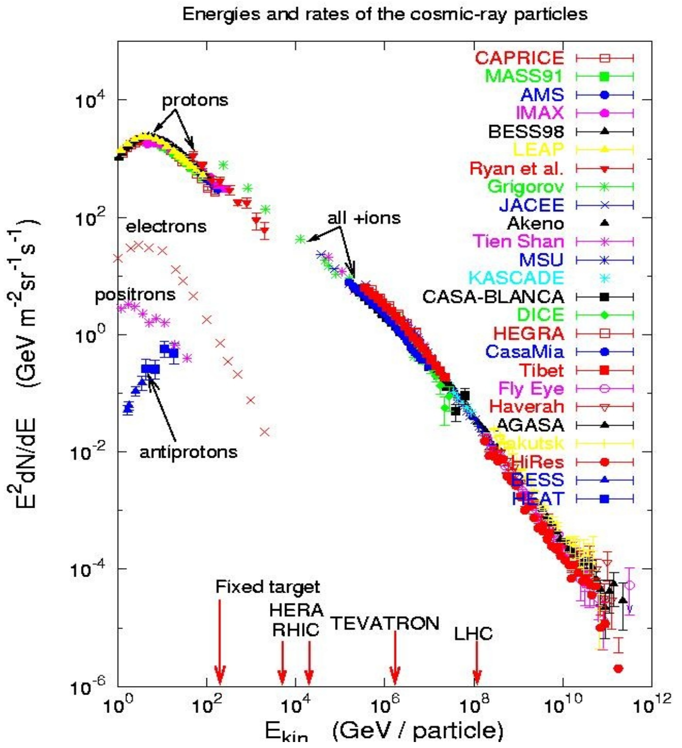
Cosmic Rays

open problems



Possible physical significance of new measurements in the energy region from the “Knee” to the “Ankle”.

Paolo Lipari
Workshop for LHAASO
Roma 20th july 2011

Project Overview

LHAASO

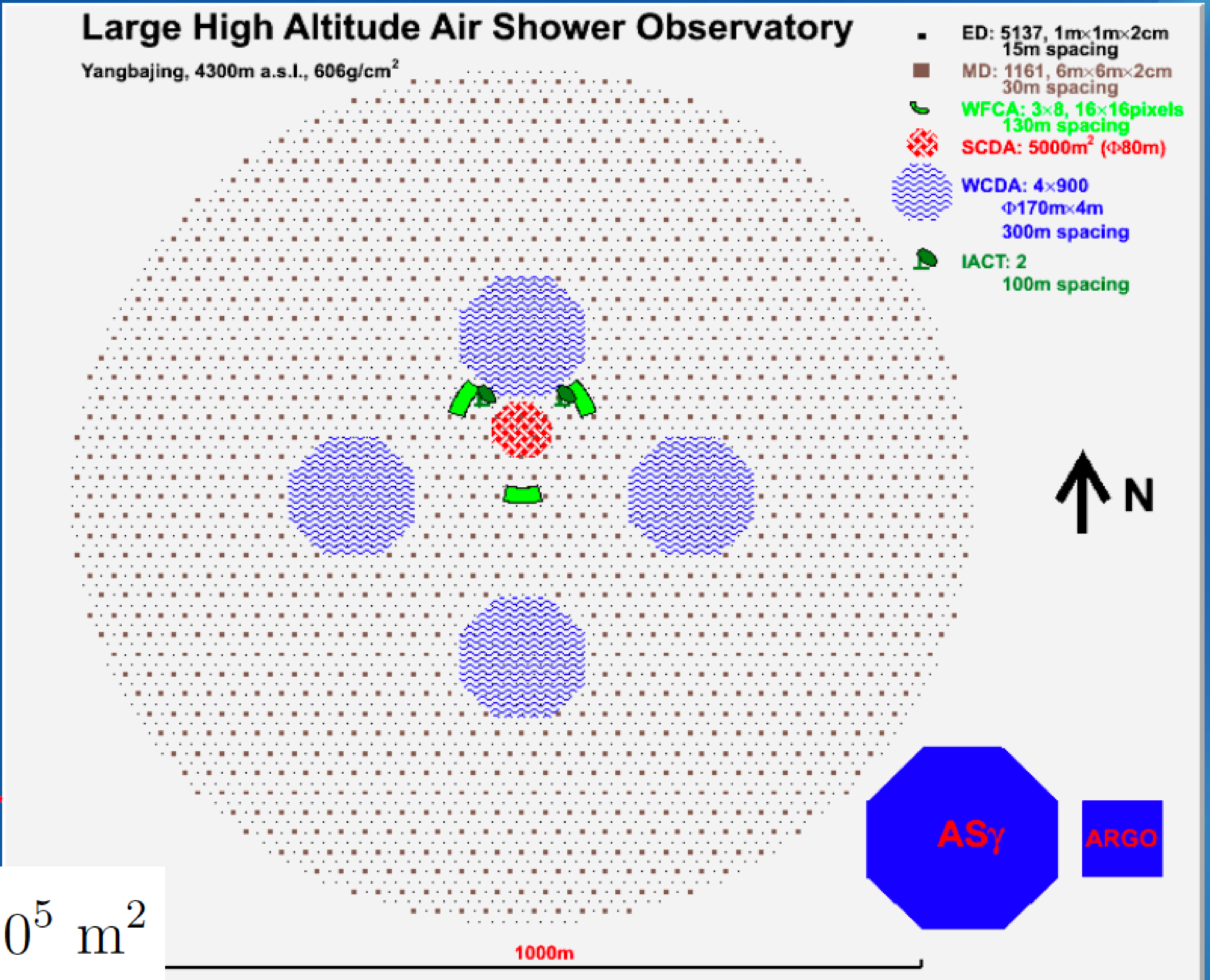
Charged Particle Array

Detector Array

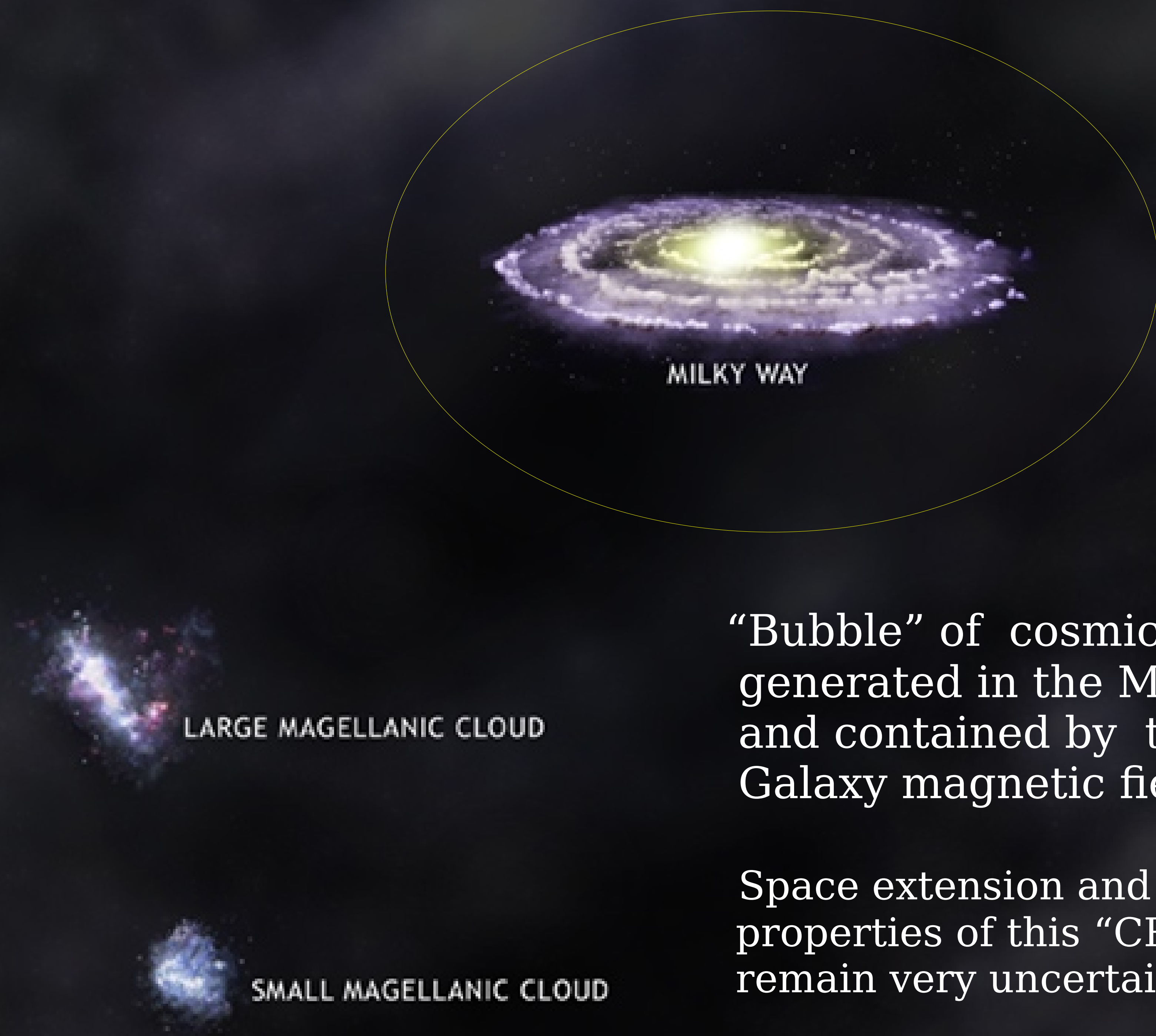
Water C Array

Wide FOV C-Telescope Array
&

Core Detector Array



$$A \simeq 8 \times 10^5 \ \mathrm{m}^2$$



"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

Galactic Cosmic Rays

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

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

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

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

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

Different particles

Injection
of cosmic rays

Containment
time

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]

Source
Identification !

Maximum Energy of the
Galactic CR sources
“PeV-atrons” (10^{15} eV)
“EeV-atrons” (10^{18} eV)

Injection
of cosmic rays

Containment
time

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

Competition of different times:

$$T_{\rm int}^{p,A}(E) \propto [\sigma_j(E)]^{-1} \sim \text{slowly varying}$$

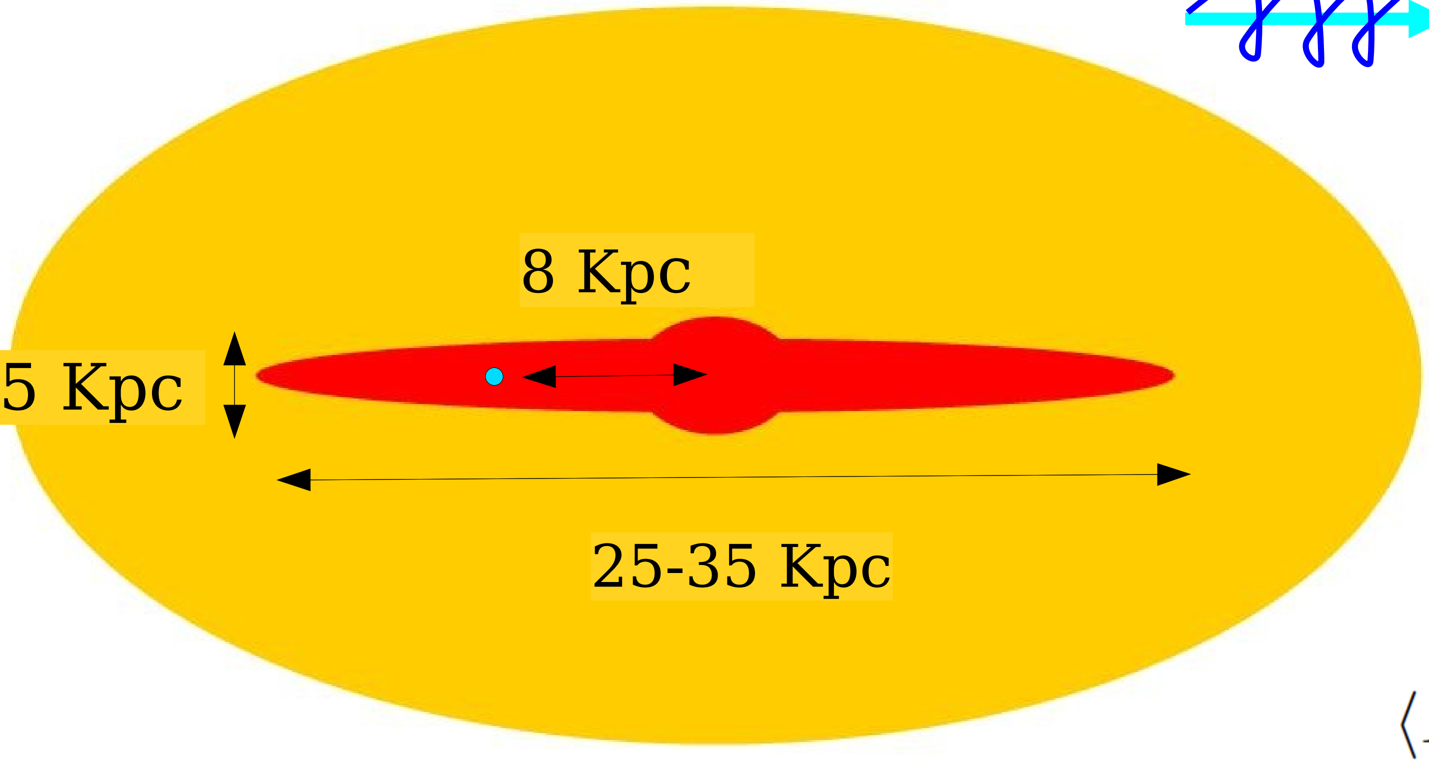
Interaction
(hadrons)

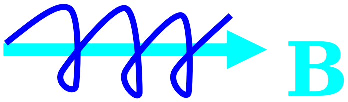
$$T_{\rm diffusion}\left(\frac{p\,c}{Z}\right) \propto \left(\frac{p\,c}{Z}\right)^{-\delta}$$

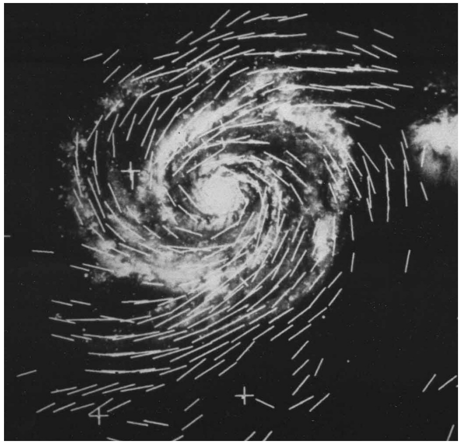
Escape
from Galaxy

$$T_{\rm loss}^{(e^{\mp})}(E) \propto \frac{1}{E}$$

Energy losses
(electrons/positrons)







$$r_L = \frac{p_\perp c}{q\,B}$$

$$\langle B_{\rm MW} \rangle \simeq 3\ \mu\mathrm{Gauss}$$

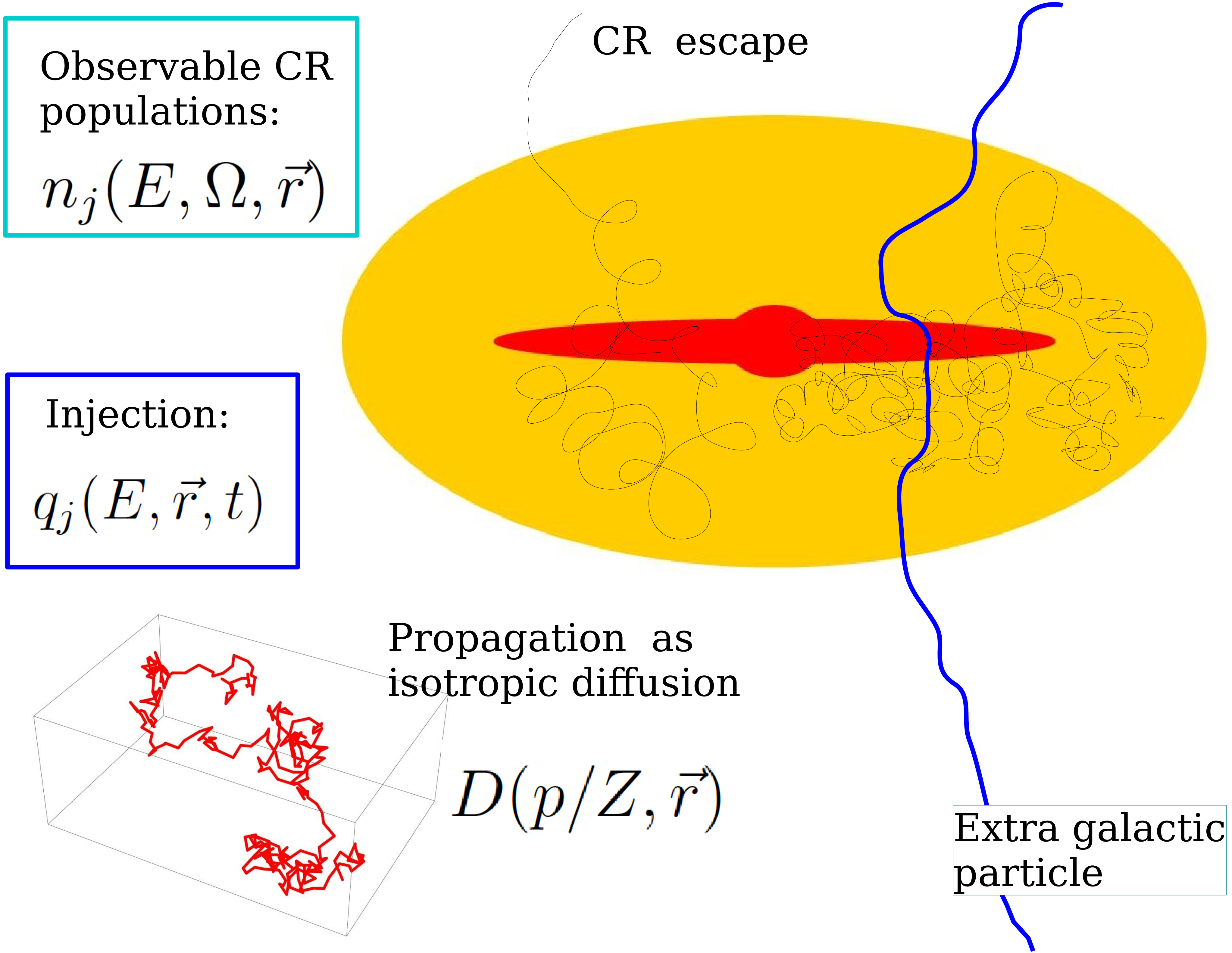
$$r_L = \frac{1.08\ \mathrm{Kpc}}{Z} \left[\frac{E}{10^{18}\,\mathrm{eV}}\right] \left[\frac{\mu\mathrm{Gauss}}{B}\right]$$

$$r^p_{\rm Larmor}(100\ \mathrm{GeV}) \simeq 3.6 \times 10^{-8}\ \mathrm{Kpc}$$

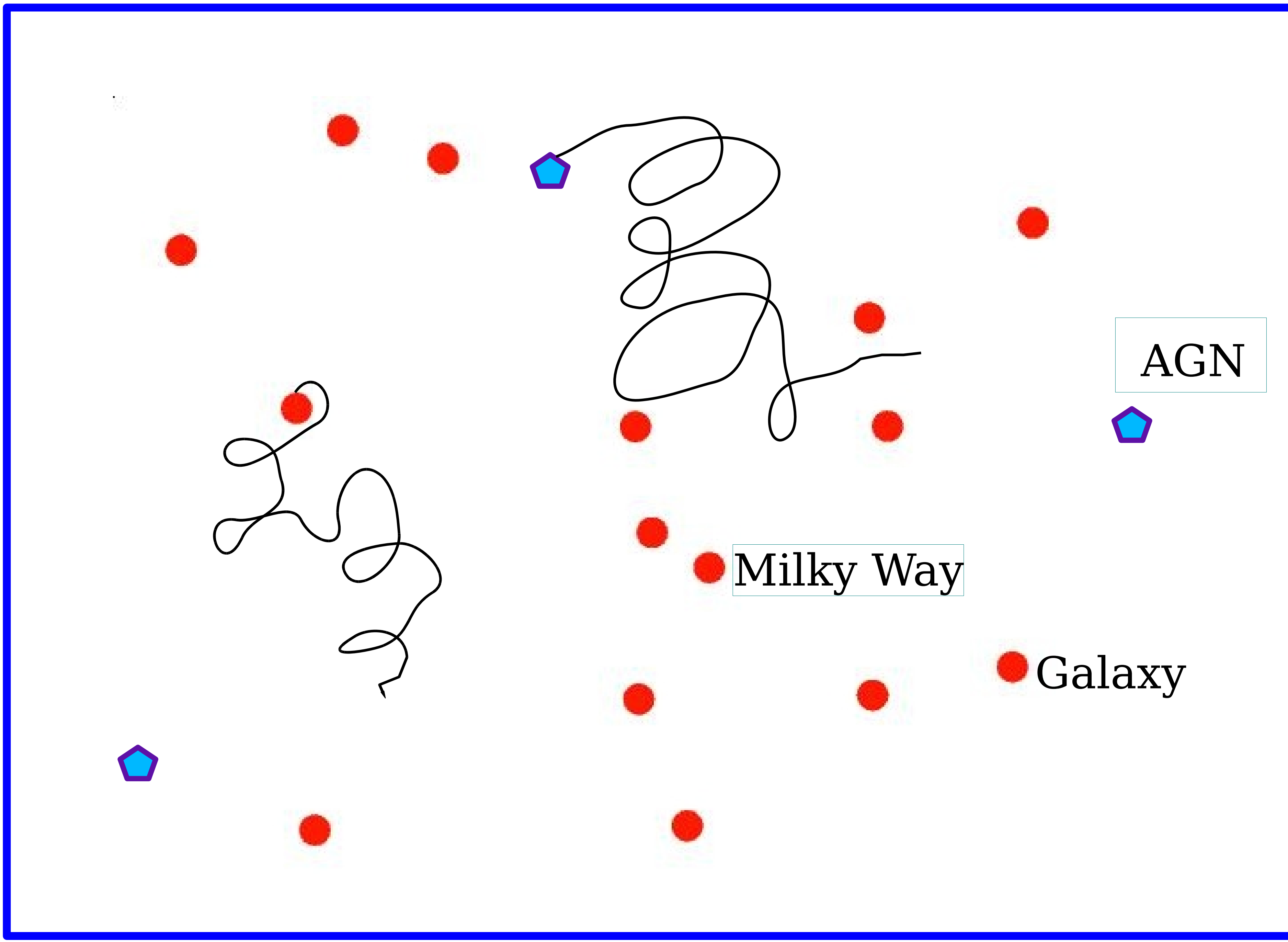
$$r^p_{\rm Larmor}(10^{20}\ \mathrm{eV}) \simeq 36\ \mathrm{Kpc}$$

$$r^{\rm Fe}_{\rm Larmor}(10^{20}\ \mathrm{eV}) \simeq 1.4\ \mathrm{Kpc}$$

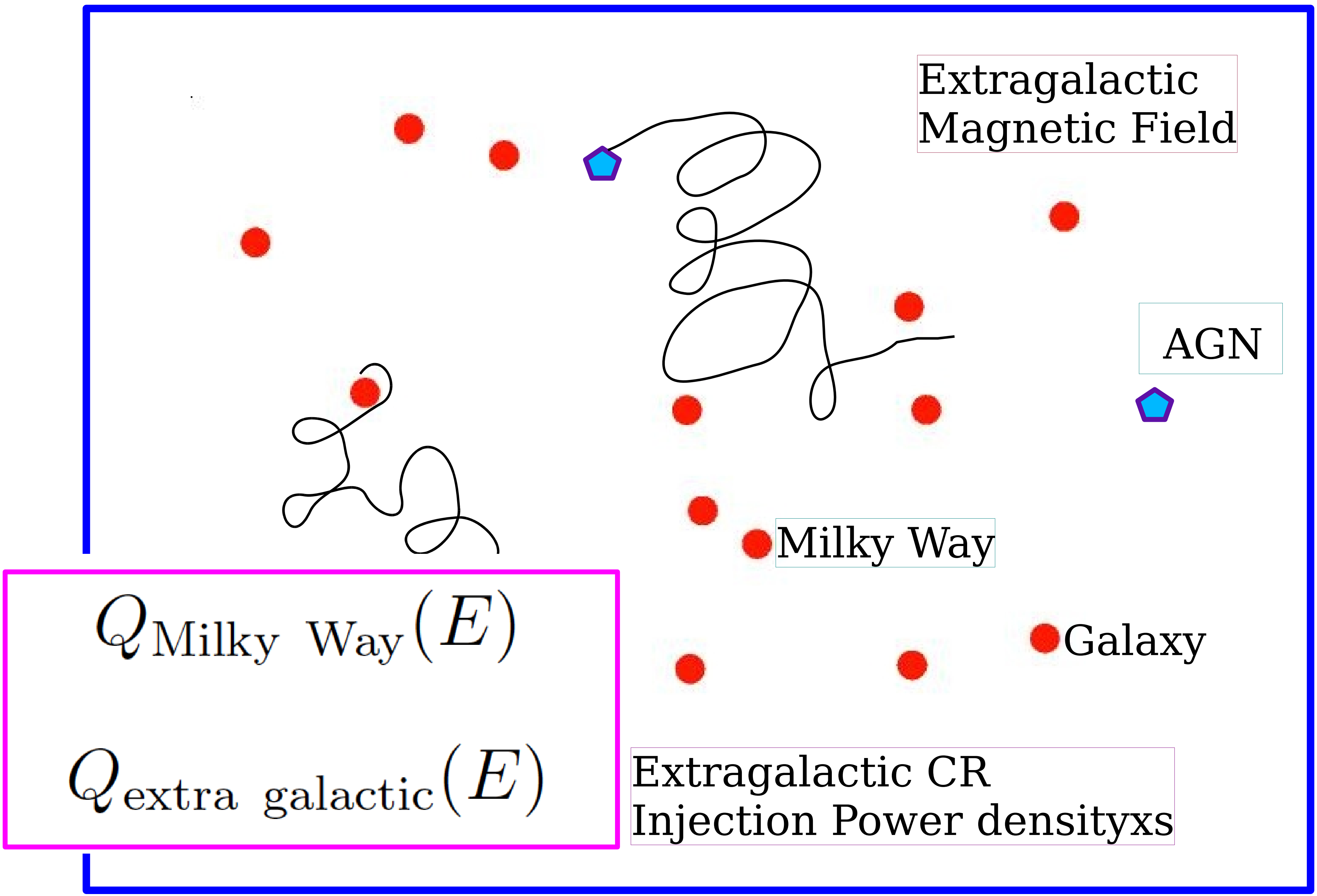
- Diffusion approximation
- Maximum energy for containment


Observable CR populations:
$n_j(E, \Omega, \vec{r})$
CR escape
Injection:
$q_j(E, \vec{r}, t)$
Propagation as isotropic diffusion
$D(p/Z, \vec{r})$
Extra galactic particle

Piece of extragalactic space: Non MilkyWay-like sources



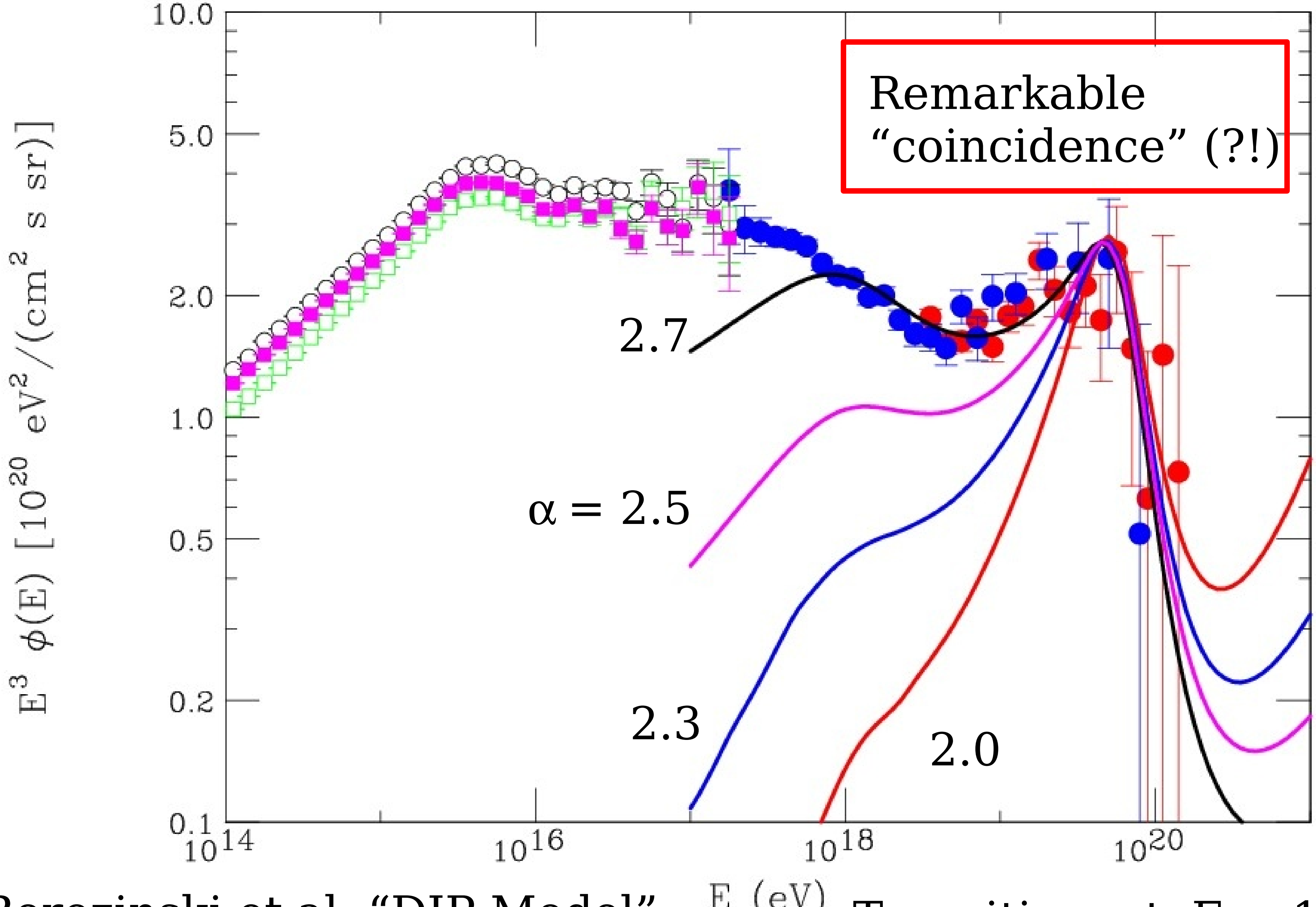
Piece of extragalactic space: Non MilkyWay-like sources



The Galactic
to Extragalactic
Transition

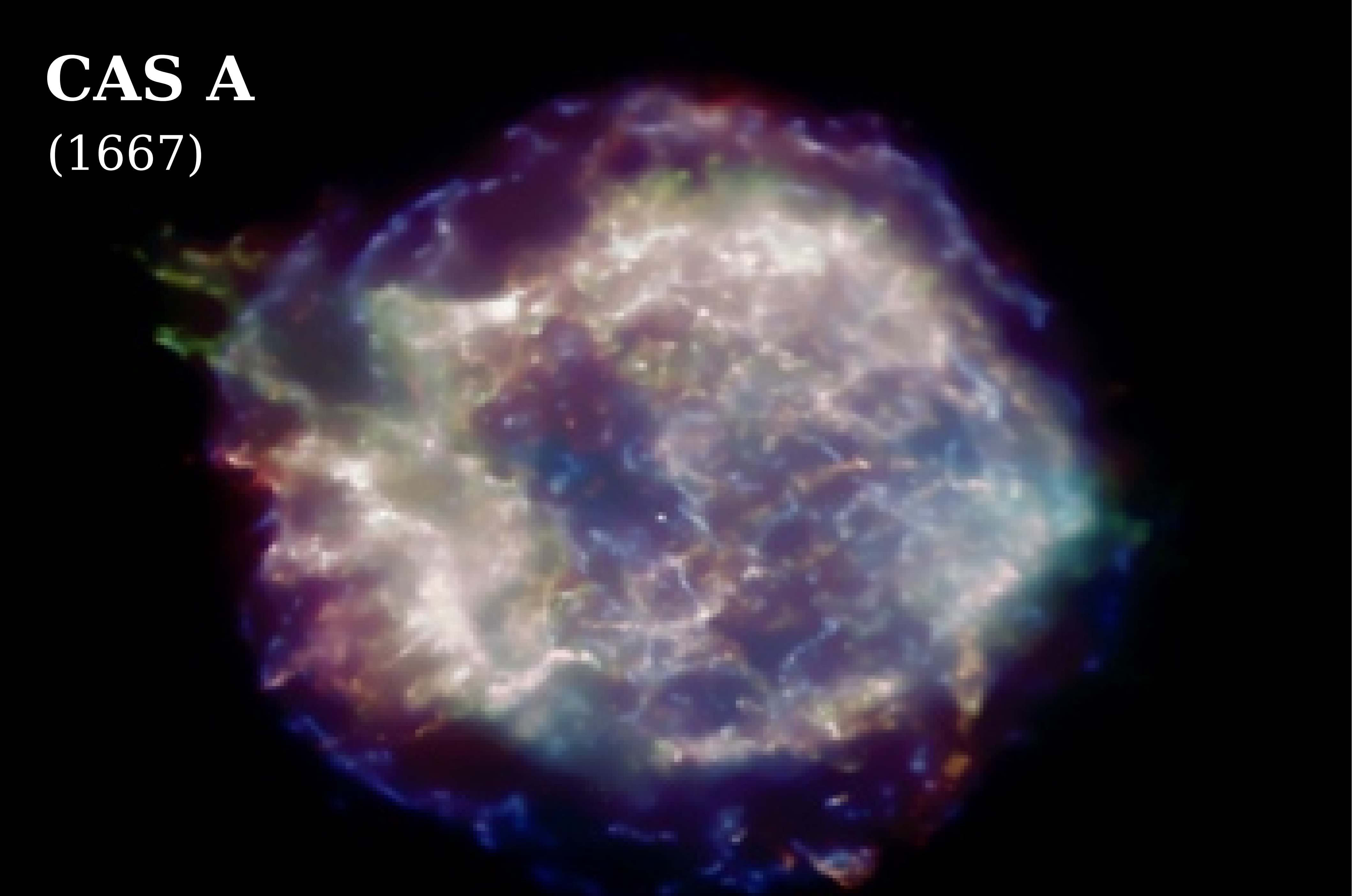
is emerging as a crucial problem for CR science.

Power Law Injection (No Cosmic Evolution)

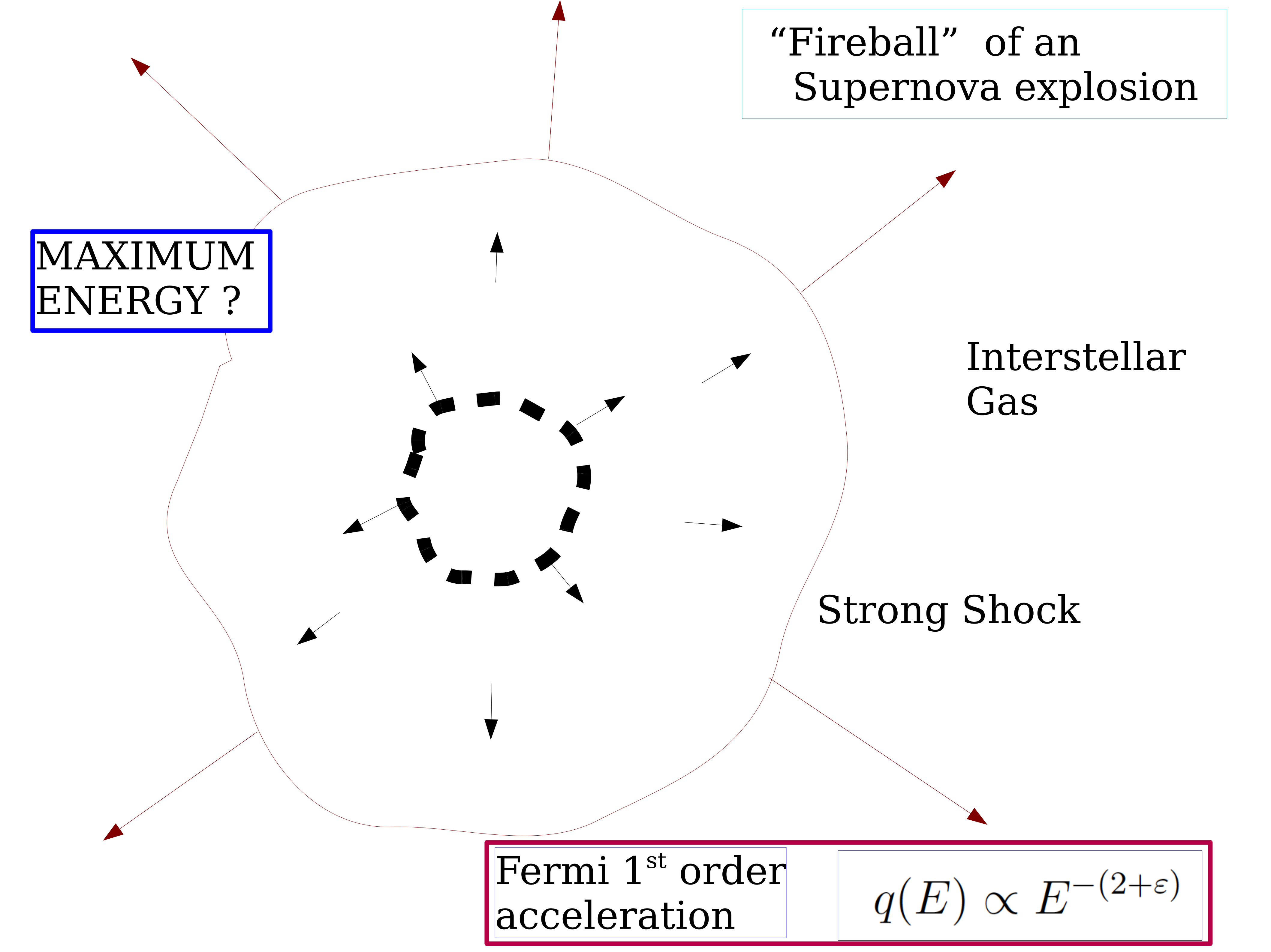


Berezinski et al "DIP Model"

Transition at $E = 10^{18}$ eV



The SuperNova Paradigm


“Fireball” of an
Supernova explosion
MAXIMUM
ENERGY ?
Interstellar
Gas
Strong Shock
Fermi 1st order
acceleration
$q(E) \propto E^{-(2+\varepsilon)}$

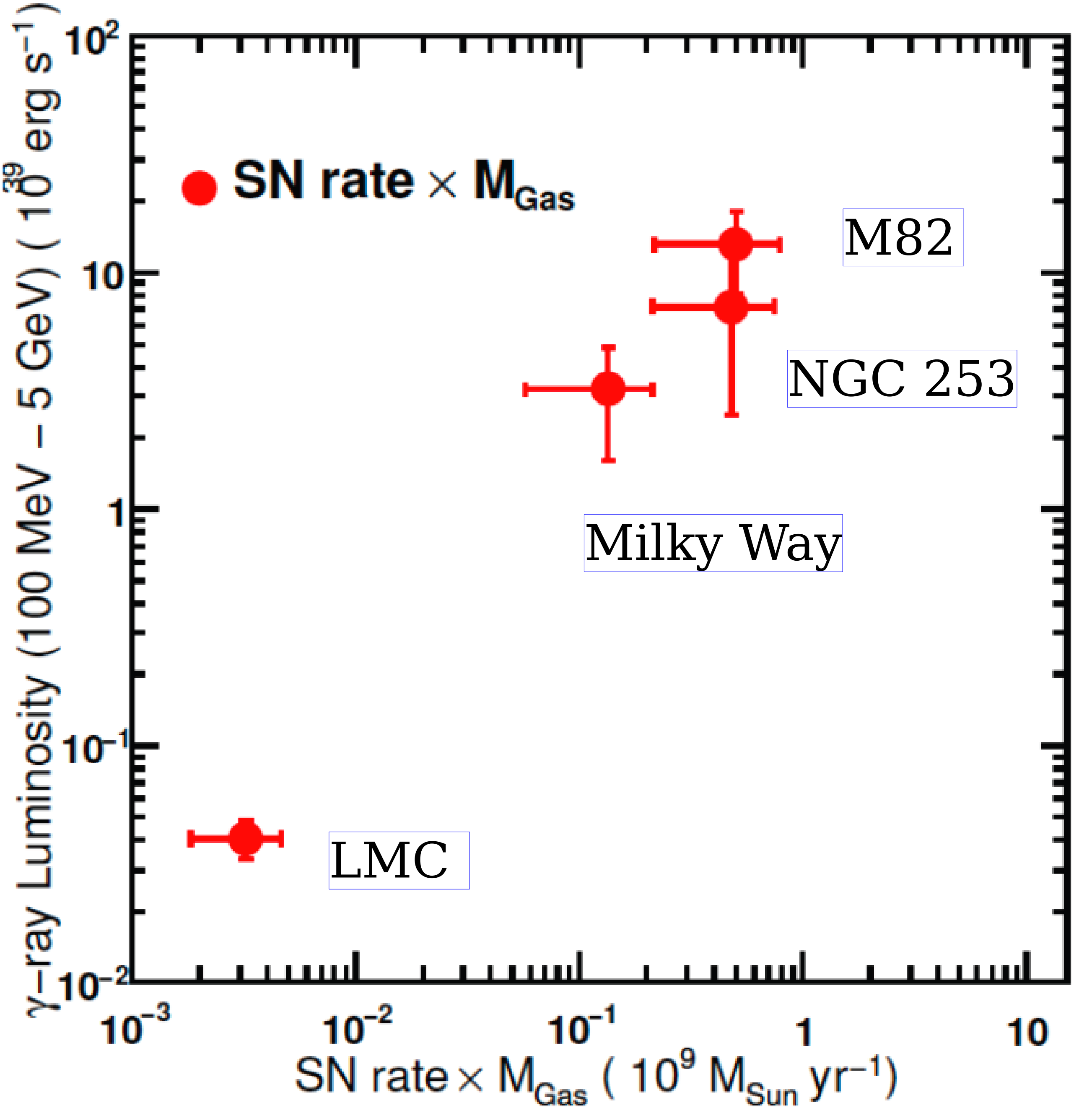
FERMI Telescope work:

Detection of Starburst galaxies

Gamma Ray Luminosities (> 100 MeV)

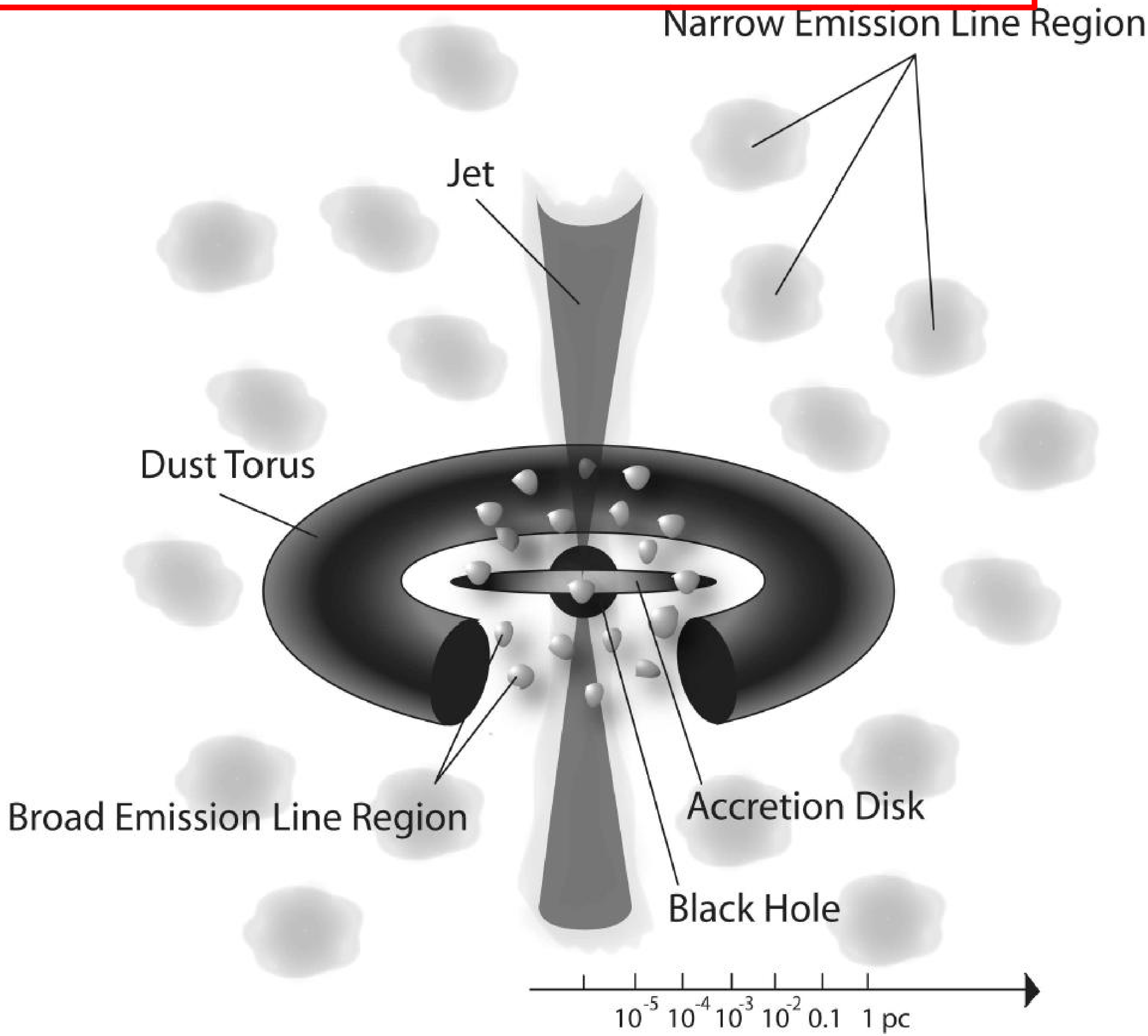
$$p + p_{\rm ISM} \to \pi^\circ$$

$$\pi^\circ \to \gamma\gamma$$

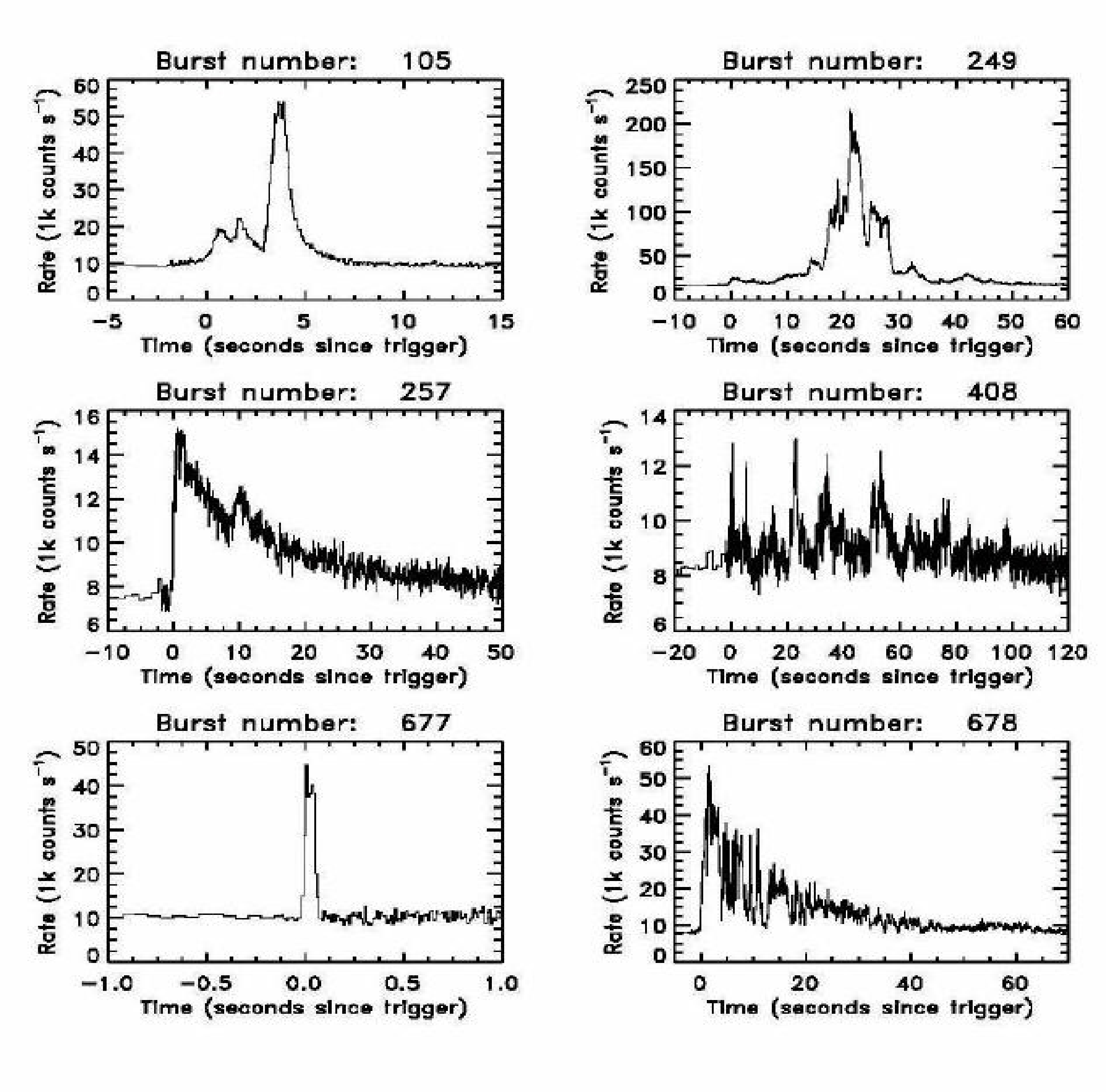


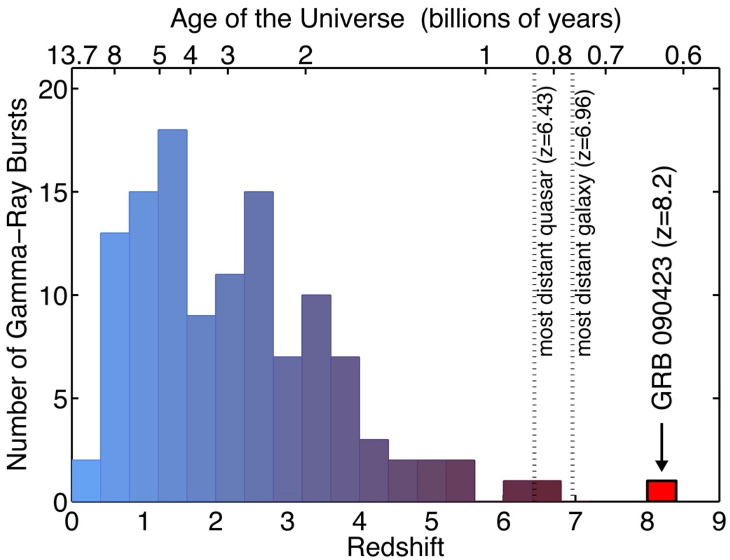
The Acceleration of CR is correlated to the Star Formation Rate (and therefore Star "Death" Rate) Compatible with the "standard scenario".

ACTIVE GALACTIC NUCLEI

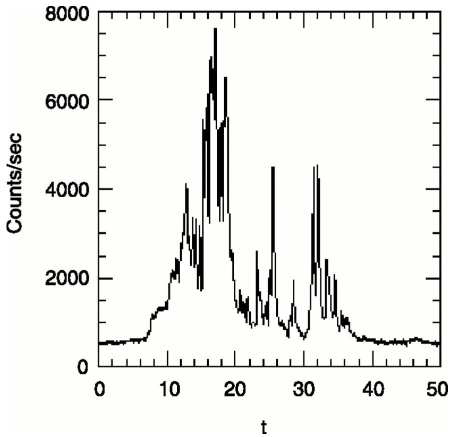


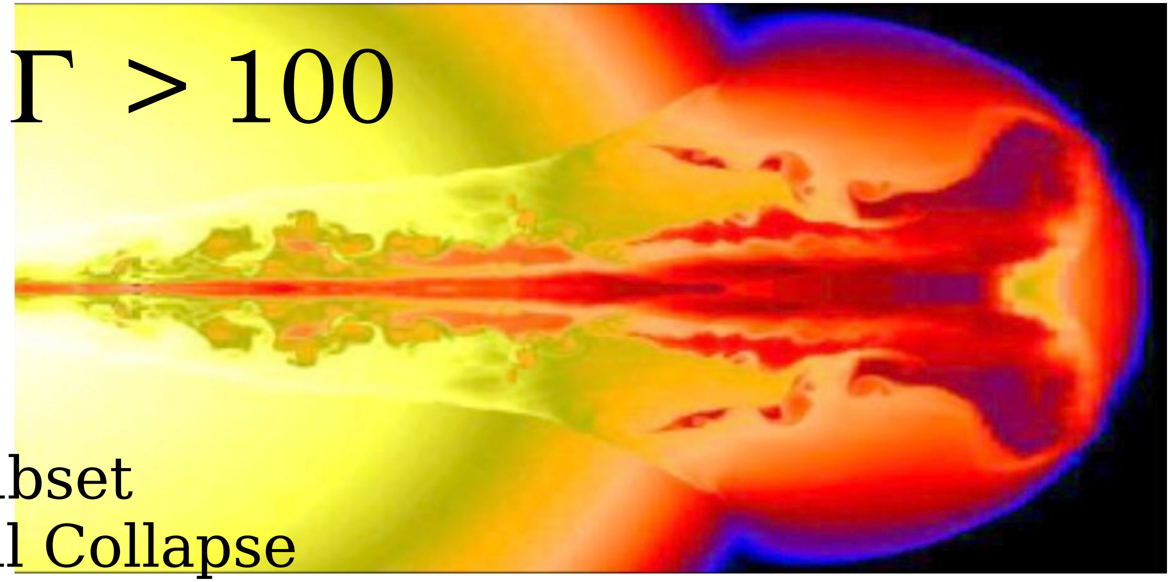
GAMMA RAY BURSTS (GRB's)



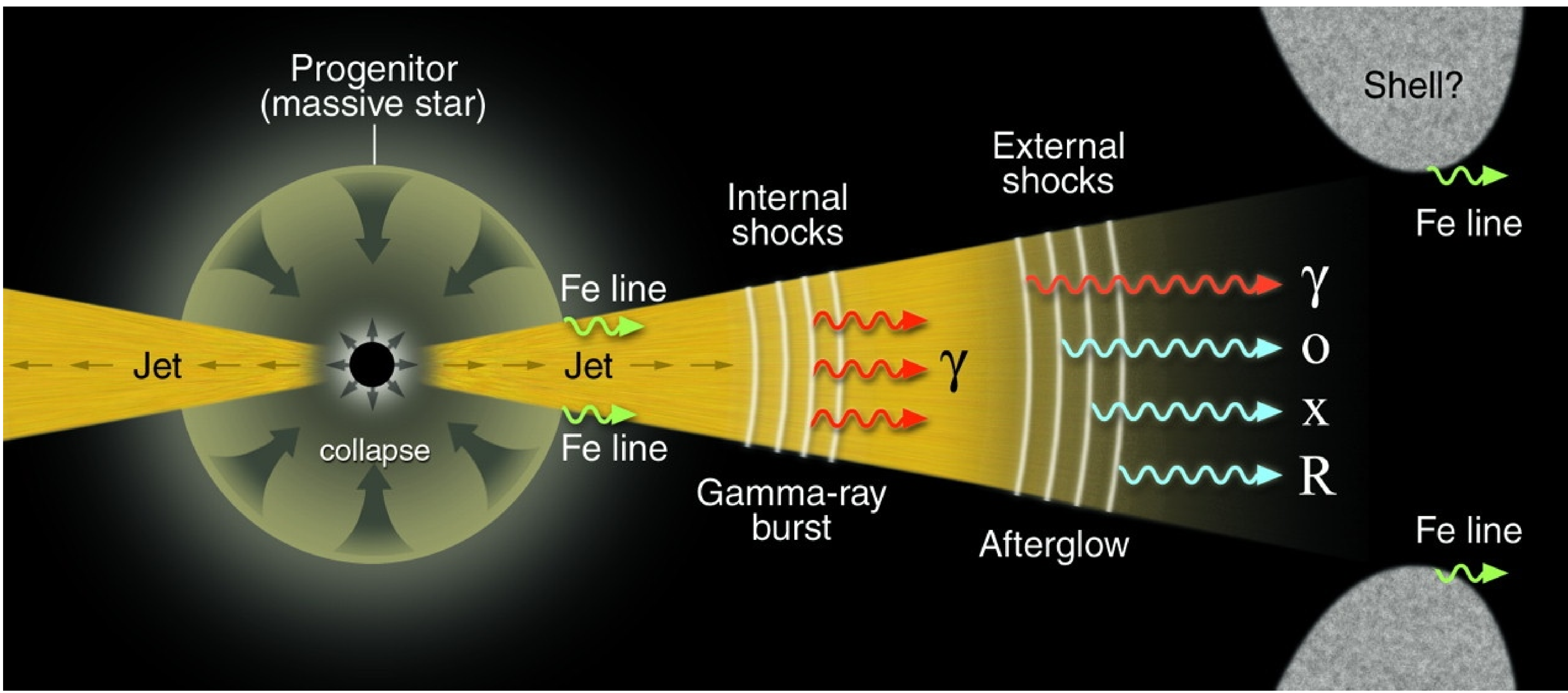


Proposed source
Of the CR





GRB : associated with a subset
of SN Stellar Gravitational Collapse



UHECR

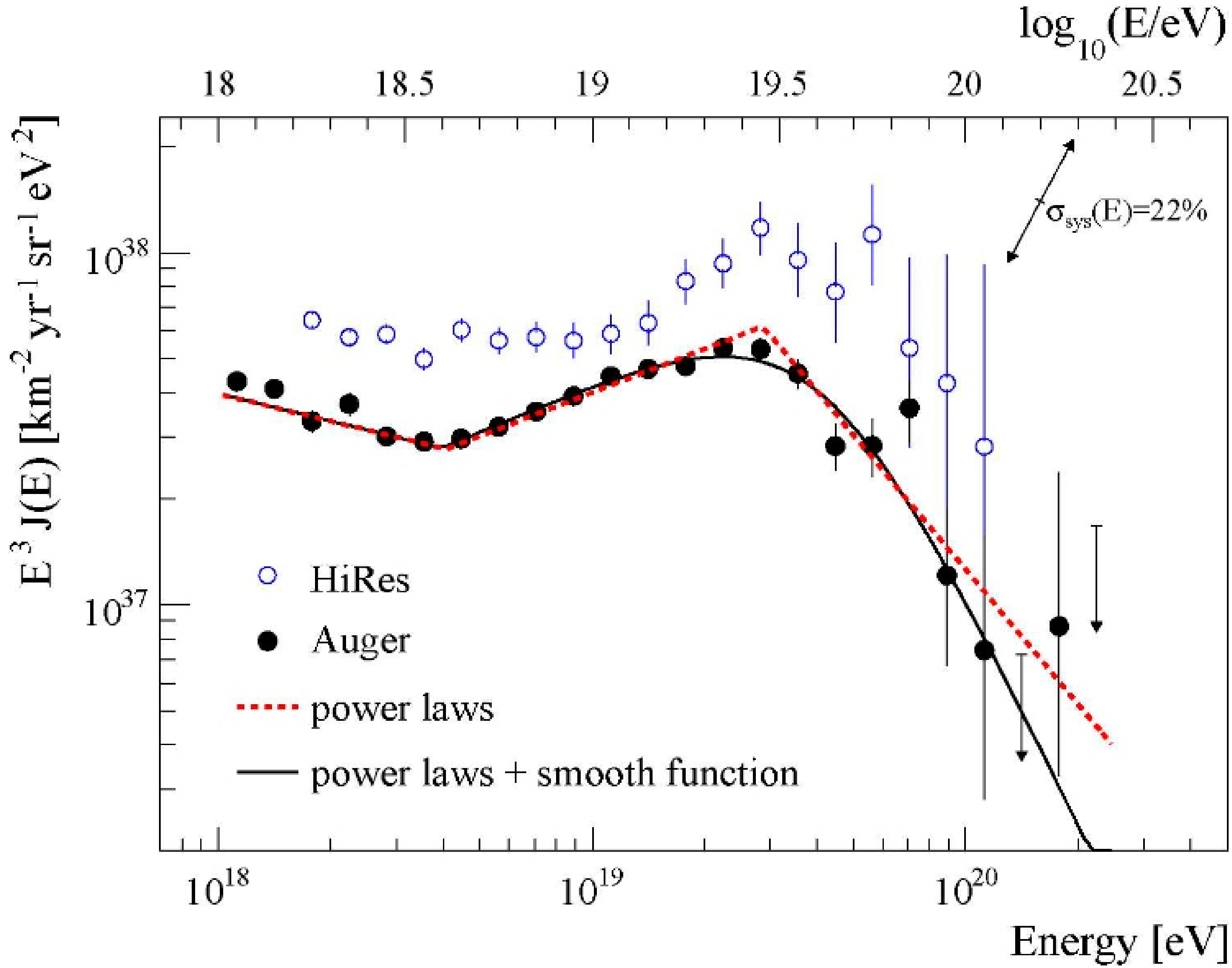
1. Energy Spectrum

- Clear identification of a high energy suppression
  [the "END" (... well the "suppression")
  of exotic/fundamental physics modeling for UHECR].

- Good agreement between experiments
  ["small" but important question about the energy scale].

- Physical interpretation strongly coupled to (2., 3.)
  (anisotropy + composition). [proton GZK ?]

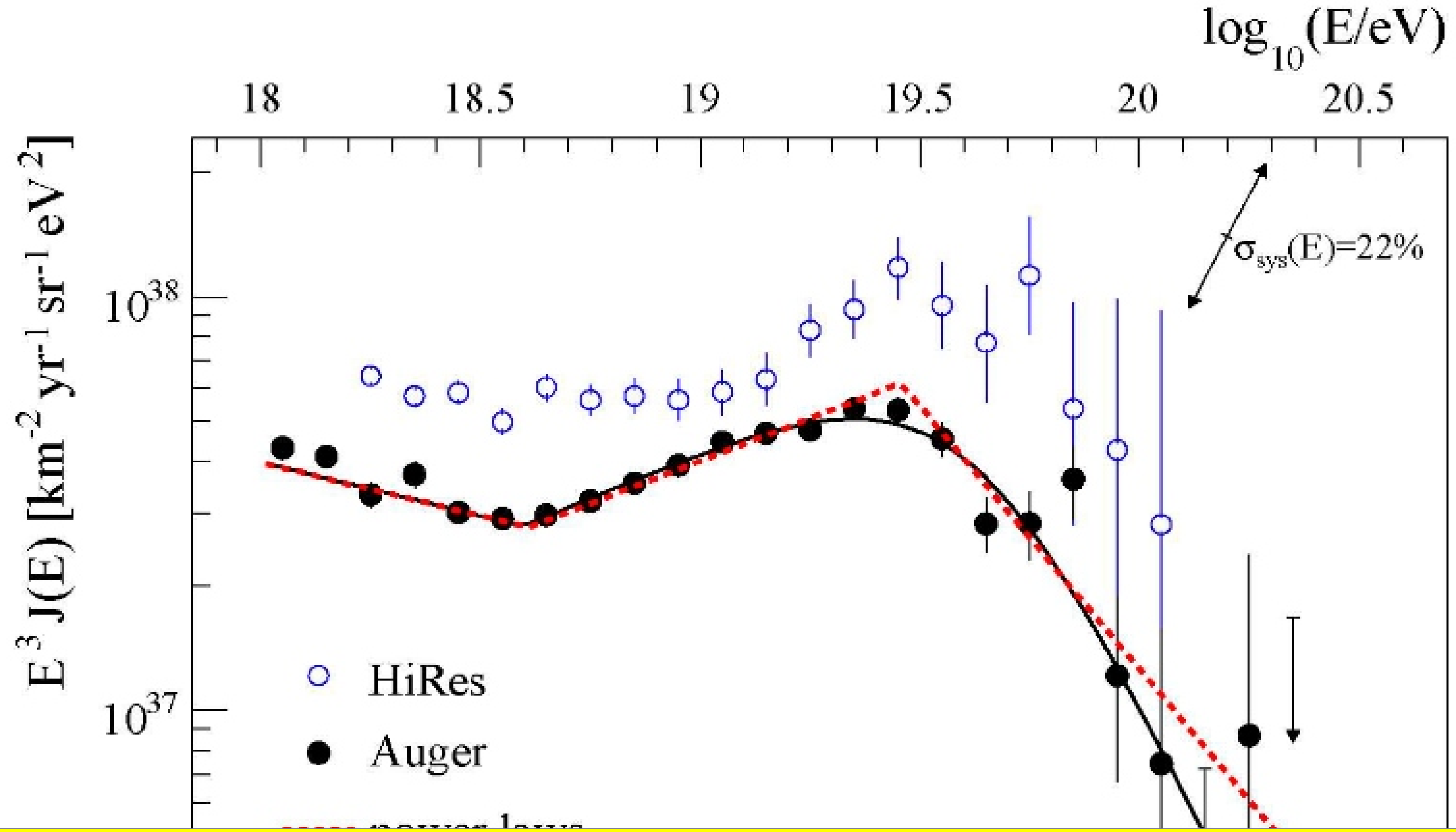
About 20 % energy scale difference !



HiRes/ TA – Auger observe the GZK suppression

But : problem on the energy scale

About 20 % energy scale difference !



HiRes/TA/Auger observe a High energy Suppression
That could be the GZK suppression
[or photo-disintegration of Iron]
[or Source Cutoff]

HiRes/ TA – Auger observe the GZK suppression

But : problem on the energy scale

UHECR

Crucial Problem:

Galactic
Extragalactic
Transition

1. Energy Spectrum

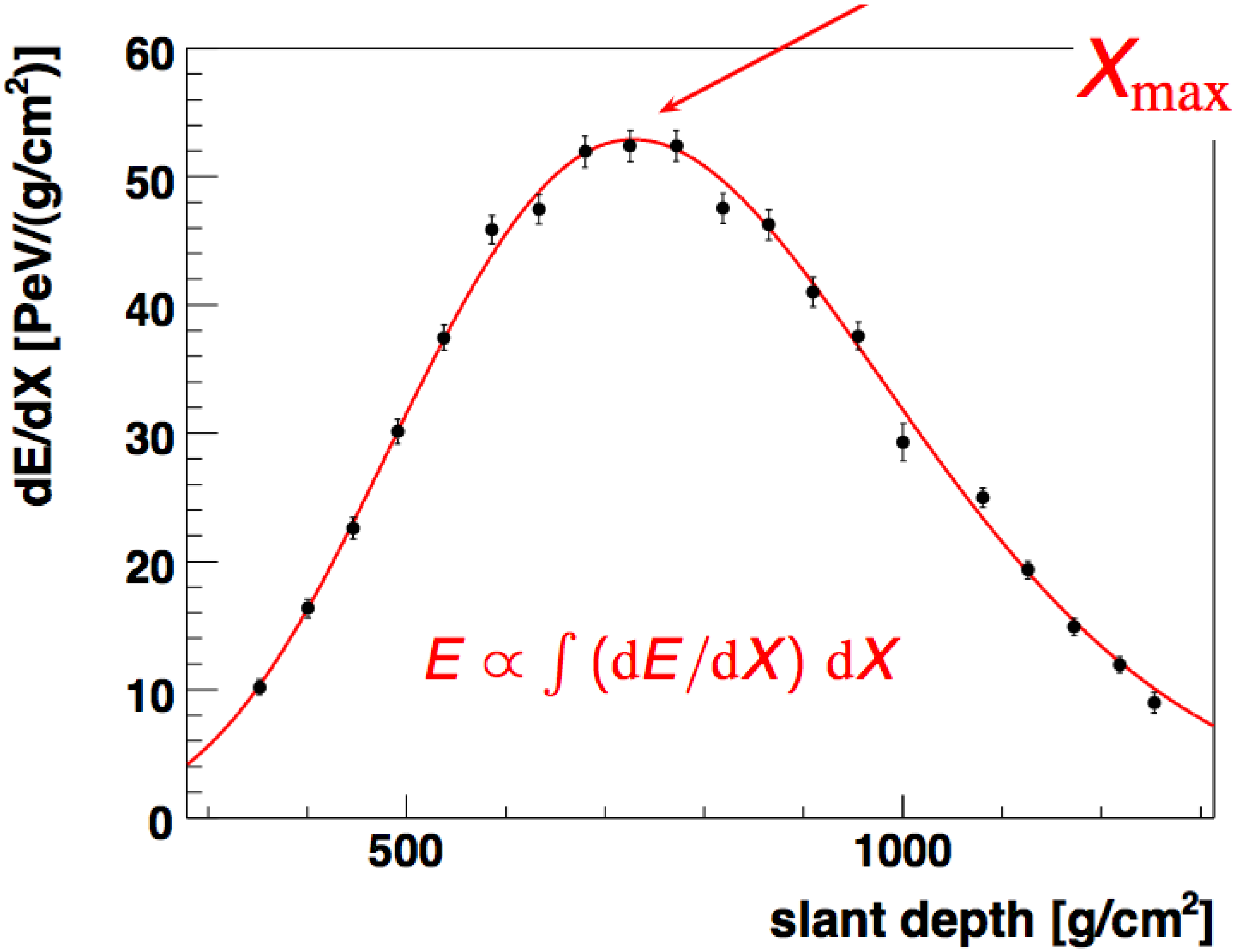
2. Anisotropy

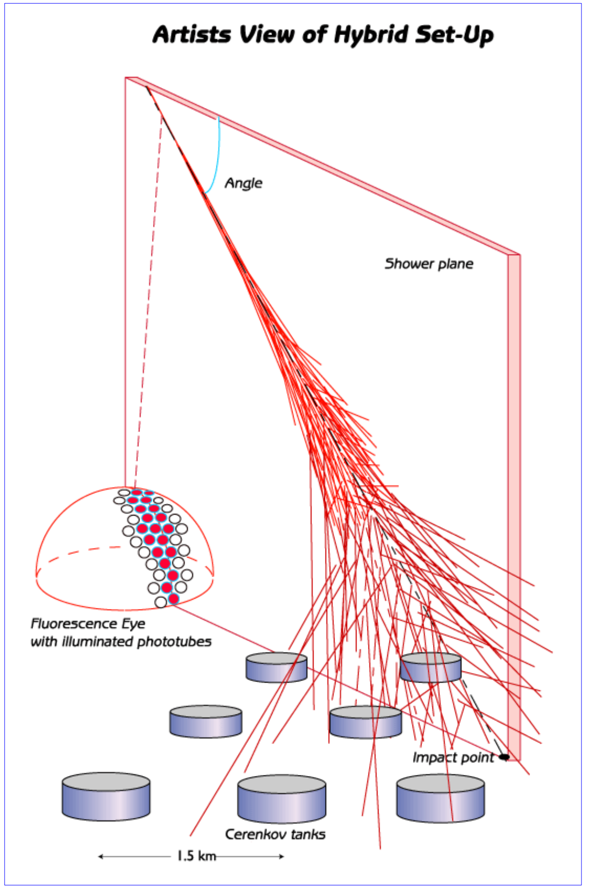
3. Composition

Significant
Experimental
Discrepancies

Auger/Hires/TA

Confusing
situation.

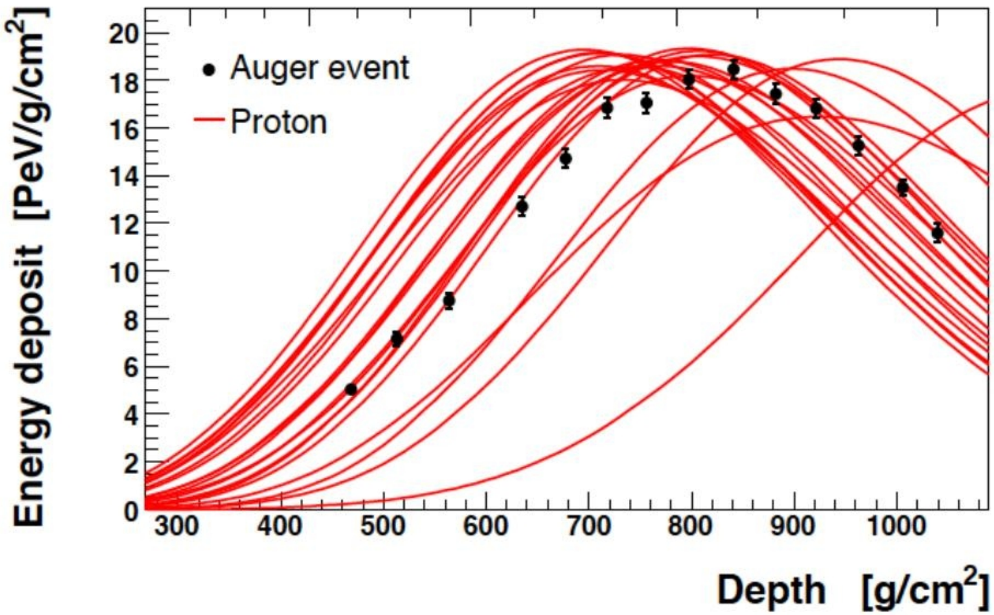




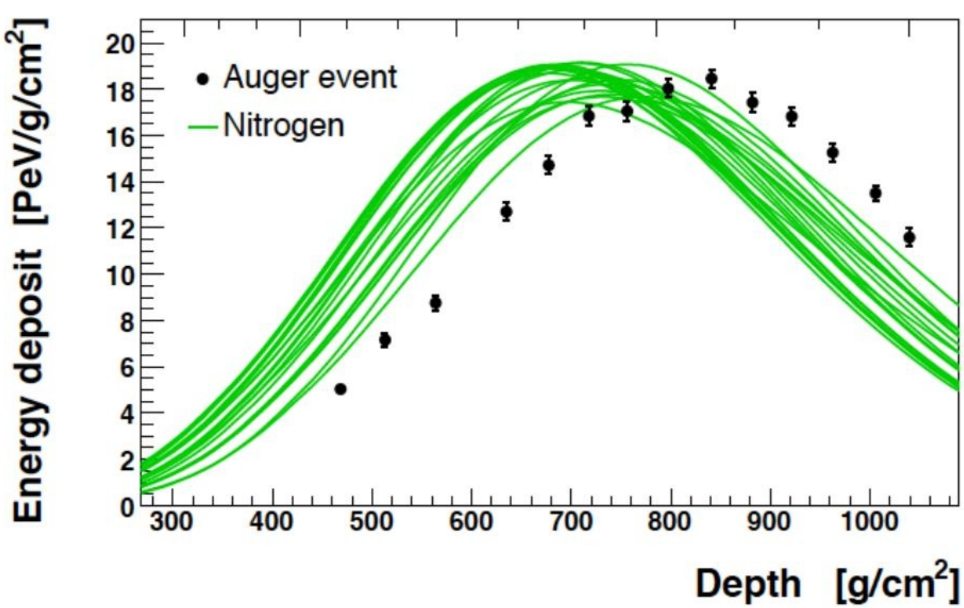
$$E_{\text{ionization}} = \int dX\ N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

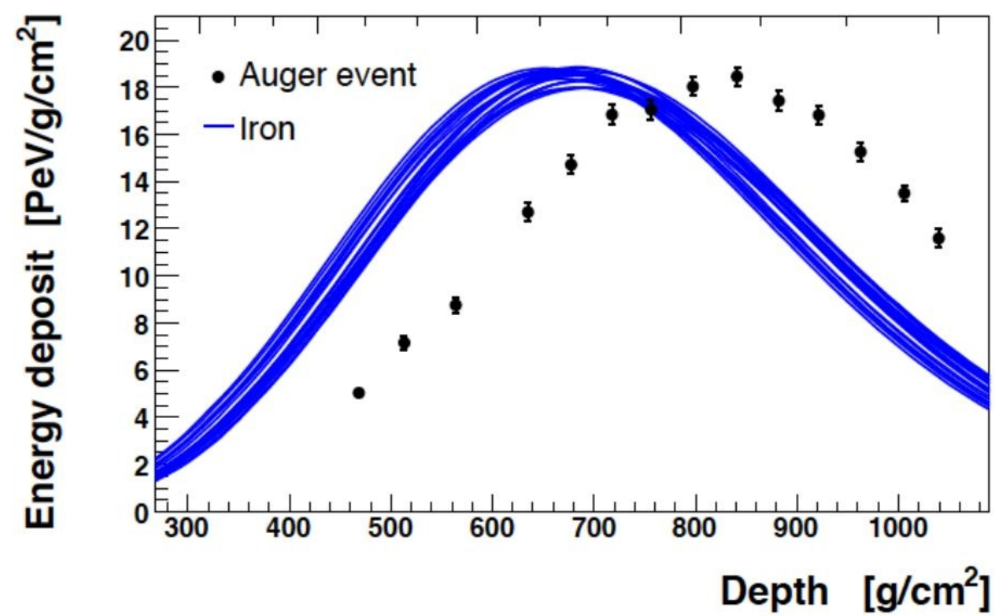
Area $\propto$ Energy

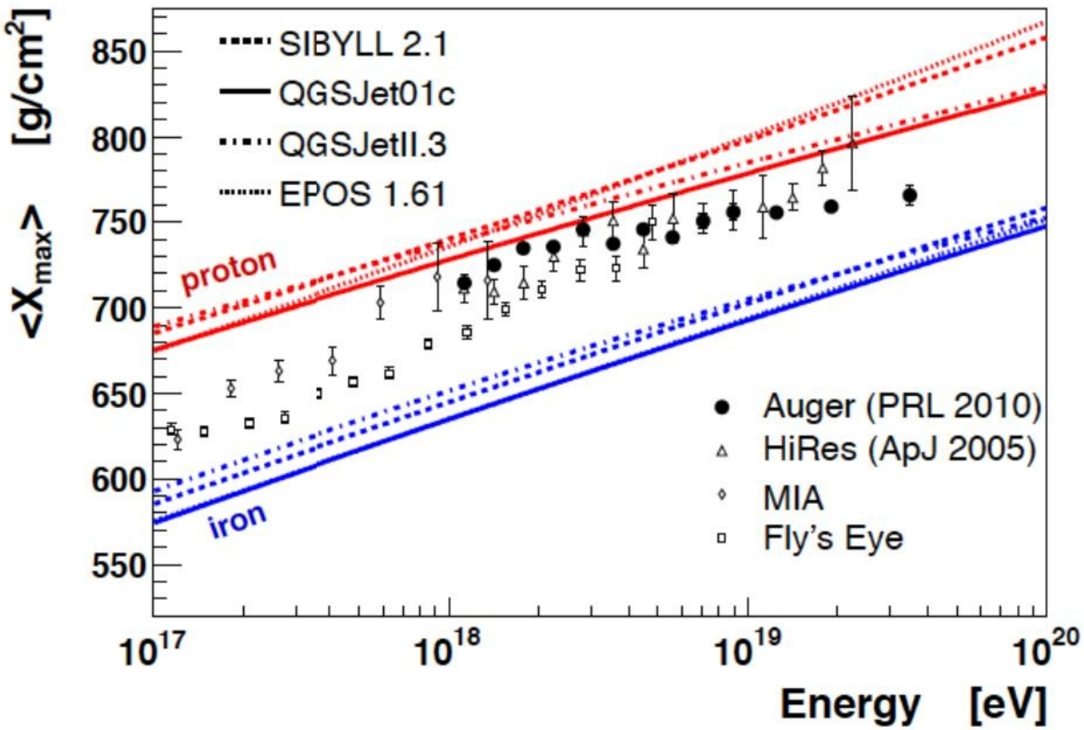
Shape depends on :
- Primary Identity
- Interaction Model



$$E \simeq 10^{20}\ \mathrm{eV}$$

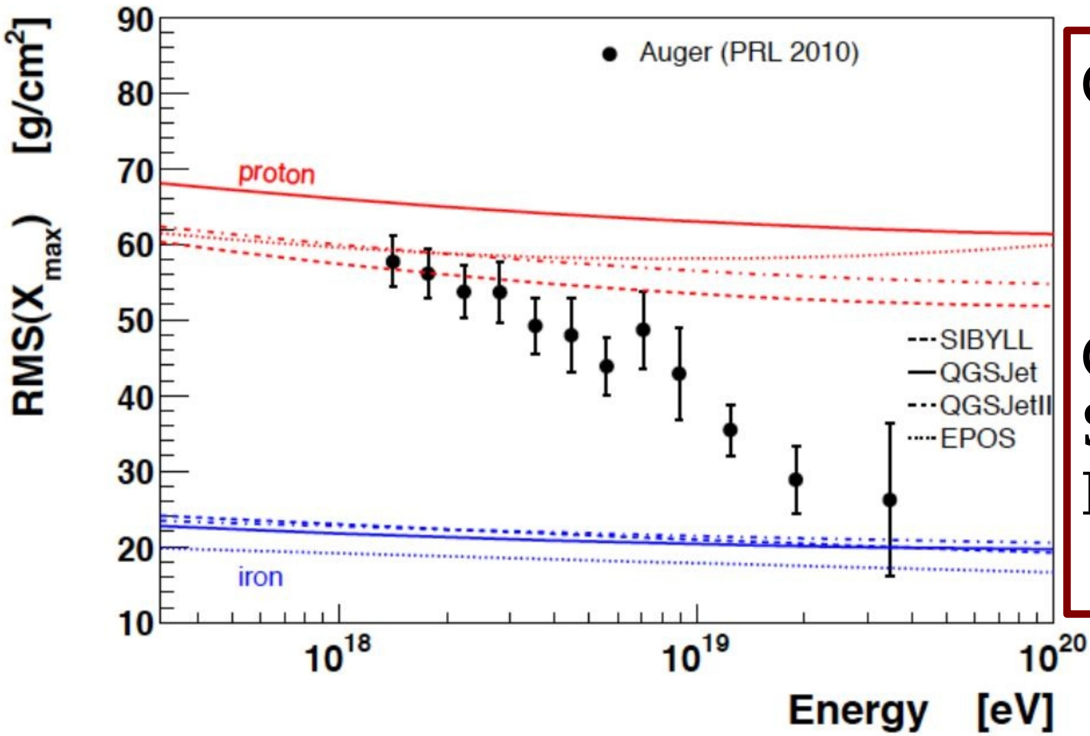






Mass Composition
becoming heavy ?
at very high energy ?

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 ?)

- Detailed measurements of the Energy Spectrum [Identification of features]

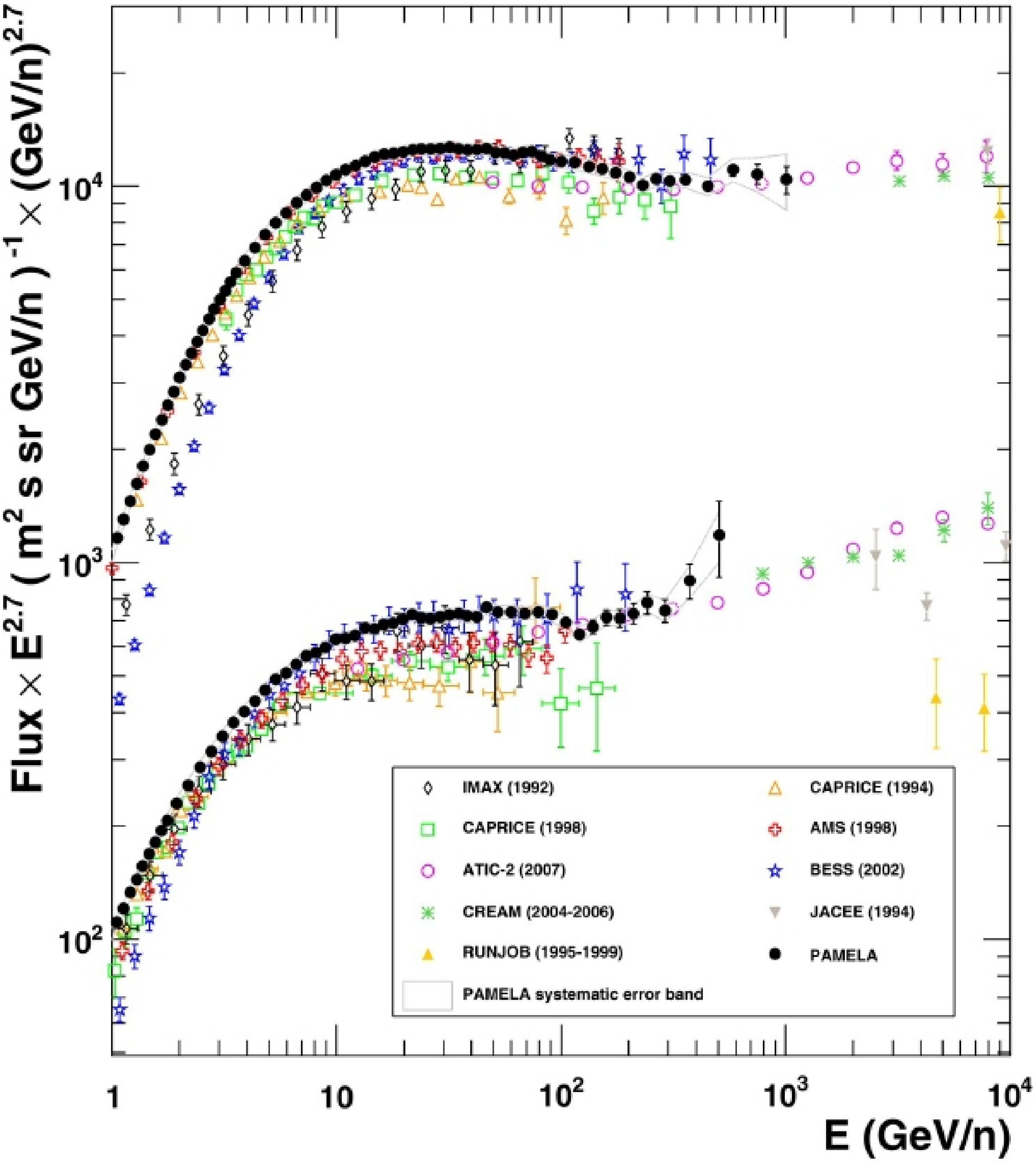
- Evolution with energy of the Chemical Composition

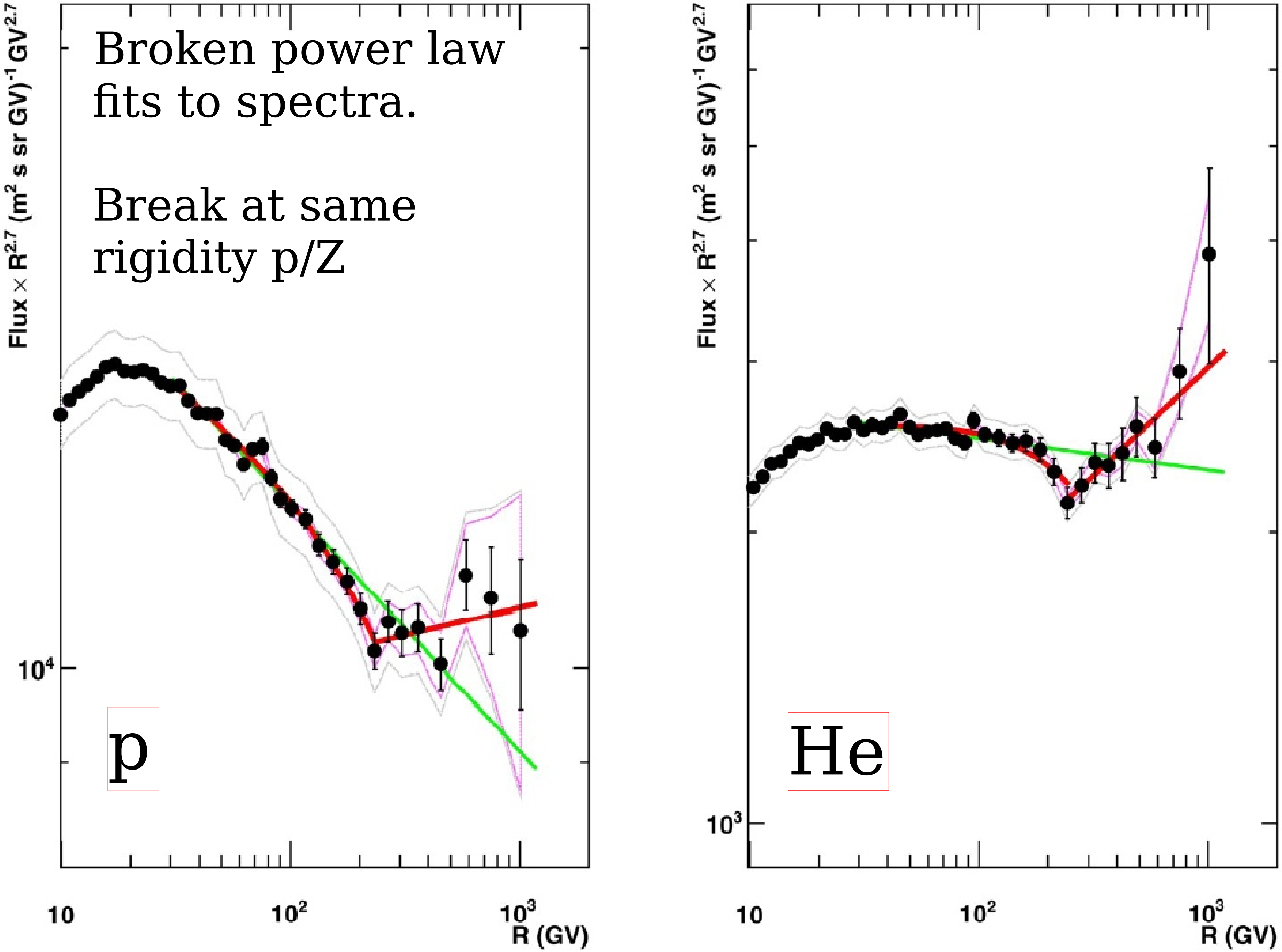
- Anisotropies of the flux

PAMELA

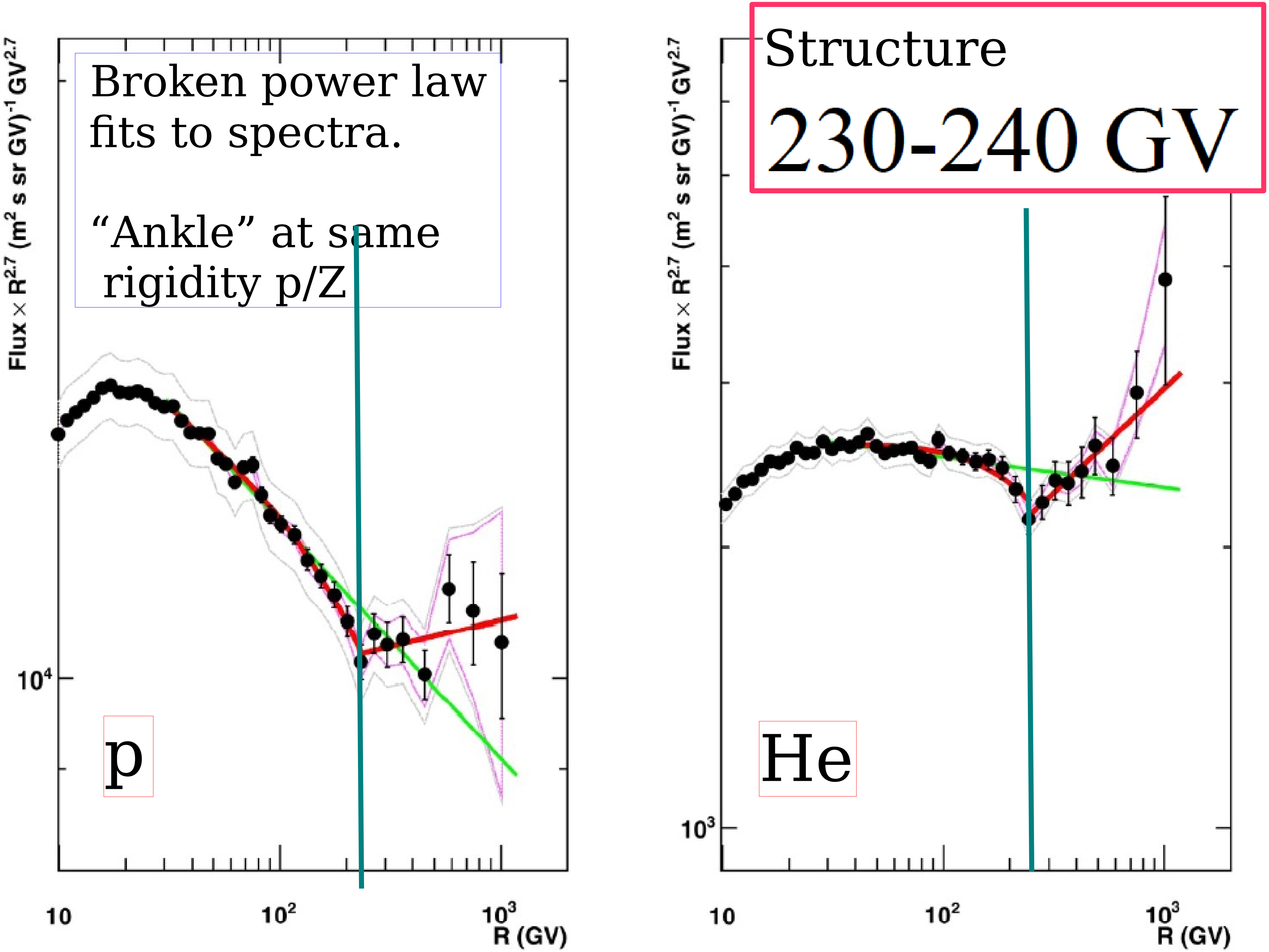
Proton/Helium
CR fluxes
1 GV – 1.2 TV

Science in press
(march 2011)





Surprising and important result.



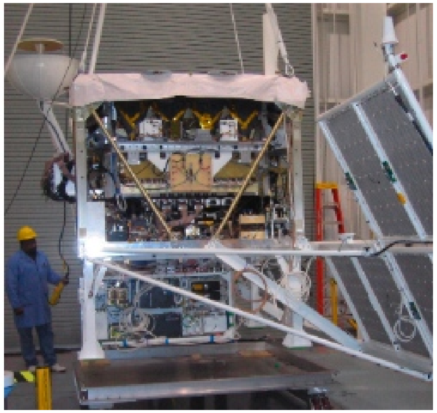
Surprising and important result.

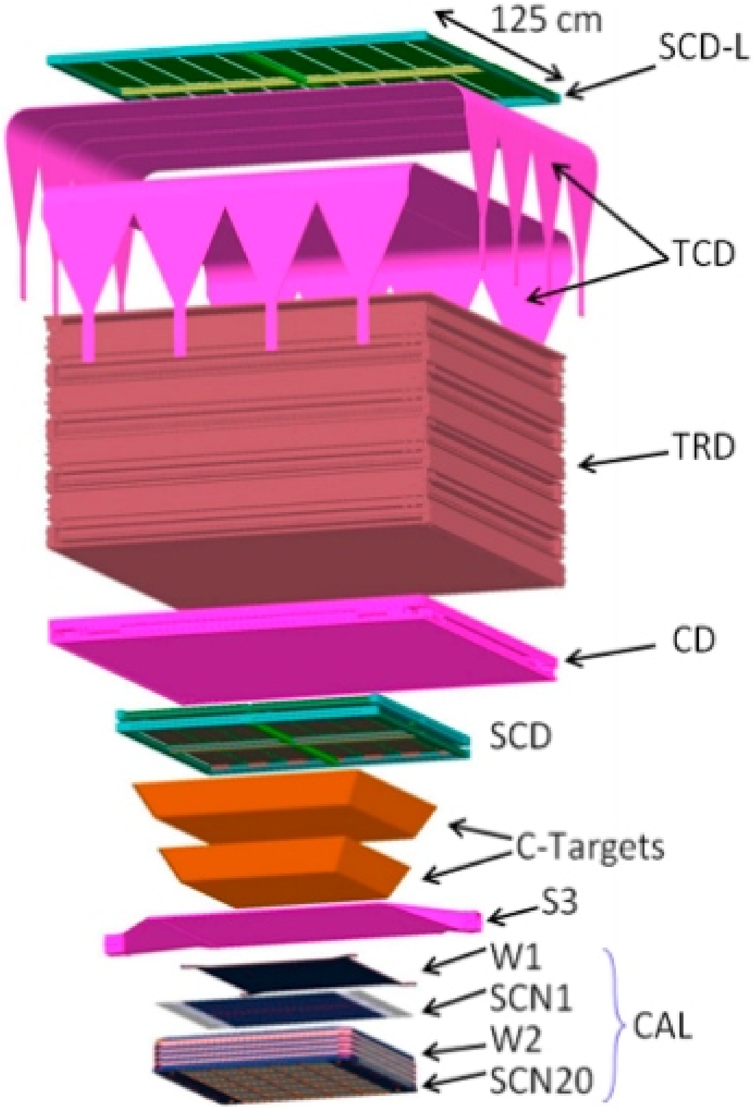
Sciencexpress Report

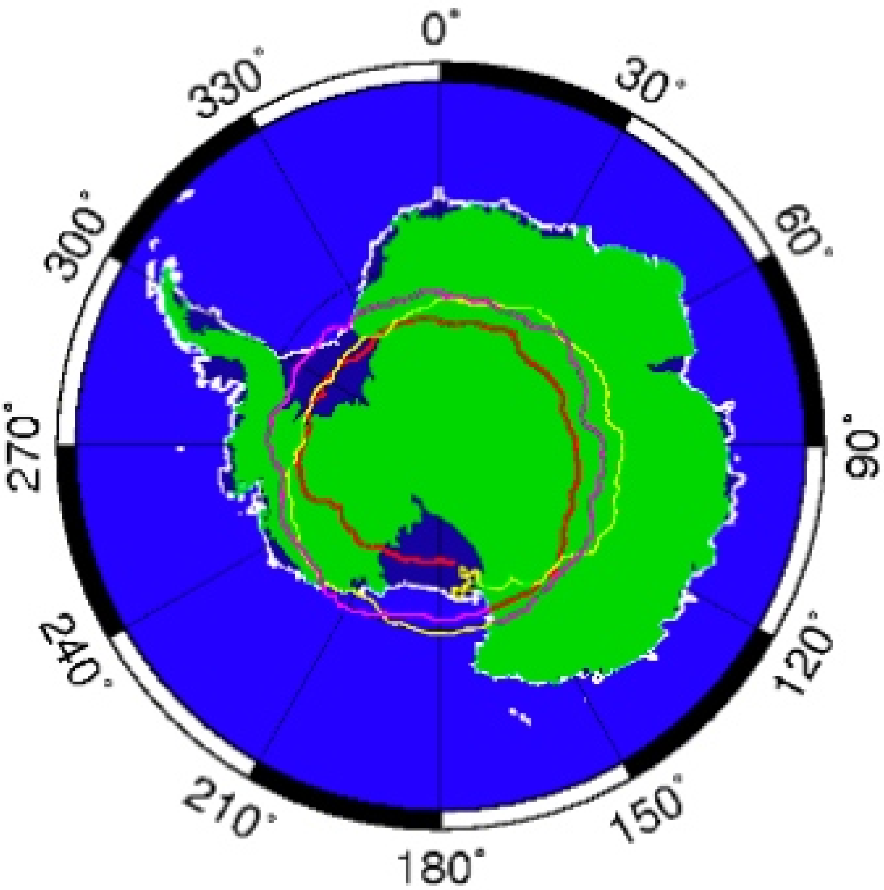
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra

We report precision measurements of the proton and helium spectra in the rigidity range 1 GV-1.2 TV performed by the satellite-borne experiment PAMELA. We find that the spectral shapes of these two species are different and cannot be well described by a single power law. These data challenge the current paradigm of cosmic-ray acceleration in supernova remnants followed by diffusive propagation in the Galaxy. More complex processes of acceleration and propagation of cosmic rays are required to explain the spectral structures observed in our data.

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

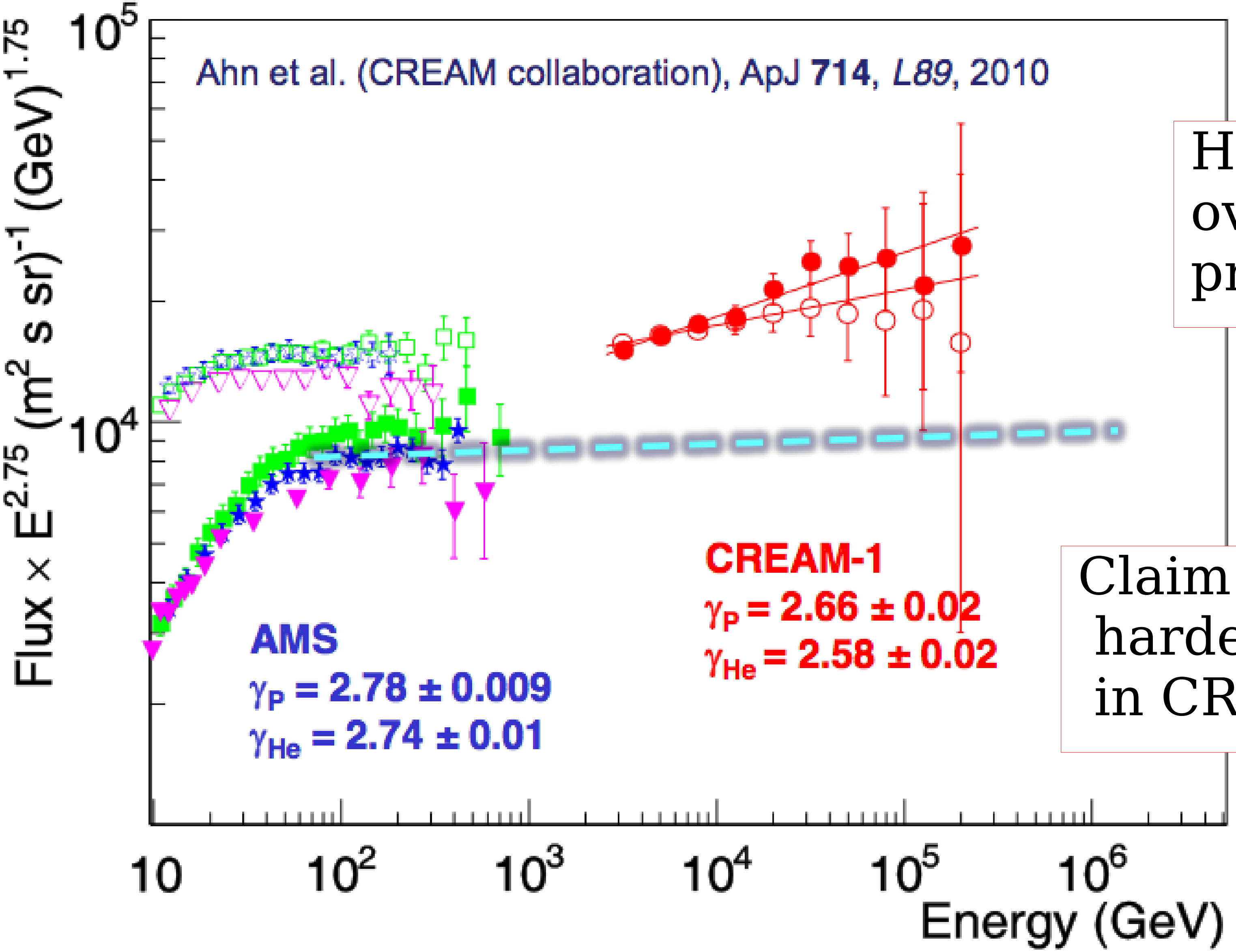






Cream 5 trajectory
37 days 12/2009-01/2010

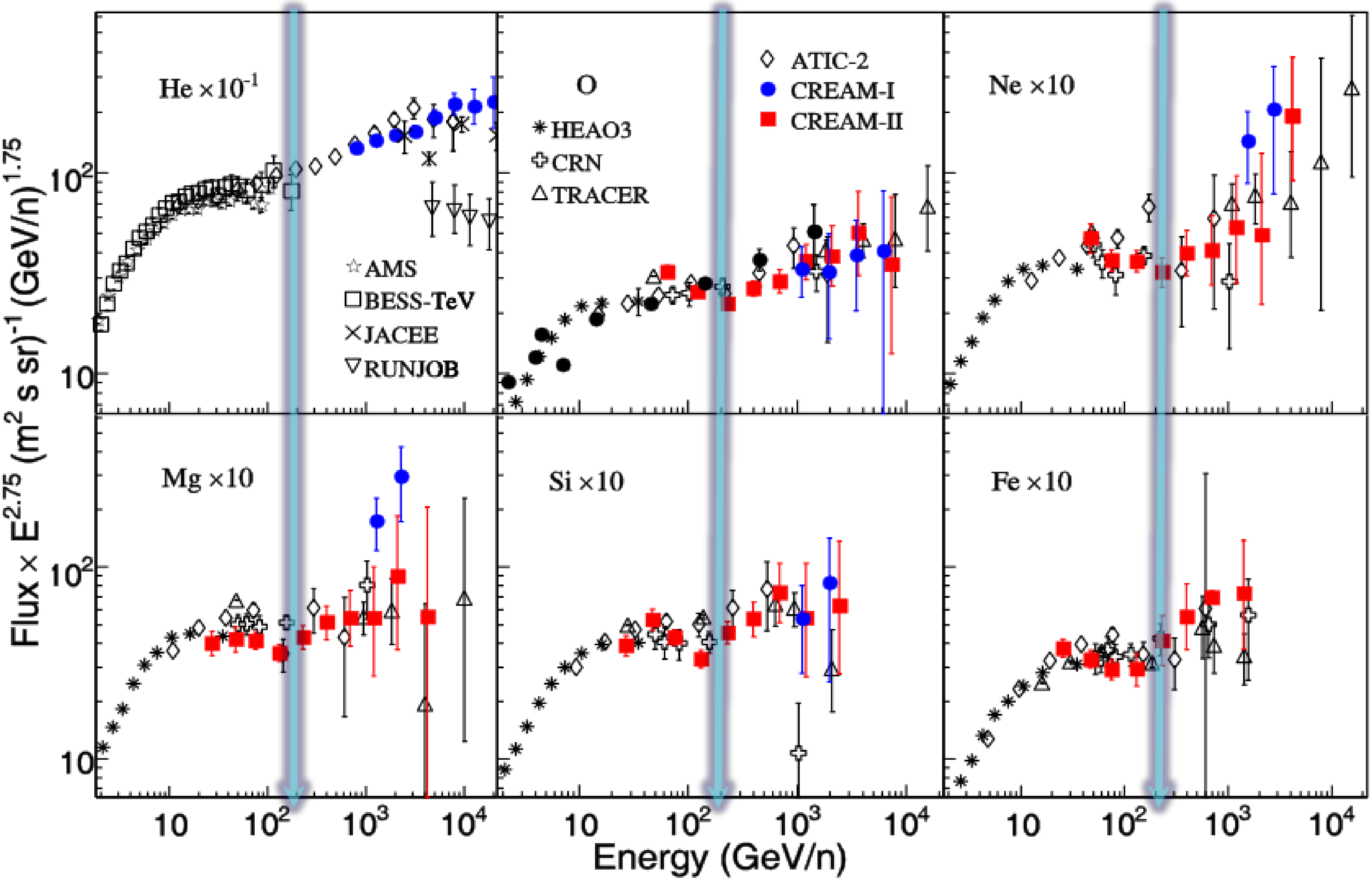
TeV spectra are harder than spectra < 200 GeV/n



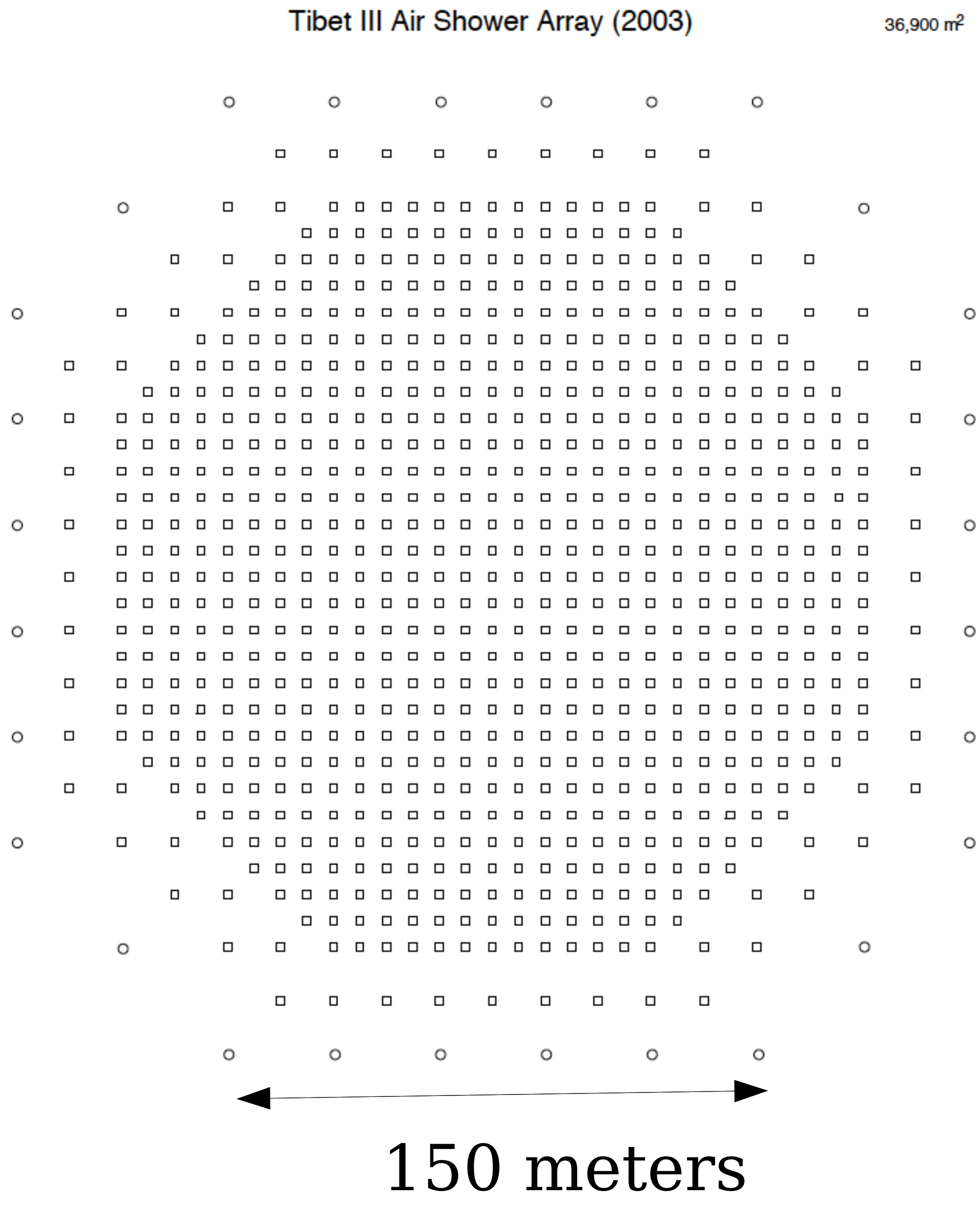
Helium overtakes protons (!)

Claim of "break" hardening in CR spectra

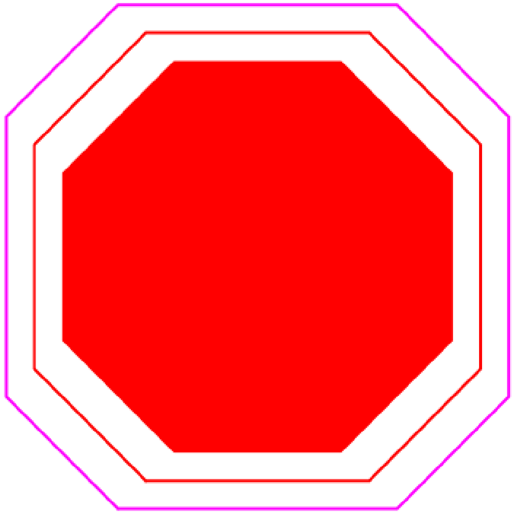
Discrepant hardening



Tibet AS Gamma Air Shower

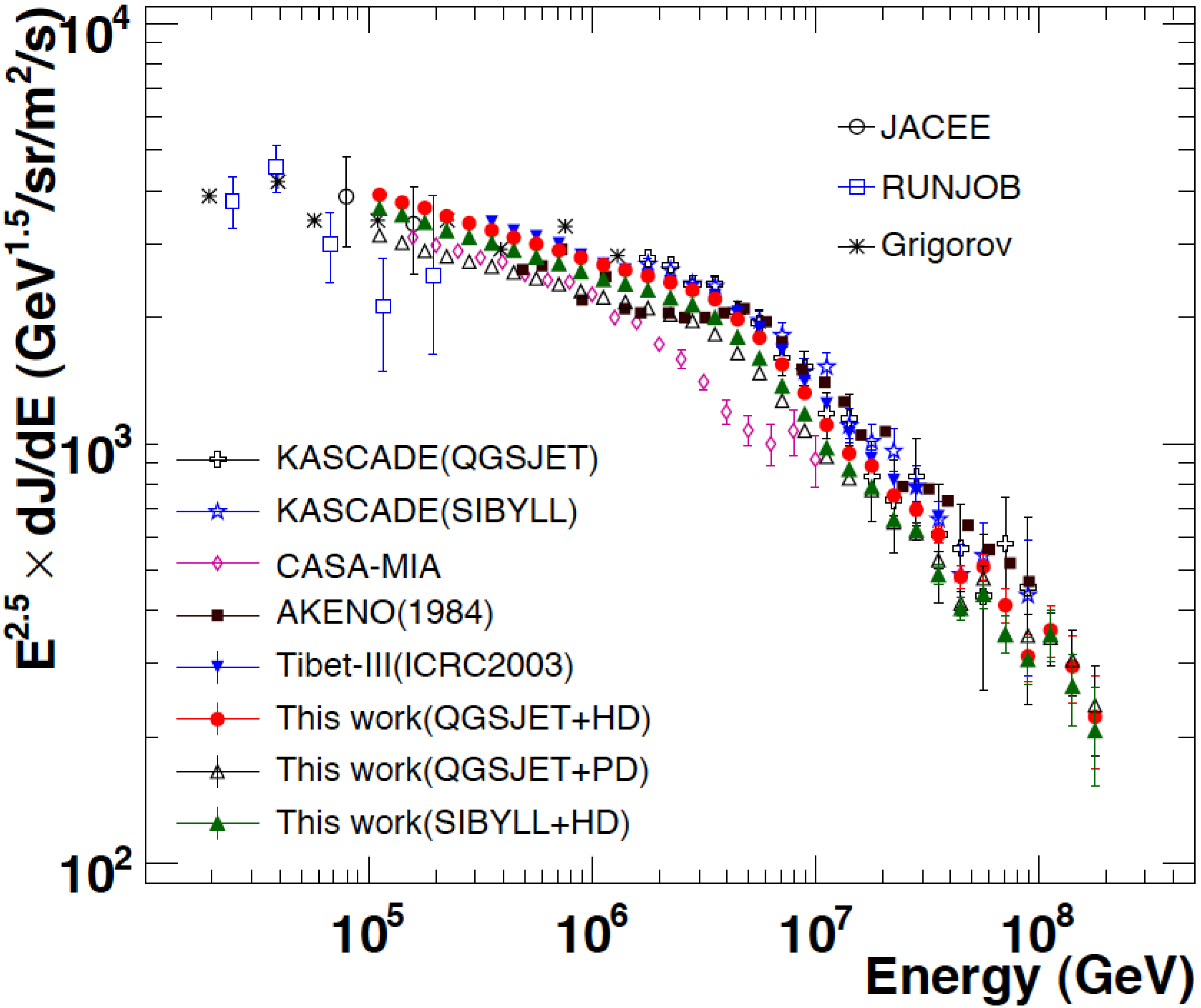


A(internal)
= 36,900 m^2

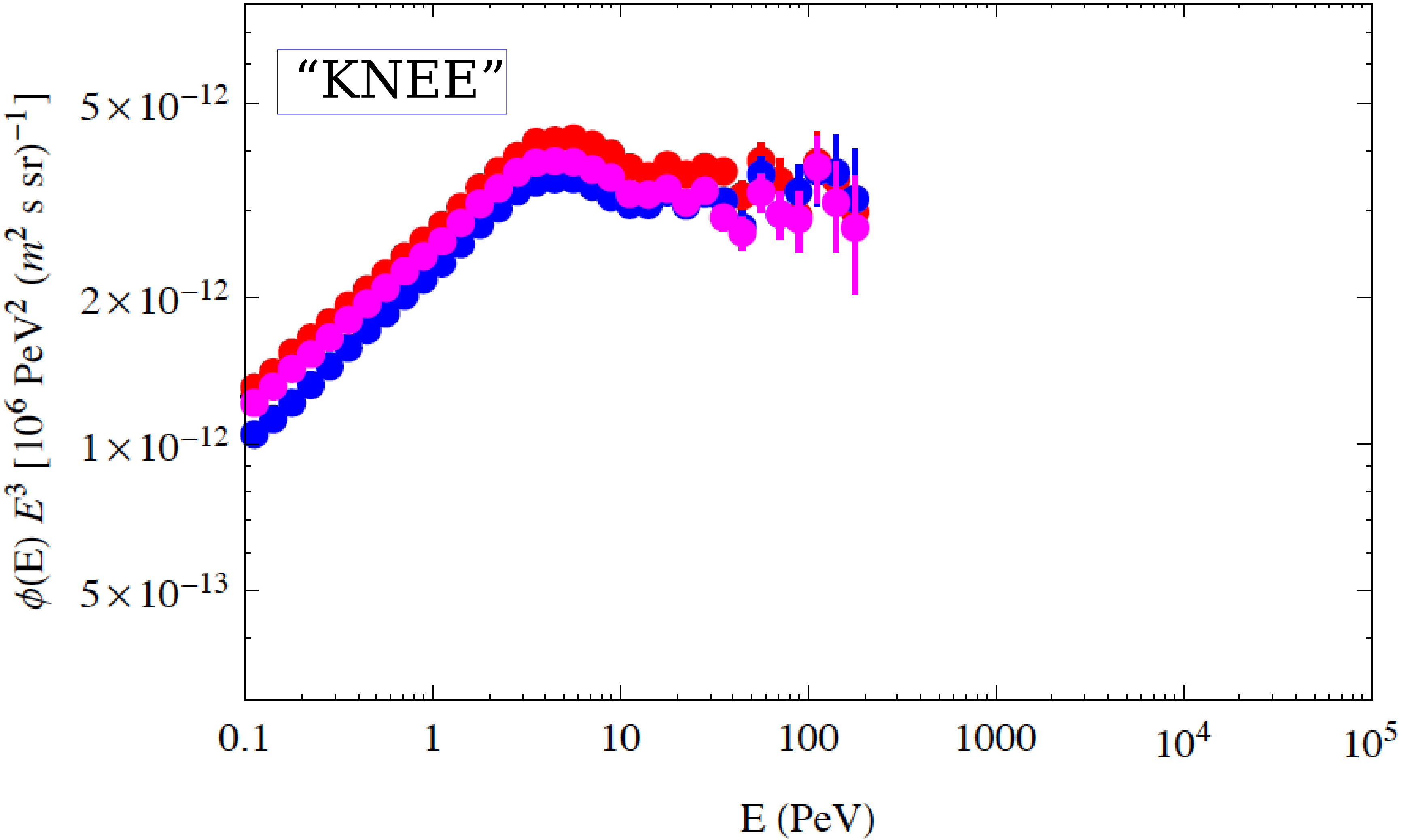


Spacing 7.5 meters (interior)

Tibet Air Shower Energy Spectrum

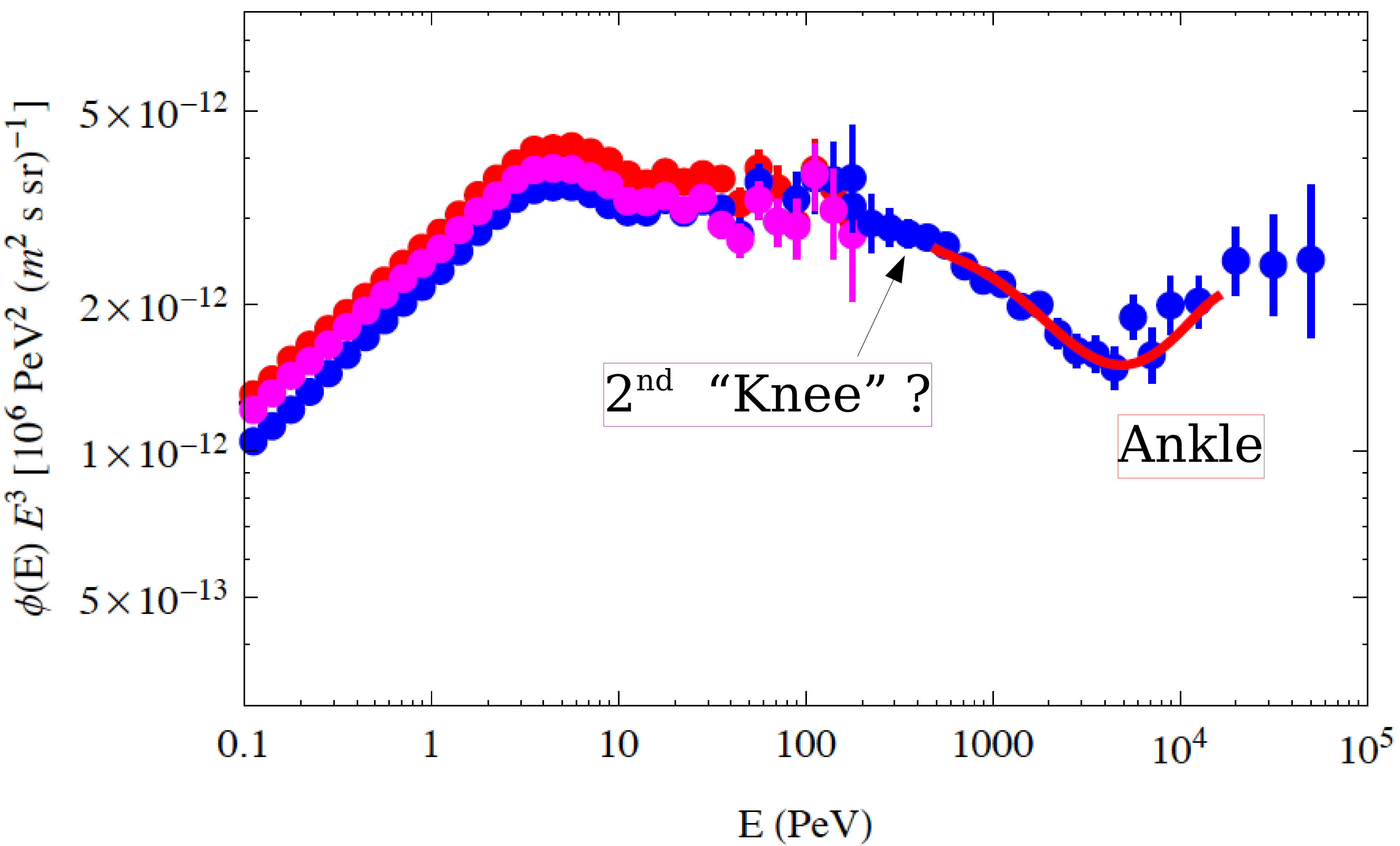


TIBET AS-gamma CR spectra



TIBET AS-gamma CR spectra

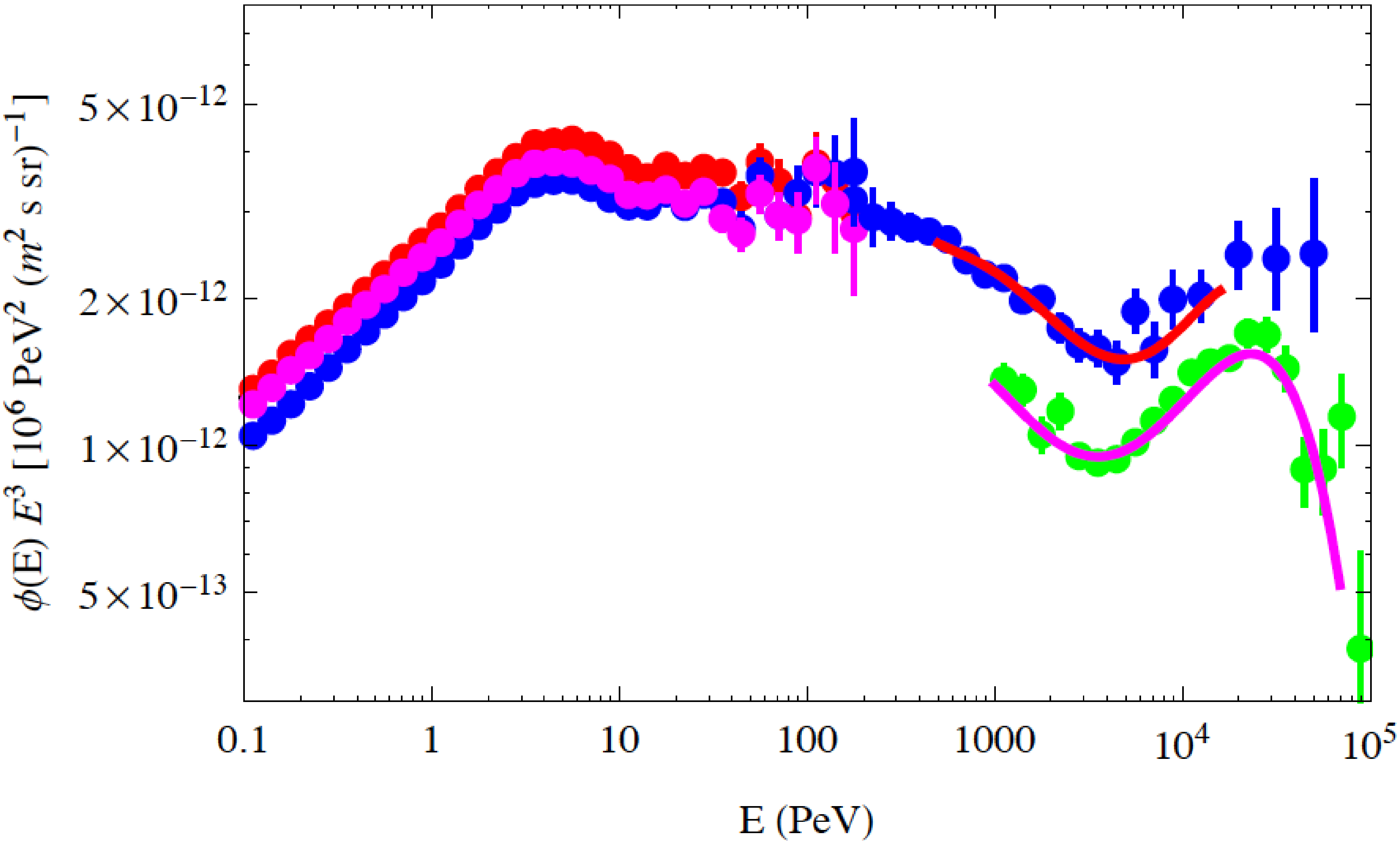
HIRES spectrum

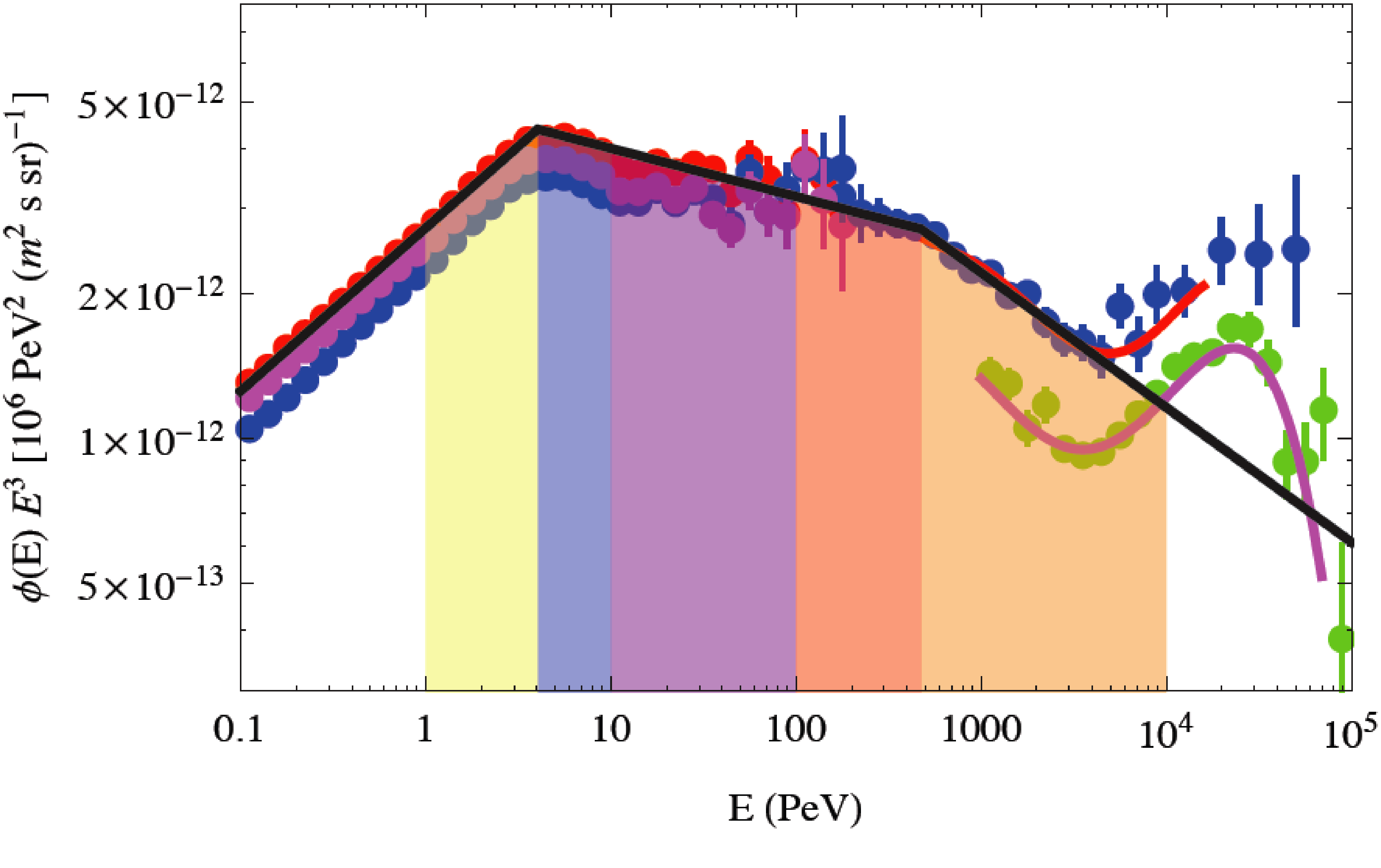


TIBET AS-gamma CR spectra

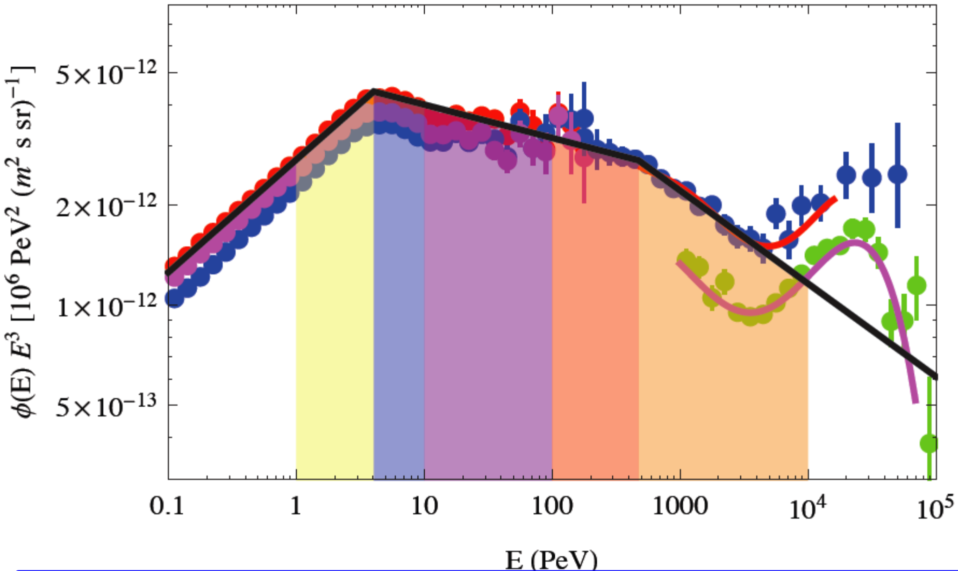
HIRES spectrum

AUGER spectrum Energy scale discrepancy.





$\phi(E)\,E^3\,[10^6\,\mathrm{PeV}^2\,(m^2\,\mathrm{s\,sr})^{-1}]$
5×10^{-12}
2×10^{-12}
1×10^{-12}
5×10^{-13}
0.1
1
10
100
1000
10^4
10^5
E (PeV)



$$[A\,t\,\Omega] = \pi \;\; [10^6 \text{ m}^2] \;\; [1 \text{ yr}]$$

$$\Phi\left[10^{15}\text{ eV}, E_{\text{knee}}\right] \;\; [A\,t\,\Omega] \simeq 1.4 \times 10^8$$

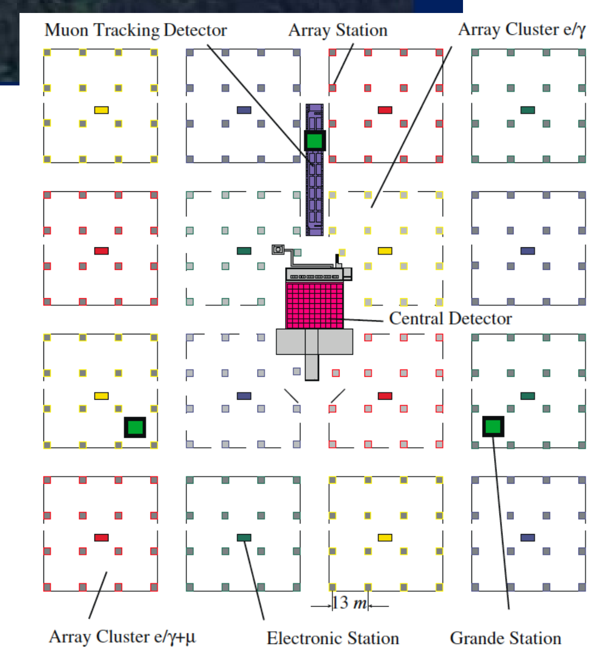
$$\Phi\left[E_{\text{knee}}, 10^{16}\text{ eV}\right] \;\; [A\,t\,\Omega] \simeq 1.2 \times 10^7$$

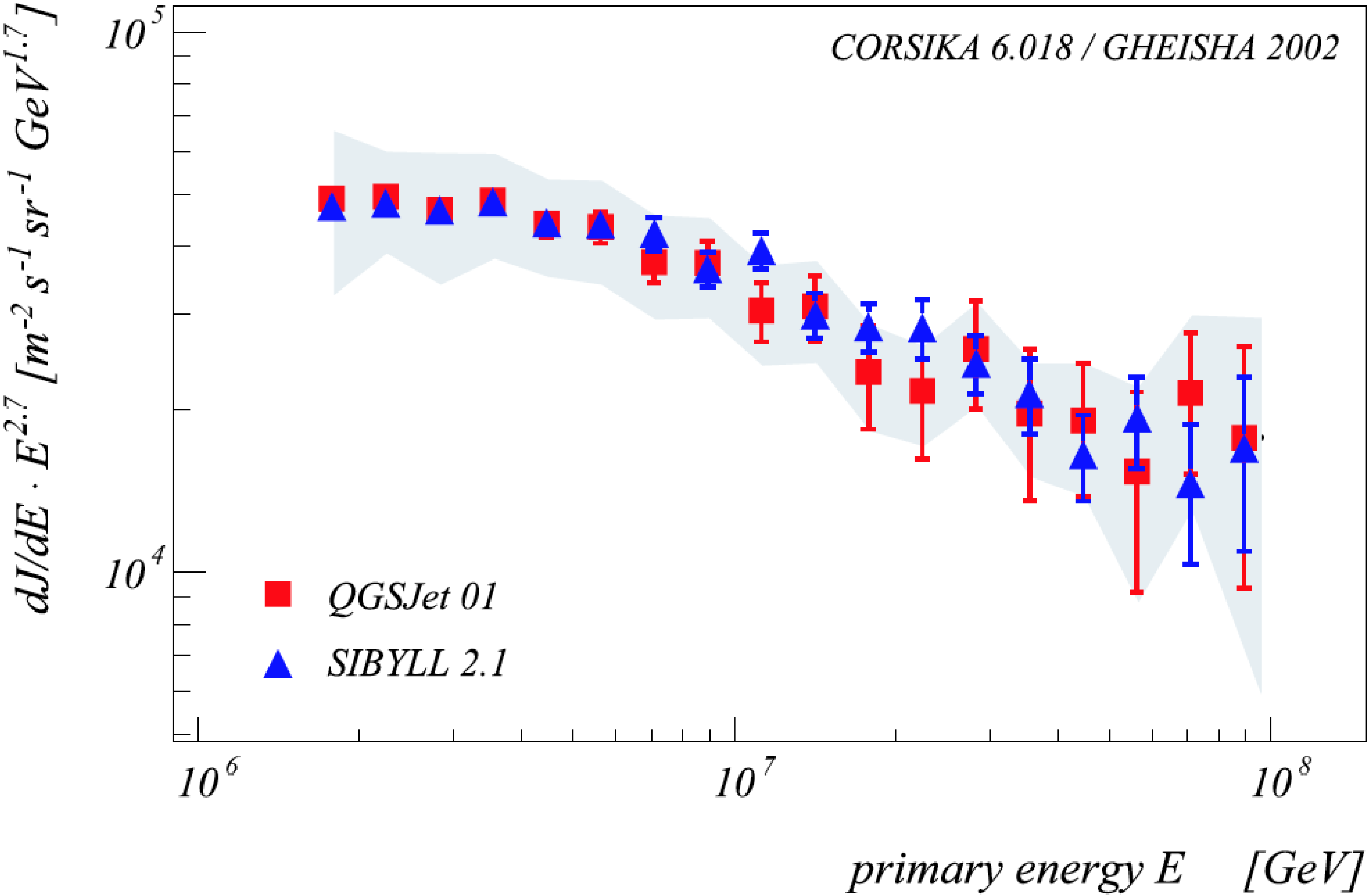
$$\Phi\left[10^{16}\text{ eV}, 10^{17}\text{ eV}\right] \;\; [A\,t\,\Omega] \simeq 1.9 \times 10^6$$

$$\Phi\left[10^{17}\text{ eV}, 5\times 10^{17}\text{ eV}\right] \;\; [A\,t\,\Omega] \simeq 1.4 \times 10^4$$

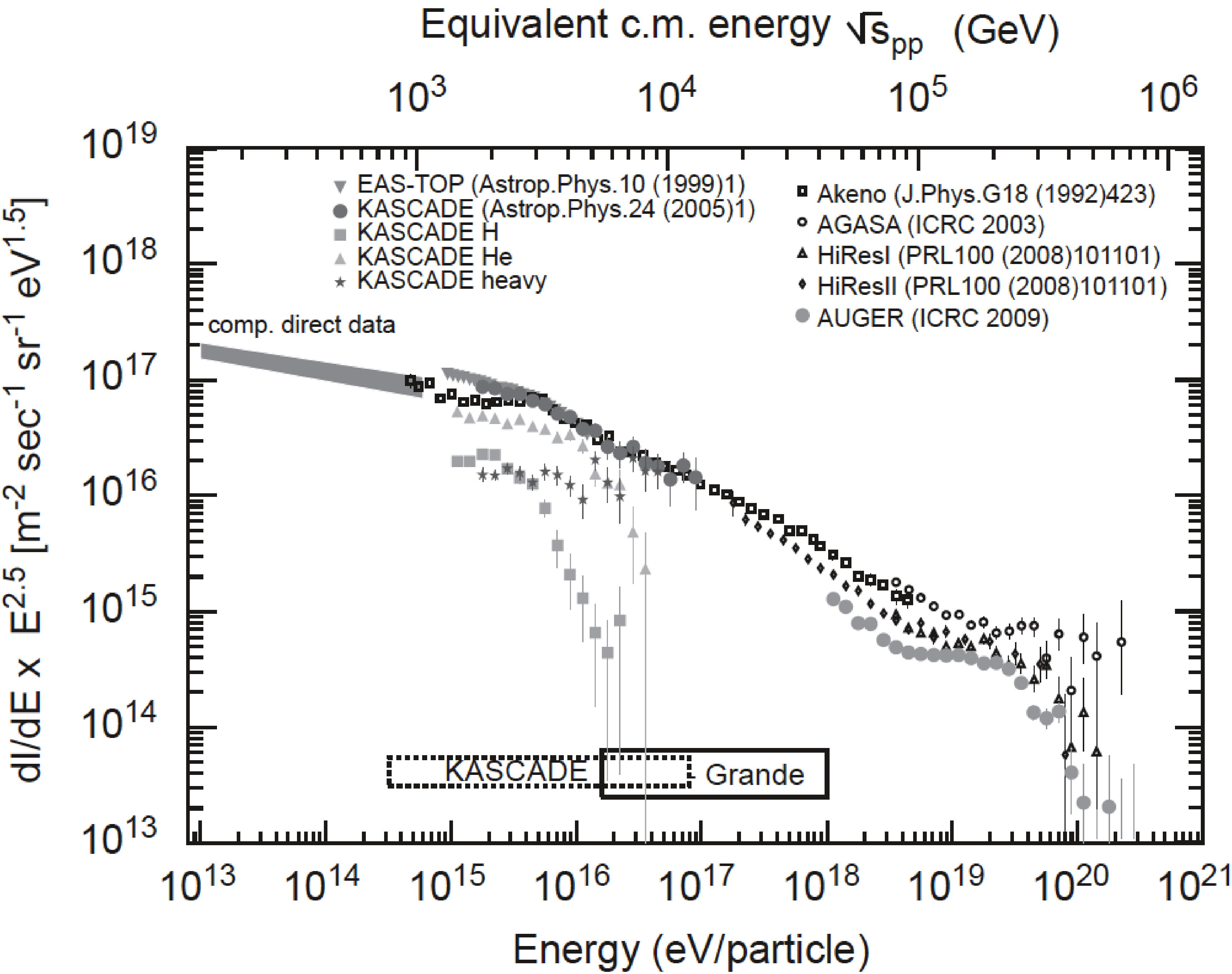
$$\Phi\left[\geq 5\times 10^{17}\text{ eV}\right] \;\; [A\,t\,\Omega] \simeq 5 \times 10^2$$

KASCADE /KASCADE-GRANDE



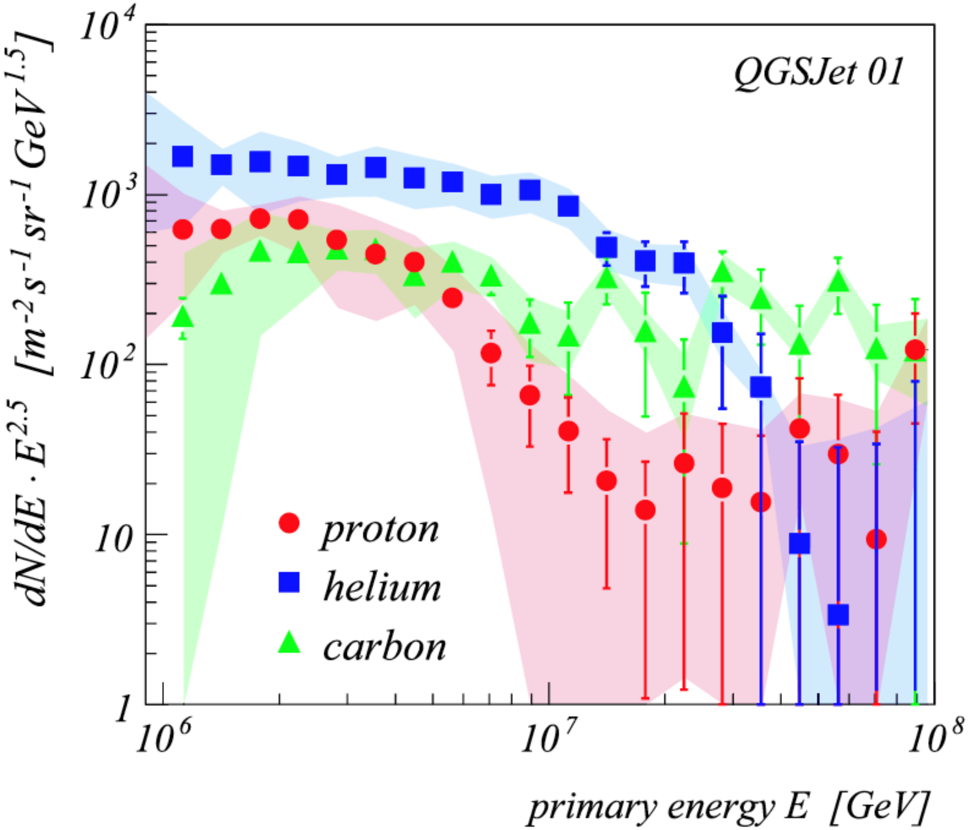


CORSIKA 6.018 / GHEISHA 2002
dJ/dE · E^2.7 [m^-2 s^-1 sr^-1 GeV^1.7]
10^5
10^4
10^6
10^7
10^8
QGSJet 01
SIBYLL 2.1
primary energy E [GeV]

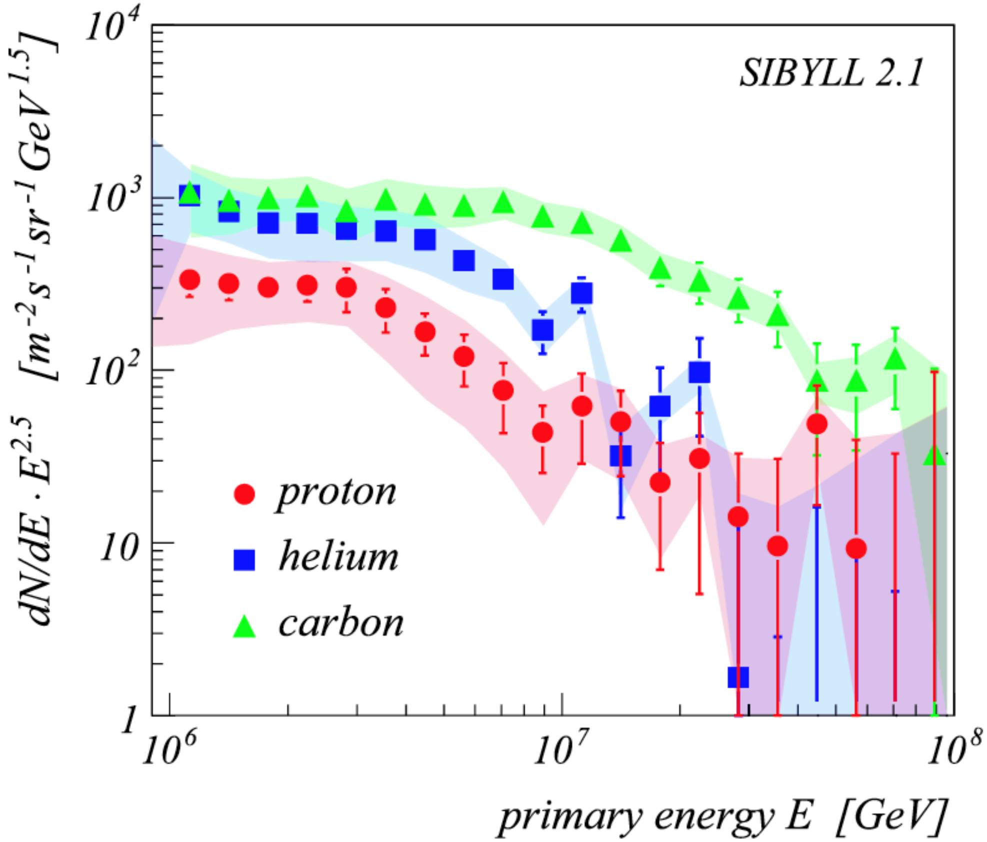


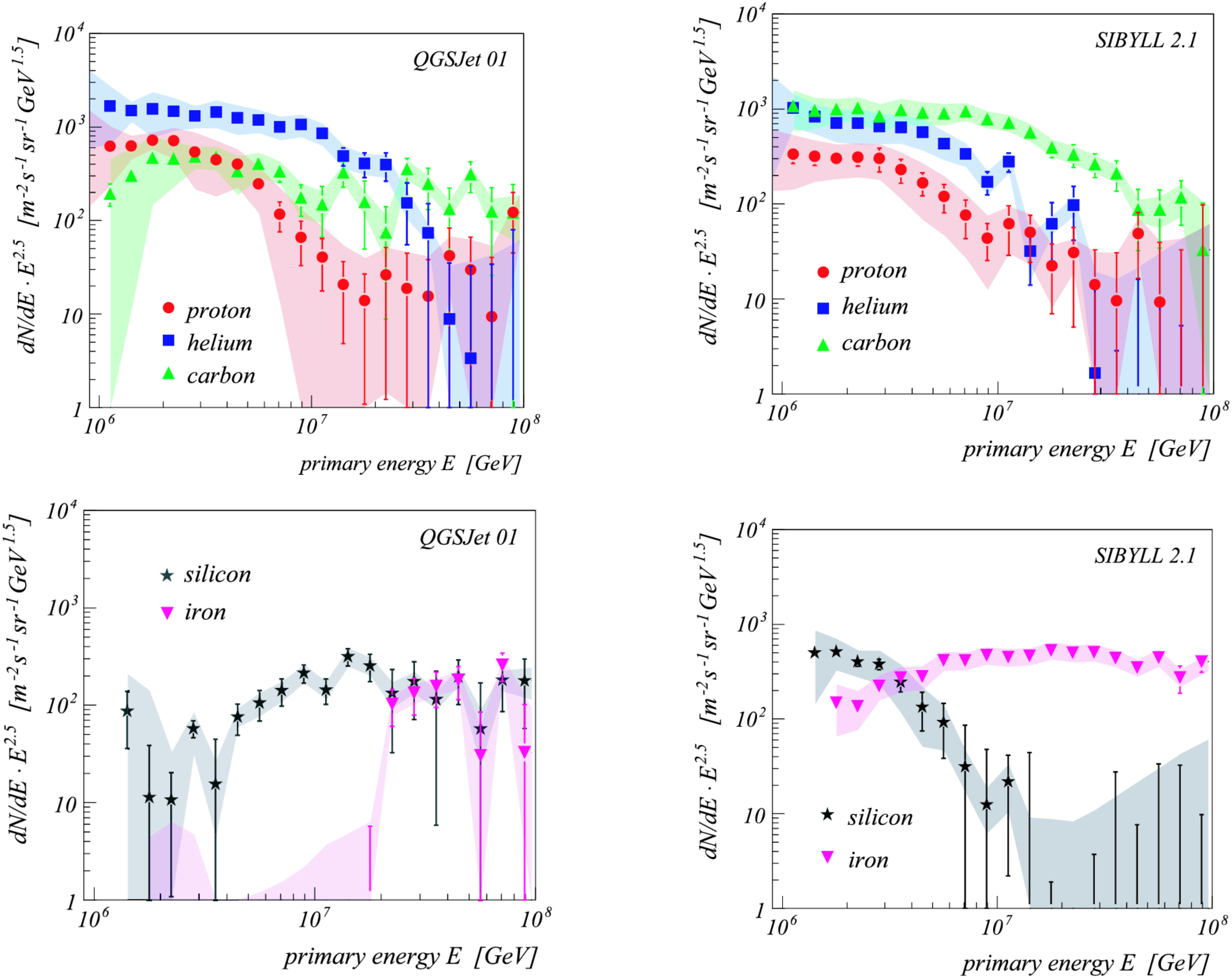
Equivalent c.m. energy √s_pp (GeV)
10^3
10^4
10^5
10^6
10^19
10^18
10^17
10^16
10^15
10^14
10^13
dI/dE x E^2.5 [m^-2 sec^-1 sr^-1 eV^1.5]
EAS-TOP (Astrop.Phys.10 (1999)1)
KASCADE (Astrop.Phys.24 (2005)1)
KASCADE H
KASCADE He
KASCADE heavy
Akeno (J.Phys.G18 (1992)423)
AGASA (ICRC 2003)
HiResI (PRL100 (2008)101101)
HiResII (PRL100 (2008)101101)
AUGER (ICRC 2009)
comp. direct data
KASCADE
Grande
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

KASCADE Results

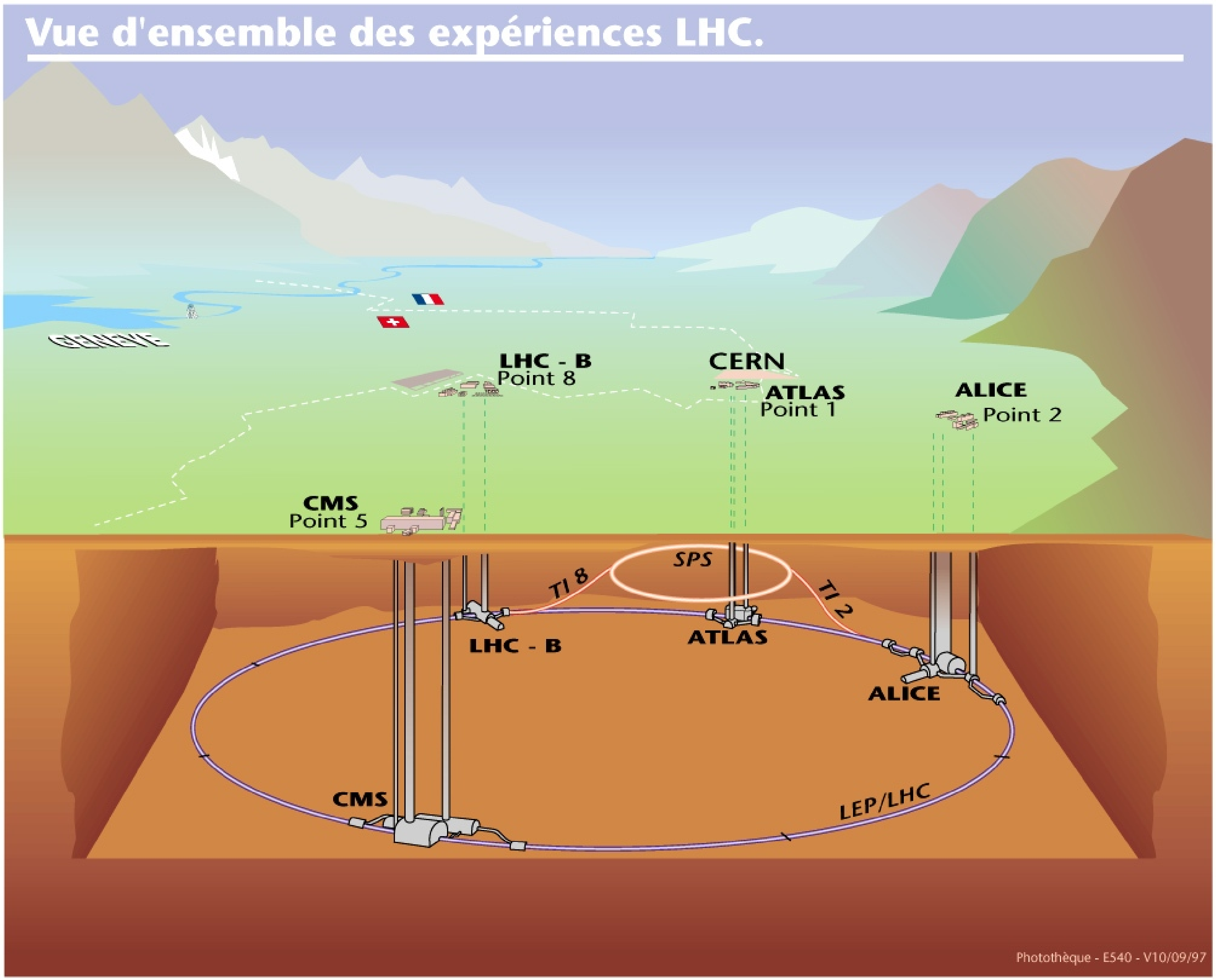


Model Dependence !

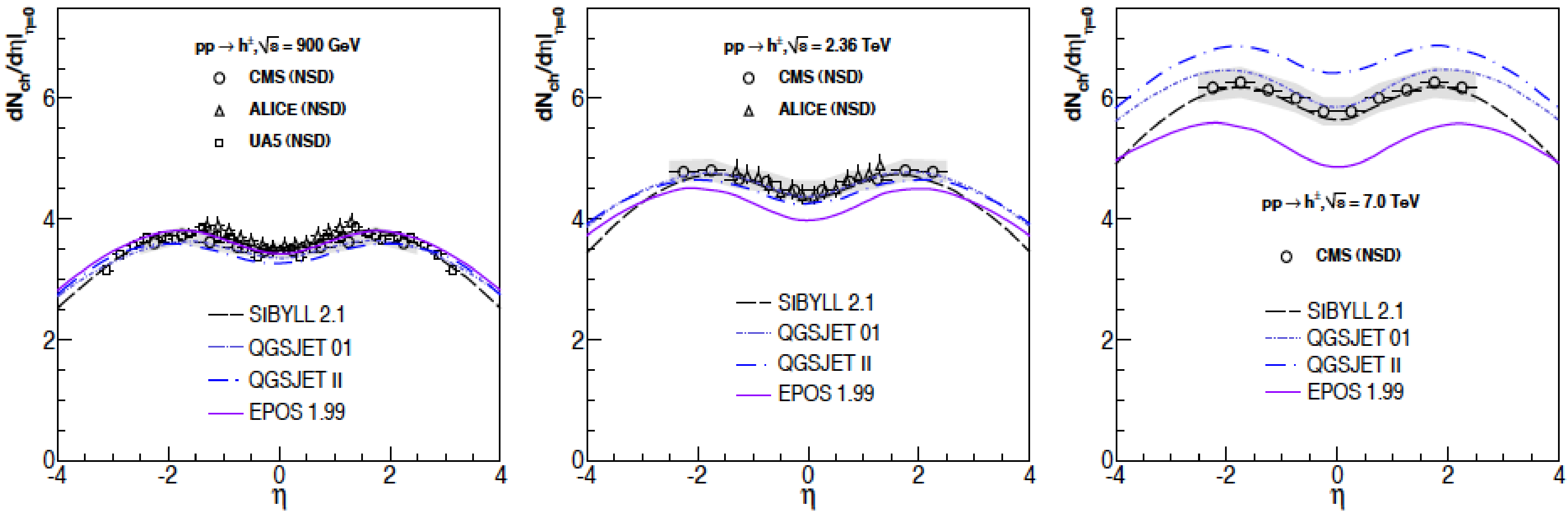



QGSJet 01
SIBYLL 2.1
QGSJet 01
SIBYLL 2.1
proton
helium
carbon
silicon
iron
dN/dE · E^2.5 [m^-2 s^-1 sr^-1 GeV^1.5]
primary energy E [GeV]

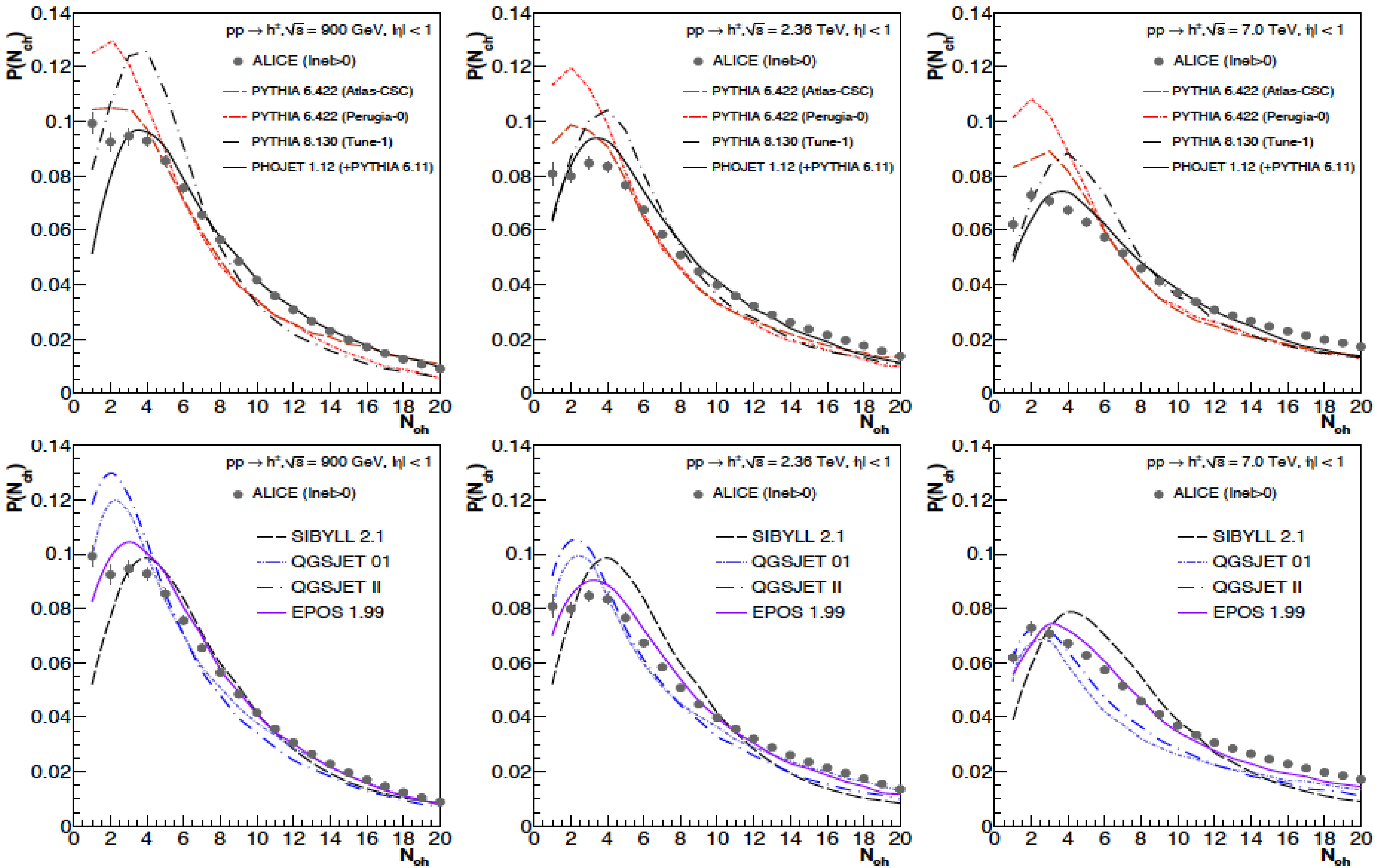
Progress in hadronic interaction modeling ?



7 + 7 TeV
PP collider



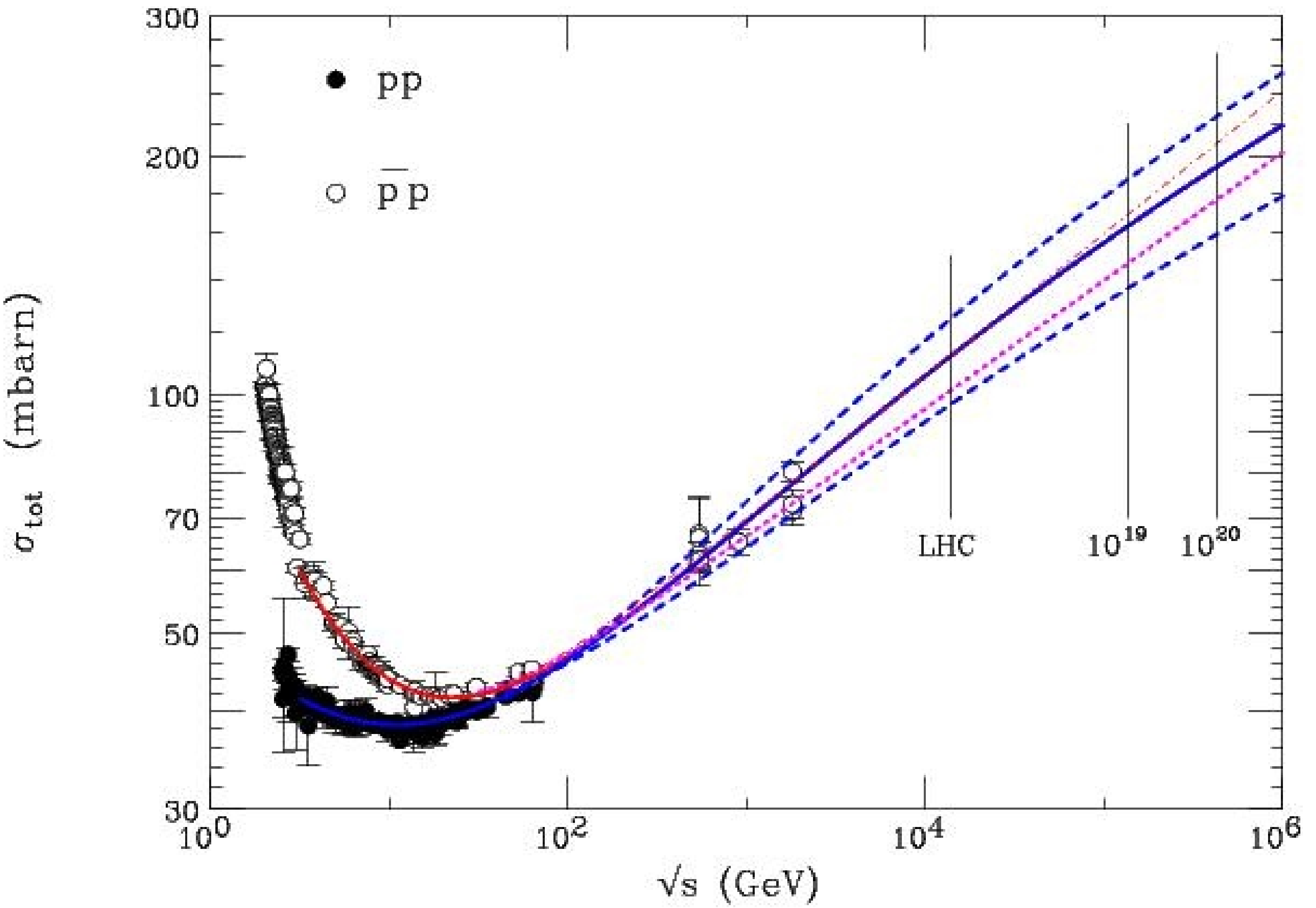
Model	QGSJET01			QGSJETII			SIBYLL 2.1			EPOS 1.99		
$\sqrt{s}$ (TeV)	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7
$dN_{ch}/d\eta\|_{\eta=0}$	✓	✓	✓	✓	✓	over	✓	✓	✓	✓	under	under
$\langle p_\perp \rangle$	over	over	✓	over	over	over	✓	under	under	✓	✓	✓
$P(N_{ch} < 5)$	over	over	under	over	over	over	over	over	over	✓	✓	✓
$P(N_{ch} > 30)$	✓	under	under	✓	✓	over	over	✓	over	under	under	under

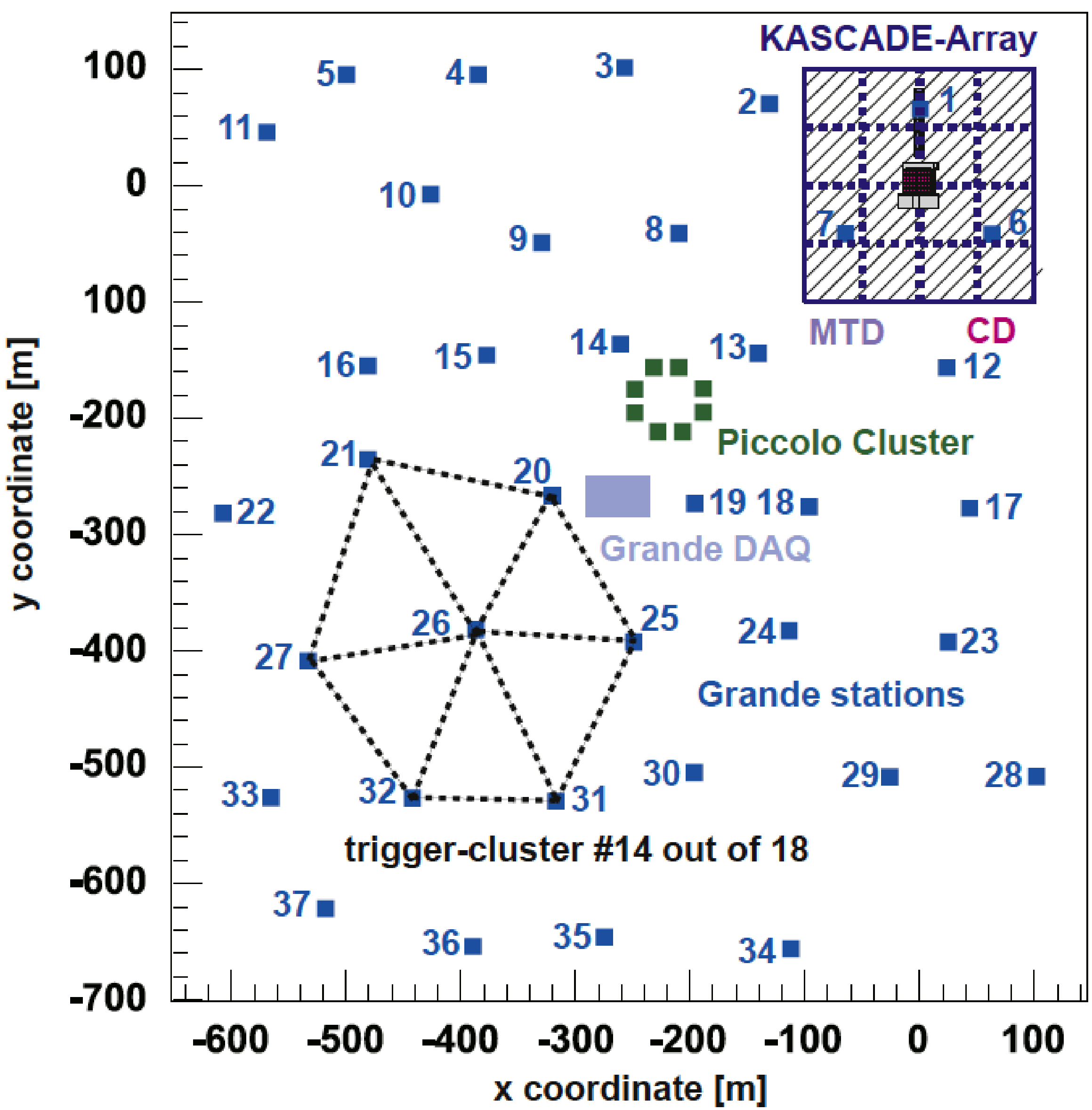


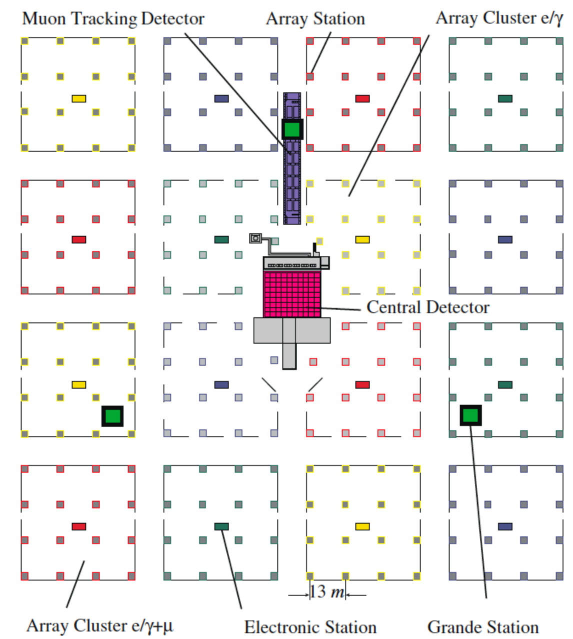
pp → h±, √s = 900 GeV, |η| < 1
pp → h±, √s = 2.36 TeV, |η| < 1
pp → h±, √s = 7.0 TeV, |η| < 1
ALICE (Inel>0)
PYTHIA 6.422 (Atlas-CSC)
PYTHIA 6.422 (Perugia-0)
PYTHIA 8.130 (Tune-1)
PHOJET 1.12 (+PYTHIA 6.11)
SIBYLL 2.1
QGSJET 01
QGSJET II
EPOS 1.99
P(N_ch)
N_ch

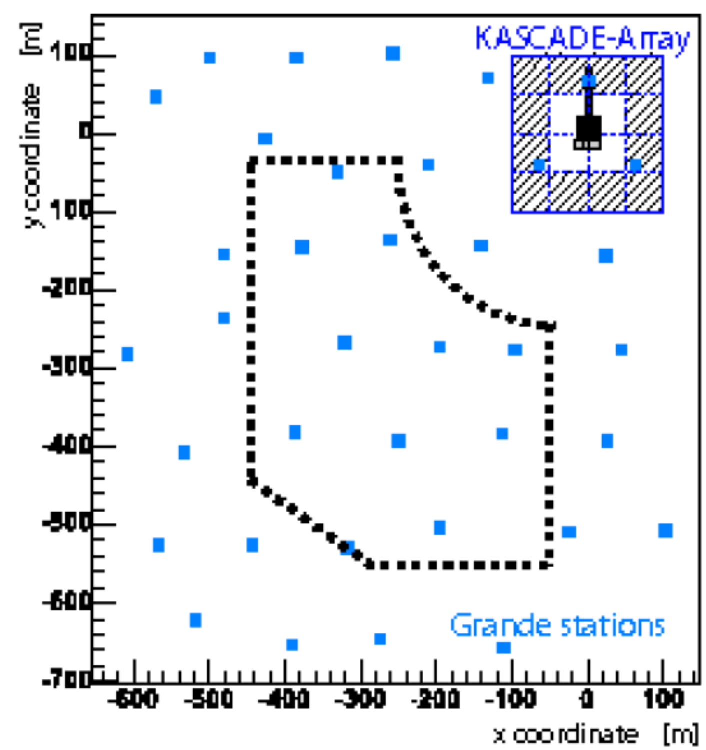
LHC and Ultra-High Energy Cosmic Rays

Total pp Cross Section





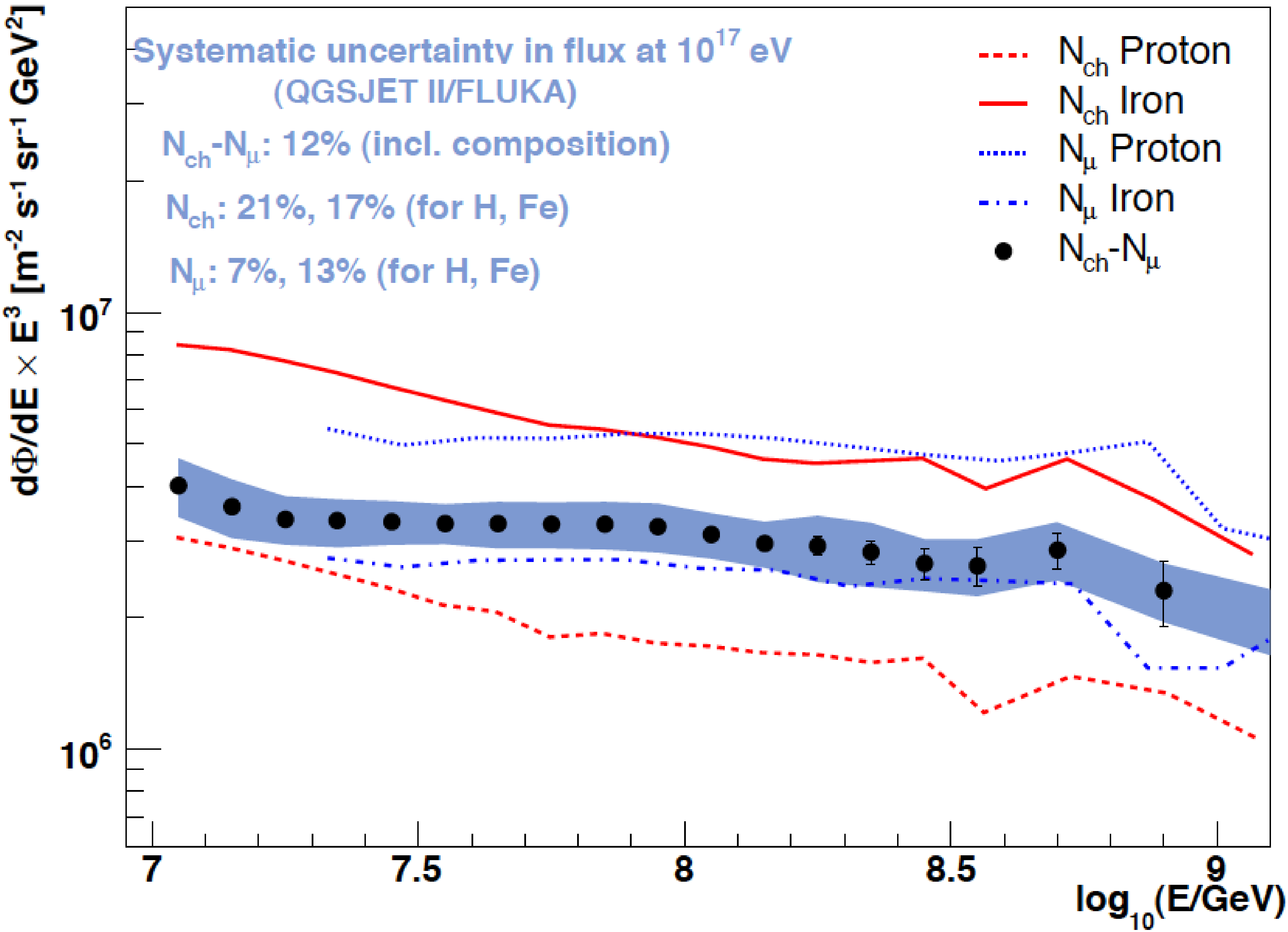




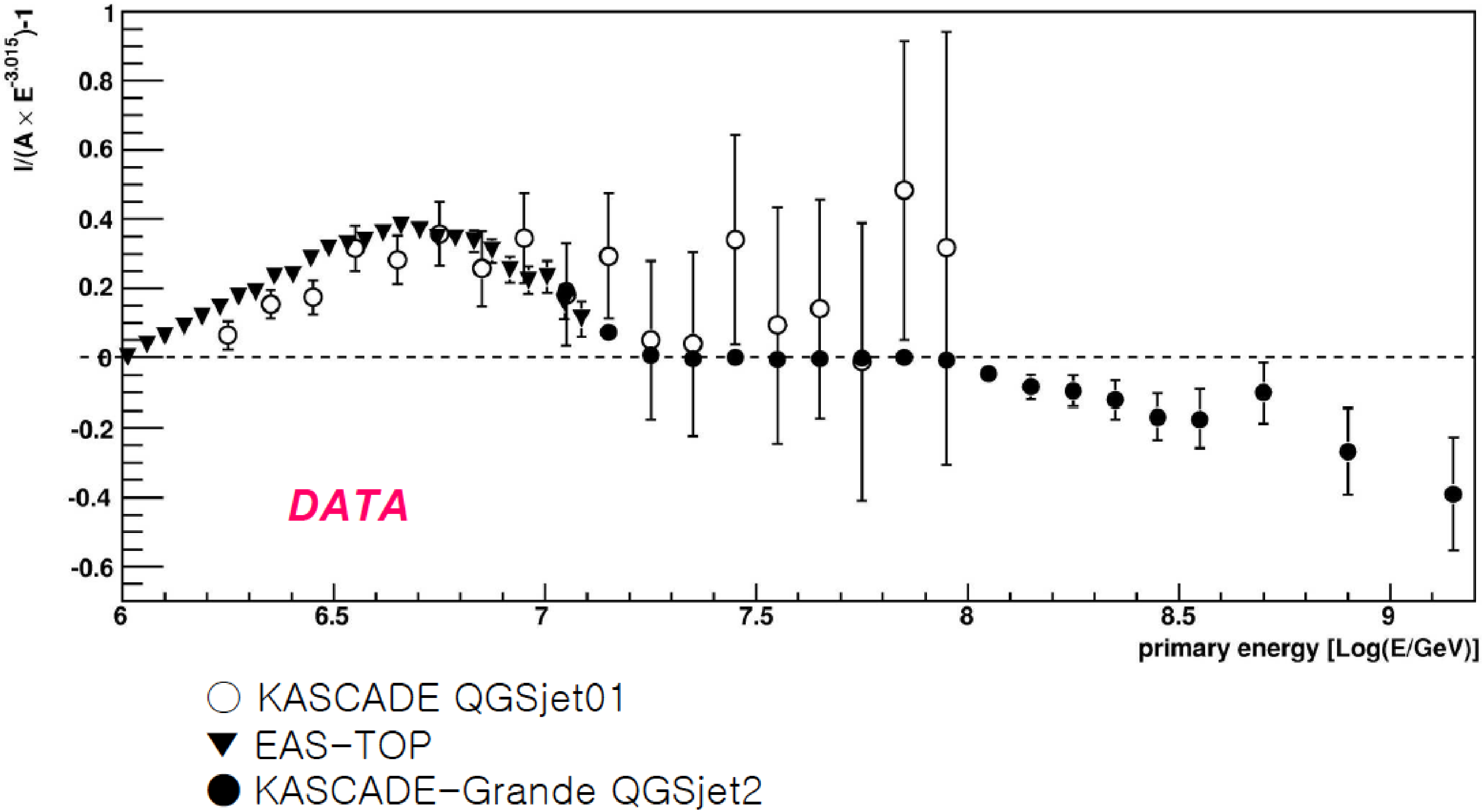
KASCADE-GRANDE

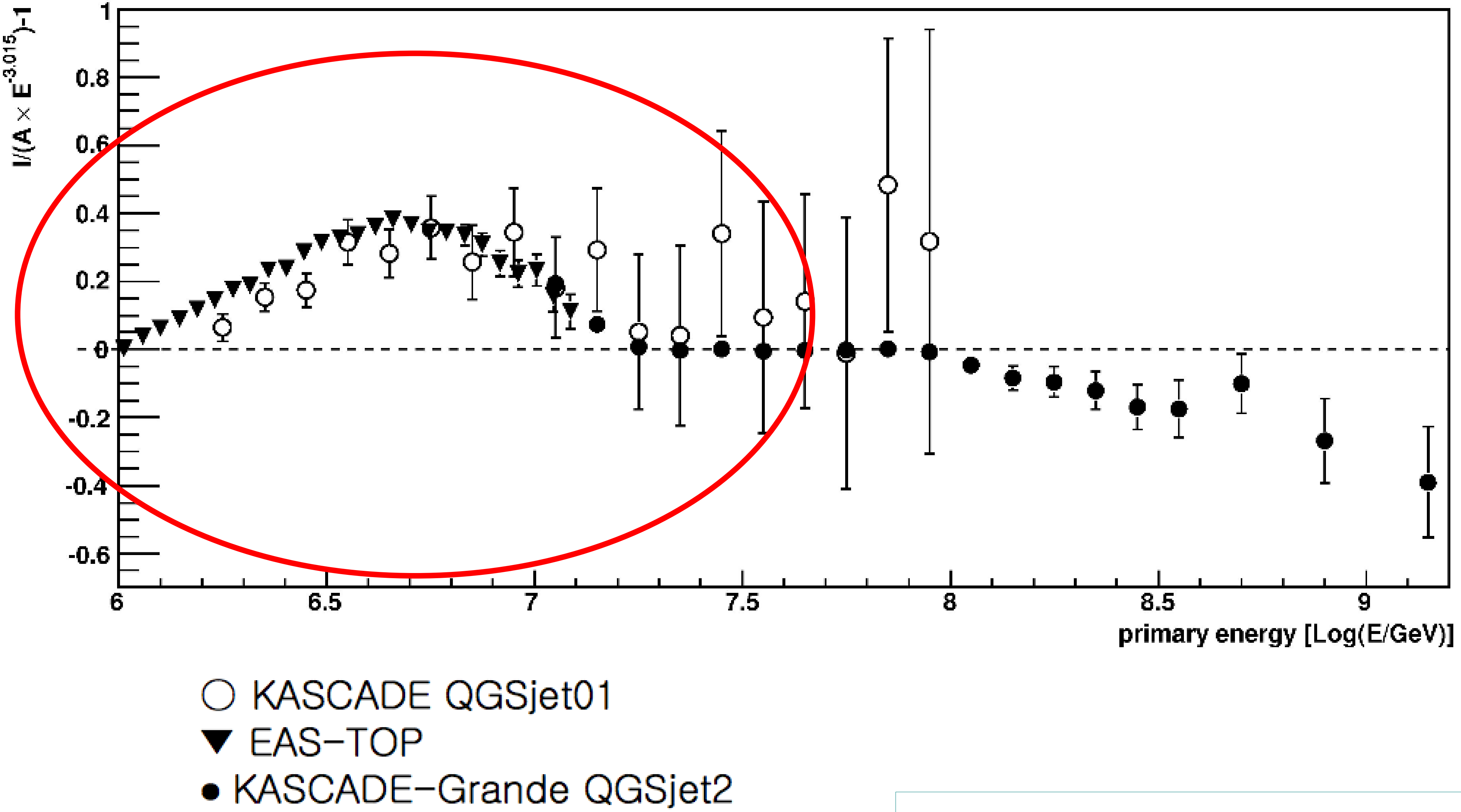
$$A \simeq 1.7 \times 10^5 \text{ m}^2$$

KASCADE-GRANDE energy spectrum



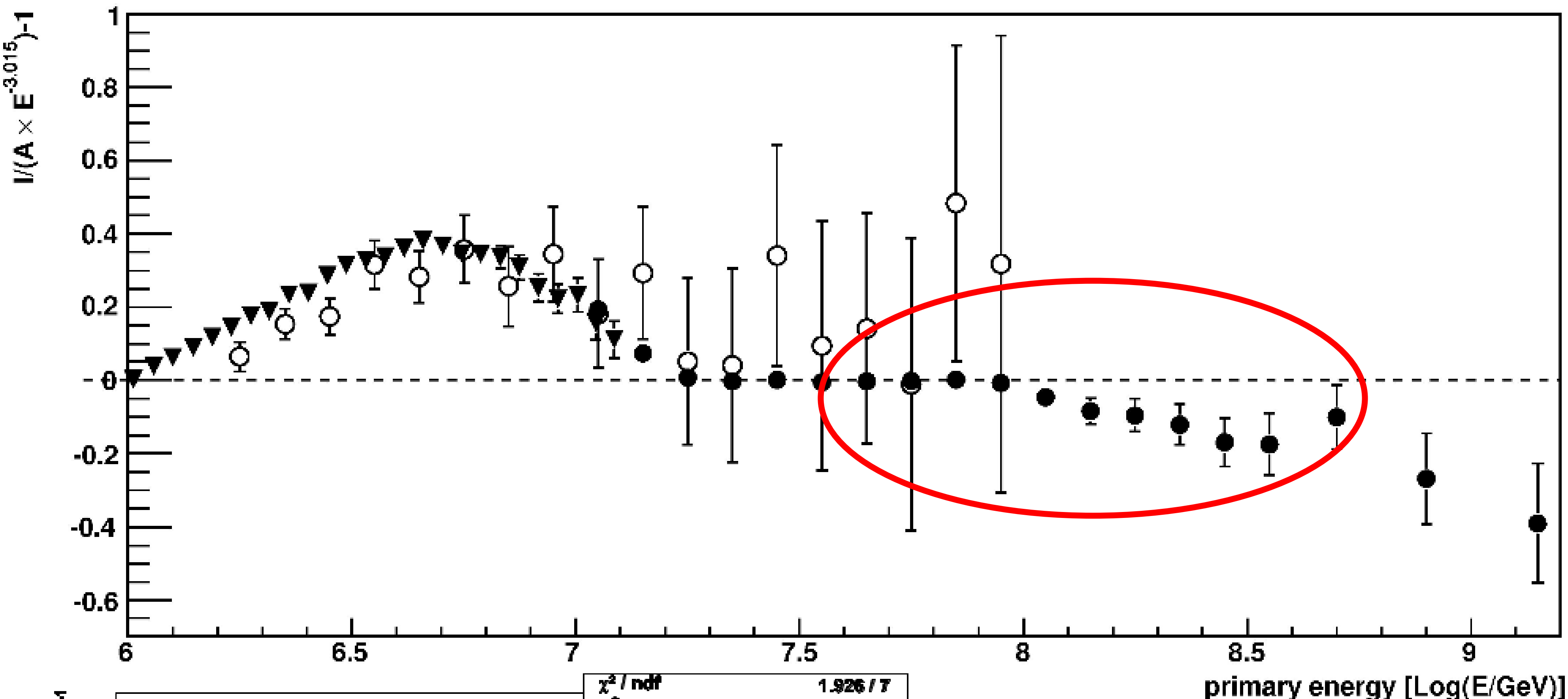
Comparison with KASCADE & EAS-TOP

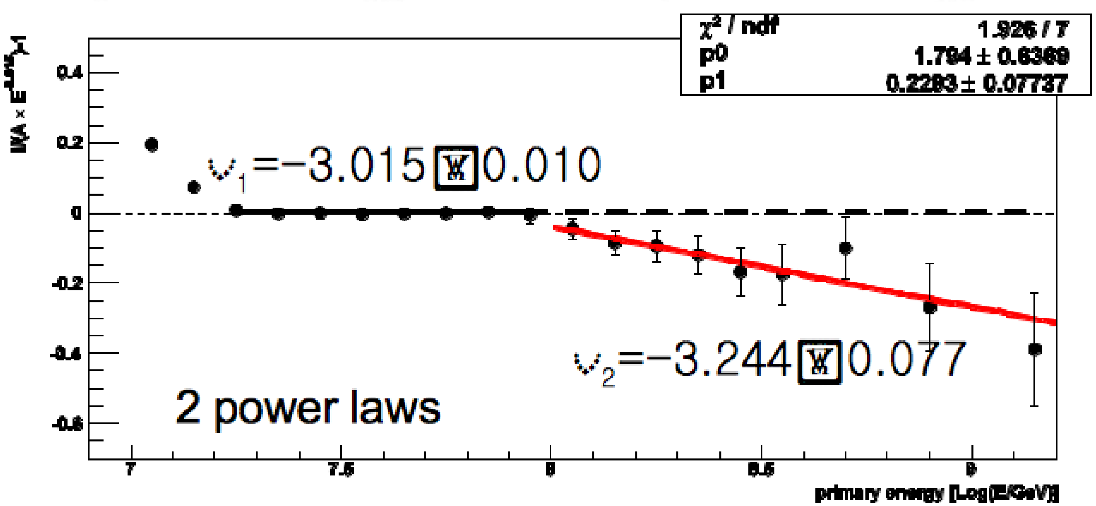




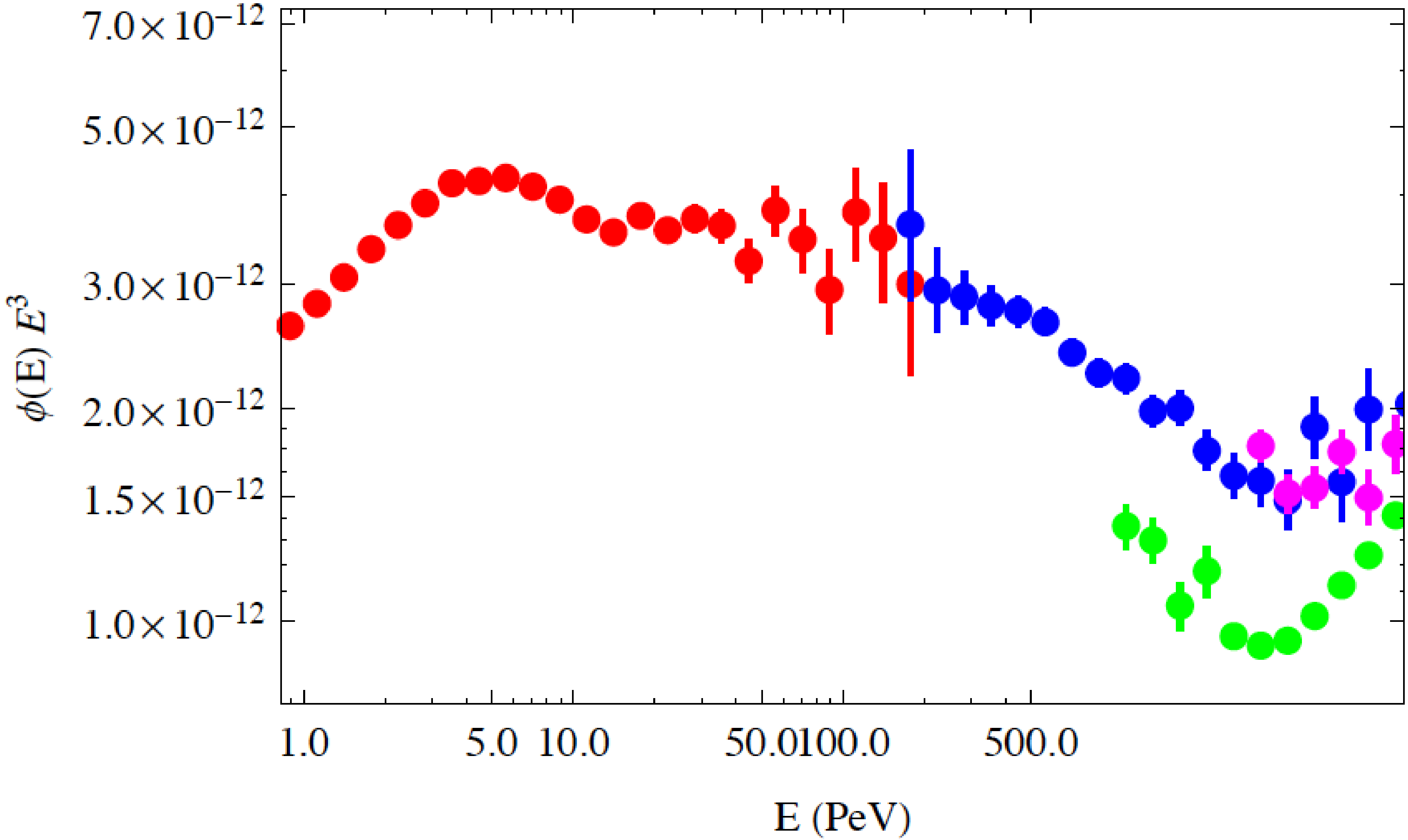
“Shape of the Knee” (?!)

Kascade Grande
(Karlsruhe KIT)


I/(A × E^-3.015)-1
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
6
6.5
7
7.5
8
8.5
9
primary energy [Log(E/GeV)]

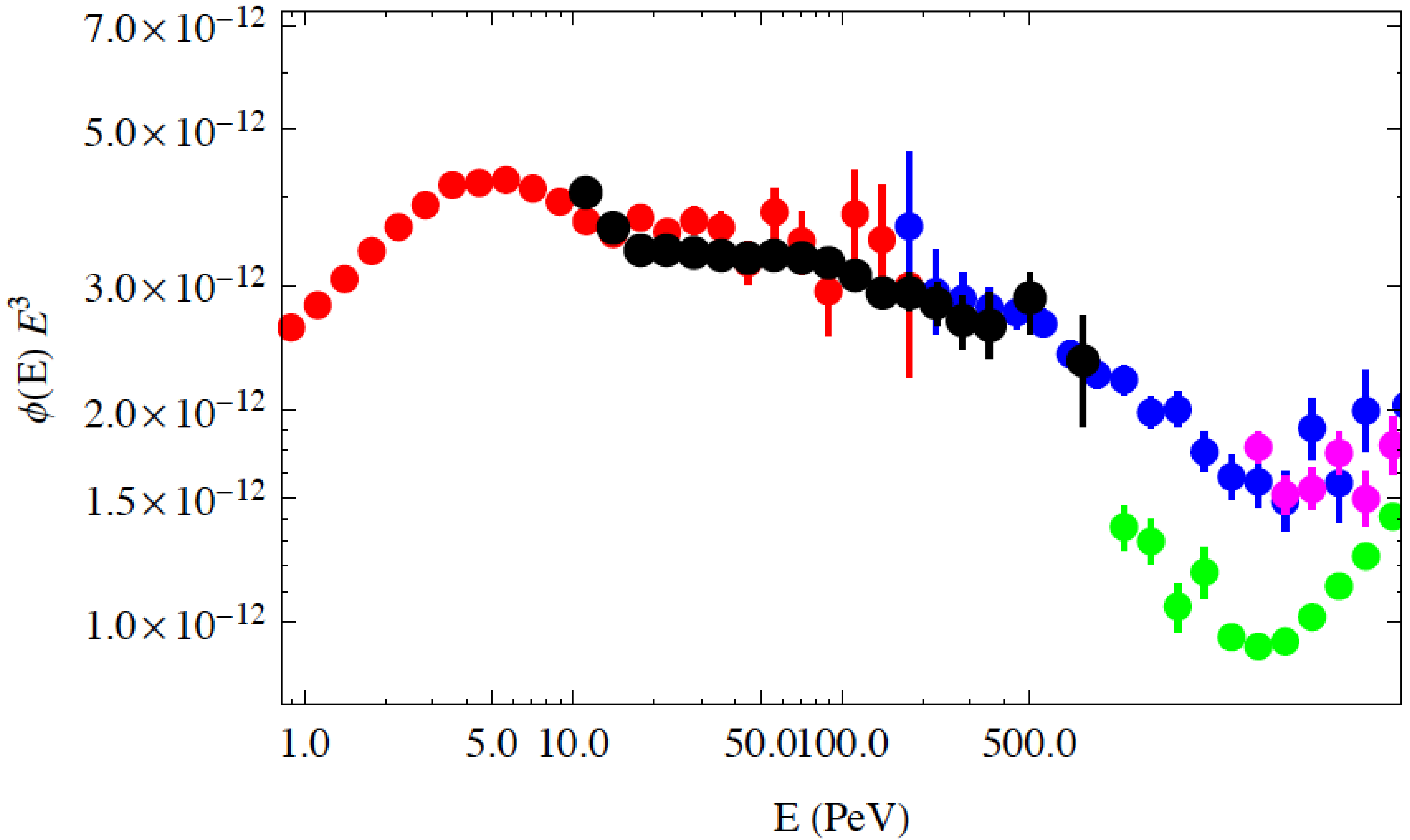

χ² / ndf 1.926 / 7
p0 1.794 ± 0.6369
p1 0.2293 ± 0.07737
=−3.015
0.010
=−3.244
0.077
2 power laws
0.4
0.2
0
-0.2
-0.4
-0.6
7
7.5
8
8.5
9
primary energy [Log(E/GeV)]

“Steepening”

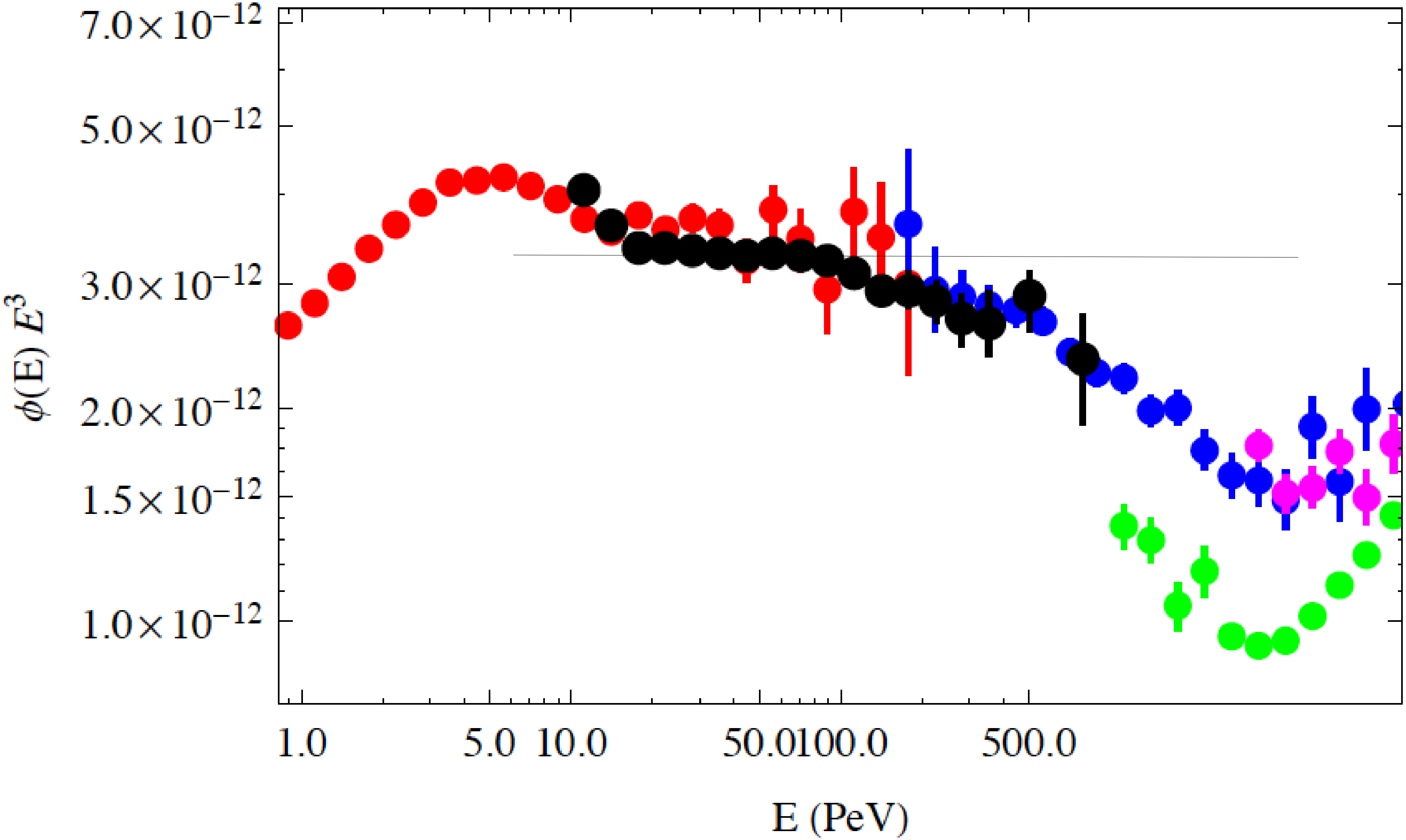


7.0×10^−12
5.0×10^−12
3.0×10^−12
2.0×10^−12
1.5×10^−12
1.0×10^−12
φ(E) E^3
1.0
5.0
10.0
50.0
100.0
500.0
E (PeV)

KASCADE-GRANDE spectrum



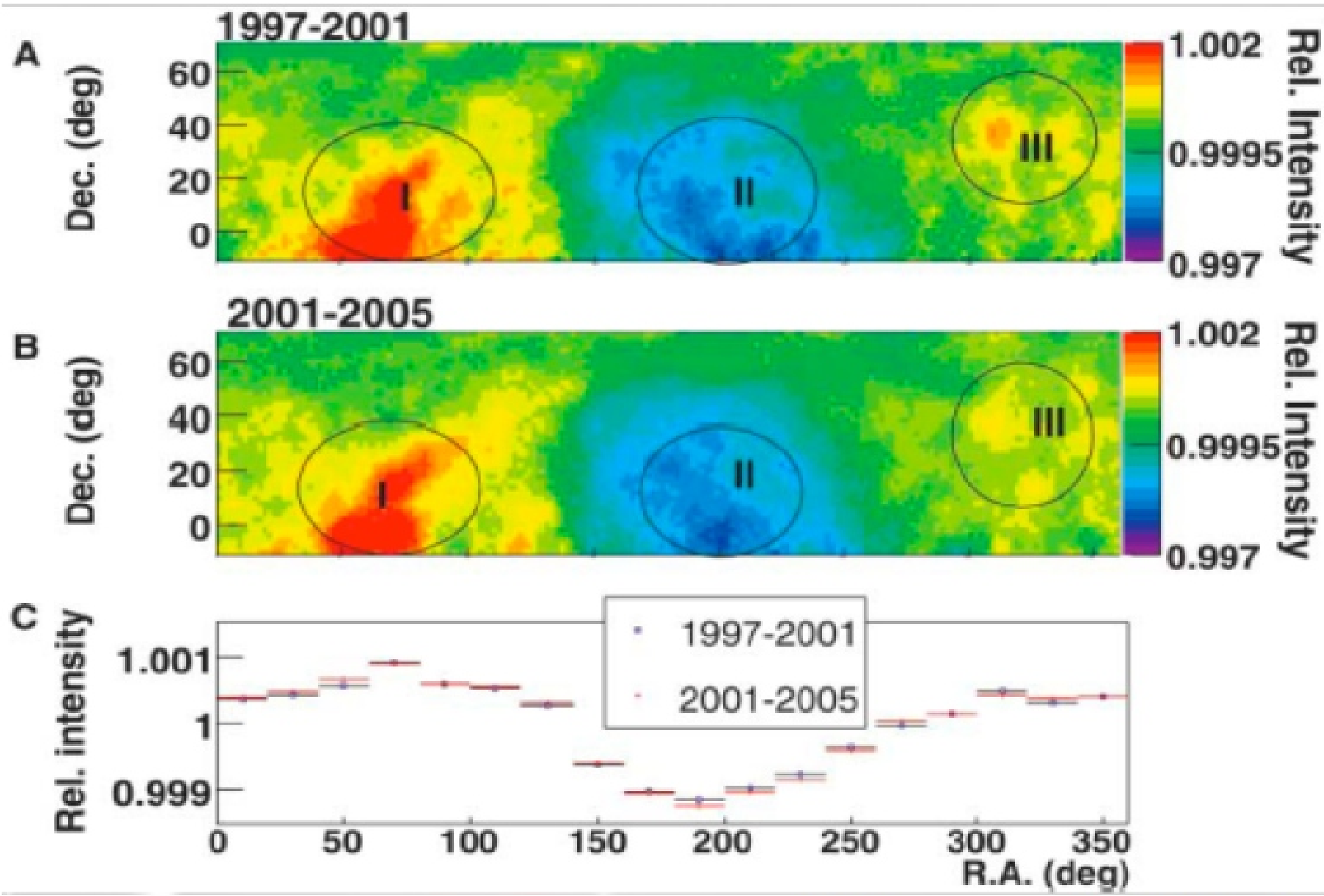
KASCADE-GRANDE spectrum   3 knees ??



COSMIC RAY

ANISOTROPIES

Tibet ASγ (verified by ARGO + IceCube)



M. Amenomori et.al. Science, 2006

TIBET AS-Gamma

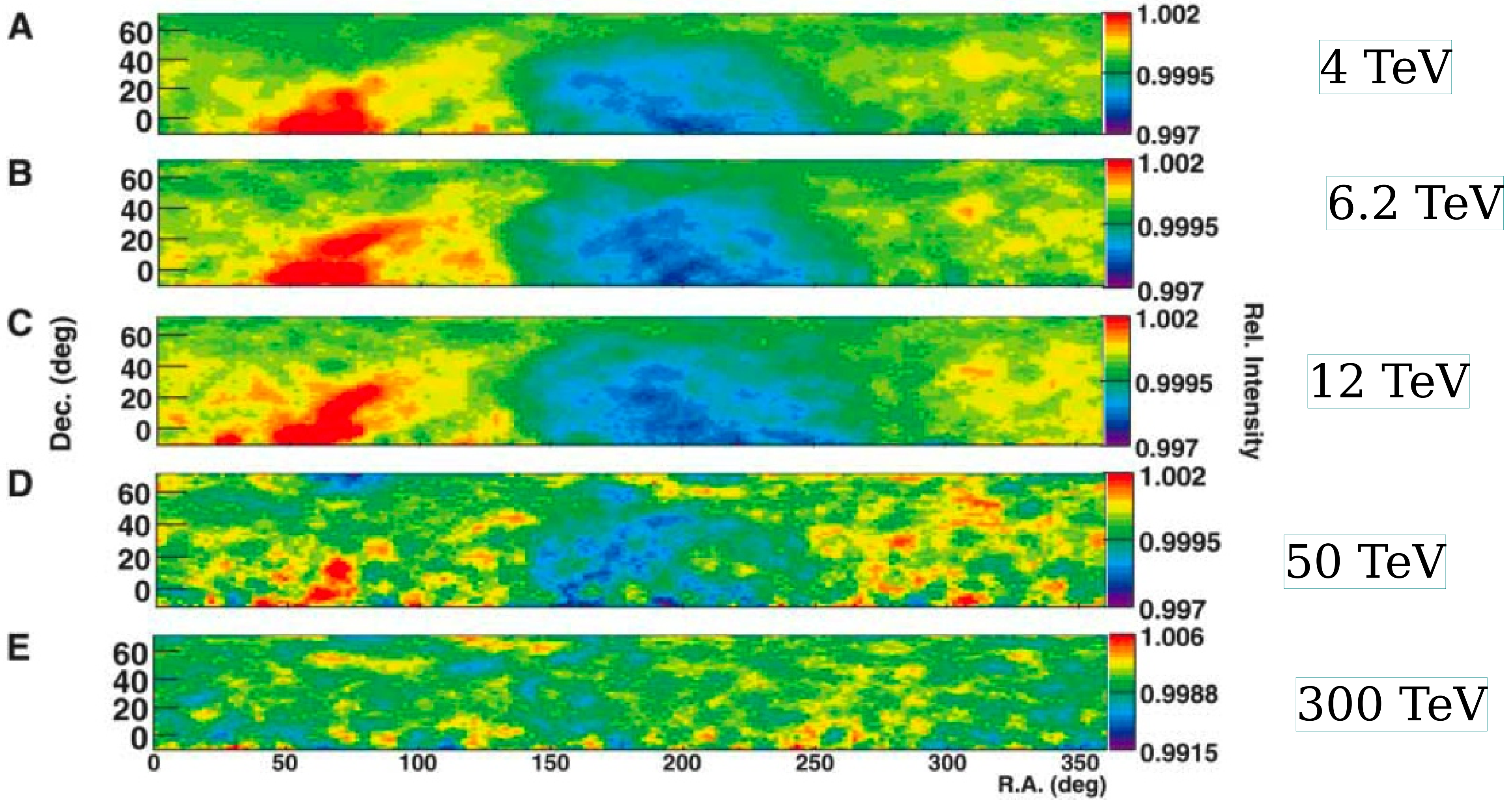
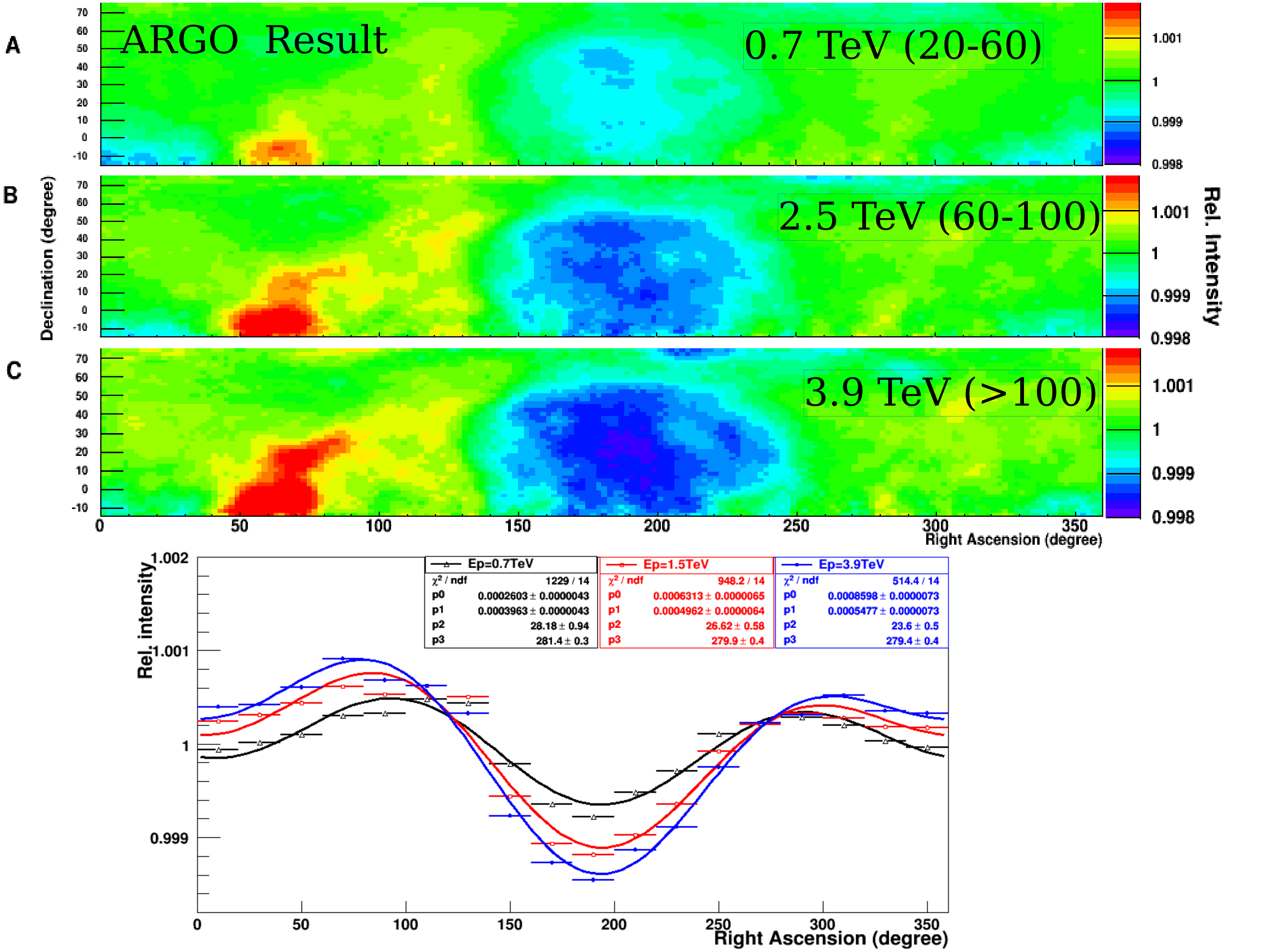
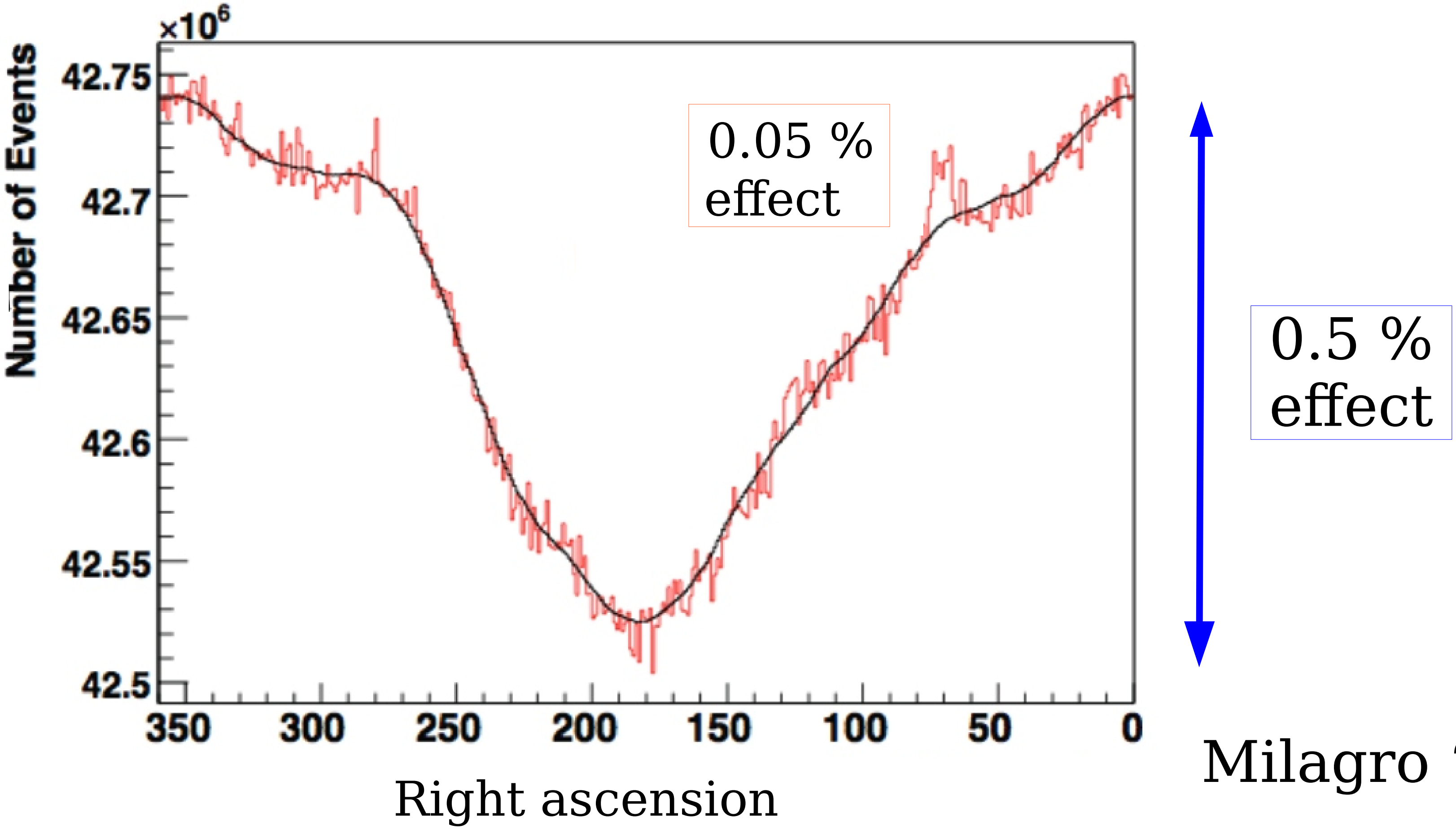


Fig. 3. Celestial CR intensity map for different representative CR energies. (**A**) 4 TeV; (**B**) 6.2 TeV; (**C**) 12 TeV; (**D**) 50 TeV; (**E**) 300 TeV. Data were gathered from 1997 to 2005. The vertical color bin width is 2.5×10^{-4} in [(A) to (D)] and 7.25×10^{-4} in (E) for different statistics,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



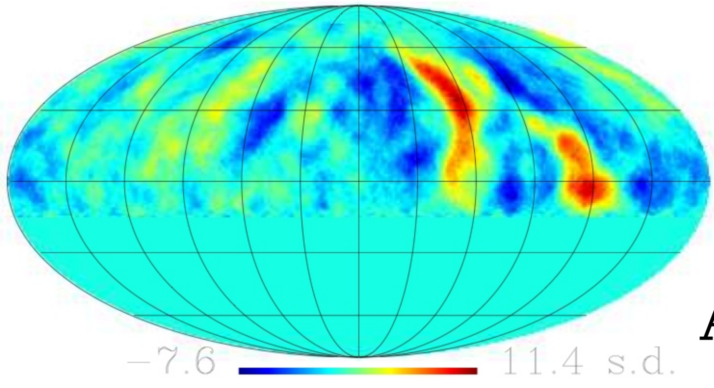
A
B
C
ARGO Result
0.7 TeV (20-60)
2.5 TeV (60-100)
3.9 TeV (>100)
Declination (degree)
Rel. Intensity
Right Ascension (degree)
Ep=0.7TeV
χ² / ndf 1229 / 14
p0 0.0002603 ± 0.0000043
p1 0.0003963 ± 0.0000043
p2 28.18 ± 0.94
p3 281.4 ± 0.3
Ep=1.5TeV
χ² / ndf 948.2 / 14
p0 0.0006313 ± 0.0000065
p1 0.0004962 ± 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)

MILAGRO data (10 TeV hadrons).

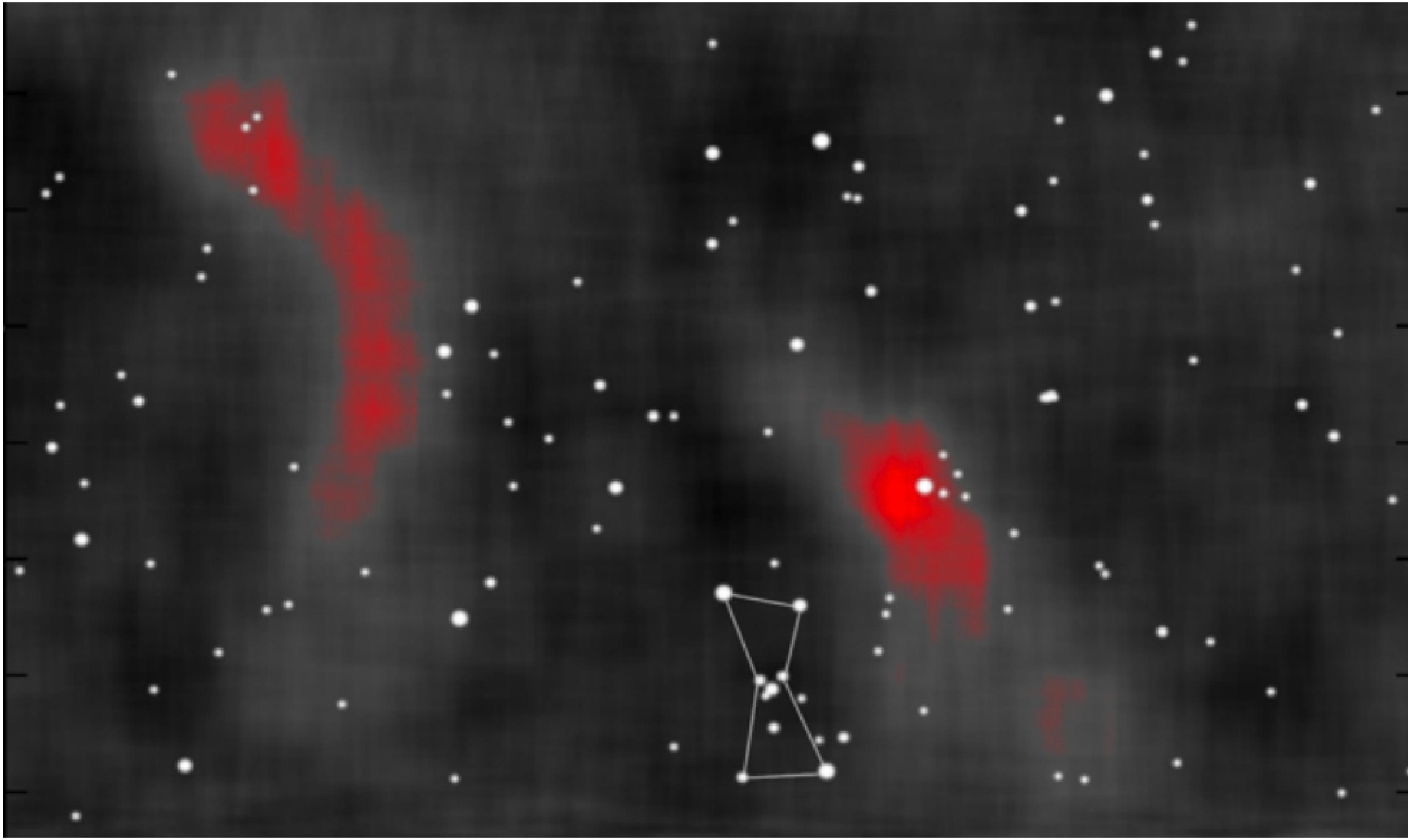


Milagro "hot spots"

2

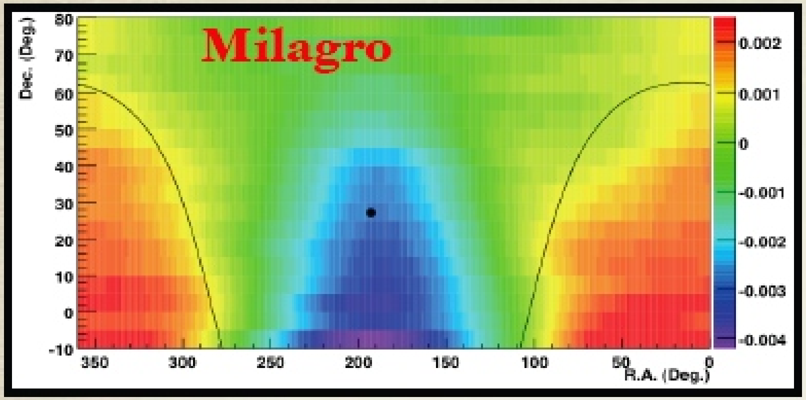


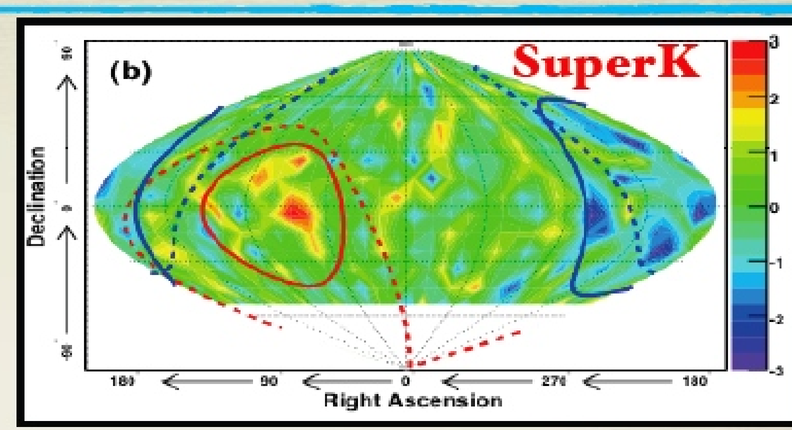
Argo

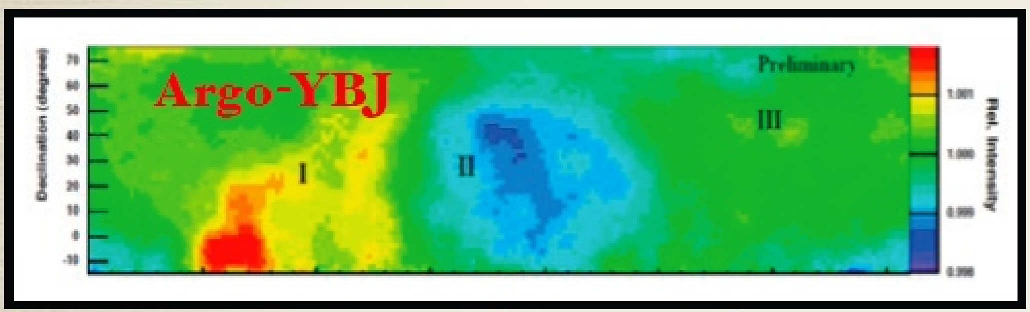


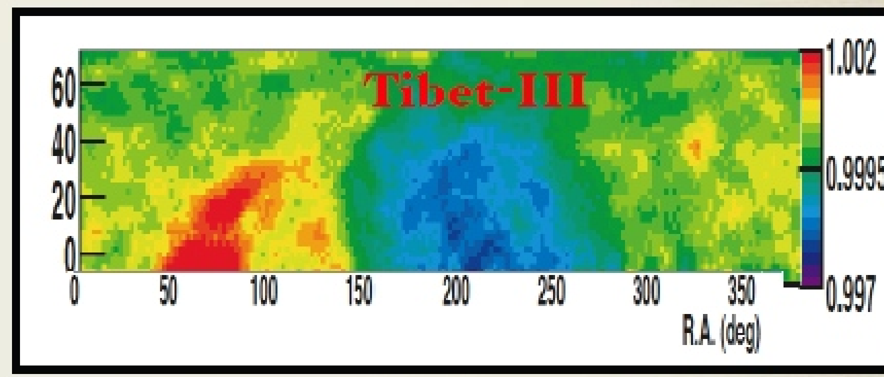
Observation of the CRs large scale anisotropy

There have been several observations of *large-scale, part- per-mille anisotropy* in cosmic ray arrival directions between 0.1 and 100 TeV.

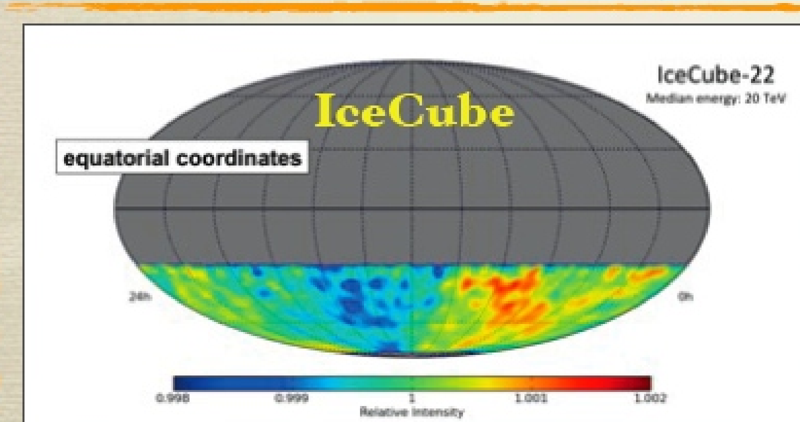






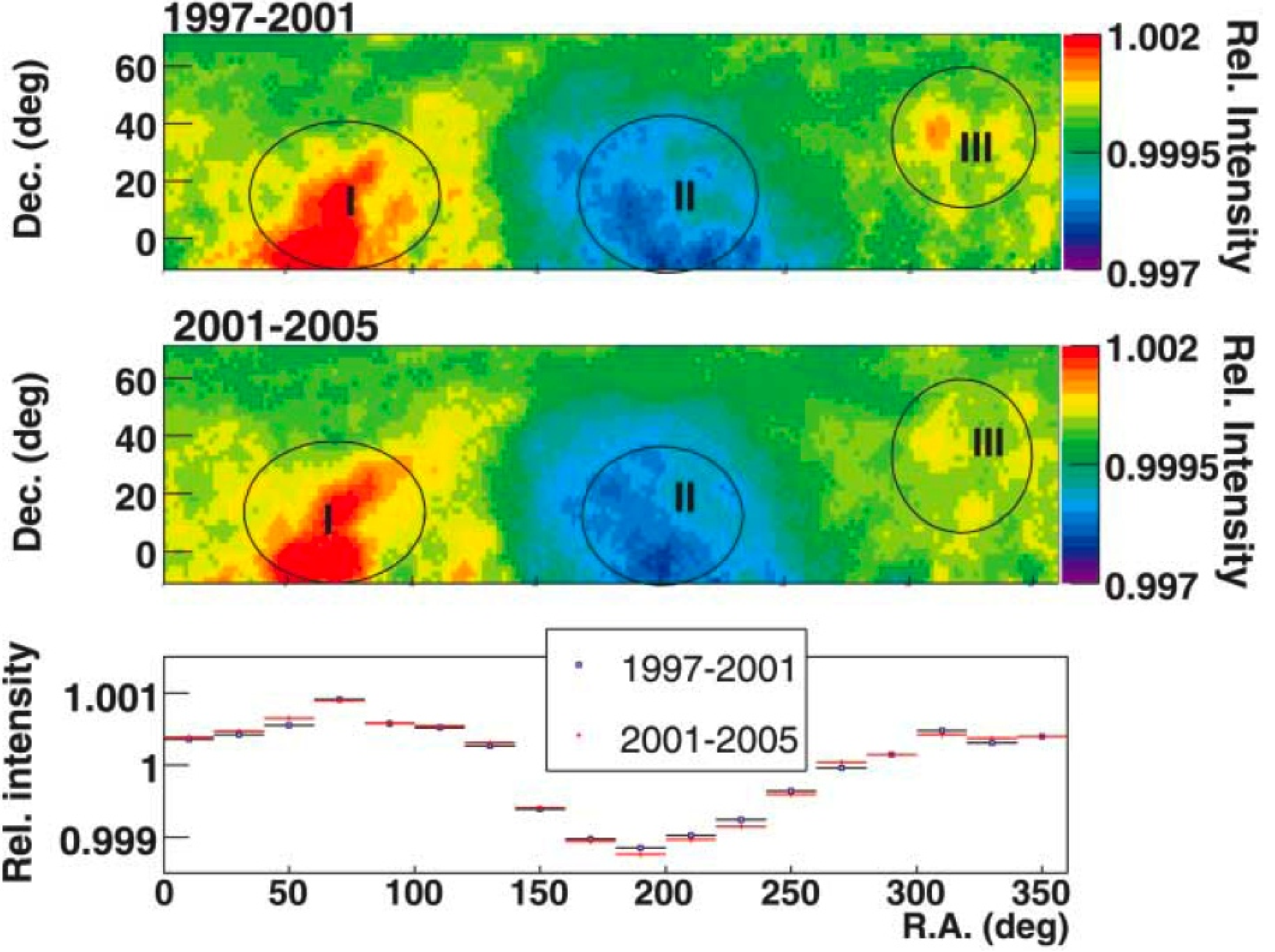


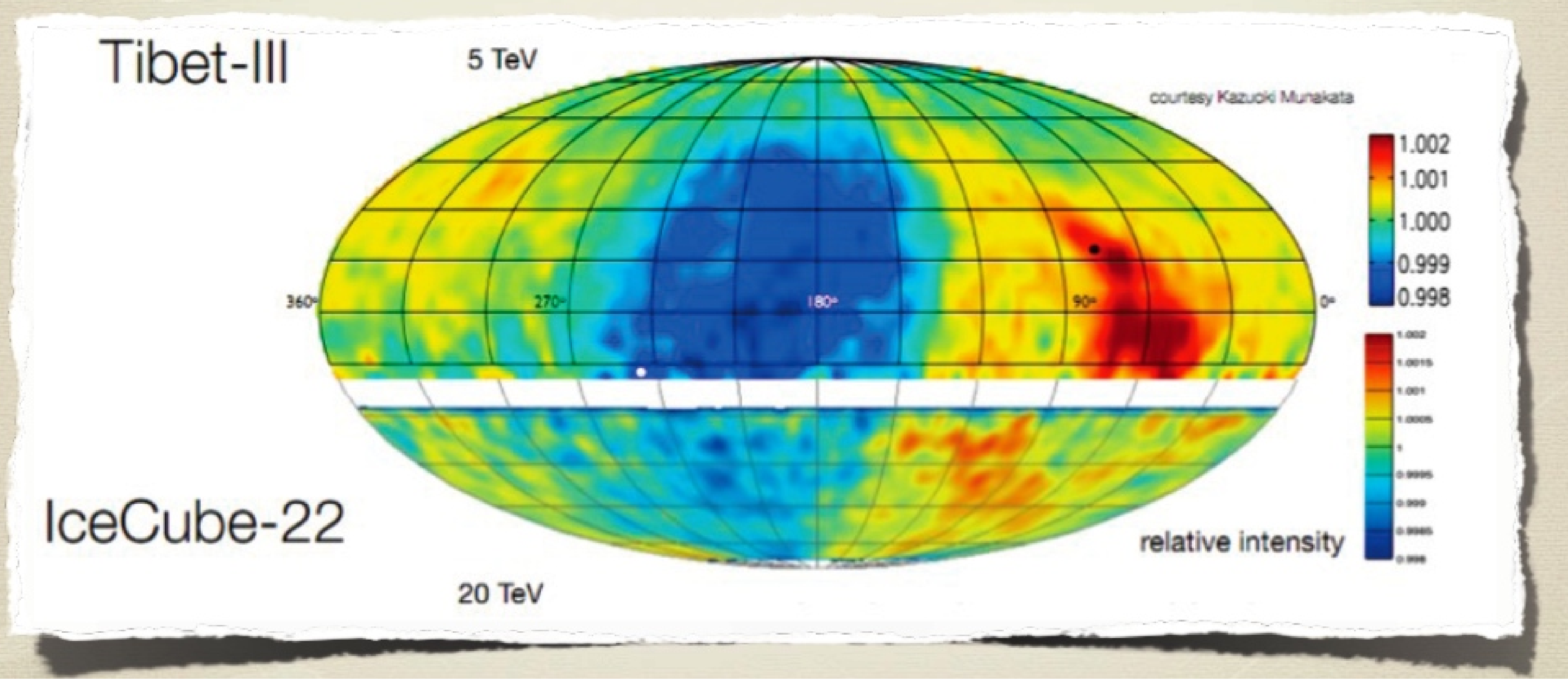
Northern Sky



Southern Sky

Tibet ASγ	M. Amenomori et al., Astrophys. J 626 (2005) L29
SuperK	G. Guillian et al., Phys. Rev. D 75 (2007) 062003
Milagro	A. Abdo et al., Astrophys. J. 698 (2009) 2121
ARGO-YBJ	S. Vernetto, Proc. 31st ICRC, 2009
EAS-Top	M. Aglietta, Astrophys. J. 692 (2009) L130
IceCube	R. Abbasi *et al*, Astrophys. J. 718 (2010) L194

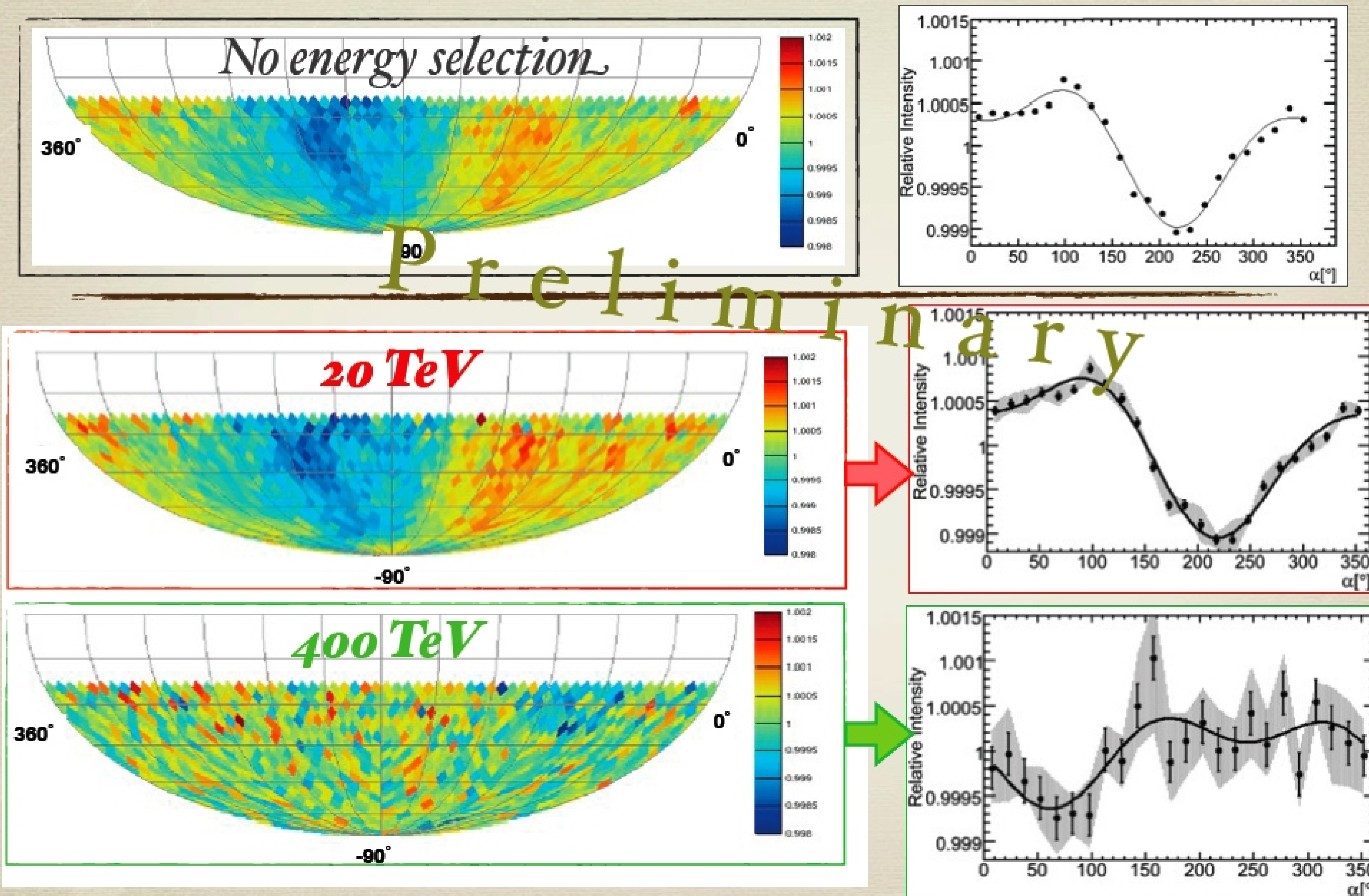

1997-2001
Dec. (deg)
60
40
20
0
I
II
III
1.002
0.9995
0.997
Rel. Intensity
2001-2005
Dec. (deg)
60
40
20
0
I
II
III
1.002
0.9995
0.997
Rel. Intensity
1997-2001
2001-2005
Rel. intensity
1.001
1
0.999
0
50
100
150
200
250
300
350
R.A. (deg)



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°***

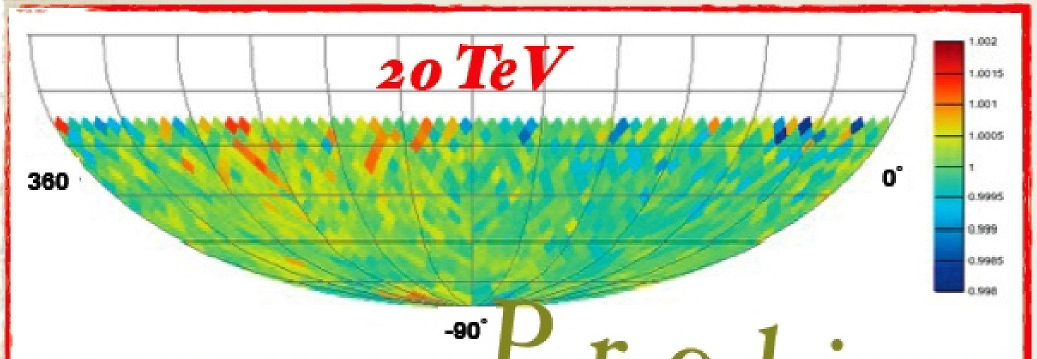


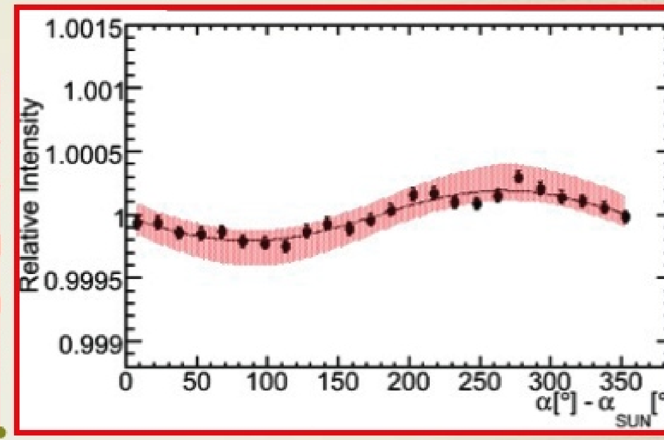
Energy dependence of the Solar dipole

✳ IceCube observes the Solar dipole in both energy bins. The observed amplitude is compatible with the expectations within the stat. and sys. uncertainties.

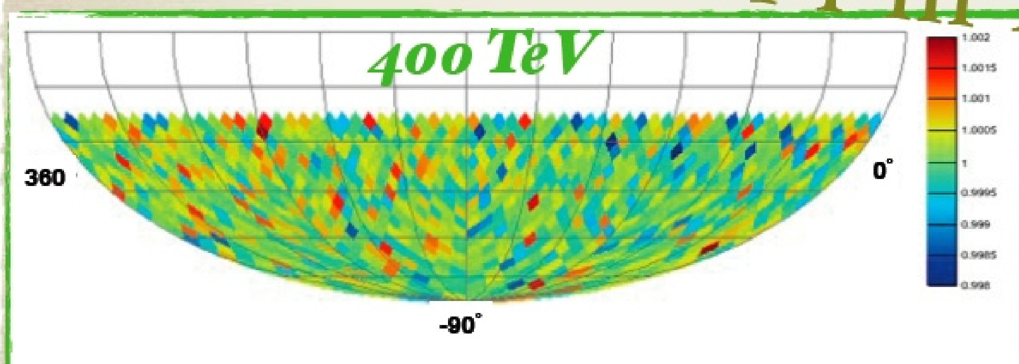
✳ The observation of the solar dipole supports the observation of the sidereal anisotropy in cosmic ray arrival direction.

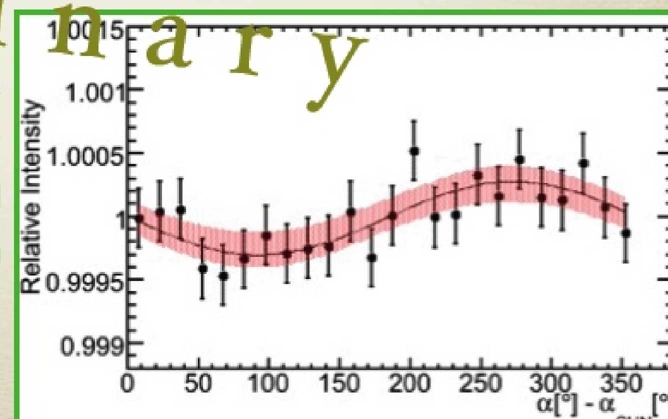
relative intensity Vs. ($\alpha[^\circ]$ - $\alpha_{SUN}[^\circ]$)





Preliminary



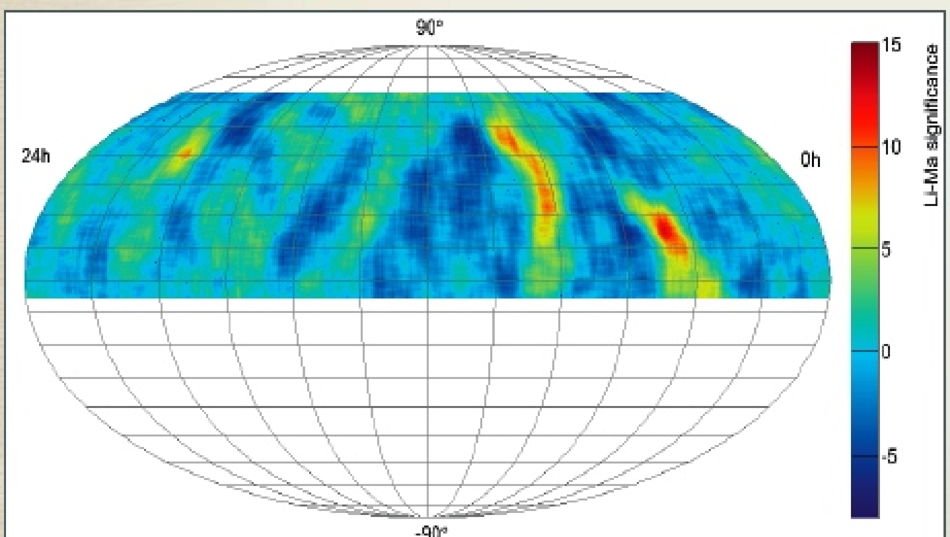


Small scale anisotropy

Several experiments have discovered anisotropies on scales of about 10°

✳ Milagro observes two localized regions with **significance > 10σ** in the total data set of 2.2 10^{11} events recorded over 7 years. The "hot" regions have fractional excesses of order several times $\mathbf{10^{-4}}$ relative to the background.

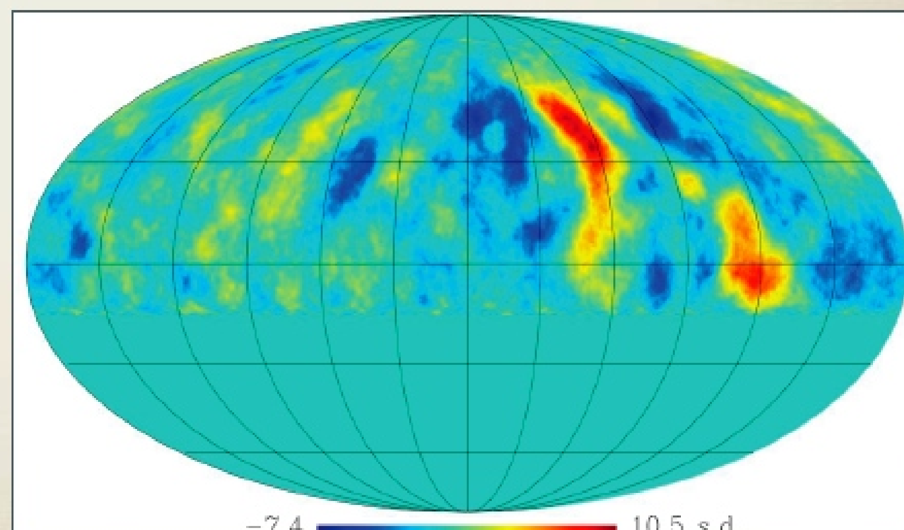
✳ Same structures observed by ARGO-YBJ.



A. Abdo et al., PRL 101 (2008) 221101

Milagro

Median Energy: 1 TeV



S. Vernetto, Proc. 31st ICRC, 2009

ARGO-YBJ

Median Energy: 2 TeV

Dipole and quadrupole fit

$$\delta I(\alpha,\delta) = m_0$$ **monopole**

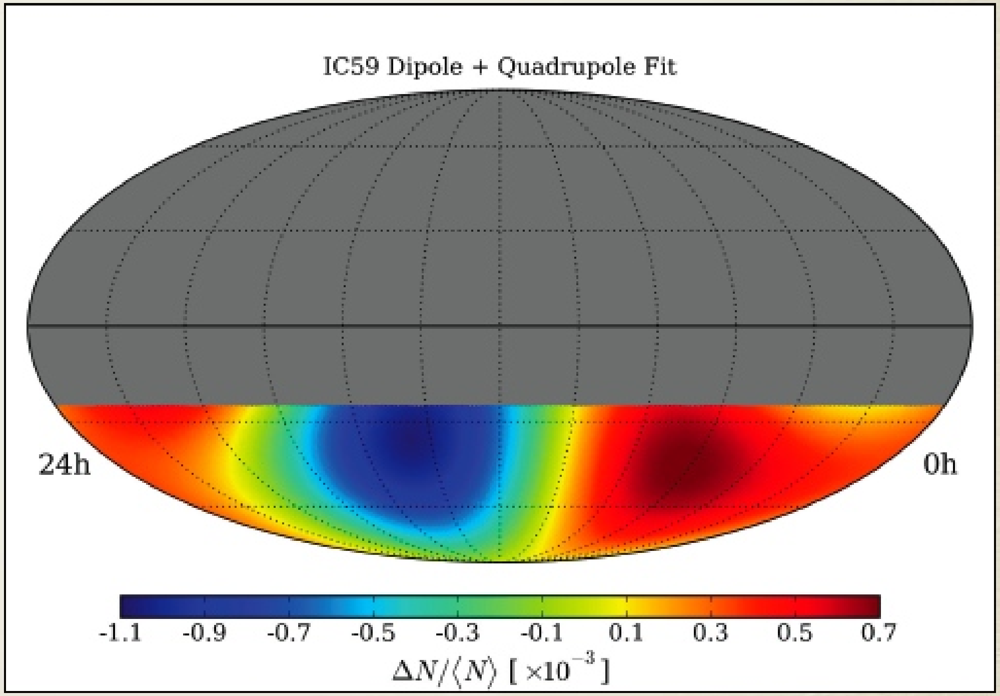
$$+p_x \cos\delta\cos\alpha + p_y\cos\delta\sin\alpha + p_z\sin\delta$$ **dipole**

$$+\frac{1}{2}Q_1(3\cos^2\delta - 1) + Q_2\sin 2\delta\cos\alpha + Q_3\sin 2\delta\sin\alpha + Q_4\cos^2\delta\cos 2\alpha + Q_5\cos^2\delta\sin 2\alpha$$ **quadrupole**

Coefficient	Fit Value
m_0	0.320 ± 2.264
p_x	2.435 ± 0.707
p_y	-3.856 ± 0.707
p_z	0.548 ± 3.872
Q_1	0.233 ± 1.702
Q_2	-2.949 ± 0.494
Q_3	-8.797 ± 0.494
Q_4	-2.148 ± 0.200
Q_5	-5.268 ± 0.200

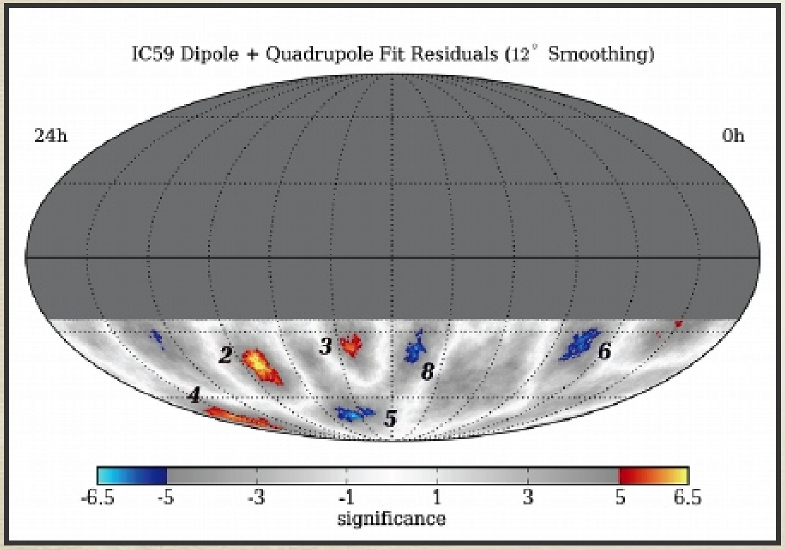
$$\chi^2/\mathrm{ndf} = 14743.4/14187$$

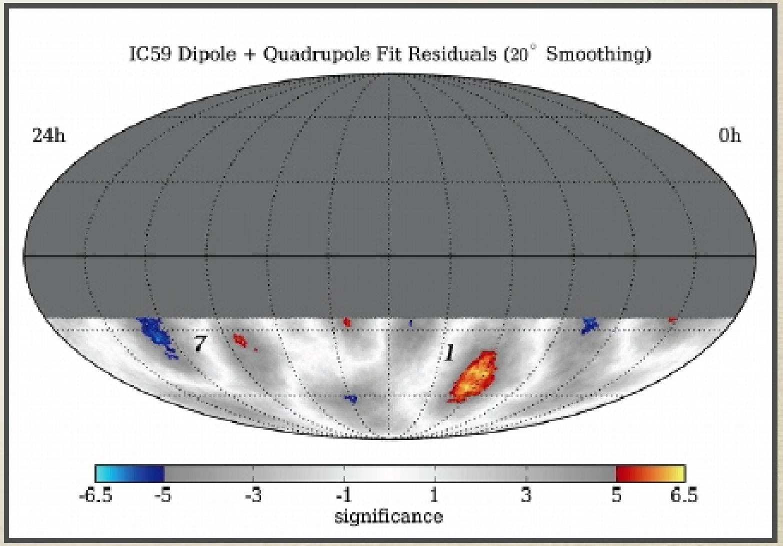
$$\Pr(\chi^2|\mathrm{ndf}) = 5.5\times 10^{-4}$$



Identification of significant structures

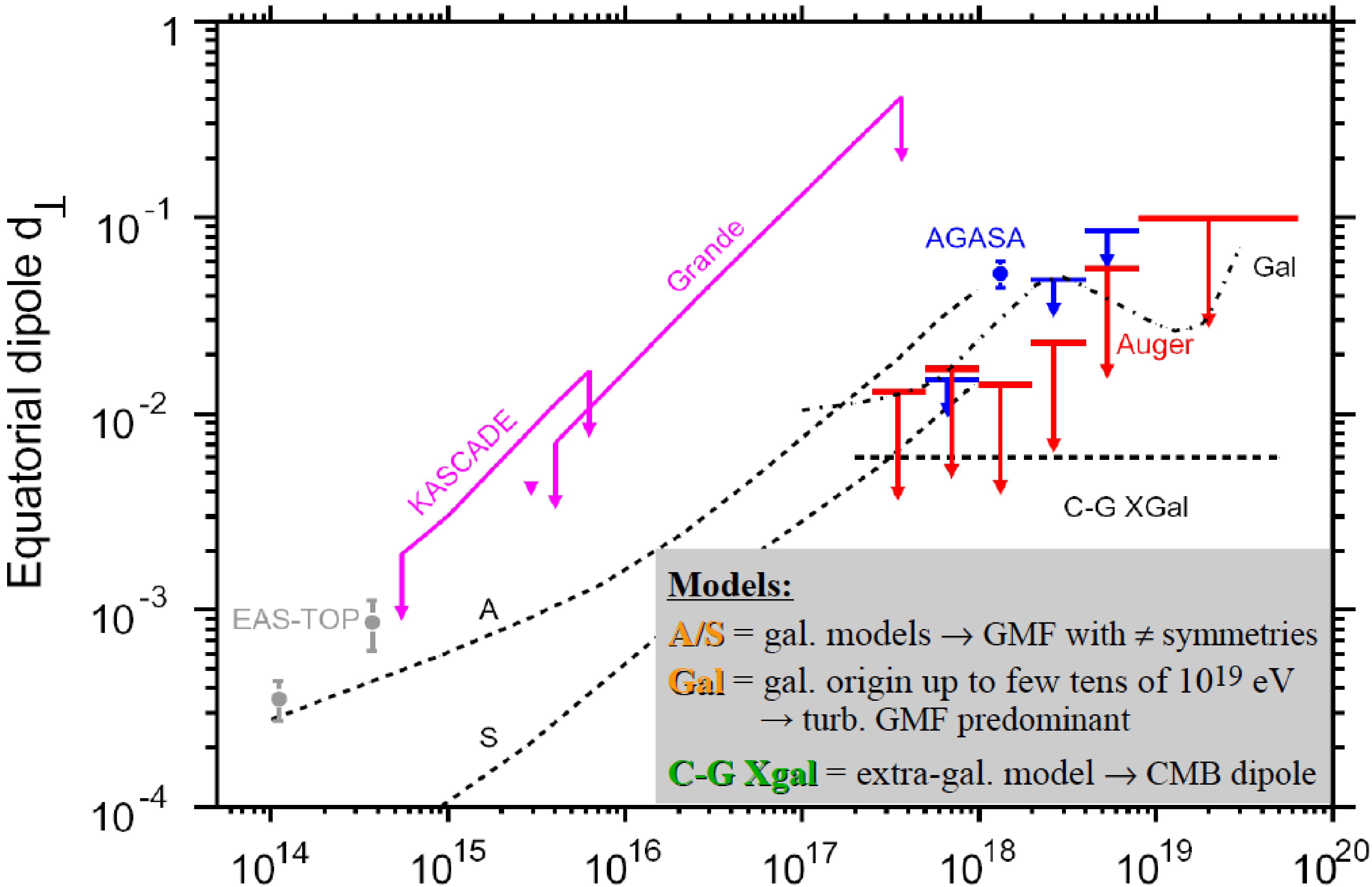
region	right ascension	declination	optimal scale	peak significance	post-trials
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ	4.4σ
4	$(332.4^{+9.5}_{-7.1})^\circ$	$(-70.0^{+4.2}_{-7.6})^\circ$	12°	6.2σ	4.2σ
5	$(217.7^{+10.2}_{-7.8})^\circ$	$(-70.0^{+3.6}_{-2.3})^\circ$	12°	-6.4σ	-4.5σ
6	$(77.6^{+3.9}_{-8.4})^\circ$	$(-31.9^{+3.2}_{-8.6})^\circ$	13°	-6.1σ	-4.1σ
7	$(308.2^{+4.8}_{-7.7})^\circ$	$(-34.5^{+9.6}_{-6.9})^\circ$	20°	-6.1σ	-4.1σ
8	$(166.5^{+4.5}_{-5.7})^\circ$	$(-37.2^{+5.0}_{-5.7})^\circ$	12°	-6.0σ	-4.0σ





AUGER

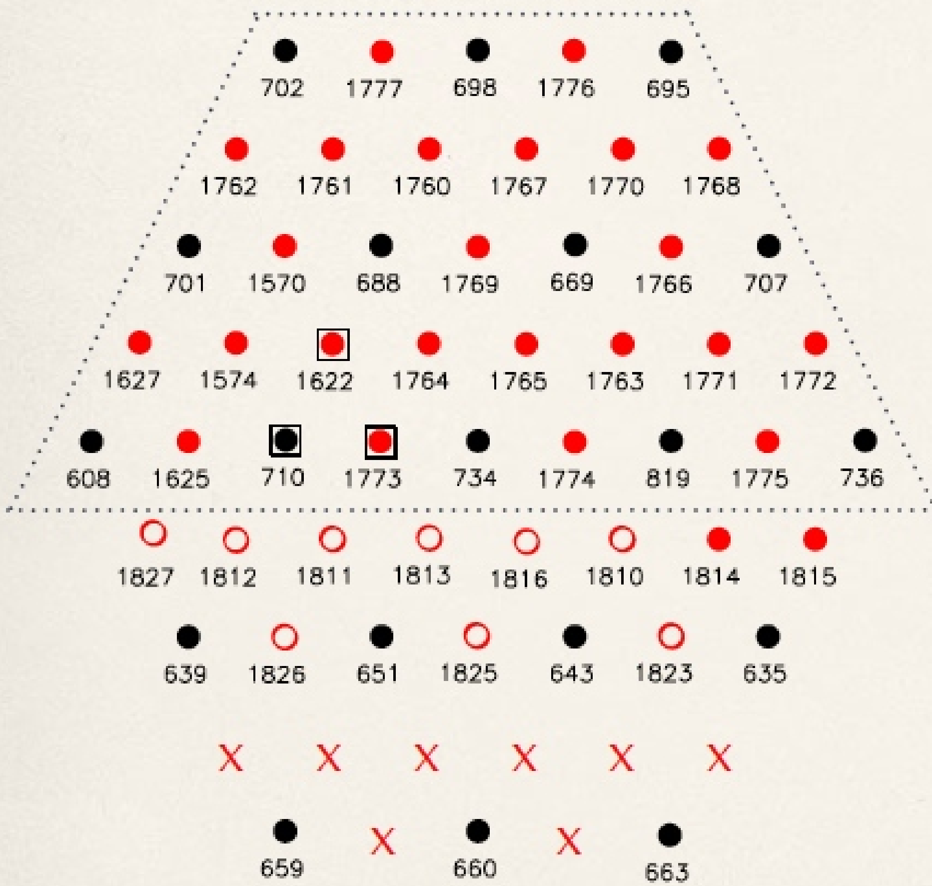
Upper limits



Need measurements [and understanding]
of Large Scale anisotropy in all energy range

from TeV to UHECR

AMIGA
Auger Muons & Infill for the Ground Array



- ● 1500 m grid stations
- ● 750 m grid stations (infill stations)
- ○ infill stations just installed
- □ associated muon detectors
- x 8 missing infill stations

Total area: 23.5 km²

Near future:
+24 stations in a 433 m grid ~ 5.9 km²

Data taking since August 2008

Water Cherenkov detectors: electromagnetic component + muons
Muon detectors: muons

Final Remarks:

New measurements of the CR fluxes in the broad energy region "from the knee to the ankle" have the Potential to give very valuable information on the "high energy universe".

The Optimization of the design of a shower detector for this purpose is a non trivial problem that requires careful discussion.

Uncertainties in the shower modeling due to our imperfect Understanding of hadronic interactions remain an important issue. LHC is a great opportunity for improvement.

The study of anisotropies is of great importance.

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.]