Cosmic Rays

- What are they?

- How we detect them: history and present time

- Main properties:
  - Energy distribution (range & power-law)
  - Composition
  - Isotropy

- Origin

Longair Chap 15, 16
Fanti & Fanti Chap 12

What are they?

High energy nuclei with ultra-relativistic velocities, devoid of any electron

Relativistic electrons (& positrons)

- Motion influenced by magnetic fields & medium crossed + energy density of radiation
- Power-law distribution
- Isotropic flux, constant in time

ų origin & refurbishment

– **primary component**: mostly p+ (88%), He (11%) and heavier nucleons; small fraction of el. (1% or less)
– **secondary component**: particles originated by collisions of primary CR particles with nuclei of atoms/ molecules (ISM or Earth atmosphere); mostly muons (μ^+,μ^-), electrons/positrons, neutrinos and photons.

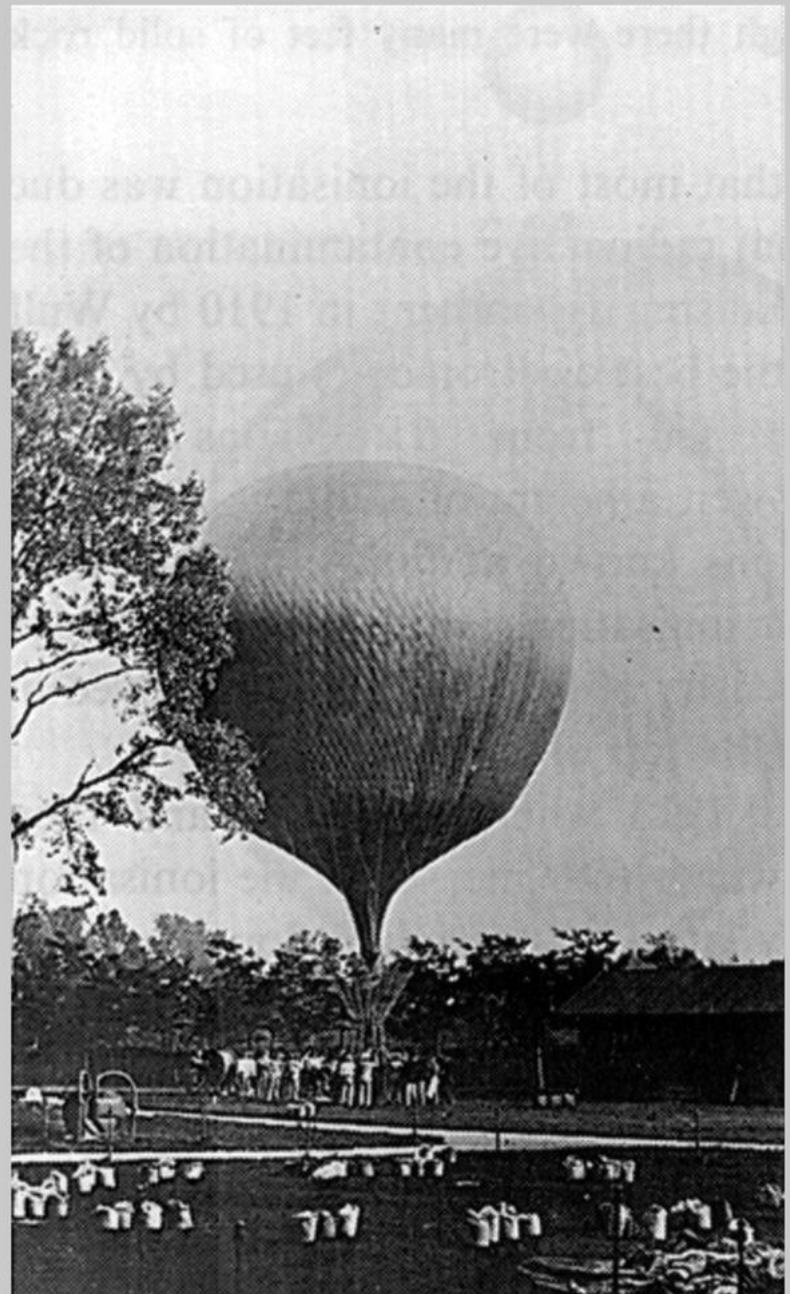
High energy radiation (gamma rays)

Radiation preserves the direction (except by encounters with other photons)

ų origin & mechanisms

Energy range: well above the rest mass of the electron (0.511 MeV) up to 10^{20} eV

High flying balloon experiments: (early) detection of primary CRs



Cosmic Rays — History (1)

Discovery of ionizing radiation by Wilson and later on by Hess (1911-12, Nobel prize in 1936) who used balloon experiments to send detectors at high altitudes and showed:

- ➔ *Increase of the flux of these particles with altitude ⍰ extraterrestrial origin.*
- ➔ *It was homogeneously distributed on the sky.*

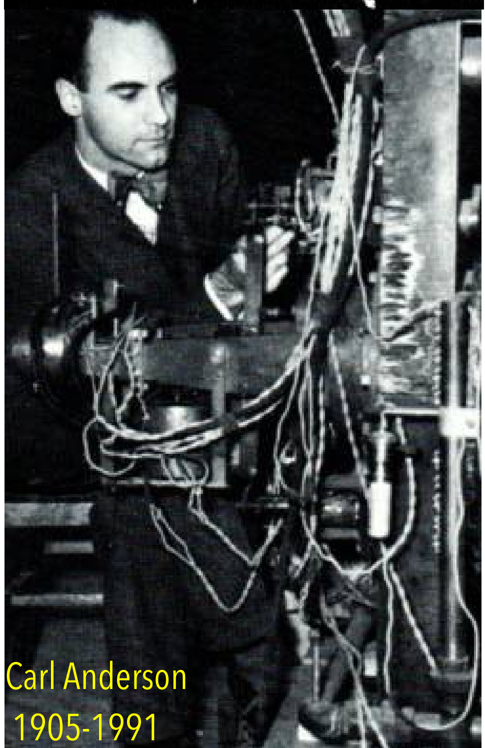
In 1929 charged particles leaving curved tracks in a cloud chamber were discovered by Skobelzyn (interpreted by Bothe and Kolhorster)

Clay discovered the latitude effect: CR intensity depends on geomagnetic latitude (interpreted by Bothe and Kolhorster)

In 1932 Anderson discovered the positron (antimatter!) and in 1936 (after, he shared the Nobel Prize with Hess) also the muon (misidentified with the pion)

In 1934-1938 Rossi (and independently Auger) discovered the "extensive air showers" through coincidence measurements. The theory of electromagnetic cascade and the generation of secondary particles on the ground were developed by Bethe and Heitler in 1934-1937.

In 1946 the first air shower experiments were carried out



Cosmic Rays History (2)

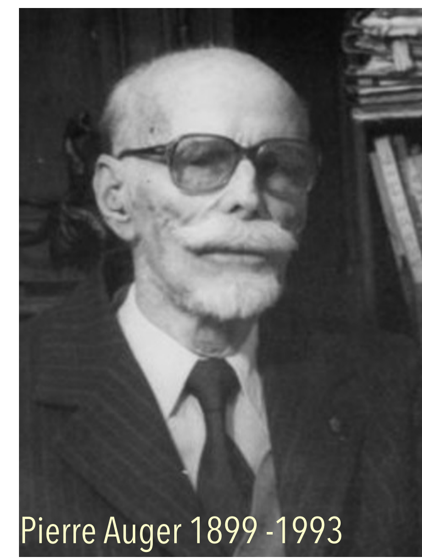
1947: The pion was discovered, and Zatsepin proposed the scaling of hadronic interactions studying the evolution of extensive air showers


Bruno Rossi 1905–1993

1949: Fermi proposed the acceleration mechanism based on magnetic diffusion of charged particles by moving magnetic clouds.

1952-54: Ground accelerators reached >~ 1 GeV, splitting high energy physics and cosmic ray physics, the latter drifting towards astrophysics.

1962: Detection of the first CR with energy 10^{20} eV


Pierre Auger 1899 -1993

1972: The SAS-2 satellite opened the high energy gamma ray astronomy

1976: The first prototype of large scale underwater neutrino detector was started in Hawaii

1998: The first detection of flavor oscillations of atmospheric neutrino at the Superkamiokande Experiment.

200X: Cherenkov telescopes entered into the business (HESS, MAGIC, VERITAS)

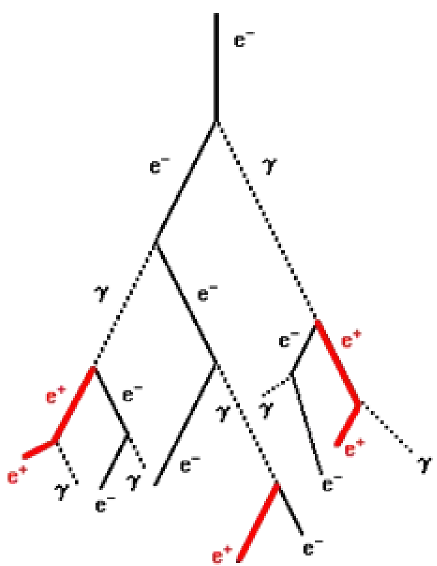
2007: The Pierre Auger observatory in Argentina becomes a combination of ground array and fluorescence telescopes in the same experiment. Discovery of extra-galactic origin of UHECR

202X Cherenkov Telescope Array (North, more specific for faint and extragalactic sources, South for galactic objects)

(Air) showers ingredients

Particle	Decay mode	Lifetime ($t_{1/2}$)	Range ($ct_{1/2}$)
Ä	2	∞	∞
e-	-	∞	∞
p+	-	∞	∞
n	n → p + e- + ν_J	886s	2.65×10^{13} cm
μ-	μ- → e- + ν_J + ν_μ	2.2×10^{-6} s	659 m
π2	π- → μ2 + ν_μ	2.6×10^{-8} s	780 cm
π^Λ	π^Λ → < γ	8.4 x 10 -17s	25.1 nm
ν	-	∞	∞

Red = antiparticle



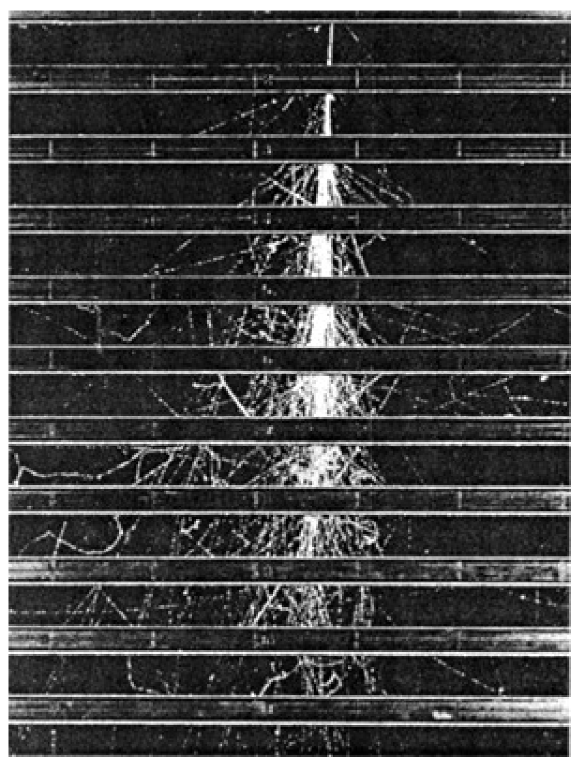


Image of a shower, as seen in a clo ud chamber at 3027 m altitude, Fretter 1949 (proton of ≈ 10 GeV)

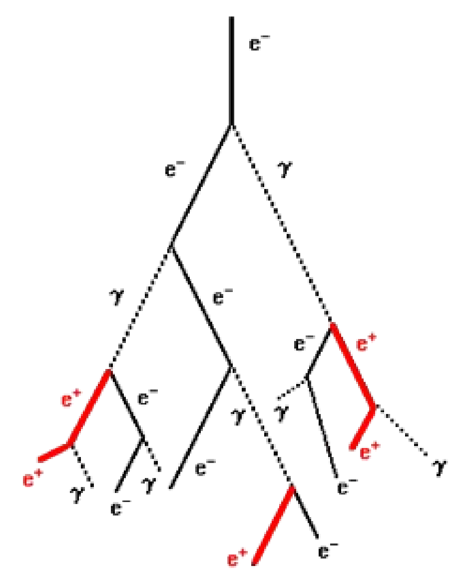
(Air) Showers: Basic information

A Primary CR interacts with the nuclei in/of molecules (atoms) and produce "secondary" particles

In the Earth atmosphere the density is high enough to completely destroy all the nuclei involved into the interaction

In the ISM / IGM this may not happen and secondaries may appear among the population of less energetic CRs

Understanding the development of these collisions is of great importance



Detection of CR particles: Extensive Air Showers

High-energy CR + air molecule ụ particles, which in turn create more particles, colliding with other molecules , + electromagnetic cascade(s).....
Cascade -> like a pancake of relativistic particles traveling through the atmosphere at ~ the speed of light.

# of particles increases rapidly downwards in the atmosphere
in each interaction particles loose energy and eventually will not be able to create new particles.

Process halts when the average energy per particle drops below about 80 MeV = shower max
Below the Shower Max, # of particles in the pancake deacrease
Interactions lead to the absorption of particles and the cascade begins to die
size of the pancake always grows as the interactions cause the particles to diffuse away from each other.

Only a small fraction of the particles may eventually reach the ground. Actual numbers are subject to large fluctuations: depends on the energy and type of the incident CR, the elevation, etc.

For most CRs nothing comes down at all. The Earth is hit by so many CRs that an area of the size of a hand is hit by about one particle per second. These secondary CRs constitute about 1/3 of the natural radioactivity.

Leptonic cascades are quite well described

The description of Hadronic cascades is somehow model dependent (simulations)

Development of electromagnetic cascades (e/γ)

⇨ Energy losses of e/γ in the atmosphere:

High energies (E>100 MeV) [TOP of the cascade]

- Bremsstrahlung ($e\gamma \to e\gamma$): $dE/dX = -E/X_0$
- pair production ($\gamma \to e+e-$) with $\lambda \sim 9/7\ X_0$

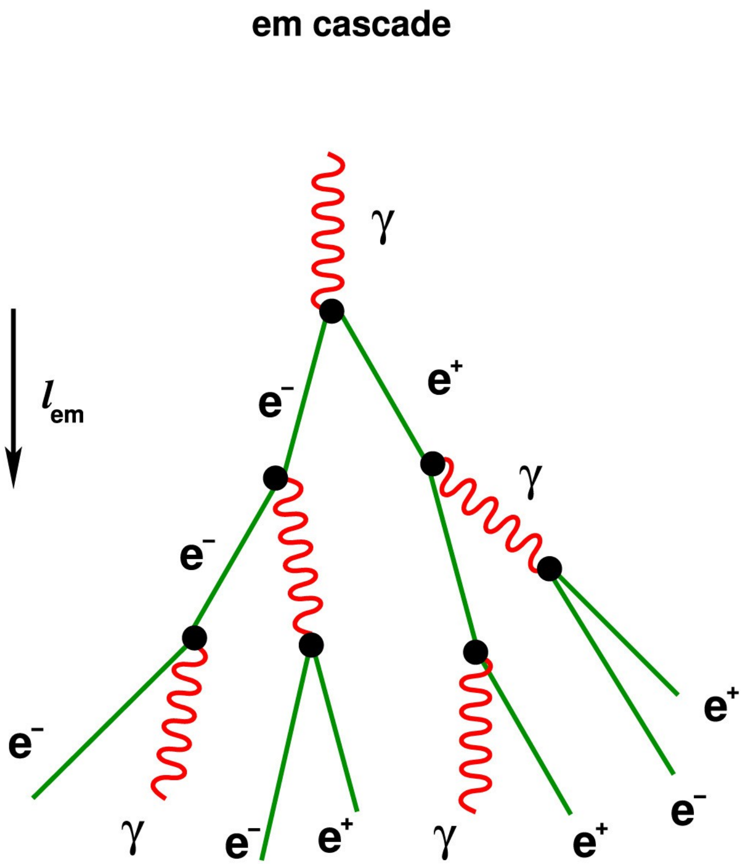
Radiation length: X_0(Atmosphere) = 37.1 g/cm2

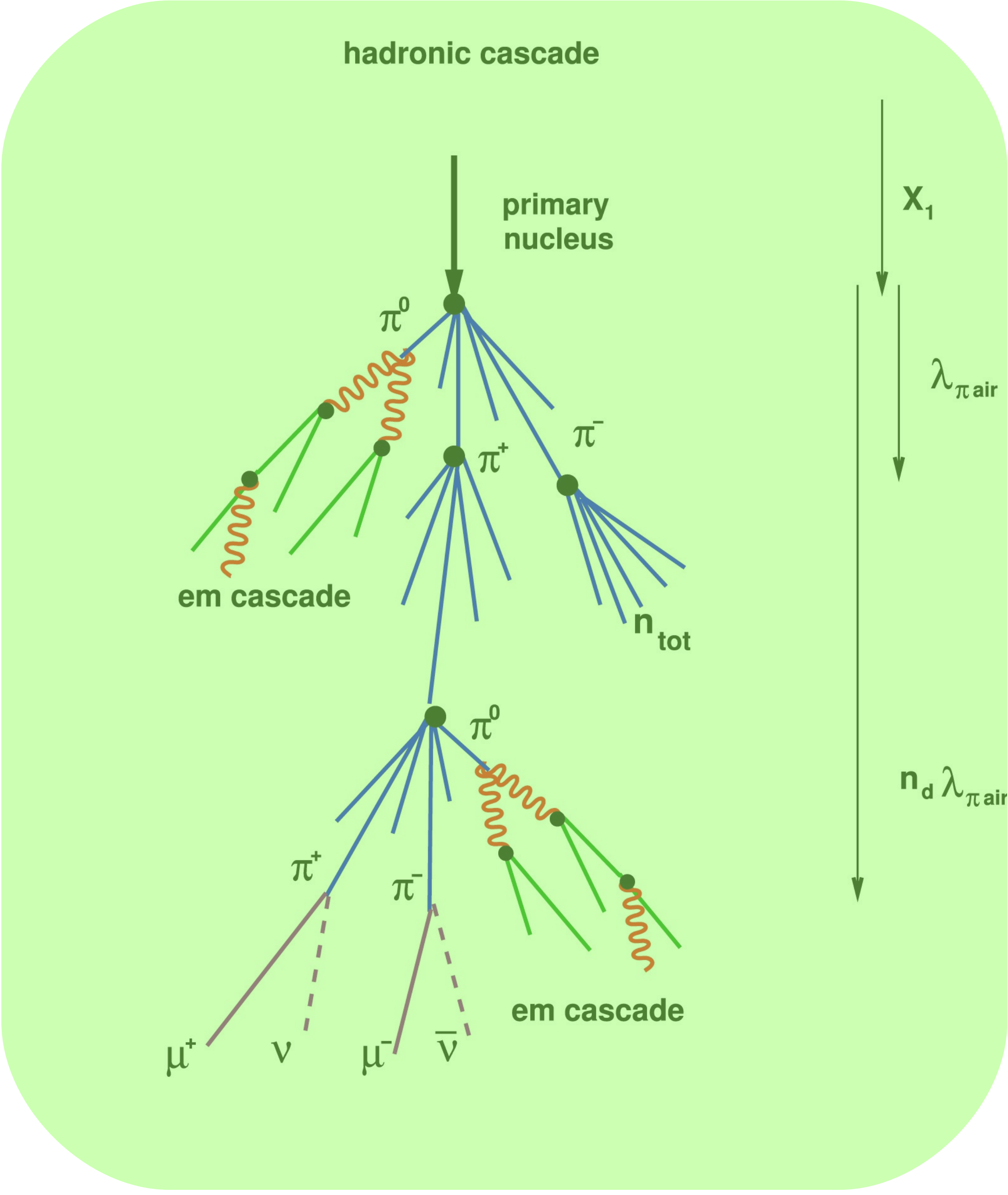
For low energies (E<100 MeV) [BOTTOM of the cascade]

- Electrons/positrons: Ionization losses
- Photons: Photo ionization, Rayleigh scattering, Compton scattering

– Coulomb (multiple) scattering* dominates lateral development (Nishimura 1967), scattering angle ~1/p

Development of electromagnetic cascades (e/γ)





Development of Hadronic air showers =air showers initiated by nucleons (p,He,..)

- Differences to electromagnetic cascades:
  - Strong interaction: Production of mesons
  - Transverse momentum!! (pt) $\rightarrow$ Lateral shower development
  - Decaying particles (competition: decay & interaction)
  - More complicated development (spatially and laterally)
  - Position of shower maximum depends on E & A $t_{max}=t_0+t_1 \log_{10}(E_0/A\ \mathrm{TeV}^{-1})$

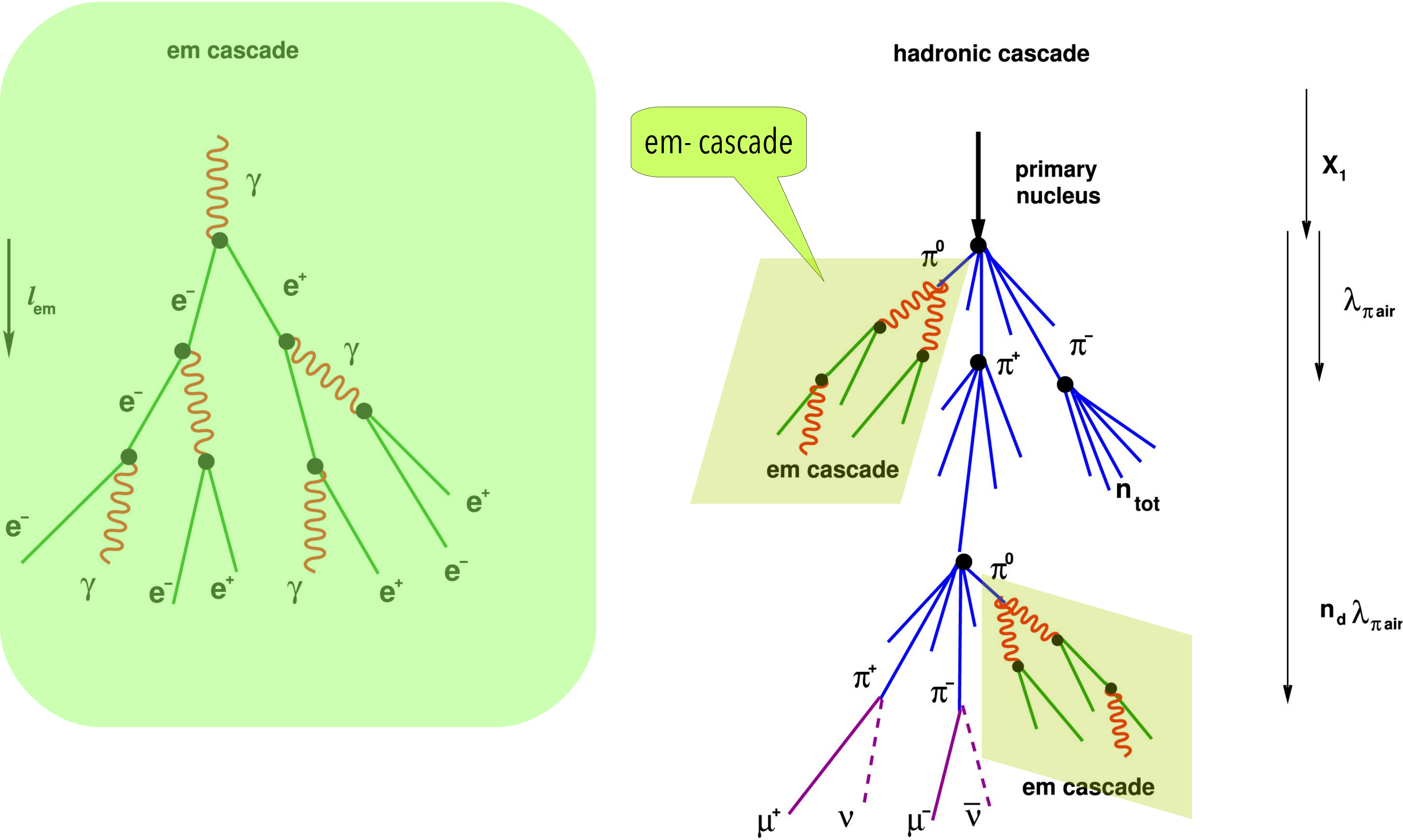
- Approximate solution of the general cascade equation (N(x,y,z,E))

Main decay modes for K^+:

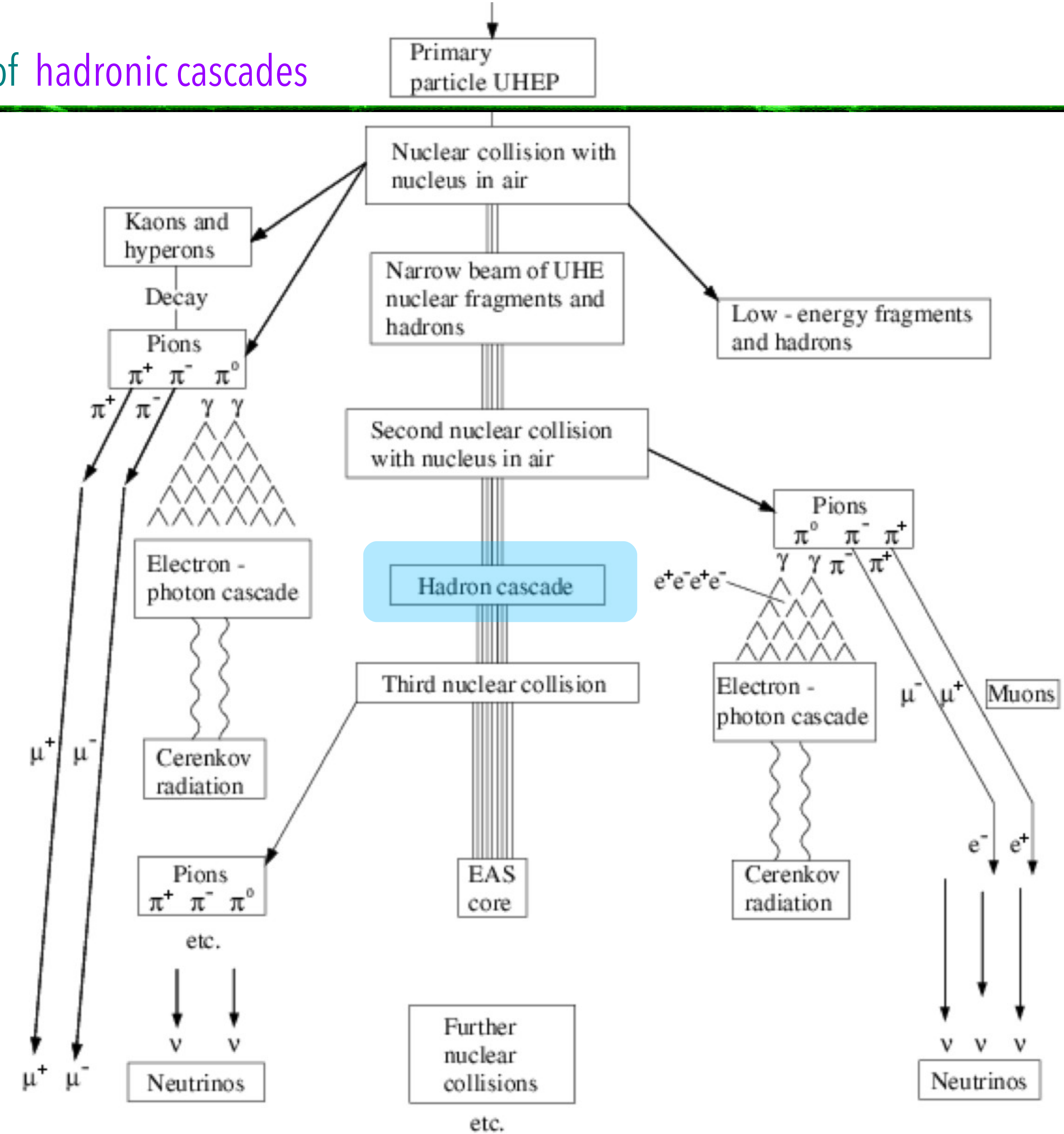
Results	Mode	Branching ratio
$\mu^+ \nu_\mu$	leptonic	63.55 ±0.11%
$\pi^+ \pi^0$	hadronic	20.66 ±0.08%
$\pi^+ \pi^+ \pi^-$	hadronic	5.59 ±0.04%
$\pi^+ \pi^0 \pi^0$	hadronic	1.761 ±0.022%
$\pi^0 e^+ \nu_e$	semileptonic	5.07 ±0.04%
$\pi^0 \mu^+ \nu_\mu$	semileptonic	3.353 ±0.034%

Decay modes for the K^- are charge conjugates of the ones above.

Development of hadronic cascades



Development of hadronic cascades



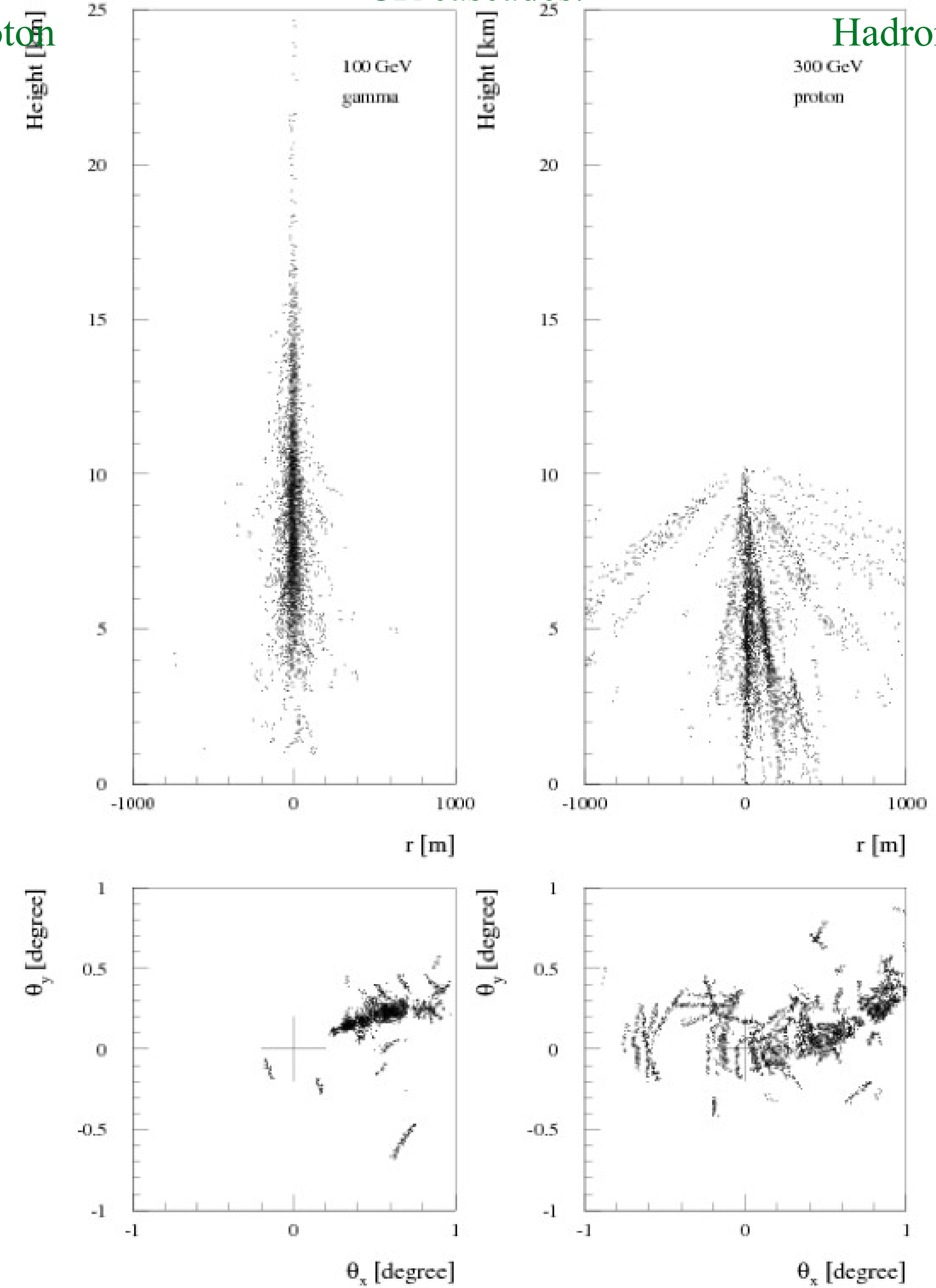
CR cascades:

Photon

Hadron (p)

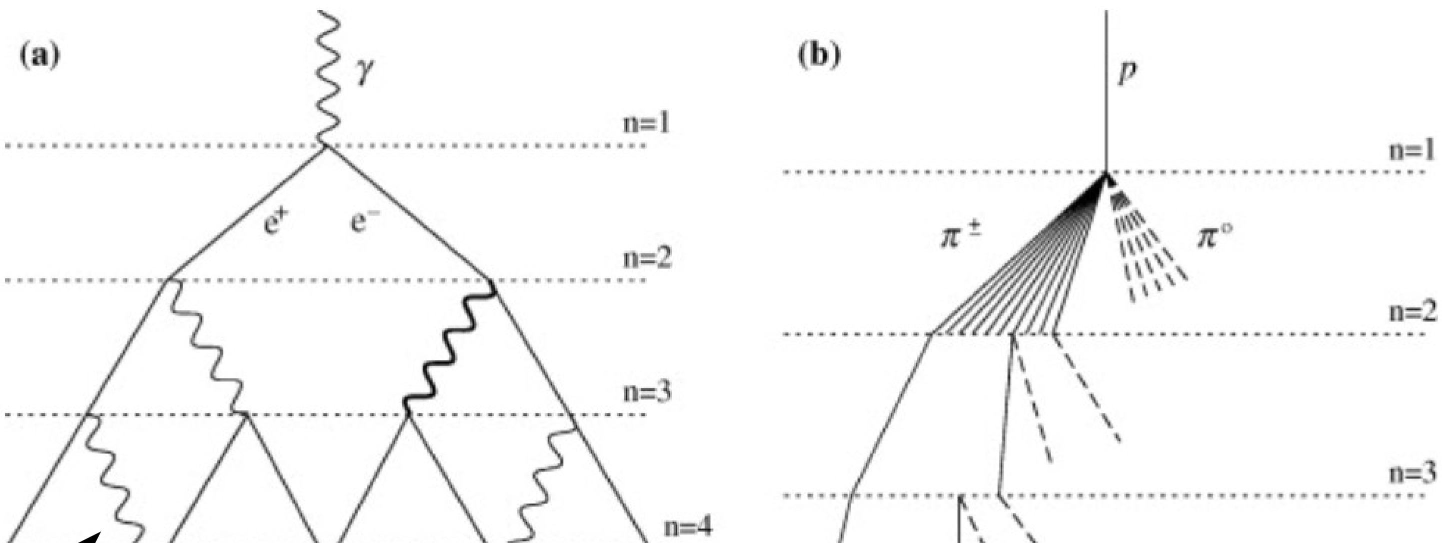
Lateral view

Front view



CR air shower: Photons/Leptons Hadrons

Heitler's model (Fig. 1a) has e^+, e^-, and photons undergoing repeated two-body splittings, either one-photon bremsstrahlung or e^+e^- pair production. Every particle undergoes a splitting after it travels a fixed distance related to the radiation length. After n splittings there are 2^n total particles in the shower. Multiplication abruptly ceases when the individual $e^\pm$ energies drop below the *critical energy* ξ_c^e, where average collisional energy losses begin to exceed radiative losses.



Bremsstrahlung emission

From each π^0 a photon cascade starts

Fig. 1. Schematic views of (a) an electromagnetic cascade and (b) a hadronic shower. In the hadron shower, dashed lines indicate neutral pions which do not re-interact, but quickly decay, yielding electromagnetic subshowers (not shown). Not all pion lines are shown after the $n = 2$ level. Neither diagram is to scale.

Matthews, 2005, Astrop. Phys, v 22, p. 387

Toy model for electromagnetic cascade (Heitler)

If $h\nu > 2 m_e c^2$ pair production may occurr in the field of the nucleus

PP unfeasable in free space since momentum & energy cannot be conserved simultaneously

Conservation of energy: energy of photon $= h\nu = 2\gamma m_e c^2$

$$\text{momentum of pair} = 2\gamma m_e v = \frac{h\nu}{c}\frac{v}{c}$$

$$\text{initial momentum of the photon} = \frac{h\nu}{c}$$

$\rightarrow$ mom & en cannot be conserved in free space, a third body is needed to absorb some of en/mom

Ultra-relativistic limit: $(h\nu / m_e c^2 \gg 1/\alpha z^{1/3})$

$$\sigma_{pair} = \alpha r_e^2 Z^2 \left[\frac{28}{9} \ln\left(\frac{183}{Z^{1/3}}\right) - \frac{2}{27} \right] \quad m^2\,\text{atom}^{-1} \qquad \text{namely} \sim \alpha\,\sigma_T Z^2$$

Cross section of interaction with electrons much smaller, then neglected

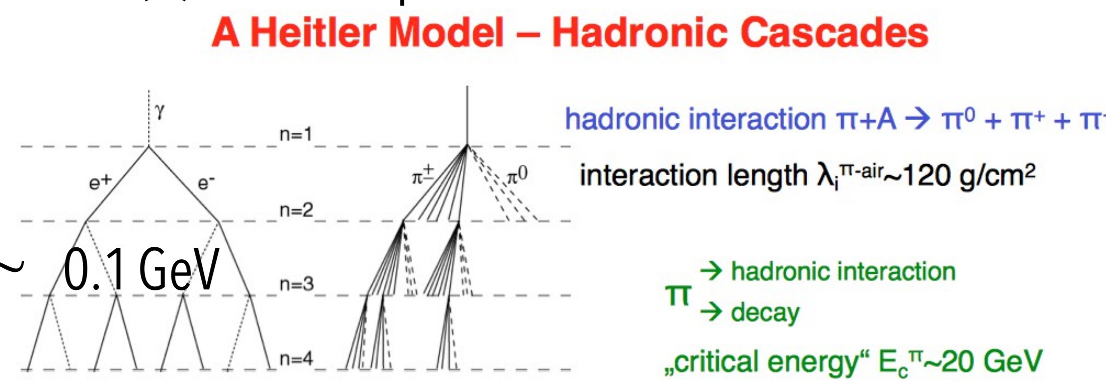
Toy model for electromagnetic cascade (Heitler)[2]

Each interaction has its characteristic, constant interaction length λ , and at the end each particle splits into two “daughter” particles each with half the energy

After $n=X/\lambda$ generations the cascade consists of $N(X) = 2^{X/\lambda}$ particles

The energy per particle is $E(X) = E_0 / N$

Particle production stops when $E(X) < E_{cr} \sim 0.1$ GeV



The maximum number of particles in the shower is reached at X_{max}

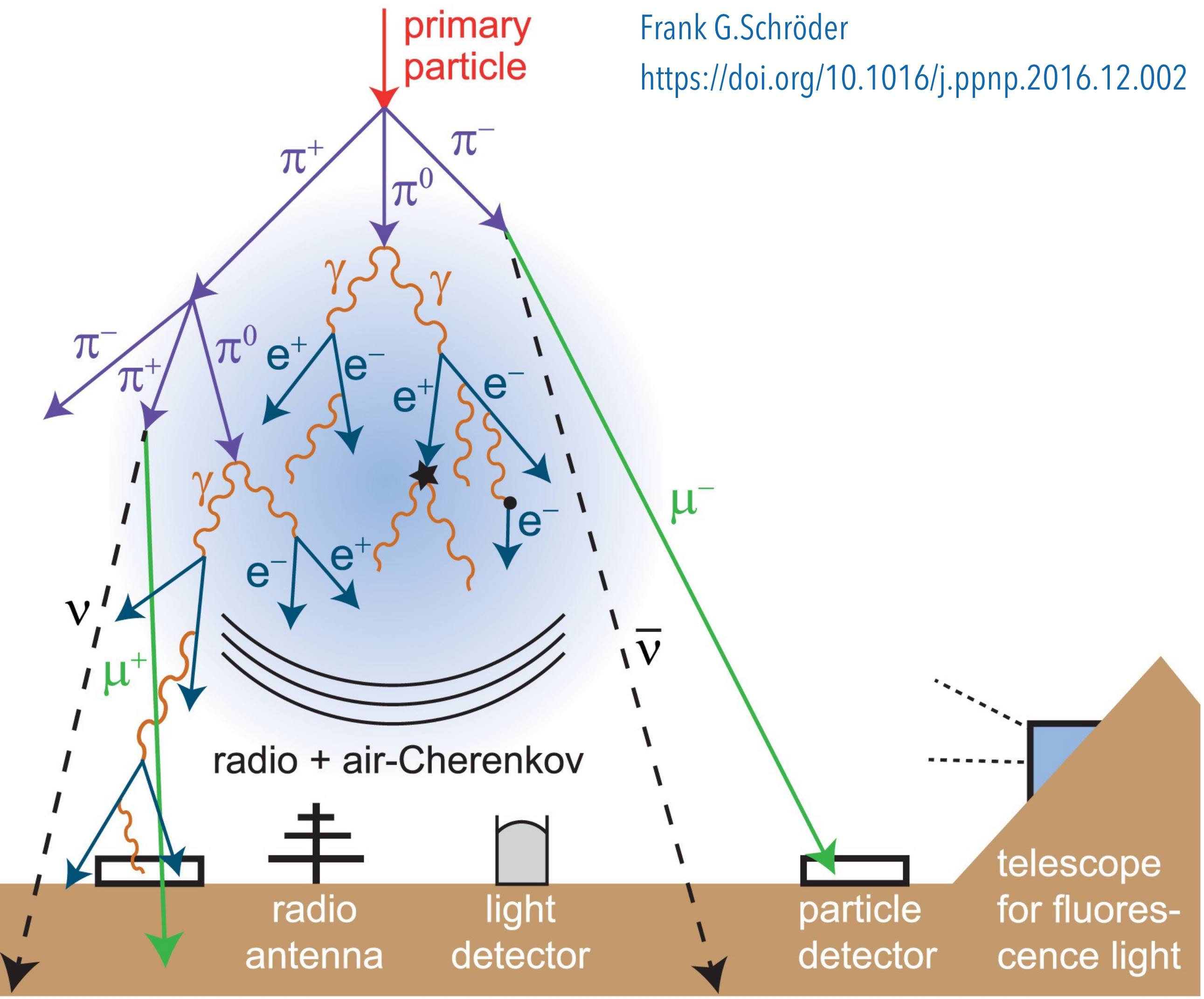
$$N(X_{max}) = \frac{E_0}{E_{cr}} \quad \text{where} \quad X_{max} = \frac{\lambda}{\ln 2} \ln \frac{E_0}{E_{cr}}$$

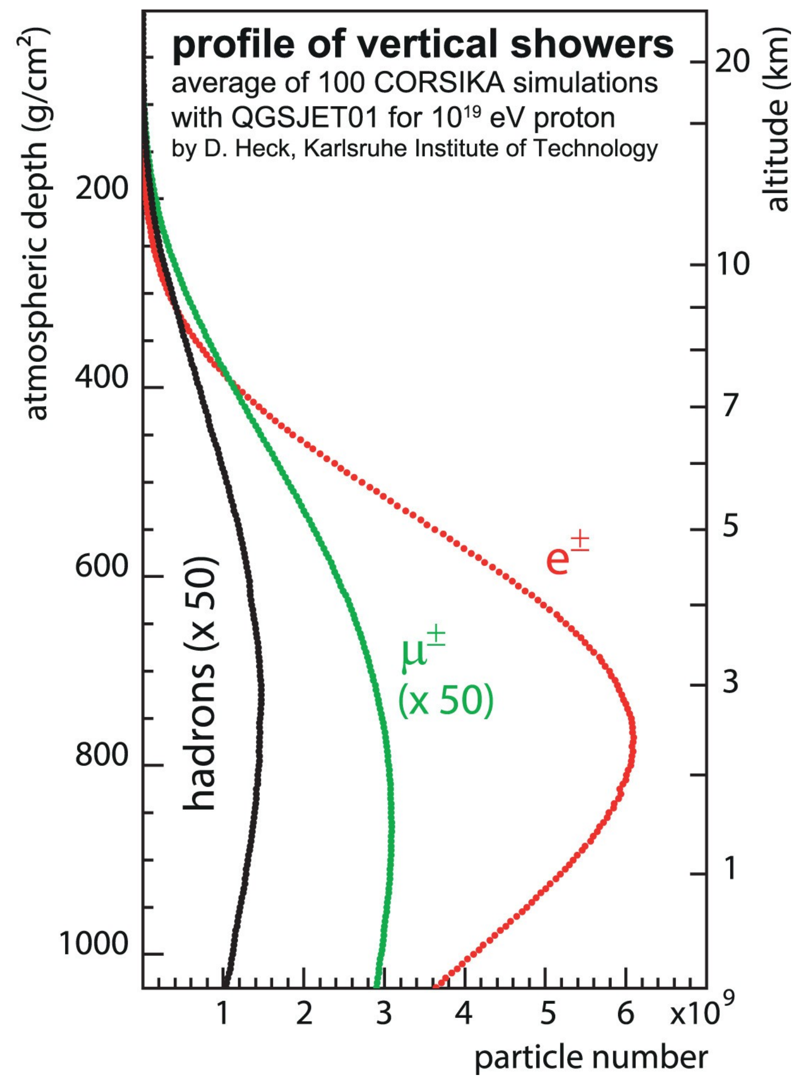
Simplifed picture of an air shower: in reality, the number of particles created in an air shower event can reach in the Billions, depending on the type and the energy of the primary particl All of the produced particles stay within about one degree of the primary particle's path. Typical particles produced in such collisions are charged mesons (e.g. positive and negative pion Cosmic rays are also responsible for the continuous production of a number of unstable isotopes in the Earth’s atmosphere, such as carbon-14, via the reaction: $n + {}^{14}N \rightarrow p + {}^{14}C$

CRs kept the level of carbon-14 in the atmosphere roughly constant (70 tons) for at least the past 100,000 years, until the beginning of above-ground nuclear weapons testing in the early

of particles and lateral size

Frank G.Schröder
https://doi.org/10.1016/j.ppnp.2016.12.002





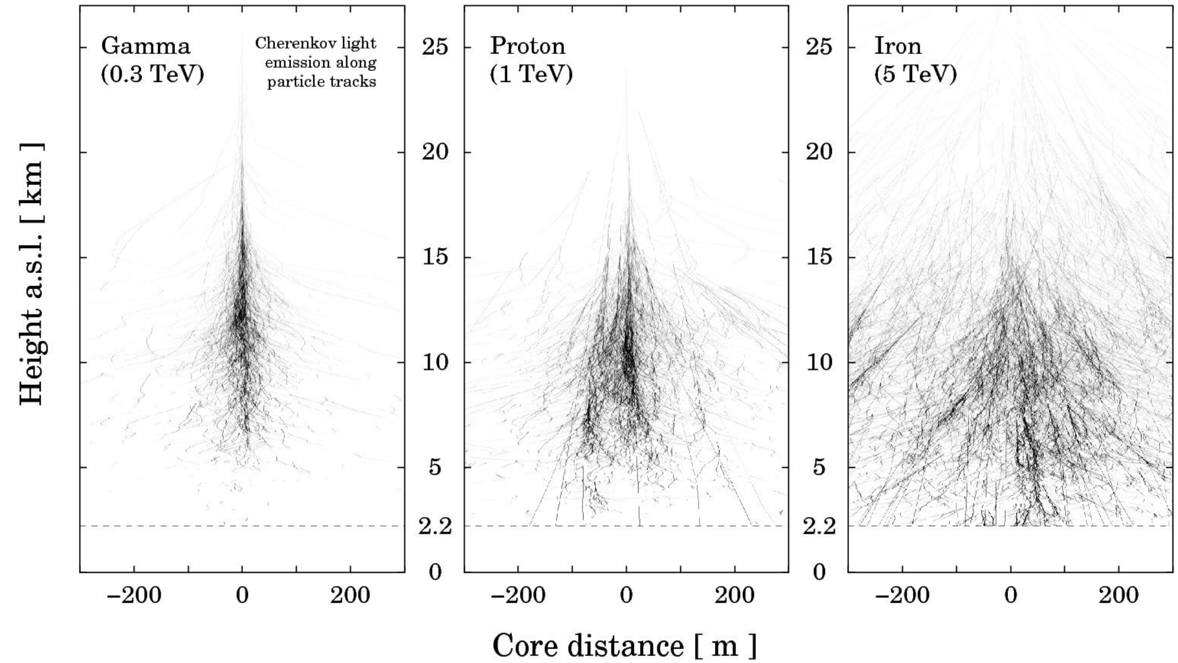
CR air shower: photons

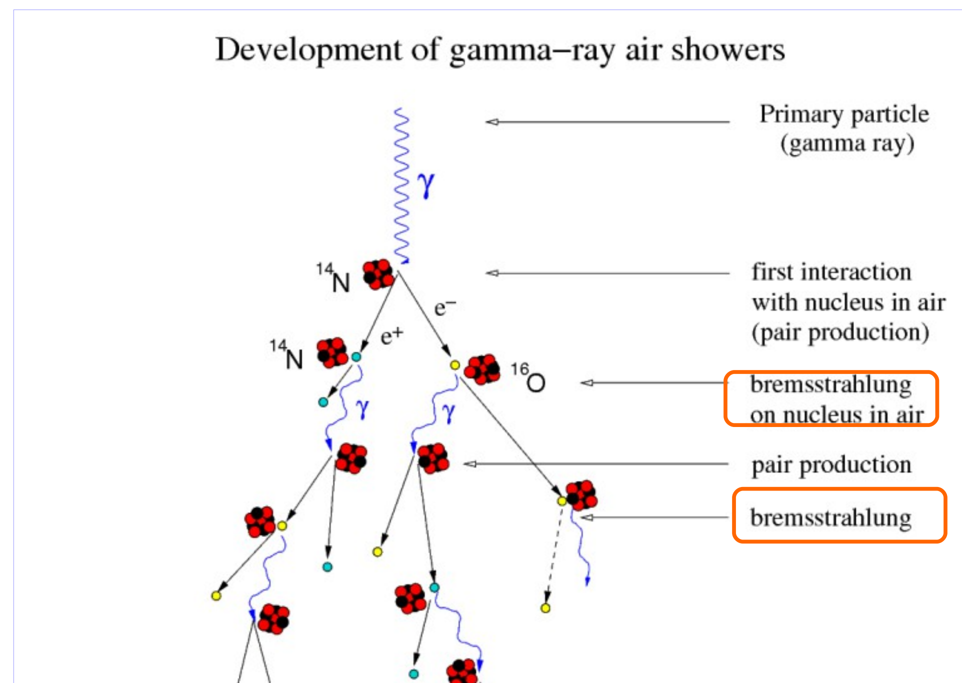
If the primary CR was a photon the "pancake" will contain electrons, positrons, and gamma rays

Number of particles left in the pancake: depends upon the energy of the primary photon, the observation altitude, and fluctuations in the development of the Shower. When the pancake reaches the ground it is roughly 100 meters across and 1-2 meters thick

https://www-zeuthen.desy.de/~jknapp/fs/photon-showers.html
https://www-zeuthen.desy.de/~jknapp/fs/proton-showers.html
https://www-zeuthen.desy.de/~jknapp/fs/iron-showers.html

Atmospheric Particle Showers and Cherenkov Radiation from Gamma Ray, Proton and Carbon-13:
https://www.youtube.com/watch?v=j-BBzWlOai0



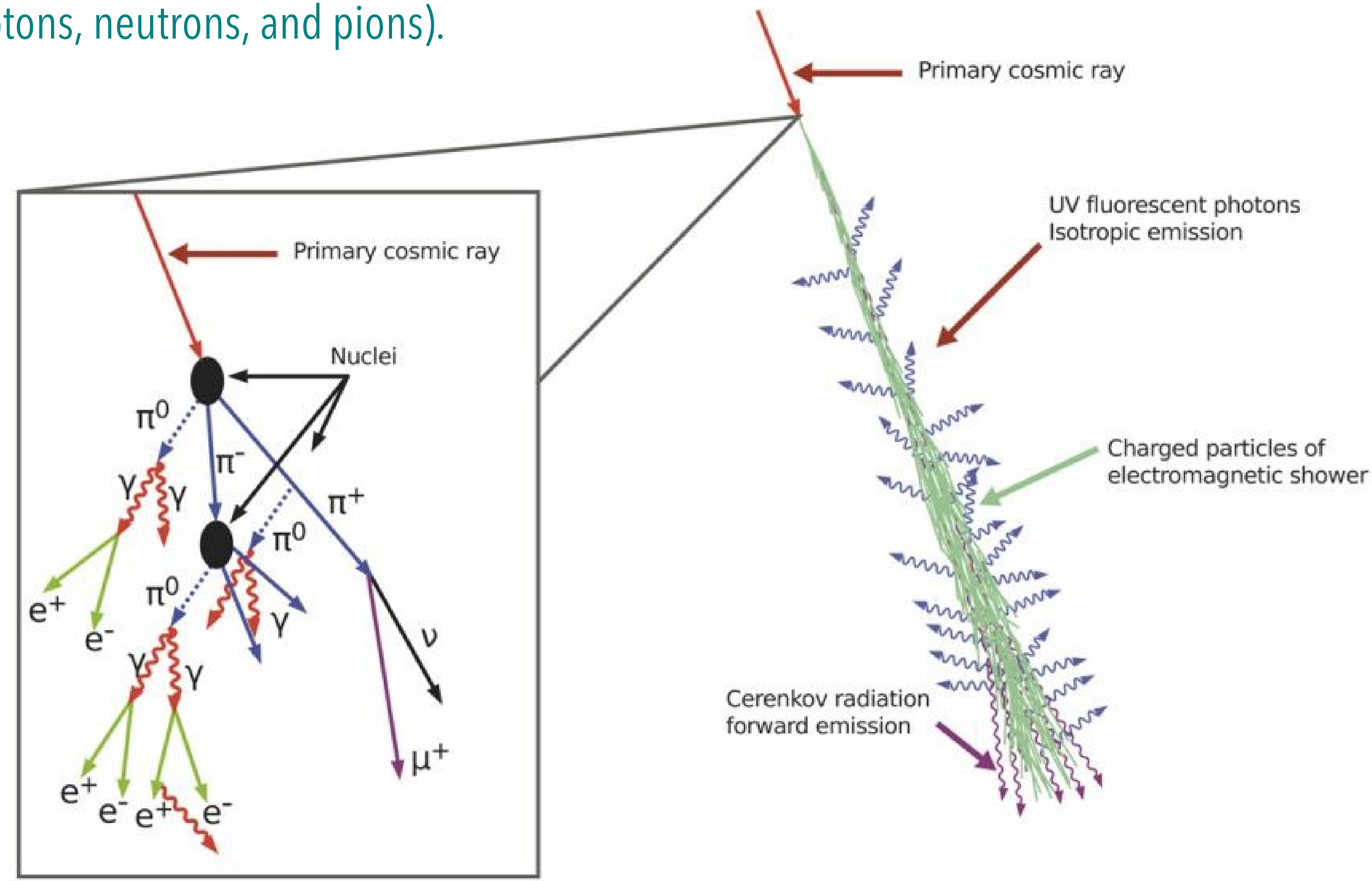


CR air shower: nucleons

The particle interacts with a particle in the atmosphere

1. fragmentation and production of Ù $^{+}$,Ù $^{-}$,Ù ^{o},
2. decay of Ù ^{o}
3. Ù $^{+}$,Ù $^{-}$ may decay into Õ $^{+}$,Õ $^{-}$, or interact with other nuclei/molecules....

If the primary cosmic ray was a nucleus the pancake will also contain muons, neutrinos, and hadrons (protons, neutrons, and pions).



Čherenkov Light

Charged particles moving in a medium with a velocity larger than the local speed of light emit Čherenkov Light

$$v > c\,/\,n$$

Refractive index of the air $n_{air} = 1.0003$

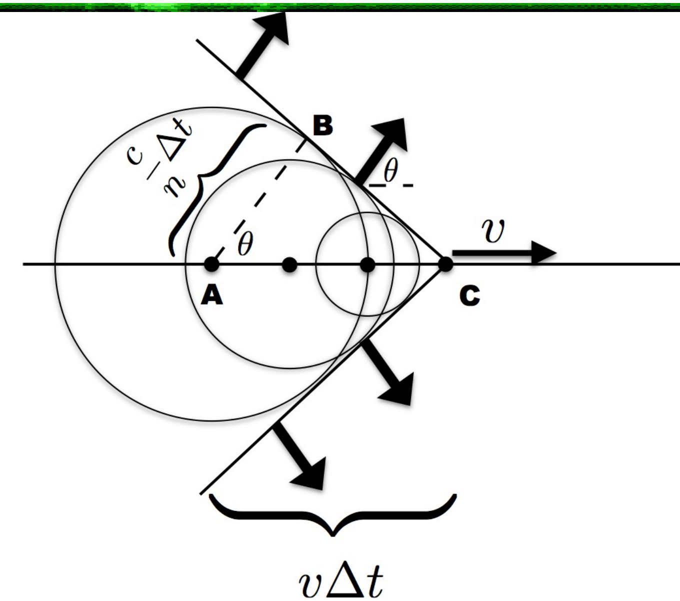
if $\beta > 0.9997$ (90 km/s slower than c)

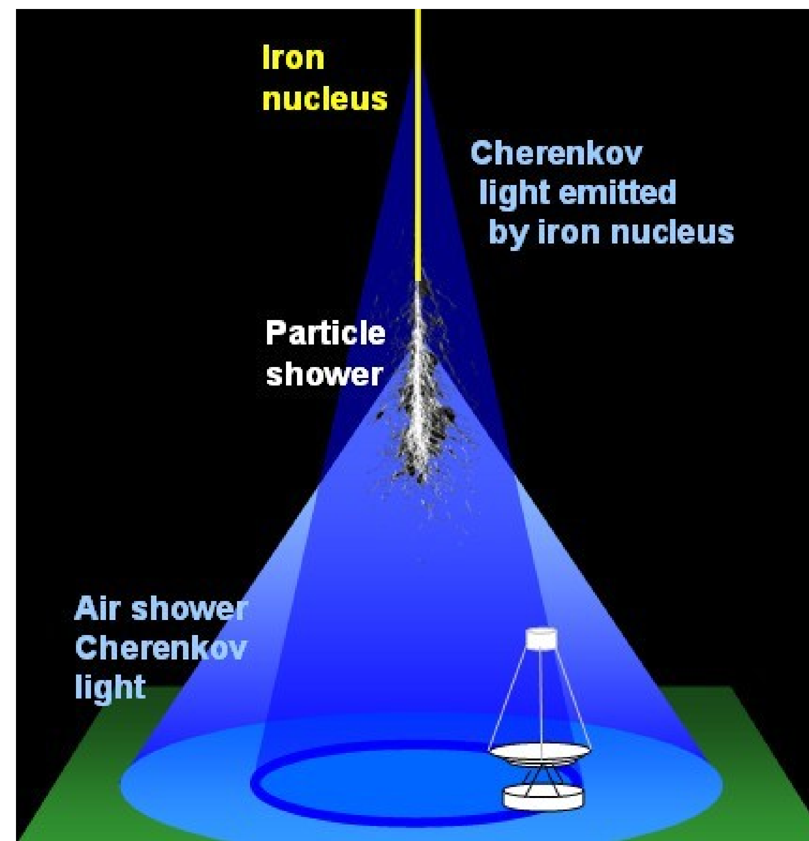
This light is emitted on a narrow cone around the direction of the particle (yet another $1/\gamma$ case!).

The final opening angle α (always less than about 1.4°) is a function of the density of the air (i.e height of emission).

From each part of the particle track the Cherenkov light arrives on a ring on the ground.

See Longair sec. 9.7





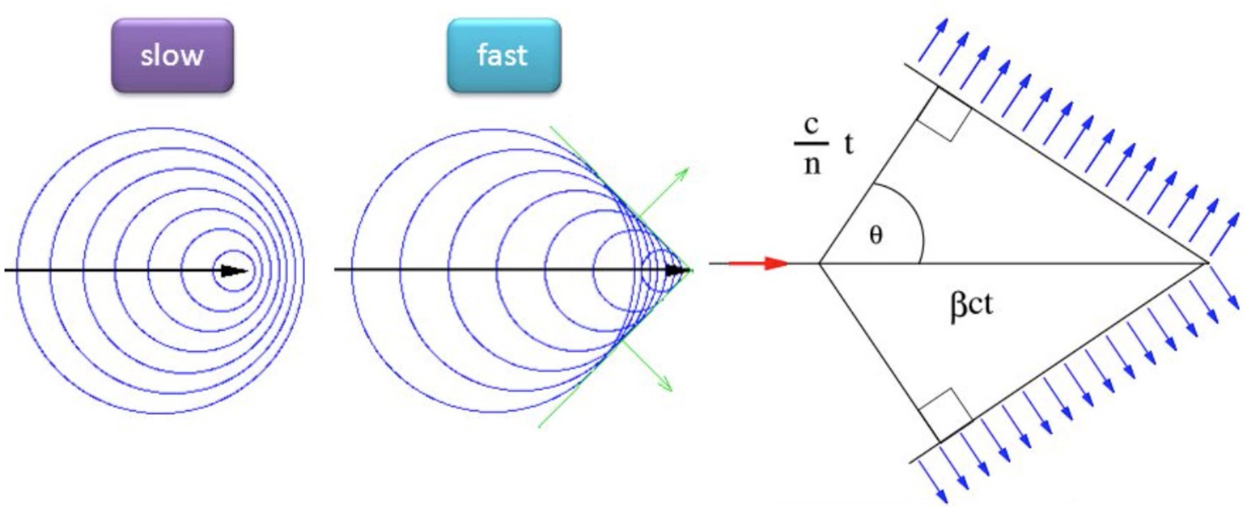
Čherenkov Light (Rybicky – Lightman pp 233-4)

Charged particles moving through the atmosphere with a velocity exceeding the local speed of light $v > \frac{c}{n_r}$ emit Čherenkov Light.

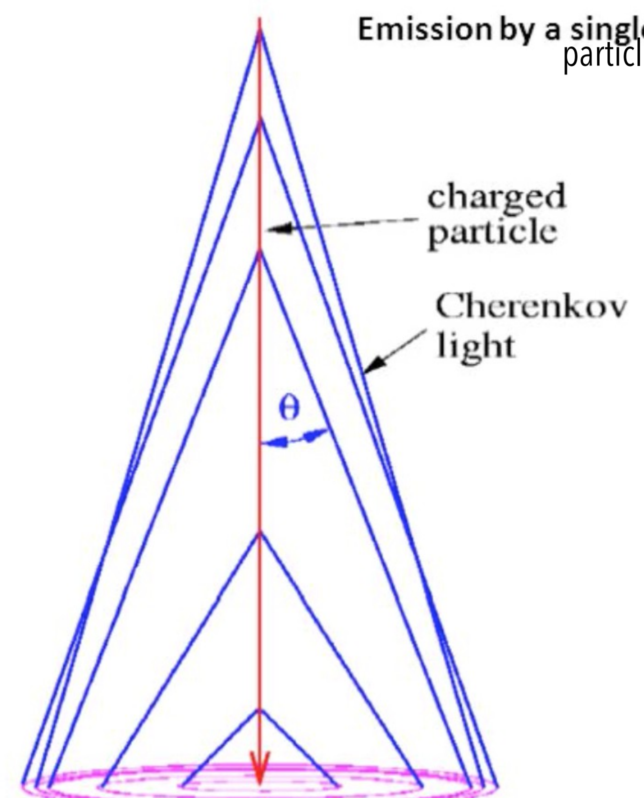
Similar to supersonic motion in fluids

The opening angle depends on the velocity (i.e. sqrt of energy) of the particle

Narrow cones, generally smaller than 1.5° wrt the particle direction

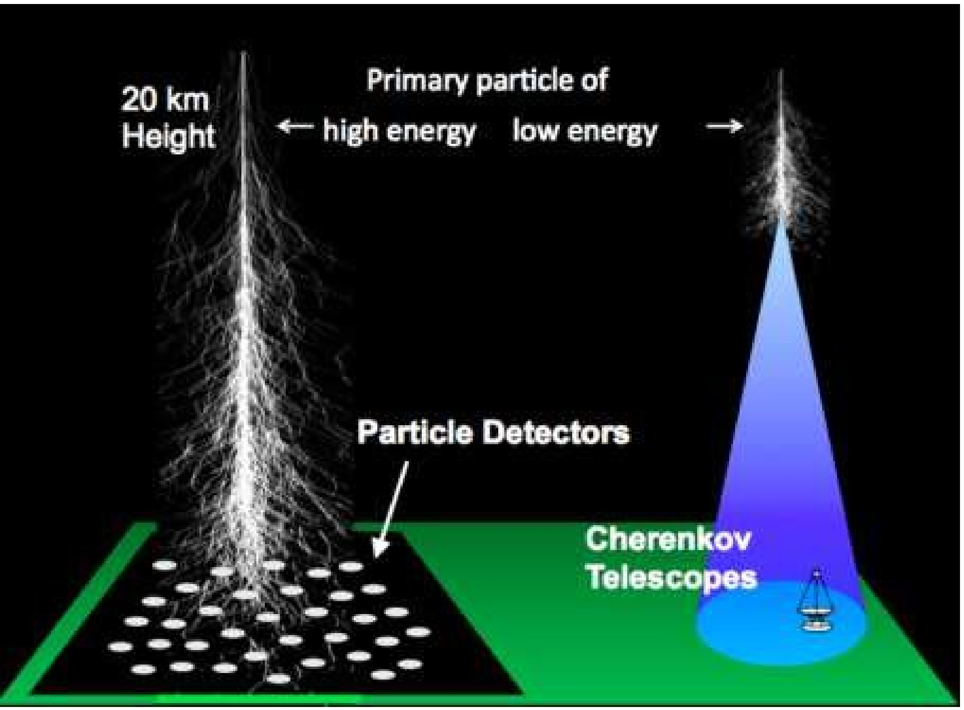


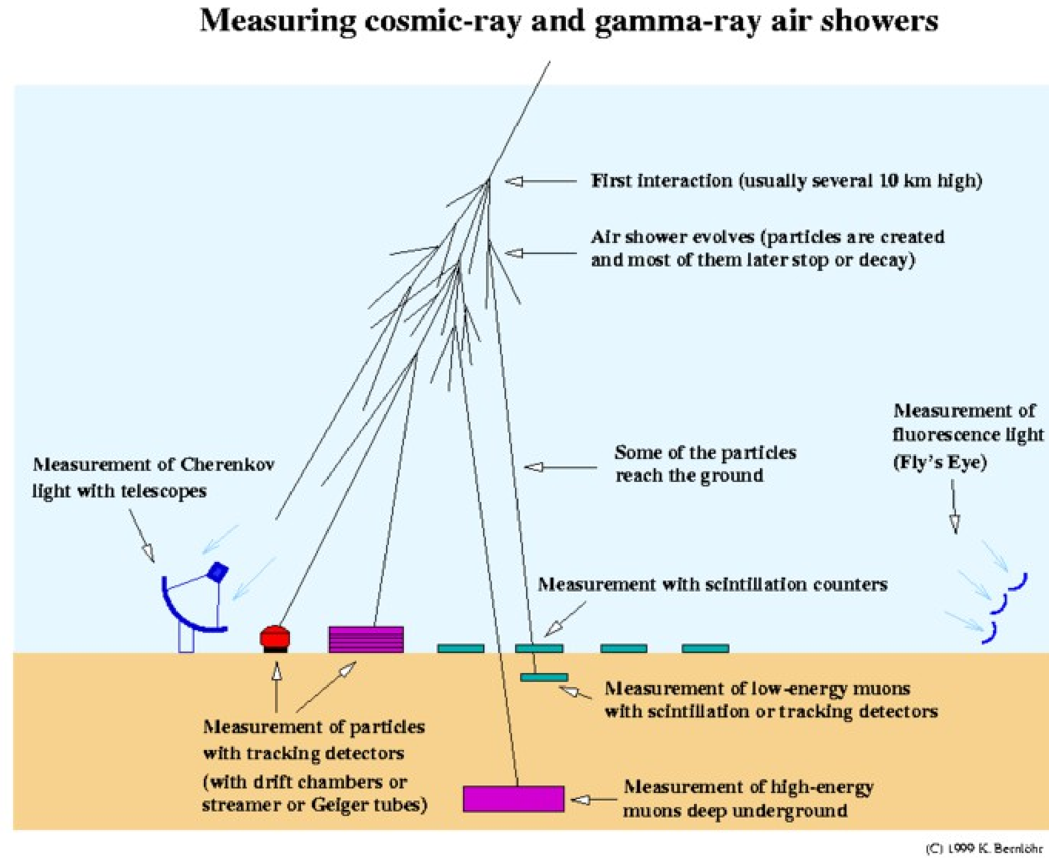
$$\cos\theta_c = 1/\beta n$$

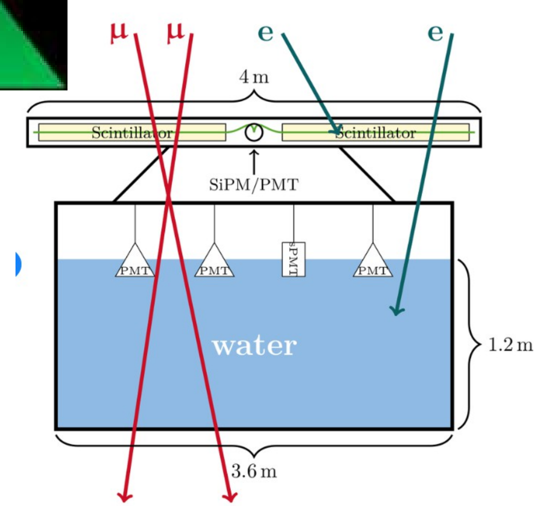


Atmospheric showers: CR detection on Earth

Secondaries via atmospheric showers: either particles (...) or radiation







A sketch of a Pierre Auger Detector Station after deployment of the SSD. The SSD is mounted on top of the water-Cherenkov detector and detects both the electromagnetic and the muonic shower component. According to the baseline design, it is read-out with a PMT. For test purposes, three detectors are equipped with a SiPM module.

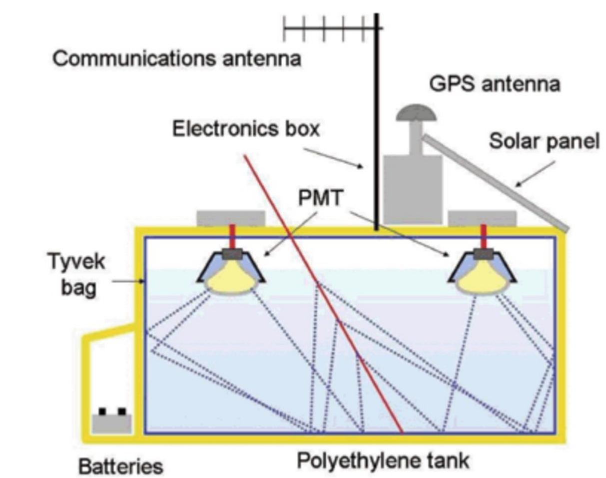
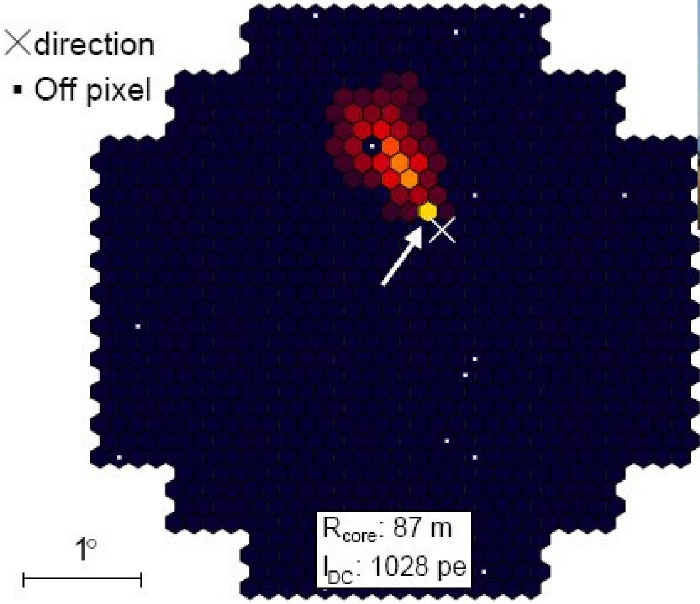


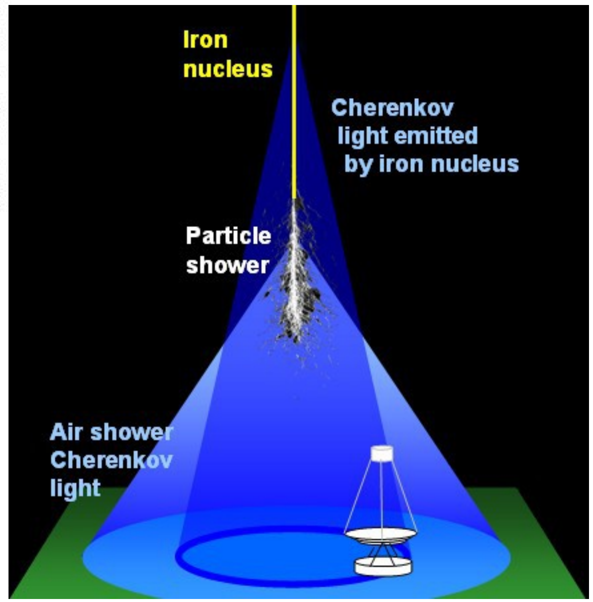
FIG. 2: A schematic view of the Cherenkov water tanks, with the components indicated in the figure.

Detectors:



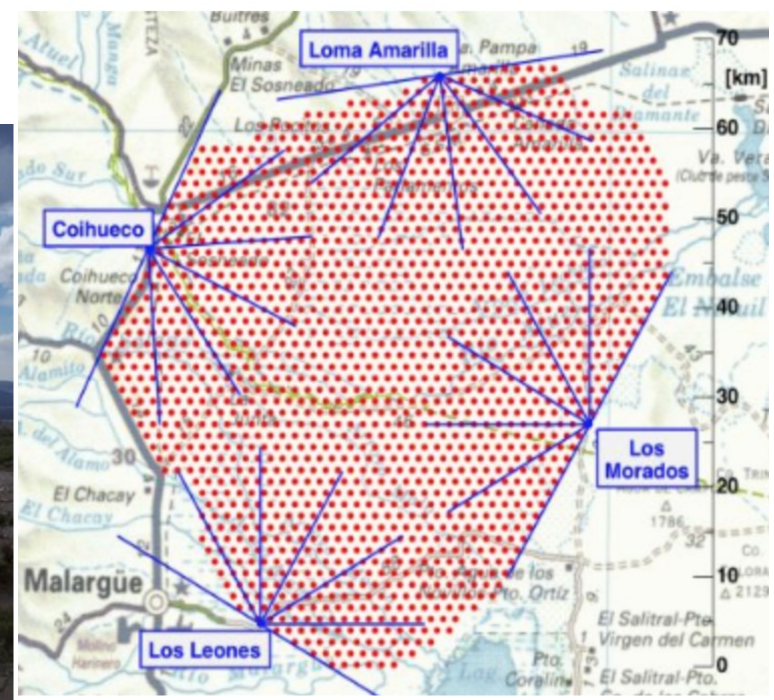
direction
Off pixel
1°
R_{core}: 87 m
I_{bc}: 1028 pe

Hess



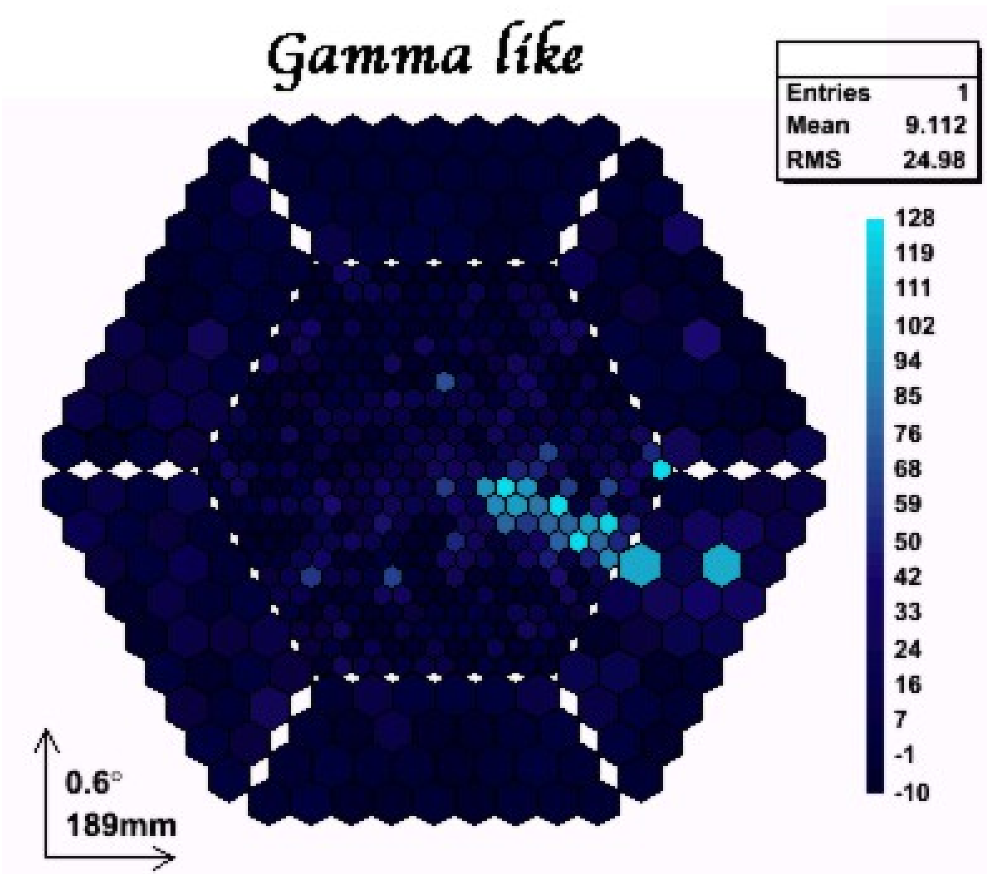
Iron nucleus
Cherenkov light emitted by iron nucleus
Particle shower
Air shower Cherenkov light

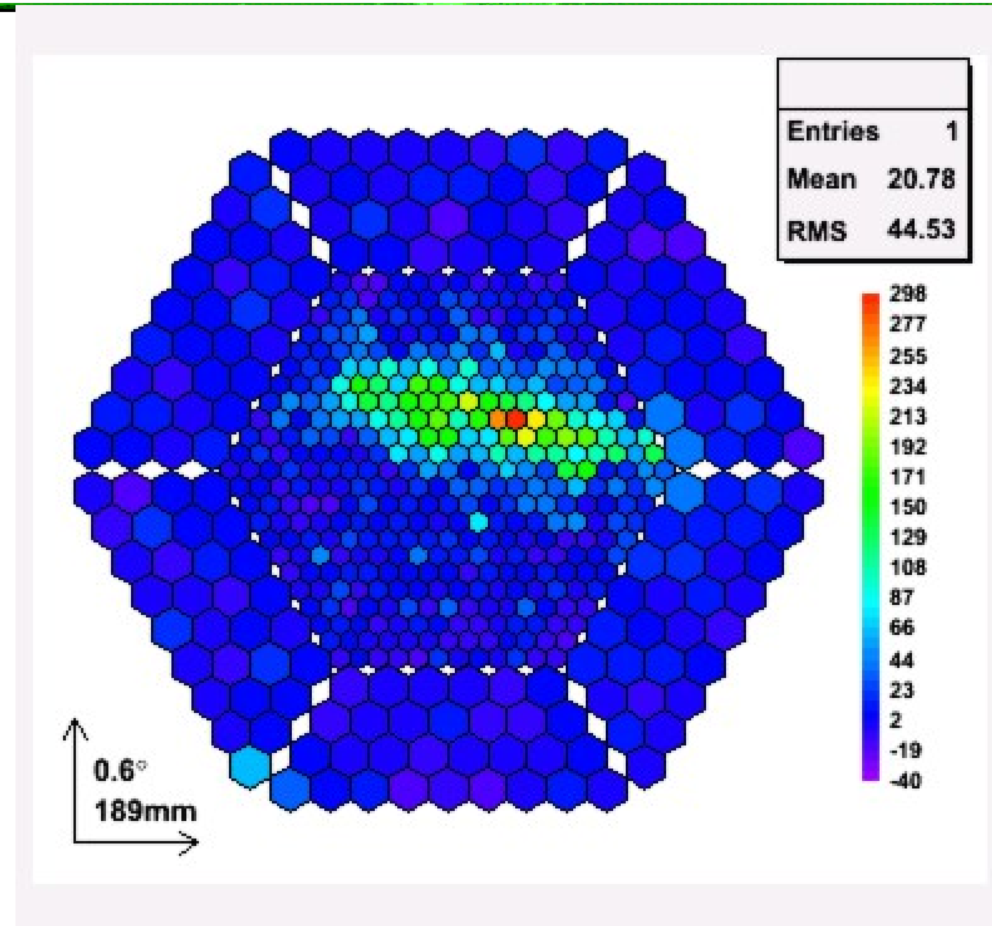
Pierre Auger observatory



Loma Amarilla
Coihueco
Los Morados
Los Leones
Malargüe
[km]
70
60
50
40
30
20
10
0

Cherenkov radiation



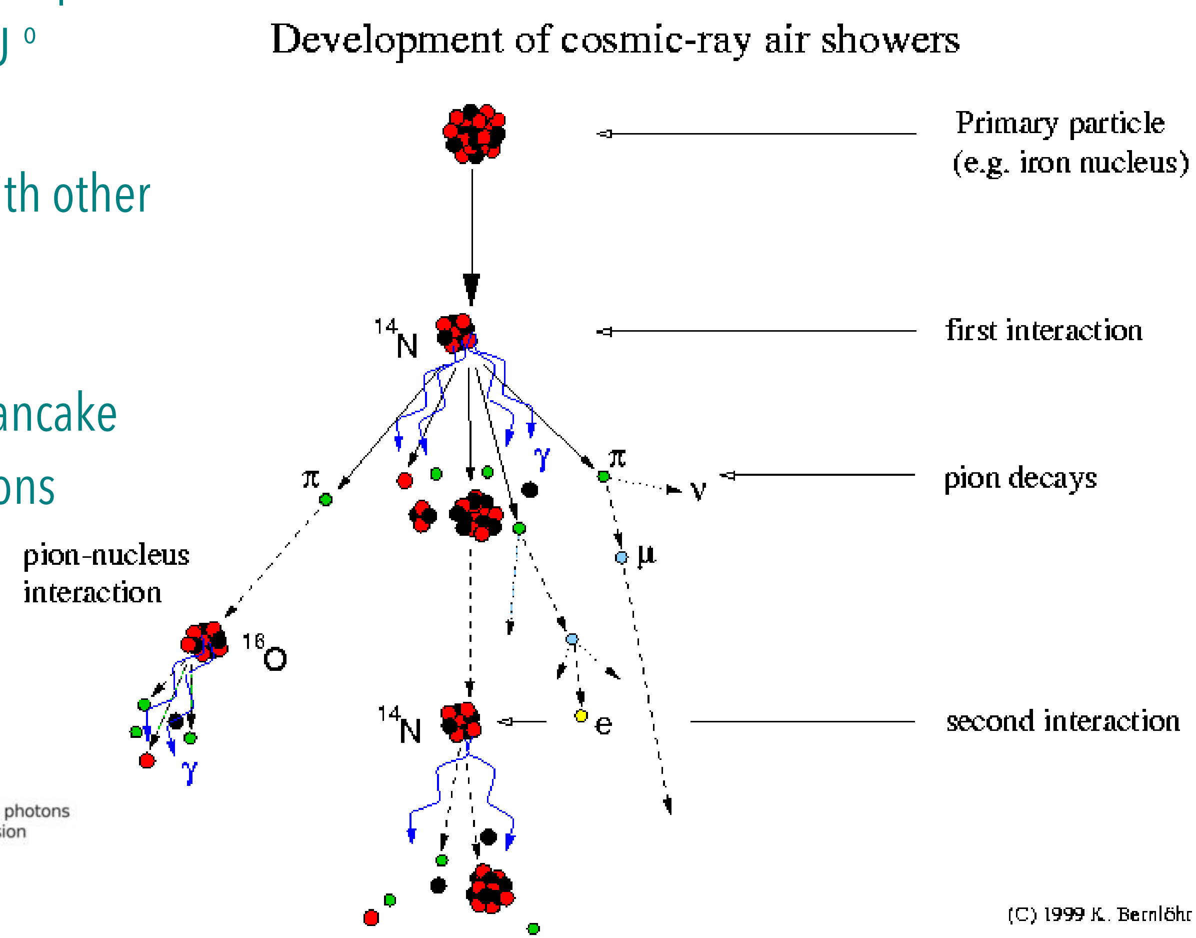


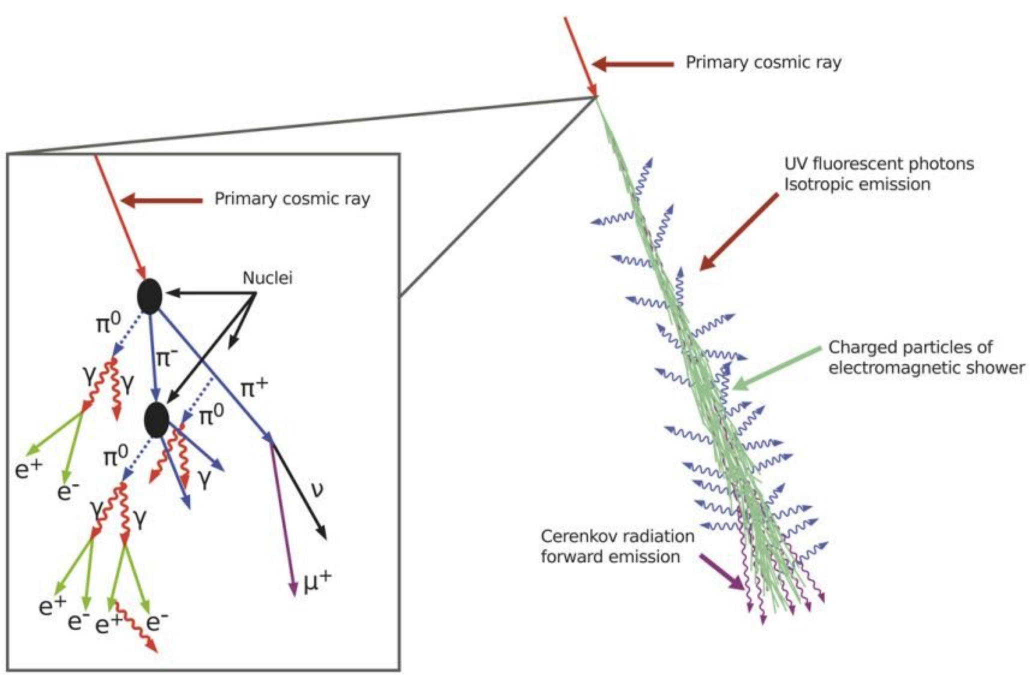
CR air shower: hadrons

The particle interacts with a particle in the atmosphere

1. fragmentation and production of Ù $^{+}$,Ù $^{-}$,Ù ^{o}
2. decay of Ù ^{o}
3. Ù $^{+}$,Ù $^{-}$ may decay into Õ $^{+}$,Õ $^{-}$, or interact with other nuclei/molecules....

If the primary cosmic ray was a nucleus the pancake will also contain muons, neutrinos, and hadrons (protons, neutrons, and pions).

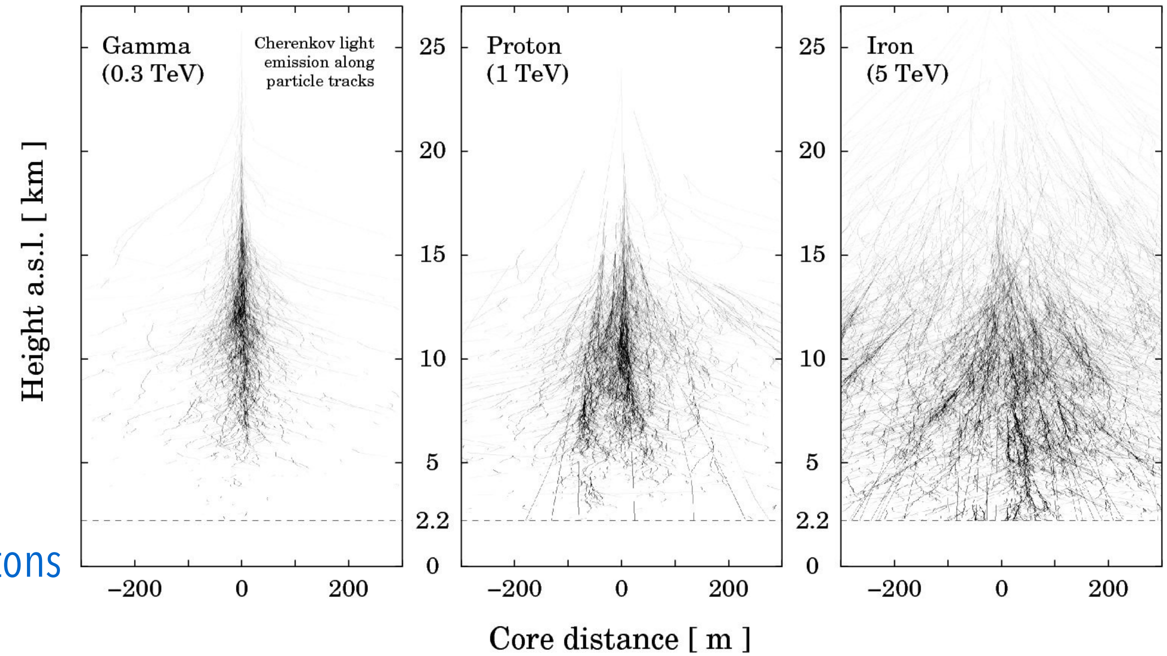


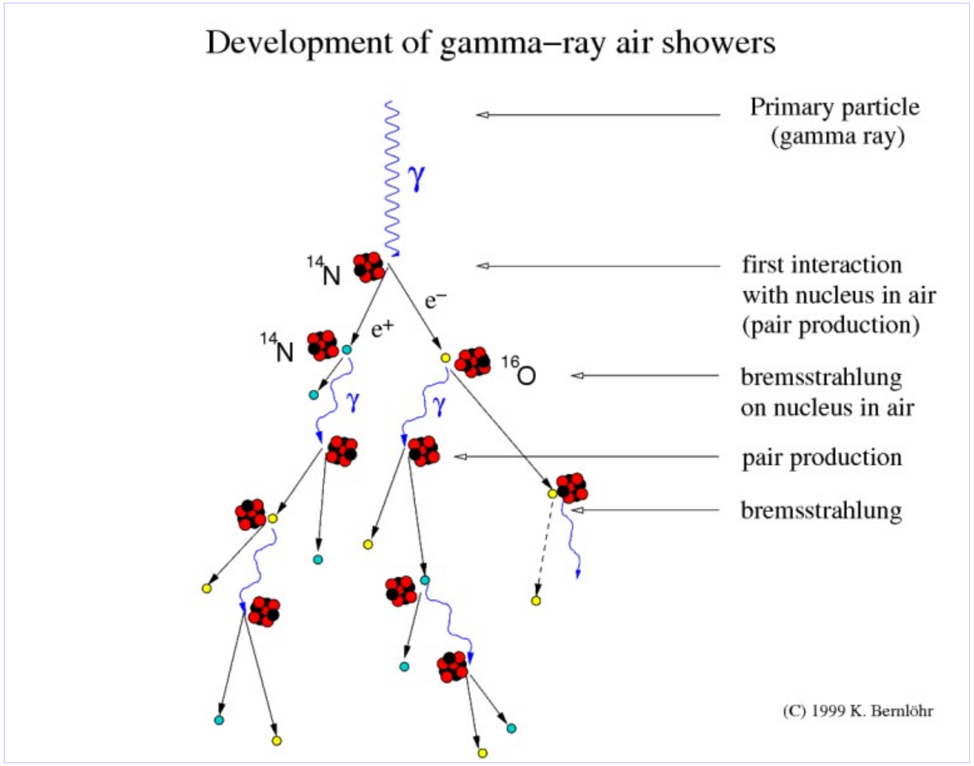


CR air shower: photons … leptons… hadrons

If the primary CR was a photon the "pancake" will contain electrons, positrons, and gamma rays

Number of particles in the pancake:
depends upon the energy of the primary photon, the altitude of the interaction, and fluctuations in the development of the shower.
Higher energies ⟹ larger number of particles & photons & thicker spatial distribtion
When the pancake reaches the ground it is roughly 100 meters across and 1-2 meters thick





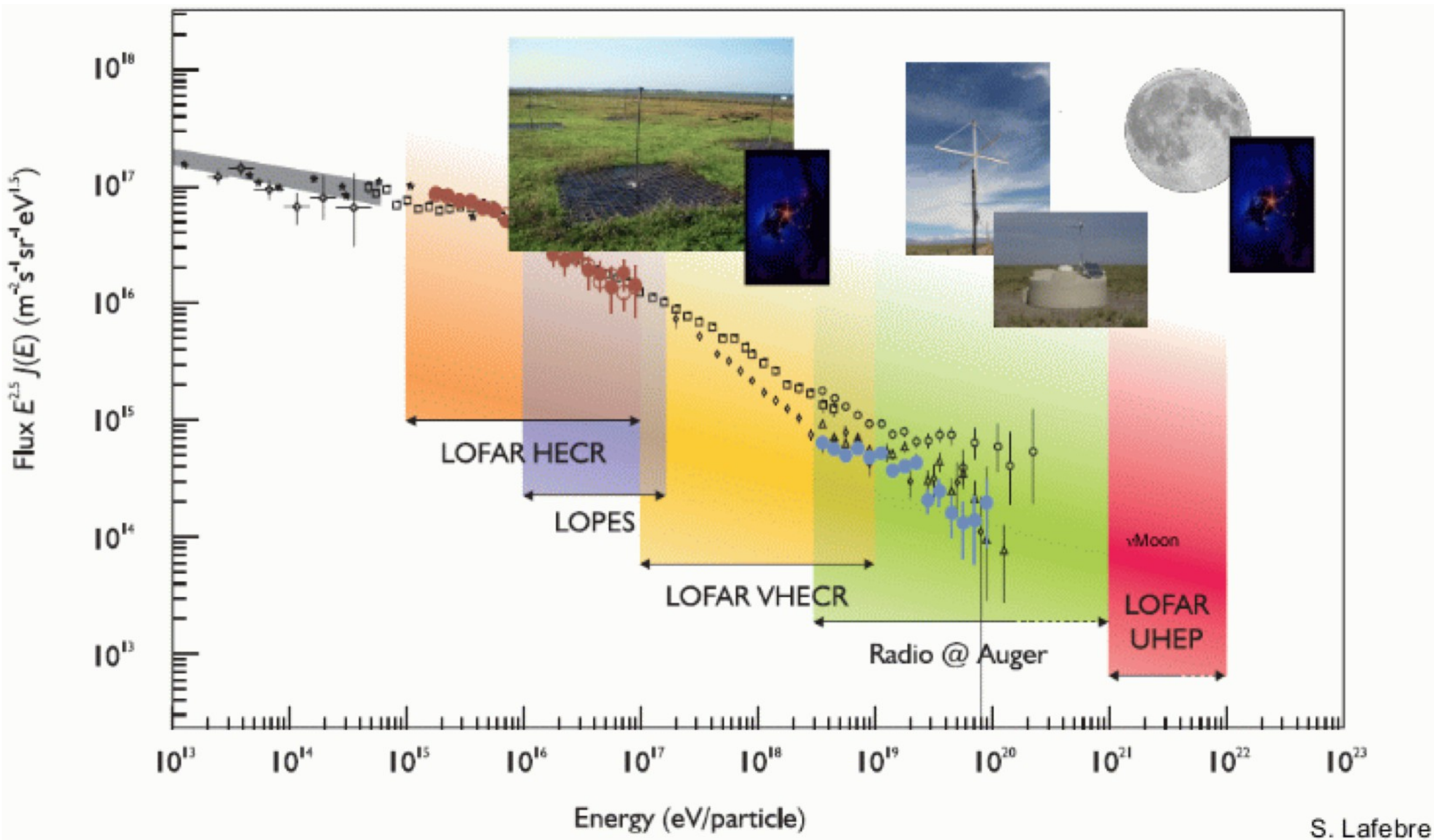
⟹ Static examples like the top-right figure:
https://www-zeuthen.desy.de/~jknapp/fs/photon-showers.html
https://www-zeuthen.desy.de/~jknapp/fs/proton-showers.html
https://www-zeuthen.desy.de/~jknapp/fs/iron-showers.html

⟹ Dynamic example of the development of the atmospheric shower:
Atmospheric Particle Showers and Cherenkov Radiation from Gamma Ray, Proton and Carbon-13 nucleus:
https://www.youtube.com/watch?v=j-BBzWlOai0

Example of measurements in the radio band (from a few to a few tens of MHz)

Discovery by Jelly +, 1965, Nature, 205, 327

Pulsed radio emission (mainly "geomagnetic", + Askaryan effect significant in dense media only, e.g. ice)



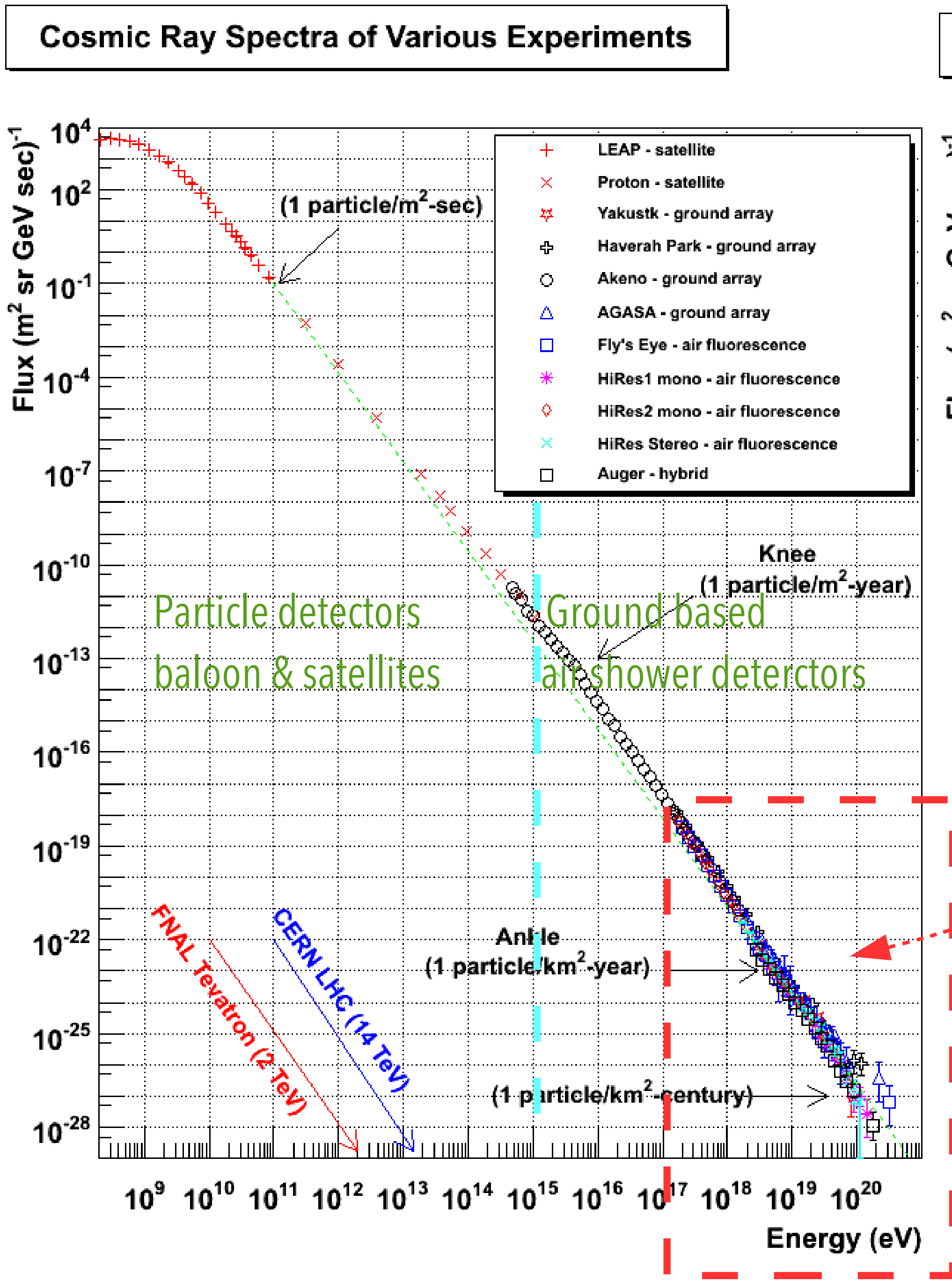
Particle energy

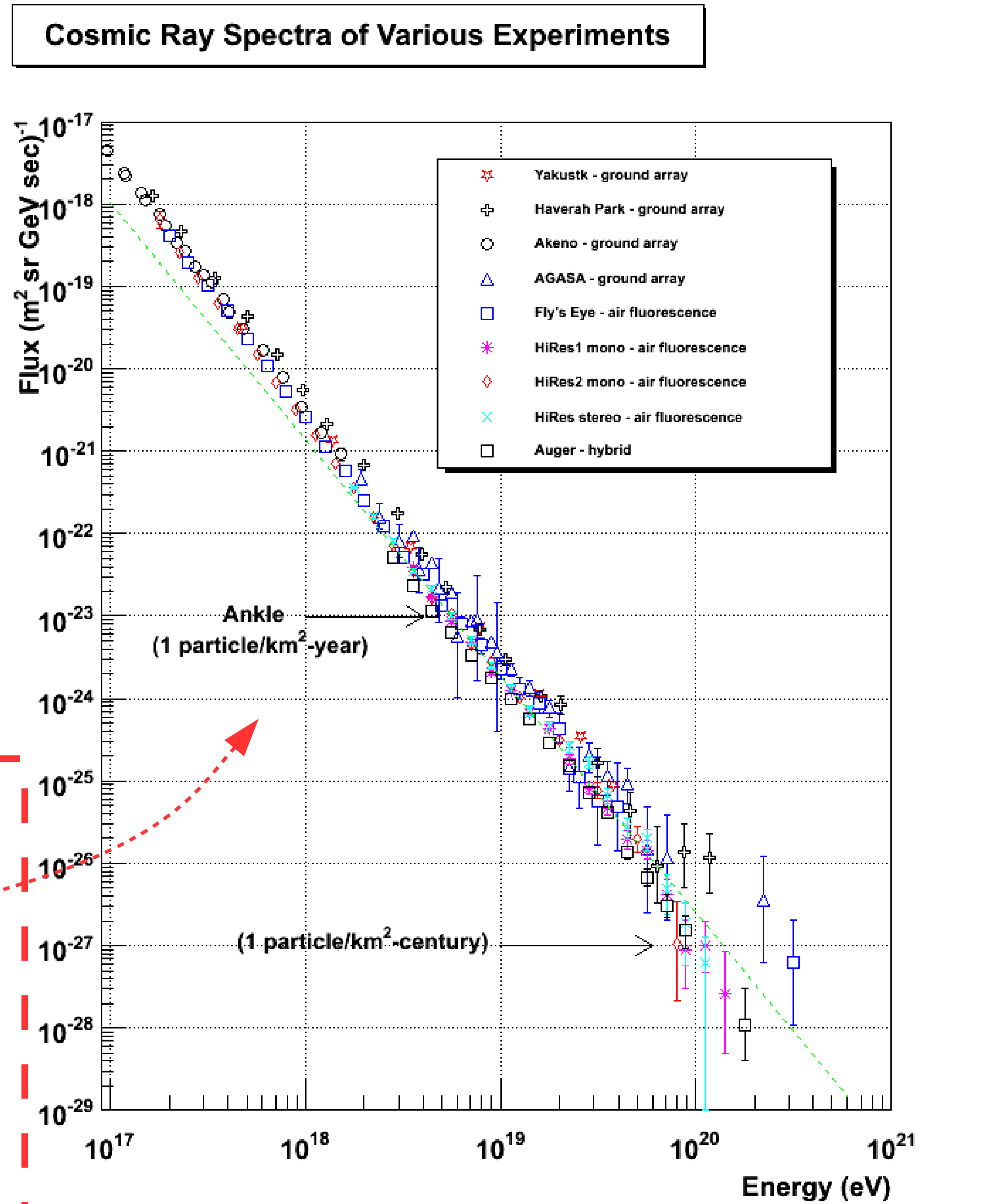
Velocity (v/c)	$\gamma = [1 - (v/c)^2]^{-1/2}$
0.9	2.29
0.99	7.09
0.999	22.4
0.9999	70.7
0.99999	224
0.999999	707
0.9999999	2236
0.99999999	7071
0.999999999	22361
0.9999999999	70711
0.99999999999	223606

$$E = \gamma m c^2$$

Particle	mc^2 (MeV)
electron	0.511
proton	938
He (nucleus)	
C (nucleus)	
^{56}Fe (nucleus)	~45000 (45 Gev)

Power- law Energy spectrum (with some features)





Features in the Power-law Energy spectrum

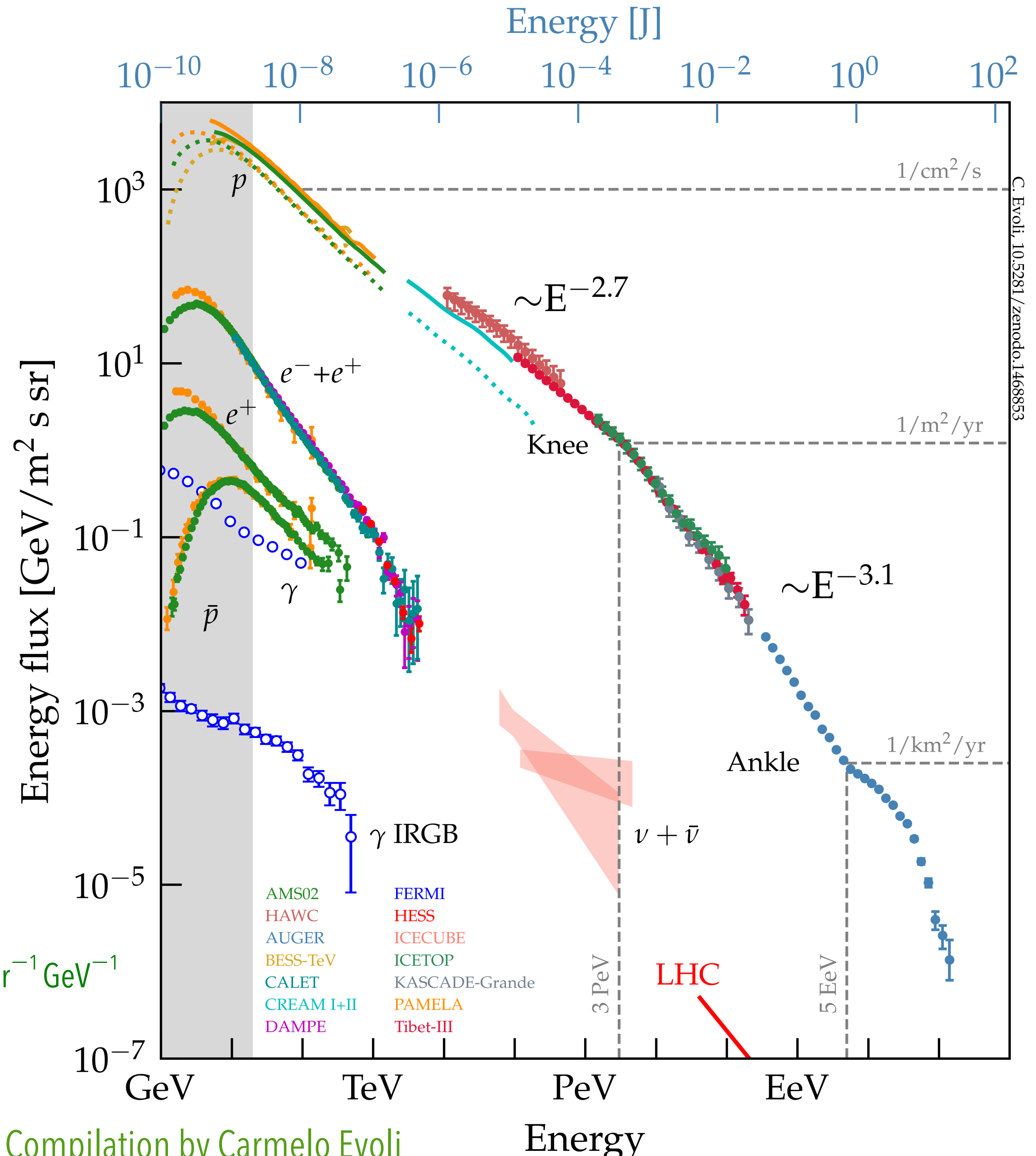
The knee @ $\approx$ 10^{15} eV

The ankle@ $\approx$ 10^{18-19} eV

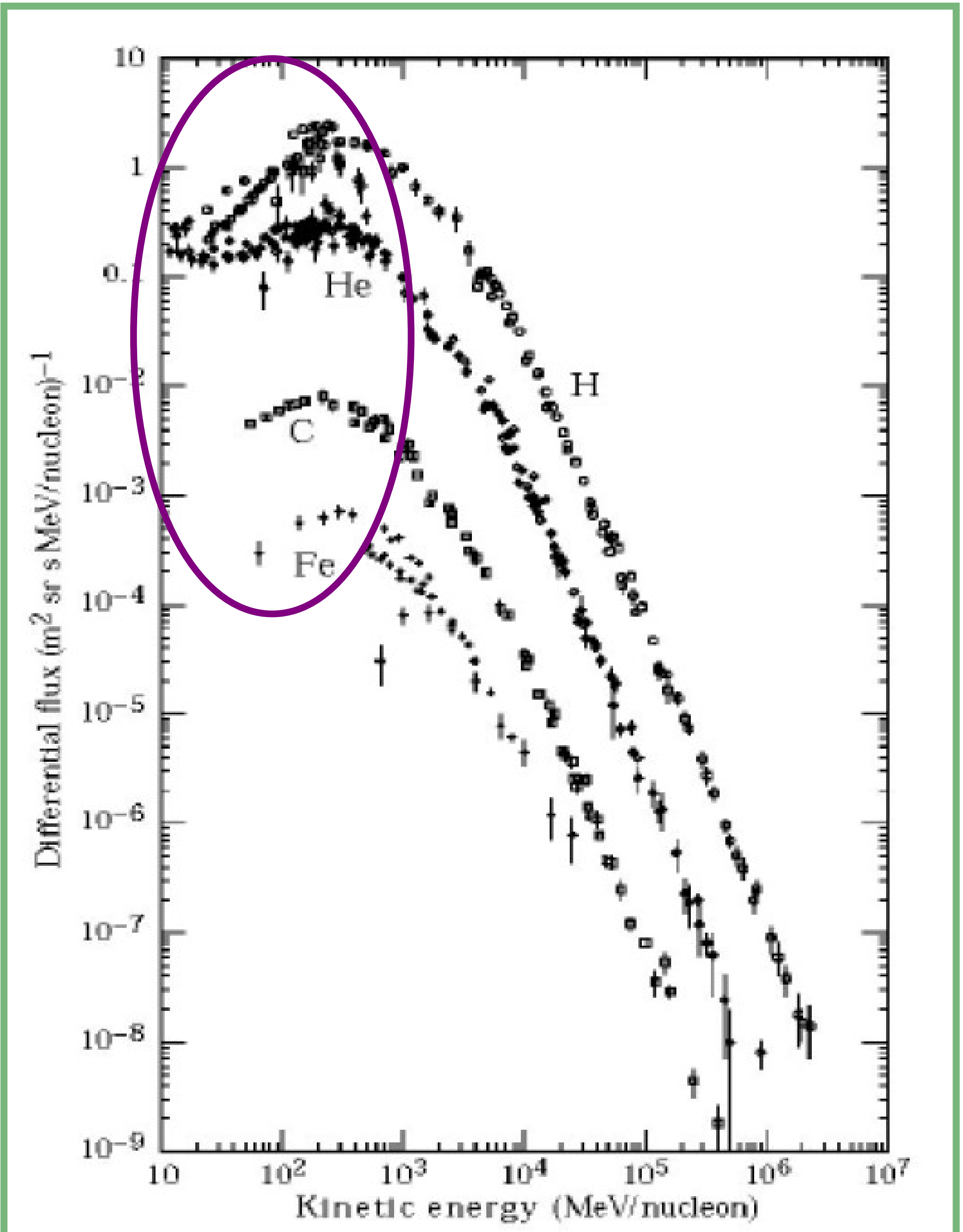
$\rightarrow$ Quite steep energy spectrum

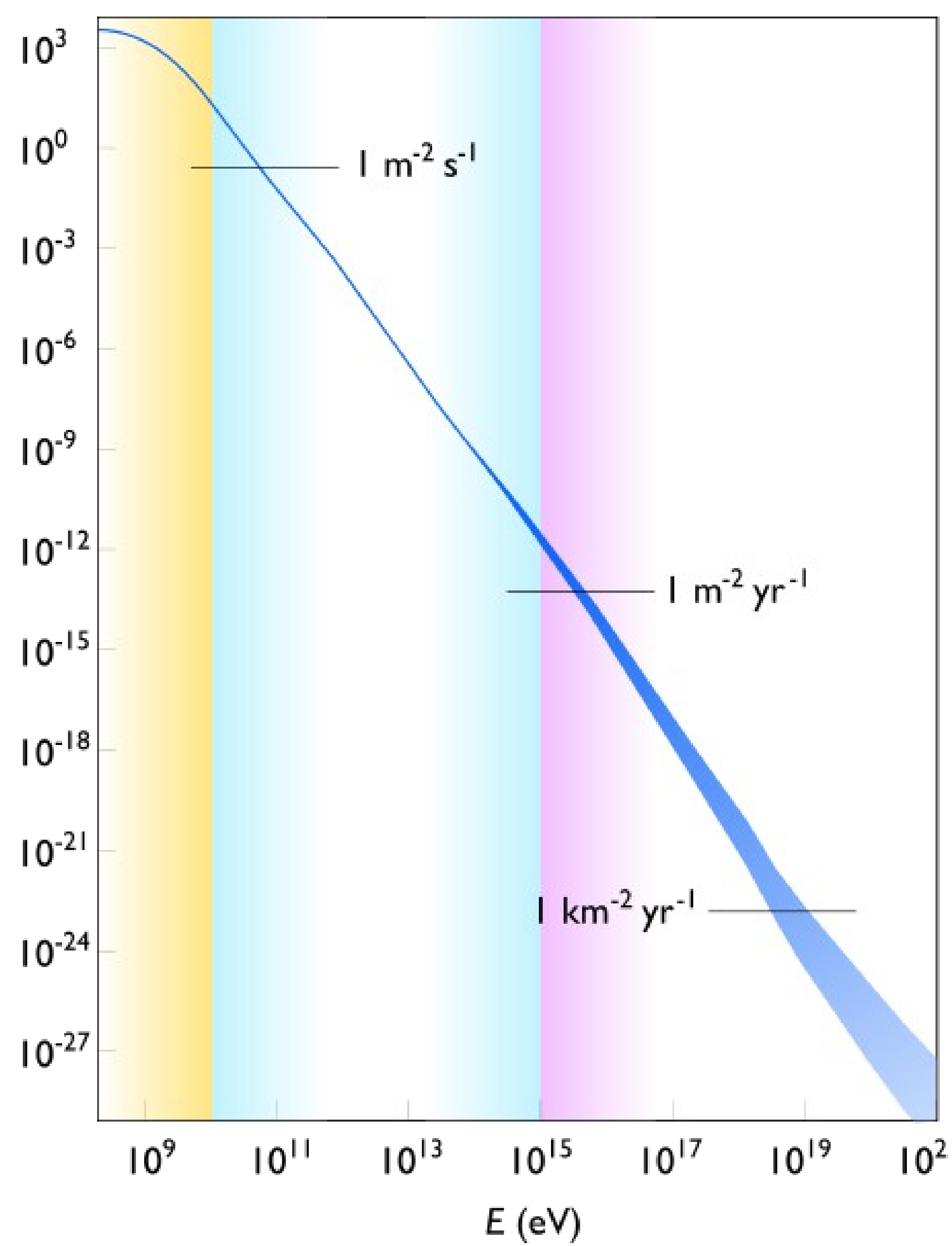
Approximated intensity of primary nucleons

$I_{nuc}(E) \approx 1.8 \cdot 10^4 E^{-\delta}$ nucleons $m^{-2} s^{-1} sr^{-1} GeV^{-1}$



Compilation by Carmelo Evoli


Differential flux (m² sr s MeV/nucleon)⁻¹
Kinetic energy (MeV/nucleon)
H
He
C
Fe
10
1
0.1
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10
10²
10³
10⁴
10⁵
10⁶
10⁷

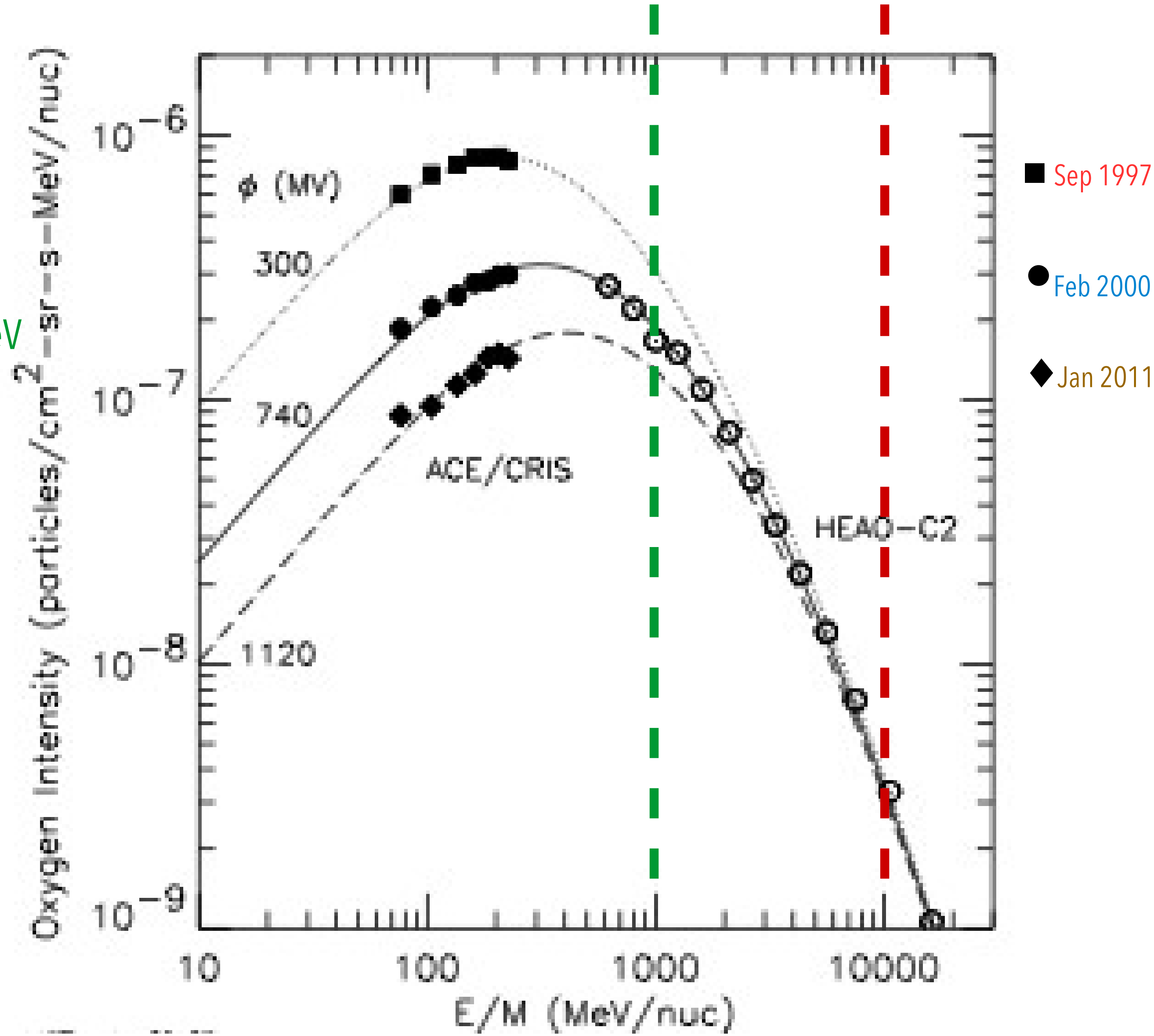

1 m⁻² s⁻¹
1 m⁻² yr⁻¹
1 km⁻² yr⁻¹
10³
10⁰
10⁻³
10⁻⁶
10⁻⁹
10⁻¹²
10⁻¹⁵
10⁻¹⁸
10⁻²¹
10⁻²⁴
10⁻²⁷
10⁹
10¹¹
10¹³
10¹⁵
10¹⁷
10¹⁹
10²¹
E (eV)

Variability in the low energy turnover ?

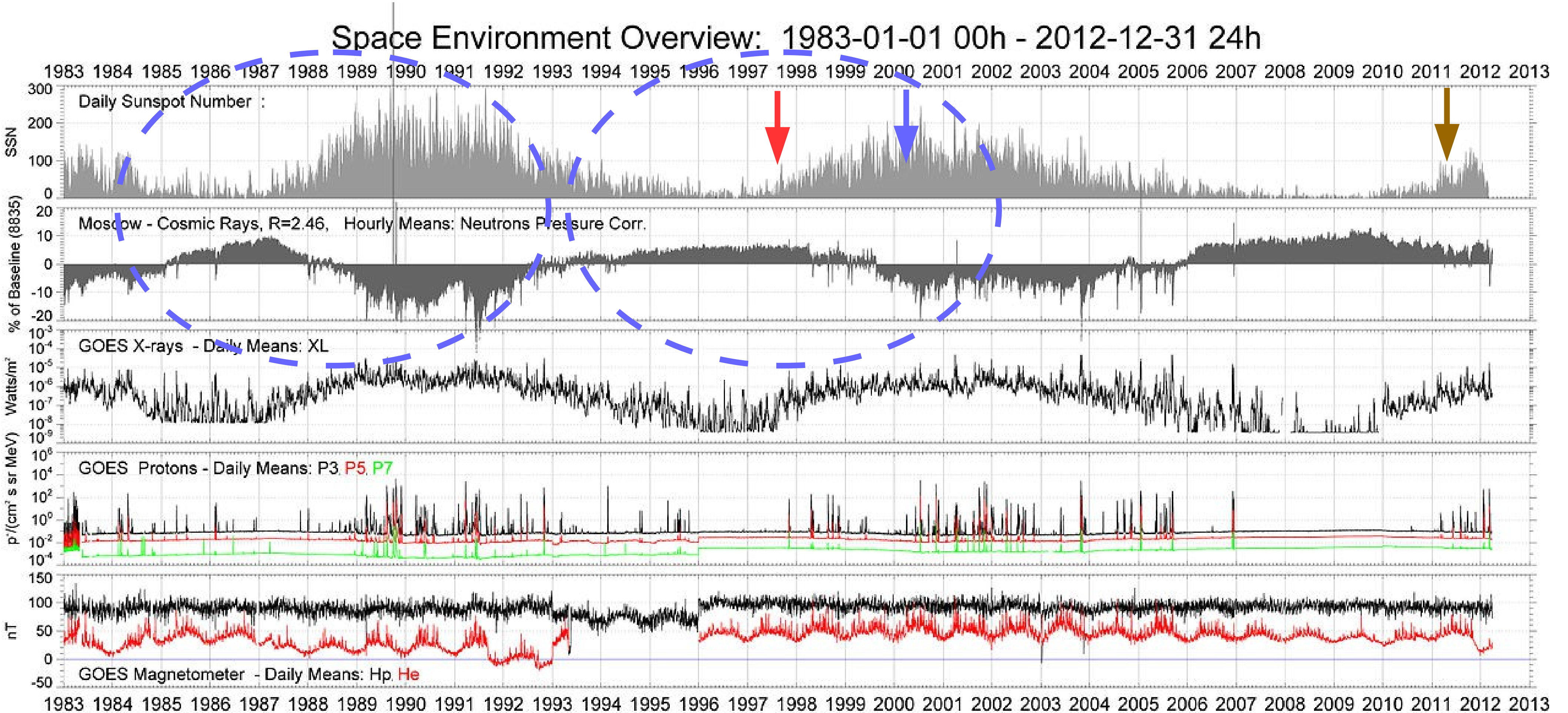
Particle flux at low energies changes with time.

Marginal difference at ~ 1 GeV

No variation at > 10 GeV



Variability in the low energy turnover



The level of solar activity determines the characteristics of the low energy turnover

Low activity $\Longrightarrow$ high CR flux density

Given the effects of the Solar modulation responsible of significant deflections of the Low-energy CRs, the evaluation of isotropy may be spoiled.

Nucleonic component (1)

- Steep energy distribution

  N(E) ~ $E^{-\delta}$ where δ is ~2.7

  Similar slope for all primary nucleons

- Possible marginal changes with E

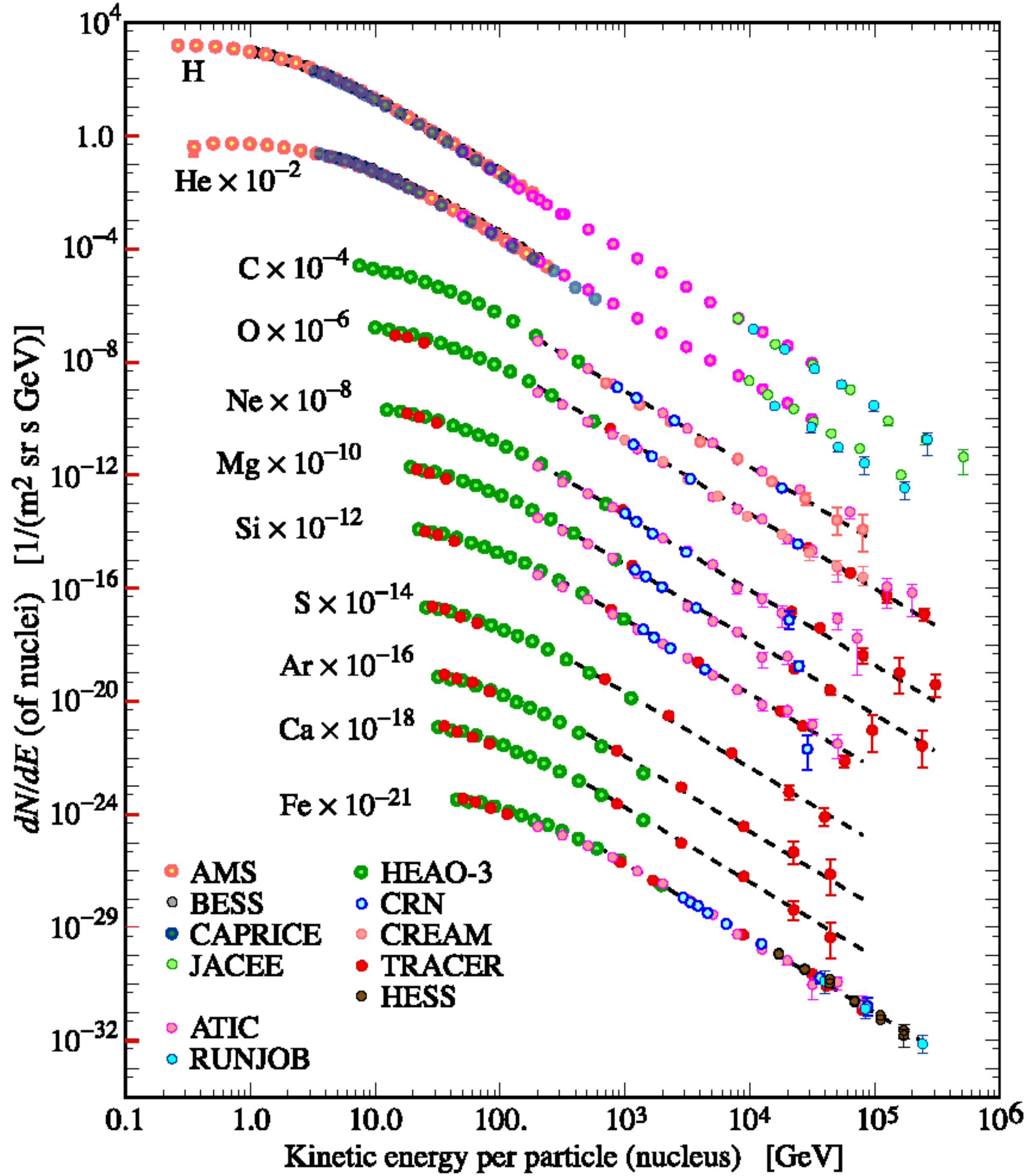
  (may be slightly steeper for secondary species)

  (possibly related to spallation, and to unstable isotopic populations)

- *Different abundances wrt solar and ISM composition (next slides)*

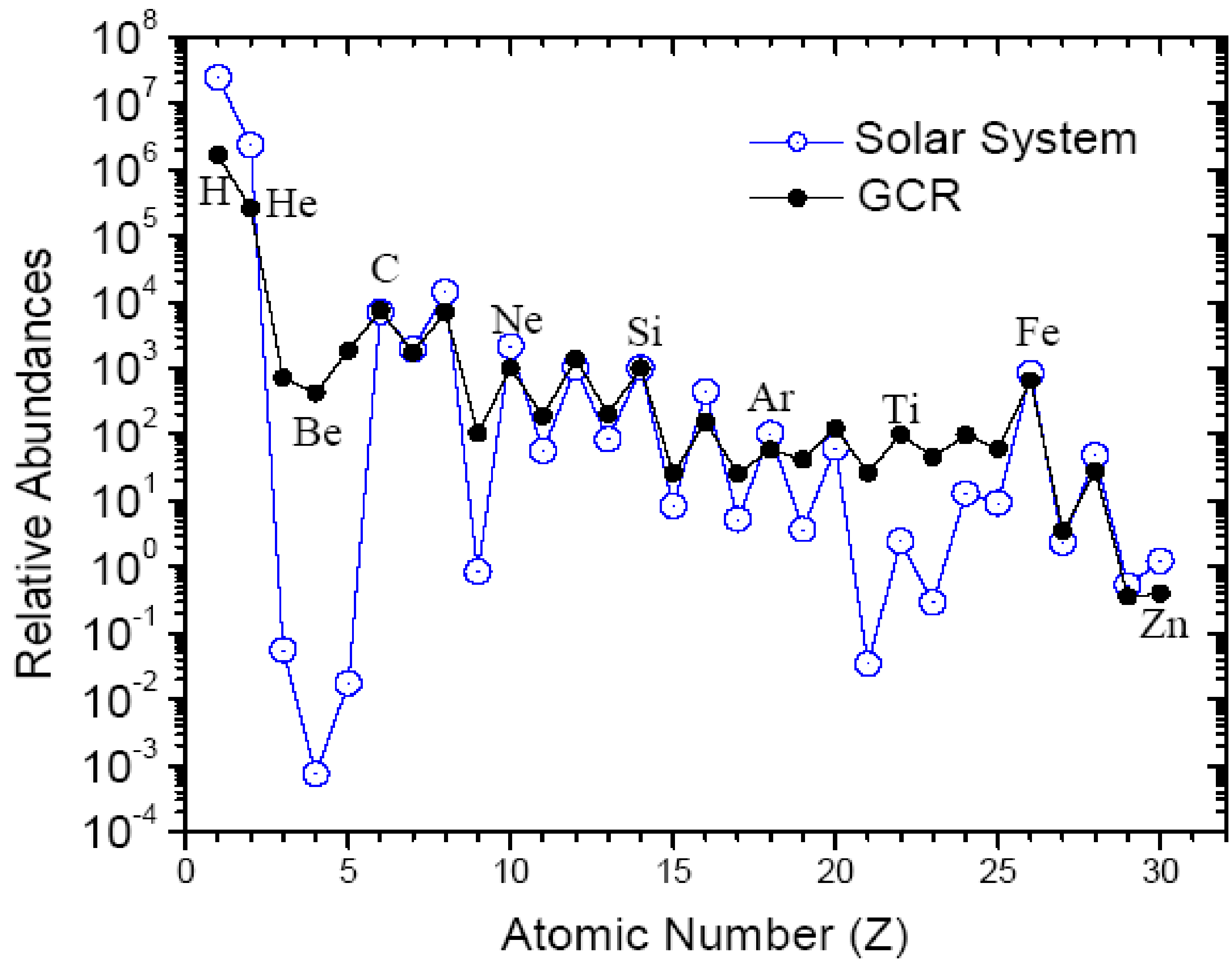
- Spallation: fragmentation of heavy CR nuclei via interaction with the ISM

  ~60% "native" CRs, 40% "fragmented"



Nucleonic component (2)

- Different abundances with respect to solar and ISM composition
- High Fe/H (Fe/C "normal") (Fe cross-section is ~3 times that of CNO)
- Origin of CRs in Fe-rich environments i.e. SNR
- Equivalent if CRs cross a slab with a thickness of
  $\langle x \rangle \sim 4 \pm 1$ g cm^{-2}
- Responsible of creation and refurbishment of radioactive isotopes (~1/3 of natural radioactivity is from CR)



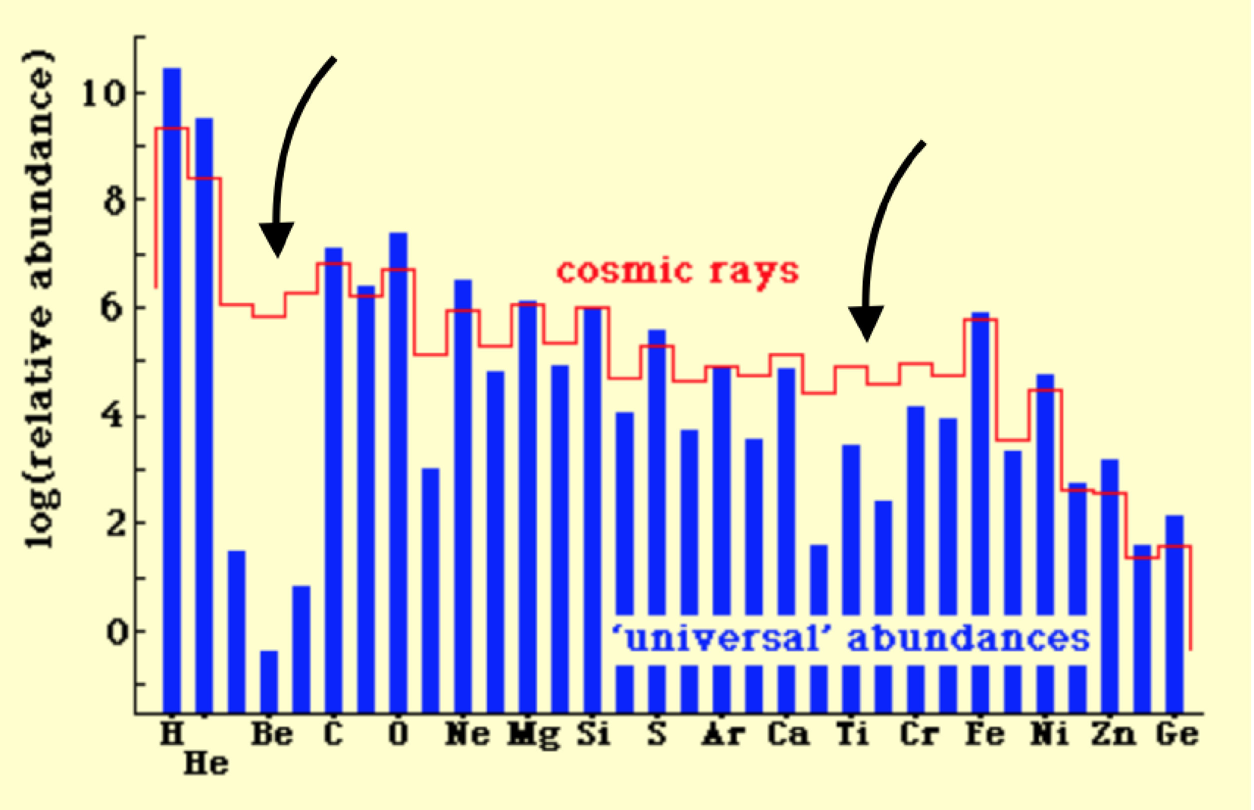
Normalization to the total number

Very overabundant (~10^5): Li, Be, B

Overabundant (~10^3): Sc,Ti, Va,Cr,Mn

Slightly underabundant: Fe, Ni, C, N, O

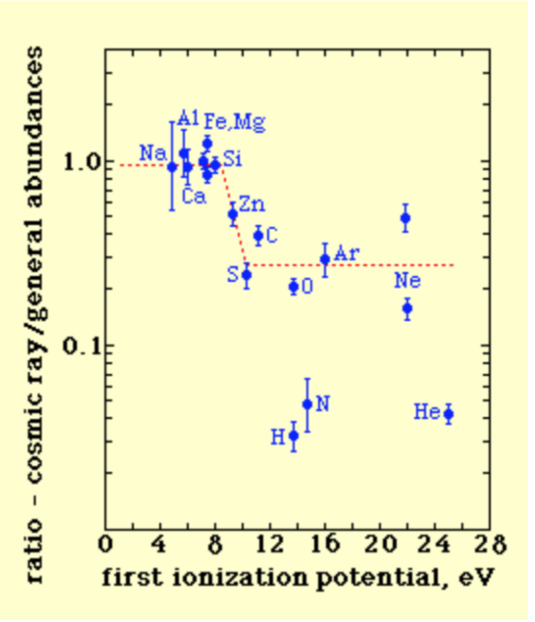
Underabundant (10^{-1}): H, He



? Generation of CR in sites with little/no H, He? (e.g. SN, NS = pulsars)

? Related to (first) ionization energy?

…..which has to be overcome before acceleration is possible. This is supported by clear evidence that other elements with high ionisation potential are also depleted in CRs. Acceleration in low temperature environments? The material of CRs seems to have been ejected into the interstellar medium and subsequently cooled before acceleration?



$\langle x \rangle$, the Lifetime of CRs and their confinment

The lifetime of a CR particle ma be detemined from the average (ISM) density

Starting from the measure $\langle x \rangle = 4\,\mathrm{g\,cm^{-2}}$.

$$\tau_{CR} = \frac{\langle x \rangle}{\rho_{ISM}\, c}$$

In the galactic disk:

$$n_{ISM} \quad 0.1\,\mathrm{cm^{-3}} \rightarrow \rho_{ISM} \approx 10^{-25}\,\mathrm{g\,cm^{-3}} \rightarrow \tau_{CR} \approx 3 \cdot 10^{7}\,\mathrm{yr}$$

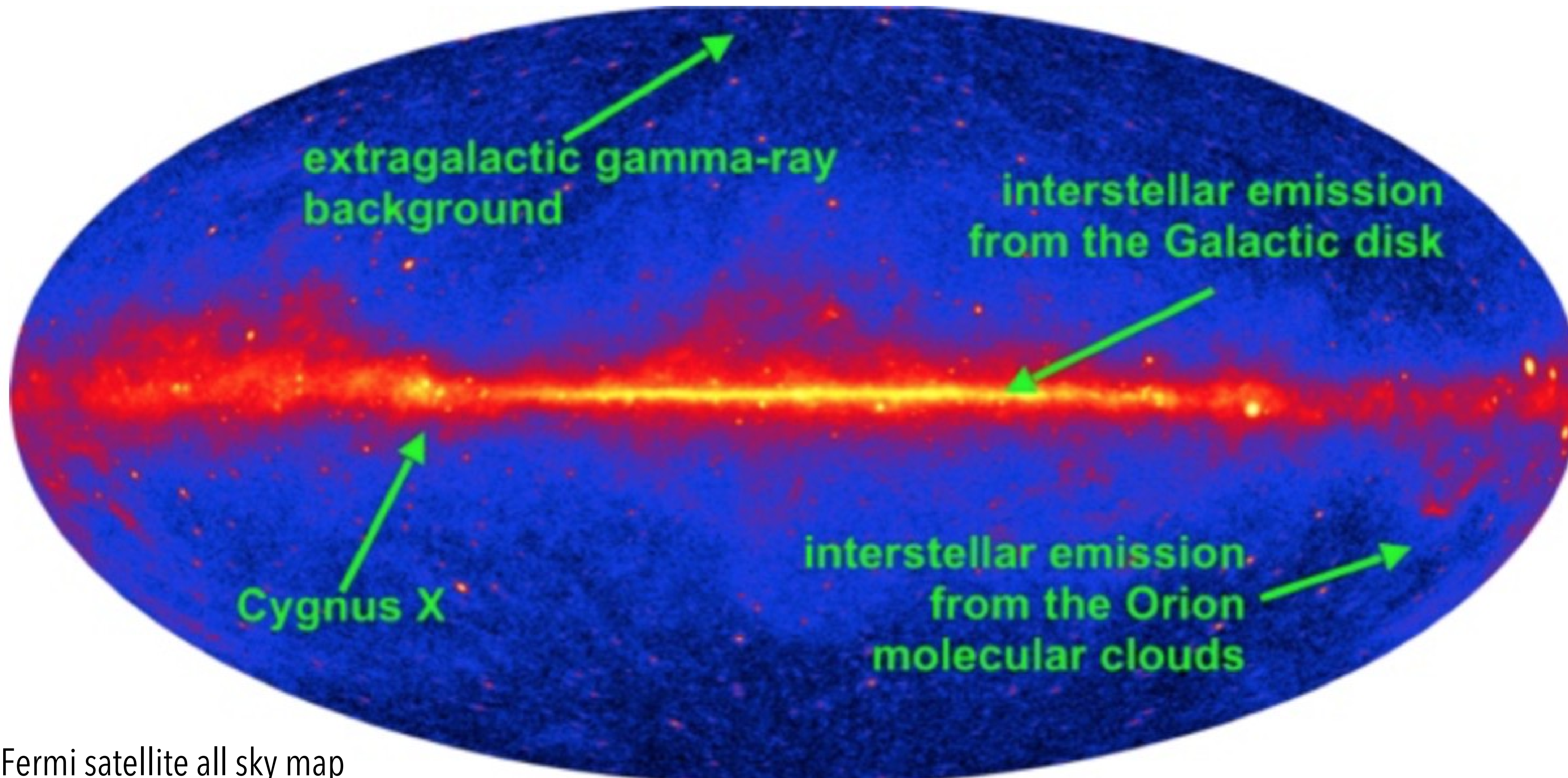
$$n_{ISM} \quad 1\,\mathrm{cm^{-3}} \rightarrow \rho_{ISM} \approx 10^{-24}\,\mathrm{g\,cm^{-3}} \rightarrow \tau_{CR} \approx 3 \cdot 10^{6}\,\mathrm{yr}$$

In such long time, CR travels > 1 Mpc therefore, confinment is needed (B field)

For the galactic halo, densities are 100 times smaller $\rightarrow \tau_{CR} \approx 3 \cdot 10^{8}\,\mathrm{yr}$

Side effect: a map of the matter distribution within our galaxy

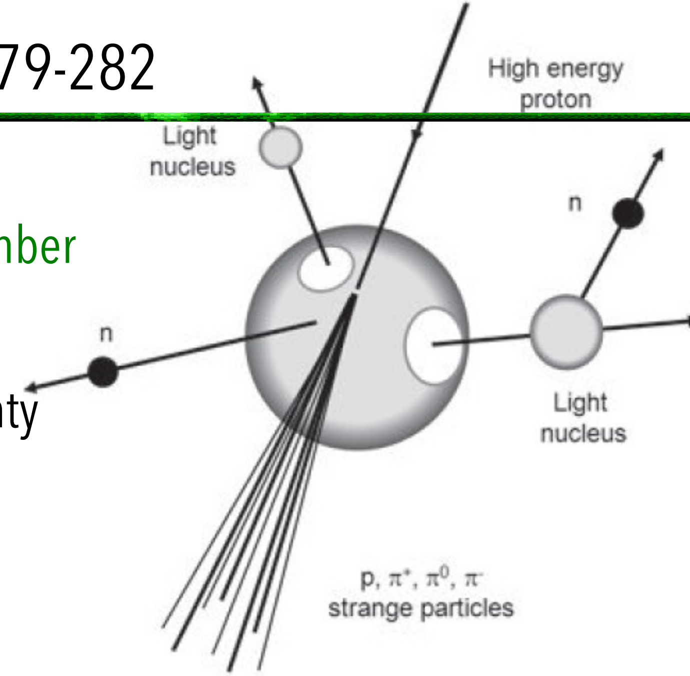
- *Spallation is responsible for creating overabundances:*
- *Fragmentation of heavy CR nuclei via interaction with the ISM: ~80 – 60% "native" CRs, 20 – 40% "fragmented"*
- *Equivalent to a slab with a thickness of* $\langle x \rangle \sim 4 \pm 1\ g\ cm^{-2}$
- *Compatible with an exponential distribution of thicknesses*
- *Responsible of creation and refurbishment of radioactive isotopes (~1/3 of natural radioactivity is from CR)*



Fermi satellite all sky map

Spallation

from Longair, p. 279-282



Nuclear radius $R = 1.2 \times 10^{-15} A^{1/3}$ m where A is the mass number

Effective 'size' of a 10 GeV proton estimated from Heisenberg's uncertainty principle: $\Delta x \approx \frac{h}{2\pi p} = \frac{h}{2\pi \gamma m_p v} = 0.02 \times 10^{-15}$ m

Incident proton as a discrete, very small particle interacting with the individual nucleons within the nucleus

# of interacting nucleons = #of nucleons along the LoS through the nucleus. E.g. a proton crossing an N or O interacts, on average, with about $15^{1/3} = 2.5$ nucleons. A model for the nuclear interactions sees the incident proton undergoing multiple scattering within the nucleus, described by the following rules:

1. The proton interacts strongly with an individual nucleon: in the collision π^+, π^- & π^0 are the main products. Strange particles may also be produced and occasionally antinucleons as well.

2. In the centre of momentum ref. frame of the p+nucleon encounter, pions emerge mostly in the forward & backward directions but they may have lateral components of momentum of $p_\perp \approx 100-200$ MeV c^{-1}

Spallation (2)

3. Nucleons & pions involved in the strong interactions all possess very high forward momentum through the lab. ref. frame: hence the products of the interaction are high energy particles.

4. Each secondary particle can have another collision inside the same nucleus, provided the initial collision occurred sufficiently close to the 'front edge' of the nucleus. Thus, a mini-nucleonic cascade can be initiated inside the nucleus.

5. Only 1 or 2 nucleons are involved the nuclear interaction with the high energy particle: they are generally removed from the nucleus leaving it in a highly excited state.

   (argument for nuclear energy levels, not considered here)

Spallation (3)

No guarantee of a stable resulting nucleus: a variety of different outcomes may come about.

Often several nuclear fragments are evaporated from the nucleus. These are called spallation fragments.

They are important in the context of the origin of the light elements in the cosmic rays.

Fragments emitted in the ref. frame of the residual nucleus which is not given much forward momentum in the nuclear collision, virtually all of it going into tearing out the nucleons which interact with the high energy particle. Therefore, these spallation fragments are emitted more or less isotropically in the laboratory frame of reference. Neutrons are also evaporated from the ravished nucleus and other neutrons may be released from the spallation fragments. We recall that, for light nuclei, any imbalance between the numbers of neutrons and protons is fatal. In high energy collisions, the pions are concentrated in a rather narrow cone, the width of which is some measure of the energy of the incoming high energy particle.

These processes are summarised diagrammatically in Fig. 10.1. (Longair), shown two slides back

Spallation: fragmentation of heavy CR nuclei via interaction with nuclei (in atoms/molecules)

- ~60% "native" Crs, (primaries)
- ~40% "fragmented" (secondaries)

The frequency of these interactions is severely dependent on the (ISM/IGM) density

Spallation may produce unstable (radioactive) isotopes, very useful to trace/characterize this process

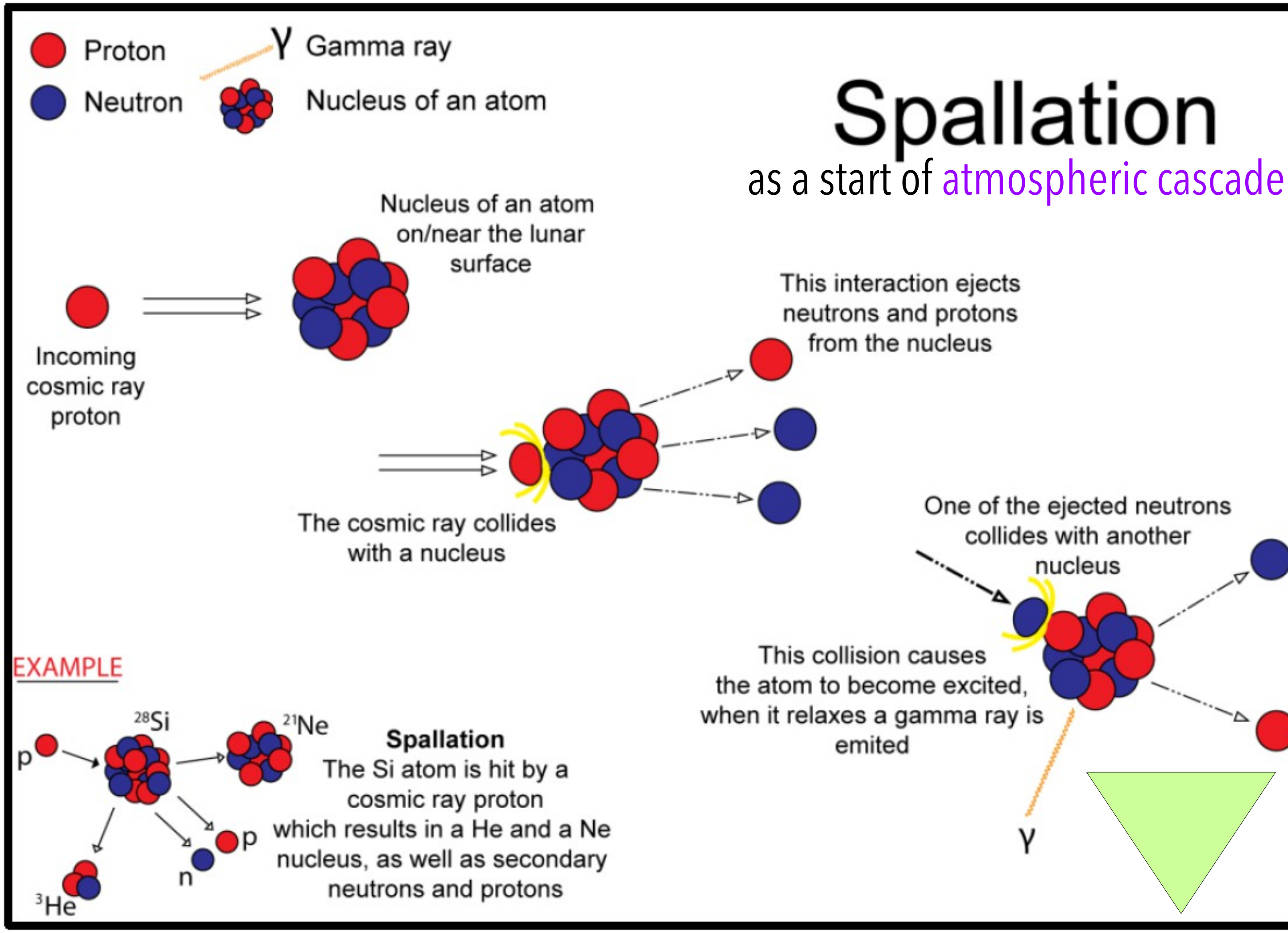


Figure 4: Schematic image illustrating the spallation reaction of an incoming cosmic ray proton. Example shows the spallation reaction that produces cosmogenic ^{21}Ne.

Curran, 2017, PhD thesis

⇒The cross section of the various elements increases with the (atomic) mass number (e.g. $\sigma_{Fe} > \sigma_{O} > \sigma_{He}$)

Primary CR are mostly stable nuclei, but spallation may create unstable nucleons

The depleted nucleon(s) may be unstable.

Examples $\,{}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^- + \bar{\nu}_e \qquad (\beta^- \text{ decay})$

$\,{}^{18}_{9}F \rightarrow {}^{18}_{8}O + e^+ + \nu_e \qquad (\beta^+ \text{ decay, or electronic capture: } p + e^- \rightarrow n + \nu_e)$

traces of the only unstable Fe nuclei: $\,{}^{60}_{26}Fe \rightarrow {}^{60}_{27}Co + e^- + \bar{\nu}_e \qquad (\beta^- \text{ decay})$

In SNR decay of ${}^{56}_{28}Ni$:

$${}^{56}_{28}Ni \rightarrow {}^{56}_{27}Co + e^+ + \nu_e \qquad (\beta^+ \text{ decay, } \tau \sim 6.1 \text{ days})$$

$${}^{56}_{27}Co \rightarrow {}^{56}_{26}Fe + e^+ + \nu_e \qquad (\beta^+ \text{ decay, } \tau \sim 77.2 \text{ days})$$

H field in our Galaxy can confine particles up to a few 10^{15} eV

If lifetime exceeds the Galaxy crossing time, particles can be redistributed and get isotropy

Upper limits to anisotropy can be determined from observations.

$\Rightarrow$ Low energies have high particle fluxes then better limits

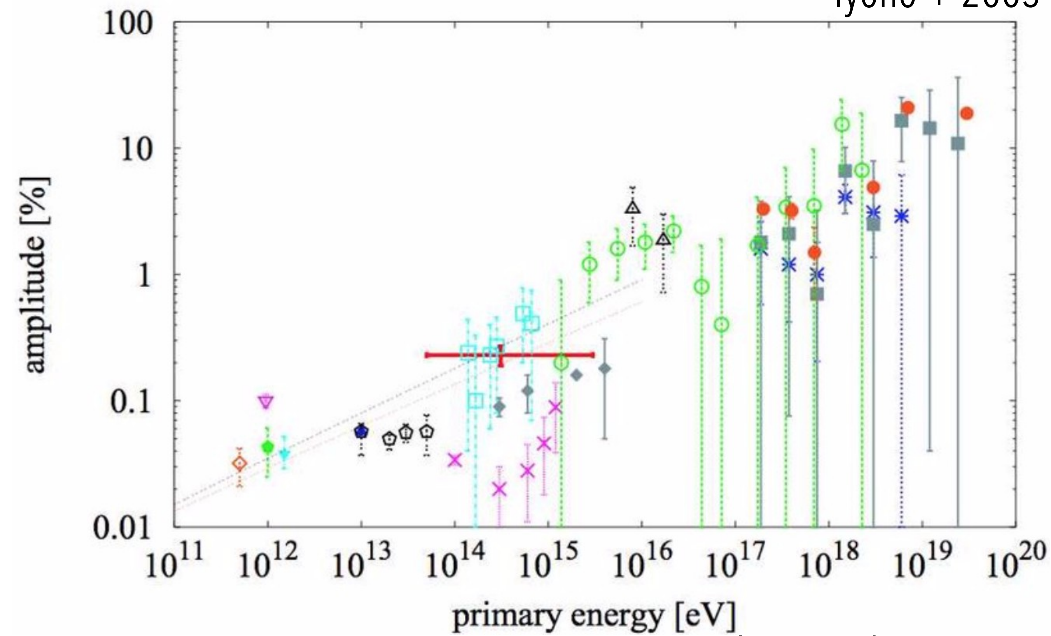
From radioactive isotopes (${}^{14}_{6}C \rightarrow 10^3 - 10^4$ yr ; ${}^{40}K \rightarrow 10^7 - 10^9$ yr)

$$@ \quad E < 10^{12}\,\mathrm{eV} \quad \rightarrow \quad \frac{\Delta F}{F} < 3\cdot 10^{-4}$$

$$@ \quad 10^{12} < E < 10^{16}\,\mathrm{eV} \quad \rightarrow \quad \frac{\Delta F}{F} < 10^{-2}$$

$$@ \quad E > 10^{16}\,\mathrm{eV} \quad \rightarrow \quad \frac{\Delta F}{F} < \text{??? low statistics!}$$

Iyono + 2005



AbuZayyad +, 2019

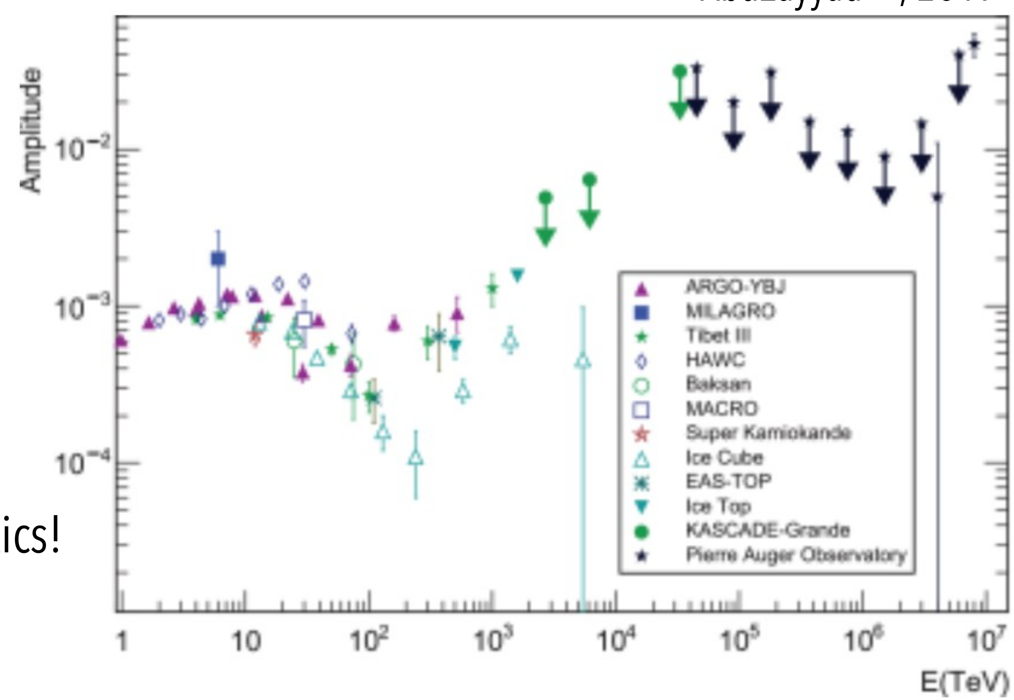


Figure 2: Large-scale cosmic-ray anisotropy: amplitude

Electronic component (1)

- Energy density: 0.001 – 0.01 eV cm $^{-3}$

- Direct measurements from satellites and balloons

- Indirect measurements:

→ *Synchrotron (radio)*
→ *Inverse Compton (X and γ / rays)*
→ *Relativistic bremsstrahlung (γ / rays)*

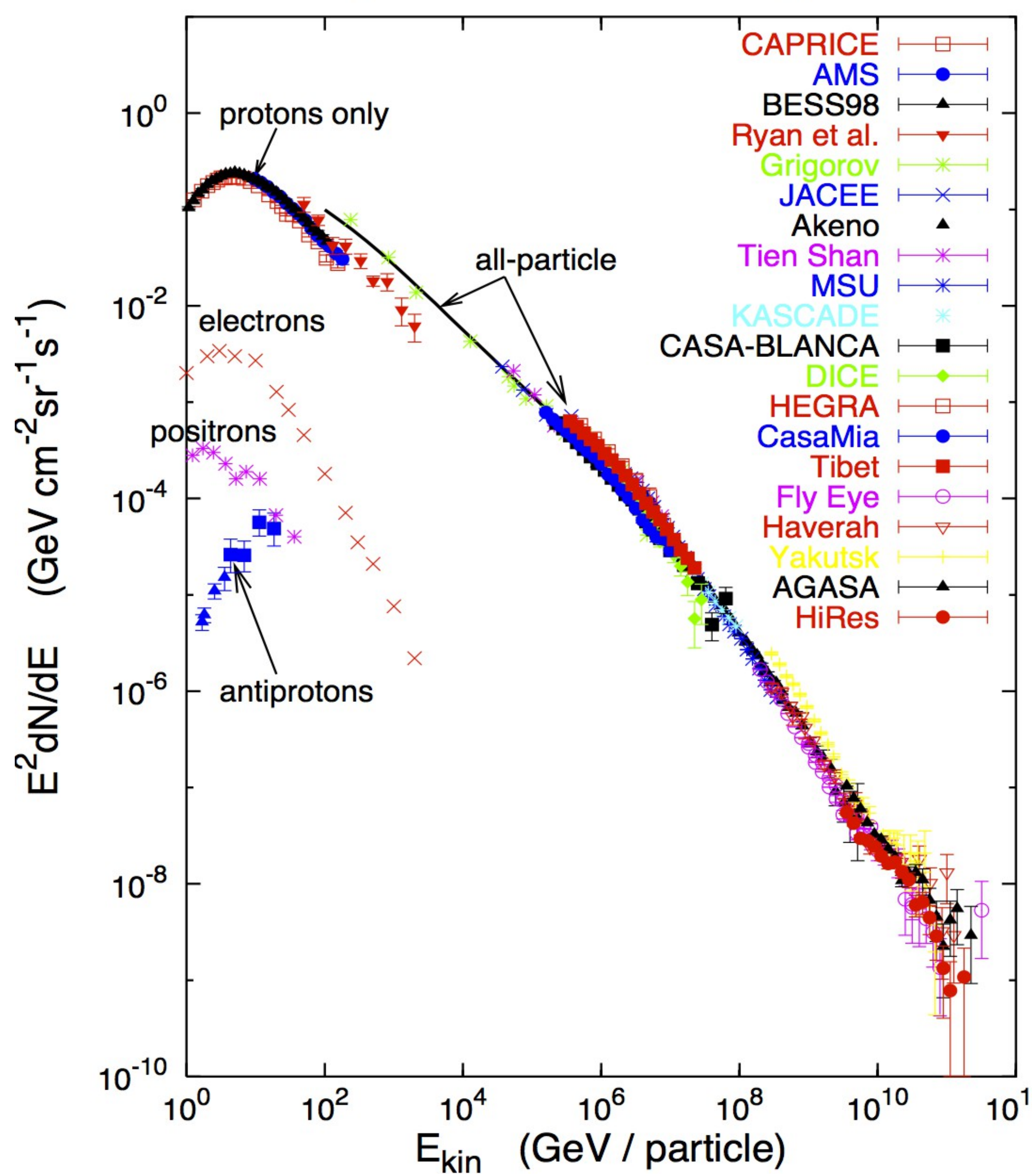
- Further losses due to ionization

CR electrons + positrons:
Fraction of positrons (i.e. secondaries) : 0.2 @ <1 Gev,
0.1 @ 1 Gev,
0.05 @ 5-20 Gev,

Electronic component (2)

- Direct counts around a few GeV, influenced from solar wind (activity).
- Problems with normalization between different experiments.
- Steeper than nucleons (~3.3 .vs. 2.7)
- Positrons belong to this component
- Energy losses are limiting the lifetime of these light particles

Energies and rates of the cosmic-ray particles



Electronic component (3)

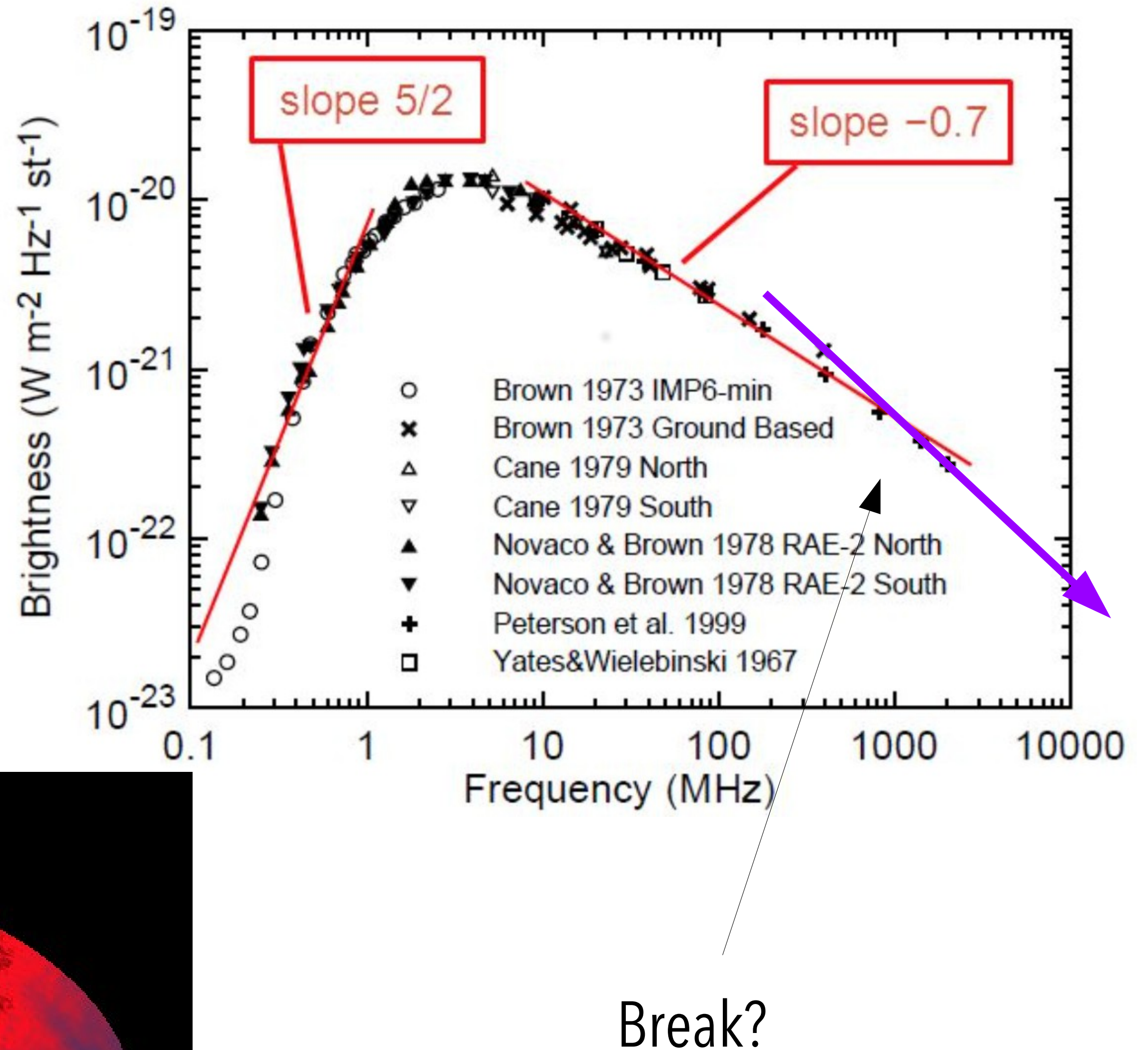
- Synchrotron emission in galactic coordinates: function of electron energy and H
- Slope 0.7, steepens to 0.9-1.0 above 0.4 GHz

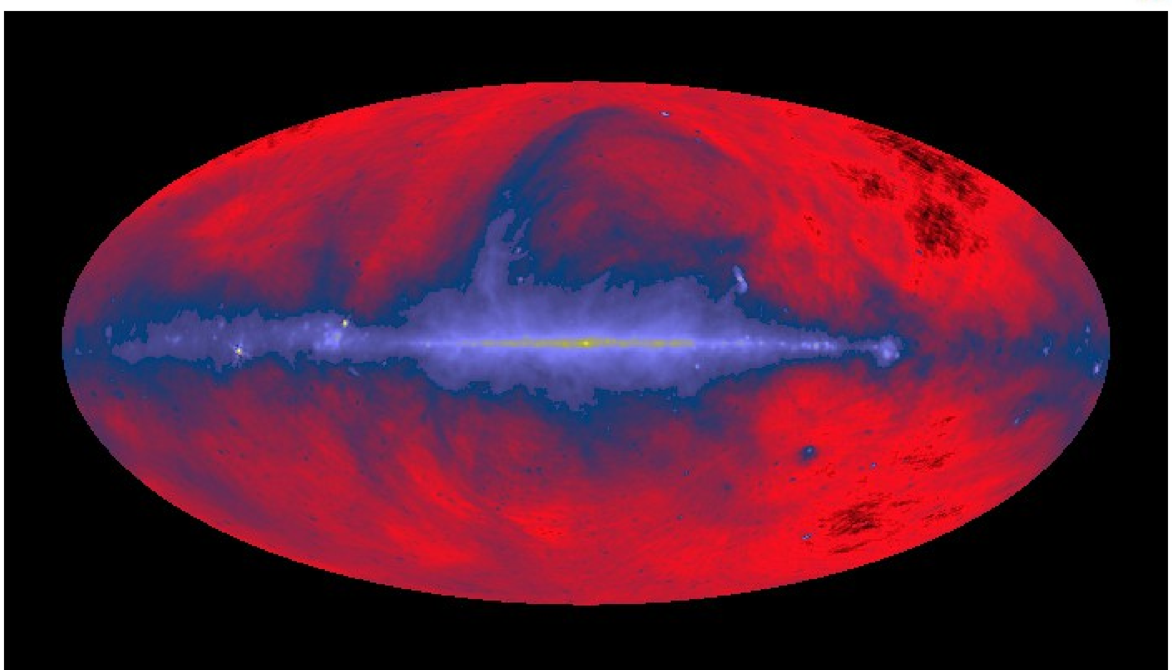
$$F_{el}(E) = K_2 \, B(\nu_{oss}) \, \nu_{oss}^{-1/2} H_{\perp}^{-1/2}$$

$F_{el}(E)$ = electron flux at a given energy E

K_2 dependent on the thickness of the plasma

Result dependent on the H field structure





Electronic component (4) & their radiative lifetime

From relativistic bremsstrahlung $(2\,\mathrm{MeV} < E < 70\,\mathrm{MeV})$

$$F_{el}(E(\mathrm{Gev})) = \frac{c \cdot B_{ph}(E(\mathrm{Gev})) \cdot (\delta - 1)}{10^{-15}\, n_N\, l}$$

Measurements of $B_{ph}(E(\mathrm{Gev}))$ made within our galaxy with gamma ray satellites

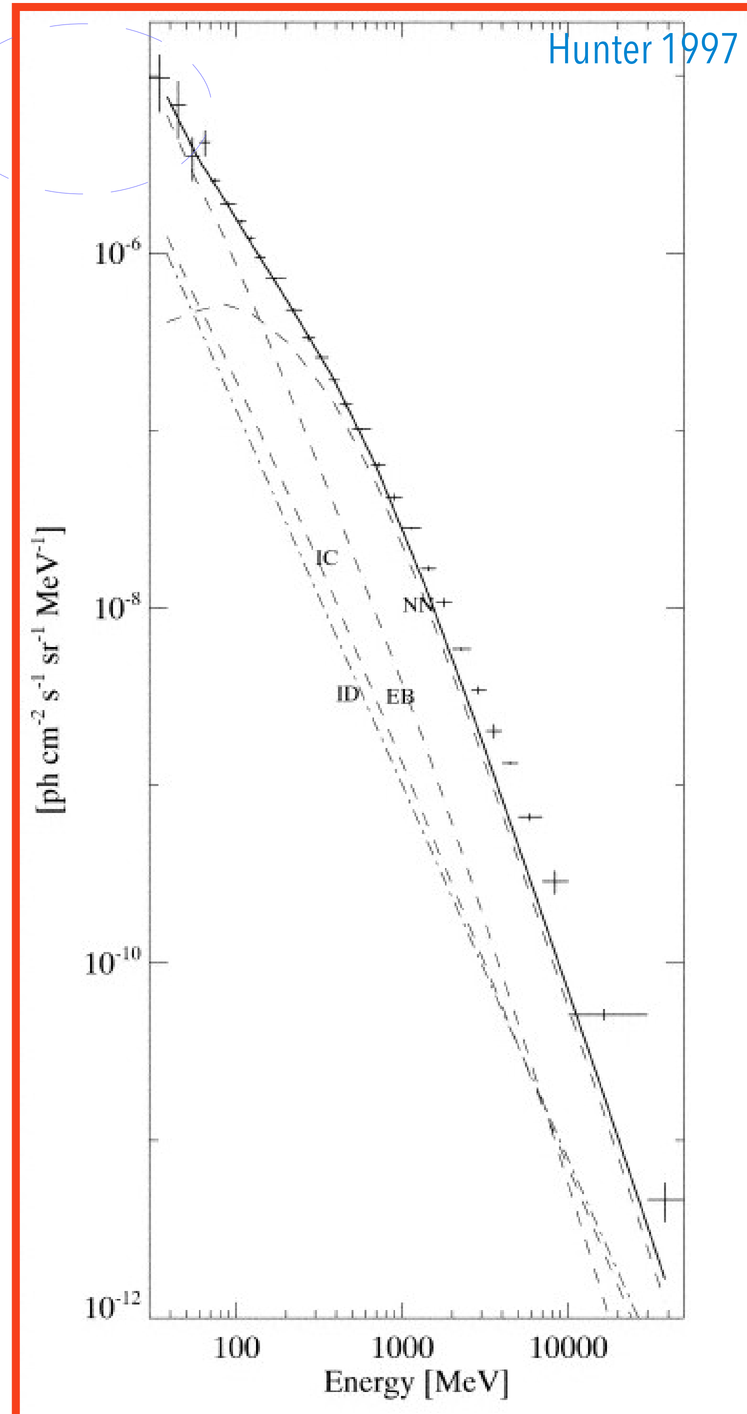
Let's consider IC of relativistic electrons with CMB photons $(E < 30\,\mathrm{MeV})$ (and their synchrotron emission as well)

Their radiative lifetime is

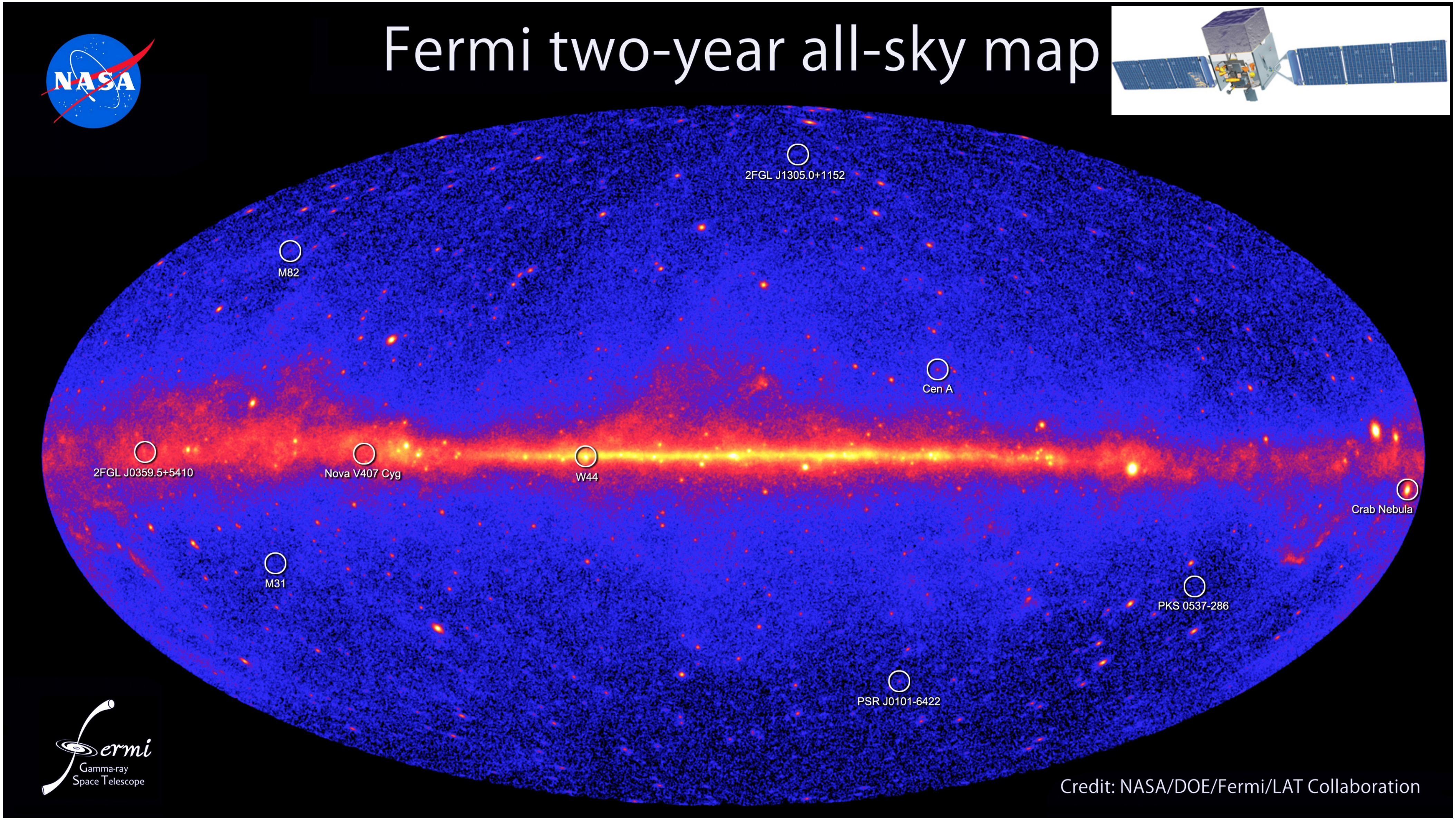
$$\tau_{el} \le \frac{3 \cdot 10^{8}}{H^2/8\pi + U_{rad}} \frac{1}{E} \le 10^{7}\ \mathrm{yr}$$

They could travel a few Mpc! (the same as nucleons)

Consequences on their origin/refurbishment



γ — ray Photons



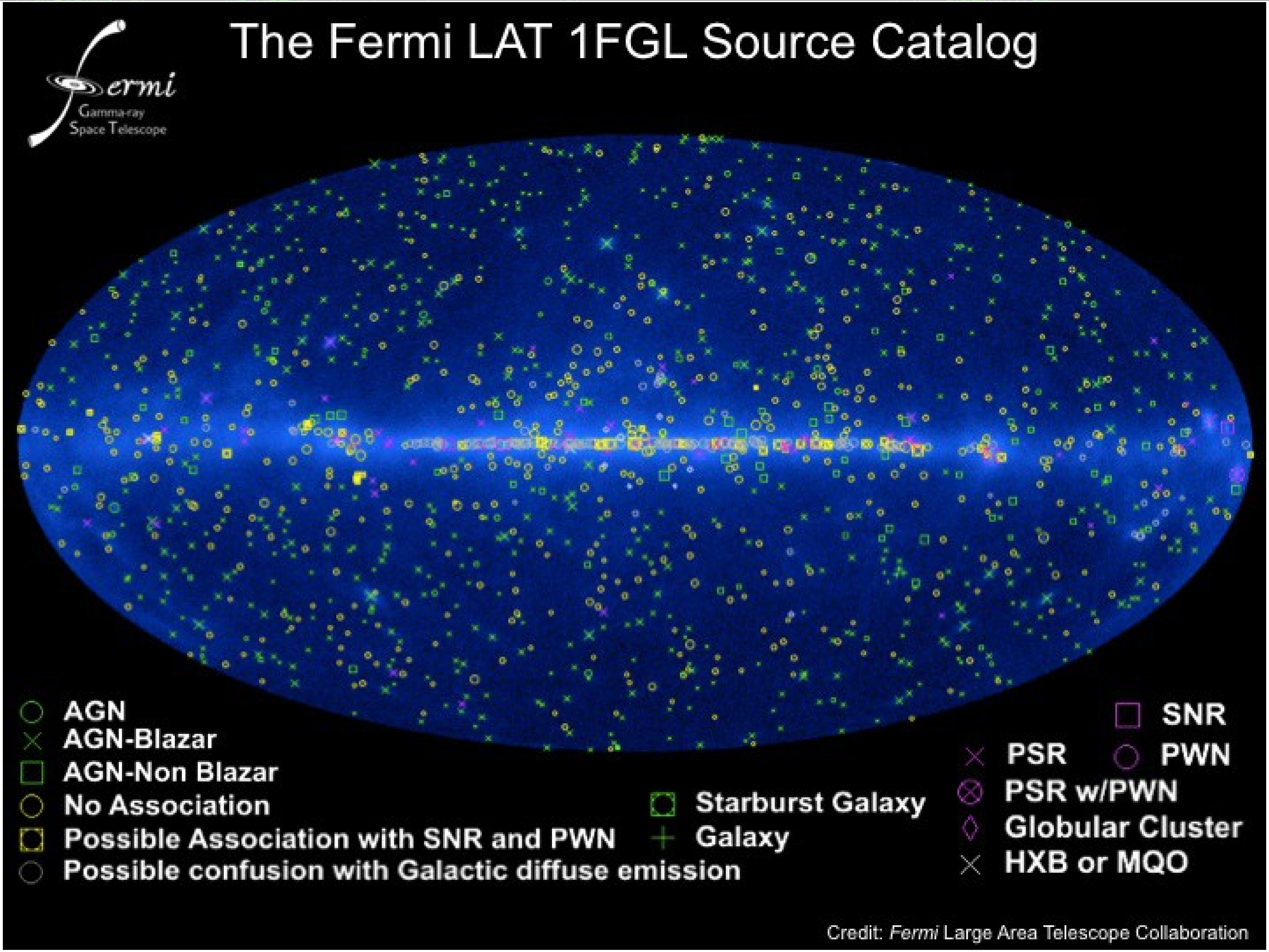
Large Area Telescope (LAT): (20 MeV to 300 GeV) whole sky image

$\Longrightarrow$ Diffuse emission traces the distribution of matter in the Galactic Plane

+Gamma-ray Burst Monitor (GBM) : (8 keV to 40 MeV)

Photonic component: Point sources above the galactic plane are extragalactic objects

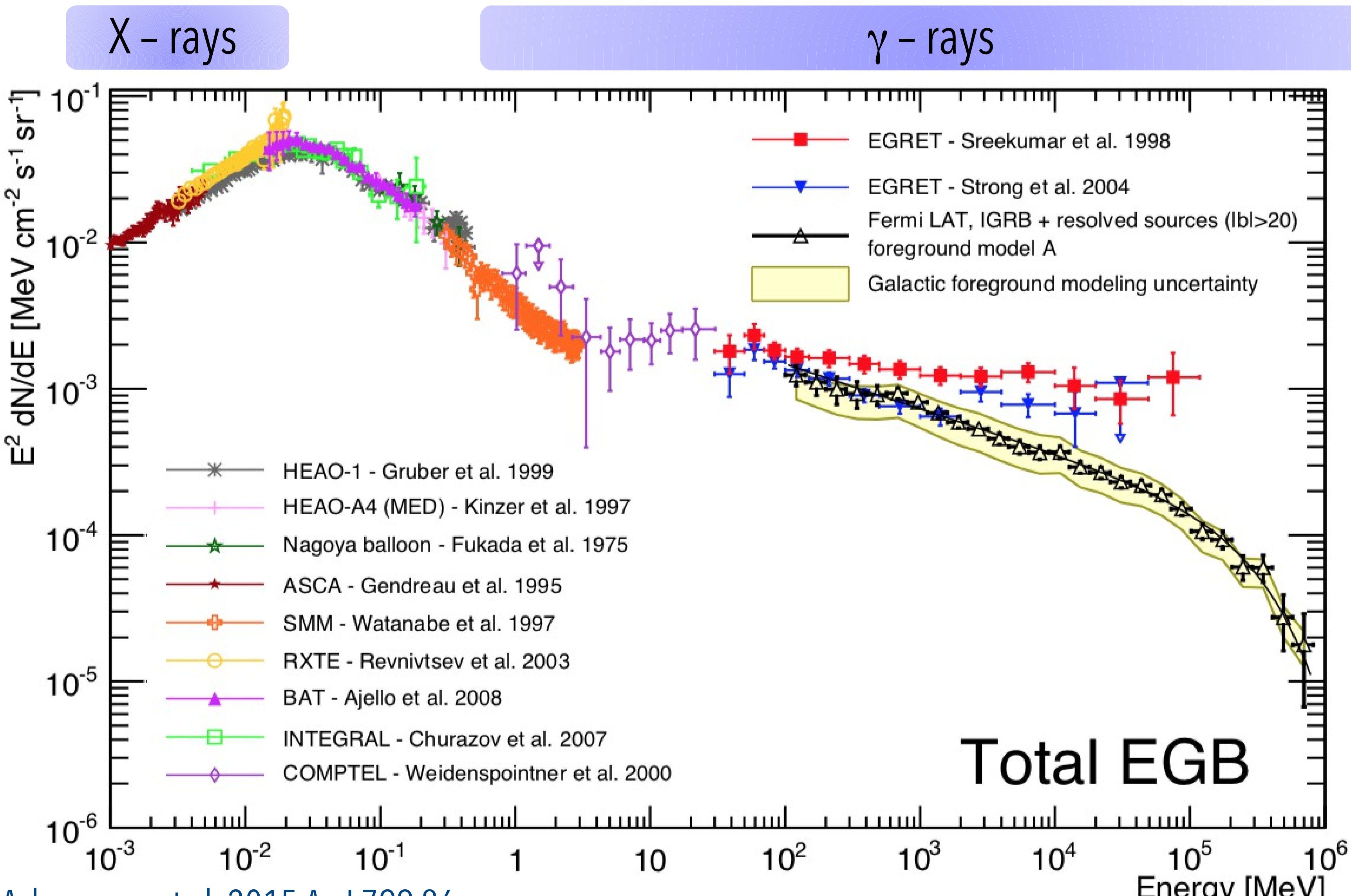
Extended sources on the galactic plane are SNR



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/4yr_catalog/3FGL-table/#aitoff

Photonic component: (energy) spectrum of the Extragalactic Gamma-ray Background (EGB)

Once the emission from individual objects and from the Milky Way has been removed, this is what is left over



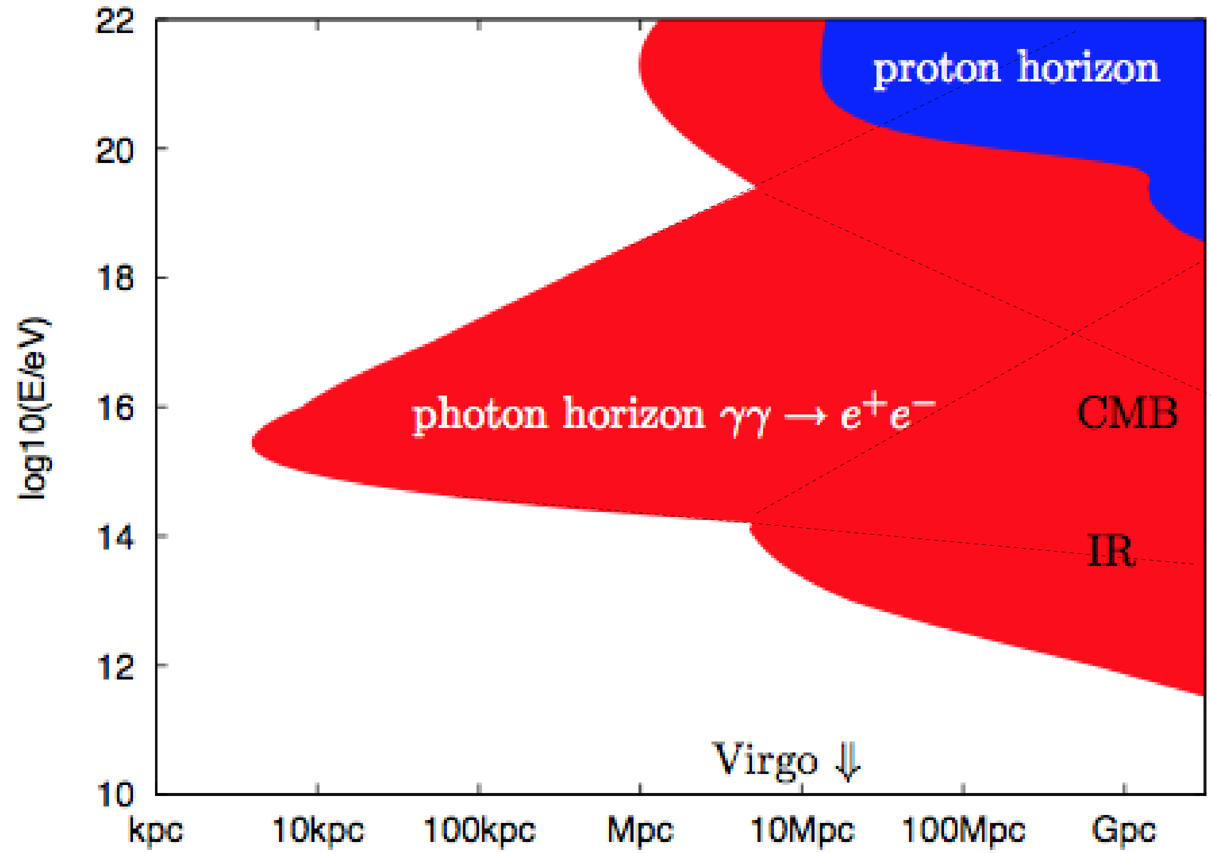
Ackermann et al. 2015 ApJ 799 86

Photonic component horizon $\gamma\gamma \rightarrow e^+ e^-$

$E = \gamma$-ray photon energy

$\epsilon =$ soft photon energy

Photon-photon scattering and pair production if $E\epsilon > (m_e c^2)^2$



If $\beta = \sqrt{1 - \frac{(m_e c^2)^2}{(E\epsilon)}}$ (Heitler 1960)

the cross section is

$$\sigma(E,\epsilon) = 1.25 \cdot 10^{-25} (1-\beta^2) \left[2\beta(\beta^2 - 2) + (3 - \beta^4) \ln\left(\frac{1+\beta}{1-\beta}\right) \right] \text{cm}^2$$

The efficiency of the $\gamma - \gamma$ interaction is determined by the low energy photon density

$\Rightarrow$ Strongly dependent on the number density of field photons

In an analogous way, also particles have horizons: e.g. protons

$p + \gamma \rightarrow \pi^+ + \pi^- + \pi^0$

Let's consider a fluid/plasma made of all the (diffuse) matter in the Milky Way

For a system in equilibrium the full expression of the Virial Theorem is

$$2K + 3(\Gamma - 1)U + M + W_{CR} + W = 0$$

where: $K = $ kinetic energy; $\Gamma = c_p/c_v$; $U = $ thermal energy;

$$M = \frac{H^2 V}{8\pi} = \text{magnetic energy}; \quad W = \text{potential energy (grav.; only term } < 0)$$

In the MW: H is ~uniform, aligned to the galactic plane

Let's consider an isothermal gas, with $\rho(z)$ [z is the height wrt the galactic plane], $\rho u^2 \rightarrow$ pressure (u mean quadratic velocity along z, costant), $g(z)$ acceleration of gravity, $P_{CR} \rightarrow$ CR pressure.

Barometric equilibrium per unit volume:

$$\frac{d}{dz}\left(\rho u^2 + \frac{H^2}{8\pi} + P_{CR}\right) = -\rho(z) \cdot g(z)$$

Hydrostatics (2)

Let's write $\frac{H^2}{8\pi} = \alpha \rho u^2$ and $P_{CR} = \beta \rho u^2$

Barometric equilibrium per unit volume: $$\frac{1}{\rho}\frac{d\rho}{dz} = -\frac{g(z)}{u^2(1+\alpha+\beta)}$$

Solution: $$\rho(z) = \rho_0 d^{-\frac{z}{\Lambda}}$$

Where $\Lambda \approx u^2 \frac{(1+\alpha+\beta)}{\langle g \rangle}$ is a length scale where $\rho(z) = \rho e^{-1}$

From measurements of $\Lambda, u, \langle g \rangle$ we get $\alpha + \beta \sim 1$

$\rightarrow$ Namely, equilibrium is achieved if the gas pressure equals $P_{CR} + P_H$

In case P_{CR} is that measured in the solar system, $H_\perp$ must be $\sim 5 \mu G$

Let's consider the energy density of CR as observed at Earth

$$w_{CR} \sim 1\,\mathrm{eV\,cm^{-3}} = 1.6\cdot 10^{-12}\,\mathrm{erg\,cm^{-3}} \qquad (**)$$

$\tau_c \sim 2-200\,\mathrm{Myr}$ confinement time (use 20)

$V_{MW} \sim 180\,\mathrm{kpc}^3$ estimated volume of the Milky Way

$$W_{CR} = \frac{w_{CR} V_{MW}}{\tau_c} \approx 2\cdot 10^{40}\ \mathrm{erg\,s^{-1}}$$

In order to have a CR constant flux, replenishment is required

SNR, pulsars and PWN are suitable origin for such refurbishment. Exercise: A SNR releases $\sim 10^{51}$ erg, and if we consider that $\leq \sim 1\%$ is transformed into CRs, we can derive the SN rate

$$\mathrm{SN-Rate} = \frac{0.01\cdot 10^{51}\,\mathrm{erg}}{2\cdot 10^{40}\,\mathrm{erg\,s^{-1}}} = 5\cdot 10^{8}\,\mathrm{s} \simeq 60\ \mathrm{yr} \qquad 3.15\cdot 10^{7}\,\mathrm{sec/yr}$$

but.... UHECRs $(>10^{19}\,\mathrm{eV})$ require more powerful accelerators!

(**) Remember that $U_{CMB} \simeq 0.26\,\mathrm{eV\,cm^{-3}}$ $\quad U_H \approx 0.2\,\mathrm{eV\,cm^{-3}}$ $\quad U_{stars} \approx 0.3\,\mathrm{eV\,cm^{-3}}$

Thermal energy density have to be considered as well

Confinement

Relativistic charged particles travelling in a magnetic field have the following (relativistic) Larmor radius

$$r_{L,rel} = 3.3\times10^{6}\,\frac{\dfrac{\gamma m c^2}{[\mathrm{GeV}]}}{\dfrac{q}{[e]}\;\dfrac{H}{[\mathrm{Gauss}]}}\left(\frac{v}{c}\right)\ \mathrm{cm} \;\rightarrow\; r_{L,rel} = 3.3\times10^{12}\,\frac{\dfrac{\gamma m c^2}{[\mathrm{GeV}]}}{\dfrac{q}{[e]}\;\dfrac{H}{[\mu\mathrm{Gauss}]}}\left(\frac{v}{c}\right)\ \mathrm{cm}$$

Table of radii (in cm) computed in a field of 10 μG $\Rightarrow$

Particle/ /Energy	1 GeV	1 TeV	1 PeV	1 EeV
E – e+, p	3.30×10^{11}	3.30×10^{14}	3.30×10^{17}	3.30×10^{20}
He	1.65×10^{11}	1.65×10^{14}	1.65×10^{17}	1.65×10^{20}
C	5.50×10^{10}	5.50×10^{14}	5.50×10^{16}	5.50×10^{19}
O	4.13×10^{10}	4.13×10^{13}	4.13×10^{16}	4.13×10^{19}
Si	2.26×10^{10}	2.26×10^{13}	2.26×10^{16}	2.26×10^{19}
Ar	1.83×10^{10}	1.83×10^{13}	1.83×10^{16}	1.83×10^{19}
Fe	1.27×10^{10}	1.27×10^{13}	1.27×10^{16}	1.27×10^{19}

$$1\,\mathrm{pc} = 3.089\cdot10^{18}\ \mathrm{cm}$$

Milky Way thin disc scale height $\sim$0.3 kpc

The H field may decrease with density at increasing height

CR origin

A) Galactic origin: if CR are from SN, the energy required is E_{SN}

$$E_{SN} \cdot f_{SN} = 6 \cdot 10^{47} \ \text{erg/yr} \qquad f_{SN} = 1/100 \ \text{yr}^{-1}$$

consequently $E_{SN} \leq \ ? \ \geq 6 \cdot 10^{49} \ \text{erg}$

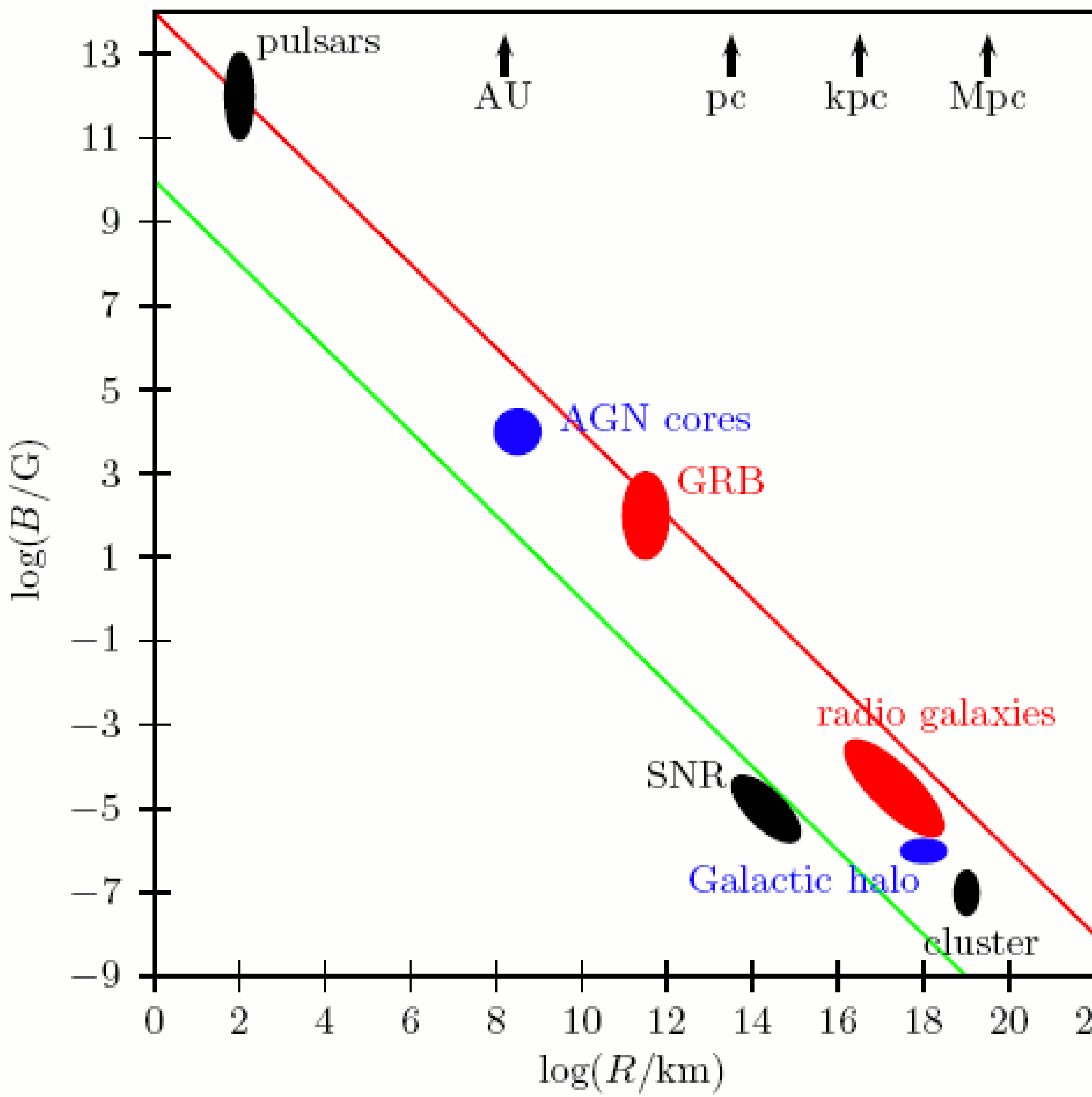
B) Extragalactic origin: Each galaxy should provide

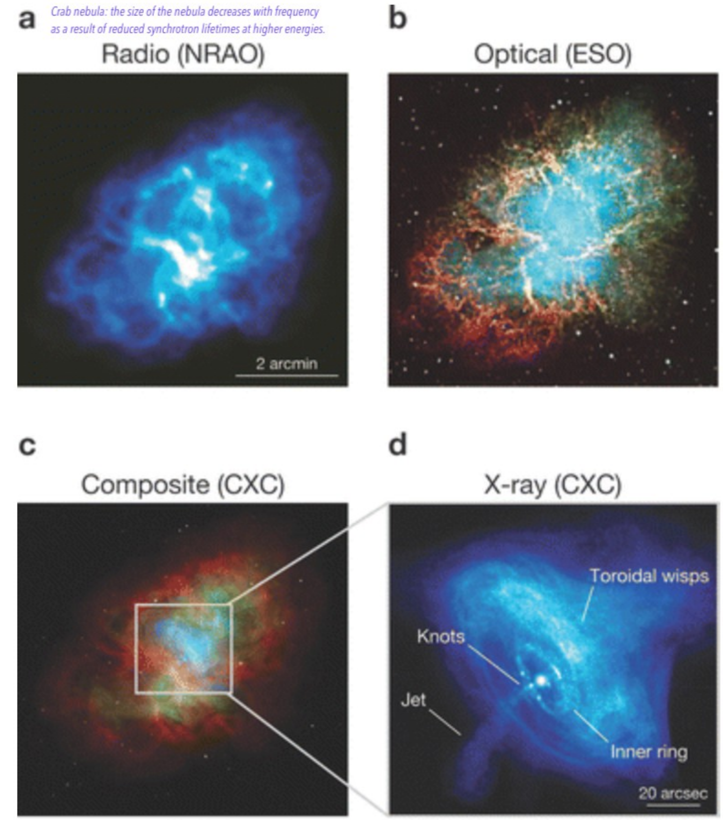
$$u_{CR} \leq 1 \ \text{eV cm}^{-3} \qquad n_{gal} \sim 10^{-2} \ \text{Mpc}^{-3}$$

$$E_{gal} = \frac{u_{CR}}{n_{gal}} = 5 \cdot 10^{63} \text{erg}$$ (about 5% of the mass in galaxies)

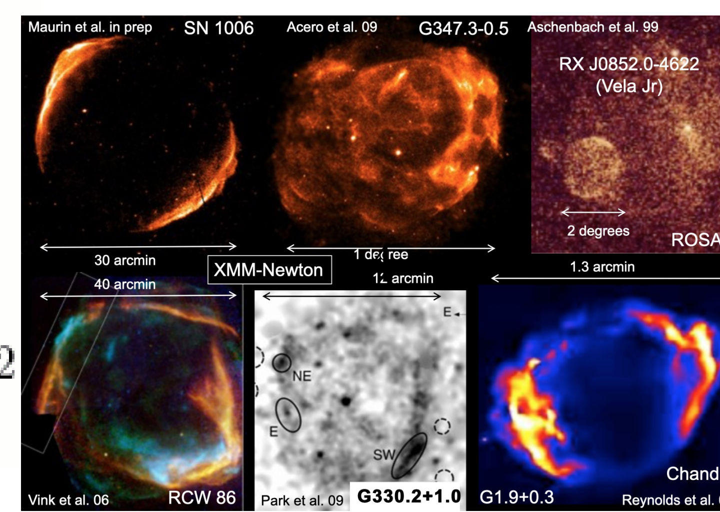
High Energy CRs: $(@ > 10^{19} \text{eV}) \rightarrow \ \gamma r_L > 3\text{kpc}$, confinement is ineffective

Sites of CR origin





Gaensler BM, Slane PO. 2006.
Annu. Rev. Astron. Astrophys. 44:17–47

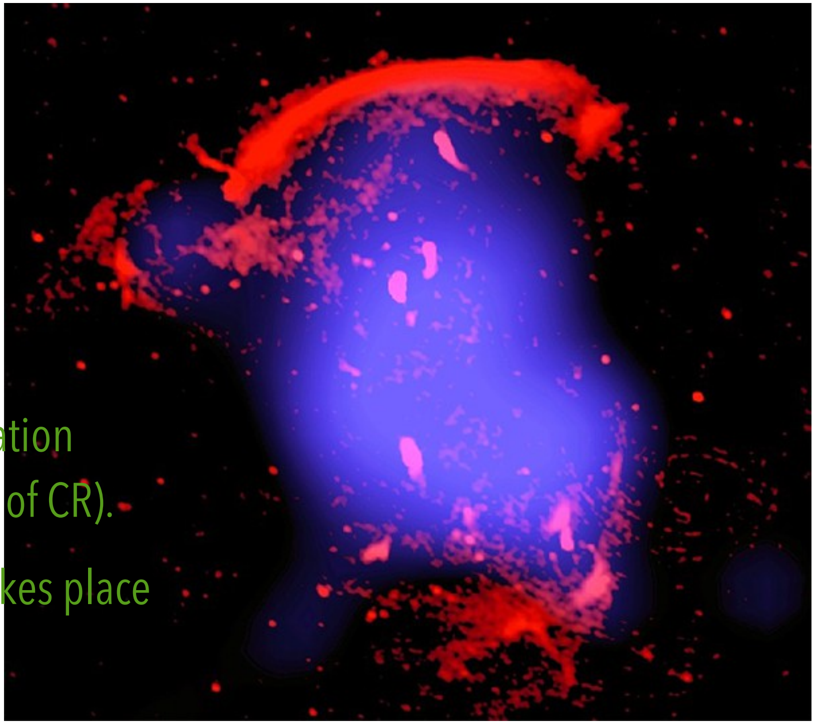


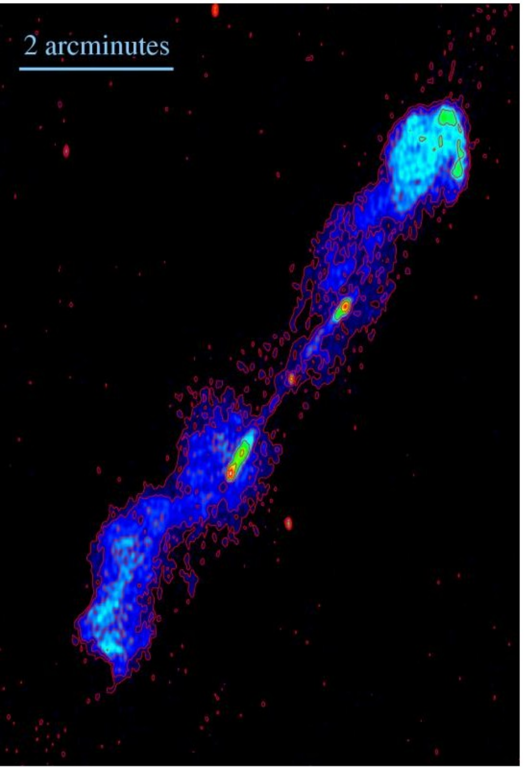
Origin for UHECRs

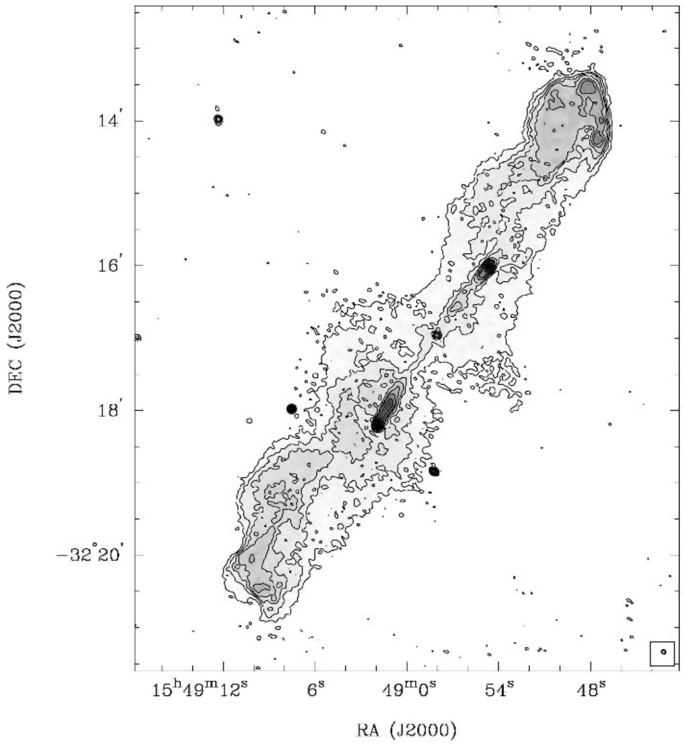
- Are originated in "large accelerators"
- Their trajectories are influenced in a marginal way with respect to lower energies CRs.
- They can travel large distances (nucleons)

Where there are relativistic electrons (e.g. synchrotron emission) the acceleration mechanism should produce also positive charges (the nucleonic component of CR).

Relatively small Mach numbers, but very large regions where acceleration takes place







Top panel: blue is the X-ray bremsstrahlung emission from the hot (10^8K) thermal plasma; red is the synchrotron radio emission. Overall size is a few Mpc

Side panel: both images are the synchrotron radio emission from an individual radio galaxy. Giant radio galaxies are as big as a few Mpc. Tyipical lifetimes are $10^7 - 10^8$ yr
for electrons radiating at ~1 GHz.

Cosmic Rays: Summary

- Nucleons, electrons/positrons & high energy radiation
- Made of primaries and secondaries
- Particle spectrum is a power–law with some features (knee, ankle) between $\sim 10^{9}$ and $\sim 10^{20}$ eV
- Abundances are different with respect to solar $\leftrightarrow$ spallation (which may produce unstable isotopes)
- Consequences on CR lifetime and distance from acceleration site that could be travelled.
- Anisotropy is marginal, may be present at the highest energies (10^{17-20} eV)
- Confinement within out galaxy only for energies below 10^{15} eV
- Energetics needs replenishment with fresh particles
- Both Galactic & Extragalactic sites for acceleration of CRs

2. Scrivere quali delle seguenti affermazioni, relative ai raggi cosmici (CR), sono vere o false, giustificando brevemente la risposta (eventualmente correggendo l'affermazione, qualora ritenuta falsa/inesatta)

A: La radiazione Cherenkov si osserva solo quando un nucleone interagisce con un atomo/molecola in atmosfera;

B: L'attivita' solare influenza il flusso da noi osservabile dei RC;

C: L'emissione di sincrotrone puo' essere utilizzata per valutare la distribuzione dei CR;

D: Le abbondanze osservate tra i nucleoni di CR sono quasi uguali a quelle della materia ordinaria;

E: Solo le supernovae o altri processi (esplosioni) di tipo stellare sono responsabili dei CR osservabili da terra.

04 Nov 2021

Particle (& antiparticle) composition/slope

Hadrons have similar slope (~90% are protons)

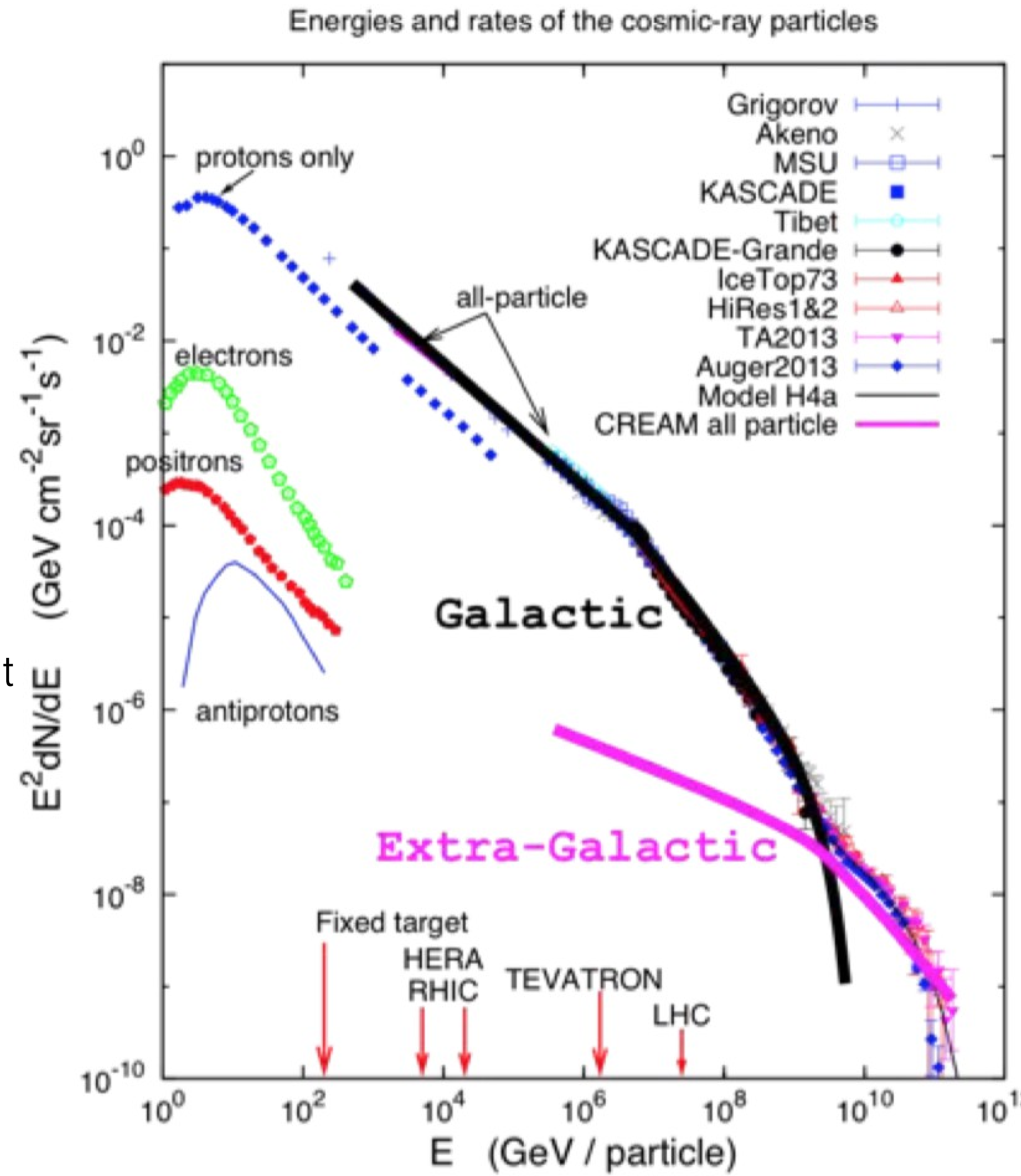
Electrons & positrons have slightly different slopes.

Are primary electrons aged?

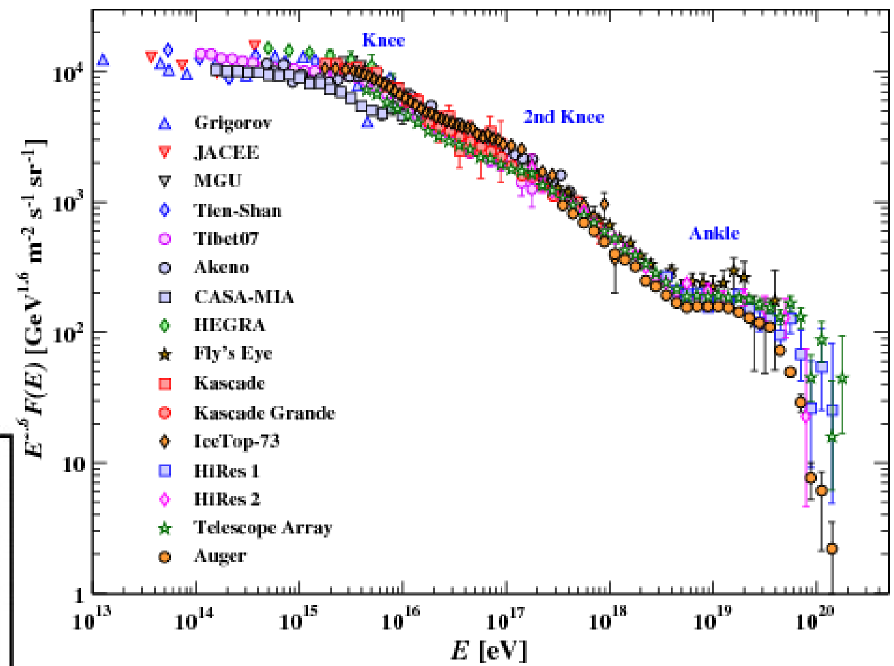
1 GeV electrons (~2000) emit at GHz in

A galactic H field of 10 G

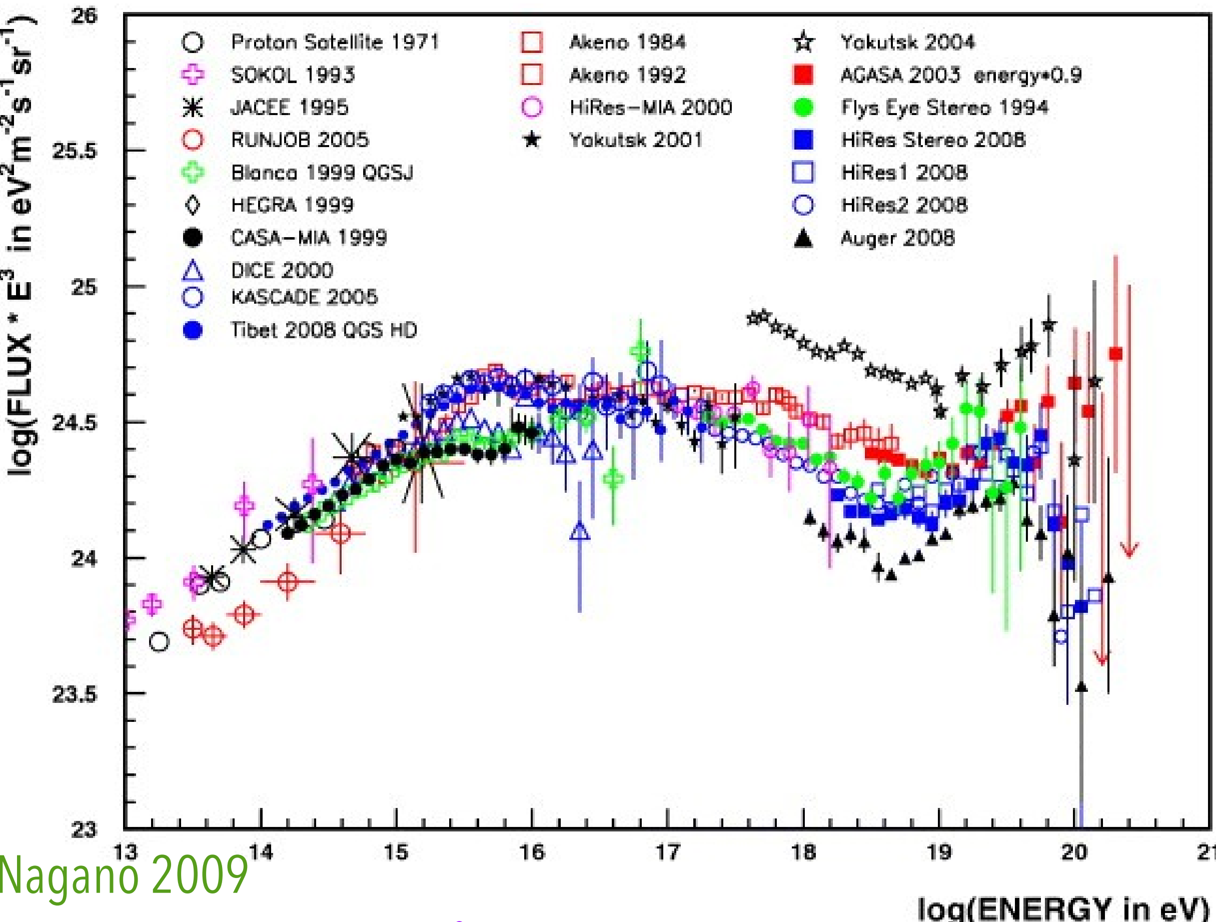
Low energy cut-off in the energy independent of particle type/charge



Highlighting slope changes



Pancheri+ 2017

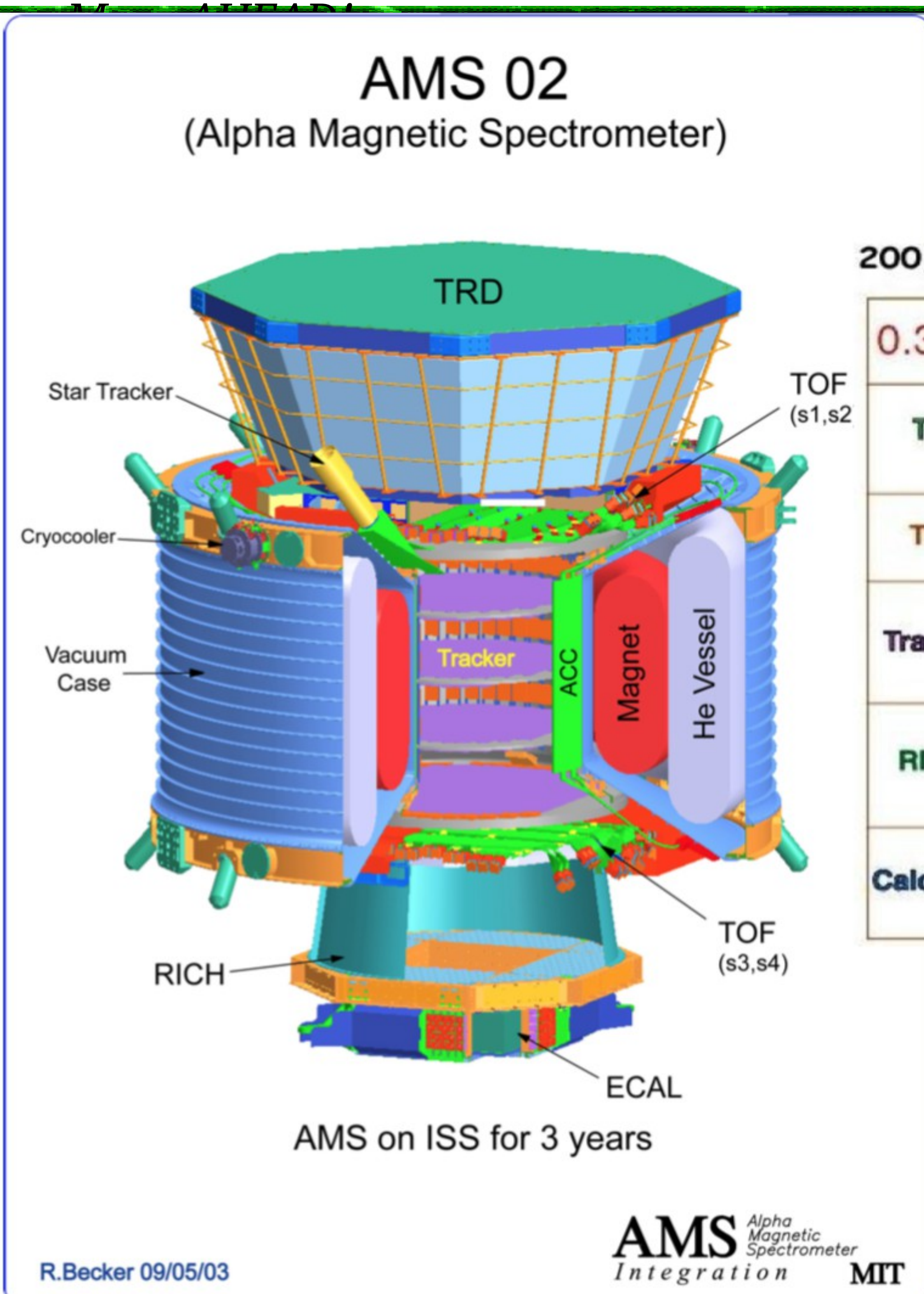


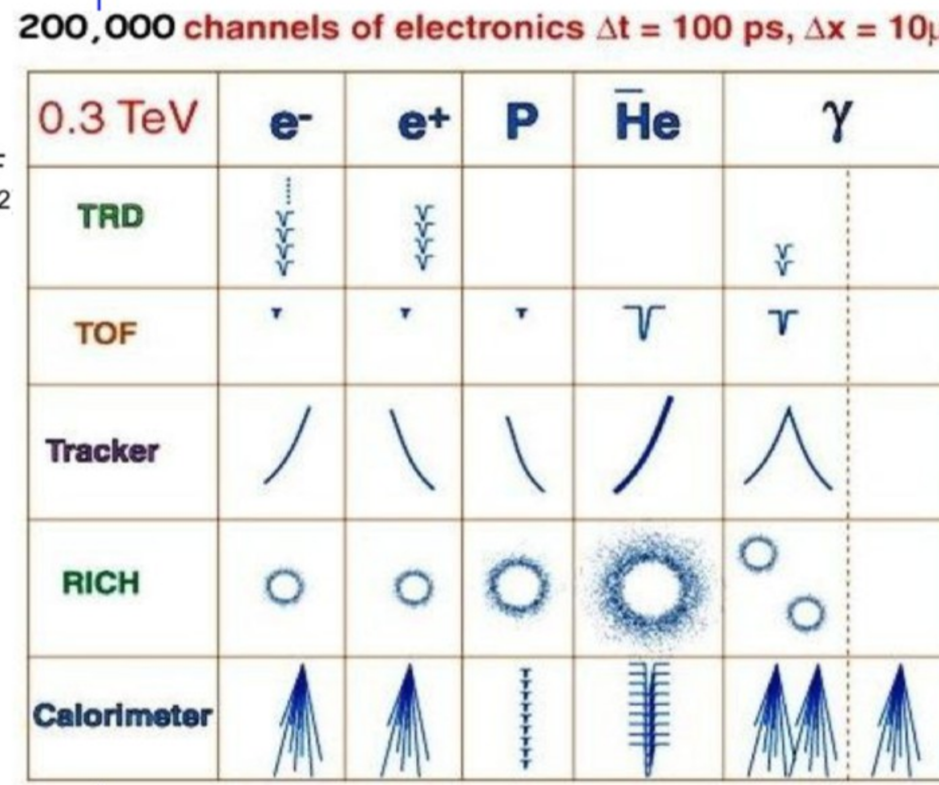
Nagano 2009

Normalized to a slope E^{-3}

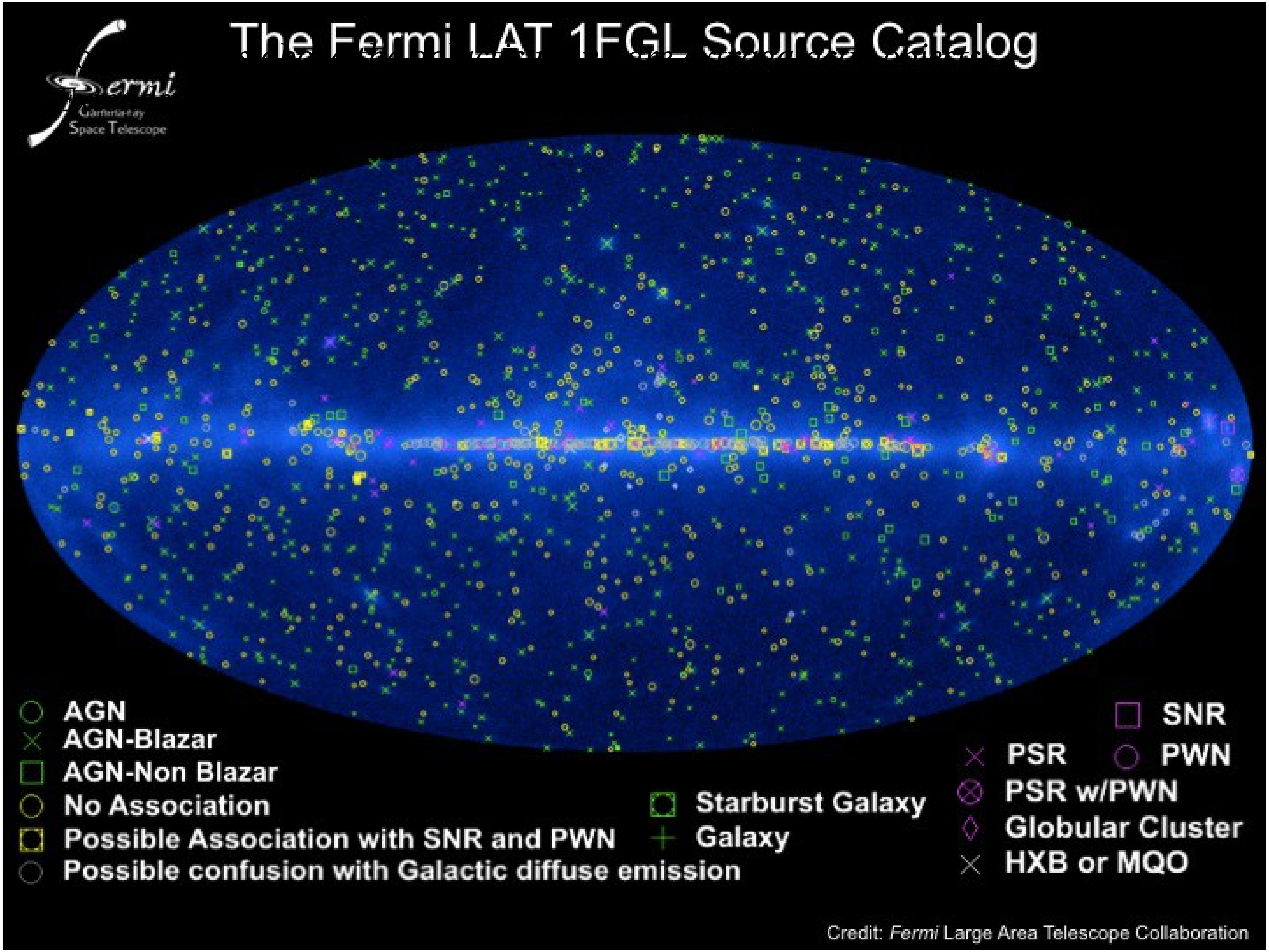
Example of particle detector

AMS on board of the ISS





Photonic component

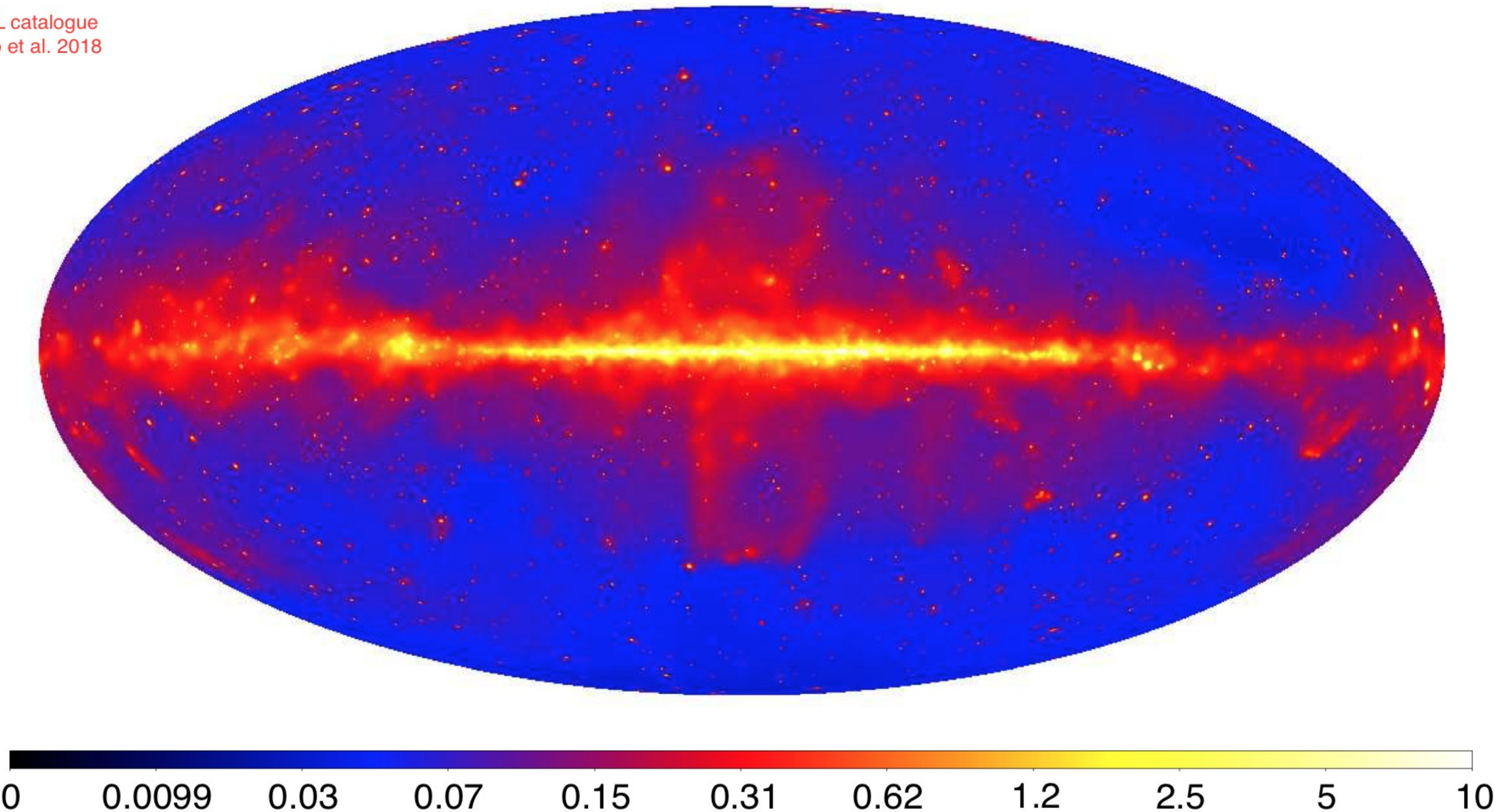


Photonic component

Point sources above the galactic plane are extragalactic objects

Extended sources on the galactic plane are SNR

3FHL catalogue
Ajello et al. 2018



H = Hard

Fig. 1.— Adaptively smoothed *Fermi*-LAT counts map in the 10 GeV–2 TeV band represented in Galactic coordinates and Hammer-Aitoff projection. The image has been smoothed with a Gaussian kernel whose size was varied to achieve a minimum signal-to-noise ratio under the kernel of 2.3. The color scale is logarithmic and the units are counts per $(0.1\ \mathrm{deg})^2$ pixel.