Understanding the origin of Cosmic Rays and high energy particles in the Milky Way and in the universe

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4th workshop on Air Shower Detection at High Altitude

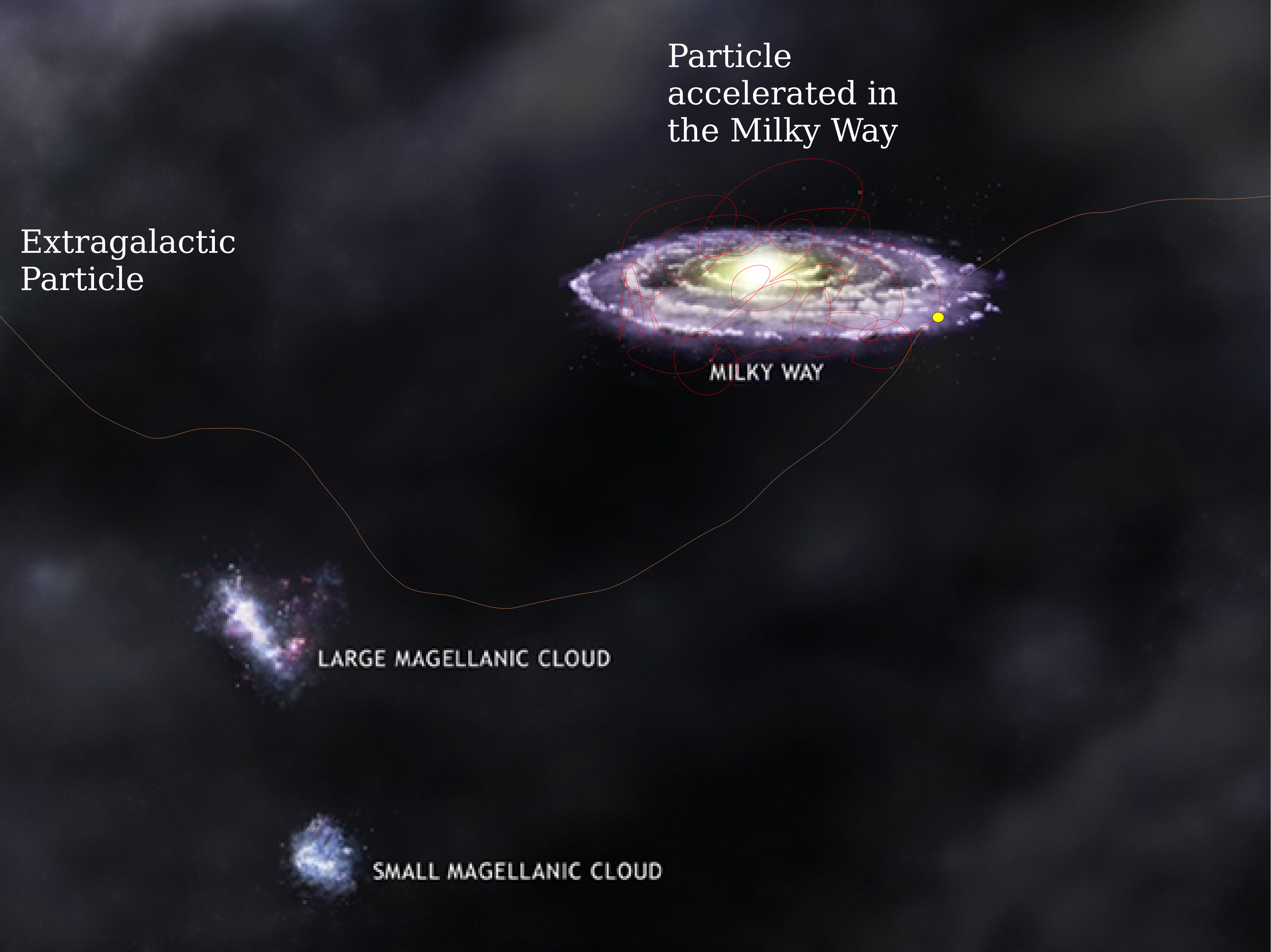
Napoli, 31st january 2013

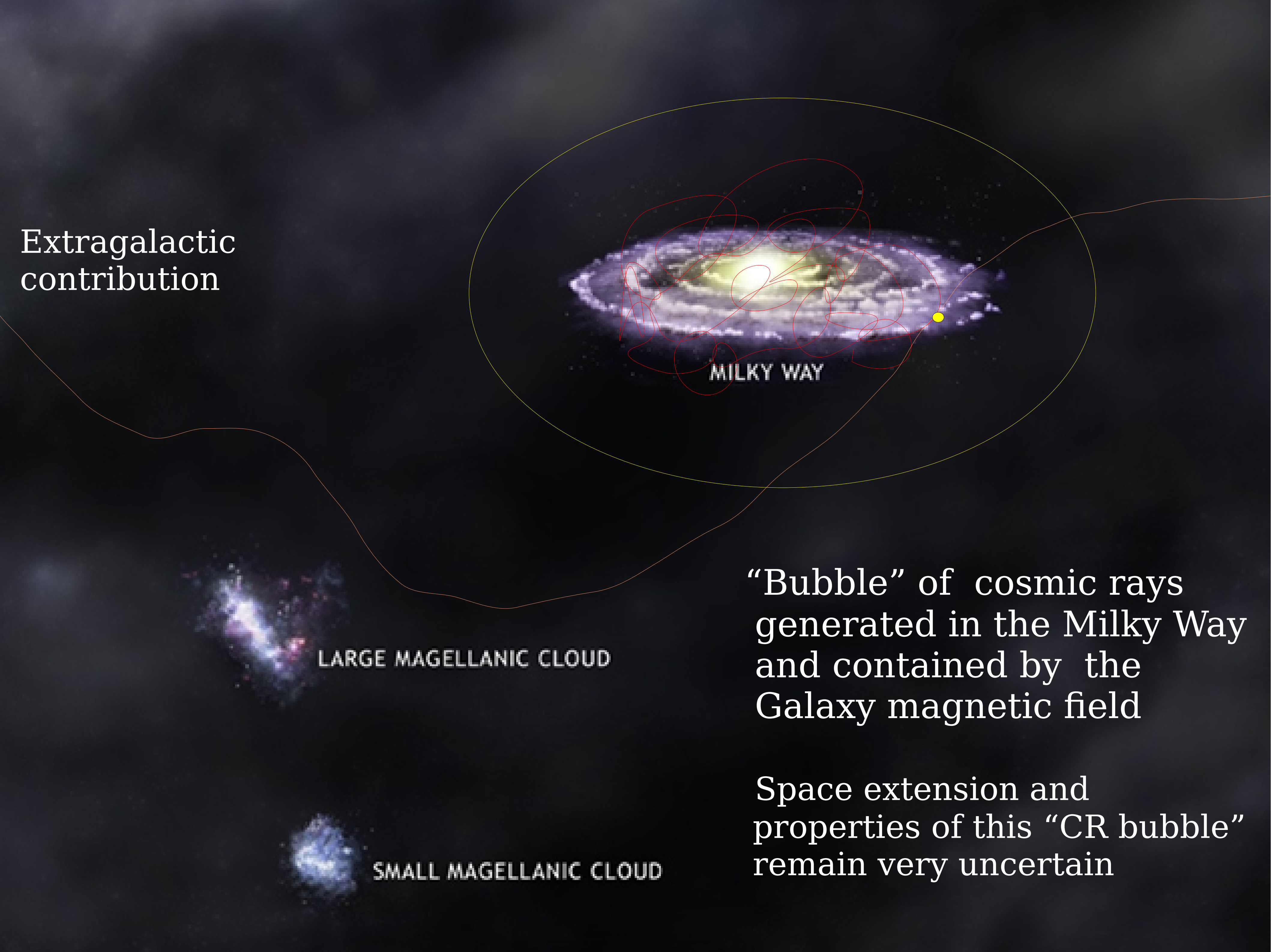
Three main sources of cosmic rays
[high energy (relativistic) charged particles] :

[1. The sun (E < 10-100 GeV)]

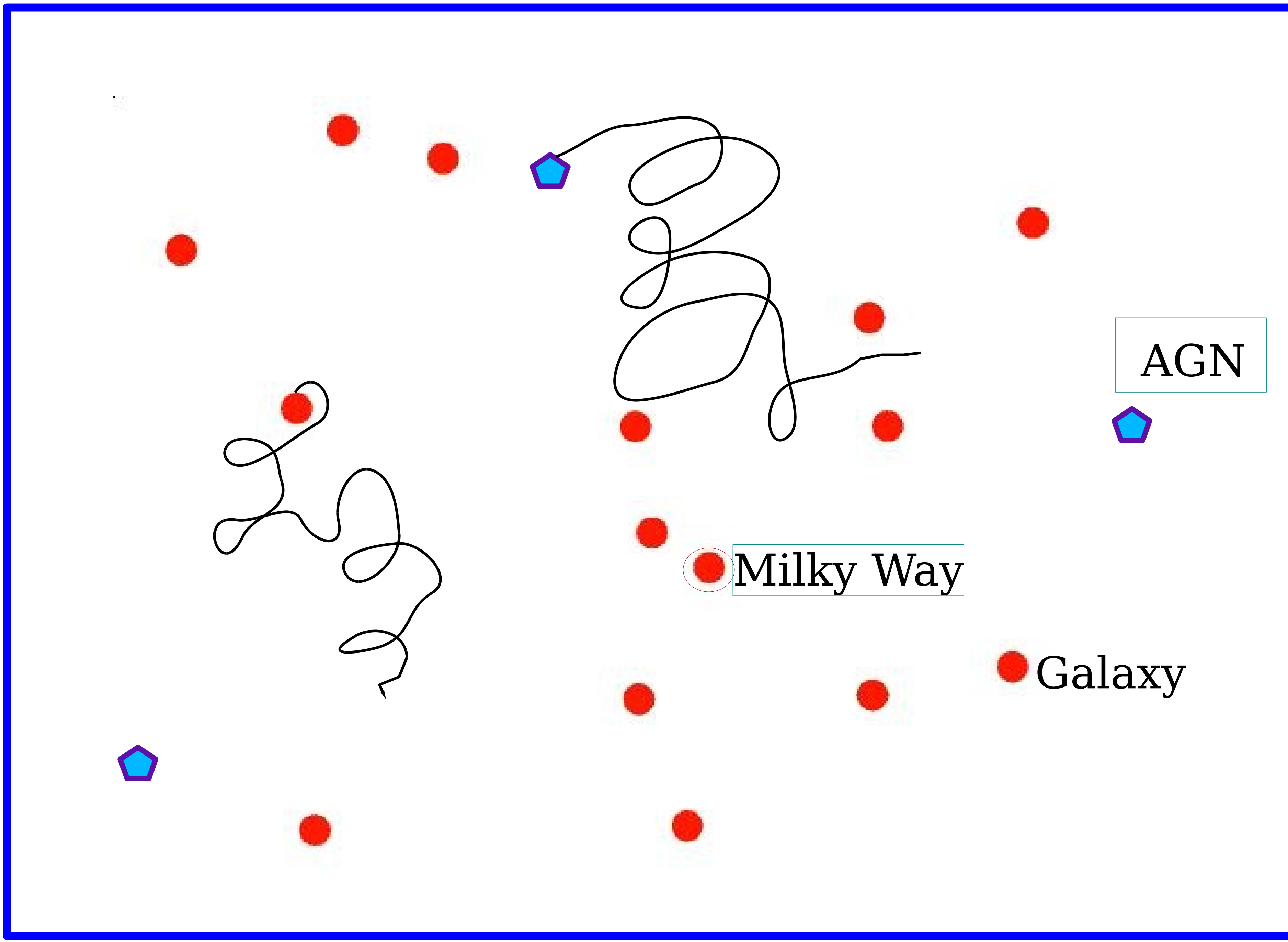
2. Galactic Sources

3. Extragalactic Sources


Particle
accelerated in
the Milky Way
Extragalactic
Particle
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD


Extragalactic
contribution
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
"Bubble" of cosmic rays
generated in the Milky Way
and contained by the
Galaxy magnetic field
Space extension and
properties of this "CR bubble"
remain very uncertain

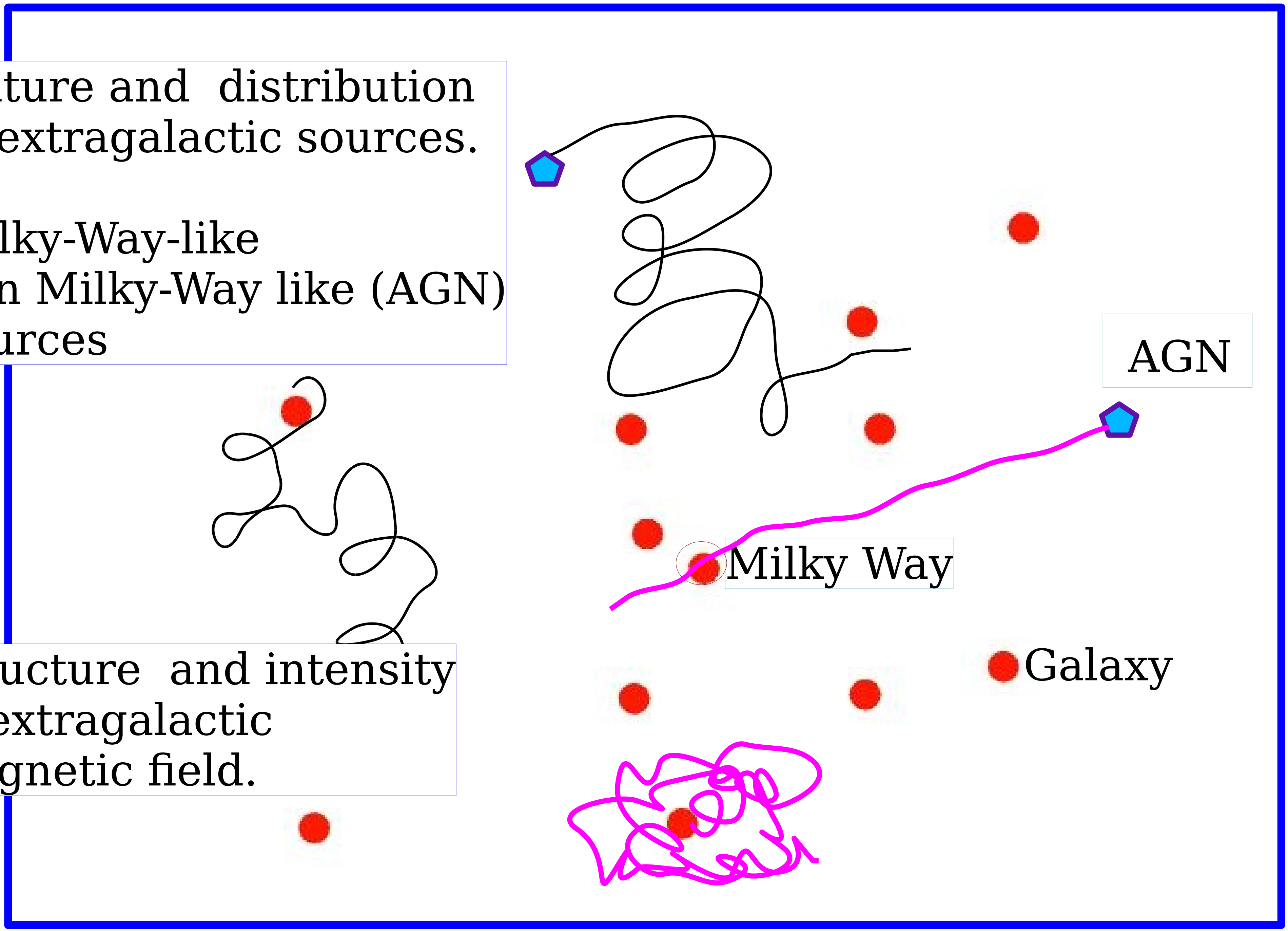
Piece of extragalactic space: Non MilkyWay-like sources



Piece of extragalactic space:

Nature and distribution
of extragalactic sources.

Milky-Way-like
non Milky-Way like (AGN)
sources



Structure and intensity
of extragalactic
magnetic field.

Galactic Cosmic Rays

$$N_j(E) = Q_j(E) \times T_j(E)$$

Different particles

$p, \quad \text{nuclei}(Z, A)$

$\overline{p}, \quad e^-, \quad e^+$

Injection
of cosmic rays

Containment
time

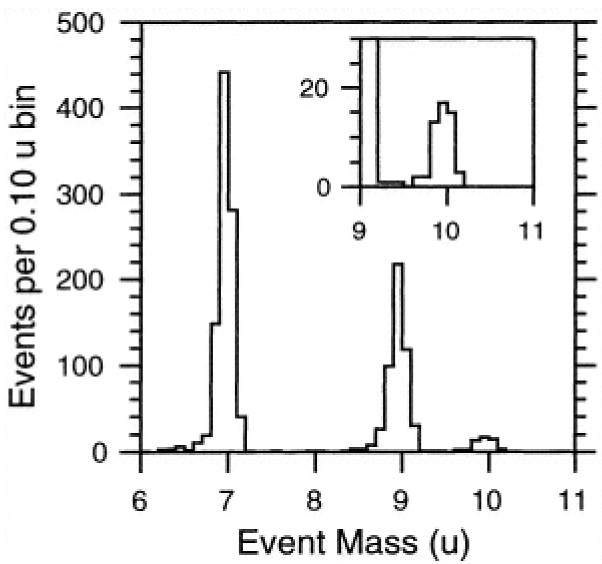
$$N_j(E) = \int d^3x \; n_j(E, \vec{x})$$

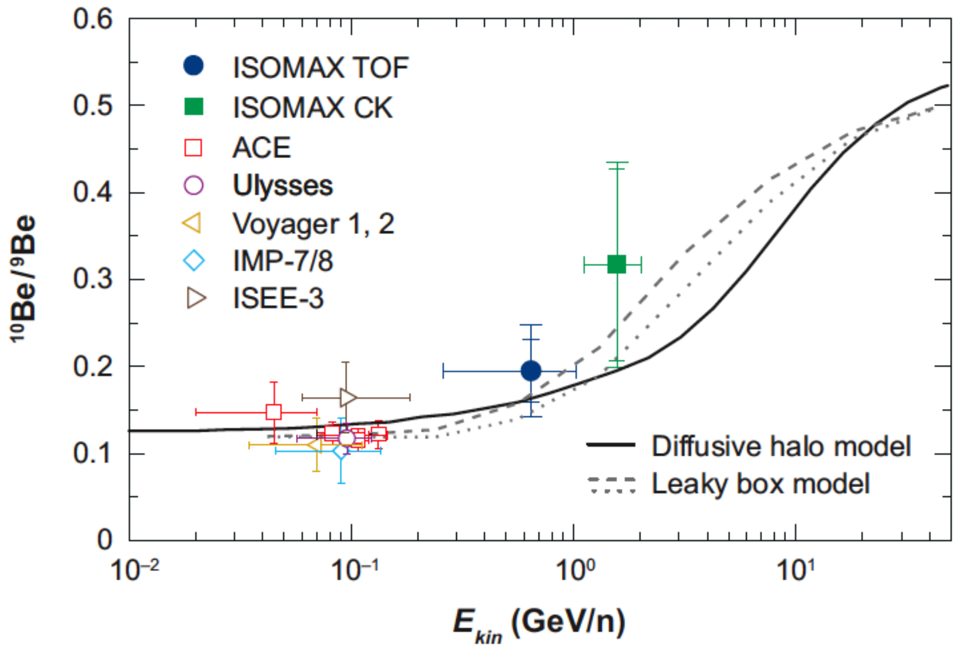
$$\phi_j(E) = \frac{c}{4\,\pi} \, n_j(E)$$

Determination of the "confinement time" $T(p/Z)$

"Cosmic clock" (Beryllium-10)

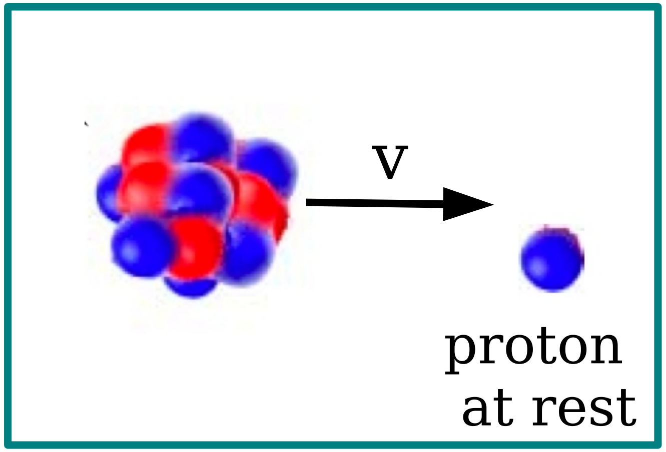
$$T_{1/2}\left[{}^{10}\mathrm{Be}\right] = 1.39 \times 10^6 \text{ years}$$

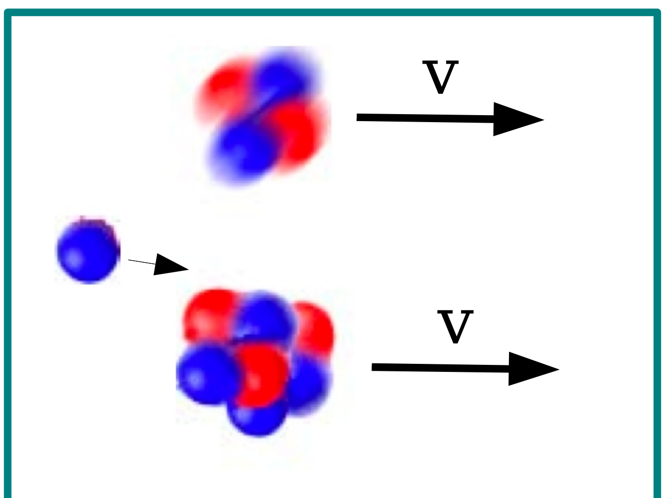


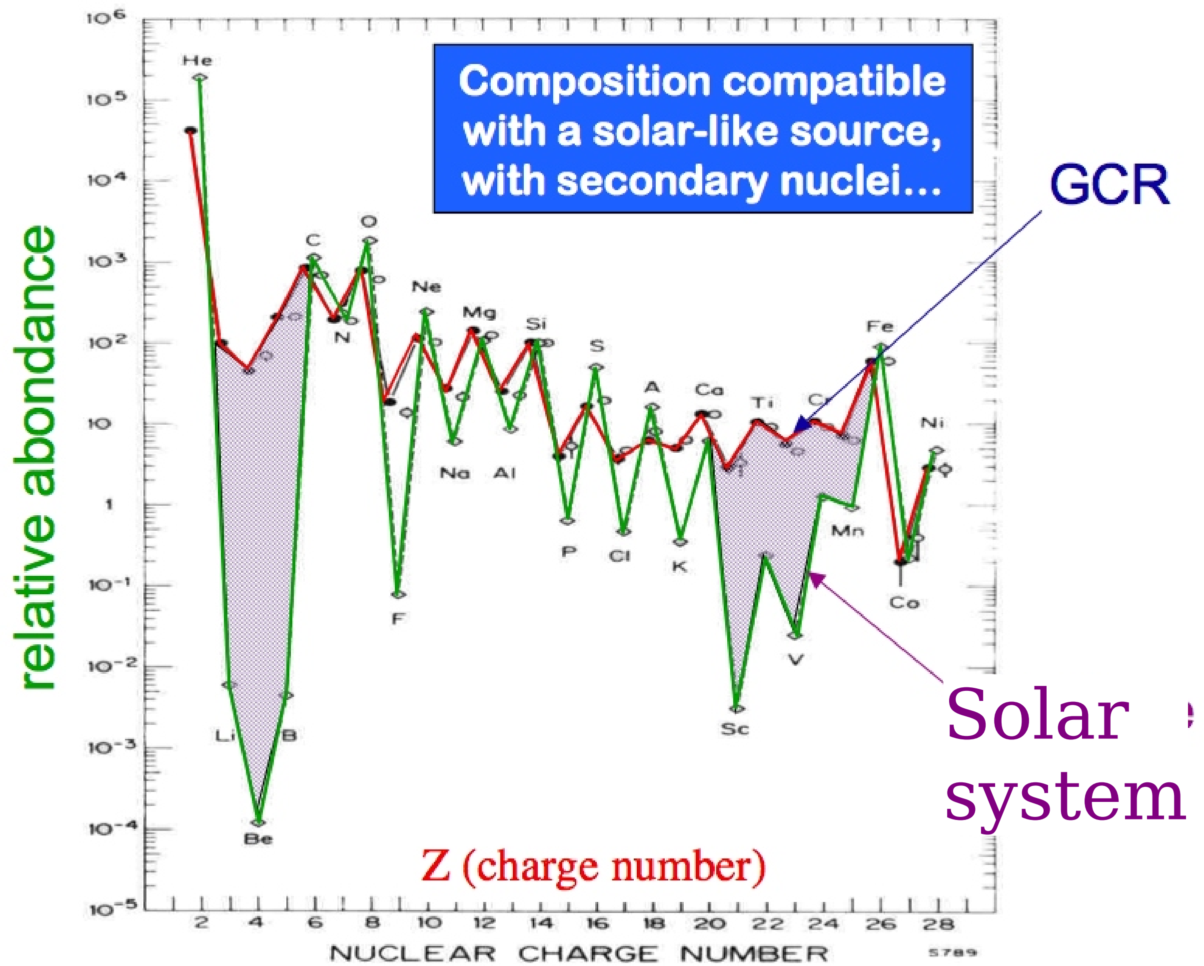


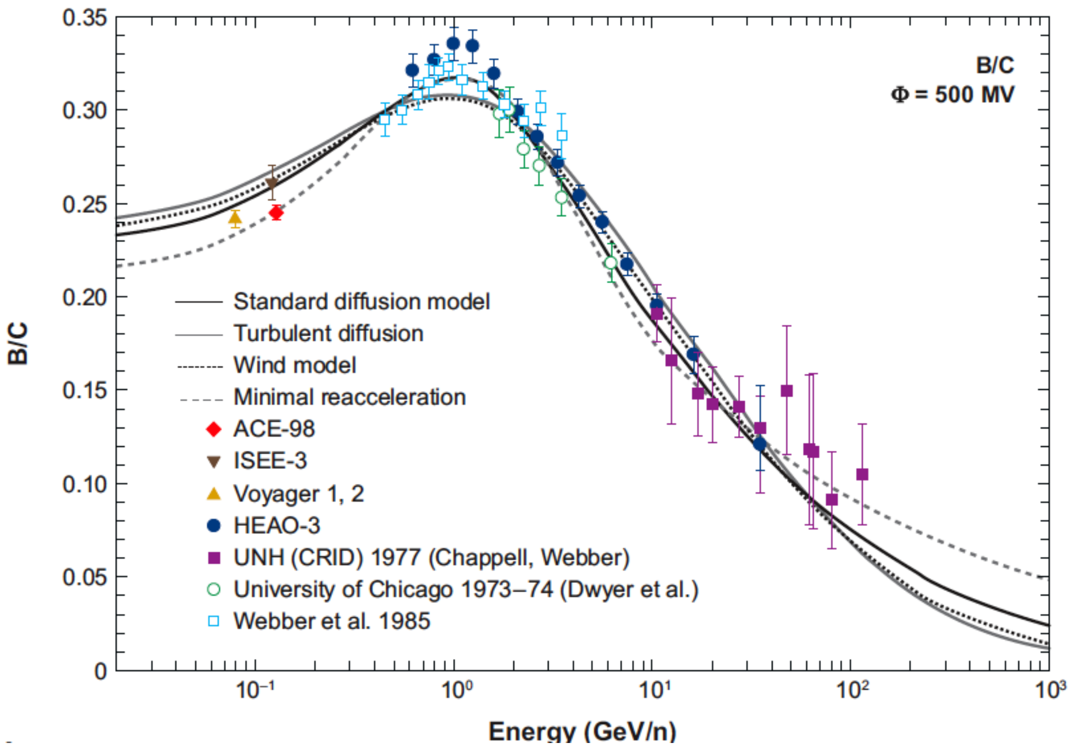
$$T \simeq 10 \text{ Myr}$$

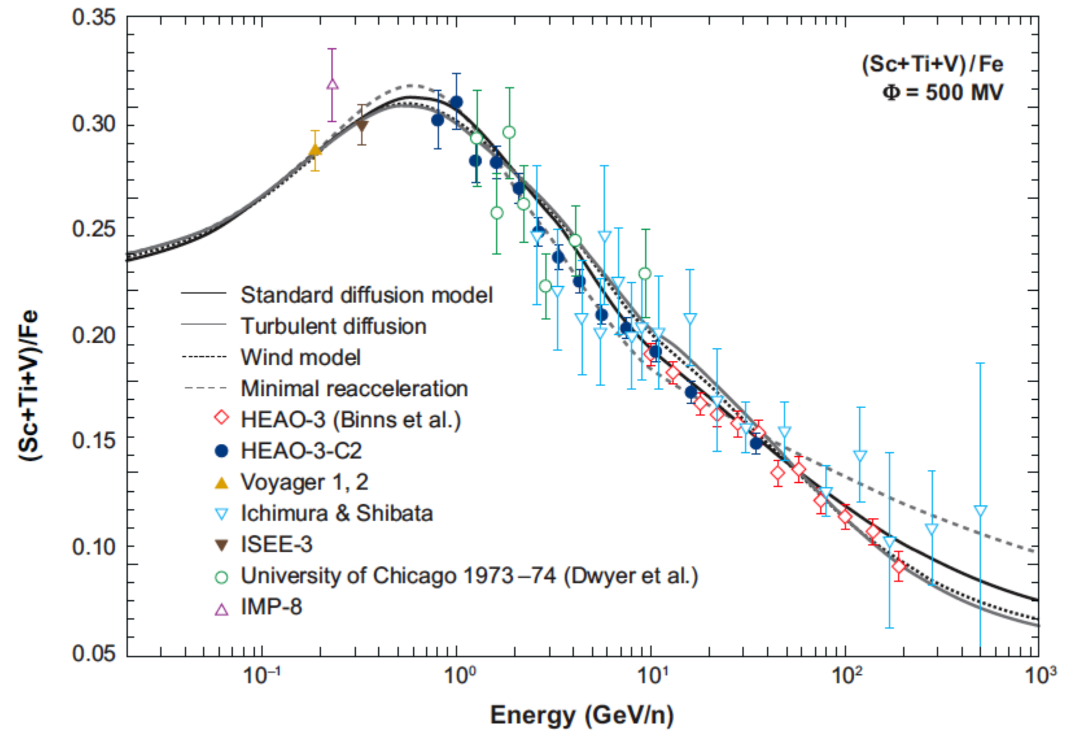
Nuclear Fragmentation
(collisions with the Inter Stellar Medium)











Column density

$$X(E) = \langle \rho \rangle \, T(E)$$

Escape faster at higher E

$$X(E) \propto E^{-\delta}$$

$$\delta \simeq 0.4 \div 0.6$$

$$\frac{\langle \rho \rangle}{m_p} \simeq 0.2 \text{ cm}^{-3}$$

(extended halo)

Injection of cosmic rays

Containment time

$$N_j(E) = Q_j(E) \times T_j(E)$$

$$L_j = \int dE \; E \; Q_j(E)$$

LARGE Power Requirement

Spectral Shape [Dynamics of acceleration process]

$$L_{\rm cr}(\text{Milky Way}) \simeq 2 \times 10^{41} \text{ erg/s}$$

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

Source Identification

Understanding the “confinement properties” for Cosmic Rays in the Milky Way at very high energy is of critical importance.

Turbulence power spectrum

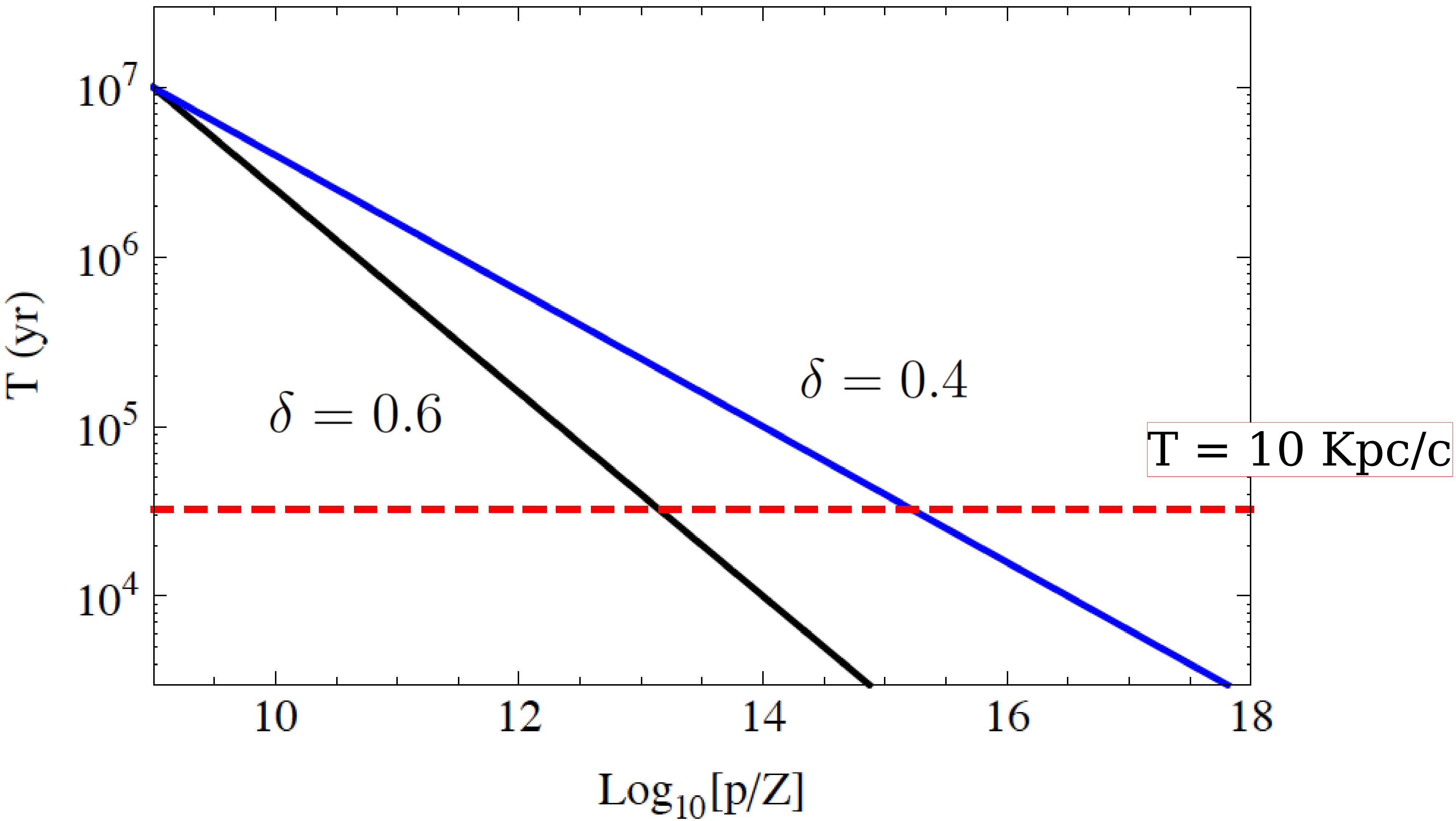
Global Structure of the Milky Way Magnetic Field

Galactic Wind ?

Confinement time as a function of rigidity (p/Ze)

$$T(E) \propto E^{-\delta}$$

Failure of a simple diffusion modeling for CR confinement and escape



[1.] Precision measurements of the shape of the energy spectra for the different particles. (protons, nuclei, electrons, positrons, antiprotons).

[2.] "Composition" measurements [identification of the mass of the nucleus in EAS]

[3.] Anisotropy (angular distribution) measurements.

Spatial distributions of cosmic rays in (and near) the Milky Way

Multi-wavelength studies of astrophysical objects (or "events") [From radio to Gamma Rays]

Neutrino Astronomy

Features in the Energy Spectrum:

[1.] The “CREAM/PAMELA” hardening

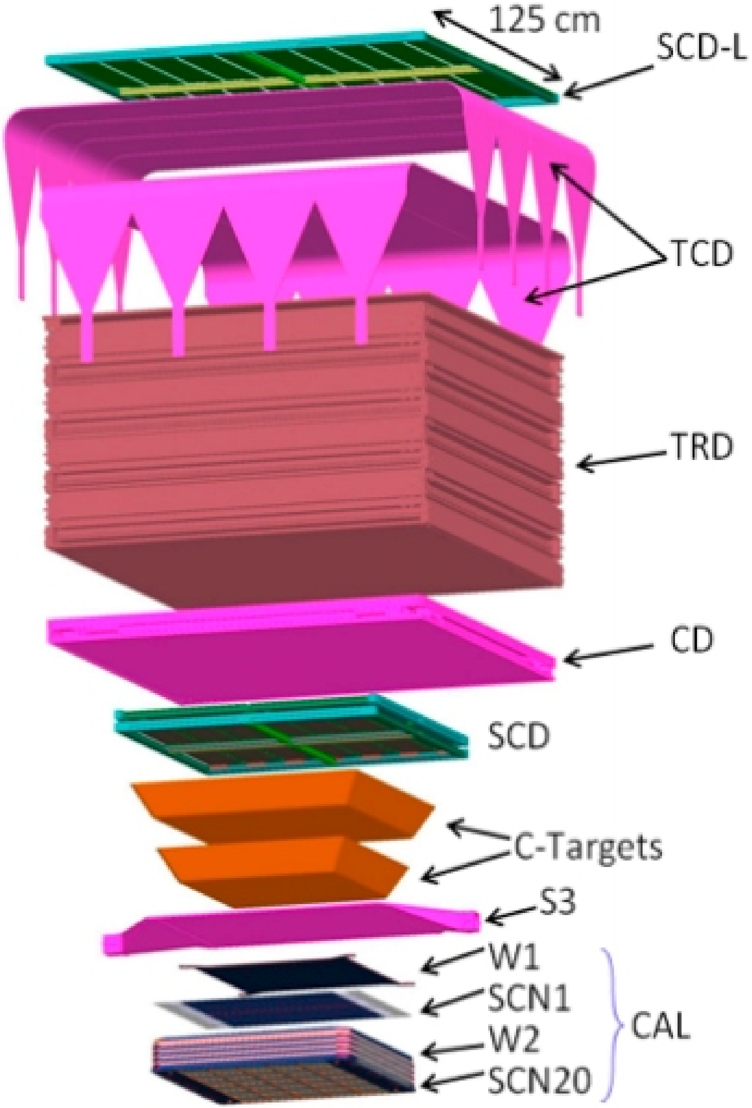
[2.] Slopes for different components

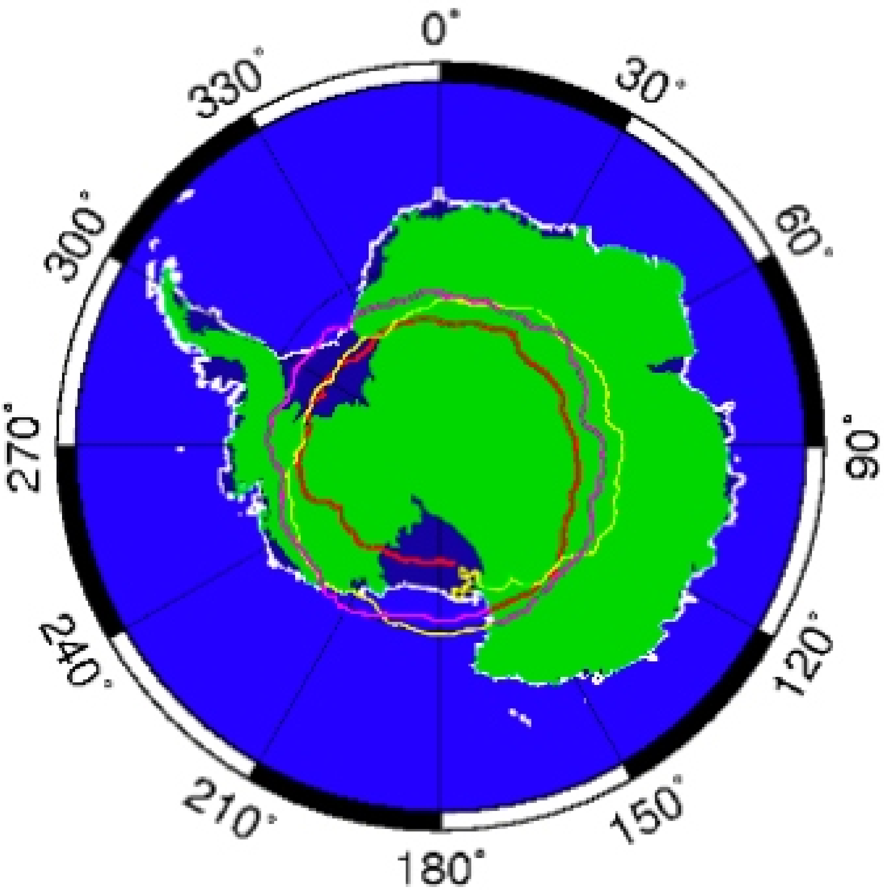
[3.] The “KNEE” at 3-5 PeV

[4.] The region: from the “Knee” to the “Ankle”

[5.] The highest energy particles (GZK or not GZK ?)

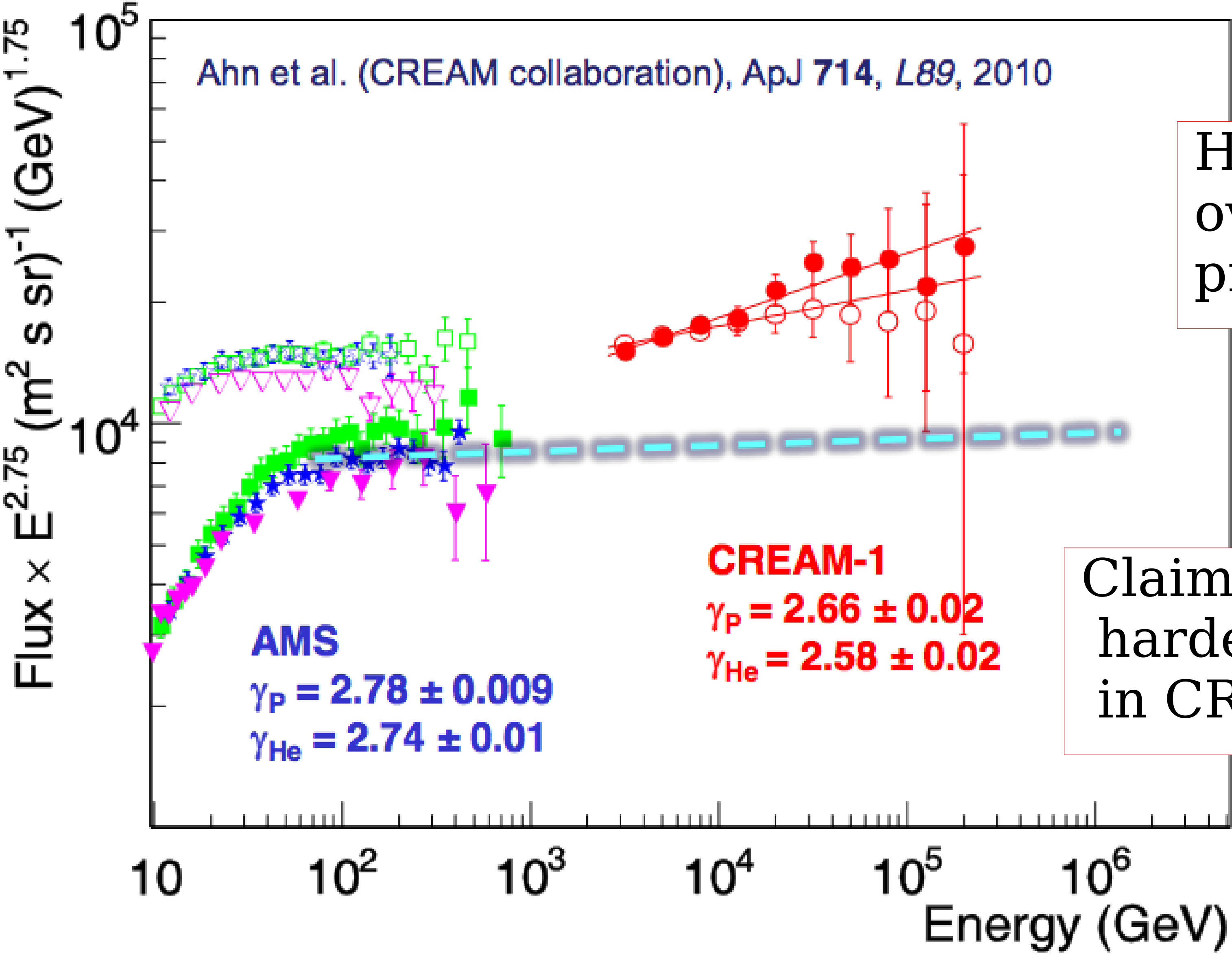
CREAM (calorimeter on balloon)
(5 flights in Antartica. Total of 156 days)





Cream 5 trajectory
37 days 12/2009-01/2010

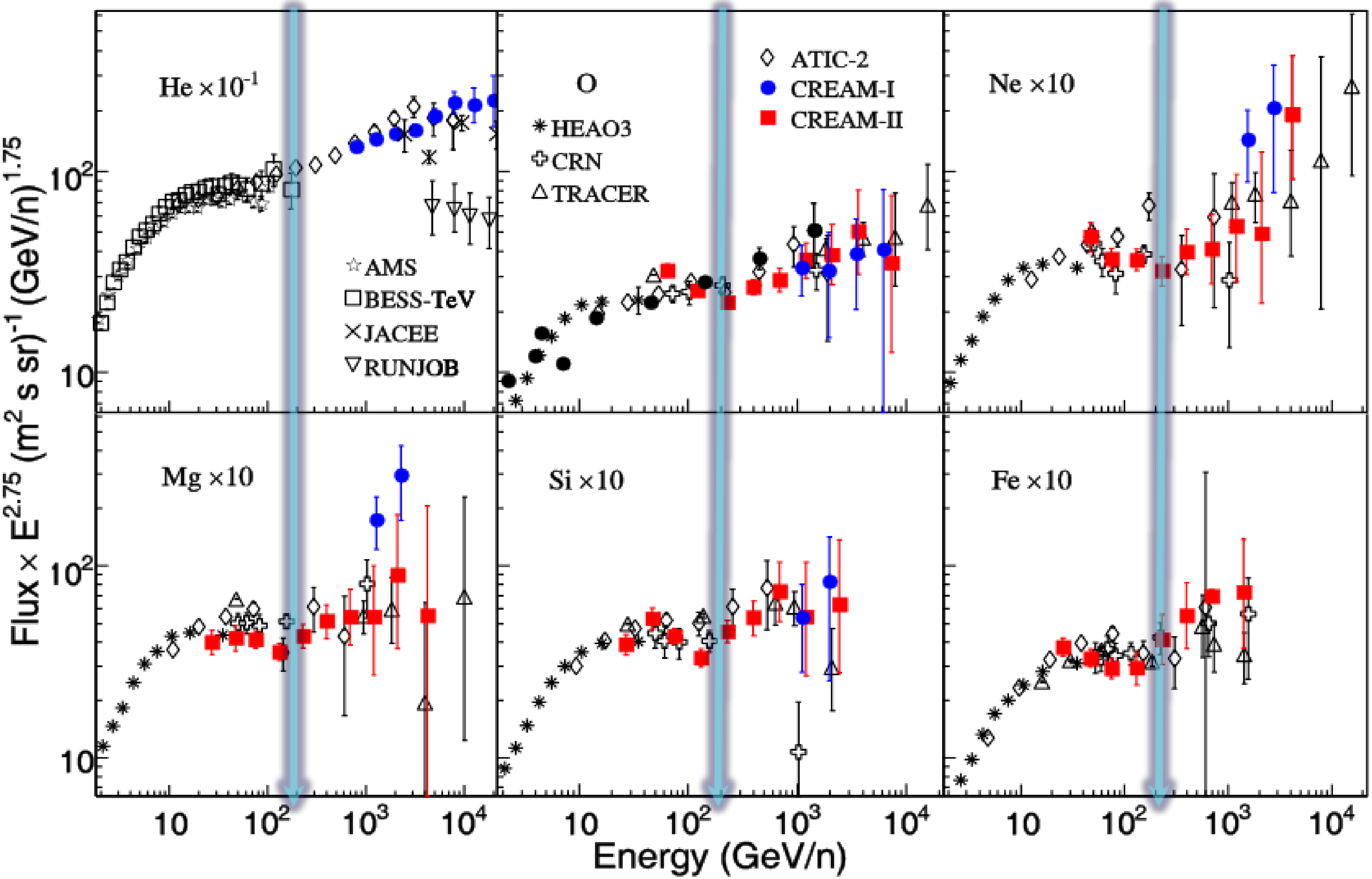
TeV spectra are harder than spectra < 200 GeV/n



Helium overtakes protons

Claim of "break" hardening in CR spectra

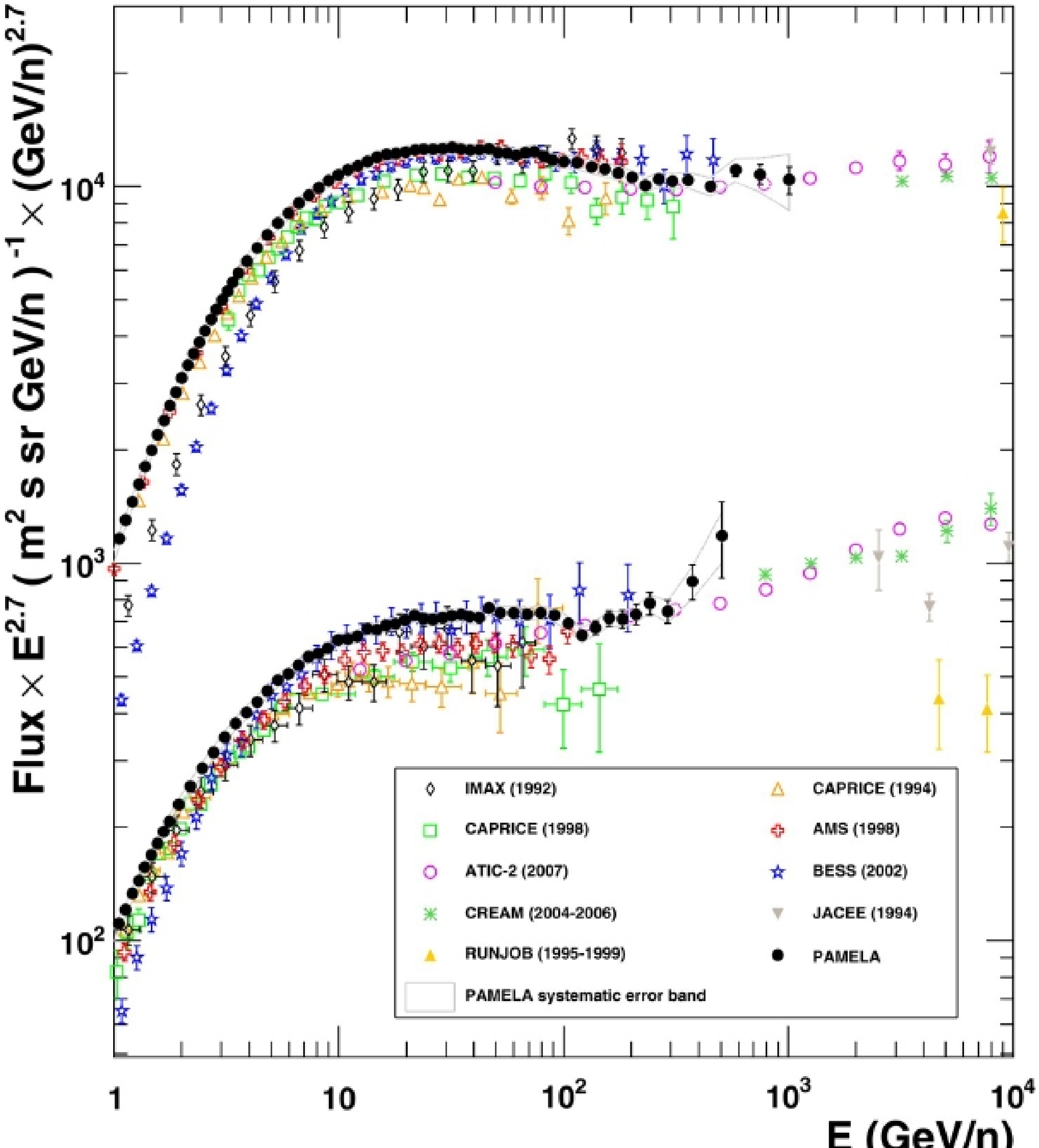
Discrepant hardening

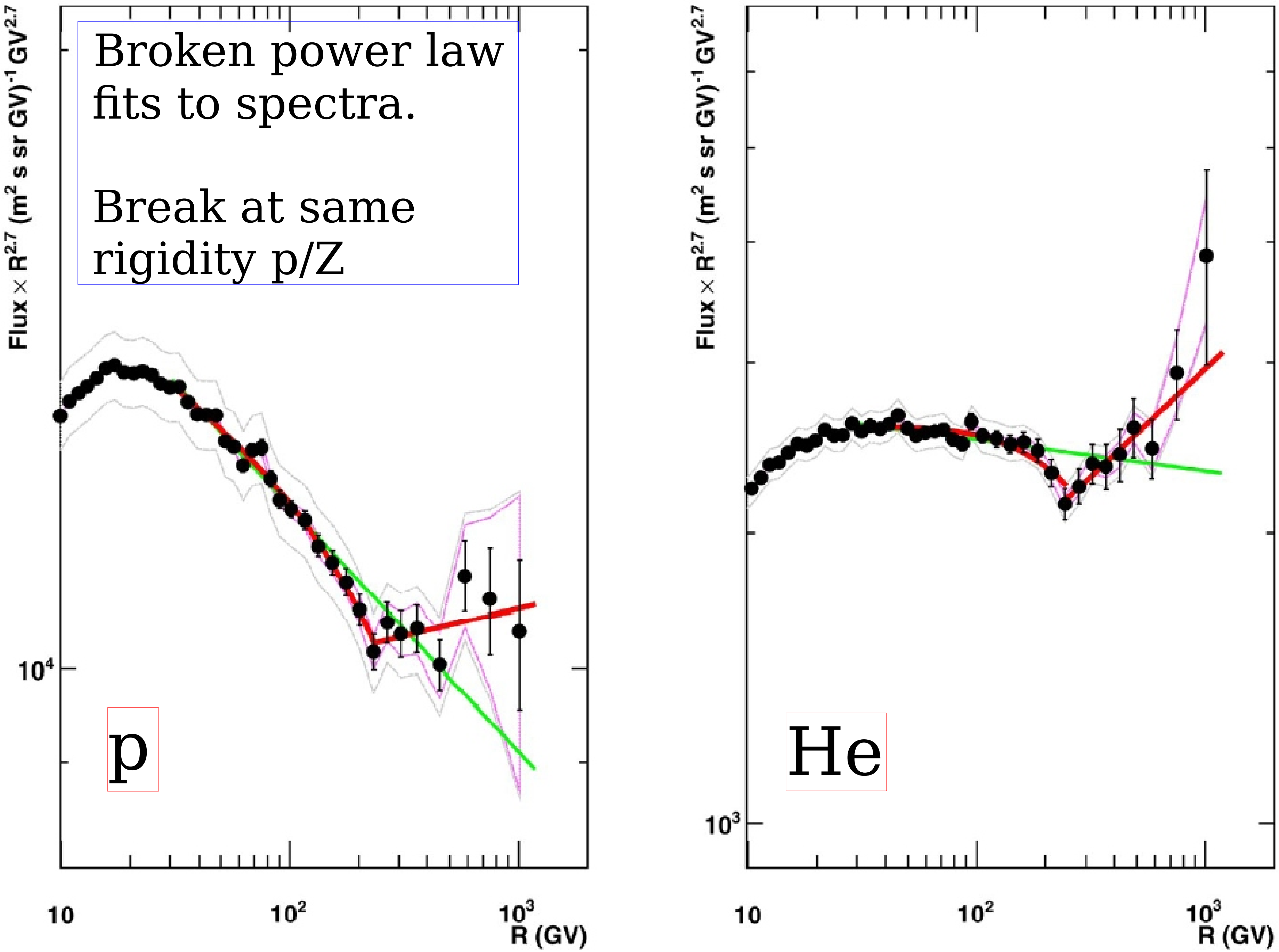


PAMELA

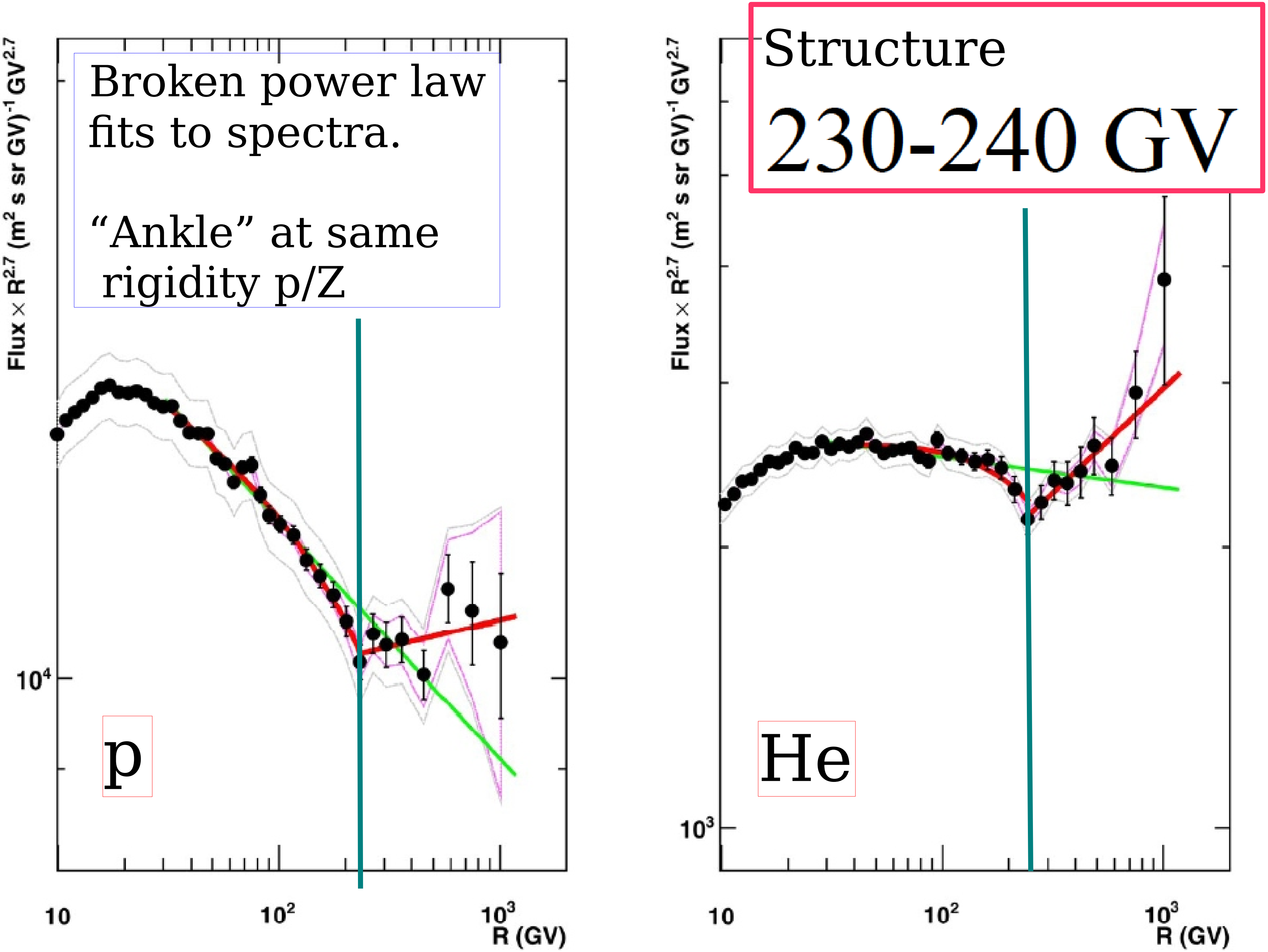
Proton/Helium
CR fluxes
1 GV – 1.2 TV

Science
(march 2011)





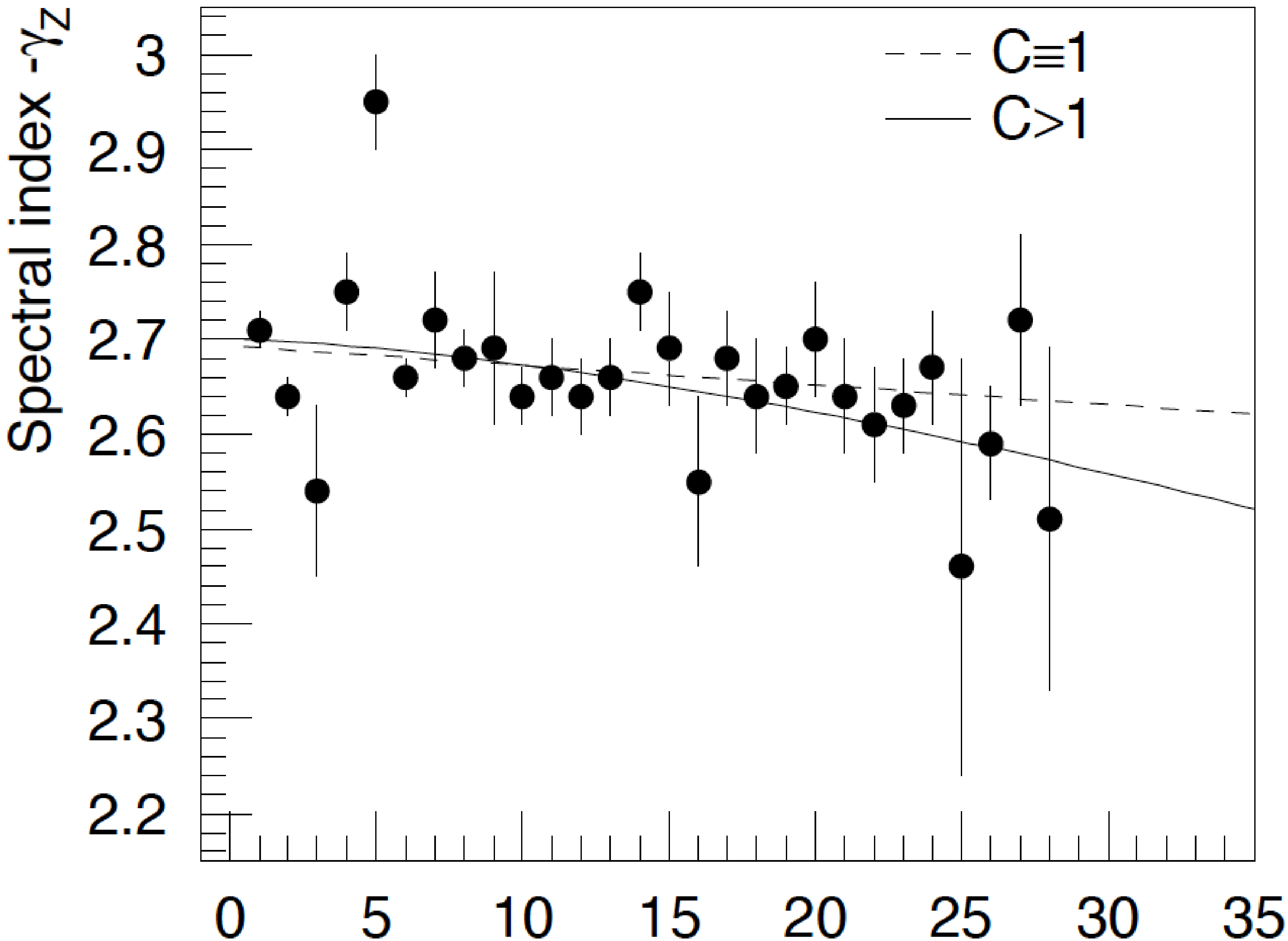
Surprising and important result.



Surprising and important result.

Spectral Index
as a function of Z

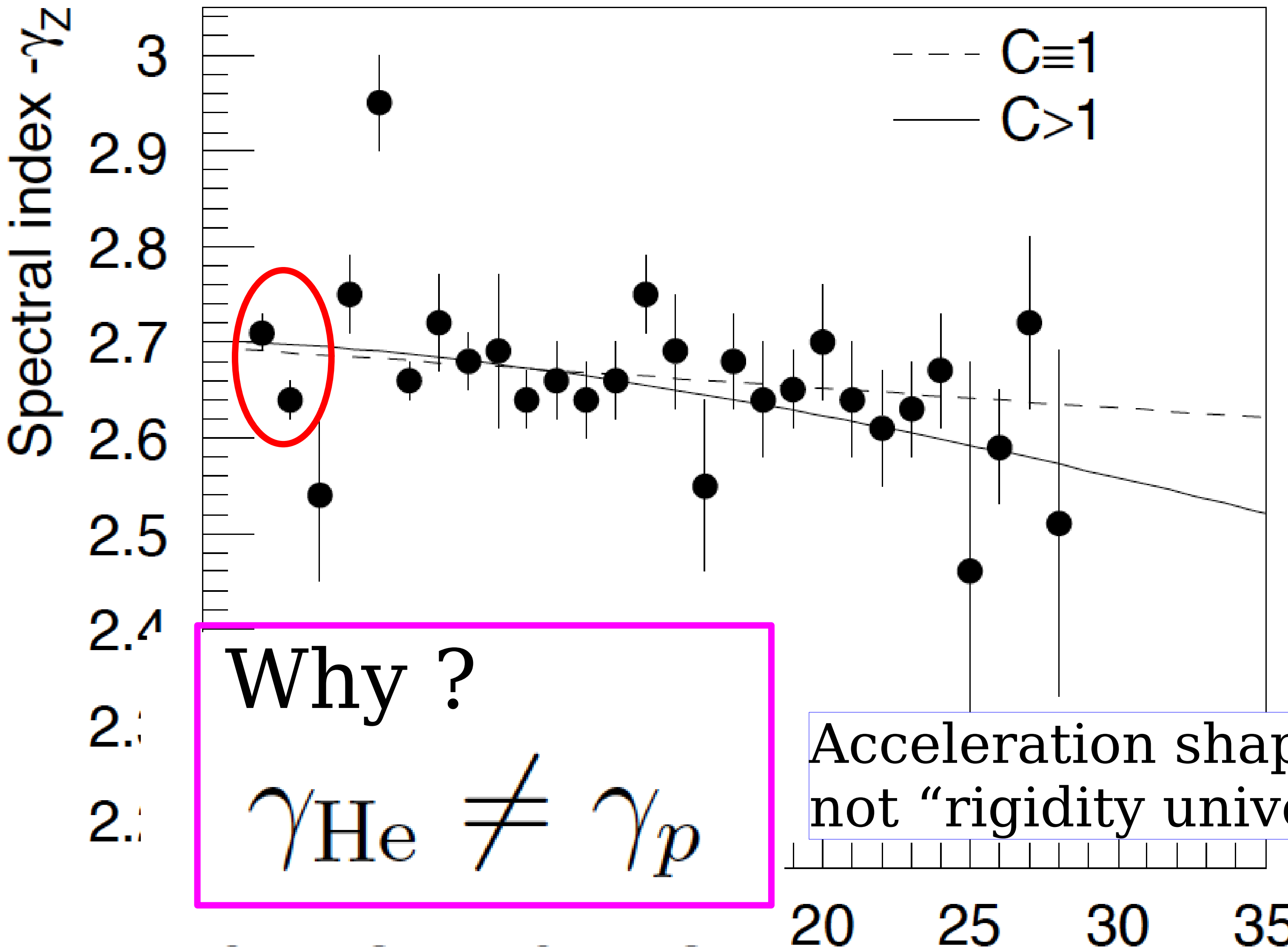
$$\phi_Z(E) \propto E^{-\gamma_Z}$$



Compilation of Horandel (2003)

Spectral Index
as a function of Z

$$\phi_Z(E) \propto E^{-\gamma_Z}$$



Why ?

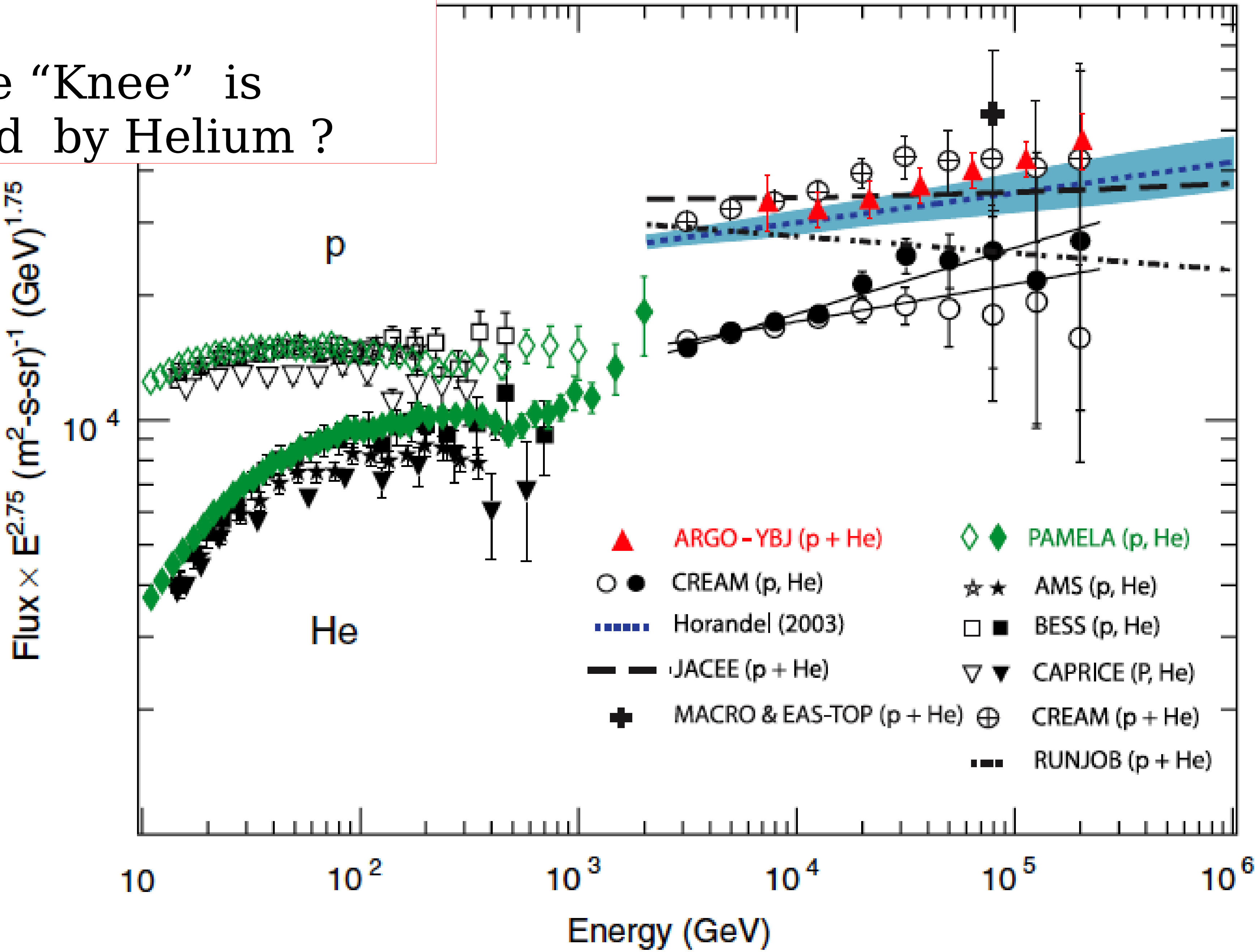
$$\gamma_{\mathrm{He}} \neq \gamma_p$$

Acceleration shape
not “rigidity universal” ?

Compilation of Horandel (2003)

Helium nuclei “overtake” protons at E = 10^4 GeV !

....
Visible “Knee” is formed by Helium ?



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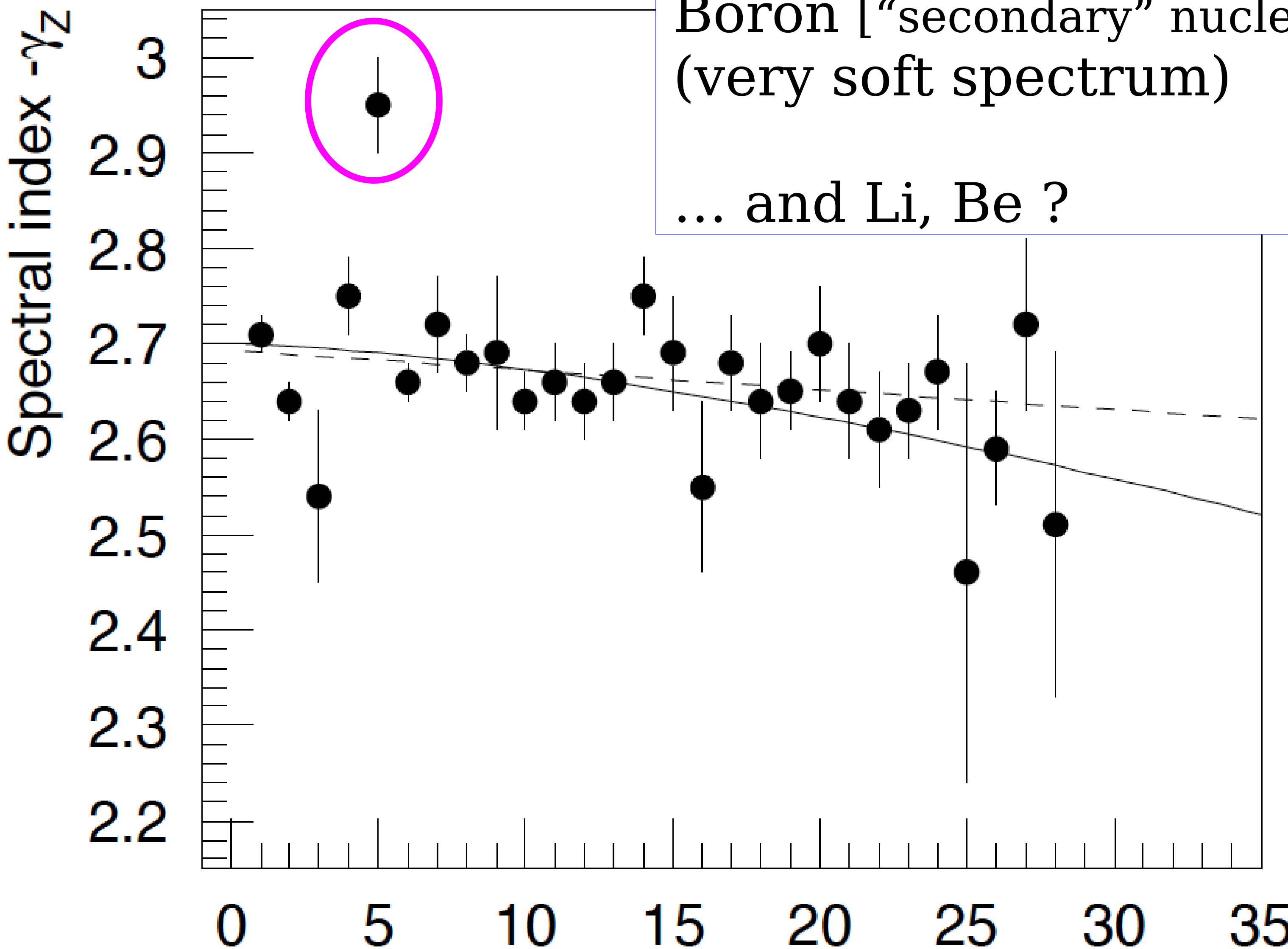


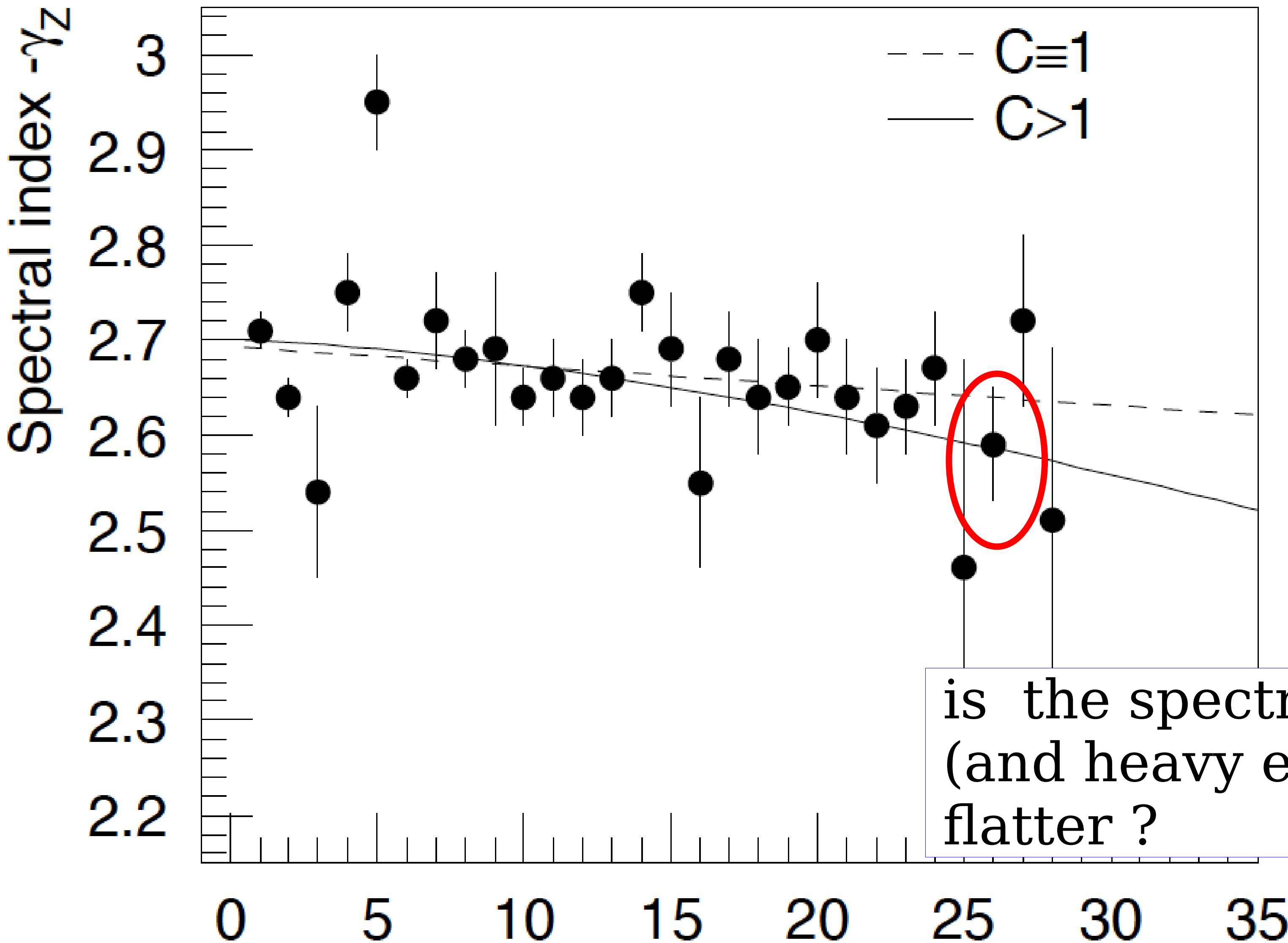
Boron [“secondary” nucleus]
(very soft spectrum)

… and Li, Be ?

Compilation of Horandel (2003)

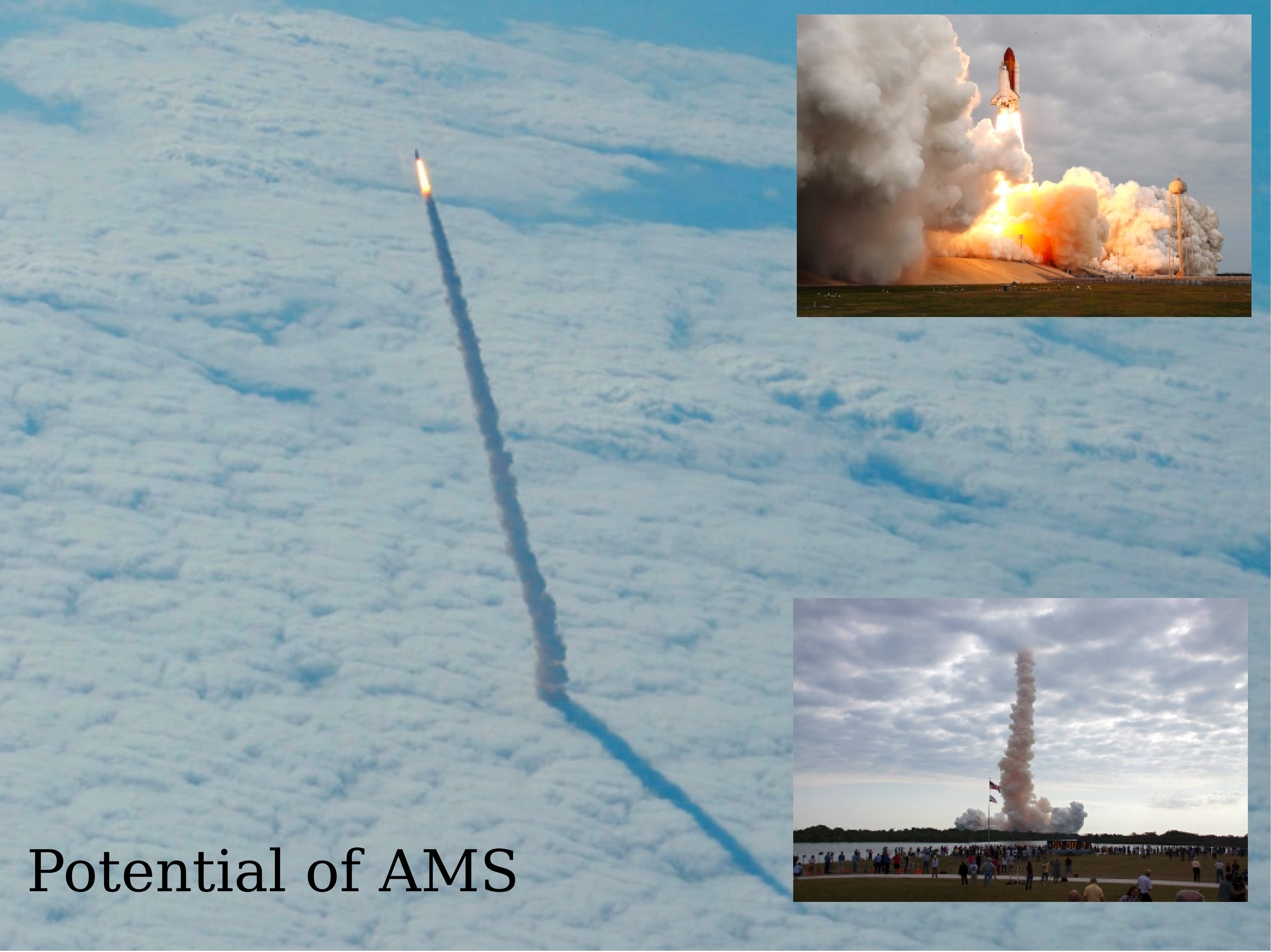
Spectral Index
as a function of Z

$$\phi_Z(E) \propto E^{-\gamma_Z}$$



is the spectrum of IRON (and heavy elements) flatter ?

Compilation of Horandel (2003)



Potential of AMS

$$E \gtrsim 100\ \mathrm{TeV}$$

Air Shower Measurements

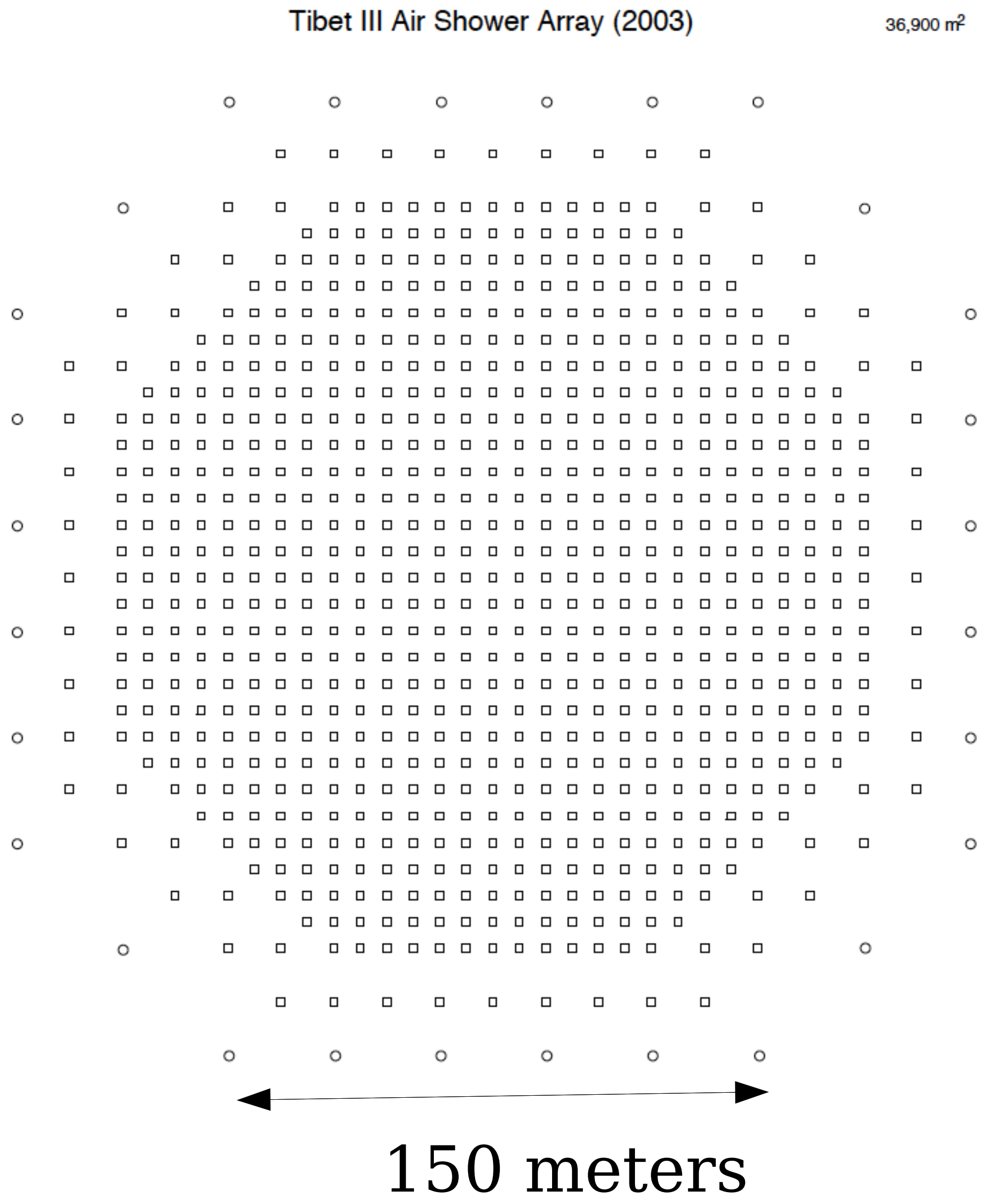
Calibration of primary energy estimate uncertain.

Resolution in energy measurement is uncertain.

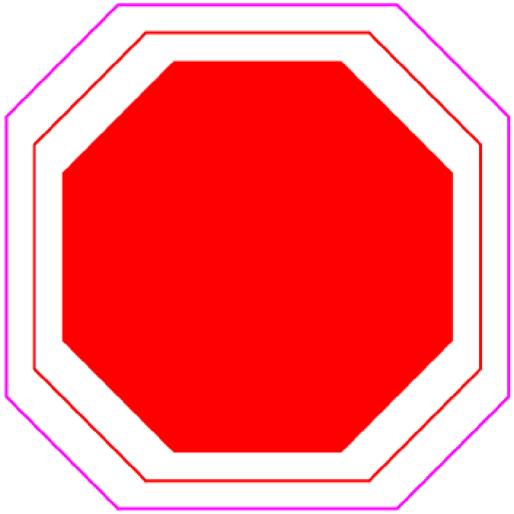
Composition measurement difficult

Modeling of SHOWER DEVELOPMENT
(hadronic interaction properties) remain central
(and difficult) problem.

Tibet AS Gamma Air Shower

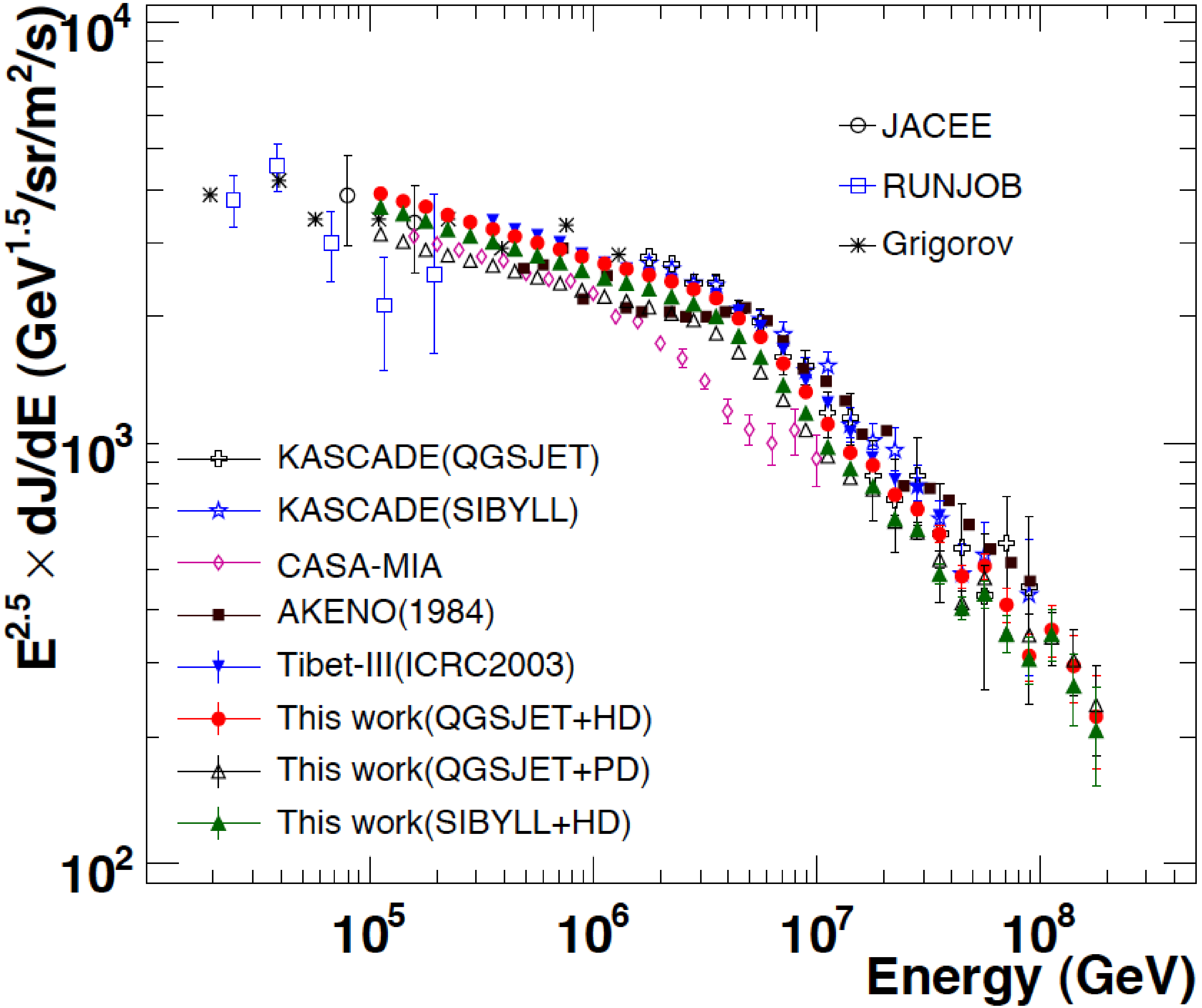


A(internal)
= 36,900 m^2

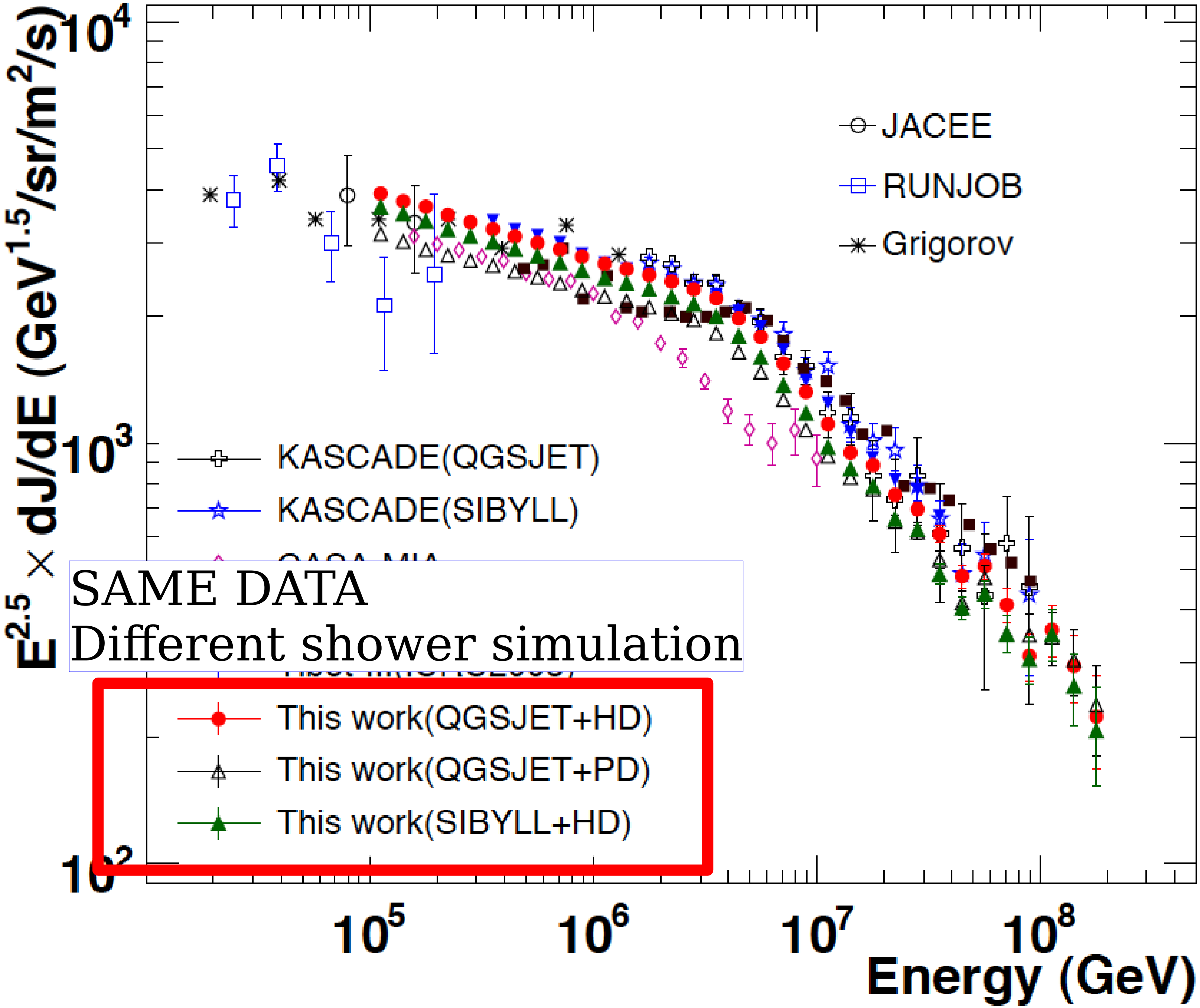


Spacing 7.5 meters (interior)

Tibet Air Shower Energy Spectrum



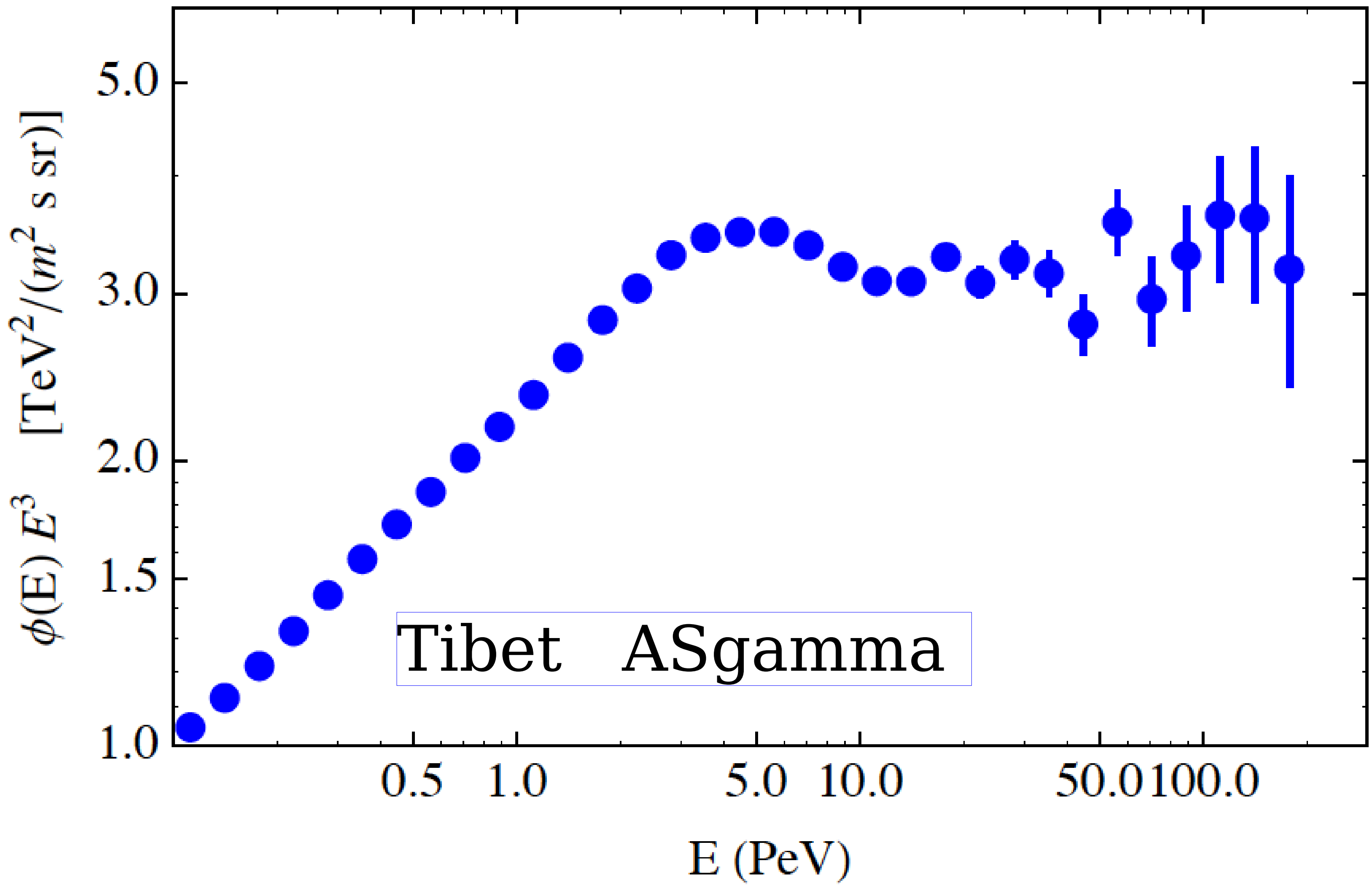
Tibet Air Shower Energy Spectrum



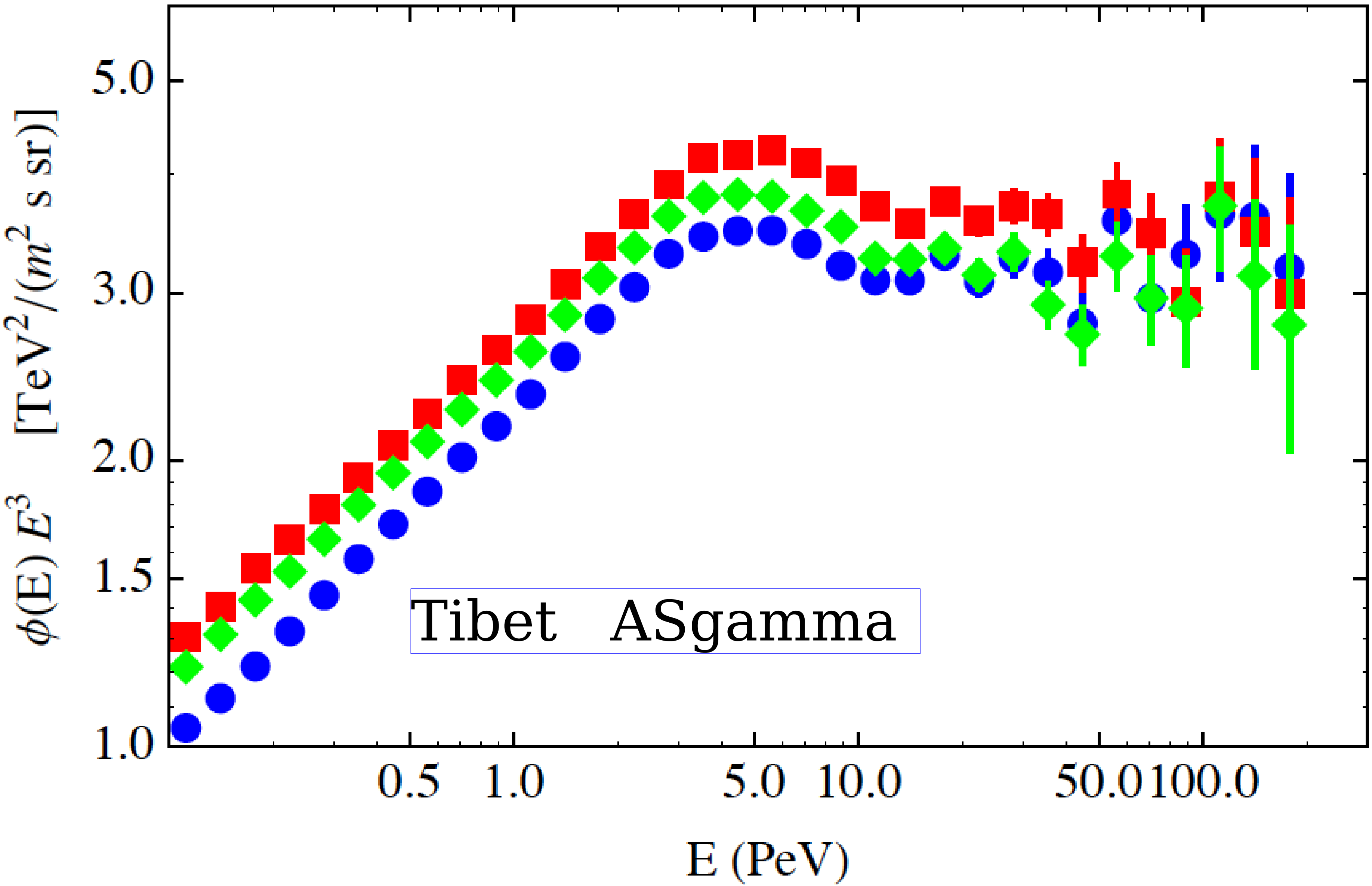
SAME DATA
Different shower simulation

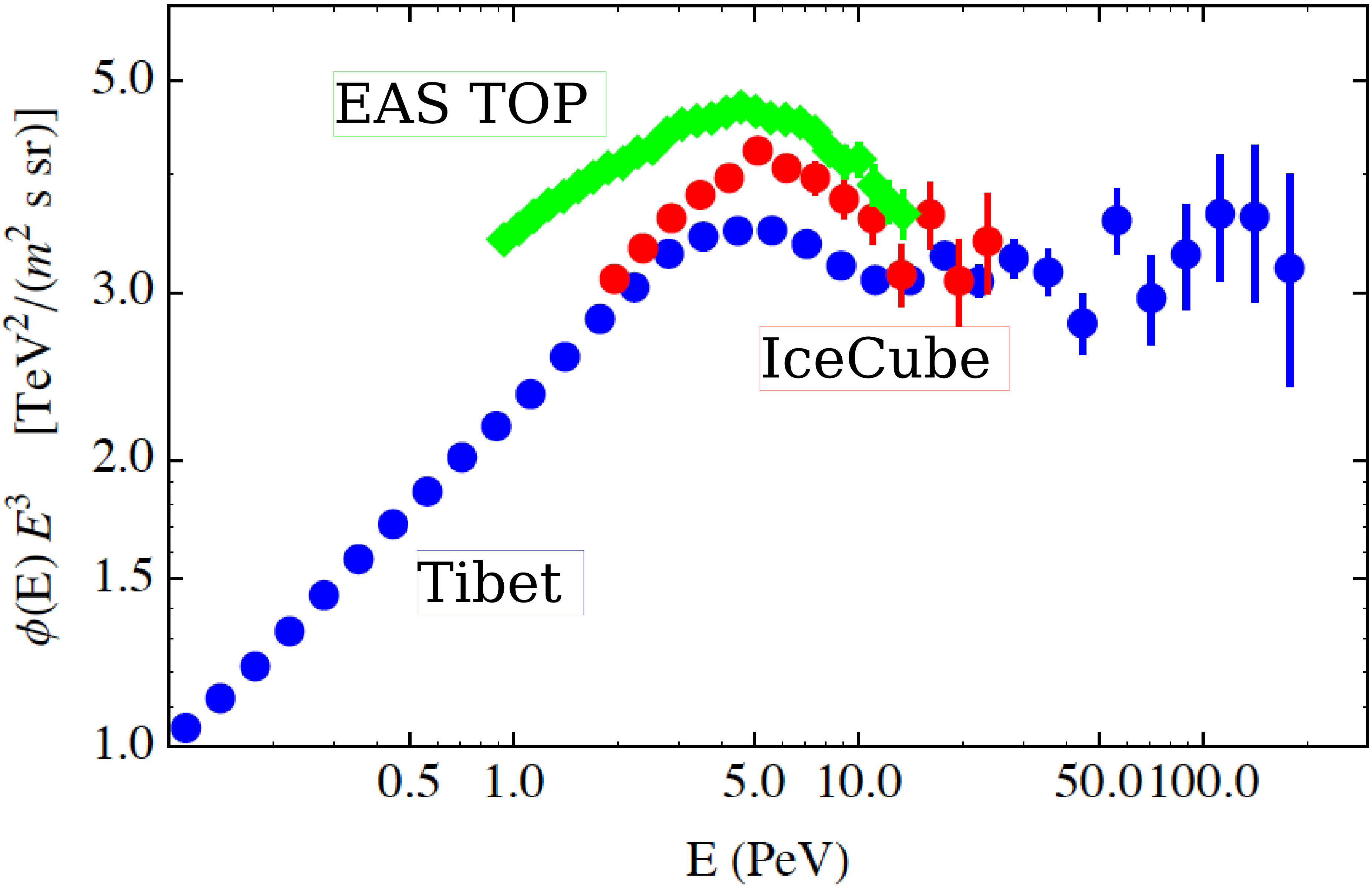
The “Shape of the KNEE”

$$E^3\ \phi(E)$$



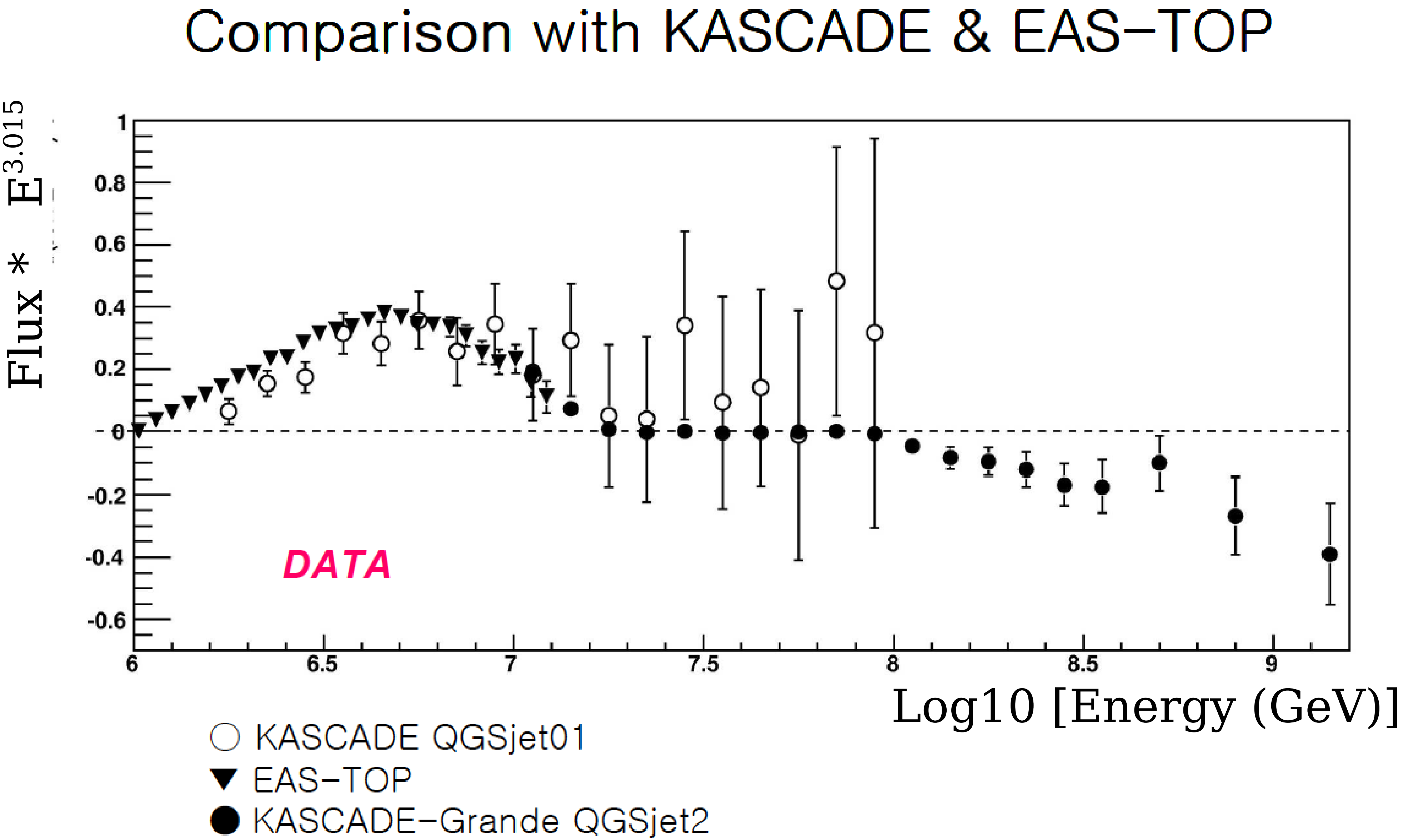
The “Shape of the KNEE”

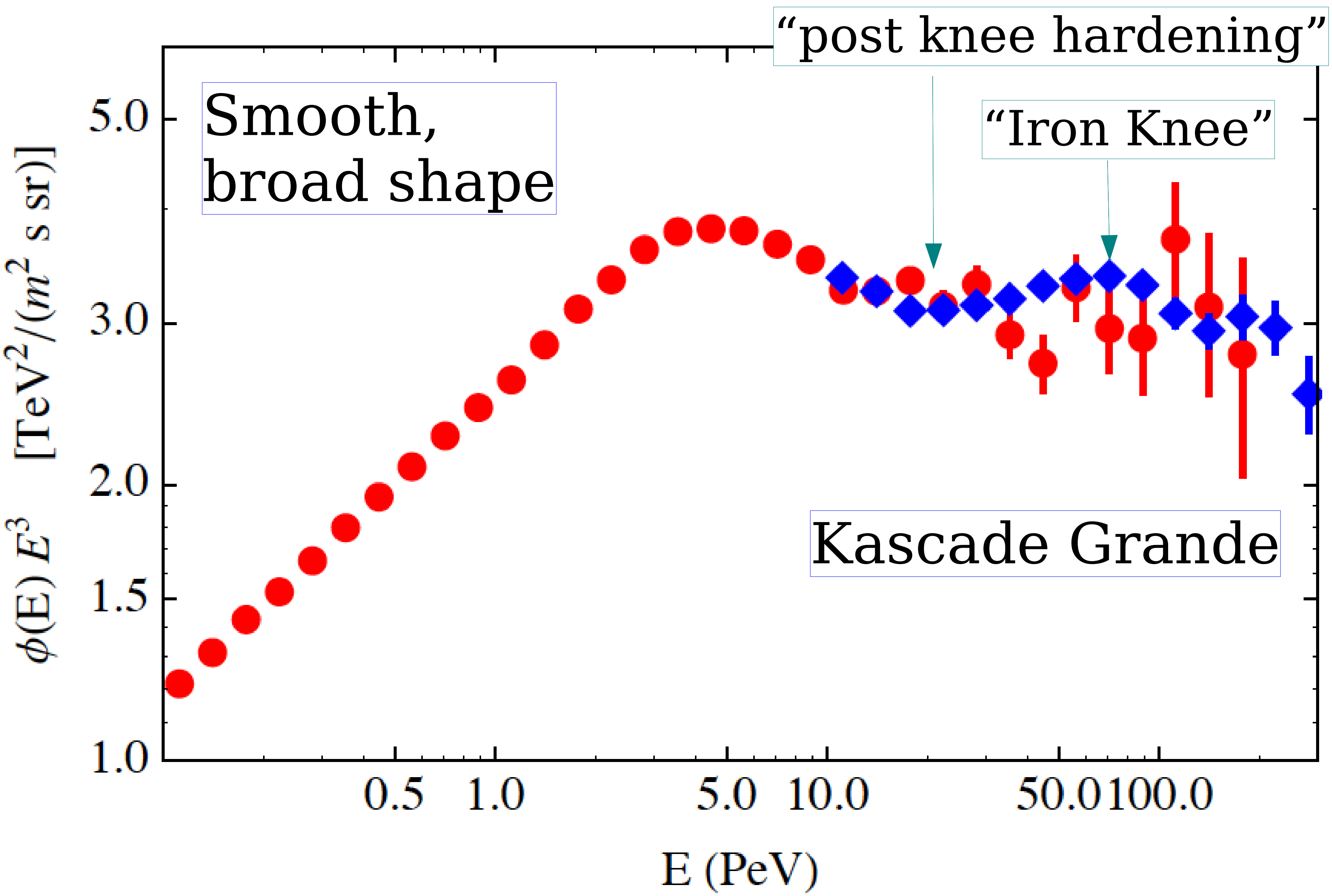




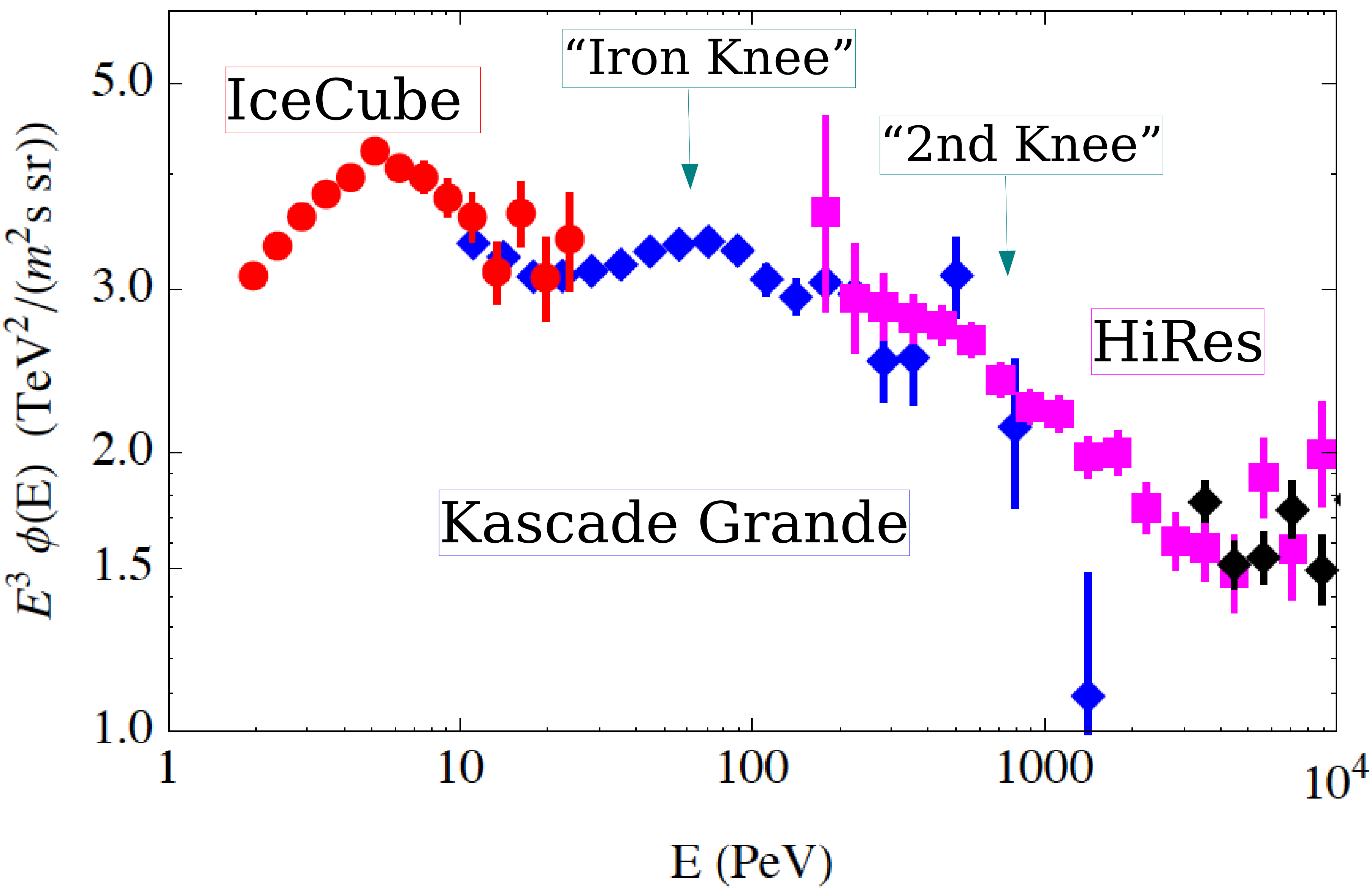
EAS TOP
IceCube
Tibet
$\phi(E)\,E^3$ [TeV^2/(m^2 s sr)]
5.0
3.0
2.0
1.5
1.0
0.5
1.0
5.0
10.0
50.0
100.0
E (PeV)

Structure of the "Knee"



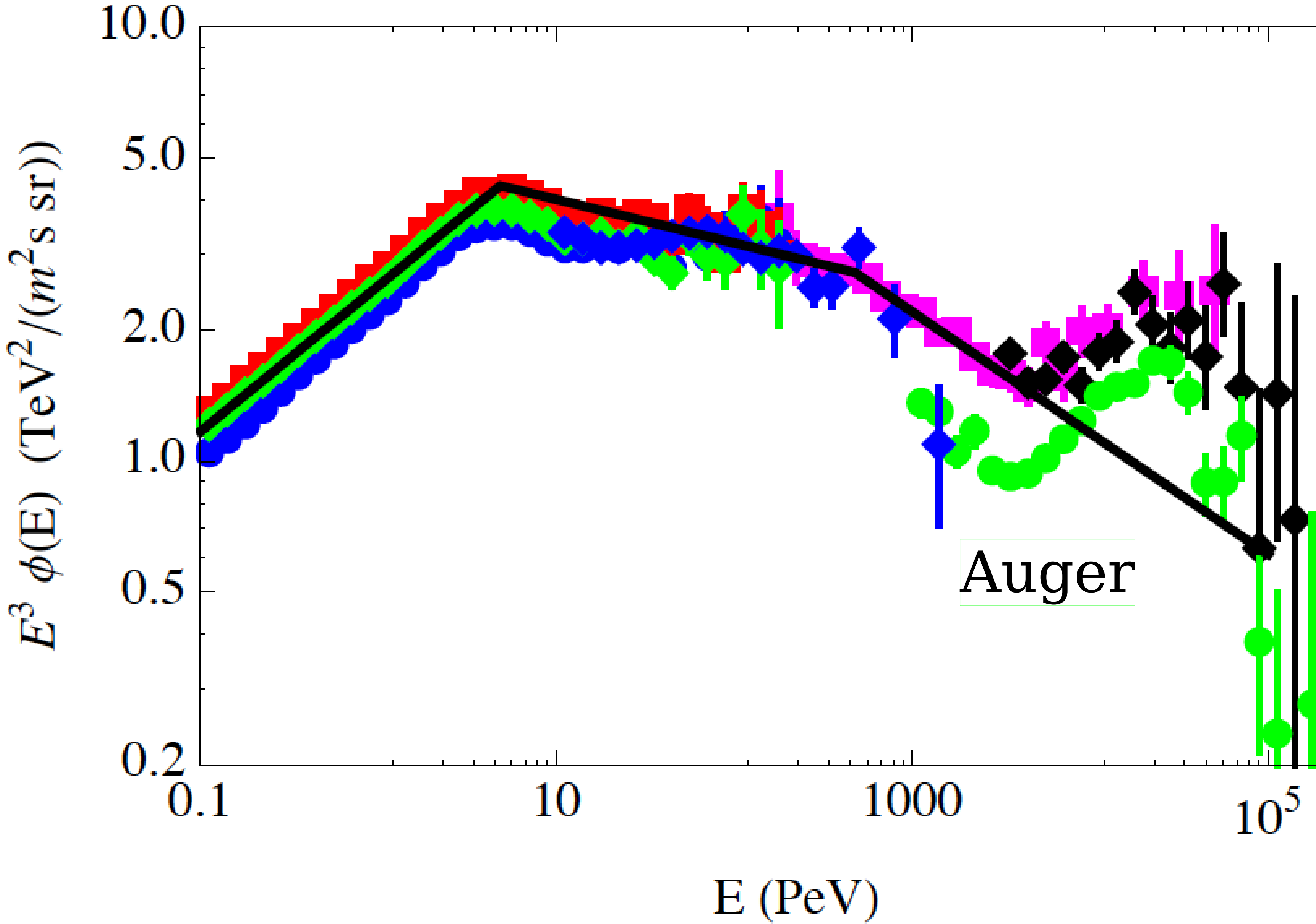


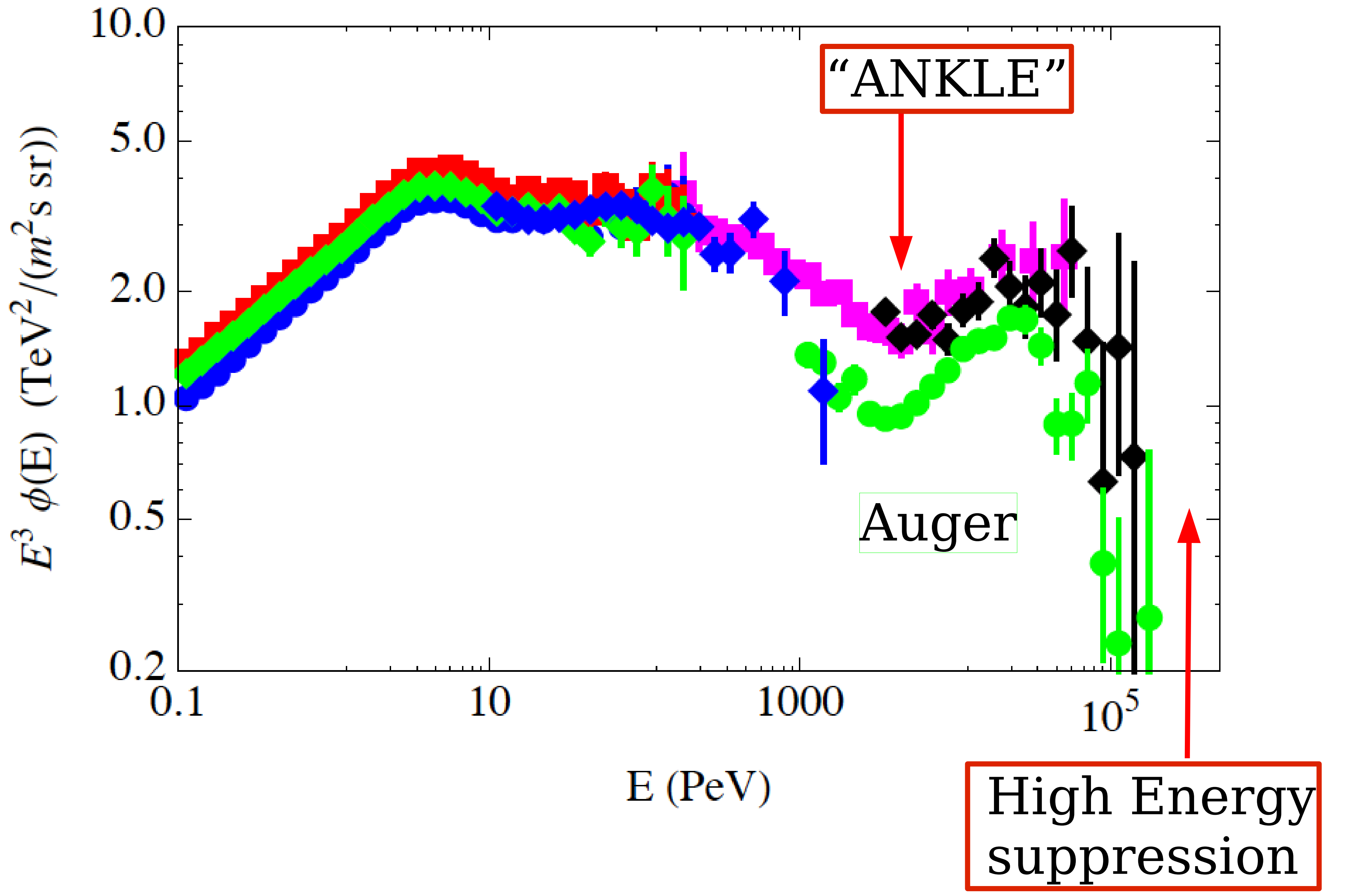
"post knee hardening"
"Iron Knee"
Smooth, broad shape
Kascade Grande
5.0
3.0
2.0
1.5
1.0
0.5
1.0
5.0
10.0
50.0
100.0
$\phi(E)\,E^3$ [TeV^2/(m^2 s sr)]
E (PeV)



IceCube
"Iron Knee"
"2nd Knee"
HiRes
Kascade Grande
5.0
3.0
2.0
1.5
1.0
1
10
100
1000
10^4
$E^3\ \phi(E)\ (\mathrm{TeV}^2/(m^2\,\mathrm{s\,sr}))$
E (PeV)

Simple “2 knees pictures” very likely insufficient.



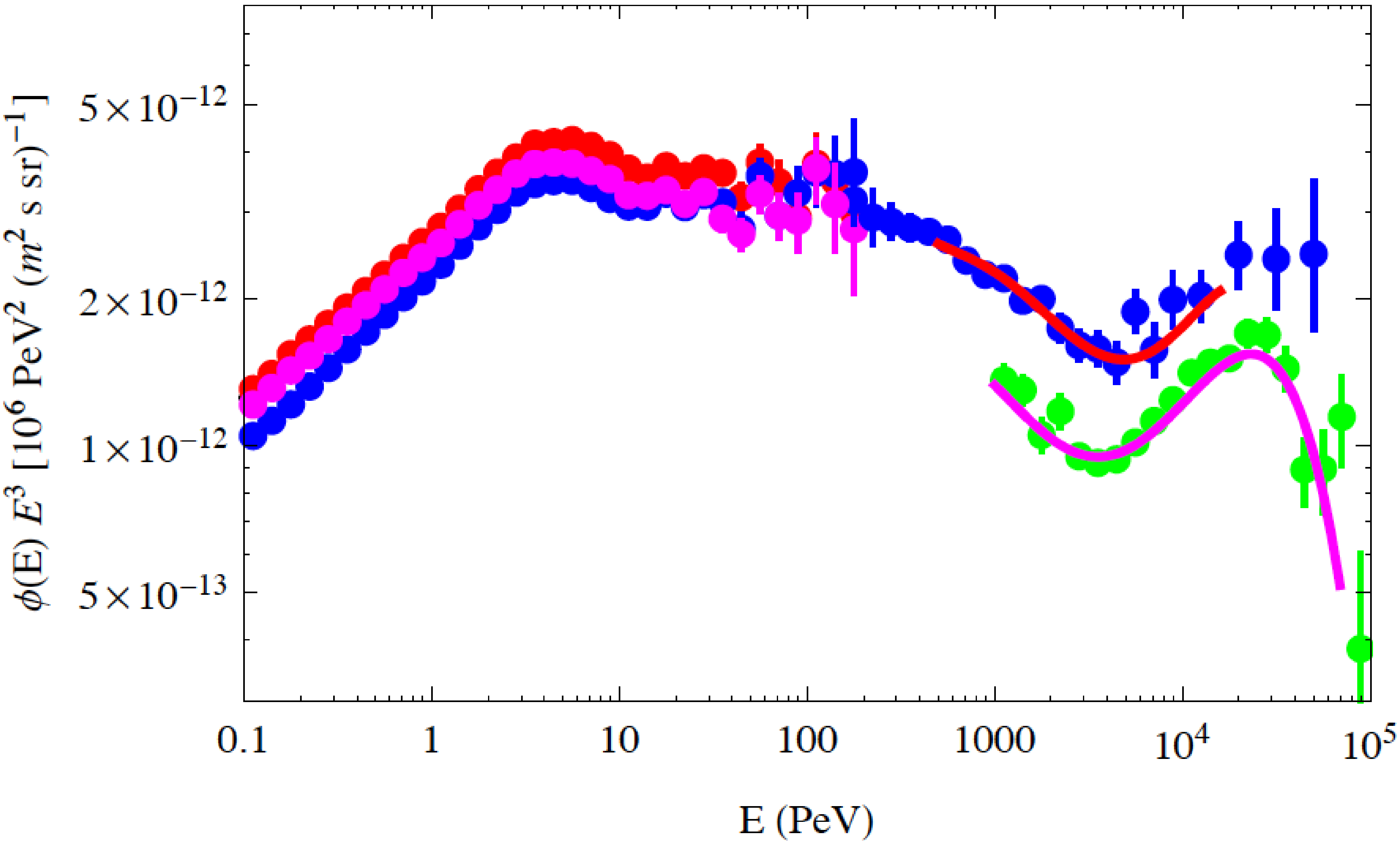


"ANKLE"
Auger
High Energy suppression
10.0
5.0
2.0
1.0
0.5
0.2
0.1
10
1000
10^5
E (PeV)
$E^3\ \phi(E)\ (\mathrm{TeV}^2/(m^2\,\mathrm{s\,sr}))$

TIBET AS-gamma CR spectra

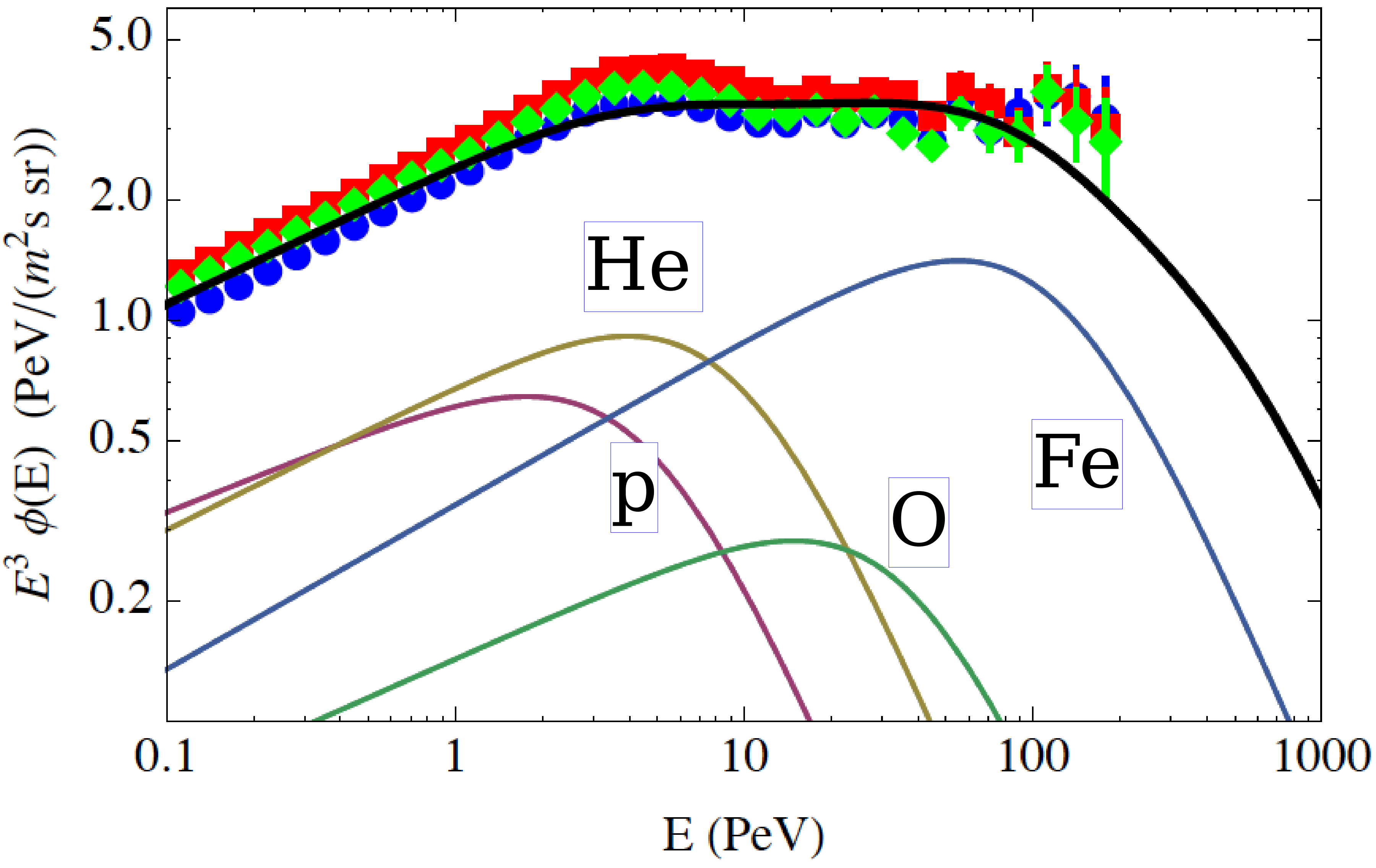
HIRES spectrum

AUGER spectrum Energy scale discrepancy.



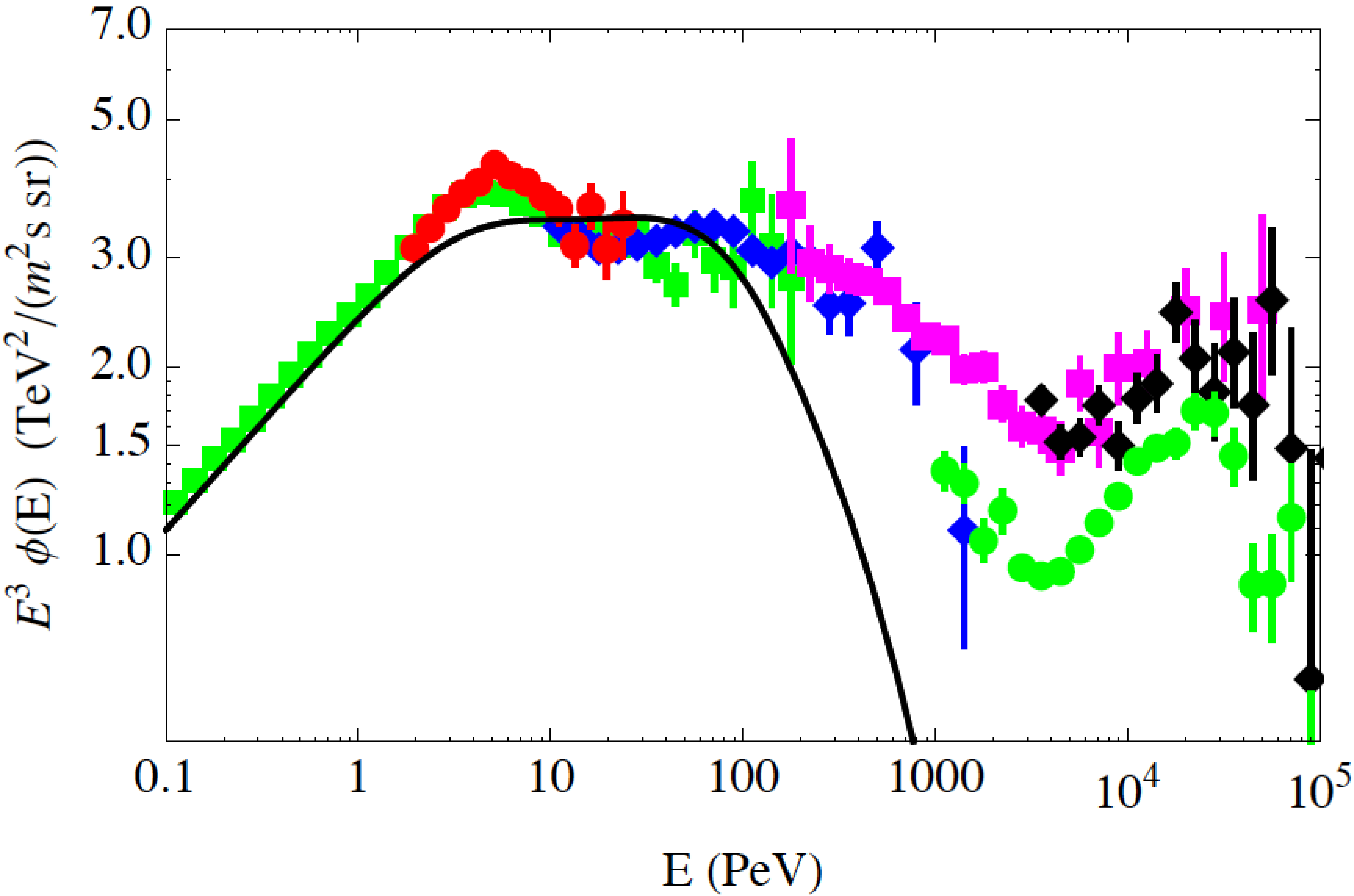
“Standard idea”

Same structure repeated “rescaled in Z”

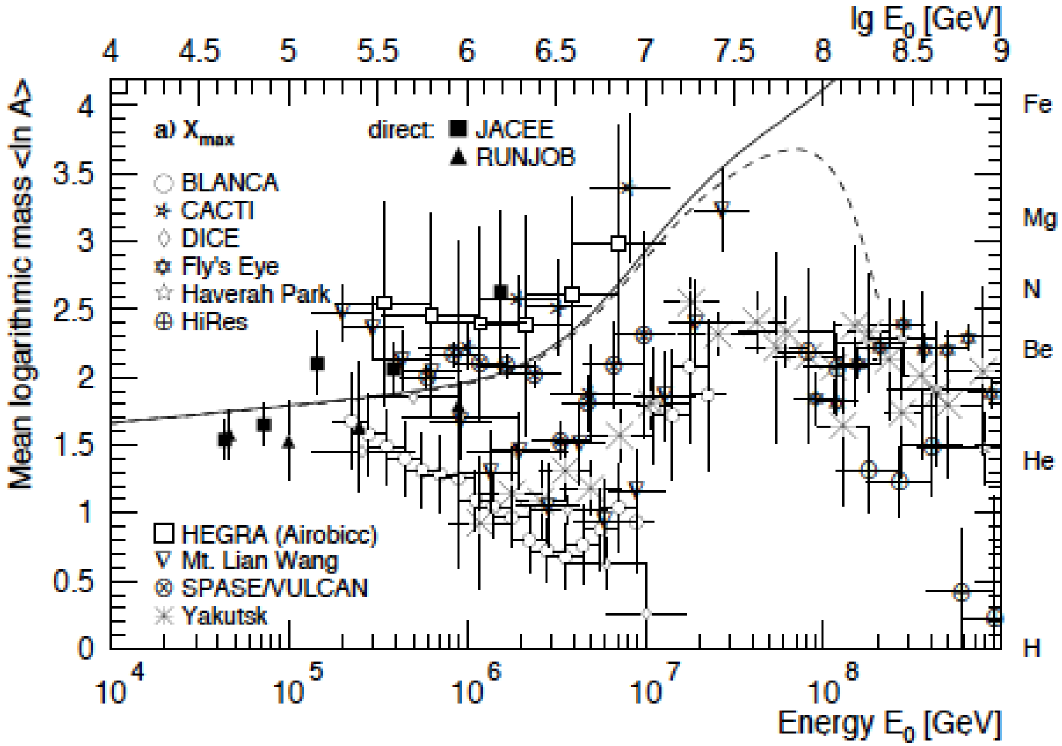


Proton Knee at 4.51 PeV

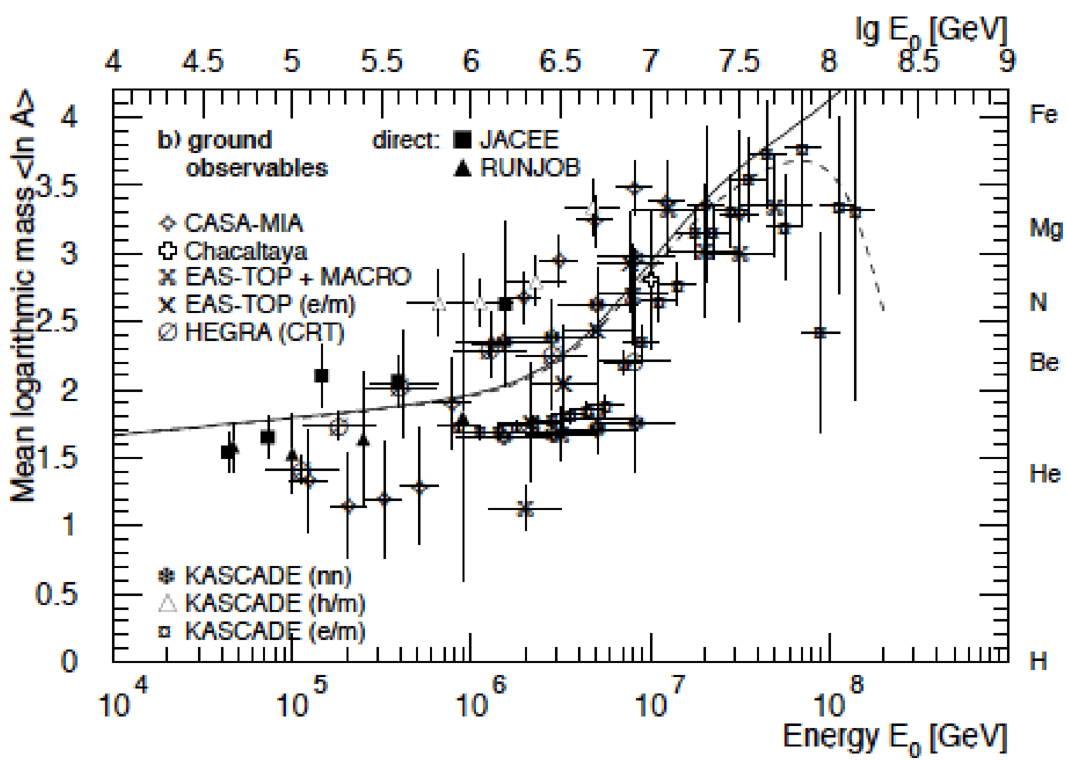
Where does the extragalactic component enters ?



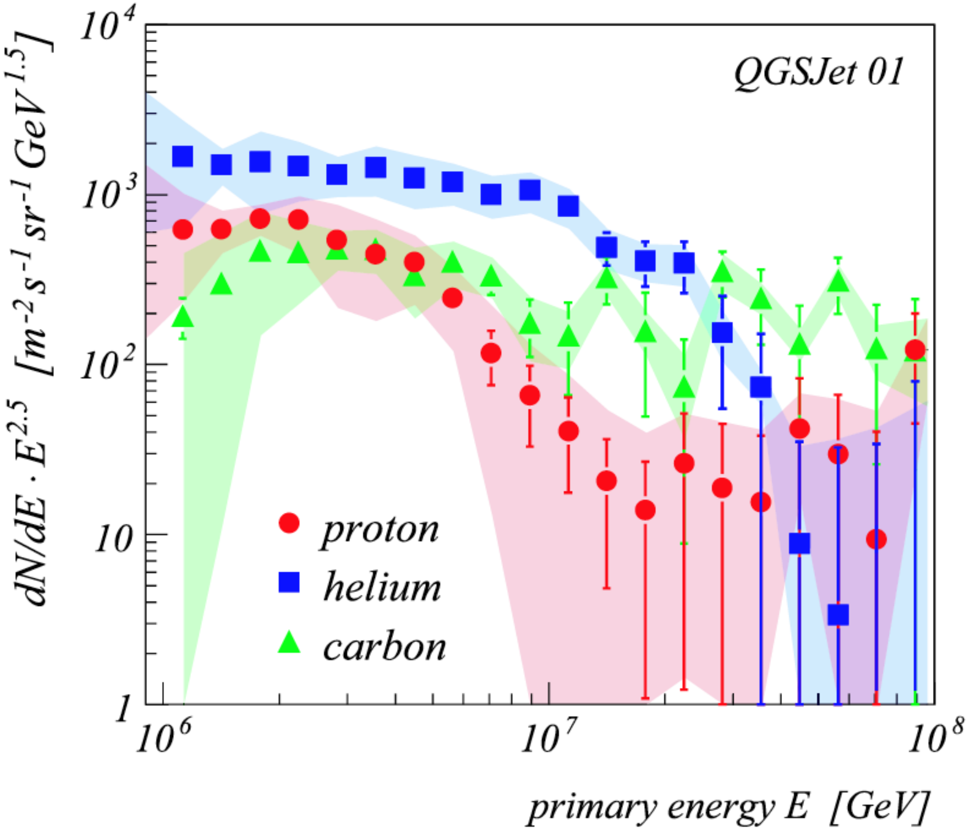
Composition Measurements



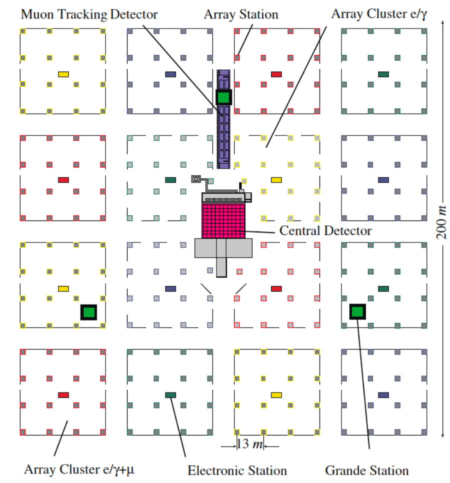
Xmax



Ground observables

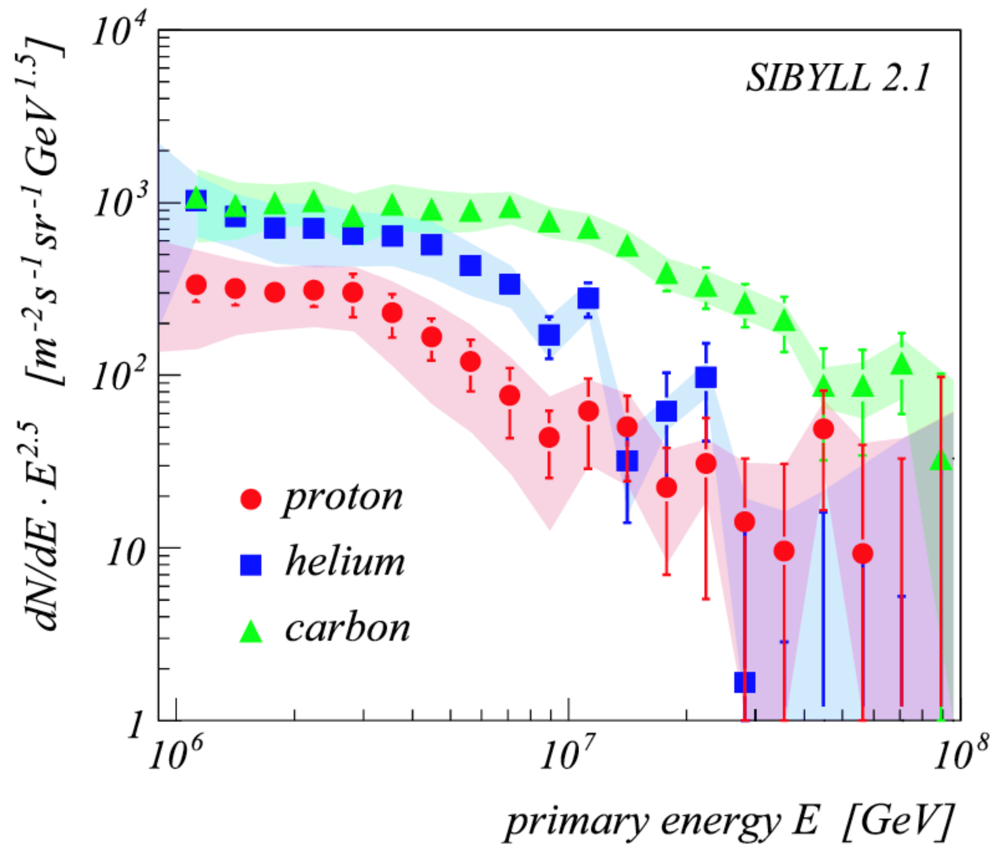


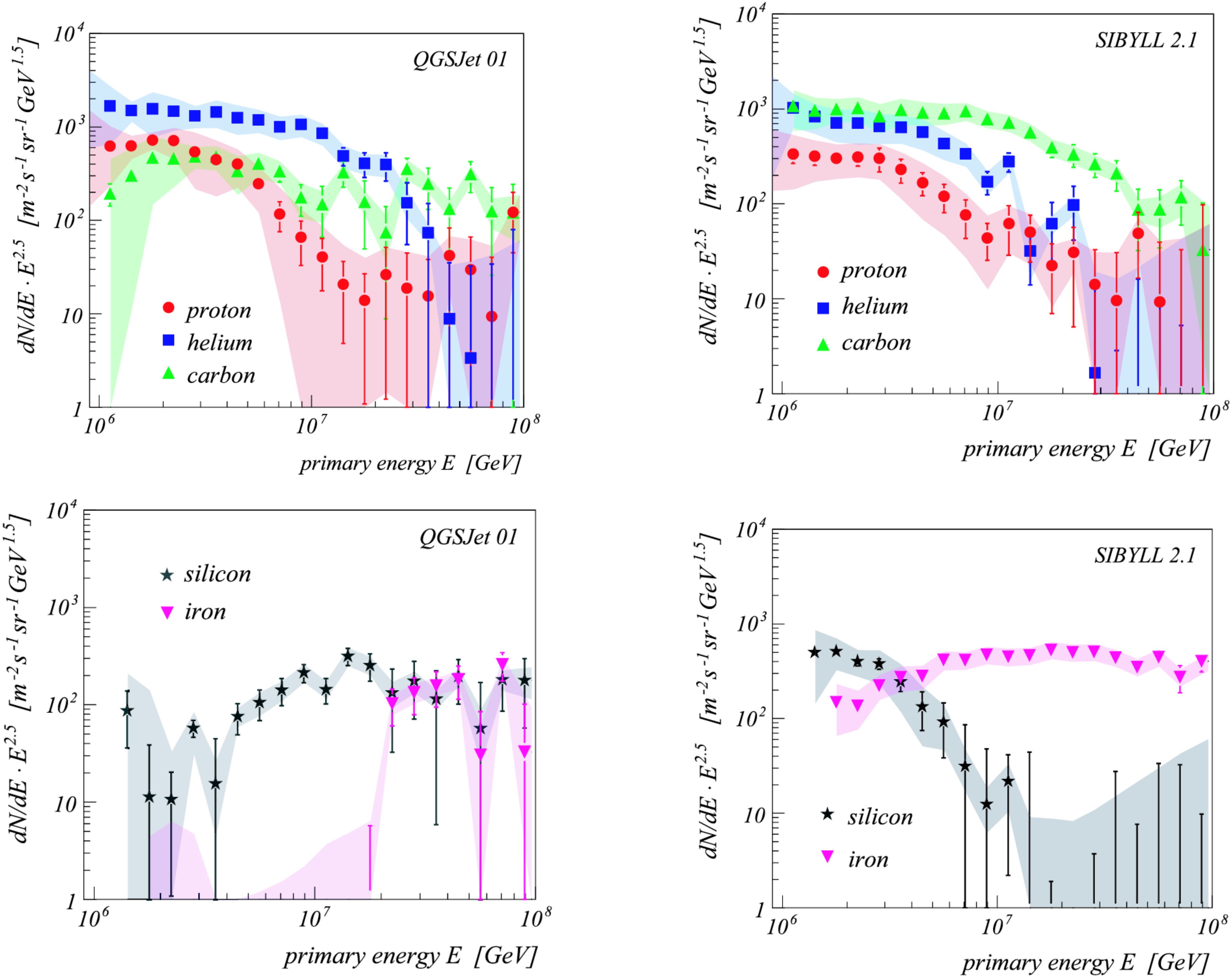
KASCADE results



Model Dependence !

KASCADE /KASCADE-GRANDE

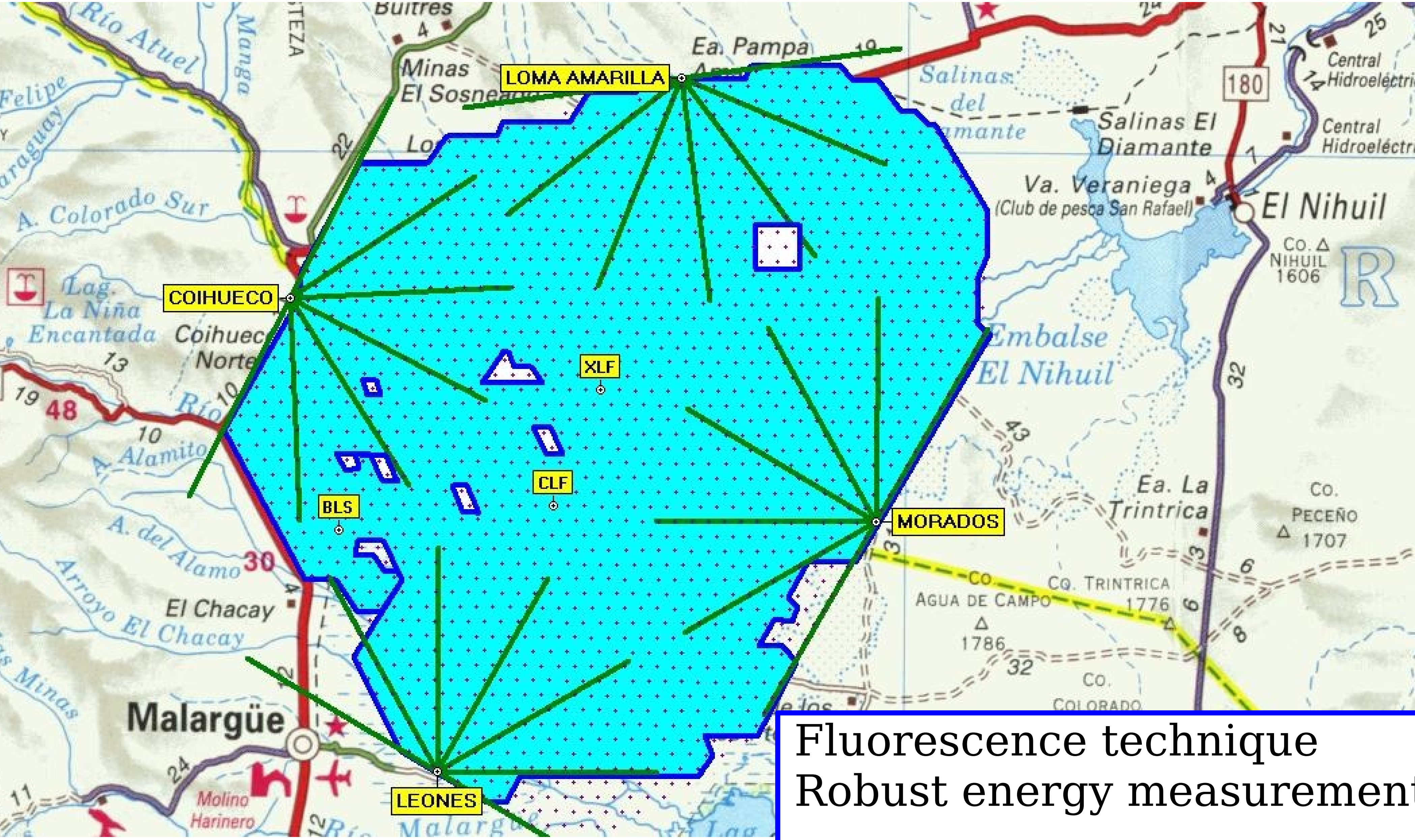




QGSJet 01
proton
helium
carbon
SIBYLL 2.1
proton
helium
carbon
QGSJet 01
silicon
iron
SIBYLL 2.1
silicon
iron
$dN/dE \cdot E^{2.5}$ $[m^{-2} s^{-1} sr^{-1} GeV^{1.5}]$
primary energy E [GeV]

The Highest Energy

Cosmic Rays

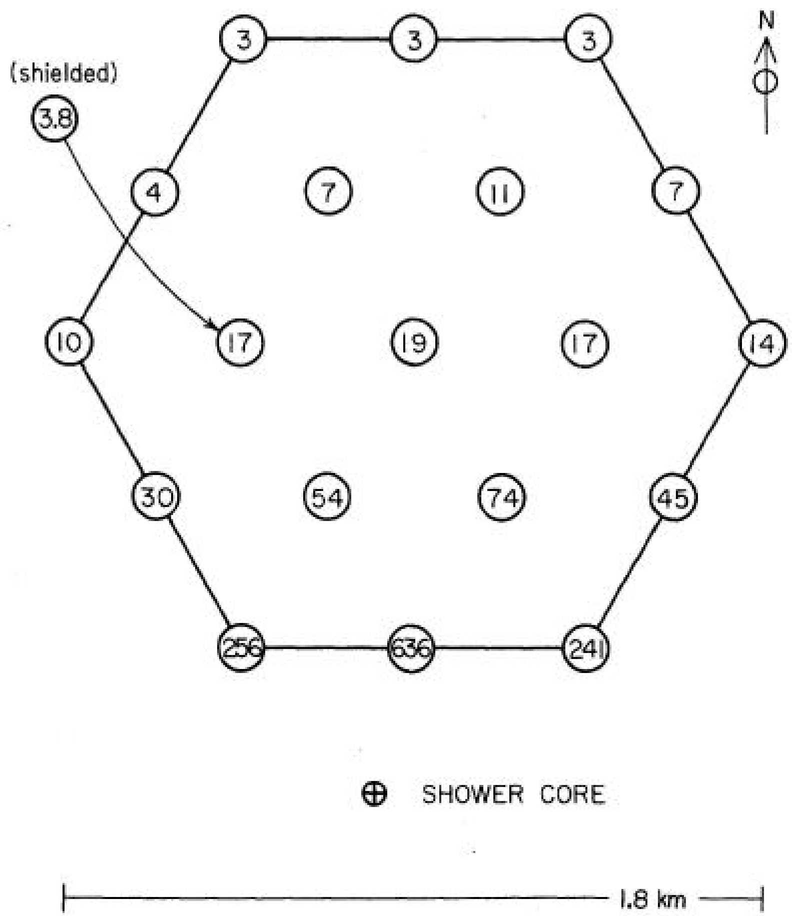


Fluorescence technique
Robust energy measurement

Hybrid detector concept

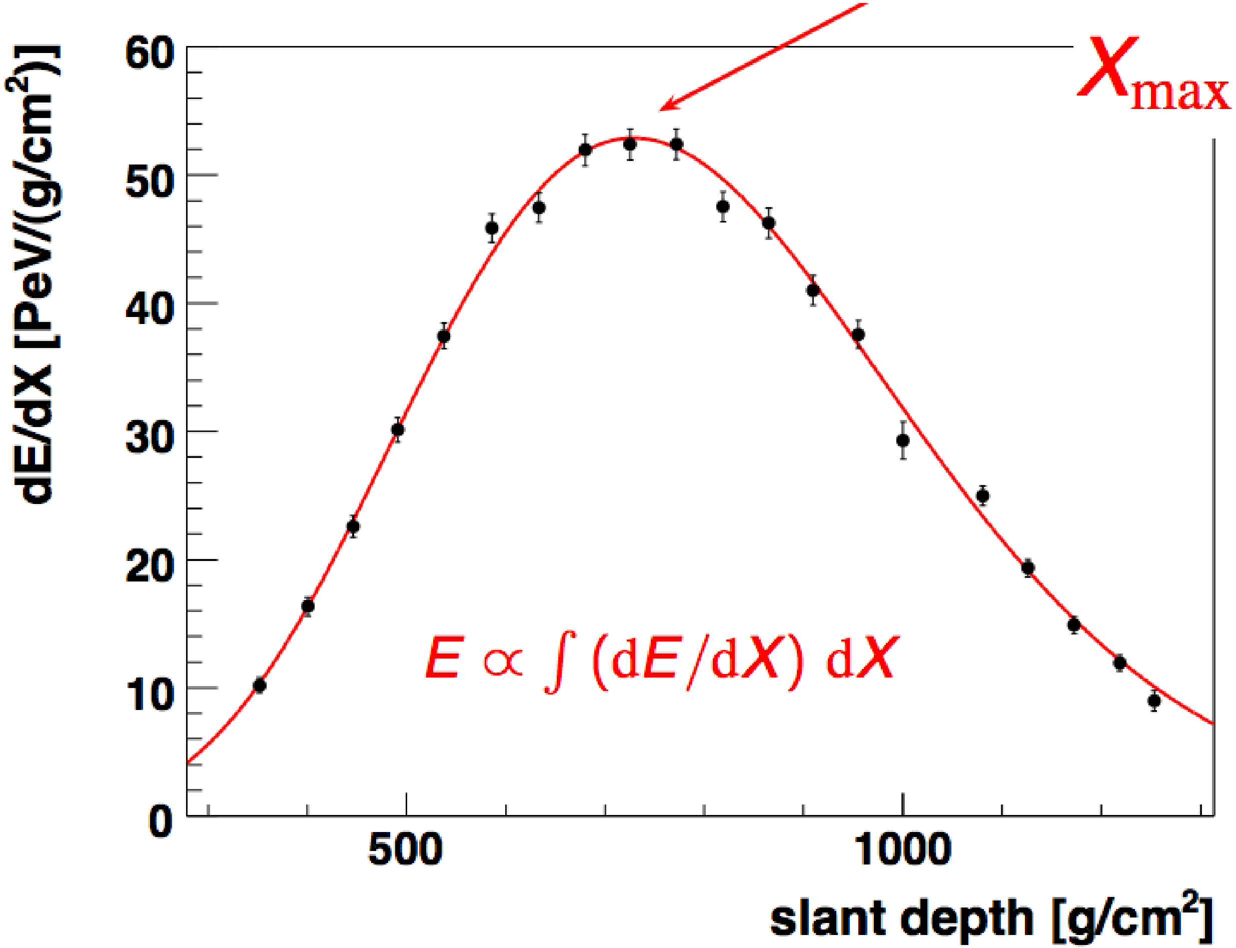
EXTREMELY ENERGETIC COSMIC-RAY EVENT*

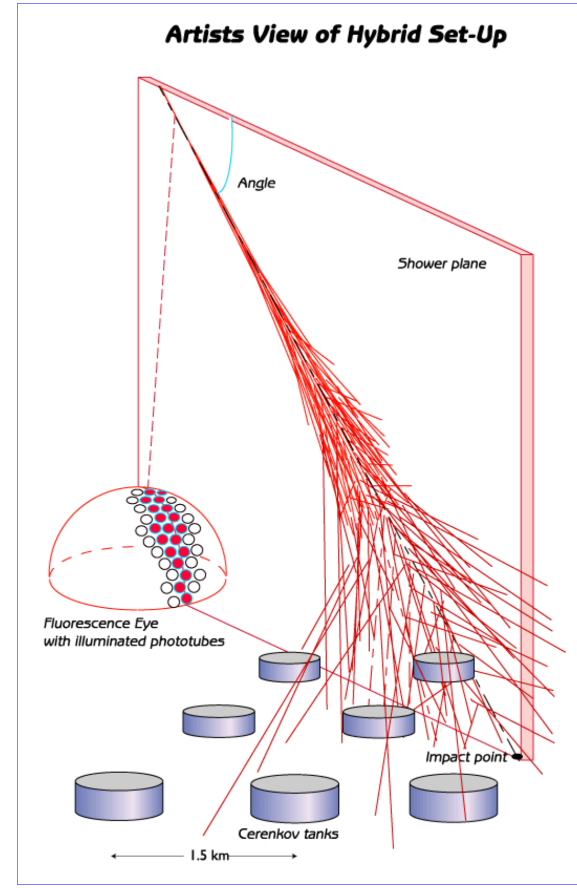
John Linsley, Livio Scarsi,† and Bruno Rossi
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received April 12, 1961)



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.



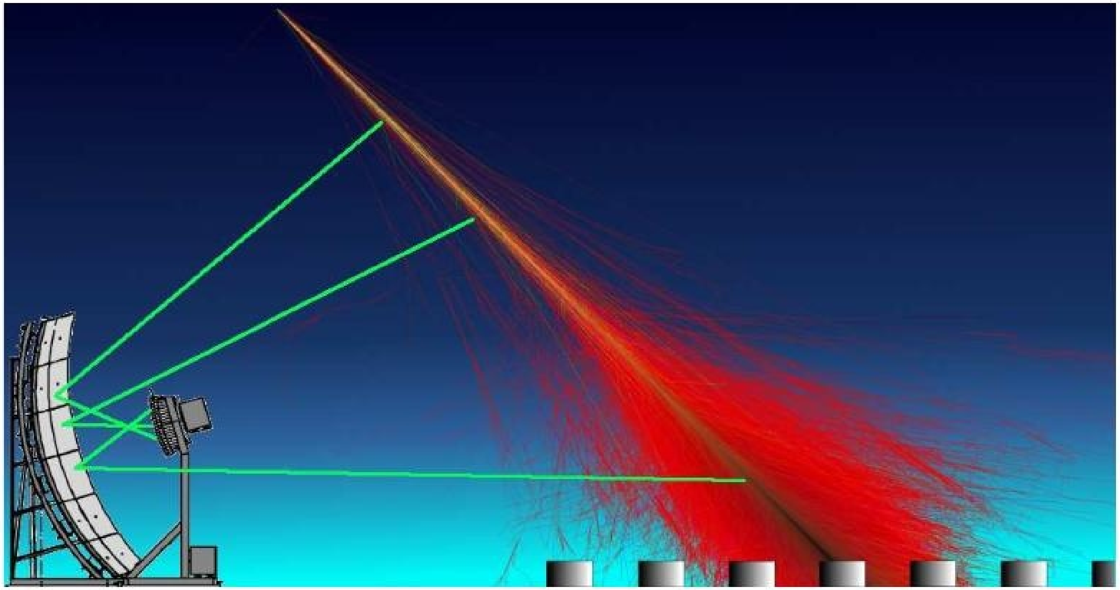


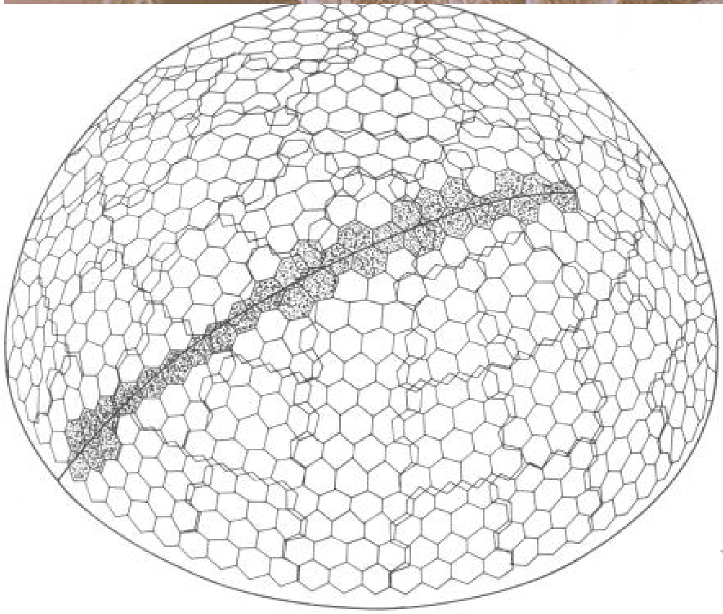
$$E_{\text{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

Area $\propto$ Energy

Shape depends on :
- Primary Identity
- Interaction Model

The **Fly's Eye** Detector concept





FLUORESCENCE DETECTION

In principle little model dependence
for shower energy determination

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

Observed Light → Emitted Photons → Shower Size

Geometry
Atmospheric
Absorption

Fluorescence
Yields

Threshold for photon-hadronic interactions:

$$p + \gamma \to p + \text{hadrons}$$

GZK

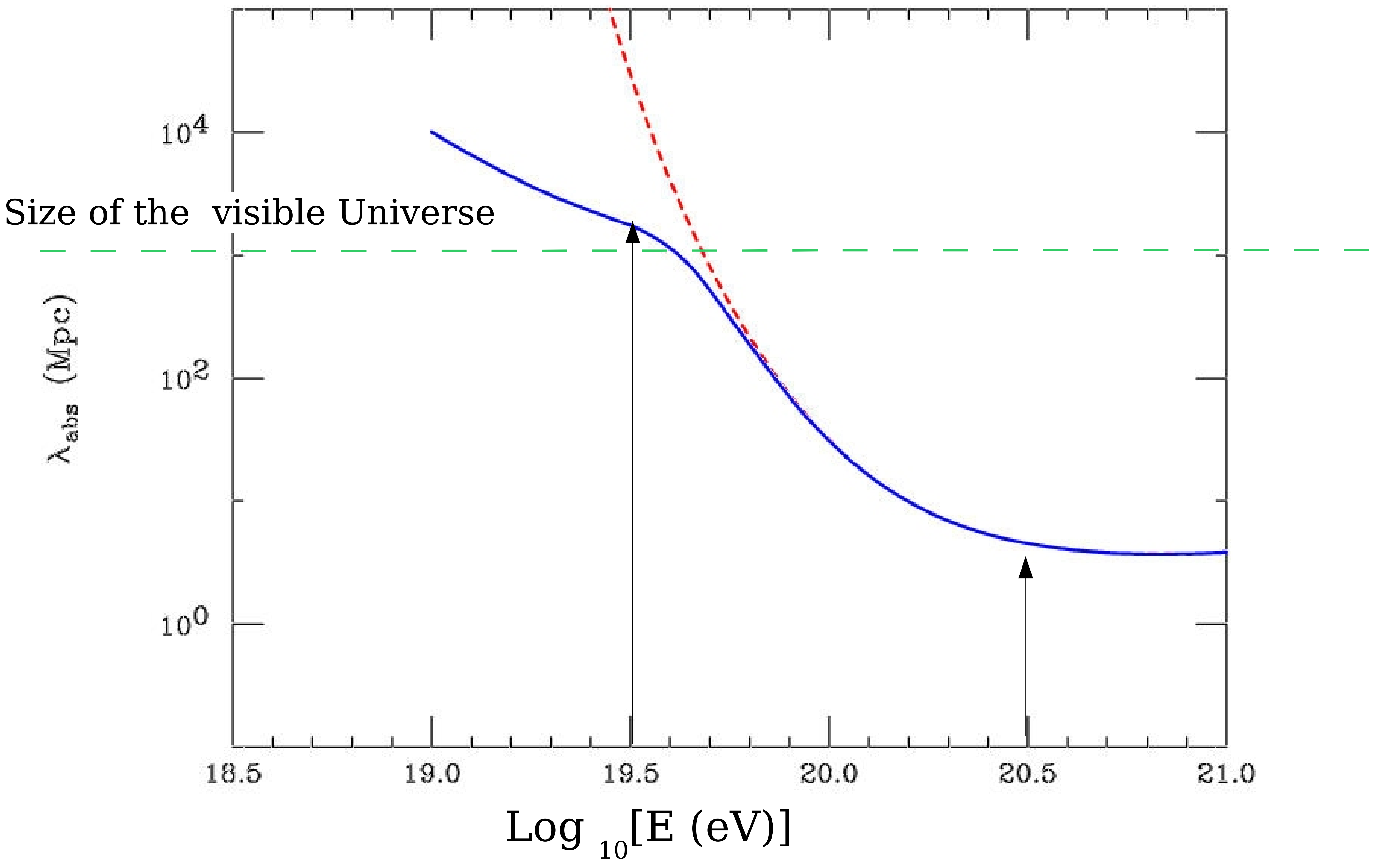
Threshold for pion production

$$p + \gamma \to p + \pi^{\circ}$$

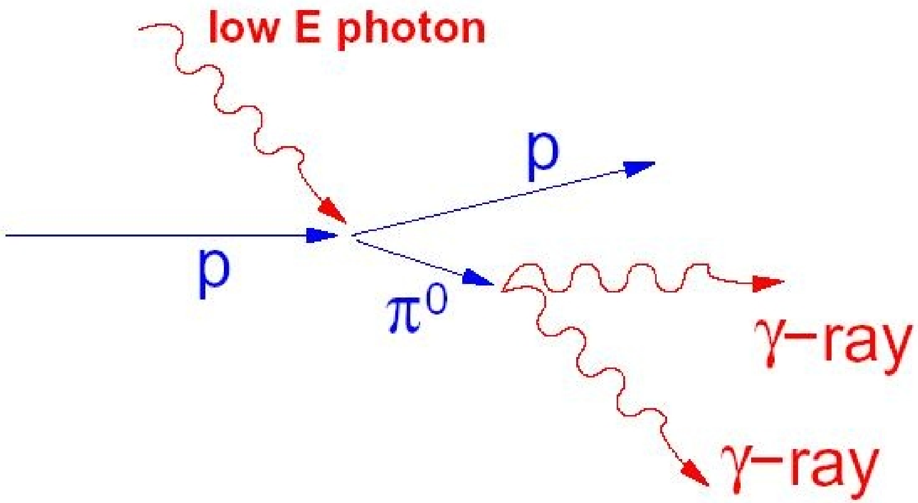
$$p + \gamma \to n + \pi^{+}$$

$$E_p \, \varepsilon_\gamma \gtrsim m_p \, m_\pi$$

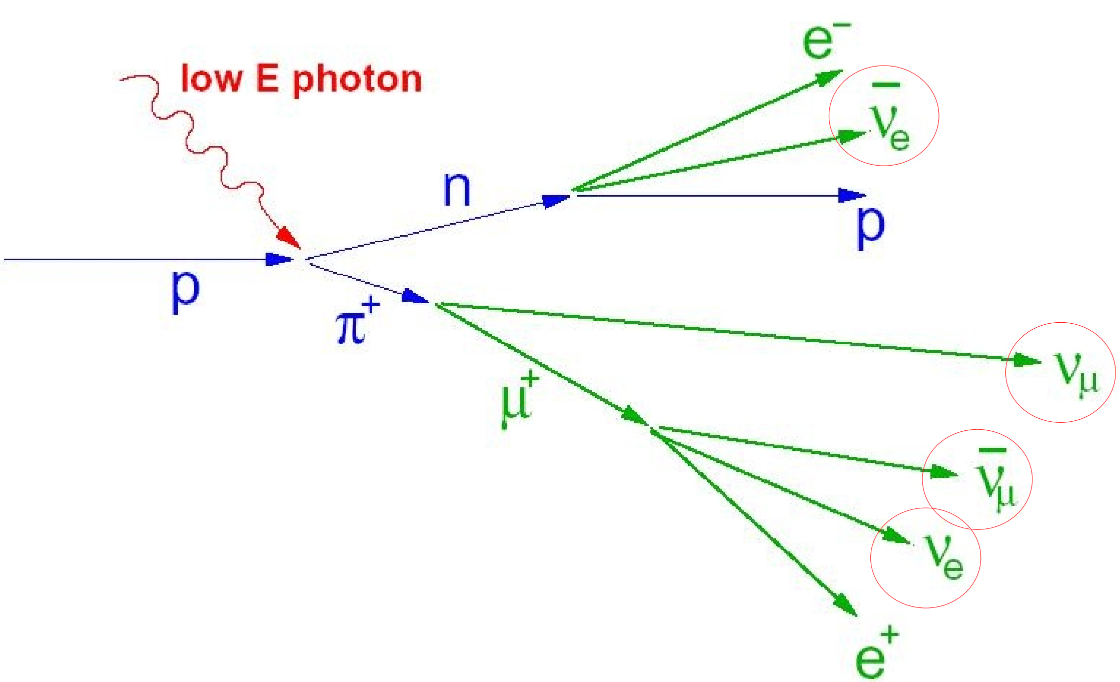
$$E \geq \frac{(m_p + m_\pi)^2 - m_p^2}{2\,\varepsilon\,(1 - \cos\theta_{\gamma e})} \geq \frac{(m_p + m_\pi)^2 - m_p^2}{4\,\varepsilon}$$


Size of the visible Universe
10^4
10^2
10^0
λ_{abs} (Mpc)
18.5
19.0
19.5
20.0
20.5
21.0
Log $_{10}$[E (eV)]

Energy Loss Mechanisms for Protons:



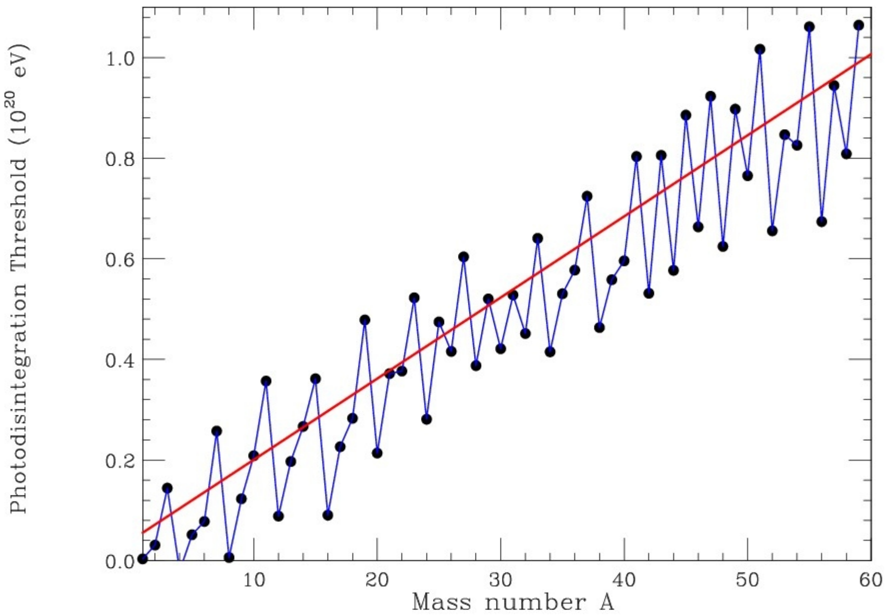
Greisen-Zatsepin- Kuzmin (GZK) suppression



NEUTRINO PRODUCTION

Energy Loss for Nuclei:
Photo-disintegration.

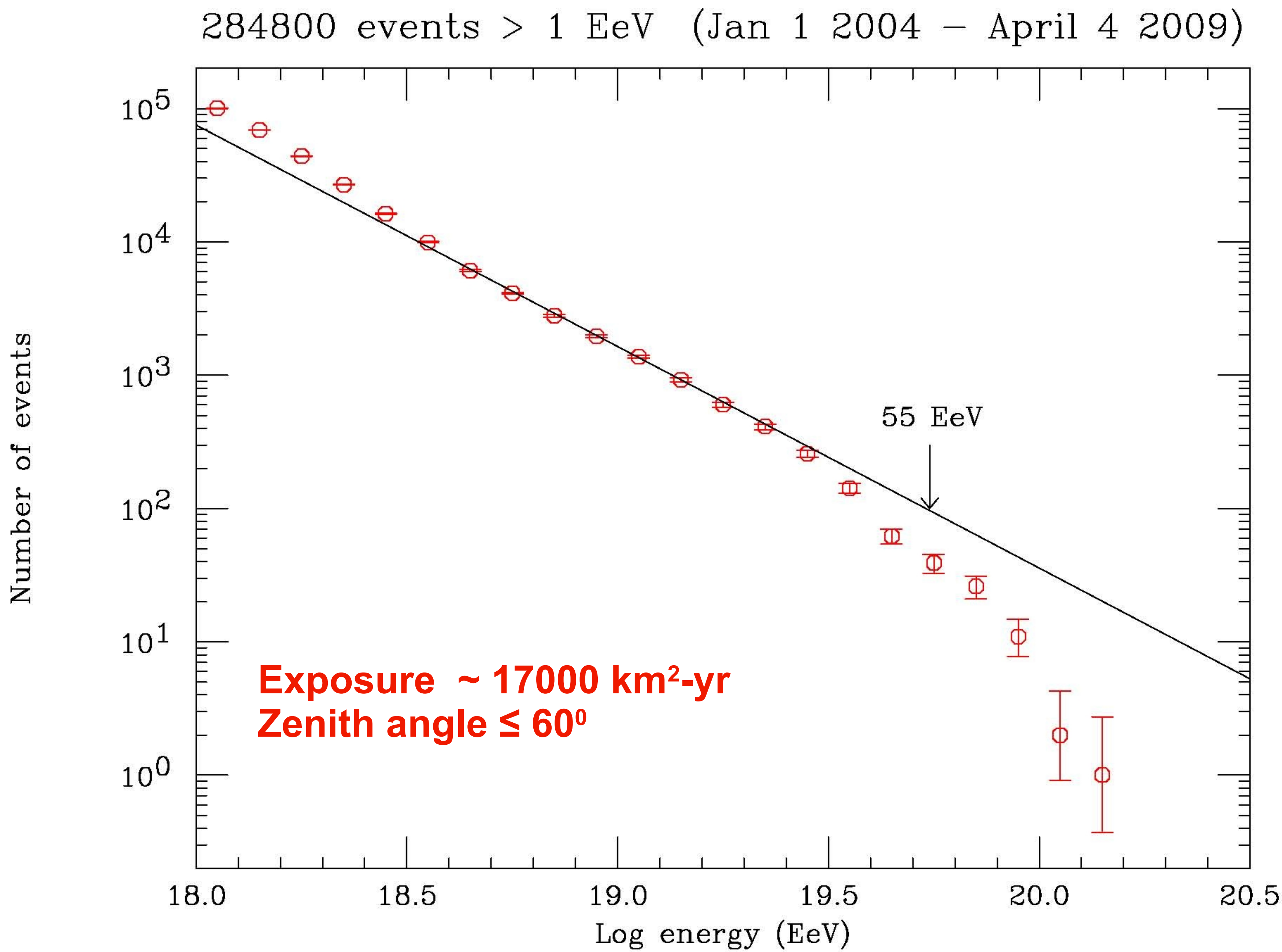
$$A + \gamma \to (A-1) + N$$



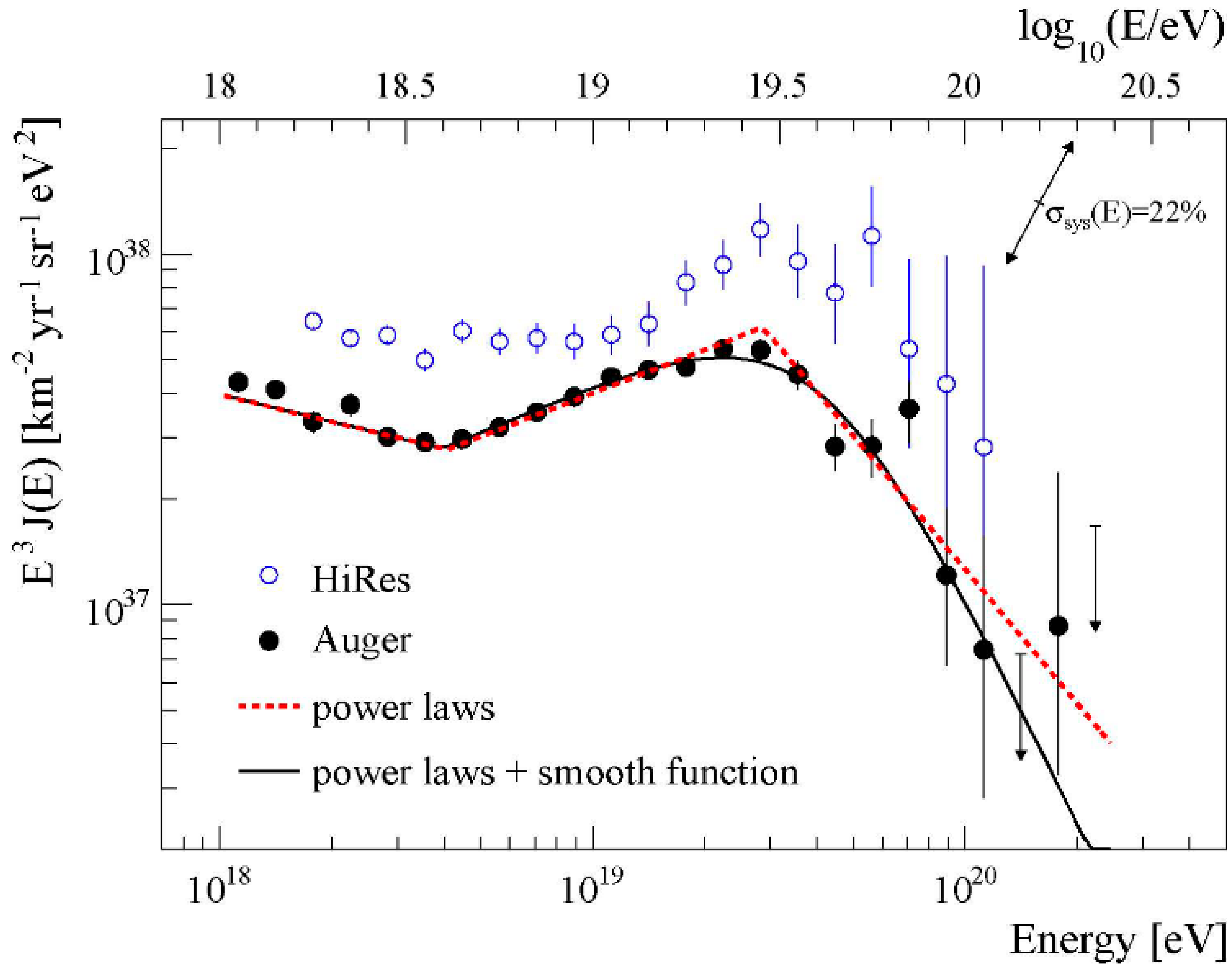
$$E_A \geq \frac{(m_{A-1} + m_N)^2 - m_A^2}{2\,\varepsilon_\gamma\,(1 - \cos\theta_{p\gamma})}$$

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

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


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

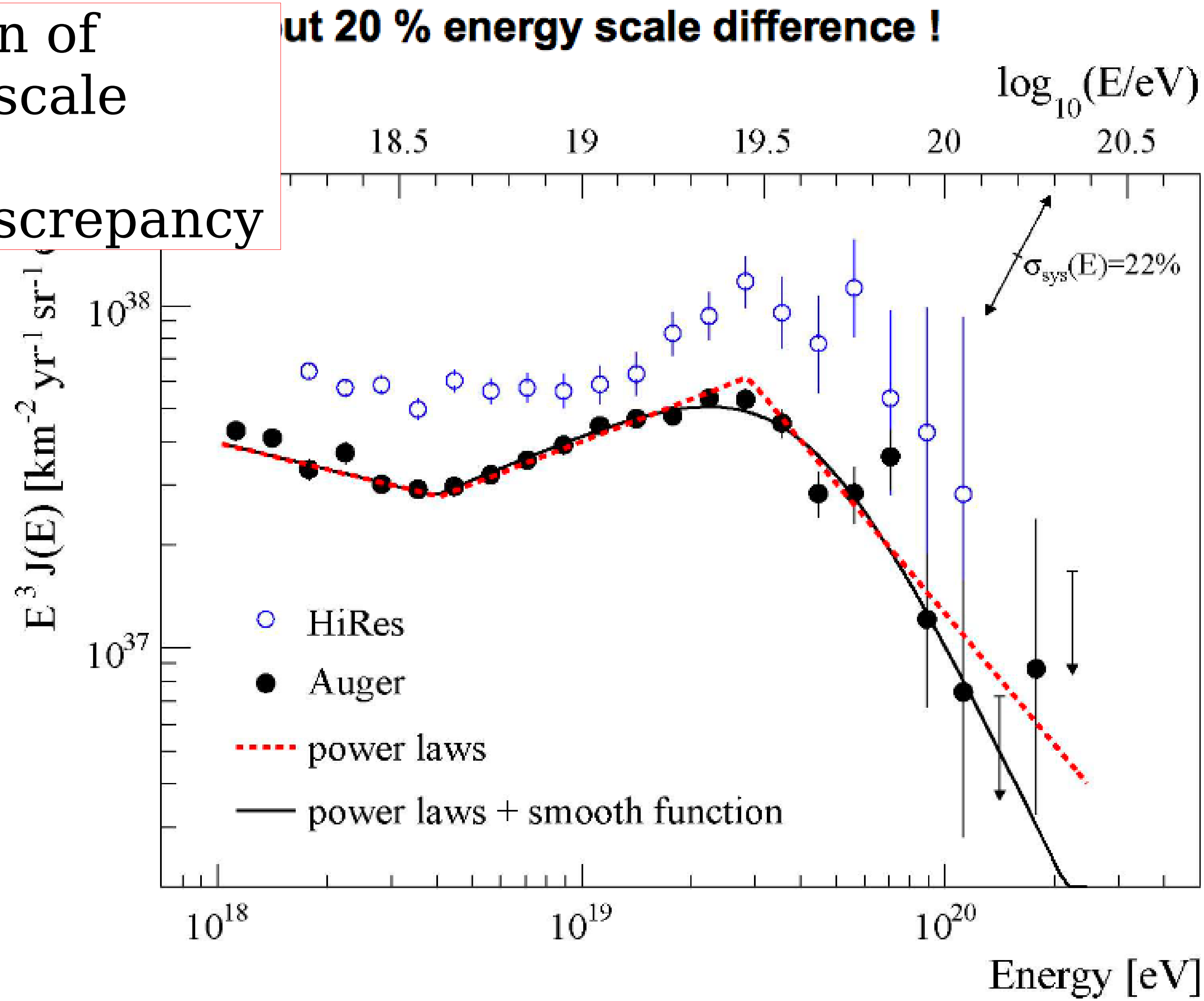
About 20 % energy scale difference !



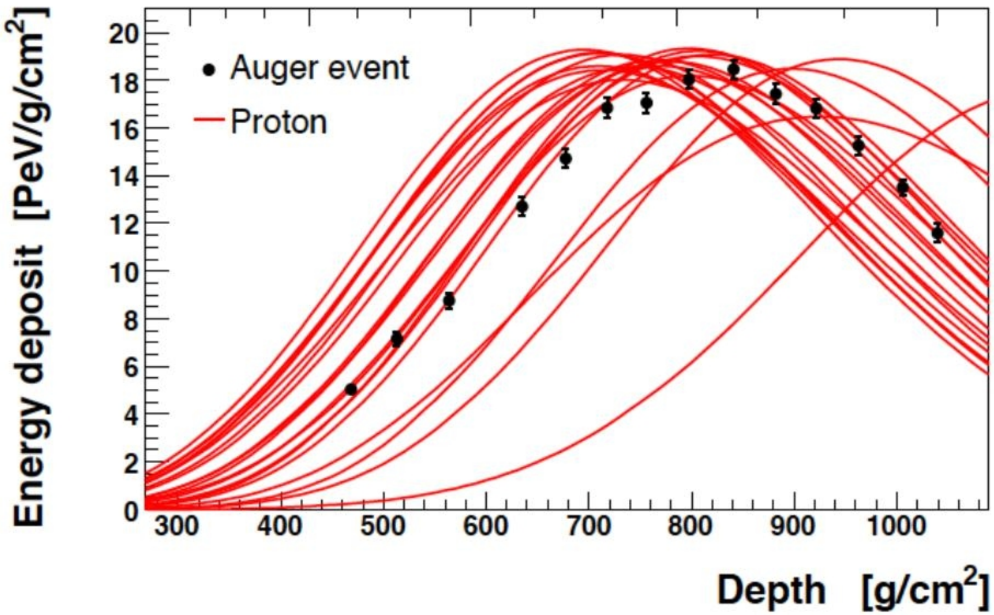
HiRes/TA/Auger observe a High Energy Suppression
Consistent with the GZK suppression
[or photo-disintegration of Iron]
[or source cutoff]

Question of
energy scale

30% discrepancy

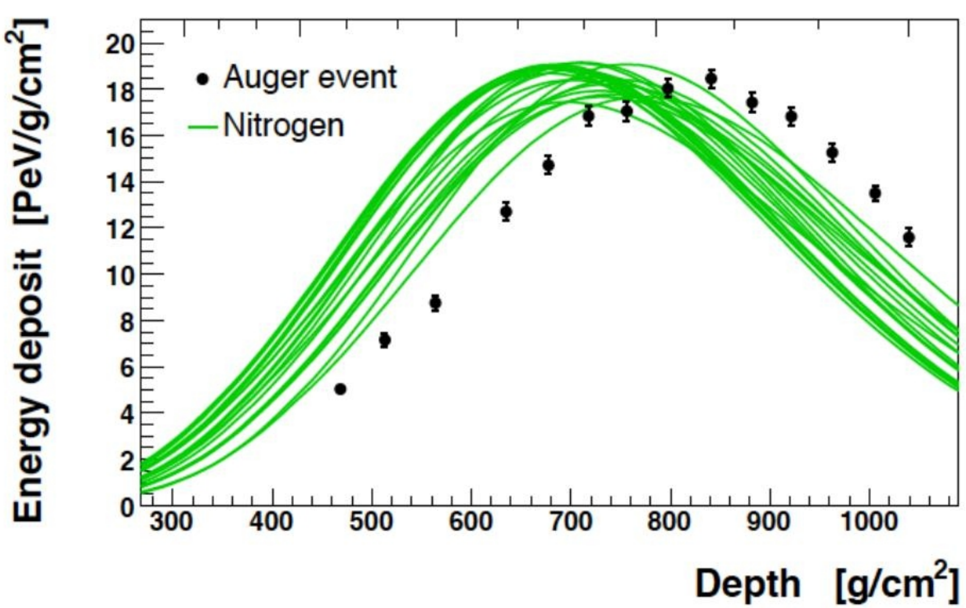


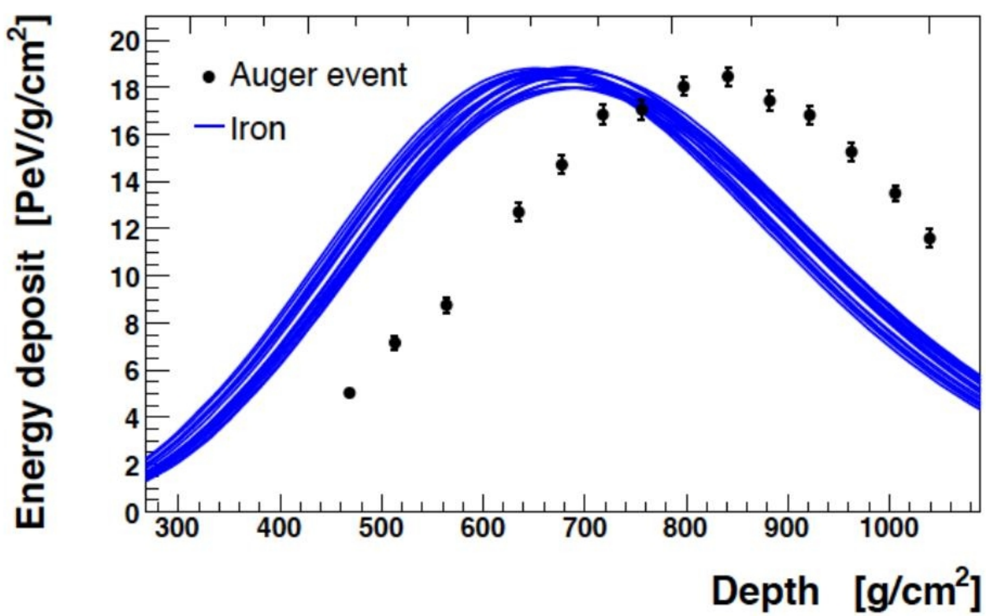
HiRes/TA/Auger observe a High Energy Suppression
Consistent with the GZK suppression
[or photo-disintegration of Iron]
[or source cutoff]



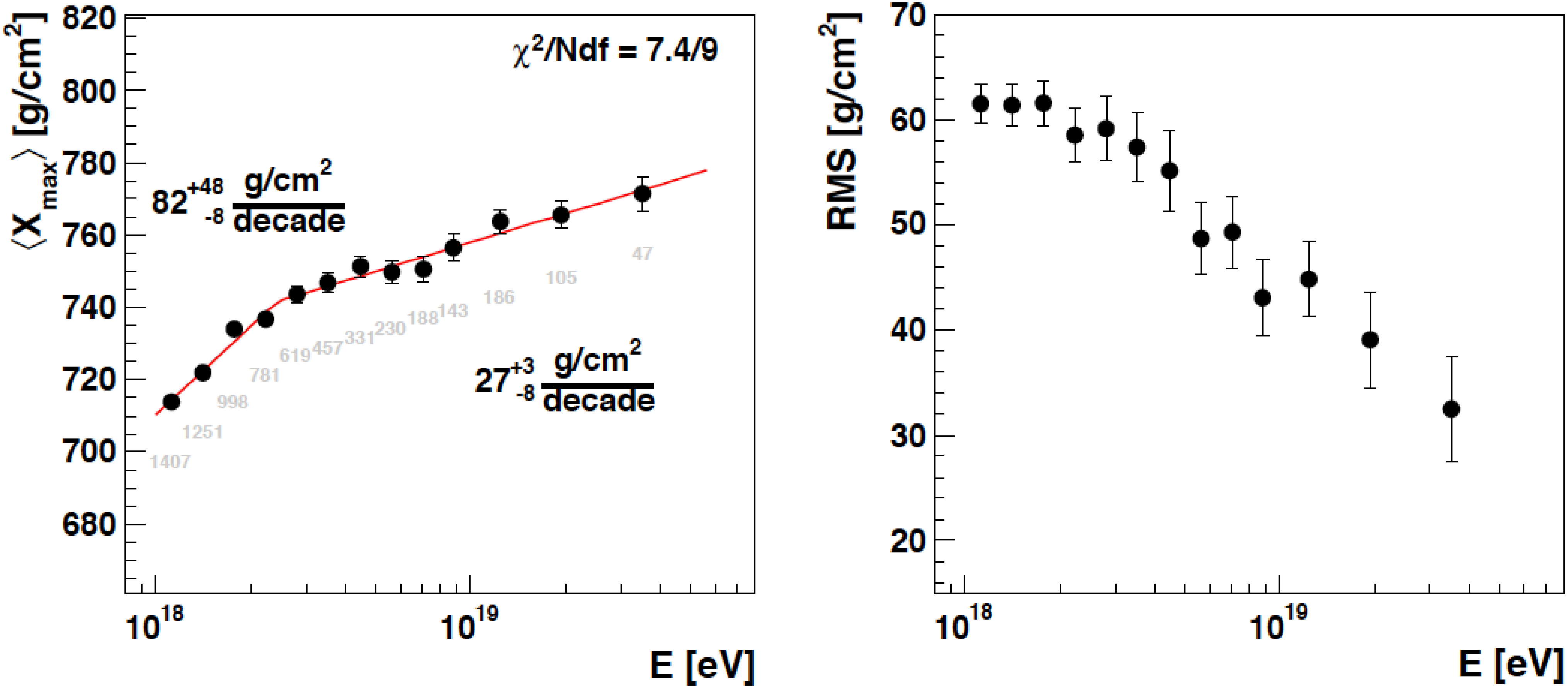
Composition
Study.

[model dependence]



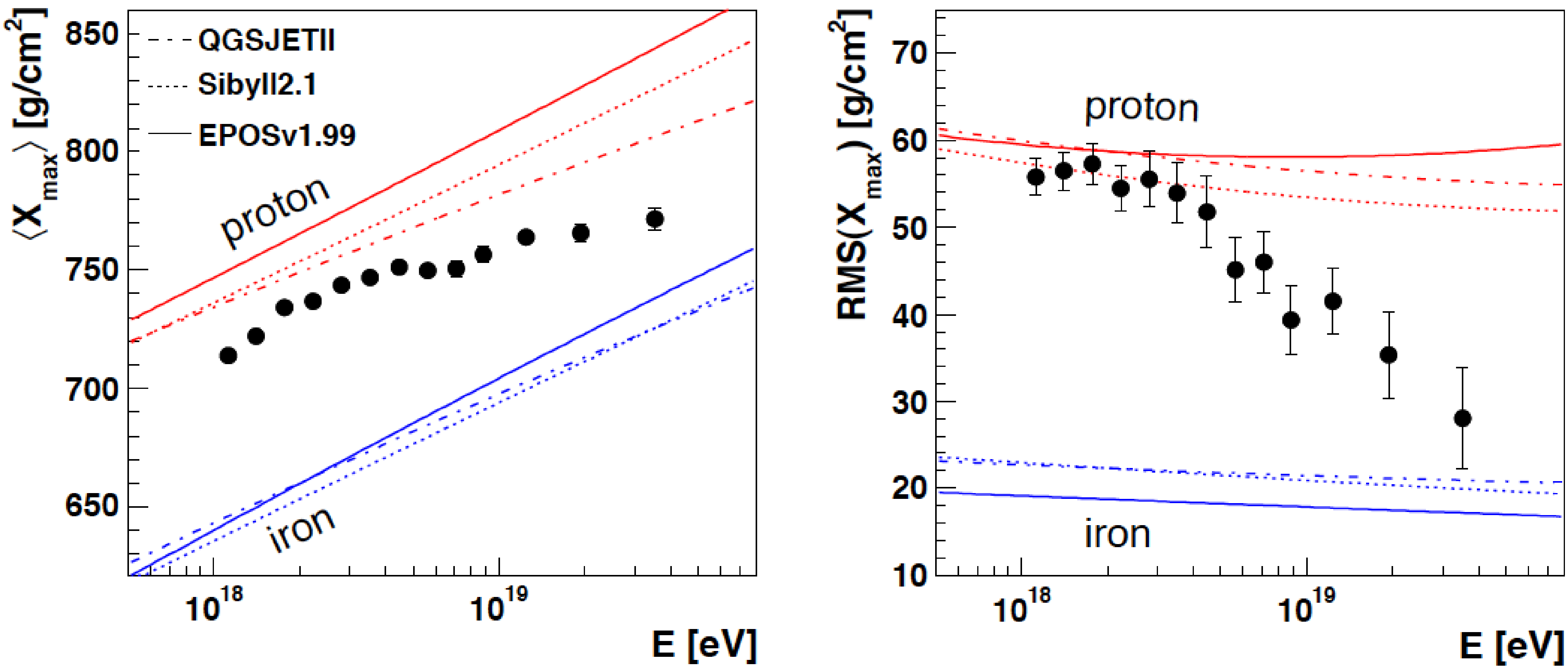


$\langle X_{max} \rangle$ and RMS

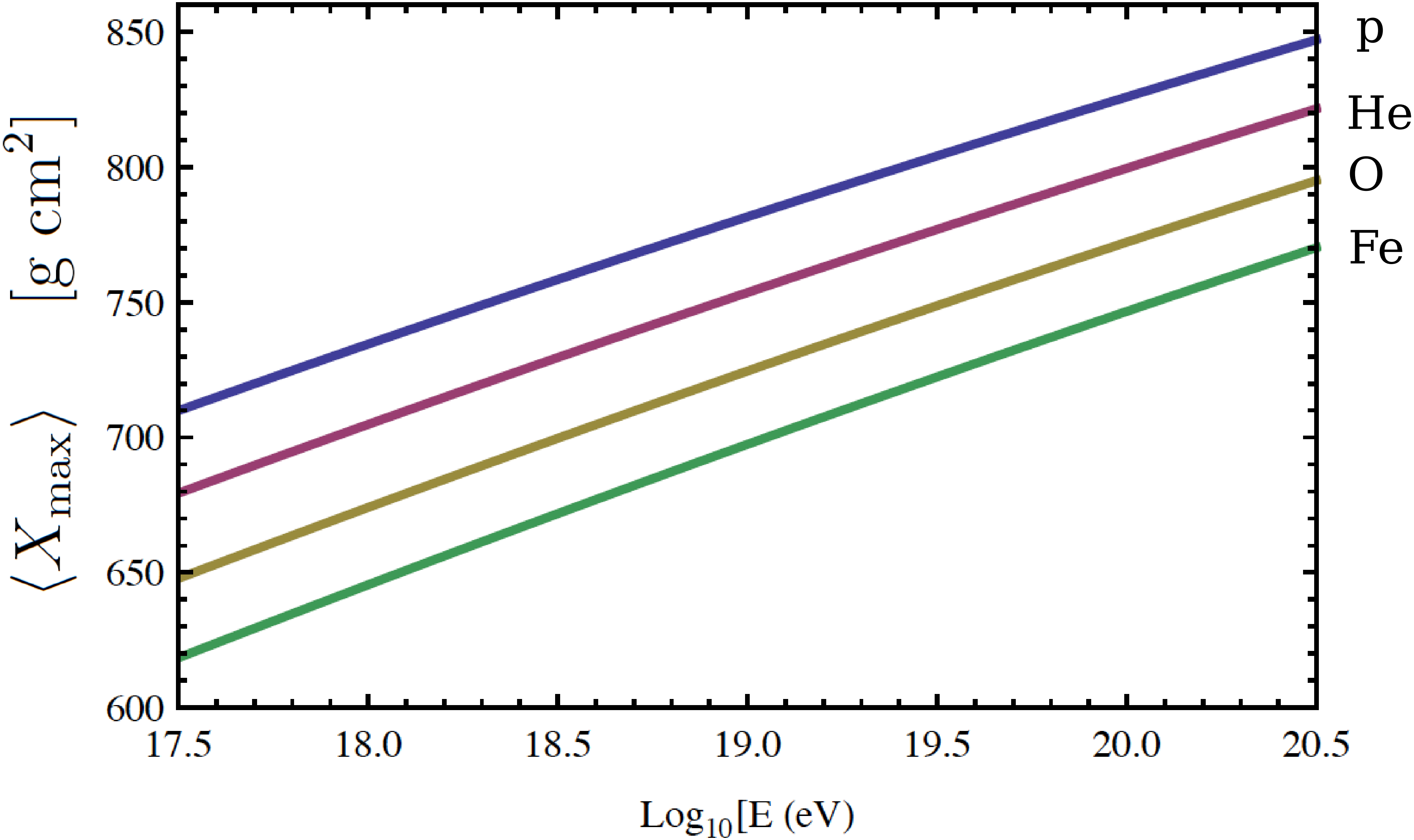


What is the
physical meaning
of these distributions?

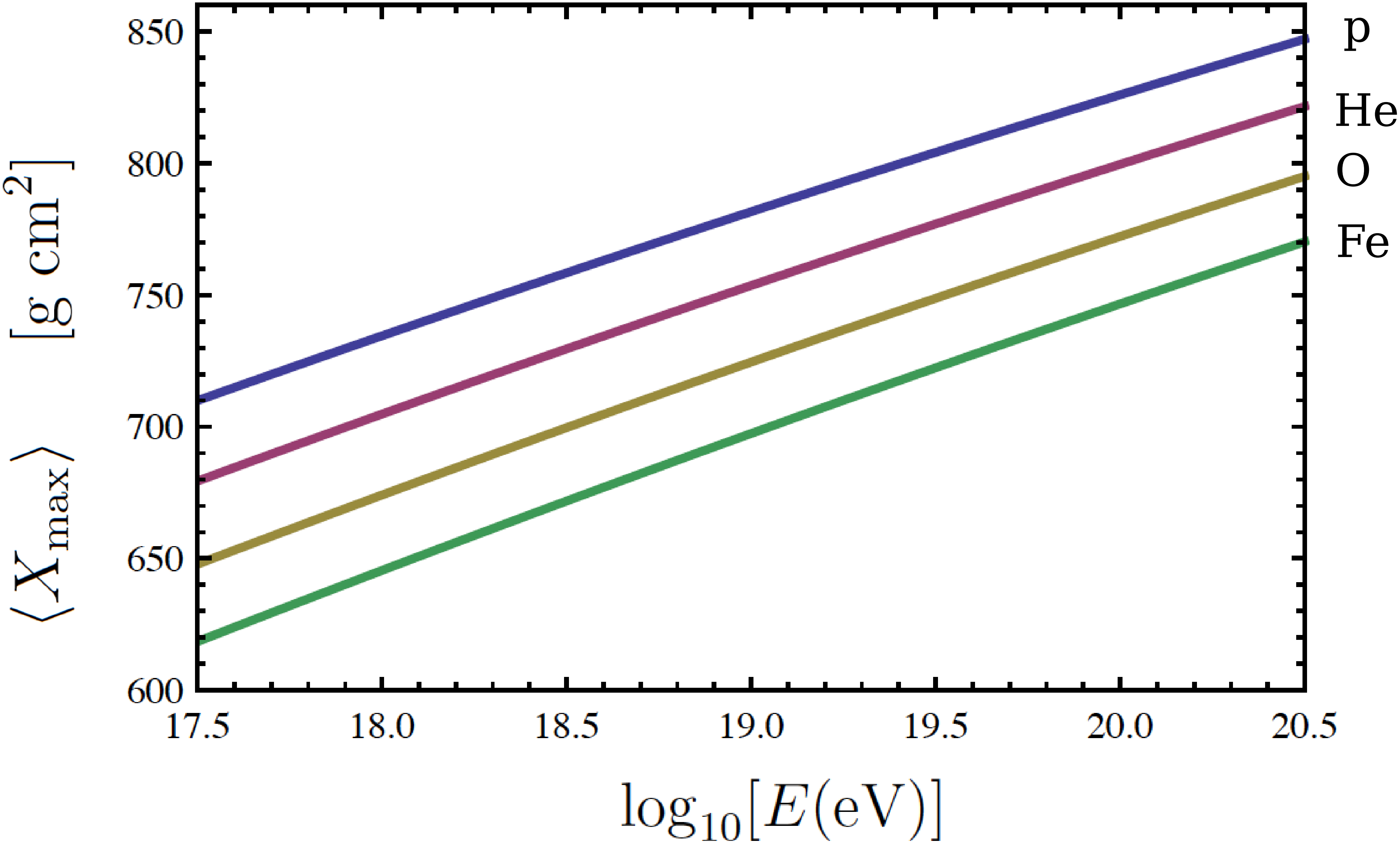
$\langle X_{\max} \rangle$ and RMS



Compare DATA with predictions based on several assumptions for hadronic interactions....



One Montecarlo Model: [Sibyll 2.1]



$$\langle X_p^{\max}(E) \rangle \simeq X_0 + D_p \ \log E$$

Small curvature

No sharp features

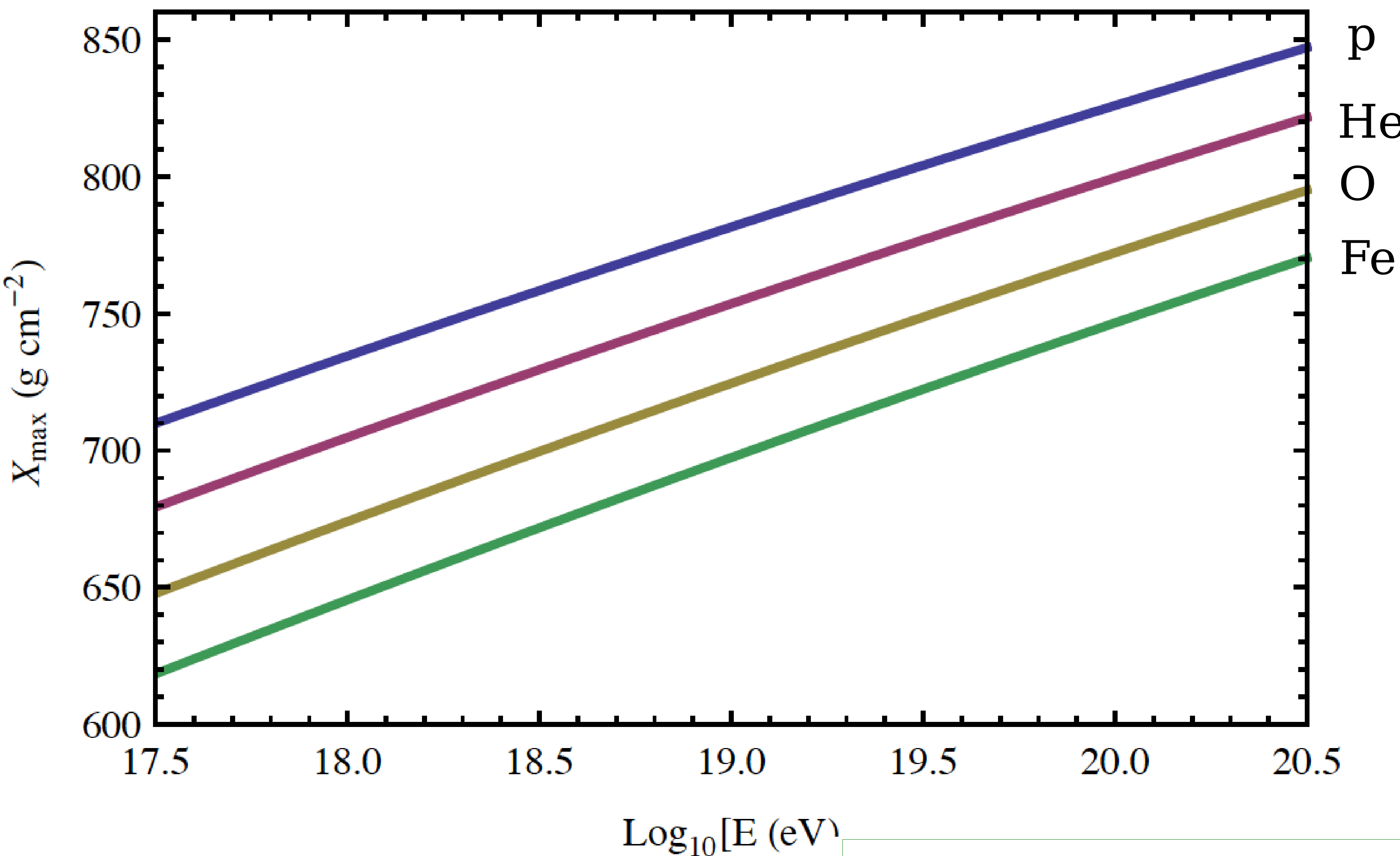
X_{max} and the Composition of Cosmic Rays

Approximate validity of the relation:

$$\langle X_A(E) \rangle \simeq \left\langle X_p\left(\frac{E}{A}\right) \right\rangle$$

$$\langle X_p(E) \rangle \simeq X_0 + D_p \, \log_{10} E$$

$$\langle X_A \rangle \simeq \langle X_p \rangle - D_p \, \log_{10} A$$

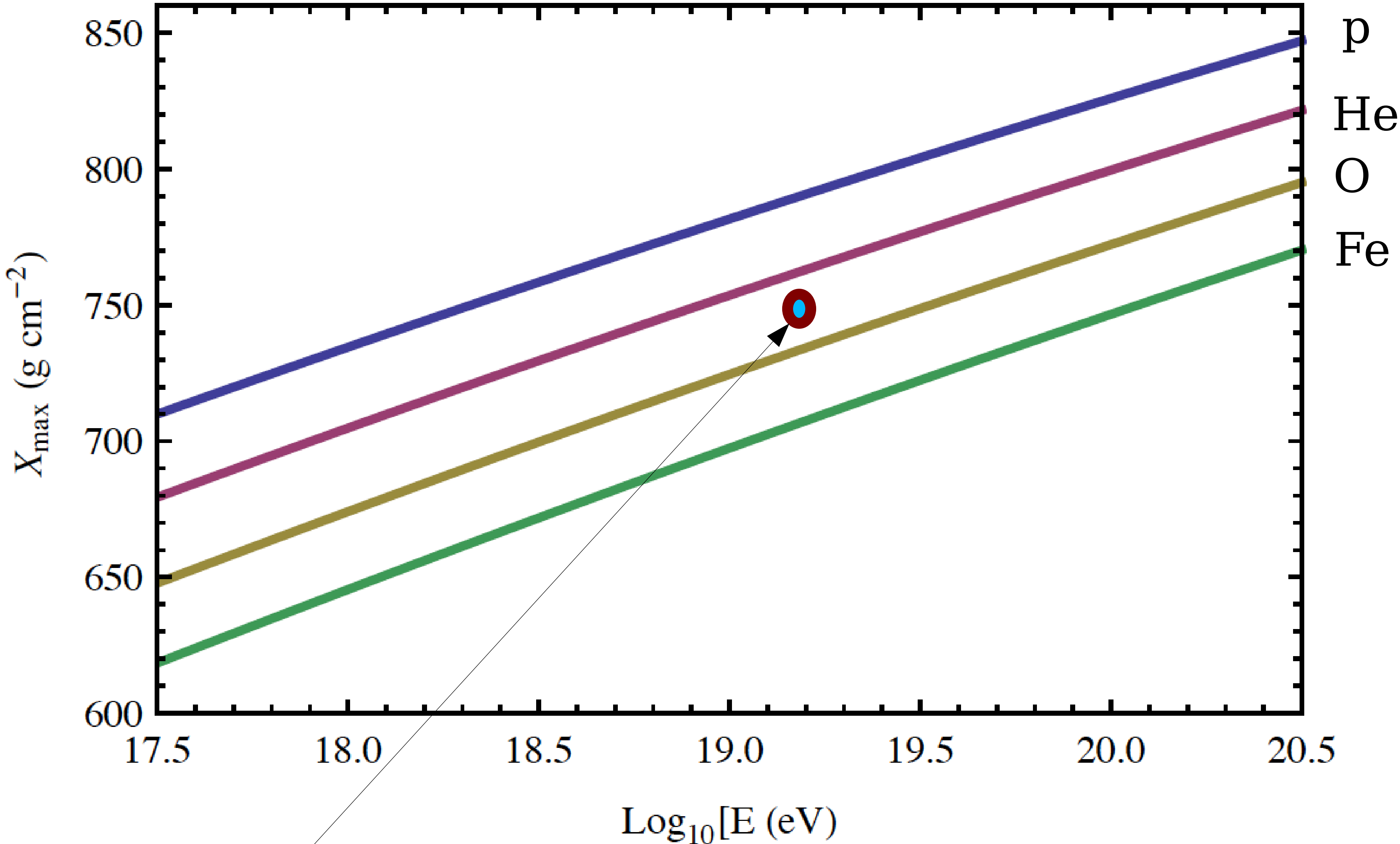


$$\langle X_A \rangle \simeq \langle X_p \rangle - D_p \ \log_{10} A$$

$$\langle X_{\rm He} \rangle \simeq \langle X_p \rangle - 30 \text{ g cm}^{-2}$$

$$\langle X_{\rm O} \rangle \simeq \langle X_p \rangle - 60 \text{ g cm}^{-2}$$

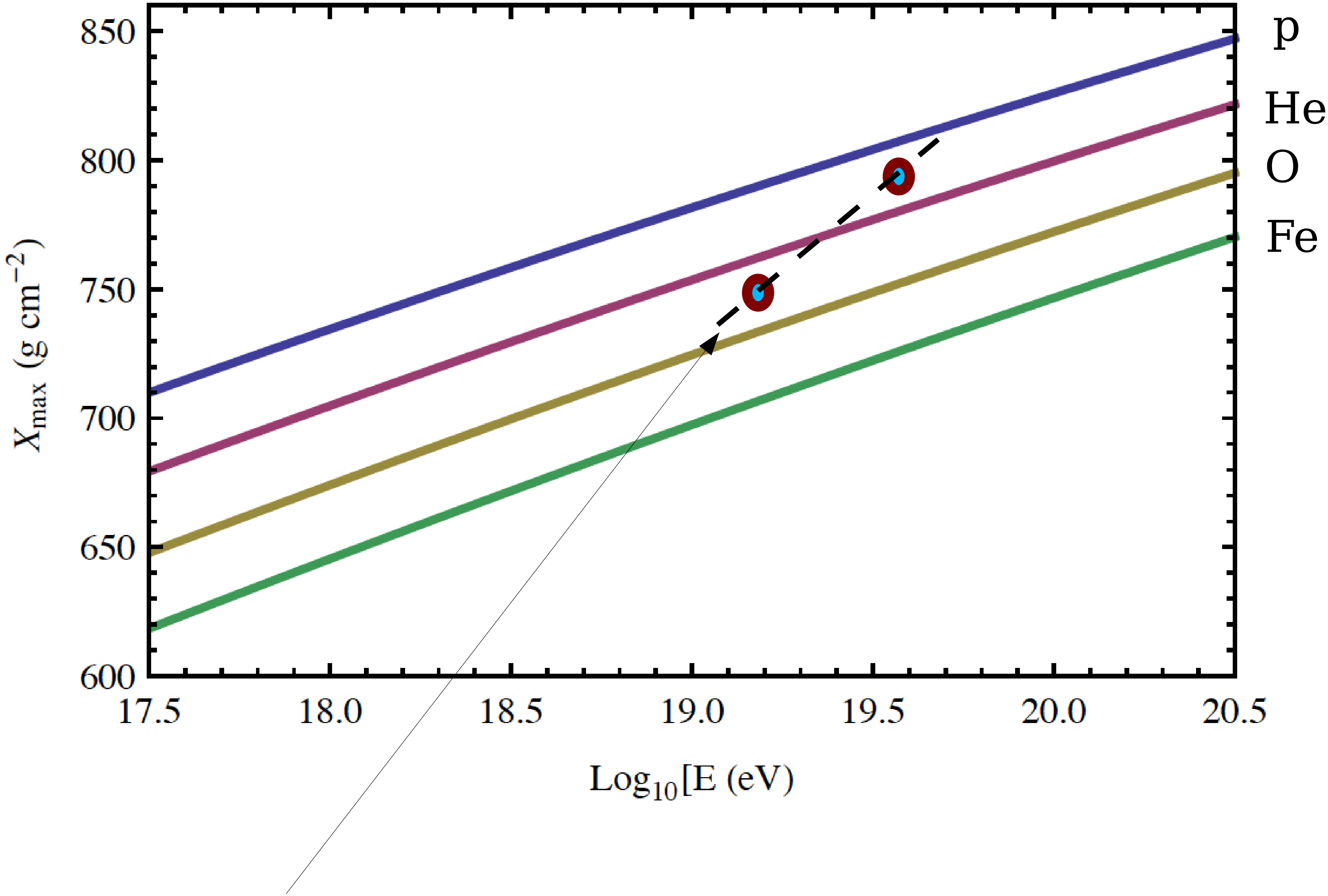
$$\langle X_{\rm Fe} \rangle \simeq \langle X_p \rangle - 90 \text{ g cm}^{-2}$$



Measurements of

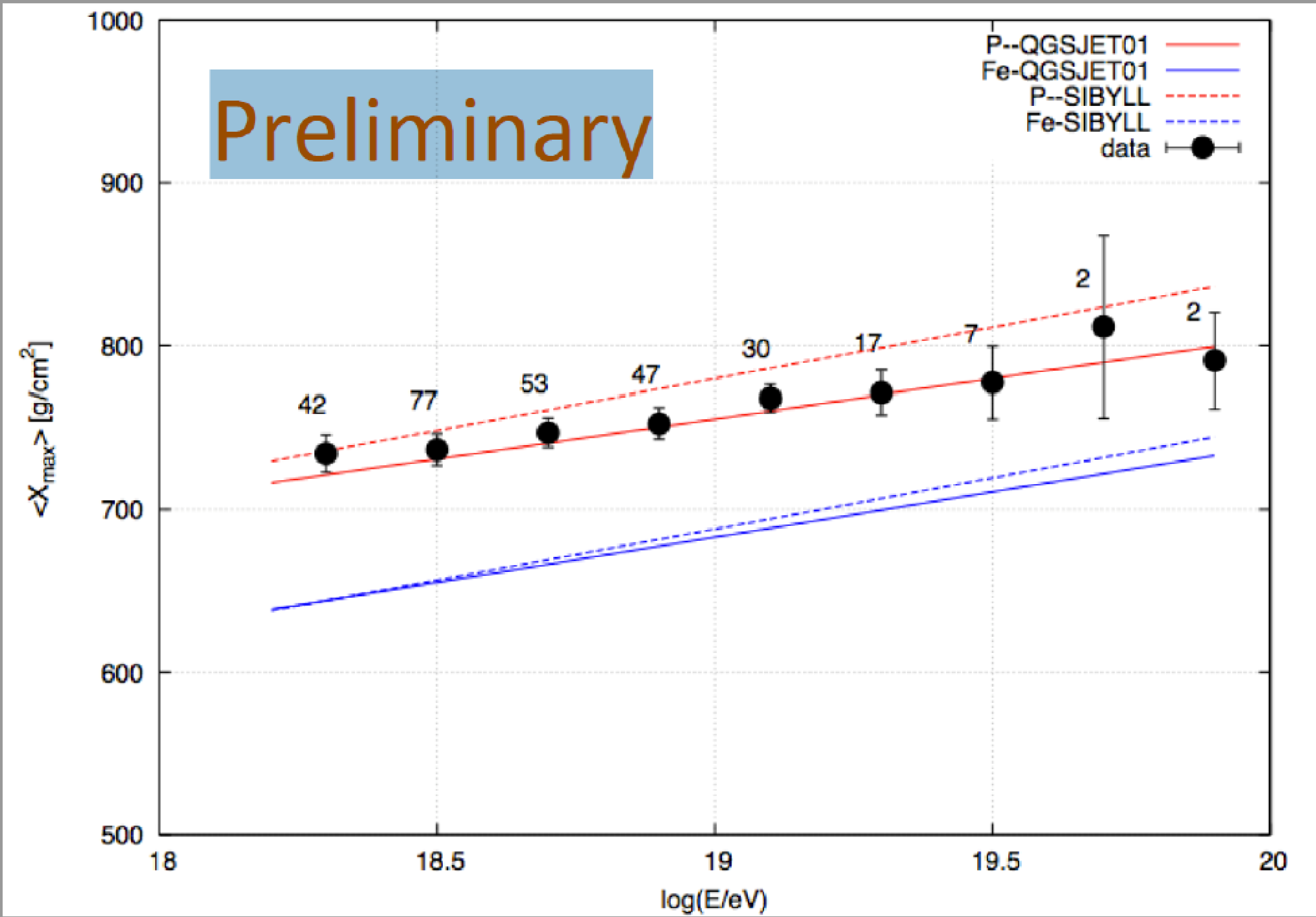
$$\langle \log A \rangle$$

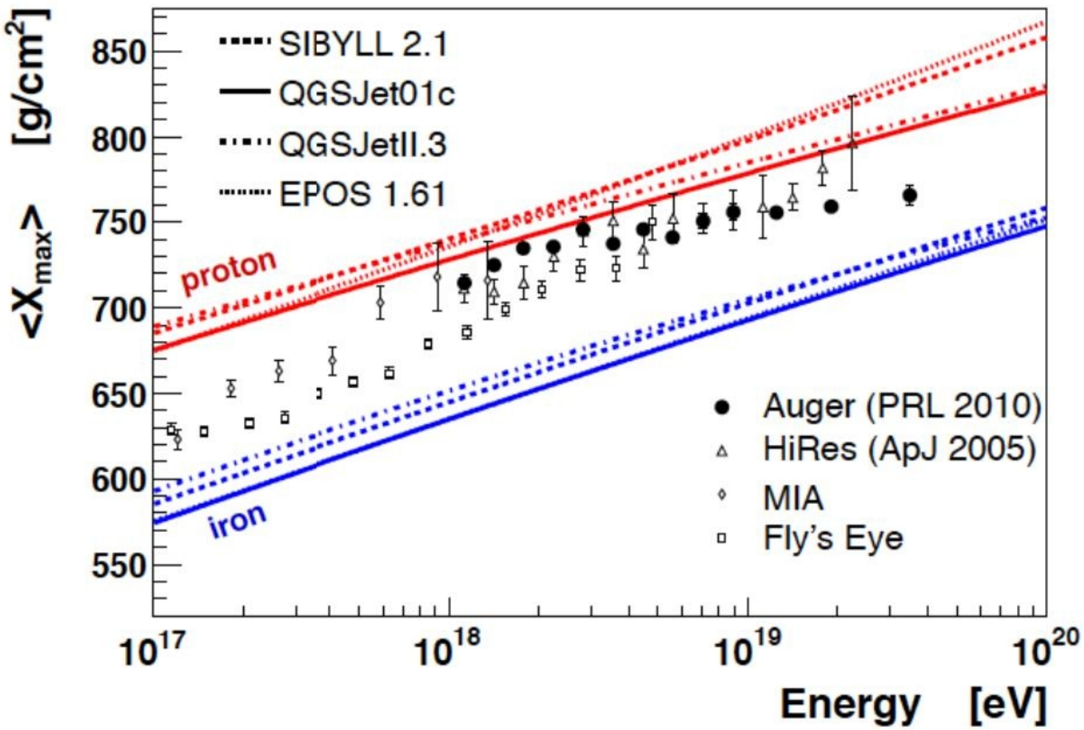
$$\langle \ln A \rangle_E = \frac{\sum_A \phi_A(E) \ \ln A}{\sum_A \phi_A(E)}$$



Measurements of Composition evolution.

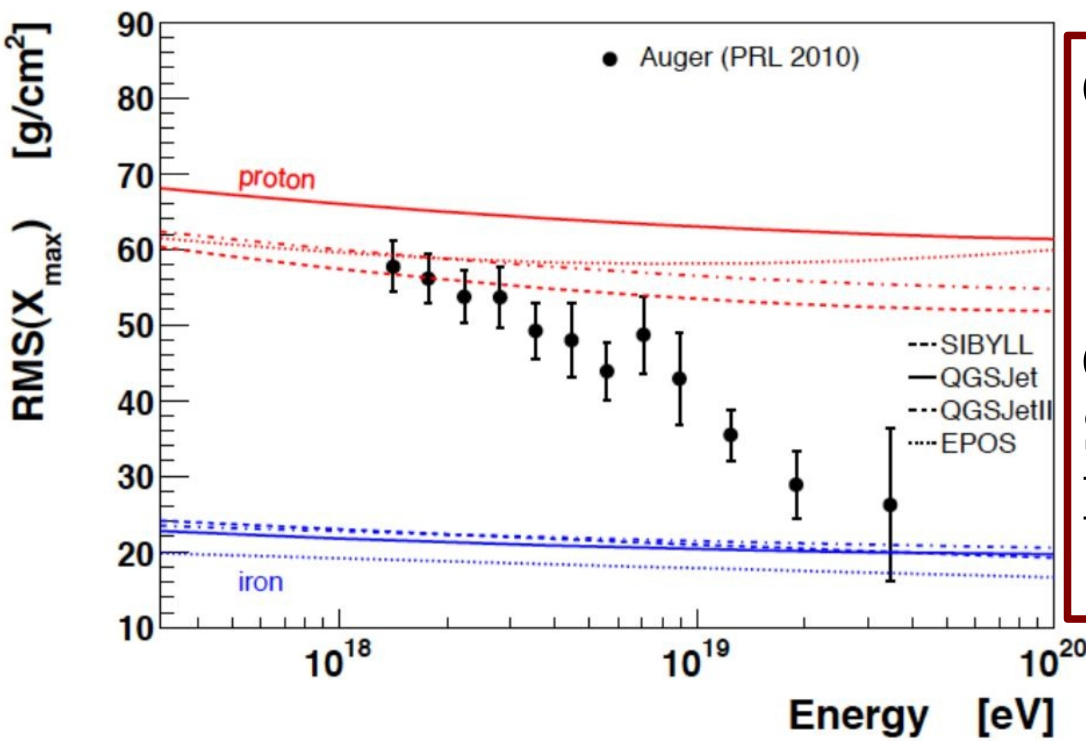
Telescope Array stereo result





Mass Composition
becoming heavy ?
at very high energy ?

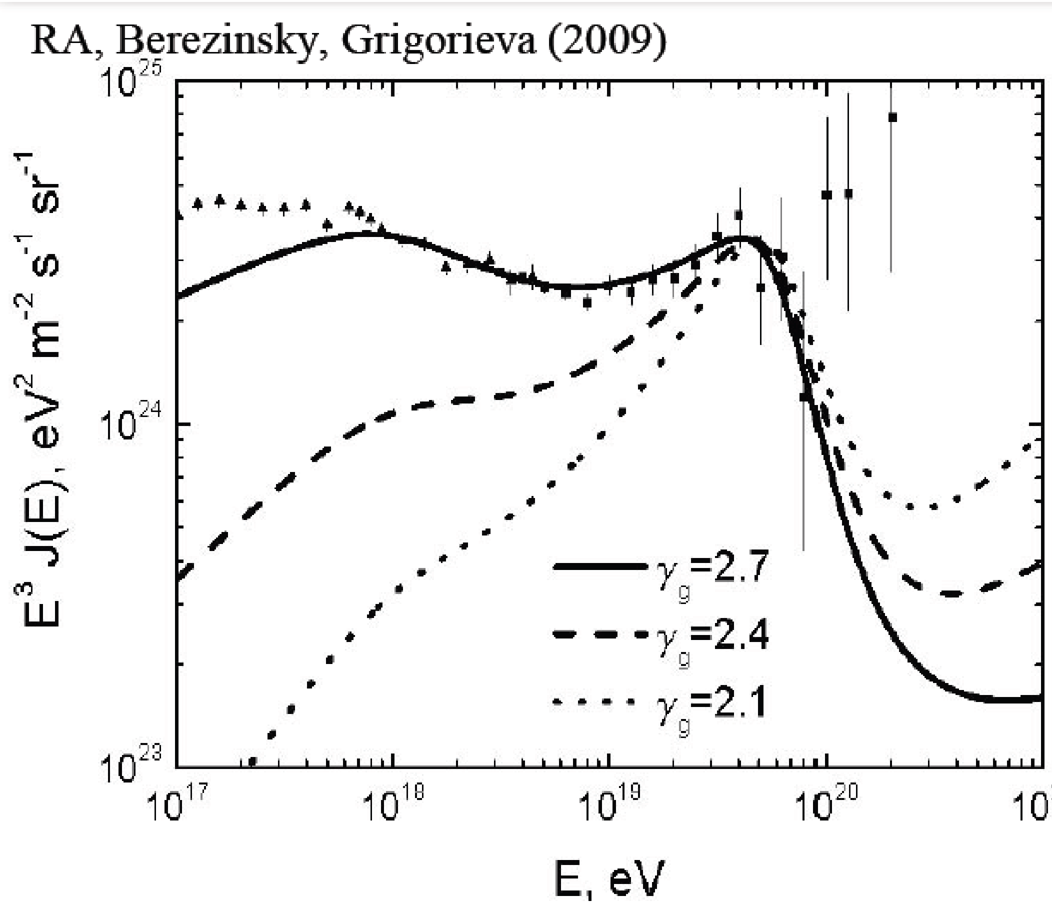
Significance would be
very important !
Constraints on the
structure and properties
of the astrophysical sources.

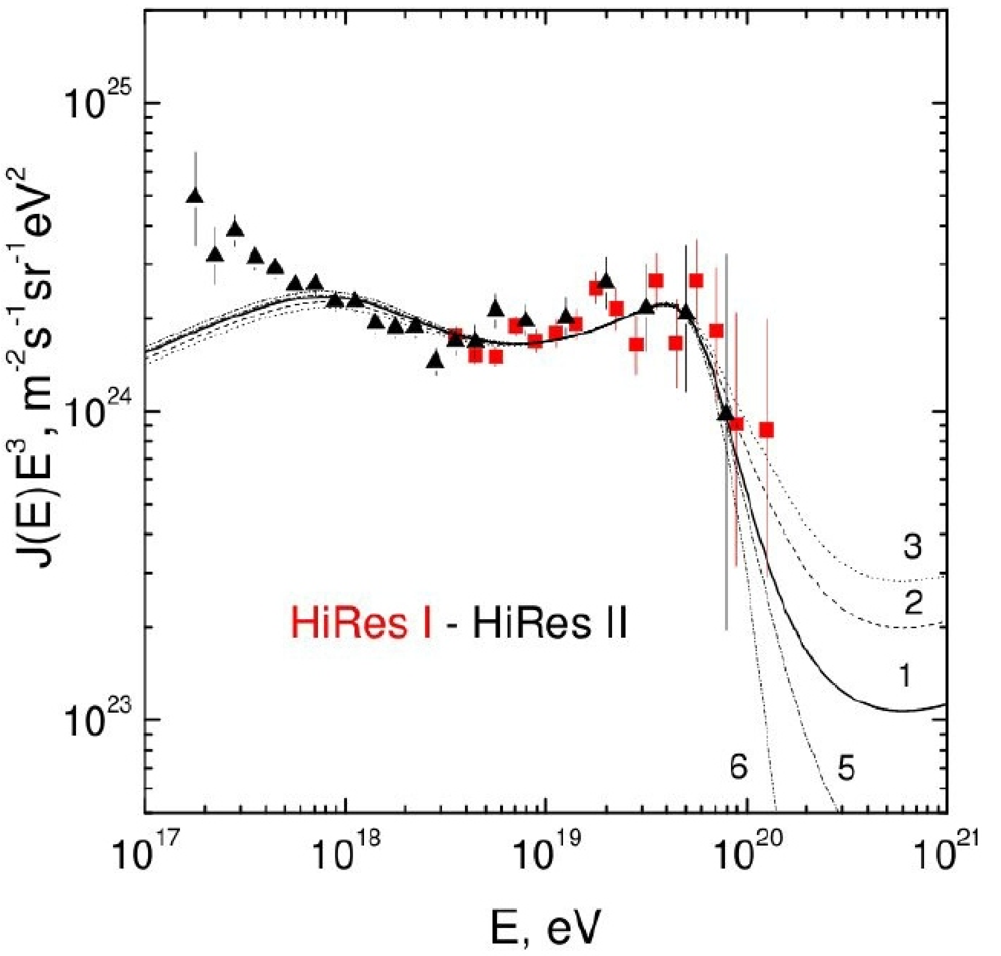


Observational controversy
NON confirmation
of HiRes

Correlation with sources
Small deviation in magnetic
Fields (Z < 3 ?)

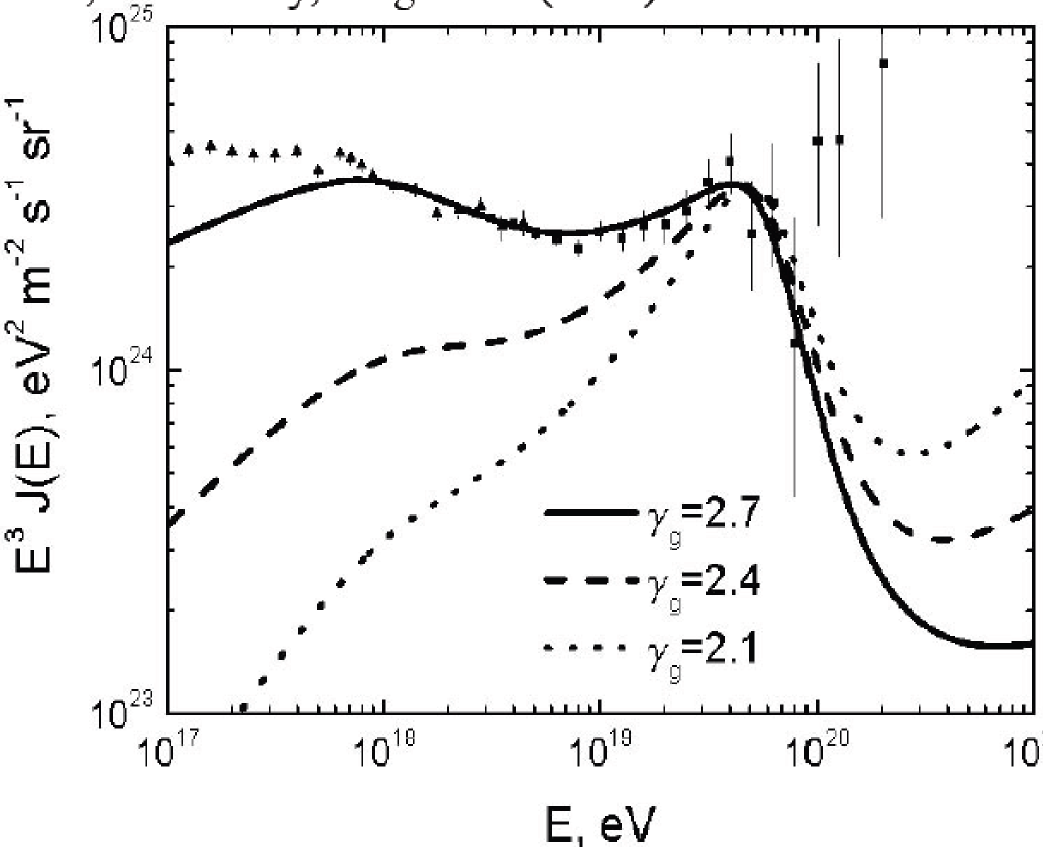
Berezinsky “DIP Model”

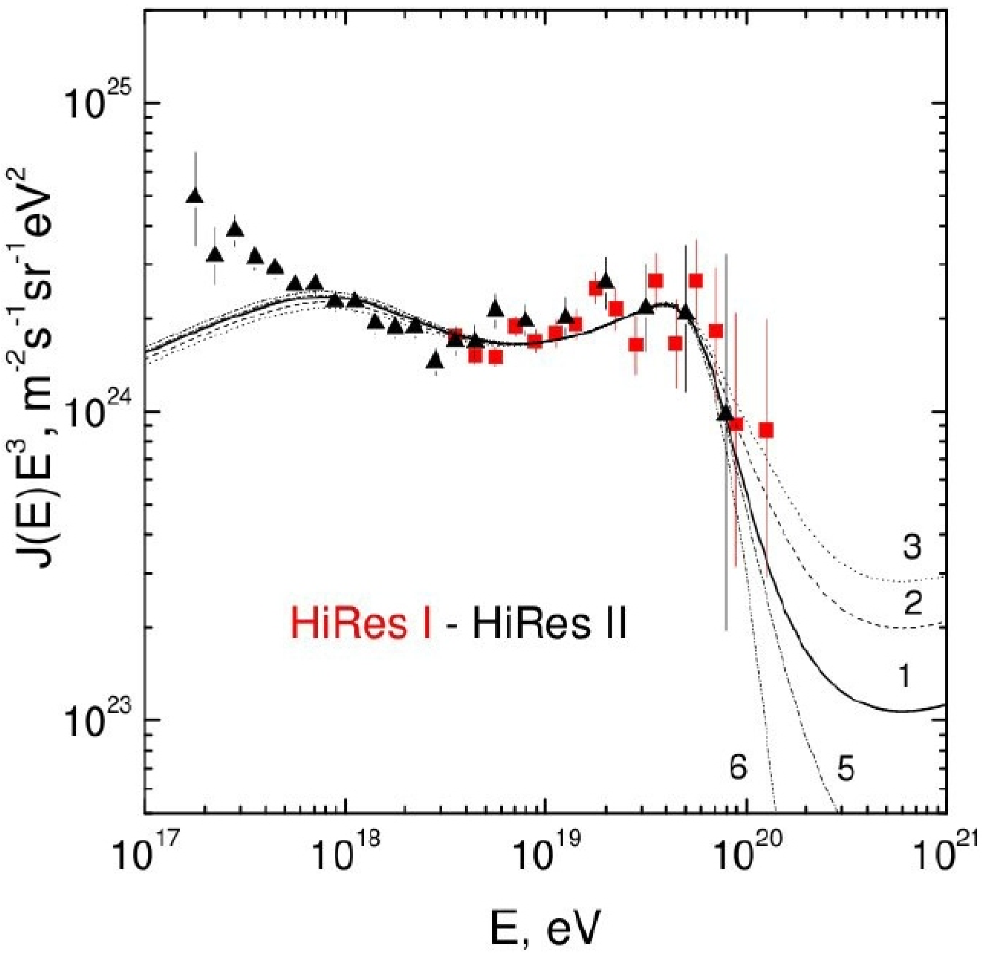




Berezinsky "DIP Model"

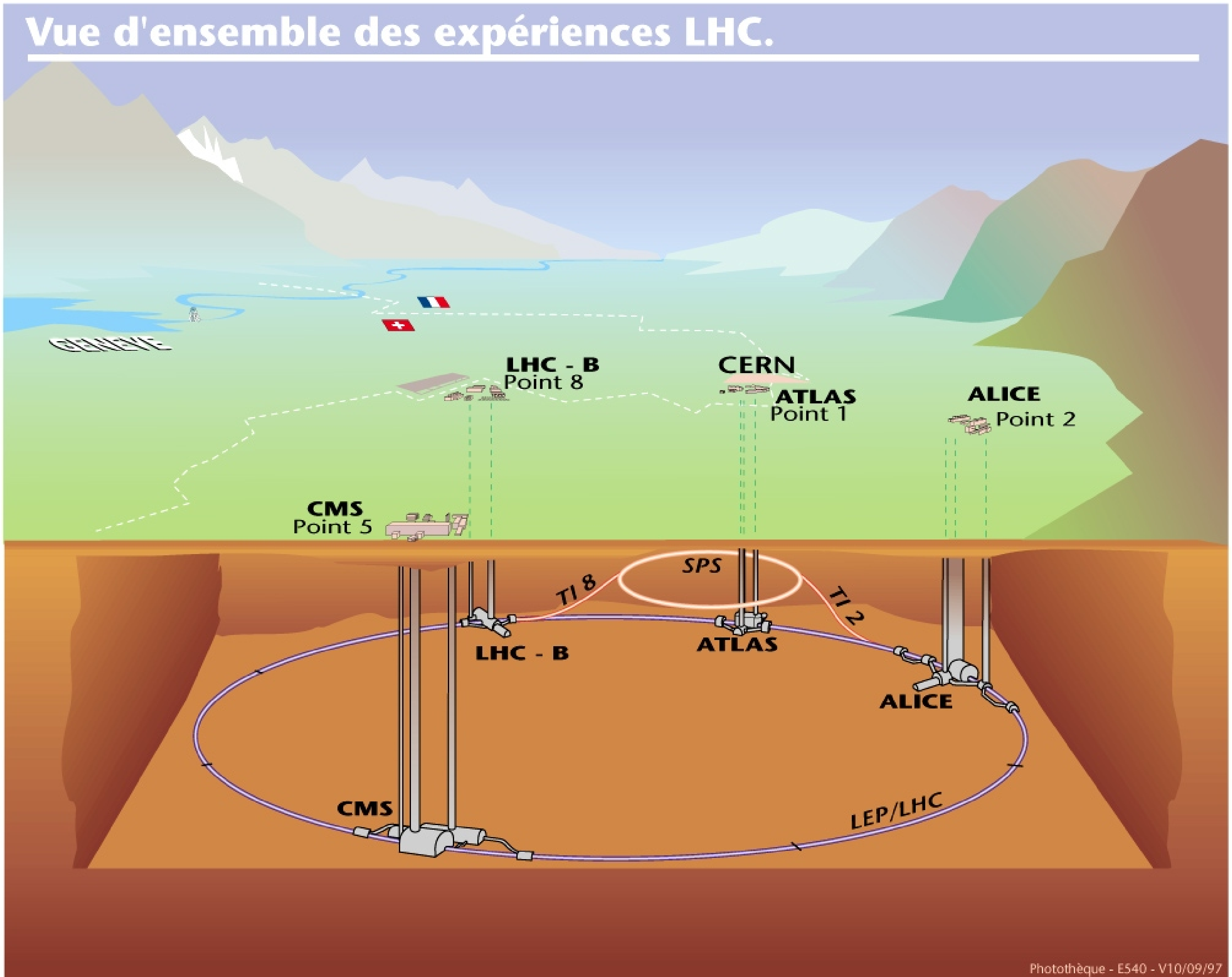
RA, Berezinsky, Grigorieva (2009)



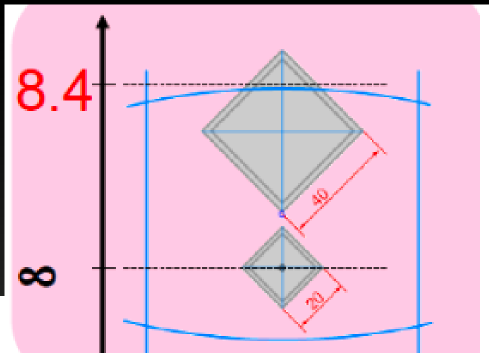


Proton dominated extragalactic component.
"fine tuned" galactic/extragalactic transition at 2nd Knee.

Progress in hadronic interaction modeling ?

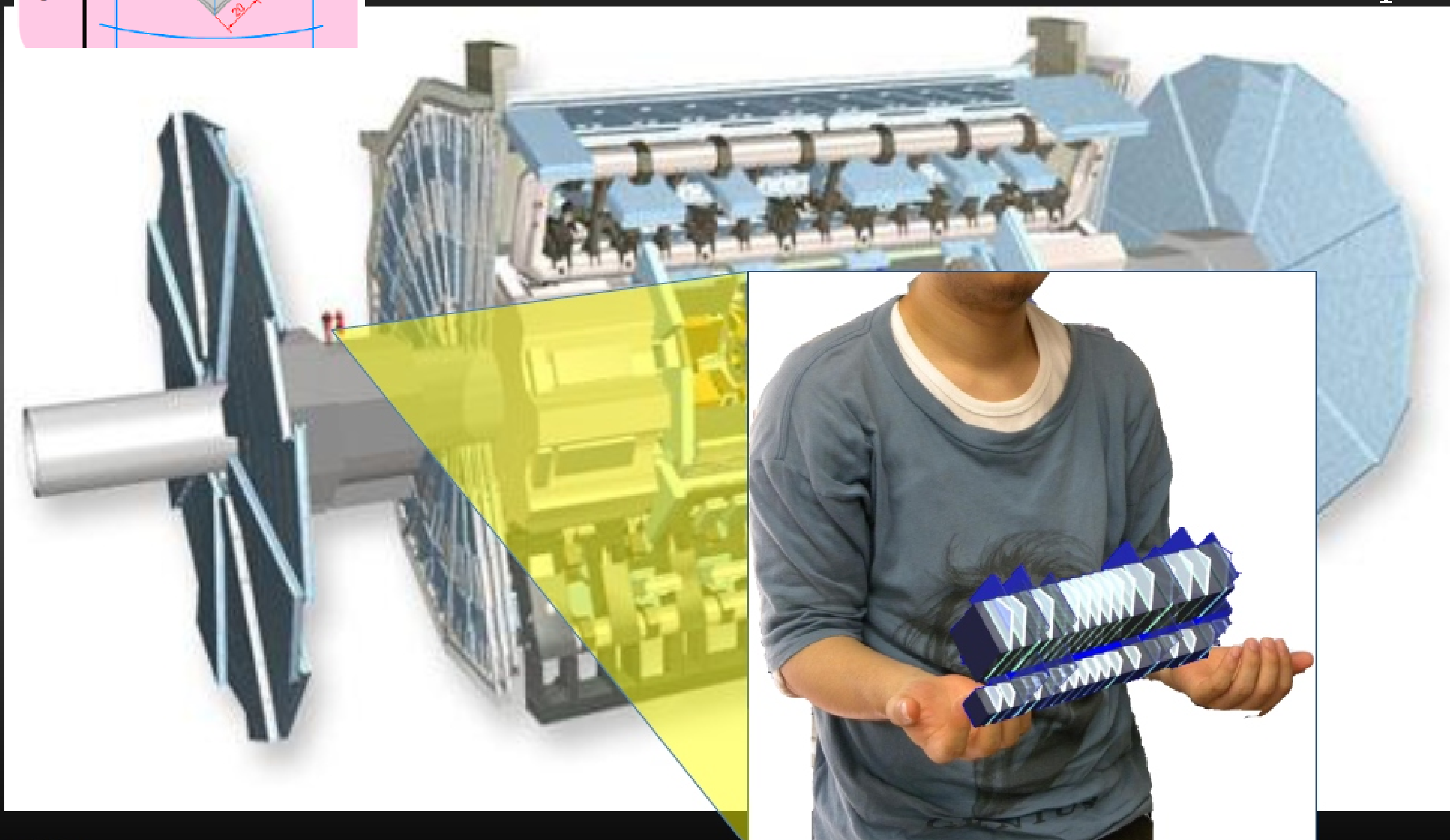


7 + 7 TeV
PP collider

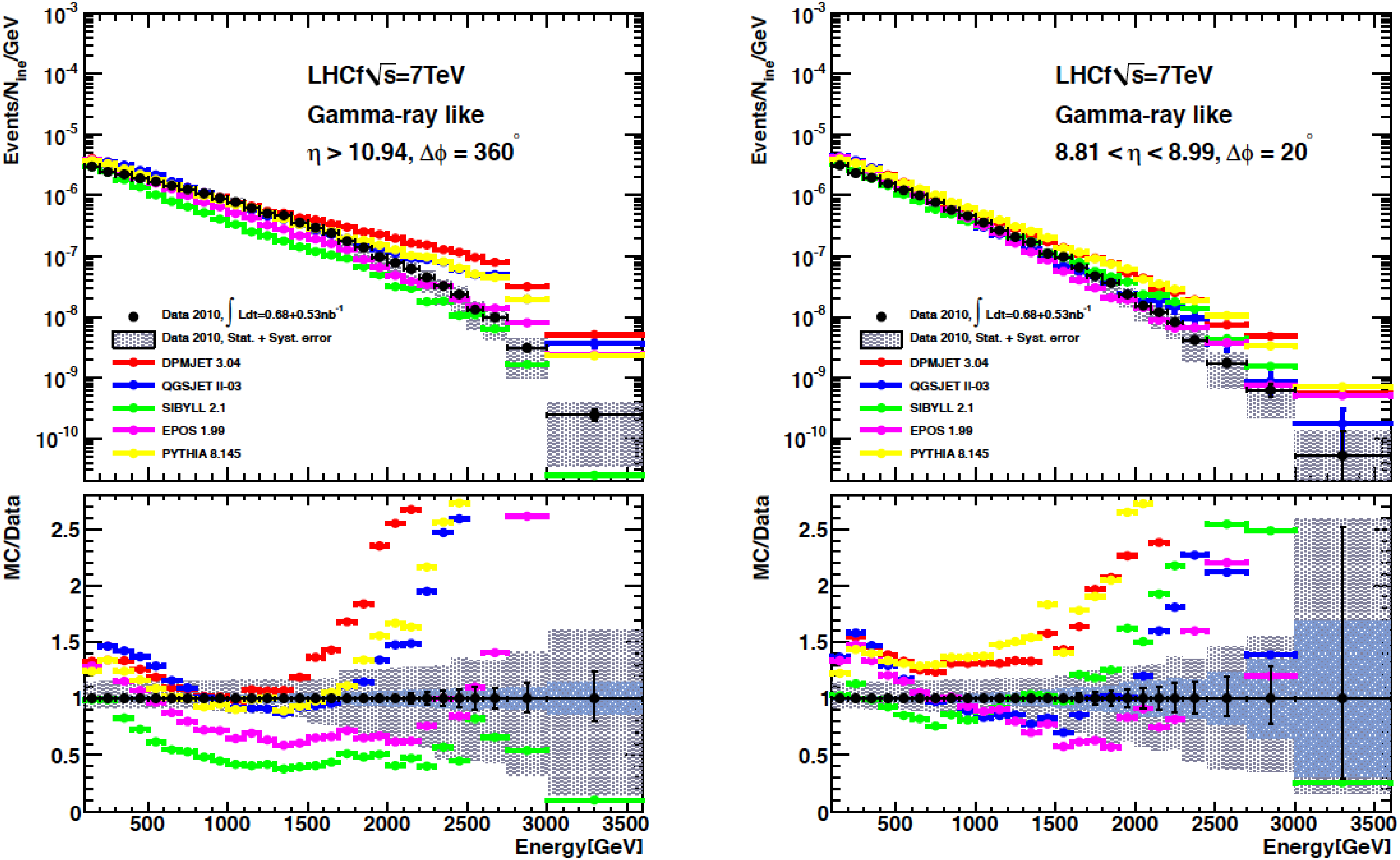


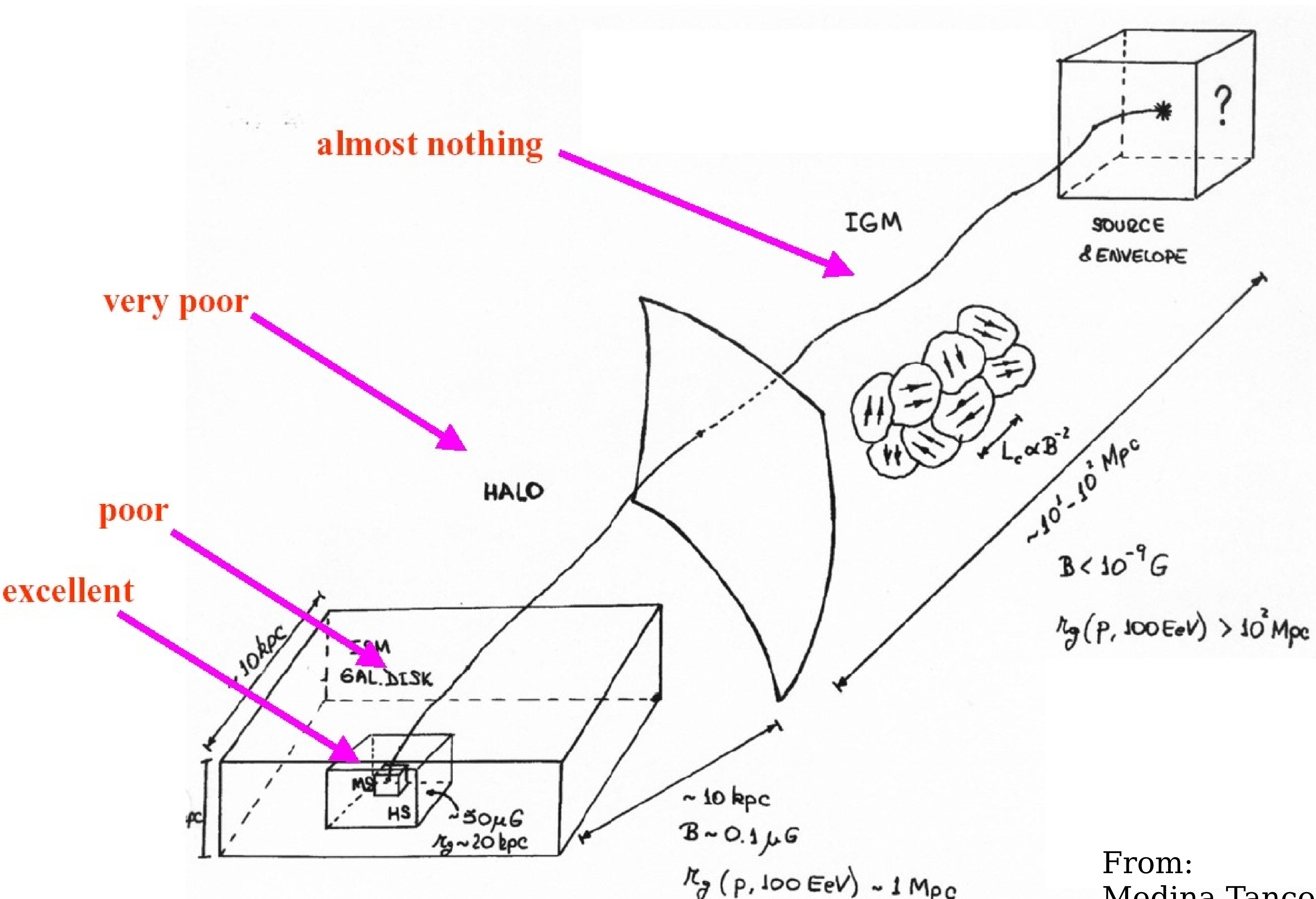
ATLAS & LHCf

140 m from interaction point



LHCF first DATA publication





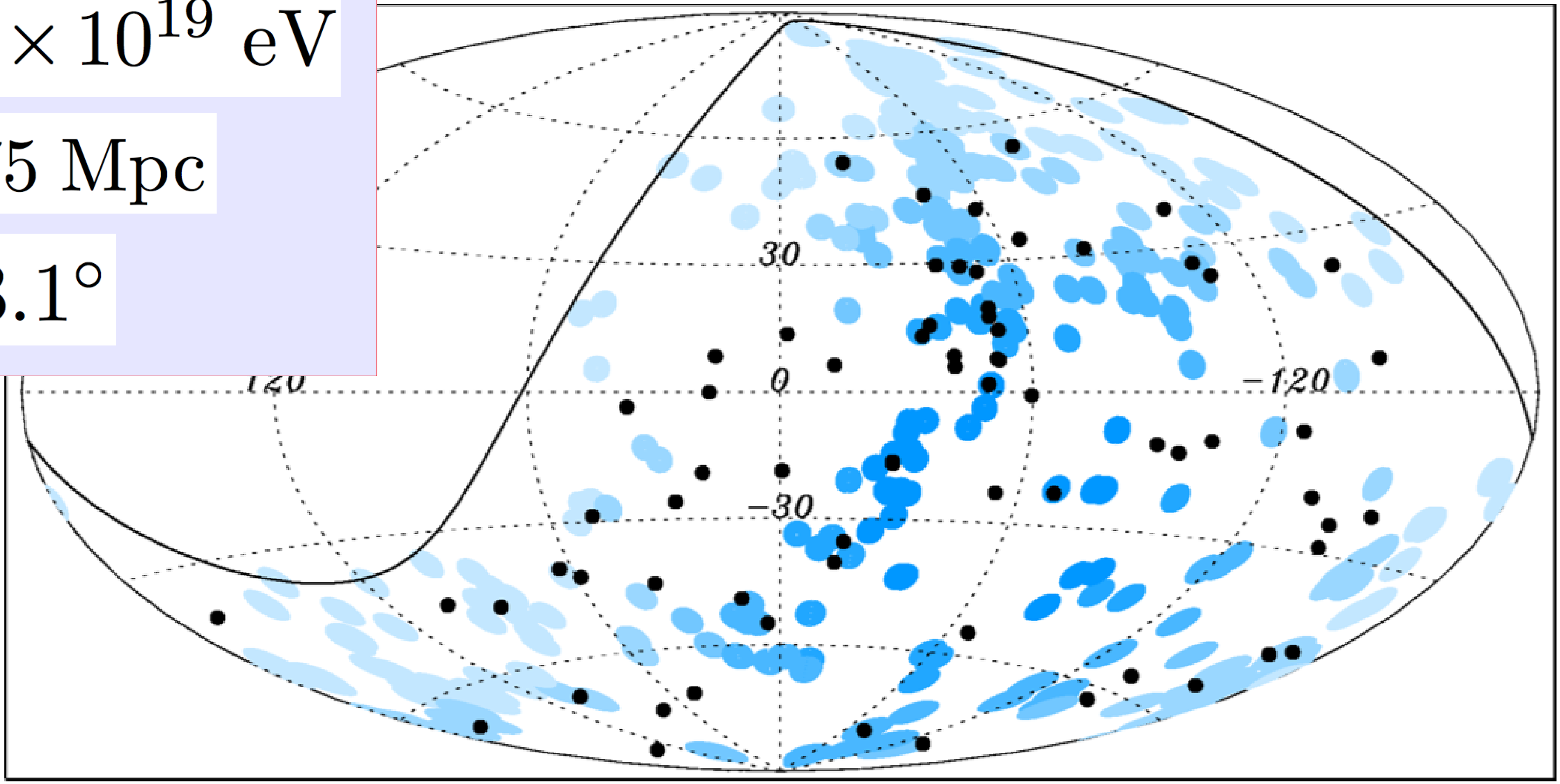
From:
Medina Tanco

AUGER result on Correlations with the VCV AGN catalogue November 2008. Update september 2010.

6×10^{19} eV

75 Mpc

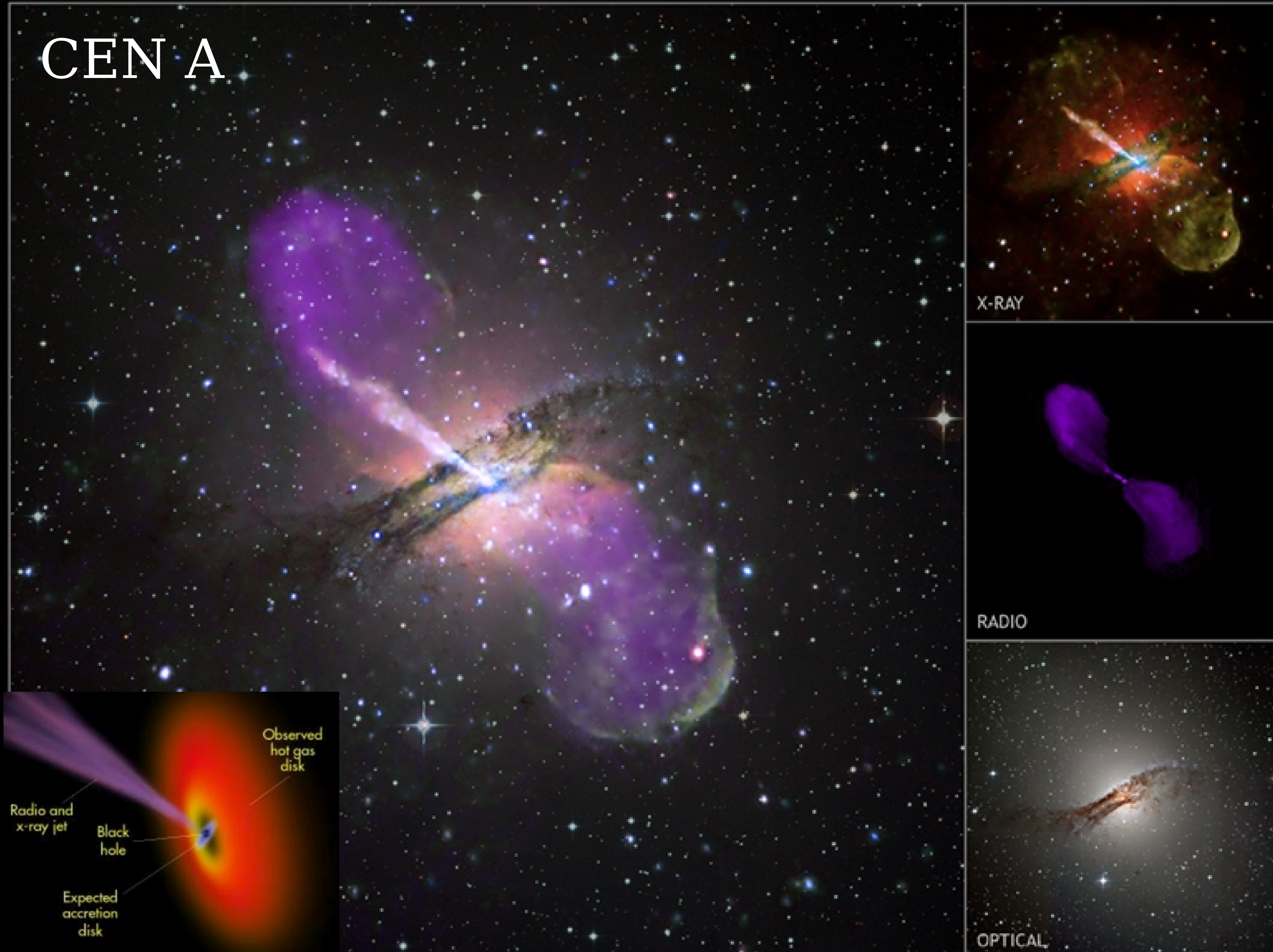
3.1°



Significant dilution
[but not disappearance]
of the statistical significance

14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)
42 ev. 12 coincid.(8.8)

CEN A


X-RAY
RADIO
OPTICAL
Observed hot gas disk
Radio and x-ray jet
Black hole
Expected accretion disk

COSMIC RAY

ANISOTROPIES

TIBET AS-Gamma

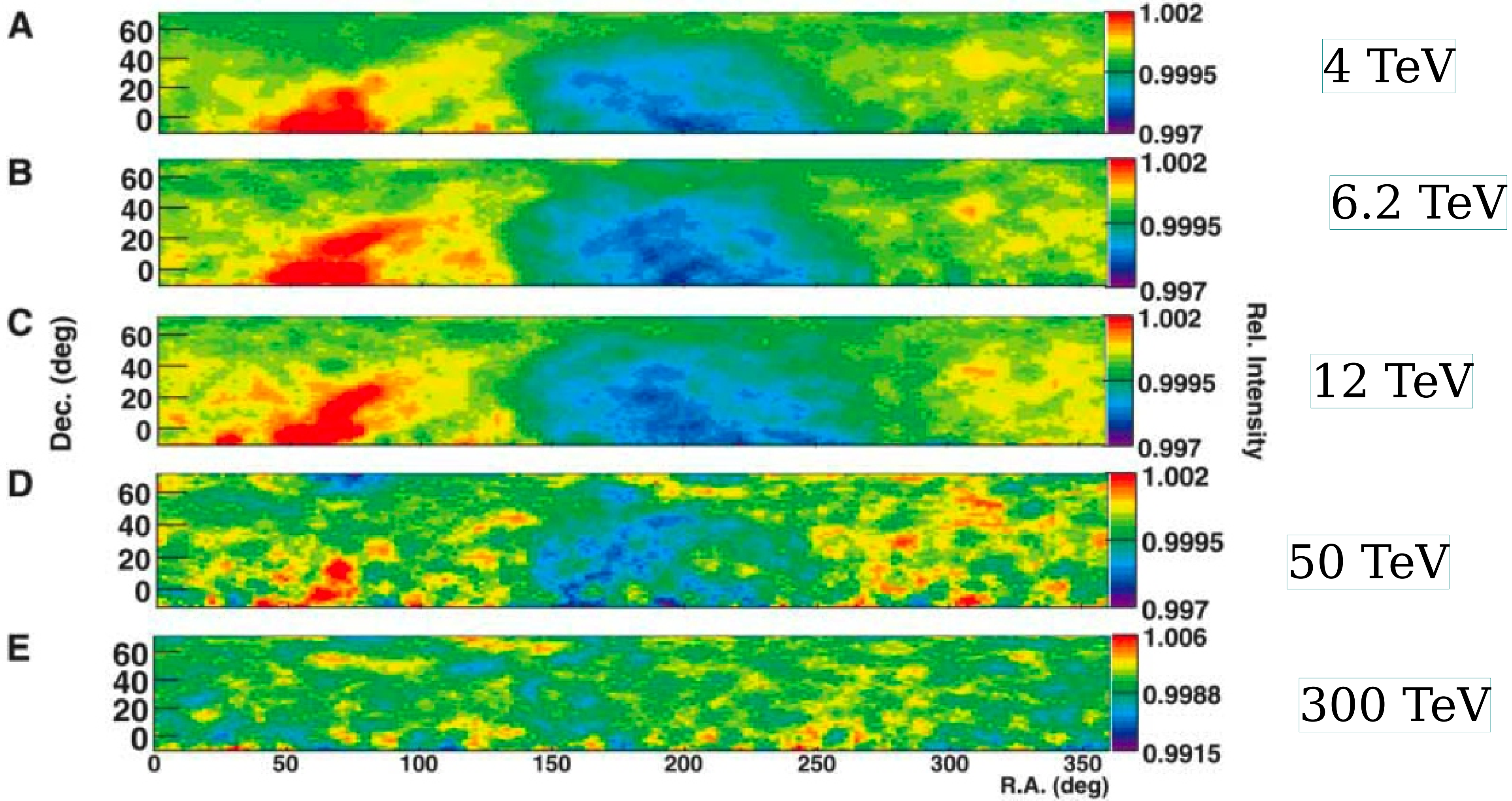
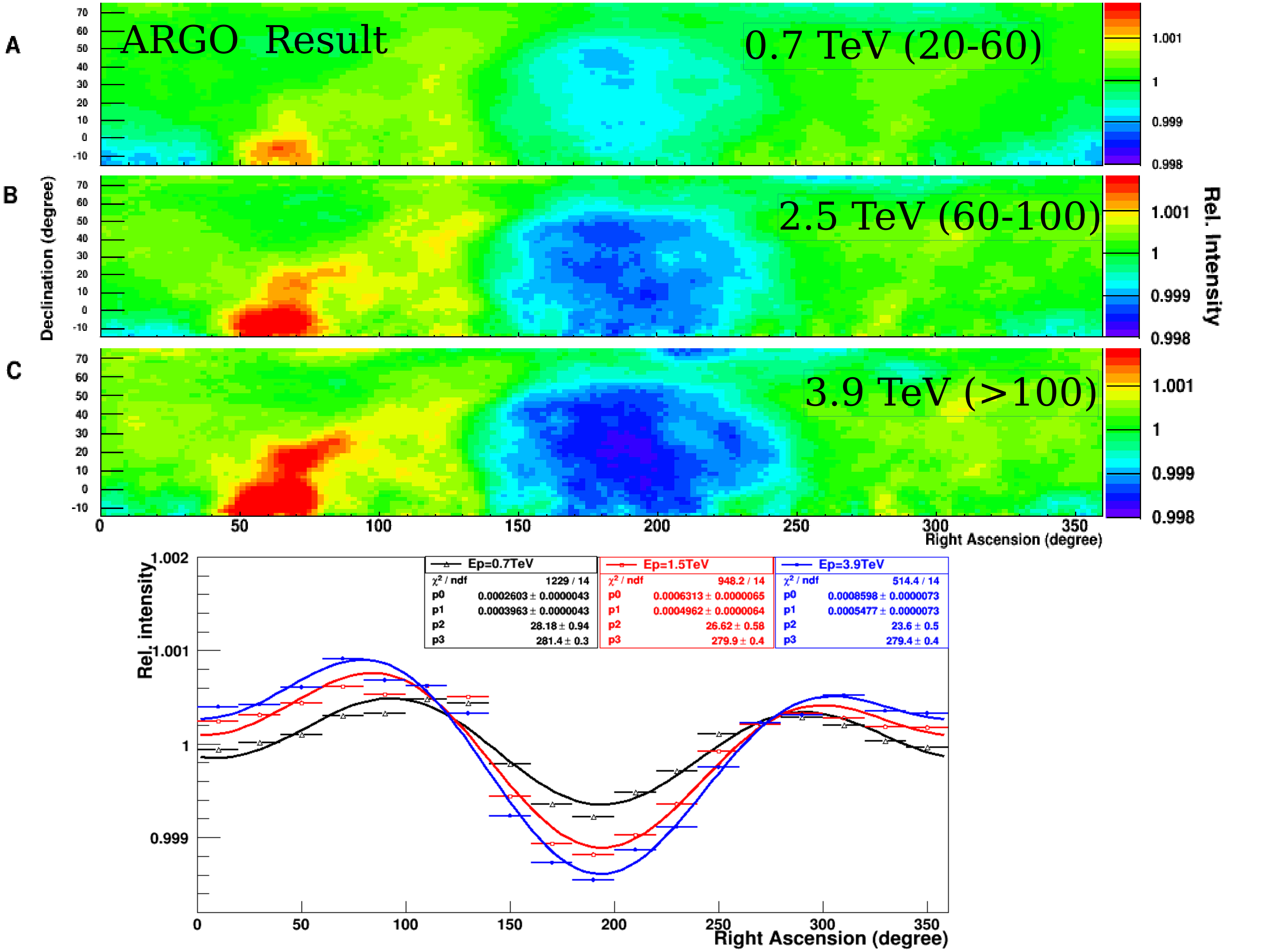
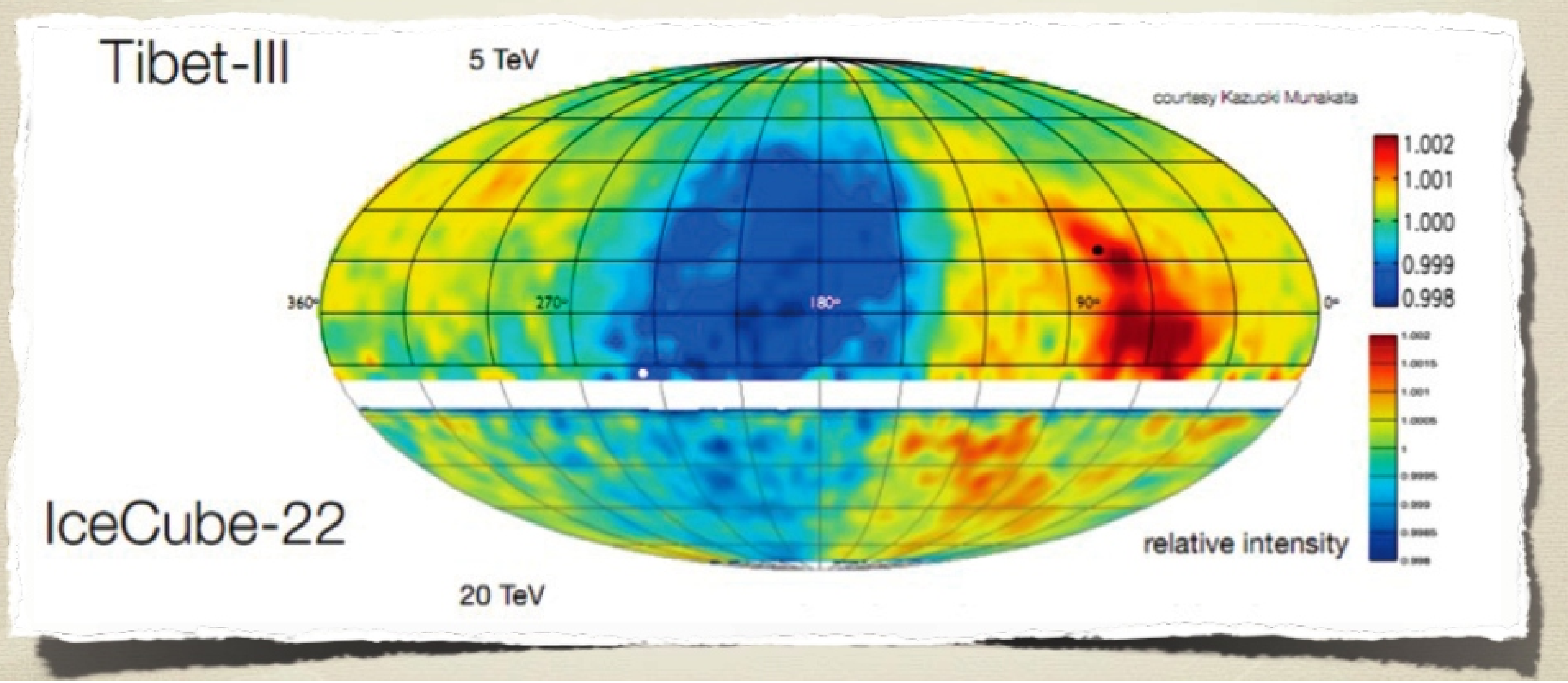


Fig. 3. Celestial CR intensity map for different representative CR energies. (**A**) 4 TeV; (**B**) 6.2 TeV; (**C**) 12 TeV; (**D**) 50 TeV; (**E**) 300 TeV. Data were gathered from 1997 to 2005. The vertical color bin width is 2.5×10^{-4} in [(A) to (D)] and 7.25×10^{-4} in (E) for different statistics, all for the relative CR intensity.



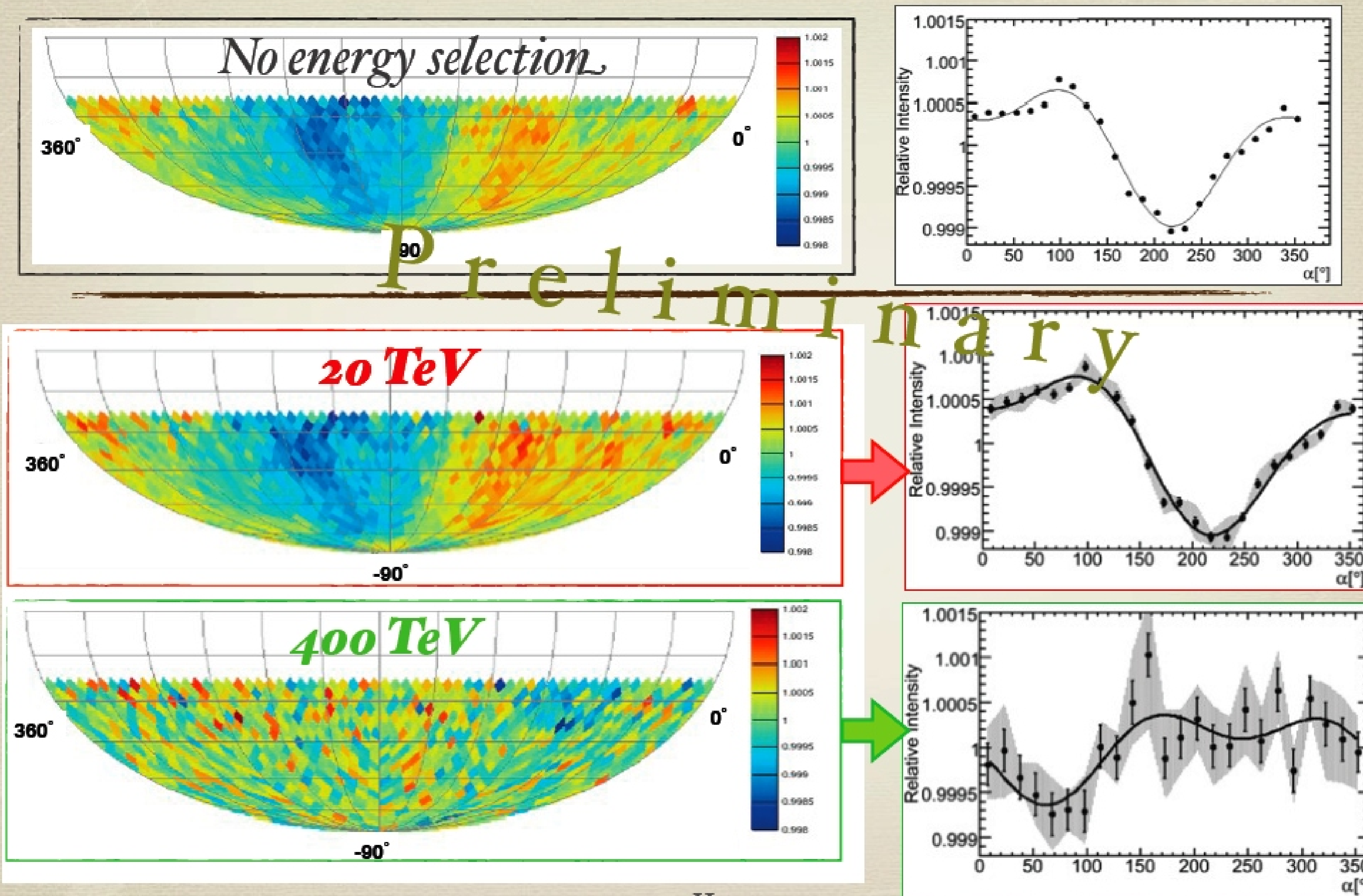
A
B
C
ARGO Result
0.7 TeV (20-60)
2.5 TeV (60-100)
3.9 TeV (>100)
Declination (degree)
Rel. Intensity
Right Ascension (degree)
Ep=0.7TeV
χ² / ndf 1229 / 14
p0 0.0002603 ± 0.0000043
p1 0.0003963 ± 0.0000043
p2 28.18 ± 0.94
p3 281.4 ± 0.3
Ep=1.5TeV
χ² / ndf 948.2 / 14
p0 0.0006313 ± 0.0000065
p1 0.0004962 ± 0.0000064
p2 26.62 ± 0.58
p3 279.9 ± 0.4
Ep=3.9TeV
χ² / ndf 514.4 / 14
p0 0.0008598 ± 0.0000073
p1 0.0005477 ± 0.0000073
p2 23.6 ± 0.5
p3 279.4 ± 0.4
Rel. intensity
Right Ascension (degree)



Tibet-III
5 TeV
courtesy Kazuoki Munakata
1.002
1.001
1.000
0.999
0.998
360°
270°
180°
90°
0°
IceCube-22
relative intensity
20 TeV

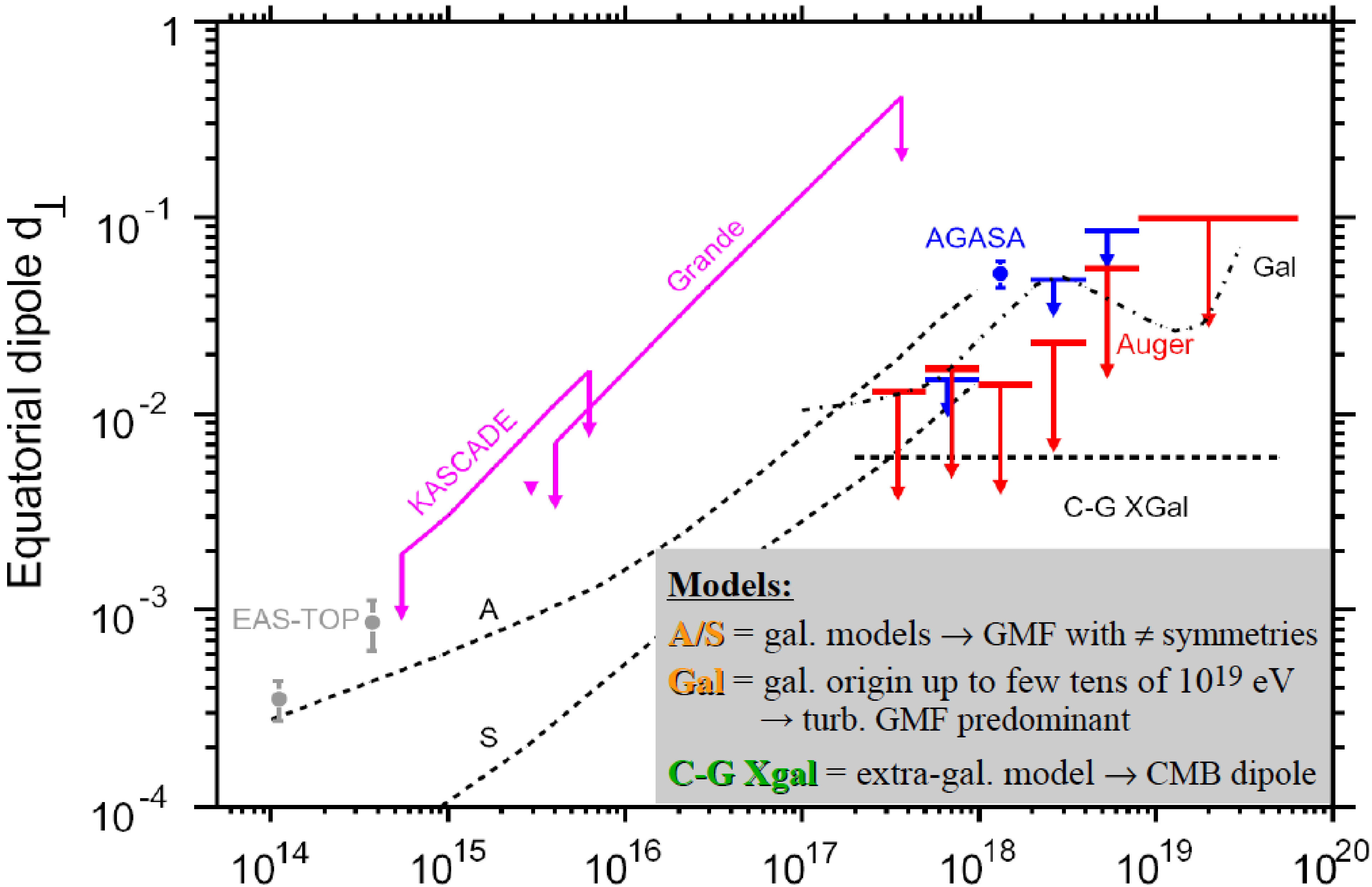
Relative Intensity

Equatorial sky maps in HEALPix with NSide= 16, ***pix resol ~ 3°***



AUGER

Upper limits



Identification of Cosmic Ray Sources

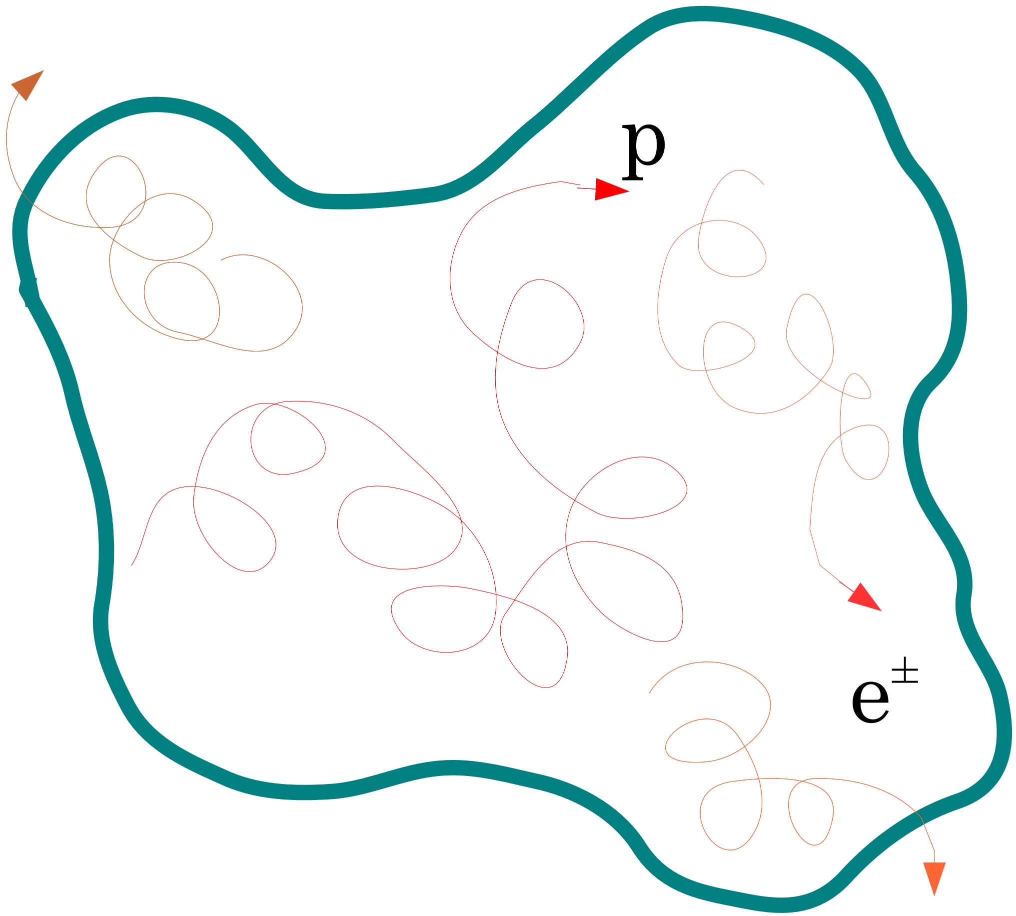
Intimate Relation between :

Cosmic Ray Physics

Gamma Astronomy

Neutrino Astronomy

Cosmic Ray Accelerator



Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, Nuclei electrons/positrons

Emission of

COSMIC RAYS

PHOTONS

NEUTRINOS

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

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

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

$$\pi^{\circ} \rightarrow \gamma + \gamma$$

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

"Hadronic Emission"

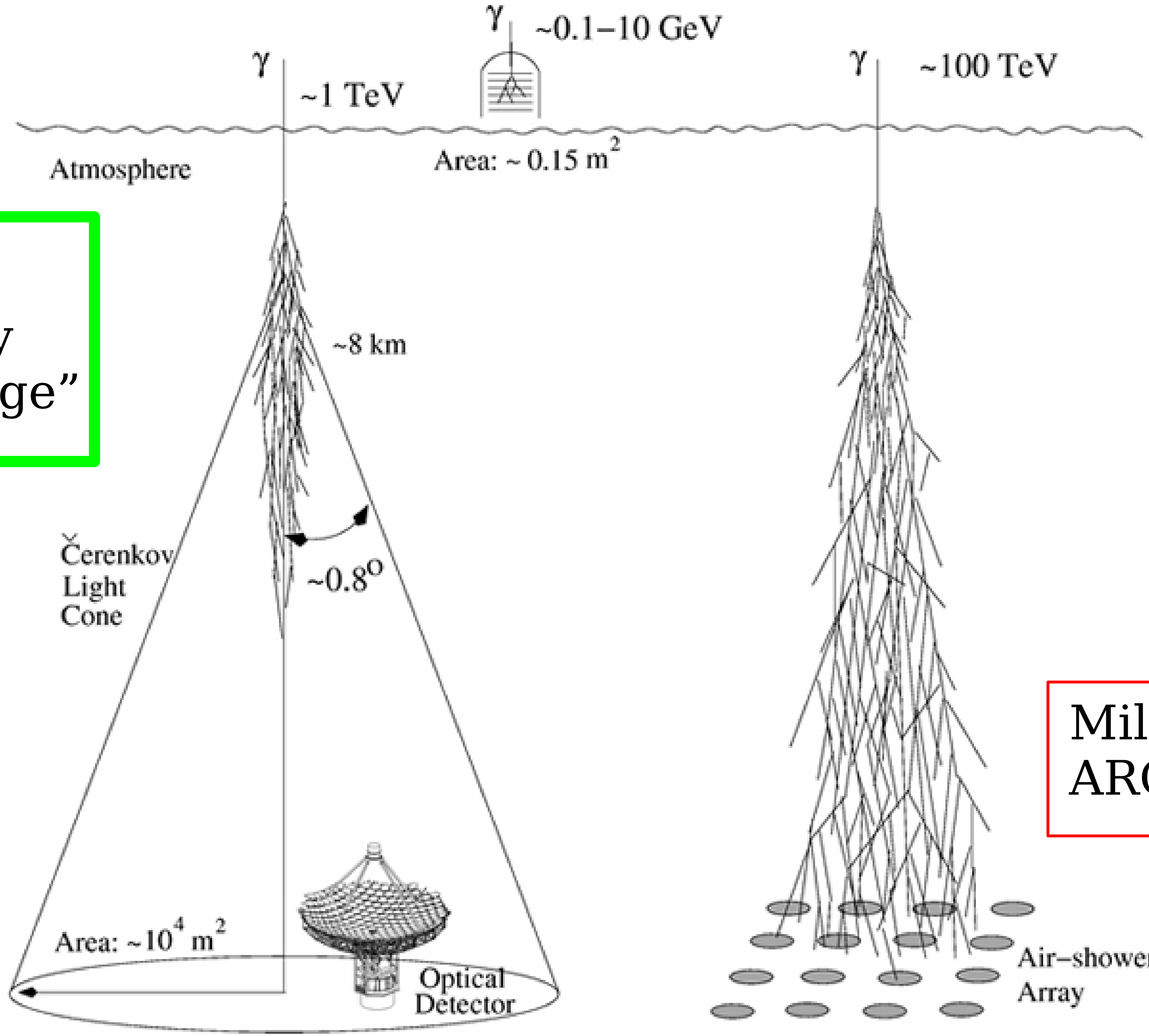
$$e^{\mp} + B \rightarrow e^{\mp} + \gamma_{\text{synchrotron}}$$

"Leptonic Emission"

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

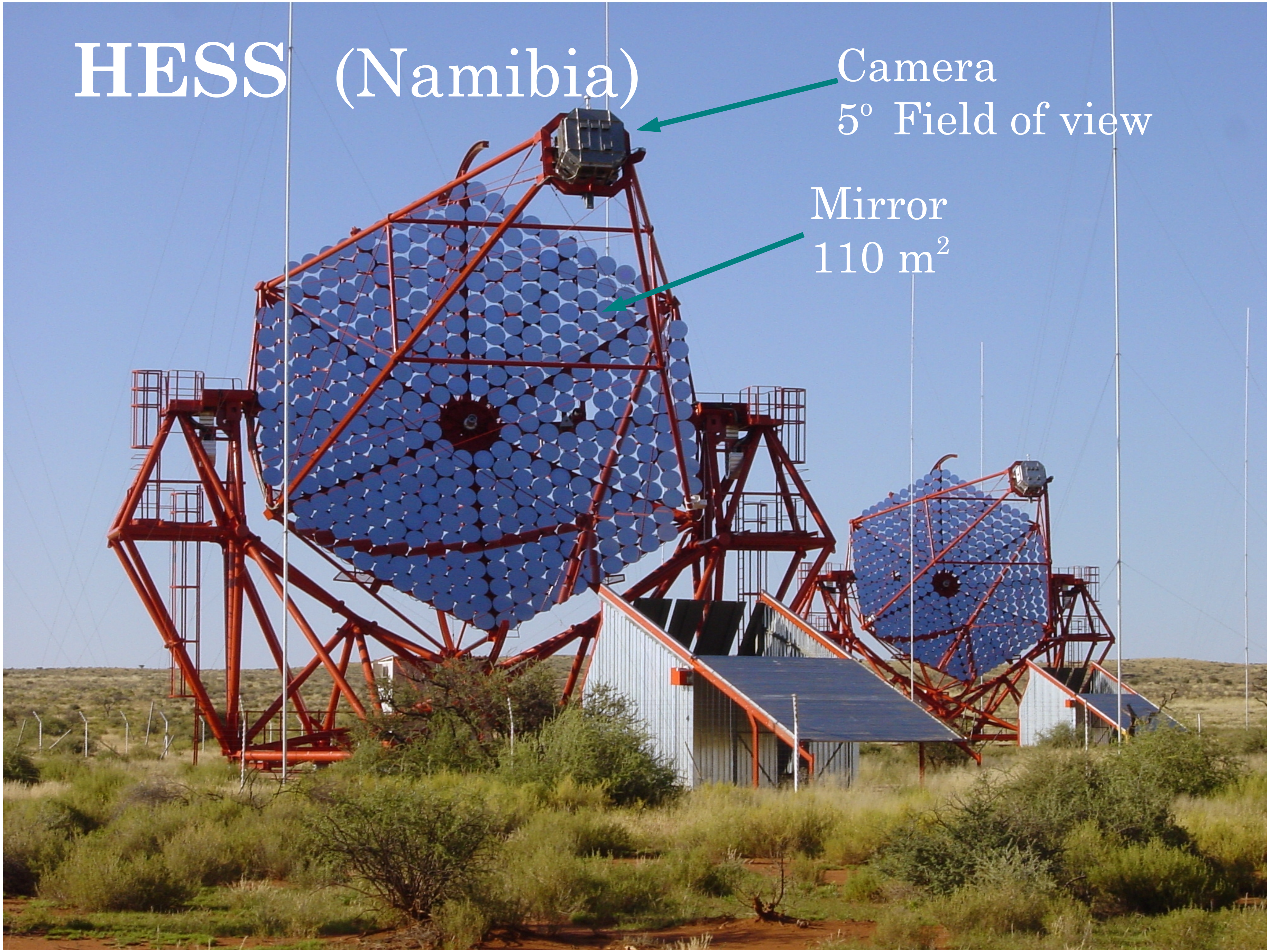
Egret
Agile
Fermi

Gamma
Astronomy
“Golden Age”



Hess
Magic
Veritas

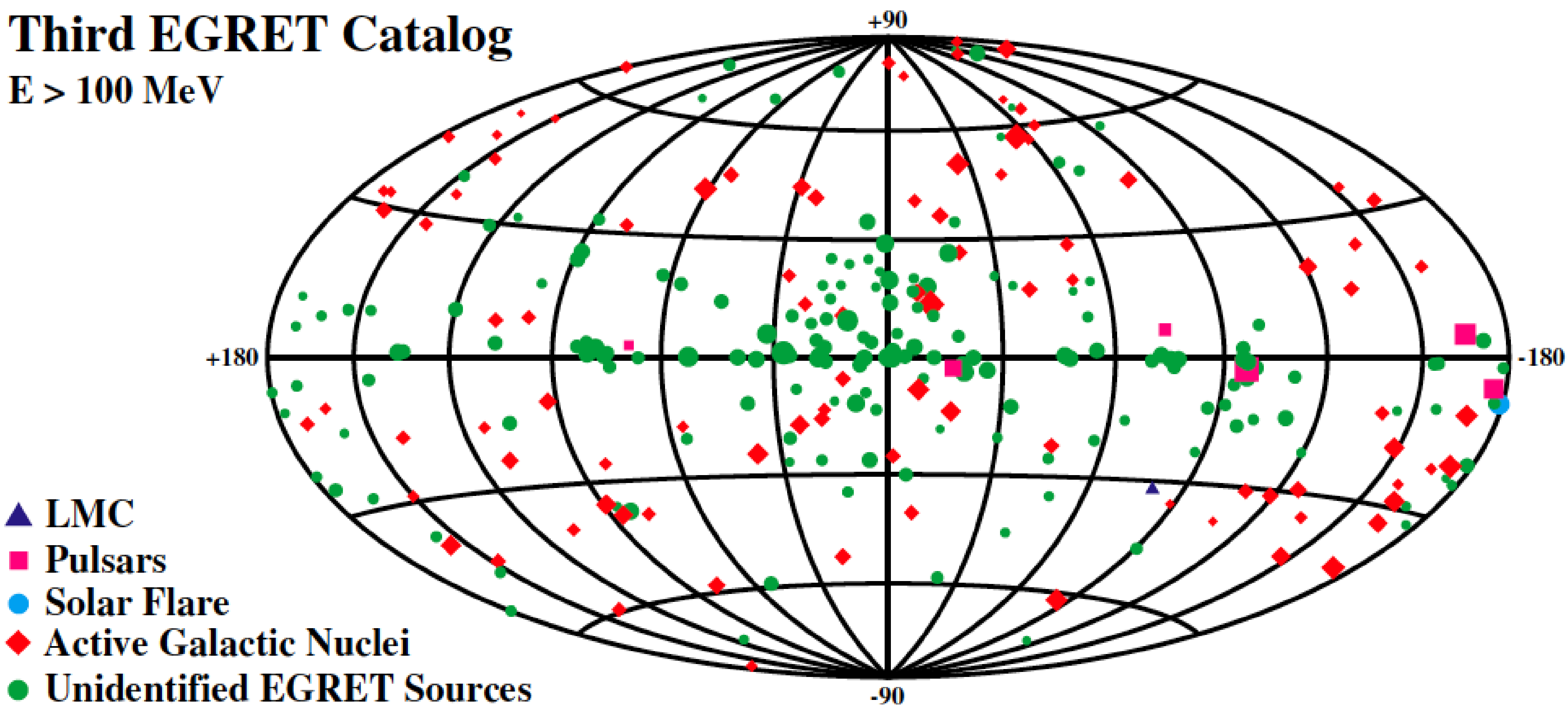
Milagro
ARGO

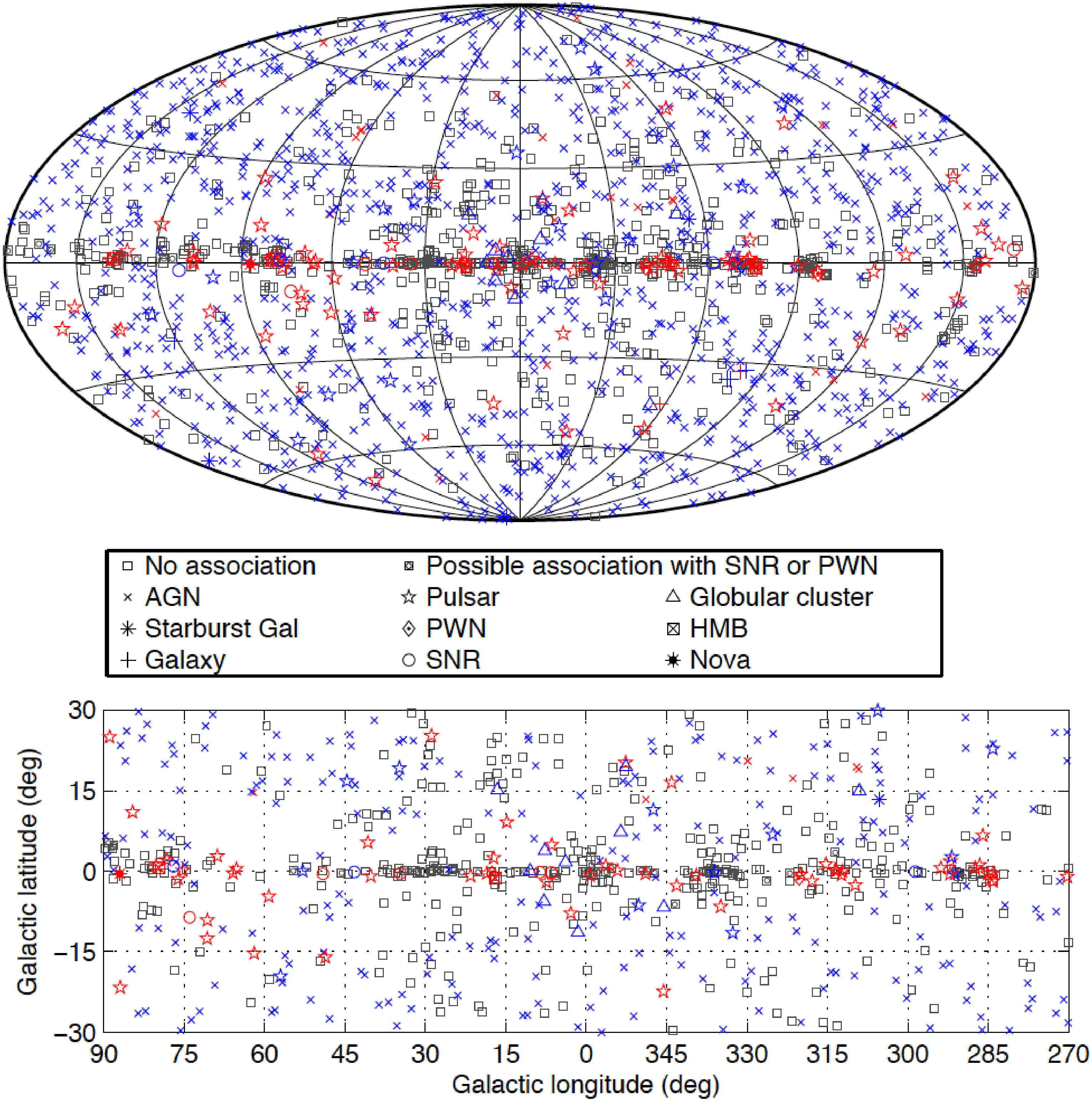

HESS (Namibia)
Camera
5° Field of view
Mirror
110 m²


Yangbajing Cosmic Ray Laboratory - TIBET
ARGO-YBJ
4300 m a.s.l.
Longitude 90° 31’ 50” East
Latitude 30° 06’ 38” North

.... Madamina il catalogo e' questo ....

Situation in year 2000





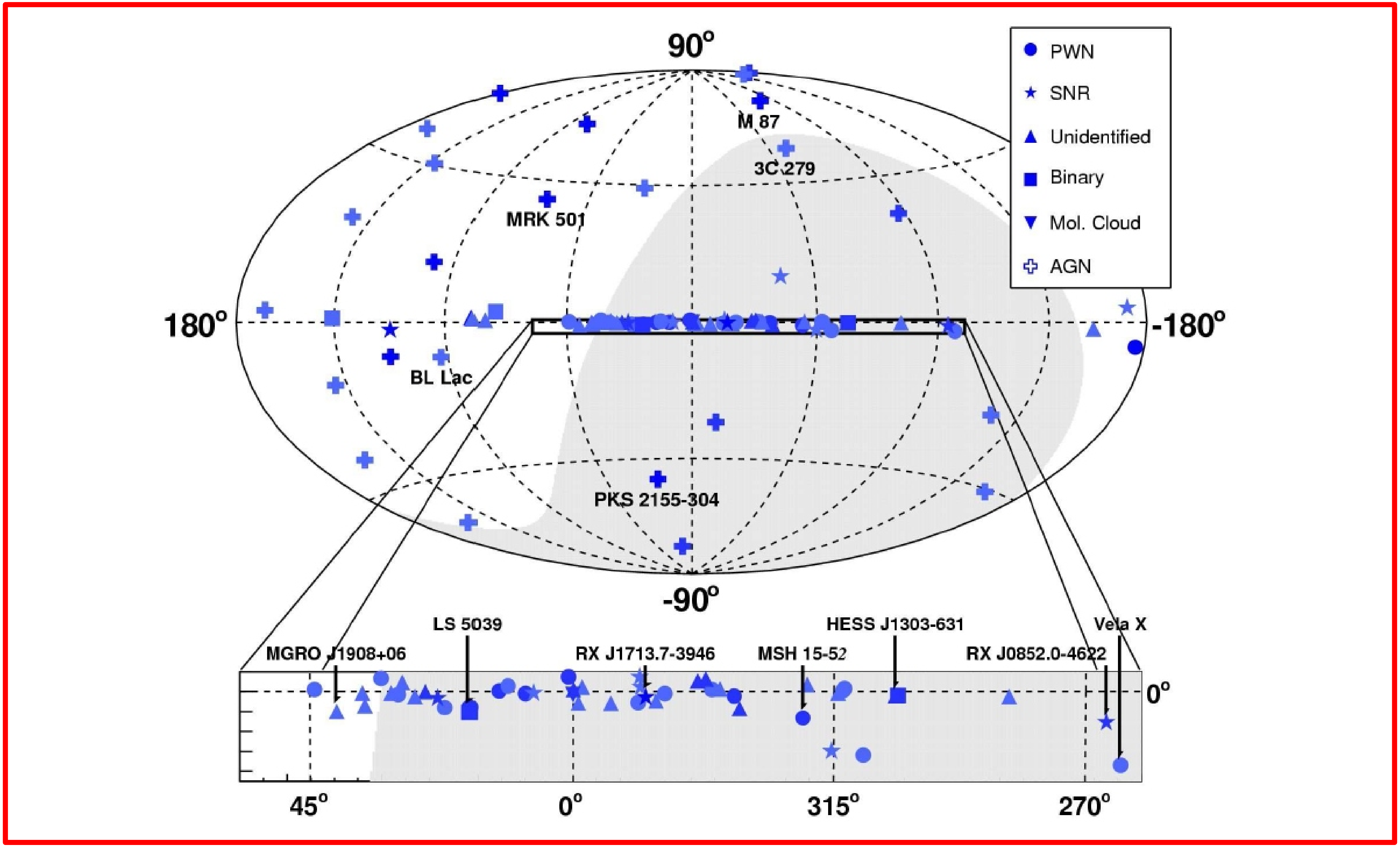
2FGL

2nd FERMI Catalog

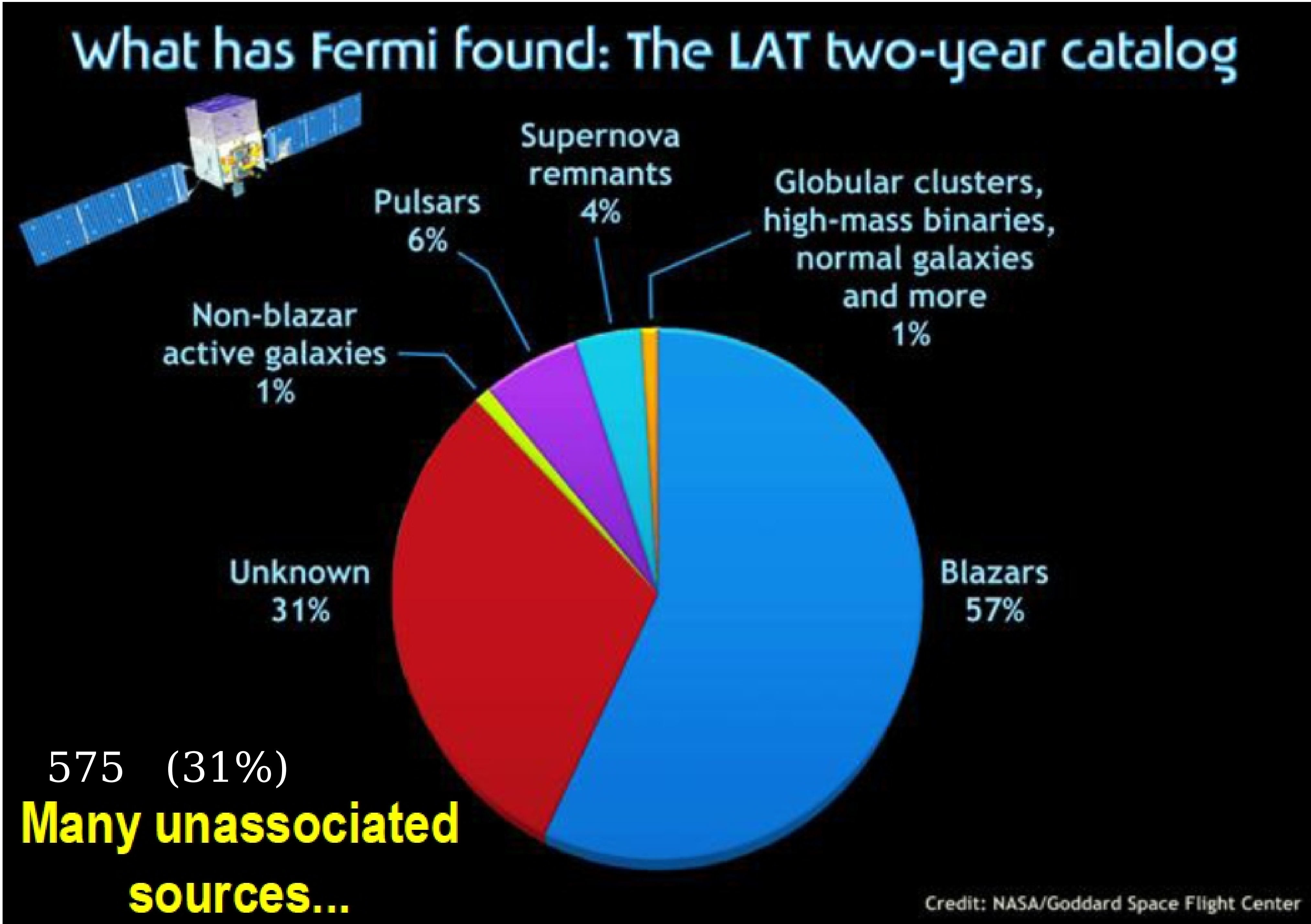
24 months of observations

1873 sources

TEV SKY



90°
-90°
180°
-180°
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
M 87
3C 279
MRK 501
BL Lac
PKS 2155-304
MGRO J1908+06
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
315°
270°



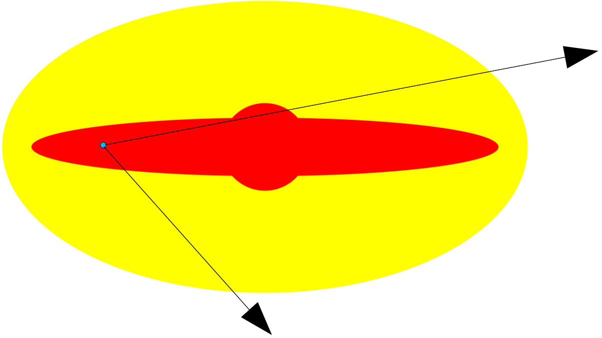
575 (31%)

Many unassociated sources...

Table 6. LAT 2FGL Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	83	...	...
Pulsar, no pulsations seen in LAT yet	...	...	psr	25
Pulsar wind nebula	PWN	3	pwn	0
Supernova remnant	SNR	6	snr	4
Supernova remnant / Pulsar wind nebula	...	...	†	58
Globular cluster	GLC	0	glc	11
High-mass binary	HMB	4	hmb	0
Nova	NOV	1	nov	0
BL Lac type of blazar	BZB	7	bzb	429
FSRQ type of blazar	BZQ	17	bzq	353
Non-blazar active galaxy	AGN	1	agn	10
Radio galaxy	RDG	2	rdg	10
Seyfert galaxy	SEY	1	sey	5
Active galaxy of uncertain type	AGU	0	agu	257
Normal galaxy (or part)	GAL	2	gal	4
Starburst galaxy	SBG	0	sbg	4
Class uncertain	...	...	...	1
Unassociated	...	...	...	575
Total	...	127	...	1746

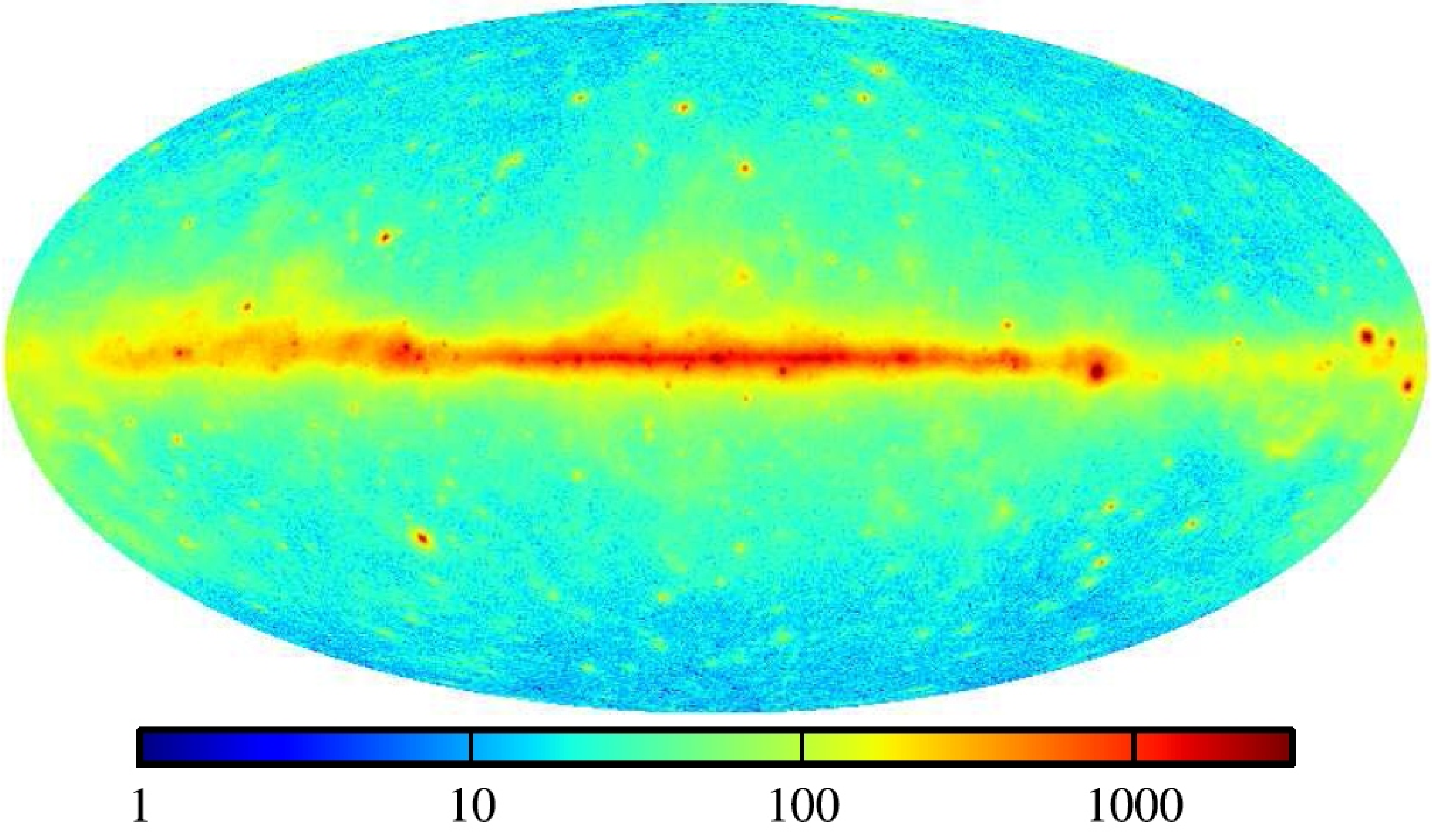
Diffuse Emission

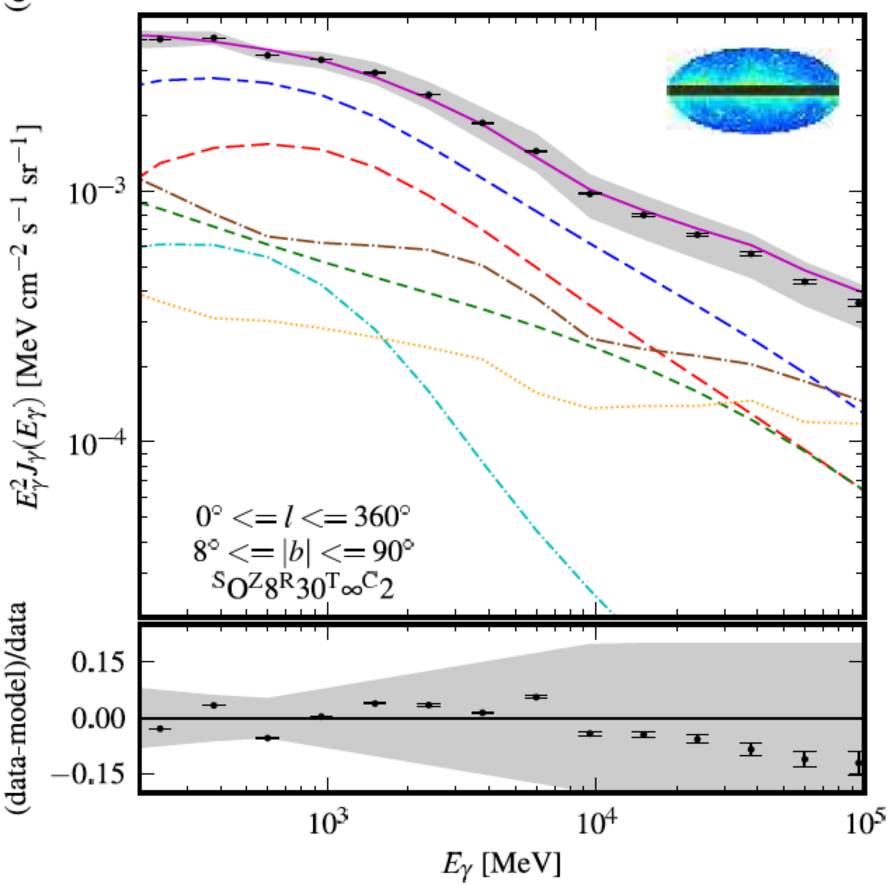


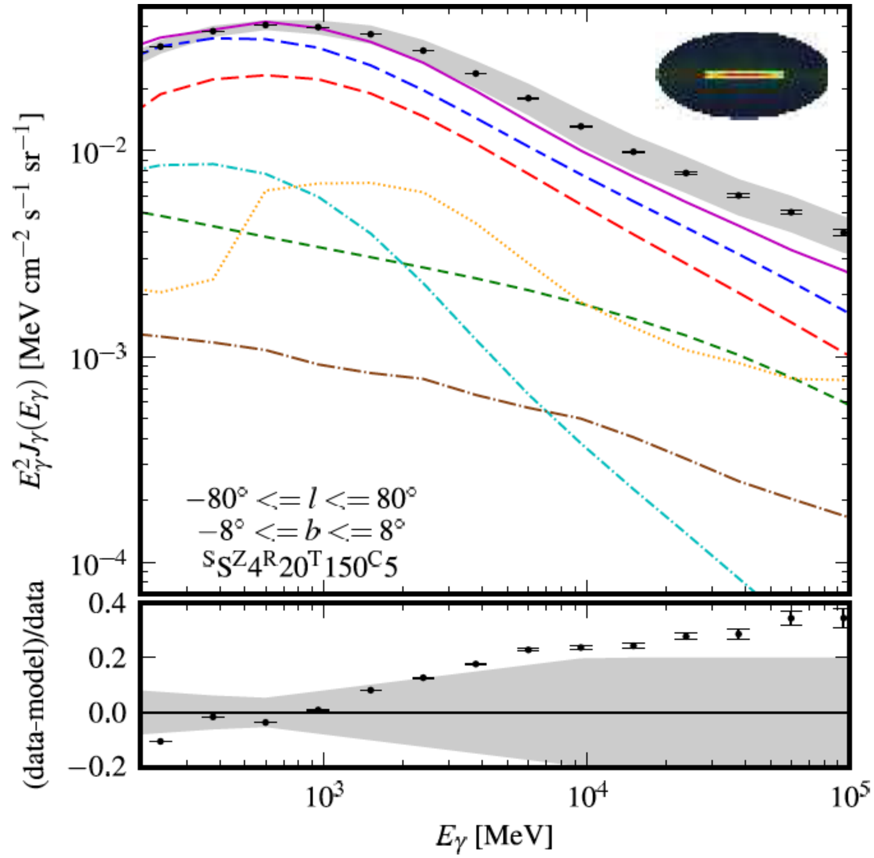
Fermi–LAT counts

Galactic coordinates

energy range 200 MeV to 100 GeV







$$p + p_{\text{i.s.m.}} \rightarrow \pi^\circ + \ldots$$

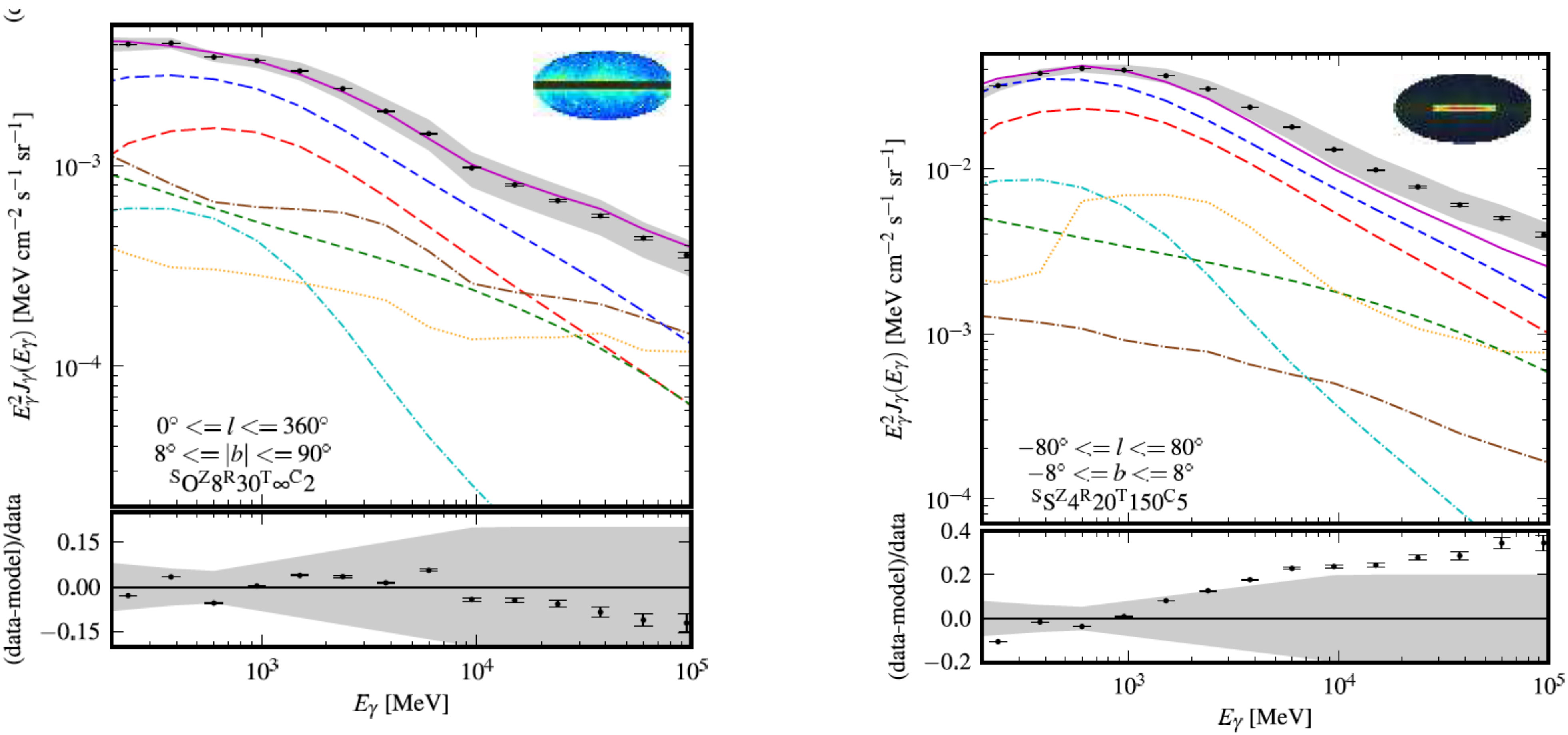
$$\pi^\circ \rightarrow \gamma + \gamma$$

Inverse Compton

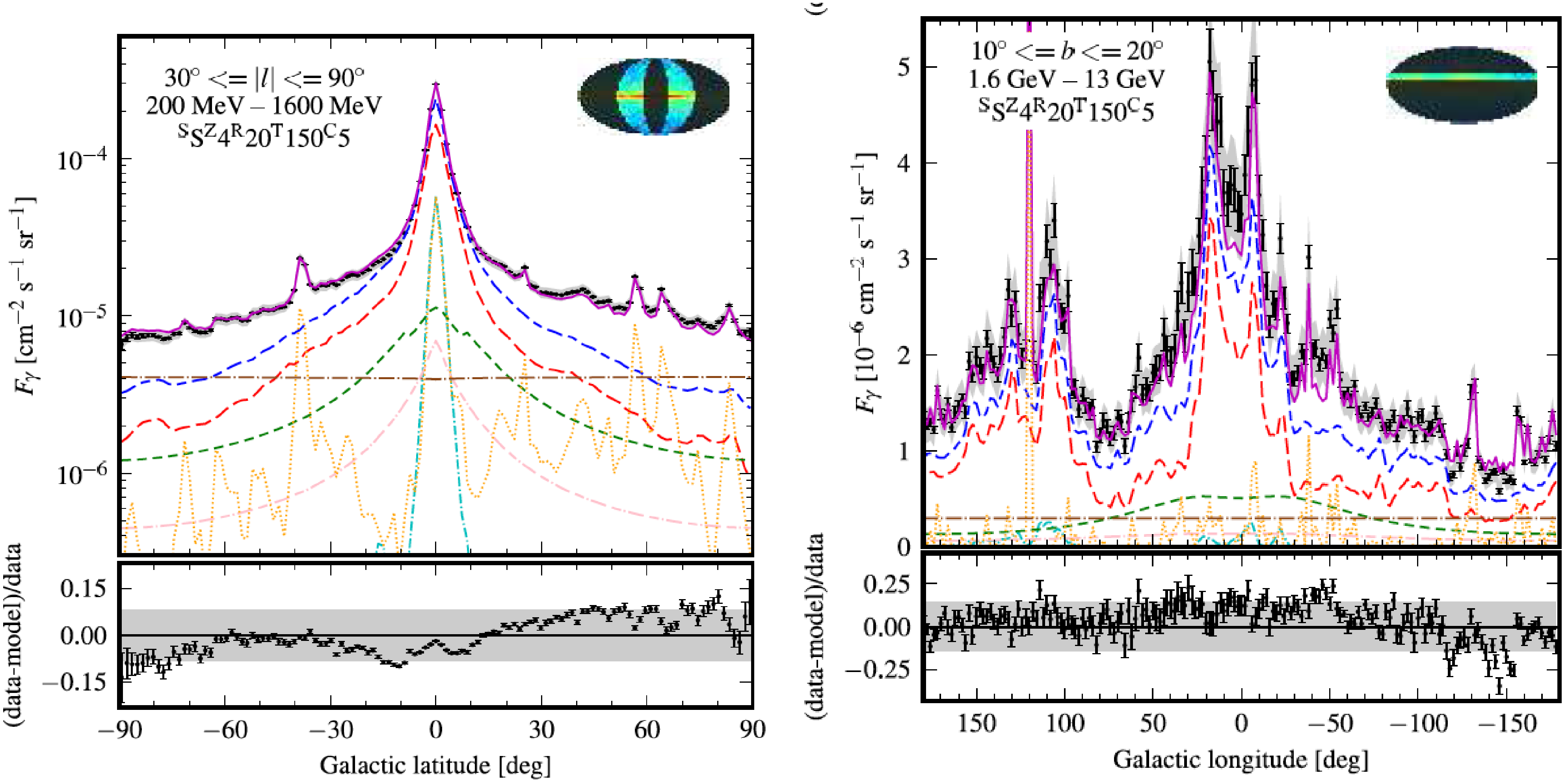
$$e^\pm + \gamma_{\text{soft}} \rightarrow e^\pm + \gamma$$

Bremsstrahlung

$$e^\pm + Z \rightarrow e^\pm + \gamma + Z$$



detected sources (orange, dotted). The models are split into the three basic emission components: π^0-decay (red, long-dashed), IC (green, dashed), and bremsstrahlung (cyan, dash-dotted). All components have been scaled with parameters found from the γ-ray-fits. Also shown is the total DGE (blue, long-dash-dashed) and total emission including detected sources and isotropic background (magenta, solid). The *Fermi*–LAT data are shown as points and the error bars represent the statistical errors only that are in many cases smaller than the point size. The gray region represents the systematic error in the *Fermi*–LAT effective area. The inset skymap in the top right corner shows the *Fermi*–LAT counts in the region plotted. Bottom panel shows the fractional residual $(data - model)/data$.



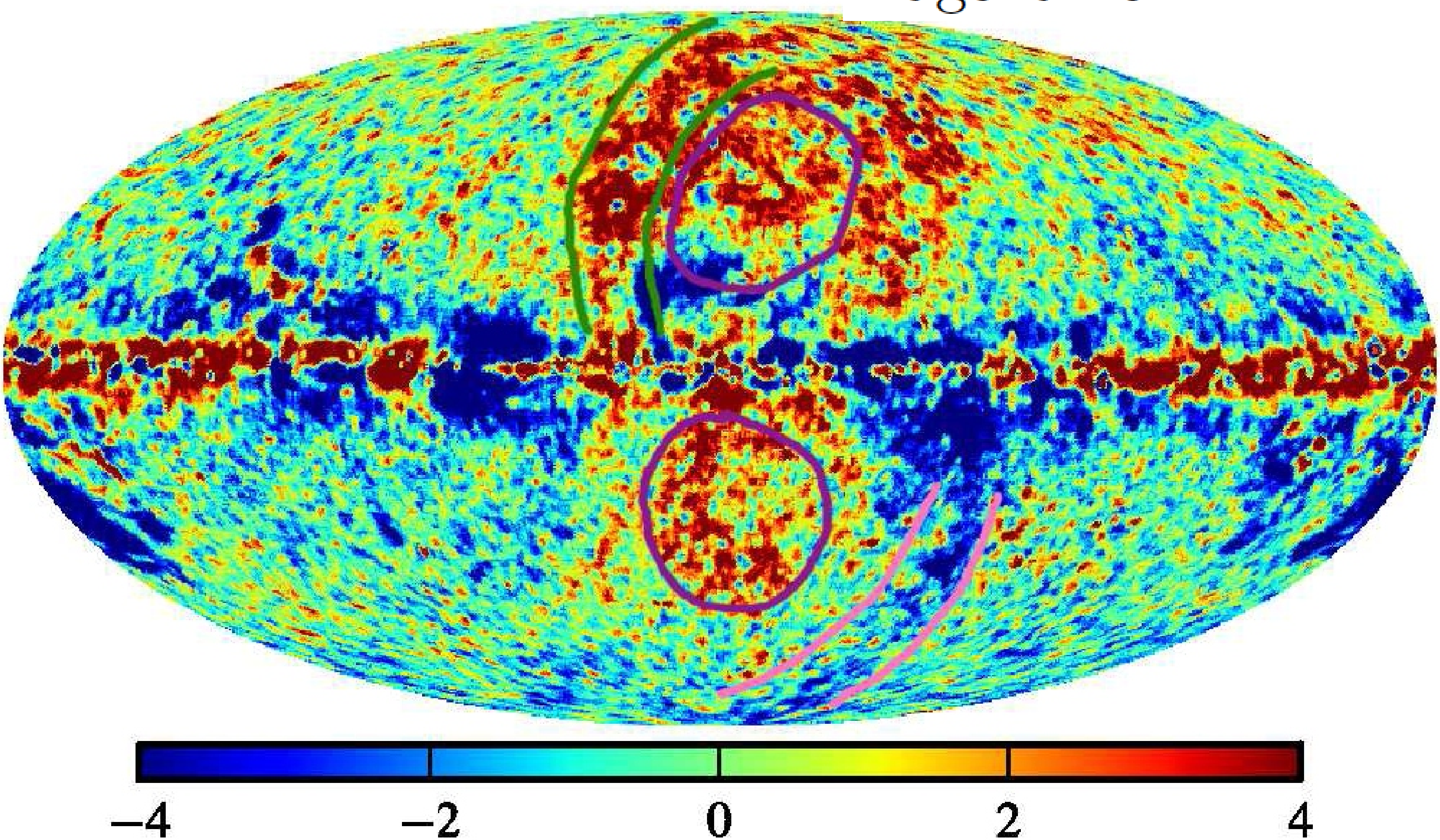
Description reasonably succcessful.
But several ambiguities and open problems remain.

Residual maps in units of standard deviation

model $^{S}S^{Z}4^{R}20^{T}150^{C}5$

Loop I (green)

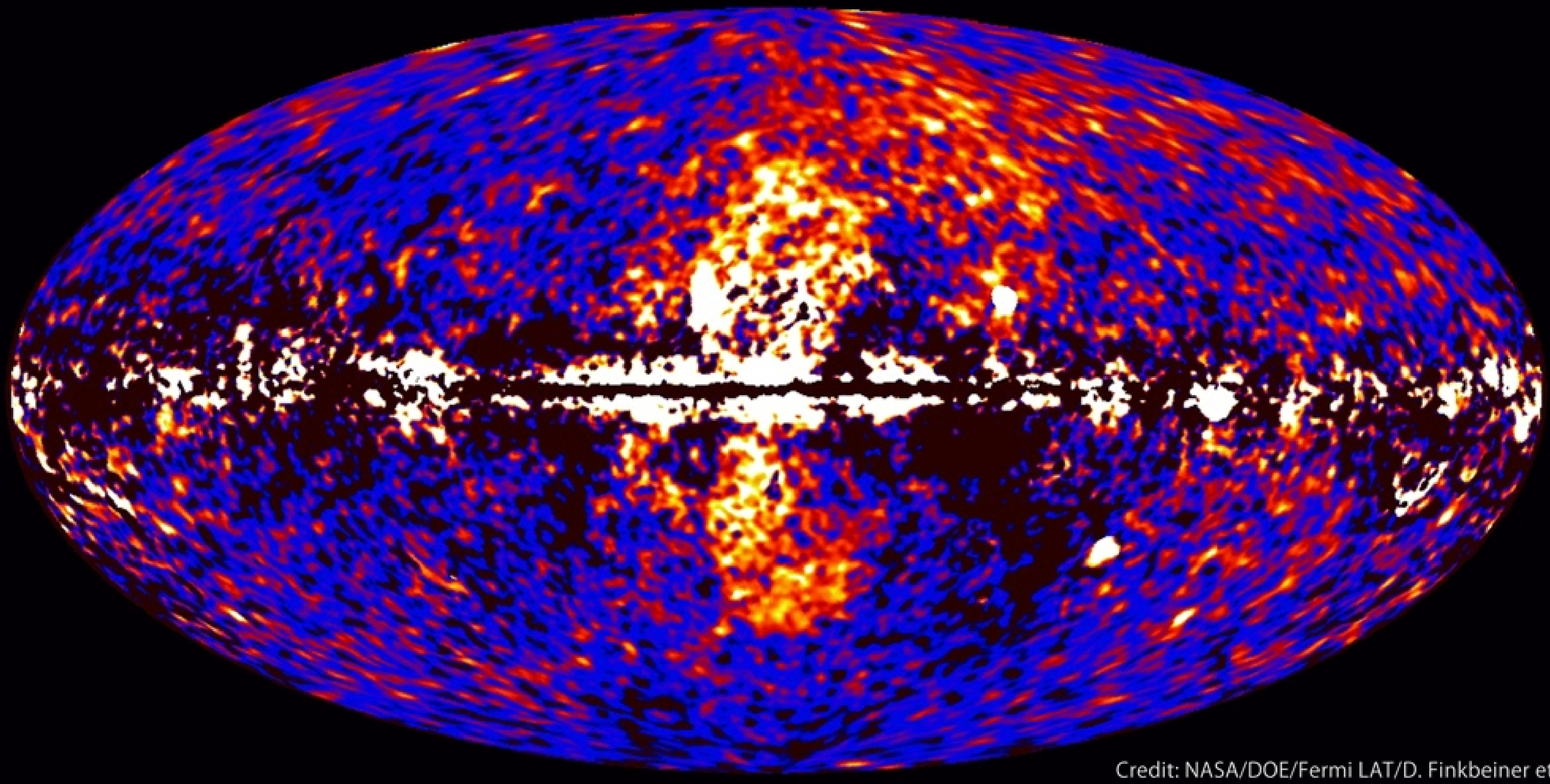
Magellanic stream (pink)



"FERMI BUBBLES"

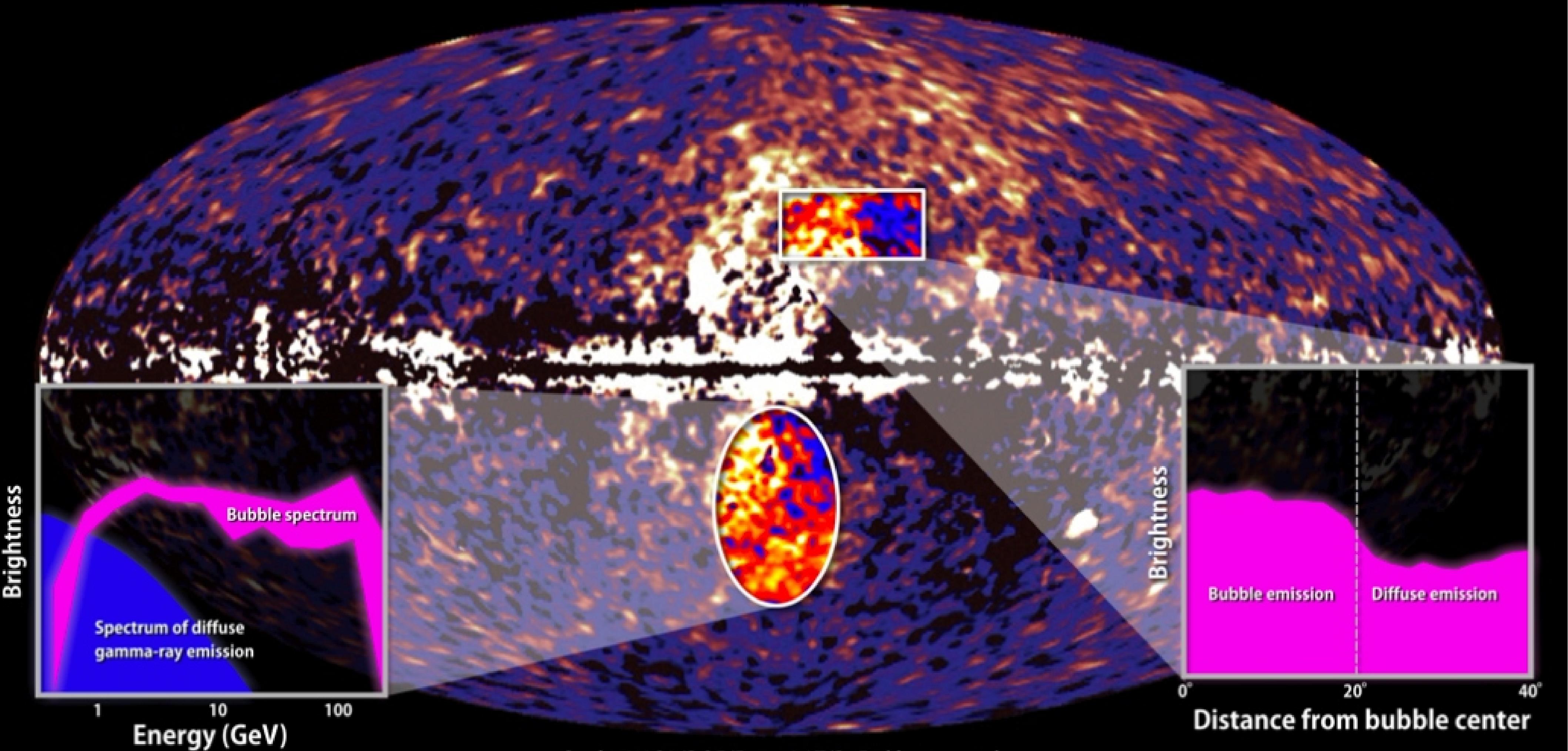
Scientific American news. Title:

Hidden in Plain Sight: Researchers Find Galaxy-Scale Bubbles Extending from the Milky Way

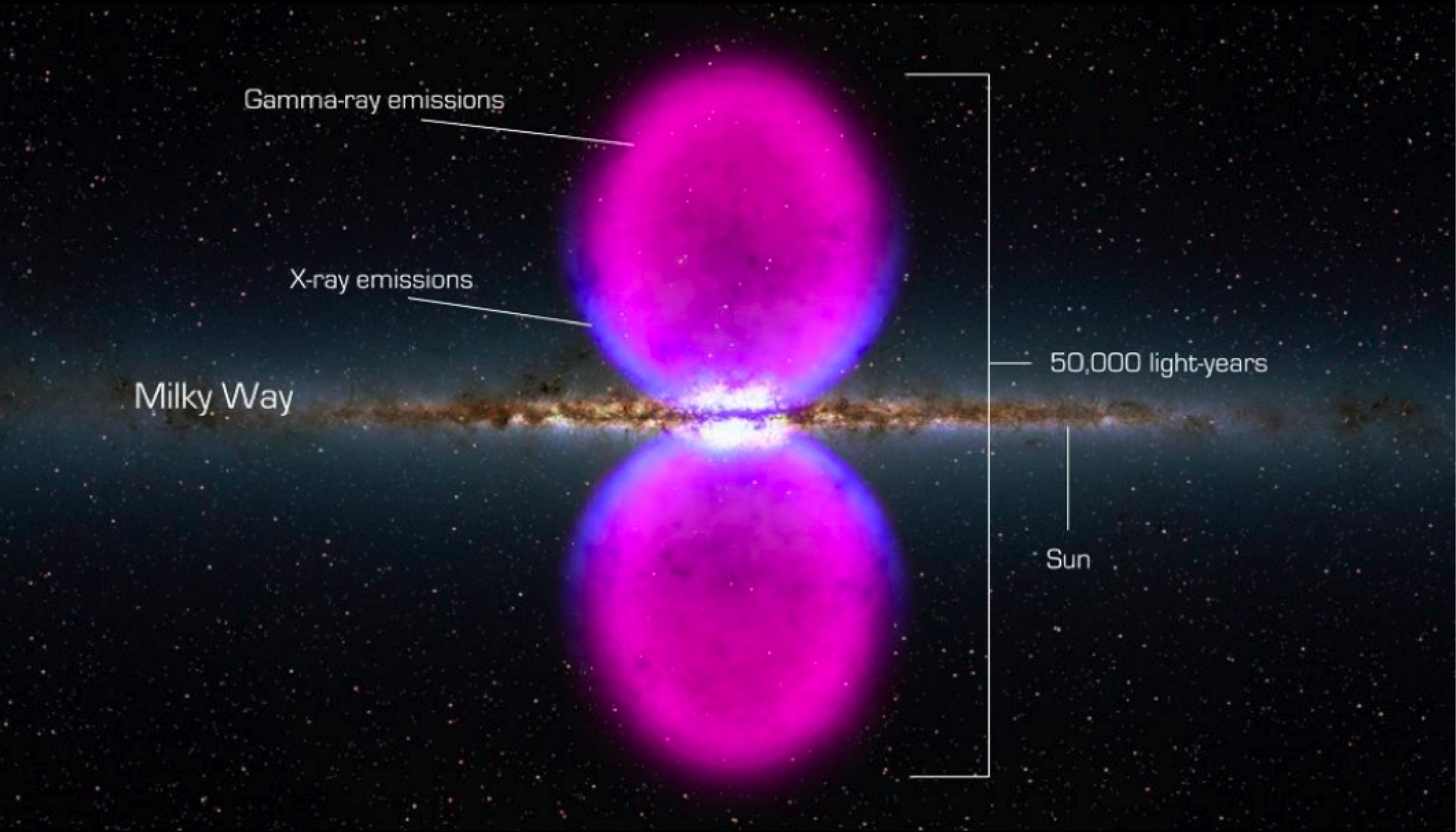


M. Su, T. R. Slatyer, D. P. Finkbeiner,
"Giant Gamma-ray Bubbles from Fermi-LAT: AGN Activity or Bipolar Galactic Wind?,"
Astrophys. J. **724**, 1044-1082 (2010). [arXiv:1005.5480 [astro-ph.HE]].

Bubbles show energetic spectrum and sharp edges



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.



Artist's view of the “Fermi bubbles”

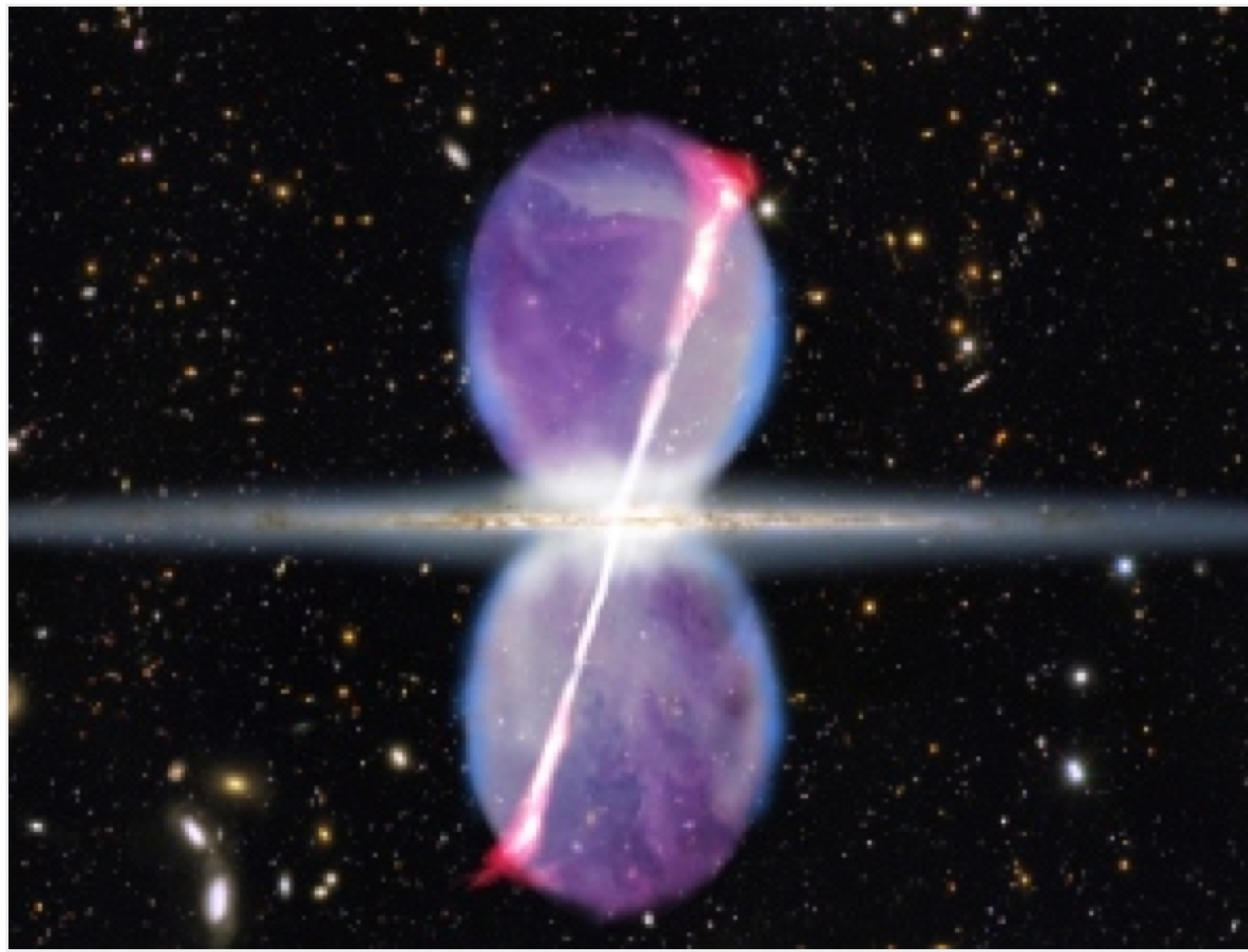
NATURE | NEWS

Ghostly jets seen streaming from Milky Way's core

Faint γ-rays indicate recent activity for Galaxy's supermassive black hole.

Ron Cowen

30 May 2012 | Corrected: 31 May 2012



Draft version May 29, 2012
Preprint typeset using LaTeX style emulateapj v. 03/07/07

EVIDENCE FOR GAMMA-RAY JETS IN THE MILKY WAY

Meng Su[1,3], Douglas P. Finkbeiner[1,2]

Draft version May 29, 2012

ABSTRACT

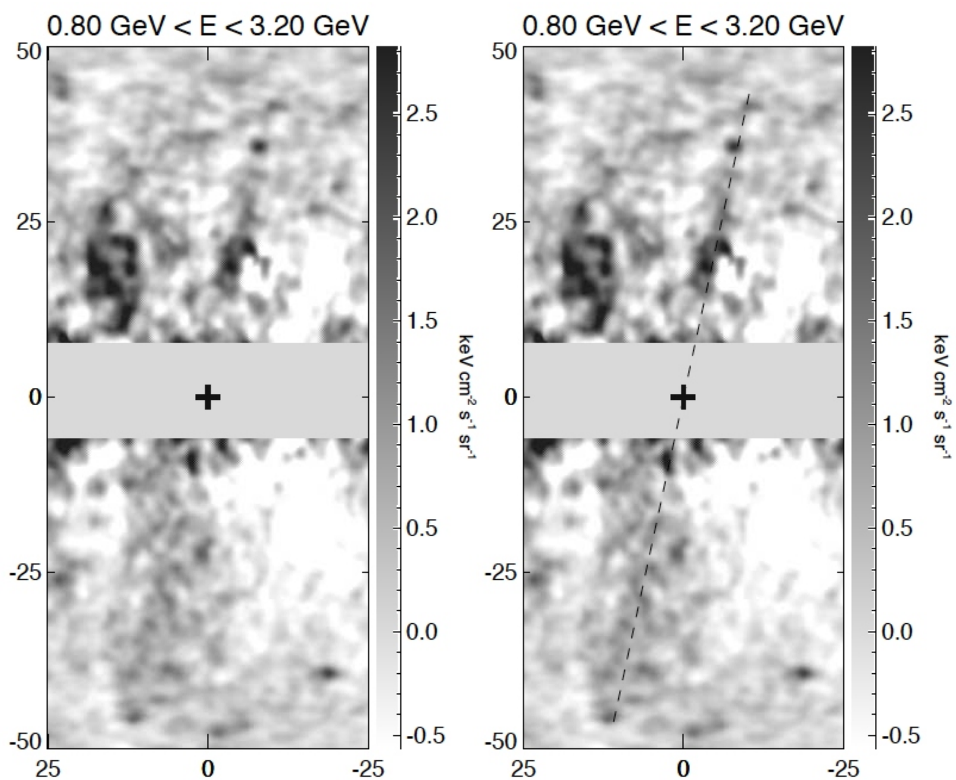
Although accretion onto supermassive black holes in other galaxies is seen to produce powerful jets in X-ray and radio, no convincing detection has ever been made of a kpc-scale jet in the Milky Way. The recently discovered pair of 10 kpc tall gamma-ray bubbles in our Galaxy may be signs of earlier jet activity from the central black hole. In this paper, we identify a gamma-ray cocoon feature in the southern bubble, a jet-like feature along the cocoon's axis of symmetry, and another directly opposite the Galactic center in the north. Both the cocoon and jet-like feature have a hard spectrum with spectral index ~ -2 from 1 to 100 GeV, with a cocoon total luminosity of $(5.5 \pm 0.45) \times 10^{35}$ and luminosity of the jet-like feature of $(1.8 \pm 0.35) \times 10^{35}$ erg/s at $1 - 100$ GeV. If confirmed, these jets are the first resolved gamma-ray jets ever seen.

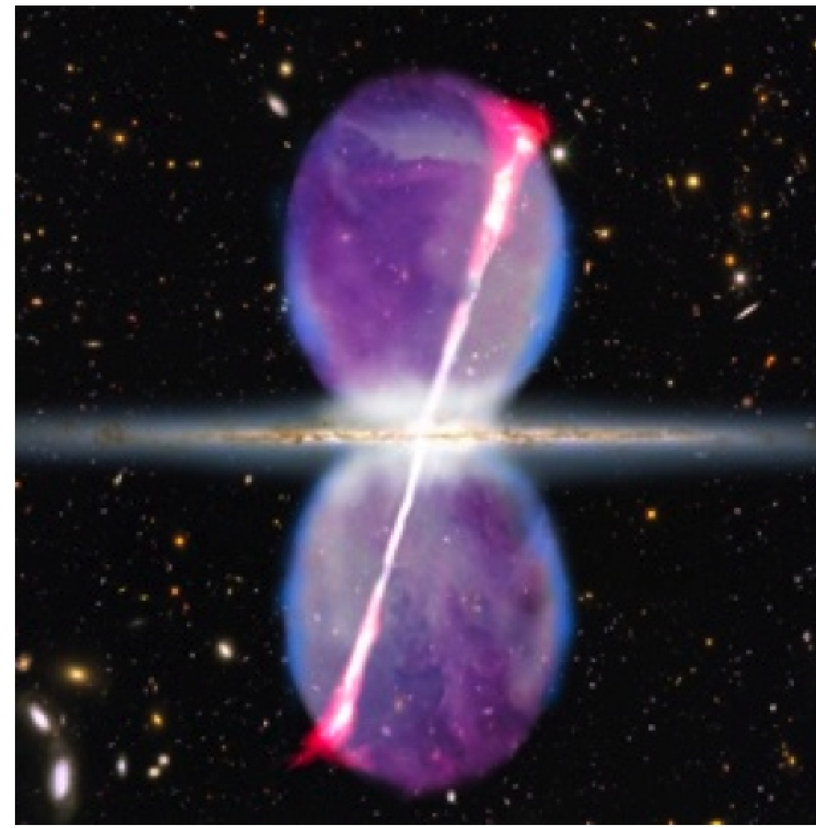
Subject headings: galaxies: active — galaxies: starburst — gamma rays — ISM: jets and outflows

Vestiges of Violence: Towering Gamma-Ray Jets Point to Past Outbursts from Milky Way's Black Hole

Black hole jets had previously been detected in other galaxies, but not in ours

By Jo





BUBBLES AND JETS: An artist's conception of the Milky Way shows the recently discovered Fermi bubbles, as well as the dual gamma-ray jets for which evidence has just emerged.
Image: David A. Aguilar (CfA)

Many questions ?

Are the jets real ?

Why are the jets inclined ?
[are we seeing the direction of the BH rotation axis?]

What is the nature of the bubbles + jets emission?

What is happening (or what – and when - happened) at the GC ?

Are we missing something important for the understanding of the Milky Way structure And magnetic confinement properties ?

Review of Gamma Astronomy
impossible here.

VERY RICH FIELD
Many beautiful results !!

Review of Gamma Astronomy
impossible here.

VERY RICH FIELD
Many beautiful results !!

[1.] Status of the “SNR paradigm”
for galactic sources

[2.] AGN as accelerators of UHECR

[3.] GRB's as accelerators of UHECR

- PULSARS (PSR)
- Pulsar Wind Nebulae (PWN)
- Binary Systems
- SuperNova Remnant (SNR)
- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRB)
- ....novae, globular clusters, starburst galaxies, ...

PULSARS

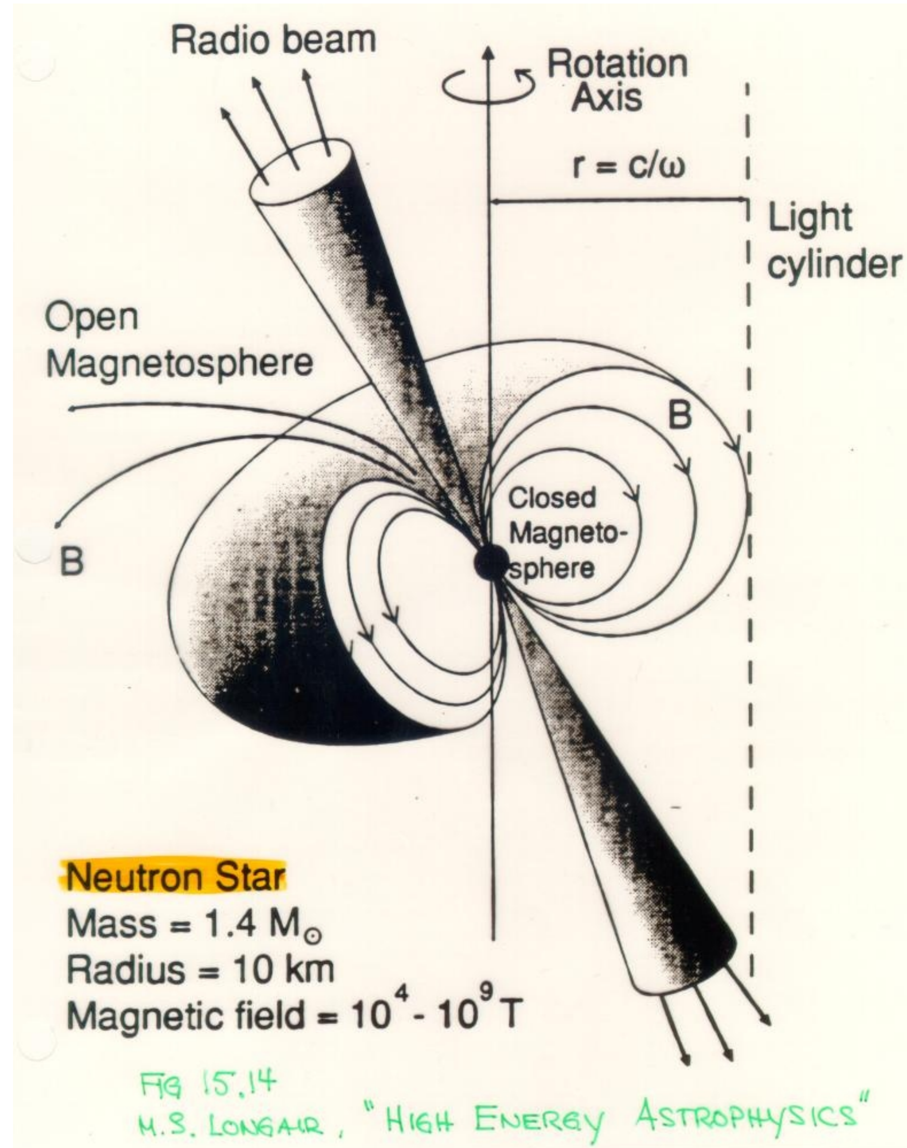
Proposed as possible Accelerators of e+ e-

CRAB Nebula

$$P_{\mathrm{Crab}} = 0.0334 \text{ s}$$

$$\dot{P}_{\mathrm{Crab}} = 4.2 \times 10^{-13} \text{ s}$$

$$(\Delta P_{\mathrm{Crab}})_{\mathrm{year}} = 13.2 \times 10^{-6} \text{ s}$$



EGRET Pulsars

VELA	89.3 ms
GEMINGA	237
CRAB	33
1706-44	102
1055-52	197

108 well identified Pulsars

Mechanism understood ?

Very large variation in the fraction of Spin Down Energy going into gamma Rays

3 PWN

VELA

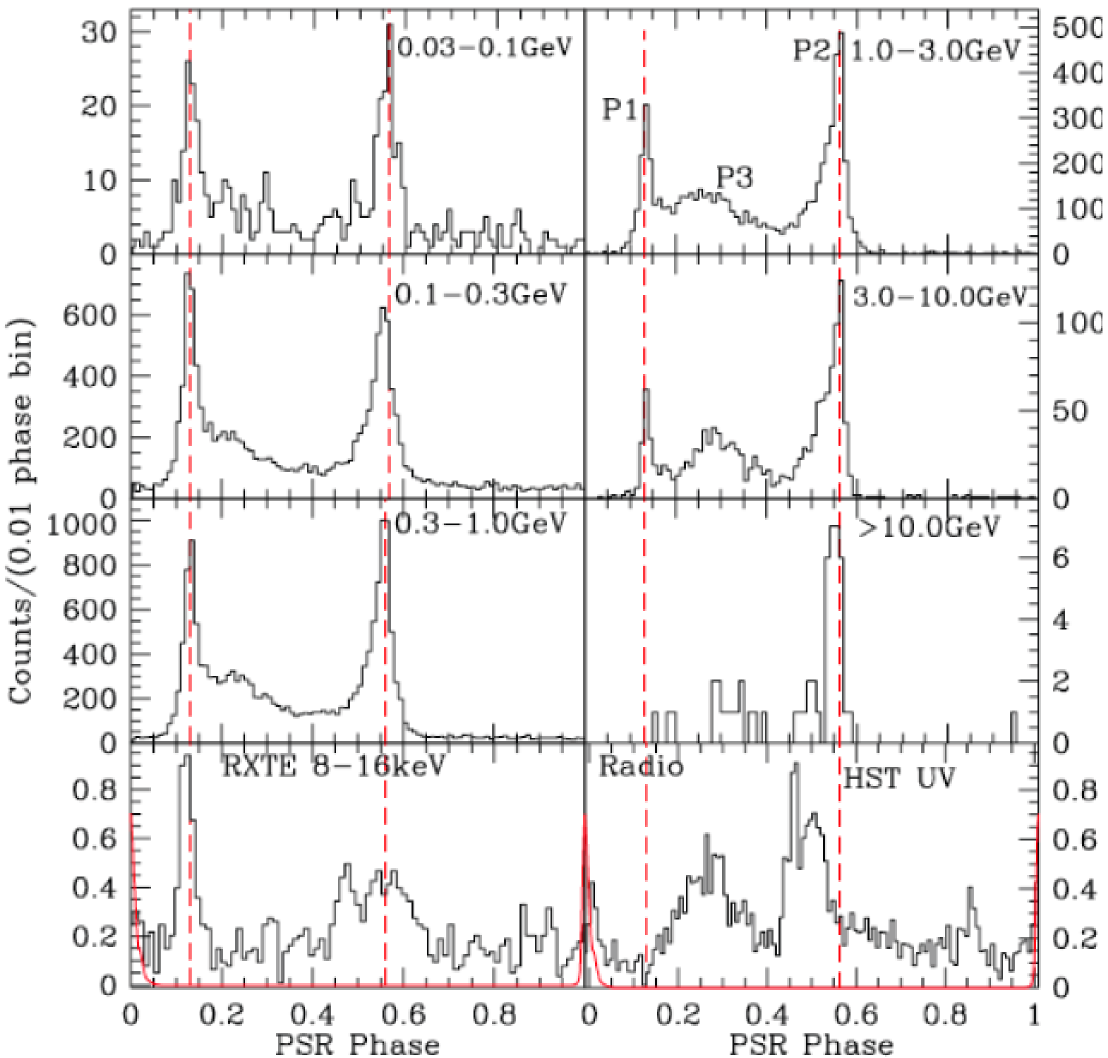
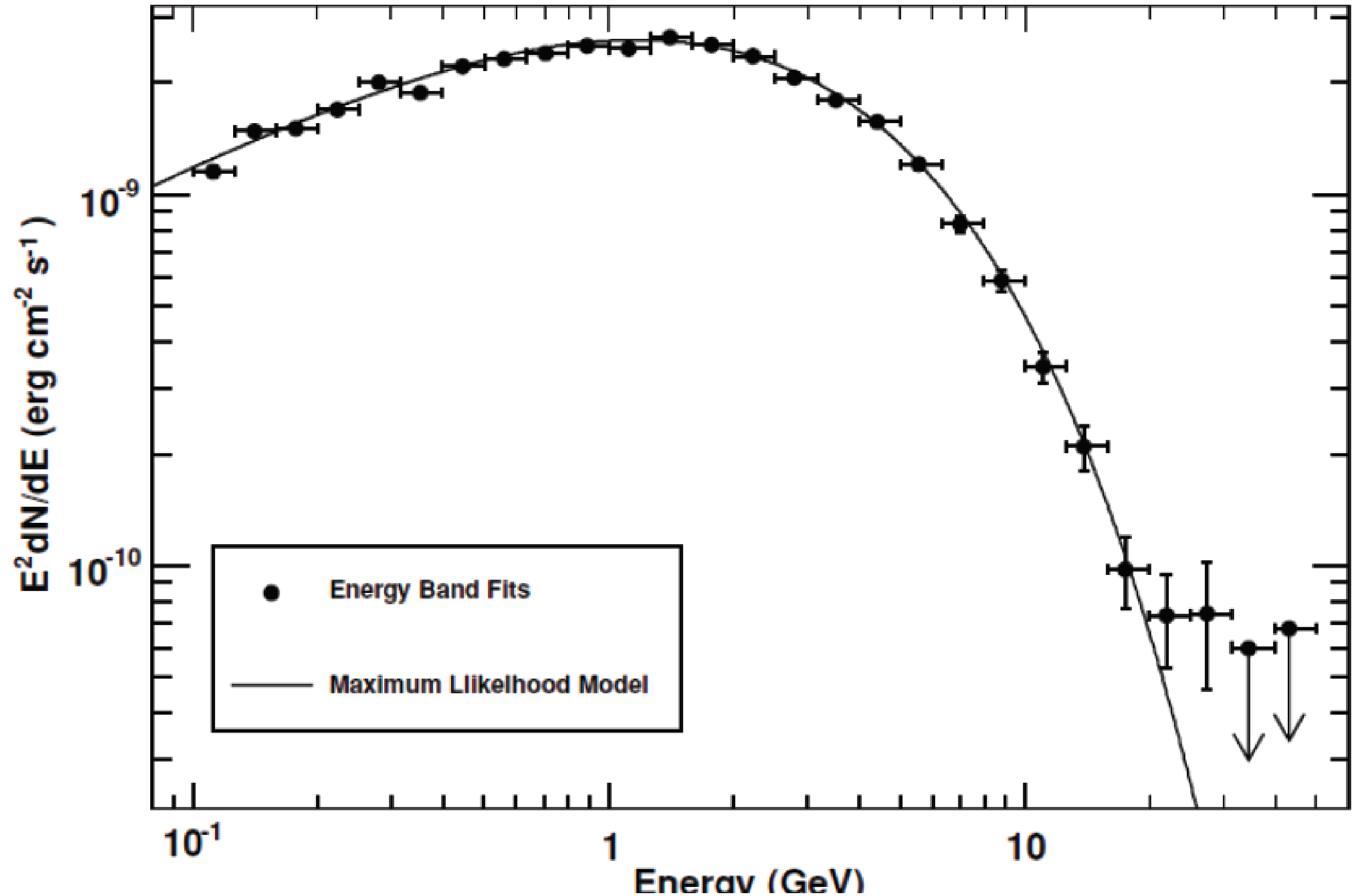


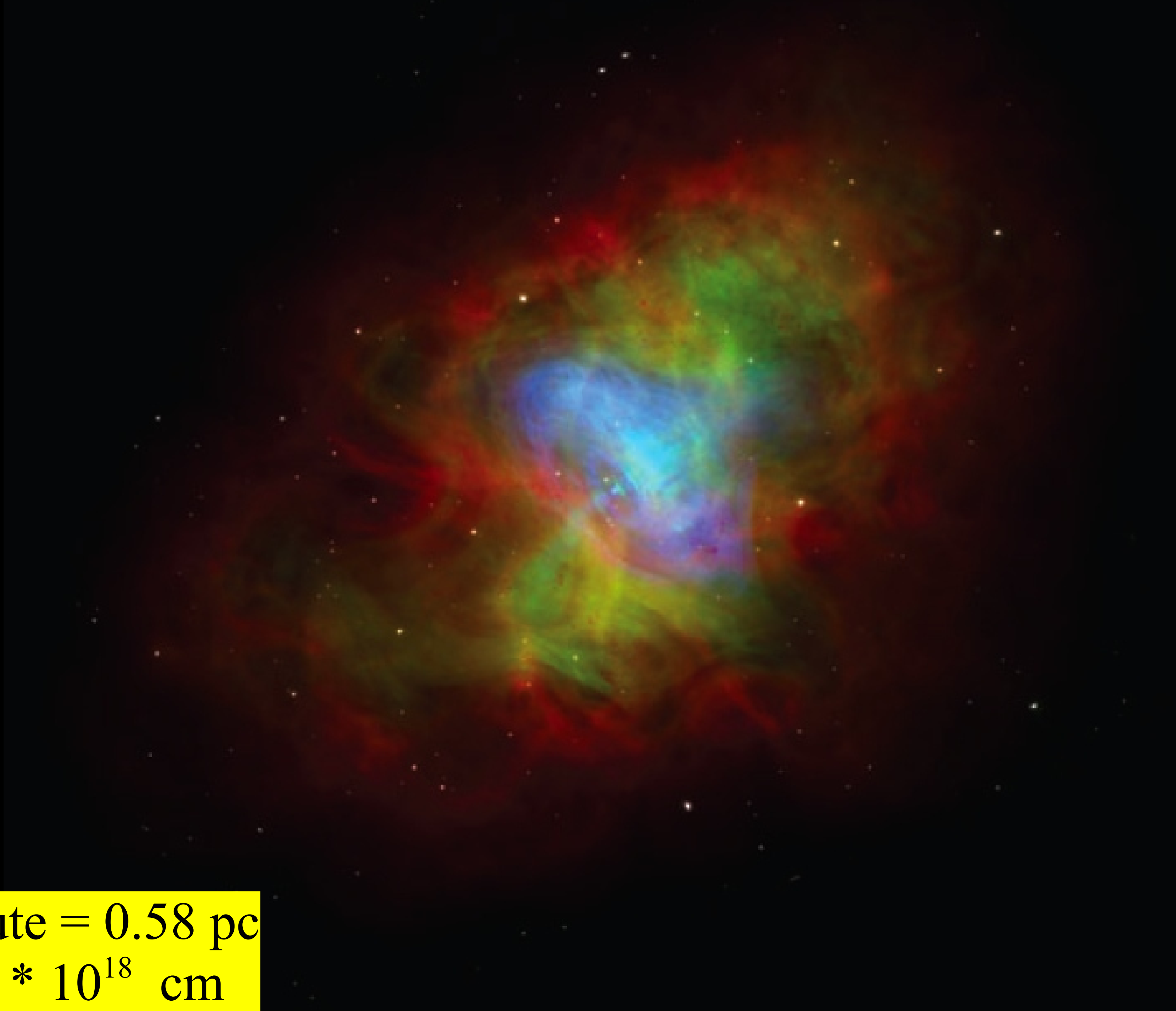
Fig. 4. Vela light curves at optical, X-ray, and γ-ray energies [58], binned to 0.01 of the pulsar phase. The main peaks P1, P2 and P3 are labeled in the top right panel. The bottom left panel shows the 8 – 16 keV *RXTE* light curve [59] along with the radio pulse profile (dashed lines). At lower right, the 4.1 – 6.5 eV *HST*/STIS NUV light curve [60] is shown.



VELA Energy Spectrum [characteristic shape For Pulsars]

$$N(E) \propto E^{-\Gamma_\gamma} \exp[-(E/E_c)^b]$$

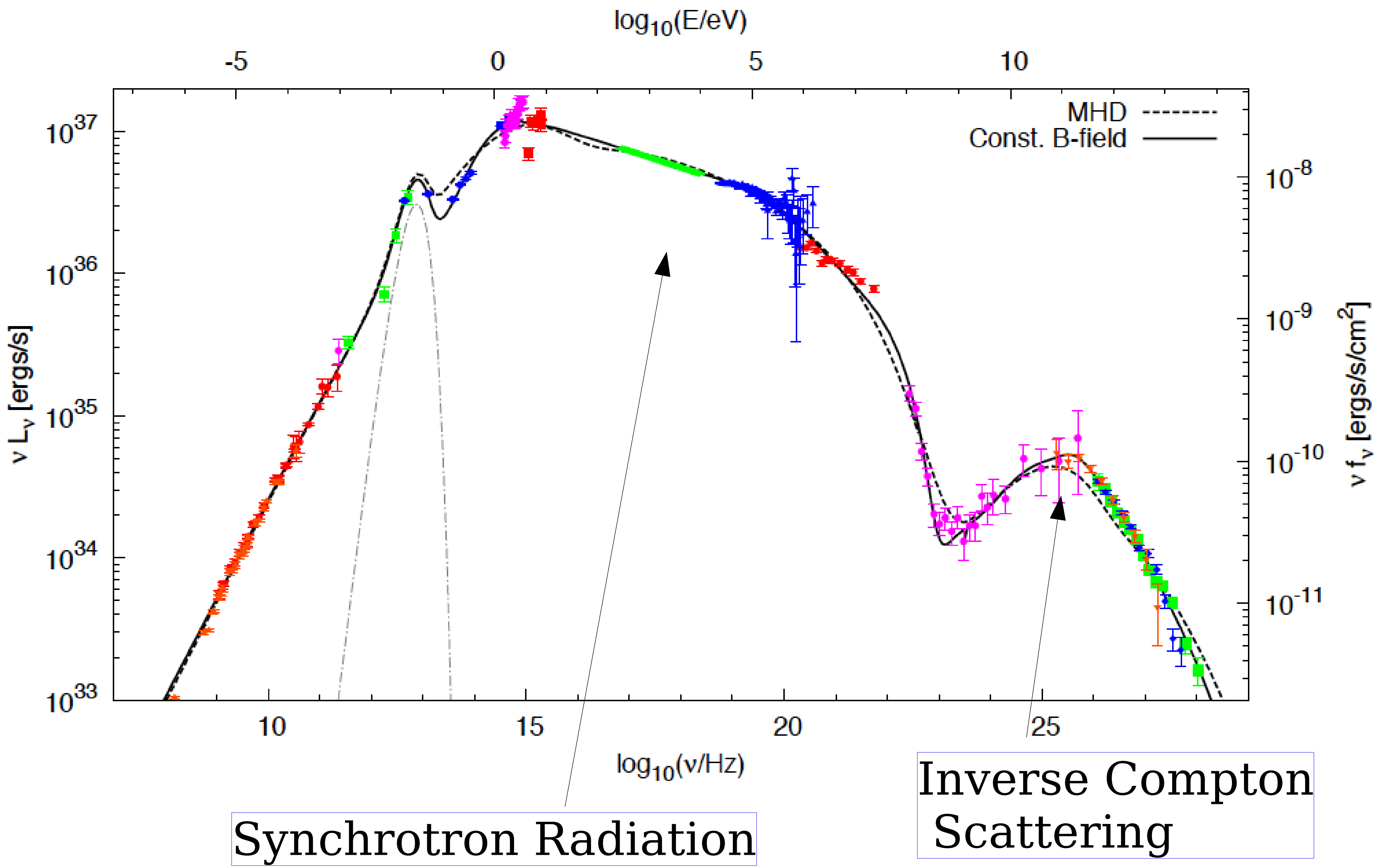
The CRAB Nebula



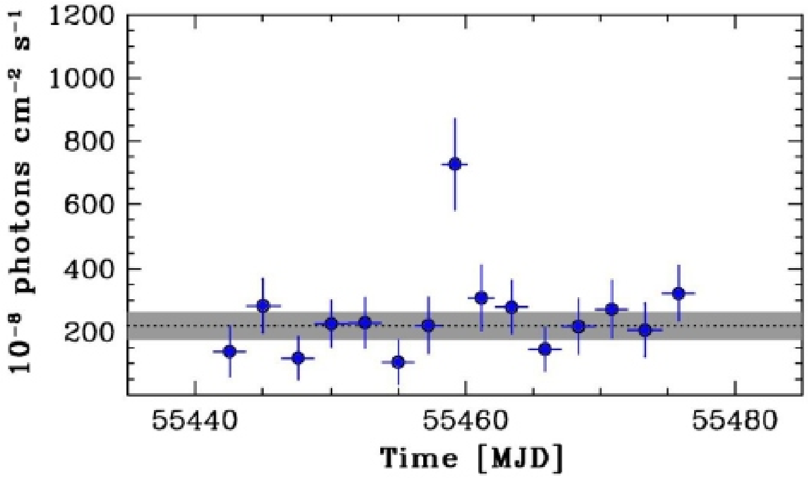
1 minute = 0.58 pc
= $1.8 * 10^{18}$ cm

CRAB Nebula Energy Spectrum

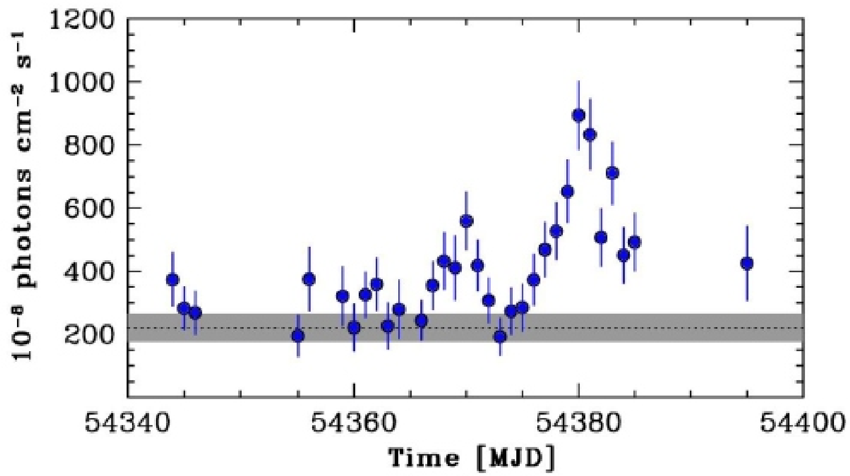
SSC (Self Synchrotron Coompton) model emission



AGILE discover of flaring of the CRAB

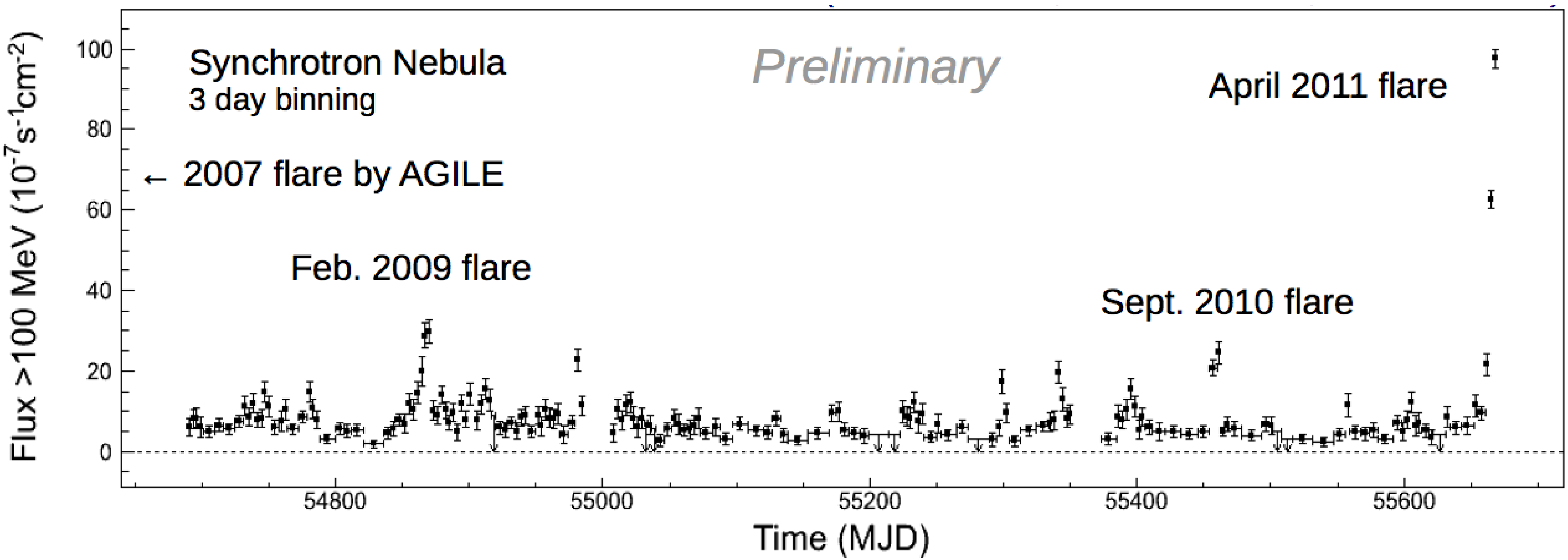


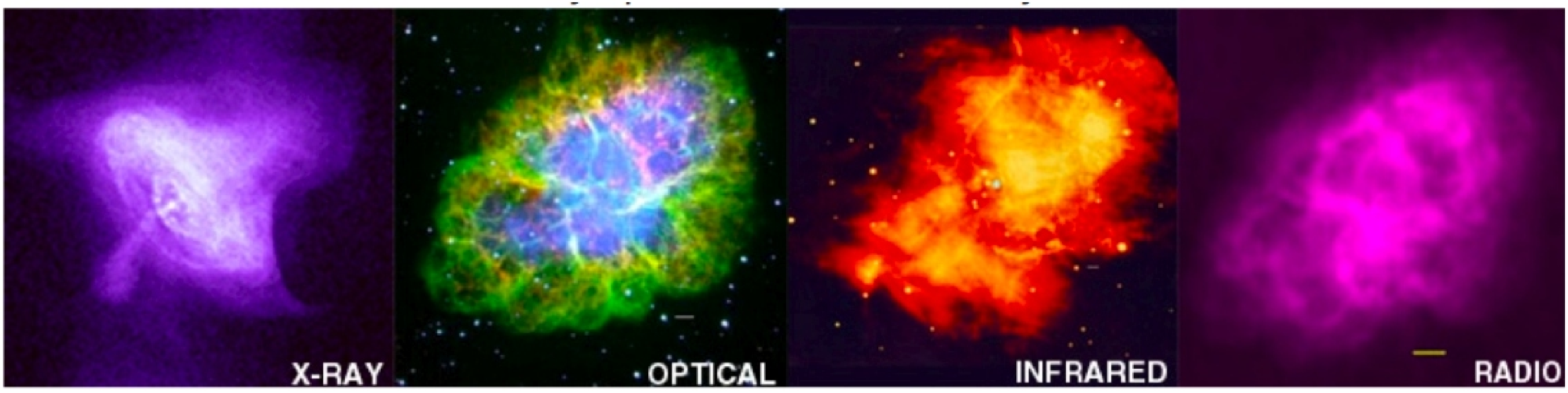
2sep – 8 oct 2010



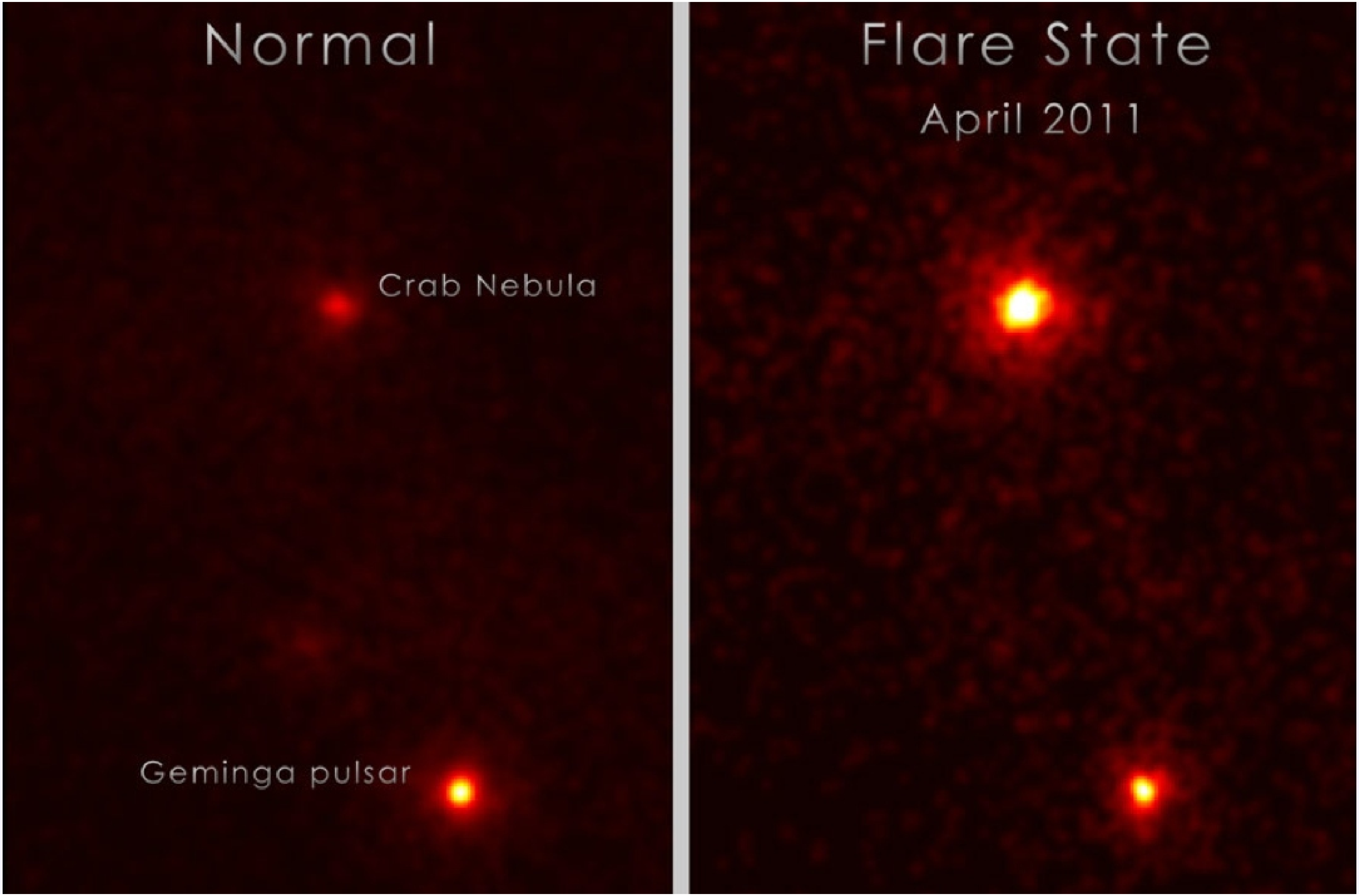
27sep – 12 oct 2007
[discovery “in the drawer”]

CRAB NEBULA Flaring [!]

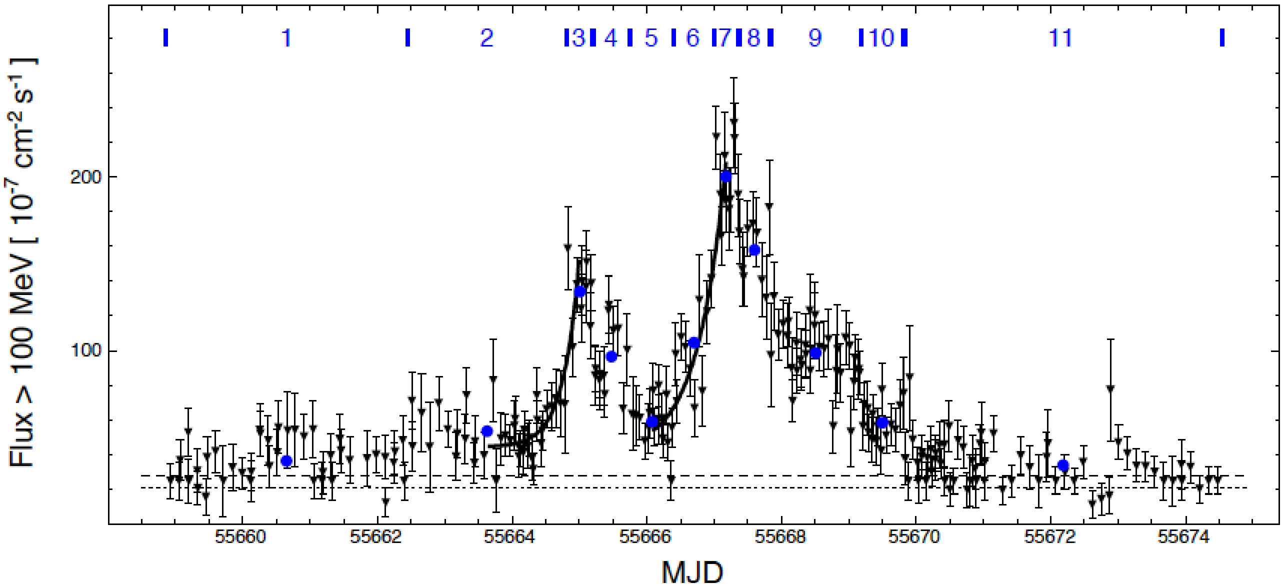




CRAB NEBULA Flaring [!]



April 2011 CRAB flare



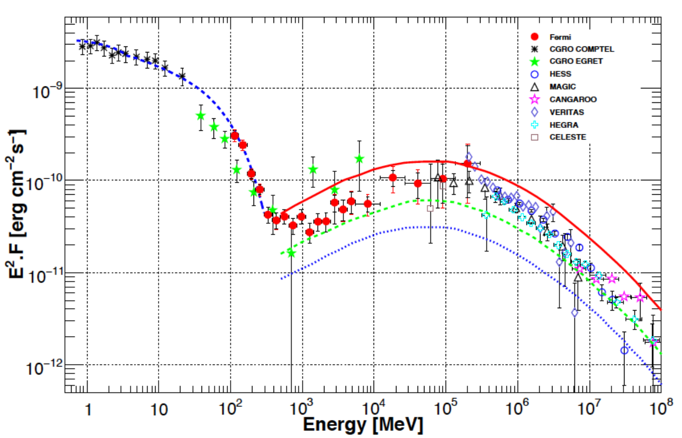
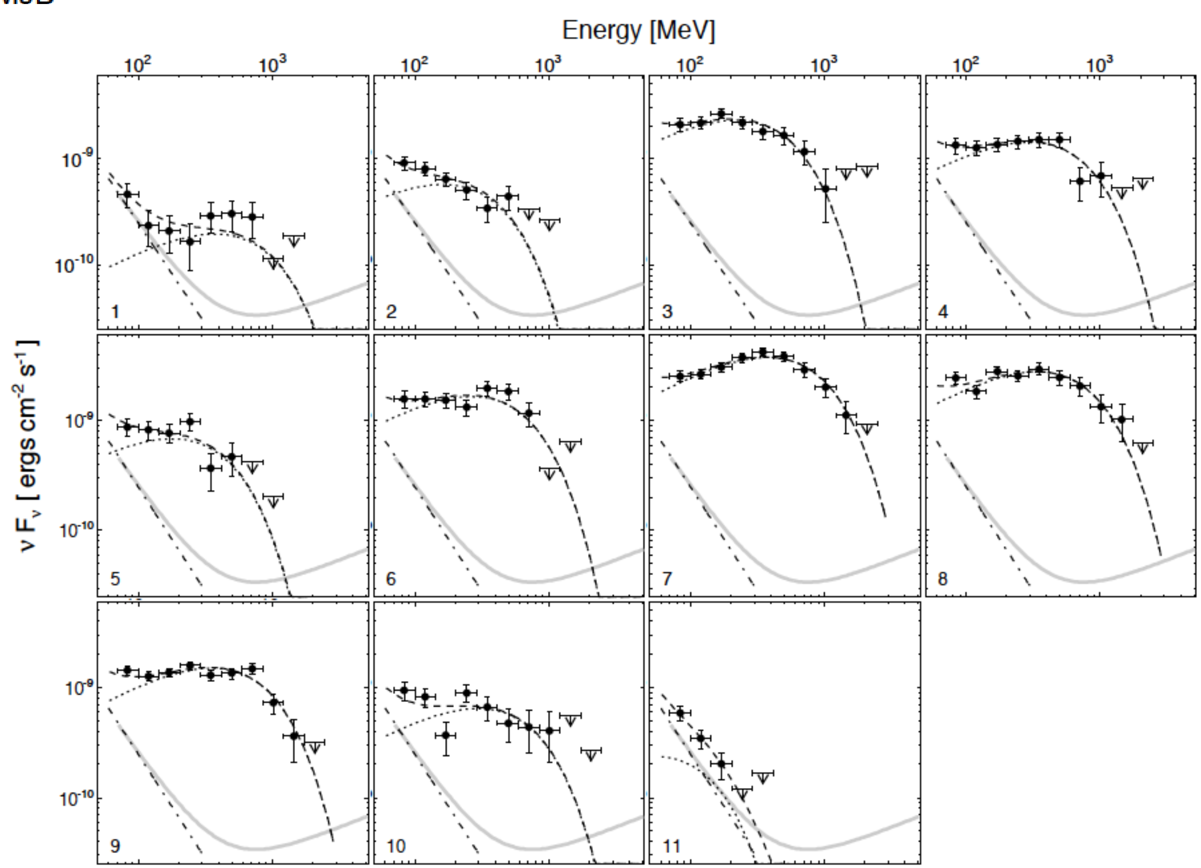


FIG. 9.— The spectral energy distribution of the Crab Nebula from soft to very high energy γ-rays. The fit of the synchrotron component, using COMPTEL and LAT data (blue dashed line), is overlaid. The predicted inverse Compton spectra from Atoyan and Aharonian (1996) are overlaid for three different values of the mean magnetic field: 100 μG (solid red line), 200 μG (dashed green line) and the canonical equipartition field of the Crab Nebula 300 μG (dotted blue line). References: CGRO COMPTEL and EGRET: Kuiper et al. (2001); MAGIC: Albert et al. (2008); HESS: Aharonian et al. (2006); CANGAROO: Tanimori et al. (1997); VERITAS: Celik (2007); **HEGRA: Aharonian et al. (2004); CELESTE: Smith et al. (2006)**



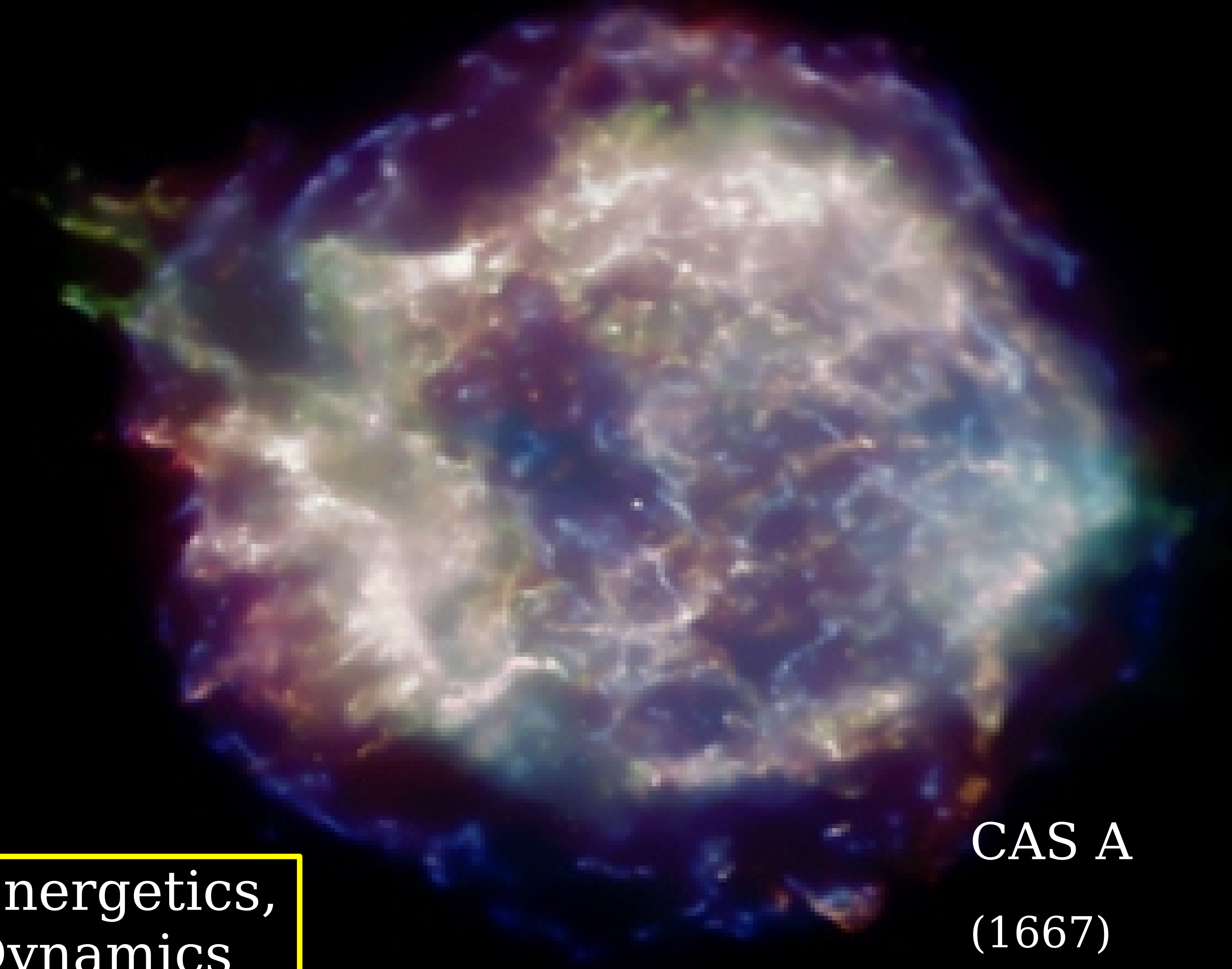
Identification of the Astrophysical Sources of COSMIC RAYS.

The "SNR paradigm"
for galactic Cosmic Rays

Debate about the acceleration sites of UHECR (Ultra High Energy Cosmic Rays).

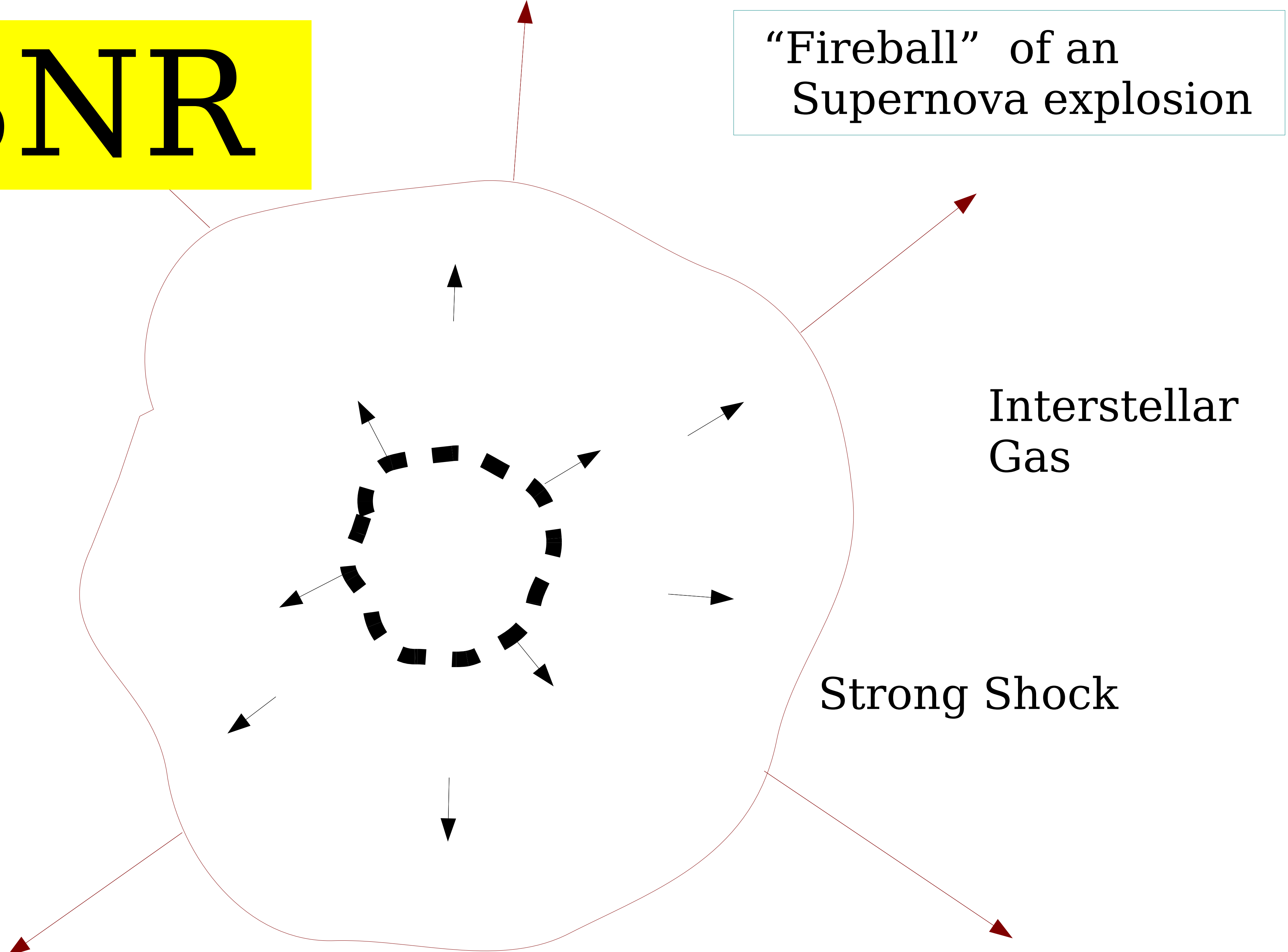
Candidate sites:
AGN's
GRB's

The SuperNova “Paradigm” for CR acceleration



Energetics,
Dynamics

SNR



Fermi 1st order acceleration

$$q(E) \propto E^{-(2+\varepsilon)}$$

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

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

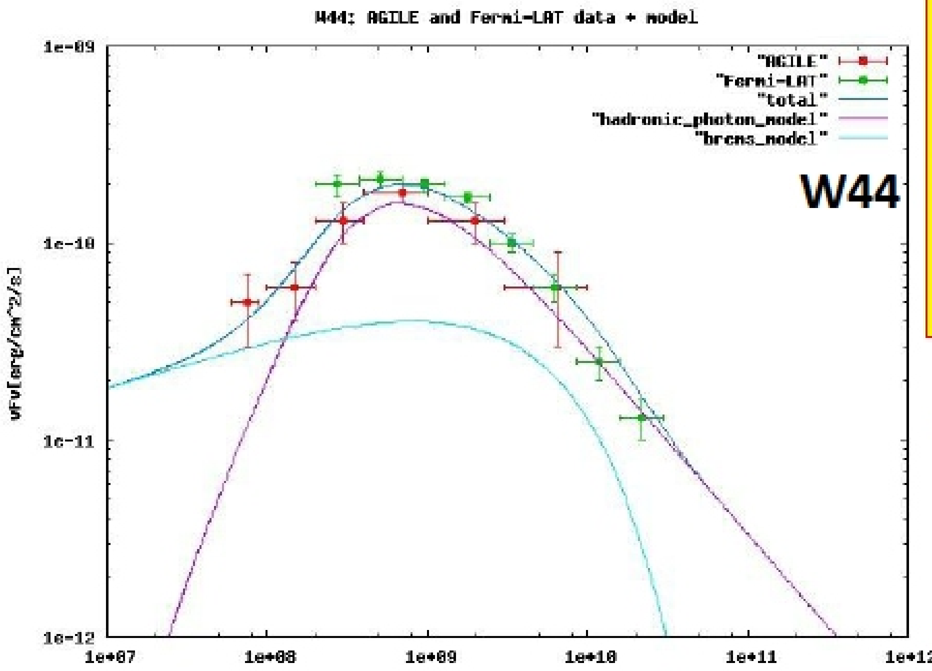
$$M = 5 \; M_{\odot}$$

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

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

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

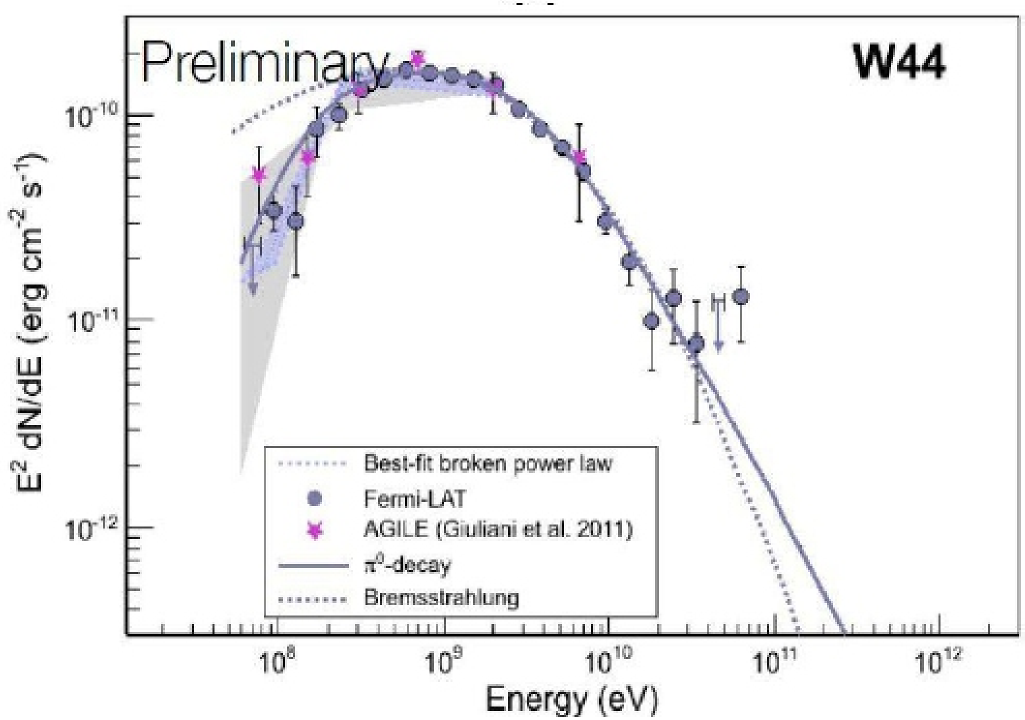
AGILE-GRID



PROOF OF HADRONIC COSMIC-RAY ACCELERATION IN THE SUPERNOVA REMNANT W44: THE π^o SPECTRUM

(Giuliani A., Cardillo M., et al., ApJ Letters, 742, L30, 2011)

***Fermi*-LAT**



(Funk S. et al., Science, in press 2012)

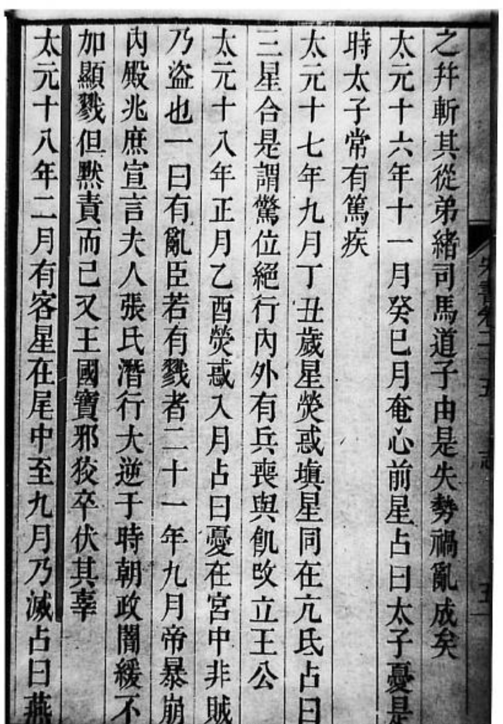
SuperNova 393A
RX J1713.7-3946

Observed in AD 393
By chinese court astromers
22-october, 19-november

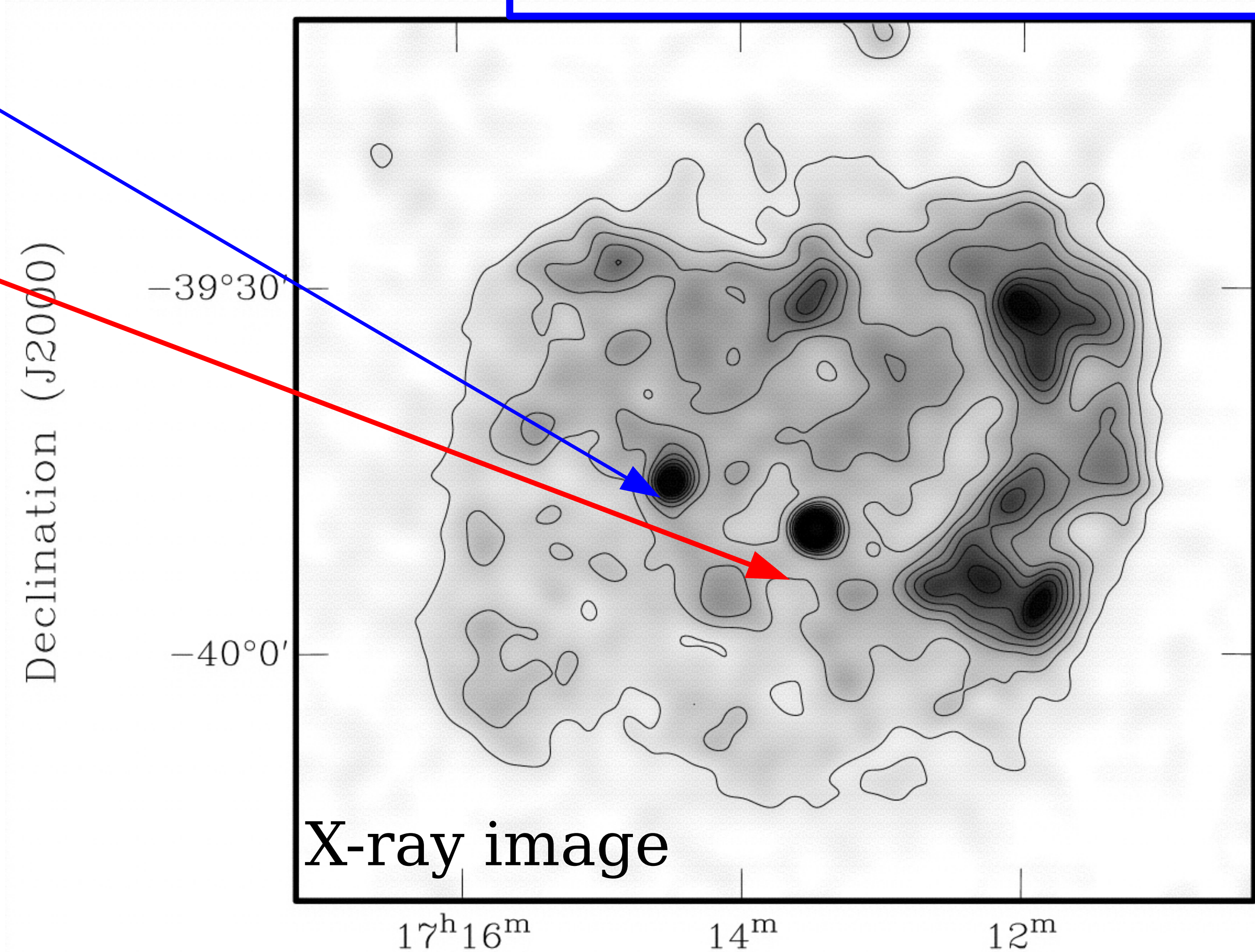
(Re)-discovered in 1996
by the Roentgen Satellite

Foreground star

Neutron Star



之幷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飢改立王公
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
加顯戮但默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

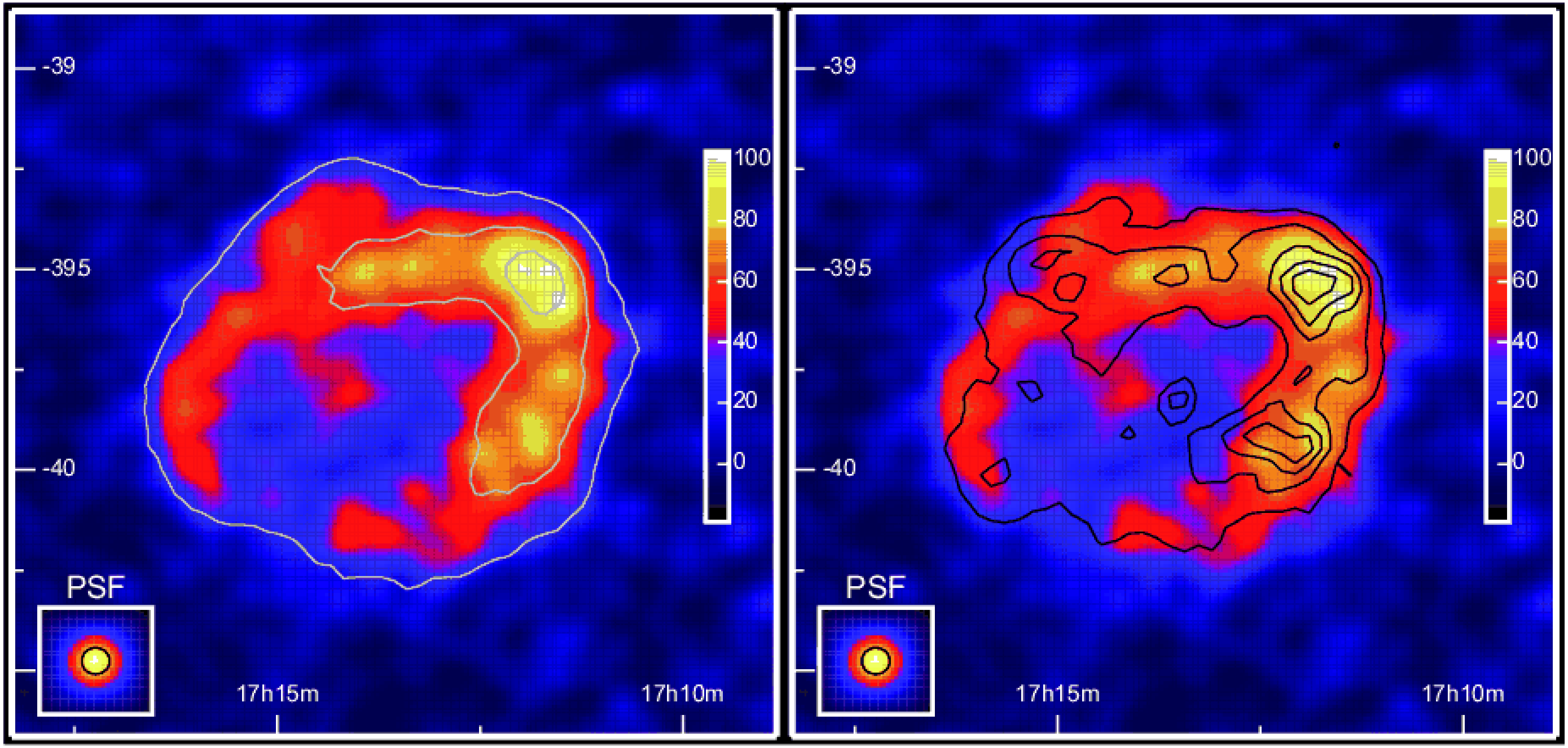


Detected in 2004 by HESS in TeV gamma rays

HESS Telescope

Observations with TeV photons

SuperNova RX J1713.7-3946

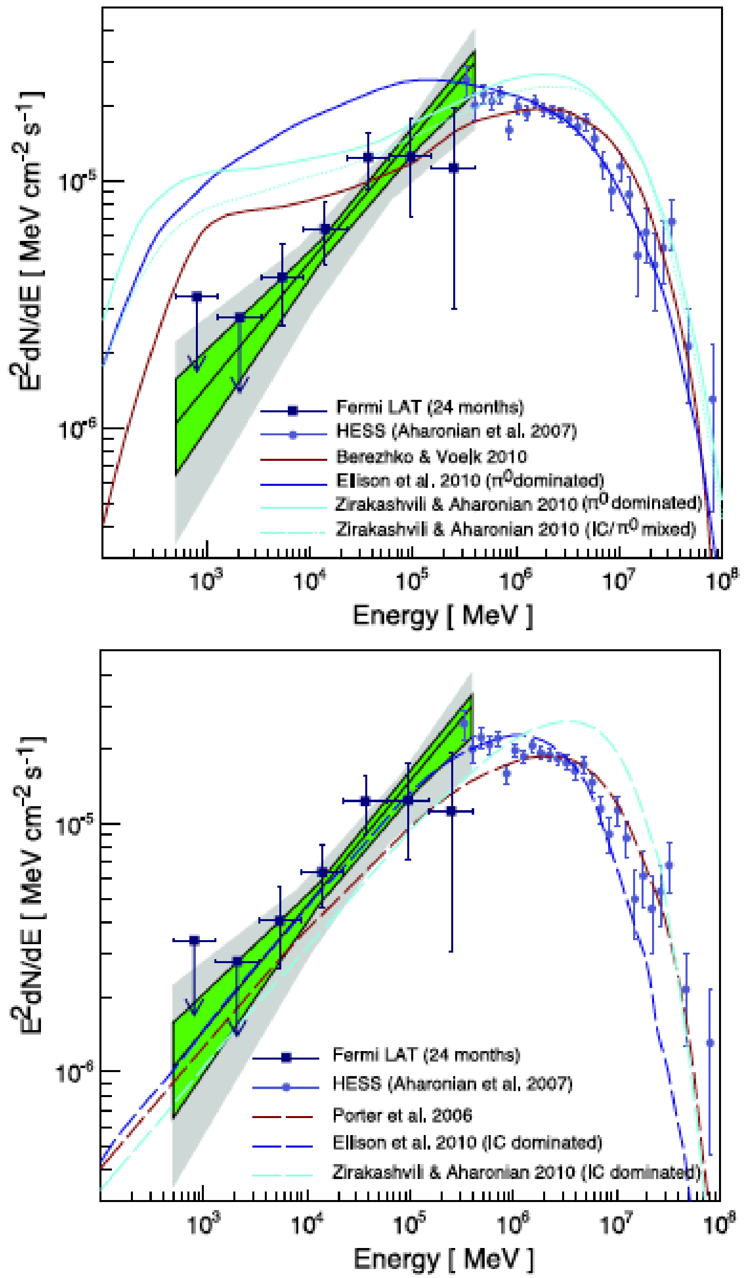


Comparison with ROSAT observation

Observations of the young Supernova remnant RX J1713.7−3946 with the *Fermi* Large Area Telescope

astro-ph/1103.5727.
29th march 2011

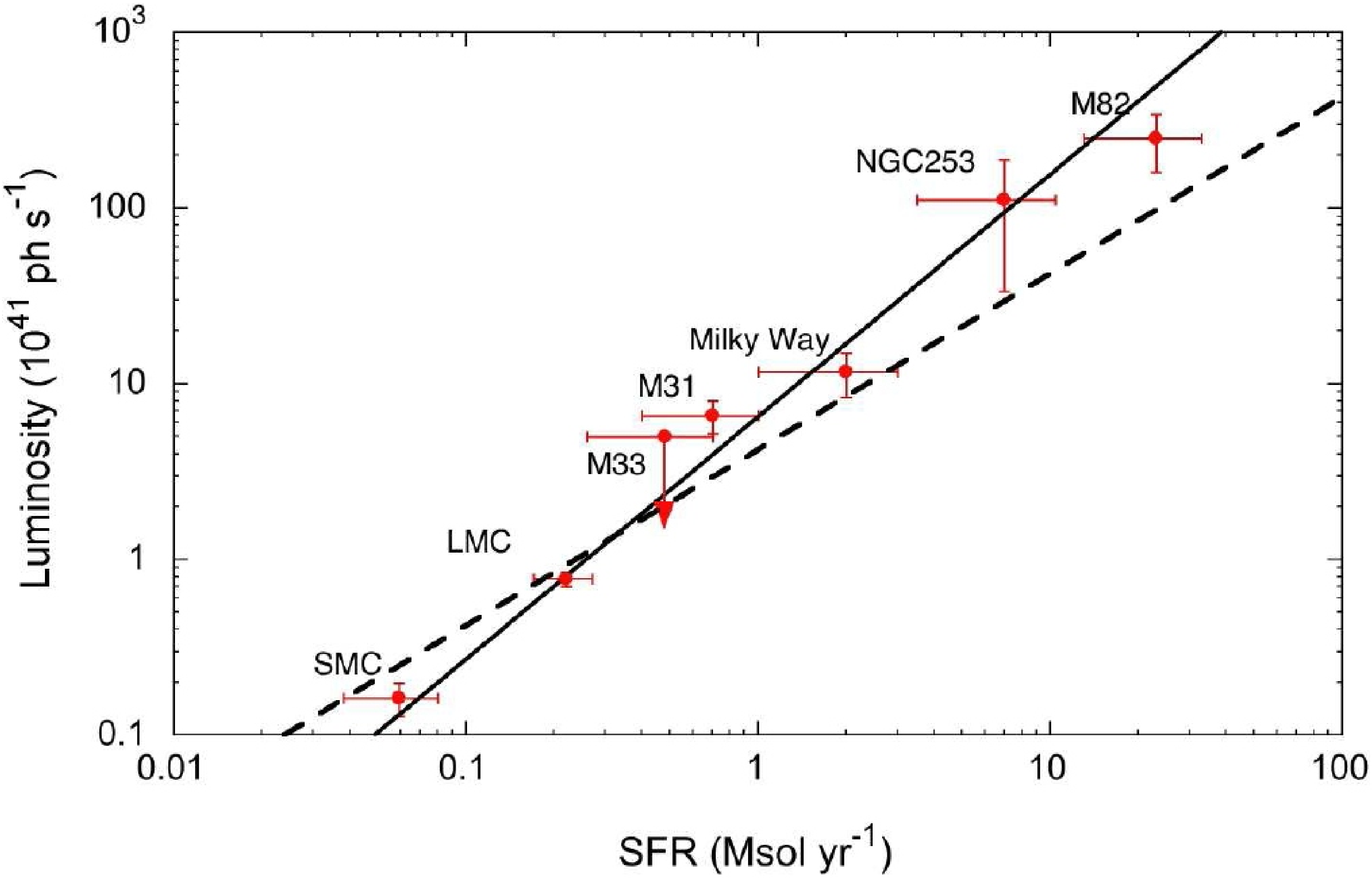
Favors
leptonic interpretation.



From FERMI:

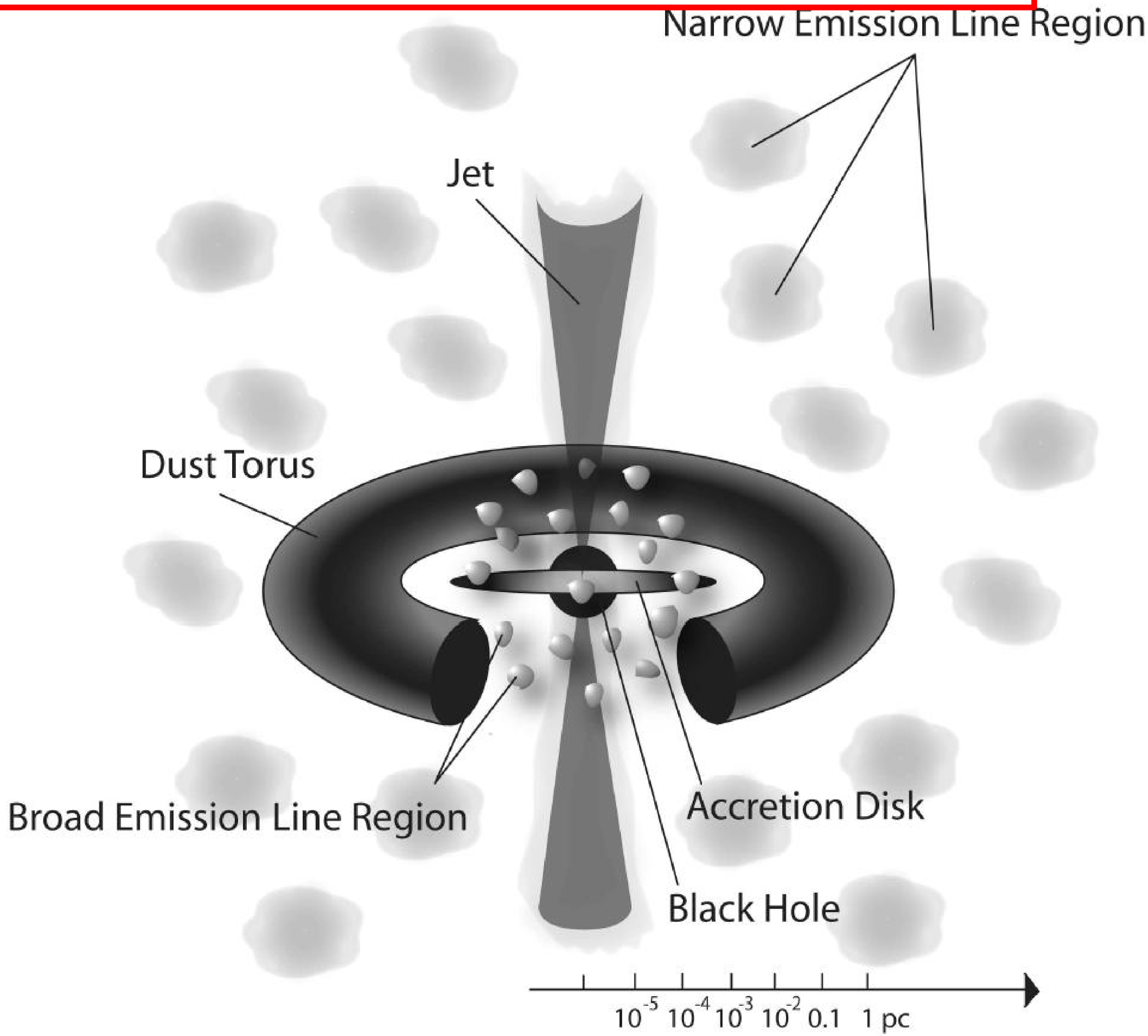
Table 1. Properties and gamma-ray characteristics of Local Group and nearby starburst galaxies (see text).

Galaxy	d kpc	M_{HI} 10^8 $M_\odot$	M_{H_2} 10^8 $M_\odot$	SFR $M_\odot$ yr^{-1}	F_γ 10^{-8} ph cm^{-2} s^{-1}	L_γ 10^{41} ph s^{-1}	$\bar{q}_\gamma$ 10^{-25} ph s^{-1} H-atom^{-1}
MW	...	35 ± 4[7]	14 ± 2[7]	1 – 3[19]	...	11.8 ± 3.4[28]	2.0 ± 0.6
M31	780 ± 33[1]	73 ± 22[8]	3.6 ± 1.8[14]	0.35 – 1[19]	0.9 ± 0.2	6.6 ± 1.4	0.7 ± 0.3
M33	847 ± 60[2]	19 ± 8[9]	3.3 ± 0.4[9]	0.26 – 0.7[20]	< 0.5	< 5.0	< 2.9
LMC	50 ± 2[3]	4.8 ± 0.2[10]	0.5 ± 0.1[15]	0.20 – 0.25[21]	26.3 ± 2.0[25]	0.78 ± 0.08	1.2 ± 0.1
SMC	61 ± 3[4]	4.2 ± 0.4[11]	0.25 ± 0.15[16]	0.04 – 0.08[22]	3.7 ± 0.7[26]	0.16 ± 0.04	0.31 ± 0.07
M82	3630 ± 340[5]	8.8 ± 2.9[12]	5 ± 4[17]	13 – 33[23]	1.6 ± 0.5[27]	252 ± 91	158 ± 75
NGC253	3940 ± 370[6]	64 ± 14[13]	40 ± 8[18]	3.5 – 10.4[24]	0.6 ± 0.4[27]	112 ± 78	9 ± 6



Luminosity (E >100 MeV) versus star formation rate (SFR).
Dashed line: Linear relation
Solid line : Power law best fit

ACTIVE GALACTIC NUCLEI



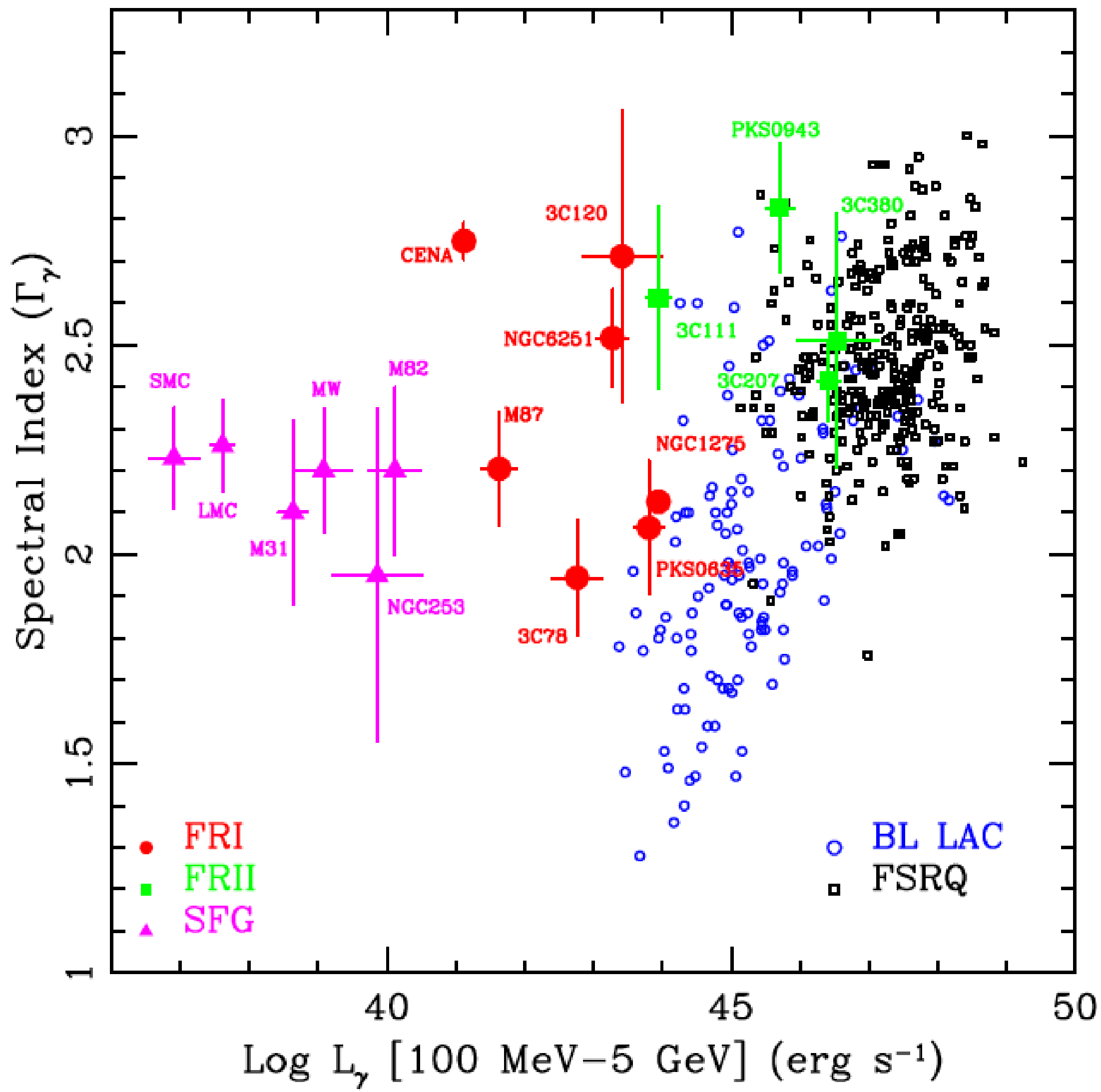
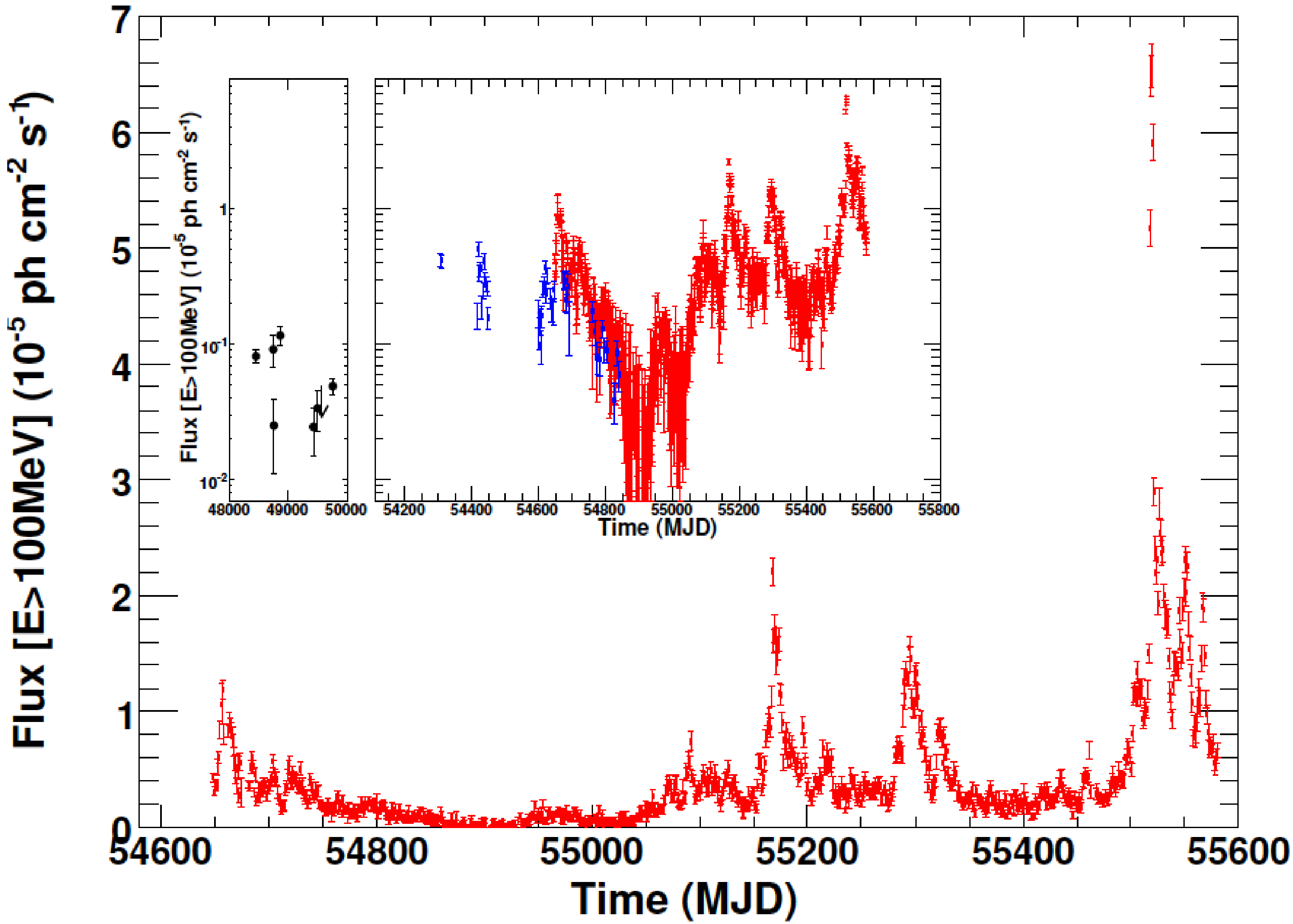
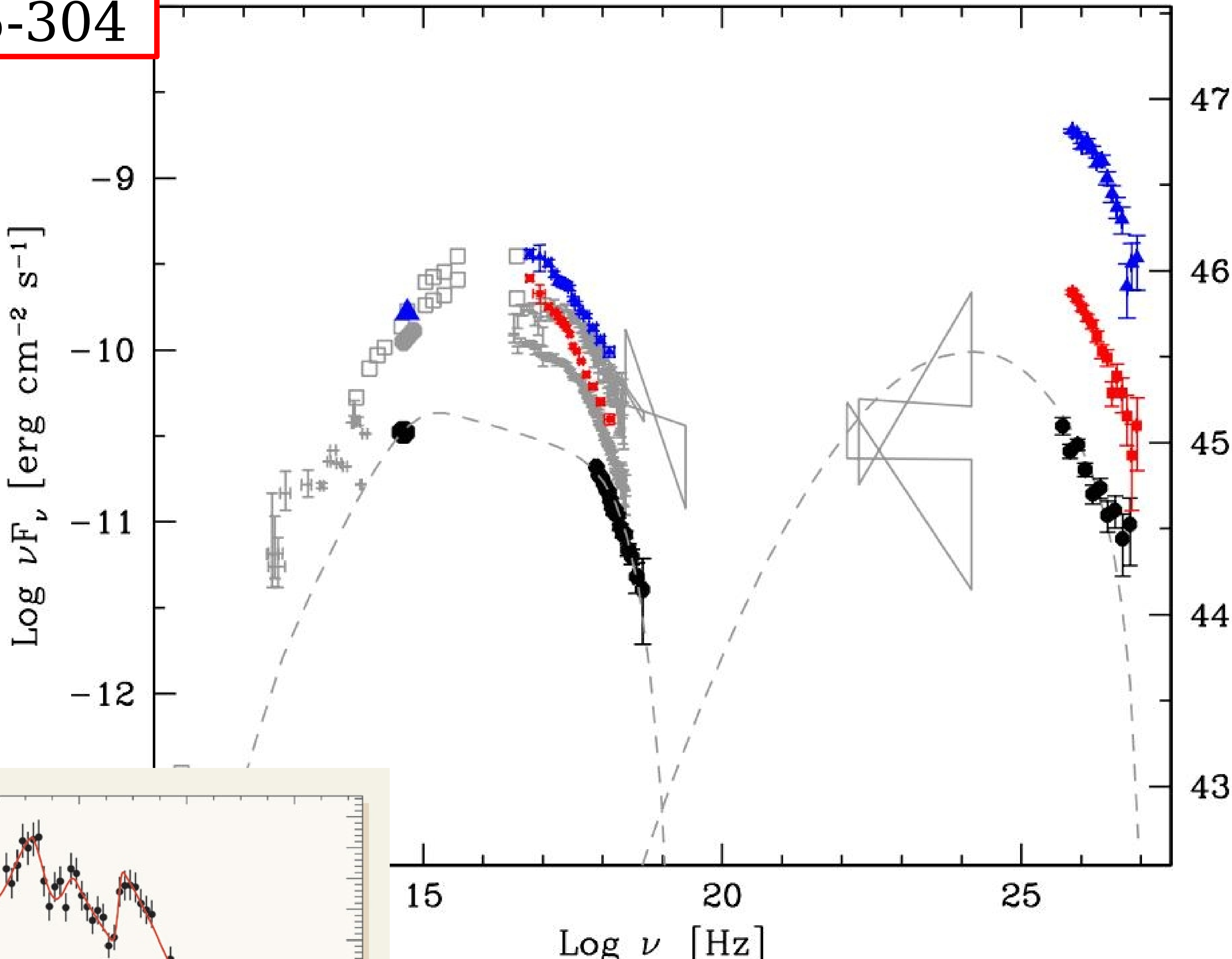


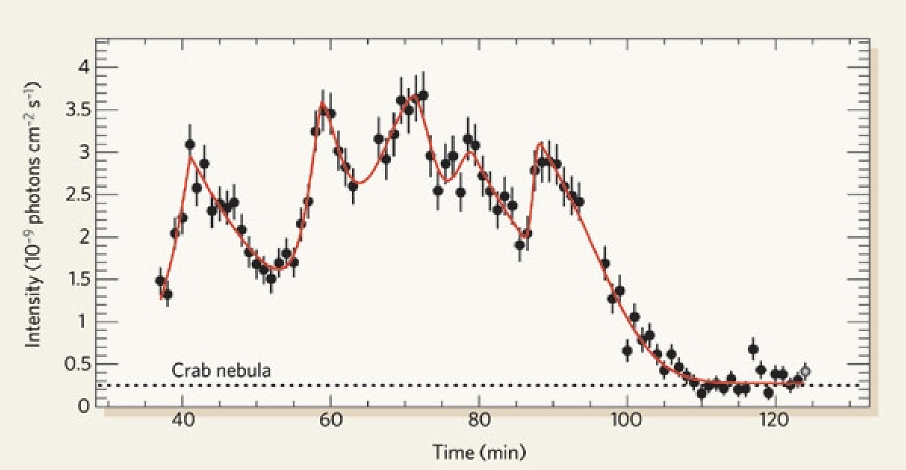
Fig. 7. Gamma-ray spectral slope Γ_γ of BL Lac objects (open blue circles), FSRQs (open black squares), FR1 radio galaxies (red circles), FR2 radio sources (green squares), and star-forming galaxies (magenta diamonds), are plotted as a function of their 100 MeV - 5 GeV γ-ray luminosity L_γ.

Mk 501 $L_{iso} \approx 10^{50}$ erg s^{-1}



PKS 2155-304

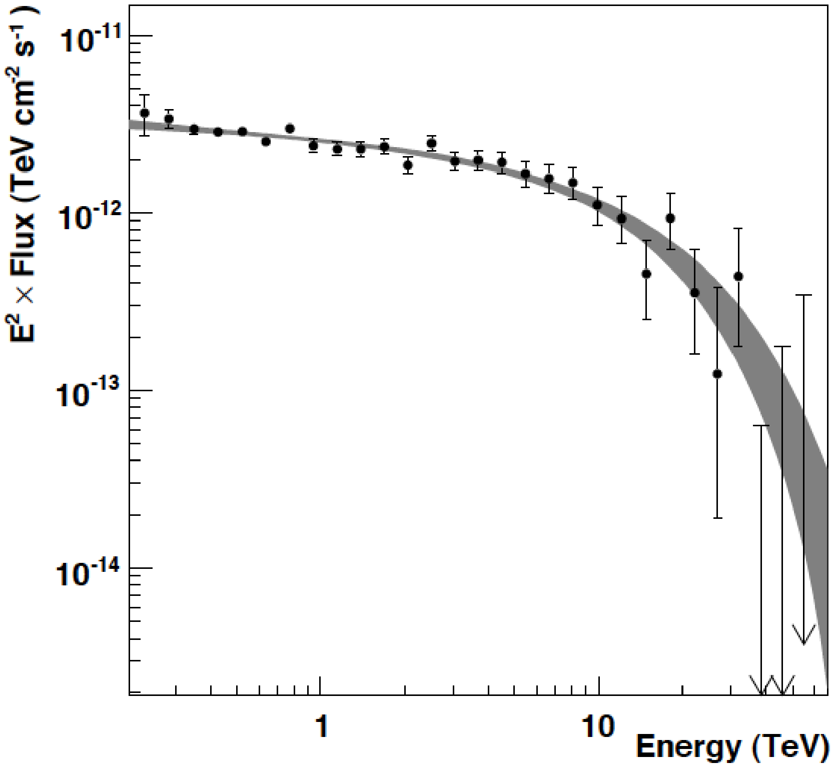


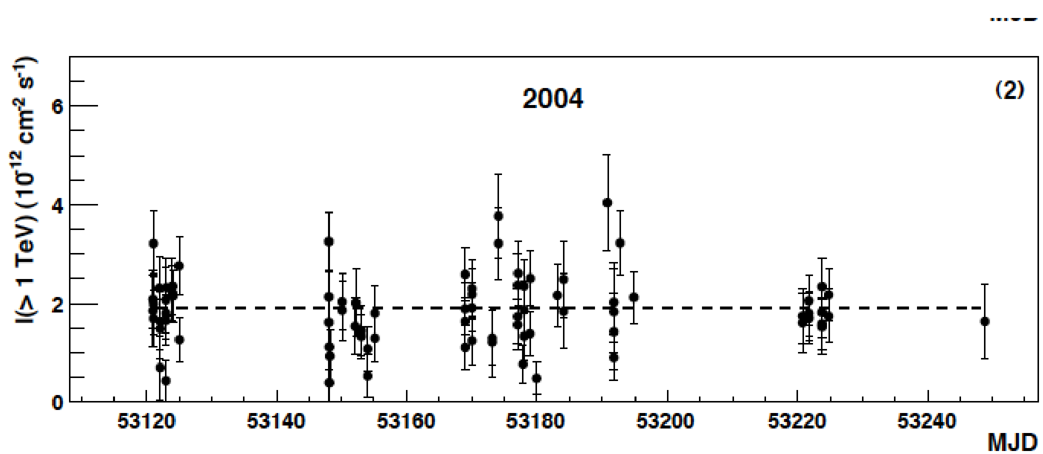


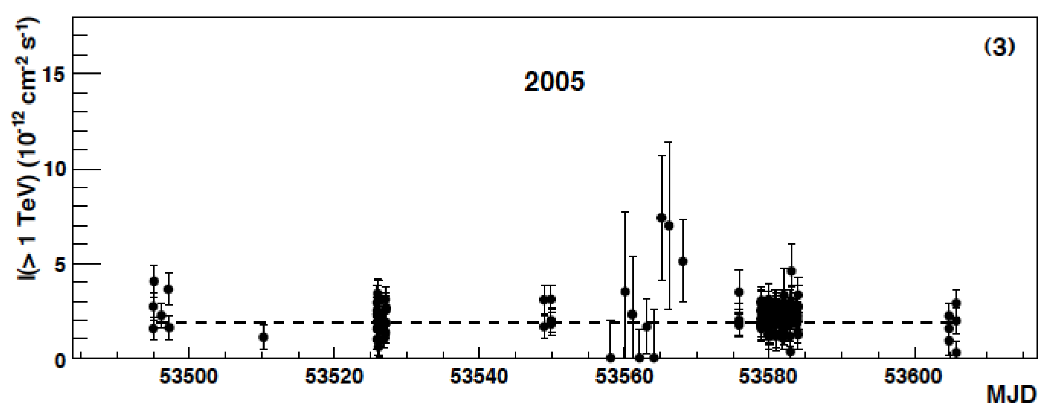
(Very rapid time variations)

Galactic Center

HESS observations of Galactic Center Sgr A*

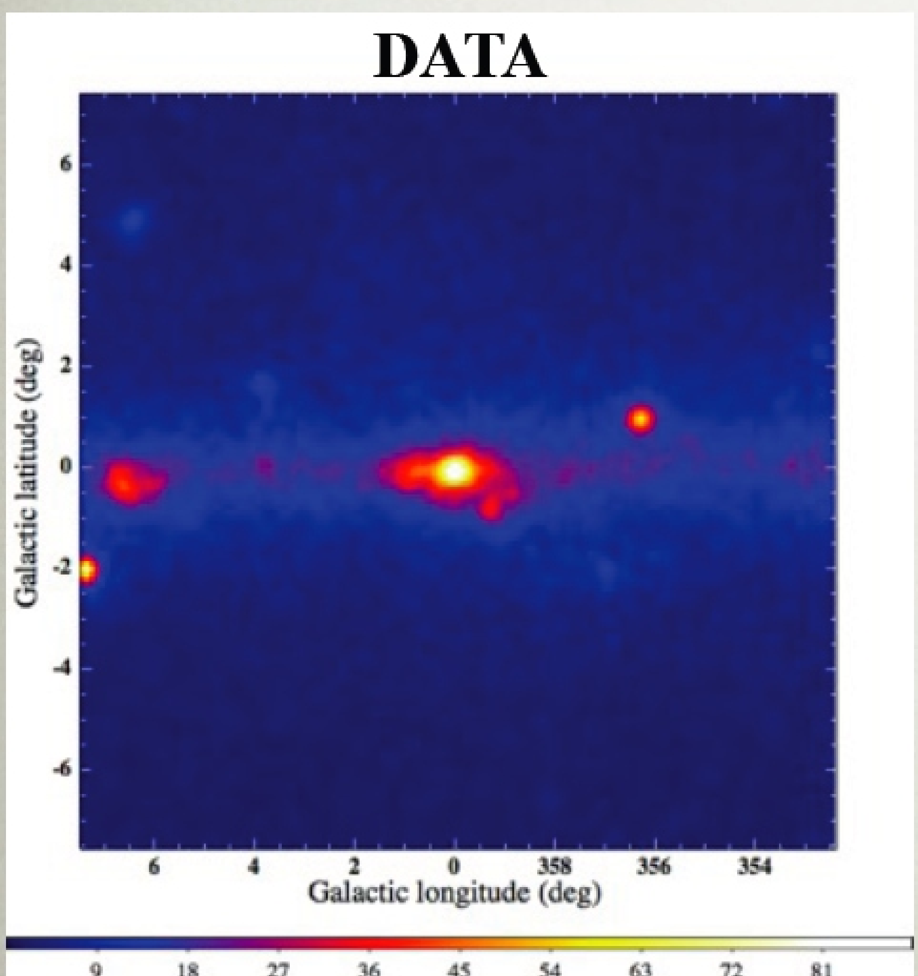


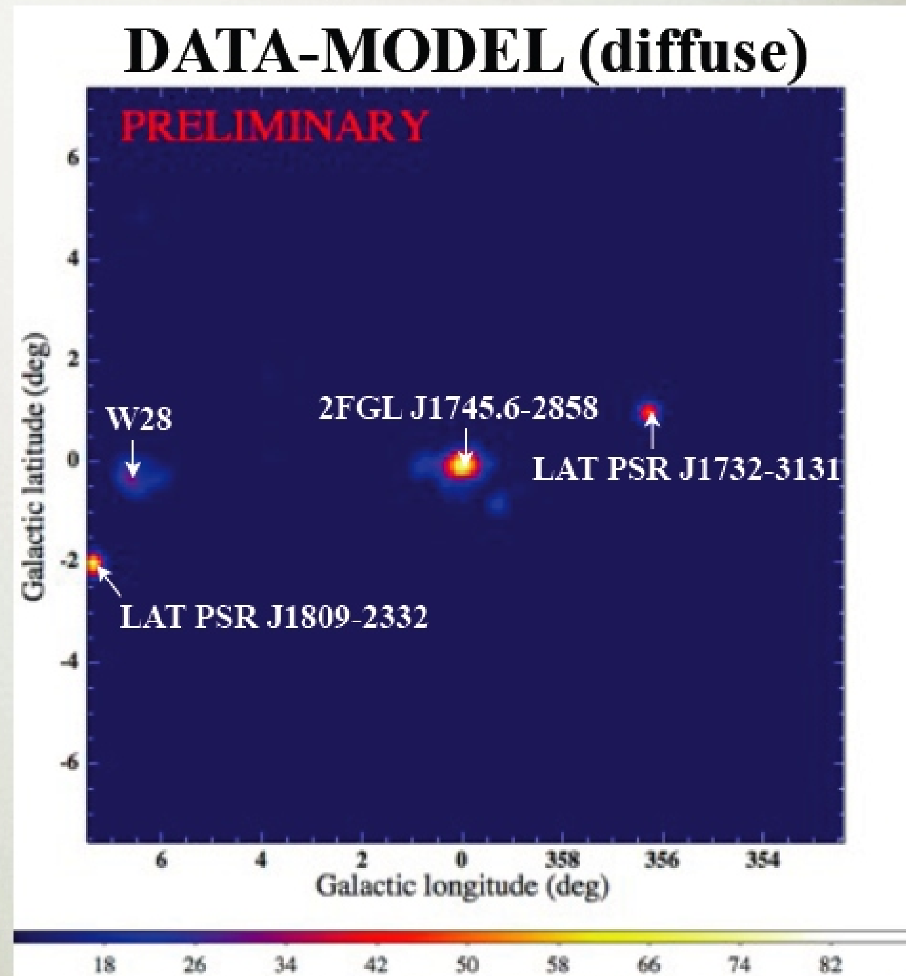




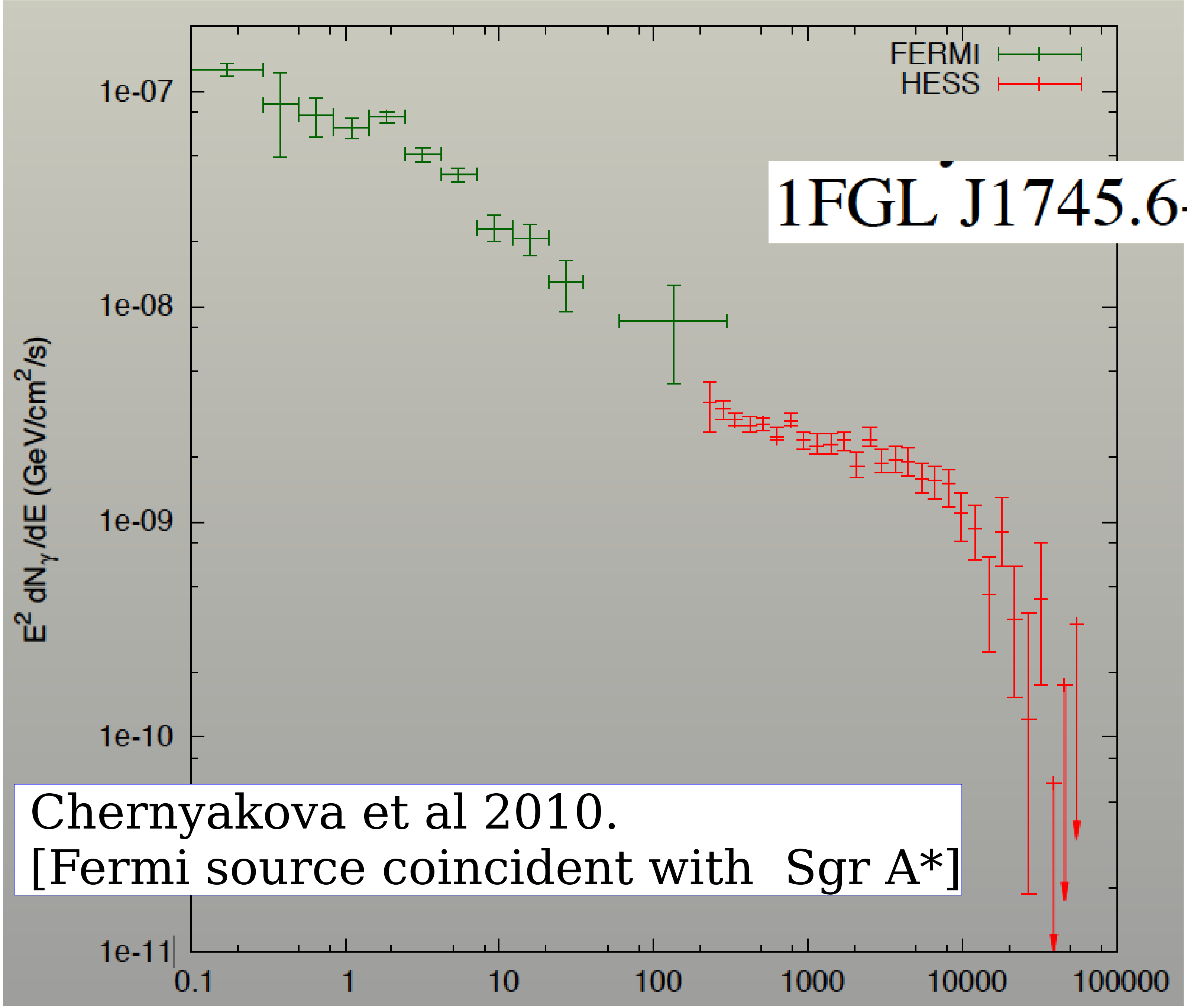
Fermi's View of the Inner Galaxy (15°x15° region)

Fermi LAT preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT):



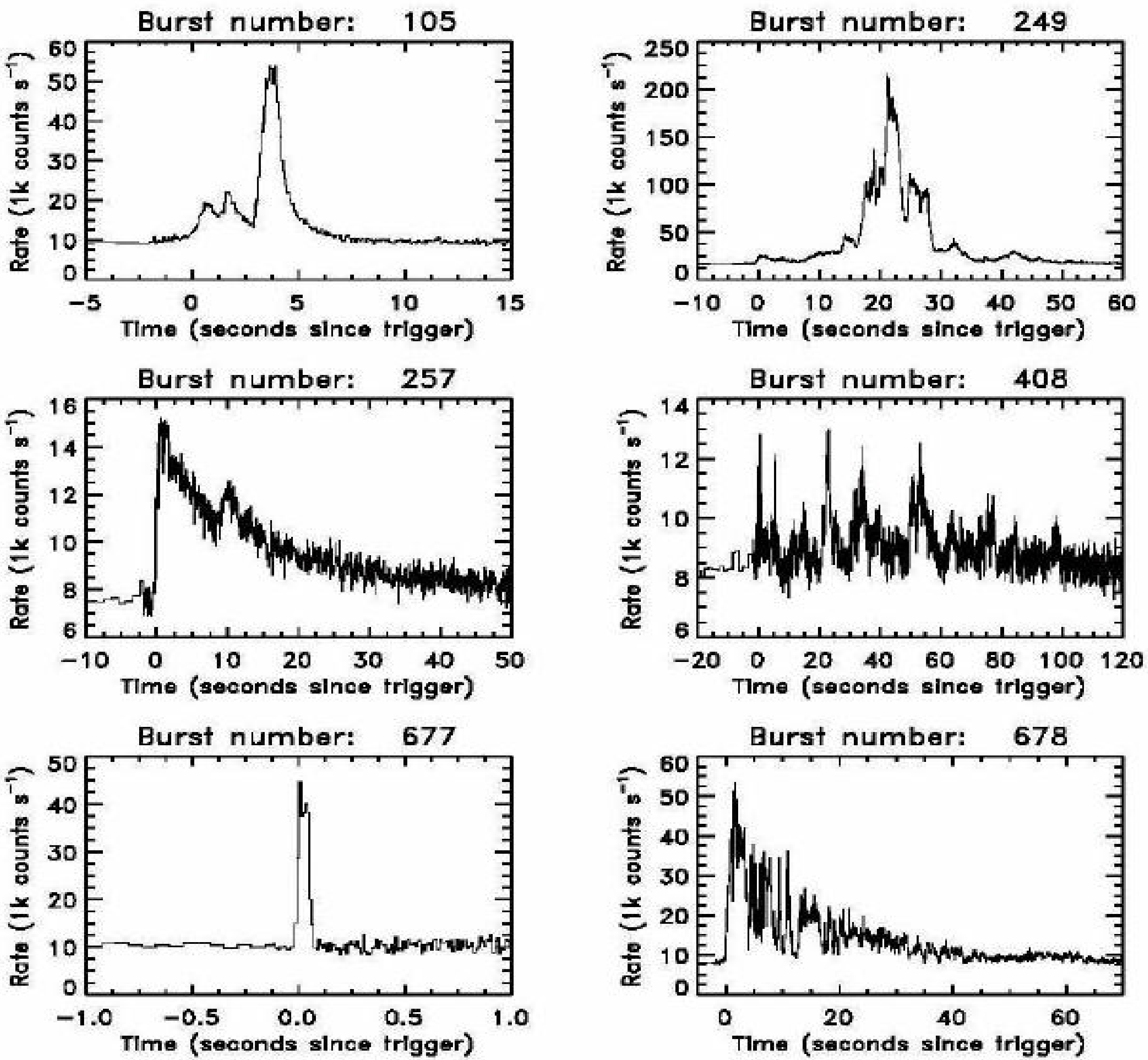


1FGL J1745.6-2900

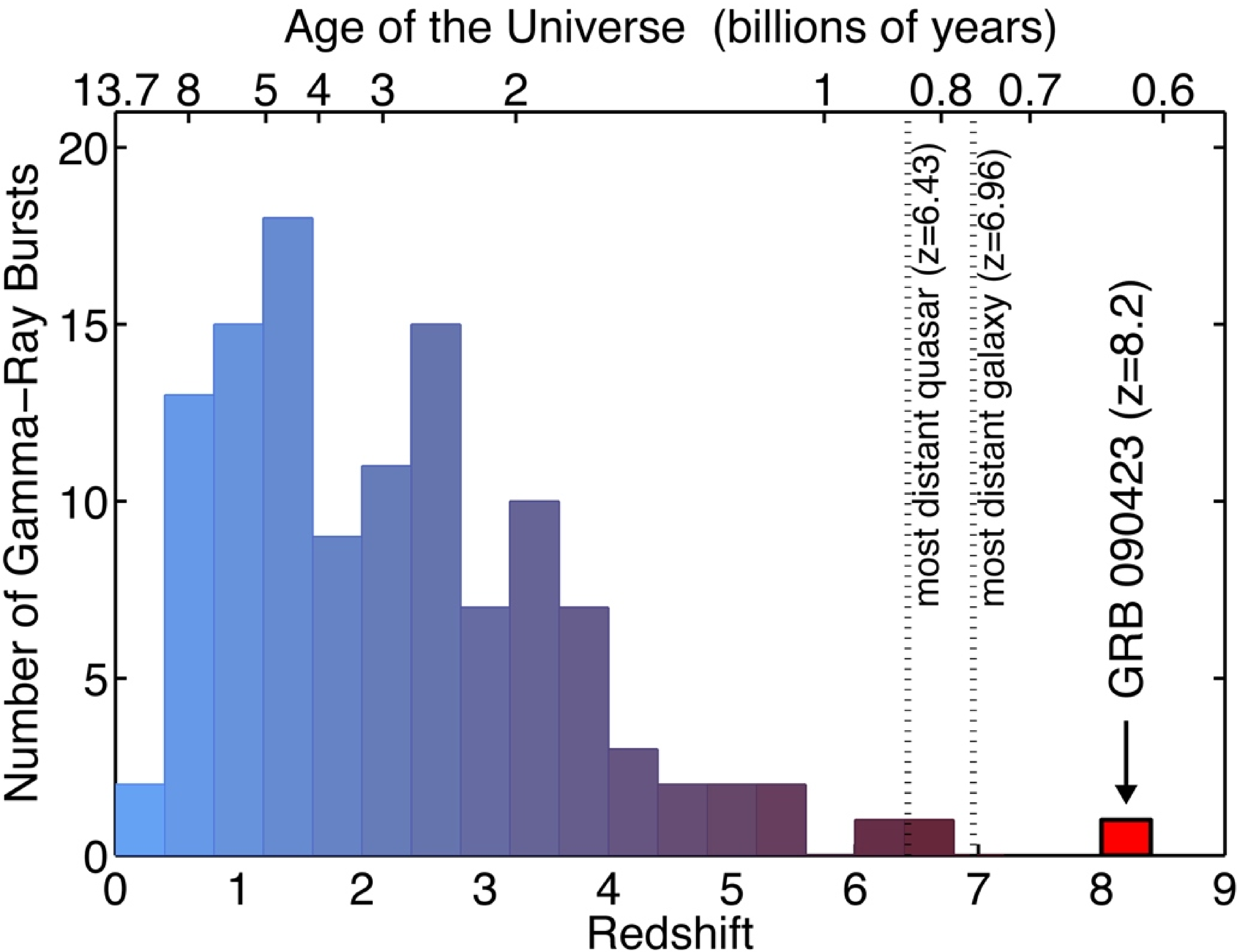


Chernyakova et al 2010.
[Fermi source coincident with Sgr A*]

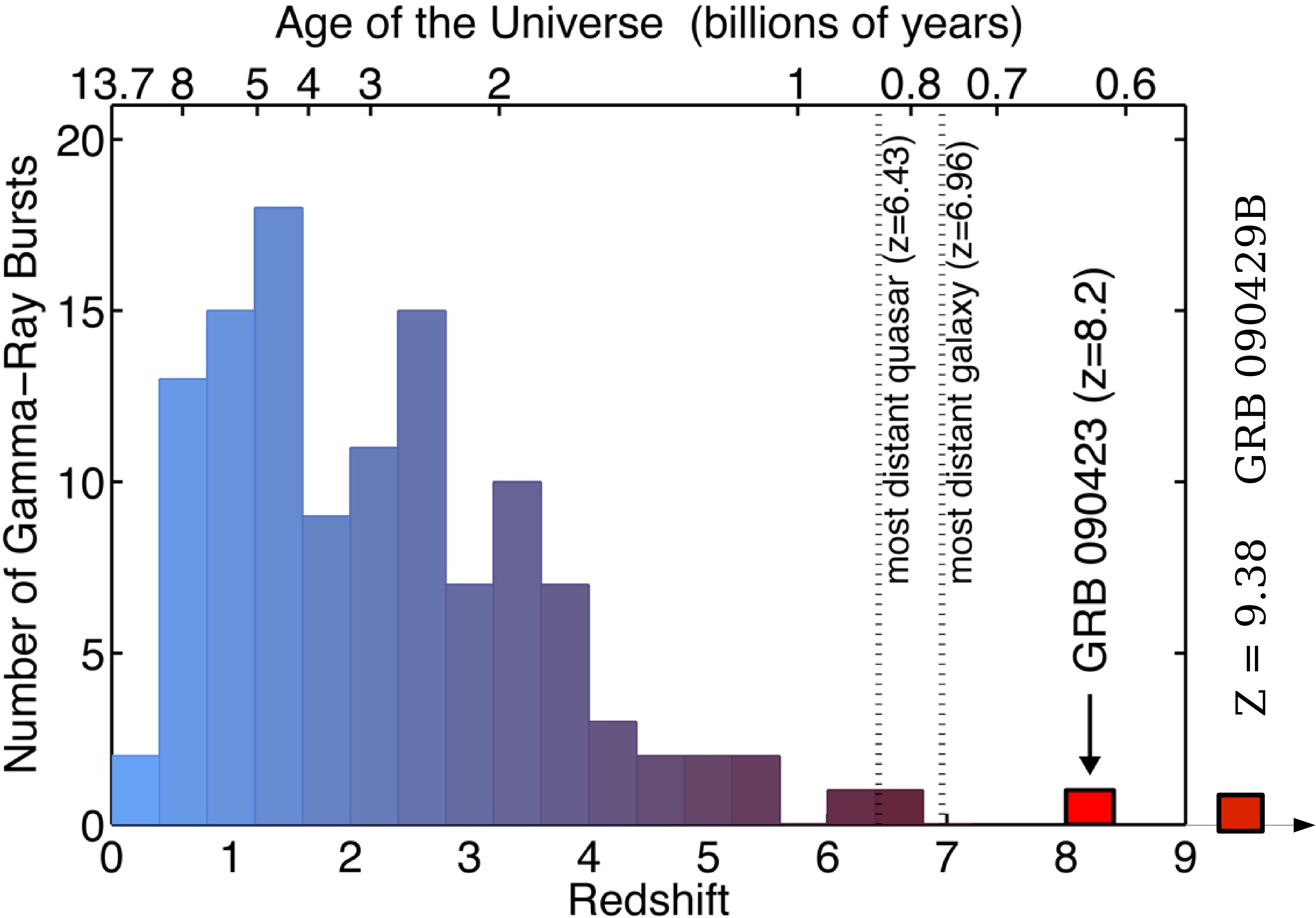
GAMMA RAY BURSTS (GRB's)



Proposed source
Of the CR



Age of the Universe (billions of years)
13.7
8
5
4
3
2
1
0.8
0.7
0.6
Number of Gamma-Ray Bursts
20
15
10
5
0
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
0
1
2
3
4
5
6
7
8
9
Redshift



Age of the Universe (billions of years)
13.7
8
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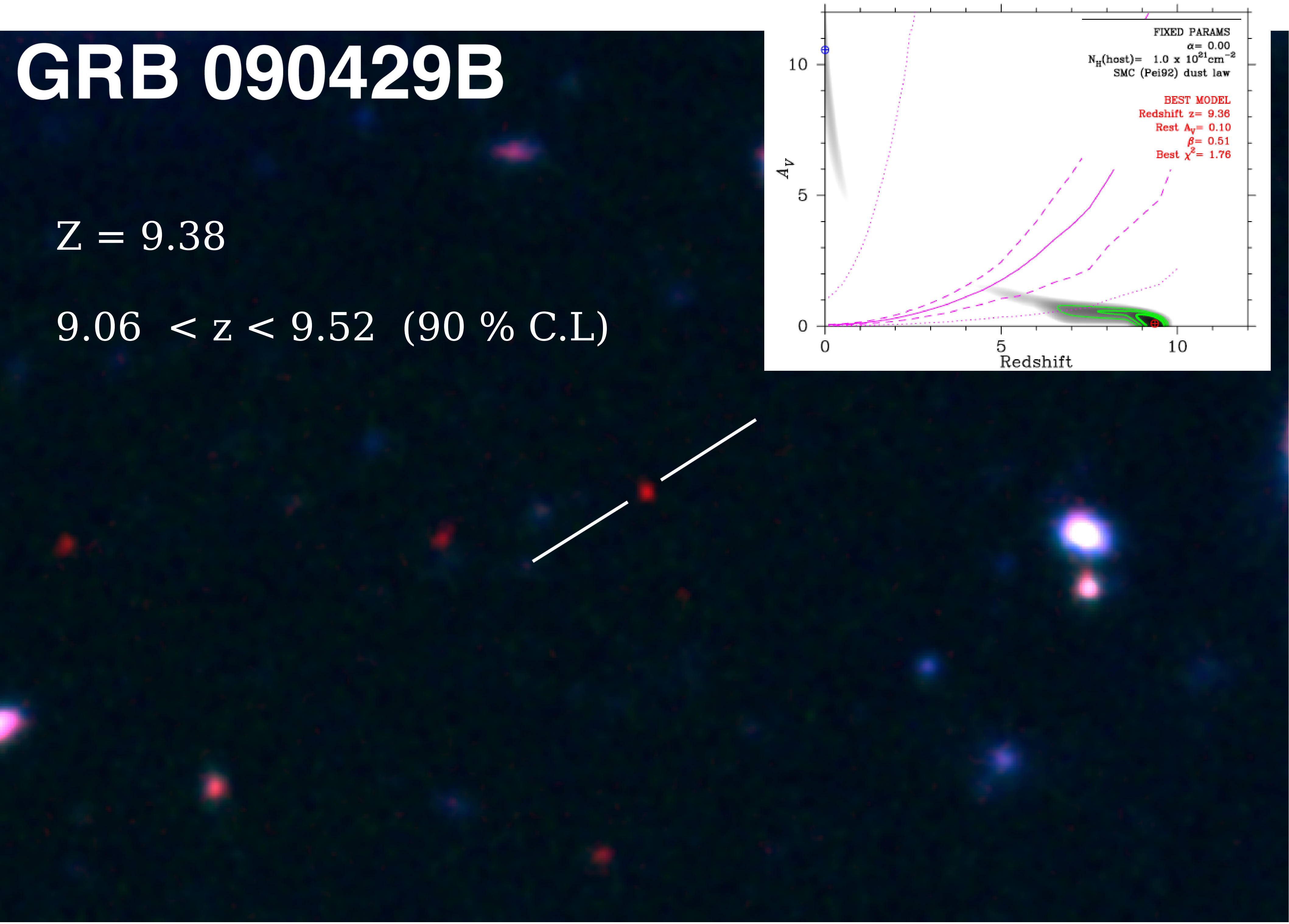
0.8
0.7
0.6
Number of Gamma–Ray Bursts
20
15
10
5
0
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
Z = 9.38 GRB 090429B
0
1
2
3
4
5
6
7
8
9
Redshift

GRB 090429B

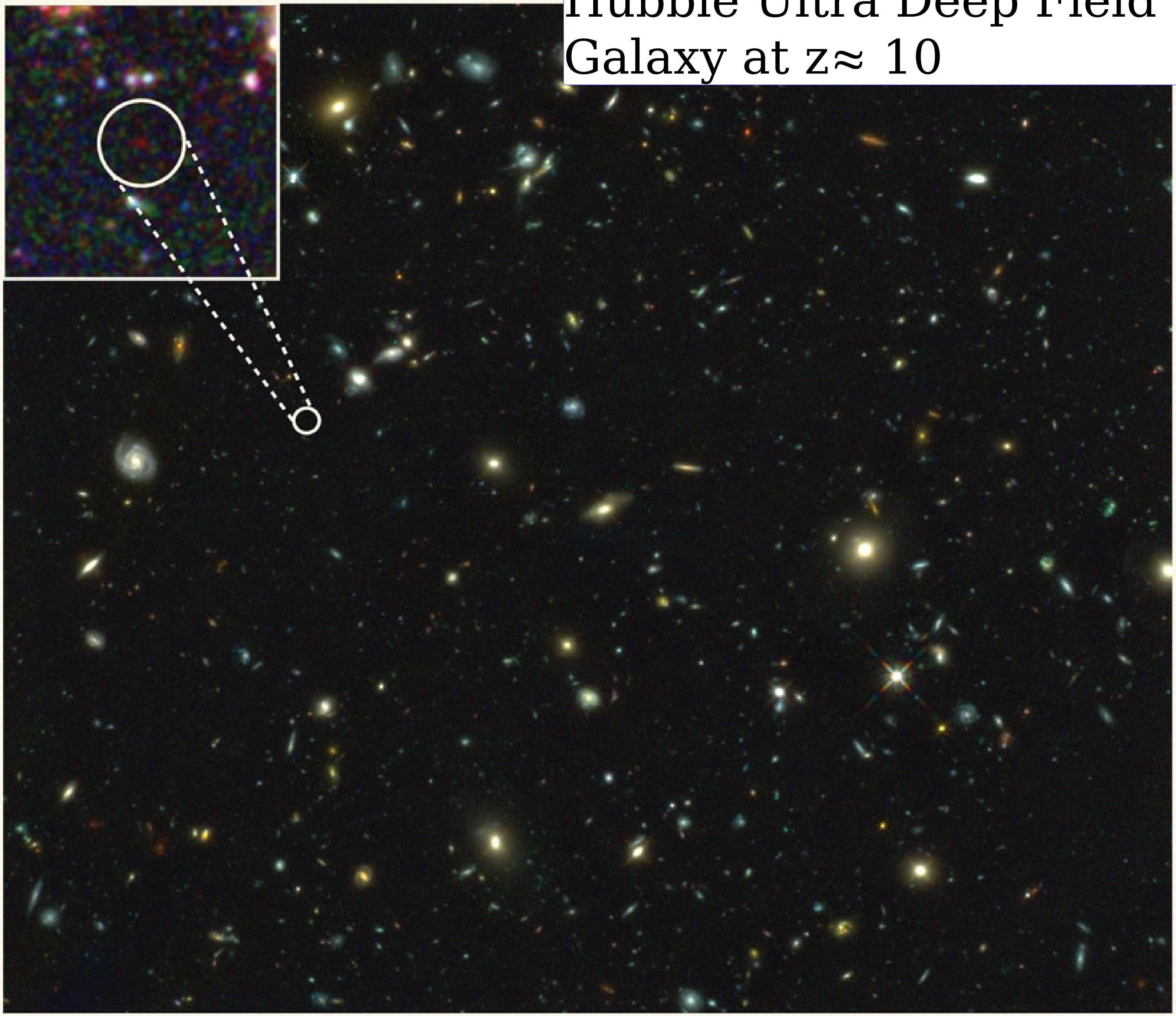
Z = 9.38

9.06 < z < 9.52 (90 % C.L)

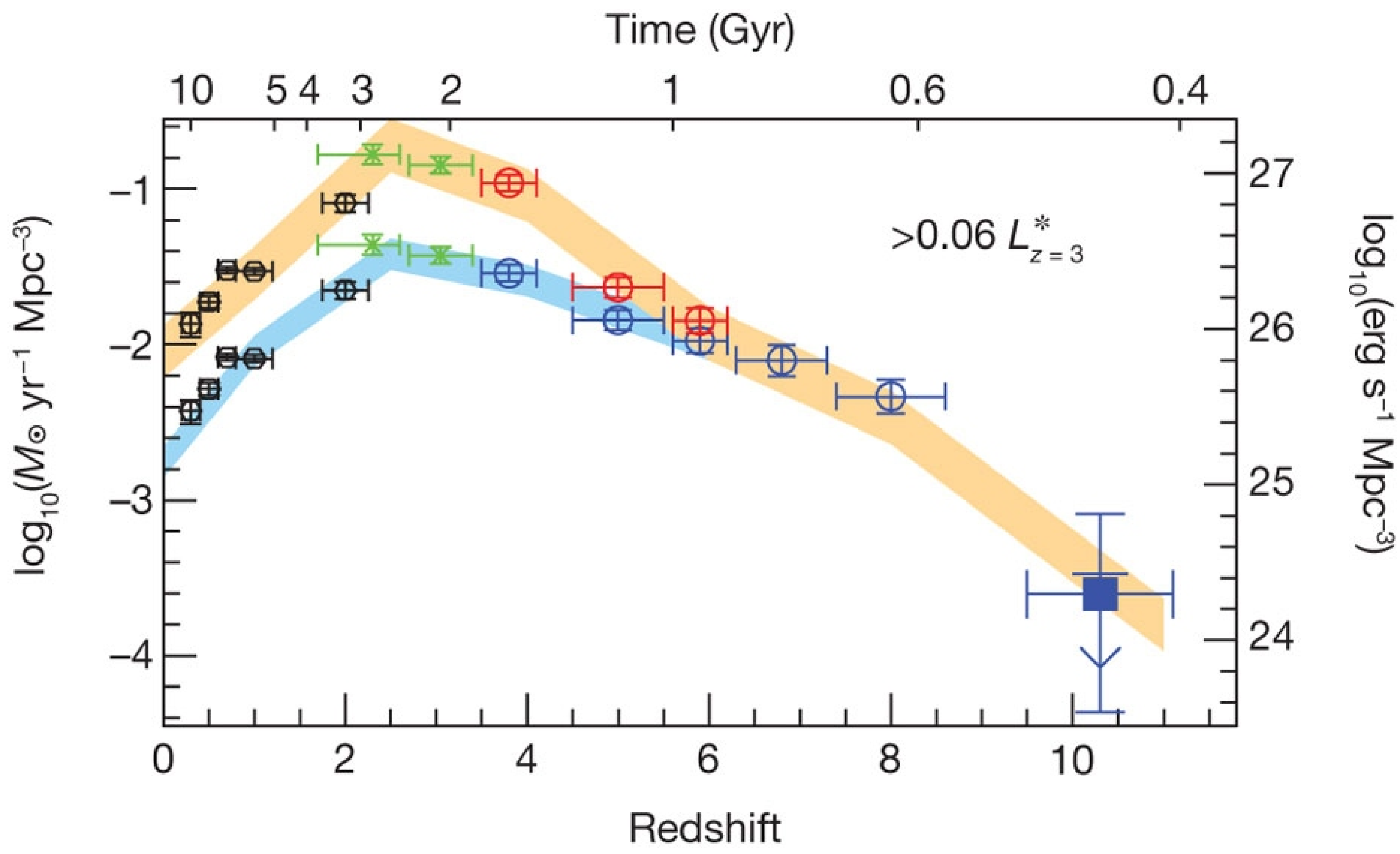


... Galaxy beat GRB's ...

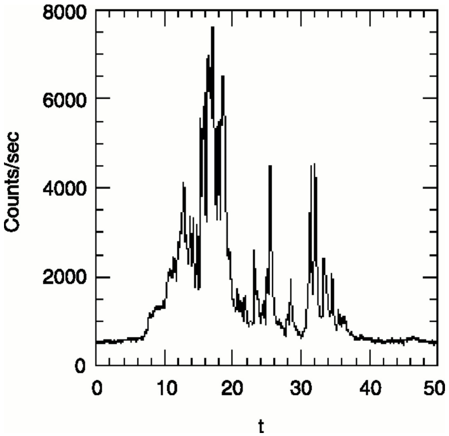
Hubble Ultra Deep Field HUD09
Galaxy at z≈ 10

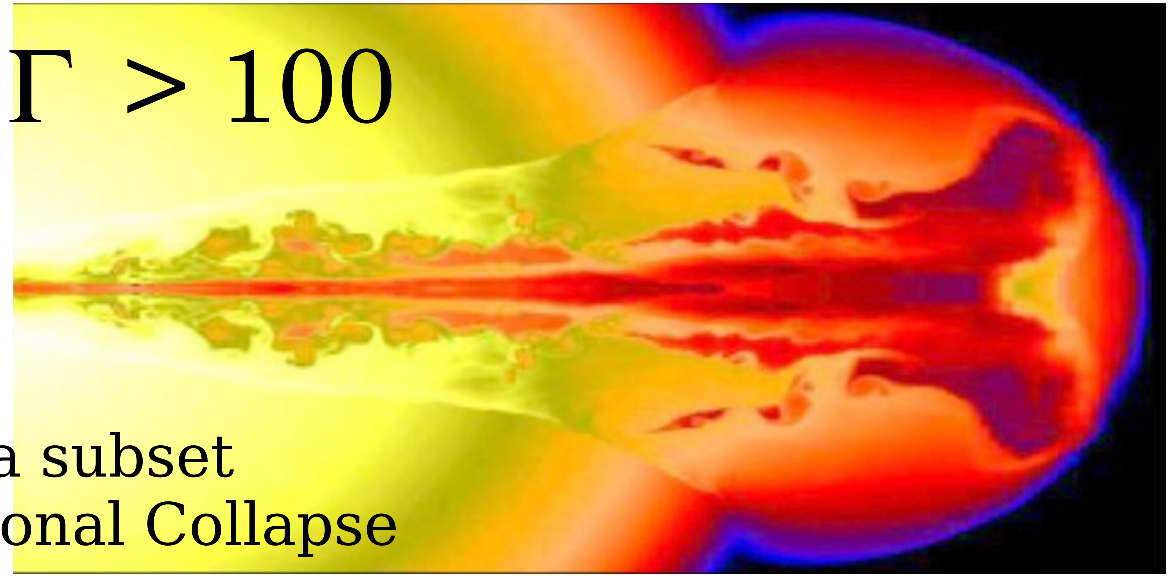


The first stars...



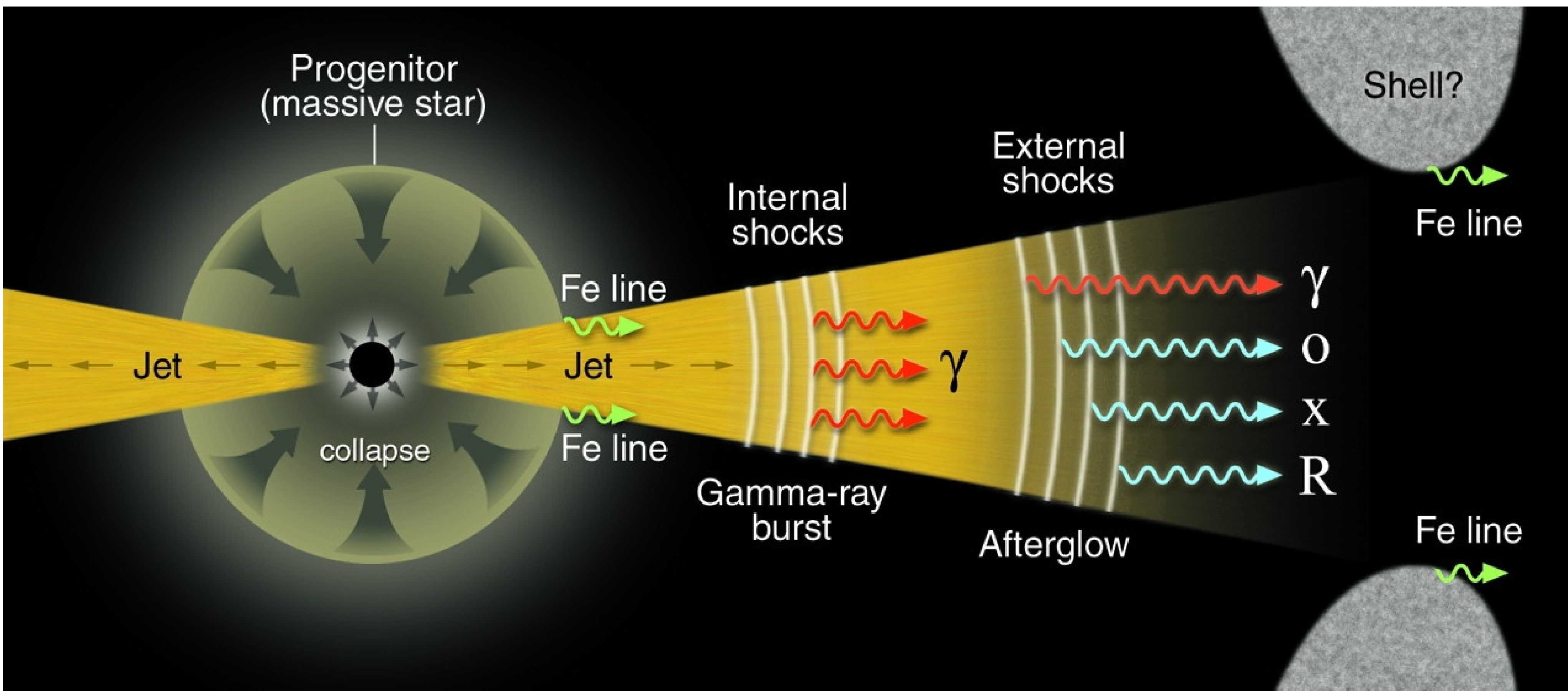
Searches for very-high-redshift galaxies over the past decade have yielded a large sample of more than 6,000 galaxies existing just 900-2,000 million years (Myr) after the Big Bang (redshifts $6 > z > 3$; ref. 1). The Hubble Ultra Deep Field (HUDF09) data[2,3] have yielded the first reliable detections of $z \approx 8$ galaxies[3–9] that, together with reports of a γ-ray burst at $z \approx 8.2$ (refs 10, 11), constitute the earliest objects reliably reported to date. Observations of $z \approx$ 7-8 galaxies suggest substantial star formation at $z >$ 9-10 (refs 12, 13). Here we use the full two-year HUDF09 data to conduct an ultra-deep search for $z \approx 10$ galaxies in the heart of the reionization epoch, only 500 Myr after the Big Bang. Not only do we find one possible $z \approx 10$ galaxy candidate, but we show that, regardless of source detections, the star formation rate density is much smaller (∼10%) at this time than it is just ∼200 Myr later at $z \approx 8$. This demonstrates how rapid galaxy build-up was at $z \approx 10$, as galaxies increased in both luminosity density and volume density from $z \approx 8$ to $z \approx 10$. The 100-200 Myr before $z \approx 10$ is clearly a crucial phase in the assembly of the earliest galaxies.





$\Gamma > 100$

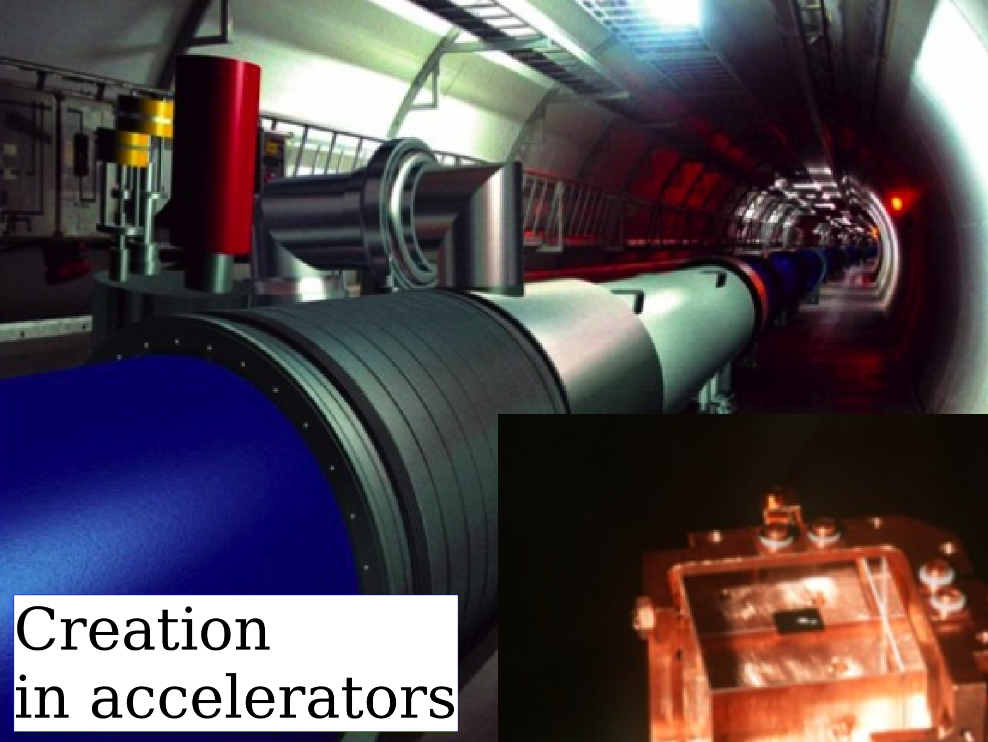
GRB : associated with a subset
of SN Stellar Gravitational Collapse



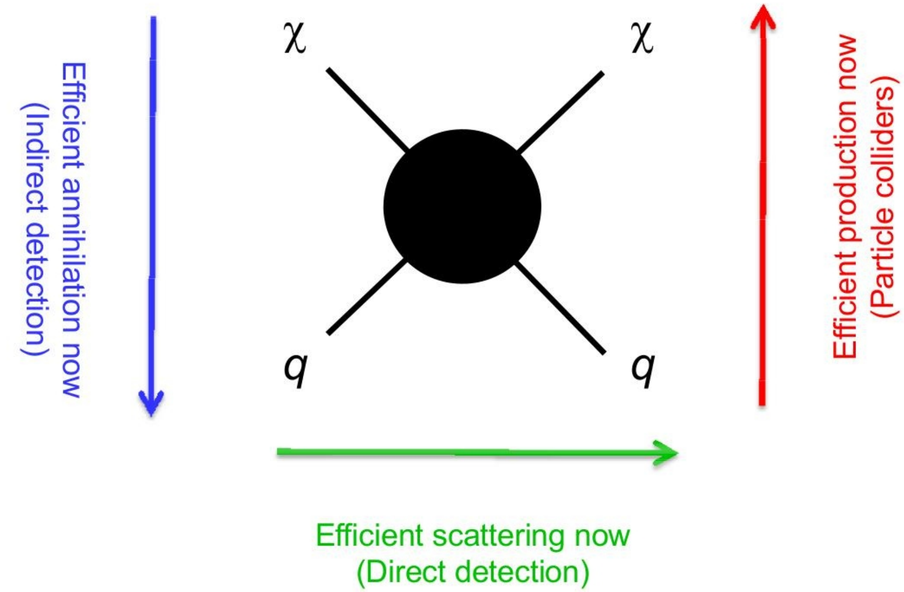
Cold Dark Matter

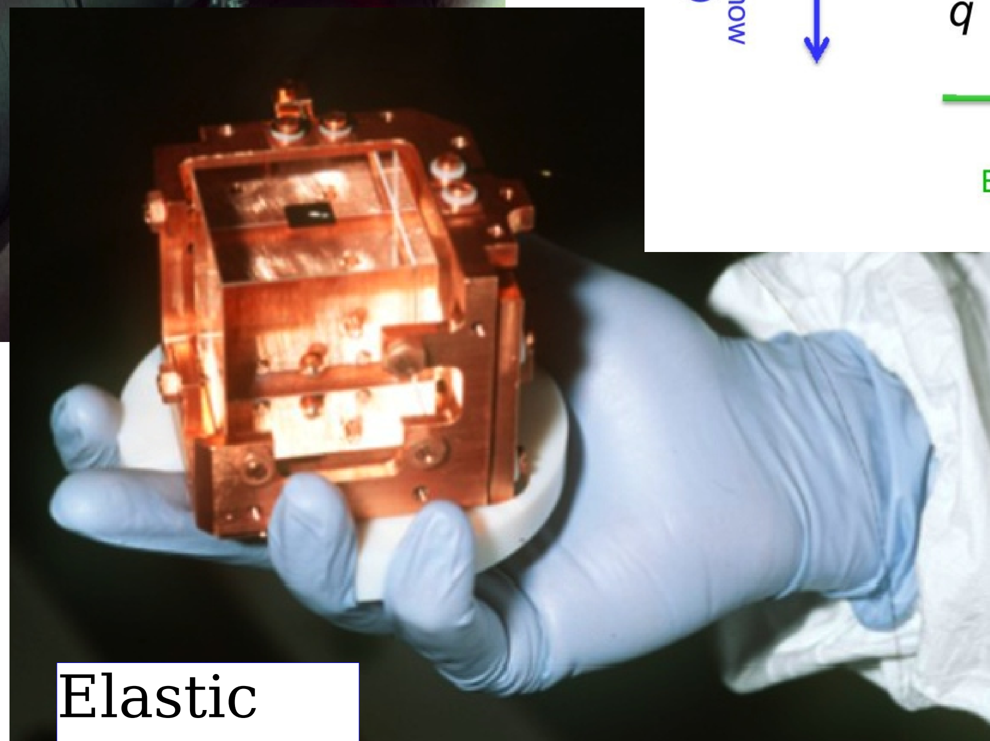
Cornelia Parker. (Tate Gallery, London)

What is the nature of the Dark Matter ?



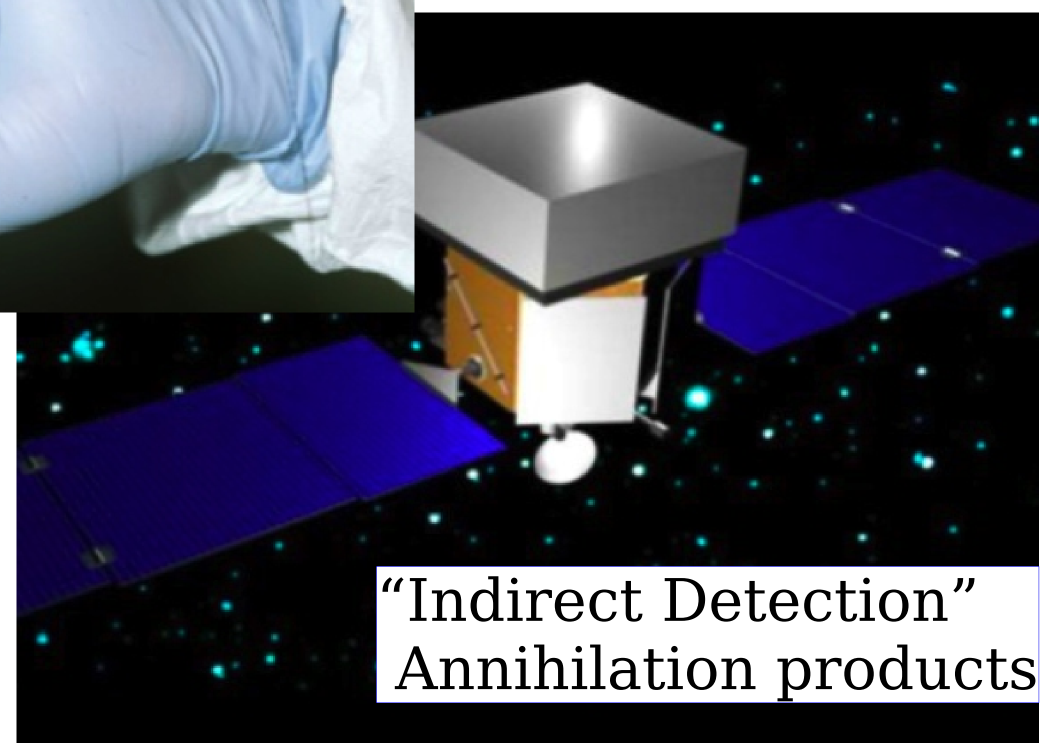
Creation
in accelerators





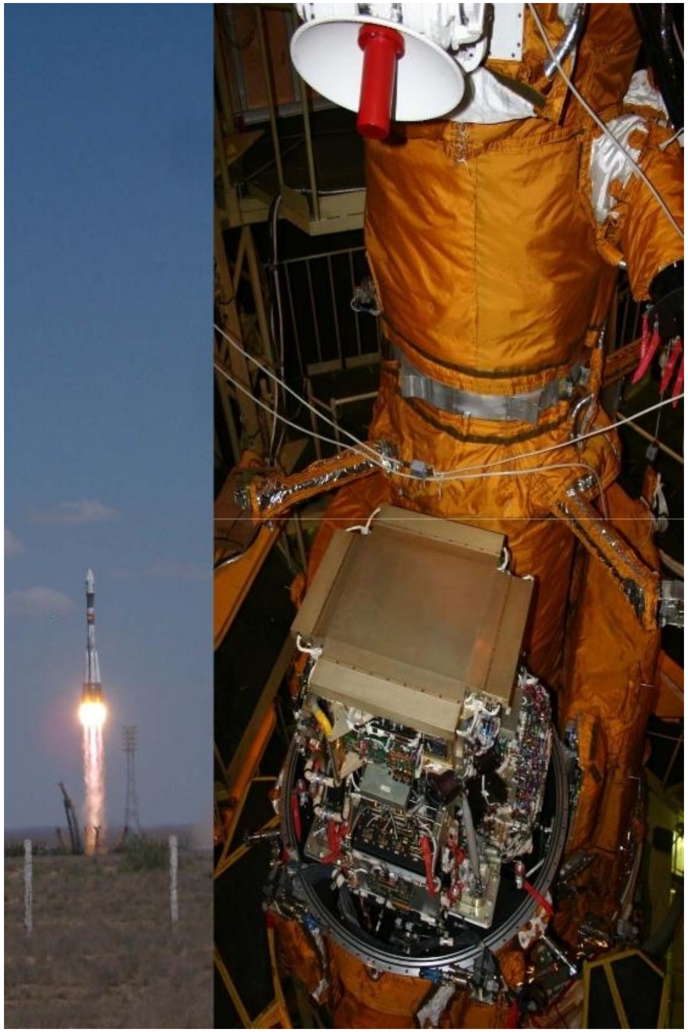
Elastic
scattering

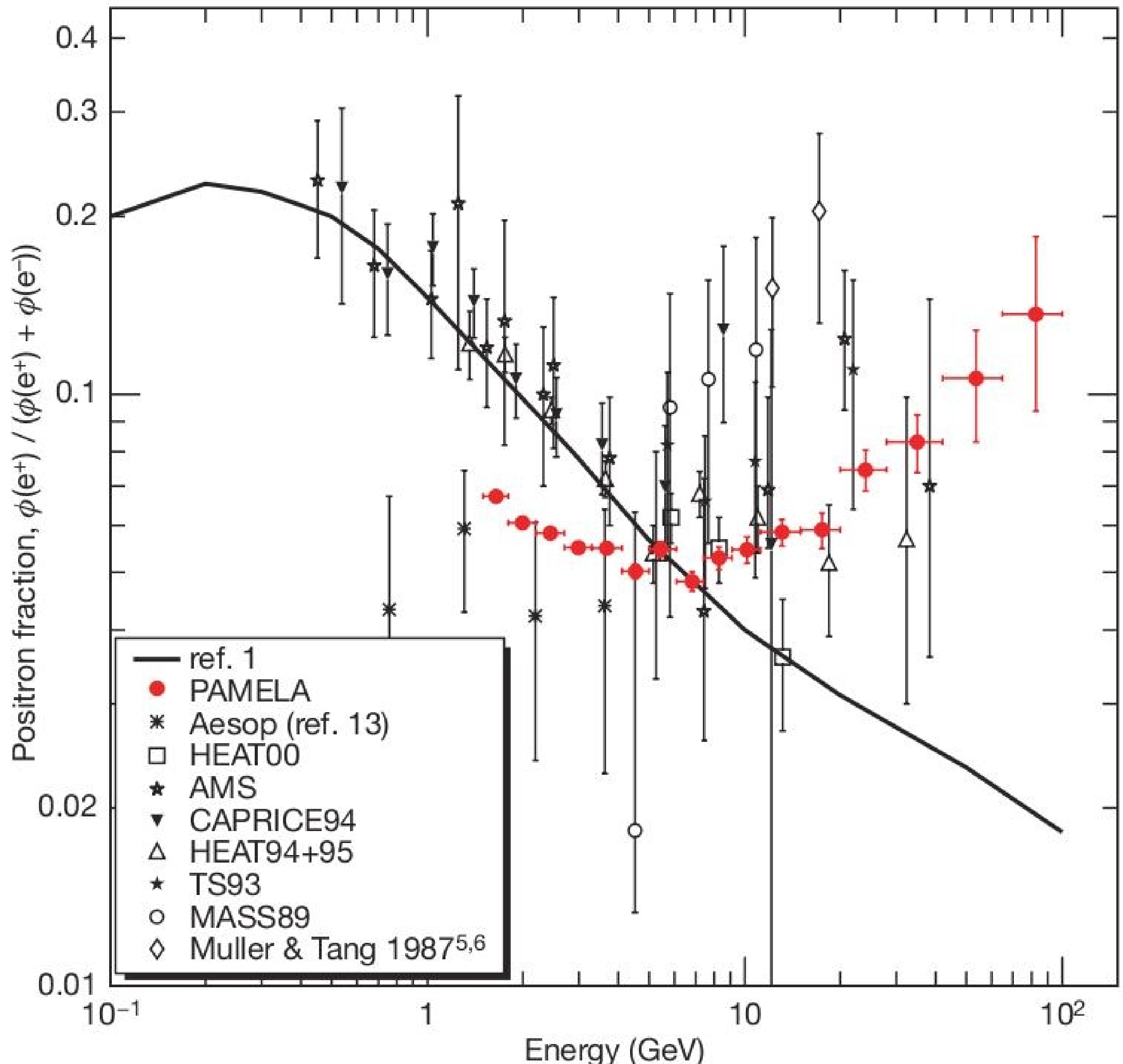
3 Roads to test the
WIMP hypothesis



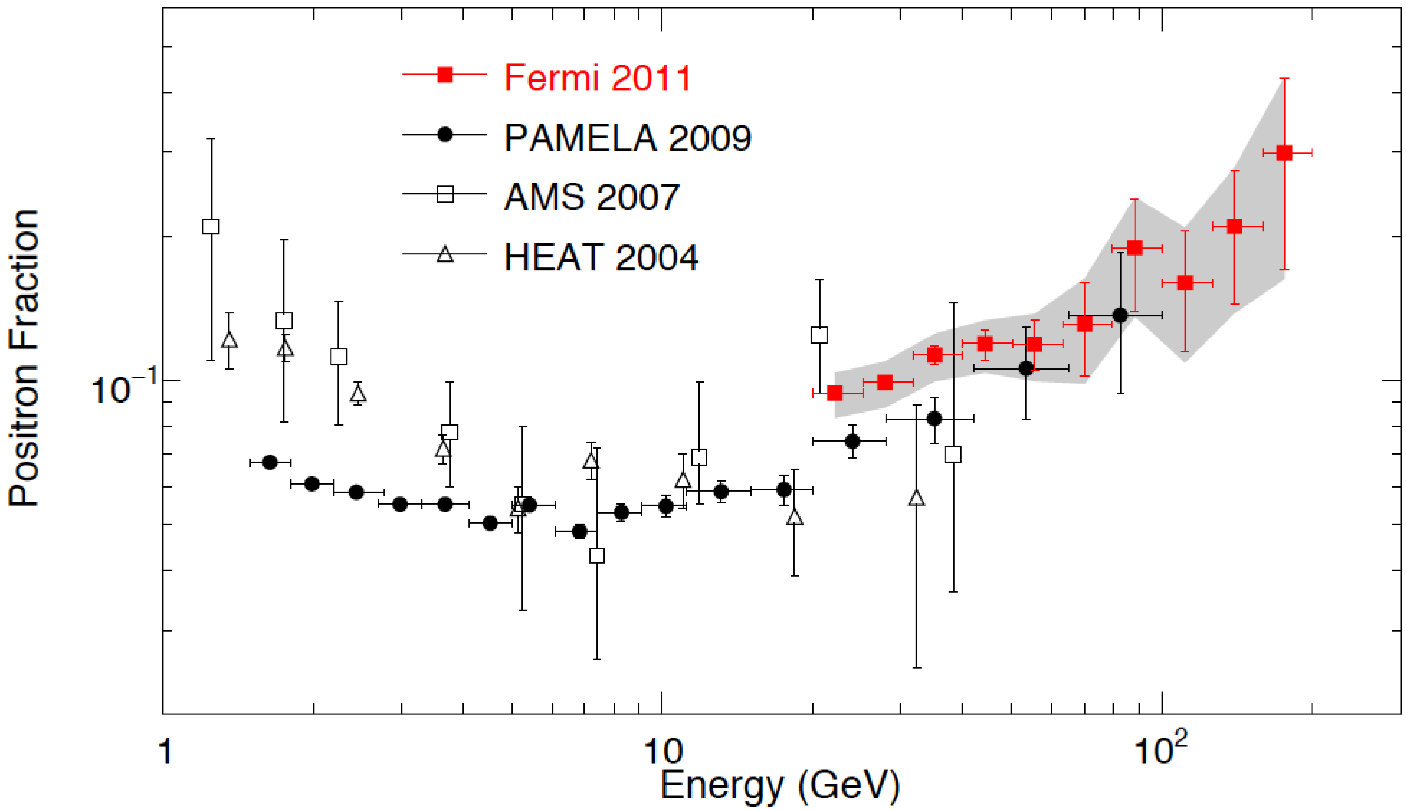
"Indirect Detection"
Annihilation products

PAMELA
“anomalous positron abundance”
E = [3 - 100 GeV]





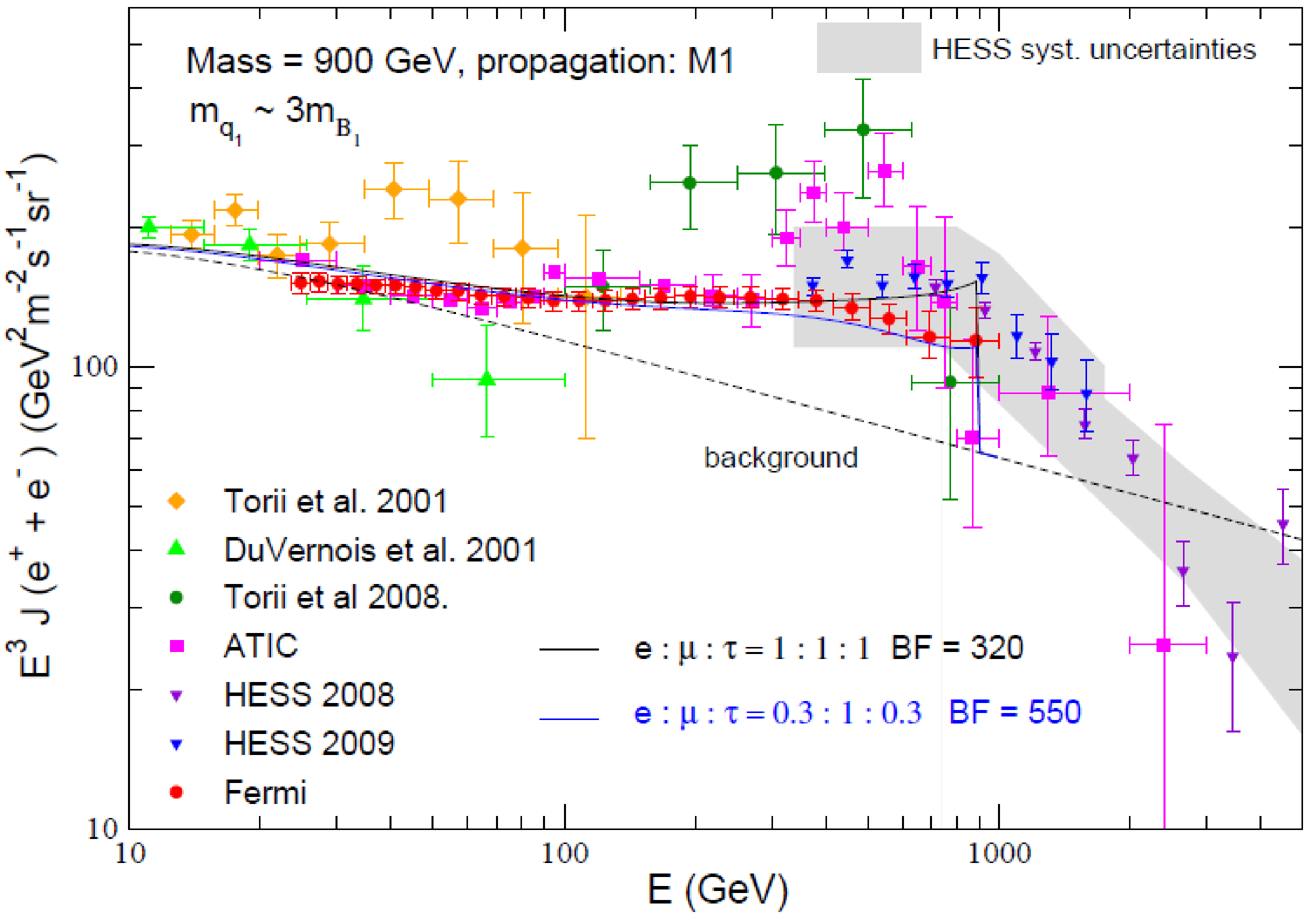
Result confirmed by FERMI ! (and extended to 200 GeV)
[using the Earth magnetic field to separate e- and e+]
{Hypothesis of systematic effect much less likely...}



Existence of a "new, hard source of positrons" is a robust conclusion (very broad consensus).

Do we have also an “electron excess” ?

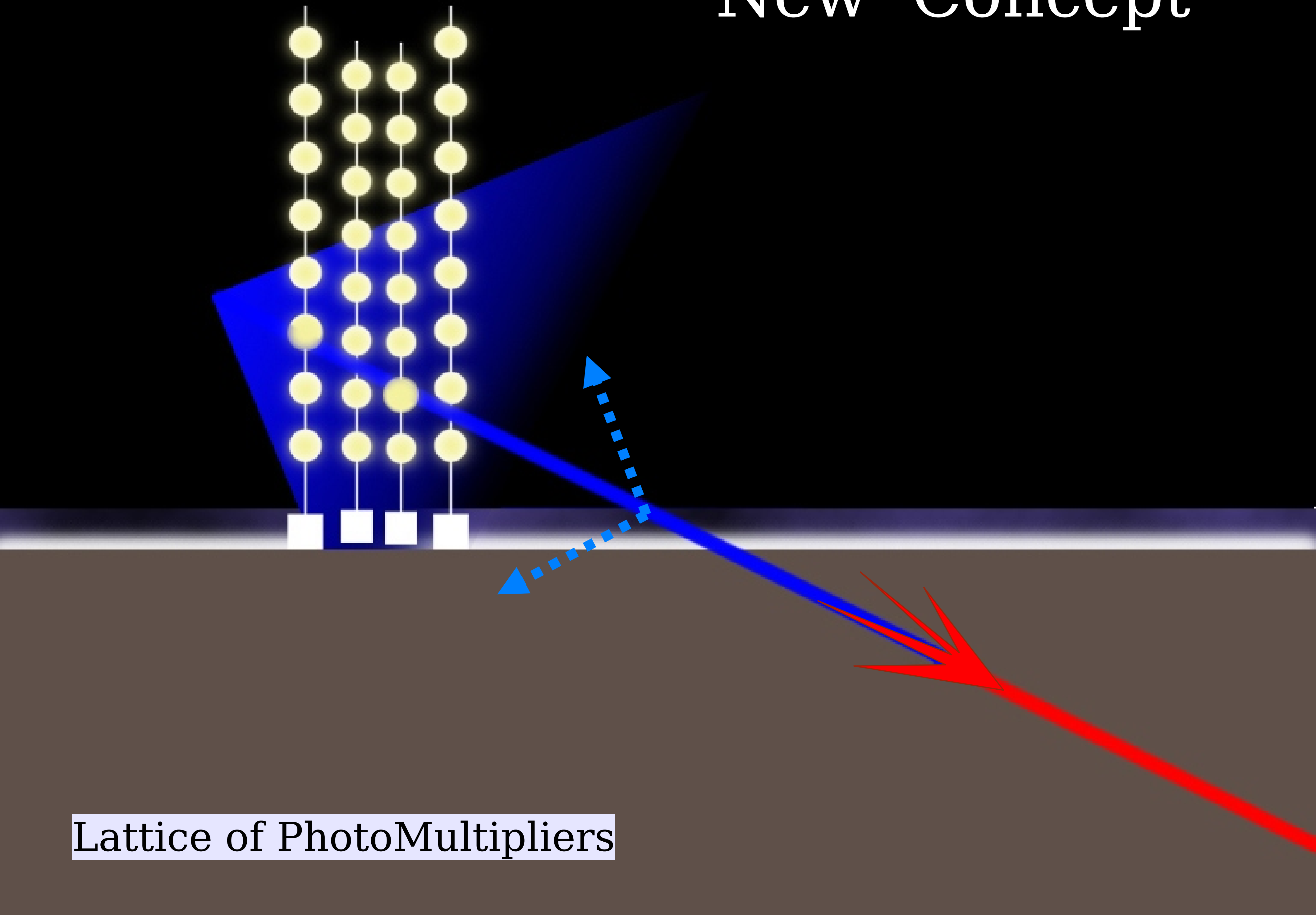
Very likely the “new source”
is approximately equal for e- and e+
and visible also in the (e- + e+) spectrum.
This allows to extend the observations to higher energy
(with FERMI + HESS)

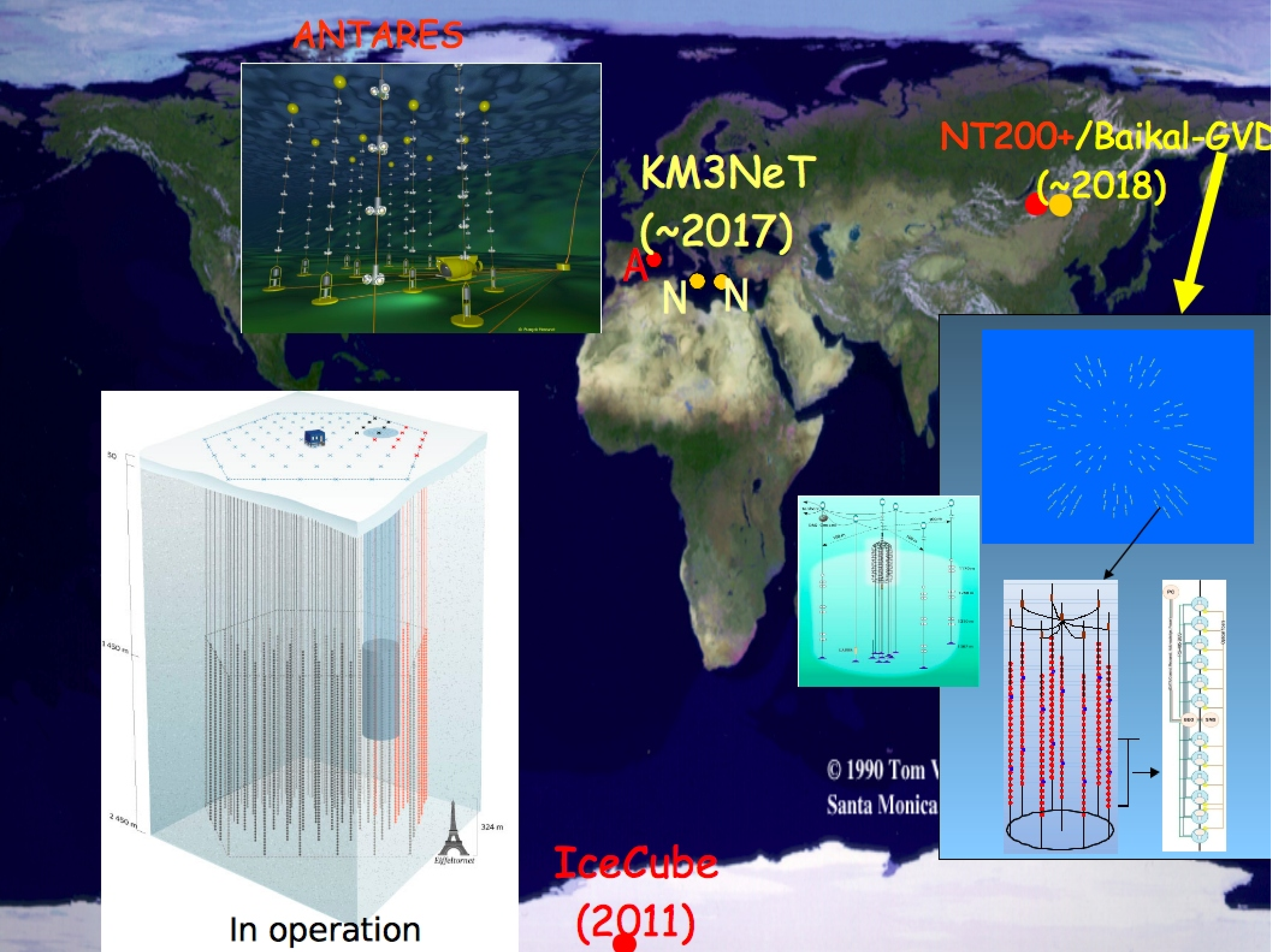


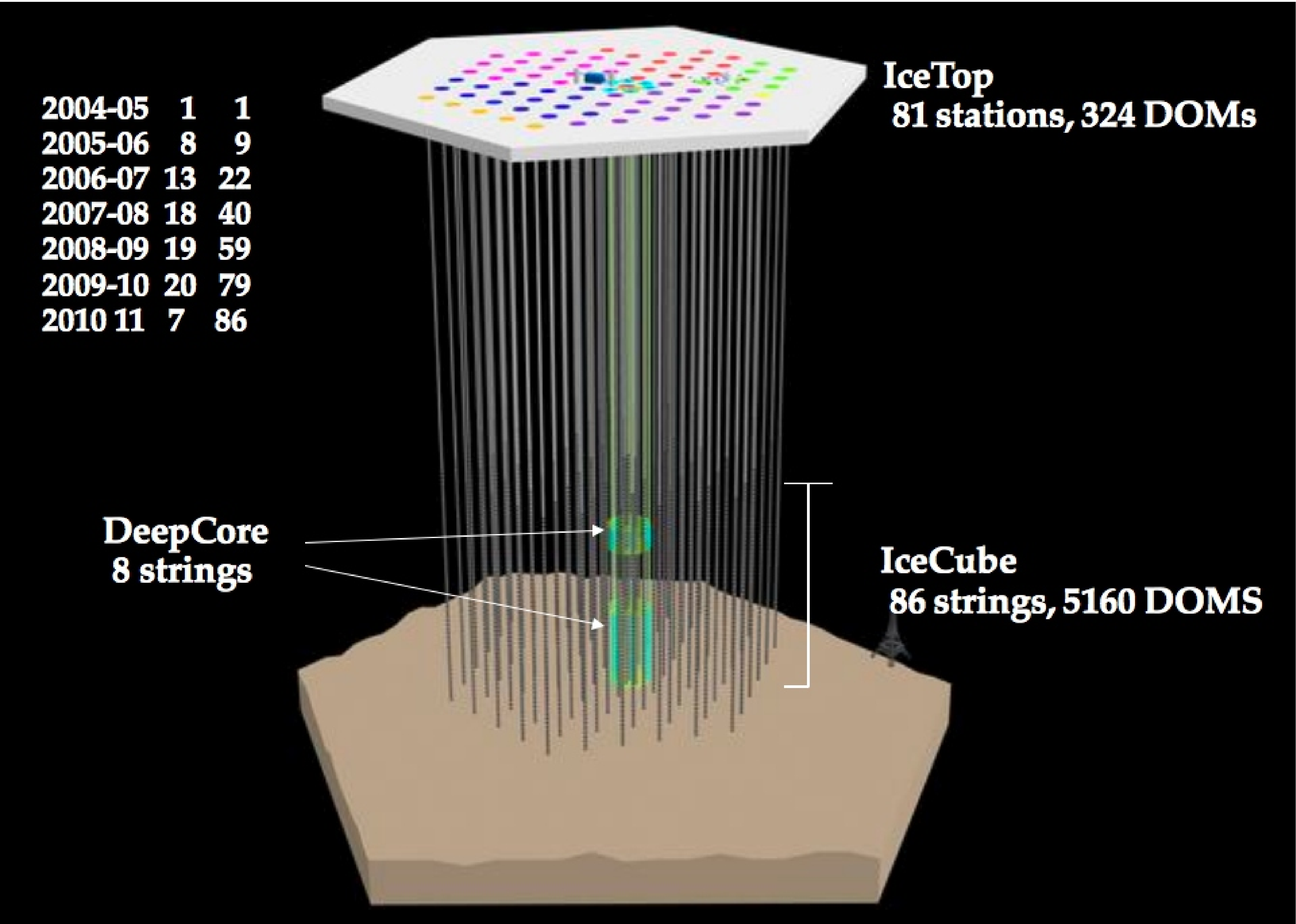
New source energy spectrum extends up to (and not beyond) 1 TeV.

NEUTRINO ASTRONOMY

New Concept

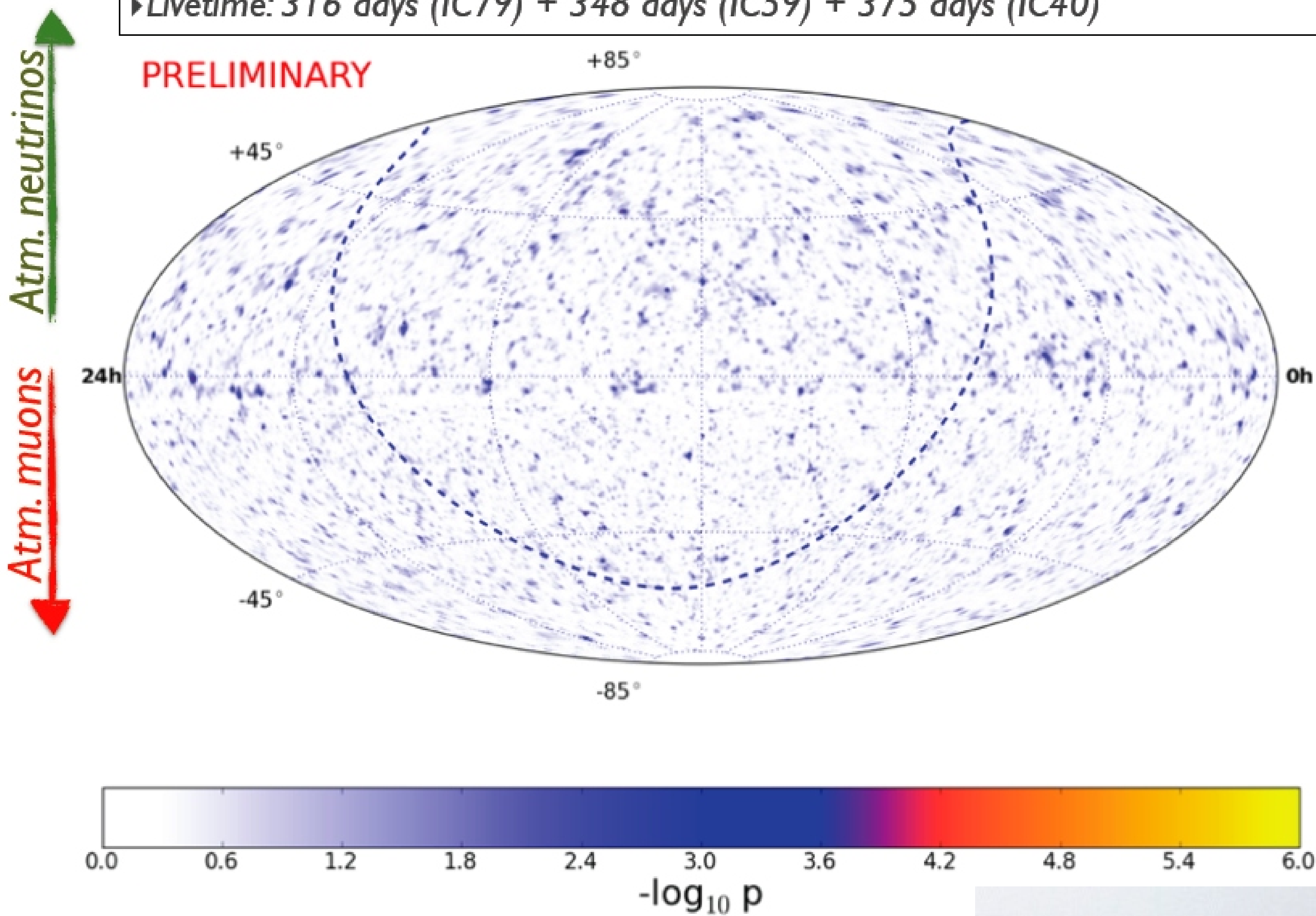



ANTARES
KM3NeT
(~2017)
A
N
N
NT200+/Baikal-GVD
(~2018)
IceCube
(2011)
In operation
50
1 450 m
2 450 m
324 m
Eiffeltornet
© 1990 Tom V
Santa Monica


2004-05 1 1
2005-06 8 9
2006-07 13 22
2007-08 18 40
2008-09 19 59
2009-10 20 79
2010 11 7 86
IceTop
81 stations, 324 DOMs
DeepCore
8 strings
IceCube
86 strings, 5160 DOMS

+IC79 SKYMAP

- Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)
- Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)



IceCube selected sources

(13 galactic SNR etc, 30 extragalactic active galaxies, etc.)

No significant detections at this point

Source	RA (deg)	Dec (deg)	Type	Distance	P-value
Cyg OB2	308.08	41.51	UNID	-	–
MGRO J2019+37	305.22	36.83	PWN	-	–
MGRO J1908+06	286.98	6.27	SNR	-	0.38
Cas A	350.85	58.81	SNR	3.4 kpc	–
IC443	94.18	22.53	SNR	1.5 kpc	–
Geminga	98.48	17.77	Pulsar	100 pc	–
Crab Nebula	83.63	22.01	SNR	2 kpc	–
1ES 1959+650	300.00	65.15	HBL	z = 0.048	–
1ES 2344+514	356.77	51.70	HBL	z = 0.044	–
3C66A	35.67	43.04	Blazar	z = 0.44	0.42
H 1426+428	217.14	42.67	HBL	z = 0.129	–
BL Lac	330.68	42.28	HBL	z = 0.069	0.4
Mrk 501	253.47	39.76	HBL	z = 0.034	0.19
Mrk 421	166.11	38.21	HBL	z = 0.031	–
W Comae	185.38	28.23	HBL	z = 0.1020	–
1ES 0229+200	38.20	20.29	HBL	z = 0.139	0.39
M87	187.71	12.39	BL Lac	z = 0.0042	0.38
S5 0716+71	110.47	71.34	LBL	z > 0.3	0.49
M82	148.97	69.68	Starburst	3.86 Mpc	–
3C 123.0	69.27	29.67	FRII	1038 Mpc	–
3C 454.3	343.49	16.15	FSRQ	z = 0.859	0.48
4C 38.41	248.81	38.13	FSRQ	z = 1.814	0.3

PKS 0235+164	39.66	16.62	LBL	z = 0.94	0.18
PKS 0528+134	82.73	13.53	FSRQ	z = 2.060	0.49
PKS 1502+106	226.10	10.49	FSRQ	z = 0.56/1.839	–
3C 273	187.28	2.05	FSRQ	z = 0.158	–
NGC 1275	49.95	41.51	Seyfert Galaxy	z = 0.017559	–
Cyg A	299.87	40.73	Radio-loud Galaxy	z = 0.056146	0.44
Sgr A*	266.42	-29.01	Galactic Center	8.5 kpc	0.49
PKS 0537-441	84.71	-44.09	LBL	z = 0.896	0.44
Cen A	***201.37***	***-43.02***	***FRI***	***3.8 Mpc***	***0.14***
PKS 1454-354	***224.36***	***-35.65***	***FSRQ***	***z = 1.42***	***0.14***
PKS 2155-304	329.72	-30.23	HBL	z = 0.116	–
PKS 1622-297	246.53	-29.86	FSRQ	z = 0.815	0.27
QSO 1730-130	263.26	-13.08	FSRQ	z = 0.902	–
PKS 1406-076	212.24	-7.87	FSRQ	z = 1.494	0.36
QSO 2022-077	306.42	-7.64	FSRQ	z = 1.39	–
3C279	194.05	-5.79	FSRQ	z = 0.536	0.45
TYCHO	6.36	64.18	SNR	2.4 kpc	–
Cyg X-1	299.59	35.20	MQSO	2.5 kpc	–
Cyg X-3	308.11	40.96	MQSO	9 kpc	–
LSI 303	40.13	61.23	MQSO	2 kpc	–
SS433	287.96	4.98	MQSO	1.5 kpc	0.48

CONCLUSIONS

- ***No evidence of a neutrino point source*** has been found in the combination of 3 datasets: IC79+IC59+IC40
- The ***IC59 untriggered flare*** analysis have the most significant result but still compatible with a background fluctuation.
- More analysis on the IC79 dataset are still on-going: time-dependent searches, stacking sources, extended sources skymaps.
- IceCube sensitivity is getting in the region where a non-discovery from a point-source is becoming meaningful.

EXTRA-GALACTIC NEUTRINOS

UNRESOLVED FLUX

Sum of all High Energy Neutrino Sources

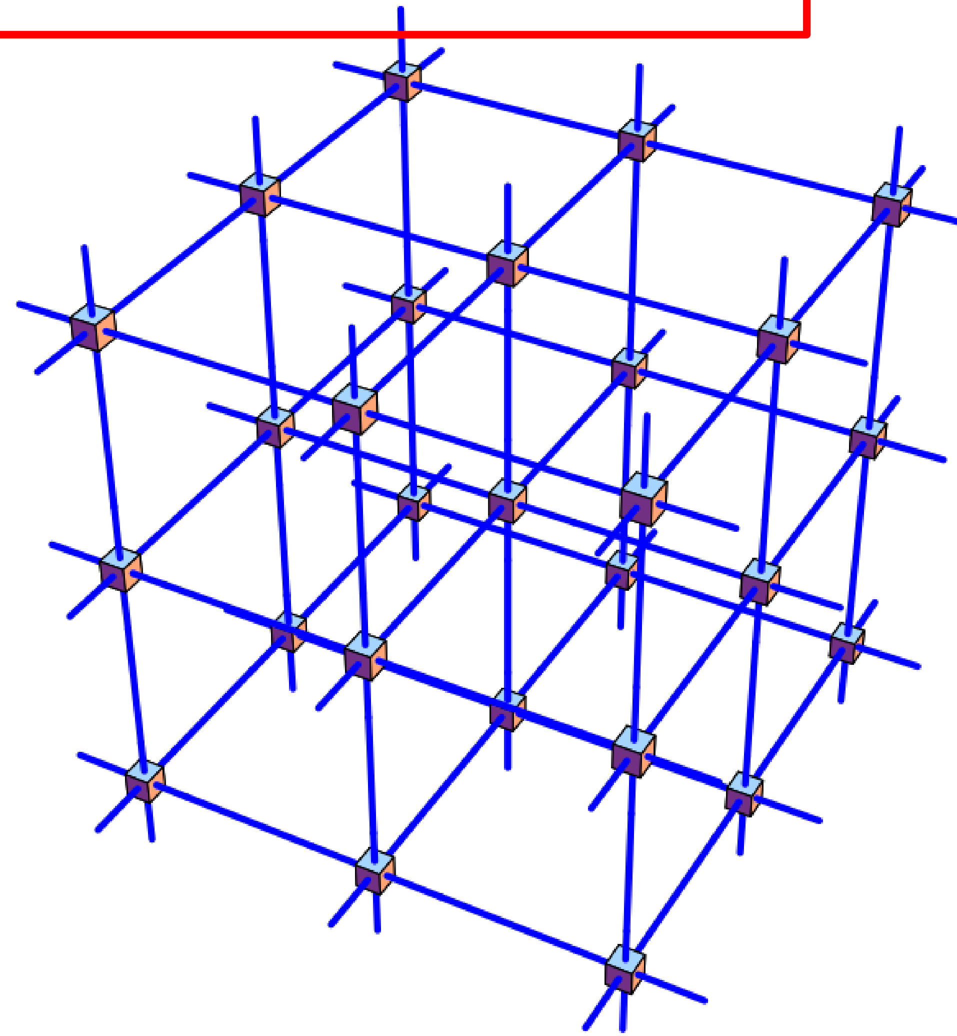
Individual Sources

AGN
GRB's

The 3-dimensional lampposts ensemble "paradox"
[Kepler – Olbers paradox].

Linear sequence of lampposts:

Most of the light you receive
from the nearest lamppost



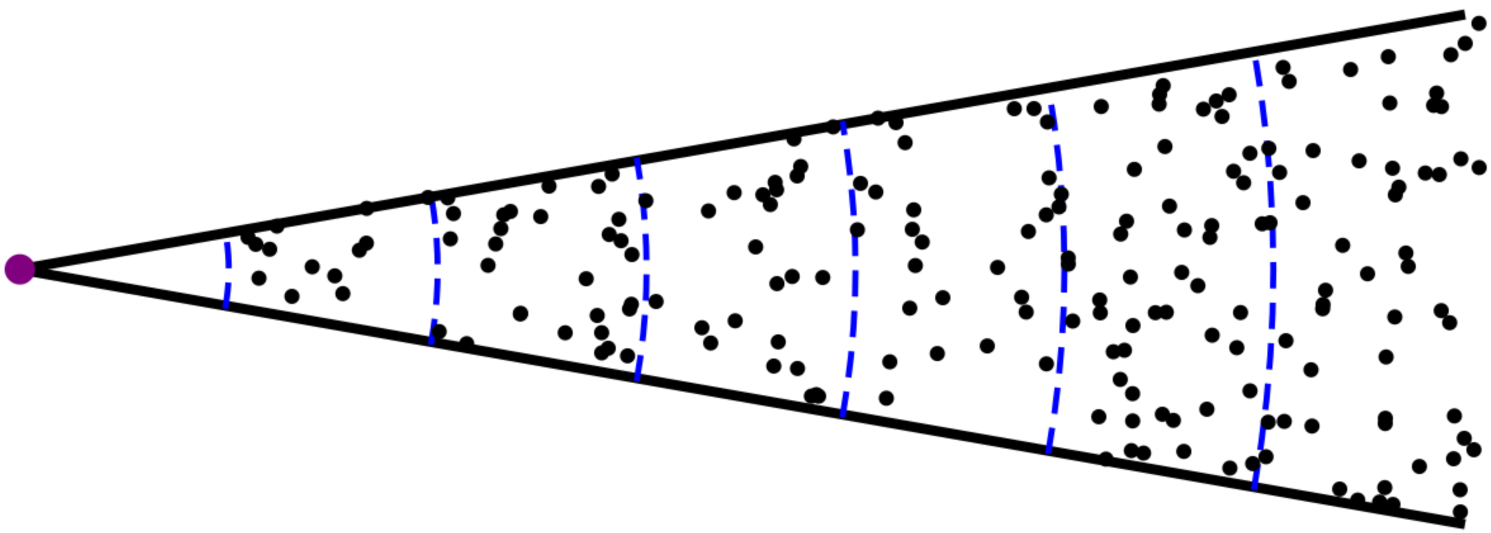
3D ensemble of lampposts:
[Euclidean static space]

Light diverges !

INCLUSIVE Extra-Galalactic Neutrino Flux

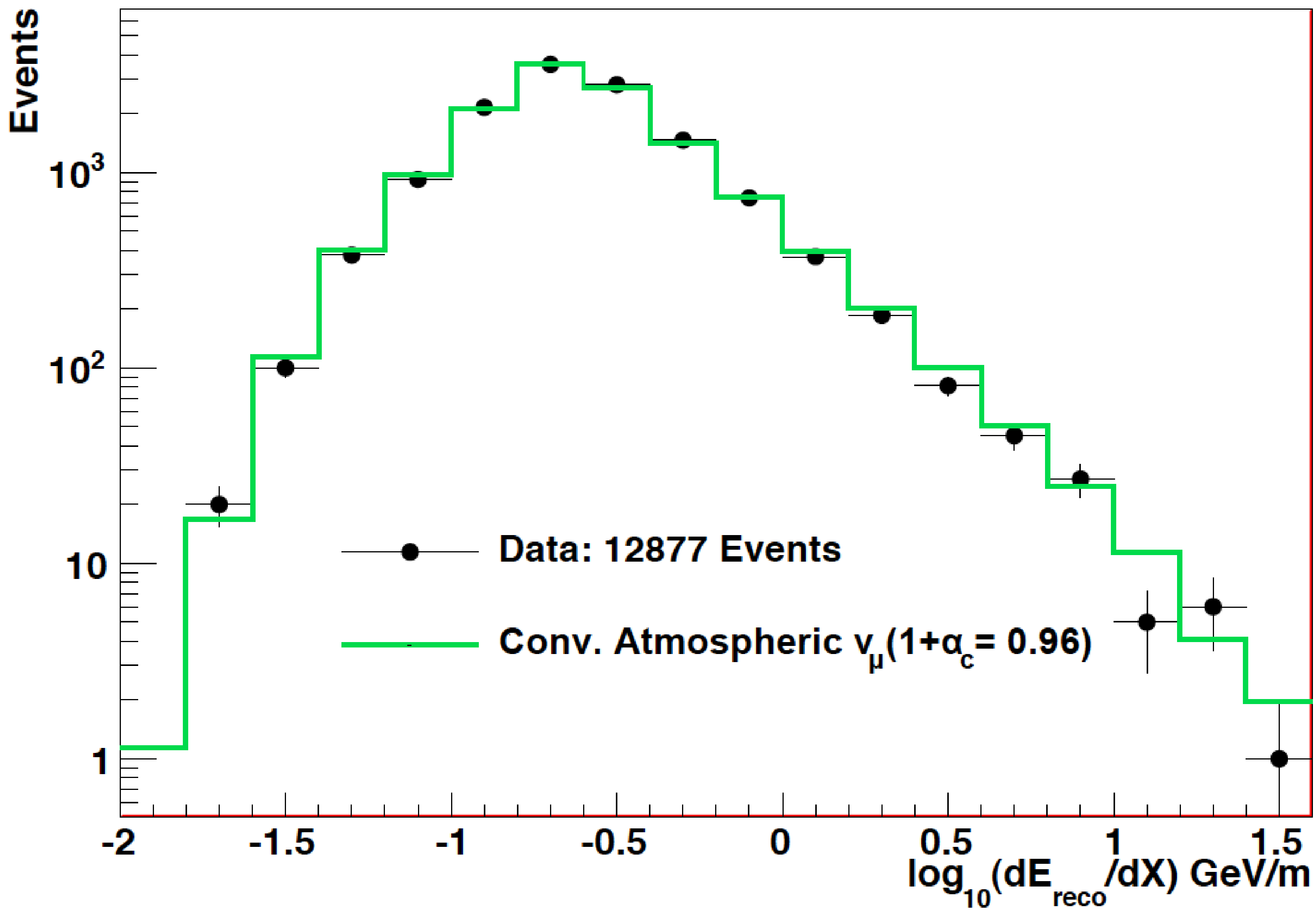
$$\phi_{\text{inclusive}} = \sum_{\text{all sources}} \phi_{\text{single source}}$$

$$\phi_{\text{inclusive}} = \int_{\text{all space}} d^3r \; \phi_{\text{source}}(\vec{r})$$



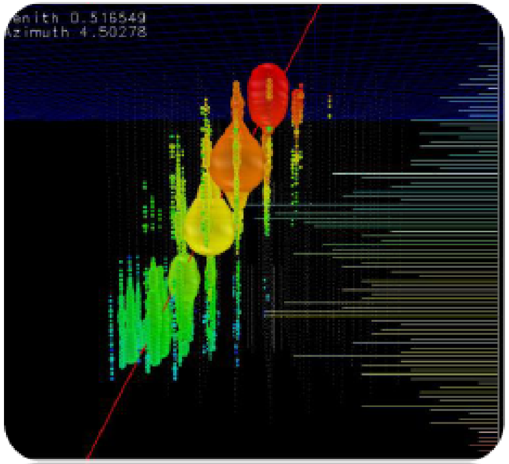
Integral dominated by large distances

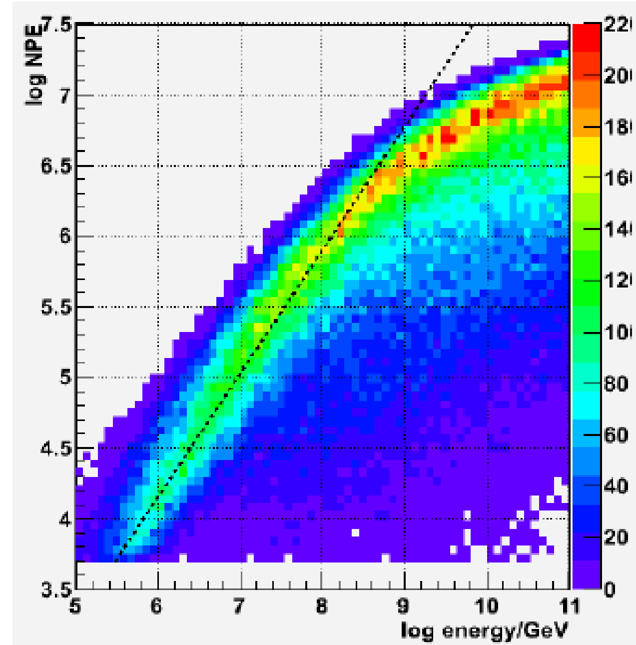
A Search for a Diffuse Flux of Astrophysical Muon Neutrinos with the IceCube 40-String Detector



No excess over atmospheric neutrinos

The Event Selection

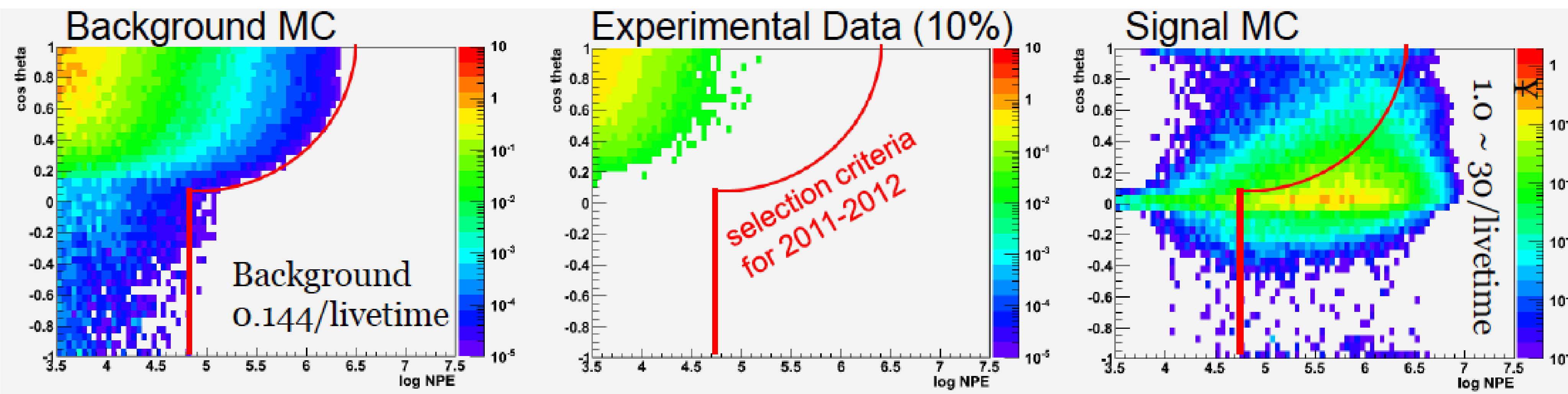




channel # > 300

Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

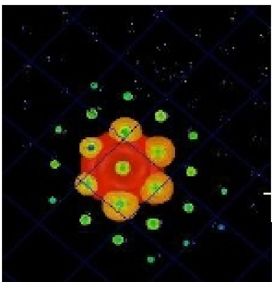
- Optimization based MC and MC verification based on 10% experimental ‘burn’ sample



Two events passed the selection criteria

2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events

preliminary p-value: 0.0094 (2.36σ)

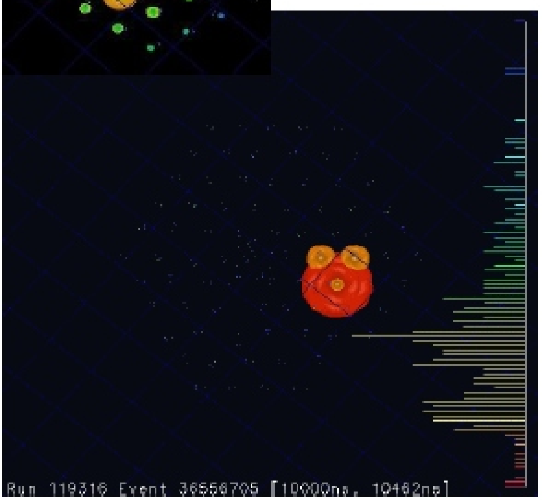


Run119316-Event36556705

Jan 3rd 2012

NPE 9.628×10^4

Number of Optical Sensors 312

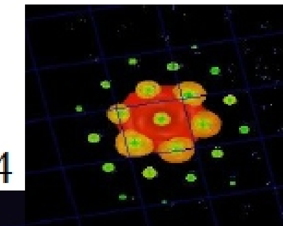


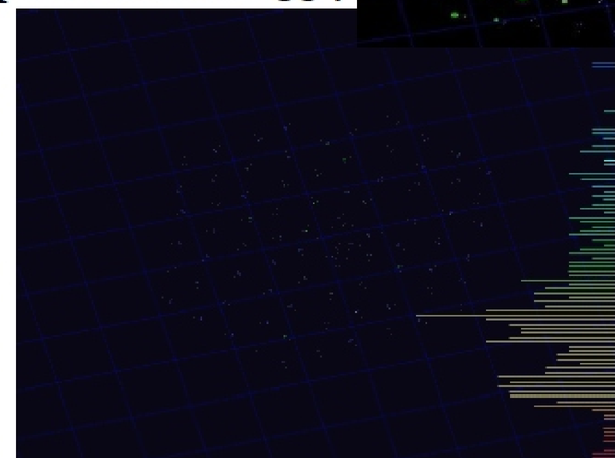
Run118545-Event63733662

August 9th 2011

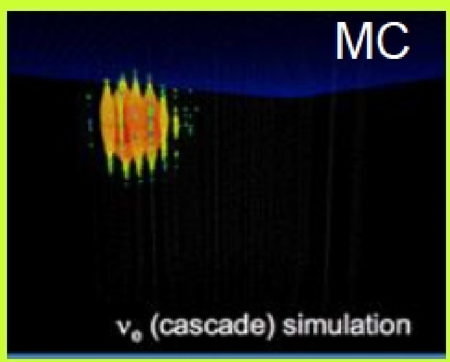
NPE 6.9928×10^4

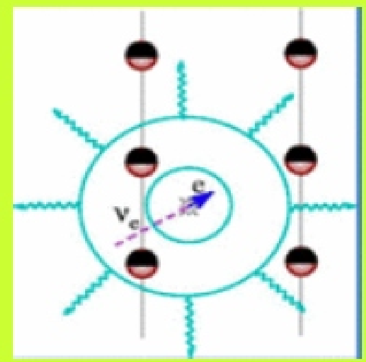
Number of Optical Sensors 354

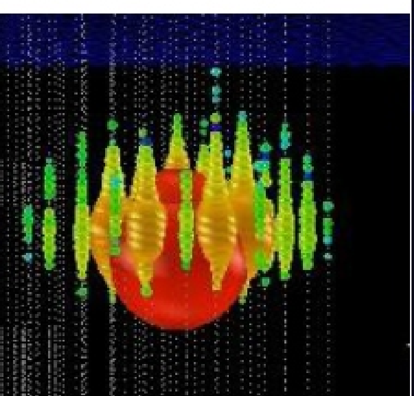


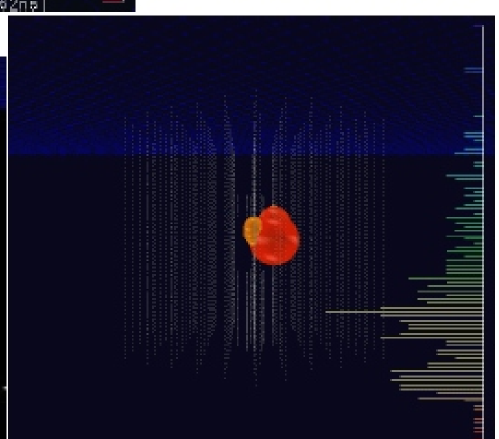


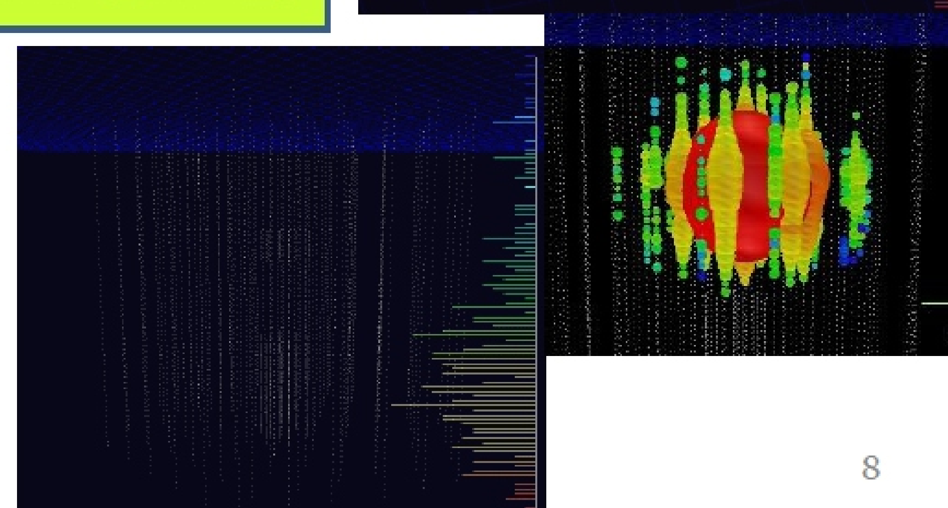
CC/NC interactions in the detector





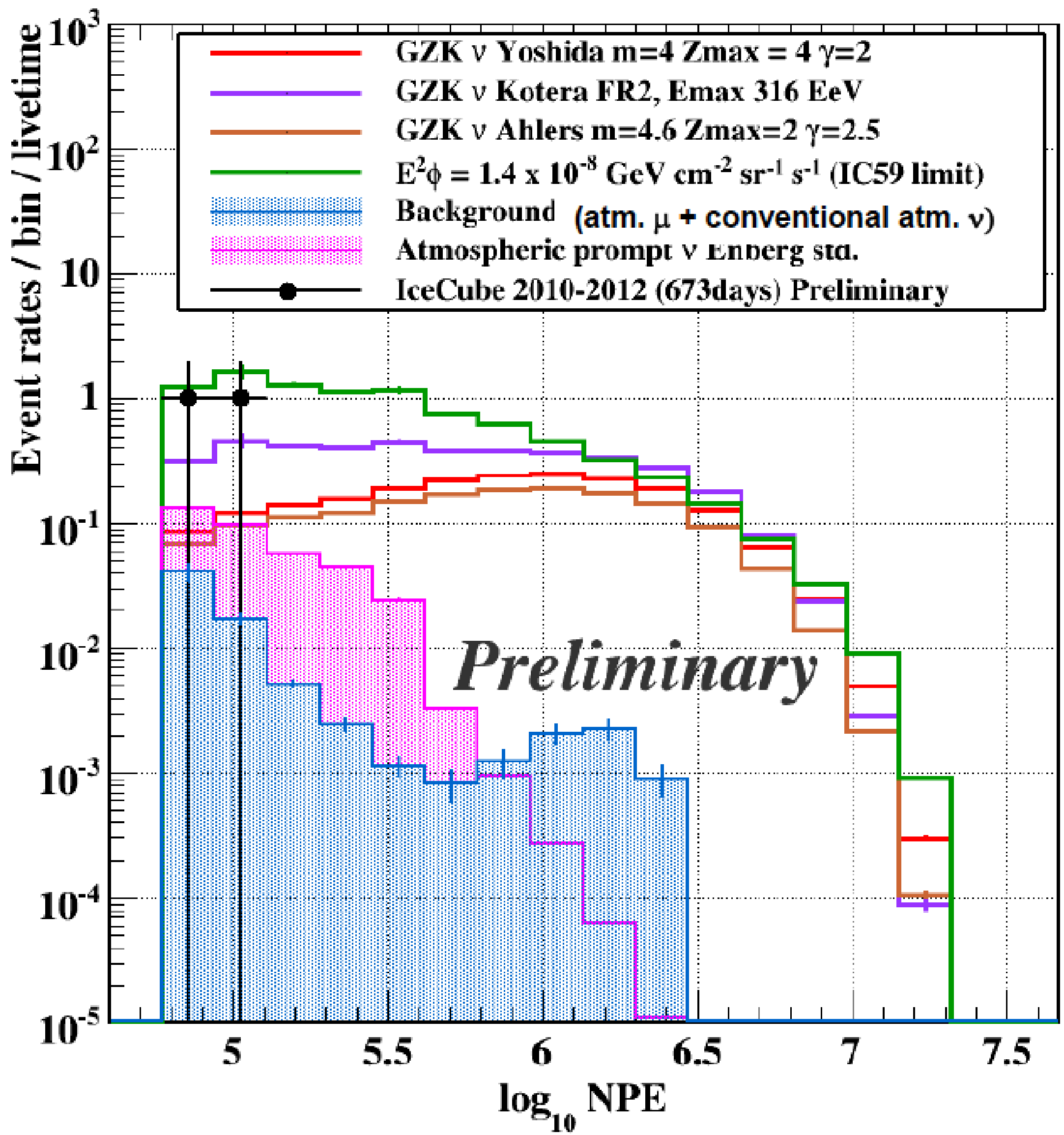






2 events with Large energy depositions in IceCube (Neutrino 2012)

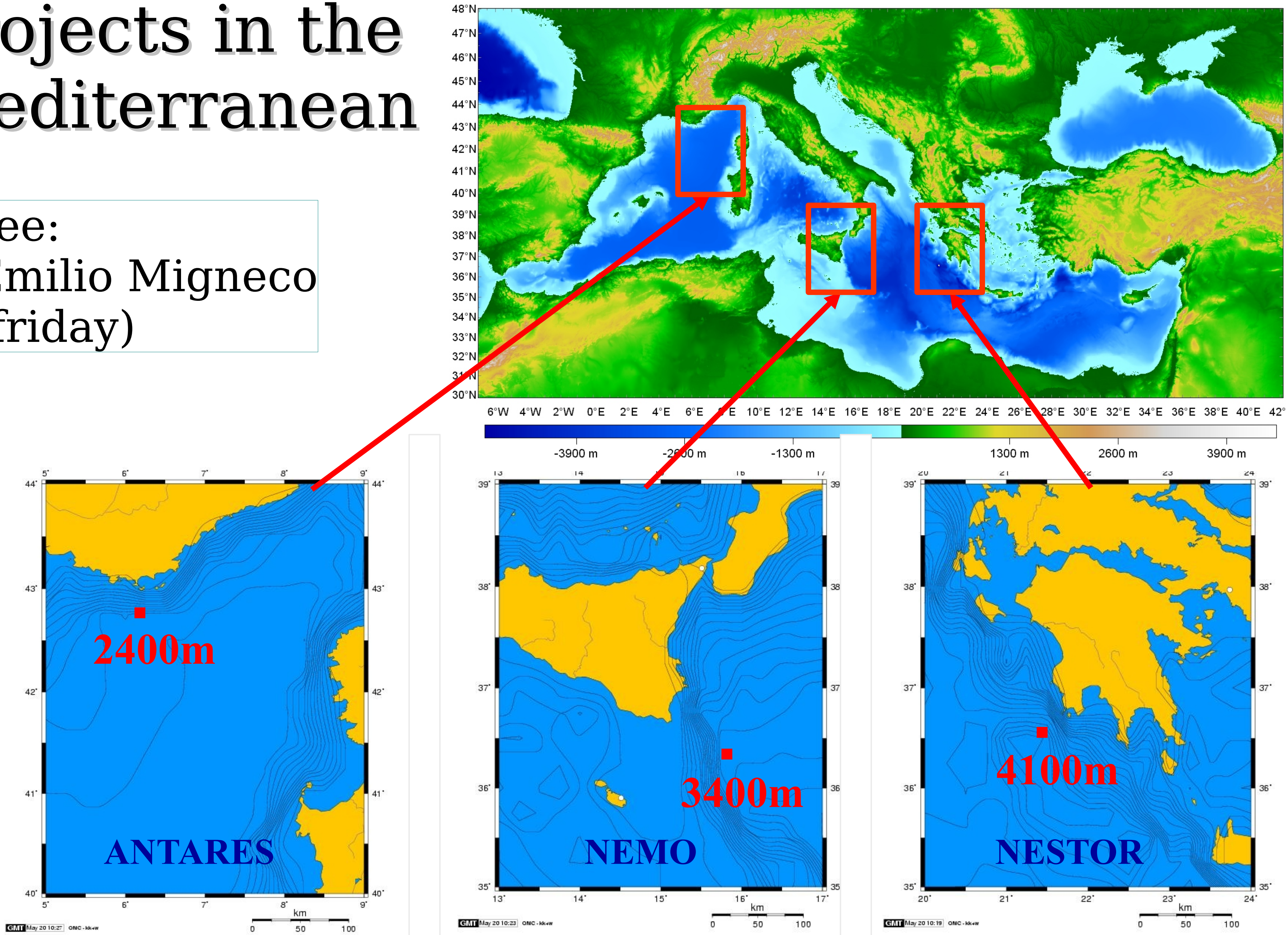
Event Brightness (NPE) Distributions 2010-2012

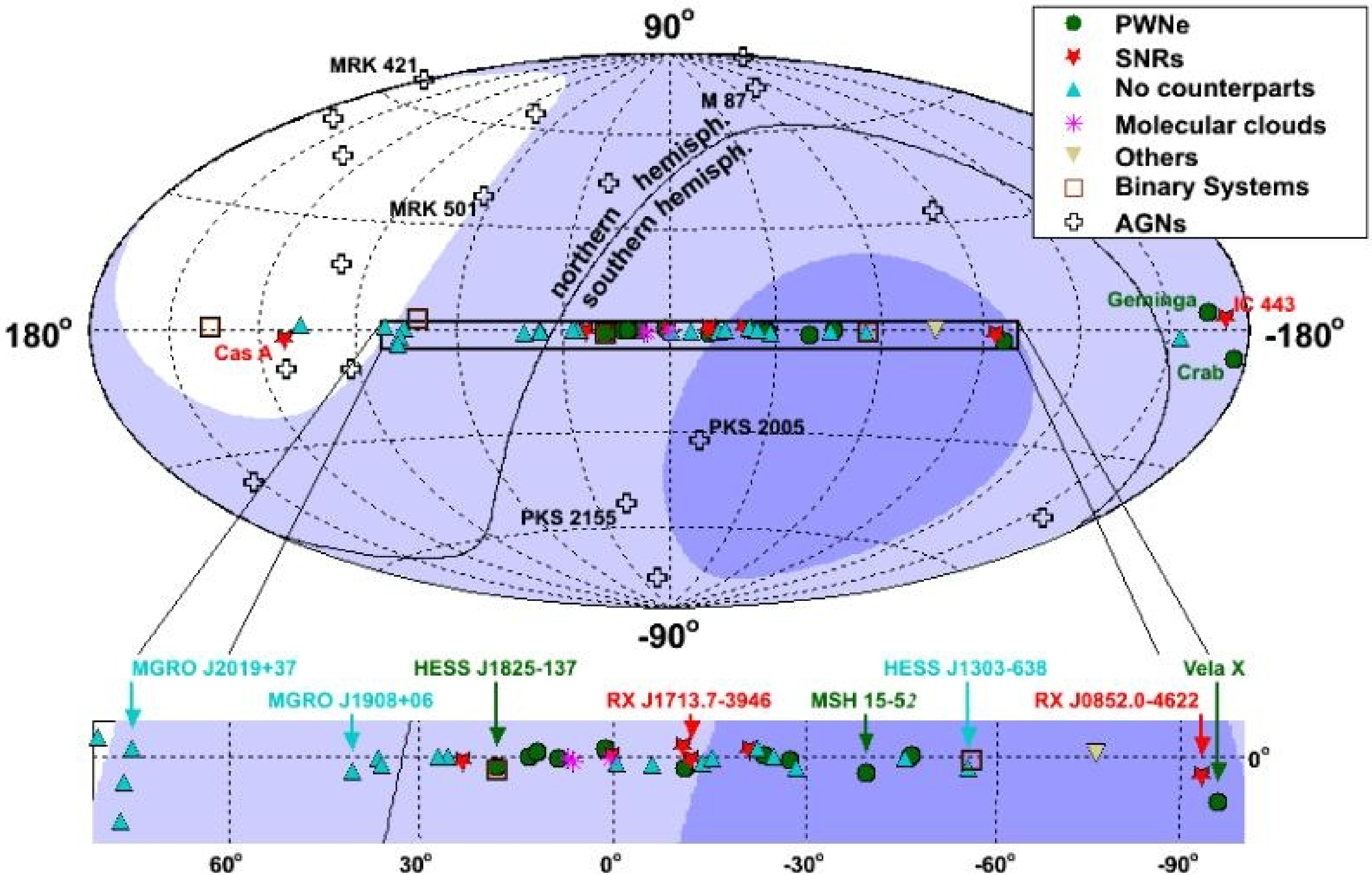


- Observed 2 high NPE events near the NPE threshold
- **No** indication
  - that they are instrumental artifacts
  - that they are cosmic-ray muon induced
- Possibility of the origin includes
  - cosmogenic ν
  - on-site ν production from the cosmic-ray accelerators
  - atmospheric prompt ν
  - atmospheric conventional ν

Projects in the Mediterranean

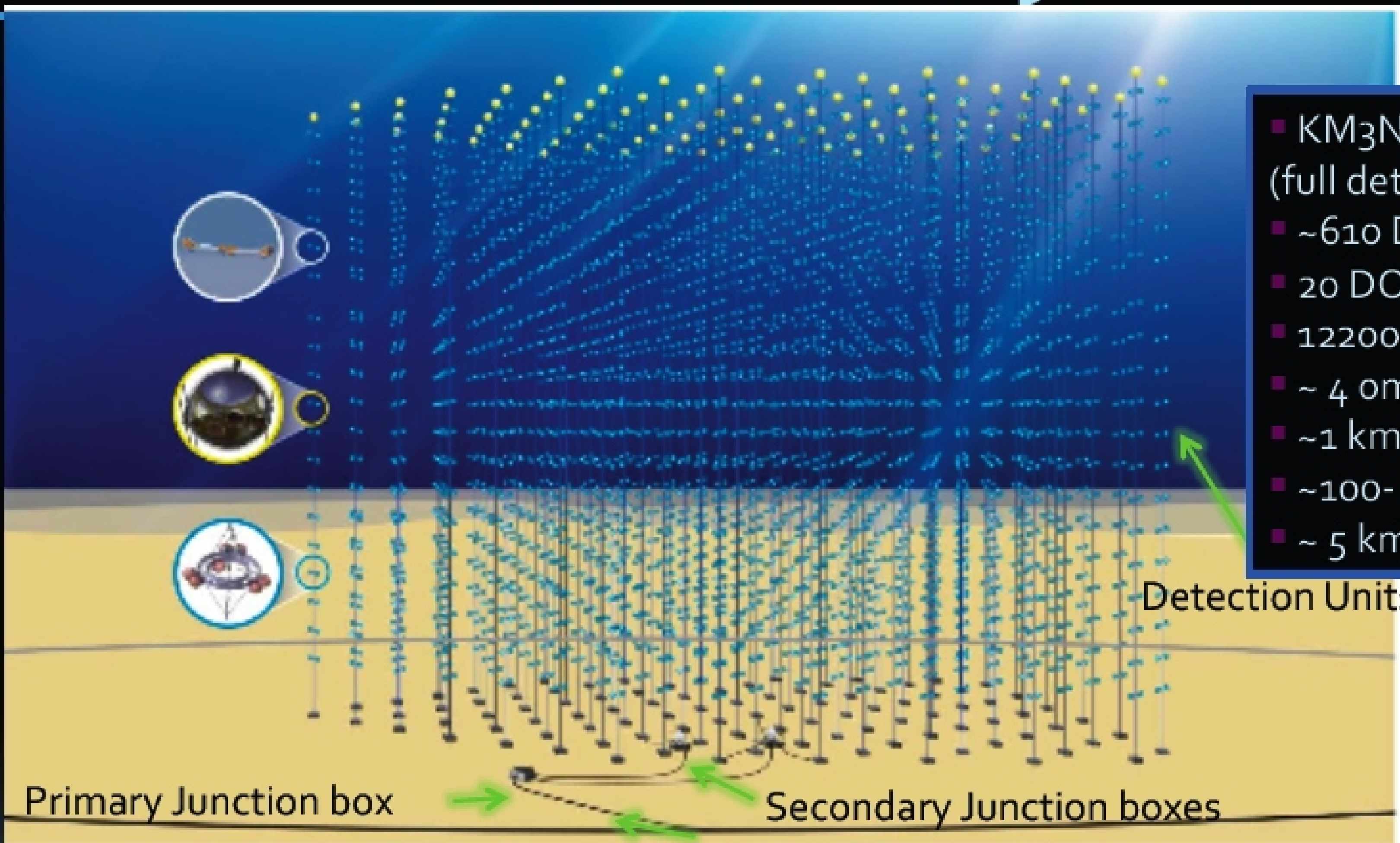
see:
Emilio Migneco
(friday)





90°
-90°
180°
-180°
PWNe
SNRs
No counterparts
Molecular clouds
Others
Binary Systems
AGNs
MRK 421
M 87
MRK 501
northern hemisph.
southern hemisph.
Geminga
IC 443
Cas A
Crab
PKS 2005
PKS 2155
MGRO J2019+37
MGRO J1908+06
HESS J1825-137
RX J1713.7-3946
MSH 15-52
HESS J1303-638
RX J0852.0-4622
Vela X
0°
60°
30°
0°
-30°
-60°
-90°

KM3NeT lay-out



- KM3NeT in numbers (full detector)
- ~610 DU
- 20 DOM/DU
- 12200 DOM
- ~ 40m DOM spacing
- ~1 km DU height
- ~100- 180 m DU distance
- ~ 5 km^3 volume

Electro-optical cable

Optical Module (OM) = pressure resistant/tight sphere cointaining photo-multplier
Detection Unit (DU) = mechanical structure holding OMs, enviromental sensors, electronics,... *DU is the building element of the telescope*
Construction in several blocks => Multi-site option

It is wrong to talk about:

NEUTRINO ASTRONOMY

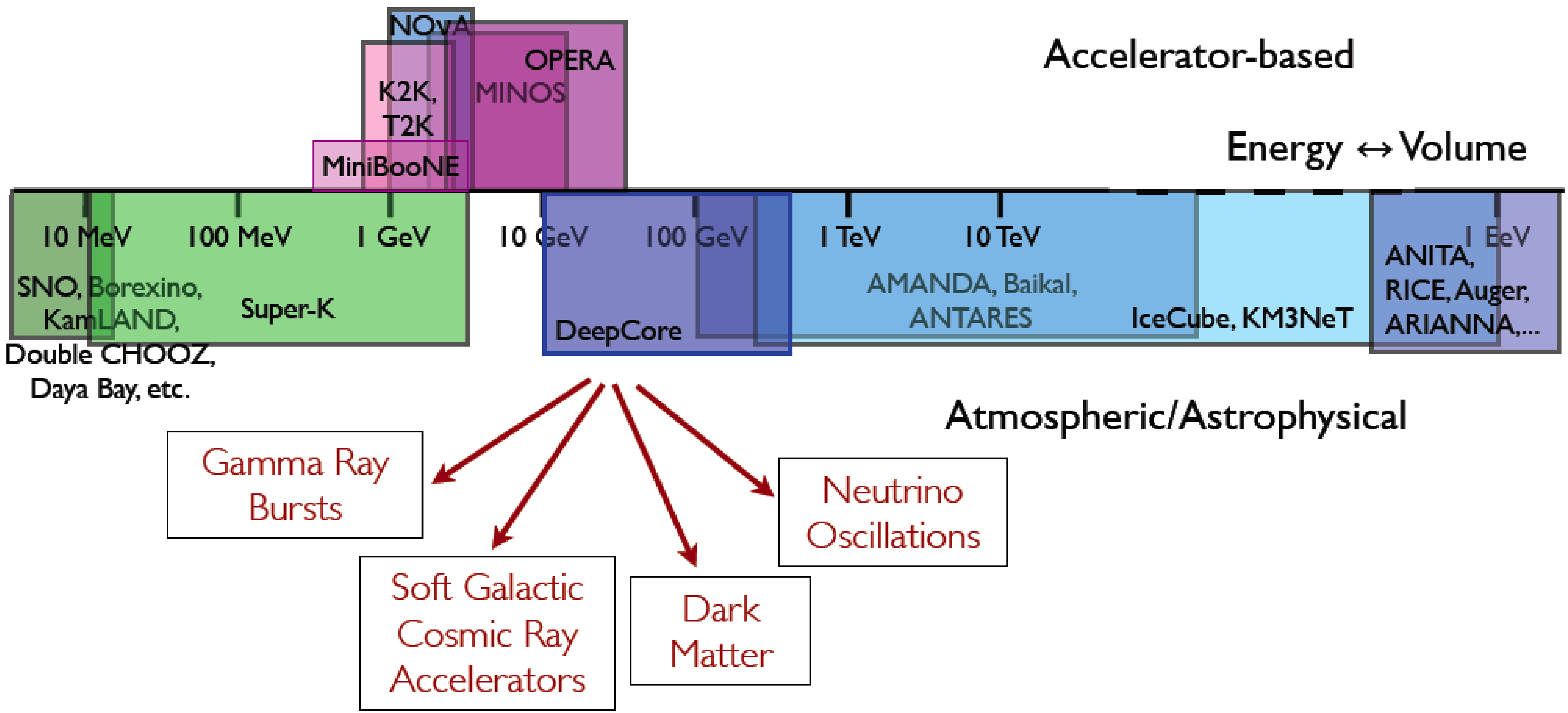
We should talk about

NEUTRINO ASTRONOMIES

10-100 GeV (DM)
1-100 TeV (Galactic Sources)
EeV (Radio, EAS...)

....

Deep Core


NOvA
OPERA
K2K,
T2K
MINOS
MiniBooNE
Accelerator-based
Energy ↔ Volume
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
1 EeV
SNO, Borexino,
KamLAND,
Double CHOOZ,
Daya Bay, etc.
Super-K
DeepCore
AMANDA, Baikal,
ANTARES
IceCube, KM3NeT
ANITA,
RICE, Auger,
ARIANNA,...
Atmospheric/Astrophysical
Gamma Ray Bursts
Soft Galactic Cosmic Ray Accelerators
Dark Matter
Neutrino Oscillations

Neutrino Astronomy: beyond the "Km3 concept"

Radio, Acoustic,.....

Radio Detection of neutrinos

ANITA-II over Antarctica

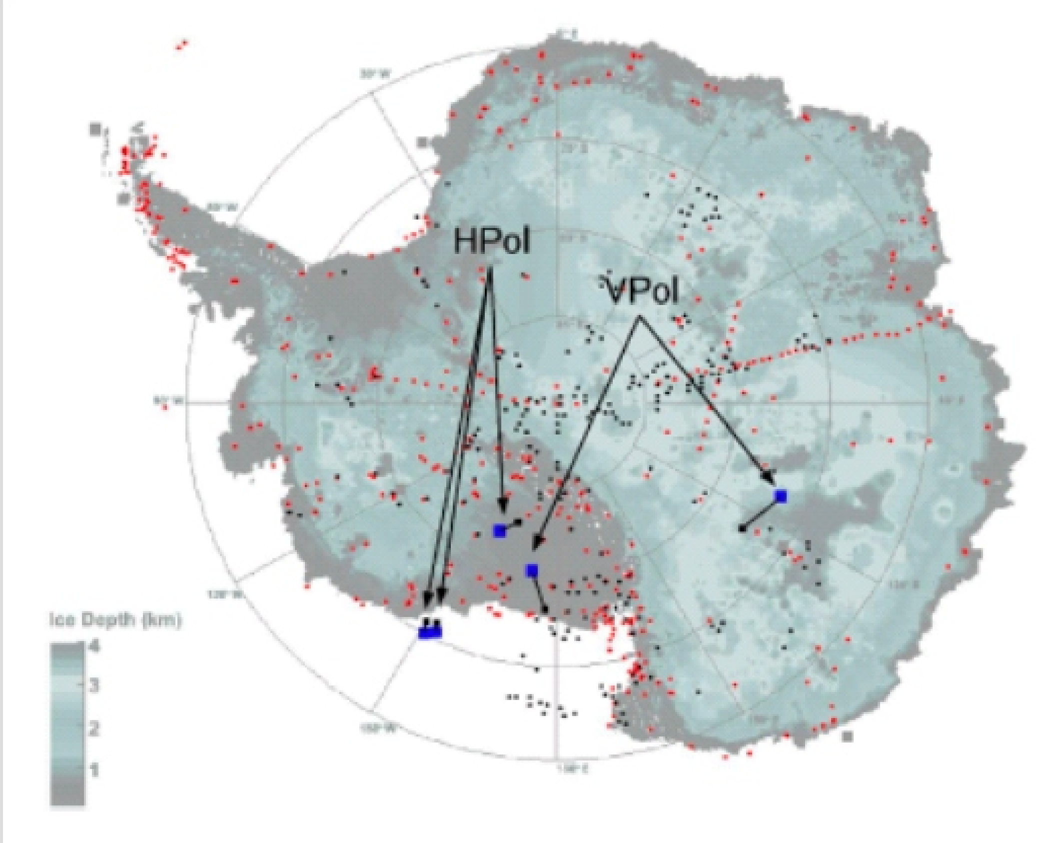


FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

Vpol:1 neutrino candidate;

HPol:3 >5 1019 eV

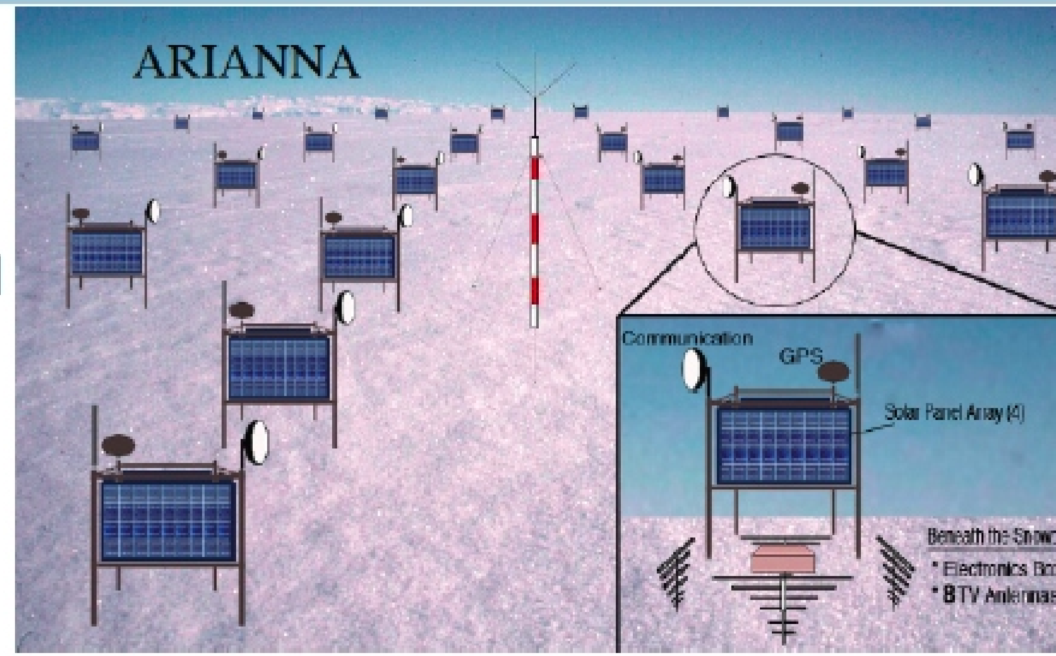
http://arxiv.org/abs/1003.2961

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

ARIANNA

- L. Gerhardt et al., Nucl.Instrum.Meth. A624 (2010) 85-91
- Poster 18-3: J. Tatar. S. Barwick

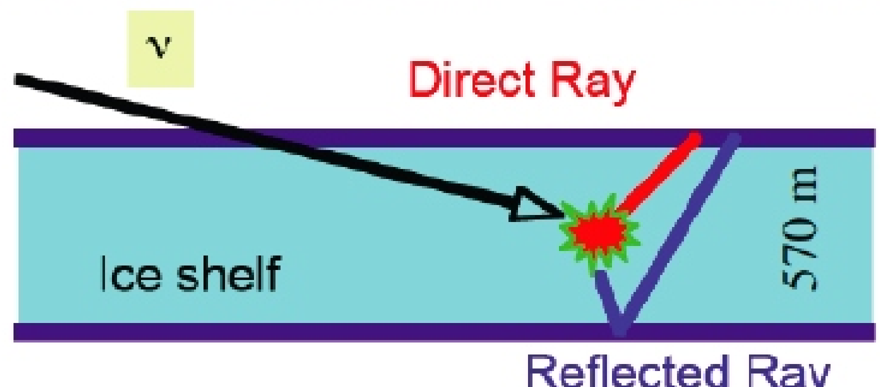
31 x 31 array
[30 km x 30 km]



ARIANNA

US, S. Korea, England, New Zealand

Barwick, astro-ph/0610631



Programs for the future:

Cosmic Rays:

Clarify the nature and origin of the highest energy particles.
Study transition of the Galactic and extra-galactic populations.

Gamma Astronomy:

Development of the Cherenkov Telescope Array (CTA)
Higher sensitivity, full aperture Air Shower Array.

Neutrino Astronomy:

Open this fascinating new window.
IceCube taking data....
Programs in the Mediterranean Sea (define the design)
Ideas in development at very high energy

The idea of constructing an instrument
that is at the same time:

a **Gamma Ray Telescope**

a **High Energy Cosmic Ray Detector**

is natural and very attractive.

There is space for significant improvement over
Existing measurements.

[but a more detailed study is required to estimate
the impact of the current LHAASO project as CR detector.]