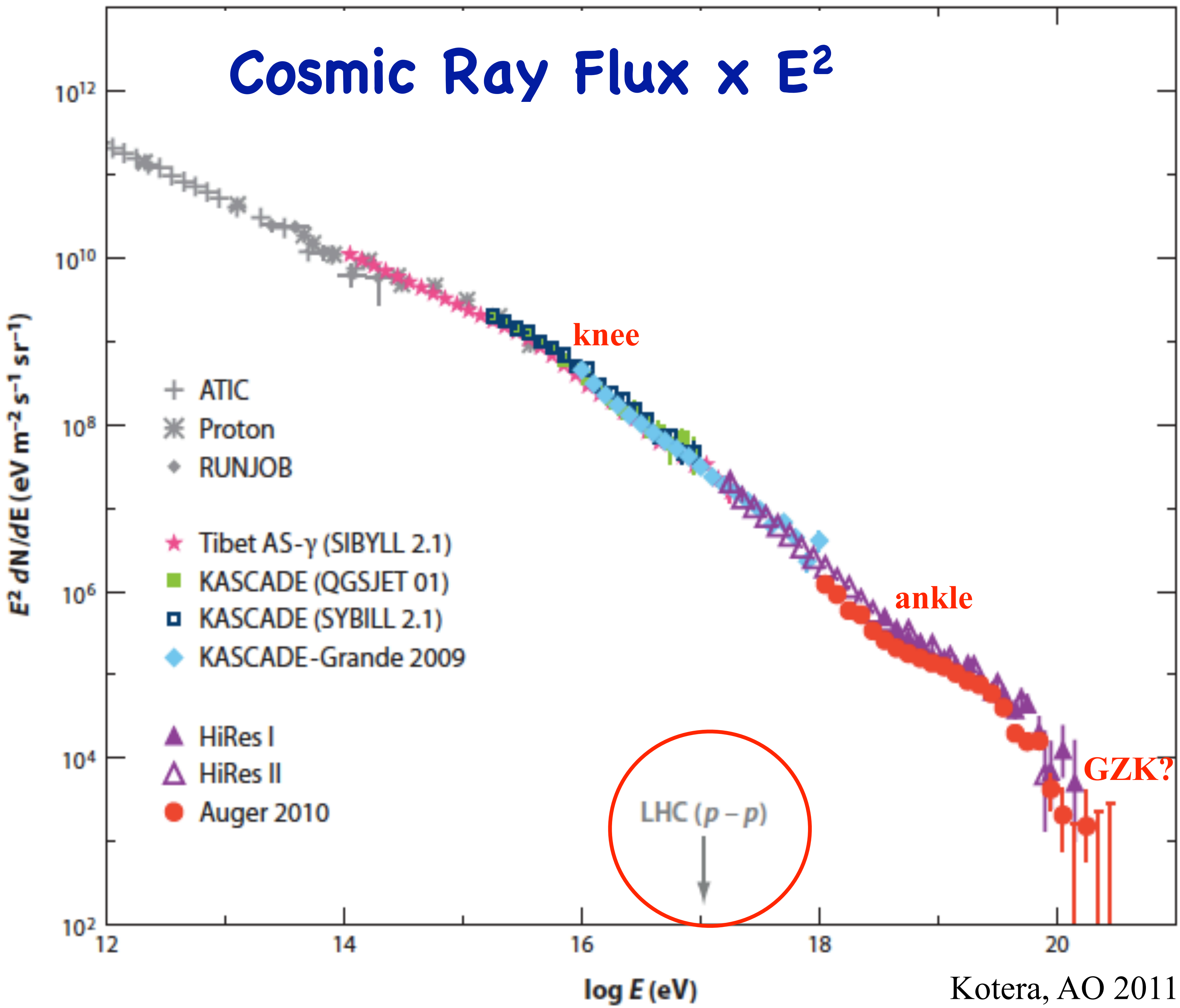
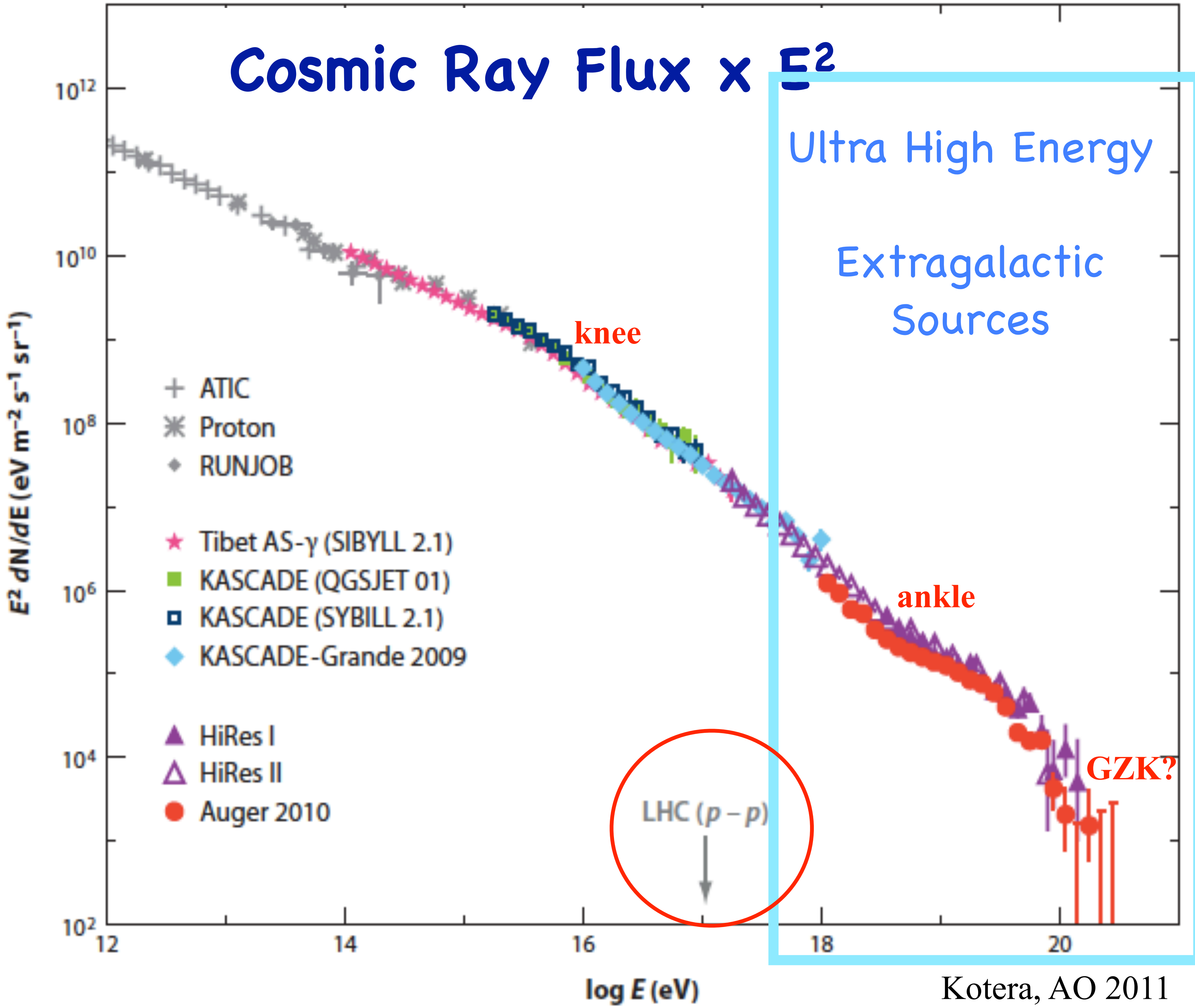

Surprises at the
Highest Energies
Angela V. Olinto
The University of



Kotera, AO 2011

Cosmic Ray Flux x E²



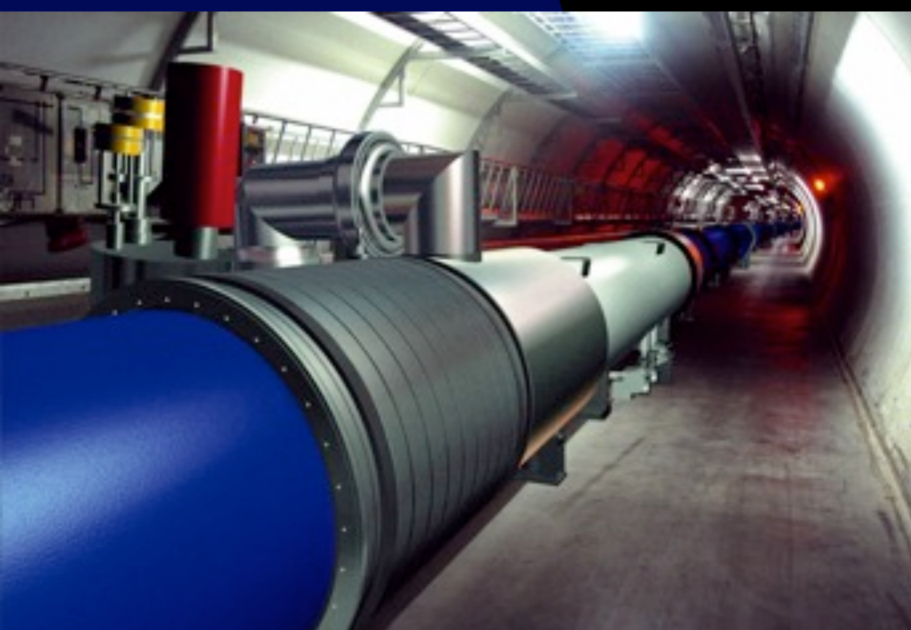
Kotera, AO 2011

Challenging Accelerators

to reach 10^{20} eV

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

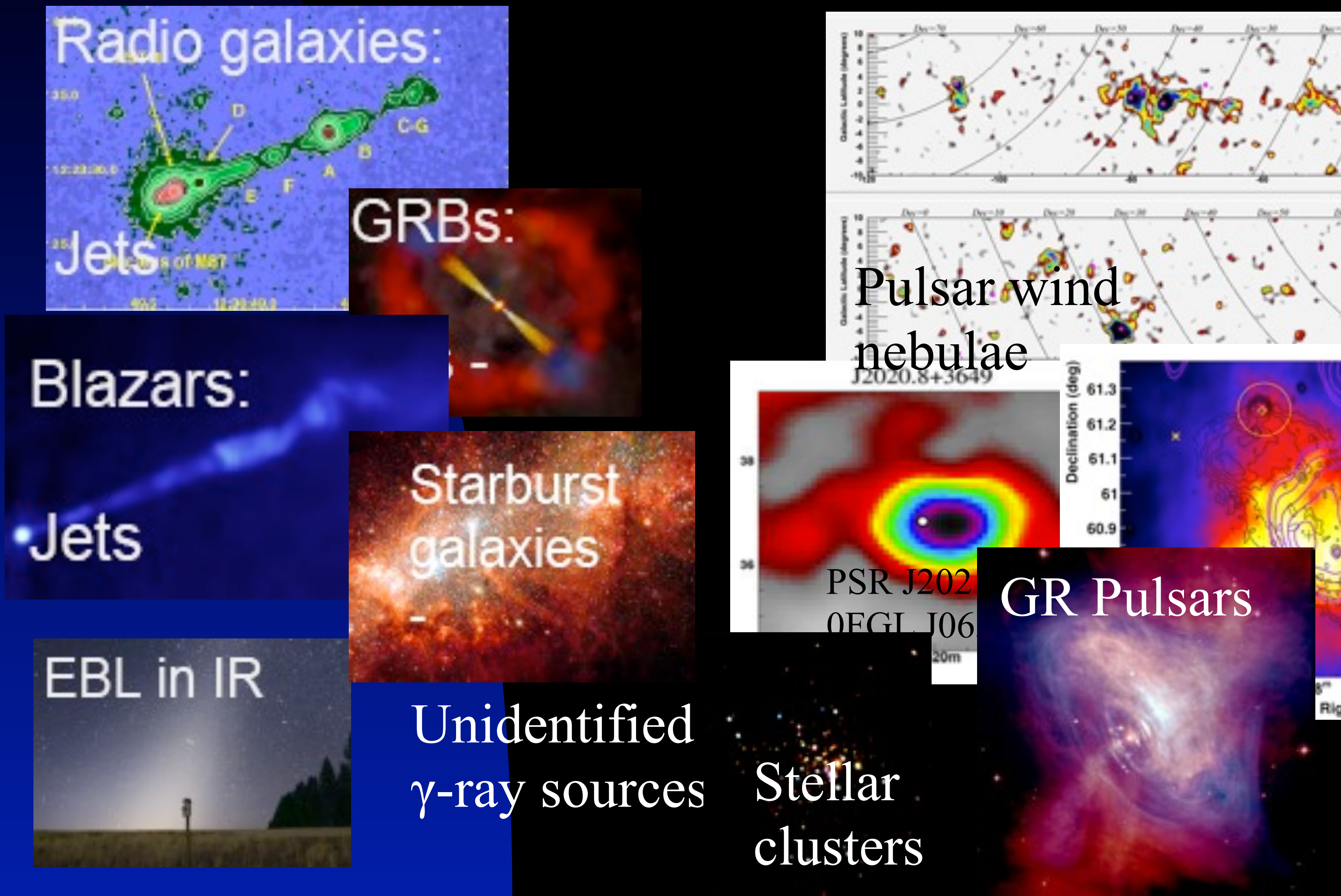
or 10 GT fields!

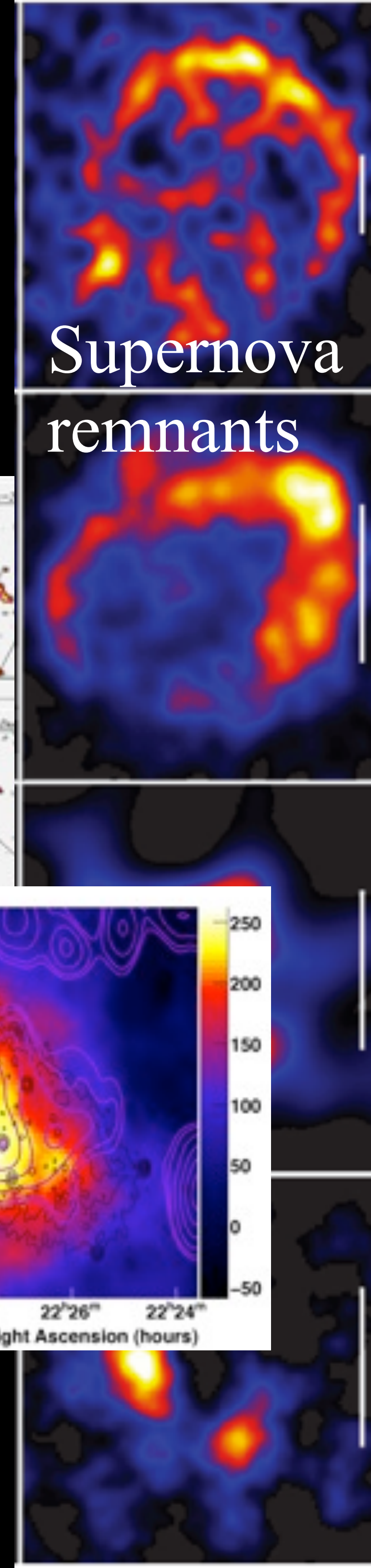


High Energy Astrophysical Accelerators

Extragalactic

Galactic





"Known unknown"

Cosmic Magnetic Fields

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

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

1 EeV = 10^{18} eV

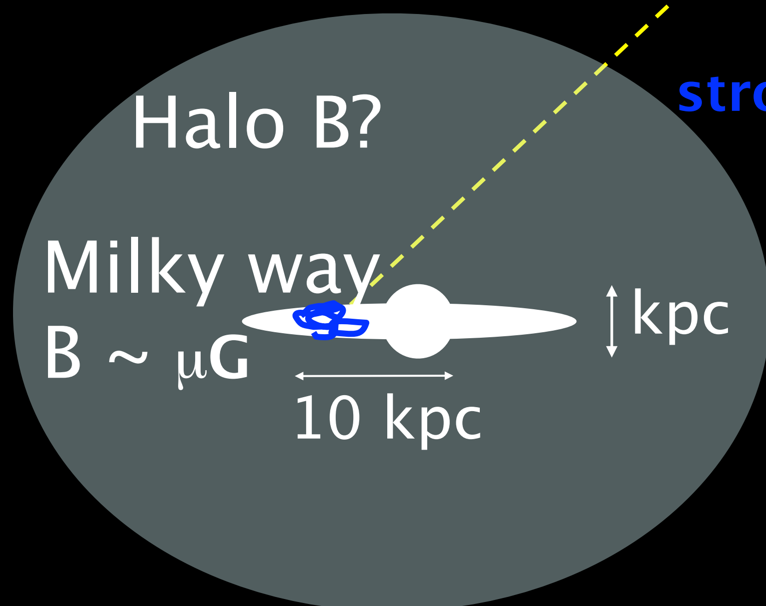
γ

Extra-galactic B?
B < **nG**

weak deflection
E > 10^{19}eV

strong deflection
E < 10^{18}eV

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



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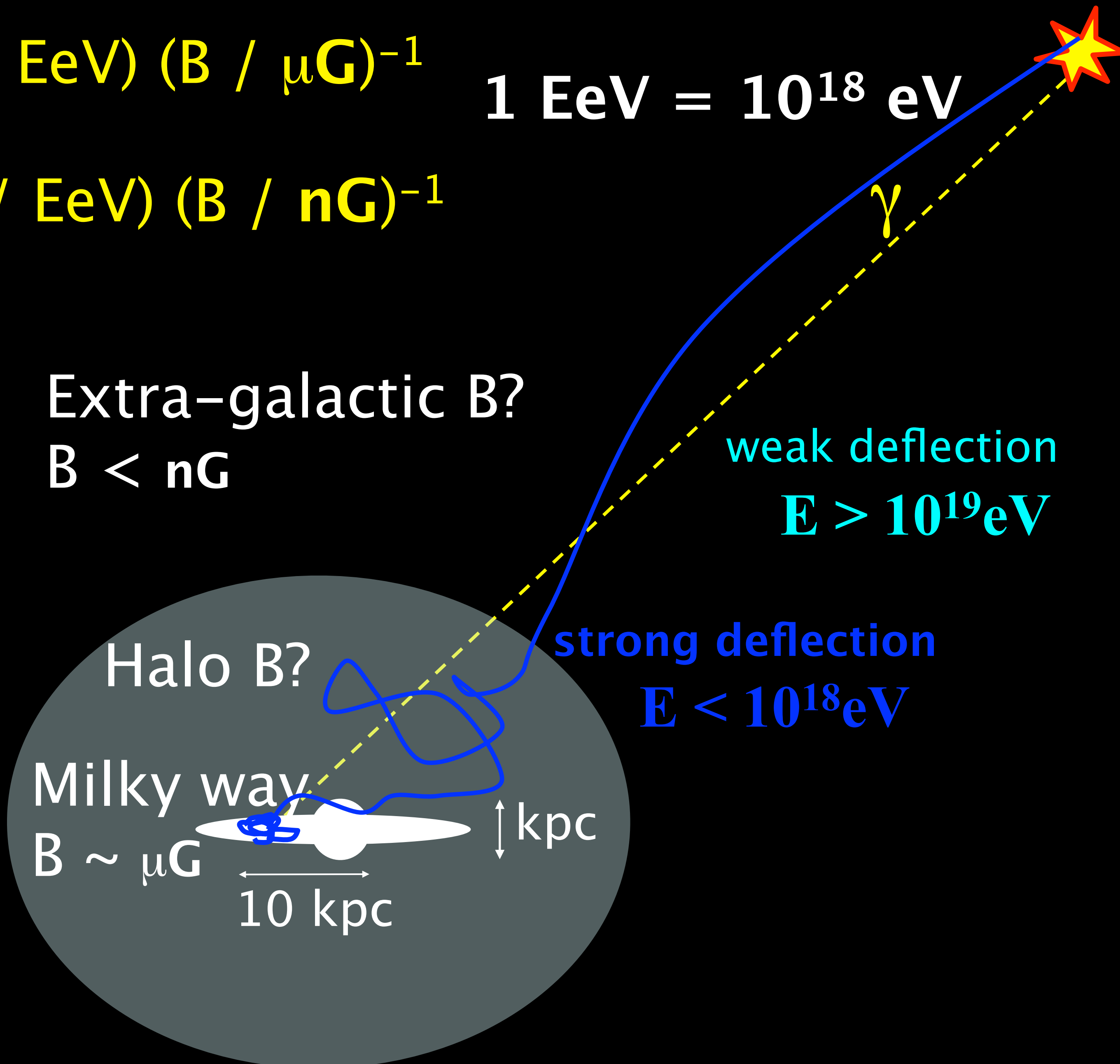

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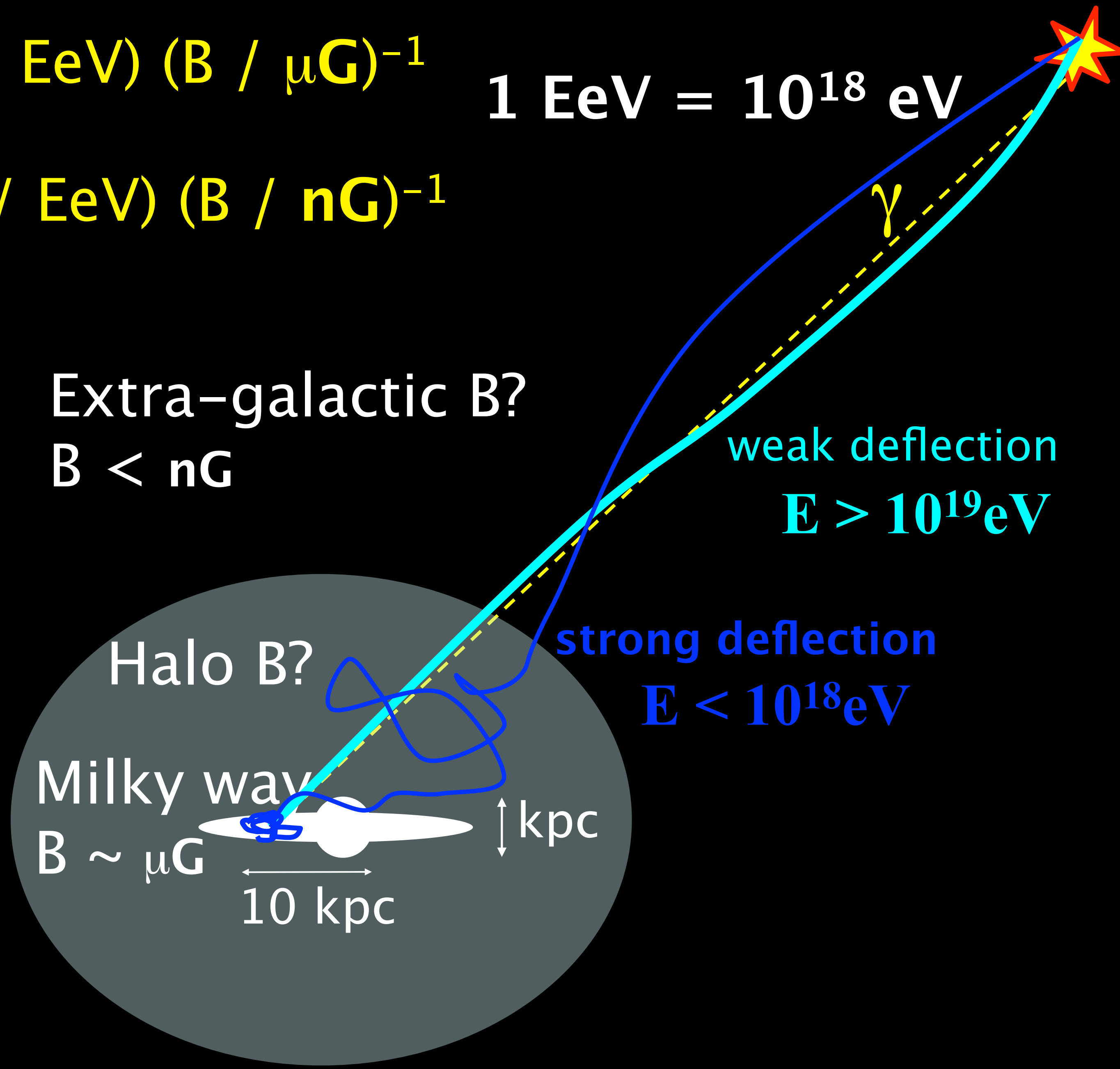

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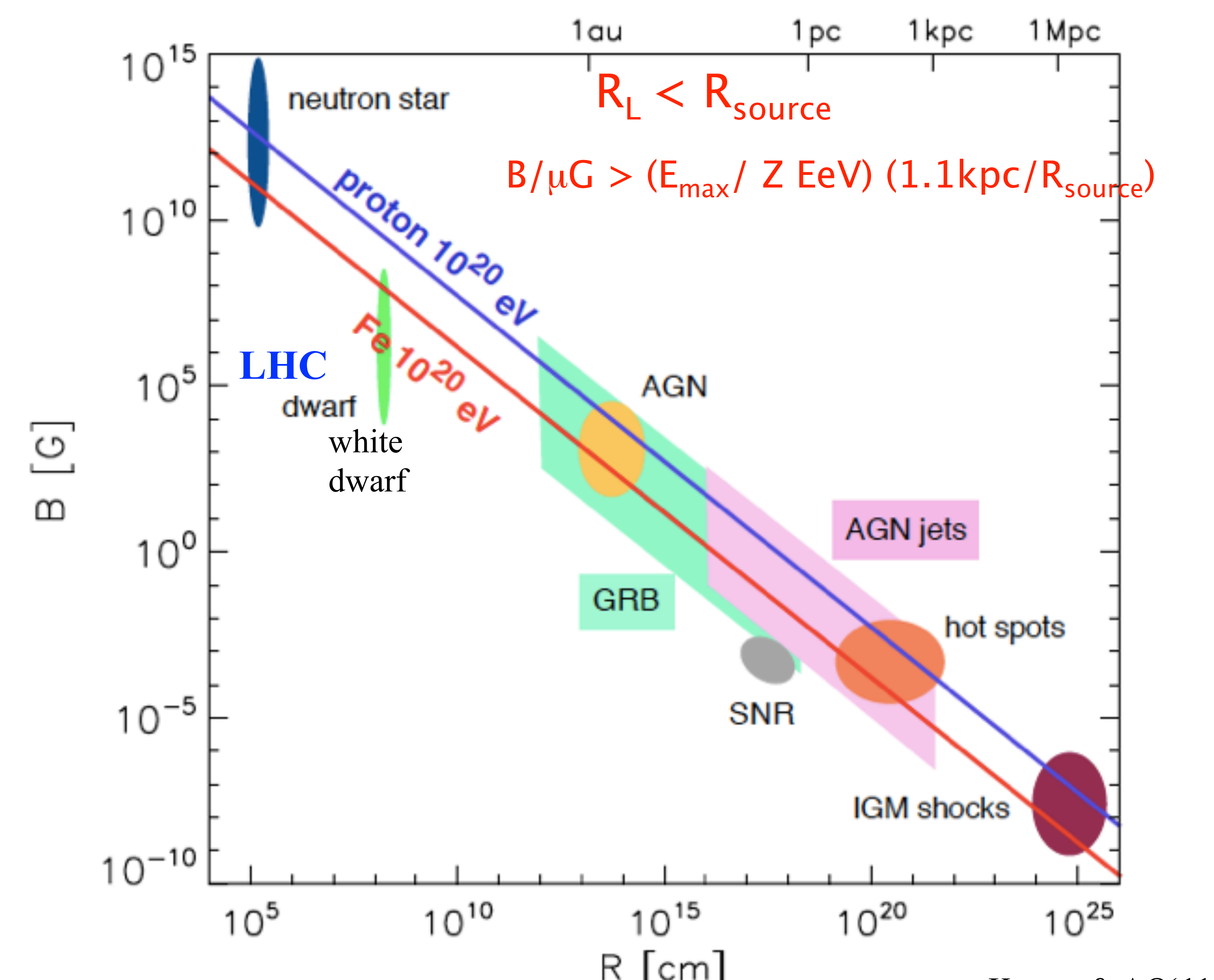
anisotropic in sky

Hillas Plot: Maximum Energy



Kotera & AO'11

High Energy Cosmic Rays

OBSERVABLES:

- Spectrum
- Composition
- Sky Distribution

High Energy Cosmic Rays

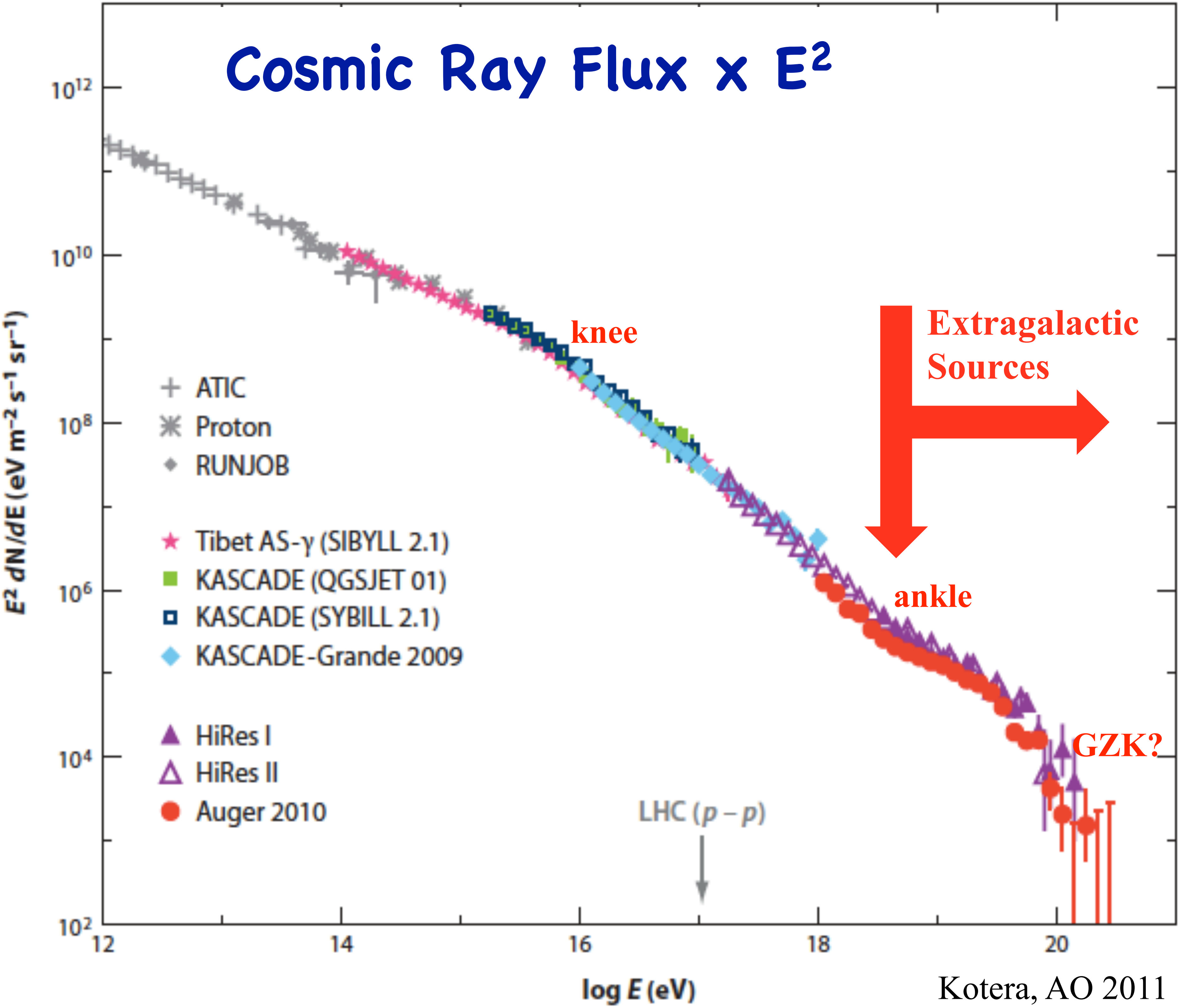
OBSERVABLES:

Spectrum

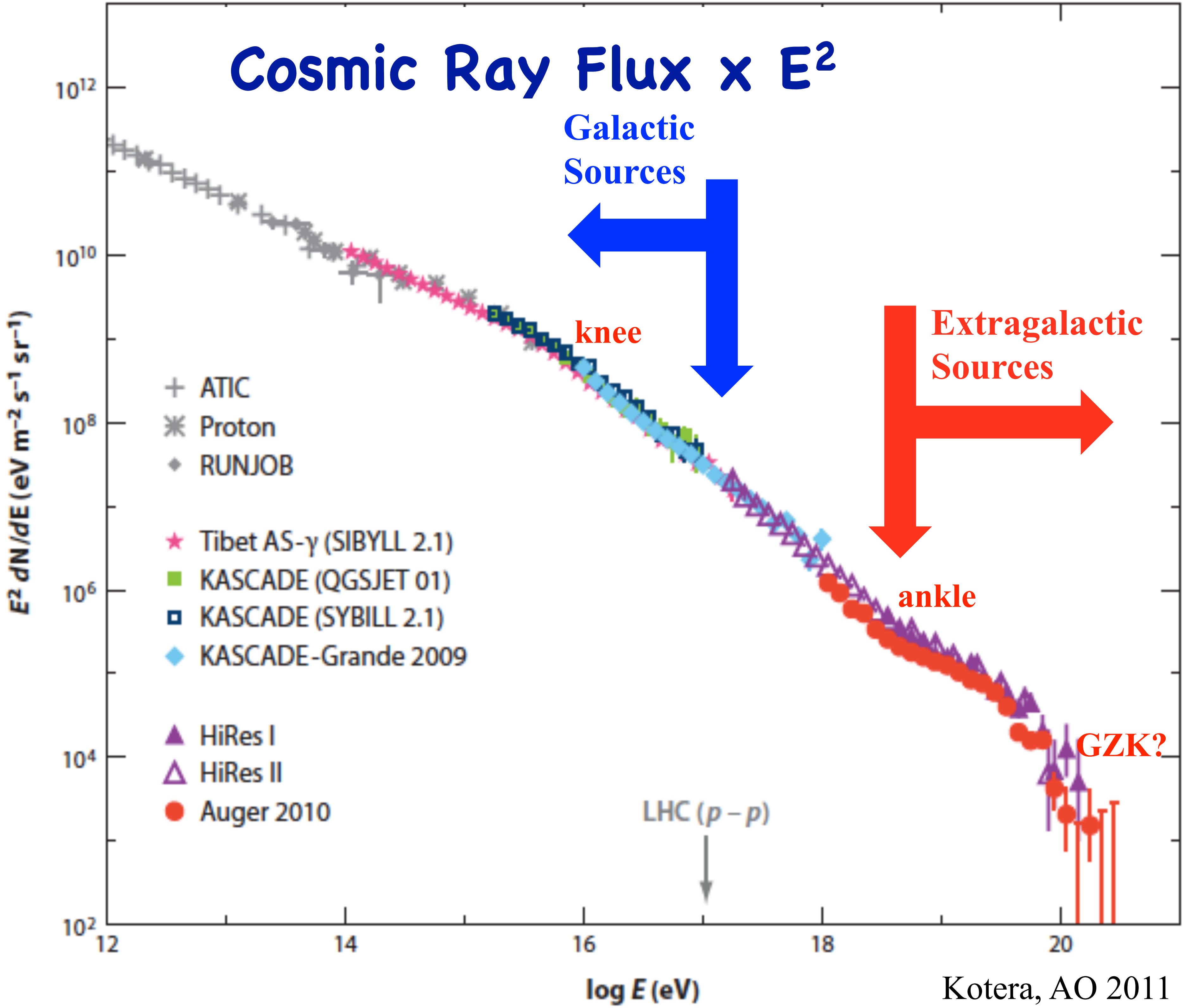
Composition

Sky Distribution

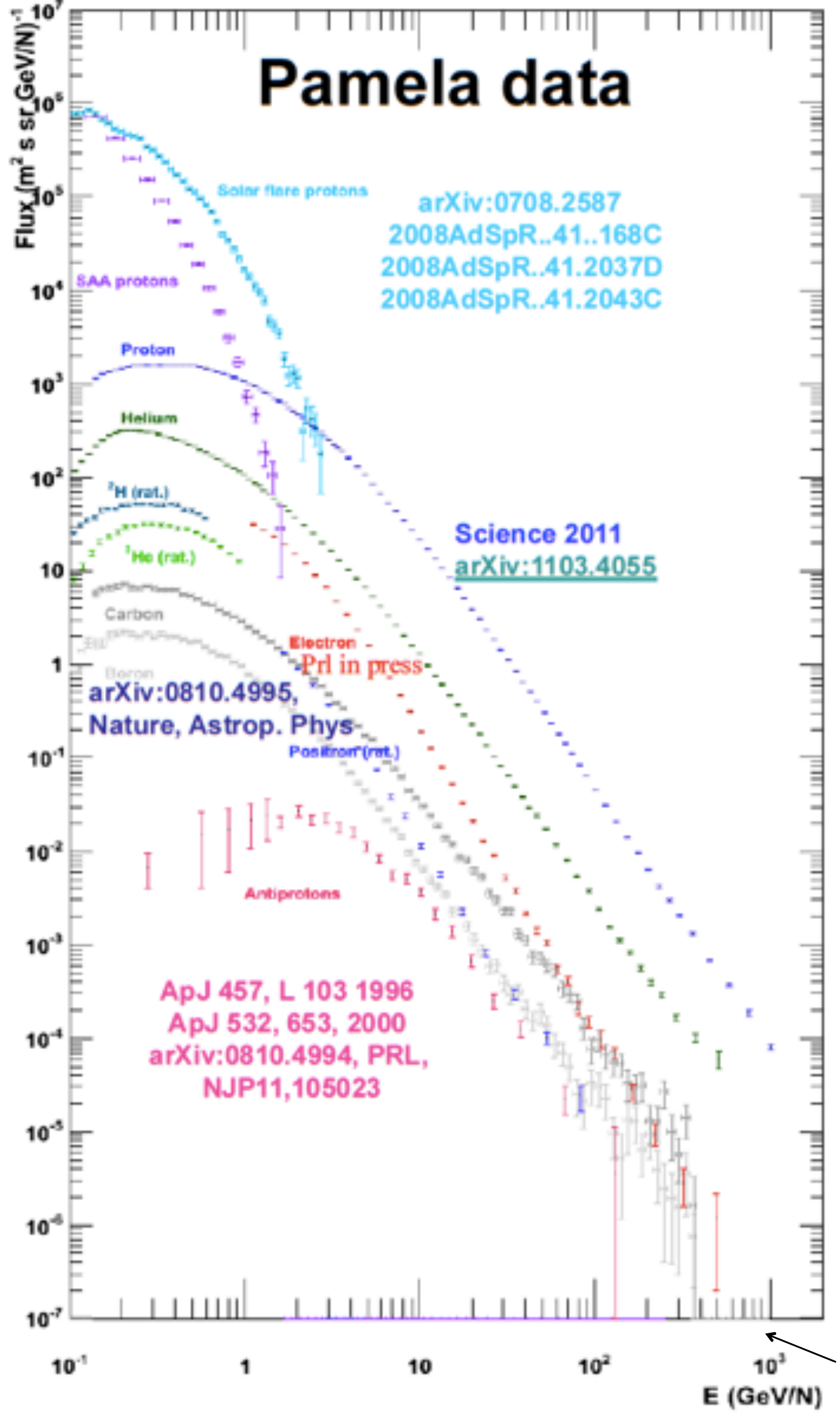
Cosmic Ray Flux x E²



Kotera, AO 2011



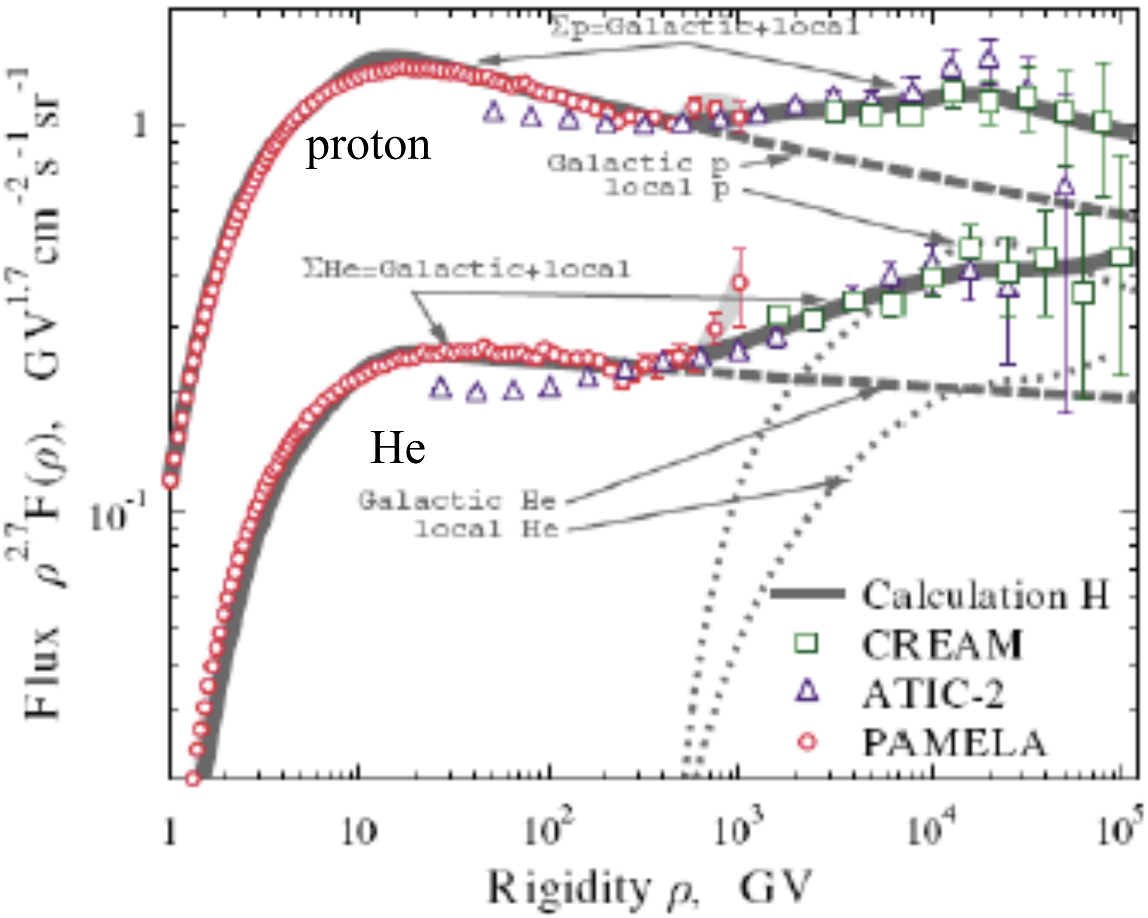
Kotera, AO 2011



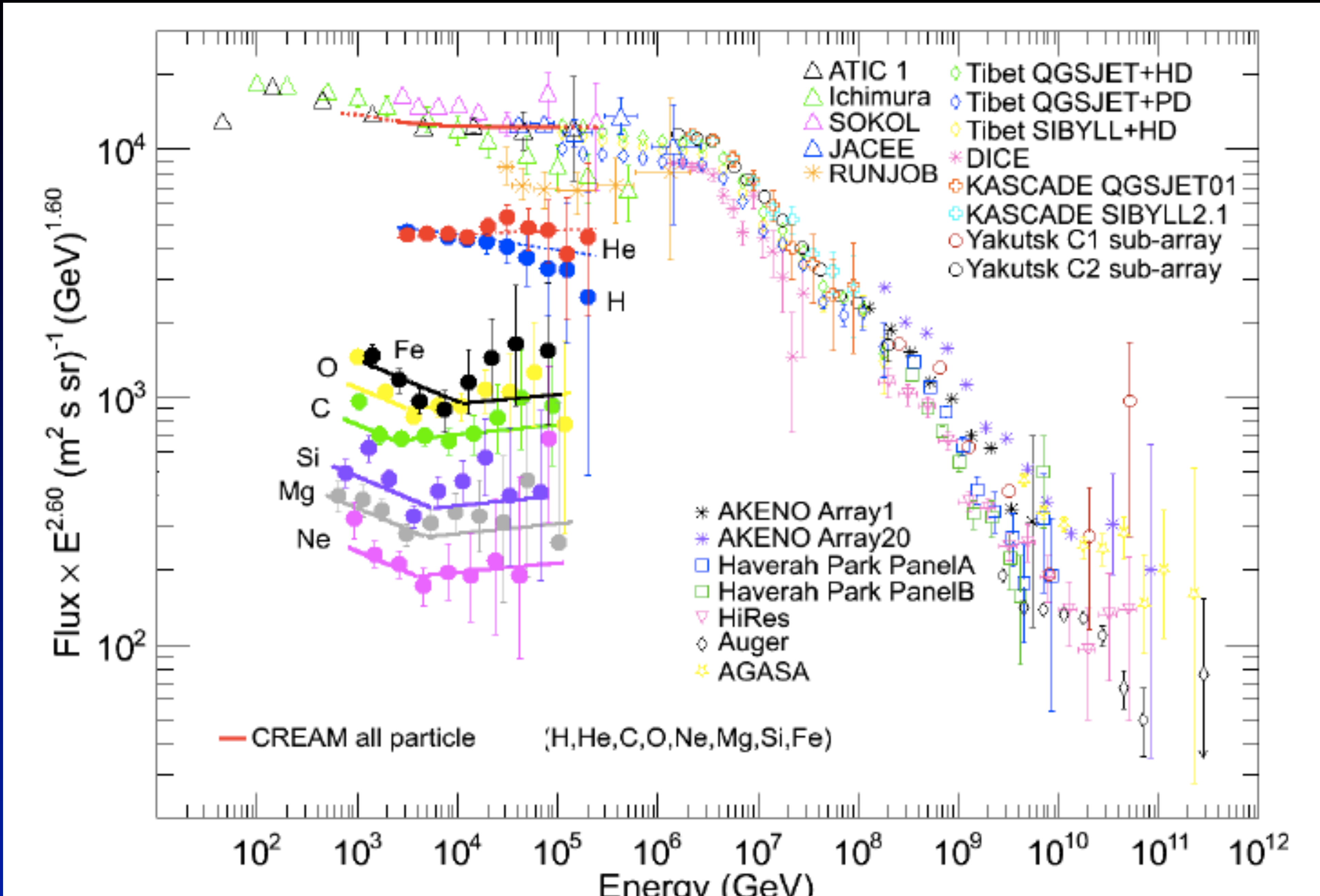
1 TeV/N

Direct Detection:

Things are getting interesting...

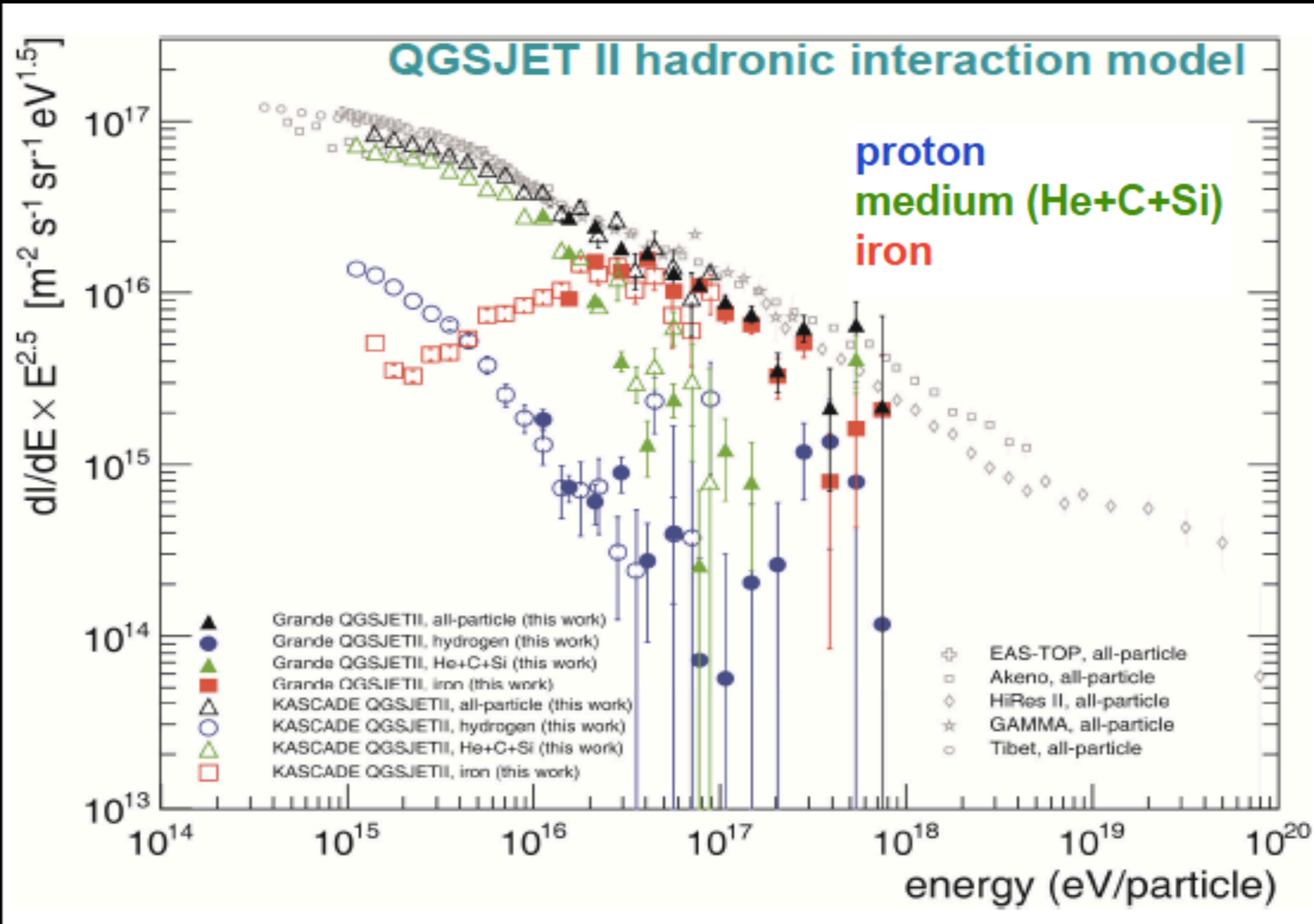


Just Below the Knee...



Above the Knee...

KASCADE + K-Grande



Above the Knee...

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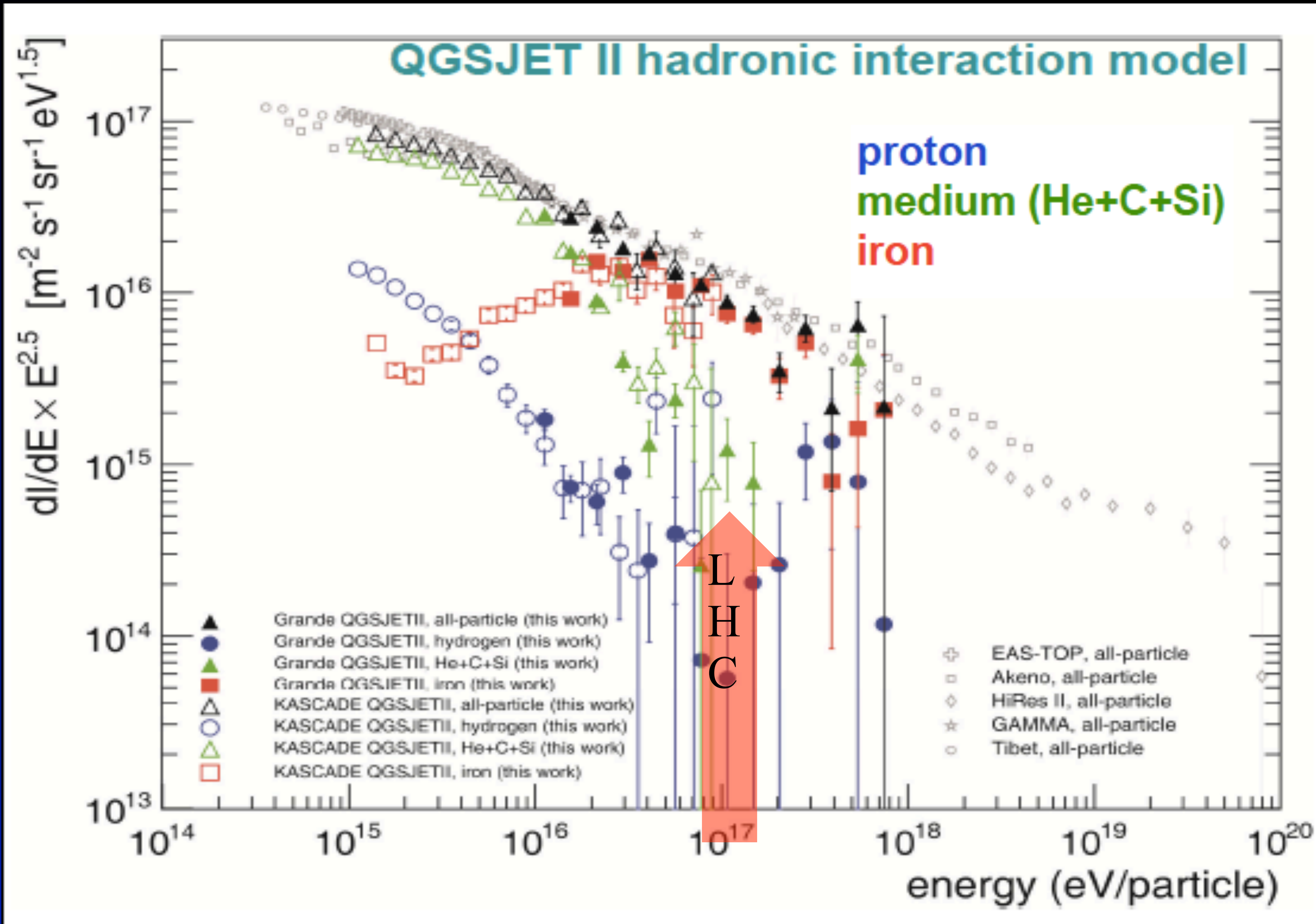
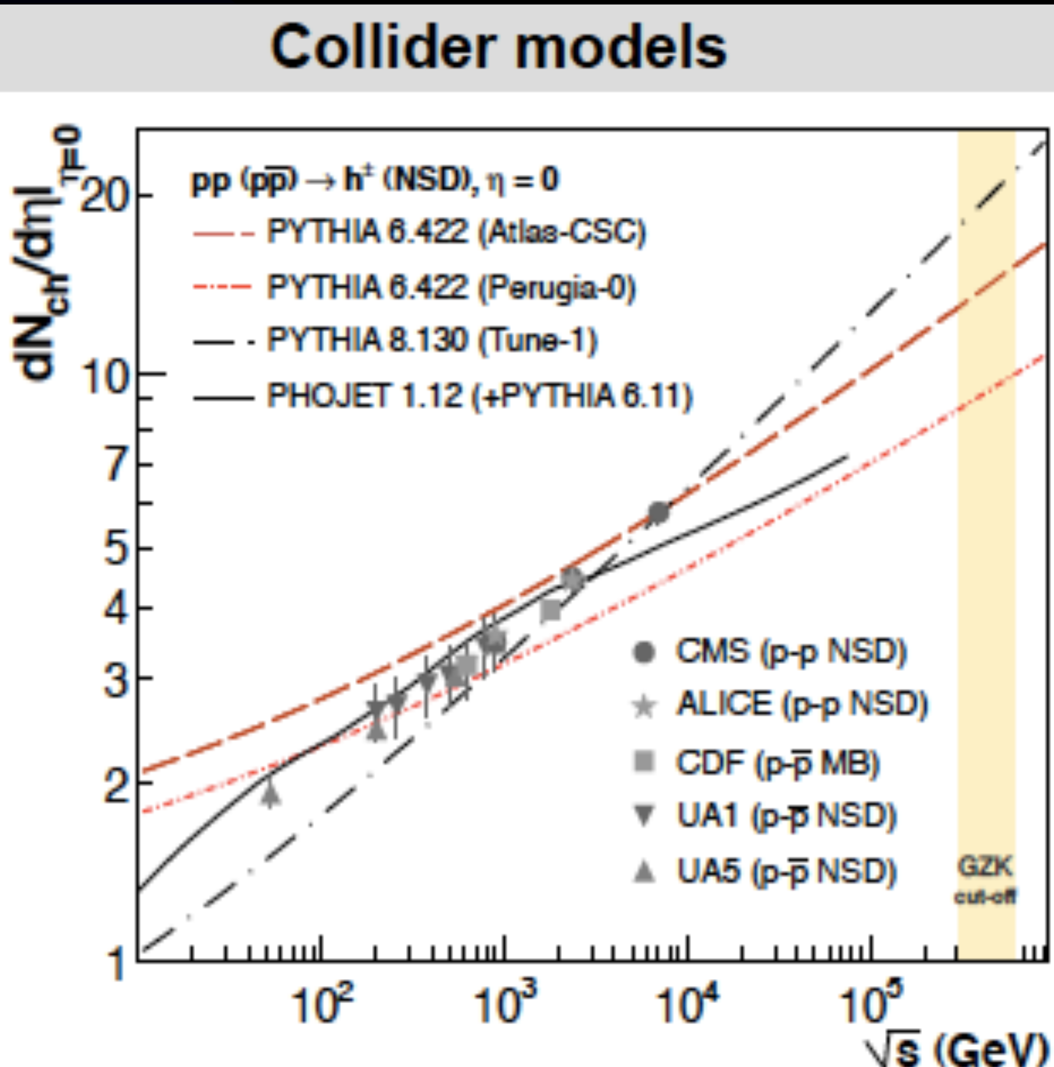
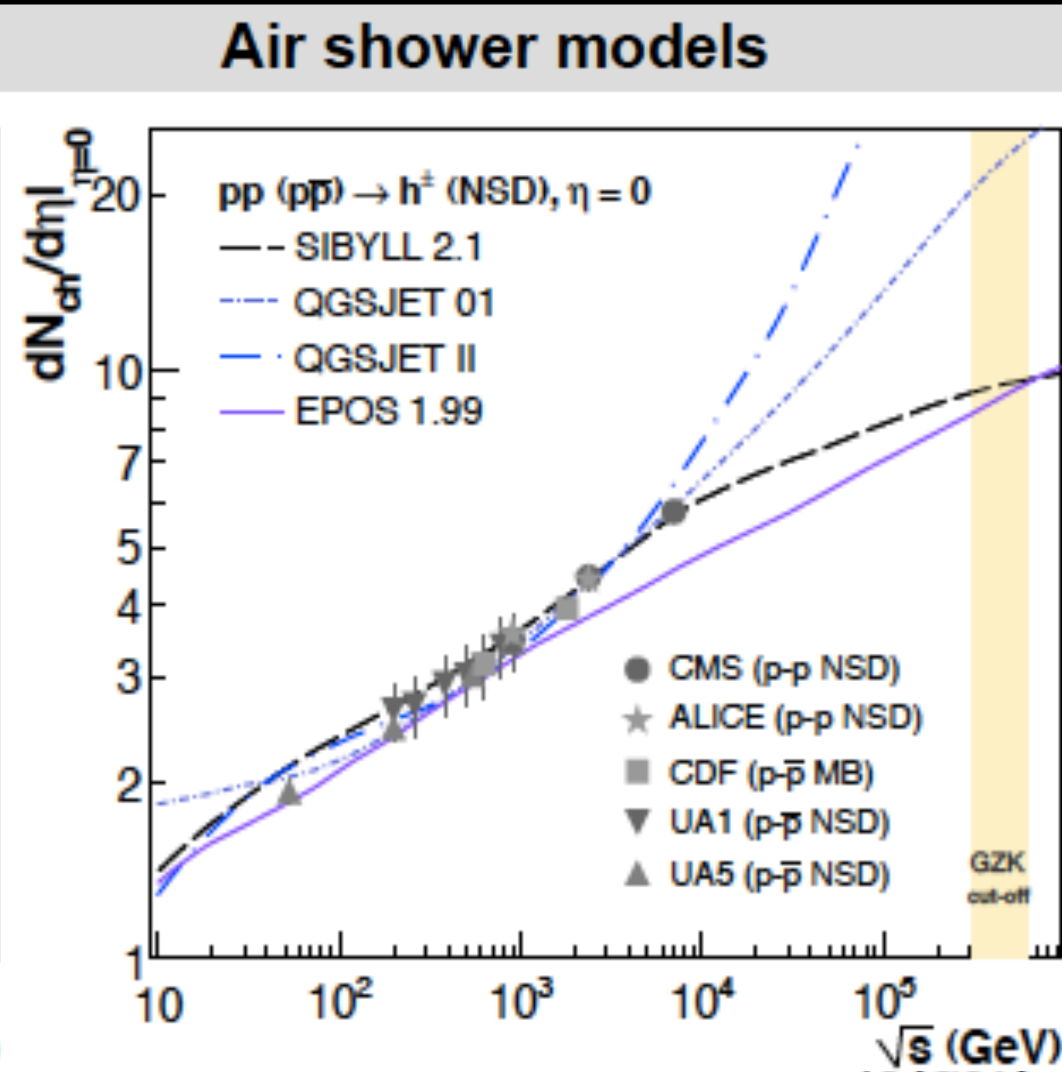
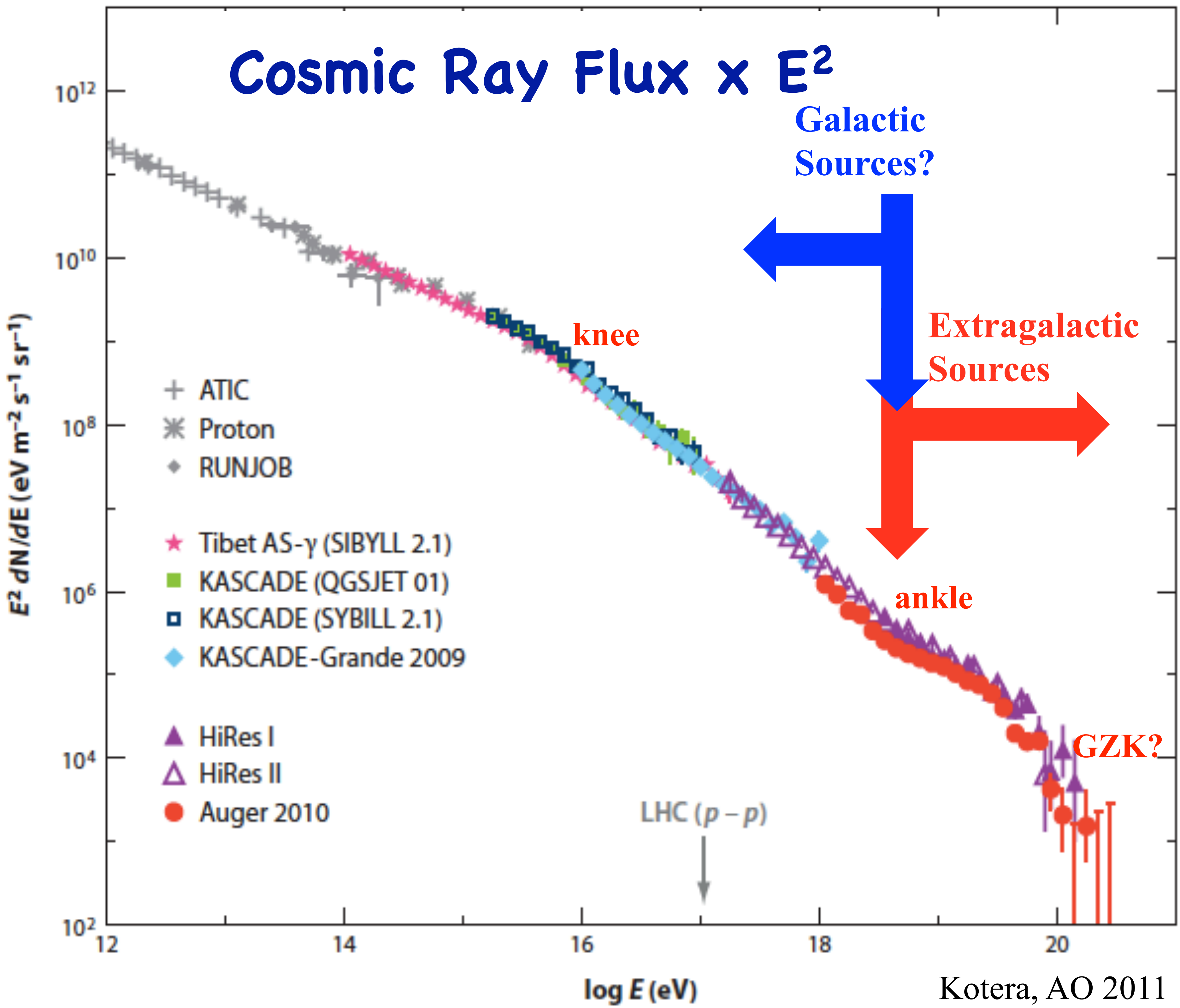


LHC tests of Hadronic Models

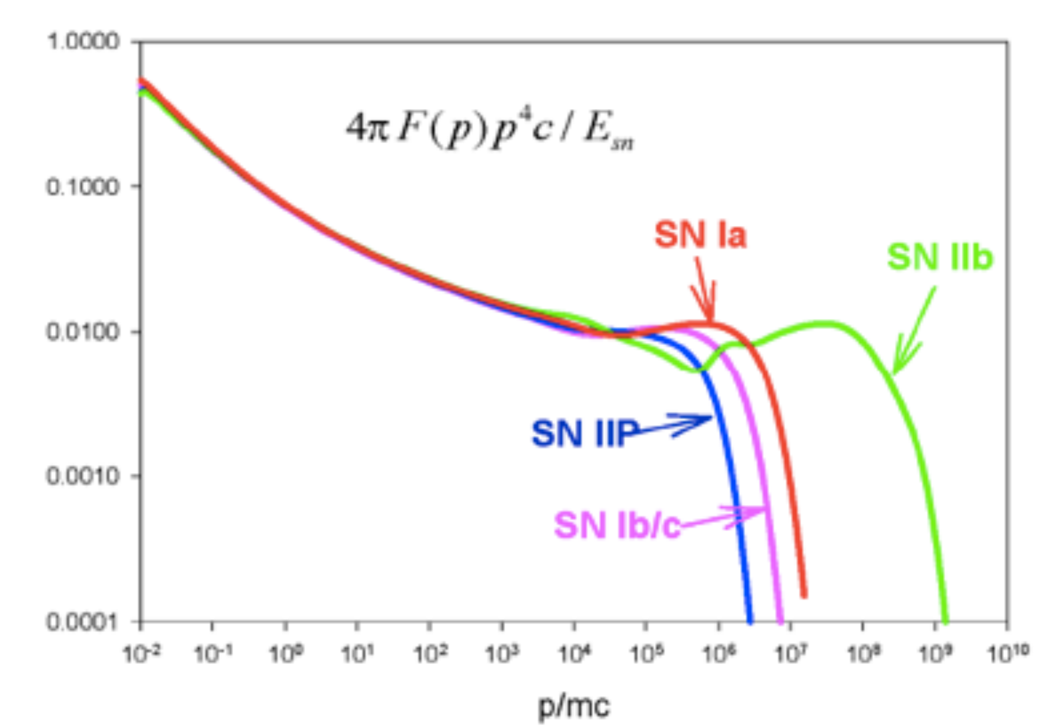


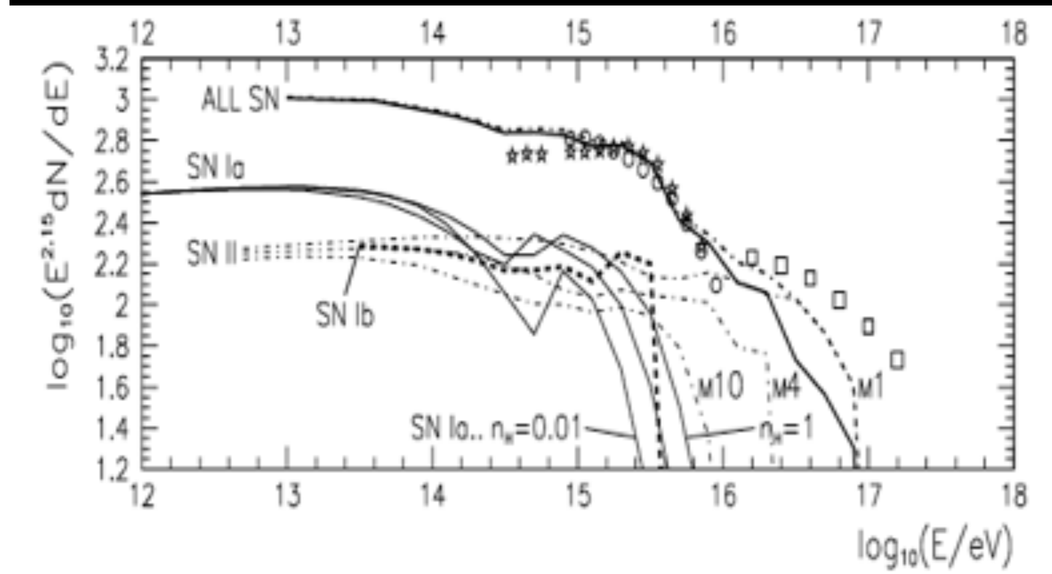


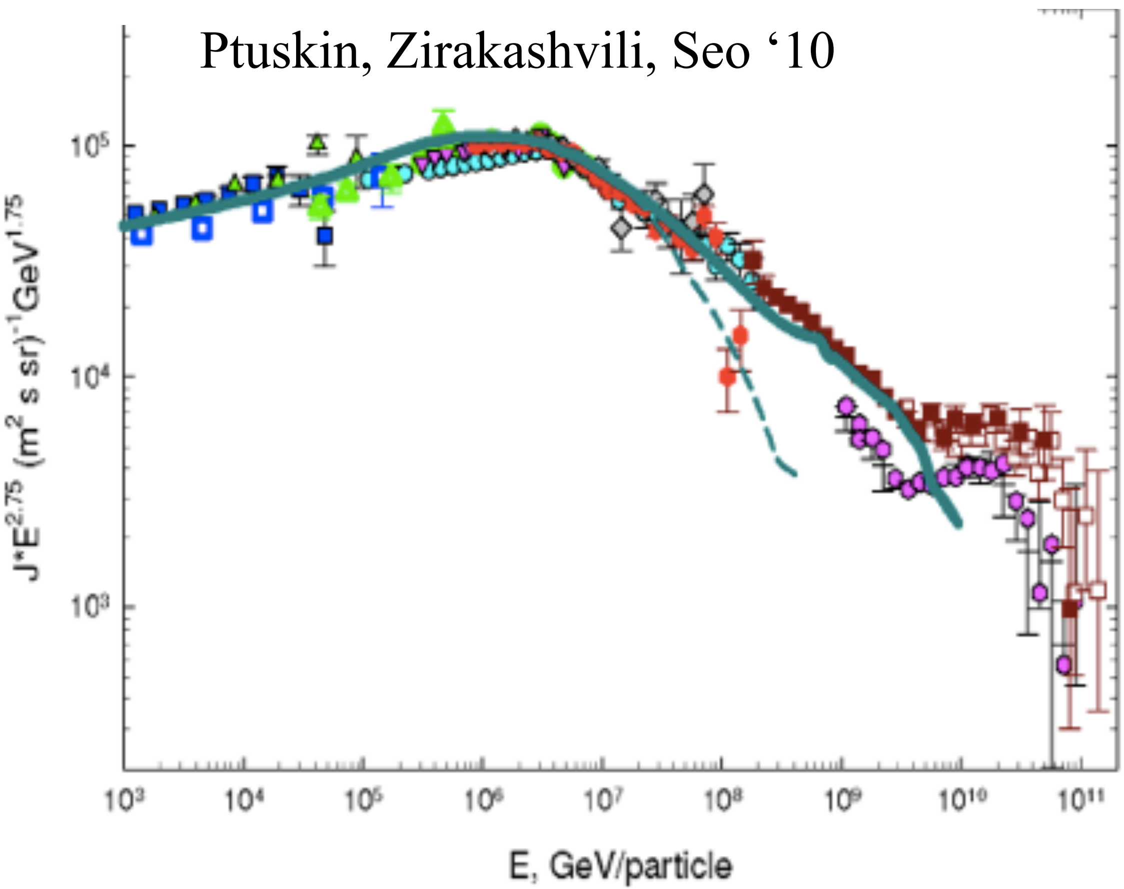
D'Enterria, Engel, Pierog, Ostapchenko, Werner arXiv:1101.5596v2

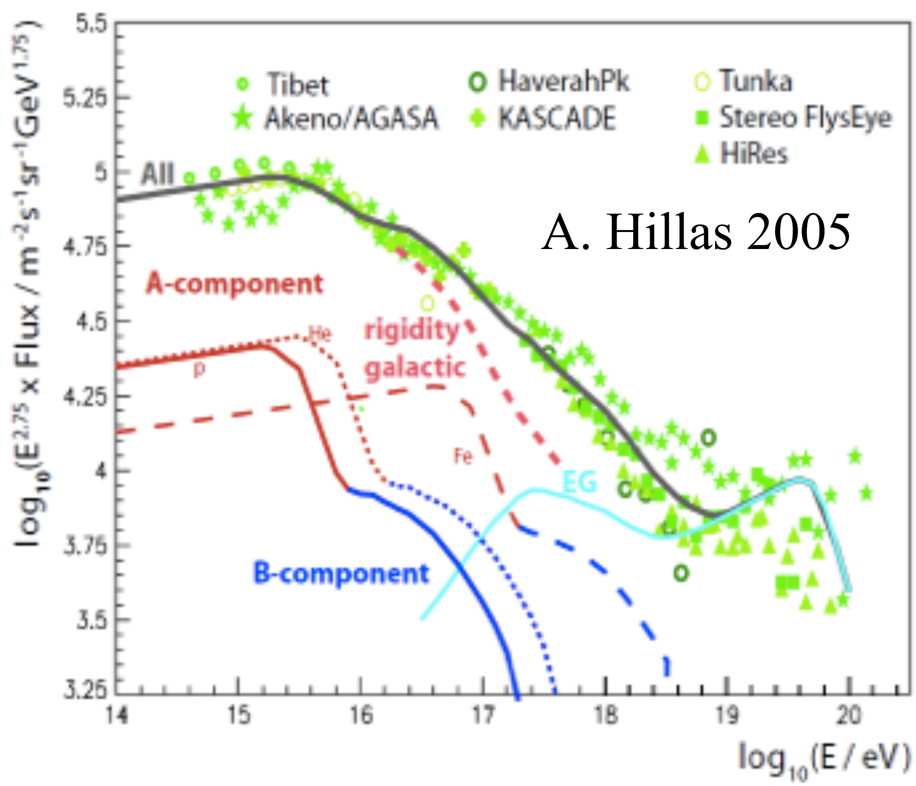


Kotera, AO 2011

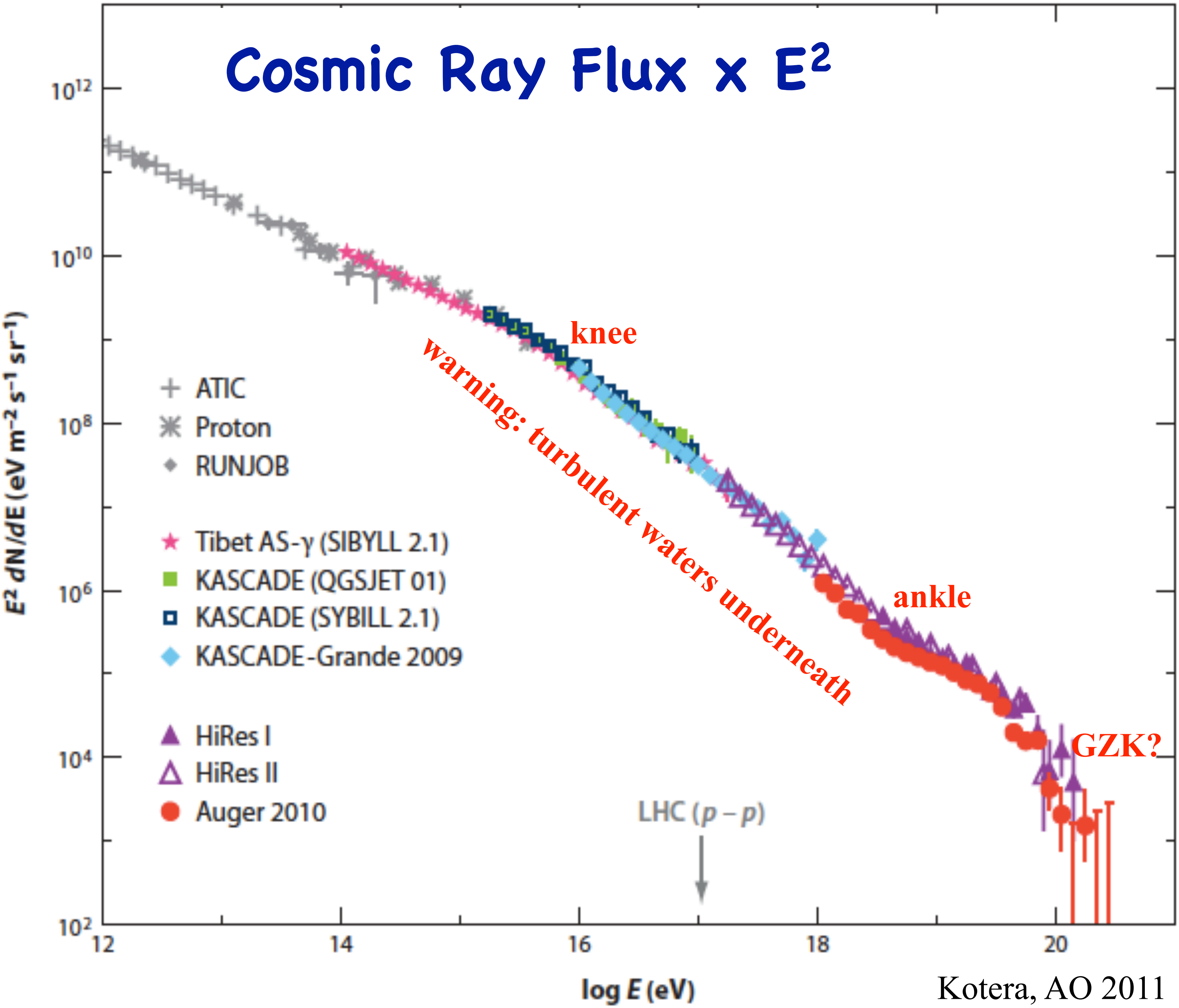

$4\pi F(p)p^4c/E_{sn}$
SN Ia
SN IIb
SN IIP
SN Ib/c
p/mc


ALL SN
SN Ia
SN II
SN Ib
SN Ia.. n_H=0.01
n_H=1
M10
M4
M1
$\log_{10}(E^{2.15}dN/dE)$
$\log_{10}(E/eV)$


Ptuskin, Zirakashvili, Seo '10
$J^*E^{2.75}$ (m^2 s sr)$^{-1}$GeV$^{1.75}$
E, GeV/particle

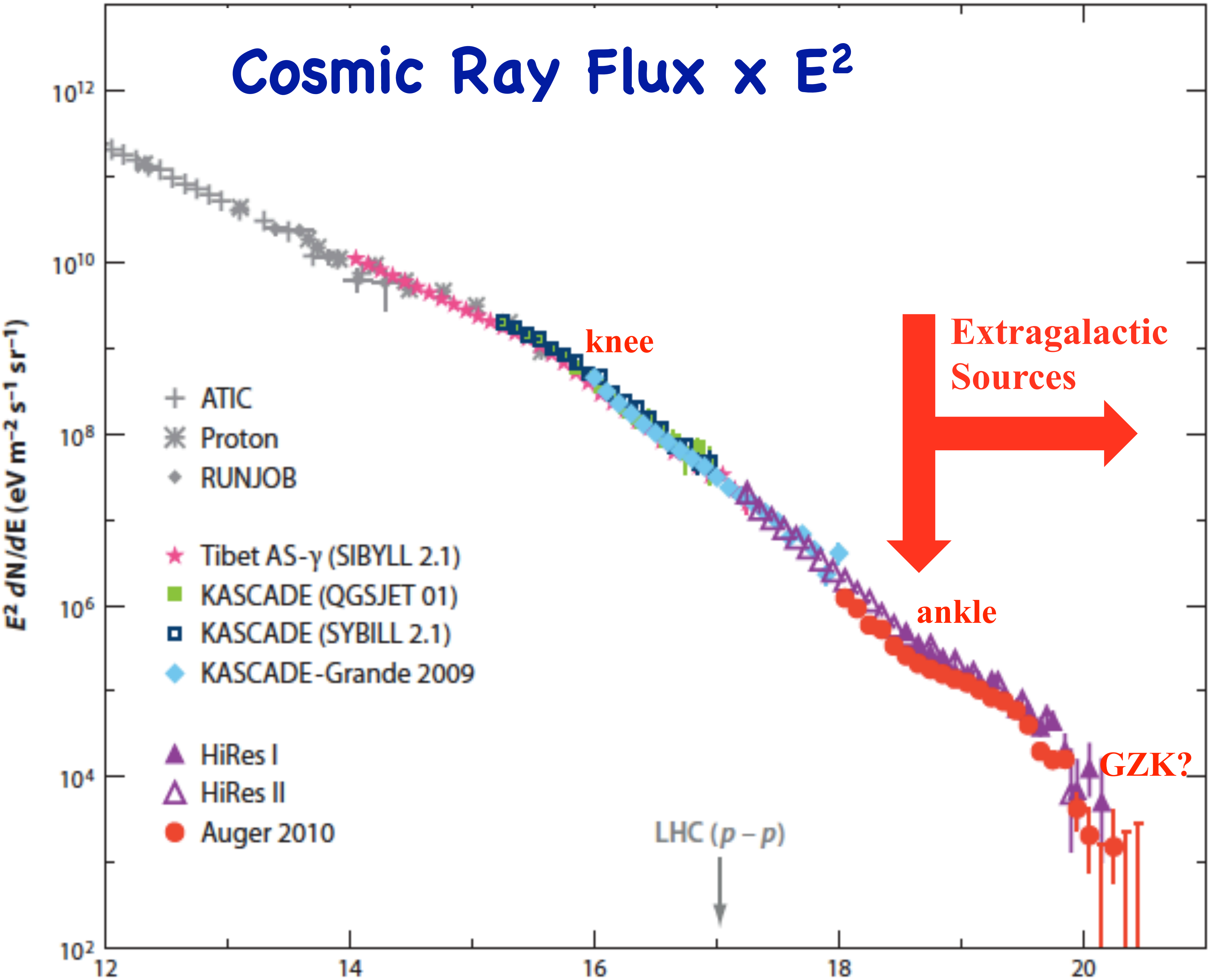

Tibet
Akeno/AGASA
HaverahPk
KASCADE
Tunka
Stereo FlysEye
HiRes
All
A. Hillas 2005
A-component
rigidity
galactic
He
p
Fe
EG
B-component
$\log_{10}(E^{2.75}$ x Flux / m^{-2}s^{-1}sr^{-1}GeV$^{1.75}$)
$\log_{10}(E/eV)$

Cosmic Ray Flux x E^2



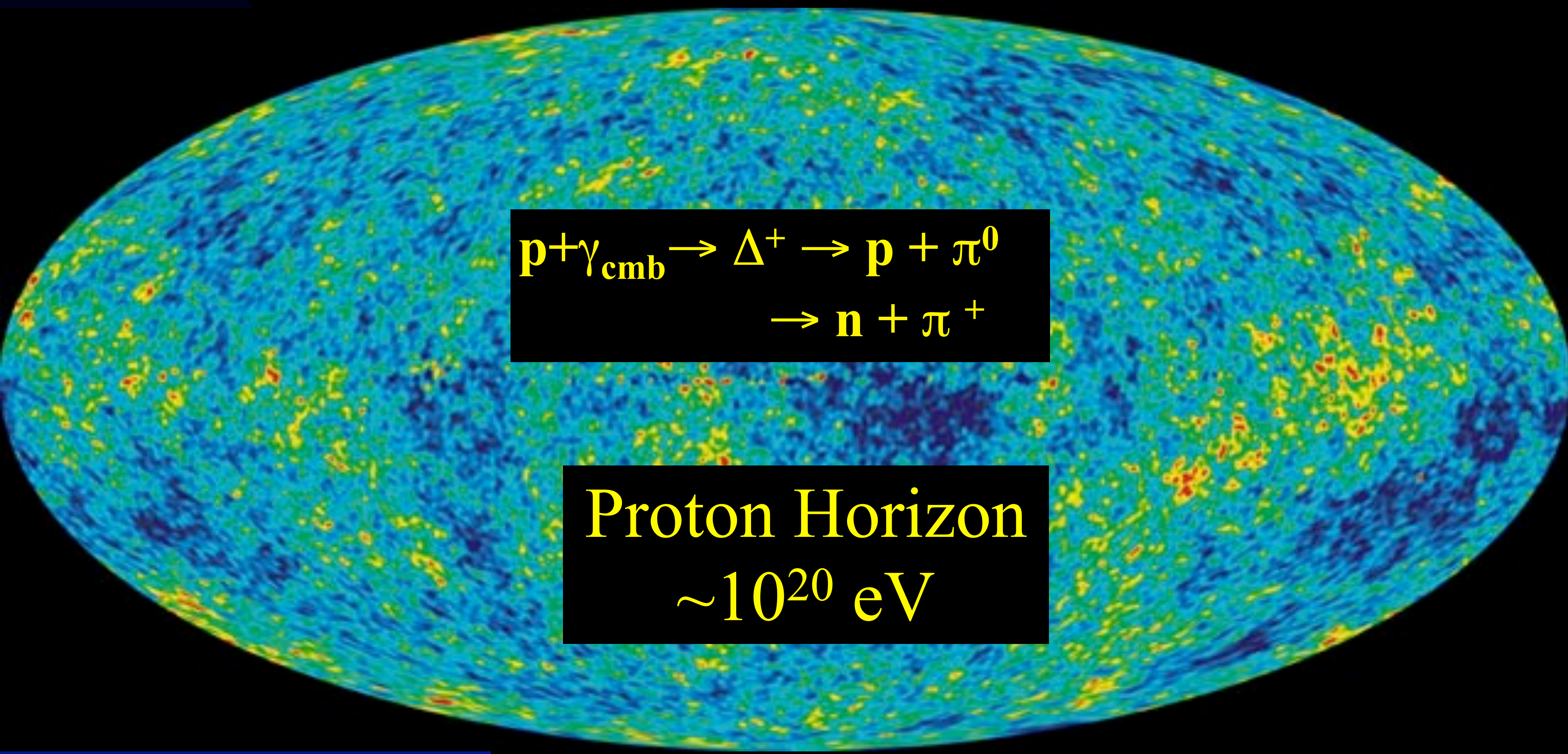
Kotera, AO 2011

Cosmic Ray Flux x E^2



Kotera, AO 2011

"Cosmologically Meaningful Termination"



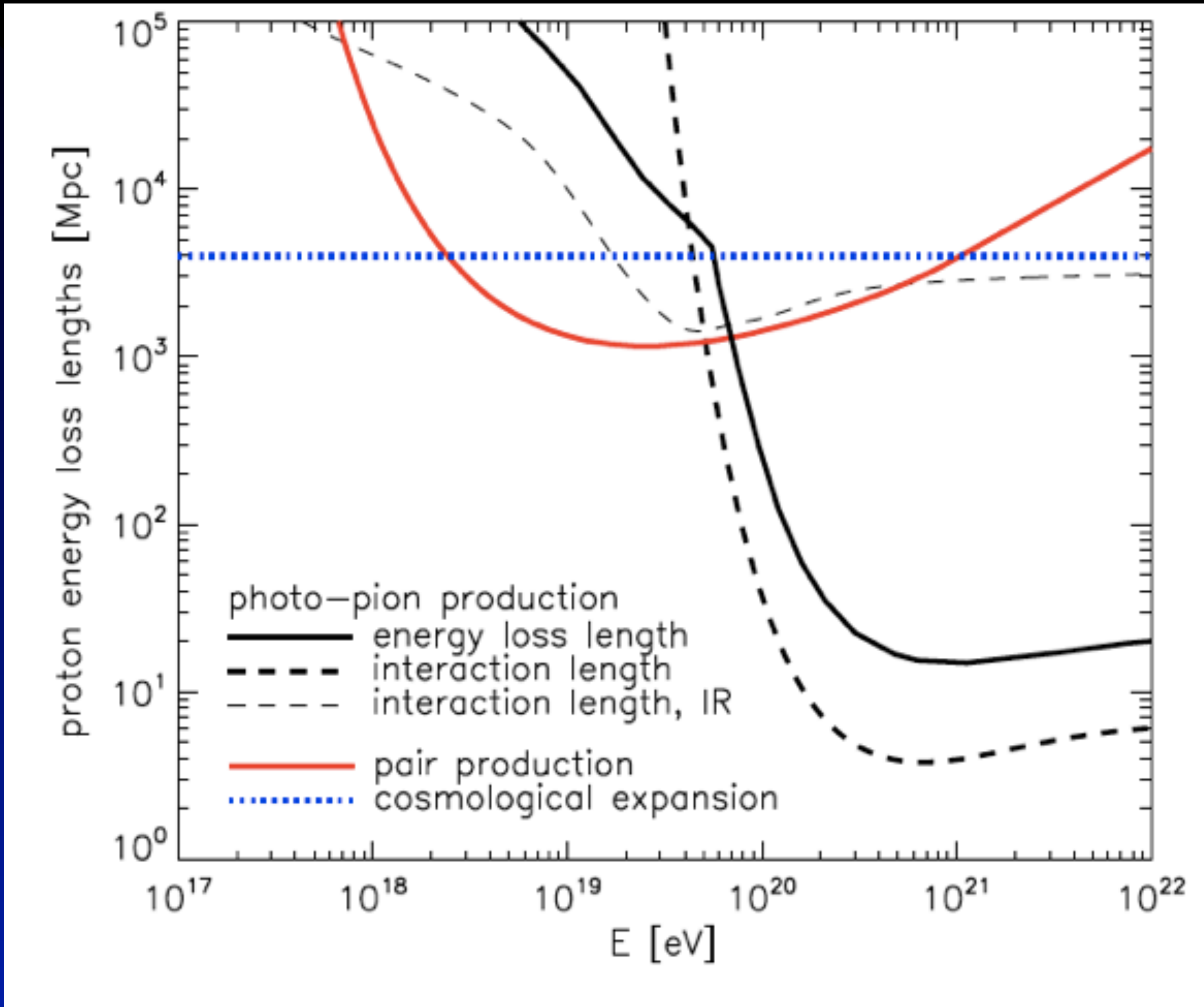
$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

Proton Horizon
$\sim 10^{20}$ eV

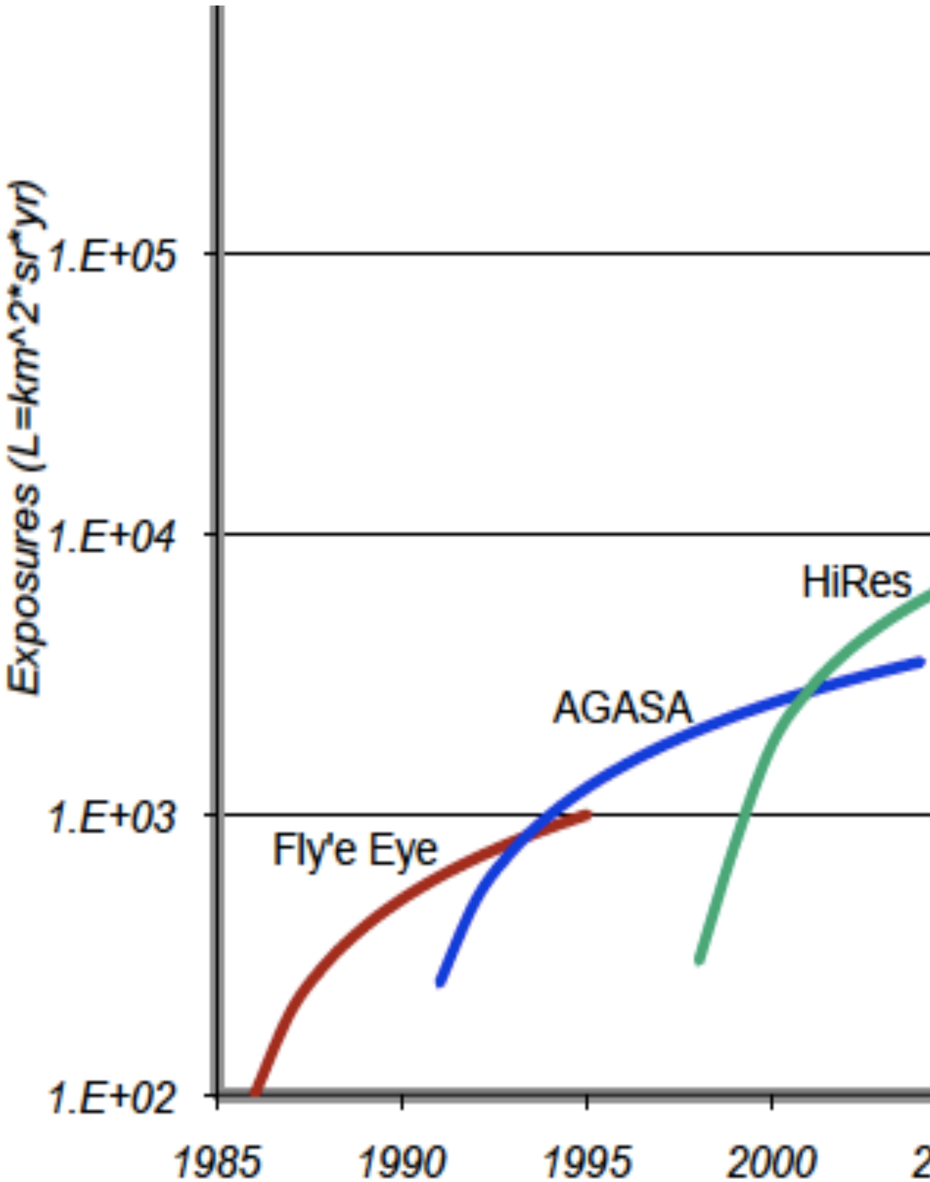
GZK Cutoff

Greisen, Zatsepin, Kuzmin
1966

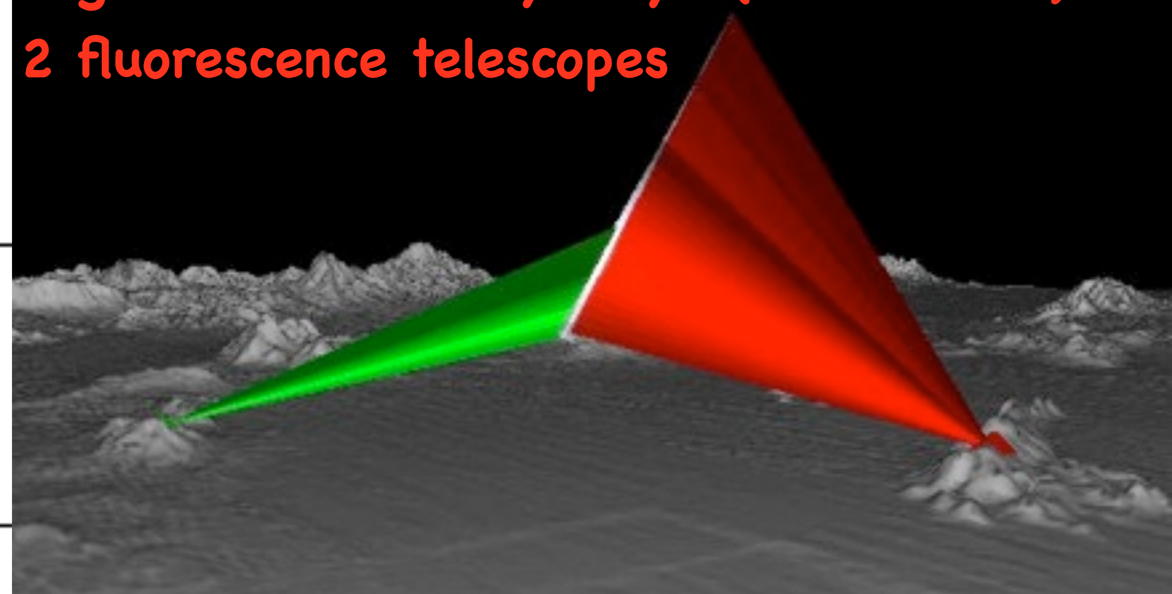
Greisen-Zatsepin-Kuzmin cutoff



Last Century's question:
GZK or No GZK?



High Resolution Fly's Eye (1997-2006)
2 fluorescence telescopes



AGASA (1984-2003) 100 km² area,

Cosmic Ray Flux x E^3

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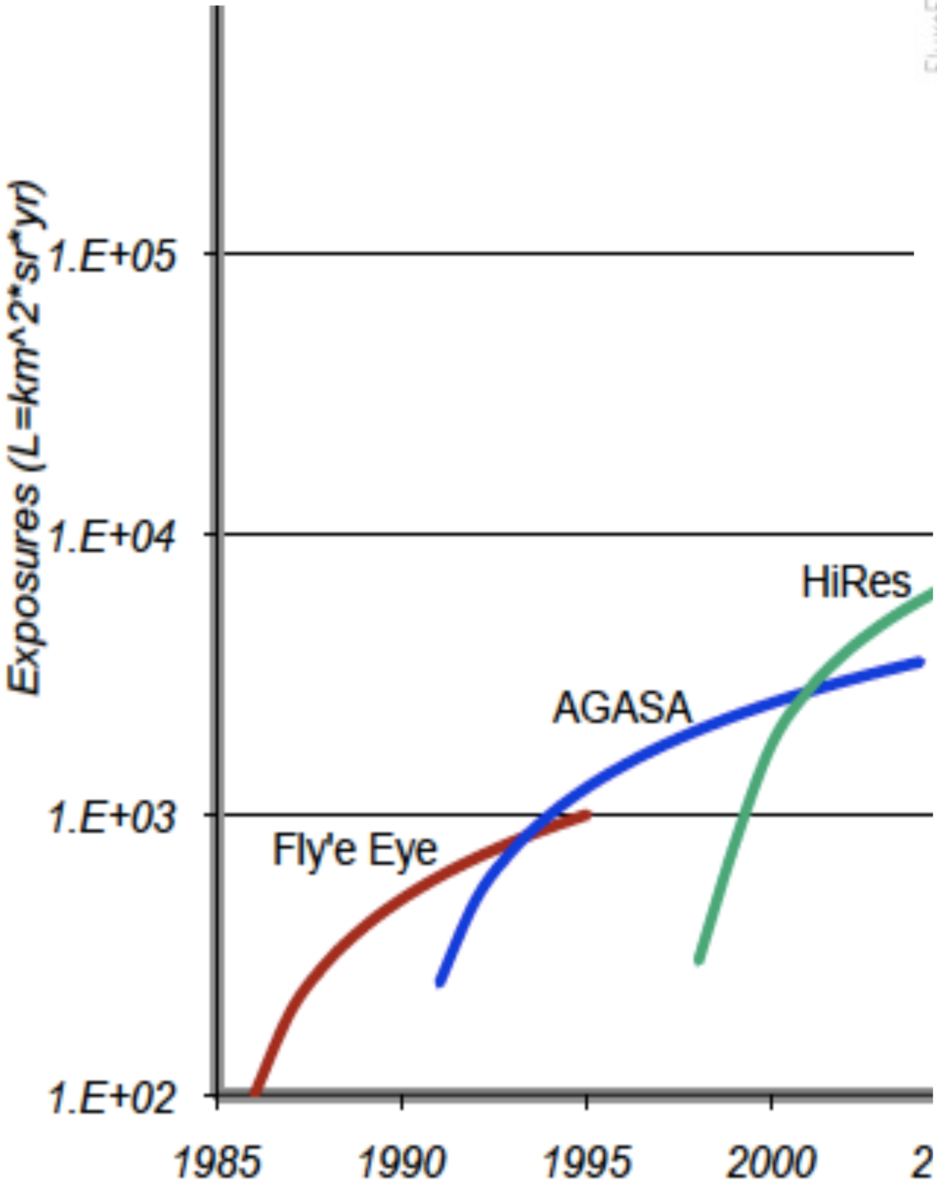
GZK or No GZK?



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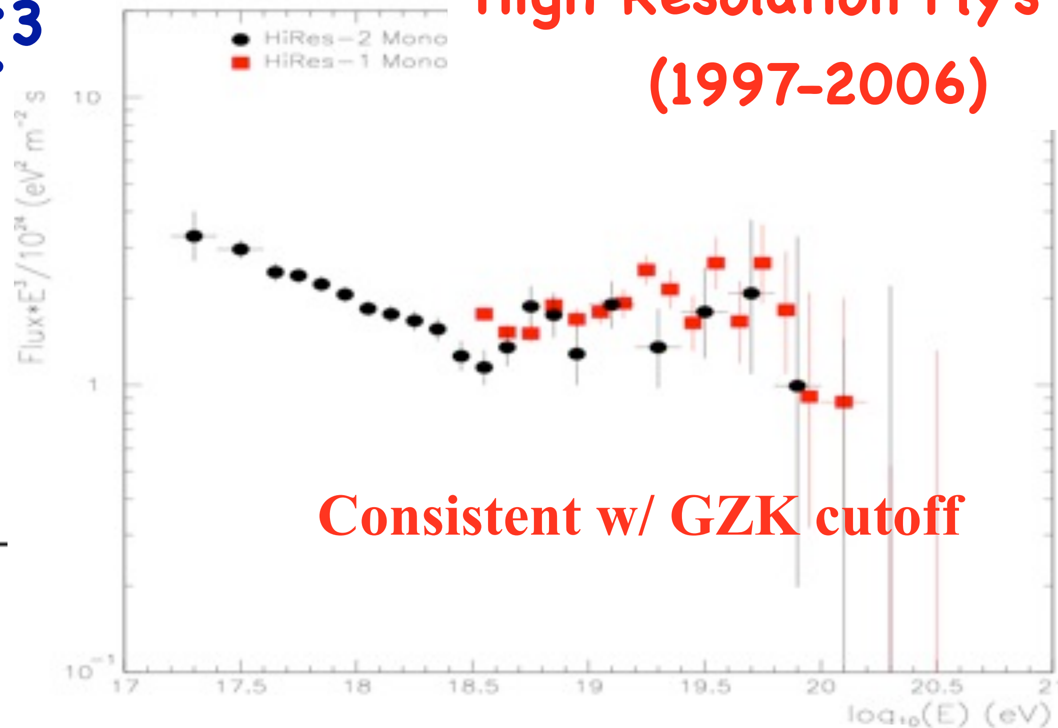
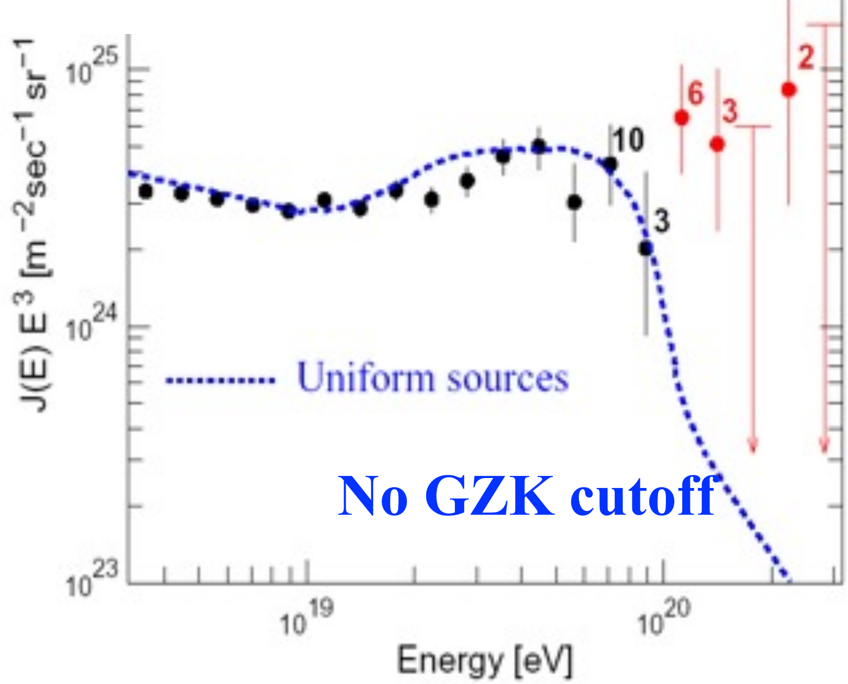


AGASA (1984-2003)



Cosmic Ray Flux x E^3

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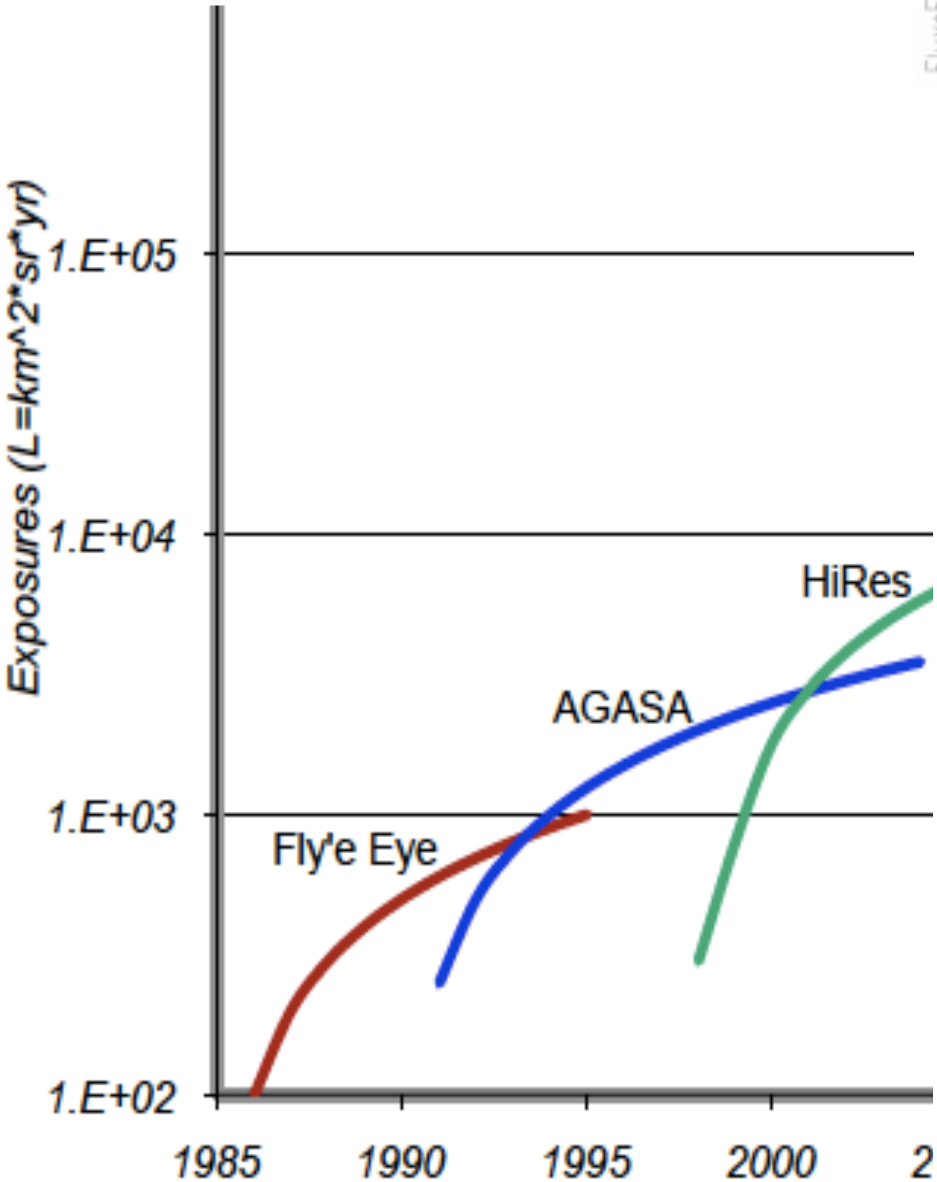

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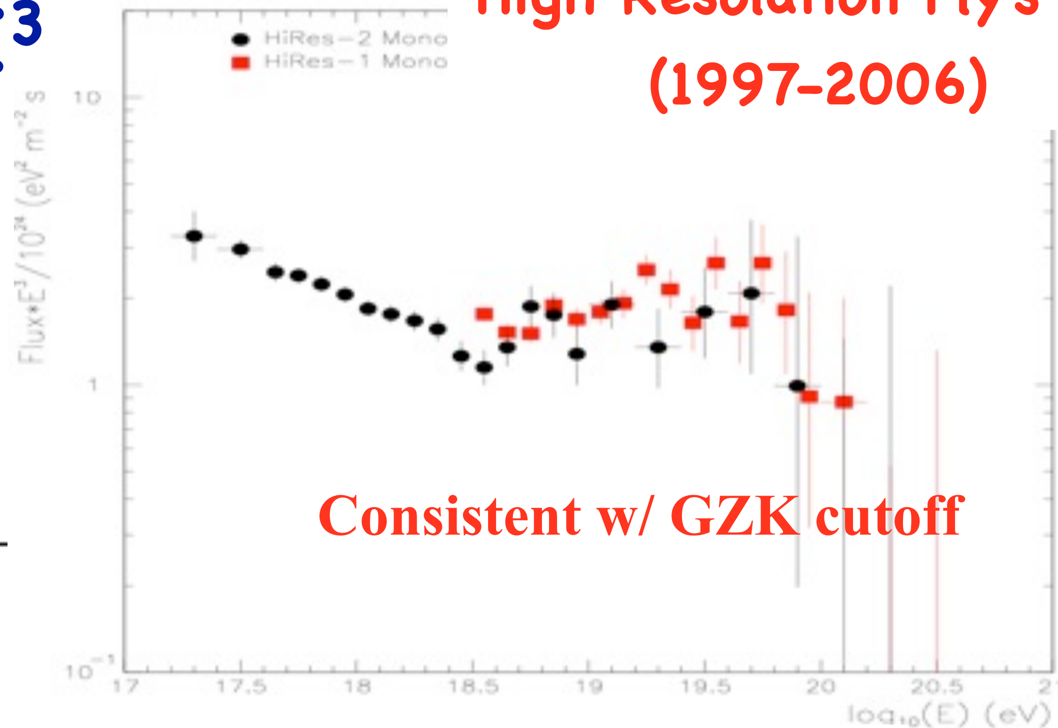
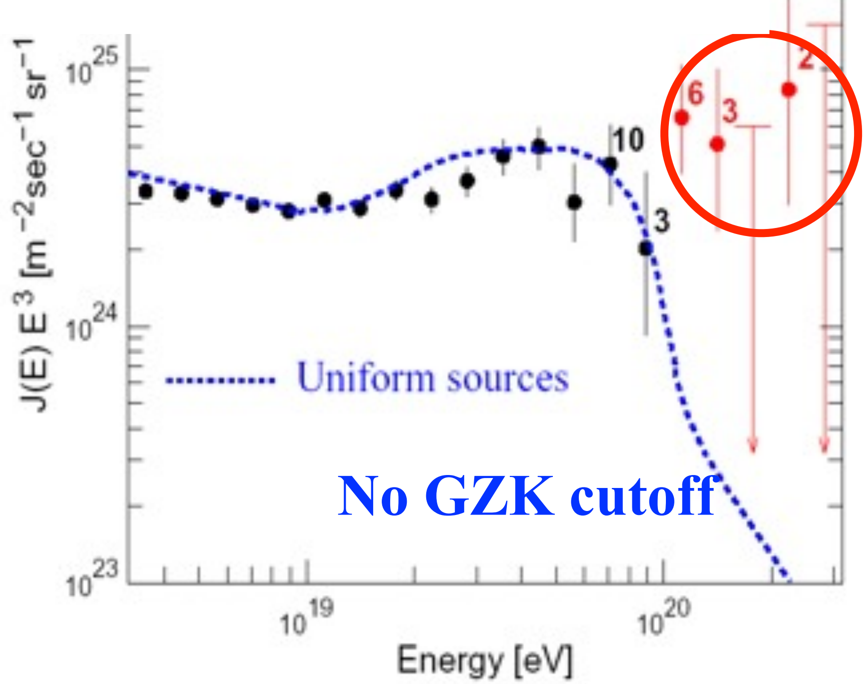
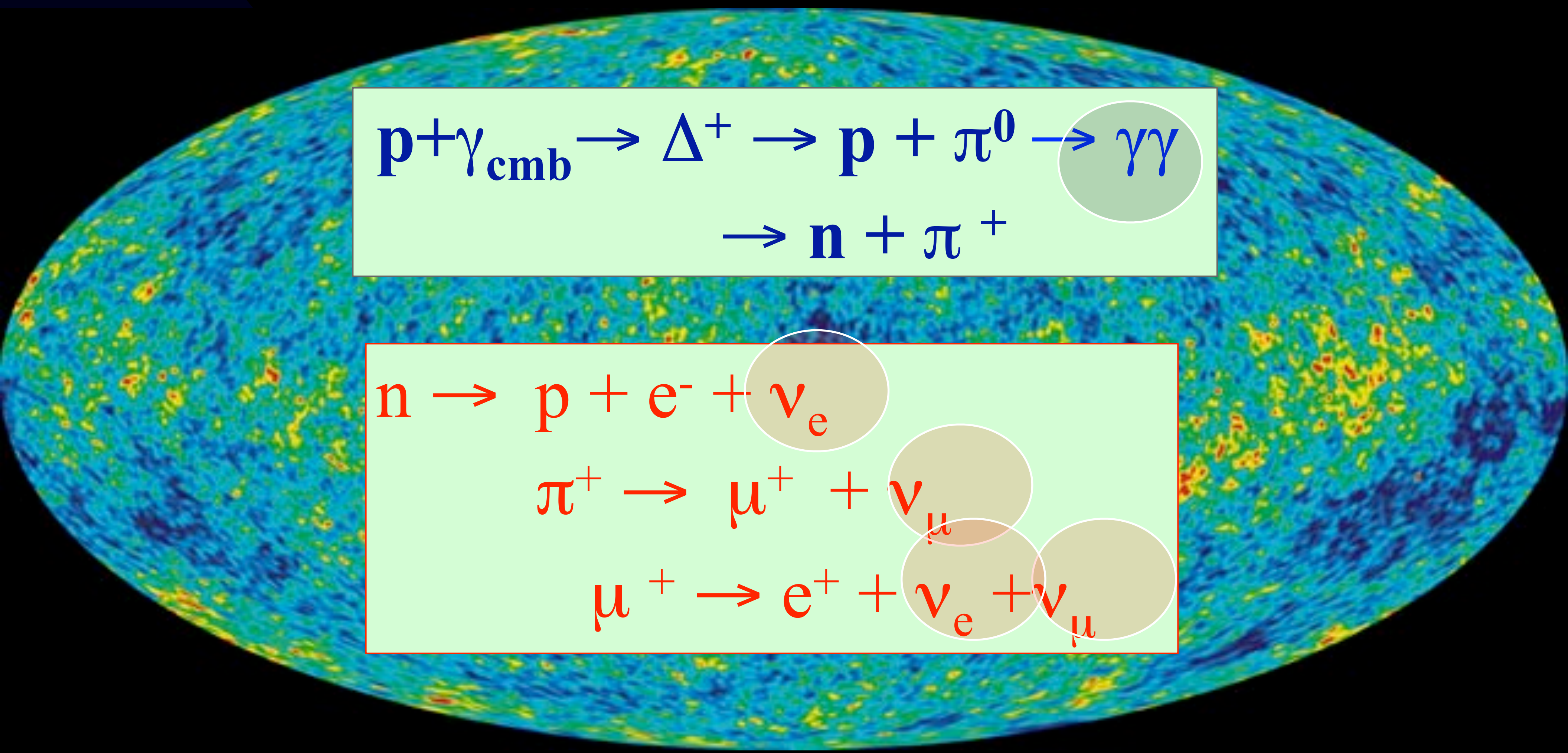


AGASA (1984-2003)



Cosmogenic (GZK) Neutrinos & Photons

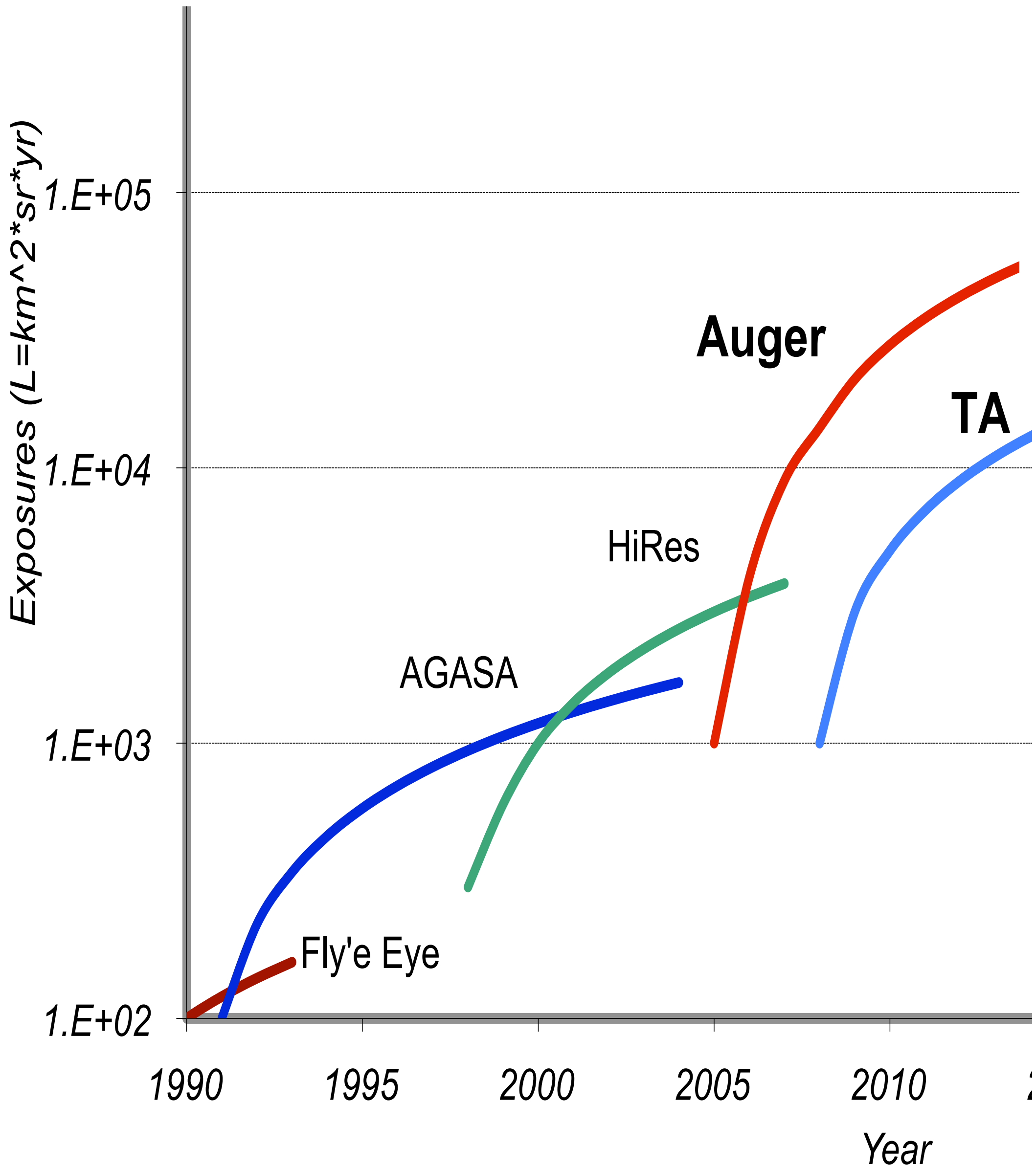


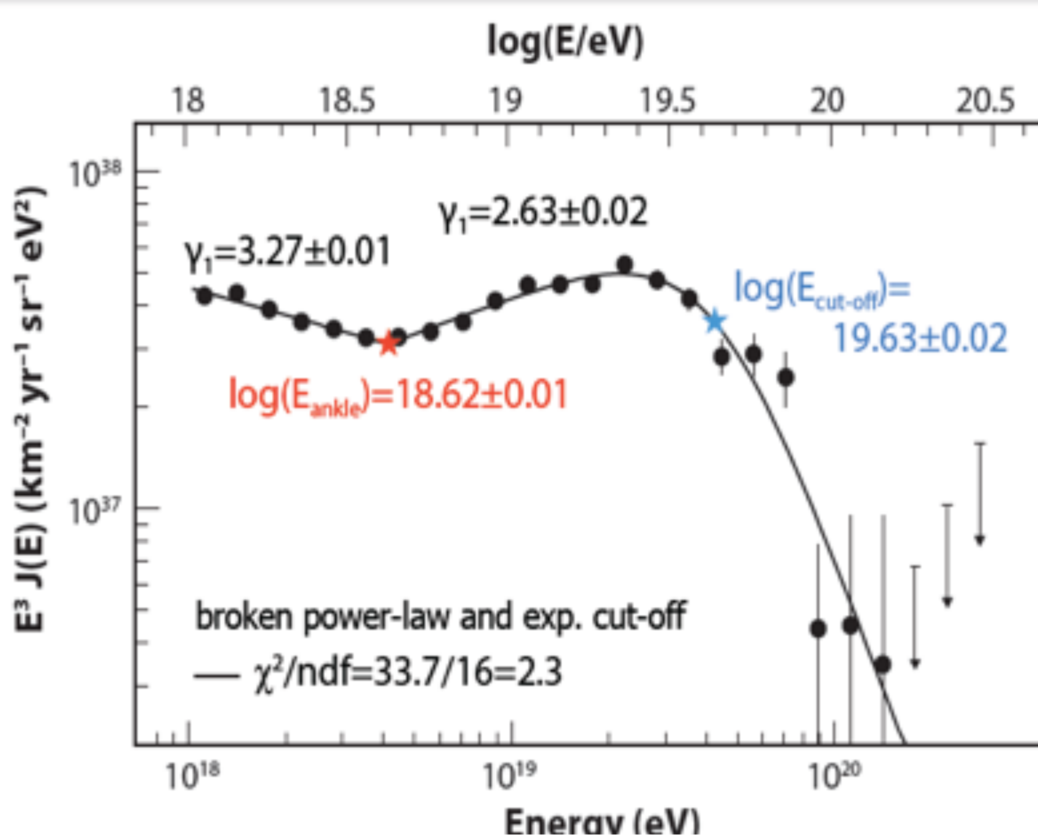
$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

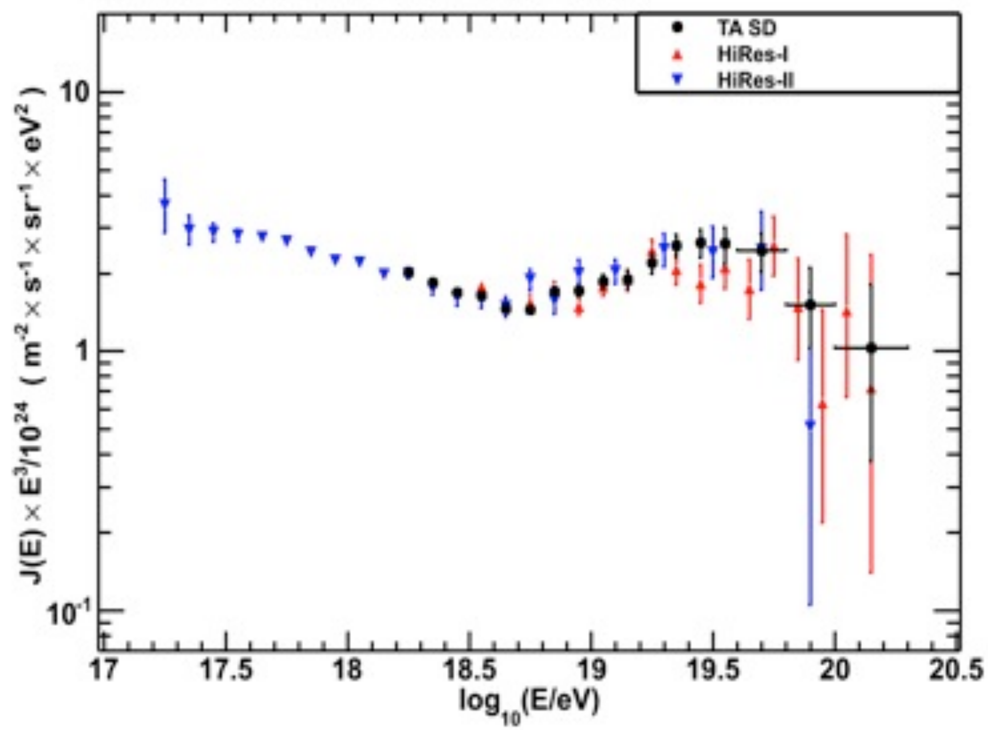
$$n \rightarrow p + e^{-} + \nu_{e}$$
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu}$$

Last Century's question: GZK or No GZK?

Observed Spectra are Consistent w/ GZK effect







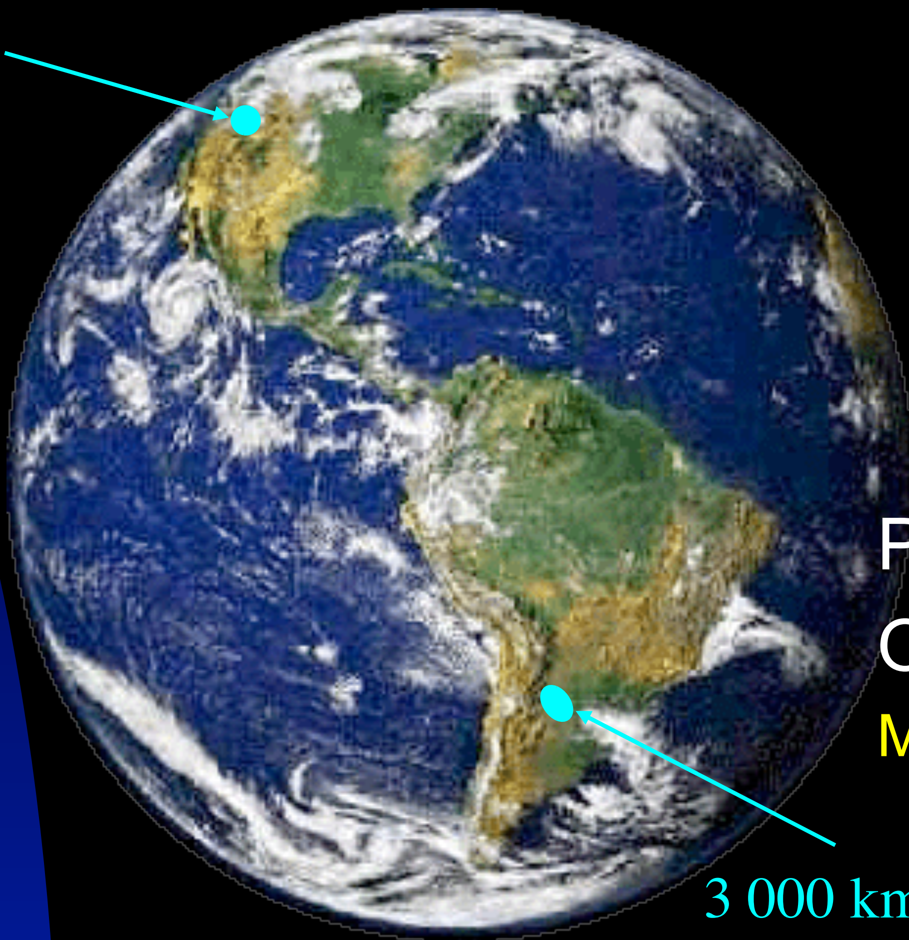
Ultrahigh Energy Cosmic Rays

Telescope Array

Utah, USA

680 km^2 array

3 fluorescence sites



Pierre Auger

Observatory

Mendoza, Argentina

3 000 km^2 array

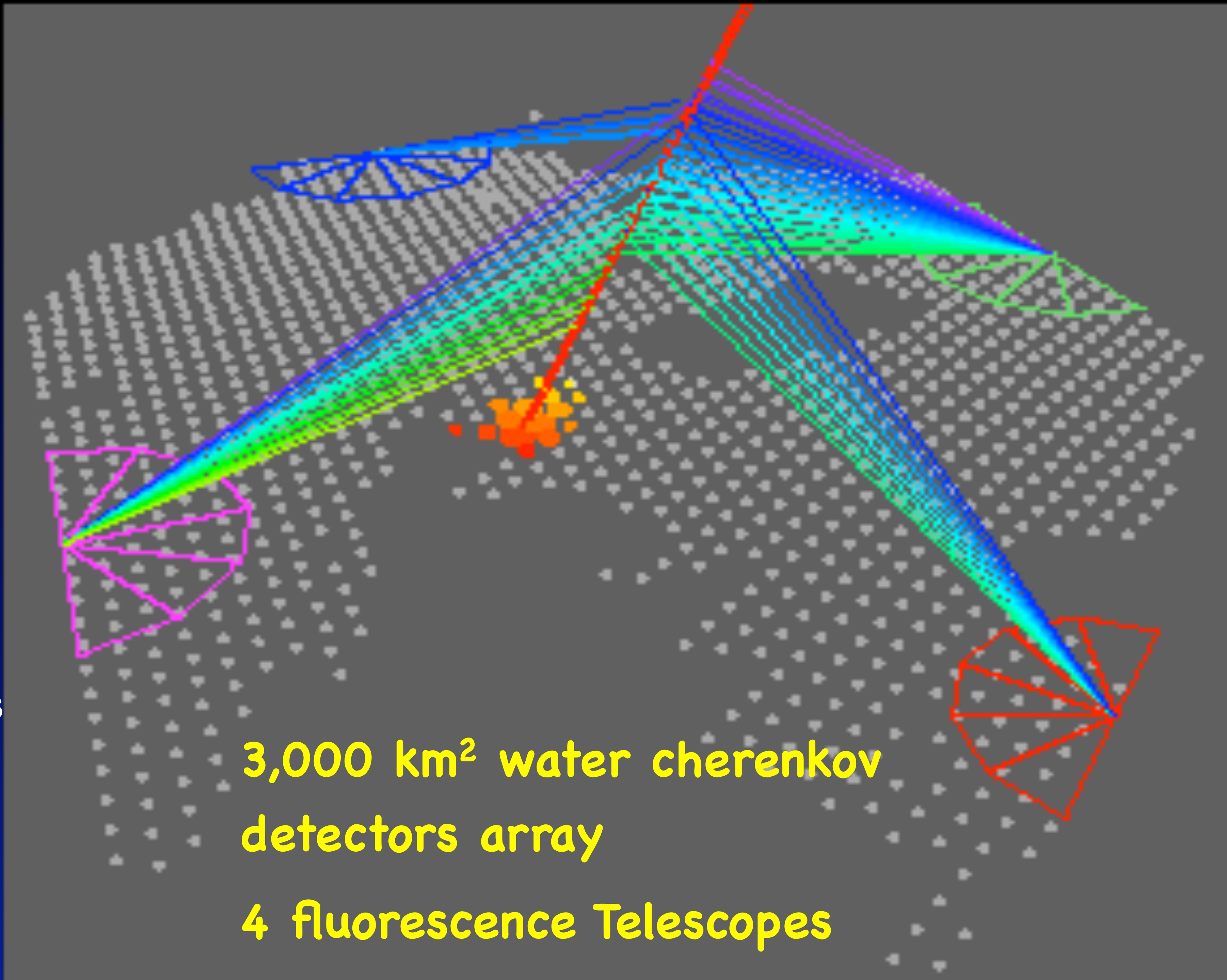
4 fluorescence sites

The Pierre Auger Observatory

Argentina
Australia
Brasil
Bolivia*
Croatia
Czech Rep.
France

Germany
Italy
Mexico
Netherlands
Poland
Portugal

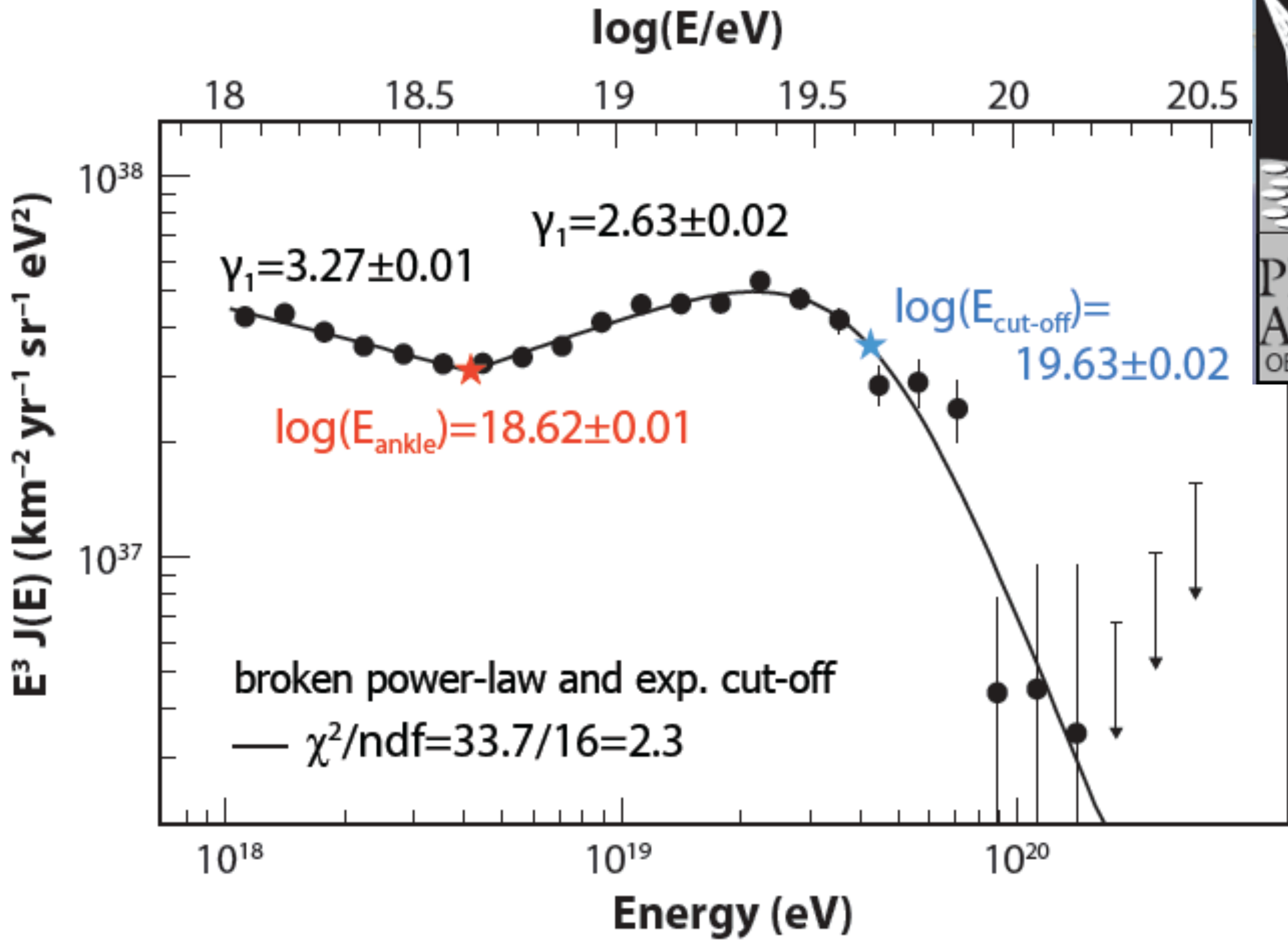
Romania*



surface detector


tanks aligned seen from Los Leones

4 times 6 telescopes overlooking the site



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

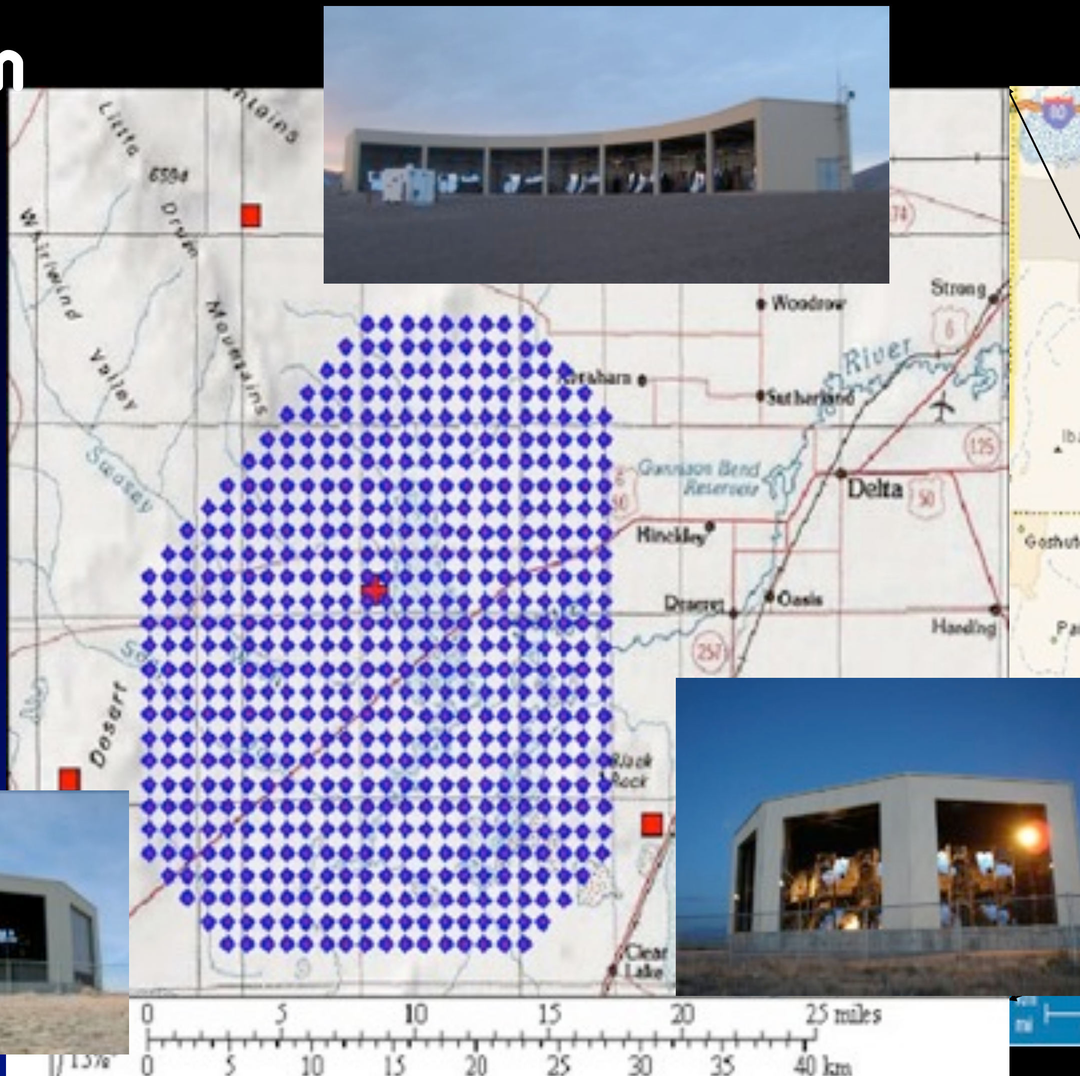
Total uncertainty of E-scale: 22% (dominated by Fl.-yield. 14%)

Exposure = 20905 km^2 sr yr

Telescope Array

Area: 680 km^2

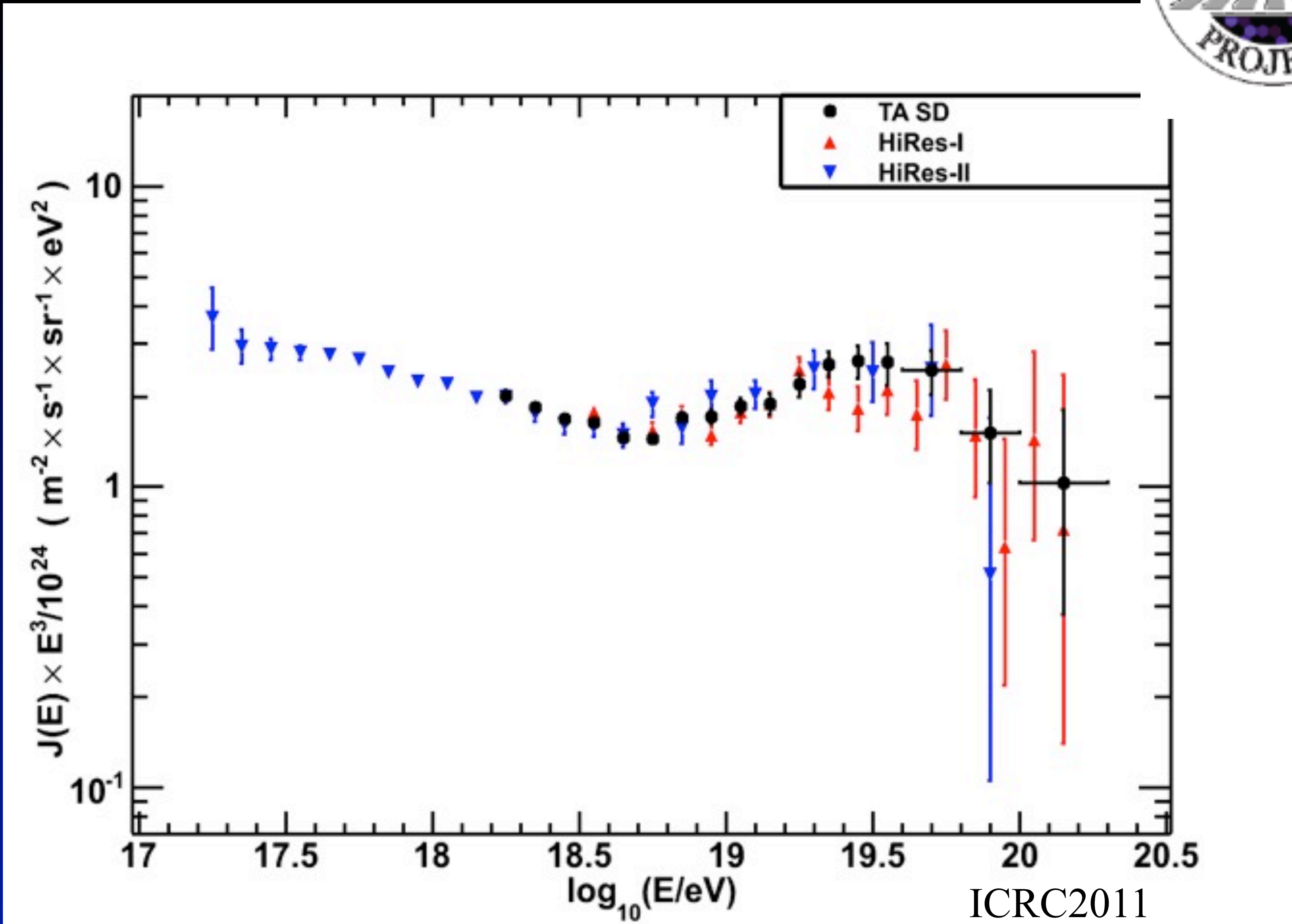
Belgium
Japan
Korea
Russia
USA

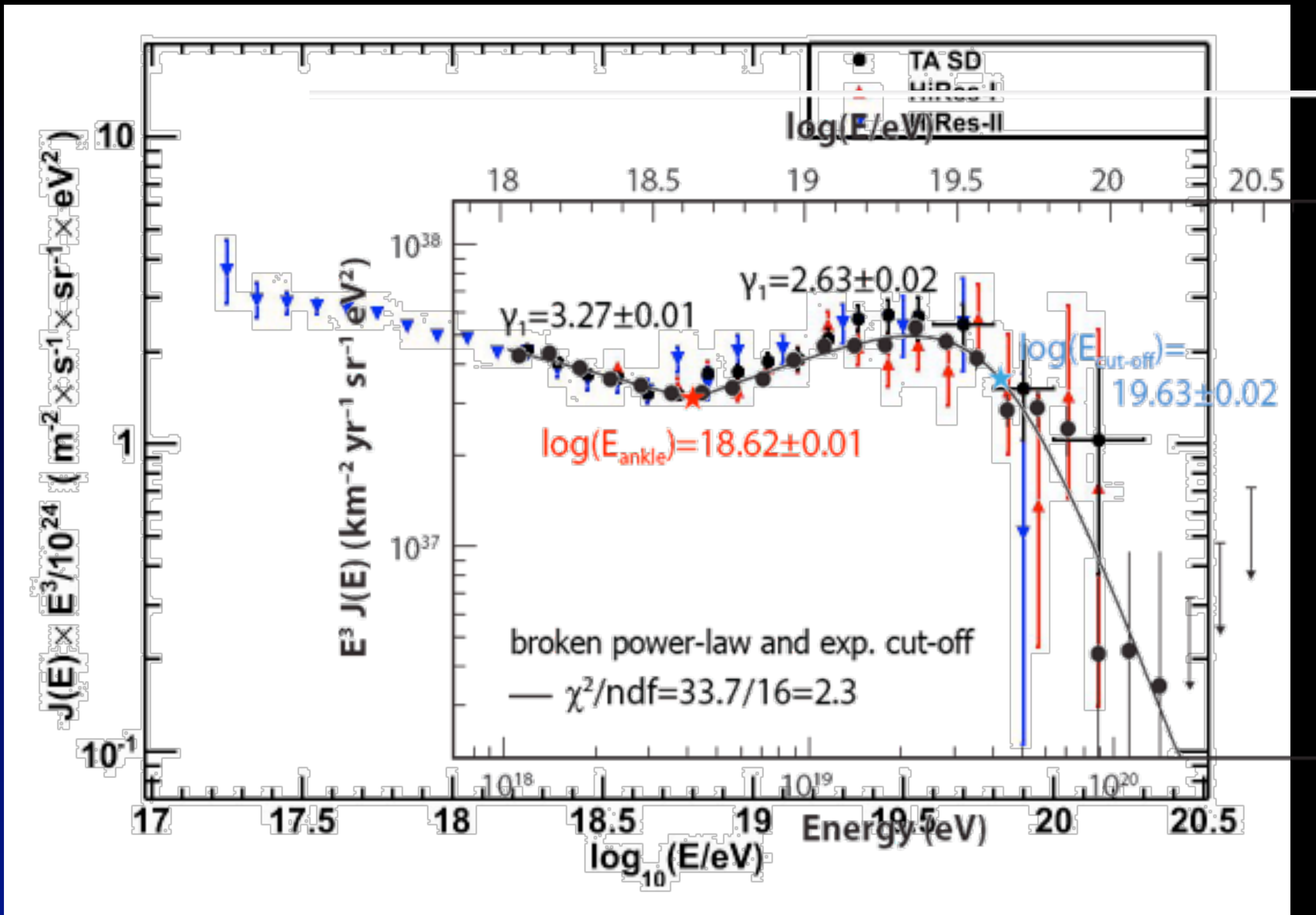


3 FD stations overlooking an array of
507 scintillator surface detectors (SD)
complete and operational as of ~1/2008.

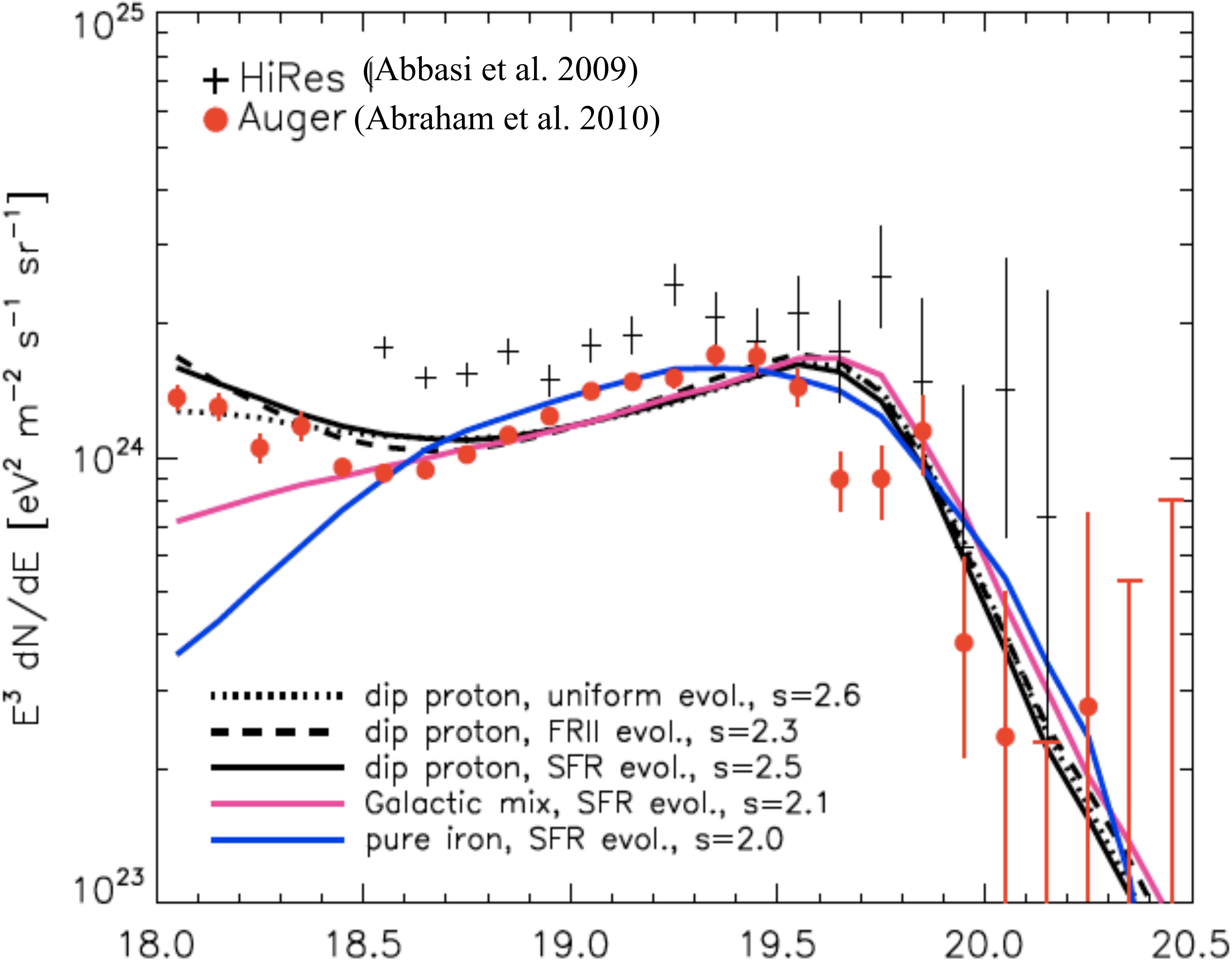
Deployment (up to 50/day)
485 SDs: 10/2006 –
3/2007

Telescope Array SD spectrum





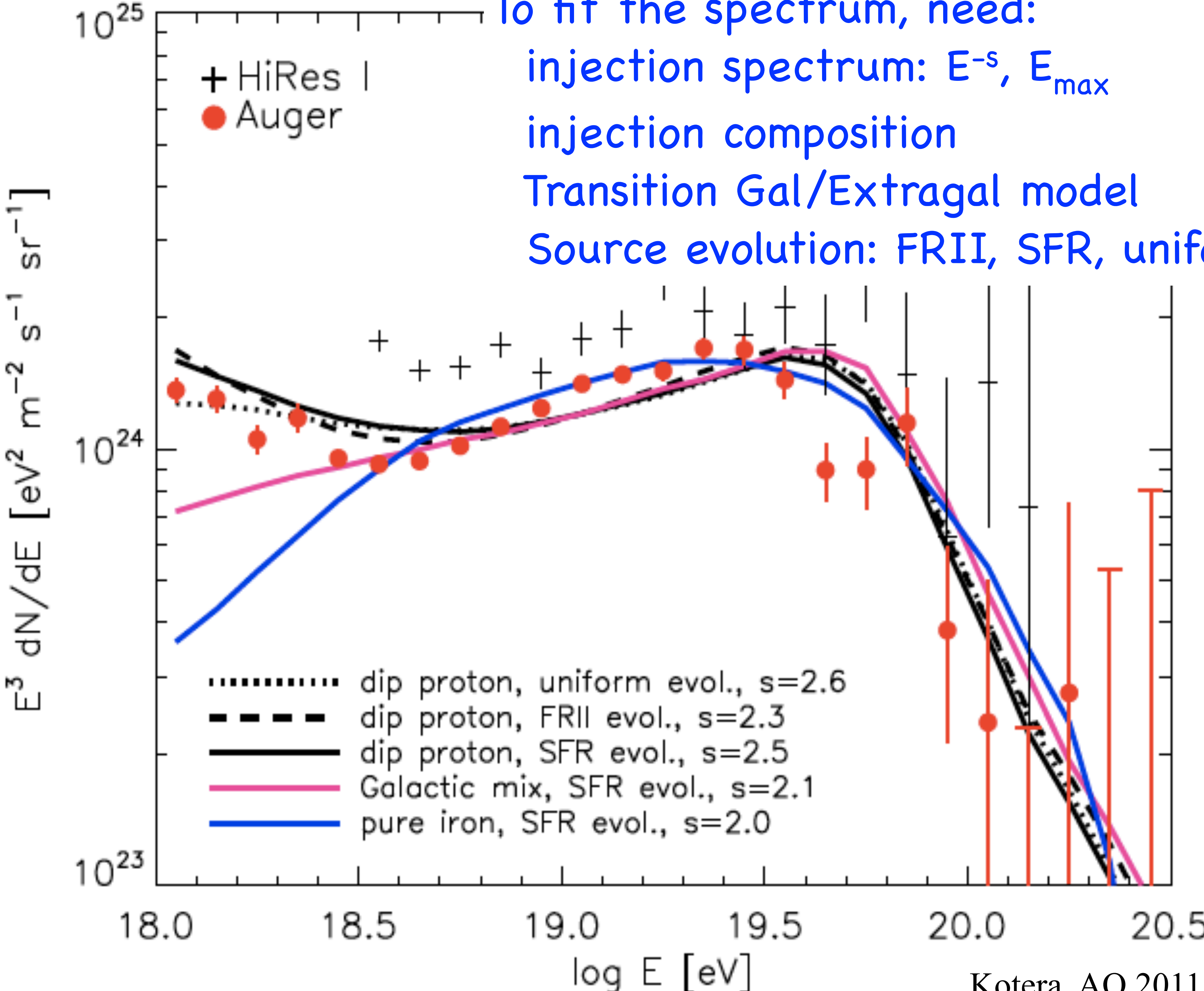
20 % "absolute" energy shift



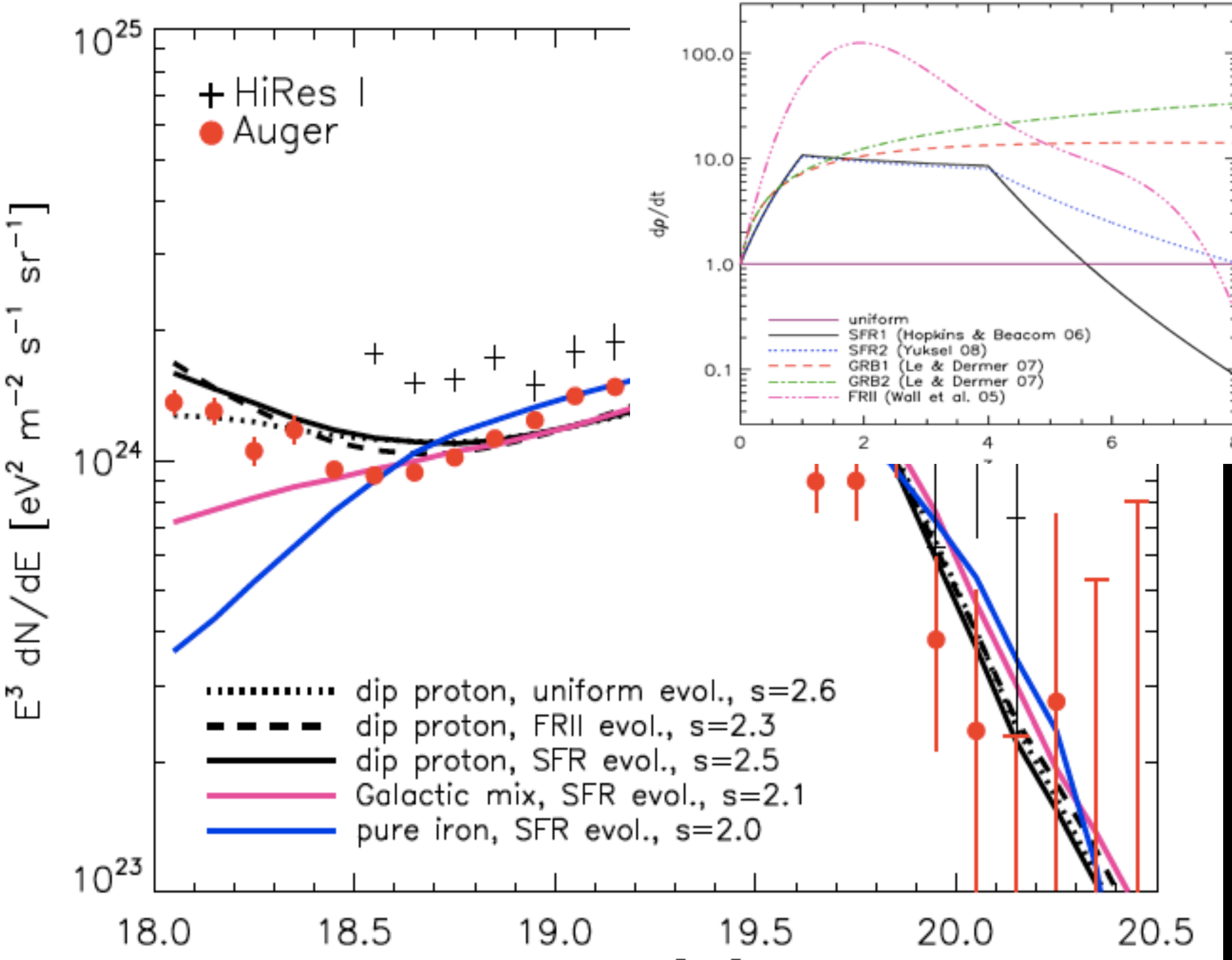
Kotera, AO 2011

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



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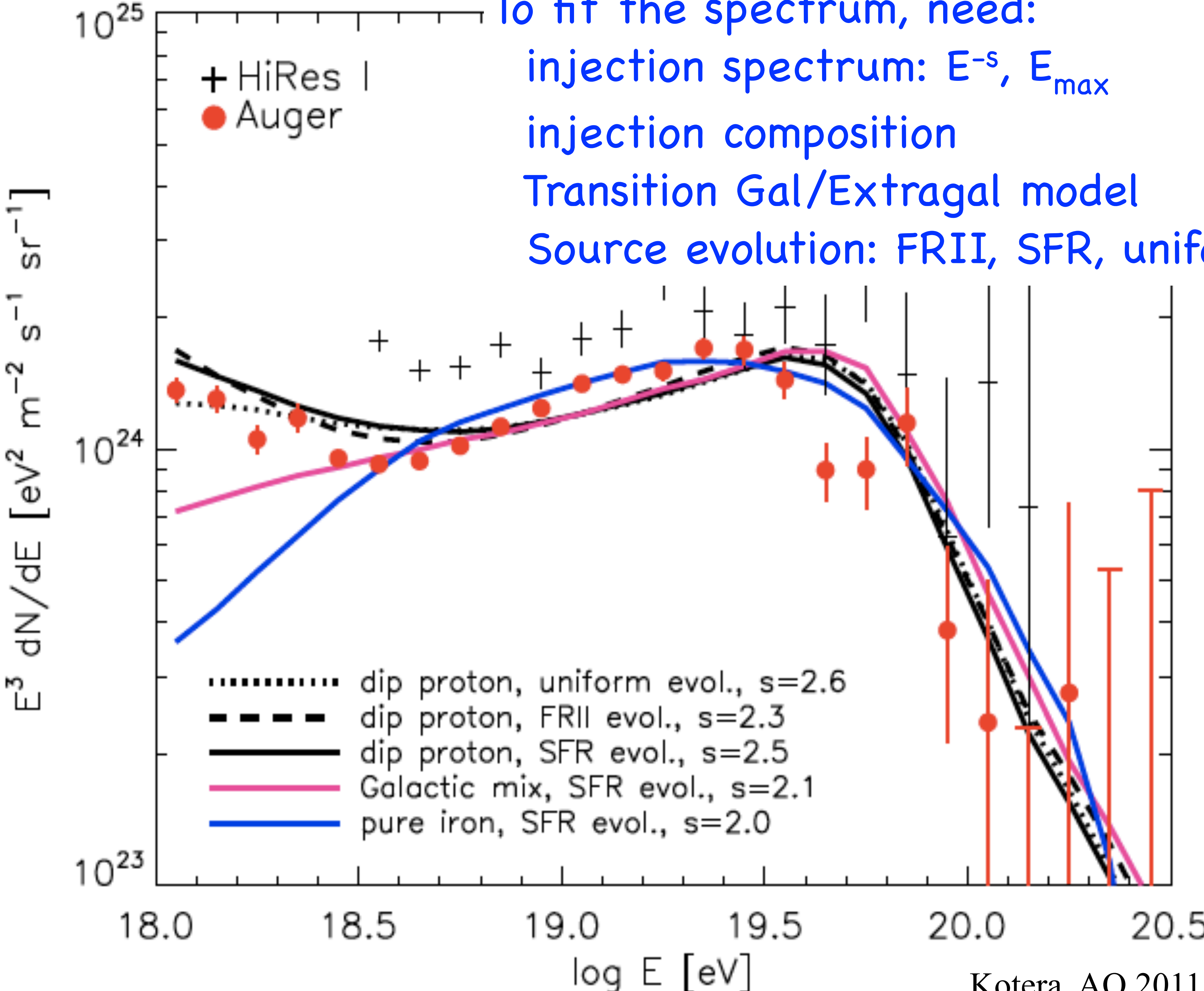

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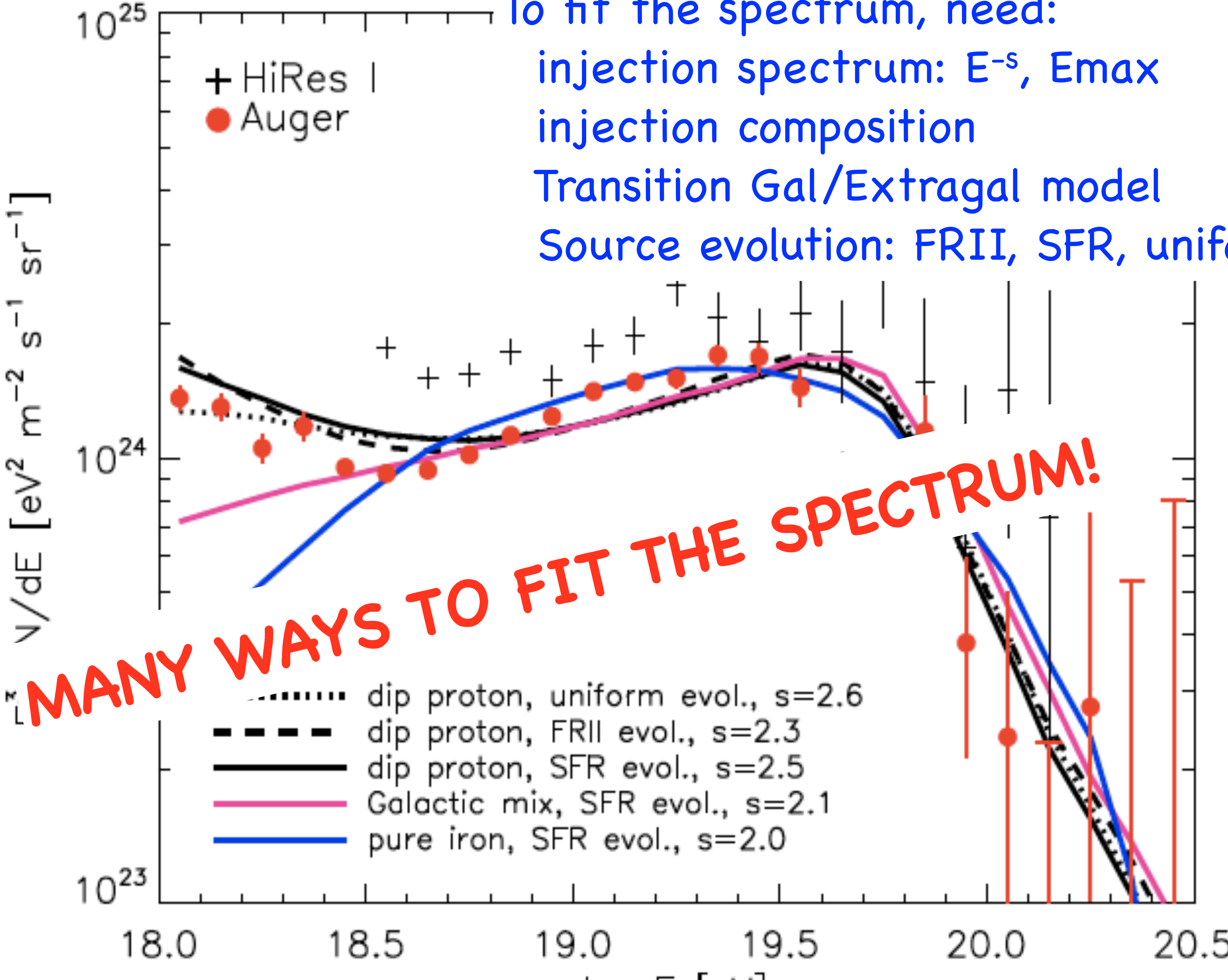


MANY WAYS TO FIT THE SPECTRUM!

Kotera, AO 2011

High Energy Cosmic Rays

OBSERVABLES:

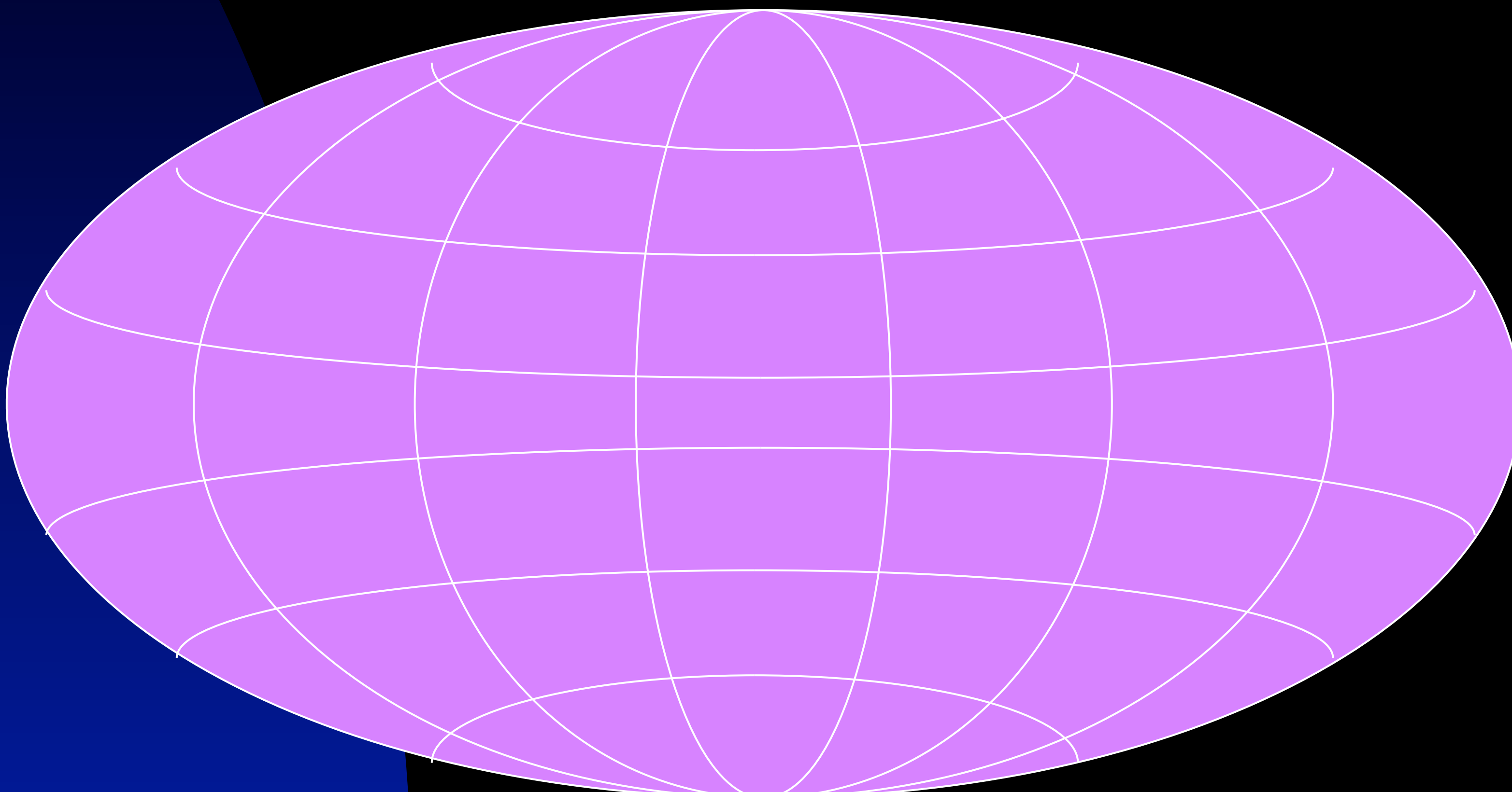
Spectrum

Composition

Sky Distribution

CR arrival directions
E < 6 10^{19} eV

Isotropic!



"Known unknown"

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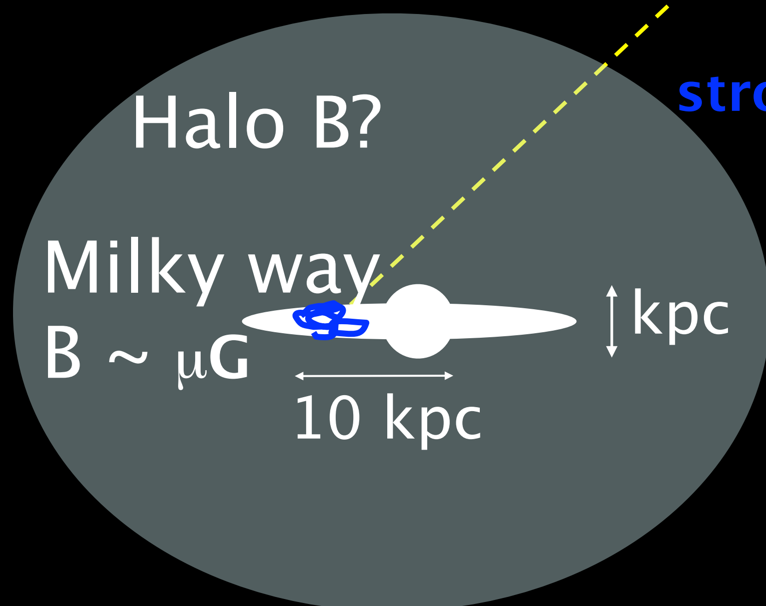
γ

Extra-galactic B?
B < **nG**

weak deflection
E > 10^{19}eV

strong deflection
E < 10^{18}eV

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



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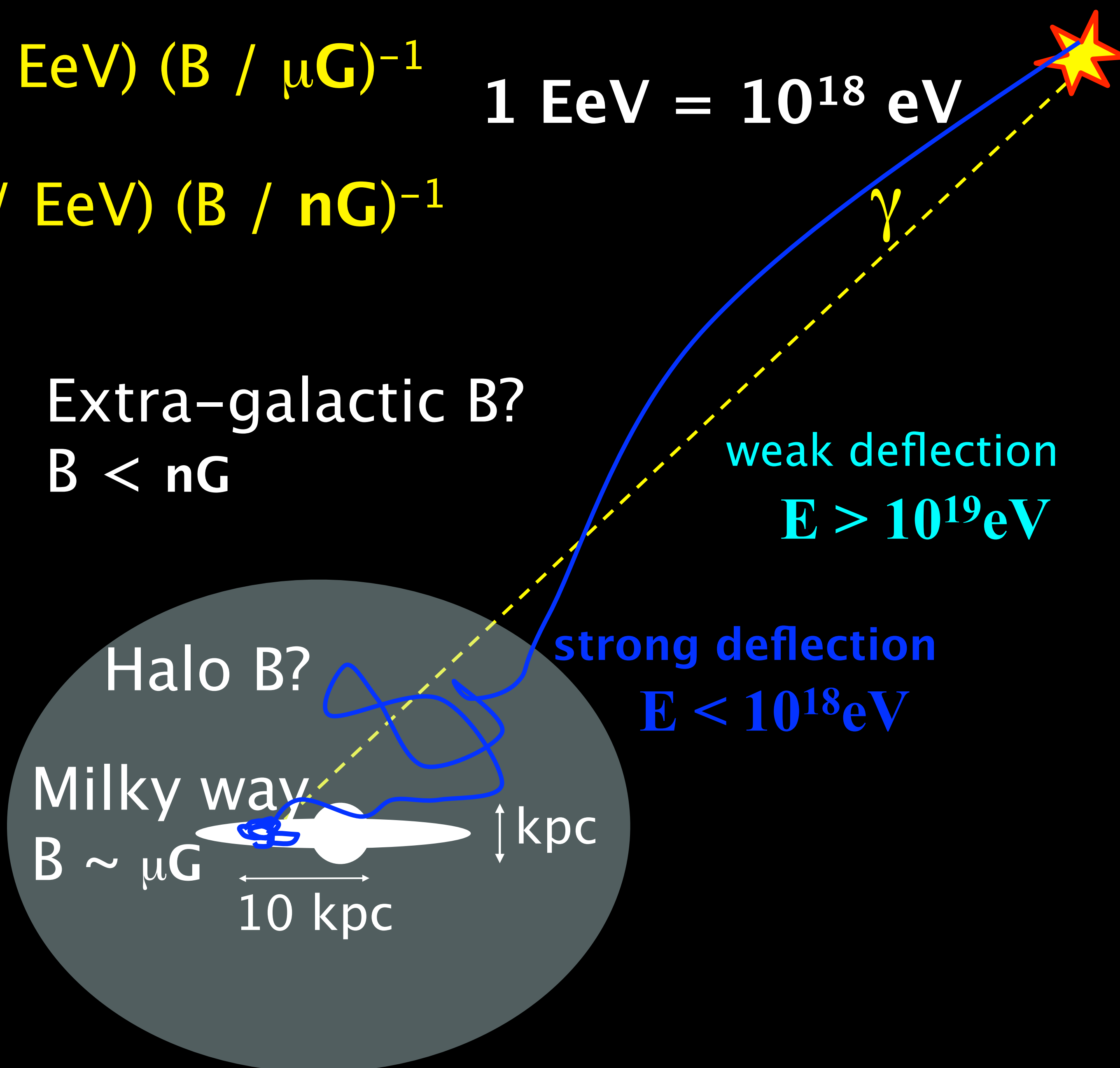

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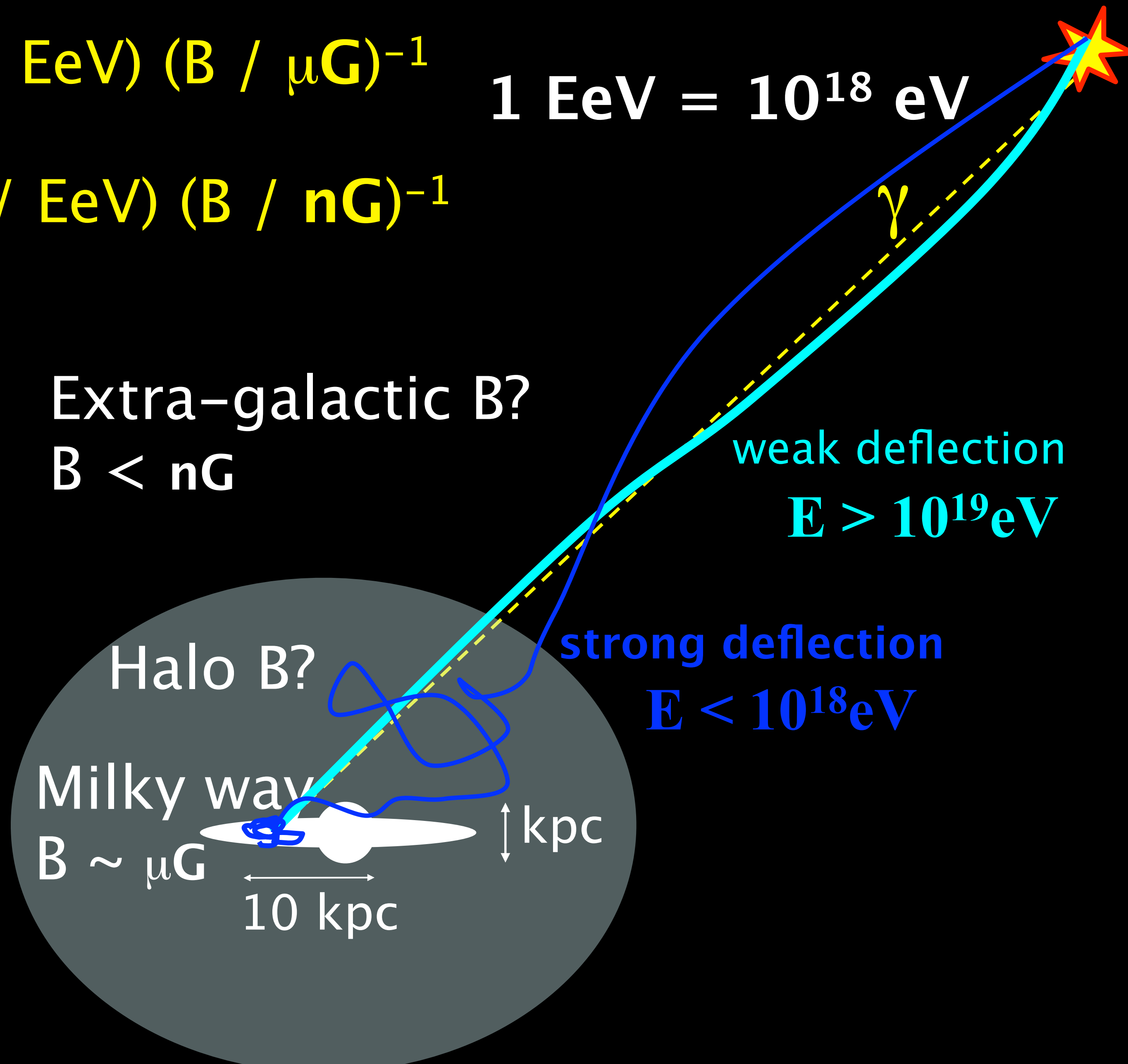
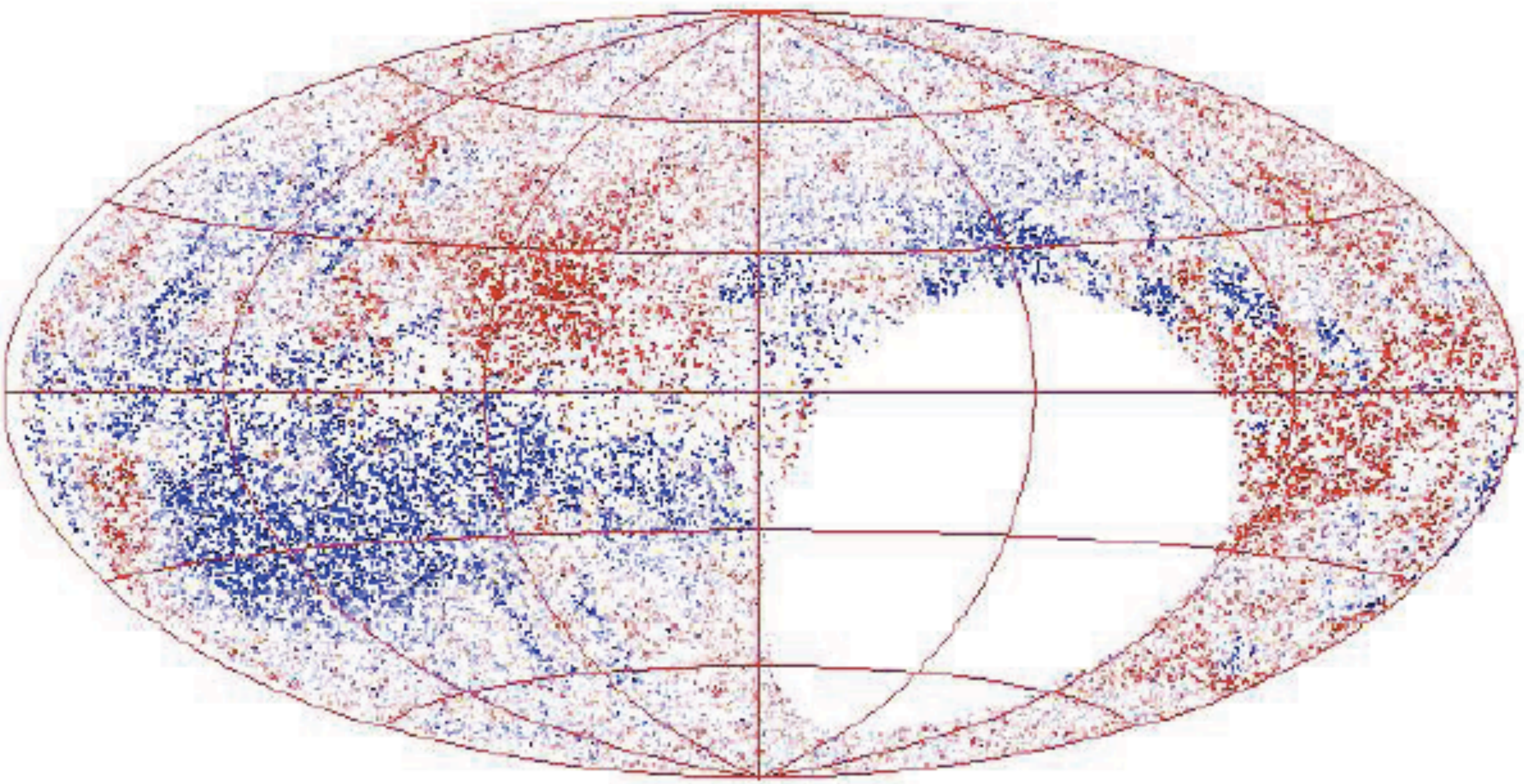


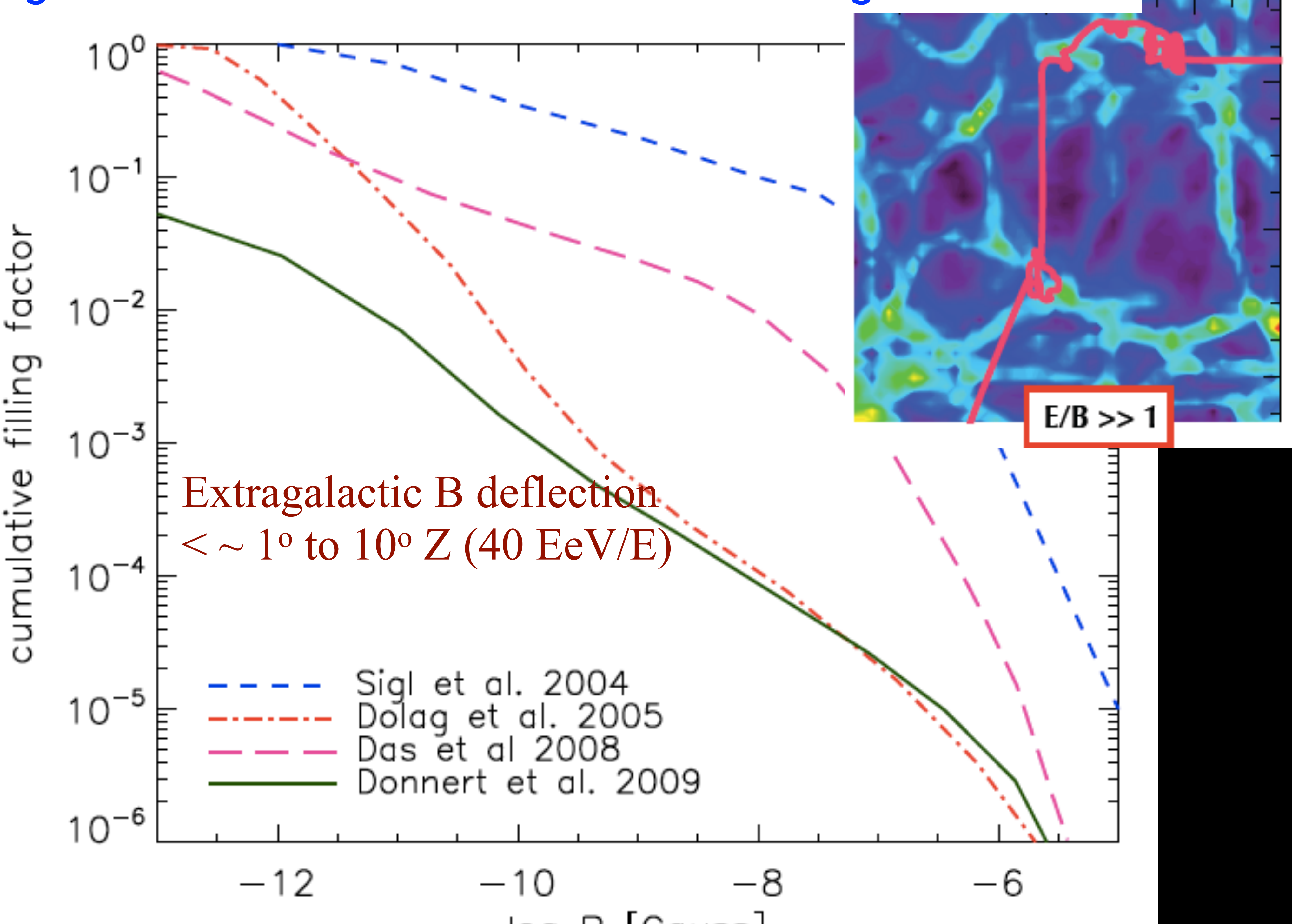
Galactic B deflection
<< 10° Z (40 EeV/E)
anisotropic in sky

Galactic Magnetic Field:
Rotation Measures



Pshirkov et al, **arXiv:1103.0814**

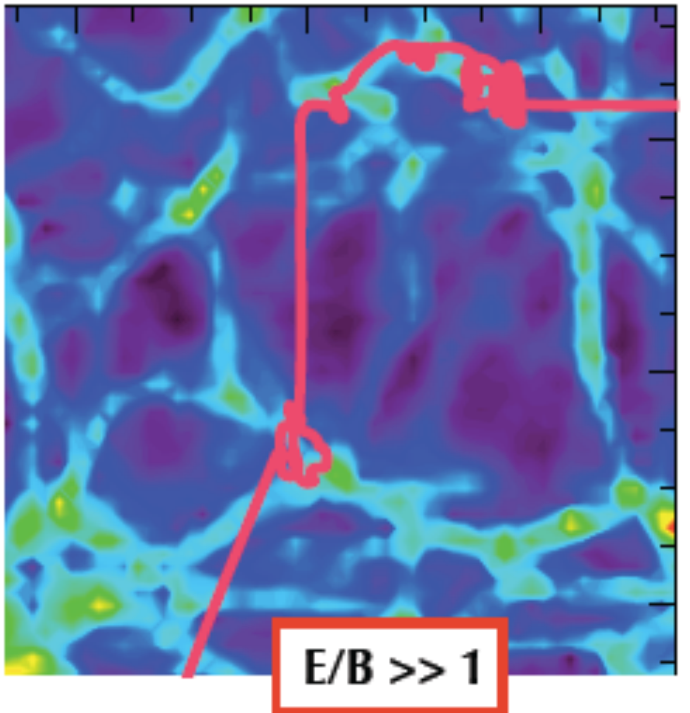
Large Scale Structure Simulations with Magnetic Fields

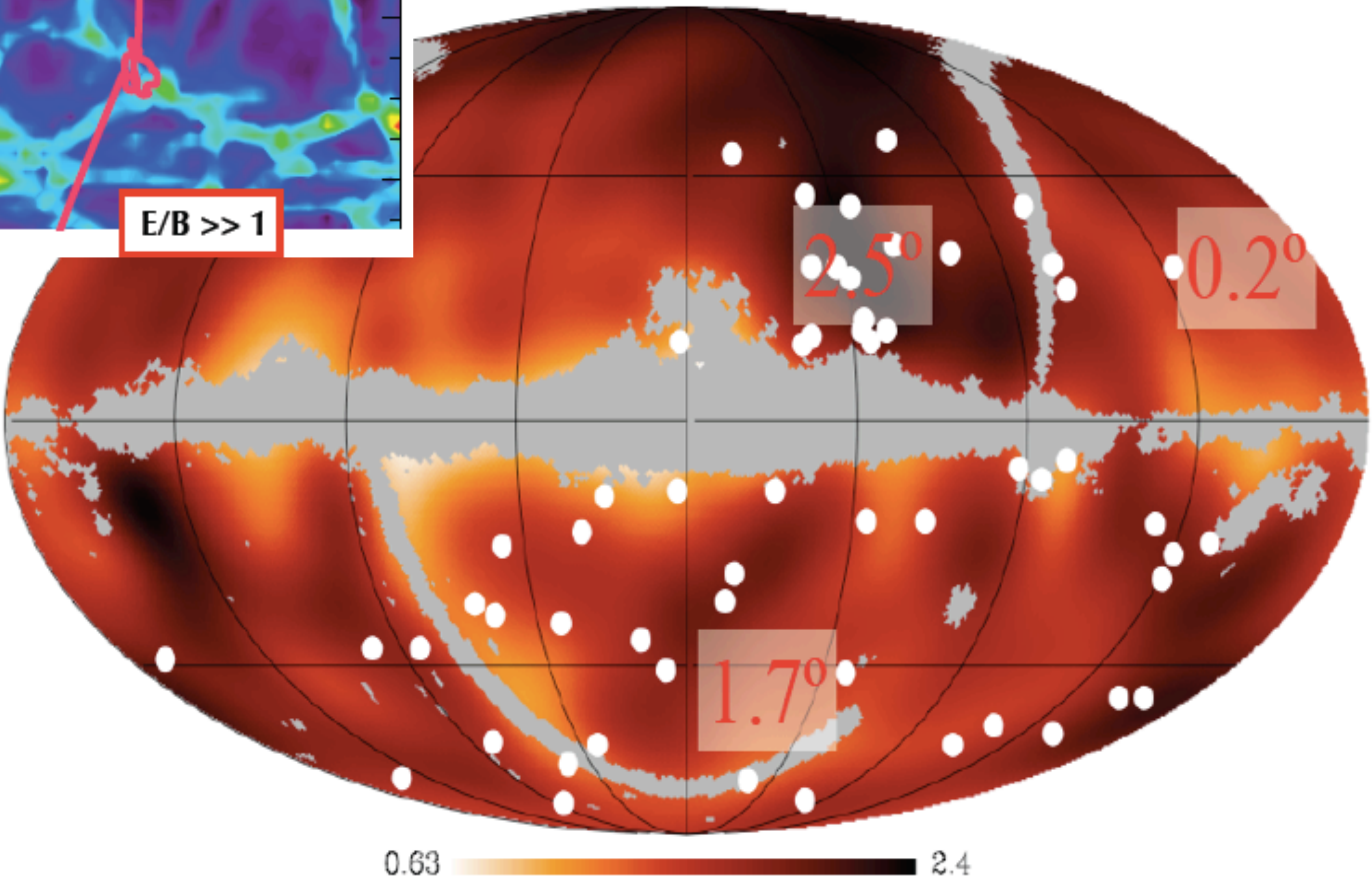


Kotera, AO 2011

Expected angular deflection (degrees) for protons $E > 6\ 10^{19}$ eV (PSCz catalog)

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





GZK Effect

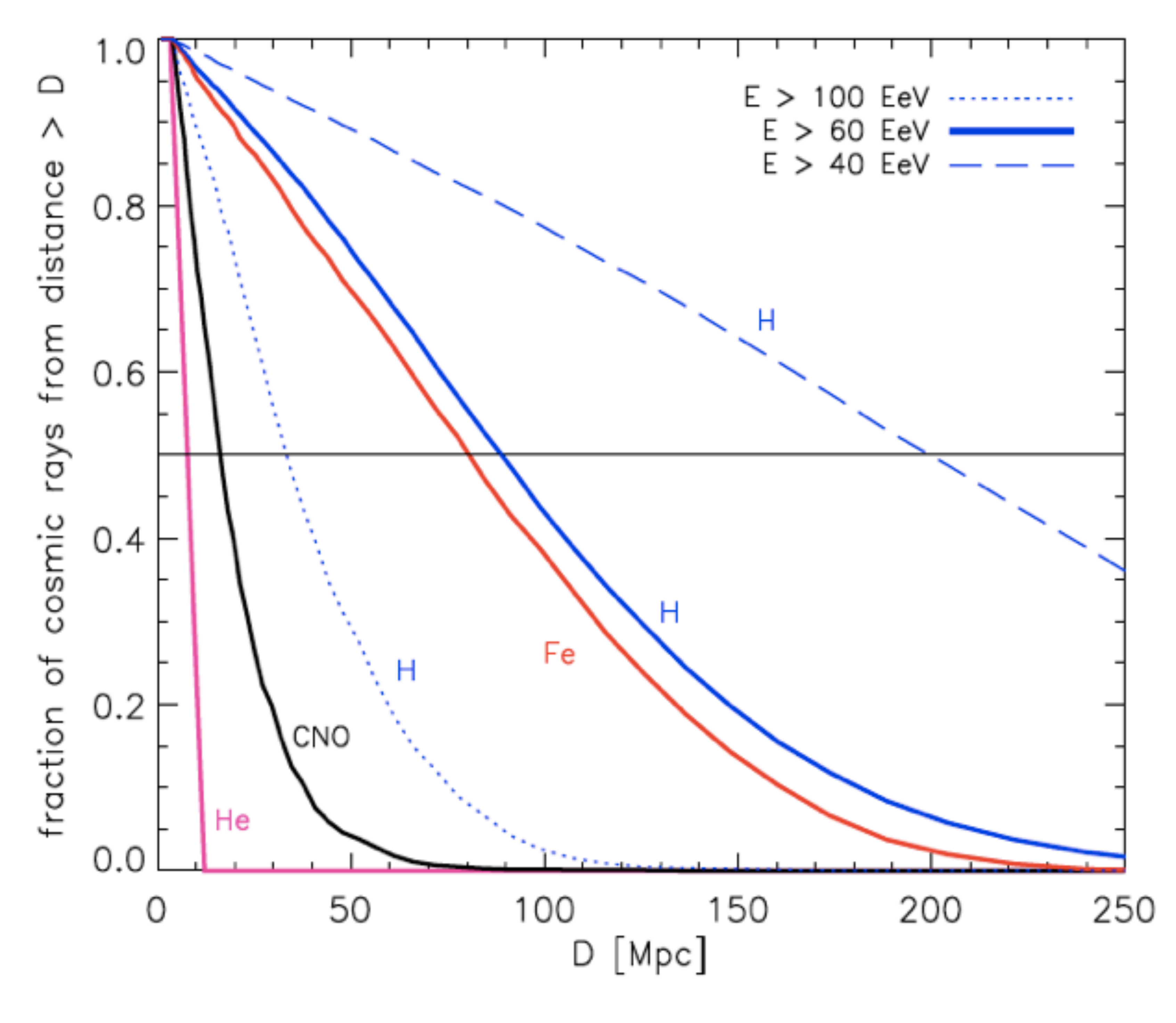
⇒ Spectral Feature

\+ LSS

⇒ **Anisotropic Sky Distribution**

E > 60 EeV

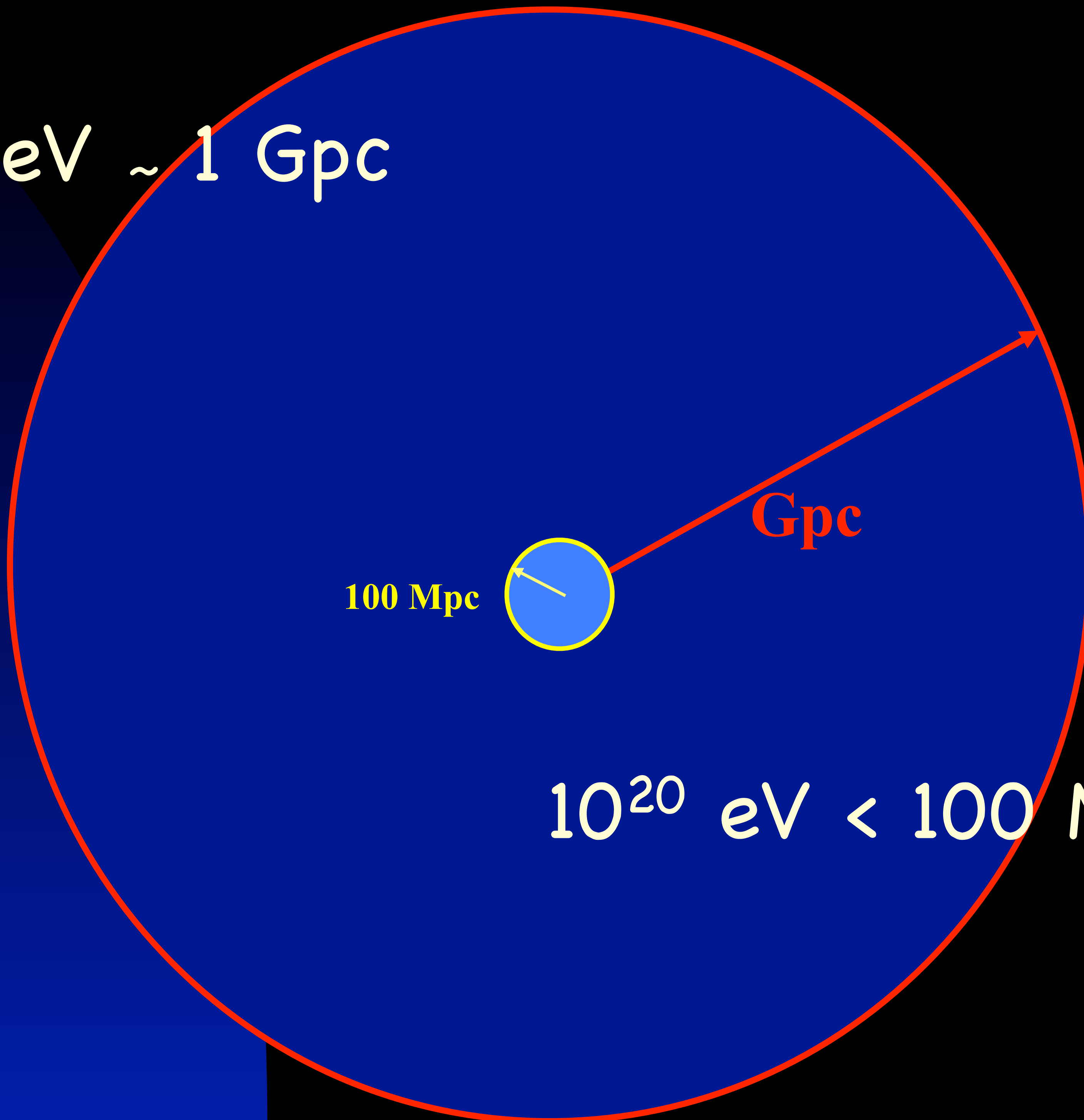
GZK Horizon



fraction of cosmic rays from distance > D
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
D [Mpc]
E > 100 EeV
E > 60 EeV
E > 40 EeV
H
H
H
Fe
CNO
He

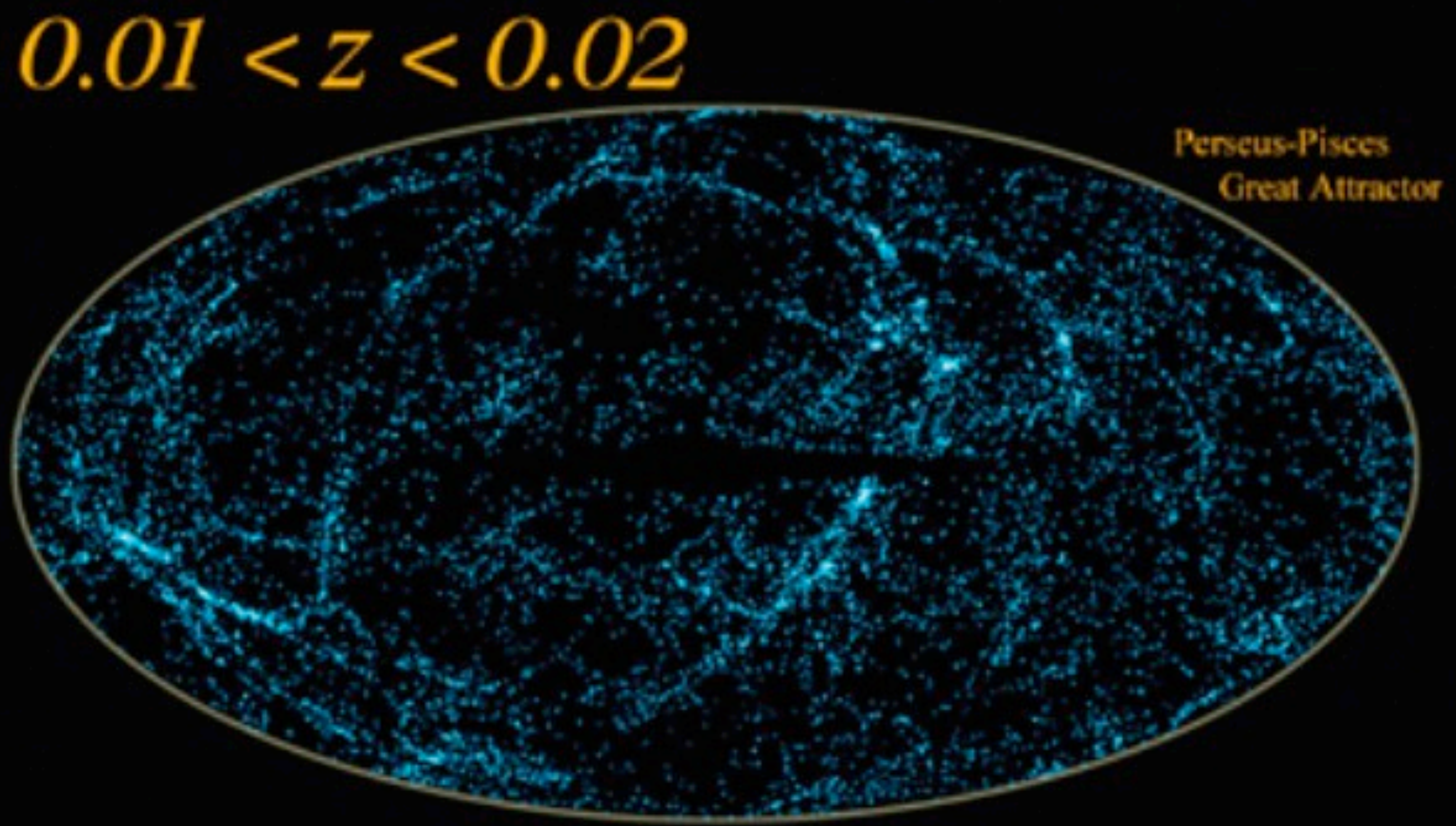
Horizons:

10^{19} eV ~ 1 Gpc



10^{20} eV < 100 Mpc

Inhomogeneous

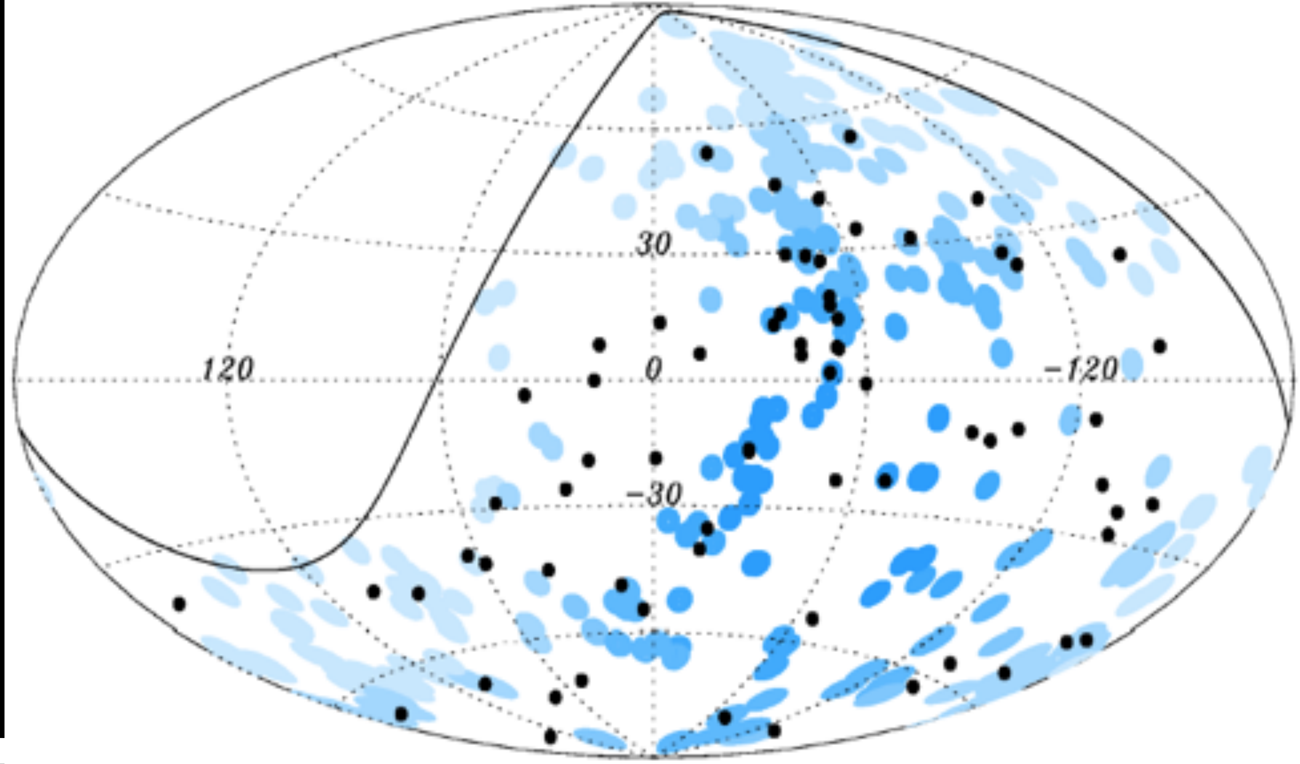


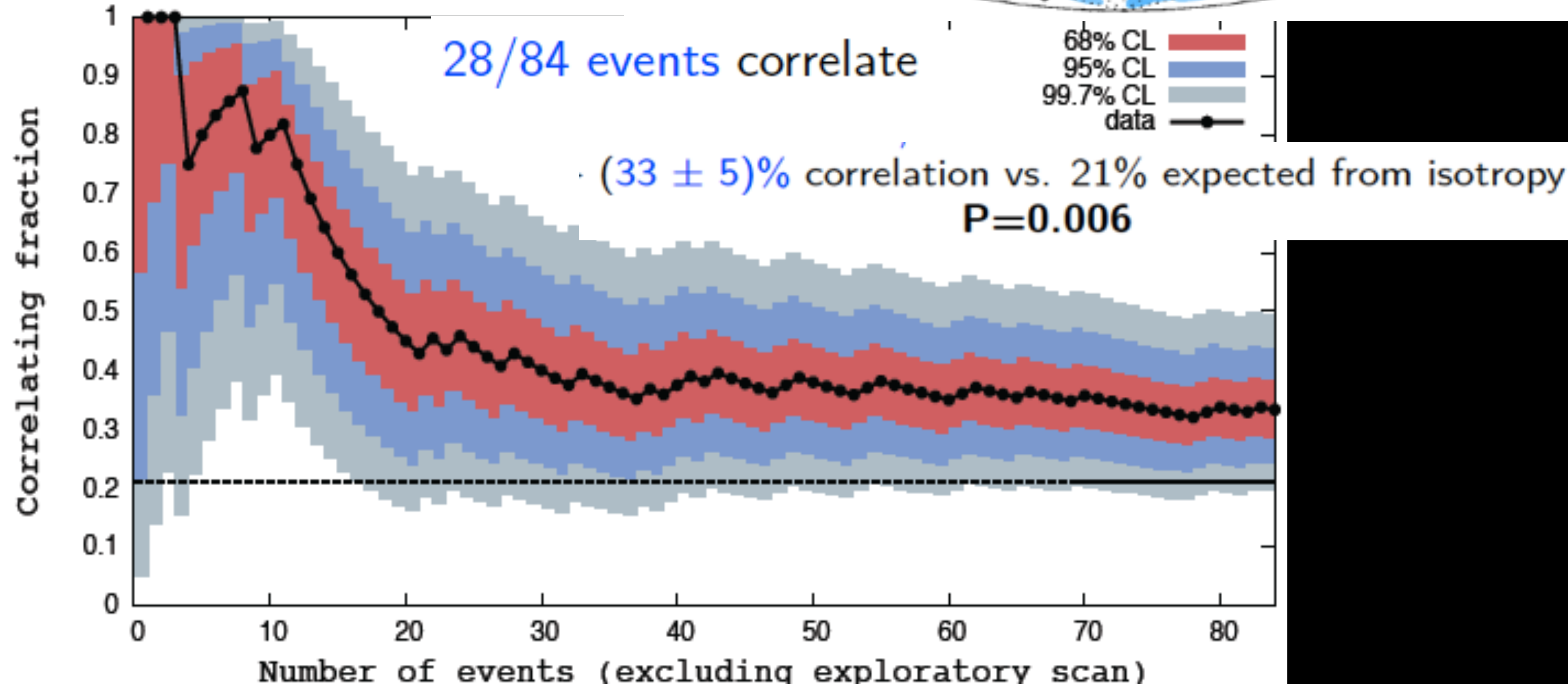
2MASS - Two Micron All Sky Survey

Pierre Auger:

consistent with Anisotropy

AGN catalog test

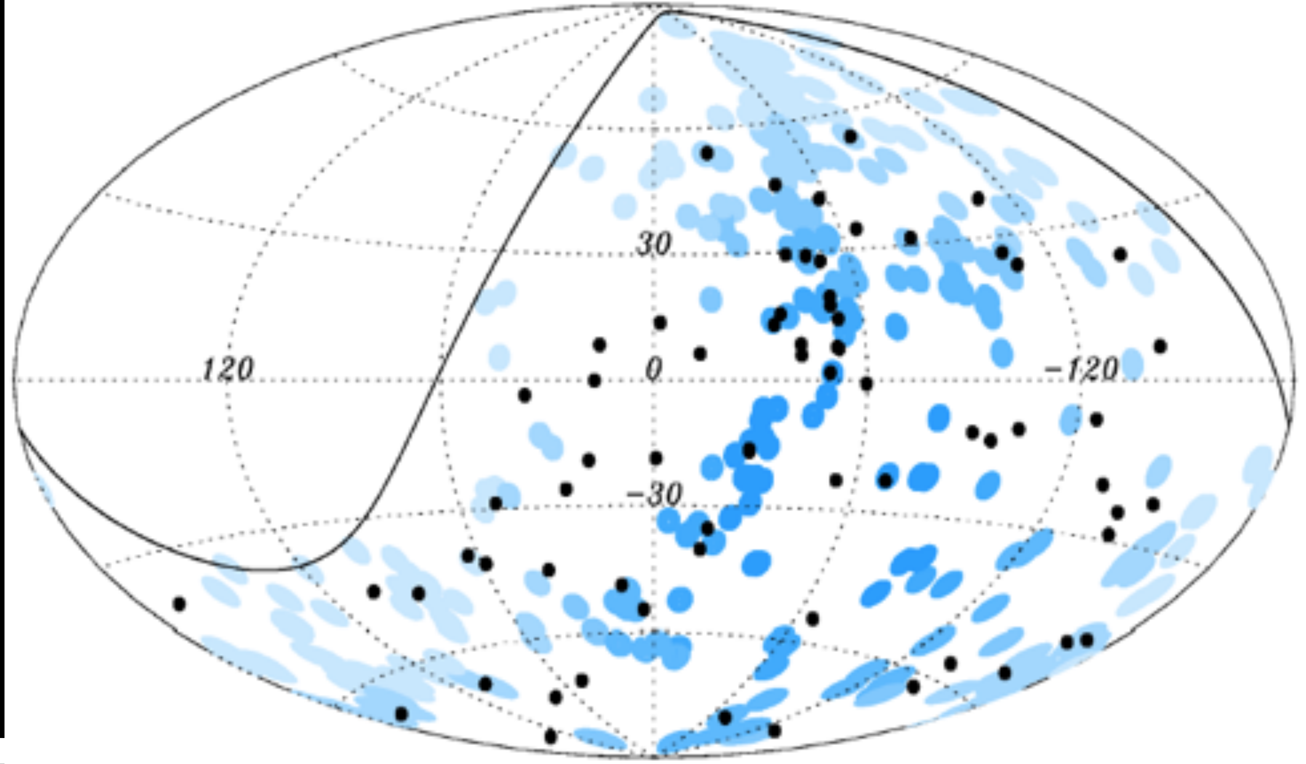


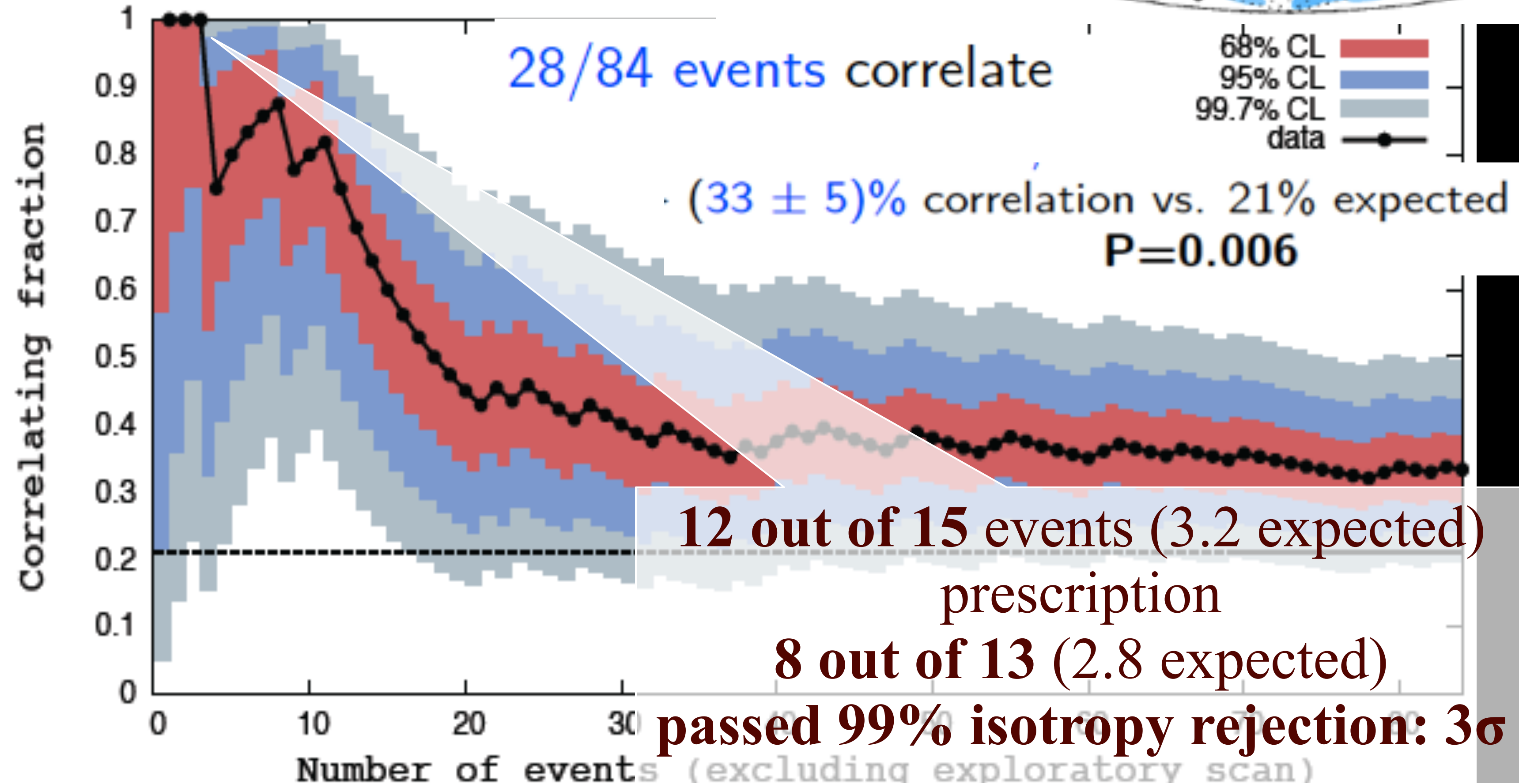


Pierre Auger:

consistent with Anisotropy

AGN catalog test





12 out of 15 events (3.2 expected)

prescription

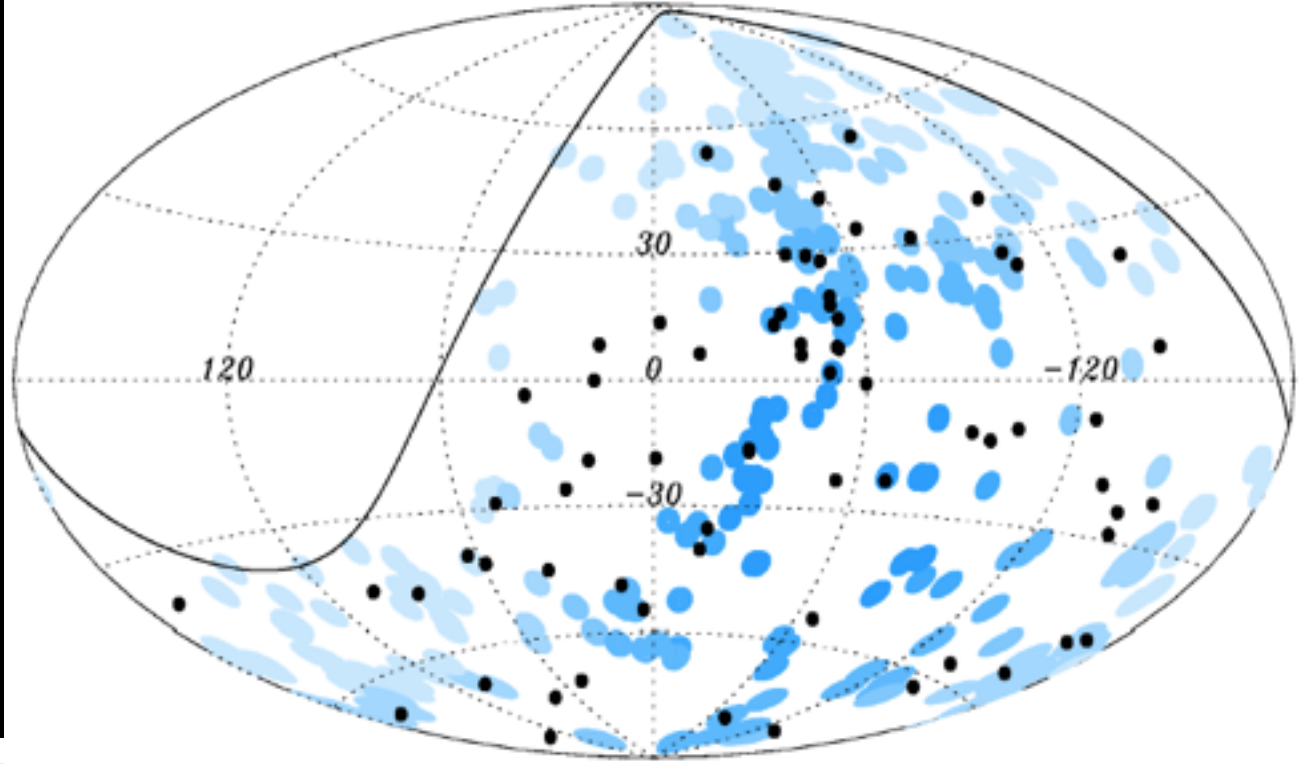
8 out of 13 (2.8 expected)

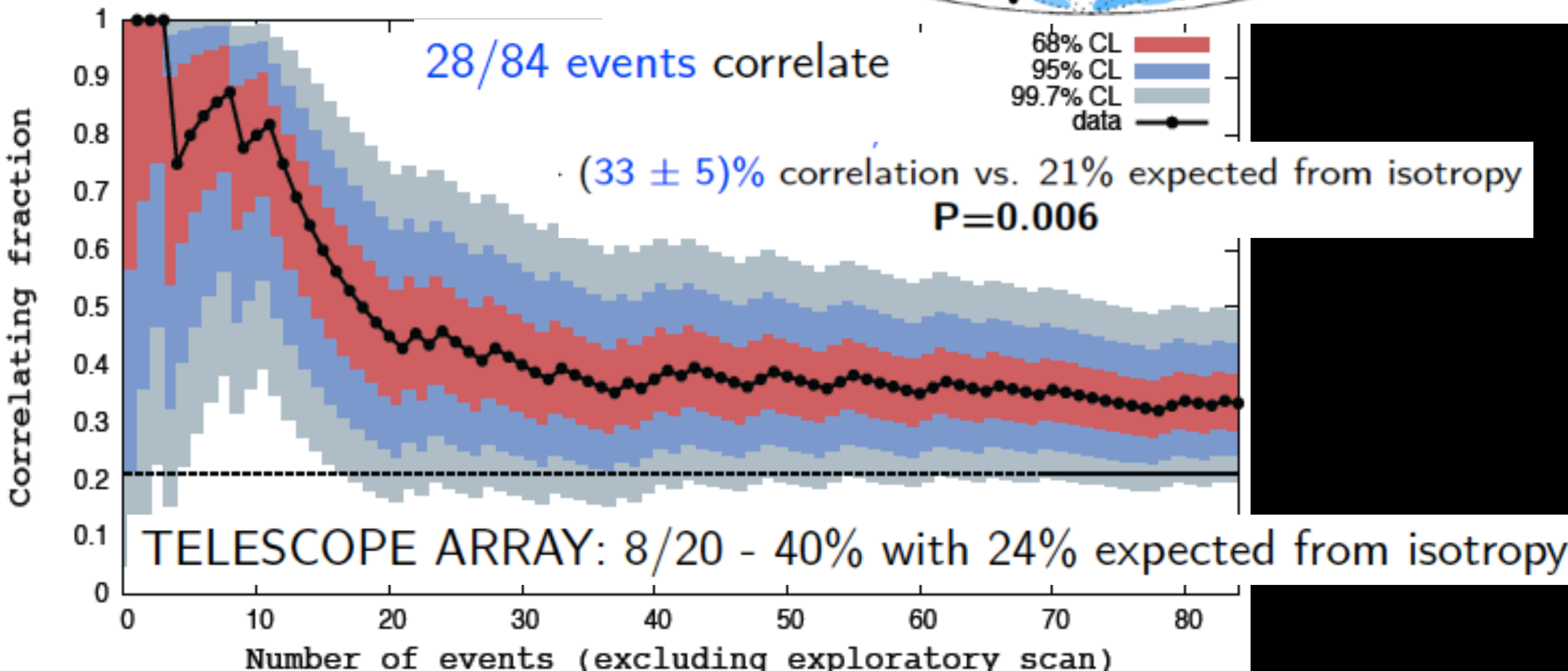
passed 99% isotropy rejection: 3σ

Pierre Auger:

consistent with Anisotropy

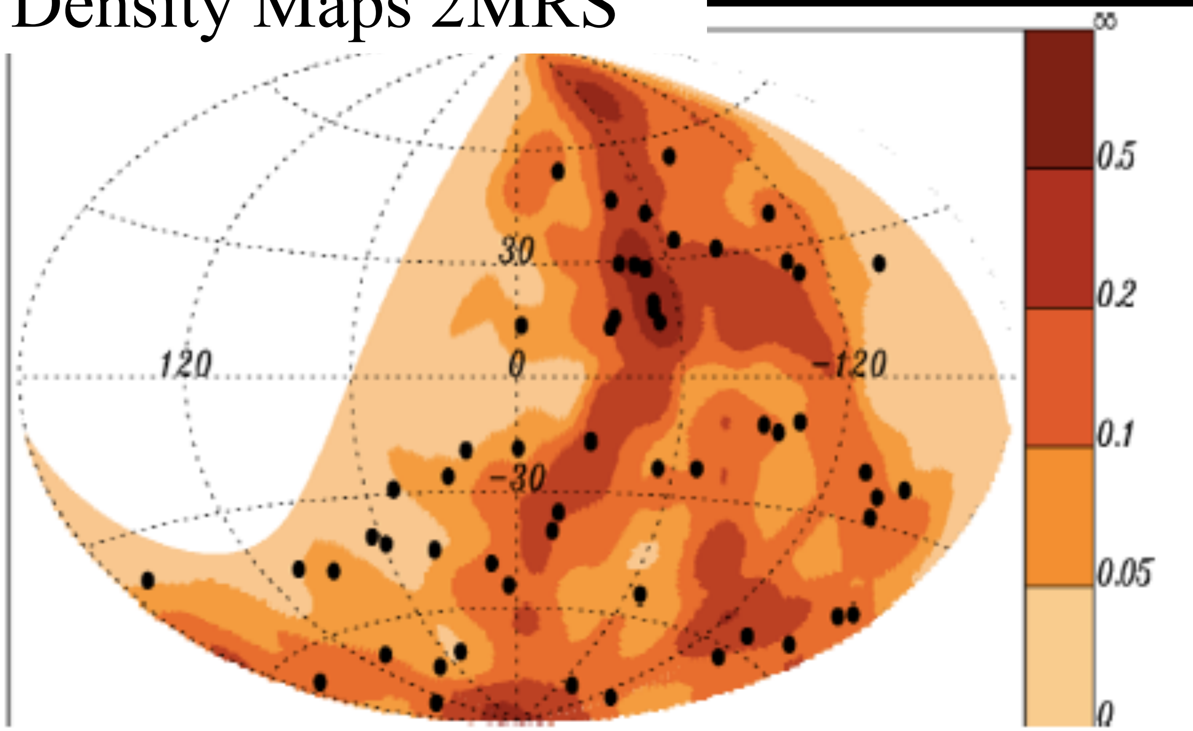
AGN catalog test



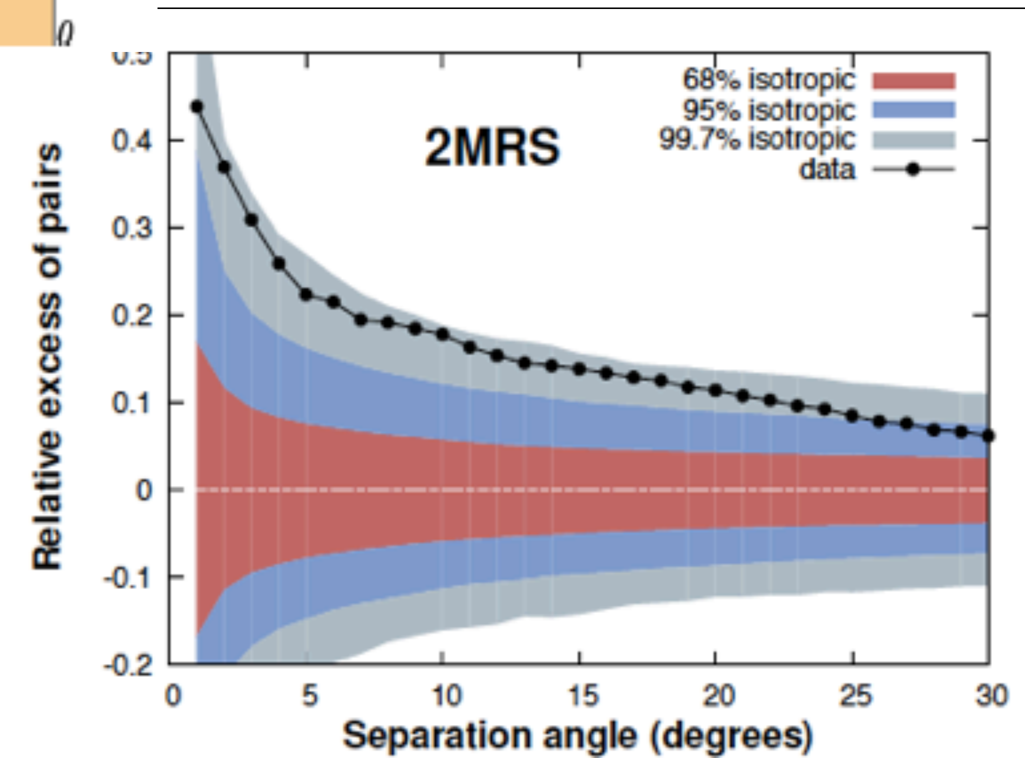


Pierre Auger : consistent with LSS Anisotropy

Density Maps 2MRS

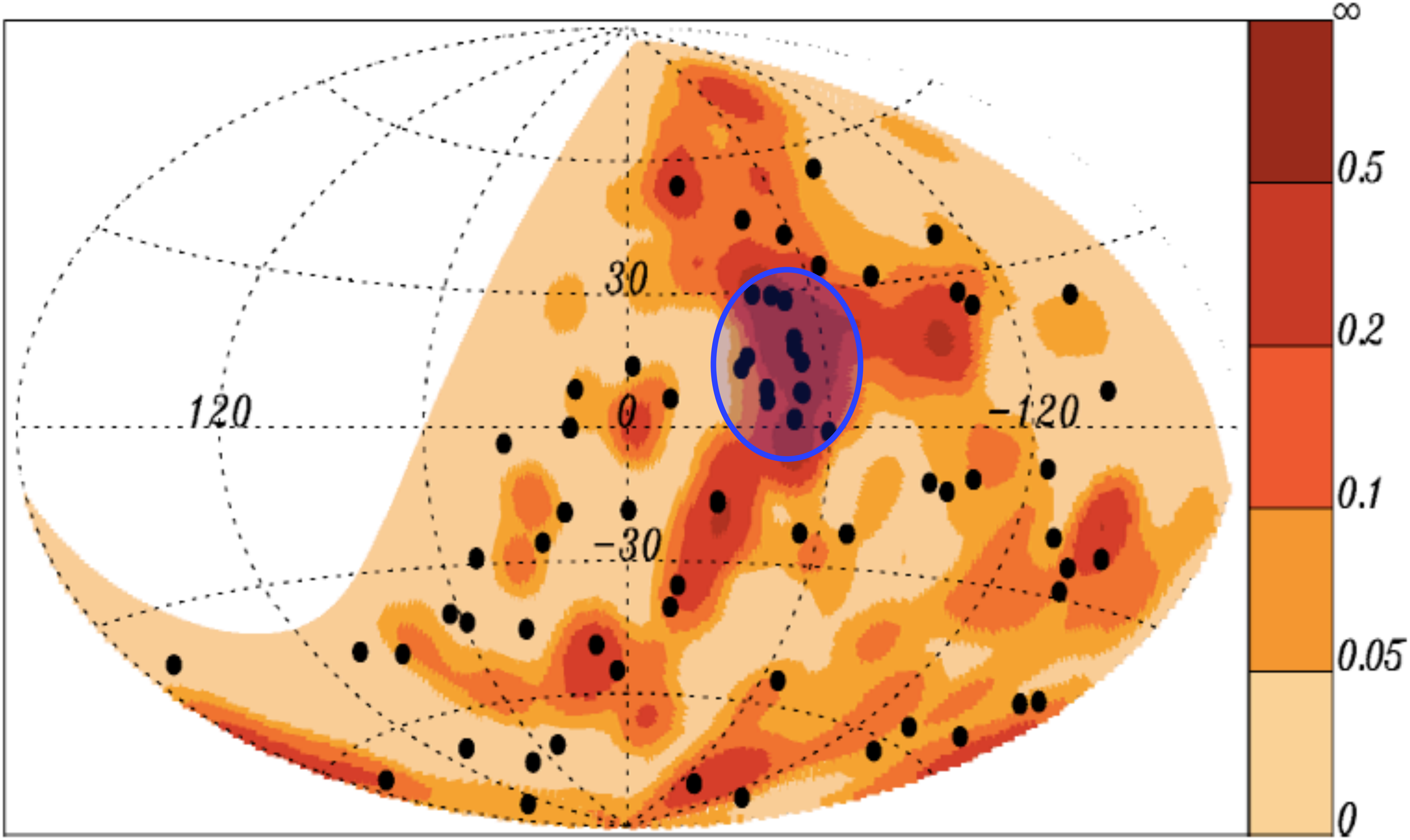


Cross-correlation d<200 Mpc

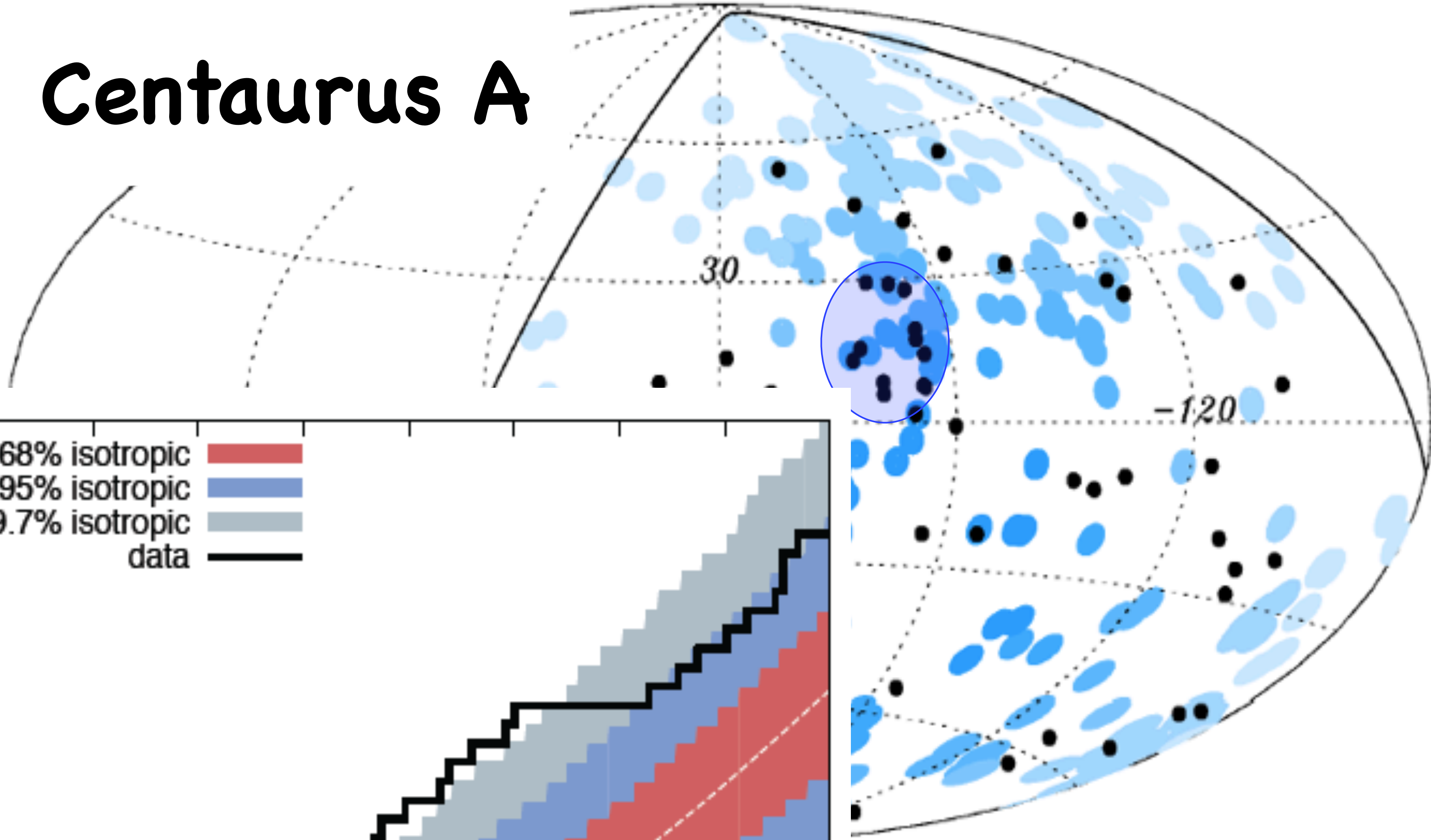


(Astropart. P. 34 (2010) 314)

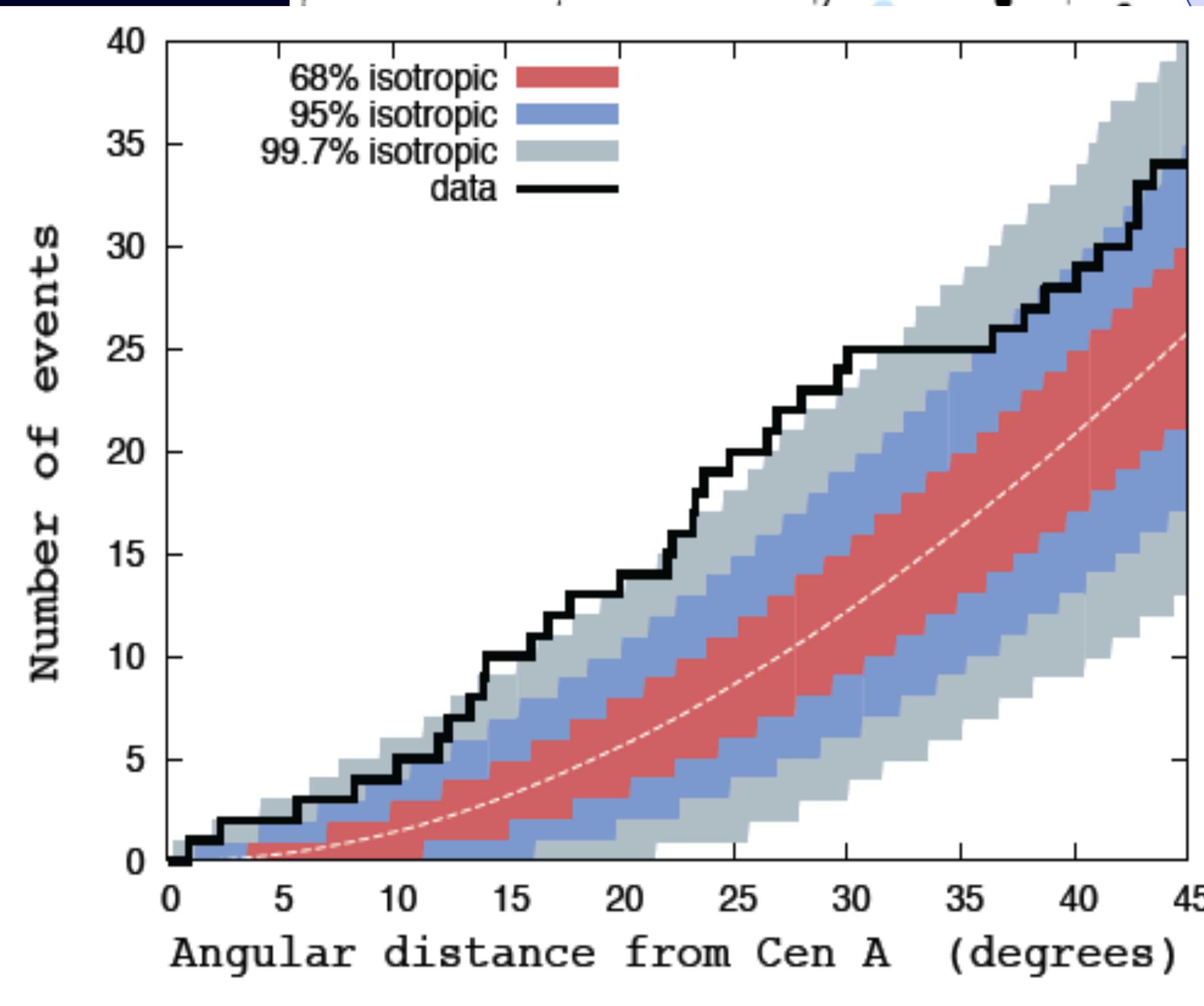
Centaurus A region



Centaurus A



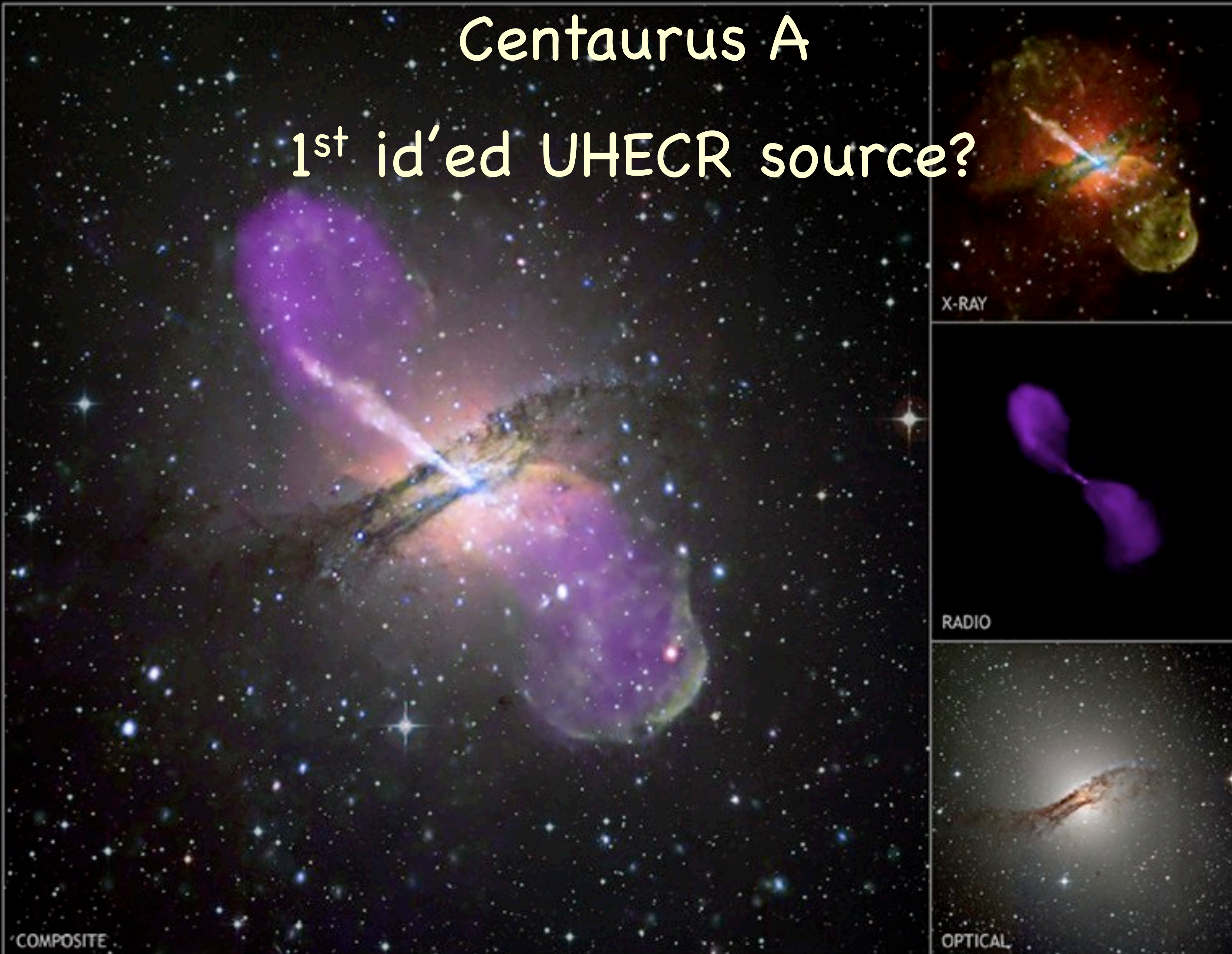
30
−120



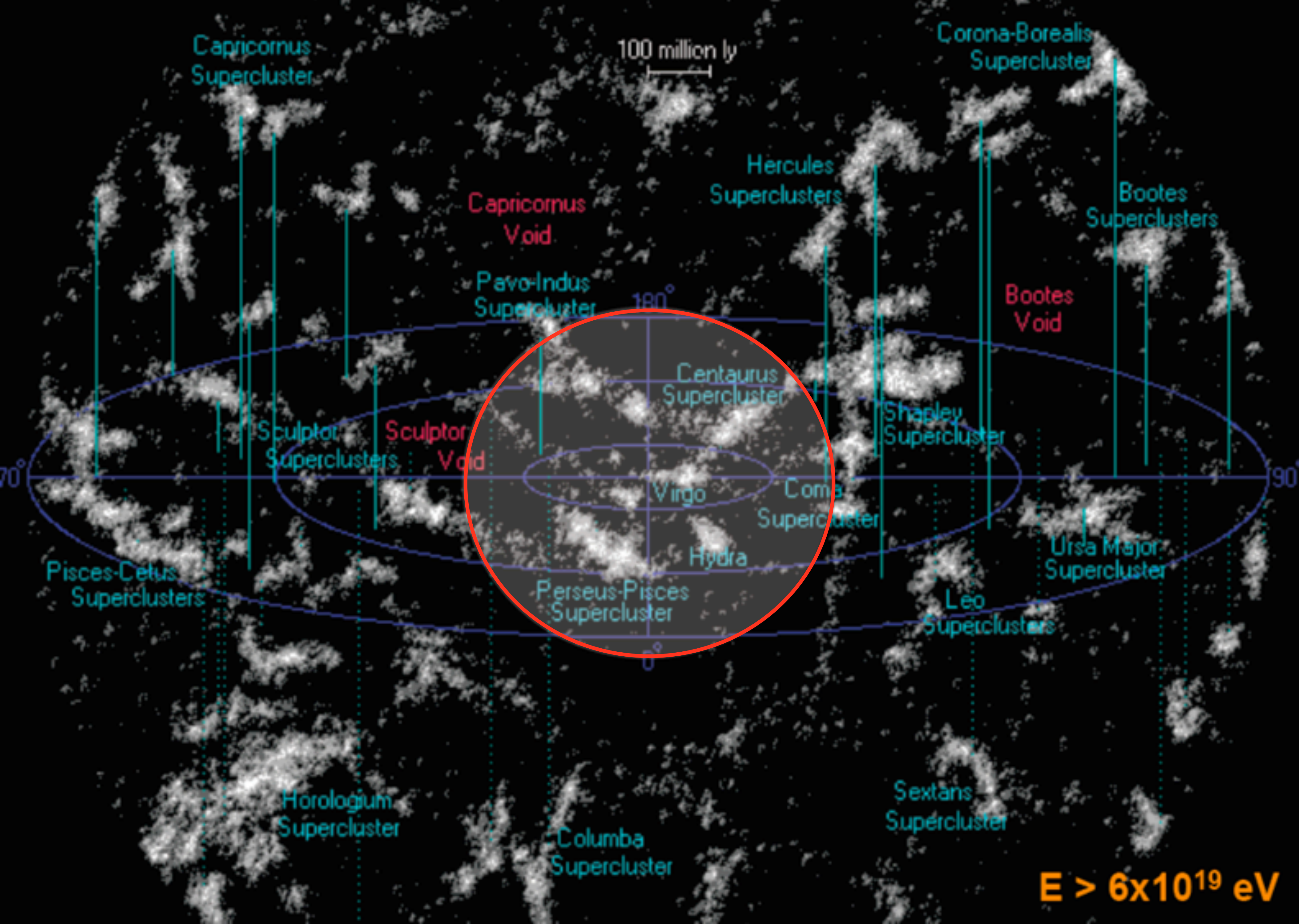
68% isotropic
95% isotropic
99.7% isotropic
data
Number of events
Angular distance from Cen A (degrees)
0
5
10
15
20
25
30
35
40
45

Centaurus A

1^{st} id'ed UHECR source?

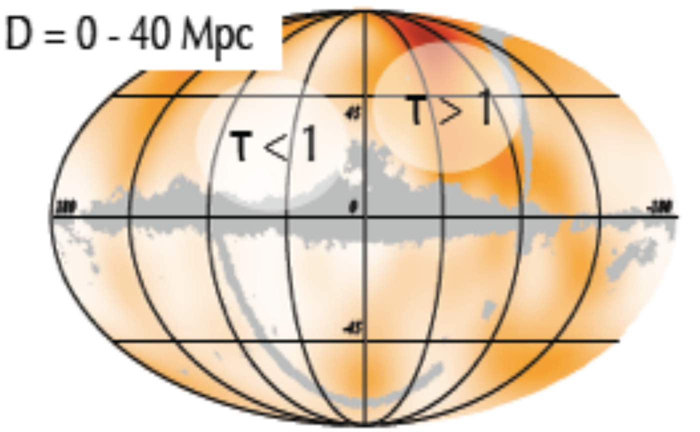


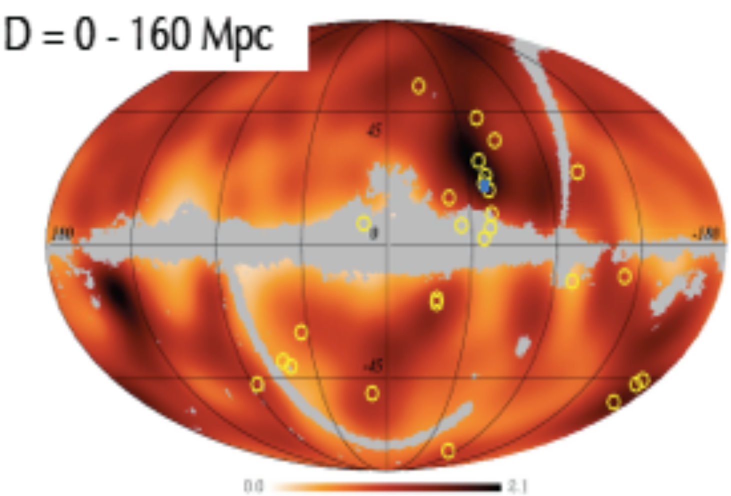
Distribution of Galaxies

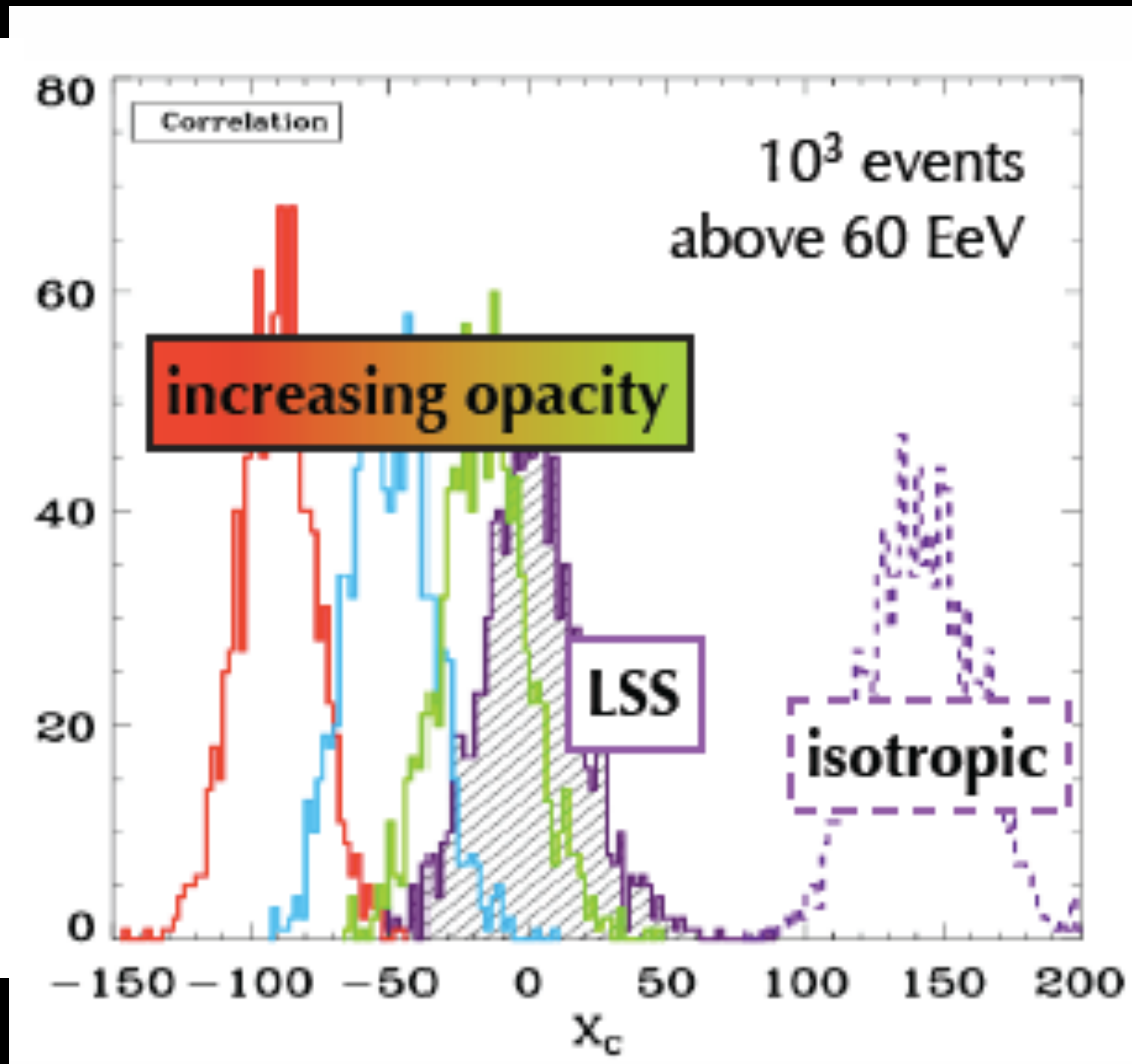


E > $6x10^{19}$ eV

Separating Populations – 1,000 events







Kalli, Lemoine, Kotera '10

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

At current rate ~ 30 events/yr

with E>60 EeV

need over 30 years!

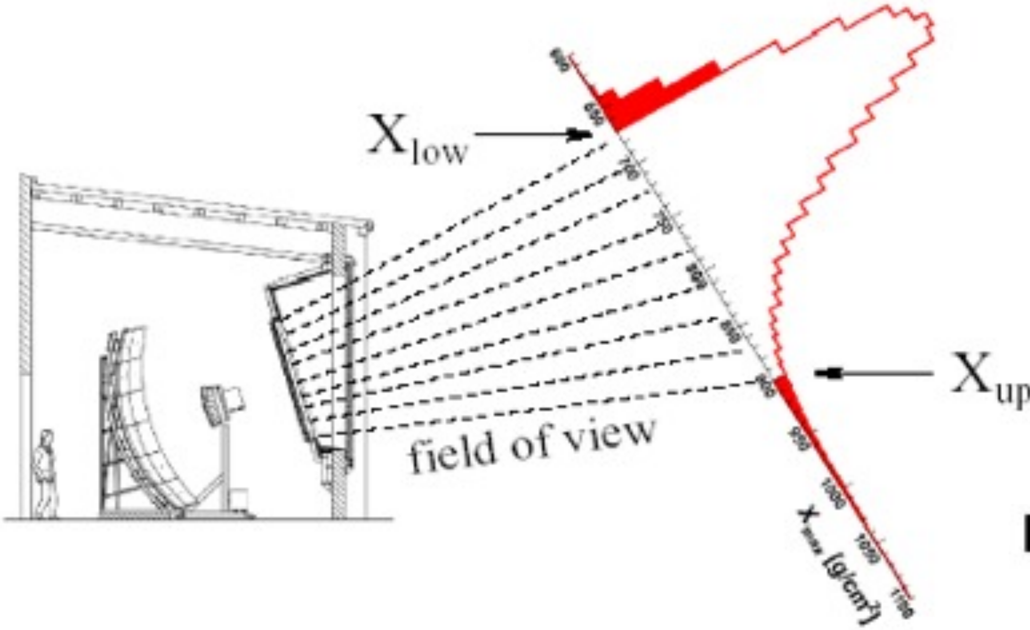
High Energy Cosmic Rays

OBSERVABLES:

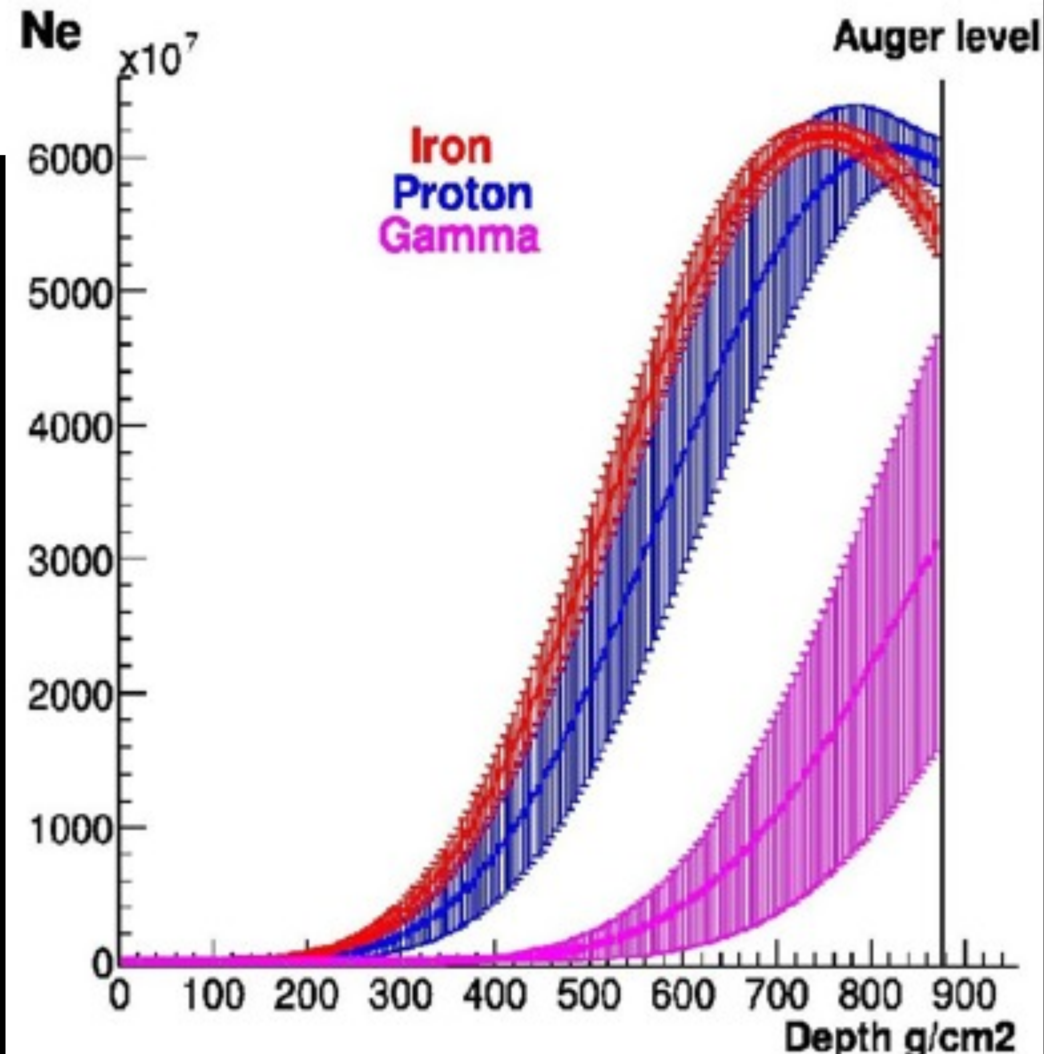
Spectrum

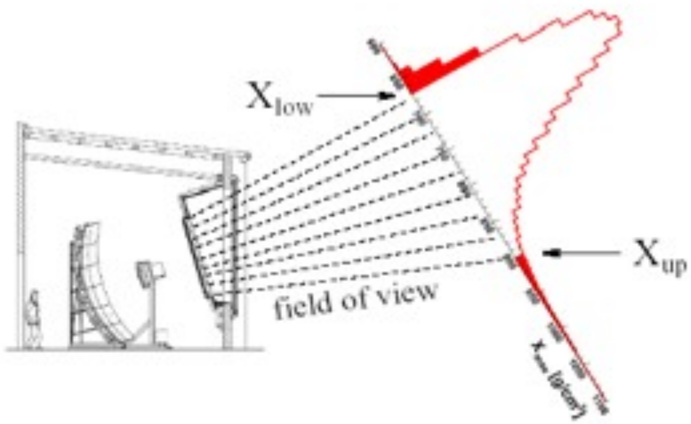
Composition

Sky Distribution

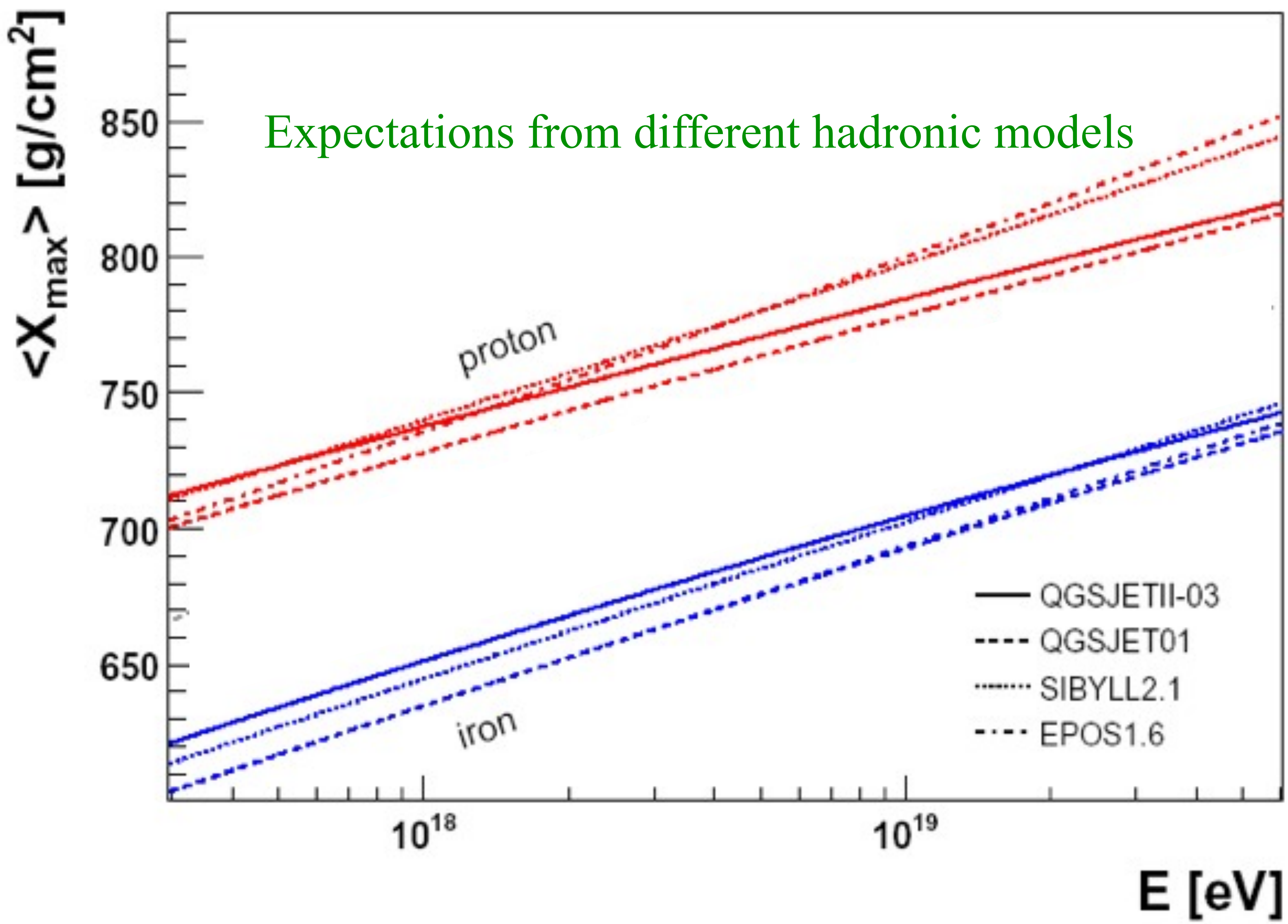


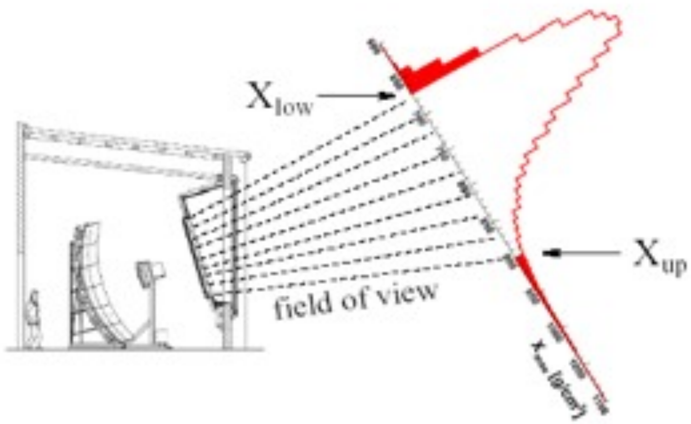
Composition observable: shower maximum



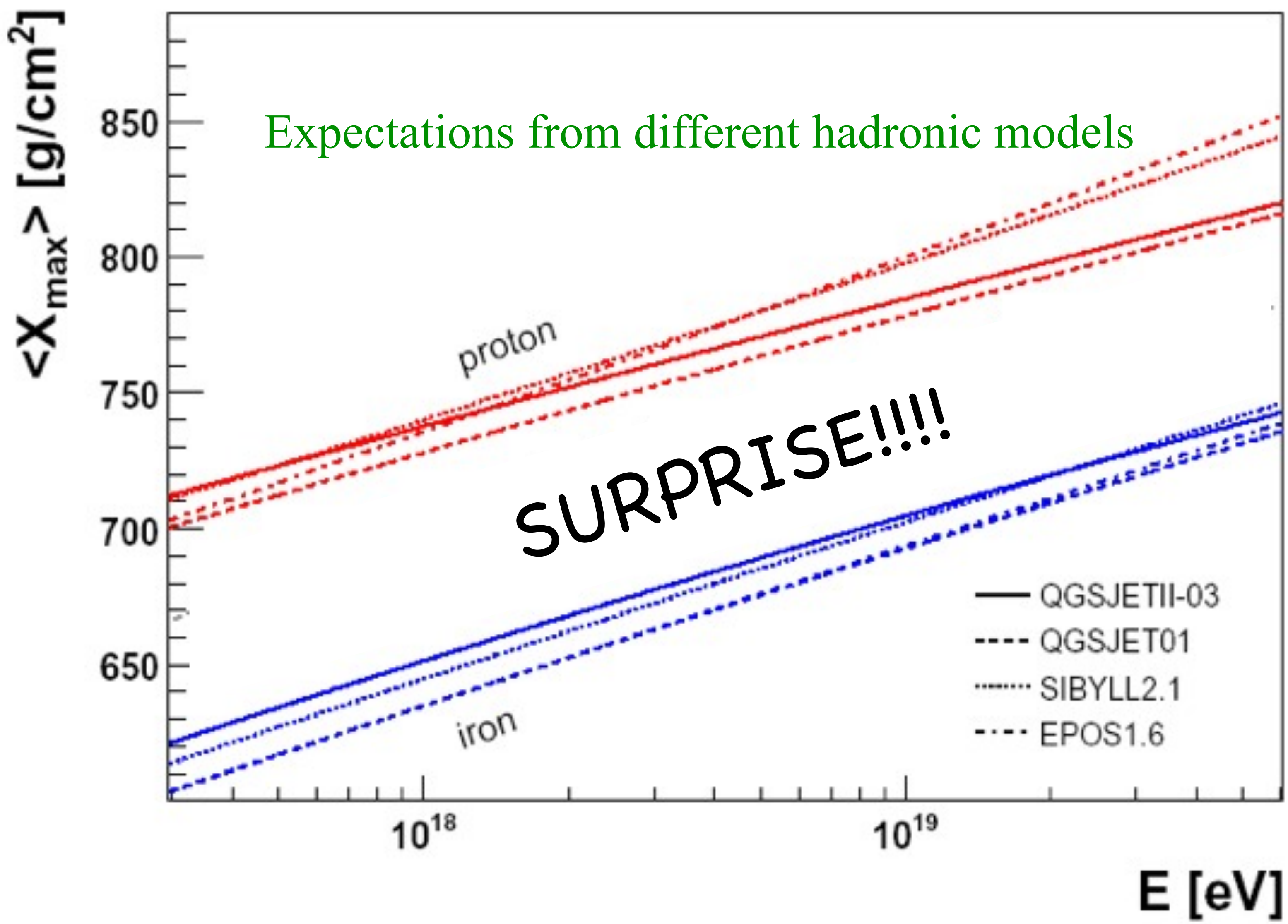


Composition observable: shower maximum

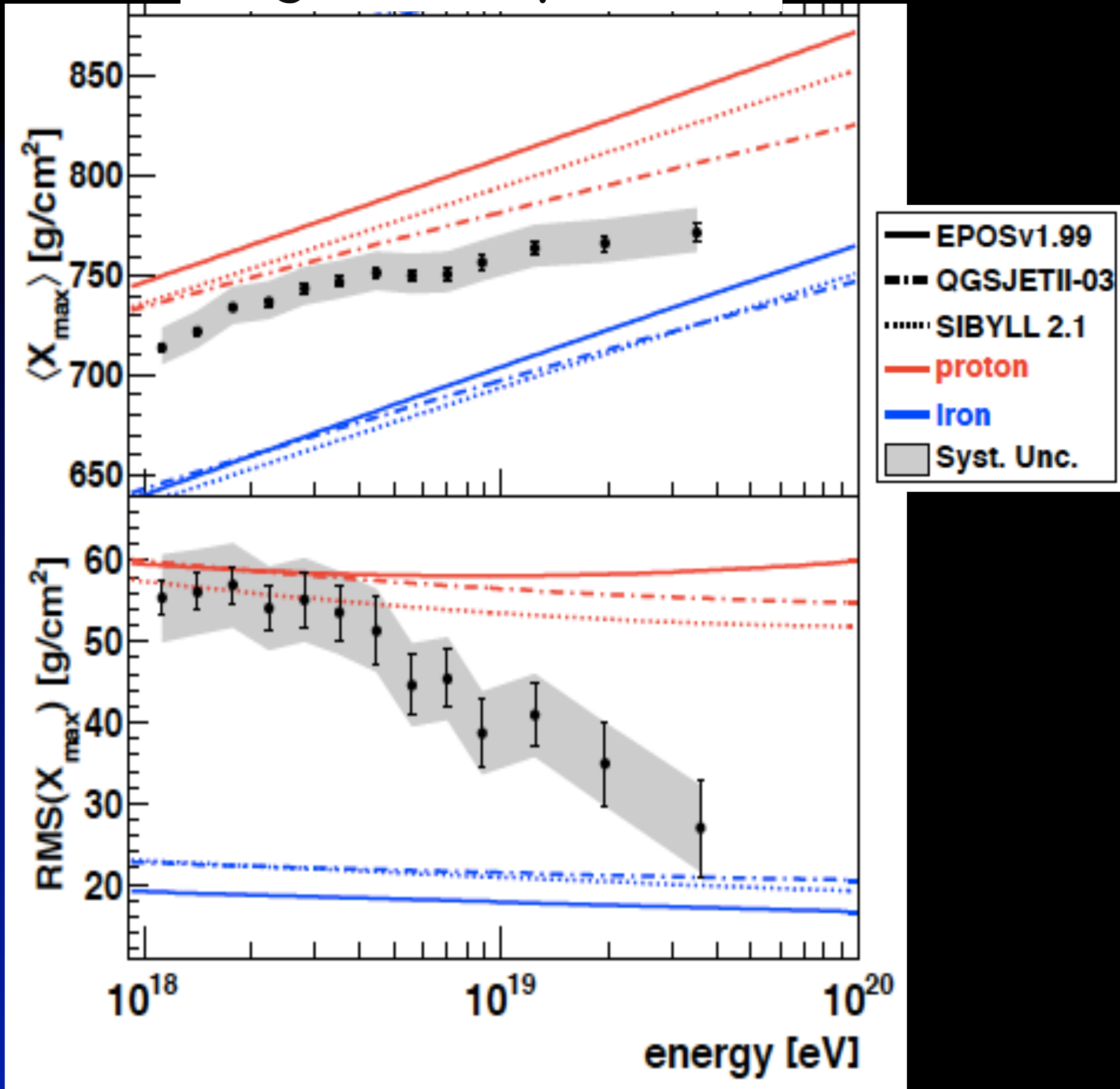




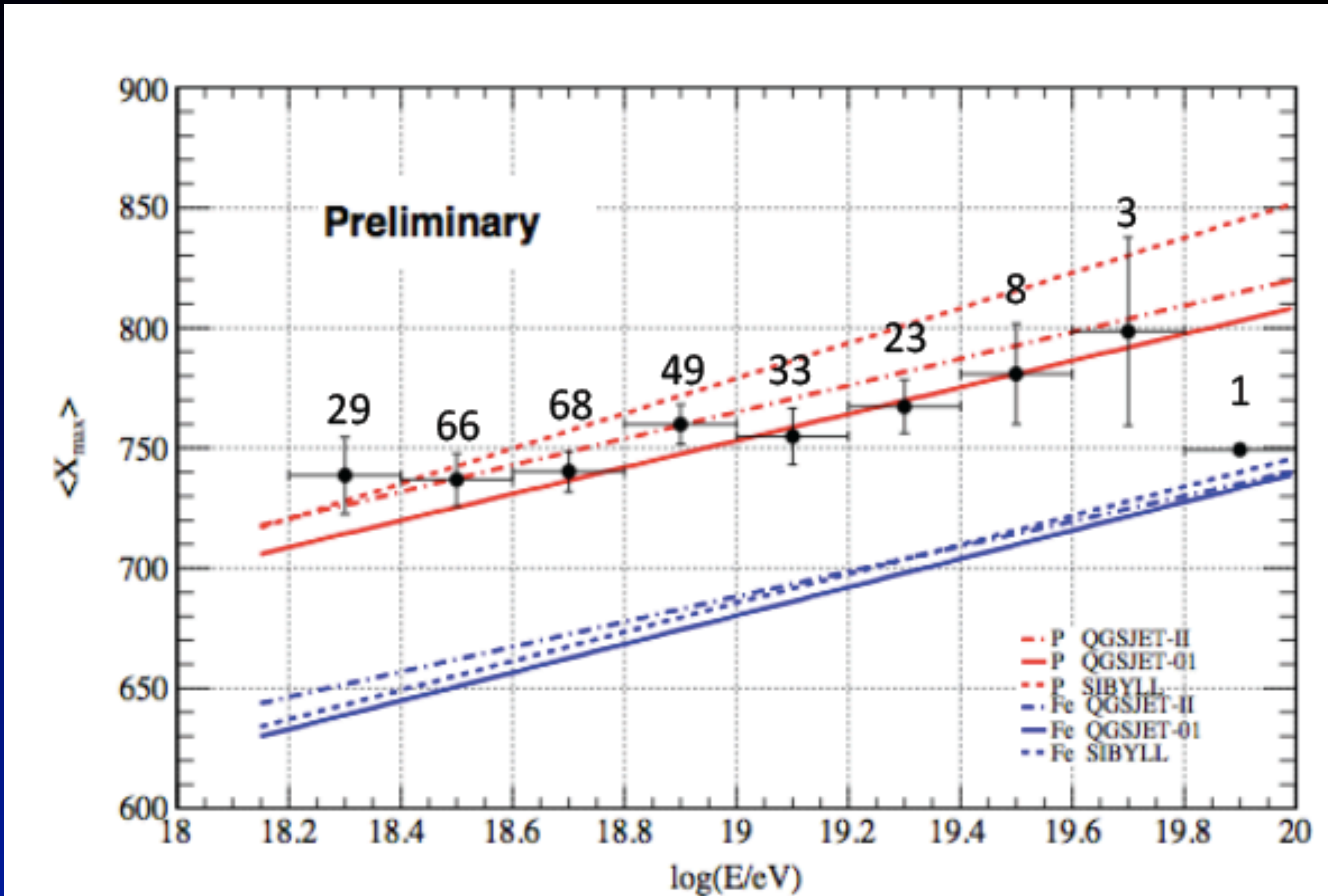
Composition observable: shower maximum

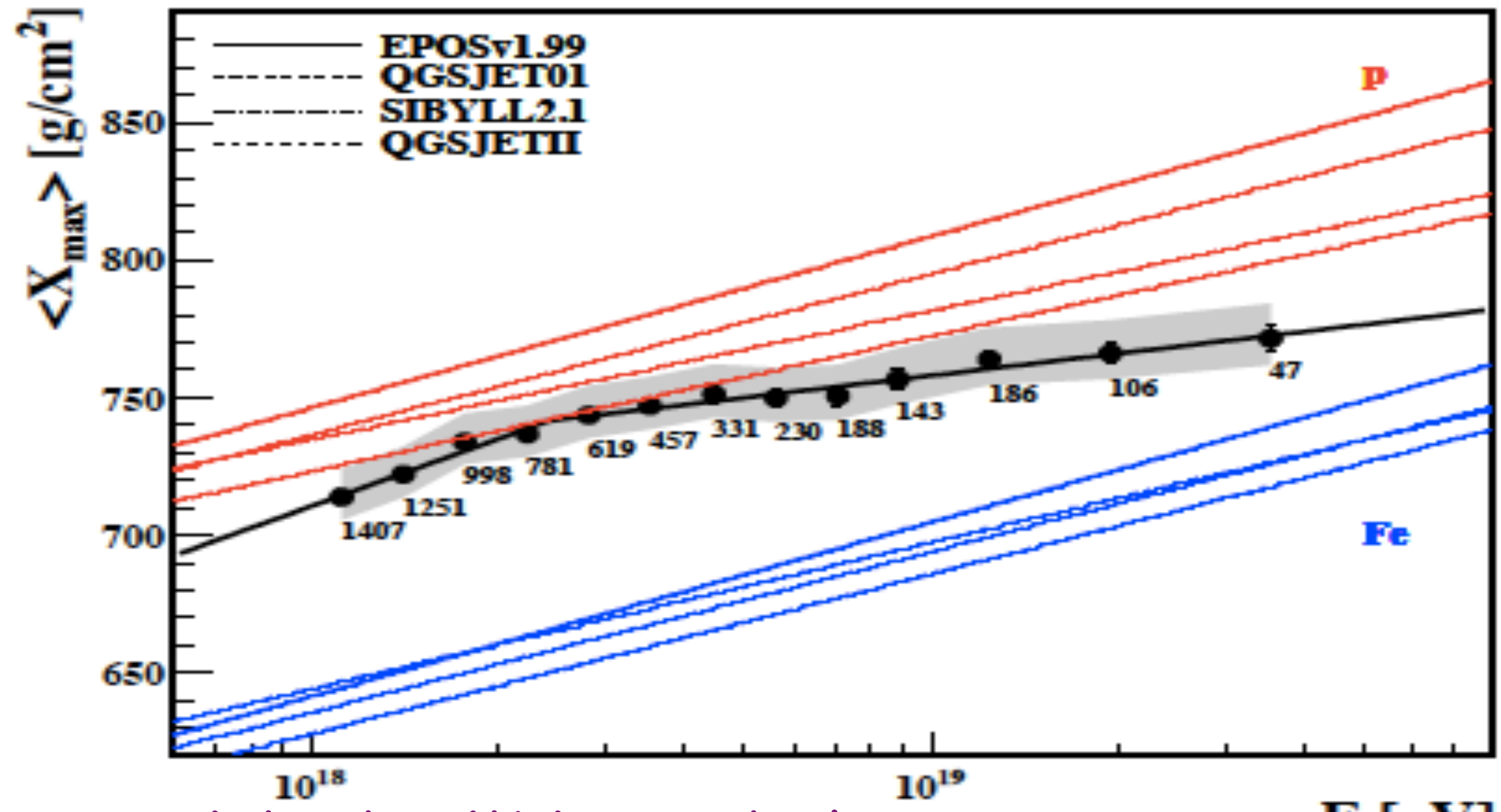


Auger Composition

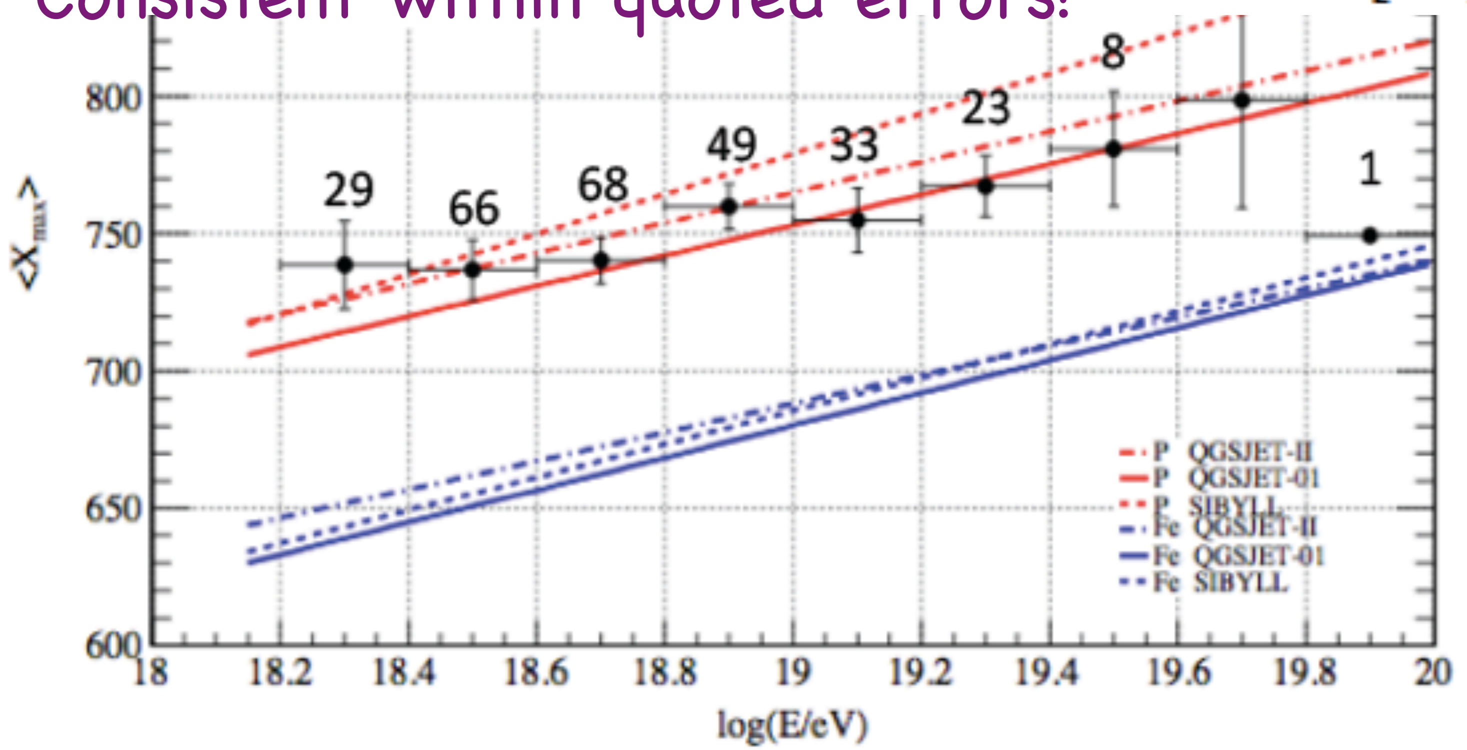


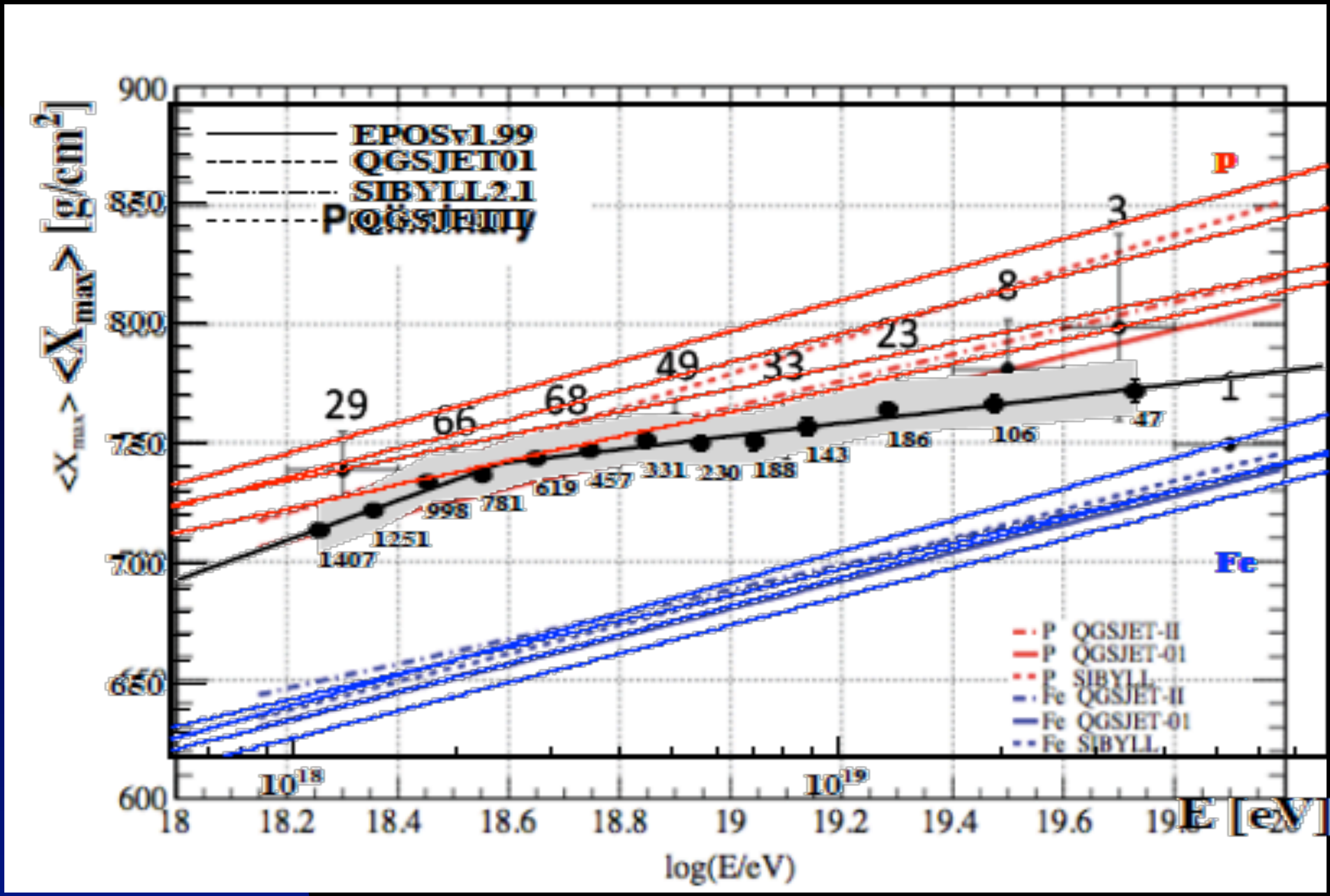
Telescope Array Composition



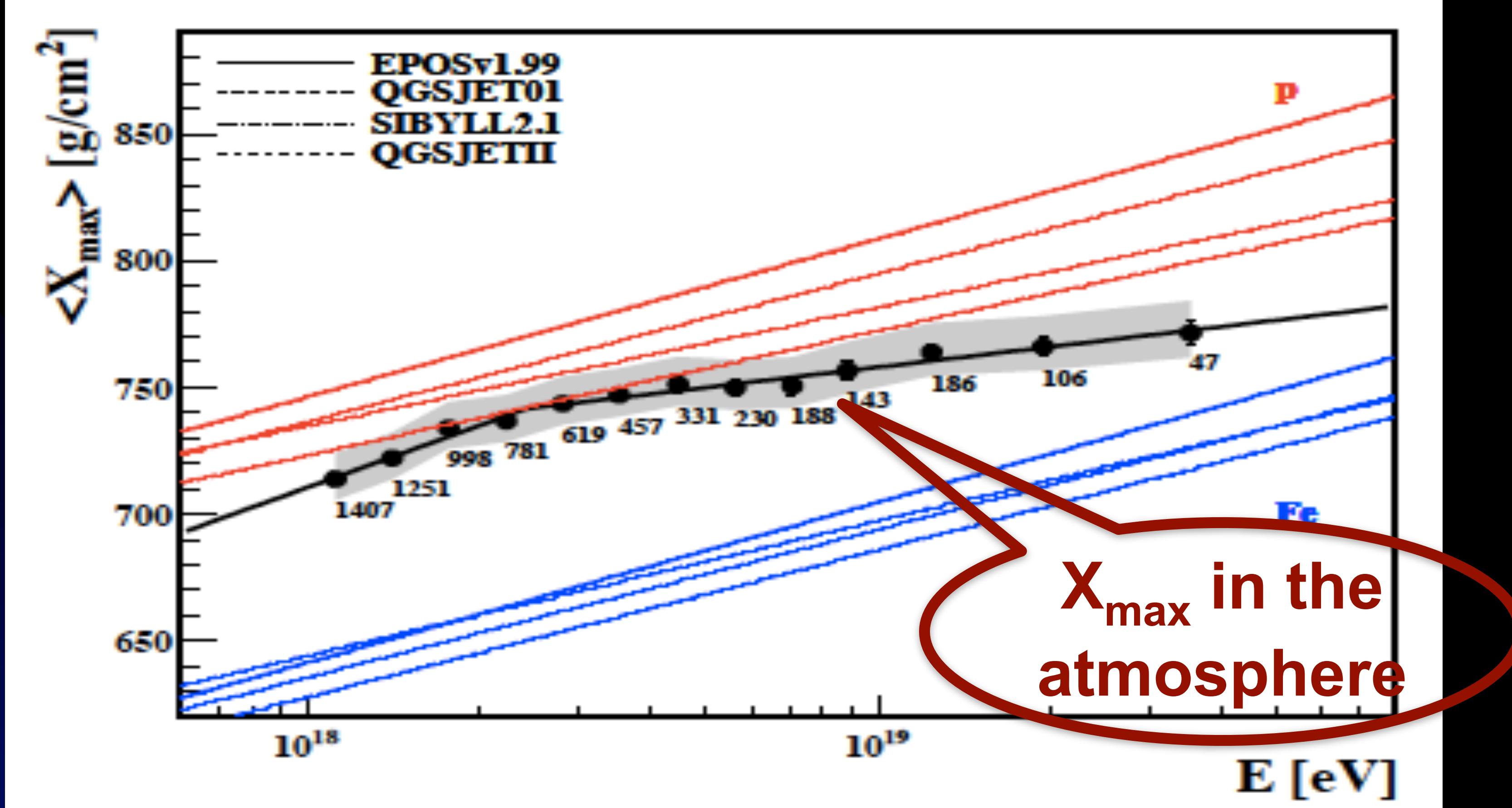


Consistent within quoted errors!

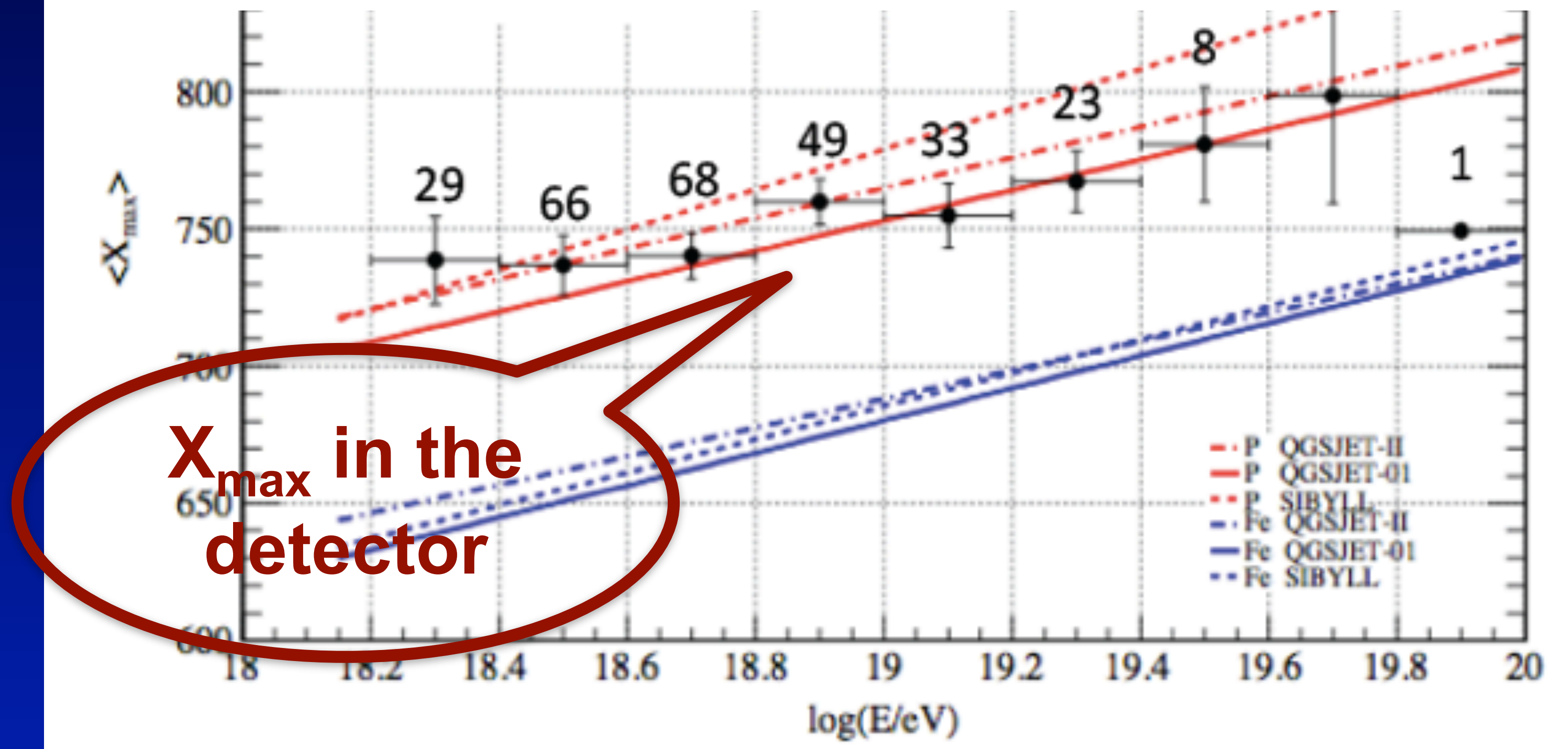




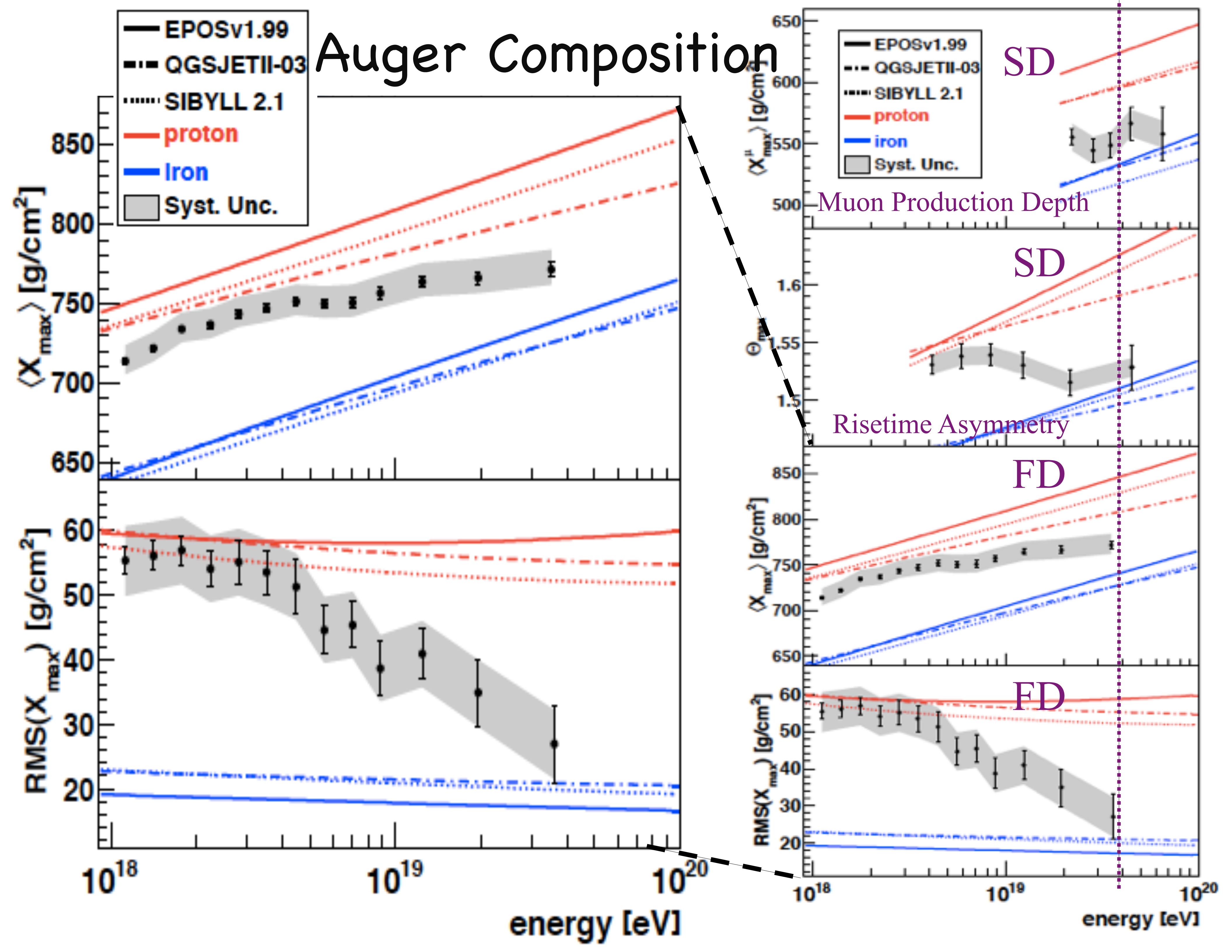
EPOSv1.99
QGSJET01
SIBYLL2.1
QGSJETII
P
Fe
29
66
68
49
33
23
8
3
1
1407
1251
998
781
619
457
331
230
188
143
186
106
47
P QGSJET-II
P QGSJET-01
P SIBYLL
Fe QGSJET-II
Fe QGSJET-01
Fe SIBYLL
$<X_{max}>$ [g/cm^2]
10^{18}
10^{19}
E [eV]
log(E/eV)

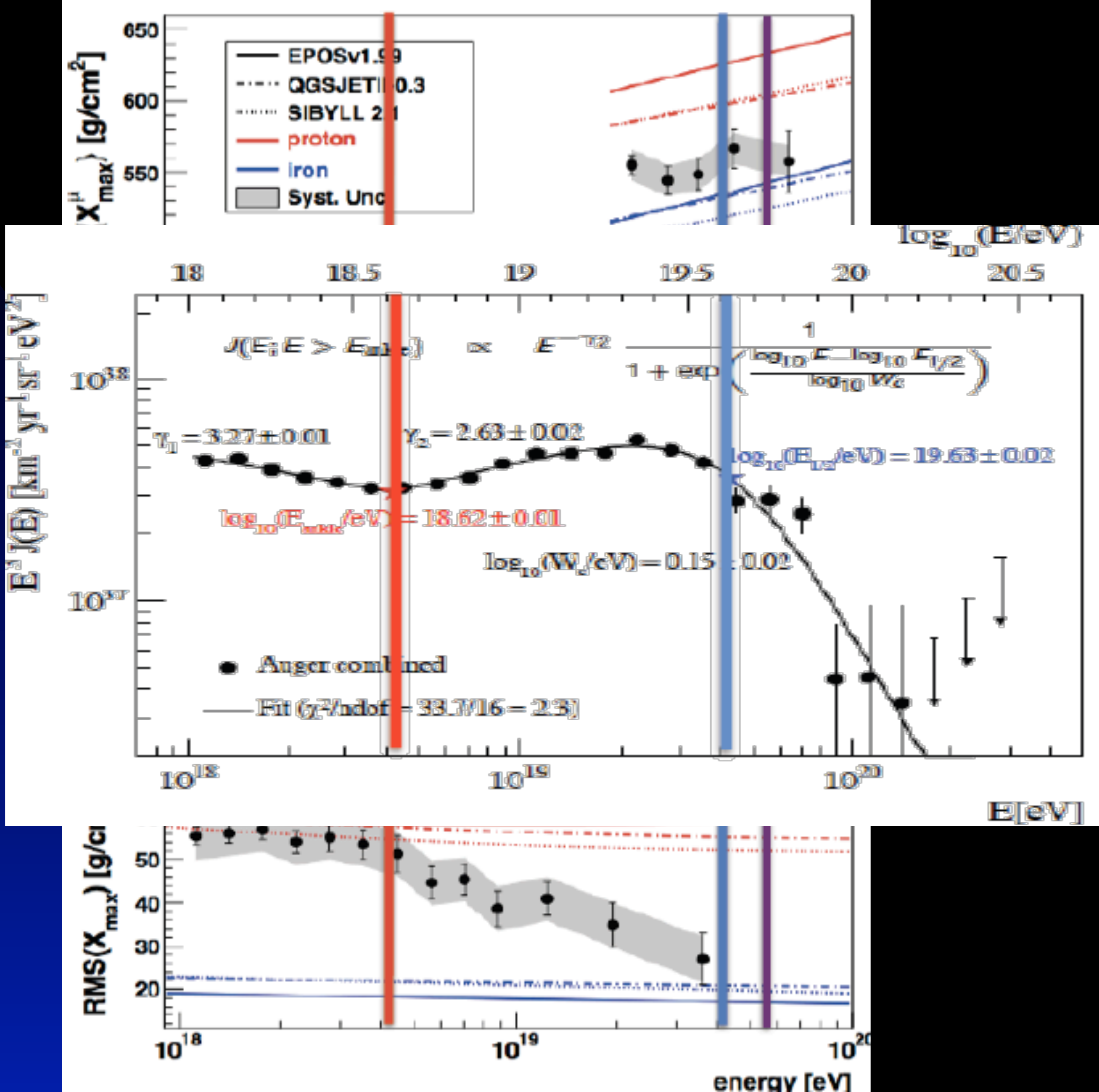


EPOSv1.99
QGSJET01
SIBYLL2.1
QGSJETII
p
Fe
<X_{max}> [g/cm^2]
850
800
750
700
650
1407
1251
998
781
619
457
331
230
188
143
186
106
47
10^{18}
10^{19}
E [eV]
X_{max} in the atmosphere

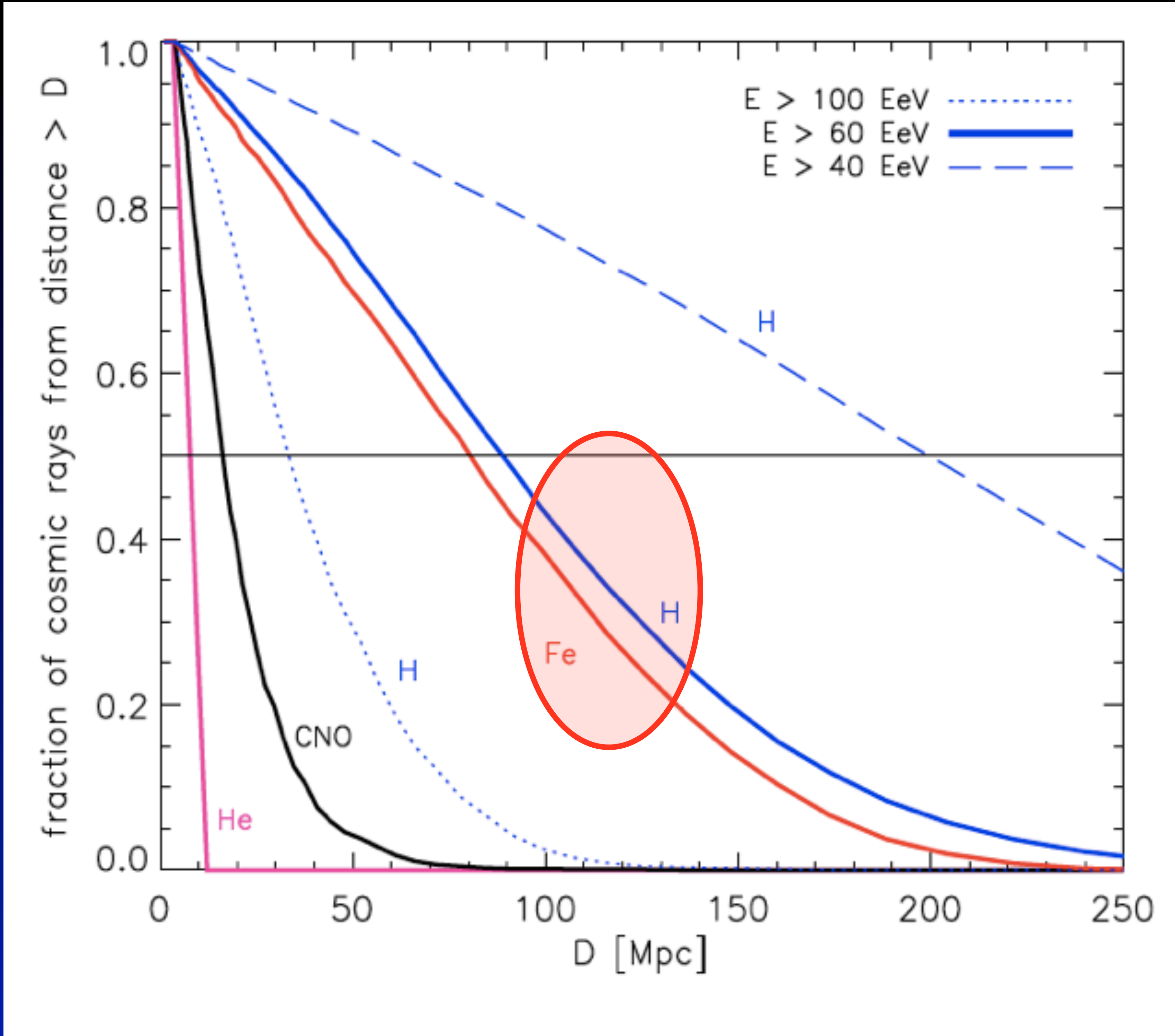


29
66
68
49
33
23
8
1
800
750
700
650
600
<X_{max}>
18
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
20
log(E/eV)
P QGSJET-II
P QGSJET-01
P SIBYLL
Fe QGSJET-II
Fe QGSJET-01
Fe SIBYLL
X_{max} in the detector


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


EPOSv1.99
QGSJETII 0.3
SIBYLL 2.1
proton
iron
Syst. Unc
650
600
550
log10(E/eV)
18
18.5
19
19.5
20
20.5
$J(E; E > E_{ankle}) \propto E^{-\gamma_2} \frac{1}{1 + \exp\left(\frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c}\right)}$
10^{38}
10^{37}
$\gamma_1 = 3.27 \pm 0.01$
$\gamma_2 = 2.63 \pm 0.02$
$\log_{10}(E_{1/2}/eV) = 19.63 \pm 0.02$
$\log_{10}(E_{ankle}/eV) = 18.62 \pm 0.01$
$\log_{10}(W_c/eV) = 0.15 \pm 0.02$
Auger combined
Fit (χ^2/ndof = 33.7/16 = 2.3)
$E^3 J(E)$ [$km^{-2} yr^{-1} sr^{-1} eV^2$]
10^{18}
10^{19}
10^{20}
E[eV]
50
40
30
20
energy [eV]

GZK Horizon



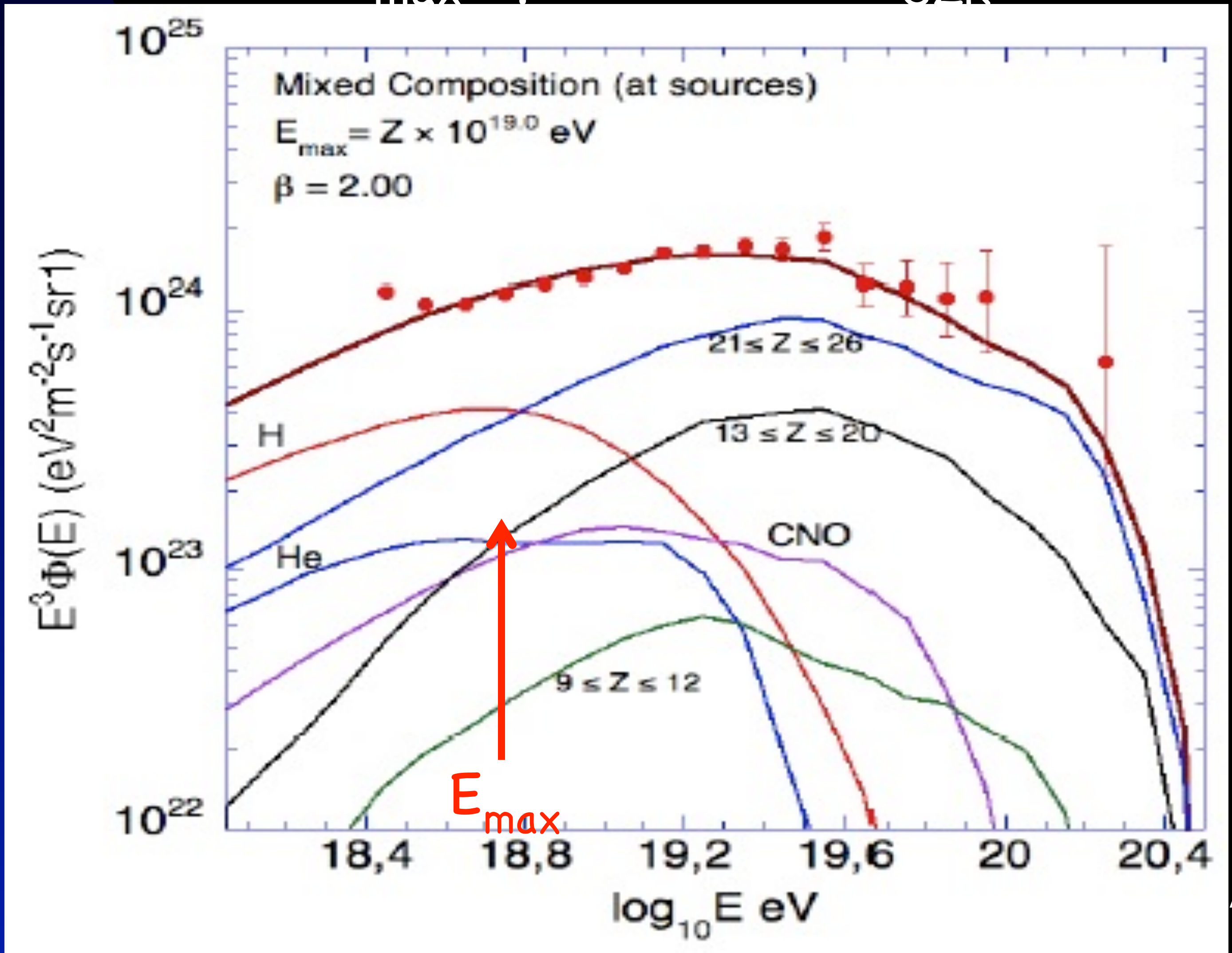
E > 100 EeV
E > 60 EeV
E > 40 EeV
H
H
H
Fe
CNO
He
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
D [Mpc]
fraction of cosmic rays from distance > D

Heavy Composition at UHEs

Unexpected Astrophysics:

Sources are very Iron rich: 4x Fe Galactic CRs!

and have low E_{max} (protons) < E_{GZK}



Allard et al 09

My Favorite Model:

Birth of fast spinning Pulsars

Newborn Pulsar with: $B_S \equiv 10^{13} B_{13}$ G *and* $\Omega_{3k} \equiv \Omega/3000 \text{ rad s}^{-1}$

At the light cylinder: $R_{\rm lc} = 10^7 \Omega_{3k}^{-1}$ cm

Magnetic wind can accelerate particles up to E_{max}, where $Z_{26} \equiv Z/26$

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

Plasma in the wind has Goldreich-Julian density: $n_{\rm GJ} = 1.7 \times 10^{11} B_{13} \Omega_{3k}^4 / Z \text{ cm}^{-3}$

Crab Pulsar wind

$$E_{\rm cr} \simeq B_{\rm lc}^2 / 8\pi n_{\rm GJ}$$

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

Maximum Energy? ✔

Blasi, Epstein, AVO ‘00

My Favorite Model:

Birth of fast spinning Pulsars

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

At the light cylinder: $R_{lc} = 10^7 \Omega_{3k}^{-1}$ cm $\quad Z_{26} \equiv Z/26$

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

Maximum Energy? ✔

Spectrum?

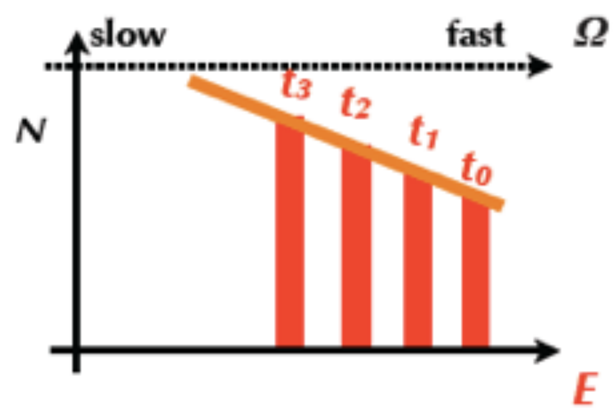
Spin down in a year:

$$\Omega_{3k}^2(t) = \frac{\Omega_{i3k}^2}{1 + t_8 B_{13}^2 \Omega_{i3k}^2}$$

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

But Pulsars are born in Supernovae!

the escape from SN remnant

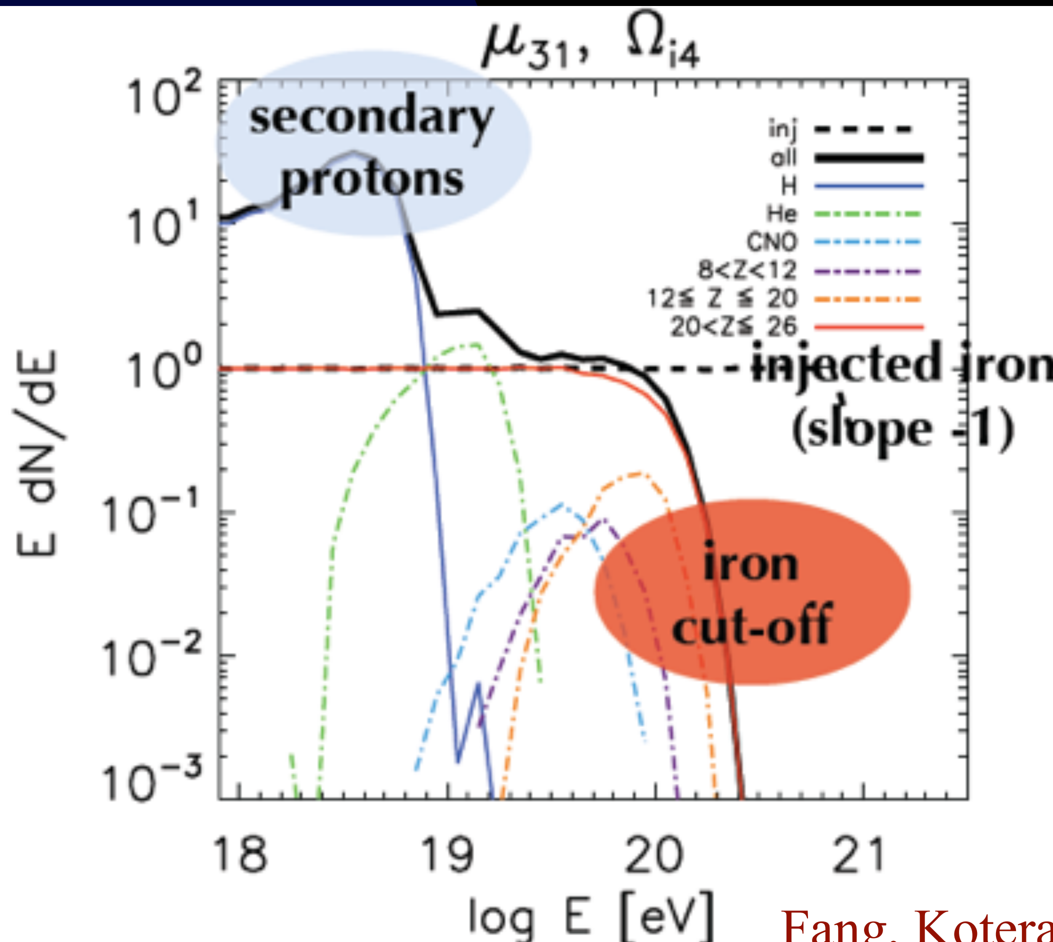
softens the spectrum and selects heavy elements above 10 EeV!!!

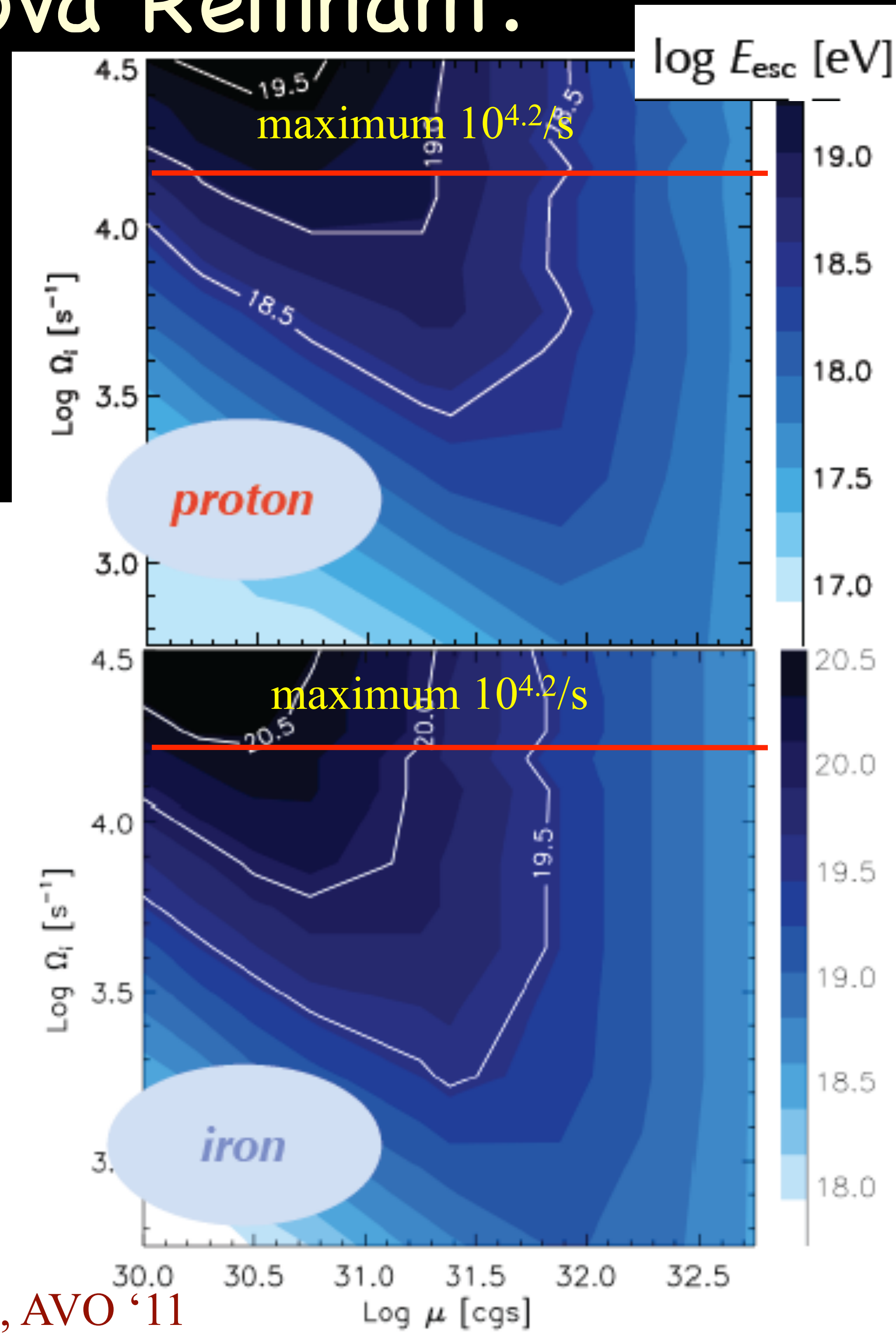
Escape from Supernova Remnant:

Monte-Carlo CR propagation:
hadronic Interactions
with EPOS + CONEX

Supernova ejecta Mas: 10 $M_\odot$

Energy ejecta: 10^{52} ergs

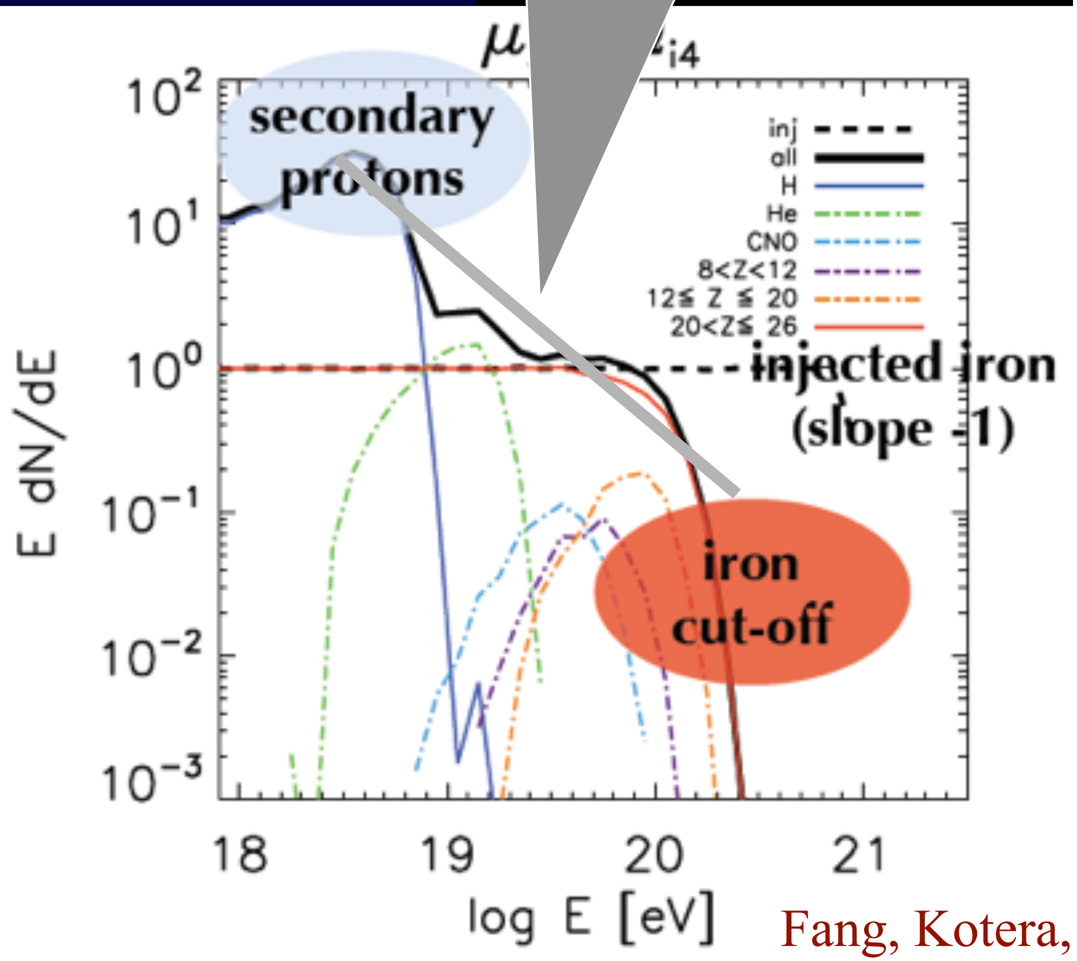


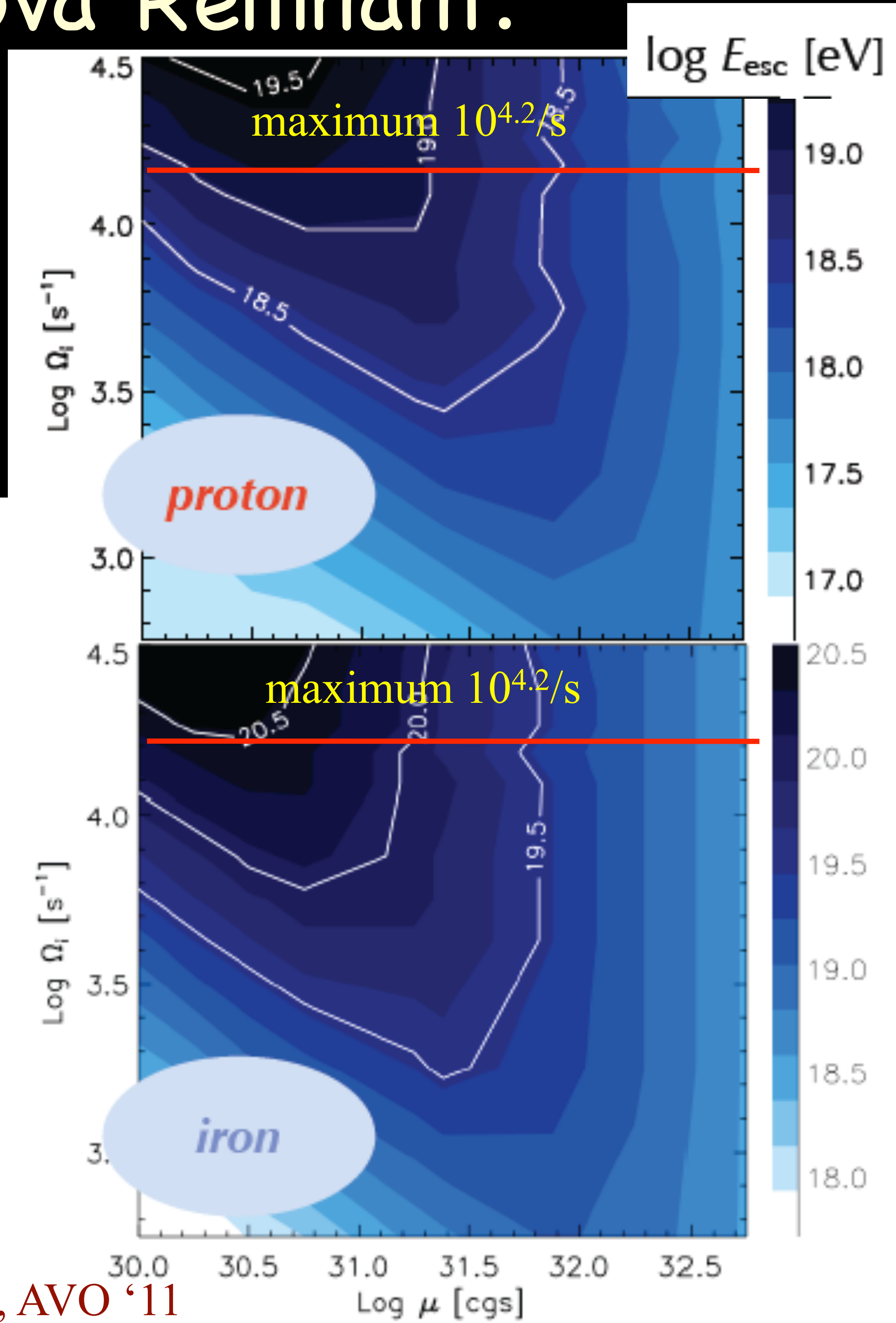


Fang, Kotera, AVO '11

Escape from Supernova Remnant:

softens the spectrum ~ E^{-2}



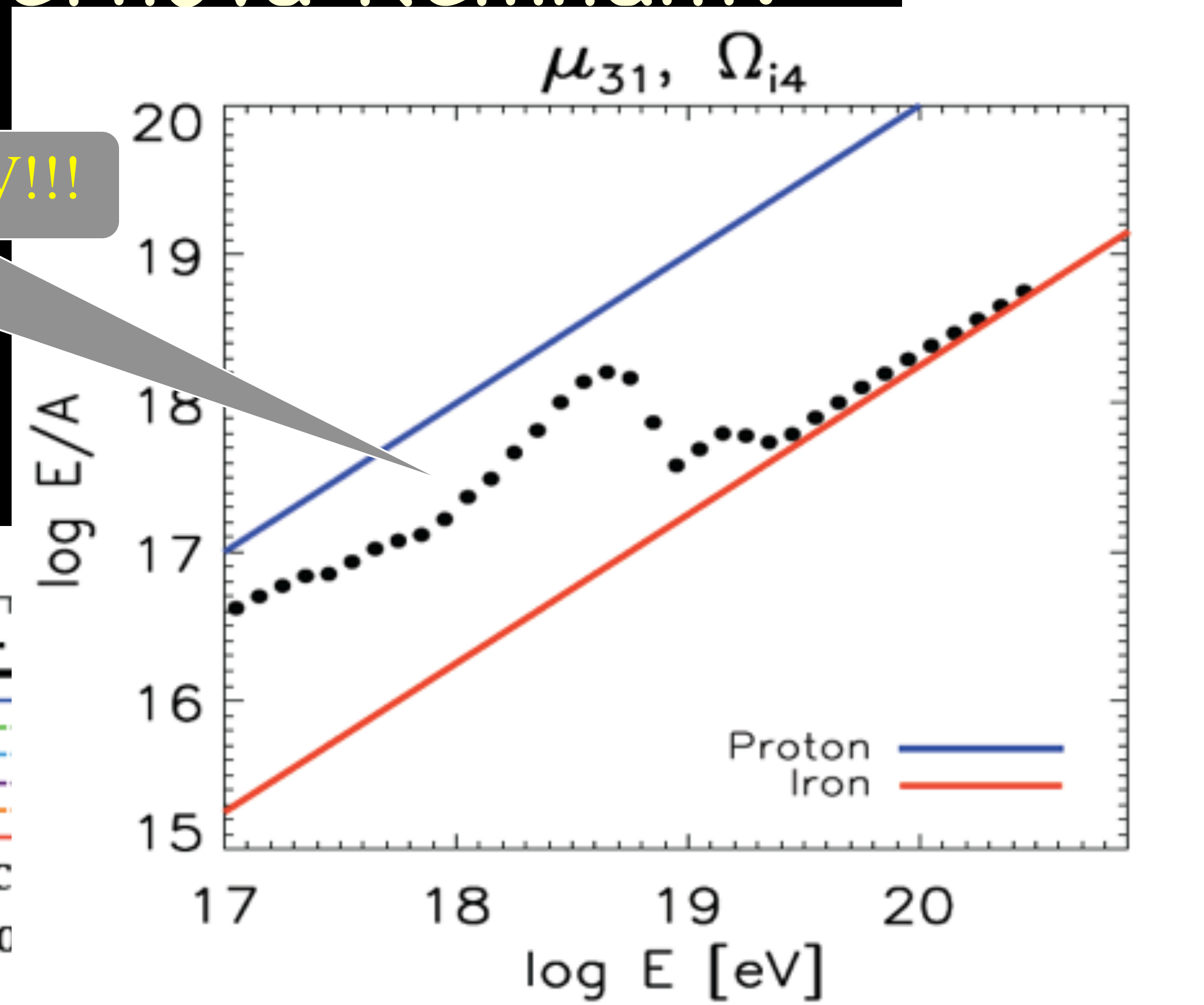


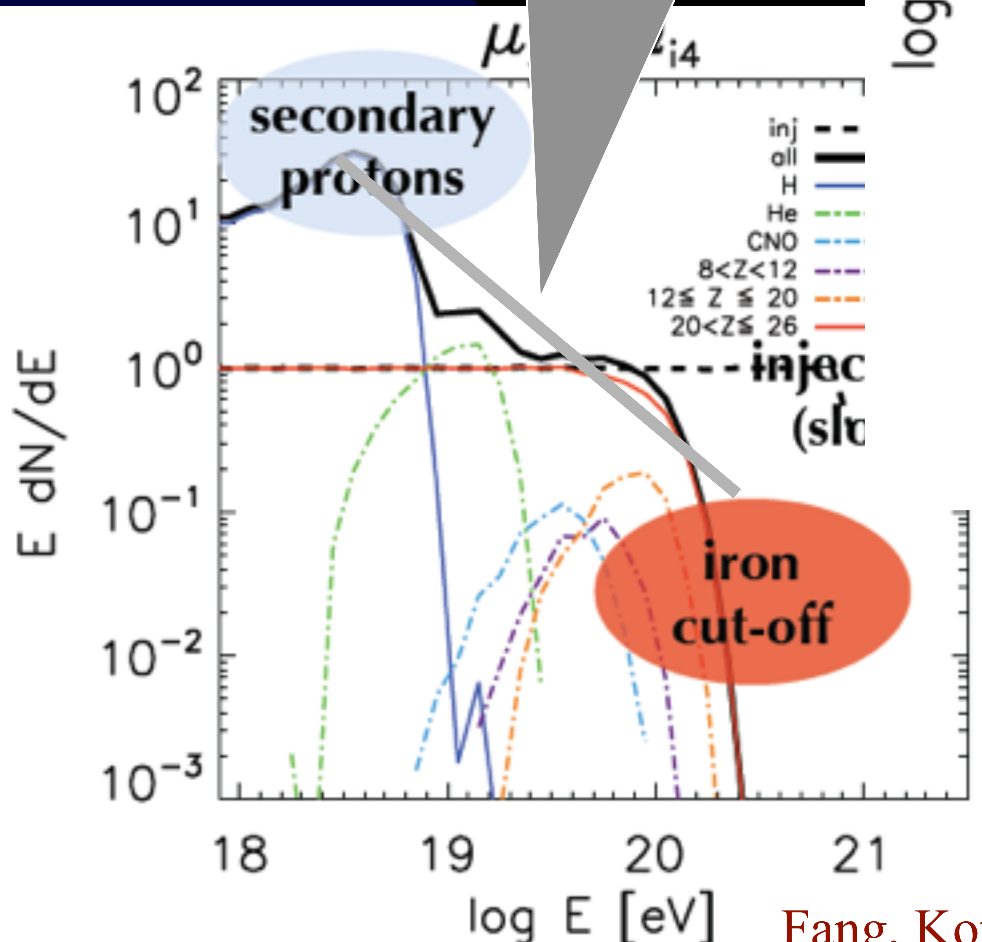
Fang, Kotera, AVO '11

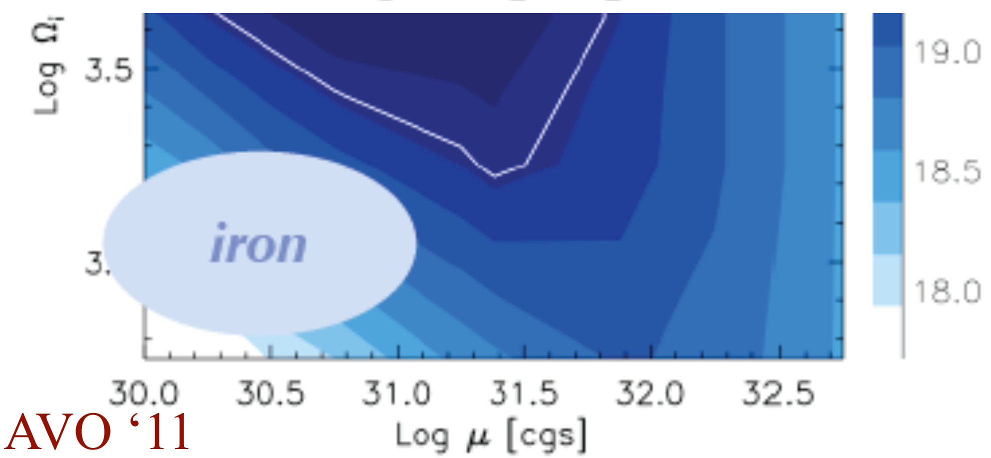
Escape from Supernova Remnant:

selects heavy elements > 10 EeV!!!

softens the spectrum ~ E^{-2}







Fang, Kotera, AVO '11

Heavy Composition

Unexpected Astrophysics:

Sources are very Iron rich and have low E_{max}

young pulsars?

Very Bad News for Neutrino Detectors

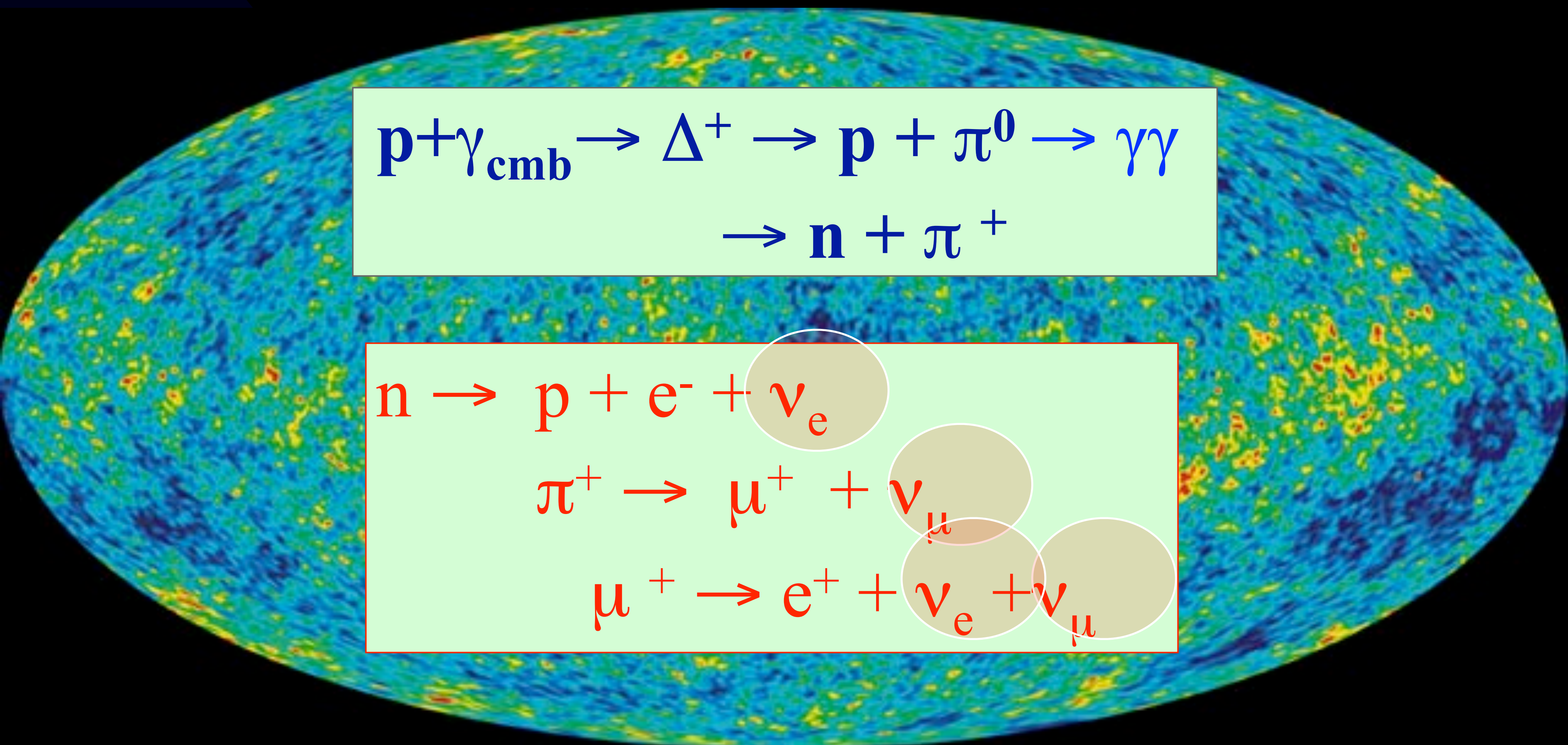
Interesting Particle Physics:

Hadronic Models do not represent well UHE interactions

Higher Cross Sections, Elasticities, Multiplicities...

Cosmogenic (GZK) Neutrinos & Photons

and UHECR composition



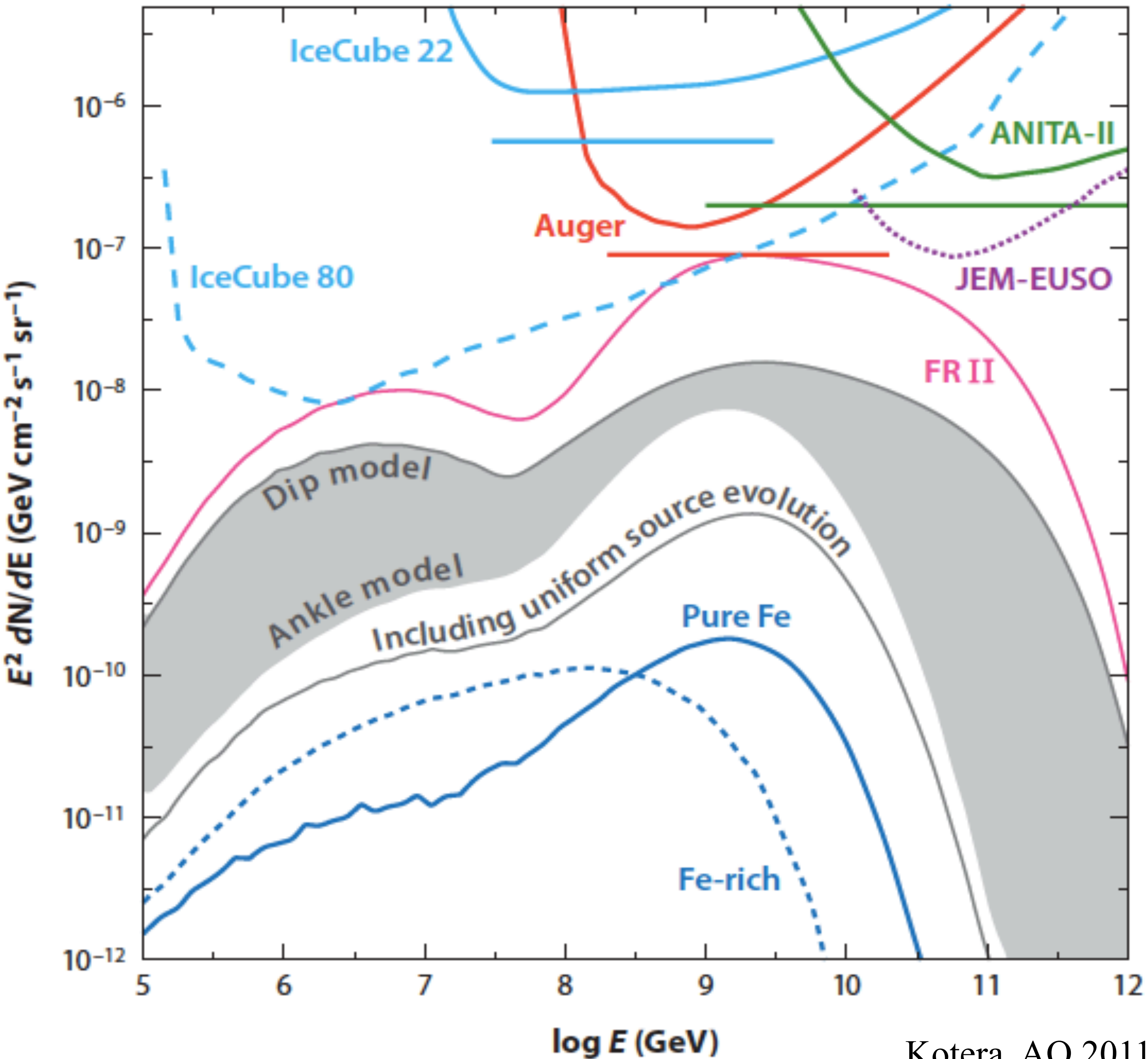
$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$

$$\rightarrow n + \pi^+$$

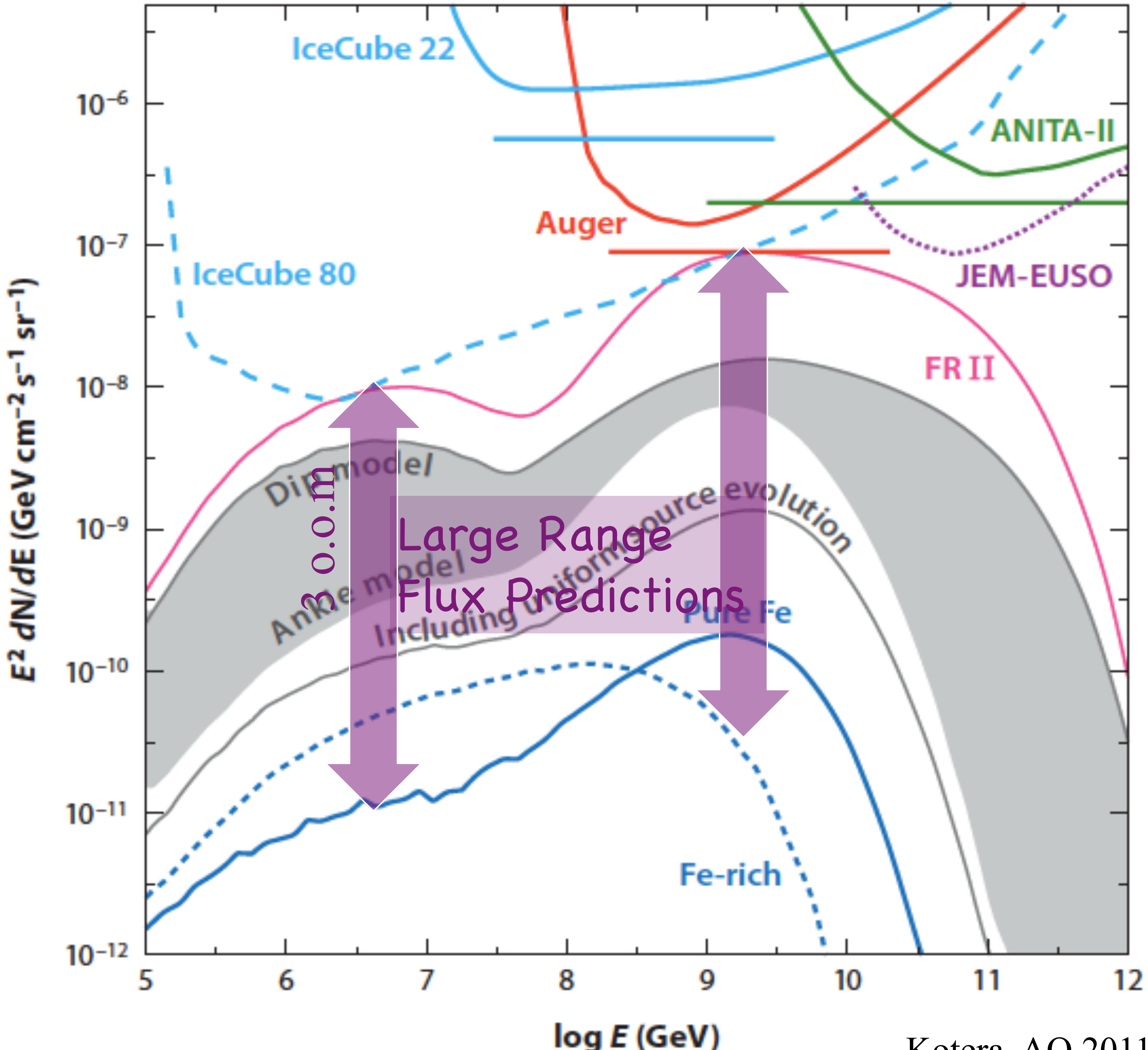
$$n \rightarrow p + e^- + \nu_e$$

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

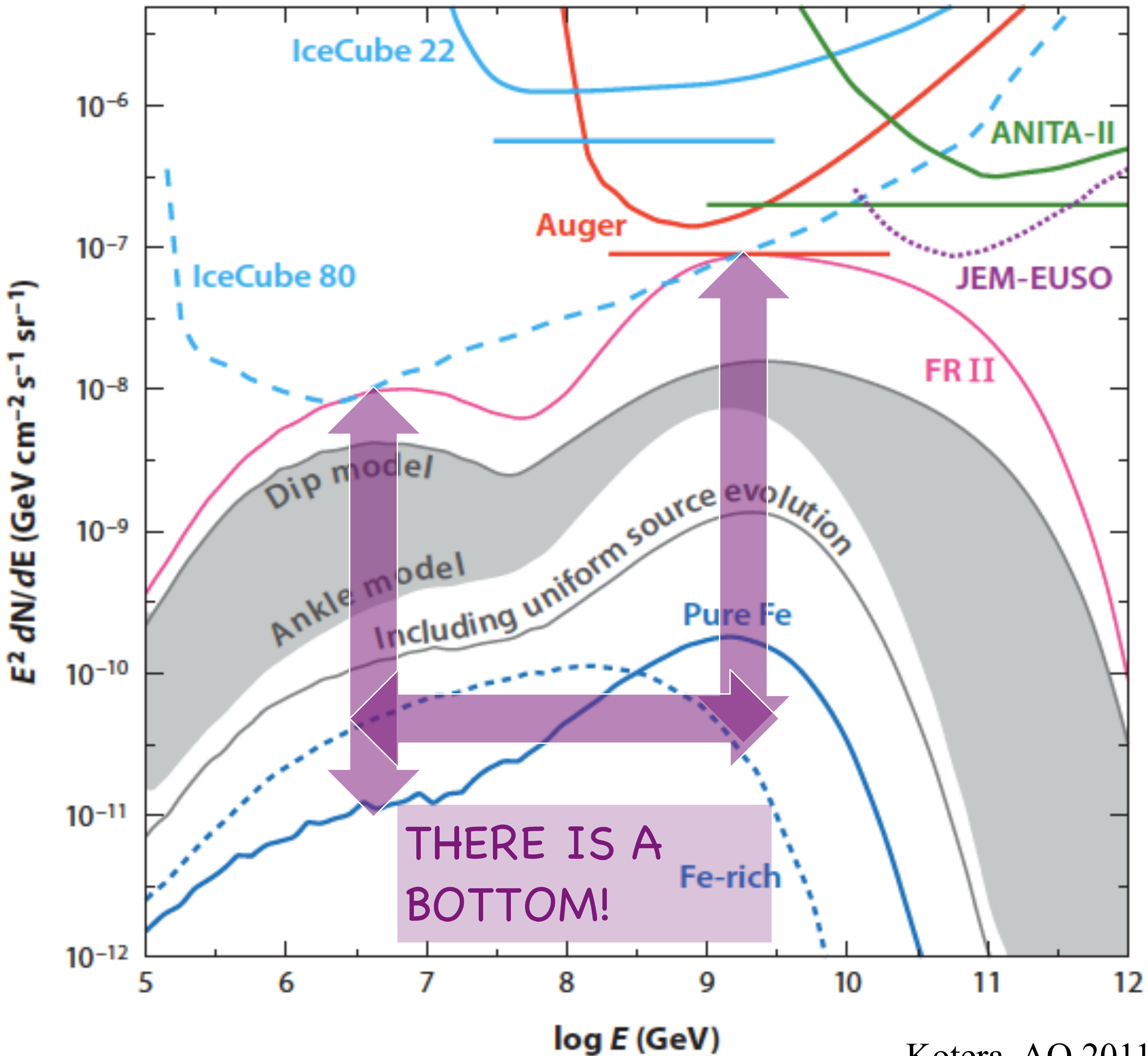
$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$



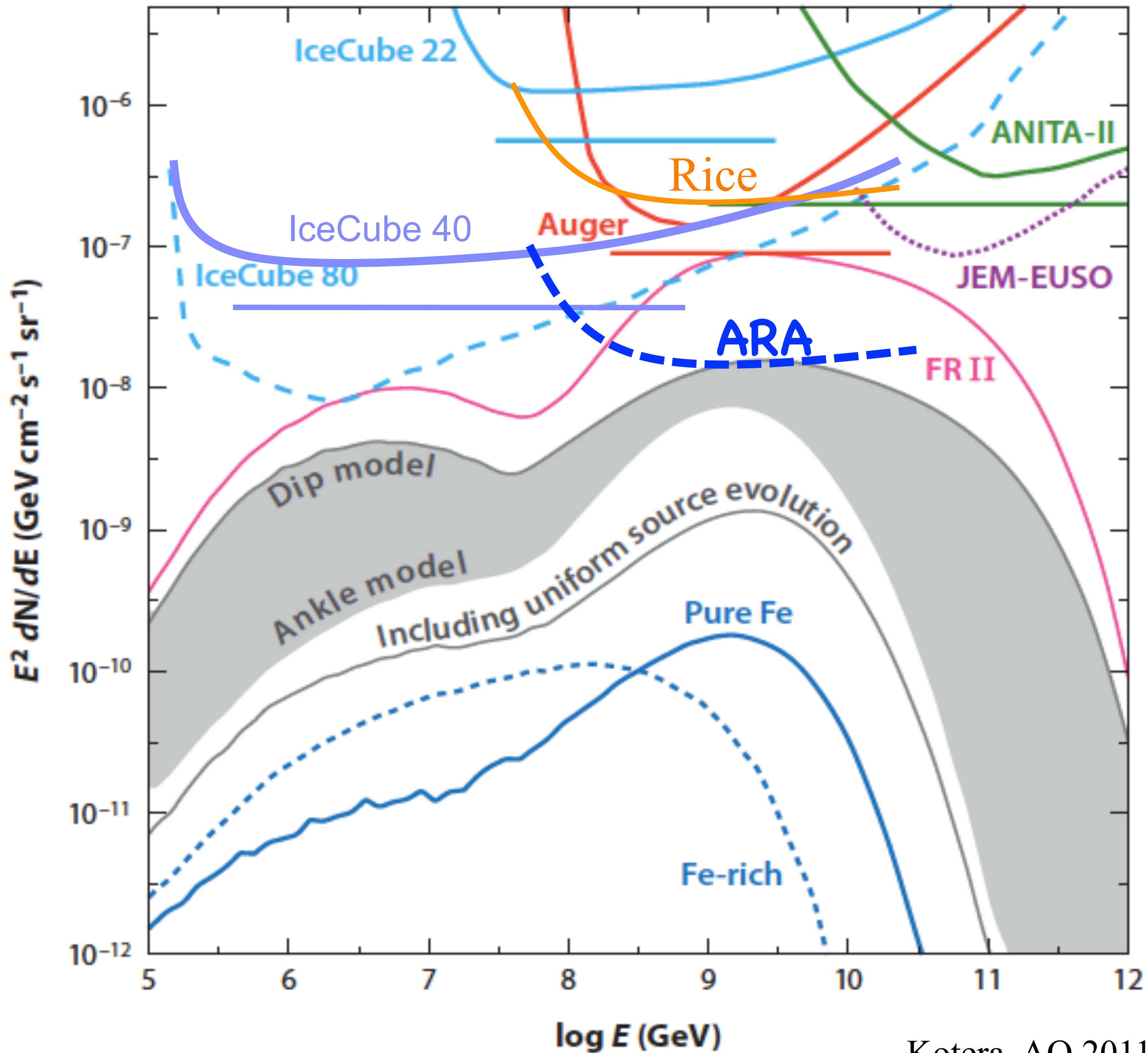
Kotera, AO 2011



Kotera, AO 2011

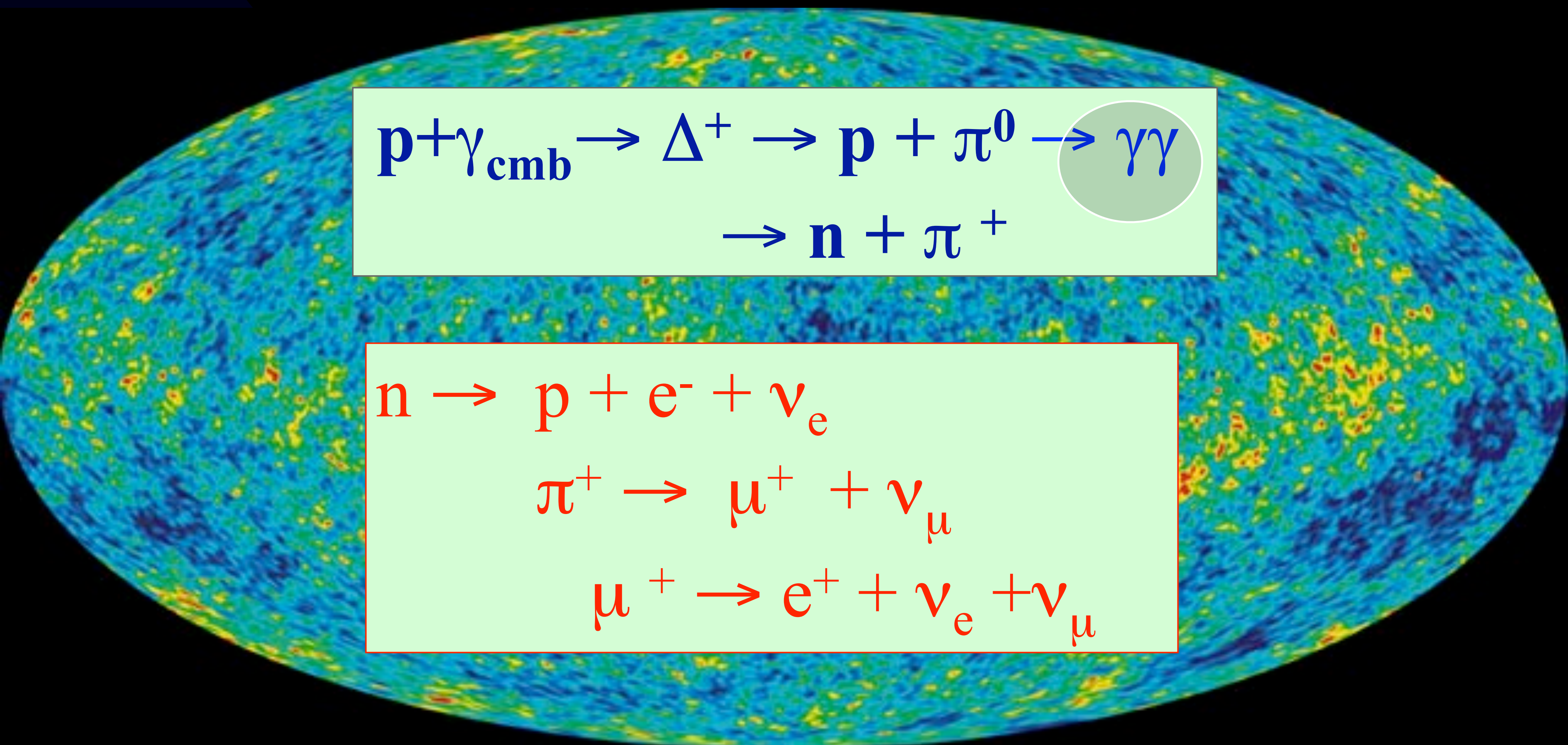


Kotera, AO 2011



Kotera, AO 2011

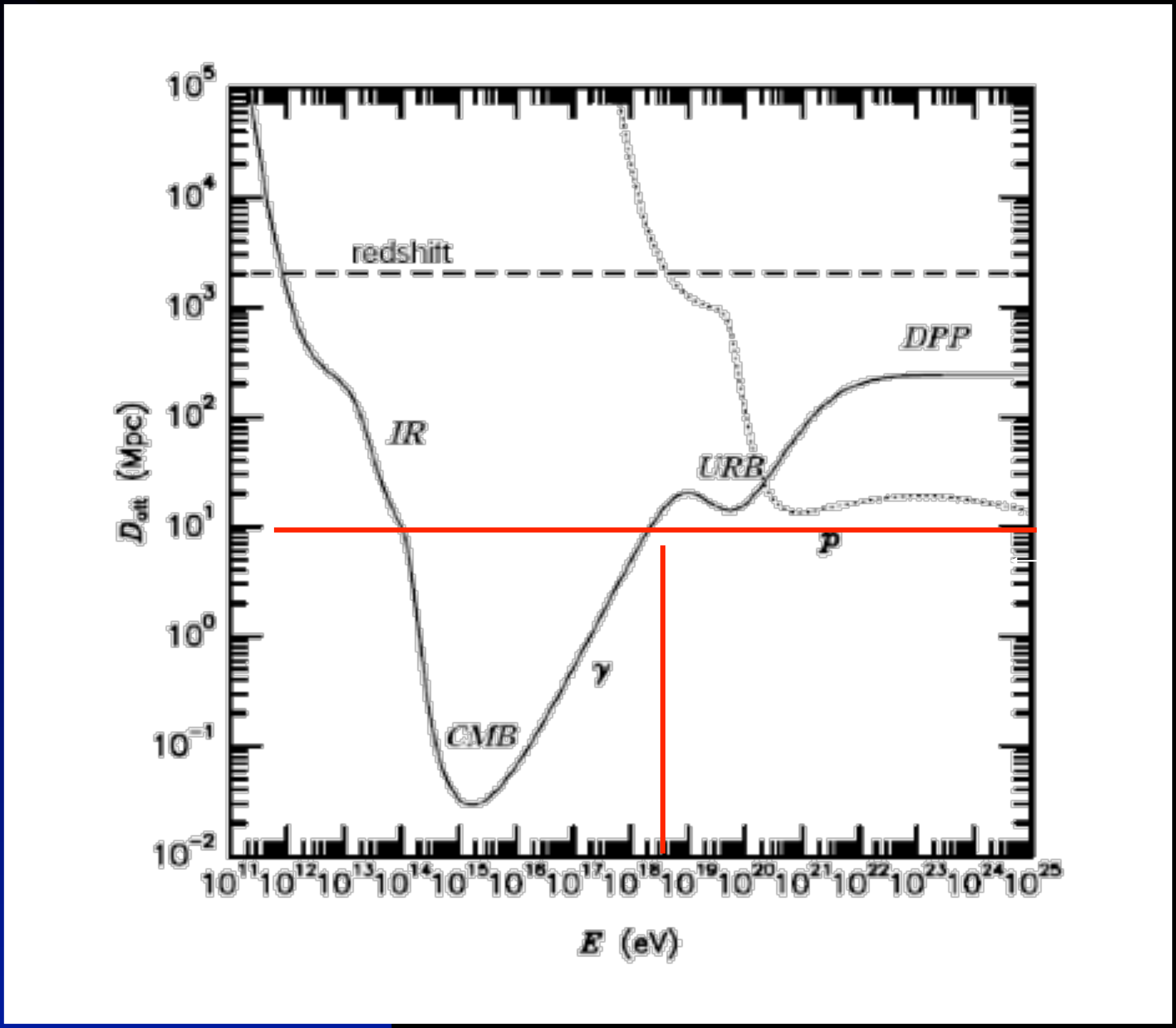
Cosmogenic (GZK) Neutrinos & Photons
and UHECR composition



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

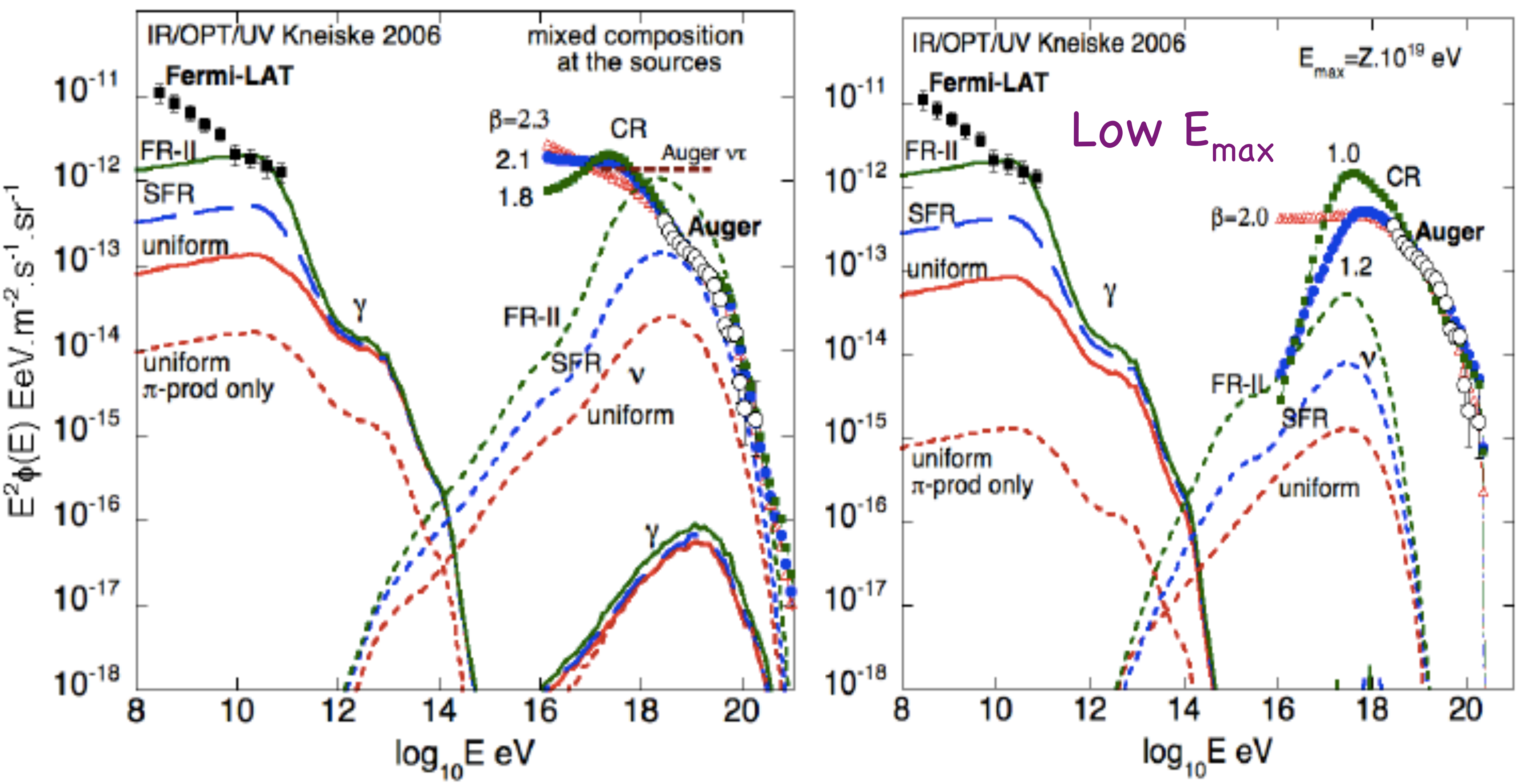
$$n \rightarrow p + e^- + \nu_e$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$

The UHE Gamma Ray Astronomical Window



Photon attenuation length 10 Mpc for E > 2 EeV

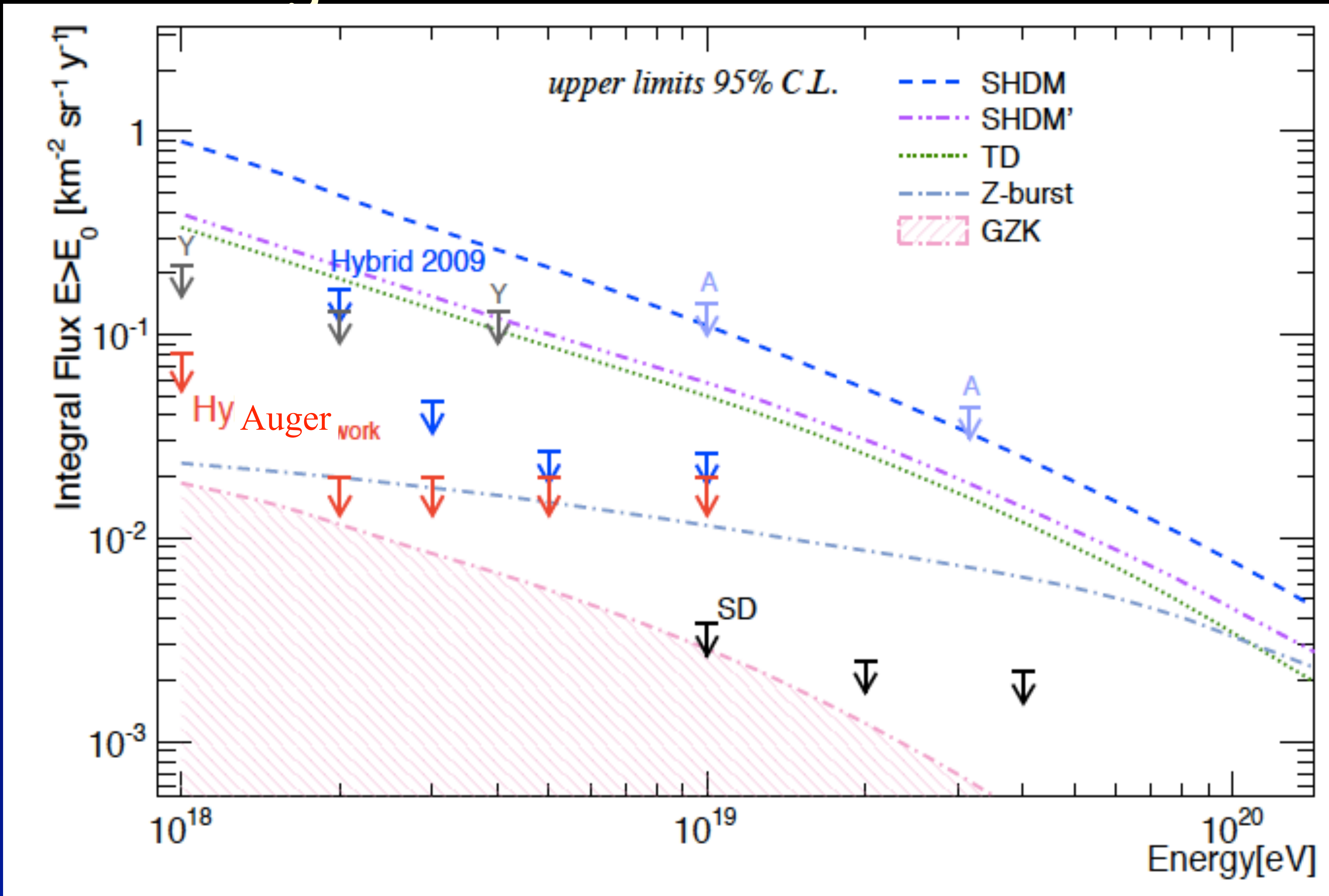
GZK/Cosmogenic Photons



Decerprit & Allard 11

Auger Photon Limits

ICRC11



TA consistent (ICRC11)

Puzzling Composition*

Unexpected Astrophysics:

Sources are very Iron rich

and have low E_{max}

Very Bad News for Neutrino Detectors

Interesting Particle Physics:

Hadronic Models do not represent well UHE interactions

Higher Cross Sections, Elasticities, Multiplicities...

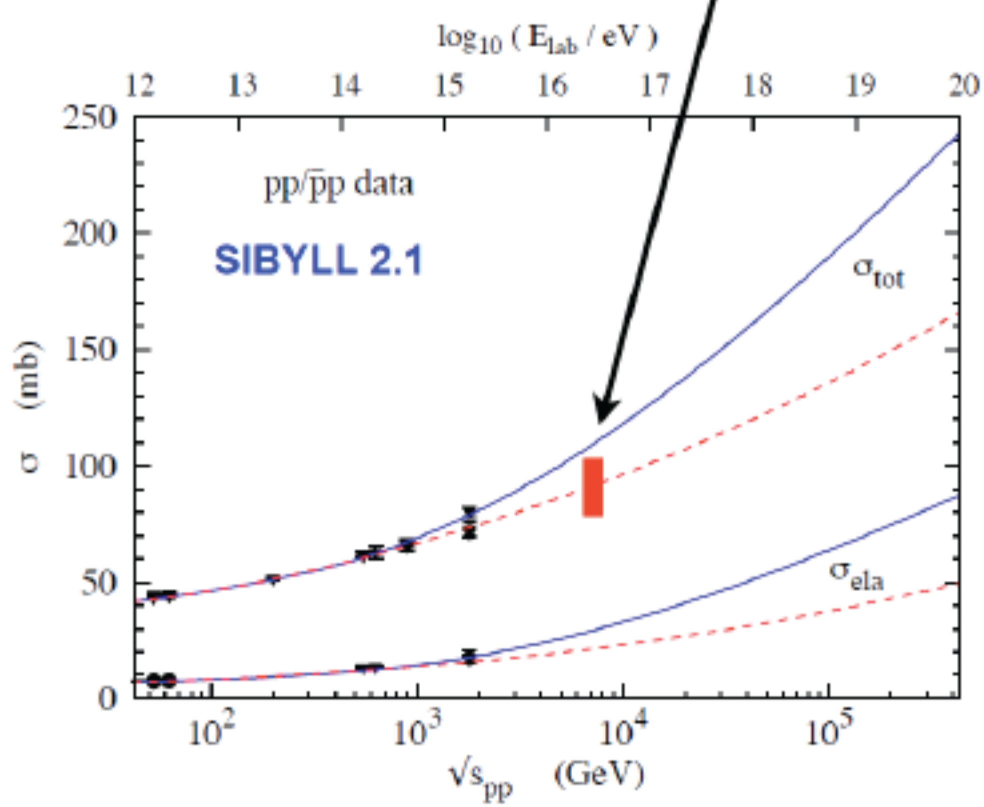
LHC data!!

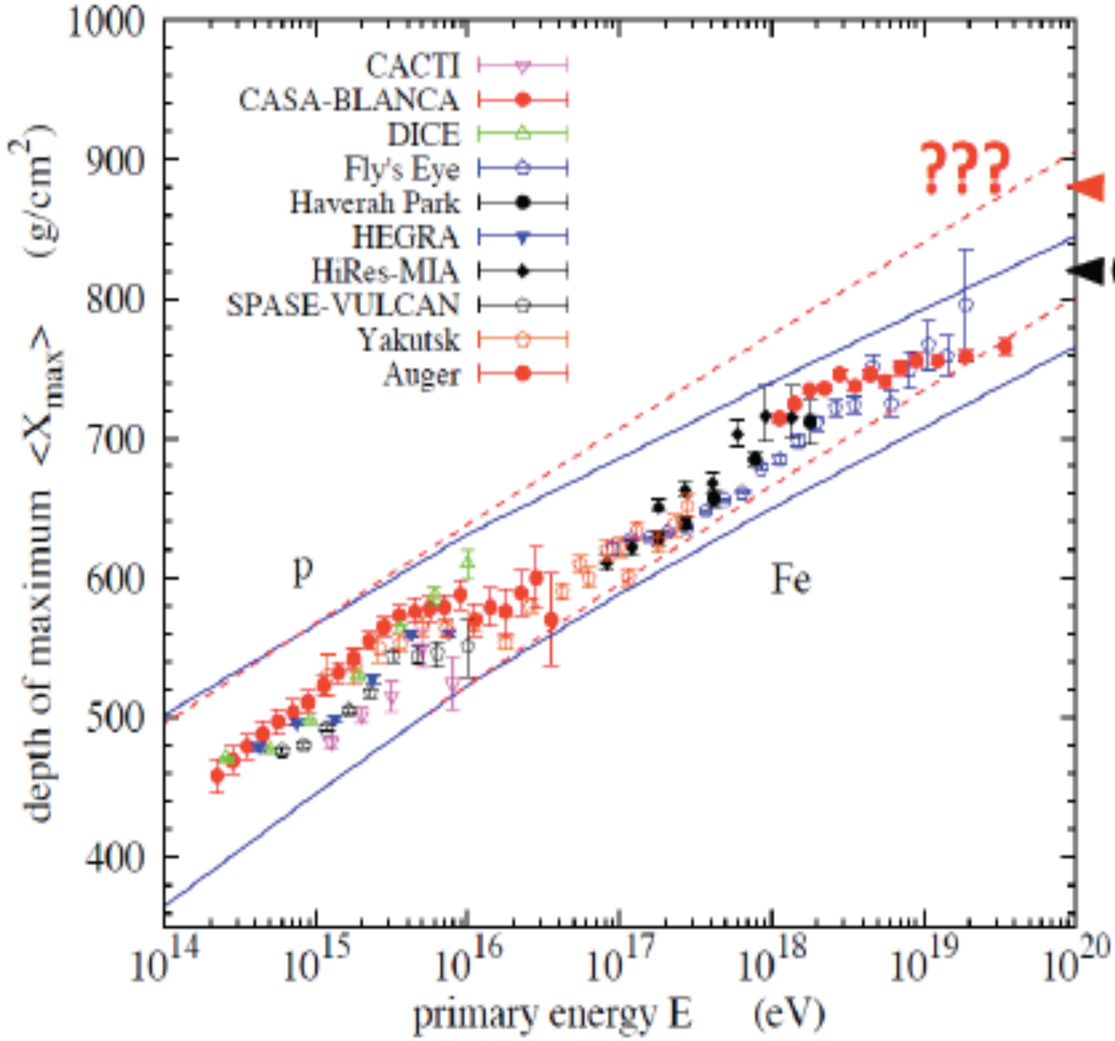
lower cross section → heavier composition with FD

ALICE $\sigma_{ine} = (72.7 \pm 1.1 \pm 5.1)$ m

LHC: ATLAS $\sigma_{ine} = (69.4 \pm 2.4 \pm 6.9)$ r

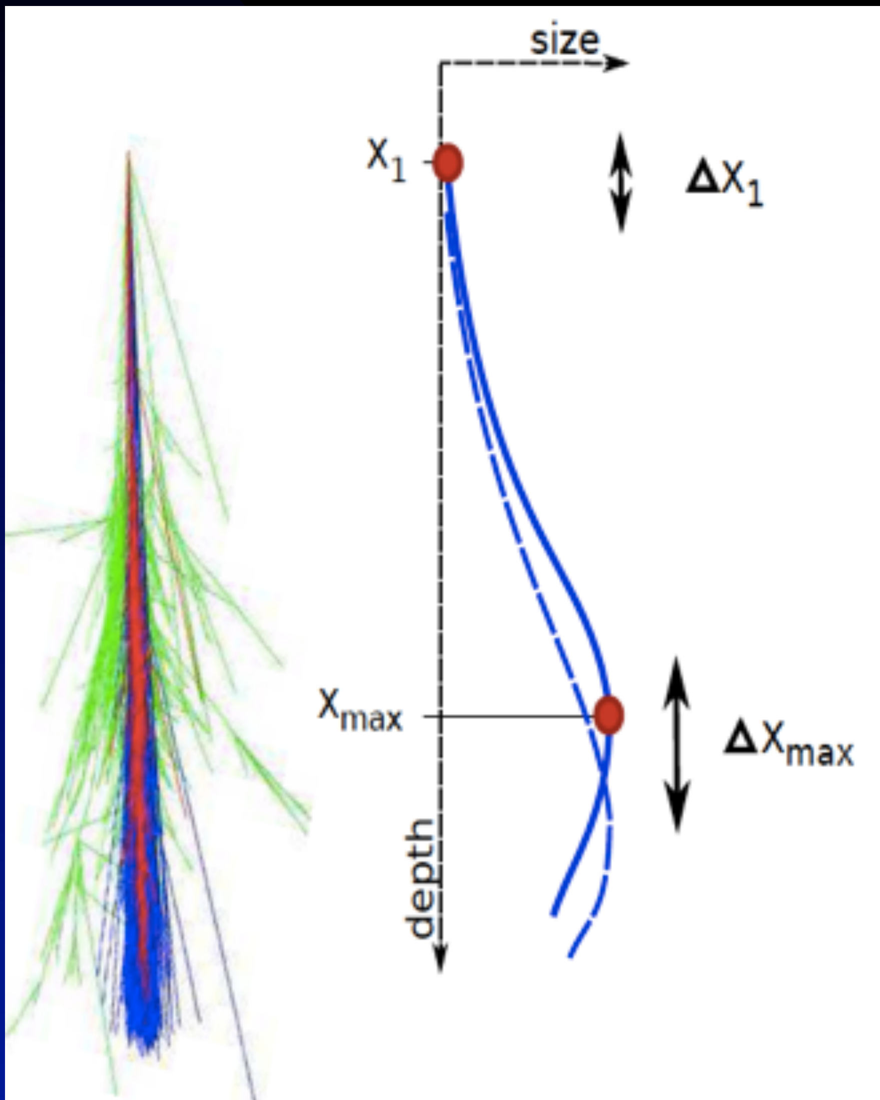
CMS $\sigma_{ine} = (68 \pm 3 \pm 4)$ mb

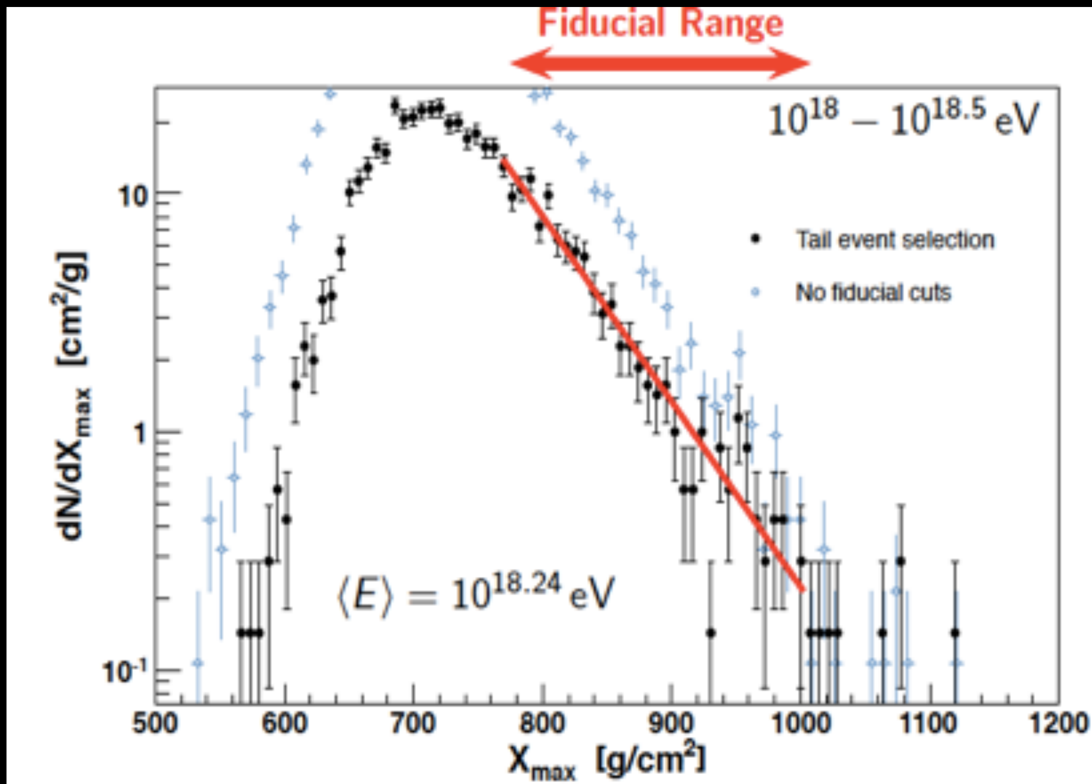




Pierog, Engel ICRC11

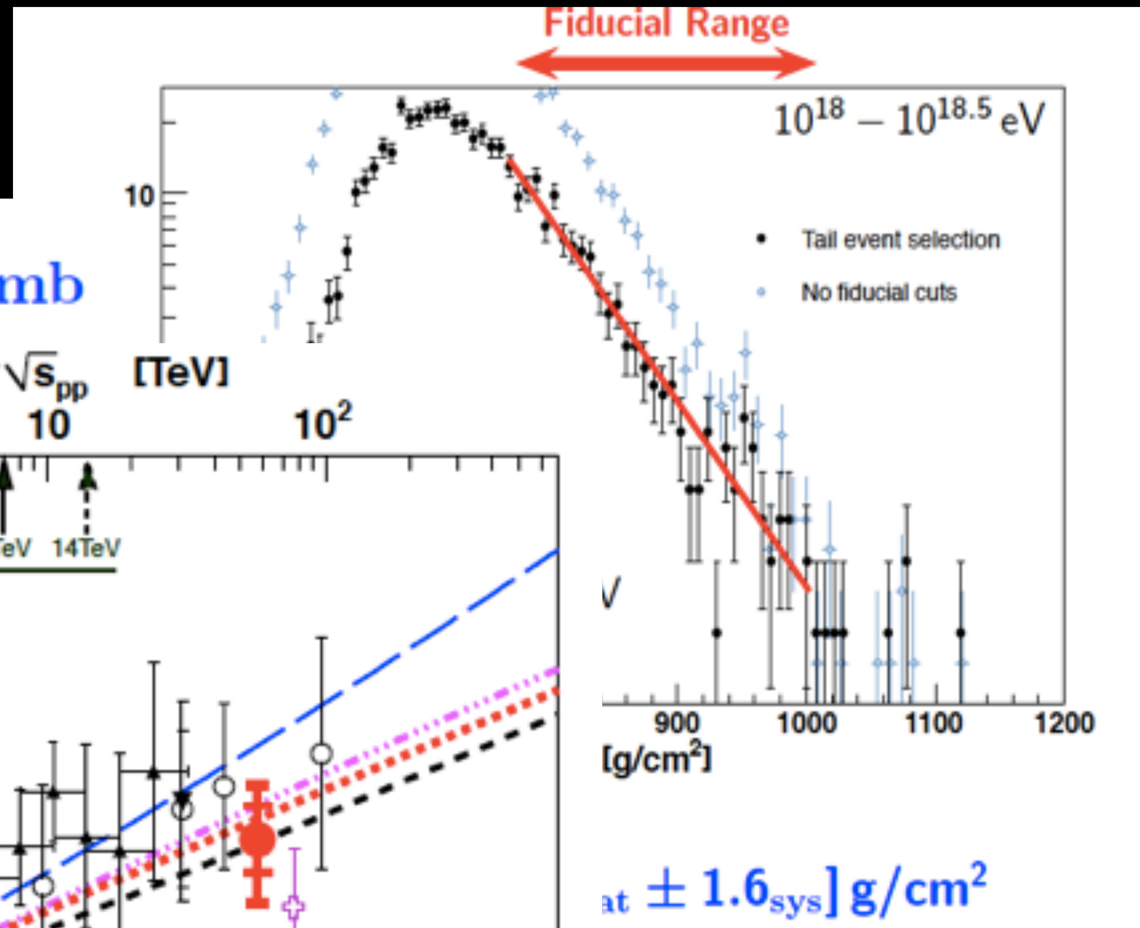
UHECRs return favor



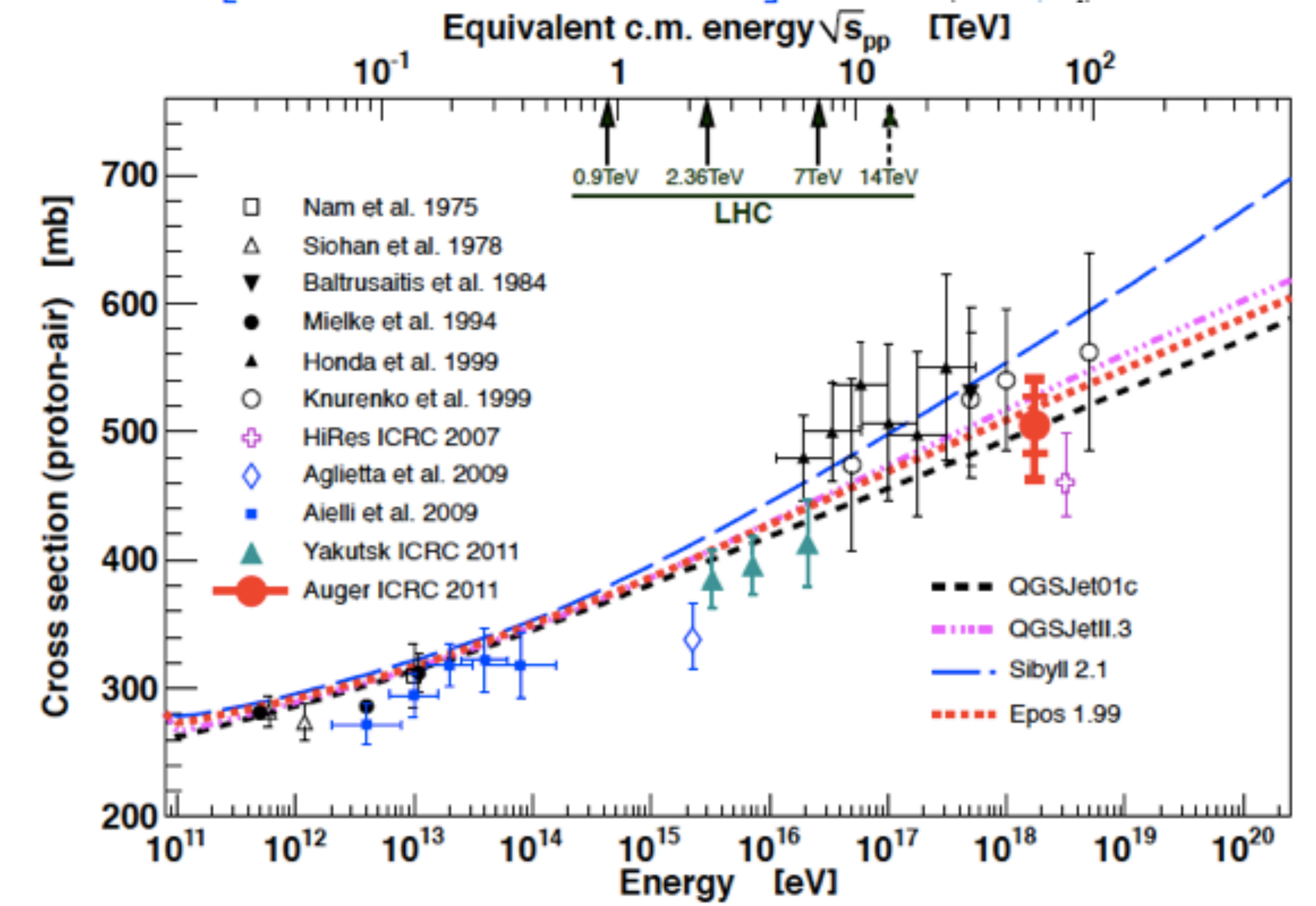


$\Lambda_\eta = [55.8 \pm 2.3_{stat} \pm 1.6_{sys}]\ g/cm^2$

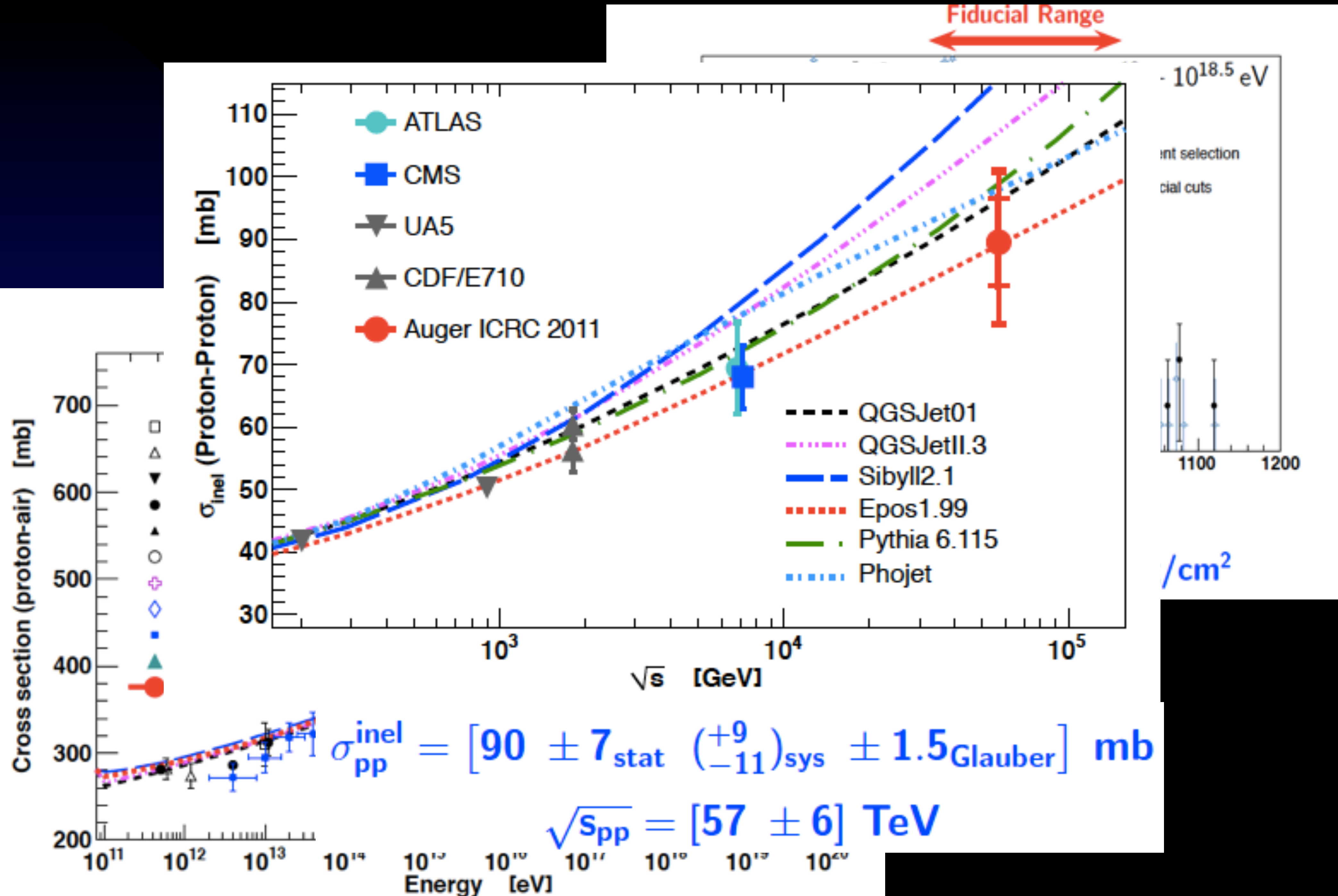
UHECRs return favor



$$\sigma_{p\text{-air}} = \left[505 \pm 22_{stat} \ (^{+28}_{-36})_{sys}\right] \text{ mb}$$



UHECRs return favor



$$\sigma_{pp}^{inel} = [90 \pm 7_{stat} \ (^{+9}_{-11})_{sys} \pm 1.5_{Glauber}] \ \text{mb}$$

$$\sqrt{s_{pp}} = [57 \pm 6] \ \text{TeV}$$

The primary composition can be determined Astrophysically at higher energies (above 60 EeV):

through ANISOTROPIES or Secondary Neutrinos & Photons

then hadronic models can be tested

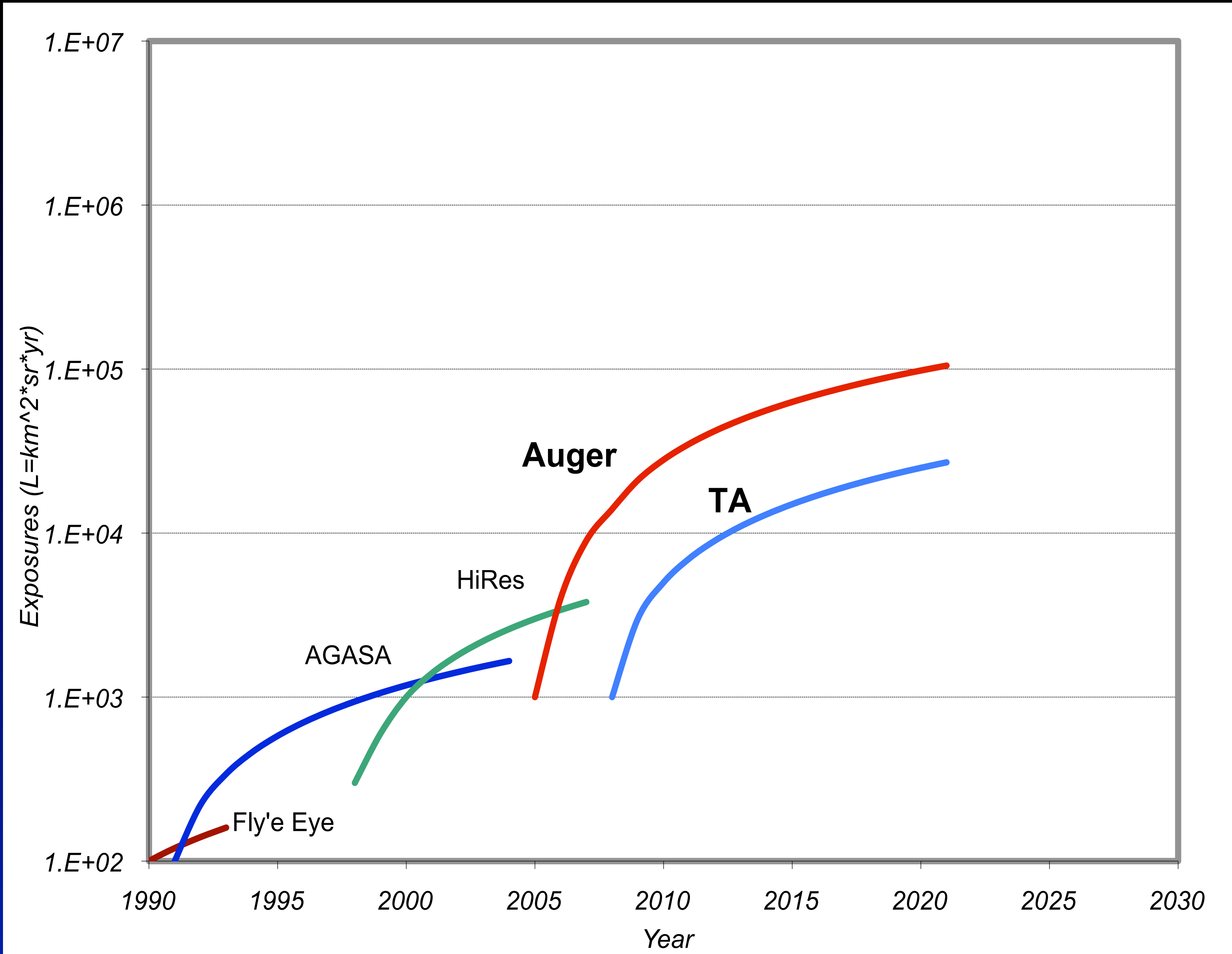
E > 100 TeV CM

More Statistics at the Highest energies

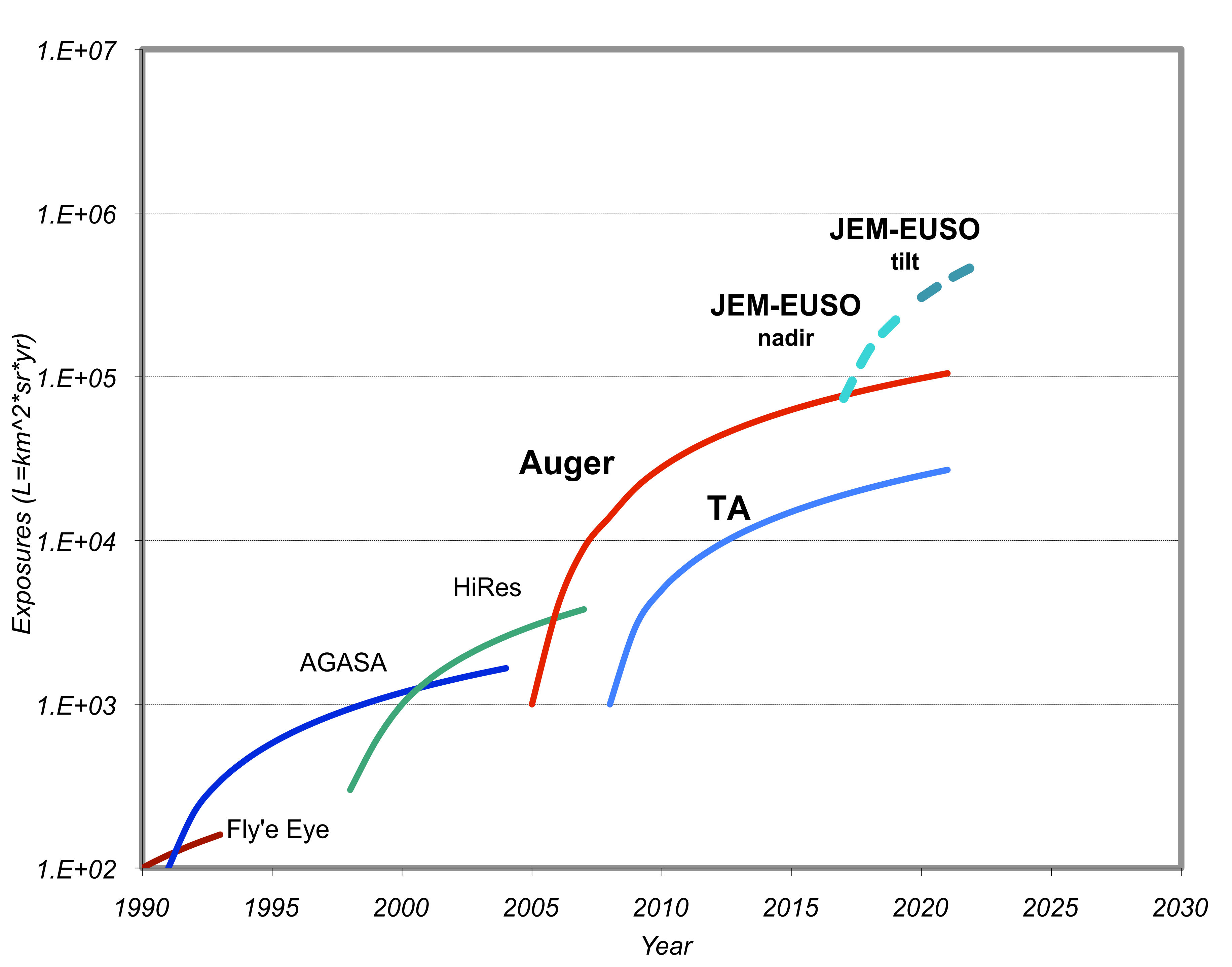
Scratching the Surface

Increase Exposure!

Exposure History



Exposure History

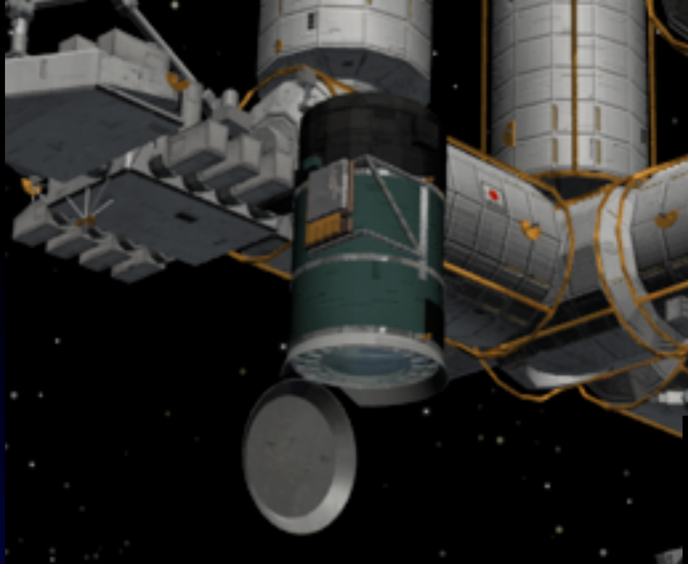


JEM-EUSO

JAXA, ESA, NASA

Japanese Experiment Module of ISS in 2017

Extreme Universe Space Observatory



Nadir (2 yrs)

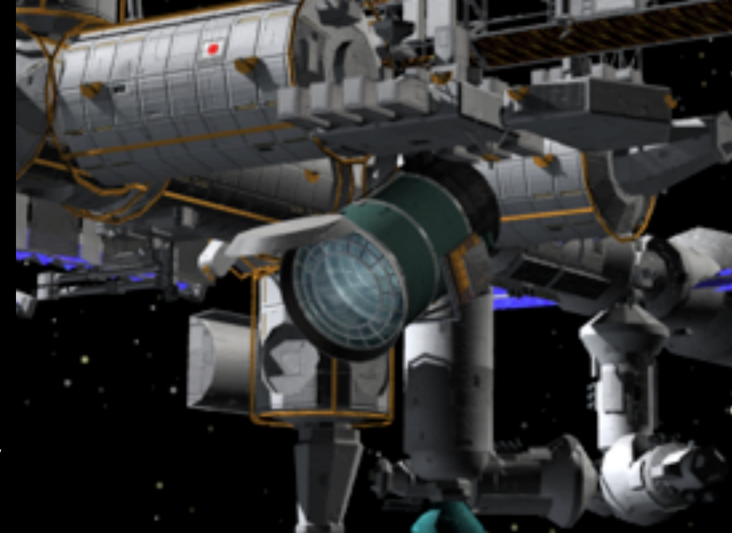
35^o tilt (3 yrs)

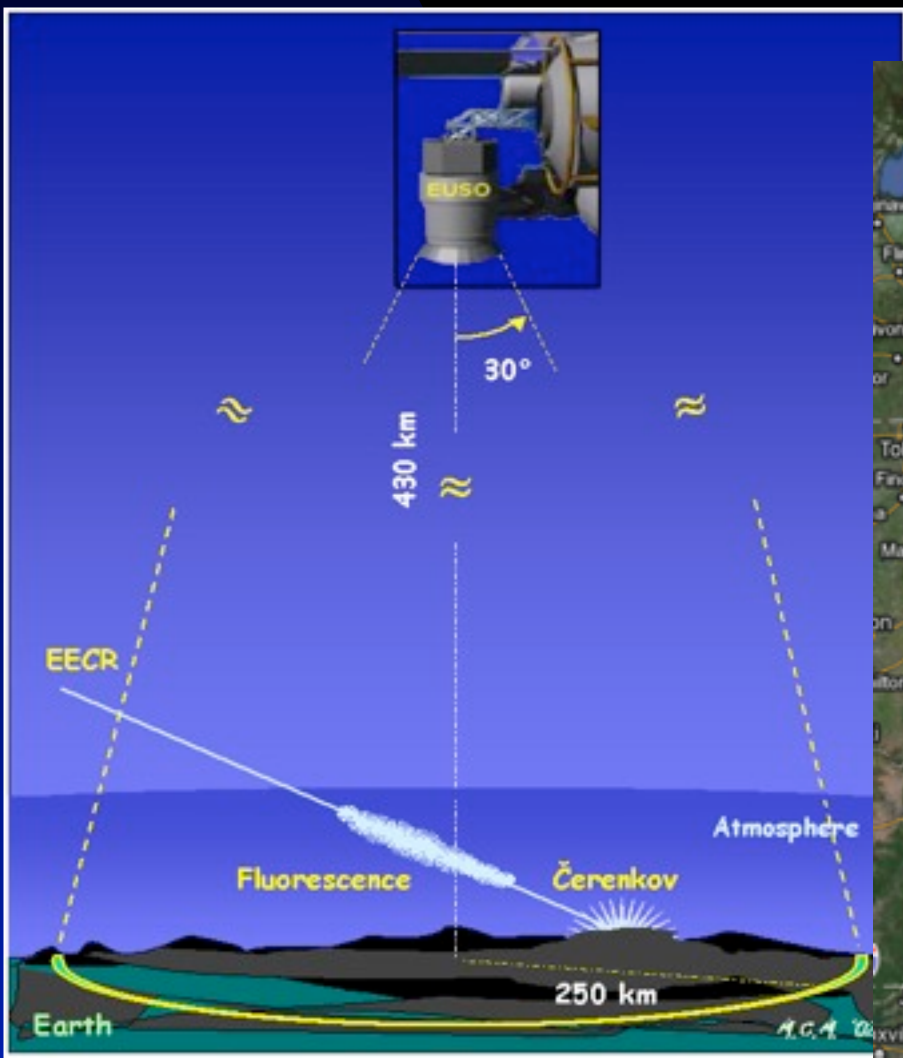
- 3 x area

$E_{th} \sim 10^{20}$ eV

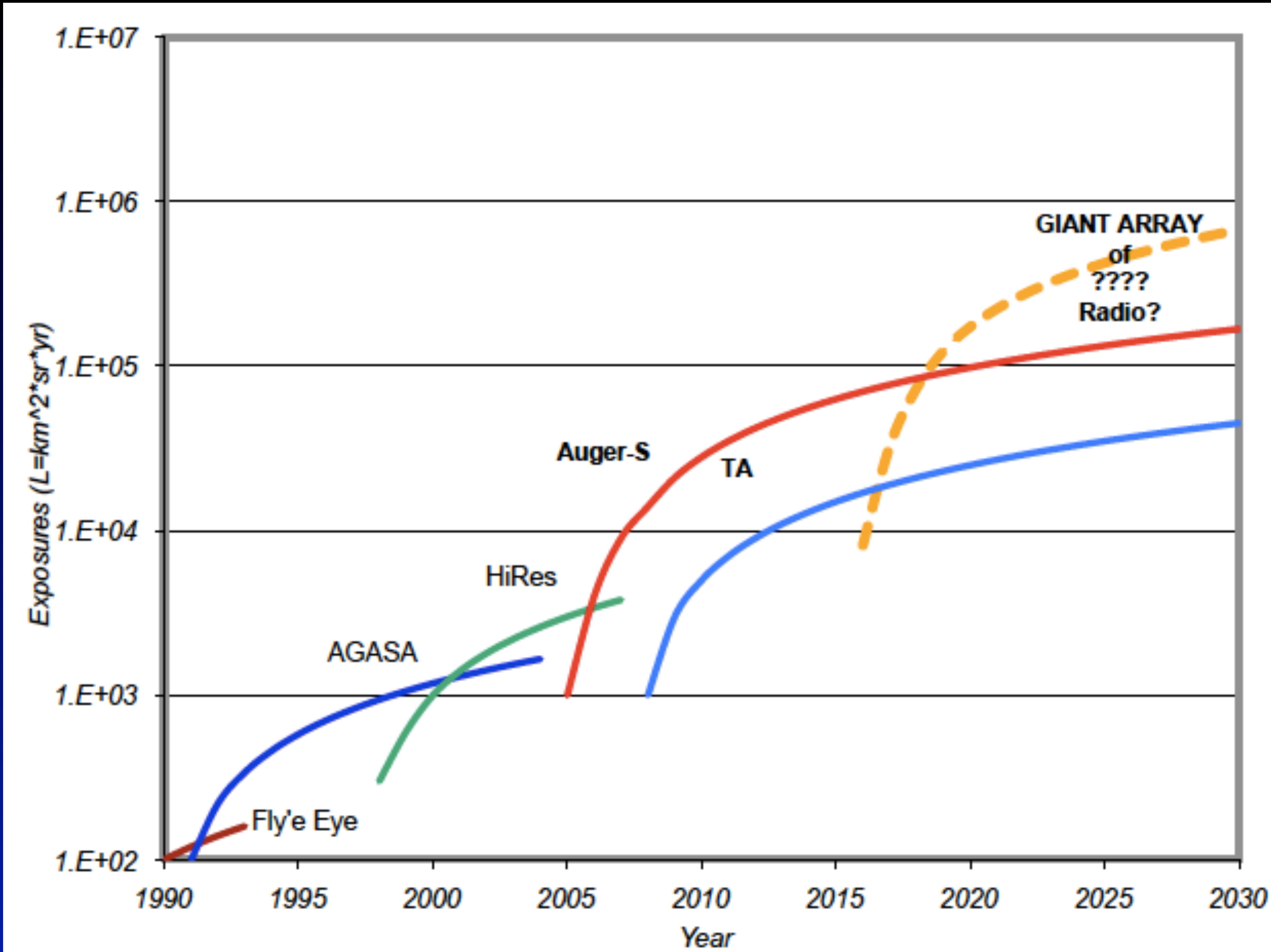
Fluorescence only

~ 20% duty cycle

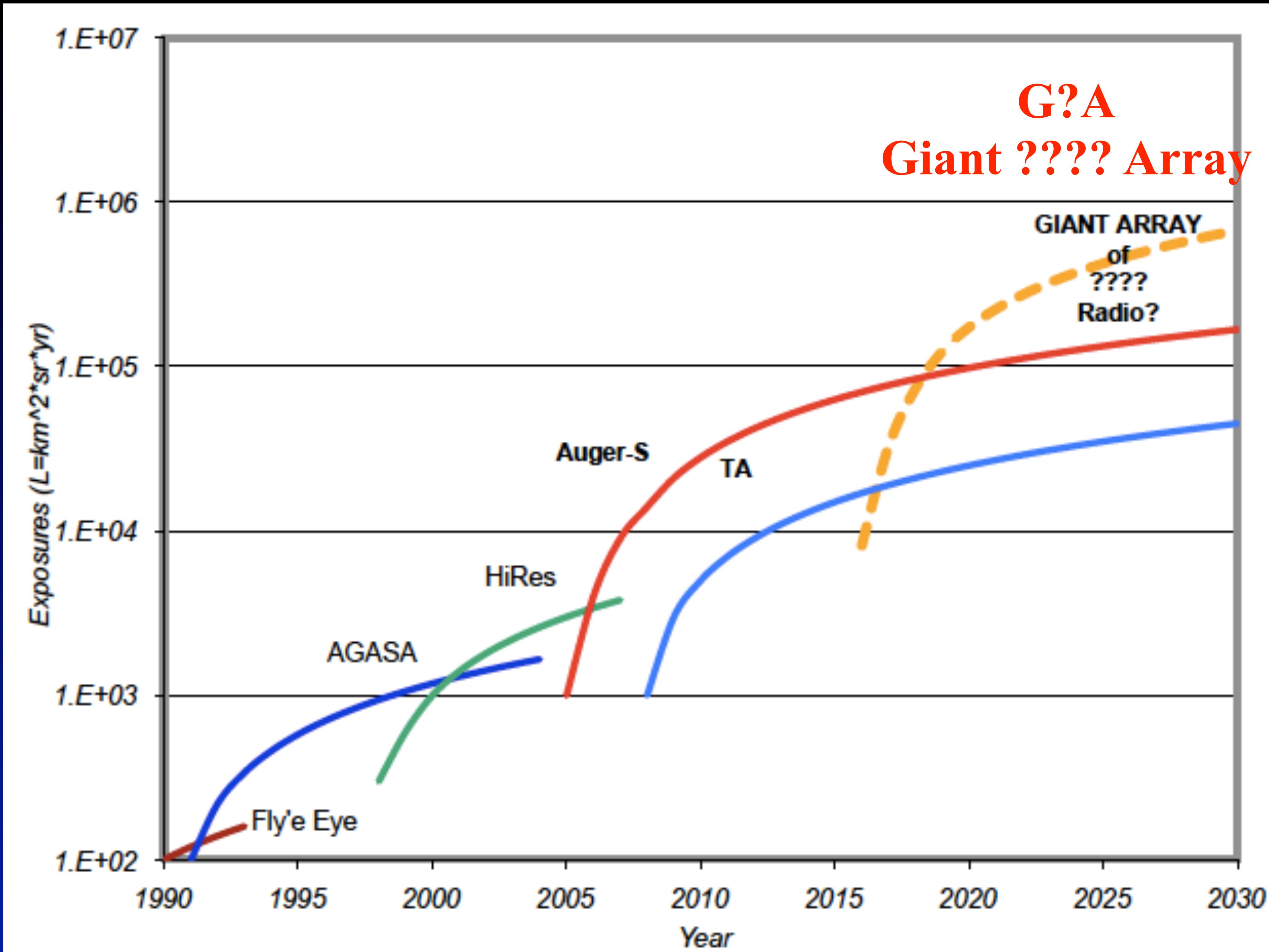




Future Wishes...

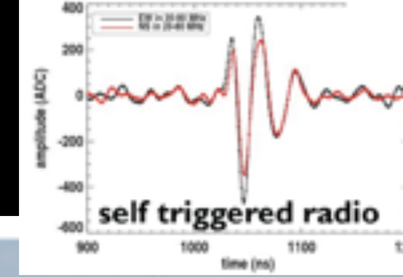


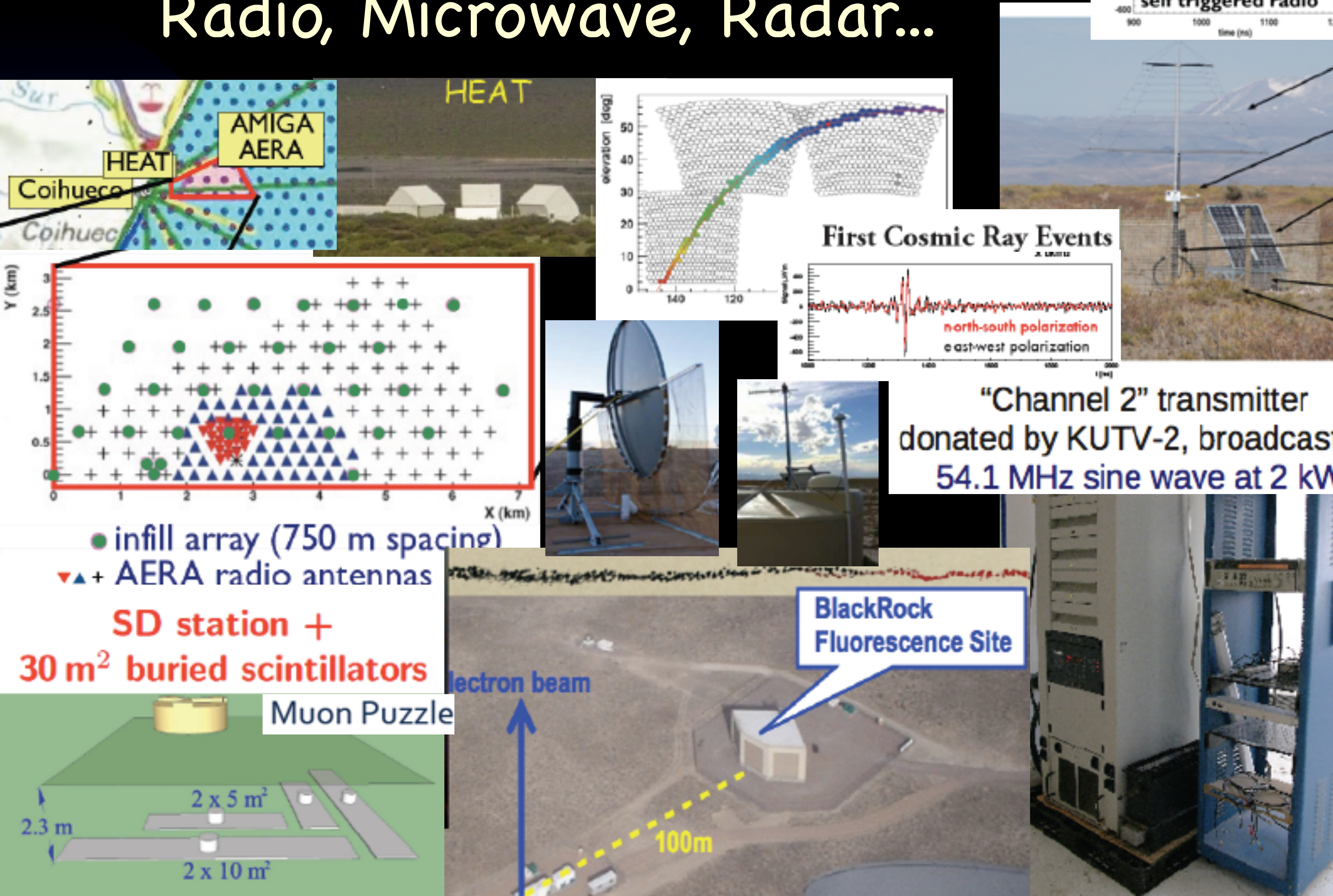
Future Wishes...



R&D Efforts:

Radio, Microwave, Radar...





AstroParticle Physics at Ultrahigh Energies:

to discover the Origin of Extragalactic Cosmic Rays to study UHE Neutrinos, UHE Gamma-rays, and UHE particle interactions

Need Significant Increase in Statistics at the highest energies.

Large-Scale International Efforts can solve this mystery!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