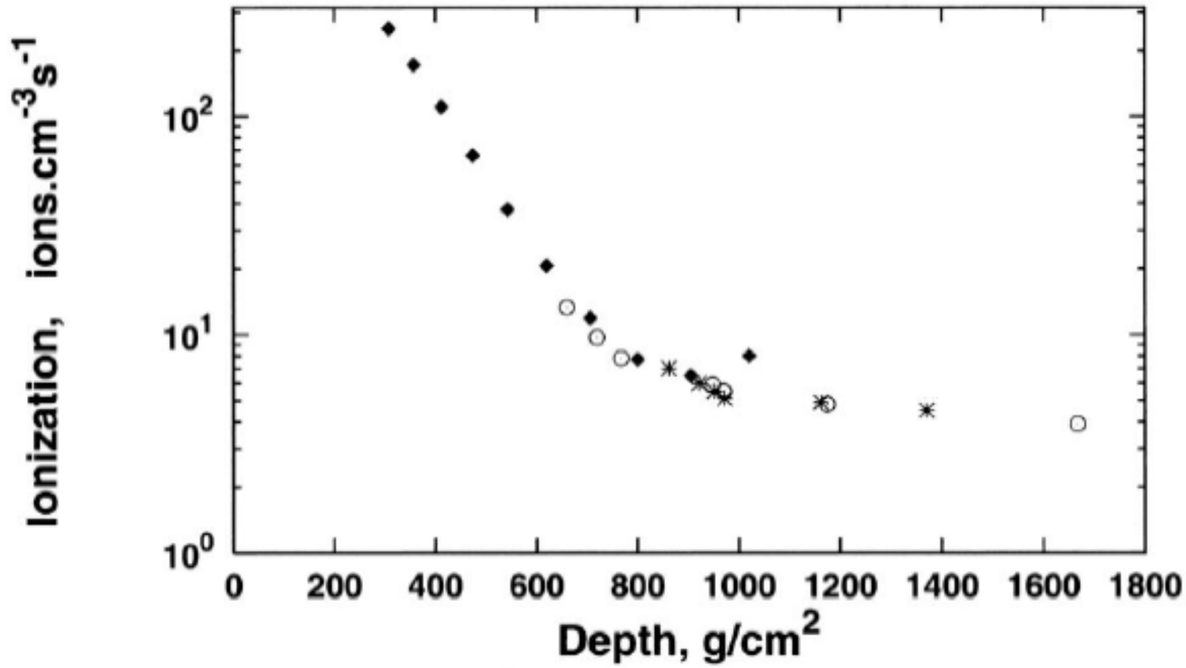
Giorgio Riccobene

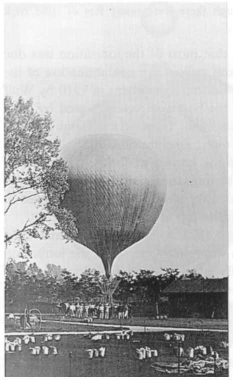
Astrofisica Particellare

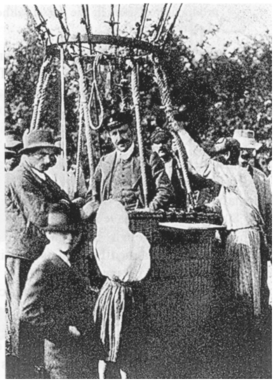
A bit of history

1900 **Wilson discovers continuous "atmospheric" ionisation**

1912 **Hess (Nobel prize 1949), Millikan and Kohlhorster measure dependence of ionisation vs. altitude**
Millikan uses the definition of "cosmic rays"







A bit of history

1932 Anderson discovers the positron in CR (Nobel prize 1936)

1937 Anderson and Neddermeyer discover the muon (birth of particle physics!)

1947 Powell discovers the pion in CR (Nobel prize, 1950)

1949 Fermi sets the first theory on CR acceleration

1970 Davis (Nobel prize, 1980) measures the solar neutrino flux
Solar model / neutrino oscillation debate

1987 First Supernova neutrino detection at Kamiokande and IMB (Koshiba, Nobel prize 2002)

1999 Superkamionande (and later SNO) probes neutrino oscillations in vacuum (Nobel prize, 2015)

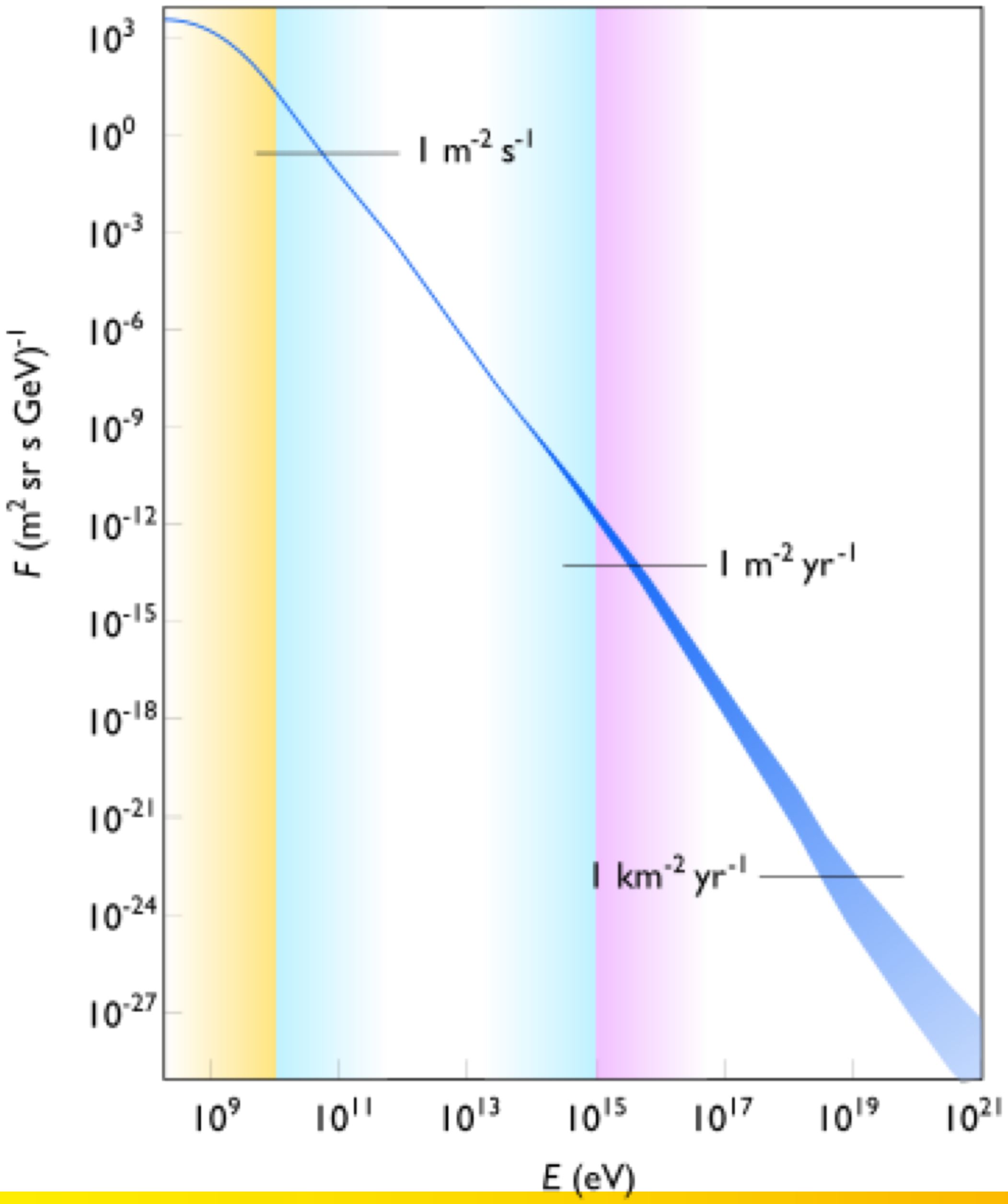
Pierre Auger

Even today accelerators have not caught up with cosmic rays. For in 1938, I showed the presence in primary cosmic rays of particles of a million Gigavolts -- a million times more energetic than accelerators of that day could produce. Even now, when accelerators have far surpassed the Gigavolt mark, they still have not attained the energy of 10^{20} eV, the highest observed energy for cosmic rays. Thus, cosmic rays have not been dethroned as far as energy goes, and the study of cosmic rays has a bright future, if only to learn where these particles come from and how they are accelerated.

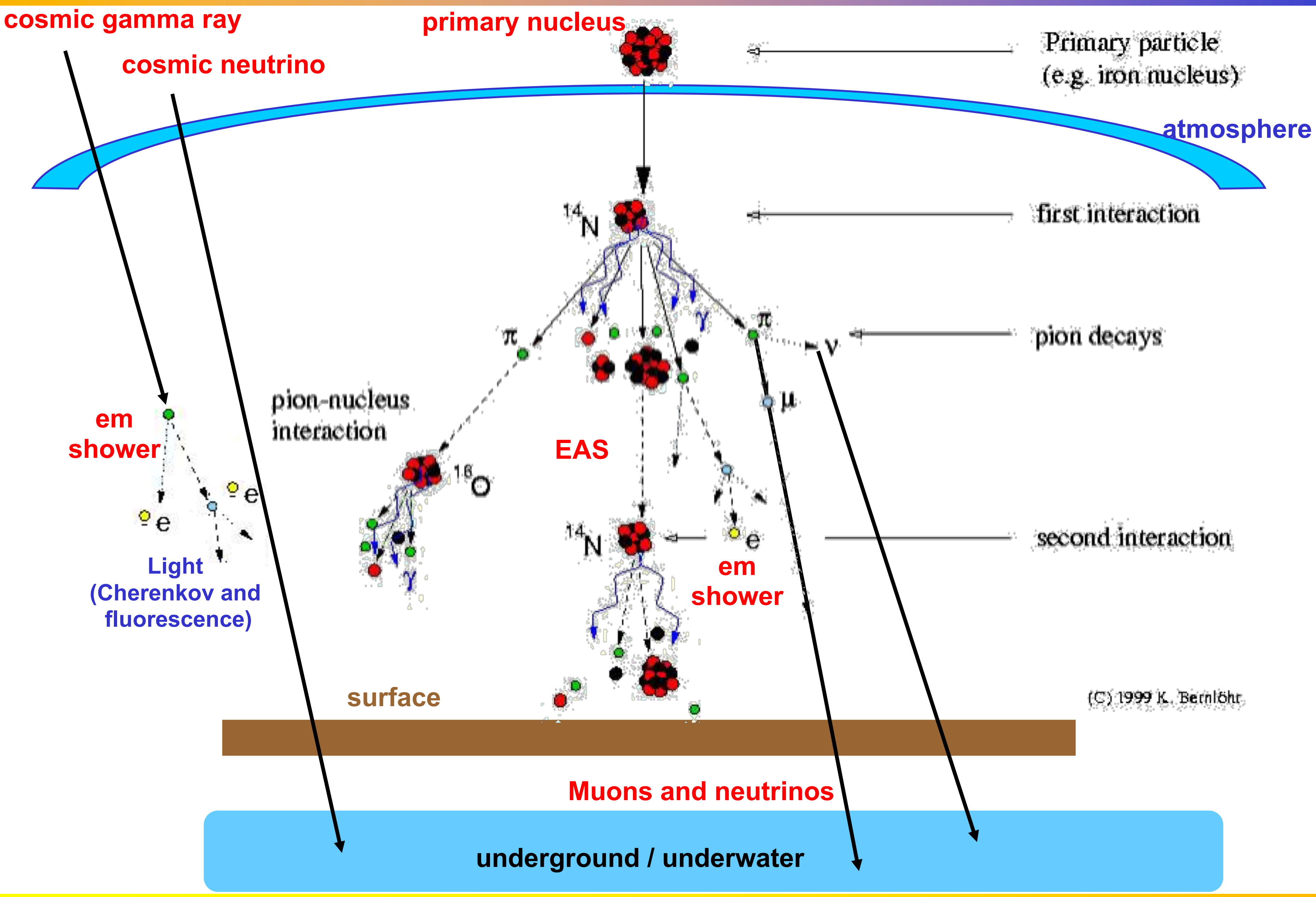
The cosmic ray spectrum

Cronin, Gaisser, Swordy 1997

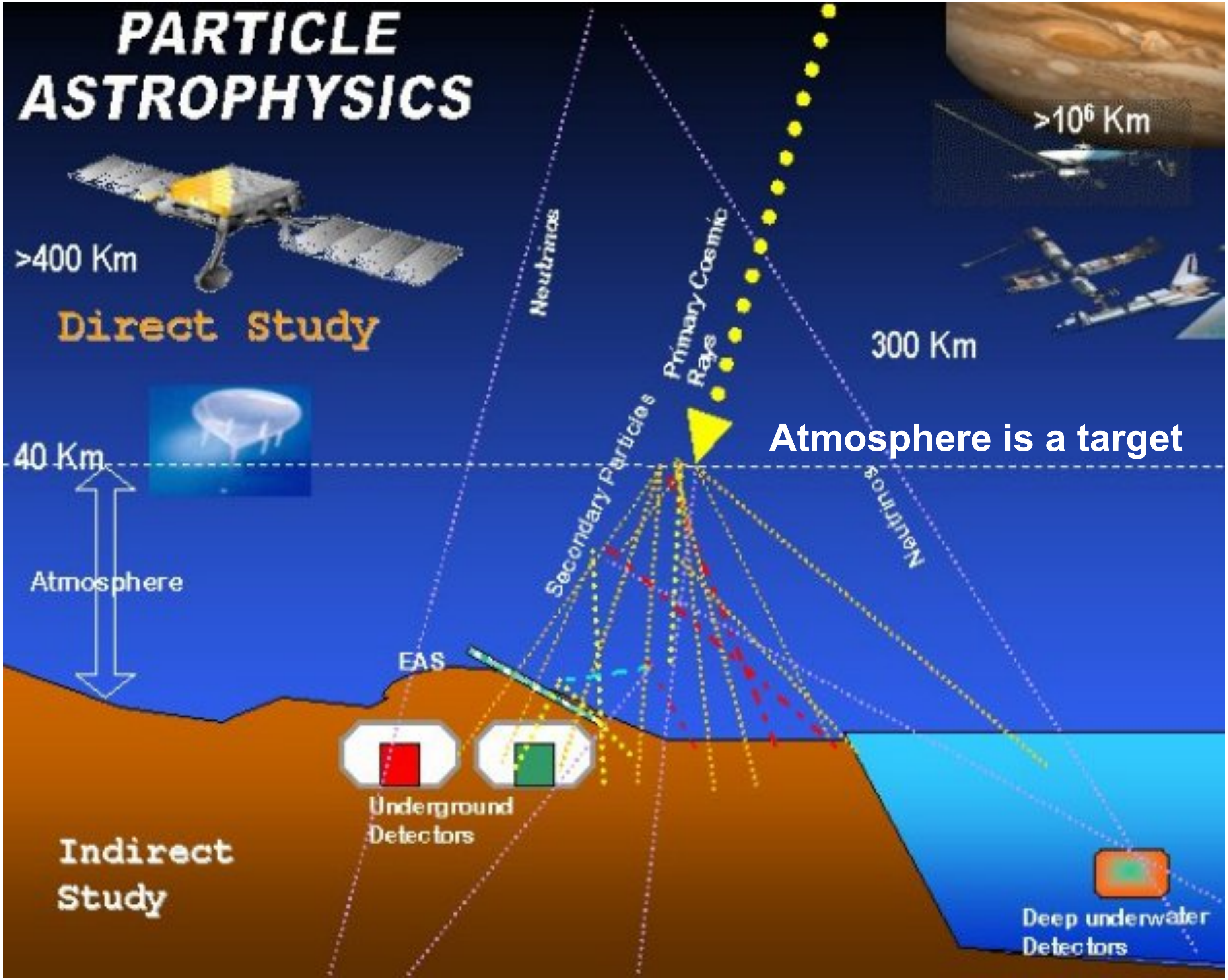
The CR flux follows a ~$E^{-2.7}$ power law (no Maxwell-Boltzman like CMBR) extended for 10 orders of magnitude in energy (27 orders of magnitude in flux).



CR Detection



Detecors for particle astrophysics



Atmosphere is a target

The cosmic ray spectrum

- **$E<10^4$ GeV**

direct detection

Spectrometers
(ΔA = 1 resolution,
good E resolution)

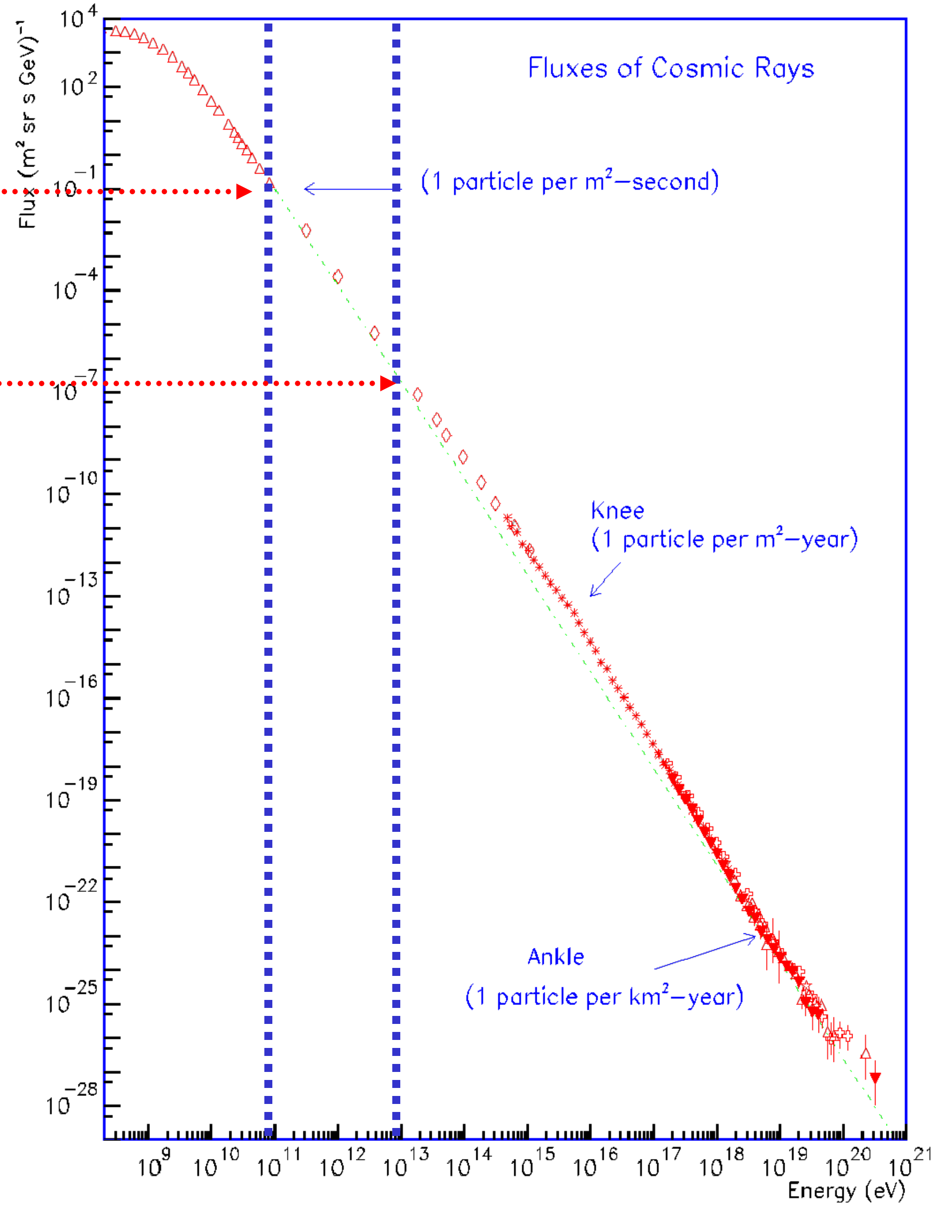
Calorimeters
(E resolution)

- **$E>10^4$ GeV**

indirect detection

Ground based array
Underground Detectors

Fluorescence detectors

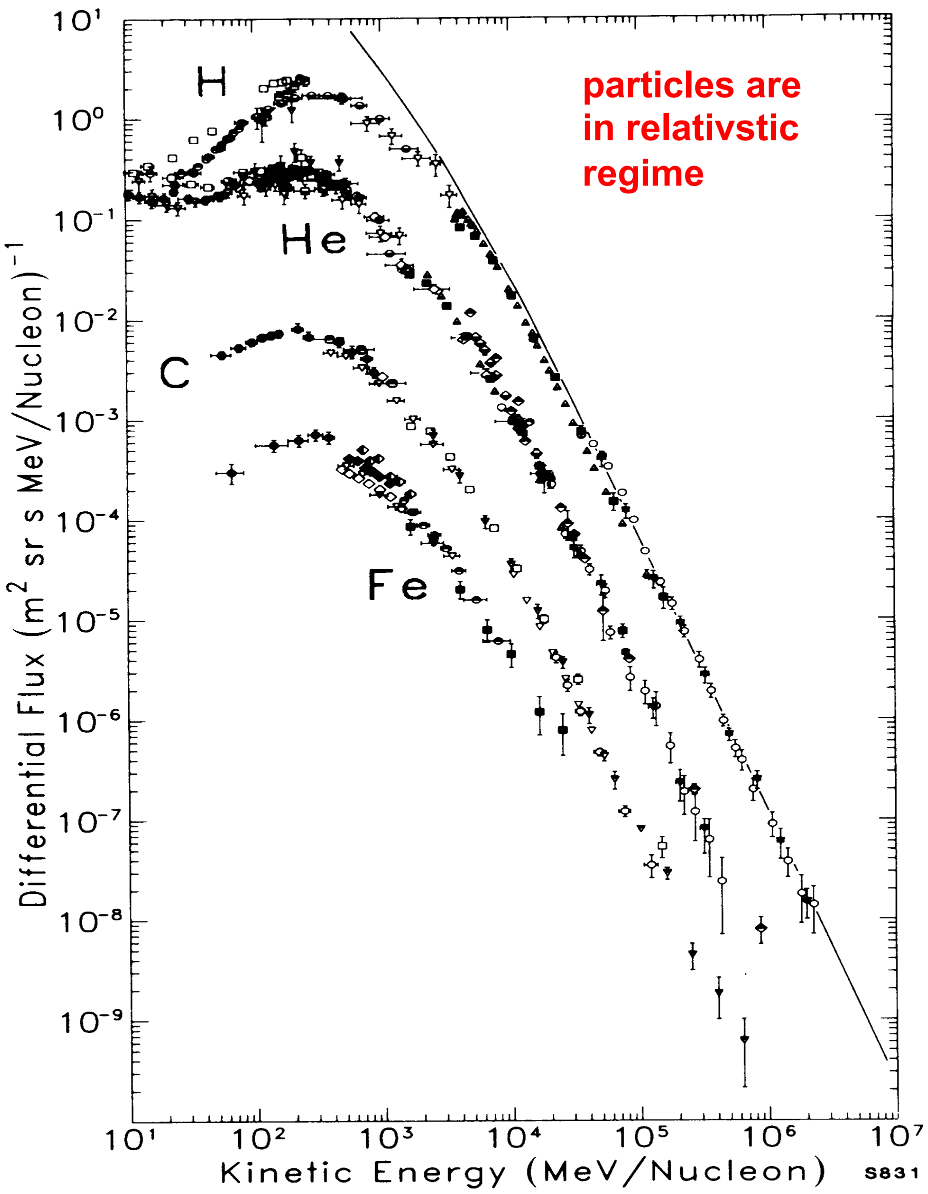


At the top of atmosphere

- 98 % nuclei
  - 87% protons
  - 12% alpha particles
  - 1% heavy nuclei
- 2% electrons, positrons, neutrinos, gamma rays

Low energy cutoff depends on rigidity of particles

$$\text{Rigidity} \equiv \frac{pc}{Ze} = Brc$$



The cosmic ray spectrum

Main features:

- $N(E)dE = K E^{-\alpha} dE$

  max at 1 GeV → 2p /m² s sr MeV

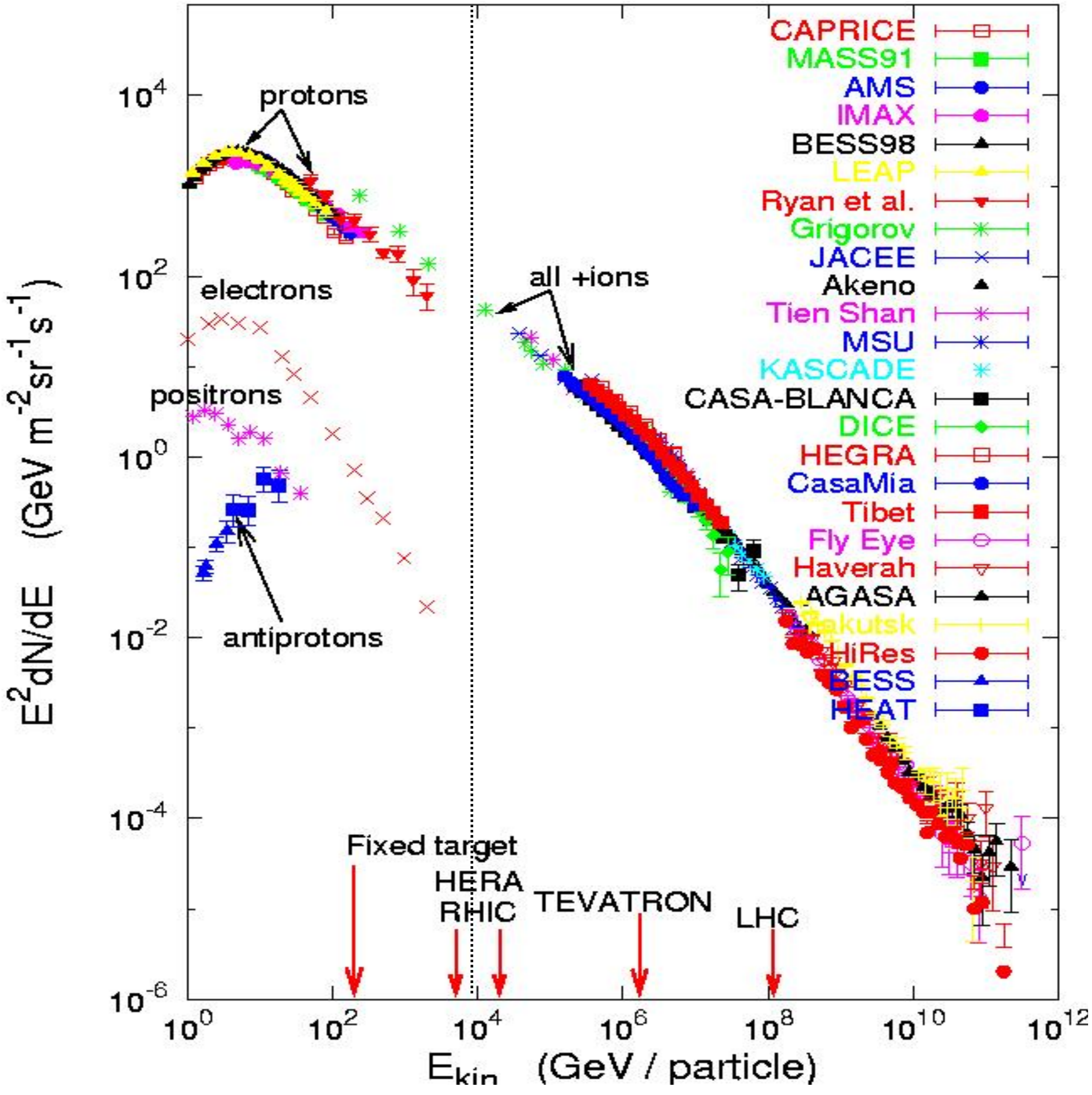
$\rho_{CR}(E) = 1 eV/cm^3$

Same orer of Magnitude of energy density in Galactic Magnetic Field

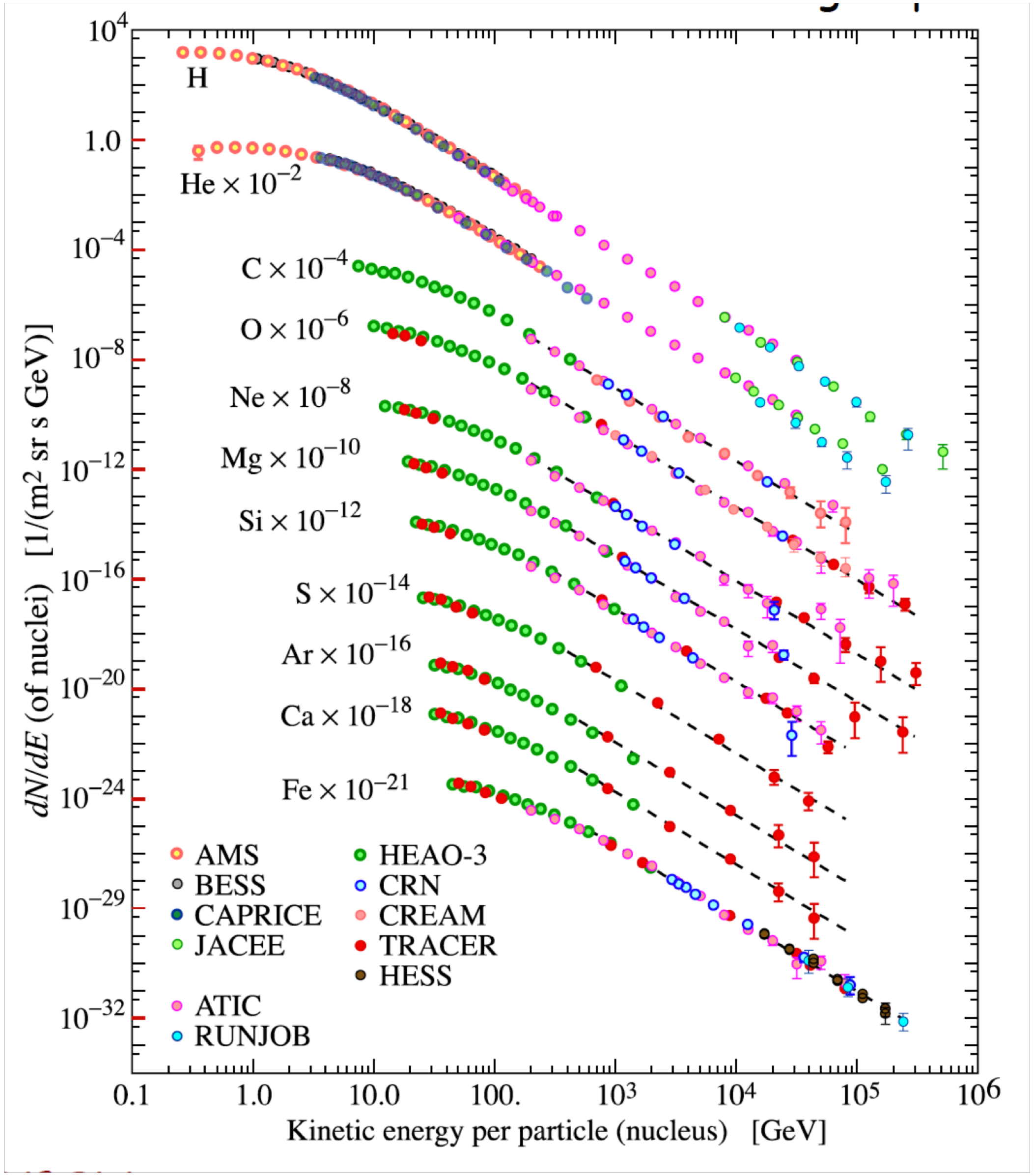
→ Energy exchange in diffusion

- cutoff at E<1 GeV/n and modulation with solar cycle

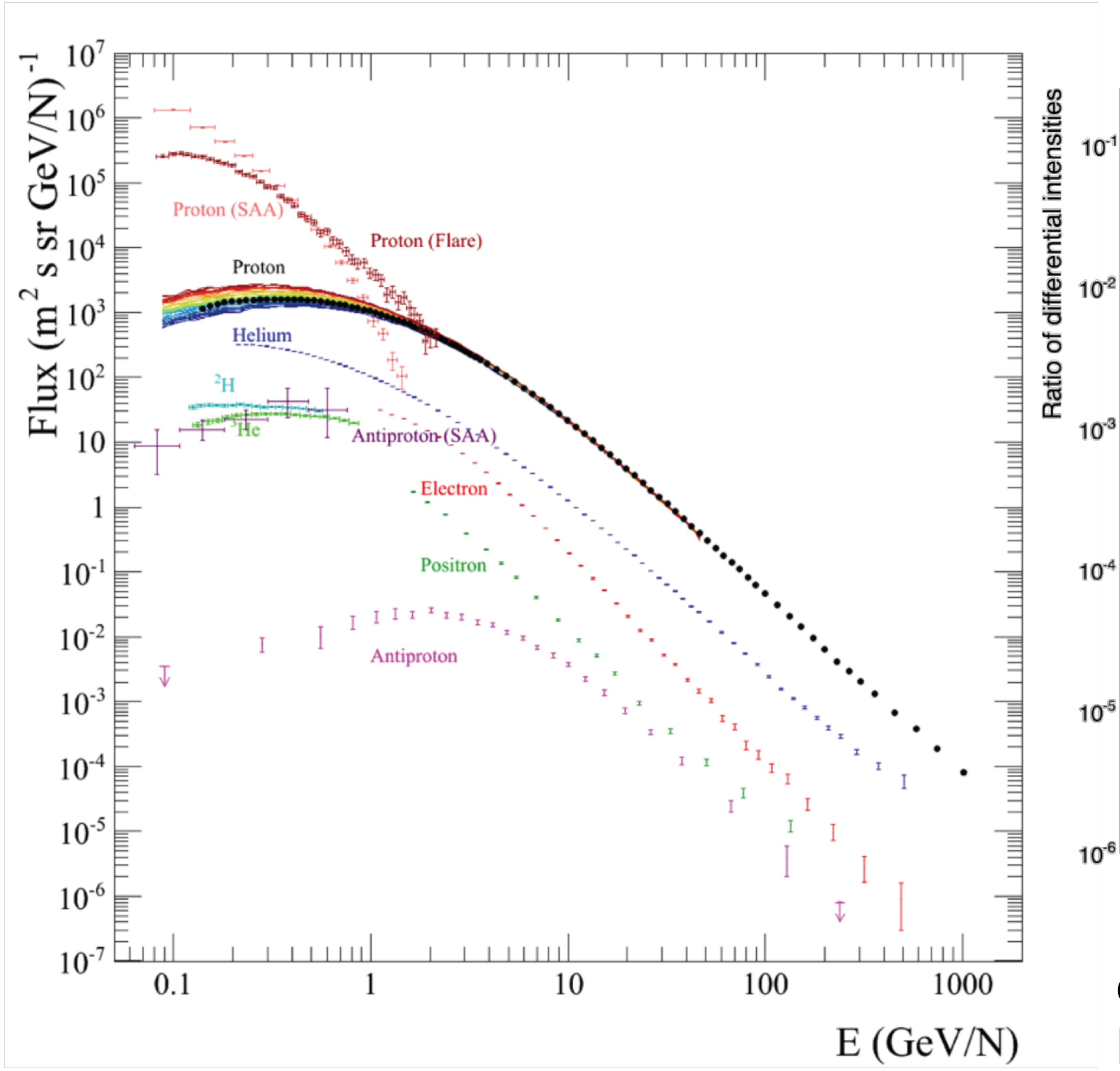
- Different elements have different abundances as a function of E



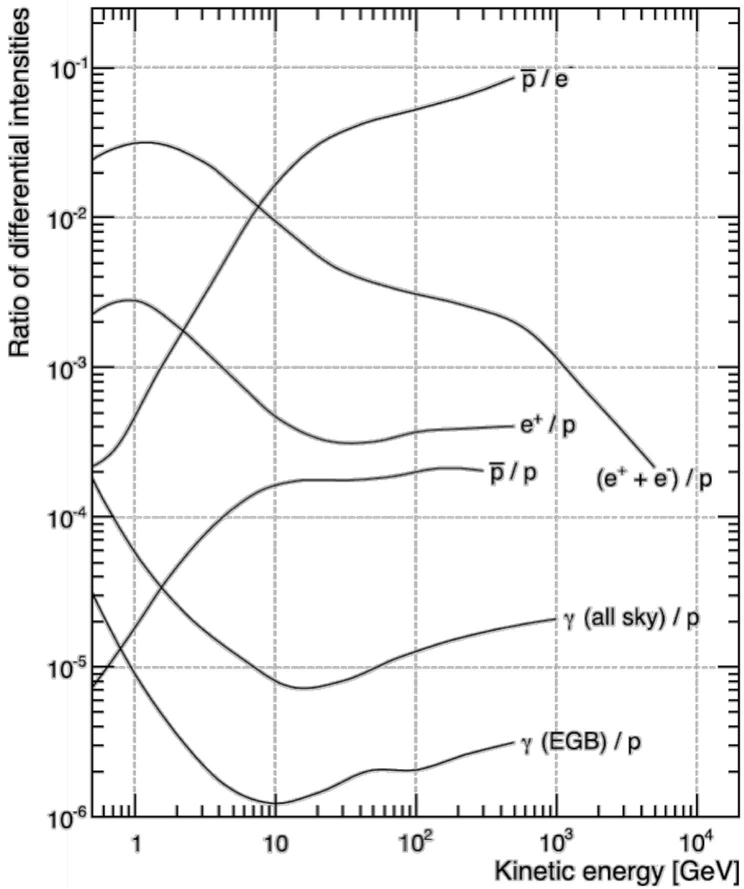
Cosmic ray composition



Cosmic ray composition



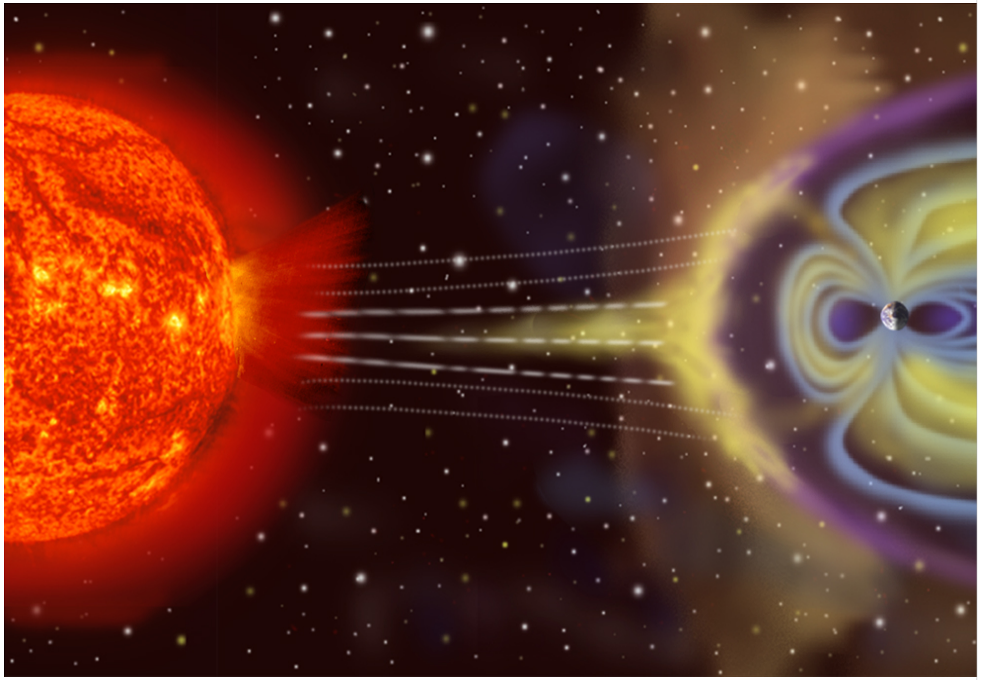
Antimatter, matter and gammas

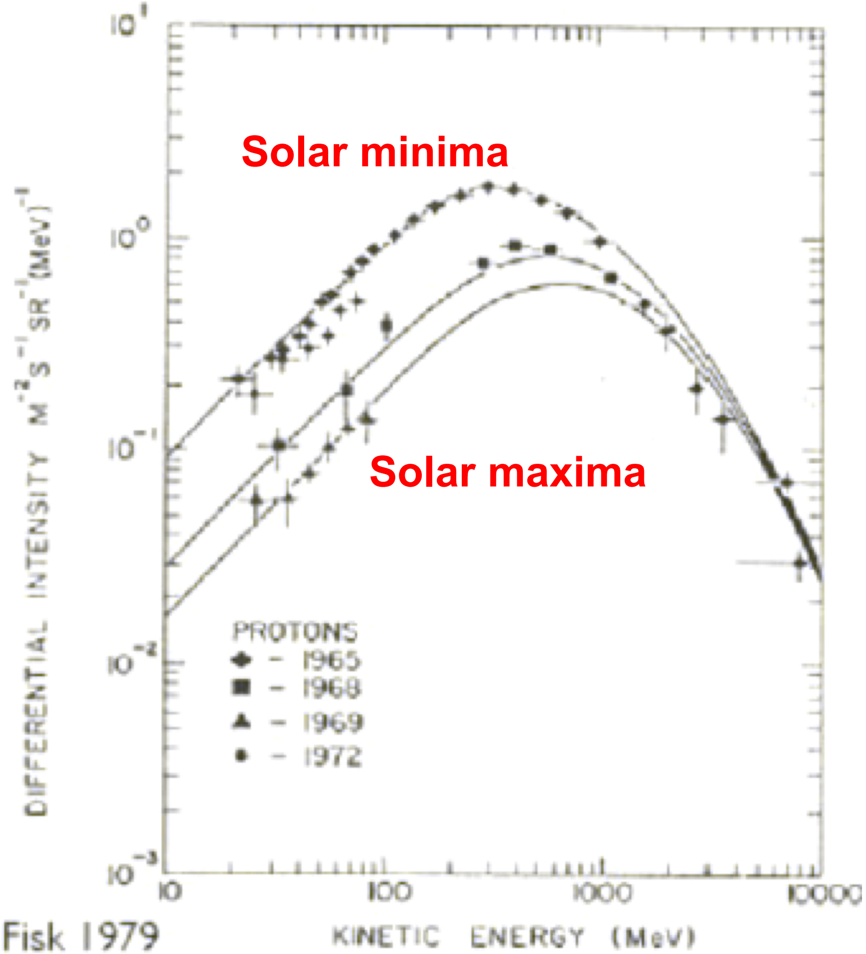


e+, p+, d+ from Dark Matter annihilation
e+ from local sources

Solar modulation

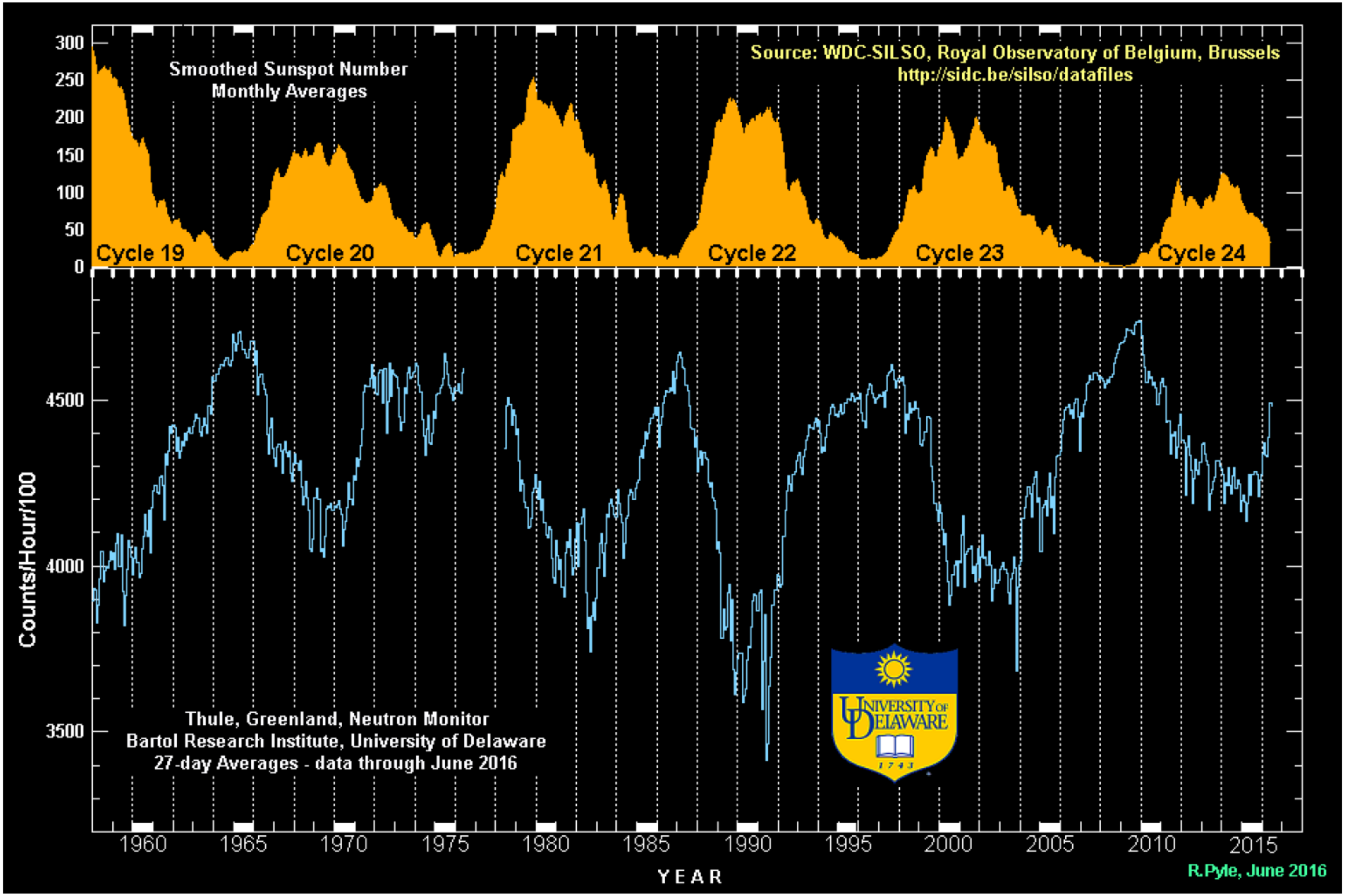
When solar activity is large the magnetic field blows away low energy particles ($T_{solar\ cyle}$ = 11 years)





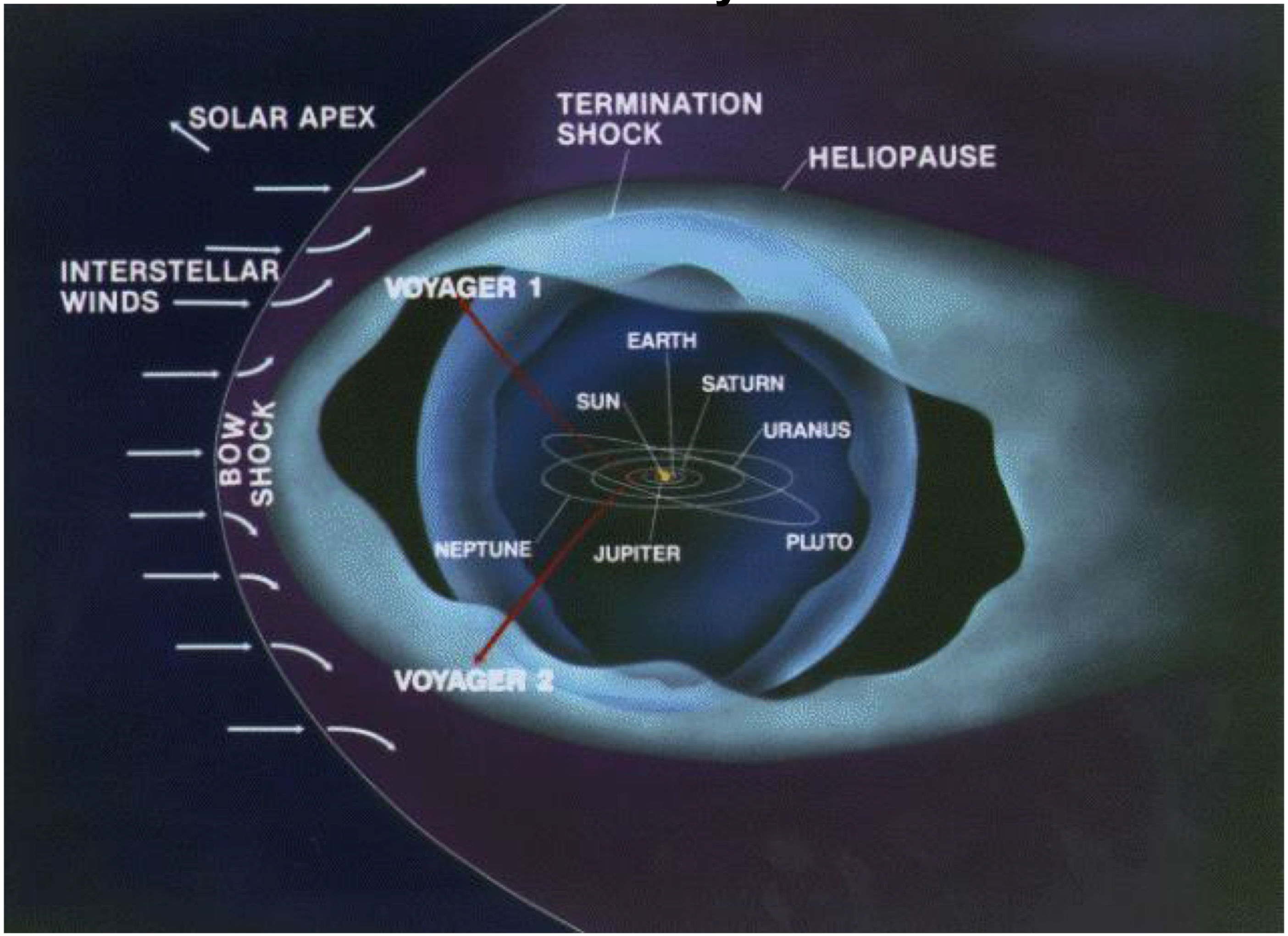
Fisk 1979

Solar modulation



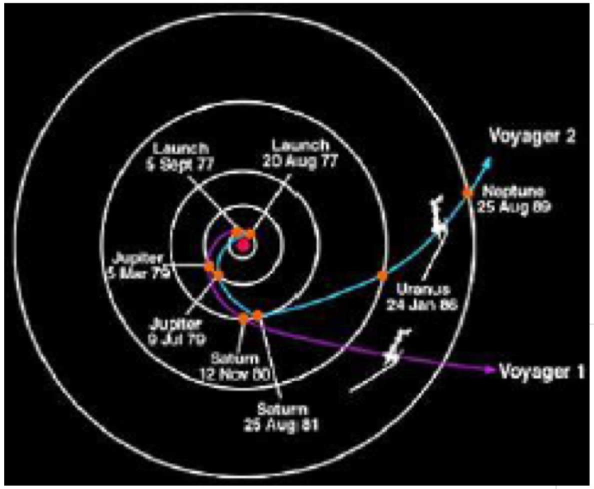
Effect of heliosphere

Distorts charged particle spectra
Below ~ 10 MeV, solar particles dominate
Above GeV → outside Solar System

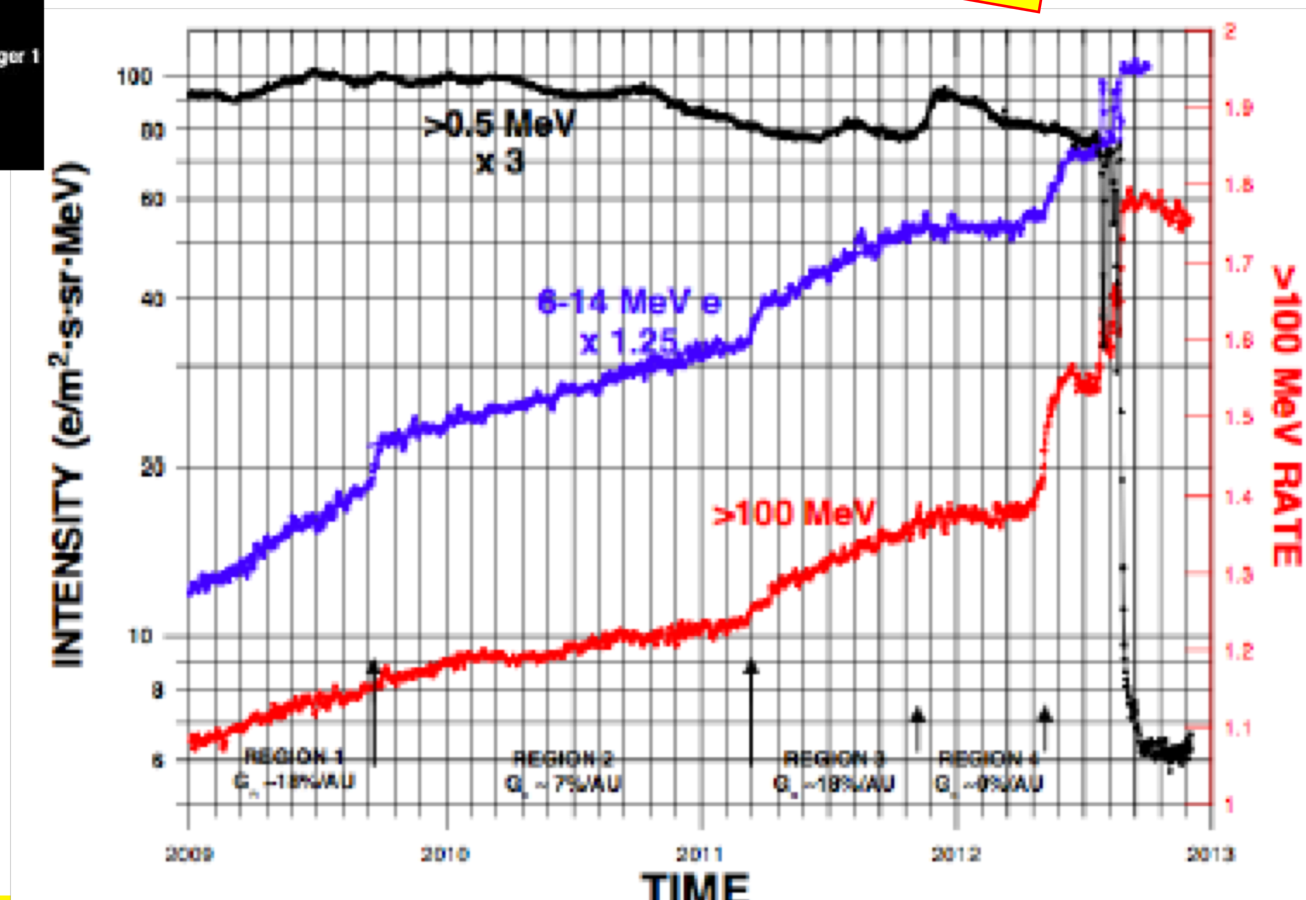


Voyager

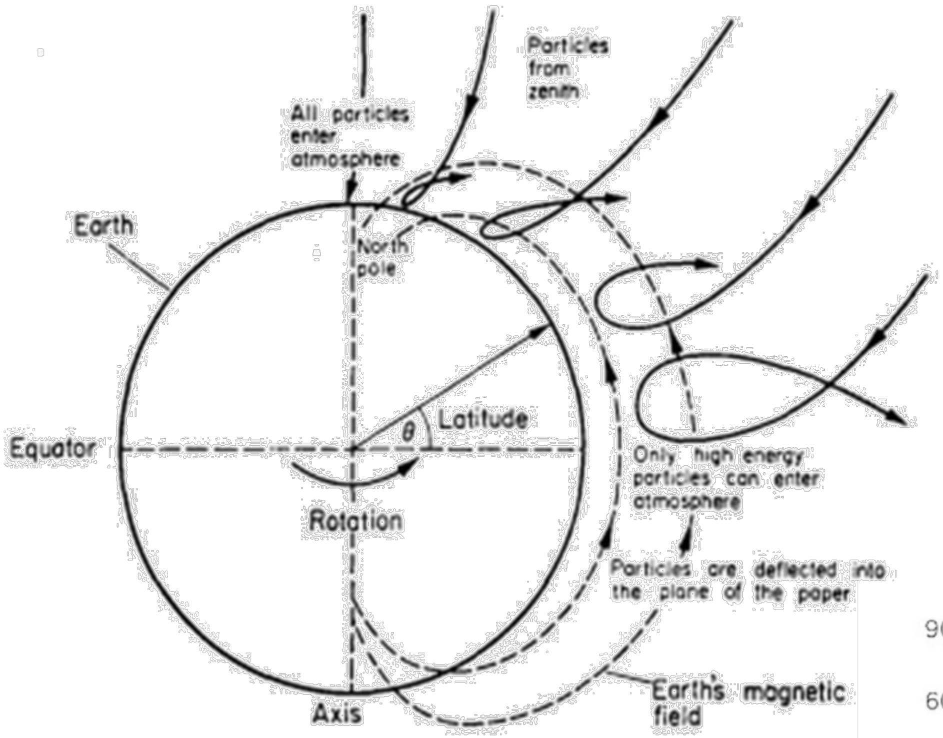
Effect of heliosphere



Voyager exits the solar system

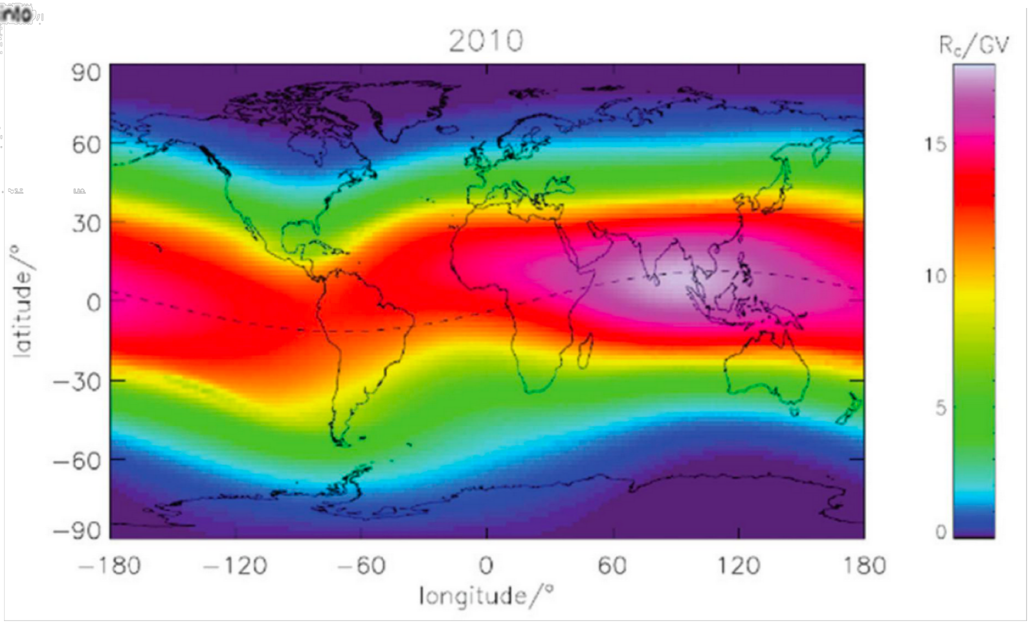


Geomagnetic Cutoff



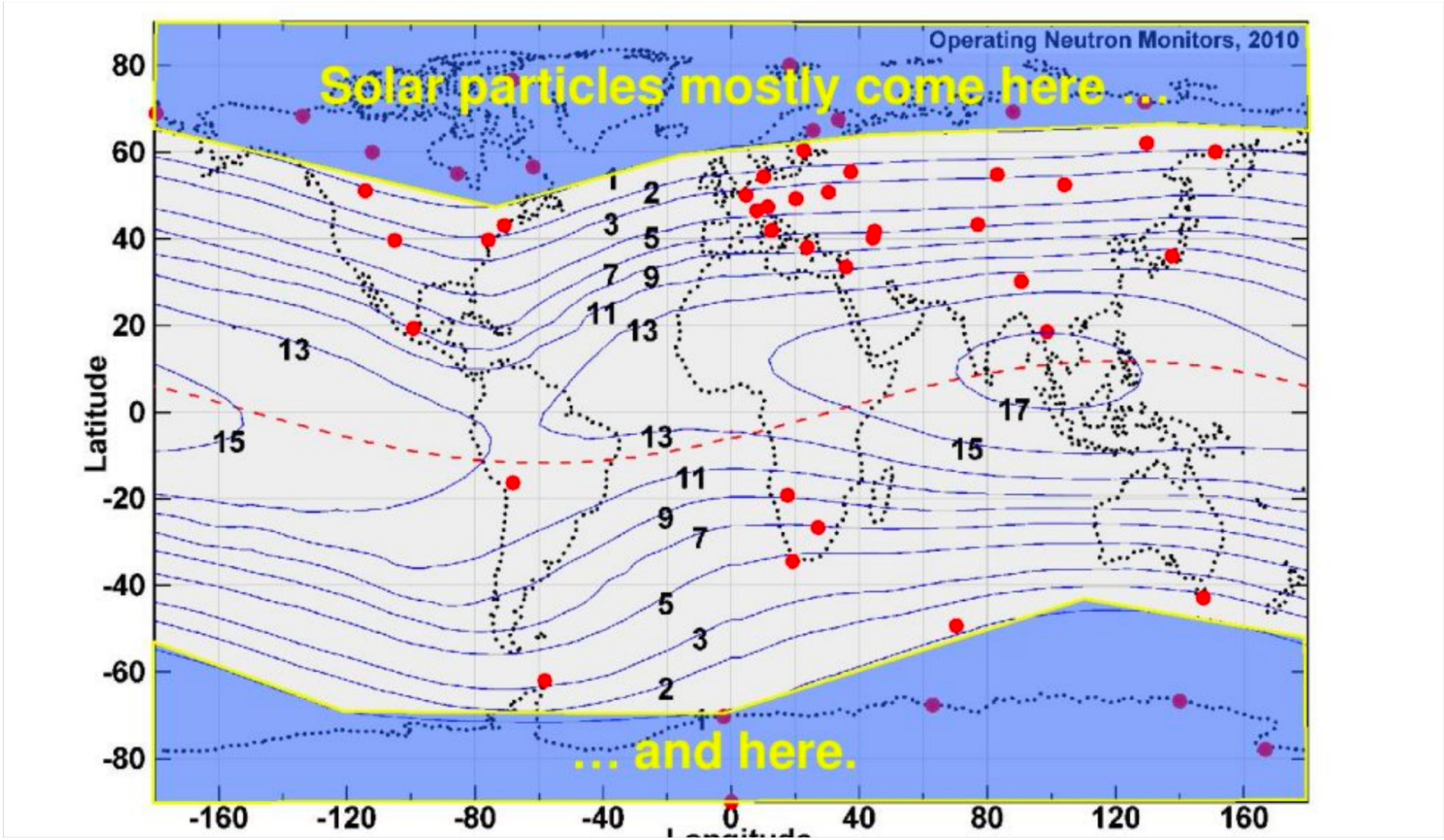
Rigidity cutoff:
$R_c \sim 15 \cos^4\lambda$ GV
(λ = Earth latitude)
Stroemer

Cutoff rigidity [GV]

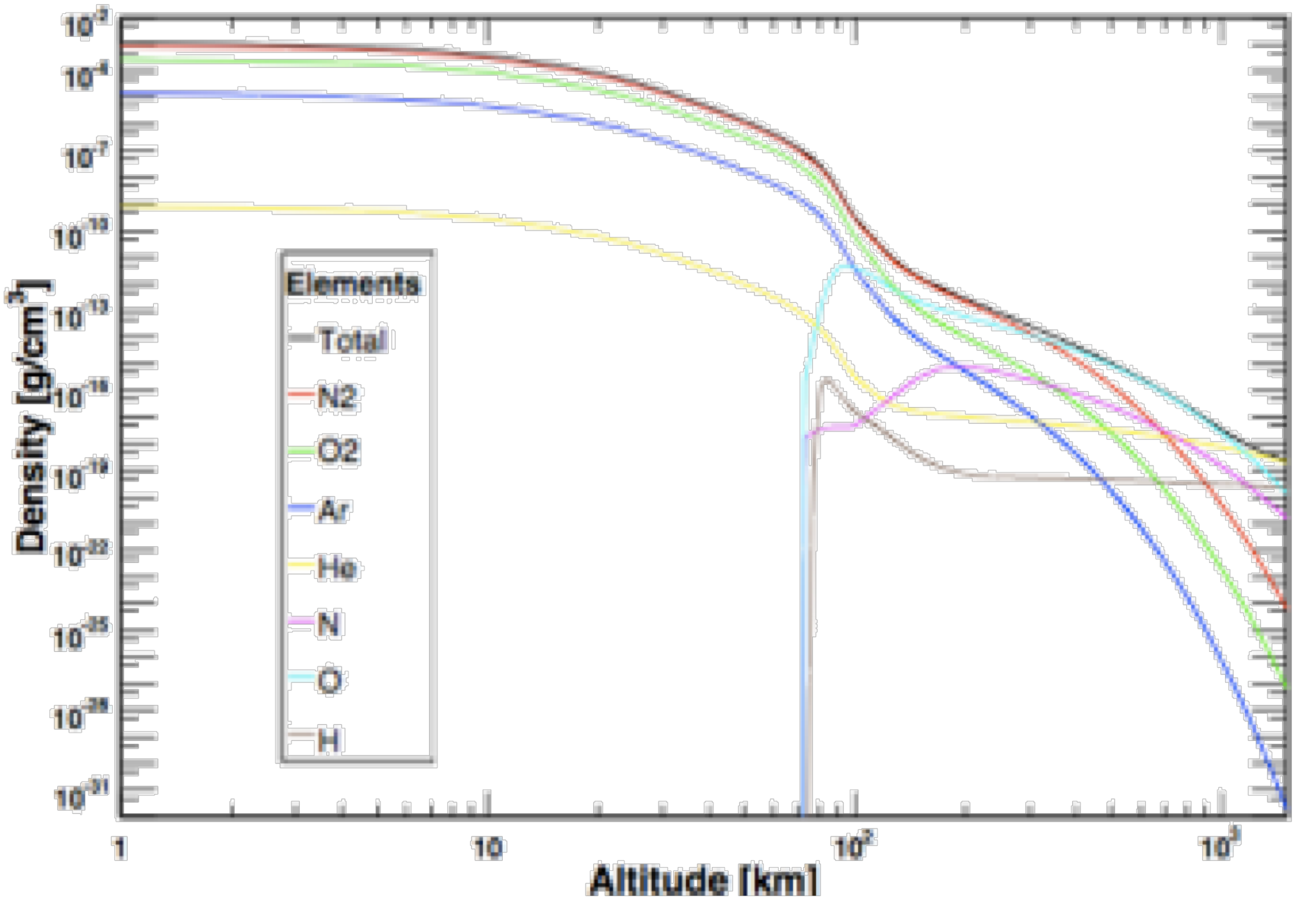


$R > R_C$
→ Particles can reach the Earth

Geomagnetic Cutoff



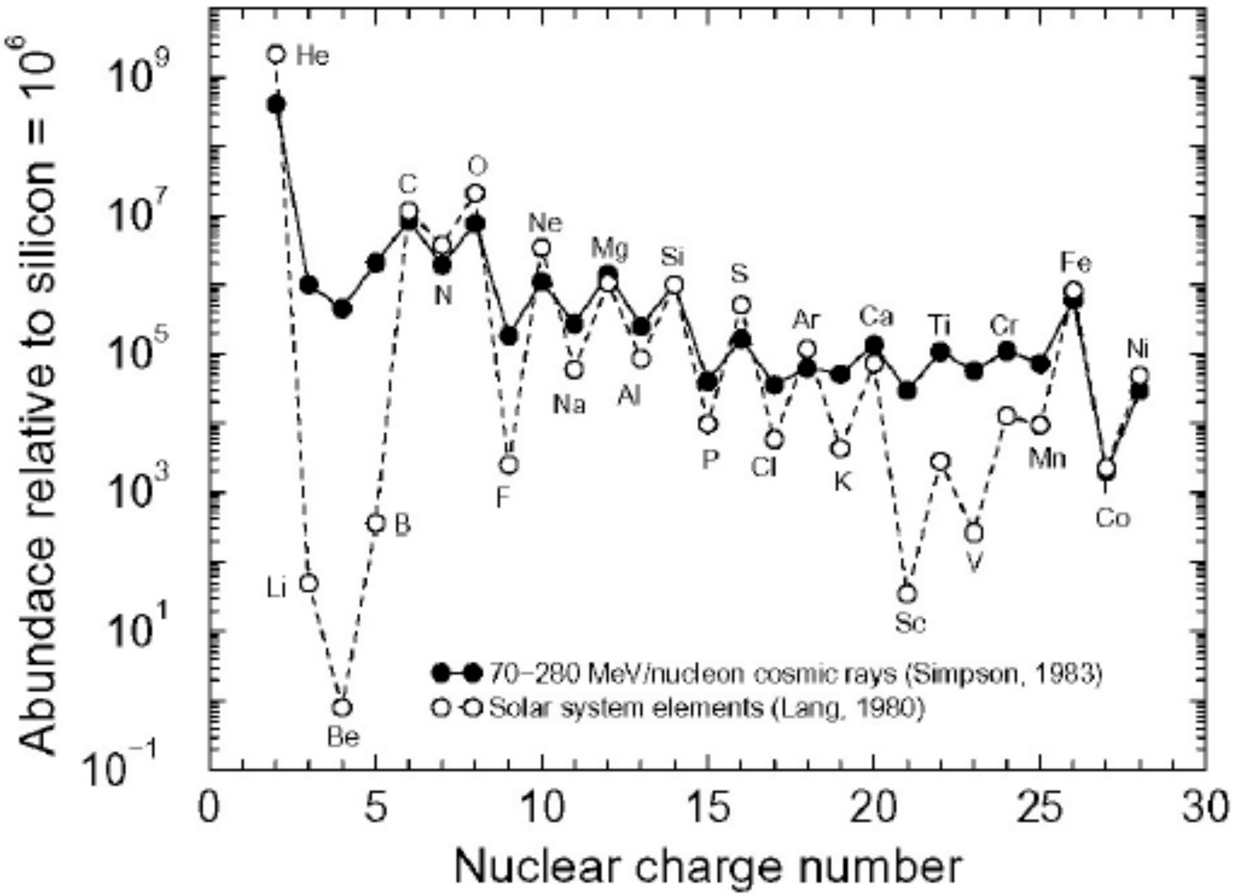
Atmosphere



Top of atmosphere:
Depth: 4 g/cm^2
(similar to matter column depth during CR journey in the Galaxy)

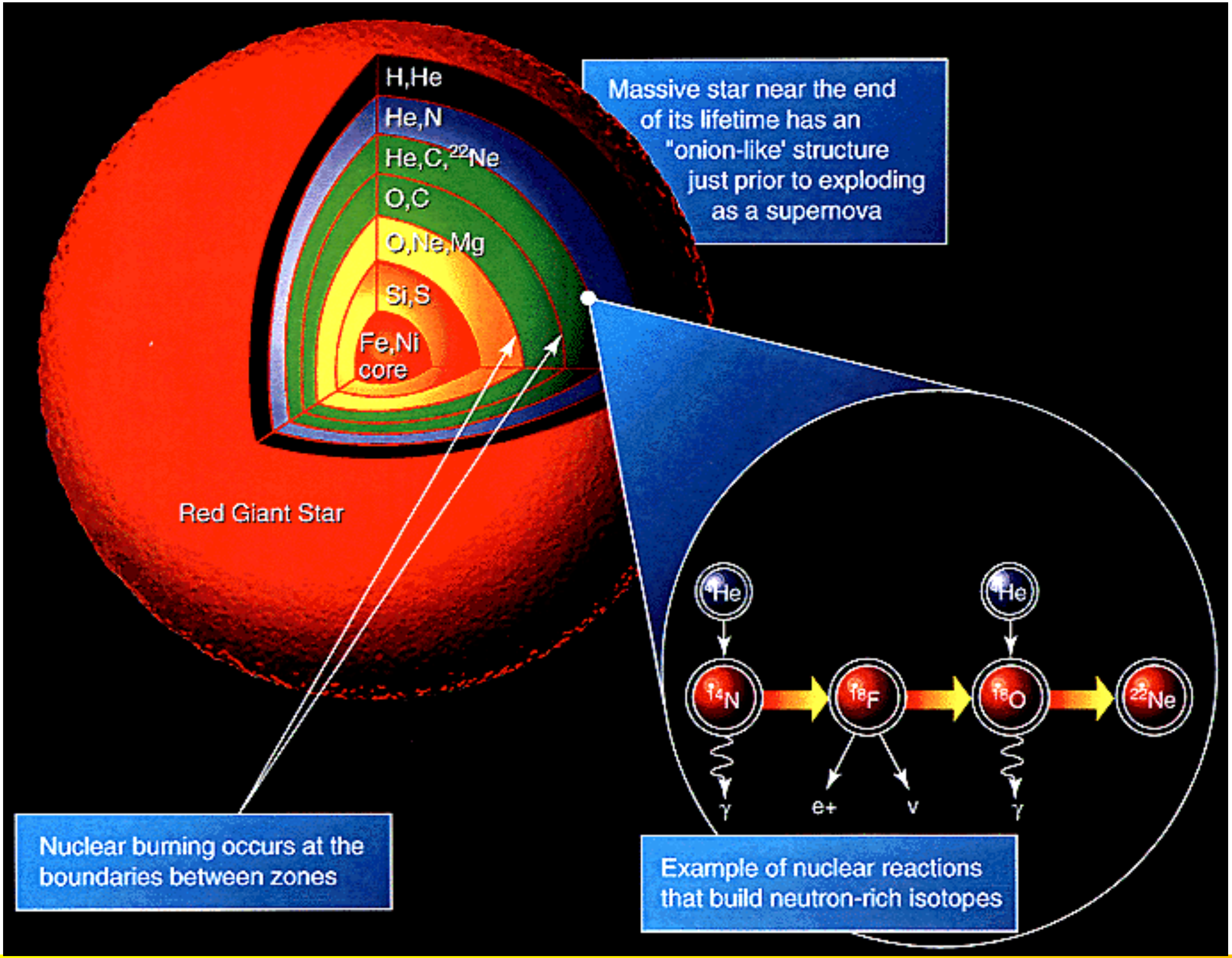
Optimal measurements: Polar orbits, solar minima, top of atmosphere

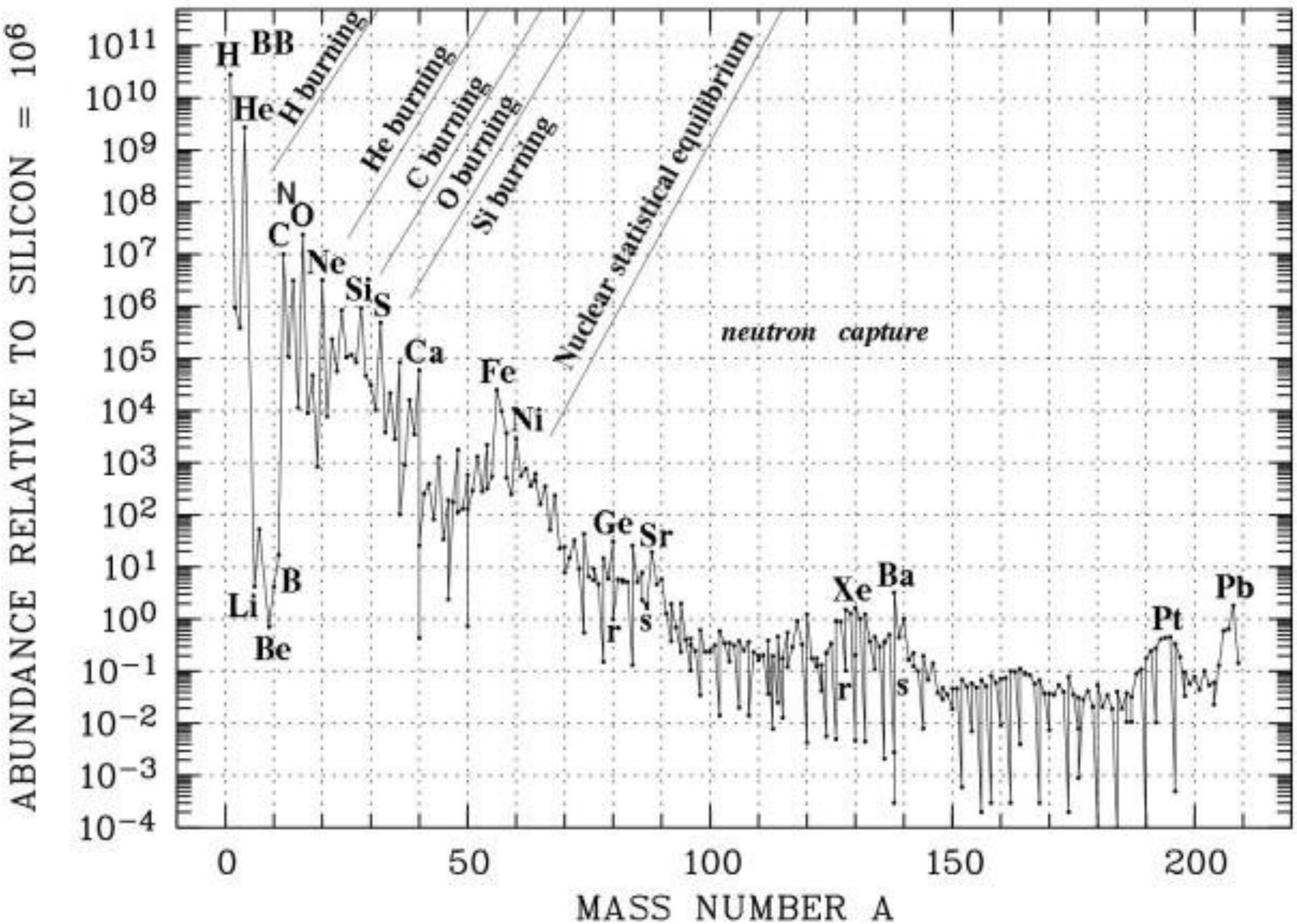
Abundance of elements



- Peaks at CNO and Fe are common in CR and solar elements
- Light elements are overabundant in CR
- H, He underabundant in CR
- Excess of sub-Fe elements in CR

SN elements propagating in the Galaxy


H,He
He,N
He,C,^{22}Ne
O,C
O,Ne,Mg
Si,S
Fe,Ni core
Red Giant Star
Massive star near the end of its lifetime has an "onion-like' structure just prior to exploding as a supernova
Nuclear burning occurs at the boundaries between zones
^{4}He
^{4}He
^{14}N
^{18}F
^{18}O
^{22}Ne
γ
e+
ν
γ
Example of nuclear reactions that build neutron-rich isotopes

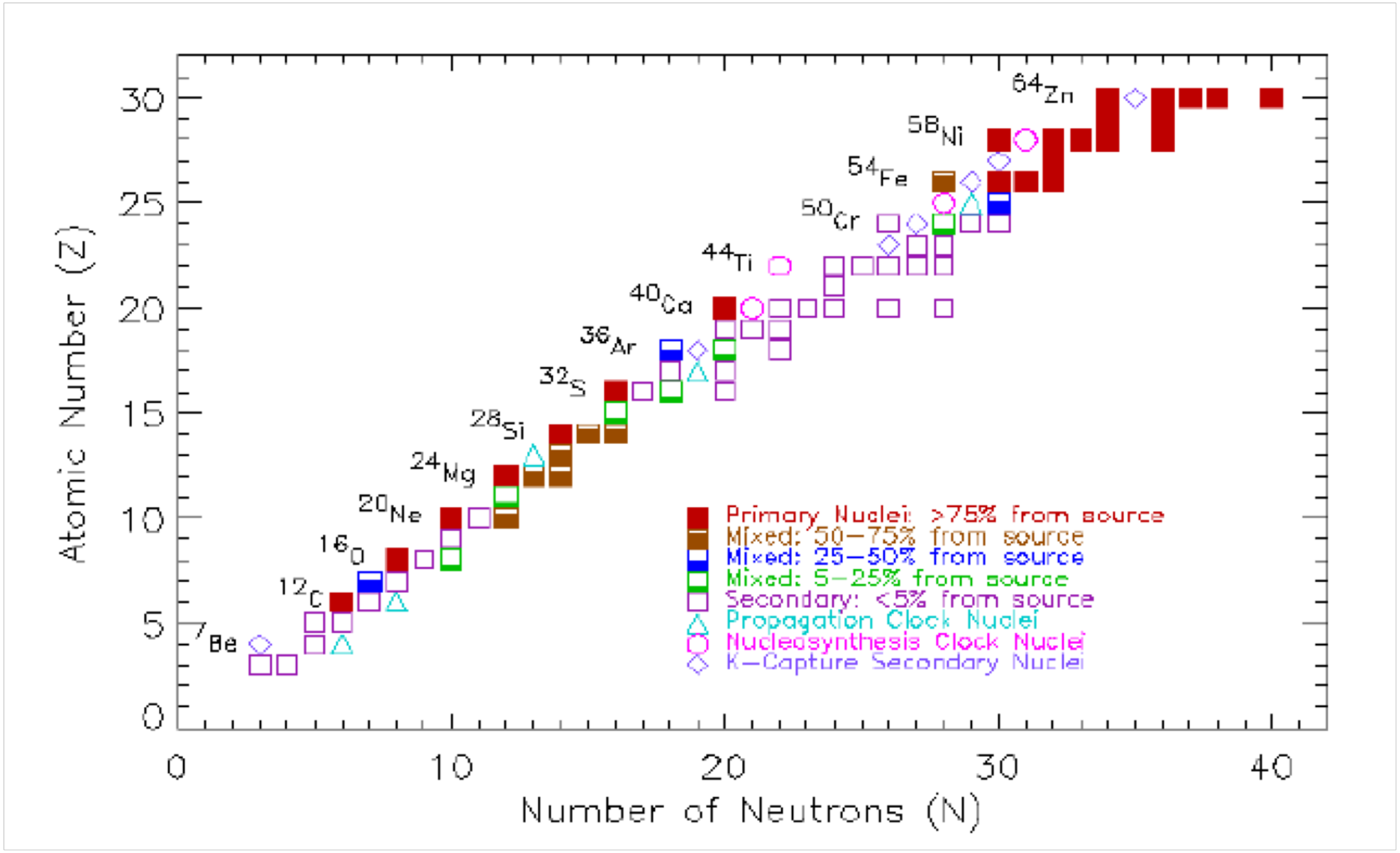

ABUNDANCE RELATIVE TO SILICON = 10^6
MASS NUMBER A
H
BB
He
H burning
He burning
C burning
O burning
Si burning
Nuclear statistical equilibrium
neutron capture
N
O
C
Ne
Si
S
Ca
Fe
Ni
Li
B
Be
Ge
Sr
r
s
Xe
Ba
Pt
Pb

Primaries produced and accelerated in sources

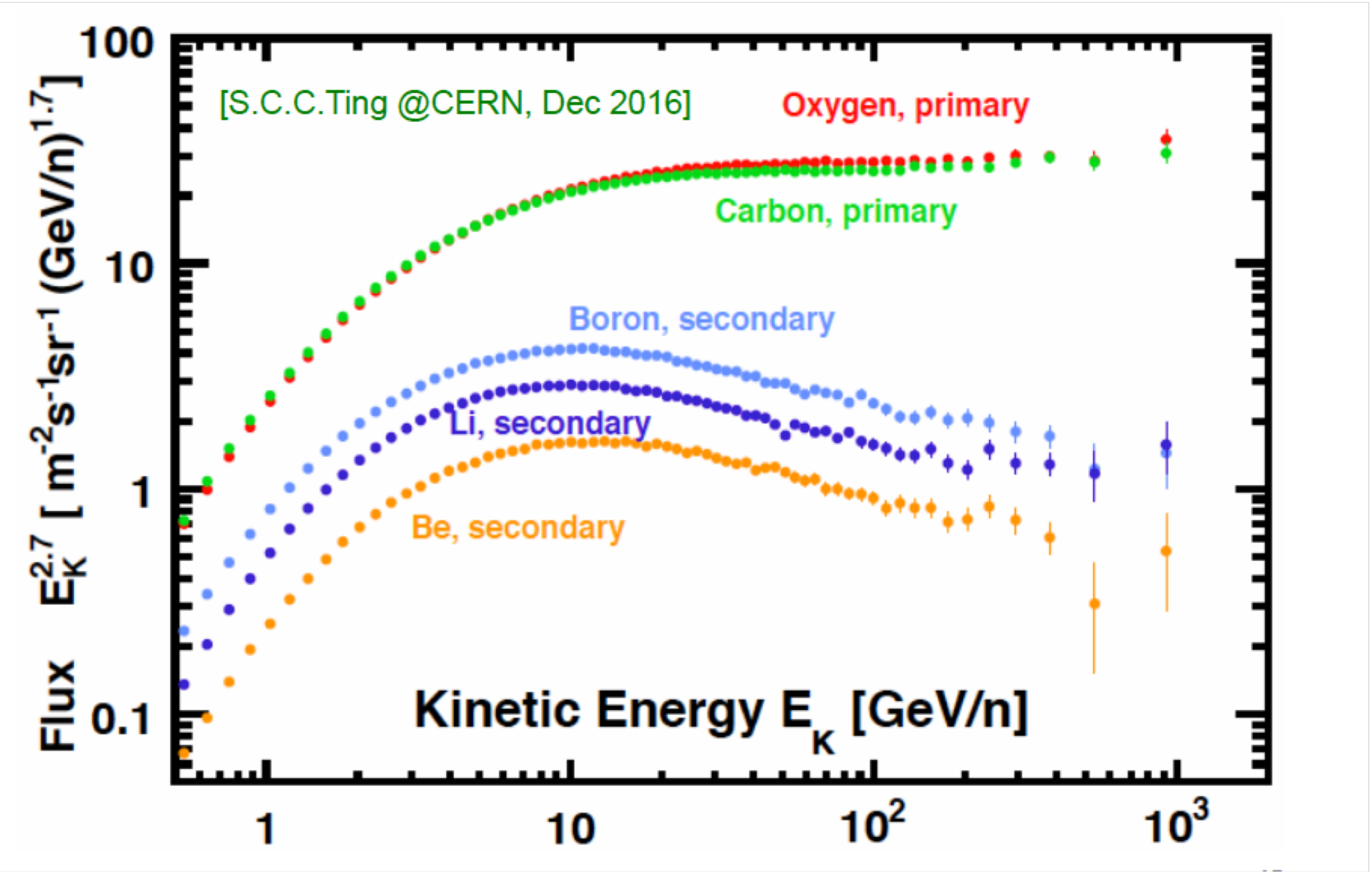
H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)

Secondaries produced by spallation of primary CRs on ISM

Li, Be, B, sub-Fe; e+, p+, d+; …



Primary to Secondary ratio vs Energy



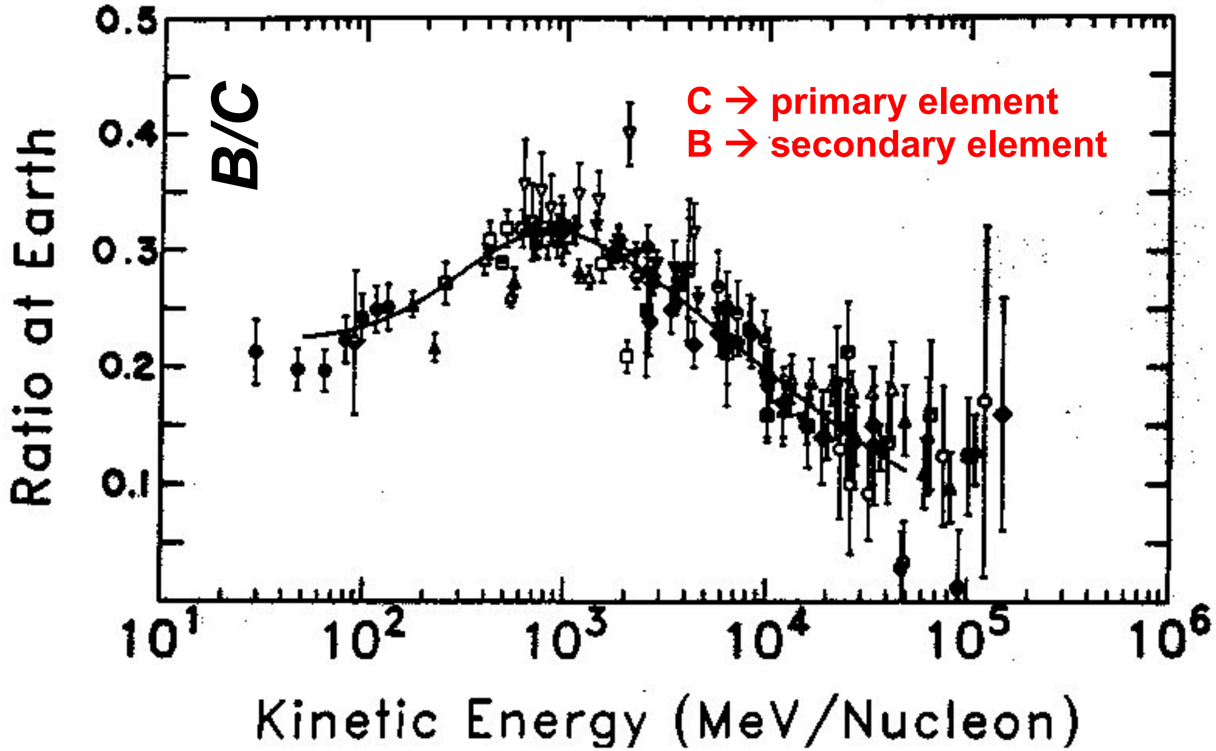
Residence time is a function of energy

CR diffusion time
Escape time

$$\tau_{esc} \propto D^{-1}(E) \propto E^{-\delta}$$

Escape length

$$\lambda_{esc} = \rho_{ISM} v \, \tau_{esc} \propto E^{-\delta}$$



for **primary** CR $N_P(E) \propto Q_P(E)\, \tau(E) \propto E^{-(\alpha+\delta)}$

for **secondary** CR $N_S(E) \propto Q_P(E)\, \tau^2(E) \propto E^{-(\alpha+2\delta)}$

$$\Rightarrow \boxed{\frac{N_S}{N_P} \propto E^{-\delta}}$$

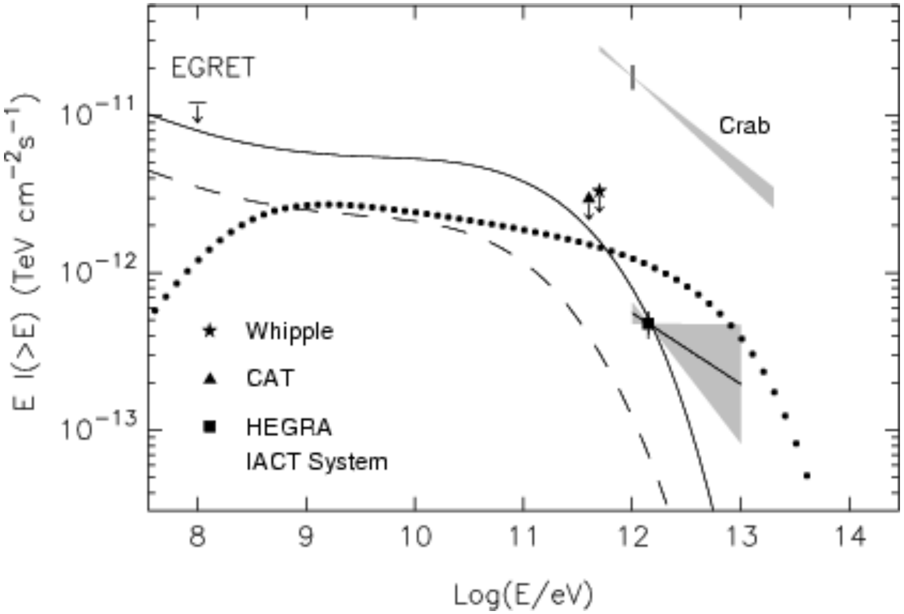
- At high energy (>10 GeV/n) the S/P ratio measures the energy dependence of the escape path-length λ
- Energy spectrum of particles injected by the source is different from observed spectrum

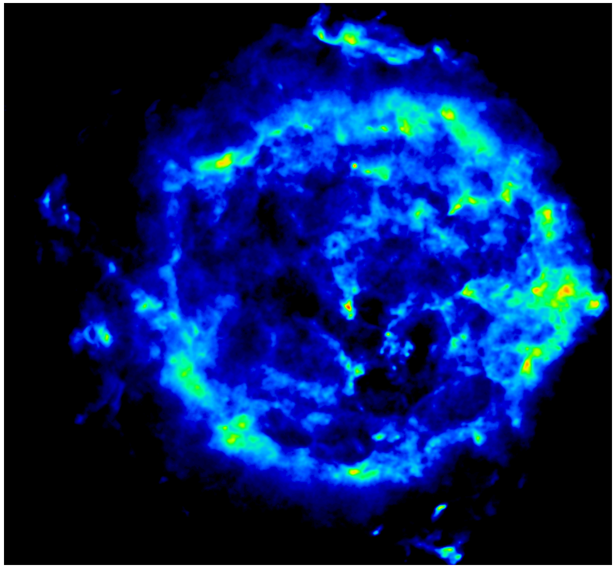
What are the Sources of Cosmic Rays?

1934 **Baade and Zwicky: SN explosions are sources of cosmic rays**

1949 **Enrico Fermi: Cosmic rays accelerated by collisions with moving magnetic fields**

1977 **Krimsky-Bell: Cosmic rays accelerated by supernova remnant shocks**





Cassiopeia A;
VLA Radio Image

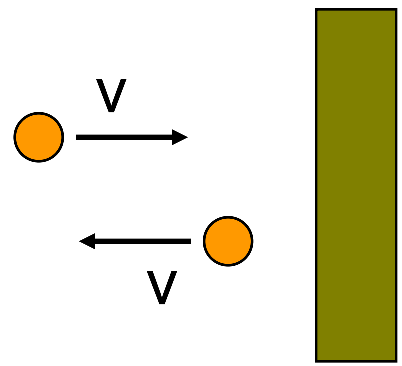
Cas A

But unusually low γ-ray flux…

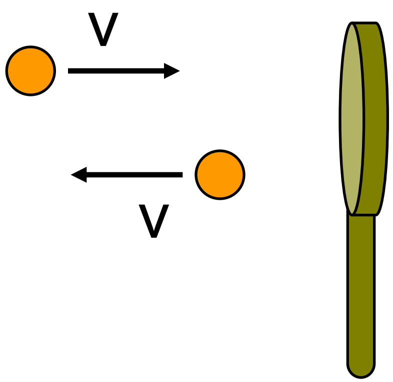
Aharonian et al. (2001)

Acceleration of CR: trivial analogy...

- Tennis ball bouncing off a wall
  - –No energy gain or loss



rebound = unchanged velocity

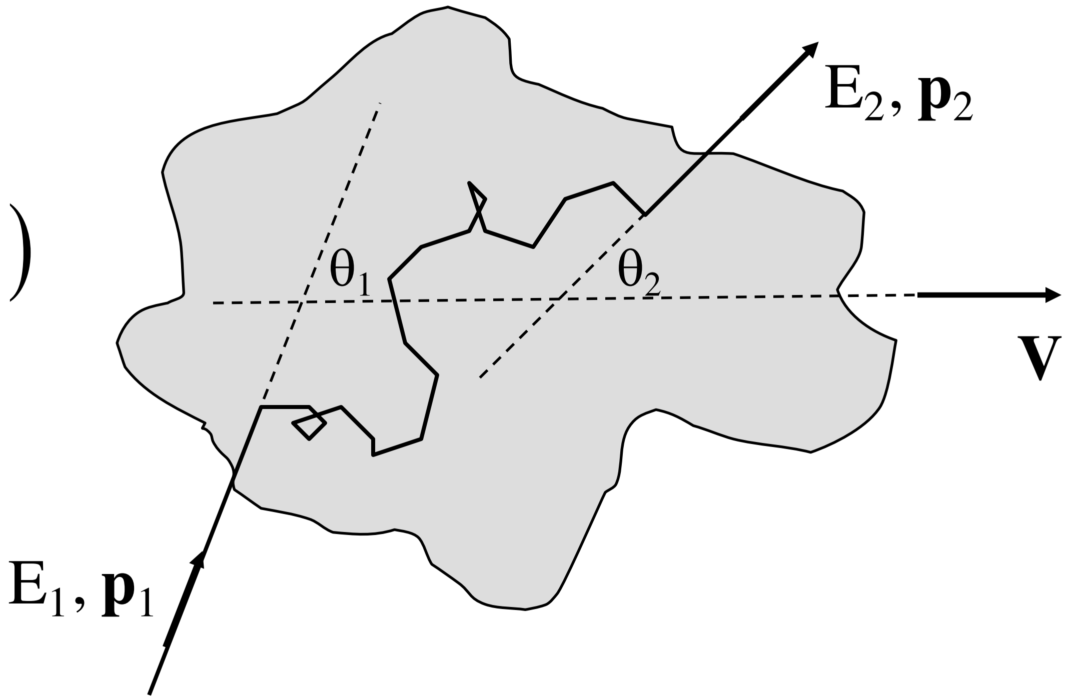


same for a steady racket...

How can one accelerate a ball and play tennis at all?!

•Direction randomized by scattering on the magnetic fields tied to the cloud

$$E_2 = \gamma E_2' \left(1 - \beta \cos\theta_2'\right)$$

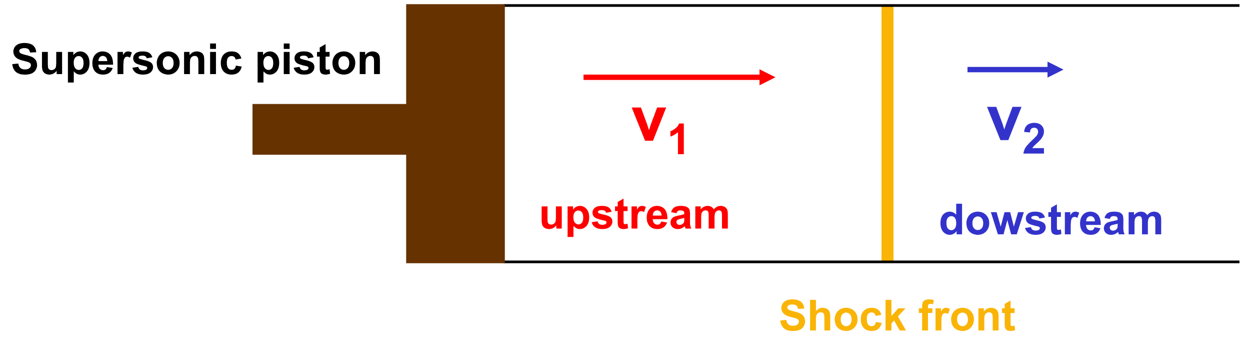


Entering angle:
probability $\propto$ relative velocity (v - V cos θ)
$\rightarrow$ < cos θ_1 > = - β / 3

Exit angle: < cos θ'_2 > = 0

second order in V/c

$$\frac{\Delta E}{E} = \frac{1 + \beta^2/3}{1 - \beta^2} - 1 \approx \frac{4}{3}\beta^2$$



Discontinuities in flow equations across (stationary) shock front

Conservation laws still hold

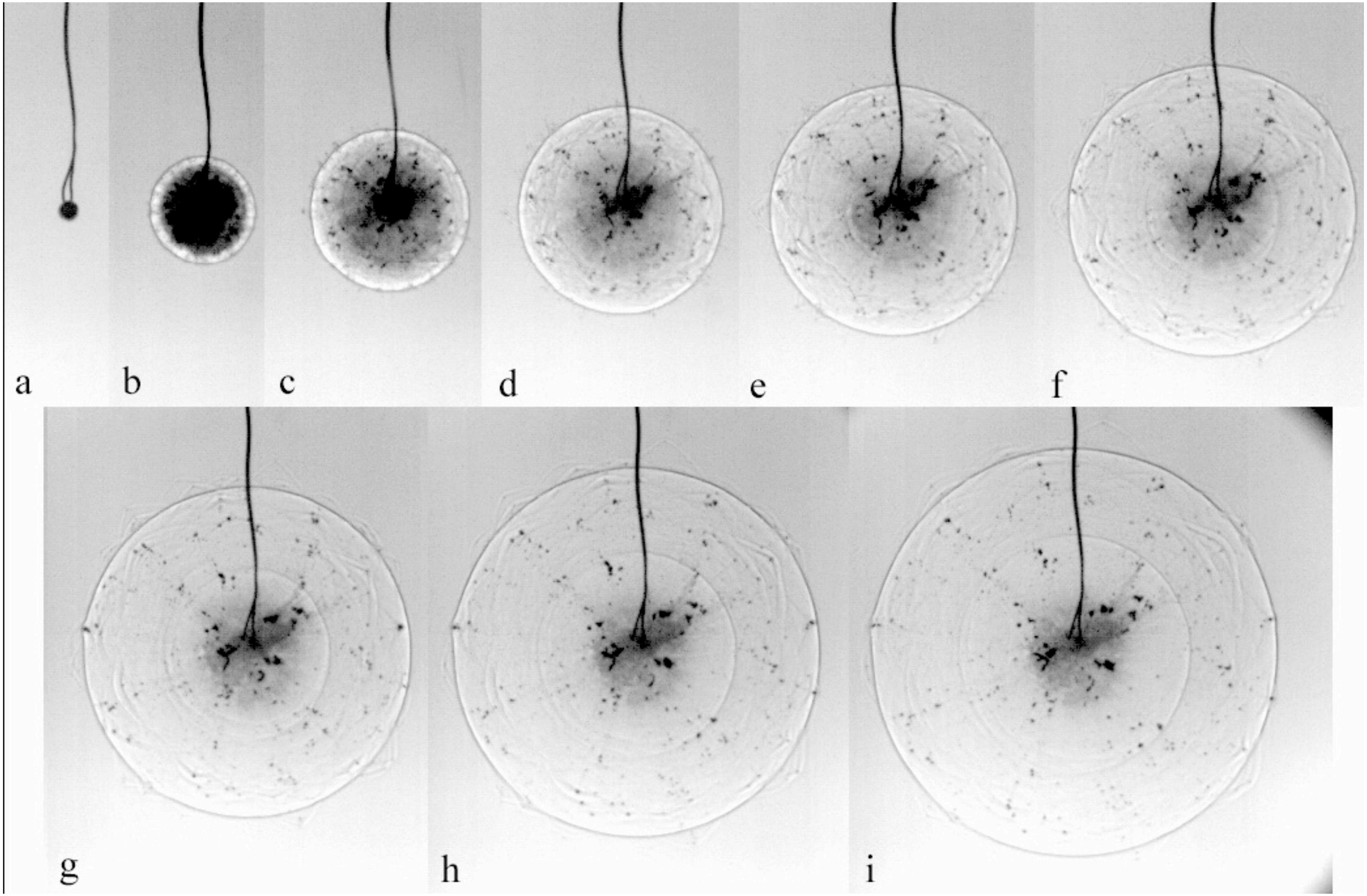
mass: $\rho_1 v_1 = \rho_2 v_2$

momentum: $p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2$

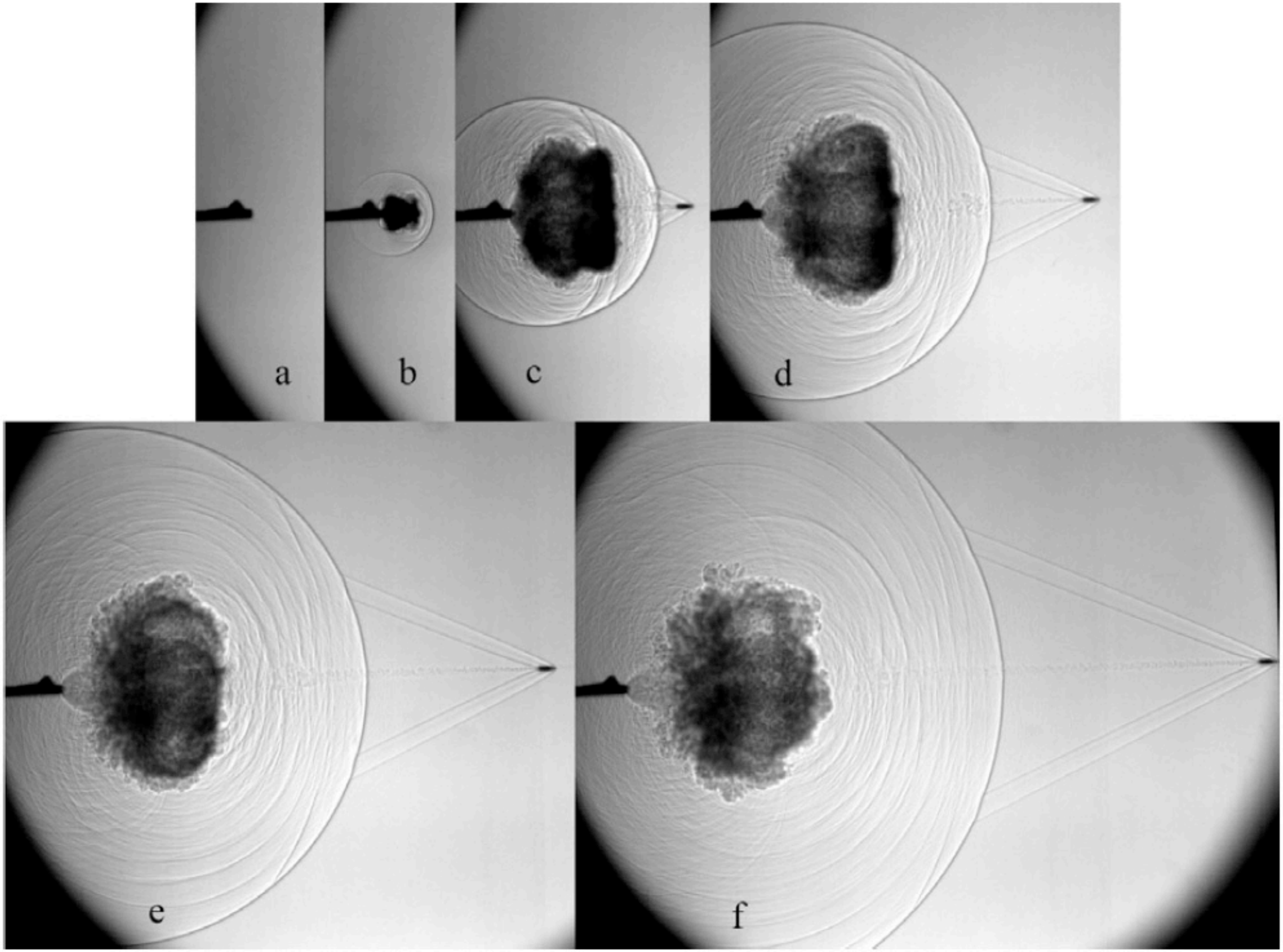
energy: $\frac{1}{2} v_1^2 + h_1 = \frac{1}{2} v_2^2 + h_2$

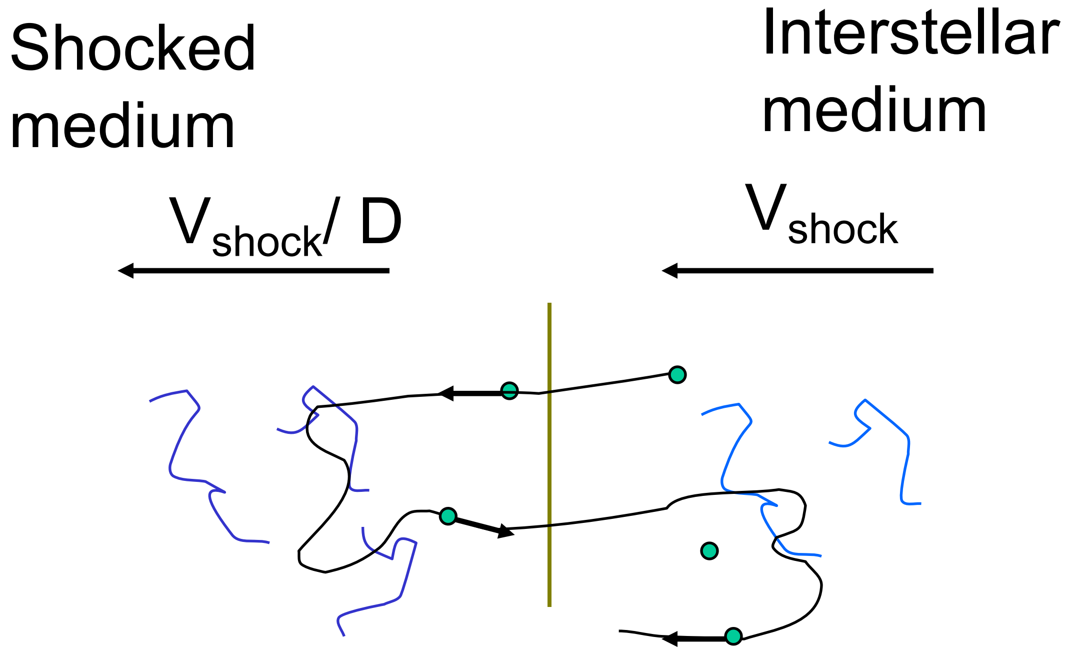
where the specific enthalpy $h = \frac{\gamma}{\gamma - 1} \frac{P}{\rho}$ in perfect gas

Shock waves: a TNT detonation



Shock wave:bullet at Mach 2.5





•At each crossing, the particle sees a 'magnetic wall' at $V = 3/4\ V_{shock}$

→ only overtaking collisions.

Fermi particles spectrum

After k rounds the number of particles having energy (E,E+ΔE) is :

$$N = N_0 P^k \qquad E = E_0\left(1+\frac{\Delta E}{E}\right)^k \quad \Longrightarrow \quad \frac{N}{N_0} = \frac{E}{E_0}^{\frac{\ln P}{\ln\left(1+\Delta E/E\right)}}$$

$$\frac{dN(E)}{dE} = C \cdot E^{-1+\frac{\ln P}{\ln\left(1+\Delta E/E\right)}} \qquad P_{surv} = 1-\frac{V}{c} \qquad \frac{\Delta E}{E} = \frac{V}{c}$$

$$V \ll c$$

$$\frac{dN(E)}{dE} = C \cdot E^{-2}$$

- First order (diffusive) shock acceleration
  - "Fermi acceleration", originally 2nd order
  - Power-law spectrum: $dN/dE \sim E^{-\alpha}$
    - α = 2 for strong shock (large Mach number)

Maximum energy gain

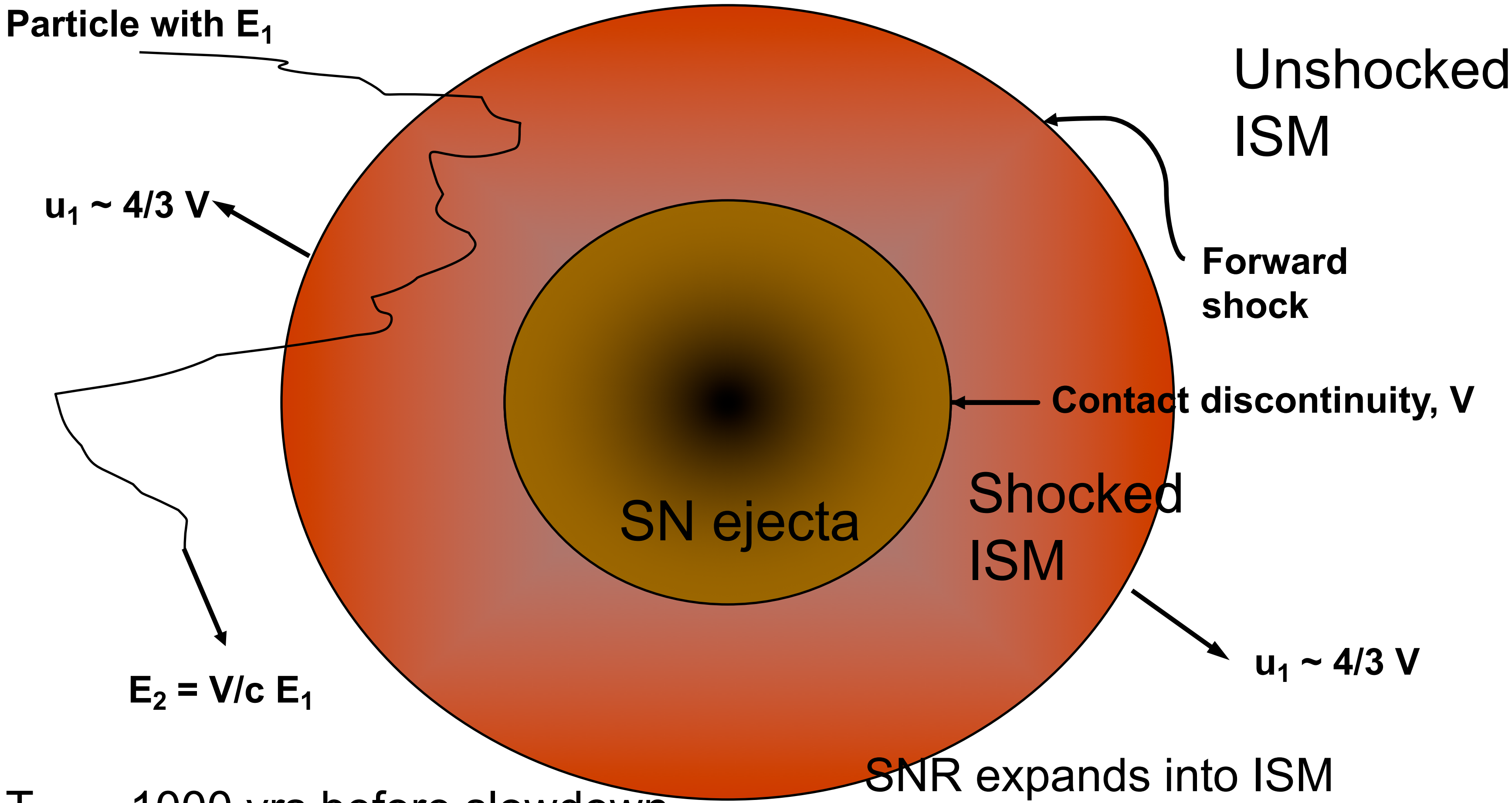
$\Delta E = \xi E$ at each shock crossing:

- $\xi \sim \beta_{shock}$
- $dE/dt = \xi E \,/\, T_{cycle}$
- with $T_{cycle} \sim r_L / c\,\beta_{shock} \sim (E / Ze\,B) / c\,\beta_{shock}$
- $dE/dt = \xi\,(Ze\,B)\,c\,\beta_{shock}$
- $E_{max} \sim \xi\,(Ze\,B)\,(c\,\beta_{shock}\,T)$, **after a time T**

The maximum energy of the particles depends on the number of rounds, then on the source dimension R and on the particle Gyroradius

$$E_{p,max} \propto \frac{R}{R_L} = \beta eBR$$

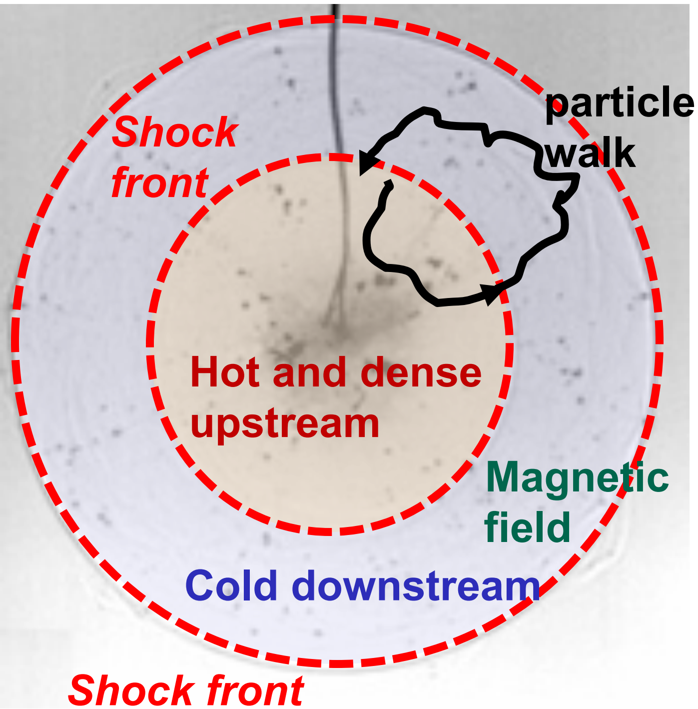
Supernova blast wave acceleration

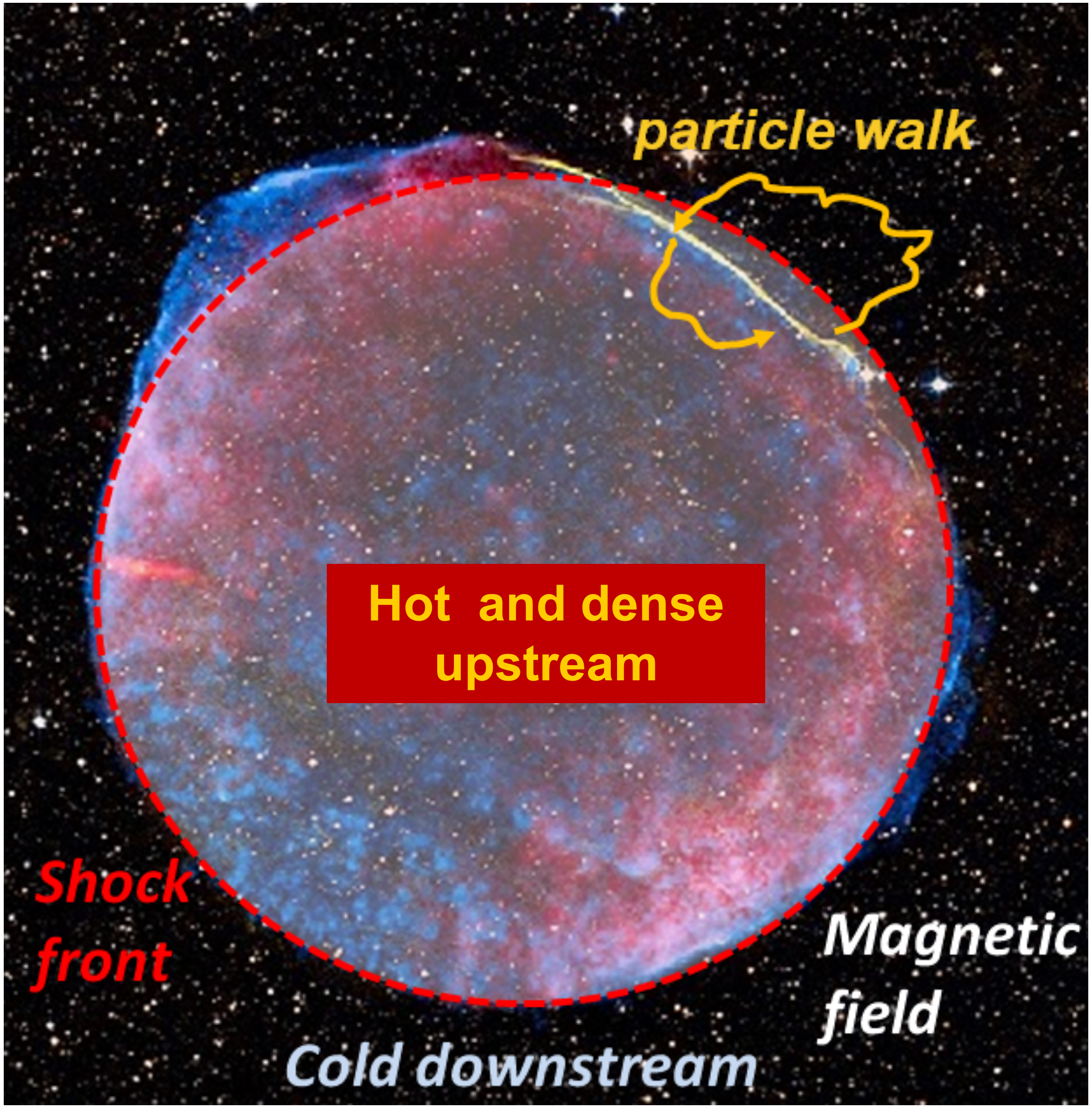


T_{SN} ~ 1000 yrs before slowdown
E_{max} ~ Z x 100 TeV

SNR expands into ISM
with velocity V~ 10^4 km/s.
Drives forward shock at 4/3 V

SNR as sources of Cosmic Rays below the ankle





SNR sources of CRs: Energetics – Ginzburg Syrovatsky

SNR (SuperNova Remnants) are the relics of SN explosions.
Shock waves generated in SN environment (blast, reverse) could be responsible for Fermi acceleration.

B (≈μG) and R constraints limit the maximum energy of accelerated protons to ≈10^{14} eV.
For higher energy stronger B is required: X Ray Binaries (XRB), pulsar wind.

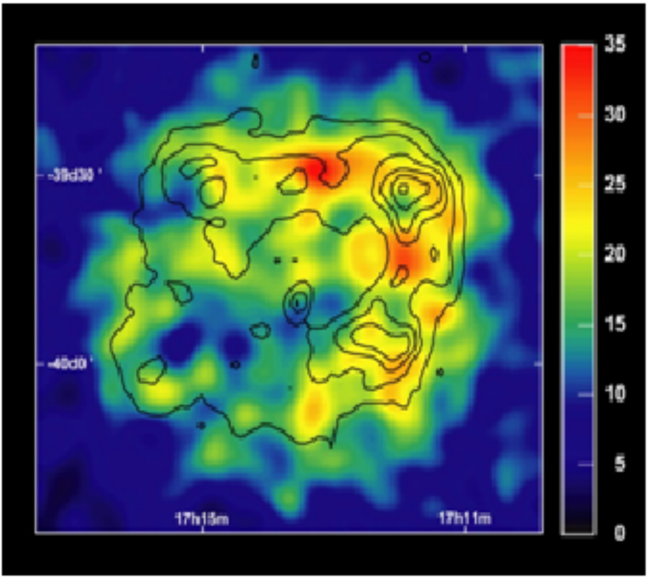
The total amount of energy generated by SN explosions largely accounts for the observed energy in cosmic rays:

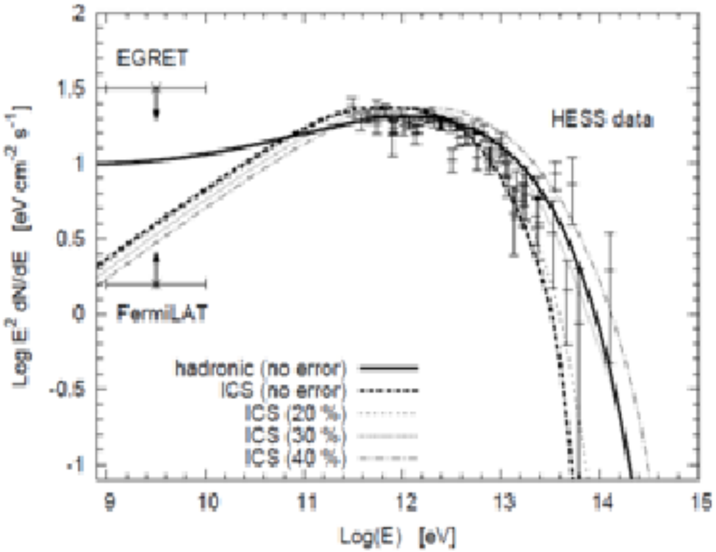
$$L_{CR}^{Galactic} = \frac{V_{Galaxy}\rho_{CR}}{\tau_{Galaxy}^{confinement}} \sim \frac{10^{66}\left[cm^3\right]\ 1.6\cdot 10^{-12}\left[\frac{erg}{cm^3}\right]}{1.8\cdot 10^{14}\left[s\right]} \sim 10^{40}\left[\frac{erg}{s}\right]$$

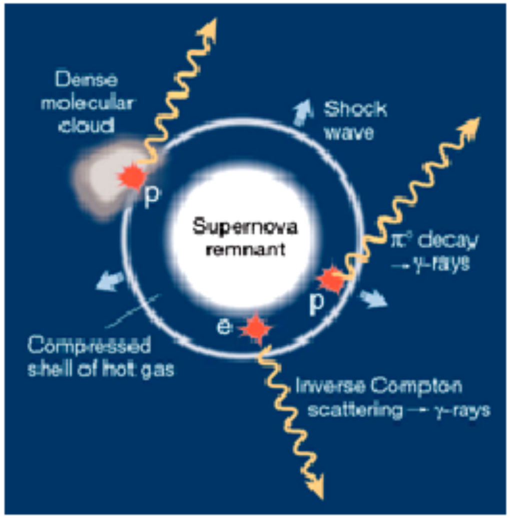
$$L_{SN}^{Galactic} \sim \frac{10^{53}\left[erg\right]}{30\cdot 3\cdot 10^{7}\left[s\right]} \sim 10^{42}\left[\frac{erg}{s}\right]$$

Under the hypotesis of 1 SN/30 years

This requires an efficiency of ~ percent for the energy conversion to particle accelarion

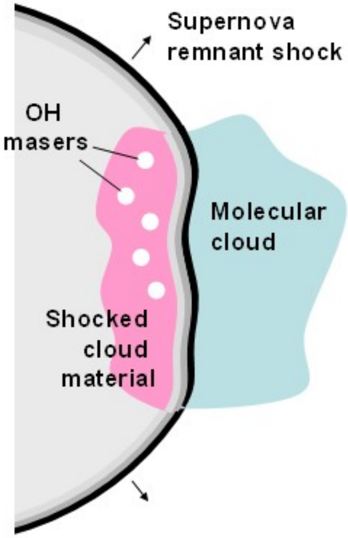




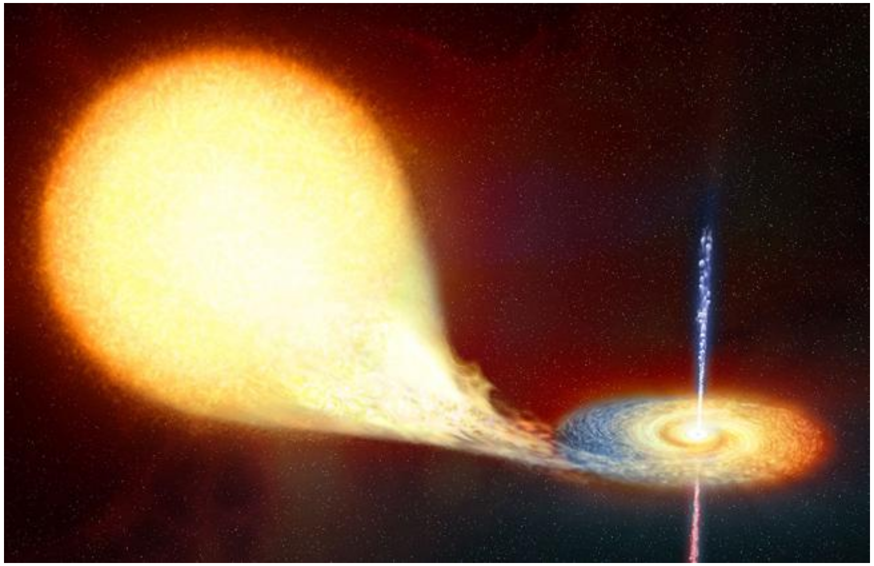


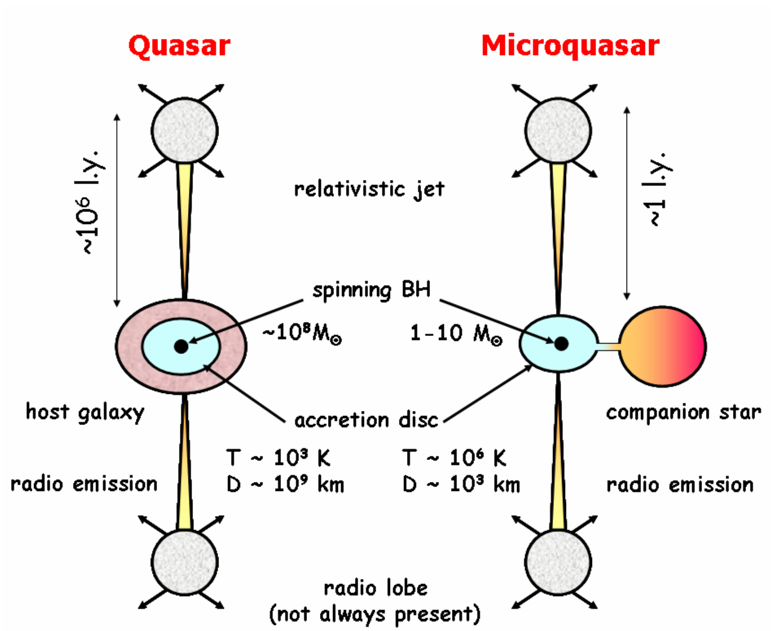
RXJ 1713

Detected in TeV gamma rays



Microquasars



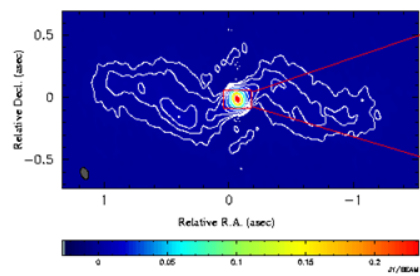


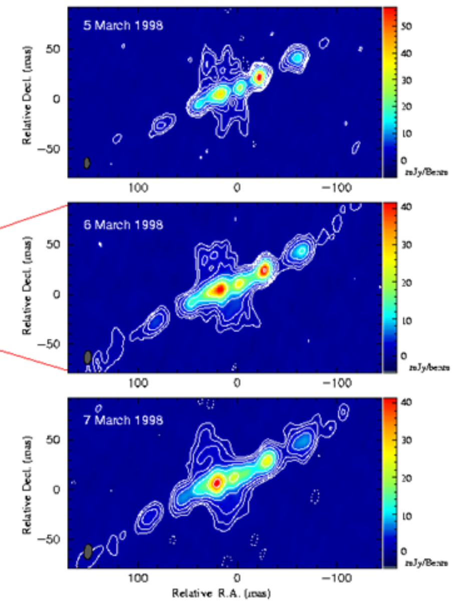
Radio observation (since 1980)

MERLIN+VLA Image of SS433

VLBA Images of SS433

persistent



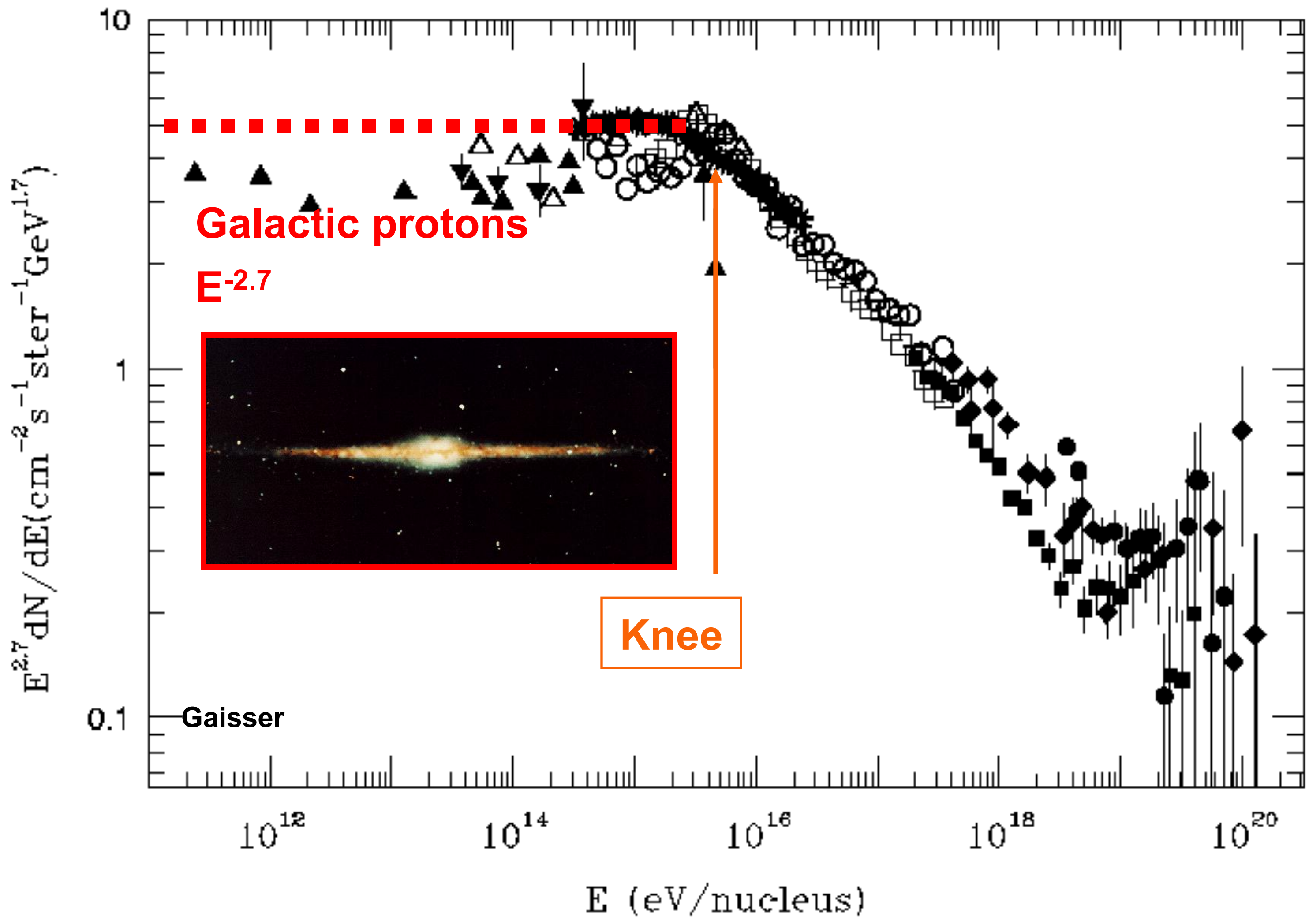


Neutron star?

v_{jet}=0.26c

Courtesy of Amy J. Mioduszewski (U. of Sydney)

The high energy cosmic ray standard paradigm

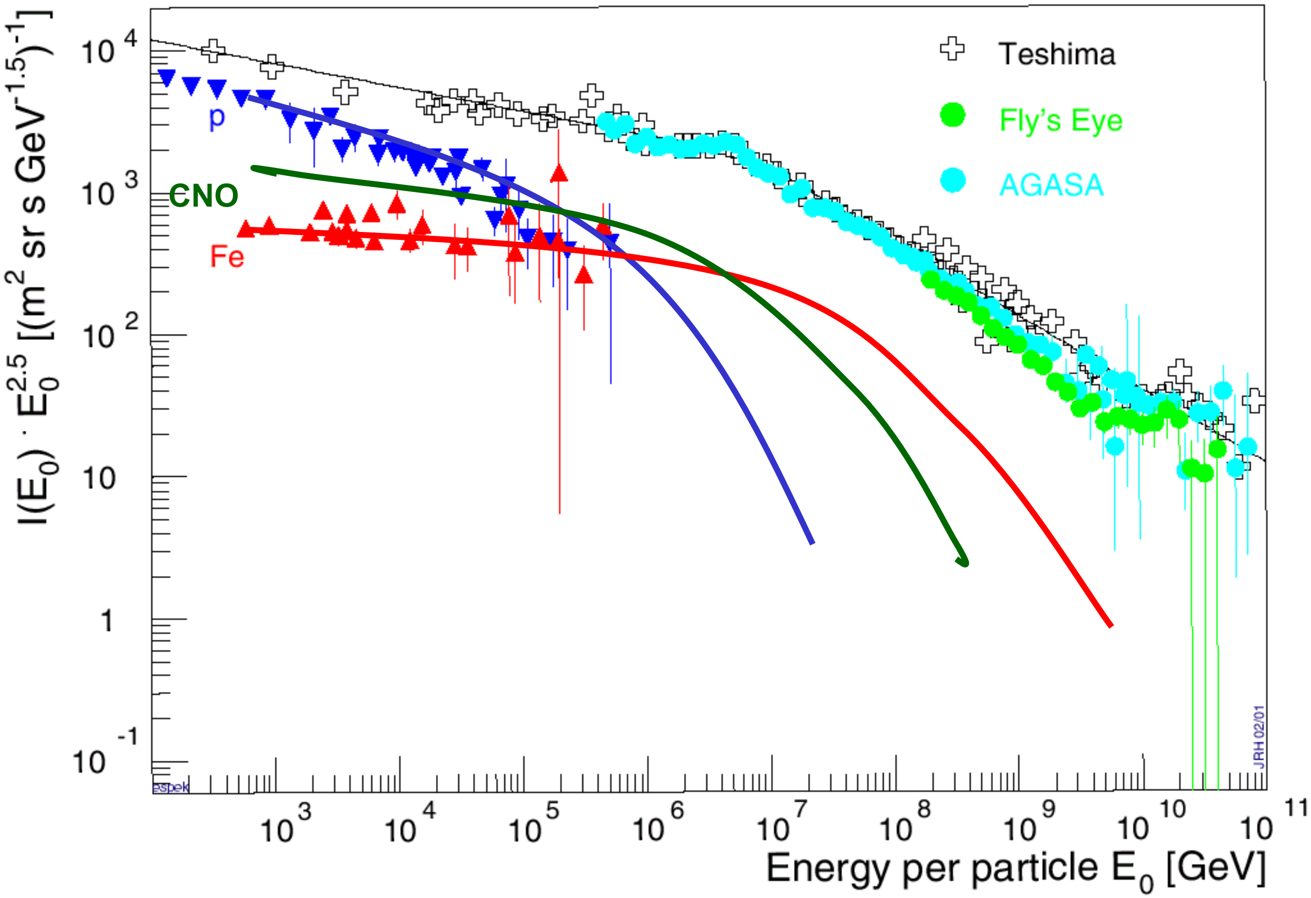


Origin of the knee

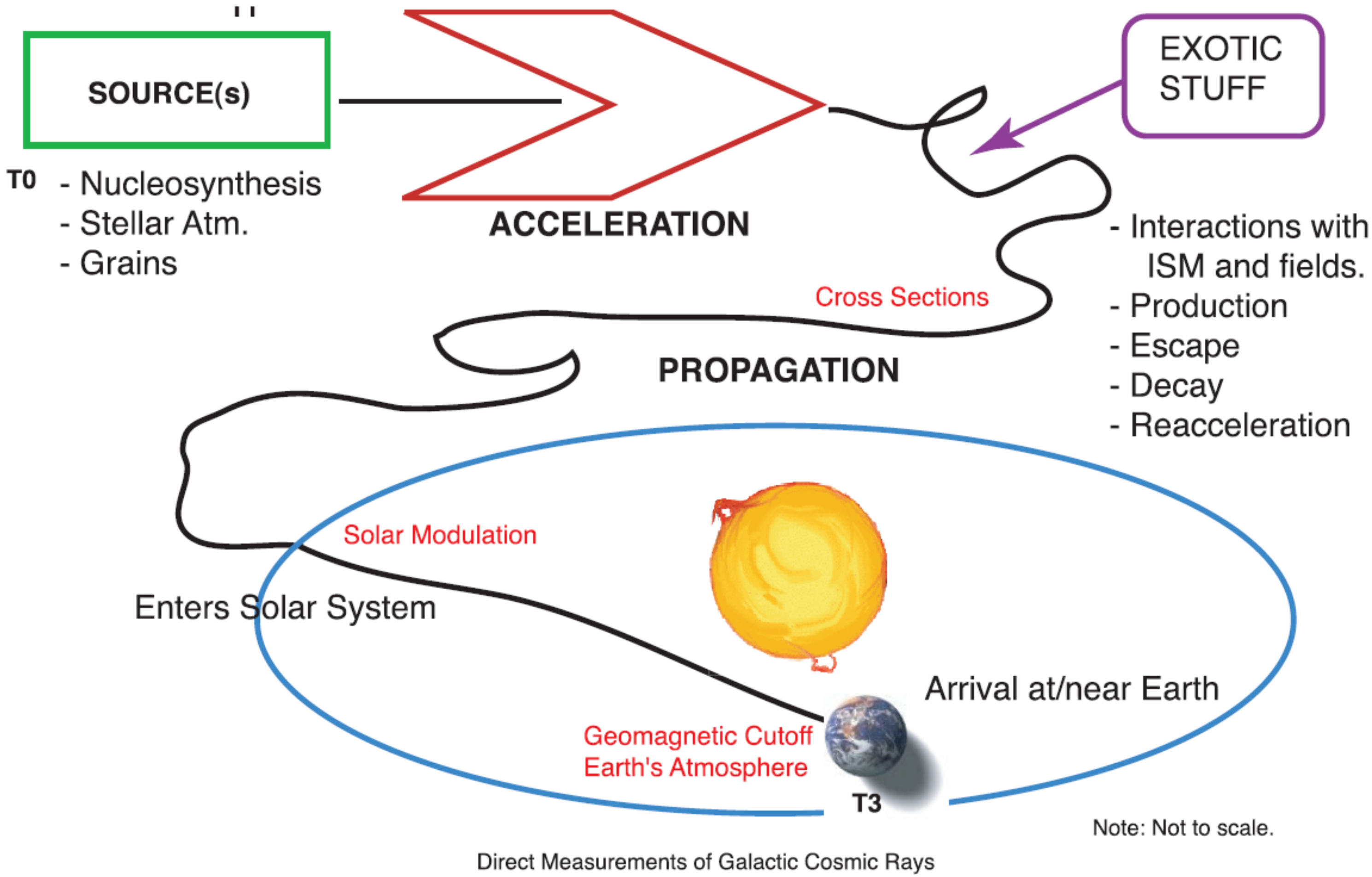
- **Fermi acceleration:** $E_{max} \sim Z\ 10^{15}$ eV
- **Leakage from Galaxy:** escape probability ~ 1/Z

rigidity dependent cut-off:

$E_k \sim Z$



Proton confinement

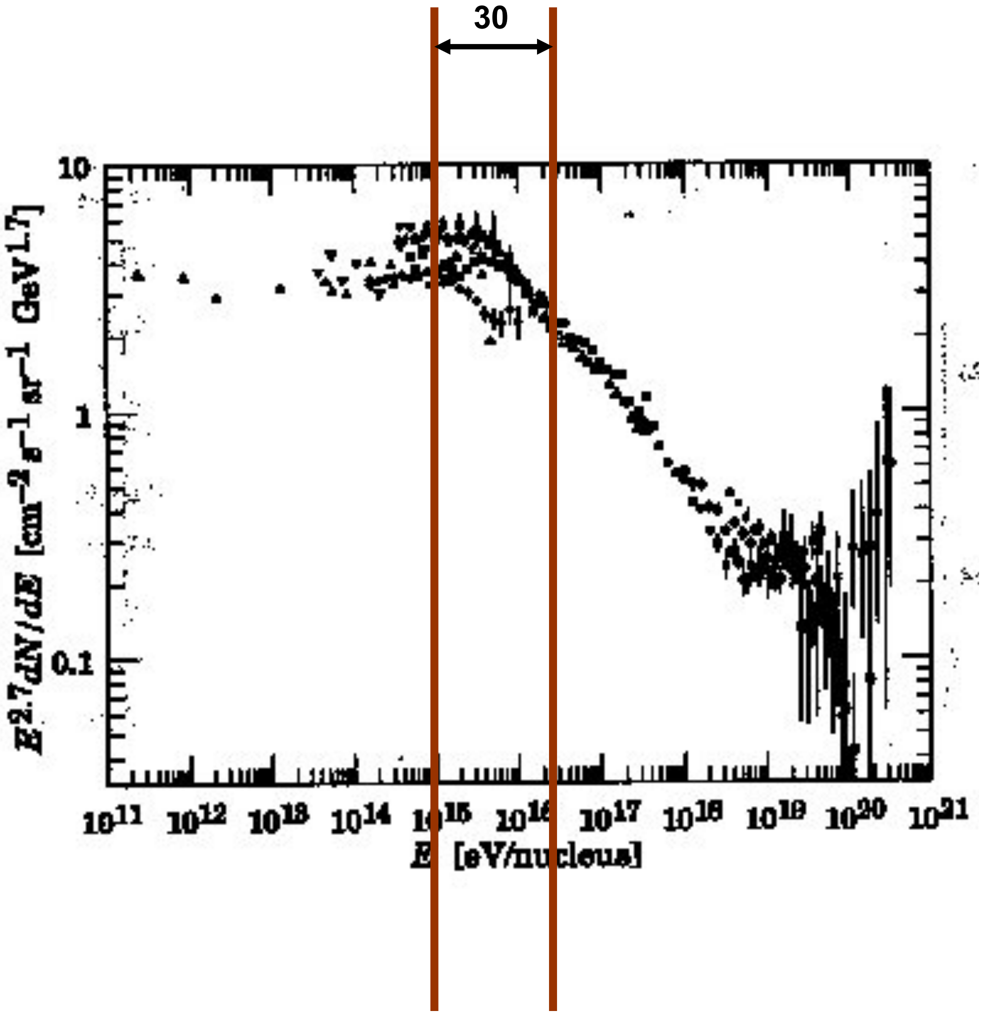


Proton Larmor radius:

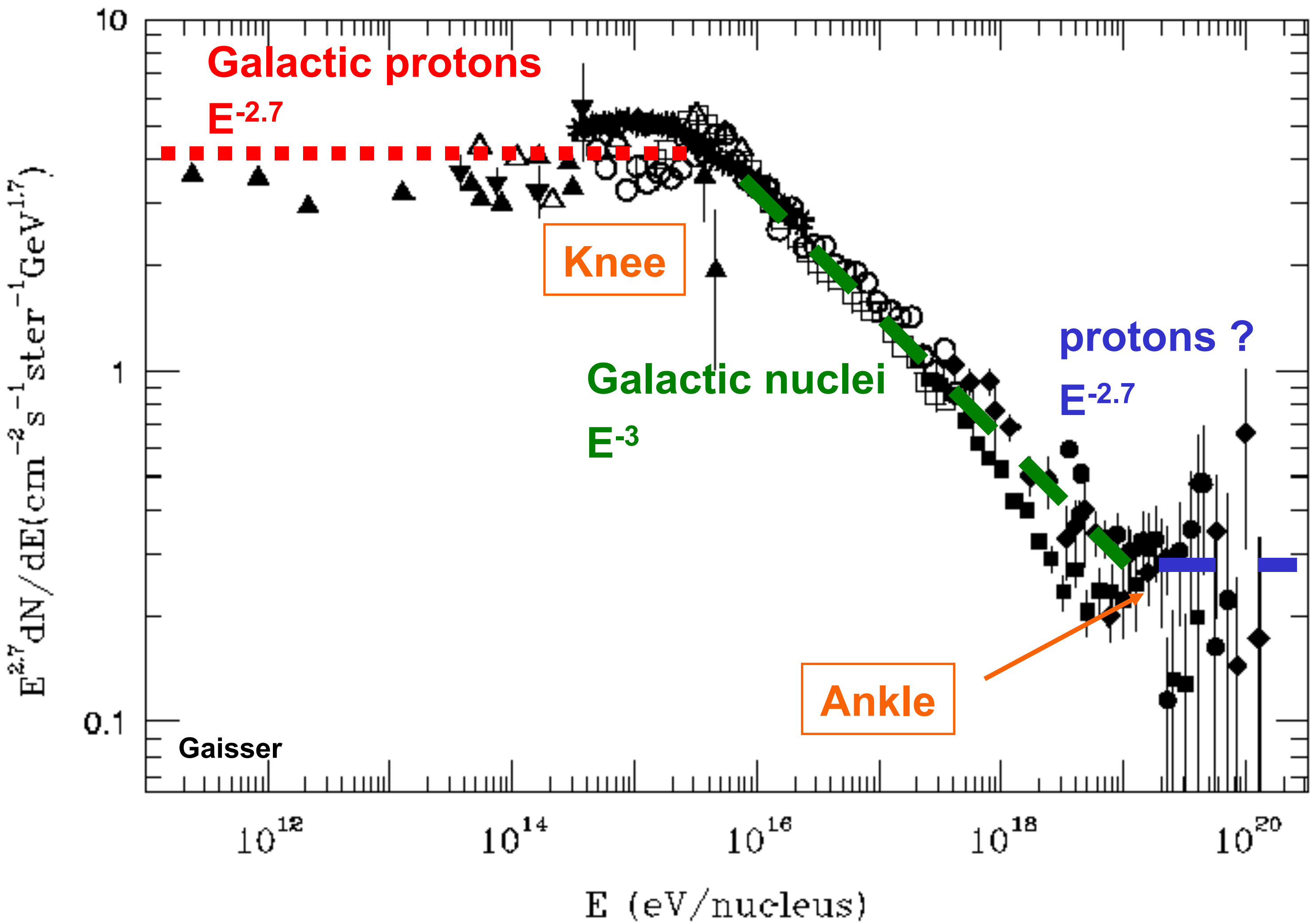
$r_L \cong 3\ \mathrm{pc}/B_{mG}$ **at** $E = 3 \times 10^{15}$ **eV (knee)**

Rigidity-dependence

- Acceleration, propagation
  - – depend on B: $r_{gyro} = R/B$
  - –Rigidity, $R = E/Ze$
  - –$E_c(Z) \sim Z\, R_c$
- $r_{SNR} \sim$ parsec
  - –→ $E_{max} \sim Z \cdot 10^{15}$ eV
  - – $1 \leq Z \leq 30$ (p to Fe)
- Slope change should occur within factor of 30 in energy
- Characteristic pattern of increasing A with energy



The high energy cosmic ray standard paradigm



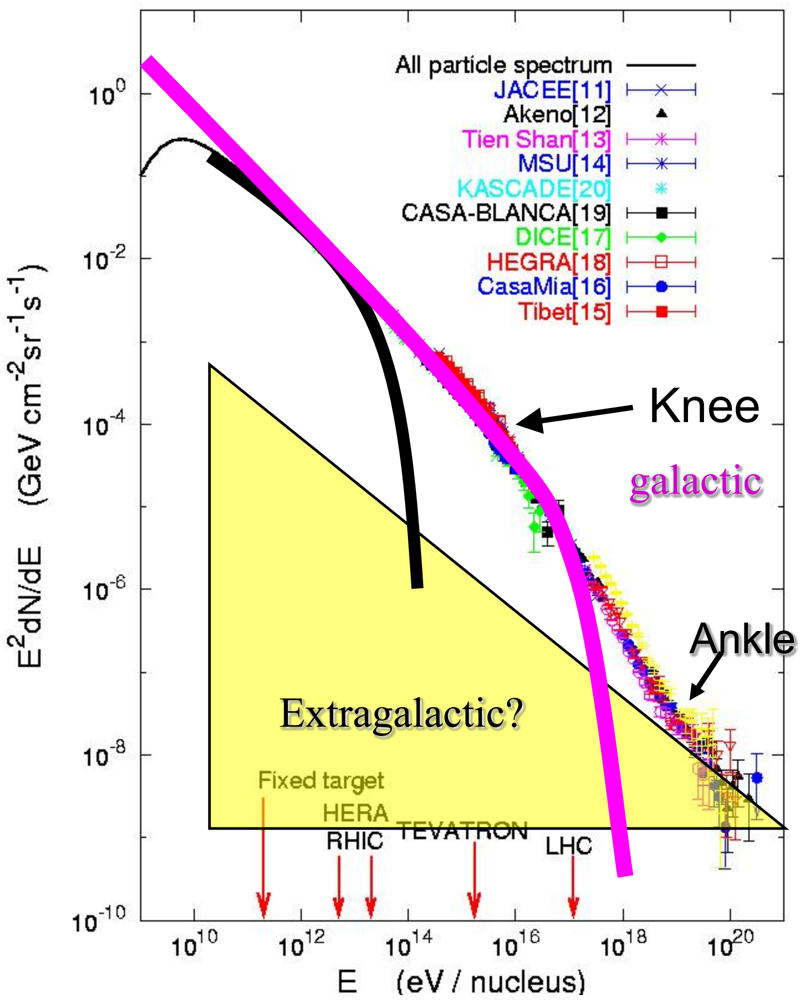
Sources of high energy protons exists and dominate the CR spectrum at $E > 10^{18.5}$ eV

Highest energy cosmic rays

- $E_{max} \sim \beta_{shock}$ Ze B R_{shock}

for SNR → E_{max} ~ Z x 100 TeV

- Knee:
  - –Differential spectral index changes at ~ 3 x 10^{15}eV
  - – $\alpha = 2.7 \rightarrow \alpha = 3.0$
  - –Some SNR can accelerate protons to ~10^{15} eV (Berezhko)
  - –How to explain 10^{17} to >10^{18} eV ?
- Ankle at ~ 3 x 10^{18} eV:
  - –Flatter spectrum
  - –Suggestion of change in composition
  - –New population of particles, possibly extragalactic?
- Look for composition signatures of "knee" and "ankle"



CR above the knee: chemical composition

Ground Based experimental data: primary CR composition recovered from interaction point in atmosphere

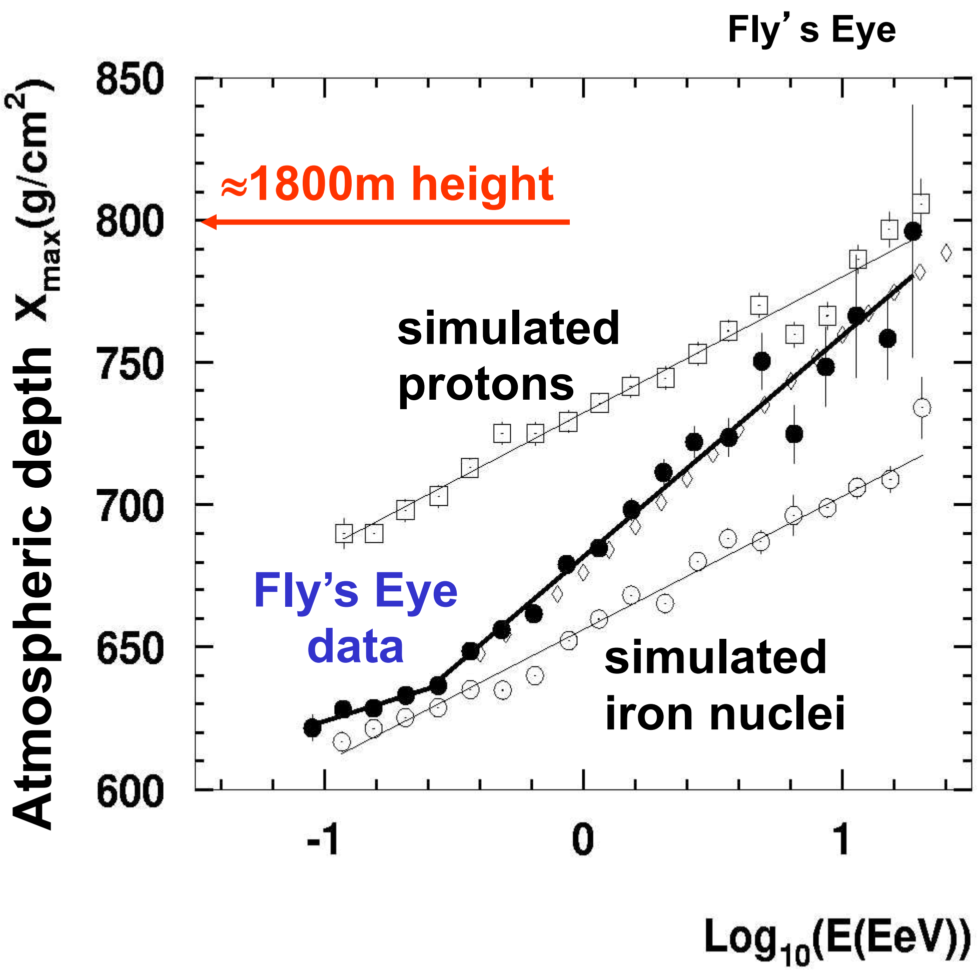
$E<10^{15}$ eV

Heavy particles (only 10% p)

$E>10^{15}$ eV

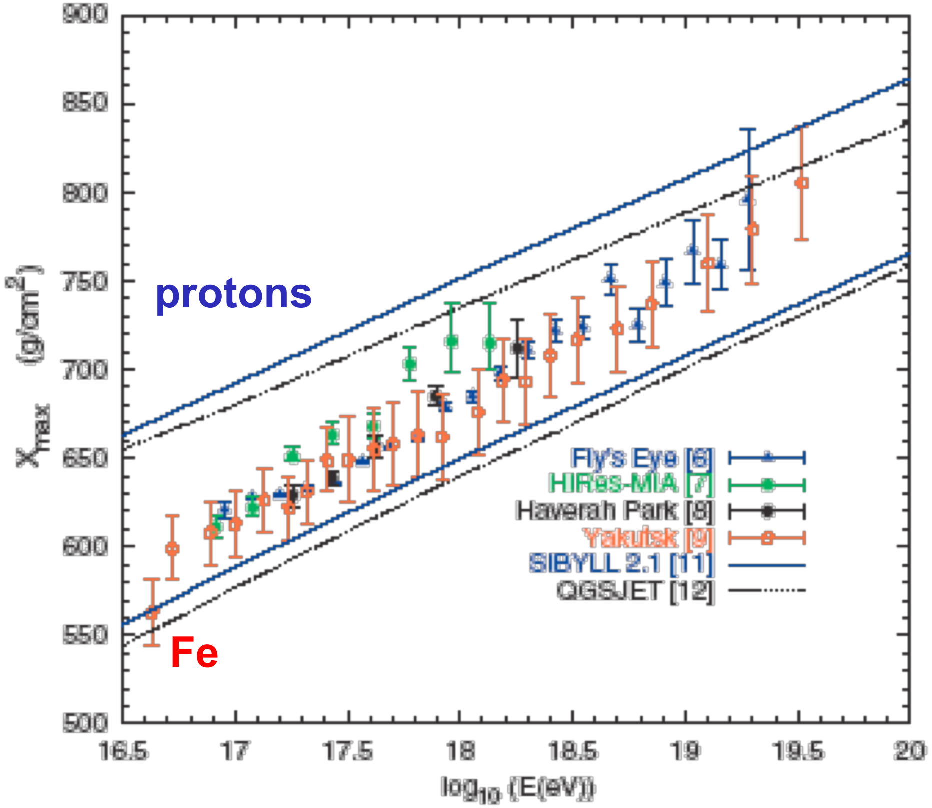
protons

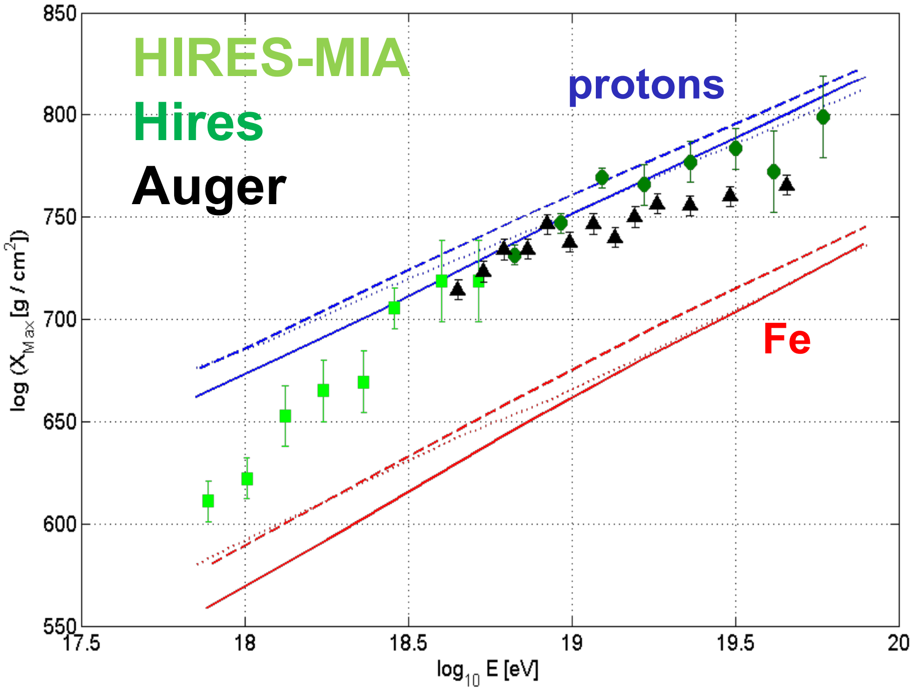
Events with more than 10^{20} eV likely to be protons



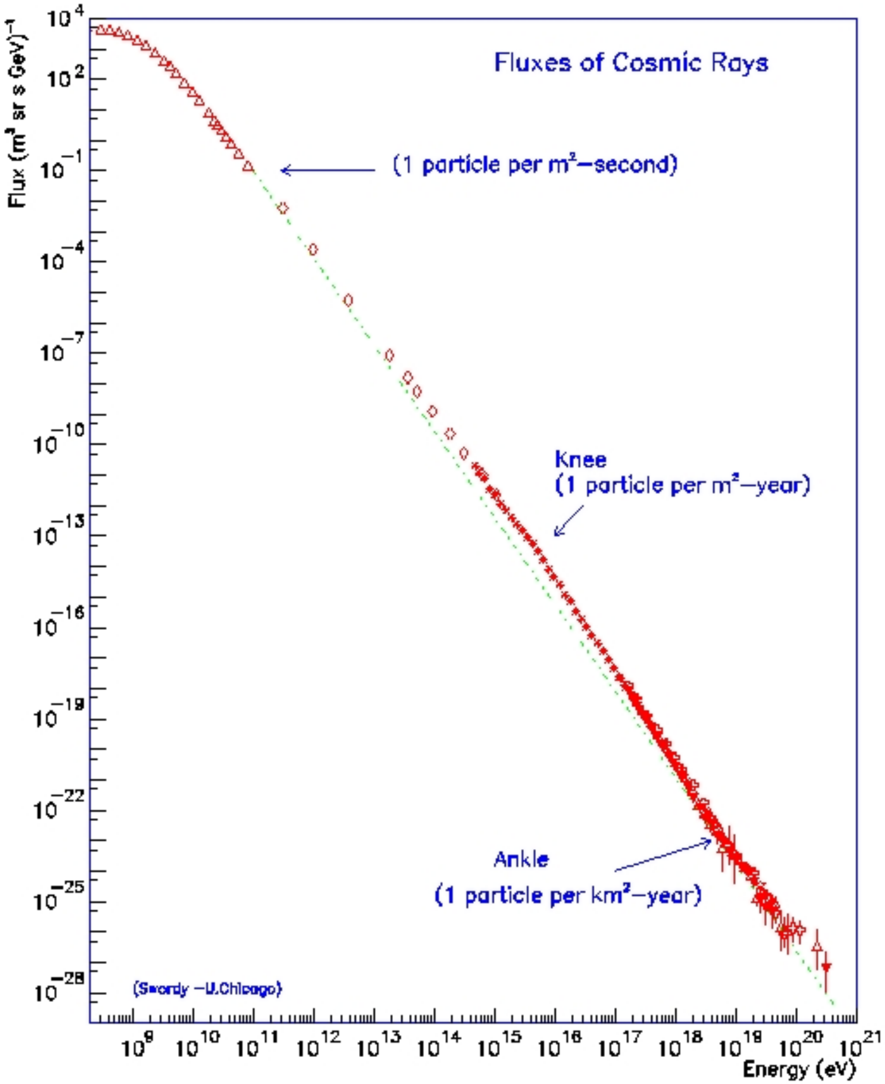
1 EeV=10^{18} eV

CR above the knee: chemical composition





The standard paradigm of the CR spectrum



Galactic: Supernovae
(mainly protons)

Galactic?, Neutron stars, superbubbles....

From protons to heavy nuclei

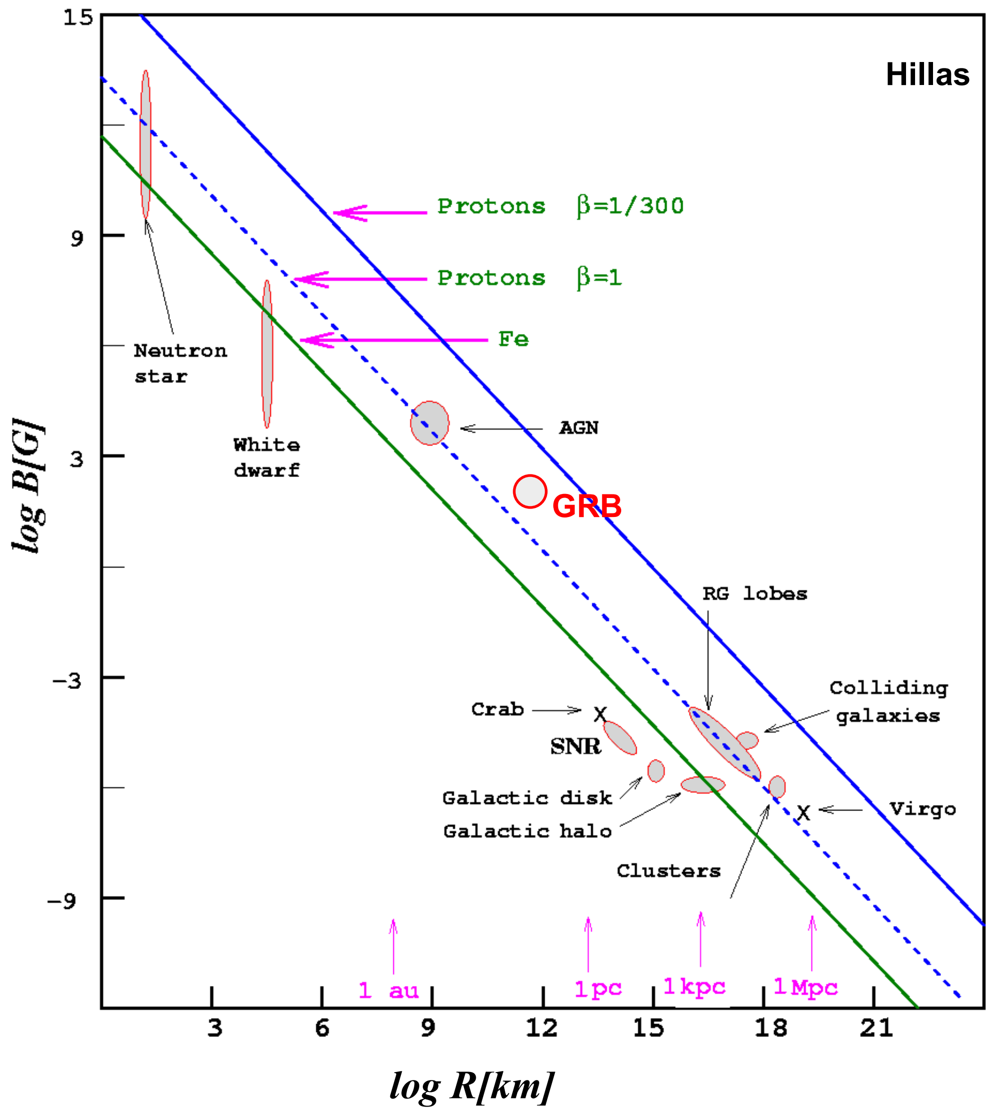
Extragalactic?
sources? composition?

Astrophysical sources of UHECR

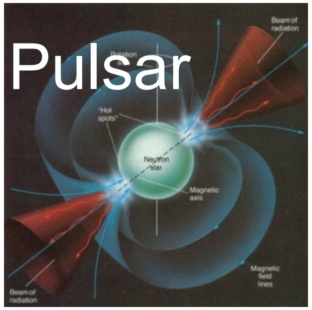
$$E_{max} \approx \beta_{shock} Z \cdot B[\mu G] \cdot R[kpc] \cdot 10^{18} eV$$

Fermi acceleration to high energies requires

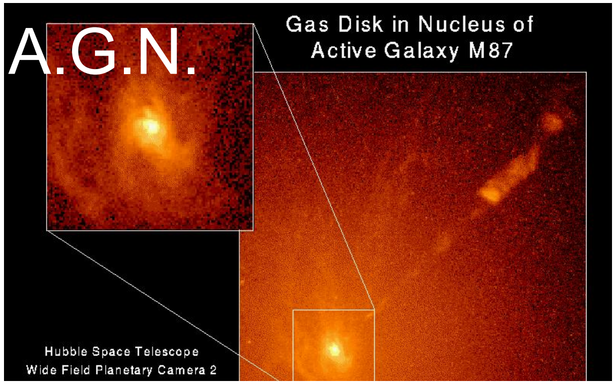
- **Large cosmic objects**
- **Intense magnetic field**
- **High shockwave velocity**

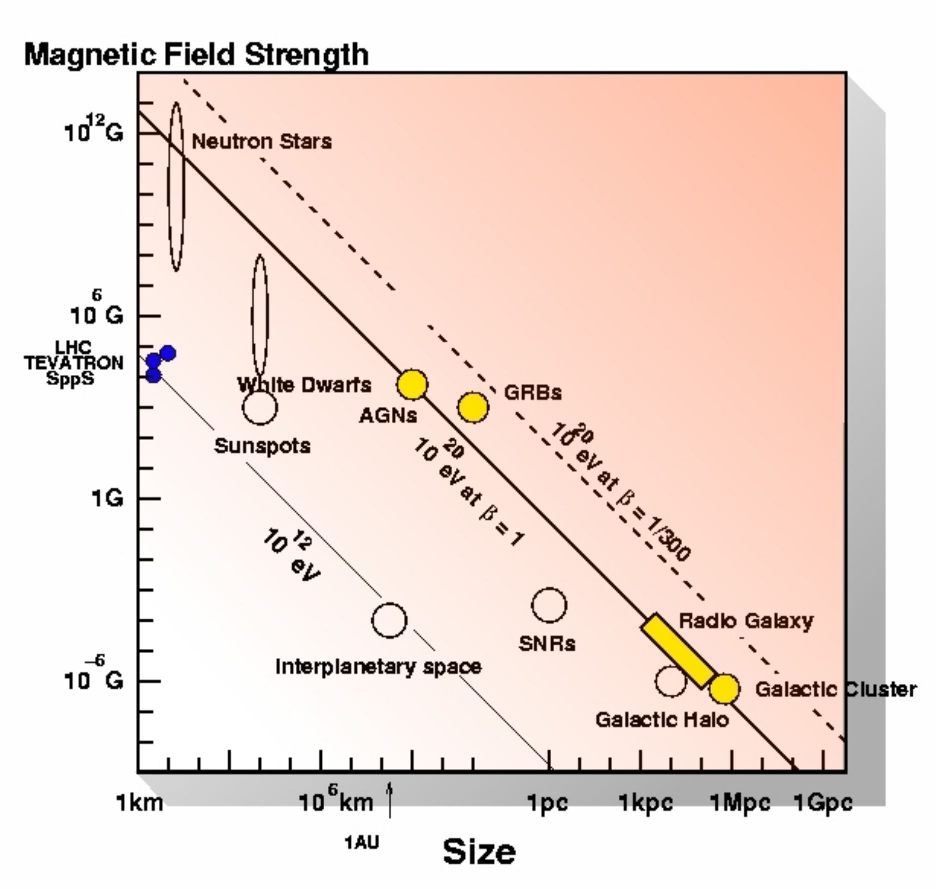


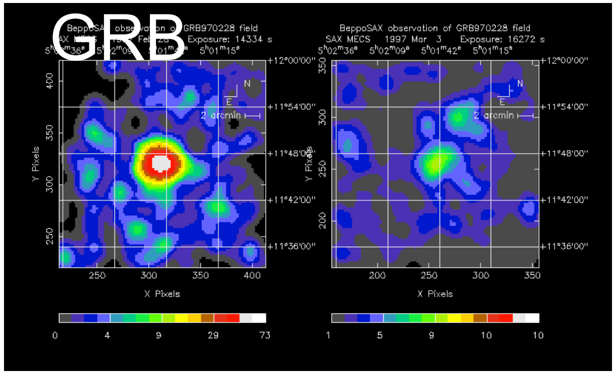
Hillas Plot

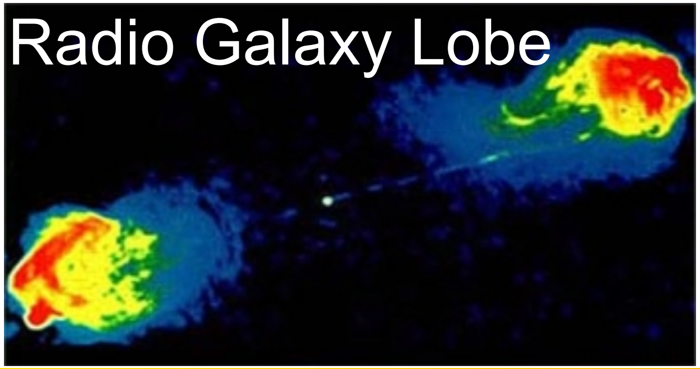

Pulsar


SNR


A.G.N.
Gas Disk in Nucleus of
Active Galaxy M87
Hubble Space Telescope
Wide Field Planetary Camera 2


Magnetic Field Strength
10^{12}G
10^{6} G
1G
10^{-6} G
LHC
TEVATRON
SppS
Neutron Stars
White Dwarfs
AGNs
GRBs
Sunspots
10^{20} eV at $\beta = 1$
10^{20} eV at $\beta = 1/300$
10^{12} eV
Interplanetary space
SNRs
Radio Galaxy
Galactic Cluster
Galactic Halo
1km
10^{6}km
1AU
1pc
1kpc
1Mpc
1Gpc
Size

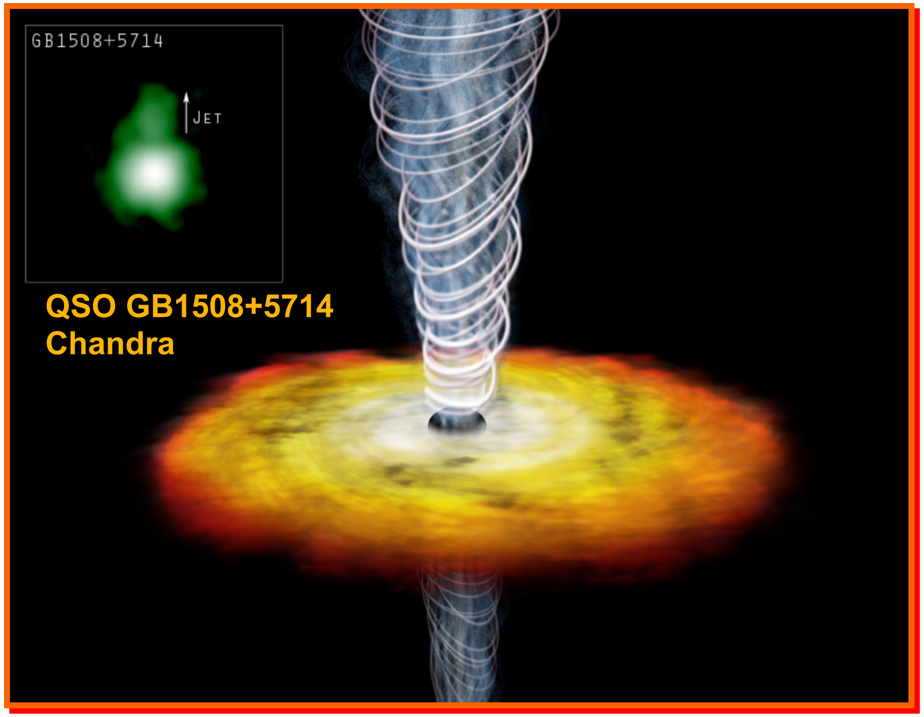

GRB


Radio Galaxy Lobe

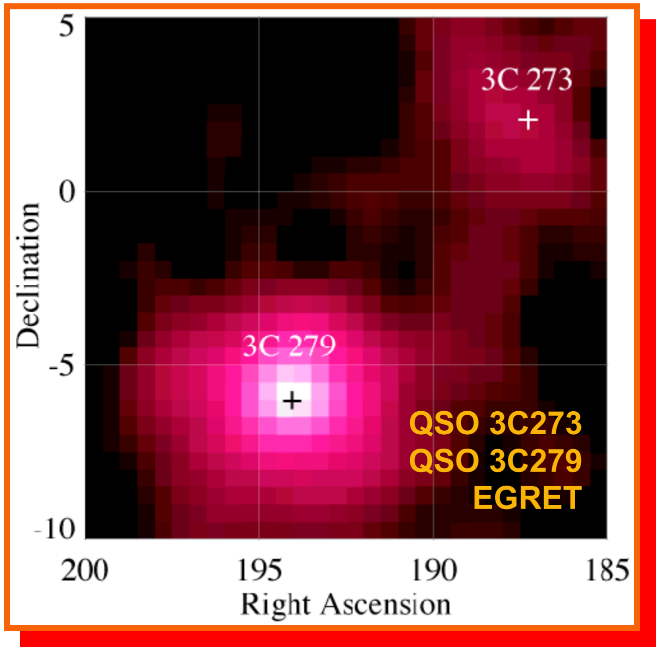
Possible extra Galactic sources of CR: AGN

First-order statistics on AGNs:

- Up to ~30% of galaxies host an AGN:
  ~4x more Type 2 AGNs (radio quiet) than Type 1 AGNs (radio loud)
- ~10% of luminous AGNs are "radio loud"



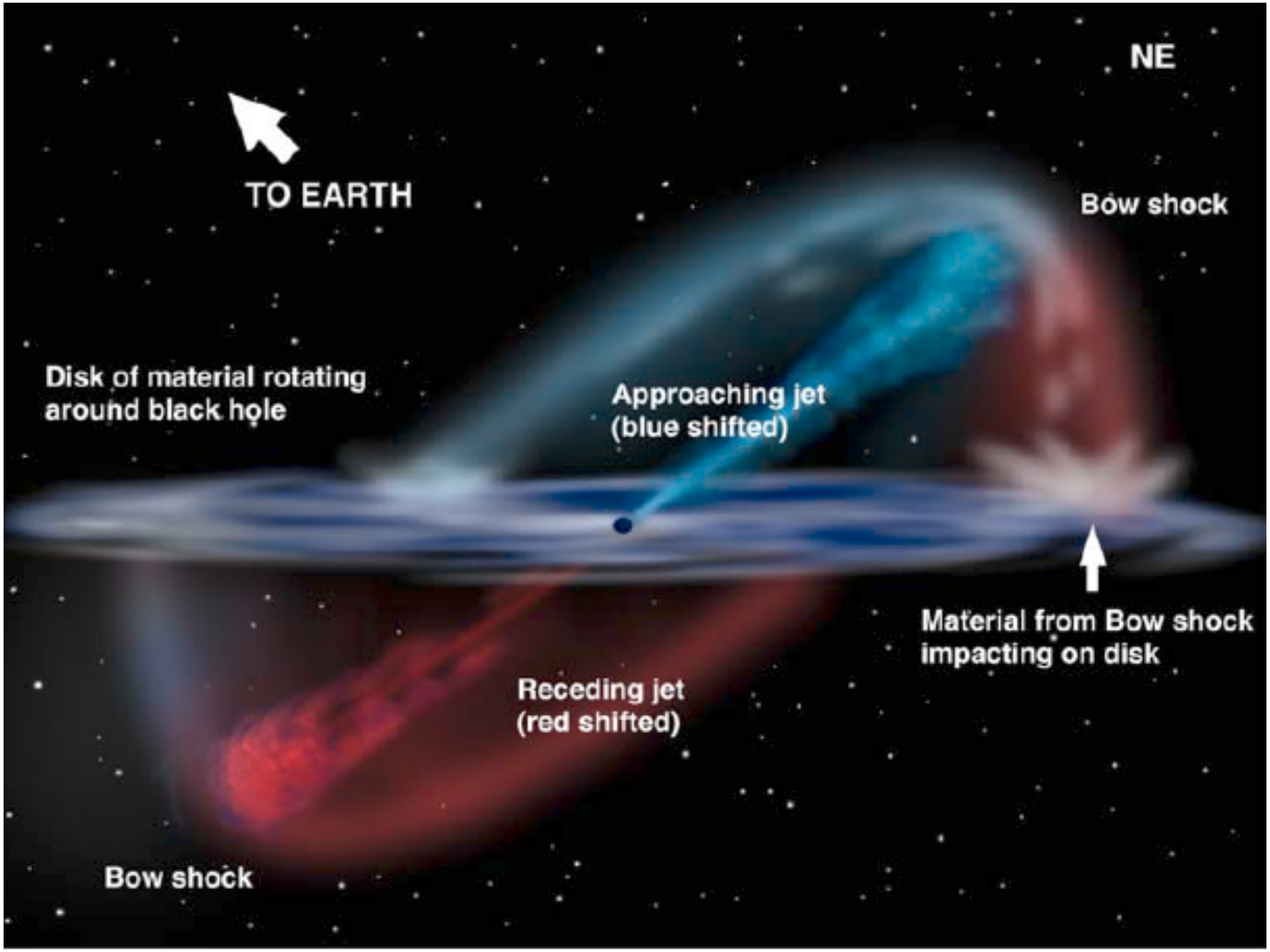
- **Massive Black Hole** $M_{BH} = 10^{6 \div 8} M_{\odot}$
- **Accretion disk** (UV + lines)
- **Collimated jets** $\Gamma \sim 10$



The brightest observed steady sources:

$L_{\gamma} = 10^{42} \div 10^{47}$ erg/s

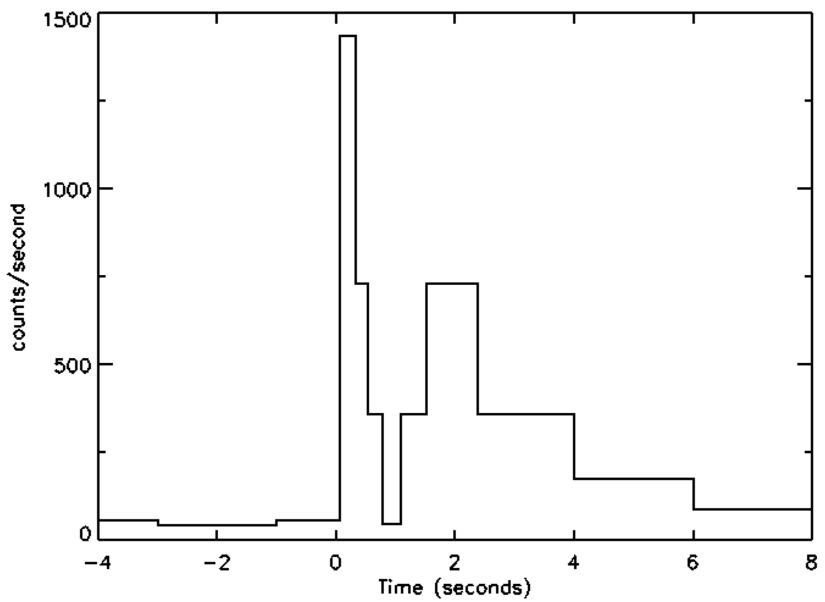
Possible extra Galactic sources of CR: AGNs



When the jet is directed towards the Earth → luminosity increases → "Blazars"

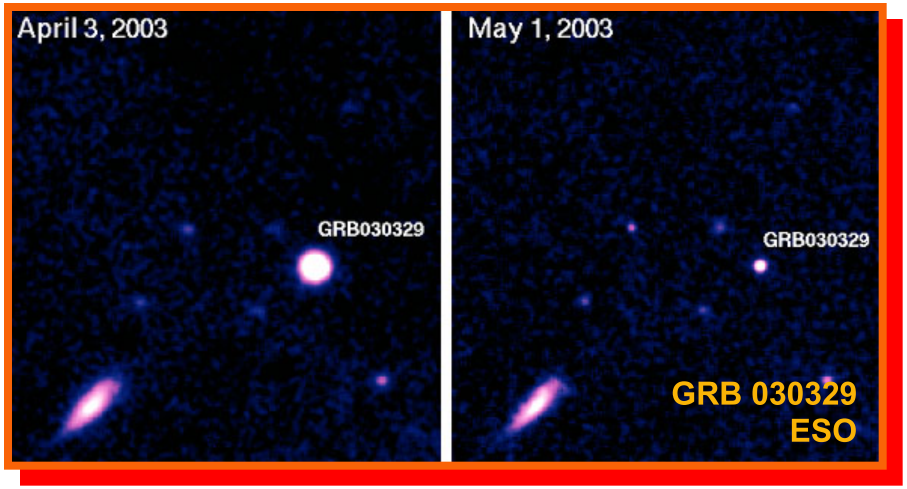
The Vela satellites that detected the first gamma-ray burst were developed in the sixties to monitor nuclear test ban treaties.

The 1[st] GRB July 2, 1967 Vela 4o Event



For > 20 years, GRB were just outbursts of gamma rays piercing an otherwise black gamma-ray sky.

Possible extra Galactic sources of CR: GRB



GRB (Gamma Ray Bursts) are the most powerful emissions of gamma rays ever observed.

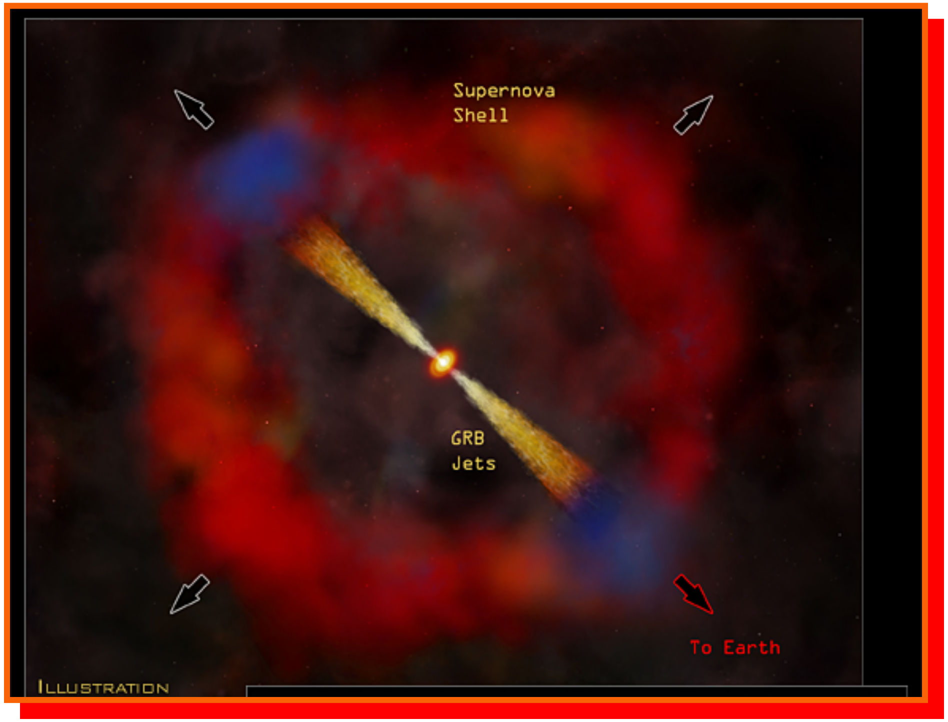
Happens at cosmological distances
The observation rate is about 1 per day

$L_\gamma = 10^{51} \div 10^{53}$ erg/s

$$\dot{M} \approx \frac{10 M_\odot}{s}$$

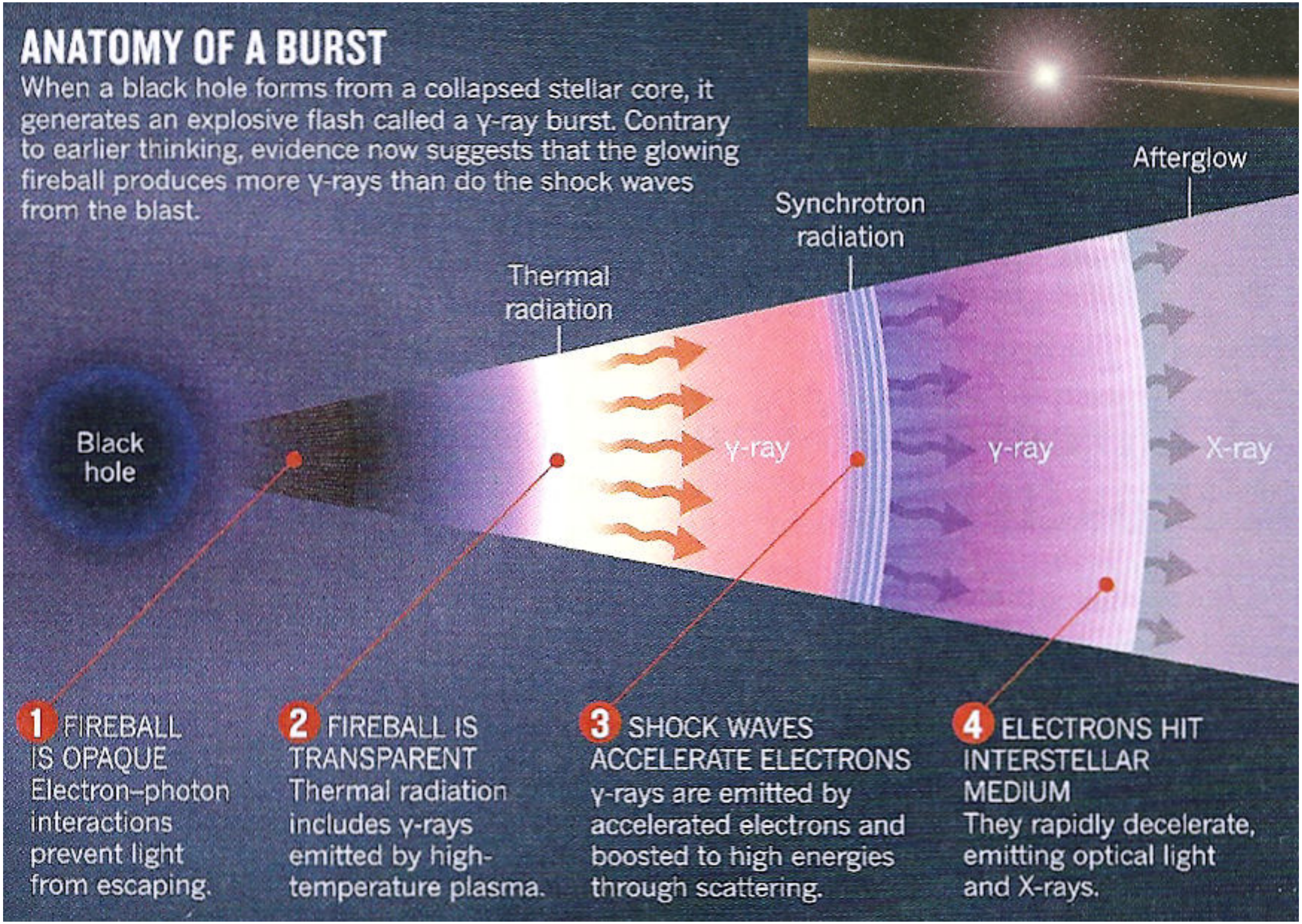
$\Delta t \approx 1 \div 100$ s (1/3 <2 sec)

$$\Gamma \approx 300$$



GRB have recentely been shown to be associated with SN, as indicated by the GRB030329 – SN 2003dh correlation

(GRB 030329 z=0.17)

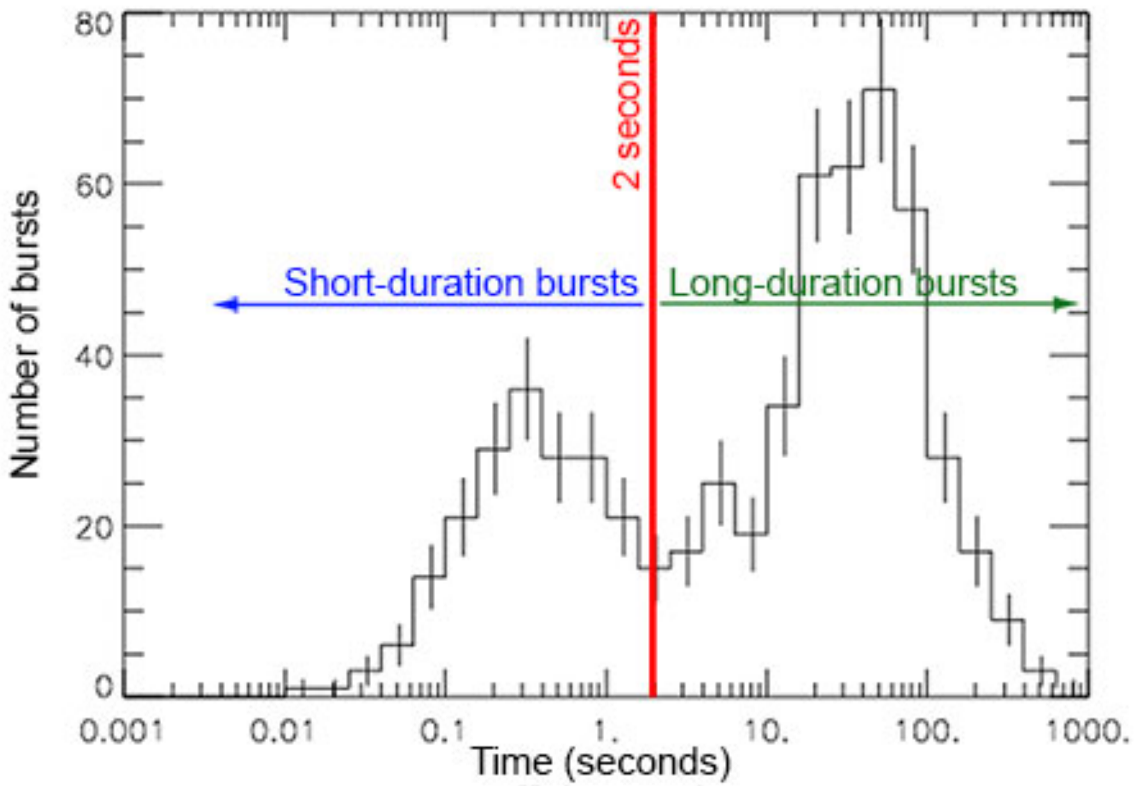

ANATOMY OF A BURST
When a black hole forms from a collapsed stellar core, it generates an explosive flash called a γ-ray burst. Contrary to earlier thinking, evidence now suggests that the glowing fireball produces more γ-rays than do the shock waves from the blast.
Afterglow
Synchrotron radiation
Thermal radiation
Black hole
γ-ray
γ-ray
X-ray
1 FIREBALL IS OPAQUE
Electron–photon interactions prevent light from escaping.
2 FIREBALL IS TRANSPARENT
Thermal radiation includes γ-rays emitted by high-temperature plasma.
3 SHOCK WAVES ACCELERATE ELECTRONS
γ-rays are emitted by accelerated electrons and boosted to high energies through scattering.
4 ELECTRONS HIT INTERSTELLAR MEDIUM
They rapidly decelerate, emitting optical light and X-rays.

Two Populations of events:

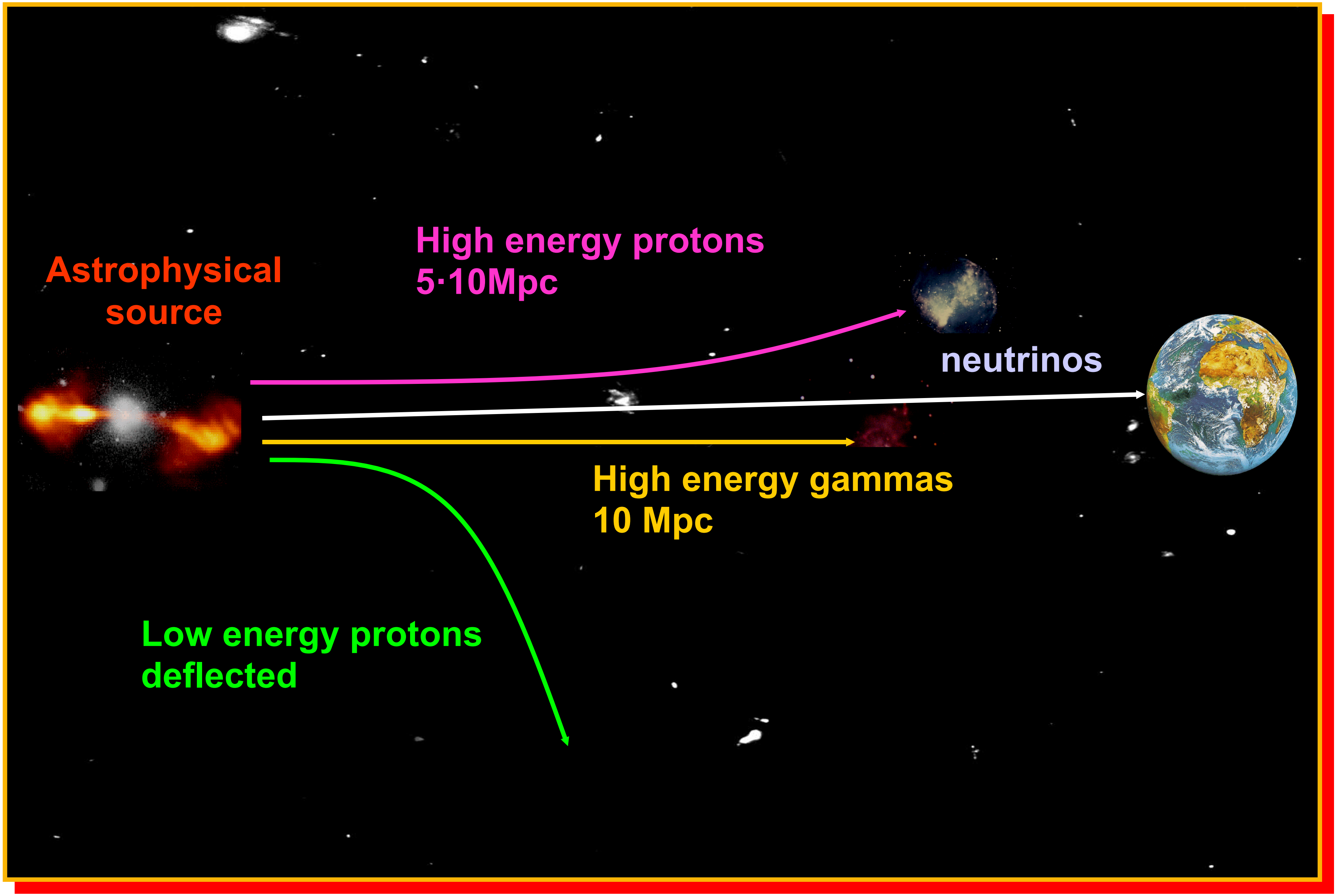
short bursts (<2 s): kilonova (merger of binary NS system)

SN170817A (GW170817)

long bursts (>2s): core collapse supernova



Limits of HE gamma and proton astronomy



The most effective energy loss mechanism for p and n of UHEs

In the NRF, $\varepsilon_{th} = m_{\pi}c^2 \sim 140$ MeV:

Cosmic microwave background (CMB)

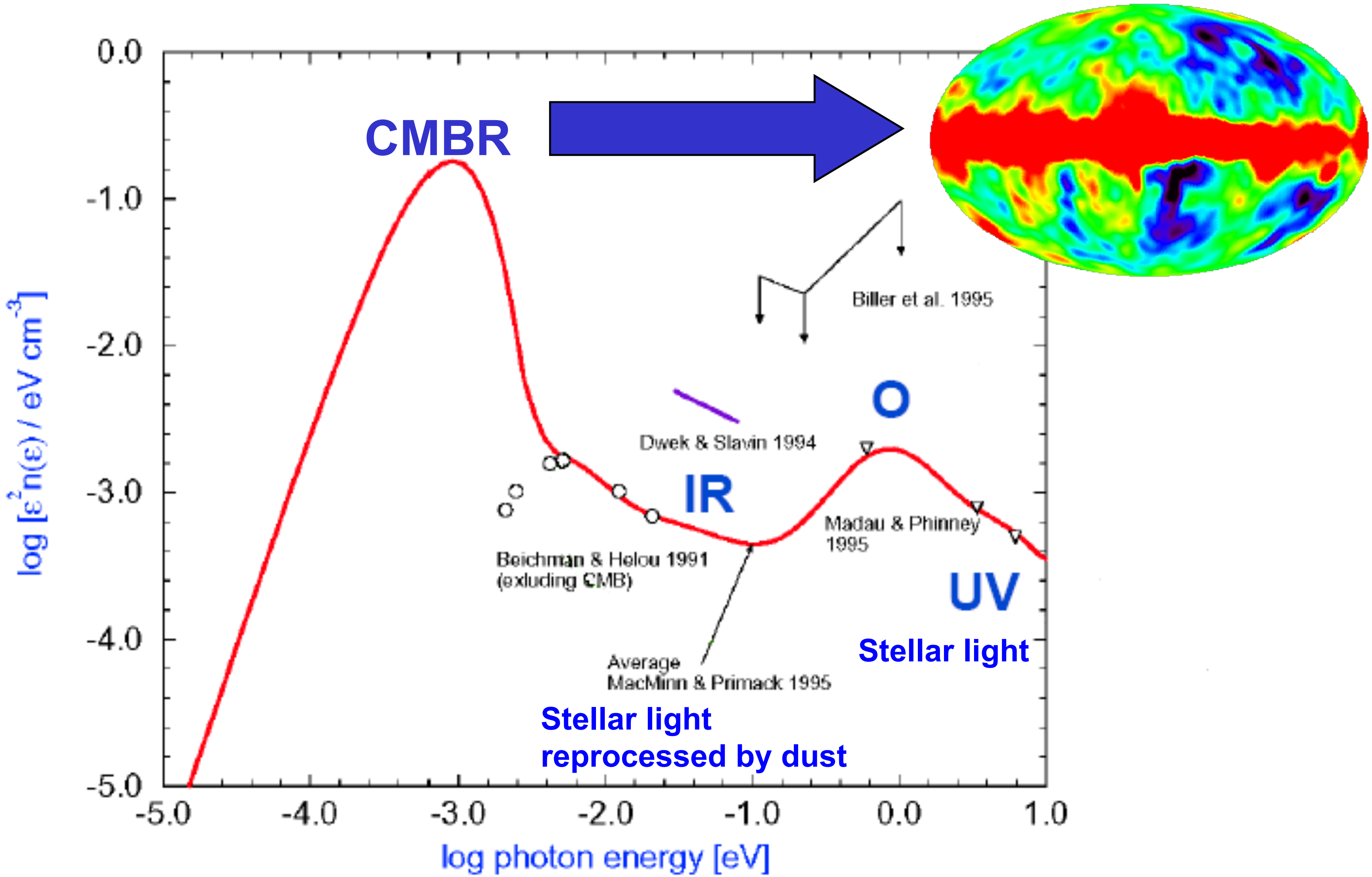
$\varepsilon_{\gamma} \sim 6 \cdot 10^{-4}$ eV $\longrightarrow \Gamma_P \sim 10^{11} \longrightarrow E_p \sim 10^{20}$ eV

$\rho_{\gamma} \sim 400$ cm^{-3}
$\sigma_{p\gamma} \sim 100$ μbarn

$$\left.\begin{array}{l}\rho_{\gamma} \sim 400\ \text{cm}^{-3} \\ \sigma_{p\gamma} \sim 100\ \mu\text{barn}\end{array}\right\} \quad \lambda_{att} = \frac{1}{\sigma_{p\gamma}\rho_{\gamma}} \sim 10\ \text{Mpc}$$

If cosmic rays originate mainly at cosmological distances D>>10 Mpc, the spectrum should cut off in the sub-ZeV regime.

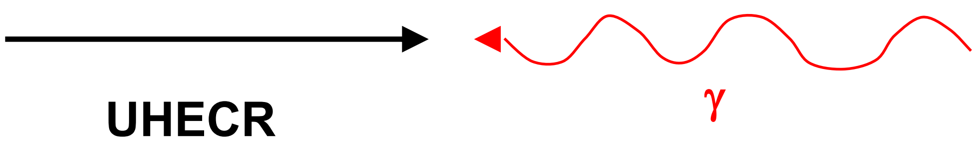
GZK Cutoff



CMBR
IR
O
UV
Stellar light
Stellar light
reprocessed by dust
Biller et al. 1995
Dwek & Slavin 1994
Beichman & Helou 1991
(exluding CMB)
Average
MacMinn & Primack 1995
Madau & Phinney
1995
log [ε²n(ε) / eV cm⁻³]
log photon energy [eV]
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0

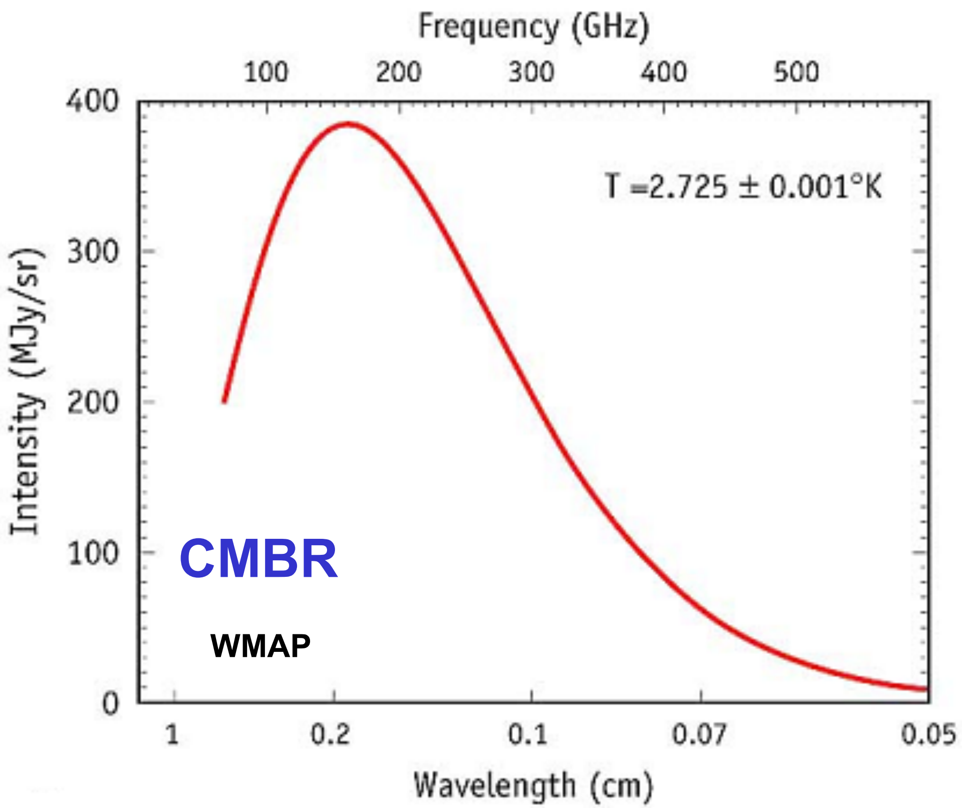
Proton interaction on CMBR

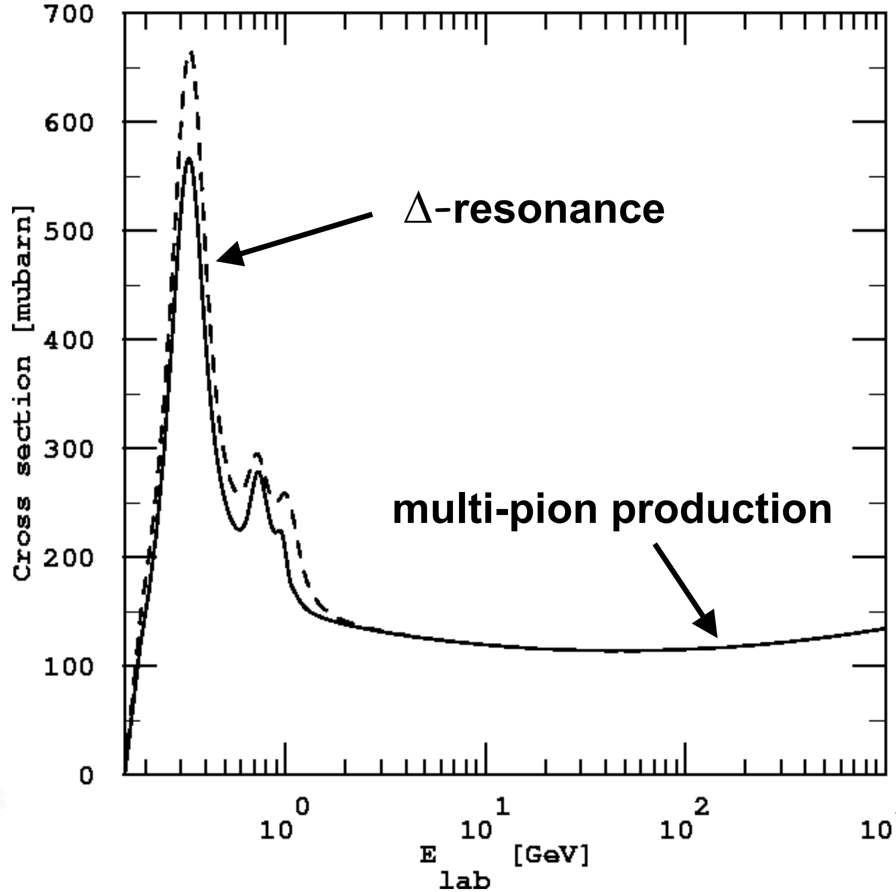
Nucleons can produce pions on the cosmic microwave background



$\varepsilon_\gamma \sim 6 \cdot 10^{-4}$ eV

$\rho_\gamma \sim 400$ cm^{-3}





Thresholds for UHECR in CMBR

nucleons: N+γ_{CMBR} → N+π

$E_{CMBR} \approx 6 \cdot 10^{-4}$ eV

$$s \equiv (p_1 + p_2)^2 = (p'_1 + p'_2)^2$$

$$s \geq \left(m_N + m_\pi\right)^2$$

$$s = \left(p_N + p_{CMBR}\right)^2$$

$$E_N \geq \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon_{CMBR}} \approx 10^{20}\, eV$$

photons: pair production

$$E_\gamma \geq \frac{m_e^2}{\varepsilon_{CMBR}} \approx 10^{15}\, eV$$

"regeneration" via Inverse Compton Scattering but at lower energy (EGRET observations)

Thresholds for UHECR in CMBR

heavy nuclei: **loose ~4 nucleons/Mpc**

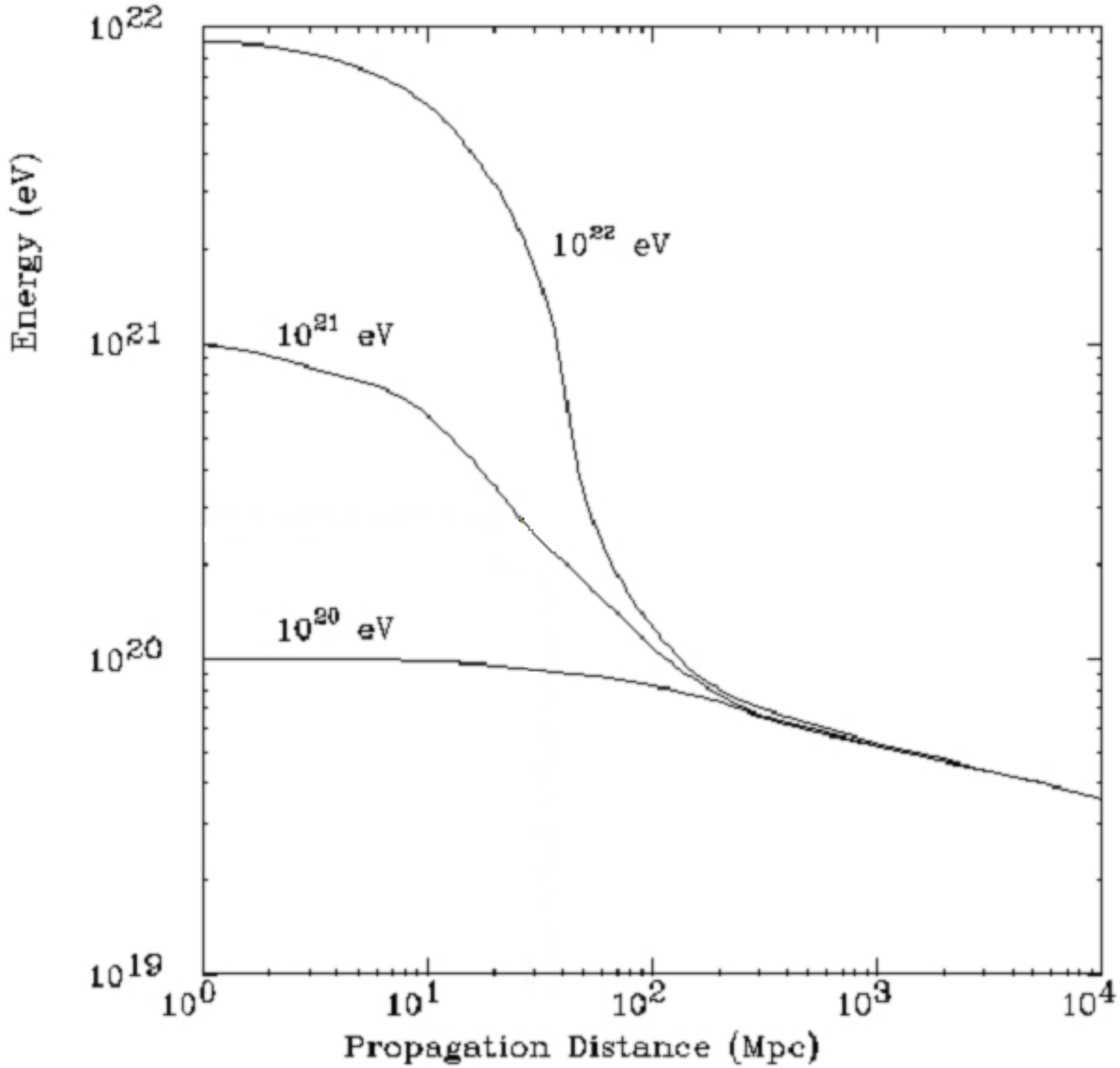
nucleons: A+γ_{CMBR} → (A-1) + N

$$E \geq \frac{(m_{A-1} + m_N)^2 - m_A^2}{4\varepsilon_{CMBR}} \approx \frac{Q_{\mathrm{binding}} m_p}{\varepsilon_{CMBR}}$$

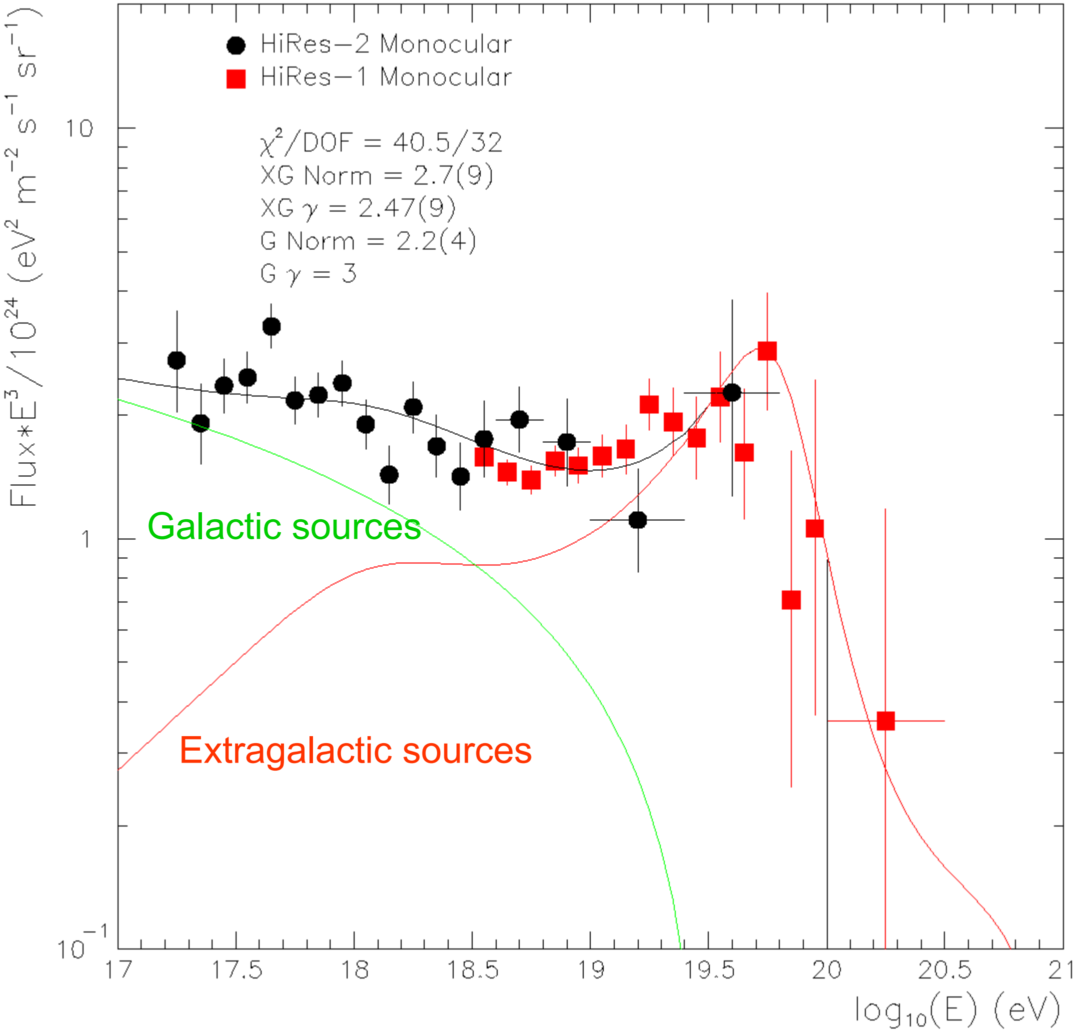
Proton and pion are produced in the same rest frame have the same Lorentz factor

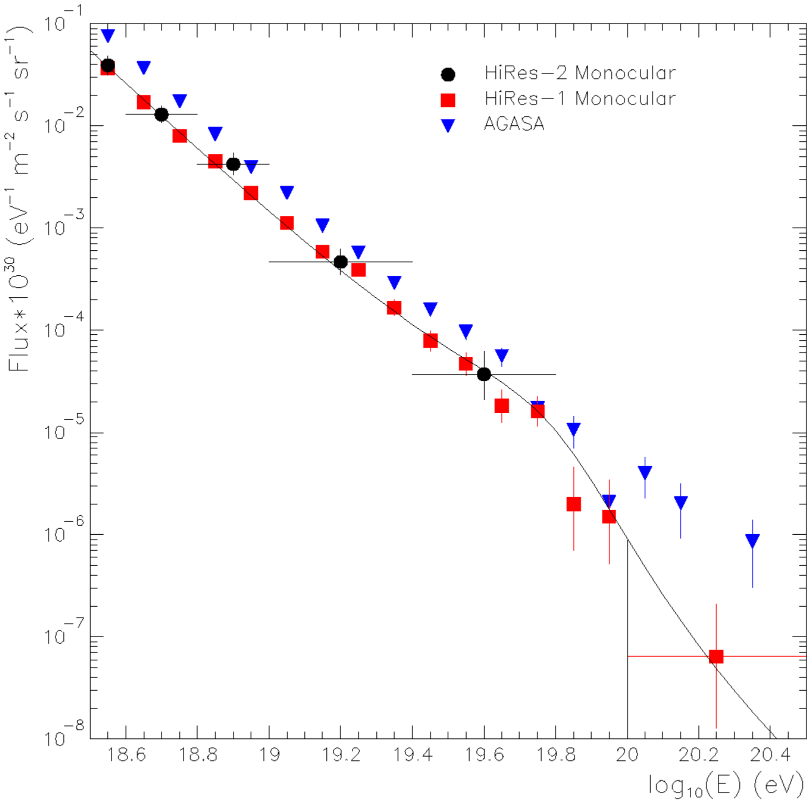
$$E_p = m_p \Gamma \qquad E_\pi = m_\pi \Gamma$$

$$\frac{\Delta E}{E} \sim \frac{m_\pi}{m_p + m_\pi} \sim 0.1$$

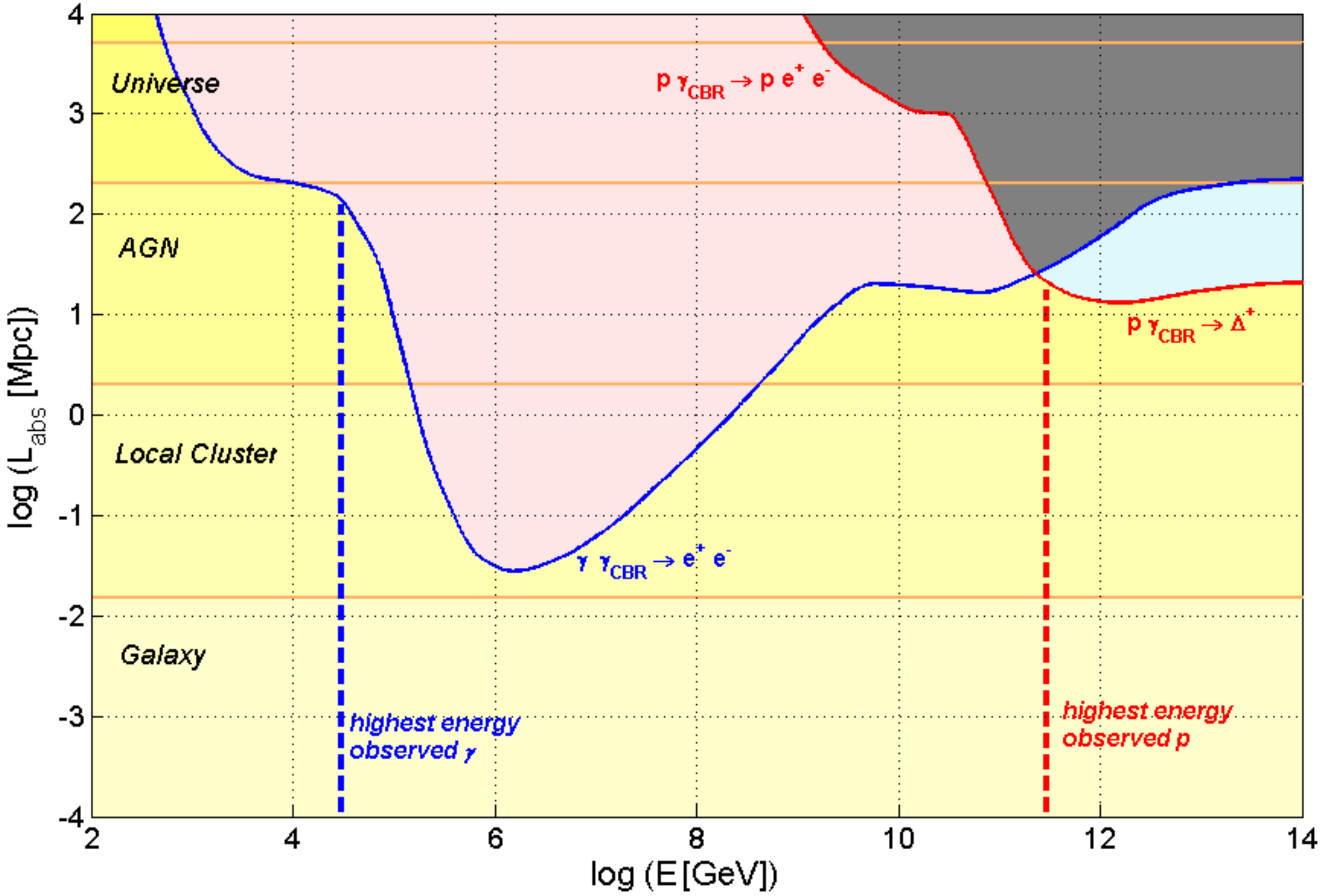


The GZK cutoff in the CR Spectrum





The GZK cutoff

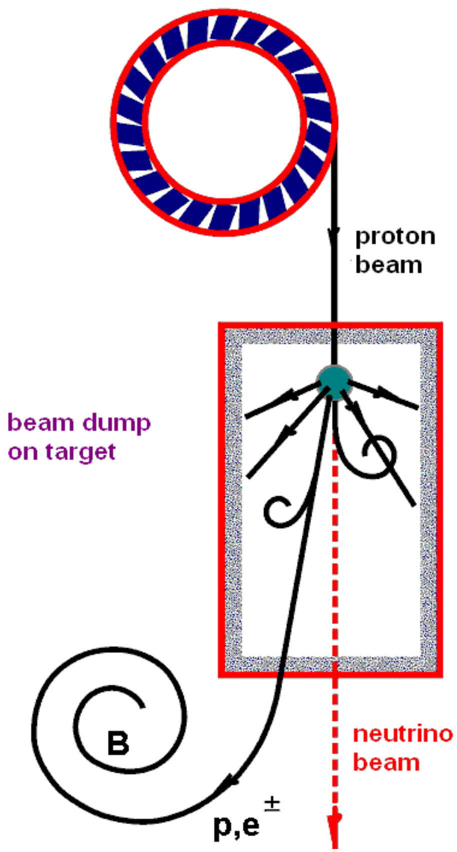


Only neutrinos can reach the Earth from cosmological sources

Neutrino production in cosmic accelerators

Halzen

Particle accelerator



Proton acceleration

• Fermi nechanism

proton spectrum $dN_p/dE \sim E^{-2}$

Neutrino production

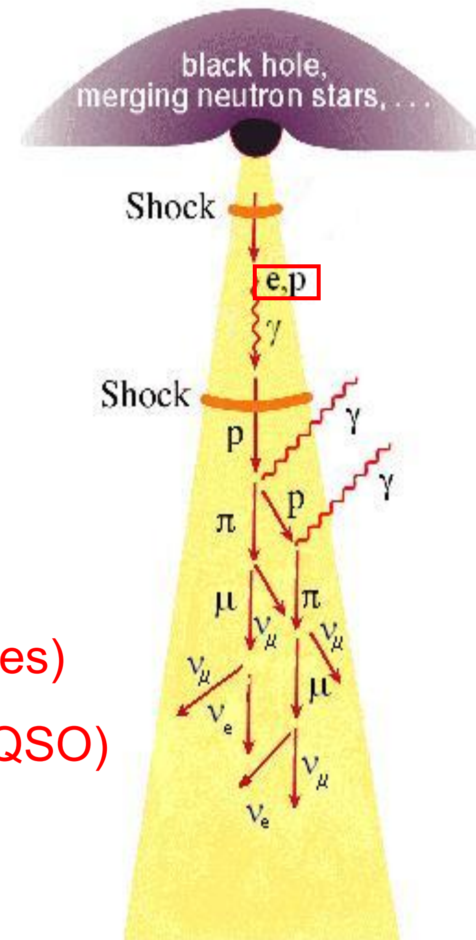
• Proton nteractions

p → p (SNR,X-Ray Binaries)

p → γ (AGN, GRB, microQSO)

• decay of pions and muons

Astrophysical jet

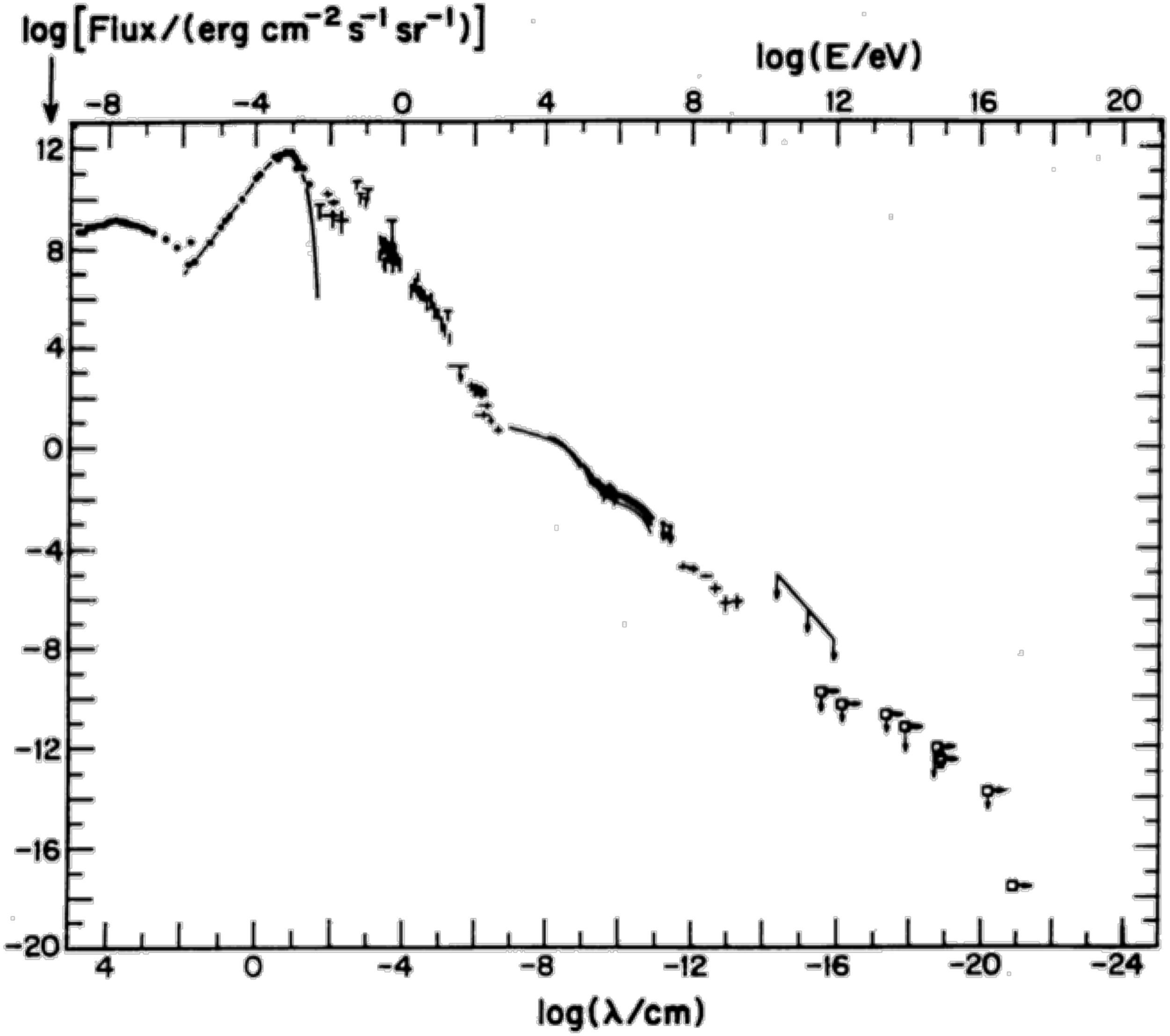


Electrons are responsible for lower energy gamma fluxes (synchrotron, IC)

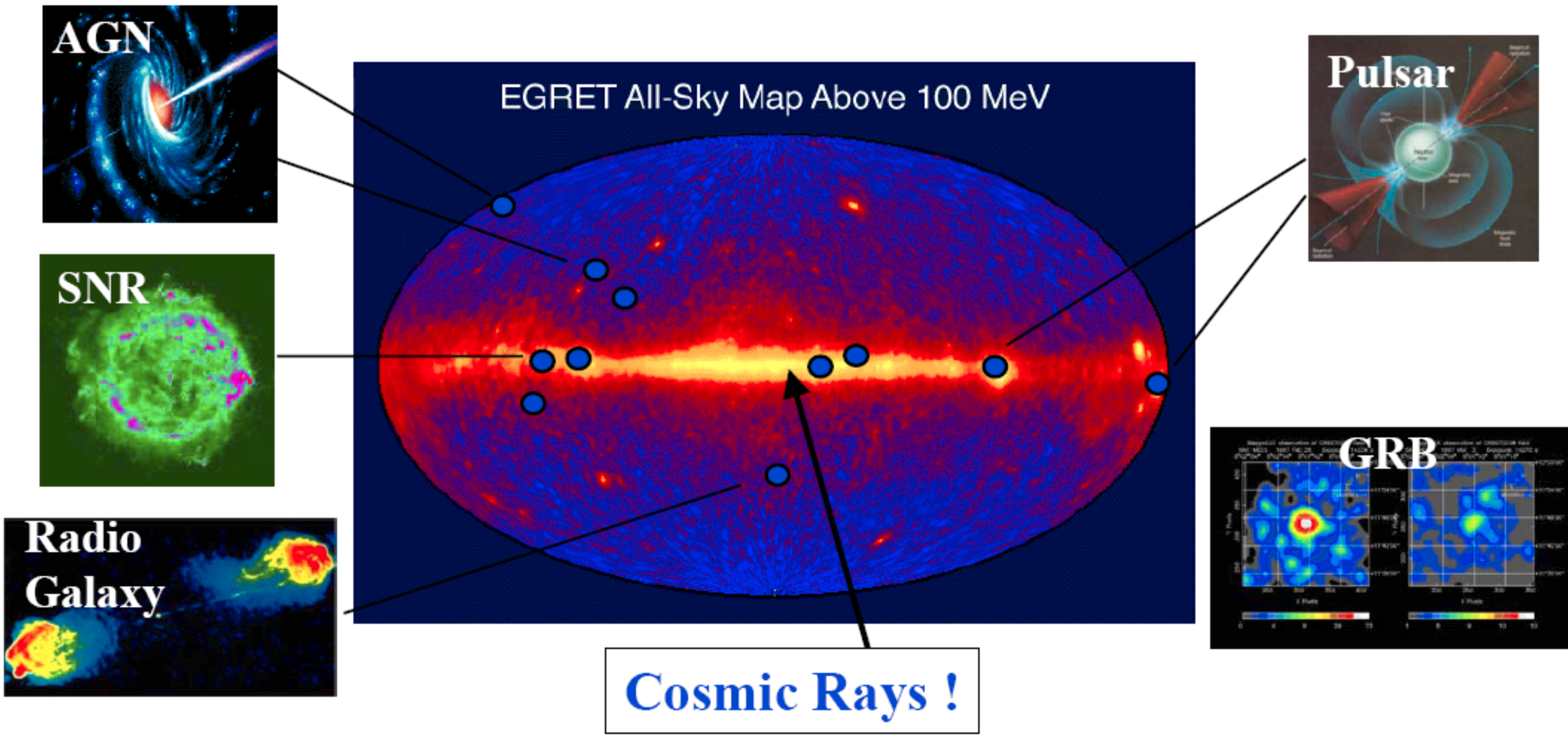
Detection of high energy cosmic particles and radiation

Gamma Rays

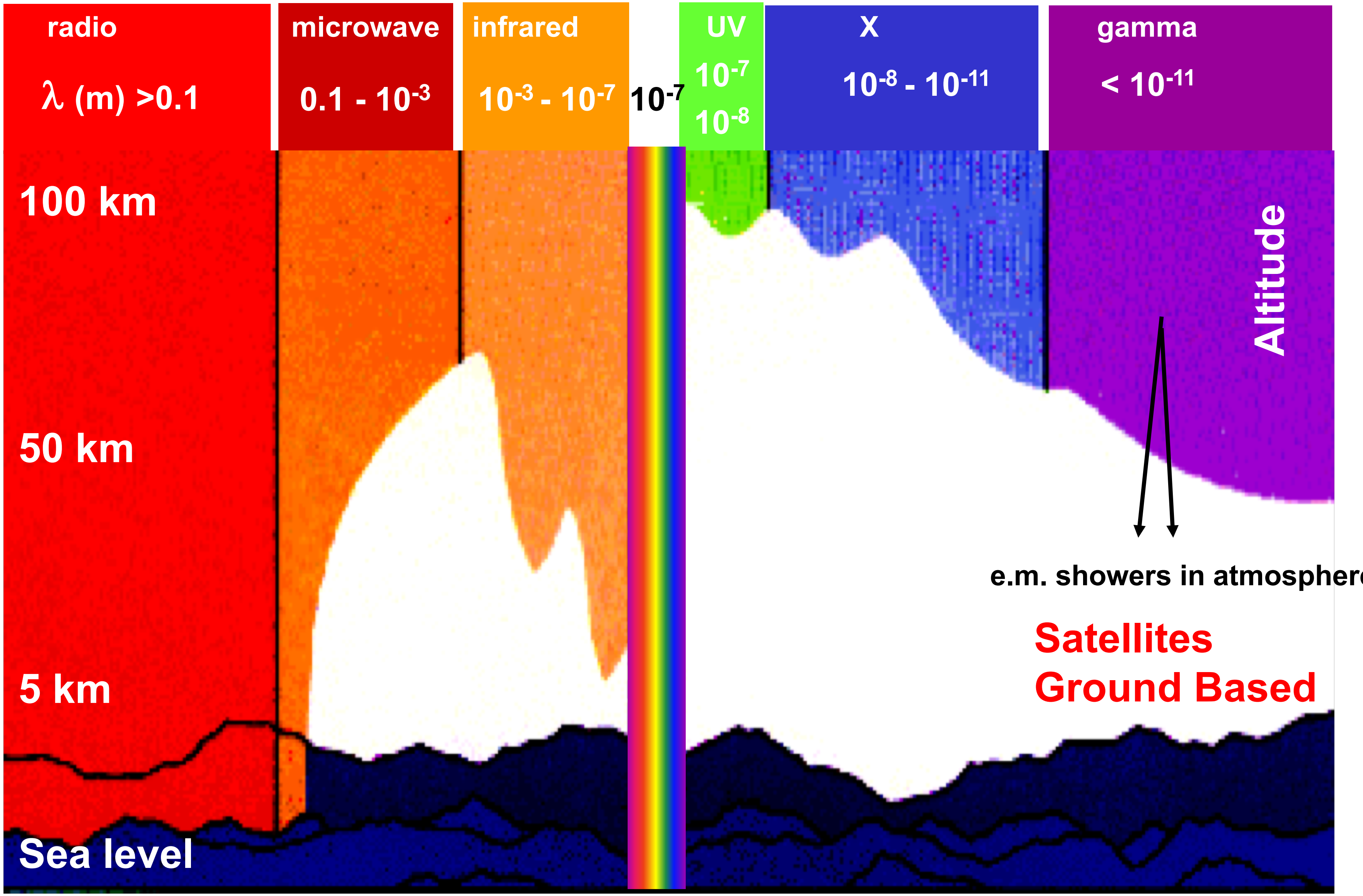
Photon fluxes in the Universe

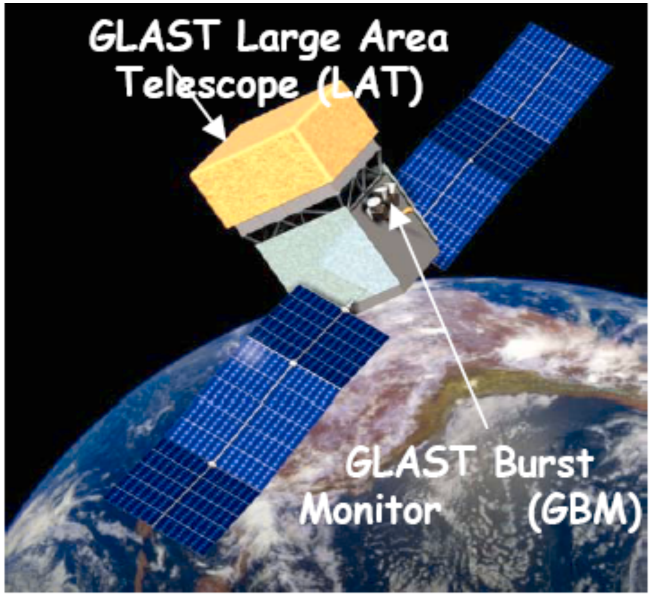


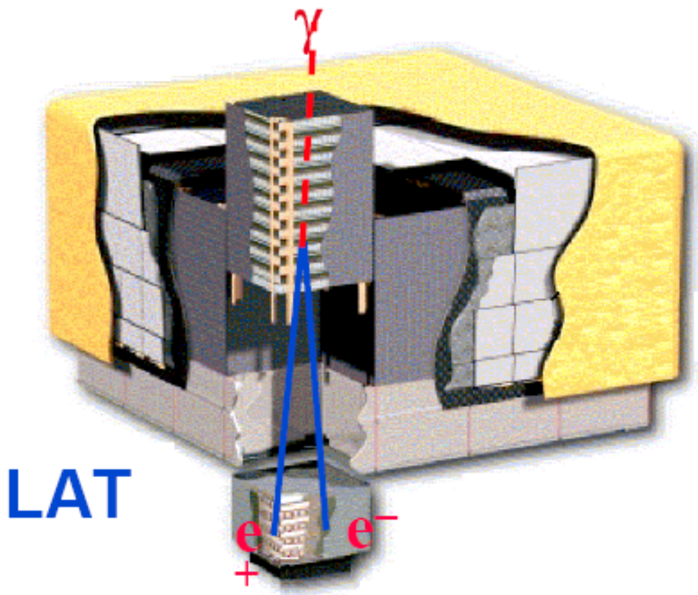
GeV range

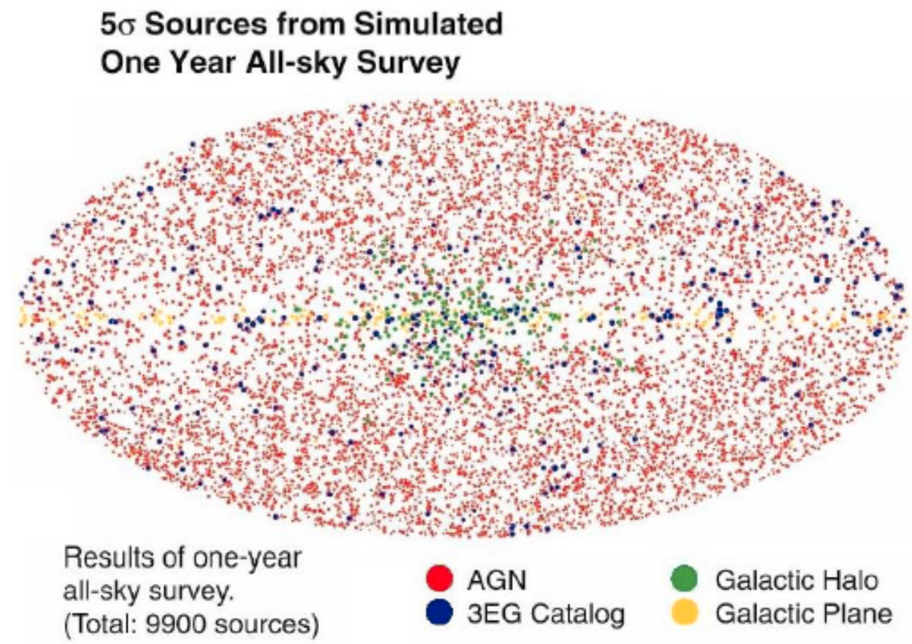


- ~ 250 HE point sources, most unidentified.

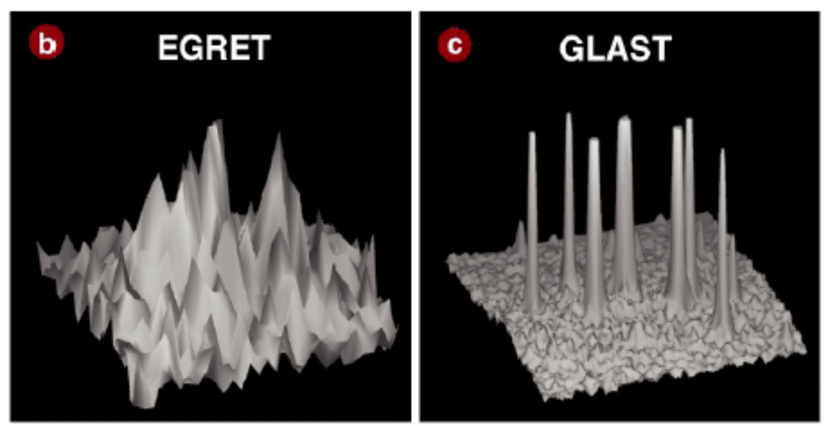

radio
λ (m) >0.1
microwave
0.1 - 10^-3
infrared
10^-3 - 10^-7
10^-7
UV
10^-7
10^-8
X
10^-8 - 10^-11
gamma
< 10^-11
100 km
50 km
5 km
Sea level
Altitude
e.m. showers in atmosphere
Satellites
Ground Based



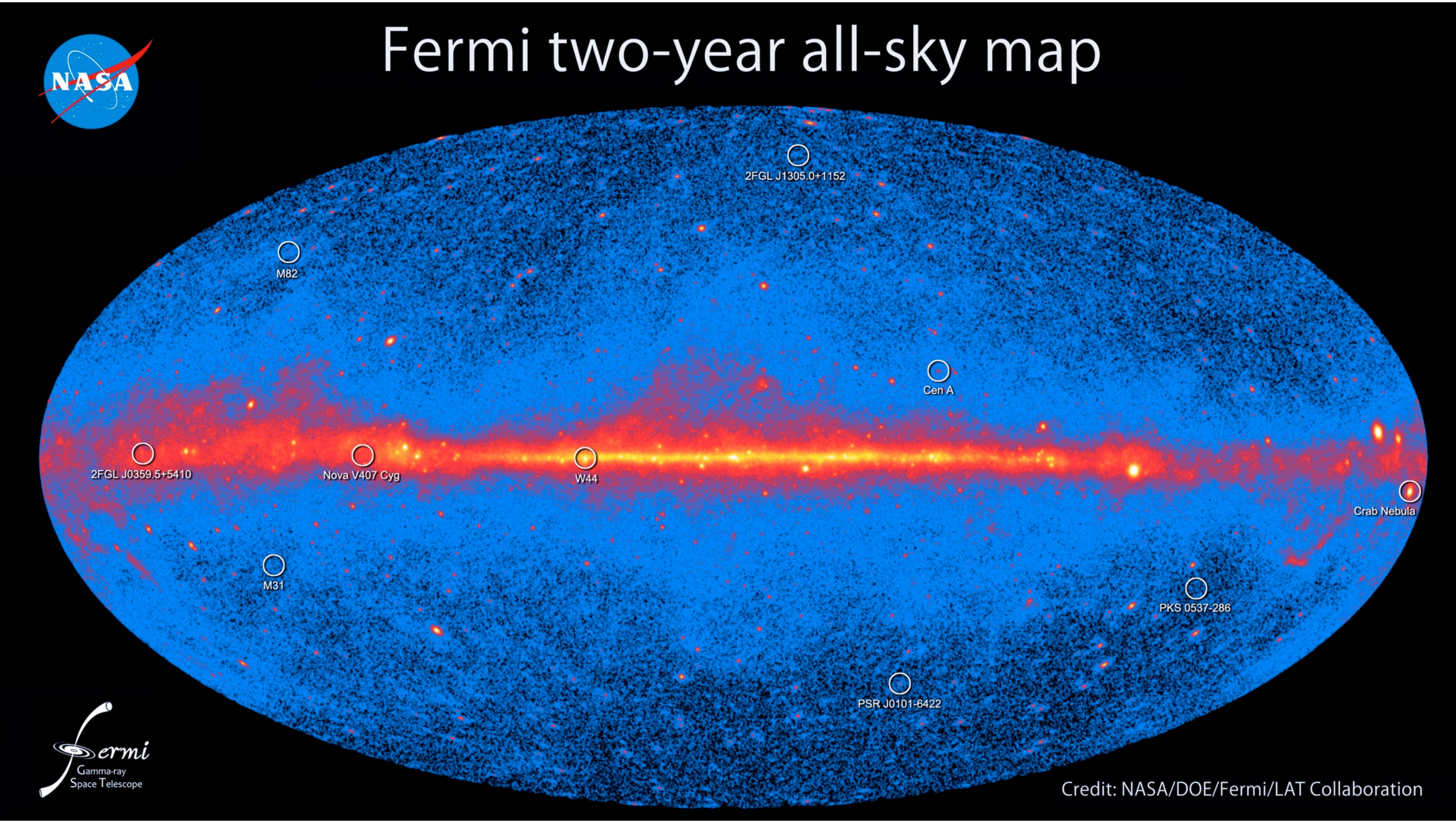




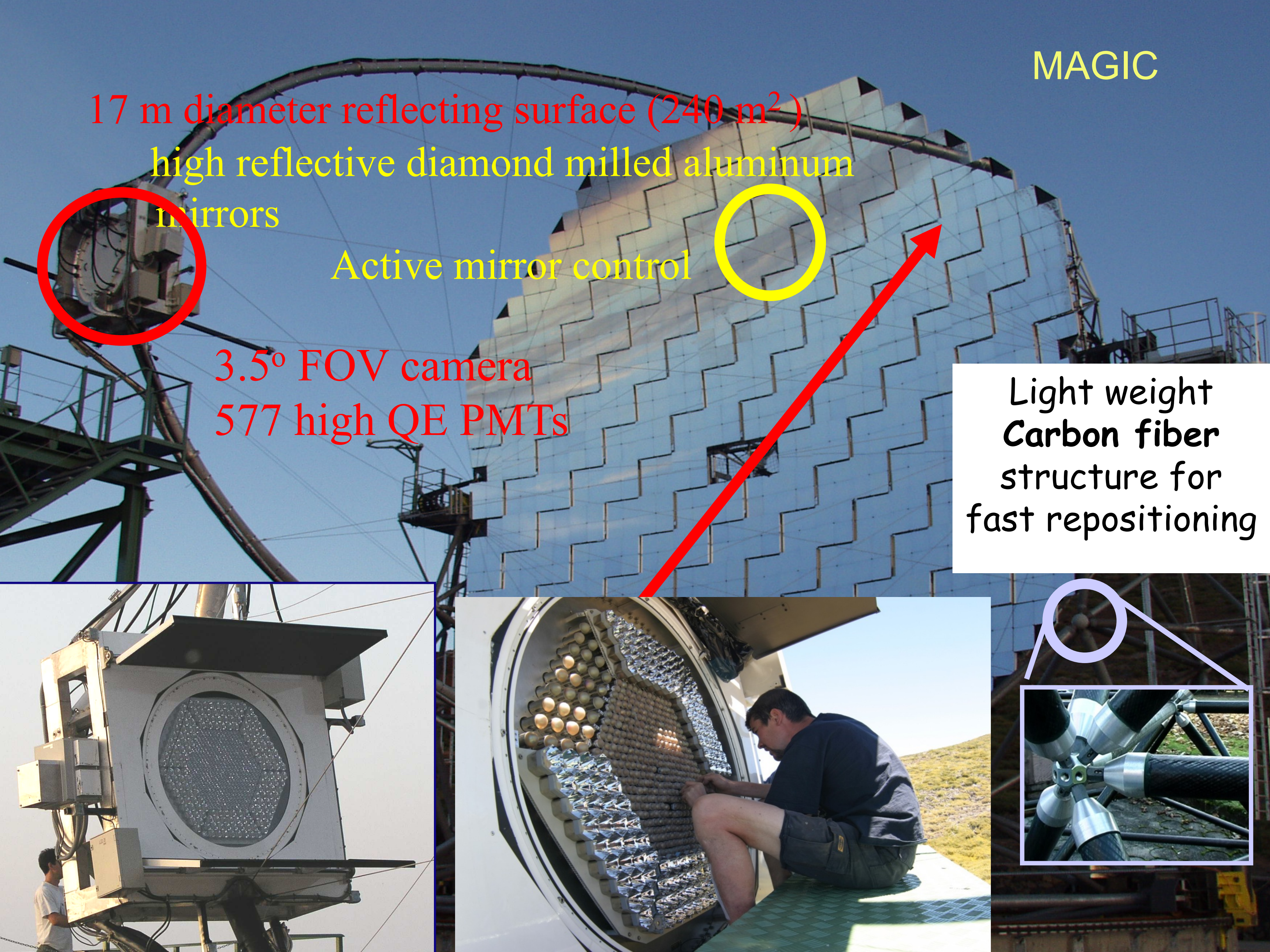
Many more sources, better localized.



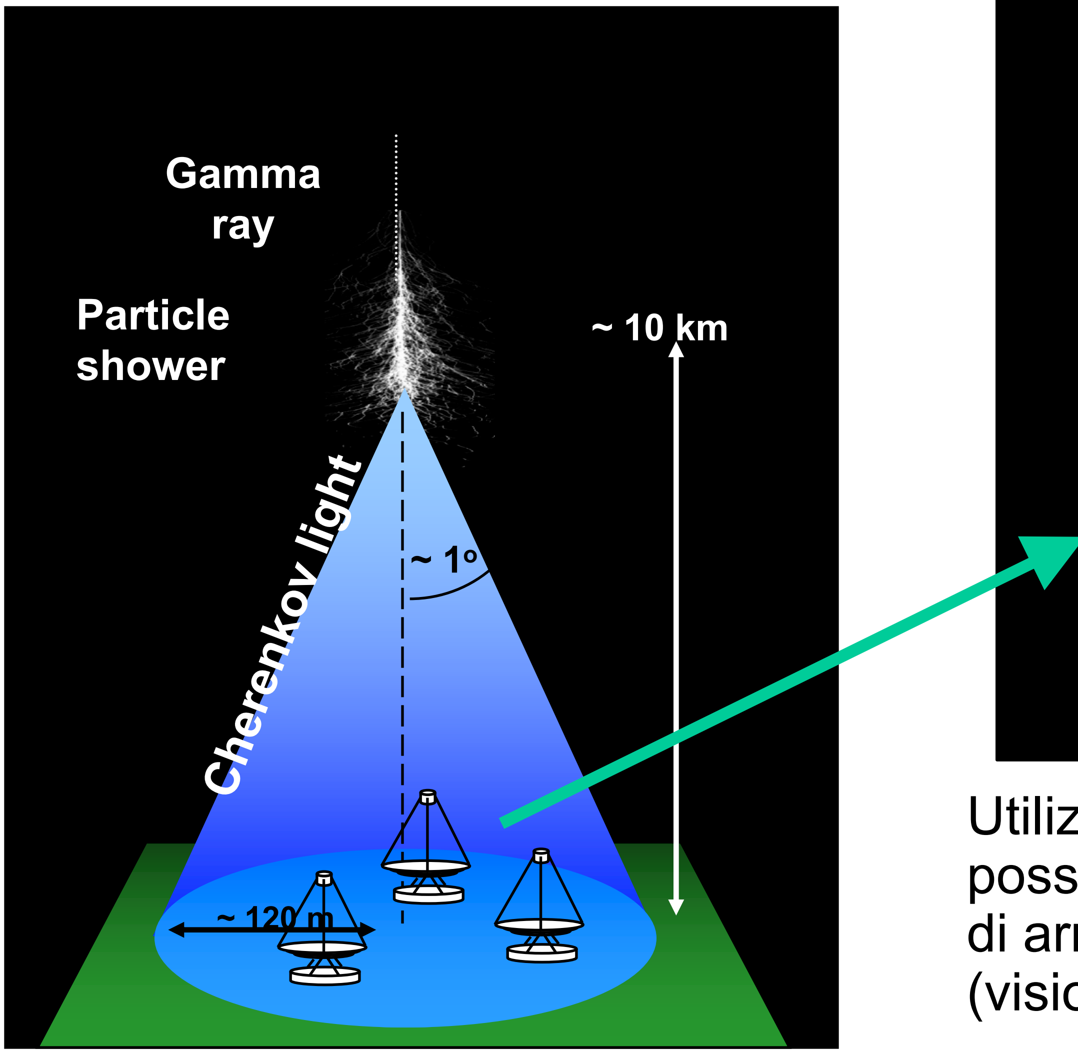
Fermi

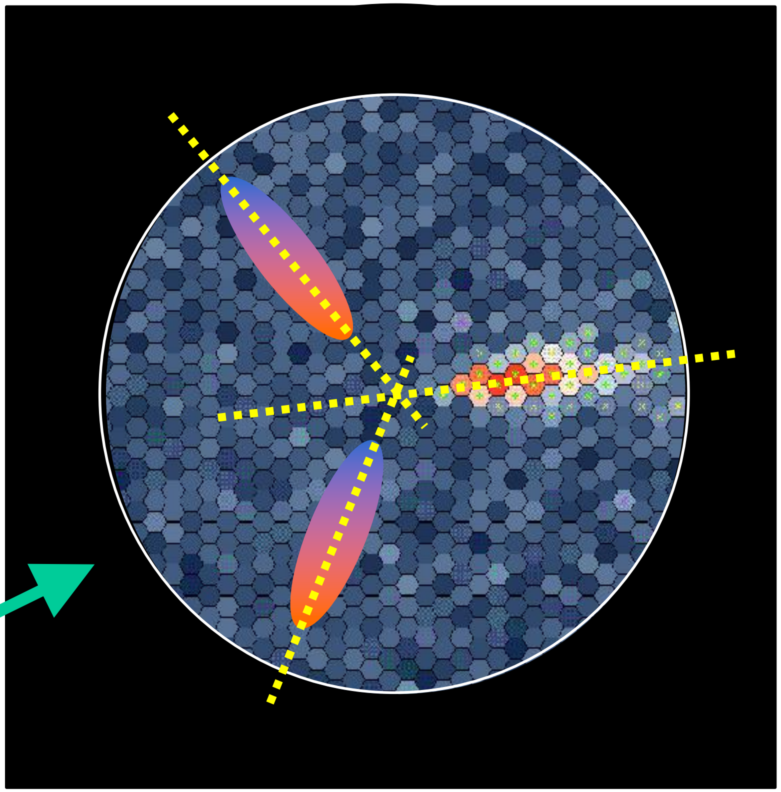


1873 sources found, nearly 600 are complete mysteries.


MAGIC
17 m diameter reflecting surface (240 m^2)
high reflective diamond milled aluminum mirrors
Active mirror control
3.5° FOV camera
577 high QE PMTs
Light weight **Carbon fiber** structure for fast repositioning

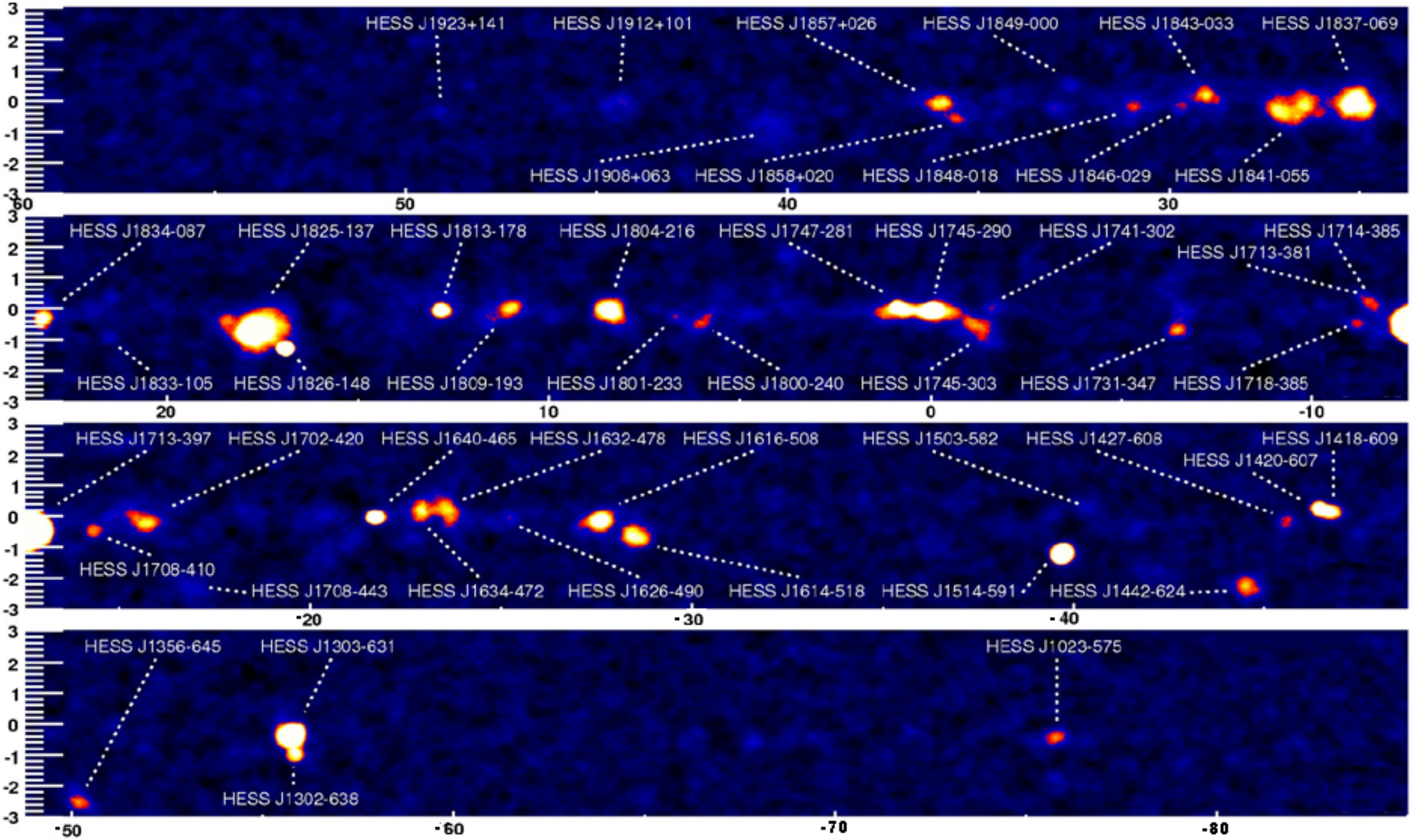
Air Cherenkov



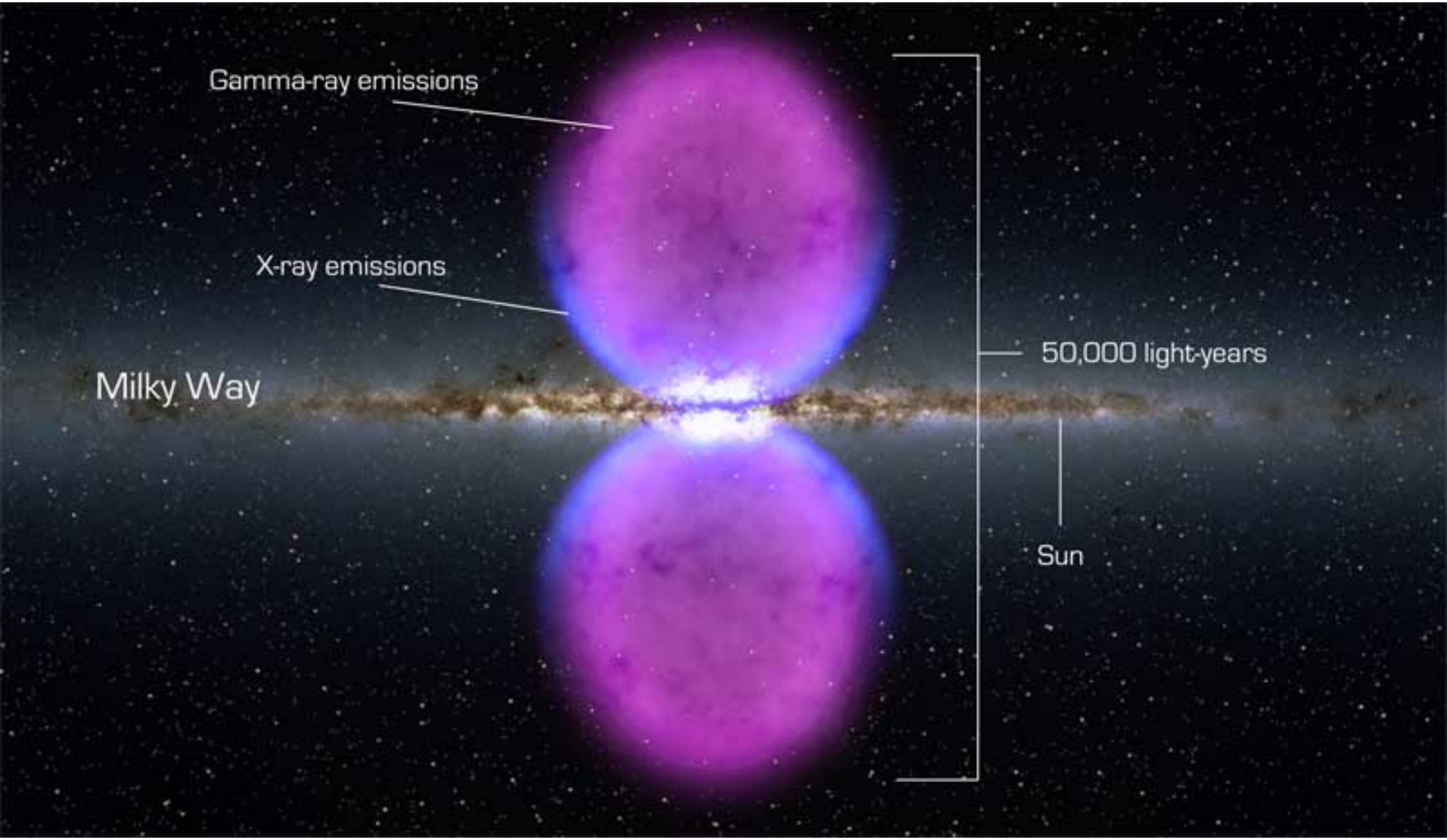


Utilizzando piu' immagini è possibile ricostruire la direzione di arrivo con maggiore precisione (visione stereo)

The Galactic Plane seen by HESS



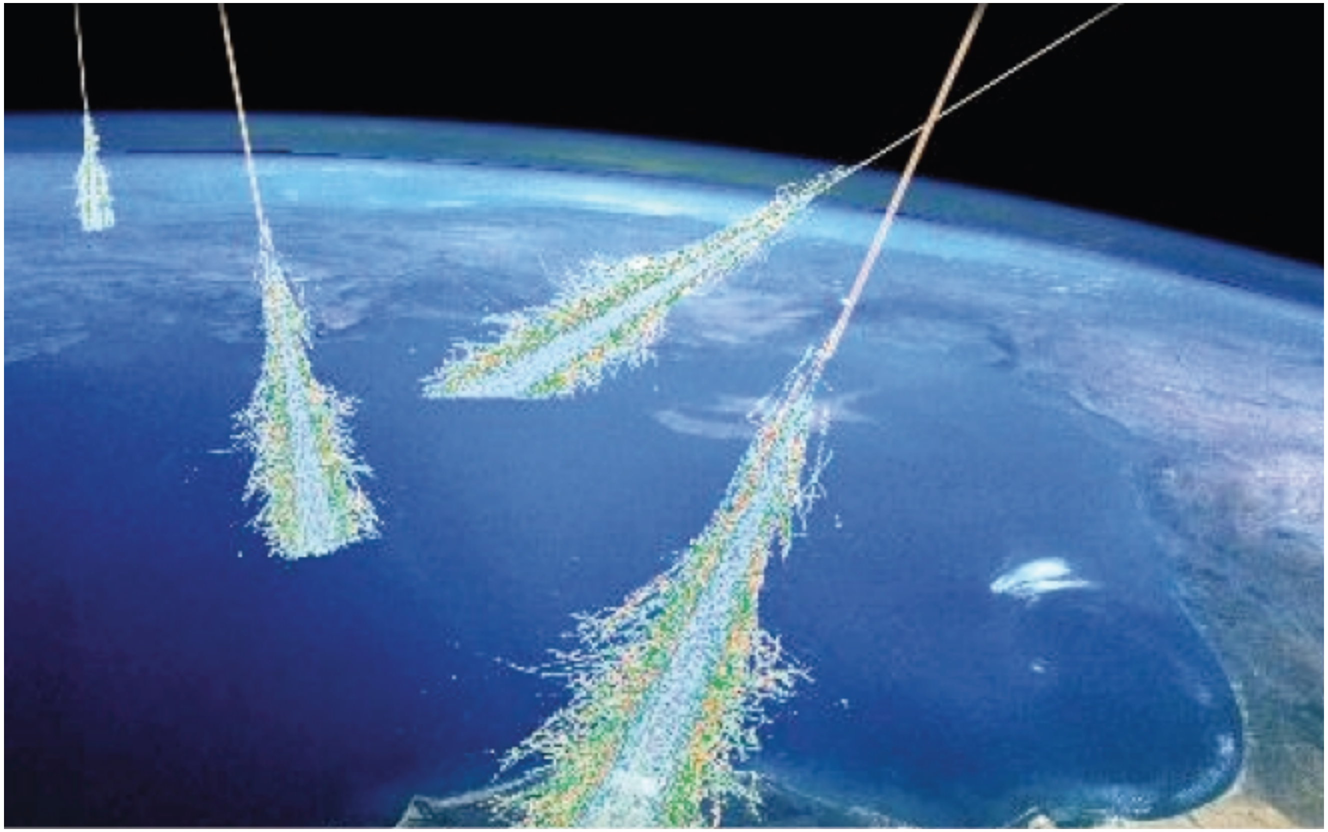
The Fermi Bubbles



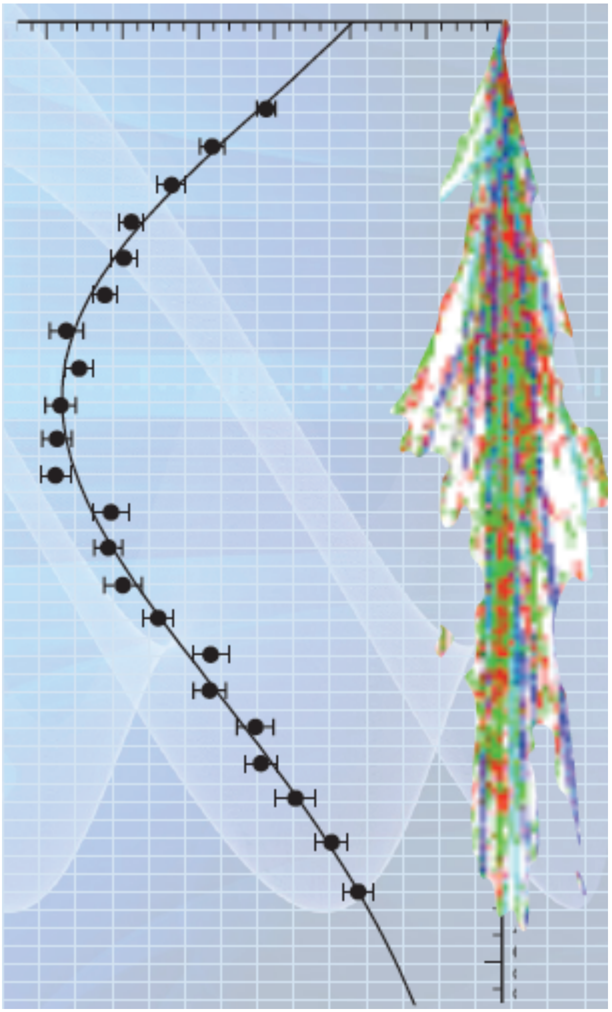
Detection of high energy cosmic particles and radiation

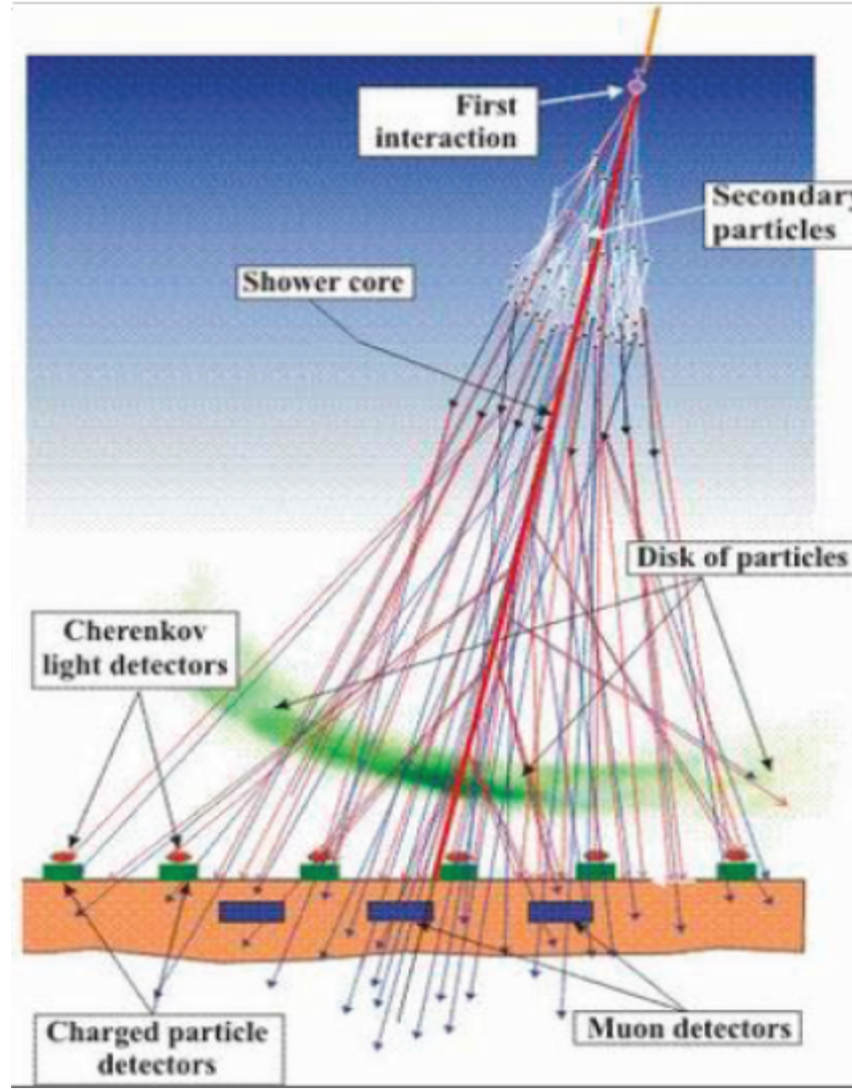
Cosmic Rays

V/U HECR detection techniques: EAS and Fluorescence

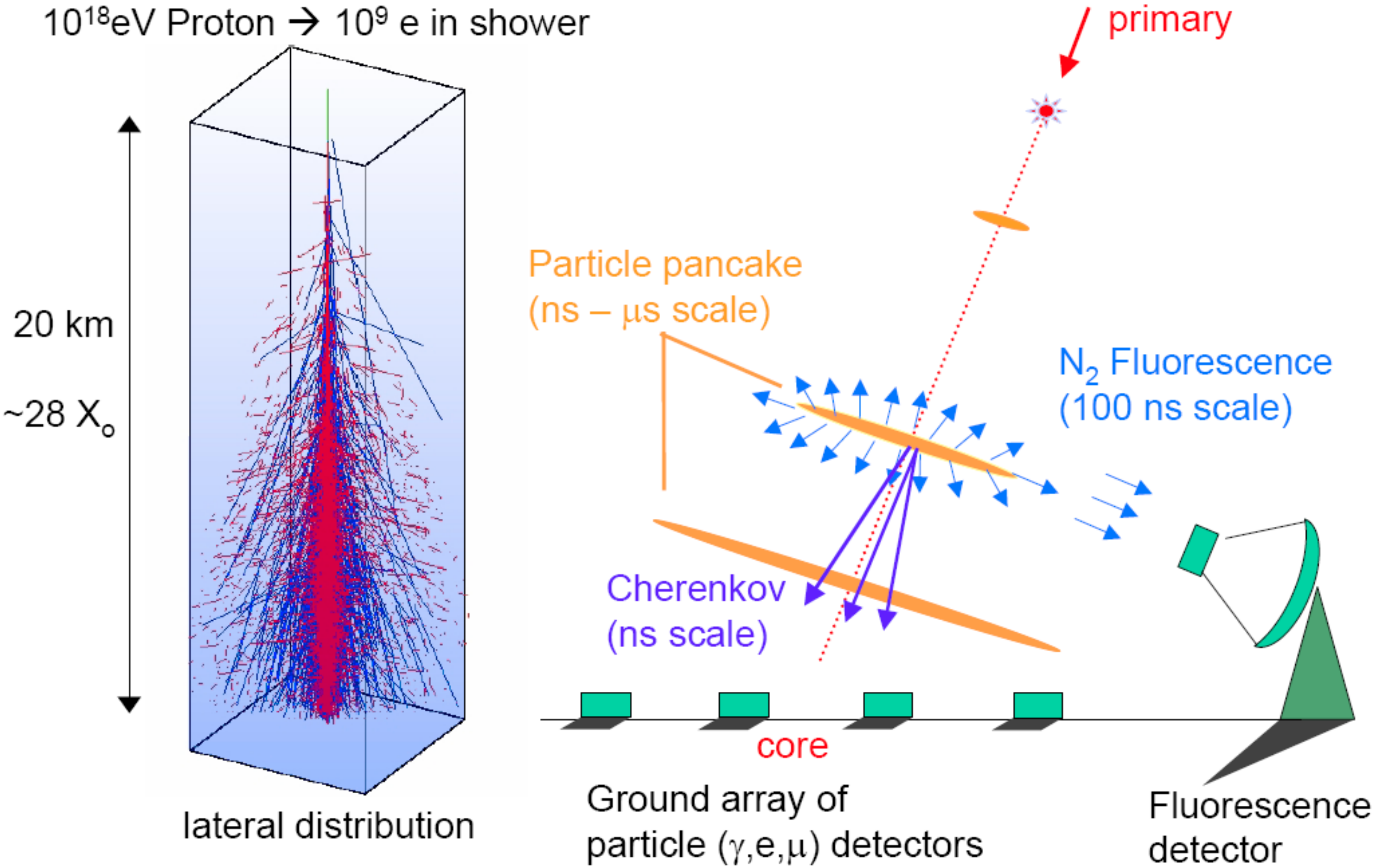


EAS Technique



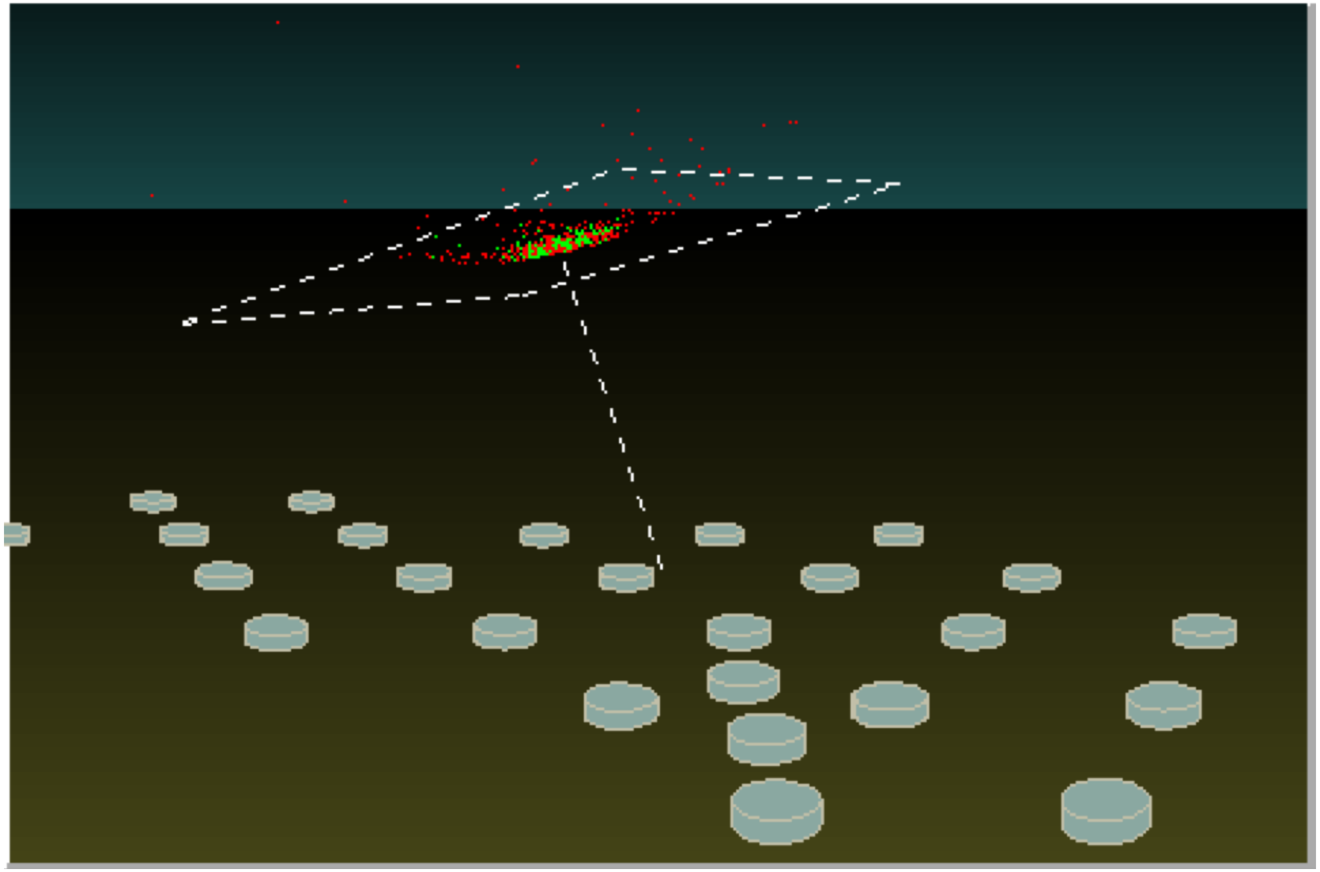


EAS and Fluorescence

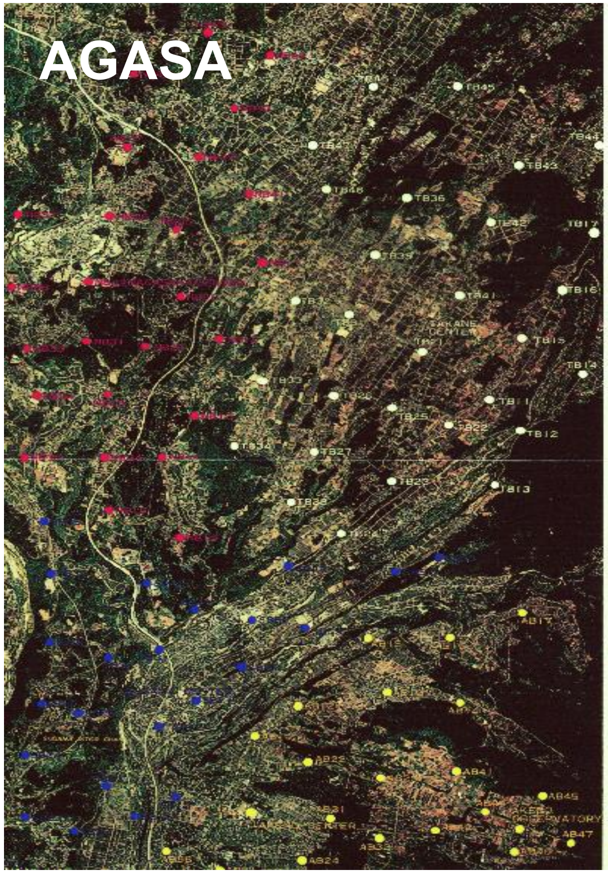


Auger: hybrid detector

EAS



EAS Detectors: AGASA and AUGER



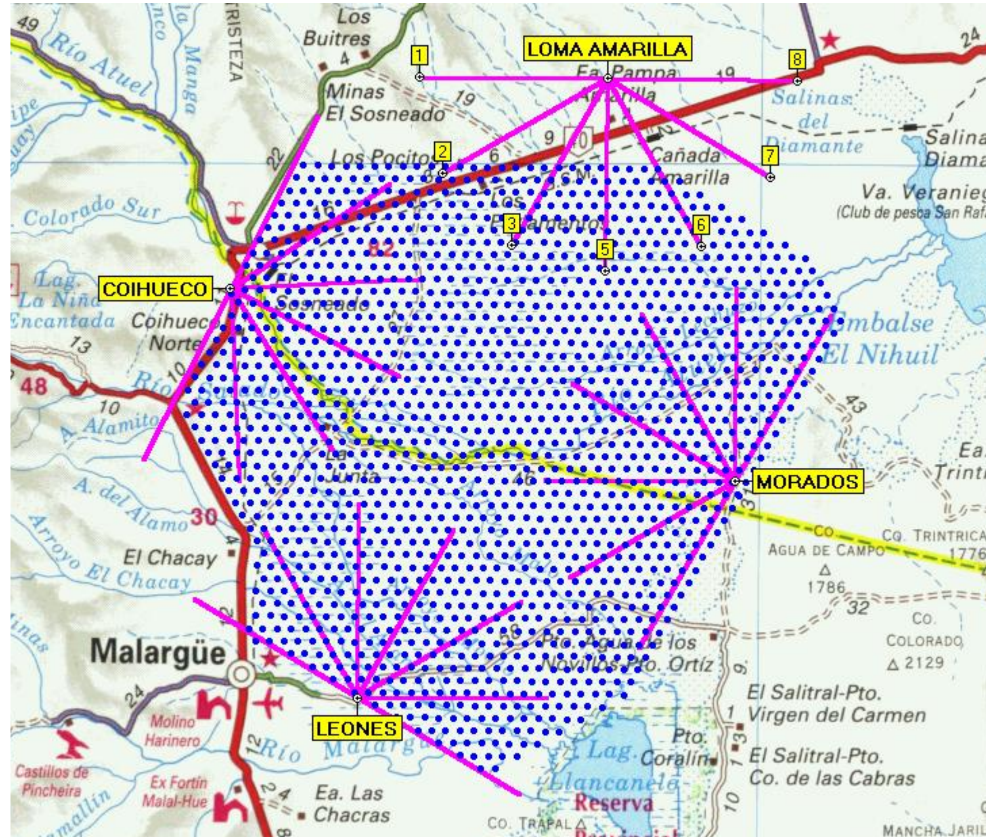
111 detectors surface detectors

27 muon detectors

(under absorbers)

AGASA area about 100 *km*^{2}

1 km spacing



AUGER

Surface Array

1600 detector stations

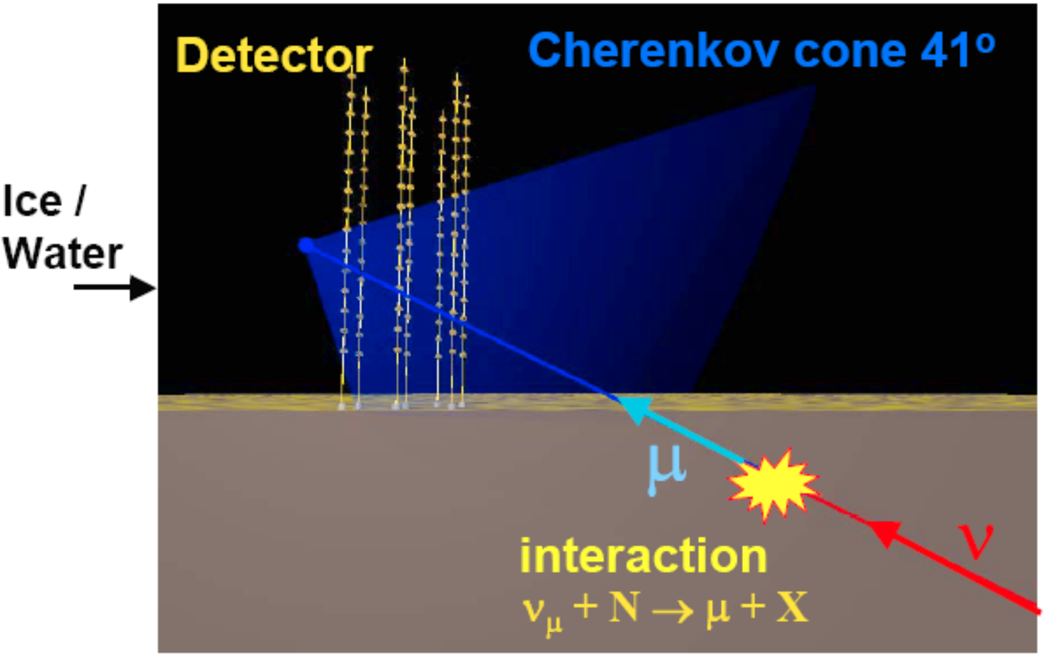
1.5 km spacing

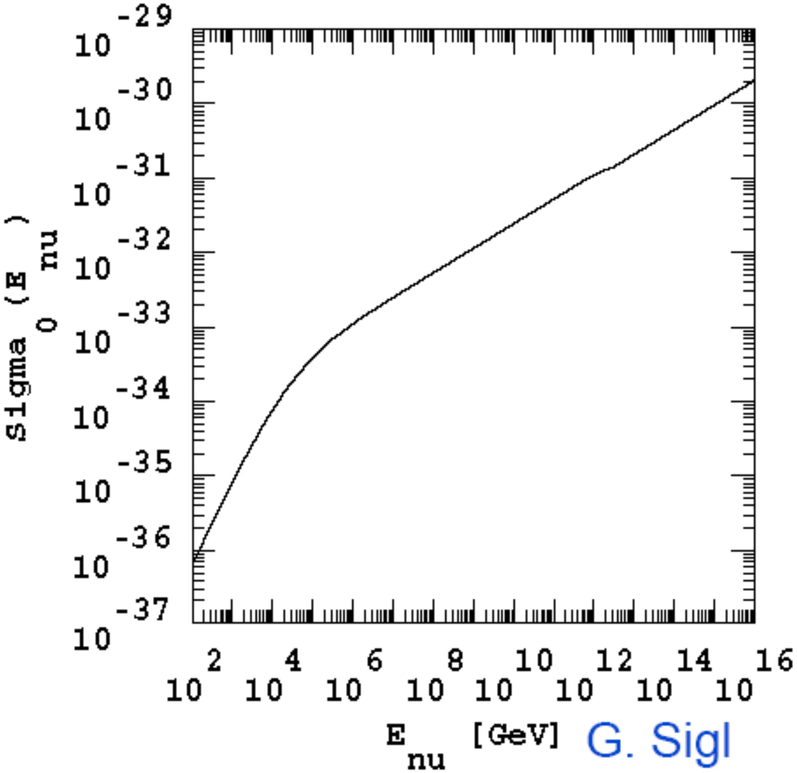
3000 km^2

Fluorescence Detectors

4 Telescope enclosures

6 Telescopes per enclosure





G. Sigl

Two signatures:

- Muon track: CC interaction
  ~7km, 20x min.i. (10 TeV)
- Casade: CC or NC interaction
  $\nu_{(e,\tau,)} + N \rightarrow (e, \tau) + X$
  $\nu_x + N \rightarrow \nu_x + X$

Neutrino cross sections have some uncertainty (~ 50% in PeV-EeV range).

Neutrino fluxes chemical composition

If the muon interaction time (IC) is larger than the muon decay time electron neutrinos and antineutrinos are also produced

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$$
$$\quad \hookrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

Tau neutrinos are unlikely produced in the sources (M_τ = 1.7 GeV)
They can be detected at the Earth as "oscillated" muon neutrinos:

$$P_{\nu_\mu \rightarrow \nu_\tau} \propto \sin^2\left(1.27\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\Delta m^2\left[\mathrm{eV}^2\right]\right)$$

$$P_{\nu_\mu \rightarrow \nu_\tau} \propto \sin^2\left(\frac{10^{16}L[\mathrm{kpc}]}{10^3E[\mathrm{TeV}]}10^{-3}\right) \approx \frac{1}{2}$$

$$\nu_\mu : \nu_\tau : \nu_e = 1:1:1$$

Neutrino energy and spectrum

Assuming $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$ **interaction channel**

$$\varepsilon_\pi \sim 0.2 \; \varepsilon_p$$

$$N_{\pi^0} \sim N_{\pi^+}$$

$$E_{\mu^+} + E_{\nu_\mu} = E_{\pi^+}$$

$$E_{\mu^+} \approx E_{\nu_\mu} \approx \frac{1}{2} E_{\pi^+}$$

⇒ $$\varepsilon_{\nu_\mu} \sim 0.05 \; \varepsilon_p$$

The same is valid for $n + \gamma \rightarrow \Delta^0 \rightarrow p + \pi^-$ **which is the source of anti-**ν_μ

If the energy fraction transferred from protons to pions (f_π**) is constant as a function of energy the neutrino spectrum follows the proton** E^{-2} **spectrum**

Quasi-two-particle channels: 2π and 3π

$$\left\{ \begin{array}{l} \gamma N \to \Delta(1232)\pi \\ \gamma N \to N\rho \\ \gamma N \to N\eta \end{array} \right. \longrightarrow \quad \gamma N \to N\pi\pi$$

$$\left\{ \begin{array}{l} \gamma N \to N\rho \\ \gamma N \to N\omega \end{array} \right. \longrightarrow \quad \gamma N \to N\pi\pi\pi$$