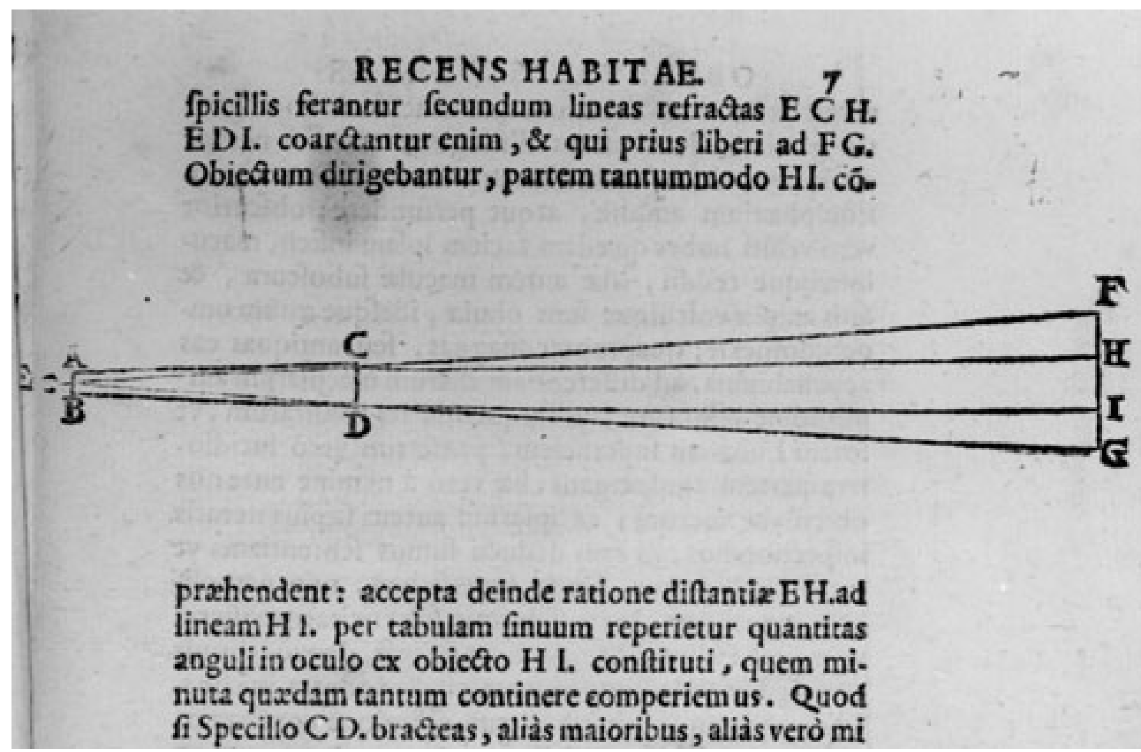
High Energy Cosmic Rays

Paolo Lipari
7th NWAP, Sao Tome
9-september-2009

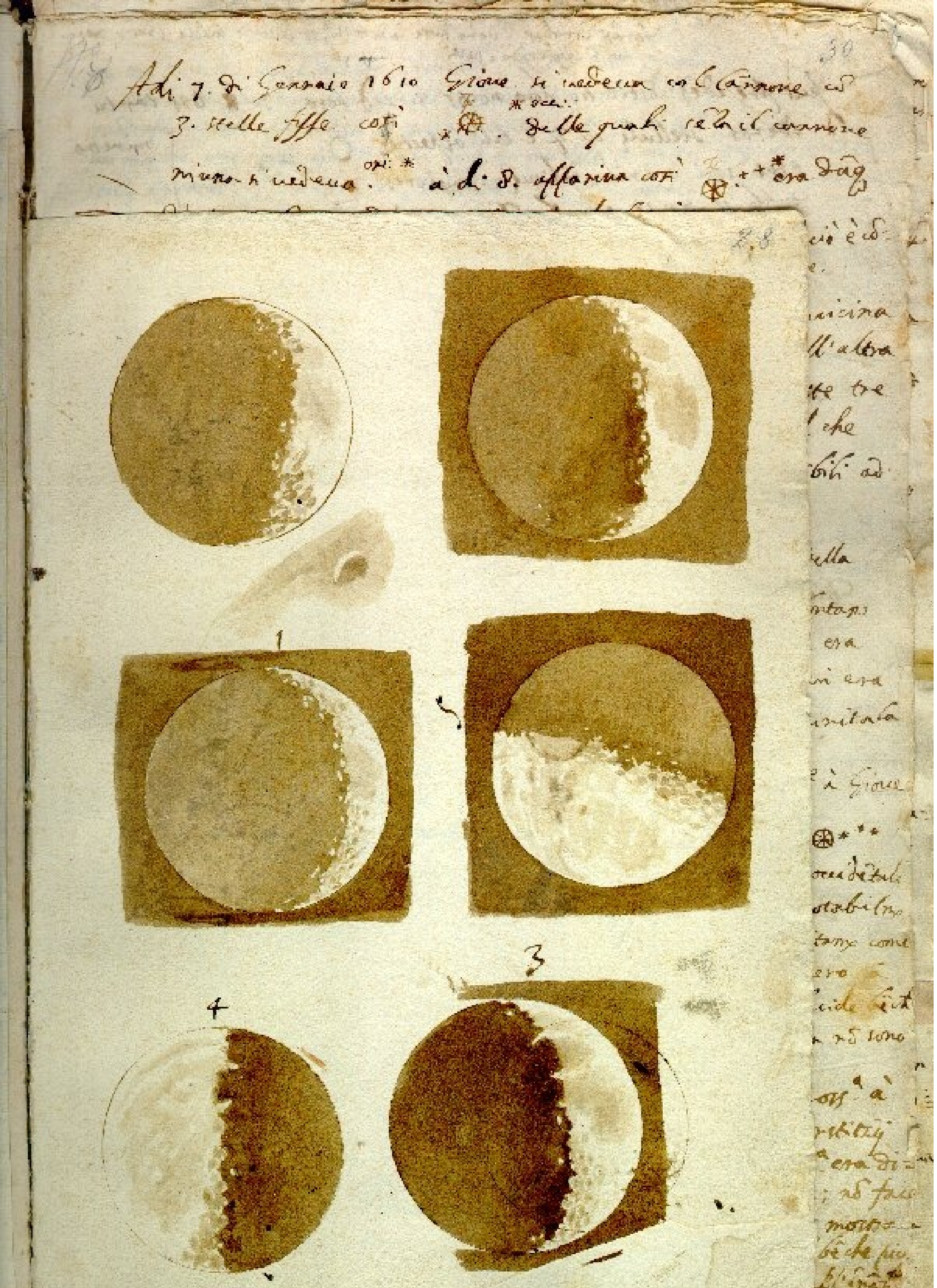
Nearly exactly 400 years ago (dec-1609)

Galileo Galilei
started to observe
the sky with a telescope


RECENS HABITAE. 7

ſpicillis ferantur ſecundum lineas refractas E C H.
E D I. coarctantur enim, & qui prius liberi ad F G.
Obiectum dirigebantur, partem tantummodo H I. cō-

præhendent: accepta deinde ratione diſtantiæ E H. ad
lineam H I. per tabulam ſinuum reperietur quantitas
anguli in oculo ex obiecto H I. conſtituti, quem mi-
nuta quædam tantum continere comperiemus. Quod
ſi Specillo C D. bracteas, aliàs maioribus, aliàs verò mi



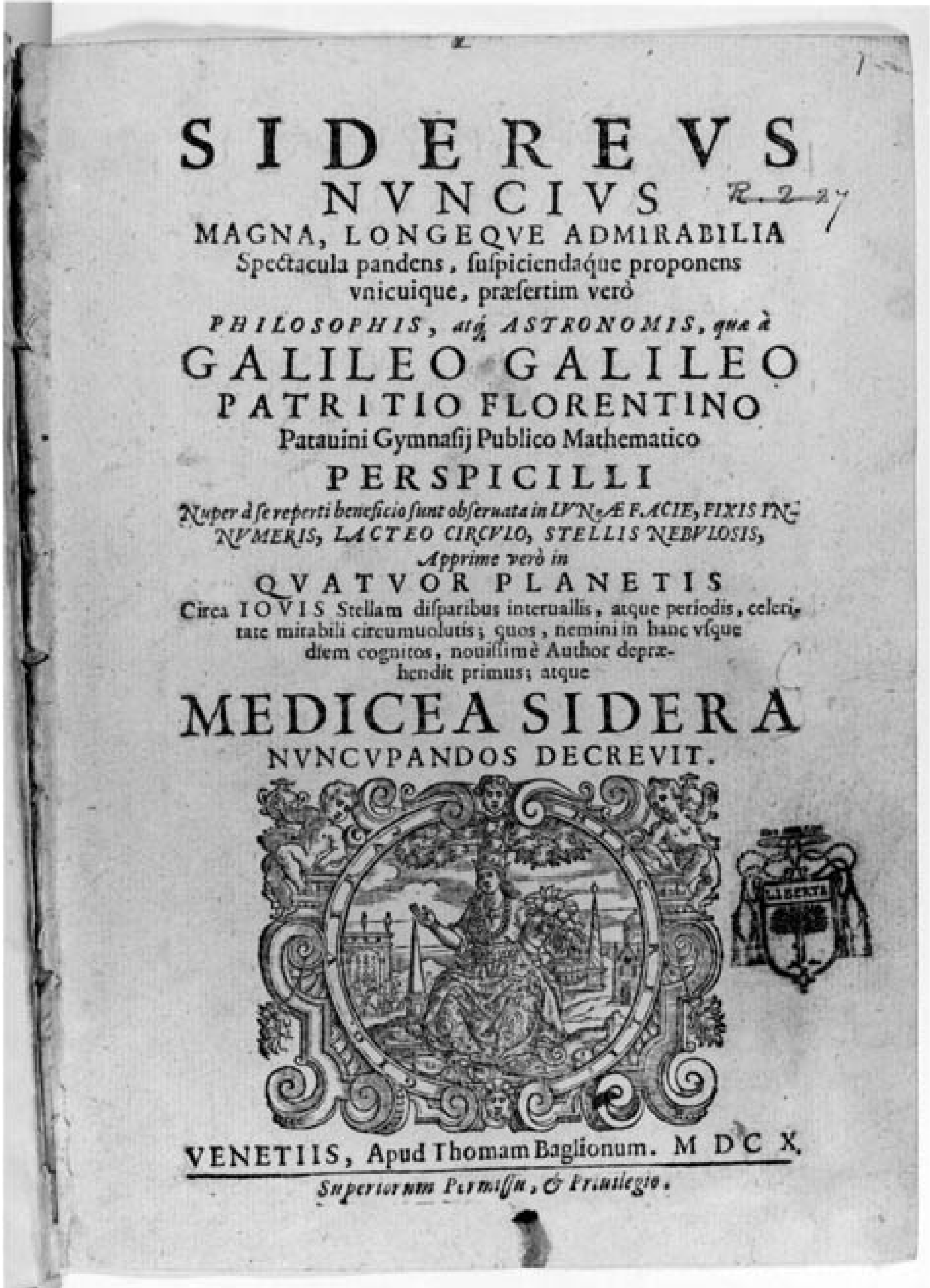
Pulcherrimum atque visu iucundissimum est, lunare corpus,......

It is extraordinarily beautiful and a source of great joy to observe the body of the Moon .....

In 1610,
Galileo published his
observations
under the title:

SIDEREUS NUNCIUS

unfolding great and very wonderful sights
and displaying to the gaze of everyone,
but especially philosophers and astronomers,
the things that were observed by
GALILEO GALILEI,
Florentine patrician
and public mathematician of the University of Padua,
with the help of a spyglass lately devised by him,
about the face of the Moon, countless fixed stars,
the Milky Way, nebulous stars,
but especially about
four planets
flying around the star of Jupiter at unequal intervals
and periods with wonderful swiftness;
which, unknown by anyone until this day,
the first author detected recently
and decided to name
MEDICEAN STARS



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author deprehendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

Title of Galileo book:

SIDEREUS NUNCIUS

Title of Galileo book:

SIDEREUS NUNCIUS

MESSENGER

from the **STARS**

Title of Galileo book:

SIDEREUS NUNCIUS

LIGHT

(photons)

Revolution

for Astronomy

Revolution

for Physics

Intimate relation between:
Astrophysical Observations,
the discovery and understanding of
new objects in the sky, and
the development of Fundamental Science:

Intimate relation between:
Astrophysical Observations,
the discovery and understanding of
new objects in the sky, and
the development of Fundamental Science:

Structure of the Solar System
(Newtonian mechanics)

Source of energy of the Sun and the stars
(Nuclear physics, weak interactions)

White Dwarfs (quantum statistics)

Neutron Stars and SuperNova explosions
(strong interactions, neutrino physics)

Astrophysics with Four MESSENGERS

- Photons

Essentially all the information
We have on the Universe around us
has been obtained with photons.

The history of Astrophysics is the
EXTENSION of the range of
wavelength available for observations

- Neutrinos
- Cosmic Rays ($p, e^-, \bar{p}, e^+, \ldots$)
- Gravitational waves

Astrophysics with Four MESSENGERS

- Photons
- Neutrinos
- Cosmic Rays ($p, e^-, \bar{p}, e^+, \ldots$)
- Gravitational waves

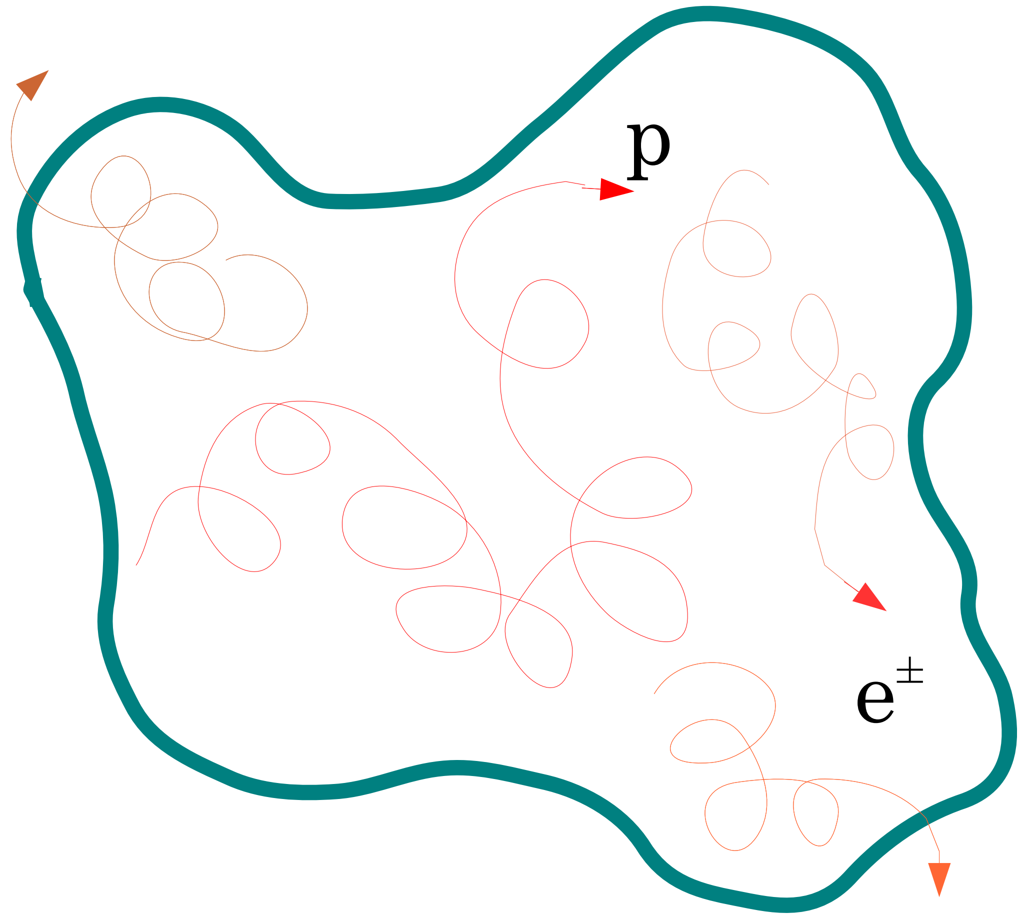
A New Messenger
with very different properties
that will allow to
"SEE" the universe
in a profoundly different way

Astrophysics with Four MESSENGERS

- Photons
- Neutrinos
- Cosmic Rays ($p, e^-, \bar{p}, e^+, \ldots$)
- Gravitational waves

Intimate Relation

Astrophysical Sources of High Energy Radiation



Astrophysical Object containing:

Populations of relativistic protons, Nuclei electrons/positrons

Emission of:

γ rays

Neutrinos

Cosmic Rays

$$p + \text{target} \rightarrow \text{many particles}$$

$$\rightarrow p(n) + \pi^{+} + \pi^{-} + \pi^{\circ}$$

$$\mu^{+} + \nu_{\mu}$$

$$\gamma + \gamma$$

$$e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

"Hadronic Emission"

$$e^{\mp} + B \rightarrow e^{\mp} + \gamma_{\text{synchrotron}}$$

"Leptonic Emission"

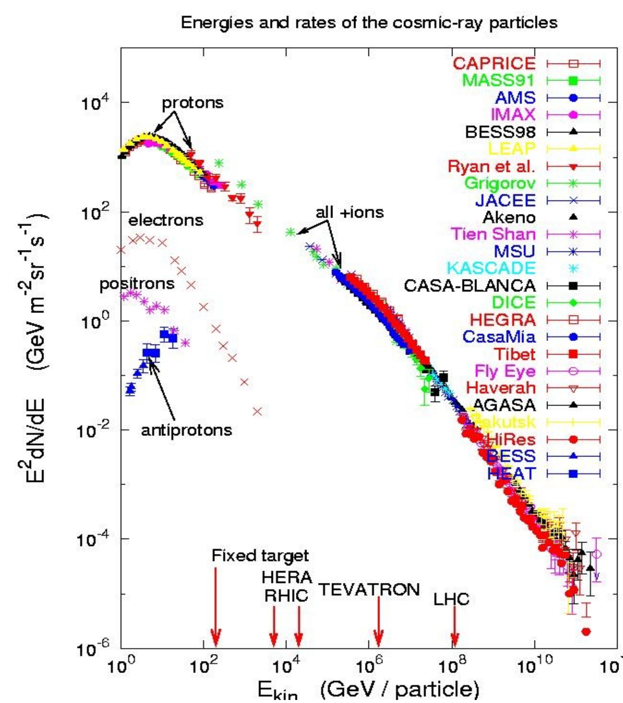
$$e^{\mp} + \gamma_{\text{soft}} \rightarrow e^{\mp} + \gamma_{\text{Inverse Compton}}$$

COSMIC RAYS

Victor Hess

before the balloon flight of 1912

Discovery of Cosmic Rays
Beginning of
High Energy Astrophysics



Review article in 1931
of Karl Darrow (Millikan collaborator).
``*Data and nature of Cosmic Rays*''

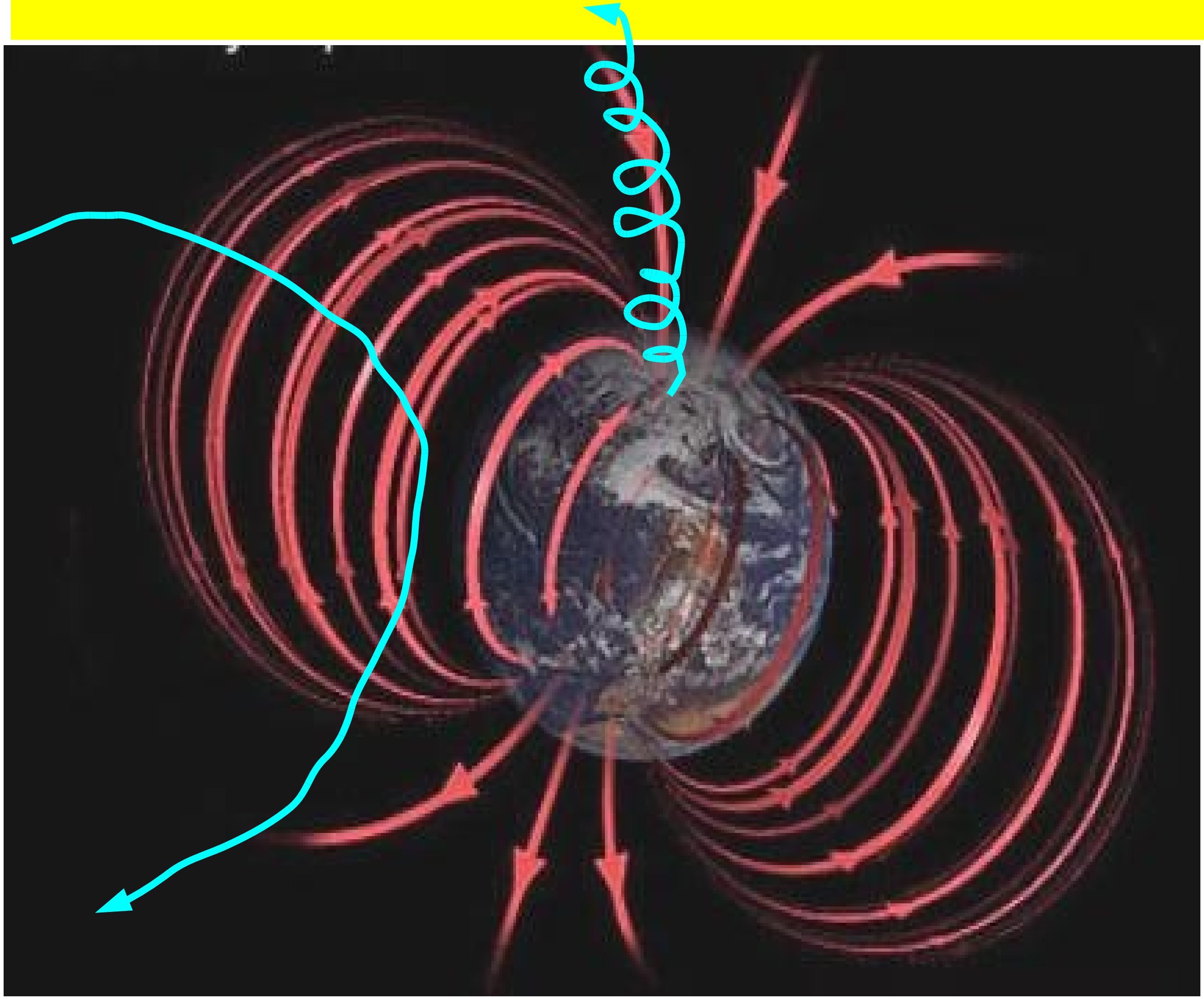
Physicists with their frail machines have gone to
high mountain ponds in the Sierras and in the Andes,
to the distant wildernesses about the Earth Magnetic poles;
they have scooped out cavities in Alpine glaciers,
they have lifted hundredweights of lead to the tops
of peaks above the snow line, they have cruised the arctic
and the tropical oceans, they have descended into
tunnels and deep mines, they have ascended into the sky
in airplanes and balloons ….

Georges-Henry Lemaitre

New York Times article:

Prof. Albert Einstein has given
his scientific blessing
to the ingenious theory proposed
by Abbe' Georges Lemaitre
that cosmic rays are
birth cries of the universe
and *the radiations from the superradioactive primeval matter that existed when the universe was young.*

GEOMAGNETIC EFFECTS



Latitude effect → Charged particles
East-West effect → Positively charged particles

COMPTON (1933) Cosmic Rays are **CHARGED**

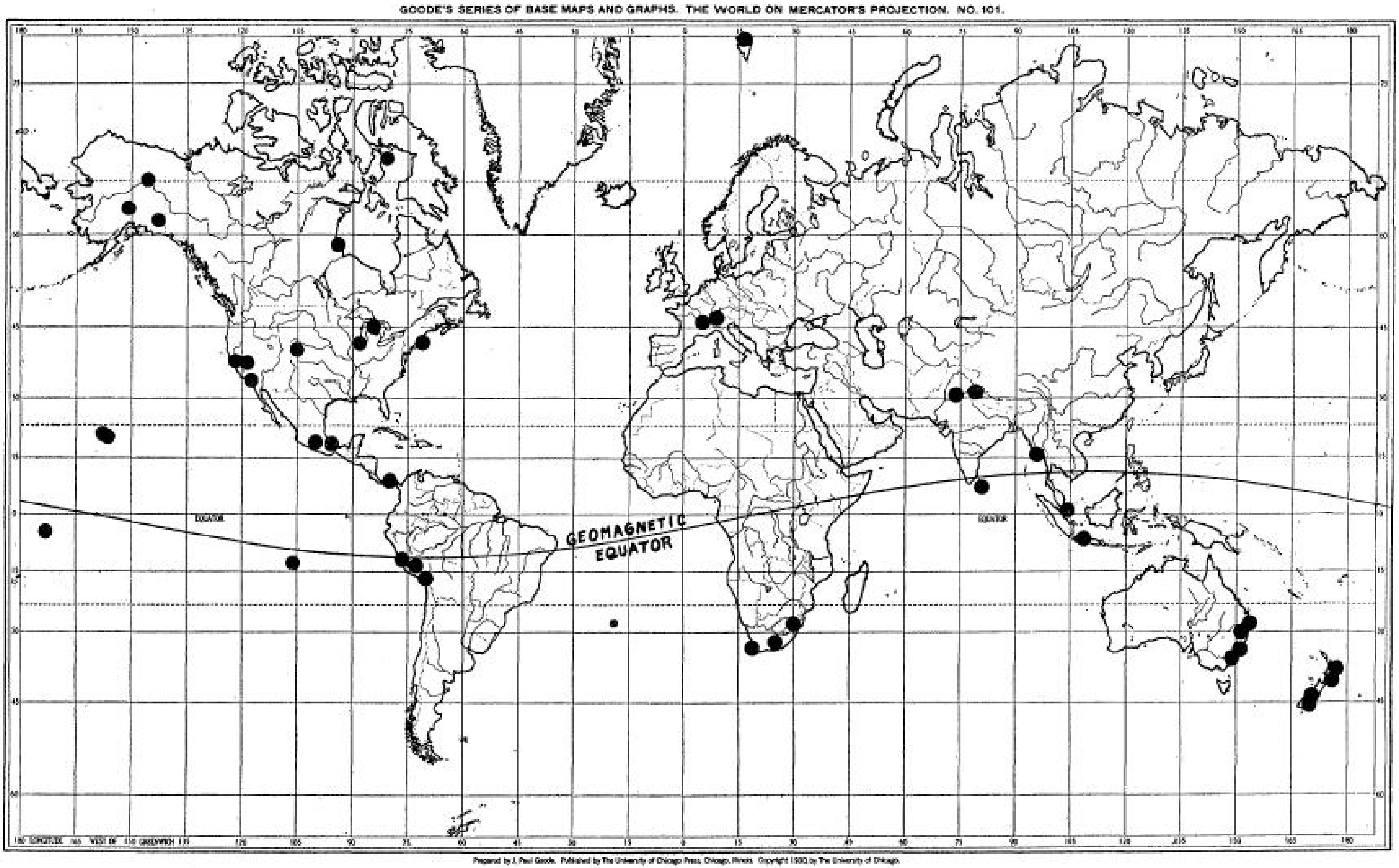
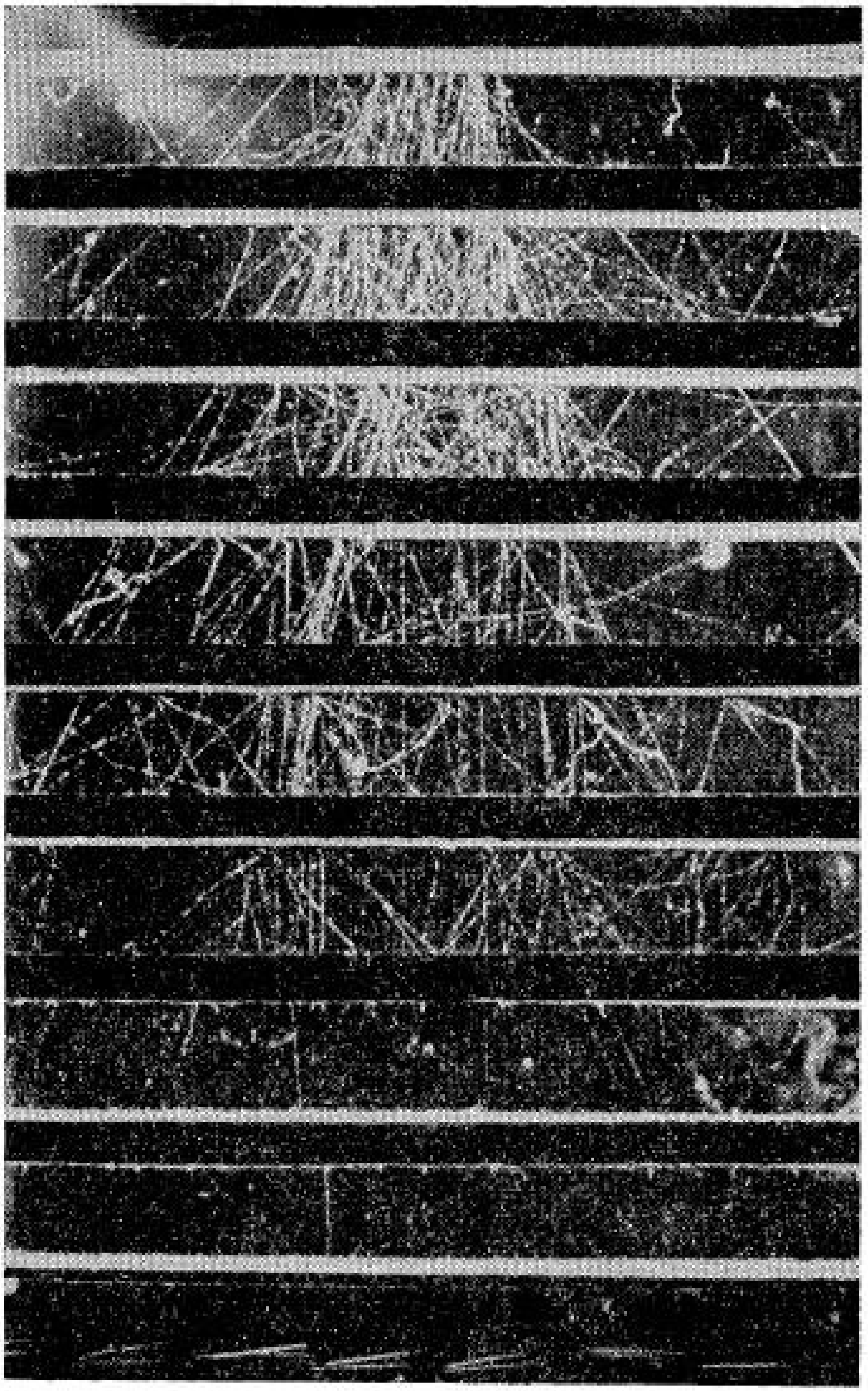


FIG. 1. Map showing location of our major stations for observing cosmic rays.

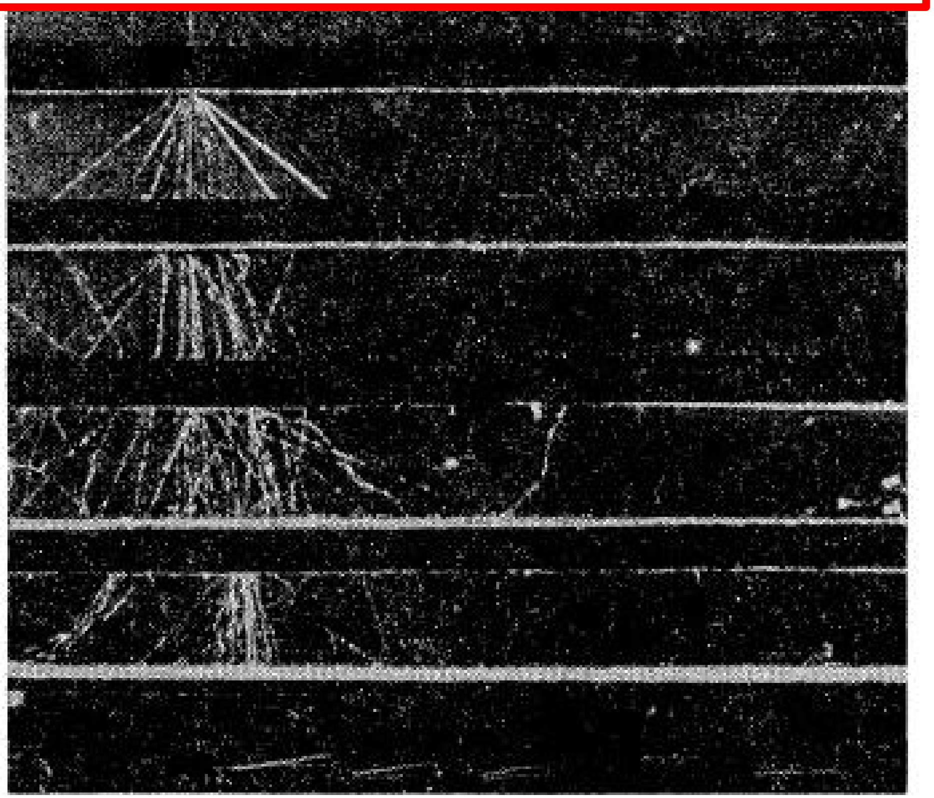
LATITUDE EFFECT



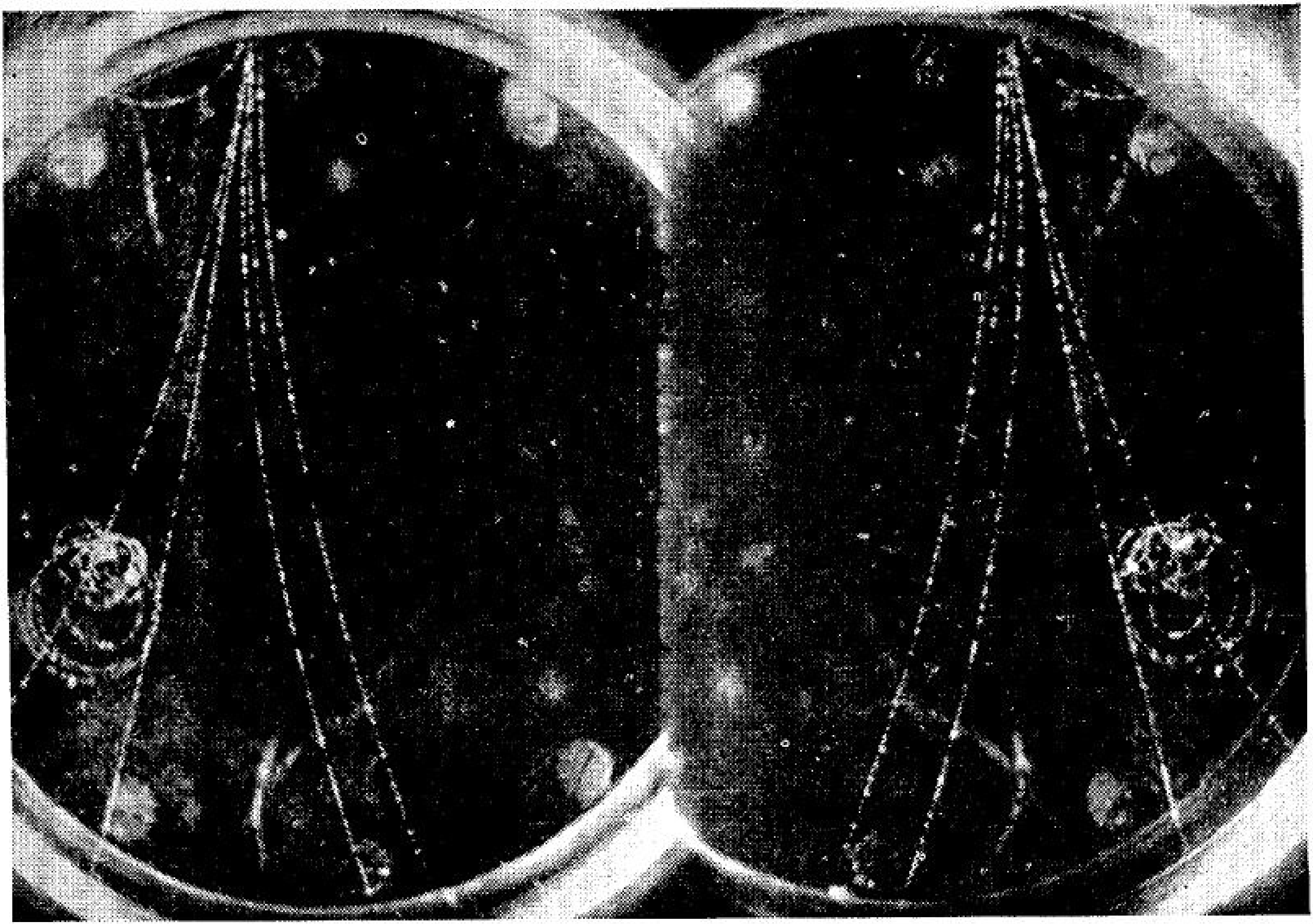
Understand the Dynamics of relativistic particles

Discover new Particles (π^+, K, Λ)

Origin of CR remains "elusive"



ELECTRONS and POSITRONS

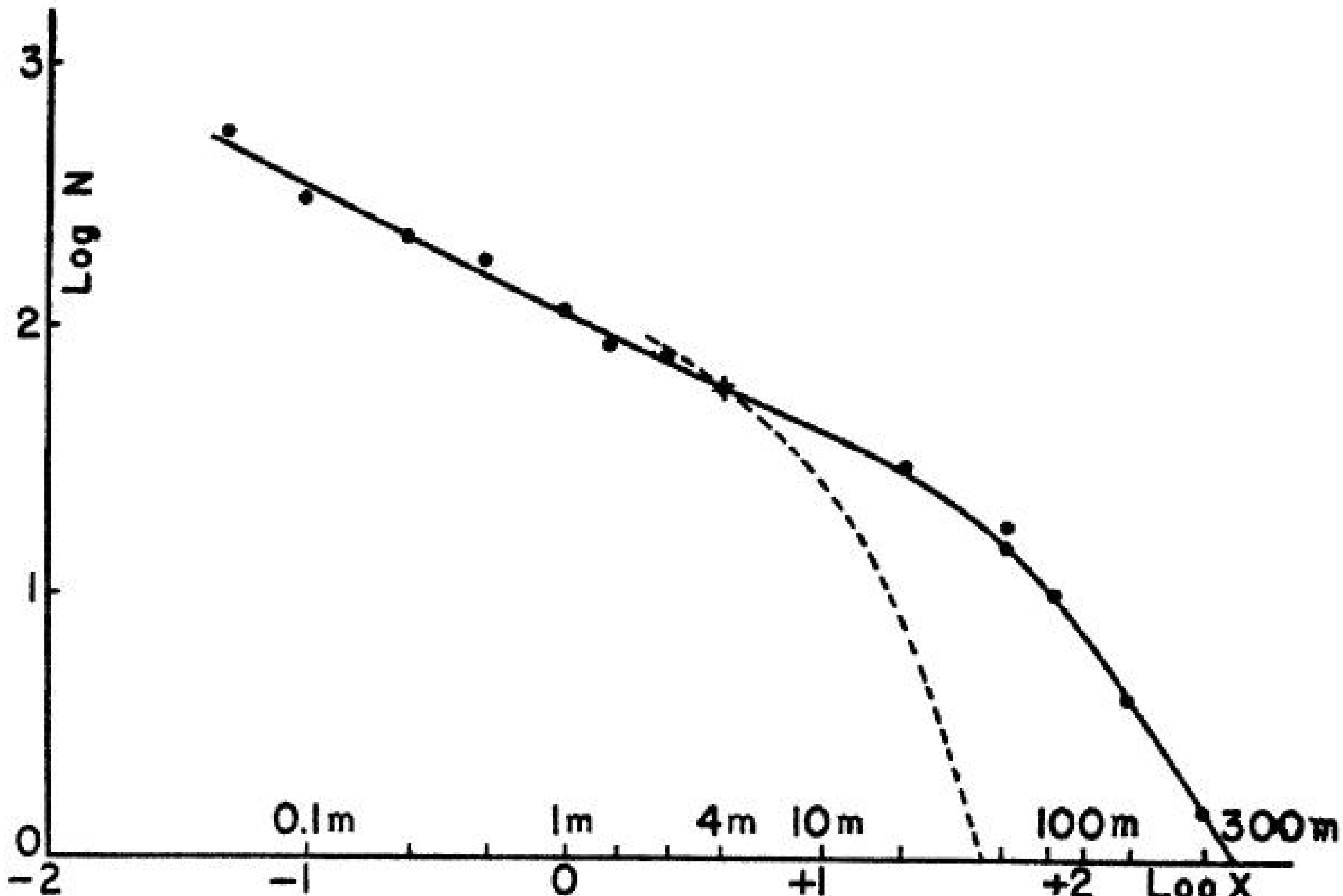


Pierre Auger

JULY-OCTOBER, 1939 REVIEWS OF MODERN PHYSICS

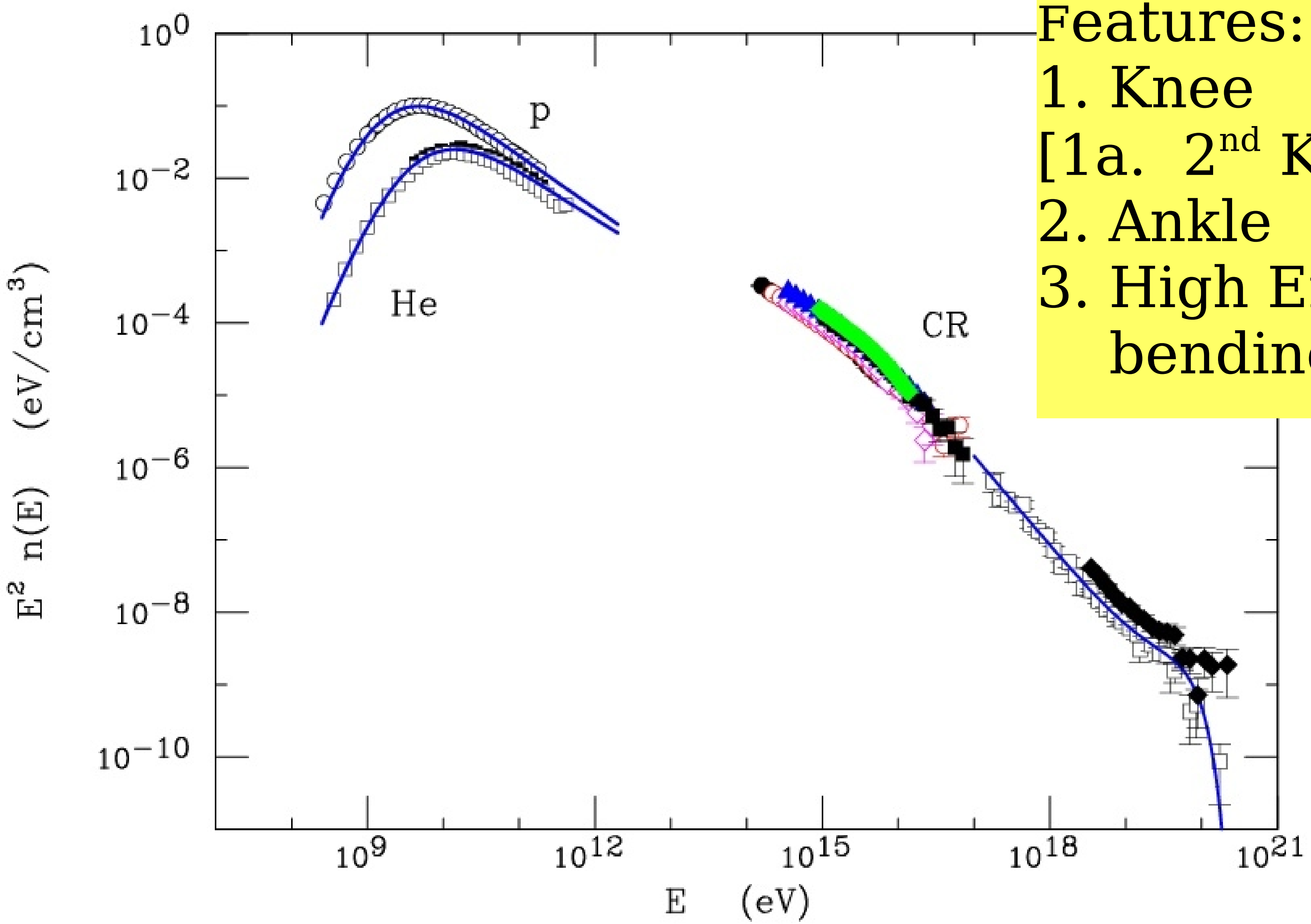
Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France



Extensive Air Showers

Cosmic Rays Spectrum



Features:
1. Knee
[1a. 2nd Knee]
2. Ankle
3. High Energy bending

We do not have a fully convincing explanation for any of the features of the CR energy spectrum.

However the perspectives to finally obtain an understanding of the origin of the Cosmic Rays are excellent.

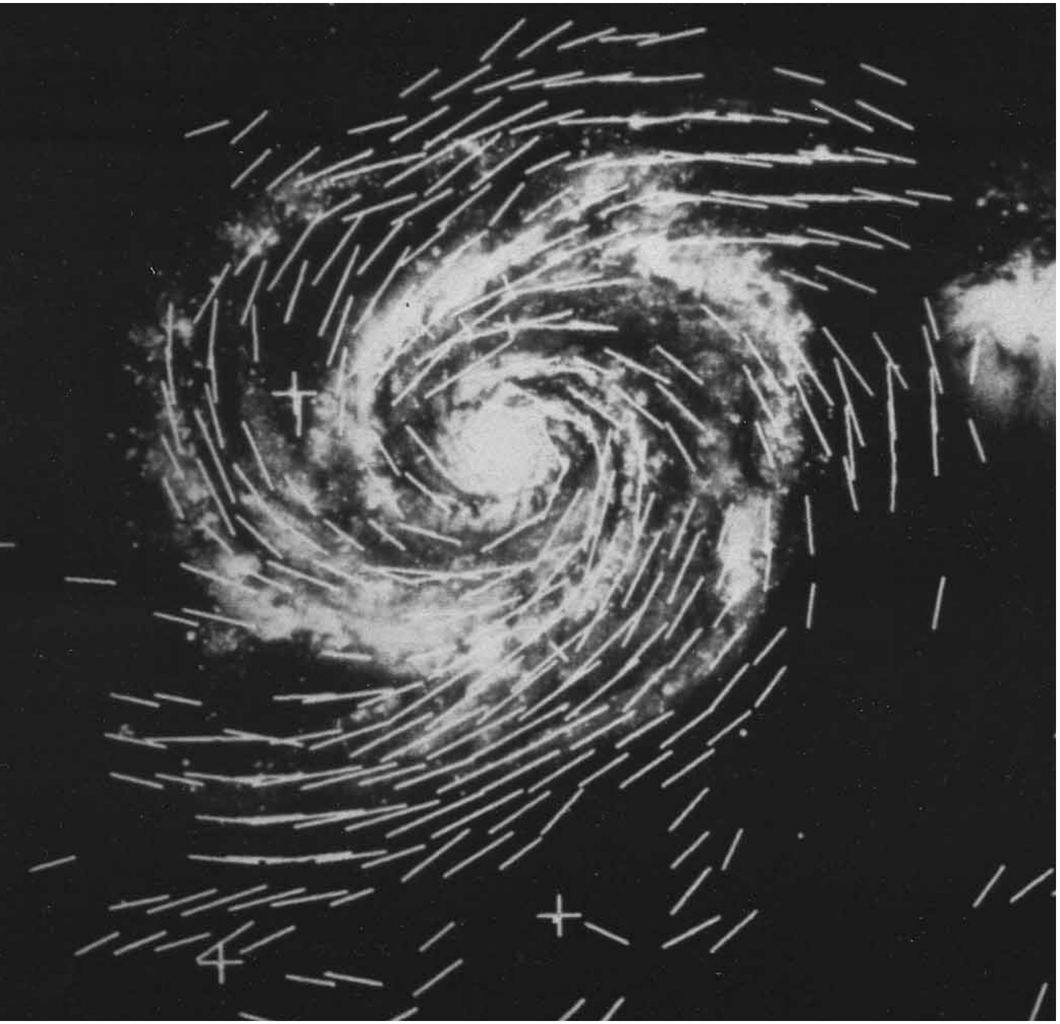
Multi-wavelength Astronomy
X-ray astronomy
Gamma-Ray Astronomy
CR ASTRONOMY [!! (?)]

NEUTRINO Telescopes.

GALACTIC

EXTRAGALACTIC

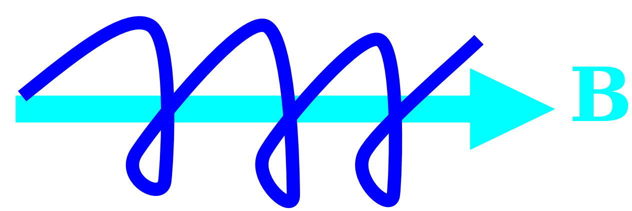
Cosmic Rays



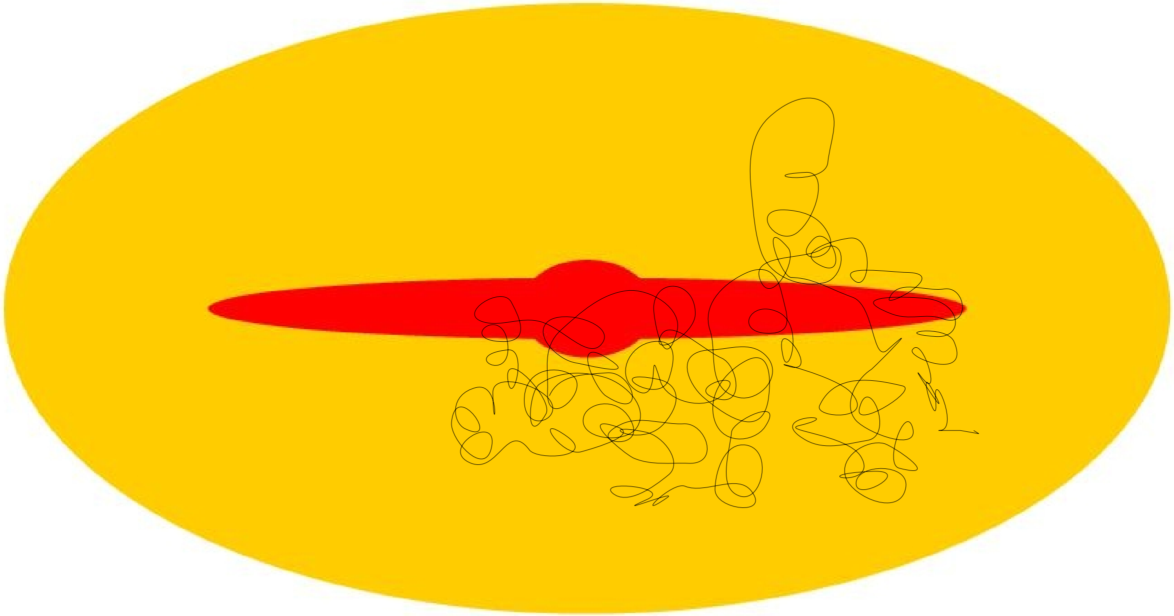
We live in a "bubble" filled with Cosmic Rays.

A "magnetic bottle" where the CR density is enhanced by magnetic trapping.

$$\langle B_{\text{galactic}} \rangle \simeq 3\ \mu\text{Gauss}$$

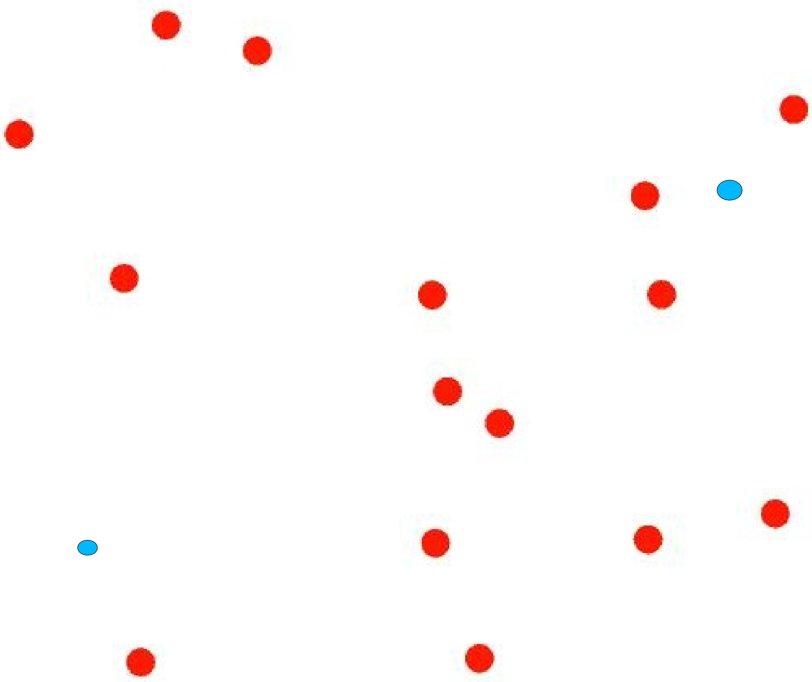


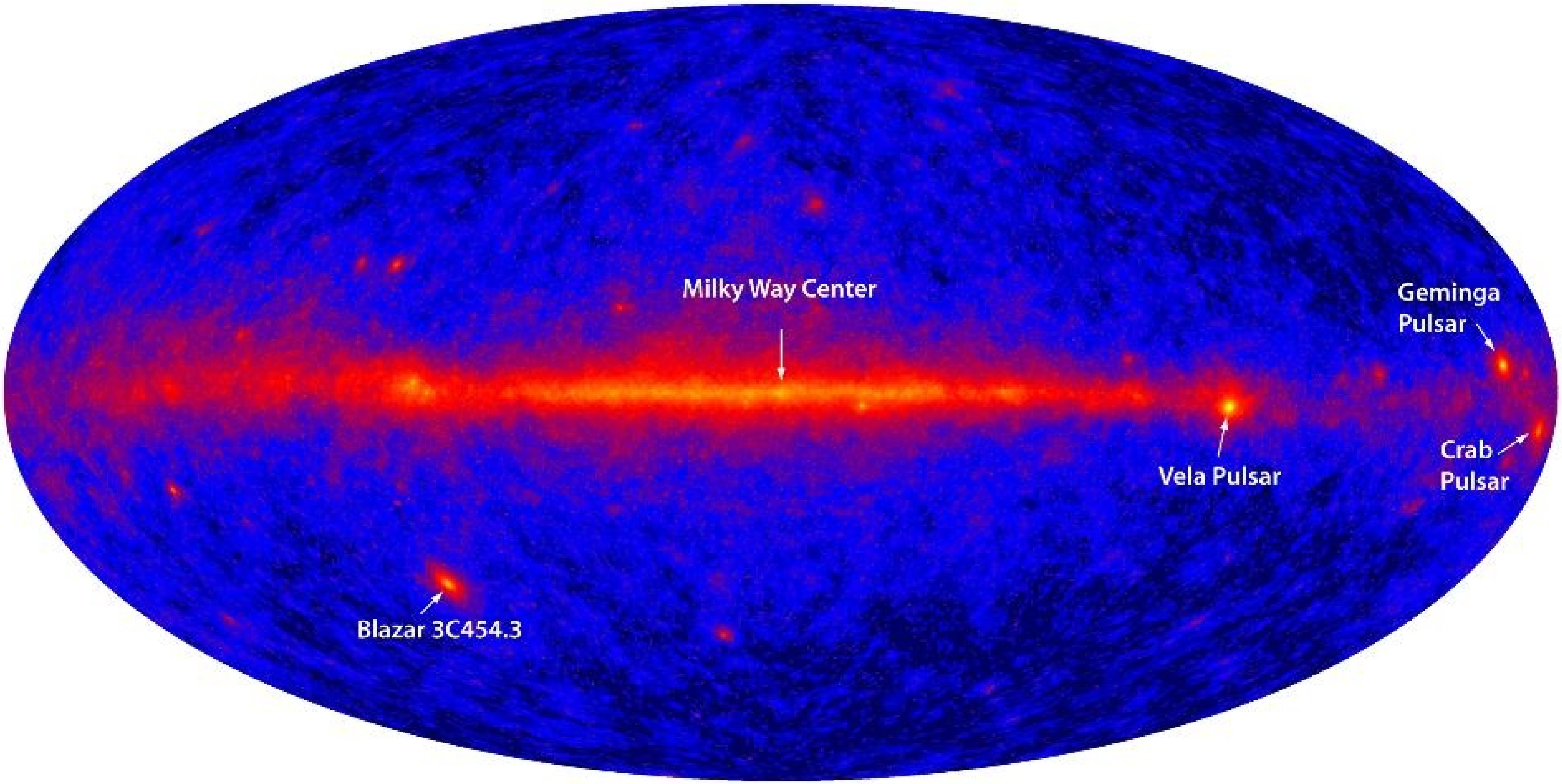
Extra-galactic space is filled by a much more tenuous gas of cosmic rays injected during the entire history of the Universe.
This "extragalactic population" emerges only at sufficiently high energy.



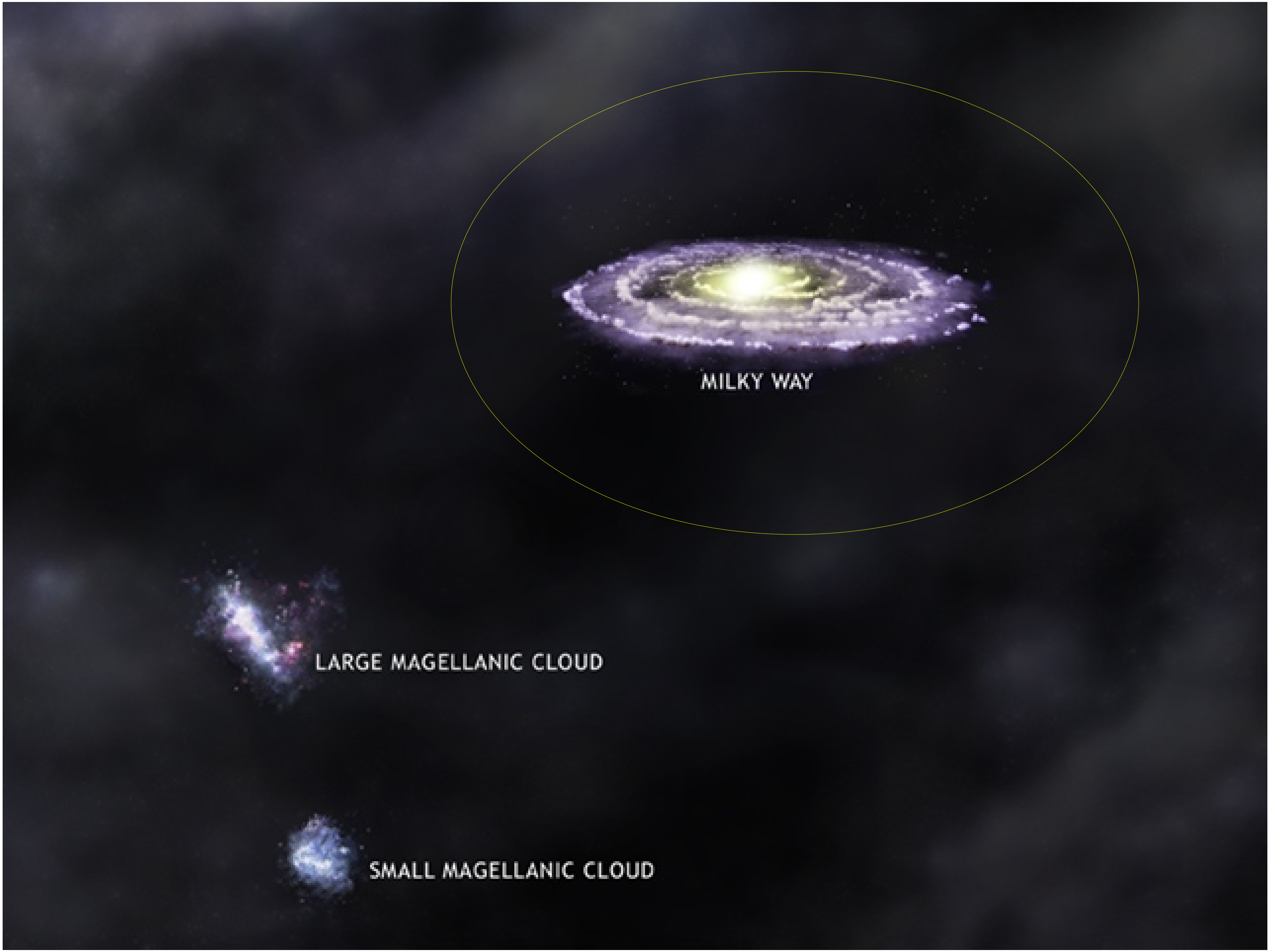
Galactic Sources
Injection Q(E,x)
D(E/Z, x) Diffusion

Extragalactic sources
Sources, q(E,x,z)
magnetic fields
Evolution of the universe





$E_\gamma > 100$ MeV

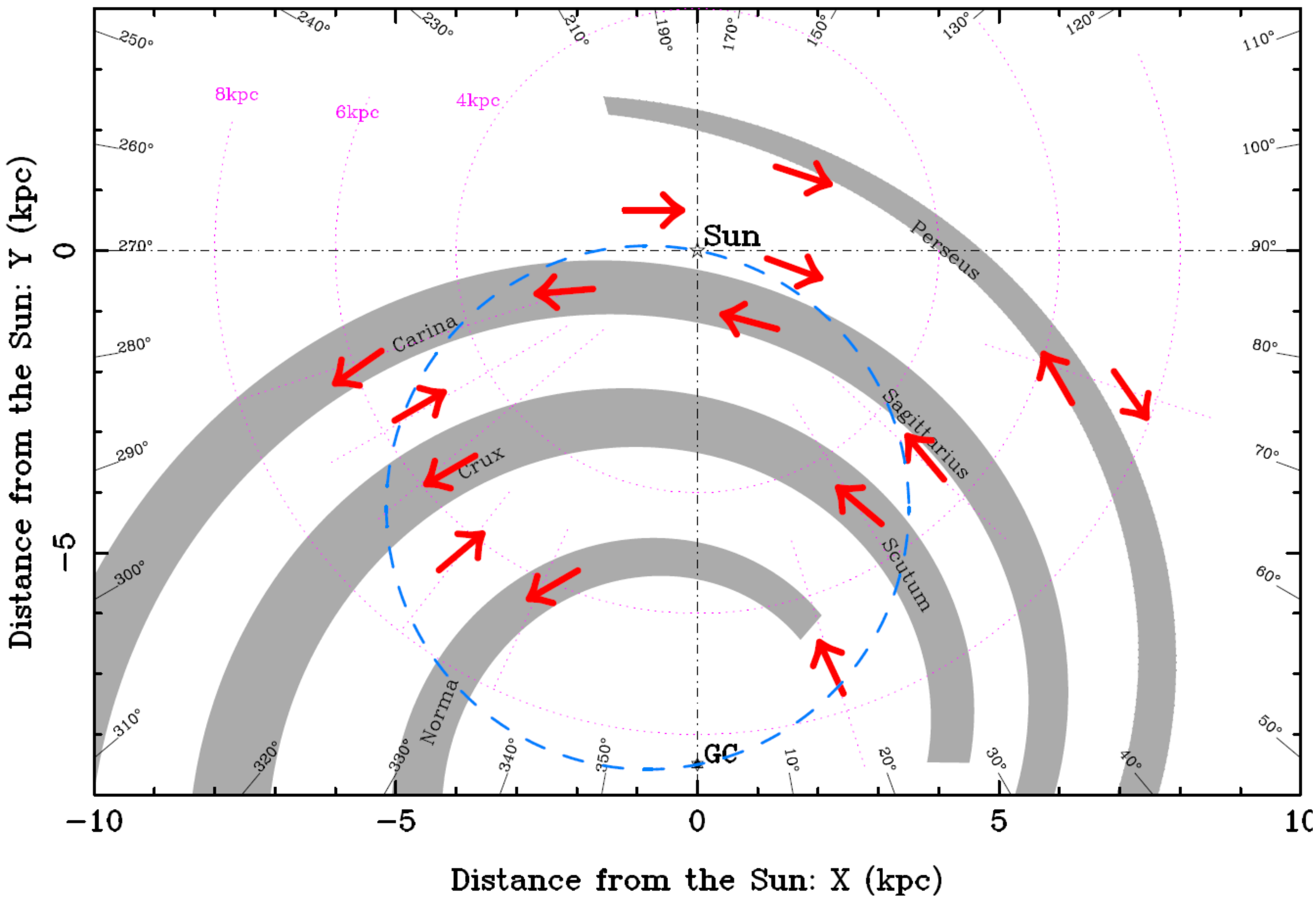

MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD

CR density in the Large and Small Magellanic Clouds much smaller than in our Milky Way

Field COUNTERCLOCKWISE in arm regions
(clockwise in interarm regions)

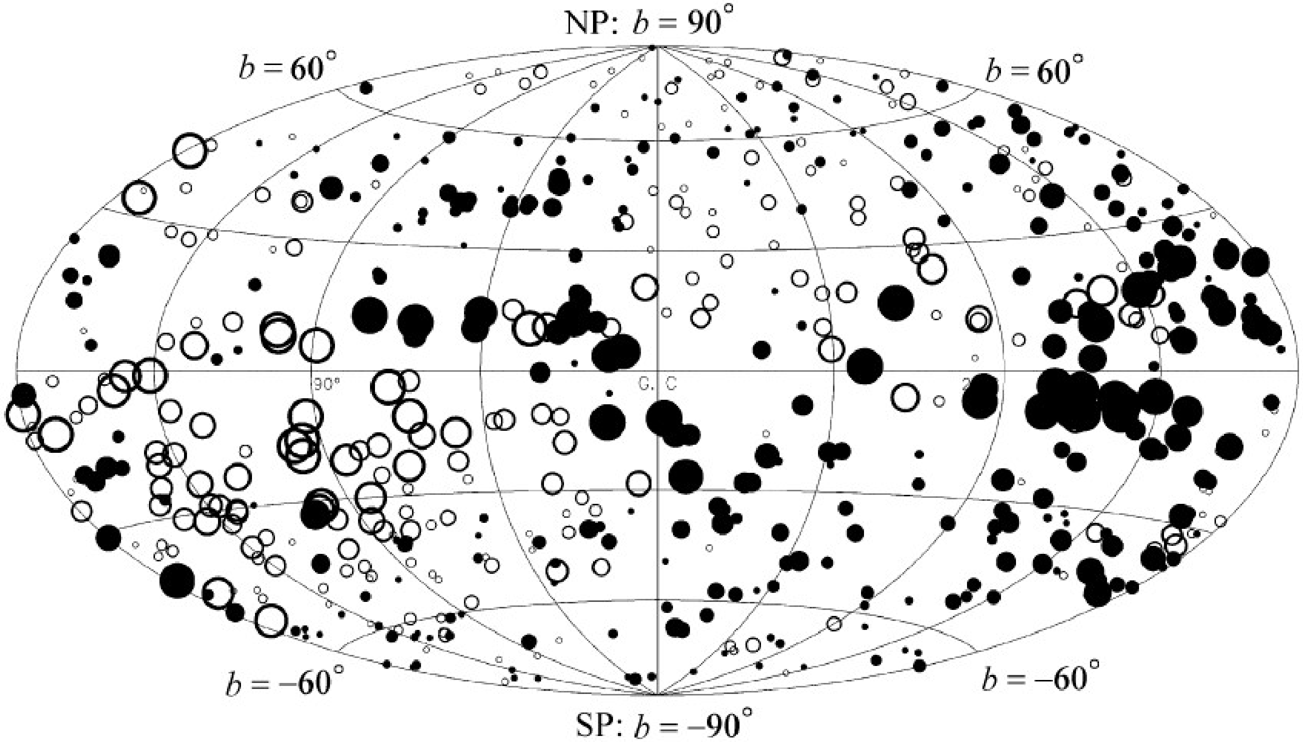
Regular
Magnetic
Field

in the plane
of the
Milky Way

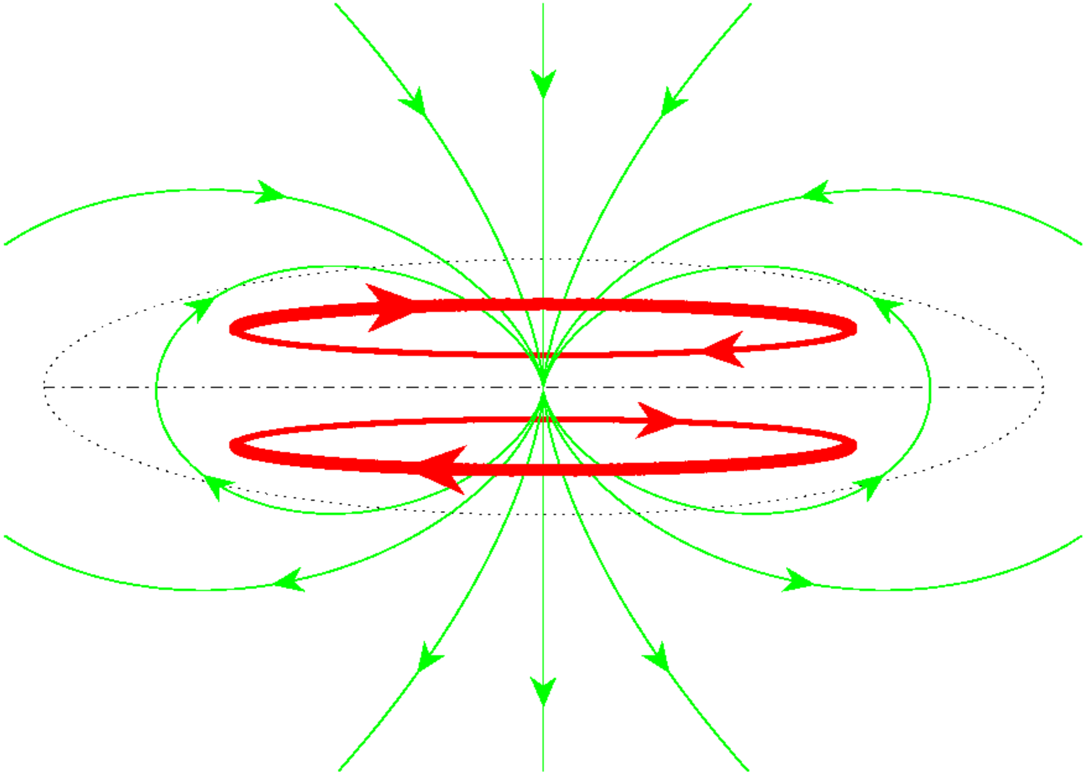


Faraday
Rotation
of
Pulsar
polarization

Han, Manchester et al. Ap.J. 642, 868 (2006)

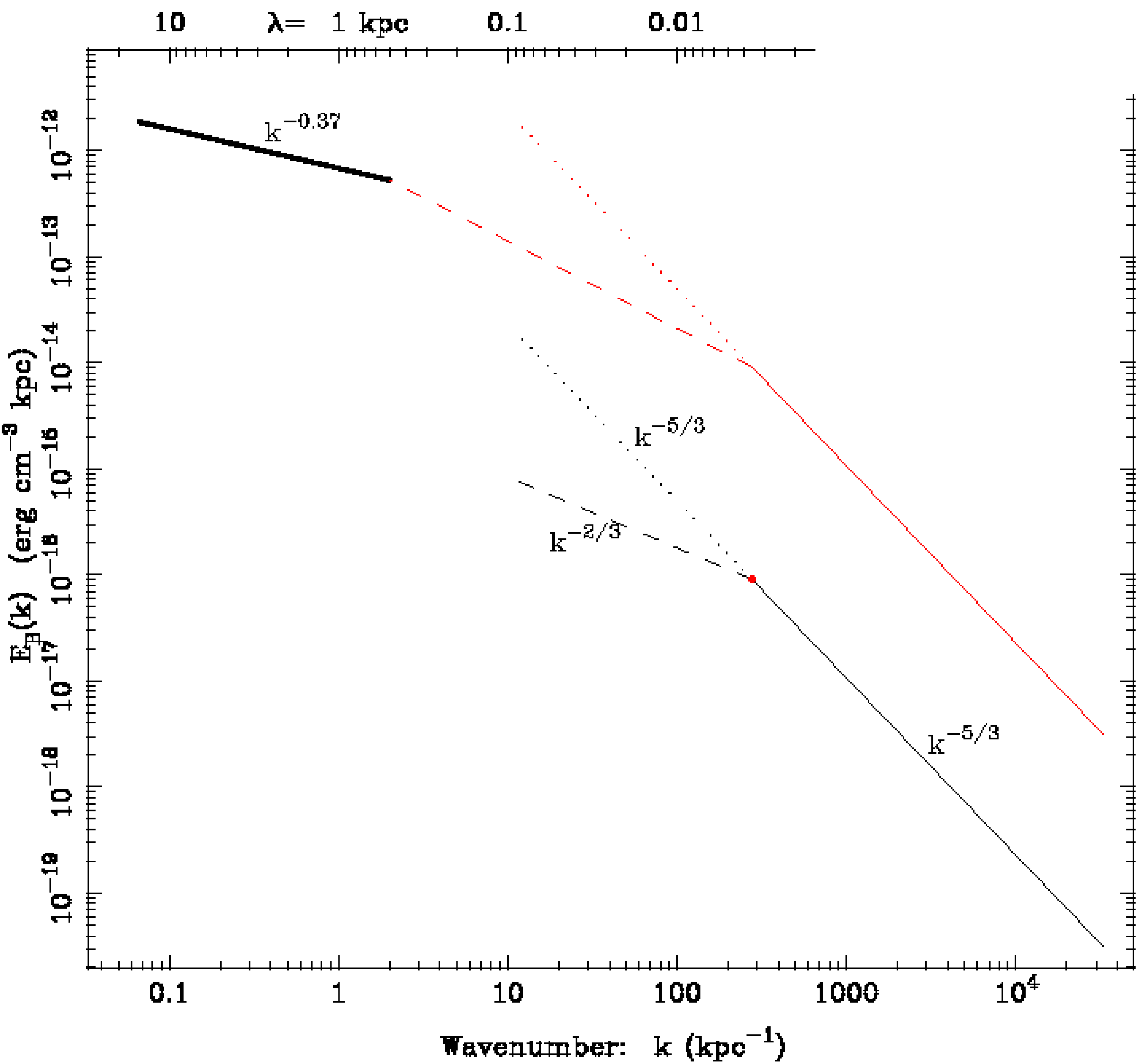


General Structure
of the Magnetic field
outside of the plane
of the Galaxy



Random Magnetic Field

$$\boldsymbol{B}(\boldsymbol{r}) = \int \tilde{\boldsymbol{B}}(\boldsymbol{k}) e^{2\pi i \boldsymbol{k} \cdot \boldsymbol{r}} \, d\boldsymbol{k}$$



Determines
the rigidity
dependence
of the diffusion
coefficient

and together
with the global
properties of the
field the
containment time

Cosmic Ray Nuclear Composition

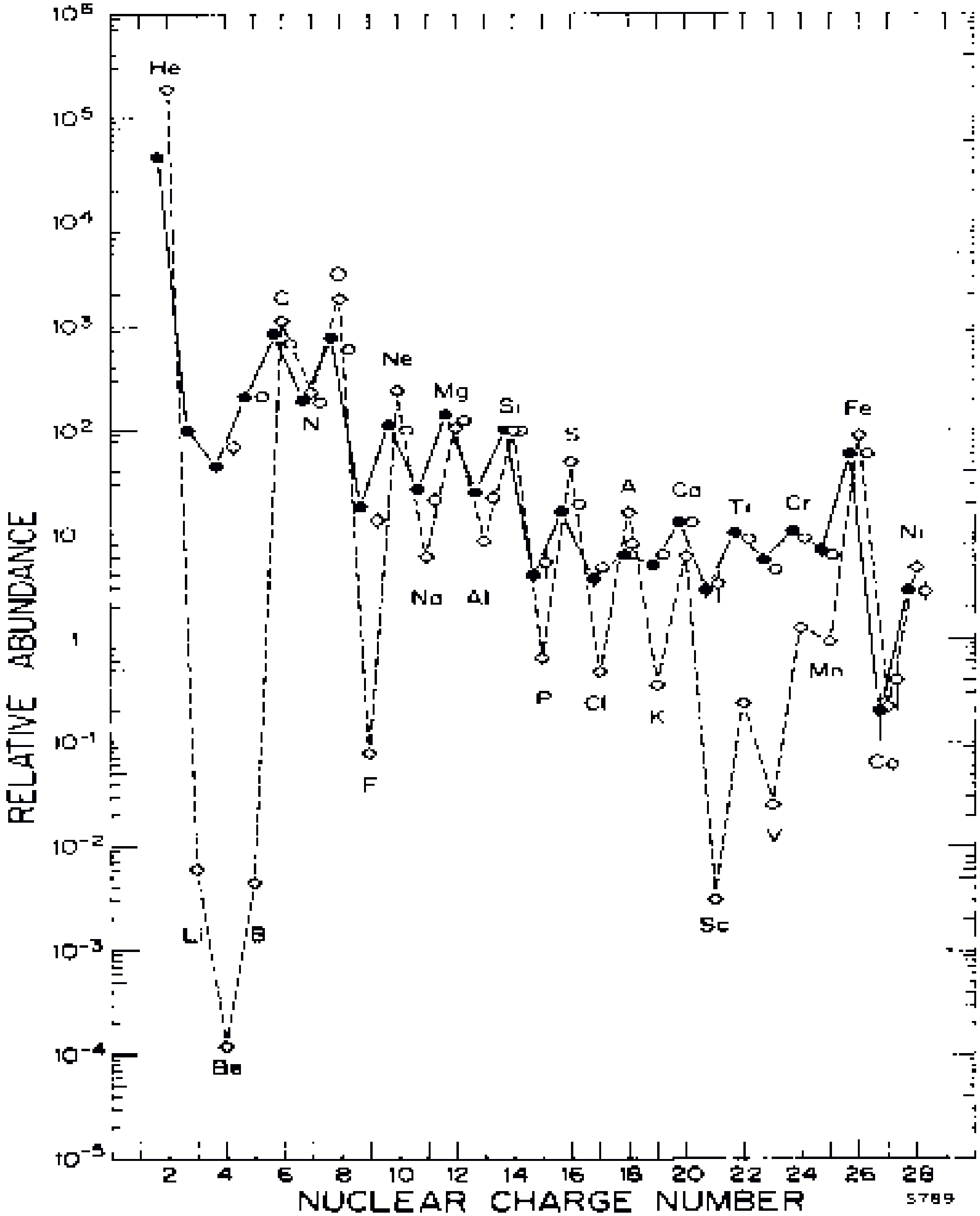
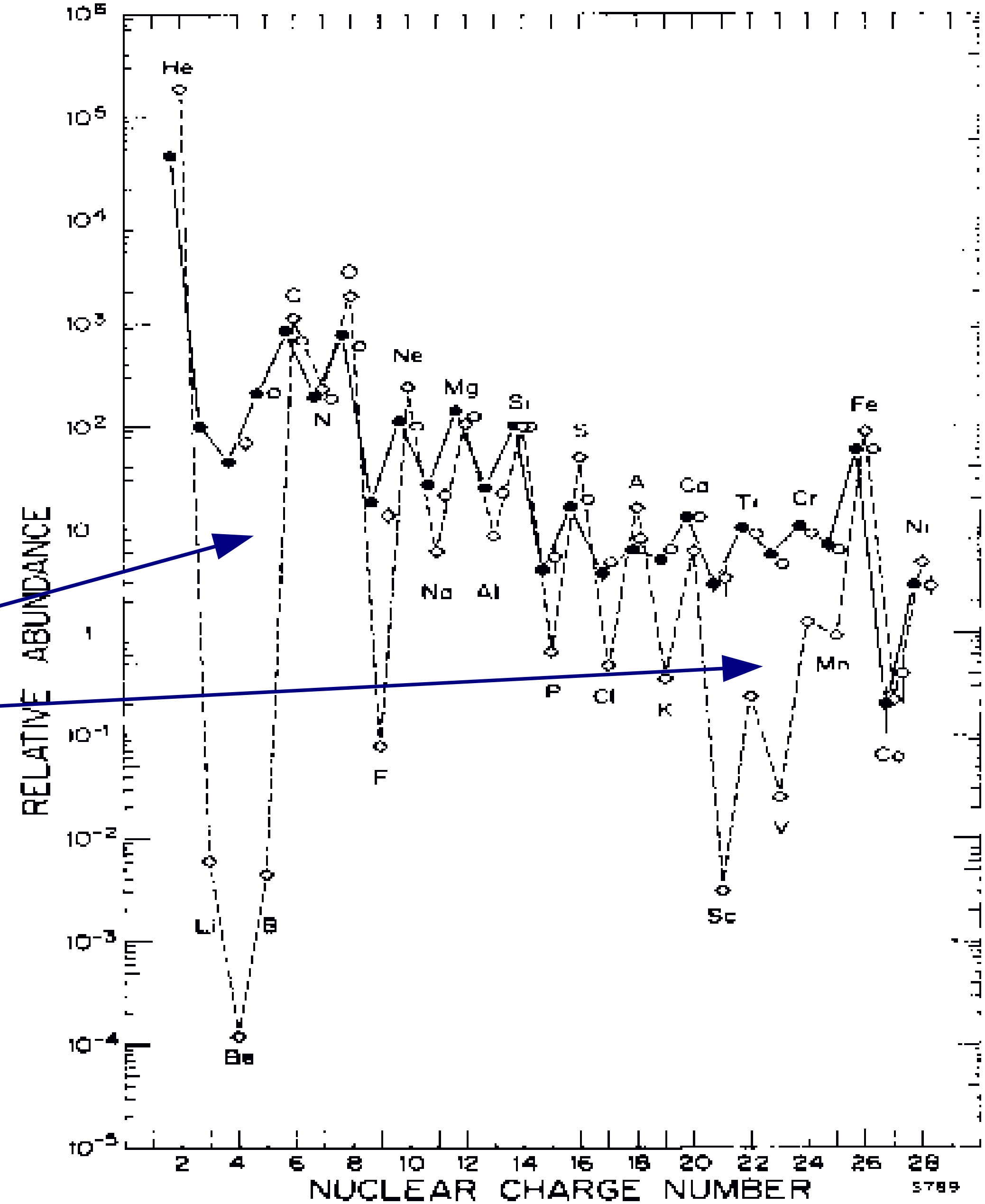


Figure 1. The relative abundance distribution of the elements in the cosmic radiation and in the solar system (normalized to Si = 100) from He to Ni (solid circles, 70–280 MeV per nucleon; open circles, 1000–2000 MeV per nucleon; open diamonds, solar system abundance distribution). [*Reproduced with permission from J. A. Simpson (1983).* Ann. Rev. Nucl. Part. Sci. **33** *by Annual Reviews, Inc.*].

Cosmic Ray Nuclear Composition



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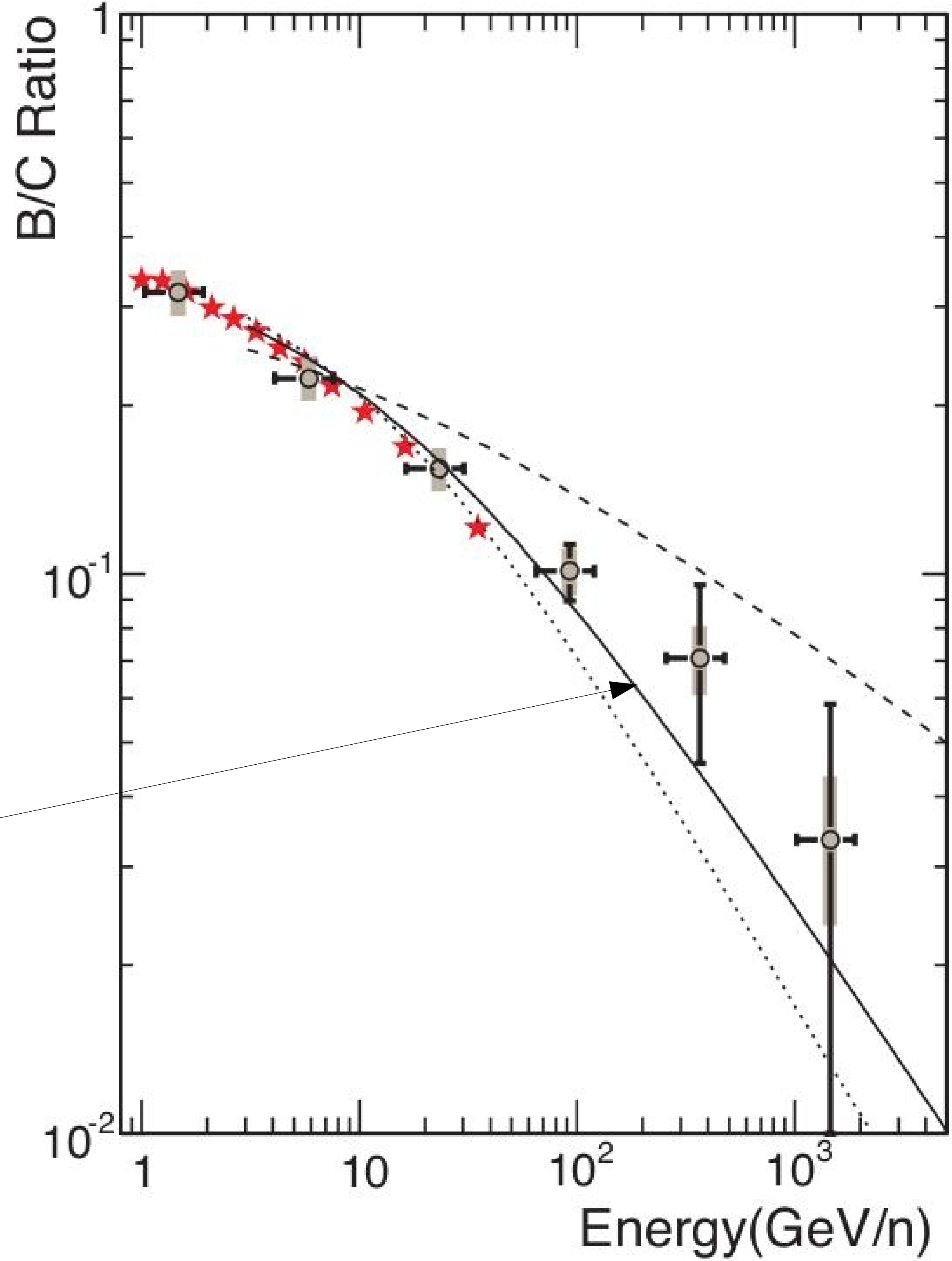
Overabundance of Li, Be, B

Sub-iron elements

Spallation effect:

Column density
Confinement time



$tau(E) \sim E^{-0.6}$

What are the SOURCES of COSMIC RAYS?

- ENERGETICS

  Where can one find the power to create the cosmic rays ?

- DYNAMICS

  How is the energy transformed into ultra-relativistic particles

Non-thermal
Non-equilibrium
"Violent"
phenomena

$$L_{\mathrm{SN\ \ kinetic}}^{\mathrm{Milky\ \ Way}} \simeq E_{\mathrm{SN}}^{\mathrm{Kinetic}} \ f_{\mathrm{SN}}$$

$$L_{\mathrm{SN\ \ kinetic}}^{\mathrm{Milky\ \ Way}} \simeq \left[1.6 \times 10^{51} \ \mathrm{erg}\right] \ \left[\frac{3}{\mathrm{century}}\right]$$

$$M = 5 \ M_{\odot}$$

$$v \simeq 5000 \ \mathrm{Km/s}$$

$$L_{\mathrm{SN\ \ kinetic}}^{\mathrm{Milky\ \ Way}} \simeq 1.5 \times 10^{42} \ \frac{\mathrm{erg}}{\mathrm{s}}$$

Power Provided by SN is sufficient
with a conversion efficiency of 15-20 %
in relativistic particles

POWERING THE GALACTIC COSMIC RAYS

$$L_{\rm cr}(\text{Milky Way}) \simeq \frac{\rho_{\rm cr}\, V_{\rm conf}}{T_{\rm conf}}$$

$$\simeq 2 \times 10^{41} \left(\frac{\rm erg}{\rm s}\right)$$

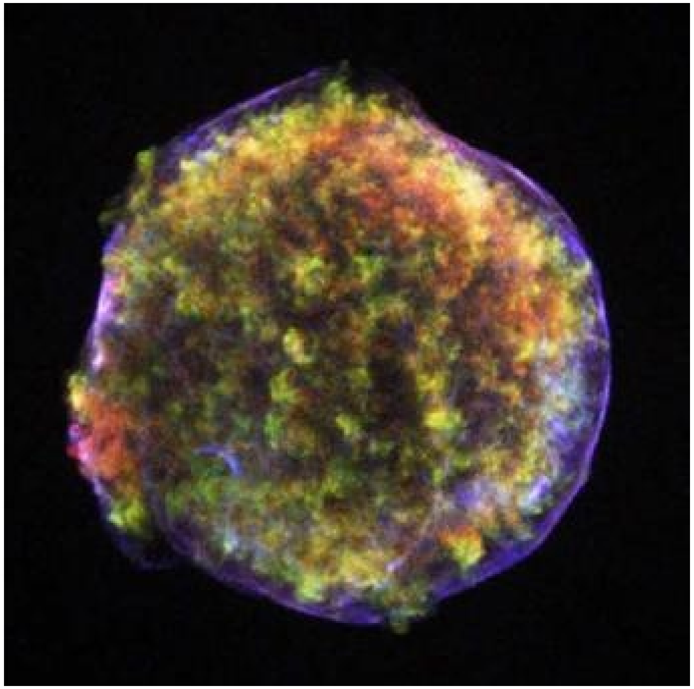
$$\simeq 5 \times 10^{7}\; L_{\odot}$$

SuperNovae types

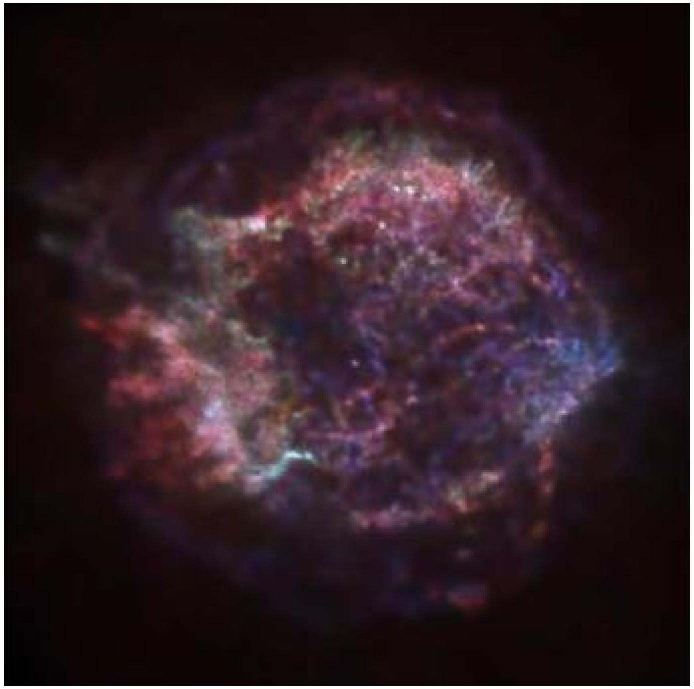
Type	fraction	Hydrogen	Star	Wind	Compact	example
Ia	15%	No	WD binary	–	–	Tycho
Ib	10%	No	16–20 $M_{\odot}$	> 1000 km/s	NS	Cas A
Ic	<5%	No	≫20 $M_{\odot}$	Yes	BH	many GRBs
II	70%	Yes	>8 $M_{\odot}$	10 km/s	NS	SN 1993J

Chandra X-Ray images

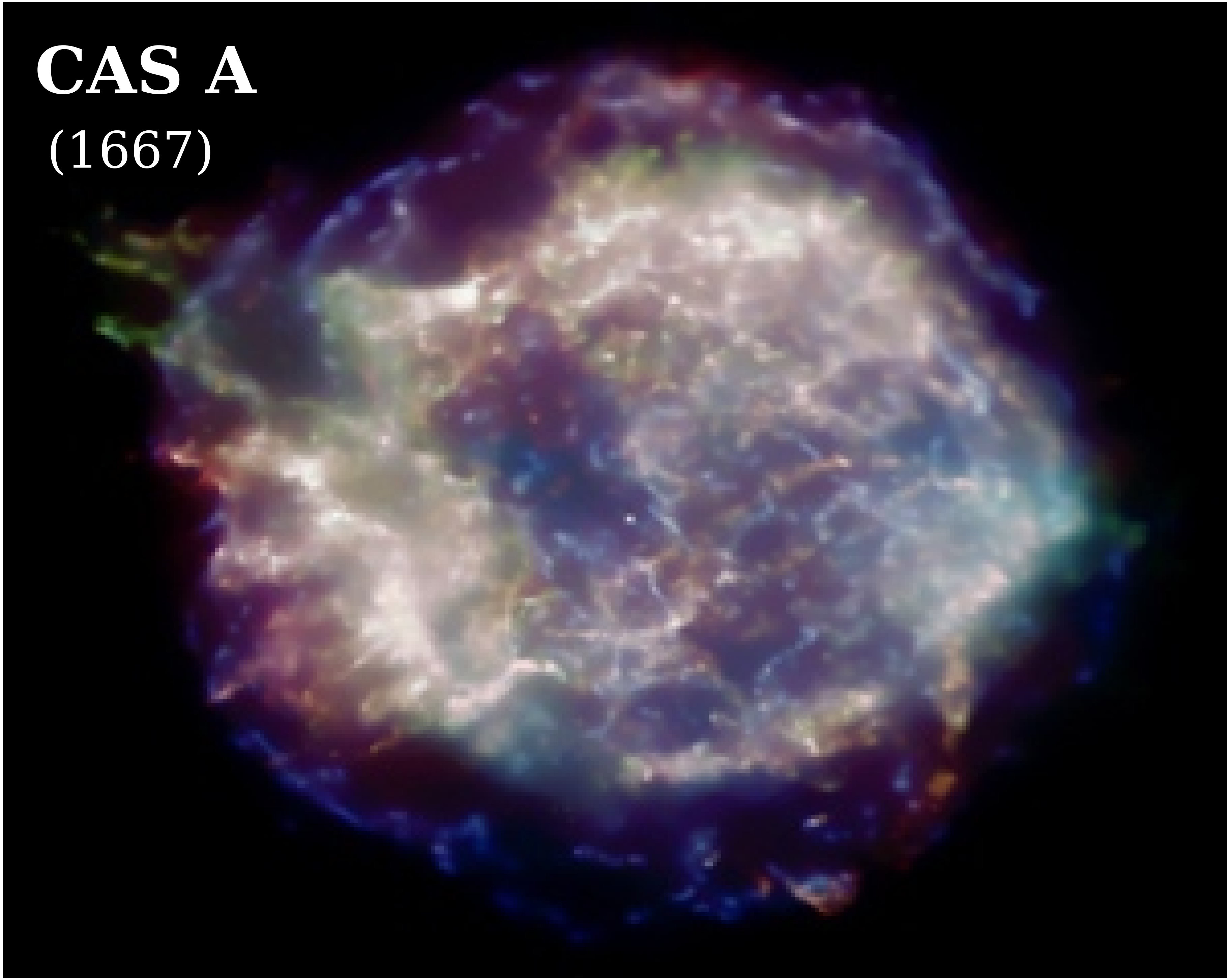
SN1006



Tycho

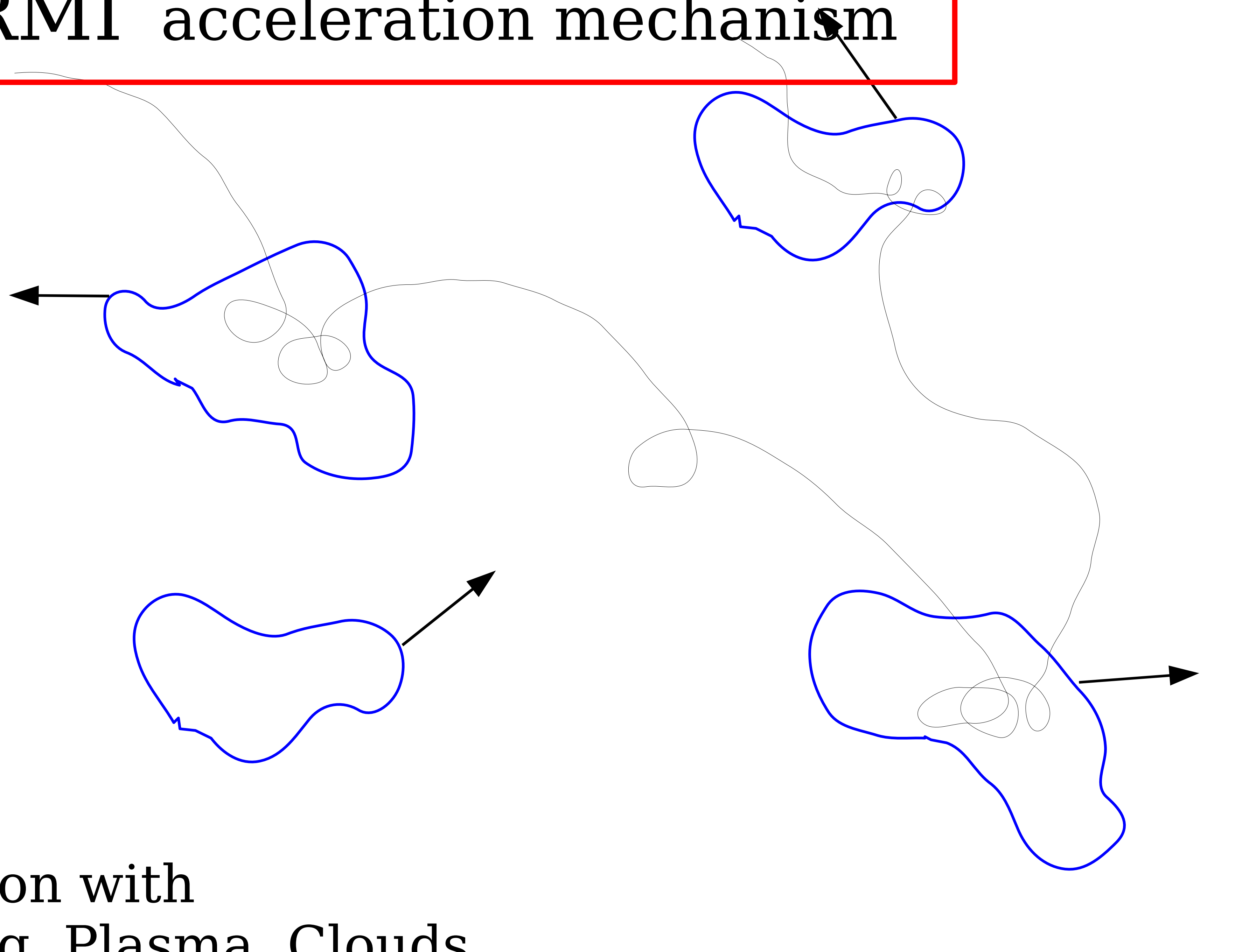


Cas A

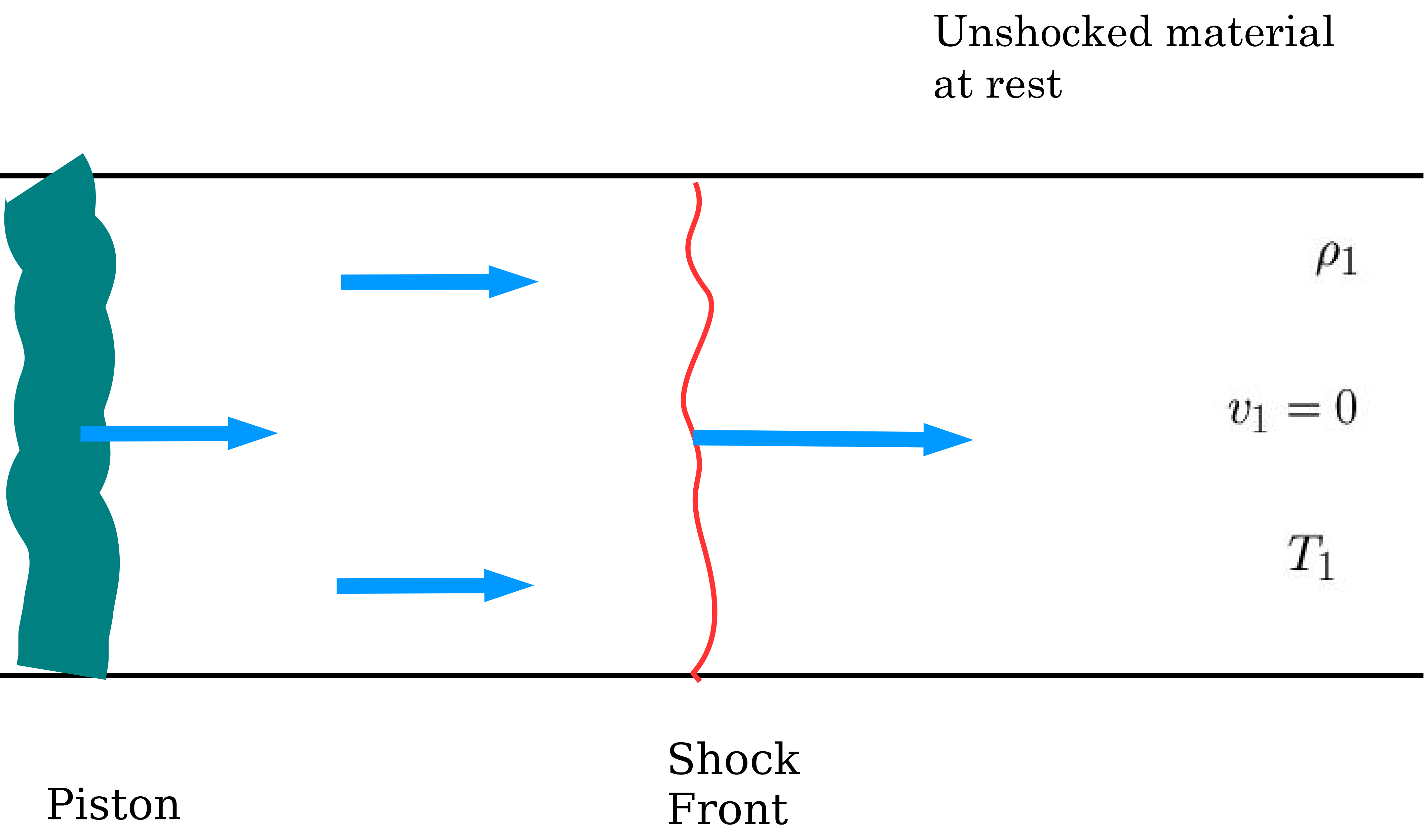

CAS A
(1667)

Trinity Test (1945)

FERMI acceleration mechanism



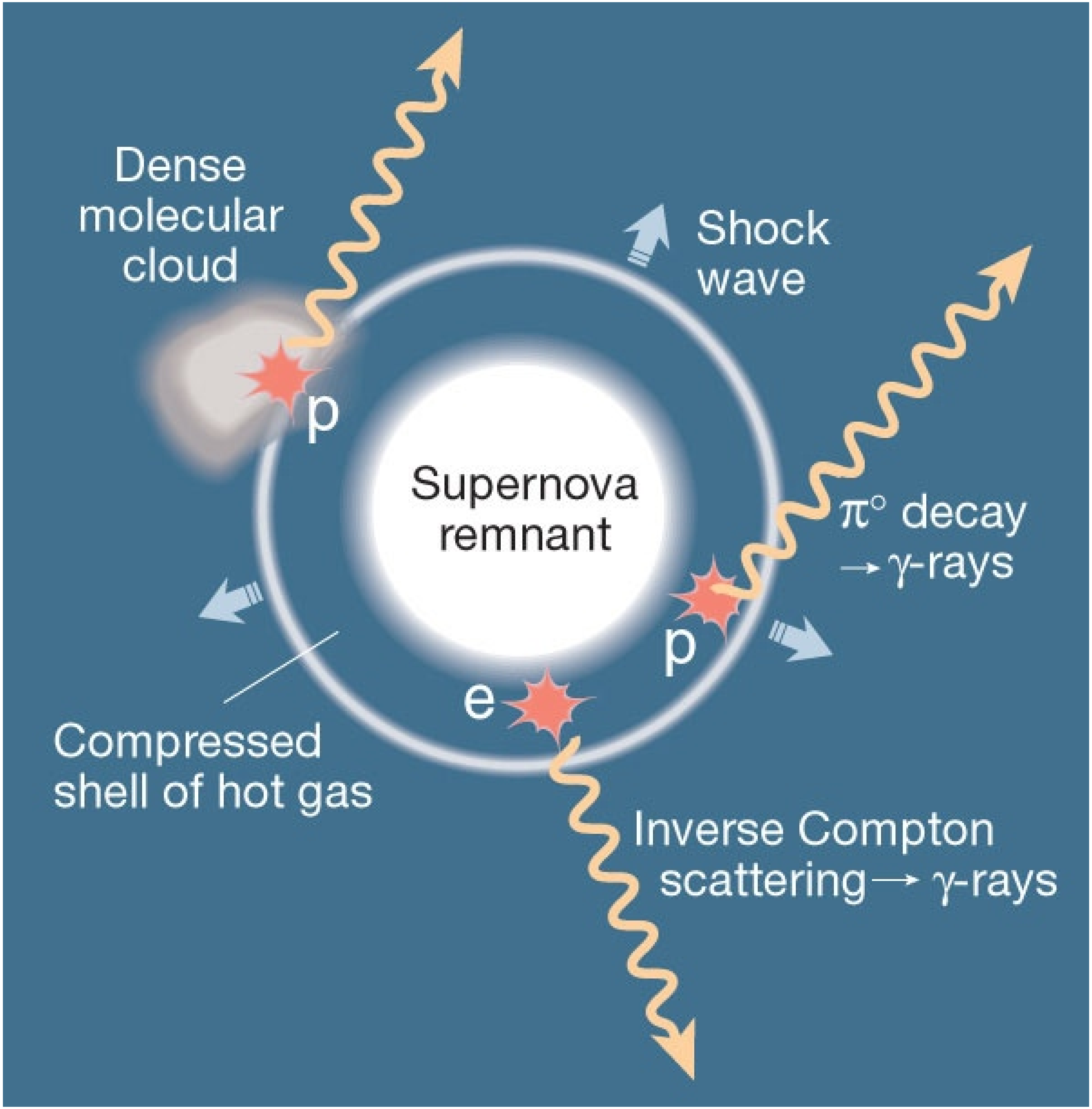
Collision with
Moving Plasma Clouds
in the Galaxy

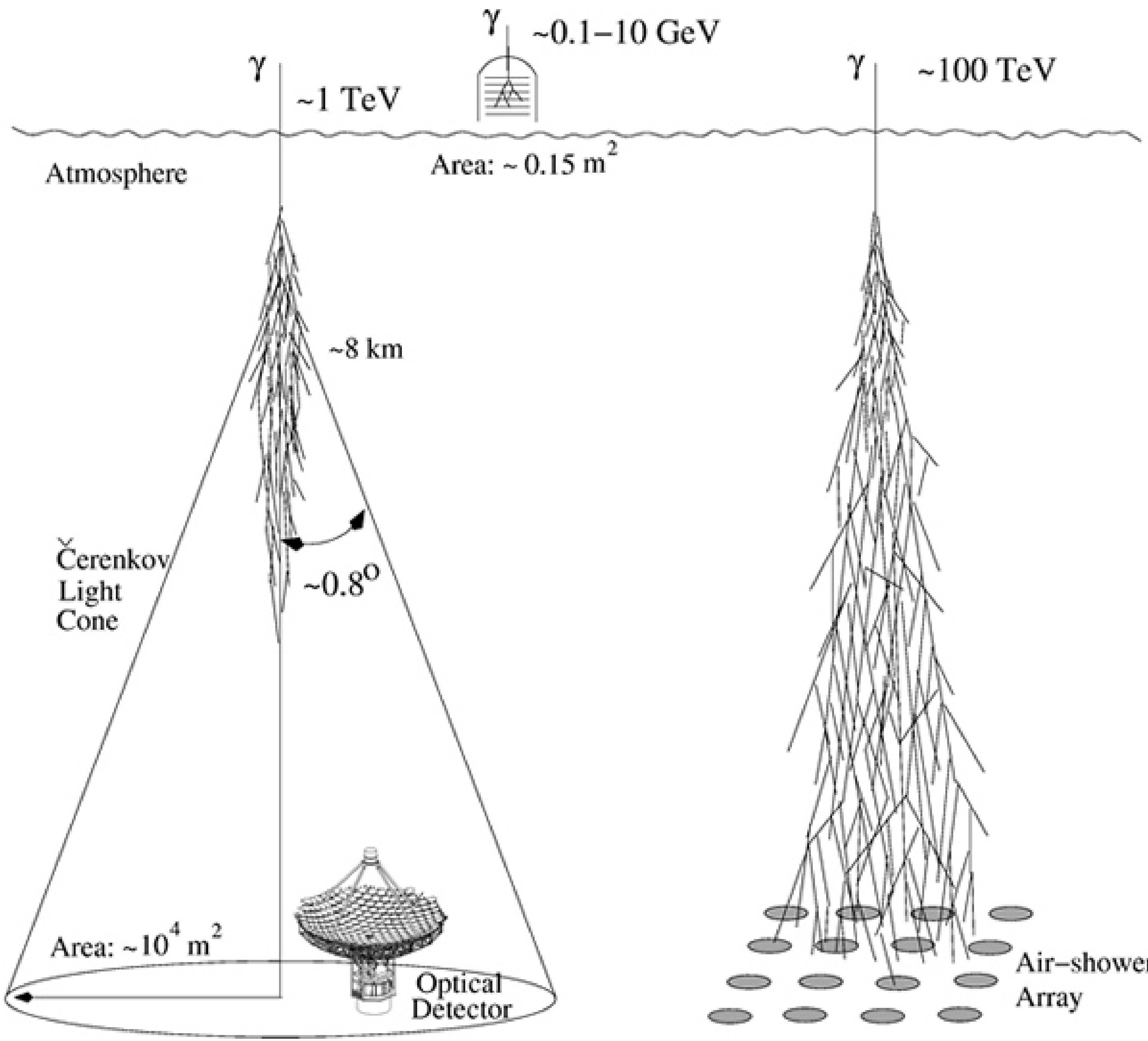

Unshocked material
at rest
ρ_1
$v_1 = 0$
T_1
Shock
Front
Piston

$$\gamma = \frac{P_{\text{esc}}}{\xi} \simeq 2 + \epsilon$$

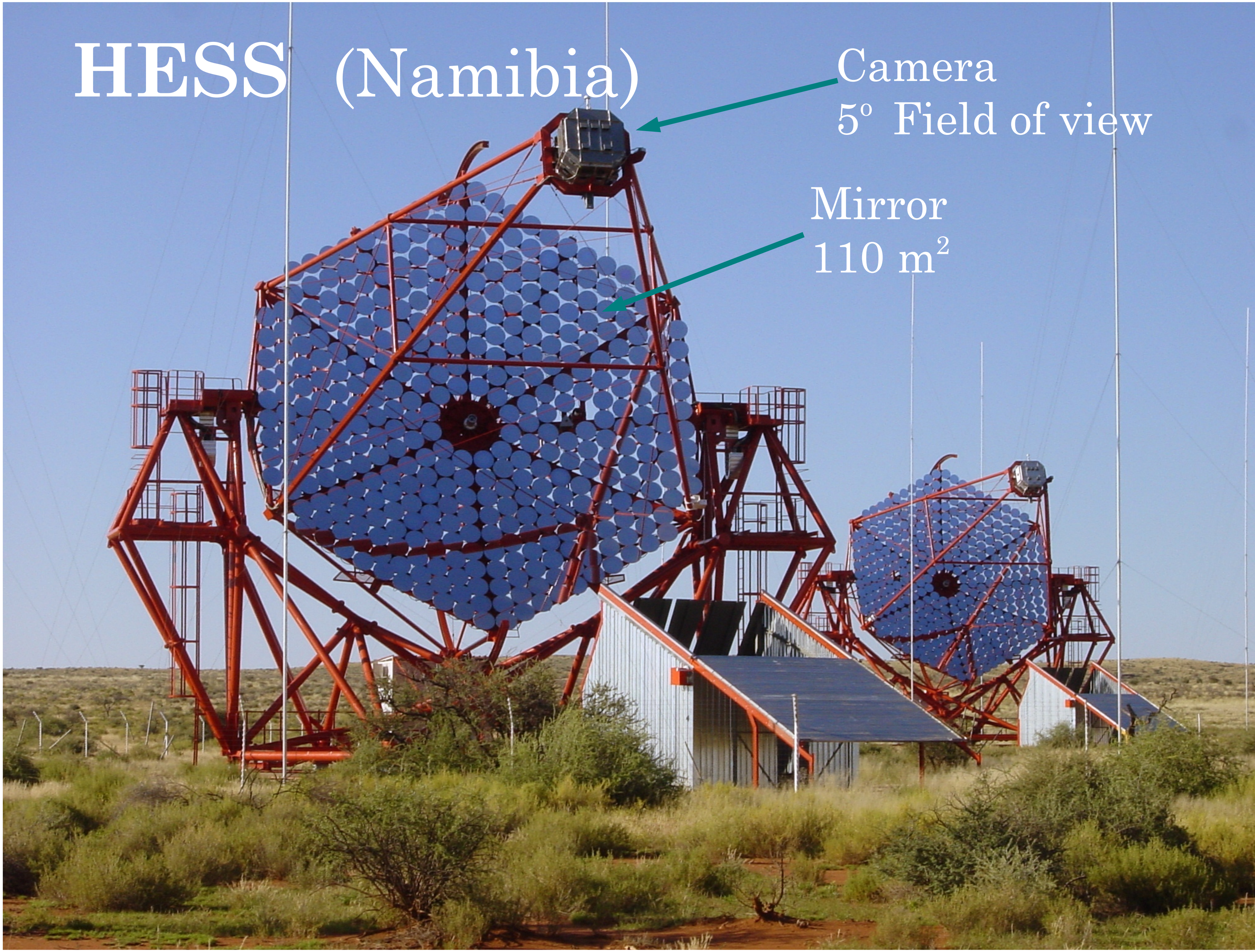
The Energy Spectrum of Particle accelerated near Shock Waves has a UNIVERSAL FORM

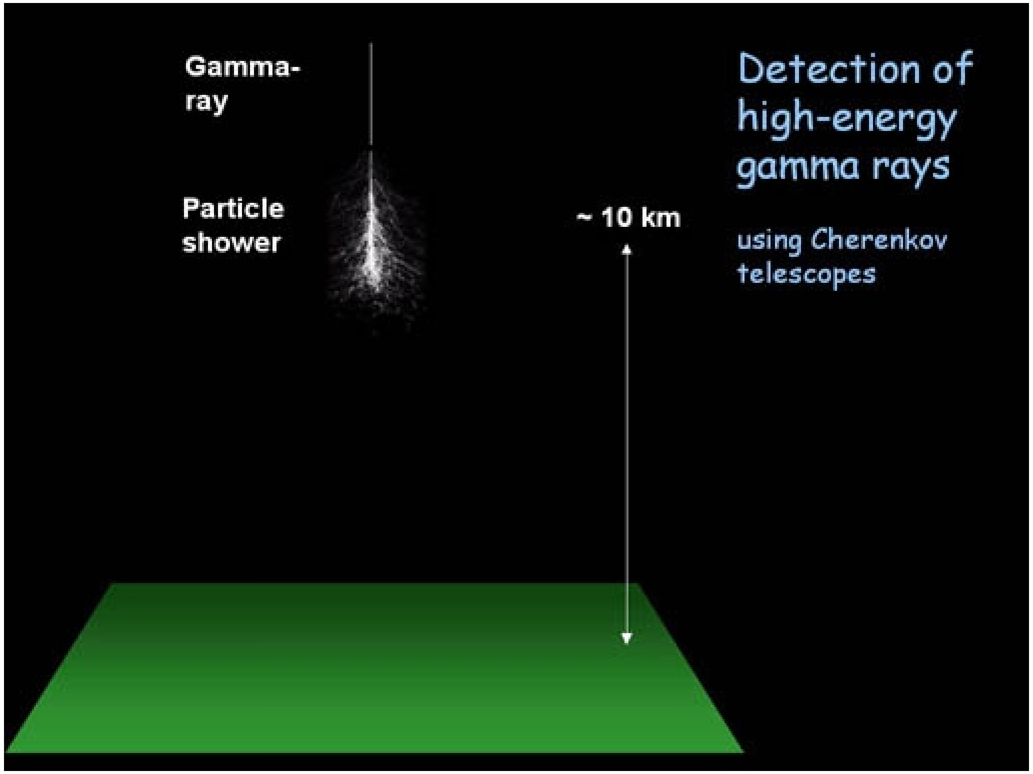
In agreement with observations.

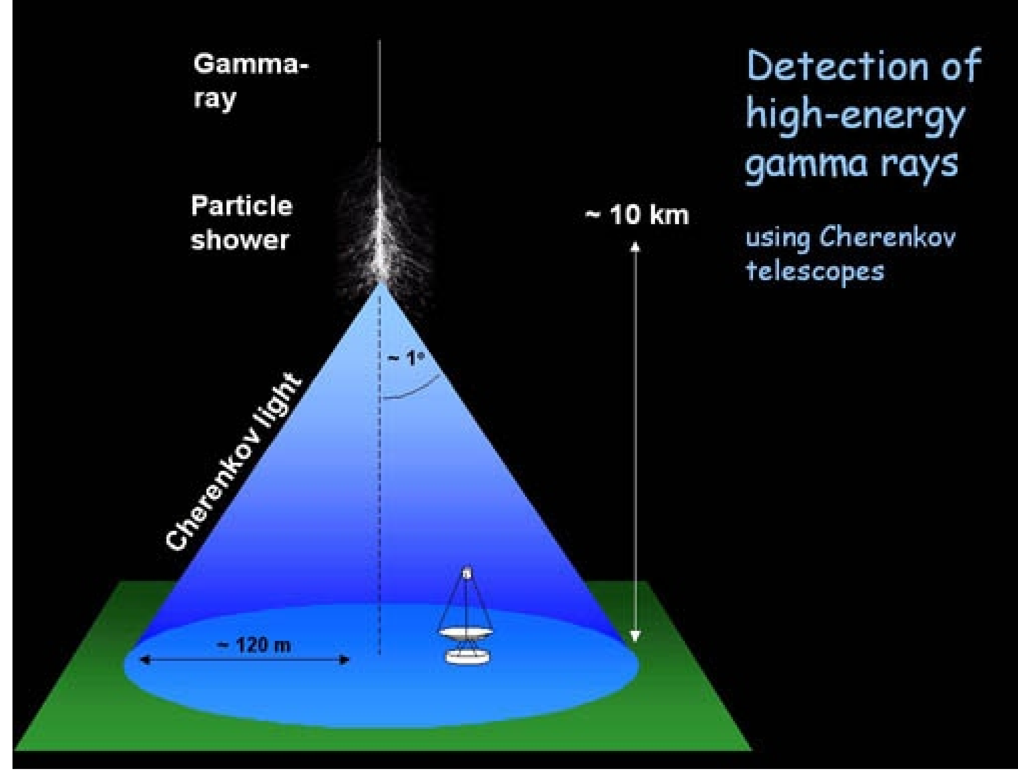

Dense molecular cloud
Shock wave
p
Supernova remnant
π° decay → γ-rays
p
e
Compressed shell of hot gas
Inverse Compton scattering → γ-rays

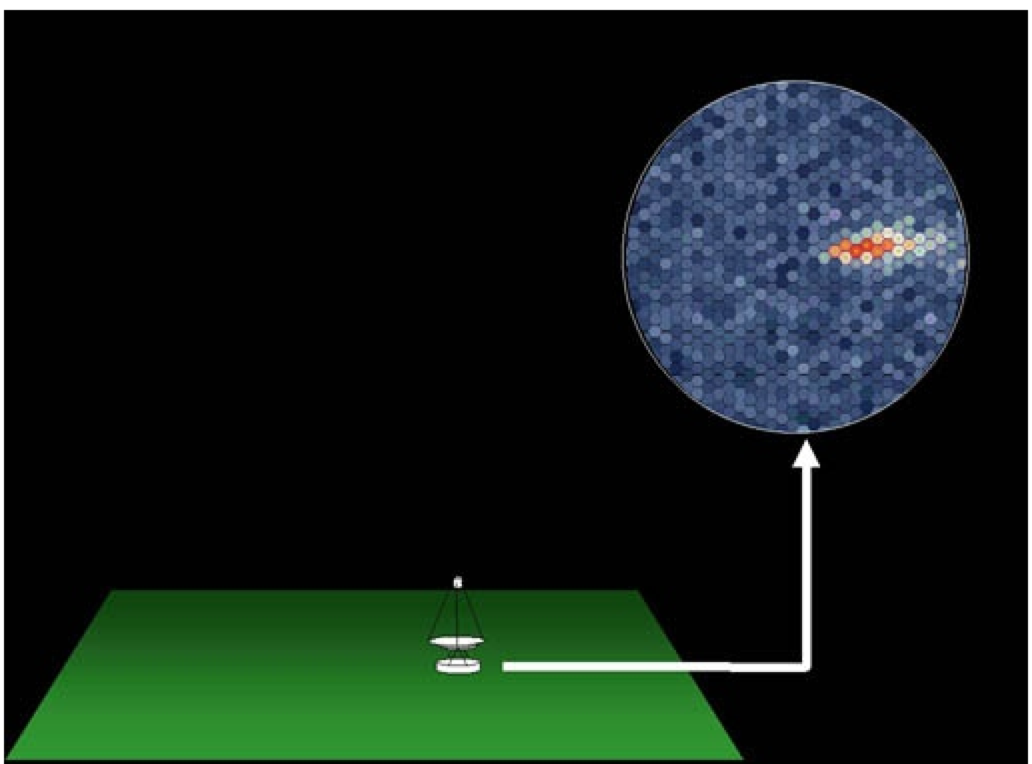


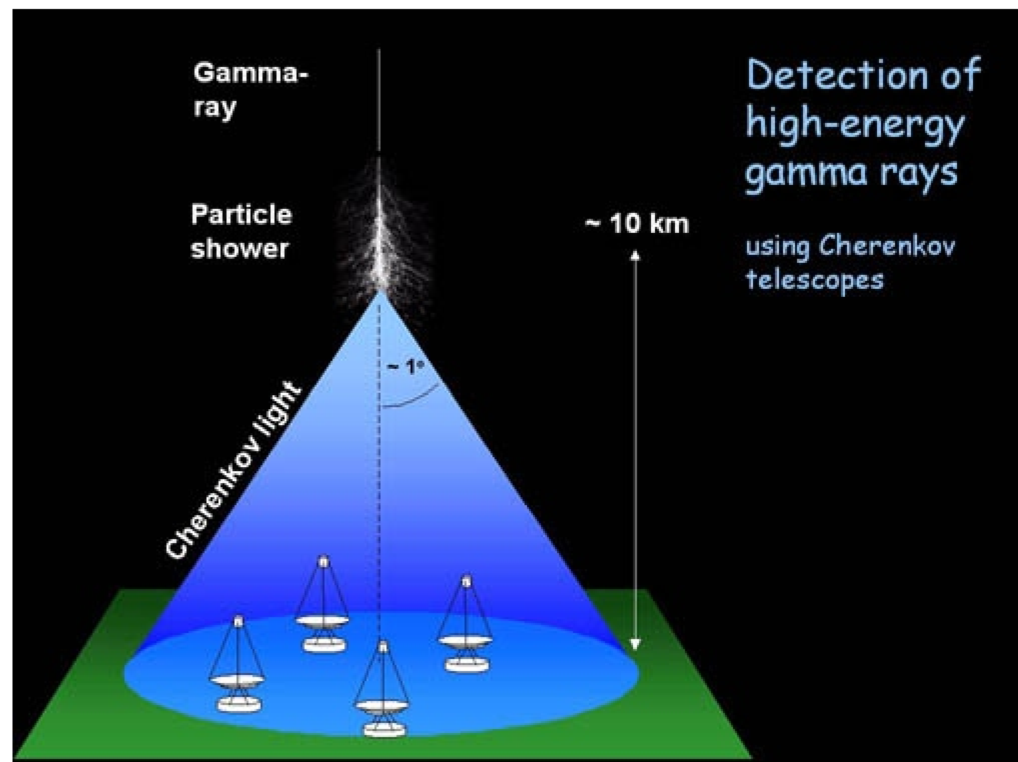
γ
~0.1–10 GeV
γ
~1 TeV
γ
~100 TeV
Atmosphere
Area: ~ 0.15 m^2
~8 km
Čerenkov
Light
Cone
~0.8°
Area: ~10^4 m^2
Optical
Detector
Air–shower
Array


HESS (Namibia)
Camera
5° Field of view
Mirror
110 m²


Gamma-ray
Particle shower
~ 10 km
Detection of high-energy gamma rays
using Cherenkov telescopes


Gamma-ray
Particle shower
~ 10 km
Detection of high-energy gamma rays
using Cherenkov telescopes
Cherenkov light
~ 1°
~ 120 m

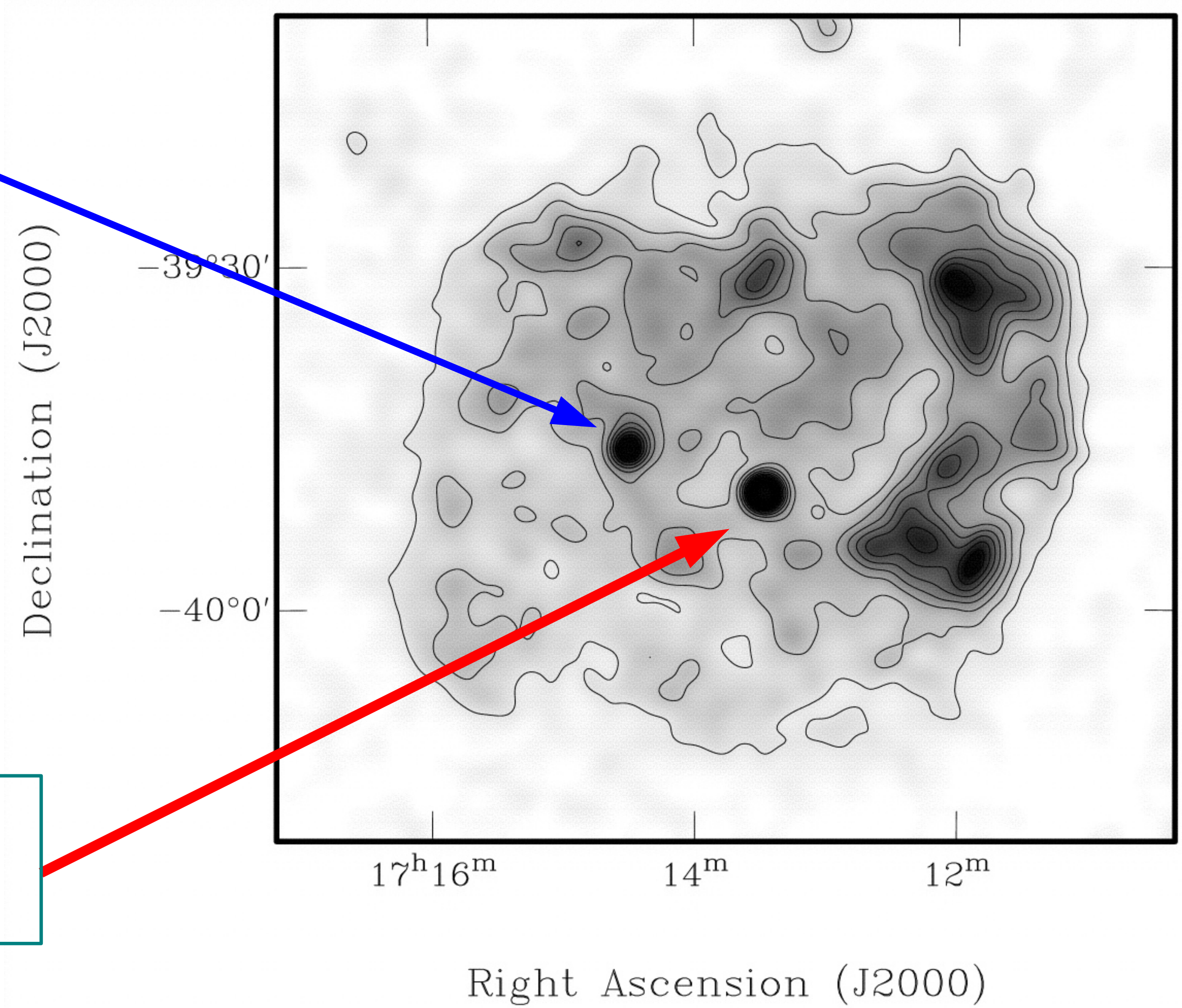



Gamma-ray
Particle shower
~ 10 km
Detection of high-energy gamma rays
using Cherenkov telescopes
Cherenkov light
~ 1°

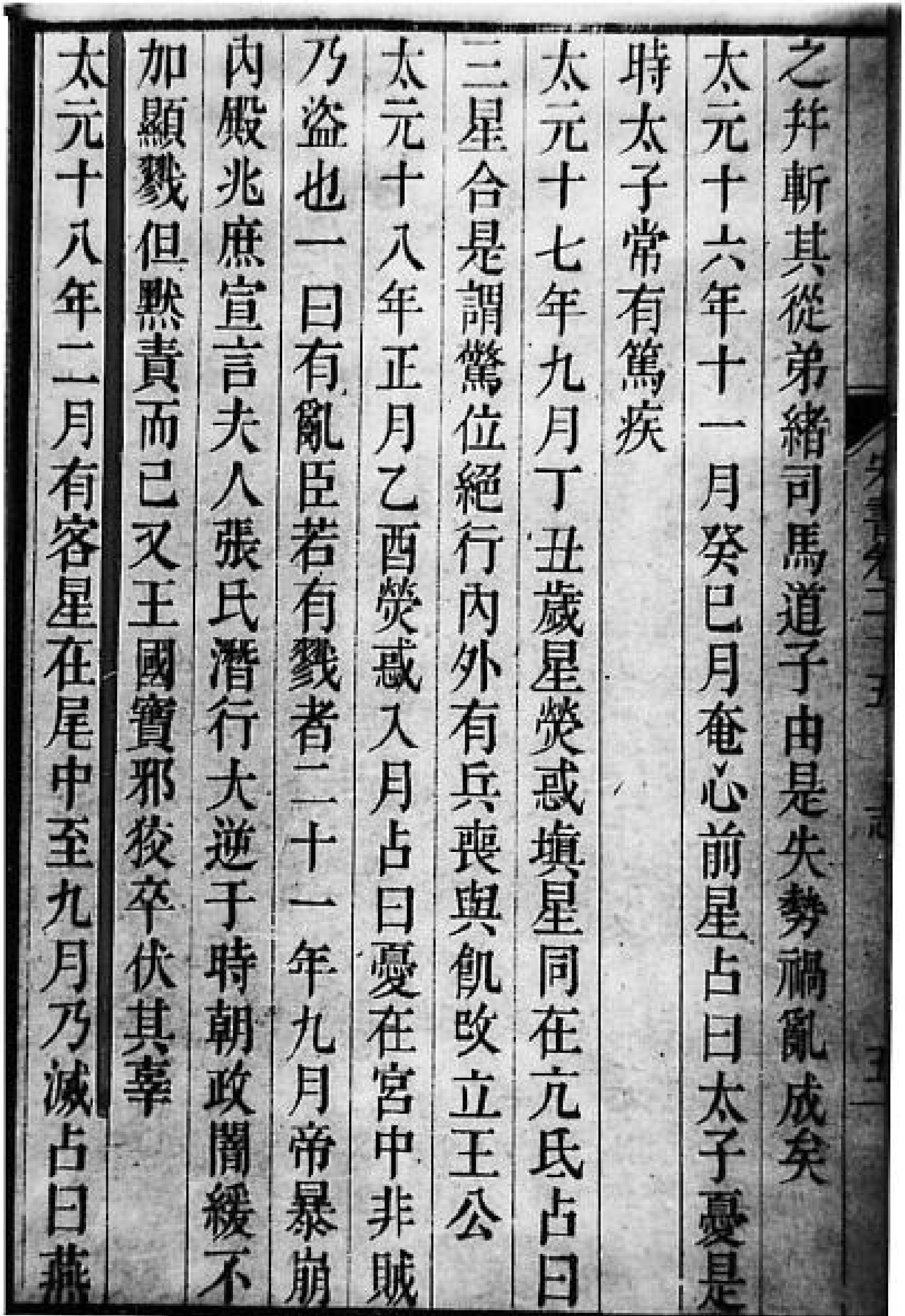
SuperNova RX J1713.7-3946

Discovered in 1996 by the Roentgen Satellite (Rosat)

Foreground star



Point Source (Neutron Star)


之弁斬其從弟緒司馬道子由是失勢禍亂成矣
太元十六年十一月癸巳月奄心前星占曰太子憂是
時太子常有篤疾
太元十七年九月丁丑歲星熒惑填星同在亢氐占曰
三星合是謂驚位絕行內外有兵喪與饑改立王公
太元十八年正月乙酉熒惑入月占曰憂在宮中非賊
乃盜也一曰有亂臣若有戮者二十一年九月帝暴崩
內殿兆庶宣言夫人張氏潛行大逆于時朝政闇緩不
加顯戮但黙責而已又王國寶邪狡卒伏其辜
太元十八年二月有客星在尾中至九月乃滅占曰燕

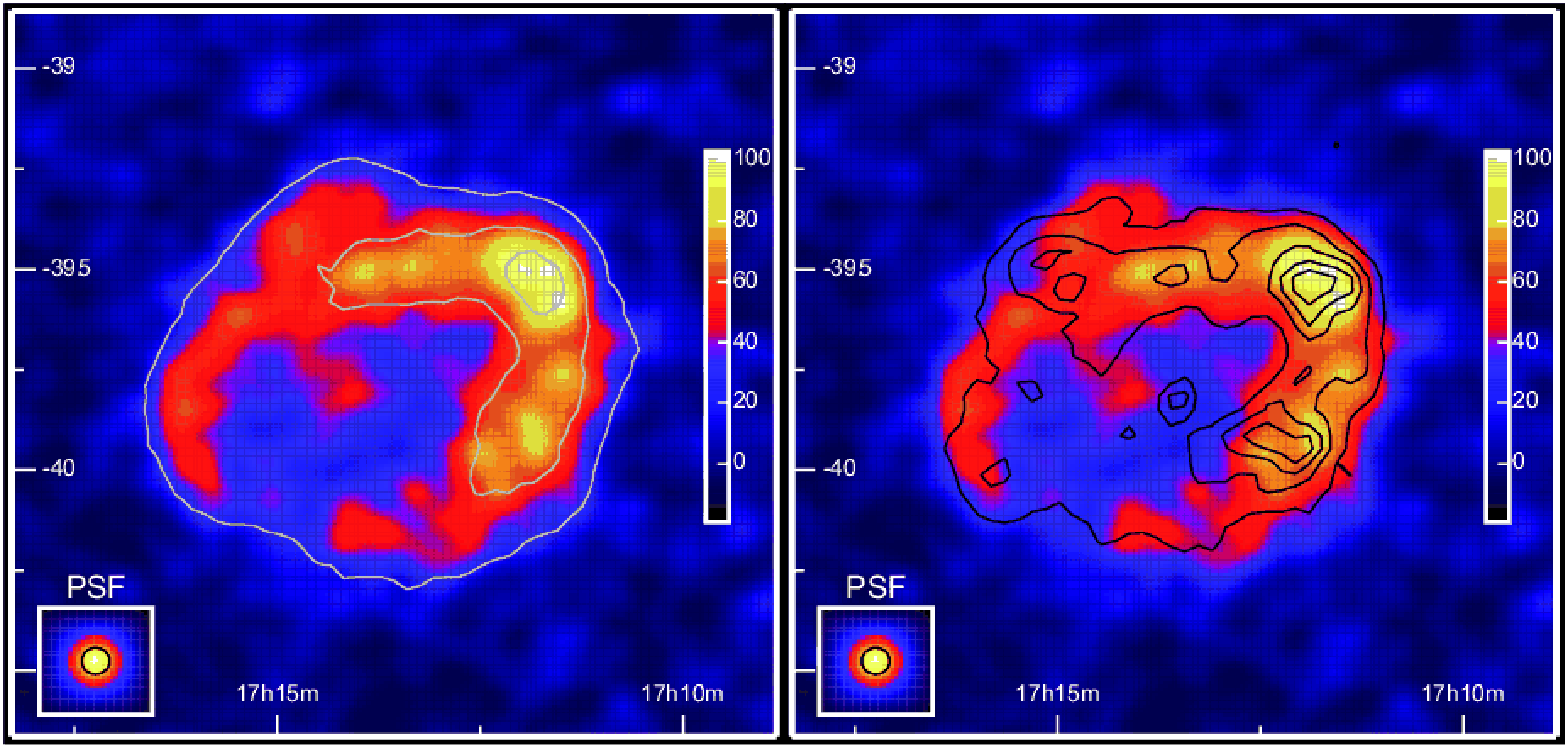
1st observation of RX J1713.7-3946

AD 393

A guest star appeared within the asterism Wei during 2nd lunar month of the 18th year of the Tai-Yuan reign period (february 27-march 28 AD 393),
and disappeared during the 9th lunar month (october 22 - november 19)

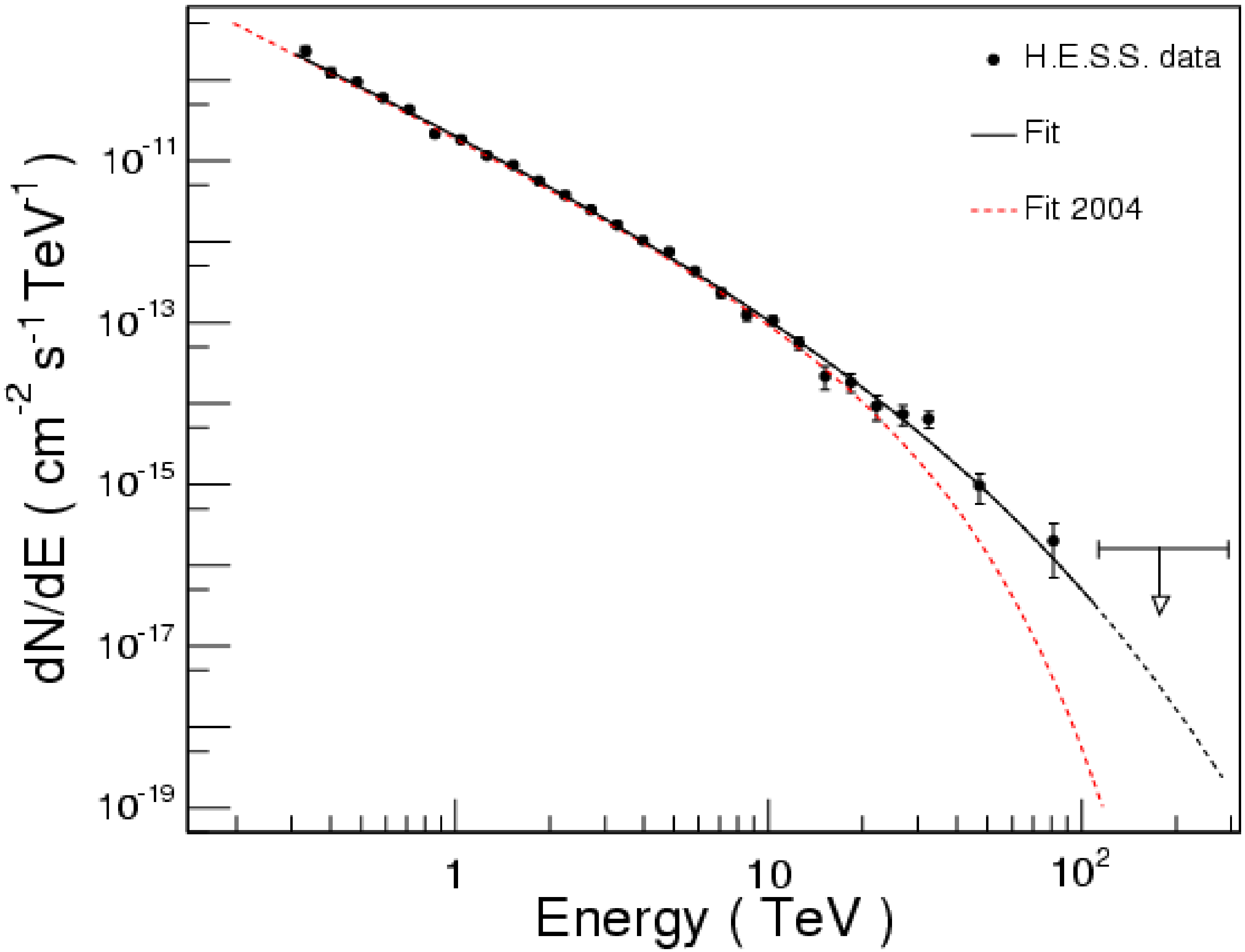
HESS Telescope

Observations with TeV photons



Comparison with ROSAT observation

ENERGY Spectrum



If gamma-rays are from π^0 decay, spectrum requires acceleration of protons to 200 TeV.

$$\phi_\gamma(E) = K\,E^{-\Gamma}$$

$$\Gamma = 2.19 \pm 0.09 \pm 0.15$$

$$\phi_\gamma(>1\ \mathrm{TeV}) = (1.47 \pm 0.17 \pm 0.37) \times 10^{-7}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$$

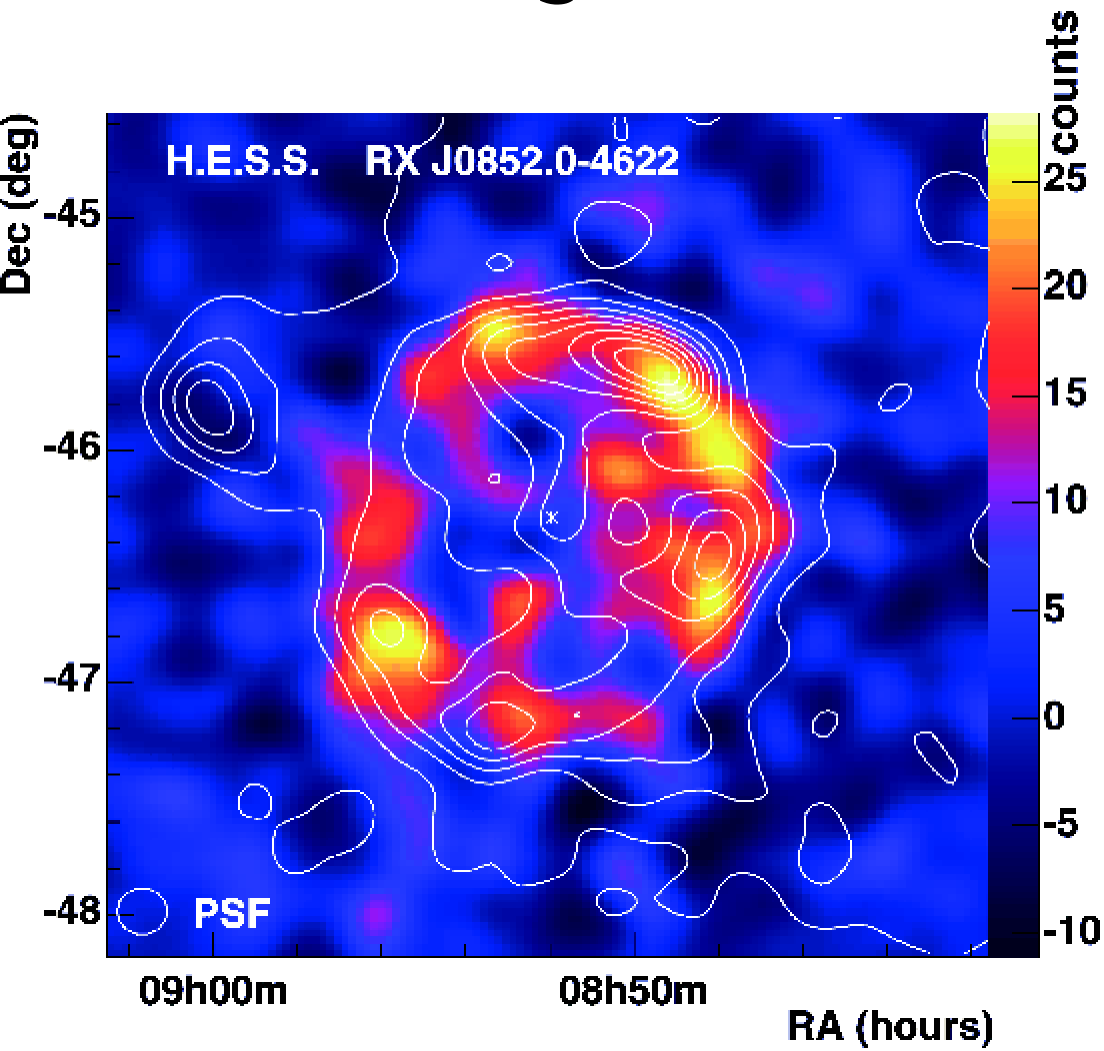
$$\frac{dN_\gamma}{dt} \propto N_p \times n_{\rm target} \times \sigma_{pp}\, c$$

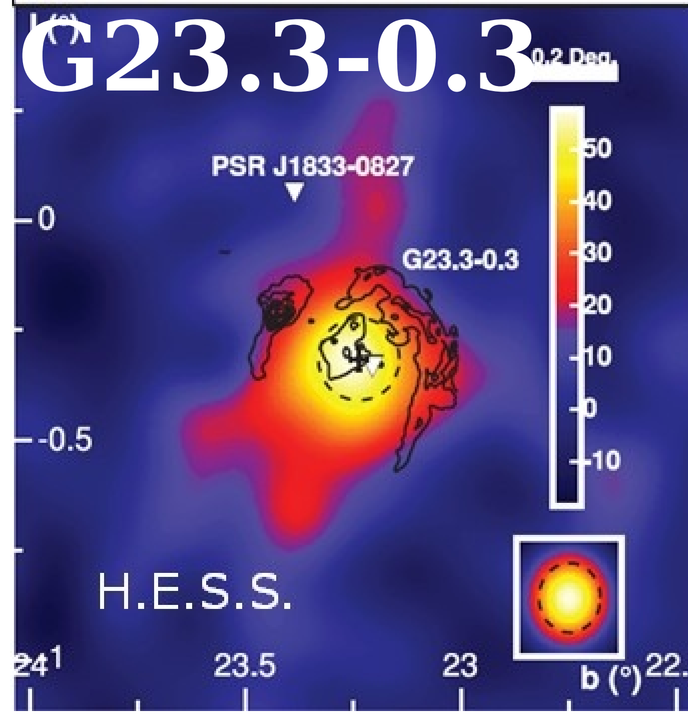
Hess estimate

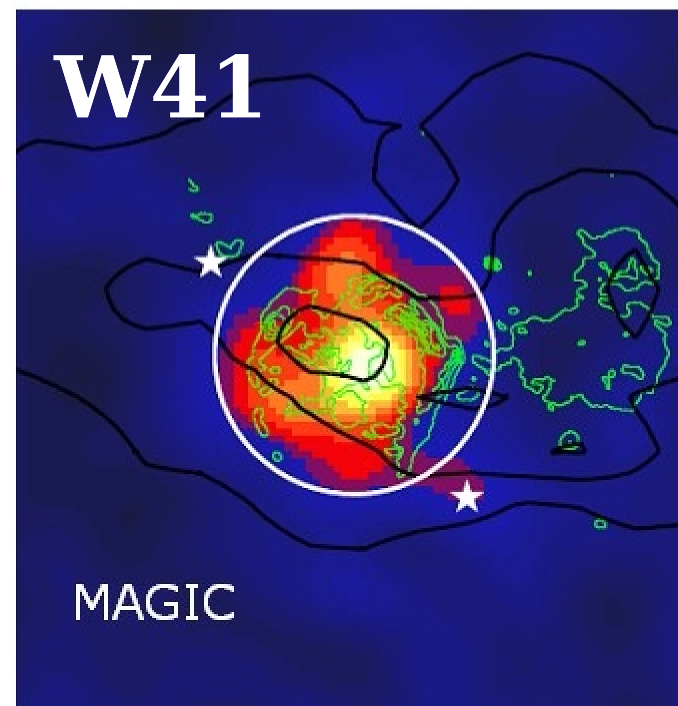
$$E^{\rm tot}_{{\rm relativistic}\ p} \simeq 0.2 \times 10^{51}\ {\rm erg}$$

Essentially compatible with the
Ortodoxy (10% conversion of SN kinetic energy
into relativisic particles)

VELA JUNIOR


H.E.S.S. RX J0852.0-4622
Dec (deg)
counts
PSF
09h00m
08h50m
RA (hours)


G23.3-0.3
0.2 Deg.
PSR J1833-0827
G23.3-0.3
H.E.S.S.
b (°)


W41
MAGIC

Have we proved that SNR are the source of the bulk of the Galactic Cosmic Rays ?

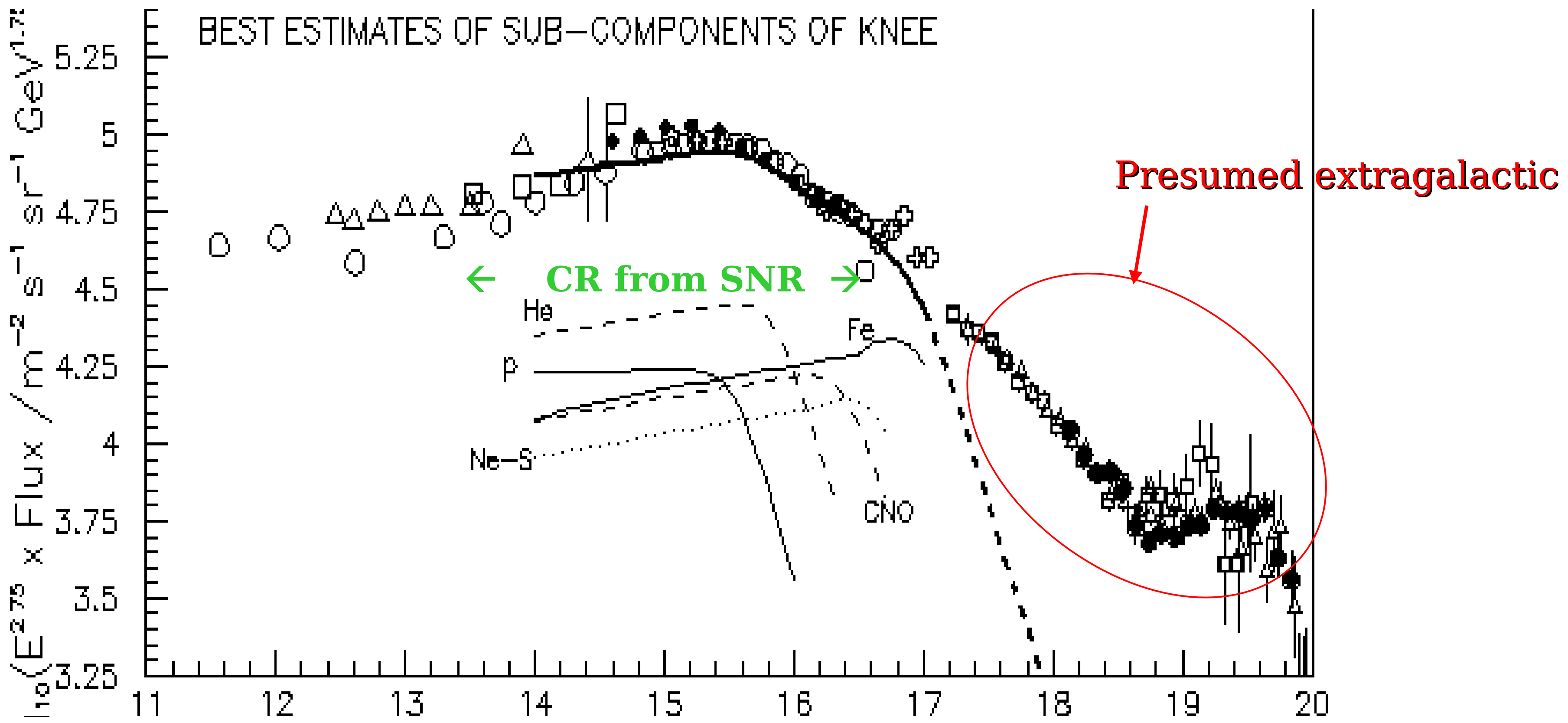
Important “Hints”
But conclusion Still Controversial.

Need additional Data.
Cherenkov telescopes, FERMI (Glast)

NEED ADDITIONAL SOURCES
at high Energy

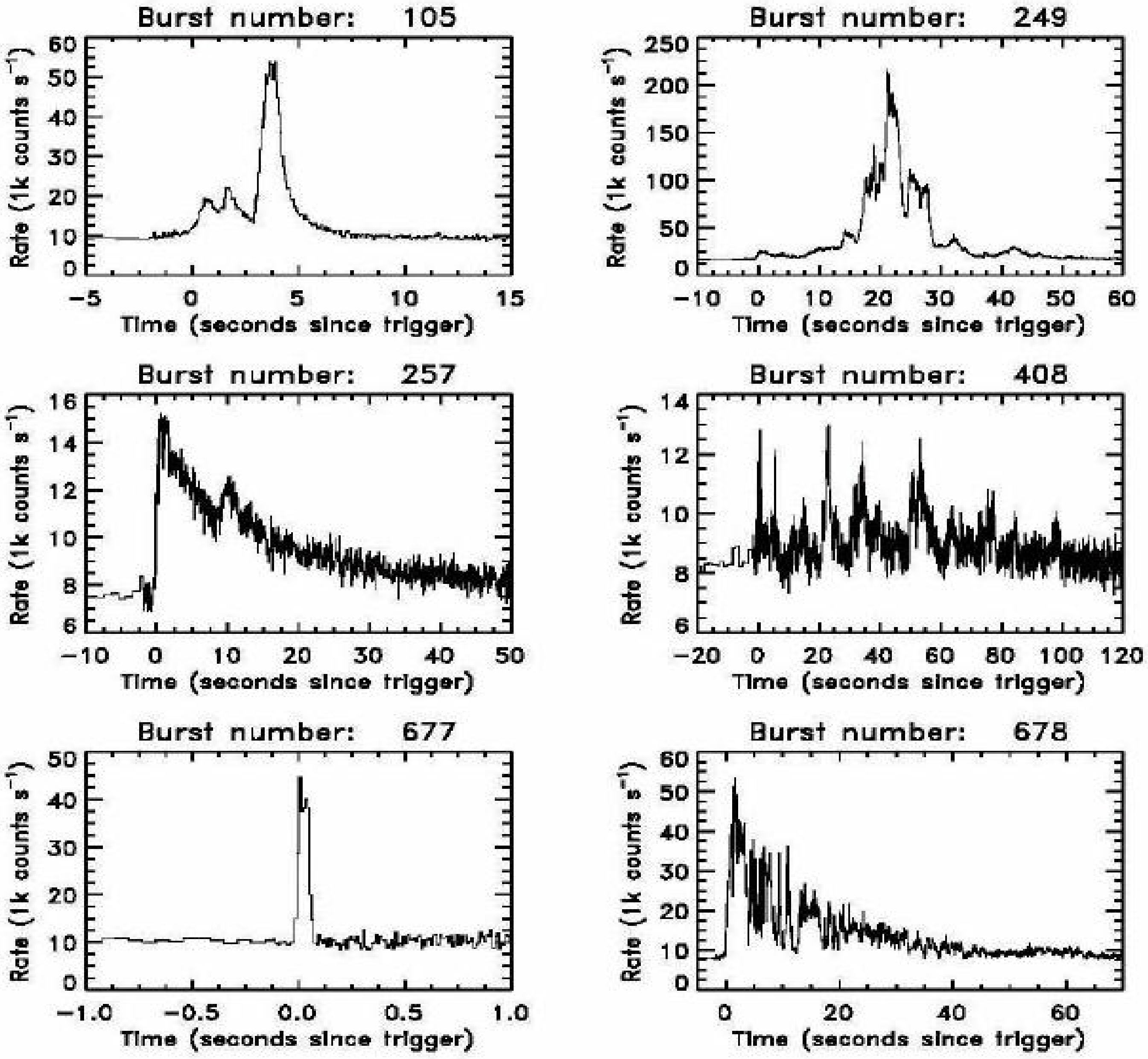
How the main components of cosmic rays fit together?

Galactic components:

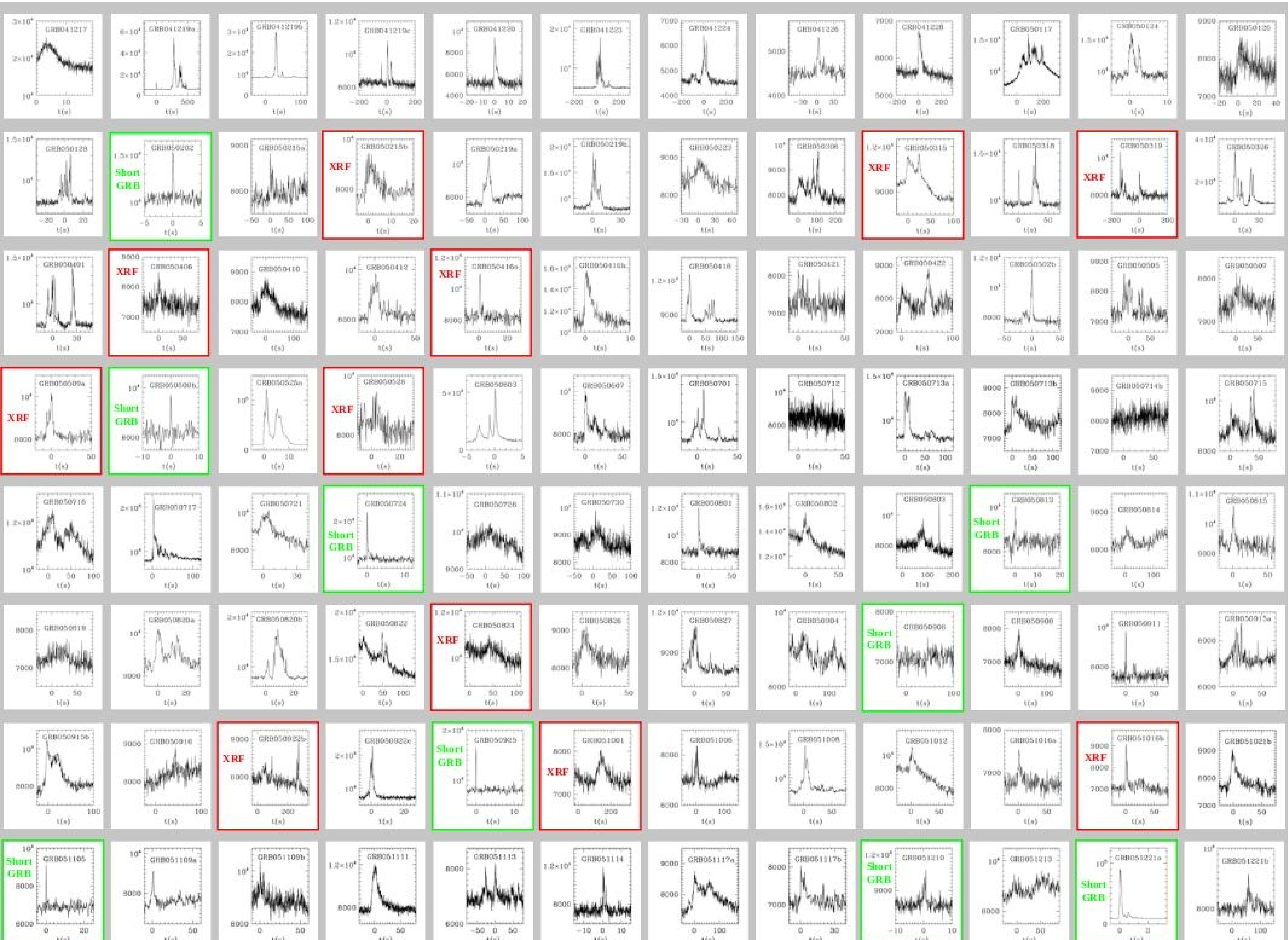


from Michael Hillas

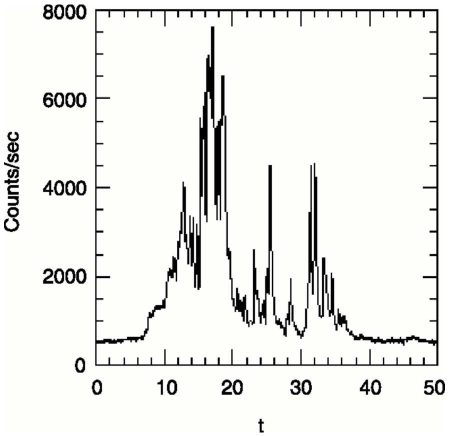
GAMMA RAY BURSTS (GRB's)

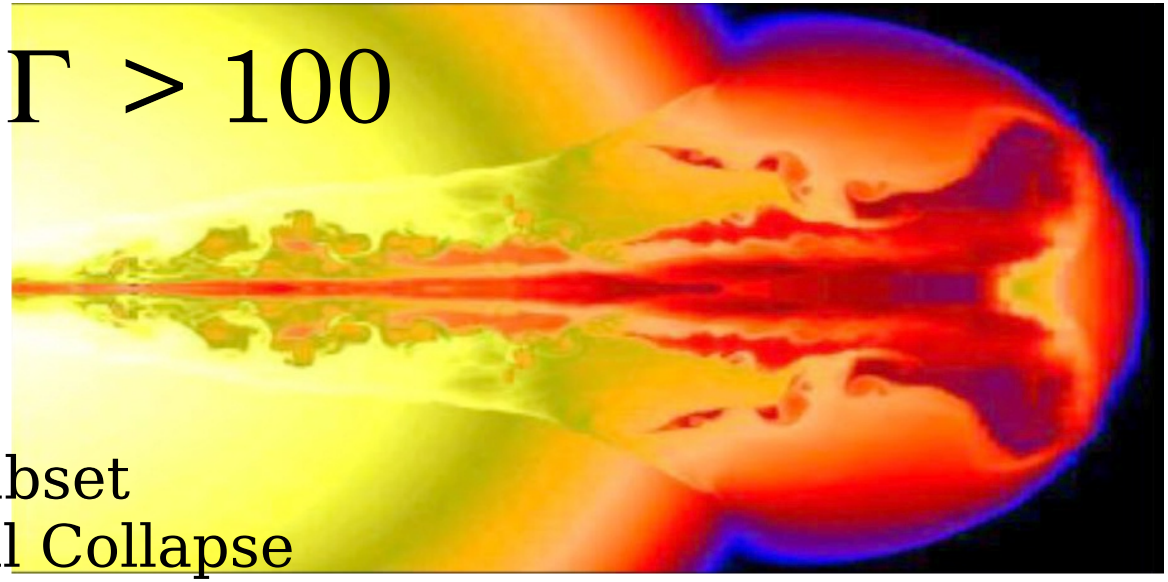


Proposed source
Of the CR



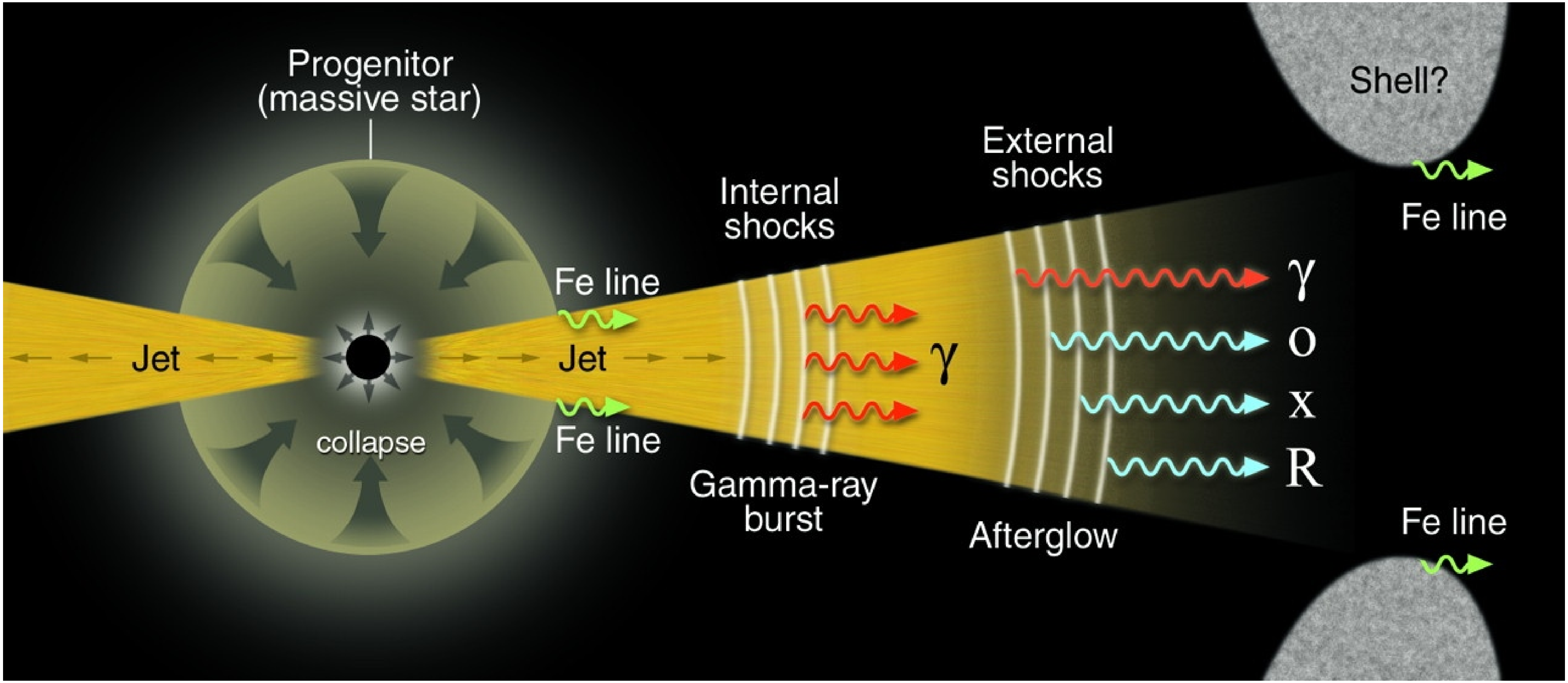
[From N. Gehrels]





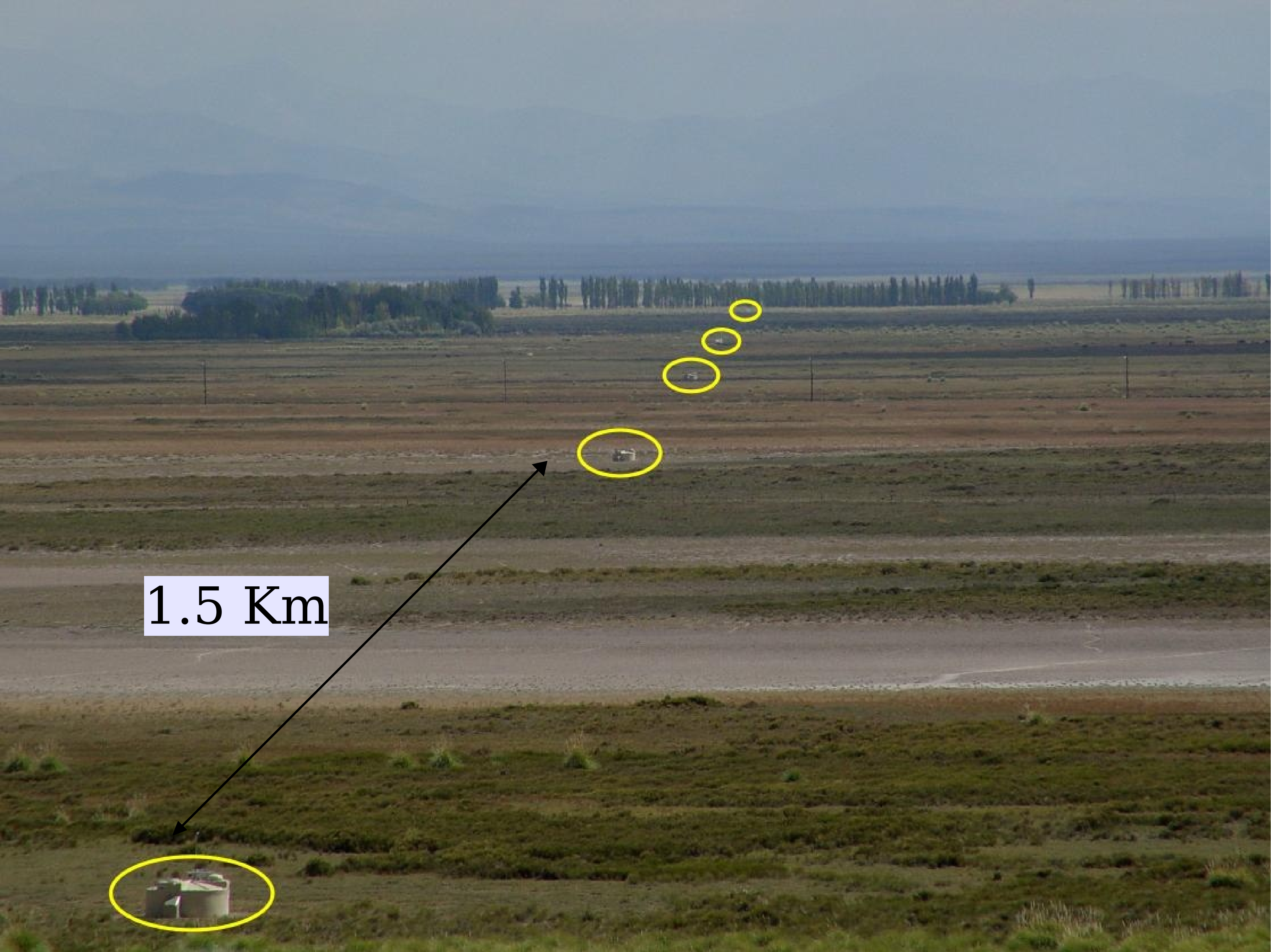
$\Gamma > 100$

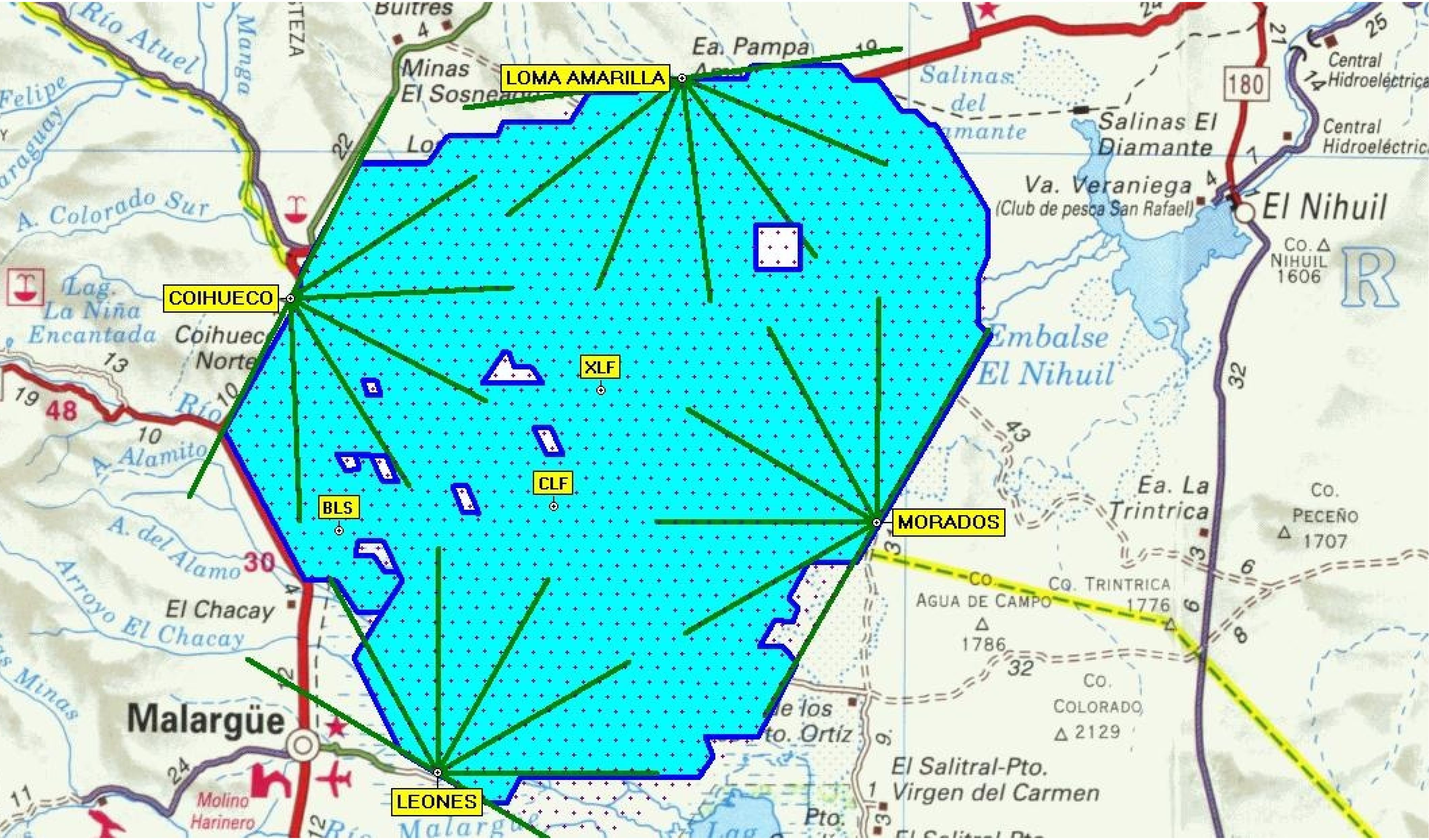
GRB : associated with a subset
of SN Stellar Gravitational Collapse



The Highest Energy Cosmic Rays

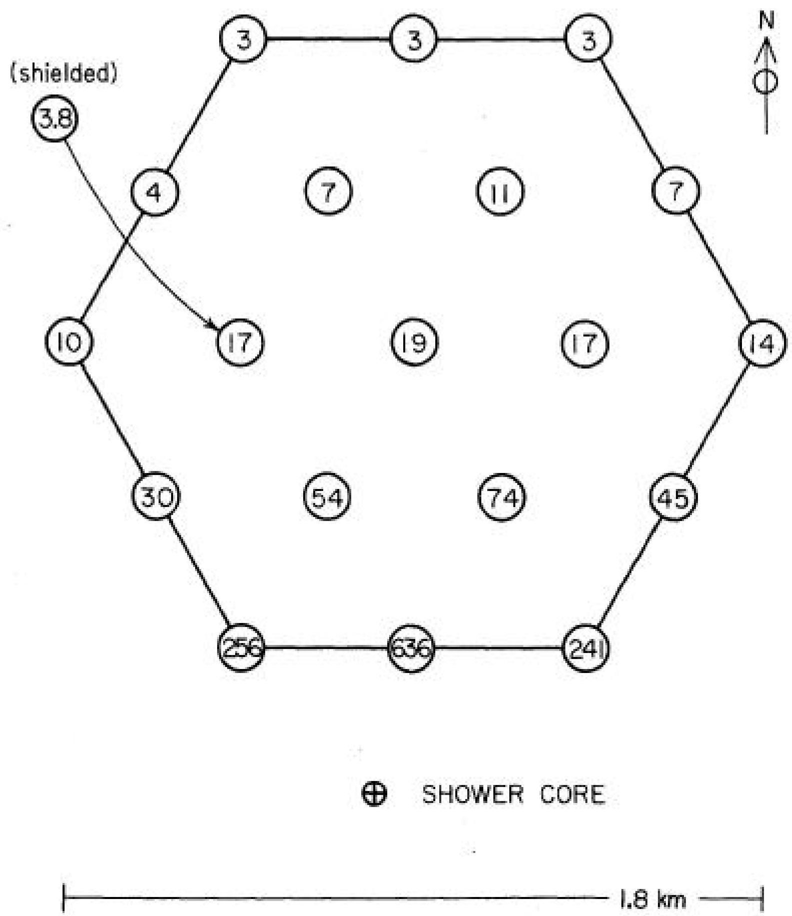
AUGER detector in ARGENTINA


1.5 Km


LOMA AMARILLA
COIHUECO
LEONES
MORADOS
XLF
CLF
BLS
Río Atuel
Manga
Bultres
Minas
El Sosneado
Ea. Pampa
Salinas del Diamante
Salinas El Diamante
180
Central Hidroeléctrica
Central Hidroeléctrica
Va. Veraniega
(Club de pesca San Rafael)
El Nihuil
Co. NIHUIL 1606
Embalse El Nihuil
A. Colorado Sur
Lag. La Niña Encantada
Coihueco Norte
48
A. Alamito
A. del Alamo
30
Arroyo El Chacay
El Chacay
Malargüe
Molino Harinero
Río Malargüe
Ea. La Trintrica
Co. PECEÑO 1707
Co. AGUA DE CAMPO 1786
Co. TRINTRICA 1776
Co. COLORADO 2129
El Salitral-Pto. Virgen del Carmen
32
43

EXTREMELY ENERGETIC COSMIC-RAY EVENT*

John Linsley, Livio Scarsi,† and Bruno Rossi
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received April 12, 1961)

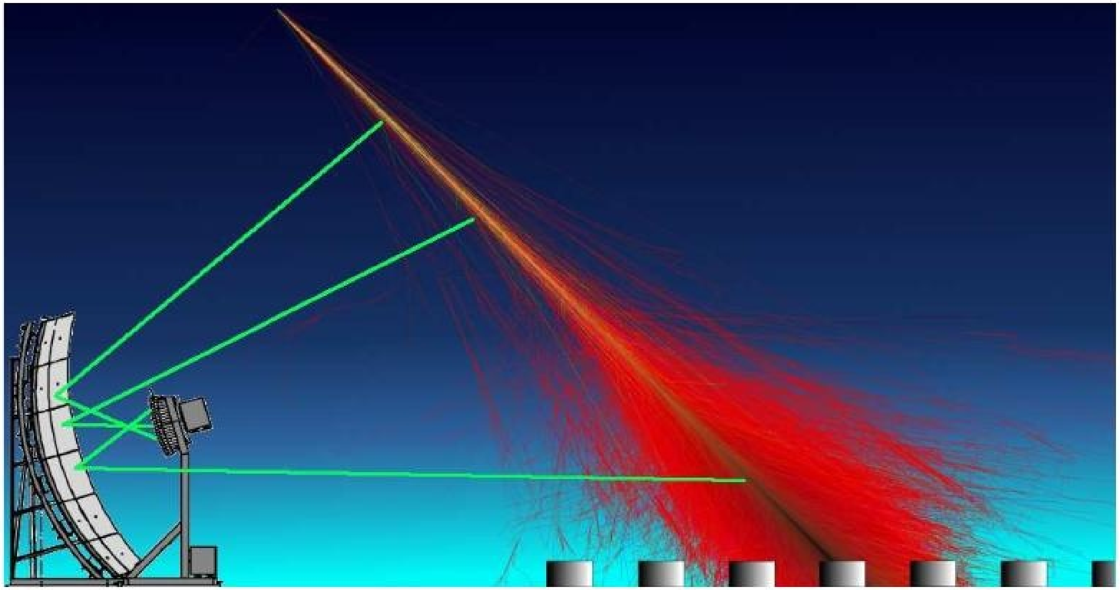


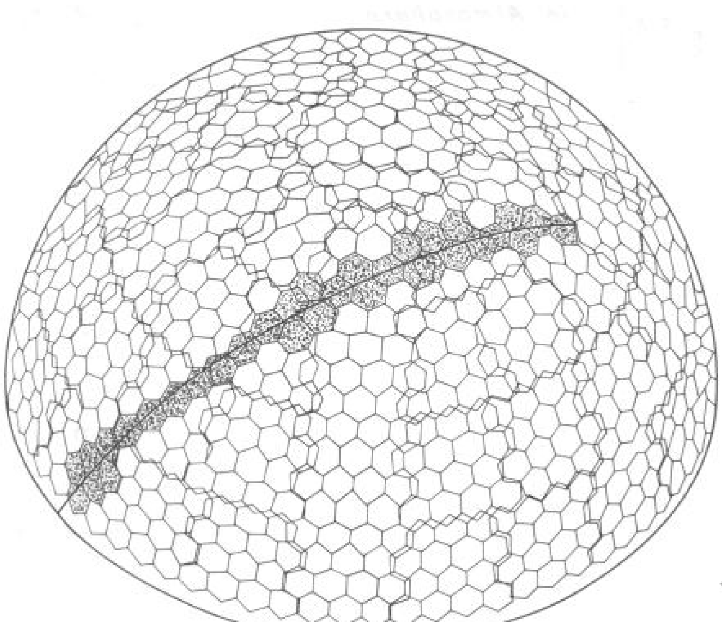
it follows on any reasonable shower model that the energy of the primary particle was about 10^{19} ev. Taking the usual estimate 3×10^{-6} gauss for the galactic magnetic field, one finds the radius of curvature of the path of a proton of such energy to be about 10^4 light years. Since, according to current estimates, the radius of the galactic halo is only about five times this value, while the thickness of the galactic disk is about five or ten times smaller, it seems certain that the primary particle acquired its energy outside our galaxy.

An important question is whether the primary particle was a proton or a heavier nucleus.

The **Fly's Eye** Detector concept

The **Fly's Eye** Detector concept

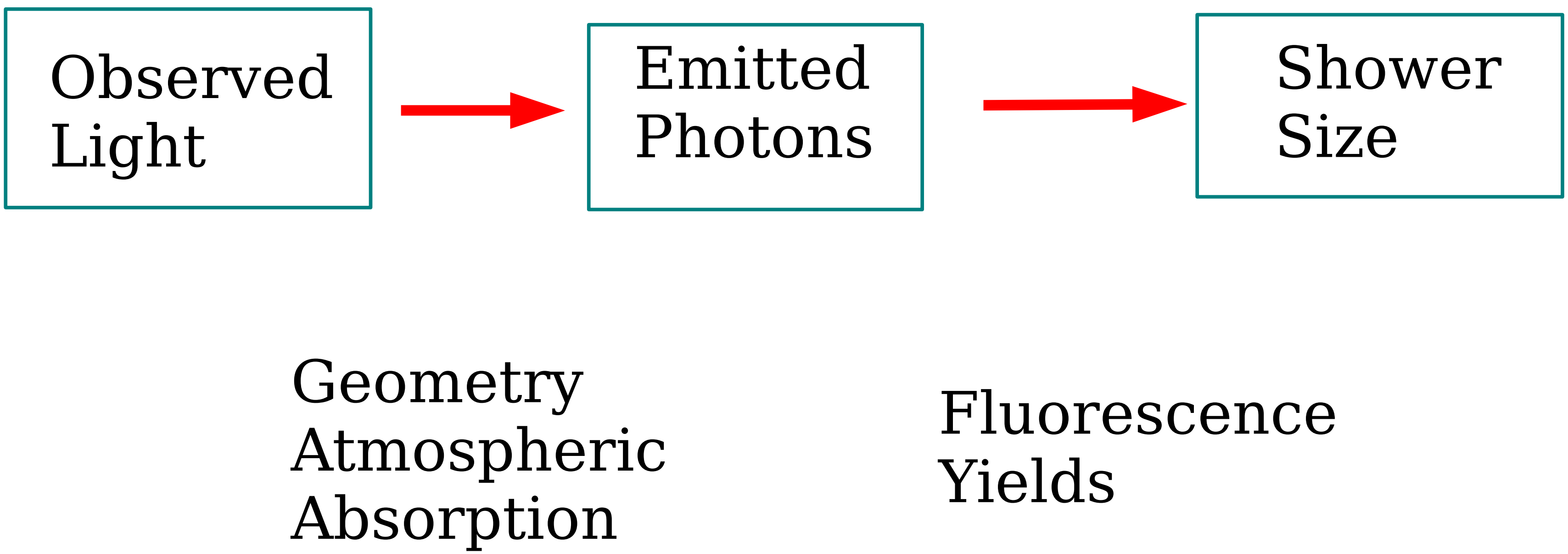




FLUORESCENCE DETECTION

In principle little model dependence
for shower energy determination

$$L(\Omega) \rightarrow F_\gamma(X) \rightarrow N_{e^\pm}(X)$$



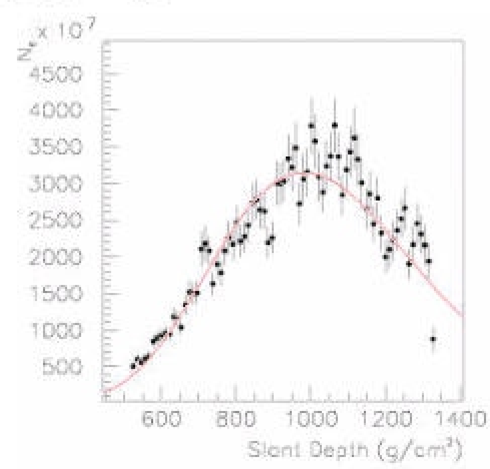
Absorption corrected

$$\frac{dN_{\text{fluo}}}{dX} = N_e(X)\left\langle -\frac{dE}{dX}\right\rangle \frac{dY_{\text{fluo}}}{dE}(X)$$

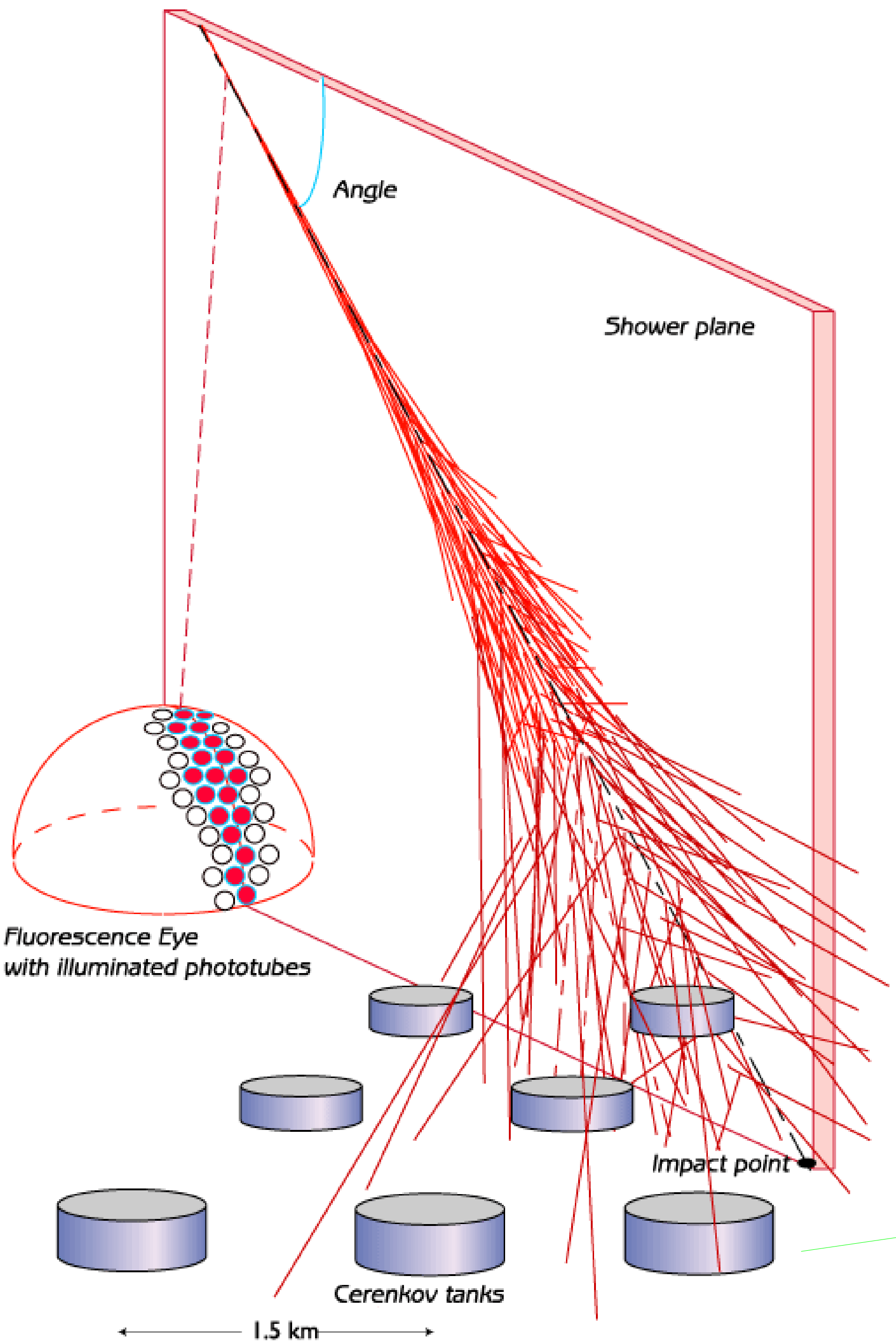
$$E_{\text{ionization}} = \int dX \; N_e(X)\left\langle -\frac{dE}{dX}\right\rangle$$

$$E_{\text{tot}} = E_{\text{ionization}} + E_{\nu} + E_{\mu} + E_{\text{ground}}$$

In principle only weak dependence in the Energy determination

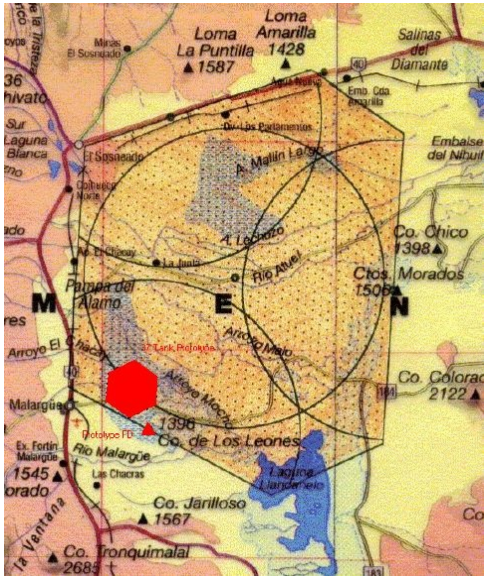


Artists View of Hybrid Set-Up

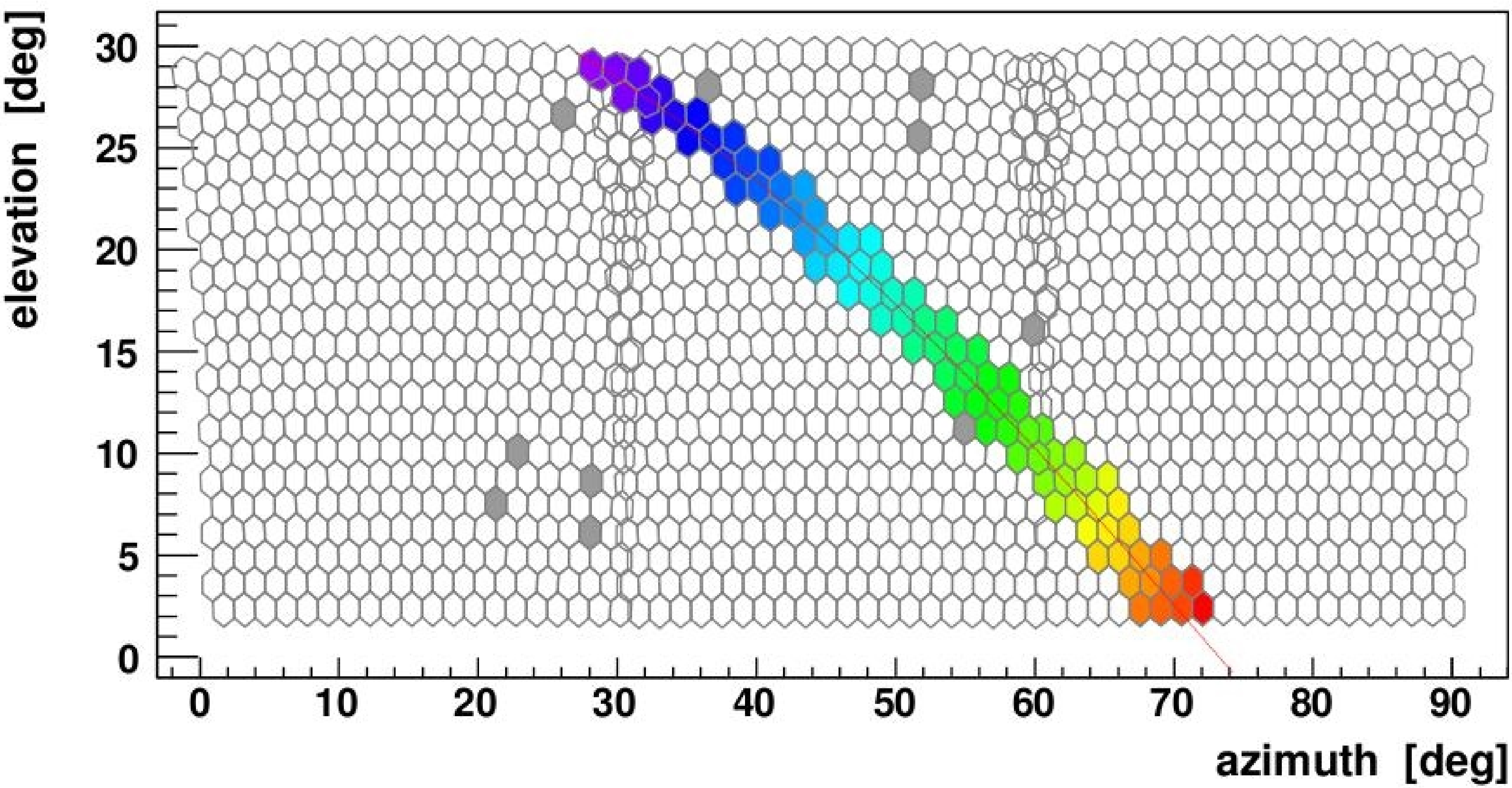


AUGER detector

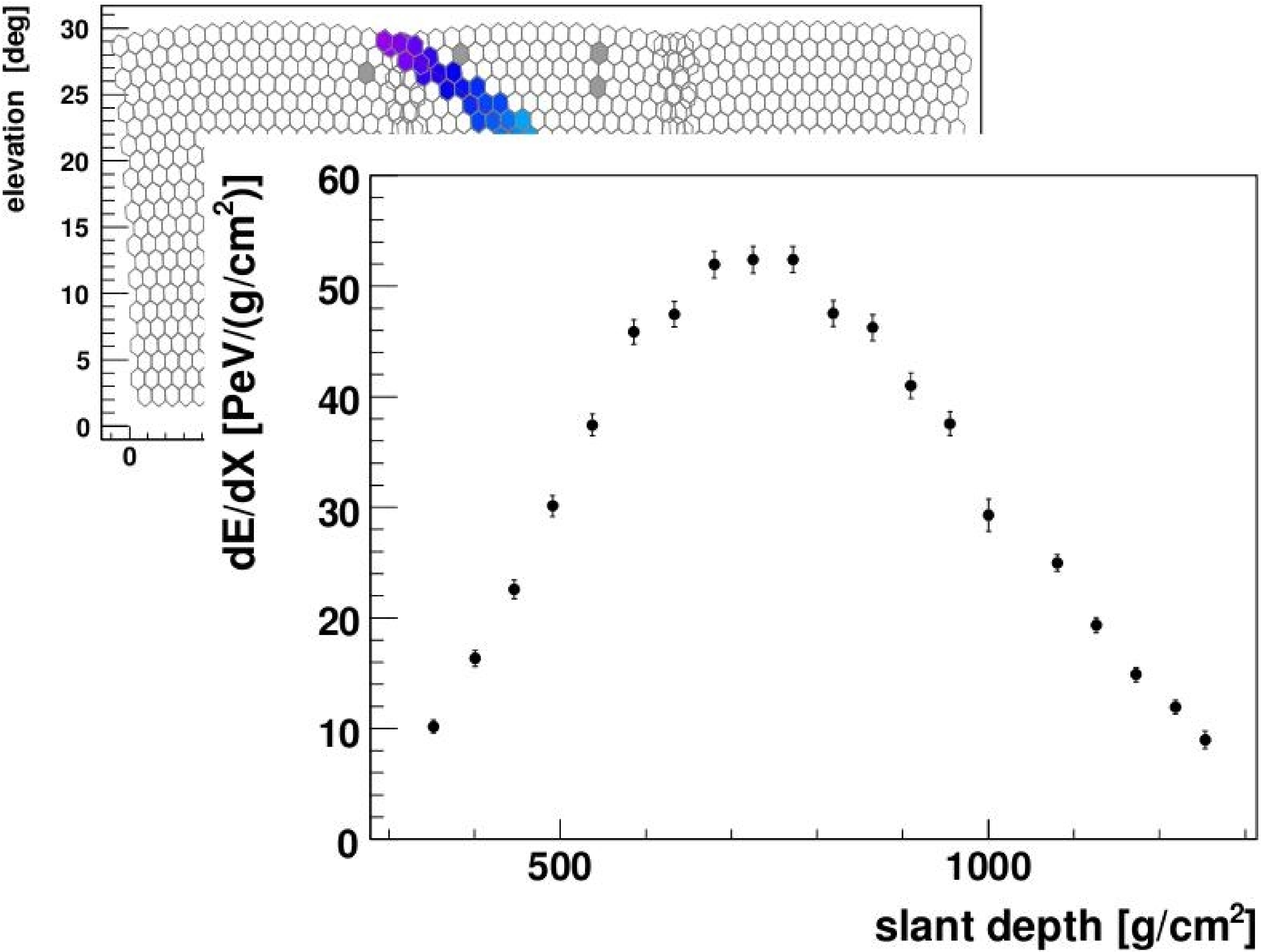
3000 Km^2
(Argentina)



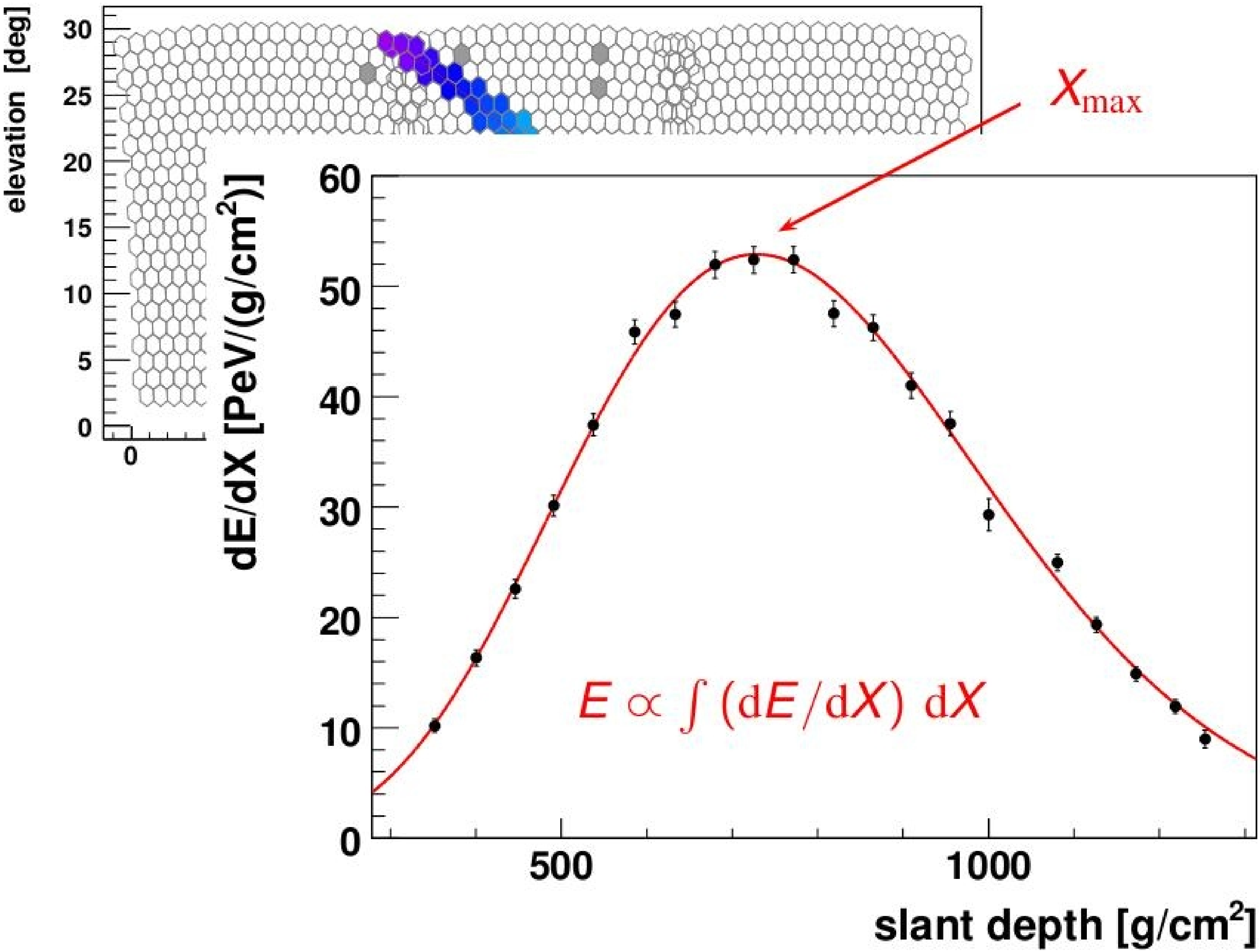
Hybrid system



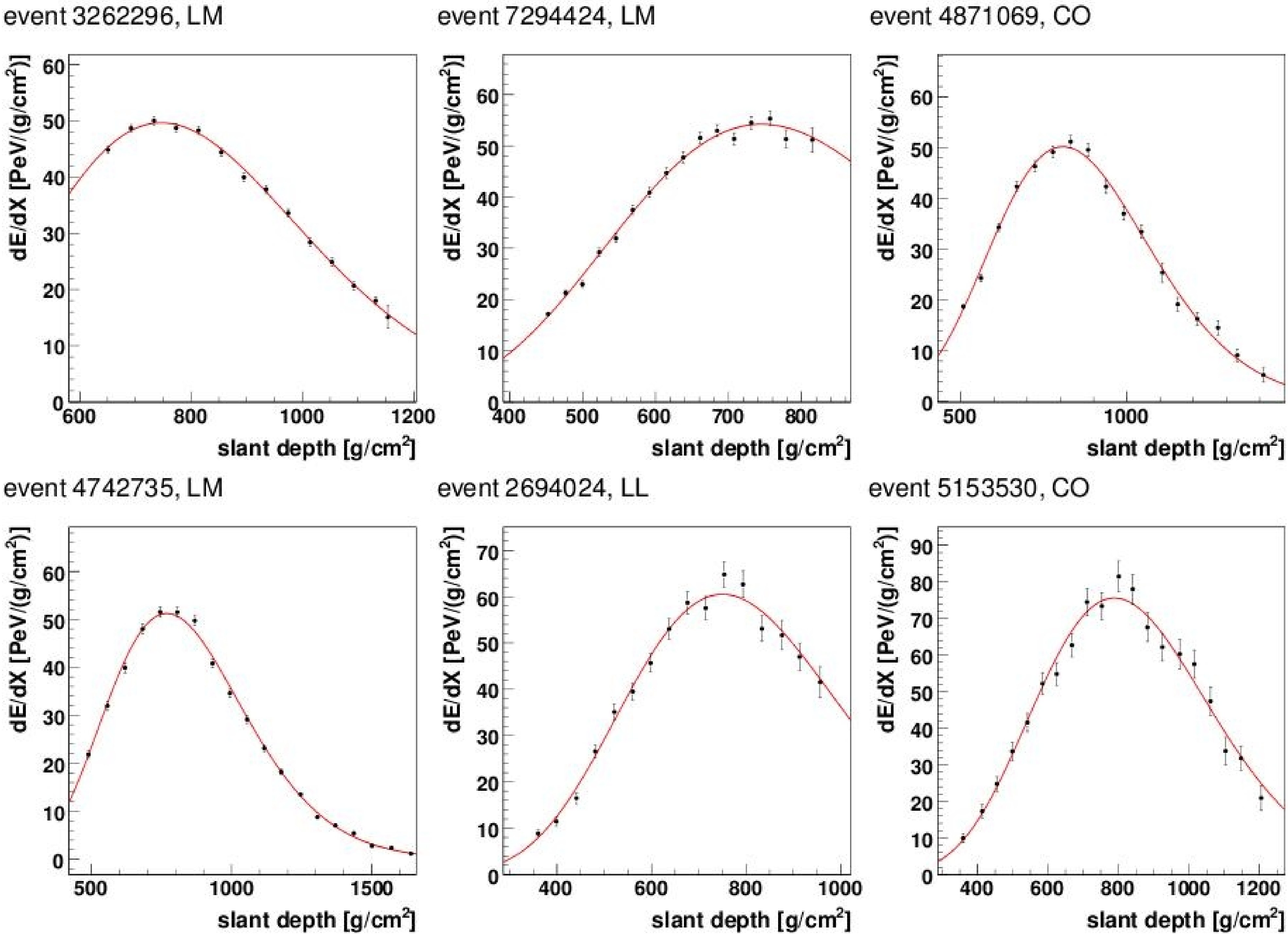
elevation [deg]
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
azimuth [deg]



elevation [deg]
30
25
20
15
10
5
0
0
dE/dX [PeV/(g/cm²)]
60
50
40
30
20
10
0
500
1000
slant depth [g/cm²]



elevation [deg]
dE/dX [PeV/(g/cm²)]
X_{max}
$E \propto \int (dE/dX)\, dX$
slant depth [g/cm²]

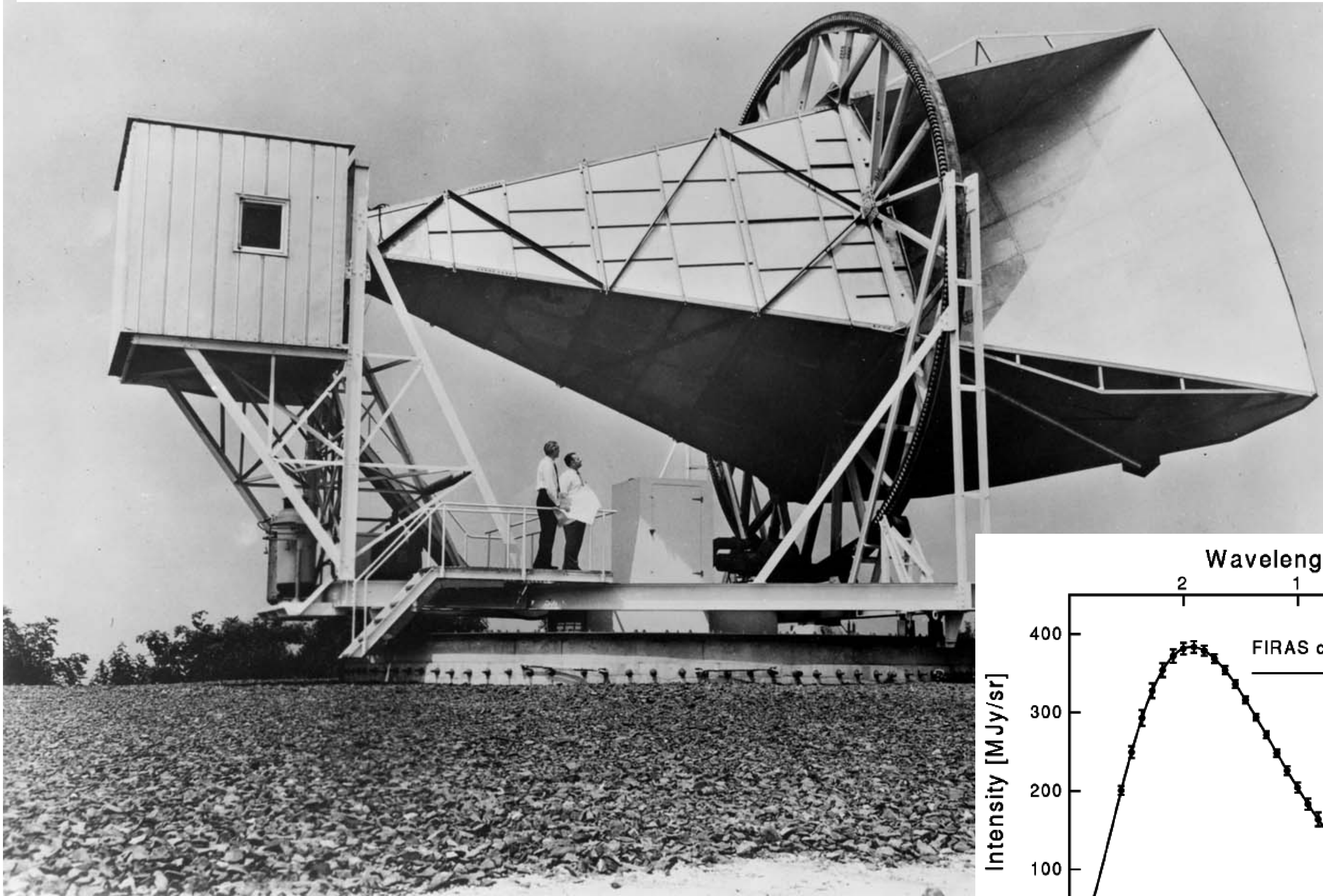

event 3262296, LM
event 7294424, LM
event 4871069, CO
event 4742735, LM
event 2694024, LL
event 5153530, CO
dE/dX [PeV/(g/cm^2)]
slant depth [g/cm^2]

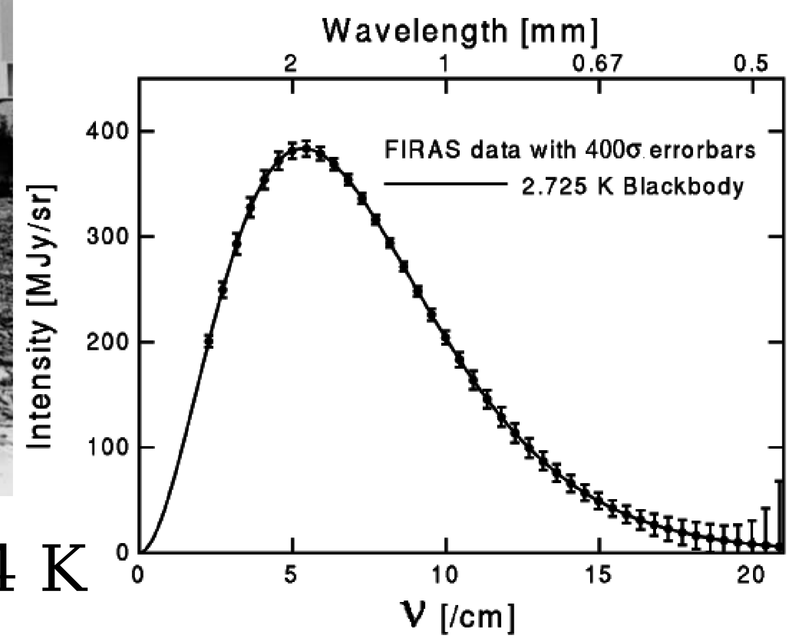
The "GZK" controversy

and the

"END of the Cosmic Ray Spectrum"

Discovery of the Cosmic Background Radiation (1965: Penzias, Wilson)





COBE: nearly perfect Black Body 2.74 K

After a few months: (1966) understanding of the consequences Of CMBR for CR.

Greisen
Zatsepin, Kuzmin

Intergalactic space full of soft photons ($410\ cm^{-3}$)
Becomes not transparent for high energy protons.

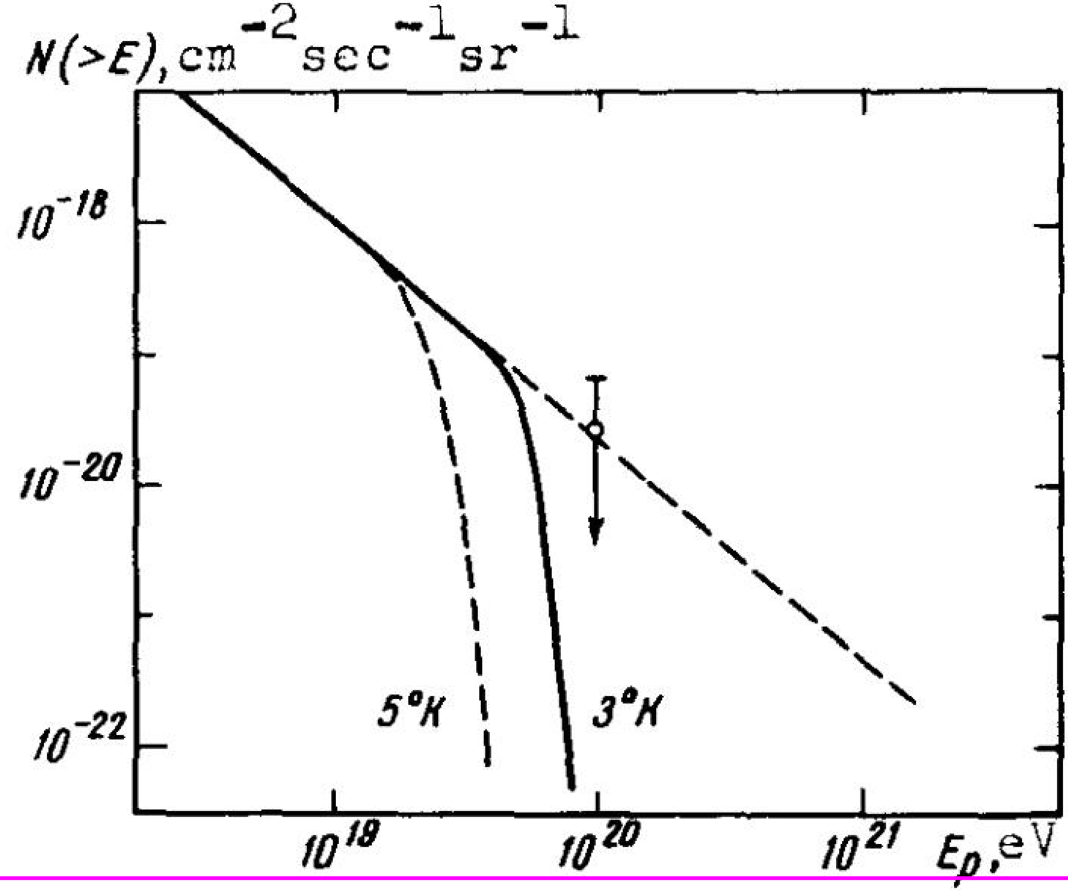
END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

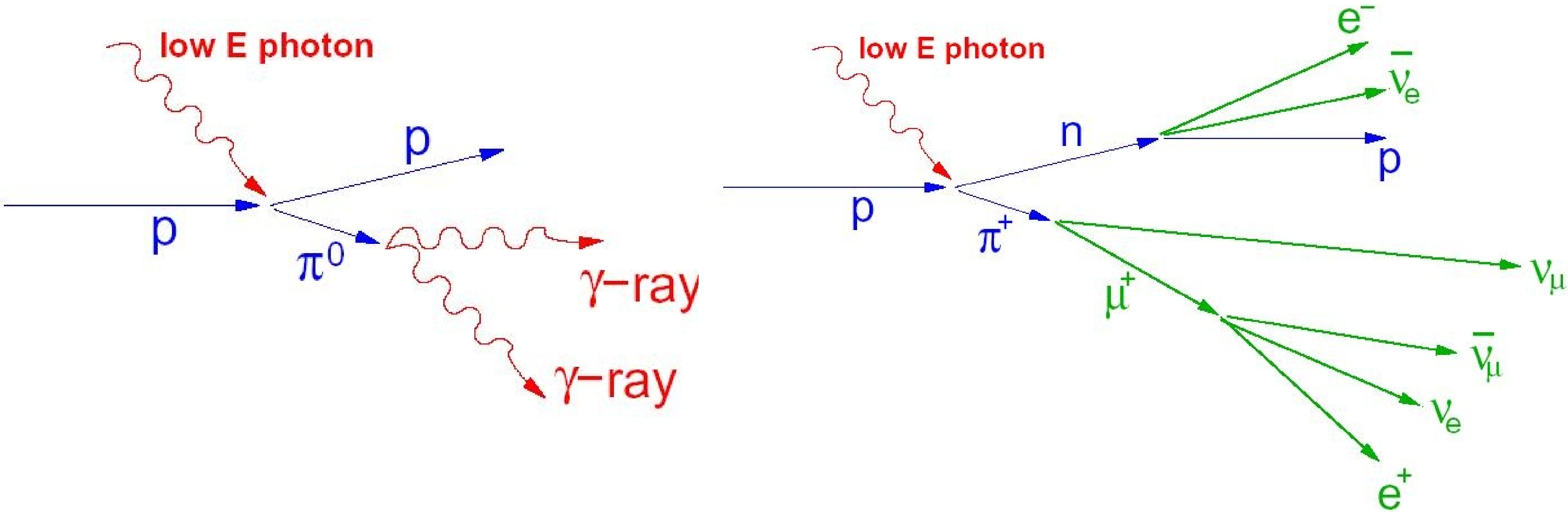
UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy
Submitted 26 May 1966



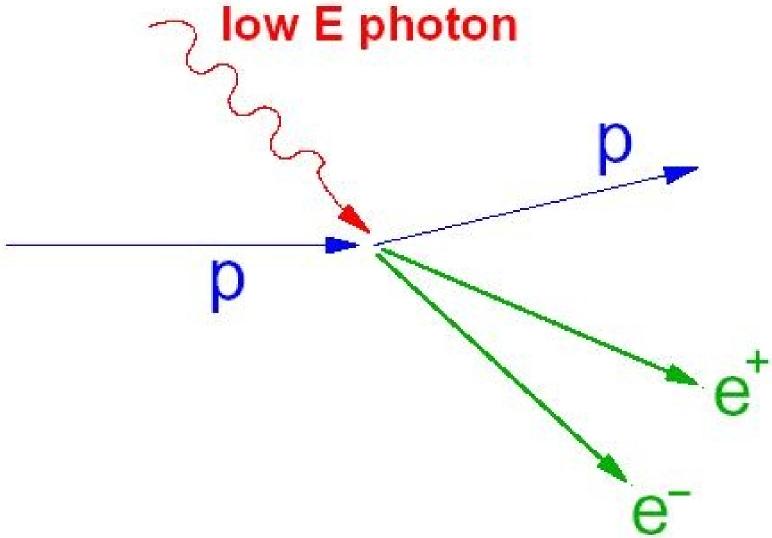
$$p + \gamma \rightarrow N + \pi$$

[neutrino production]



$$E_{\rm th}^{\pi} \sim \frac{m_\pi \; m_p}{10 \; T_\gamma} \simeq 6 \times 10^{19} \; {\rm eV}$$

$$p + \gamma \rightarrow p + e^+ e^-$$

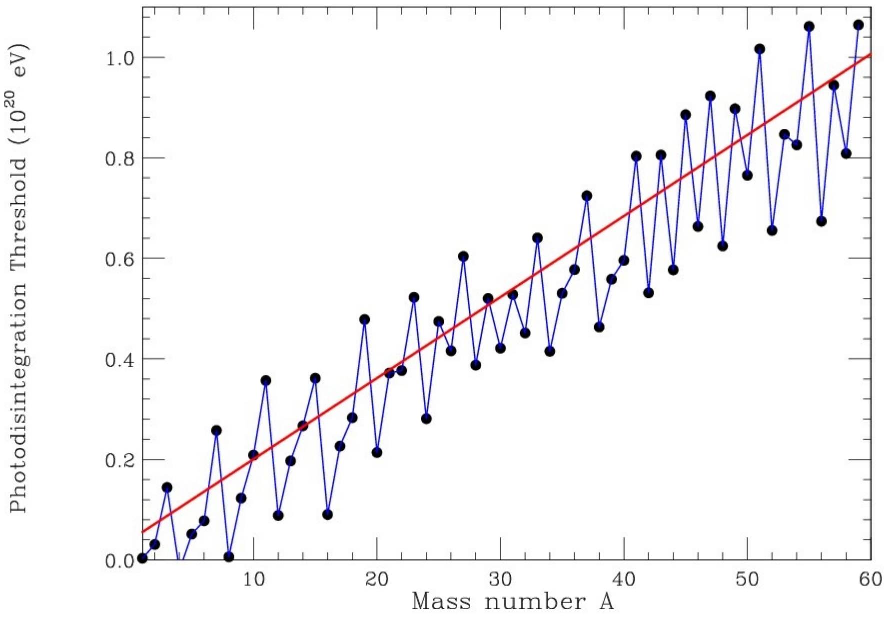


Additional (less effective)
Energy loss mechanism
For protons:

$$E_{\rm th}^{e^+e^-} \sim \frac{2\, m_e\, m_p}{10\, T_\gamma} \simeq 4 \times 10^{17}\ \mathrm{eV}$$

Energy Loss for Nuclei:
Photo-disintegration.

$$A + \gamma \rightarrow (A-1) + N$$



$$E_A \geq \frac{(m_{A-1} + m_N)^2 - m_A^2}{2\,\varepsilon_\gamma\,(1-\cos\theta_{p\gamma})}$$

$$m_A \simeq A\ (m_N - \epsilon_B)$$

$$E_A \gtrsim \frac{A\,m_N \epsilon_B}{2\,\varepsilon_\gamma\,(1-\cos\theta_{p\gamma})} \simeq \frac{A}{56} \times 10^{20}\ \text{eV}$$

Volcano Ranch

[John Linsley PRL 10 (1963).]

Haverah Park

AGASA

Suppression Effect not Seen.... ??!

Volcano Ranch
(John Linsley PRL 10 (1963).

Haverah Park

AGASA

Suppression
Effect not
Seen.... ??!

Top Down Models
[Decay of
Super massive
Particles
M_{GUT} ~10^{24} eV]

Violations of
Lorentz Invariance

Great excitement !

Several hundred
speculative theoretical works...

Volcano Ranch
(John Linsley PRL 10 (1963).

Haverah Park

AGASA

Suppression
Effect not
Seen.... ??!

Great excitement !

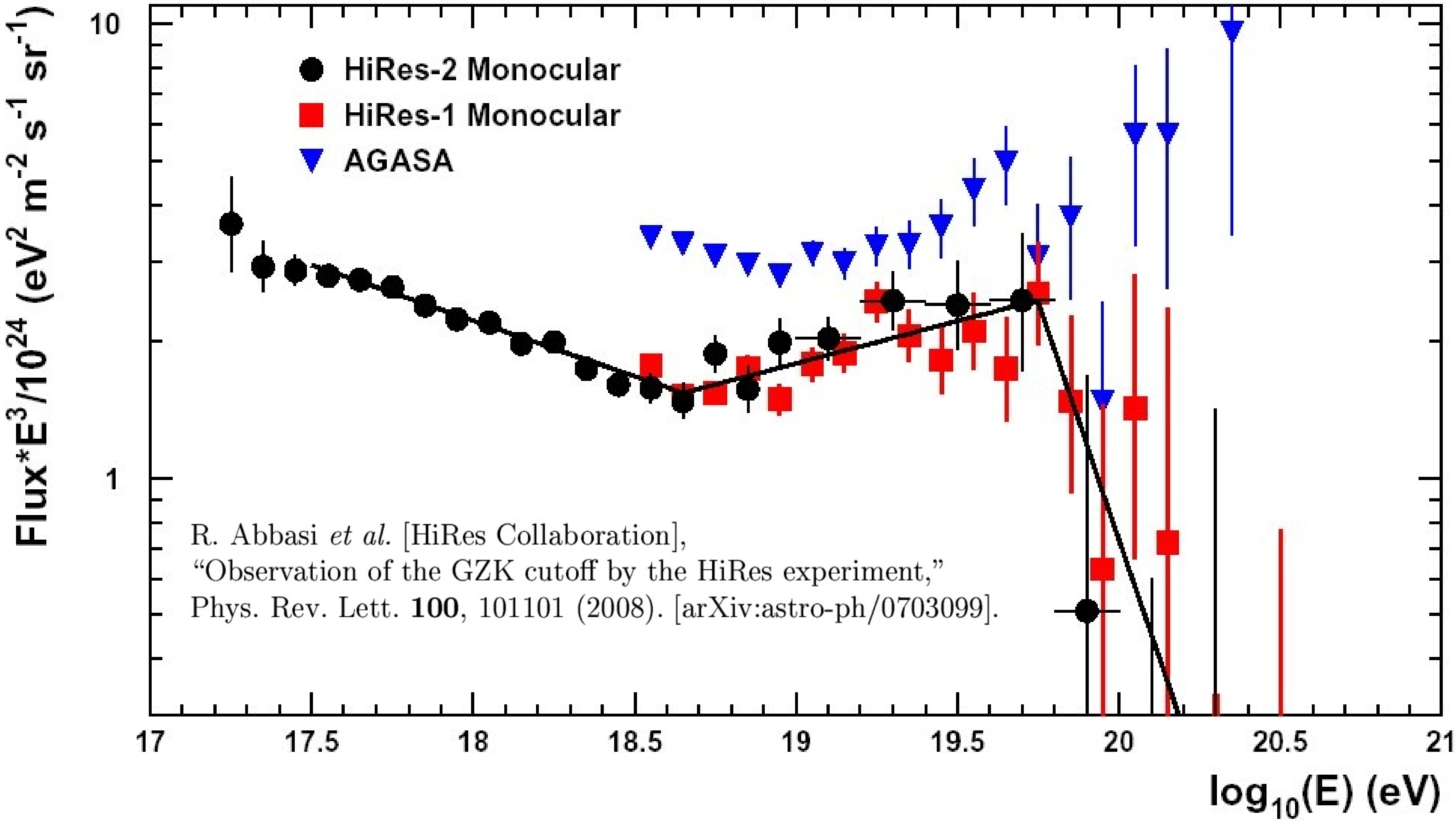
Several hundred
speculative theoretical works...

Clarification:
(2008, 2009)

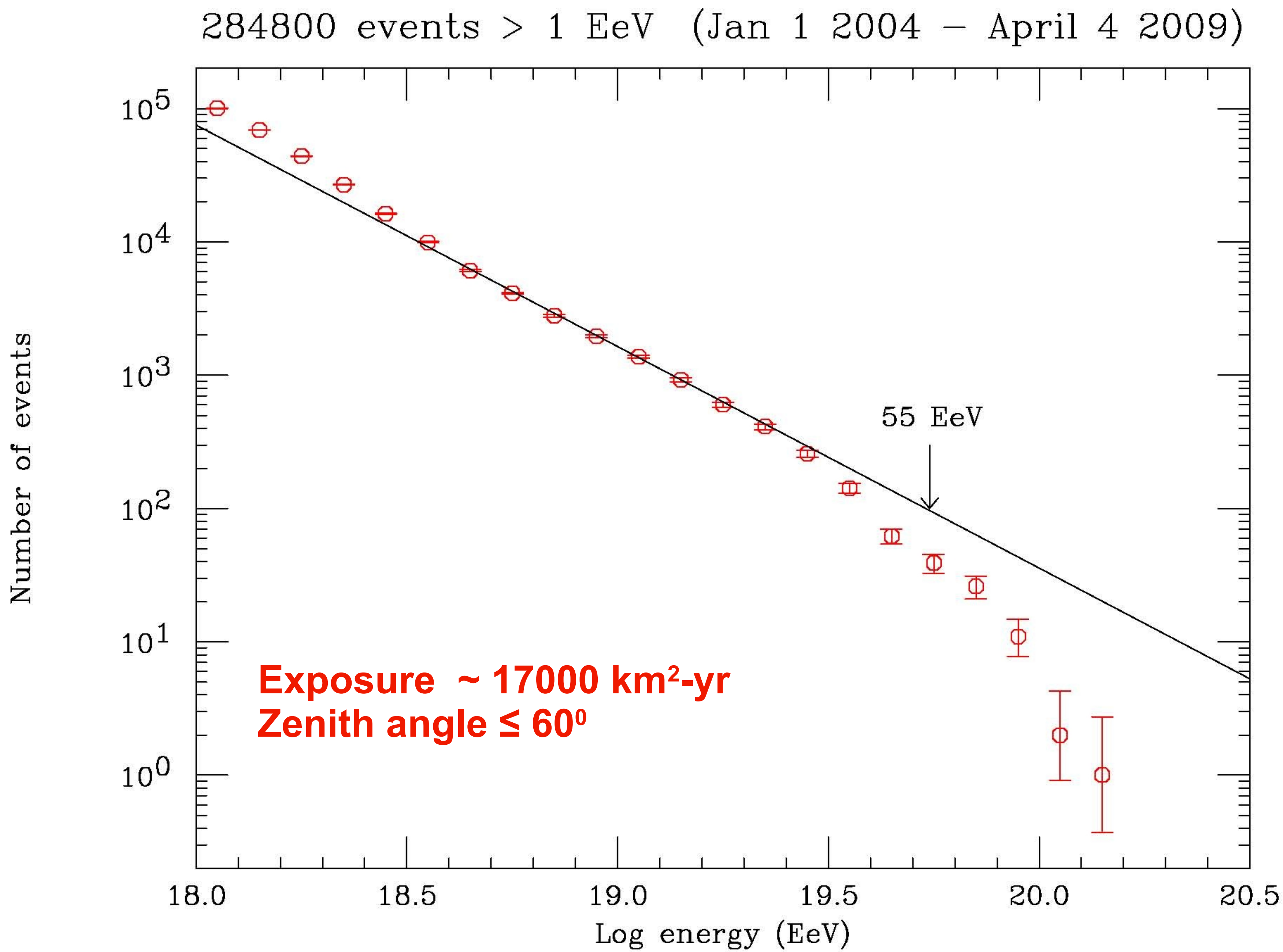
HIRES

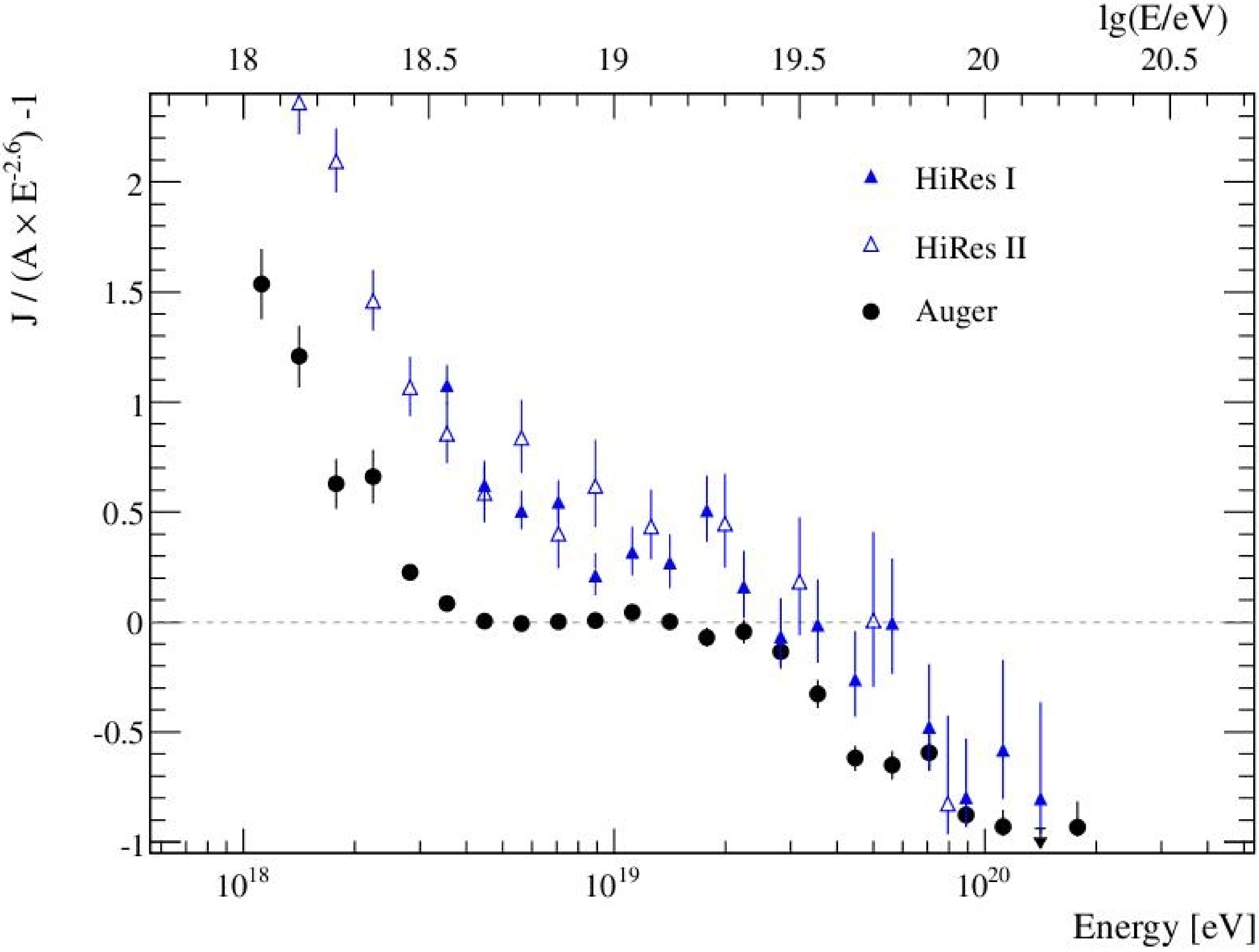
AUGER

Claim of Evidence for the
Existence of the GZK suppression
by the HiRes Collaboration:



HiRes I , HiRes II , Agasa Energy Spectra


284800 events > 1 EeV (Jan 1 2004 – April 4 2009)
Number of events
Log energy (EeV)
55 EeV
Exposure ~ 17000 km²-yr
Zenith angle ≤ 60⁰
18.0
18.5
19.0
19.5
20.0
20.5
10⁰
10¹
10²
10³
10⁴
10⁵



lg(E/eV)
18
18.5
19
19.5
20
20.5
J / (A × E^-2.6) -1
2
1.5
1
0.5
0
-0.5
-1
HiRes I
HiRes II
Auger
10^18
10^19
10^20
Energy [eV]

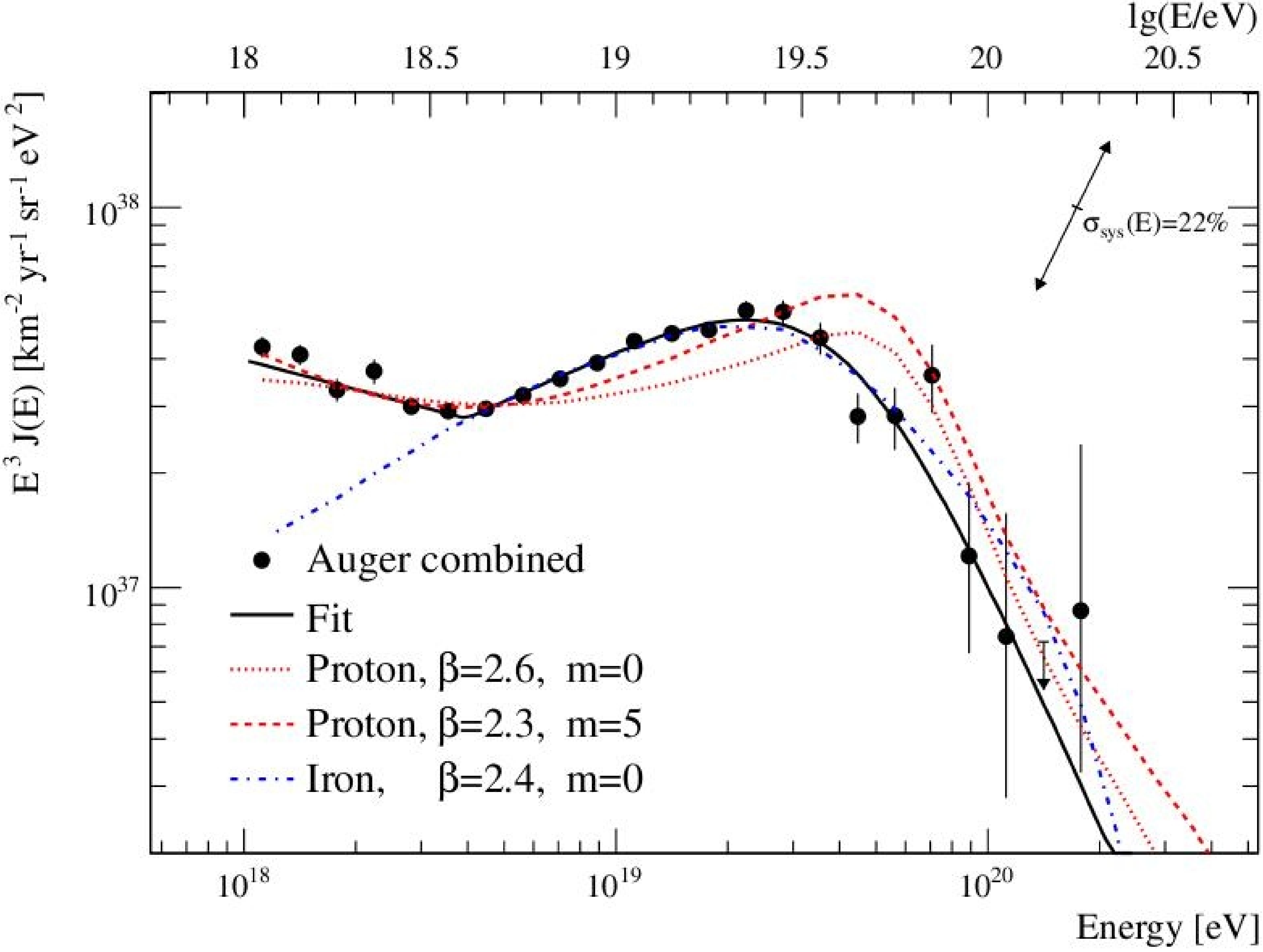
A “bending” in the UHECR spectrum is now convincingly observed by the HIRES and AUGER collaborations.

Its structure is CONSISTENT with the “GZK” bending for a spectrum of protons.

Its nature is not yet firmly established.

Other explanations are also possible:

- Photo-disintegration of nuclei
- “End of Acceleration”



lg(E/eV)
18
18.5
19
19.5
20
20.5
E^3 J(E) [km^{-2} yr^{-1} sr^{-1} eV^2]
10^{38}
10^{37}
σ_{sys}(E)=22%
Auger combined
Fit
Proton, β=2.6, m=0
Proton, β=2.3, m=5
Iron, β=2.4, m=0
10^{18}
10^{19}
10^{20}
Energy [eV]

The “Scientific Landscape” is deeply modified.

The study of UHECR is now predominantly
an essential branch of High Energy Astrophysics.

Speculations and searches for “ New Physics” effects
in UHECR can (and will) continue.

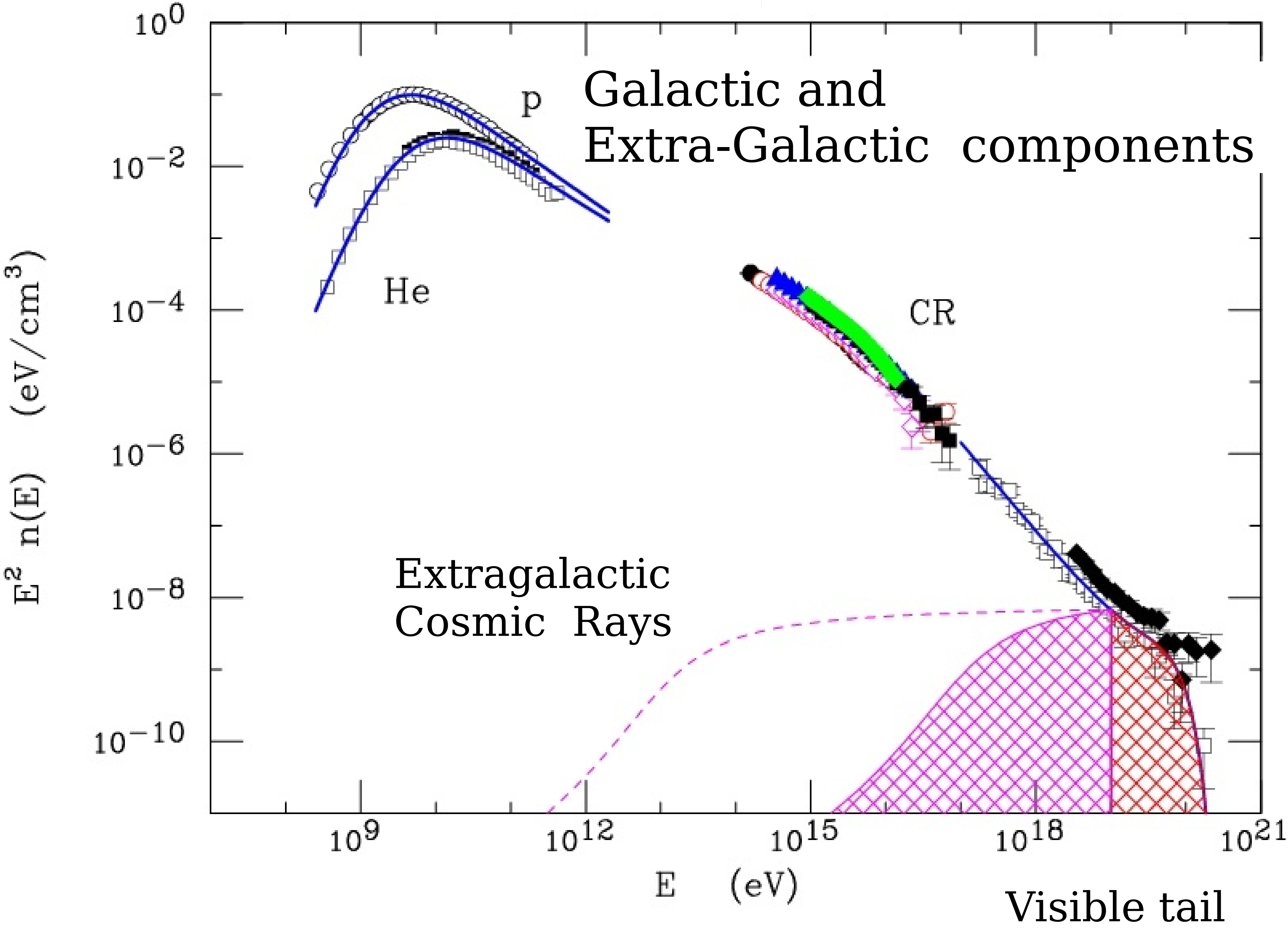
Some interesting ideas have been put forward
and their test and study remain valid goals.

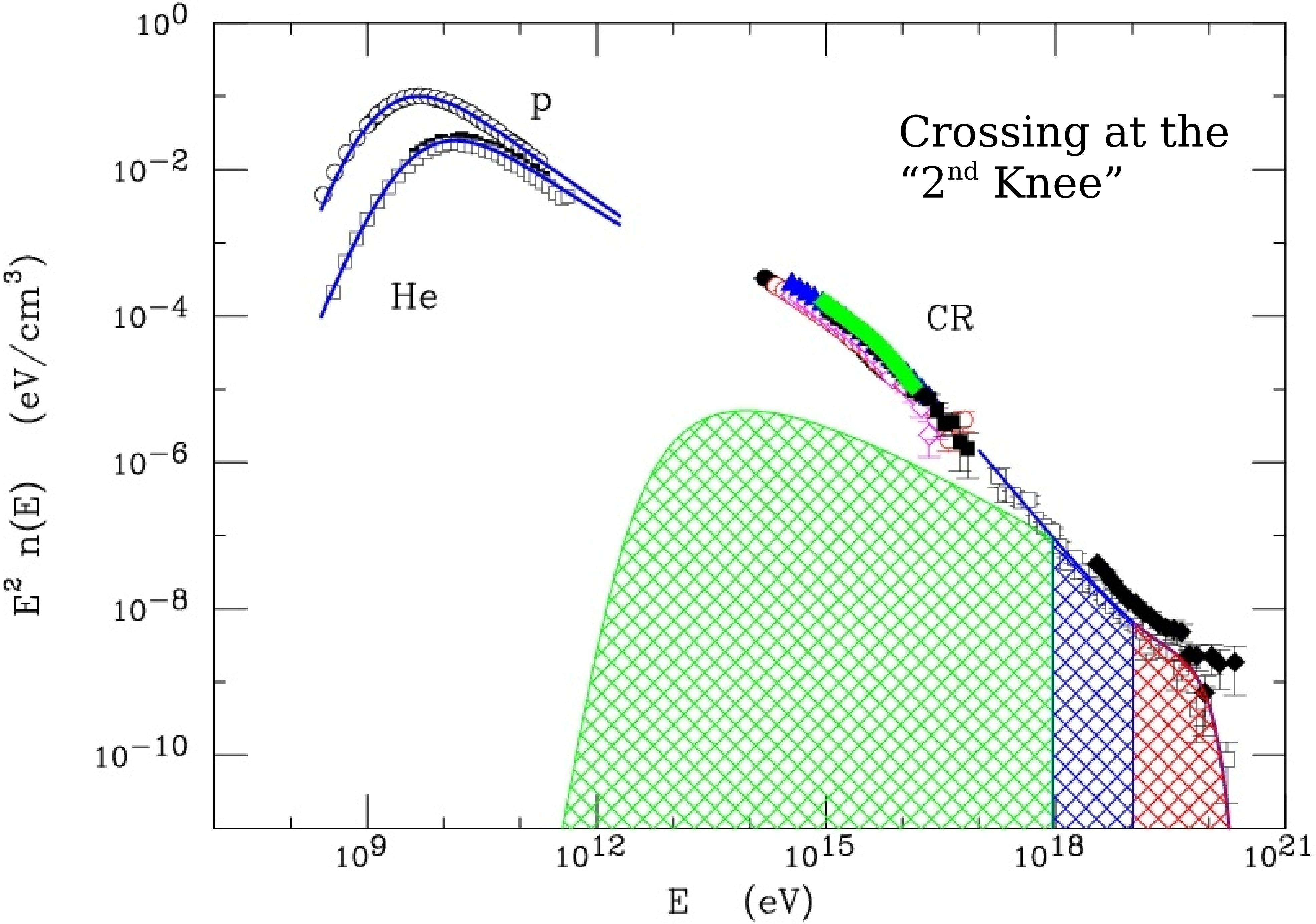
(Violation of LORENTZ INVARIANCE).
“TOP DOWN” Models.

Highest energy cosmic rays
must be extra-galactic

Magnetic Field of the Milky Way
Dimension of the milky way to small for confinement.

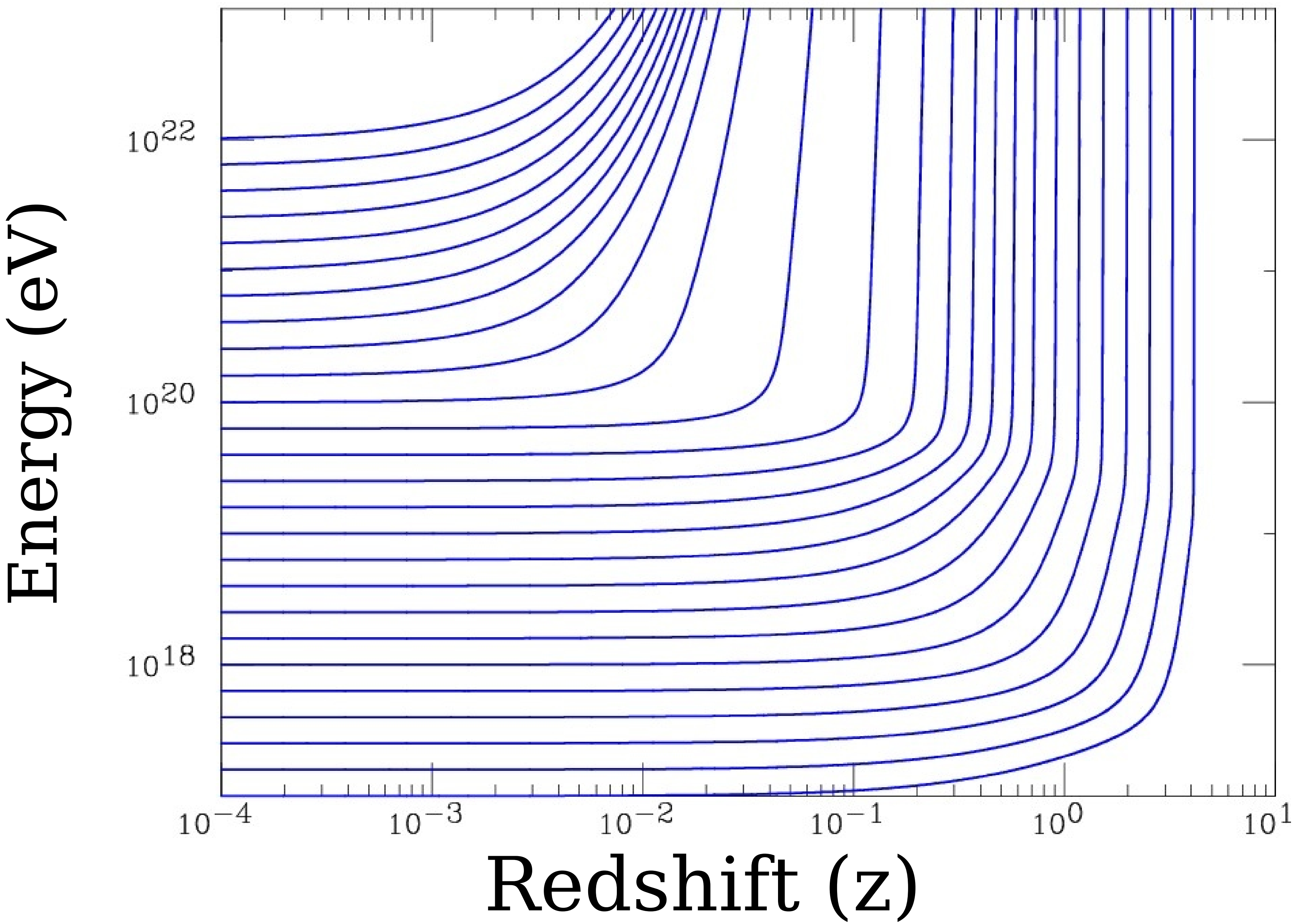
$$r_{\rm Larmor} = \frac{E}{Z\,e\,B} \simeq \frac{1.08}{Z}\ \left(\frac{E}{10^{18}\ {\rm eV}}\right)\ \frac{\mu{\rm Gauss}}{B}\ {\rm kpc}$$


Galactic and
Extra-Galactic components
p
He
CR
Extragalactic
Cosmic Rays
Visible tail
E² n(E) (eV/cm³)
E (eV)
10⁰
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁹
10¹²
10¹⁵
10¹⁸
10²¹

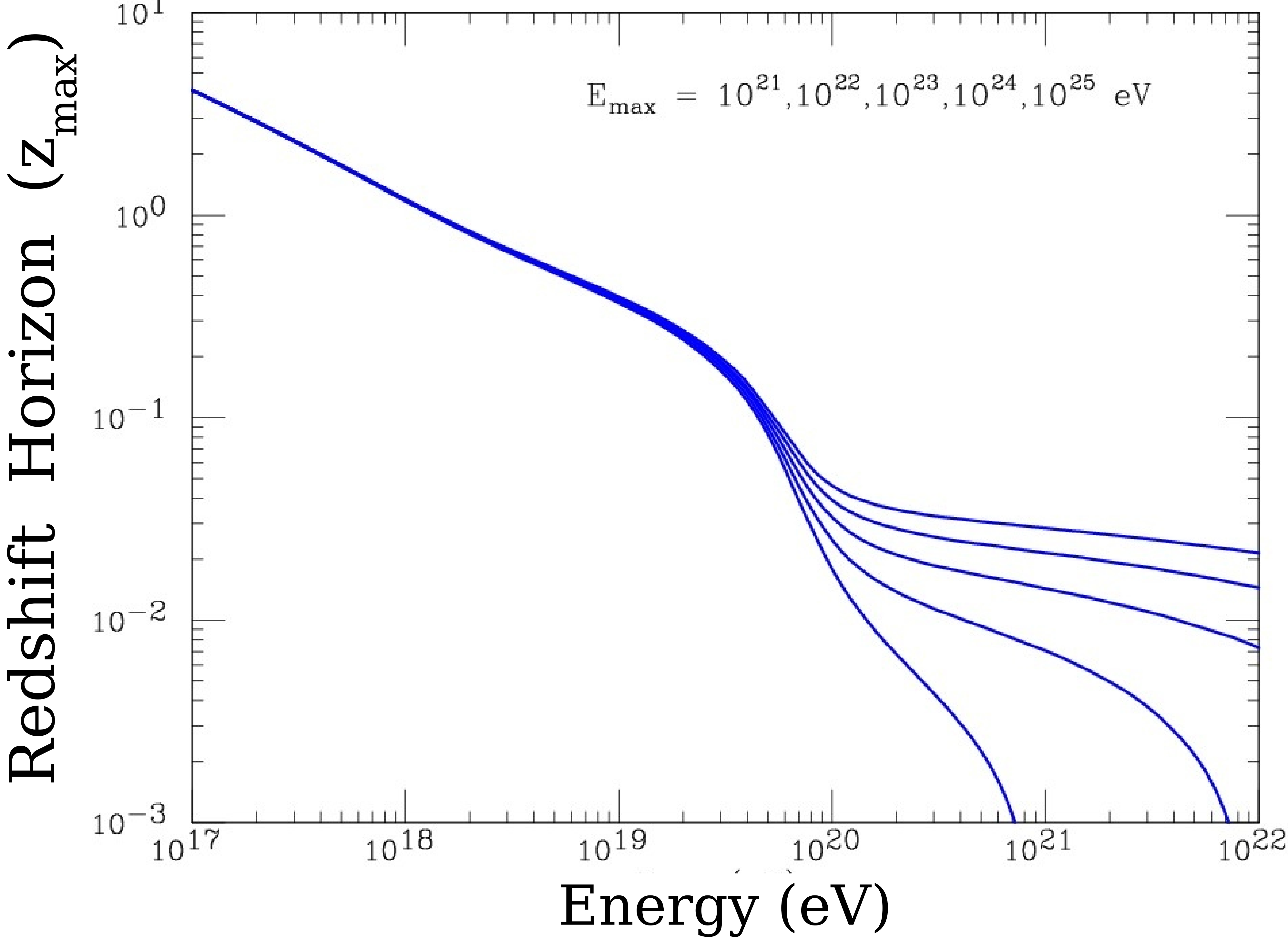


Crossing at the
"2nd Knee"
p
He
CR
E² n(E) (eV/cm³)
E (eV)
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^9
10^12
10^15
10^18
10^21

Proton Energy Evolution with Redshift



“Horizon” (in time) for protons



$$q(E,z) = q_0 \; E^{-\alpha} \; F_{\text{evolution}}(z)$$

Power law injection of particles

$$\phi(E) = \frac{c}{4\pi} \frac{1}{H_0} \left[q_0 \; E^{-\alpha}\right] \; \xi(E)$$

Resulting spectrum at the present epoch is deformed

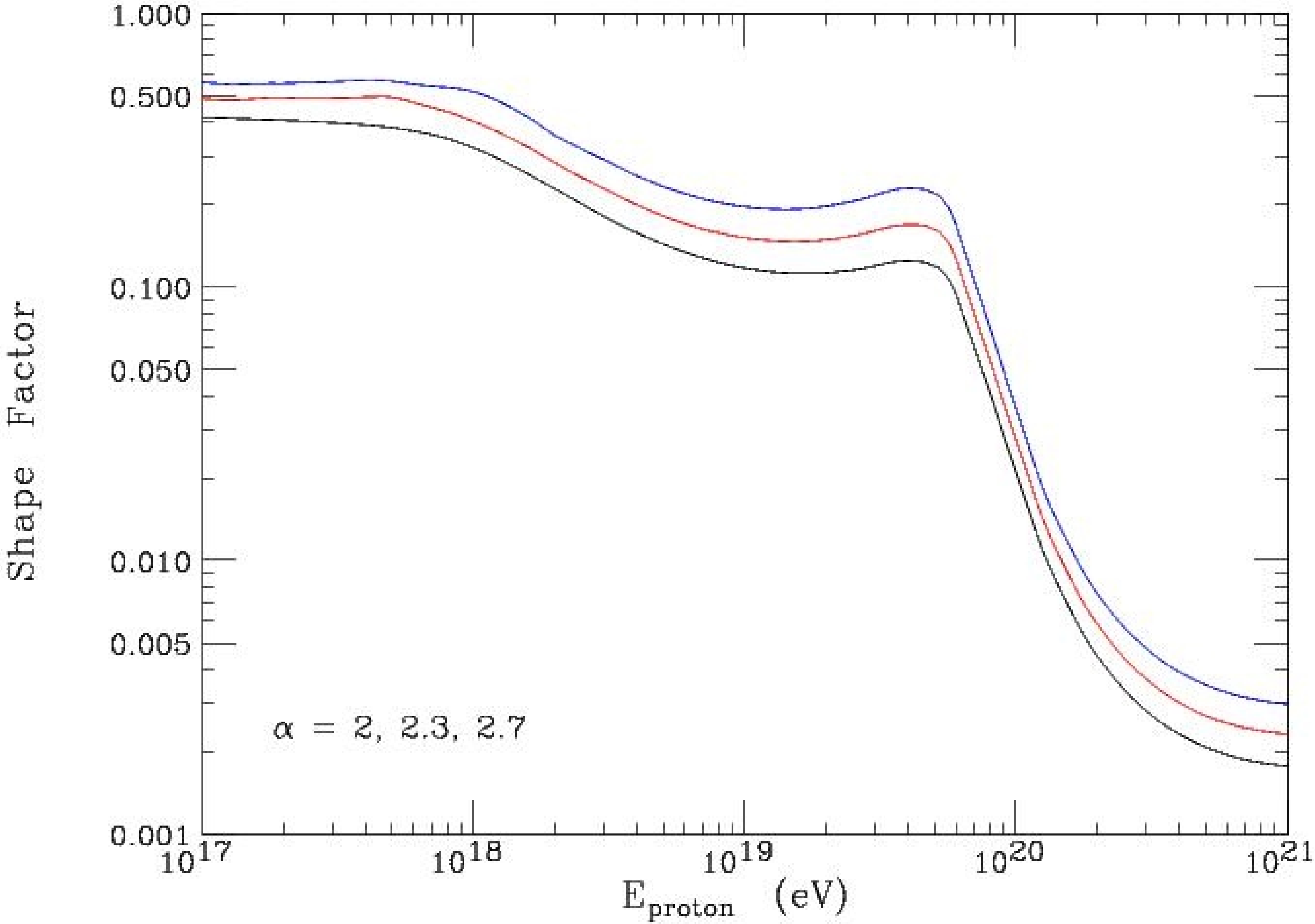
Adimensional Shape Factor

$$\xi(E) = \int_0^\infty dz \; \left|\frac{dt}{dz}\right| \frac{q[E_g(E,z)]}{q(E)} \; \frac{dE_g[E,z]}{dE} \quad F_{\text{evolution}}(z)$$

$$\xi(E) = \int_0^{E_{\max}/E-1} dz \; \frac{H_0}{H(z)} \; (1+z)^{-\alpha}$$

Only Redshift losses: Constant

Shape factor (Berezinski "Modification factor")
for different power law indices. (No cosmic evolution)



The "Olbers (Kepler) Paradox"

Why is night sky dark ?

Eternal, infinite
Euclidean Universe

n of identical sources

Q particles per unit time

$$\Phi = \frac{1}{4\pi} \int_0^\infty dr \; (4\,\pi\, r^2 \; n) \; \frac{Q}{4\pi\, r^2}$$

$$\Phi = \frac{n\;Q}{4\pi} \int_0^\infty dr \; 1 \quad \to \infty$$

Infinite flux

The "Olbers (Kepler) Paradox"

Why is night sky dark ?

Eternal, infinite
Euclidean Universe

n of identical sources

Q particles per unit time

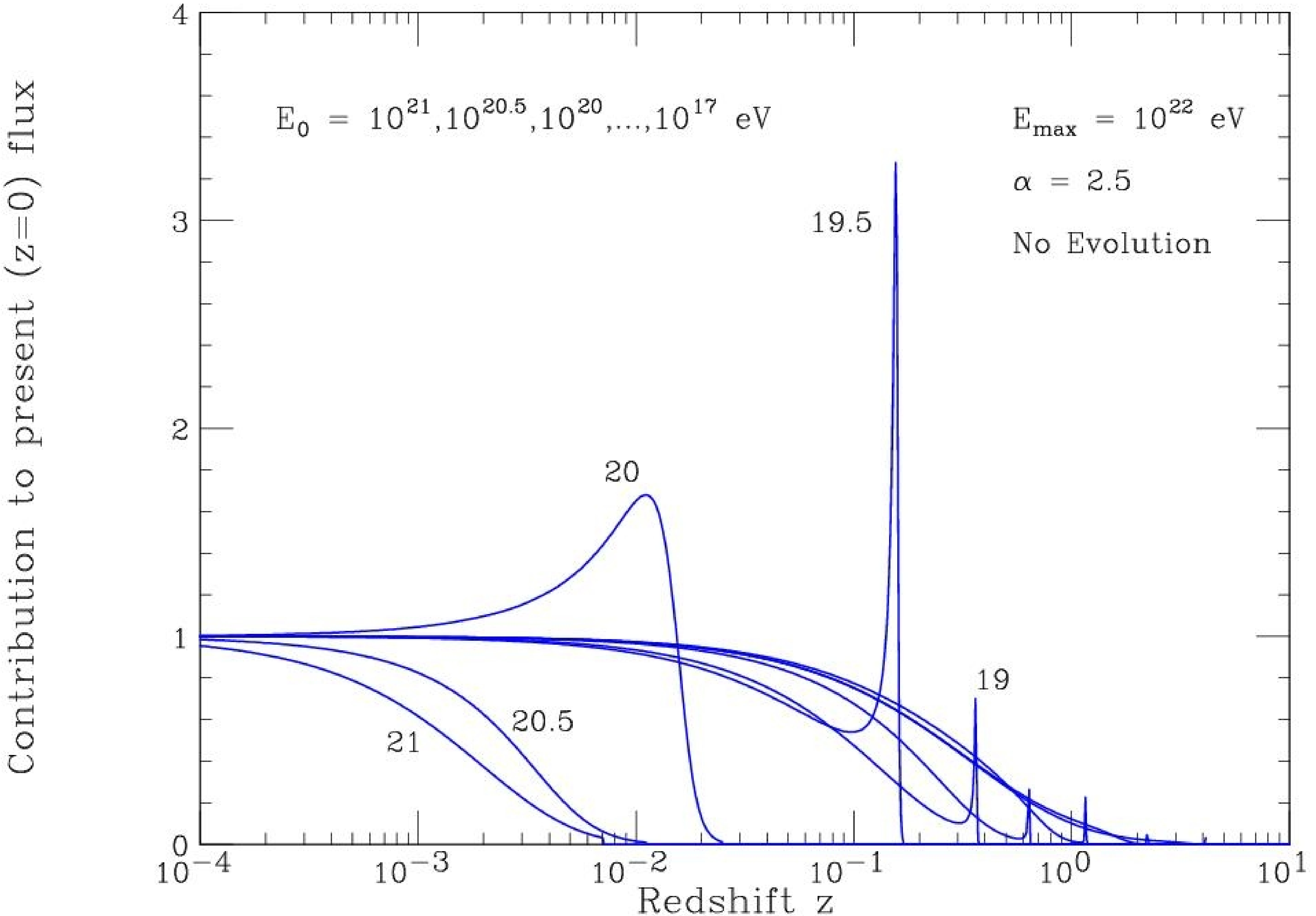
$$\Phi = \frac{1}{4\pi} \int_0^\infty dr \; (4\,\pi\, r^2 \; n) \; \frac{Q}{4\pi\, r^2}$$

$$\Phi = \frac{n\; Q}{4\pi} \int_0^\infty dr \; 1 \qquad \to \infty$$

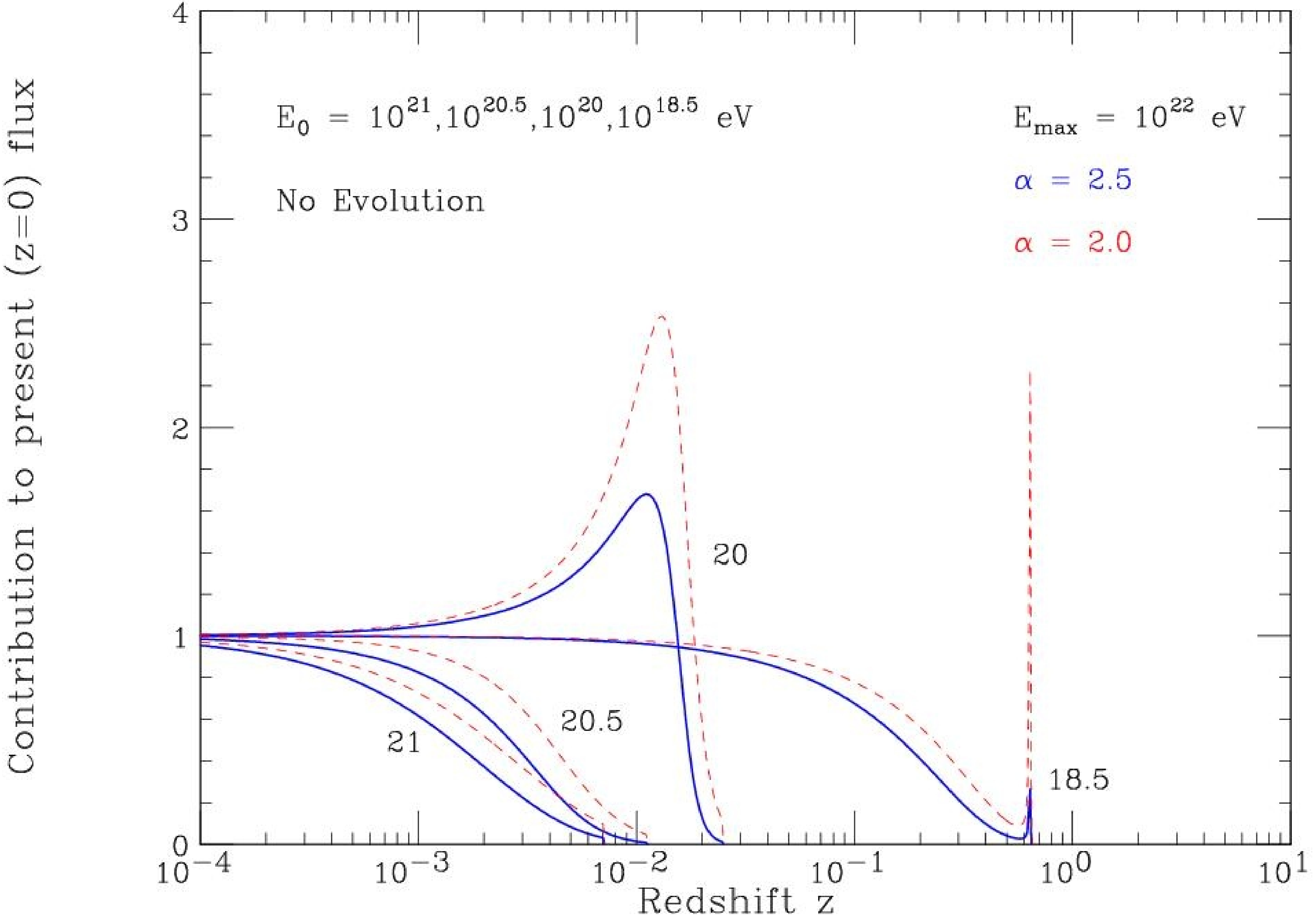
Infinite flux

Solution : Finite time for the universe
Redshift effects.

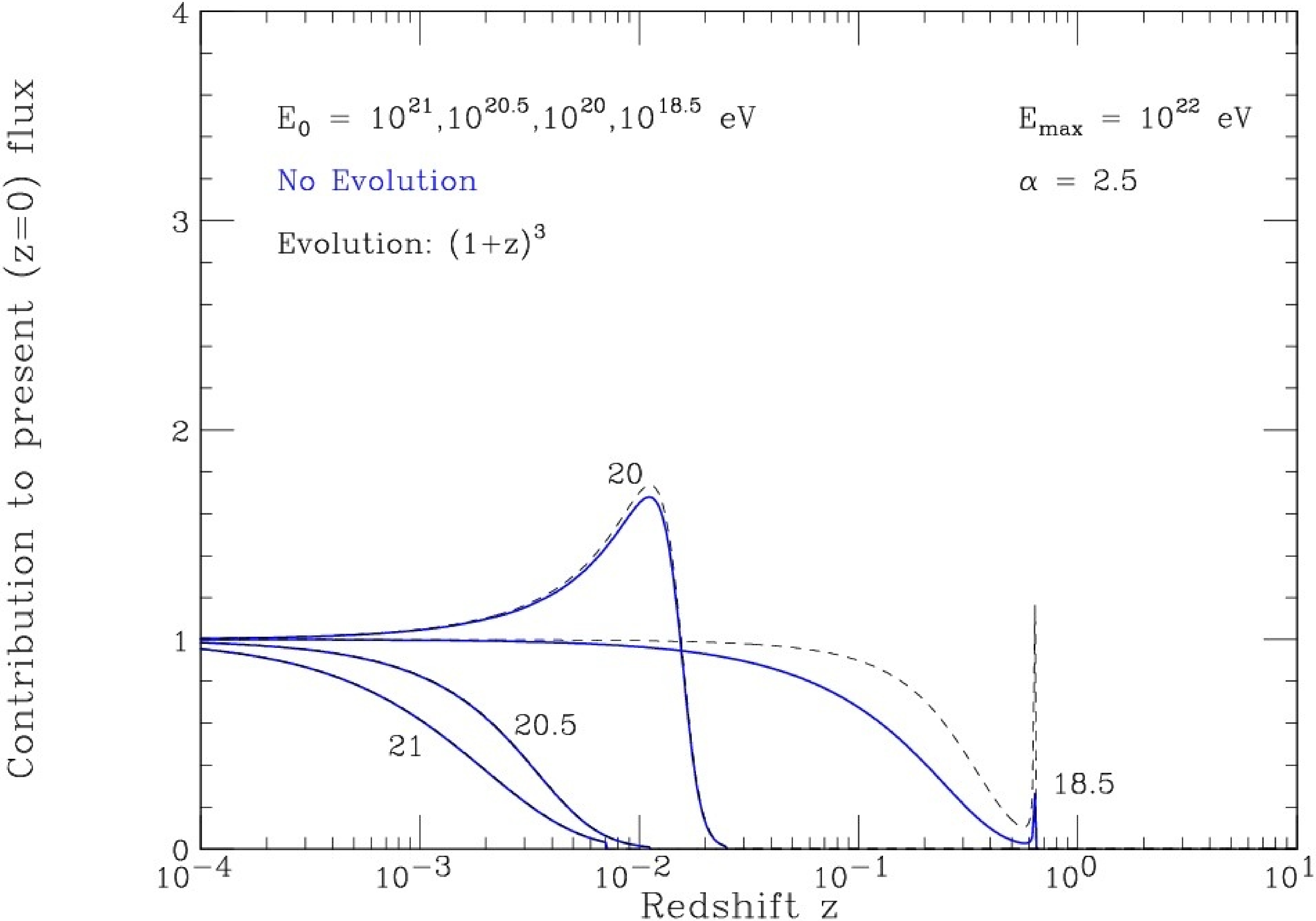
Homogeneous distribution of sources



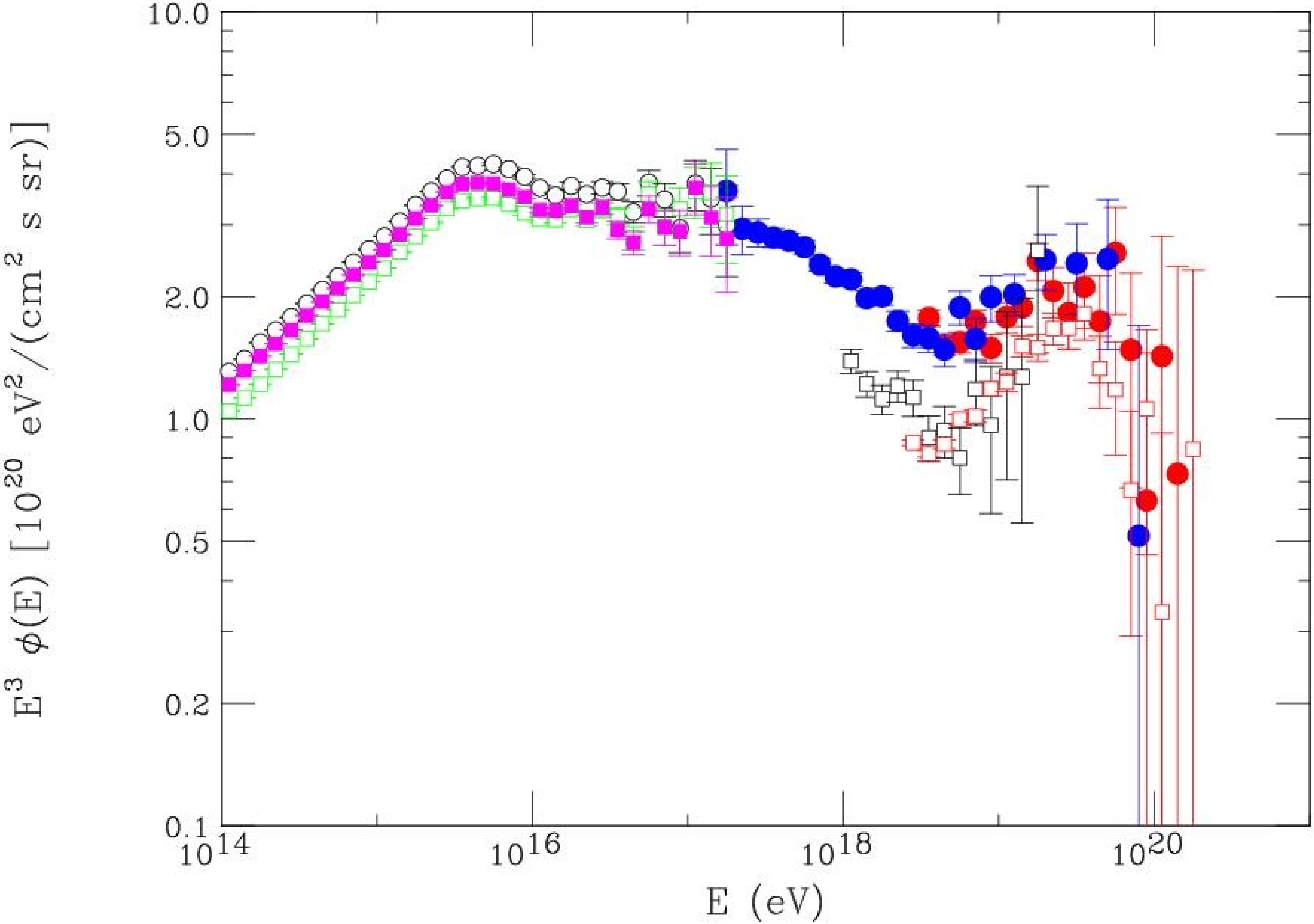
Different Injection spectra



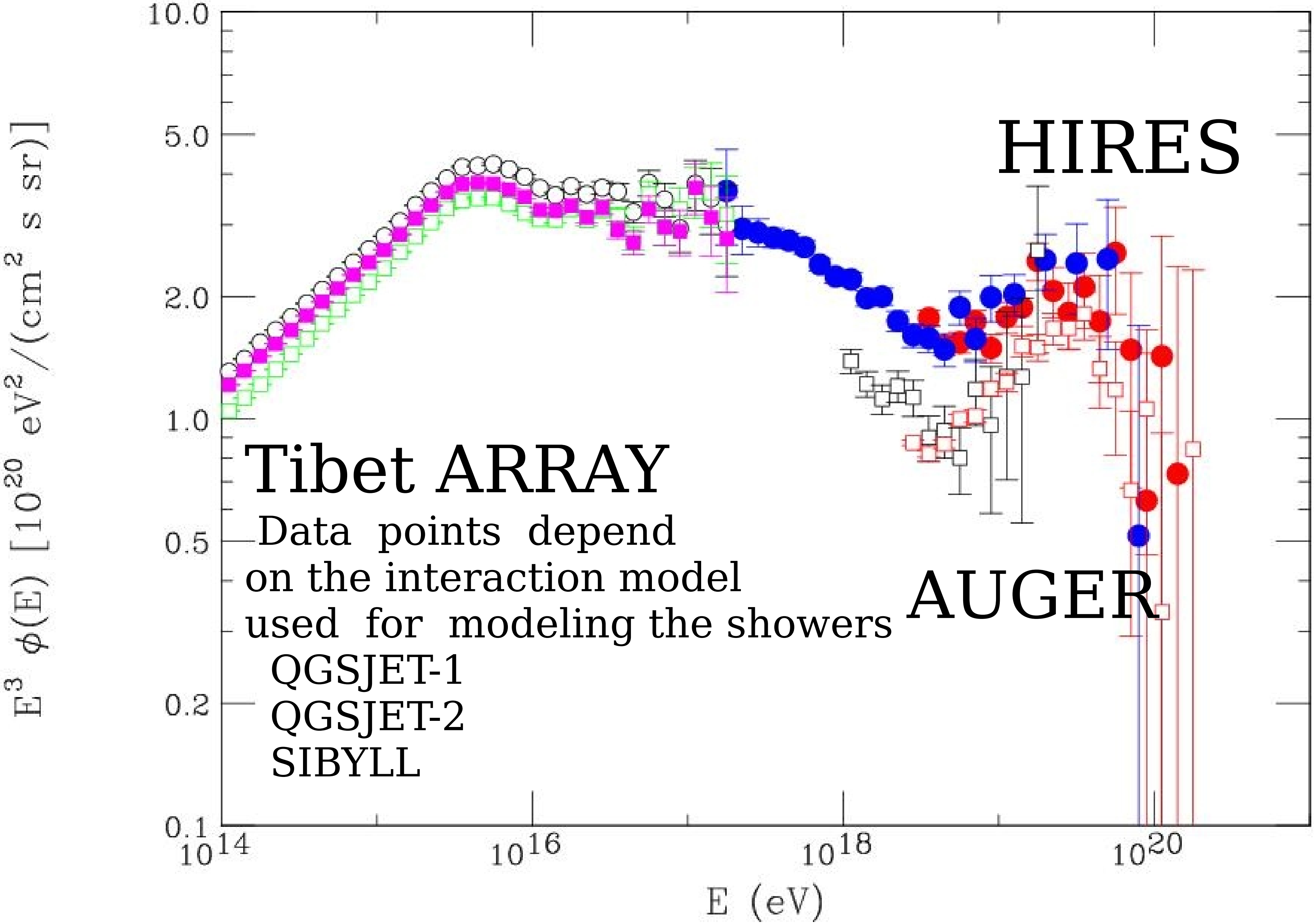
Possible effects of evolution



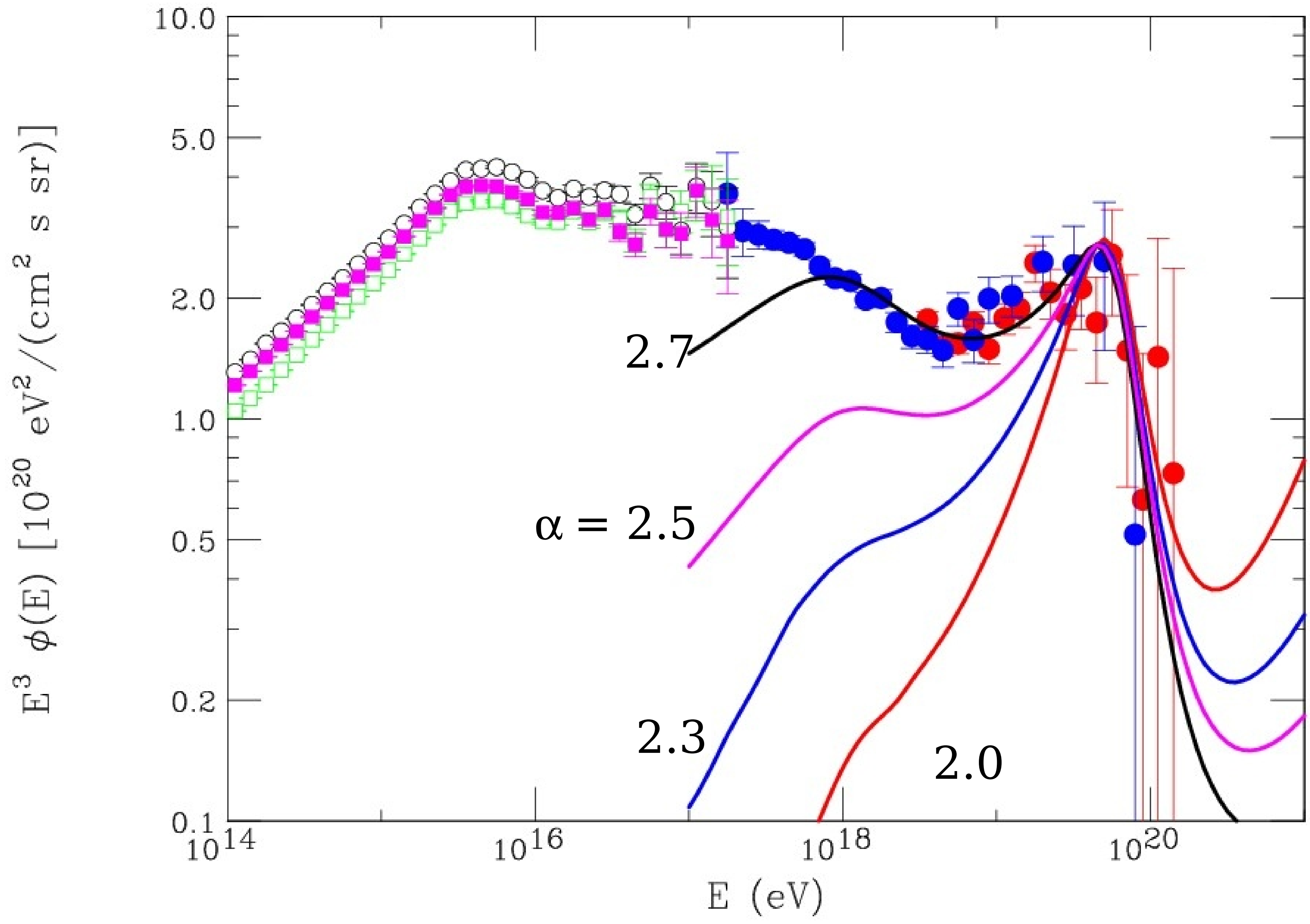
UHECR Flux * E^3 representation.



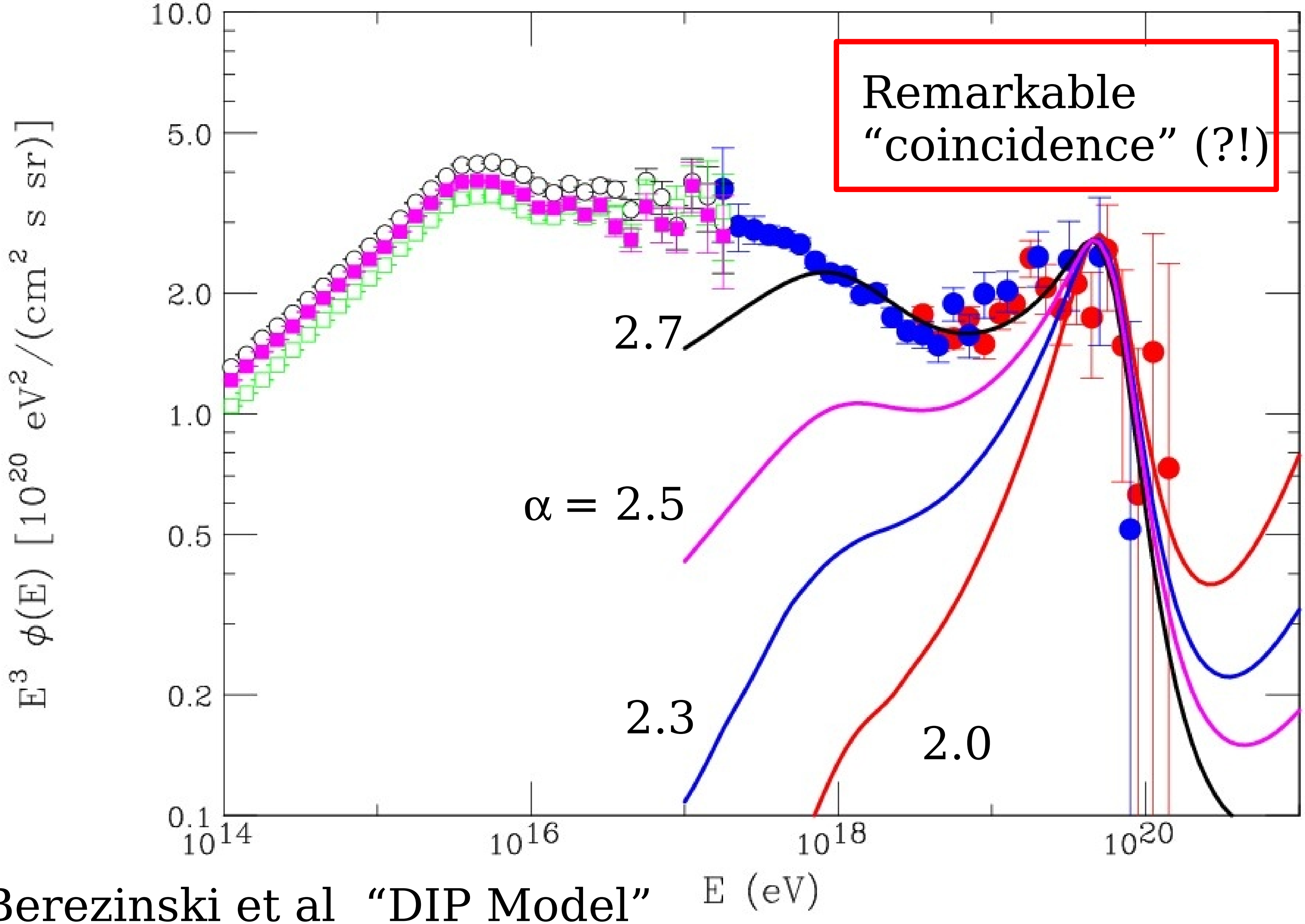
UHECR Flux * E^3 representation.



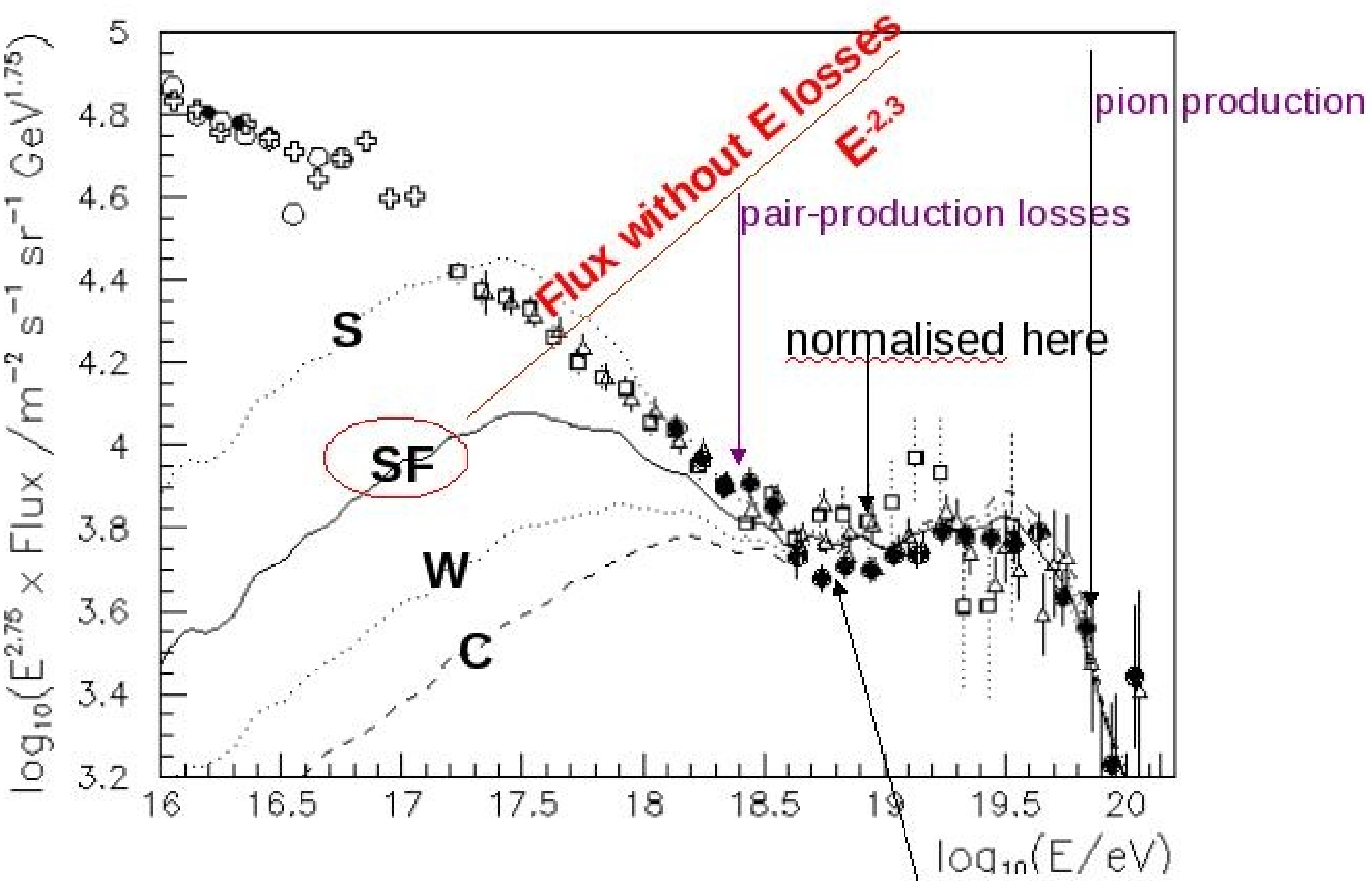
Power Law Injection (No Cosmic Evolution)



Power Law Injection (No Cosmic Evolution)



Berezinski et al "DIP Model"



Spectrum of **protons** after struggling through the microwave treacle:

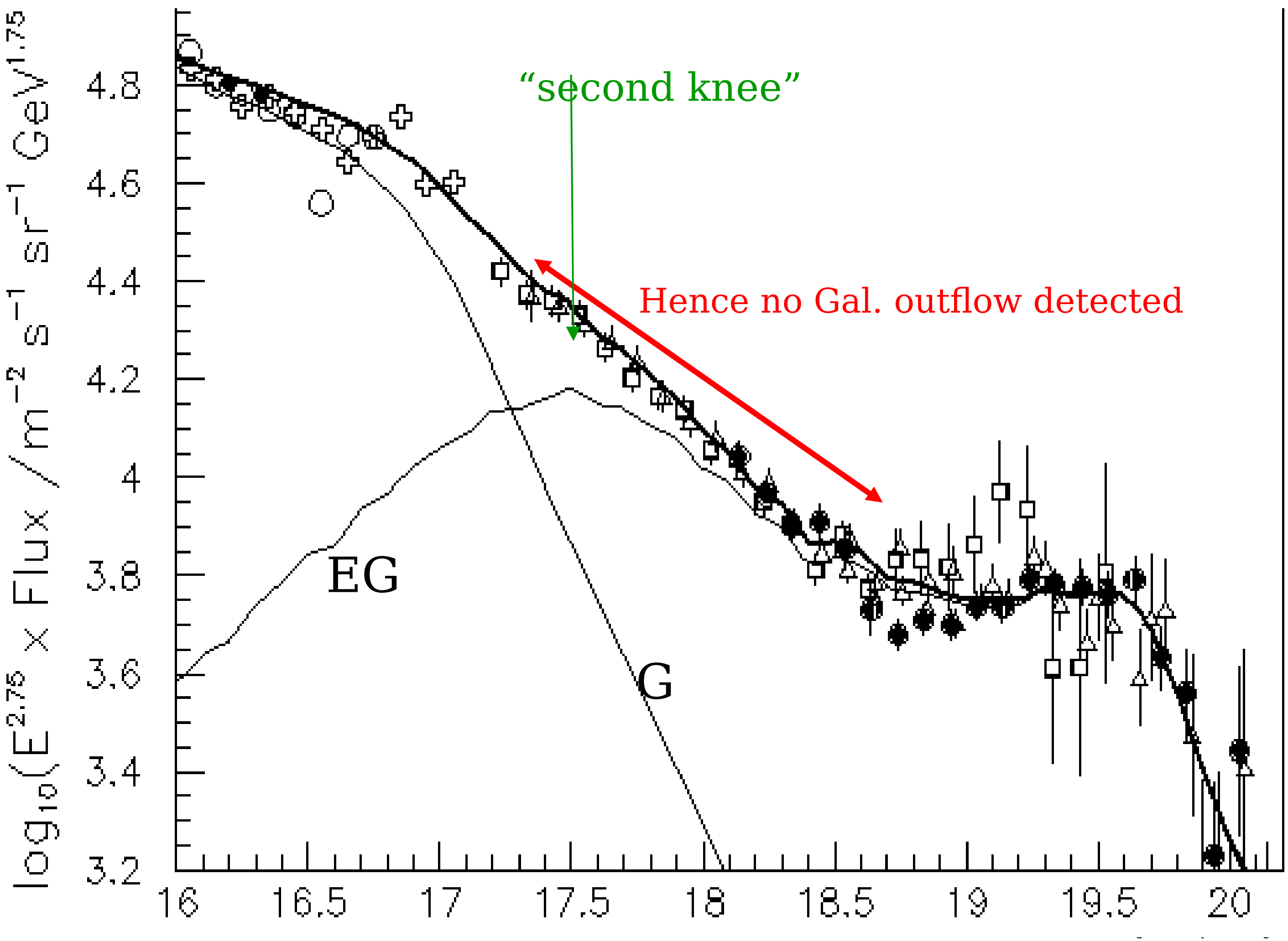
If initial spectrum dN/dE ~ $E^{-2.3}$,

Production rate in universe: **SF** = like Porciani-Madau star formation rate SF2; **C**=constant; **W**=$PM^{0.5}$; **S**= $PM^{1.5}$

The (e^+e^-)energy losses in CMBR produce an ANKLE in right place.

from Michael Hillas

Combine galactic and extragalactic part



from Michael Hillas

"Average Power Density"

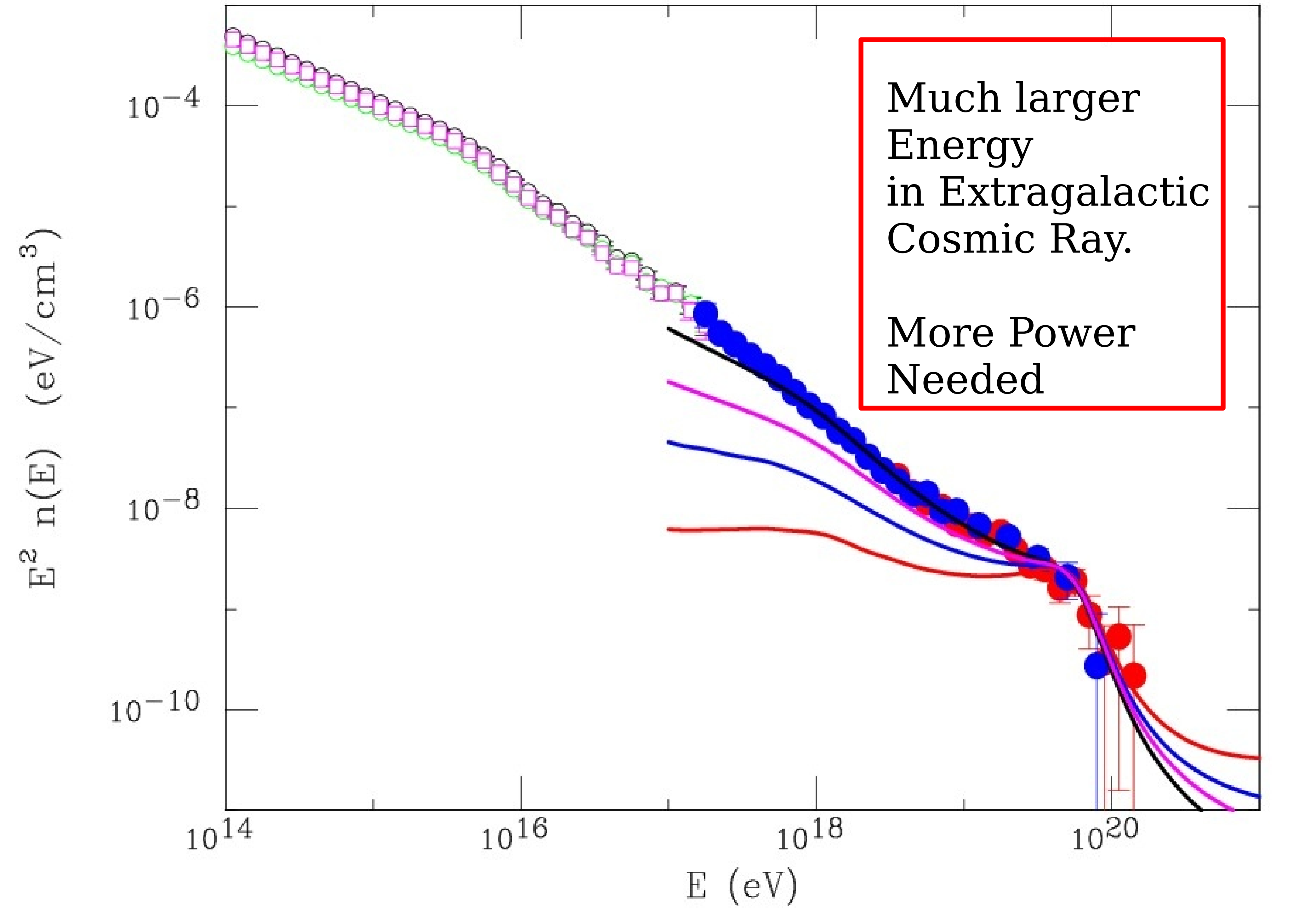
needed to produce
the Extra-Galactic Cosmic Rays

$$\rho_{\rm cr}^{\rm extra} = \int dt \; \frac{\mathcal{L}_{\rm cr}(t)}{1+z(t)} = \int dz \; \frac{\mathcal{L}_{\rm cr}(z)}{H(z)\,(1+z)^2} = \frac{\mathcal{L}_{\rm cr}(0)}{H_0} \; f$$

Present CR
Energy density

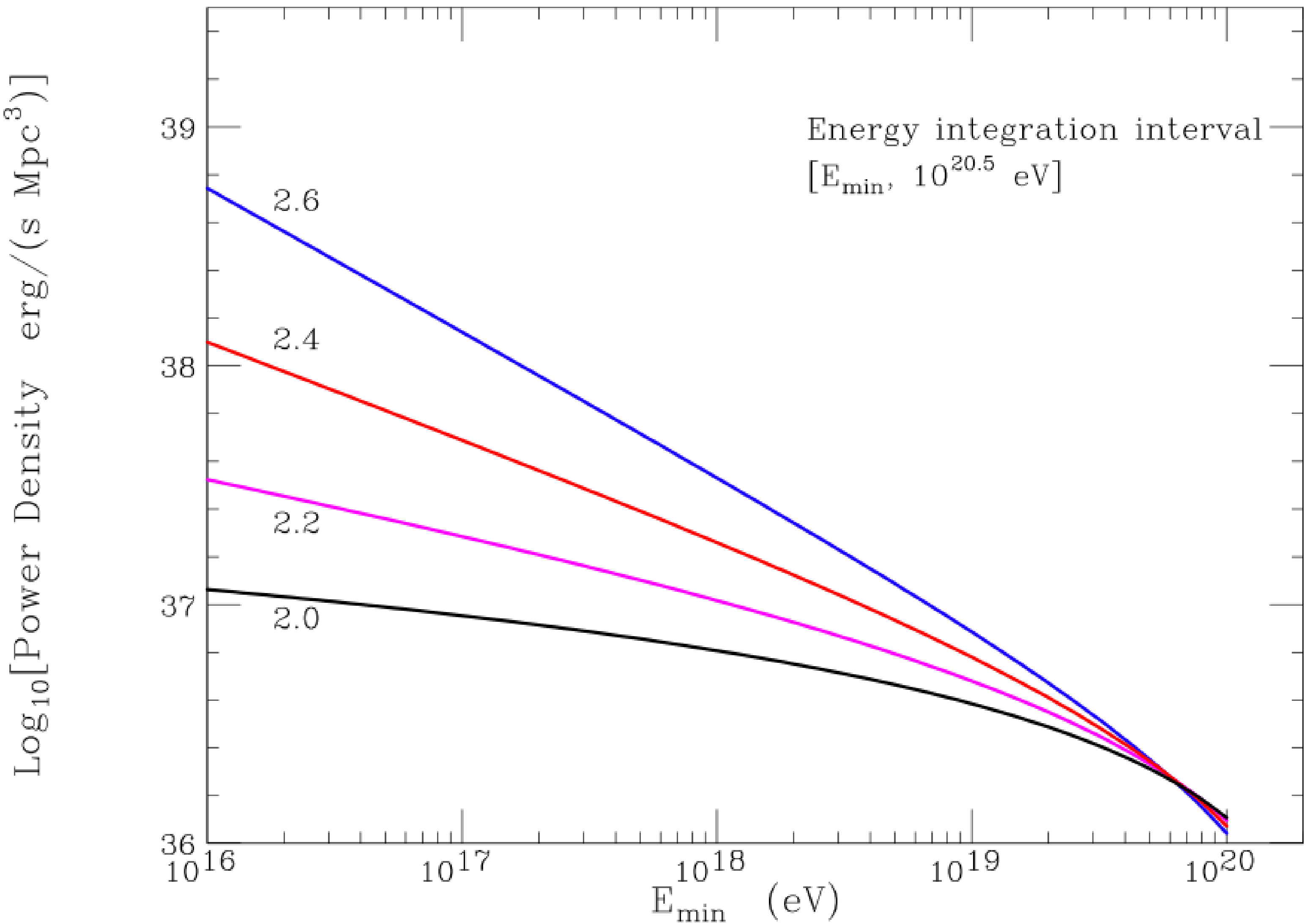
Accumulation of cosmic rays emitted
During the history of the universe

Cosmic Ray Energy Density



Much larger
Energy
in Extragalactic
Cosmic Ray.

More Power
Needed

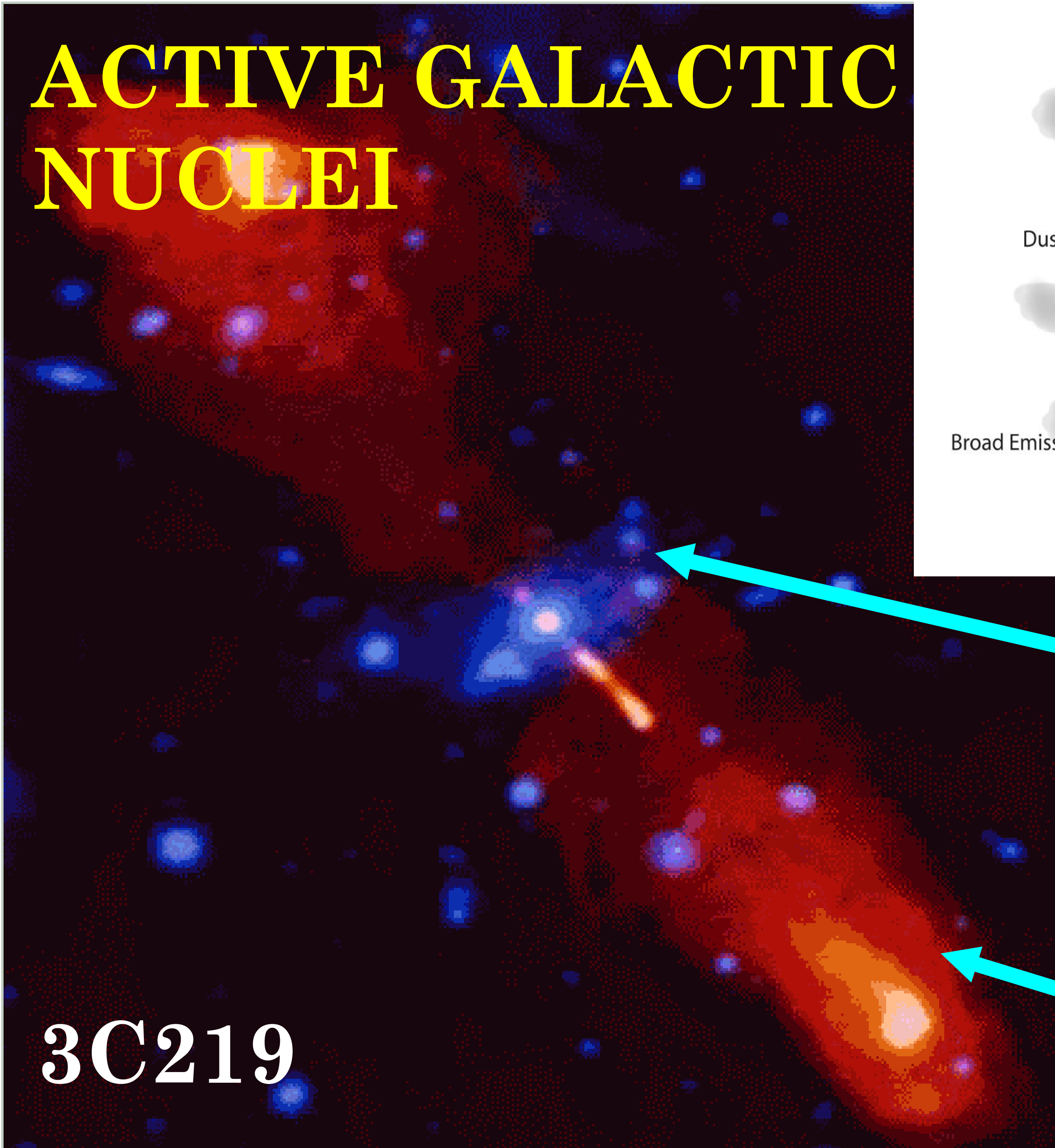


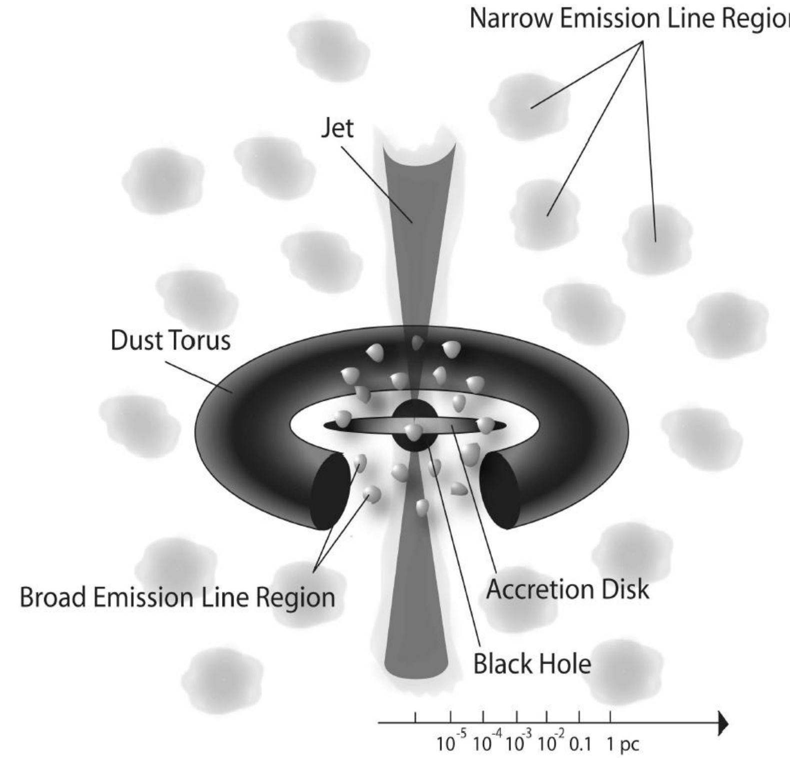
$$\mathcal{L}^0_{cr}[E \geq 10^{19}\ \mathrm{eV}] \simeq (3 \div 6) \times 10^{36}\ \frac{\mathrm{erg}}{\mathrm{Mpc}^3 s}$$

Available Energy Sources in the Universe

$$\mathcal{L}_{\rm SN}^{\rm kin} \simeq 3 \times 10^{40}\ {\rm erg/(Mpc^3 s)}$$

$$\mathcal{L}_{\rm AGN}^{\rm bolometrix} \simeq 2 \times 10^{40}\ \left(\frac{\rm erg}{\rm s\ Mpc^3}\right)$$


ACTIVE GALACTIC NUCLEI
3C219
Optical
Radio


Narrow Emission Line Region
Jet
Dust Torus
Broad Emission Line Region
Accretion Disk
Black Hole
10^-5 10^-4 10^-3 10^-2 0.1 1 pc

Super-Massive Black Hole

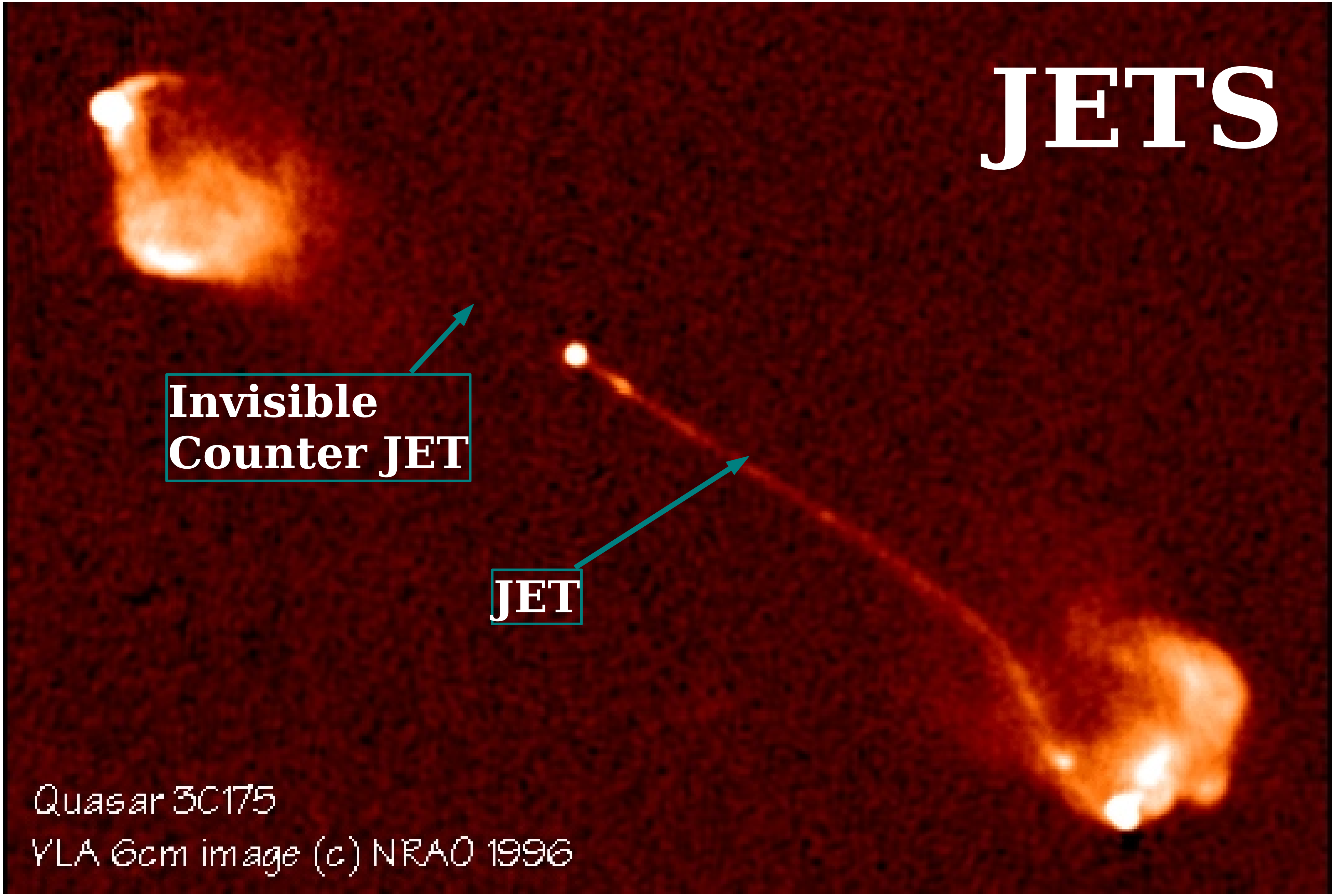
$$M = 10^4 \div 10^{10}\ M_\odot$$

Accretion Power

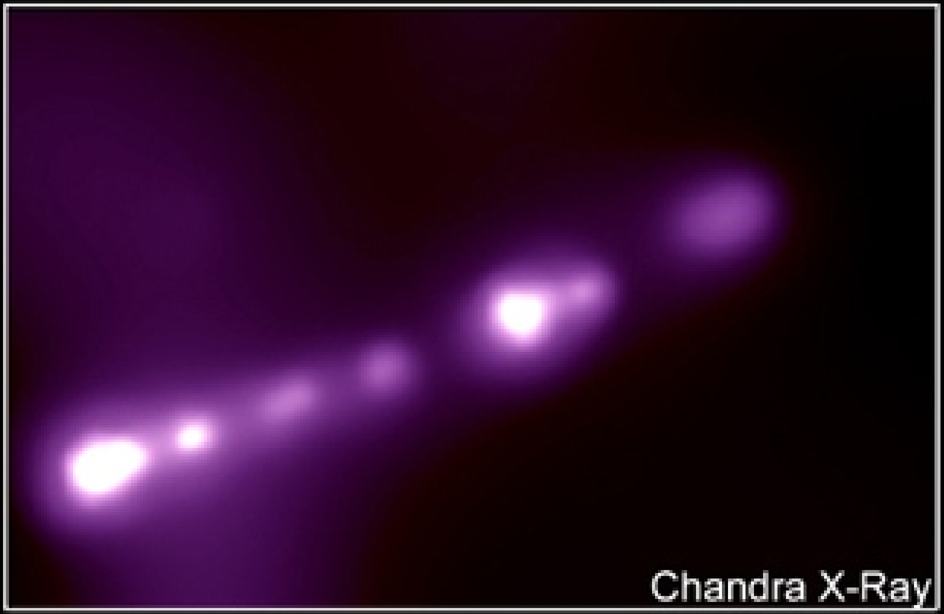
$$L = \frac{G\ M\ \dot{m}\, c^2}{R}$$

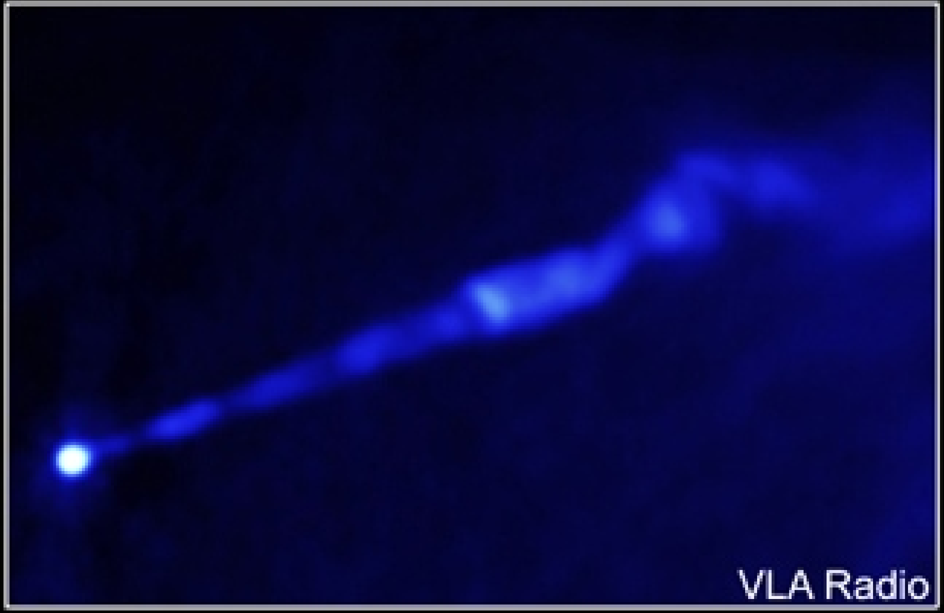
$$R \sim 5 R_{\mathrm{Schwarzschild}} = 10\ G\ M$$

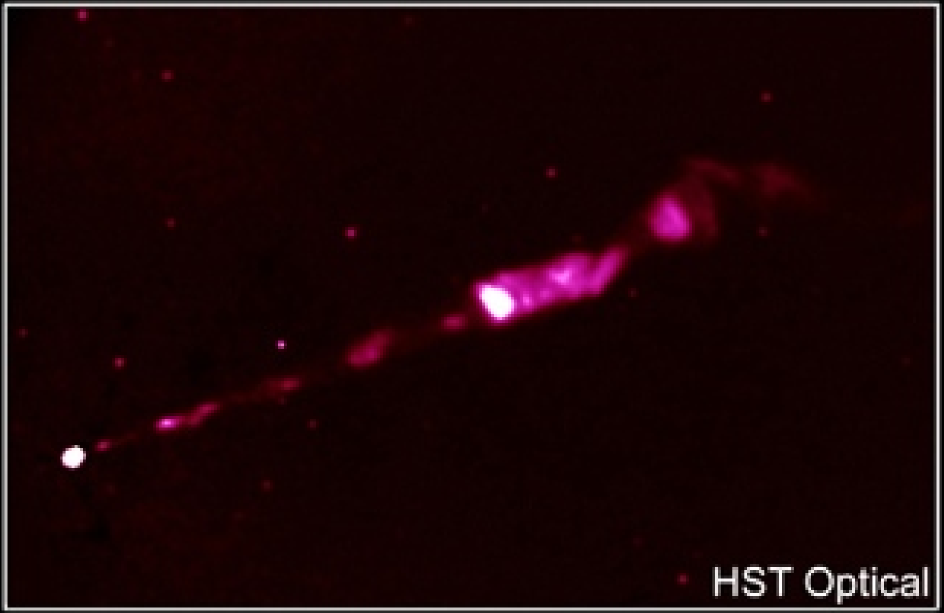
$$L \sim 0.1\, \dot{m}\, c^2$$


JETS
Invisible
Counter JET
JET
Quasar 3C175
VLA 6cm image (c) NRAO 1996

M87







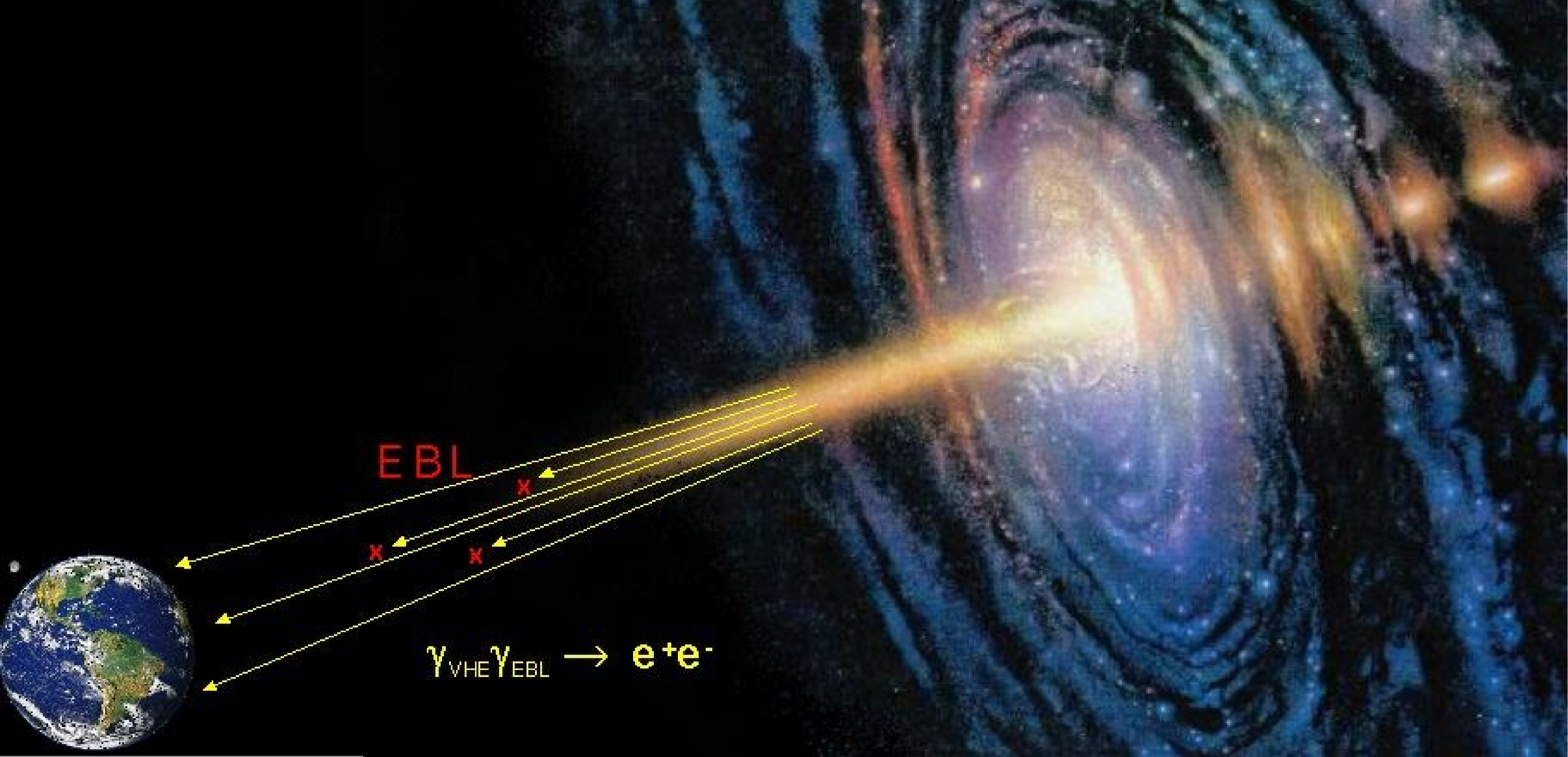
Extragalactic VHE Gamma-Ray Sources

	Name	Discovered	Year	z	Contributions
	M 87	HEGRA	2003	0.004	VERITAS-Colin, HESS-Beilicke, MAGIC-
	Mrk 421	Whipple	1992	0.031	MILAGRO-Smith, VERITAS-Fegan, +
	Mrk 501	Whipple	1996	0.034	TACTIC-Godambe, MAGIC-Paneque, +
	1ES 2344+514	Whipple	1998	0.044	MAGIC-Wagner
→	Mrk 180	MAGIC	2006	0.046	MAGIC-Mazin
	1ES 1959+650	TA	2002	0.047	MAGIC-Hayashida
→	BL Lac	MAGIC	2006	0.069	MAGIC-Hayashida
→	PKS 0548-322	HESS	2006	0.069	HESS-Superina
	PKS 2005-489	HESS	2005	0.071	HESS-Costamante
	PKS 2155-304	Durham	1999	0.116	HESS-Punch, CANGAROO-Sakamoto, +
	H 1426+428	Whipple	2002	0.129	VERITAS-Krawczynski
→	1ES 0229+200	HESS	2007	0.140	HESS-Raue
	H 2356-309	HESS	2005	0.165	HESS-Costamante
	1ES 1218+304	MAGIC	2005	0.182	MAGIC-Hayashida
	1ES 1101-232	HESS	2005	0.186	HESS-Puelhofer
→	1ES 0347-121	HESS	2007	0.188	HESS-Raue
→	1ES 1011+496	MAGIC	2007	0.212	MAGIC-Mazin
→	PG 1553+113	HESS/MAGIC	2005	?	MAGIC-Wagner, HESS-Benbow
→	3C 279	MAGIC	2007	0.536	MAGIC-Teshima

8 new AGN

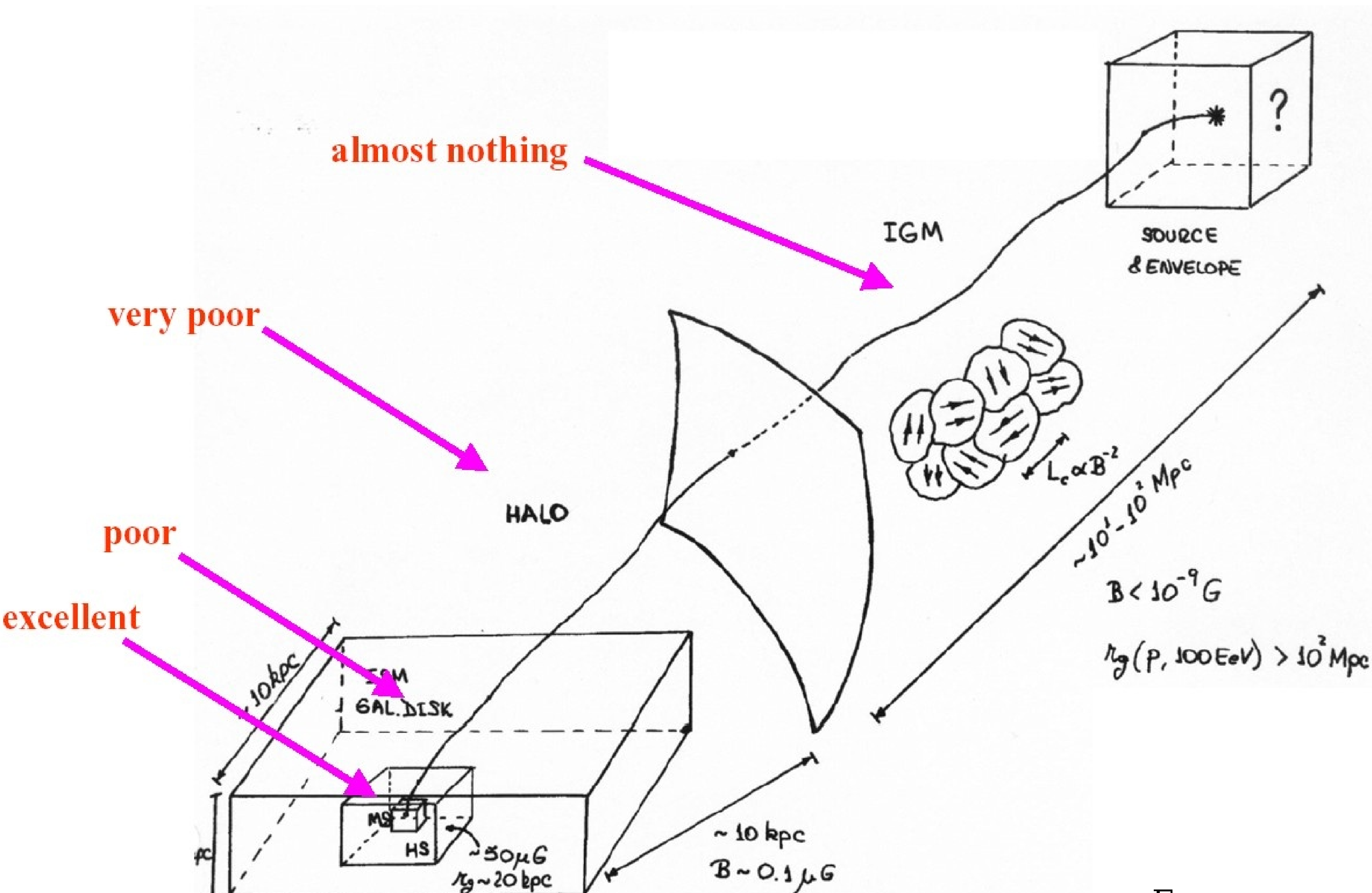
Extragalactic TeV astronomy

- Physics of AGN jets
- Density of cosmological extragalactic background light (EBL)



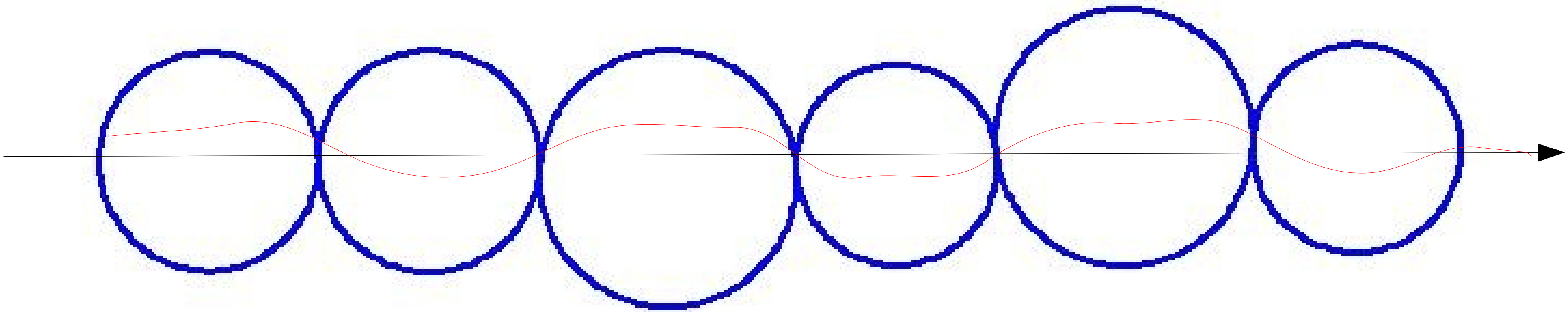
Opening of

Cosmic Ray Astronomy [?]



From:
Medina Tanco

$$(\delta\theta)_{\rm ExtraGalactic} \simeq \frac{d}{r_{\rm L}} \sqrt{N_{\rm regions}} \simeq \frac{d}{r_{\rm L}} \sqrt{\frac{D}{d}}$$



D Distance of source

$$r_{\rm Larmor} = \beta_\perp \frac{E}{q\ B}$$

d Coherence Length of Magnetic Field

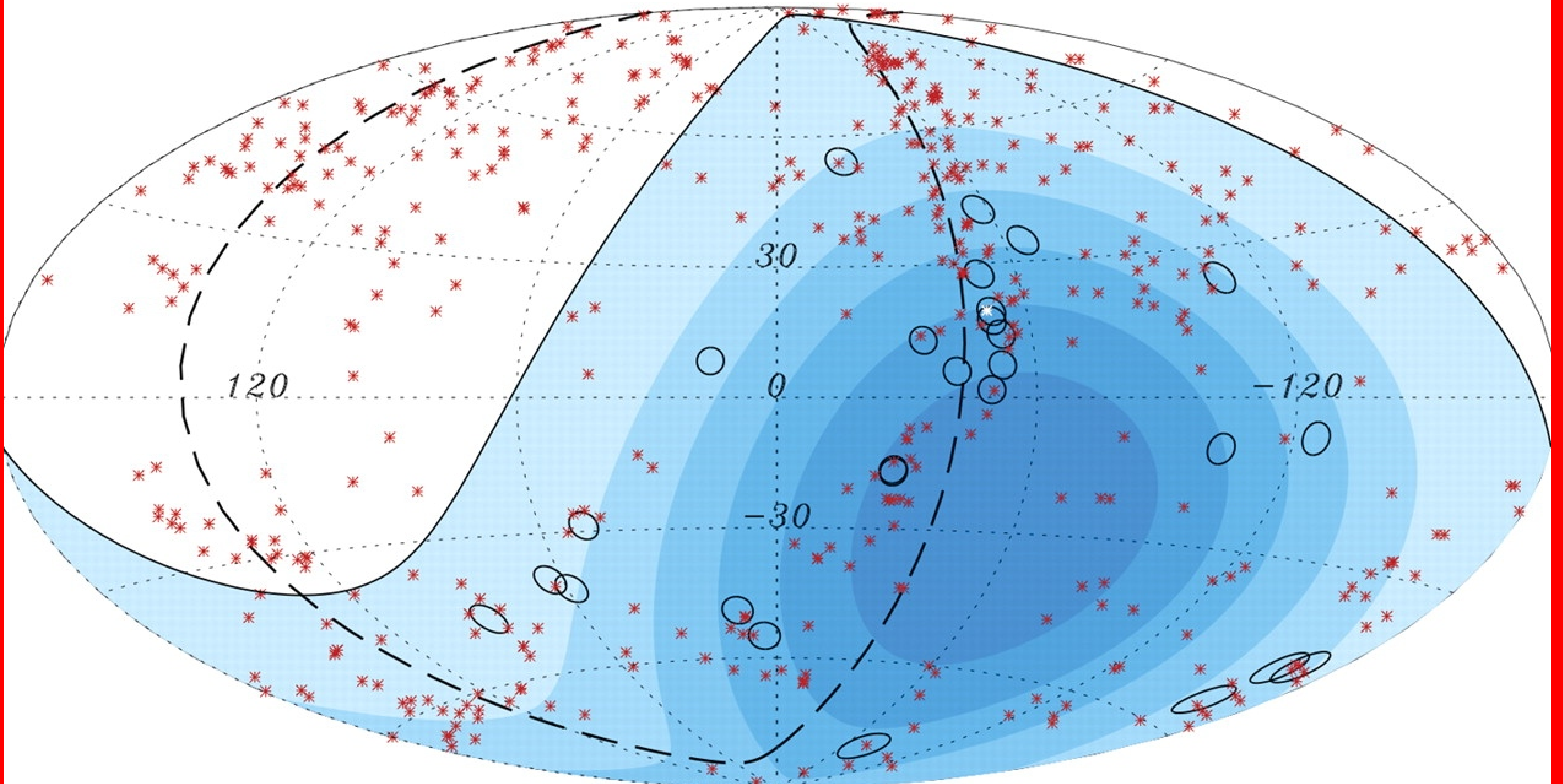
AUGER RESULT

$D \lesssim 75$ Mpc

CR come from
3.1 degrees from the sources
20/27 coincident with near AGN

$E \gtrsim 0.56 \times 10^{20}$ eV

$\delta\theta \lesssim 3.1^\circ$



$$(\delta\theta)_{\rm ExtraGalactic} = \frac{0.53^\circ}{Z} \left(\frac{10^{20}\ {\rm eV}}{E}\right) \left(\frac{\sqrt{D\ d}}{\rm Mpc}\right) \left(\frac{\rm nGauss}{\langle B\rangle_{\rm Extra}}\right)$$

$$D \lesssim 75\ {\rm Mpc}$$

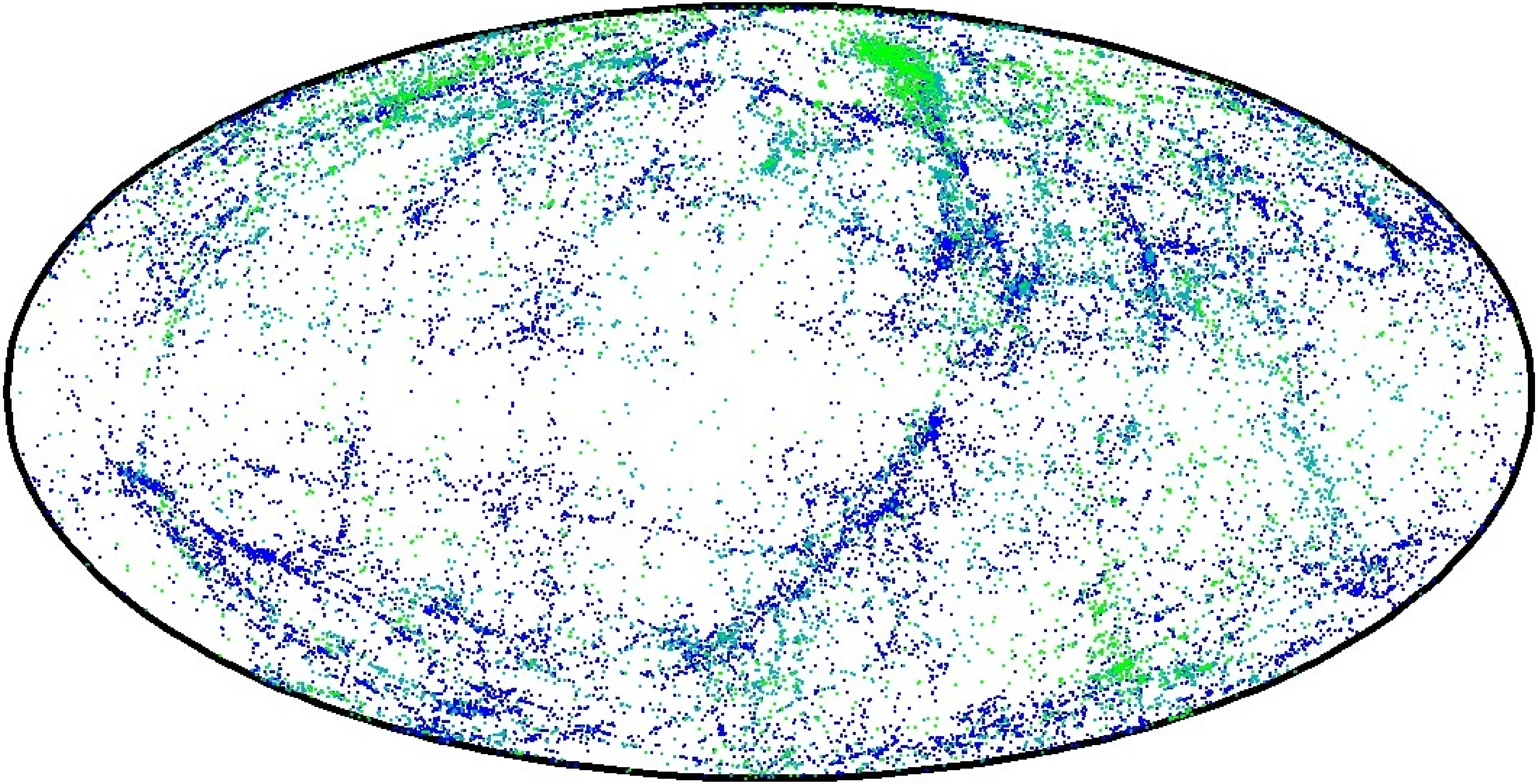
$$E \gtrsim 0.56 \times 10^{20}\ {\rm eV}$$

$$\delta\theta \lesssim 3.1^\circ$$

$$\langle B\rangle_{\rm Extra} \lesssim \frac{0.38}{Z\ \sqrt{d_{\rm Mpc}}}\ {\rm nGauss}$$

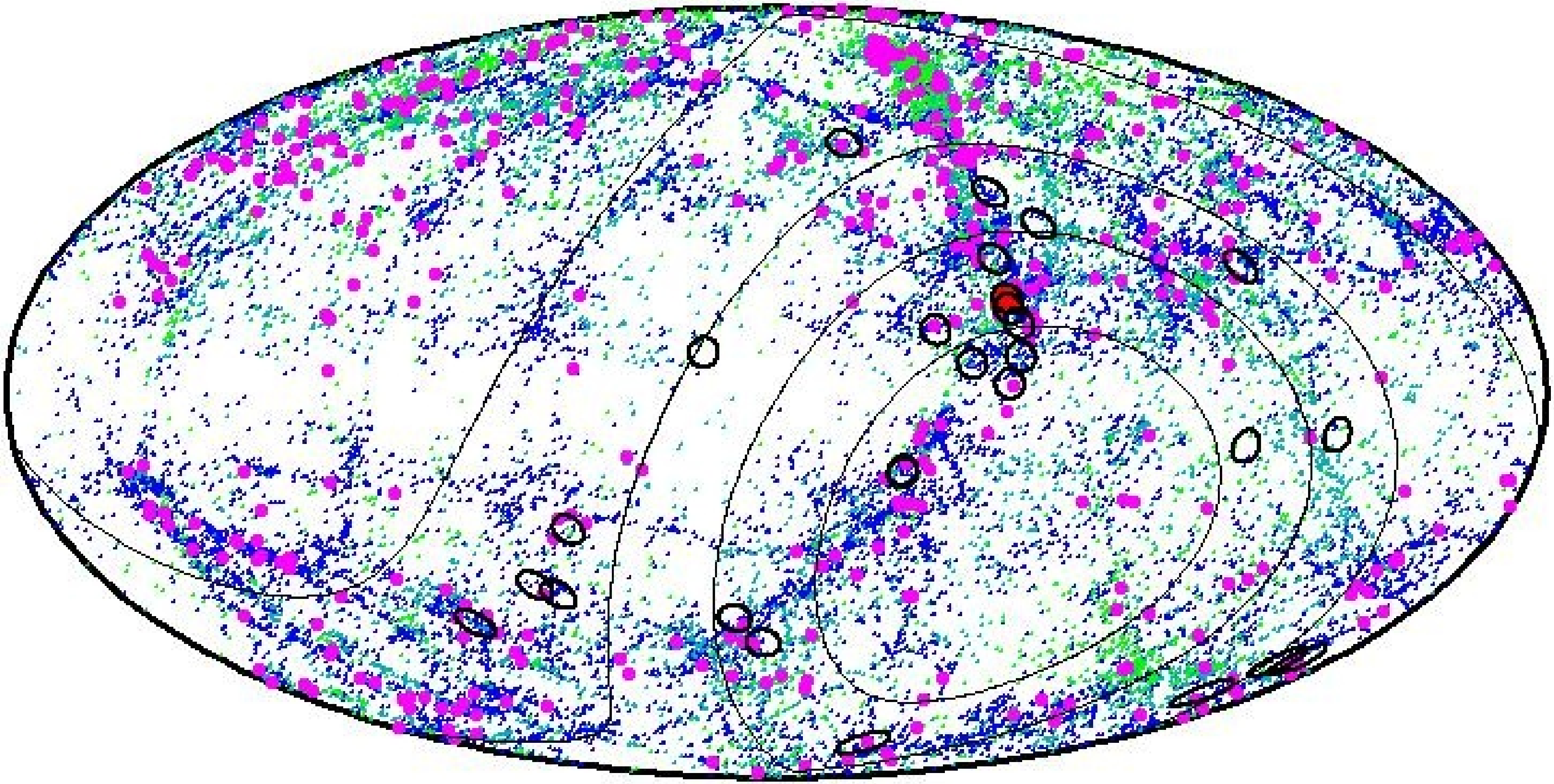
Estimate of the Extragalactic Magnetic Field

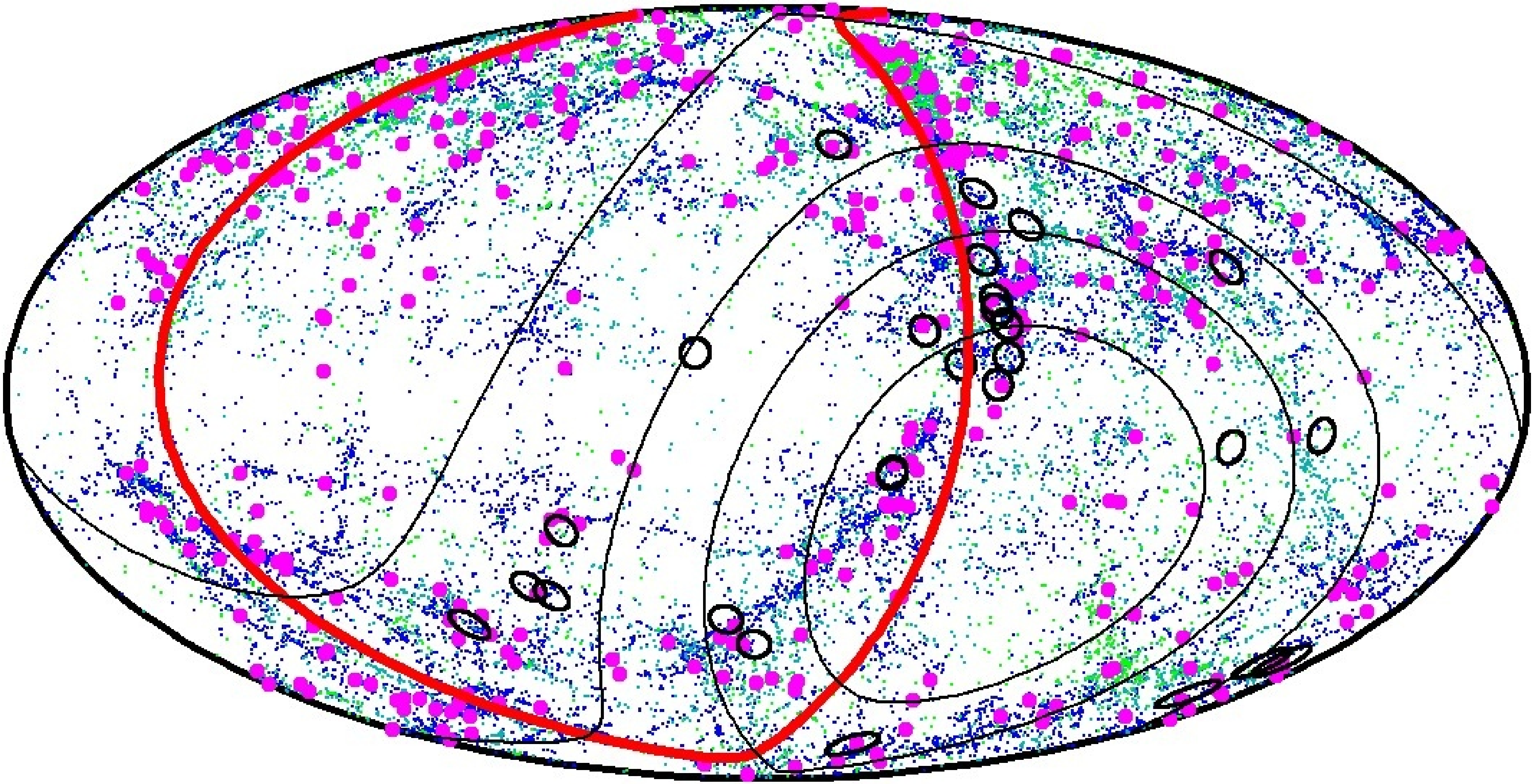
Galaxies with Redshift z < 0.018



- Graphics -

Galaxies with Redshift z < 0.018
AGN in same Volume
Auger Events

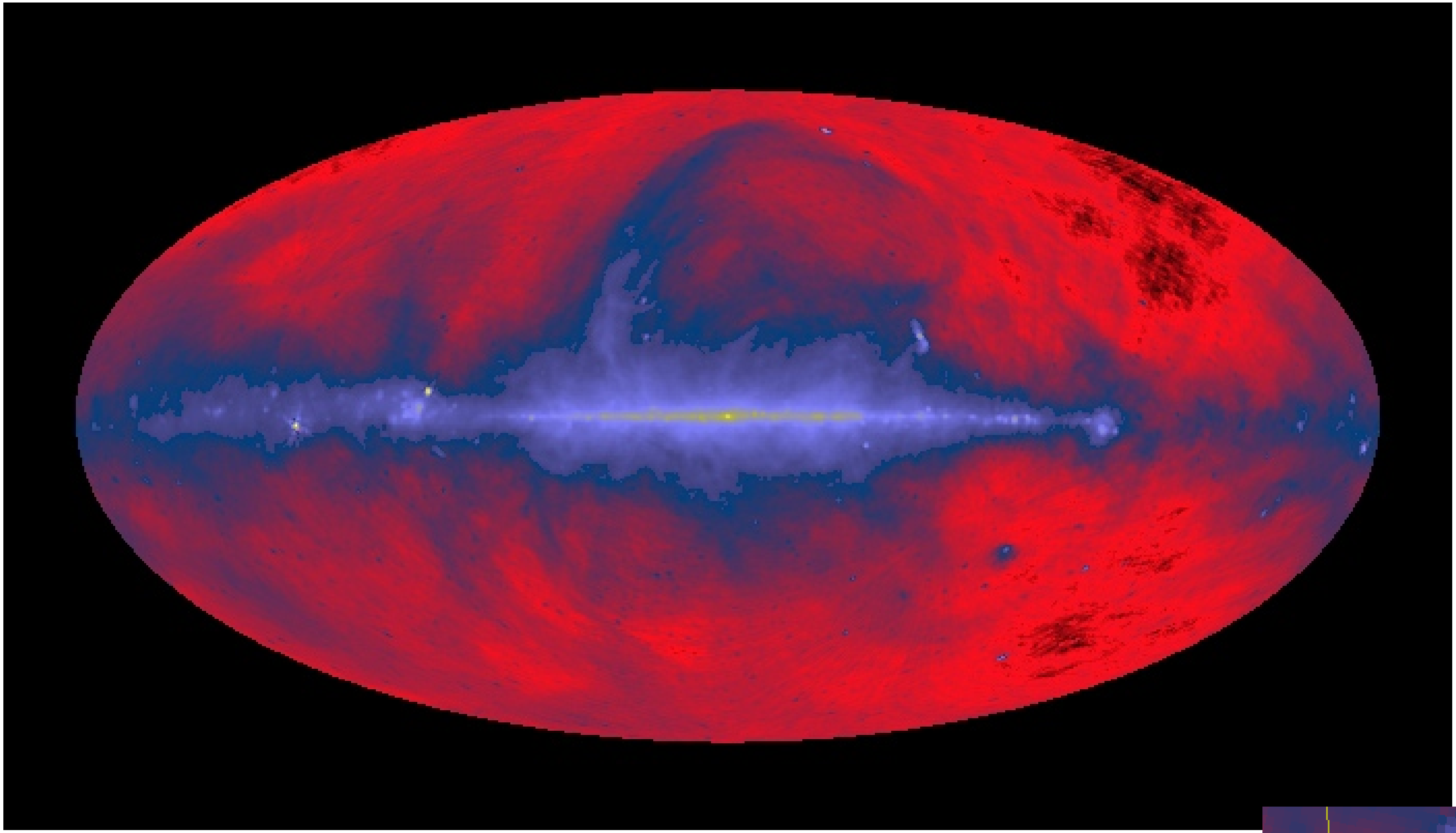




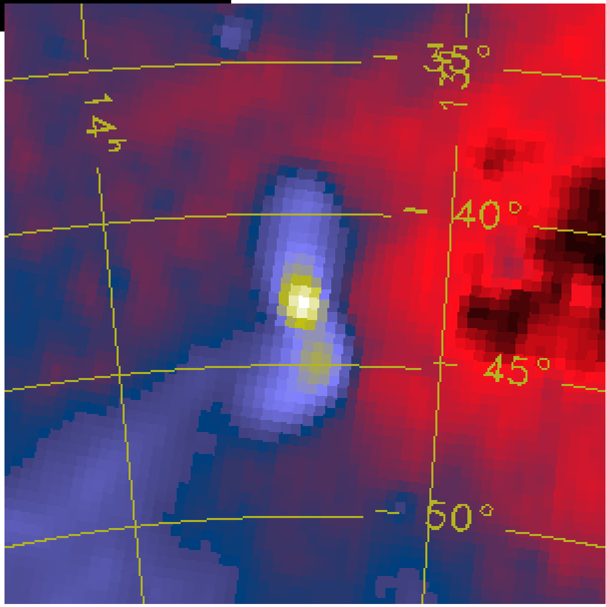
CENTAURUS A

(with very high probability)

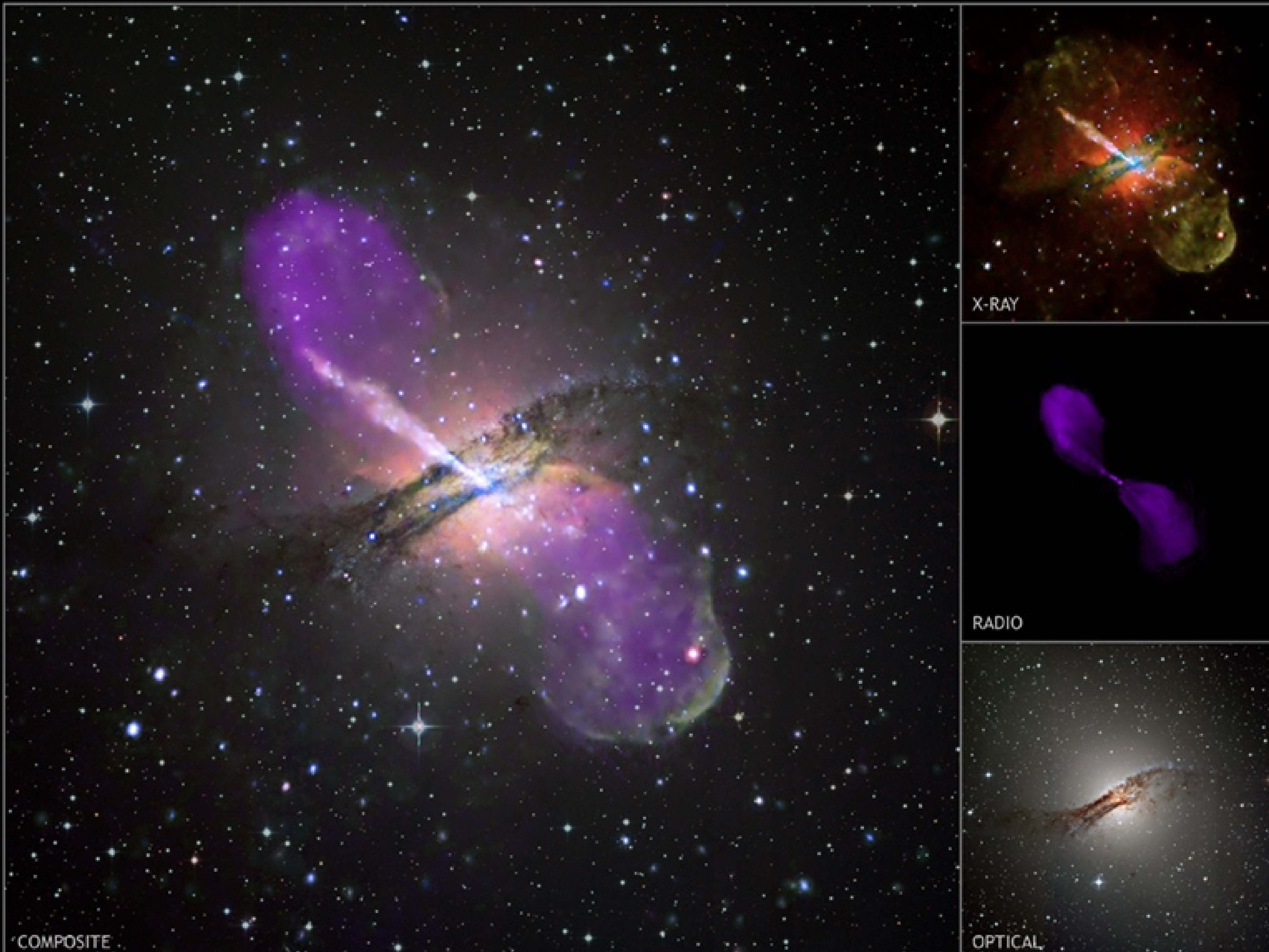
First object imaged with Cosmic Rays

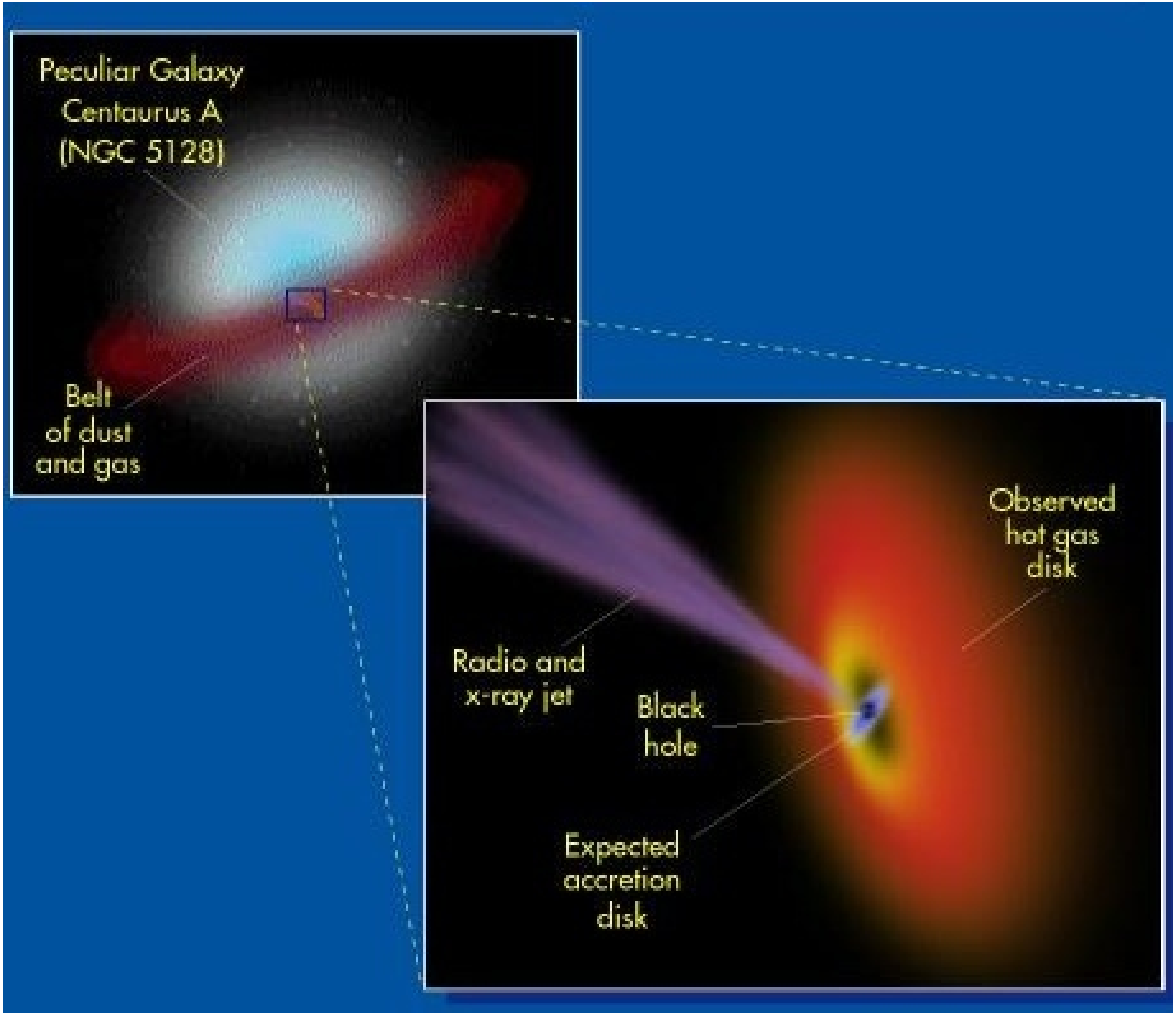


Radio Image
408 MHz



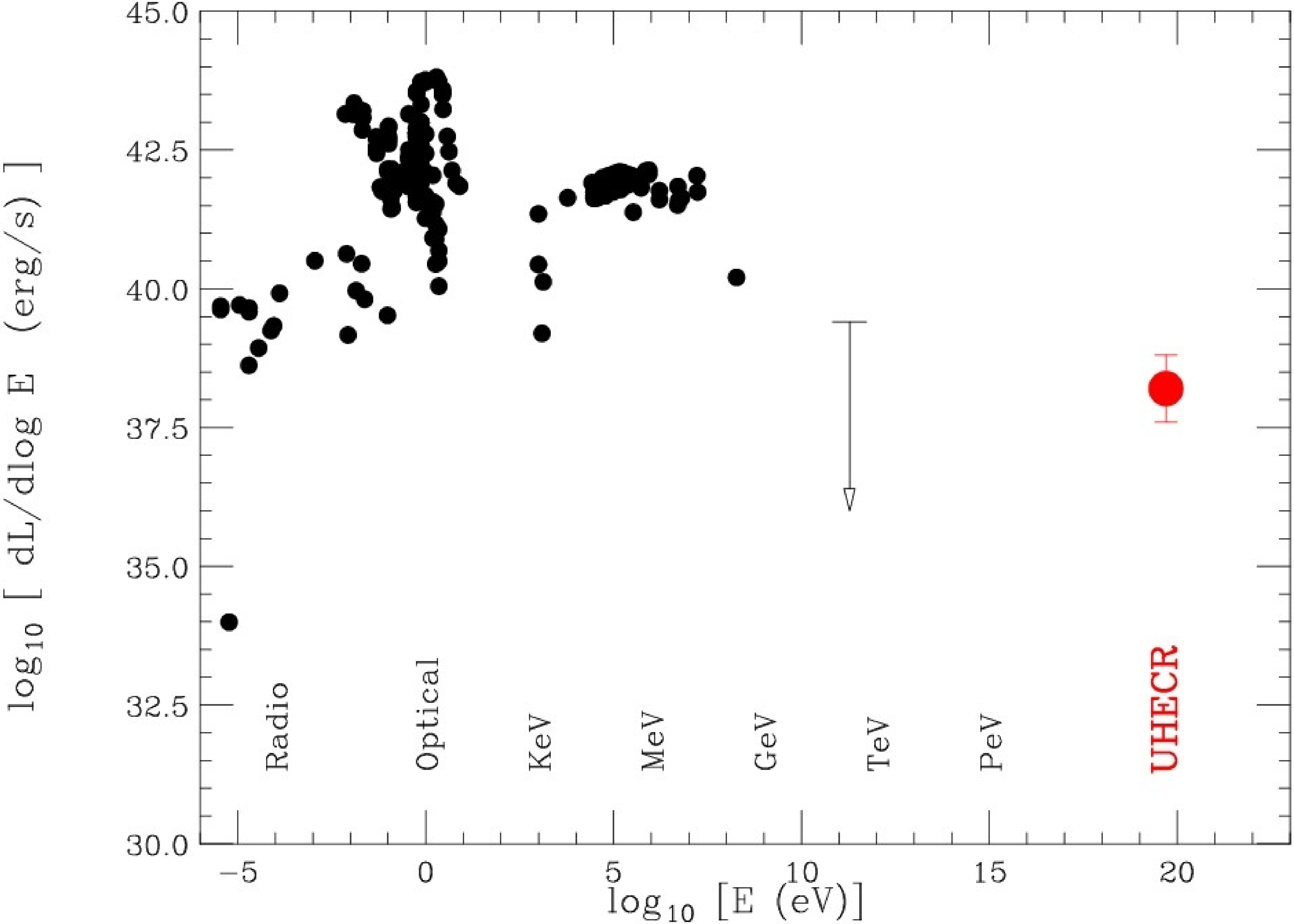
Chandra
X-ray
image


COMPOSITE
X-RAY
RADIO
OPTICAL



Peculiar Galaxy
Centaurus A
(NGC 5128)
Belt
of dust
and gas
Observed
hot gas
disk
Radio and
x-ray jet
Black
hole
Expected
accretion
disk

Spectral Energy Distribution of CEN A

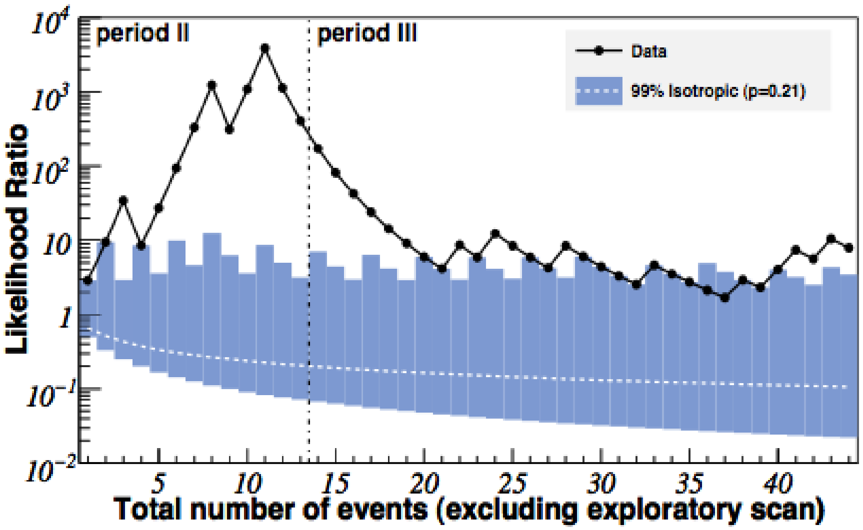


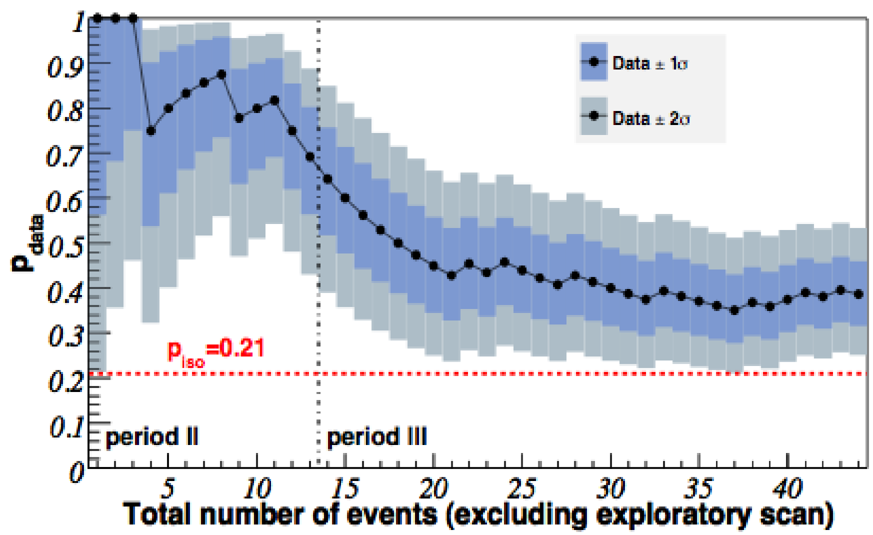
Several puzzles:

Non confirmation by HIRES

New (just released) AUGER data

18/27 events in correlation in first data set
8/31 in new data set





Cosmic Ray Composition

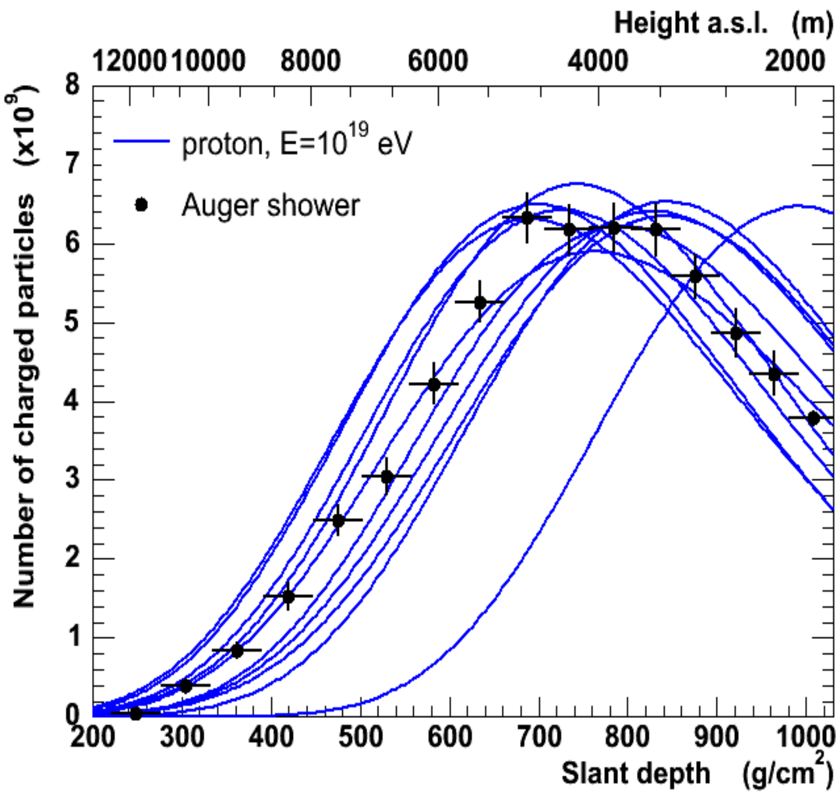
and

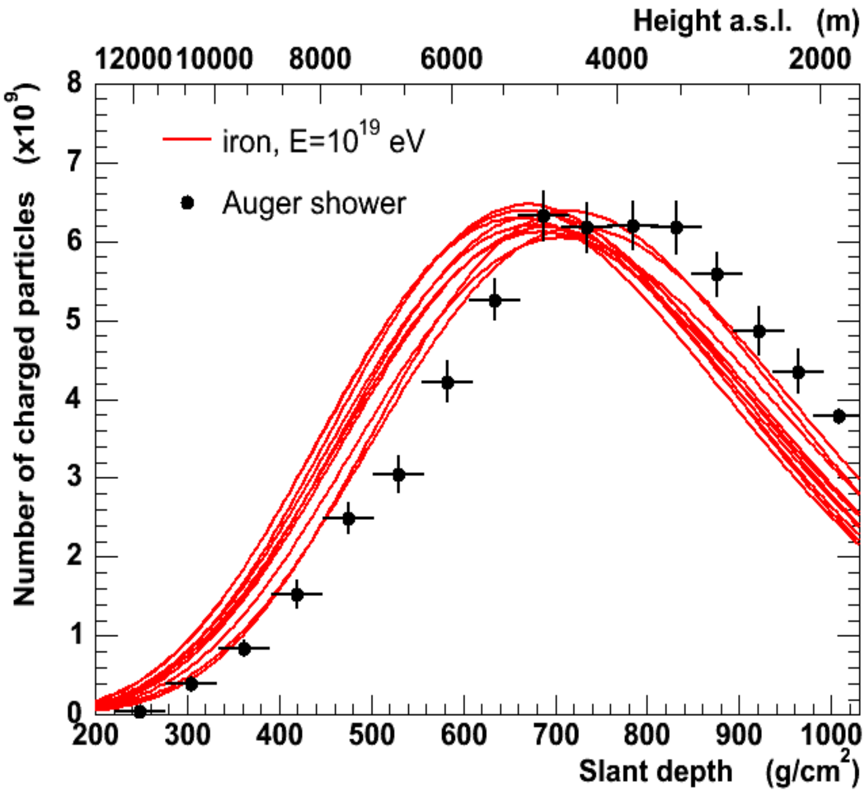
Hadronic interactions

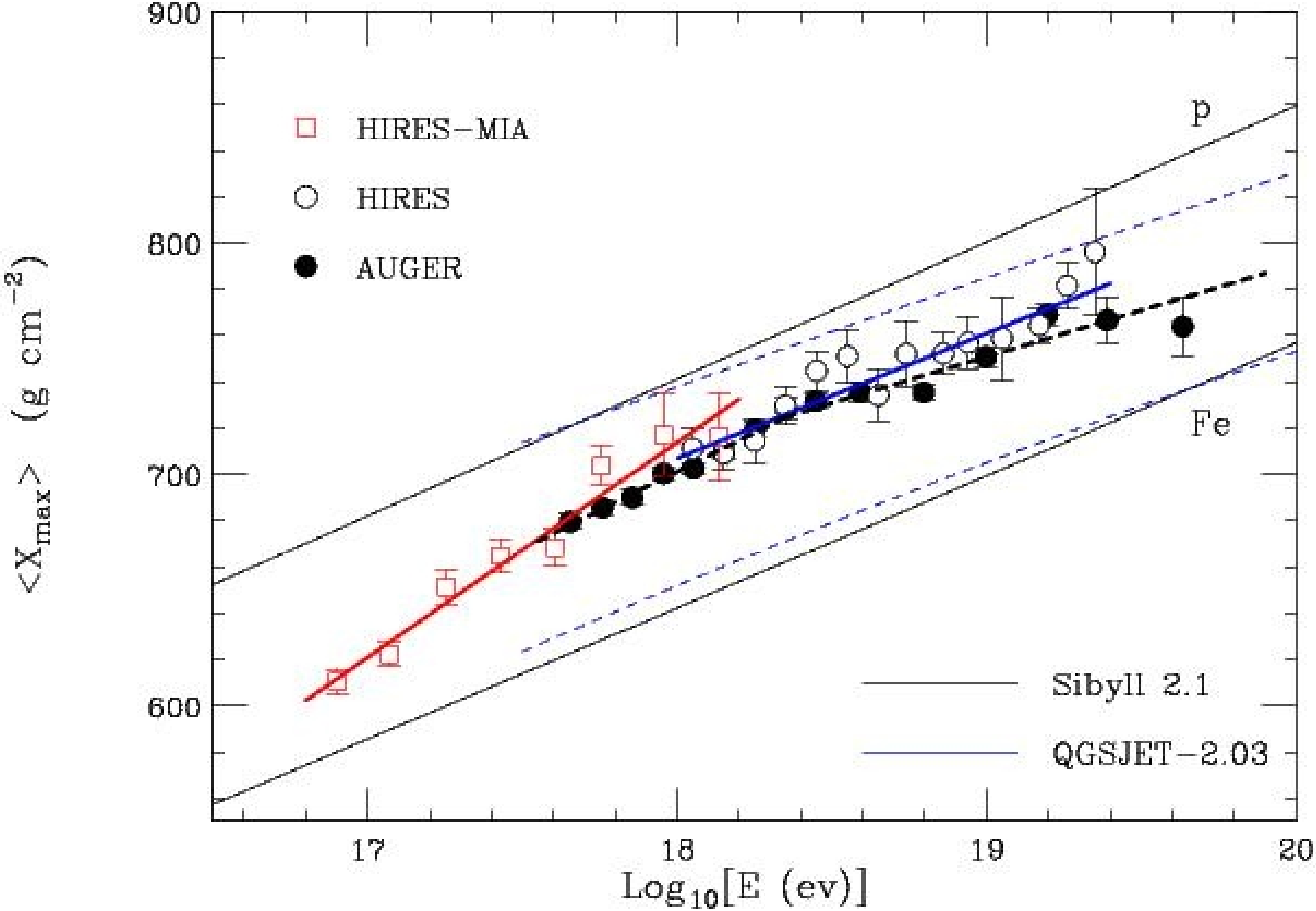
Fluorescence Light Composition Measurements

SHAPE of the Shower Longitudinal Development dependences:

Composition
Hadronic Interaction Modeling







900
800
700
600
$\langle X_{max} \rangle$ (g cm^{-2})
HIRES−MIA
HIRES
AUGER
p
Fe
Sibyll 2.1
QGSJET−2.03
17
18
19
20
Log$_{10}$[E (ev)]

X_{max} and the Composition of Cosmic Rays

Proton Showers

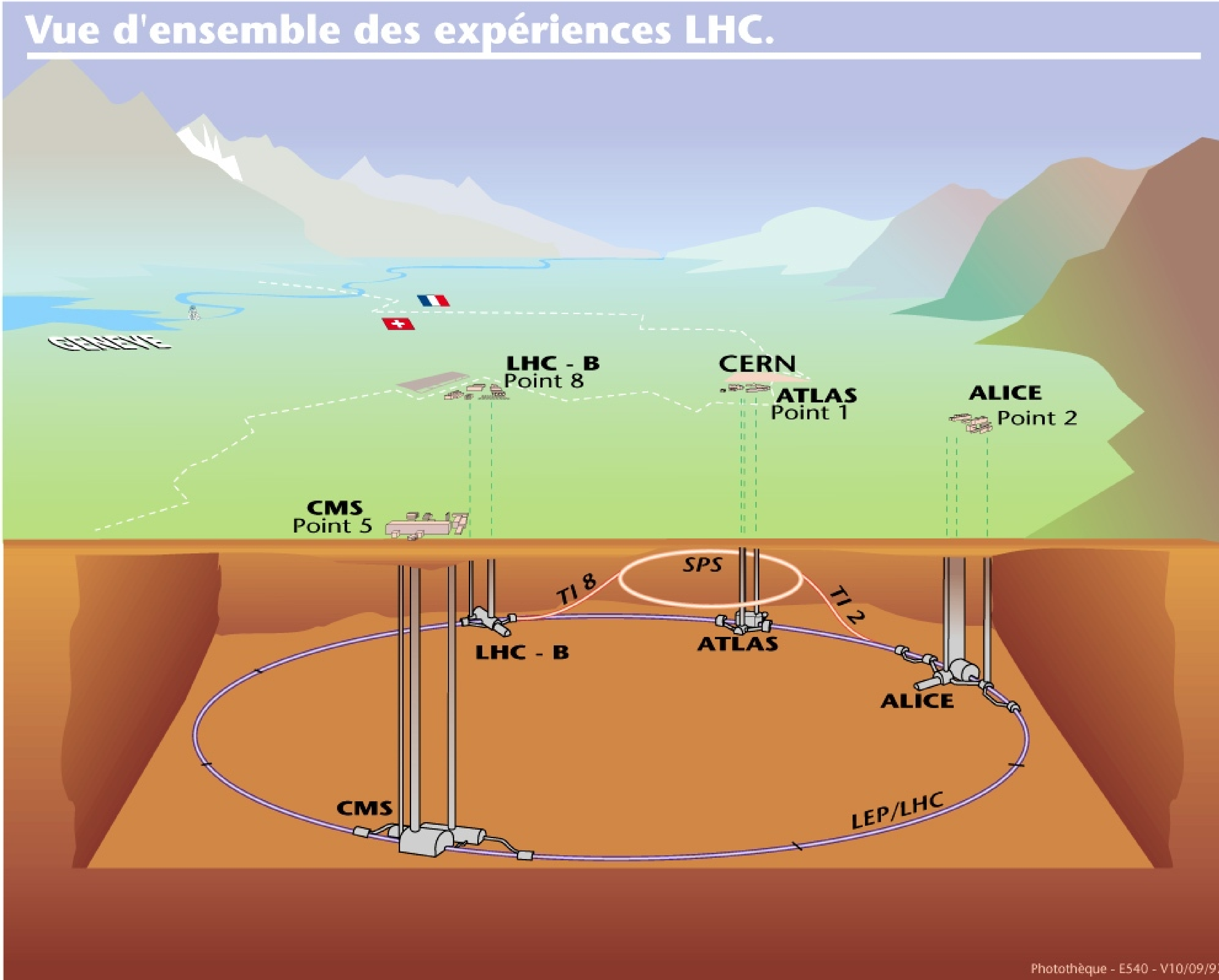
$$X^p_{\rm max}(E) = X^p_{\rm max}(E^*) + D_p(E^*)\ \ln\left(\frac{E}{E^*}\right)$$

Logarithmic growth of average X_{max} with energy

$$X^A_{\rm max}(E) \simeq X^p_{\rm max}\left(\frac{E}{A}\right)$$

Mass dependence

$$\langle X_{\rm max}(E)\rangle \simeq X^p_{\rm max}(E) - D_p(E)\ \ \langle \ln A\rangle$$


Vue d'ensemble des expériences LHC.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
Photothèque - E540 - V10/09/97

Obtain the average mass and its variation with energy

$$\langle \ln A \rangle_E = \frac{\sum_A \phi_A(E)\ \ln A}{\sum_A \phi_A(E)}$$

$$\langle \ln A \rangle_E = \frac{\langle X_{\max}(E) \rangle - X_p(E)}{D_p}$$

$$\frac{d\langle \ln A \rangle_E}{d \ln E} = 1 - \frac{D_{\exp}}{D_p}$$

Sibyll-Interpretation

$$\langle \log_{10} A \rangle_{\rm Sibyll} \simeq 0.83 \pm 0.21$$

$$\langle \log_{10} A \rangle_{\rm Sibyll} \simeq \log \left[6.8 \; {}^{+4.1}_{-2.1} \right]$$

$$\left[\frac{p}{\rm Fe} \right]_{\rm Sibyll} = 1.1 \pm 0.2$$

$$\left[\frac{d\langle \log A \rangle}{d \log E} \right]_{\rm Sibyll} \simeq 0.32 \pm 0.07$$

$$[\beta]_{\rm Sibyll} = -0.7 \pm 0.15$$

SYSTEMATIC UNCERTAINTY ??

Composition is Mixed

50% p
50% Fe

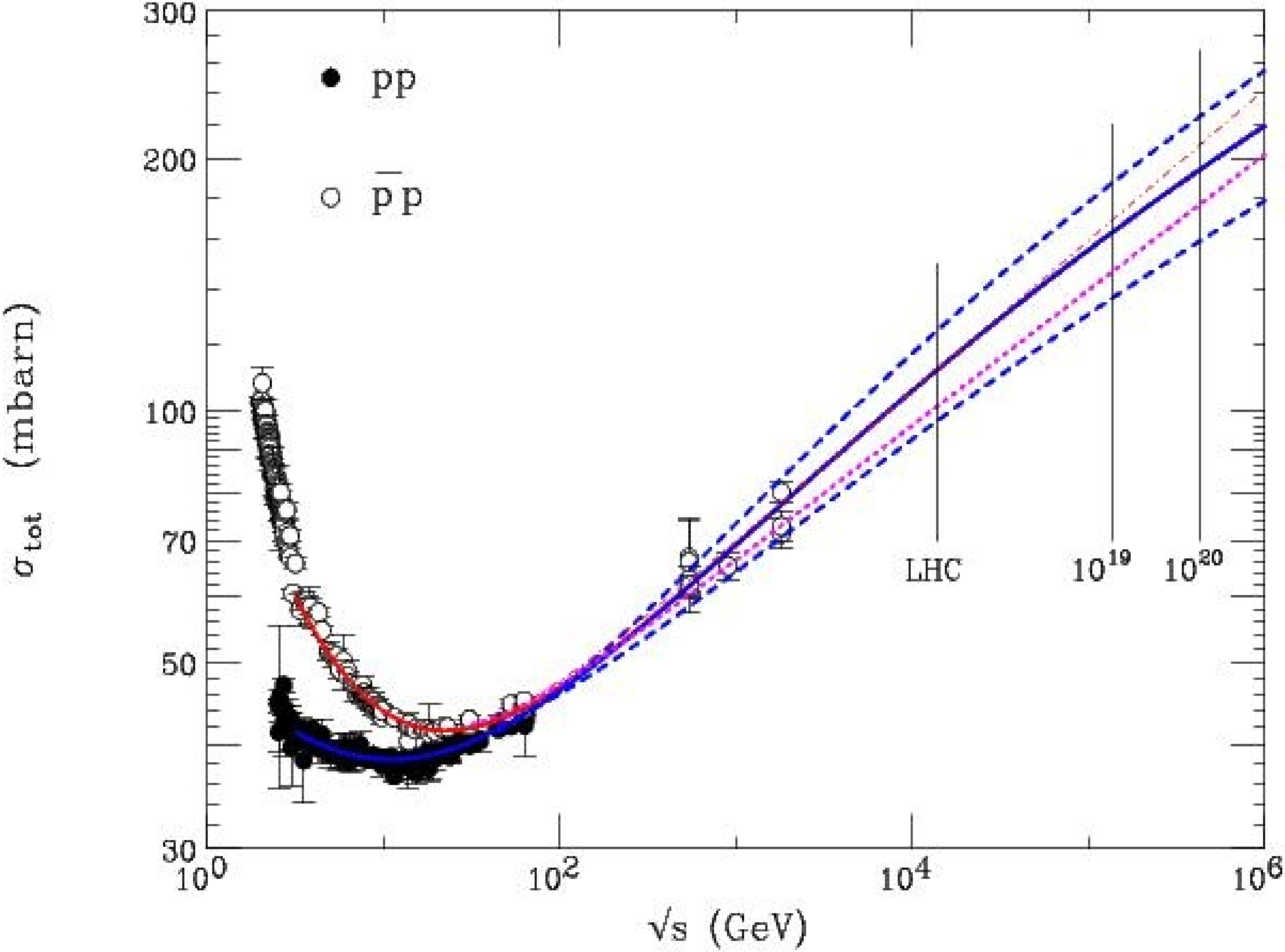
Composition become heavier with increasing Energy

Data

$$\langle \ln A \rangle_E = \frac{\langle X_{\max}(E) \rangle - X_p(E)}{D_p}$$

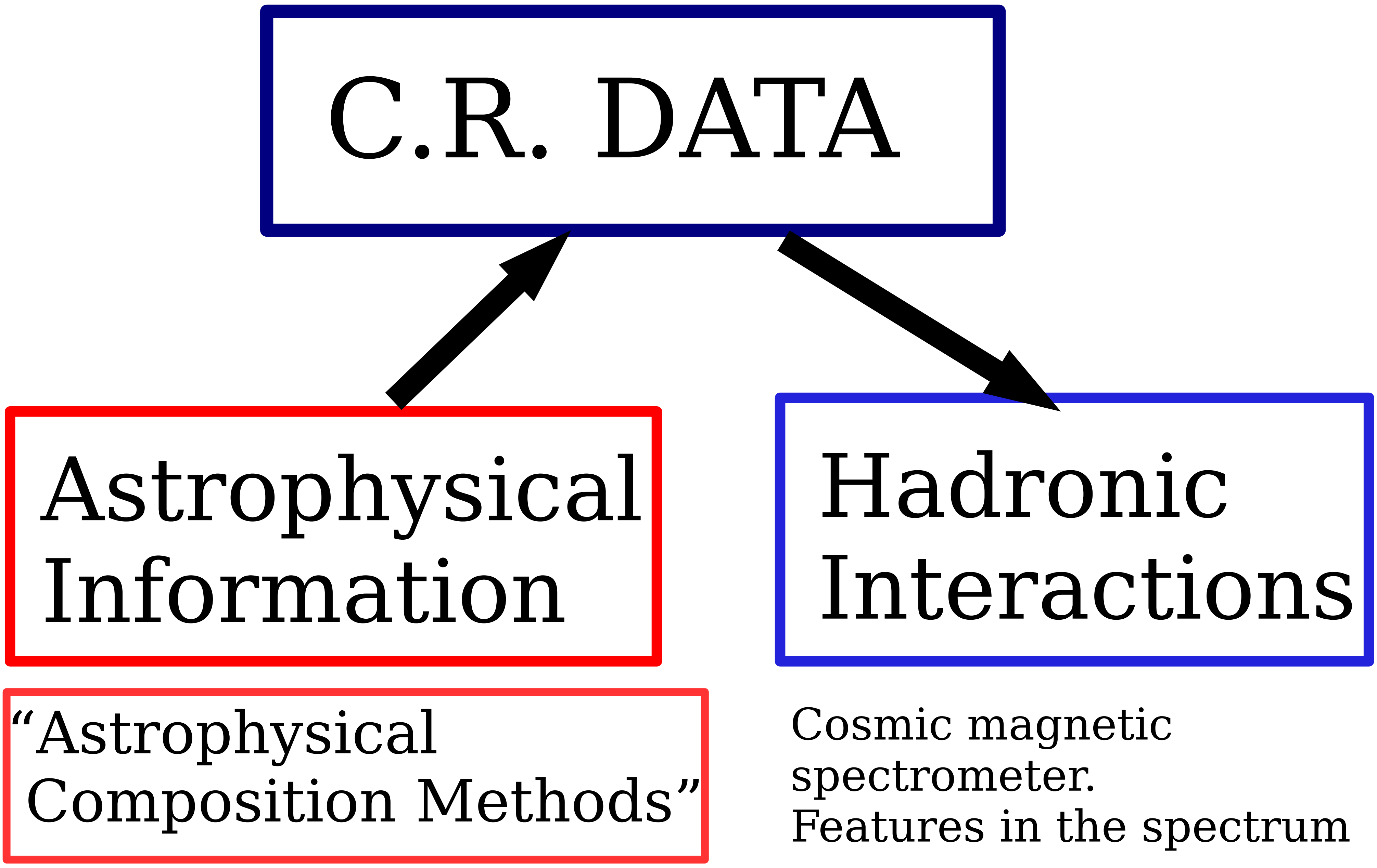
Astrophysical Information

Hadronic Interactions

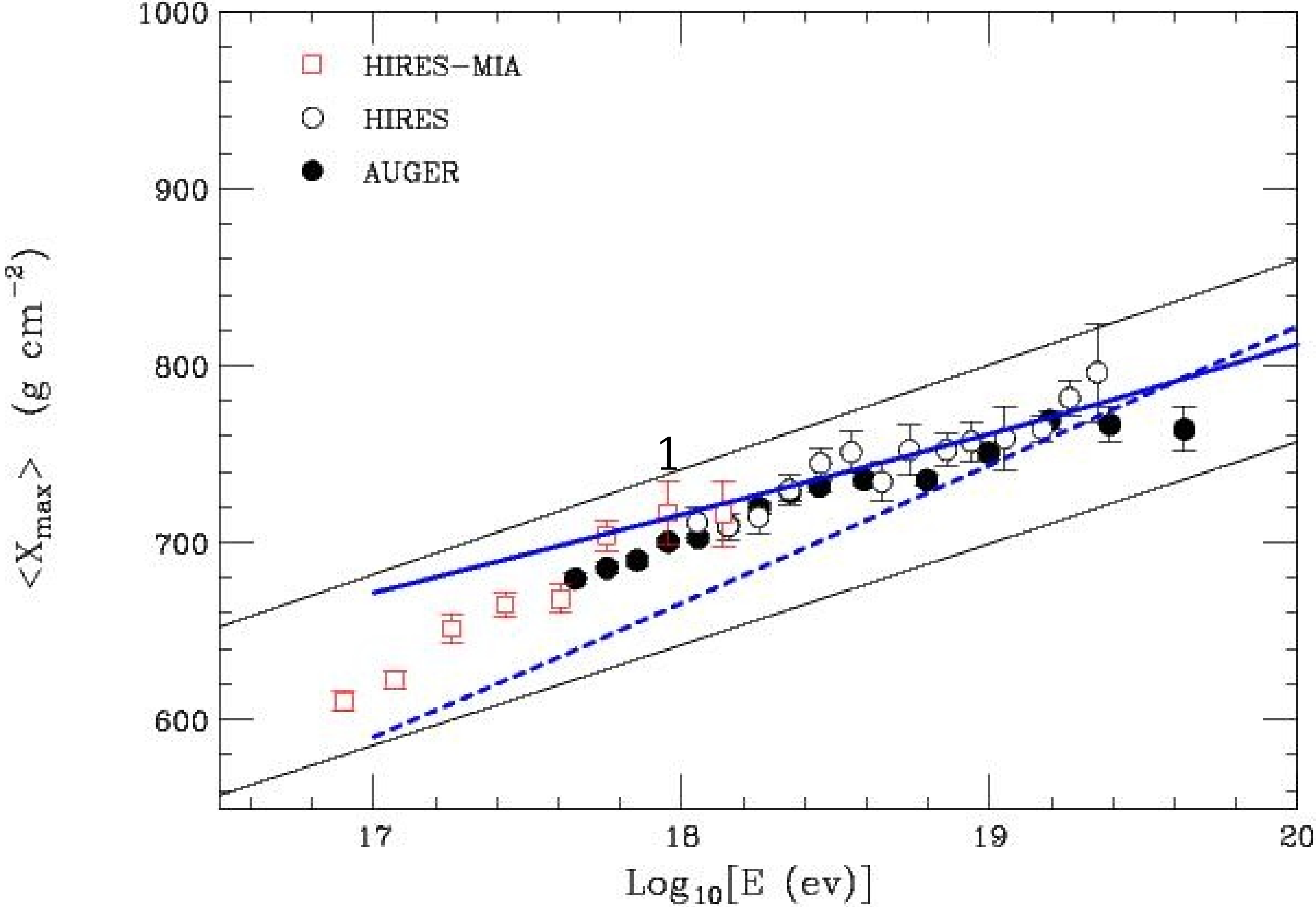


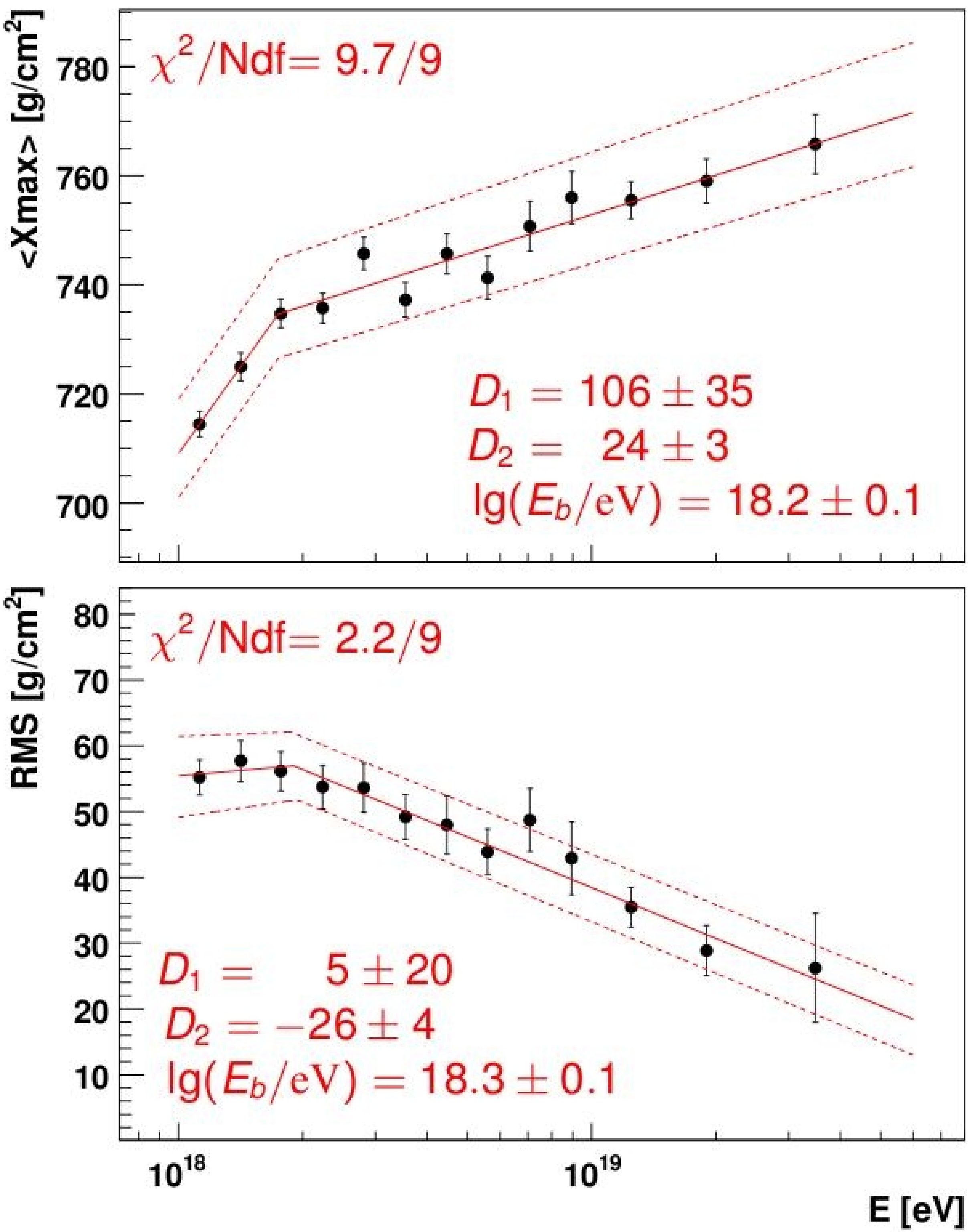
pp
$\bar{p}p$
300
200
100
70
50
30
σ_{tot} (mbarn)
LHC
10^{19}
10^{20}
10^0
10^2
10^4
10^6
$\sqrt{s}$ (GeV)

From Cosmic Ray Data → Hadronic Interactions

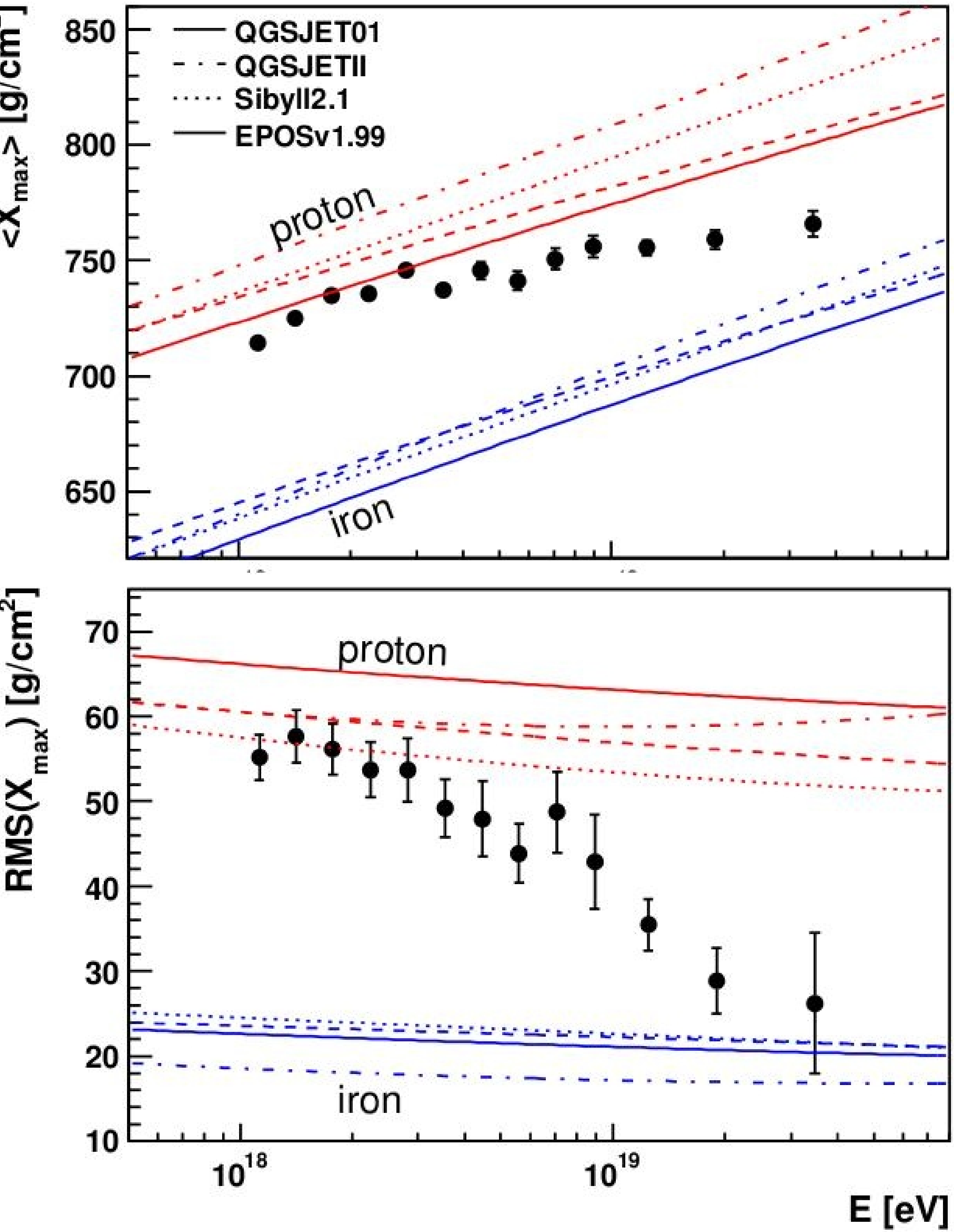


Introduce Energy dependence In Particle Production





<Xmax> [g/cm²]
χ^2/Ndf= 9.7/9
$D_1 = 106 \pm 35$
$D_2 = 24 \pm 3$
$\lg(E_b/\mathrm{eV}) = 18.2 \pm 0.1$
RMS [g/cm²]
χ^2/Ndf= 2.2/9
$D_1 = 5 \pm 20$
$D_2 = -26 \pm 4$
$\lg(E_b/\mathrm{eV}) = 18.3 \pm 0.1$
E [eV]



QGSJET01
QGSJETII
Sibyll2.1
EPOSv1.99
proton
iron
<X_{max}> [g/cm^2]
850
800
750
700
650
RMS(X_{max}) [g/cm^2]
70
60
50
40
30
20
10
10^{18}
10^{19}
E [eV]

COMPOSITION:
(becoming heavier with E)

AGN correlation
(small Z particles: p, He)

COMPOSITION:
(becoming heavier with E)

AGN correlation
(small Z particles: p, He)

Contradiction ??

Conflicting
Results
From HIRES
detector

Elongation rate corrected for detector acceptance and comparison with previous results

HIRES
Xmax
analysis

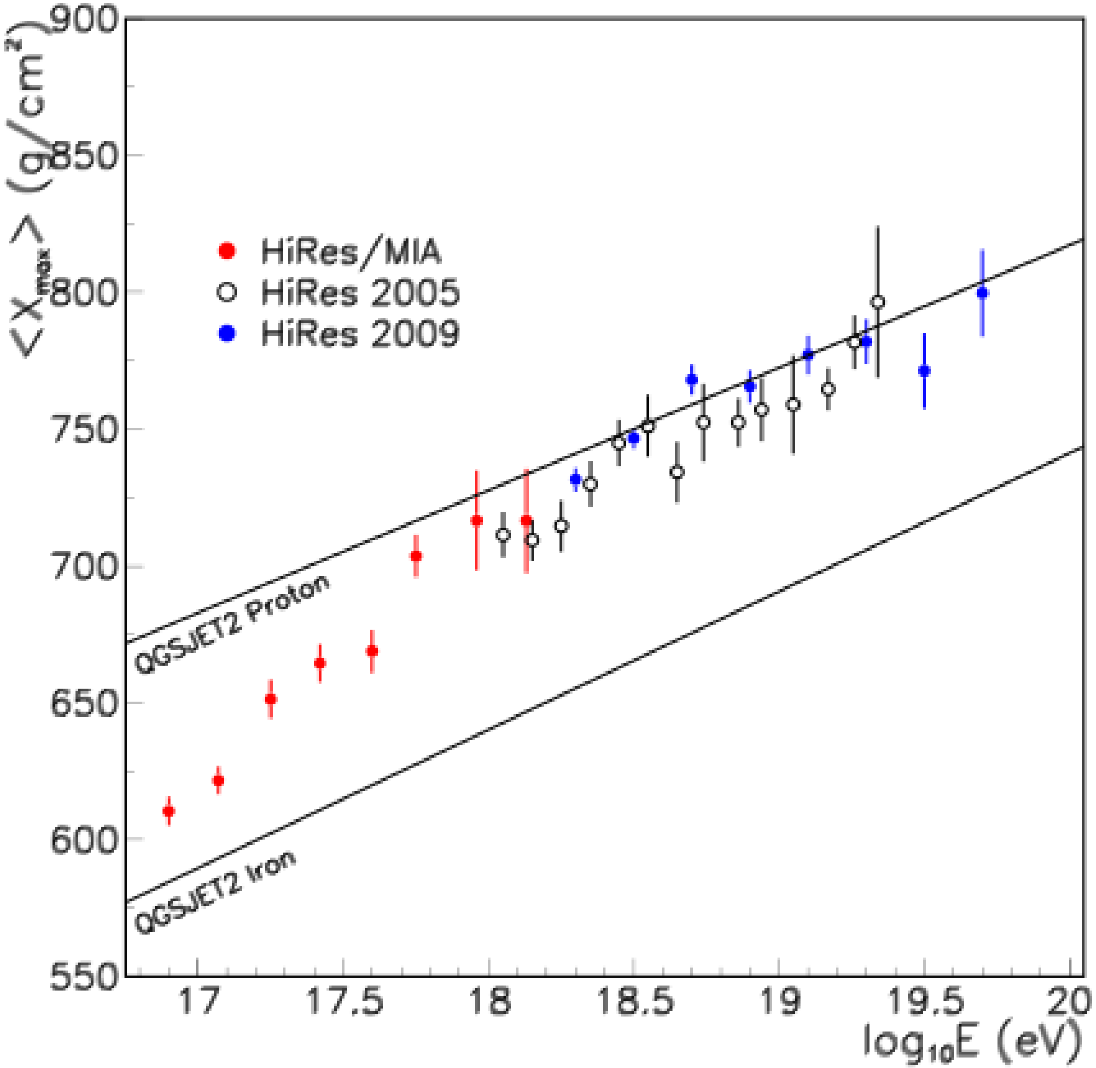


Fig. 25.— Comparison of current HiRes stereo $<X_{max}>$ results with results from the HiRes-prototype/MIA hybrid (Abu-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).

Comparison of data and p-QGSJET02 fluctuation widths
Use 2-sigma truncated gaussian width to fit Xmax distr.
Detector resolution is NOT deconvoluted!

HIRES Fluctuations analysis

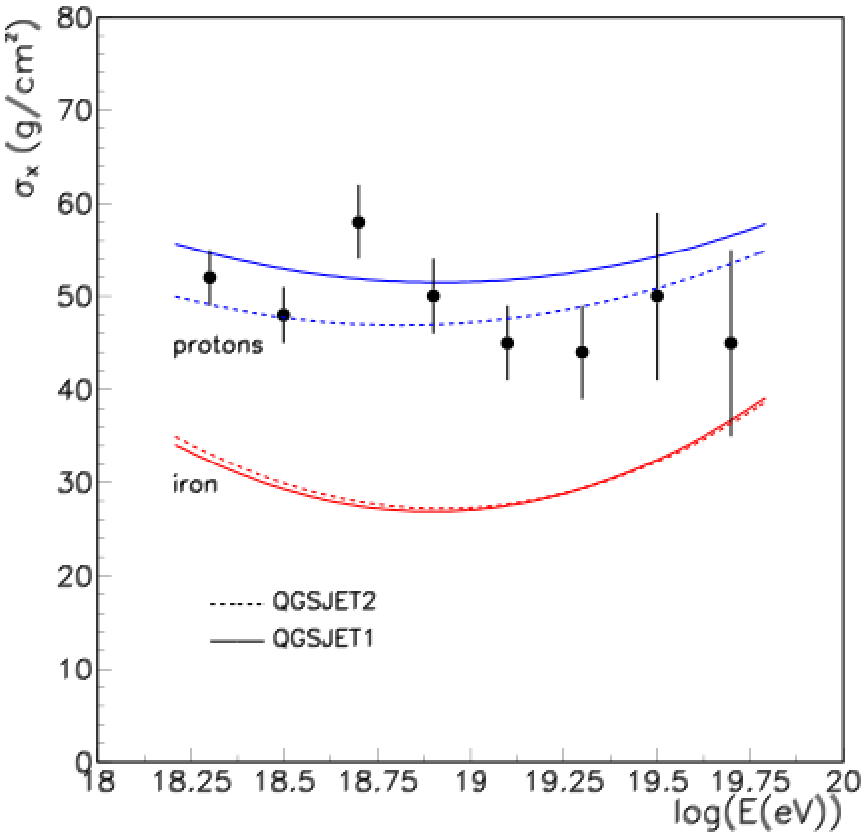


Fig. 28.— Results of fitting HiRes stereo data X_{max} distribution to Gaussian truncated at 2 × RMS (black points). Superimposed are curves representing expectations based on QGSJET1 and QGSJET2 proton and iron Monte Carlo. Gaussian-in-age parametrization used in reconstruction.

....Many problems remain open...

... but are finally beginning to understand
the mechanisms that produce
the highest energy particles in the Universe

MULTI-MESSENGER ASTRONOMY
Is a new way to observe the Universe
With remarkable potential
for new discoveries
and a deeper understanding of Nature

PLEIADVM CONSTELLATIO.

Quod tertio loco à nobis fuit obſeruatum, eſt ipſiuſ-
met LACTEI Circuli eſſentia, ſeu materies, quam Per-
ſpicilli beneficio adeò ad ſenſum licet intueri, vt & alter-
cationes omnes, quæ per tot ſæcula Philoſophos excrucia
runt ab oculata certitudine dirimantur, noſq; à verboſis

PLEIADUM CONSTELLATIO

aliud, quam innumerarum Stellarum coacervatim conſi-


Best wishes for the observations
Of our colleagues !