Cosmic Rays

A mysterious radiation

1903: Rutherford and others found that that the ionization was reduced when electroscopes were shielded of radioactivity.

- The belief spread that the penetrating radiation came from radioactive material in Earth's crust…!
- How should such radiation decrease with increasing height …?

1909: Theodor Wulf could measure ion-production rates as low as one ion-pair/s. Took his electroscope to top of Eiffel Tower and found the rate much larger than expected.

1909-11: Swiss physicist Albert Gockel carried a Wulf-type electroscope on three balloon flights (4500m). He ascribed a considerable part of the ionization to gamma rays from 'radioactive substances in the atmosphere'.

Mysterious radiation from above

1910-14: **Italian physicist Domenico Pacini made important but little noticed ionization measurements with an electroscope on land, at sea, and underwater He concluded that there was penetrating radiation in the atmosphere, independent of radioactive material in the crust...!**

1911-13: **Hess designed Wulf-type electroscopes with 3 mm thick brass walls. He then made 10 balloon flights. On 7 August 1912 the hydrogen filled balloon would carry him to an altitude of about 5000 m.**

This flight revealed a very significant increase of the ionization at high altitude

A month after the decisive flight he reported his results which became known as the discovery of galactic cosmic rays at a meeting in Munster.

V. F. Hess (1912). "Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten".

Physikalische Zeitschrift 13: 1084–1091

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Victor Hess

1883: Born in Austria…
1910: Earned his PhD at the University of Graz.

1912: August 7, conclusive 6 hour balloon flight to 4500m drifted 200 km north.

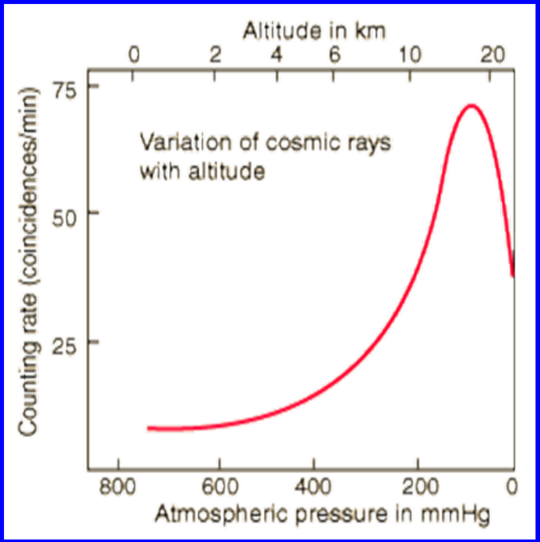
1925: Professor of Experimental Physics, University of Graz.
1931: Professor, and Director Institute of Radiology, University of Innsbruck.
1936: He was awarded Nobel Prize in Physics in 1936.

1938: Relocated to the USA. Fordham University appointed Professor of Physics.
1944: Became an American citizen.
1964: Died on December 17th.

Mysterious space radiation

1914: **Werner Kolhörster improved the Wulf electroscope, made five balloon flights in 1914. He reached 9300 m, measuring an ionization six times larger than at ground level, confirming Hess' result.**

An unknown radiation from space with extreme penetrating power was causing the ionization.



No mentioning of cosmic rays or particles.

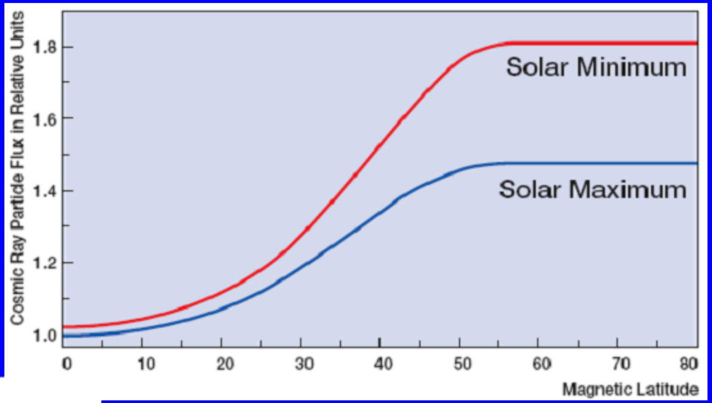
Some scientists were sceptical, especially Millikan in the USA. He could NOT confirm results with an unmanned balloon flight to 15 km over Texas.

Mysterious cosmic radiation

1926-32:
Millikan denied a latitude effect – said it was local radiation.
But, Arthur Compton supported the 'particle' view.
The debate between the two giants went on for some time.

Compton undertook several expeditions in 1932 to confirm the latitude effect.

Millikan finally accepted the latitude effect after making measurements from airplanes in 1933.



He coined the name "cosmic rays."
In Central Europe, the names 'Höhenstrahlung' (high-altitude radiation) and 'Ultra-Gammastrahlung' became current.

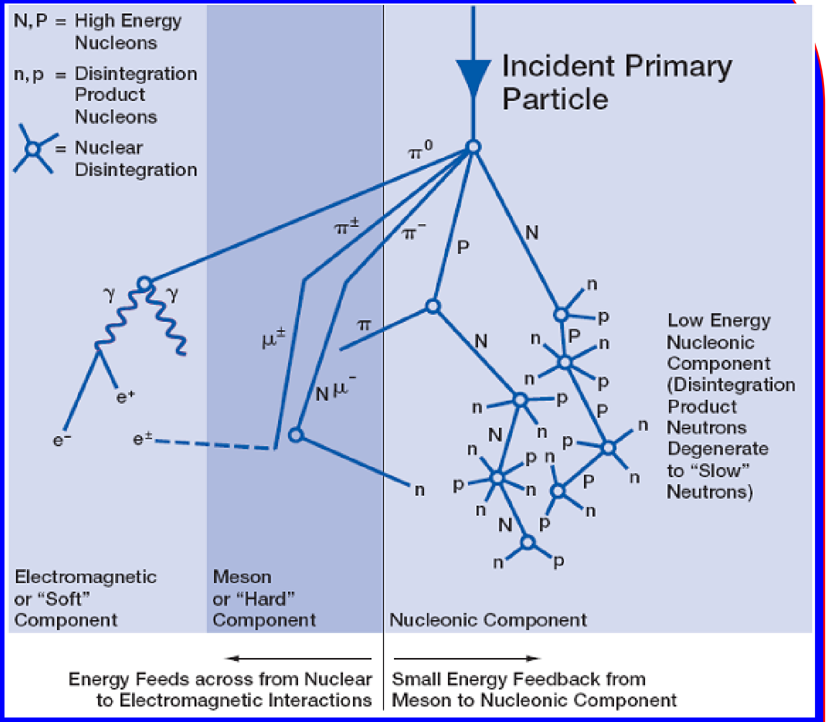
It took a long time before the particle nature and composition of cosmic rays were understood.

Cosmic rays as charged particles

1927: Dmitri Skobeltsyn in the Soviet Union had obtained a cloud-chamber photo that showed a cosmic-ray track…!

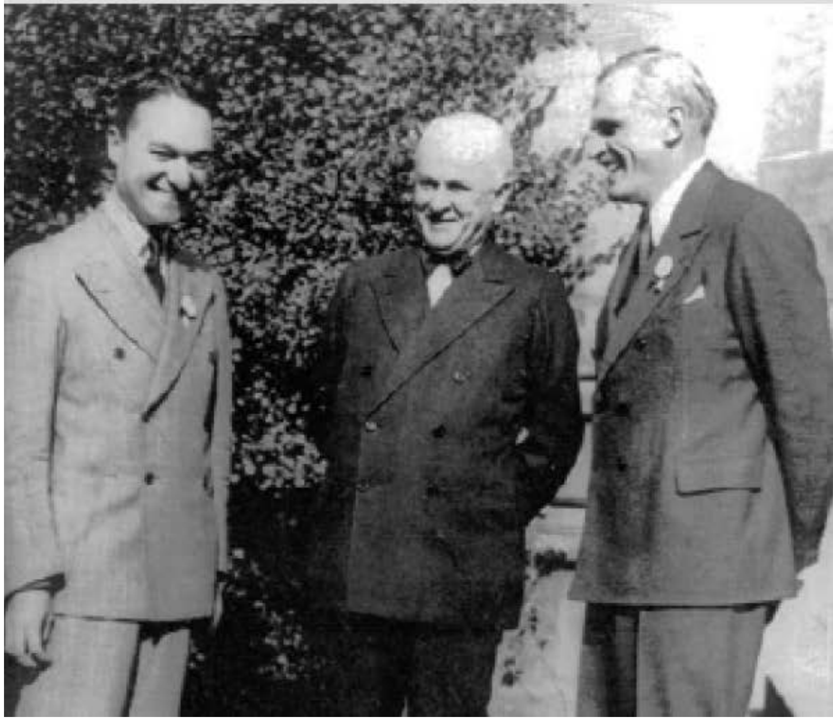
1932: Bruno Rossi found that the cosmic-ray flux contained a soft component and a hard component of charged particles with energies above 1 GeV…!

Then Carl Anderson (Caltech) discovered the positron. For this he shared the Nobel Price with Hess…!



1932-1953: Many new particles were discovered by studying cosmic ray showers… After two decades of such fundamental discoveries, 1953 marked the transition to accelerator-based particle physics.

Per Carlson's paper in Physics Today Feb. 2012



Bruno Rossi, Robert A. Millikan, and Arthur H. Compton at the Rome conference, October 11–18, 1931.

The Rome conference 1931 "marked the beginning of the historical debate about the nature of cosmic rays…."

…"At the invitation of Fermi, I gave an introductory speech on the problem of cosmic rays. The main thrust of this talk was to present what, to my mind, were irrefutable arguments against Millikan's theory of the "birth cry" of atoms. Such a brash behavior on the part of a mere youngster (I was then 26 years old) clearly did not please Millikan, who for a number of years thereafter, chose to ignore my work altogether."

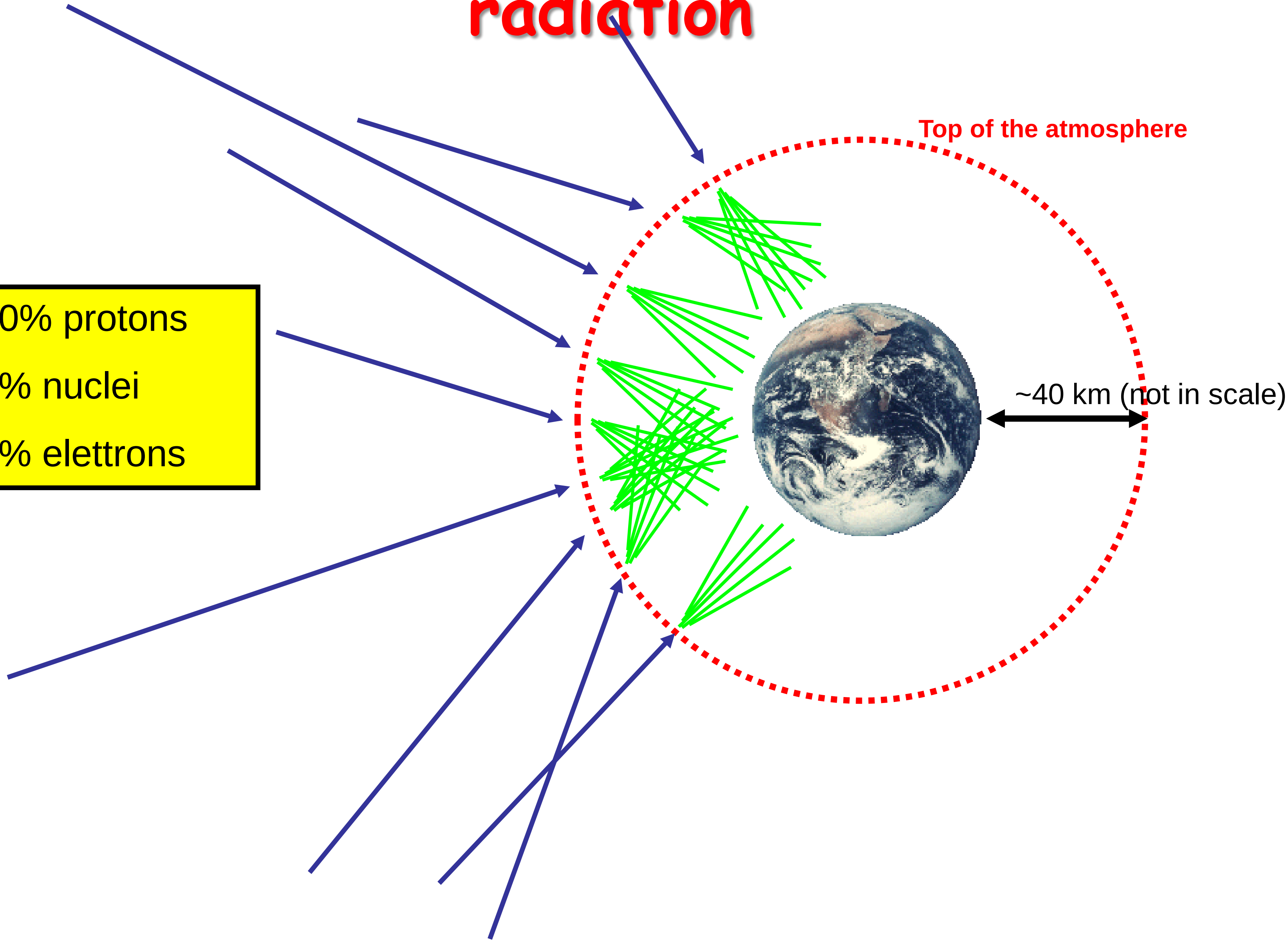
Rossi Physics Today October 1981

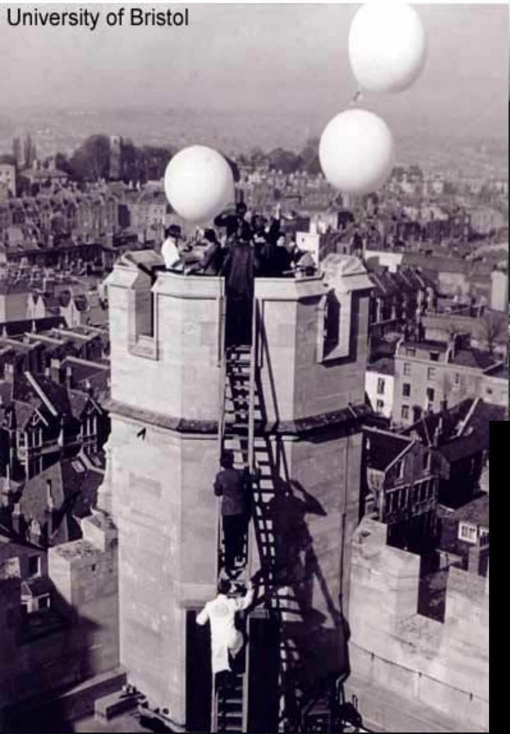
A modern picture of the cosmic radiation

~90% protons

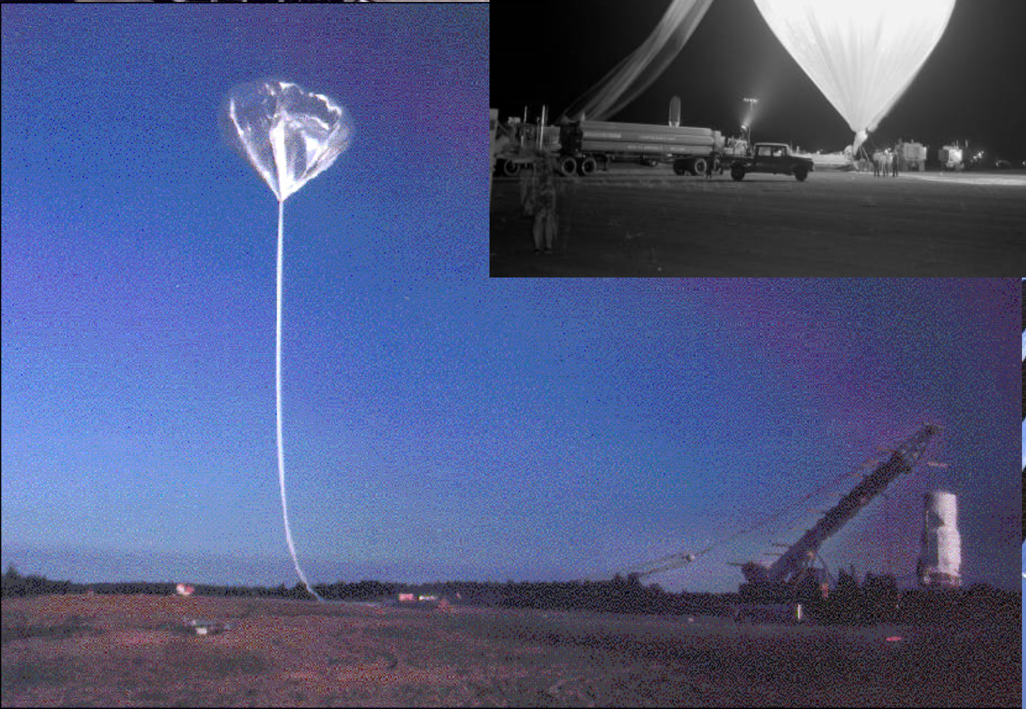
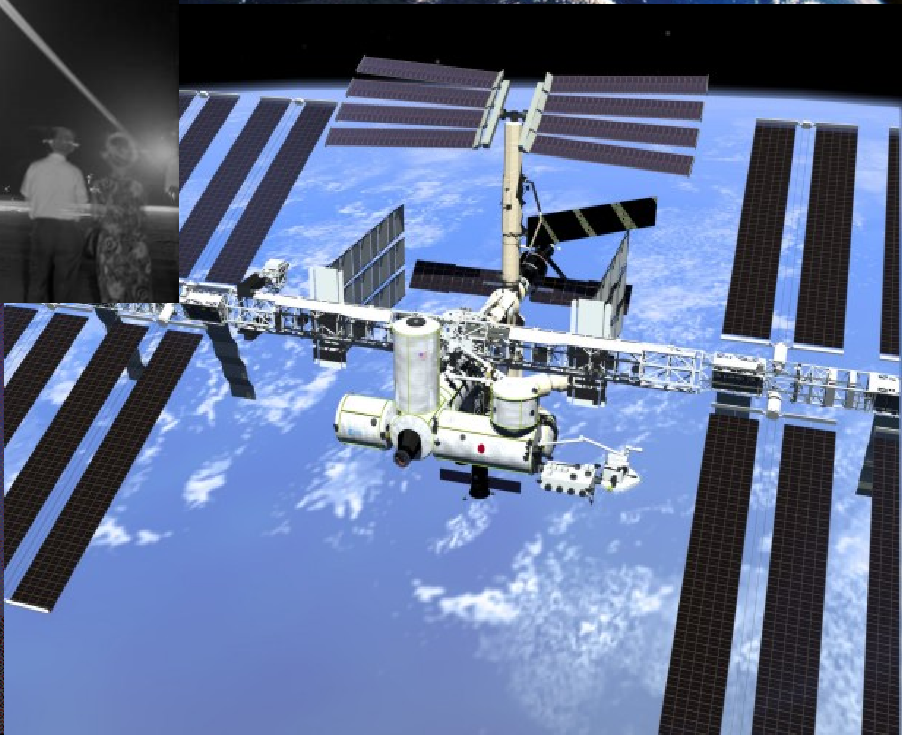
~9% nuclei

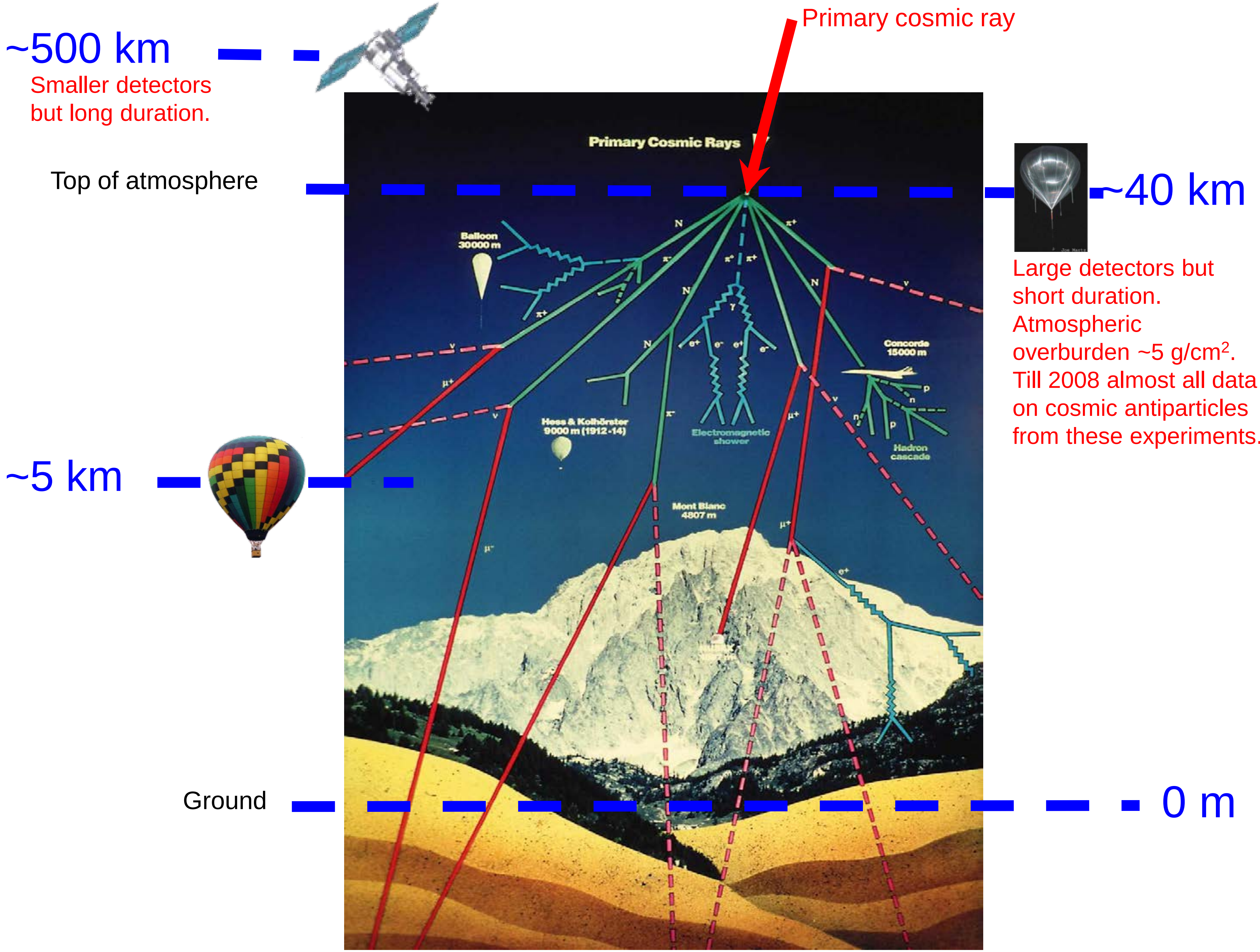
~1% elettrons




University of Bristol

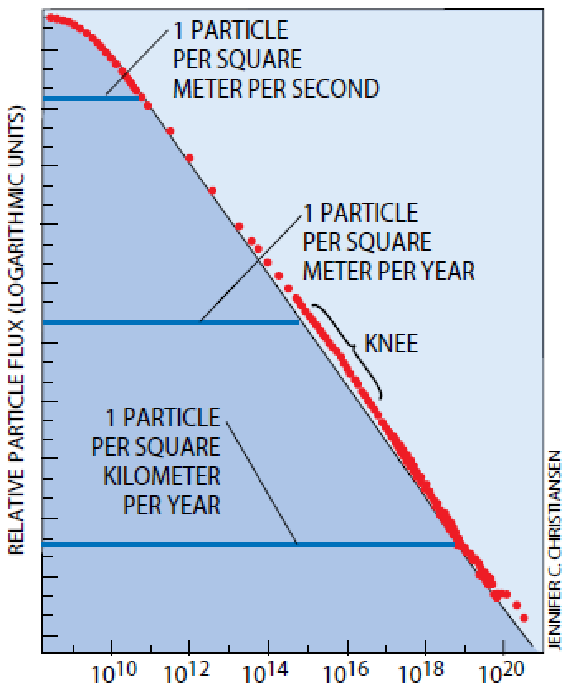


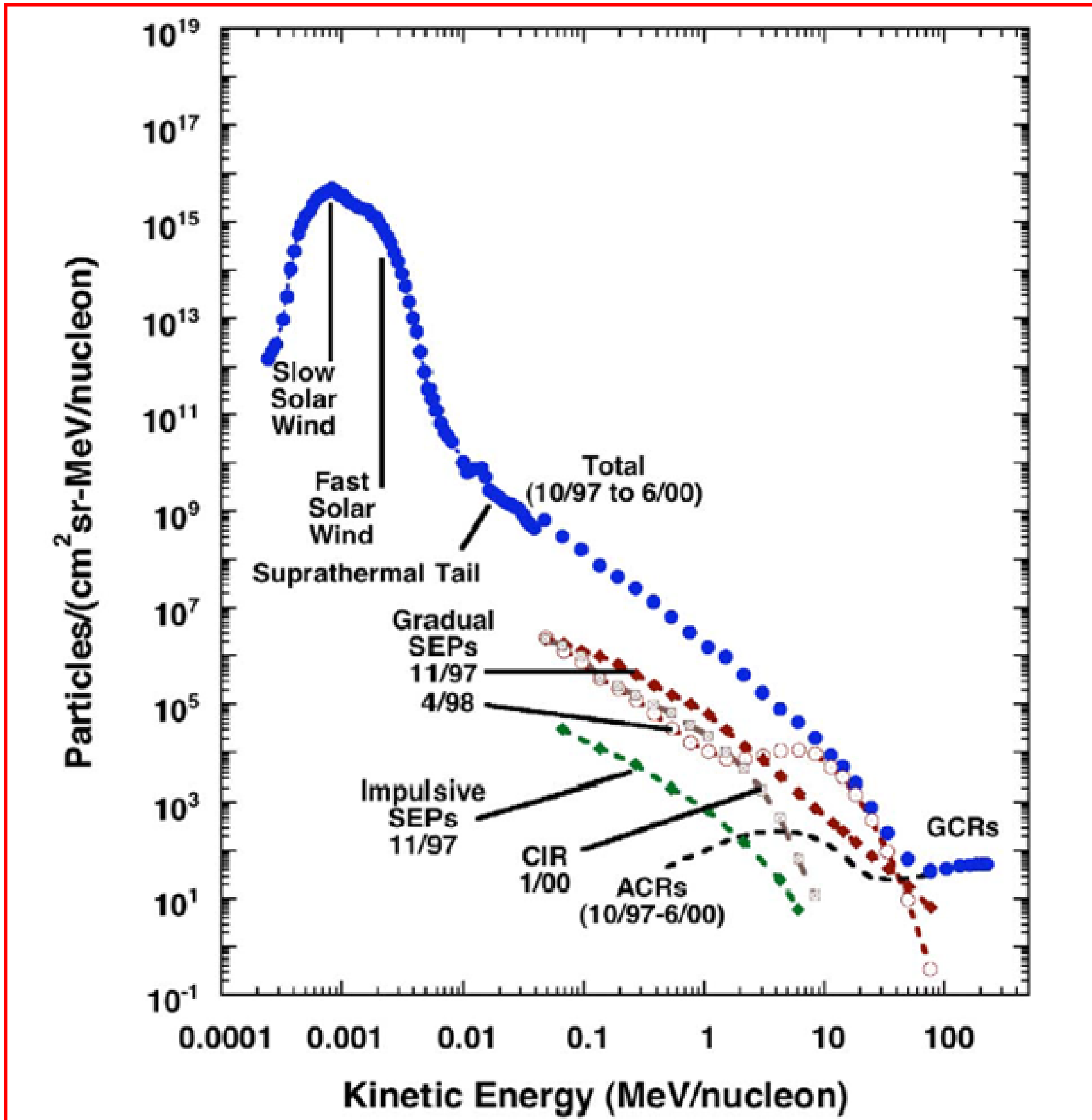





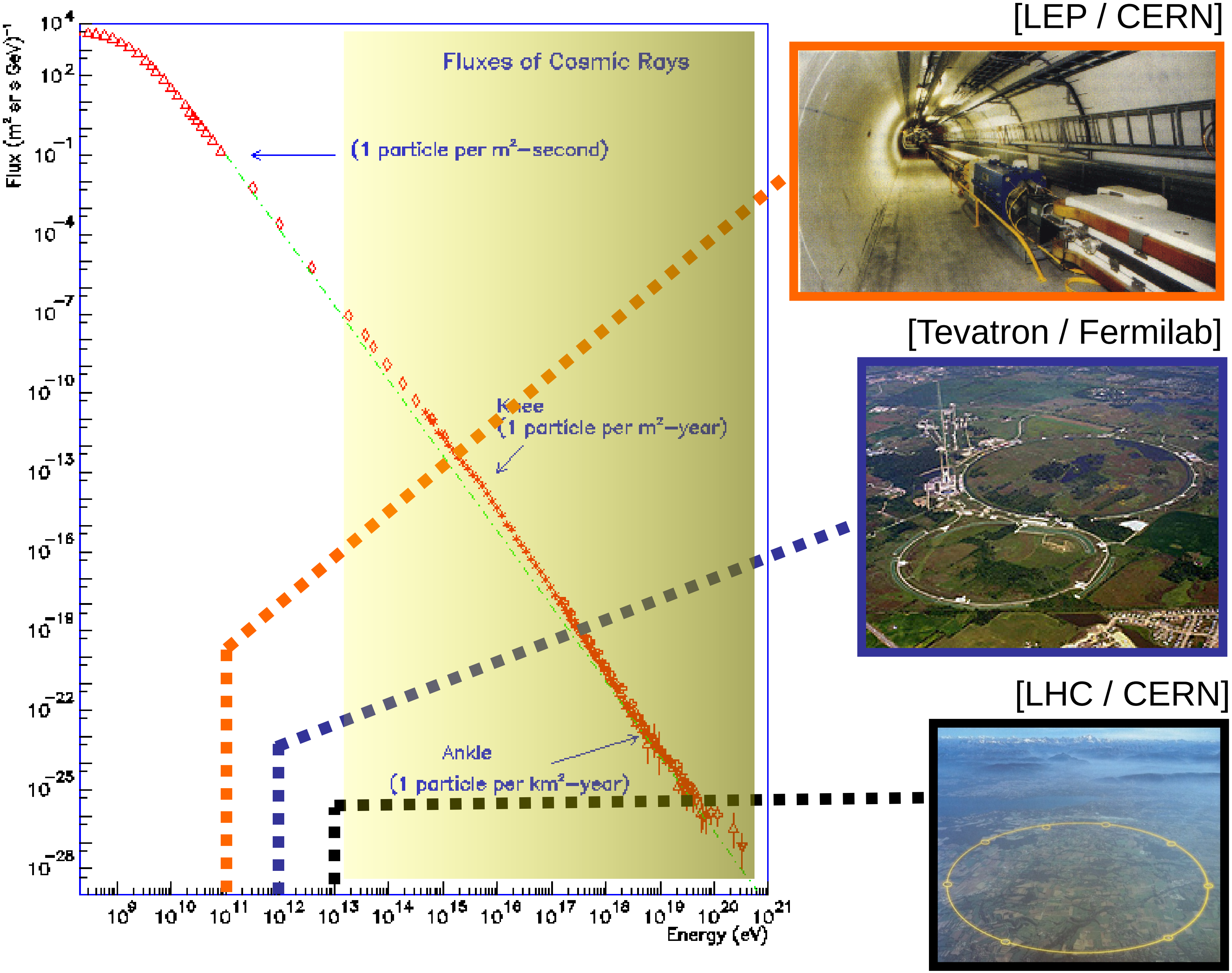
~500 km
Smaller detectors
but long duration.
Primary cosmic ray
Top of atmosphere
~40 km
Large detectors but
short duration.
Atmospheric
overburden ~5 g/cm^2.
Till 2008 almost all data
on cosmic antiparticles
from these experiments.
~5 km
Ground
0 m
Primary Cosmic Rays
Balloon
30000 m
Hess & Kolhörster
9000 m (1912-14)
Electromagnetic
shower
Concorde
15000 m
Hadron
cascade
Mont Blanc
4807 m

Galactic Cosmic Ray Abundance and Composition

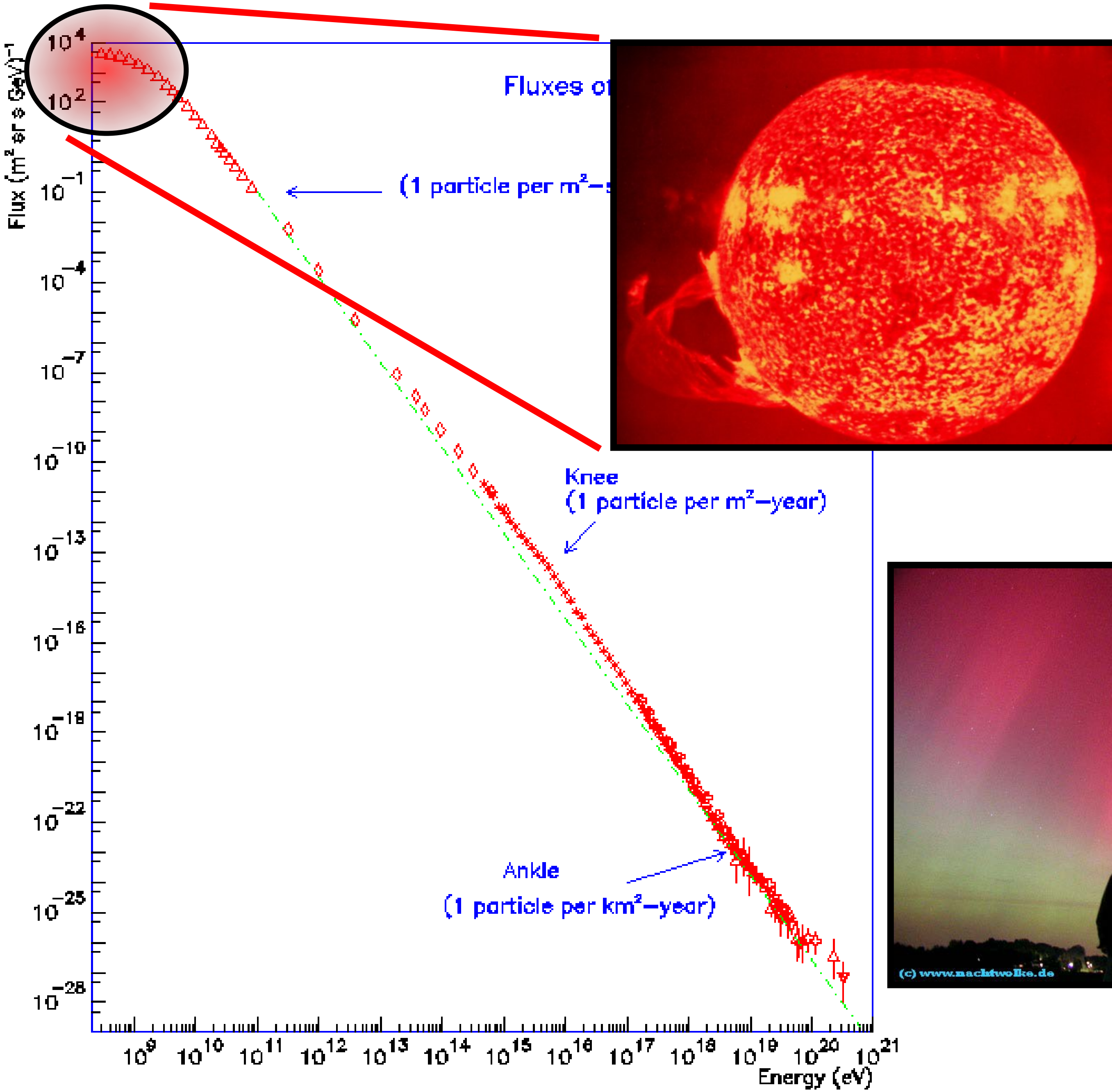




Composition (at ~ 1 GeV):
85% H (p)
12% He (α)
1% heavier nuclei
2% e$^{\pm}$ (> 90% e^{-})
10^{-5}-10^{-4} antiprotons.

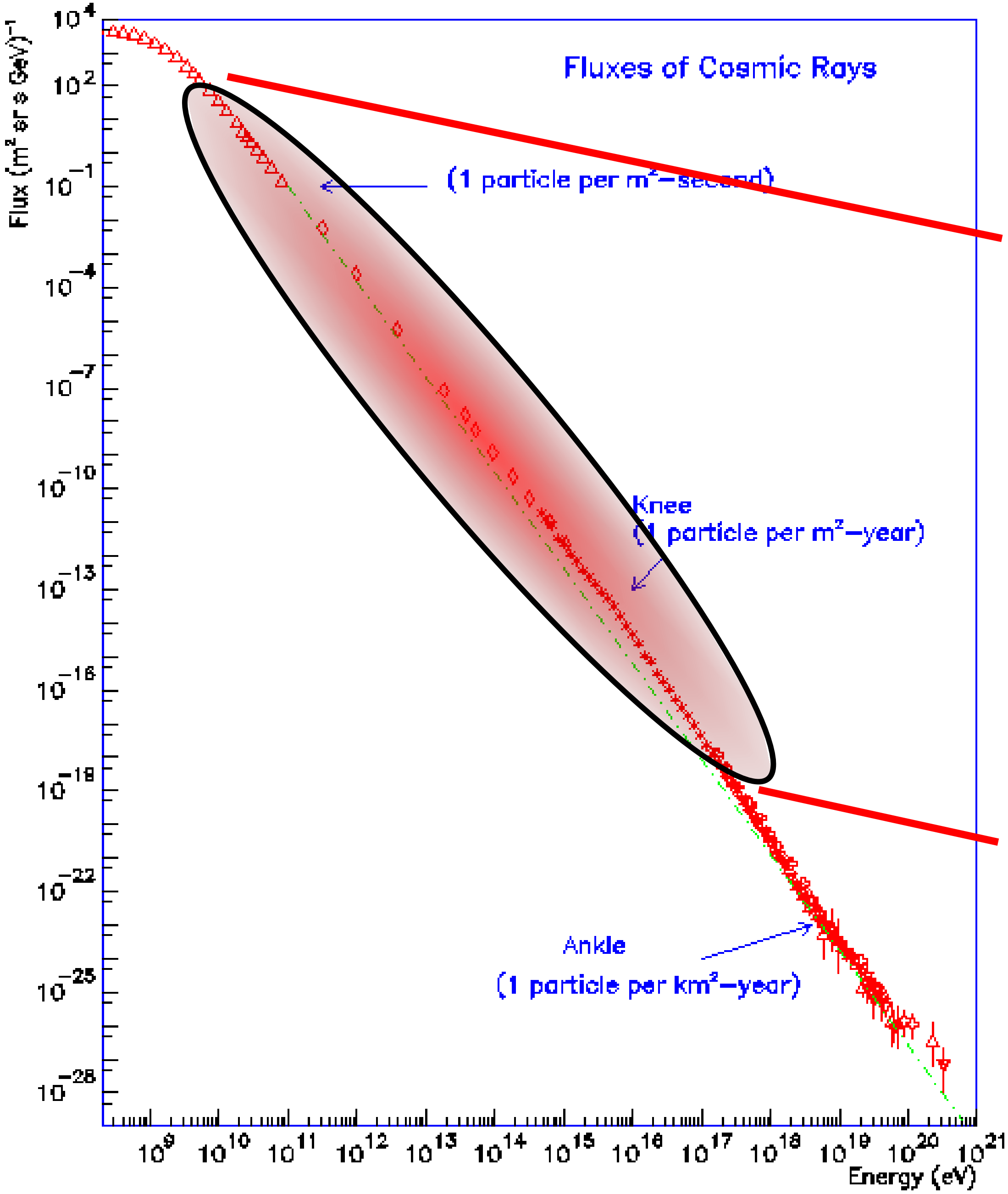


[LEP / CERN]
[Tevatron / Fermilab]
[LHC / CERN]
Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

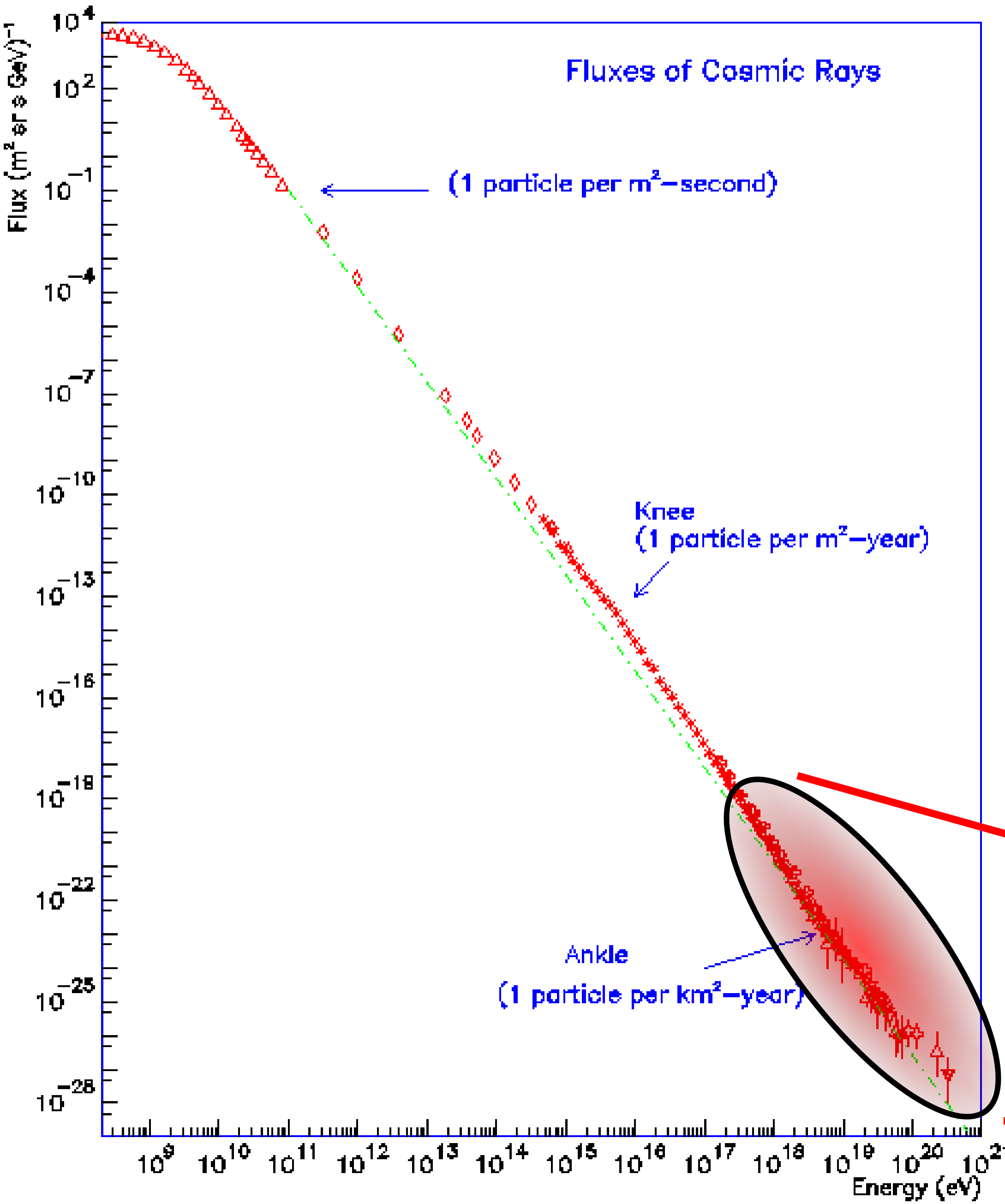


Solar Flare

Northern Ligths

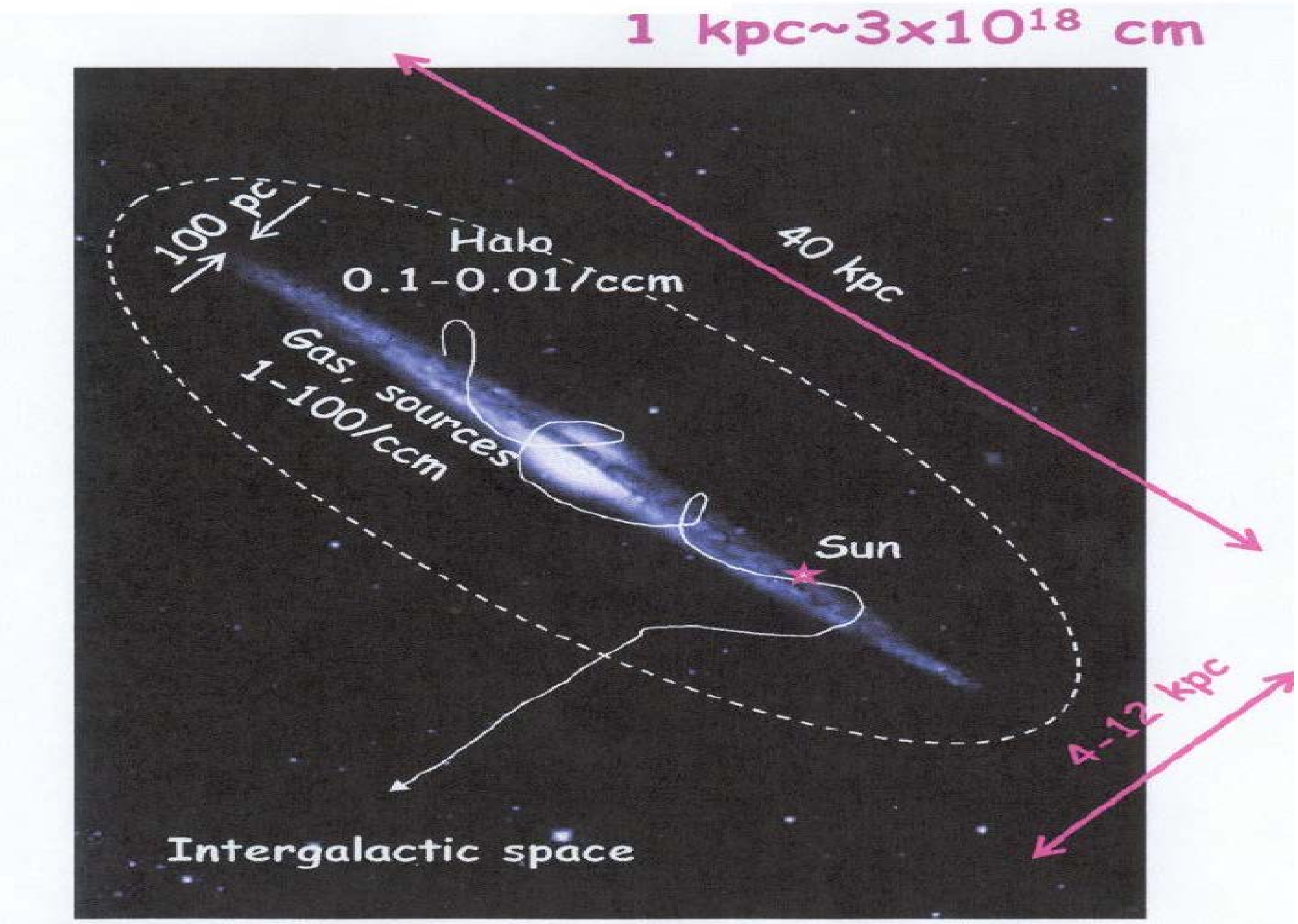


- SuperNova Explosion



- Extragalactic Component: AGNs?

Cosmic Rays in the Milky Way



- $\rho_{E,p} \simeq 0.83 \ \frac{eV}{cm^3}$

Energy density

$\rho_{E,\,nuclei} \simeq 0.27 \ \frac{eV}{cm^3}$

Magnetic field energy density

$\varepsilon = \frac{B^2}{2\mu} \qquad B \simeq 3 \mu \text{ Gauss}$

$\stackrel{!}{=} \frac{(3 \times 10^{-10})^2 \ T}{2 \times 12.57 \times 10^{-7} \ NA^{-2}} \ \frac{eV}{1.6 \times 10^{-19} \ J}$

$\stackrel{!}{\simeq} 0.2 \ \frac{MeV}{m^3} = 0.2 \ \frac{eV}{cm^3} = 3.2 \times 10^{-13} \ \frac{erg}{cm^3}$

- Power required to supply all galactic cosmic rays

$L_{CR} = \frac{V_D \rho_E}{\tau_R} \sim 3.3 \times 10^{40} \ \frac{erg}{s}$

V_D = volume of galactic disk

$\stackrel{!}{=} \pi R^2 d \sim \pi (15 \ Kpc)^2 (200 \ pc) \sim 4 \times 10^{66} \ cm^3$

τ_R = residence time

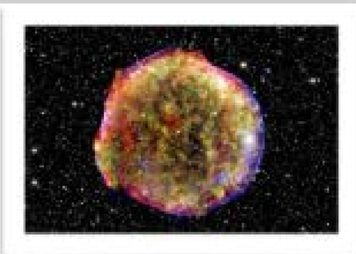
$\stackrel{!}{\sim} 6 \times 10^6$ years $\sim 1.9 \times 10^{14}$ s

- Release of energy from type II supernovae, 30 years on average, 10 $M_\odot$ (solar mass), speed $\sim 5 \times 10^8$ cm/s

$L_{SN} \sim 3 \times 10^{42} \ \frac{erg}{s}$

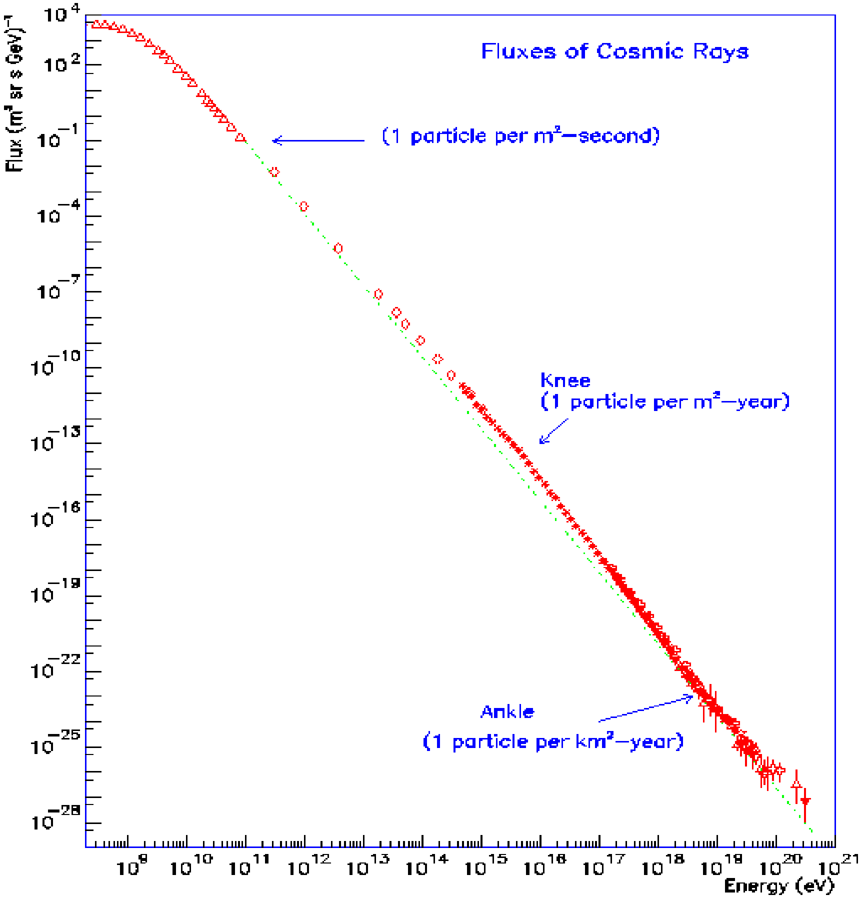
Galactic cosmic rays - energetics

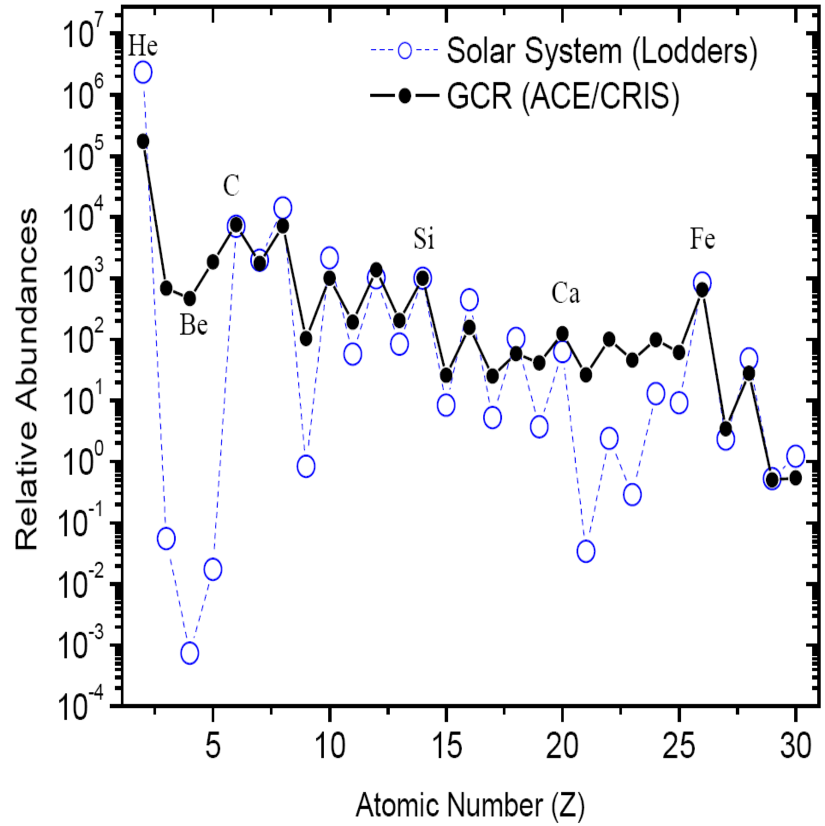
Ginzburg, 1958, ...




- Cosmic ray power in our Galaxy: ~ **5 x 10^{40} ergs/s**
  - **Supernovae and their remnants:**
    Release 10^{51} ergs, happen 1/30 years. **Q ~ 10^{42} ergs/s**
  - **Novae** (accretion of matter onto white dwarf):
    100/year, release 10^{47} ergs, **Q ~ 10^{42} ergs/s**
  - **Rotating neutron stars:**
    Majority of Galactic Fermi-LAT sources, **Q ~ 10^{41} ergs/s**
  - **Stellar winds from hot O/B stars:**
    Strong winds from rad. pressure (10^9 $\dot{M}_{sun}$), **Q~10^{41} ergs/s**

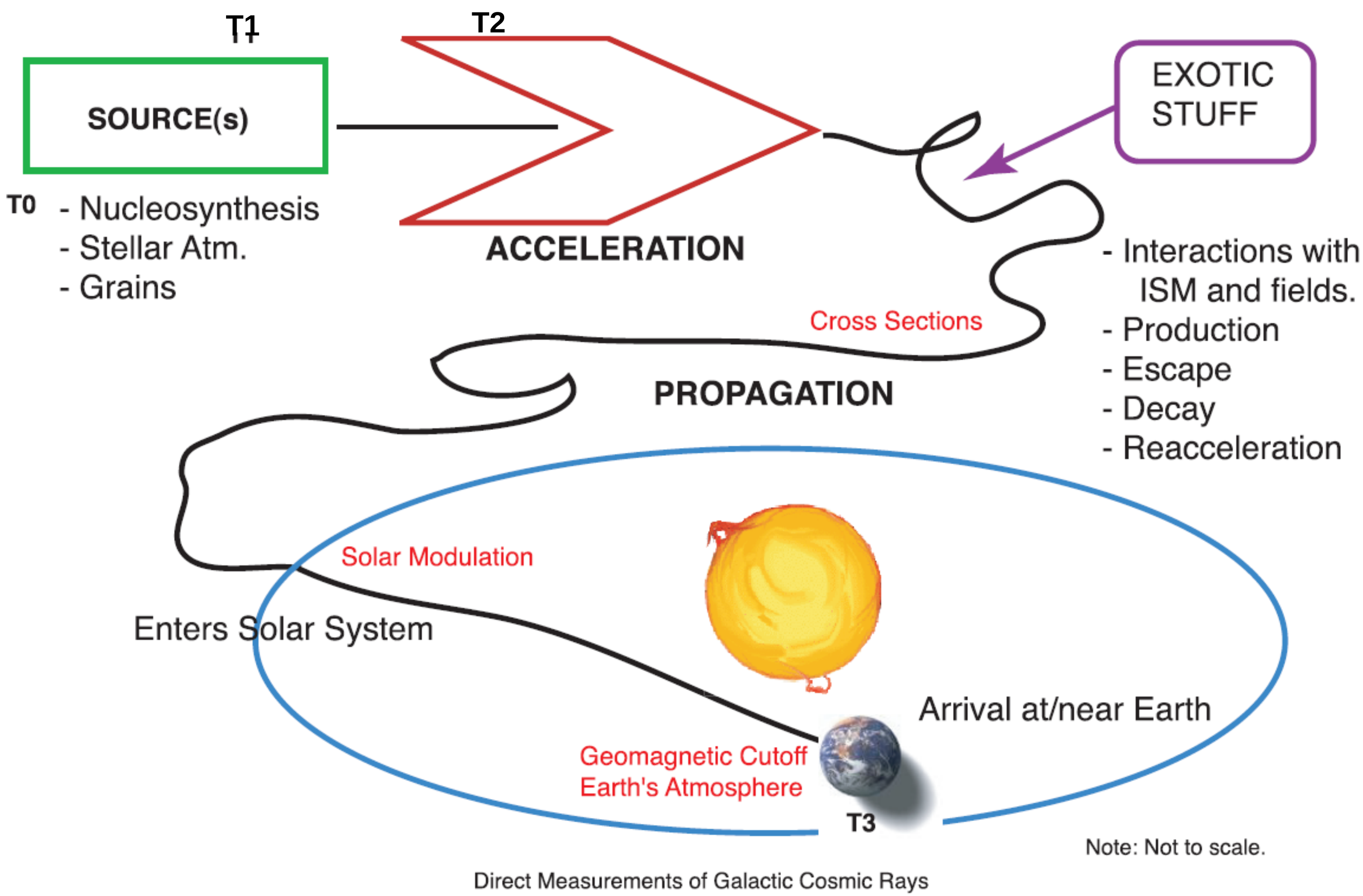
Cosmic Rays





Solar System: Lodders, ApJ 591 (2003) 1220
GCR: Israel, ECRS 2004

Cosmic-Rays' "Life"



Acceleration and Sources

$\Delta E = \xi E$ per encounter

$\overset{n}{\Rightarrow} \quad E_n = E_0 (1 + \xi)^n$

P_{esc} probability of escape from acc. region

$\overset{|}{=} \dfrac{T_{cycle}}{T_{esc}}$ time acc. cycle / time for escape

$\overset{n}{\Rightarrow} \quad (1 - P_{esc})^n$

$n = \ln\left(\dfrac{E}{E_0}\right) / \ln(1 + \xi)$

$N(\geq E) \propto \sum_{m=n}^{\infty} (1 - P_{esc})^m = \dfrac{(1 - P_{esc})^n}{P_{esc}}$

number of particles with $> E$

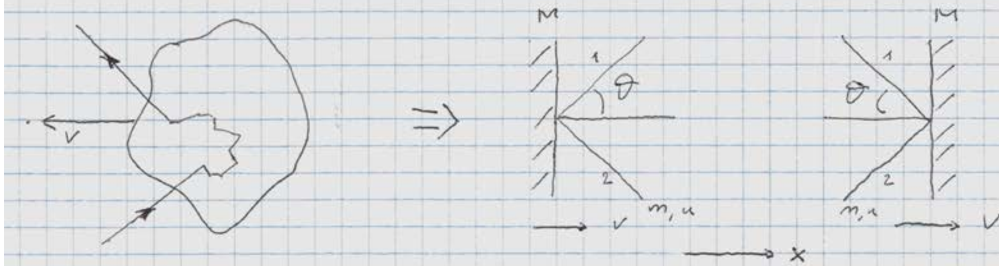
$N(\geq E) \propto \dfrac{(1 - P_{esc})}{P_{esc}}^{\frac{\ln(E/E_0)}{\ln(1+\xi)}} =$

$\simeq \dfrac{1}{P_{esc}} \dfrac{E}{E_0}^{\frac{\ln(1 - P_{esc})}{\ln(1+\xi)}} = \dfrac{1}{P_{esc}} \left(\dfrac{E}{E_0}\right)^{-\gamma}$

$\gamma = - \dfrac{\ln(1 - P_{esc})}{\ln(1 + \xi)} \approx \dfrac{P_{esc}}{\xi}$

$J(E) =$ flux $\Rightarrow N \geq E = \int_E^{\infty} J(E)\, dE \Rightarrow$

$\Rightarrow J(E) \propto E^{-1-\gamma}$



- Diffuse by scattering on the irregularities of the magnetic field
- Cloud infinitely massive (M >> m)

Cloud Frame (C.M. F.) : $E' = \gamma_V \left(E + Vp \cos\theta \right)$

$$\gamma_V = \sqrt{1 - \frac{V^2}{c^2}}$$

$$p_x' = \gamma_V \left(p_x + \frac{VE}{c^2} \right) \quad , \quad p_x = p \cos\theta$$

$$E'_1 = E'_2 \quad , \quad p'_{x_1} = p'_{x_2}$$

Obs. F. : $E'' = \gamma_V \left(E' + V p'_x \right)$

$$\overset{!}{=} \gamma_V^2 \, E \left[1 + \frac{2 V u \cos\theta}{c^2} + \left(\frac{V}{c}\right)^2 \right]$$

$$\gamma_V^2 \simeq 1 + \left(\frac{V}{c}\right)^2 \Rightarrow \frac{E'' - E}{E} = \frac{\Delta E}{E} = \frac{2 V u \cos\theta}{c^2} + 2\left(\frac{V}{c}\right)^2$$

$u \simeq c$ and isotropic flux

$$\left\langle \frac{2 V \cos\theta}{c} \right\rangle = \left(\frac{2V}{c}\right) \frac{\int_{-1}^{1} x \left[1 + (V/c) x \right] dx}{\int_{-1}^{1} \left[1 + (V/c) x \right] dx} \quad , \quad x = \cos\theta$$

$$\overset{!}{=} \frac{2}{3} \left(\frac{V}{c}\right)^2$$

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{8}{3} \left(\frac{V}{c}\right)^2 \Rightarrow \xi = \frac{8}{3} \left(\frac{V}{c}\right)^2$$

II - order Fermi acceleration

Problems

i. $\frac{V}{c} \le 10^{-4}$ Mean free path $\approx$ 0.1 pc $\rightarrow$ collision about 1 per year;

ii. Energy losses: ionization?

iii. Why $\gamma \approx 1$? Why the same for all species?

- Perturbations are propagated away from their sources at the speed of sound in the medium.
If fast than sound $\Rightarrow$ discontinuity behind and ahead of disturbance; ahead region no knowledge of discontinuity arrival.
Discontinuities $\equiv$ shock waves.

Conservation of mass : $\rho_1 u_1 = \rho_2 u_2$

Conservation of energy flux : $\rho_1 u_1 \left(\frac{1}{2} u_1^2 + w_1 \right) = \rho_2 u_2 \left(\frac{1}{2} u_2^2 + w_2 \right)$

$w = \varepsilon + pV$ enthalpy per unit mass
$\varepsilon_m \equiv$ internal energy per unit mass
$V = \frac{1}{\rho}$ volume per unit mass

Conservation of momentum flux : $p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$

These are the shock conditions.

Shock waves in a perfect gas : $w = \frac{\gamma p V}{\gamma - 1}$

γ ratio of specific heats

$M \equiv \frac{u_1}{c_1}$ Mach number $\quad c_1 = \left(\frac{\gamma p_1}{\rho_1} \right)^{1/2}$ sound velocity

$$\frac{p_2}{p_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{(\gamma + 1)} \xrightarrow{M_1 \gg 1} \frac{2\gamma M_1^2}{(\gamma+1)}$$

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)}{(\gamma-1) + 2/M_1^2} \xrightarrow{M_1 \gg 1} \frac{\gamma+1}{\gamma-1}$$

$$\frac{T_2}{T_1} = \frac{[2\gamma M_1^2 - (\gamma-1)][2 + (\gamma-1) M_1^2]}{(\gamma+1)^2 M_1^2} \xrightarrow{M_1 \gg 1} \frac{2\gamma(\gamma-1) M_1^2}{(\gamma+1)^2}$$

Temperature and pressure can become very large but density ratio attains a finite value. For monoatomic gas :

$$\gamma = \frac{5}{3} \Rightarrow \frac{\rho_2}{\rho_1} = 4 \Rightarrow u_2 = \frac{u_1}{4}$$

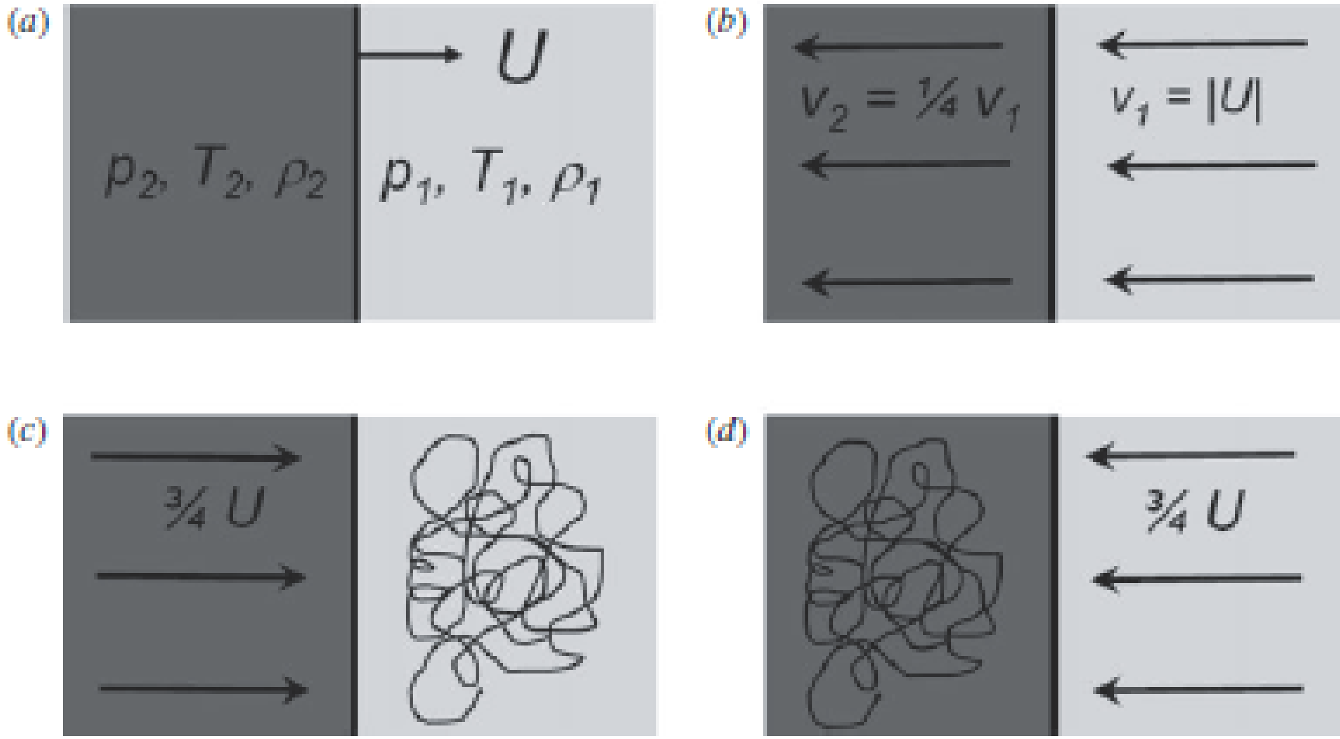


Fig. 17.3 The dynamics of high energy particles in the vicinity of a strong shock wave. (*a*) A strong shock wave propagating at a supersonic velocity U through stationary interstellar gas with density ρ_1, pressure p_1 and temperature T_1. The density, pressure and temperature behind the shock are ρ_2, p_2 and T_2, respectively. The relations between the variables on either side of the shock front are given by the relations (11.72)–(11.74). (*b*) The flow of interstellar gas in the vicinity of the shock front in the reference frame in which the shock front is at rest. In this frame of reference, the ratio of the upstream to the downstream velocity is $v_1/v_2 = (\gamma + 1)/(\gamma - 1)$. For a fully ionised plasma, $\gamma = 5/3$ and the ratio of these velocities is $v_1/v_2 = 4$ as shown in the figure. (*c*) The flow of gas as observed in the frame of reference in which the upstream gas is stationary and the velocity distribution of the high energy particles is isotropic. (*d*) The flow of gas as observed in the frame of reference in which the downstream gas is stationary and the velocity distribution of high energy particles is isotropic.

M. S. Longair, "High Energy Astrophysics", Volume 2.

- Particle from upstream to downstream

Down stream ref frame: $E' = \gamma_V (E + p_x V)$

$$V = \frac{3}{4} U \quad , \quad \gamma_V \simeq 1 \qquad E = pc$$

$$\frac{\Delta E}{E} = \frac{V}{c} \cdot \cos\theta$$

$u \gg v_1, v_2$ isotropic distribution at the shock front

$$(1) \quad \left\langle \frac{\Delta E}{E} \right\rangle = \frac{V}{c} \int_0^{\pi/2} \cos\theta \, p(\theta) \, d\theta = \frac{2}{3} \frac{V}{c}$$

$$p(\theta) = 2 \sin\theta \cos\theta \, d\theta \qquad \left(\int_0^{\pi/2} p(\theta) \, d\theta = 1 \right)$$

- Particle from downstream to upstream

$$(2) \quad \left\langle \frac{\Delta E}{E} \right\rangle = \frac{2}{3} \frac{V}{c}$$

- $(1) + (2)$ $\quad \left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3} \frac{V}{c} = \frac{U}{c} = \xi$

$$\gamma \simeq \frac{P_{esc}}{\xi}$$

- Total flux of particles crossing the shock into down stream

$$\frac{1}{4\pi}\int_0^{\pi/2} \sin\theta \, d\theta \int_0^{2\pi} d\phi \; n v \cos\theta = \frac{nc}{4}$$

$v = c$, $n \equiv$ number density of part.

- Downstream particles are removed at a rate : $n u_2 = n \frac{U}{4}$

- Fraction of particles lost per unit of time, prob. of escape : $P_{esc} = n\frac{U}{4} \Big/ \frac{nc}{4} = \frac{U}{c}$

$$\gamma \simeq \frac{P_{esc}}{\xi} = 1$$

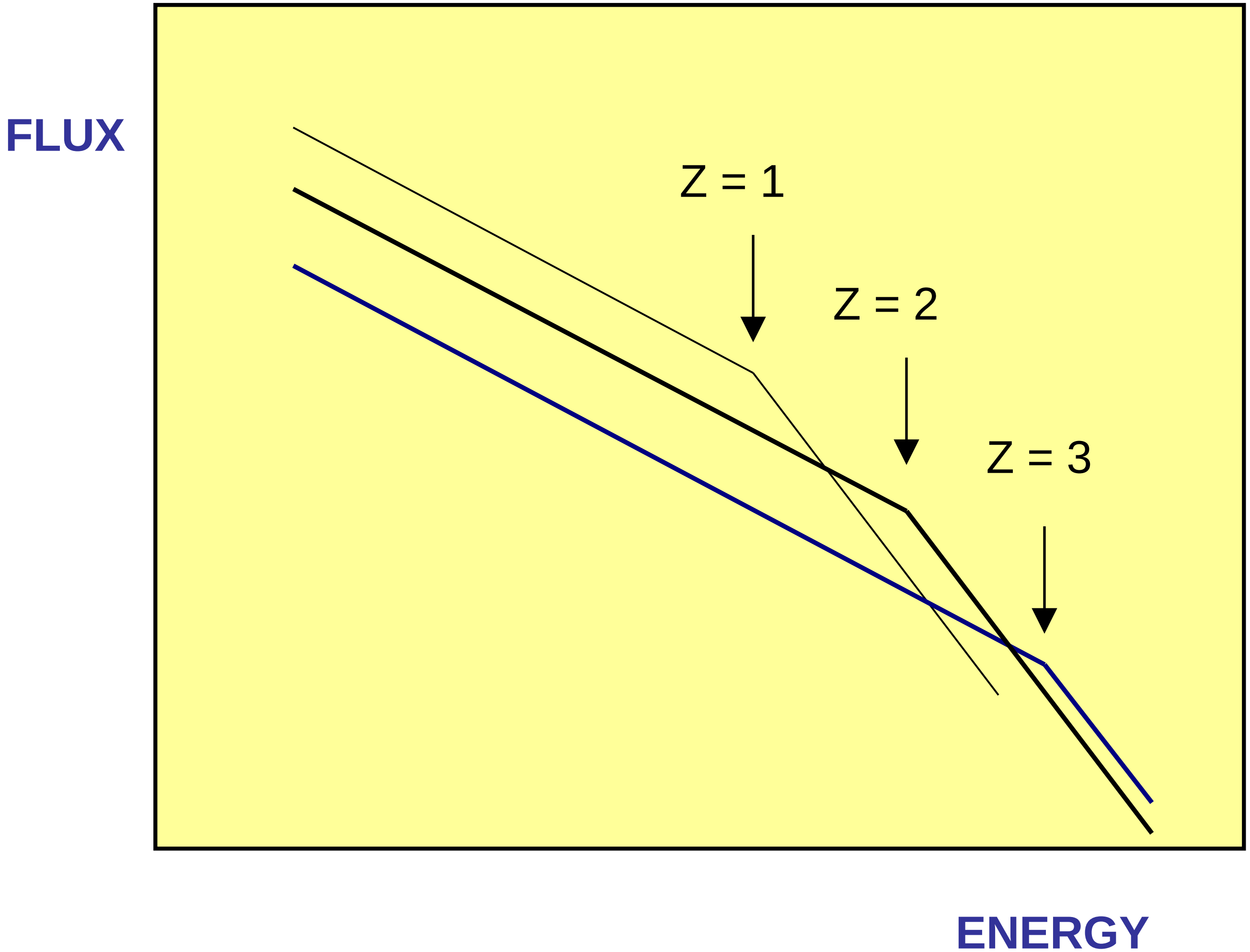
- Acceleration occurs before the time when the supernova has swept up its own mass, after which the shock weakens :

$$\underbrace{\frac{4}{3}\pi\,(u_1\,T_A)^3}_{u_1 \,=\, 5\times10^8 \text{ cm/s}}\;\underbrace{\rho_{ISM}}_{1\ p/cm^3} \simeq \underbrace{M_{ejecta}}_{10\ M_\odot} \;\Rightarrow\; T_A \sim 1000\ y$$

$$B_{ISM} \sim 3\,\mu\text{ Gauss} \;\Rightarrow\; E_{max} \leq 2\times3\times10^4\ \text{GeV}$$

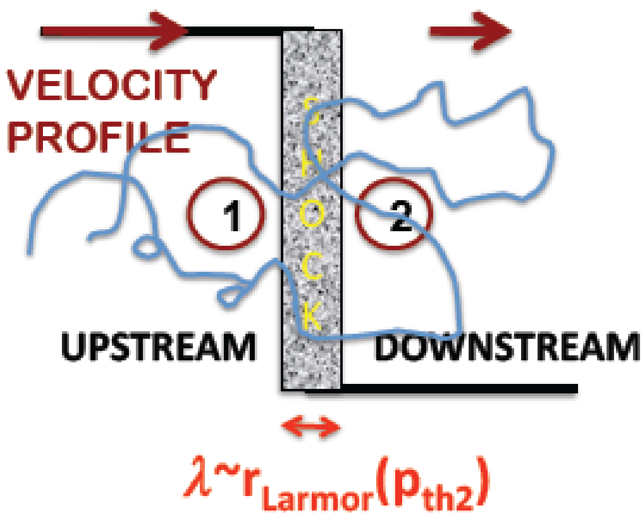
$$E_{max} \sim 100\ \text{TeV}$$

Maximum energy from any EM accelerator is proportional to Z



- Steepeing of the spectrum
- Composition becomes progressively enriched in jeavir nuclei as energy increases
- But not unique characteristic of this model

DIFFUSIVE ACCELERATION AT COLLISIONLESS NEWTONIAN SHOCKS
'test particles'



In test particle theory, all approaches lead to:

-POWER LAW SPECTRA

-SLOPE ONLY FUNCTION OF COMPRESSION

-INDEPENDENT OF D(E)

-NO CLEAR RECIPE FOR E_{MAX}

-NO DESCRIPTION OF WHY PARTICLES RETURN TO THE SHOCK (SCATTERING)

-NO DESCRIPTION OF INJECTION

Cortesy of E. Amato & P. Blasi

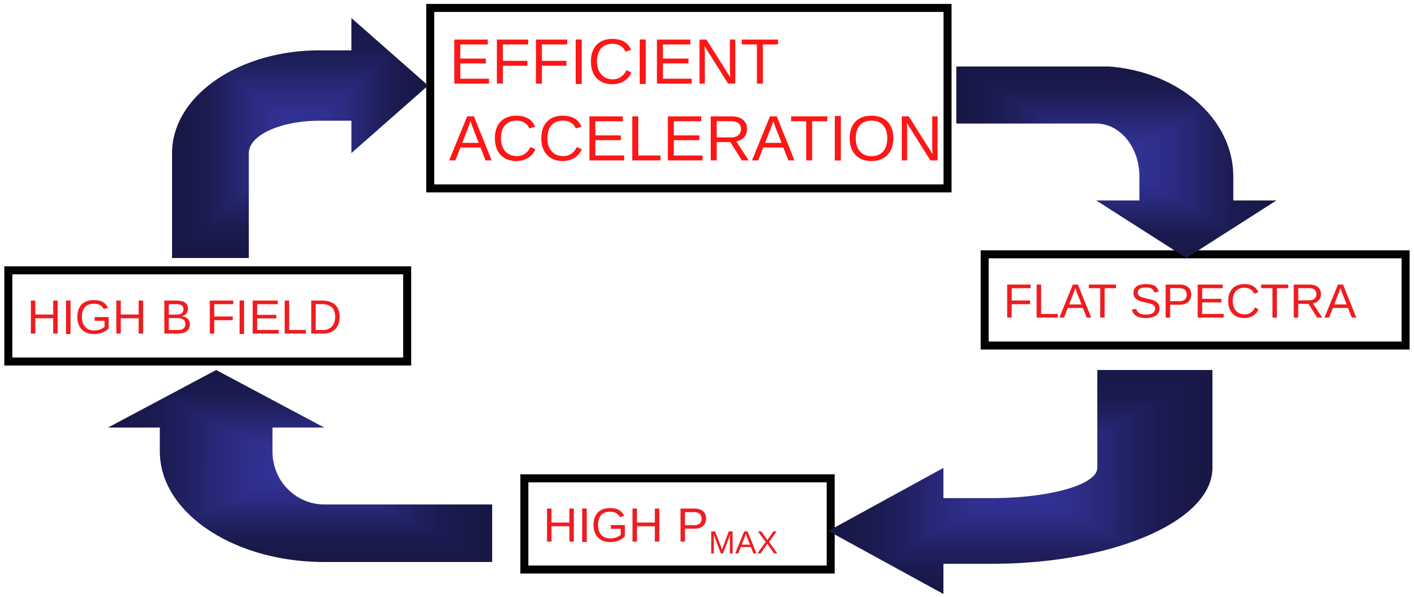
NON LINEAR THEORY

A theory of particle acceleration that allows one to describe:

1. ***Dynamical reaction of accelerated particles***
2. ***Streaming instability CR-induced B-field***
3. ***Dynamical reaction of amplified fields***
4. ***Phenomenological recipe for injection (self-regulation of the system)***
5. ***Escape of particles from boundaries (Cosmic Rays)***

Cortesy of E. Amato & P. Blasi

THEORY CONFRONTS OBSERVATIONS

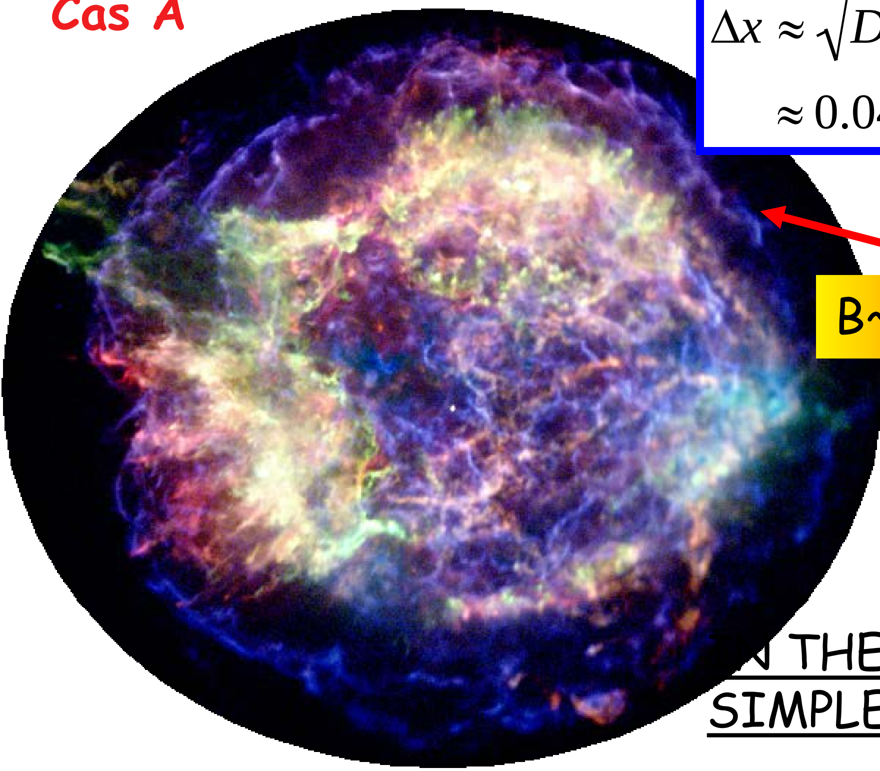


BUT DO WE OBSERVE ANY OF THESE?

Cortesy of E. Amato & P. Blasi

AMPLIFIED MAGNETIC FIELDS

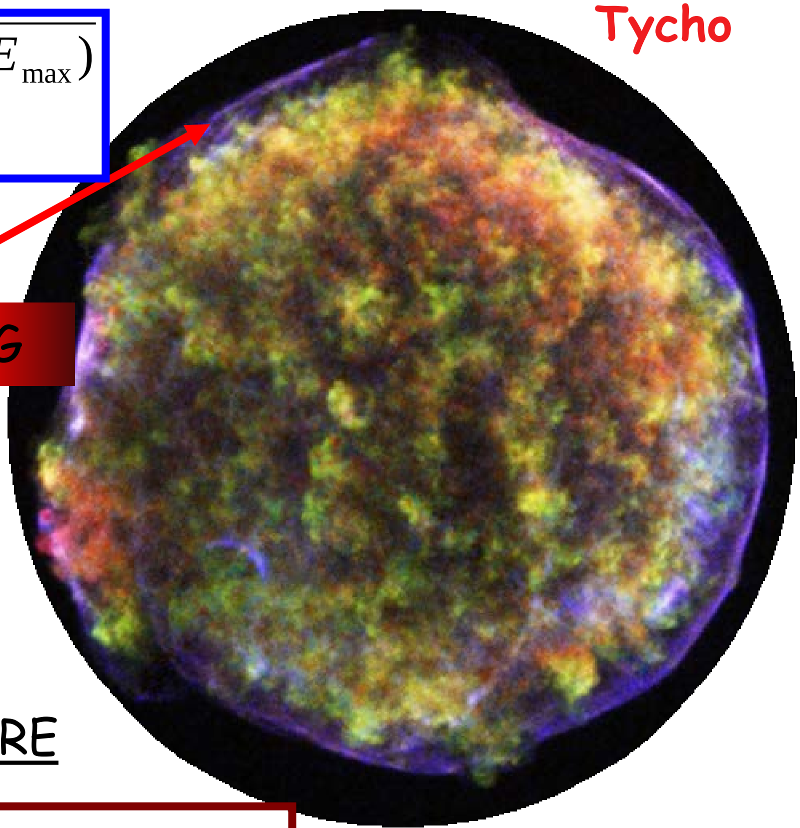
Cas A



$$\Delta x \approx \sqrt{D(E_{\max})\tau_{loss}(E_{\max})}$$
$$\approx 0.04 B_{100}^{-3/2}\, pc$$

B~100-300μG

Tycho



N THE
SIMPLEST PICTURE

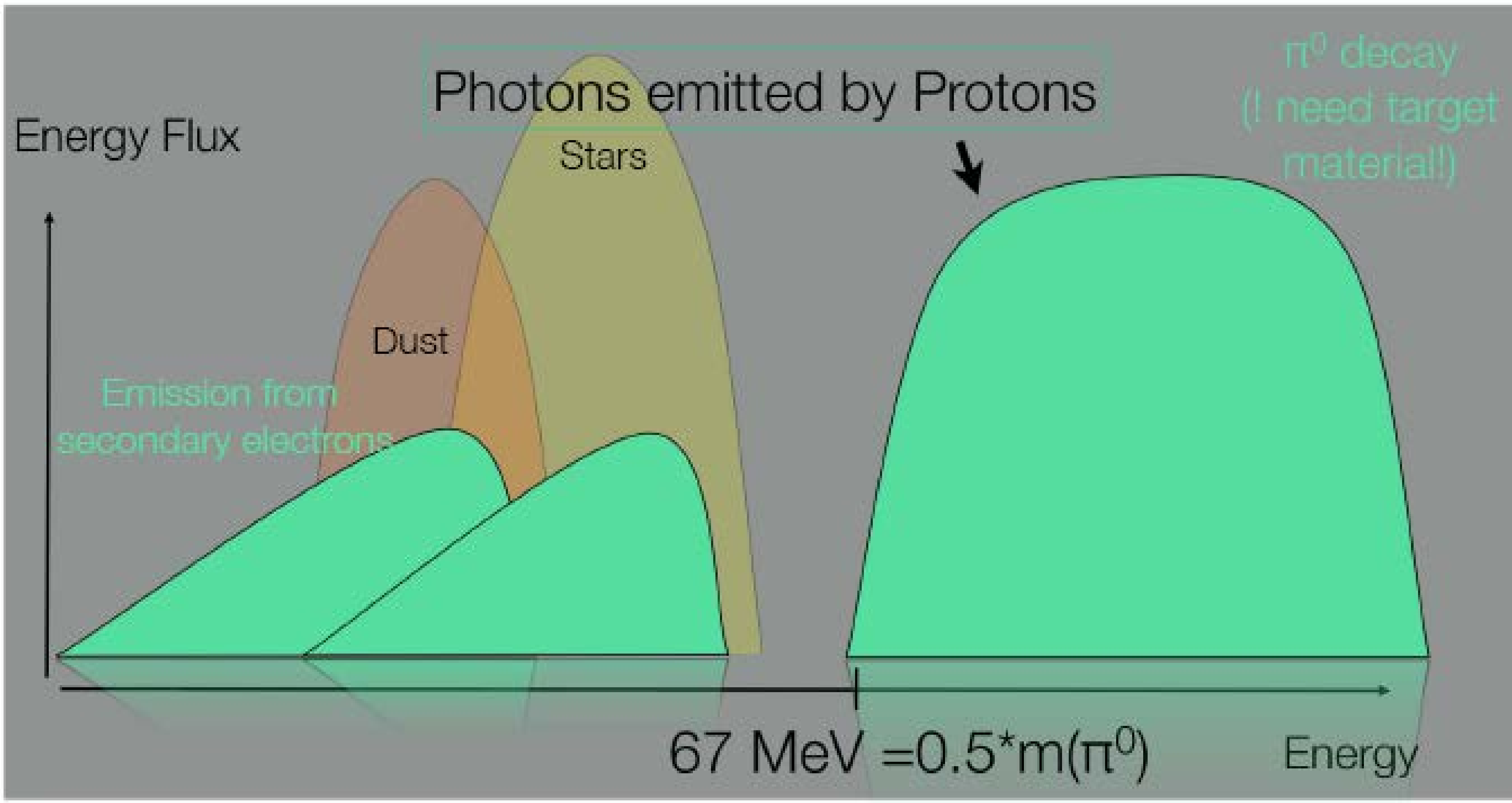
EFFICIENT PARTICLE ACCELERATION BECAUSE OF HIGH B-FIELD

HIGH B-FIELD BECAUSE OF EFFICIENT PARTICLE ACCELERATION

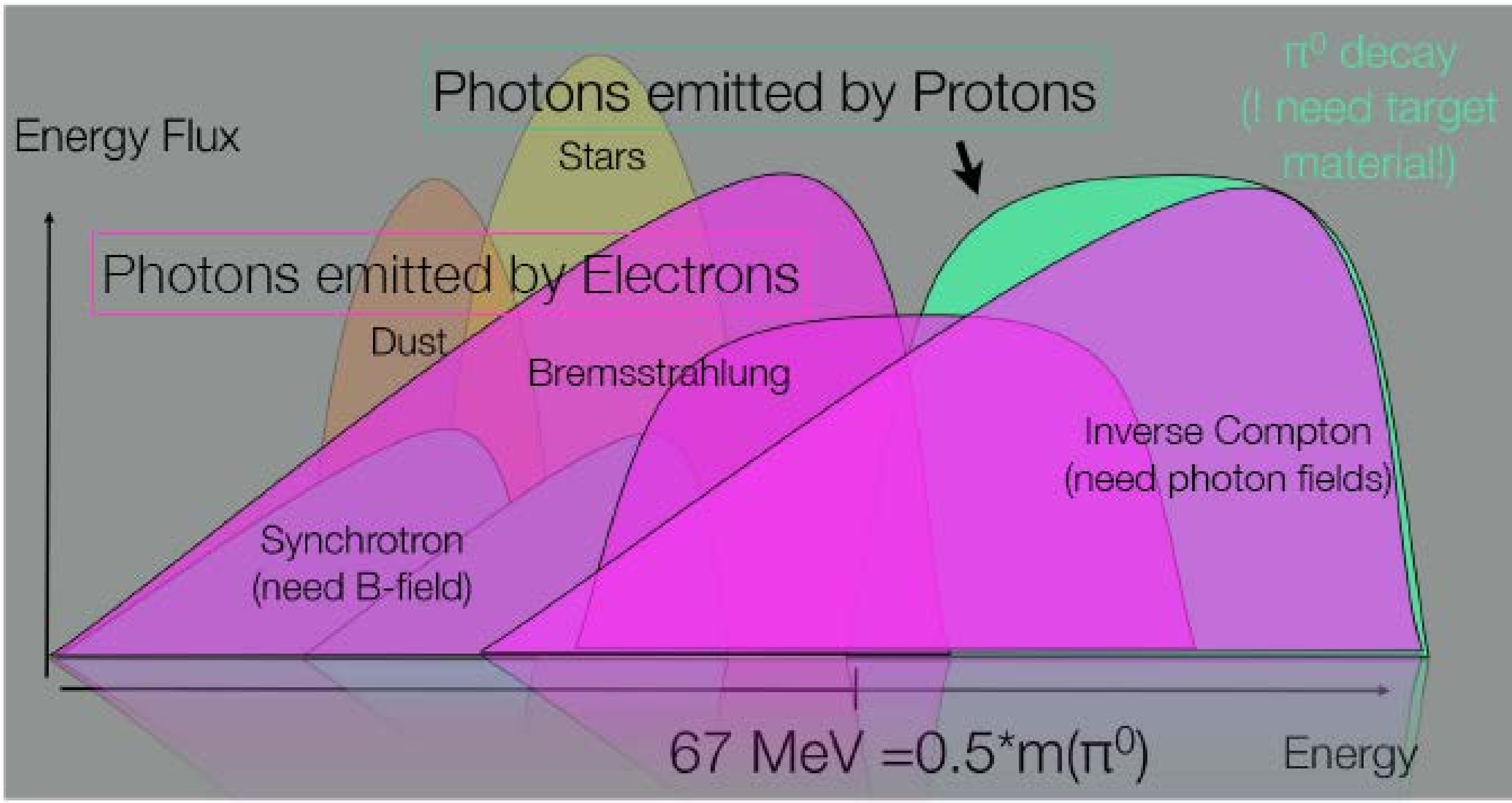
CAVEAT:
LARGE MAGNETIC FIELDS MIGHT HAVE DIFFERENT ORIGIN AND DO NOT IMPLY EFFICIENT SCATTERING...

Cortesy of E. Amato & P. Blasi

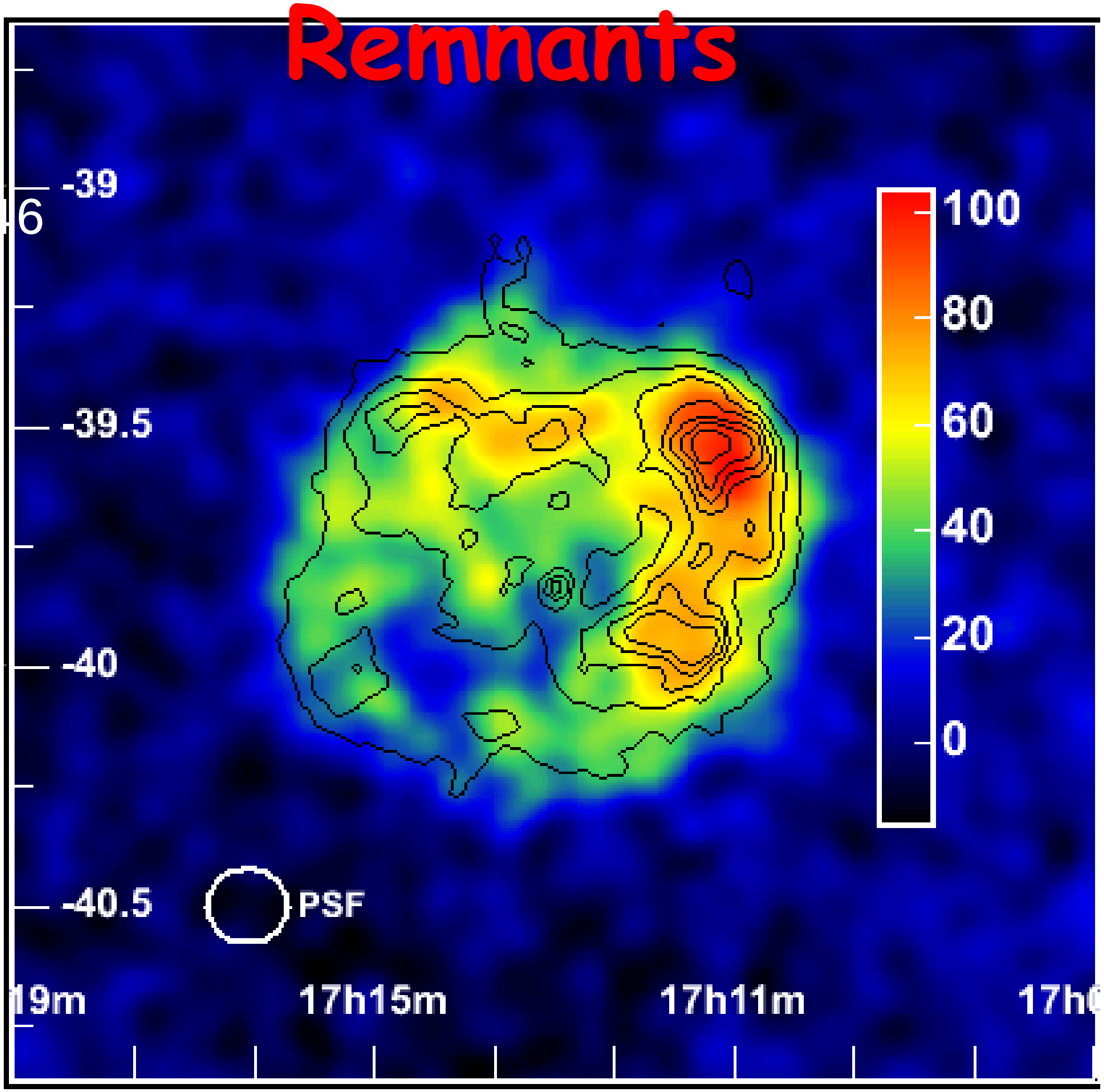
Photon emission by accelerated charged particles



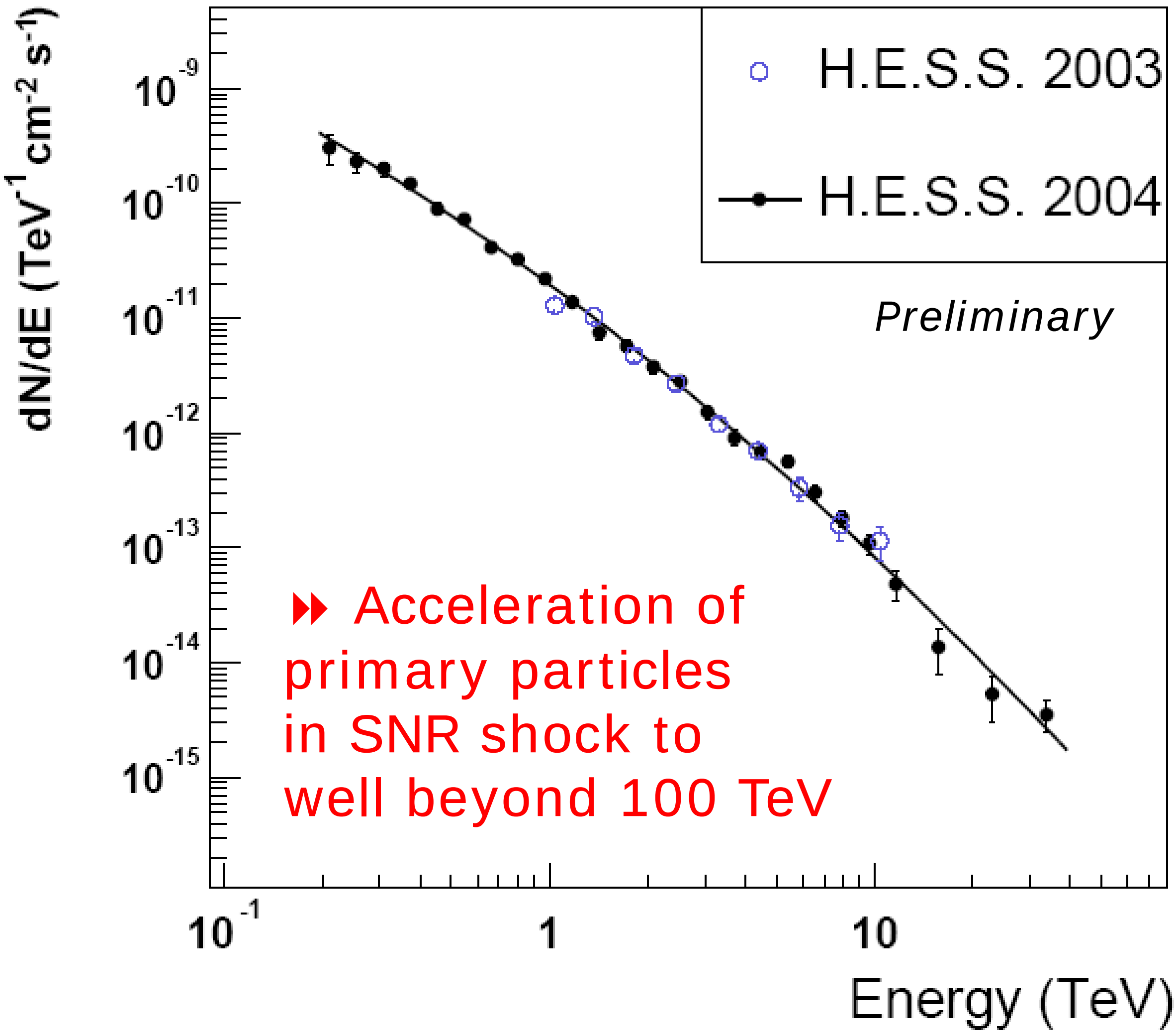
Photon emission by accelerated charged particles



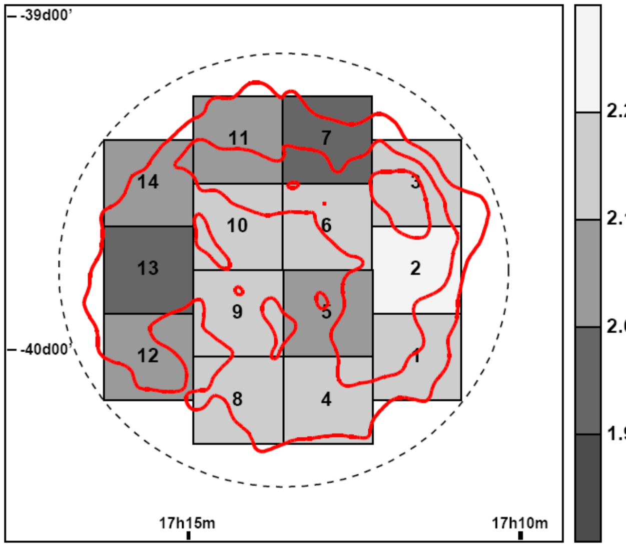
H.E.S.S. Highlight: Resolved Supernova-Remnants



Spectra



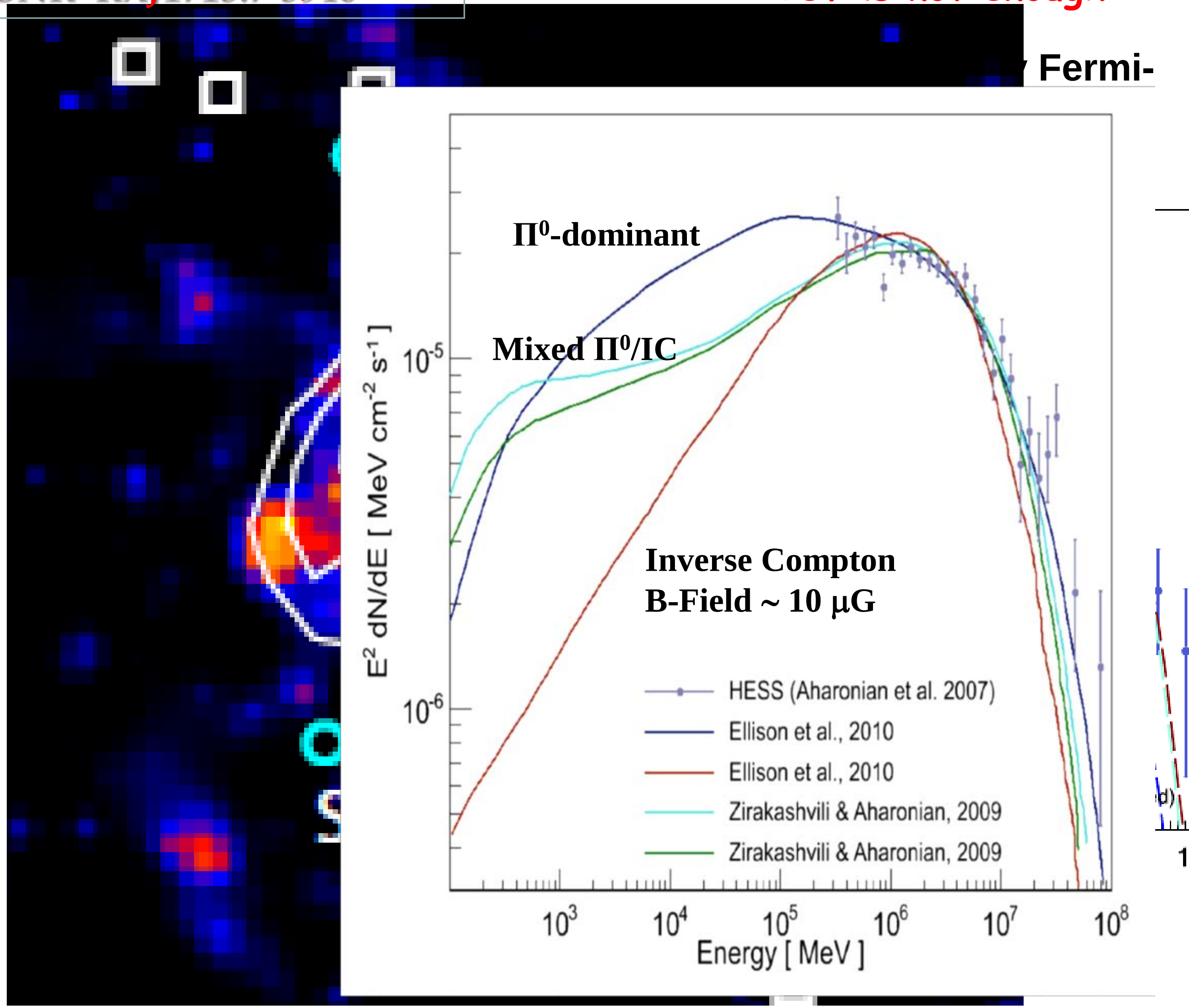
⏩ Acceleration of primary particles in SNR shock to well beyond 100 TeV



- Index ~ 2.1 – 2.2
- Little variation across SNR
- Cutoff or break at high energy

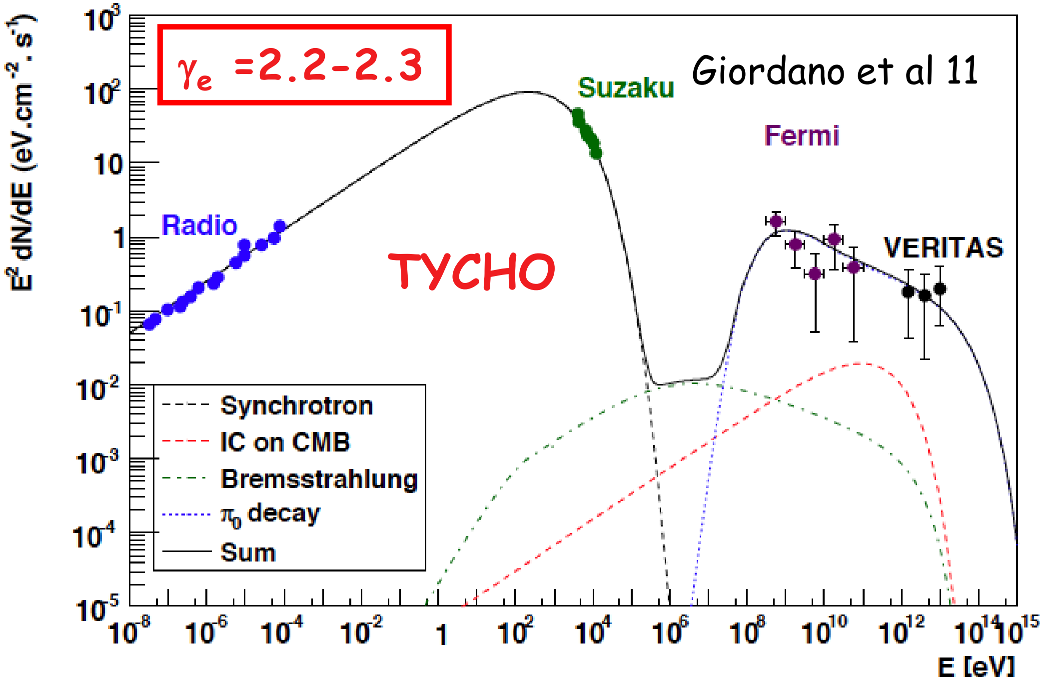
EXAMPLE: SNR RXJ1713.7-3946

TeV is not enough



GeV image by Fermi-LAT (Abdo et al. 2011)

Cosmic Rays & the γ-ray Sky



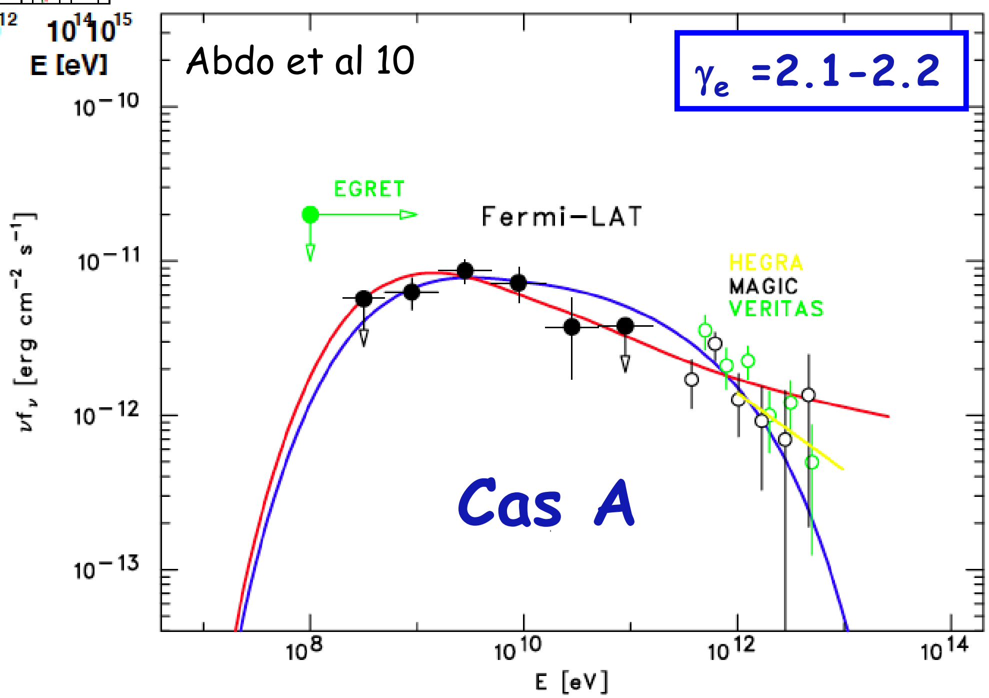
NO PEVATRONS
AND
STEEP SOURCE SPECTRA

BUT ARE THESE THE
SOURCES
OF GALACTIC CRs?

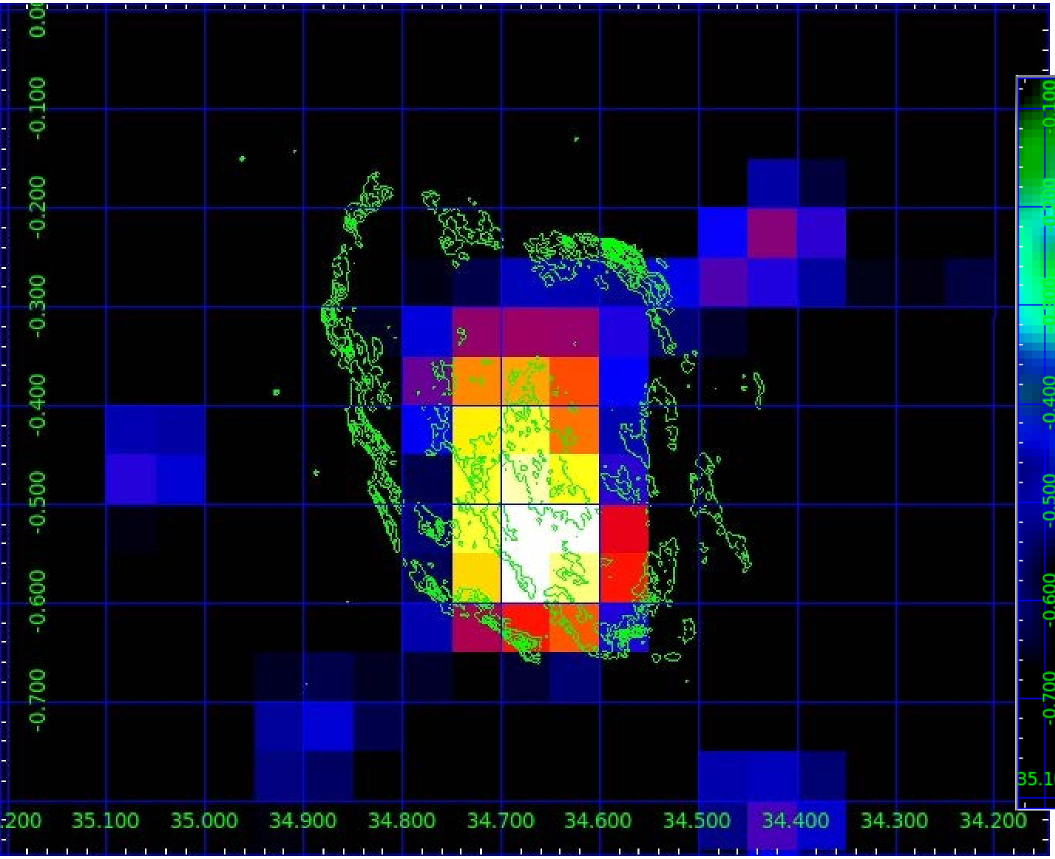
Fermi (Abdo et al 09,10,11)

AND

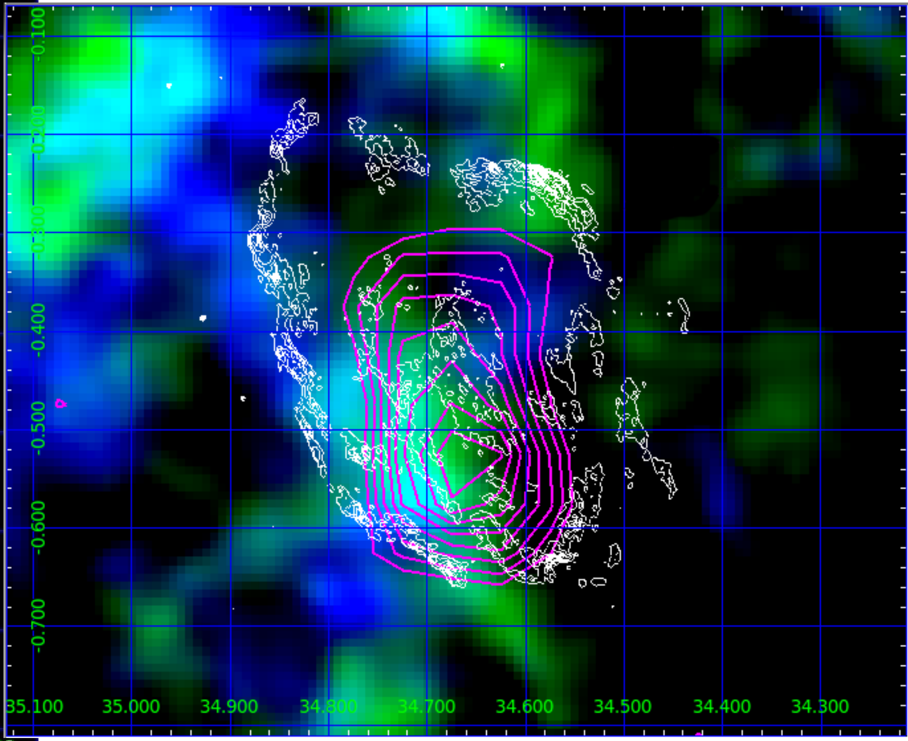
Agile (Giuliani et al 10,11)



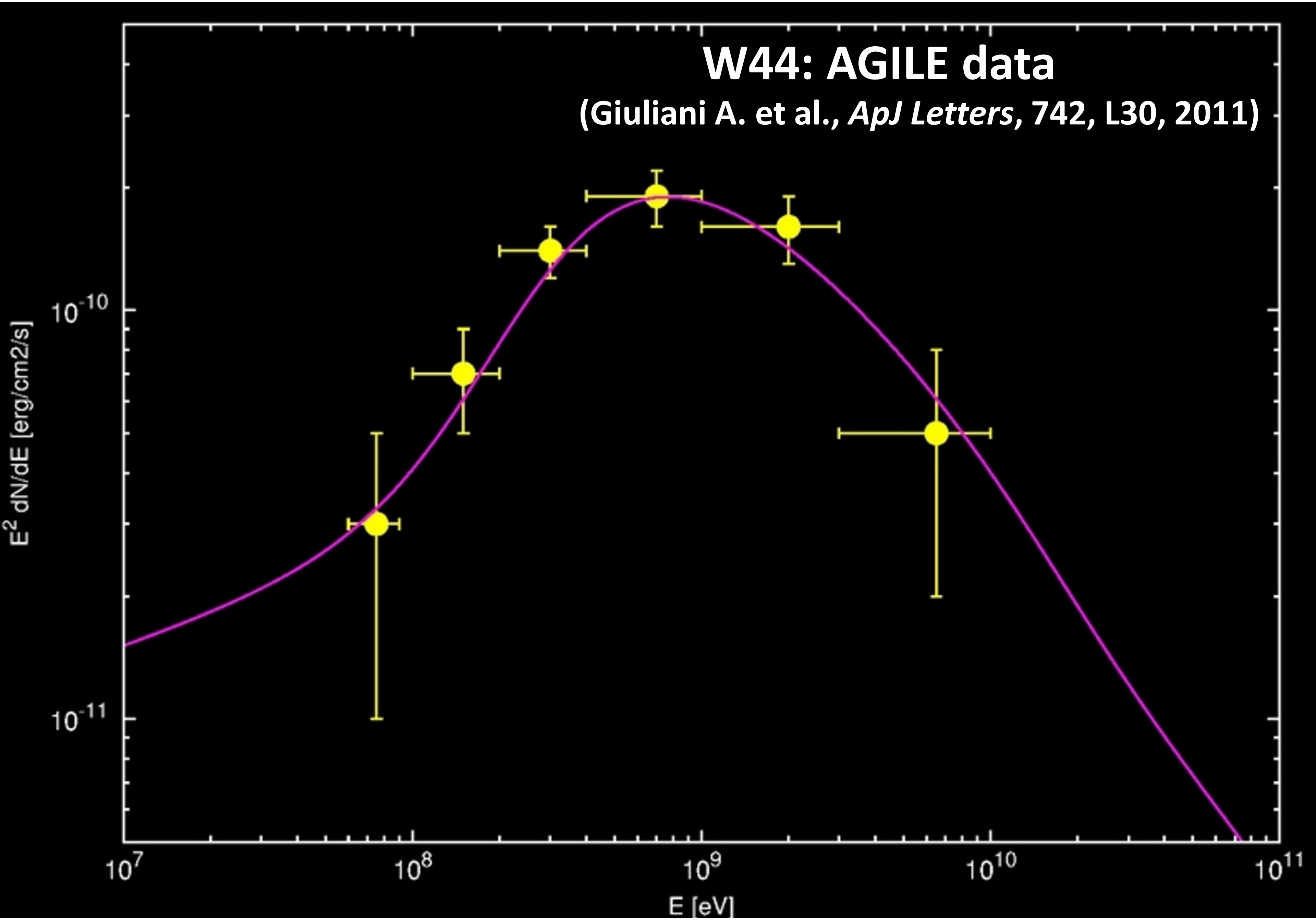
AGILE discovery of pion emission from the SNR W44



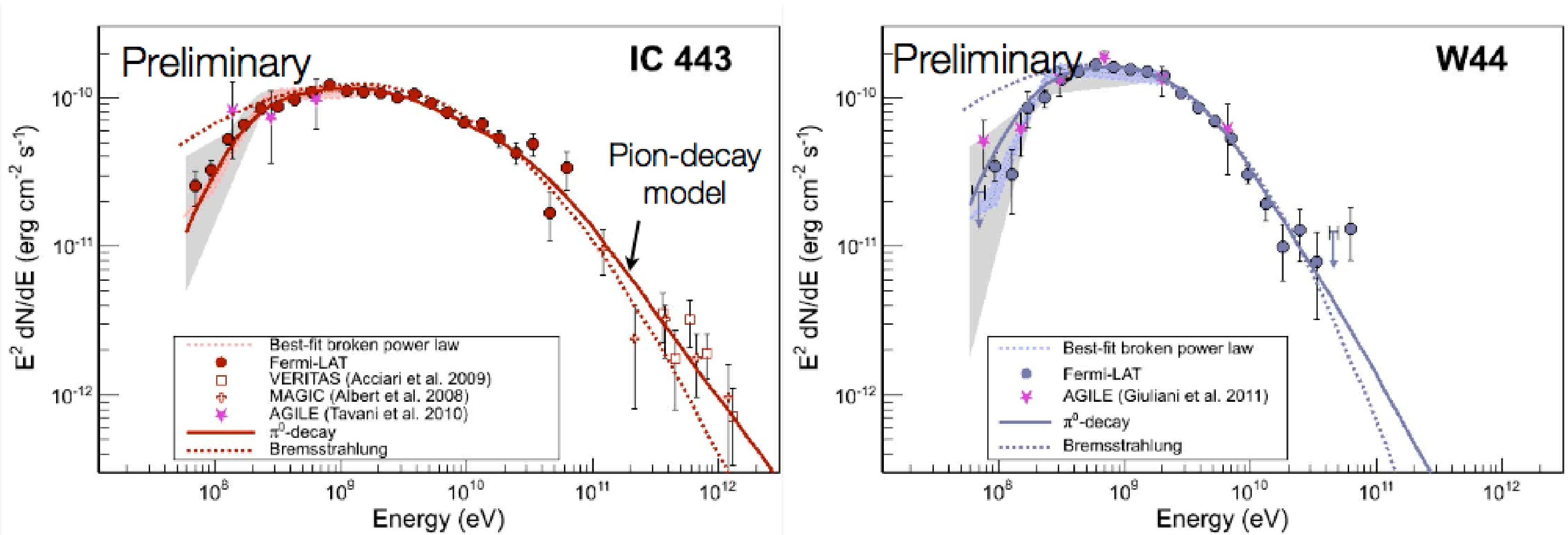
AGILE intensity map,
smoothing3
E: 400-10000
VLA contours (green)



NANTEN2 CO map
41 km/s (green), 43 km/s (blue)
AGILE 400-10000 cont. (magenta)
VLA contours (white)


W44: AGILE data
(Giuliani A. et al., ApJ Letters, 742, L30, 2011)
E^2 dN/dE [erg/cm2/s]
10^{-10}
10^{-11}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
E [eV]

Fermi: CR protons in SNR



- Unambiguous and robust detection of the pion-decay bump in W44 and IC443
- Possible for the two brightest LAT SNRs due to significant increase in effective area at 100 MeV through Pass 7
- Proof that SNRs accelerate protons

Detection of the pion-decay cutoff in Supernova remnants
2013, Science, 339, 807