- What are they?

- How we detect them: history and present time

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

- *High energy nuclei with (ultra) relativistic velocities, devoid of any electron*
- *Relativistic electrons (and positrons)*
- *High energy radiation (gamma rays)*

Motion influenced by magnetic fields and medium crossed and energy density of radiation (particles). Radiation is unaffected (except by encounters with other photons)

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

Power-law distribution

Isotropic flux, constant in time $\rightarrow$ origin & refurbishment

Cosmic Rays

– CR are high energy (relativistic) **particles** with a roughly constant flux

– the **primary component** is mostly protons(87-89%), He (12-10%) and heavier nucleons; electrons represent a small fraction (1% or less)

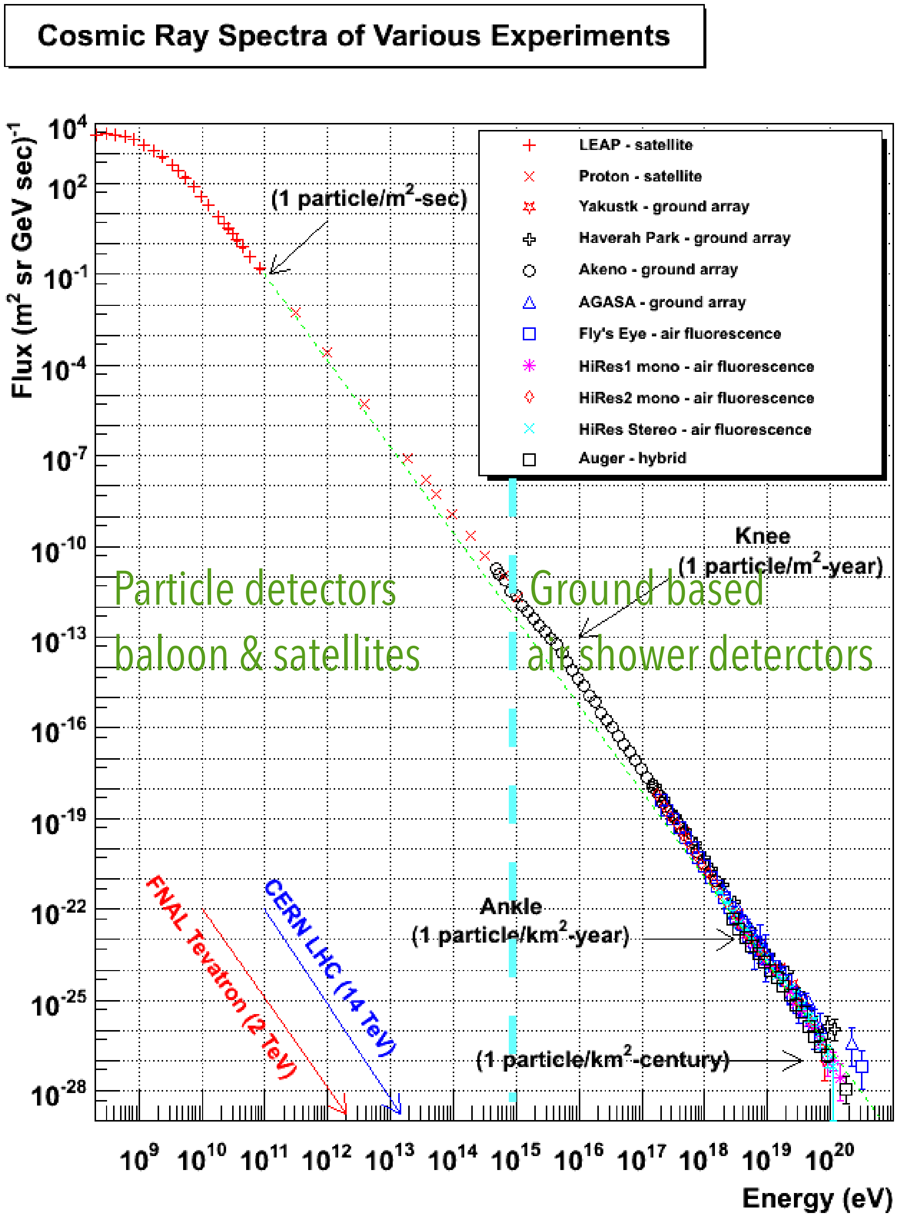
– the **secondary component** is made of particles originated by collision of primary CR particles with nuclei of molecules in the Earth atmosphere; the secondary component is mostly made of muons (μ^+,μ^-), electrons/positrons, neutrinos and photons. They are originated either in the ISM (only photons may reach The Earth), or in the atmosphere, generating (extensive) "air showers"

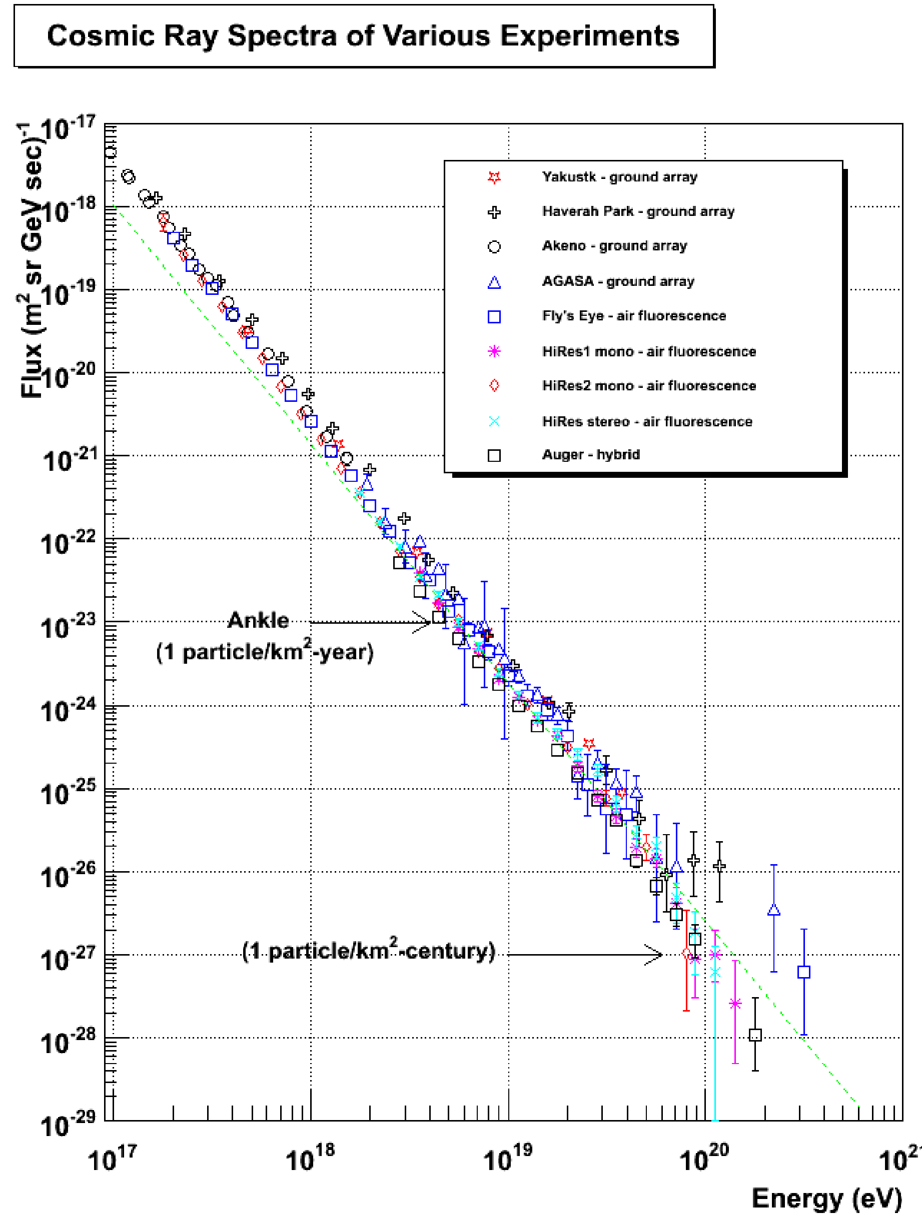
– CR also include high energy **photons**, preserving information on their direction of origin

Simplified 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 particle and chemical environment (i.e. atmospheric). 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 pions and kaons). 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 1950s. This is an important fact used in radiocarbon dating which is used in archeology.


Cosmic Ray Spectra of Various Experiments
Flux (m² sr GeV sec)⁻¹
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m²-sec)
Knee
(1 particle/m²-year)
Particle detectors
baloon & satellites
Ground based
air shower deterctors
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)


Cosmic Ray Spectra of Various Experiments
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Yakustk - ground array
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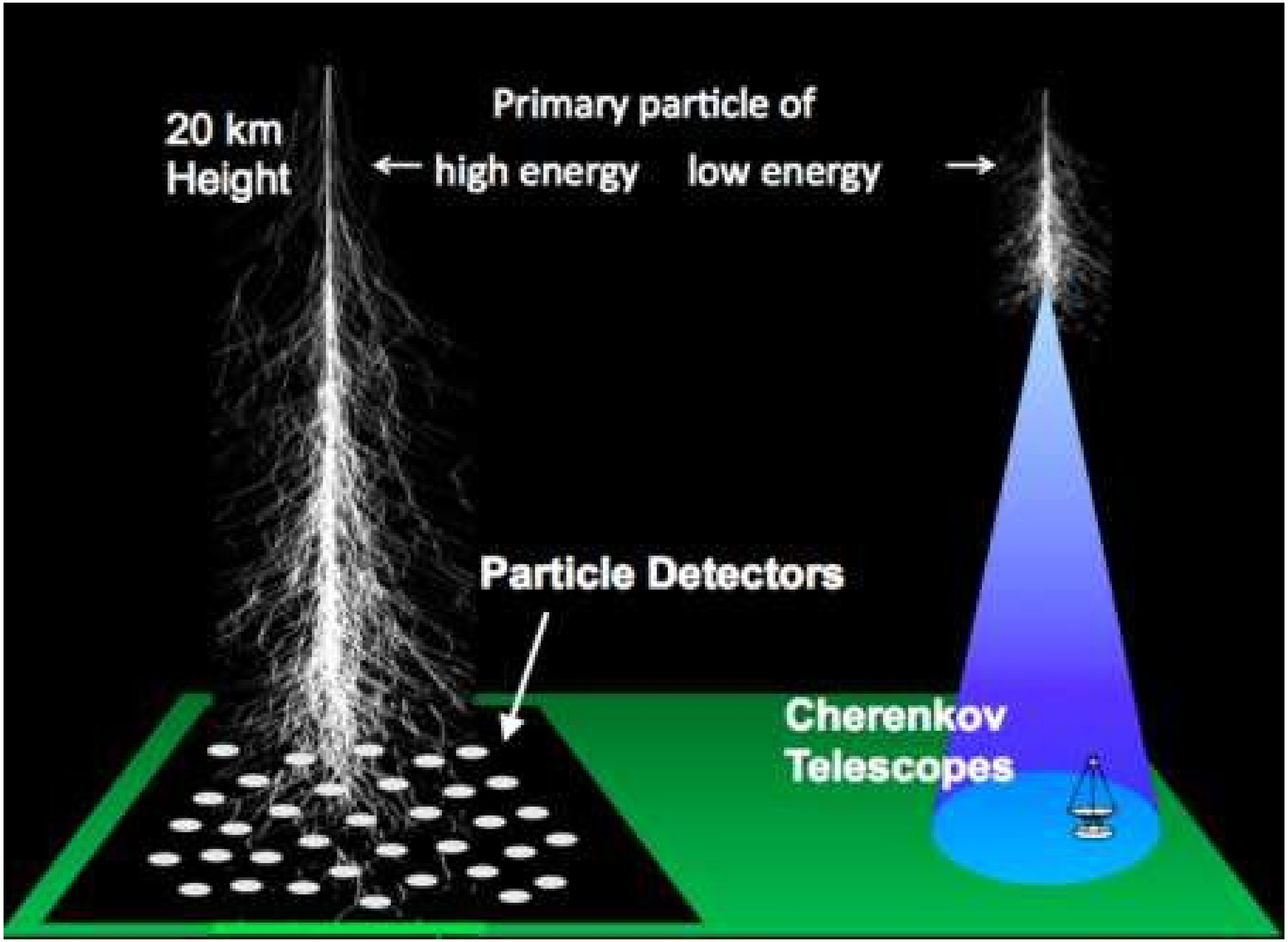
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes stereo - air fluorescence
Auger - hybrid
Ankle
(1 particle/km²-year)
(1 particle/km²-century)

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

- Secondaries via atmospheric showers



When a high-energy CR enters the atmosphere it loses its energy via interactions with the nuclei that make up the air. At high energies these interactions create particles. These new particles go on to create more particles, etc. This multiplication process is known as a particle cascade. This process continues until the average energy per particle drops below about 80 MeV (million electron-volts). At this point the interactions lead to the absorption of particles and the cascade begins to die. This altitude is known as shower maximum. The particle cascade looks like a pancake of relativistic particles traveling through the atmosphere at the speed of light.

Though the number of particles in the pancake may be decreasing, the size of the pancake always grows as the interactions cause the particles to diffuse away from each other.

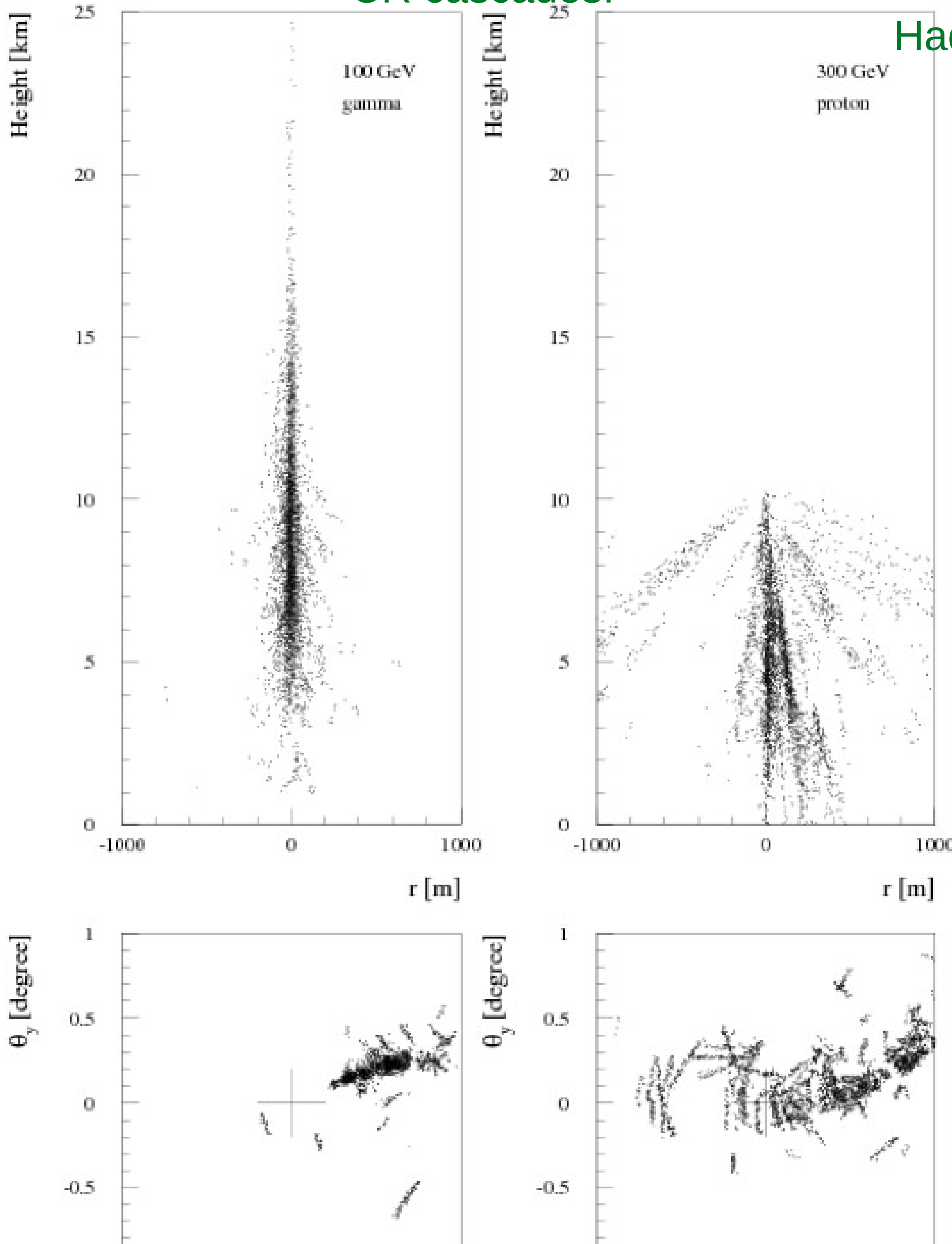
The number of particles starts to increase rapidly as this shower or cascade of particles moves downwards in the atmosphere. On their way and in each interaction the particles loose energy, however, and eventually will not be able to create new particles. After some point, the shower maximum, more particles are stopped than created and the number of shower particles declines. Only a small fraction of the particles usually comes down to the ground. How many actually come down depends on the energy and type of the incident cosmic ray and the ground altitude (sea or mountain level). Actual numbers are subject to large fluctuations.

In fact, from most cosmic rays nothing comes down at all. Because the earth is hit by so many cosmic rays, an area of the size of a hand is still hit by about one particle per second. These secondary cosmic rays constitute about one third of the natural radioactivity.

CR cascades:

Photon

Hadron (p)

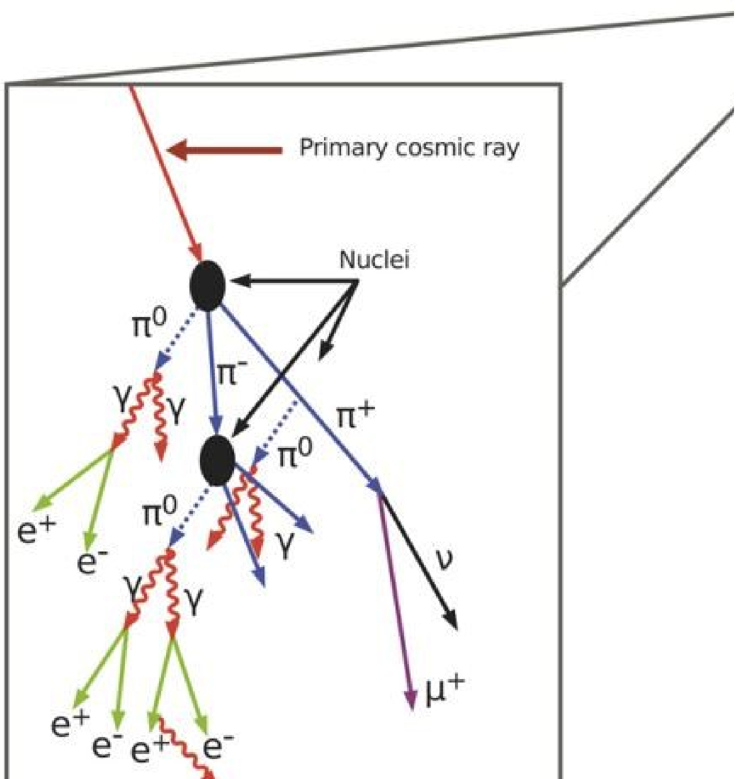


CR air shower: nucleons

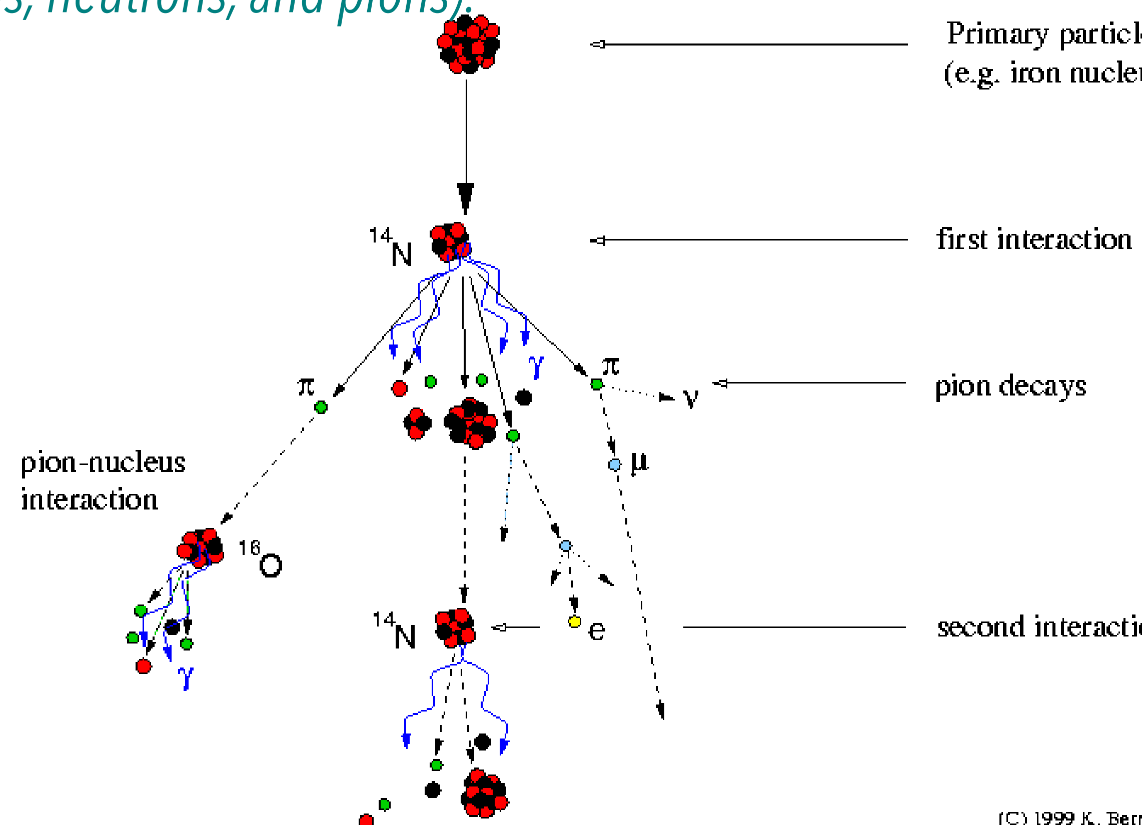
The particle interacts with a particle in the atmosphere

1. *fragmentation and production of π^+, π^-, π^0,*
2. *decay of π^0*
3. *π^+, π^- may decay into μ^+, μ^-, 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).



Development of cosmic-ray air showers

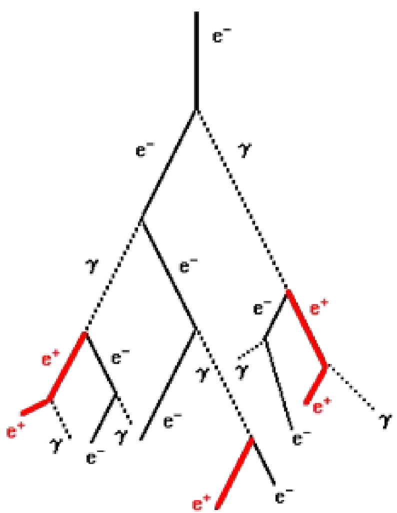


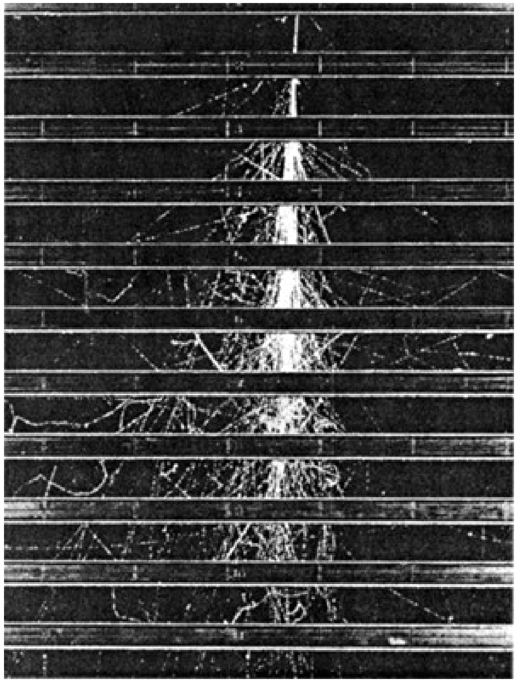
(Air) showers ingredients

Particle	Decay mode	Lifetime ($t_{1/2}$)	Range ($ct_{1/2}$)
γ	-	∞	∞
e-	-	∞	∞
p+	-	∞	∞
n	$n \rightarrow p + e^- + \nu_e$	886s	2.65 x 10 13 cm
μ^-	$\mu^- \rightarrow e^- + \nu_e + \nu_\mu$	2.2 x 10 -6s	659 m
π^-	$\pi^- \rightarrow \mu^- + \nu_\mu$	2.6 x 10 -8 s	780 cm
π^o	$\pi^o \rightarrow 2\ \gamma$	8.4 x 10 -17s	25.1 nm
ν	-	∞	∞

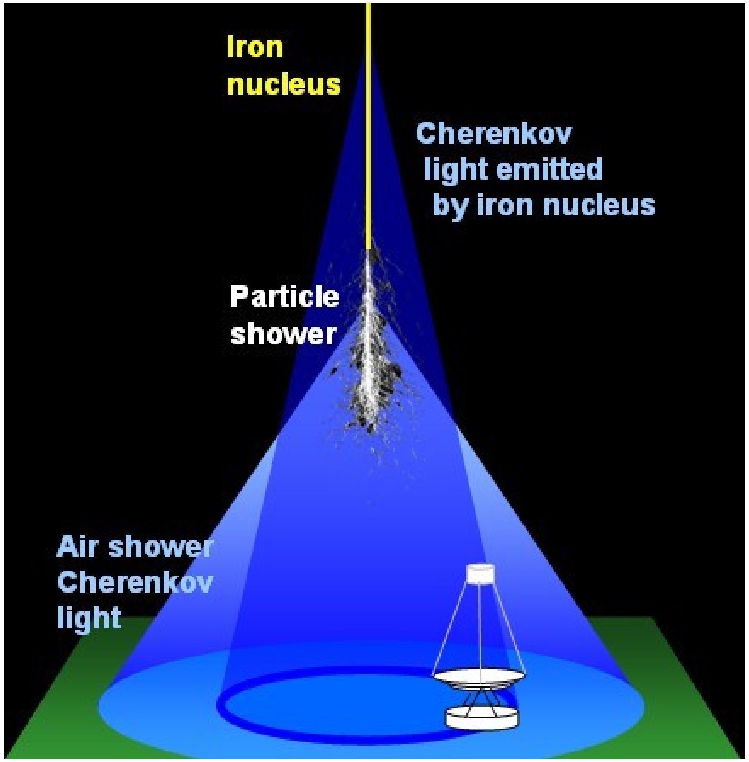
Red = antiparticle

!





Čherenkov Light



Charged particles moving through the atmosphere with a velocity larger than the local speed of light(the vacuum speed of light divided by the refractive index of the air) emit Čherenkov Light. This light is emitted on a narrow cone around the direction of the particle.

The opening angle alpha is a function of the density of the air and, thus, of the height of emission. It is increasing downwards but is always less than about 1.4 degrees. From each part of the particle track the Cherenkov light arrives on a ring on the ground. In an air shower, the initial particle interacts with the air atoms, producing many new particles. Most of those particles will be stopped or decay before they reach the ground. The Cherenkov light of all those shower particles faster than the local speed of light overlaps on the ground.

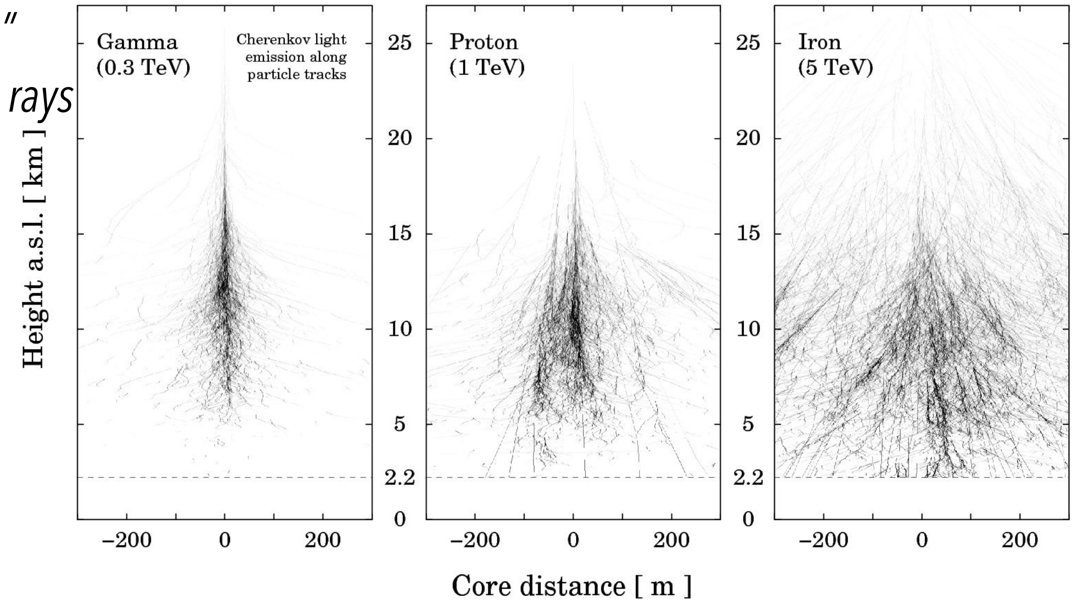
CR air shower: photons

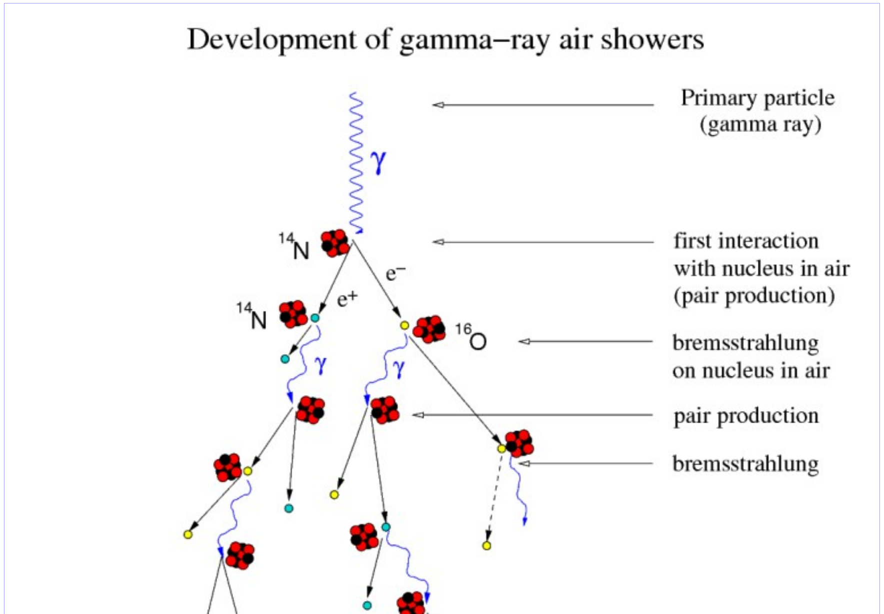
If the primary CR was a photon the "pancake" will contain electrons, positrons, and gamma rays

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

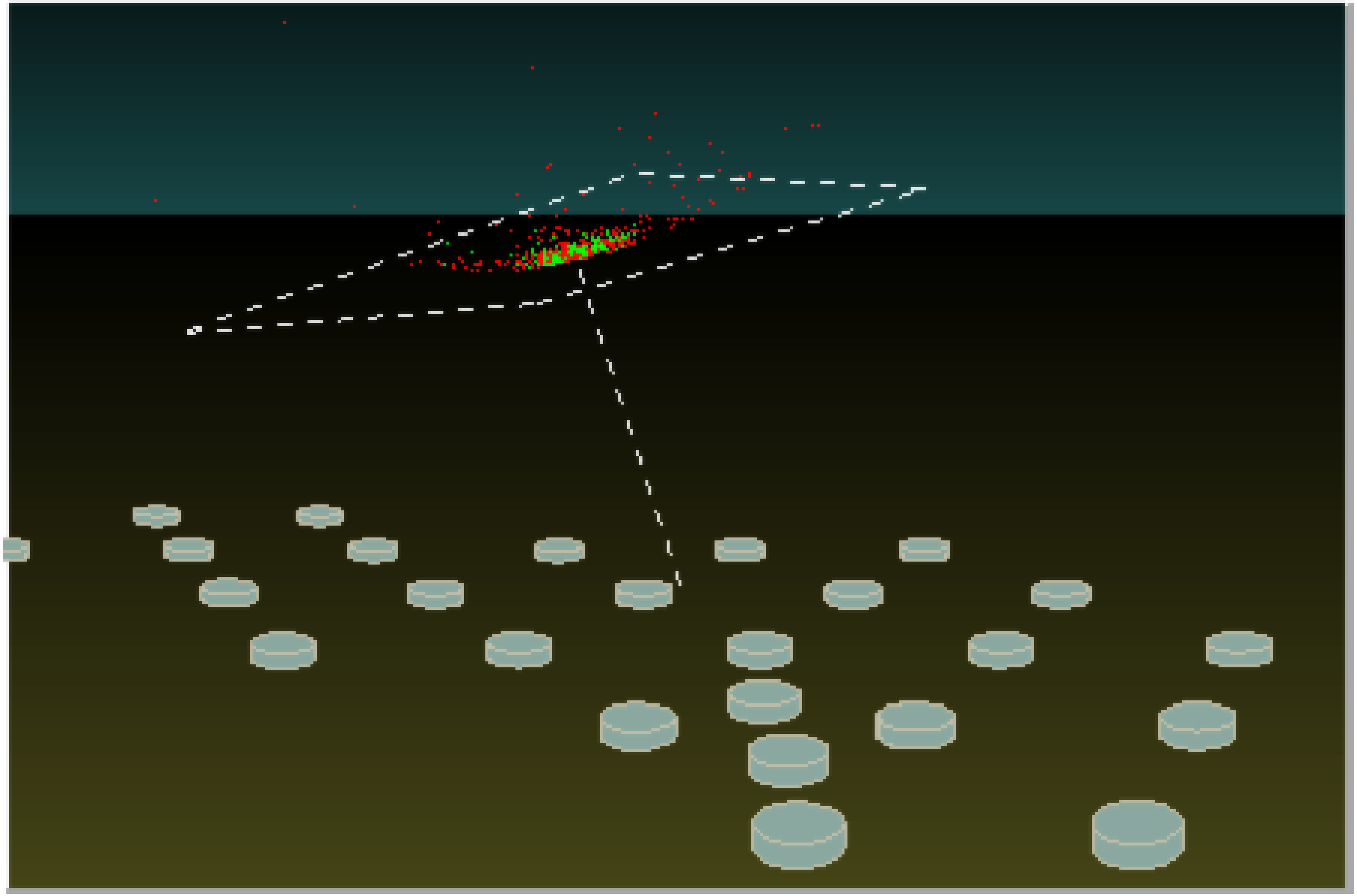
https://www-zeuthen.desy.de/~jknapp/fs/photon-showers.html
https://www-zeuthen.desy.de/~jknapp/fs/proton-showers.html
https://www-zeuthen.desy.de/~jknapp/fs/iron-showers.html

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



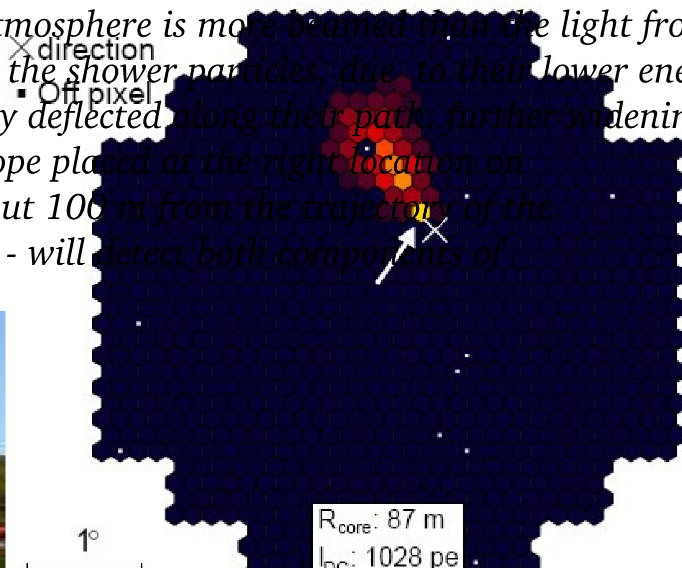


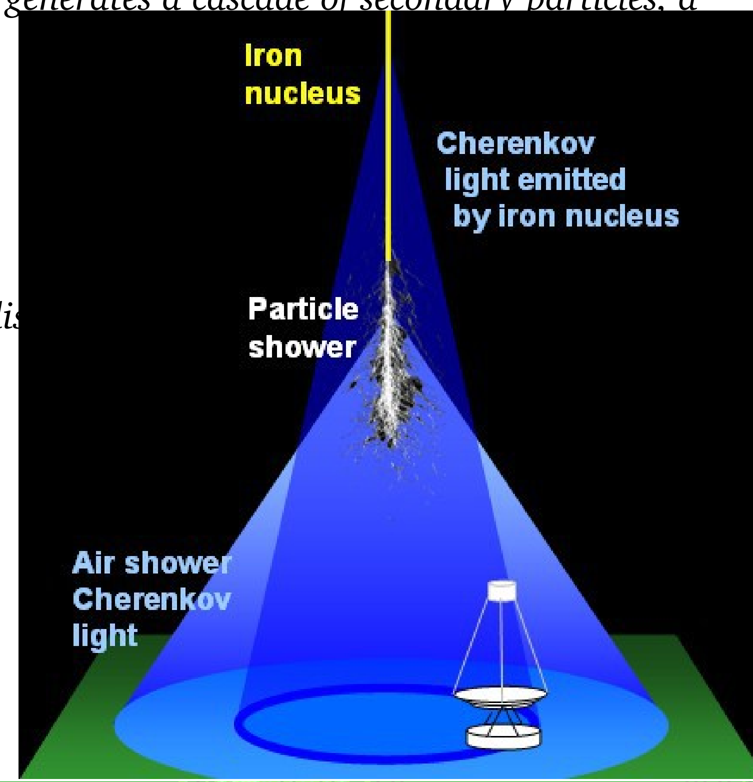
Cosmic Ray air shower



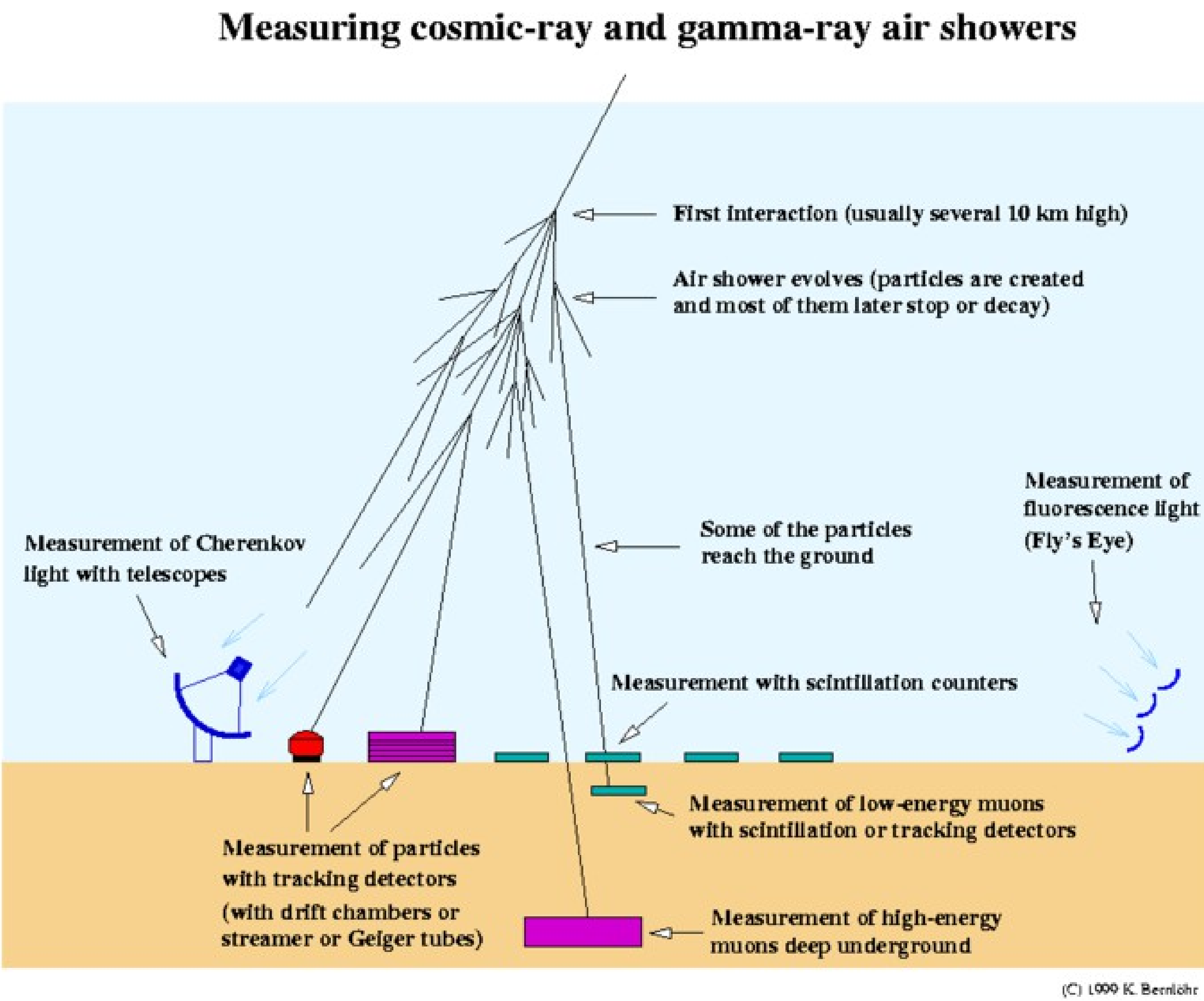
Cherenkov radiation: detection

Cherenkov light generated in the atmosphere by heavy nuclei among cosmic rays: while traversing the atmosphere, the nucleus radiates "direct" Cherenkov light. Then, it interacts and generates a cascade of secondary particles, a particle shower. These secondary particles in turn emit Cherenkov light. Since the opening angle of the Cherenkov cone - the "beam width" - is governed by the refractive index of air and hence by the air density, the Cherenkov light emitted by the primary nucleus high up in the atmosphere is more beamed than the light from the air shower. Also, the shower particles, due to their lower energy, are more strongly deflected along their path, further widening the dis of light. A telescope placed at the right location on the ground - about 100 m from the trajectory of the primary particle - will detect both components of Cherenkov light.

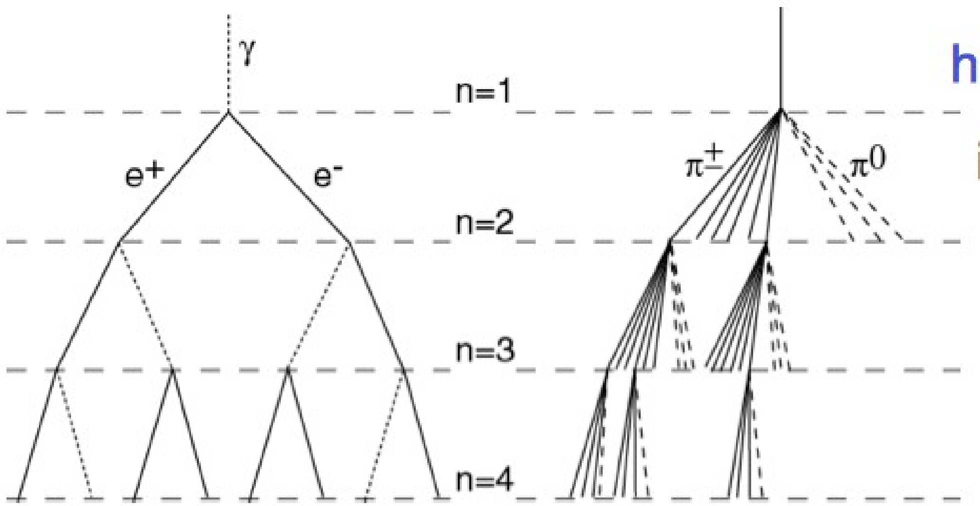




CR Detection on Earth



A Heitler Model – Hadronic Cascades



hadronic interaction π+A → $\pi^0 + \pi^+ + \pi^-$

interaction length $\lambda_i^{\pi\text{-air}}$~120 g/cm²

π → hadronic interaction
→ decay

„critical energy" E_c^{π}~20 GeV

Toy model for electromagnetic cascade (Heitler)

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

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

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

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}

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

Cosmic Rays

Discovery of ionizing radiation by Wilson and later on by Hess (1911-12) who used balloon experiments to send detectors at high altitudes and showed an increase of the flux of these particles with amplitude ⇨ extraterrestrial origin. It was also homogeneously distributed on the sky. Hess got the Nobel prize in 1936.

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

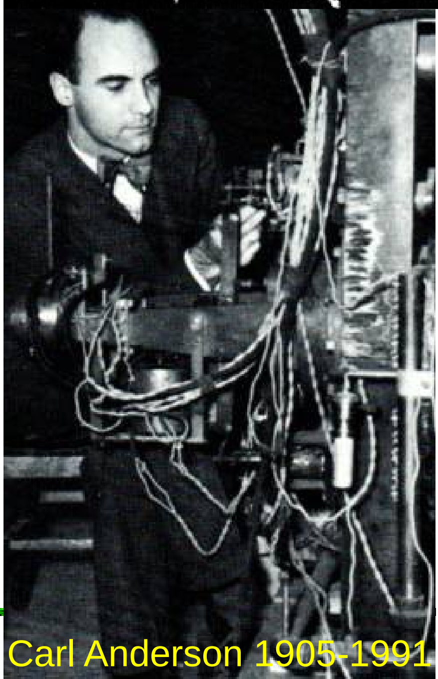
Clay discovered the latitude effect: CR intensity depends on geomagnetic latitude (interpreted by Bothe and Kolhorster)

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

Victor Hess 1883 – 1964



Carl Anderson 1905-1991

Cosmic Rays: history (2)

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

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

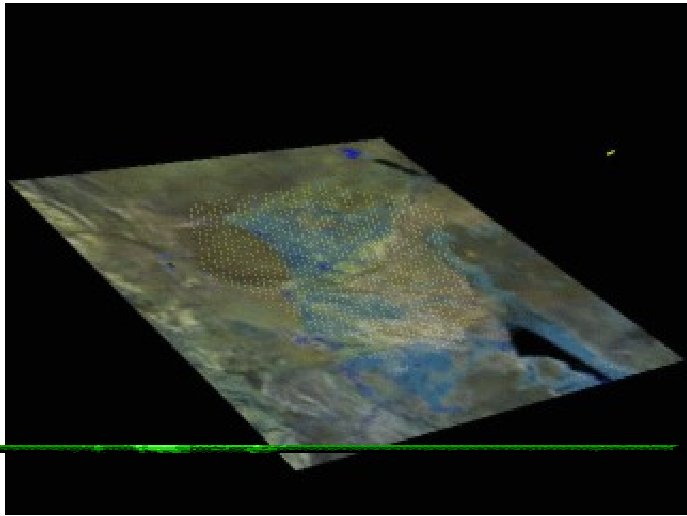
1972: The SAS-2 satellite opened the high energy gamma ray astronomy

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

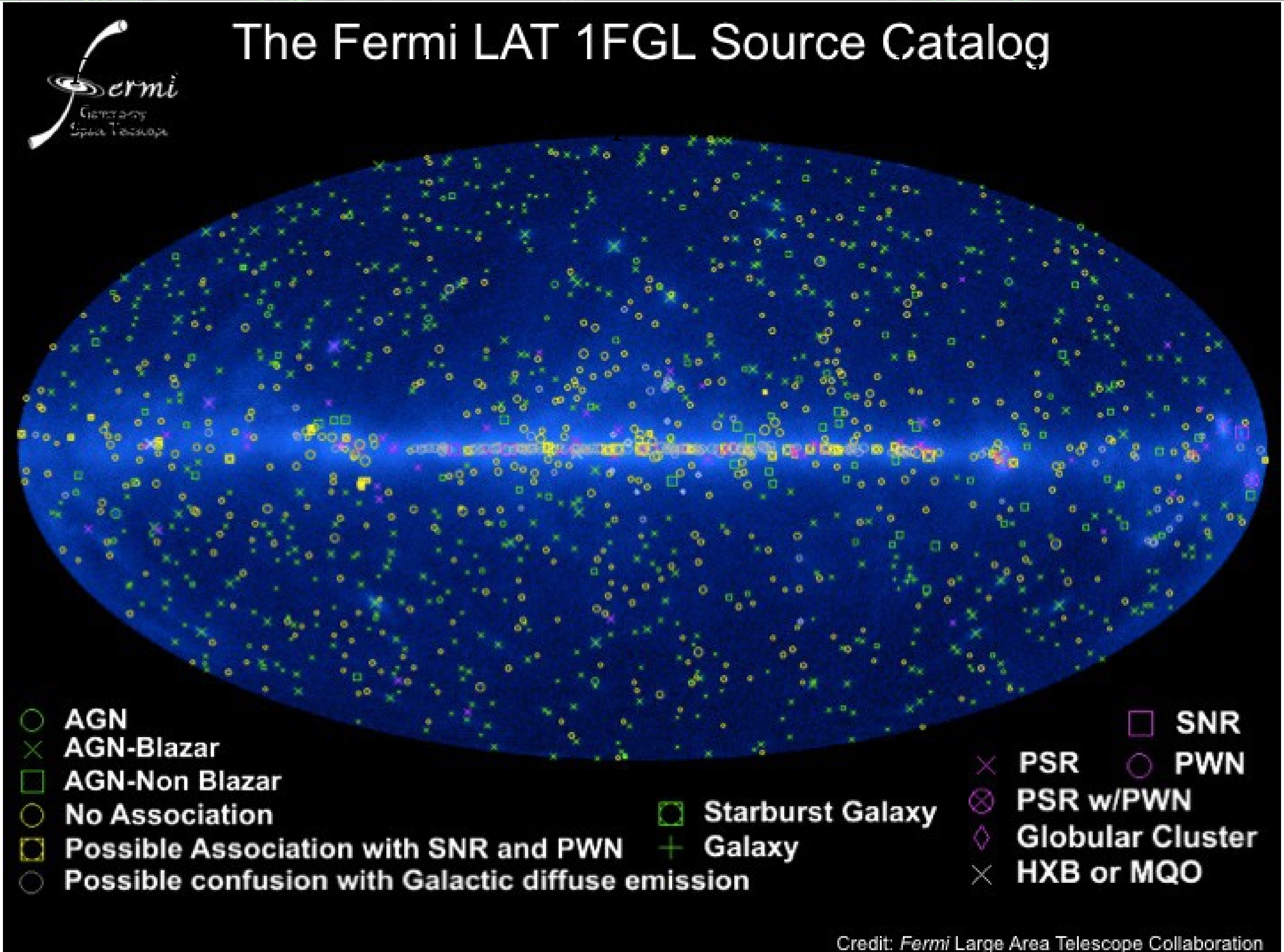
1998: The first detection of flavor oscillations of atmospheric neutrino sat the Superkamiokande experiment.

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

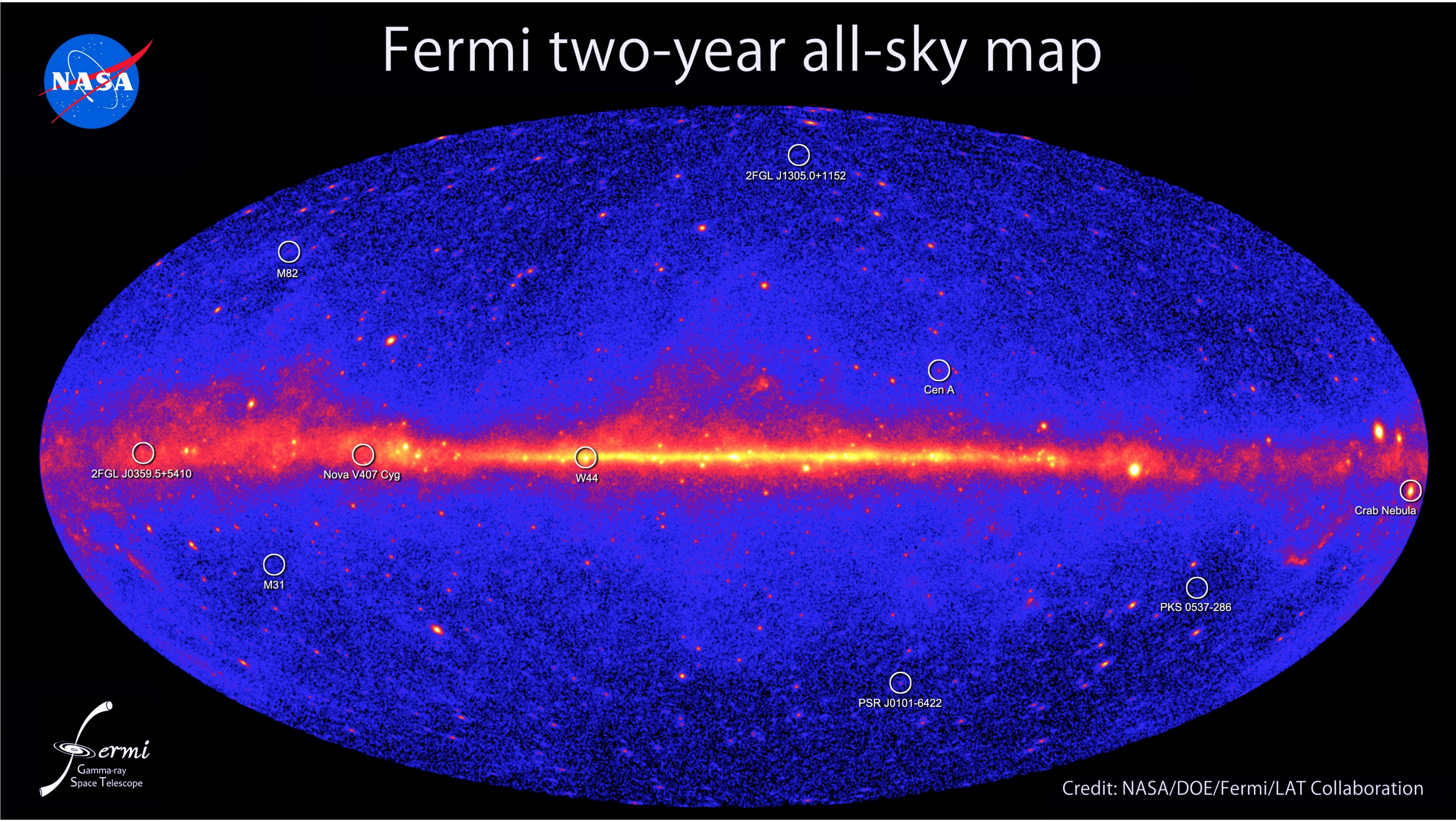
201X CTA



Photonic component



Photonic component



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)	
^{56}Fe (nucleus)	~45000 (45 Gev)

Composition:

CR nuclei

CR electrons (with positrons: 0.2 < 1 Gev, 0.1 @ 1 Gev, 0.05 @ 5-20 Gev, secondaries)

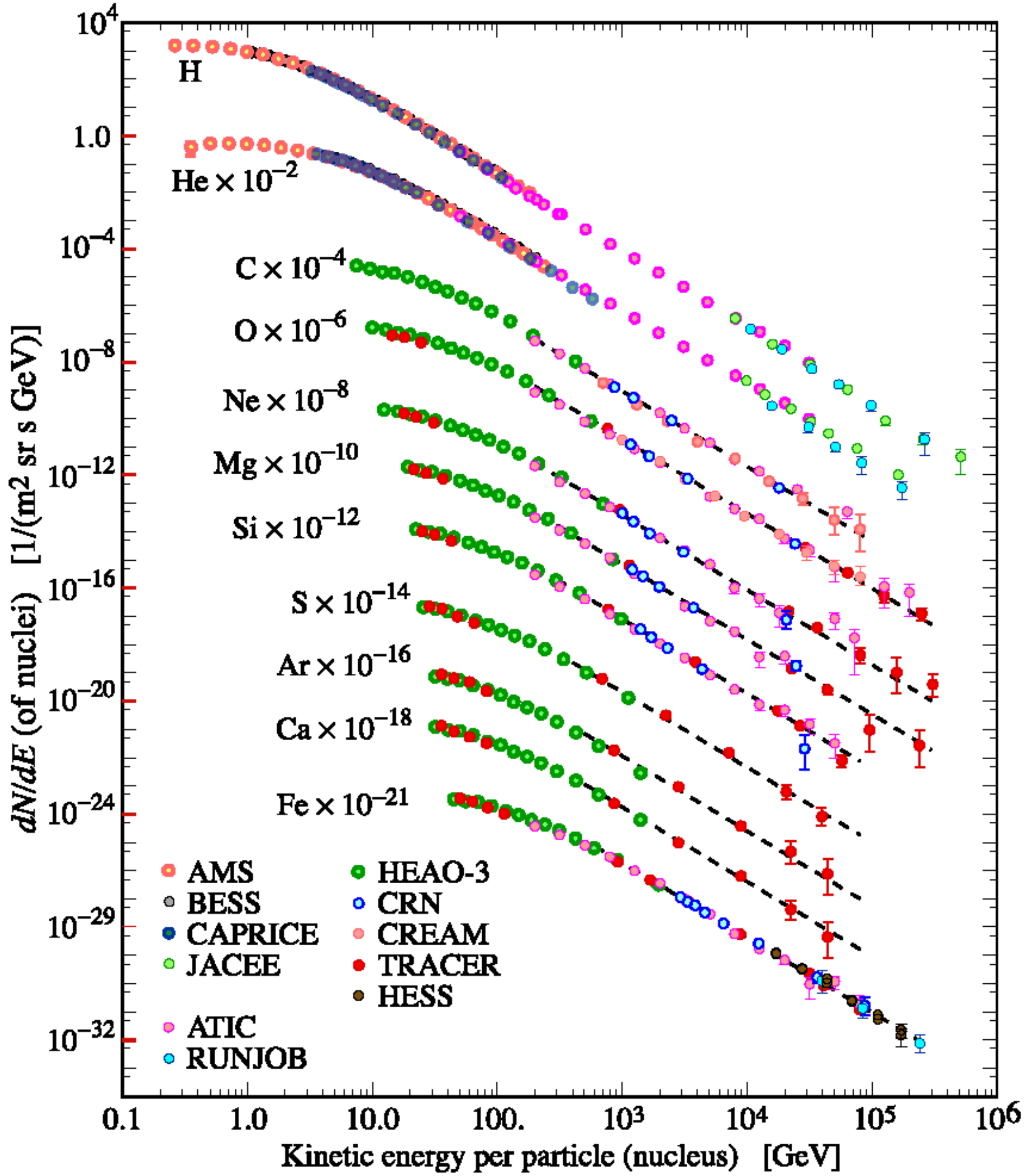
CR photons

Nucleonic component (1)

- Different abundances wrt solar and ISM composition
- Spallation: fragmentation of heavy CR nuclei via interaction with the ISM
  ~60% "native" CRs, 40% "fragmented"

- 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

- Steep energy distribution
  $N(E) \sim E^{-\delta}$ where δ is ~2.7
  Similar slope for all primary nucleons
- (may be slightly steeper for secondary species)

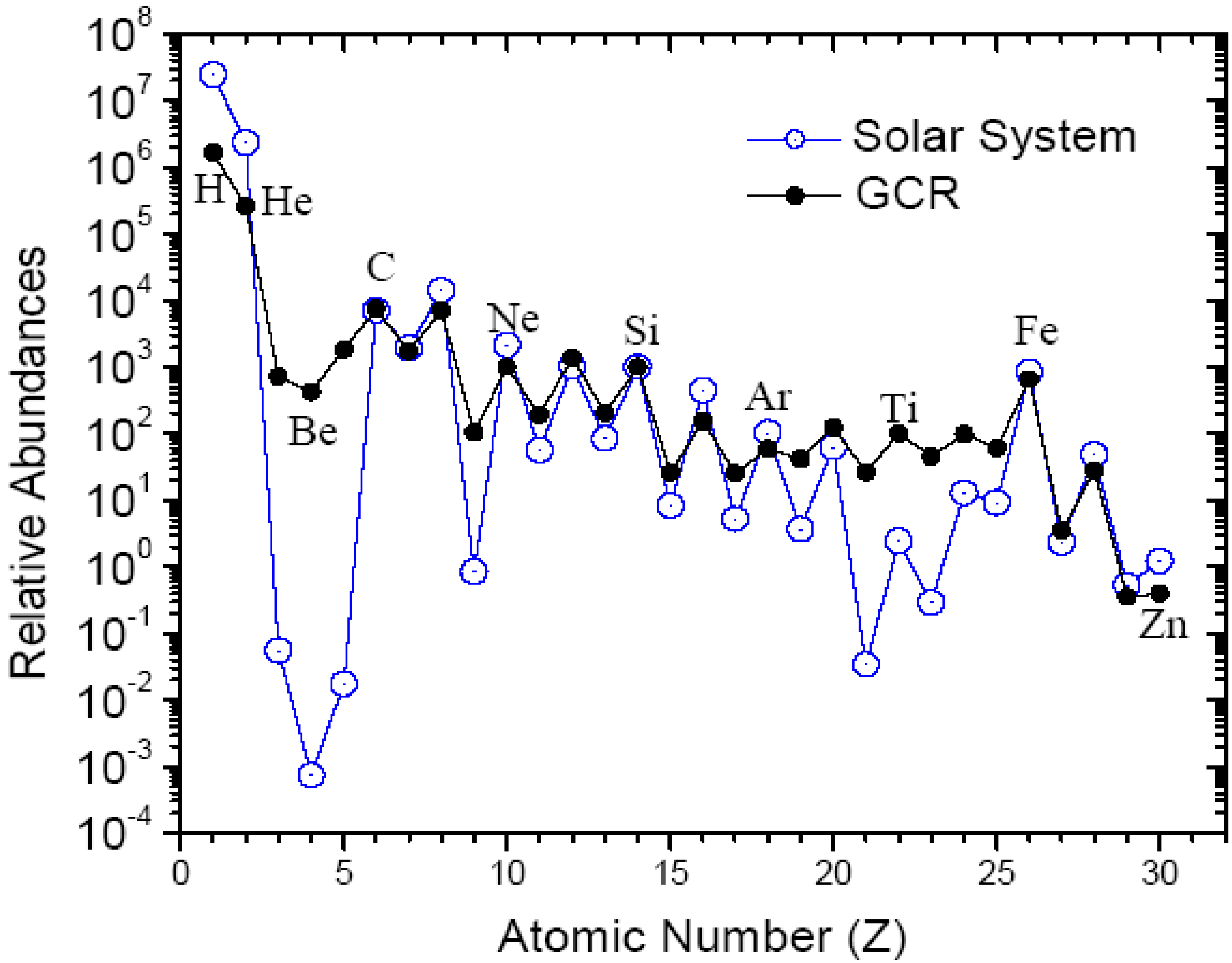


Nucleonic component (2)

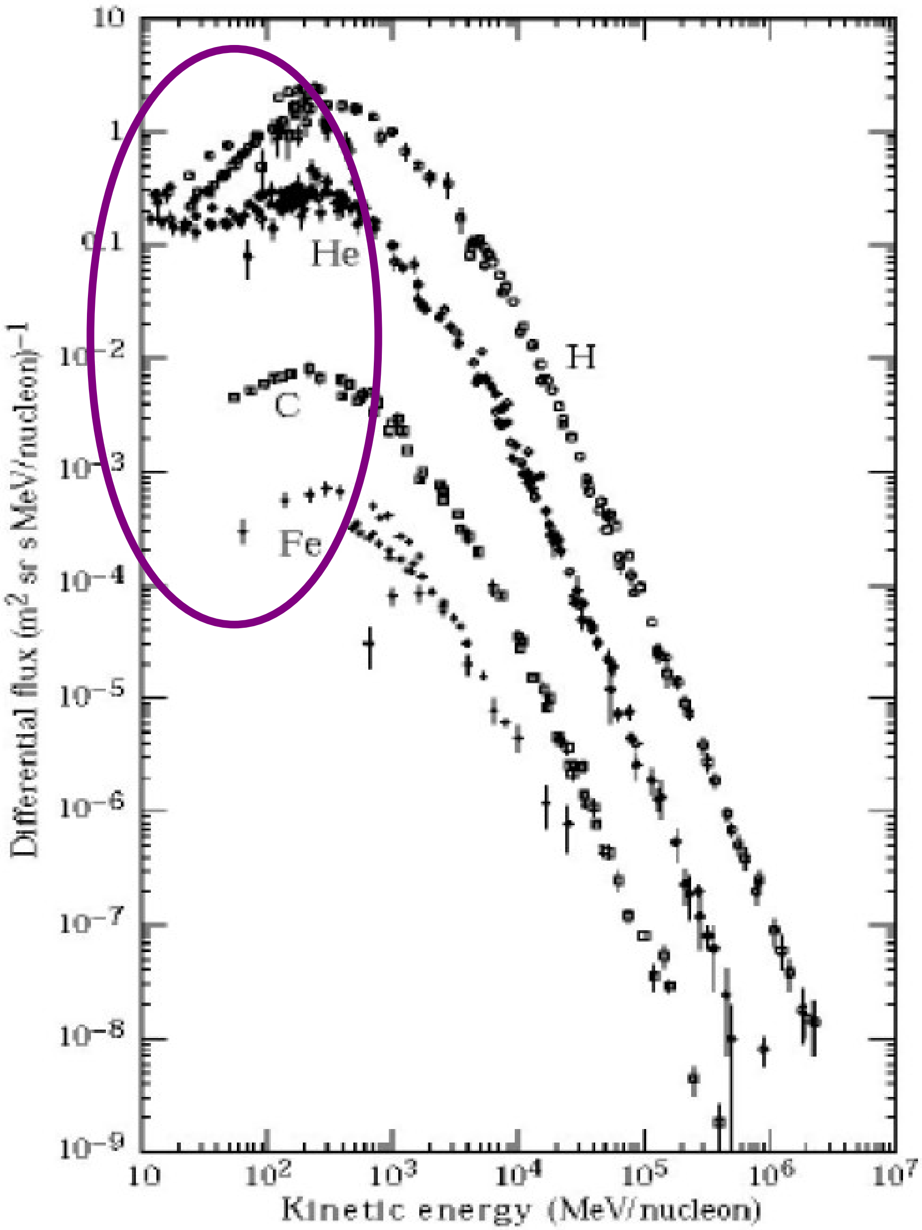
• Spallation: fragmentation of heavy CR nuclei via interaction with the ISM: ~60% "native" CRs, 40% "fragmented"

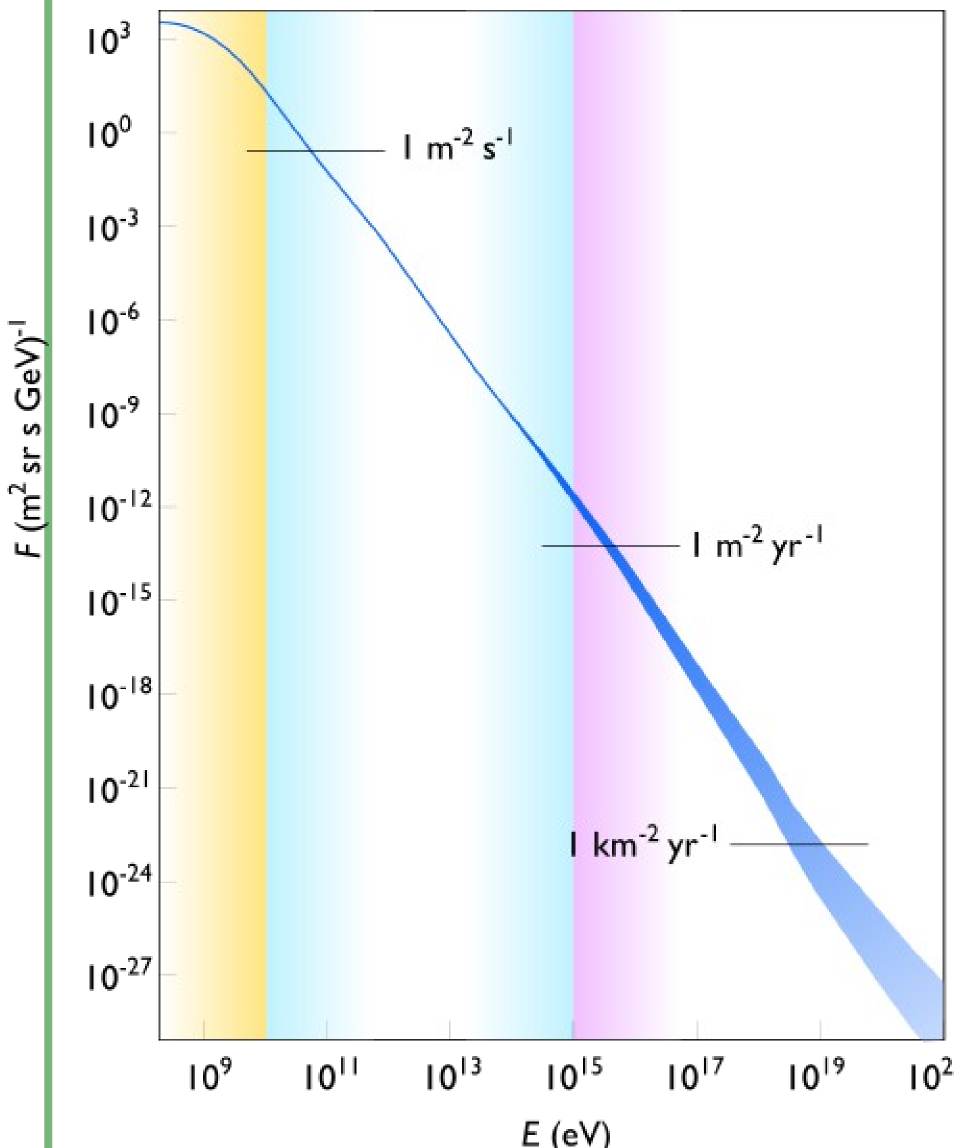
• Equivalent to a slab with a thickness of
$\langle x \rangle \sim 4 \pm 1 \text{ g cm}^{-3}$

• Responsible of creation and refurbishment of radioactive isotopes (~1/3 of natural radioactivity is from CR)



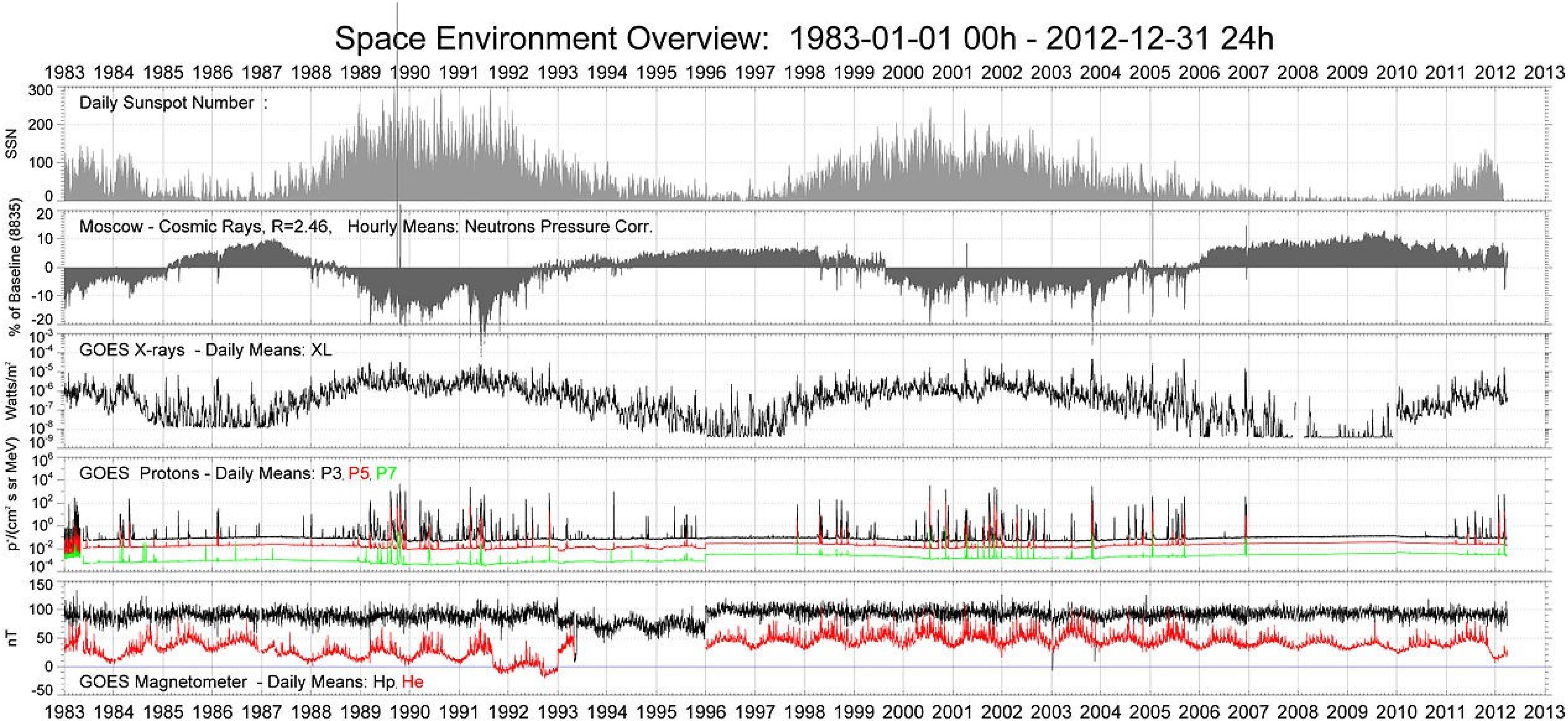
Nucleonic component (3) THE FULL ENERGY SPECTRUM



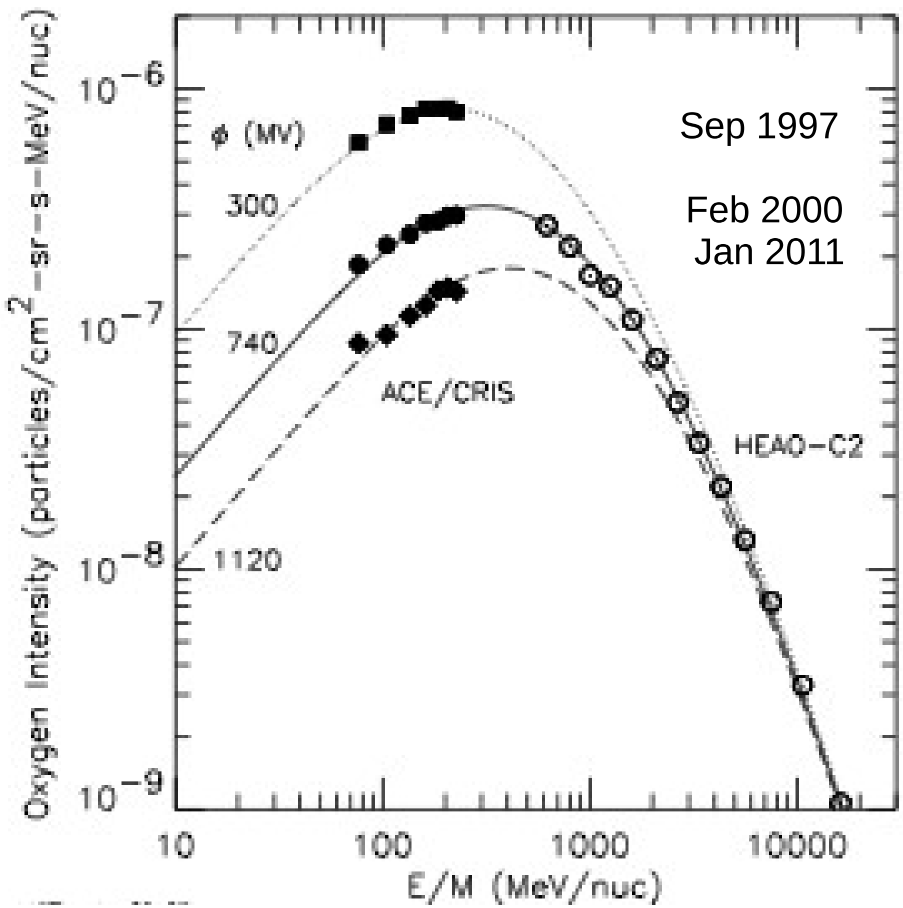


Nucleonic component (4)

solar modulation



Nucleonic component (5): effect of solar activity (< ~ 1GeV)



Nucleonic component (6)

From radioactive isotopes ($^{14}C \rightarrow 10^3$-10^5 yr; $^{40}K \rightarrow 10^7$-10^9 yr, i.e. various location in the Milky Way):

upper limits to anisotropy:

$\Delta F/F < 3\ \ 10^{-4}$	$E < 10^{12}$ eV
$< 10^{-2}$	$10^{12} < E < 10^{16}$ eV
??	$E > 10^{18}$ eV

Lifetime:

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

if $\langle x \rangle = 4\,\mathrm{g\,cm^{-3}}$ and $n_{ISM}\ \ 1\,\mathrm{cm^{-3}} \rightarrow \rho_{ISM} \approx 10^{-24}\,\mathrm{g\,gm^{-3}} \rightarrow \tau_{CR} \approx 3 \cdot 10^{6}\,\mathrm{yr}$ in the galactic disk.

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

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

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 ;

$M = H^2 V/8\pi$; $W =$ potential energy (grav.; only term <0)

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

Let's consider an isothermal gas, with $\rho(z)$ where z is the height wrt the galactic plane

ρu^2 pressure (u mean quadratic velocity along z, costant) $g(z)$ acceleration of gravity

P_{CR} is the CR pressure.

Barometric equilibrium per unit volume:

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

let's write $\dfrac{H^2}{8\pi} = \alpha\rho u^2$ 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:

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

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

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

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 must be $\sim 5\mu G$

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

$w_{CR} \sim 1\,\mathrm{eV\,cm^{-3}} = 1.6 \cdot 10^{-12}\,\mathrm{erg\,cm^{-3}}$ (as observed on the Earth);

$\tau_c \sim 2 - 200$ Myr confinement time (use 20)

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

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

SNR, pulsars and PWN are suitable origin for such refurbishment

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

Electronic component (1)

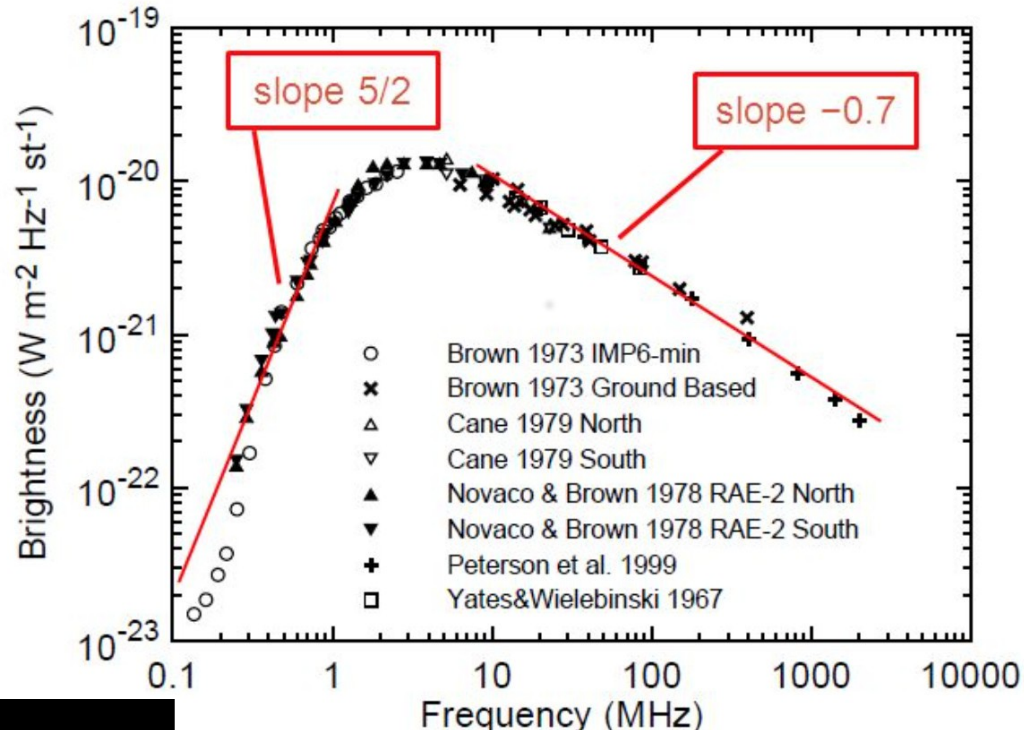
- Energy density: $0.001 - 0.01$ eV cm $^{-3}$
- CR electrons + positrons: Fraction of positrons (i.e. secondaries) : 0.2 @ <1 Gev,
  0.1 @ 1 Gev,
  0.05 @ 5-20 Gev,

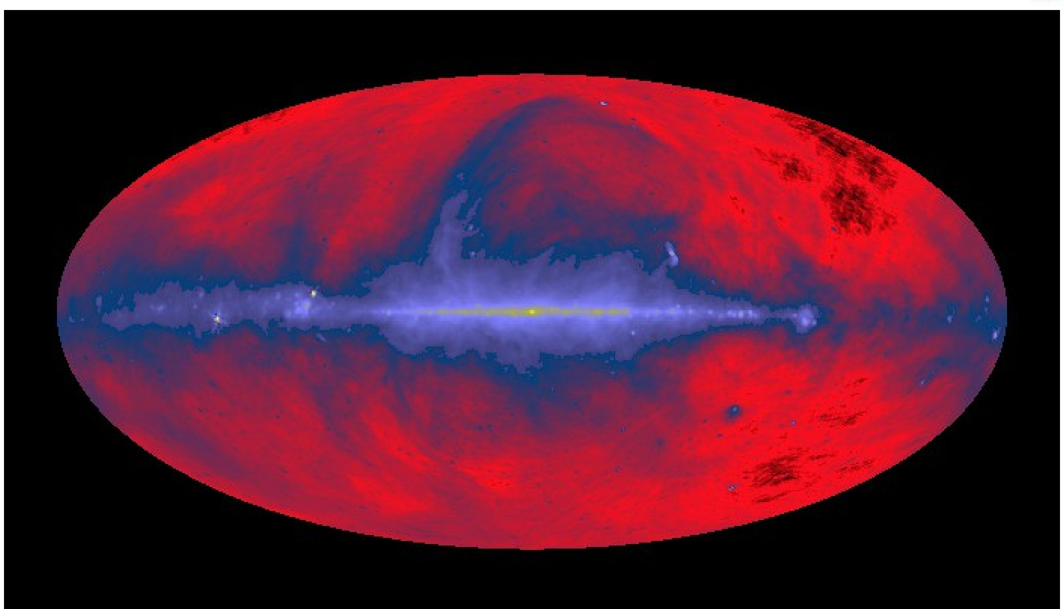
- Direct measurements from satellites and balloons
- Indirect measurements:
- Synchrotron (radio)
- Inverse Compton (X and γ – rays)
- Relativistic bremsstrahlung (γ – rays)

- Further losses due to ionization

Electronic component (2)

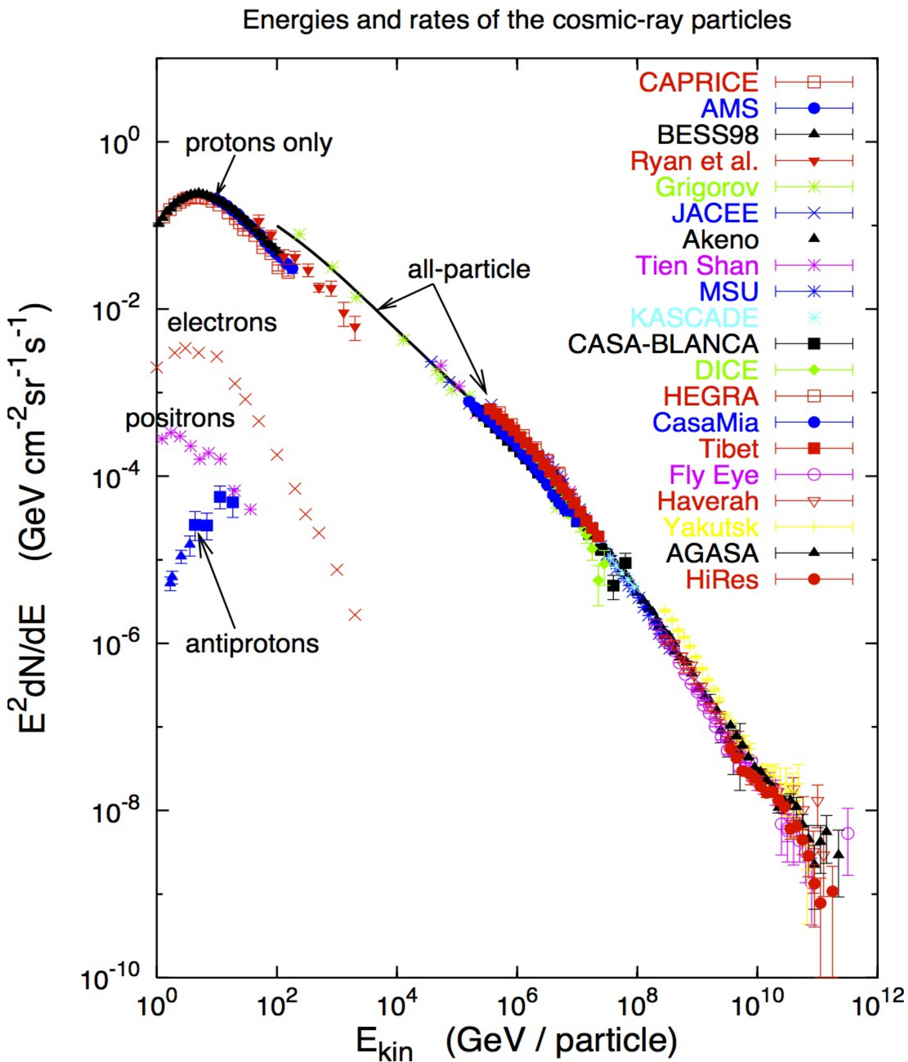
- *Synchrotron emission in galactic coordinates: function of electron energy and H*
- *Slope 0.7, steepens to 0.9-1.0 above 0.4 GHz*





Electronic component (3)

- Direct counts above a few GeV, influence from solar wind. Problems with normalization between different experiments. Steeper than nucleons (~3.3 .vs. 2.7)



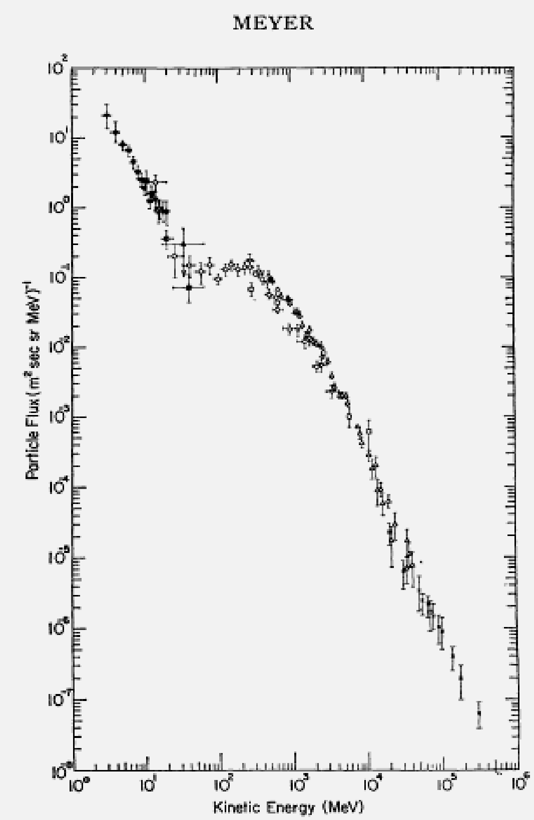


FIG. 14. The energy spectrum of cosmic-ray electrons.

× 1965–66 Anand et al. (1968)
△ 1965–66 Bleeker et al. (1968a)
■ 1968 Fan et al. (1969)
▲ 1967 Israel & Vogt (1968)
▽ 1964–66 L'Heureux & Meyer (1968)
▼ 1967 McDonald & Simnett (1968)

Electronic component (4)

Lo spettro di energia degli elettroni cosmici presenti nella Galassia, ricavato da osservazioni dell'emissione radio da sincrotrone, dell'emissione di bremsstrhalung relativistica e da misure dirette, e' stato confrontato.

DATI RADIO: si utlizza la seguente formula, ottenendo il flusso di elettroni calcolato per diversi valori del campo magnetico:

$$I_{el}(E)=K_2 B(\quad_{oss})\quad_{oss}{}^{-1/2} H_{¿}^{-1/2}$$

K_2 dipende dallo spessore attraversato dalla radiazione lungo la linea di vista

DATI GAMMA: si utilizza la formula per ottenere il flusso di elettroni;

$$I_{el}(E(GeV))=\frac{B_{ph}(E(GeV))\cdot(\quad -1)\cdot c}{10^{-15} n_H l}$$

DATI DA MISURE DIRETTE

Electronic component (5)

- L'accordo migliore fra i diversi dati si ha per: $H_{\perp} \sim 6 \quad G$
- Moderato accordo per la pendenza dello spettro: per E<1GeV $\backslash$ da un valore di $\alpha \sim 0.65$ in accordo con i dati radio per frequenze<0.4GHz; per E>1GeV si ottiene $\alpha \sim 1-1.5$ che non e' in accordo con valore radio $\sim 0.8-0.9$ (forse le osservazioni radio hanno incertezze di calibrazione non individuate)
- Il break: per E<3GeV lo spettro ha pendenza <2.3, mentre fra E~3GeV ed E~20GeV la pendenza e' circa 3-3.3. L'irripidimento puo' indicare un'invecchiamento per perdite radiative; se gli elettroni vengono immessi (es. SNR) lo spettro si irripidisce di +1, quindi l'indice di iniezione e' ~ 2-2.3, stesso valore che si ha per I protoni (potrebbe testimoniare lo stesso meccanismo di produzione e di accelerazione).

Considerando quindi che

- l'indice dello spettro di energia degli elettroni sia 2-2.3 per E<3GeV e 3-3.3 per E>3Gev
- le vite medie degli elettroni siano confrontabili con i tempi di confinamento degli elettroni ~10-30 Myr

si puo' calcolare per quali valori del campo magnetico effettivo perpendicolare si ha un'energia di break ~3GeV

$$E_{break}^{rad} \sim 8.04 \cdot 10^{3} H_{¿eff}^{-2} (\quad G) \; _{conf}^{-1} (Myr)$$

$$H_{¿eff}^{2} = H_{¿}^{2} + H_{¿IC}^{2}$$

Electronic component (6)

- NON esistono valori del campo magnetico in grado di fornire un buon compromesso tra energia di break, frequenza di break e vita media degli elettroni.

  Per ottenere $E_{break}^{rad} \sim 3GeV$ il valore $H_{\perp} = 6 \quad G$ comporta un tempo di vita degli elettroni troppo lungo e una frequenza di break> 0.4 GHz (non osservato).

- L'unica conclusione certa e' che $H_{\perp} > H_{//} \sim 3 \quad G$ stimato da RM delle pulsars

Bisogna pero' ricordare che il campo magnetico non e' uniforme e che la radiazione di sincrotrone e' maggiormente dominata dalle regioni con H alto quindi $H_{\perp}$ non e' un valore medio.

Electronic component (7)

Gli elettroni relativistici subiscono l'effetto IC con i fotoni della radiazione cosmica di fondo per cui hanno una vita media radiativa:

$$_{el} \leq \frac{3 \cdot 10^{8}}{\frac{H^{2}}{8} + w_{f}} \frac{1}{E}$$

per E~100GeV e w_f ~0.25eV cm^{-3} (densita' media dei fotoni responsabili dell'effetto IC)

$$_{el} \leq 10^{7}\, yr$$

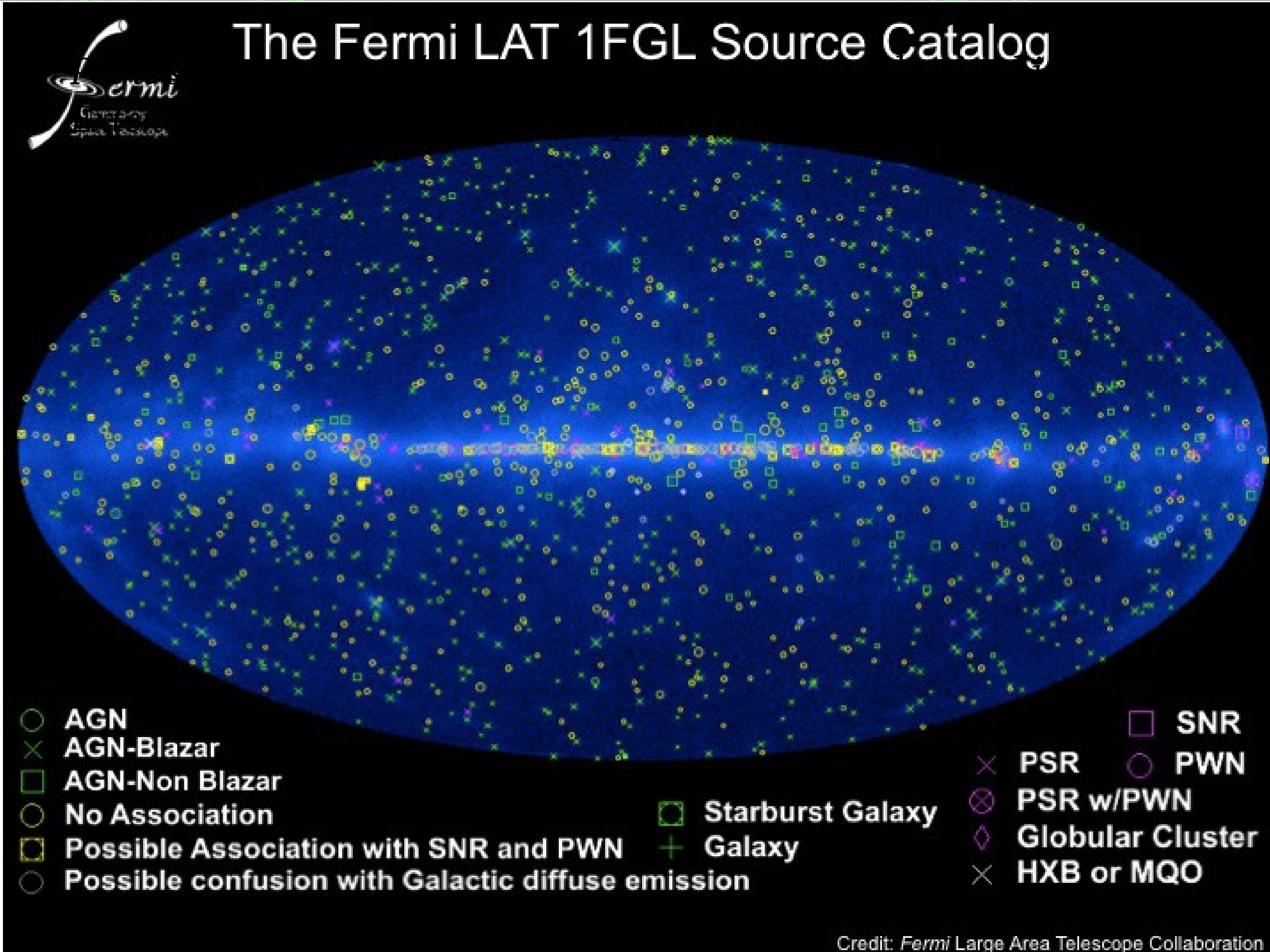
Non possono percorrere distanze superiori a qualche Mpc.

I RC di altissima energia sono quasi certamente di origine extragalattica.

A queste energie (>10^{19} eV) si ha r >3kpc e non si ha piu' confinamento, il flusso quindi dovrebbe essere anisotropo, contrariamente a quanto osservato.

L'interazione fra questi RC e i fotoni della radiazione di fondo limita lo spazio percorso, devono provenire da distanze < 30Mpc.

Photonic component



Photonic component

I processi per la produzione di raggi gamma nella Galassia sono:

•Decadimento del π^0 , emissione con una distribuzione a campana centrata su energie di ~ 70 MeV

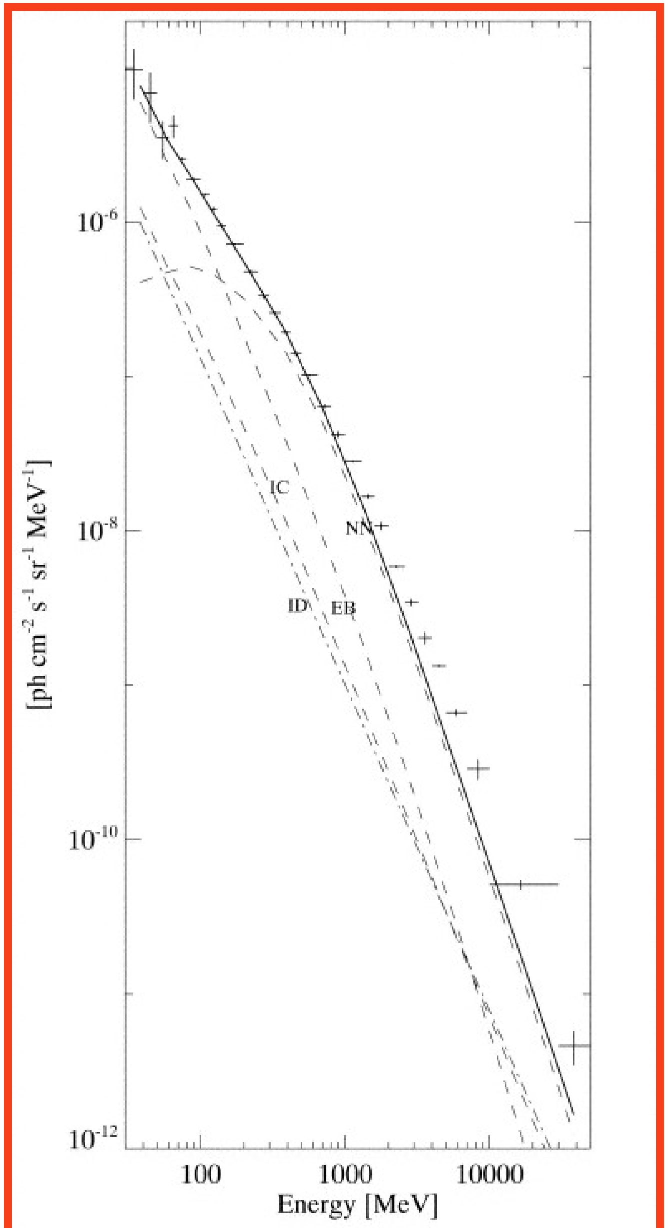
•Bremsstrhalung relativistica, interazione fra elettroni e mezzo interstellare, domina fra 2 e 70 MeV

•Effetto Compton Inverso con i fotoni della CBR dominano sul decadimento per energie <30 MeV, con i fotoni stellari per energie <20 MeV.

Dai dati EGRET si puo' ricavare il flusso tra 35MeV e 100MeV, che per 80% e' dovuto a bremsstrhalung e quindi agli elettroni:

$$\sim 1.45\cdot 10^{-7}\, ph\cdot cm^{-2}\cdot ster^{-1}\cdot s^{-1}\cdot MeV^{-1}$$

per $\delta \sim 2.0$

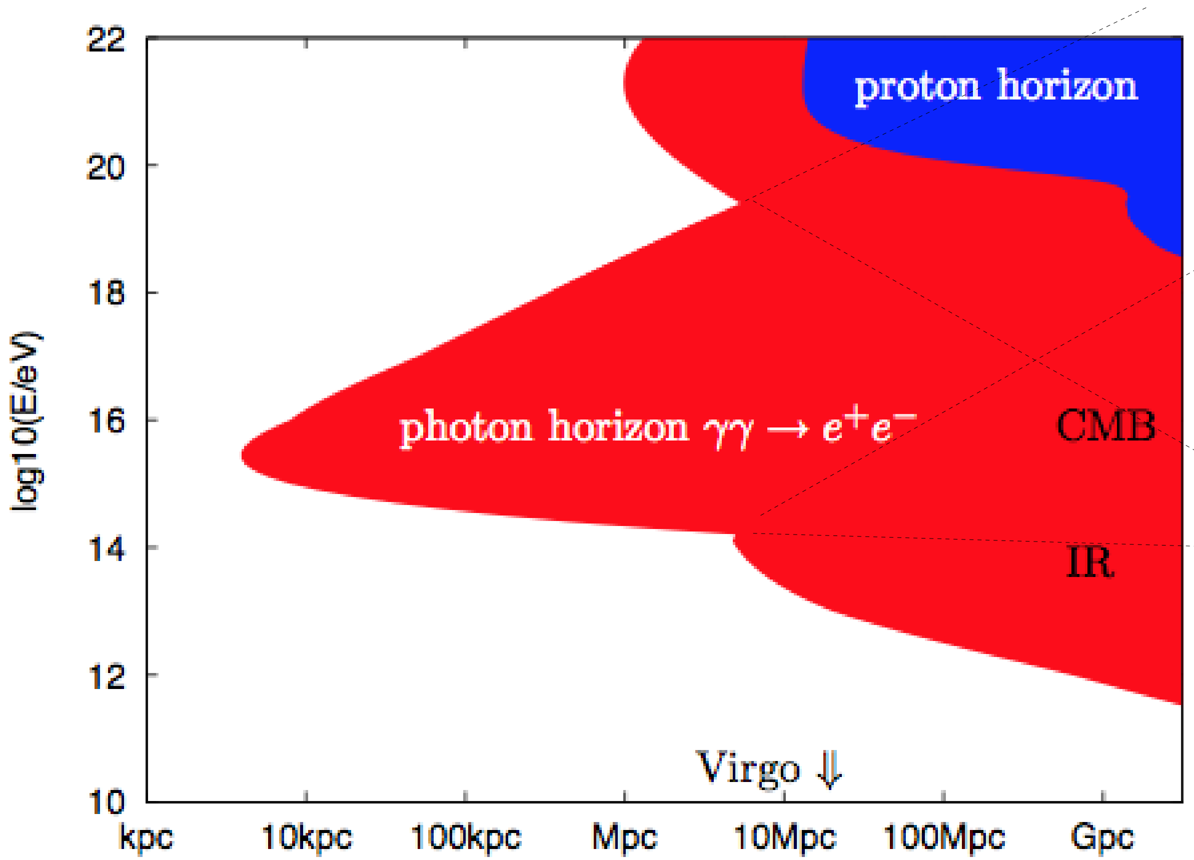


EGRET nel piano galattico, spettro dell'emissione diffusa

Hunter, 1997

Photonic component: horizon

$$p + \gamma \rightarrow \pi^{+} + \pi^{-} + \pi^{o}$$



A) Origine extragalattica

$$u_{Rc} \leq 1\, eV/cm^3$$

$$n_{gal} \sim 10^{-2}\, Mpc^{-3}$$

Ogni galassia deve fornire una energia $E_{gal} = \frac{u_{Rc}}{n_{gal}} \sim 5 \cdot 10^{63}\, erg$ sotto forma di RC, pari a ~ 5% della massa della galassia

B) Origine galattica

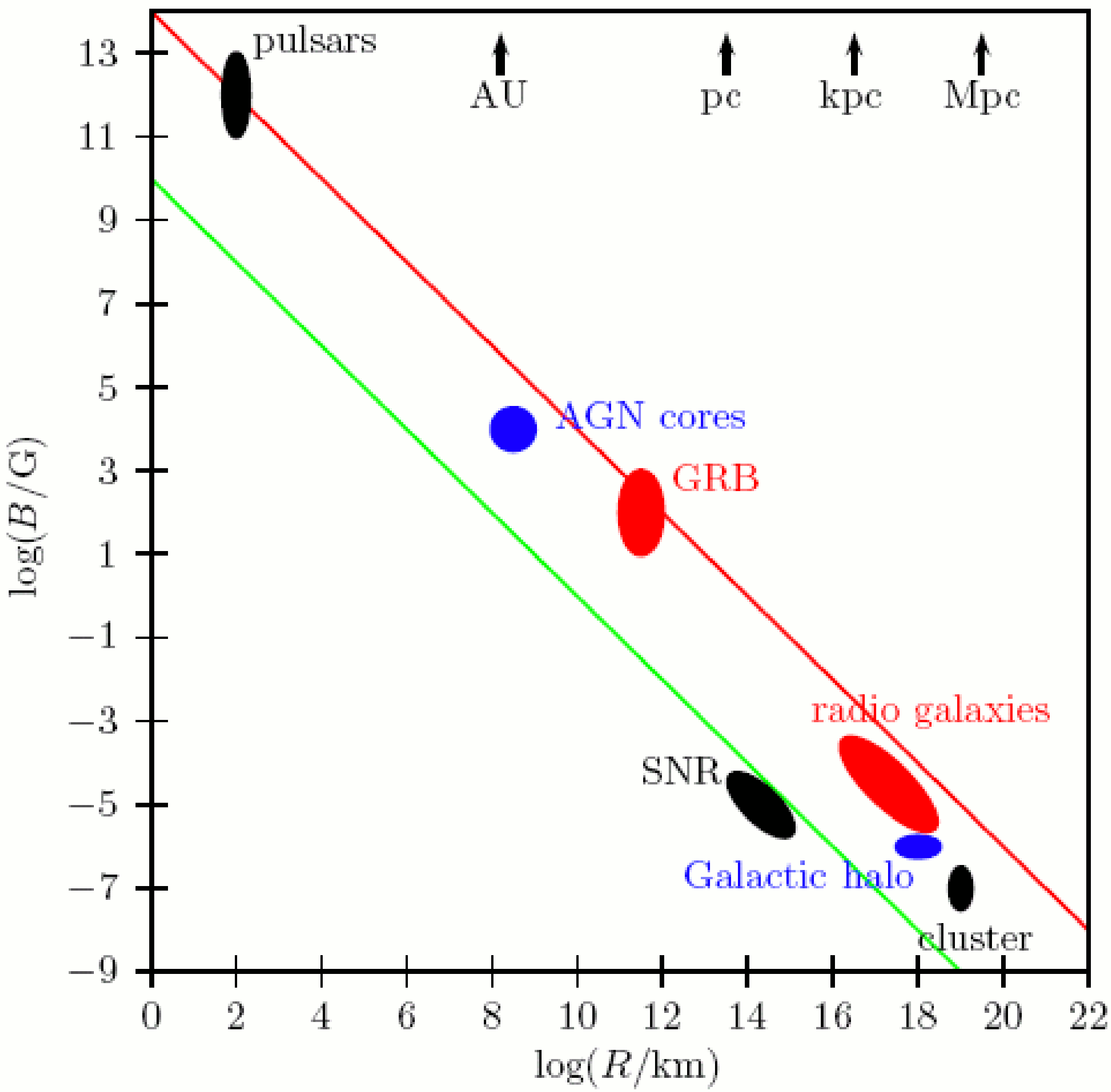
Se i RC sono prodotti dalle SN, allora e' necessaria da ogni SN una produzione di energia E_{SN} data da:

$$E_{SN} \cdot f_{SN} = 6 \cdot 10^{47}\, erg/yr \qquad f_{SN} \geq 1/100$$ frequenza supernovae in un anno

per cui:

$$E_{SN} \leq 6 \cdot 10^{49}\, erg$$

CR origin



pulsars
AU
pc
kpc
Mpc
AGN cores
GRB
radio galaxies
SNR
Galactic halo
cluster
13
11
9
7
5
3
1
−1
−3
−5
−7
−9
0
2
4
6
8
10
12
14
16
18
20
22
log(B/G)
log(R/km)

Origin for UHECRs