最高エネルギー宇宙線の現在の理解と次世代計画で期待されるサイエンス

Review and Future Prospects of the Highest-energy Cosmic Rays

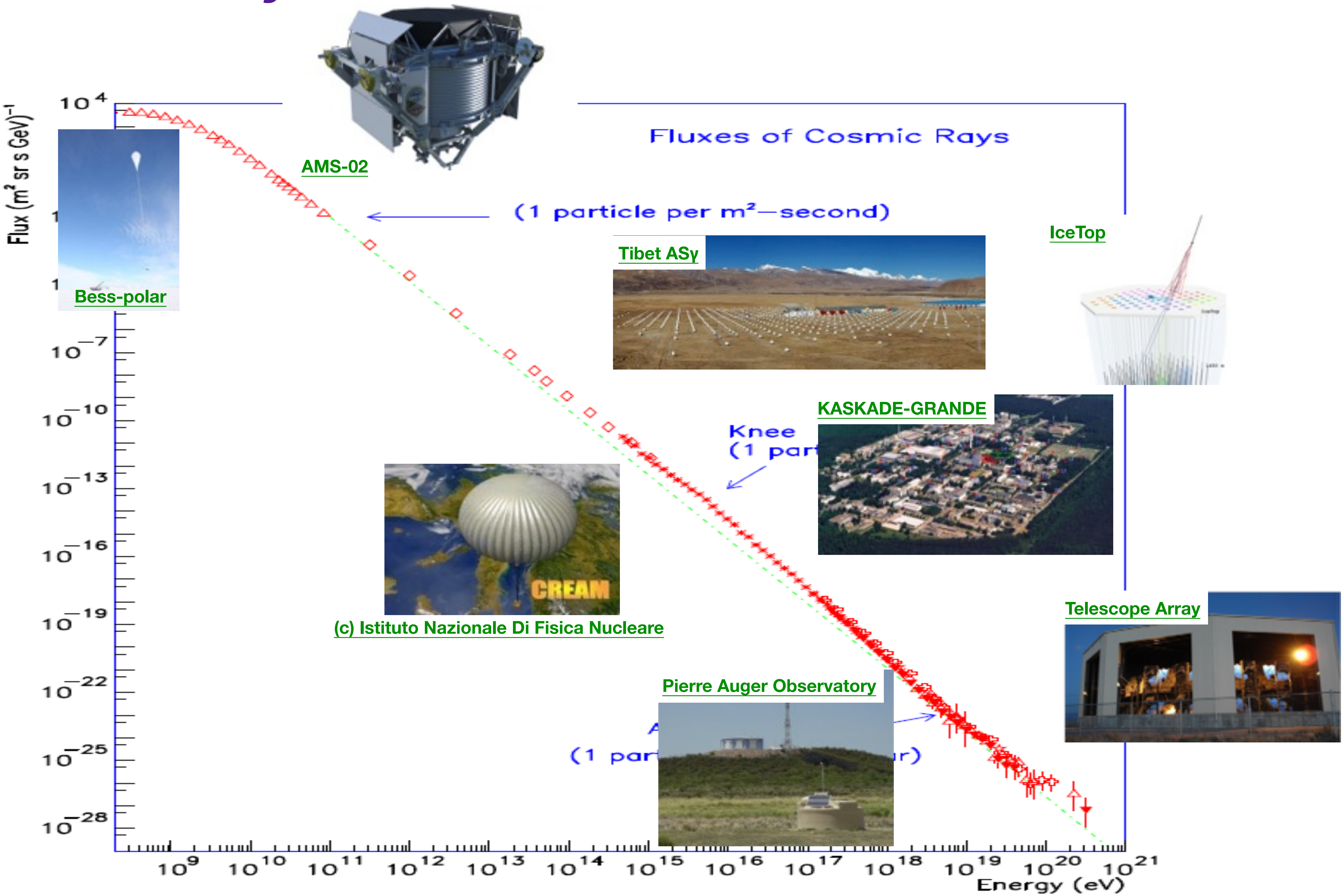
Hajime Takami
KEK, JSPS Fellow

独立行政法人 JSPS 日本学術振興会
Japan Society for the Promotion of Science

高エネルギー加速器研究機構　素粒子原子核研究所　理論センター
宇宙物理グループ
KEK Theory Center Cosmophysics Group

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

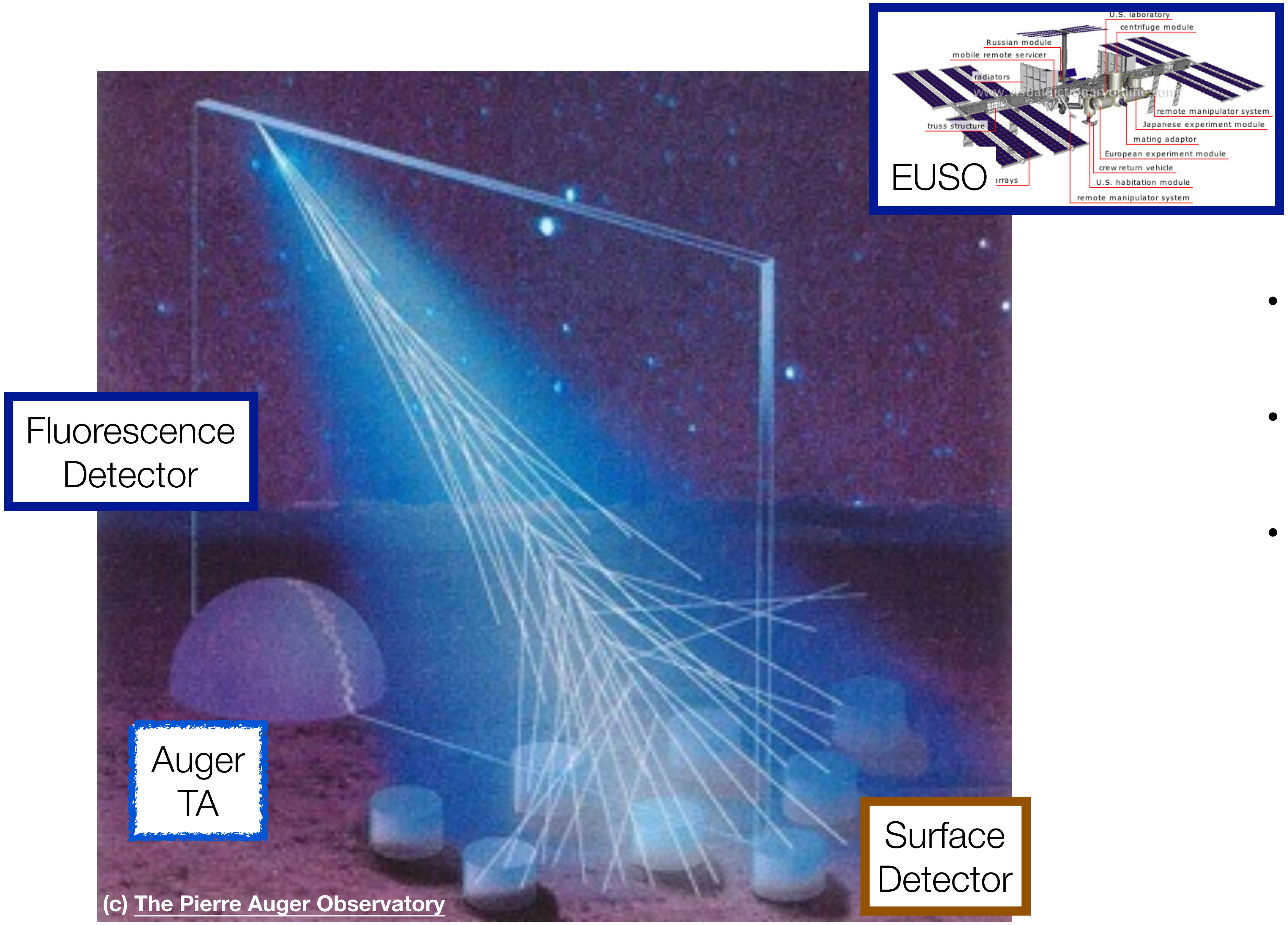
Cosmic rays ~ detectors ~



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

Detection Techniques

Atmosphere as a calorimeter

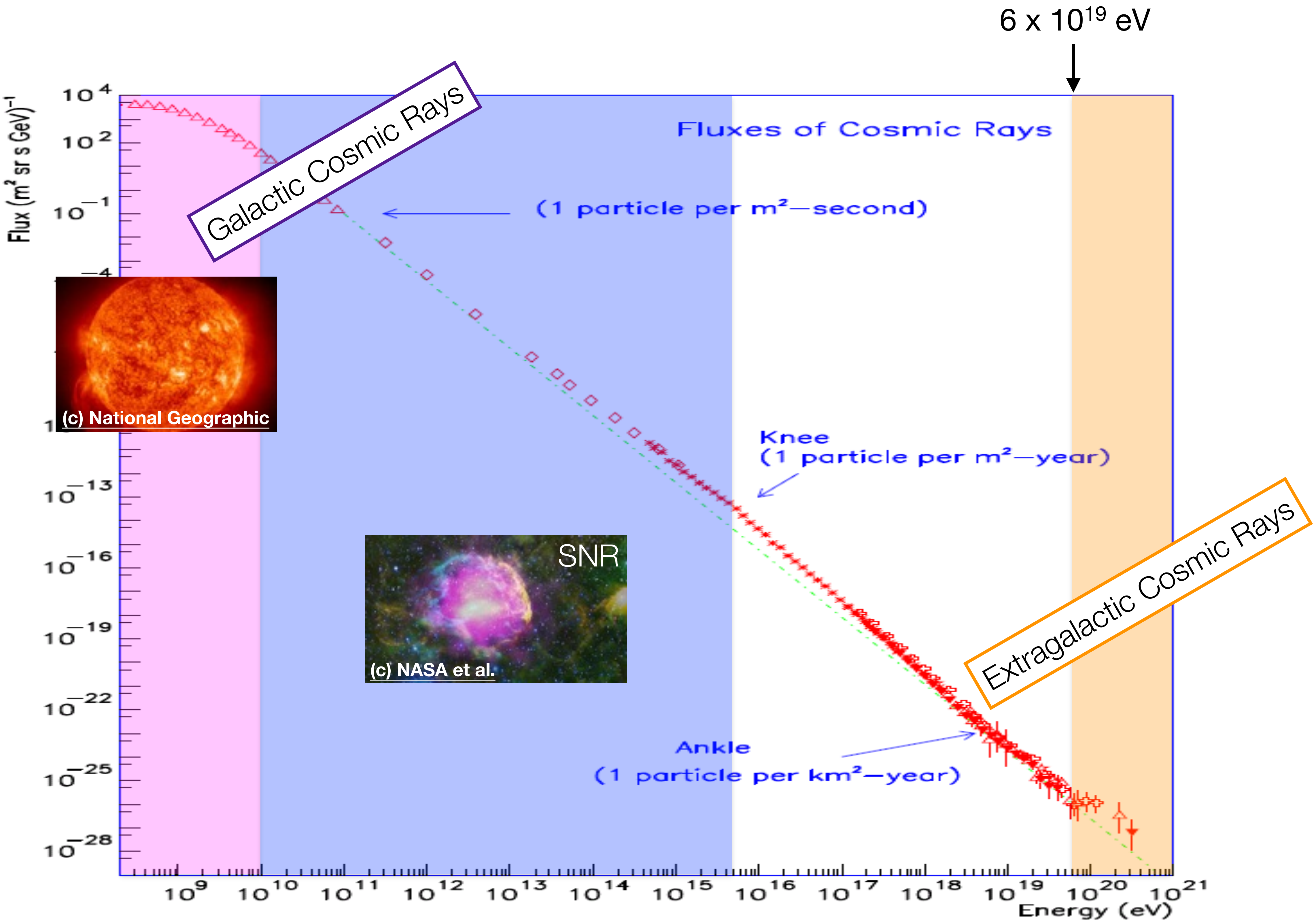


- Primary energy
- Arrival direction
- Composition

Primary Aims of Cosmic-ray Researches

- **Origin of cosmic rays**
- **Propagation of cosmic rays**

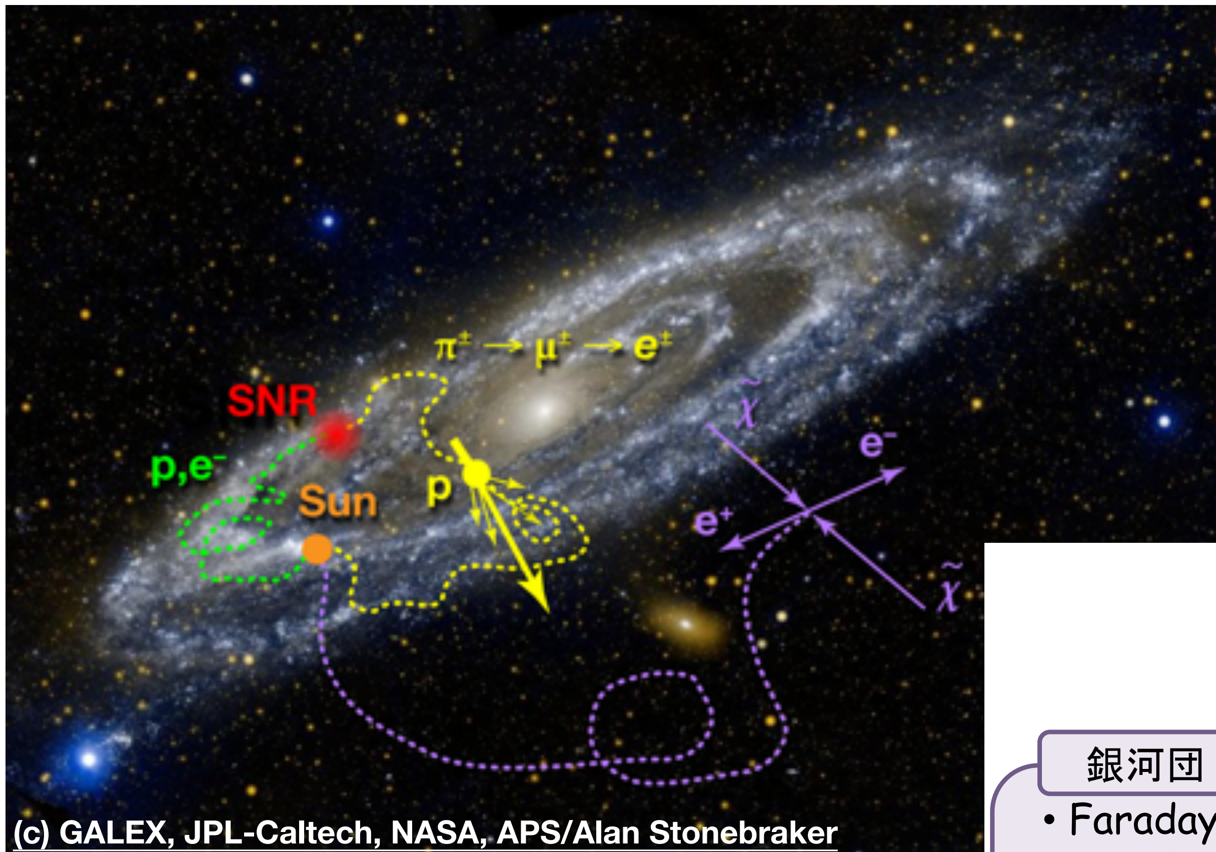
Cosmic rays ~ origin ~



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

Difficulty in Identifying Cosmic-ray Origin

Charge and cosmic magnetic fields



(c) GALEX, JPL-Caltech, NASA, APS/Alan Stonebraker

平均磁場

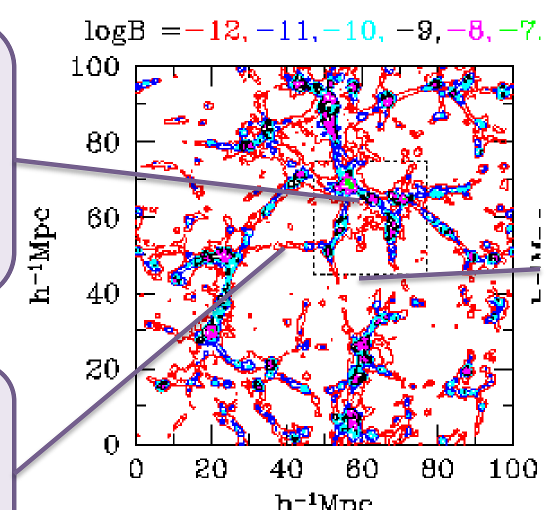
Faraday rotation : $B\lambda^{1/2} < (1\ nG)(1\ Mpc)^{1/2}$
Kronberg (1994), Ryu et al. (1998), Blasi et al. (1999)

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

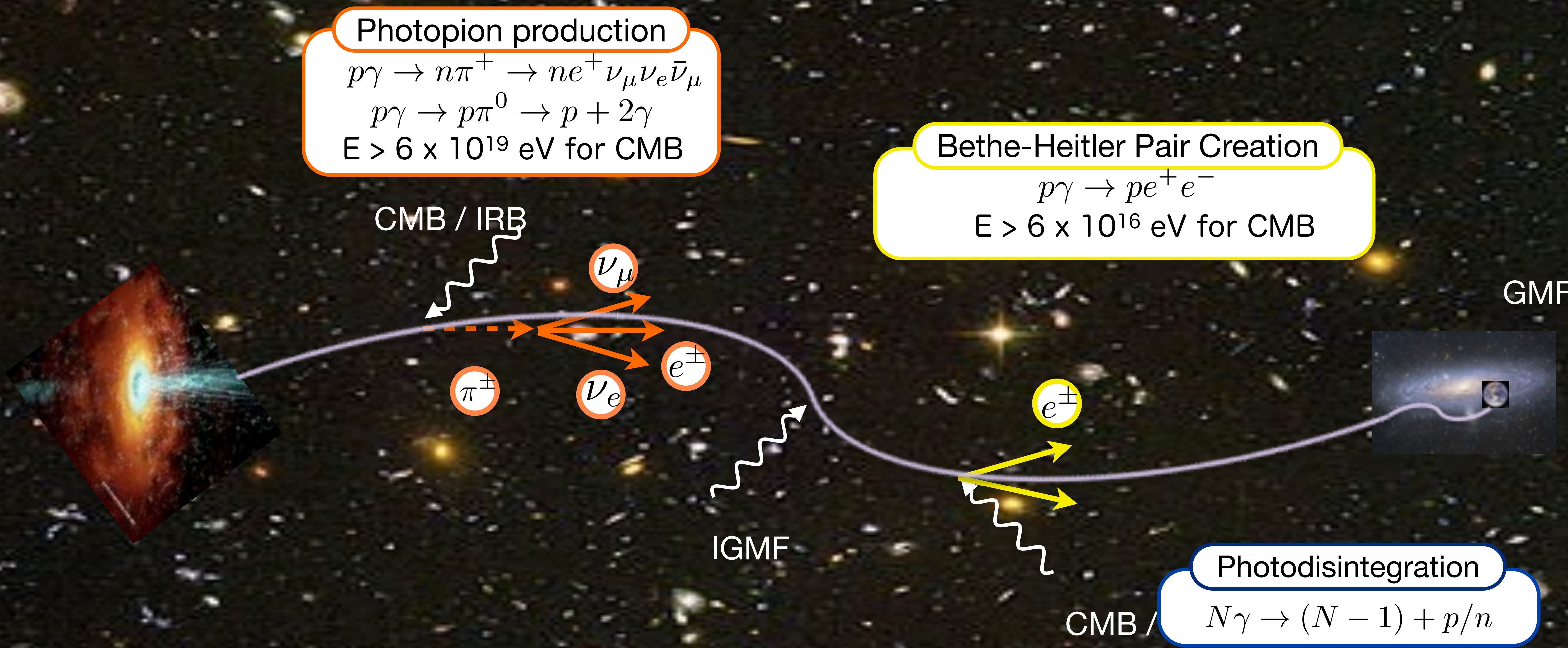
1. Deflection can be minimized.

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

2. Greisen-Zatsepin-Kuz'min horizon

   — low-background observations

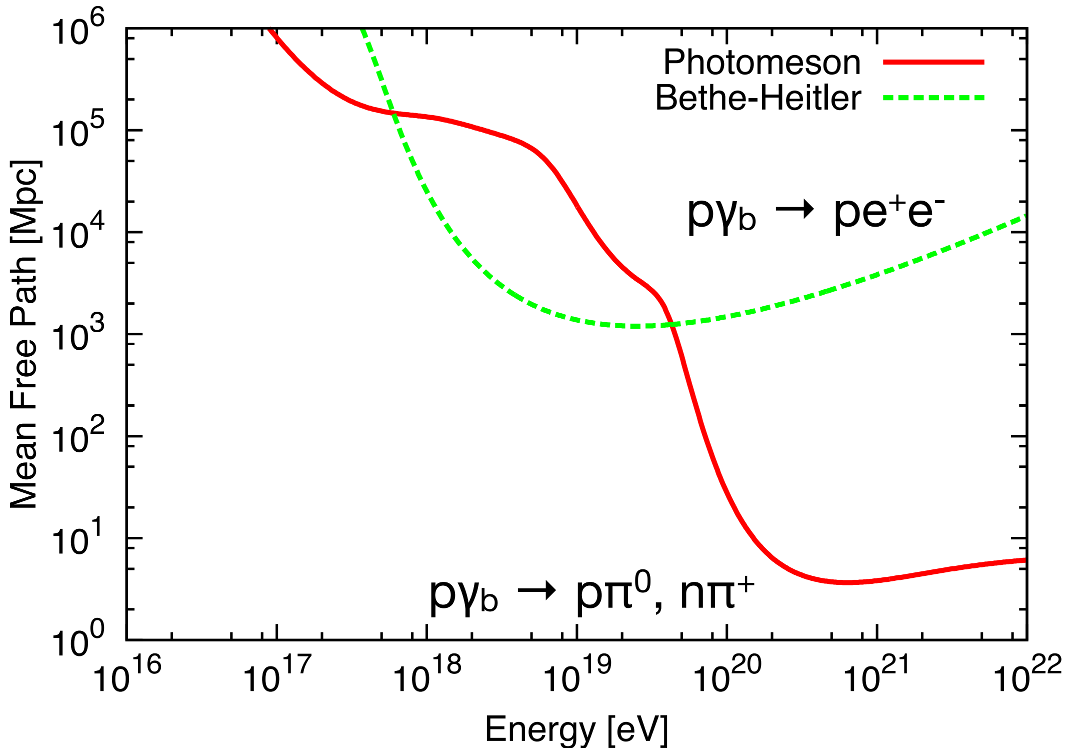
Propagation of UHECRs



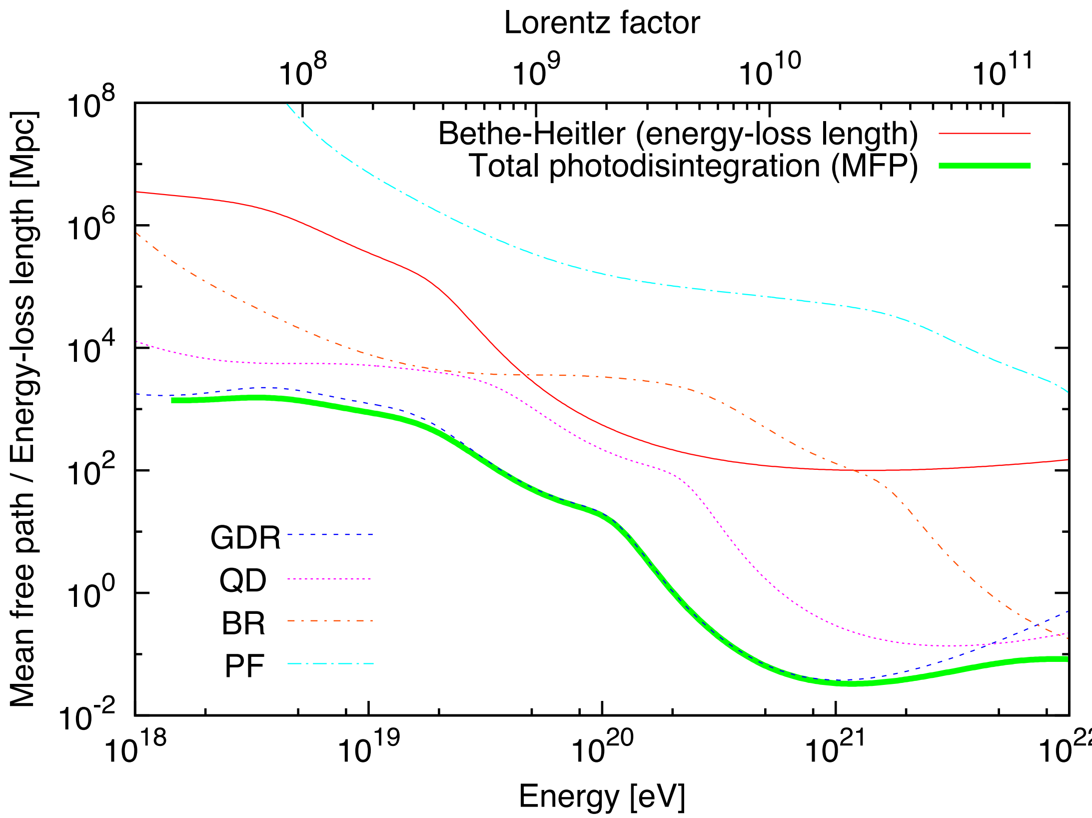
Mean Free Path

Mean free path drastically decreases at the highest energies.

Proton



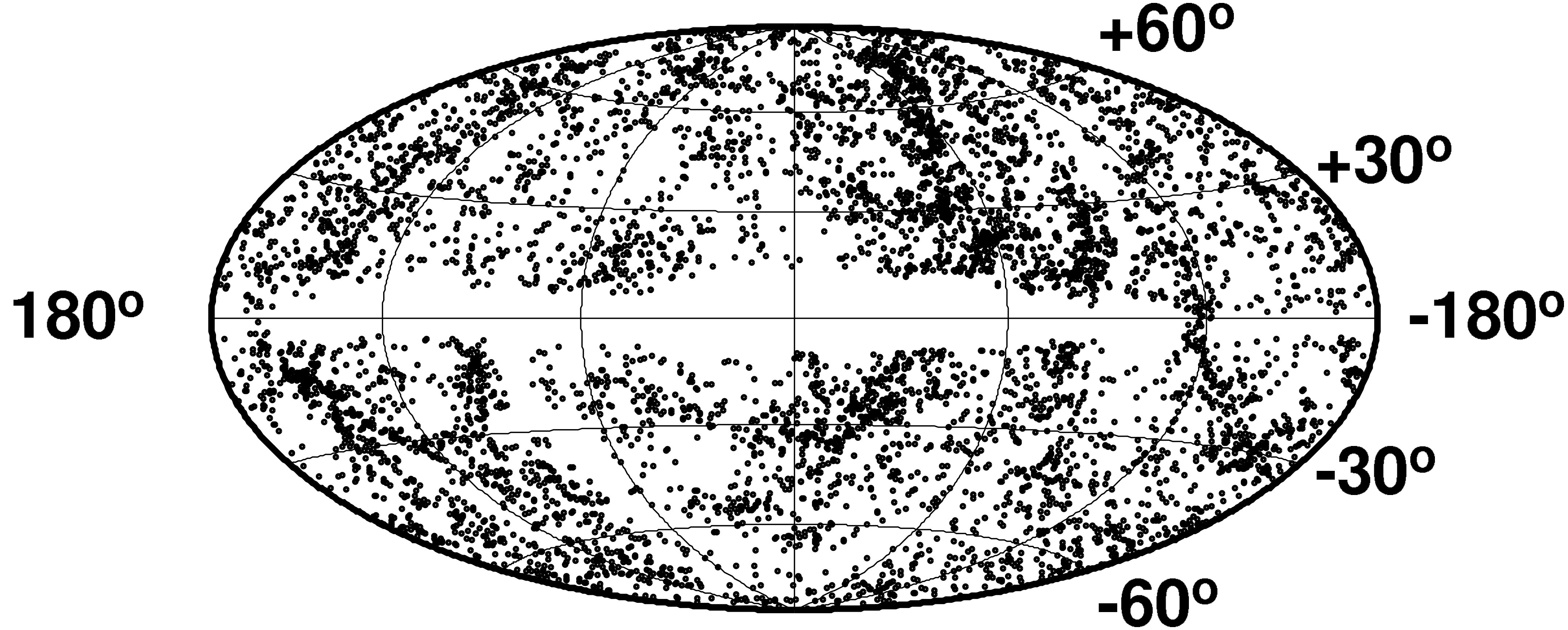
Iron



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

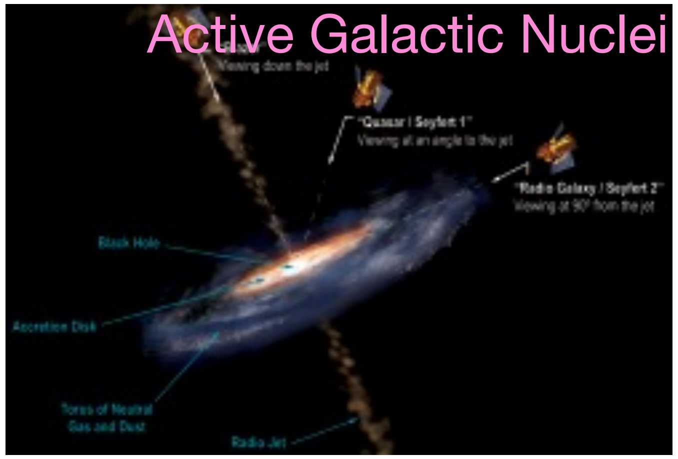
Galaxies in the Local Universe

D < 100 Mpc



Saunders et al., MNRAS 317 (2000) 55

UHECR Source Candidates

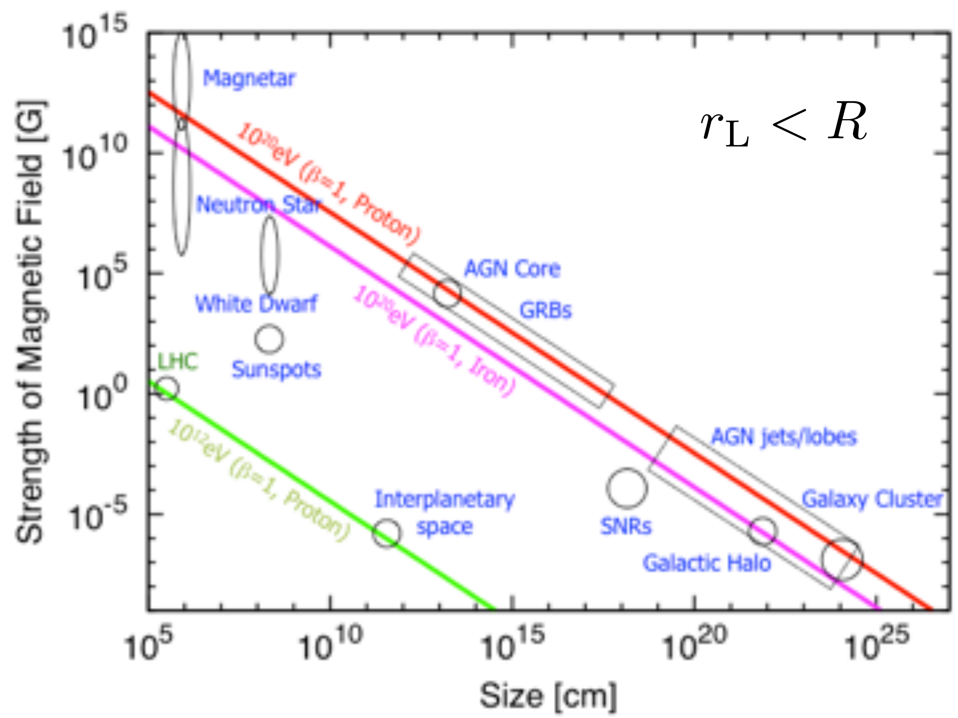


e.g., Biermann & Strittmatter, ApJ 322 (1987) 643,
Takahara, PTP 83 (1990) 1071,
Rachen & Biermann, A&A 272 (1993) 161,
Norman et al., ApJ 454 (1995) 60,
Farrar & Gruzinov, ApJ 693 (2009) 329,
Dermer et al., New J. Phys. 11 (2009) 065016
Pe'er et al., PRD 80 (2009) 123018,
HT & Horiuchi, Aph 34 (2011)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

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

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., 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
- Interest to extreme Universe

1. Introduction

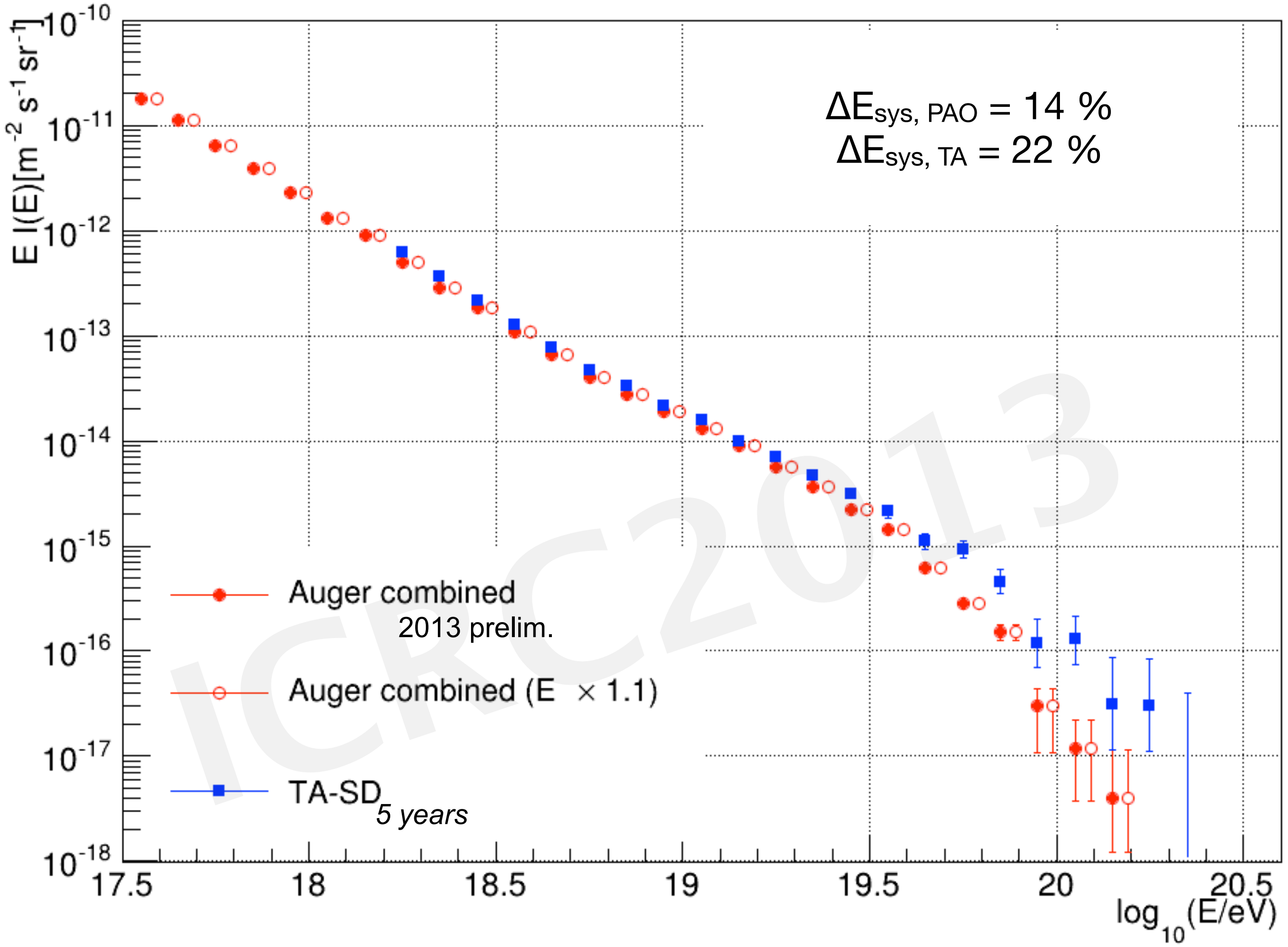
2. Review

3. Future Prospects

4. Summary

Energy Spectrum

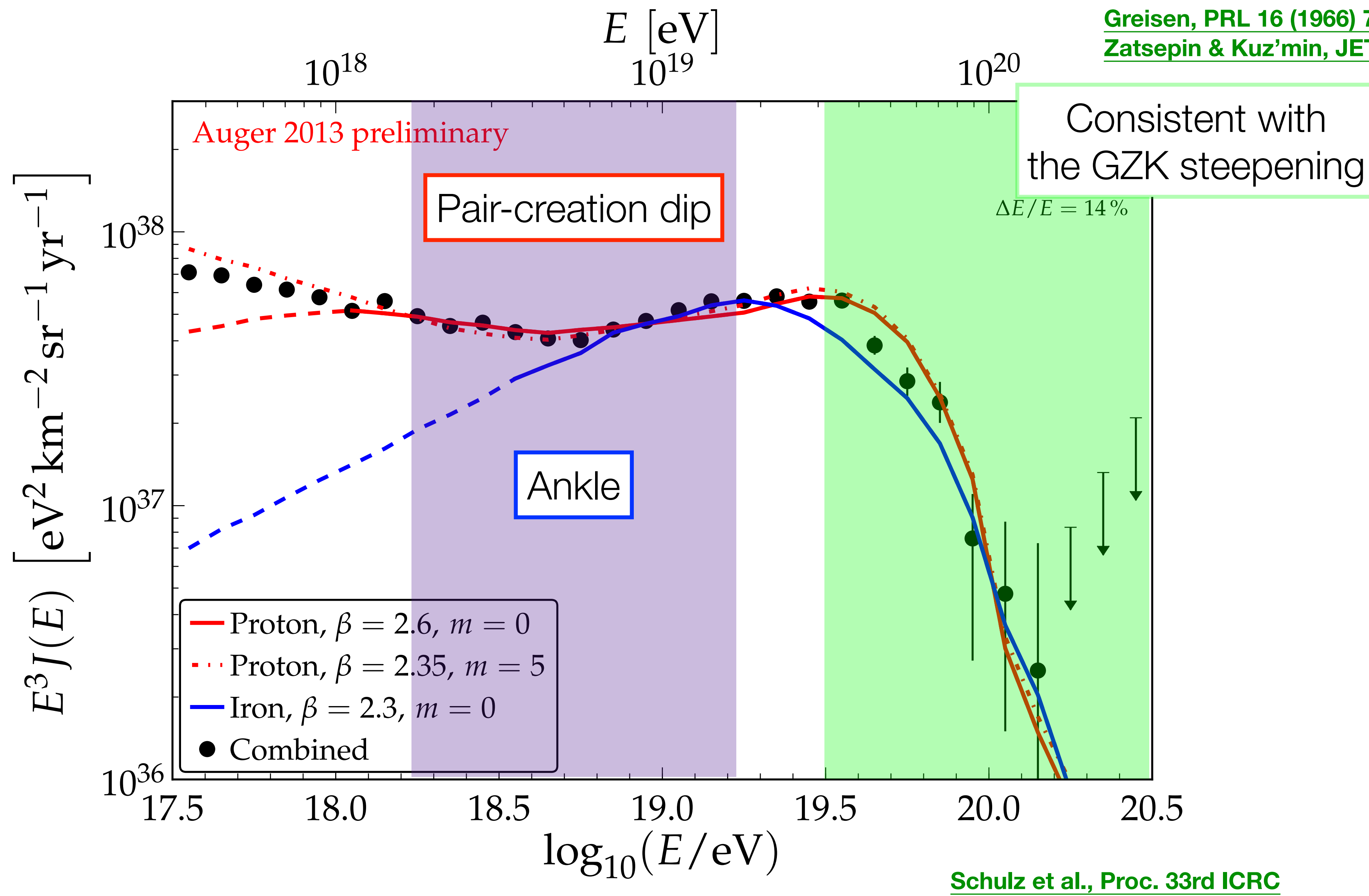
The spectra of Auger and Telescope Array are consistent within systematic errors.



Tsunesada, Rapporteur talk, ICRC 2013

Spectral Modeling

Two interpretations are possible.

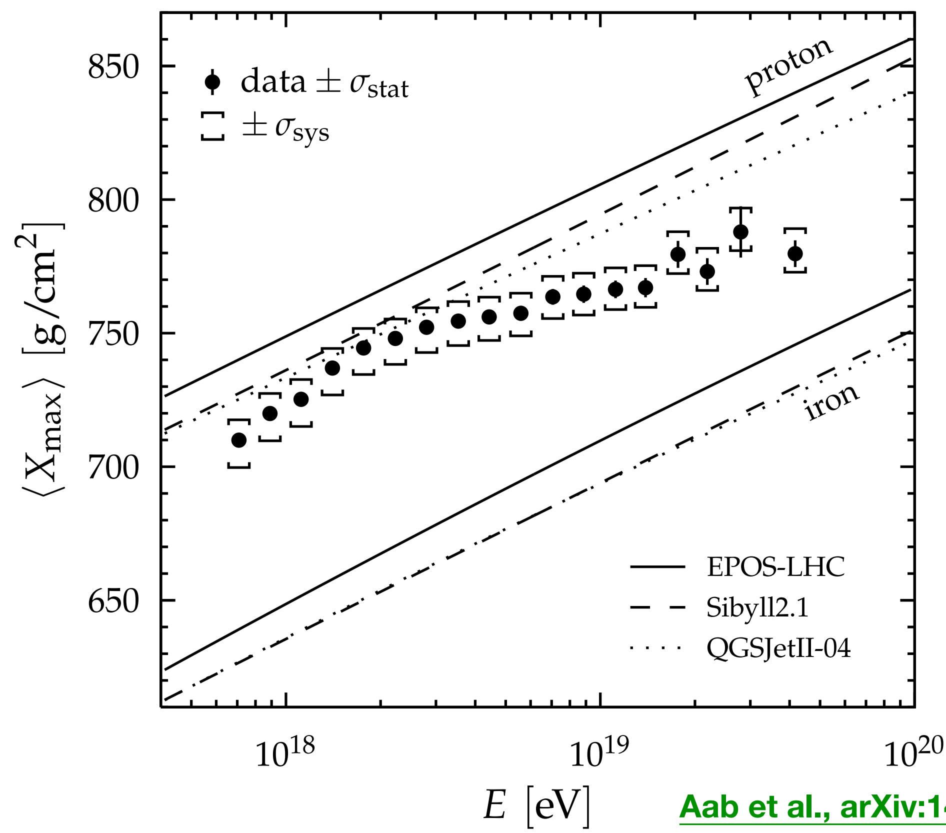


Greisen, PRL 16 (1966) 748

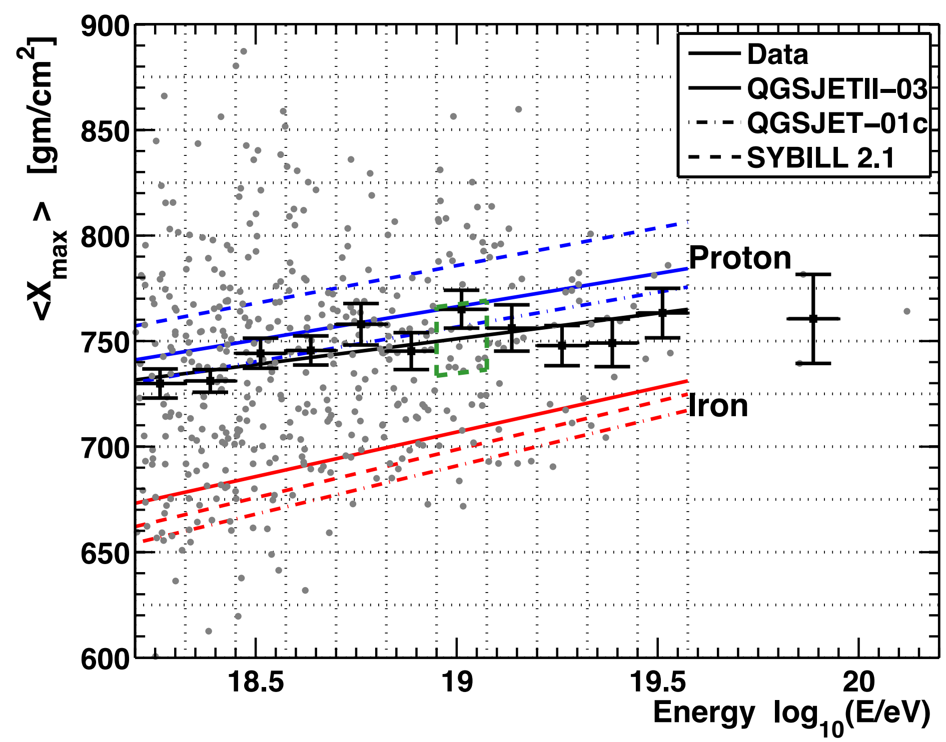
Zatsepin & Kuz'min, JETP Lett. 4 (1966) 78

Schulz et al., Proc. 33rd ICRC

Shower Maximum Measurements



Aab et al., arXiv:1409.4809



Abassi et al., arXiv:1408.1726

Auger

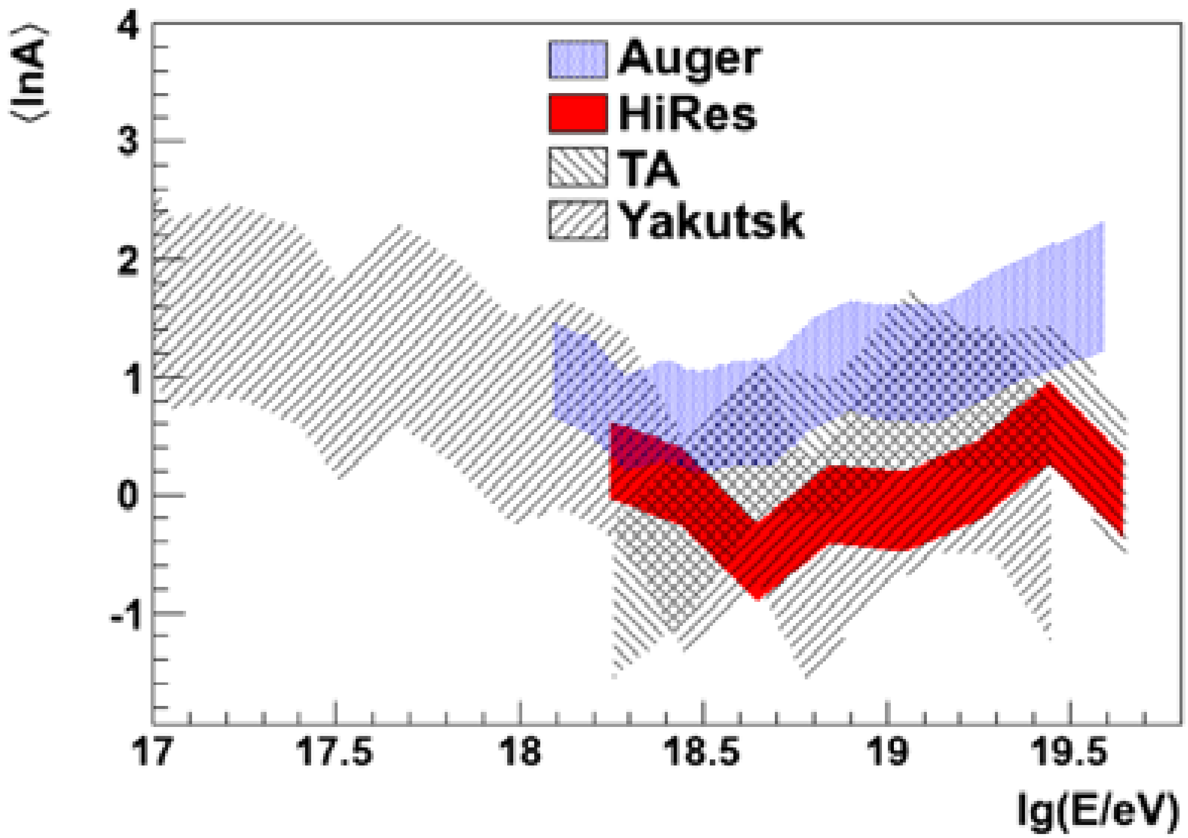
- Gradually changing to heavy nuclei

TA

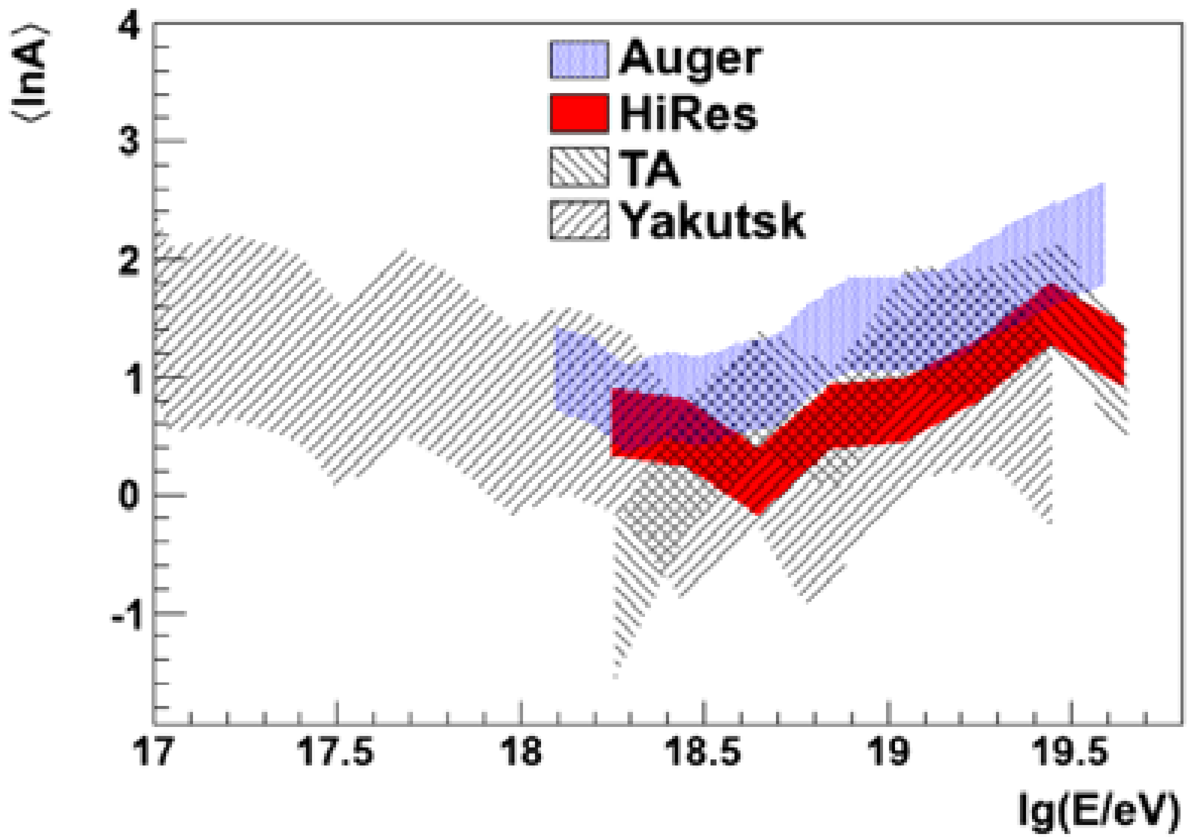
- Consistent with protons

Comparison between Experiments

Auger and TA are compatible within systematic uncertainties.



(a) using QGSJet-II model.

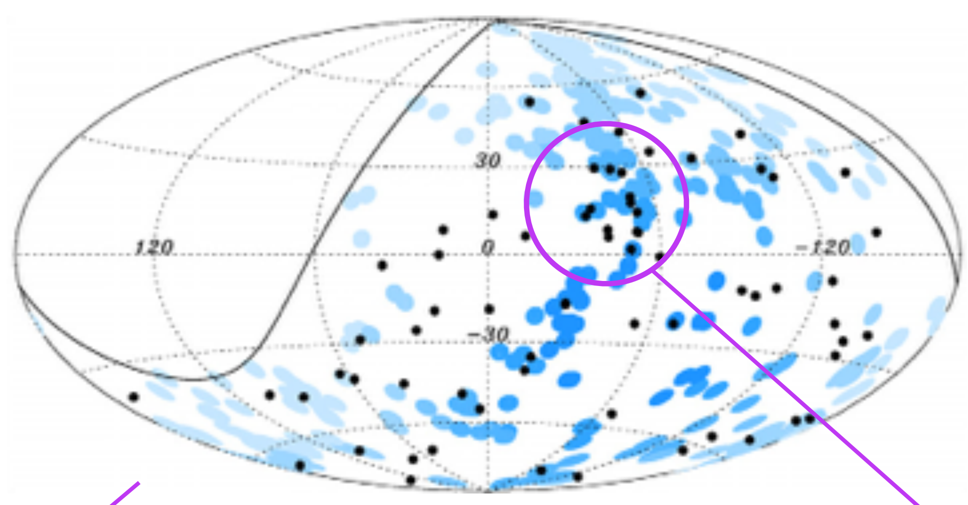


(b) using SIBYLL model.

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

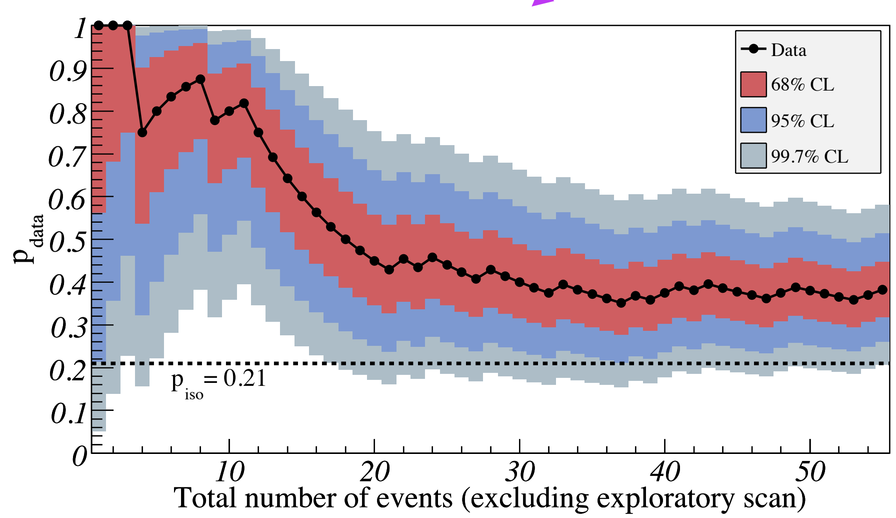
Anisotropy Signals by Auger

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

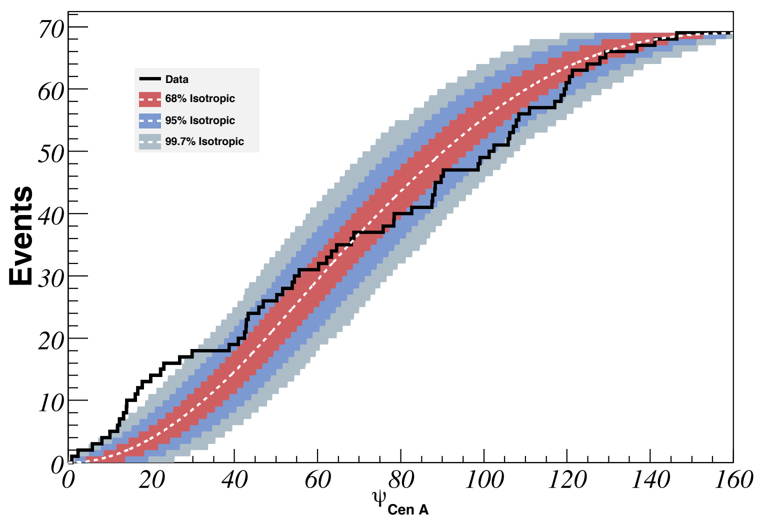


Abreu et al., Aph 34 (2010) 314

AGN correlation



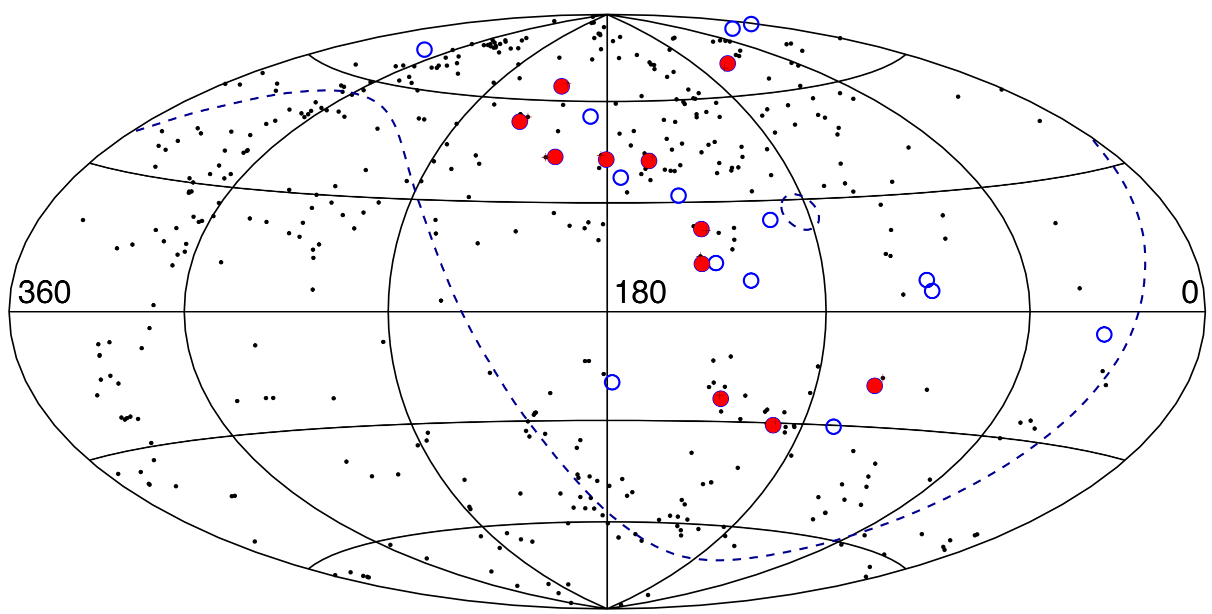
Cen A cluster

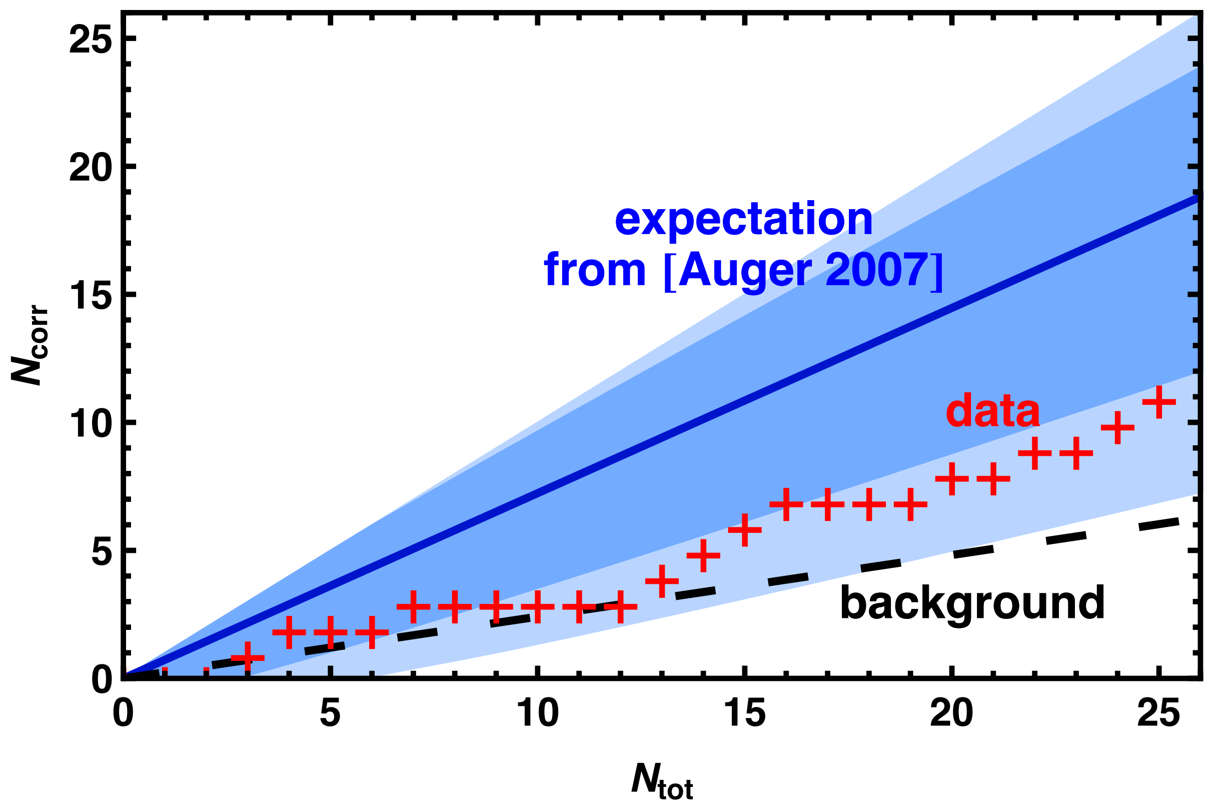


The anisotropy signals are marginal.

Anisotropy Signals by TA

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

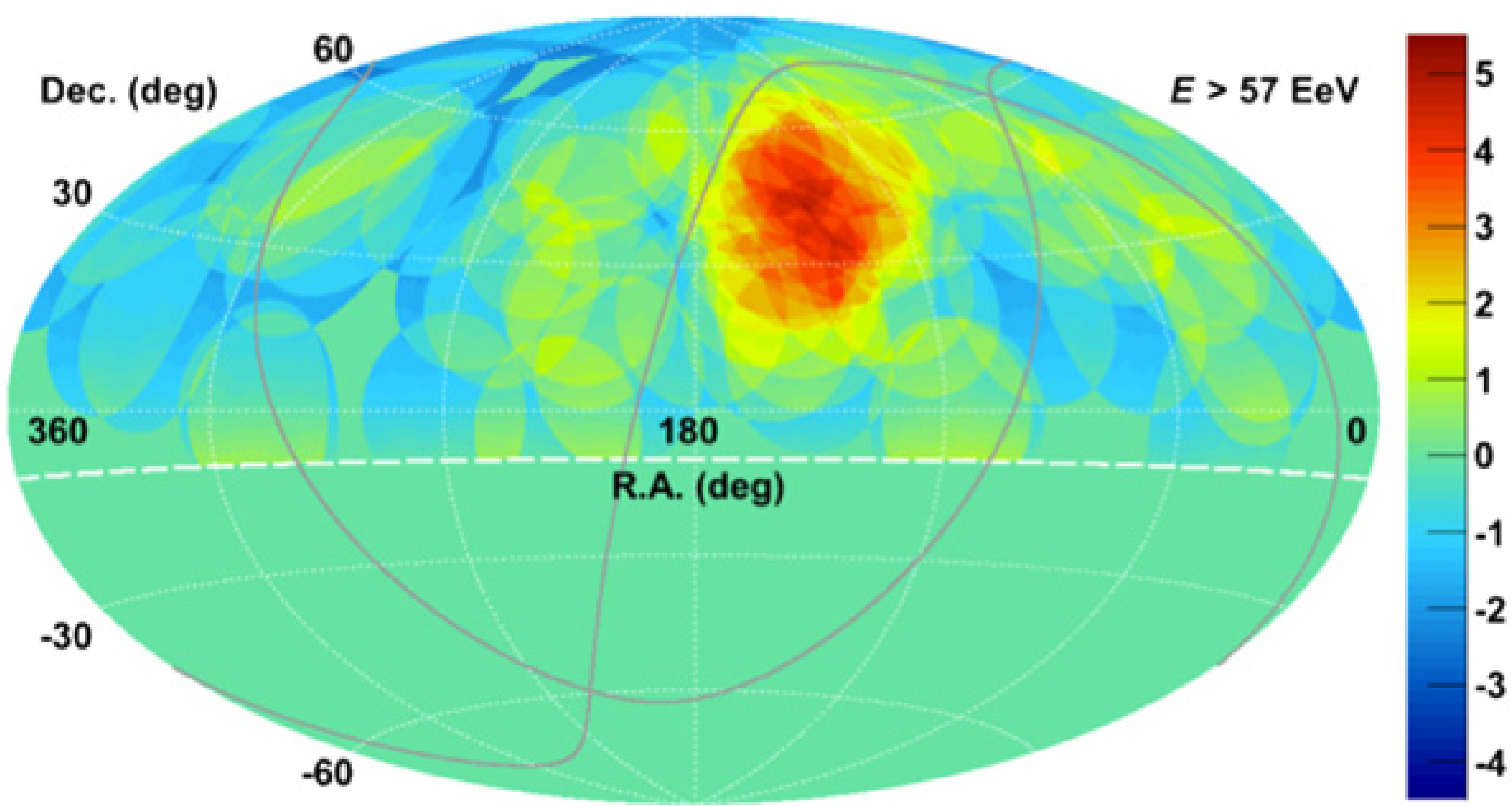




Abu-Zayyad et al., ApJ 757 (2012) 26

Telescope Array Hot Spot

3.4 σ excess using 20º circles



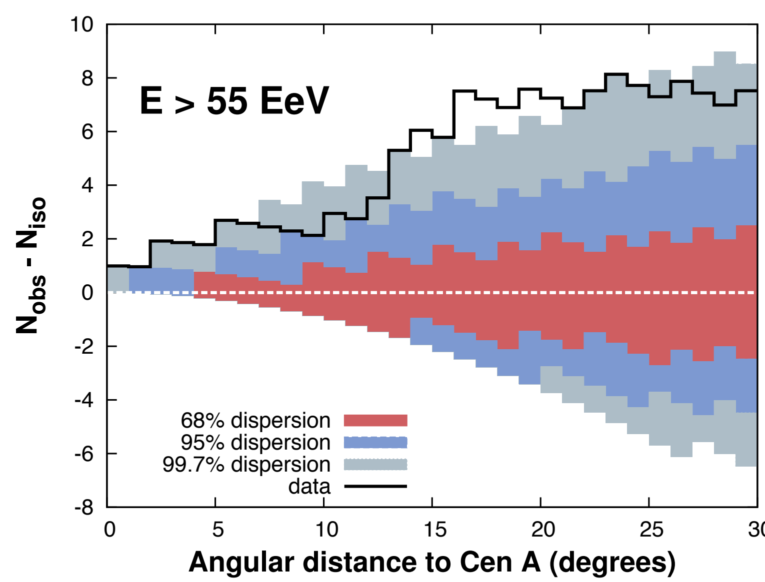
E > 5.5 x 10^{19} eV
72 events
loose-cut

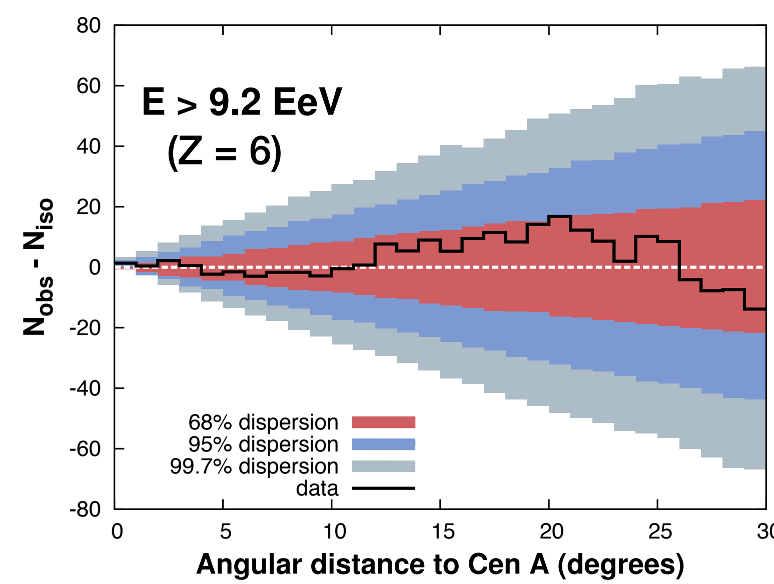
No clear source candidate in this direction

Anisotropy versus Chemical Composition

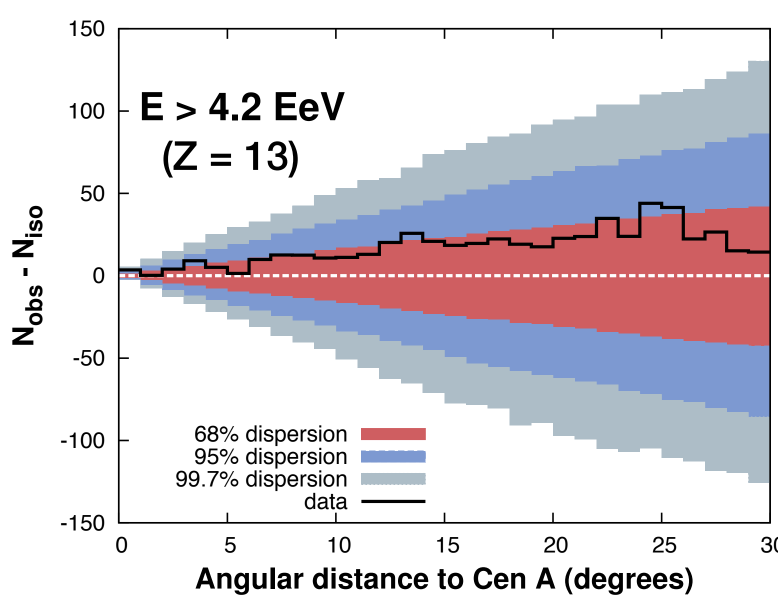
Even stronger anisotropy by protons appears at > E / Z,
if anisotropy produced by nuclei with Z appears at > E.

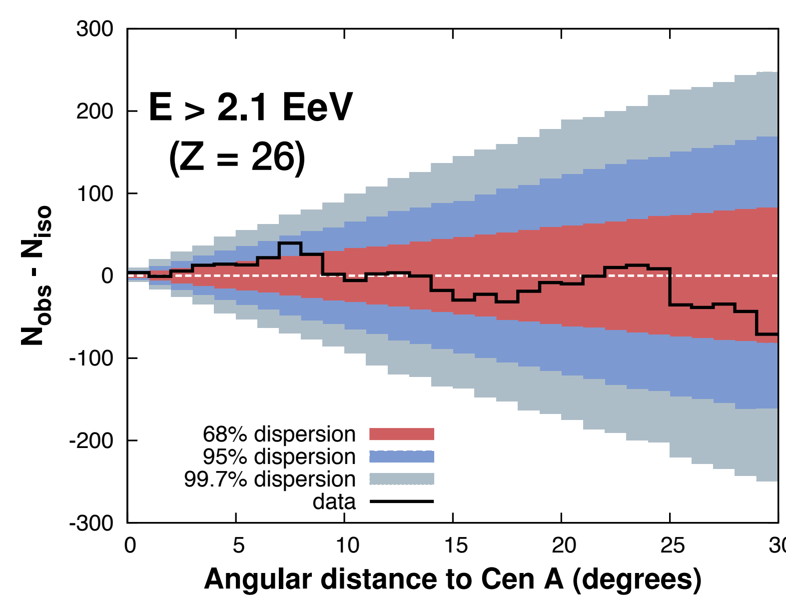
Lemoine & Waxman, JCAP 11 (2009) 009





Abreu et al., JCAP 06 (2011) 022





Possibilities

- Proton-dominated composition at the highest energies

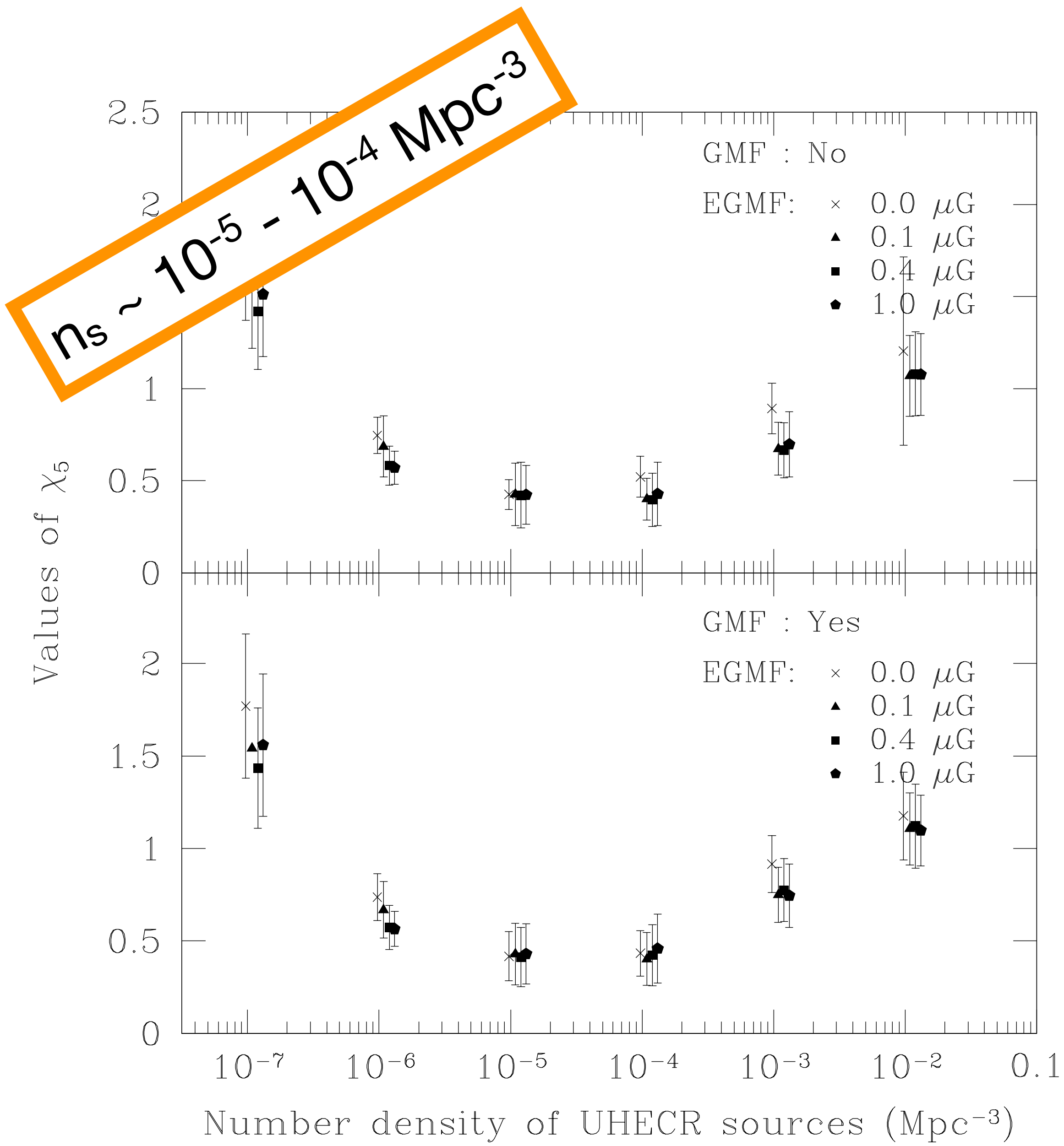
- Heavy-nucleus-dominated in a wide energy range

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.

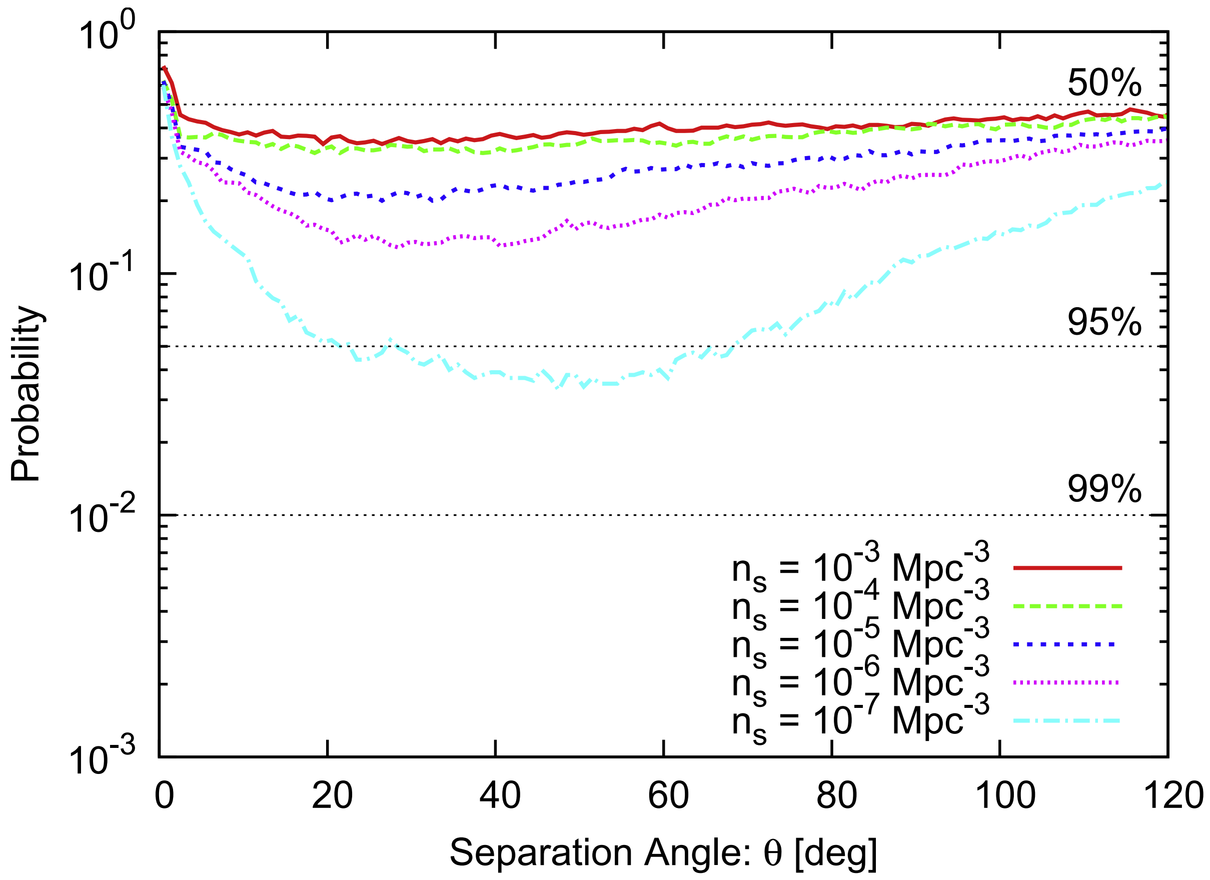


HT & Sato, Aph 30 (2009) 306
See also Cuoco et al., ApJ 702 (2009) 825

- 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

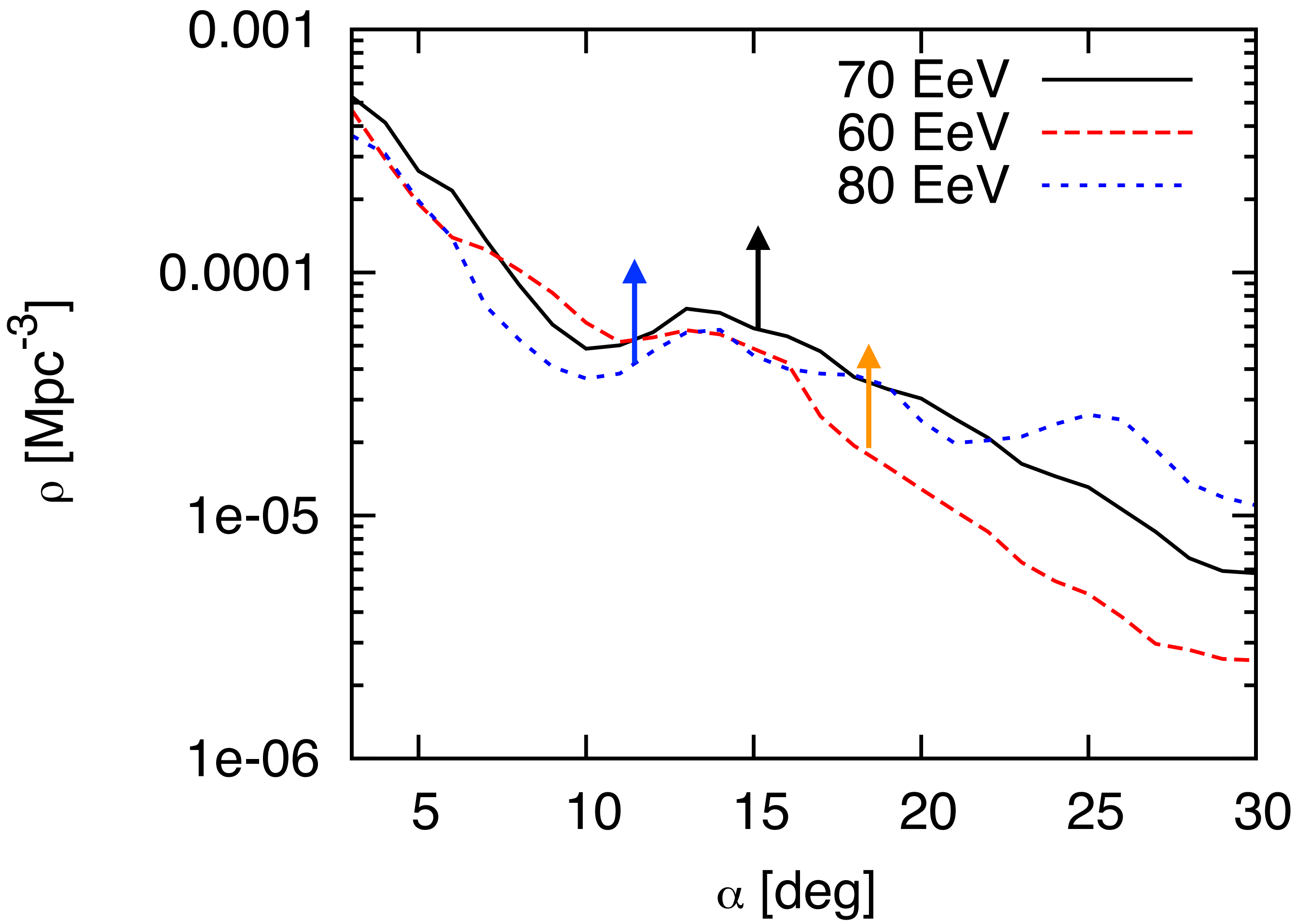
Source Number Density



- 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

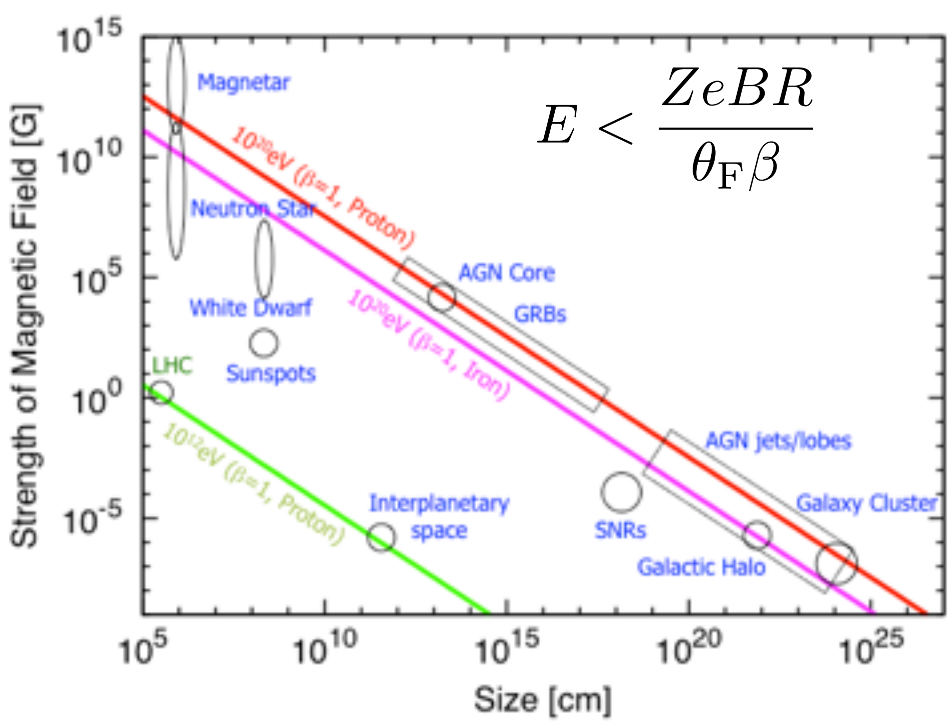
The Pierre Auger Observatory, JCAP, 05 (2013) 009

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



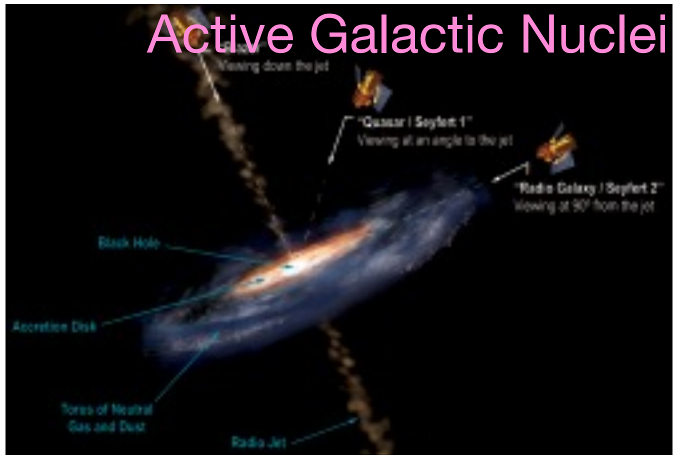
Magnetic Luminosity

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

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

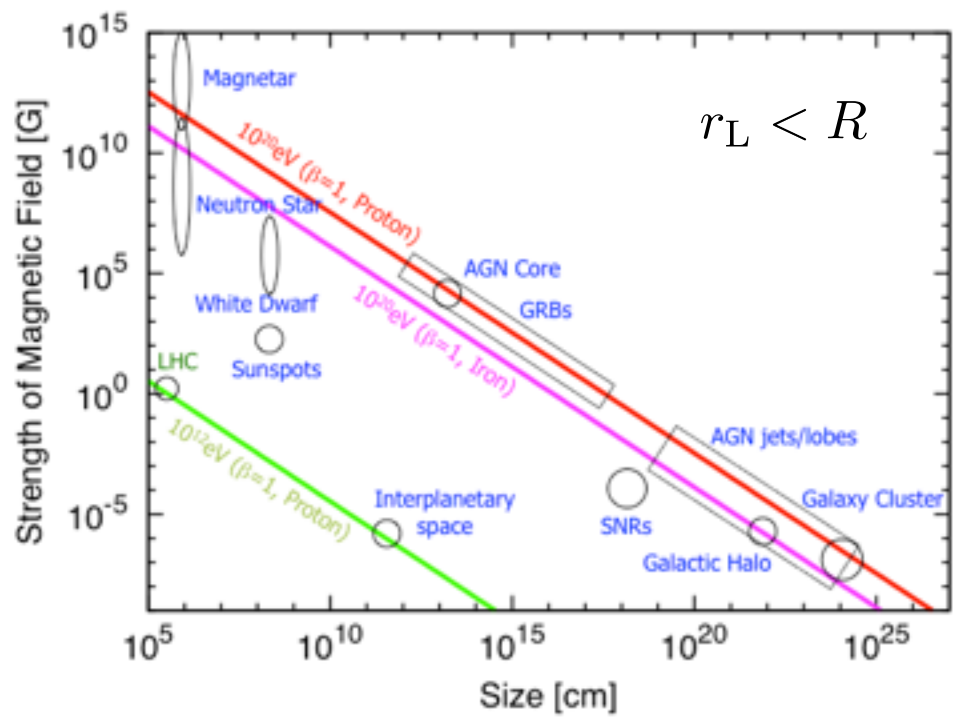


e.g., Biermann & Strittmatter, ApJ 322 (1987) 643,
Takahara, PTP 83 (1990) 1071,
Rachen & Biermann, A&A 272 (1993) 161,
Norman et al., ApJ 454 (1995) 60,
Farrar & Gruzinov, ApJ 693 (2009) 329,
Dermer et al., New J. Phys. 11 (2009) 065016
Pe'er et al., PRD 80 (2009) 123018,
HT & Horiuchi, Aph 34 (2011)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

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

Source Classification

Proton / Steady

Proton / Transient

Heavy / Steady

Heavy / Transient

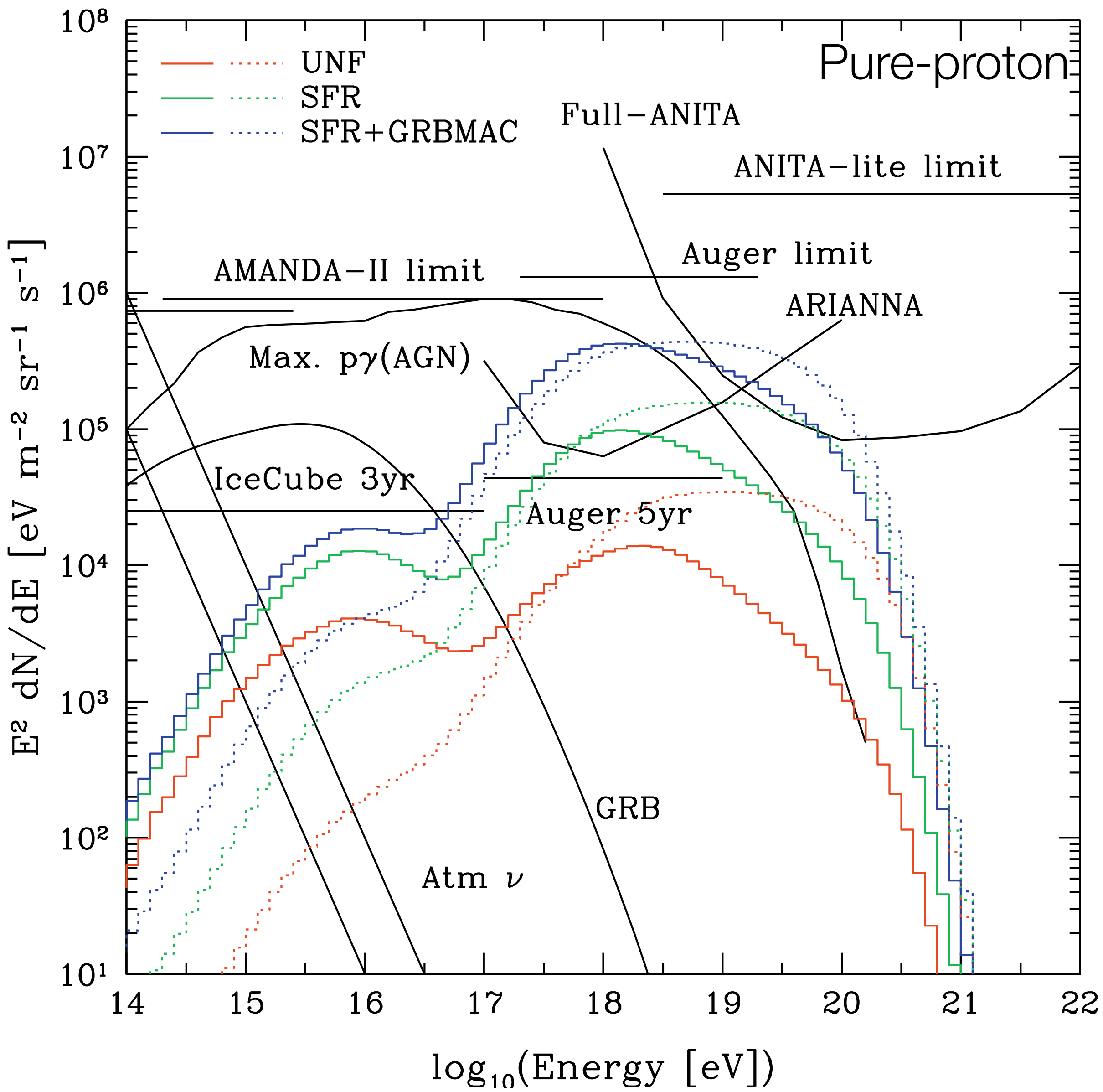
Cosmic-ray Secondaries ~ Multi-messenger ~

$p_{CR} + p_{gas}$
$p_{CR} + \gamma_{bkd}$

$\pi^0 \rightarrow 2\gamma$
$\pi^\pm \rightarrow \mu^\pm \nu_\mu$
$\rightarrow e^\pm \nu_\mu \nu_e$

Cosmogenic Neutrinos

Neutrinos produced during CR propagation in intergalactic space



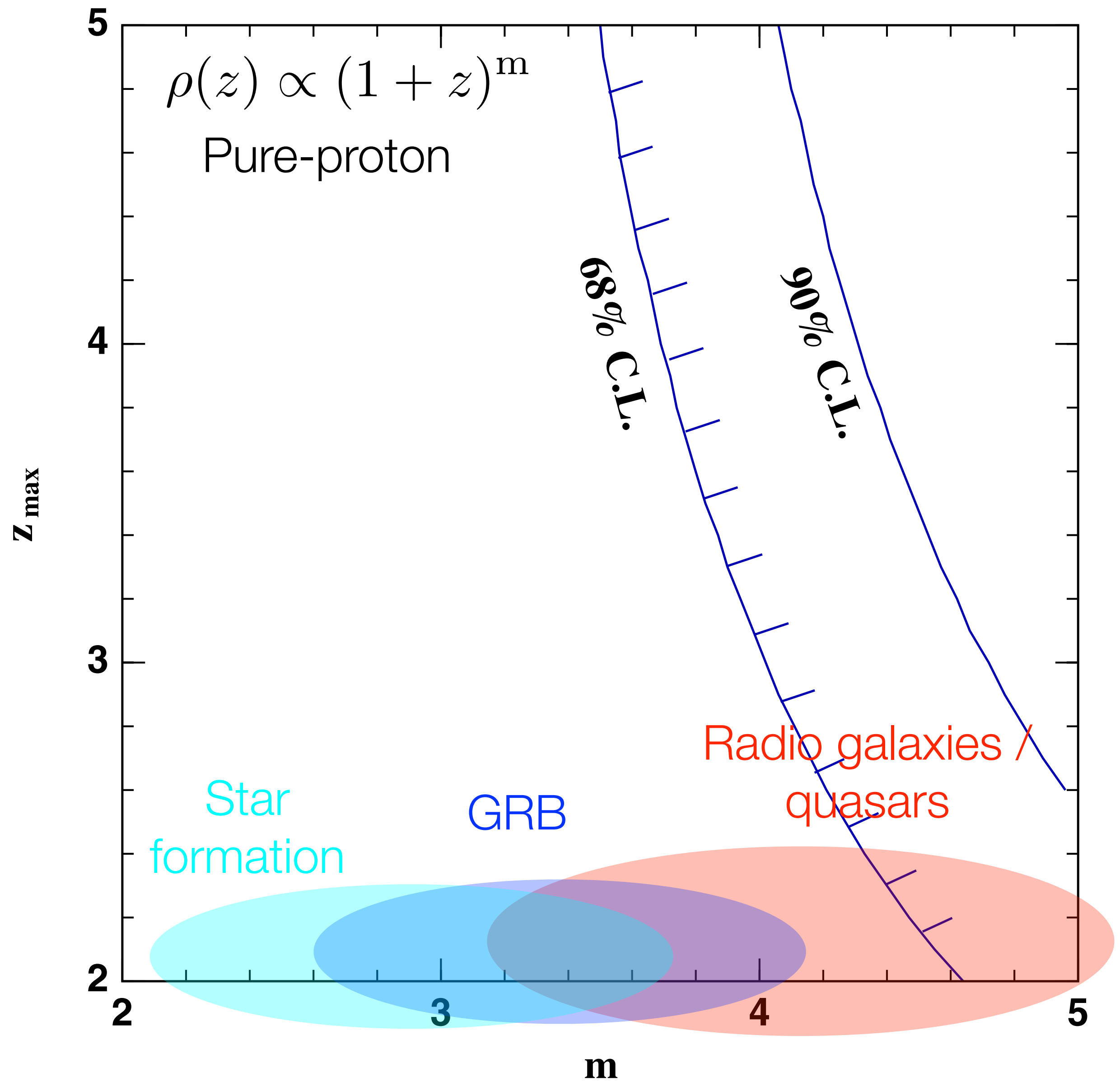
HT et al., Aph 31 (2009) 201

Depending on

- Cosmological evolution of UHECR sources
- Galactic-to-extragalactic CR transition
- Composition

Cosmogenic Neutrinos

Strongly evolved sources are already ruled out.



Aartsen et al., PRD 88 (2013) 112008

See also, Yoshida & Ishihara, PRD 85 (2012) 063002

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 >~ 10^{-4} Mpc^{-3}
  - heavy-nucleus-dominated >~ 10^{-6} Mpc^{-3}
- If proton-dominated composition,
  - the luminosity requirement → transient for jet-sources
  - Strong evolution is ruled out by neutrinos.

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

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

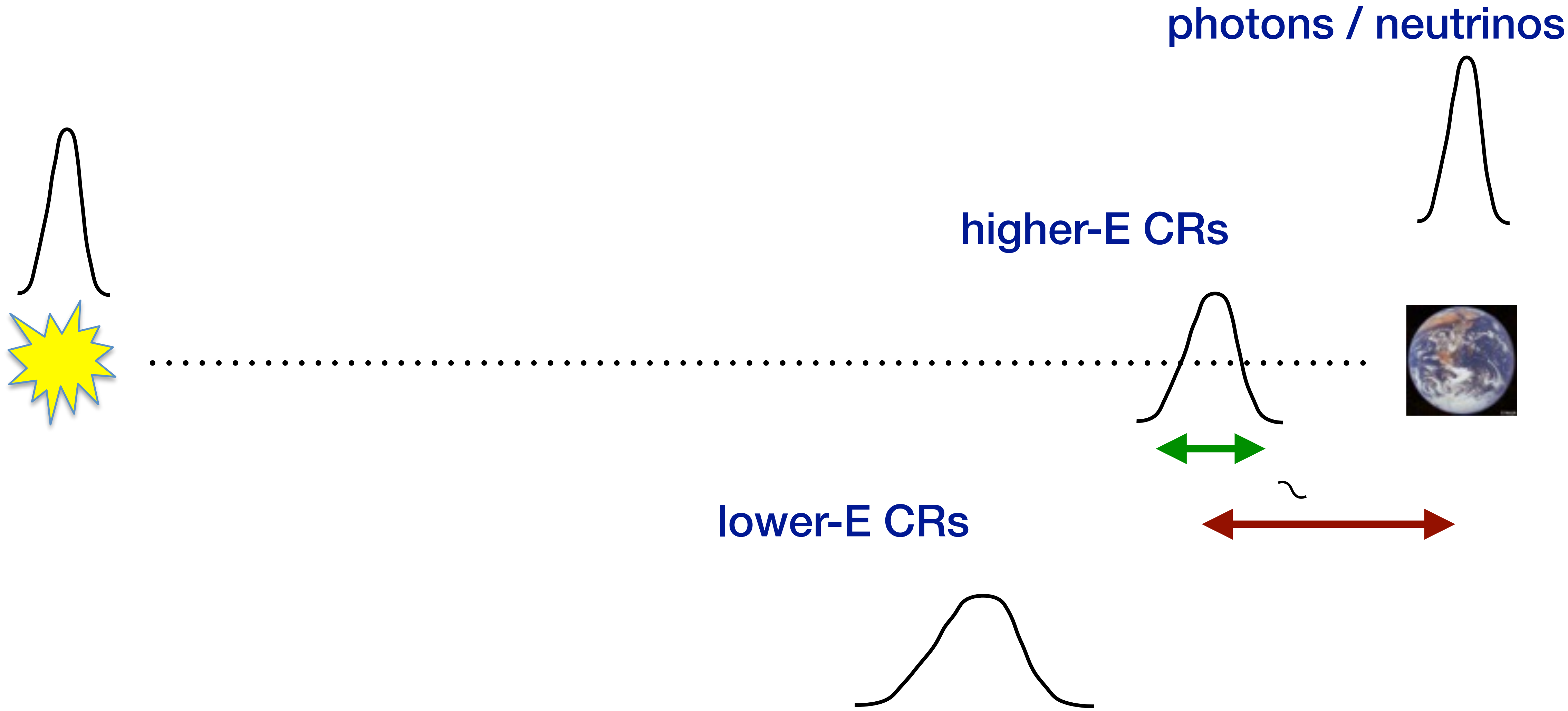
Source Classification

Proton / Steady	Proton / Transient
Heavy / Steady	Heavy / Transient

Transient Sources

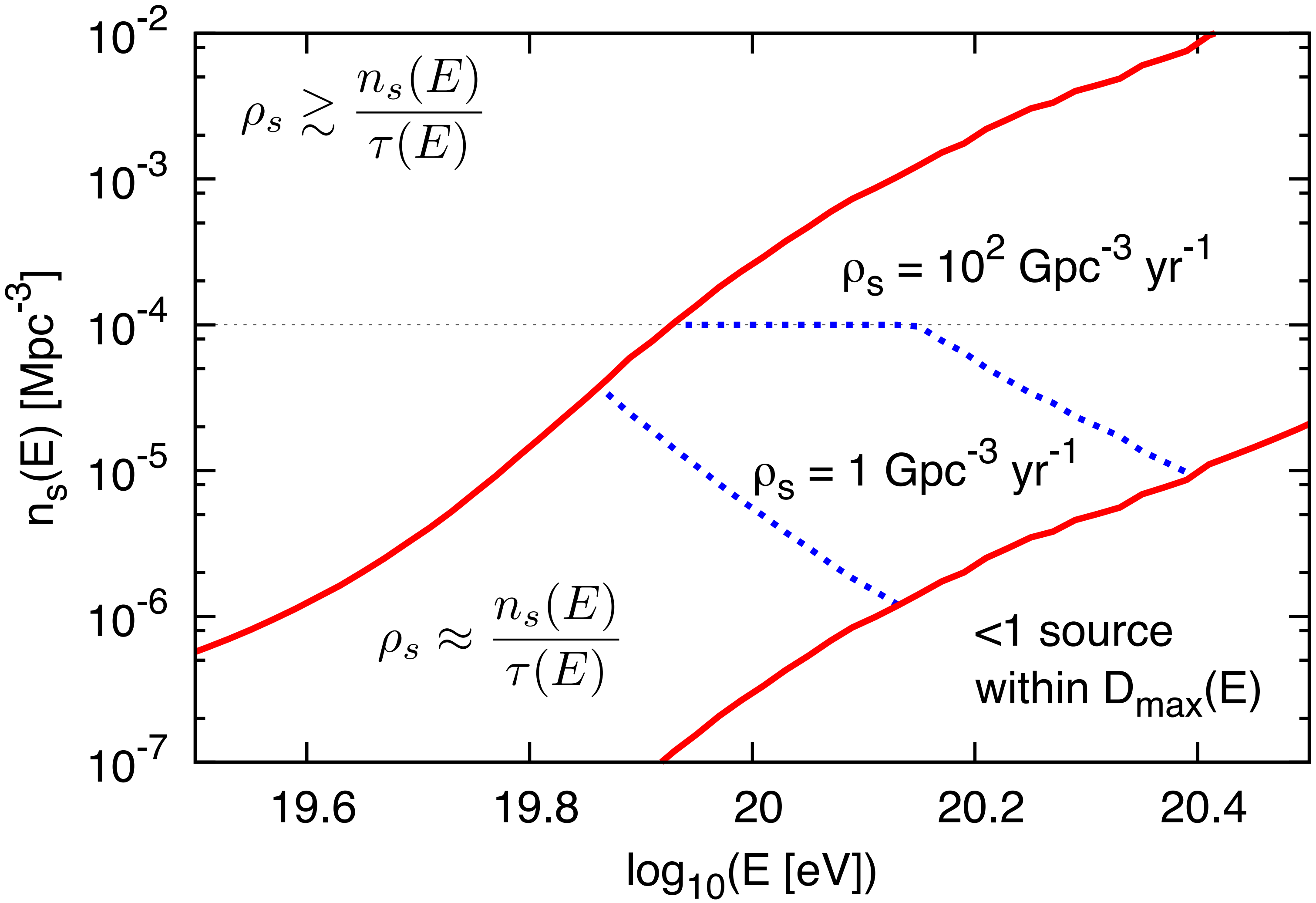
Time-delay and time-profile dispersion

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



Evidence for Transient Sources

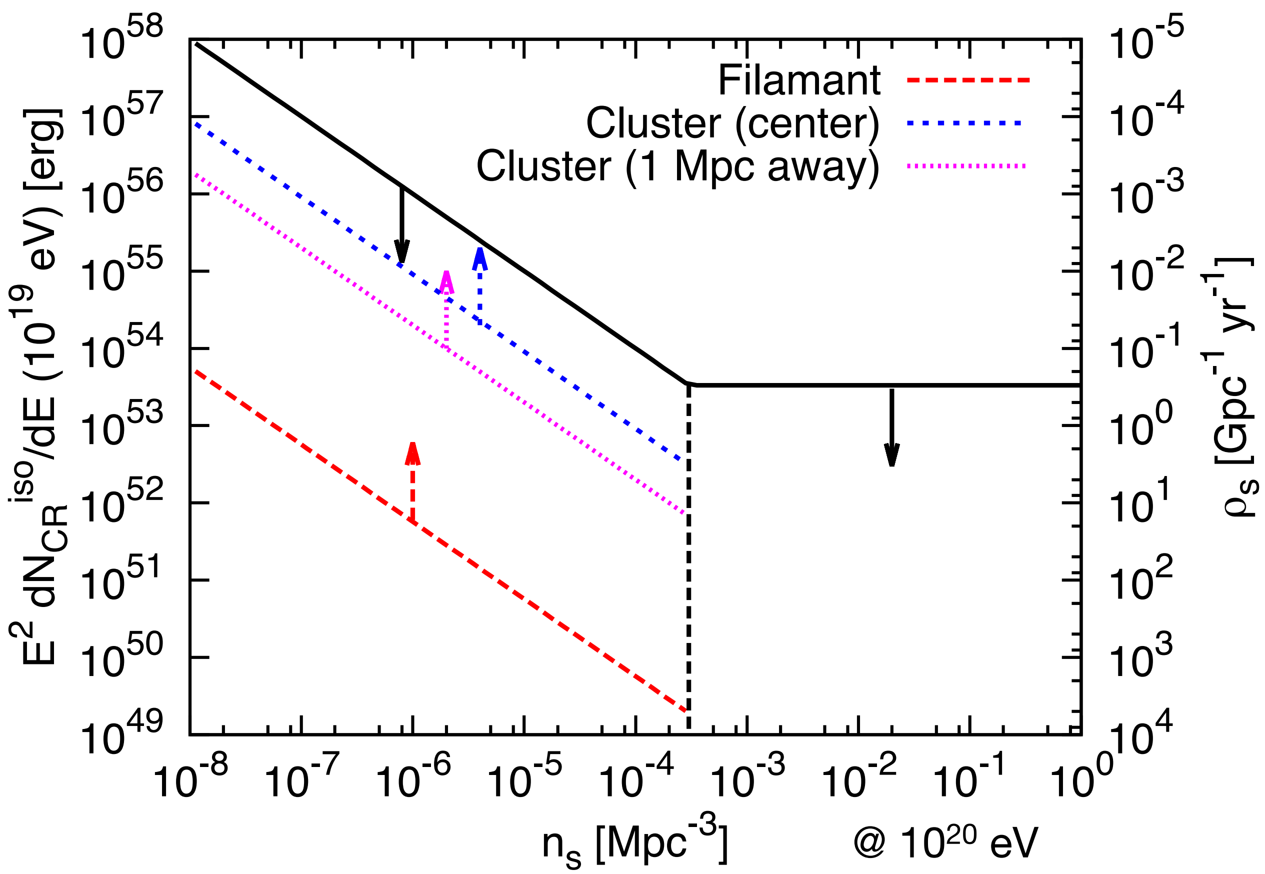
Strong energy dependence of apparent source number density



HT & Murase, ApJ 748 (2012) 9

Constraints on ρ_s and Energy Budget

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



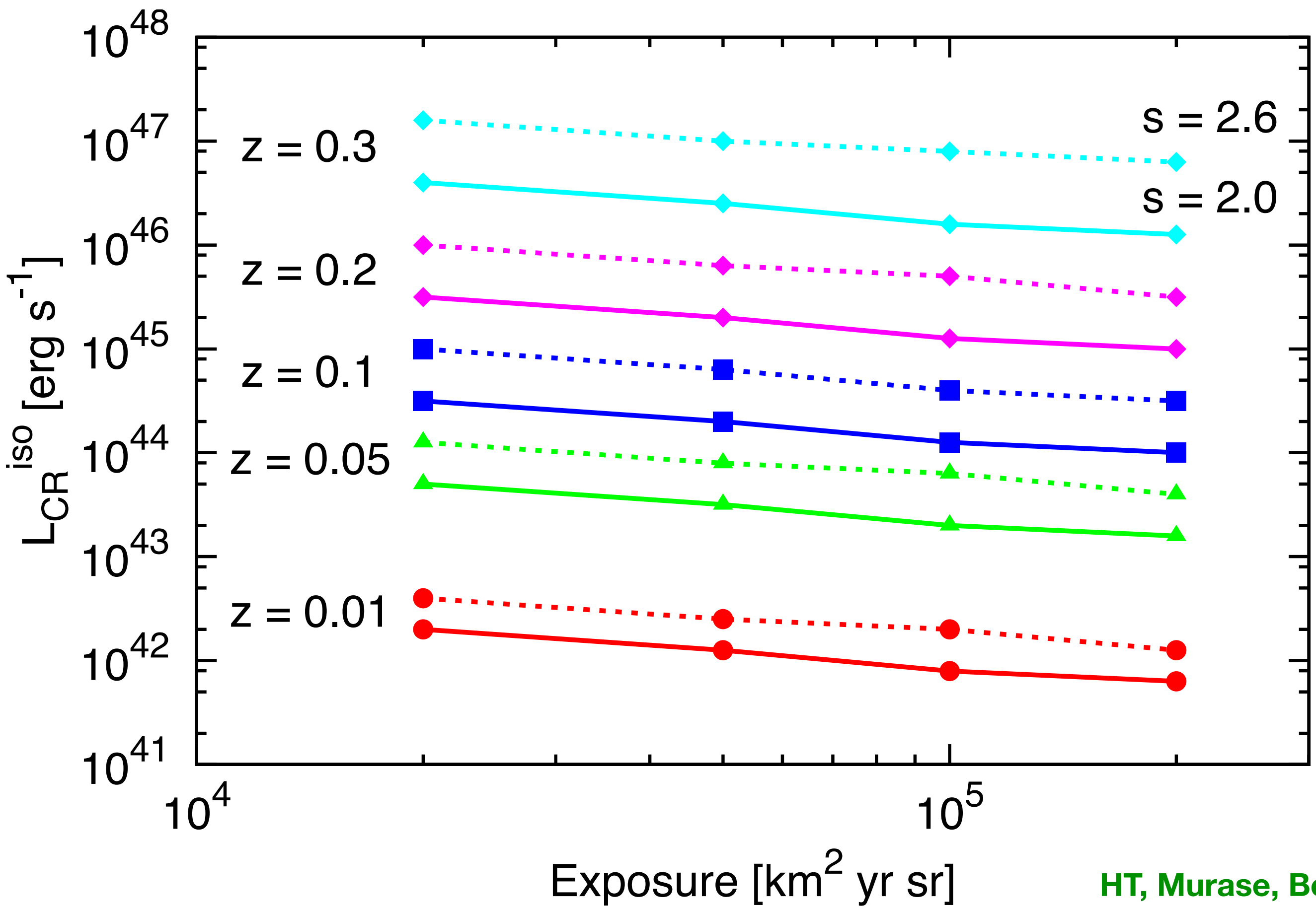
- τ_{min} : GMF, EGMF surrounding sources
- τ_{max} : GMF, EGMF surrounding sources, IGMF

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.



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

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)

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

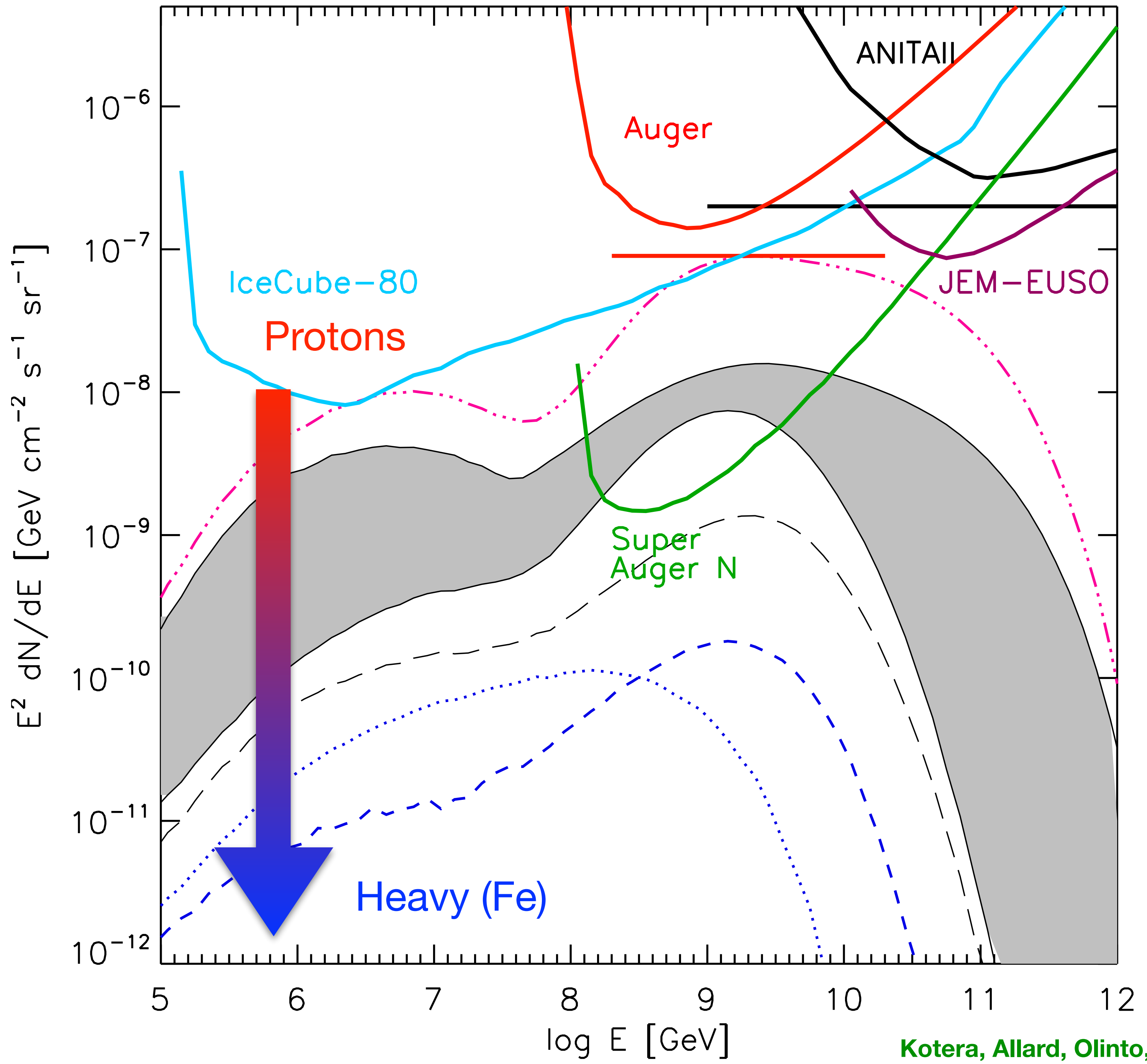
$$\frac{n_s(E_{\rm l})}{n_s(E_{\rm h})} \sim \frac{t_{\rm d}(E_{\rm l})}{t_{\rm d}(E_{\rm h})} \sim \left(\frac{E_{\rm l}}{E_{\rm h}} \right)^{-2} \sim 40$$

See also HT & Sato (2009)

What Can We Do of Composition?

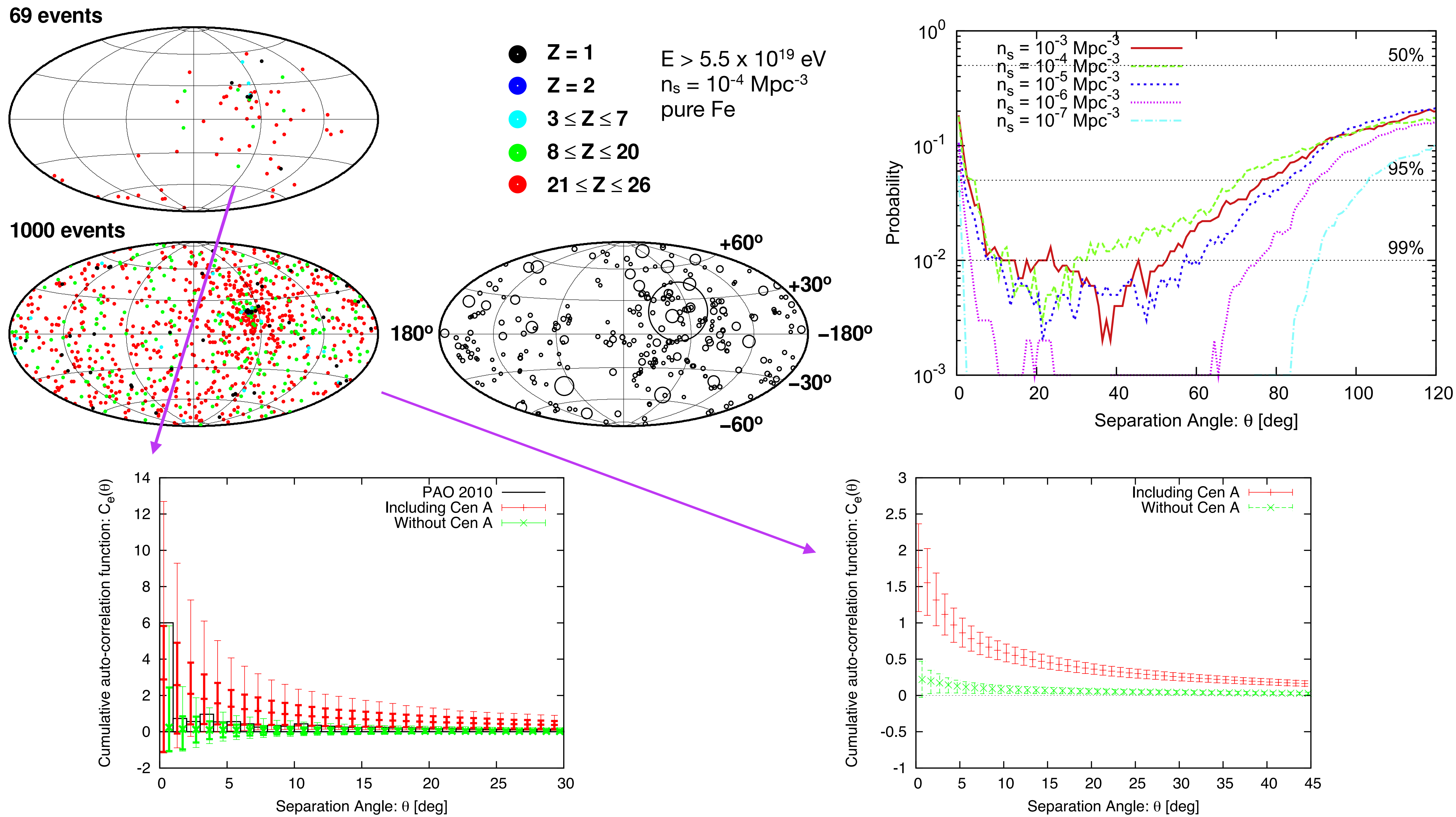
- $\sqrt{s_{\rm pp}} = 433~{\rm TeV}$ collider required
- Anisotropy measurements
- Cosmogenic neutrinos

Cosmogenic Neutrinos ~ Composition ~



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

Anisotropy in a heavy-nuclei-dominated case



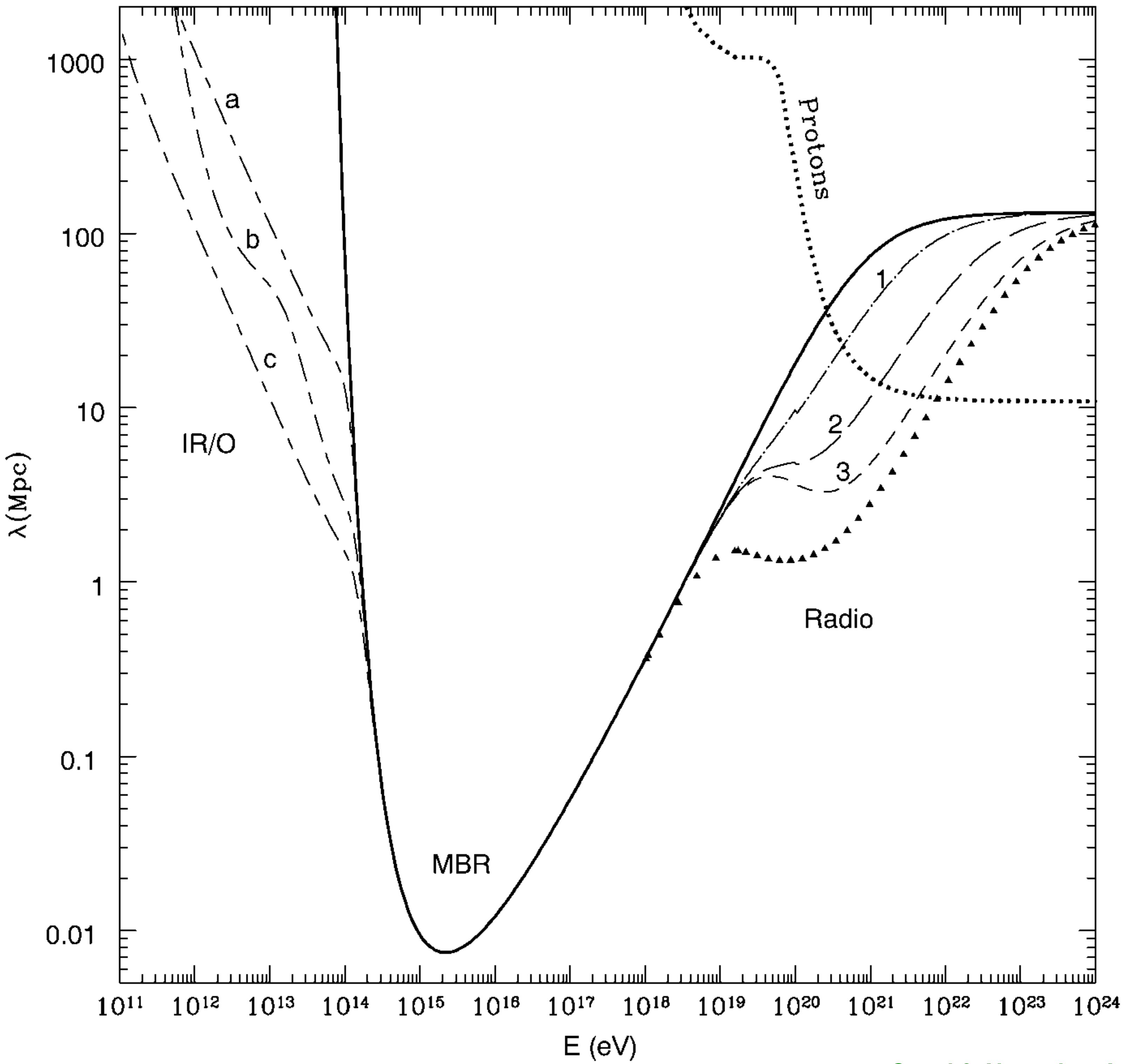
HT, Inoue, Yamamoto, Aph 35 (2012) 767

Anisotropy studies may be doable in the future.

Smoking Guns

- Ultrahigh energy *on-source* neutrinos
- Ultrahigh energy *on-source* gamma rays

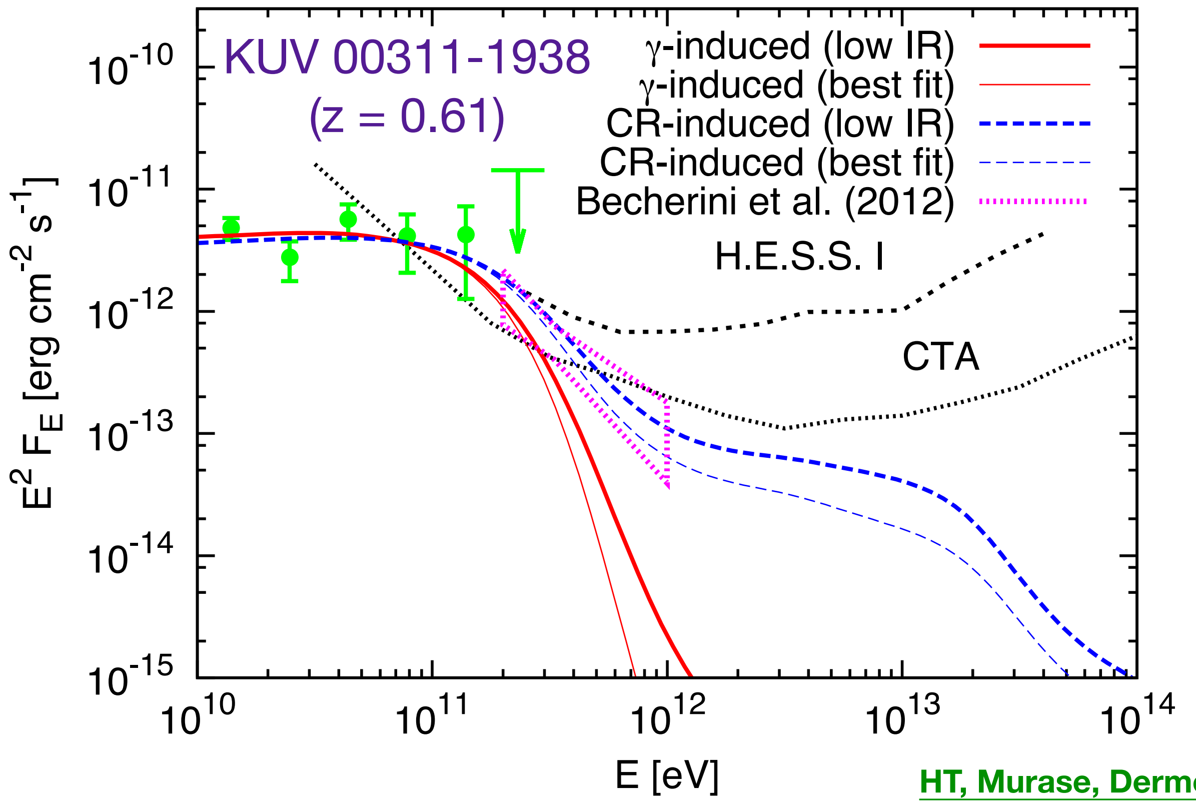
Mean Free Path of Photons



Coppi & Aharonian, ApJ 487 (1997) L9

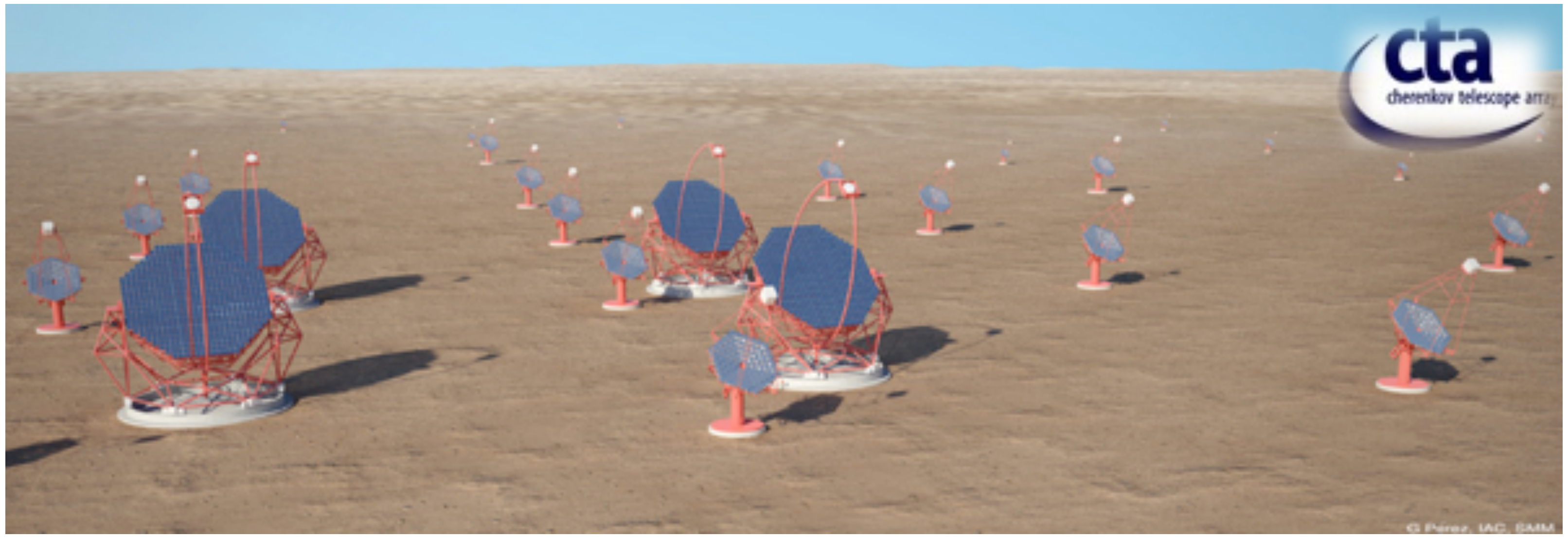
UHECR Source Signature in Gamma Rays

Hadronic secondary gamma-rays are promising for hard-spectrum blazars.



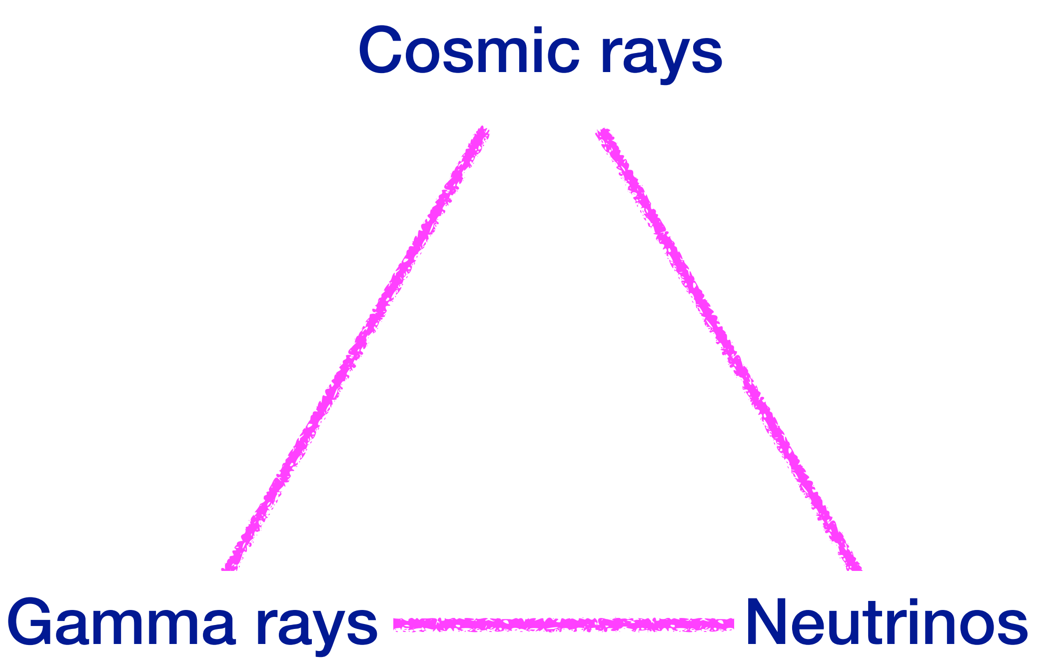
HT, Murase, Dermer, ApJL, 771 (2013) L32

- Primary gamma rays
  → sharp cutoff by EBL photons
- Hadronic secondaries
  → hard spectrum above the cutoff energy



The first international workshop on multi-messenger astronomy for ultrahigh-energy cosmic rays!

MACROS 2013



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!

Multi-messenger approaches will be essential to identify the sources of UHECRs.