Current status and future prospects for ultrahigh energy cosmic rays from a theoretical point of view

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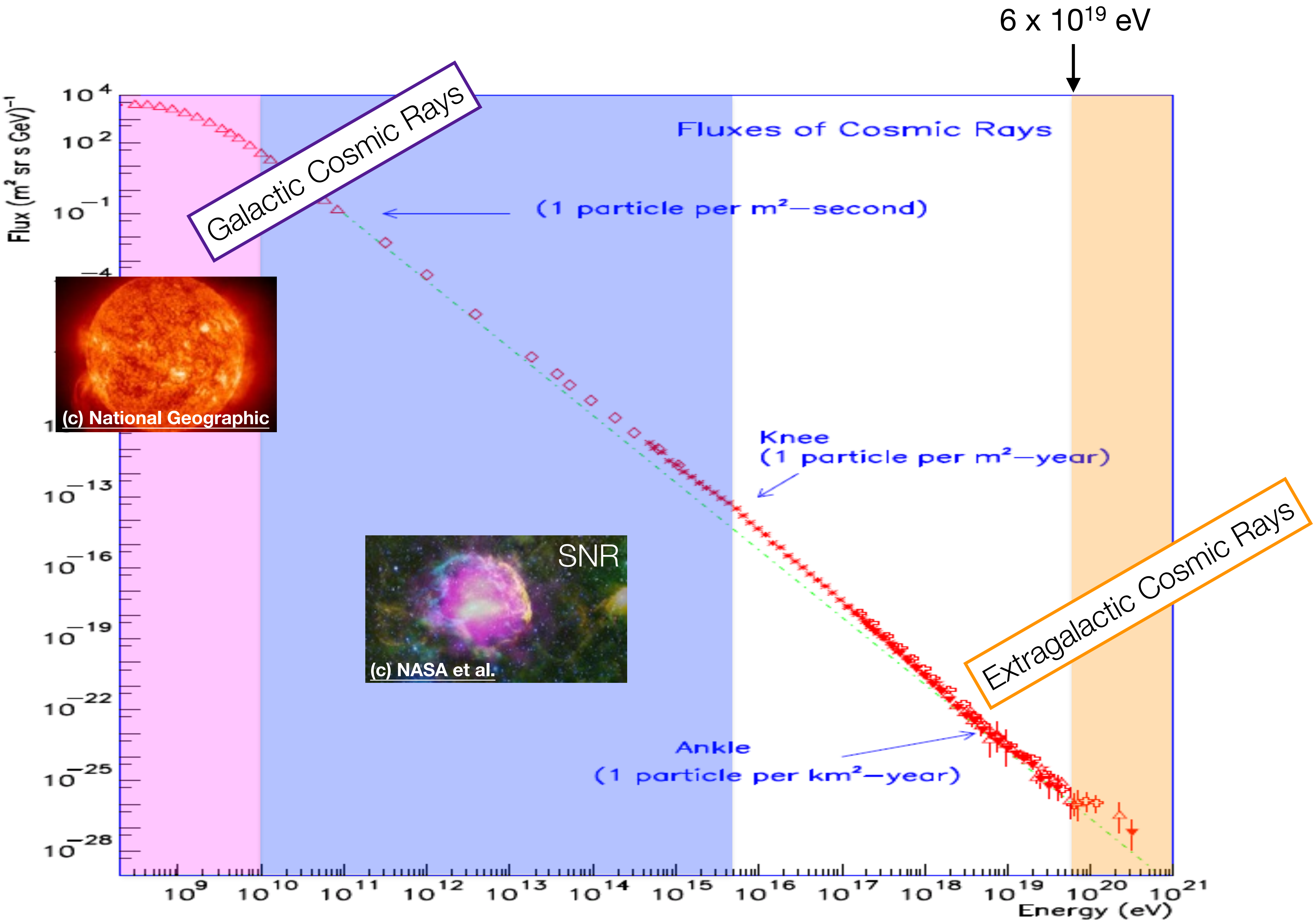
KEK Theory Center Cosmophysics Group

1. Introduction
2. Review
3. Future Prospects
4. Summary

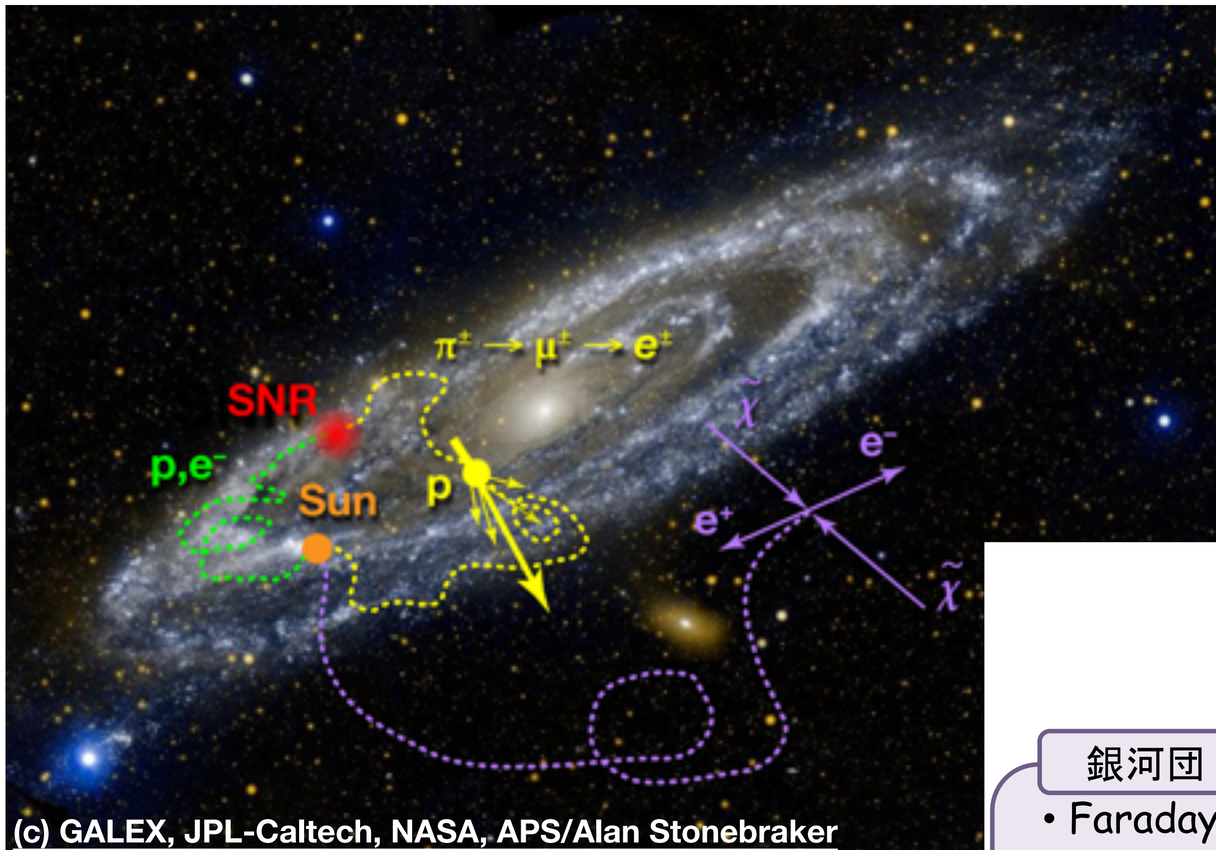
Cosmic rays ~ origin ~



Bhattacharjee & Sigl, Phys. Rep. 327 (2000) 109, Originally from S. Swordy

Difficulty in Identifying Cosmic-ray Origin

Charge and cosmic magnetic fields



平均磁場

Faraday rotation : $B\lambda^{1/2} <$ (1 nG)(1 Mpc)$^{1/2}$

Kronberg (1994), Ryu et al. (1998), Blasi et al. (1999)

銀河団

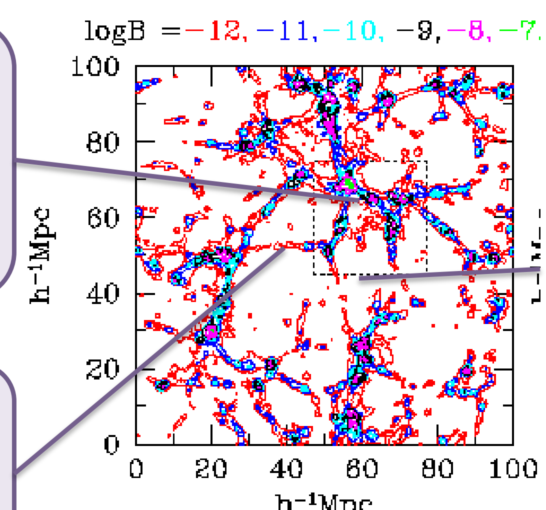
- Faraday rotation : ~ 1 - 10 μG
- Synchrotron : ~ 0.1 - 1 μG

フィラメント構造

No constraint

Simulations : ~ 10 nG

e.g., Ryu et al. (2008)



Das et al. (2008)

void領域

- γ-ray cascades : > 10^{-18} – 10^{-17} G
  e.g., Dolag et al. (2011), Dermer et al. (2011), Takahashi et al. (2011)
- CMB / LSS : < 2.5 nG for λ = 1 Mpc
  Jedamzik et al. (2000), Yamazaki et al. (2010)

Highest Energy Cosmic Rays as a Good

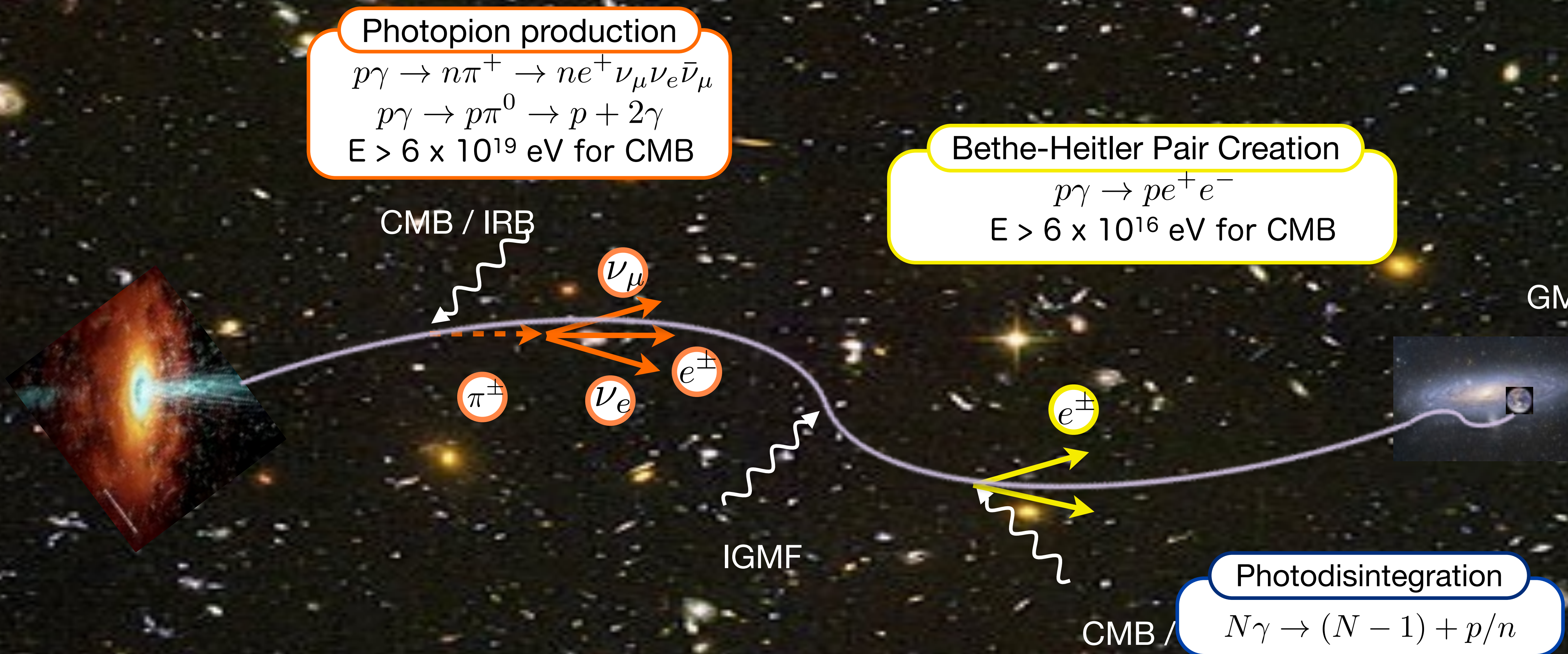
1. Deflection can be minimized.

$$\theta(E,D) \simeq 2.5^\circ Z \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1} \left(\frac{D}{100\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{1\ \mathrm{nG}}\right) \left(\frac{\lambda}{1\ \mathrm{Mpc}}\right)^{1/2}$$

2. Greisen-Zatsepin-Kuz'min horizon

   — low-background observations

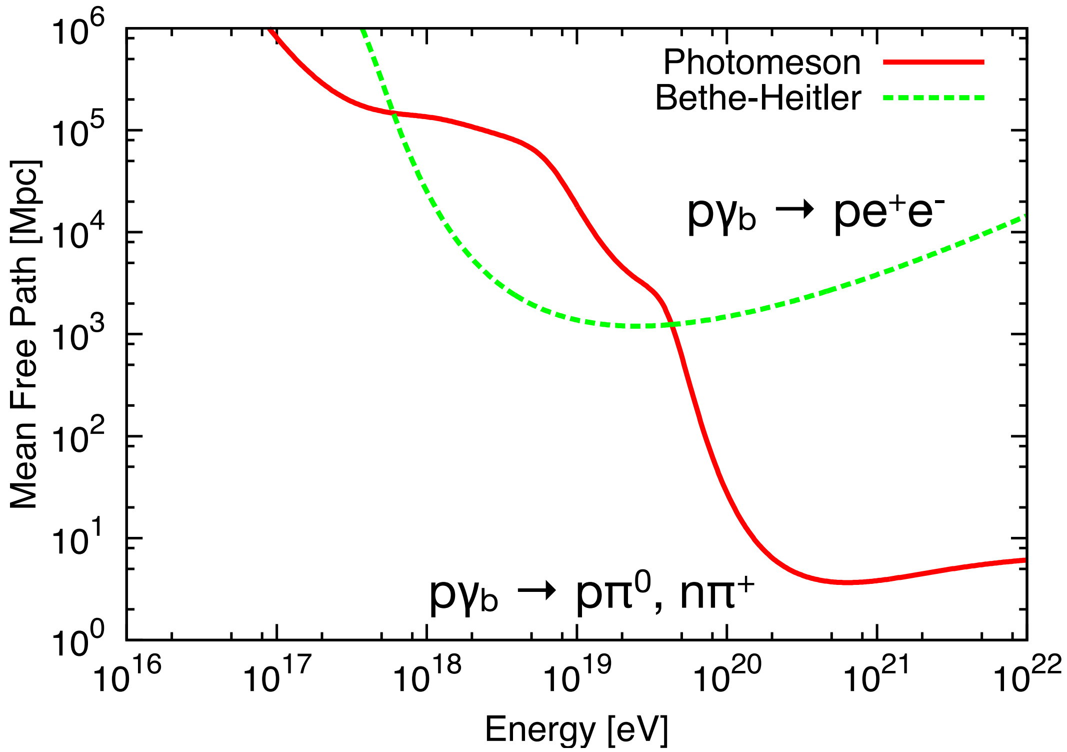
Propagation of UHECRs



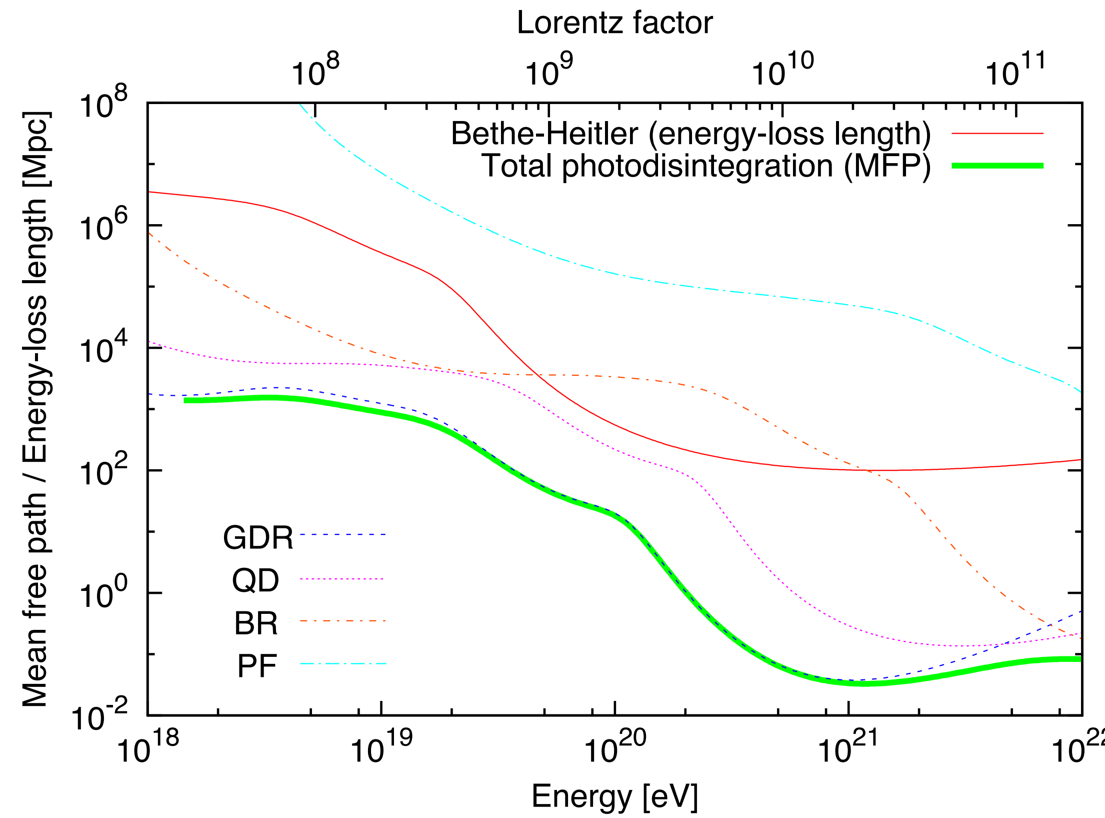
Mean Free Path

Mean free path drastically decreases at the highest energies.

Proton



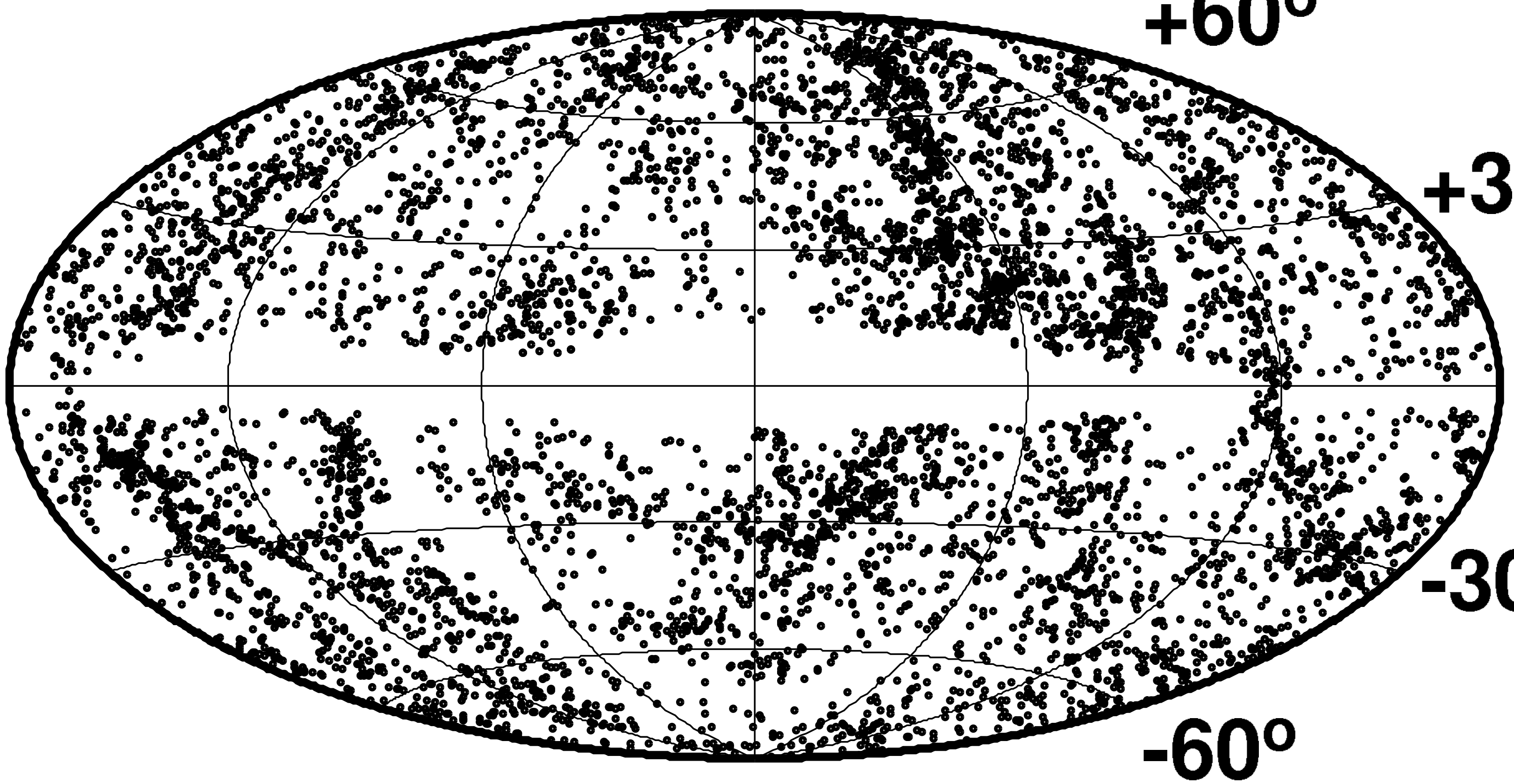
Iron



HT, Inoue, Yamamoto, Aph 35 (2012) 767

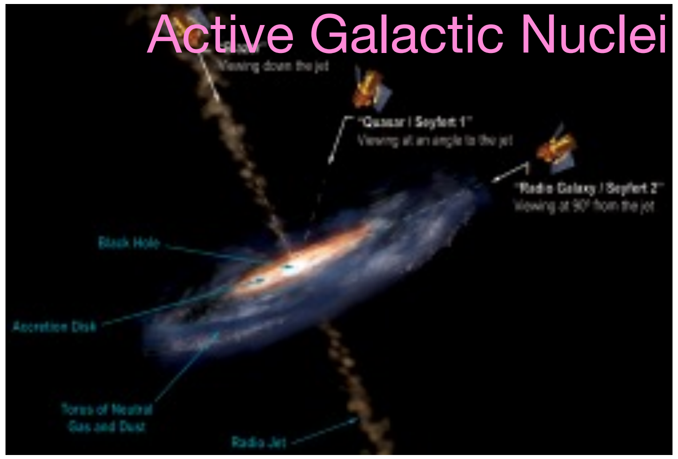
Galaxies in the Local Universe

D < 100 Mpc



Saunders et al., MNRAS 317 (2000) 55

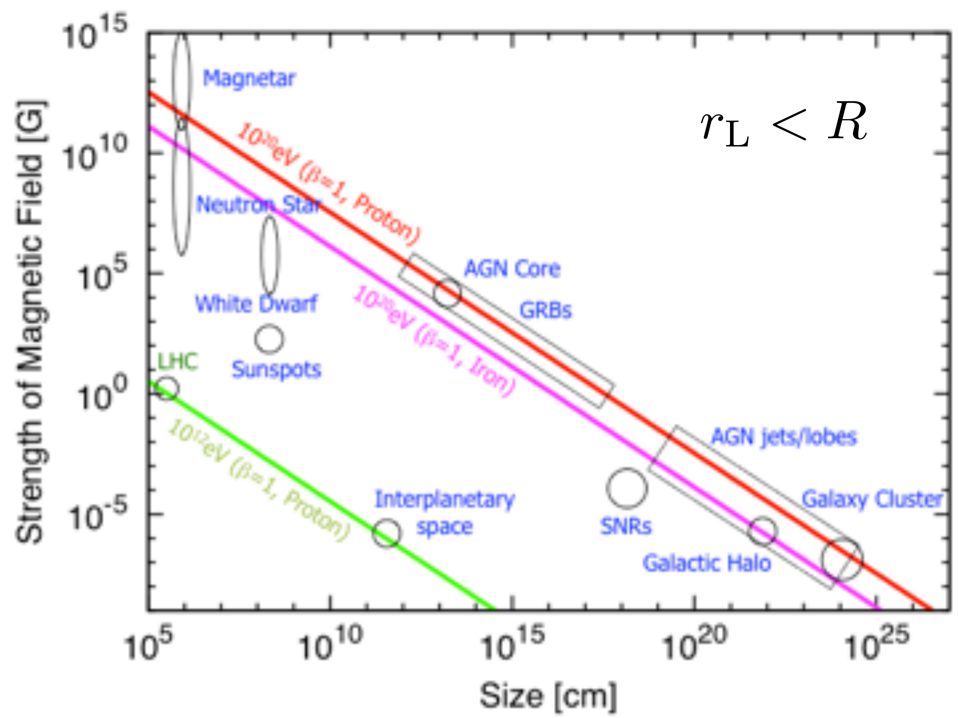
UHECR Source Candidates



e.g., Biermann & Strittmatter, ApJ 322 (1987) 643,
Takahara, PTP 83 (1990) 1071,
Rachen & Biermann, A&A 272 (1993) 161,
Norman et al., ApJ 454 (1995) 60,
Farrar & Gruzinov, ApJ 693 (2009) 329,
Dermer et al., New J. Phys. 11 (2009) 065016
Pe'er et al., PRD 80 (2009) 123018,
HT & Horiuchi, Aph 34 (2011) 749,
Murase, Dermer, HT, Migliori, ApJ 749 (2012) 63

Hillas Criterion

Larmor radius < Source size



JEM-EUSO purple book 2010
edited by HT

e.g., Waxman, PRL 75 (1995) 386,
Vietri, ApJ 453 (1995) 883,
Murase et al., PRD 78 (2008) 023005,
Wang et al., ApJ 677 (2008) 432

e.g., Blasi et al., ApJ 533 (2000) L123,
Arons, ApJ 589 (2003) 871,
Kotera, PRD 84 (2011) 023002,
Fang et al., ApJ 750 (2012) 118

e.g., Norman et al., ApJ 454 (1995) 60,
Kang et al., ApJ 456 (1996) 422,
Inoue et al., astro-ph/0701167

Why do we focus on the highest energies?

- Small deflections in cosmic magnetic fields
- GZK limitation to source candidates in local Universe
- Few theoretical source candidates

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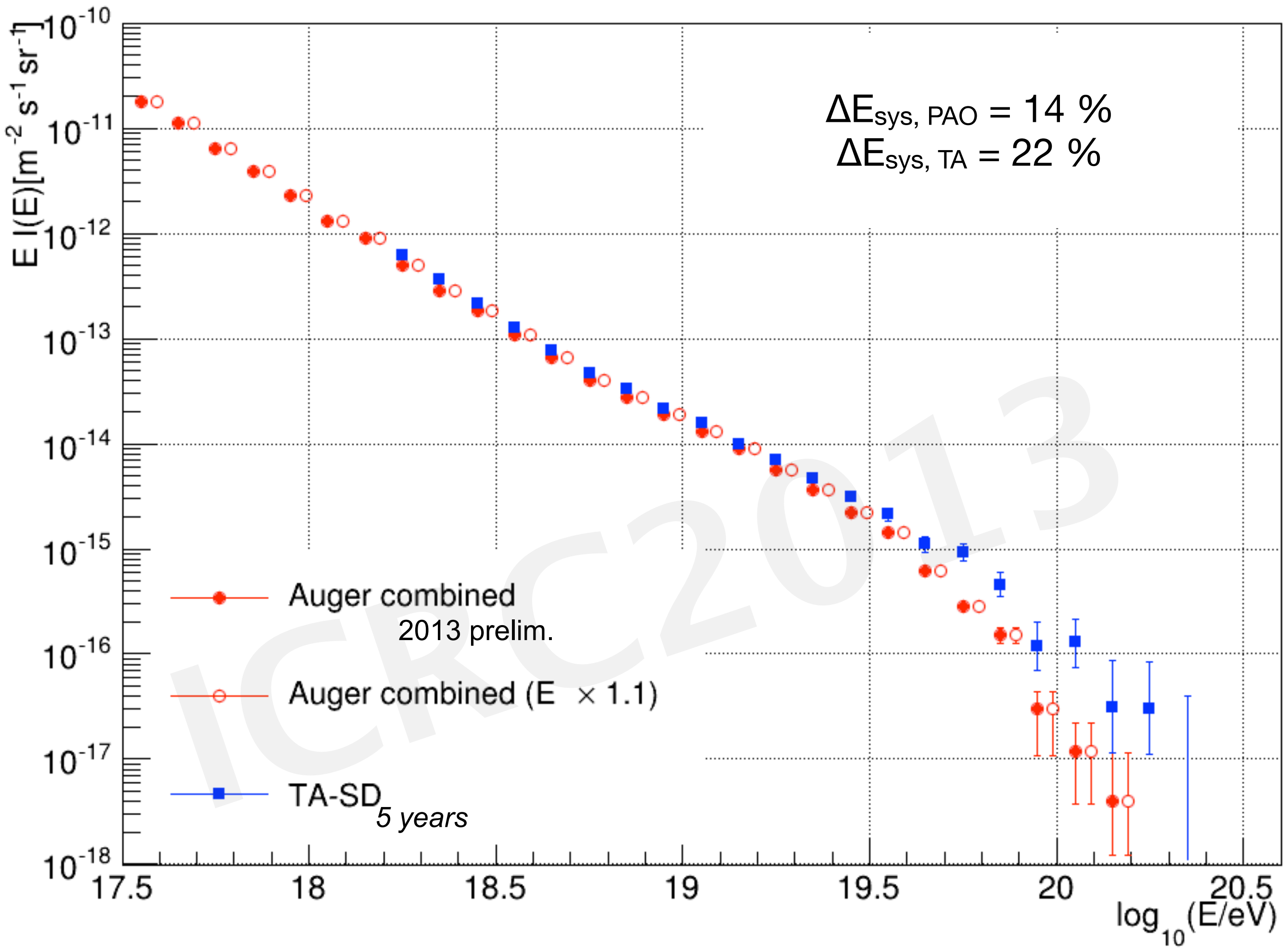
Energy Spectrum

The spectra of Auger and Telescope Array are consistent within systematic errors.

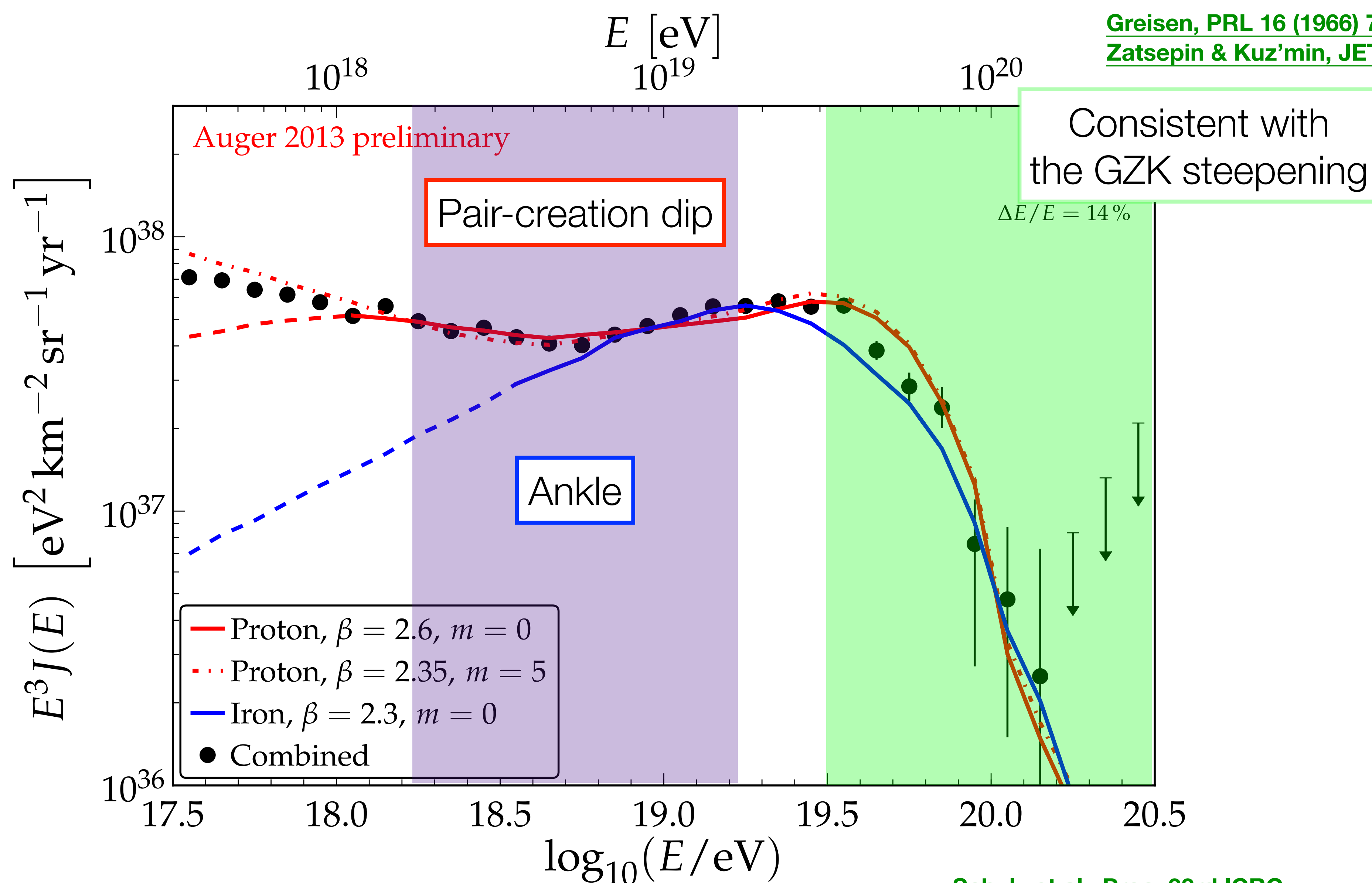


Tsunesada, Rapporteur talk, ICRC 2013

Spectral Modeling

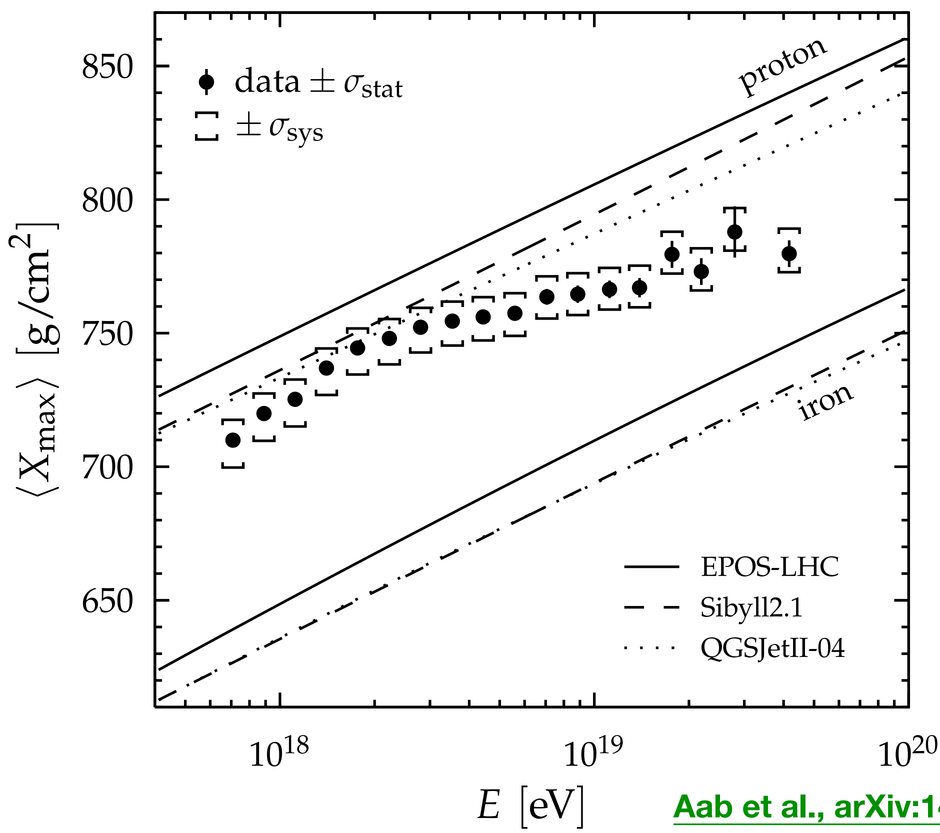
Two interpretations are possible.

Greisen, PRL 16 (1966) 748
Zatsepin & Kuz'min, JETP Lett. 4 (1966) 78

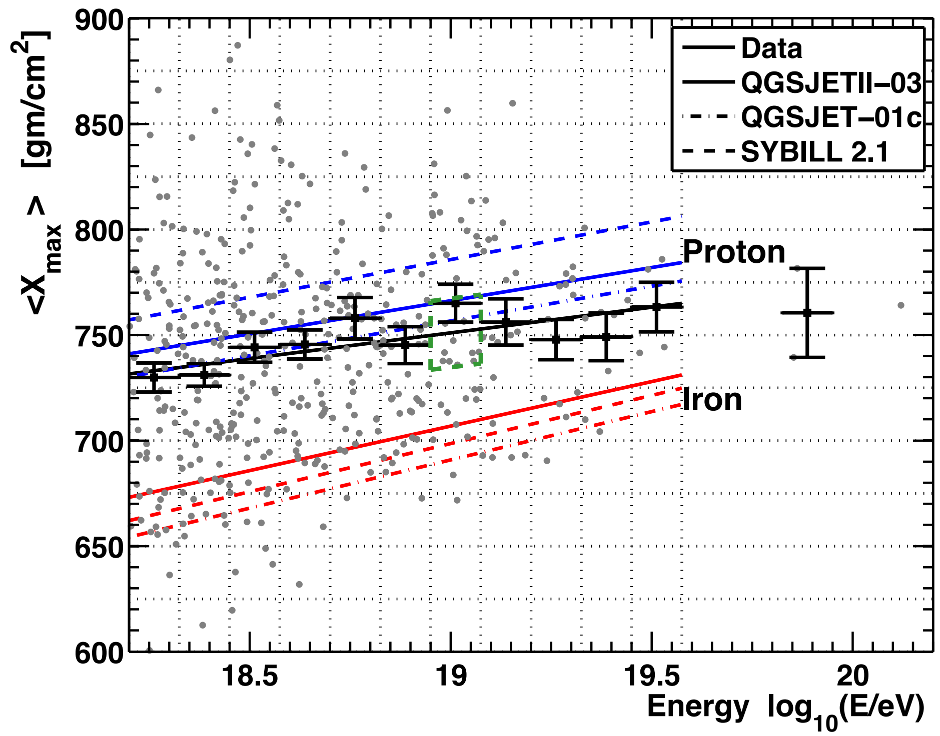


Schulz et al., Proc. 33rd ICRC

Shower Maximum Measurements



Aab et al., arXiv:1409.4809



Abassi et al., arXiv:1408.1726

Auger

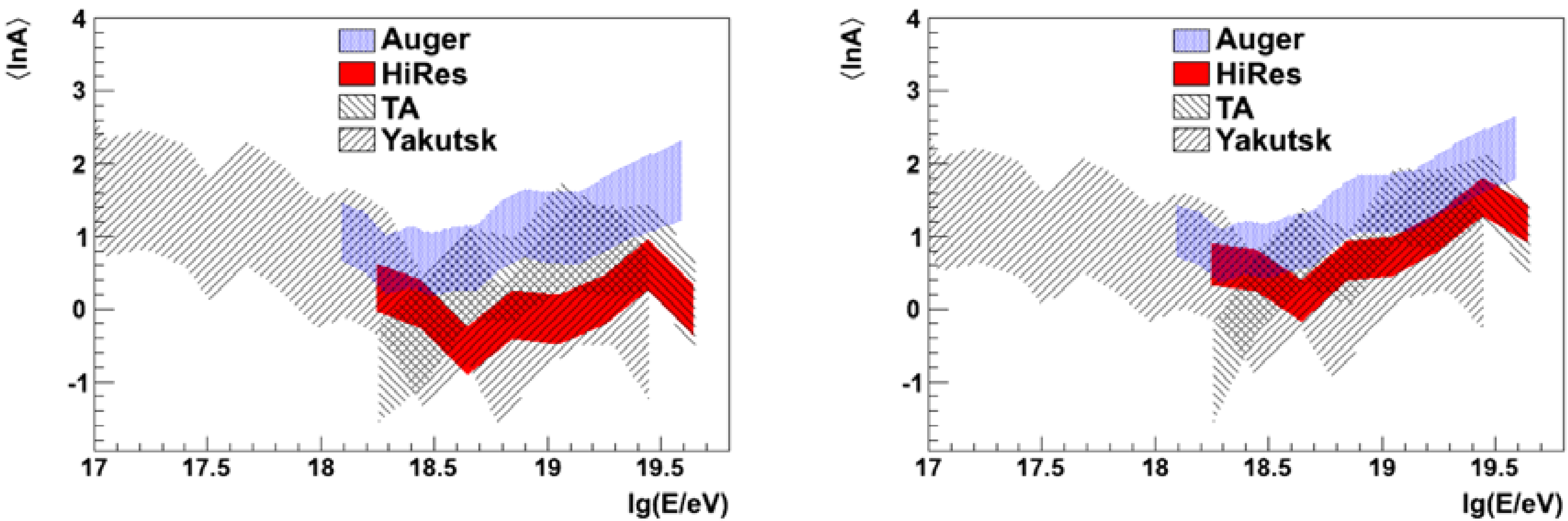
- Gradually changing to heavy nuclei

TA

- Consistent with protons

Comparison between Experiments

Auger and TA are compatible within systematic uncertainties.



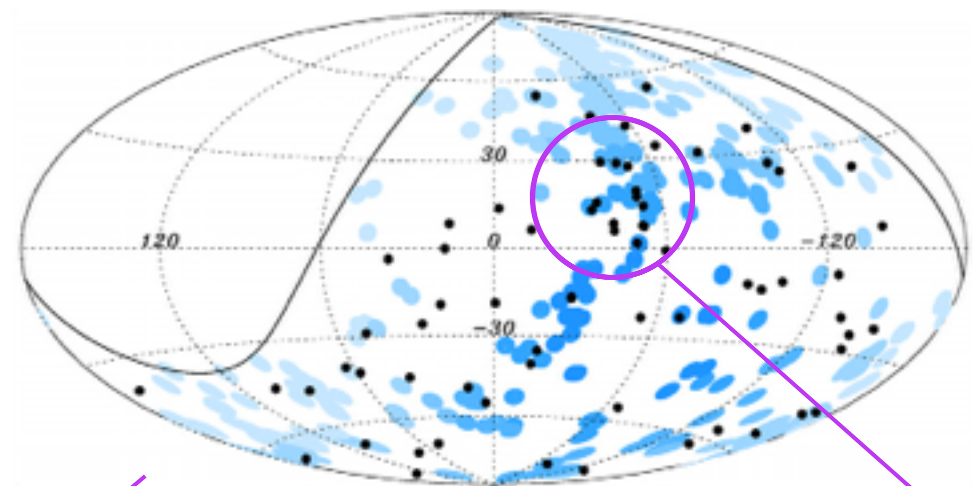
(a) using QGSJet-II model.

(b) using SIBYLL model.

Barcikowski et al., EPJ Web of Conf. 53 (2013) 01006

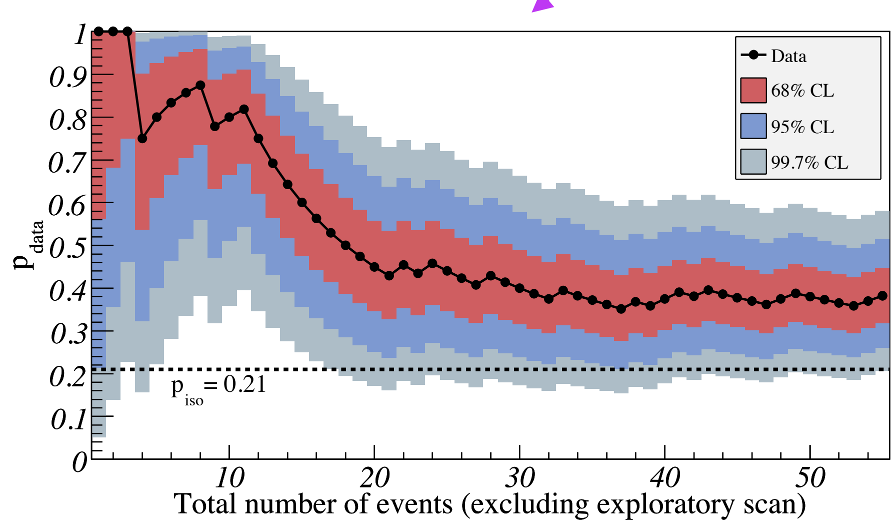
Anisotropy Signals by Auger

E > 5.5 x 10^{19} eV
69 events

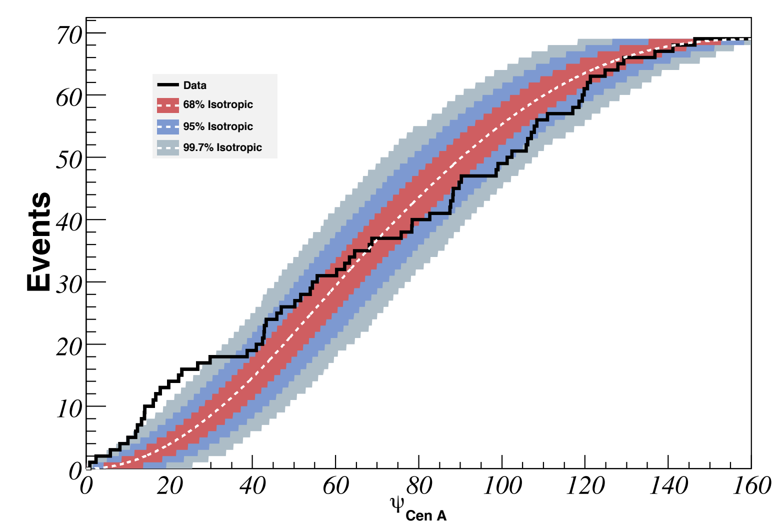


Abreu et al., Aph 34 (2010) 314

AGN correlation



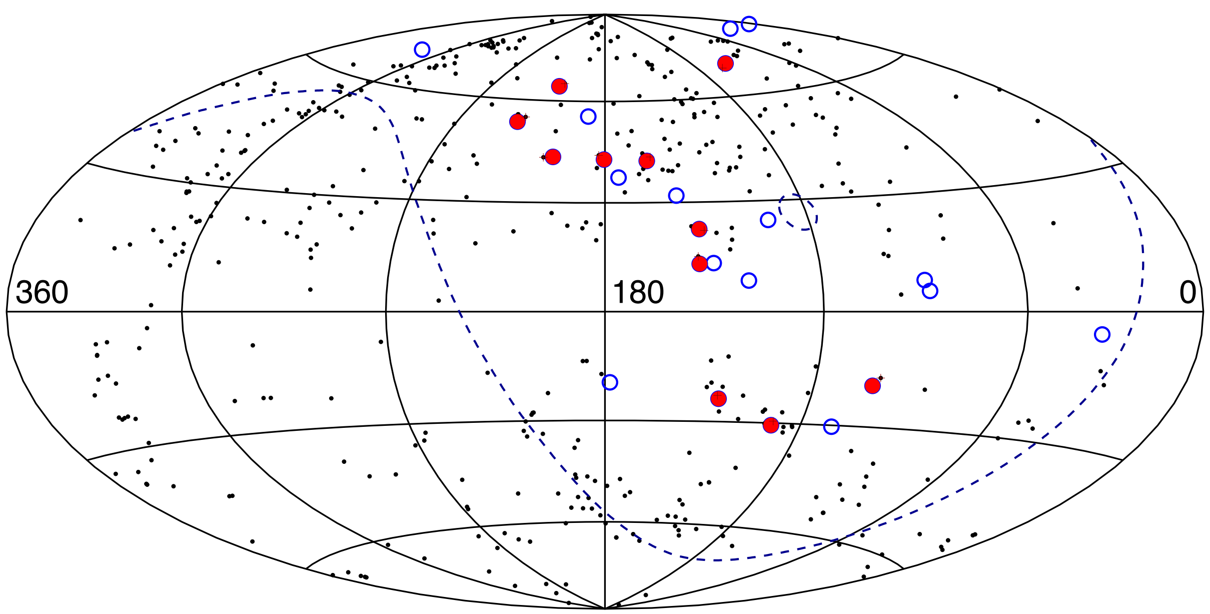
Cen A cluster

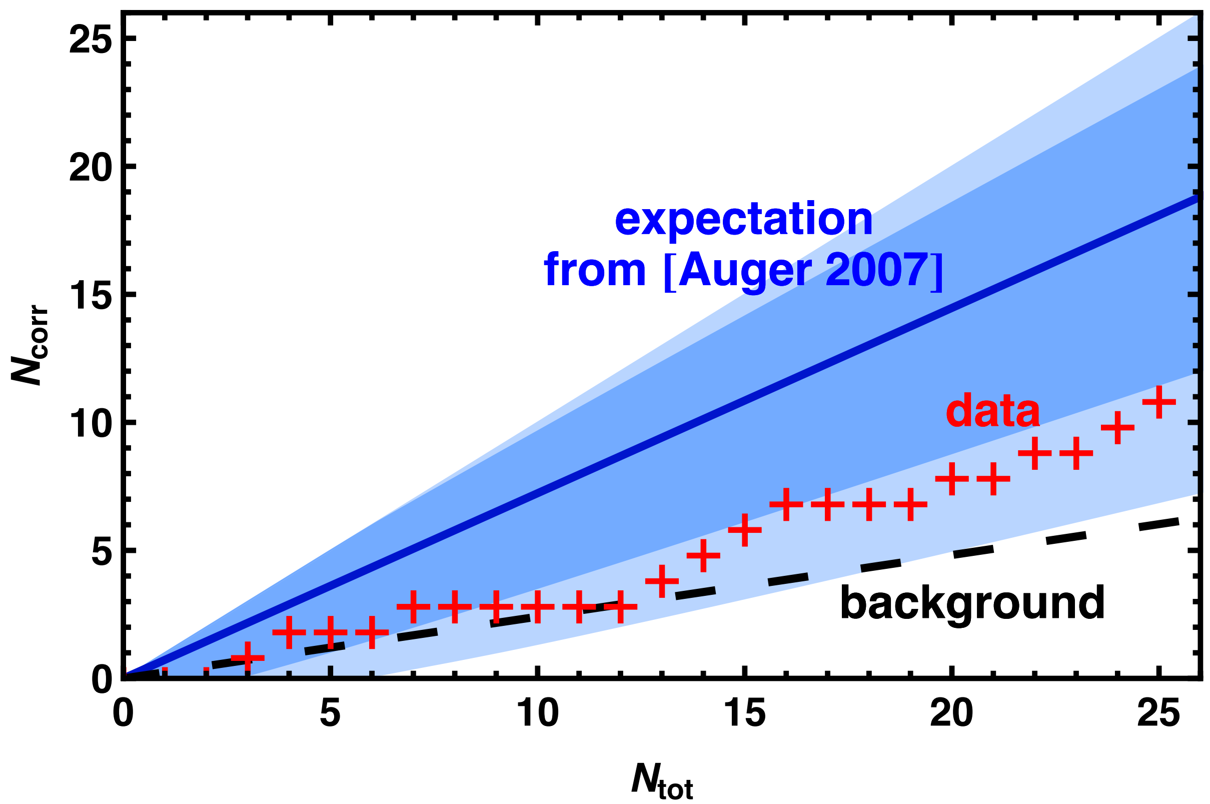


The anisotropy signals are marginal.

Anisotropy Signals by TA

E > 5.7 x 10^{19} eV
25 events

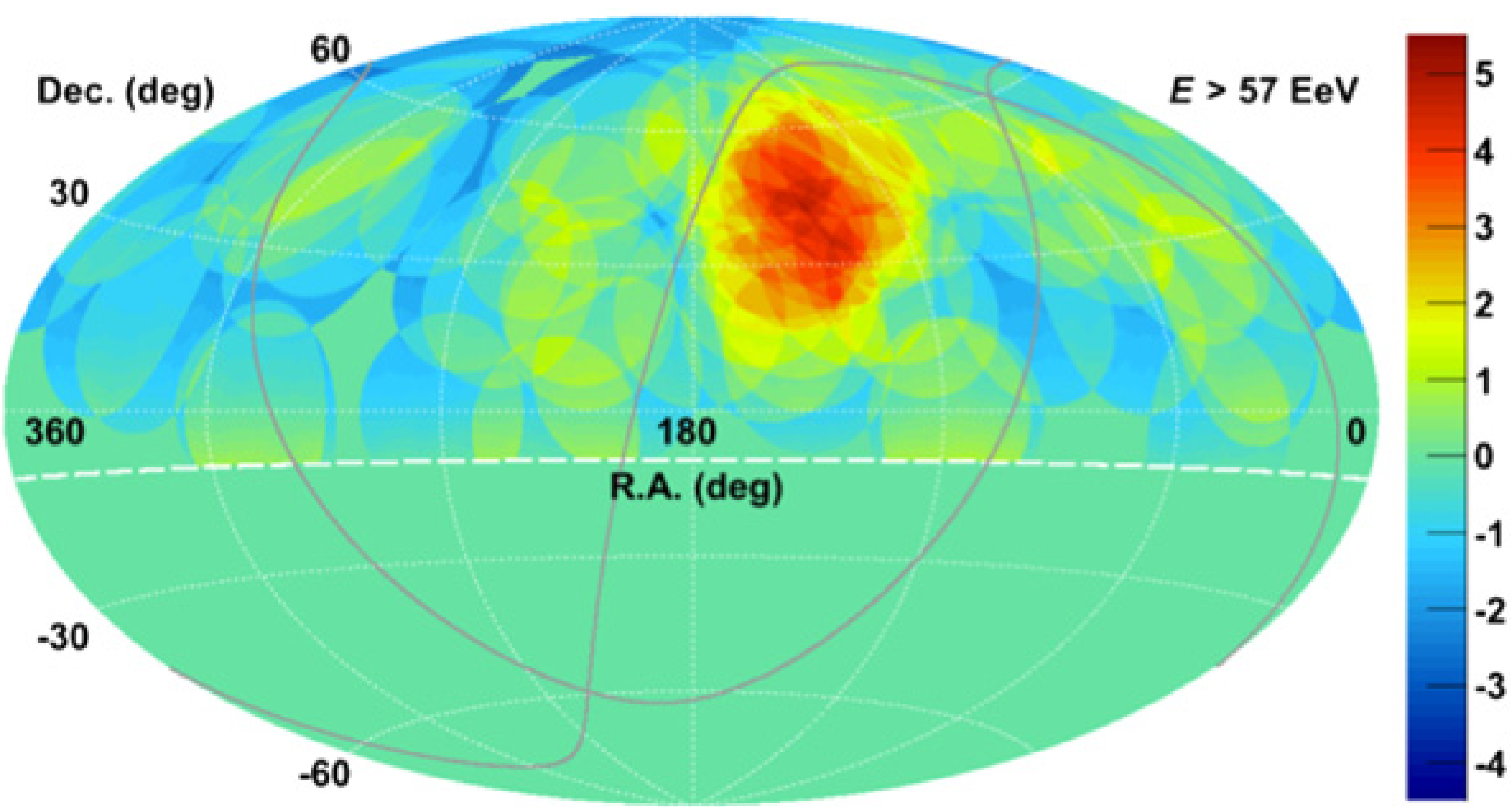




Abu-Zayyad et al., ApJ 757 (2012) 26

Telescope Array Hot Spot

3.4 σ excess using 20° circles



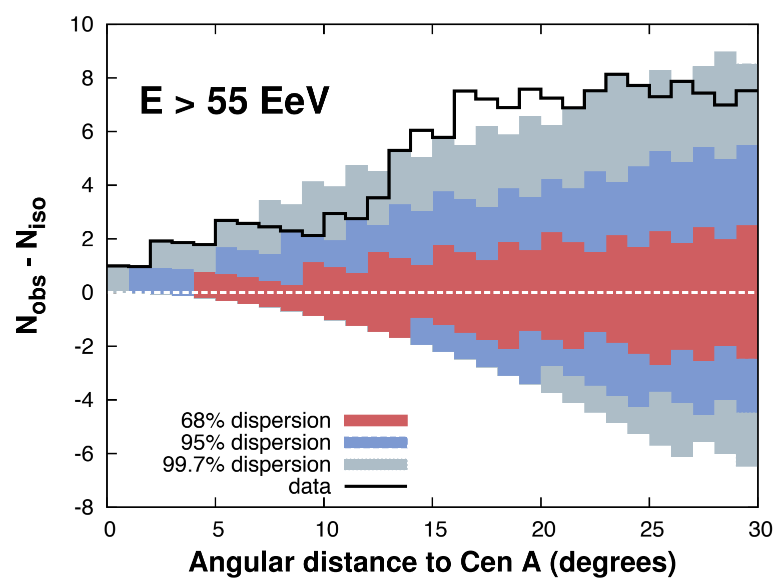
E > 5.5 x 10^{19} eV
72 events
loose-cut

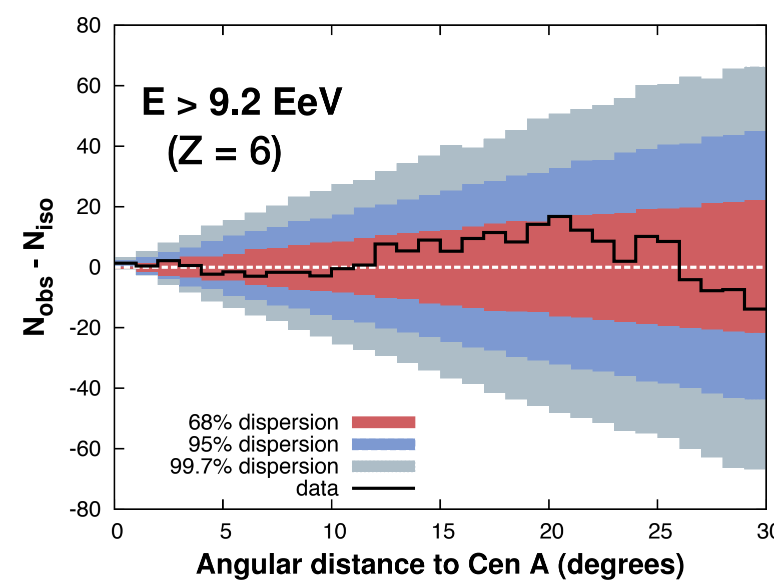
No clear source candidate in this direction

Anisotropy versus Chemical Composition

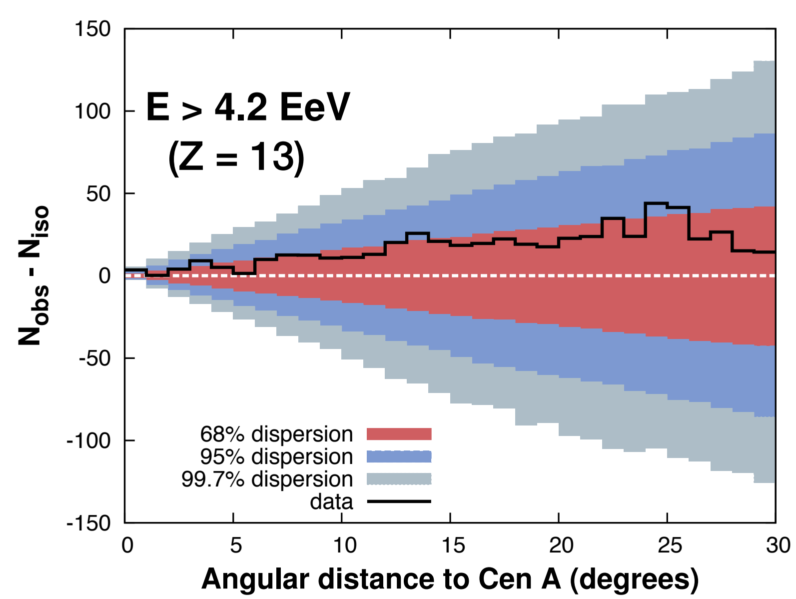
Even stronger anisotropy by protons appears at > E / Z,
if anisotropy produced by nuclei with Z appears at > E.

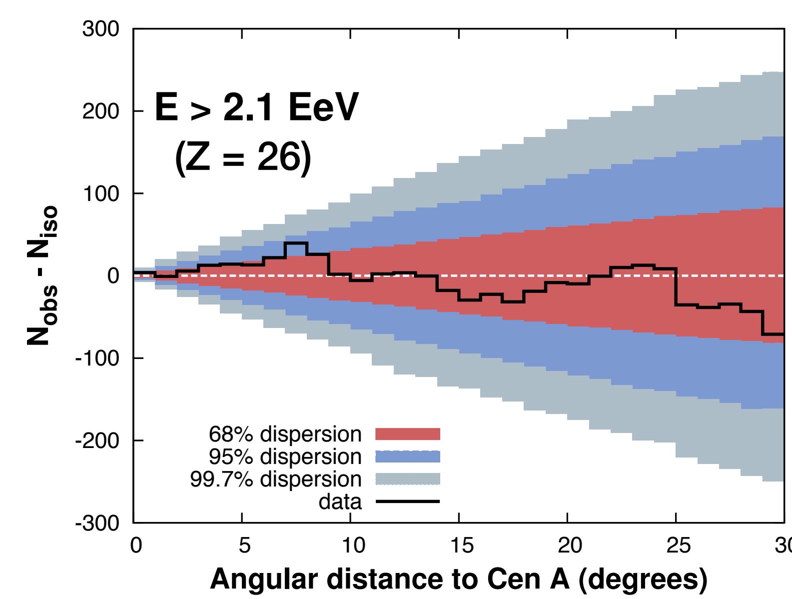
Lemoine & Waxman, JCAP 11 (2009) 009





Abreu et al., JCAP 06 (2011) 022





Possibilities

- Proton-dominated composition at the highest energies

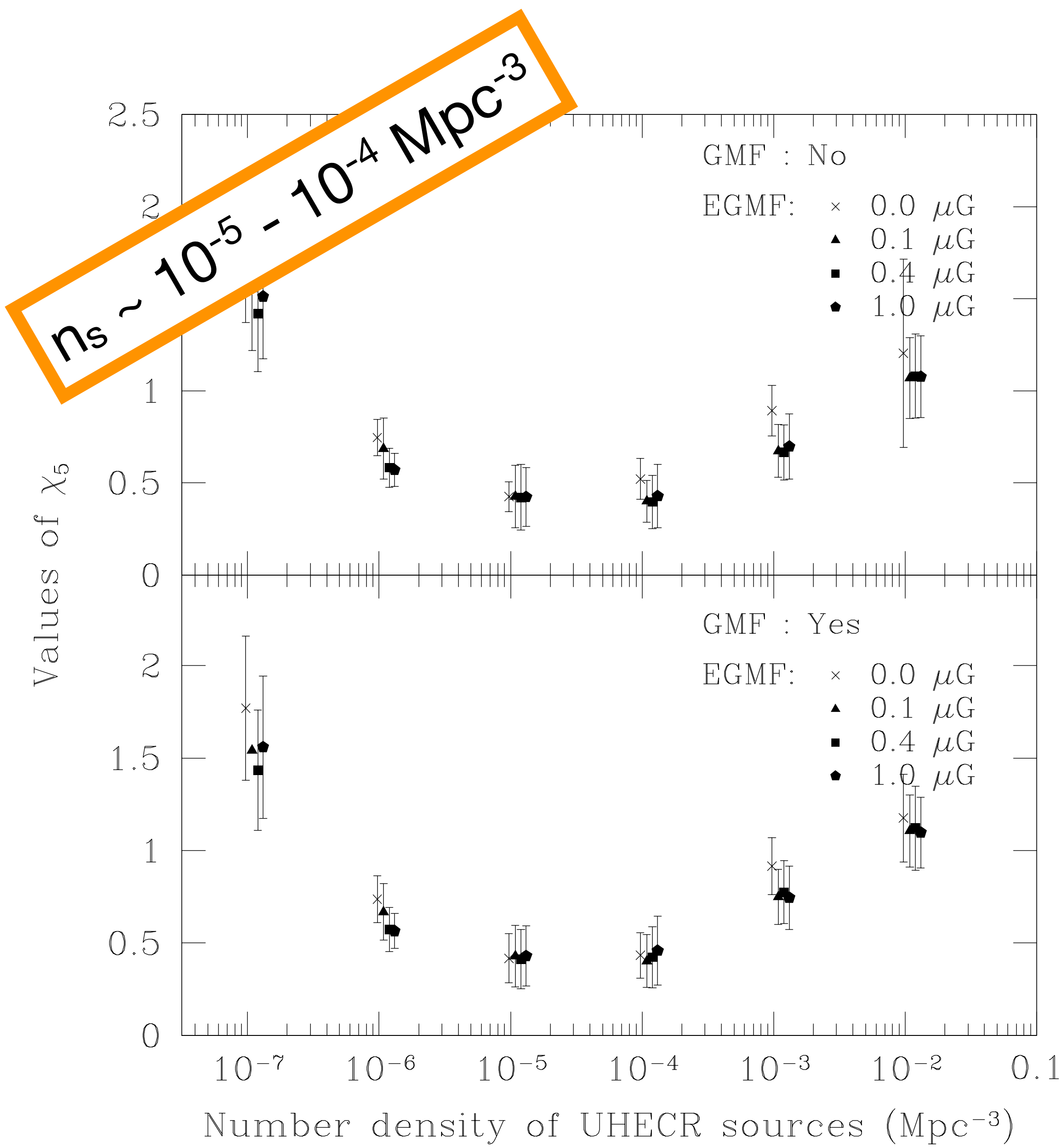
- Heavy-nucleus-dominated in a wide energy range

e.g., Horiuchi et al., ApJ 753 (2013) 69 (GRBs), Fang et al., 03 (2013) 010 (pulsars)

- The anisotropy is a statistical fluctuation.

Source Number Density @ the Highest Energies

Strong candidates are ruled out as main contributors.



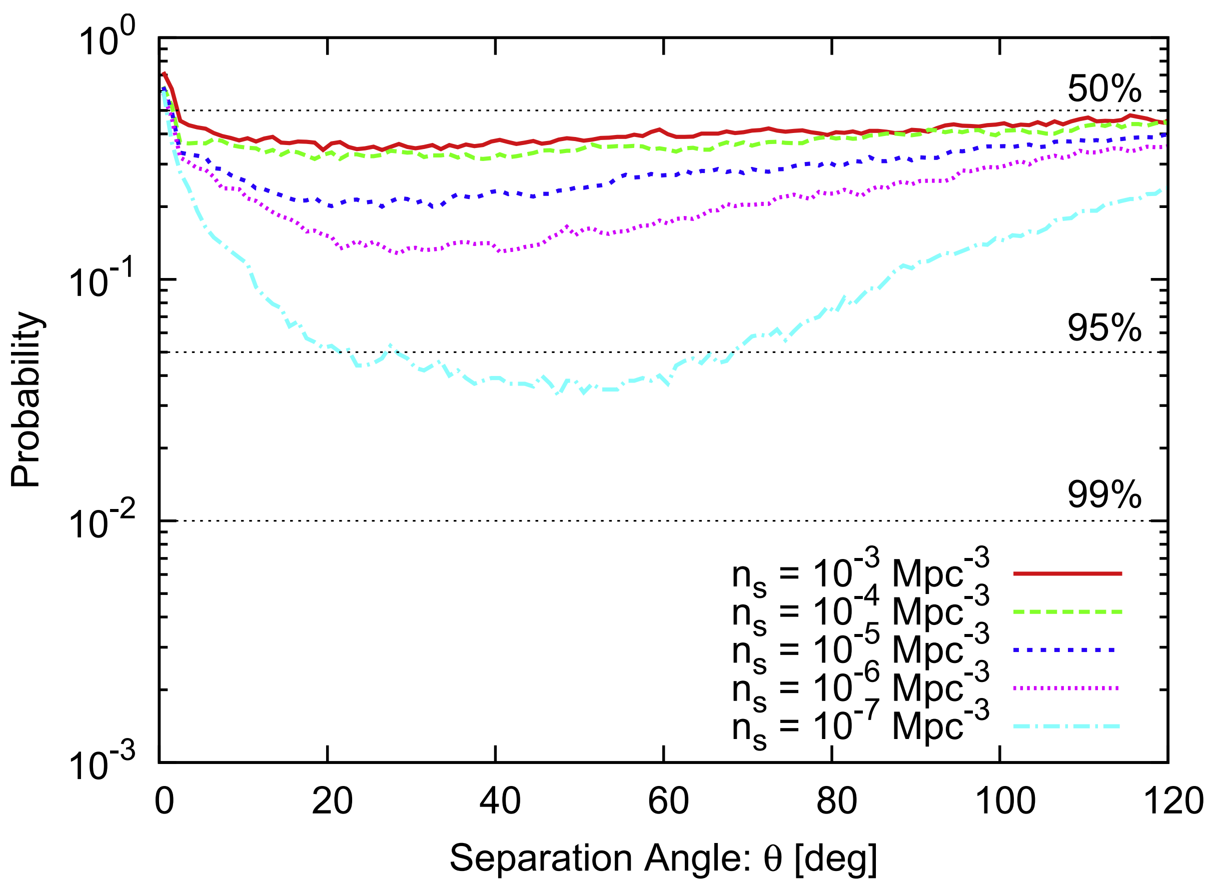
HT & Sato, Aph 30 (2009) 306

See also Cuoco et al., ApJ 702 (2009) 825

- Proton-dominated composition (weak deflection cases)
- Steady sources
- The first Auger public data set

Objects	ns [Mpc
Bright galaxy	1.3 x 10
Seyfert galaxy	1.25 x 10
Dead Quasar	5 x 10
Fanaroff-Riley I	8 x 10
Bright quasar	1.4 x 10
Colliding galaxies	7 x 10
BL Lac objects	3 x 10
Fanaroff-Riley II	3 x 10

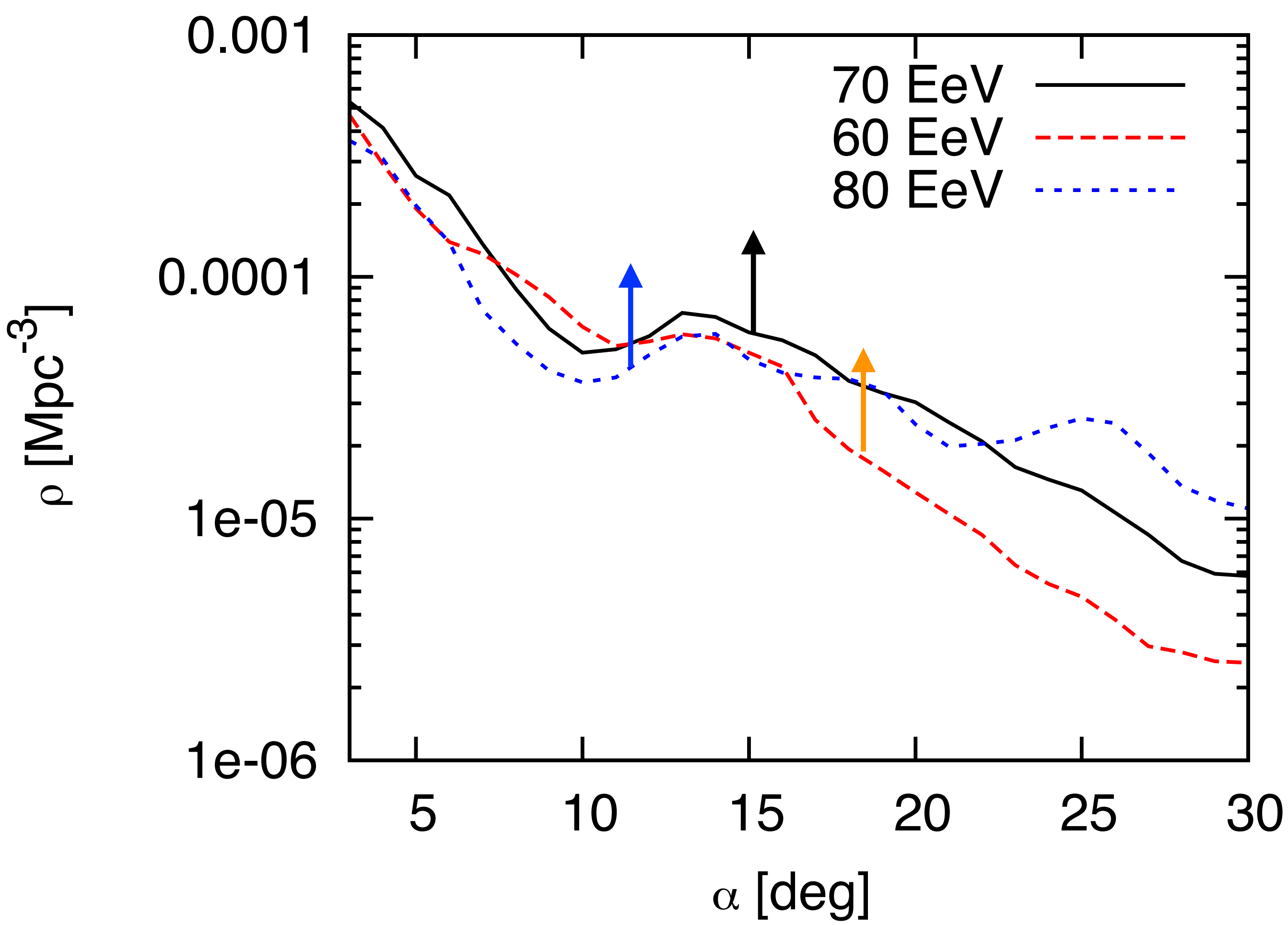
Source Number Density



- Pure-iron case
  (maximal deflection case)
- Steady sources
- The second Auger public data set mocked

HT, Inoue, Yamamoto, Aph 35 (2012) 767

Source Number Density



- Uniform source distribution
- ΔE, Δα fluctuations included
- Available as long as the deflection angle is smaller than α

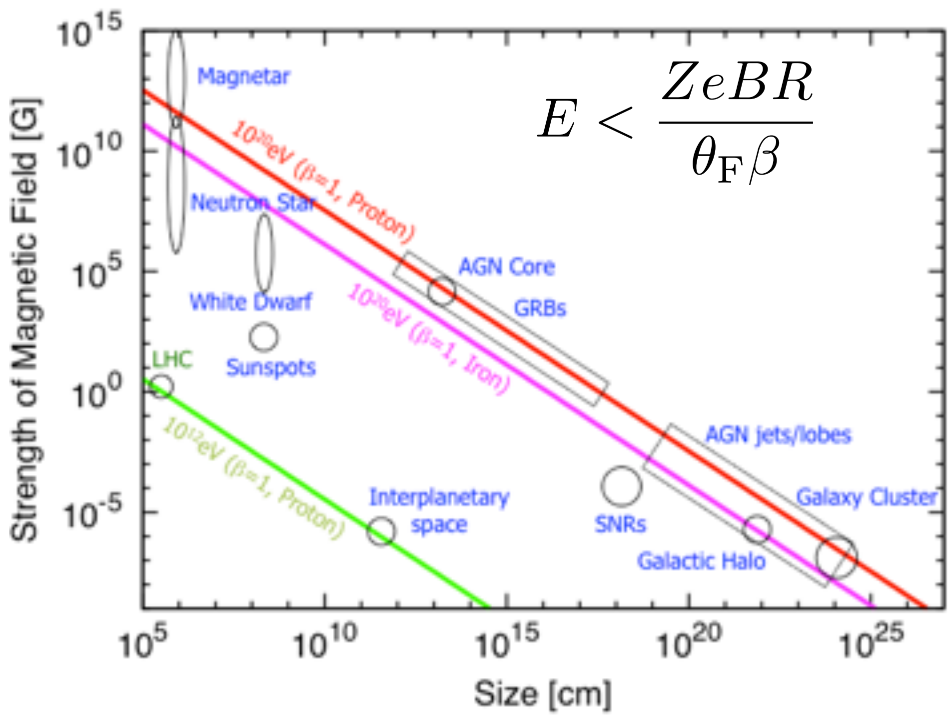
The Pierre Auger Observatory, JCAP, 05 (2013) 009

Luminosity Requirement

$$L_{\rm tot} > 2 \times 10^{45} \, \frac{\theta_{\rm F}^2 \beta^3 \Gamma^2}{Z^2} \left(\frac{E}{10^{20}\ {\rm eV}} \right)^2 \ {\rm erg\ s^{-1}}$$

Norman et al., ApJ 454 (1995) 60
Blandford, Physica Scripta, T85 (2000) 191
Waxman, Pramana 62 (2004) 483

Hillas Condition



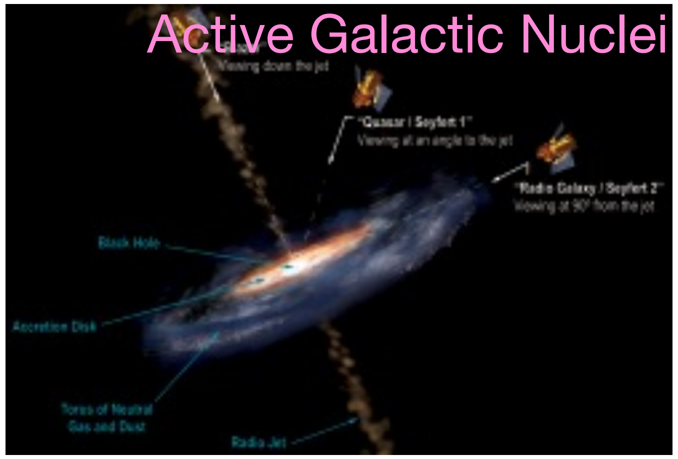
Magnetic Luminosity

$$u_{\rm B} = \frac{L_{\rm B}}{4\pi R^2 \Gamma^2 \beta c}$$

Steady objects with $L_{\rm bol} > 10^{45}$ erg are rare within the GZK radius, namely << 10^{-4} Mpc^{-3}.

e.g., Zaw et al., ApJ 696 (2009) 1218

UHECR Source Candidates



e.g., Biermann & Strittmatter, ApJ 322 (1987) 643,
Takahara, PTP 83 (1990) 1071,
Rachen & Biermann, A&A 272 (1993) 161,
Norman et al., ApJ 454 (1995) 60,
Farrar & Gruzinov, ApJ 693 (2009) 329,
Dermer et al., New J. Phys. 11 (2009) 065016
Pe’er et al., PRD 80 (2009) 123018,
HT & Horiuchi, Aph 34 (2011) 749,
Murase, Dermer, HT, Migliori, ApJ 749 (2012) 63

e.g., Blasi et al., ApJ 533 (2000) L123,
Arons, ApJ 589 (2003) 871,
Kotera, PRD 84 (2011) 023002,
Fang et al., ApJ 750 (2012) 118

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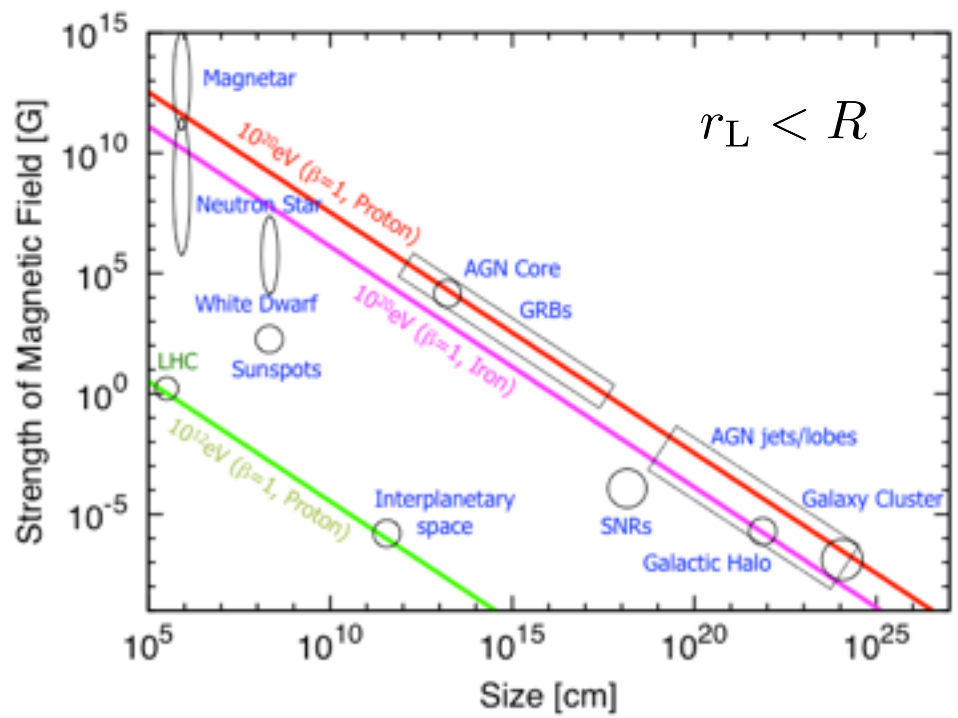

JEM-EUSO purple book 2010
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e.g., Waxman, PRL 75 (1995) 386,
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Murase et al., PRD 78 (2008) 023005,
Wang et al., ApJ 677 (2008) 432

e.g., Norman et al., ApJ 454 (1995) 60,
Kang et al., ApJ 456 (1996) 422,
Inoue et al., astro-ph/0701167

Summary on Current Status

Spectrum

GZK steepening + dip/ankle are established.

Composition

	Anisotropy	**Interaction model**
Composition at the highest E	Proton-dominated	Heavy nuclei
Anisotropy	Protons	Statistical error
Galactic-to-Xgal transition	Proton-dip (p-) ankle transition	Ankle transition
etc.	Interaction models may be modified.	

※ Compromised scenario: heavy in a wide range + very weak magnetic fields

Summary on Current Status

Source properties

- Steady sources
  - proton-dominated $\gtrsim 10^{-4}$ Mpc^{-3}
  - heavy-nucleus-dominated $\gtrsim 10^{-6}$ Mpc^{-3}

- If proton-dominated composition,
  - the luminosity requirement → transient for jet-sources
  - Strong evolution is ruled out by neutrinos.

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What is the Next Step?

How / why are particles accelerated up to such extreme high energies?

↑

Where are particles accelerated up to such extreme high energies?

↑

What is the nature of UHECR sources?

to establish strategies to unveil the sources

Source Classification

Proton / Steady

Proton / Transient

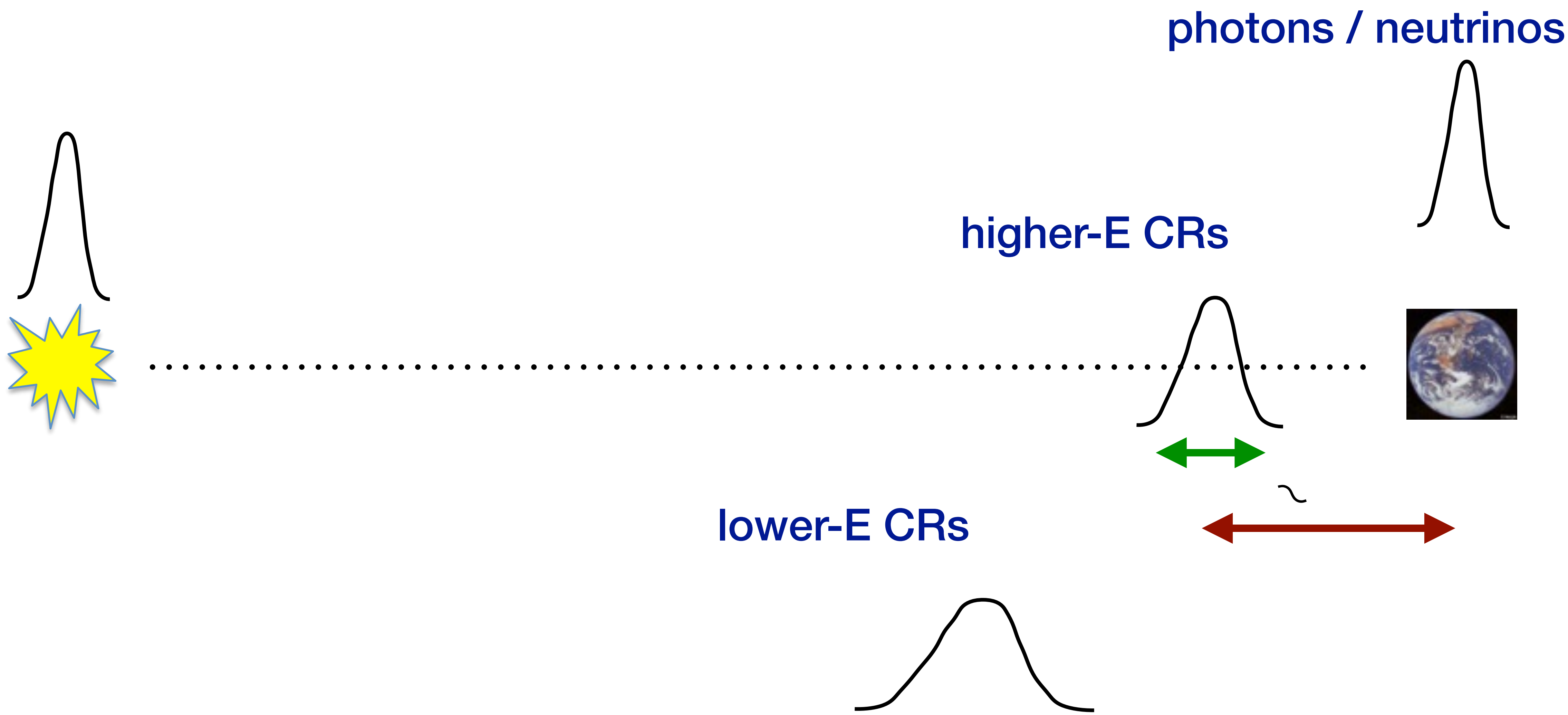
Heavy / Steady

Heavy / Transient

Transient Sources

Time-delay and time-profile dispersion

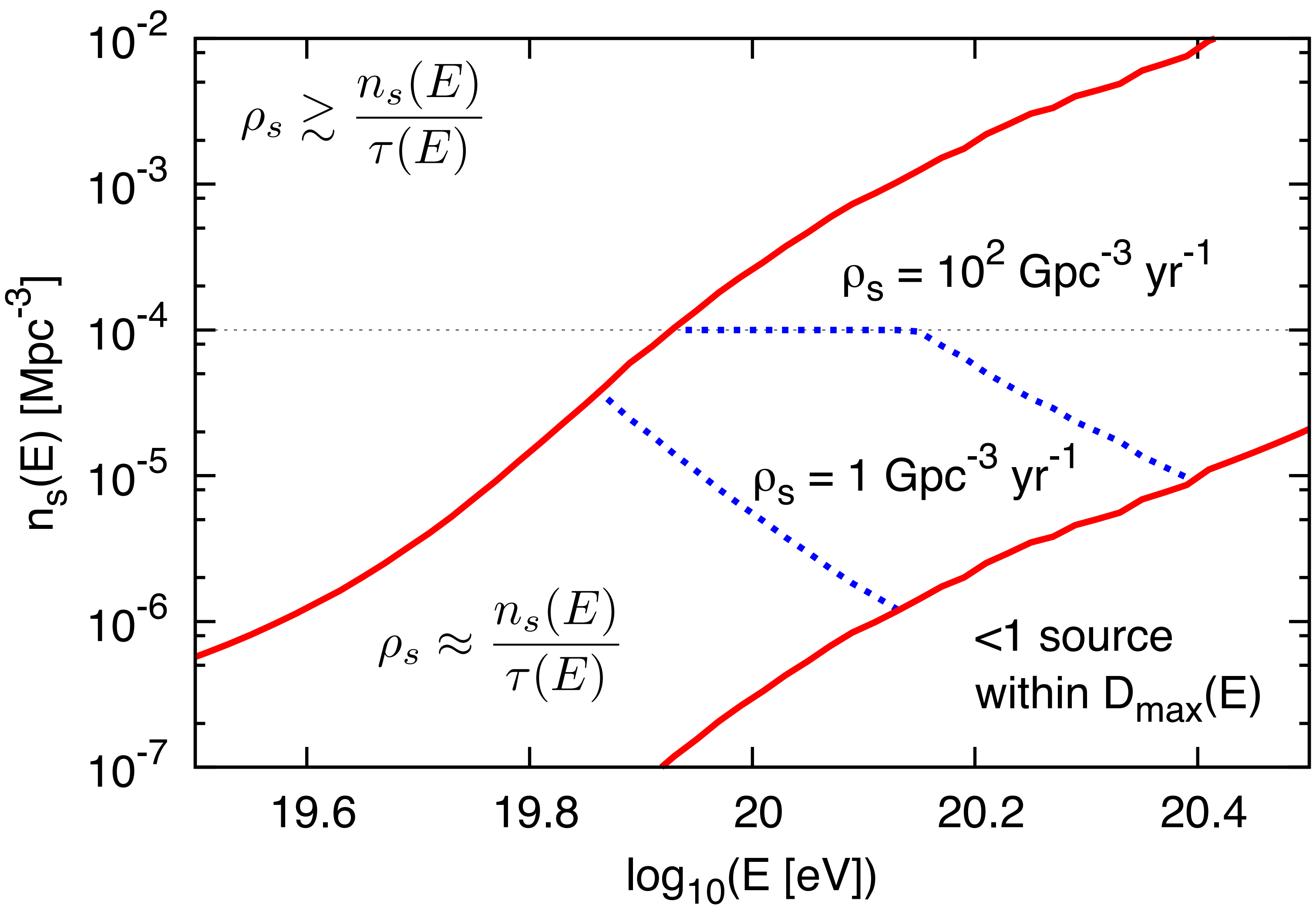
$$t_d(E,D) \simeq 1.5 \times 10^5 Z^2 \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-2} \left(\frac{D}{100\ \mathrm{Mpc}}\right)^2 \left(\frac{B}{1\ \mathrm{nG}}\right)^2 \left(\frac{\lambda}{1\ \mathrm{Mpc}}\right)\ \ \mathrm{yr}$$



More sources are observed at lower energy that at higher energy.

Evidence for Transient Sources

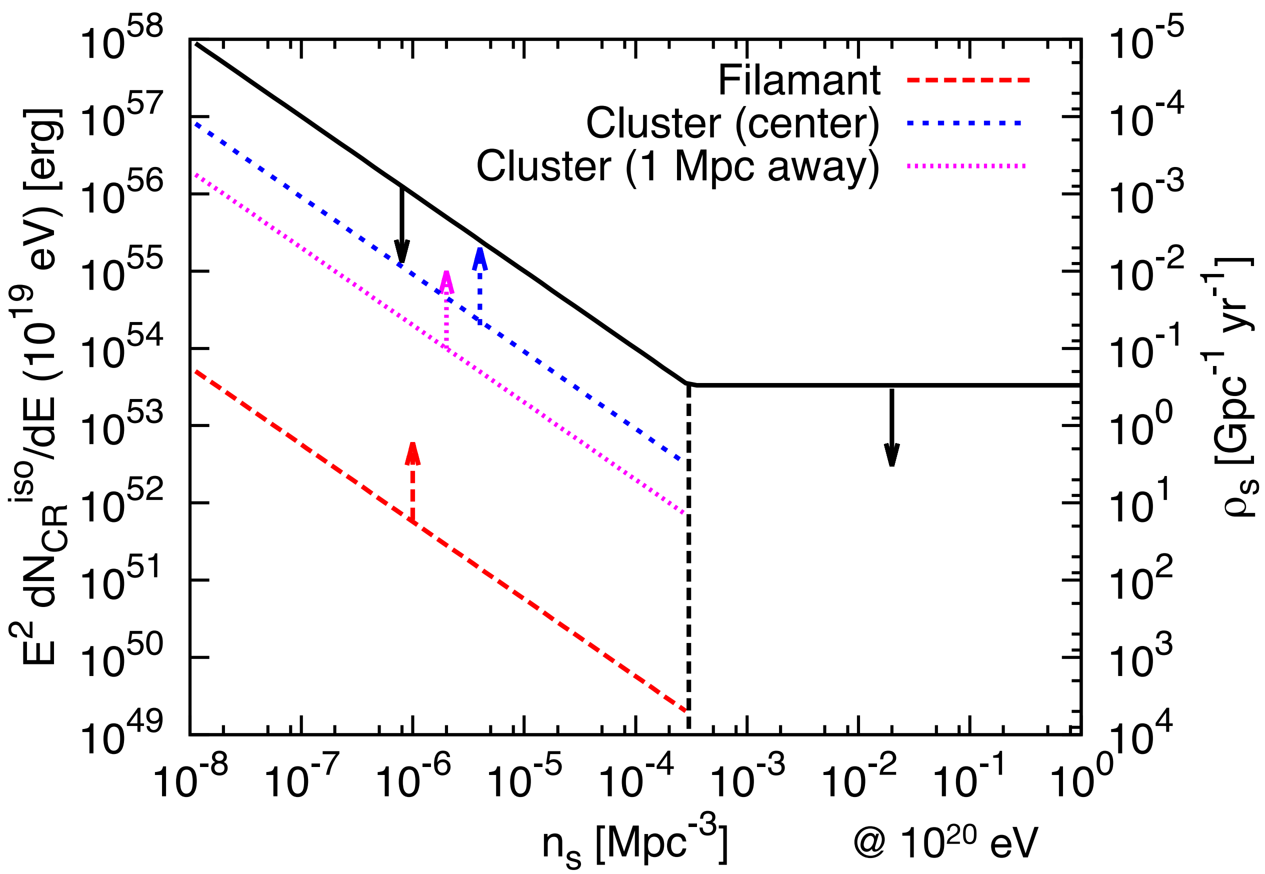
Strong energy dependence of apparent source number density



HT & Murase, ApJ 748 (2012) 9

Constraints on ρs and Energy Budget

$$\rho_s \approx \frac{n_s(E)}{\tau(E)} \quad \Rightarrow \quad \frac{n_s(E)}{\tau_{\max}(E)} \lesssim \rho_s \lesssim \frac{n_s(E)}{\tau_{\min}(E)}$$



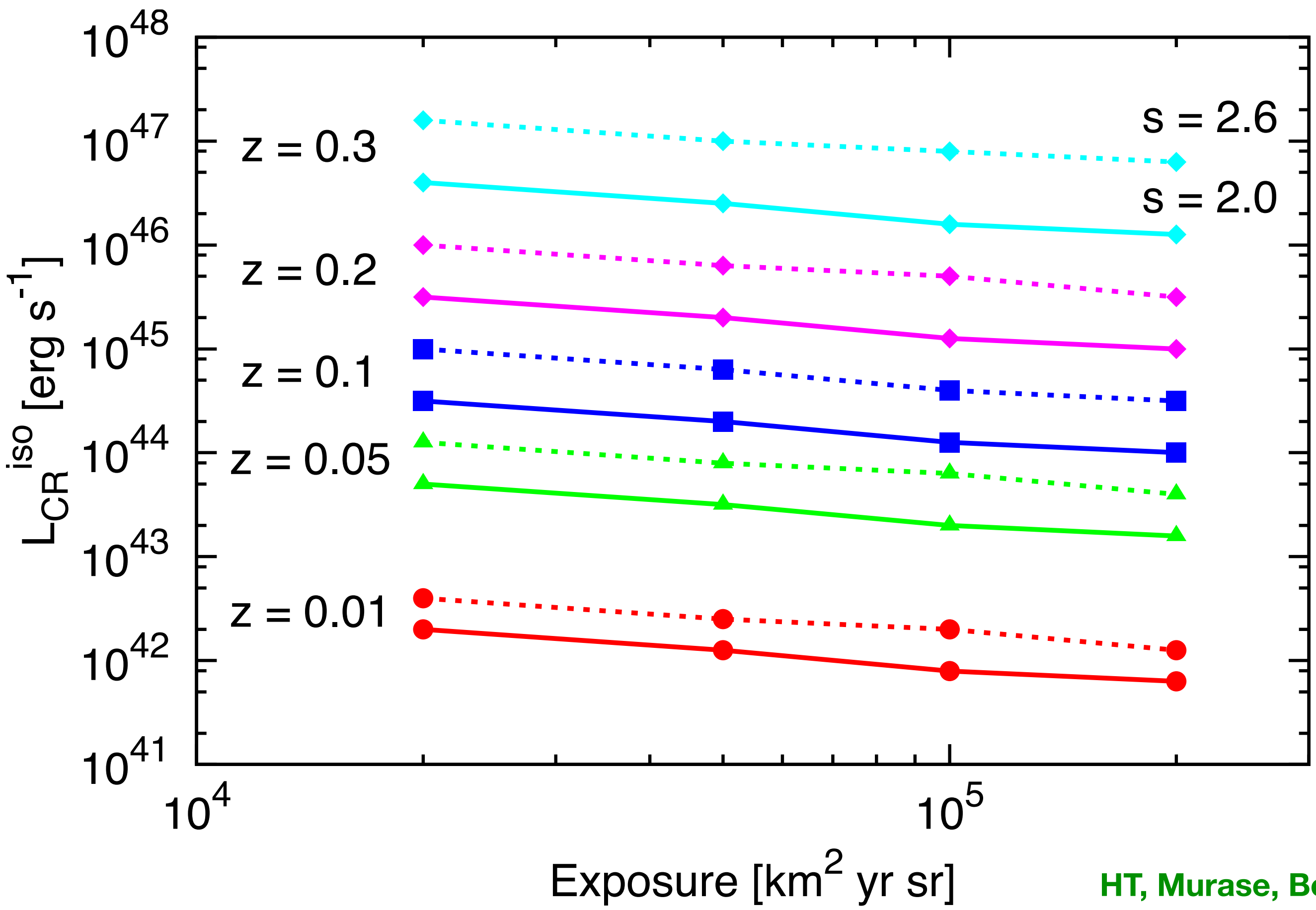
- $\tau_{\min}$: GMF, EGMF surrounding sources
- $\tau_{\max}$: GMF, EGMF surrounding sources, IGMF

Source	Typical Rate ρ_0 (Gpc^{-3} yr^{-1})
HL GRB	~0.1
LL GRB	~400
Hypernovae	~2000
Magnetar	~12000
Giant Magnetar Flare	~10000
Giant AGN Flare	~1000
SNe Ibc	~20000
Core Collapse SNe	120000

HT & Murase, ApJ 748 (2012) 9

Evidence for Transient Sources?

The lower energy (~10^{19} eV) anisotropy indicates transient sources.



Lower energy (~10^{19} eV)

$$n_s > 3 \times 10^{-3} \left(\frac{L_{\rm CR}^{\rm ul,19}(z = 0.01)}{10^{41}\ {\rm erg\ s^{-1}}} \right)^{-3} \quad {\rm Mpc}^{-3}$$

Higher energy (~6 x 10^{19} eV)

$$n_s \sim 10^{-4}\ {\rm Mpc}^{-3}$$

HT, Murase, Beacom, Dermer, to be submitted.

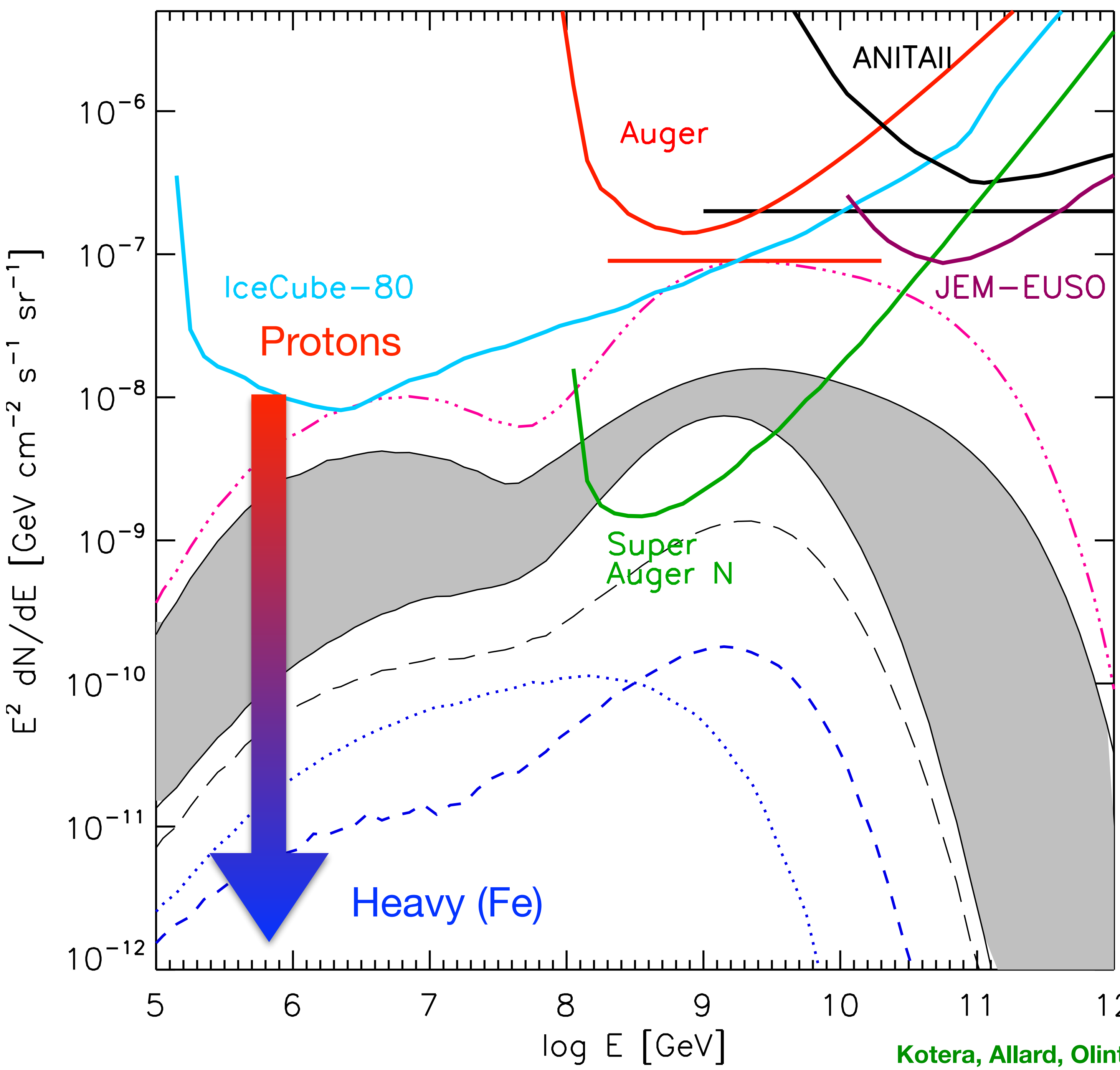
$$\frac{n_s(E_{\rm l})}{n_s(E_{\rm h})} \sim \frac{t_{\rm d}(E_{\rm l})}{t_{\rm d}(E_{\rm h})} \sim \left(\frac{E_{\rm l}}{E_{\rm h}} \right)^{-2} \sim 40$$

See also HT & Sato (2009)

What Can We Do for Composition?

- $\sqrt{s_{\rm pp}} = 433 \ \mathrm{TeV}$ collider required
- Anisotropy measurements
- Cosmogenic neutrinos

Cosmogenic Neutrinos ~ Composition ~

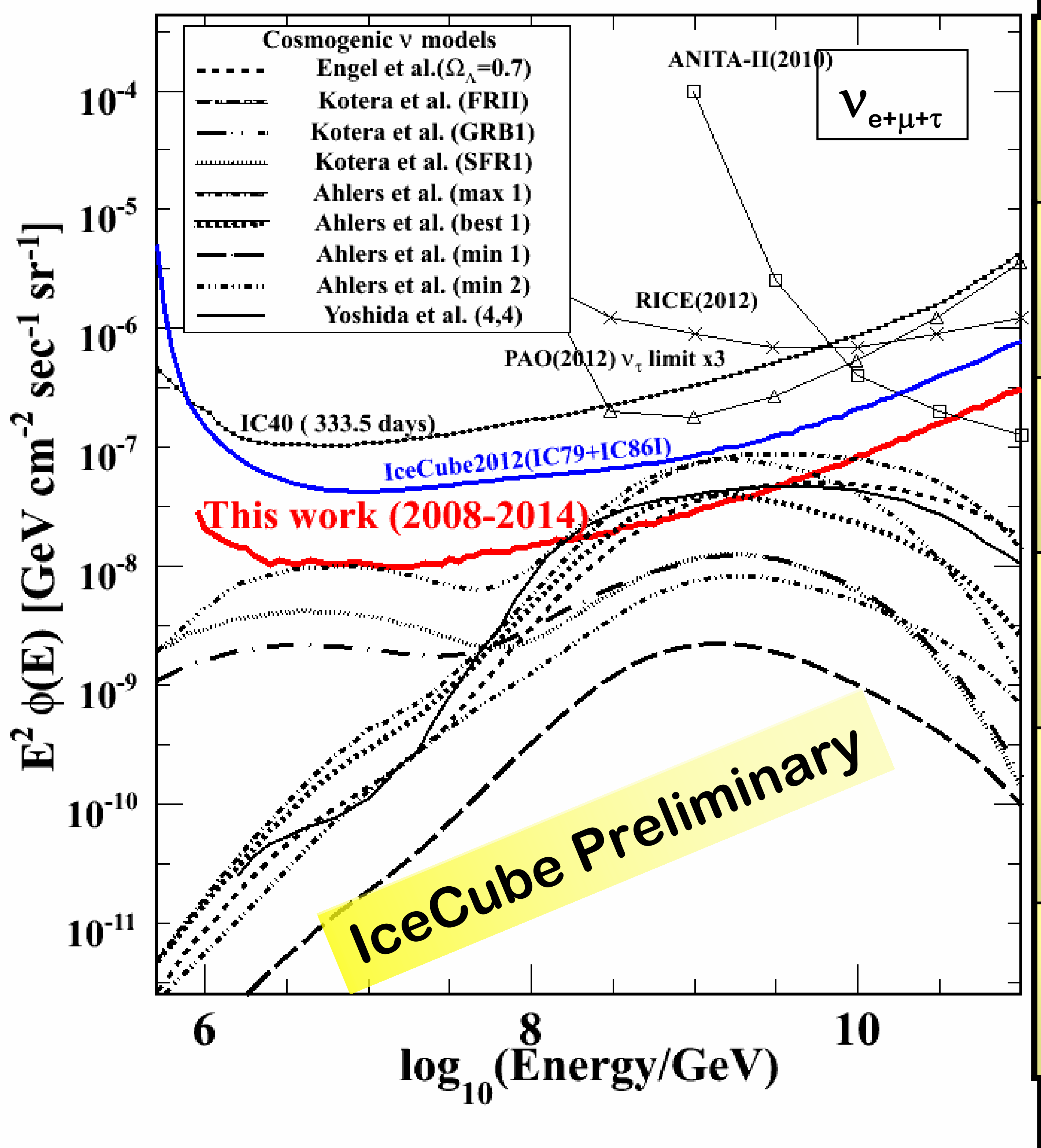


Kotera, Allard, Olinto, JCAP 10 (2010) 013

TeV PeV EeV

UHE (PeV-EeV)

IceCube 6 years data (2008-2014) all combined



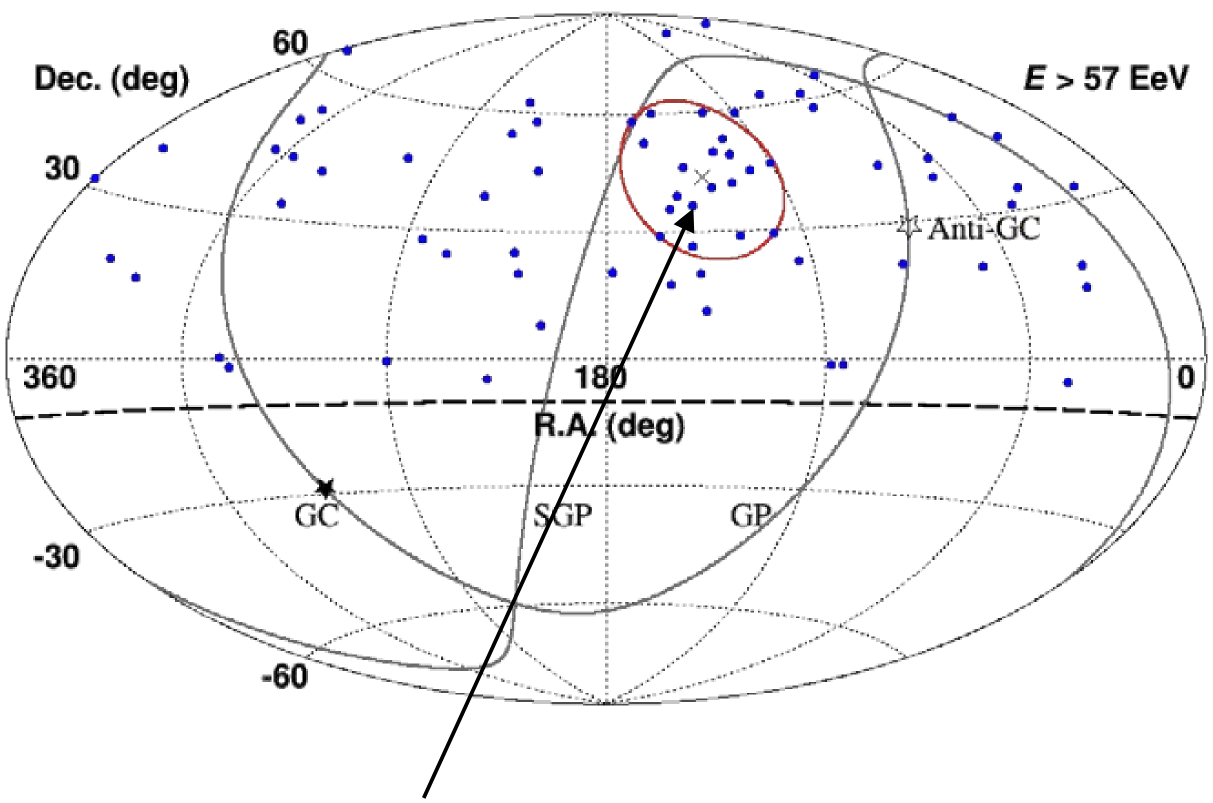
Model	Event Rate [/(2008-20014)]
Yoshida (FR-II compat.)	6.5
Ahlers (Best fit to HiRes)	5.0
Ahlers (Minimum)	1.1
Kotera (GRB)	3.9
Kotera (STF)	2.9

S. Yoshida, JPS meeting, 2014

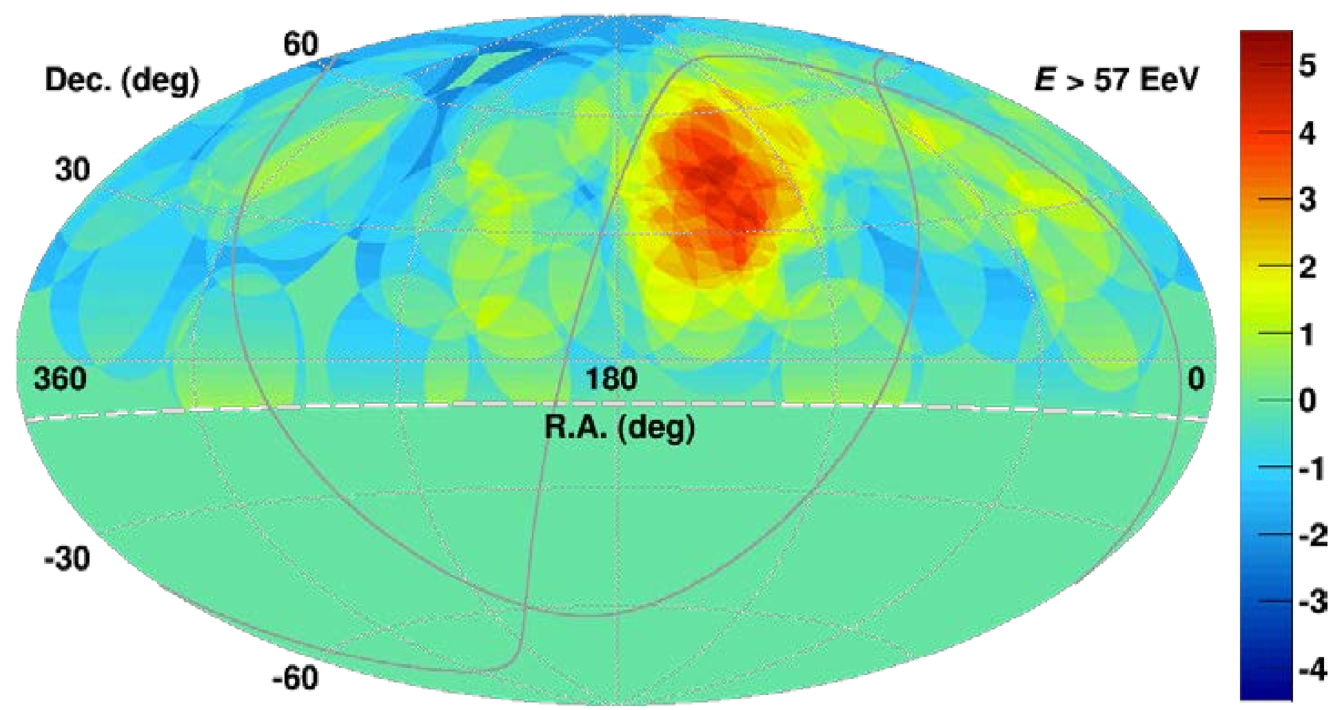
Hotspot
最高エネルギー宇宙線の異方性

5年のデータ

データを20度の半径の円でoversampling



Significance map



- 最大のsignificance
  - 方向：R.A. = 146.7°, Dec. = 43.2°
  - 観測数：19　(19/72=26%)
  - 等方的分布の期待値：4.5 (4.5/72=6%)
  - Li-Ma significance: 5.1σ
- 等方的な分布の場合に5.1σ以上の有意度を得る偶然の確率：3.7×10^{-4} (3.4σ)
  - MC：15, 20, 25, 30, 35度の半径の円

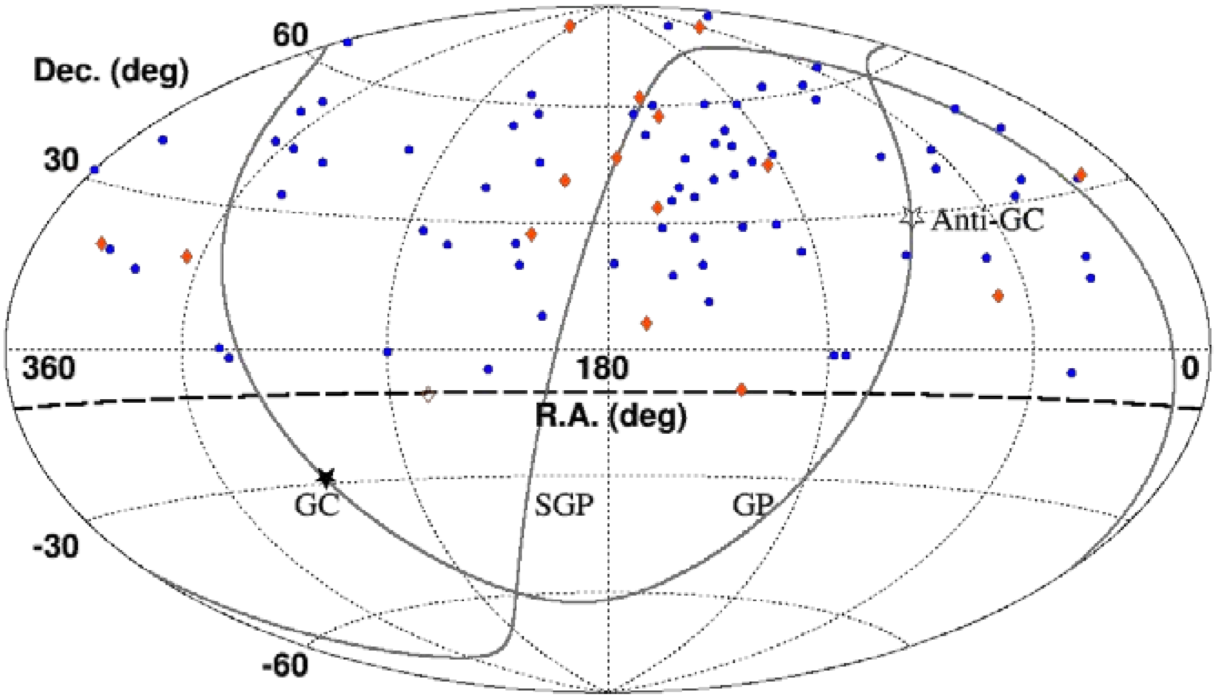
ApJ 790, L21 (2014)

D.Bergman
COSPAR 2014

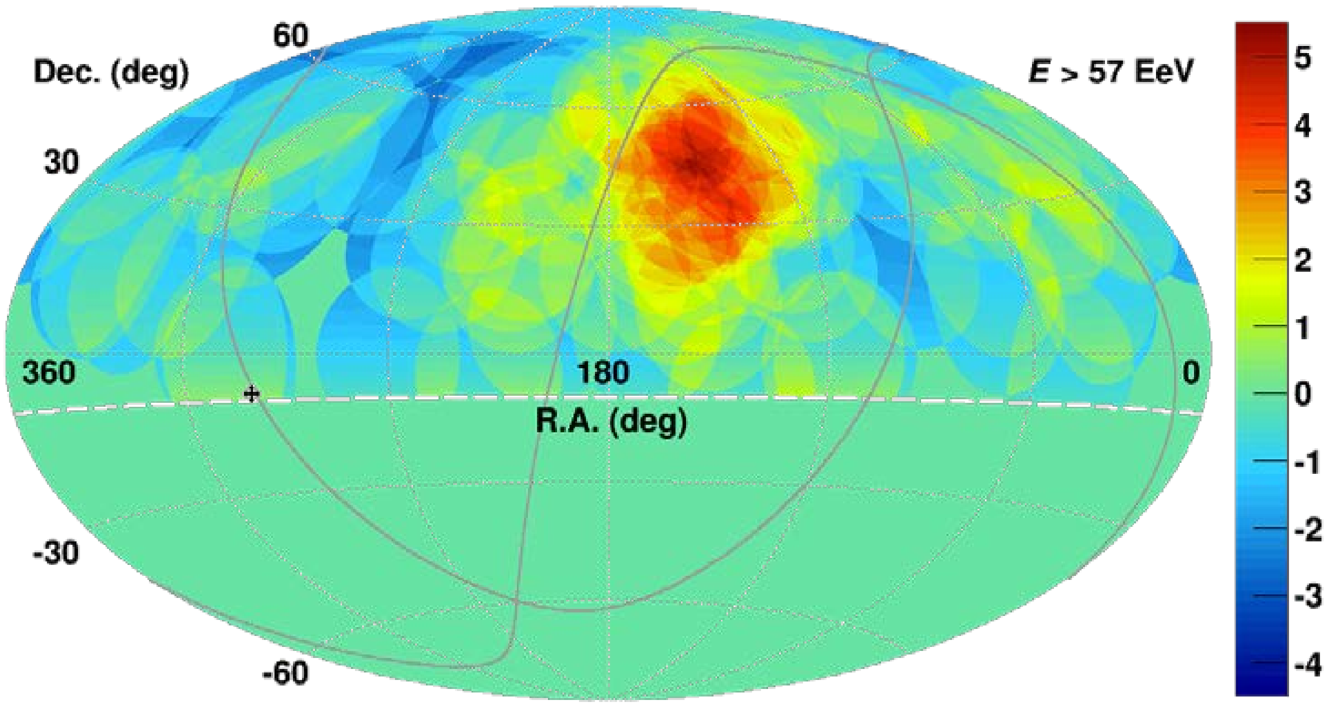
Hotspot +1年間

- 2008年5月—2014年5月（6年間）

到来方向分布



Significance map



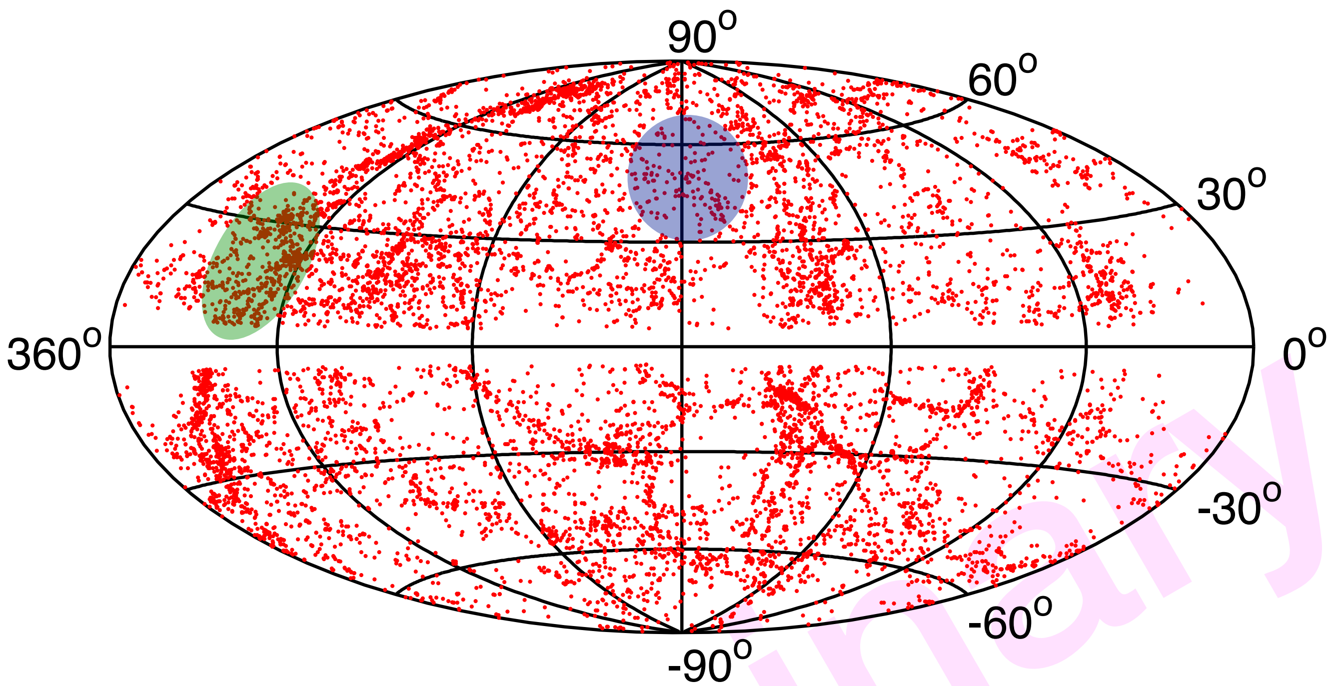
青：5年間のデータ
赤：最近の１年間のデータ

- E ＞5.7x10^{19}eV: 72事象→87事象（+15）
- Hotspot内：　　19事象→23事象（ +4）

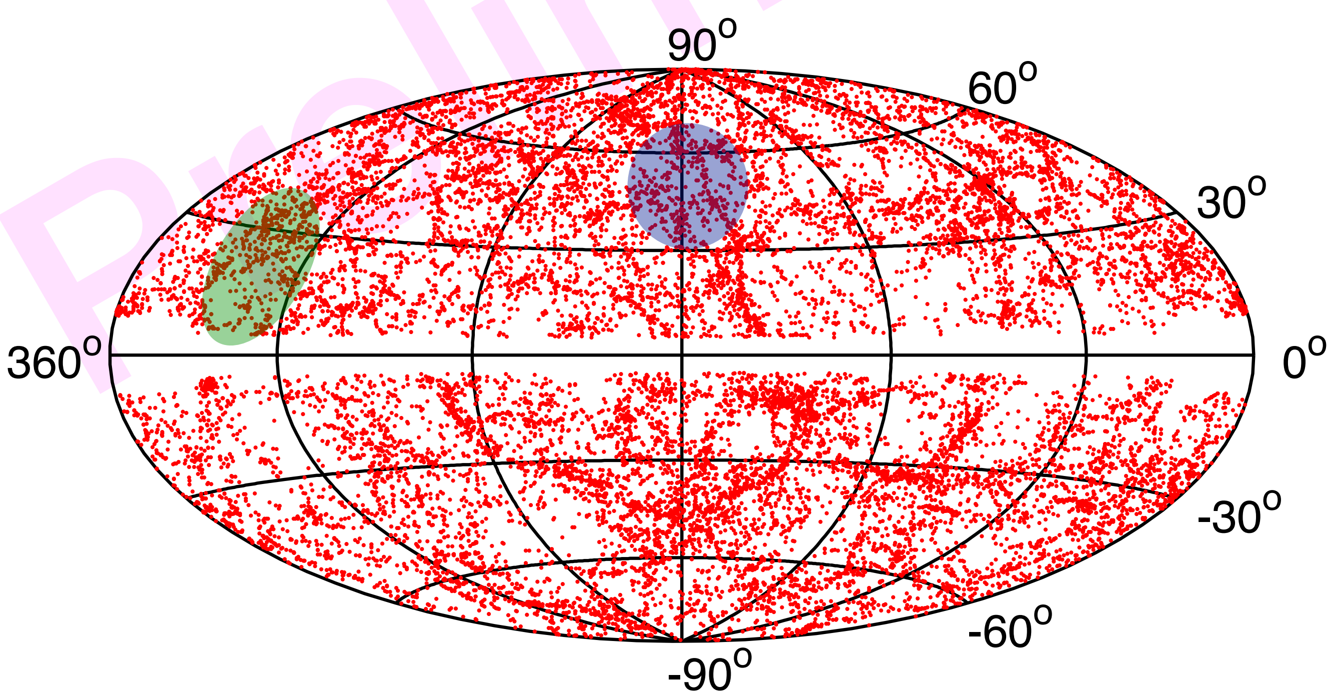
5年　　+1年
(19/72~26%, 4/15~26%)

- 最大のLi-Ma significance: 5.1σ →5.5σ ⟹ 偶然の確率 = 3.4σ →4.0σ

Comparison with Galaxy Distribution



0 < z < 0.018



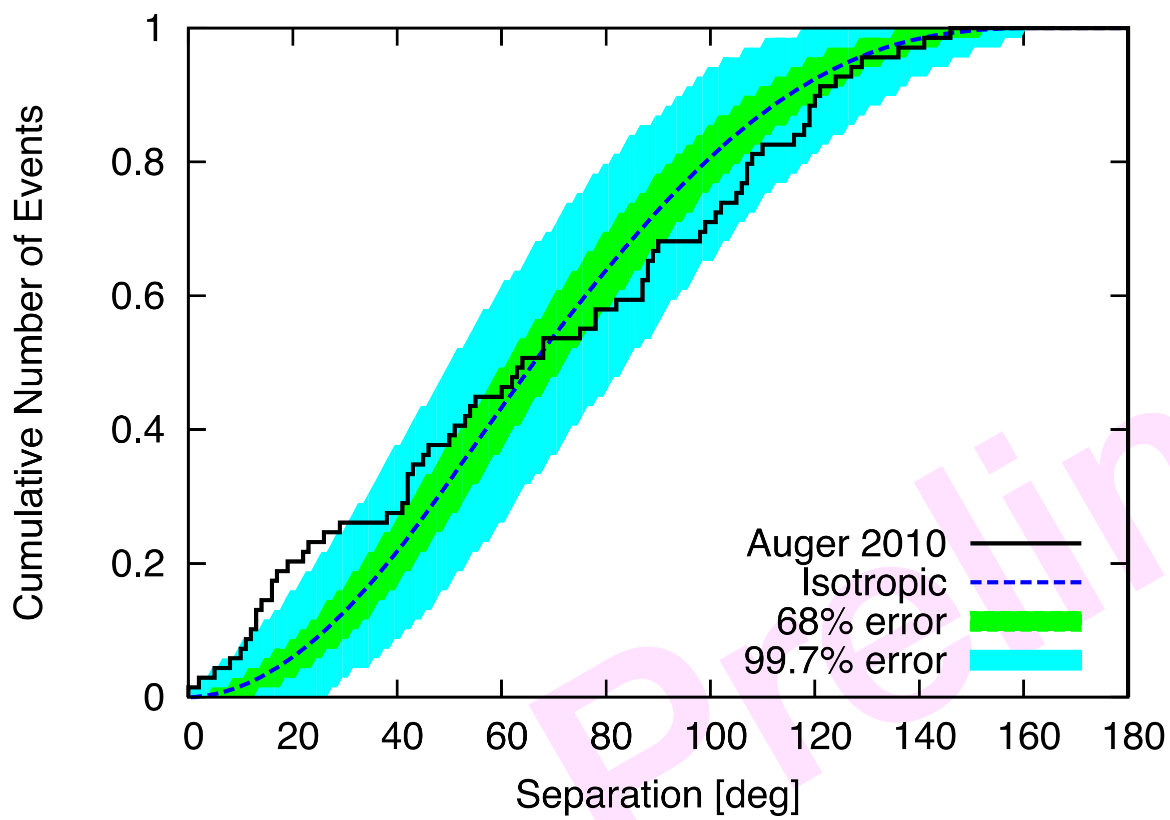
0.018 < z < 0.036

Preliminary

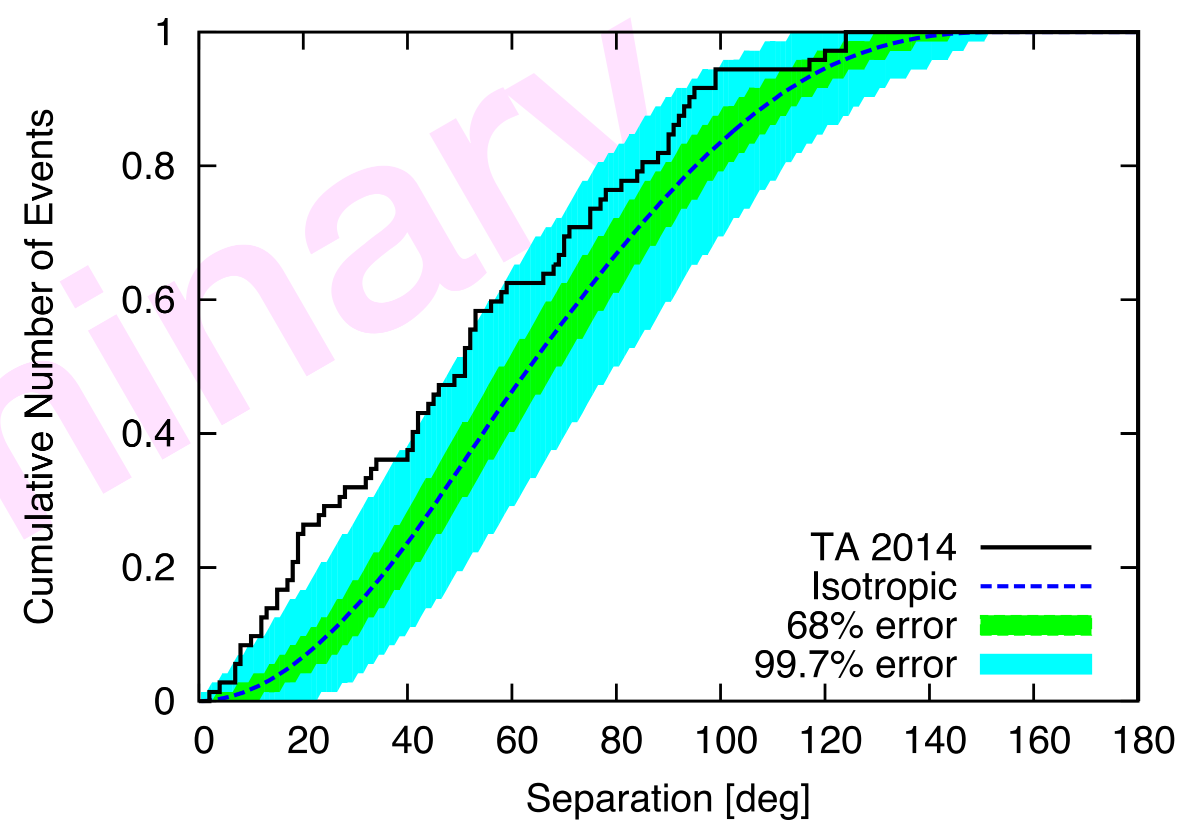
HT et al., in prep.

Event Distribution from Specific Positions

Auger - Cen A

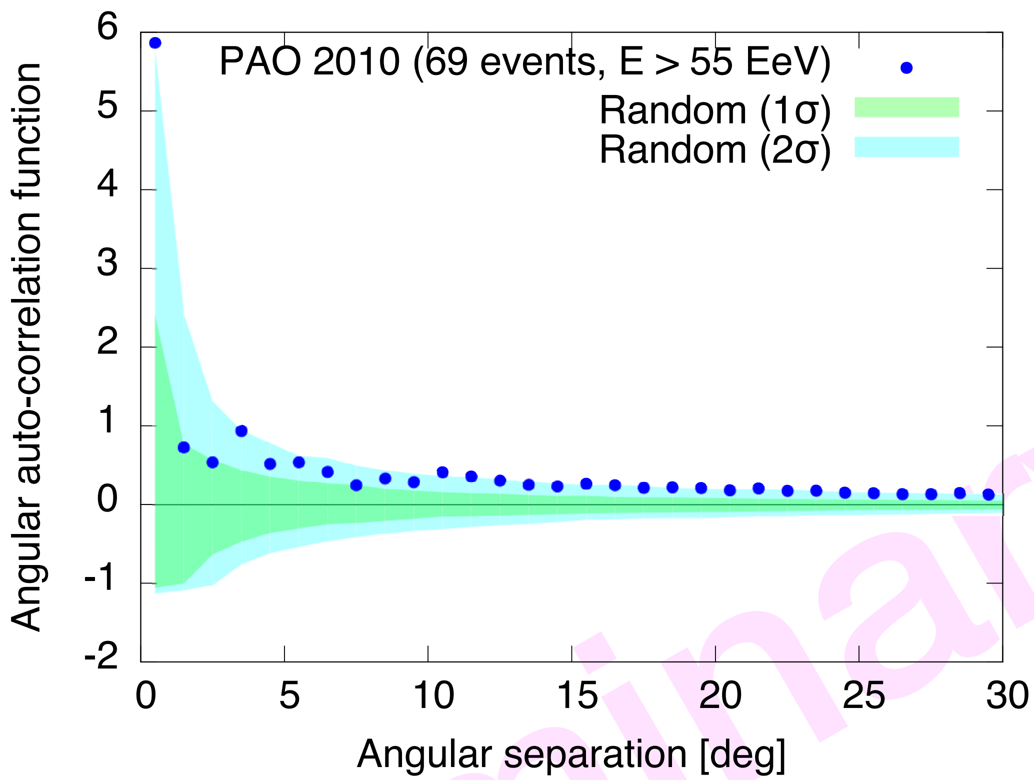


Telescope Array - Hotspot center



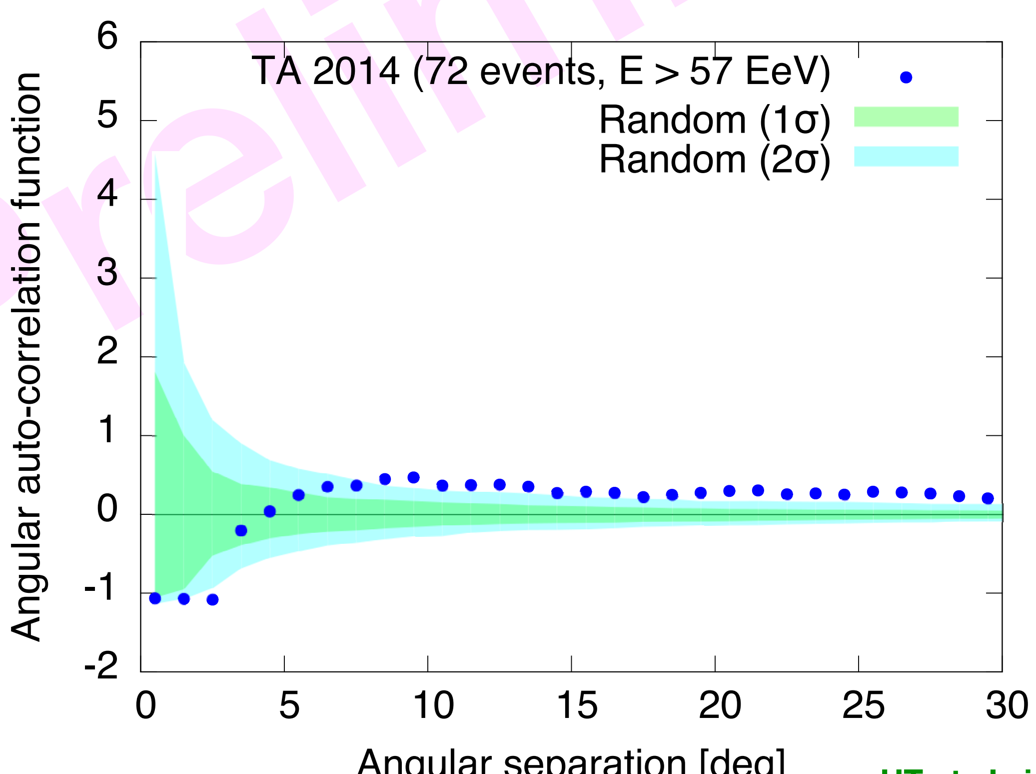
HT et al., in prep.

Angular Auto-correlation Functions



Auger

- Consistent with isotropy at 2σ



TA

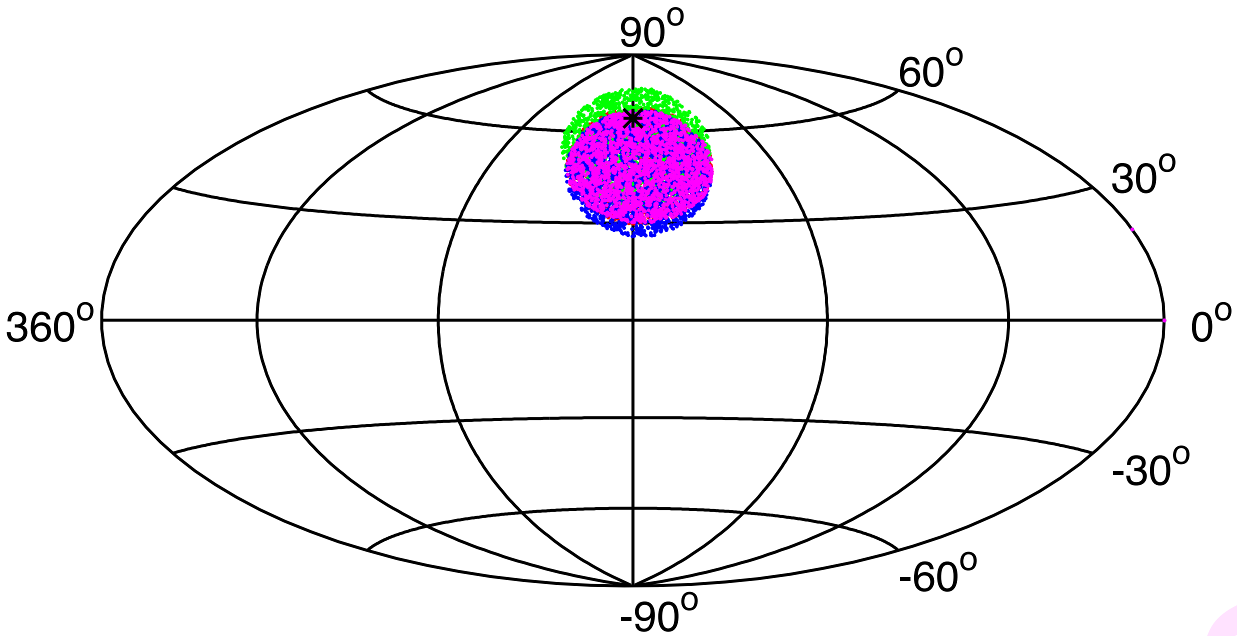
- Medium-scale anisotropy at 2σ

HT et al., in prep.

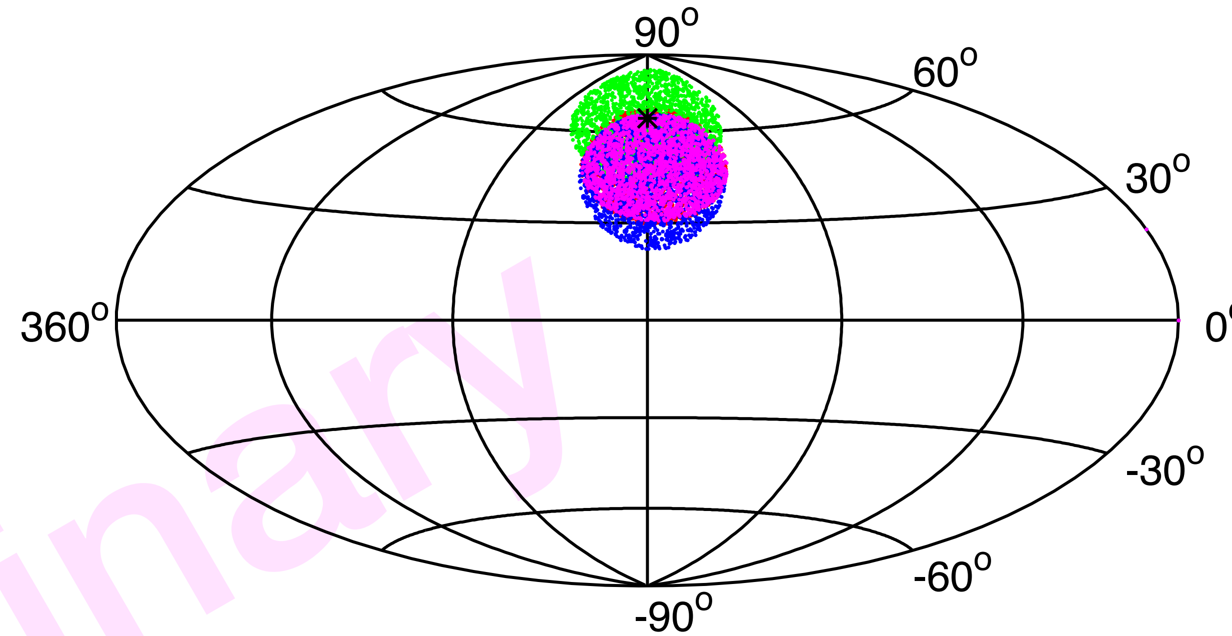
Effects of Galactic Magnetic Fields

E = 60 EeV

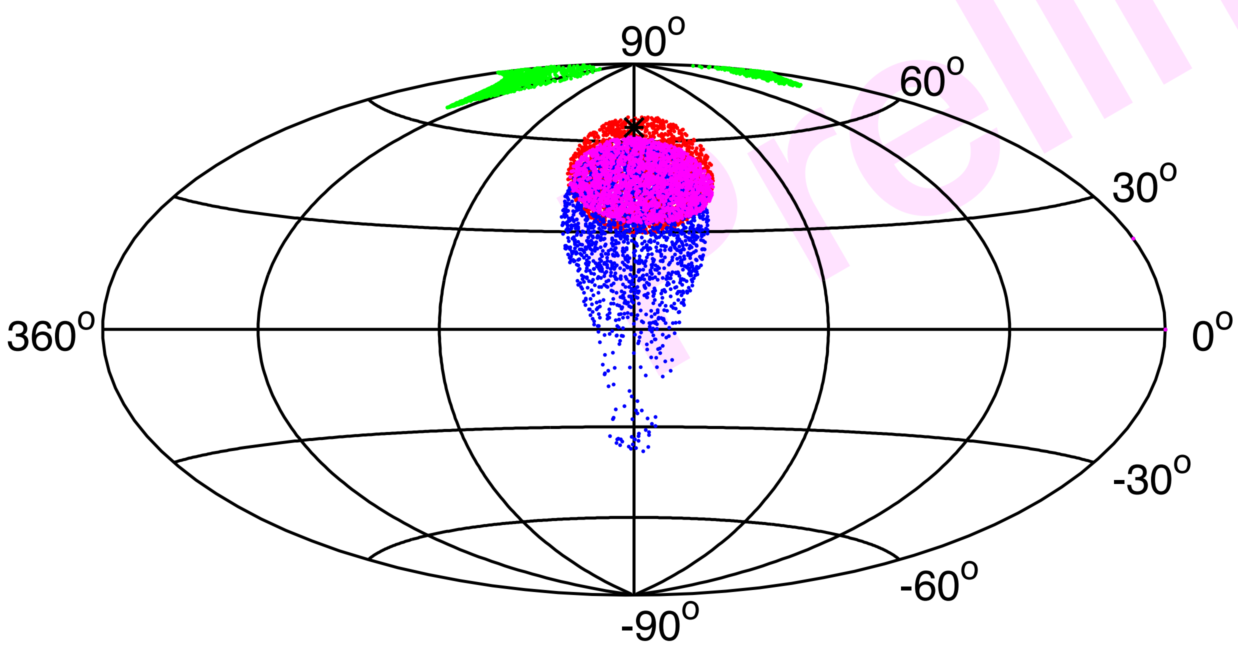
Proton



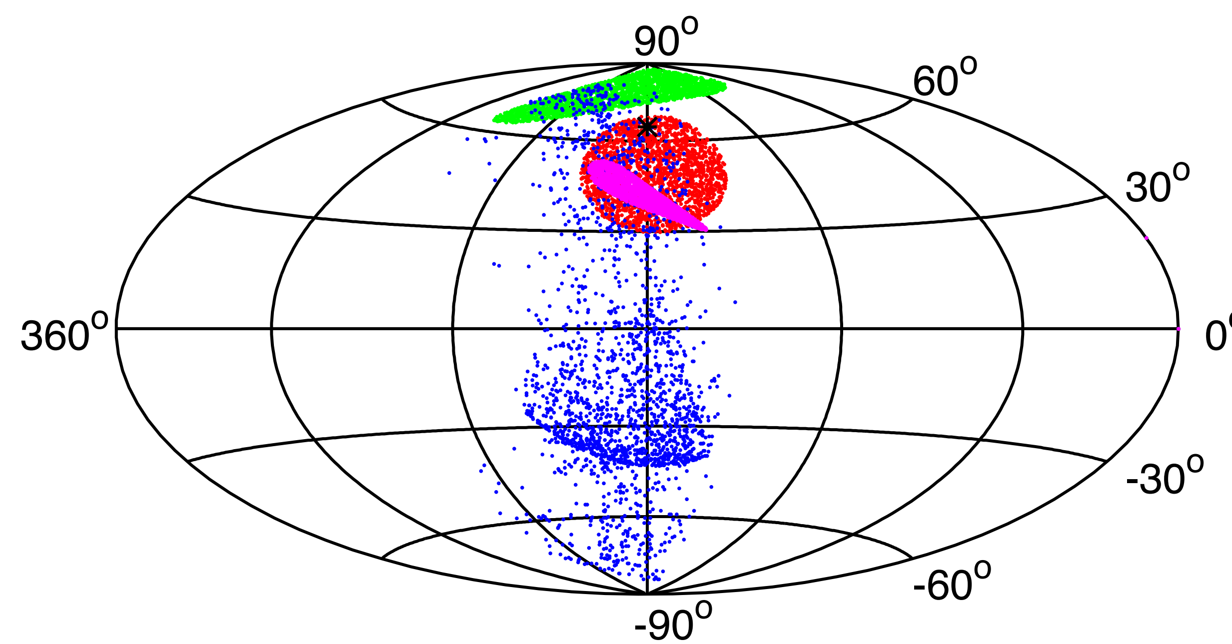
Helium



Nitrogen



Iron

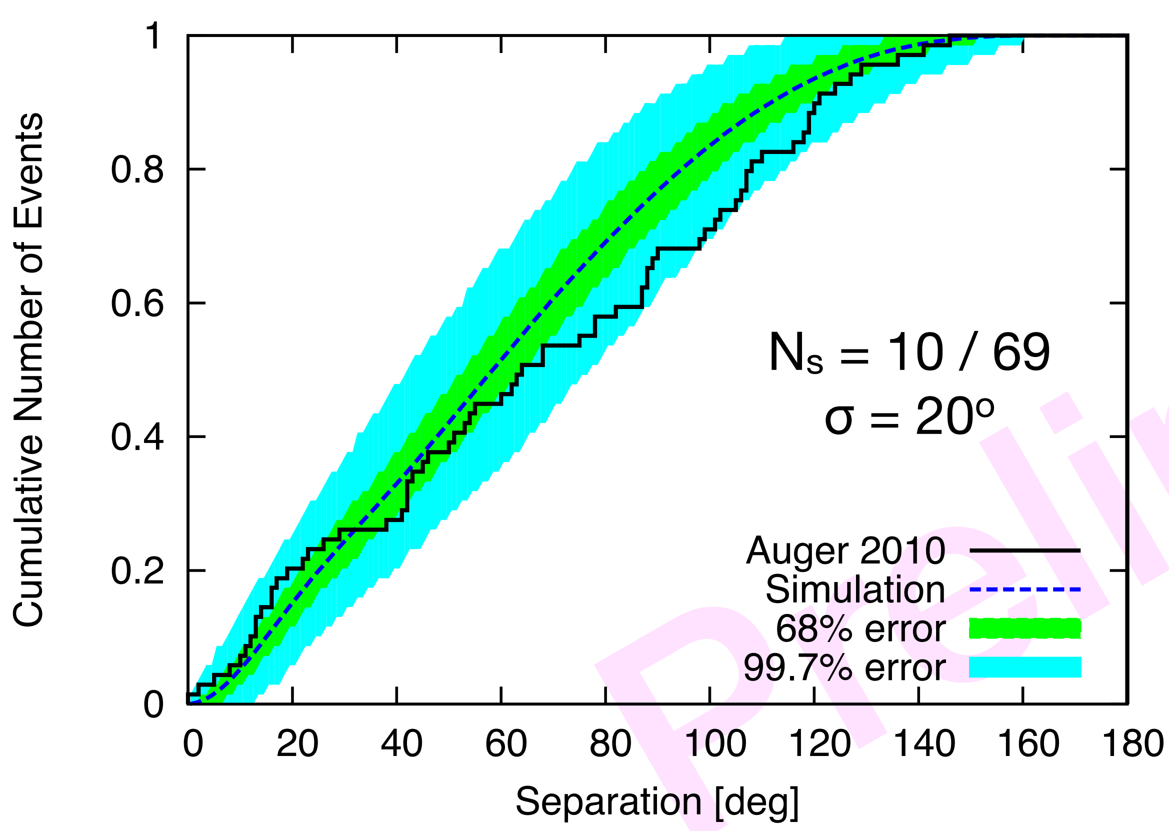


Preliminary

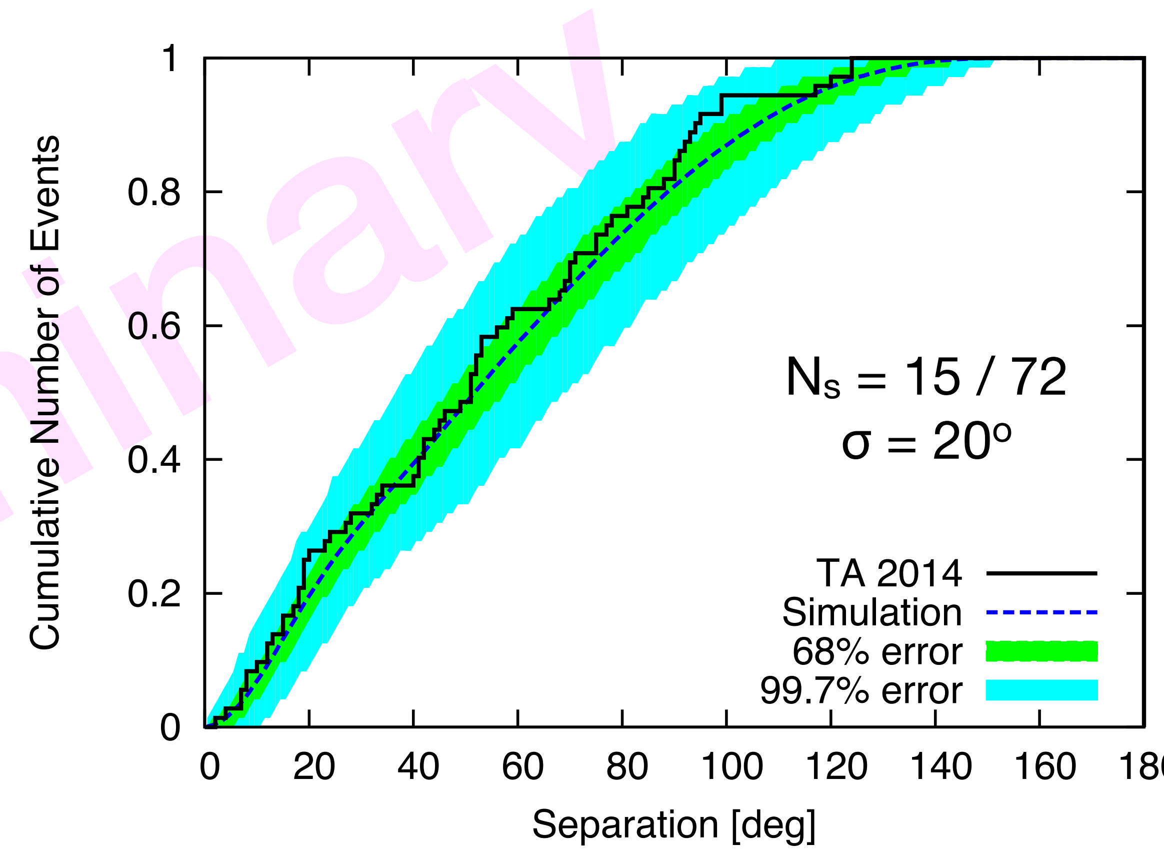
HT et al., in prep.

Isotropic Background + Source Contribution

Auger



Telescope Array



HT et al., in prep.

Deflection is ~ 20°.

Indicated Magnetic Fields

Cosmological

$$\theta(E,D) \simeq 4.2^\circ Z \left(\frac{E}{6\times10^{19}\ \mathrm{eV}}\right)^{-1}\left(\frac{D}{100\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{1\ \mathrm{nG}}\right)\left(\frac{\lambda}{1\ \mathrm{Mpc}}\right)^{1/2}$$

Local

$$\theta(E,D) \simeq 18.6^\circ Z \left(\frac{E}{6\times10^{19}\ \mathrm{eV}}\right)^{-1}\left(\frac{D}{2\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{B}{100\ \mathrm{nG}}\right)\left(\frac{\lambda}{100\ \mathrm{kpc}}\right)^{1/2}$$

1. Introduction
2. Review
3. Future Prospects
4. Summary

Summary

Current Status

- Anisotropy versus chemical composition
- Transient sources?

Future prospects

The nature of UHECR sources should be understood to establish strategies for source identification.

- Generation: steady or transient
- Composition: proton-dominated or heavy nuclei

Anisotropy!

The hotspots indicates ~ 100 nG magnetic fields around the Milky Way — Multi-messenger!