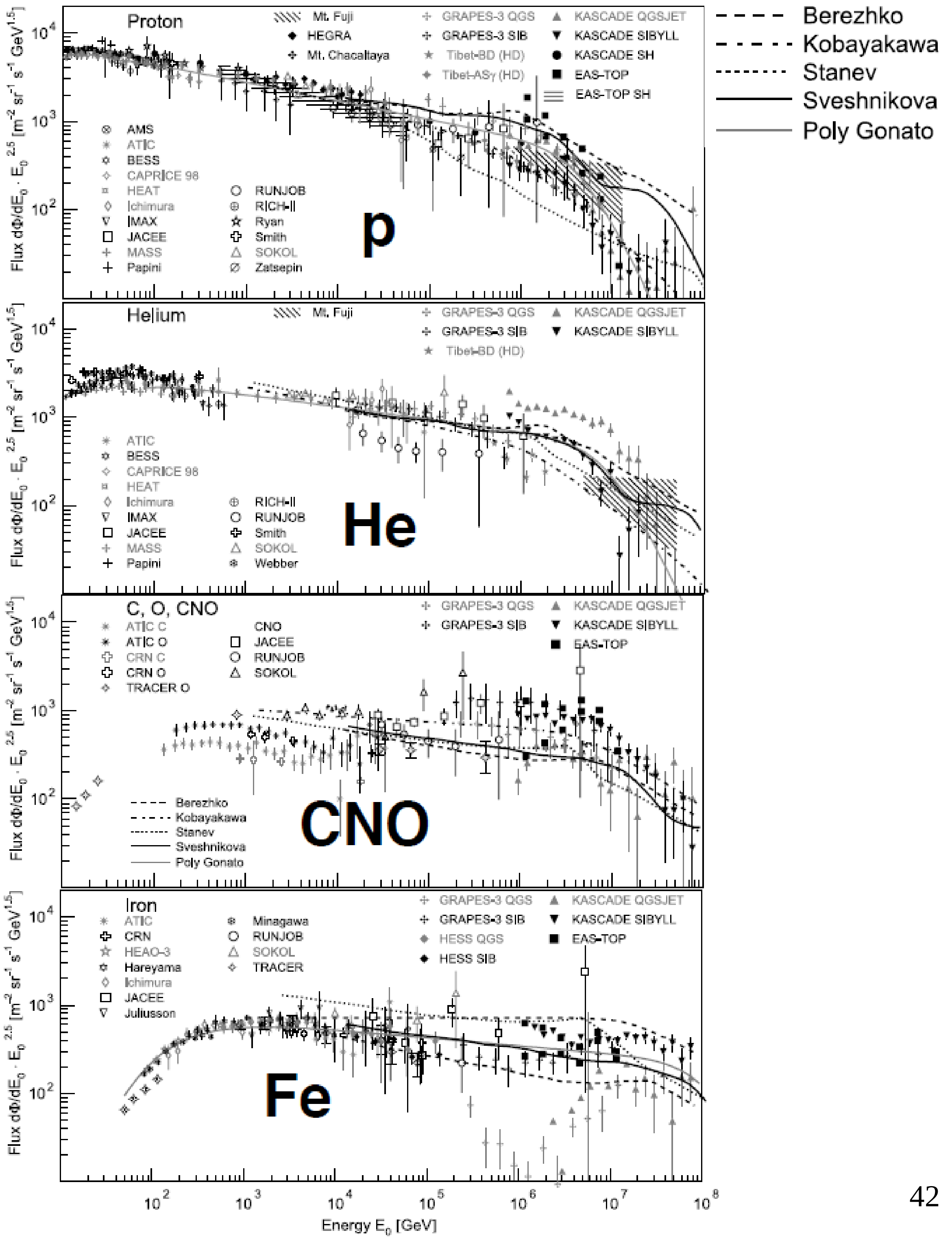
Z dependent cutoff at the knee ?



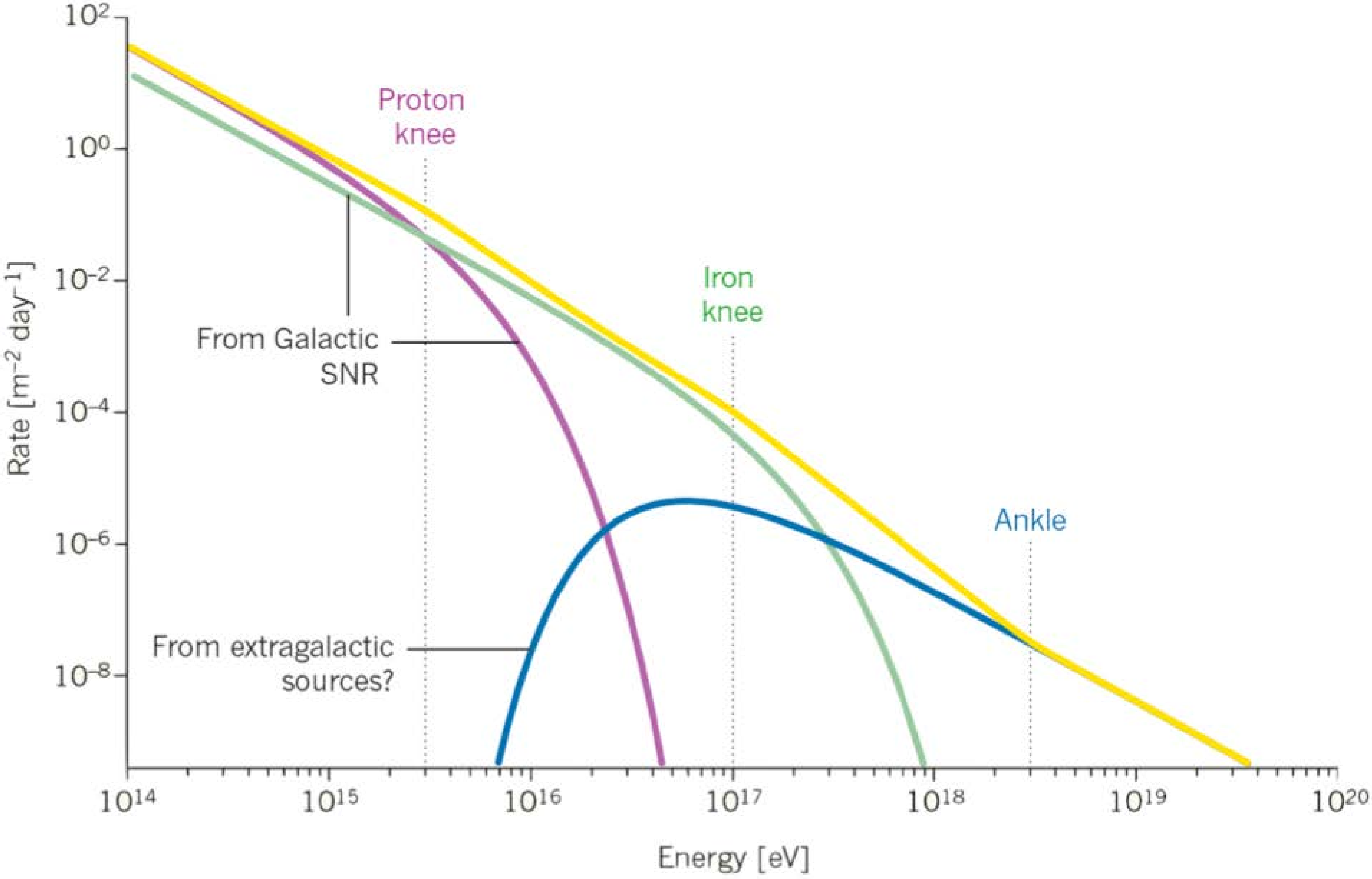
Z dependent cutoff at the knee ?

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

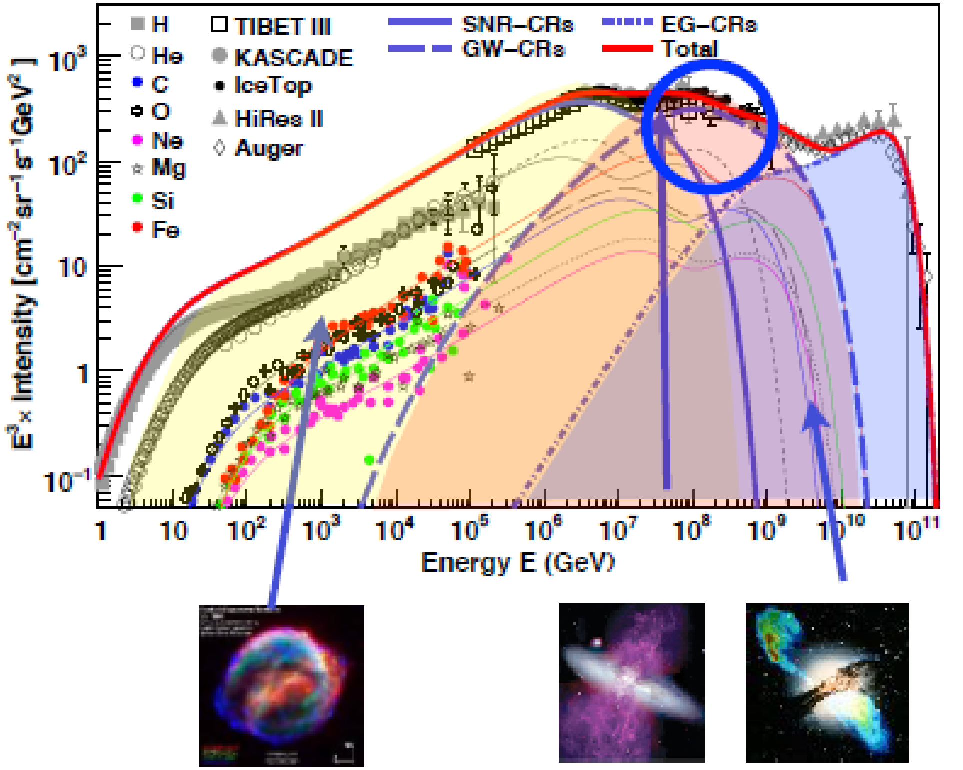
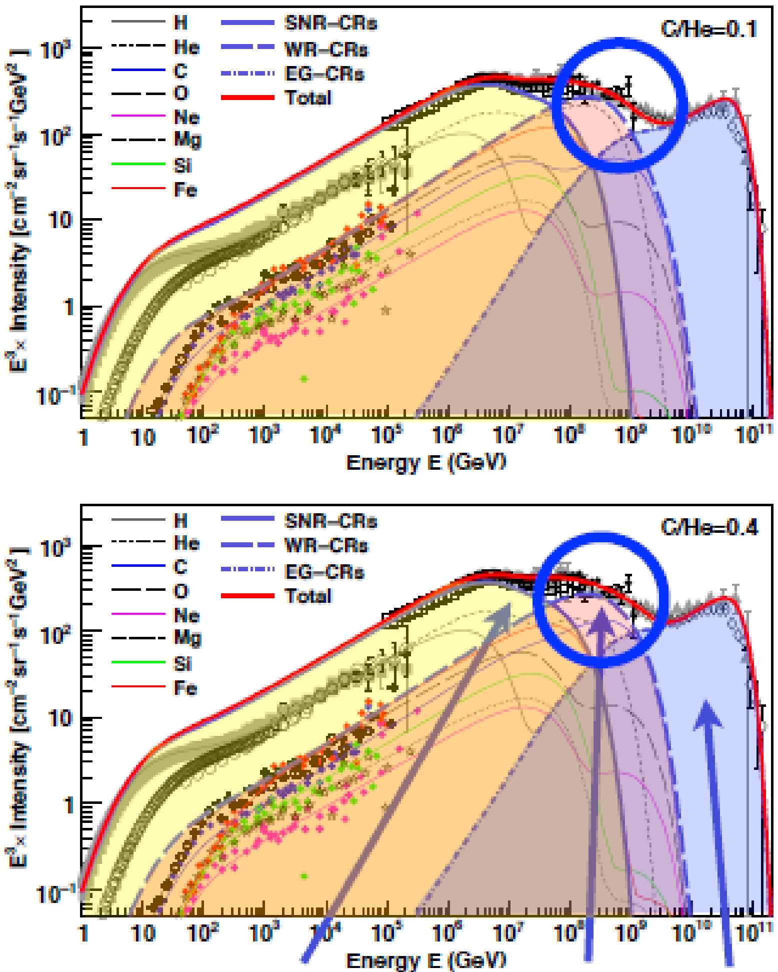
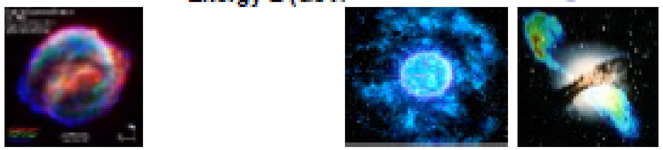


Table 3. Injection energy of SNR-CRs used in the calculation of all-particle spectrum in the WR-CR model (Figure 6).

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}



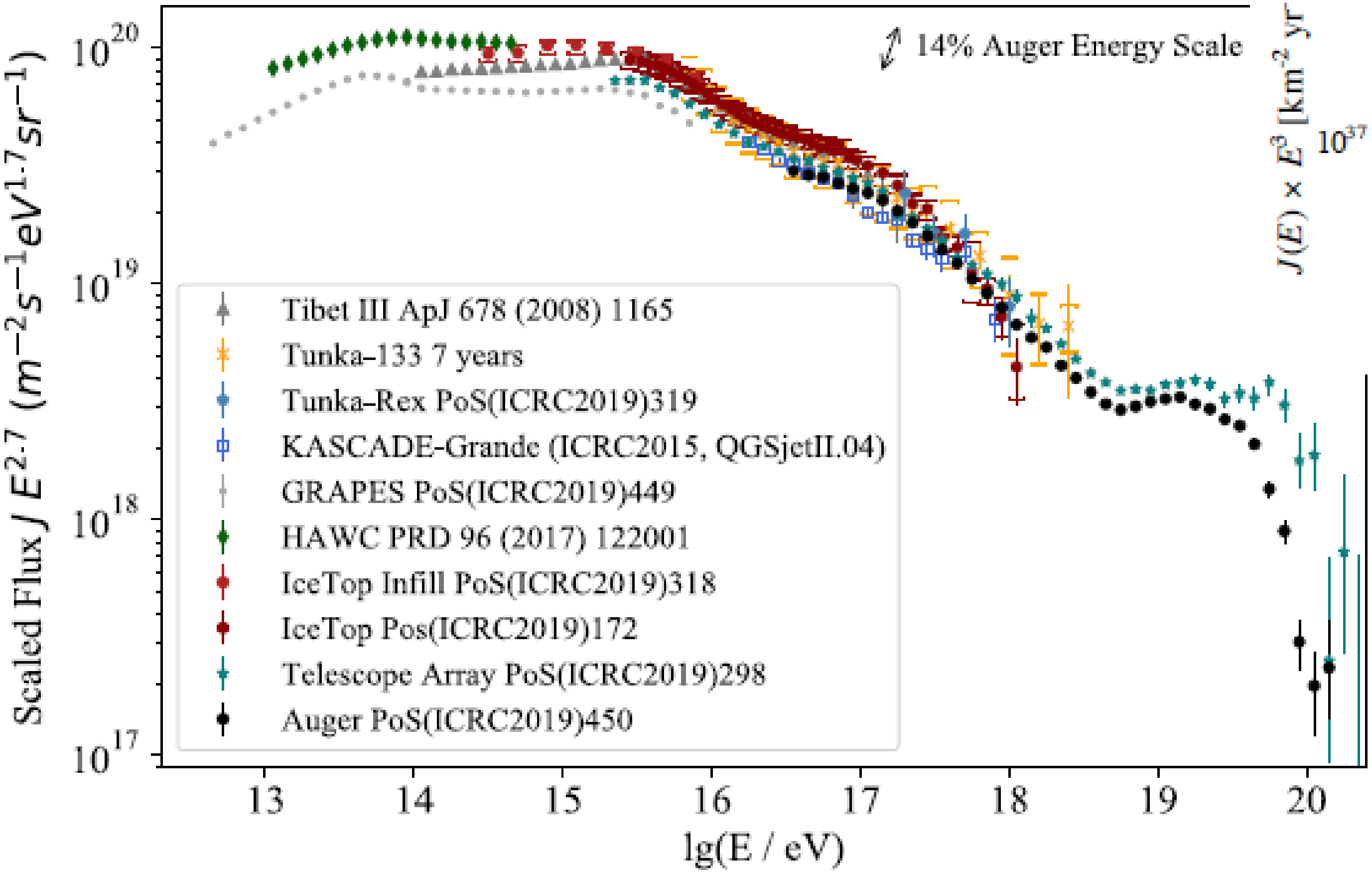


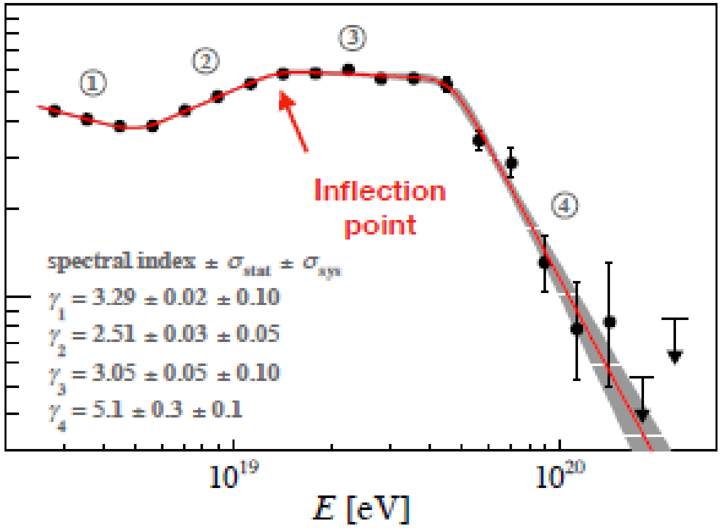
S. Thoudam et al., A&A 595 (2016) A33

Spectum @ UHE

1. Energy spectrum – status today

(Schröder, rapporteur talk, ICRC 2019)



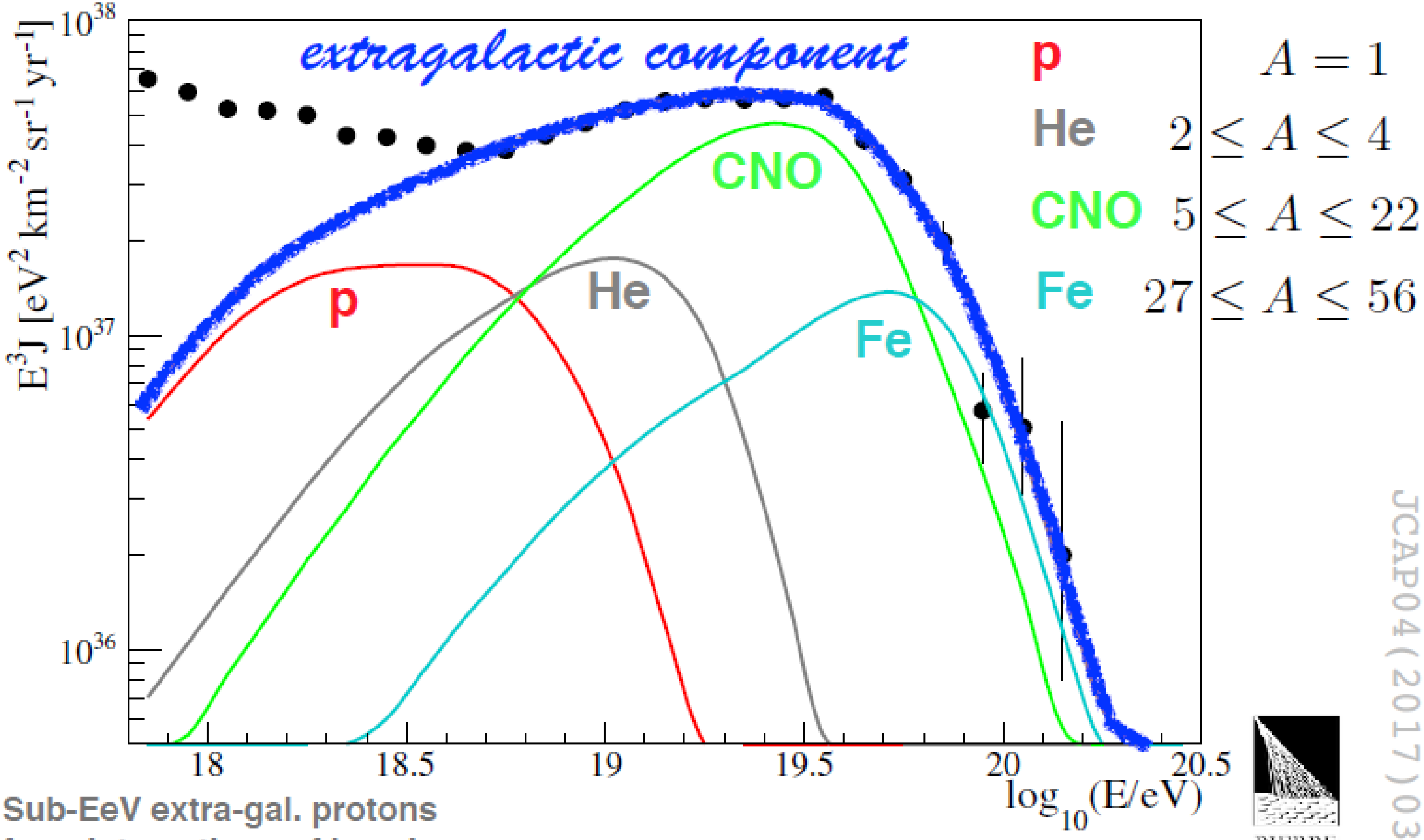


(Auger, Phys. Rev. Lett. & Phys. Rev. D 2020)

- **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



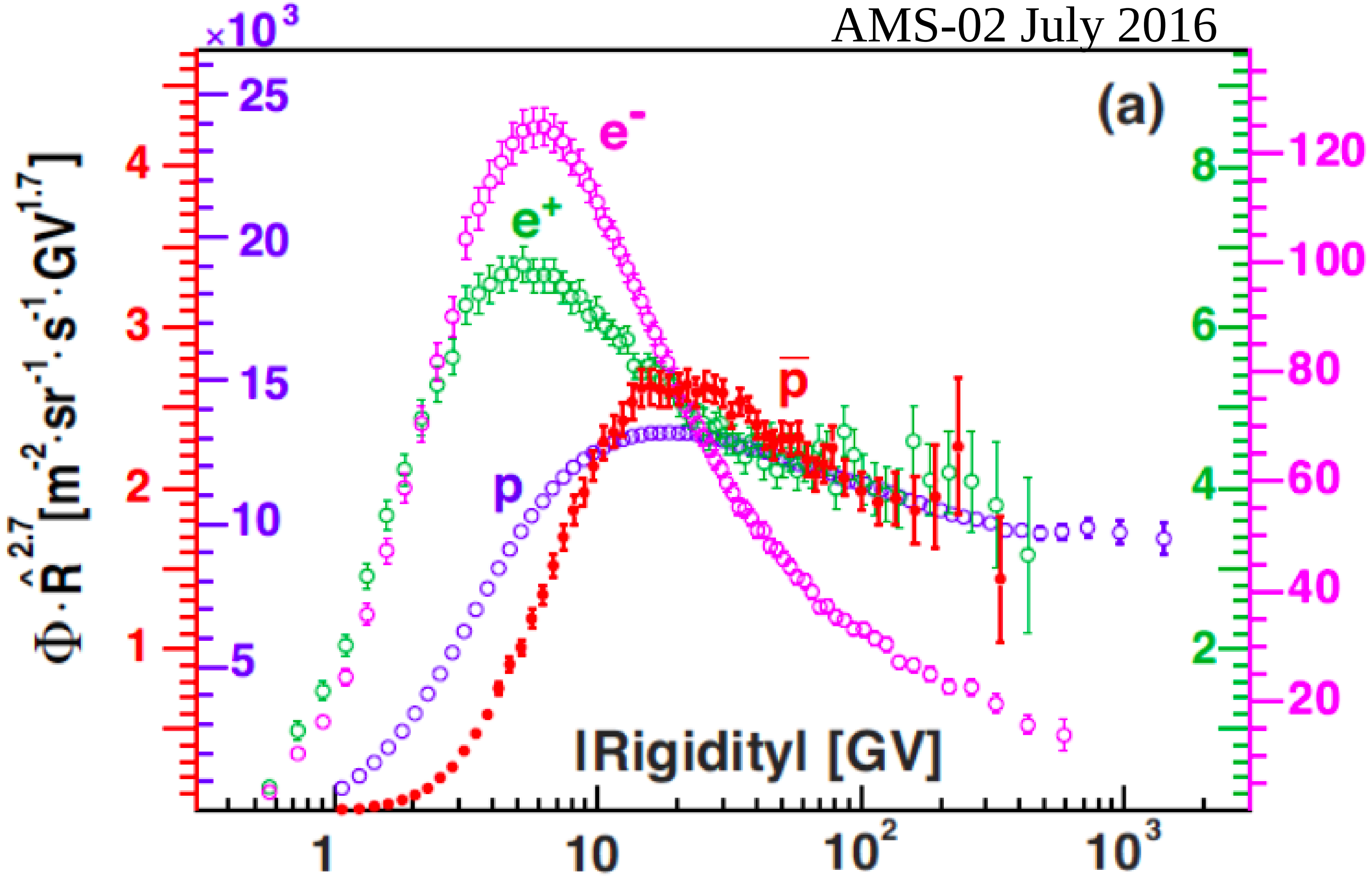
JCAP04(2017)038

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

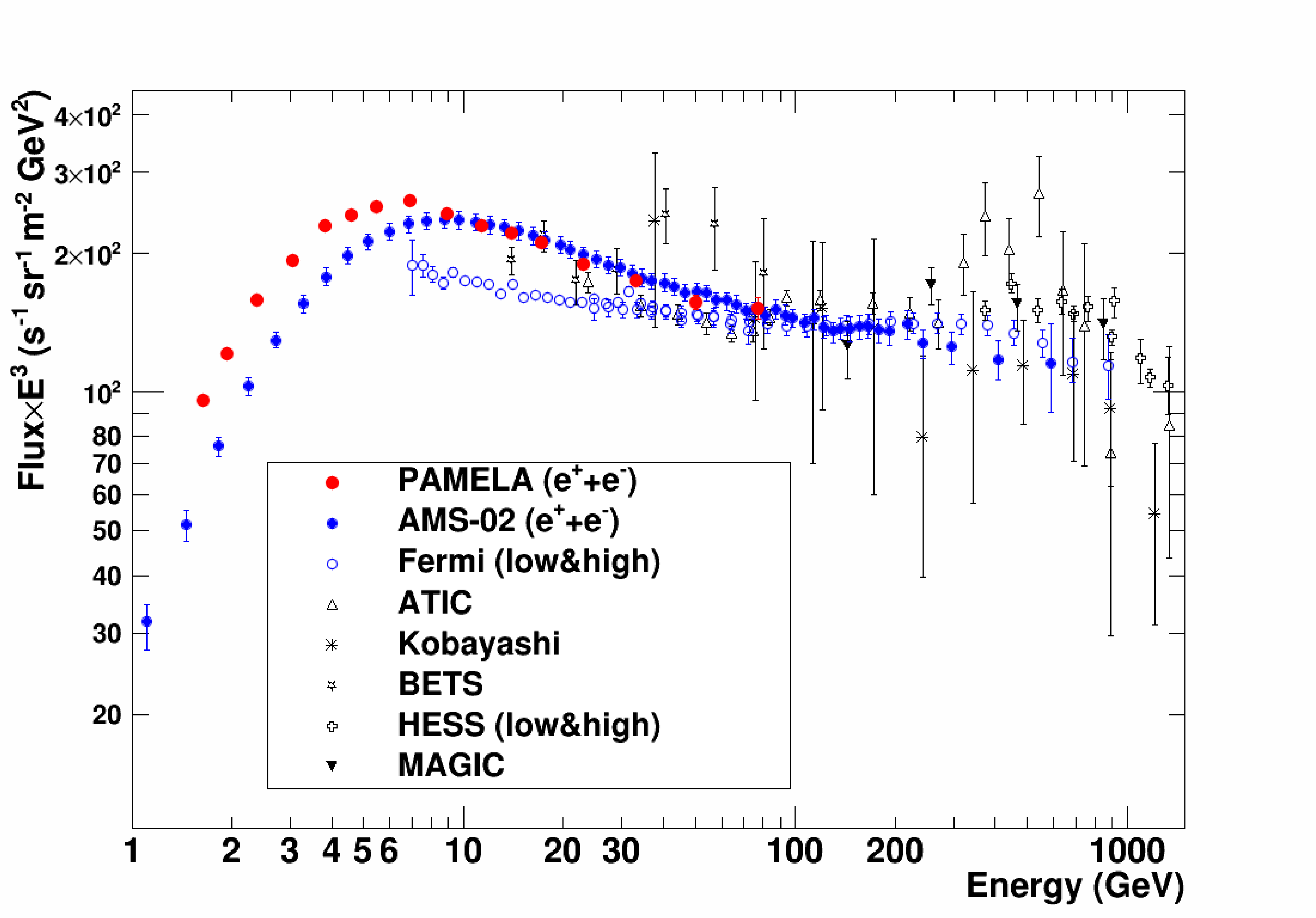
PIERRE AUGER OBSERVATORY

Fluxes of e⁺, e⁻, p and anti-p

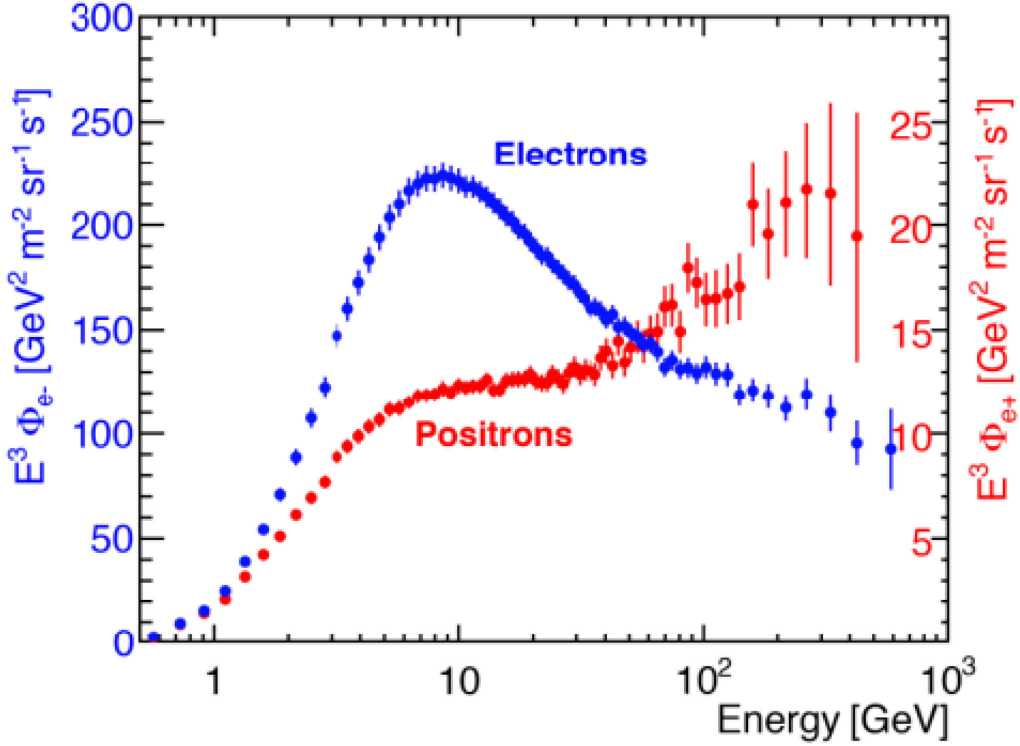
AMS-02 July 2016

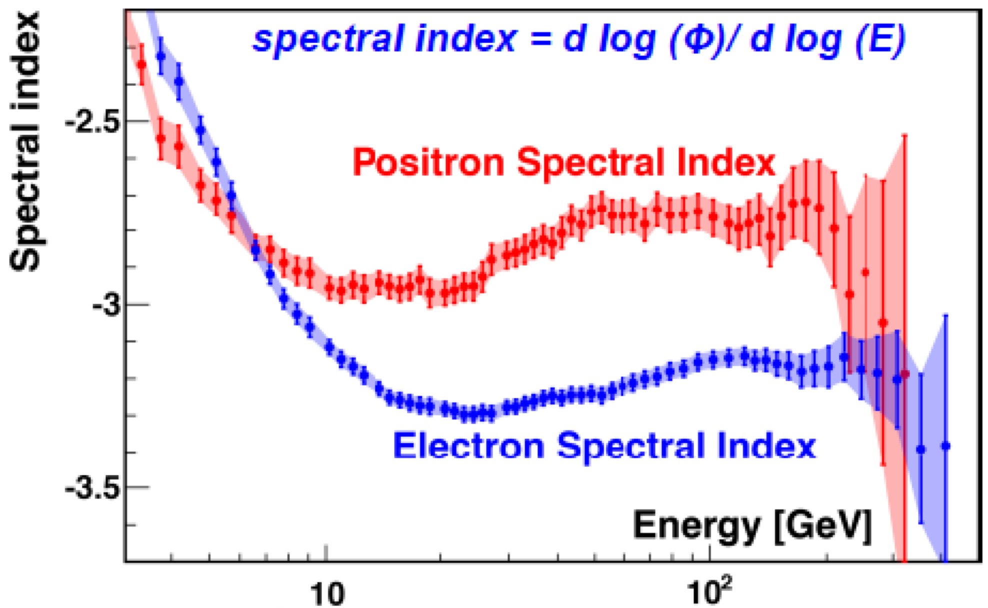


Electron and positron primary flux



Electron and positron primary flux





AMS-02 July 2016

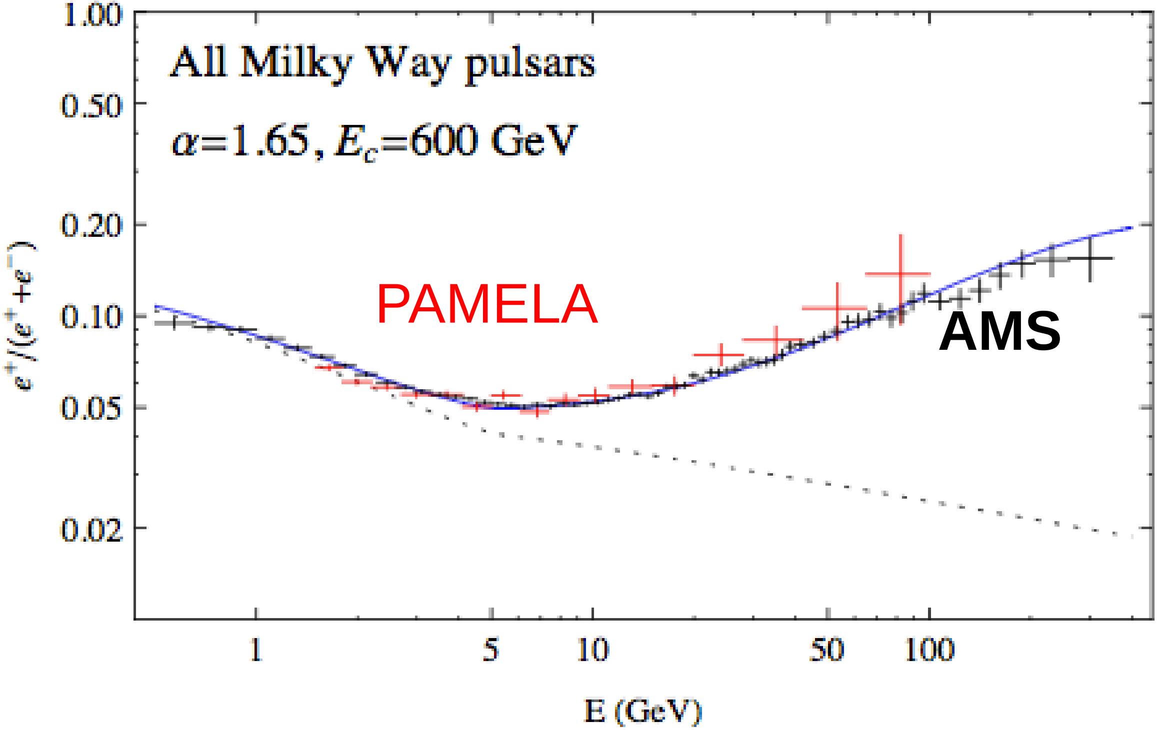
Observations:

1. The electron flux and the positron flux are different in their magnitude and energy dependence.
2. Both spectra cannot be described by single power laws.
3. The spectral indices of electrons and positrons are different.
4. Both change their behavior at ~30GeV.
5. The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder).

Origin of the positron excess

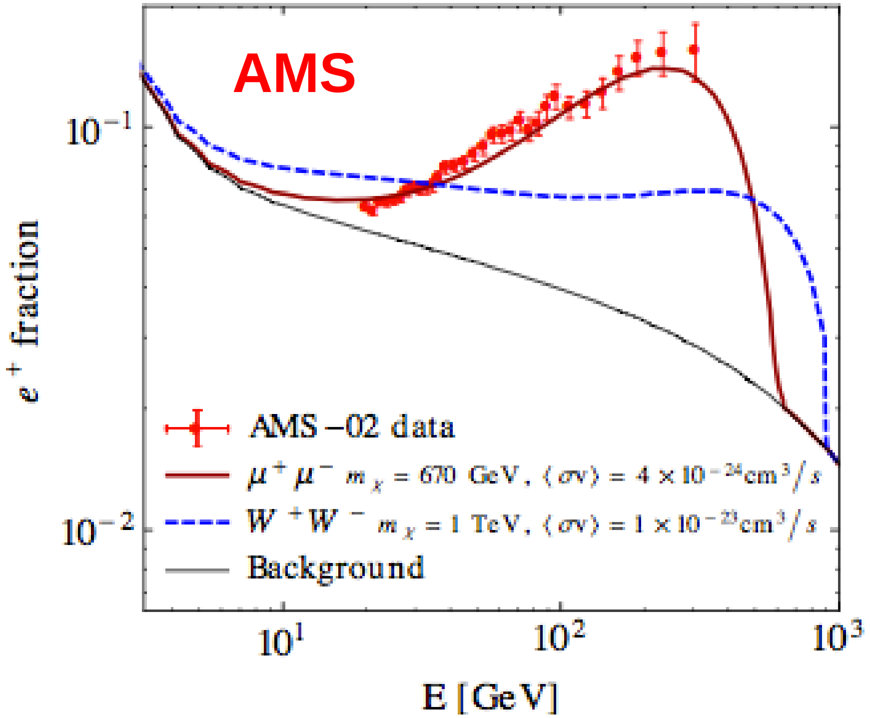
Astrophysical objects

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

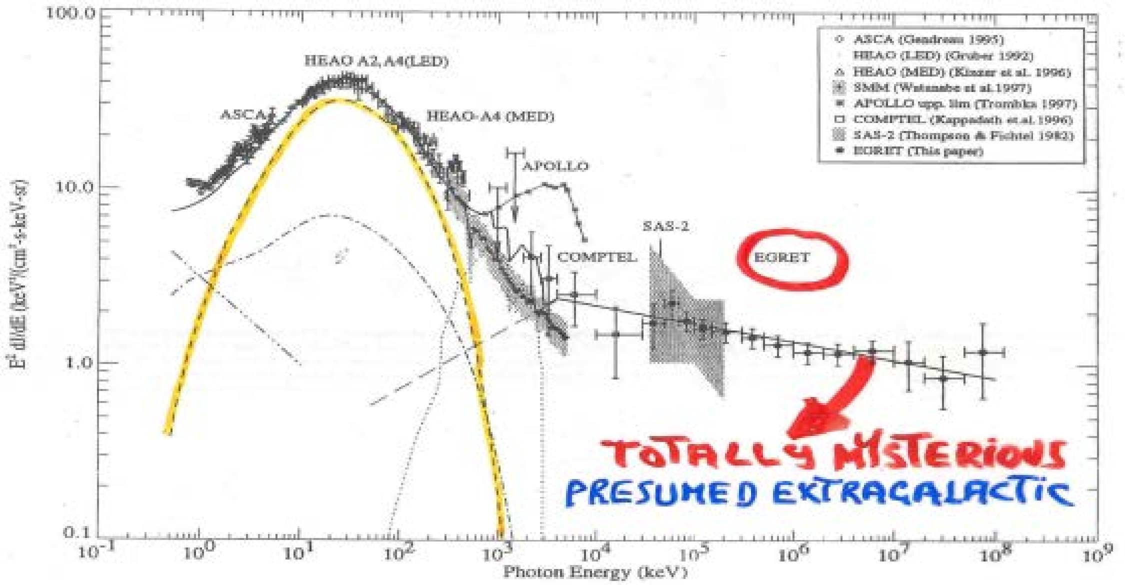
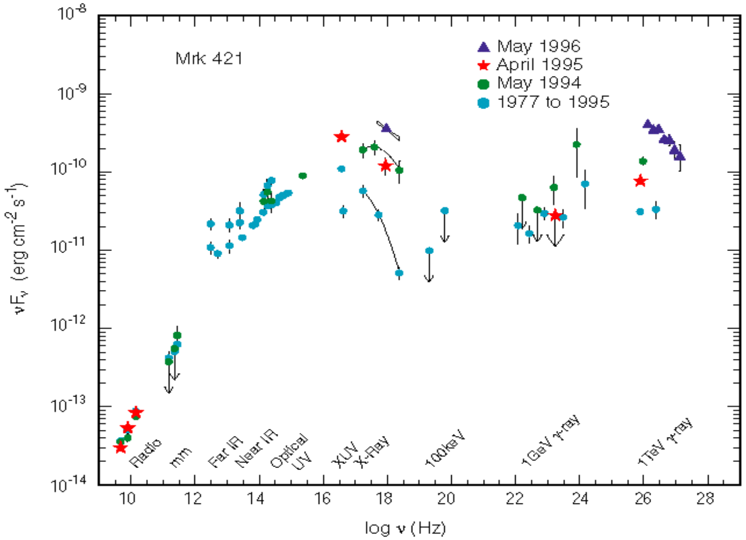


FIG. 10.—Multiwavelength spectrum of the extragalactic gamma-ray spectrum from X-rays to high-energy gamma rays. The estimated contribution from Seyfert I (*dot-dashed line*), and Seyfert II (*dashed*) are from the model of Zdziarski (1996); steep-spectrum quasar contribution (*triple-dot–dashed line*) 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.



Why all this non thermal equilibrium radiation?

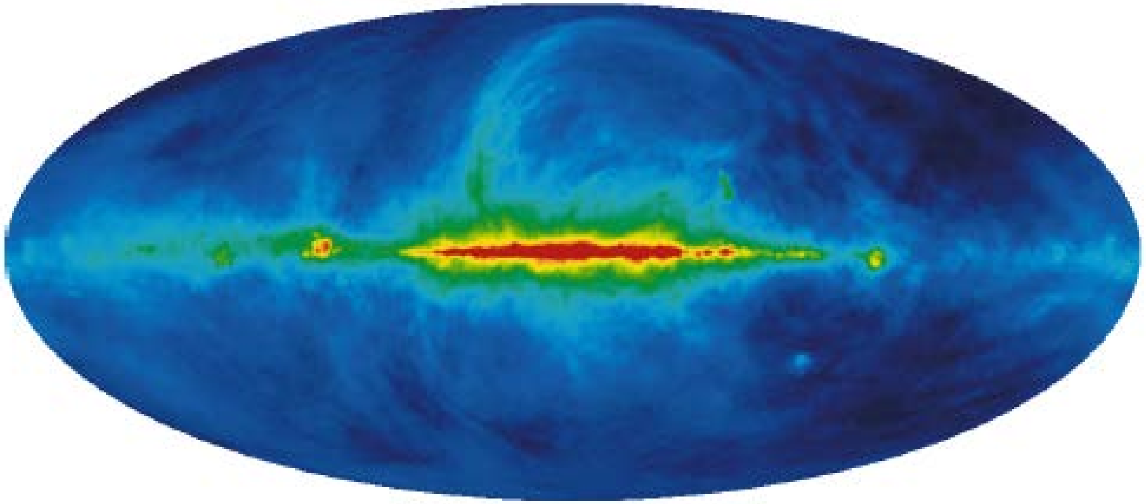
Gamma, diffuse emission

Emission due to:

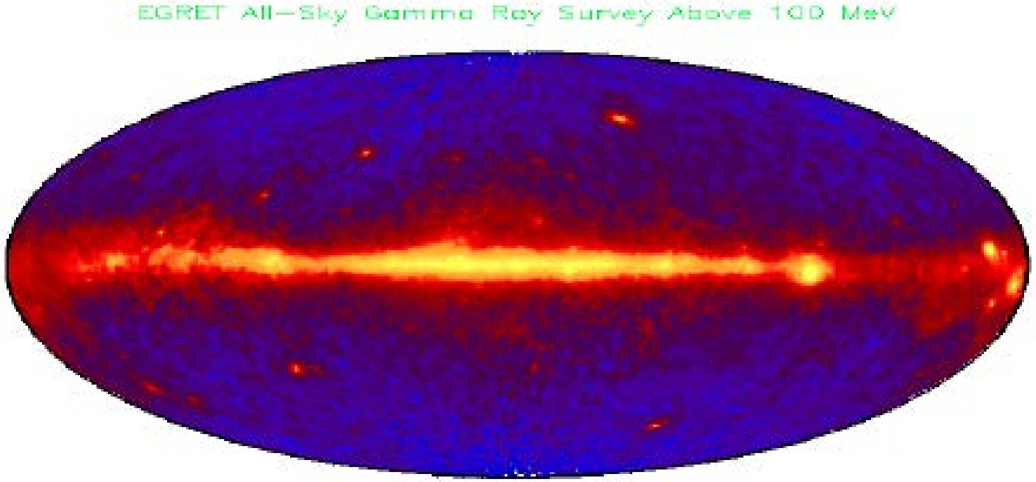
- the interactions of cosmic electrons with:
  - the magnetic fields (synchrotron radiation dominates the radio emission of the Galaxy up to a few GHz)
  - interstellar Matter (ISM); bremsstrahlung important bellow 100 MeV
  - Interstellar photon: Inverse Compton above GeV
- the decay of π^0 produced 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 definite 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: $2.5 \times 10^{-7} cm^{-2}.s^{-1}$

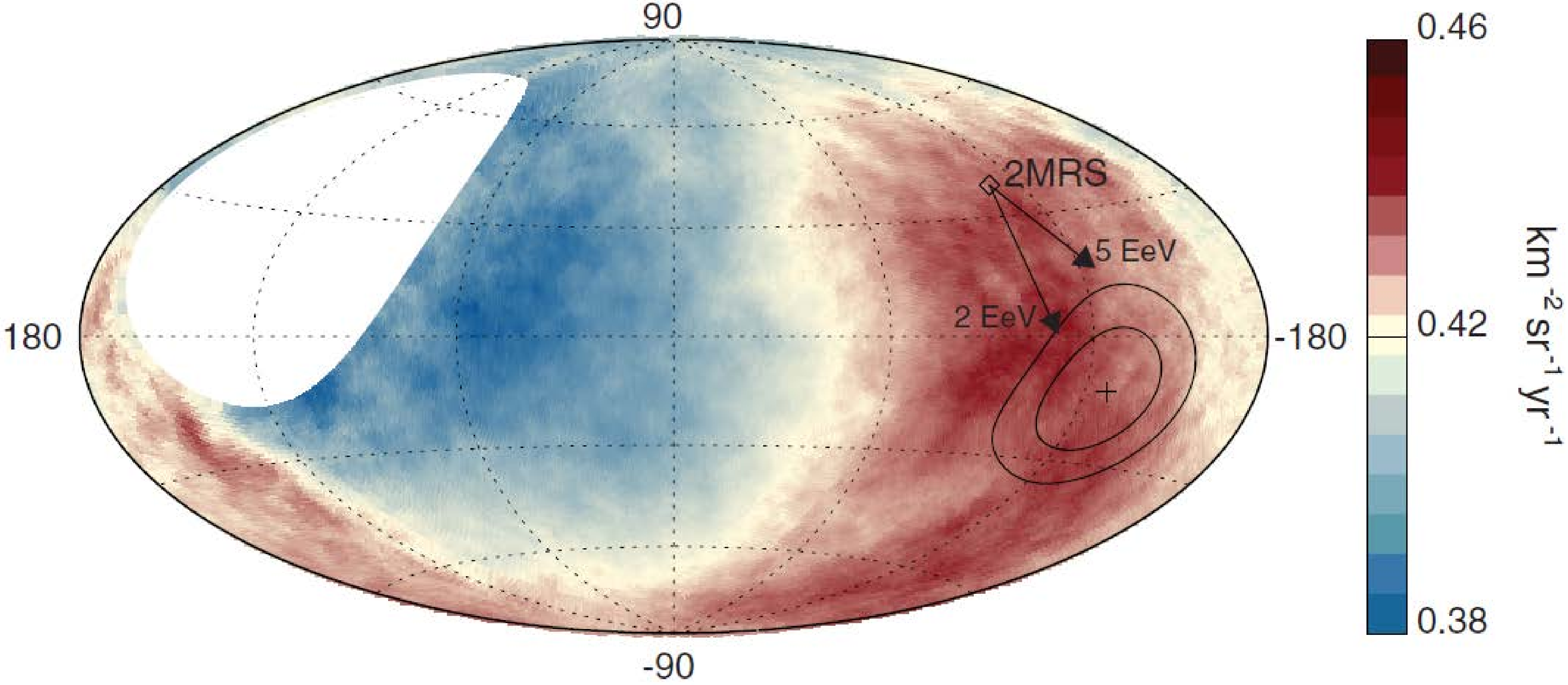
$$F_\gamma \propto M_H N_{CR} R_q$$

- 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

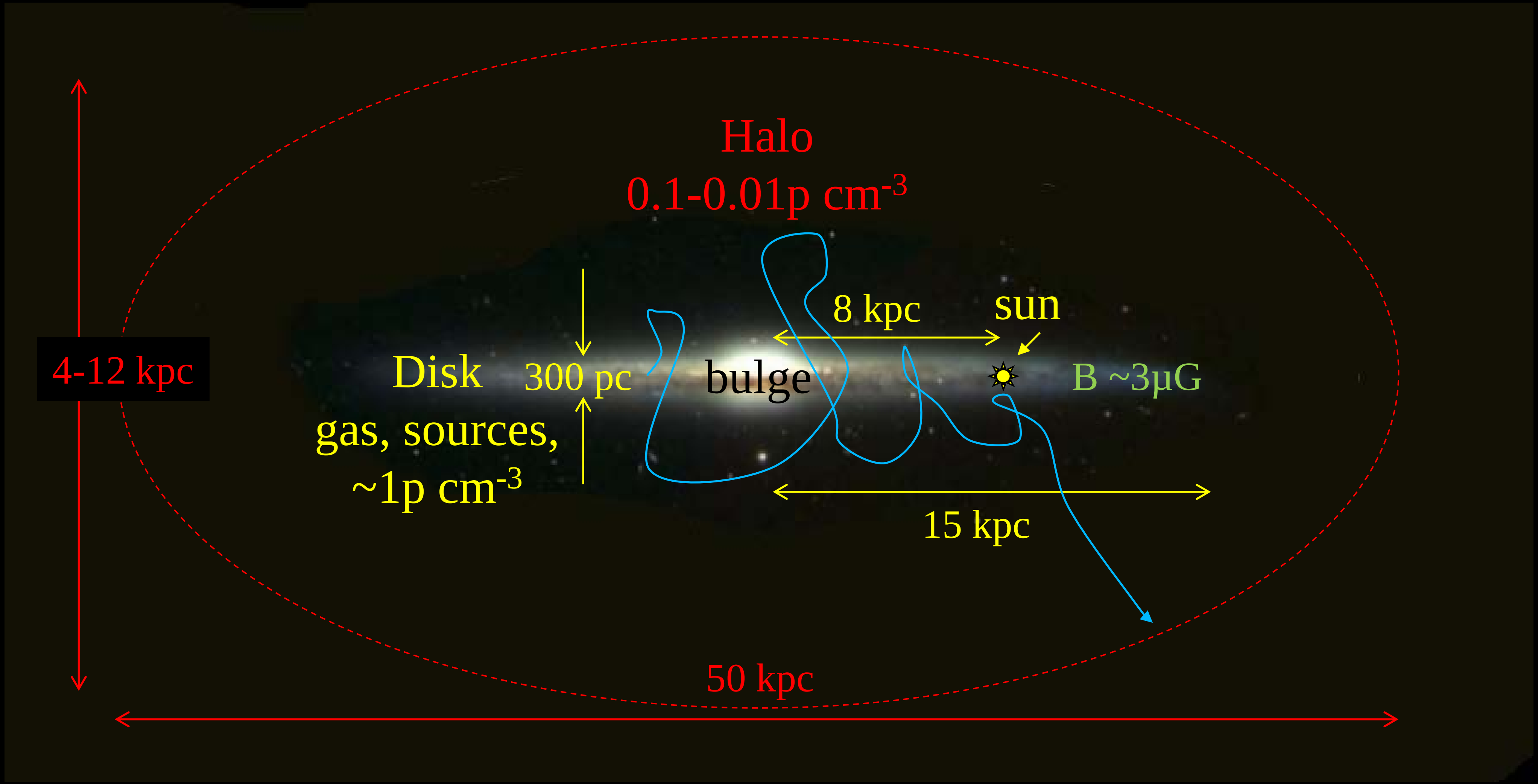
Detect them

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

Propagation medium, IGM, ISM and atmosphere

Dimensions of the Milky Way

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

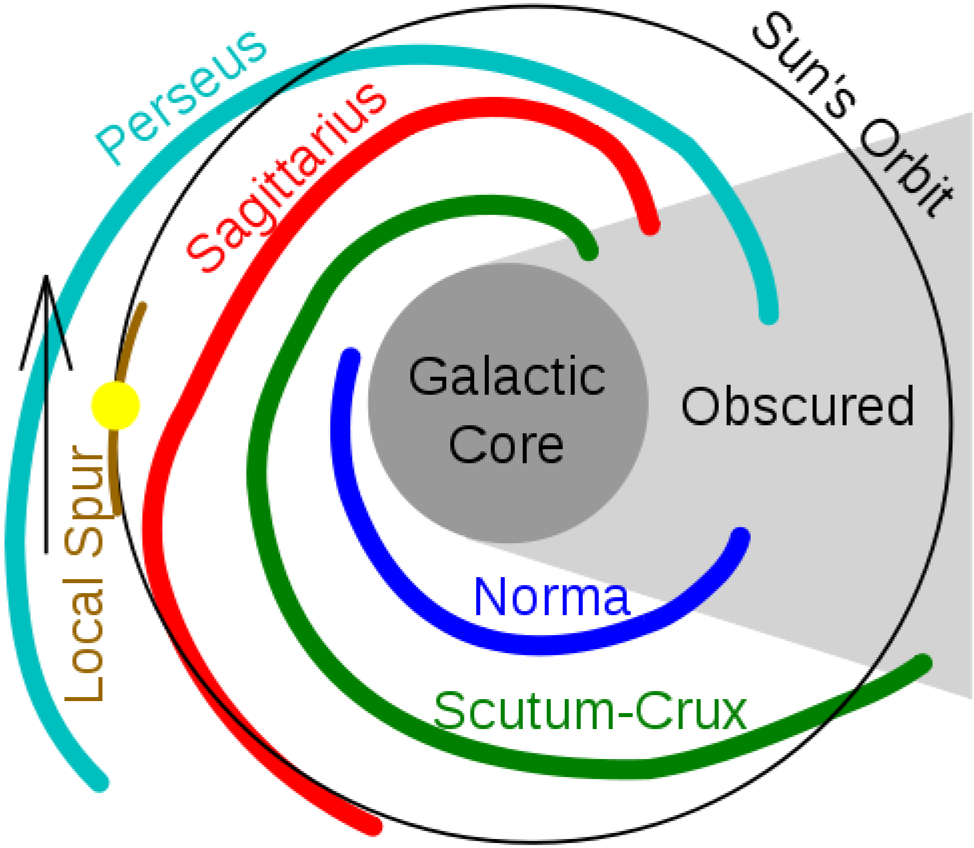


Milky Way, a spiral galaxy

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.

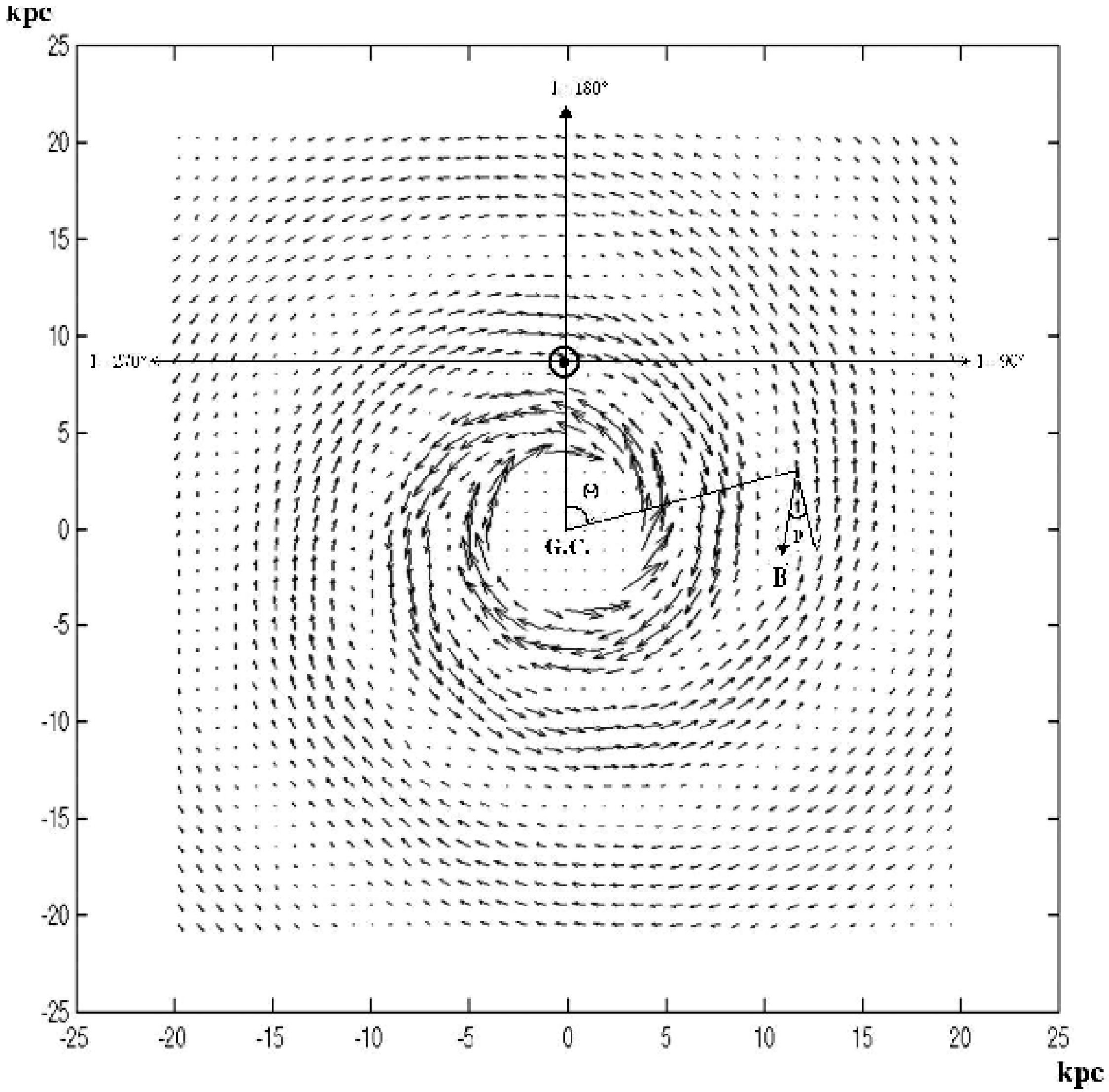


Milky Way, a spiral galaxy

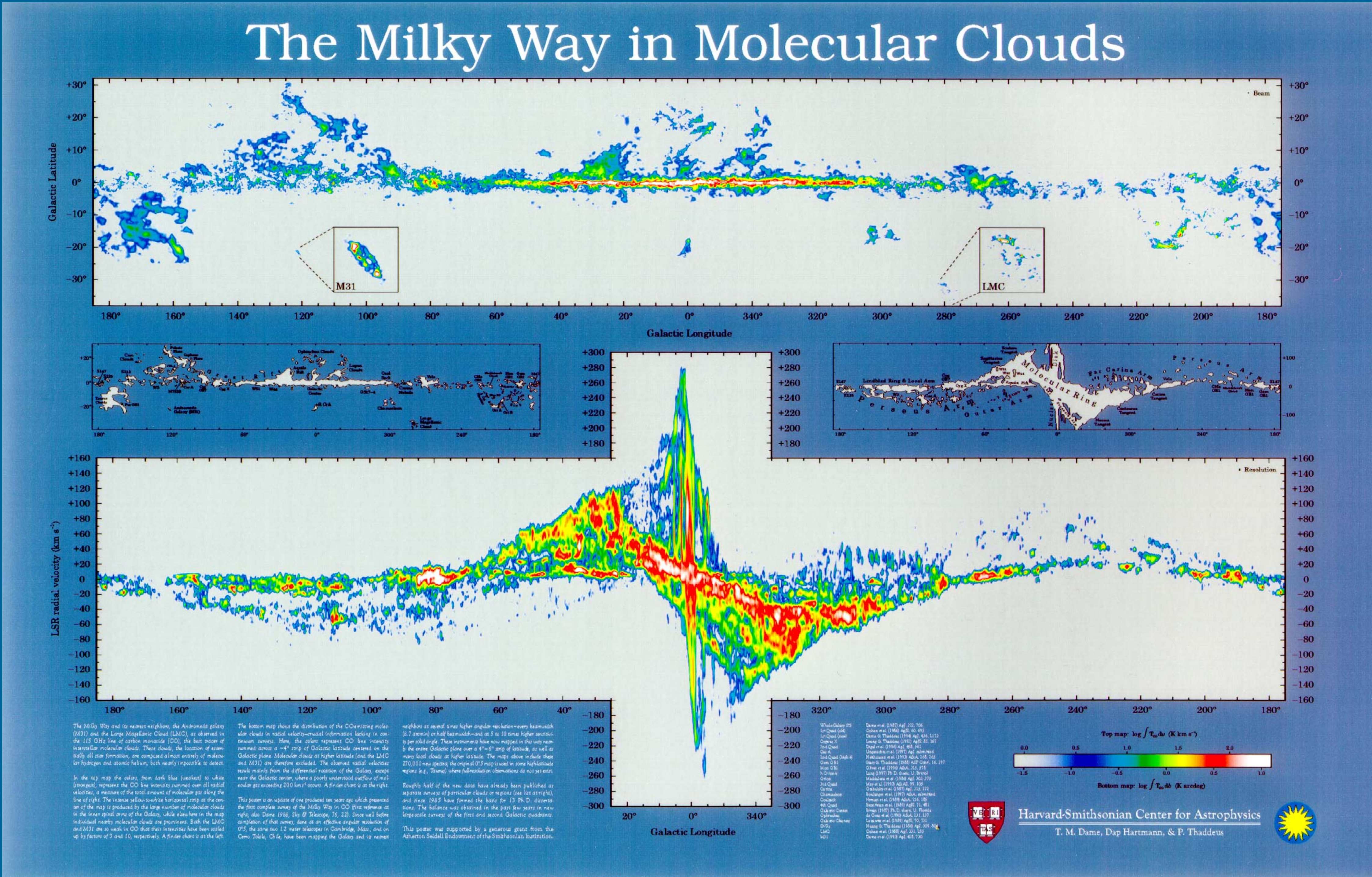
Local spur and neighboring arms) local matter and B field inhomogeneity.

"Regular" B field ~ 3μG 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.

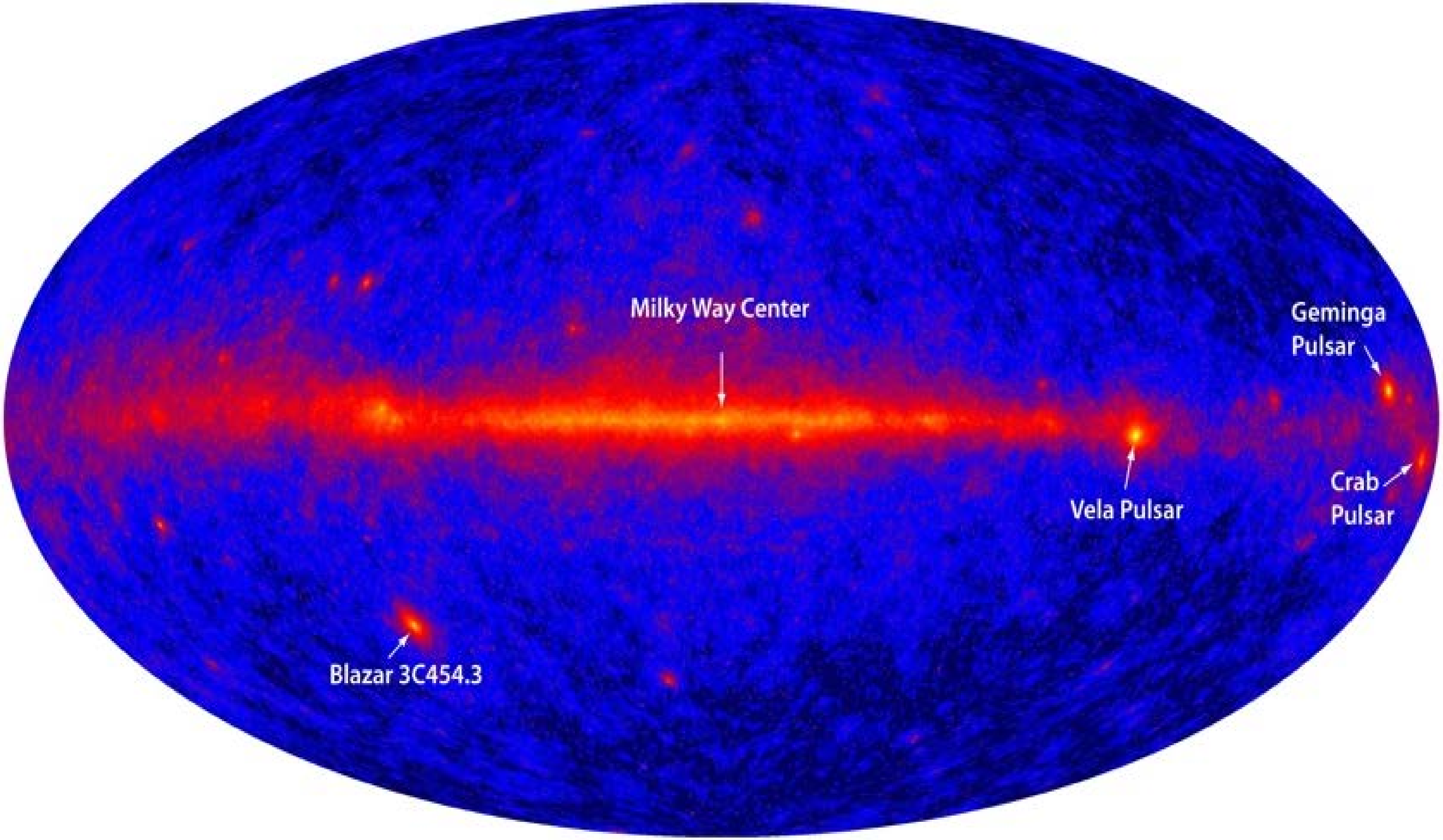
Whole Galaxy 0°5	Dame et al. (1987) ApJ, 322, 706
1st Quad (old)	Cohen et al. (1986) ApJS, 60, 695
1st Quad (new)	Dame & Thaddeus (1994) ApJ, 436, L173
Cygnus X	Leung & Thaddeus (1992) ApJS, 81, 267
2nd Quad	Digel et al. (1996) ApJ, 458, 561
Cas A	Ungerechts et al. (1997) ApJ, submitted
2nd Quad (high b)	Heithausen et al. (1993) A&A, 268, 265
Gem OB1	Stacy & Thaddeus (1988) ASP Conf. 16, 197
Mon OB1	Oliver et al. (1996) A&A, 315, 578
λ Orionis	Lang (1997) Ph.D. thesis, U. Bristol
Orion	Maddalena et al. (1986) ApJ, 303, 375
3rd Quad	May et al. (1993) A&AS, 99, 105
Carina	Grabelsky et al. (1987) ApJ, 315, 122
Chamaeleon	Boulanger et al. (1997) A&A, submitted
Coalsack	Nyman et al. (1989) A&A, 216, 185
4th Quad	Bronfman et al. (1989) ApJS, 71, 481
Galactic Center	Bitran (1987) Ph.D. thesis, U. Florida
Ophiuchus	de Geus et al. (1990) A&A, 231, 137
Galactic Clusters	Leisawitz et al. (1989) ApJS, 70, 731
SNRs	Huang & Thaddeus (1986) ApJ, 309, 804
LMC	Cohen et al. (1988) ApJ, 331, L95
M31	Dame et al. (1993) ApJ, 418, 730

Harvard-Smithsonian Center for Astrophysics

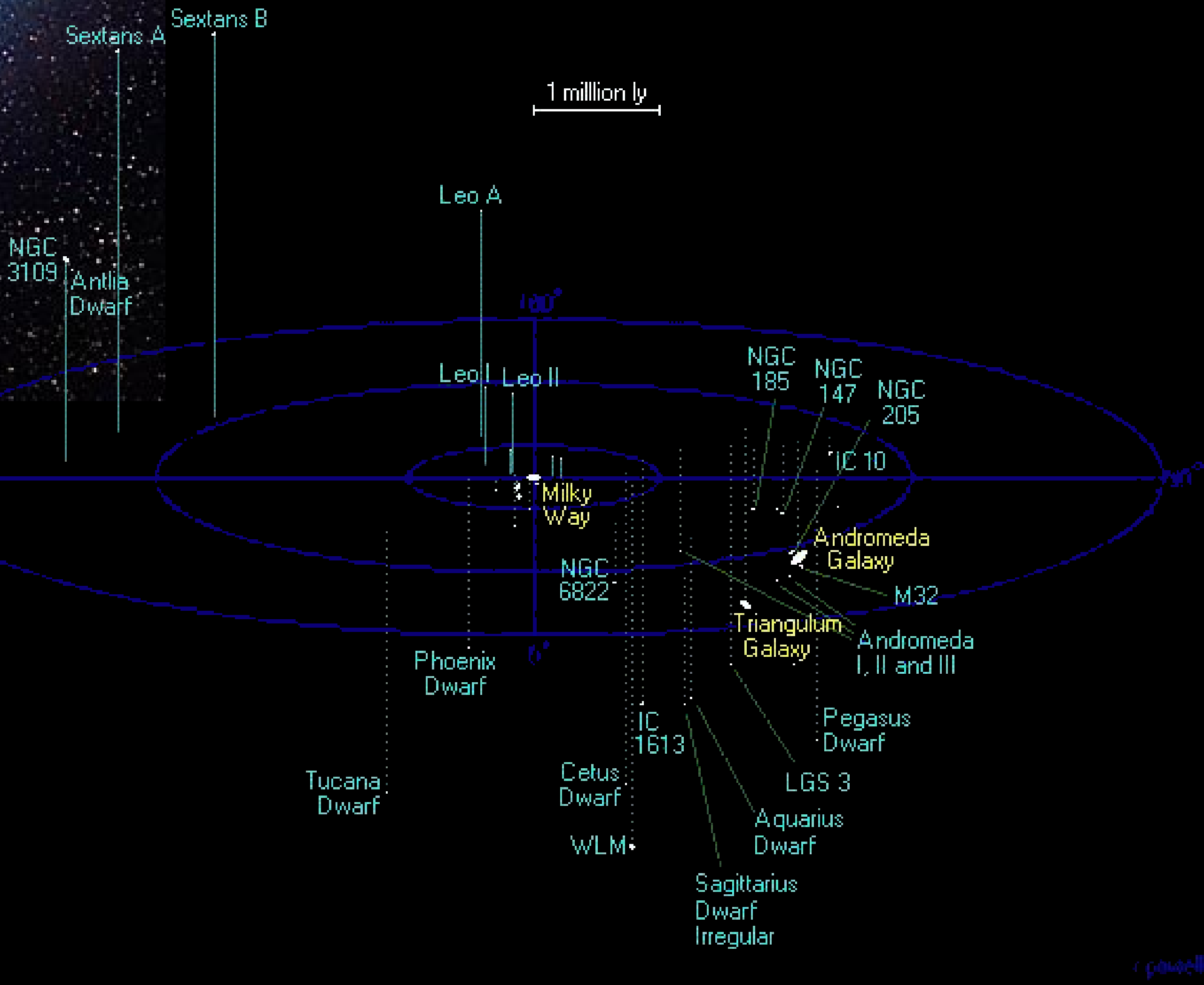
T. M. Dame, Dap Hartmann, & P. Thaddeus

A thick target

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



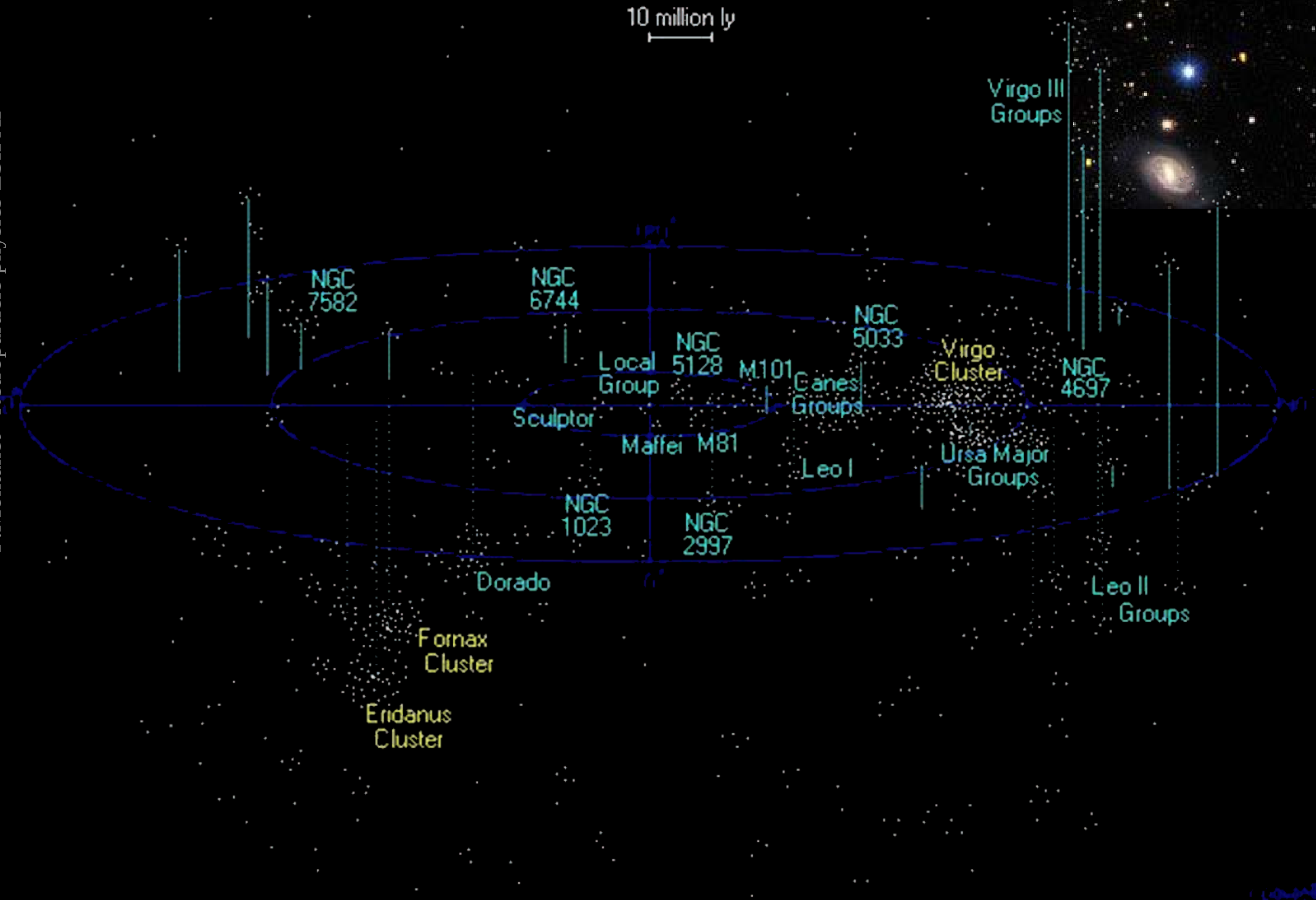
The nearby islands…



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

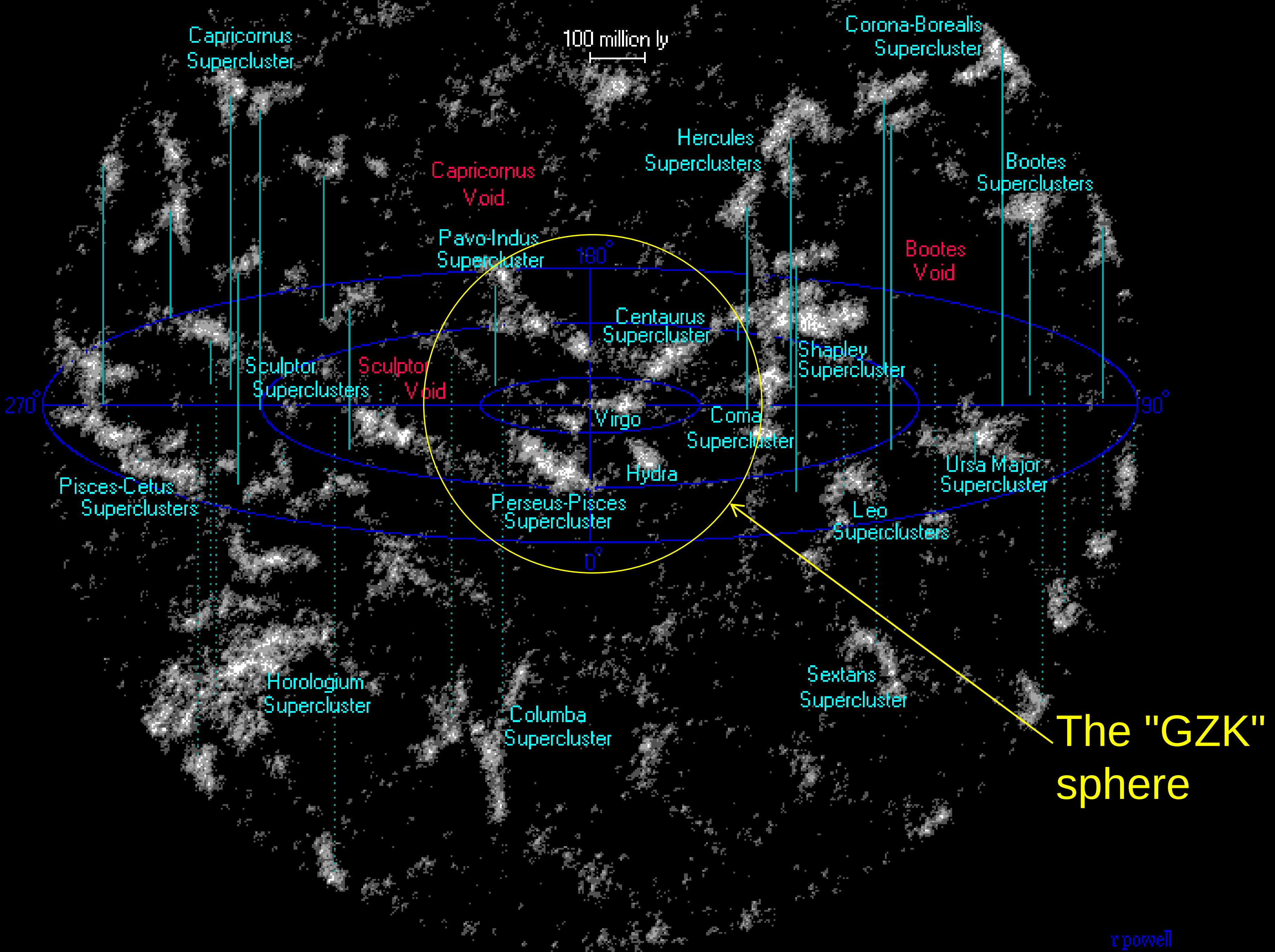
The local group and the Virgo cluster

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



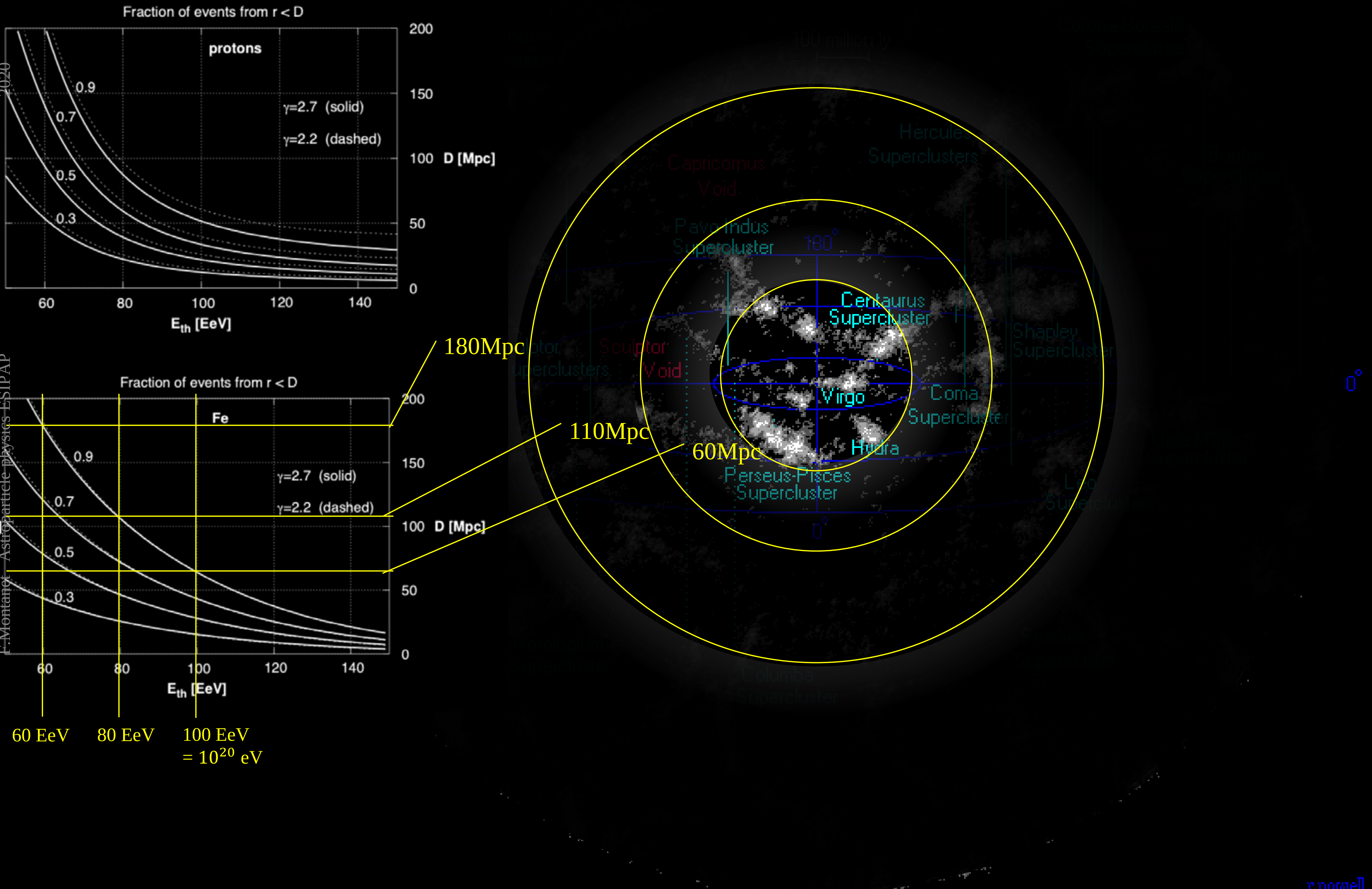
Another super cluster: Abel 1689

Horizon < 200Mpc at UHE

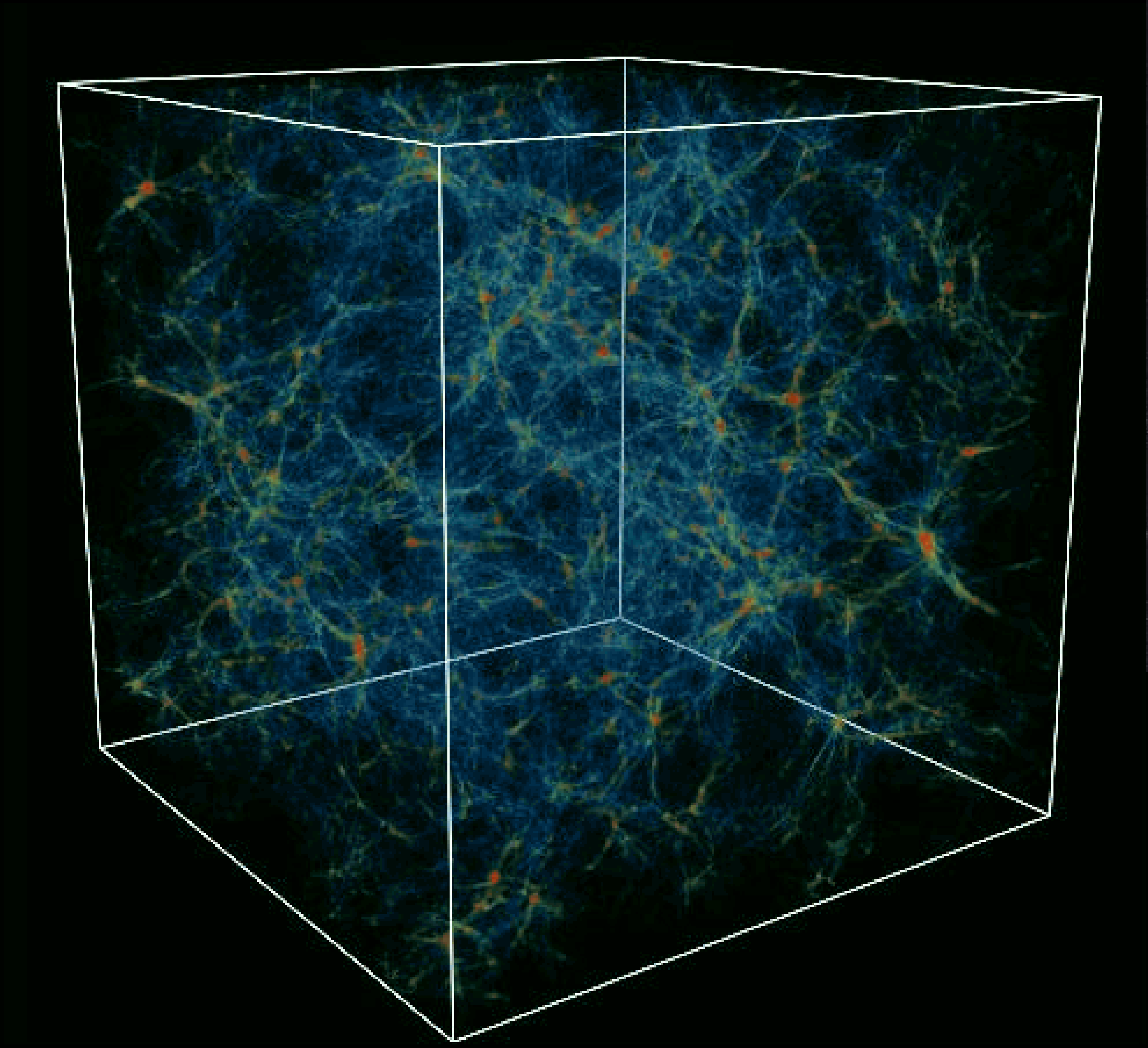


The "GZK" sphere

Horizon < 200Mpc at UHE

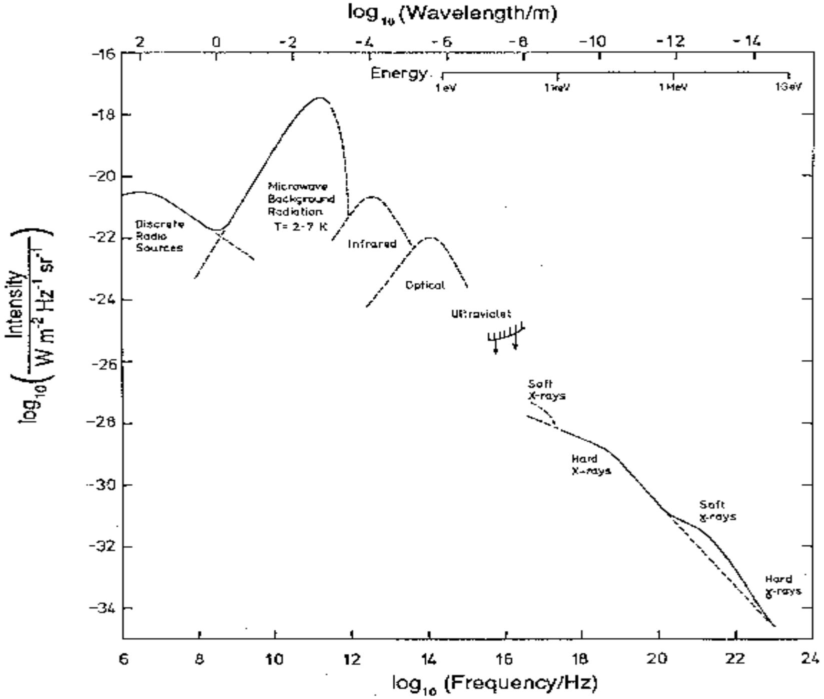


Large scale filamentary structures

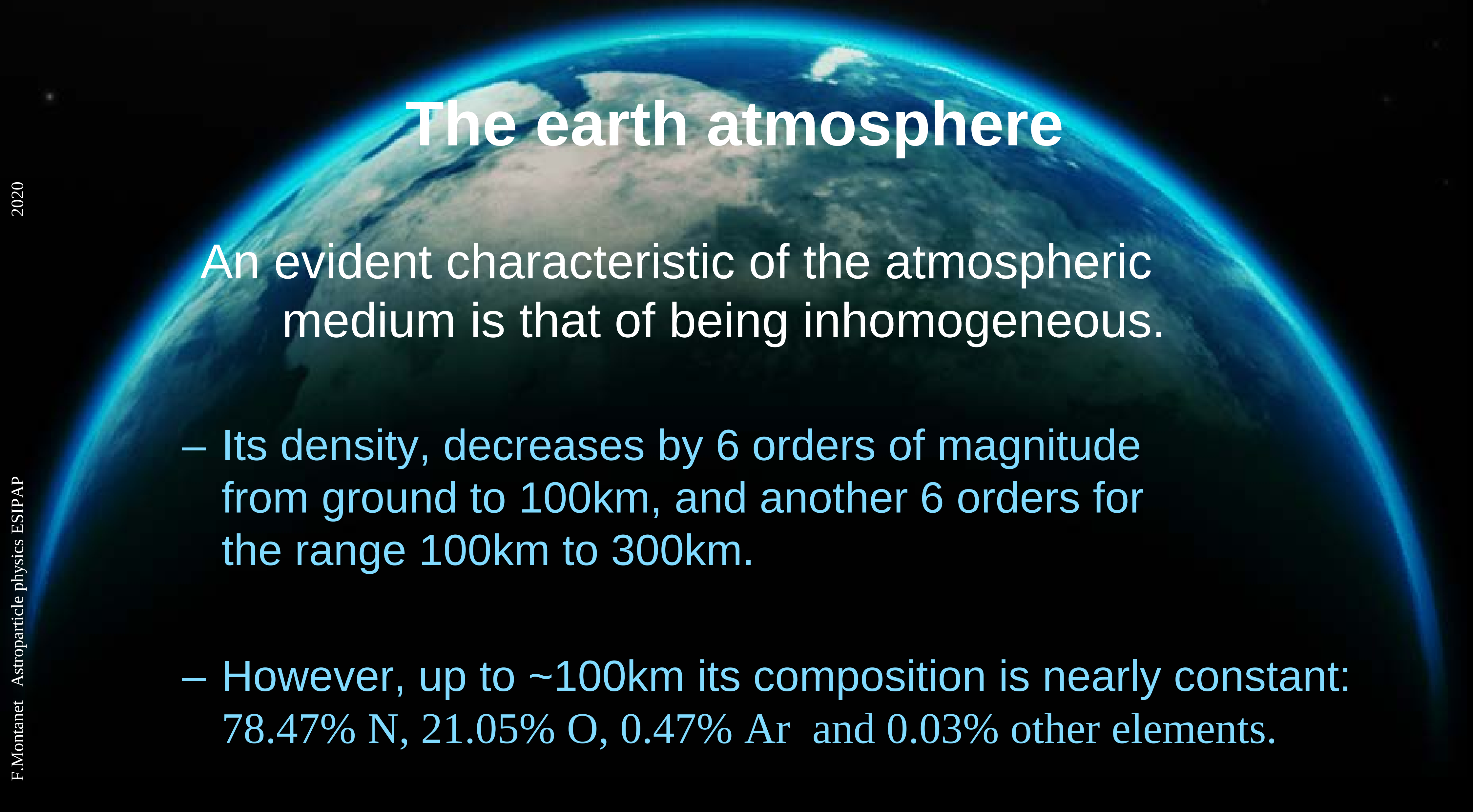


Vacuum is not emptiness !

- 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

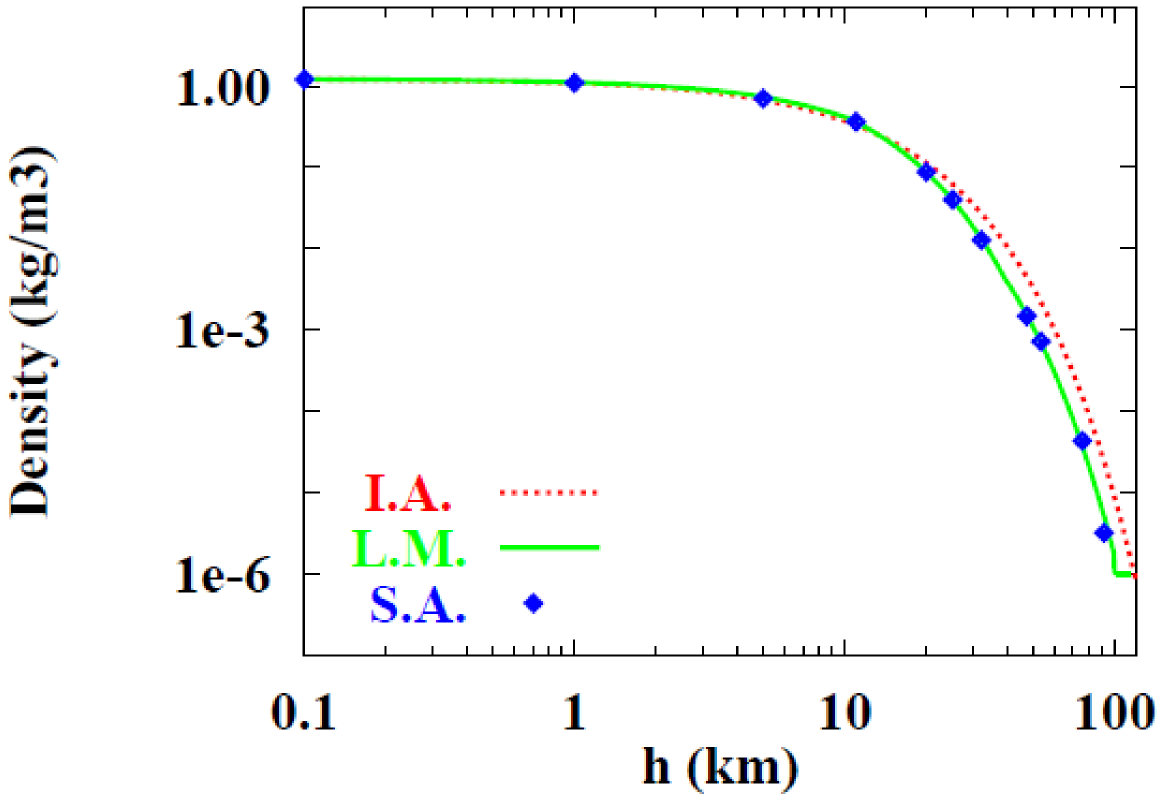


Figure 2.3. *Density of the air as a function of the vertical altitude. The dots represent the US standard atmosphere data [14], while the full green line corresponds to Linsley's model [16] and the dashed red one to the isothermal atmosphere*

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

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

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

The earth atmosphere

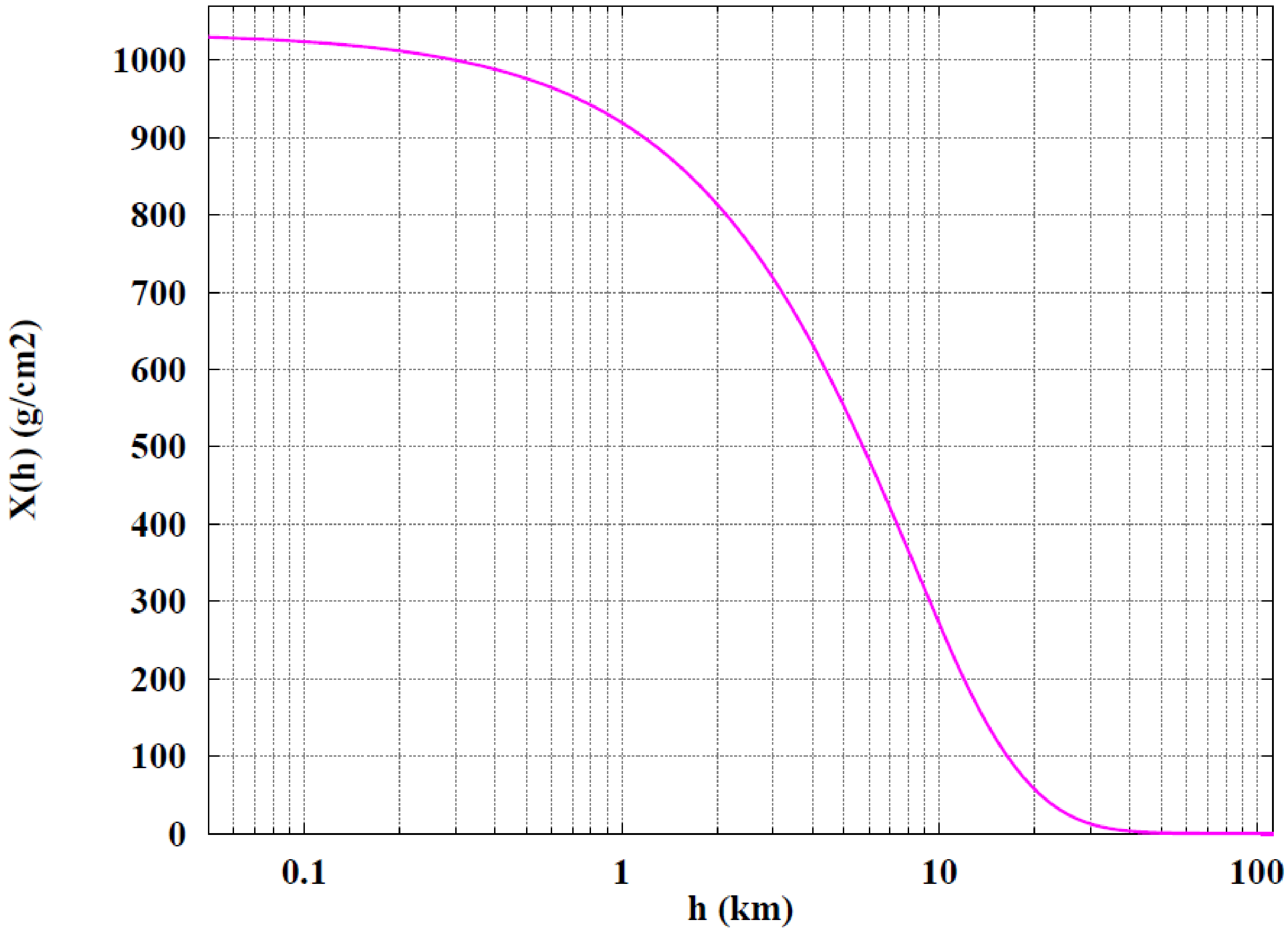


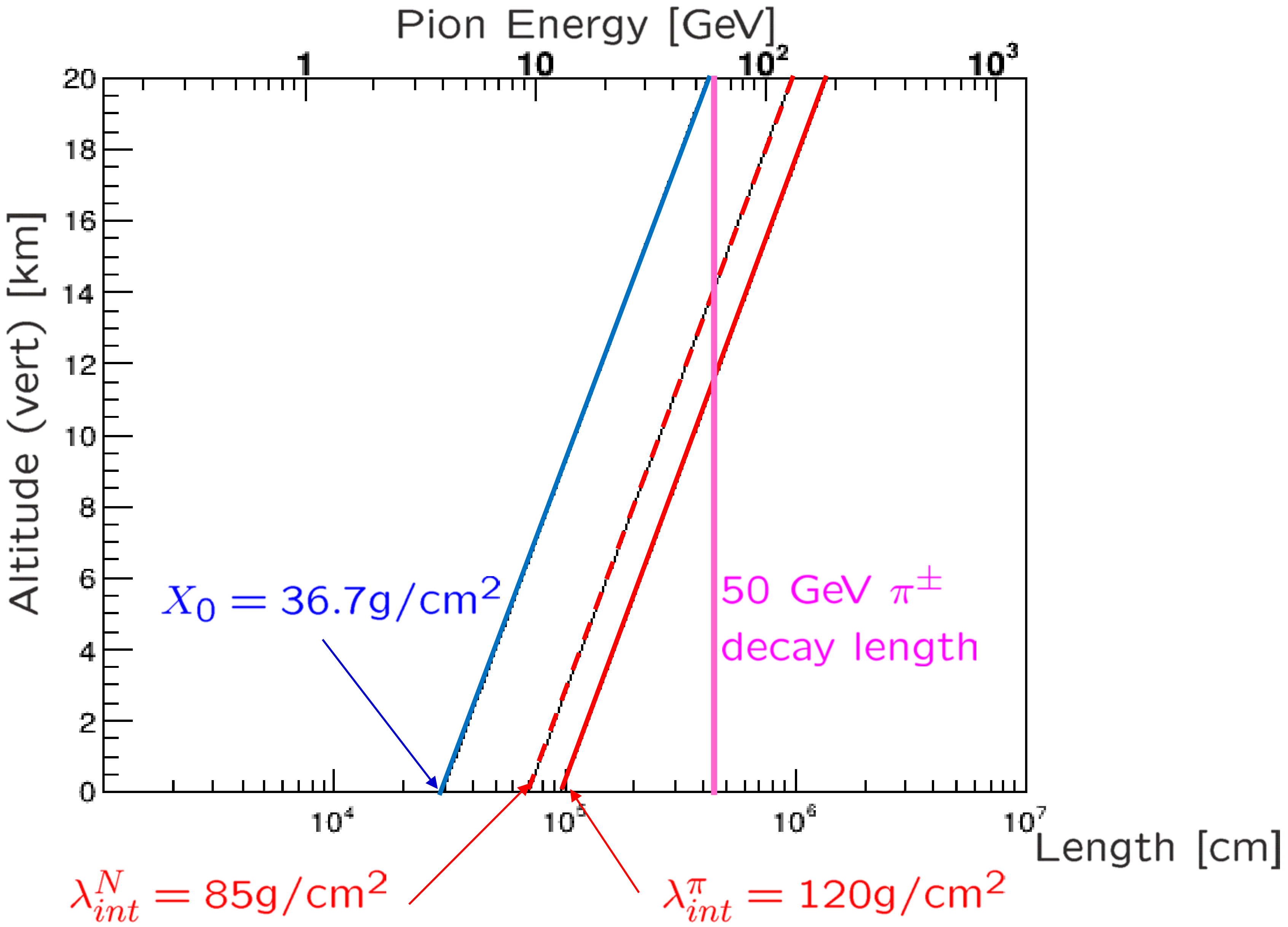
Figure 2.4. *Vertical atmospheric depth,* X_v, *versus vertical altitude over sea level,* h, *accordingly with Linsley's model [16].*

The earth atmosphere

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

- A total of ≈ 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$^2 \approx 300$ 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.

The shower development

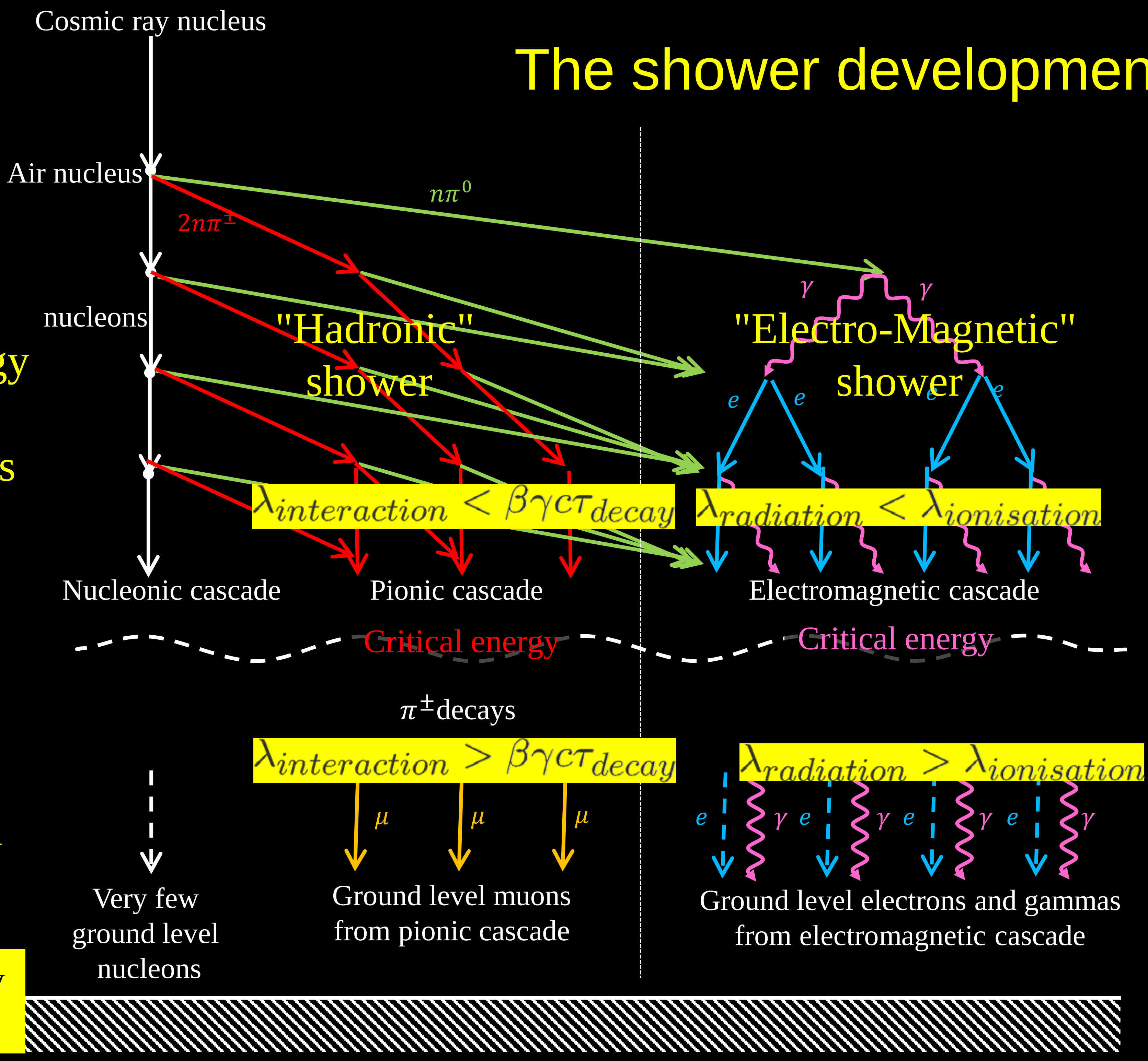
Physics well out of reach of colliders !

At each step energy is shared by more numerous particles

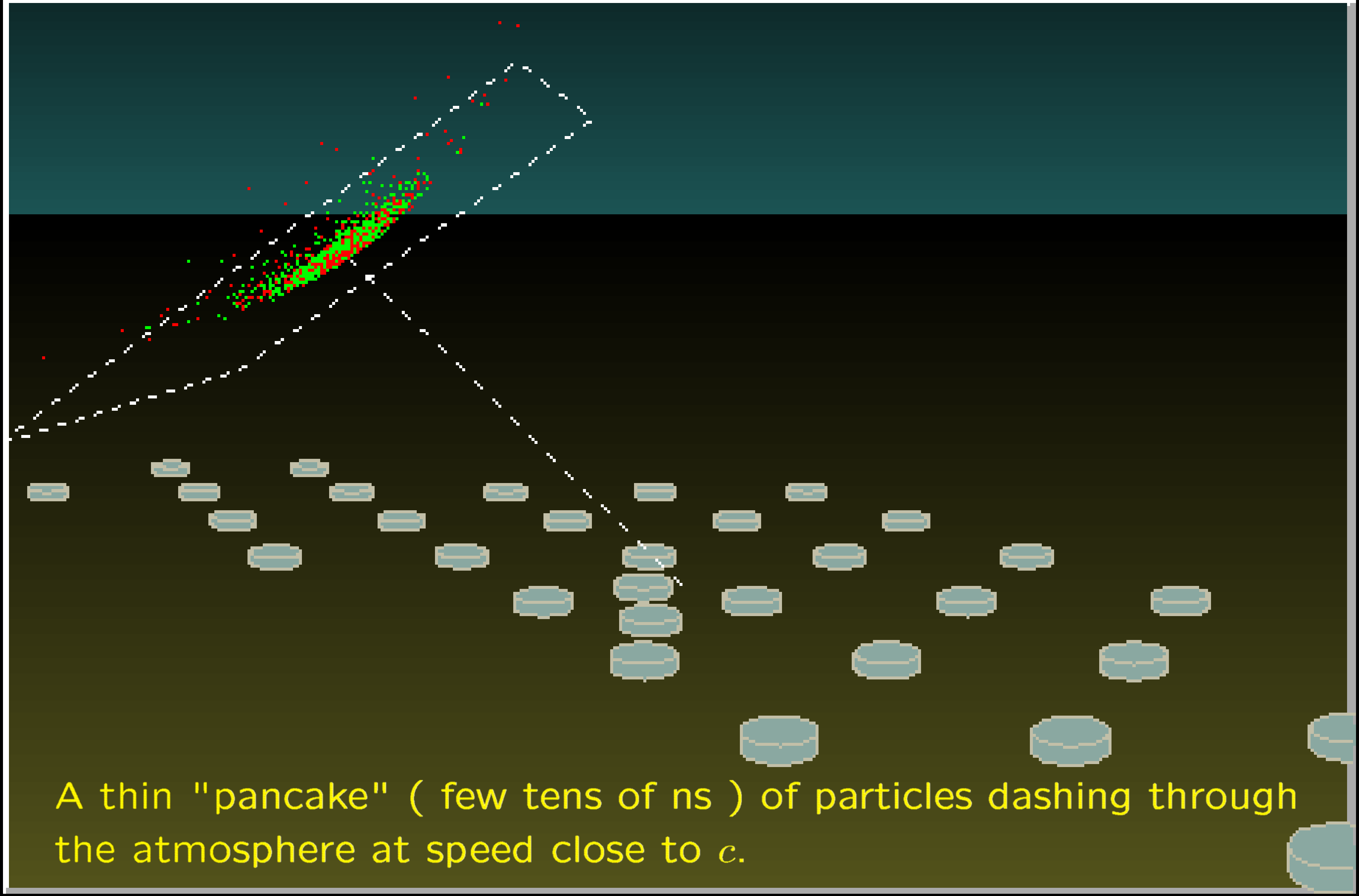
Maximum of development

No more multiplication, decrease by decay and energy loss

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

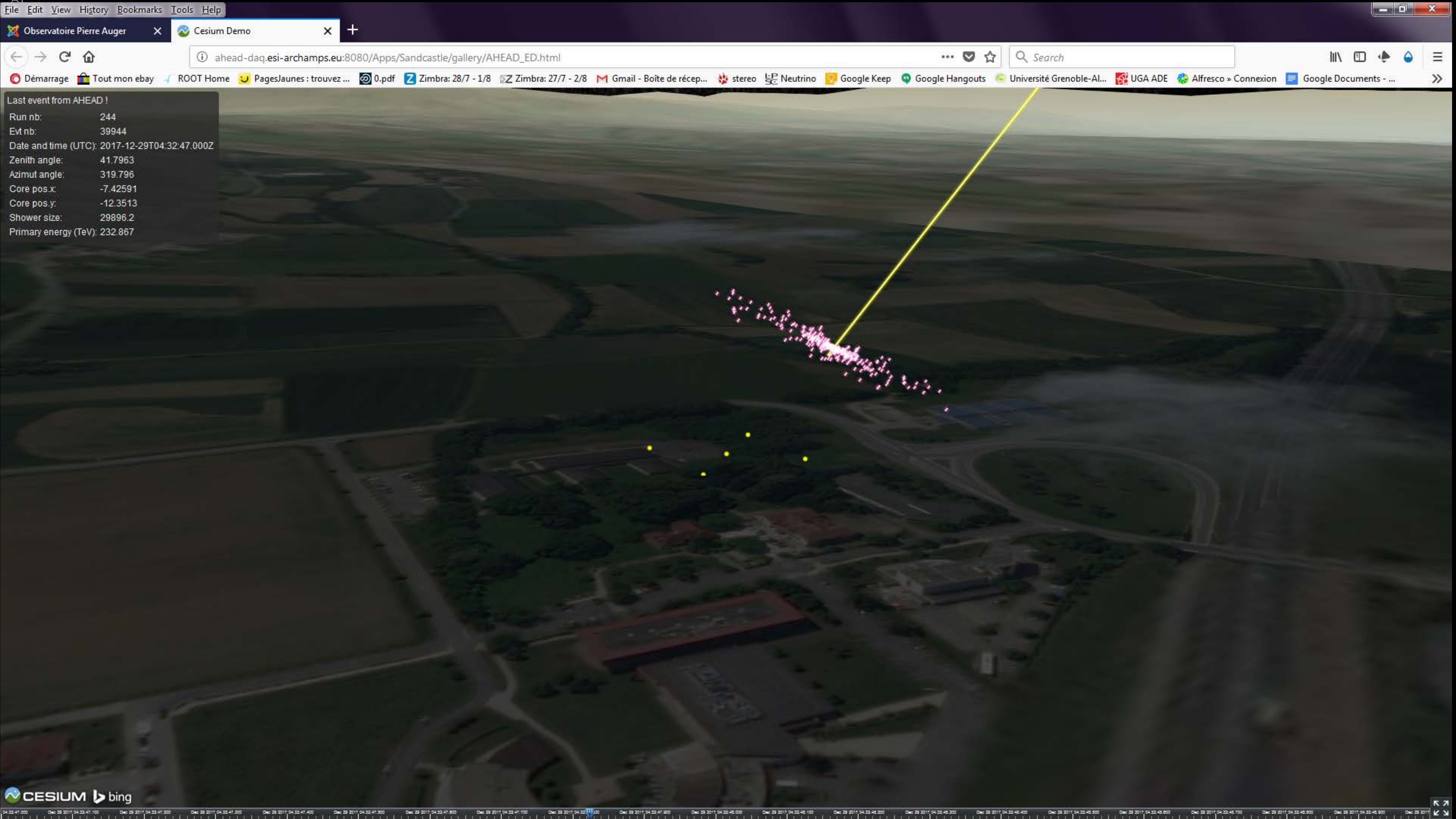


Time structure



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

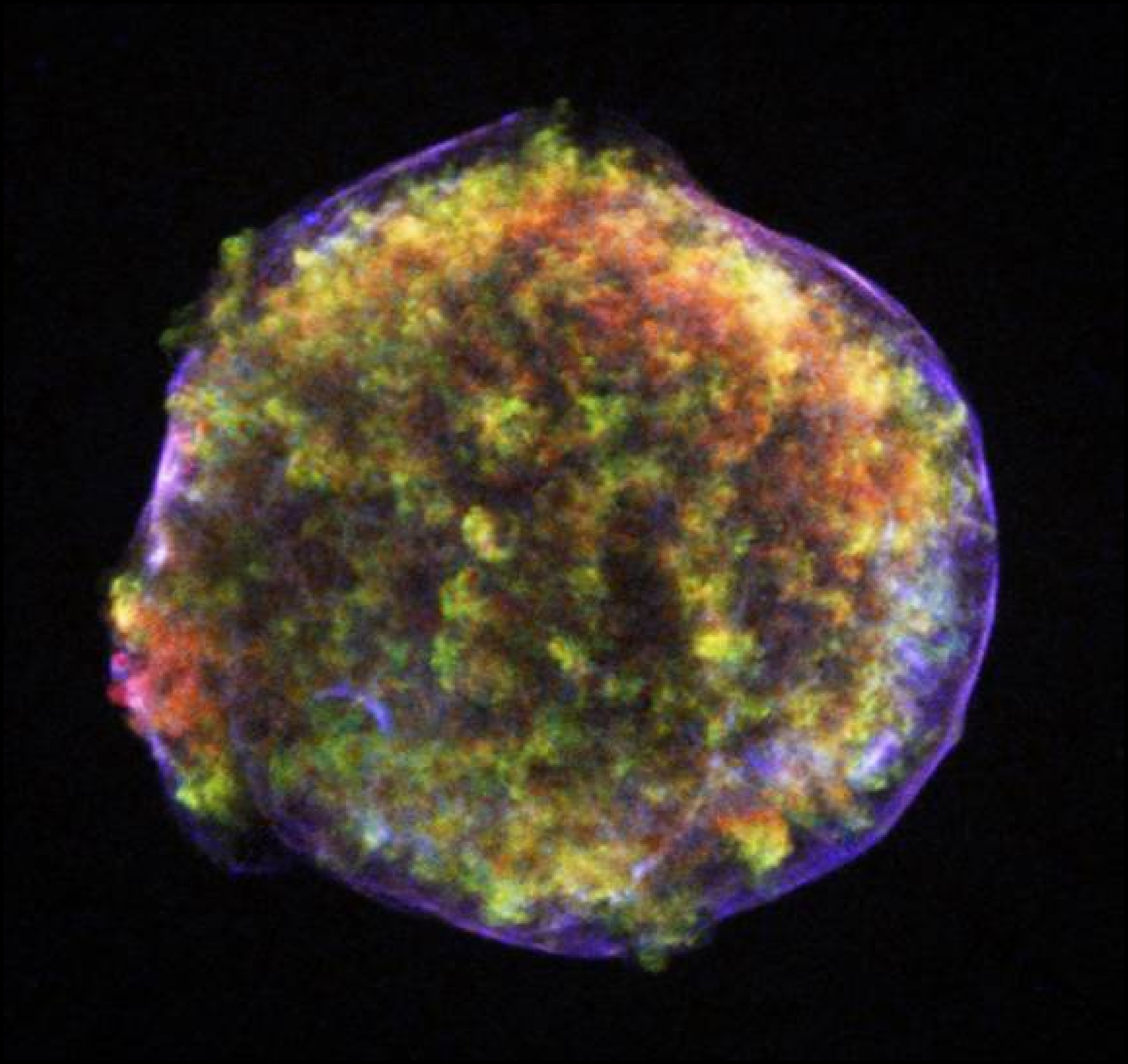
AHEAD



Last event from AHEAD !

Run nb: 244
Evt nb: 39944
Date and time (UTC): 2017-12-29T04:32:47.000Z
Zenith angle: 41.7963
Azimut angle: 319.796
Core pos.x: -7.42591
Core pos.y: -12.3513
Shower size: 29896.2
Primary energy (TeV): 232.867

Astrophysical Sources
Cosmic Accelerators



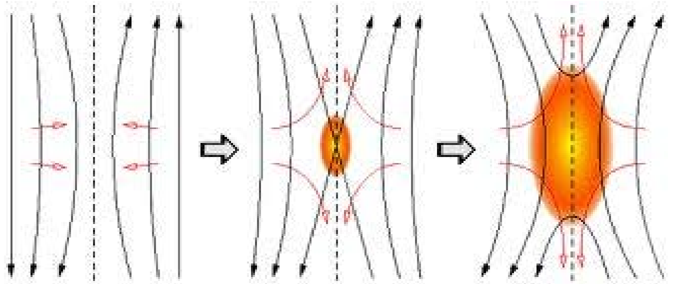
General ideas on acceleration

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

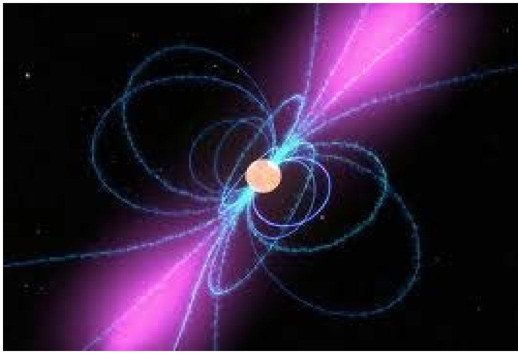
→ Energy transfert through EM fields !

E and B fields in Universe

- In ISM as on earth, $< E > \approx 0$
  - ISM is neutral or conducting
- Transient electric fields:
  - Magnetic re-connections (e.g. solar flares...)
  - EM waves



- Producing E fields in EM "engines"
  - Astrophysical dynamos, induction machines



- Magnetic fields :
  - Energy densities:

$$\varepsilon_B \approx \frac{1\mathrm{eV}}{\mathrm{cm}^3} \approx \varepsilon_{optical} \approx \varepsilon_{CMB} \approx \varepsilon_{CR}!!!$$

  - Astrophysical plasmas :
    ISM, stars, accretion disks, IGM, jets, etc...

Magnetic field production

- Large scale movements of ionized media

  → generating magnetic fields, magnetized clouds...
- Turbulence in interstellar medium

  → Magnetic turbulence, inhomogeneous B fields, plasma waves...
- Hydro and MHD instabilities
  - e.g. Rayleigh-Taylor in supernova remnants
- "Streaming" instabilities
  - CR generates waves in a magneto-active plasma

  → creating the conditions for their own diffusion

Magnetic field production

In many cases, **equipartition** can be reached

- for ex: behind a shock wave :
  thermal energy ~ kinetic energy ~ magnetic energy

⇒ Energy exchange between macroscopic structures and individual particles

⇒ individual particles may reach very high energies!

Magnetic fields and acceleration !

- How is it possible at all?
  magnetic fields don't work !

- Well, variable $\vec{B}(t)$ fields do ! (example: Betatron) $\vec{\nabla} \times \vec{E} = -\frac{\vec{\partial}\{\vec{B}\}}{\partial t}$

- In a different reference frame, $\vec{B}$ field is felled as a $\vec{E}$ field...
  $\overrightarrow{E'} = \vec{v} \times \vec{B}$ for $v \cong c$

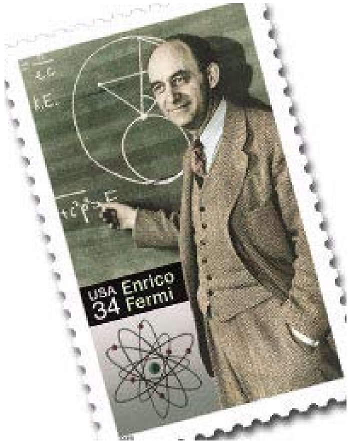
- In principle, one can always identified an effective $\vec{E}$ field that works, but the description in terms of $\vec{B}$ fields is often simpler (and more physical !)

→ Acceleration by "change of reference frame"

Where to accelerate

- At creation :
  - For example: e^- extracted from the surface of a neutron star by an intense E field.
- Within the source neighborhood :
  - For example: Fermi acceleration in plasma shocks in a SNR.
- During transport:
  - "reacceleration" by shock waves and excitation of Alfven waves during diffusive transport in the Galaxy.

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 un 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:

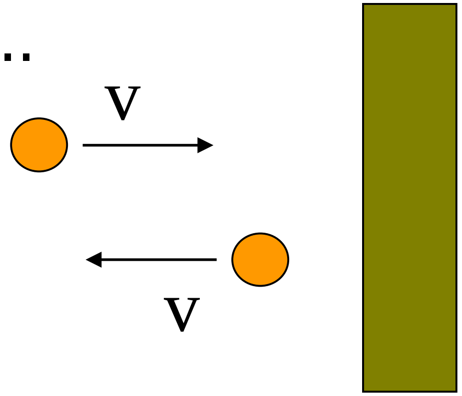
$$N(\geq E) \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

➡ Power laws are natural !

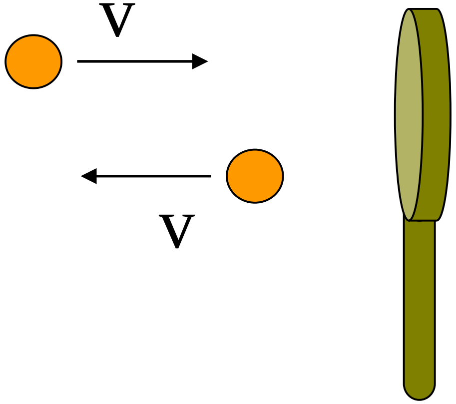
with $\gamma = -\frac{\ln(1-P_{esc})}{\ln(1+\varepsilon)} \approx \frac{P_{esc}}{\varepsilon} = \frac{1}{\varepsilon} \times \frac{T_{cycle}}{T_{esc}}$

A small analogy…

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



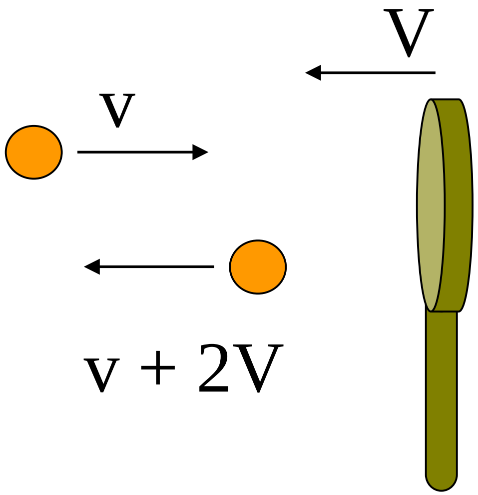
bounce = speed unchanged



Same thing with
a motionless racquet...

Then how does one accelerate a tennis ball ?!

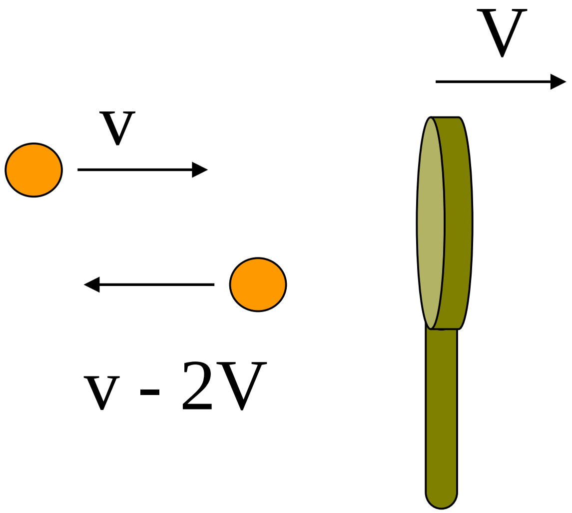
- Moving racquet !
  - Neither gain nor loss of energy… in the racquet reference frame !



Speed unchanged with respect to the racquet

→ acceleration through a change of reference frame

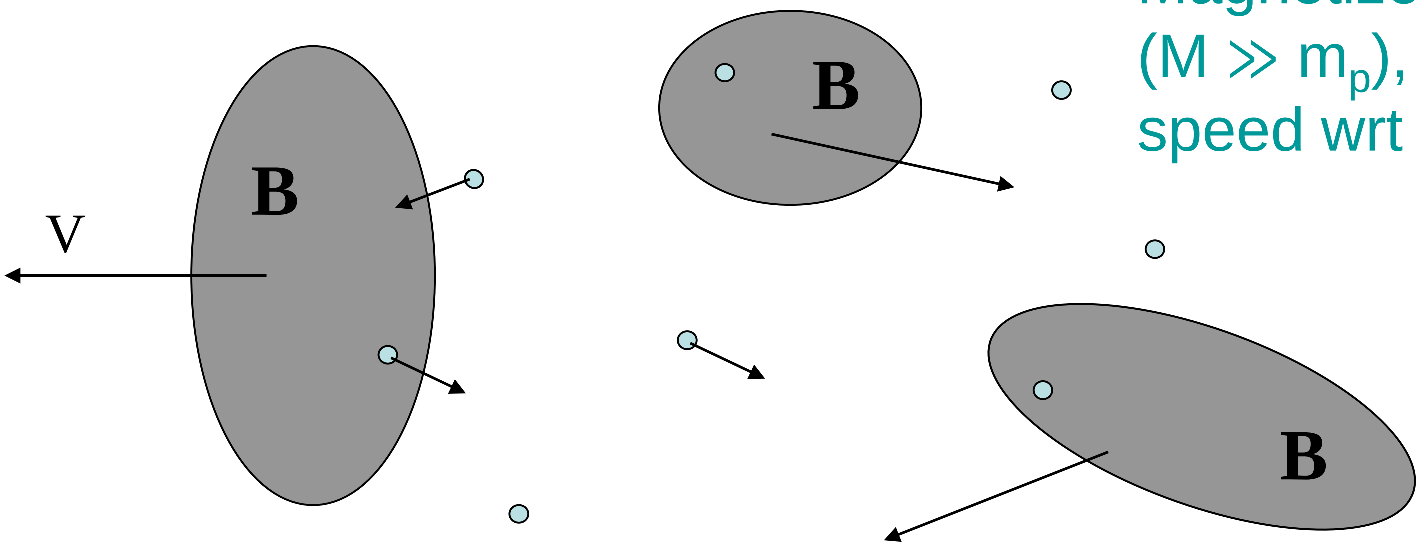
- But this can also decelerate
  A drop shot:



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.

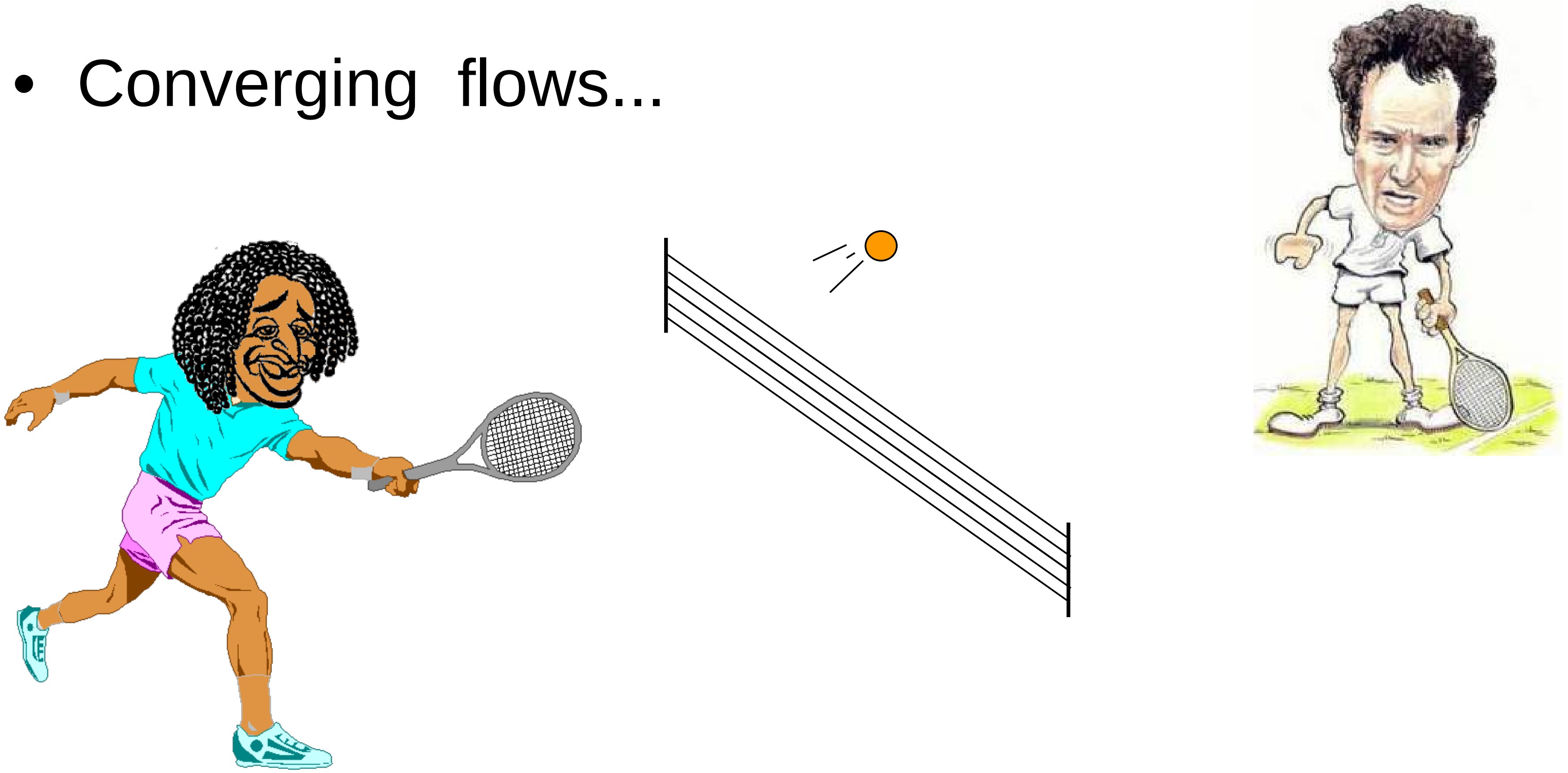
2. When a particle bounces on a **receding** magnetic mirror that it catches back, it **loses** energy.

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

⇒ Net energy gain in average (stochastic process)

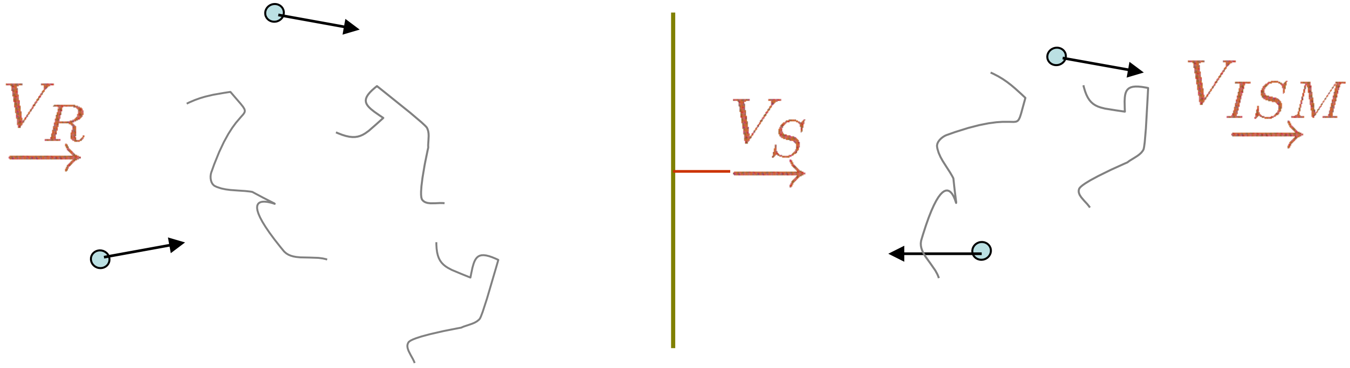
Add a second player...

- Converging flows...



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).

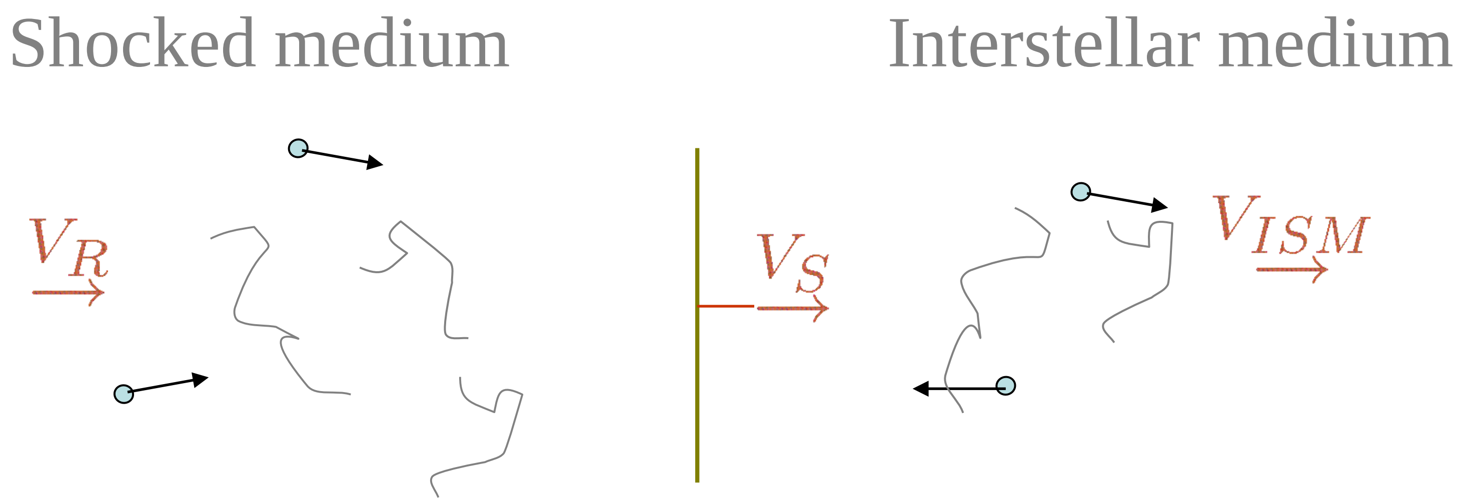


Shocked medium

Insterstellar medium

Shocks hydrodynamics

- Shock wave:

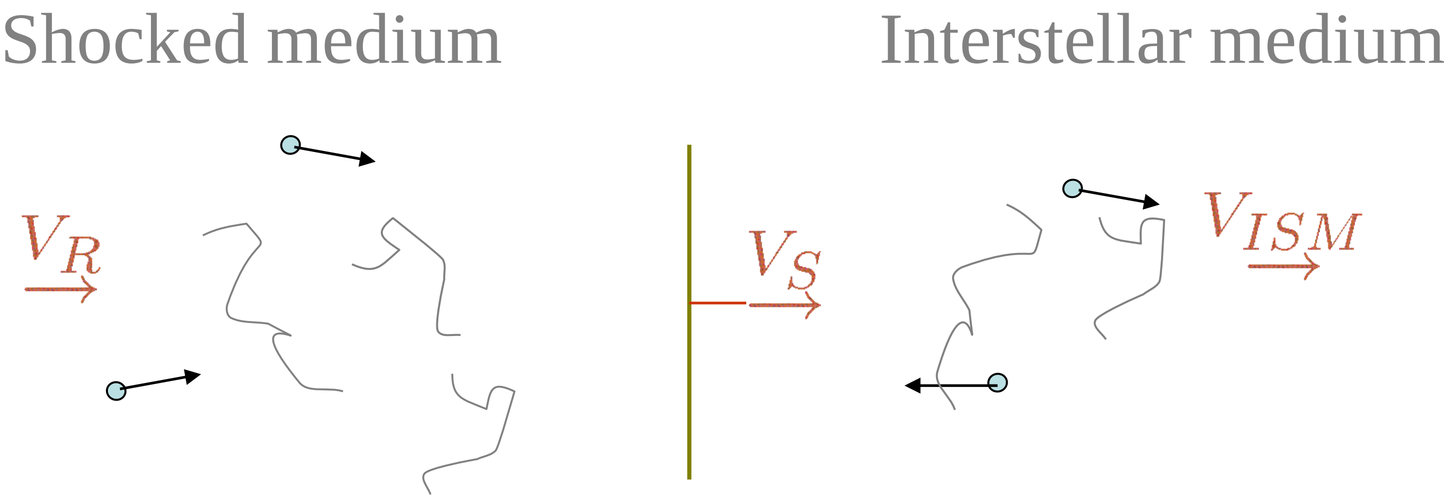


- The shock moves at a speed V_S which depends on V_R and the specific heat of both media.

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

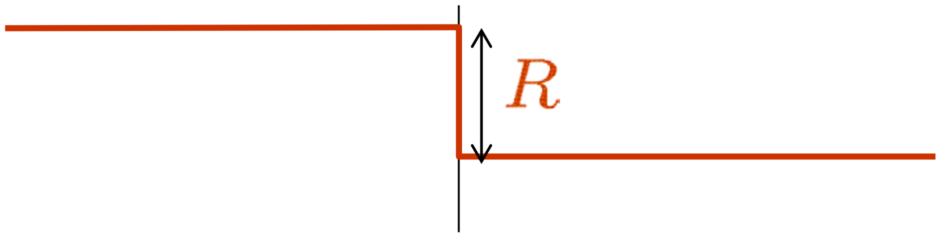
Shocks hydrodynamics

- Shock wave:



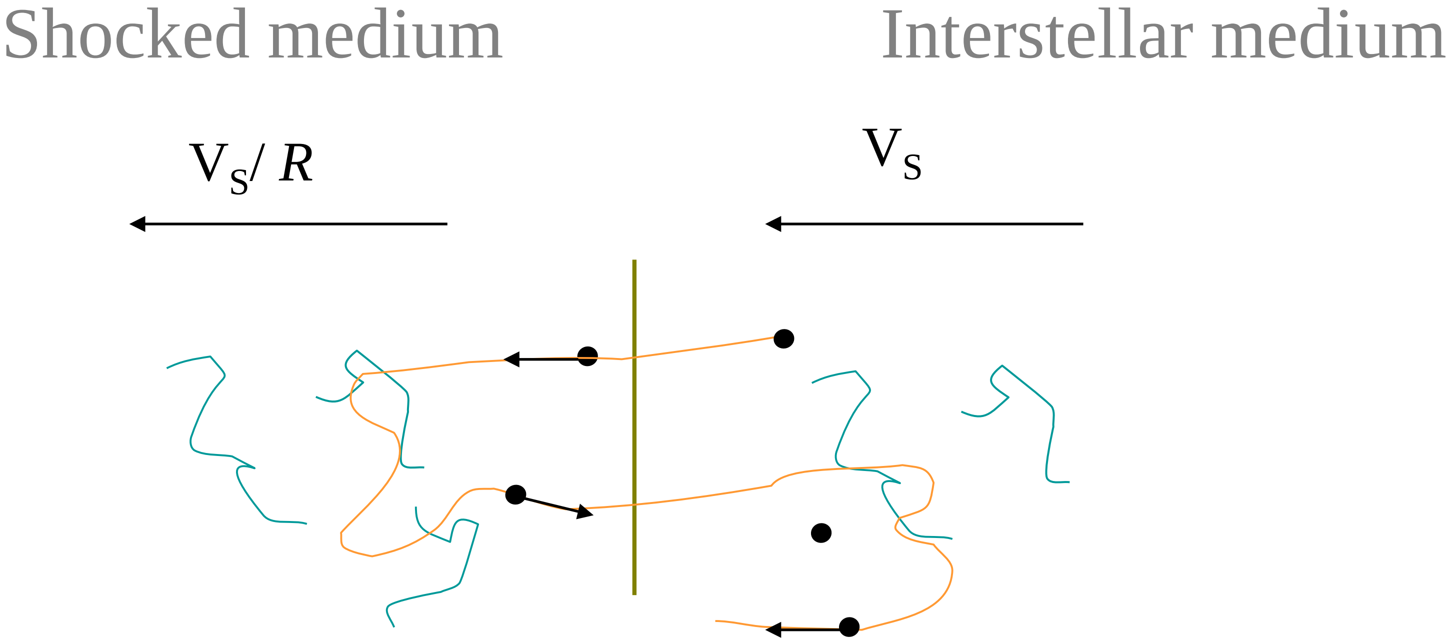
- The shock intensity is characterized by the compression factor:

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



Shocks hydrodynamics

In the shock frame

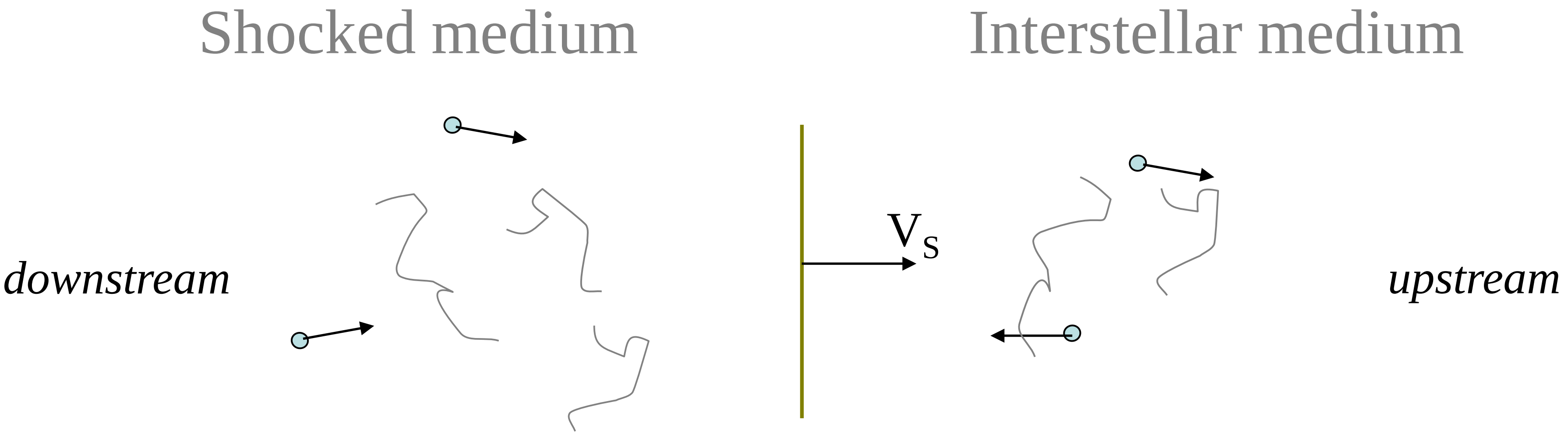


- In the shock frame, the upstream (non-shocked) medium flows toward the shock at a speed V_S and the downstream (shocked) medium flows away with a speed reduced by the compression factor (mass flow conservation) :

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

Shock wave diffusive acceleration

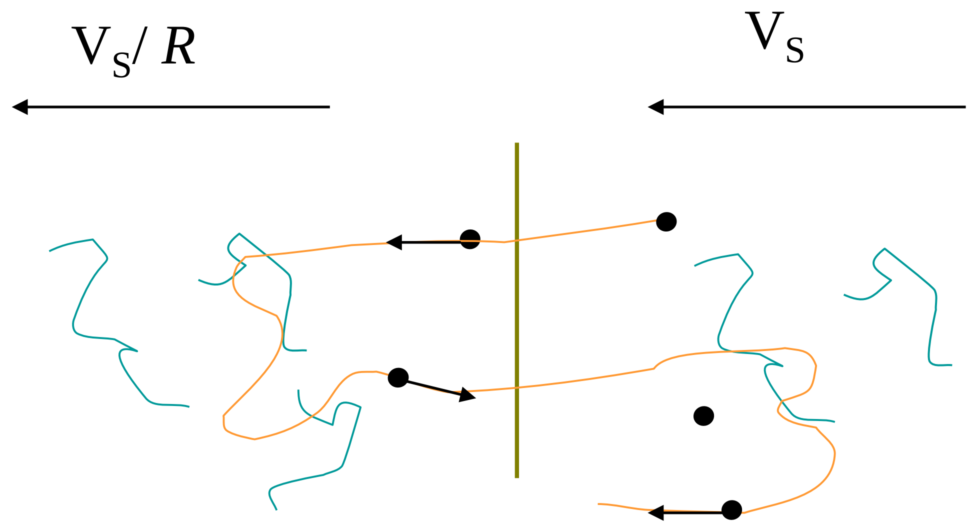
- Shock wave (e.g. supernova explosion)



- 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 diffusive (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

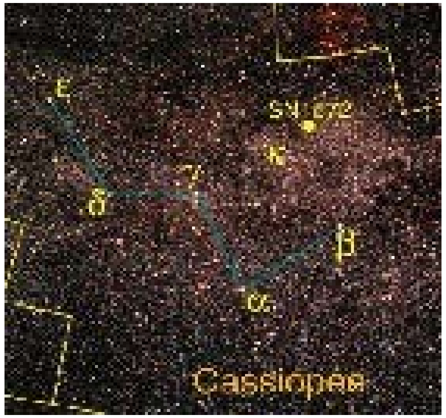
The CR standard model

- Analytic calculations, simulations and observations show that diffusive shock acceleration works !

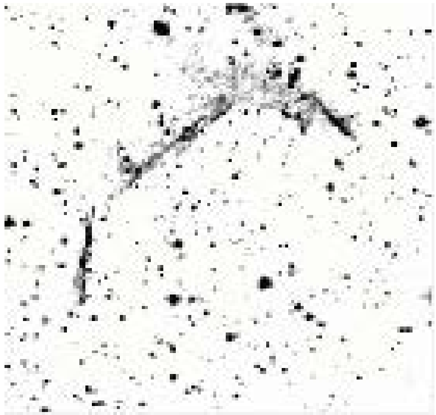
- Supernovae and GCRs
  - Estimated efficiency of shock acceleration :… $10-50\%$
  - Power required to sustain CR energy density: …… $\varepsilon_{CR}\times V_{conf}/\tau_{conf}$ $\sim 10^{41}\mathrm{erg/s}$!
  - Power injected by SN power in the Galaxy: ……… $10^{42}\mathrm{erg/s}$!

→ Enough power for Galactic CR

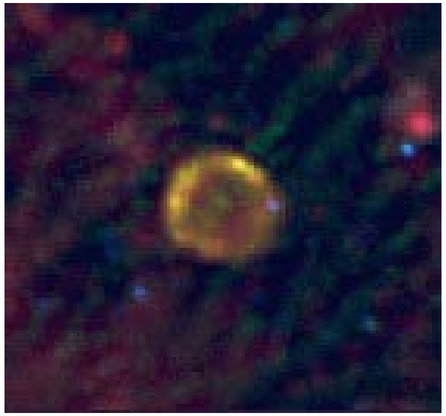
Tycho, 11 November 1572...



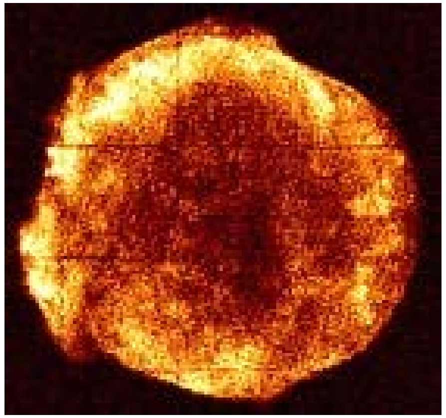
position



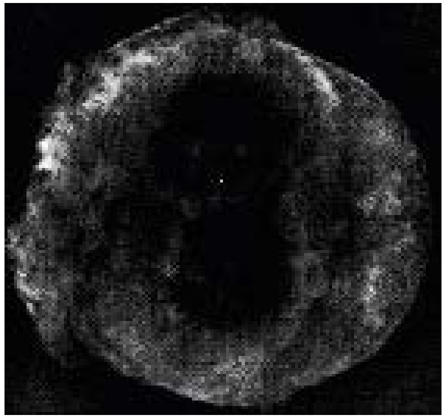
visible



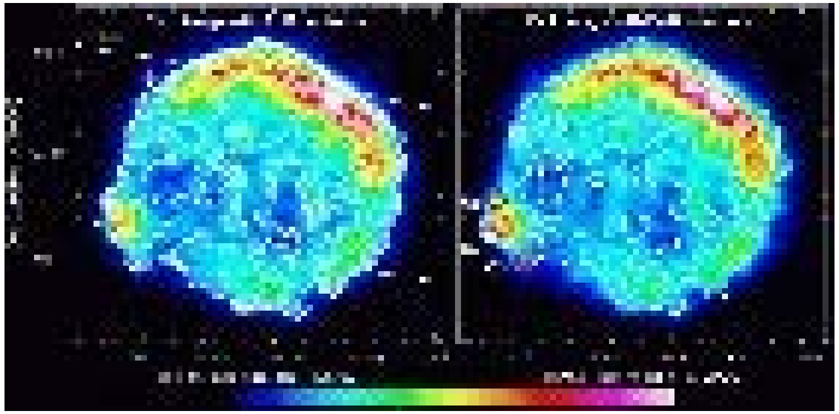
IRAS



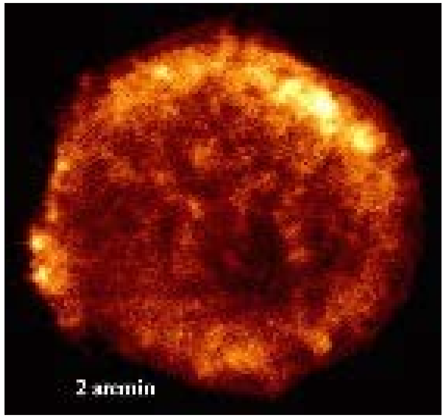
Km (VLA)



6 cm (VLA)



Si K (XMM) Fe K



X (ROSAT)

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.

The CR standard model

- Shock waves in isolated SNe (SNR)
  - Source composition source ~ interstellar medium + modifications (ionizability, volatility, Z/A effects, ^{22}Ne...)
  - Source spectrum: E^{-2} power law
  - Maximal energy reached: $E_{max} \sim 10^{15}$ eV
- Energetics :
  - Measured flux / speed = CR density
  - CR density × mean energy = energy density
  - Energy density × confinement volume = total energy
  - Total energy / confinement time = necessary injected power
  - $P_{CR} \sim 1.5 \times 10^{41}$ erg/s
- Required efficiency ~ 10-30%...

Finite size

Finite size of
confinement
magnetic field

⇕

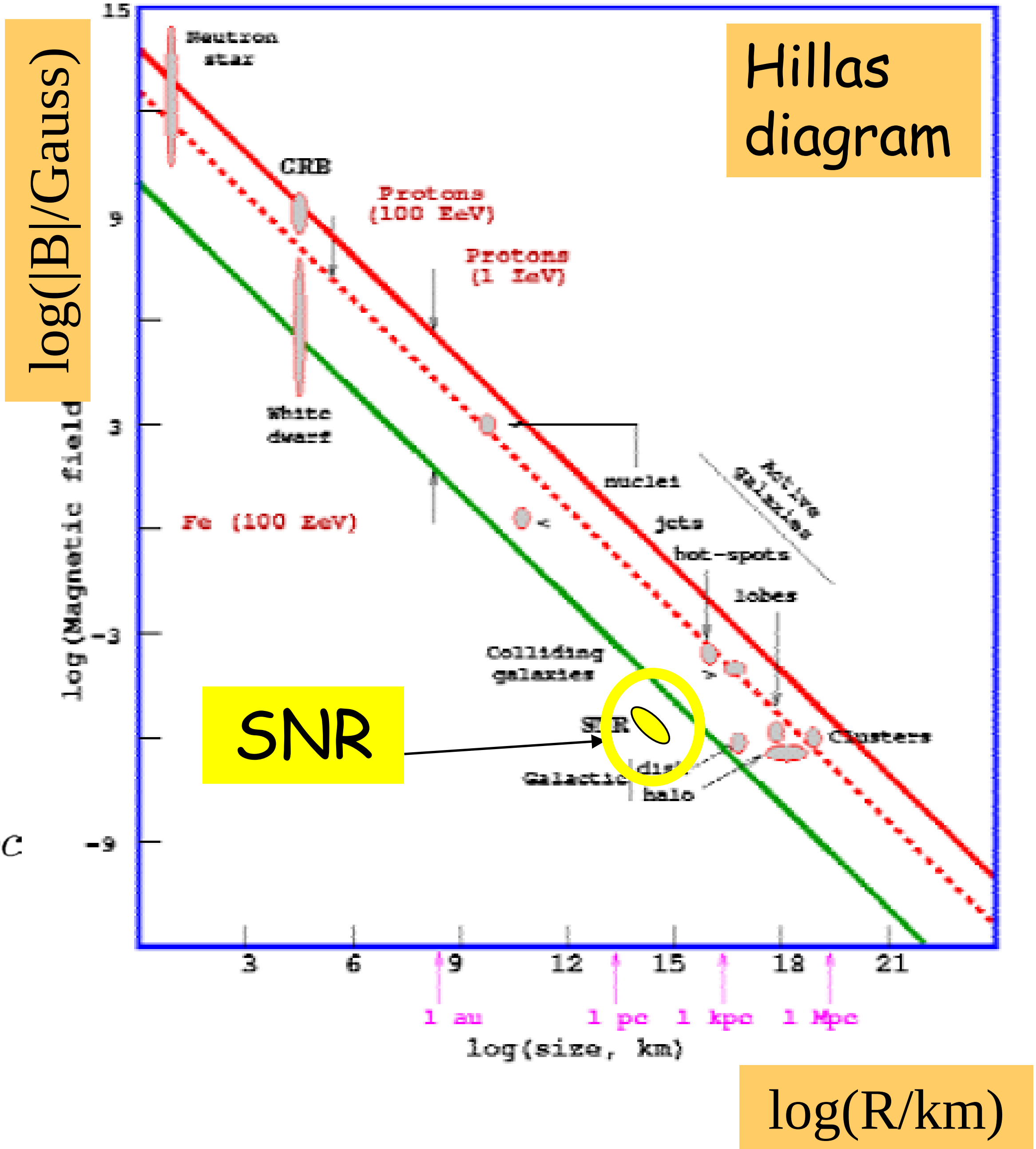
Larmor radius

$$r_g \le R$$

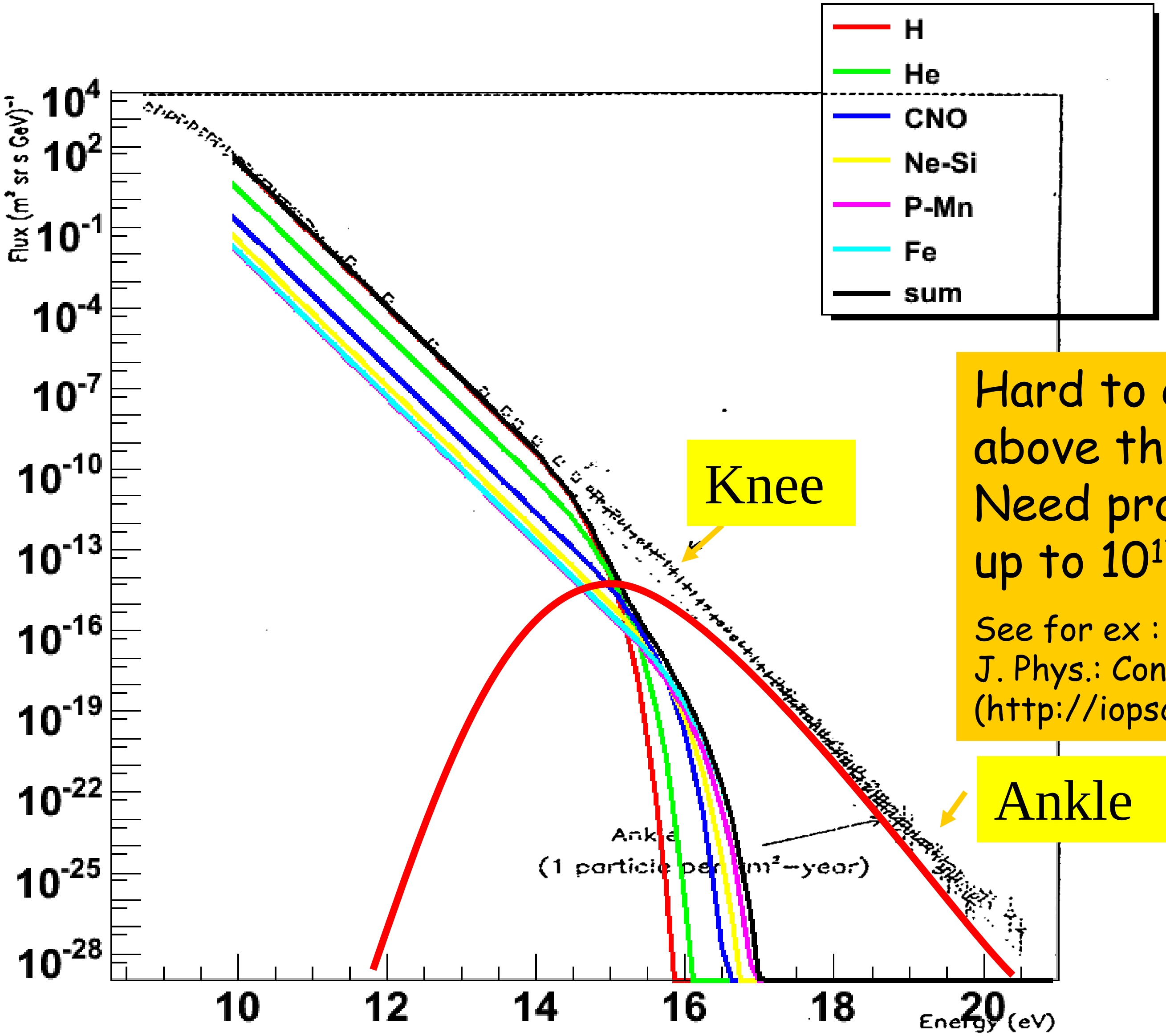
$$\Leftrightarrow \quad \frac{p}{ZeB} \le R$$

$$\Leftrightarrow \quad E \le Ze \times B \times R$$

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



CR SM with Emax / Z



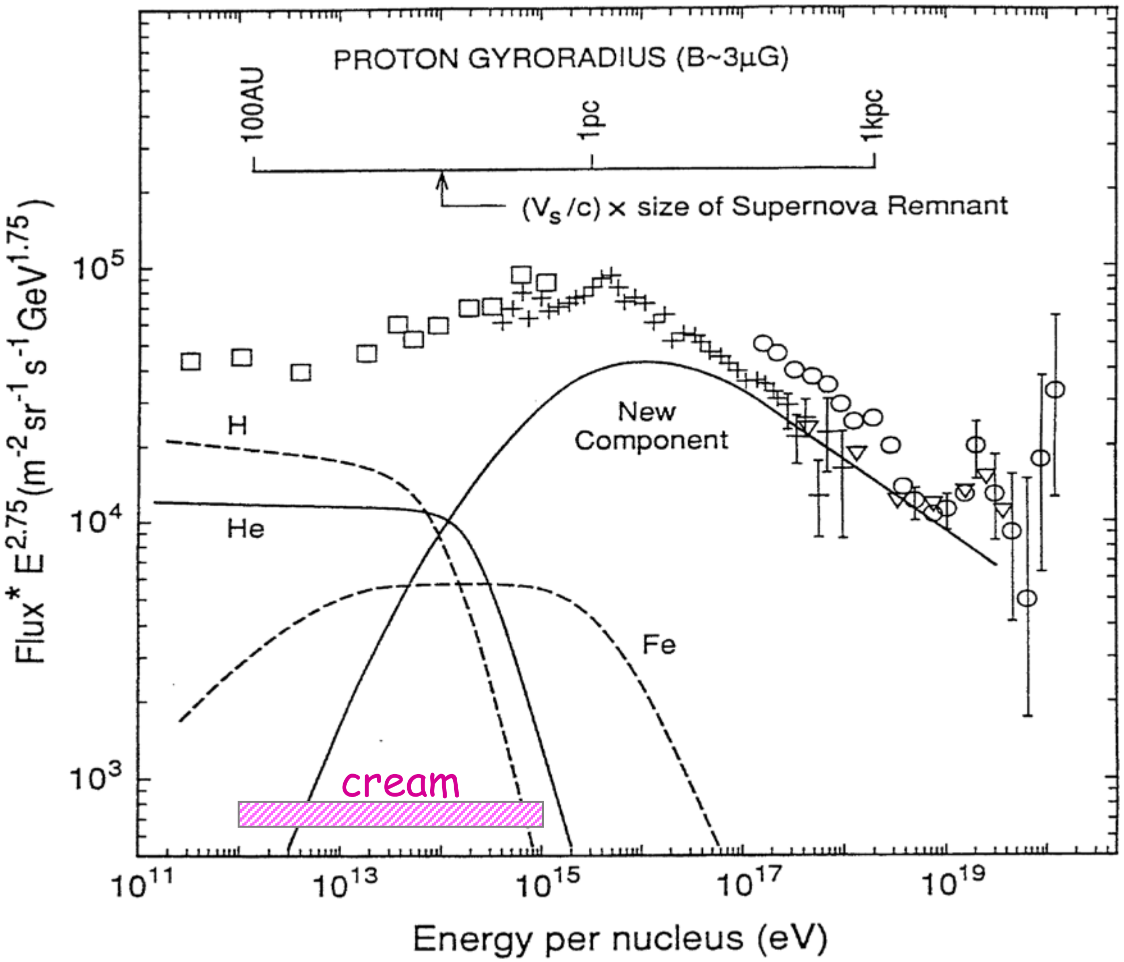
Knee

Ankle

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)

The knee



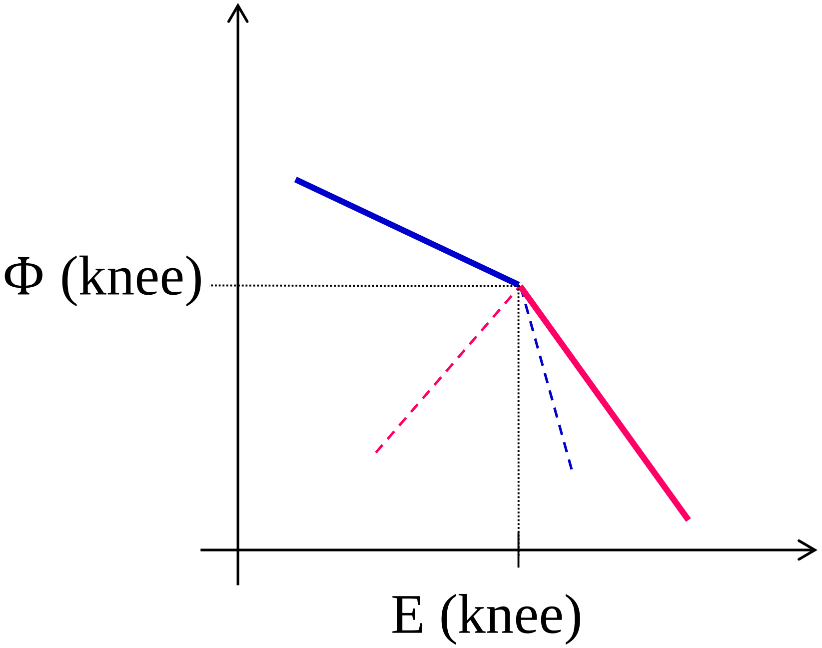
- Is the knee simply the consequence of an energy cut-off of accelerators (SNR) or is it due to :
  - a propagation effect ?
  - different CR sources ?
  - a physics threshold at ~E_{LHC} ?

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

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

Explaining the knee is tough !

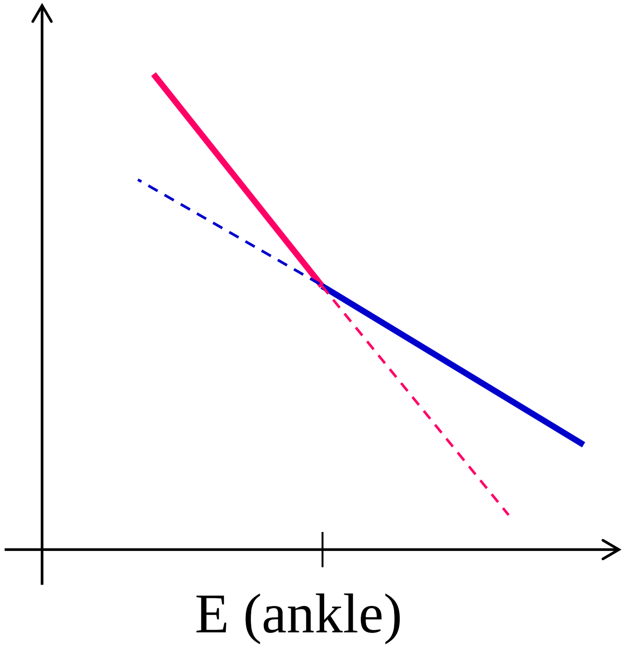
- Need two components matching precisely both energy and flux right at the knee !



→ quite an unnatural coincidence but why not ?

Explaining the ankle is much easier...

- Two components with two different slopes...



- For example, galactic → extragalactic...

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).

- 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 non relativistic shocks:

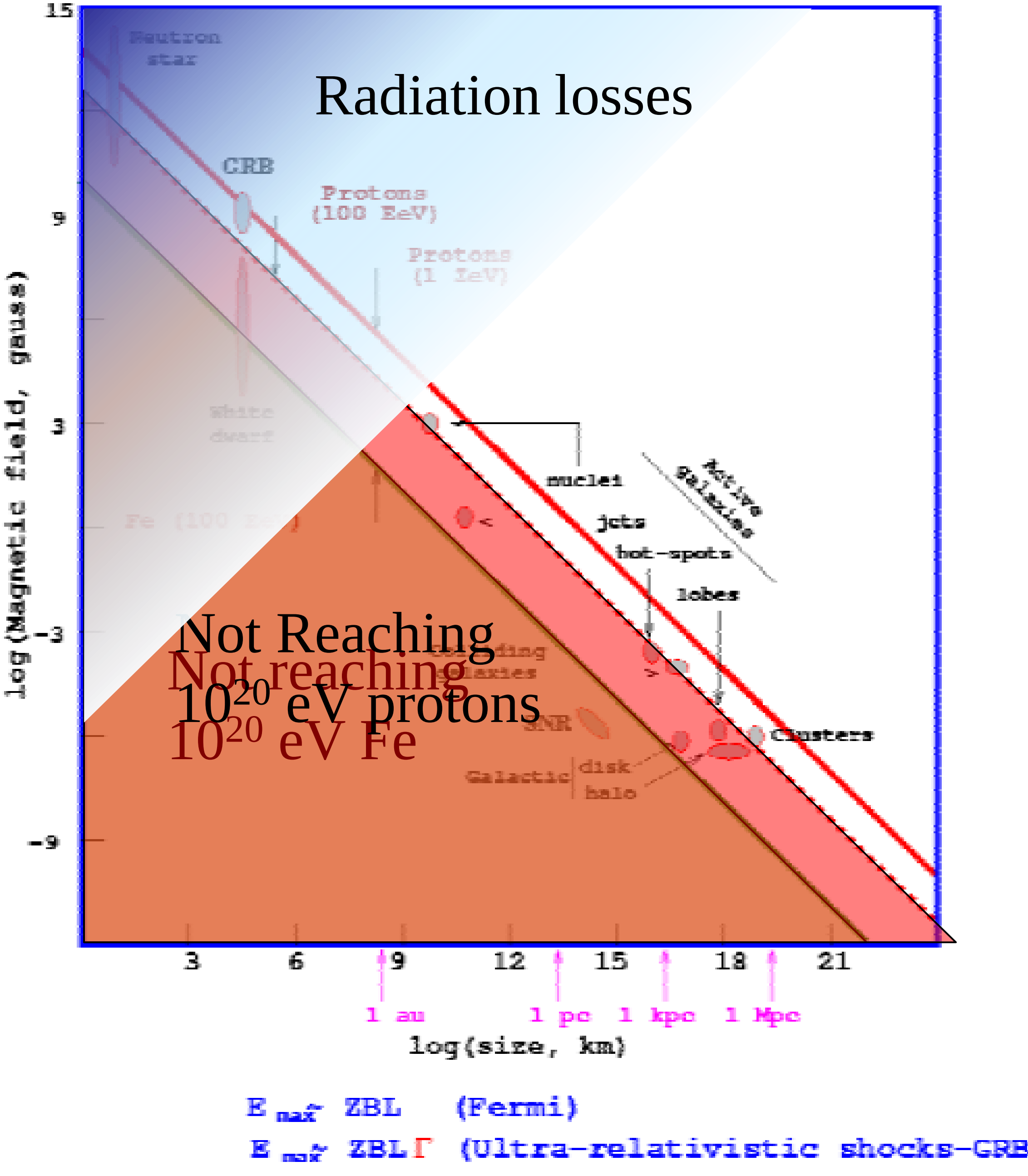
  $\tau_{acc} \approx 10\kappa/u_s^2 < R/u_s$ avec $\kappa > r_g c$

  $\Rightarrow E < \beta_s ZeBR$
- Diffusive acceleration

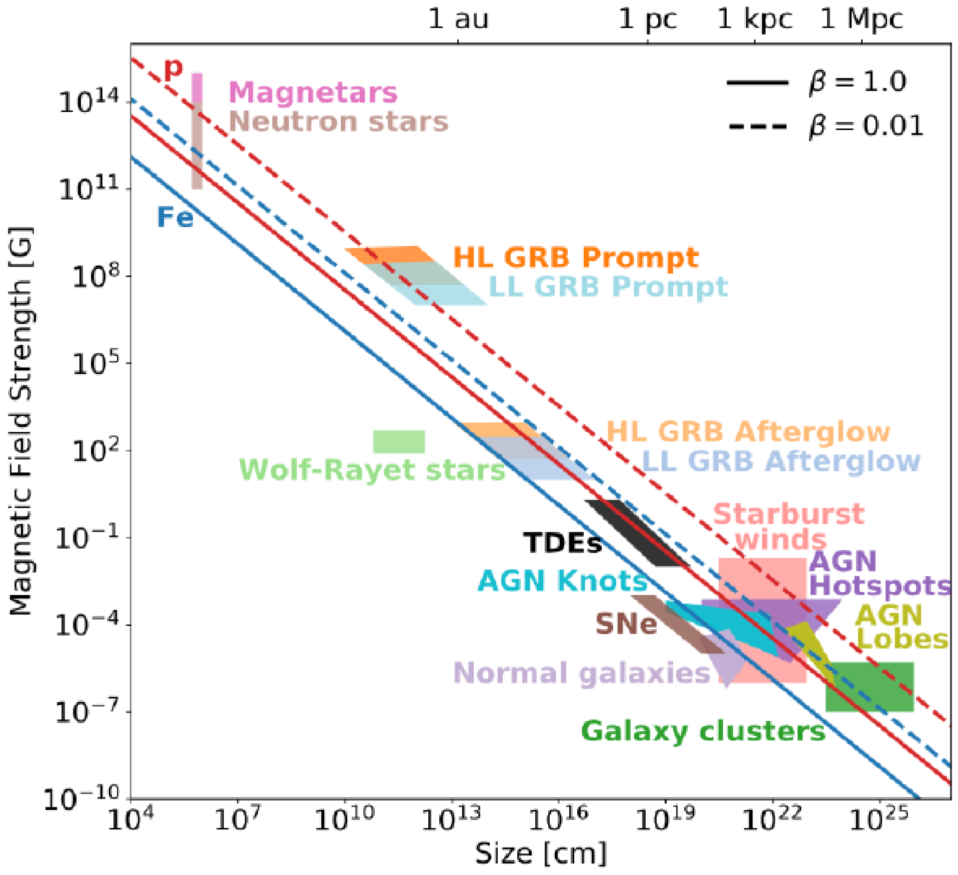
  by relativistic shocks:

  $E < \Gamma_s ZeBR$
- General Hillas condition:

  $E < 0.9\beta\Gamma ZeB_{Gauss}R_{pc}\ ZeV$



Constraints on source candidates



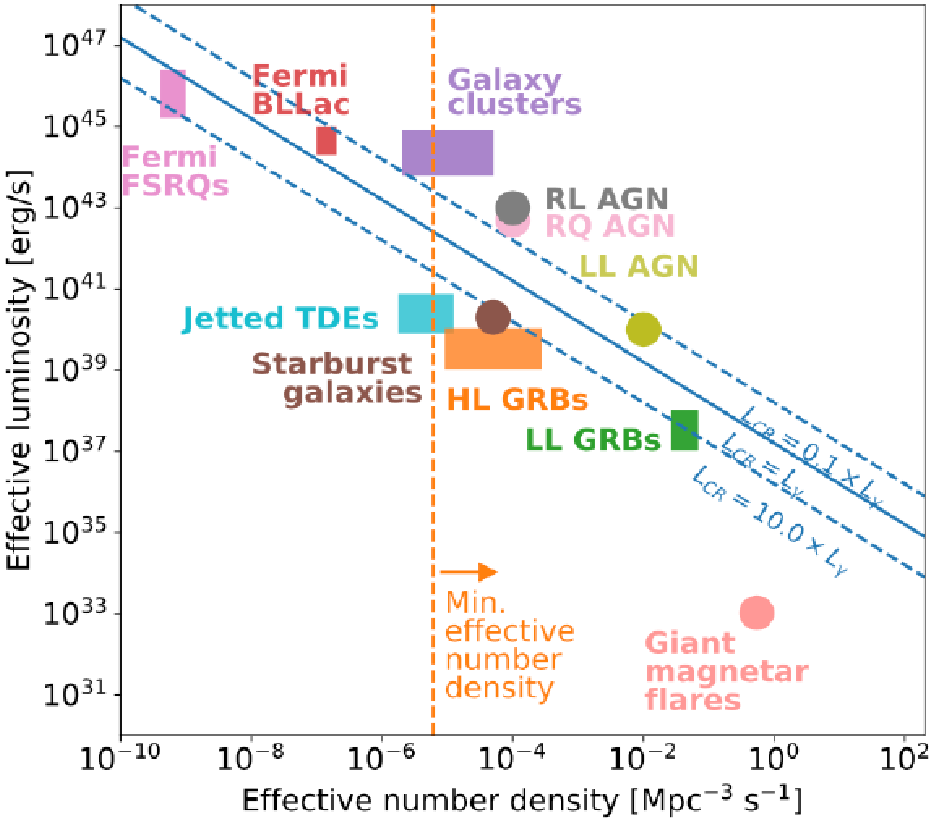
↳ $L_{pc} >> r_L$ d

↳ ρ_{rad} and ρ_{mat} low

↳ $B_{\mu G}$ → fast t_{acc}

→ small energy losses

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



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

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

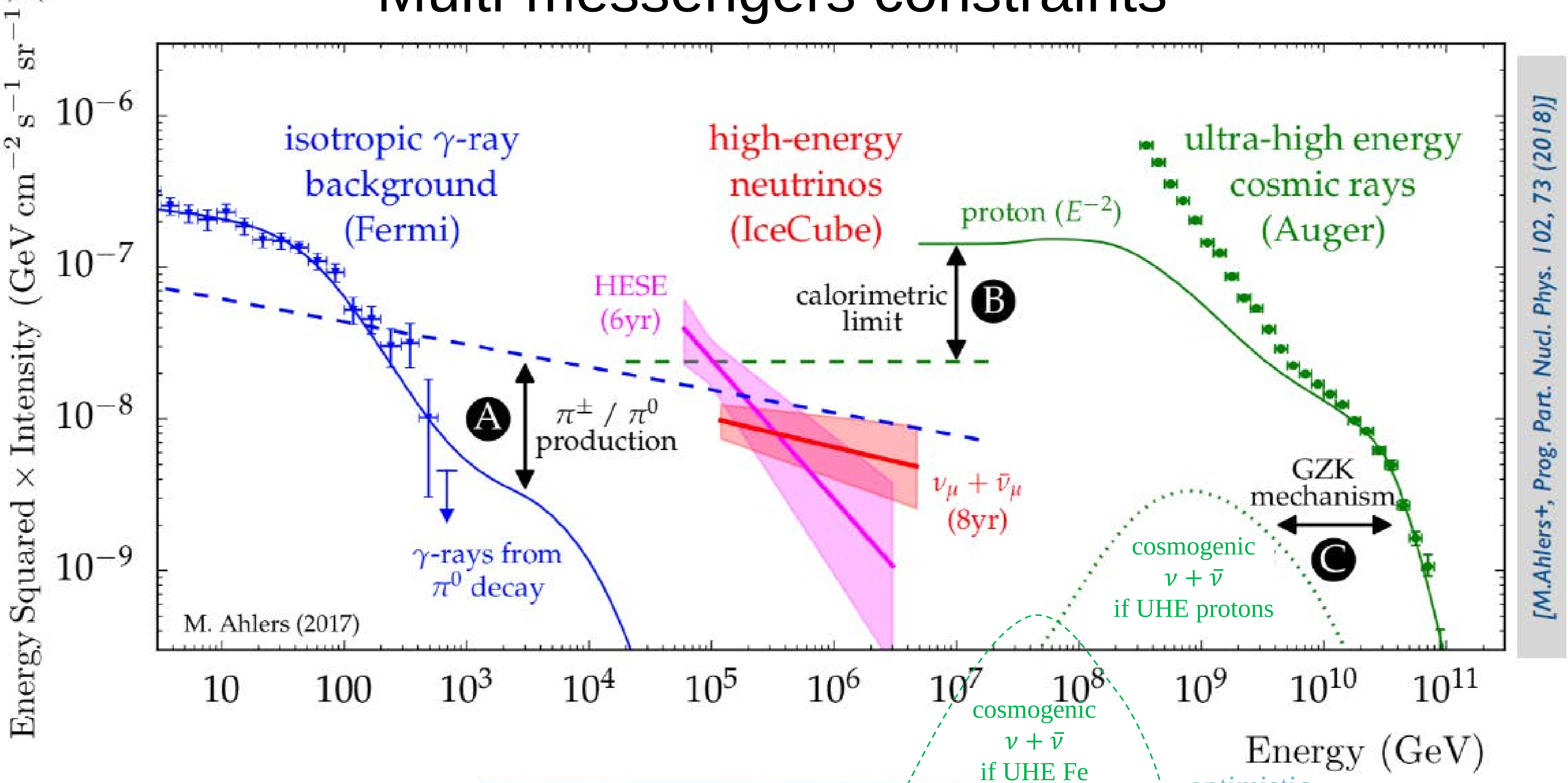
Angular coincidences to be confirmed…

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

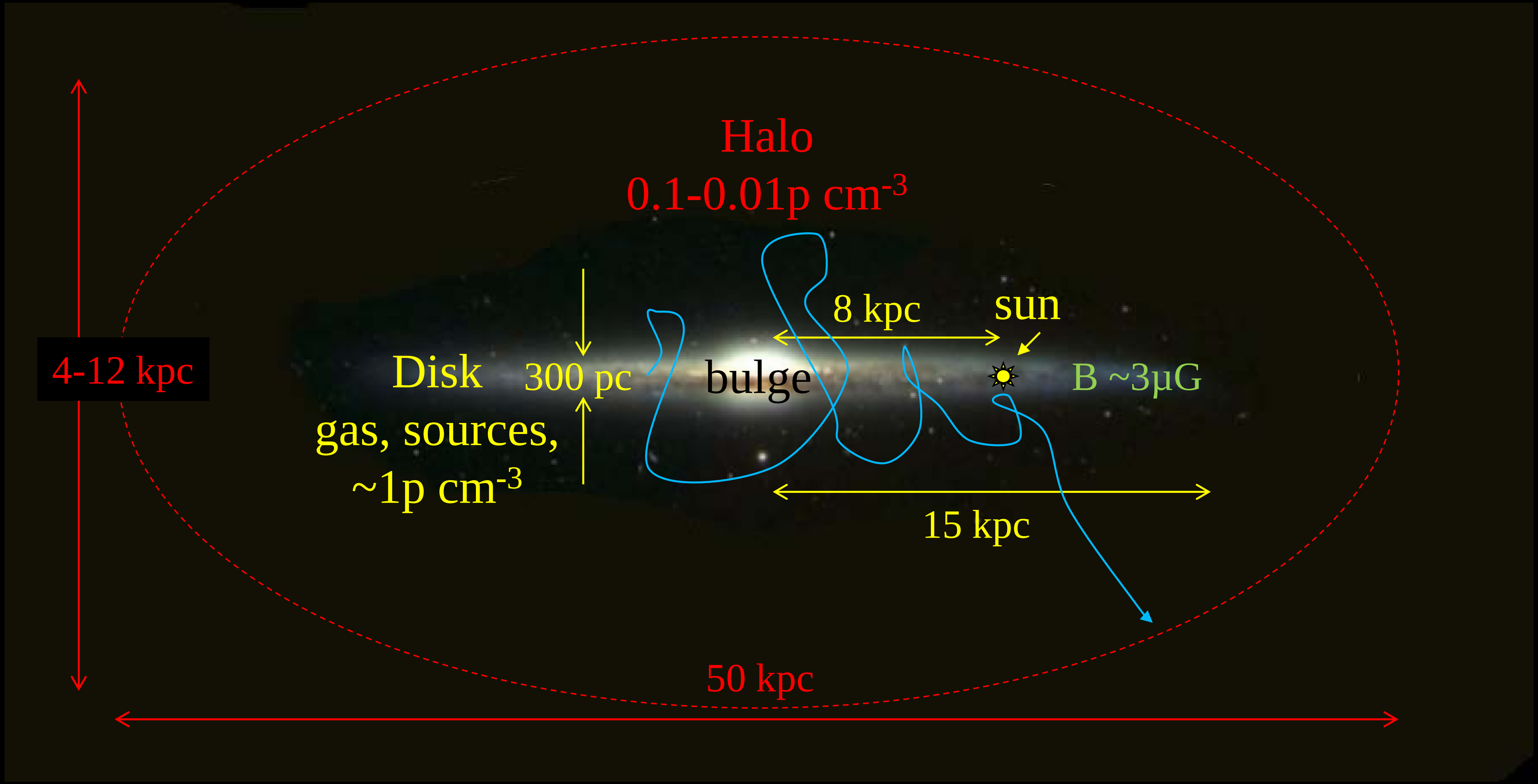
Special Relativity Violation

etc…

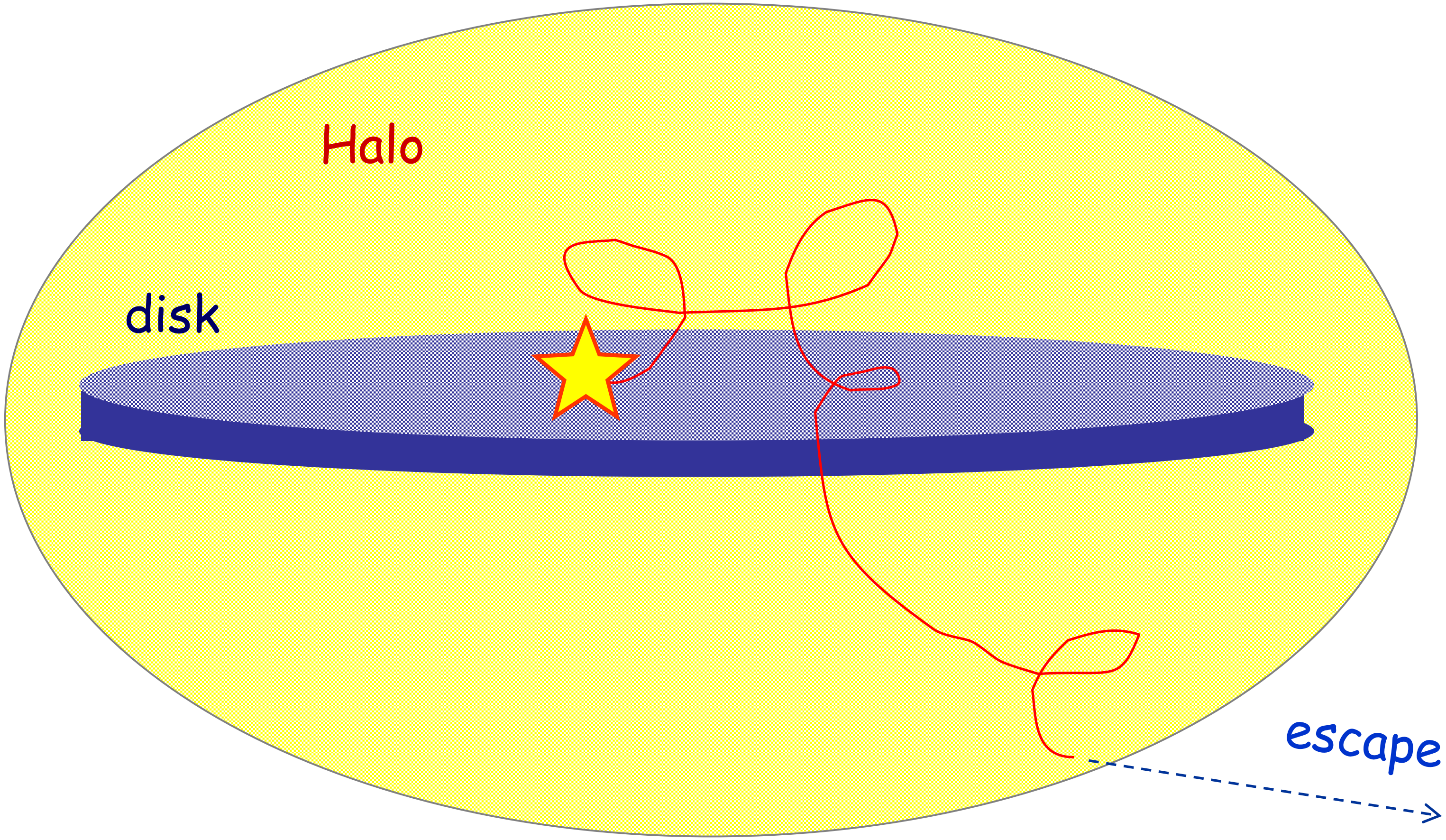
Propagation

Dimensions of the Milky Way

1 pc ≈ 3 l.y. ≈ 3×10^{16} m

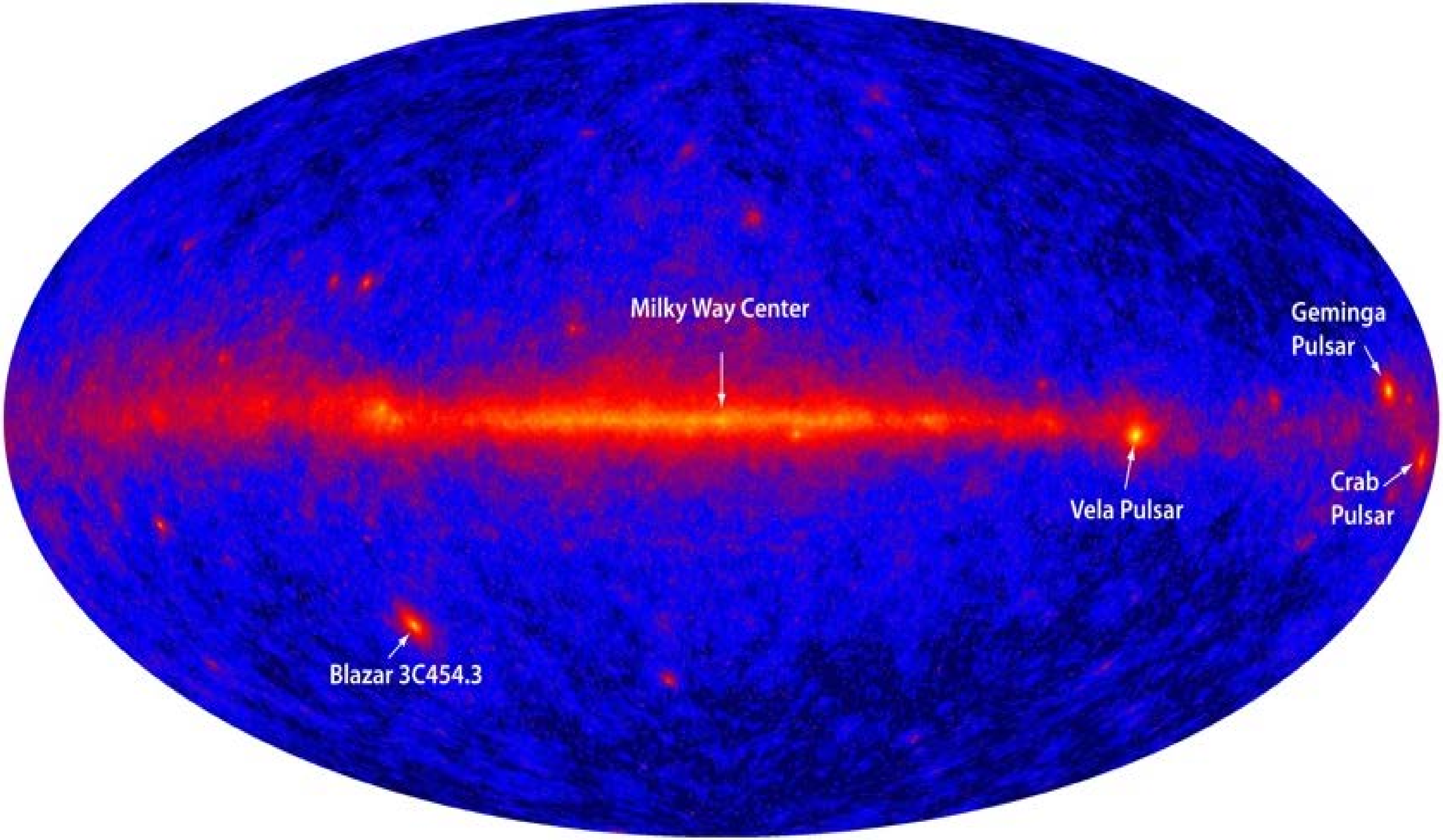


RC propagation in the Galaxy : the Leaky Box Model



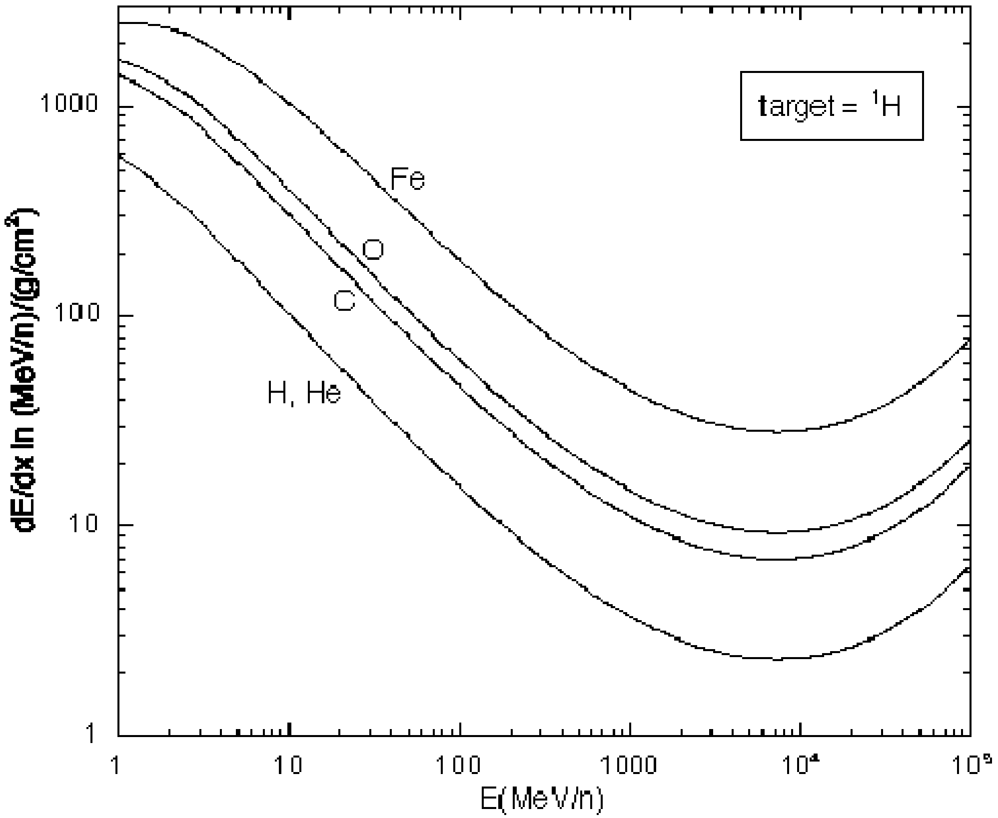
A thick target

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

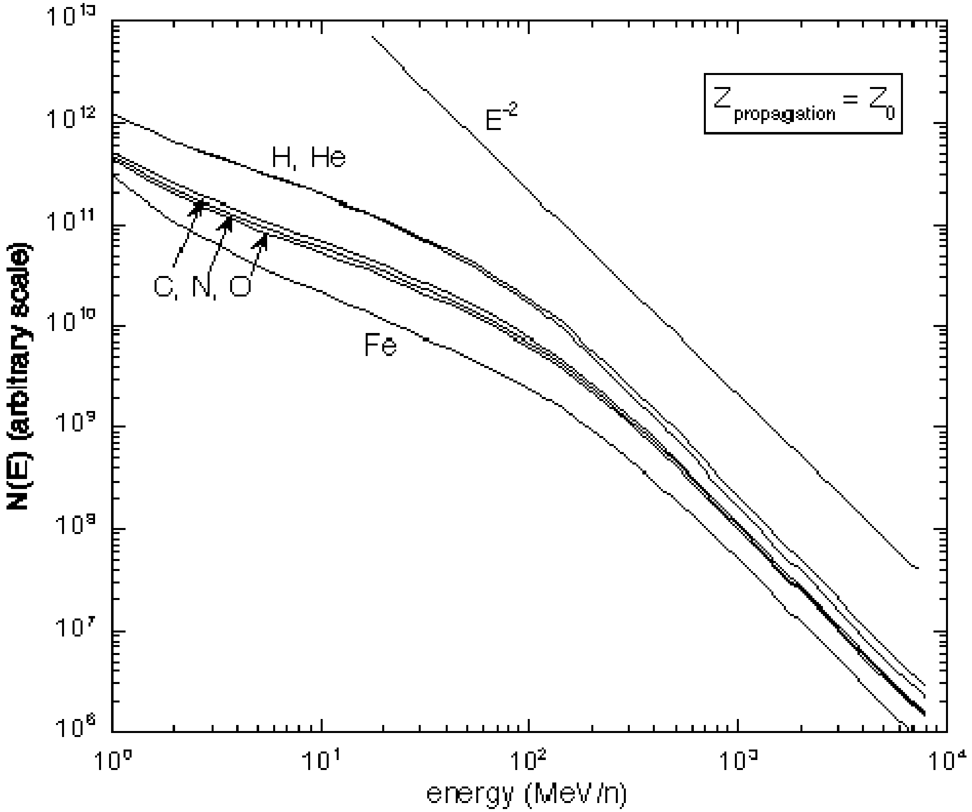


Cosmic rays transport

- Propagation in the interstellar medium



Energy loss: ionization, Coulombian interactions



Propagated spectra ionization losses only (thick target)

Grammage

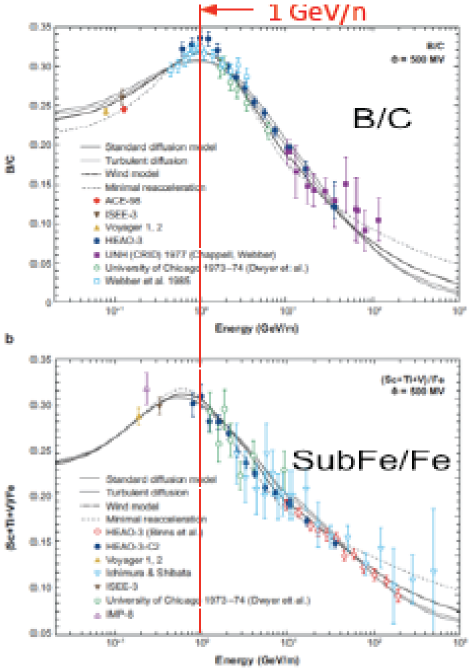
- Column density or quantity of matter traversed by the CR from its production site to earth (in kg × m^{-2} or g × cm^{-2})
- Given the diffusion time known from cosmic clocks (see below) the measurement of grammage allows understanding the diffusion extension zone.
- The ratio secondary/primary allows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

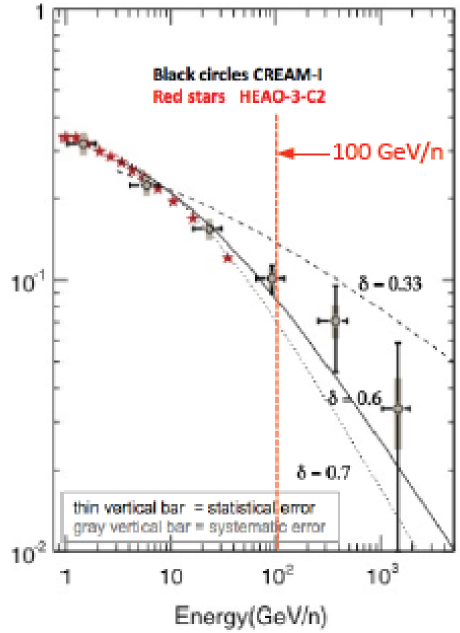
$$\begin{aligned} \frac{dN_S}{dx} &= -\frac{\sigma_P}{m} N_P \\ \text{donc} \quad N_S &= N_P \exp -\frac{\sigma_P}{m} x \\ \text{et} \quad x &= -\frac{m}{\sigma_P} \log(S/P) \end{aligned}$$

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

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

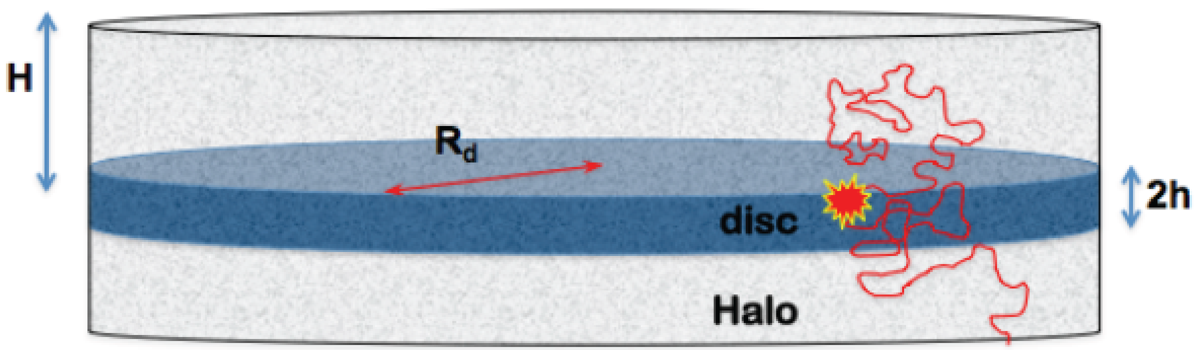
Secondary/Primary Nuclei Ratios





ECRS 2016 Torino, *P.S. Marrocchesi*

- Secondary/primary nuclei ratios decline for E > 1 GeV/n
- At high energy (E > 100 GeV/n) the S/P ratios measure the **rigidity R dependence of diffusion D(R)**
- Source spectra observed at Earth soften as a result of propagation in the Galaxy. In first approximation they factorize as $E^{-\delta}$



PRIMARY COSMIC RAY SPECTRUM AT EARTH

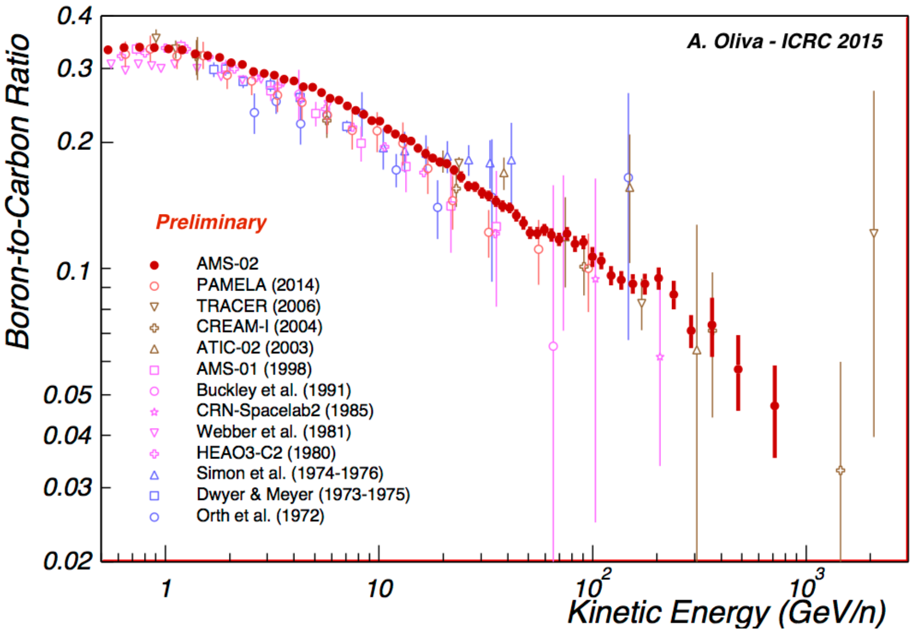
$$n_{CR}(E) = \frac{N(E)\mathcal{R}}{2\pi R_d^2}\frac{H}{D(E)} \equiv \frac{N(E)\mathcal{R}}{2H\pi R_d^2}\frac{H^2}{D(E)} \propto E^{-\gamma-\delta}$$

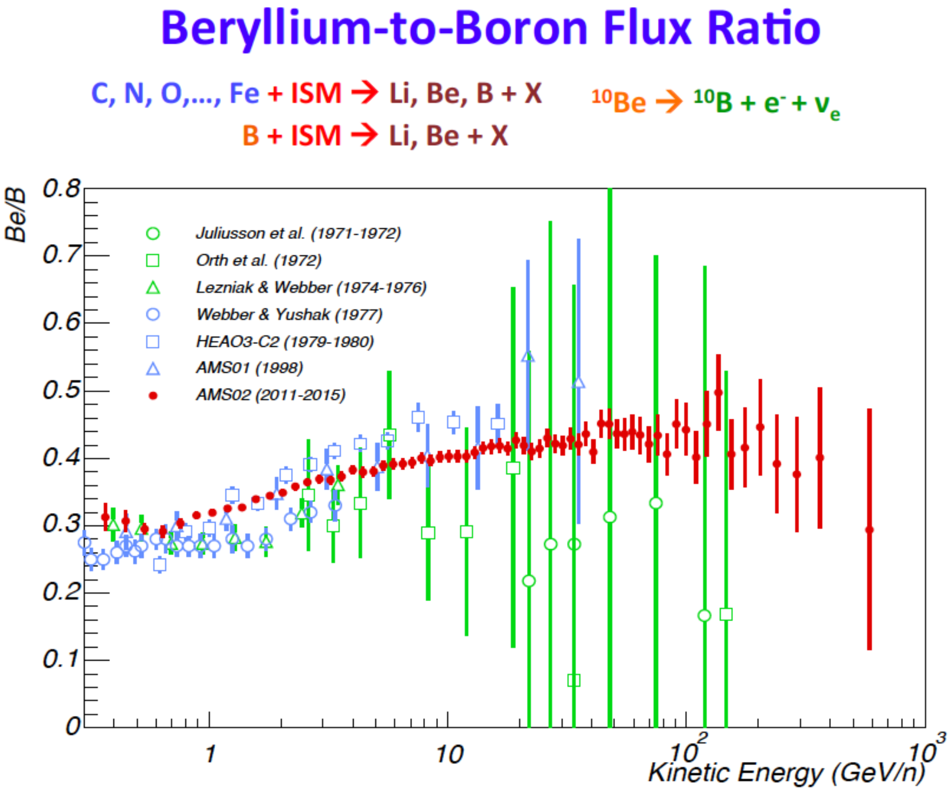
Secondary / Primary ratio

The grammage depend on the parent nucleus:

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

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





Secondary / Primary ratio

- A complete CR transport model
  - **The secondary to primary ratio can be expressed by:**

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

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

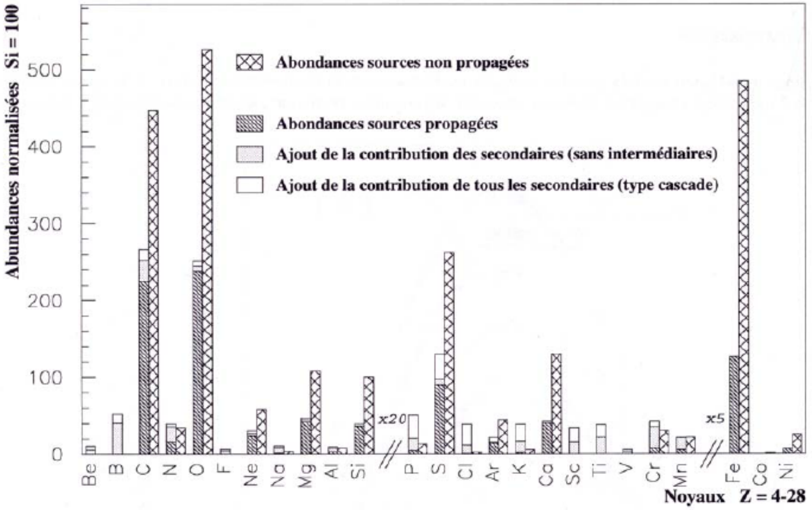
$$\frac{N_S}{N_P} = \frac{\sigma_{P\rightarrow S}}{\sigma_S + 1/\lambda_{esc}}$$

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

Cosmic clocks

Unstable nuclei with lifetimes comparable to the escape time $T_{1/2} \approx \tau^{esc}$ can be used as cosmic clocks.
The ratio unstable/stable isotope helps desantangling density and escape time.

$$\begin{aligned} {}^{10}Be &\rightarrow \tau = 2.17 Myr \\ {}^{26}Al &\rightarrow \tau = 1.31 Myr \\ {}^{36}Cr &\rightarrow \tau = 0.44 Myr \end{aligned}$$



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

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

Measure isotopic ratio

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

Estimate escape time.

On gets $\tau_e \approx 20 Myr$

Cosmic clocks and halo size

- Radioactive decay:

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

Measure isotopic ratios

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

Estimate escape time

- $^{12}C + H \to {}^{9}Be$ (stable secondary nucleus)
  $^{12}C + H \to {}^{10}Be$ (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.

Cosmic clocks and halo size

- $^{12}C + H \to {}^{9}Be$ (stable secondary nucleus)
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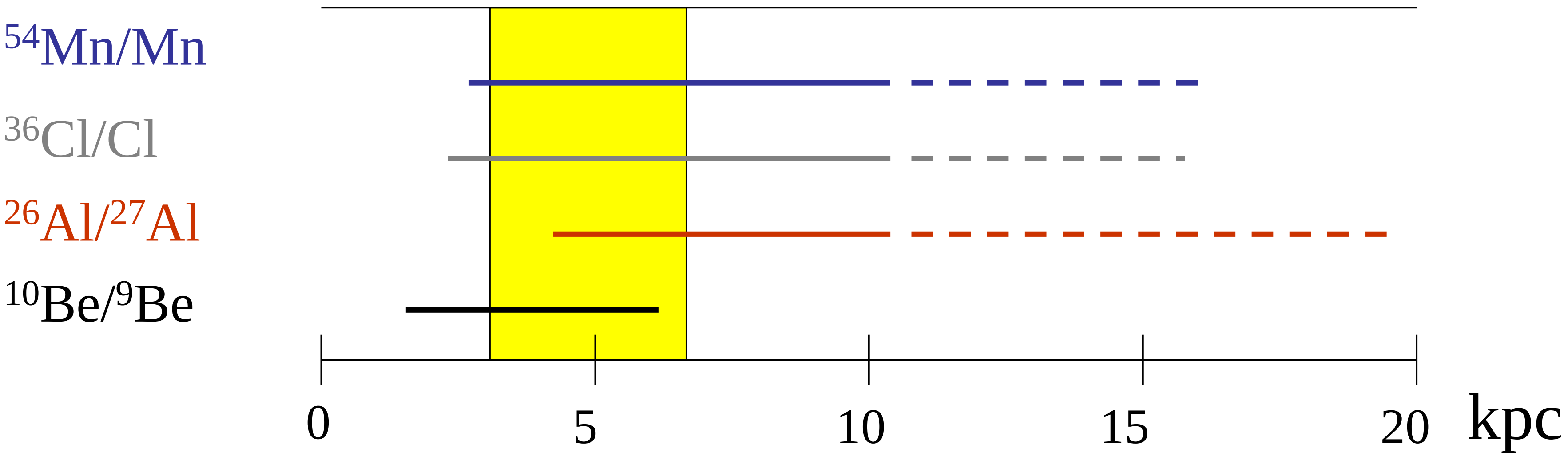
- The ratio $^{10}Be / {}^{9}Be$ depends on secondaries **history** (and on cross sections).
  - Link between quantity of matter traversed and diffusion time.
- Diffusion parameters adjustments (excursion in the less dense galactic halo)

  ⇒ determination of the CR confinement zone



Confinement and escape

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

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

- $\lambda_{esc} \gg R = 20 kpc$ ⇒ 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:

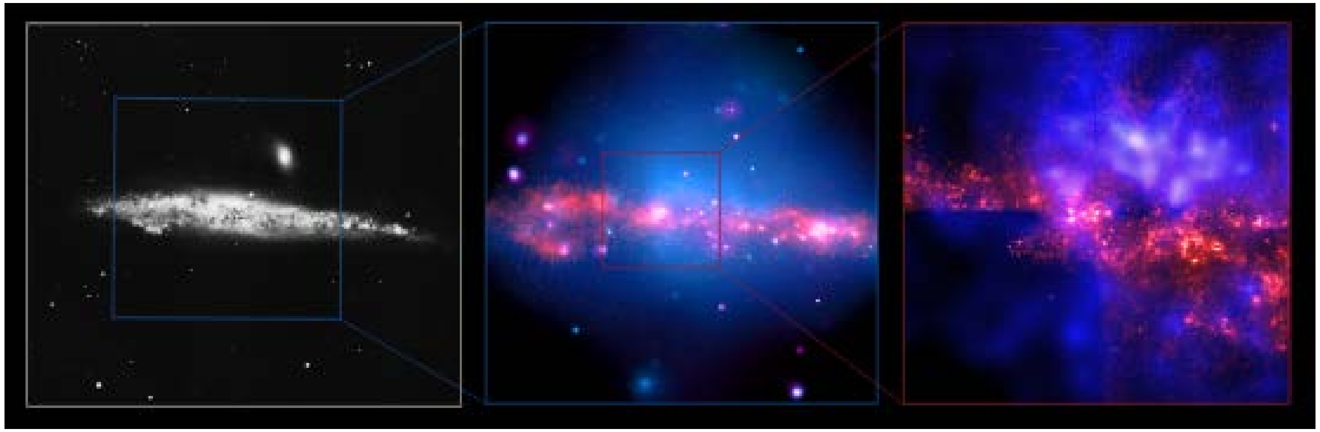
$$n_H \;=\; \lambda_{esc}/c\, \tau_{esc}\, m_p \approx 0.3 cm^{-3} < n_{disk} = 1 cm^{-3}$$

⇒ 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

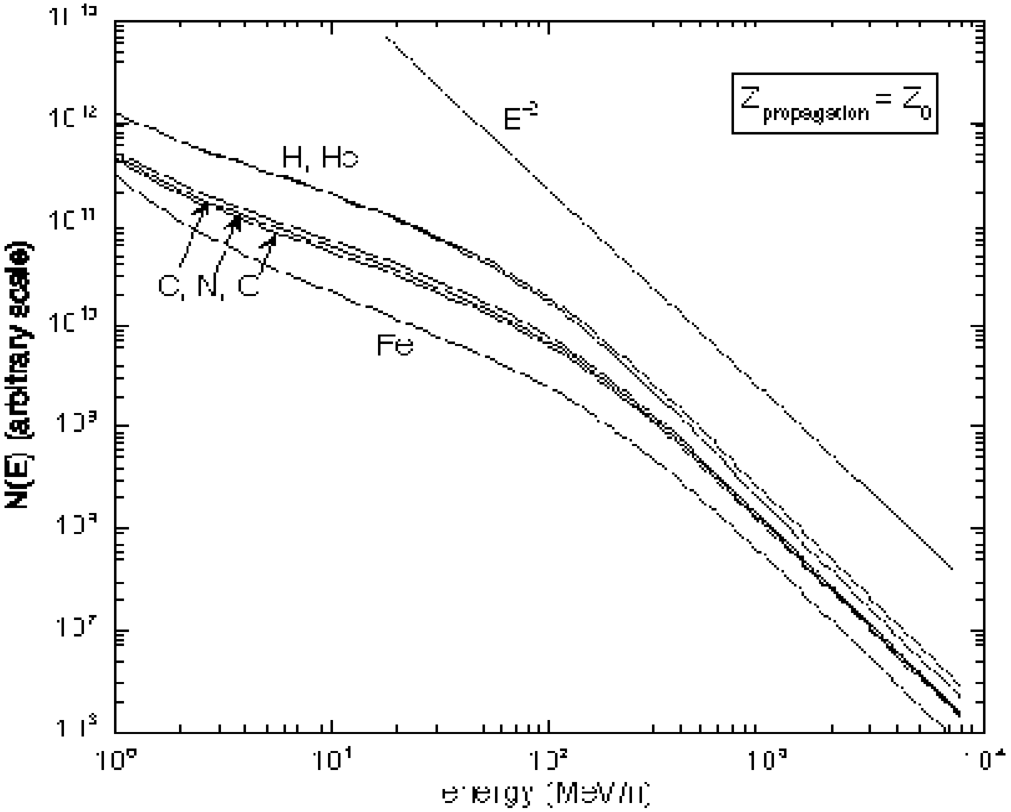
$$T = 10^6\ K \quad \text{et } n = 10^{-3} cm^{-3}$$



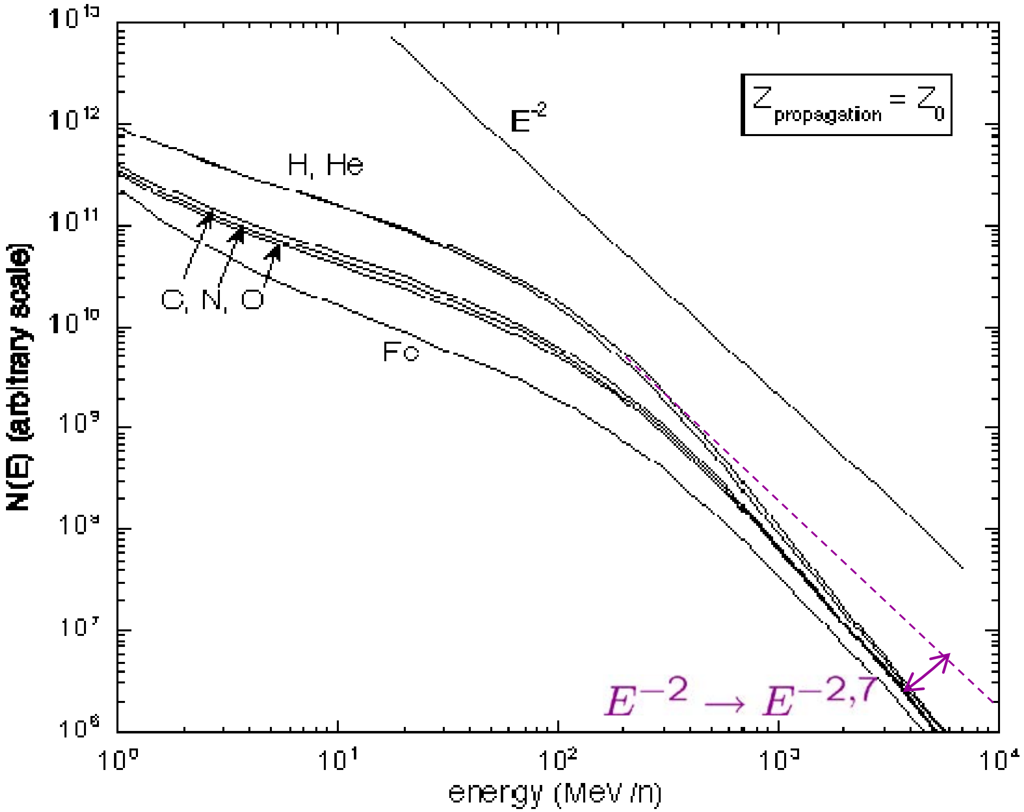
- NGC 4631 galaxy and its halo of hot ionized matter emitting X-rays as seen by Chandra

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

CR confinement

- Escape depends on E
  - Diffusion on magnetic inhomogeneities
  - When $E \nearrow$, $r_g \nearrow$ thus interaction with inhomogeneities with larger wavelengths.
- $D(E)$ is an increasing function

$$D = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^x$$ where ρ is the particle rigidity

$$\to \tau_{conf}(E) \propto E^{-x}$$

- Kolmogorov spectrum $\to \tau_{conf}(E) \propto E^{-1/3}$
  - $x - 2 = 1/3 < 0,7$ … clearly not enough but…
  - ISM perturbations ? Diffusion-convection, MHD ?
- Determination of $\tau_{conf}(E)$ a posteriori :

$$2,7 - 2 = 0,7 \;\; !!!$$

Full transport equation

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

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

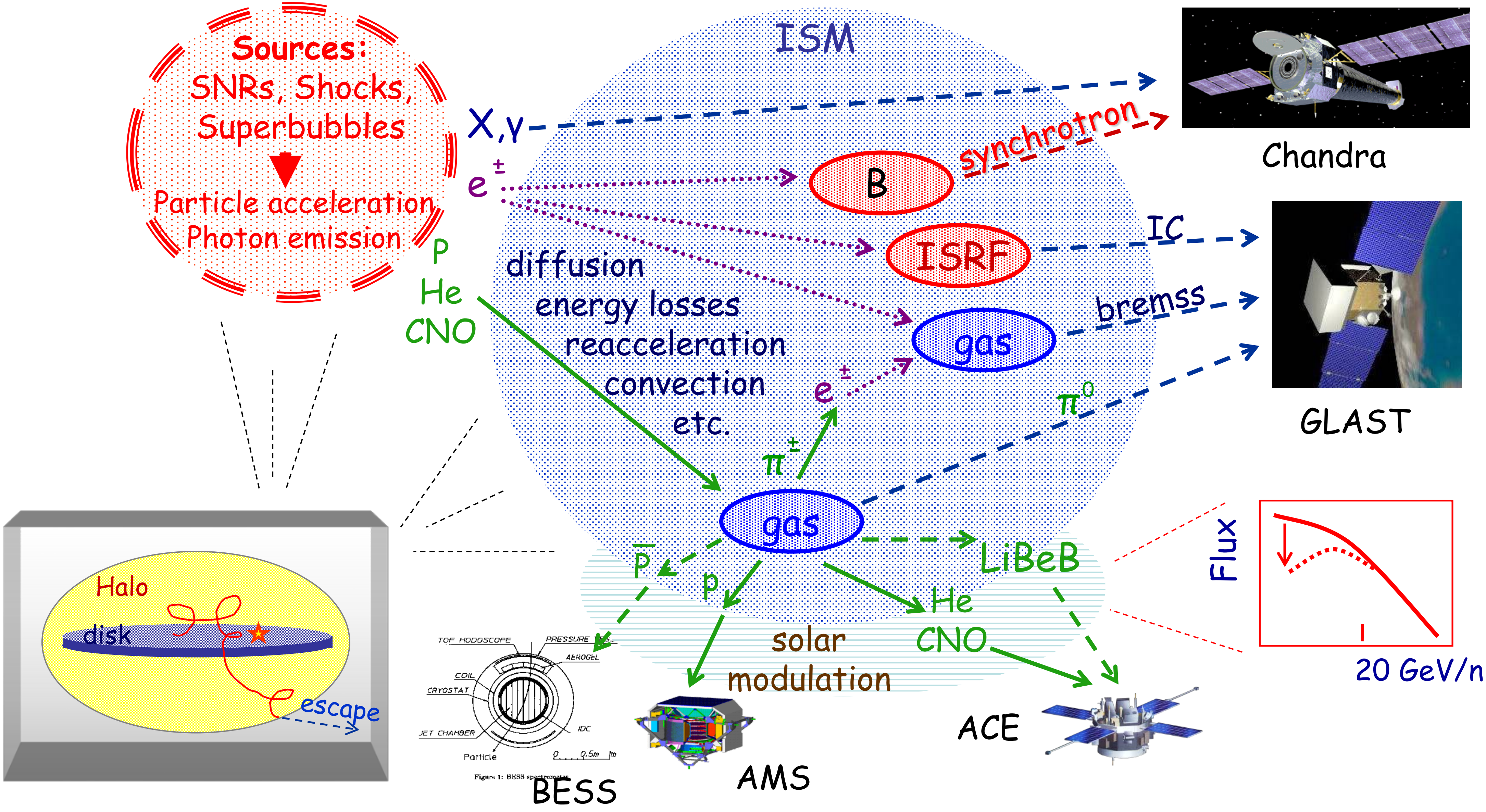
diffusive reacceleration $+ \dfrac{\partial}{\partial p}\left[p^2 D_{pp}\dfrac{\partial}{\partial p}\left(\dfrac{\psi}{p^2}\right)\right]$

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

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

*ψ(**r**,p,t) – momentum density*

Propagation in the ISM
et observational contrains



Summary for galactic CR

Everything works fairly well…

- Propagation in the ISM:
  - Complete theory with energy losses, diffusion, in flight nuclear reactions, CR escape, reacceleration, … impressive results.

(see for example GLAPROP model, A. Strong et I Moskalenko)

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

...except naive acceleration models!

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

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

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

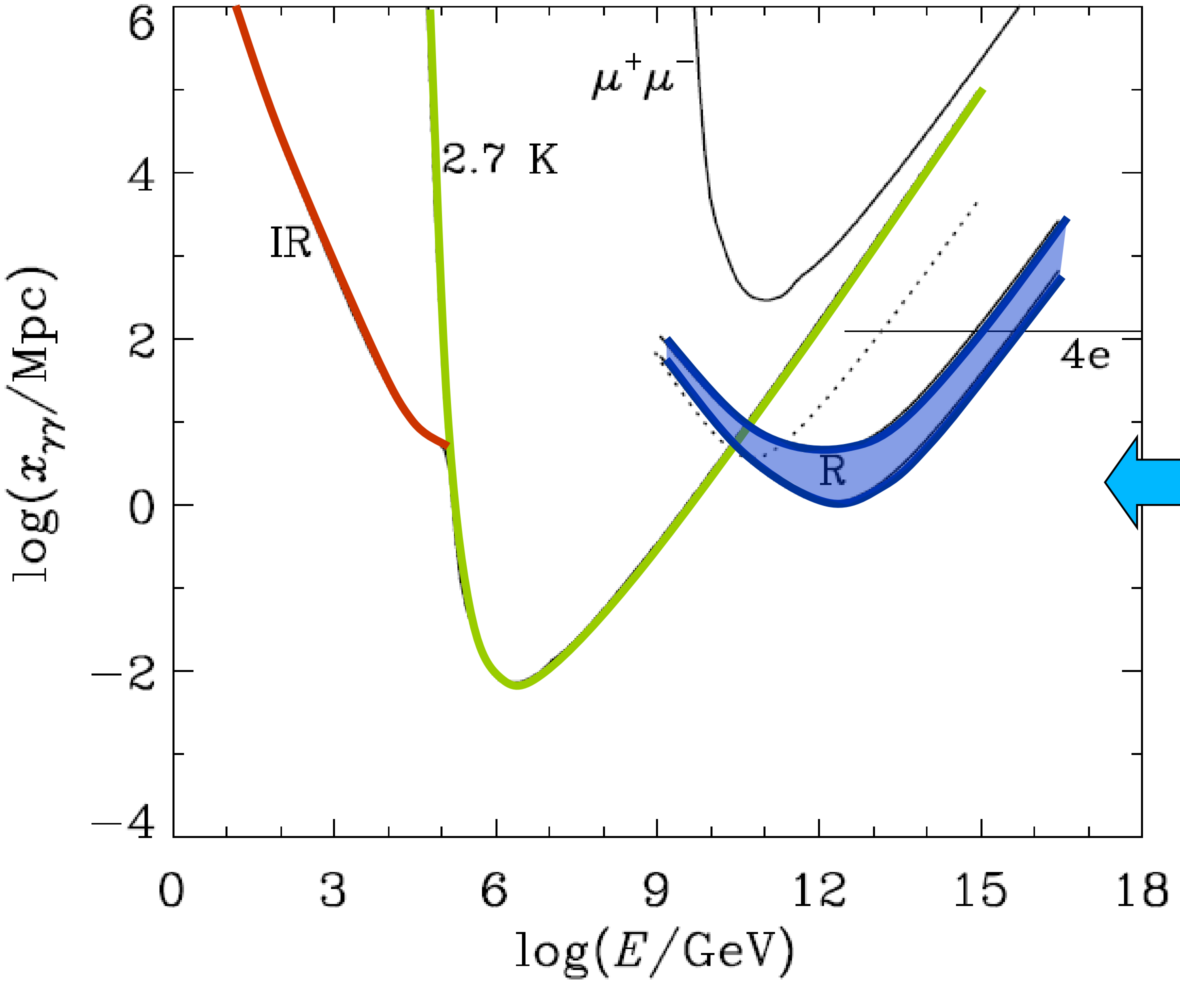
Many parameters) need many observational constrains.

UHE GAMMA-RAY PROPAGATION

Photon attenuation at VHE by intergalactic photon backgrounds

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

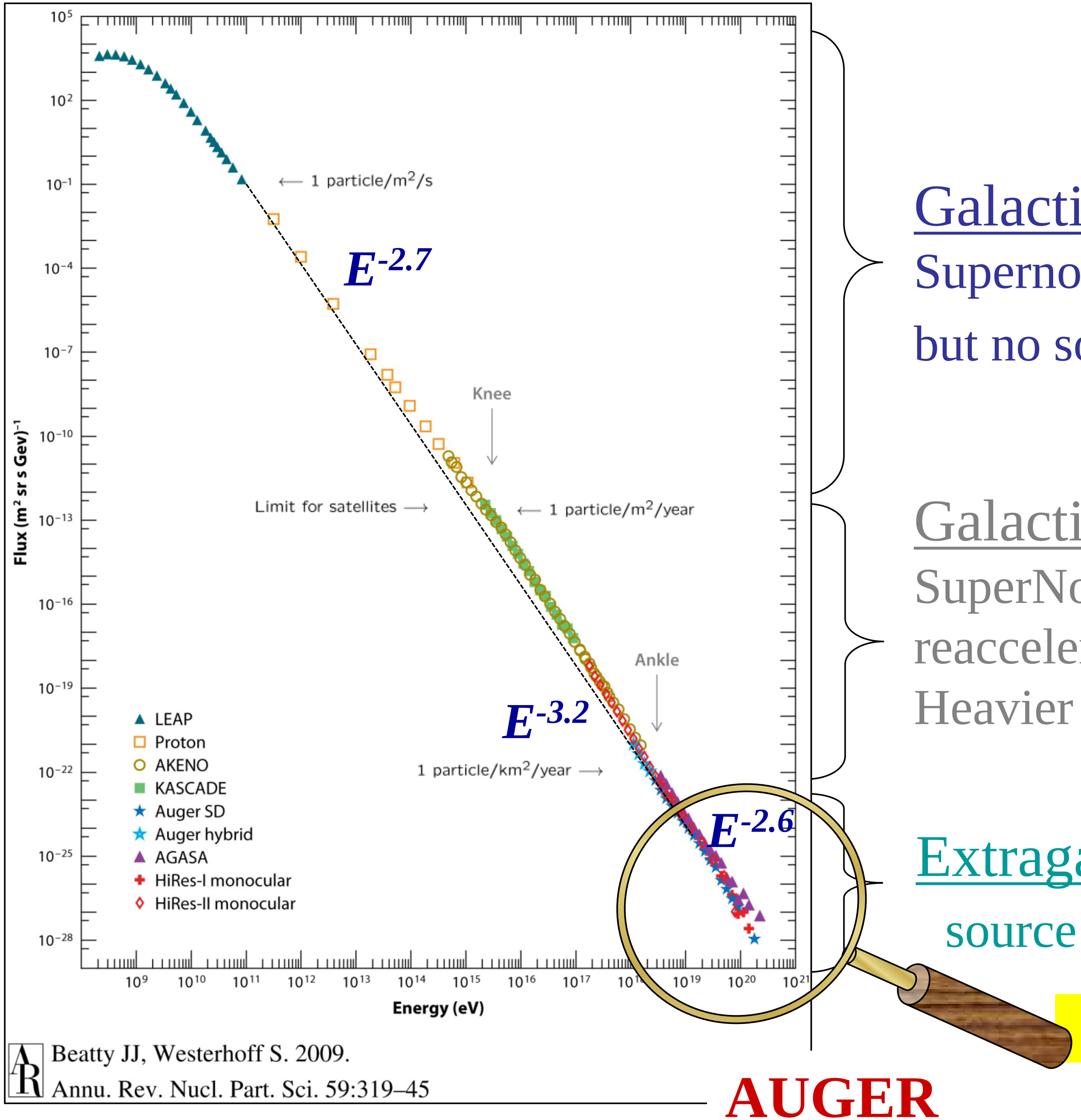
Low energy γ diffuse flux



Effective γ horizon:
100Mpc at 1TeV
1Mpc at 10 TeV
and above

UHECR PROPAGATION

The CR spectrum



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

AUGER

Galactic CR :

Supernovae, MIS,

but no source pointing!

Galactic ?

SuperNovae? Superbubles?

reacceleration?

Heavier nuclei → protons ?

Extragalactic ?

source ? composition ?

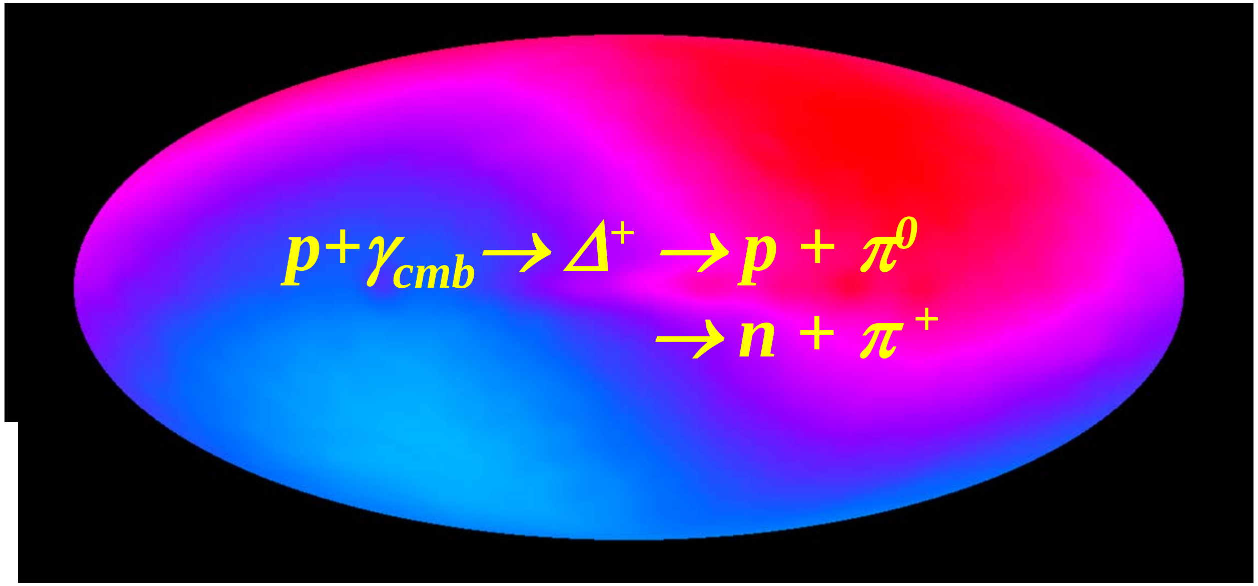
UHECR, terra incognita

UHECR propagation

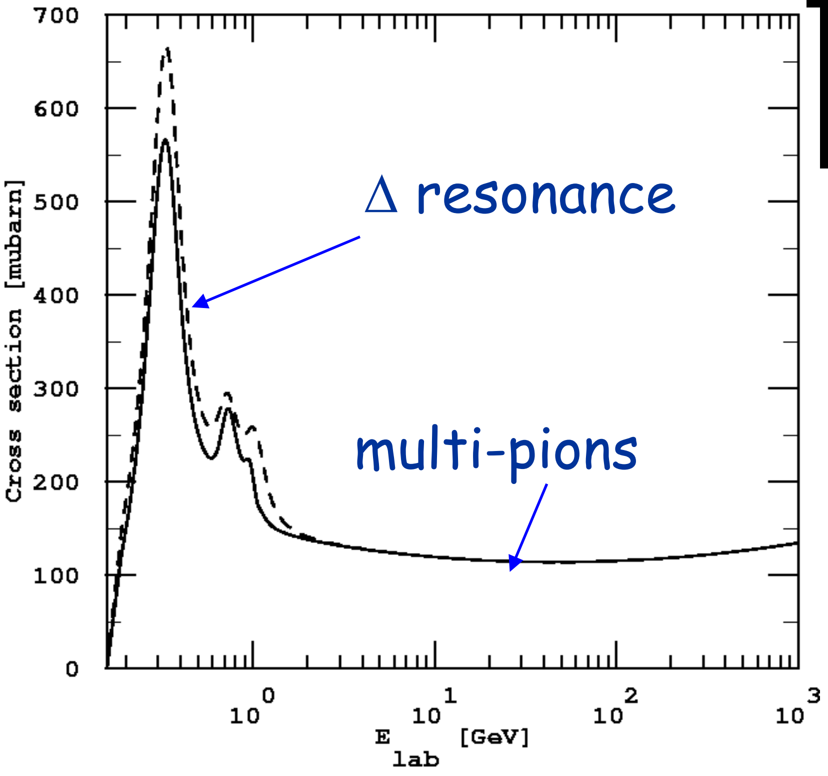
3 essential effects :

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

An extreme case of relativistic kinematics !!!



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

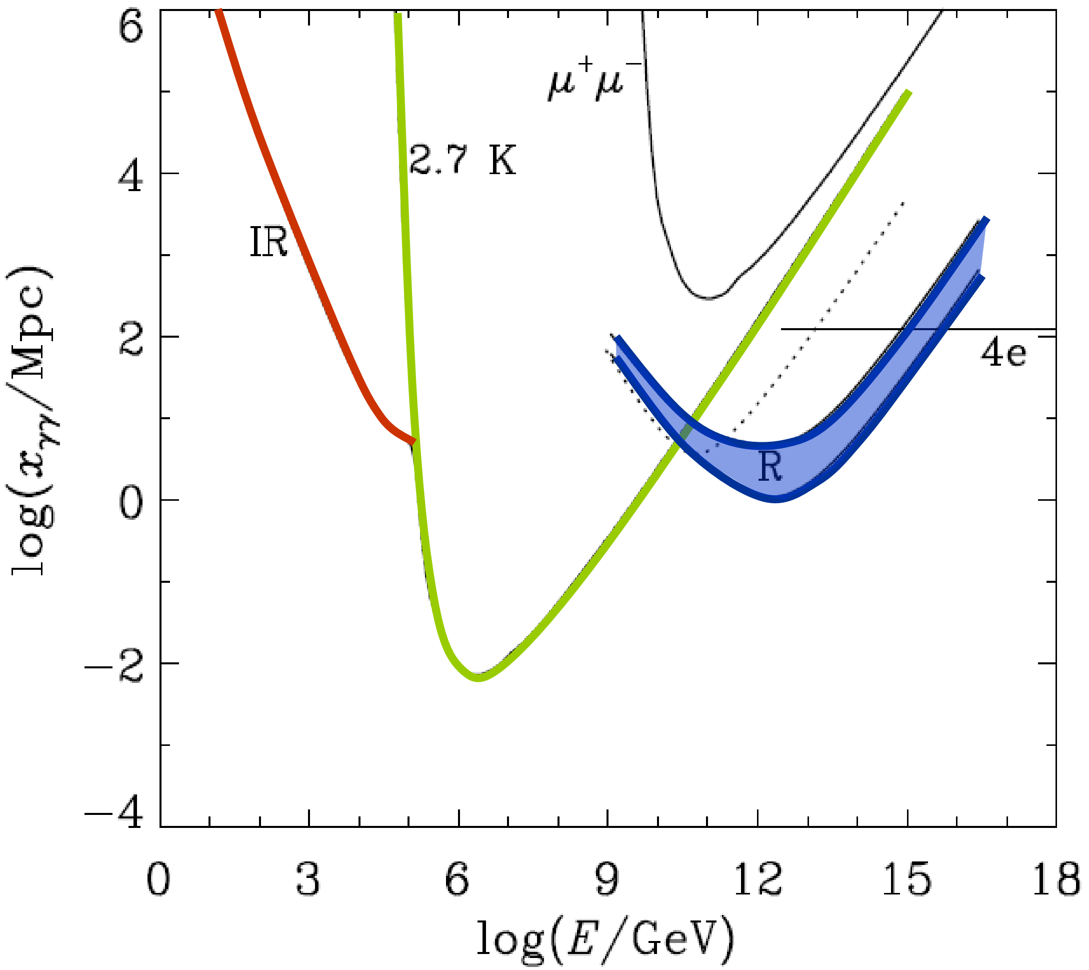


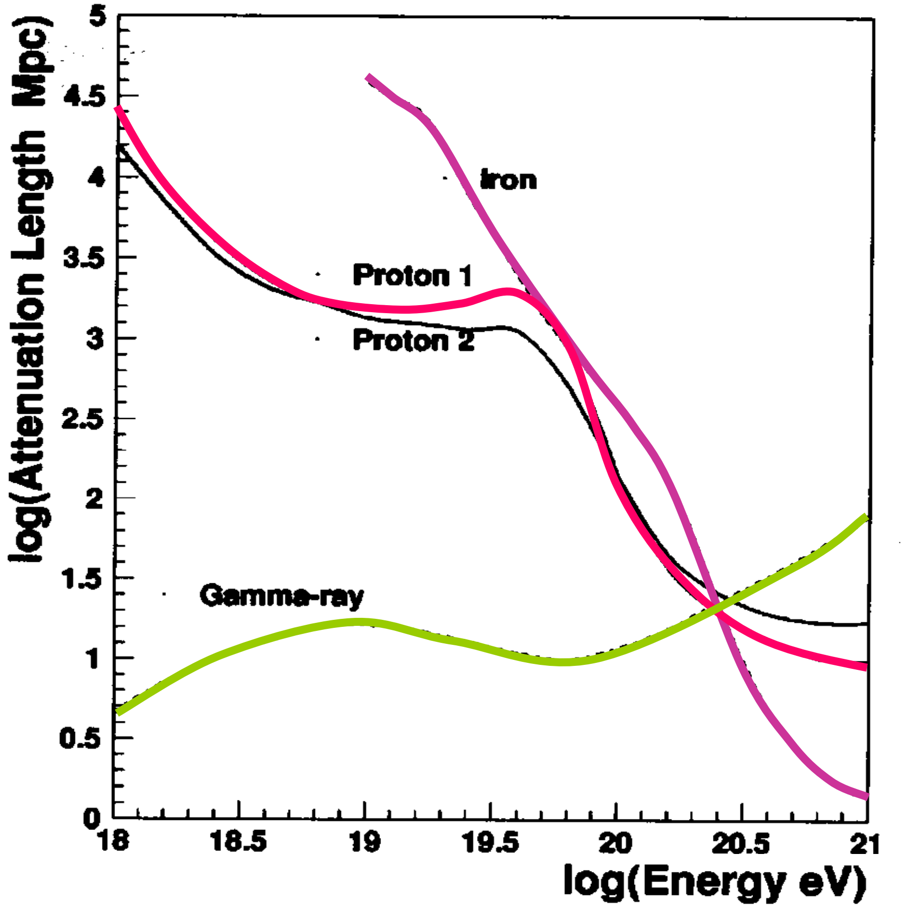
GZK "cutoff"

Greisen '66, Zatsepin & Kuzmin '66

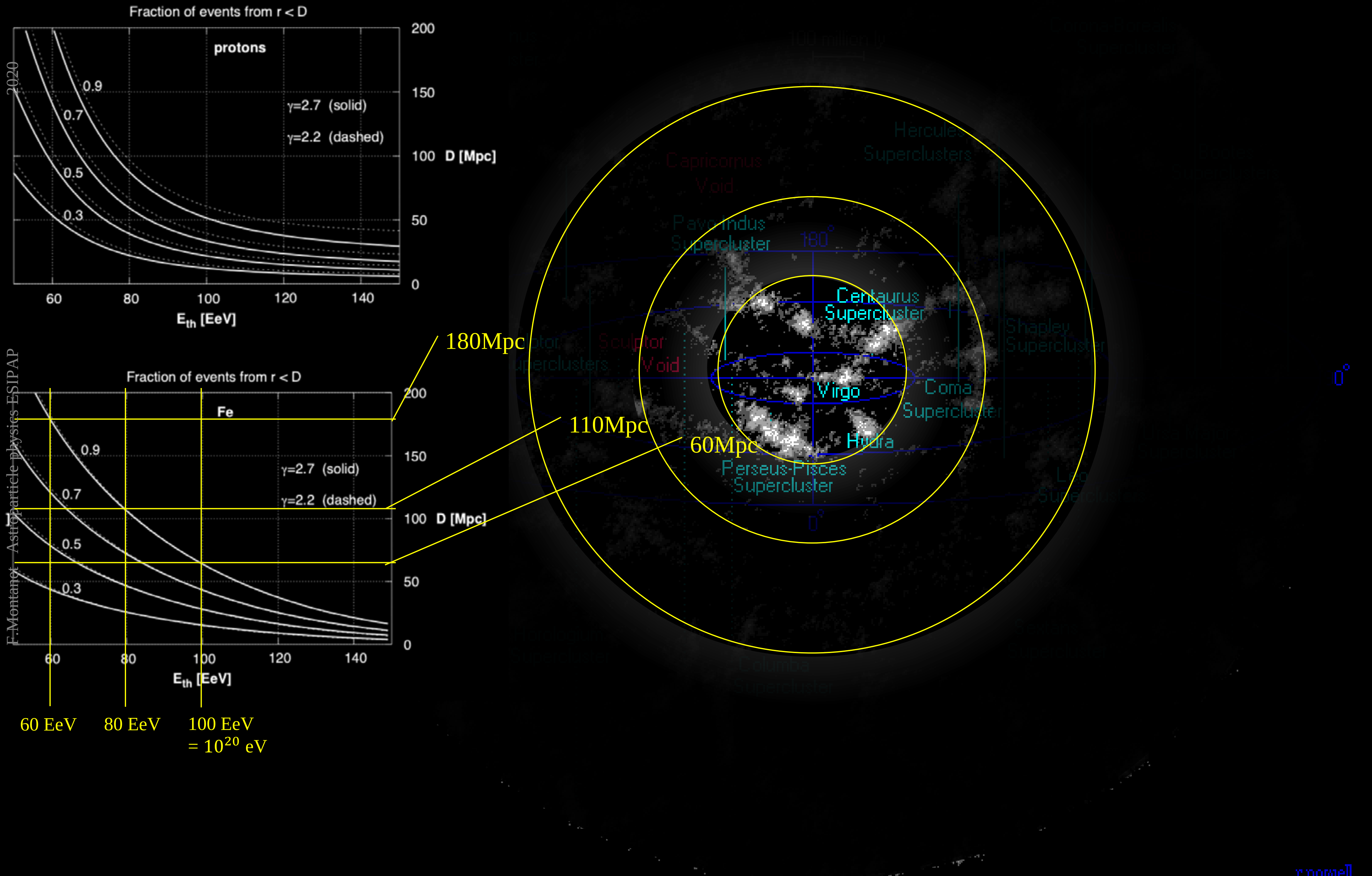
Energy losses

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





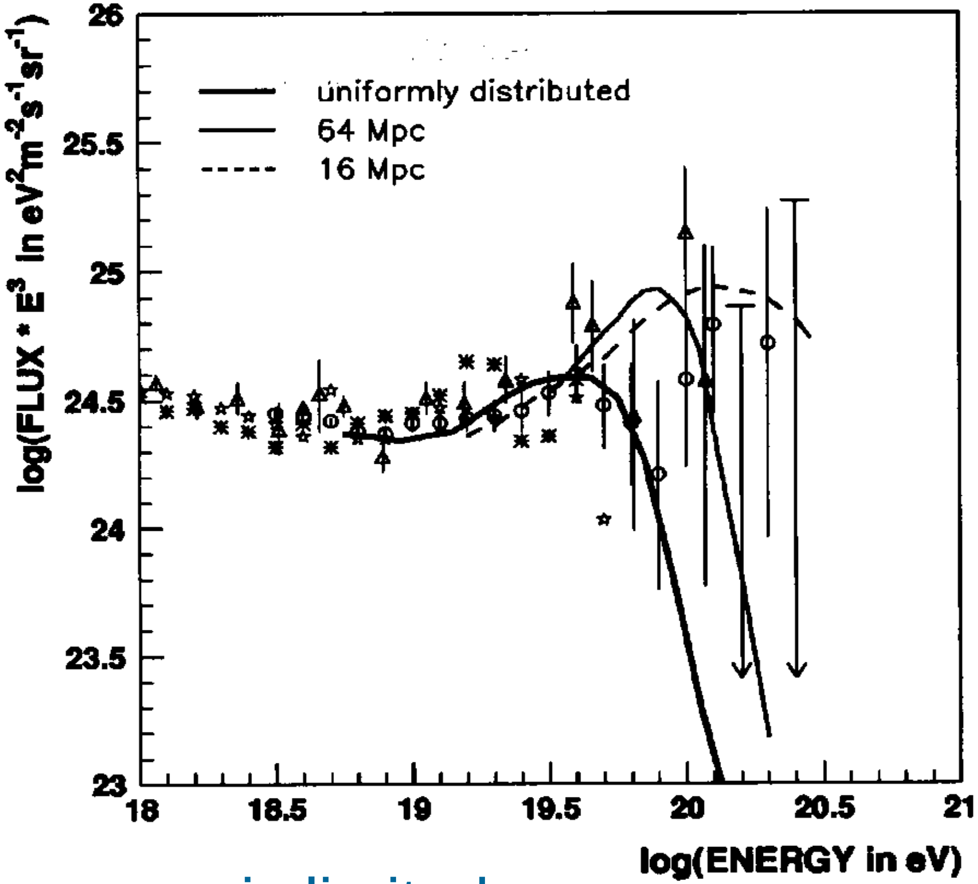
Horizon < 200Mpc at UHE



F.Montanet – Astroparticle physics ESIPAP 2020

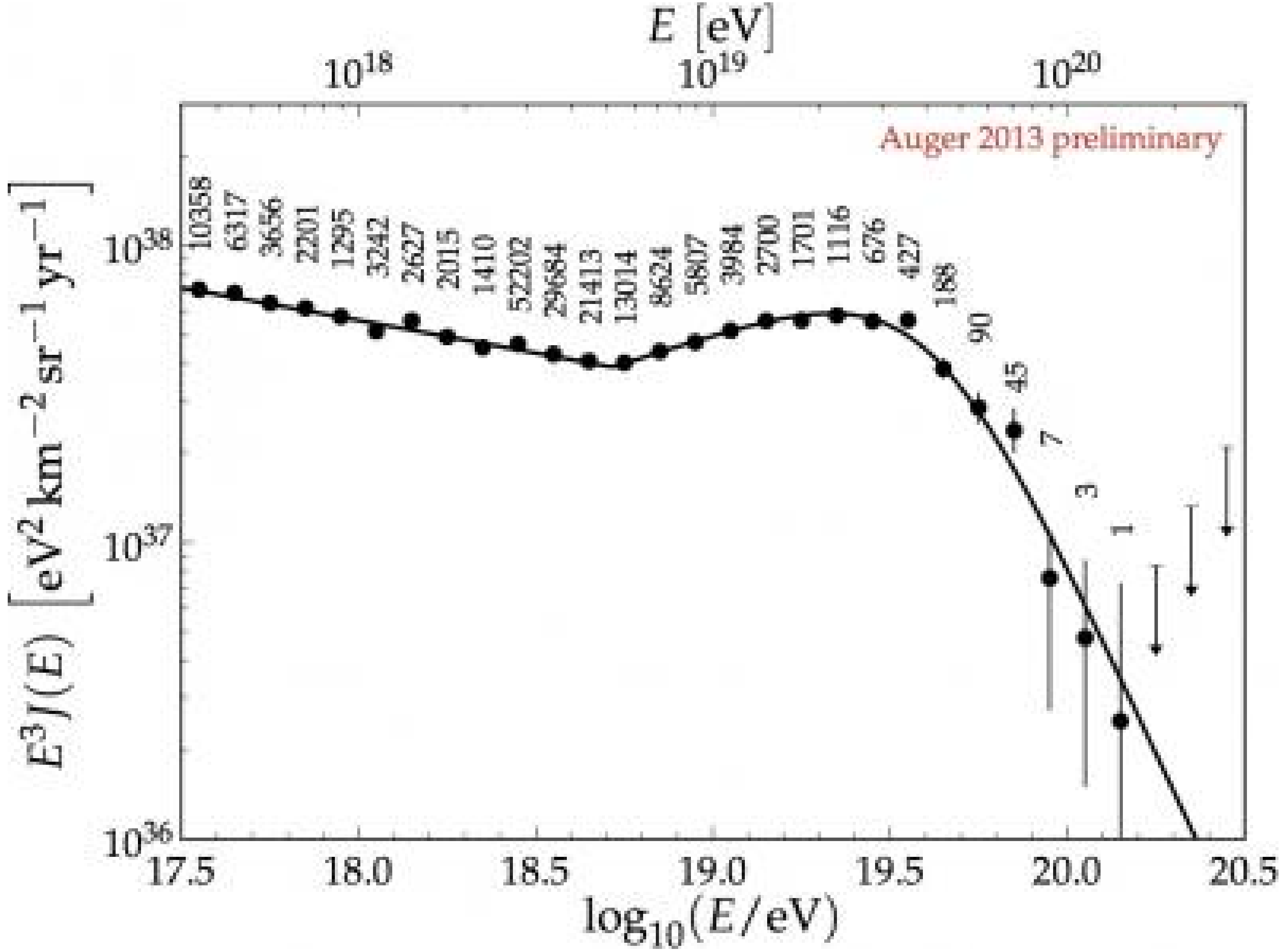
GZK suppression

- Greisen-Zatsepin-Kuz'min

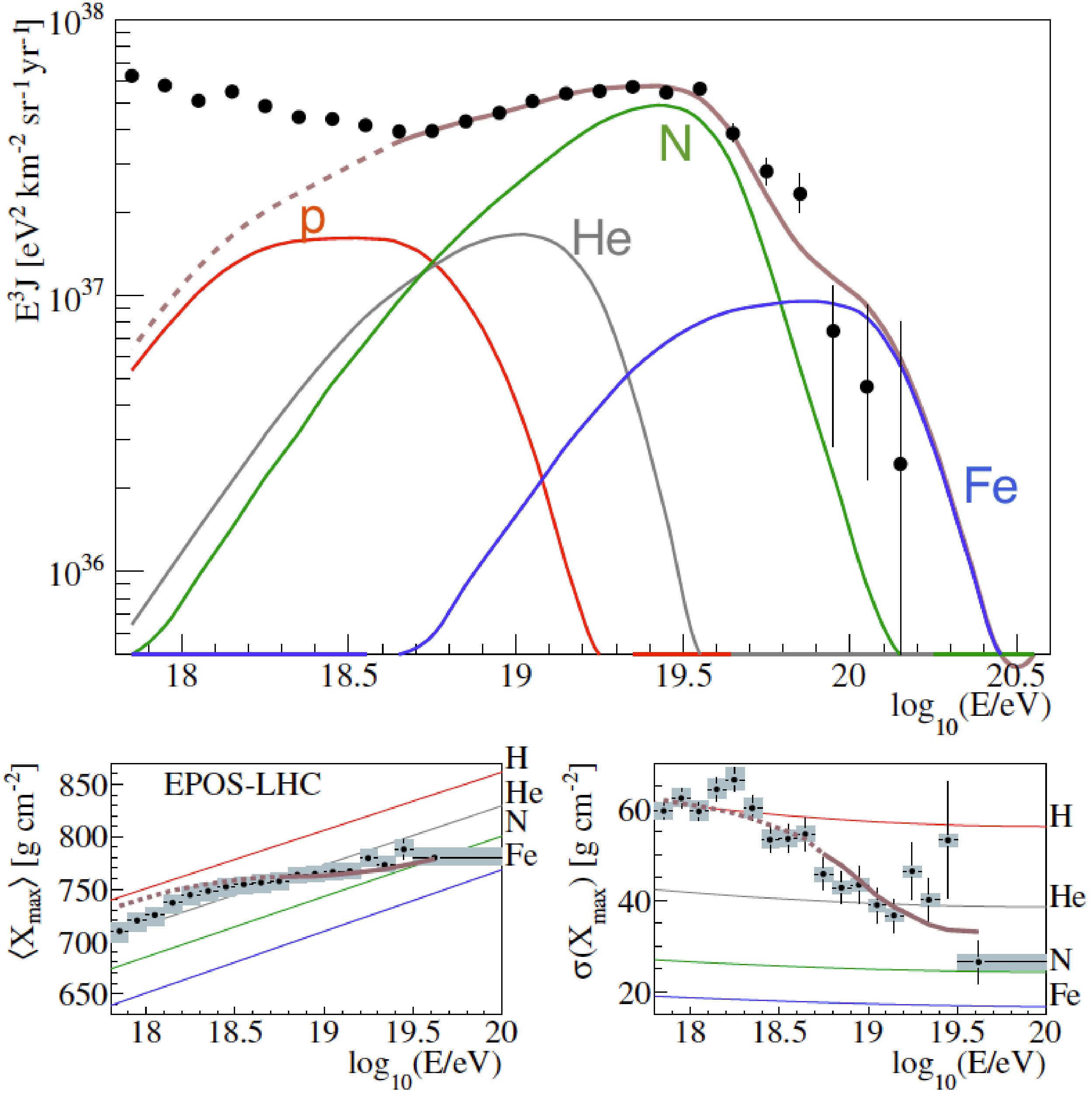


- Distance to the source is limited to 100 Mpc for 10^{20} eV protons, and 15 Mpc for 3×10^{20} !
- Actually even less if particles are deflected ($D_{effectif} > D_{linear}$)

GZK like suppression (Auger)



Flux suppression (Auger)



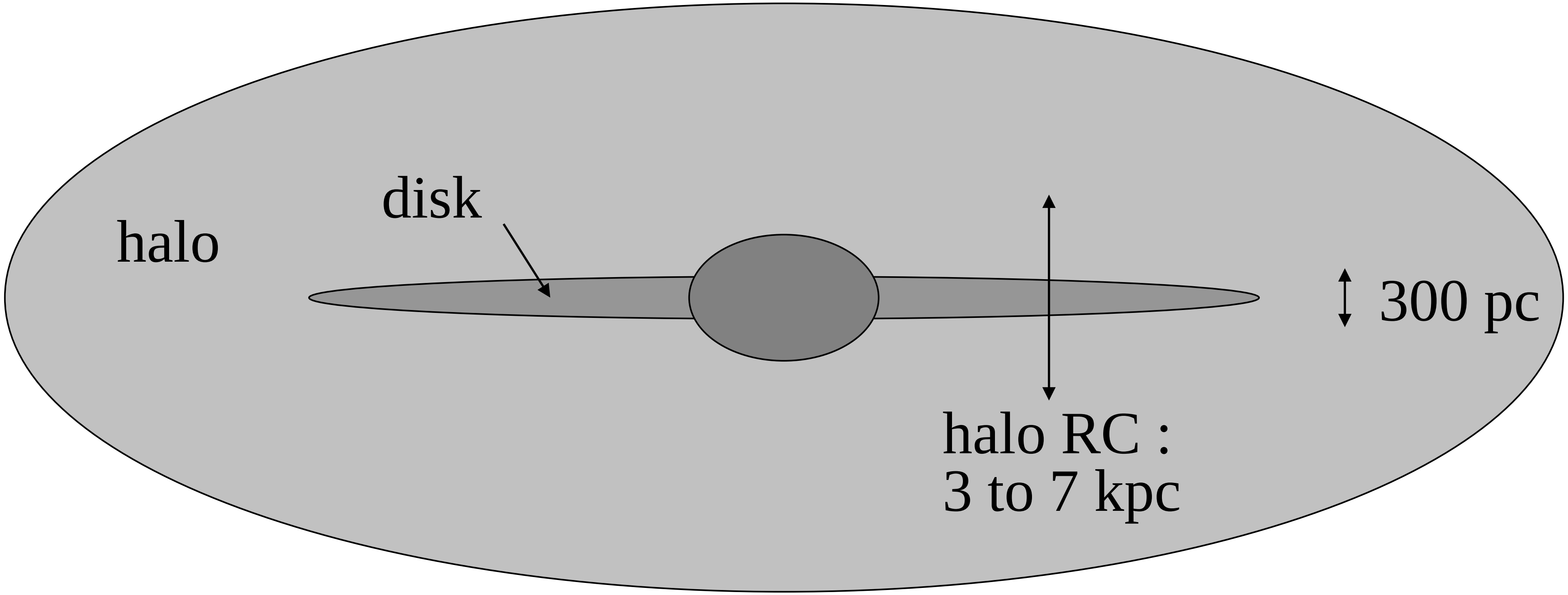
The spectrum is best fitted by a succession of cutoffs of the different groups of elements, with $R_{cut} = 10^{18.67\pm0.03}V$, thus pointing to the flux at Earth being partly limited by the maximum energy at the source. The best fit returns $\gamma = 0.94^{+0.09}_{-0.10}$, suggesting a very hard source 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 μG field ⇒ $r_g \sim 370$ pc

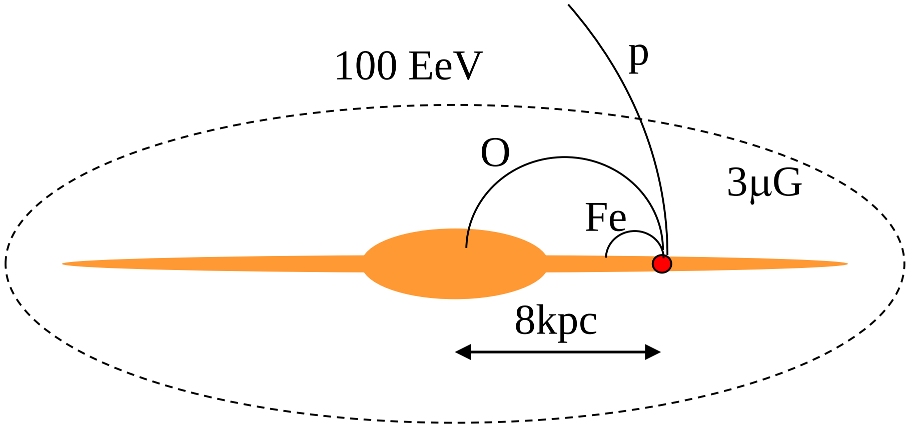


- 2×10^{19} eV **proton in** B = 3 μG ⇒ $r_g \sim 7$ kpc
- 5×10^{20} eV **Fe in** B = 3 μG ⇒ $r_g \sim 7$ kpc

Propagation in the Galaxy

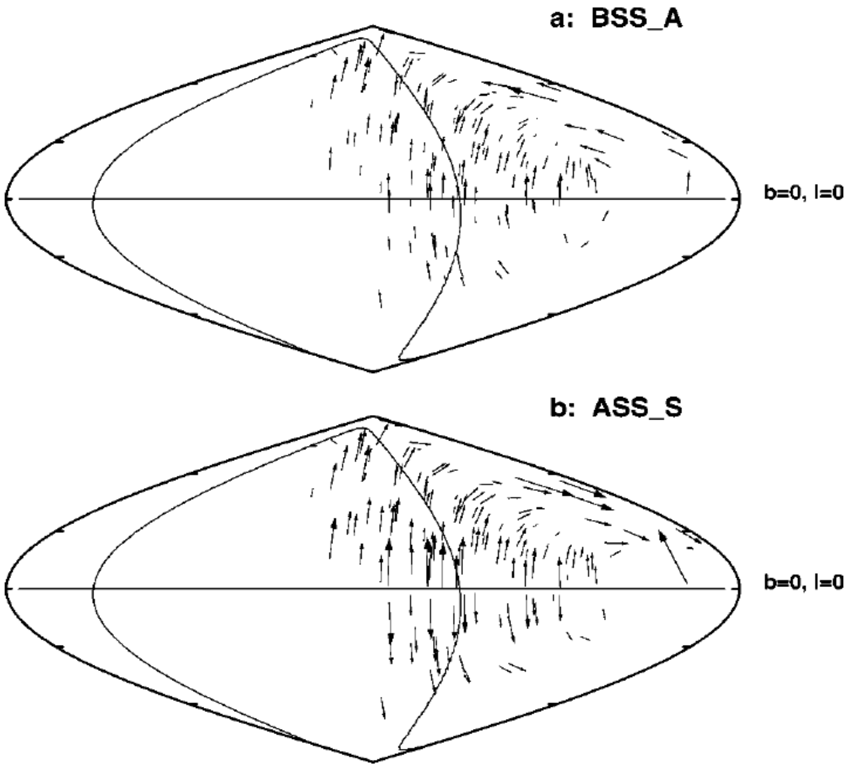
- Galactic magnetic field model, given that:

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



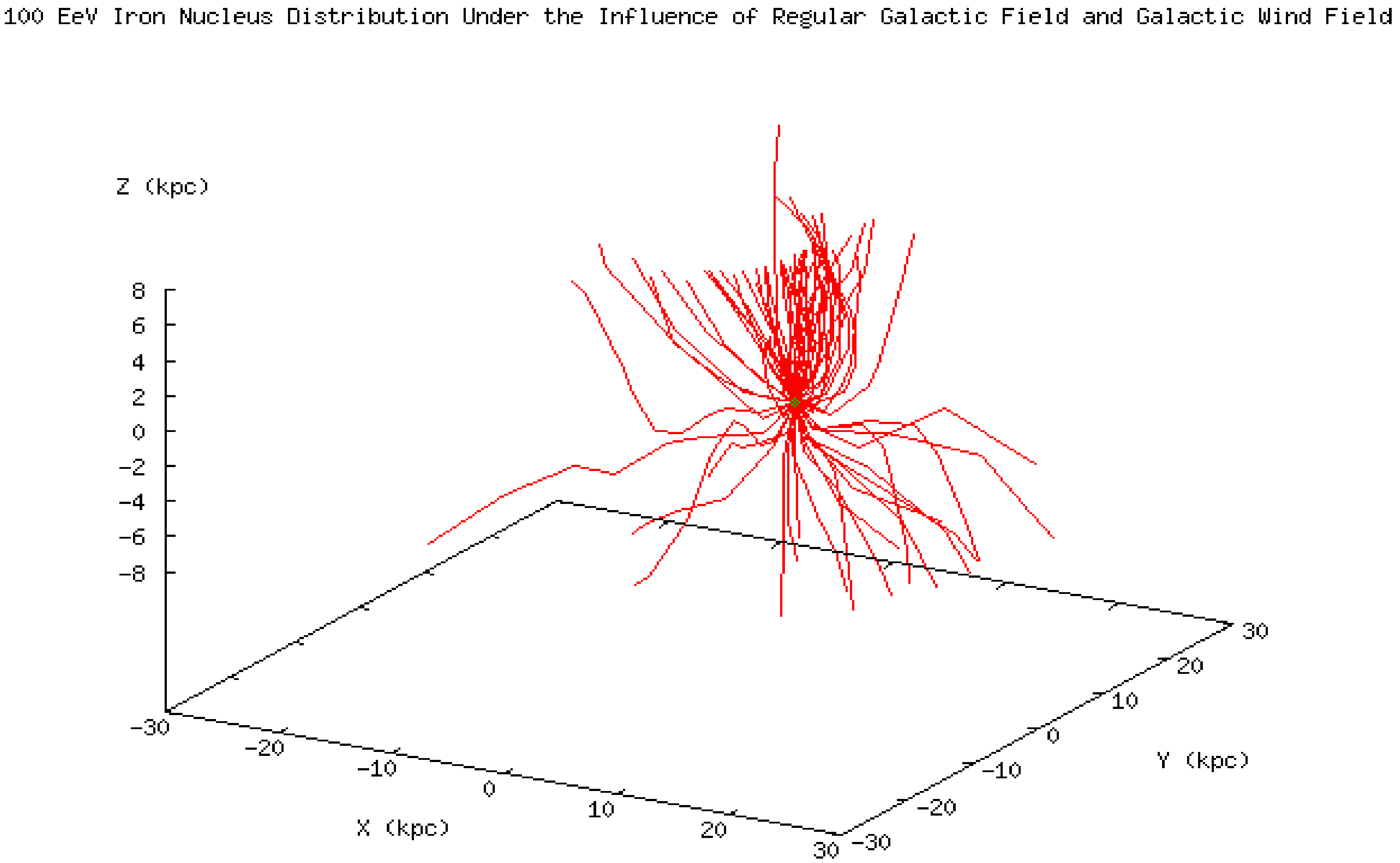
- Possible galactic confinement of 10^{20}eV nuclei

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



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

Pointing at UHECR sources?



O’Neil, Olinto, Blasi ‘01

Pointing at UHECR sources?

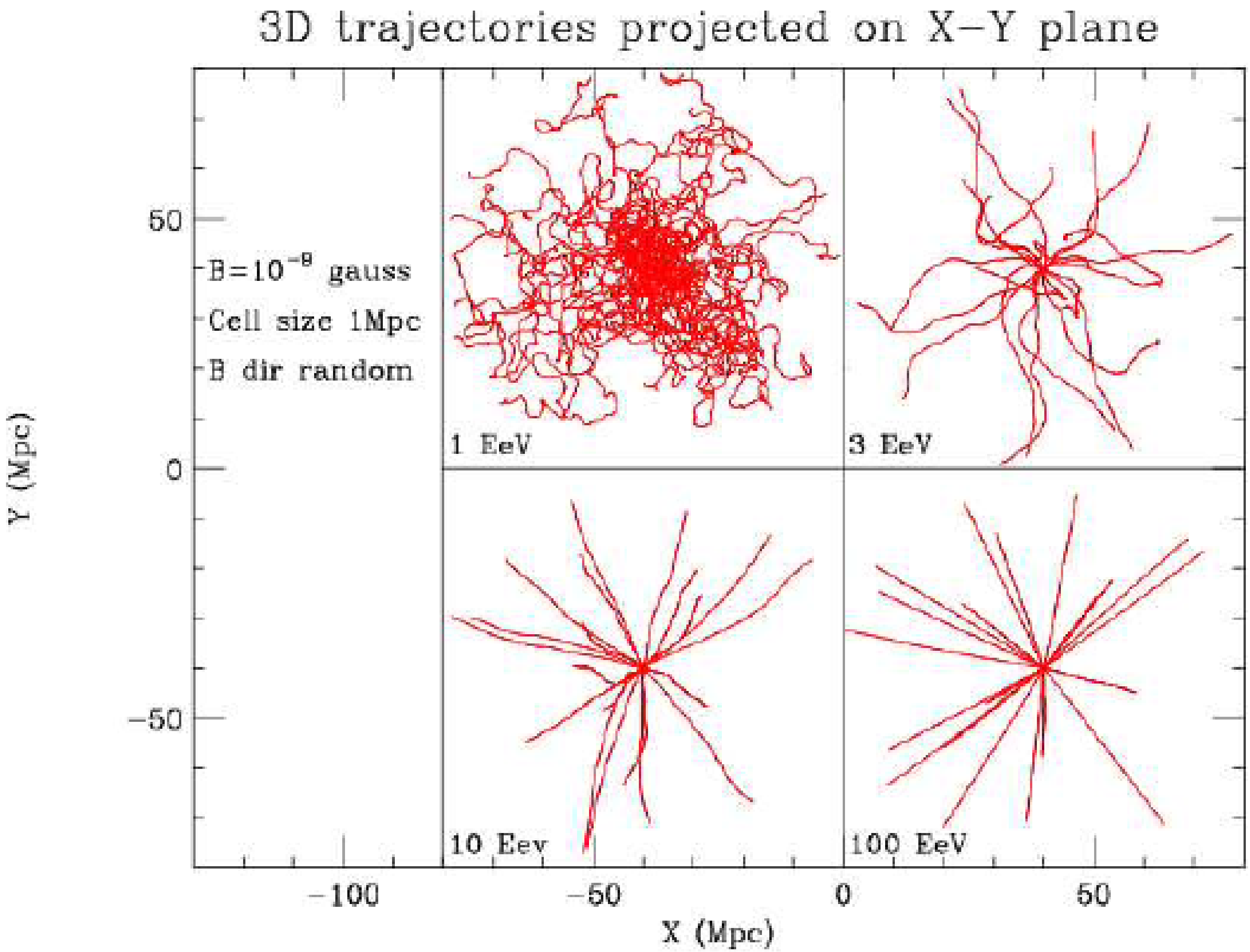
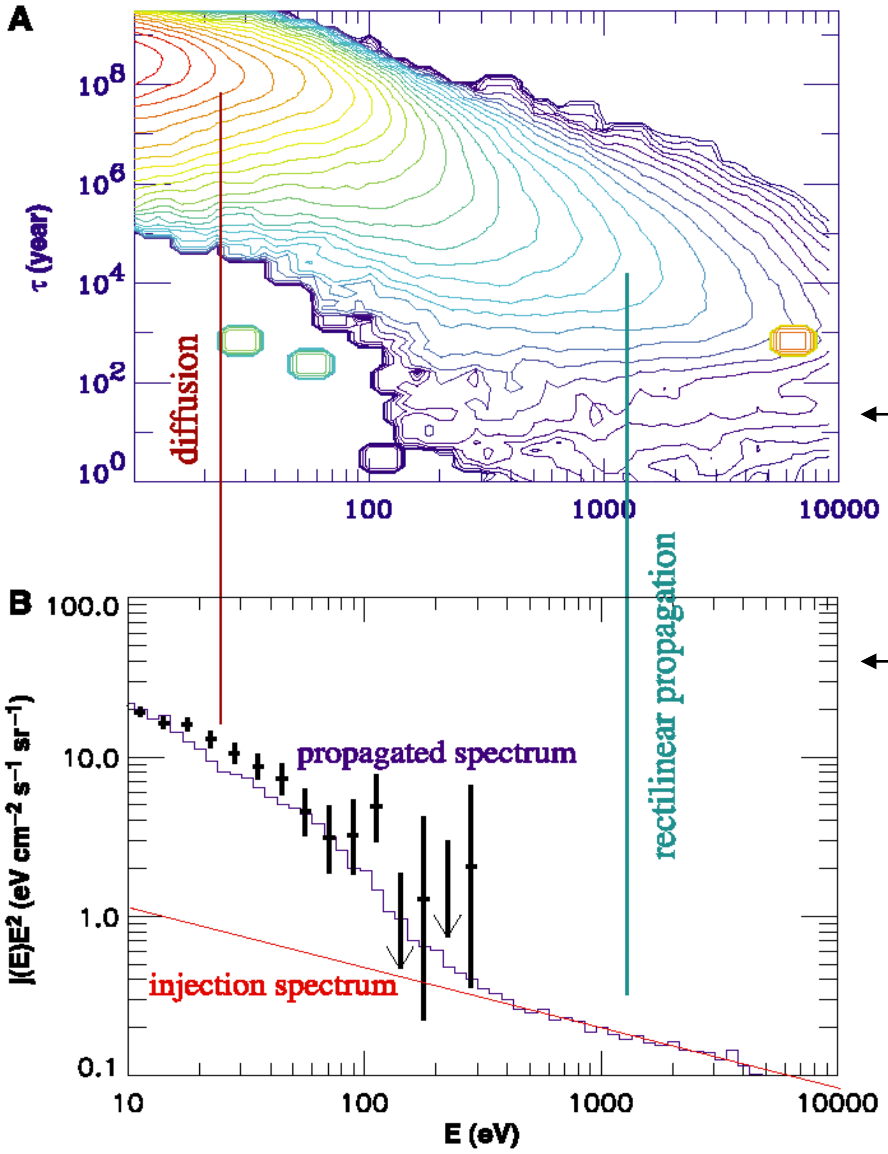


Figure 7: Projected view of 20 trajectories of proton primaries emanating from a point source for several energies. Trajectories are plotted until they reach a physical distance from the source of 40Mpc. See text for details.

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

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

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

Mapping IG fields with UHECR?

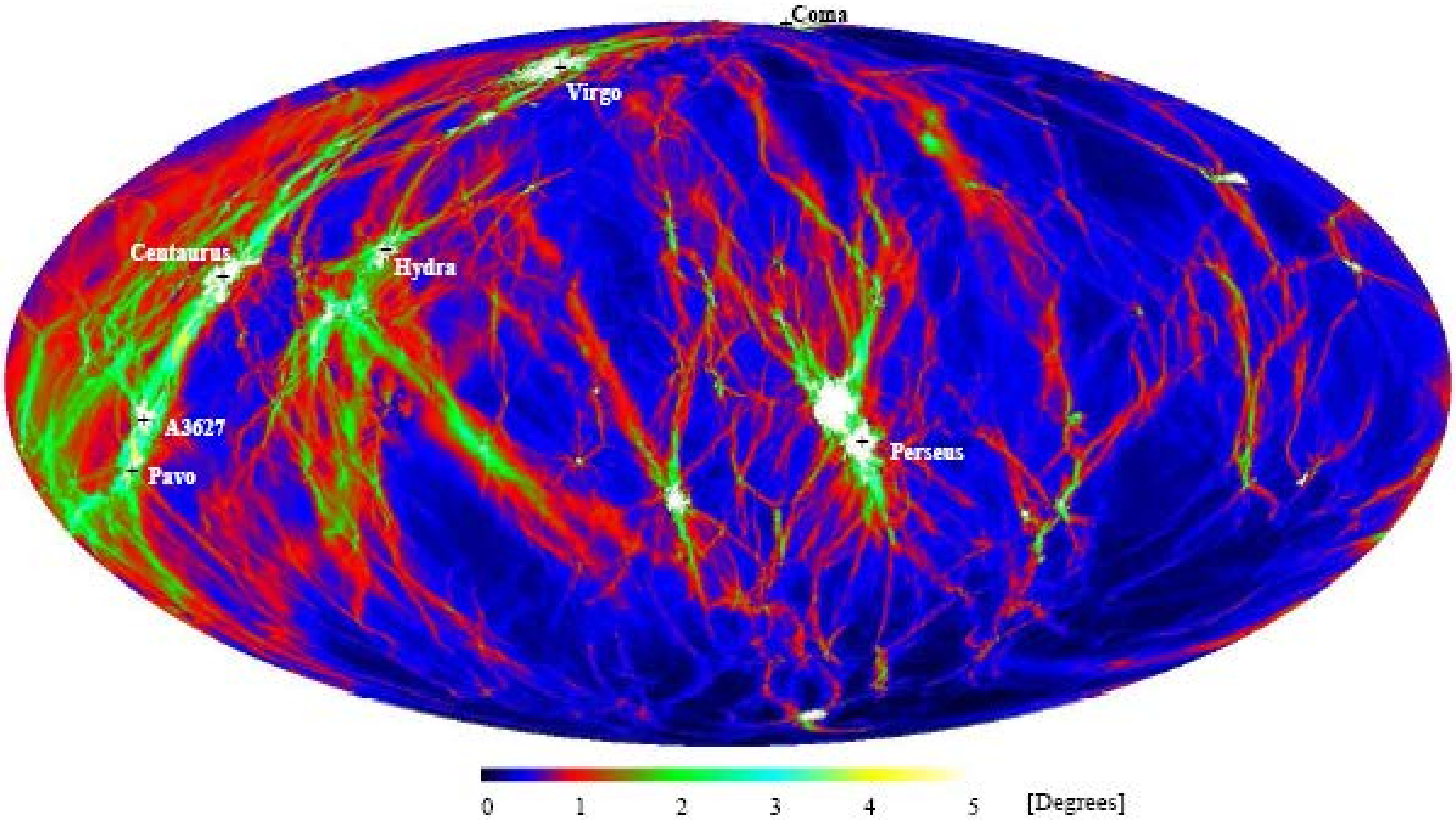


FIG. 1. Full sky map (area preserving projection) of deflection angles for UHECRs with energy 4×10^{19} eV using a linear color scale. All structure within a radius of 107 Mpc around the position of the Galaxy was used. The coordinate system is galactic, with the galactic anti-center in the middle of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

Diffusion in the Universe

- If they are protons,

  arrival direction ≈ source direction $r_L \approx 100\ kpc \times Z \times \left(\frac{E}{10^{20}\mathrm{eV}}\right) \times \left(\frac{B}{10^{-6}G}\right)^{-1}$

  and $\delta\theta \sim \lambda_B / r_L$ so the deviation per field correlation length is $\Delta\theta \sim \sqrt{D\lambda_B / r_L}$

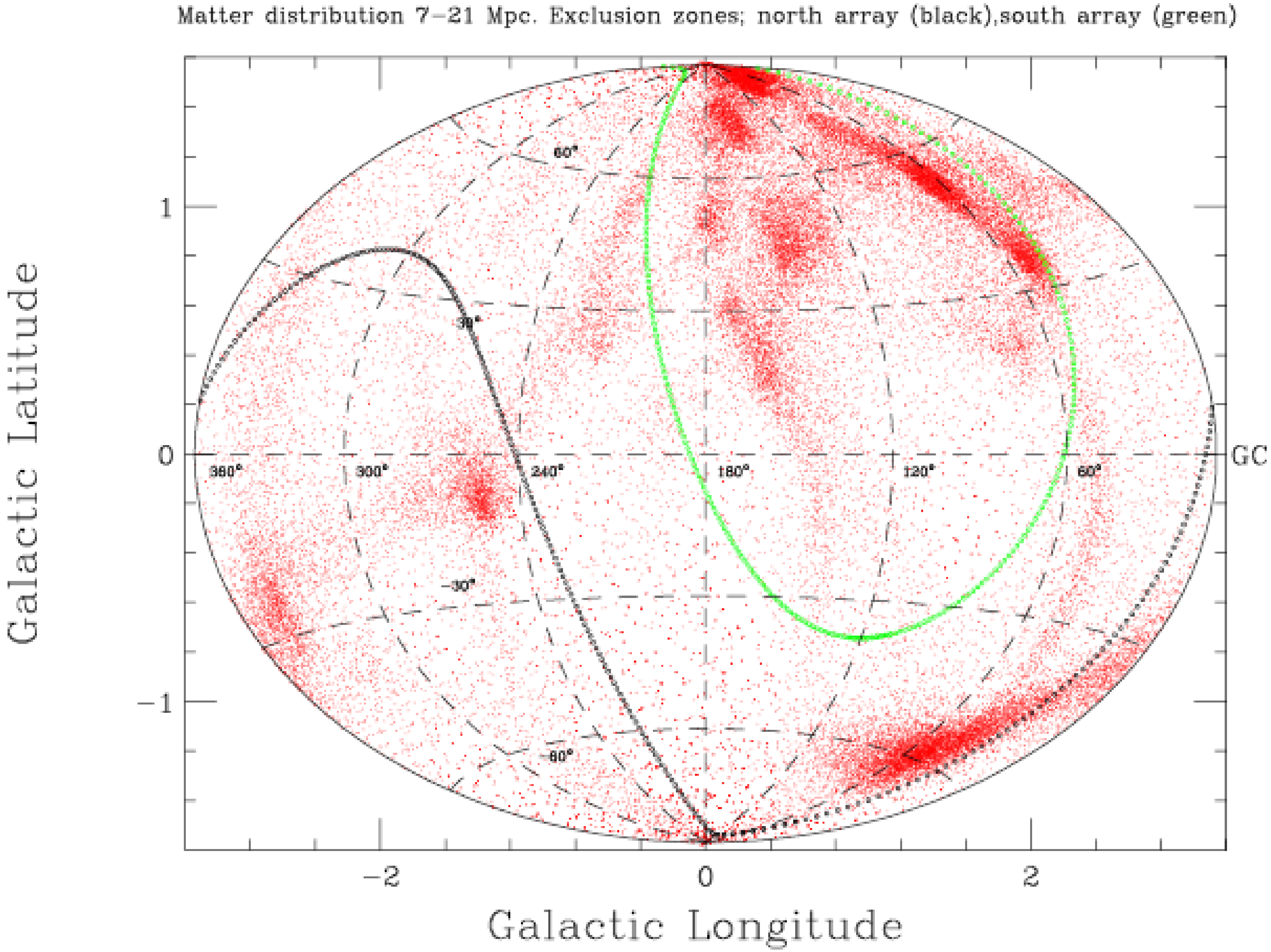
  → Expect proton astronomy to be possible!

- Correlations between arrival directions and sources:
  UHECR distribution is not isotropic! (AUGER 2007)
  - Confirmation of a GZK limited horizon
  - Few sources in the GZK sphere → anisotropy & correlations
  - Astrophysical origin is confirmed!
  - Observed dipolar anisotropy inconsistent with galactic matter distribution ⇒ UHECR are from extragalactic origin (2017)
  - Hint of a medium angle correlation with closest StarBurst galaxies (2017)

- Arrival time delay
  - $\Delta t \sim \Delta\theta^2 d/c \sim D^2 \lambda_B / r_L^2 c$
  - If eruptive or transient sources (GRBs, TDs), the must overlap in time (otherwise E(t)!)
  - Multiplets of events from same direction observed but no significant ordering in E or deviation.

→ Correlation with source catalogues (hints… but too early to conclude)

Matter distribution in the GZK sphere



Observables & Observations

Some of the detector aspects will be covered
in my other lecture
on Cherenkov and Imaging detectors (3rd week).