Multi-messenger prospective II

UHECR-centric

Angela V. Olinto
The University of Chicago

References

Books:

Cosmic Rays – Tom Gaisser 1990 – new one to come!
Ultra High Energy Cosmic Rays – Todor Stanev – 2011
Gamma-ray Astro – Feliz Aharonian
Neutrino Physics and Astrophysics – Carlo Giunti & Chung W. Kim
Extensive Air Showers:...– Peter K. F. Grieder
High Energy Astrophys – M. Longair 2011
HE Radiation from Black Holes – C. Dermer & Menon 2011

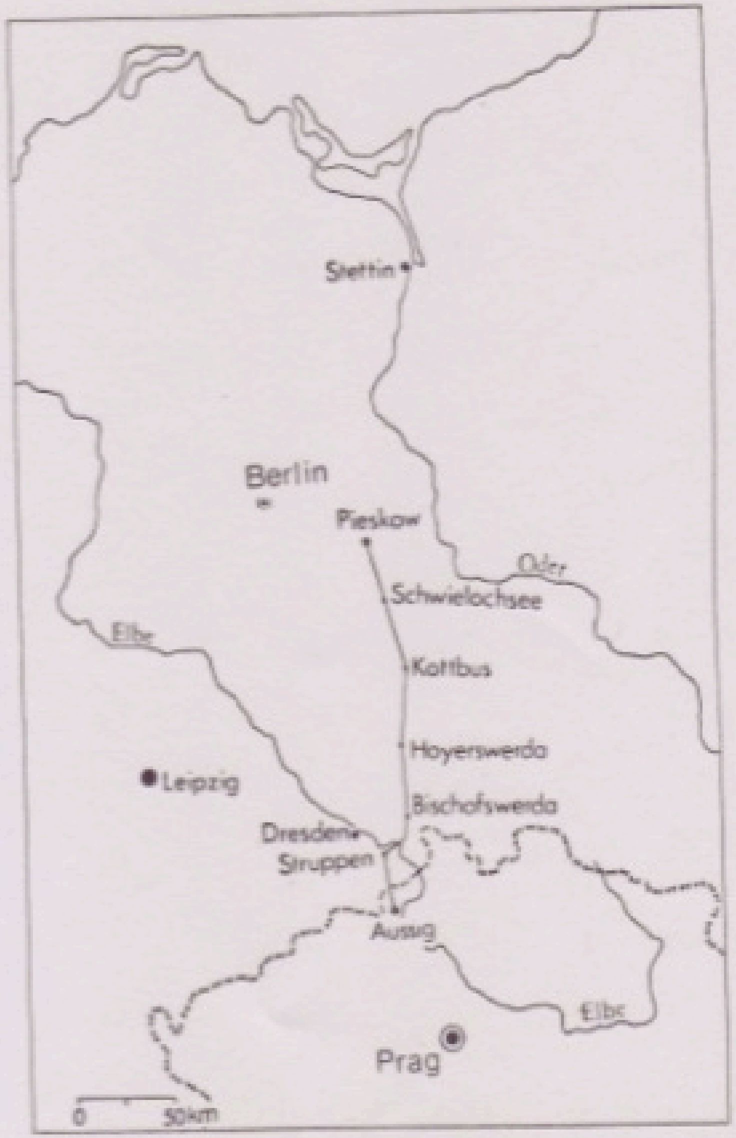
Reviews: UHECRs
Kotera & AVO: 2011 Annual Reviews Astronomy & Astrophysics
Letessier-Selvon & Stanev (2011),
Beatty & Westerho (2009),
Bluemer et al. (2009),
HE neutrinos: Anchordoqui & Montaruli 2010, Sigl 2012 (ISAPP)
HE gamma-rays: Hinton & Hofmann 2009

100th Anniversary

Victor Hess balloon flights – 1912
establishes the cosmic nature of ionizing radiation

Flight path of 7th flight

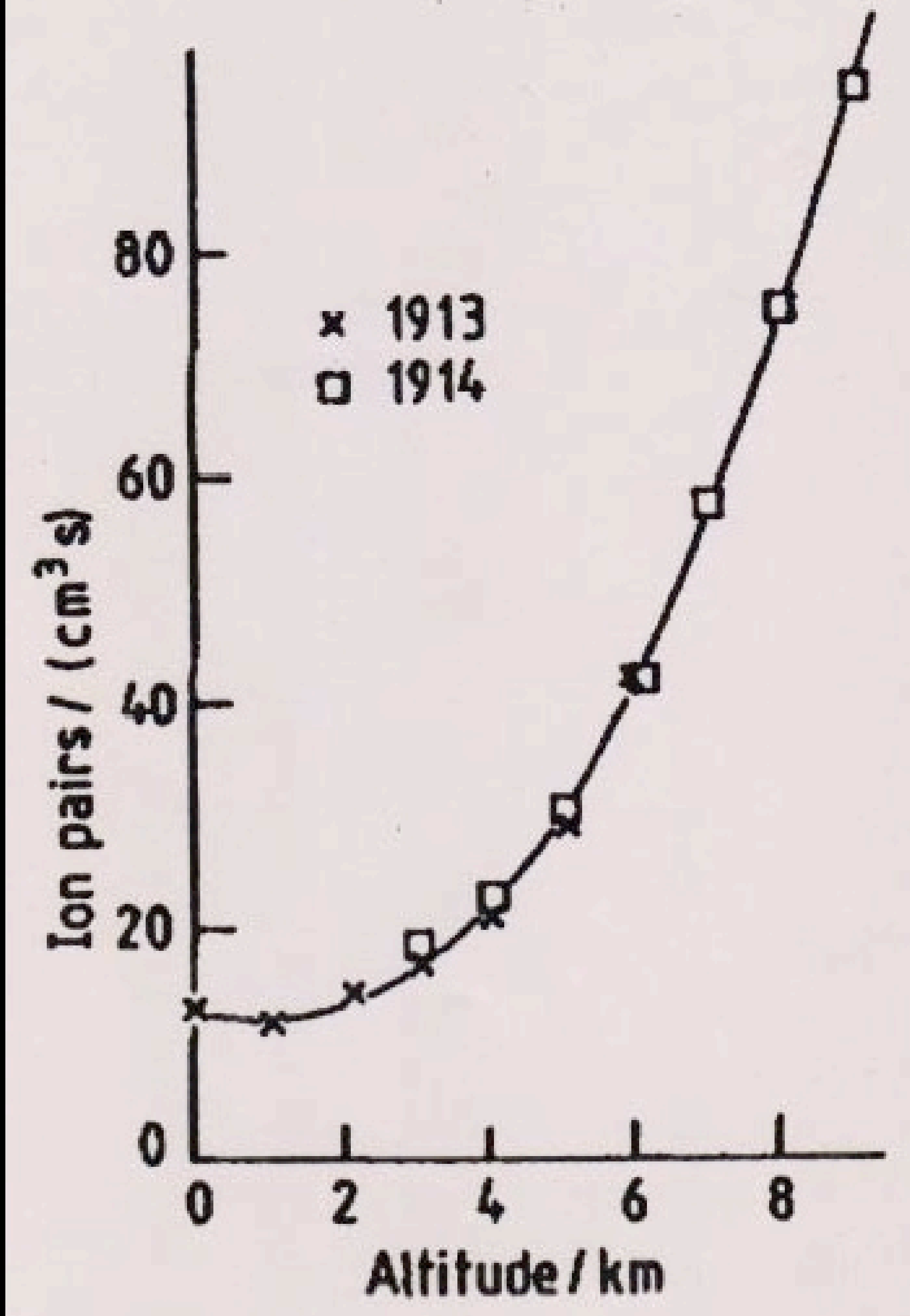
5000 m altitude



Route des Entdeckungsfluges der kosmischen Strahlung.

Werner Kölhoster

Dr. Werner Kolhörster im Jahre 1912.



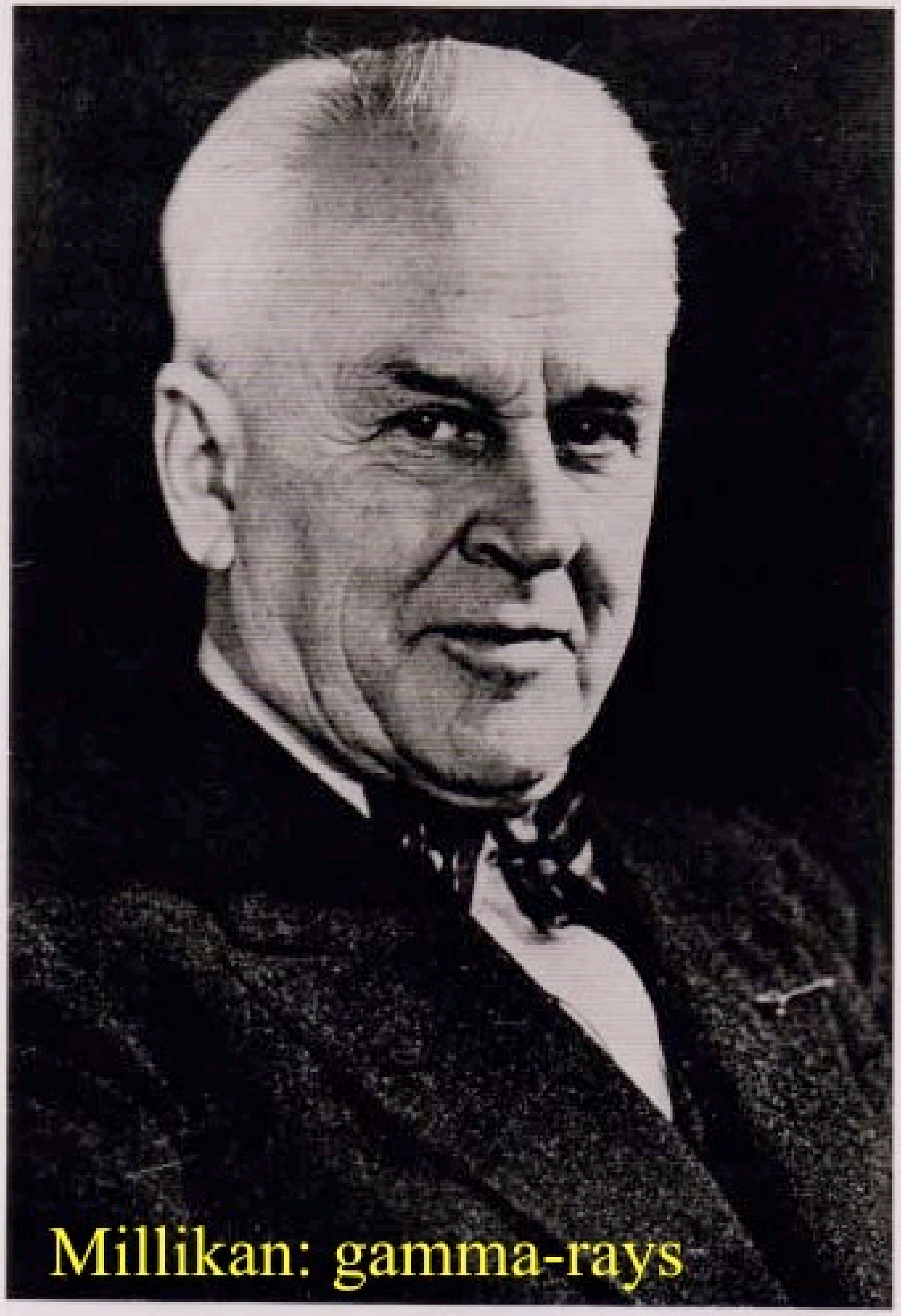
Kohlhörster's team: balloon flight 13 May 1934

Assistent: Schrenk;

Grad Student: Masuch

did not survive the flight.

Fig. 6. Compton with the special ionization chamber which he designed and used for his world-wide cosmic-ray survey during 1931–33, which proved that cosmic rays are charged particles.



ROBERT A. MILLIKAN

Fig. 8. Compton with the special
he designed and used for his world
during 1931–33, which proved that
charged particles.

The New York Times

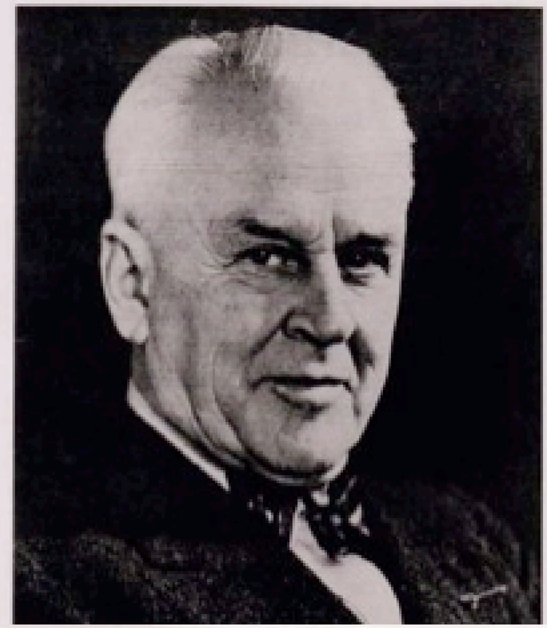
VOL. LXXXII....No. 27,370. December 31, 1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.



In an atmosphere surcharged with drama, in which the human element was by no means lacking, the two protagonists presented their views with the vehemence and fervor of those theoretical debates of bigone days when learned men clashed over the number of angels that could dance on the point of a needle. Dr. Millikan particularly sprinkled his talk with remarks directly aimed at his antagonist's scientific acumen. There was obvious coolness between the two men when they met after the debate was over.

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

THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics

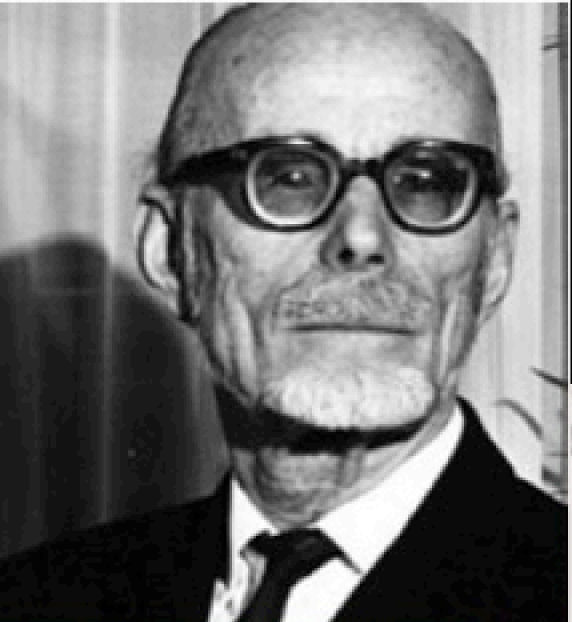
VOL. 43, No. 6 MARCH 15, 1933 SECOND SERIES

A Geographic Study of Cosmic Rays

ARTHUR H. COMPTON, *University of Chicago*

(Received January 30, 1933)

Data are given from measurements of the intensity of cosmic rays by 8 different expeditions at 69 stations distributed at representative points over the earth's surface. Each set of apparatus consisted of a 10 cm spherical steel ionization chamber filled with argon at 30 atmospheres, connected to a Lindemann electrometer, and shielded with 2.5 cm of bronze plus 5.0 cm of lead. Measurements were made by comparing the ionization current due to the cosmic rays with that due to a capsule of radium at a measured distance, the radium standards used with the several sets of apparatus having been intercompared. The method of detecting and correcting for the following disturbing effect is discussed: insulation leak and absorption, local gamma-radiation, radioactive contamination of the ionization chamber, and shielding from cosmic rays by roof and horizon. Intensity *vs.* barometer (altitude) curves are given for various latitudes. These show not only the rapid increase with altitude noted by previous observers, but also the fact that at each altitude the intensity is greater for high latitudes than near the equator. At sea level the intensity at high latitudes is 14 ± 0.6 percent greater than at the equator; at 2000 m elevation, 22 percent greater; and at 4360 m, 33 percent greater. This variation follows the geomagnetic latitude more closely than the geographic or the local magnetic latitude, and is most rapid between geomagnetic latitudes 25 and 40 degrees. Consideration of the conditions necessary for deflection of high-speed electrified particles by the earth's magnetic field indicates that if the cosmic rays are electrons, they must originate not less than several hundred kilometers above the earth. The data can be quantitatively explained on the basis of Lemaitre and Vallarta's theory of electrons approaching the earth from remote space. Acknowledgment is made of the cooperation of more than 60 physicists in this program, 25 of whom are named.

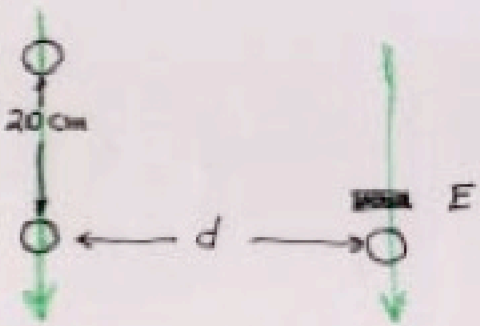


Pierre Auger

Discovered Extensive Airshowers

PHYSIQUE NUCLÉAIRE. — *Les grandes gerbes cosmiques de l'atmosphère.* Note [1] de MM. **Pierre Auger** et **Roland Maze**, présentée par M. Jean Perrin.

1. Nous avons montré [2] l'existence de gerbes de rayons cosmiques produites dans l'atmosphère et dont les branches peuvent être distantes de plusieurs mètres. Nous avons pu étendre cette étude jusqu'à des distances de plusieurs dizaines de mètres et mettre ainsi en évidence les effets de corpuscules de très haute énergie dans leur traversée de l'atmosphère.



d.	3 compteurs. E = 0,2.	5.	10.	15.	4 compteurs.	A.
2m	1,7	0,86	0,2	< 0,1	0,8	40
5m	1,4	0,7	–	–	–	–
20m	0,9	0,4	0,1	< 0,1	0,45	30

CONGRÈS INTERNATIONAL SUR LE RAYONNEMENT COSMIQUE
BAGNÈRES-DE-BIGORRE, 6-12 Juillet 1953

Photo ALIX

L. Leprince-Ringuet

J de Physique (Colloque #8) V 43 (1982)

Au Pic du Midi c'était Ch. Peyrou, B. Grégory, A. Lagarrigue, R. Armenteros, F. Muller puis A. Astier. Ont participé non seulement les français mais aussi des étrangers comme Ronald Rao de Princeotn, Tinlot de Rochester, Destaebler de Mit et aussi B. Le Fretter, en partie. Vous savez ce qui a été étudié au Pic. Le congrès de Bagnères de Bigorre en 1953, je dirais, a sonné le glas des rayons cosmiques et c'est Powell lui-même qui, dans son discours de clôture a dit : "Messieurs, maintenant nous sommes envahis, nous sommes sumbergés, ce sont les accélérateurs". Effectivement, la plupart des laboratoires de rayons cosmiques dont le nôtre, ici à l'Ecole Polytechnique, puis au Collège de France, se sont orientés vers les grands accélérateurs de particules et je voudrais vous dire aussi que le mot hypéron a été annoncé pour la première fois au congrès de Bagnères. Il y avait B. Rossi, E. Amaldi, C. Powell. Et on s'est demandé comment appeler ces nouvelles particules qui s'arrêtaient, qui étaient lourdes et qui donnaient un méson. Alors on a proposé divers noms. Et je dois dire que c'est ma principale contribution à la physique, j'ai prononcé le mot hypéron : le mot hypéron n'a pas été bien accueilli par Rossi. Rossi a dit "oh, hypéron, piperone, ça va pas". Et au contraire Powell était là et a dit "oh hypéron (prononcer haiperon) mervelous". Et on a dopté le mot hypéron. Et il a à Bagnères de Bigorre l'avenue de l'hypéron: c'est peut être le seul endroit au monde où une particule fondamentale a donné un nom à une avenue.

50^{th} Anniversary

1962 J. Linsley's observation of a 10^{20} eV event

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

10^{20} eV

Analysis of a cosmic-ray air shower recorded at the MIT Volcano Ranch station in February 1962 indicates that the total number of particles in the shower (Serial No. 2-4834) was 5×10^{10}. The total energy of the primary particle which produced the shower was 1.0×10^{20} eV. The shower was about twice the size of the largest we had reported previously (No. 1-15832, recorded in March 1961).[1]

The existence of cosmic-ray particles having such a great energy is of importance to astrophysics because such particles (believed to be atomic nuclei) have very great magnetic rigidity. It is believed that the region in which such a particle originates must be large enough and possess a strong enough magnetic field so that $RH \gg (1/300)\times(E/Z)$, where R is the radius of the region (cm) and H is the intensity of the magnetic field (gauss). E is the total energy of the particle (eV) and Z is its charge. Recent evidence favors the choice $Z=1$ (proton primaries) for the region of highest cosmic-ray energies.[2] For the present event one obtains the condition $RH \gg 3\times10^{17}$. This condition is not satisfied by our galaxy (for which $RH \approx 5\times10^{17}$, halo included) or known objects within it, such as supernovae.

The technique we use has been described elsewhere.[1] An array of scintillation detectors is used to find the direction (from pulse times) and size (from pulse amplitudes) of shower events which satisfy a triggering requirement. In the present case, the direction of the shower was nearly vertical (zenith angle $10\pm5°$). The values of shower density registered at the various points of the array are shown in Fig. 1. It can be verified by close inspection of the figure that the core of the shower must have struck near the point marked "A," assuming only (1) that showe[r] particles are distributed symmetrically about a[n] axis (the "core"), and (2) that the density of par-ticles decreases monotonically with increasing distance from the axis. The observed densities

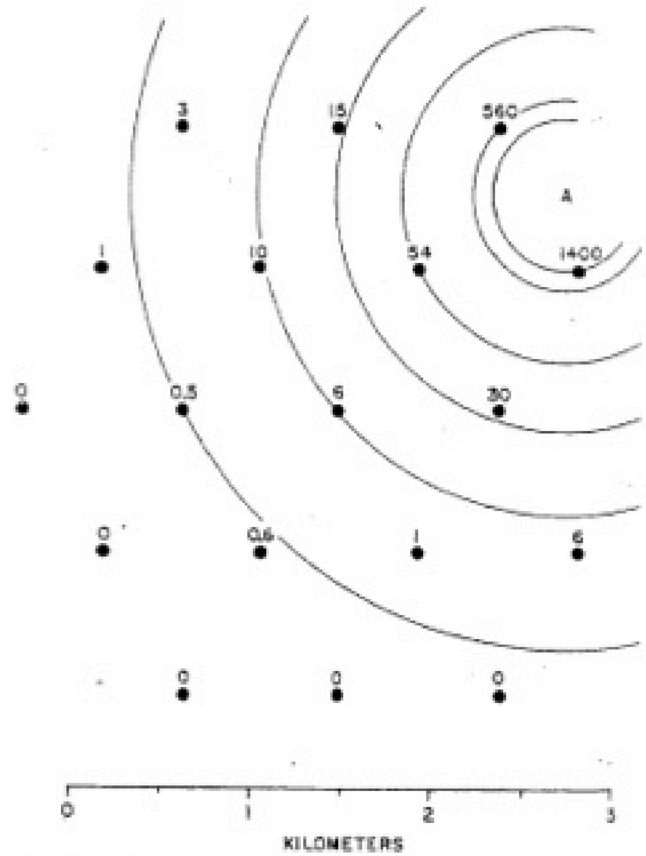


FIG. 1. Plan of the Volcano Ranch array in Febru[ary] 1962. The circles represent 3.3-m² scintillation de-tectors. The numbers near the circles are the show[er] densities (particles/m²) registered in this event, No 2-4834. Point "A" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

Some "Simple" Questions

How cosmic particles reach 10^{20} eV?

Can we use them as probes of high energy interactions?

Some "Simple" Questions

How cosmic particles reach 10^{20} eV?

- what are the particles? injected & observed?
- how do they get here?
- where are the sources?
- how do they get accelerated?
- what are the sources?

Can we use them as probes of high energy interactions?

- CM energies > 100 TeV

Theorists

How cosmic particles reach 10^{20} eV?

- what are the particles? injected & observed?
- how do they get here?
- where are the sources?
- how do they get accelerated?
- what are the sources?

Propagation

Source Models

Can we use them as probes of high energy interactions?

- CM energies > 100 TeV

Hadronic Interactions

Ultrahigh Energy Cosmic Rays

OBSERVABLES:

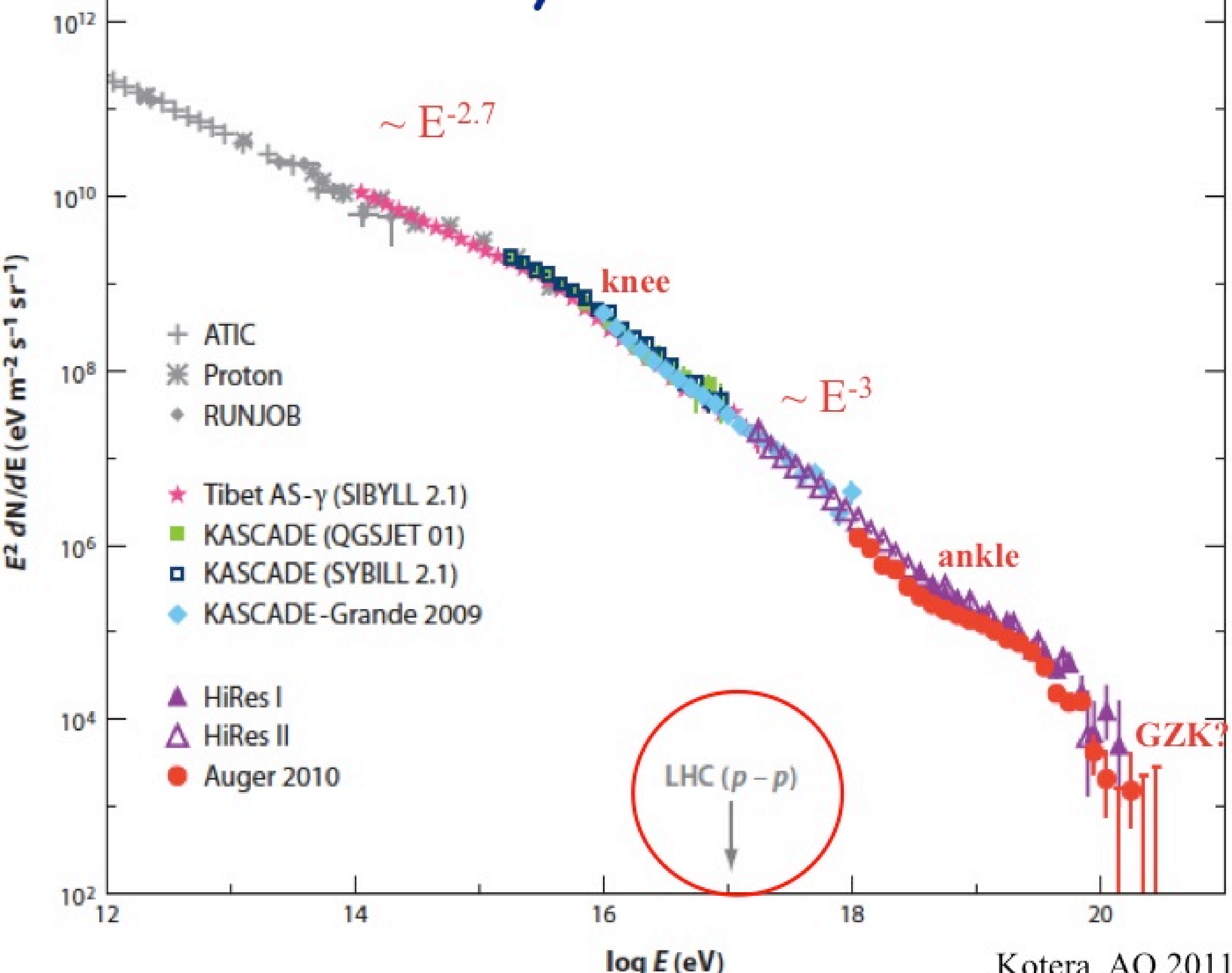
Spectrum

Composition

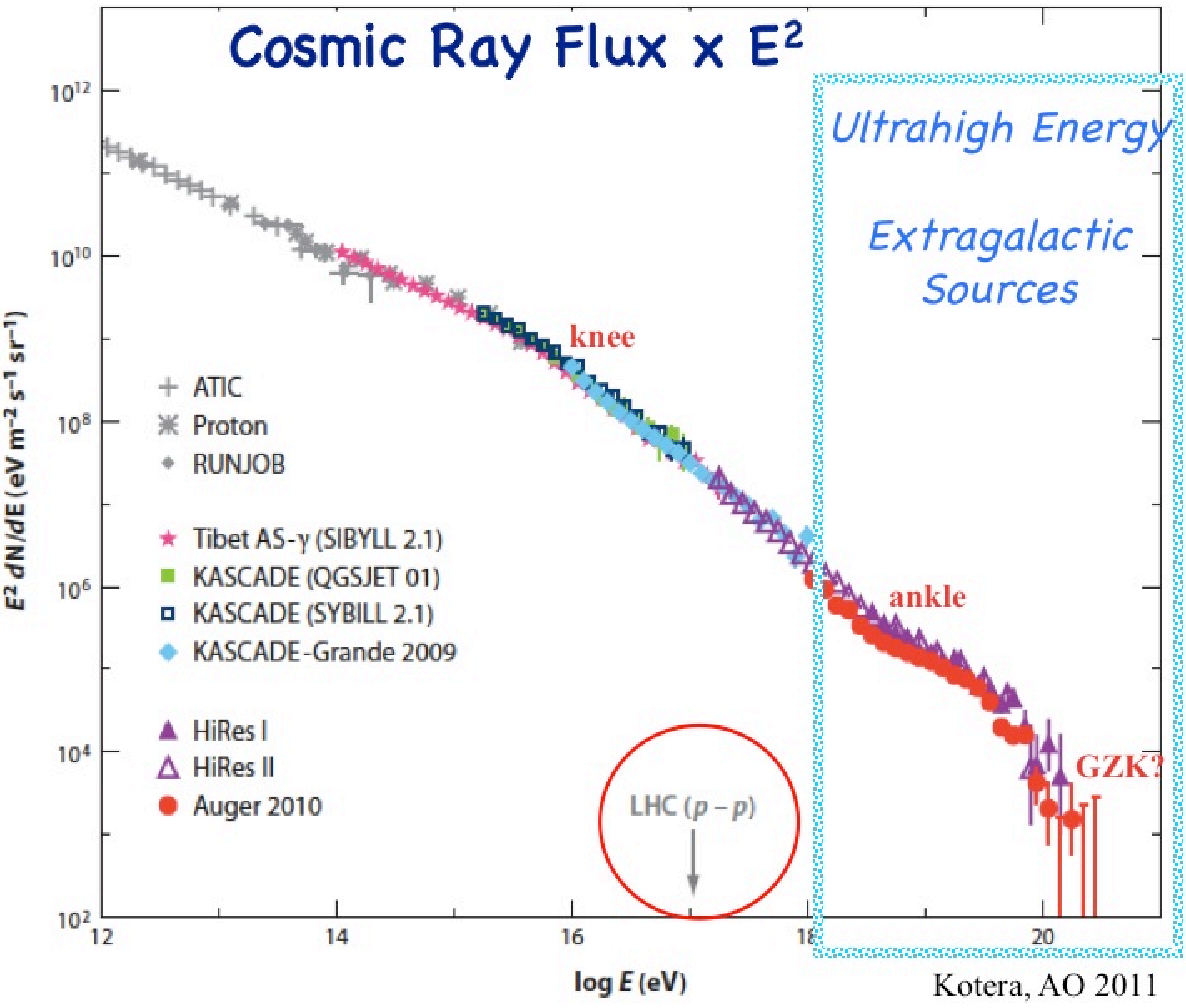
Sky Distribution

Multi-messengers

Cosmic Ray Flux x E²



Kotera, AO 2011



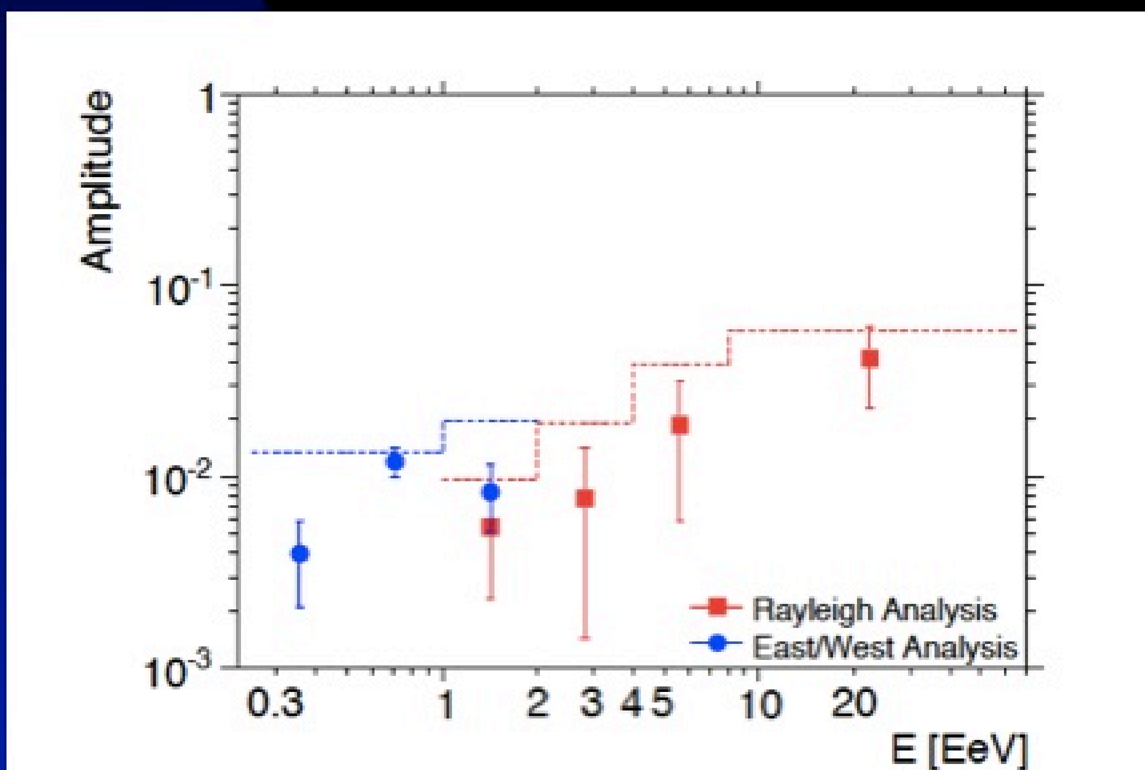
Cosmic Ray Flux x E²
Ultrahigh Energy
Extragalactic Sources
knee
ankle
GZK?
LHC (p – p)
ATIC
Proton
RUNJOB
Tibet AS-γ (SIBYLL 2.1)
KASCADE (QGSJET 01)
KASCADE (SYBILL 2.1)
KASCADE-Grande 2009
HiRes I
HiRes II
Auger 2010
E² dN/dE (eV m⁻² s⁻¹ sr⁻¹)
log E (eV)
10¹²
10¹⁰
10⁸
10⁶
10⁴
10²
12
14
16
18
20
Kotera, AO 2011

Plausible Sources of UHECRs

1. Extragalactic $E > 10^{18}$ eV (maybe even @ lower E)

Why Extragalactic?

No significant Anisotropy towards the Galactic Plane



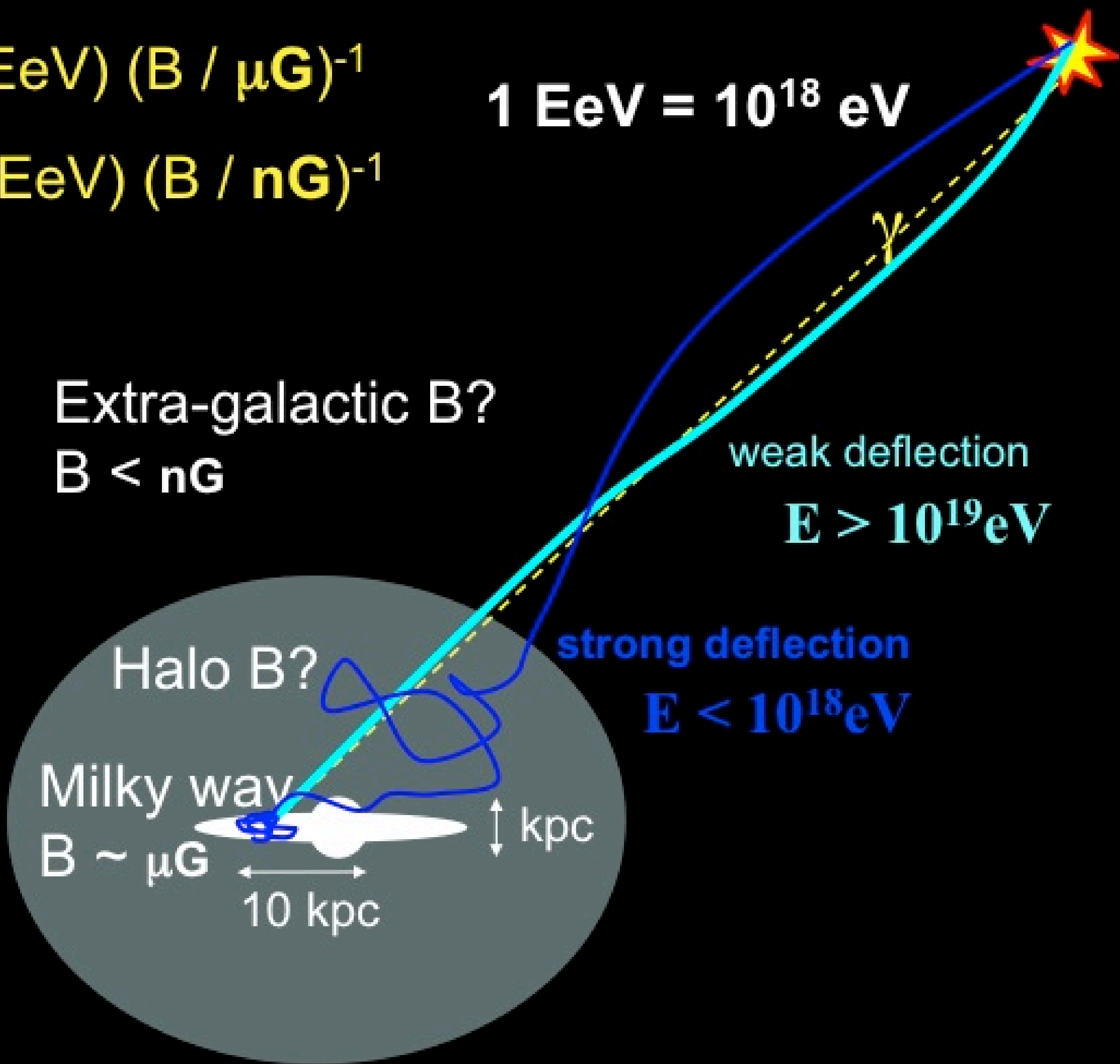
Pierre Auger Collab
Abreu et al '11

"Known unknown"

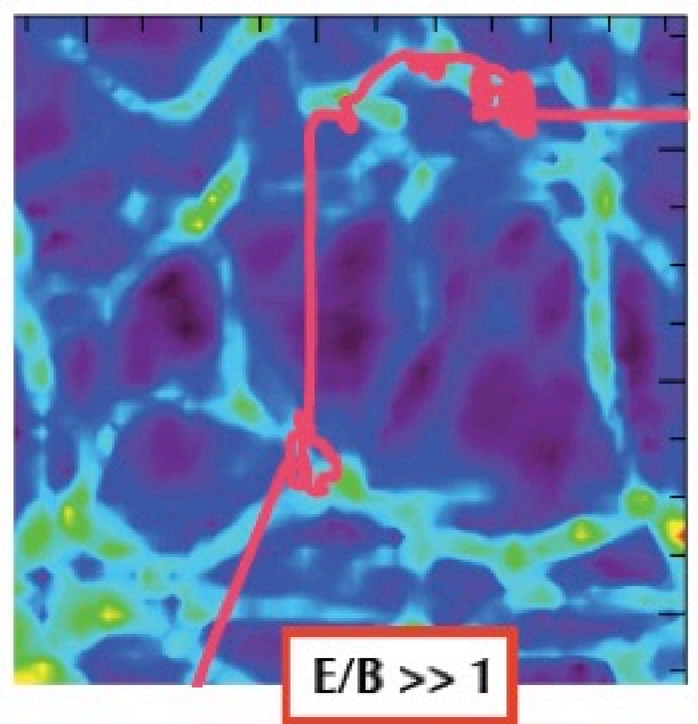
Cosmic Magnetic Fields

R_L = **kpc** Z^{-1} (E / EeV) (B / **μG**)$^{-1}$

R_L = **Mpc** Z^{-1} (E / EeV) (B / **nG**)$^{-1}$

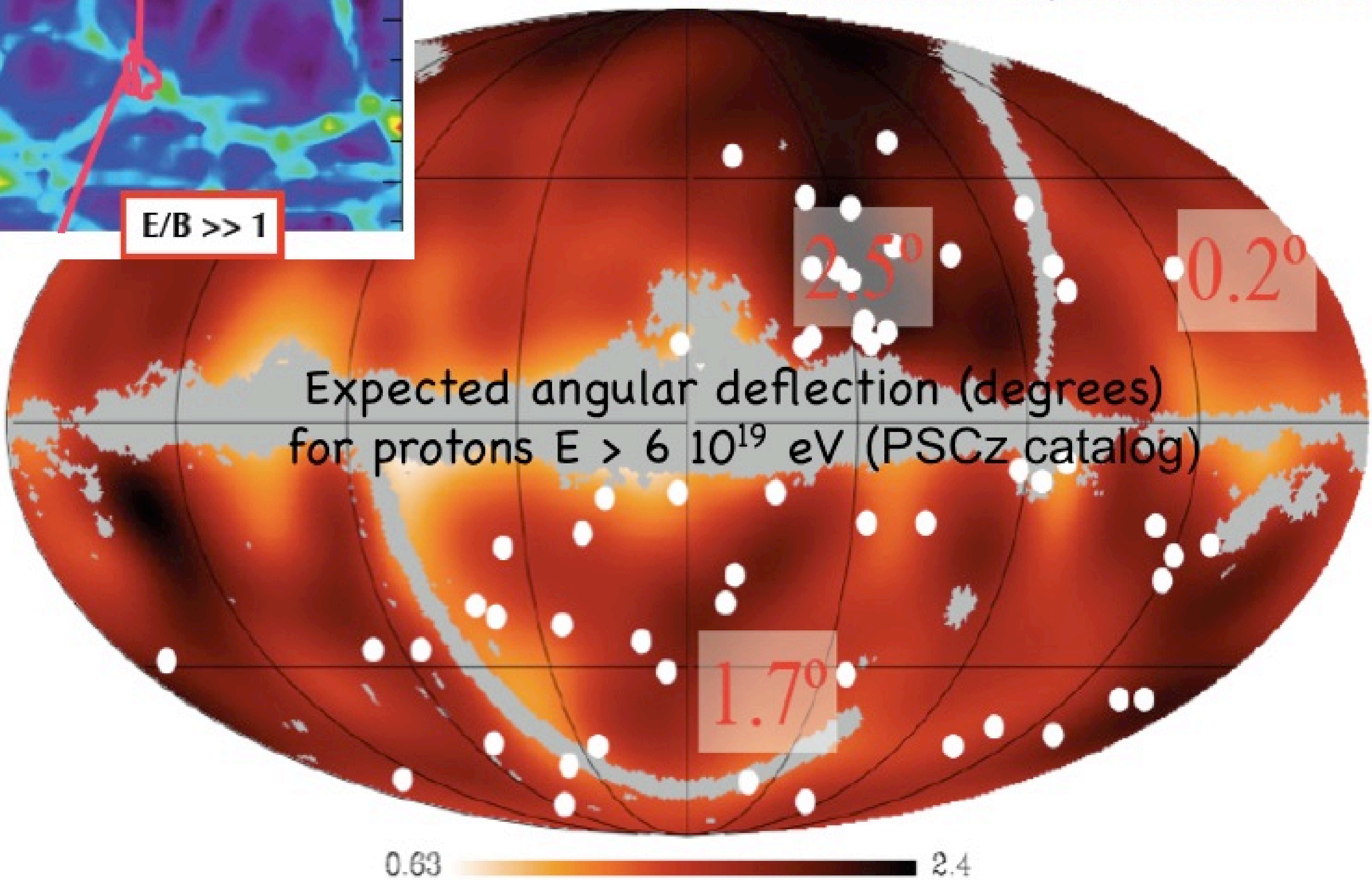


Galactic B deflection
<< 10^o Z (40 EeV/E)
anisotropic in sky

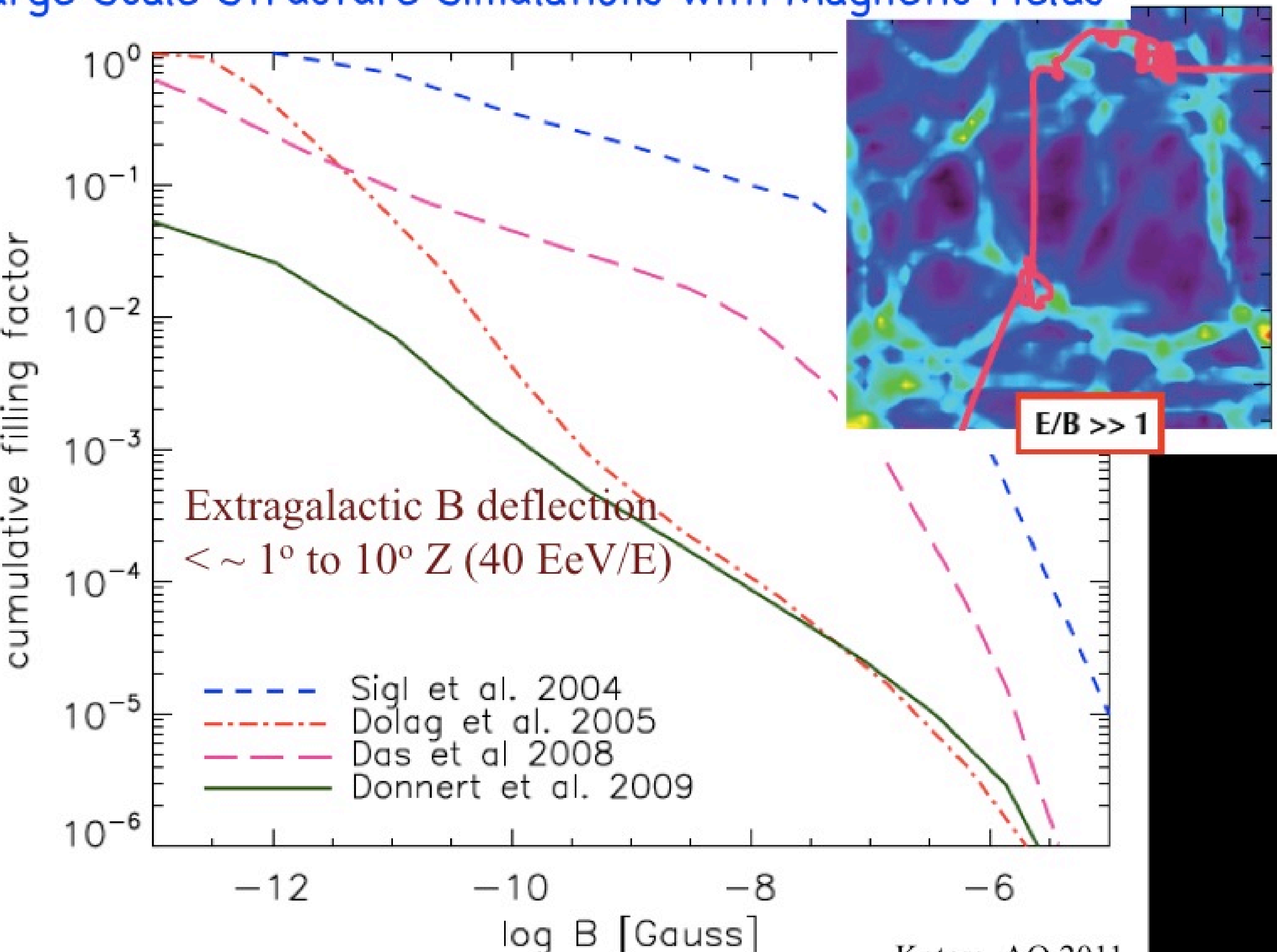


Extragalactic Magnetic Fields

Kotera & Lemoine'08; Kotera & A.O. '11

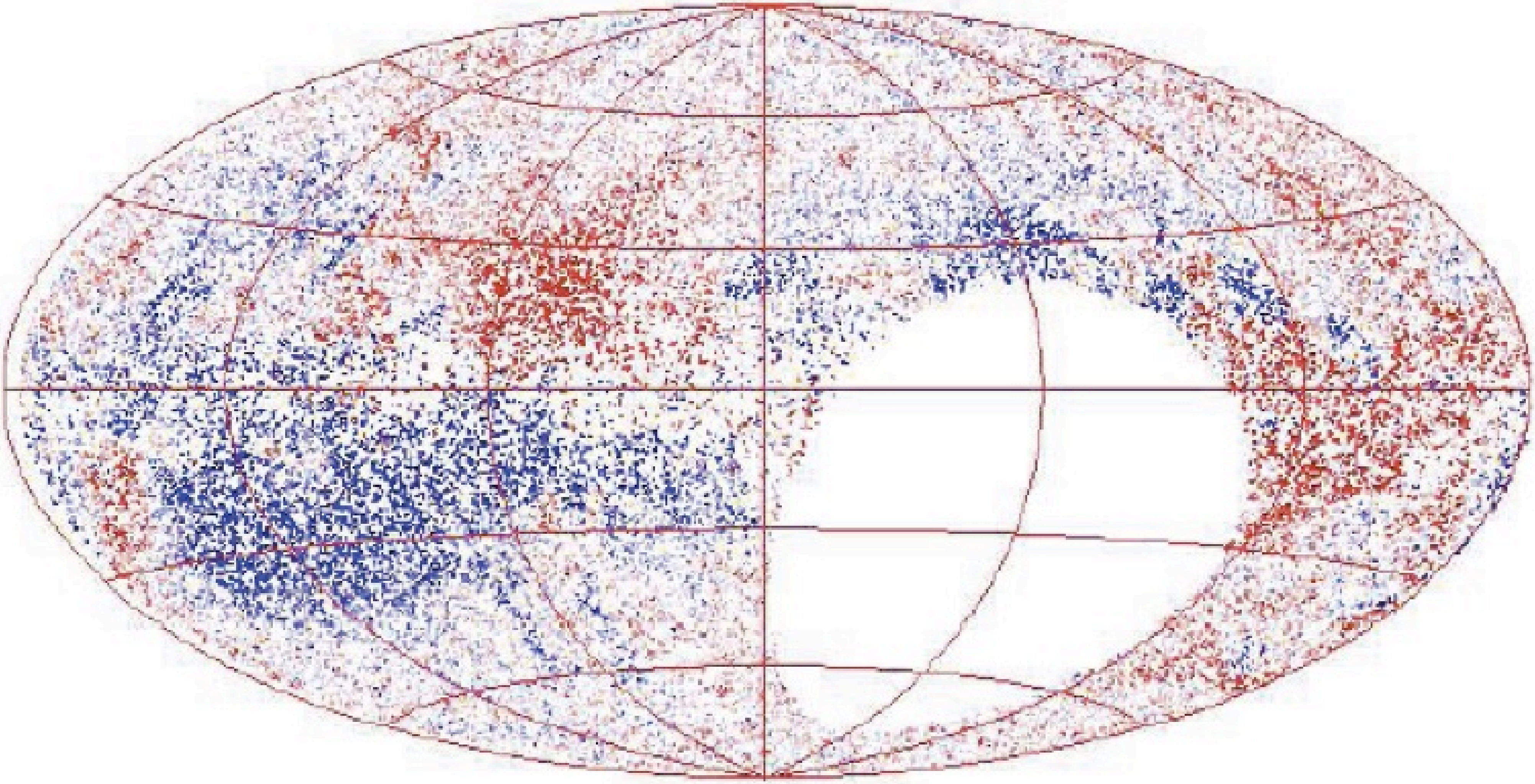


Large Scale Structure Simulations with Magnetic Fields



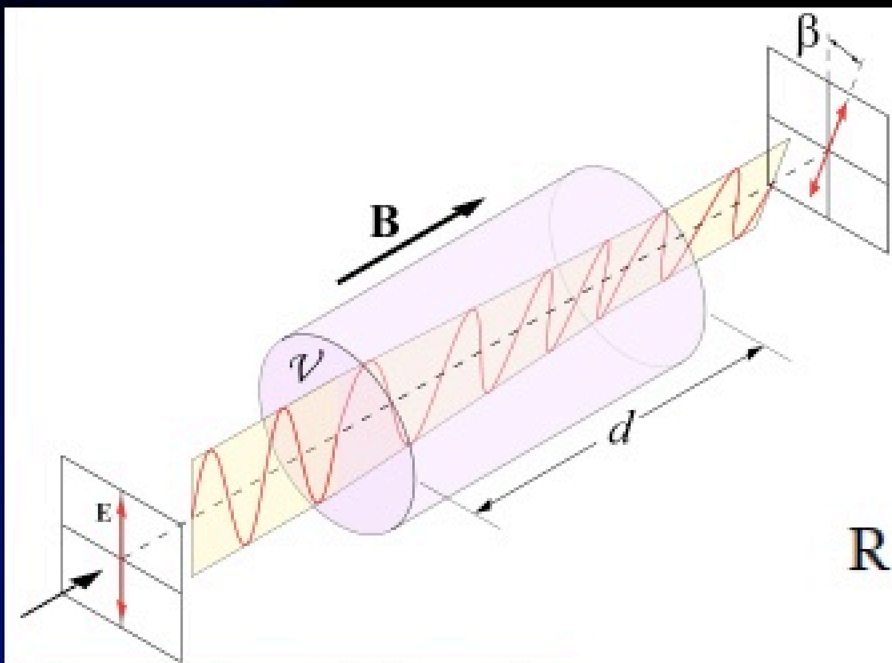
Kotera, AO 2011

Galactic Magnetic Field:
Rotation Measures



Pshirkov et al, **arXiv:1103.0814**

Faraday Rotation



Rotation Measure:

$$\mathrm{RM} \equiv \frac{\psi}{\lambda_{\mathrm{obs}}^2} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^{l_s} n_e(l) B_{\|}(l) \left[\frac{\lambda(l)}{\lambda_{\mathrm{obs}}}\right]^2 \, dl$$

RMs for QSOs up to z=2.5 limit

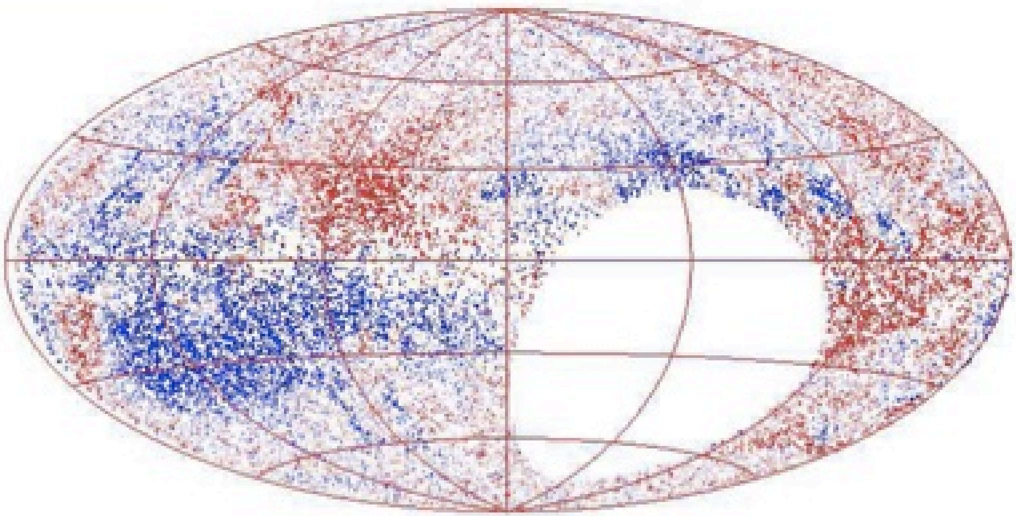
$$\langle B_{\|}^2 \, \lambda_B \rangle^{1/2} \lesssim 10^{-8} \, \mathrm{G} \, \mathrm{Mpc}^{1/2}$$

$$B_{H_0^{-1}} \lesssim 10^{-9} \ \mathrm{G}$$

Blasi, Burles, AVO ‘99

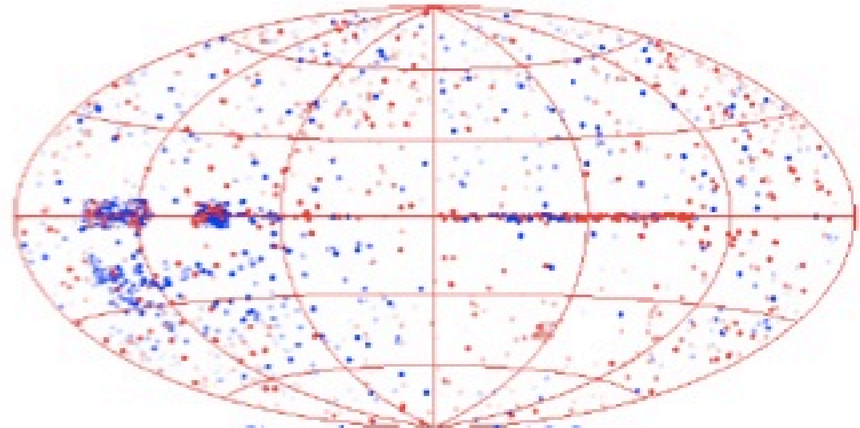
Galactic Magnetic Fields

Better constrained

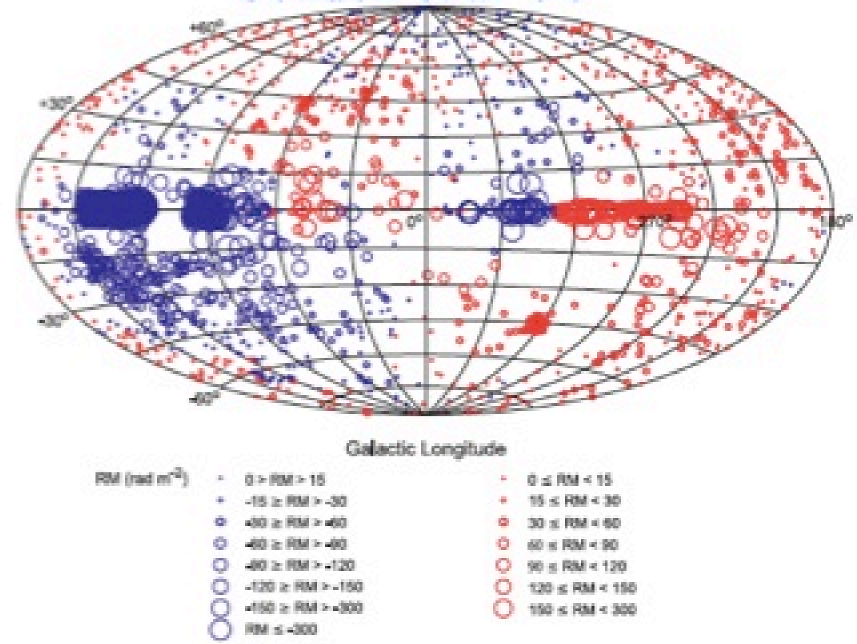


Taylor et al '09

Fig. 1.— Locations and RM signs of the NVSS sources. Red (blue) color corresponds to positive (negative) values of RM.



Condon et al '98



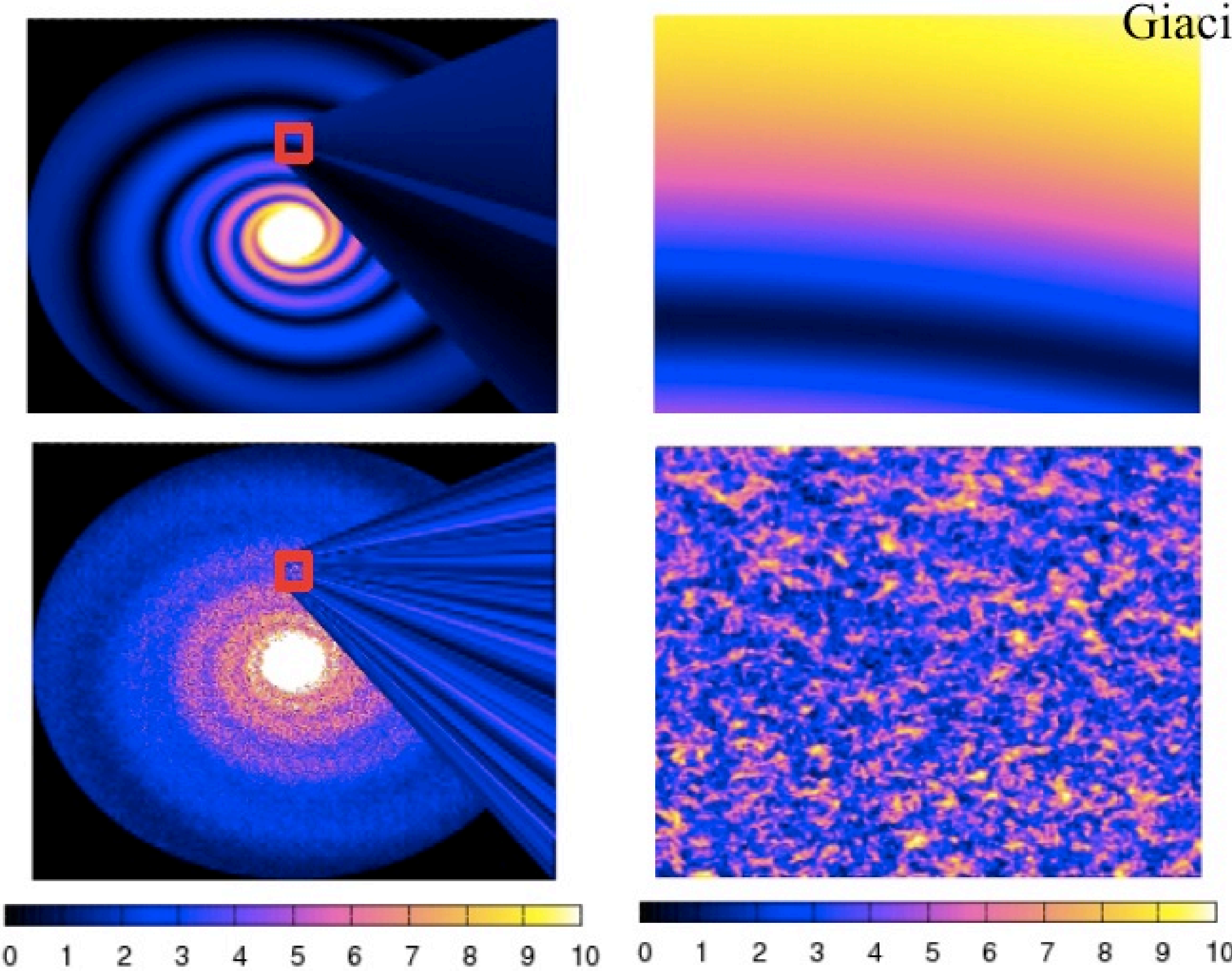
Pshirkov et al '11

Model of Galactic Field:

symmetric spiral disk and antisymmetric halo – reproduce best RM data.

Propagation of UHECRs in Galaxy

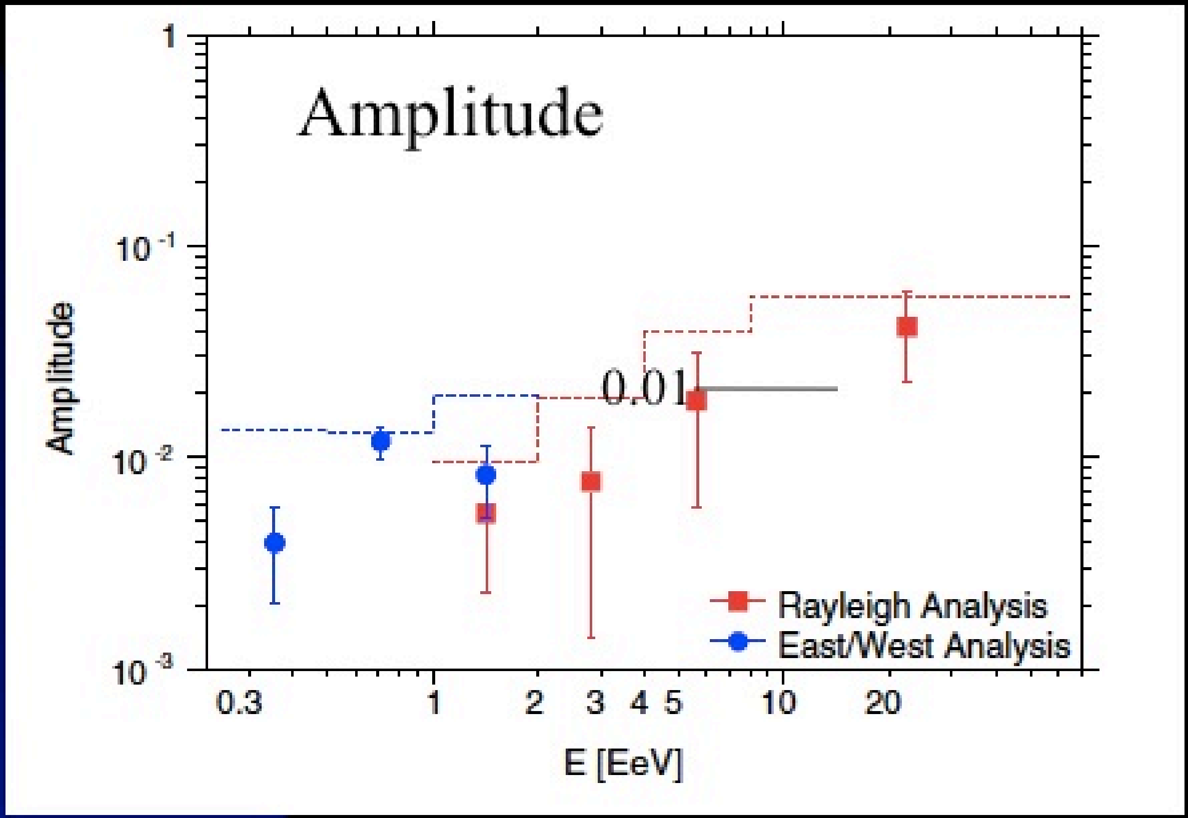
Giacinti et al ‘11



Reg. GMF (PS)

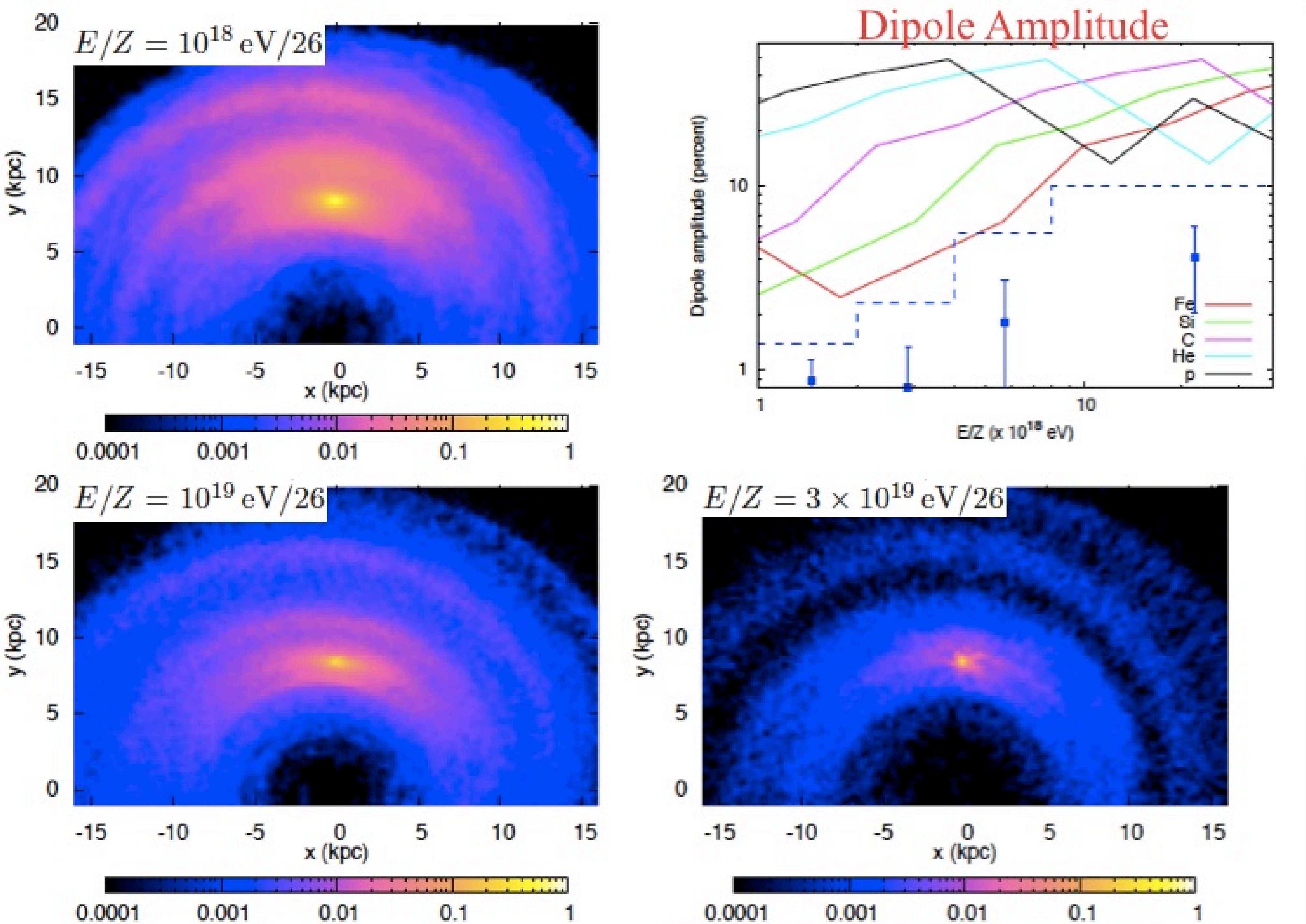
+ Turb. GMF

Auger Dipole Measurement



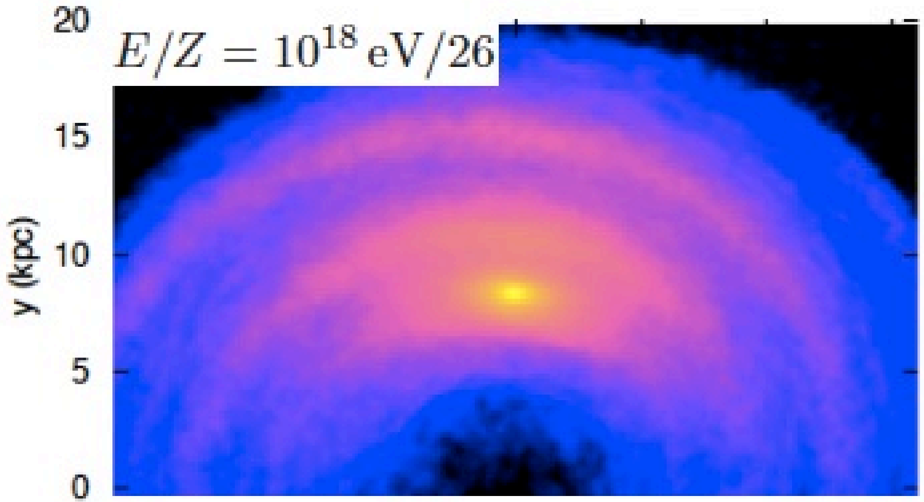
P. Abreu et al. '11

Galactic plane Region contributing to CRs at Earth

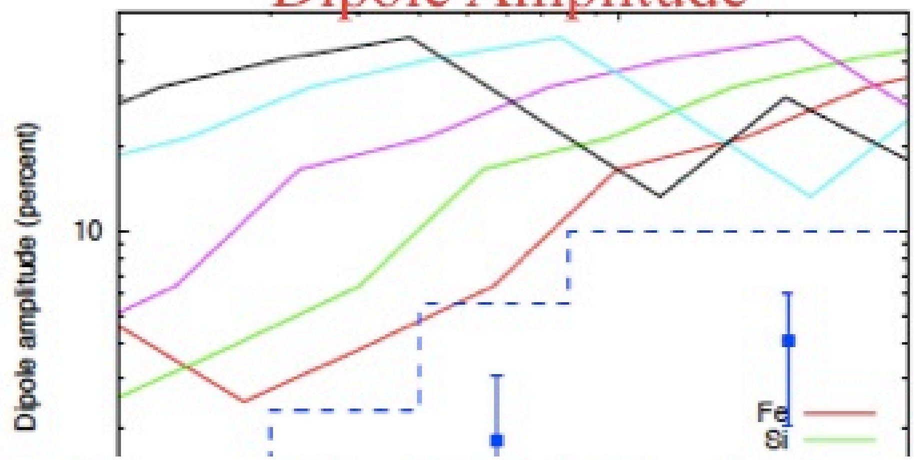


Giacinti, Kachelrieß, Semikoz, Sigl ‘11

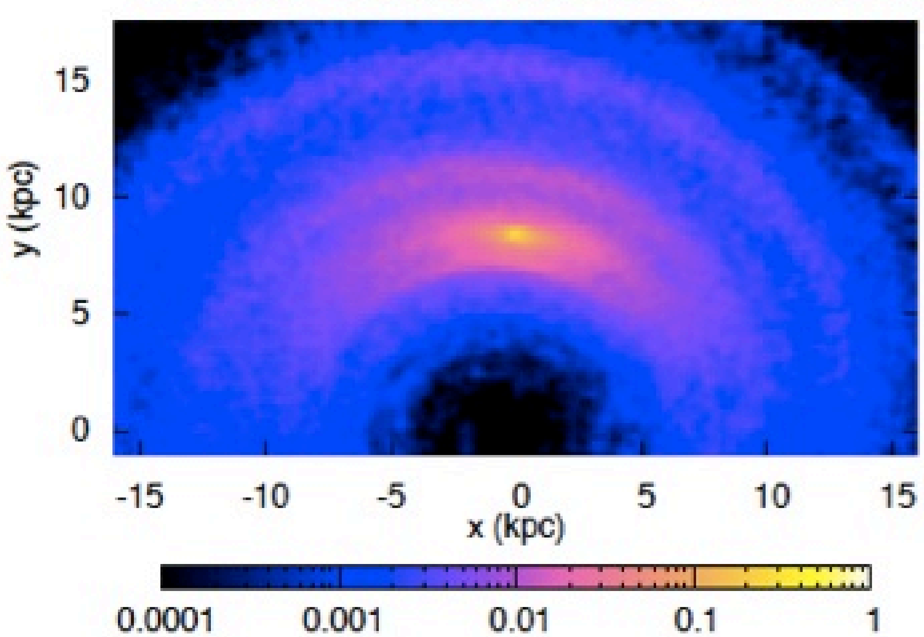
Galactic plane Region contributing to CRs at Earth

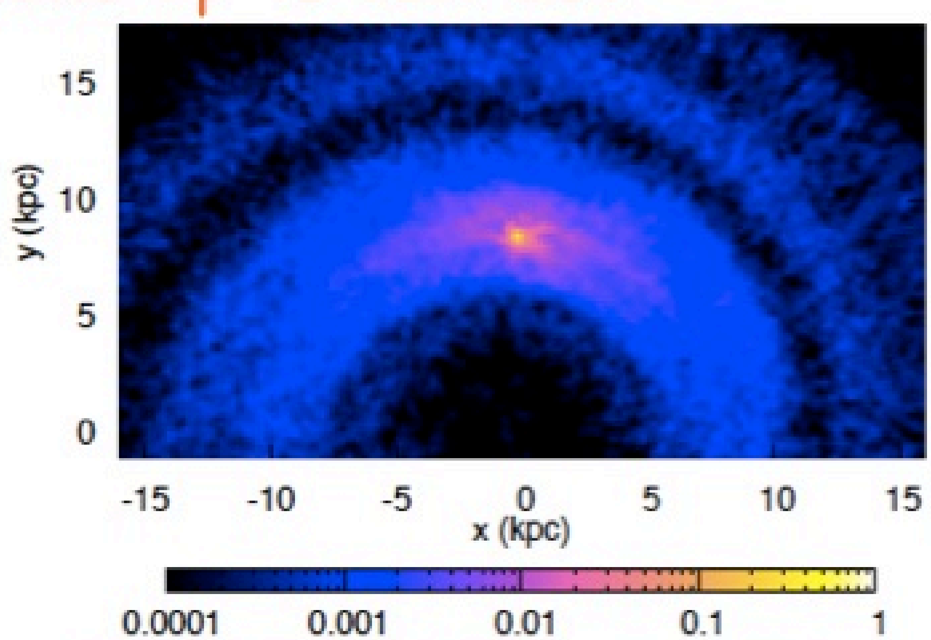


Dipole Amplitude



For a wide range of Galactic Magnetic Field Models
Protons to CNO above 1 EeV have to be **Extragalactic**
while **Iron could be Galactic** up to few EeV



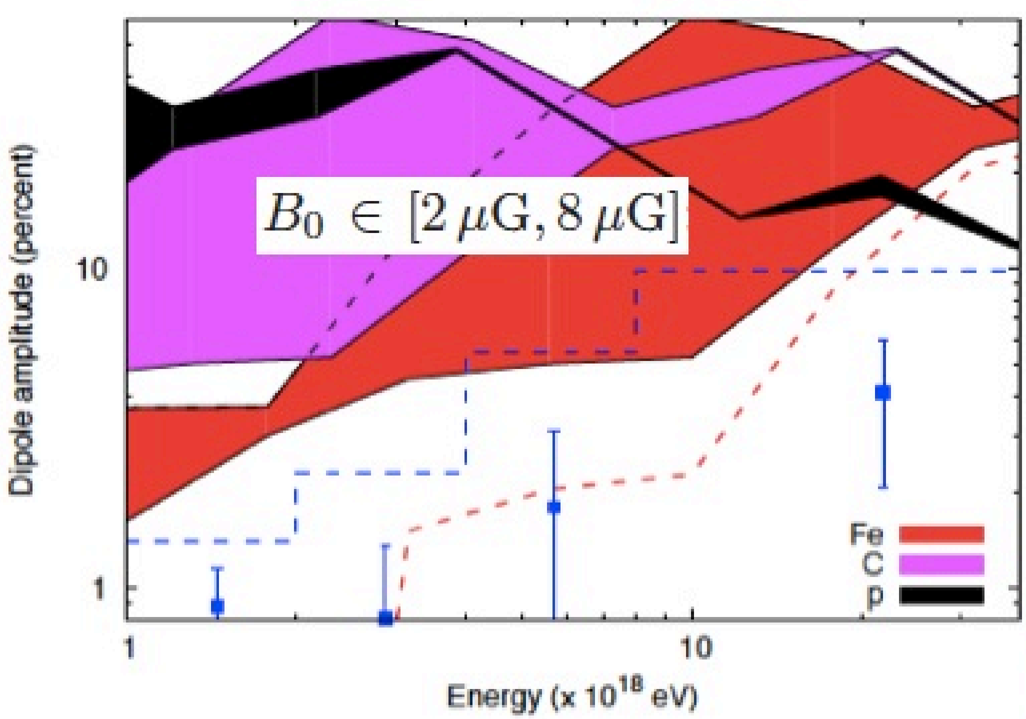


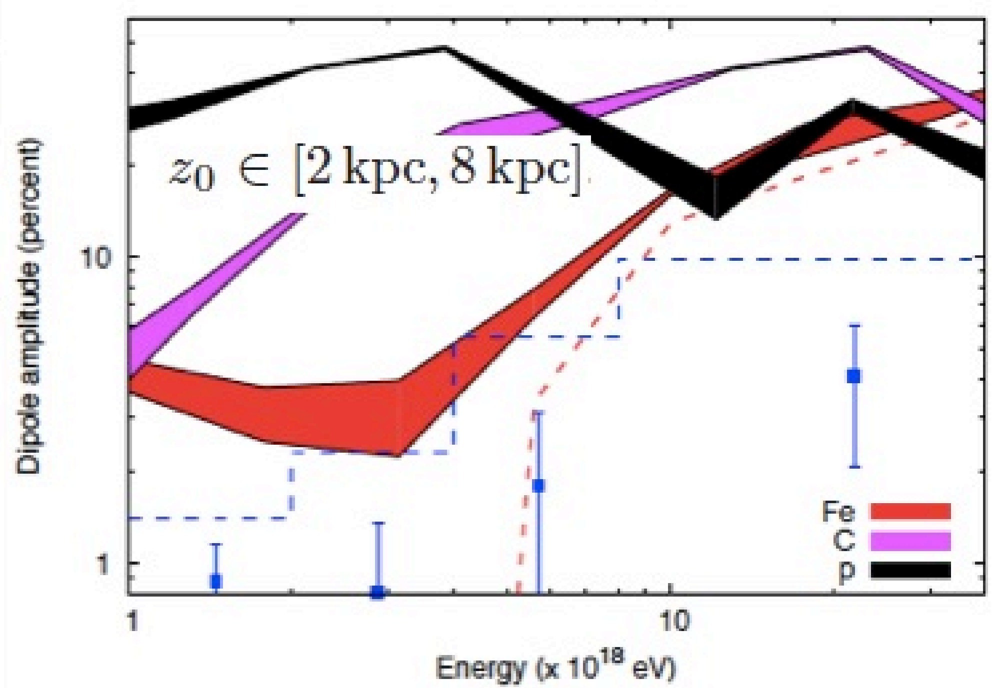
Giacinti, Kachelrieß, Semikoz, Sigl '11

Anisotropy Limits

rule out Galactic components of
protons to CNO as dominant CR component E>1 EeV

and Fe above ~20 EeV

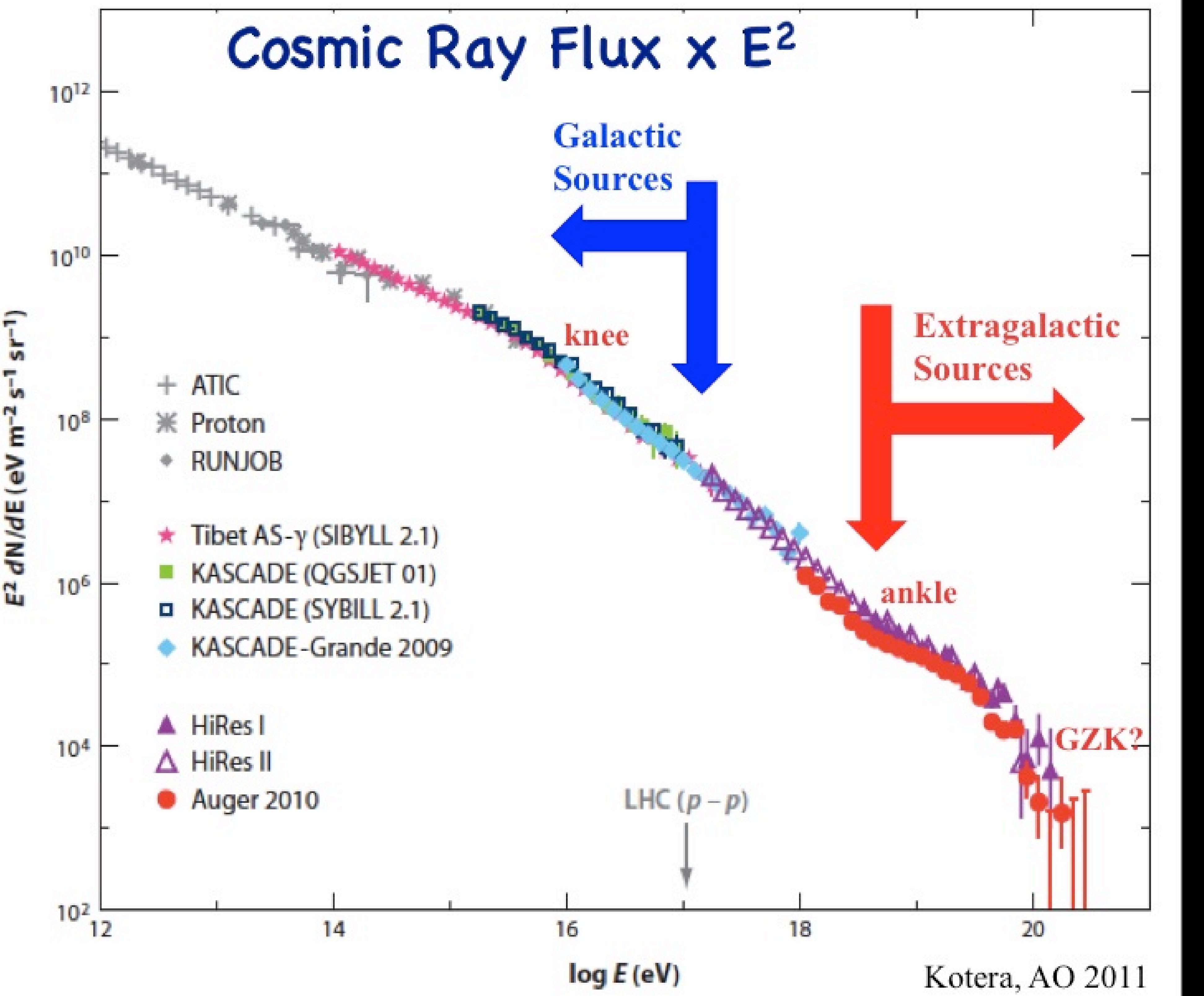




Giacinti et al '11

Plausible Sources of UHECRs

1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained. Interplay between composition and possible transition scenarios



Cosmic Ray Flux x E²
Galactic Sources
Extragalactic Sources
knee
ankle
GZK?
ATIC
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E² dN/dE (eV m⁻² s⁻¹ sr⁻¹)
10¹²
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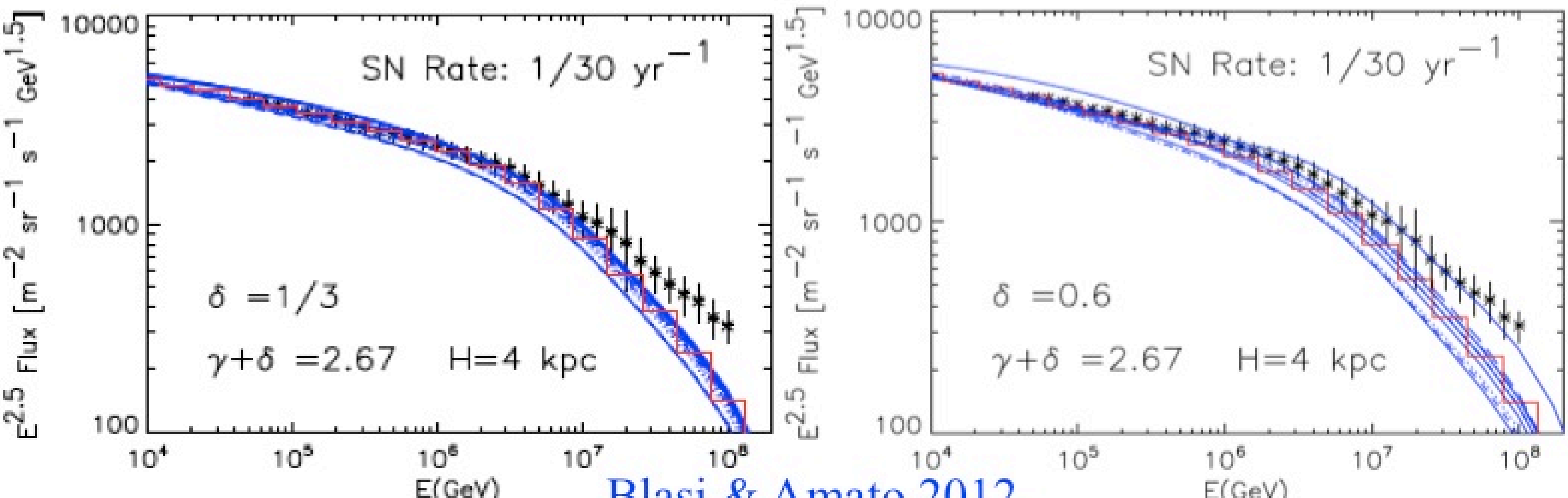
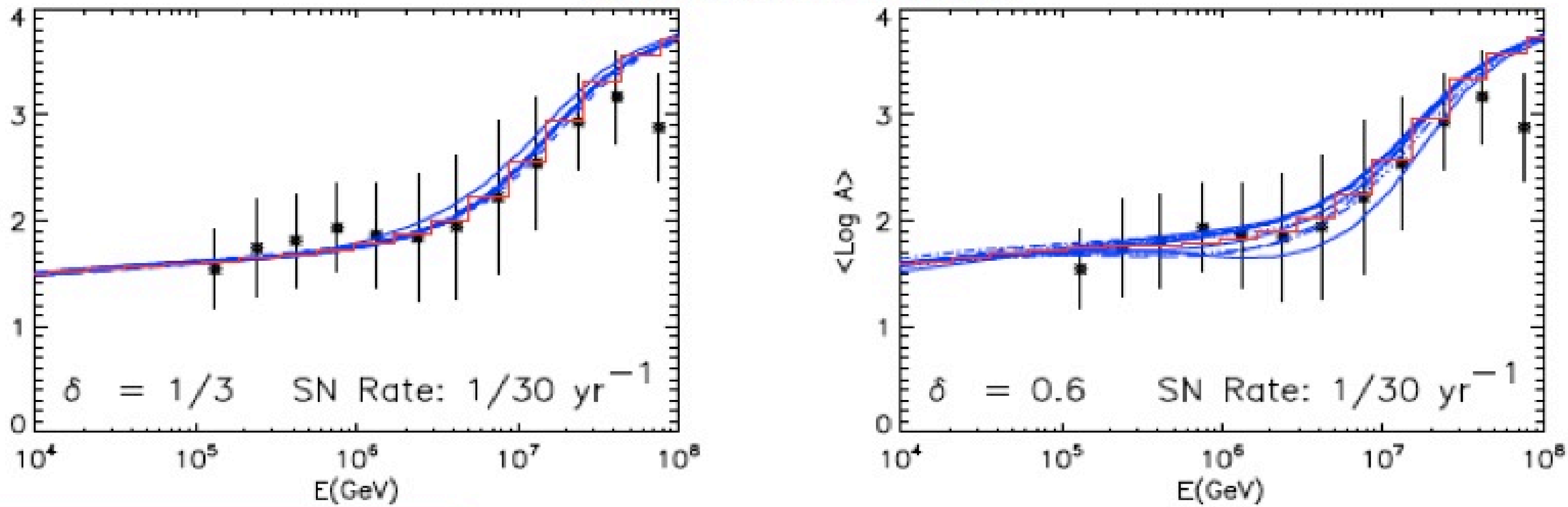
14
16
18
20
log E (eV)
Kotera, AO 2011

The SNR paradigm: Acceleration + Diffudion



Blasi & Amato 2012



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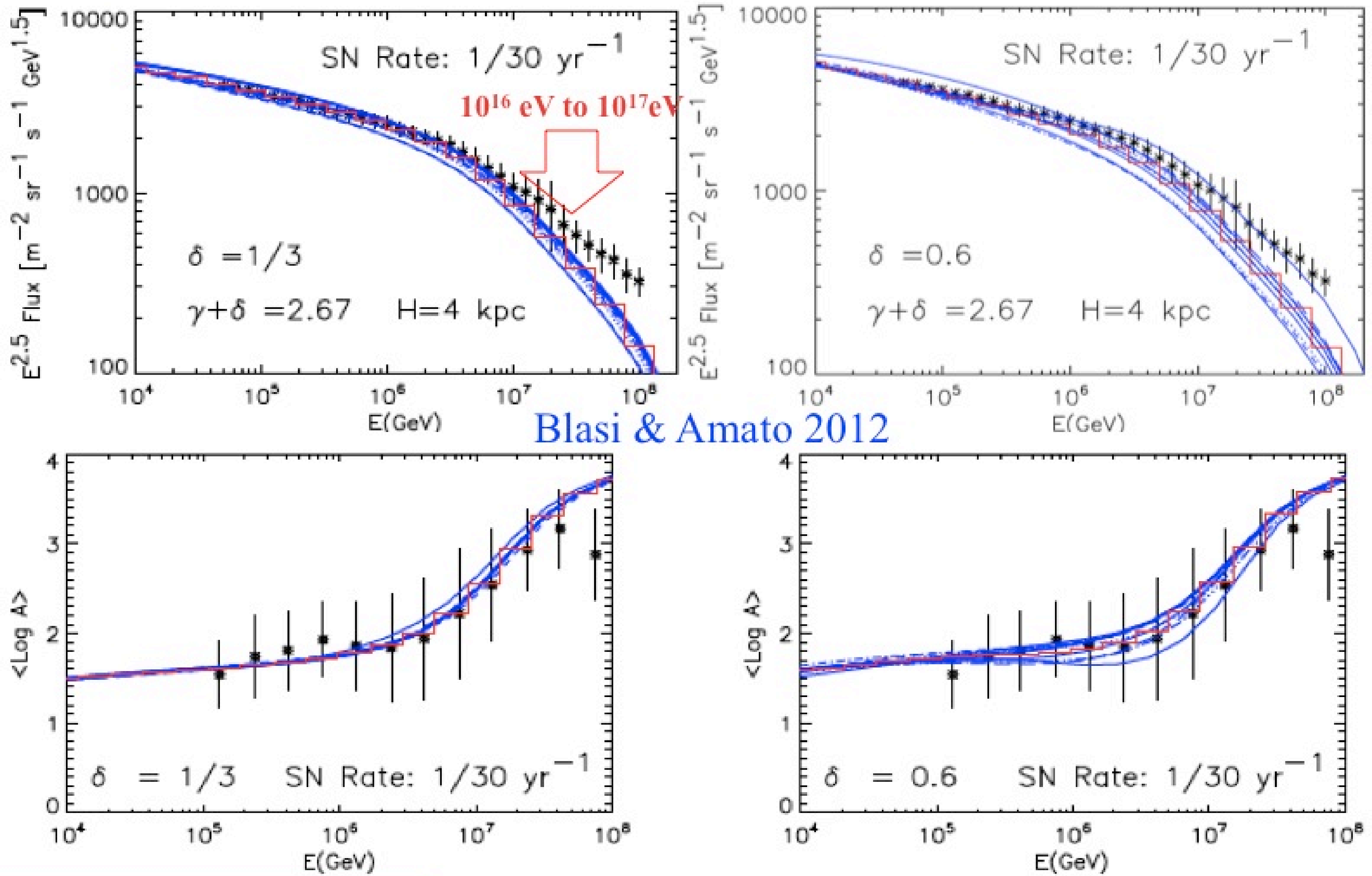

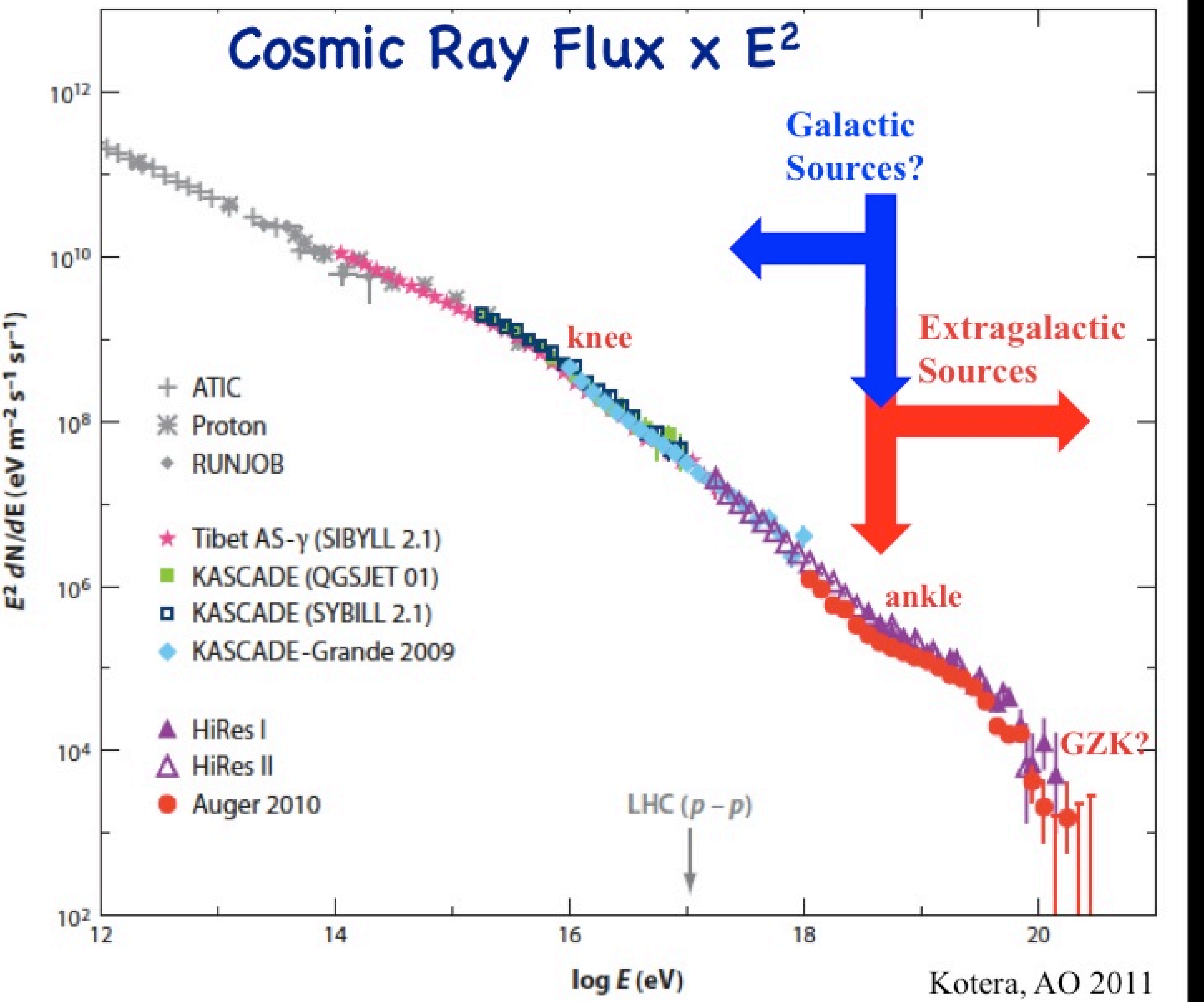

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10⁶
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12
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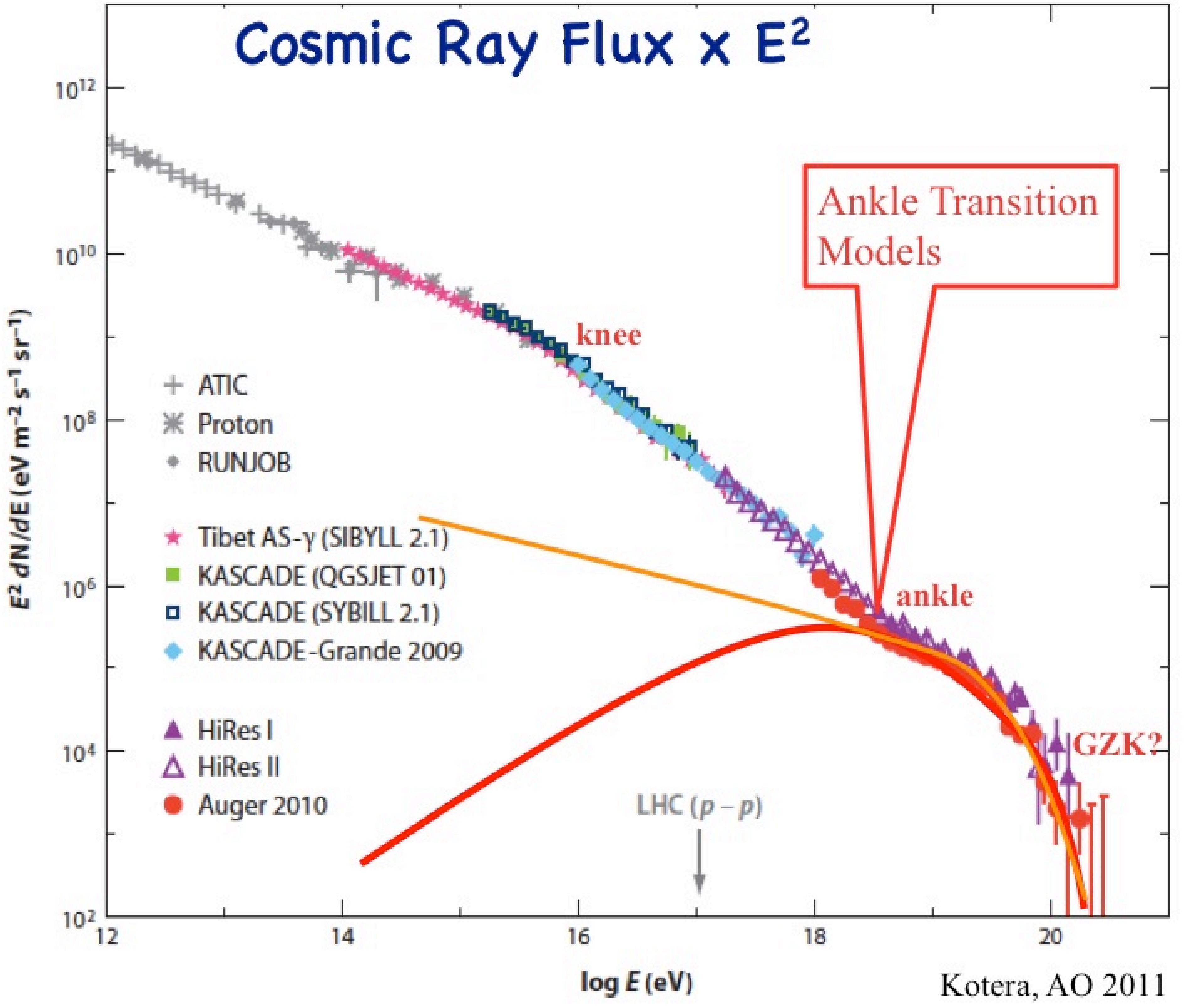
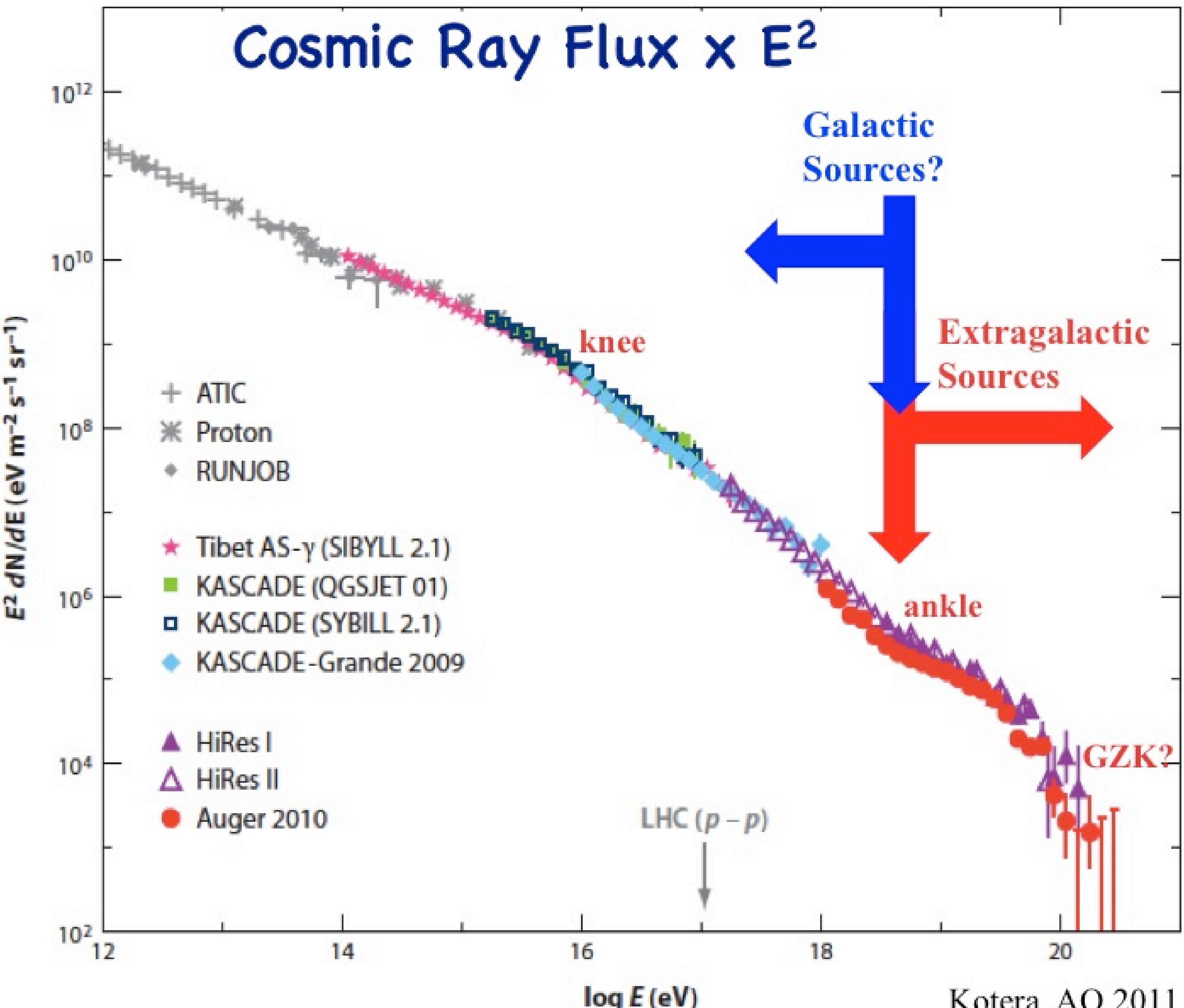
16
18
20
Kotera, AO 2011

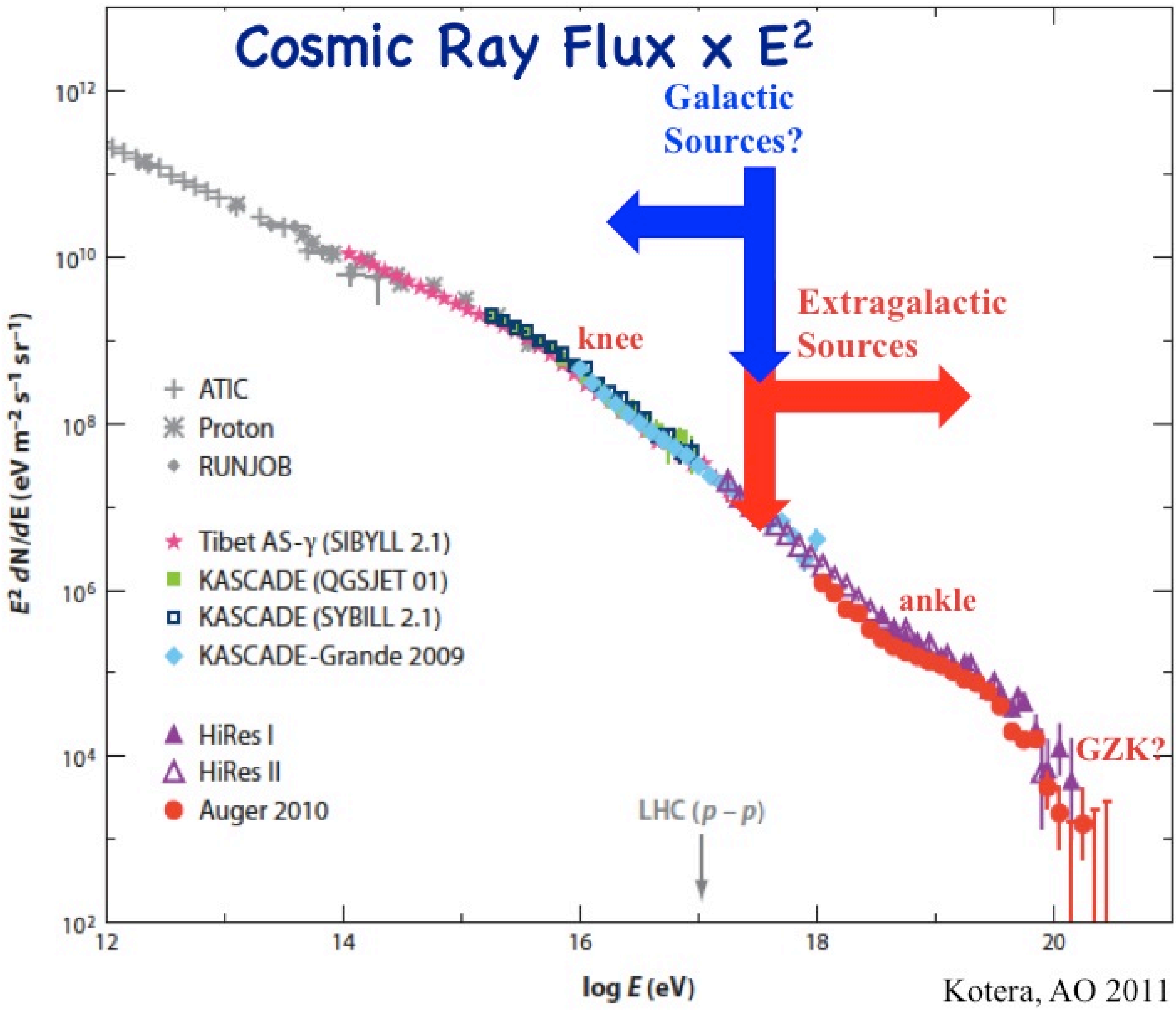


Cosmic Ray Flux x E²
10¹²
10¹⁰
10⁸
10⁶
10⁴
10²
E² dN/dE (eV m⁻² s⁻¹ sr⁻¹)
ATIC
Proton
RUNJOB
Tibet AS-γ (SIBYLL 2.1)
KASCADE (QGSJET 01)
KASCADE (SYBILL 2.1)
KASCADE-Grande 2009
HiRes I
HiRes II
Auger 2010
knee
Ankle Transition Models
ankle
GZK?
LHC (p – p)
12
14
16
18
20
log E (eV)
Kotera, AO 2011

Cosmic Ray Flux x E^2

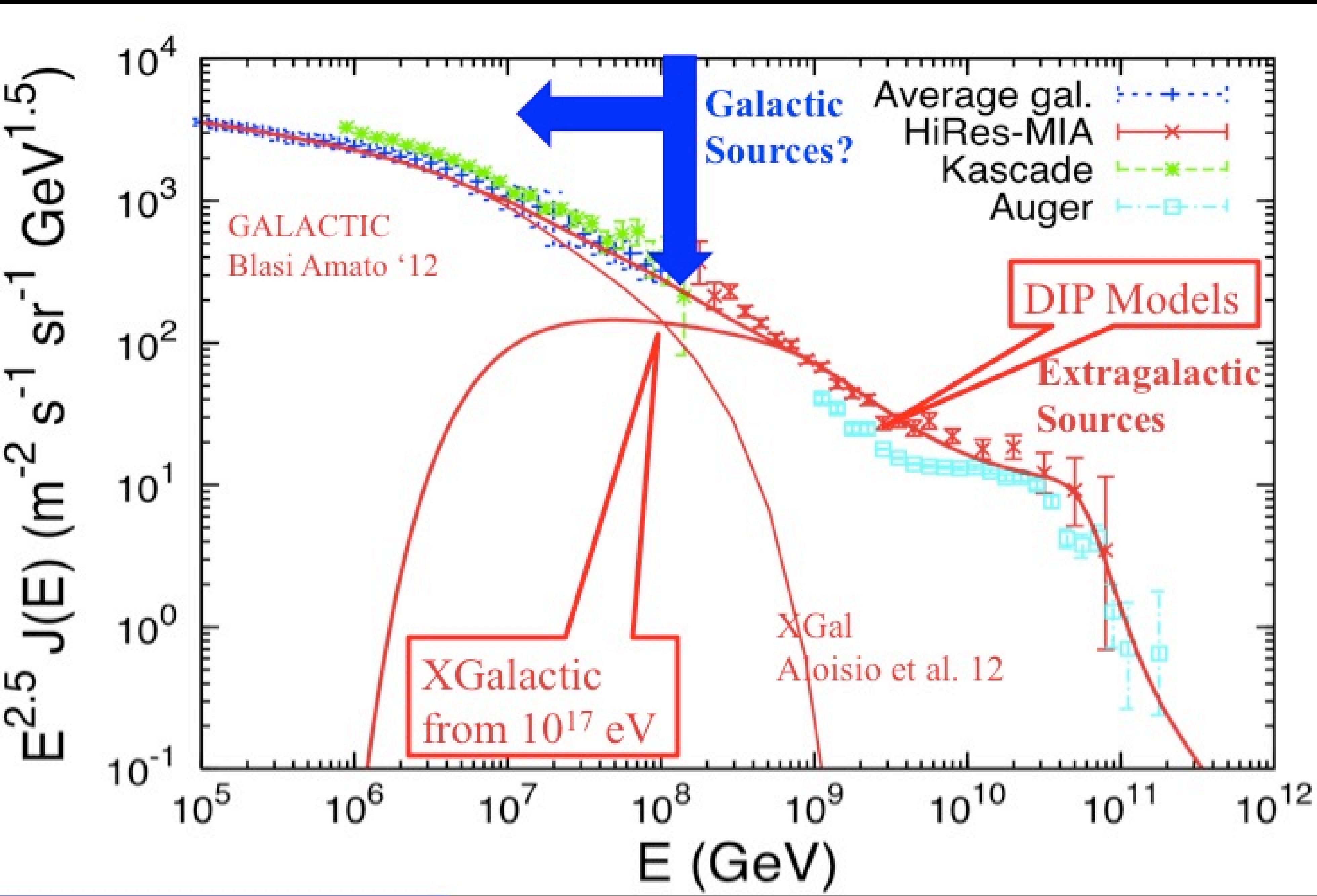


Kotera, AO 2011

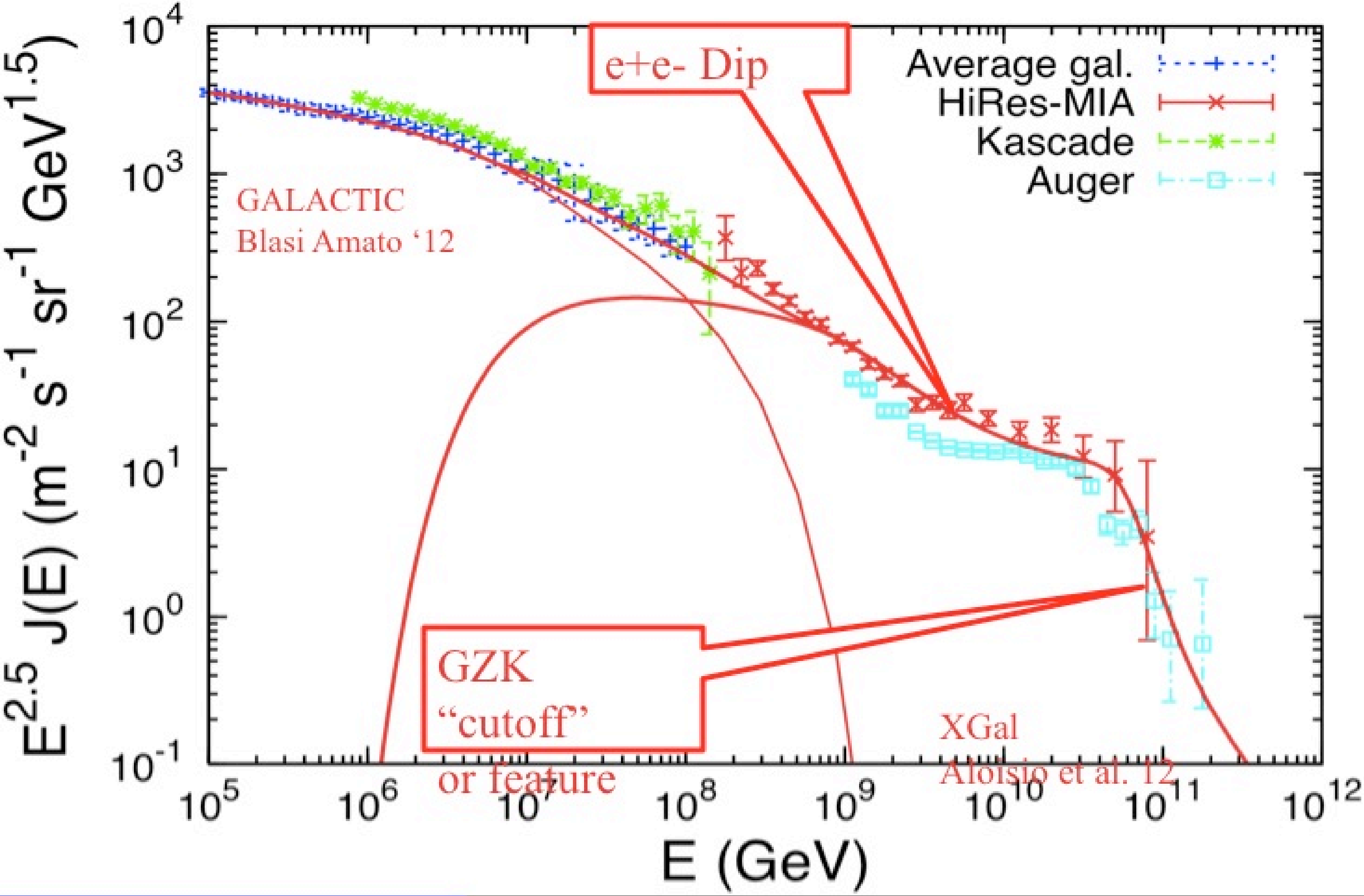


Cosmic Ray Flux x E²
Galactic Sources?
Extragalactic Sources
knee
ankle
GZK?
LHC (p – p)
ATIC
Proton
RUNJOB
Tibet AS-γ (SIBYLL 2.1)
KASCADE (QGSJET 01)
KASCADE (SYBILL 2.1)
KASCADE-Grande 2009
HiRes I
HiRes II
Auger 2010
E² dN/dE (eV m⁻² s⁻¹ sr⁻¹)
log E (eV)
10¹²
10¹⁰
10⁸
10⁶
10⁴
10²
12
14
16
18
20
Kotera, AO 2011

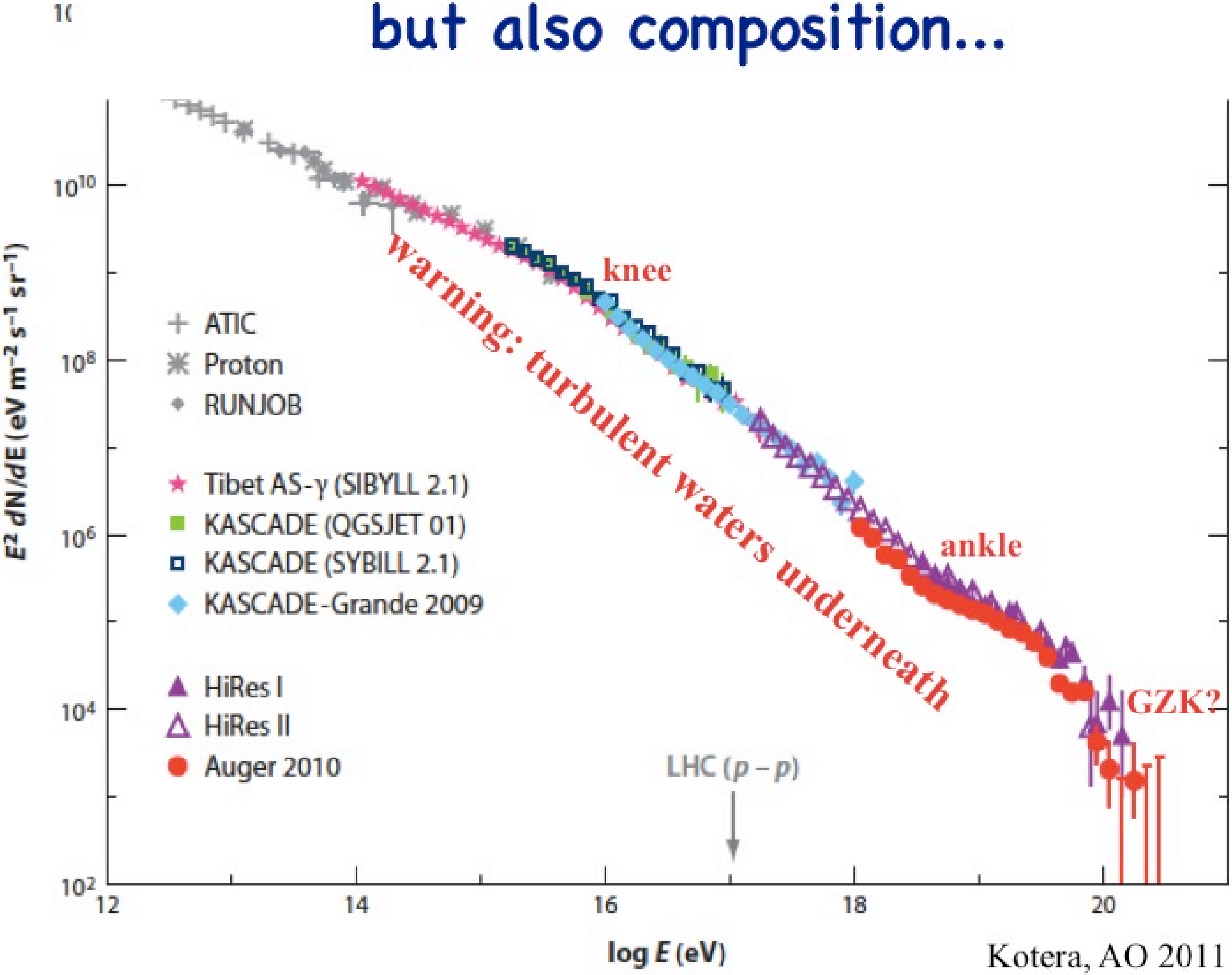
Dip Transition: Galactic to Extragalactic at lower E



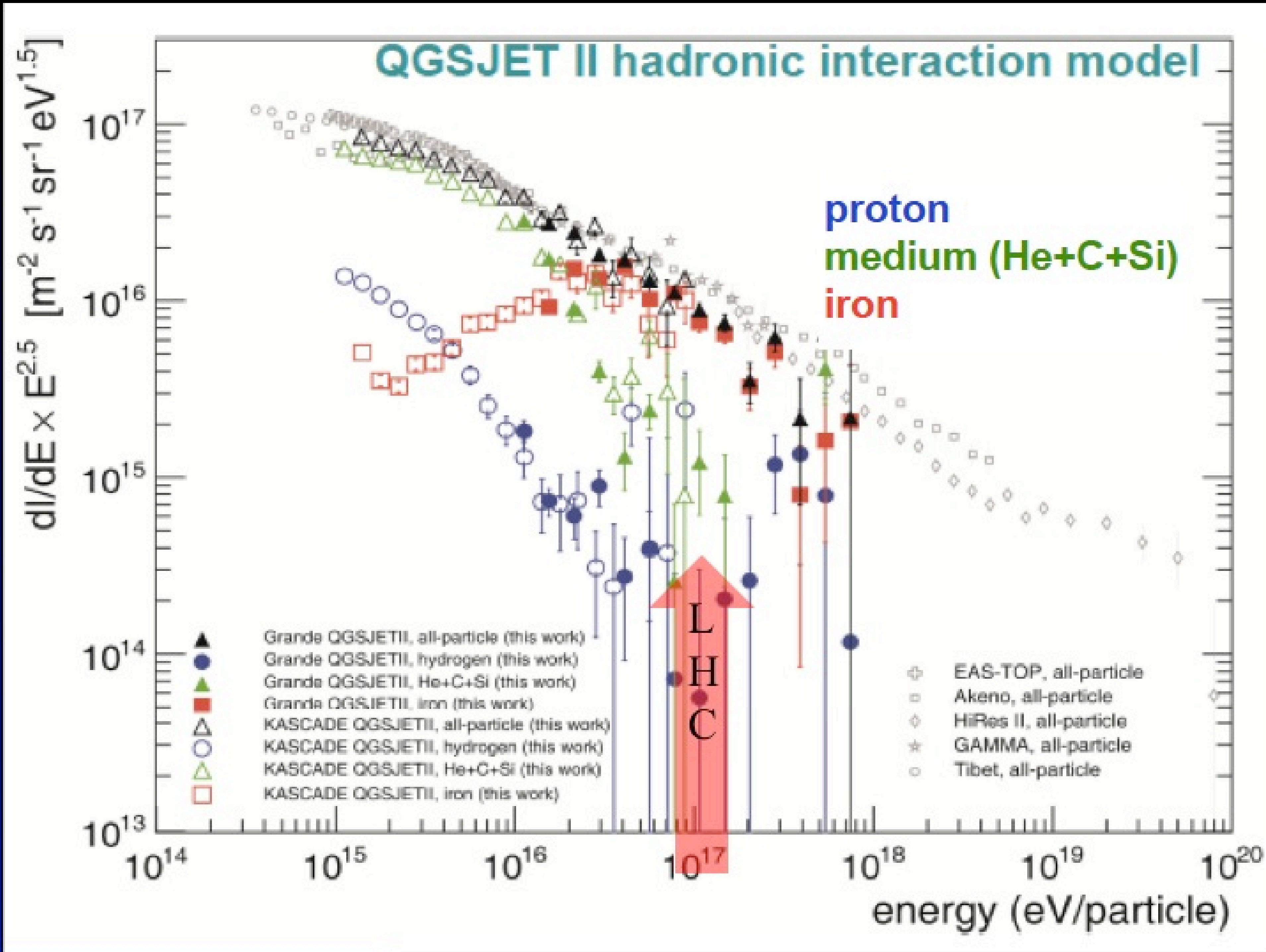
Dip Transition: Galactic to Extragalactic



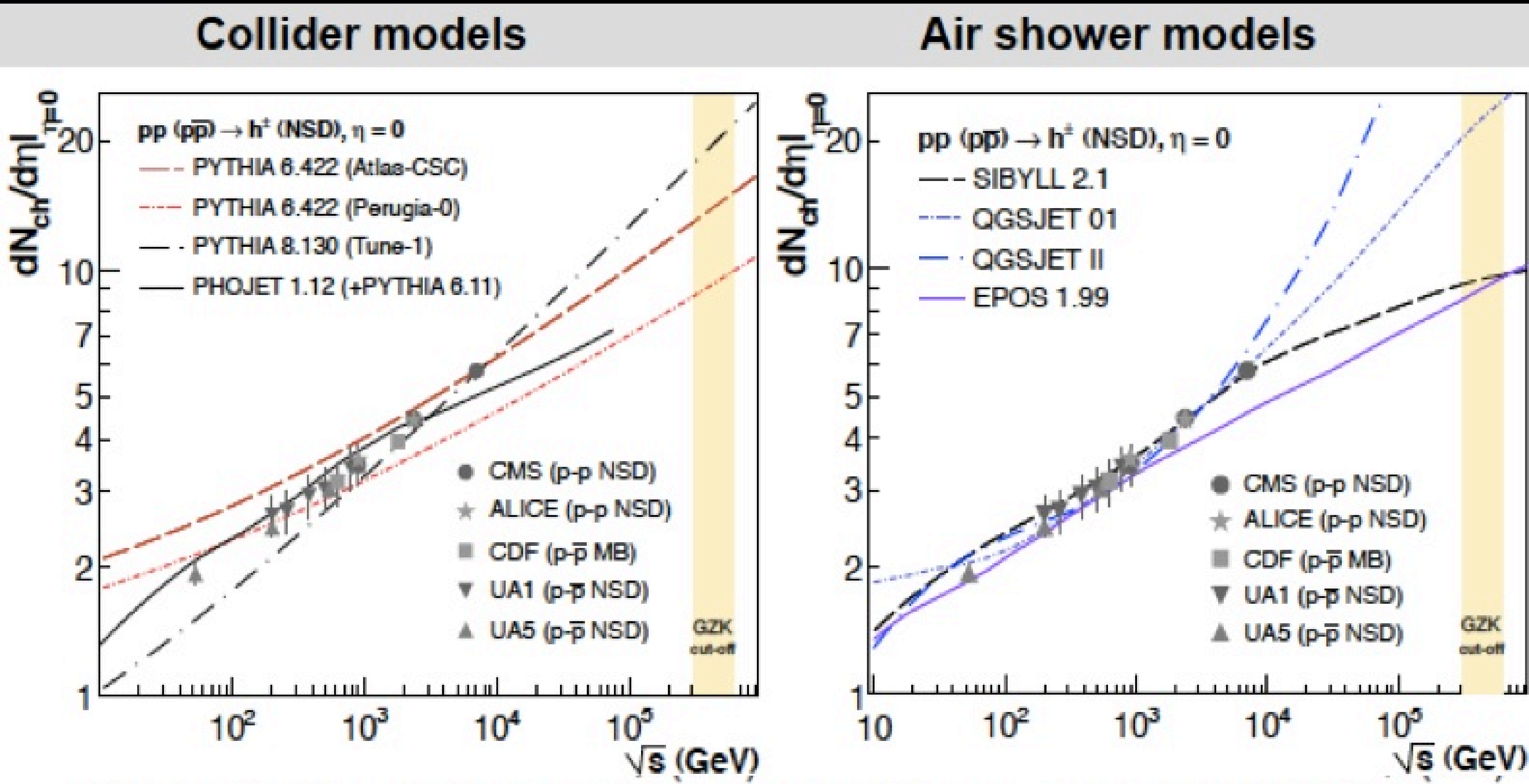
Not just the spectral shape, but also composition...



Above the Knee..KASCADE + K-Grande

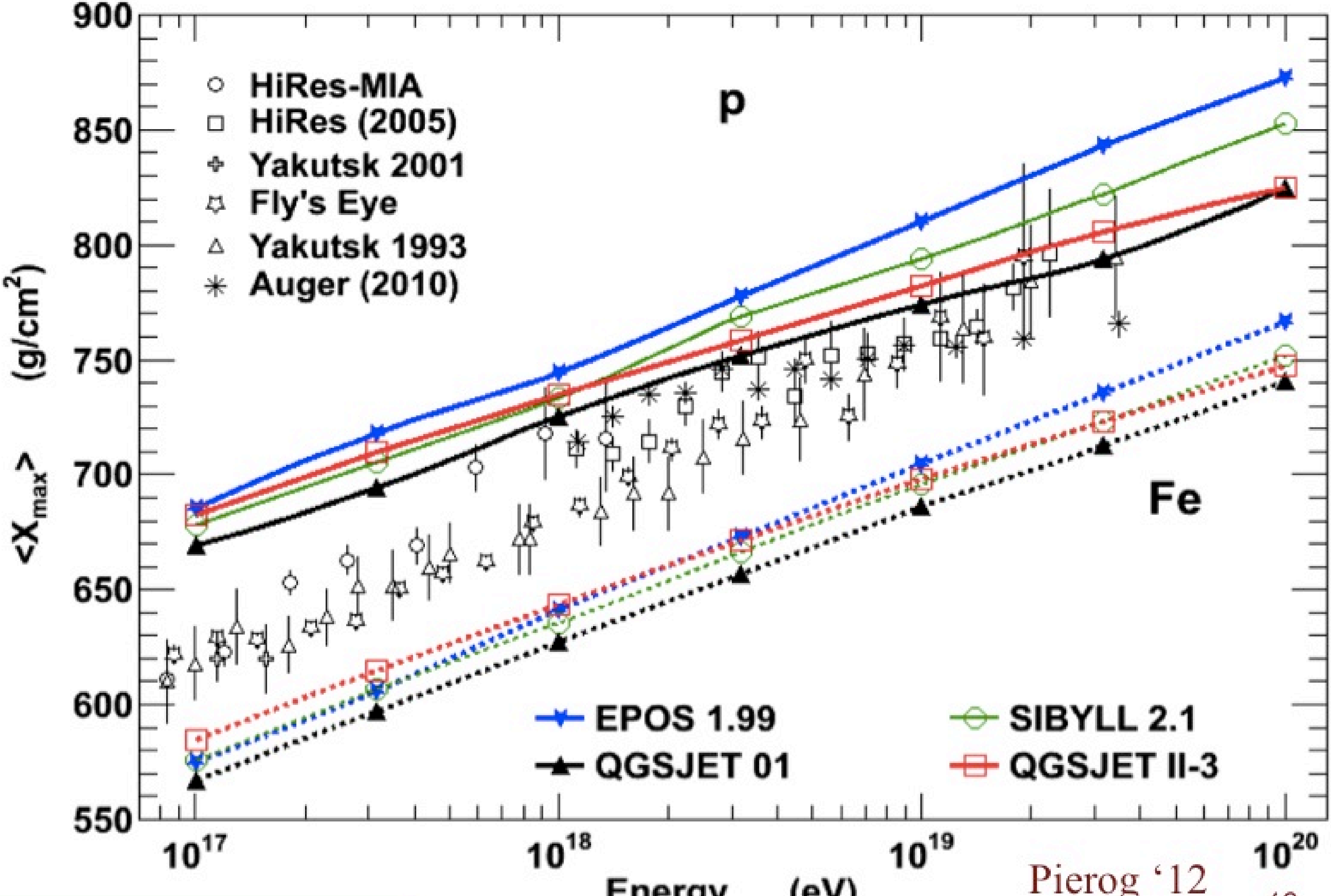


LHC tests of Hadronic Models



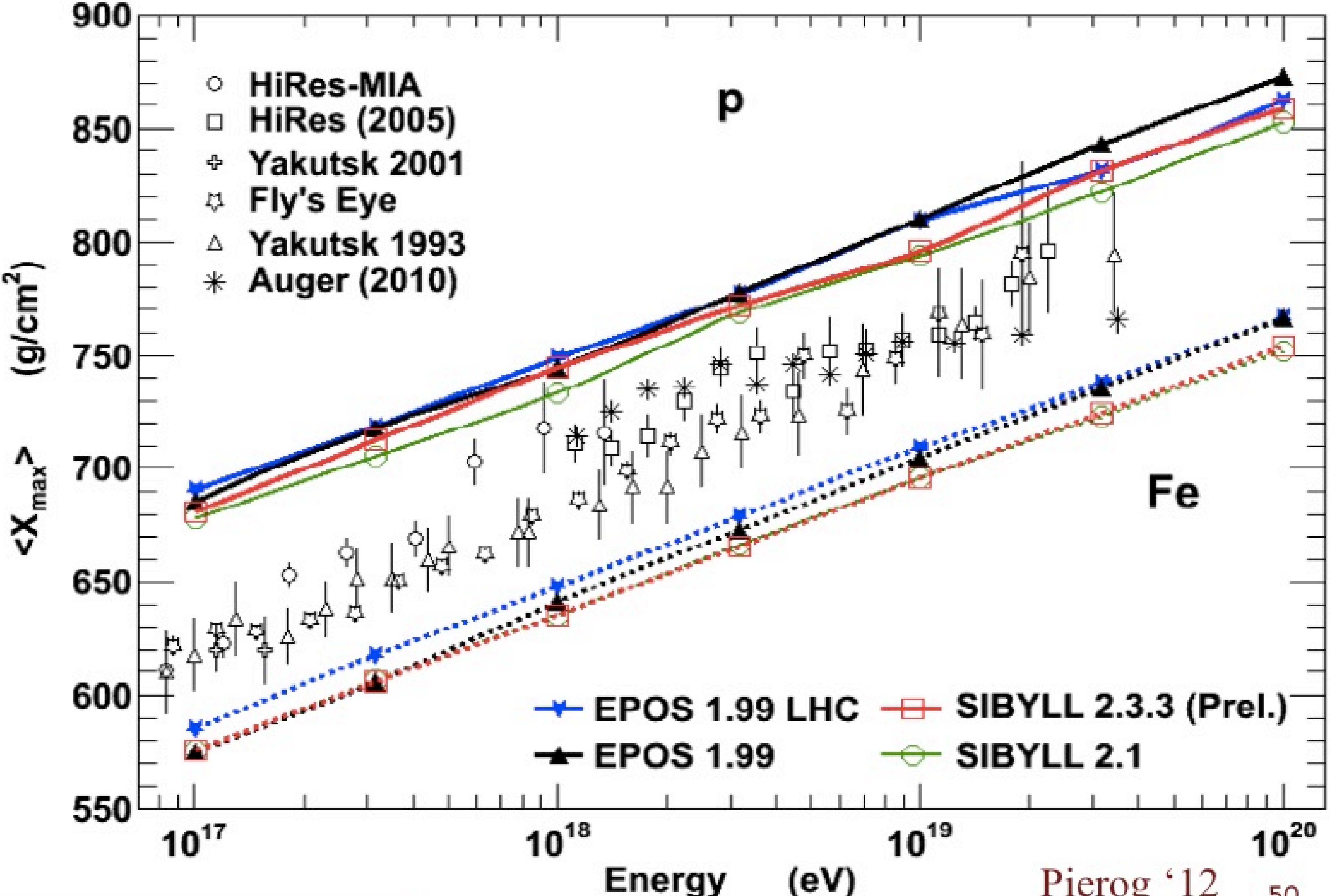
D'Enterria, Engel, Pierog, Ostapchenko, Werner arXiv:1101.5596v2

BEFORE LHC



Pierog '12

AFTER LHC



Pierog '12

Plausible Sources of UHECRs

1. Extragalactic $E > 10^{18}$ eV (maybe even lower)

Extragalactic implies GZK feature!

Propagation of UHECRs

Greisen-Zatsepin-Kuzmin (GZK) pioneered the field in 1966

protons & nuclei

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

One cannot save the day for superhigh-energy cosmic rays by calling on heavy nuclei. The threshold for photodisintegration against photons of 7×10^{-4} eV is only 5×10^{18} eV/nucleon, and at 10^{19} eV/nucleon most of the photons can excite the giant dipole resonance, for which the cross section is on the order of 10^{-25} cm^2. At this energy the mea

G. T. Zatsepin and V. A. Kuz'min

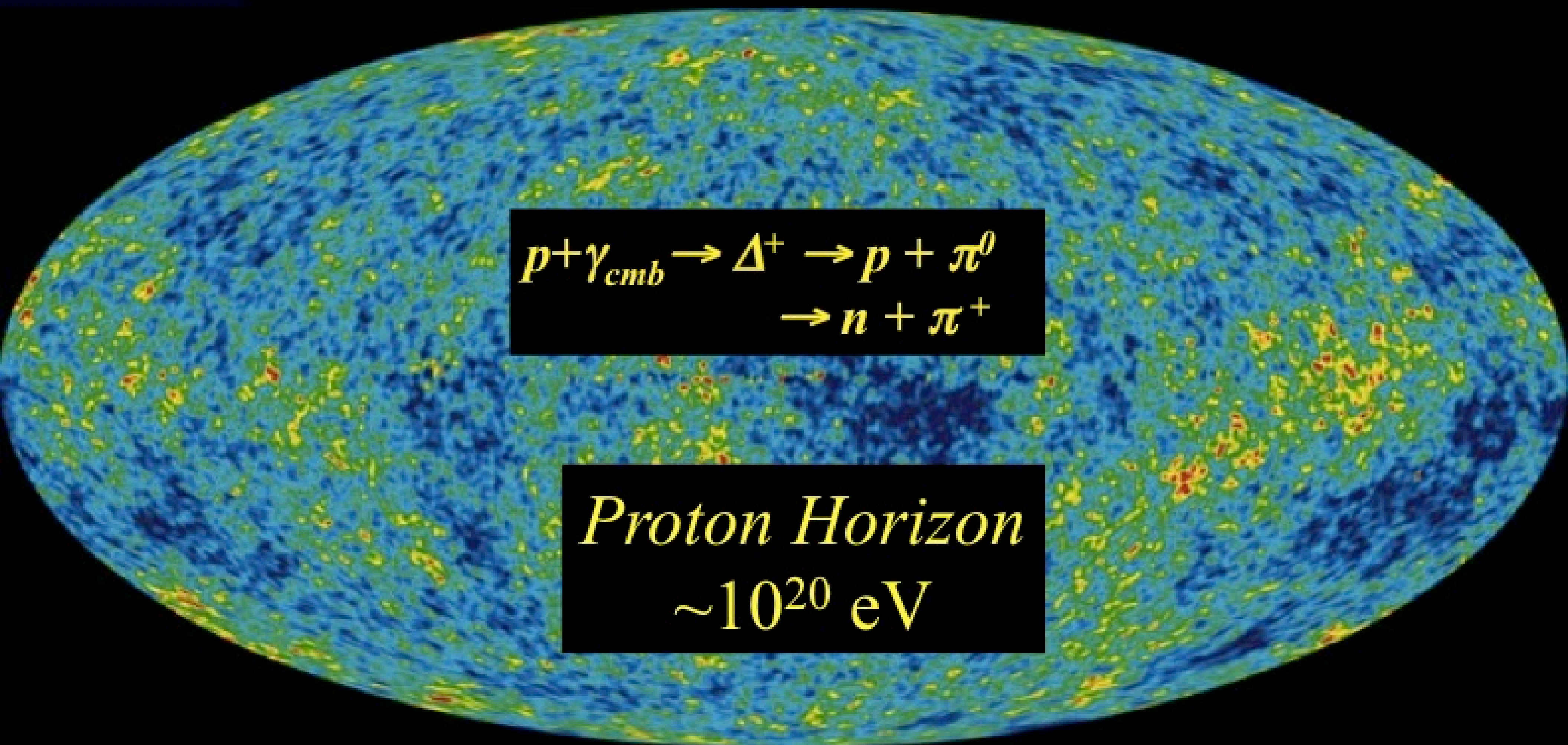
P. N. Lebedev Physics Institute, USSR Academy of Sciences

Submitted 26 May 1966

ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

Notice should be taken of the disintegration of α particles and other nuclei [6] as they pass through metagalactic space. This occurs at an α-particle energy somewhat lower than the proton energy at which the pion photoproduction process begins. The rather large cross section of this process should lead to total disappearance of the nuclei from the cosmic rays at energies above 10^{19} eV.

"Cosmologically Meaningful Termination"



$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

Proton Horizon

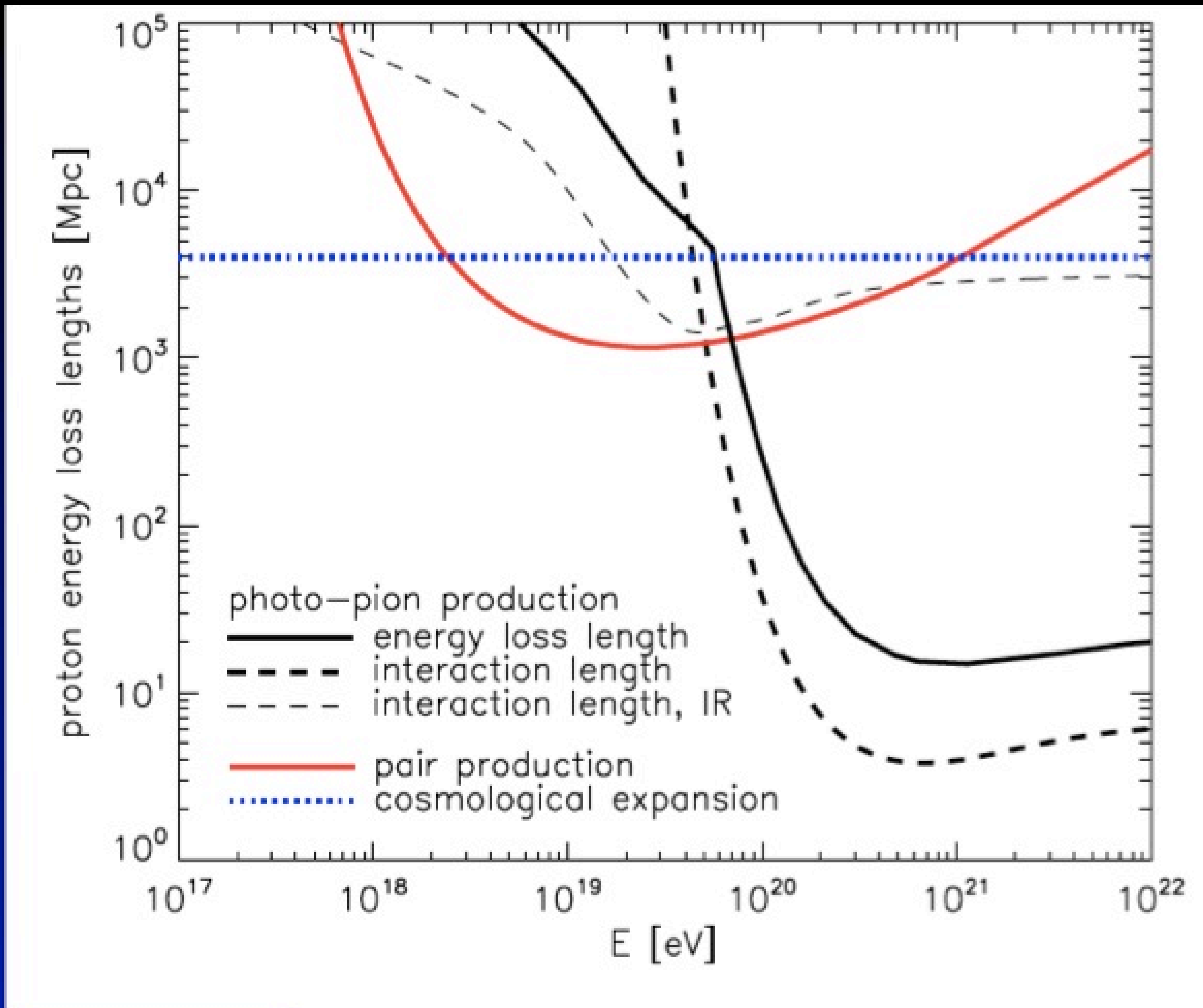
$\sim 10^{20}$ eV

GZK Cutoff

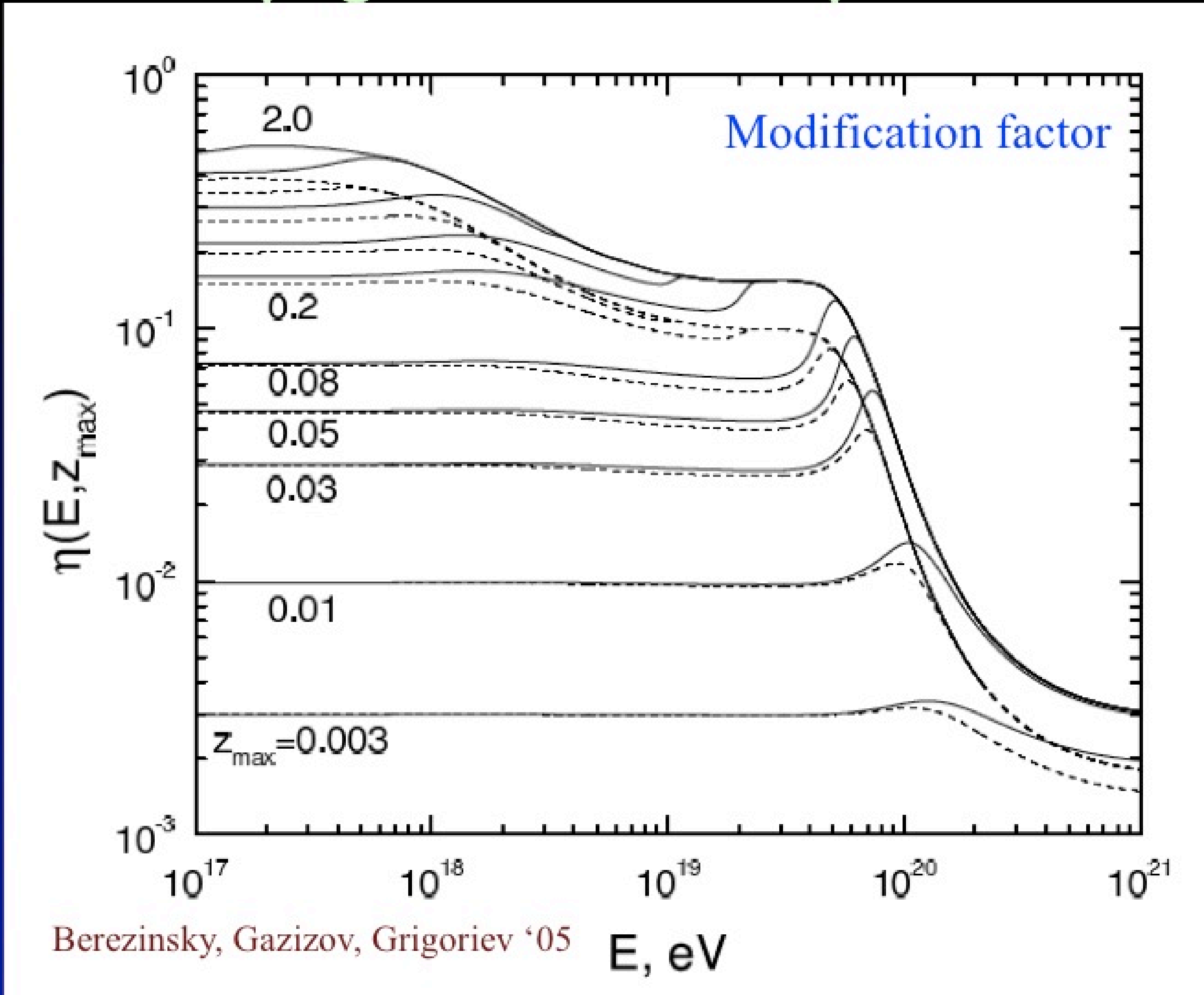
Greisen, Zatsepin, Kuzmin

1966

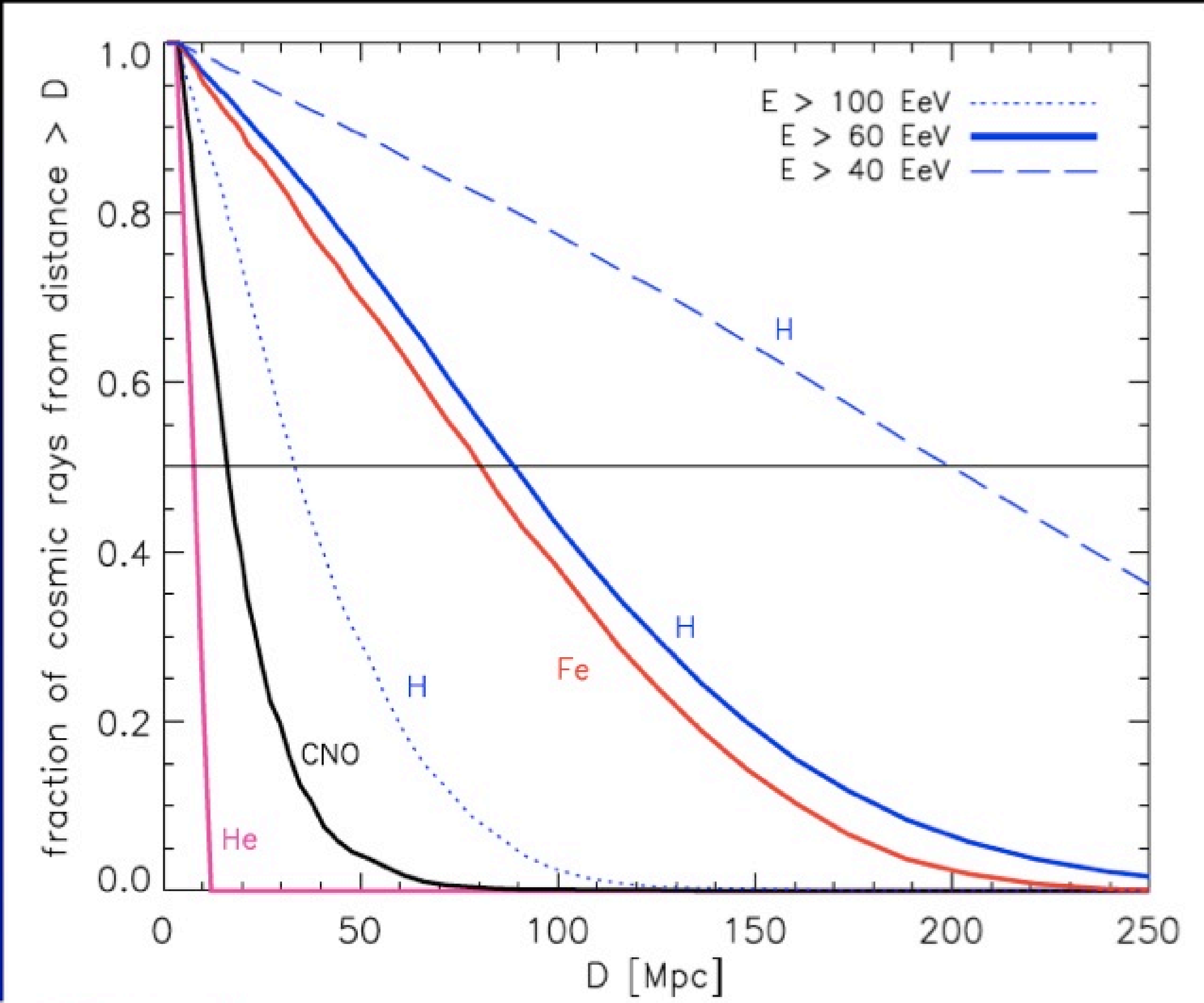
Greisen-Zatsepin-Kuzmin cutoff



Propagation of UHE protons

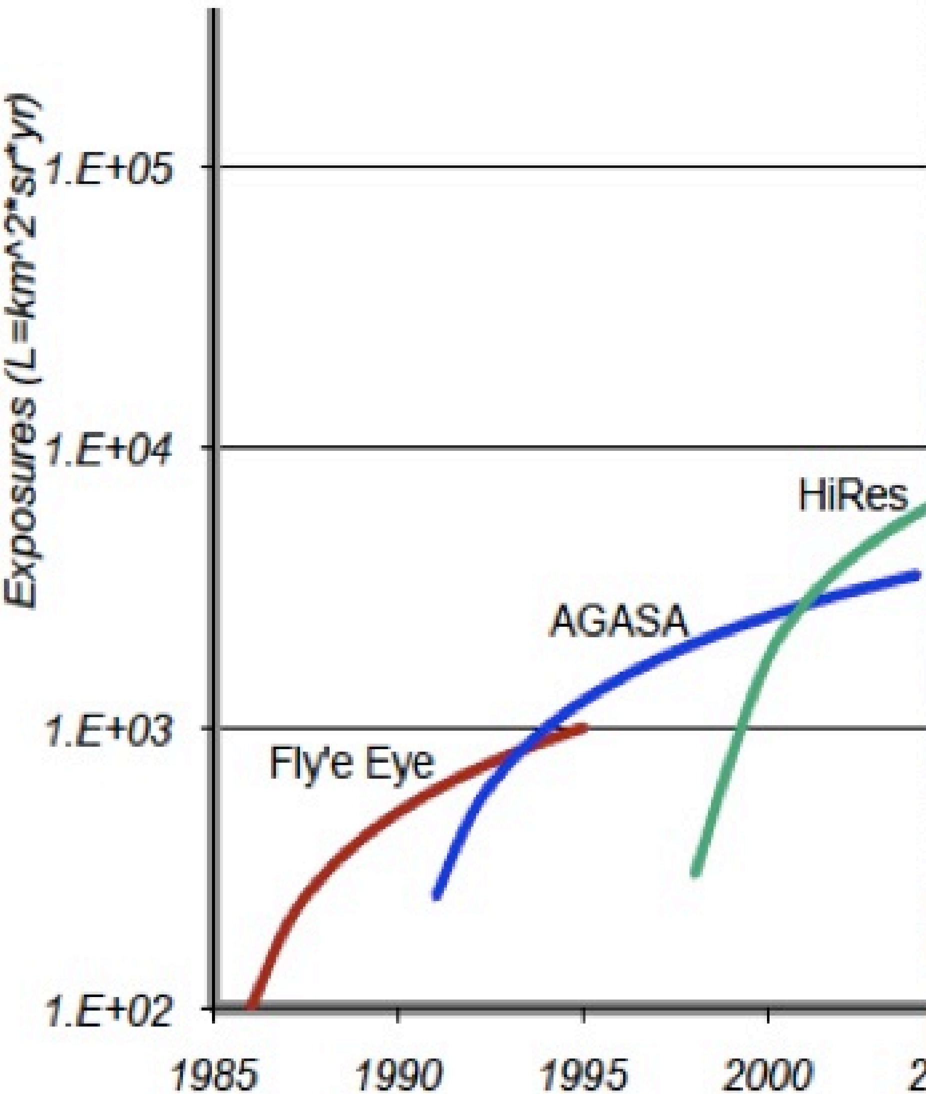


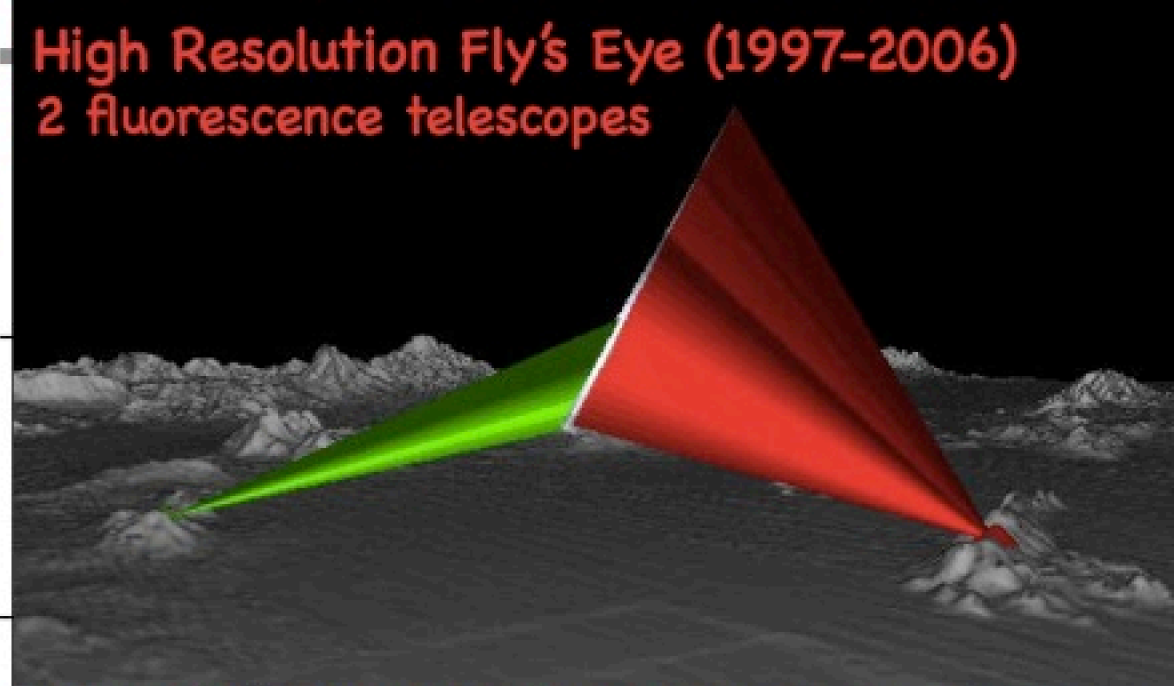
GZK Horizon



Allard, AVO, Parizot '07

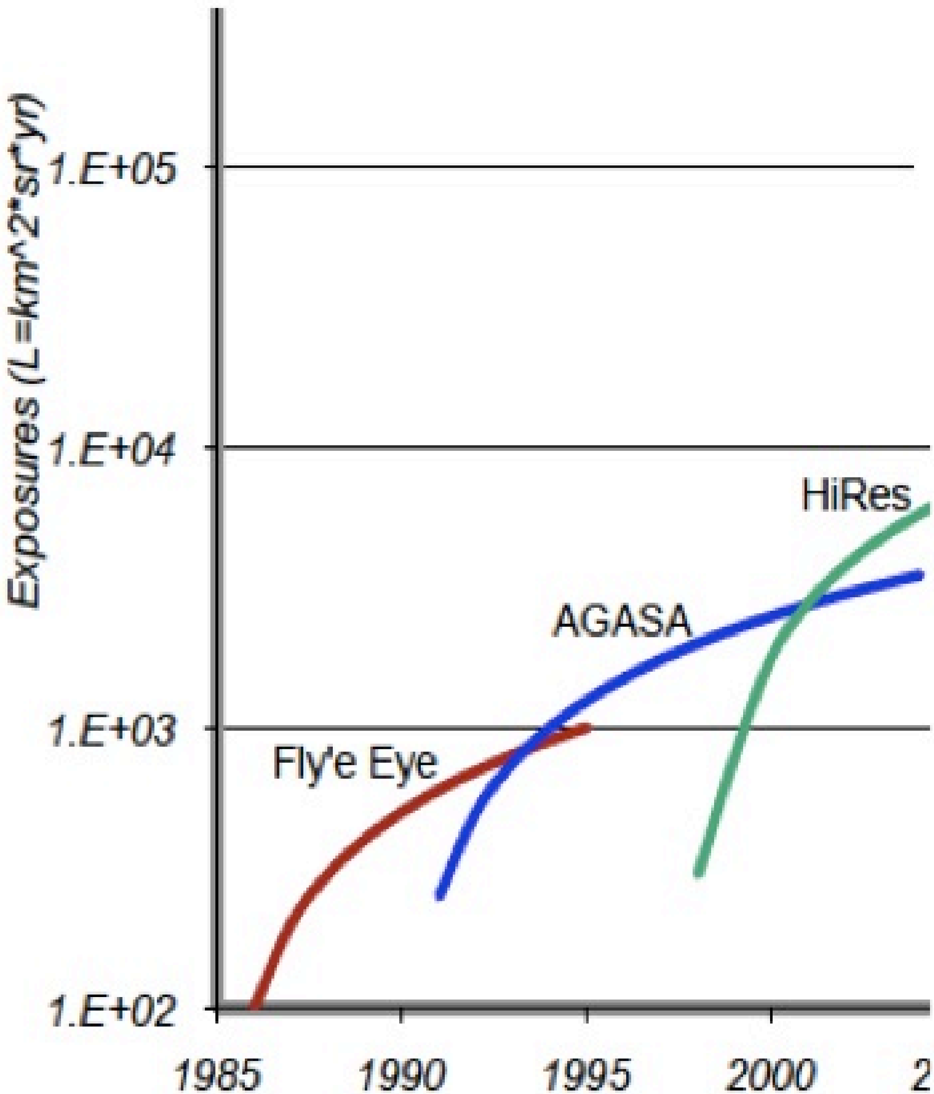
Last Century's question:
GZK or No GZK?



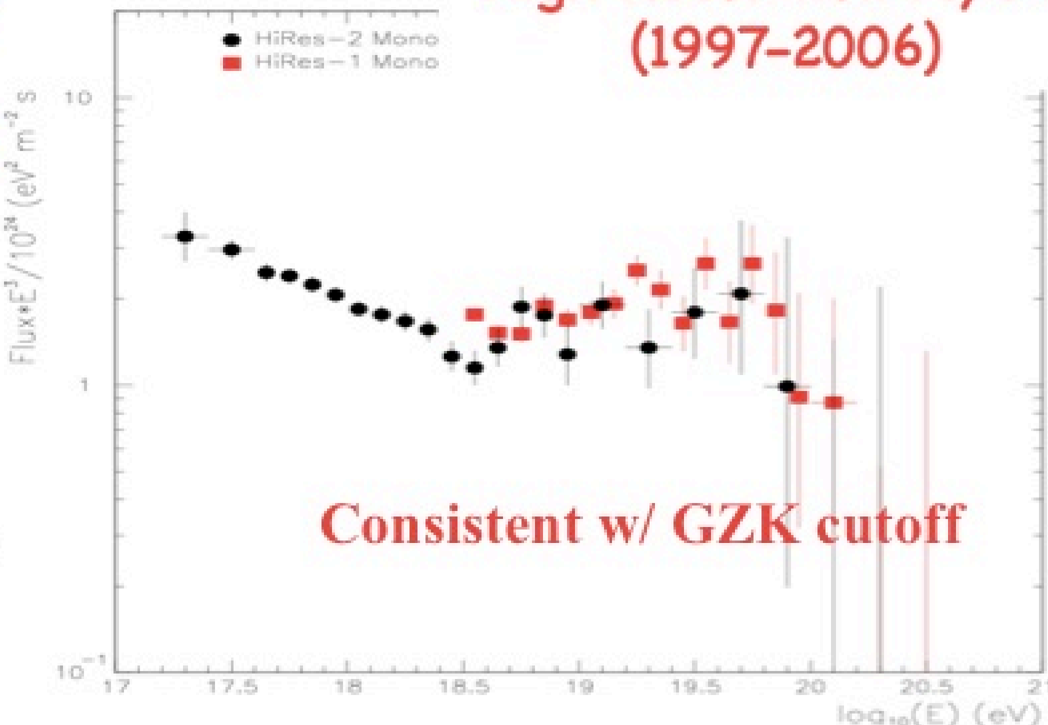


Cosmic Ray Flux x E^3

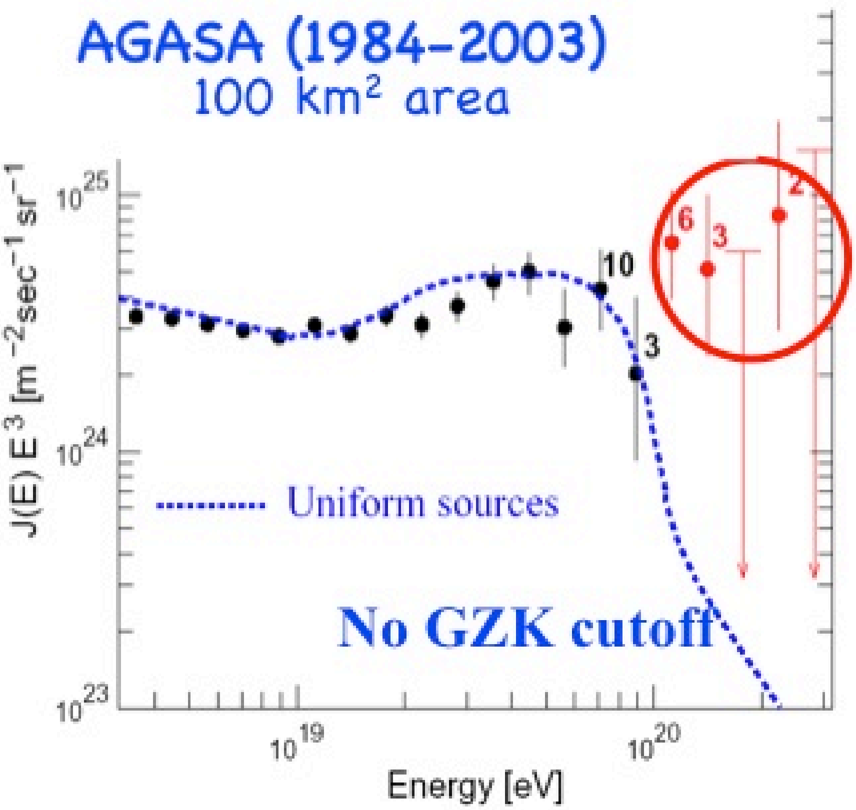
Last Century's question:
GZK or No GZK?



High Resolution Fly's Eye
(1997-2006)

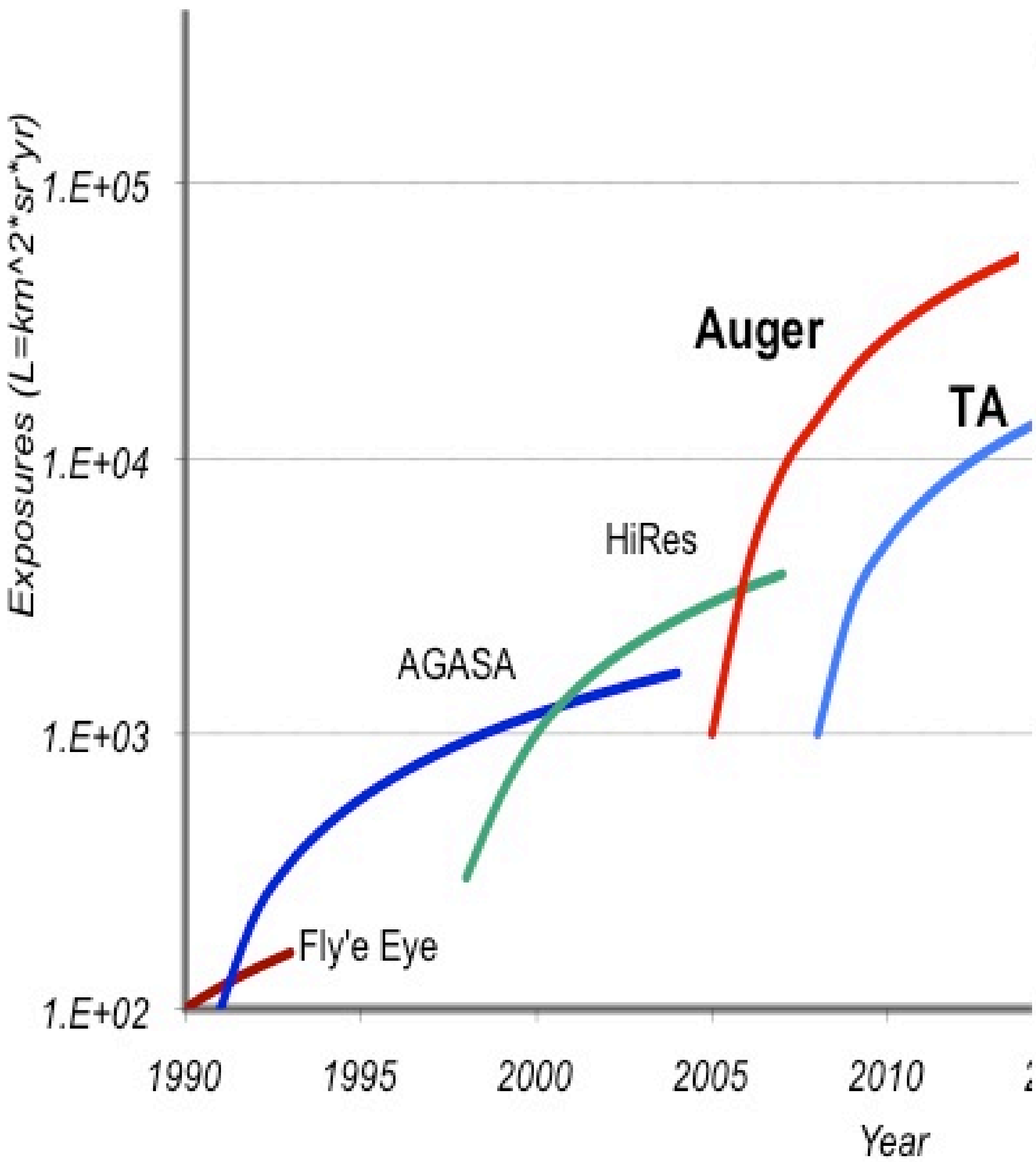


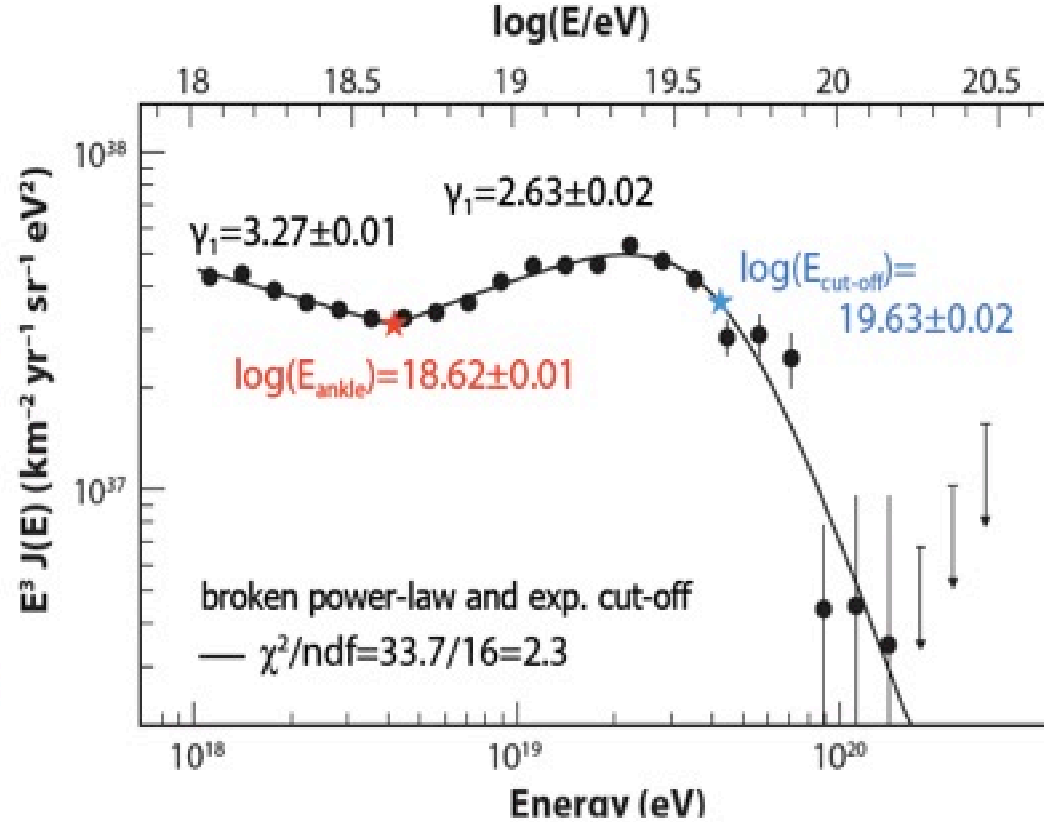
AGASA (1984-2003)
100 km² area

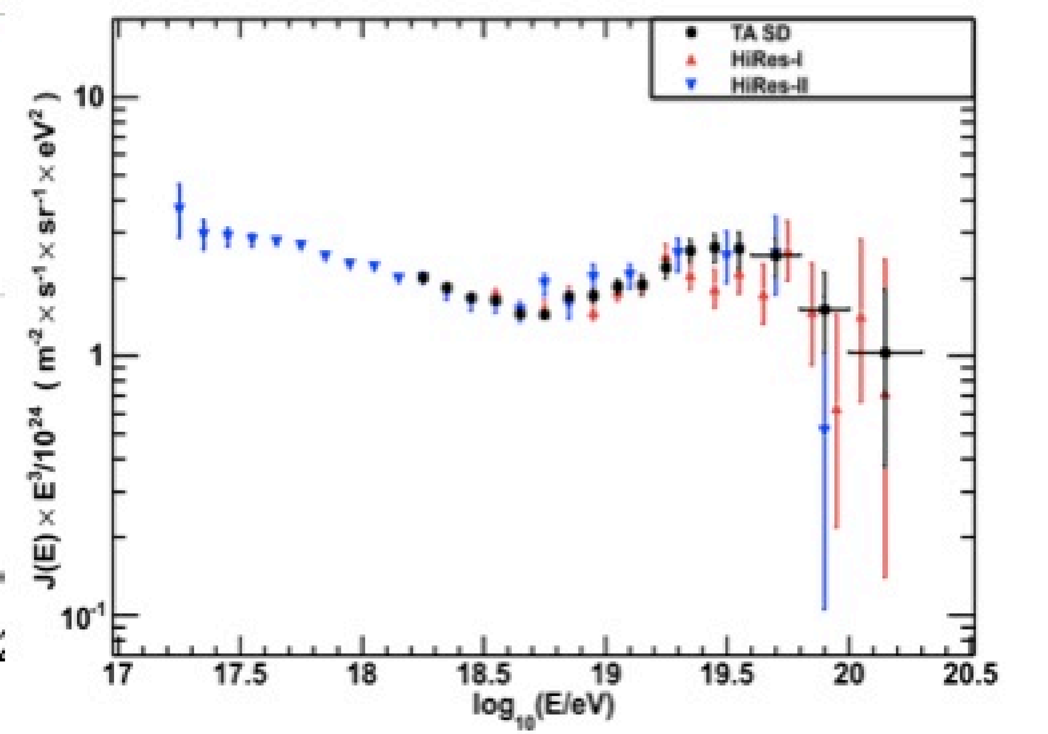


Last Century's question: GZK or No GZK?

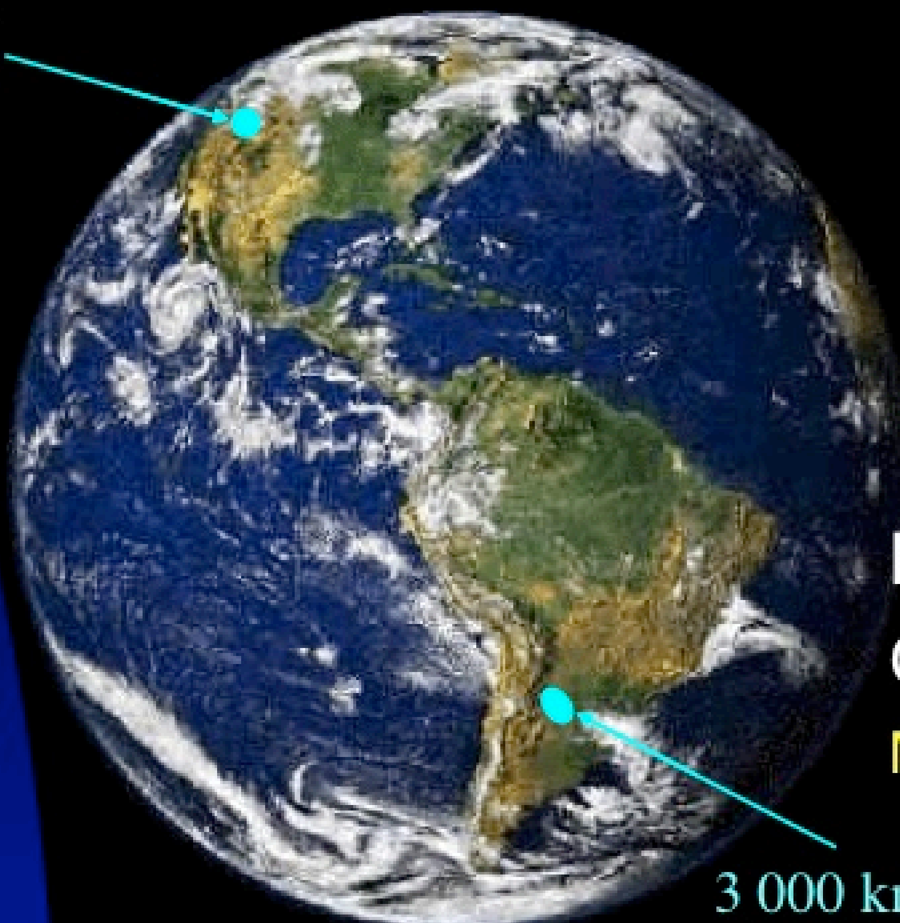
Observed Spectra are Consistent w/ GZK effect

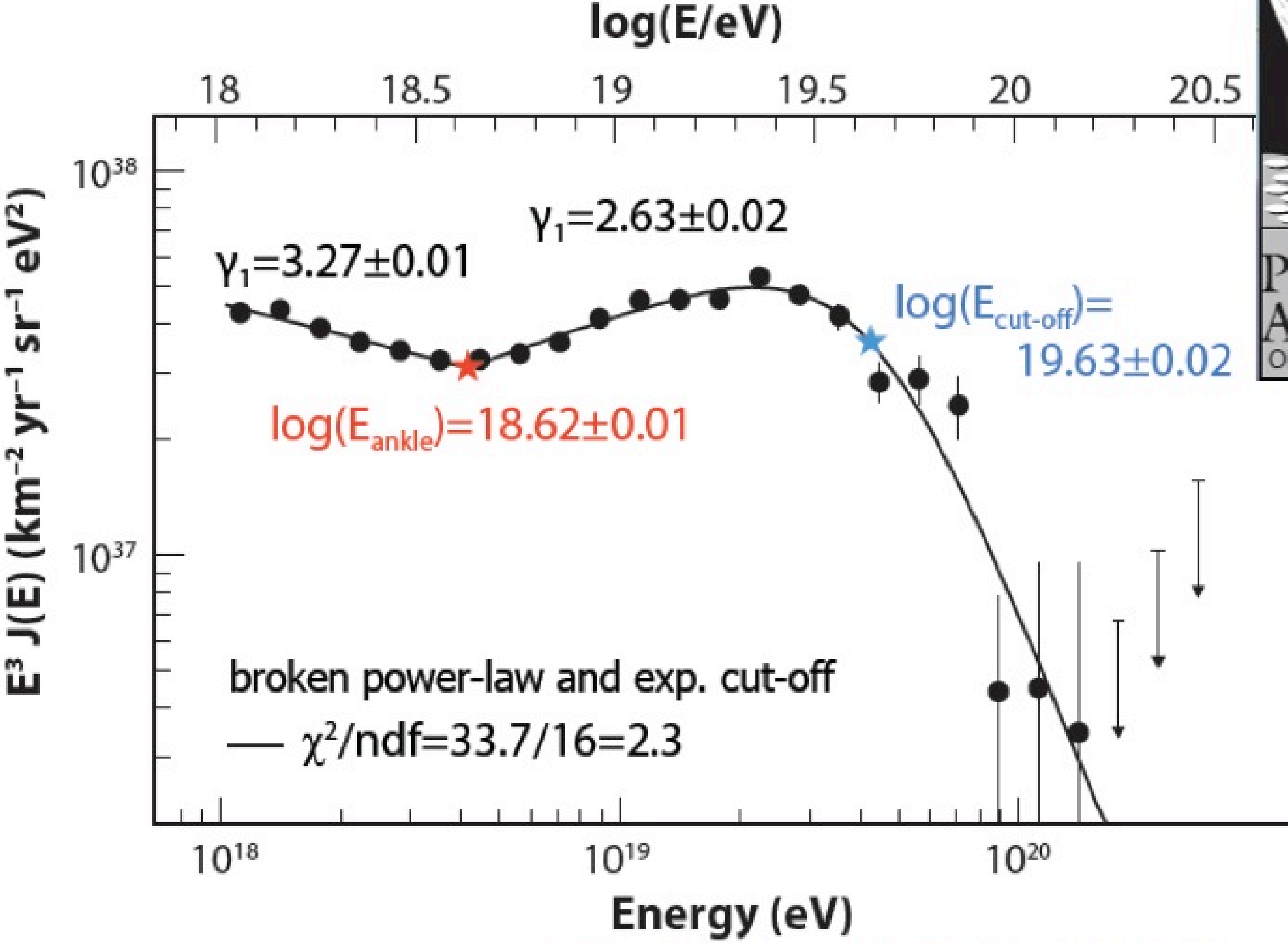






Ultrahigh Energy Cosmic Rays Leading Observatories



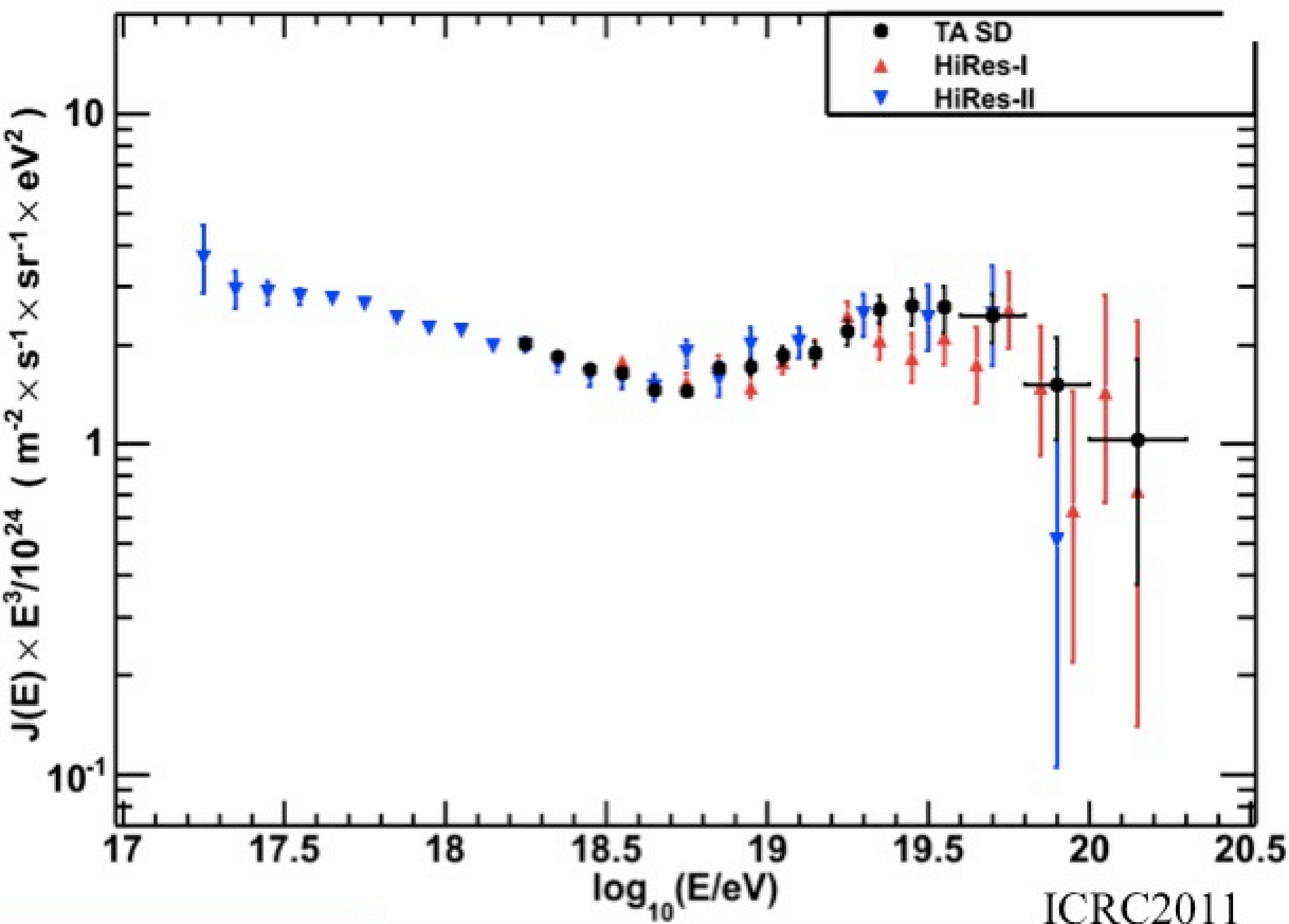


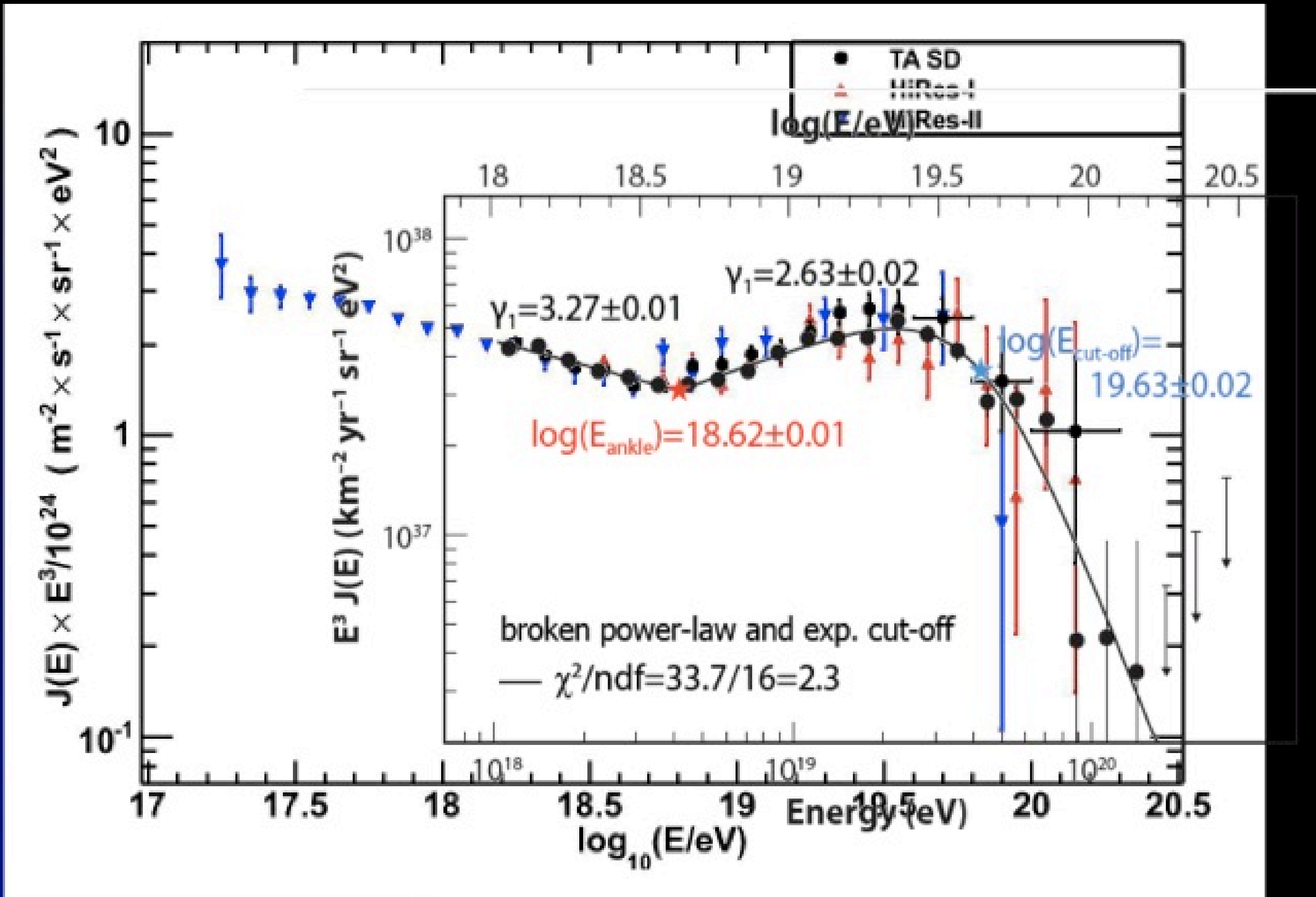
Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)

Total uncertainty of E-scale: 22% (dominated by Fl.-yield. 14%)

Exposure = 20905 km^2 sr yr

Telescope Array SD spectrum

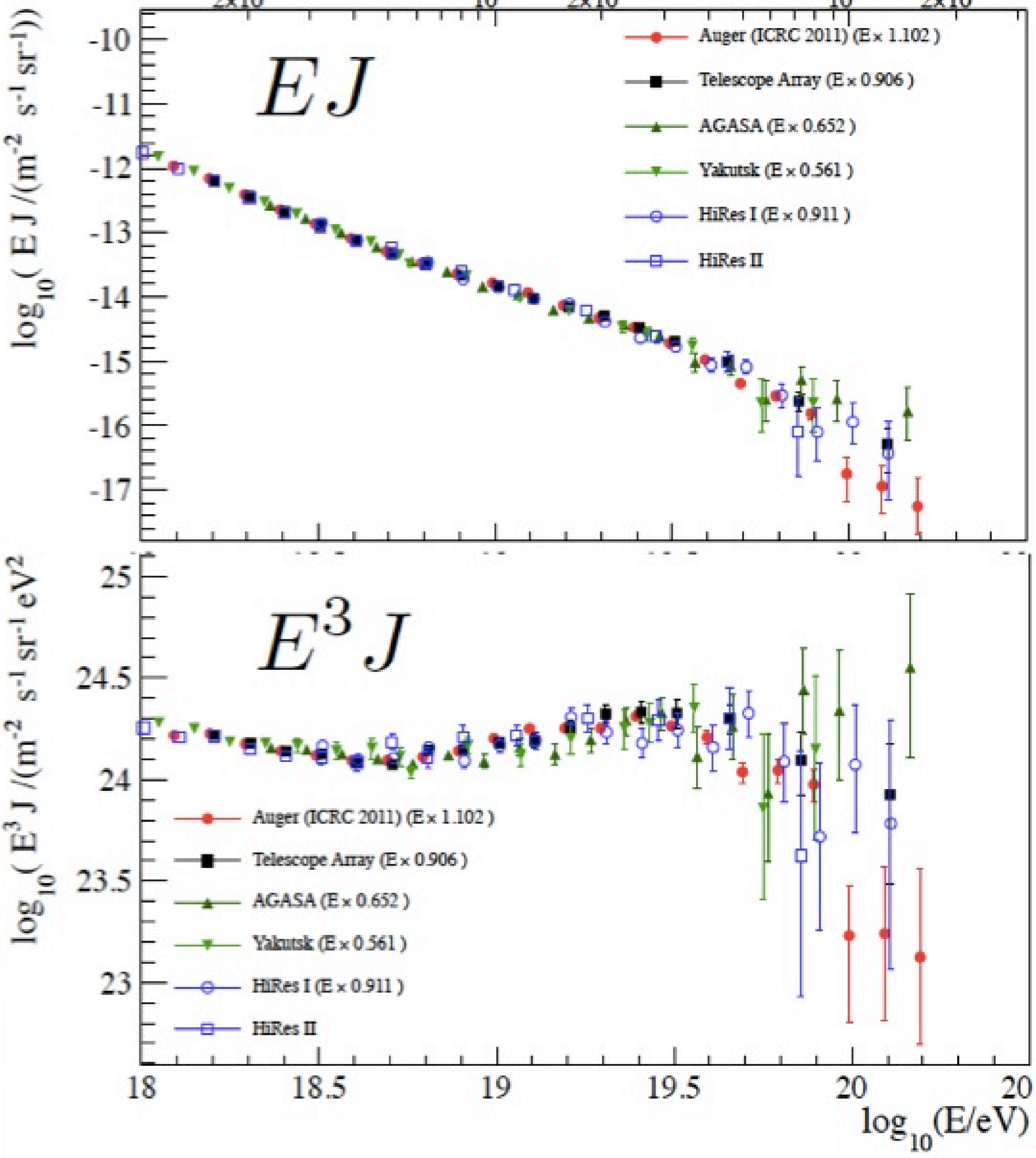




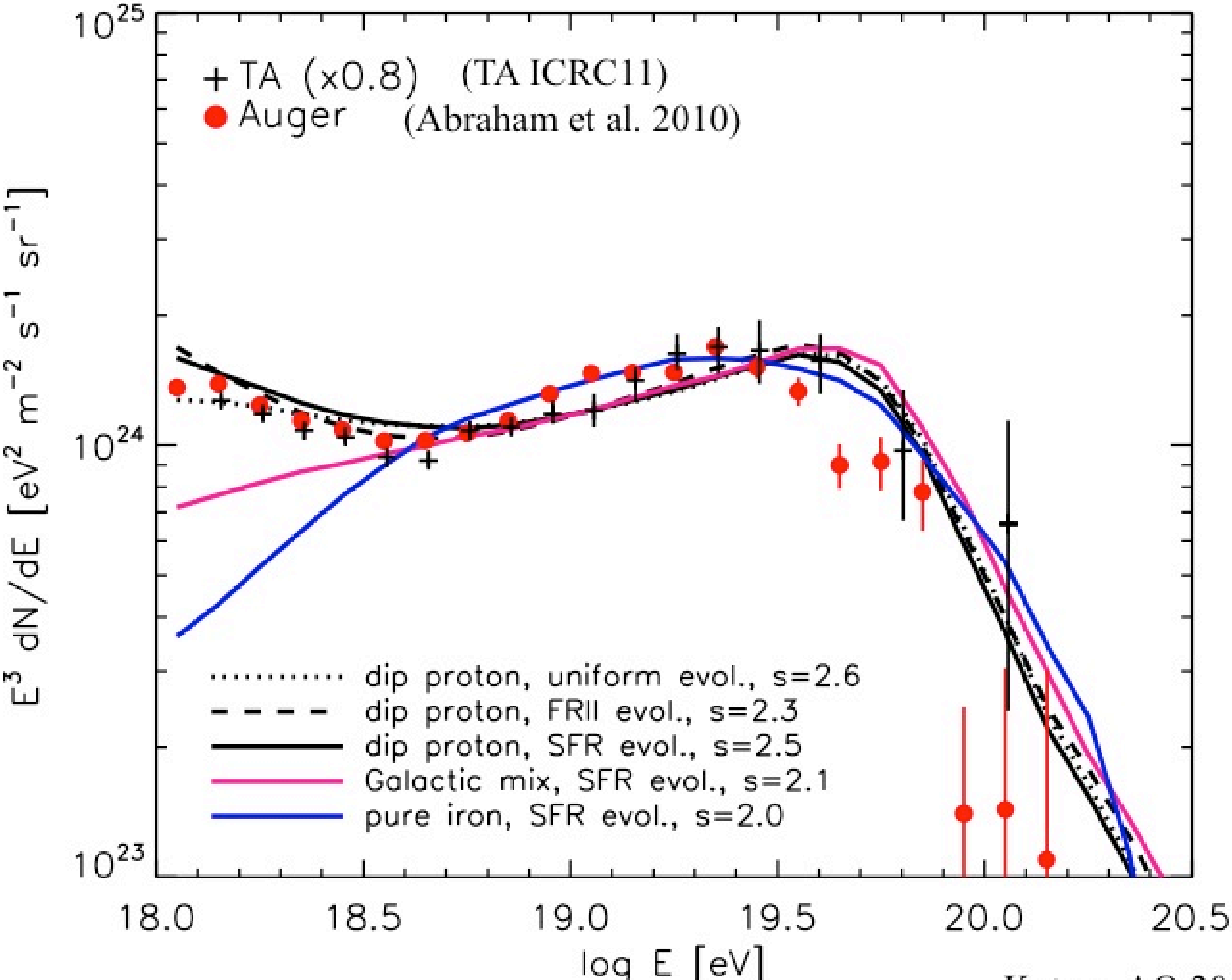
20 % "absolute" energy shift

2012 CERN Working Group

Unified Spectrum

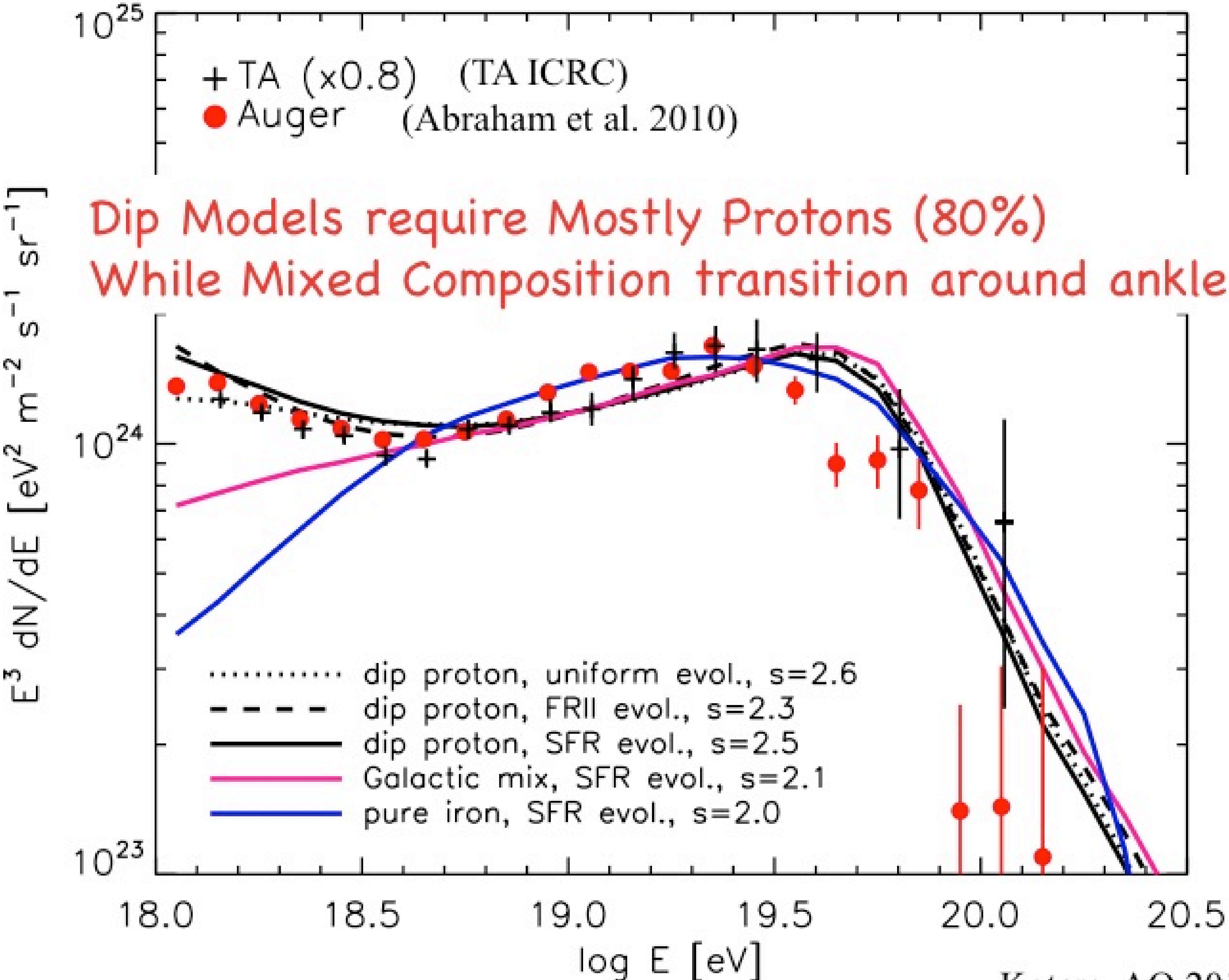


Composition and Transition from Gal to XGal



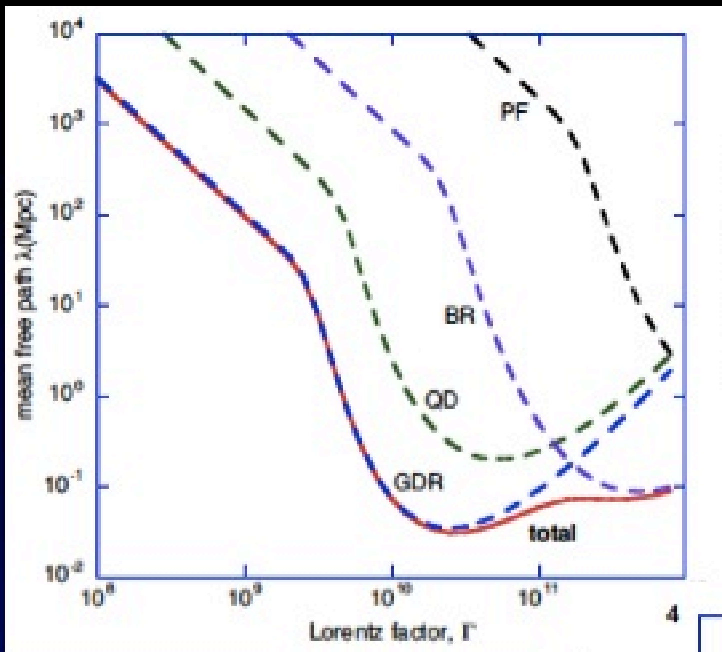
Kotera, AO 2011

Composition and Transition from Gal to XGal

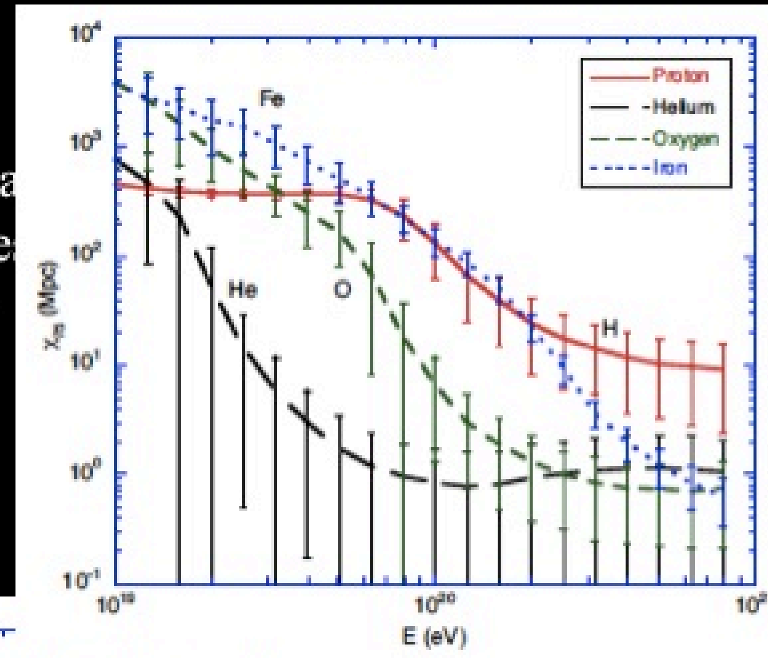


Kotera, AO 2011

Propagation of UHE nuclei

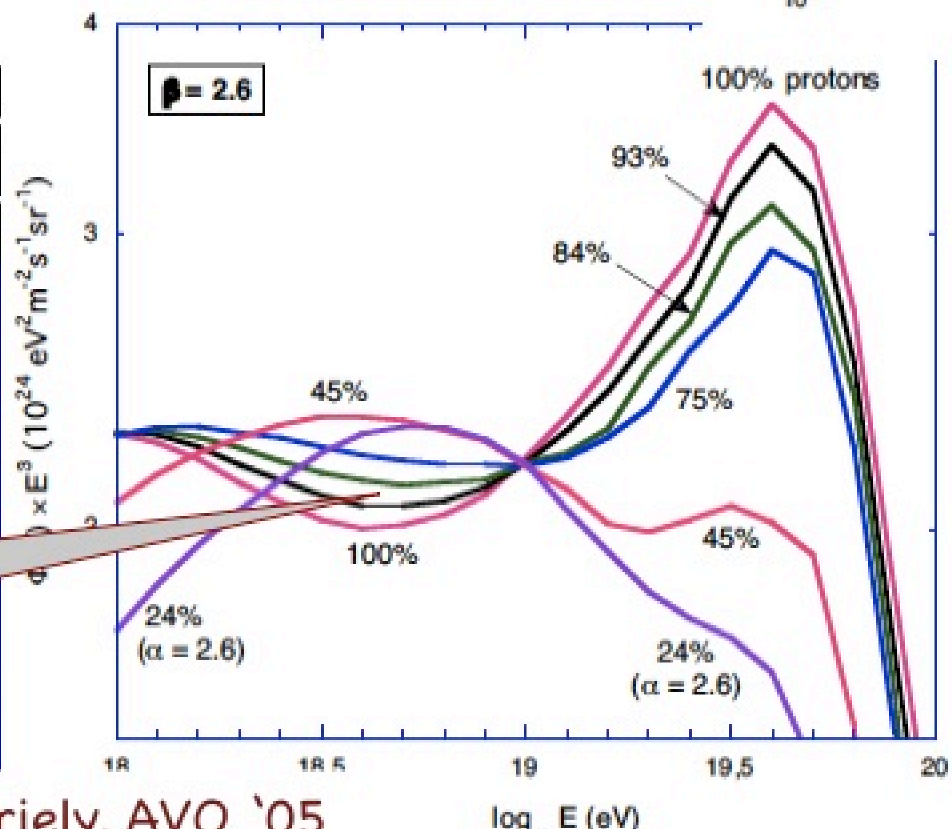


GDR: giant dipolar resona
QD: quasi-deuteron proce
BR: baryonic resonances
PF: photo-fragmentation



^{56}Fe mean-free-path
CMB IRB interaction

Energy Loss Length



dip only for protons

Allard, Parizot, Khan, Goriely, AVO '05

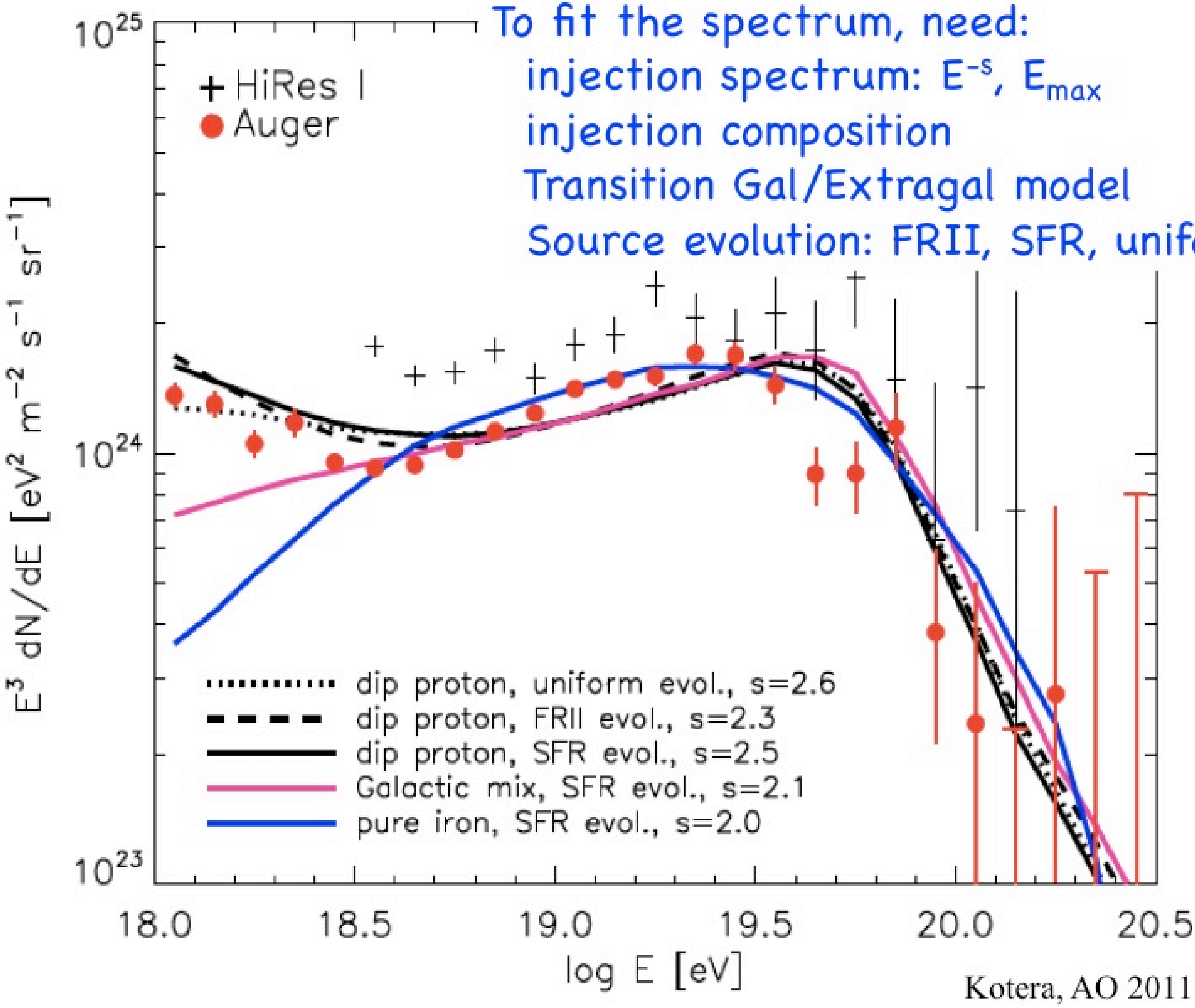
Plausible Sources of UHECRs

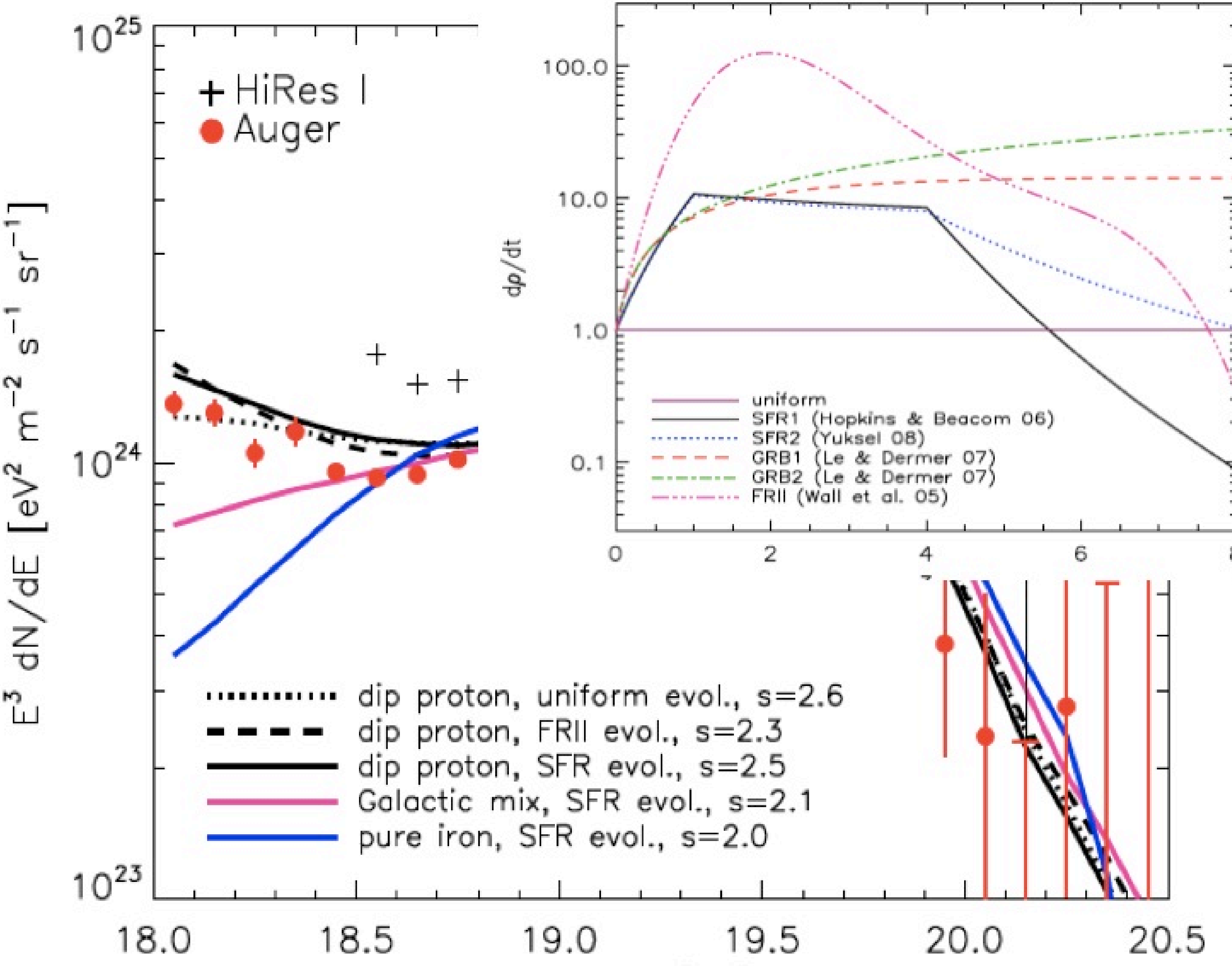
1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained.
3. UHE Spectral shape depends on many parameters: injection spectrum, source evolution, composition.

Many degeneracies.

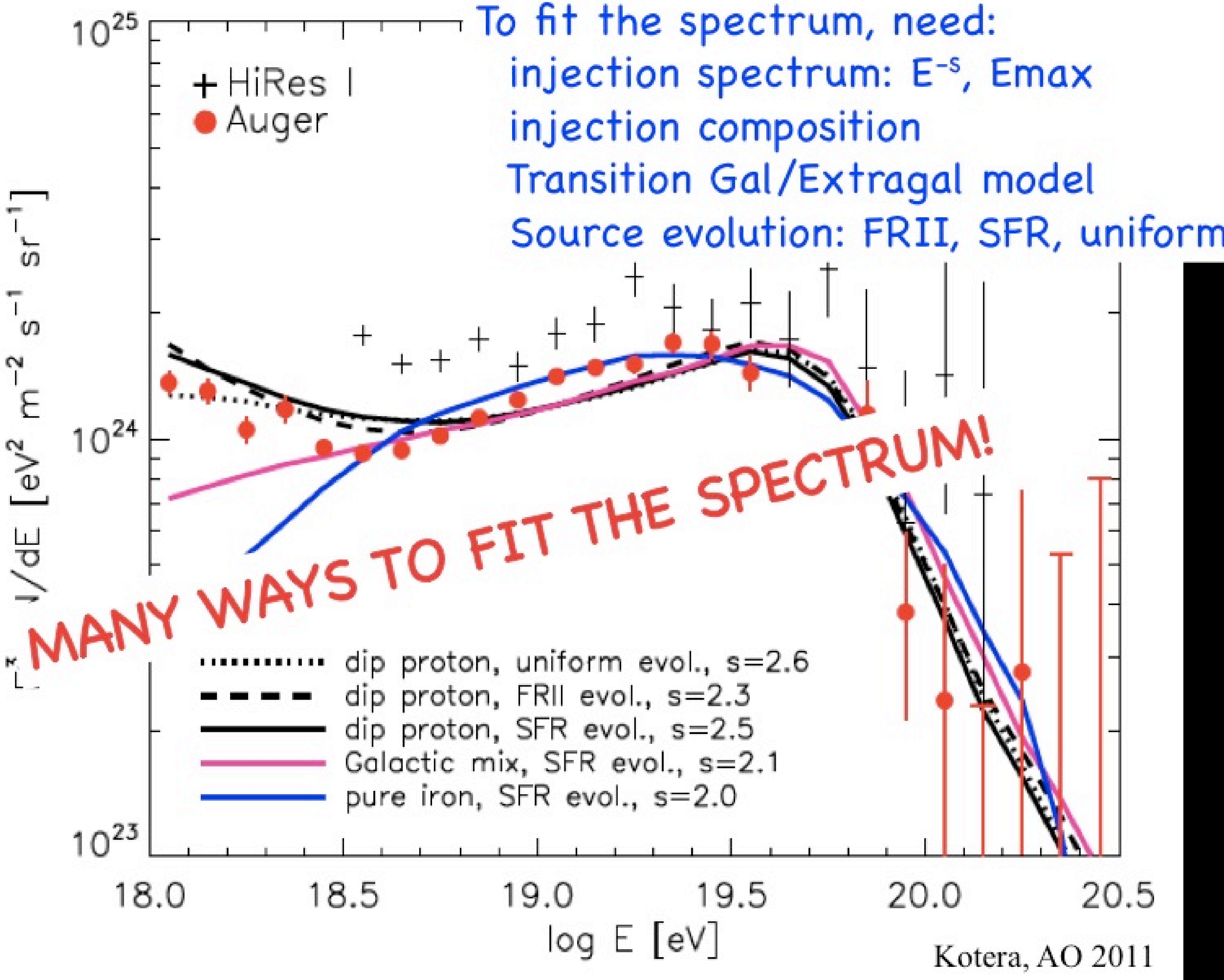
To fit the spectrum, need:

- injection spectrum: E^{-s}, E_{max}
- injection composition
- Transition Gal/Extragal model
- Source evolution: FRII, SFR, uniform





Kotera, AO 2011



To fit the spectrum, need:
injection spectrum: E^-s, Emax
injection composition
Transition Gal/Extragal model
Source evolution: FRII, SFR, uniform
MANY WAYS TO FIT THE SPECTRUM!
HiRes I
Auger
dip proton, uniform evol., s=2.6
dip proton, FRII evol., s=2.3
dip proton, SFR evol., s=2.5
Galactic mix, SFR evol., s=2.1
pure iron, SFR evol., s=2.0
/dE [eV² m⁻² s⁻¹ sr⁻¹]
10^25
10^24
10^23
18.0
18.5
19.0
19.5
20.0
20.5
log E [eV]
Kotera, AO 2011

Plausible Sources of UHECRs

1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained.
3. UHE Spectral shape fit ➔ degeneracies.
4. Flux implies Luminosity-number density relationship

Observed Flux → local production rate of UHECR

Continuous Sources:

$$(E^3 \mathrm{d}N/\mathrm{d}E)_{E=E_{19}} \sim 10^{24}\ \mathrm{eV}^2\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}(n_\mathrm{s}/10^{-5}\ \mathrm{Mpc}^{-3})(L_{19}/10^{42}\ \mathrm{erg\,s}^{-1})$$

galactic abundance n ~ $10^{-2}\ \mathrm{Mpc}^{-3}$

Faranoff-Riley II n ~ $10^{-9}-10^{-8}\,\mathrm{Mpc}^{-3}$

Transient Sources

$$(\dot{n}_\mathrm{s}/10^{-9}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1})\ (E_{\mathrm{tot},19}/3\times10^{53}\,\mathrm{ergs})$$

Constraints on n → constraints on source Luminosity

For Ex.: assuming **PROTONS, NO observed MULTIPLETS**
→ Lower Limit on Source Density

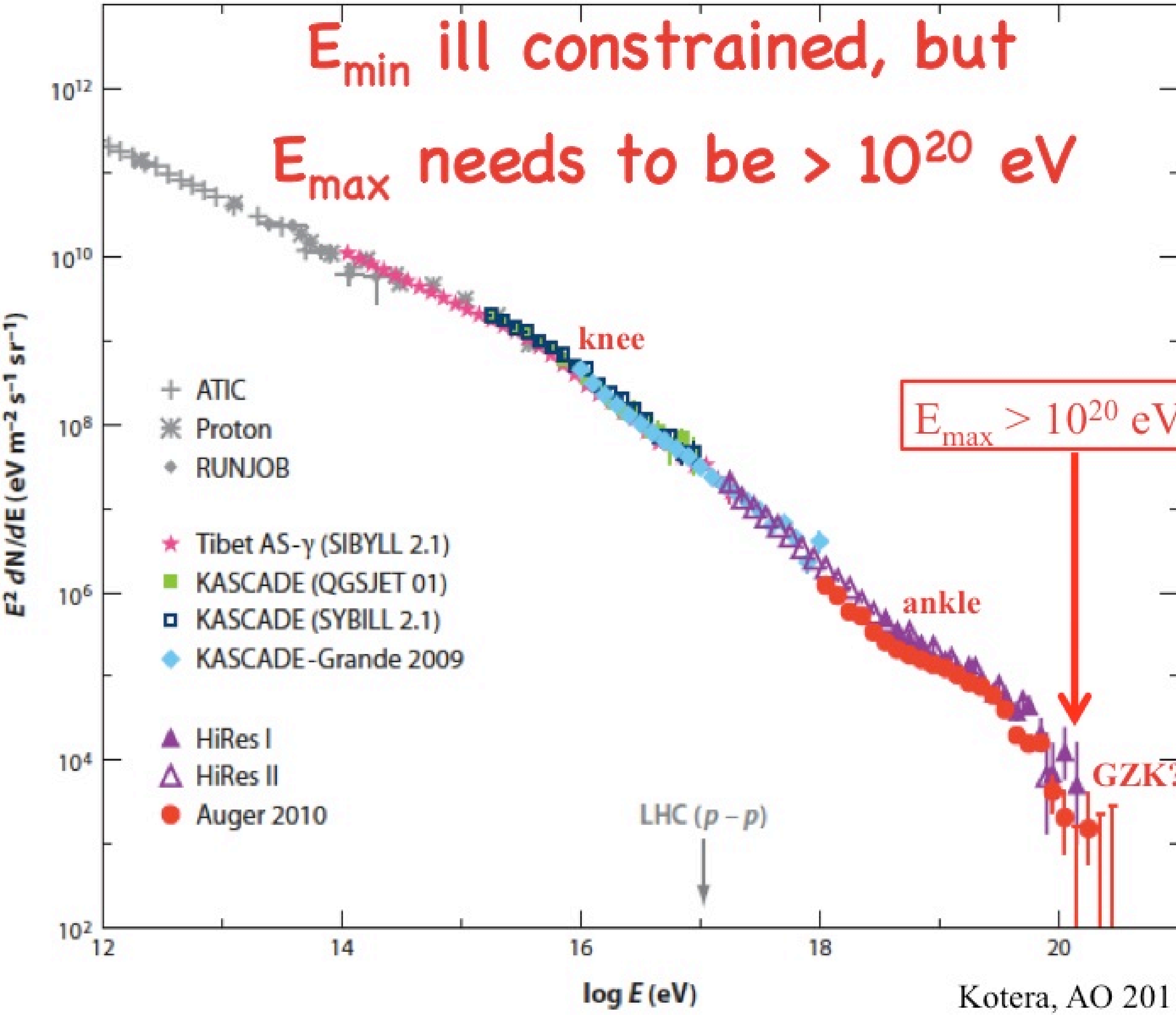
$n > 10^{-4}\ \mathrm{Mpc}^{-3}$ → $L_{19} > 10^{41}$ erg/s or 10^{48} erg/yr

Blasi & De Marco 2003, Waxman arXiv:1101.1155

Plausible Sources of UHECRs

1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained.
3. UHE Spectral shape fit ➔ degeneracies.
4. Flux implies Luminosity-number density relationship
5. Very few astrophysical sources can reach E_{max}
   GRBs, AGN, Young NSs, ?

E_{min} ill constrained, but E_{max} needs to be > 10^{20} eV



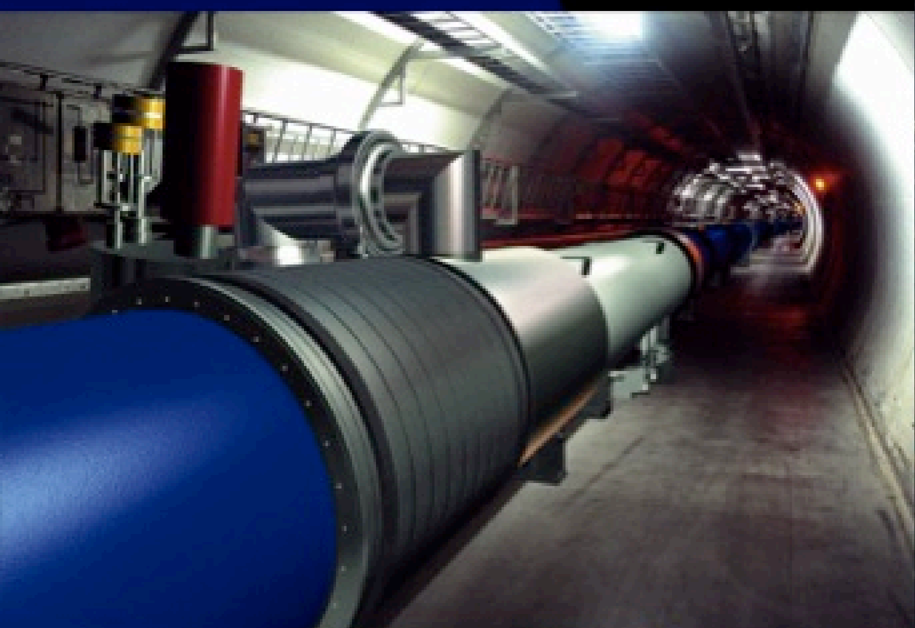
Kotera, AO 2011

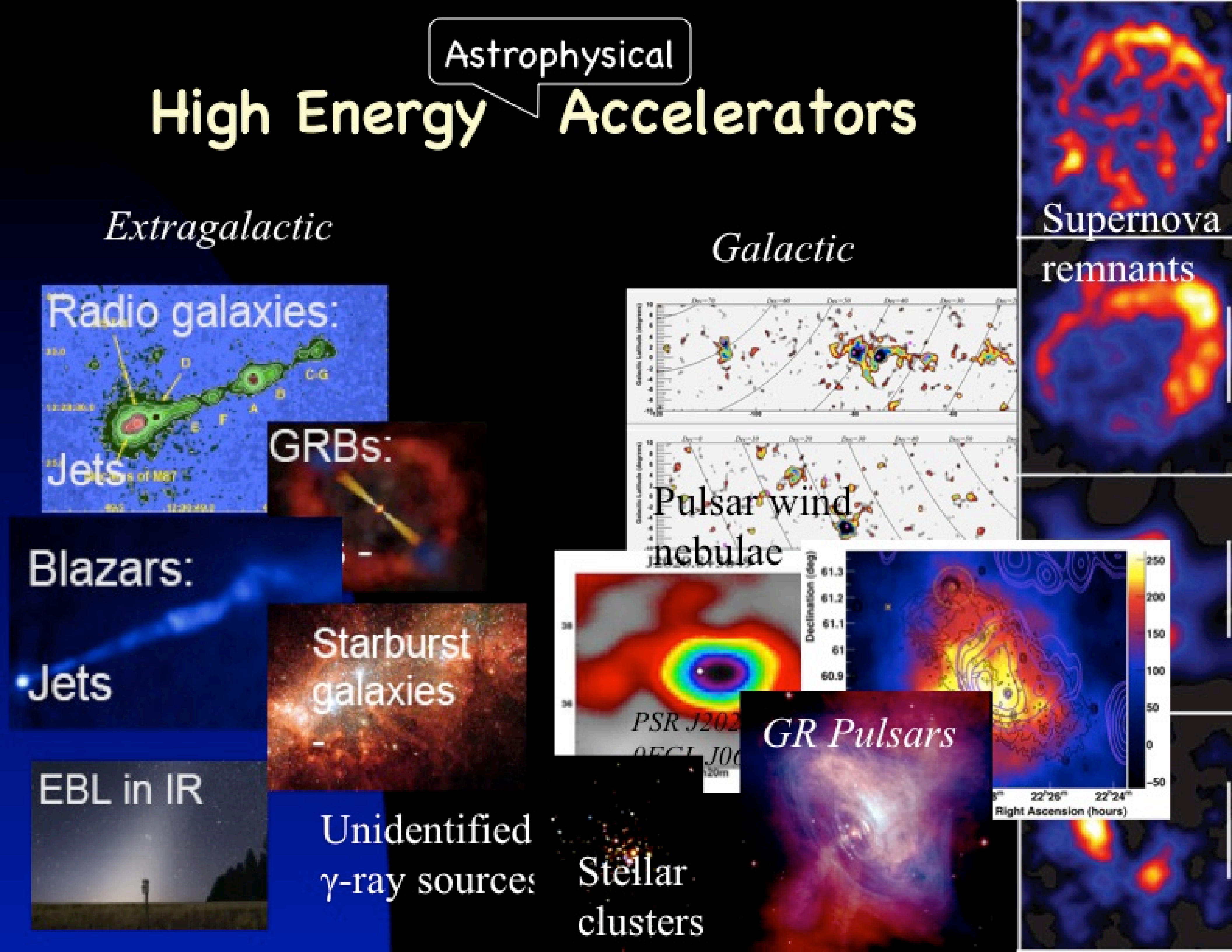
Challenging Accelerators

to reach 10^{20} eV

LHC magnetic field,
radius ~ 10^7 km (Sun - Mercury)

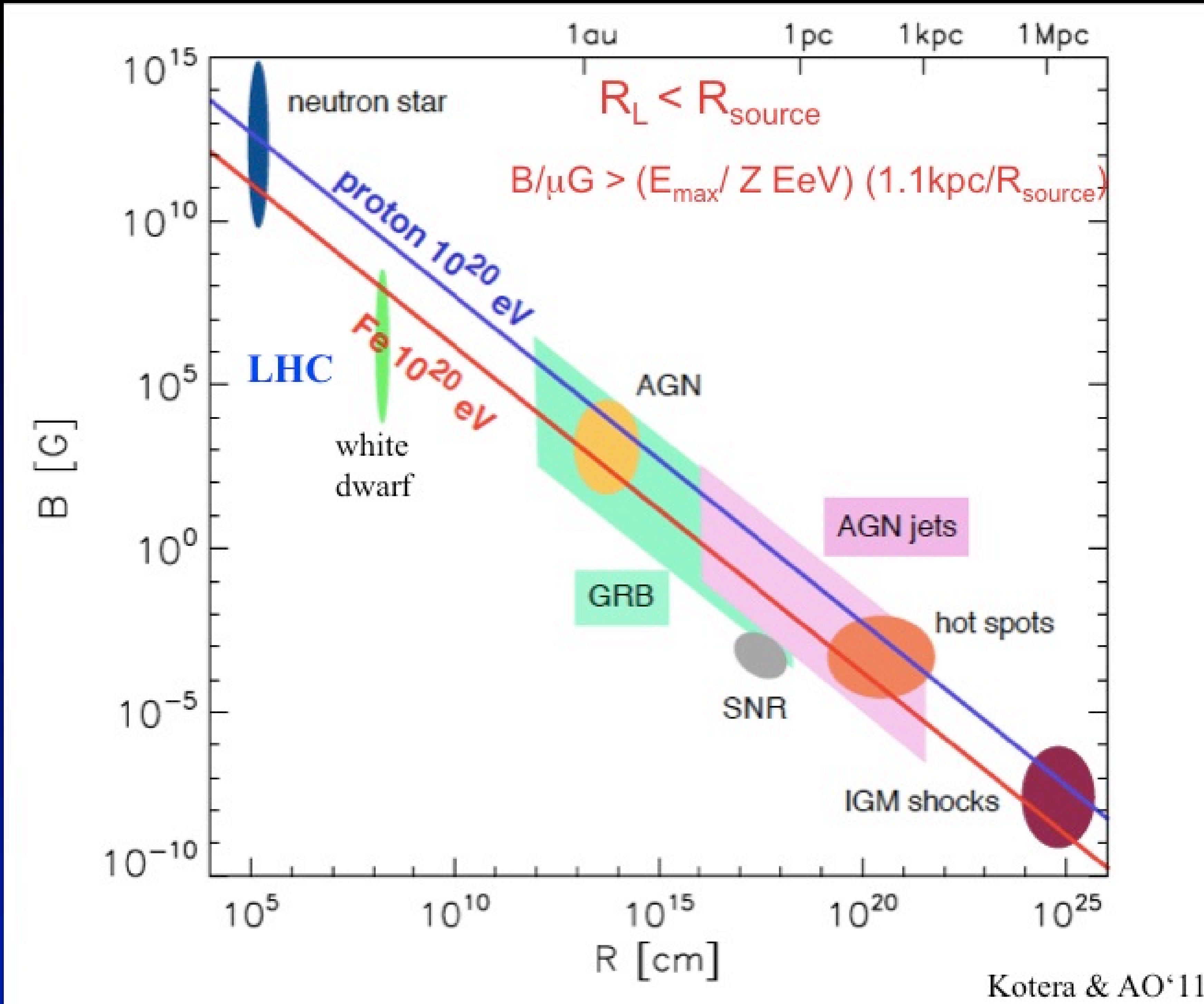
or 10 GT fields!



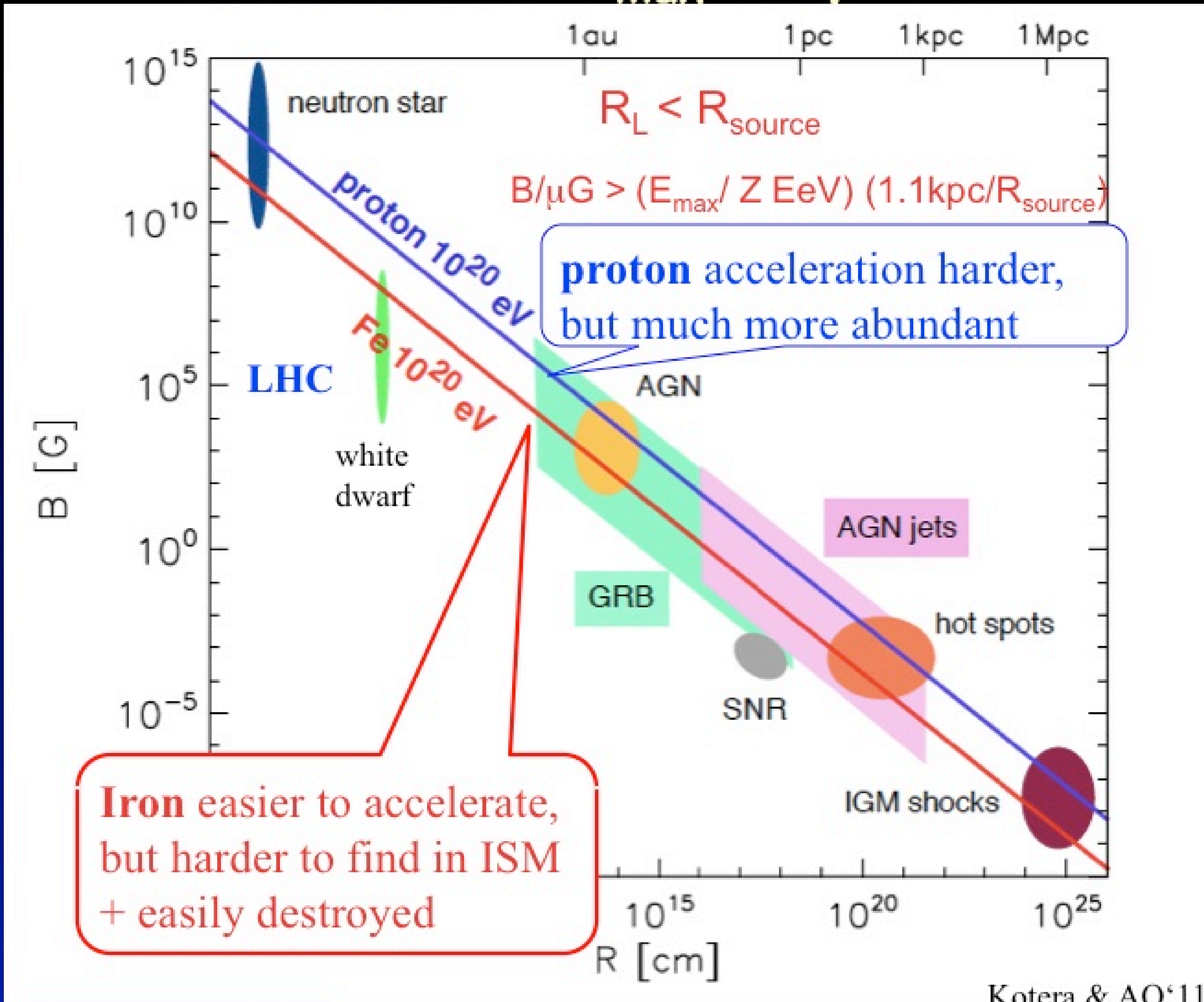


Astrophysical
High Energy Accelerators
Extragalactic
Galactic
Radio galaxies:
Jets
GRBs:
Blazars:
Jets
Starburst galaxies
EBL in IR
Unidentified γ-ray sources
Stellar clusters
Pulsar wind nebulae
GR Pulsars
Supernova remnants
Declination (deg)
Right Ascension (hours)

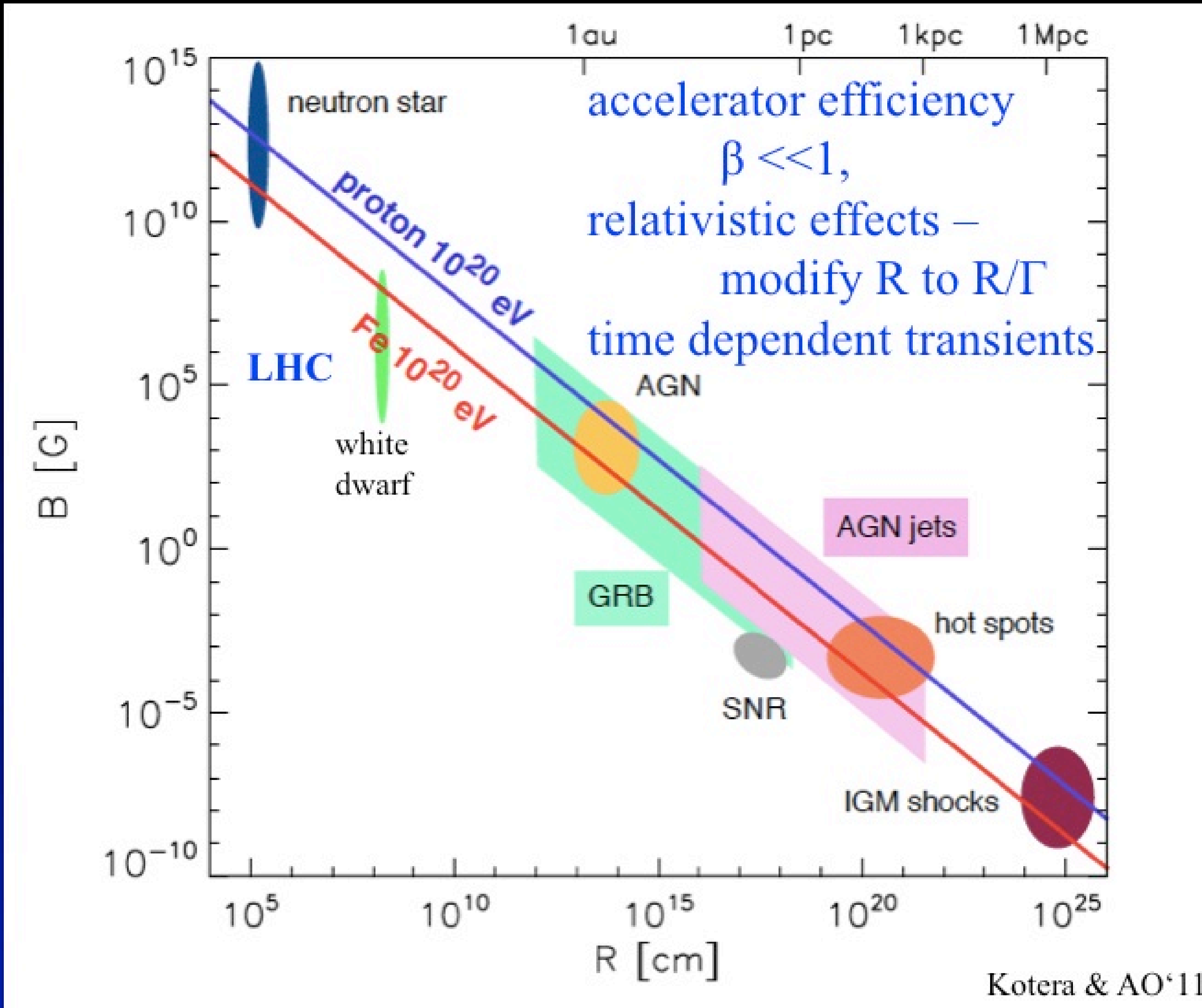
Hillas Plot: E_{max} required



Hillas Plot: E_{max} required



Hillas Plot: E_{max} required



Plausible Sources of UHECRs

1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained.
3. UHE Spectral shape fit ➔ degeneracies.
4. Luminosity-number density relationship
5. E_{max} hard to reach: GRBs, AGN, NSs, IGM shocks,?

E_{max} selects

Inter Galactic Medium Accretion Shocks

Active Galactic Nuclei

Gamma-ray Bursts

Neutron Stars (Magnetars, $B > 10^{14}$ G)

E_{max} selects

IGM shocks: Norman et al. (1995b); Kang et al. (1996, 1997); Miniati et al.(2000); Ryu & Kang (2003); Inoue et al. (2005, 2007); Murase et al. (2008a).

but Vannoni et al. (2009) says E_{max} < few 10^{19} eV

Active Galactic Nuclei

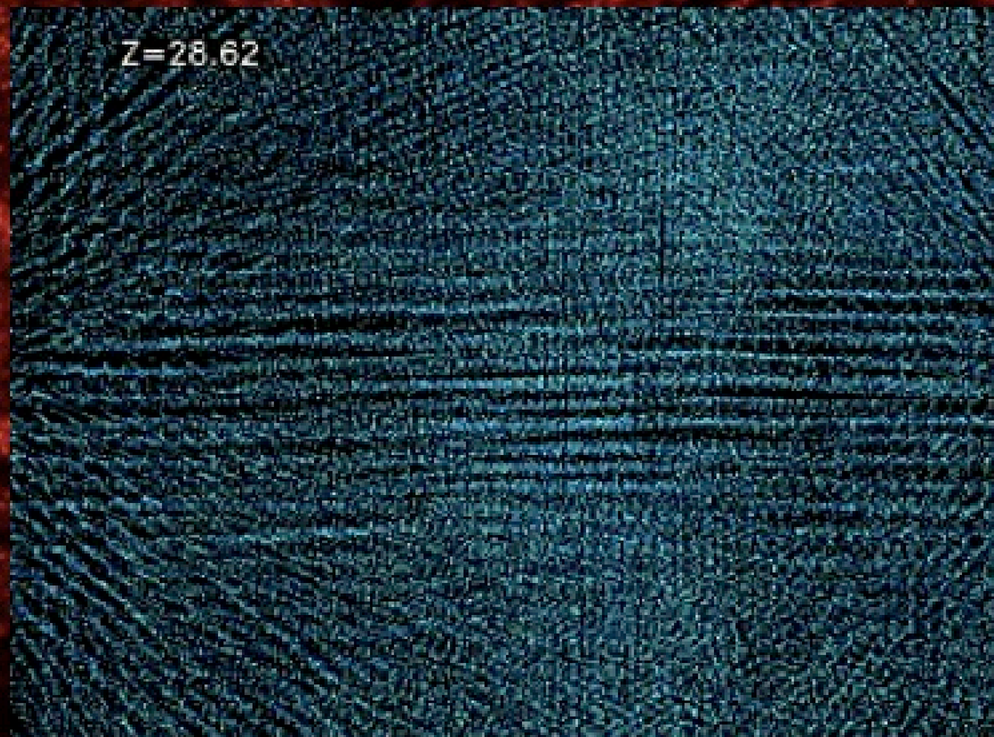
- Central regions – Boldt & Ghosh 1999, but Mannheim 1993, Henri et al. 1999; Rieger & Mannheim 2000 – losses are fatal
- AGN flares – Farrar & Gruzinov 2009
- Hot Spots & Radio Lobes – Rachen & Biermann 1993

Gamma-ray Bursts – Waxman 95, Vietri 95; Gialis & Pelletier 2003; Murase et al 2006, 2008b, Guetta & Piran 2007; Zitouni et al. 2008; Budnik et al. 2008,

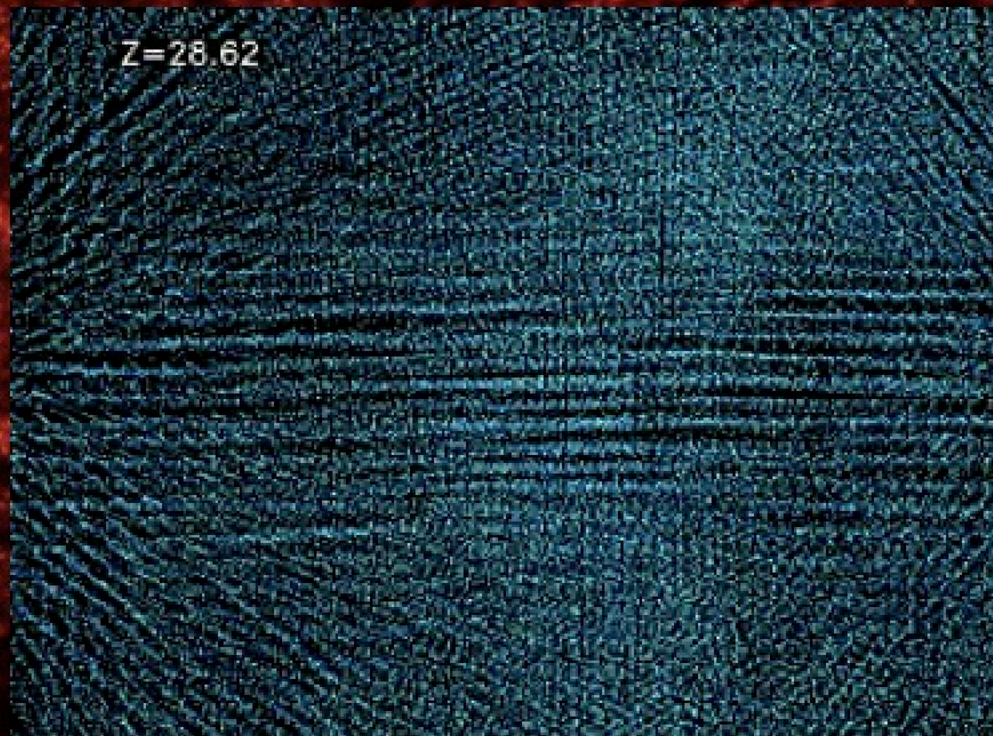
Neutron Stars – Blasi, Epstein, AVO '00, Fang, Kotera, AVO '12

Magnetars – Arons '03,

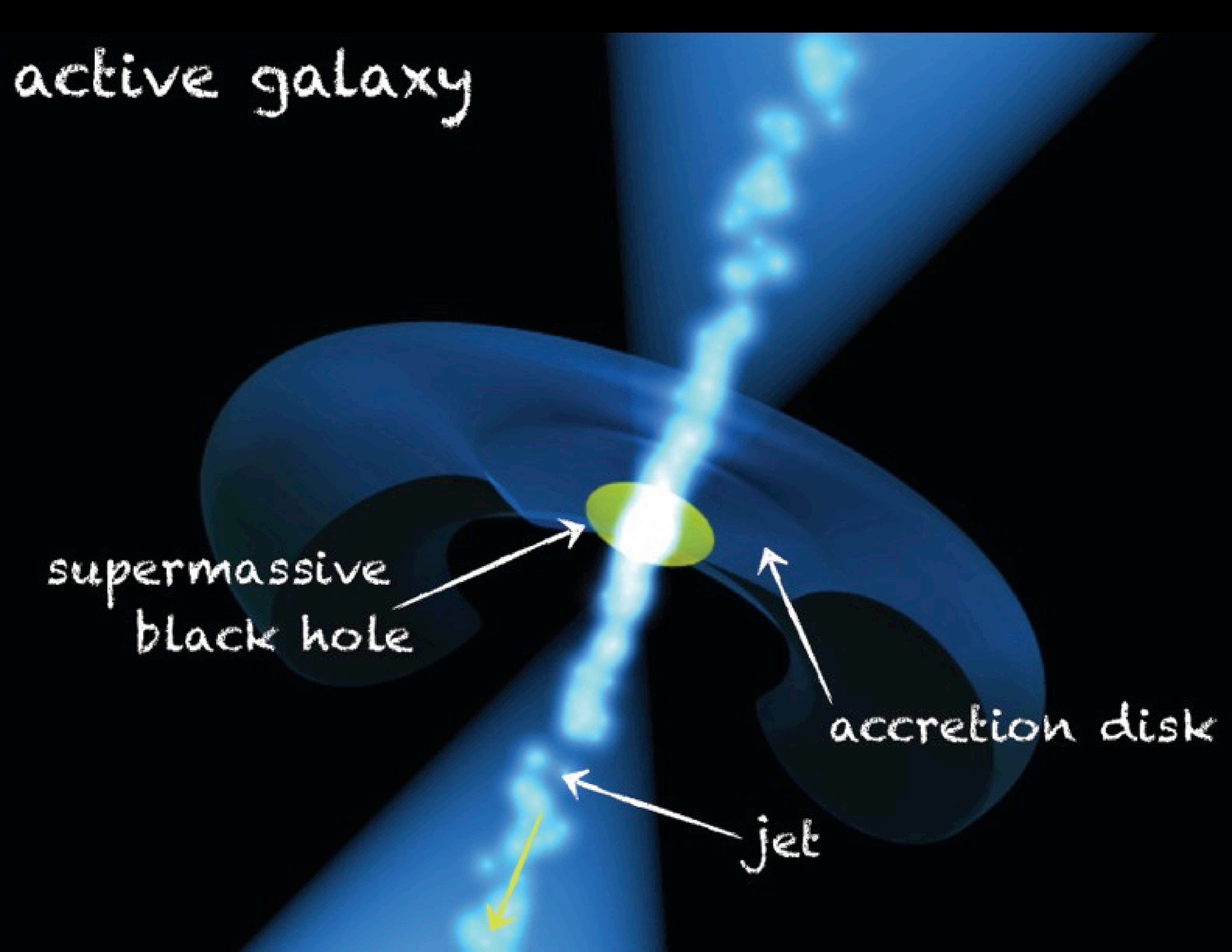
Inter Galactic Medium
Accretion Shocks



Inter Galactic Medium
Accretion Shocks



but Vannoni et al. (2009) says E_{max} < few 10^{19} eV


active galaxy
supermassive black hole
accretion disk
jet

Active Galactic Nuclei

AGN

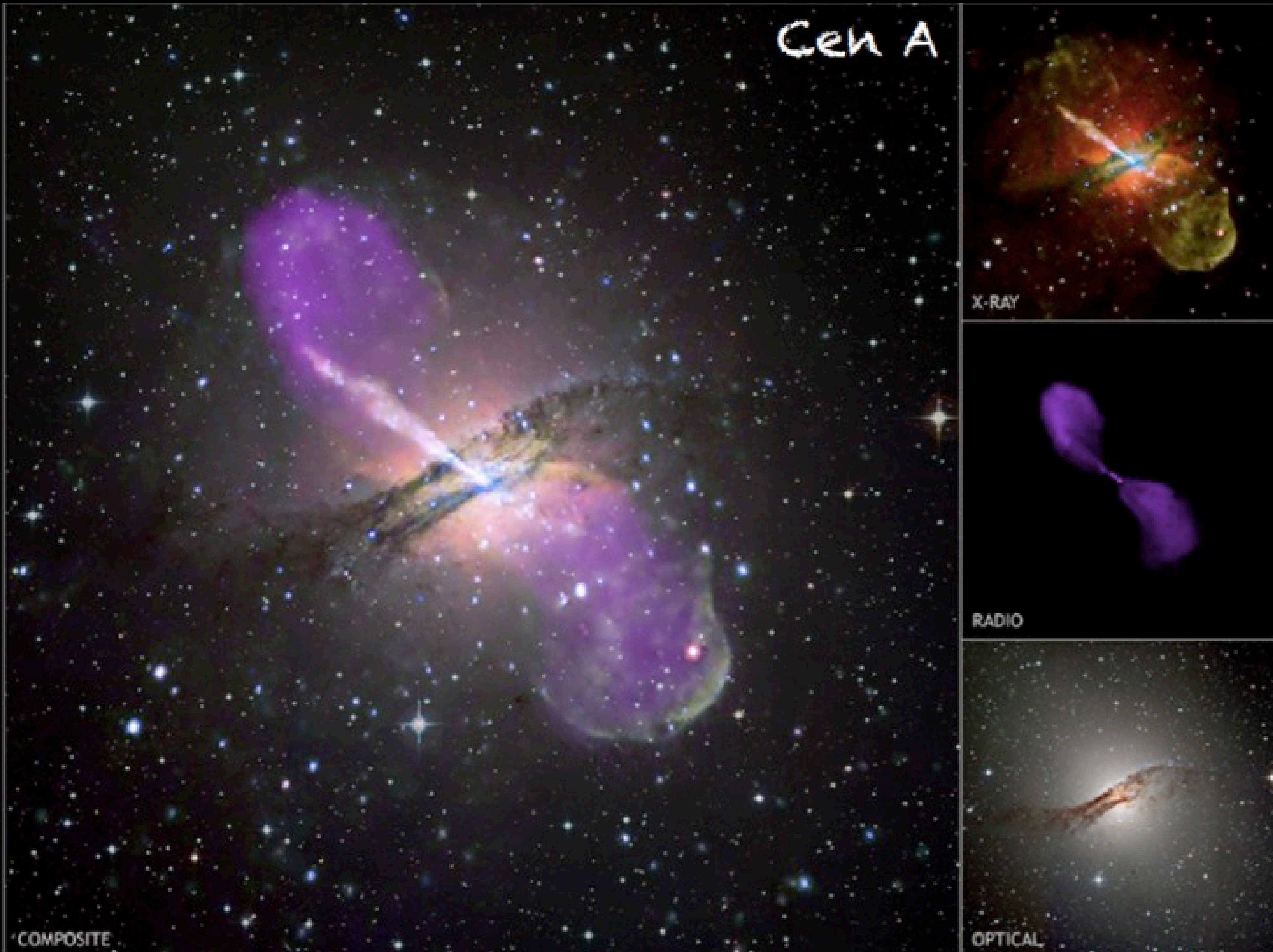
- Central regions - Boldt & Ghosh 1999,

but Mannheim 1993, Henri et al. 1999; Rieger & Mannheim 2000 – losses are fatal

- AGN flares - Farrar & Gruzinov 2009
- Hot Spots & Radio Lobes - Rachen & Biermann 1993

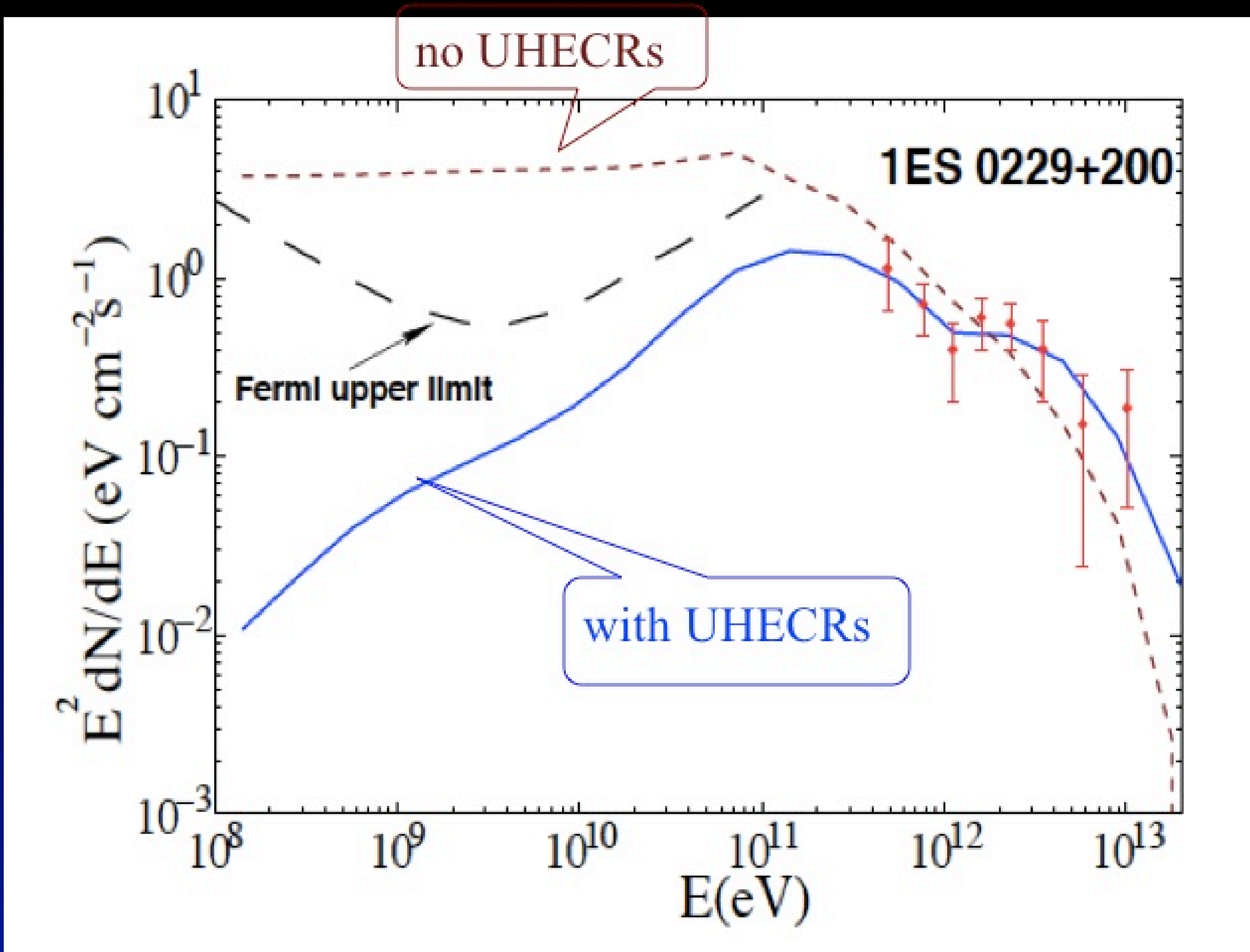
Recent work:

- need for UHECRs in Blazars to explain HE gamma-ray observation



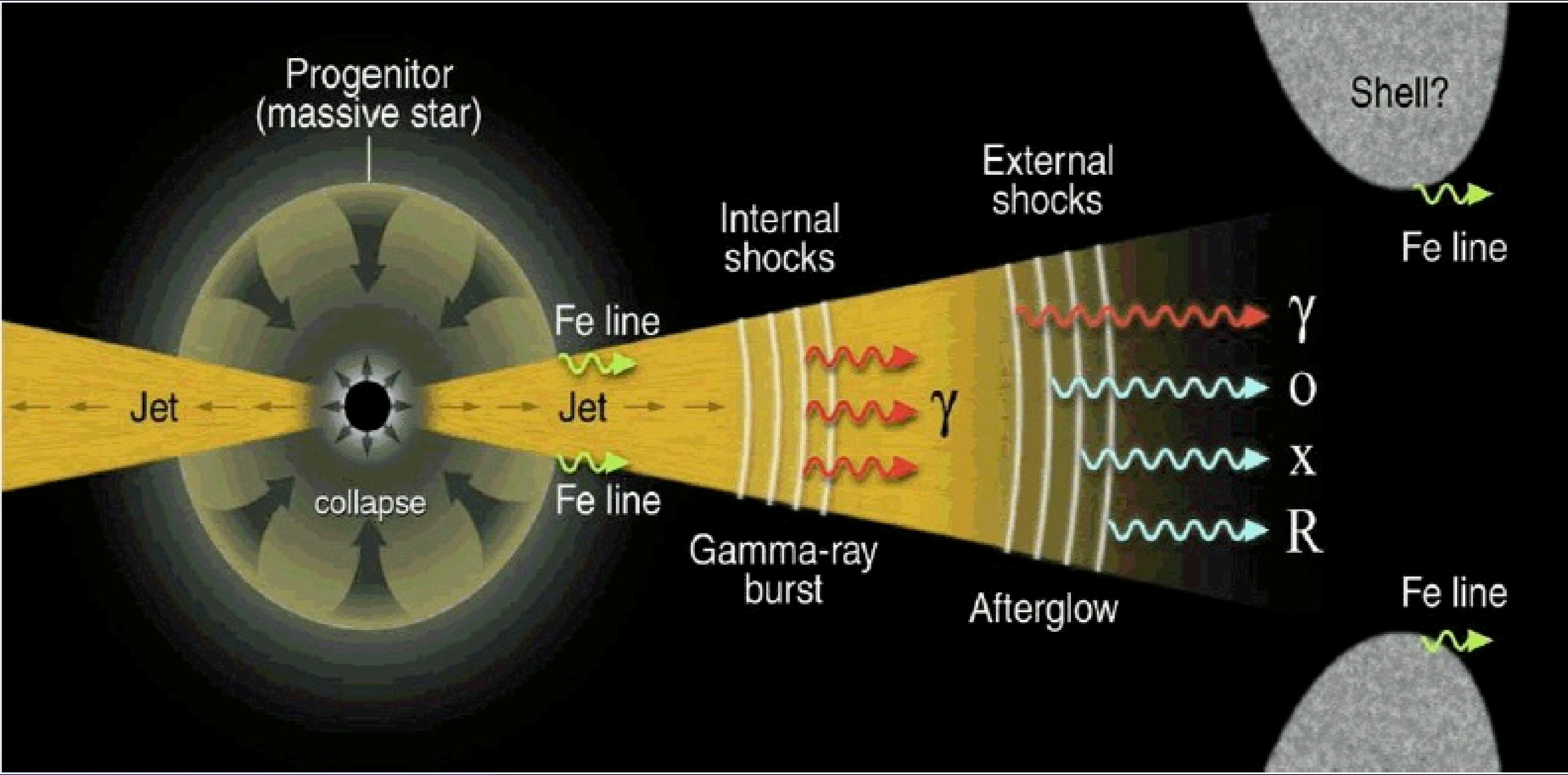
$L_{\rm bol} = 10^{43}$ erg/s $\quad d = 3.4\,\mathrm{Mpc} \quad L_{\gamma > 100\mathrm{MeV}} \approx 10^{41}$ erg/s

Blazars need UHECRs?



Essey et al. 10

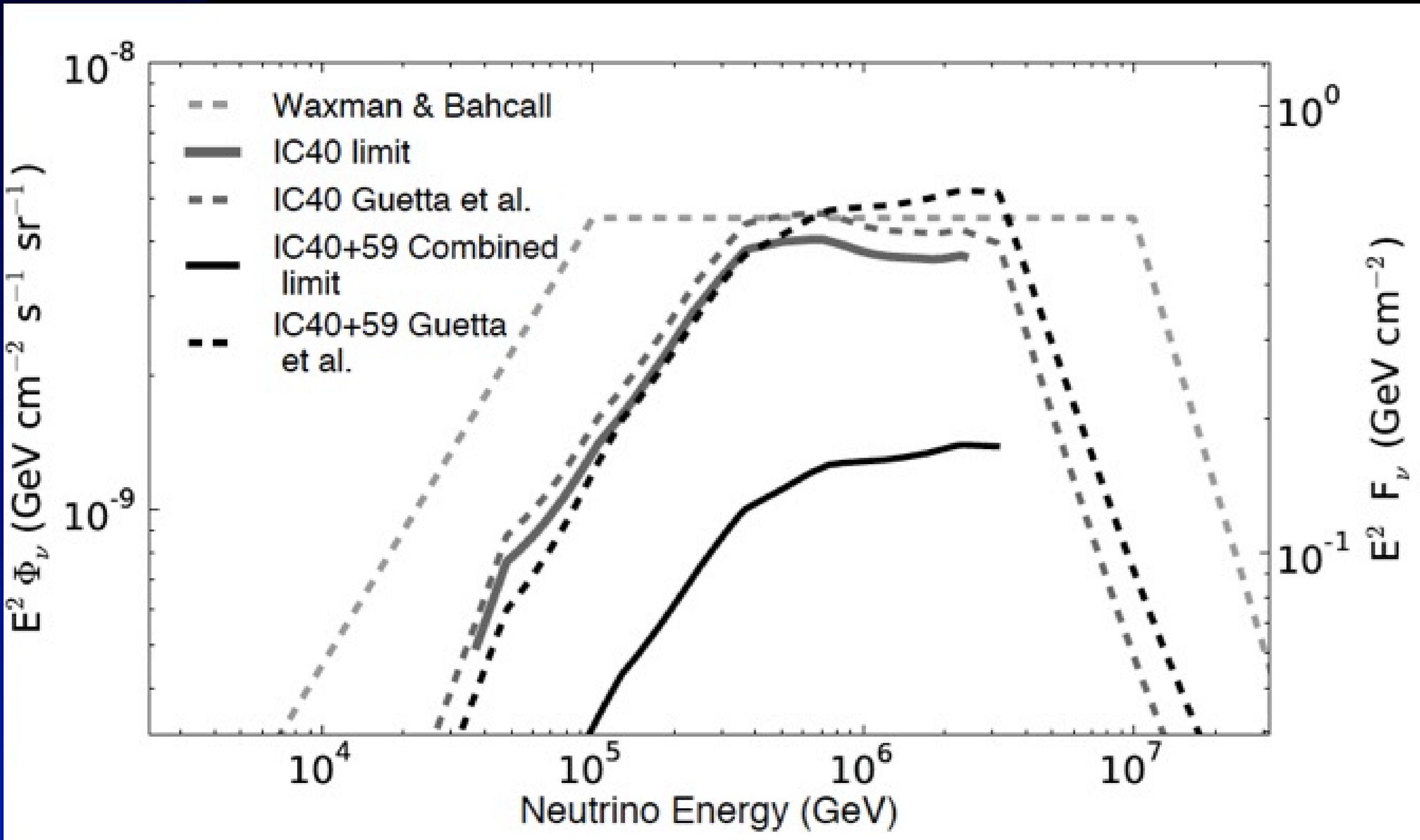
Gamma-ray Bursts



Meszaros '01

HE Neutrino Limits – thus far

- IceCube Nature '12 – constraints on (some)
- Gamma-ray Bursts (GRB) Fireball Models



Young (Ultrafast) Pulsars

Plausible Sources of UHECRs

1. Extragalactic $E > 10^{18}$ eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained.
3. UHE Spectral shape fit → degeneracies.
4. Luminosity-number density relationship
5. E_{max} hard to reach: GRBs, AGN, Young NSs, ?
6. Diffusive Shock Acceleration (DSA) fits well Galactic Cosmic Rays: power-law spectrum $\sim E^{-2}$

GRBs & AGN models mostly based on

Stochastic Shock Acceleration

Fermi 1949

2nd order $\Delta E/E \propto \beta^2$

1st order Fermi $\Delta E/E \propto \beta$

Axford et al. 1977; Bell 1978;
Blandford & Ostriker 1978; ...

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

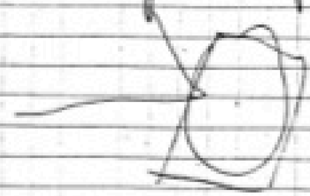
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

Dec 4 1948

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields



Non relativistic case

$$MV^2$$

(M = mass of particle V = velocity of moving field

(Prob: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV+2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision (prob $= \frac{v-V}{2v}$) gives energy gain

$$M(-2vV+2V^2)$$

Average gain order

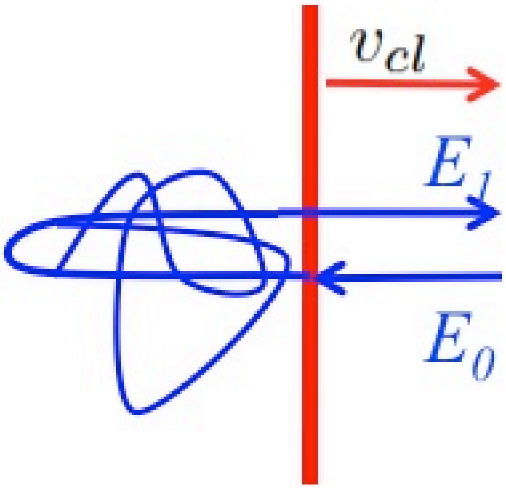
$$MV^2$$

Relativistic: order

$$w\beta^2$$

Fermi: Magnetized Clouds

Transfer of Macroscopic Kinetic Energy to Microscopic Particles



Relativistic Particles $E_0 \simeq p_0$

Non relativistic clouds $\beta_{cl} << 1$

1D version

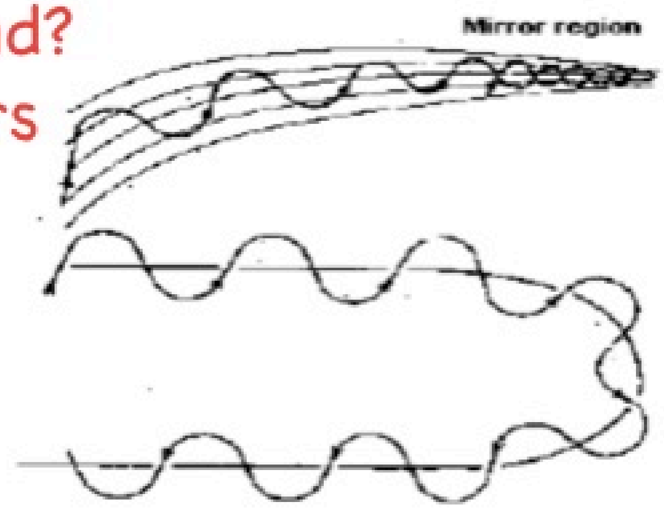
Frame of cloud $E_0^* = \gamma_{cl}(E_0 + \beta_{cl} p_0)$

$$E_1 = \gamma_{cl}(E_0^* + \beta_{cl} p_0^*) = E_0 \;\; \gamma_{cl}^2 (1 + \beta_{cl})^2$$

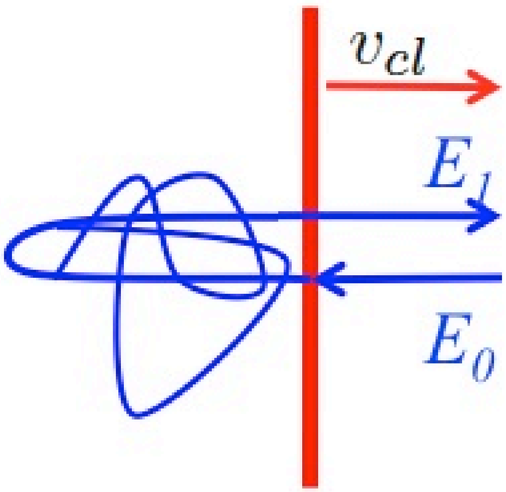
$$\frac{\Delta E}{E} = \frac{E_1 - E_0}{E_0} = \gamma_{cl}^2 (1 + \beta_{cl})^2 - 1 \equiv \xi \sim \beta_{cl}$$

Why turn around?

Magnetic Mirrors



Fermi: Magnetized Clouds



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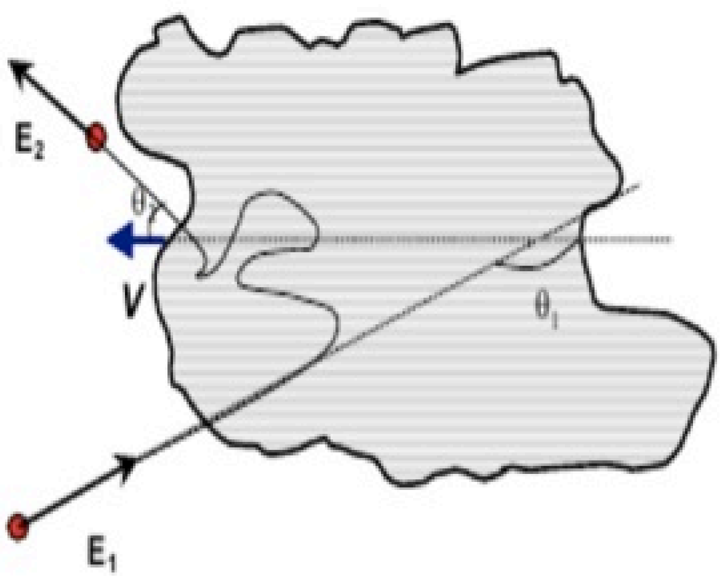
$$\frac{\Delta E}{E} = \frac{E_1 - E_0}{E_0} = \gamma_{cl}^2 (1 + \beta_{cl})^2 - 1 \equiv \xi \sim \beta_{cl}$$

In 2 D can gain or lose energy $E_1 = \gamma^2 E_0 (1 - \beta\cos\theta_1)(1 + \beta\cos\theta_2')$



$$\frac{\Delta E}{E} =$$

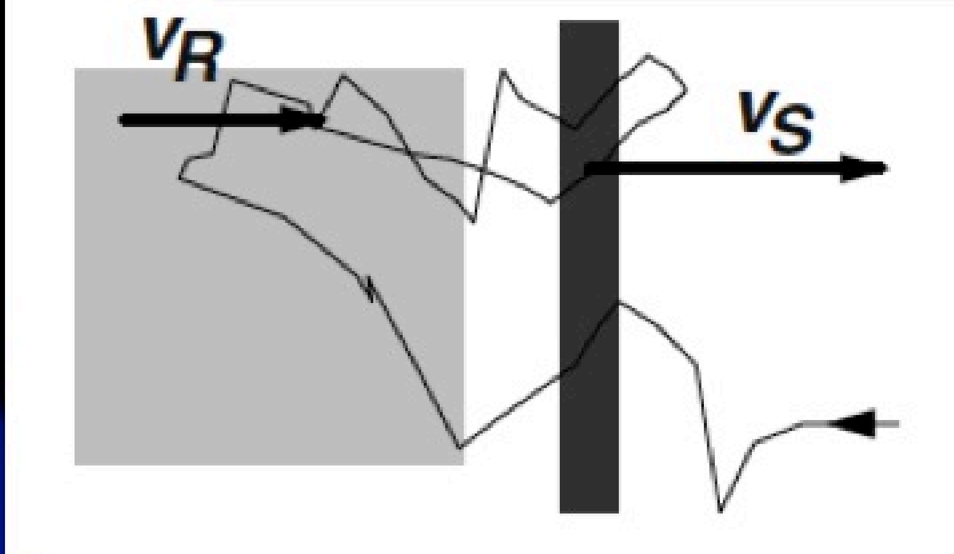
$$-1 + (1 - \beta\cos\theta_1 + \beta\cos\theta_2' - \beta^2\cos\theta_1\cos\theta_2')/1 - \beta^2$$

$$\langle \cos\theta_1 \rangle = -\beta/3 \quad \langle \cos\theta_2 \rangle = 0$$

$$\xi \simeq 4/3\, \beta_{cl}^2 \quad \textit{second order in } \beta_{cl}$$

First Order Fermi: shock acceleration

$$\frac{\Delta E}{E} = -1 + (1 + 4\beta/3 + 4\beta^2/9)\ /1-\beta^2 \approx 4\beta/3$$

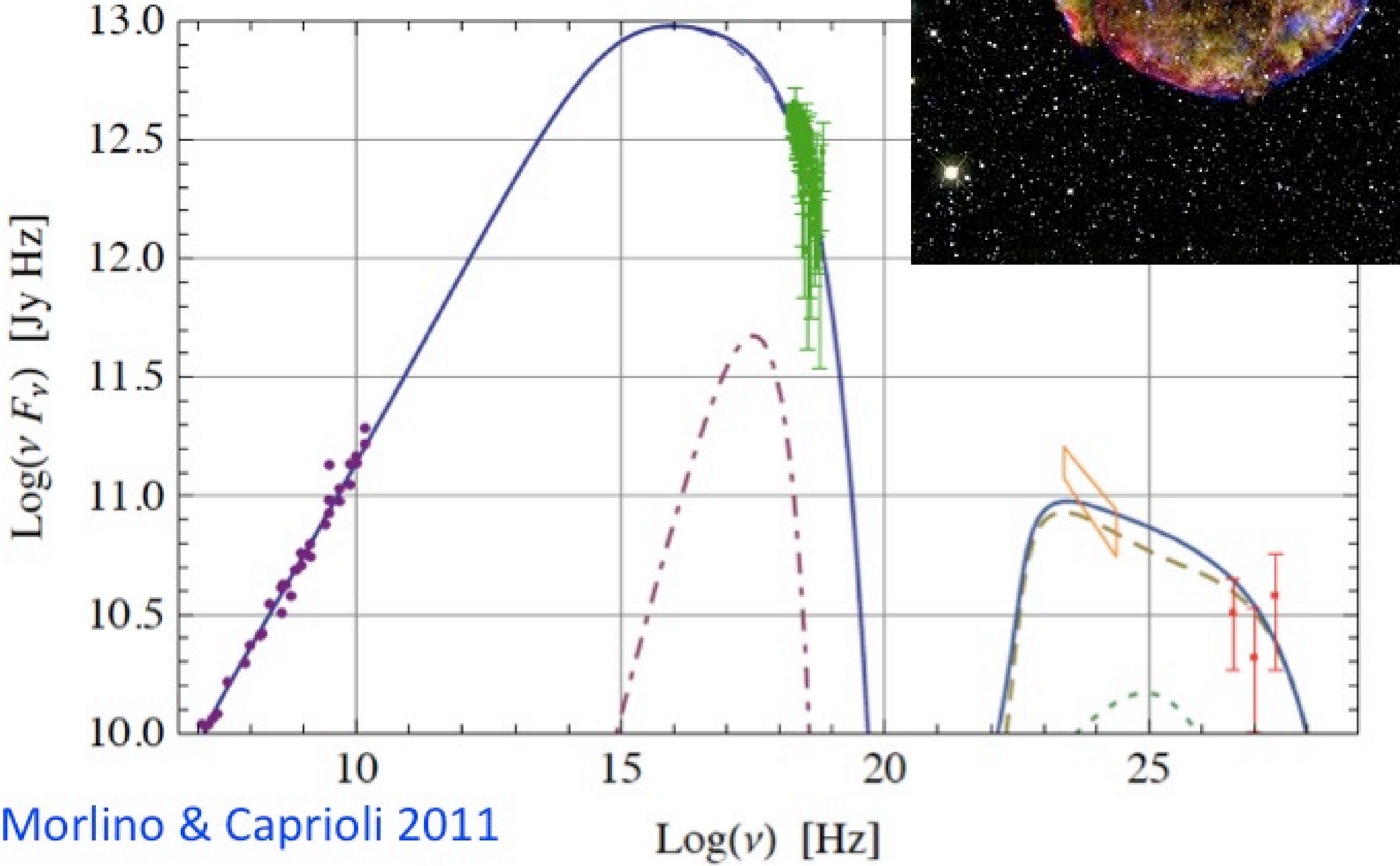


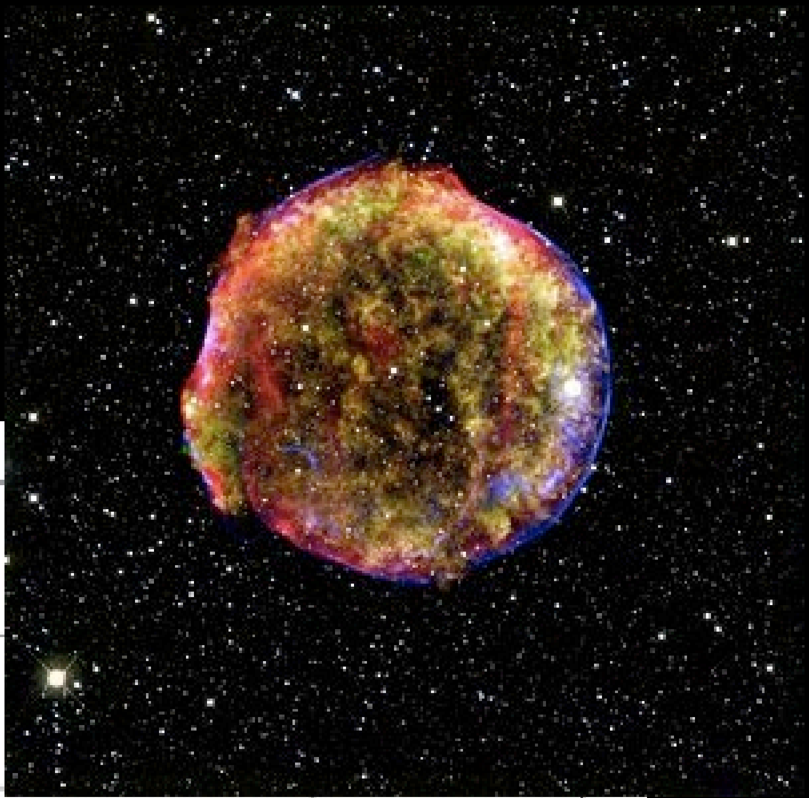
β_{shock} β_{shock}

success for **Galactic Cosmic Ray** acceleration in Supernova Remnants Sedov-Taylor phase

Galactic Cosmic Ray

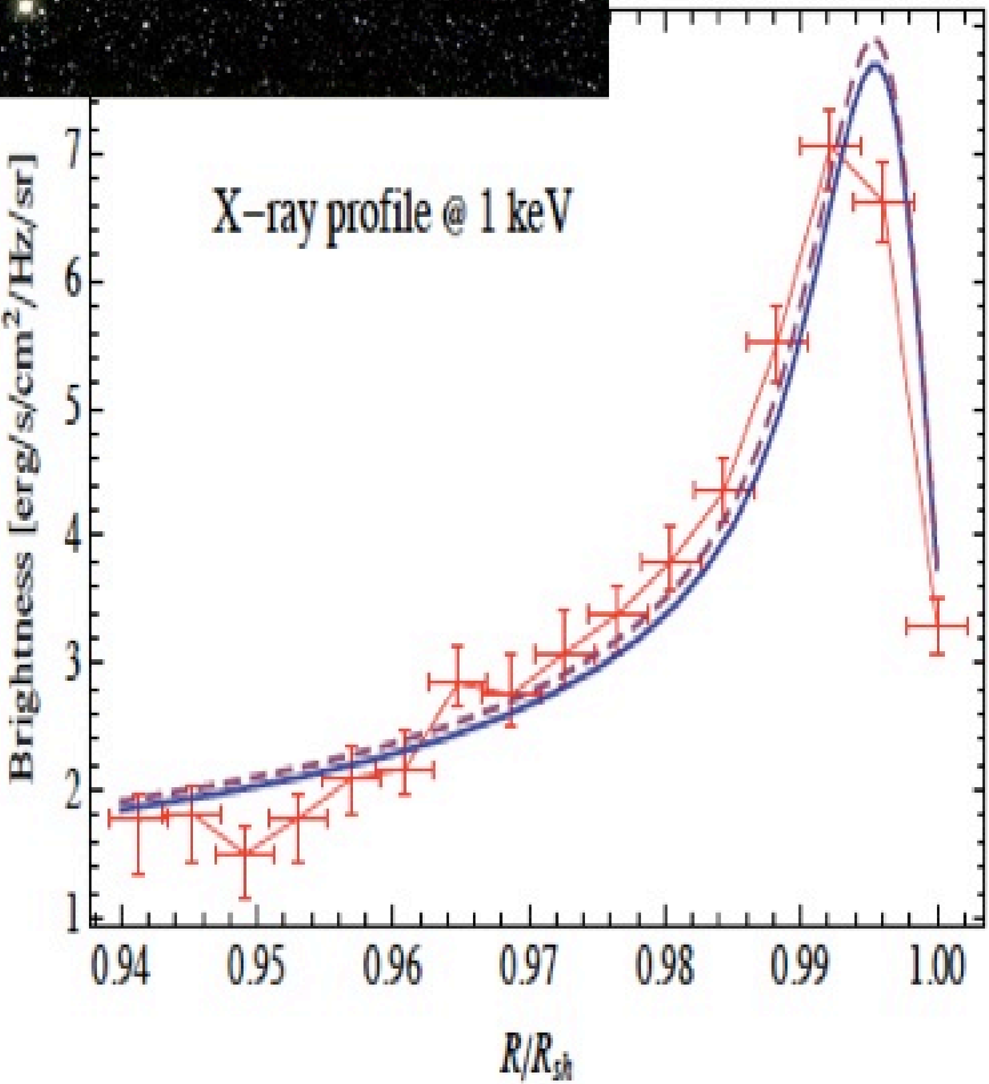
TYCHO SNR – SN 1572

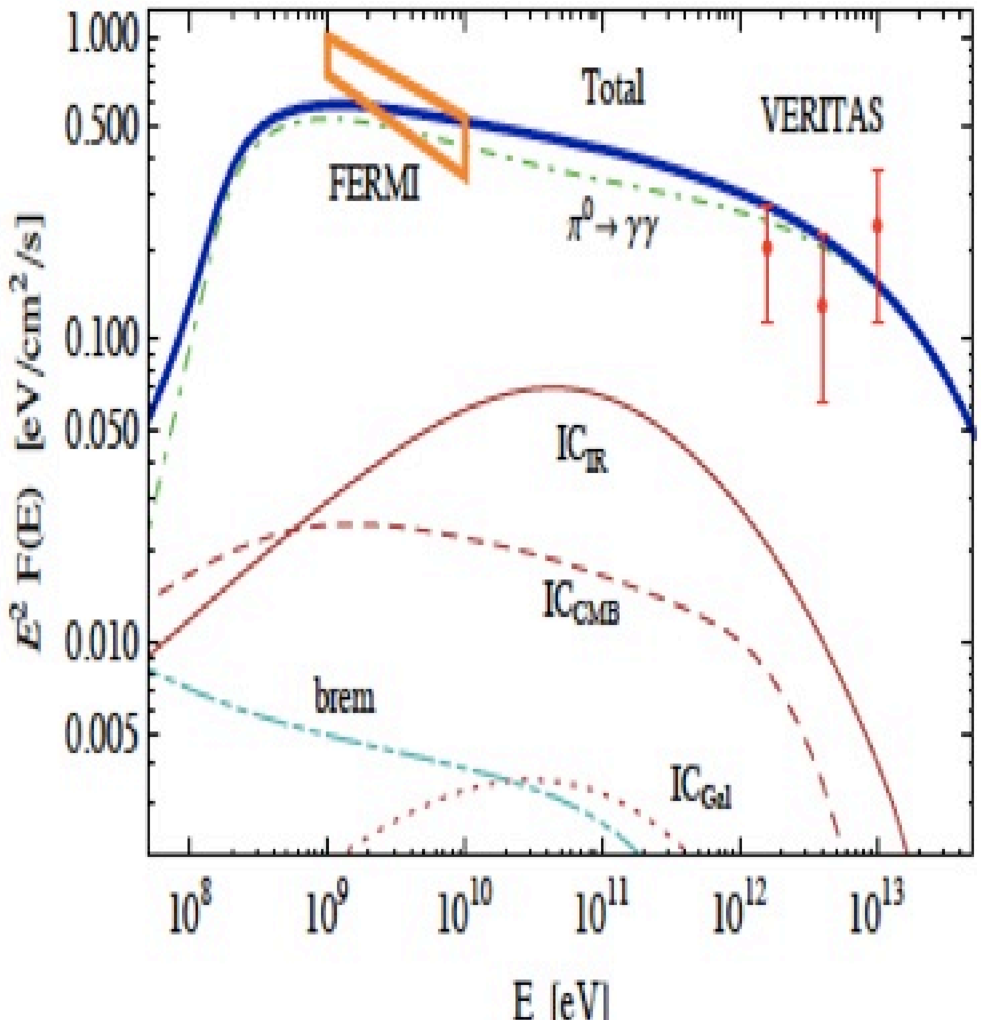




Morlino & Caprioli 2011

TYCHO: SMOKING GUN?





Power Law Spectrum

$$\frac{\Delta E}{E} \equiv \xi$$ independent of energy ($\xi \simeq 4/3\,\beta_{cl}^2$ or β_{cl})

After n cycles (encounters)

$$E_n = E_0(1+\xi)^n \qquad n = \ln\left(\frac{E_n}{E_0}\right)/\ln(1+\xi)$$

P_{esc} probability of escape *in each cycle*
Number of particles that reach E >E_n :

$$N(>E_n) = N_0 \sum_n^{\infty} (1-P_{esc})^m \propto A\left(\frac{E_n}{E_0}\right)^{-\gamma} \qquad \gamma \simeq P_{esc}/\xi$$

Shock Acceleration $$P_{esc} = \frac{\rho_{CR} u_2}{c\rho_{CR}/4} = \frac{4u_2}{c}$$

$$\gamma = \frac{P_{esc}}{\xi} = \frac{3}{u_1/u_2 - 1} \sim 1 + O(M^{-2})$$

$$dN/dE \sim E^{-(2 + O(1/M^2))}$$

Power Law Spectrum

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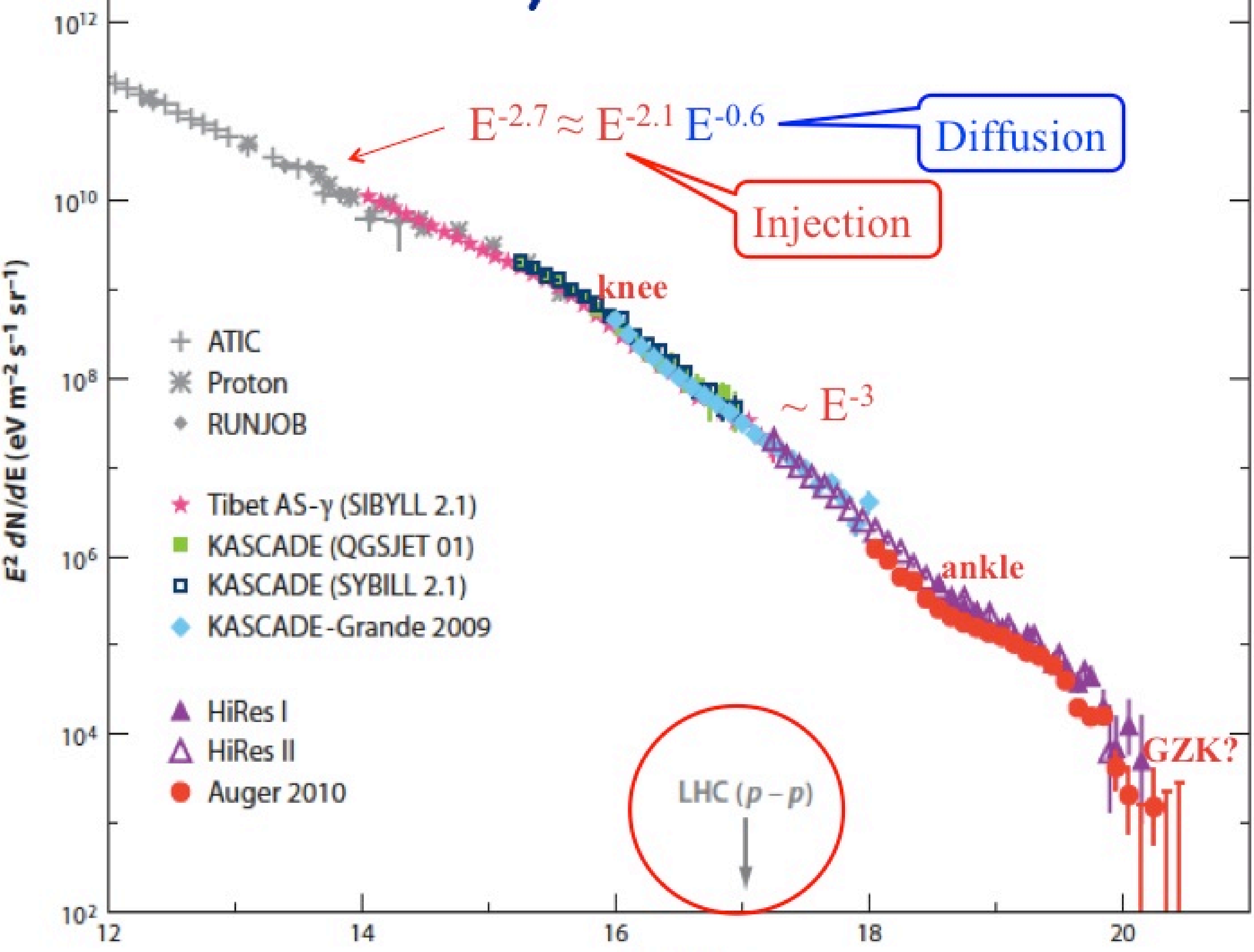
$$\gamma = \frac{P_{esc}}{\xi} = \frac{3}{u_1/u_2 - 1} \sim 1 + O(M^{-2})$$

Success!!

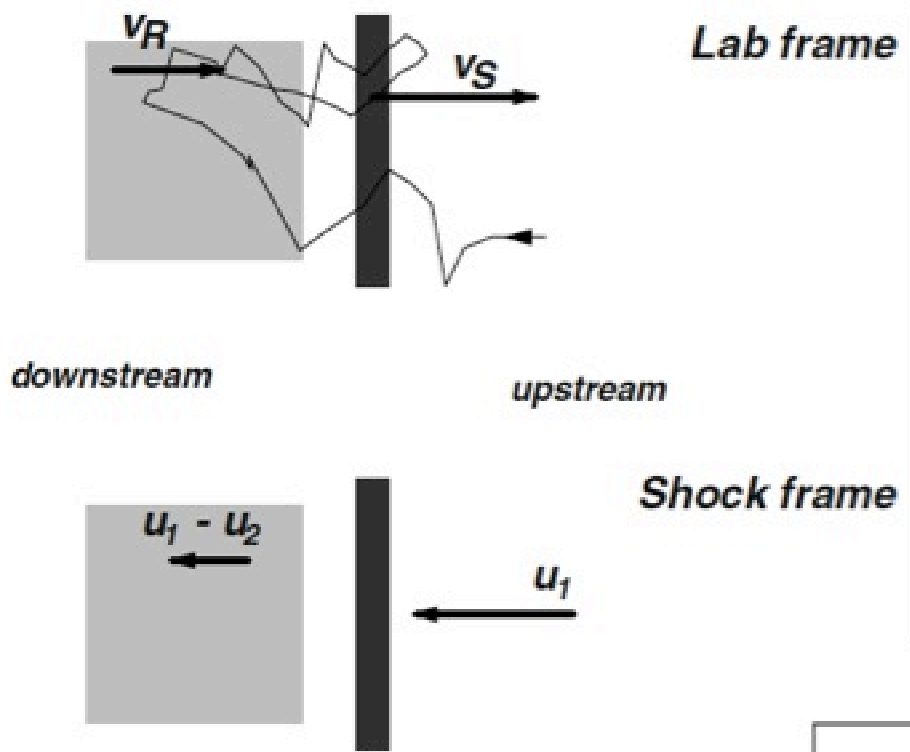
$dN/dE \sim E^{-(2 + O(1/M^2))}$

Cosmic Ray Flux x E²

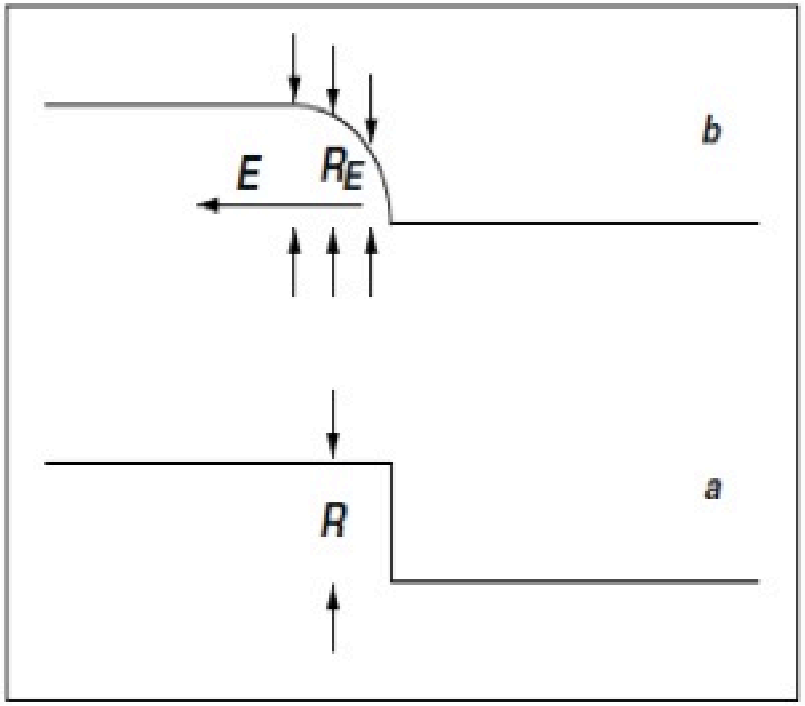


Kotera, AO 2011

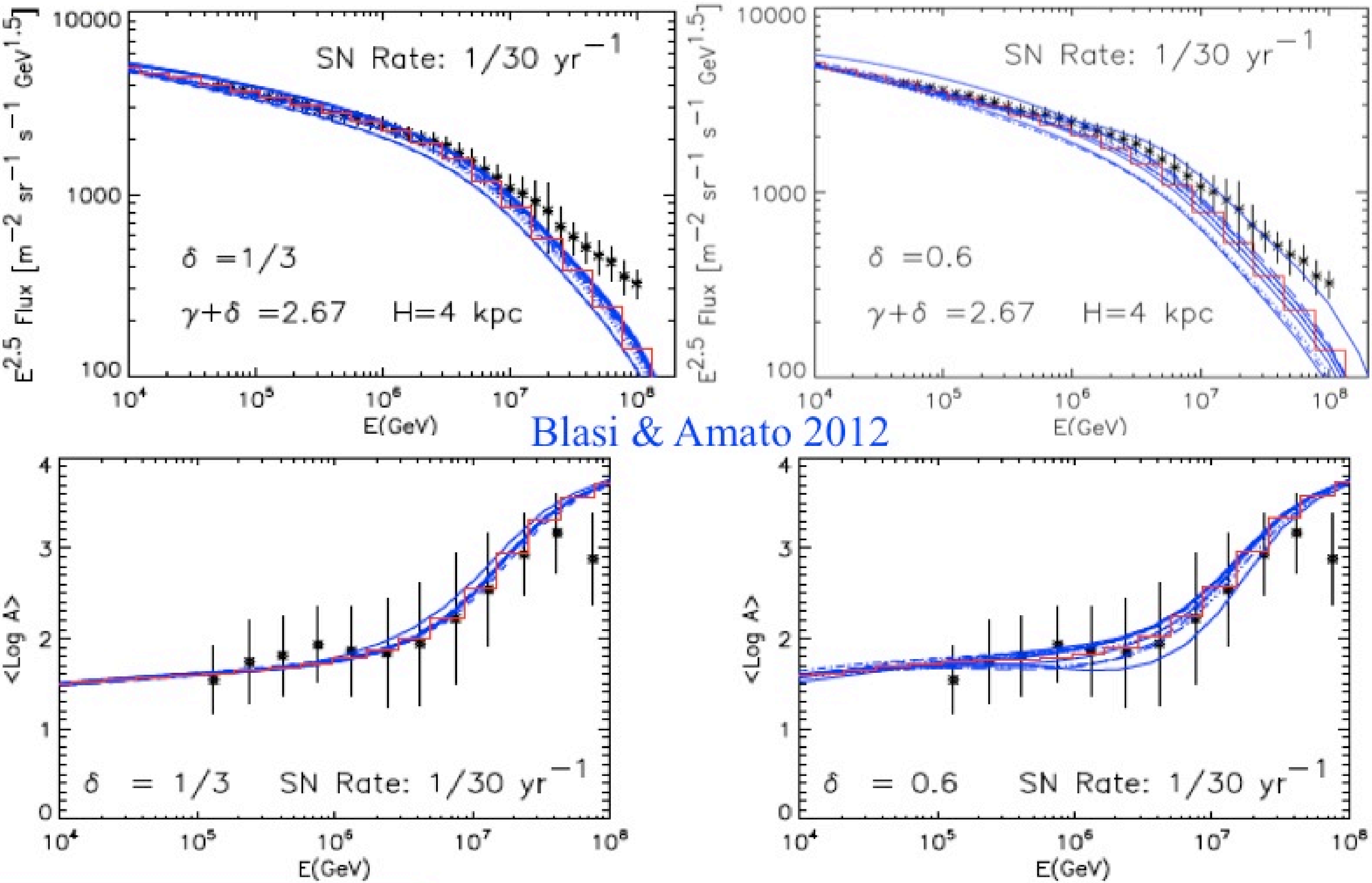
Stochastic Shock Acceleration



Non-linear effects:
backreaction of particles
on magnetic field



The SNR paradigm: Acceleration + Diffudion



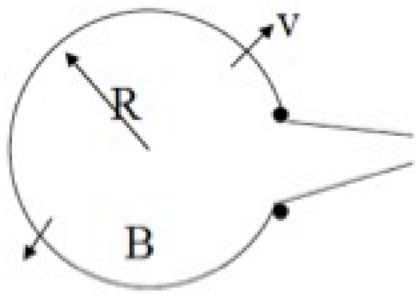
Blasi & Amato 2012

Plausible Sources of UHECRs

1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained.
3. UHE Spectral shape fit ➔ degeneracies.
4. Luminosity-number density relationship
5. E_{max} hard to reach: GRBs, AGN, Young NSs, ?
6. Diffusive Shock Acceleration (DSA) fits well Galactic Cosmic Rays: power-law spectrum ~ E^{-2}
7. Extension to Relativistic Shocks in AGN & GRBs

Lower bound on Luminosity

Norman et al. 1995, Waxman 1995, Lyutikov & Ouyed 2005, Waxman 2005, Lemoine Waxman 2009, see Waxman arXiv:1101.1155



$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/v} = \beta BR$$

FIG. 7: Potential drop generated by an unsteady outflow of magnetized plasma.

$$L > \frac{\Gamma^2}{\beta}\left(\frac{E}{e}\right)^2 c = 10^{45.5}\frac{\Gamma^2}{\beta}\left(\frac{E}{10^{20}\mathrm{eV}}\right)^2 \mathrm{erg/s}.$$

$$\Gamma > 10^2\left(\frac{E}{10^{20}\mathrm{eV}}\right)^{3/4}\left(\frac{\delta t}{10\mathrm{ms}}\right)^{-1/4}$$

Very high luminosity, Relativistic flows, transient time-scales

No known (steady) sources of 10^{46} erg/s within 100 Mpc!

assuming protons

Plausible Sources of UHECRs

1. Extragalactic $E > 10^{18}$ eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained. composition is important.
3. Very few astrophysical sources can reach E_{max} GRBs, AGN, Young NSs, ?
4. Most acceleration models based on 1st order Fermi Acceleration : spectrum E^{-2}
5. UHECR sources have large Luminosity
6. Challenges for Relativistic Shocks
7. Alternative scenarios: unipolar inductors; wake field acceleration; relativistic shear jet acceleration, ...

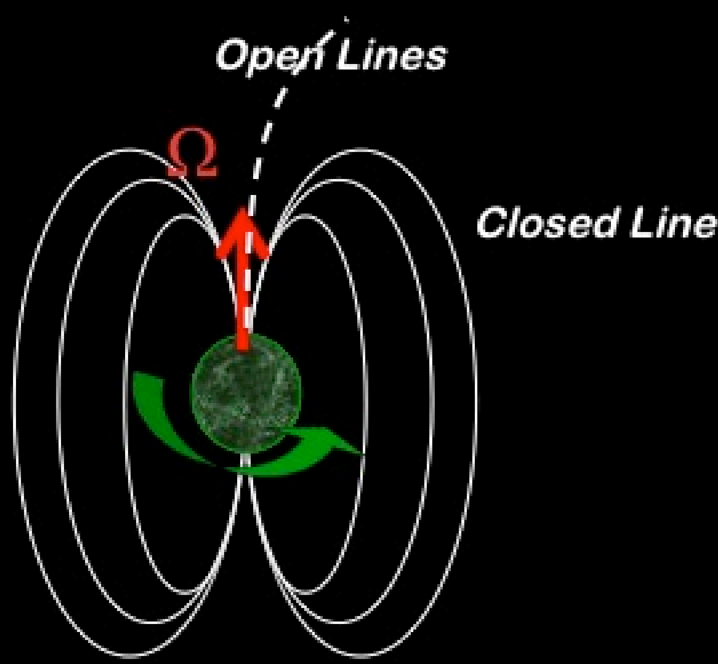
Example:

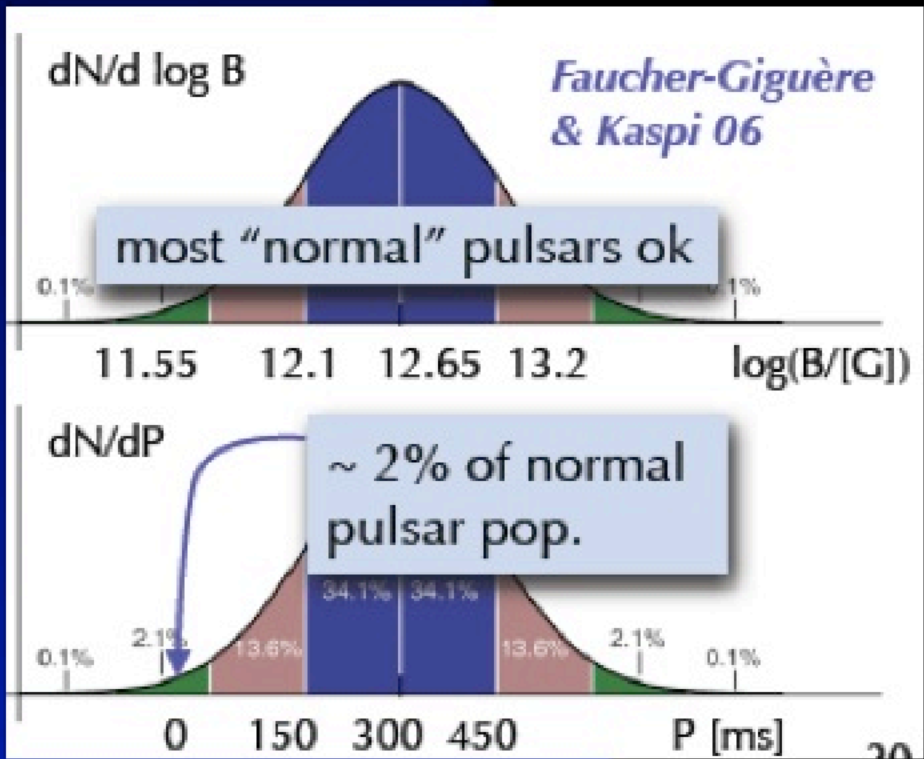
Birth of ultrafast spinning

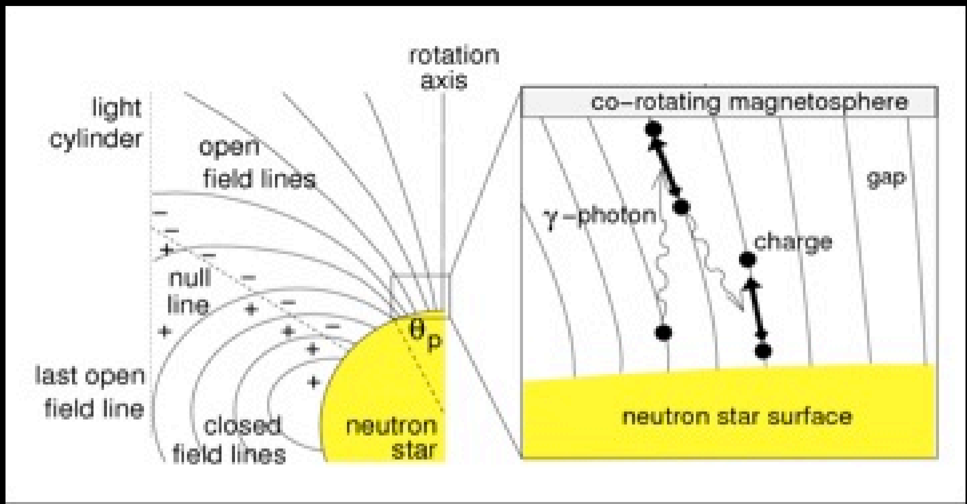
Pulsars

Young Neutron Stars & Magnetars

$M \sim 1\ M_{solar}$ $R \sim 10$km compact stars
Born Fast spinning <P> ~ 300 ms
– slows down due to magnetic breaking
(and gravitational radiation early one)
Born $B \sim 10^{12\text{-}13}$ G







Blasi, Epstein & AVO '00, Arons '03

Ex: Birth of ultrafast spinning Pulsars

Newborn Pulsar with: $B_S \equiv 10^{13} B_{13}$ G $\quad Z_{26} \equiv Z/26 \quad \Omega_{3k} \equiv \Omega/3000$ rad s^{-1}

At the light cylinder: $R_{\rm lc} = 10^7 \Omega_{3k}^{-1}$ cm $\qquad n_{\rm GJ} = 1.7 \times 10^{11} B_{13} \Omega_{3k}^4 / Z$ cm^{-3}

Magnetic wind can accelerate particles up to $\qquad E_{\rm cr} \simeq B_{\rm lc}^2 / 8\pi n_{\rm GJ}$

$$E_{\rm max} = \frac{Ze\, B_{\rm lc} R_{\rm lc}}{c} \simeq 8 \times 10^{20} Z_{26} B_{13} \Omega_{3k}^2 \text{ eV}$$

$$E_{\rm cr} \simeq 4 \times 10^{20} Z_{26} B_{13} \Omega_{3k}^2 \text{ eV}$$

Maximum Energy? ✔

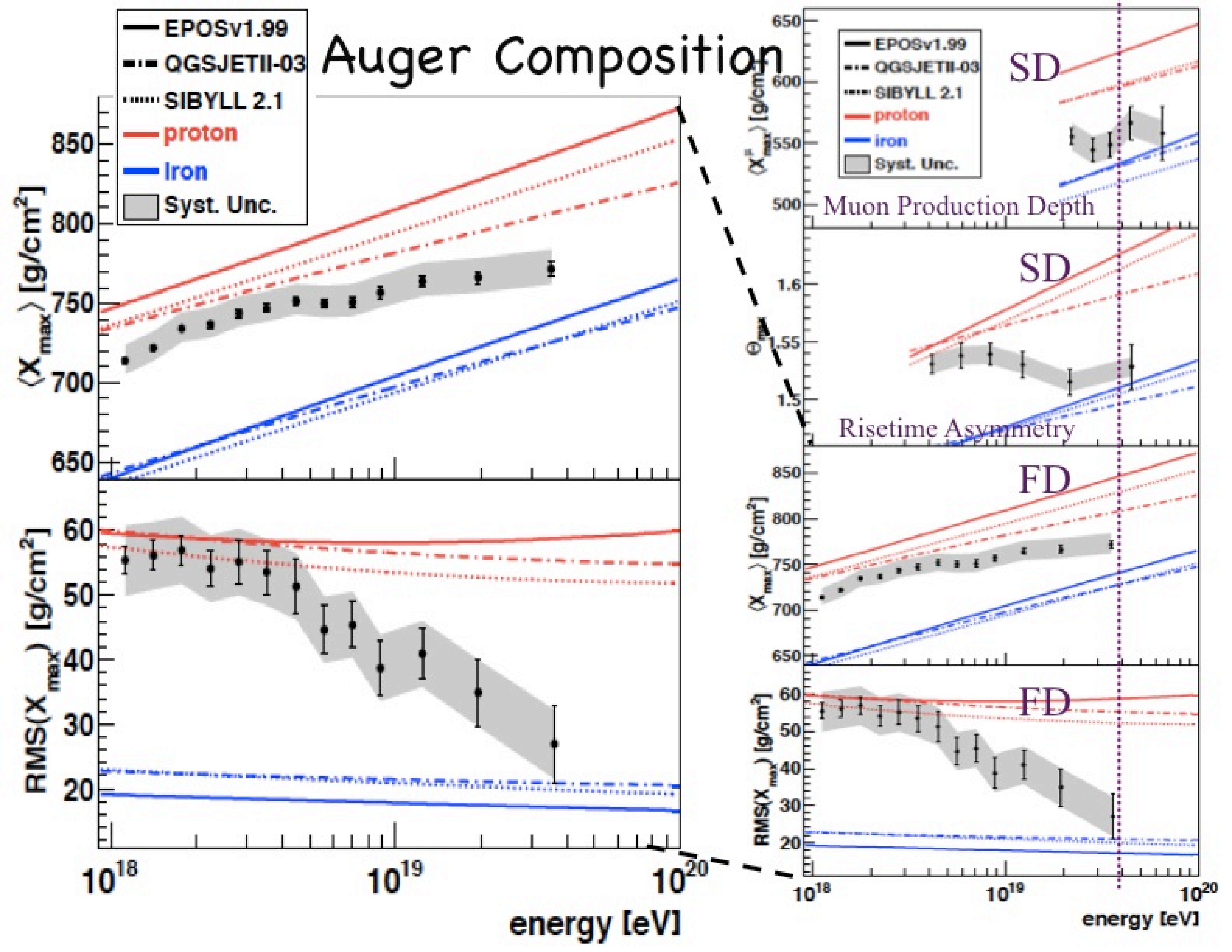
Spectrum too hard:

The predicted UHECR flux at the Earth is

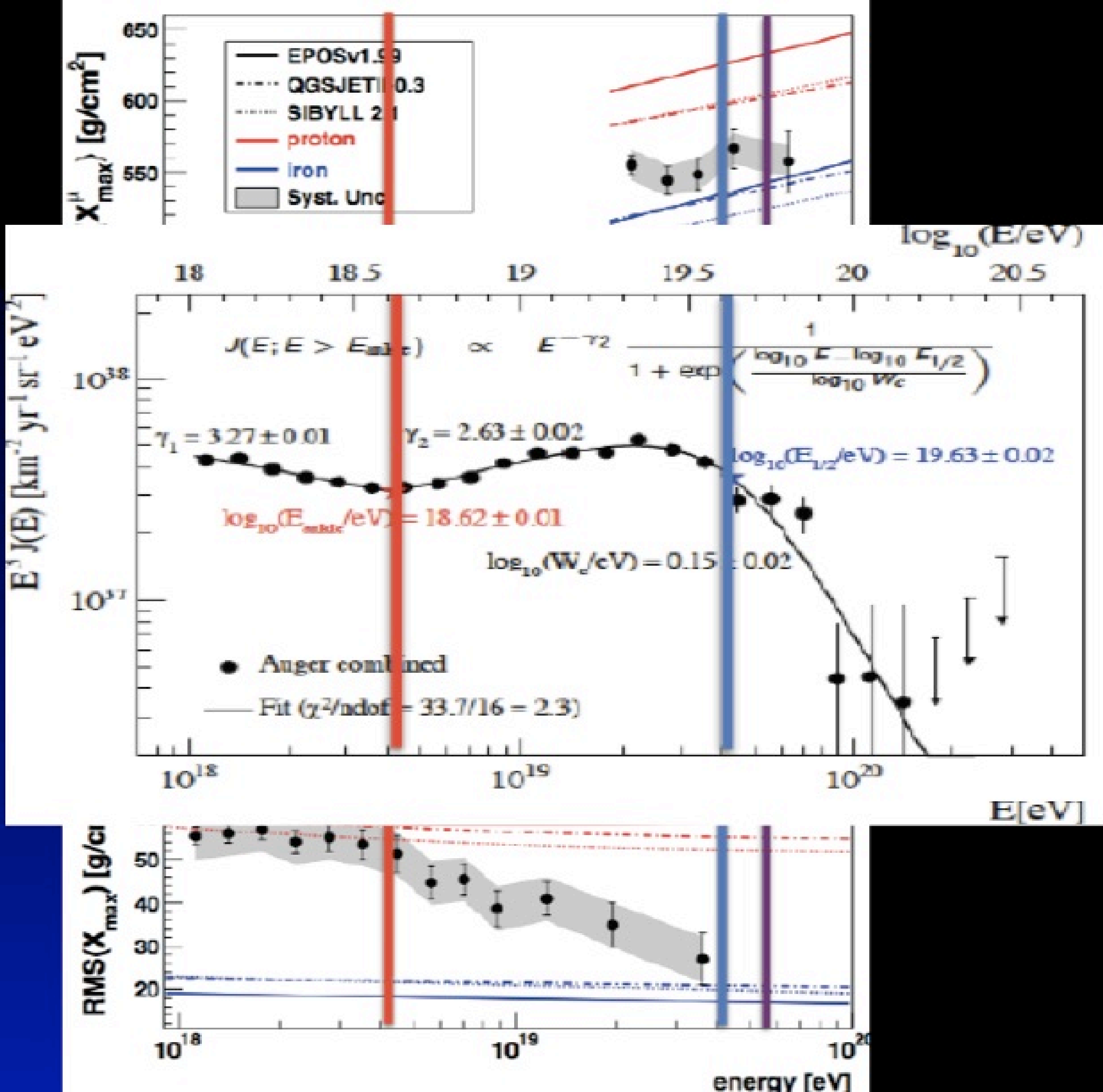
$$F(E) = 10^{-24} \frac{\xi \epsilon Q}{\tau_2 R_1^2 B_{13} E_{20} Z_{26}} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

Spectrum is too hard ~ E^{-1}

Blasi, Epstein, AVO ‘00

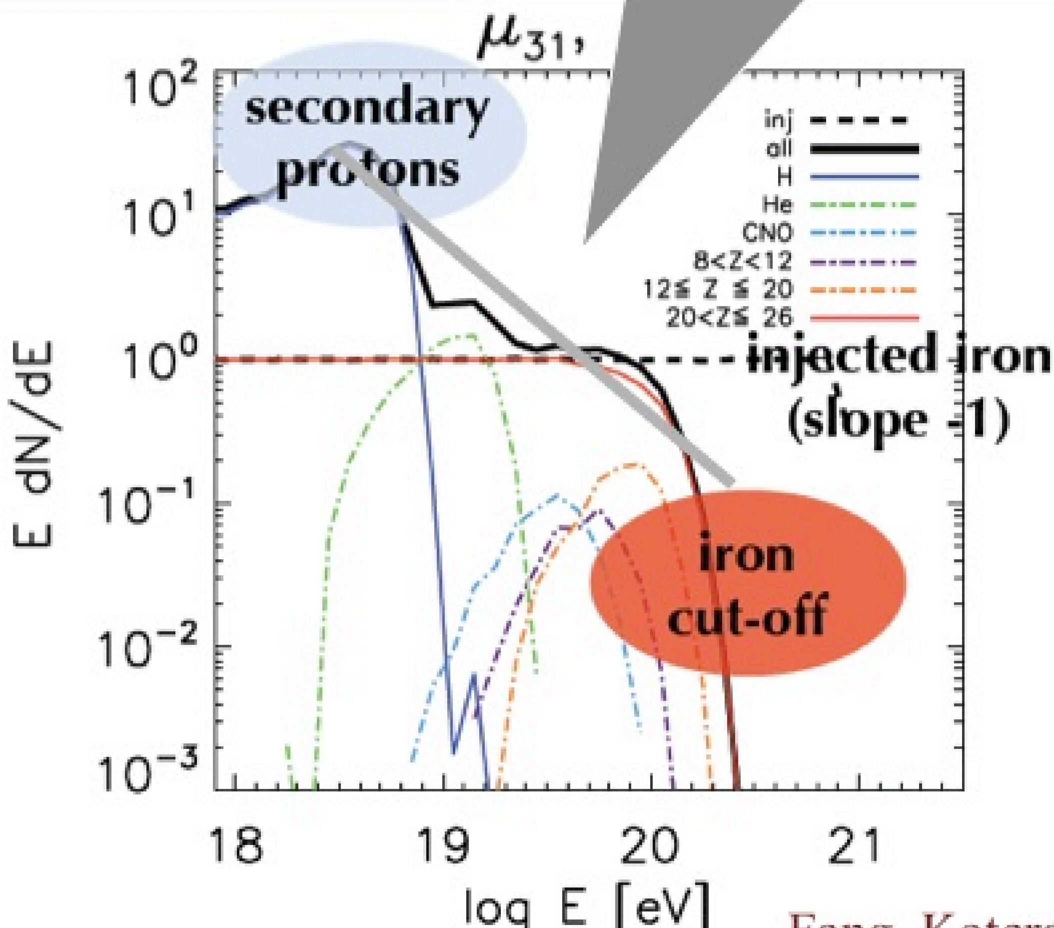


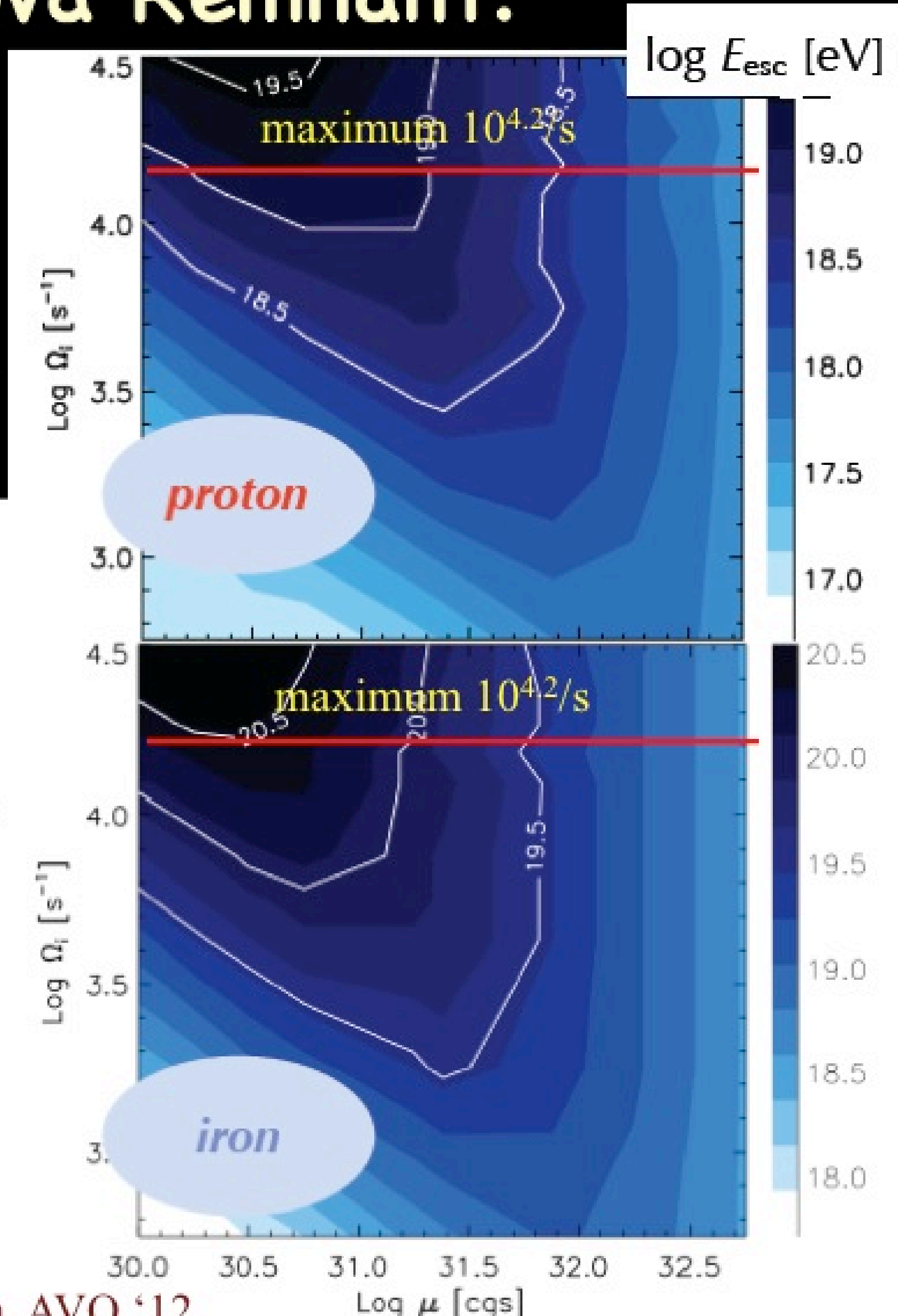
Auger Composition
EPOSv1.99
QGSJETII-03
SIBYLL 2.1
proton
iron
Syst. Unc.
⟨X_max⟩ [g/cm²]
RMS(X_max) [g/cm²]
energy [eV]
SD
Muon Production Depth
SD
Risetime Asymmetry
FD
FD


650
600
550
EPOSv1.99
QGSJETII-0.3
SIBYLL 2.1
proton
iron
Syst. Unc
$\langle X^{\mu}_{max} \rangle$ [g/cm^2]
$\log_{10}$(E/eV)
18
18.5
19
19.5
20
20.5
$E^3 J(E)$ [km^{-2} yr^{-1} sr^{-1} eV^2]
10^{38}
10^{37}
$J(E; E > E_{ankle}) \propto E^{-\gamma_2} \frac{1}{1+\exp\left(\frac{\log_{10}E - \log_{10}E_{1/2}}{\log_{10}W_c}\right)}$
$\gamma_1 = 3.27 \pm 0.01$
$\gamma_2 = 2.63 \pm 0.02$
$\log_{10}(E_{1/2}/eV) = 19.63 \pm 0.02$
$\log_{10}(E_{ankle}/eV) = 18.62 \pm 0.01$
$\log_{10}(W_c/eV) = 0.15 \pm 0.02$
Auger combined
Fit (χ^2/ndof = 33.7/16 = 2.3)
10^{18}
10^{19}
10^{20}
E[eV]
RMS(X_{max}) [g/cm^2]
50
40
30
20
energy [eV]

Escape from Supernova Remnant:

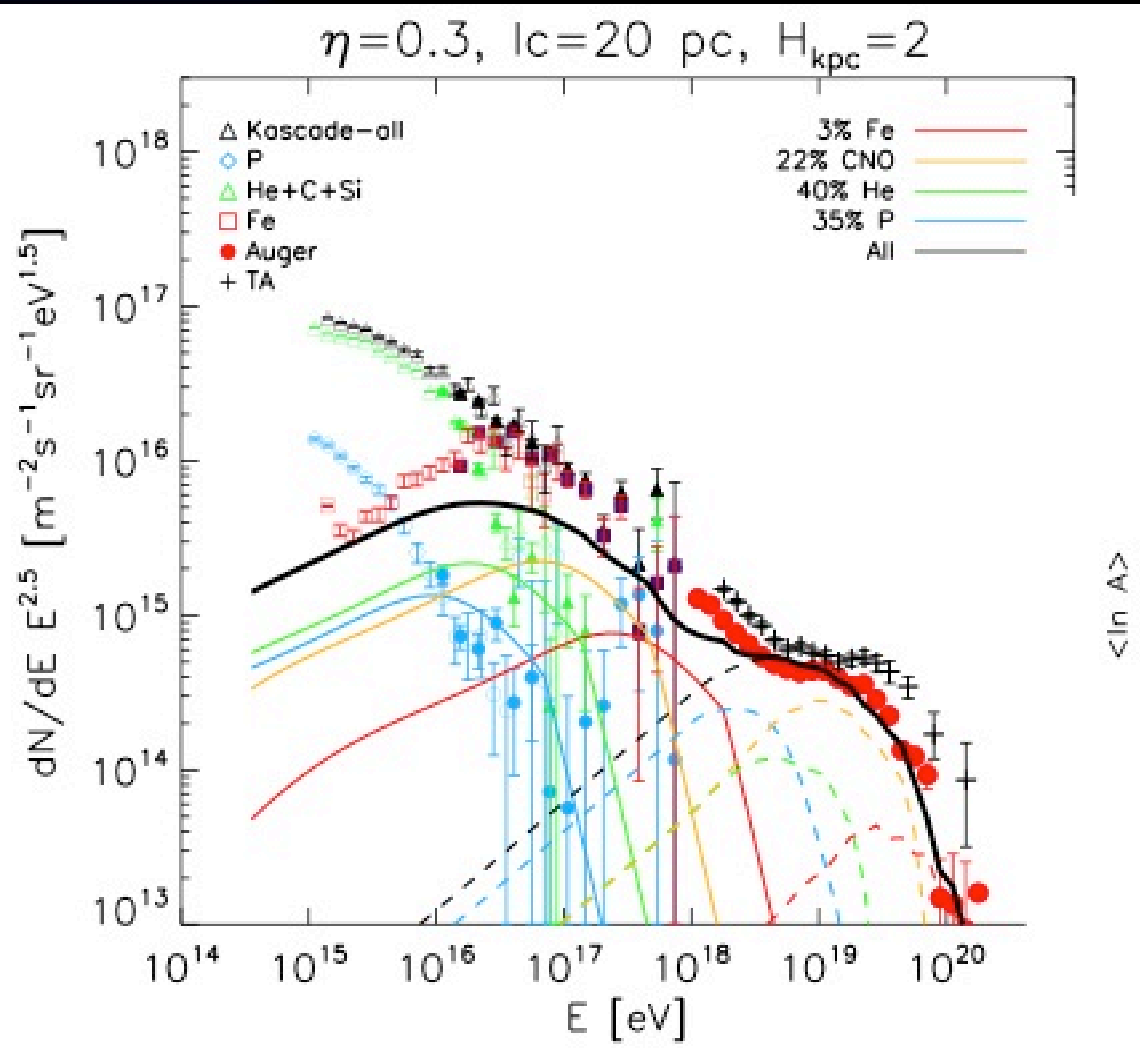
softens the spectrum between protons and iron + pulsar distribution & propagation



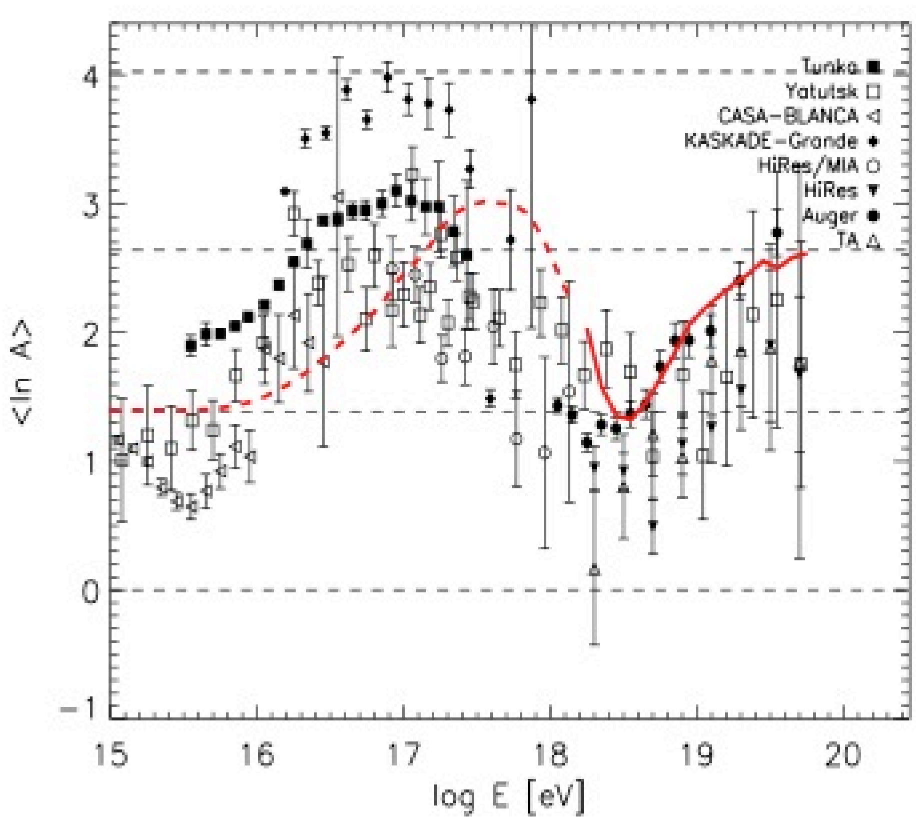


Fang, Kotera, AVO '12

Fit to UHECR spectrum & composition ➔ Galactic Contribution: 10 PeV to EeV



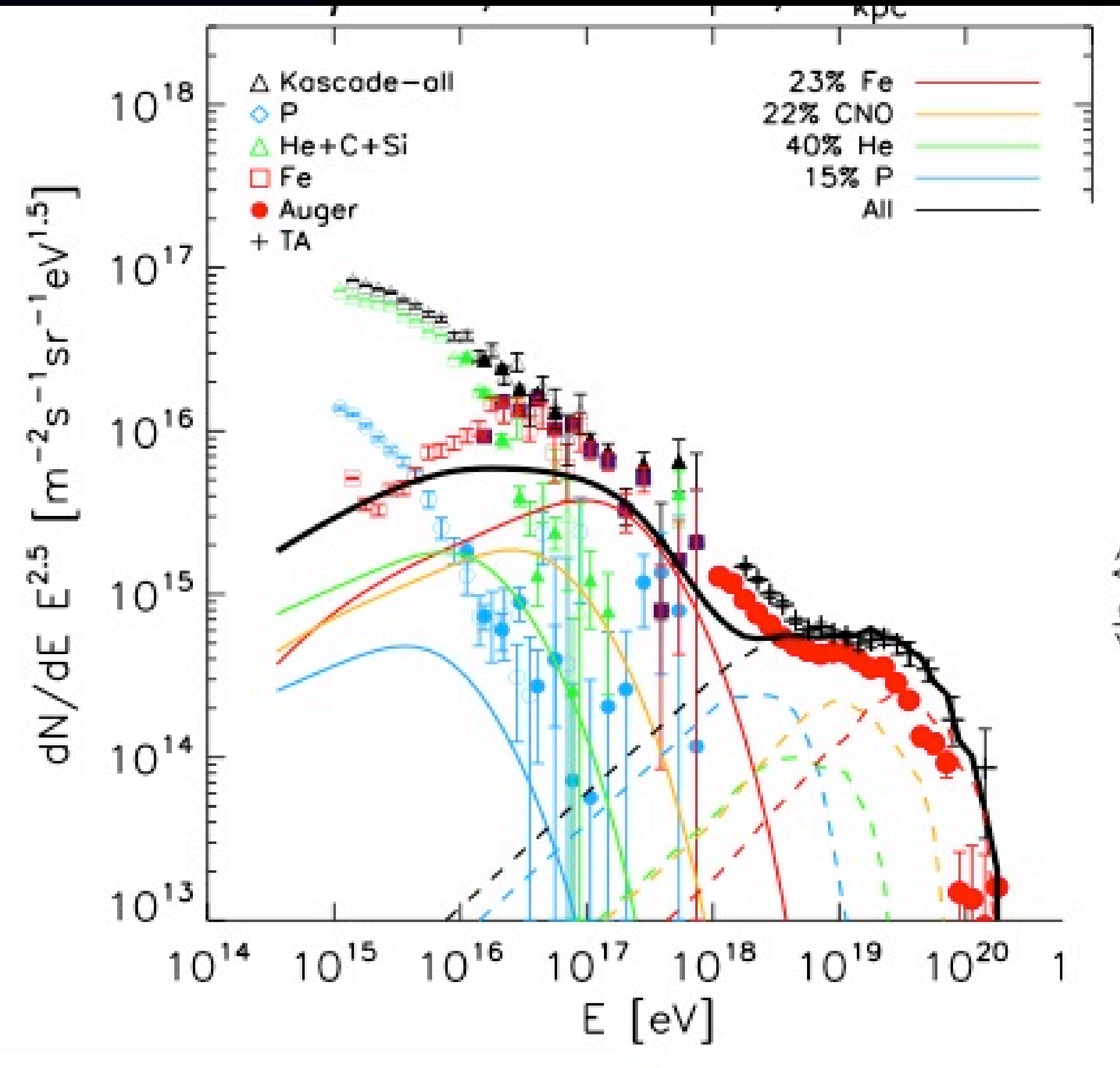
Fang, Kotera, AVO '12

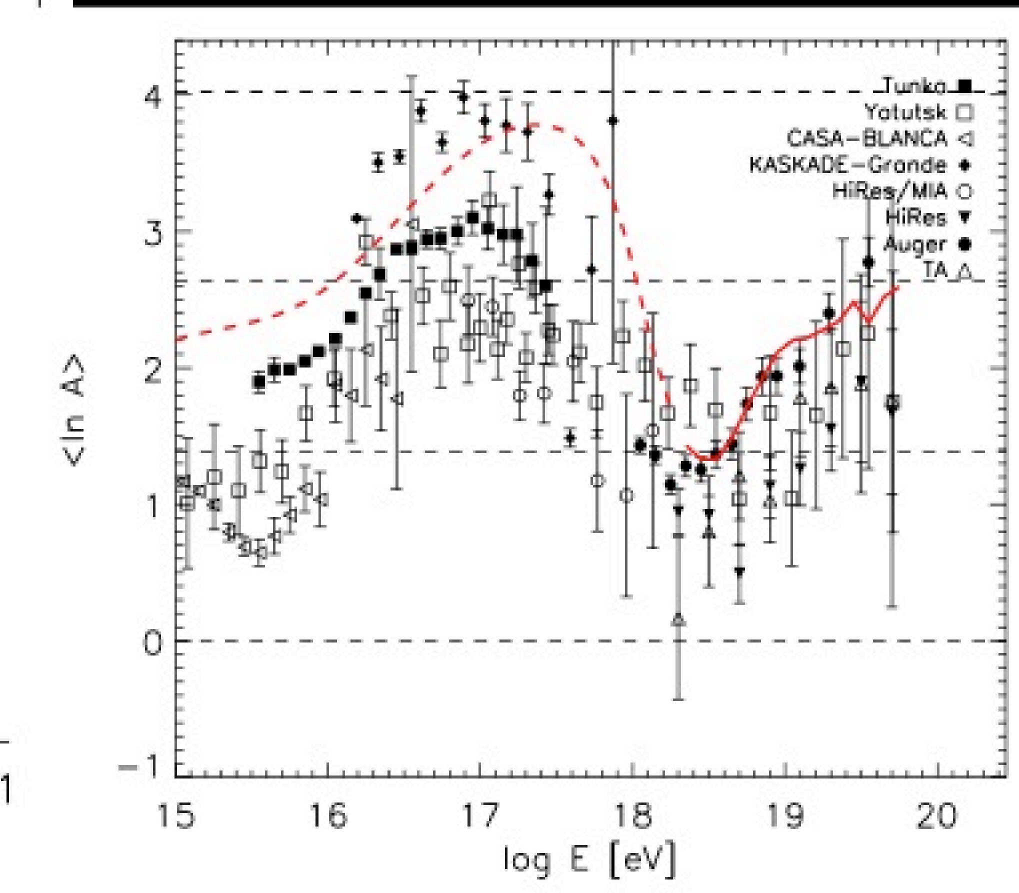


Fit to Auger Energy Scale

Fit to UHECRs implies a Galactic Contribution 10^{16} –10^{18} eV

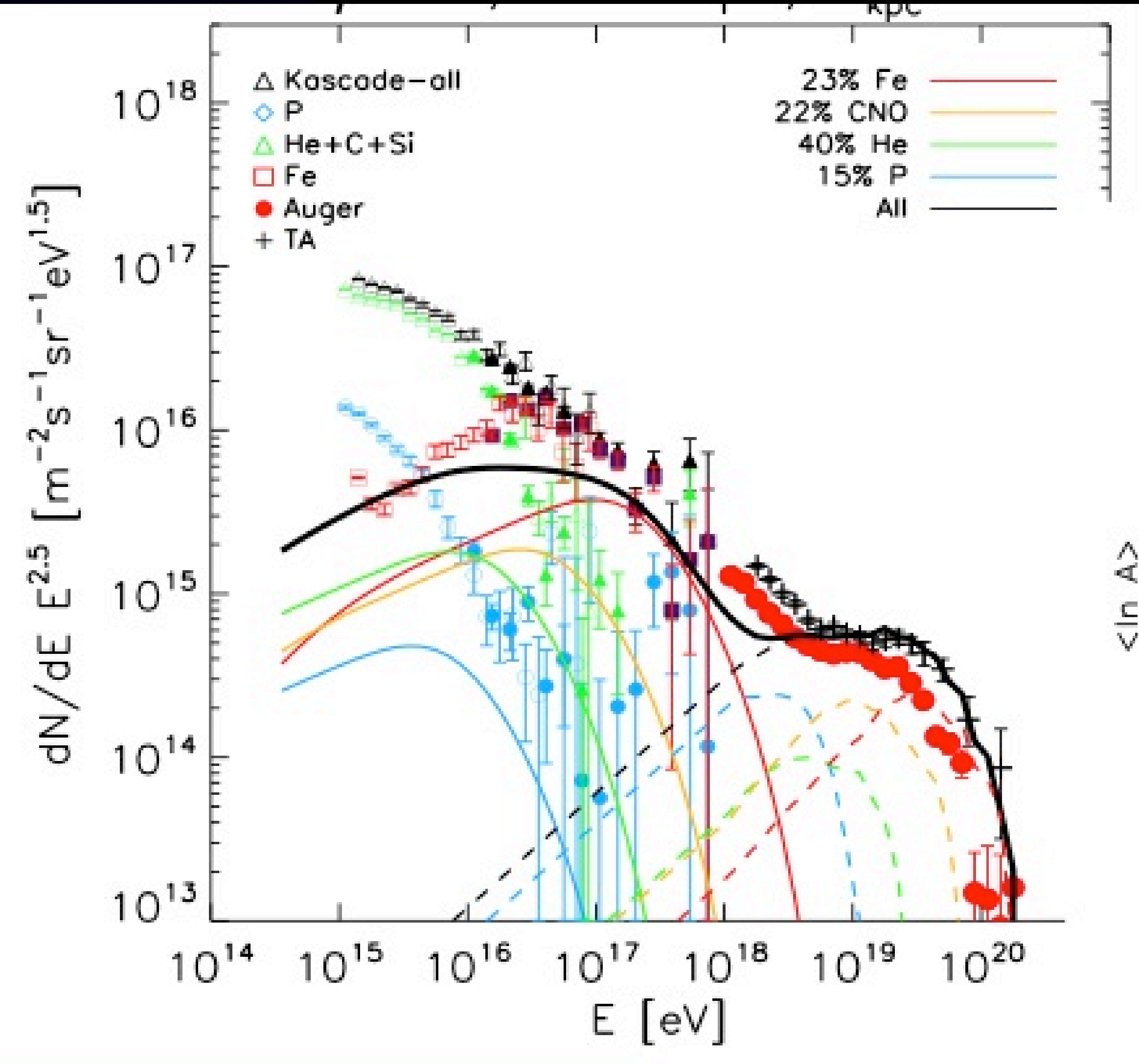
Fang, Kotera, AVO '12



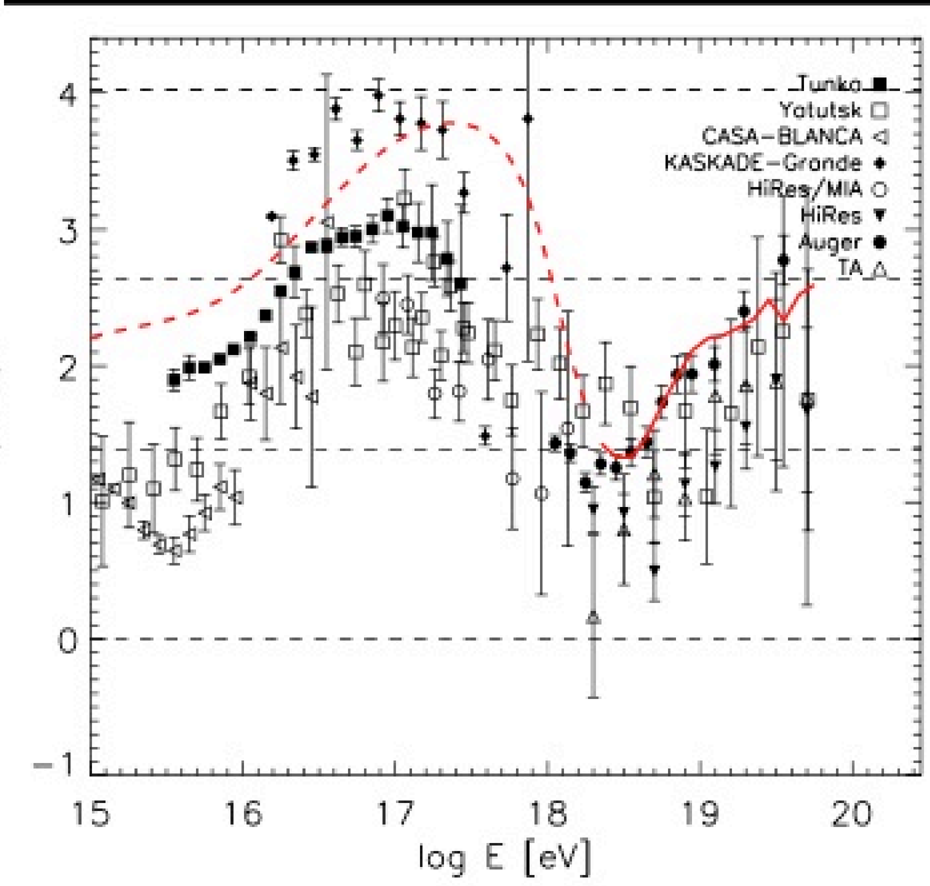


Fit to TA/HiRes Energy Scale

Fit to UHECRs implies a Galactic Contribution 10^{16} –10^{18} eV

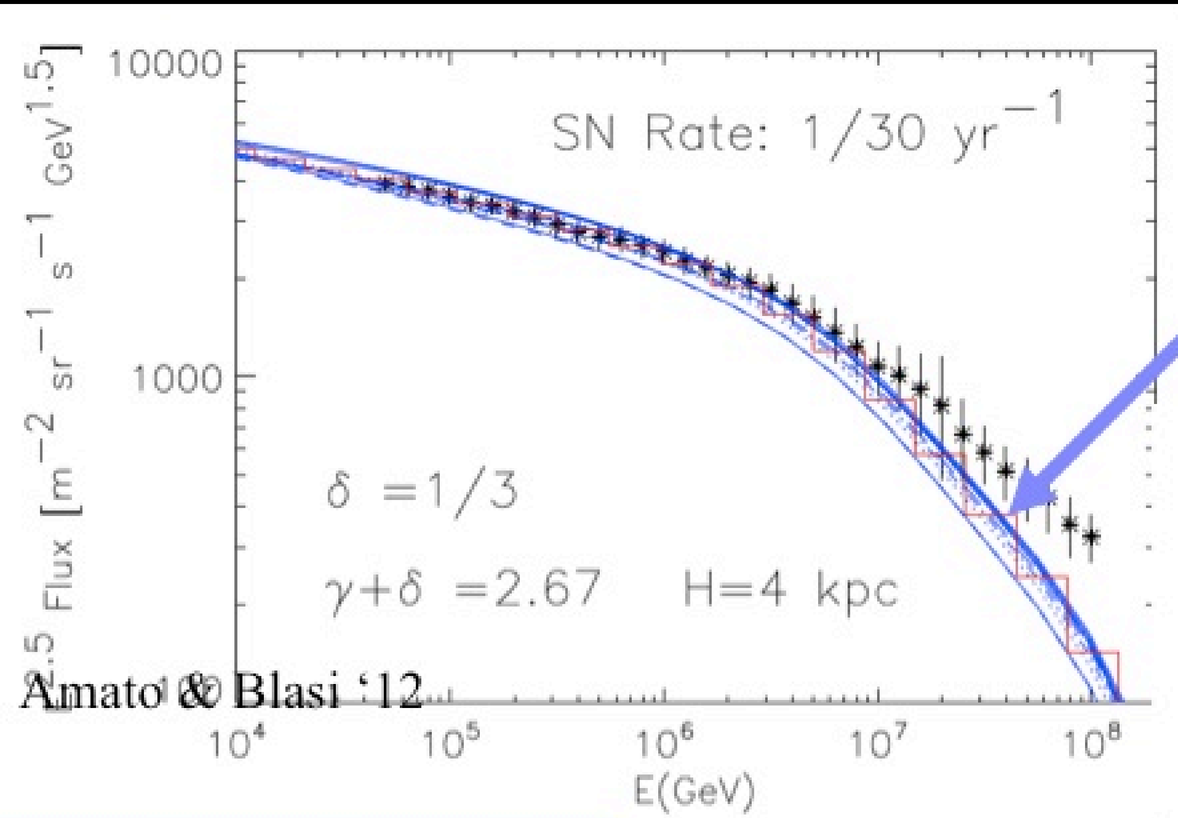


Fang, Kotera, AVO '12



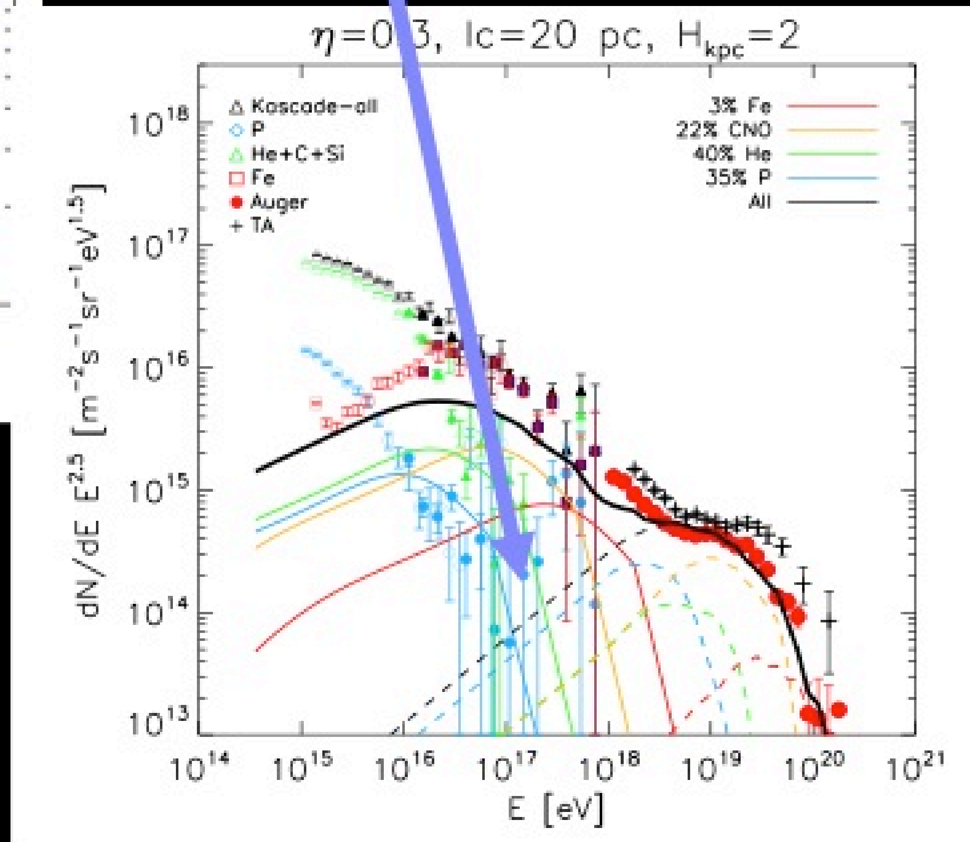
Fit to TA/HiRes Energy Scale, BUT Heavy Composition!

Galactic Cosmic Rays



Amato & Blasi '12

mind the gap

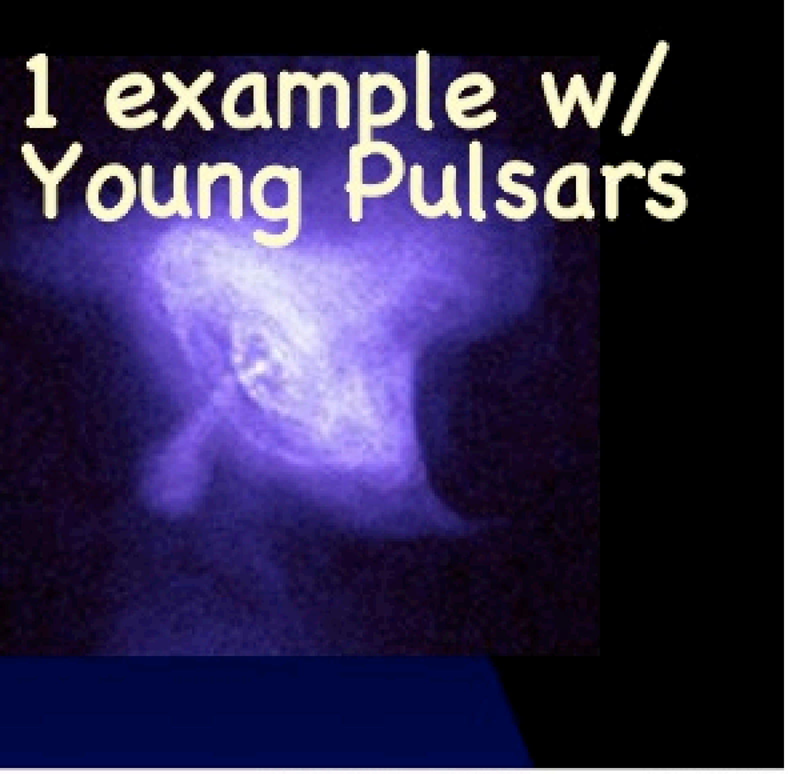


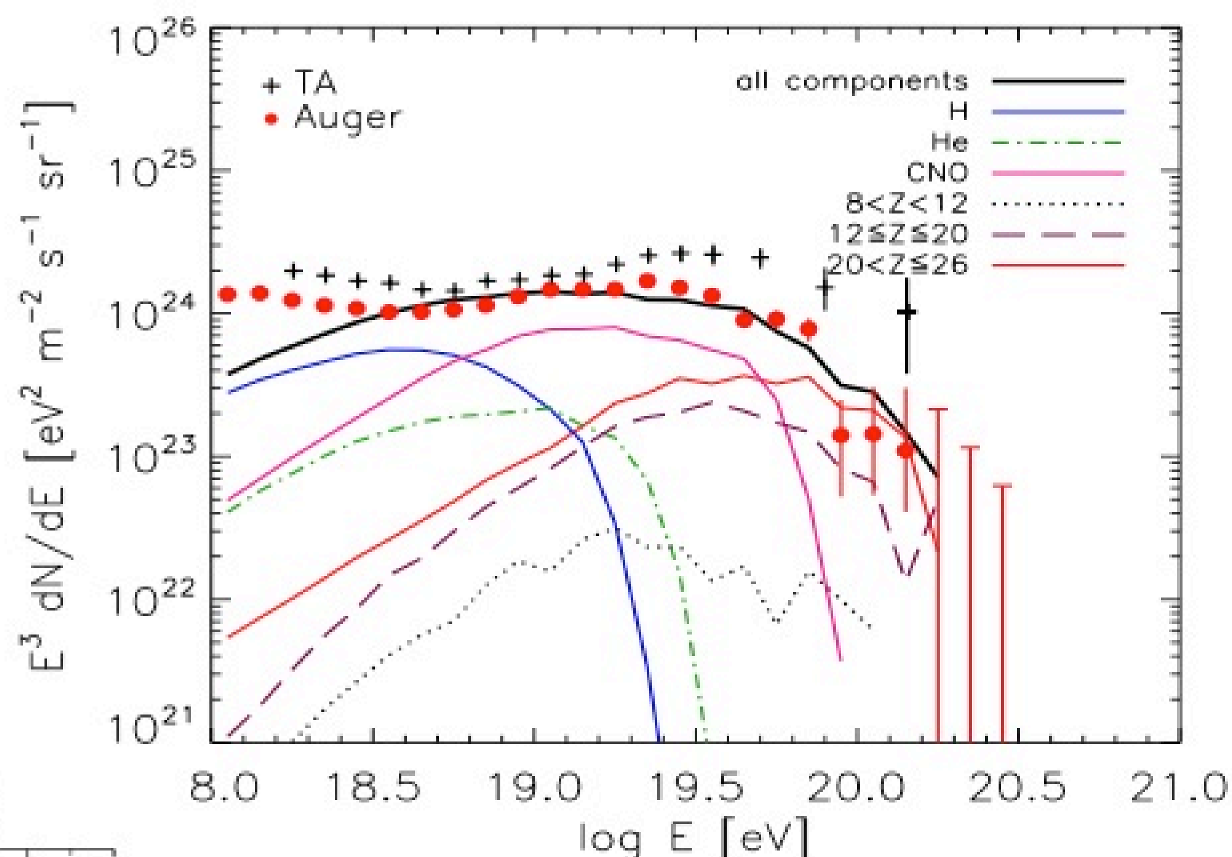
Fang, Kotera, AVO '12

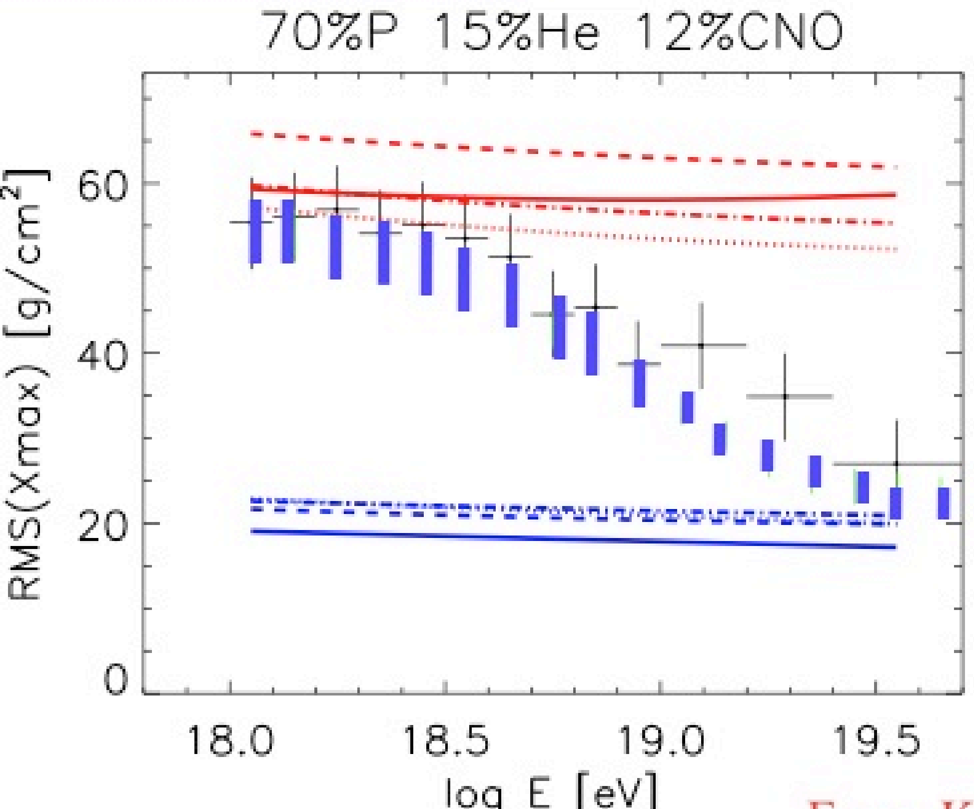
Example:

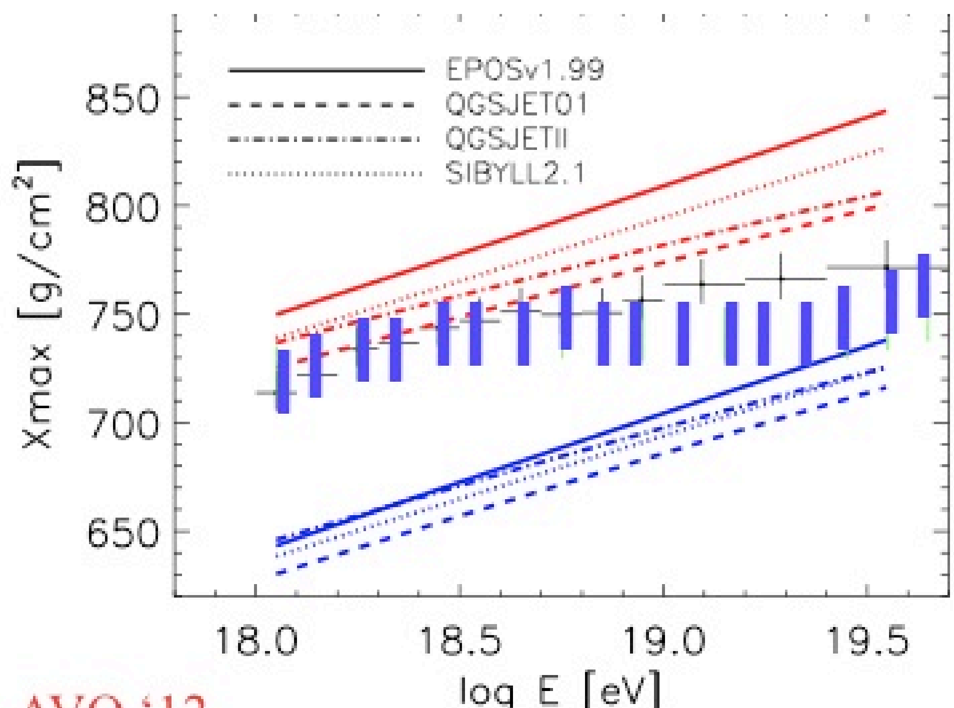
Birth of ultrafast spinning Pulsars

Heavy Composition above 10 EeV
No spectral recovery above 100 EeV
Galactic component above 10 PeV
(due to more common slow spinning newborn pylsars)
Different composition for different energy scales
Anisotropies should track Large Scale Structure
Rate of ultrafast births similar to GRBs



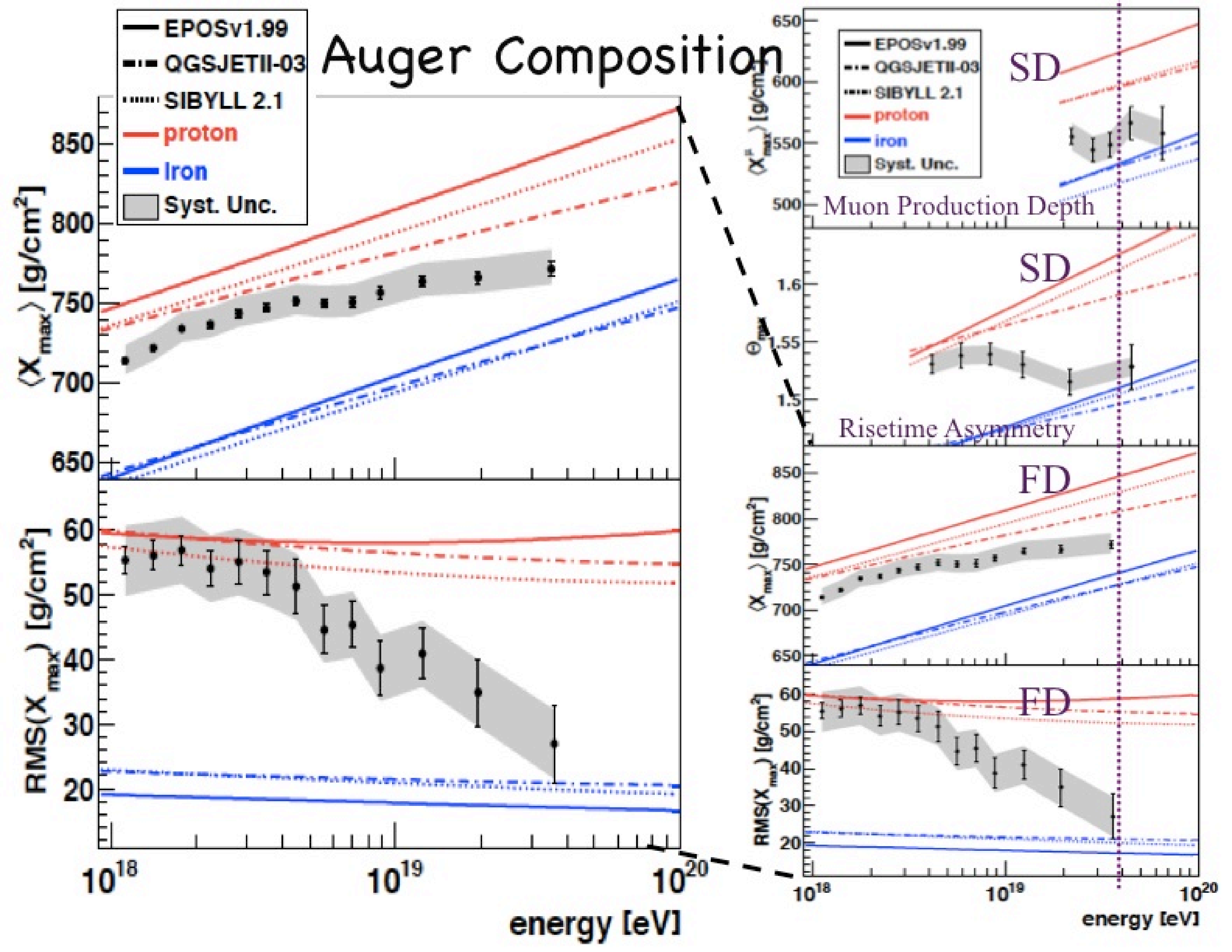




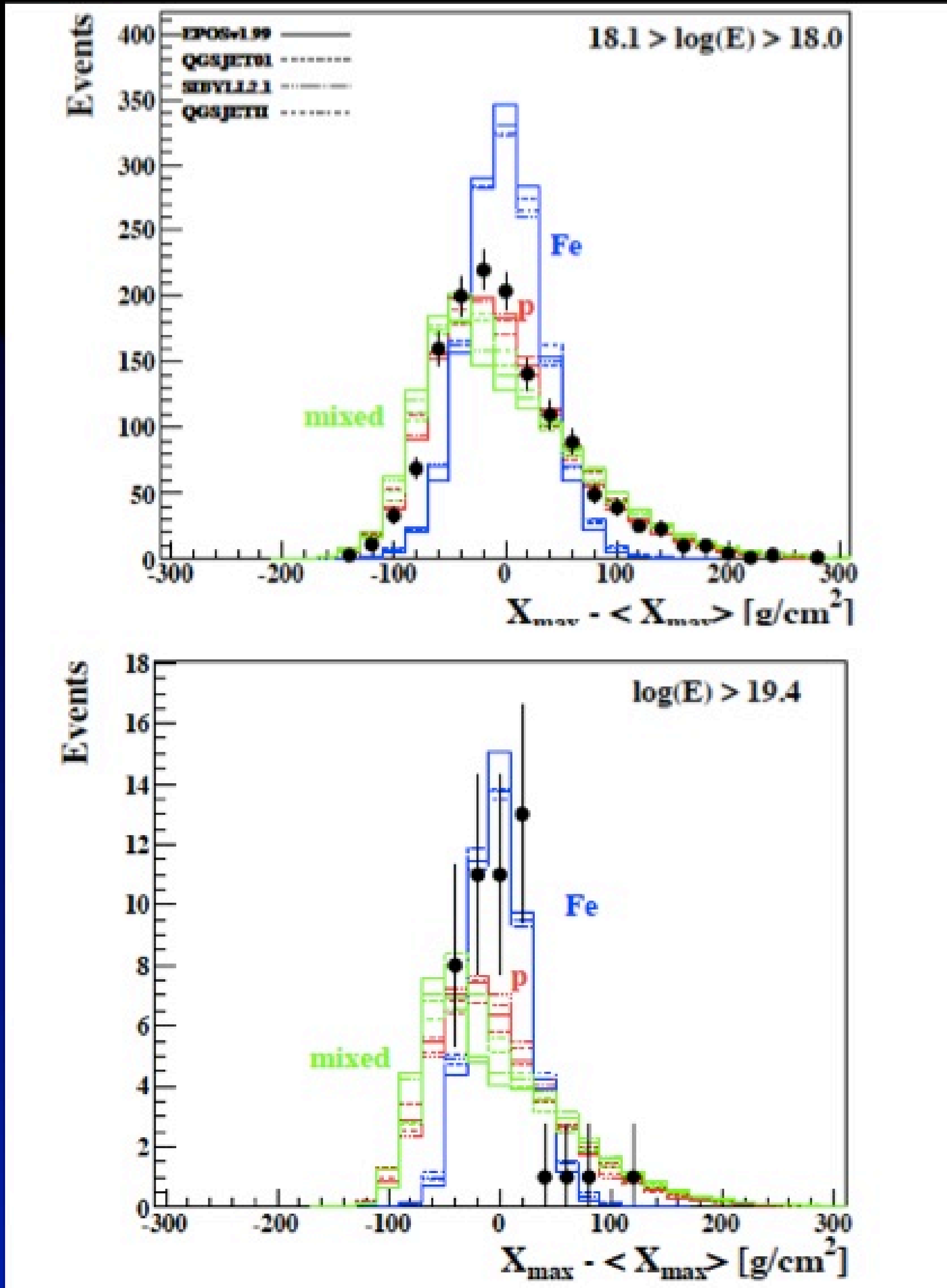


Fang, Kotera, AVO '12

Auger Composition

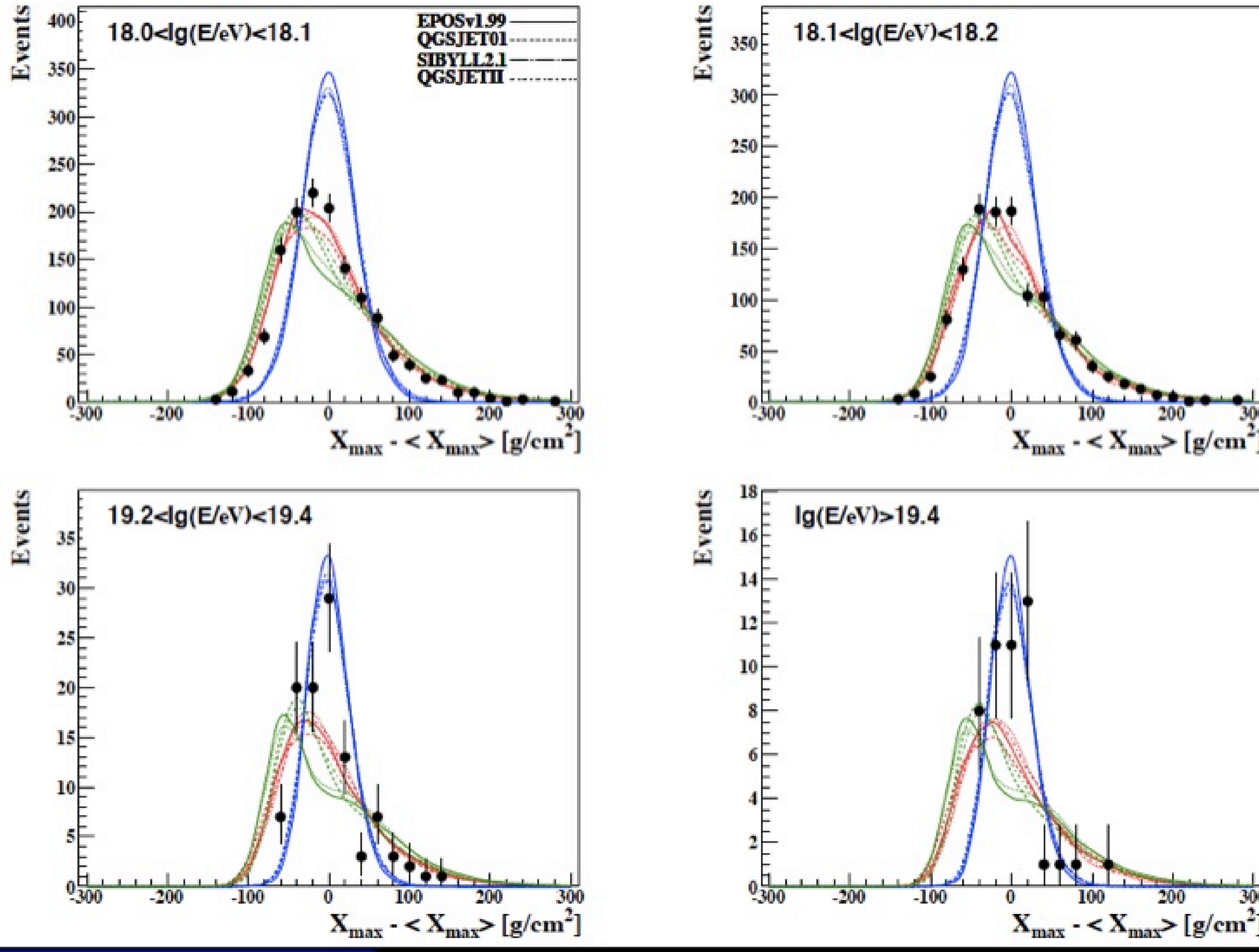


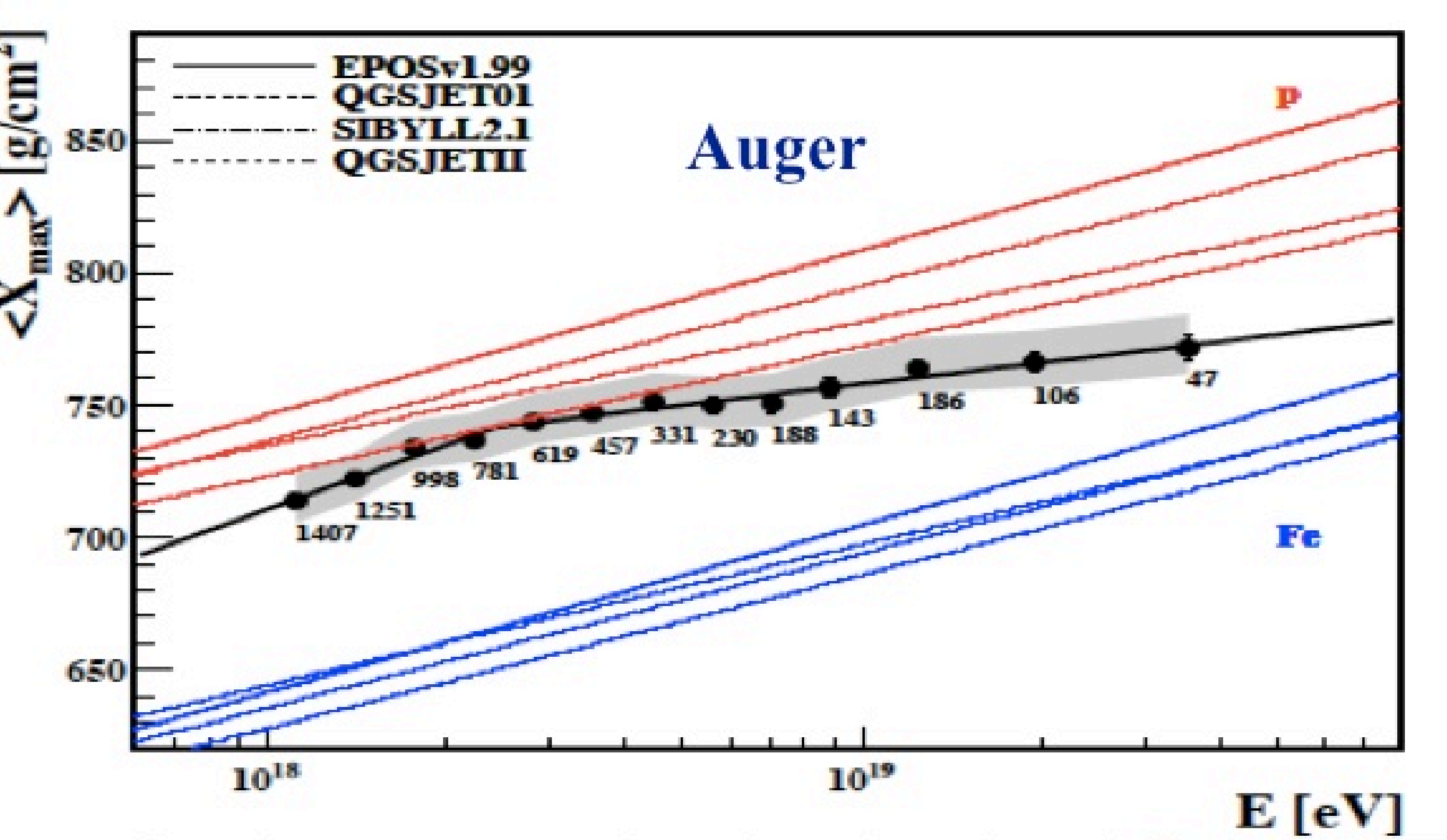
Auger Distribution



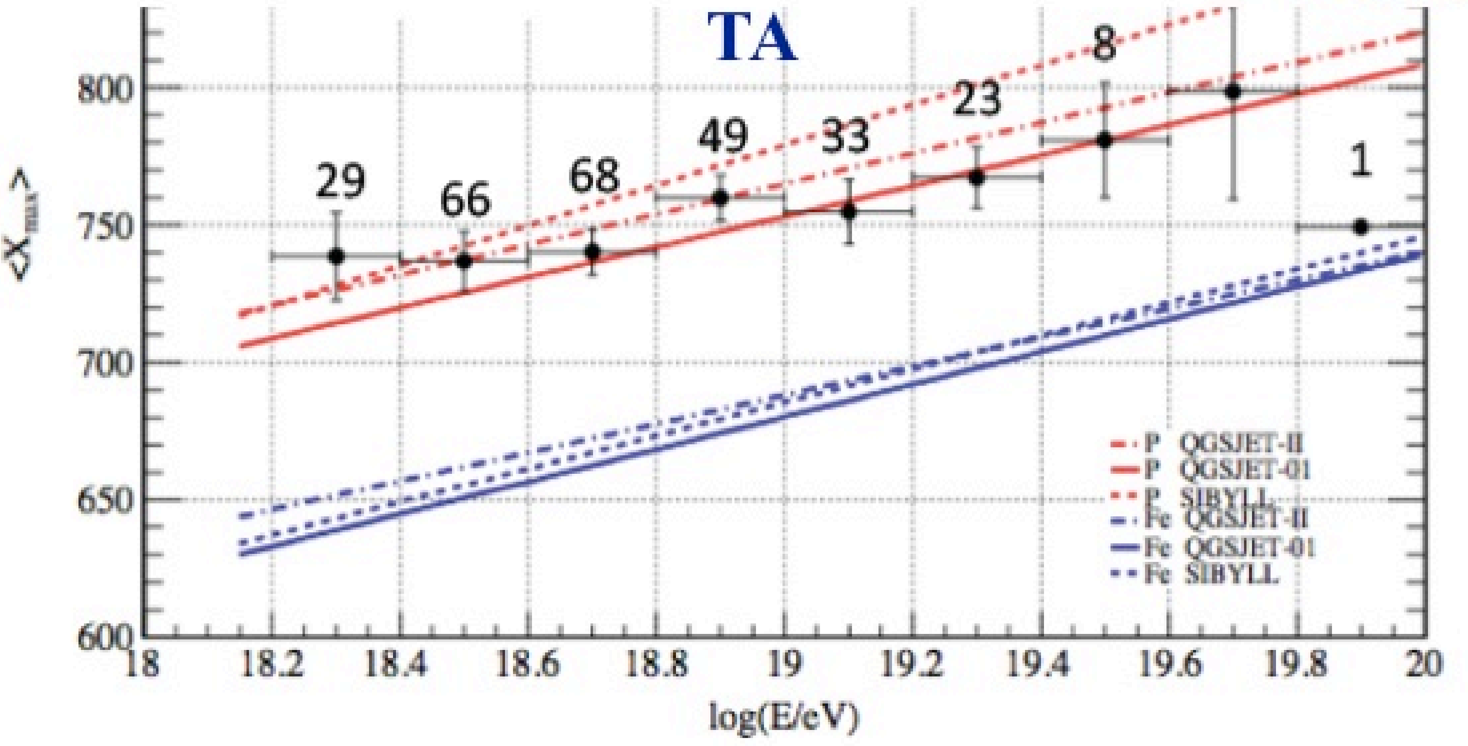
X_{max} Distributions

p, Fe, 50:50

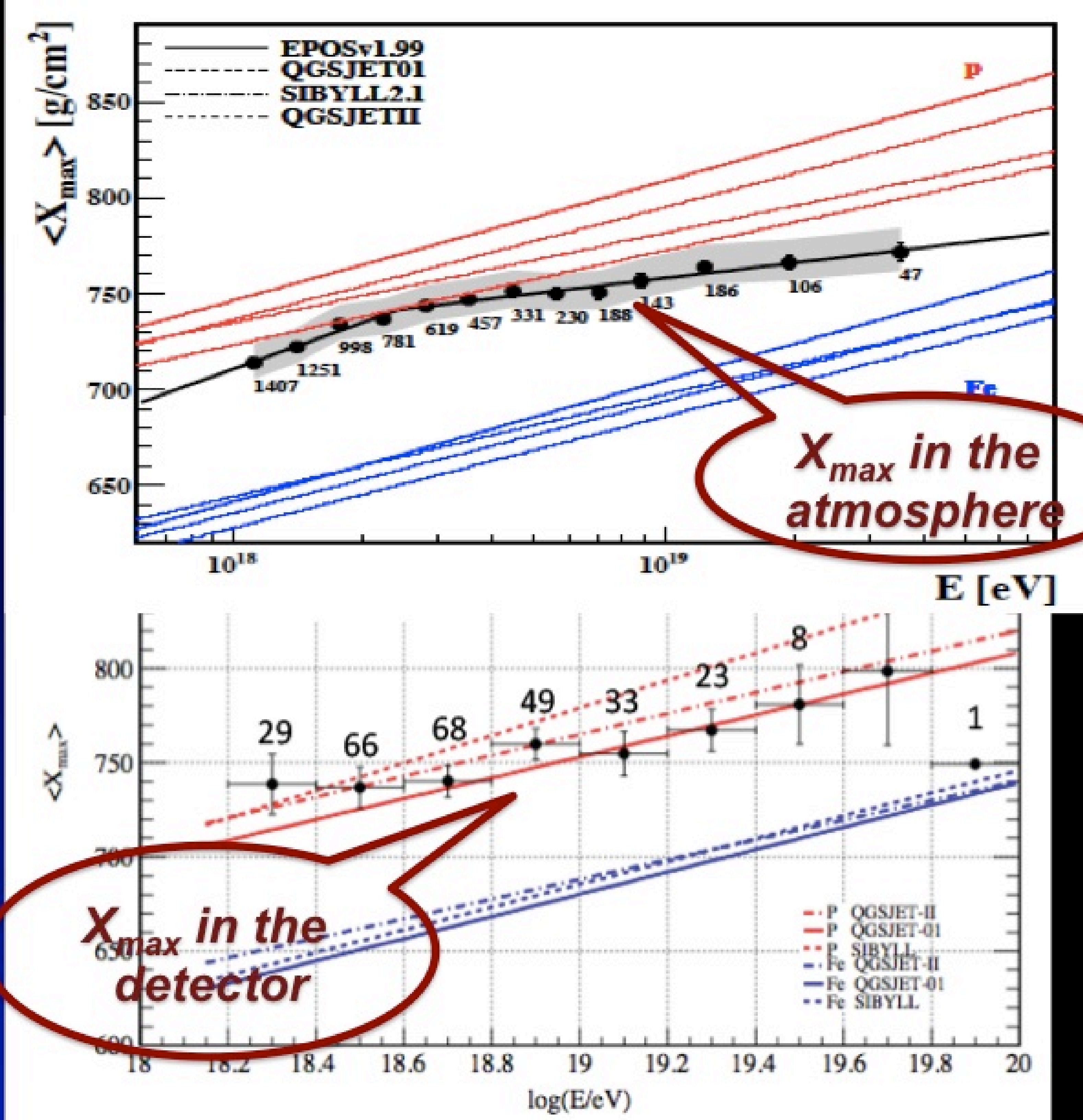




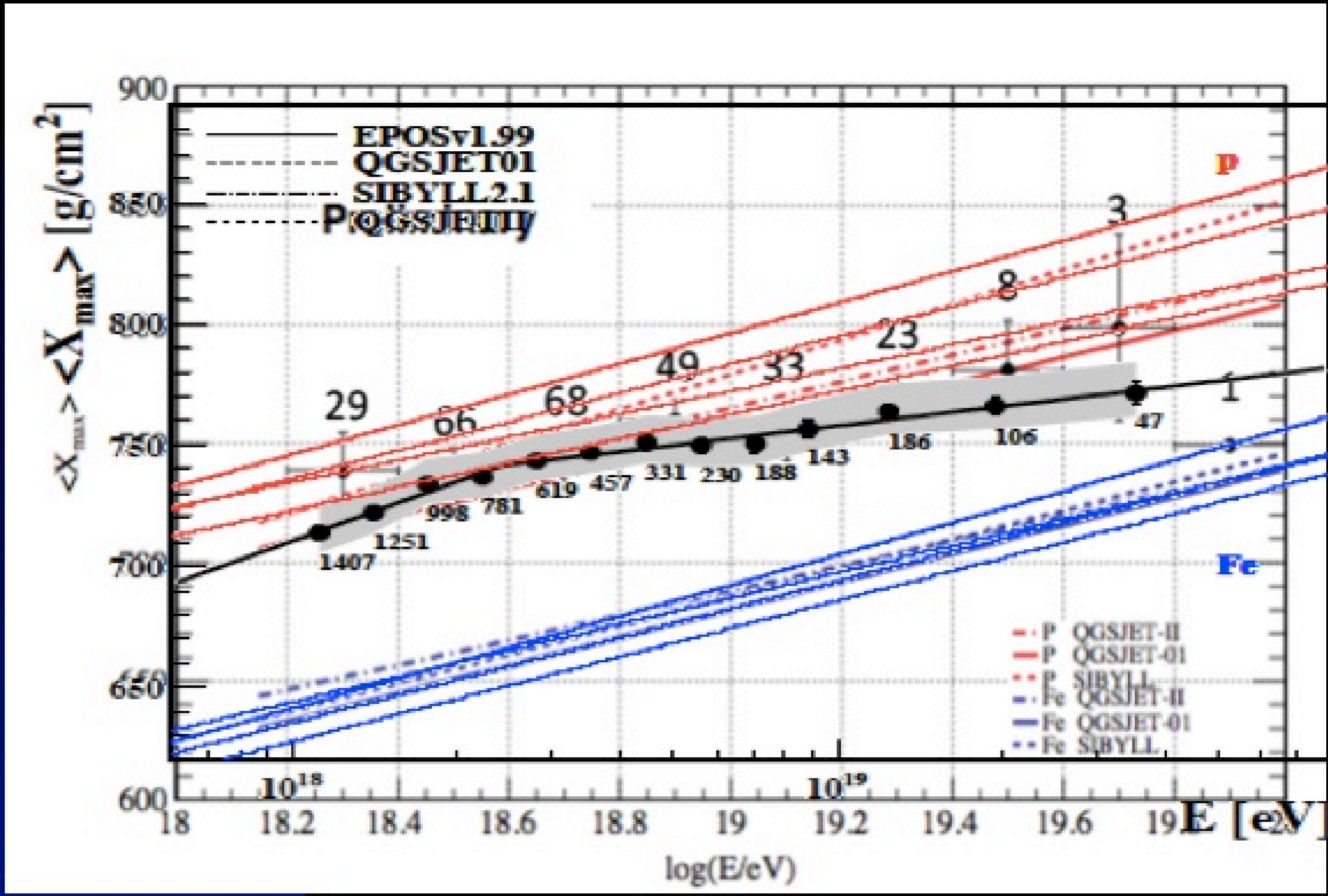
Auger
EPOSv1.99
QGSJET01
SIBYLL2.1
QGSJETII
p
Fe
<X_max> [g/cm²]
E [eV]
1407
1251
998
781
619
457
331
230
188
143
186
106
47



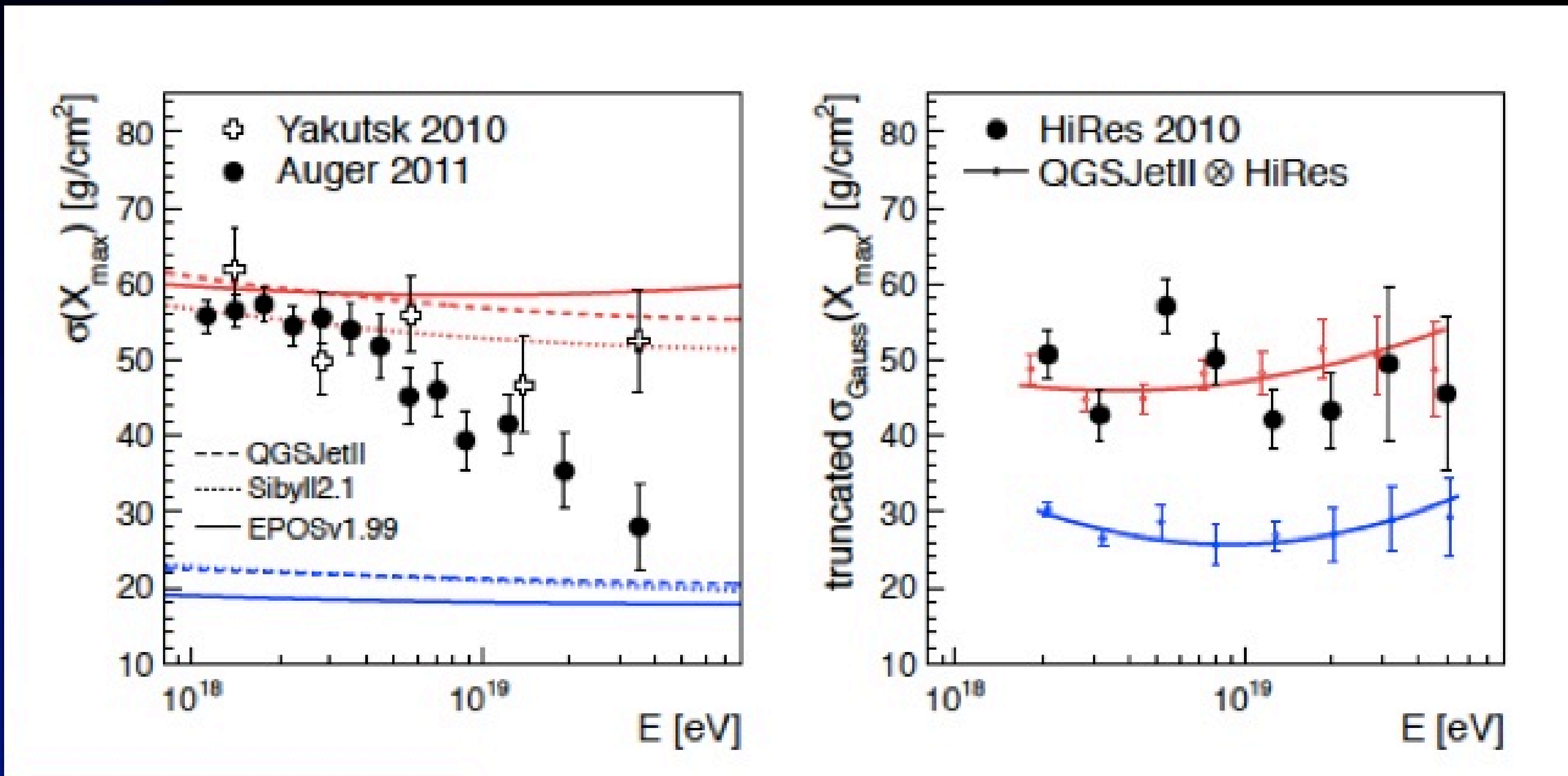
TA
29
66
68
49
33
23
8
1
P QGSJET-II
P QGSJET-01
P SIBYLL
Fe QGSJET-II
Fe QGSJET-01
Fe SIBYLL
<X_max>
log(E/eV)



EPOSv1.99
QGSJET01
SIBYLL2.1
QGSJETII
p
Fe
<X_max> [g/cm²]
E [eV]
1407
1251
998
781
619
457
331
230
188
143
186
106
47
X_max in the atmosphere
29
66
68
49
33
23
8
1
P QGSJET-II
P QGSJET-01
P SIBYLL
Fe QGSJET-II
Fe QGSJET-01
Fe SIBYLL
<X_max>
log(E/eV)
X_max in the detector



EPOSv1.99
QGSJET01
SIBYLL2.1
QGSJETII
P
Fe
P QGSJET-II
P QGSJET-01
P SIBYLL
Fe QGSJET-II
Fe QGSJET-01
Fe SIBYLL
<Xmax> [g/cm2]
log(E/eV)
E [eV]


Yakutsk 2010
Auger 2011
QGSJetII
Sibyll2.1
EPOSv1.99
σ(X_max) [g/cm²]
E [eV]
HiRes 2010
QGSJetII ⊗ HiRes
truncated σ_Gauss(X_max) [g/cm²]
E [eV]

Plausible Sources of UHECRs

1. Extragalactic E > 10^{18} eV (maybe even lower)
2. Transition from Galactic to Extragalactic is ill constrained. composition is important.
3. Very few astrophysical sources can reach E_{max} GRBs, AGN, Young NSs, ?
4. Most acceleration models based on 1st order Fermi Acceleration : spectrum E^{-2}
5. UHECR sources have large Luminosity
6. Challenges for Relativistic Shocks
7. Alternative scenarios: unipolar inductors; wake field acceleration: Tajima & Dawson `79; Chen et al.`02 relativistic shear jet acceleration: Rieger et al. 2007, Rieger & Duffy 2005, Lyutikov & Ouyed 2007

Ultrahigh Energy Cosmic Rays

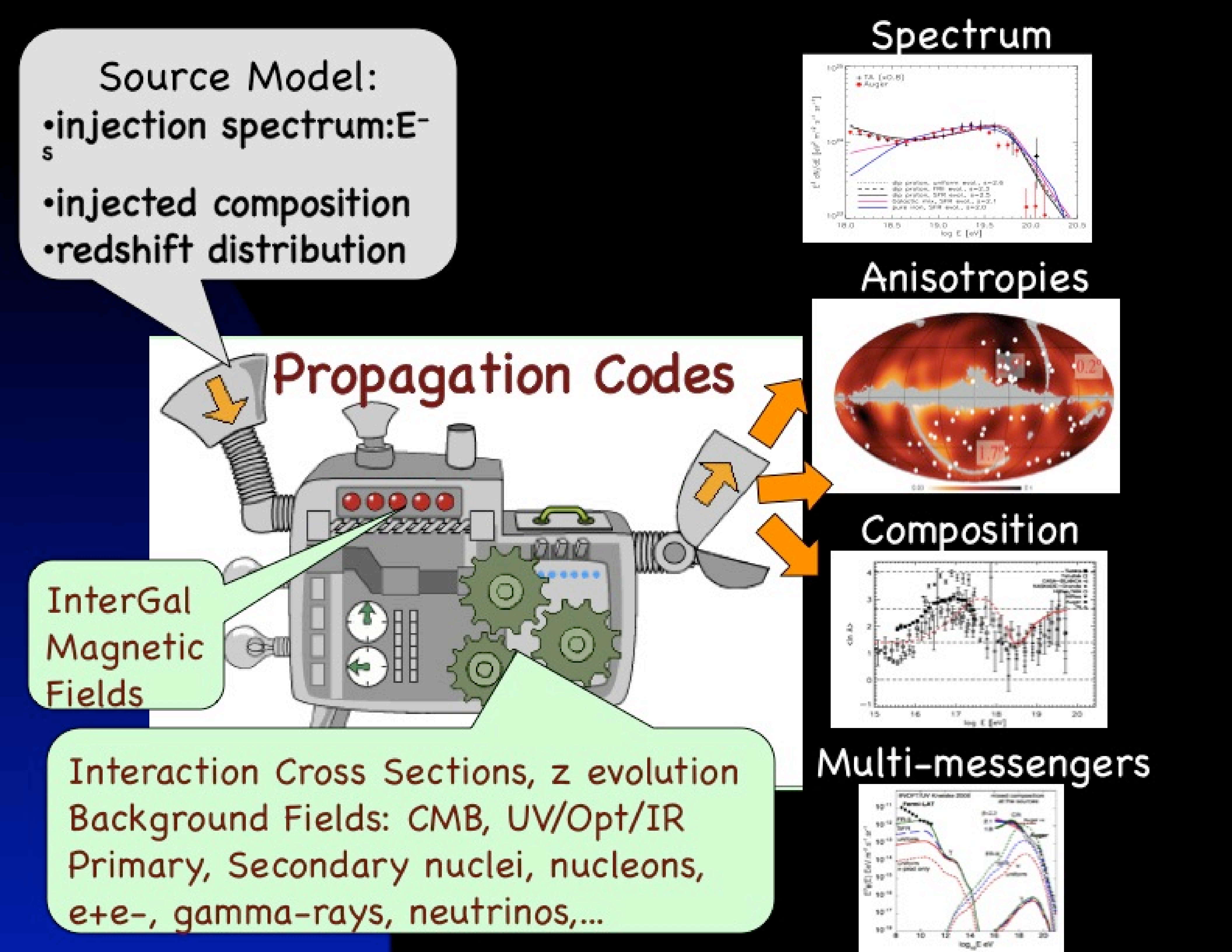
OBSERVABLES:

Spectrum

Composition

Sky Distribution

Multi-messengers



Source Model:
•injection spectrum:E-s
•injected composition
•redshift distribution
Propagation Codes
InterGal Magnetic Fields
Interaction Cross Sections, z evolution
Background Fields: CMB, UV/Opt/IR
Primary, Secondary nuclei, nucleons,
e+e-, gamma-rays, neutrinos,...
Spectrum
Anisotropies
Composition
Multi-messengers

Ultrahigh Energy Cosmic Rays

OBSERVABLES:

Spectrum

Composition

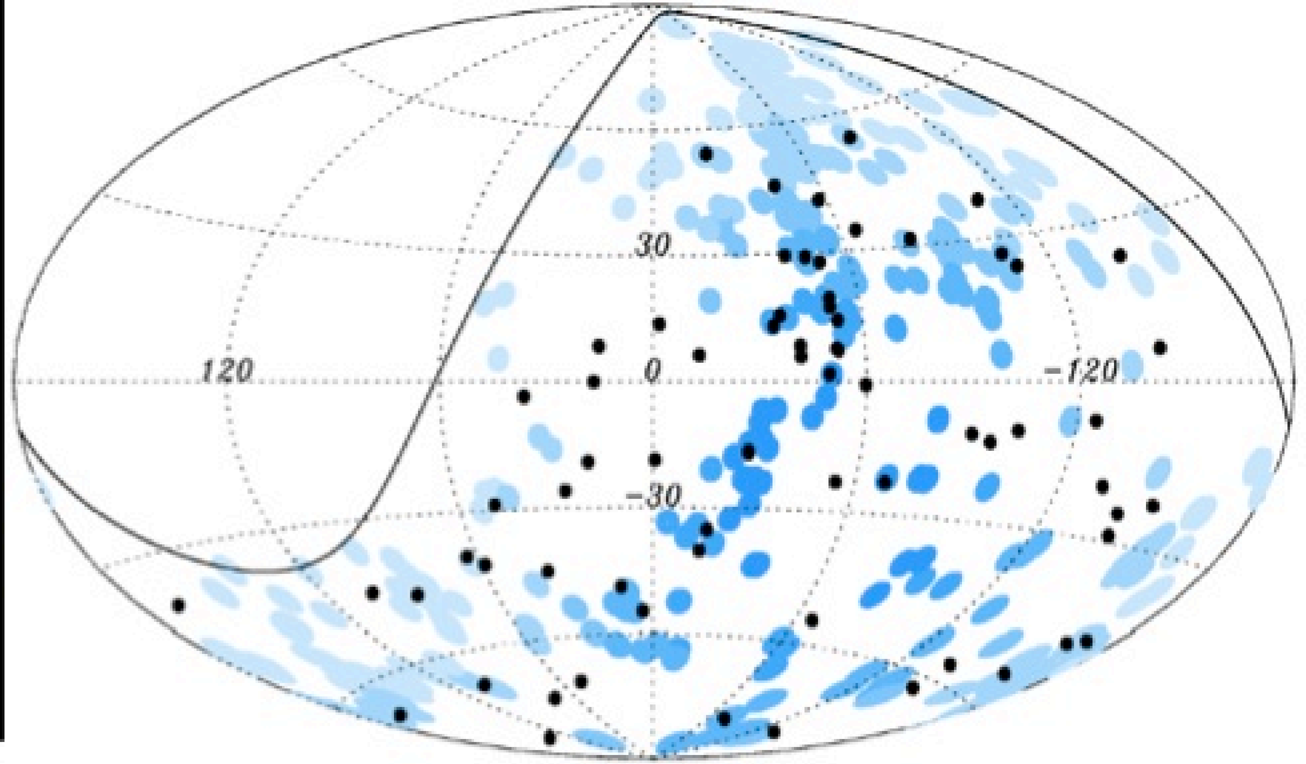
Sky Distribution

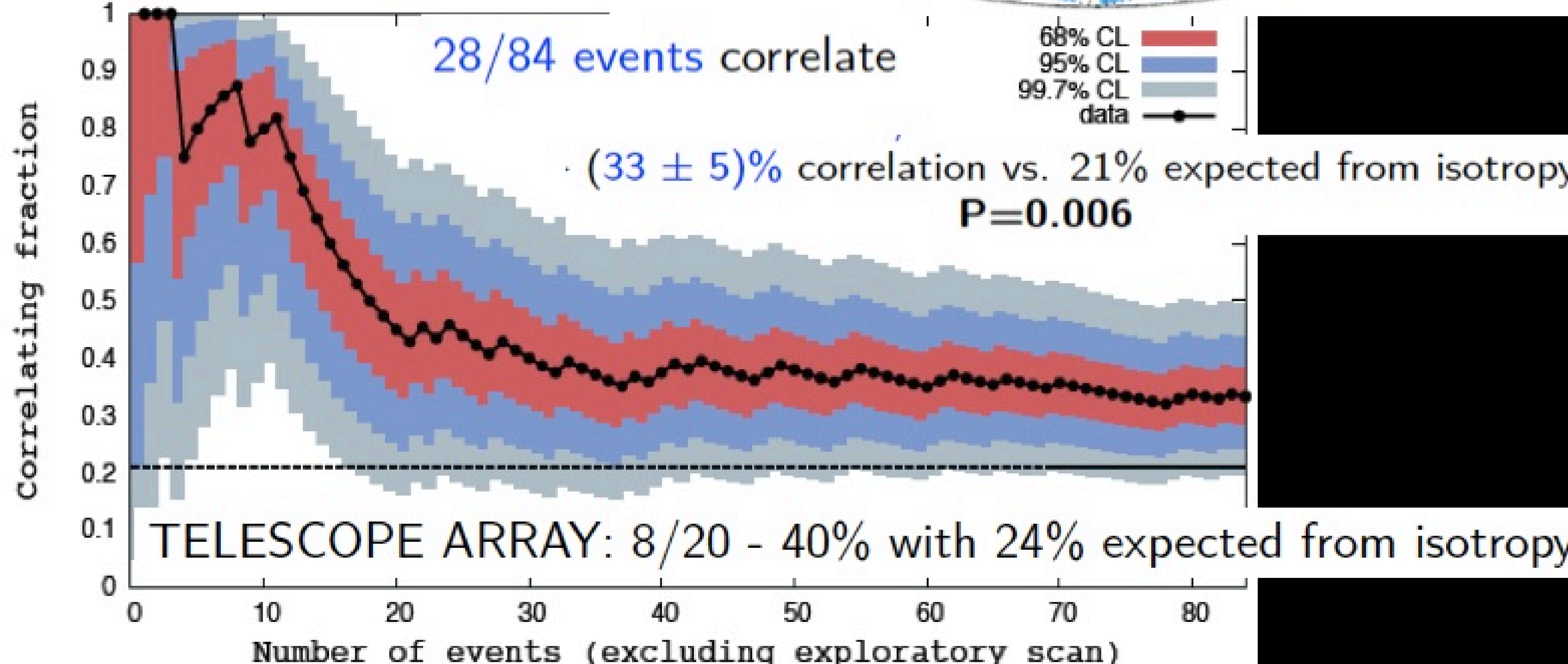
Multi-messengers

Auger:

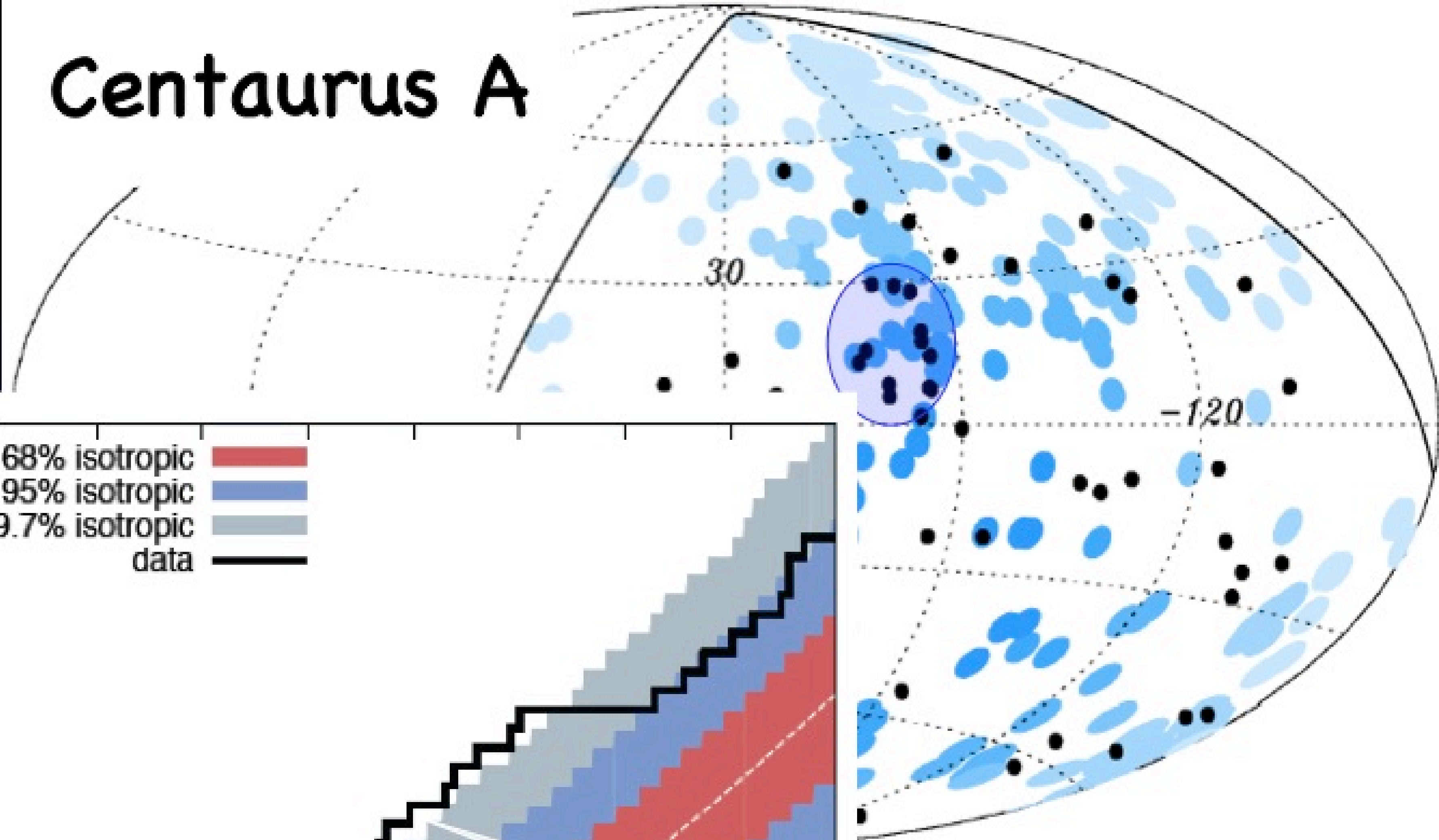
consistent with Anisotropy

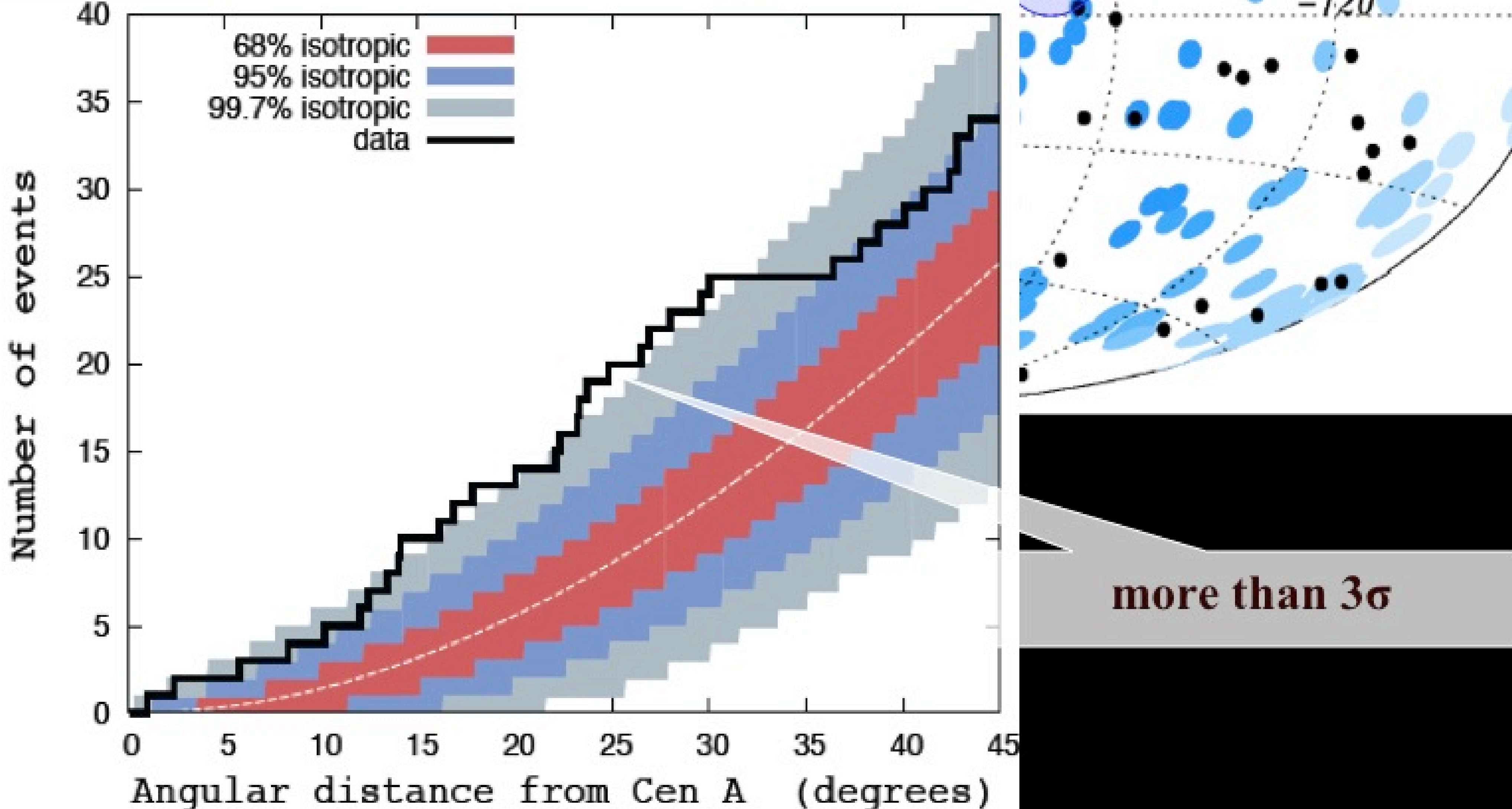
AGN catalog test



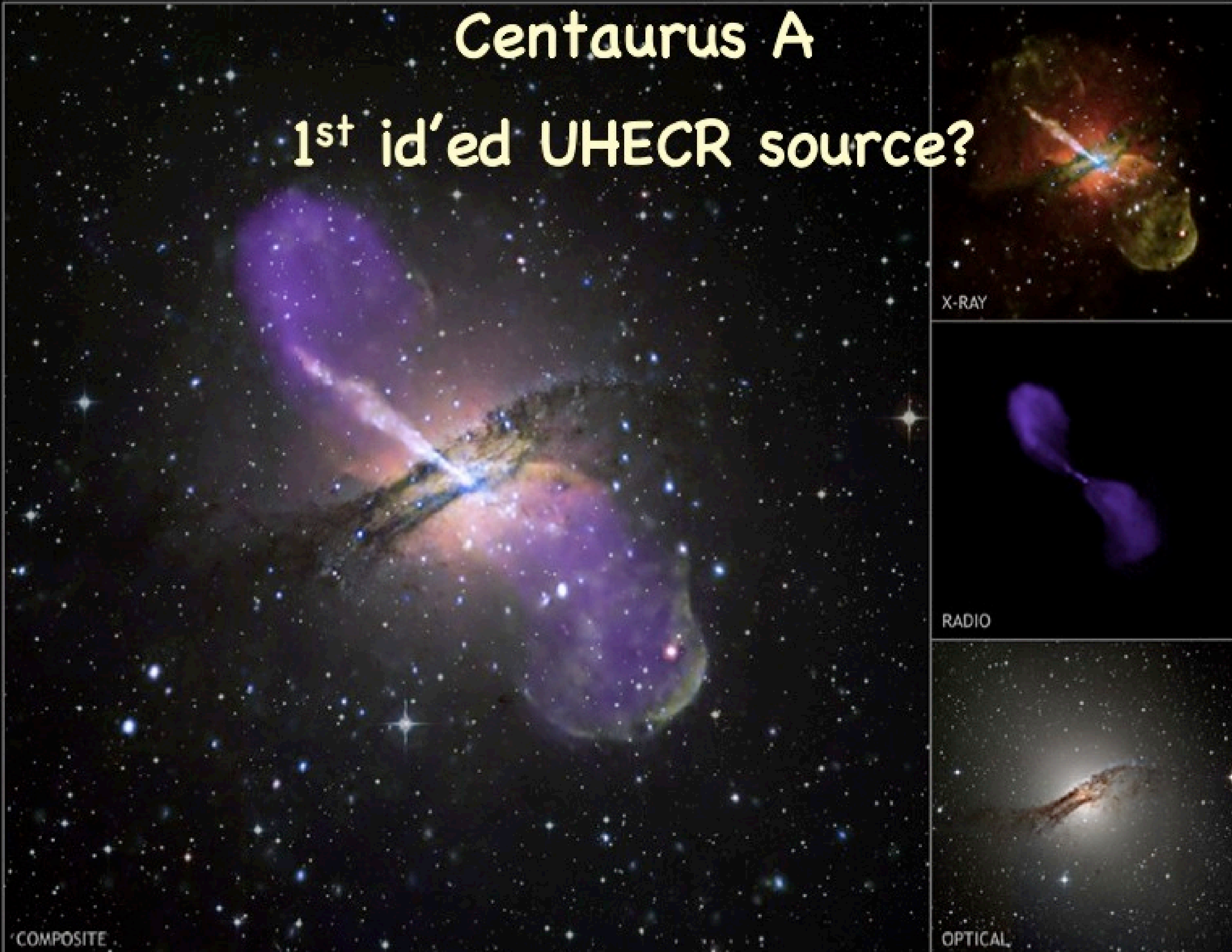


Auger: **Centaurus A**

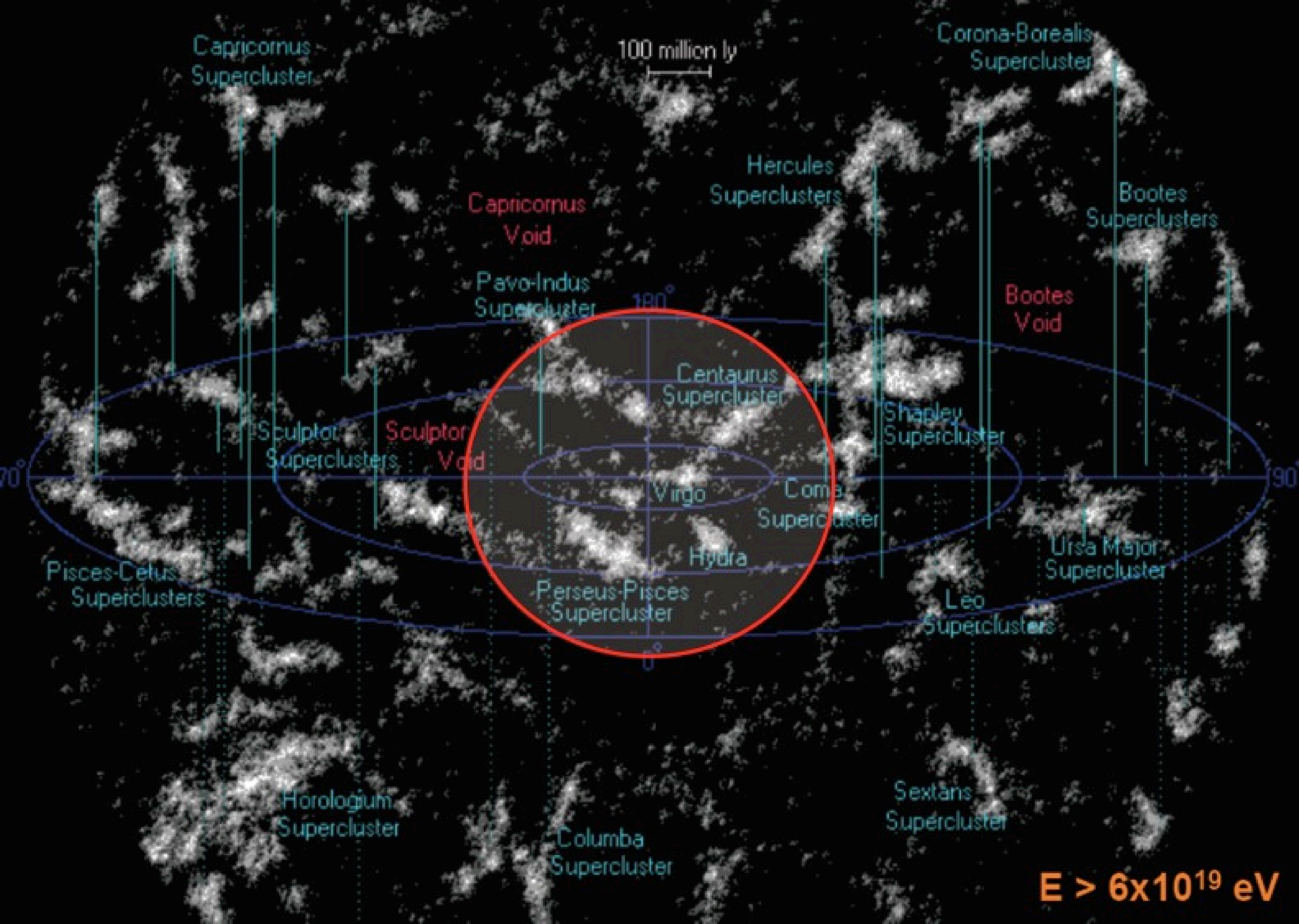




Centaurus A
1^{st} id'ed UHECR source?



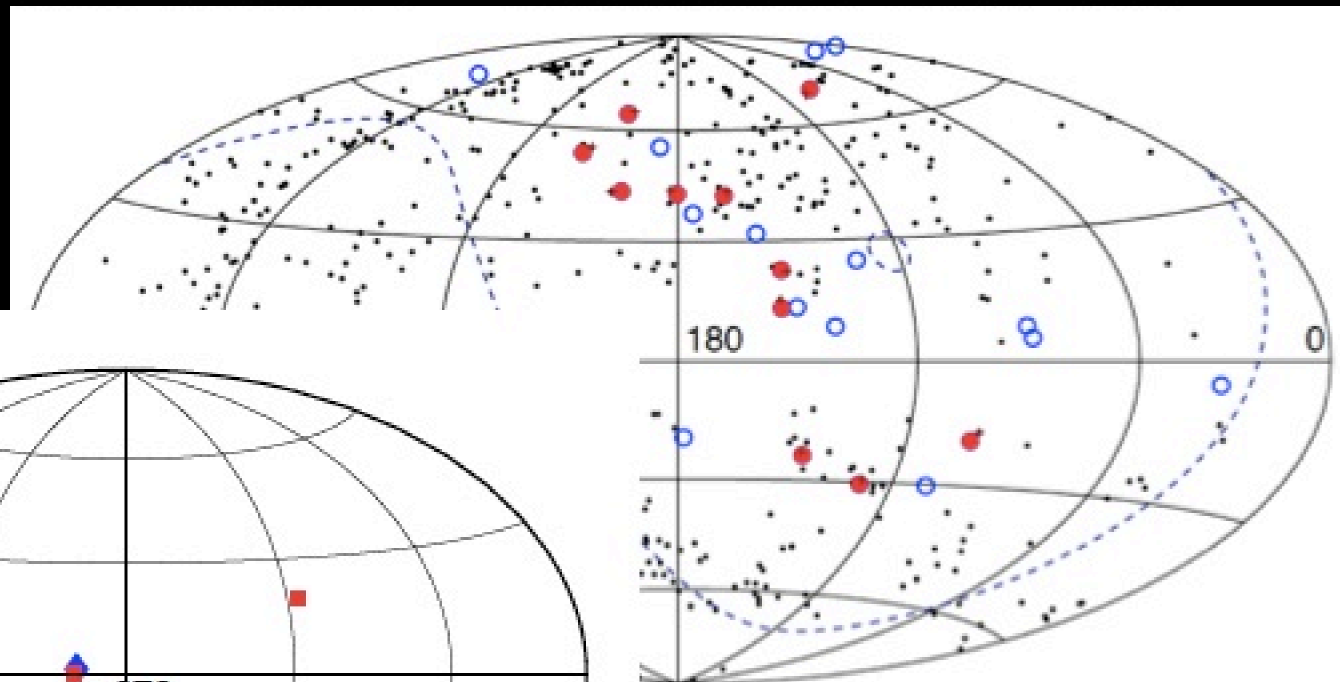
Distribution of Galaxies

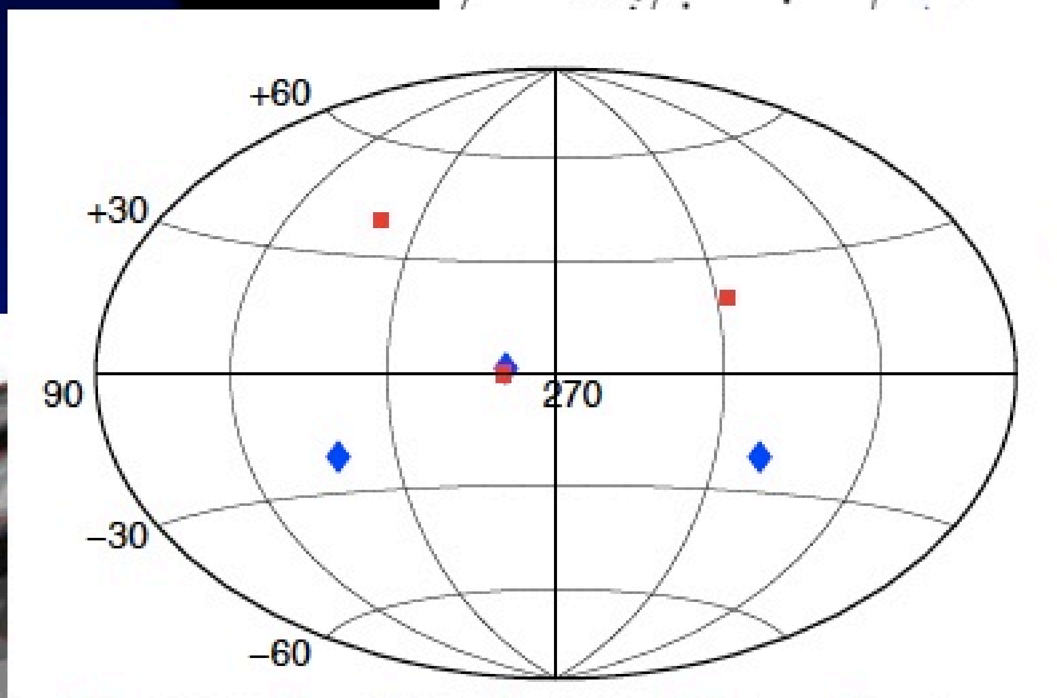


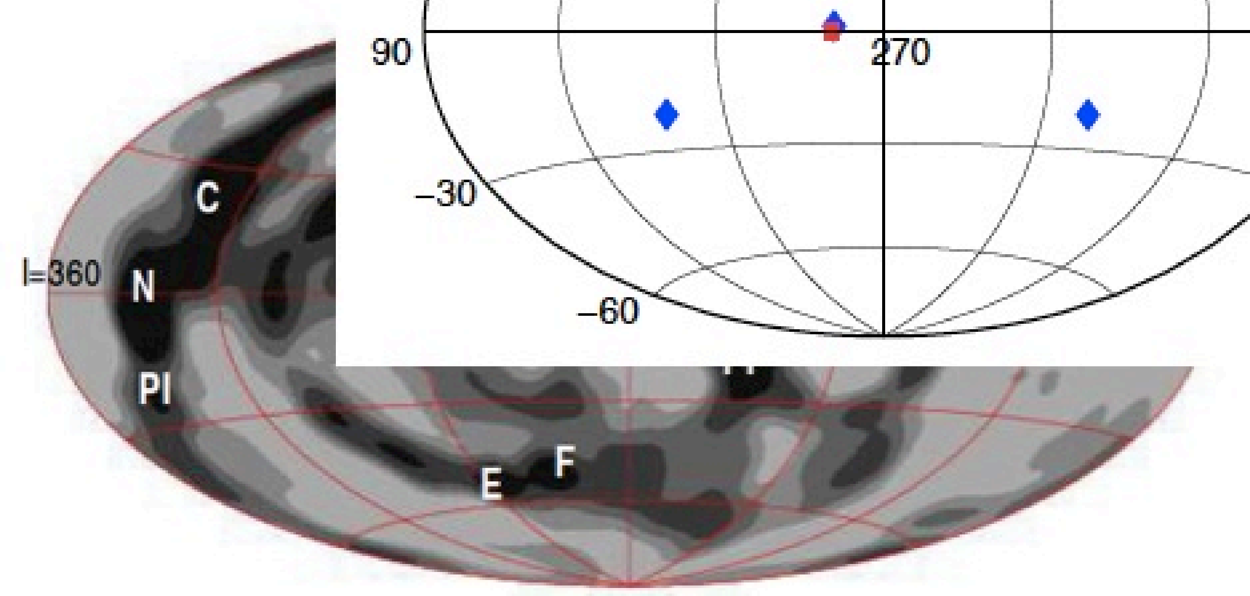
E > 6×10^{19} eV

Telescope Array

May 29, 2012: 25 events above 57 EeV consitent with LSS







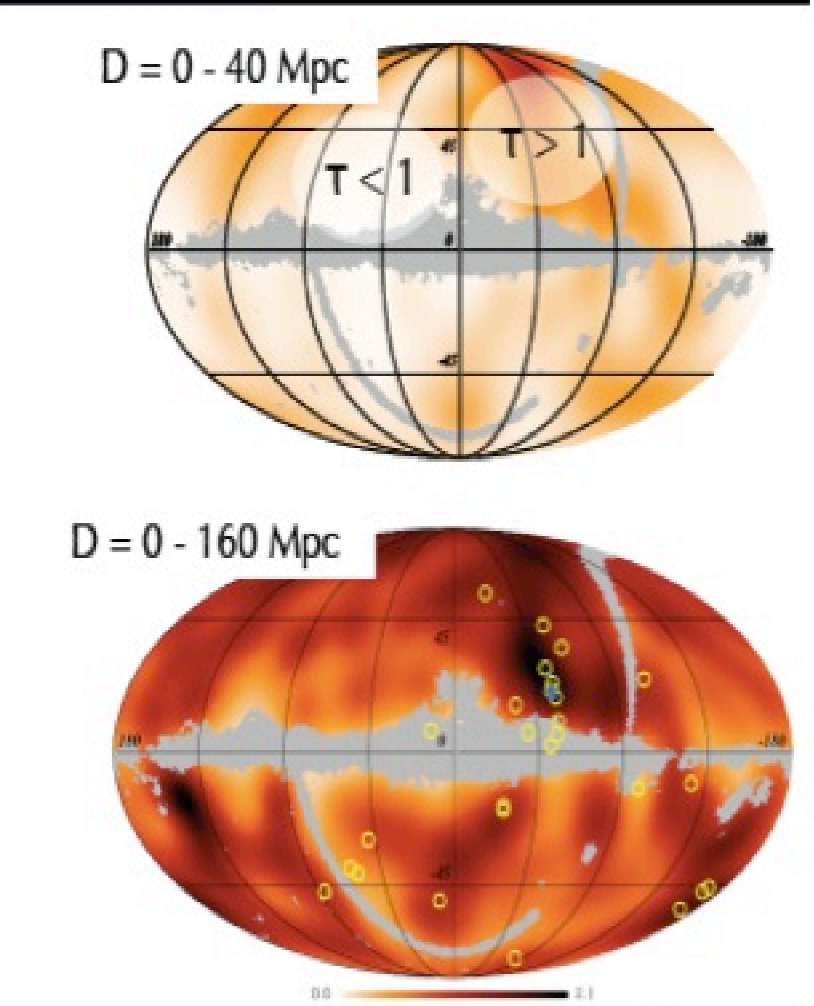
above 100 EeV

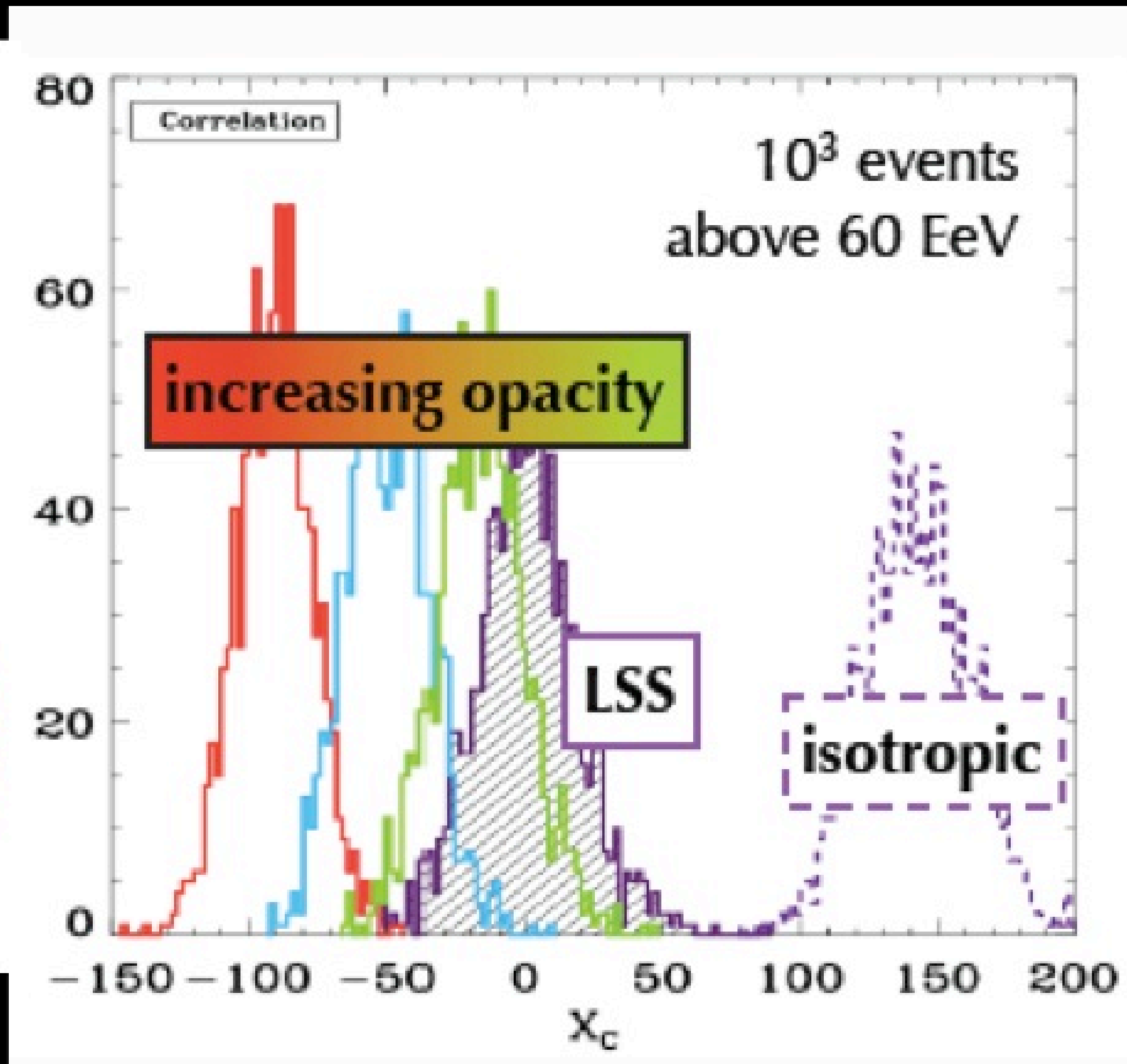
Auger/TA doublet

$P \approx 3.7 \times 10^{-3}$

Troitsky ‘ May 29 ‘12

Population Separation: need 1,000 events above 60 EeV

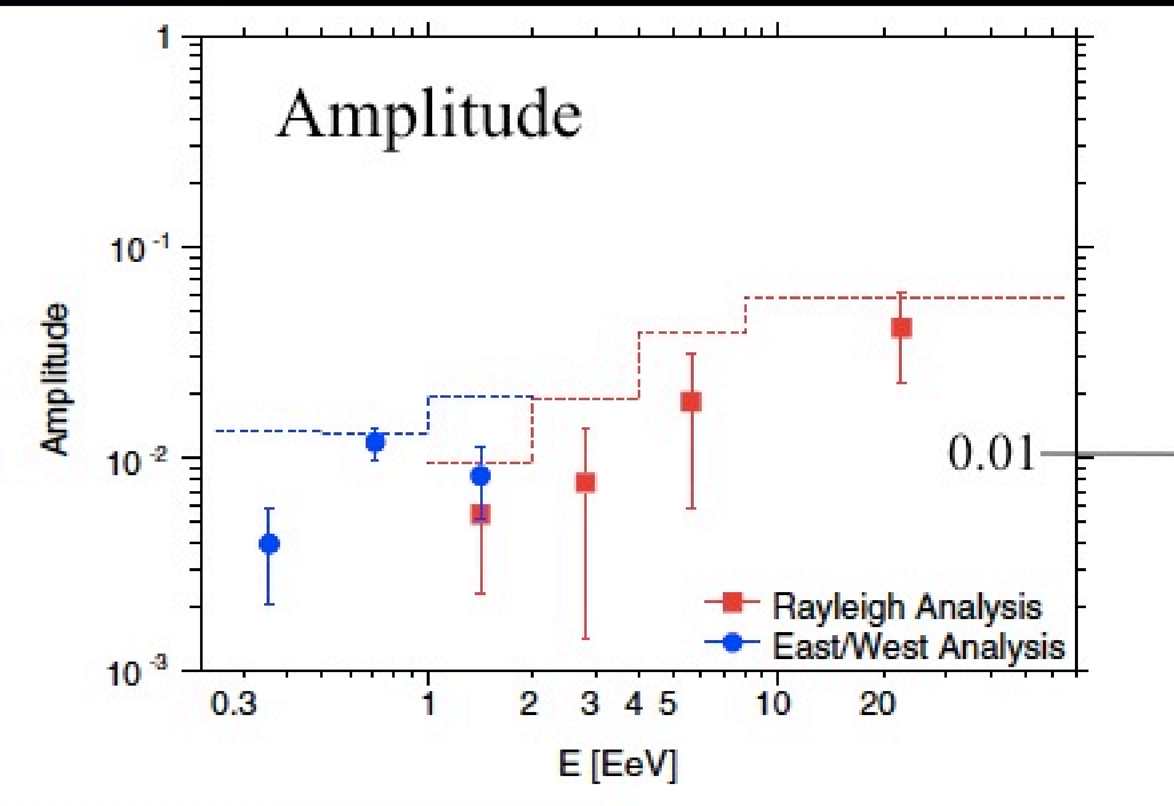




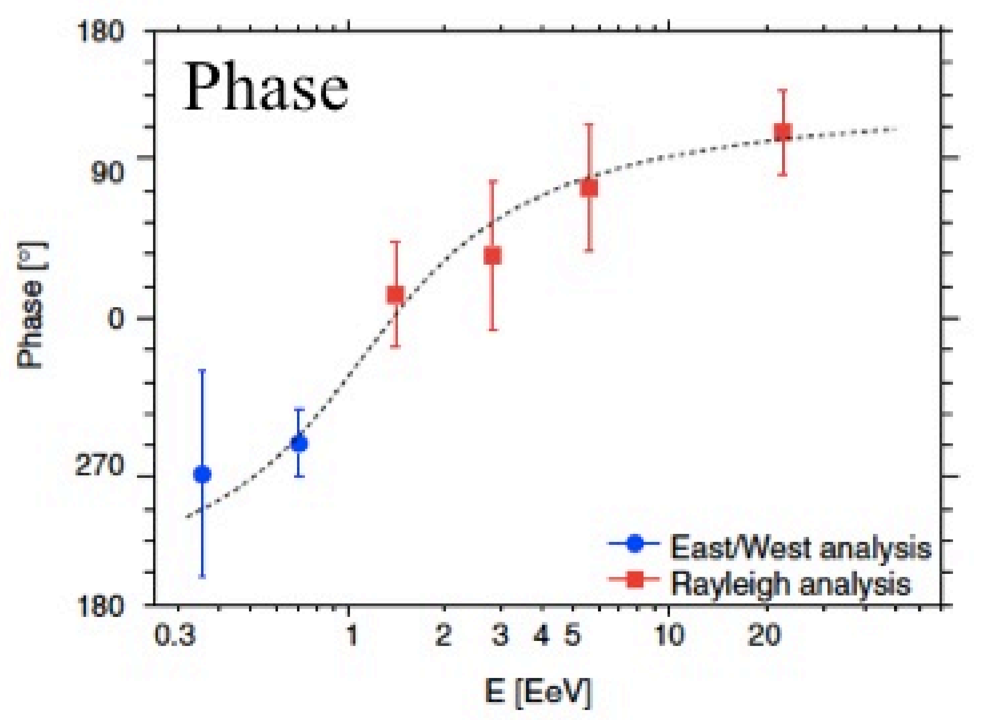
Kalli, Lemoine, Kotera '10

$$X_C = \sum_{i=1}^{N_{tot}} \frac{(N_i^{\mathrm{T}} - \langle N_{i,\mathrm{LSS}}\rangle)(\langle N_{i,\mathrm{iso}}\rangle - \langle N_{i,\mathrm{LSS}}\rangle)}{\langle N_{i,\mathrm{LSS}}\rangle}$$

Auger Dipole Measurement



P. Abreu et al. '11



coherent phase shift

How many UHECRs > 60 EeV

- Before we see a source?
- 1,000 is a good o.o.m. estimate

- Dipole from direction of Cen A in Auger > 60 EeV:
- (a posteriori) right ascension harmonic analyses

Anchordoqui, Goldberg & Weiler '11

$$\alpha_d \, \hat{d} = \frac{3}{\mathcal{N}} \int J(\hat{u}) \, \hat{u} \, d\Omega$$

$\alpha_d = 0.25$

- 5σ discovery requires 1,000 events
- (over the whole sky coverage)

How many UHECRs > 60 EeV?

- Auger w/ 3,000 km^2
- (annual exposure of 6,000 km^2 sr yr)
- ~20 events > 55 EeV/ yr
- Telescope Array w/ 700 km^2
- (annual exposure of ~ 1,400 km^2 sr yr)
- ~4.6 events > 55 EeV/ yr
- ~ 30 events/year – 30 years to reach 1000.

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- Earth – land ~1.5 10^8 km^2 = 5 10^4 Auger
- 10^6 events/yr
  - full surface ~5.1 10^8 km^2 = 1.7 10^5 Auger

    3.4 10^6 events/yr

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- ~20 events > 55 EeV/ yr
- Telescope Array w/ 700 km^2
- (annual exposure of ~ 1,4[illegible] km
- ~4.6 events > 55 EeV/ yr
- ~ 30 events/year - 30 years to reach 1000
- Earth land ~1.5 10^8 km^2 = 5 10^4 Auger
- 10^6 events/yr
  - full surface ~5.1 10^8 km^2 = 1.7 10^5 Auger
    3.4 10^6 events/yr

5 o.o.m to go!

Ultrahigh Energy Cosmic Rays

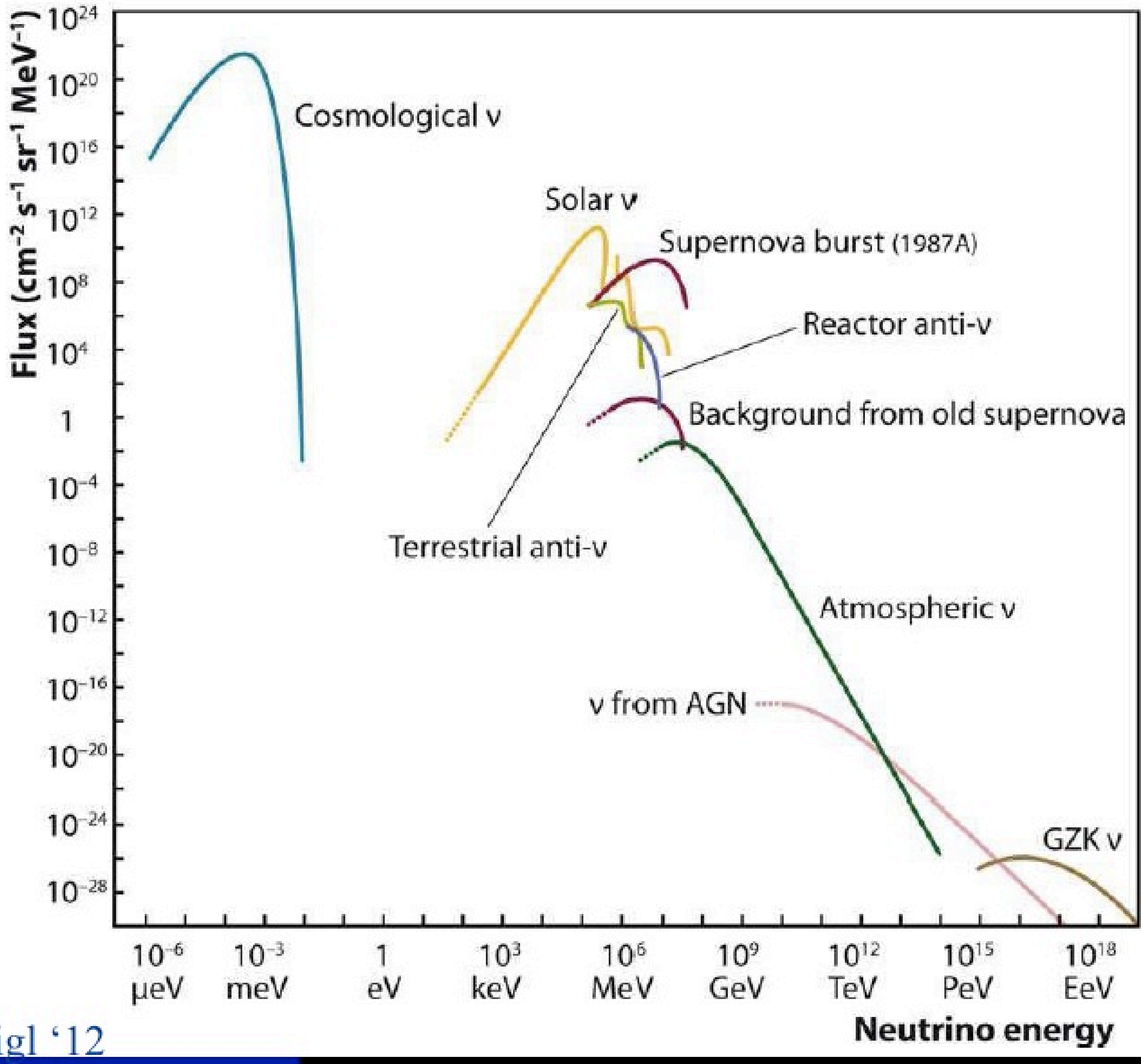
OBSERVABLES:

Spectrum

Composition

Sky Distribution

Multi-messengers

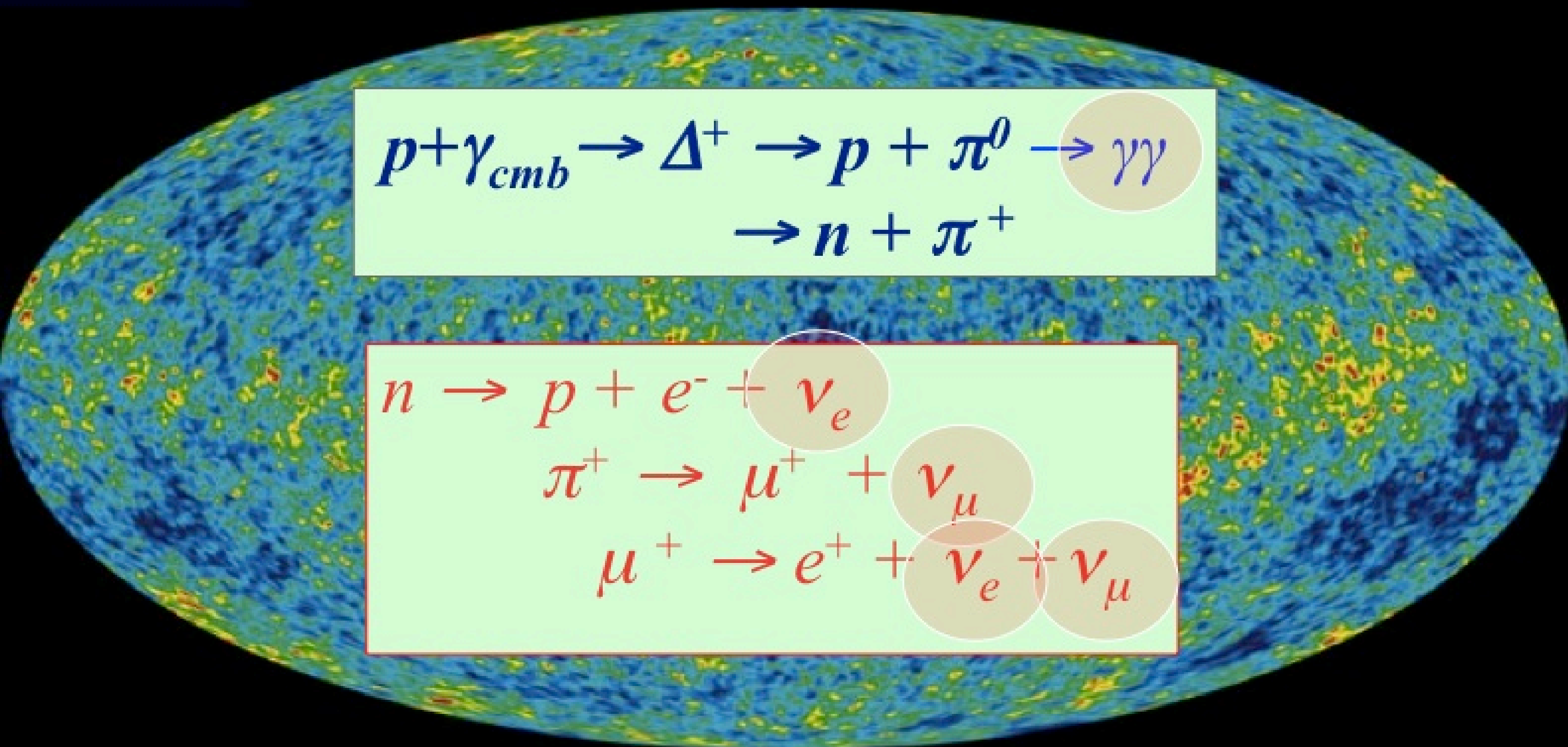


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
10^-6 μeV
10^-3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy

Sigl '12

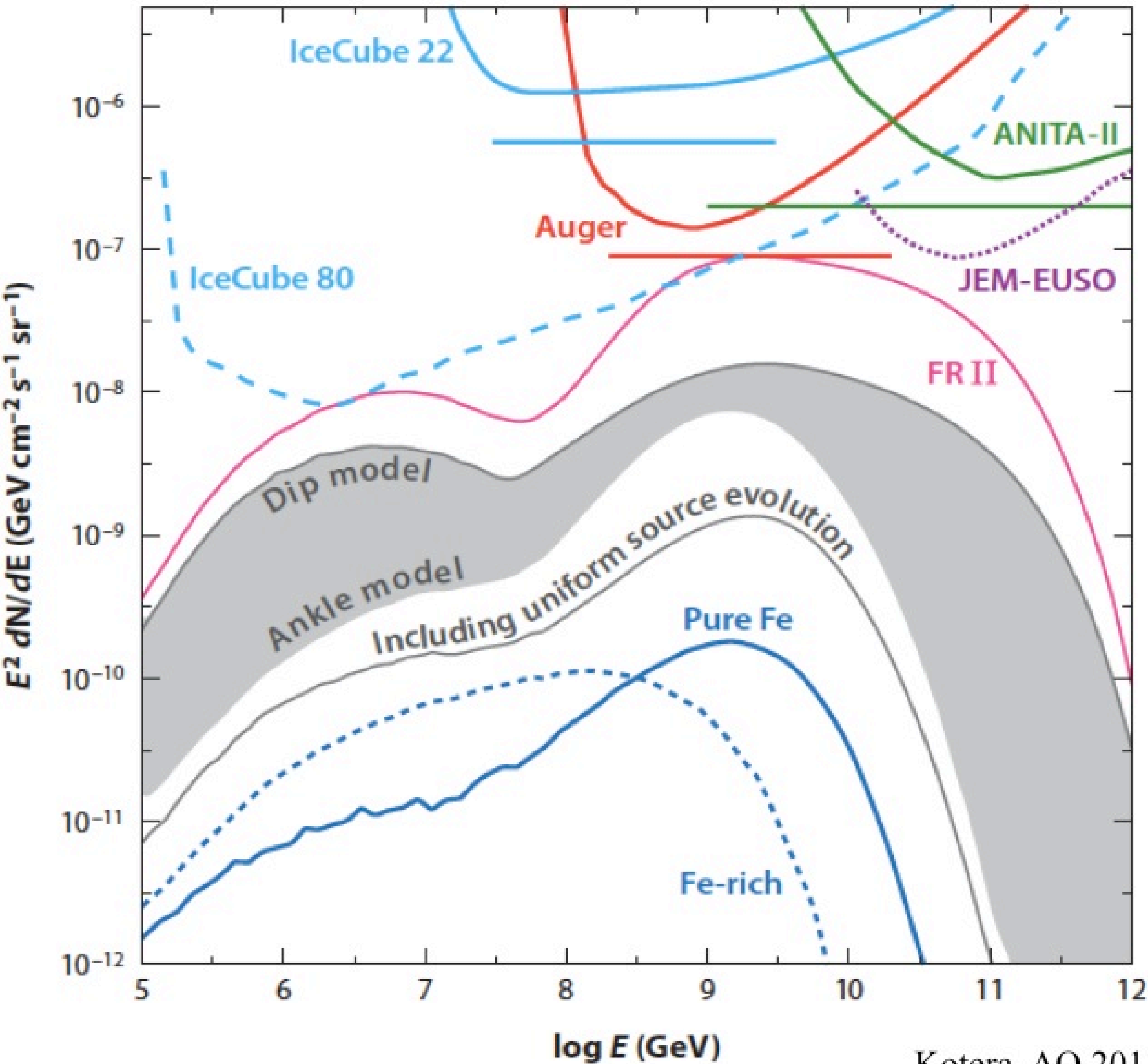
Cosmogenic (GZK) Neutrinos & Photons

and UHECR composition

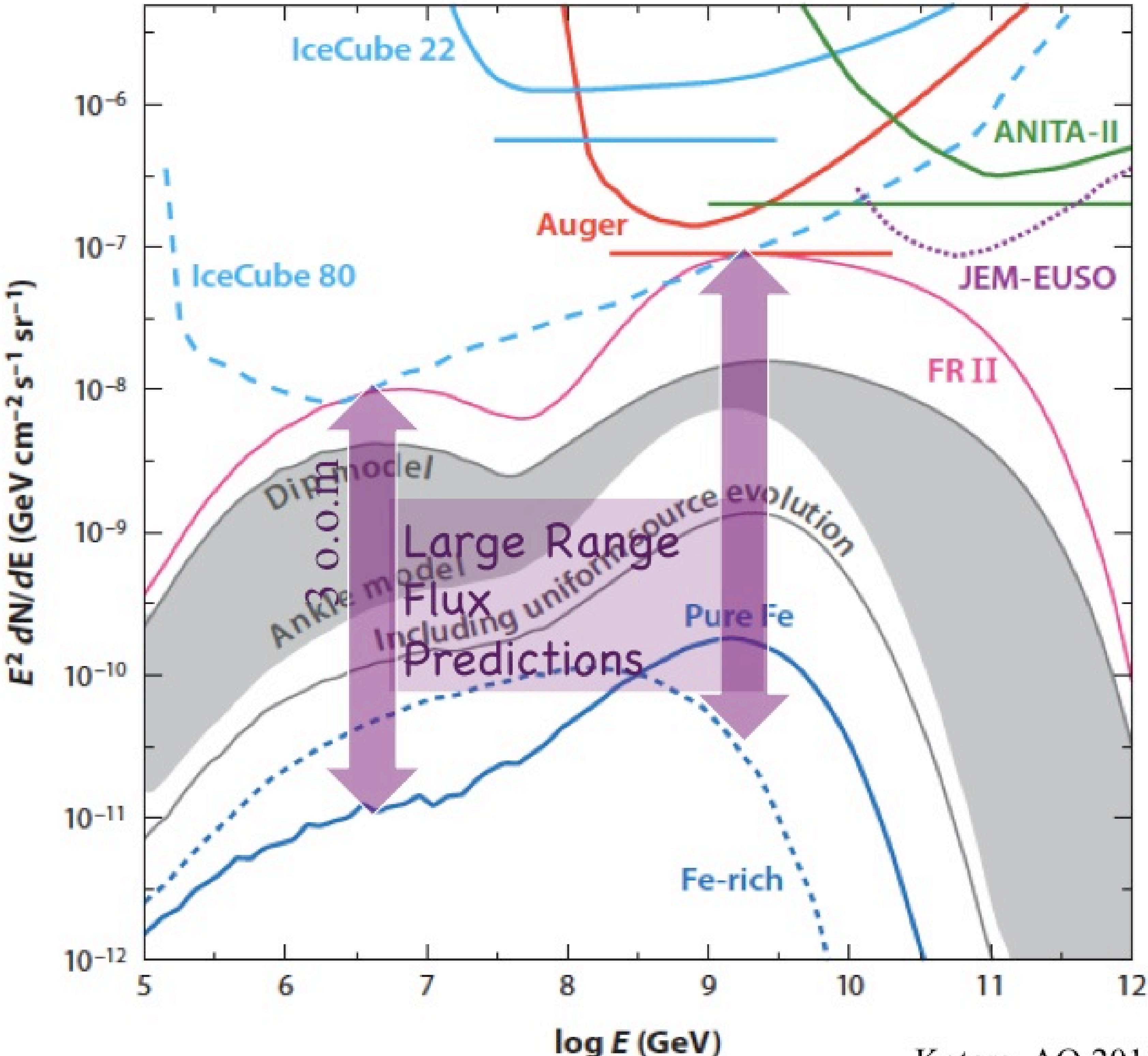


$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

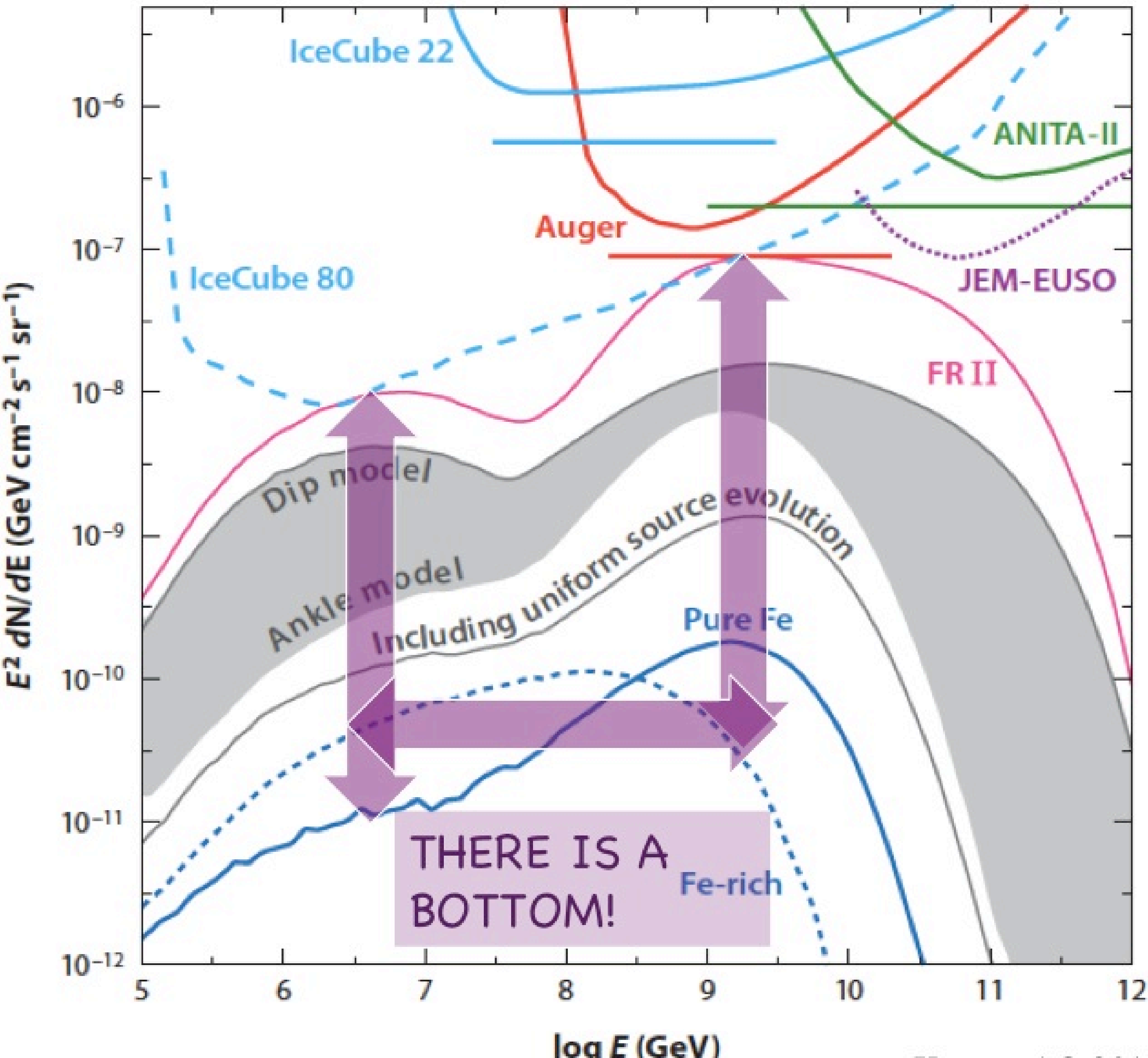
$$n \rightarrow p + e^{-} + \nu_{e}$$
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu}$$



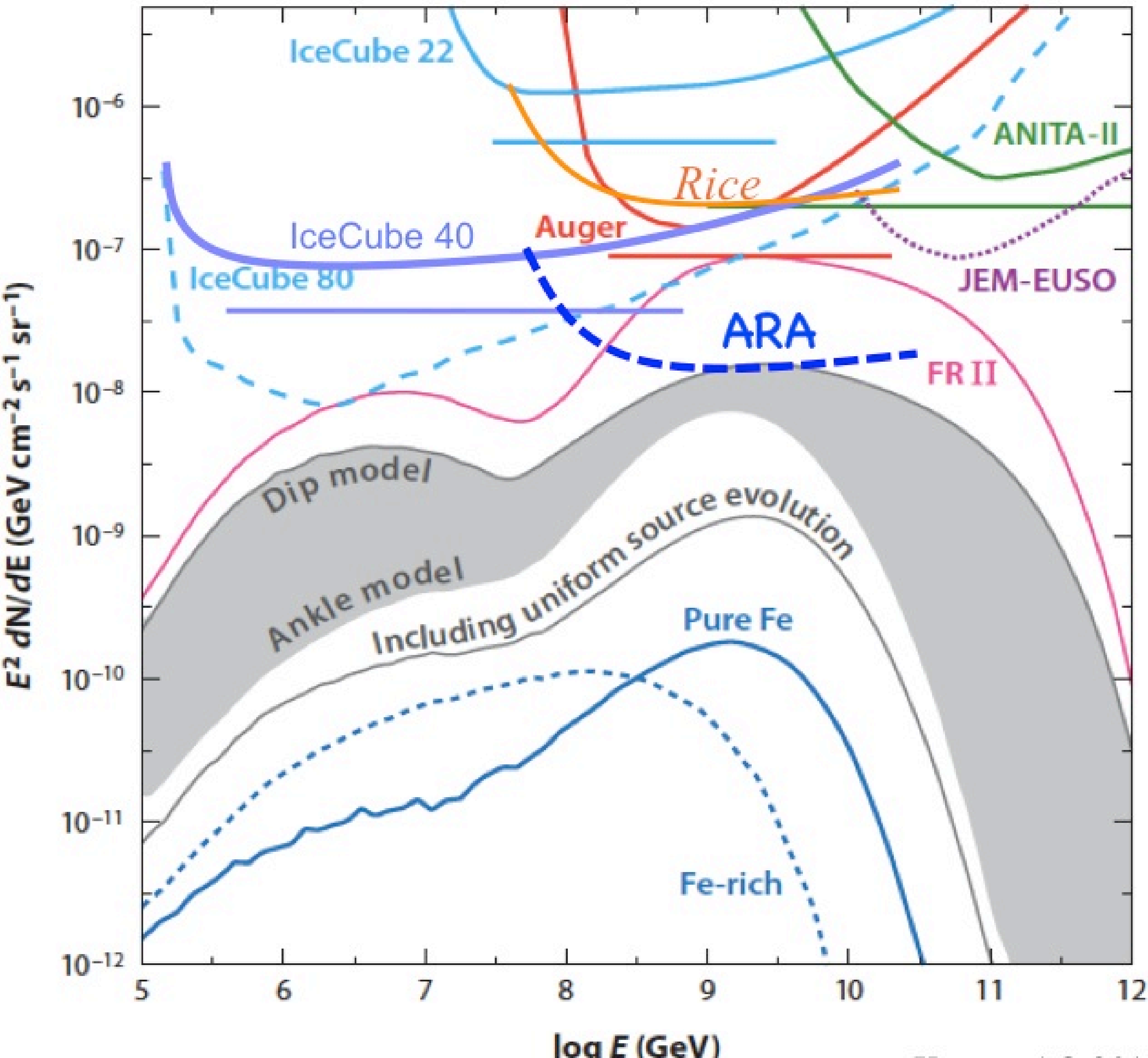
Kotera, AO 2011



Kotera, AO 2011



Kotera, AO 2011

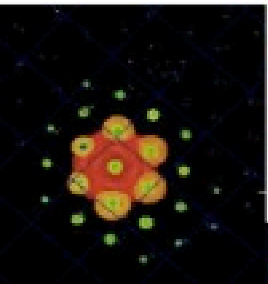


Kotera, AO 2011

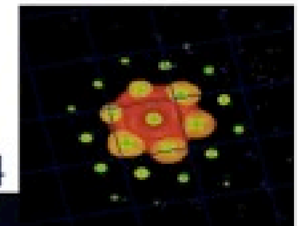
Beginning of PeV Neutrino "Astronomy"?

Two events passed the selection criteria

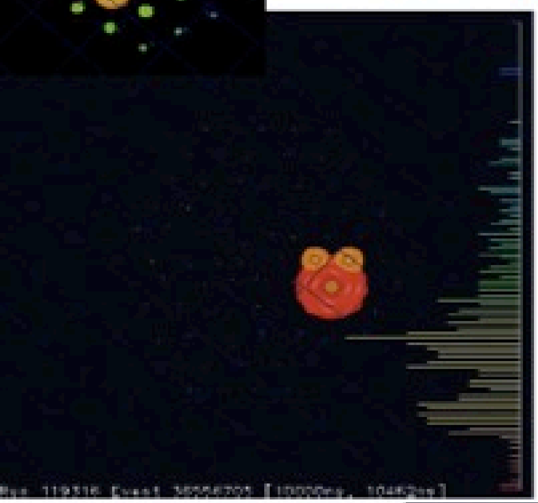
2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events
preliminary p-value: 0.0094 (2.36σ)

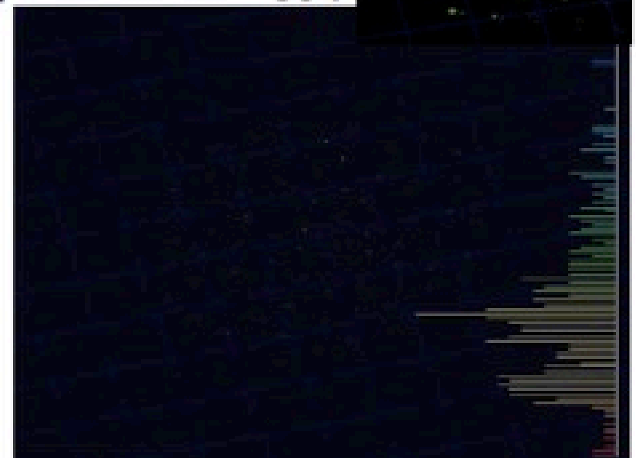


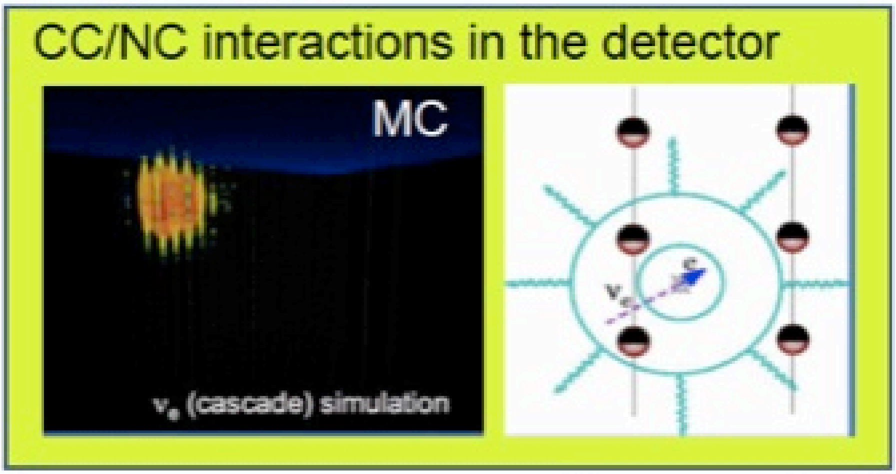
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10⁴
Number of Optical Sensors 312

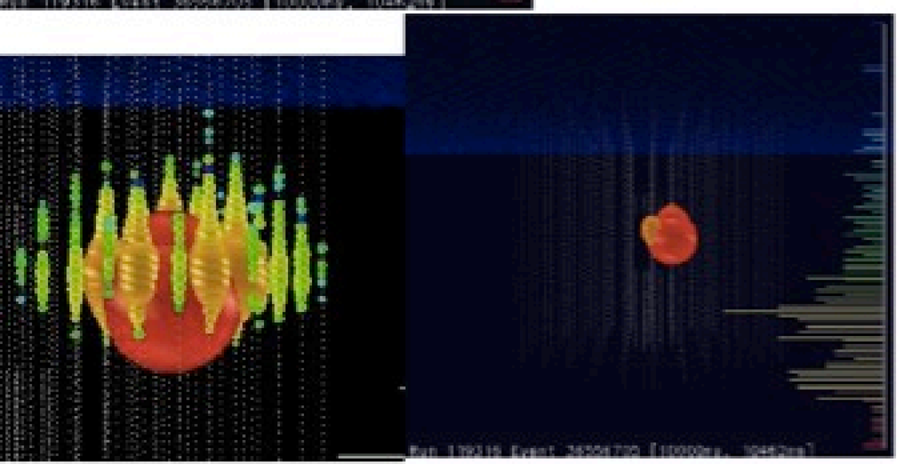


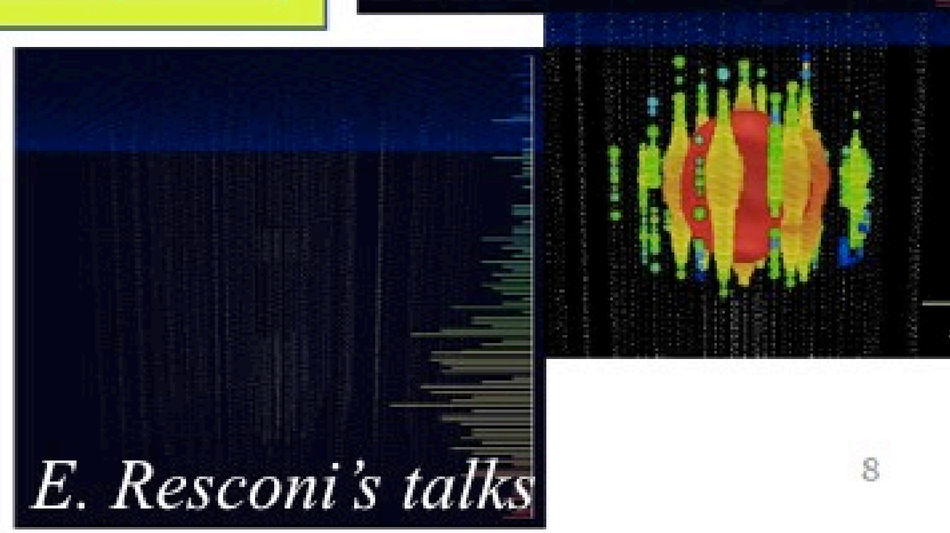
Run118545-Event63733662
August 9th 2011
NPE 6.9928x10⁴
Number of Optical Sensors 354





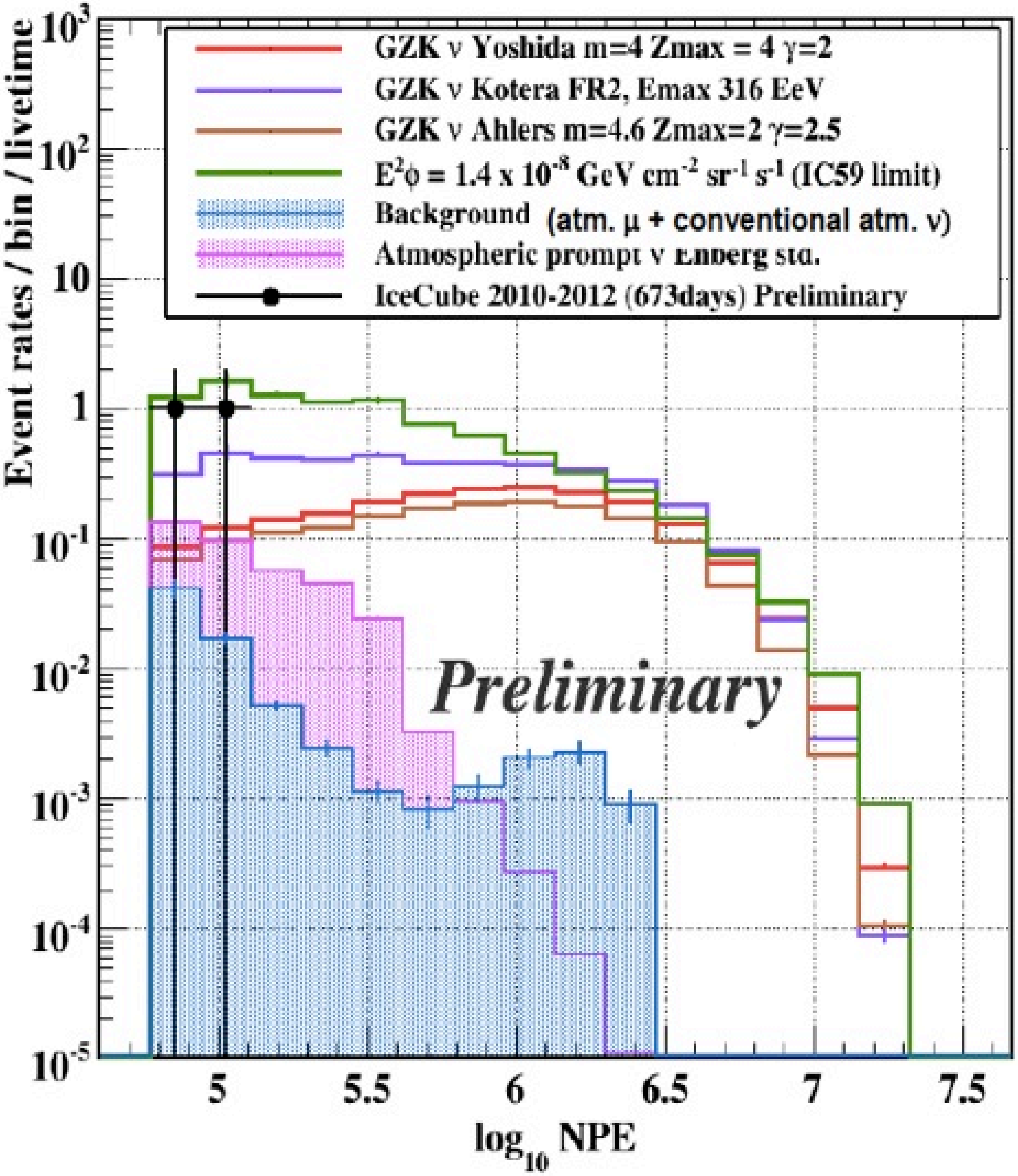




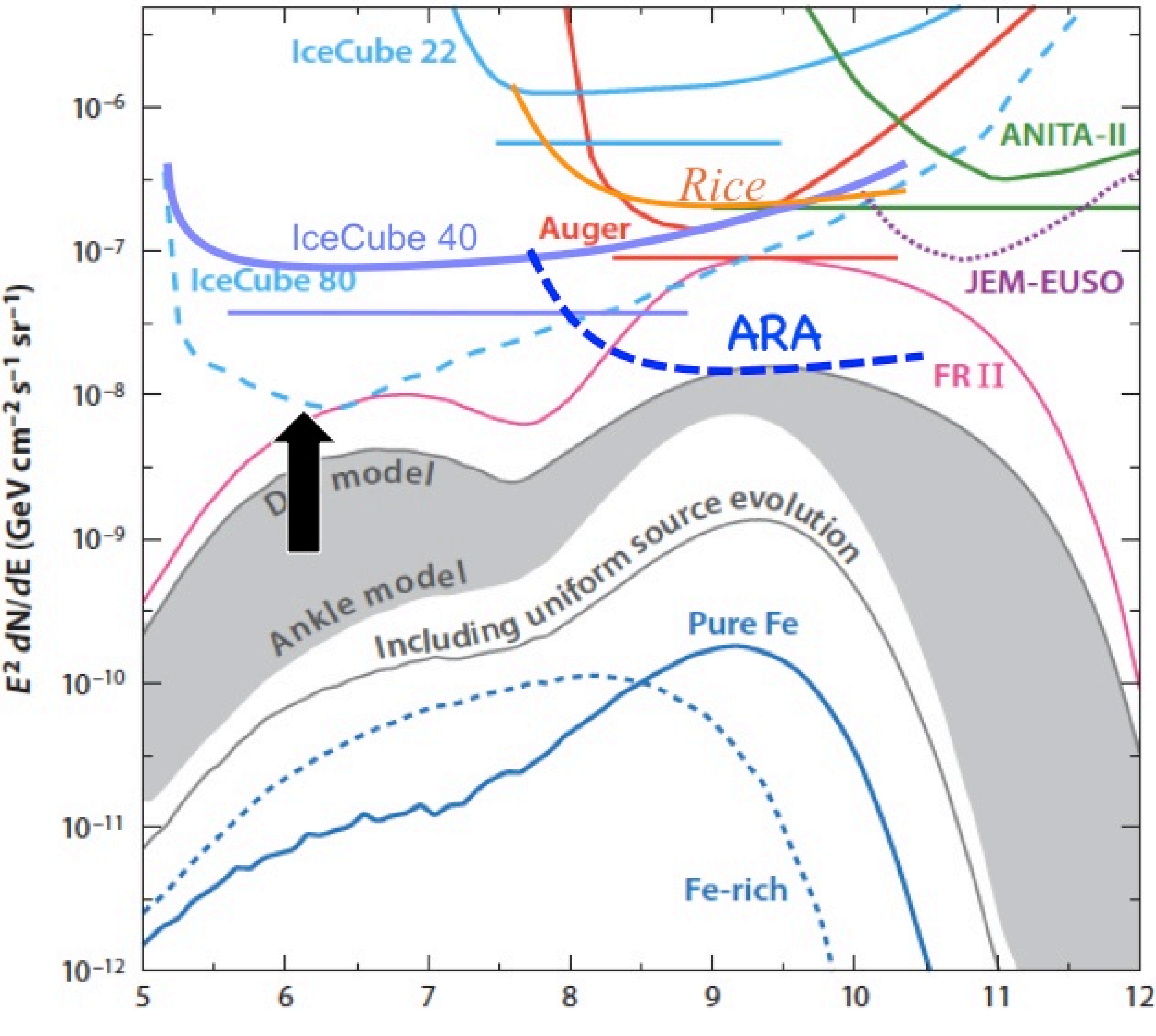


E. Resconi's talks

Event Brightness (NPE) Distributions 2010-2012

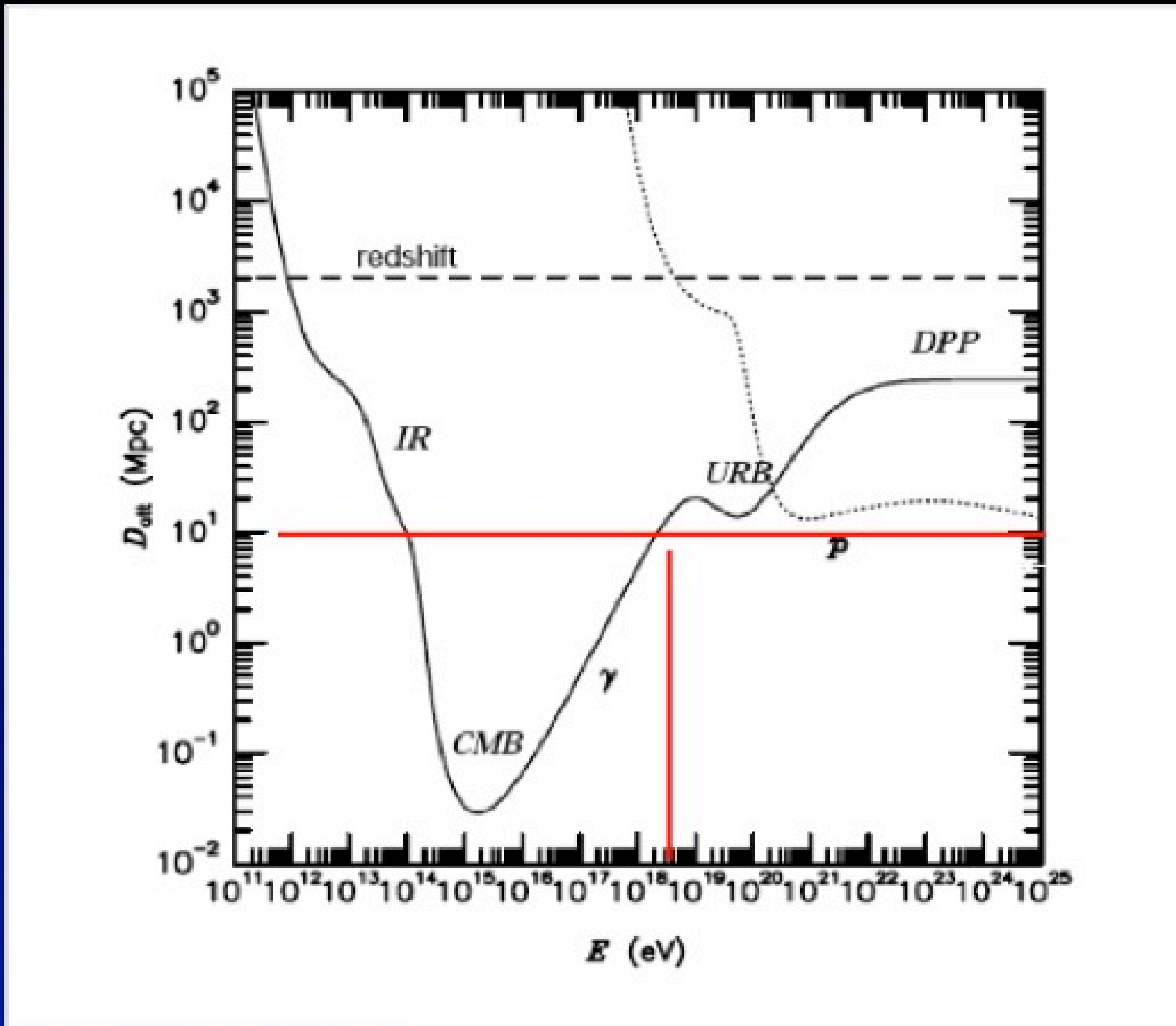


- Observed 2 high NPE events near the NPE threshold
- **No** indication
  - that they are instrumental artifacts
  - that they are cosmic-ray muon induced
- Possibility of the origin includes
  - cosmogenic ν
  - on-site ν production from the cosmic-ray accelerators
  - atmospheric prompt ν
  - atmospheric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



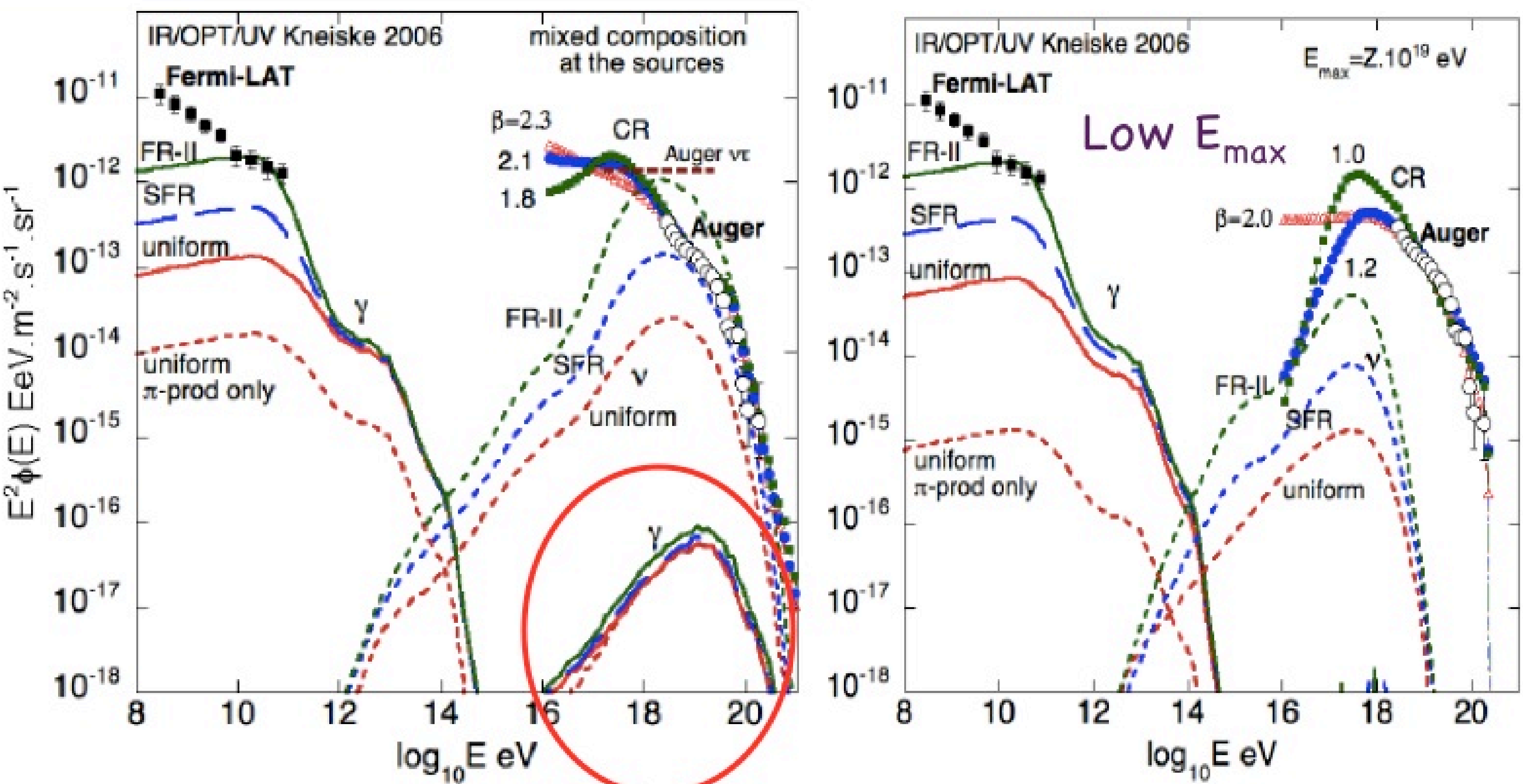
Kotera, AO 2011

The UHE Gamma Ray Astronomical Window



Photon attenuation length 10 Mpc for E > 2 EeV

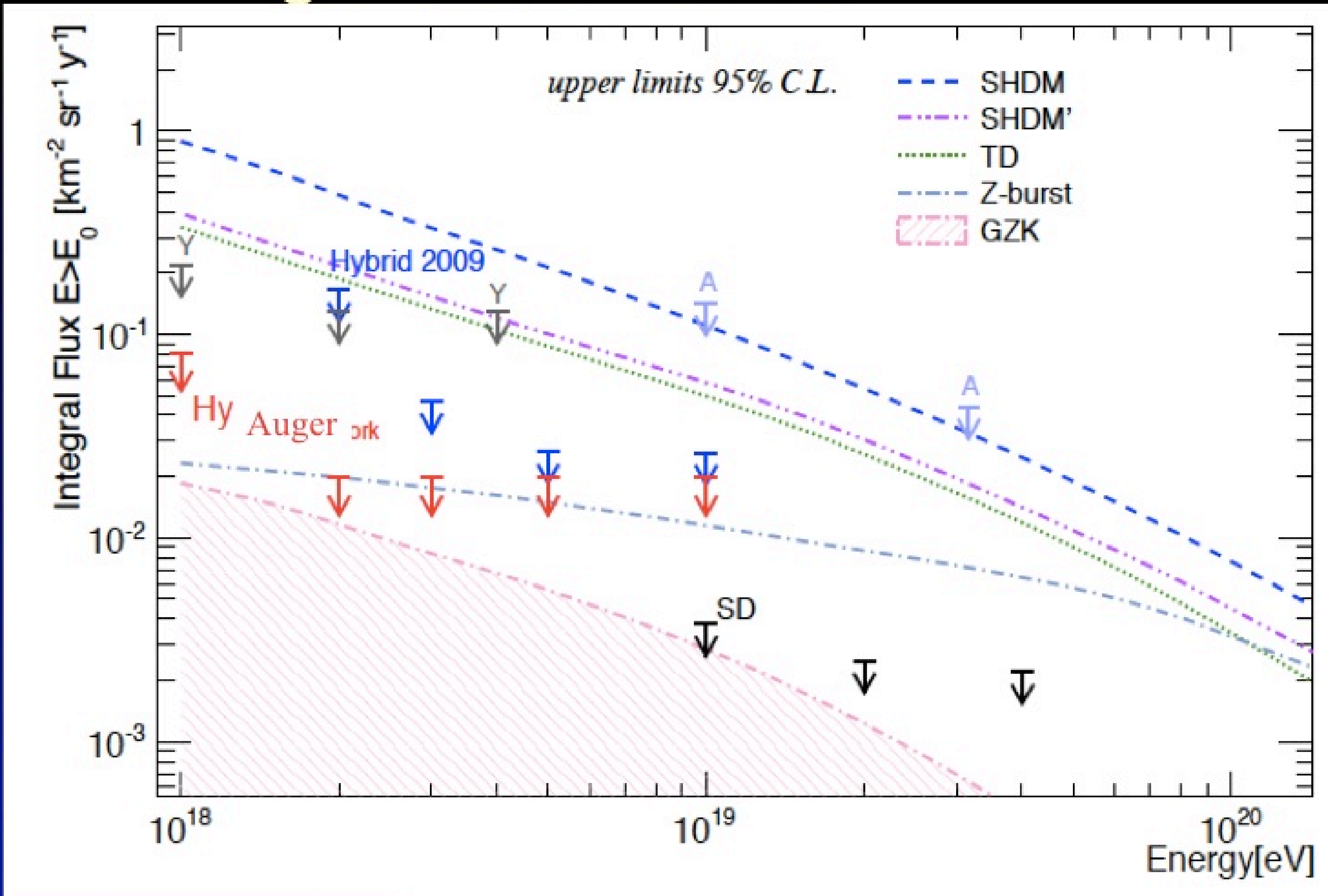
GZK/Cosmogenic Photons



Decerprit & Allard 11

Auger Photon Limits

ICRC11



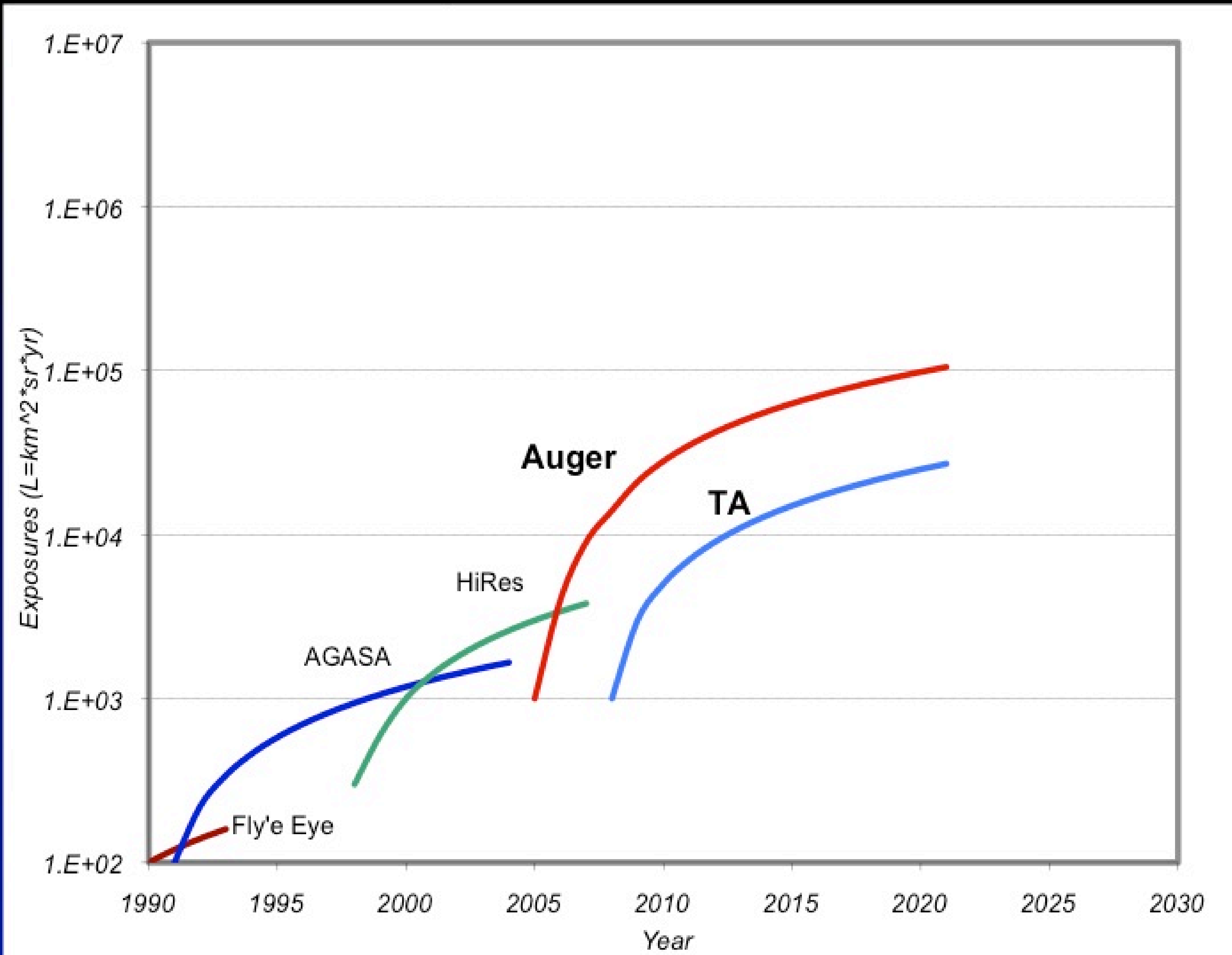
TA consistent (ICRC11)

How many UHECRs > 60 EeV?

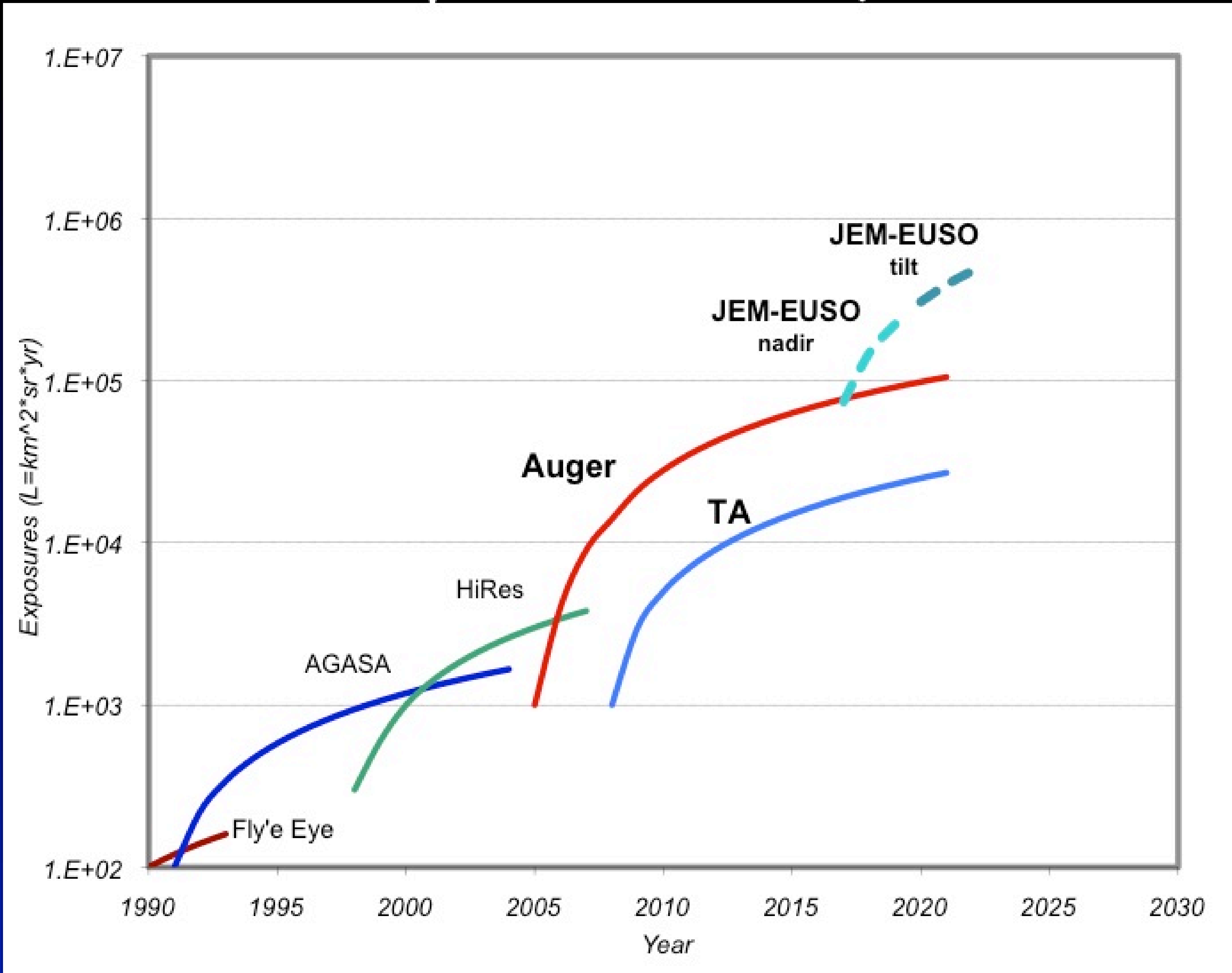
- Auger w/ 3,000 km^2
- (annual exposure of 6,000 km^2 s
- ~20 events > 55 EeV/ yr
- Telescope Array w/ 700 km^2
- (annual exposure of ~ 1,4?? km
- ~4.6 events > 55 E... / yr
- ~ 30 events/year → 30 years to reach 1000
- Earth land ~1.5 10^8 km^2 = 5 10^4 Auger
  - 10^6 events/yr
  - – full surface ~5.1 10^8 km^2 = 1.7 10^5 Auger
    - 3.4 10^6 events/yr

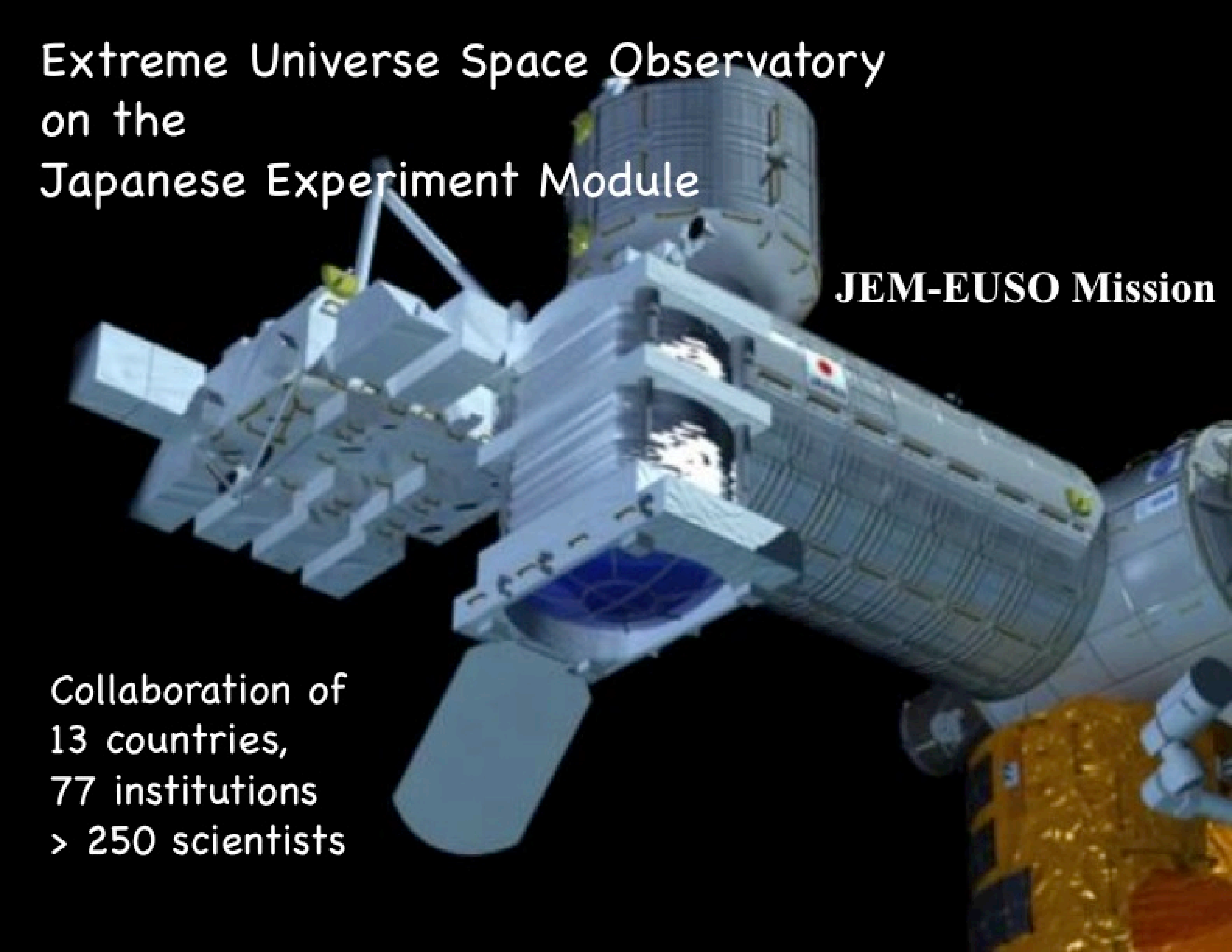
5 o.o.m to go!

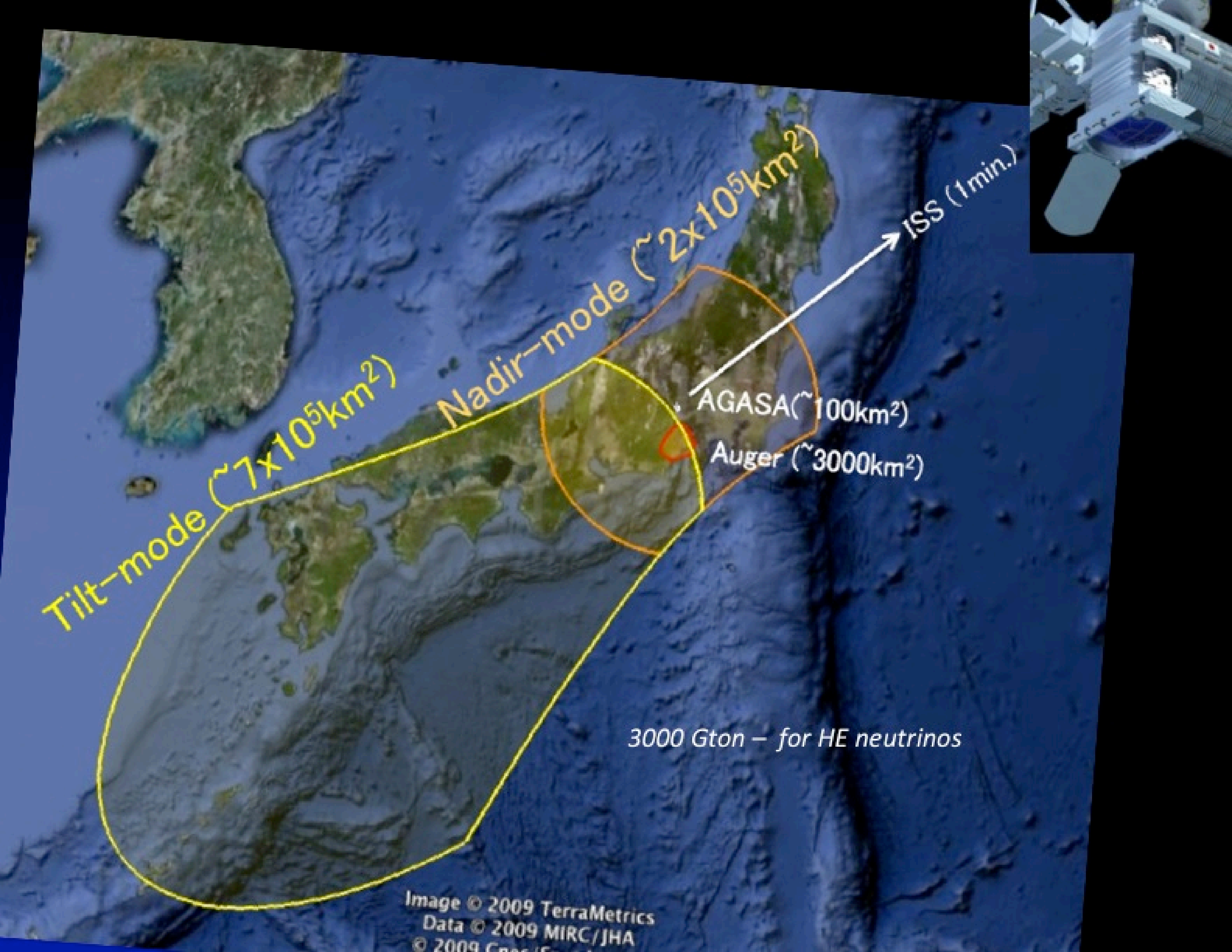
Exposure History



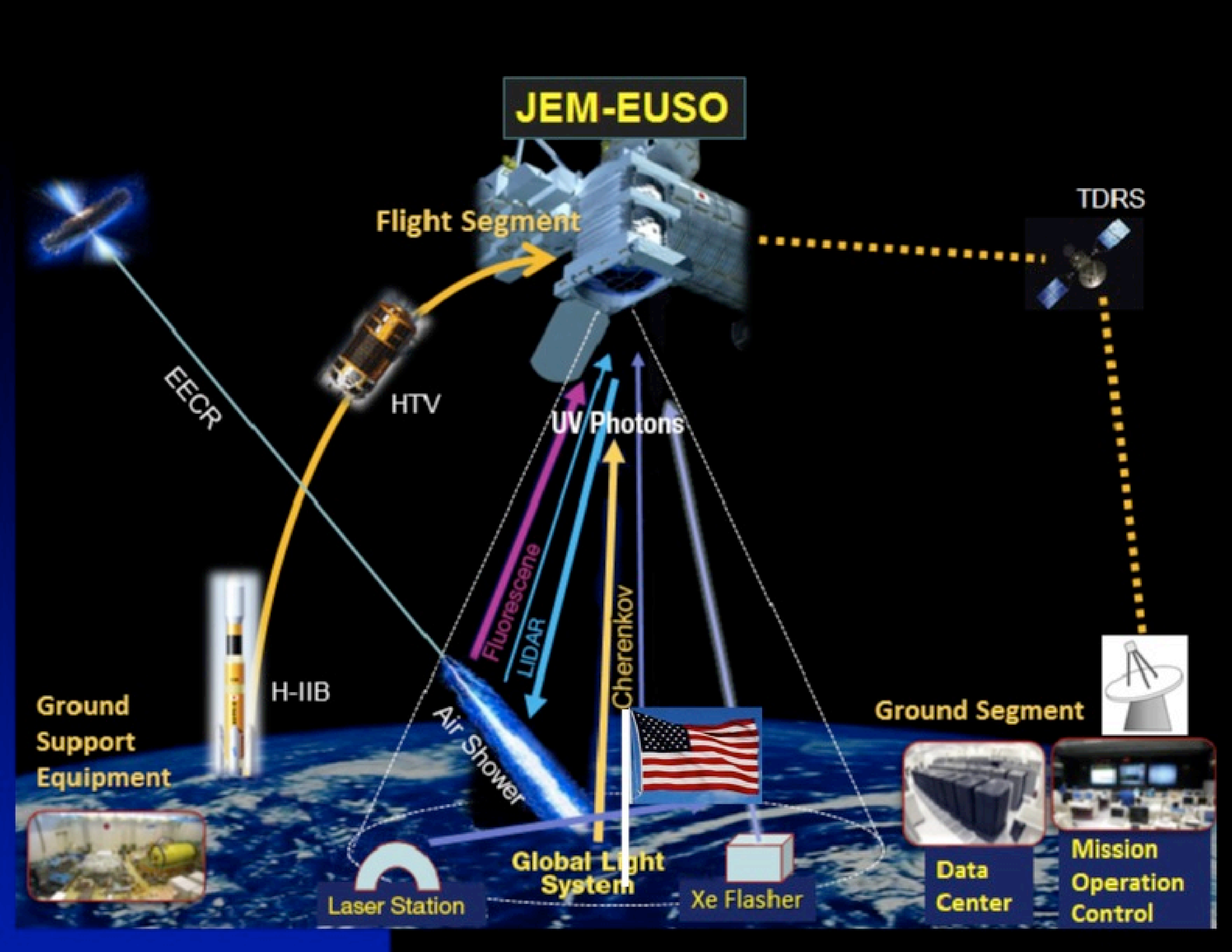
Exposure History




Extreme Universe Space Observatory
on the
Japanese Experiment Module
JEM-EUSO Mission
Collaboration of
13 countries,
77 institutions
> 250 scientists

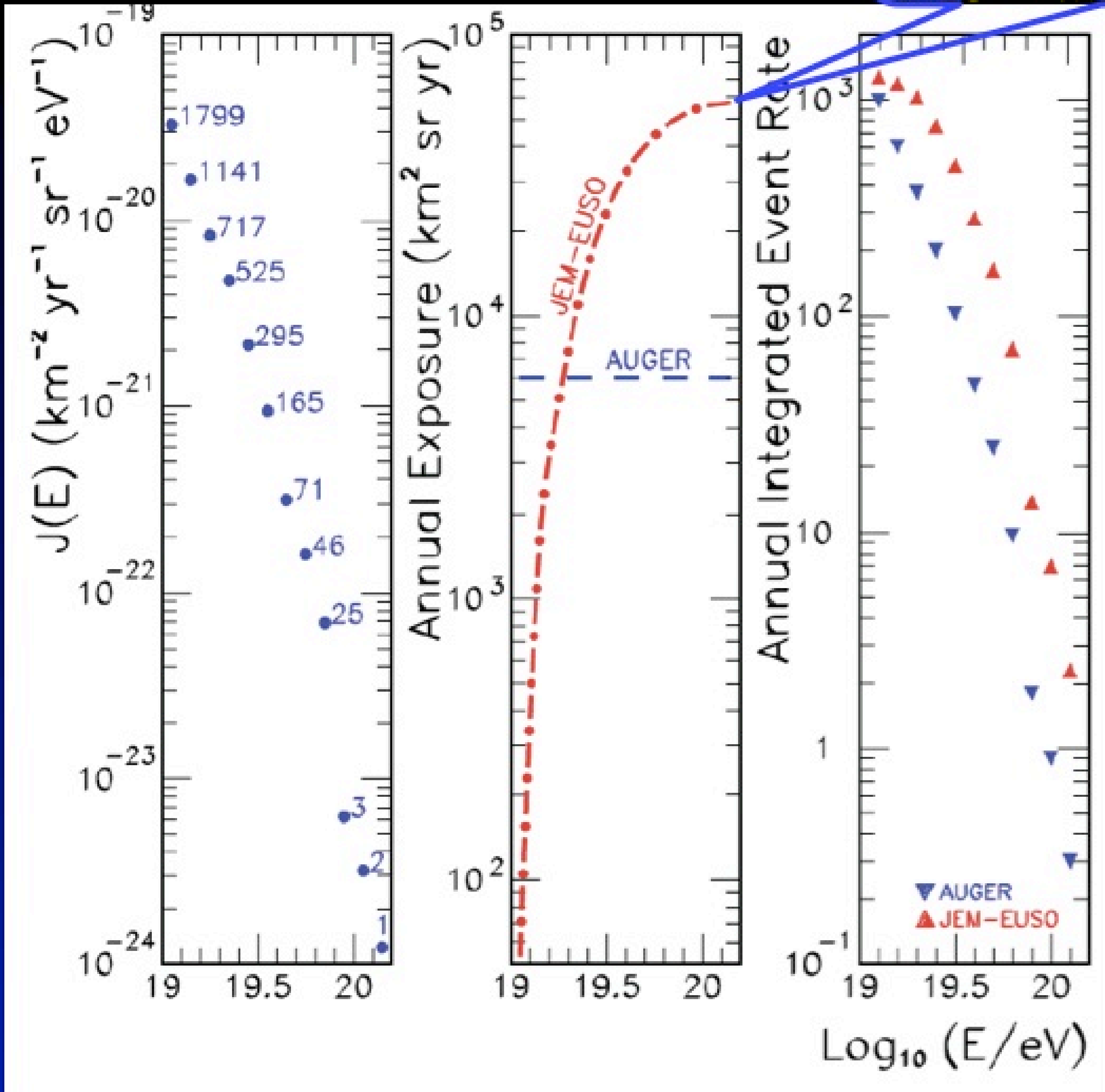


Tilt-mode (~7x10^5km^2)
Nadir-mode (~2x10^5km^2)
ISS (1min.)
AGASA(~100km^2)
Auger (~3000km^2)
3000 Gton – for HE neutrinos
Image © 2009 TerraMetrics
Data © 2009 MIRC/JHA


JEM-EUSO
Flight Segment
TDRS
HTV
EECR
UV Photons
Fluorescene
LIDAR
Cherenkov
H-IIB
Air Shower
Ground Support Equipment
Ground Segment
Global Light System
Laser Station
Xe Flasher
Data Center
Mission Operation Control

JEM-EUSO

annual exposure =
10 x Auger
6 10^4 km2 sr yr



How many UHECRs > 60 EeV?

Auger w/ 3,000 km^2 (A.E. = 6,000 km^2 sr yr)

~20 events > 55 EeV/ yr

~ 1 events > 100 EeV/ yr

Telescope Array w/ 700 km^2 (A.E.~ 1,400 km^2 sr yr)

~5 events > 55 EeV/ yr

JEM-EUSO annual exposure: A.E.= 60,000 km^2 sr yr

at 100 EeV and 80% at 55 EeV

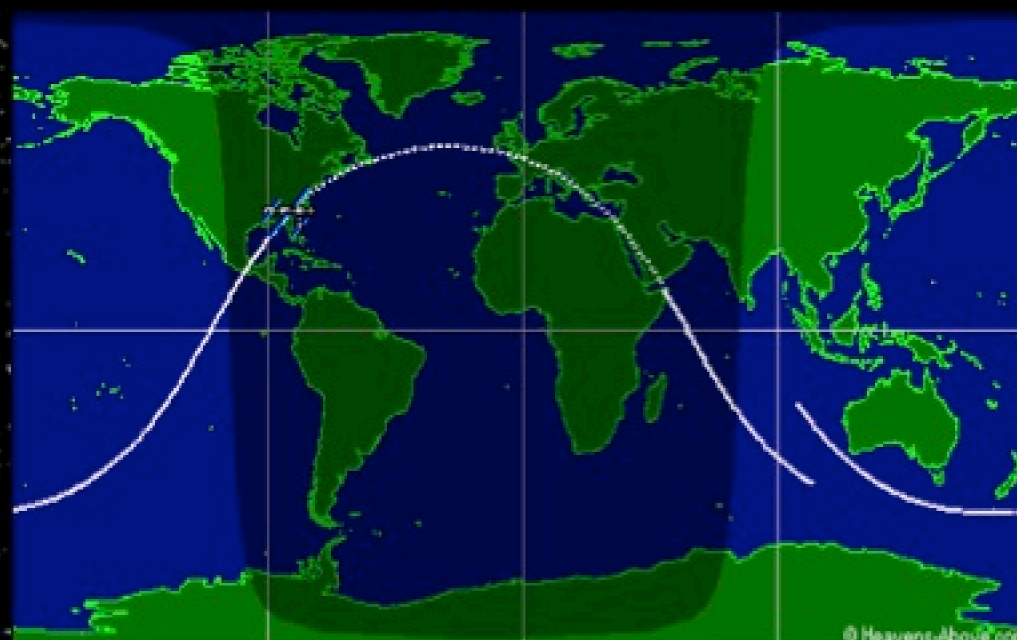
~160 events > 55 EeV/ yr

~ 10 events > 100 EeV/ yr

REACH the magic 1,000 events in ~ 6.25 years over the full sky

Full Sky Coverage
with nearly uniform exposure

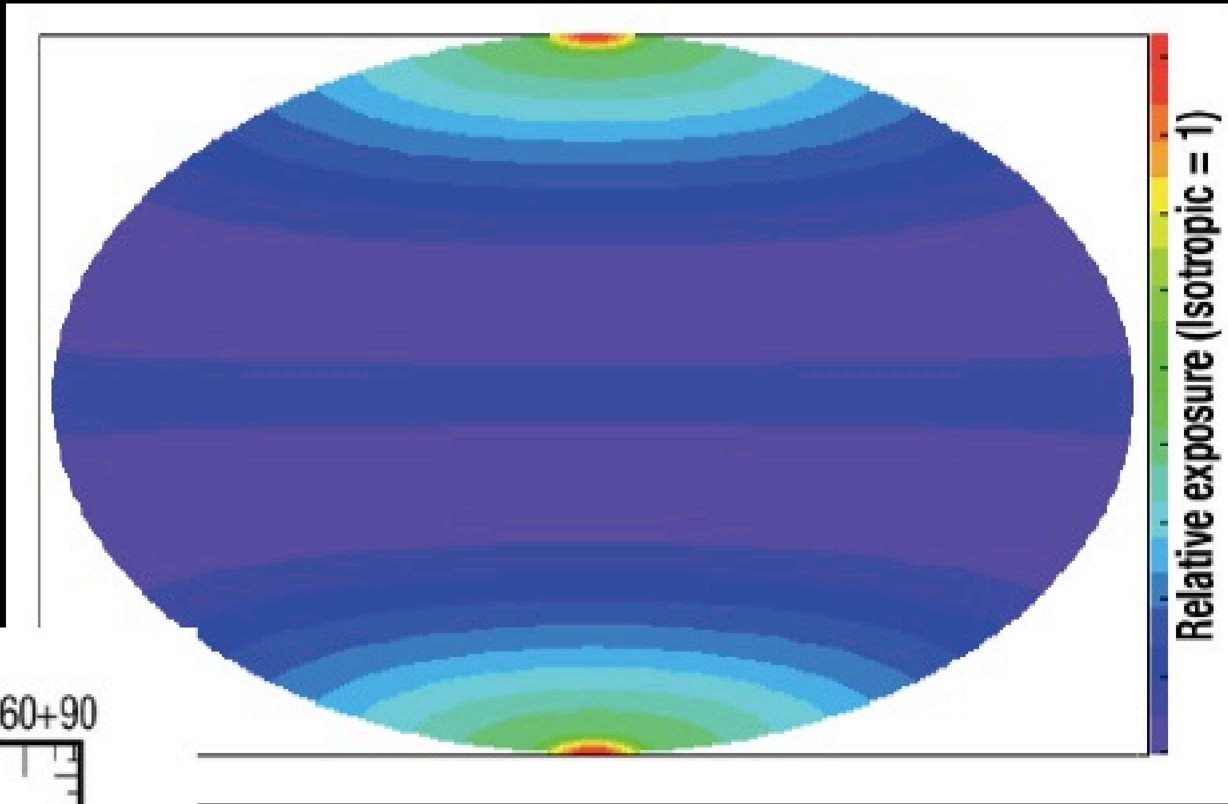
The ISS ORBIT

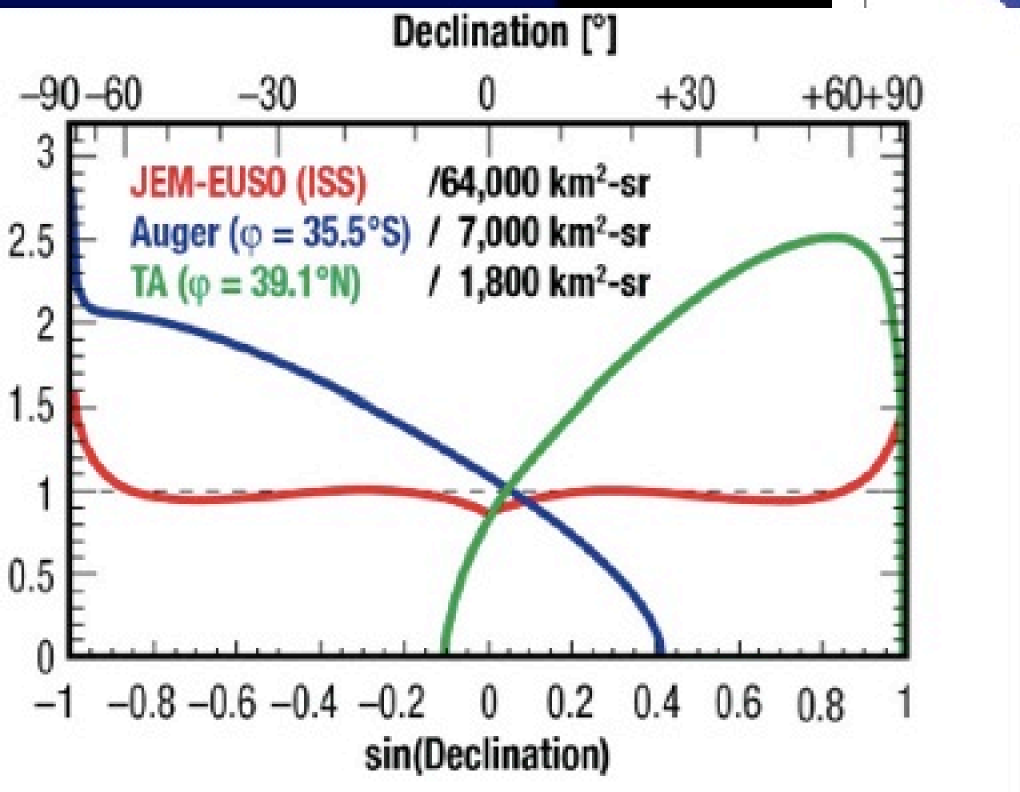


Inclination: 51.6°
Height: ~400km

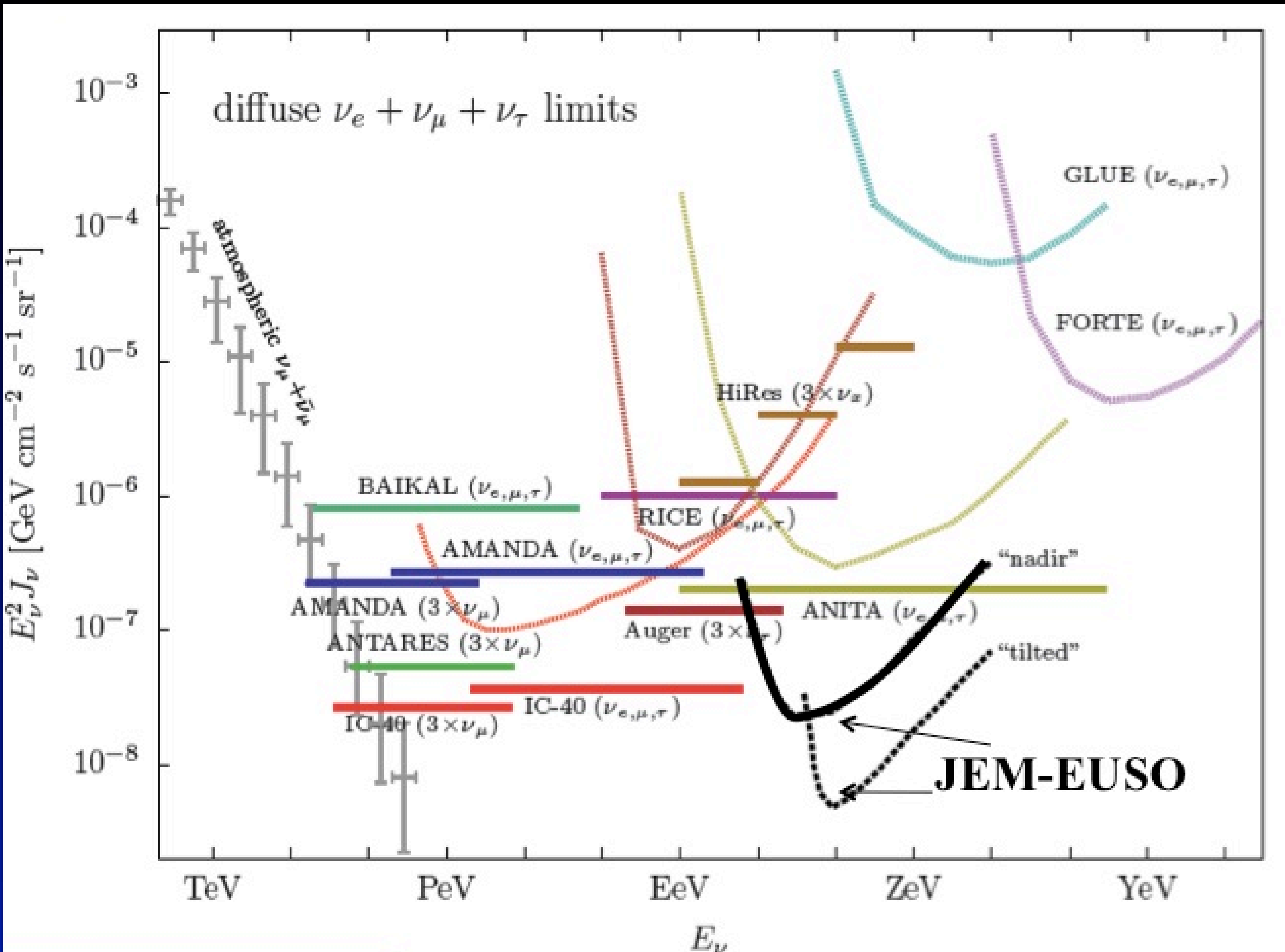
JEM-EUSO

- Full sky coverage



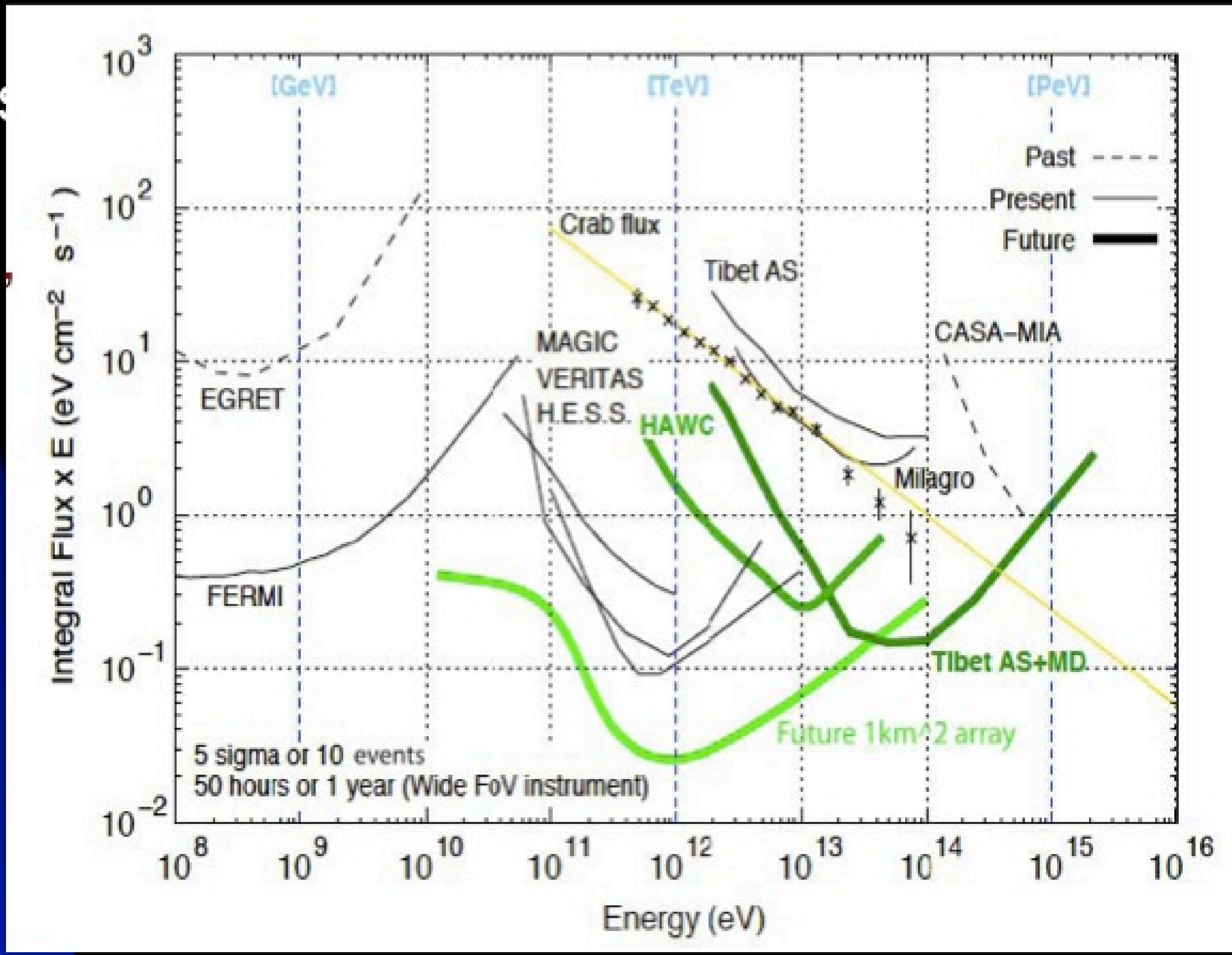


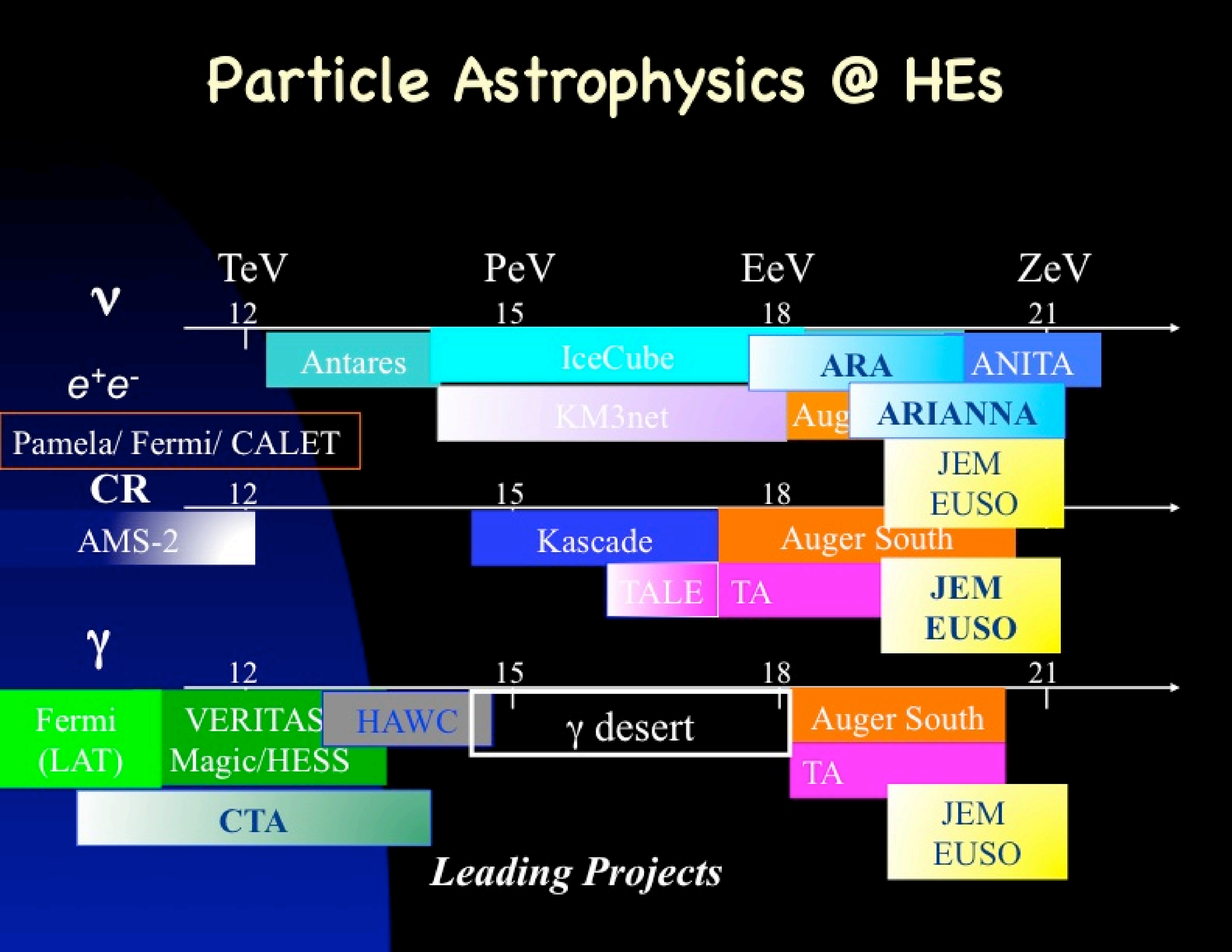
Serendipity: ZeV neutrinos



Tools for HE Gamma-Rays: Present/ Future

Ground arrays
VERITAS,
HESS, Magic,
Tibet
HAWC, CTA
Space
Fermi





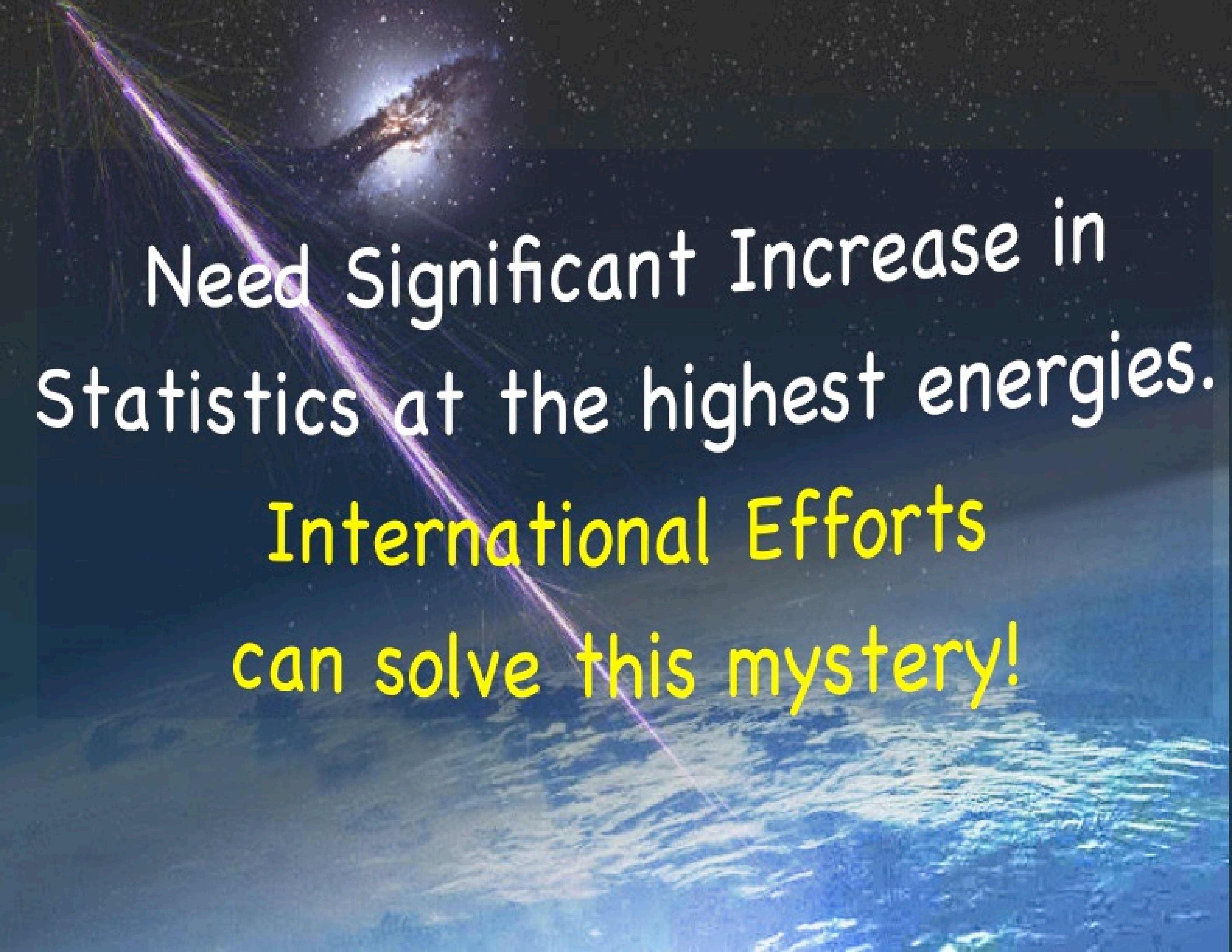
Particle Astrophysics @ HEs
TeV
PeV
EeV
ZeV
ν
12
15
18
21
Antares
IceCube
ARA
ANITA
e+e-
KM3net
Aug
ARIANNA
Pamela/ Fermi/ CALET
JEM
EUSO
CR
12
15
18
AMS-2
Kascade
Auger South
TALE
TA
JEM
EUSO
γ
12
15
18
21
Fermi
(LAT)
VERITAS
Magic/HESS
HAWC
γ desert
Auger South
TA
CTA
JEM
EUSO
Leading Projects

The ORIGIN OF UltraHigh Energies Cosmic Rays:

still a great puzzle!

Multimessenger Approach:

UHECRS, UHE Neutrinos,Gamma-rays, and UHE particle interactions, needed!


Need Significant Increase in
Statistics at the highest energies.
International Efforts
can solve this mystery!


Thanks !