Arrival distribution of ultra-high-energy cosmic rays and implications to their sources

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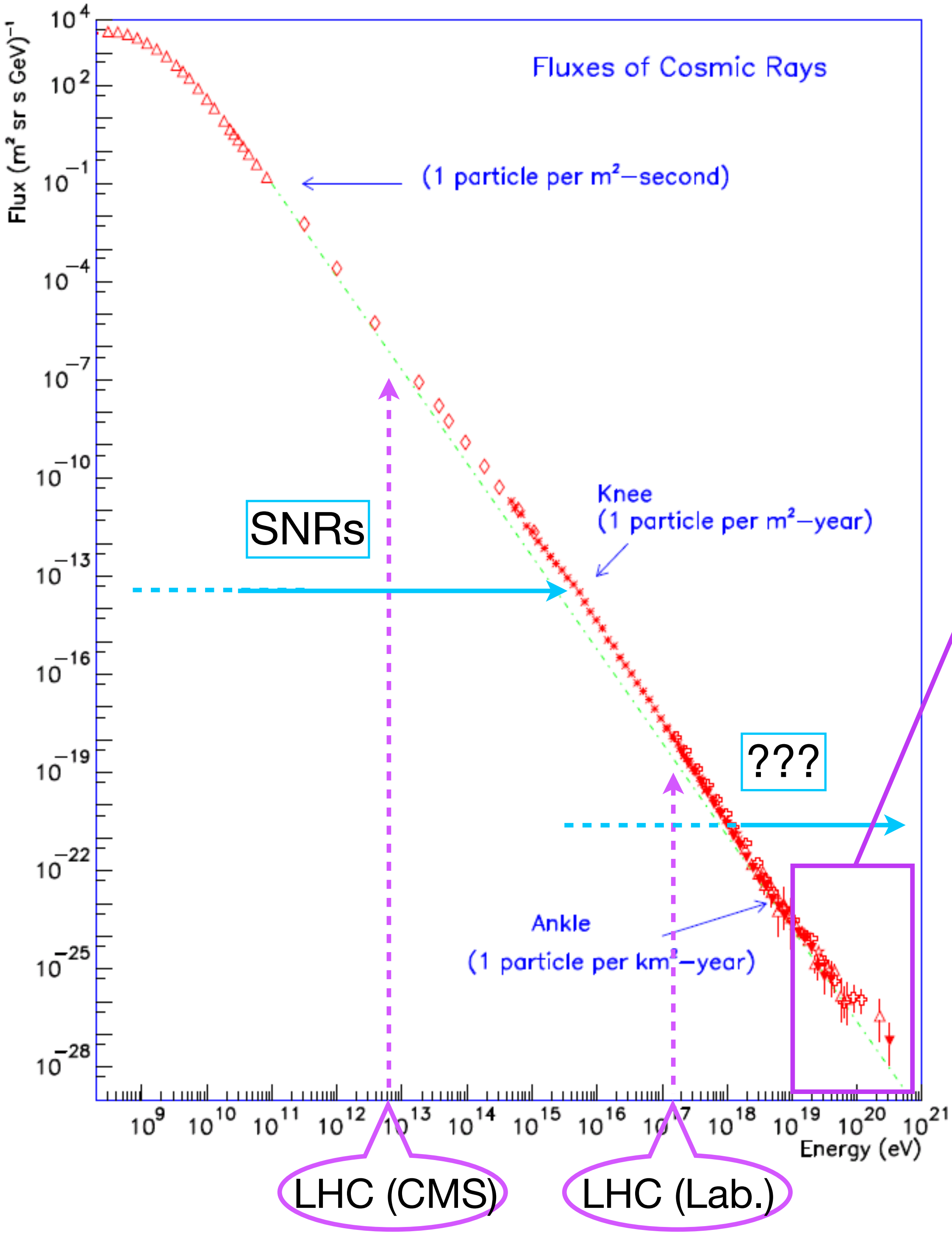
KEK Theory Center Cosmophysics Group

Cosmic rays

Bhattacharjee & Sigl '00, originally from S. Swordy

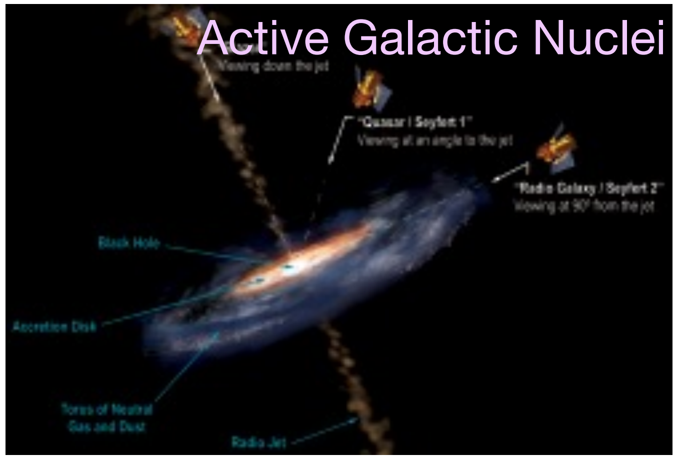


Ultra-high-energy cosmic rays

- Highest-energy particles ever detected
  - up to 3 x 10^{20} eV
- Extremely low flux
  - ~ 1 km^{-2} $millennium^{-1}$ @ 10^{20} eV
  - huge detectors are required to study
- None of their origin is not identified yet.

Source identification of UHECRs is an important first step to understand physics on the production of such extremely energetic particles.

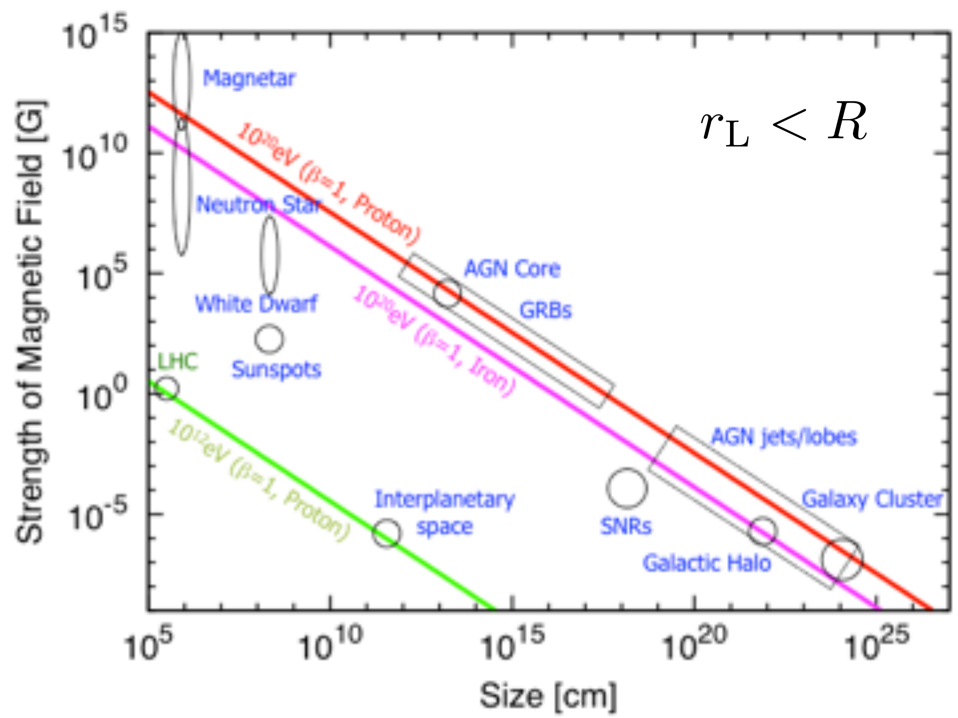
UHECR Source Candidates



e.g., Biermann & Stritmatter '87, Takahara '90, Rachen & Biermann '93, Farrar & Gruzinov '09, Dermer+ '09, Pe'er+ '09, HT & Horiuchi '11, Murase+ '11

Hillas Criterion

Larmor radius < Source size



JEM-EUSO purple book (2010)

e.g., Waxman '95, Vietri '95, Murase+ '08, Wang+ '09

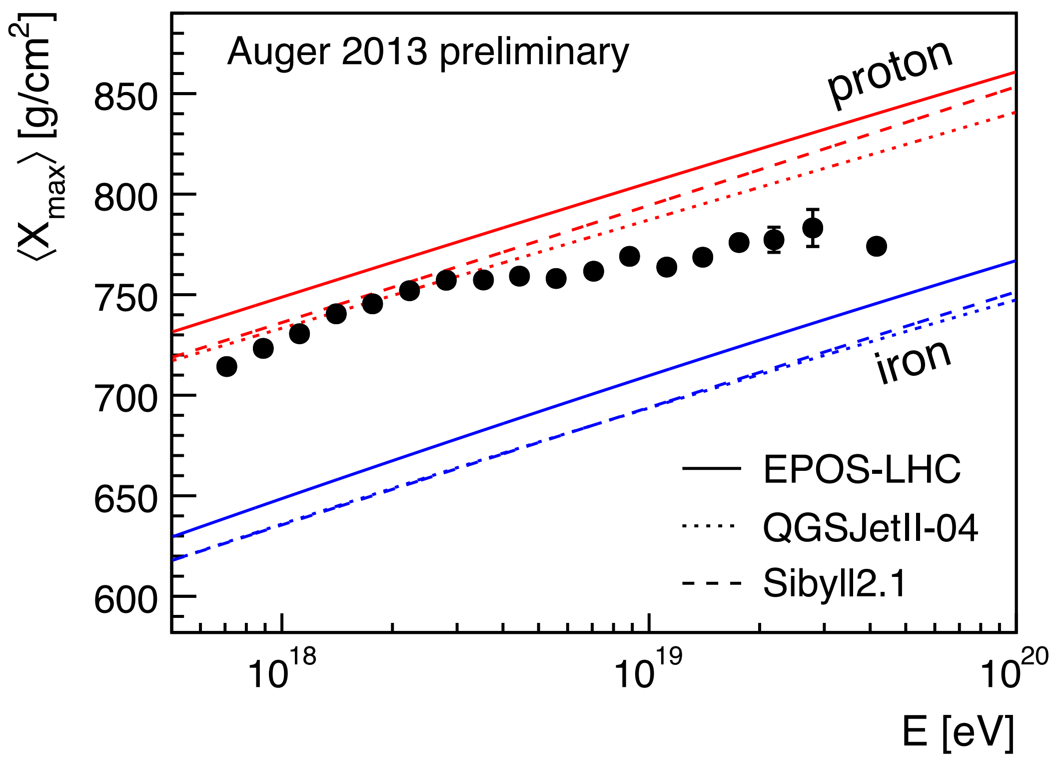
e.g., Blasi+ '00, Arons '03, Kotera '11, Fang+ '12

Only extreme phenomena or objects in the universe can produce the highest energy cosmic rays.

e.g., Norman+ '95, Kang+ '96, Inoue+ '07

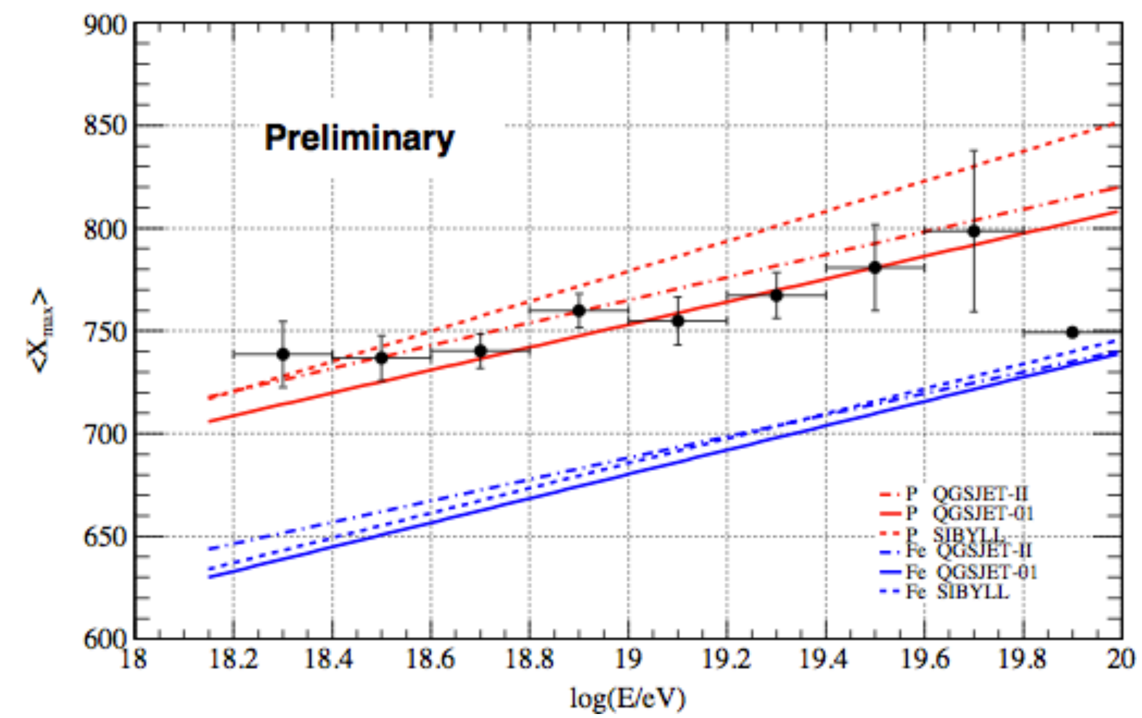
Estimated Composition of UHECRs

Auger : heavy elements are mixed



Letessier-selvon+ 2013

Telescope Array : consistent with protons

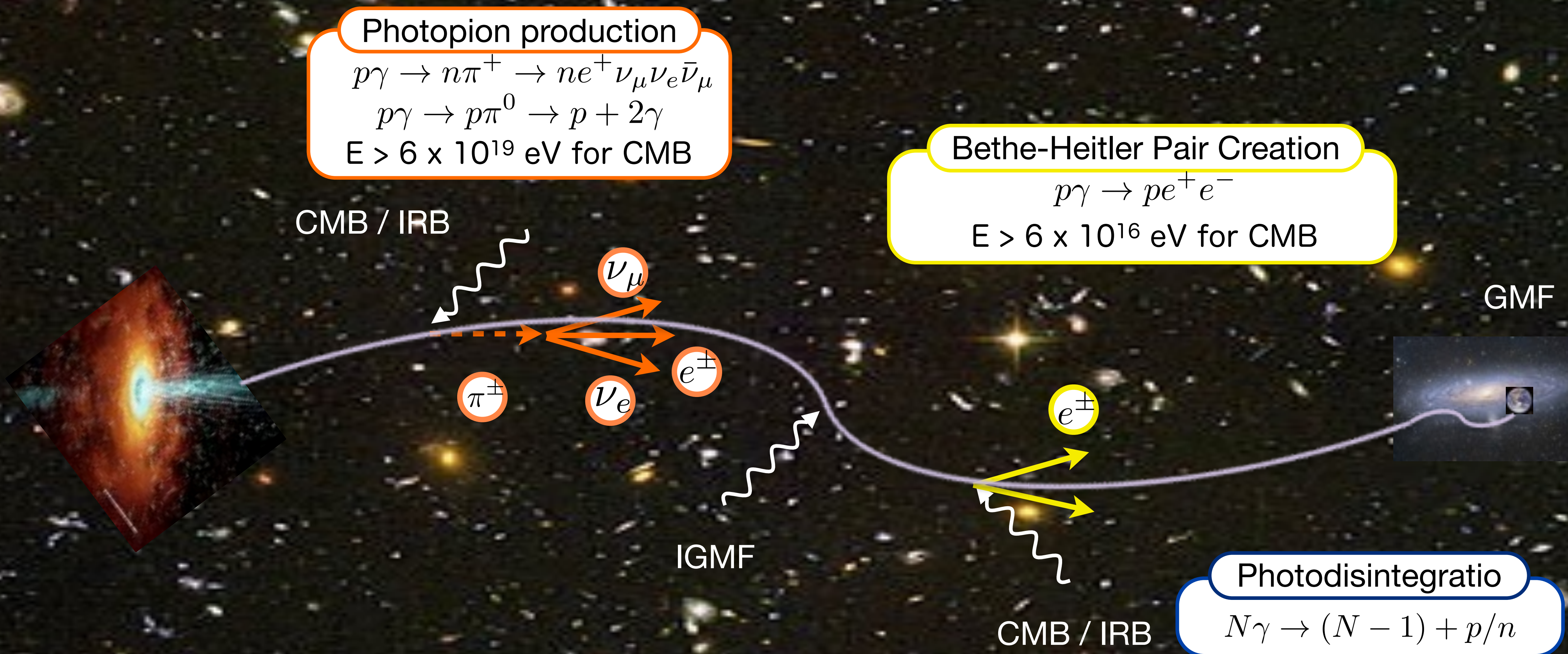


TA Collaboration 2011

The recent results are significantly inconsistent within the quoted systematic errors.

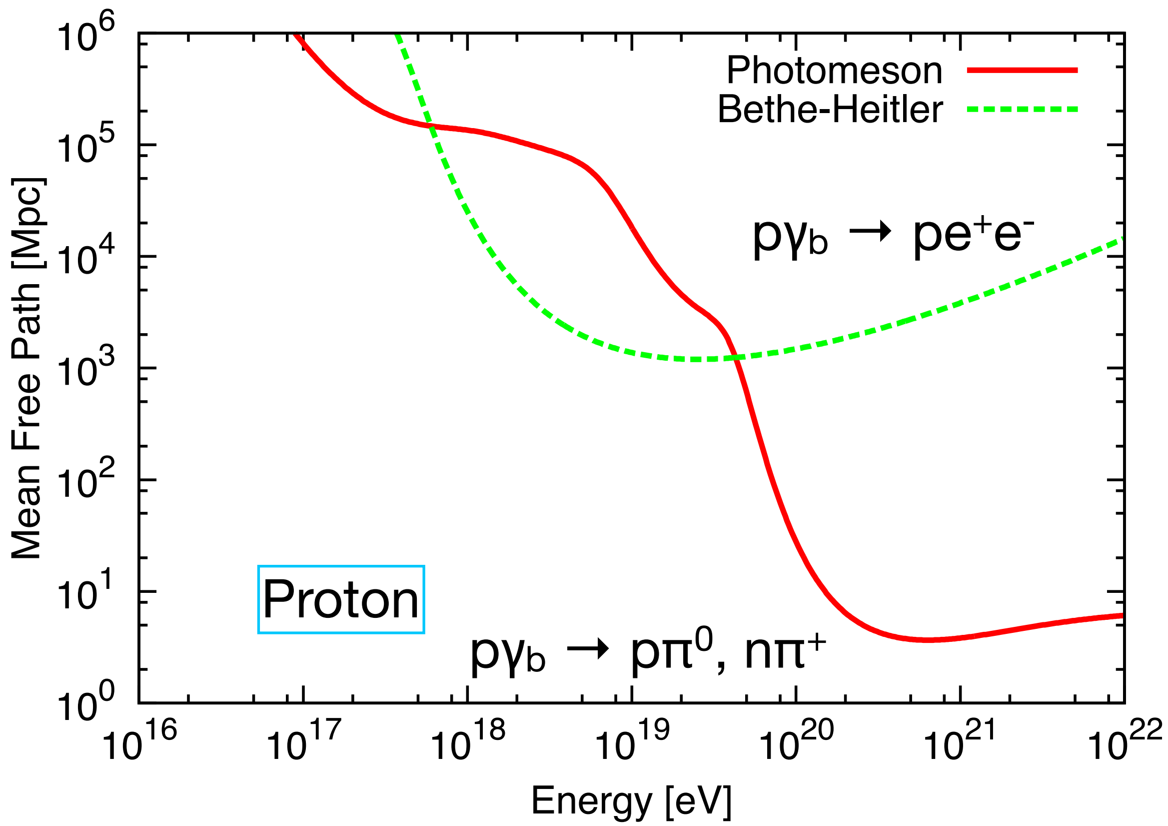
A joint working group of Auger and TA is collaborating to solve this problem.

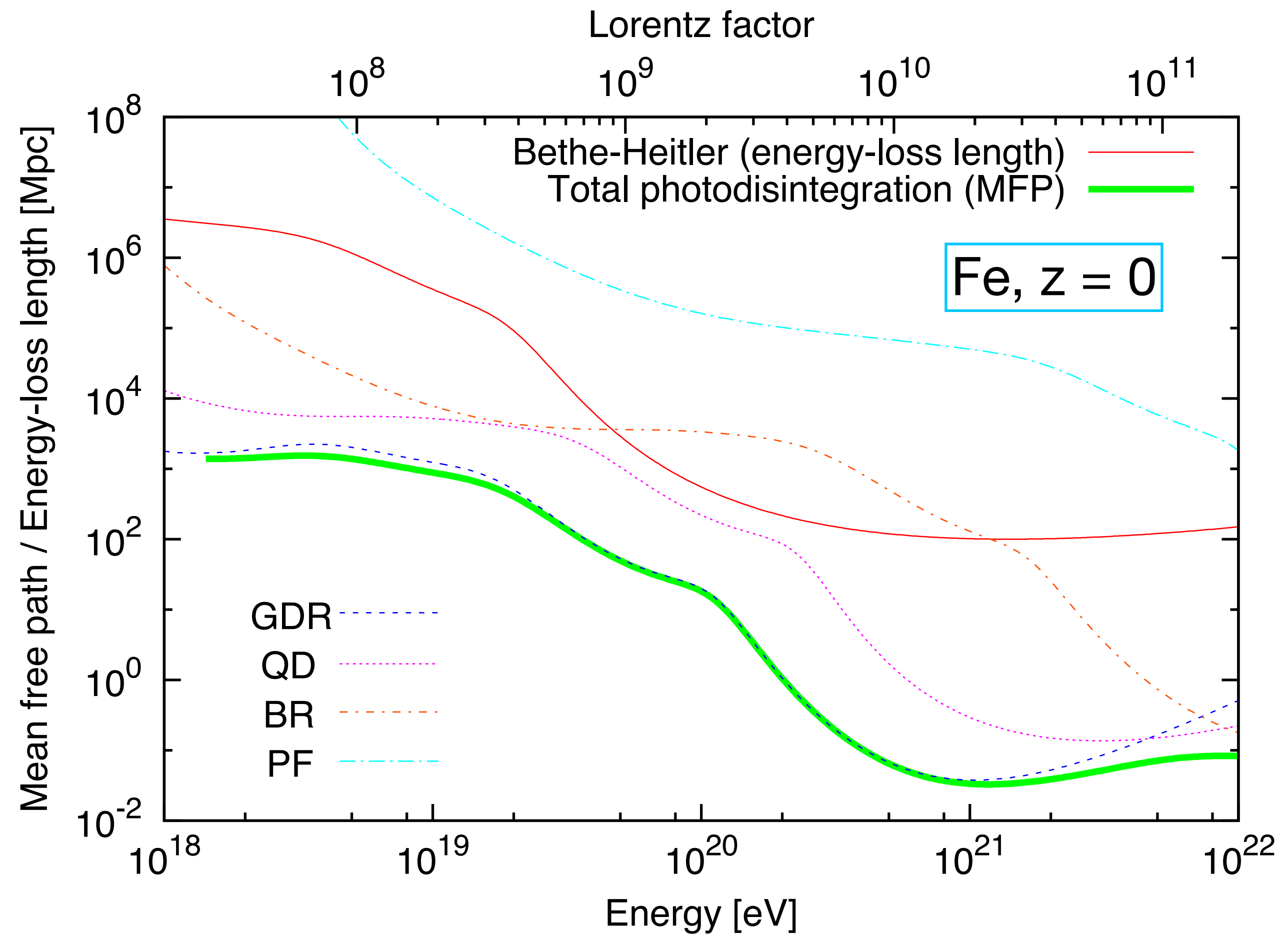
Propagation of UHECRs



Cosmic magnetic fields deflect the propagation trajectories of UHECRs and make it difficult to identify sources by UHECR experiments

Mean Free Paths of UHECRs in Intergalactic Space





HT, Inoue, Yamamoto 2012

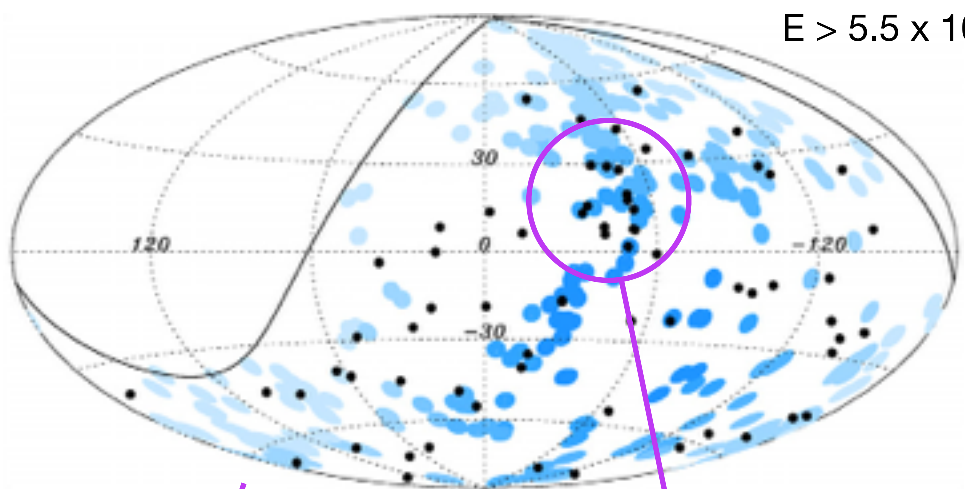
The mean free path of UHECRs rapidly decreases above ~10^{20} eV

Sources of UHECRs detected with >~ 10^{20} eV are dominantly located within several tens Mpc.

UHECR Anisotropy

Auger

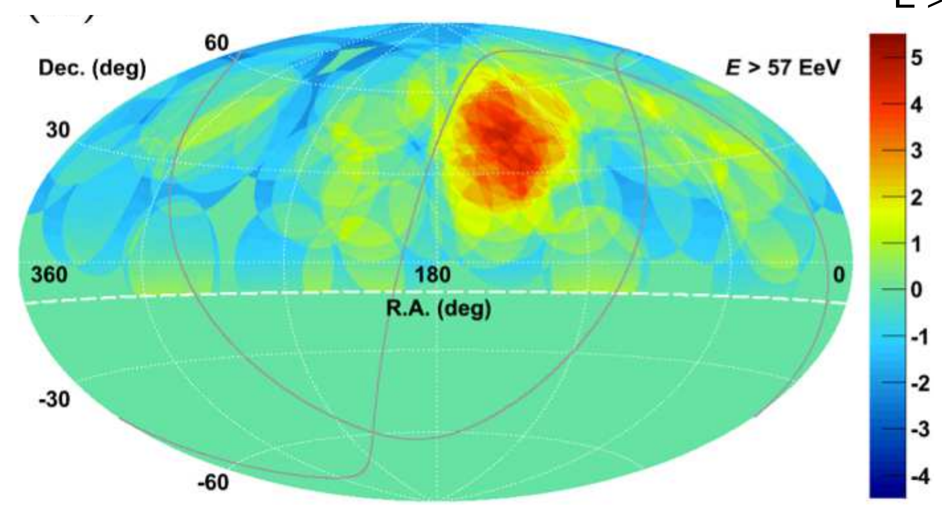
69 events
E > 5.5 x 10^{19} eV



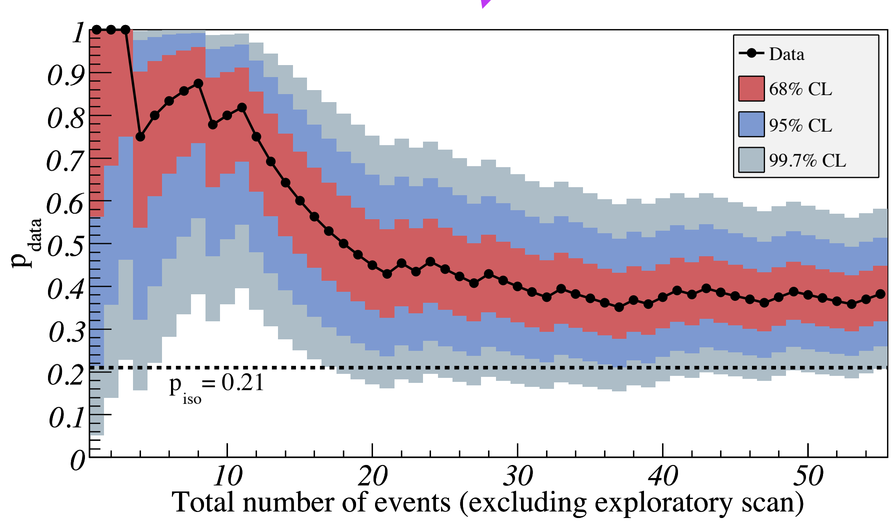
Abreu+ 2010

Telescope Array

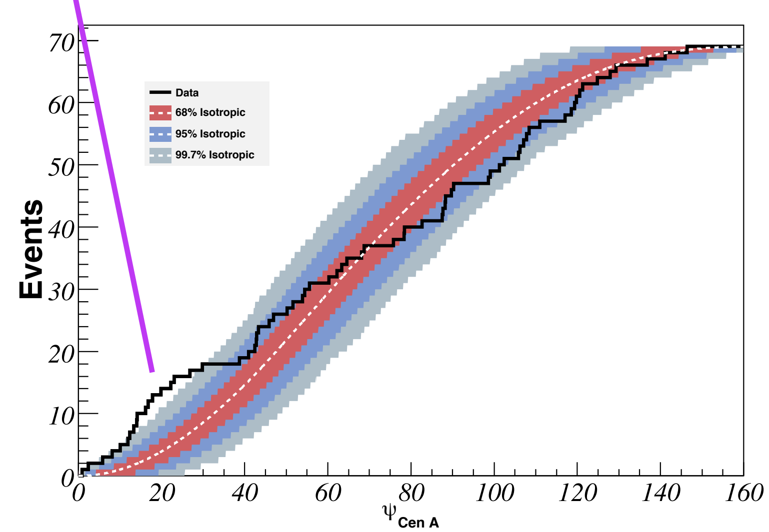
72 events
E > 5.7 x 10^{19} eV



Abassi+ 2014



Abreu+ 2010



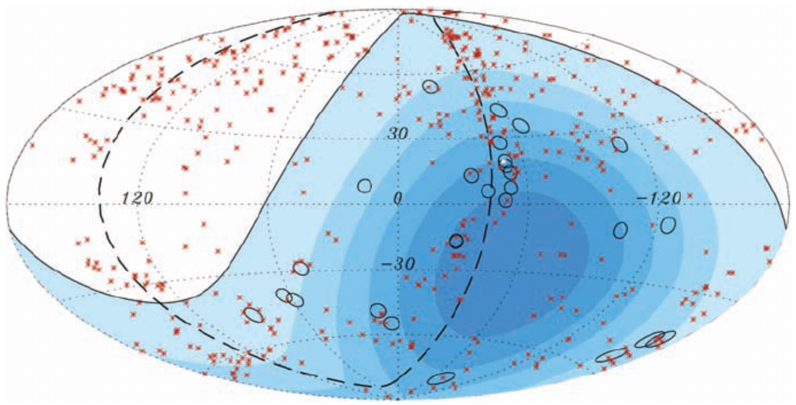
Abreu+ 2010

Hints of anisotropy have been reported, but no clear evidence of point-like sources so far.

→ **Statistical approach**

Anisotropy and UHECR Source Number Density

Experimental result

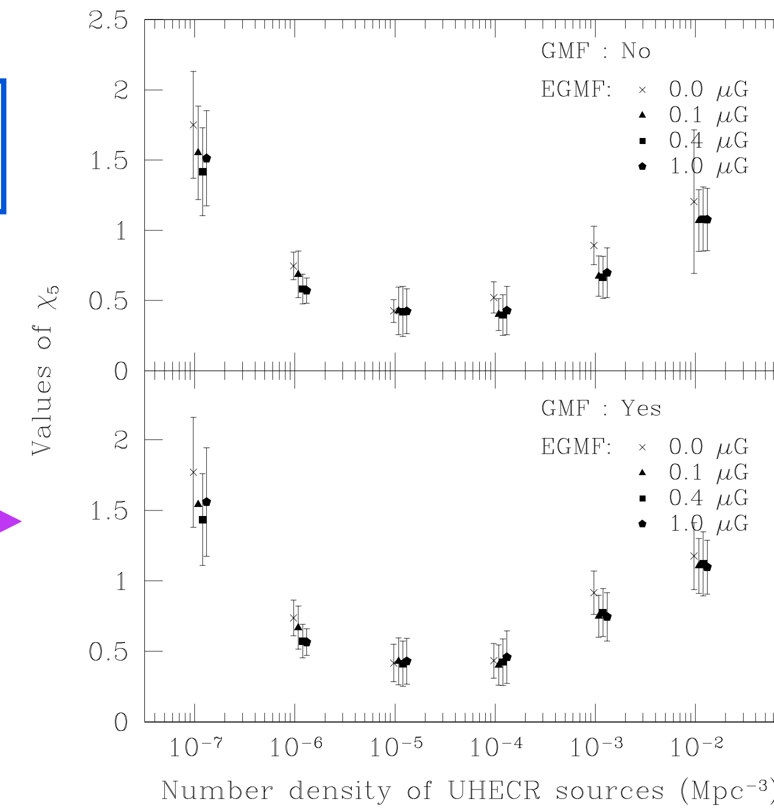


Abraham+ 2007

$n_s = 10^{-5} - 10^{-4}$ Mpc^{-3}
for E > 5.5 x 10^{19} eV

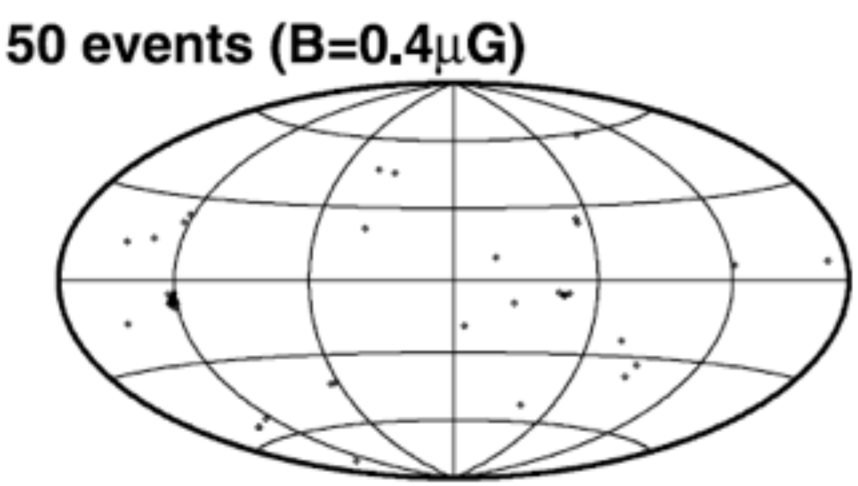
HT & Sato 2009
Cuoco+ 2009

statistical comparison



HT & Sato 2009

Simulations under assumed n_s

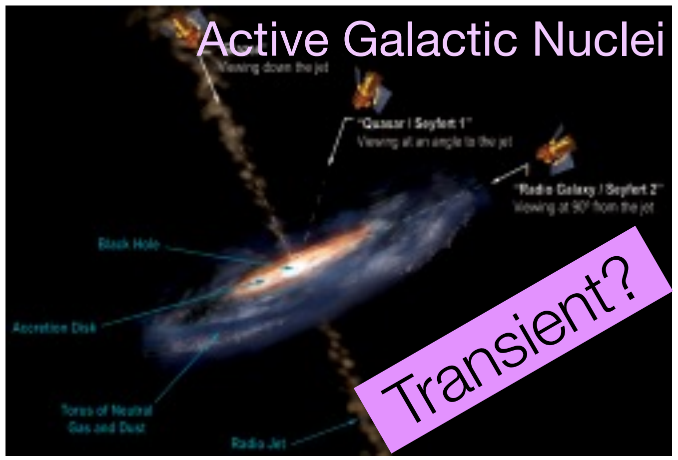


HT & Sato 2008

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

Assuming steady sources

UHECR Source Candidates



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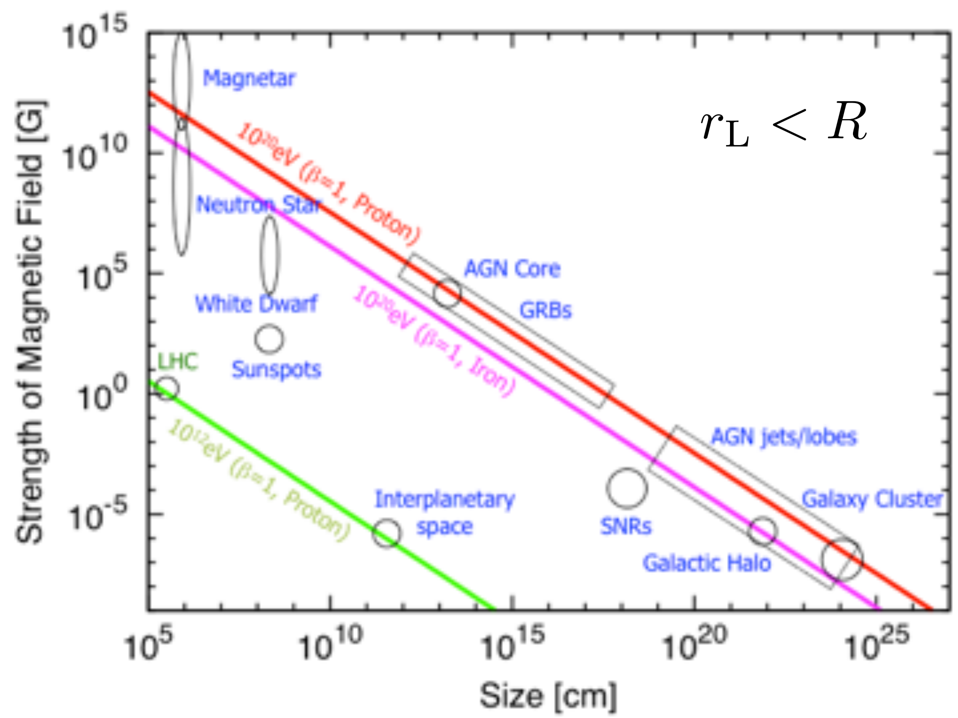
Hillas Criterion



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Only extreme phenomena or objects in the universe can produce the highest energy cosmic rays.

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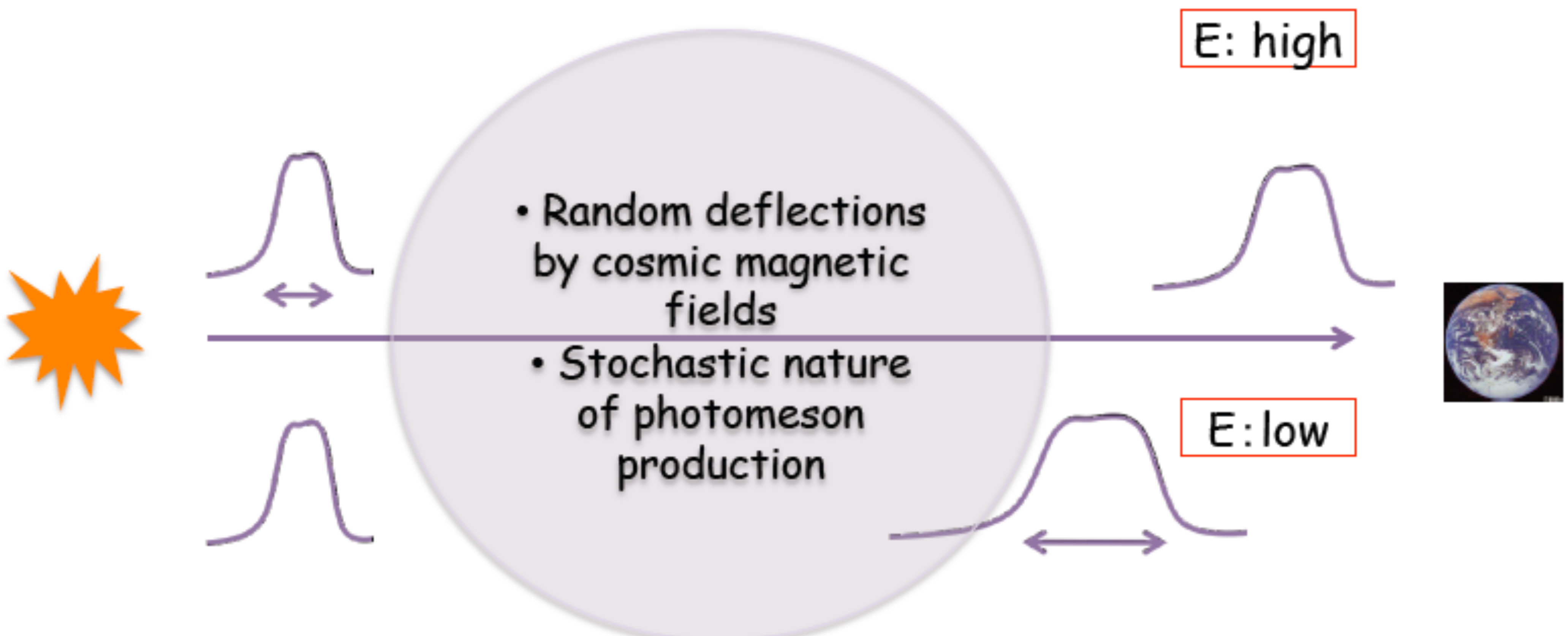
Propagation of UHECRs from a Transient Source

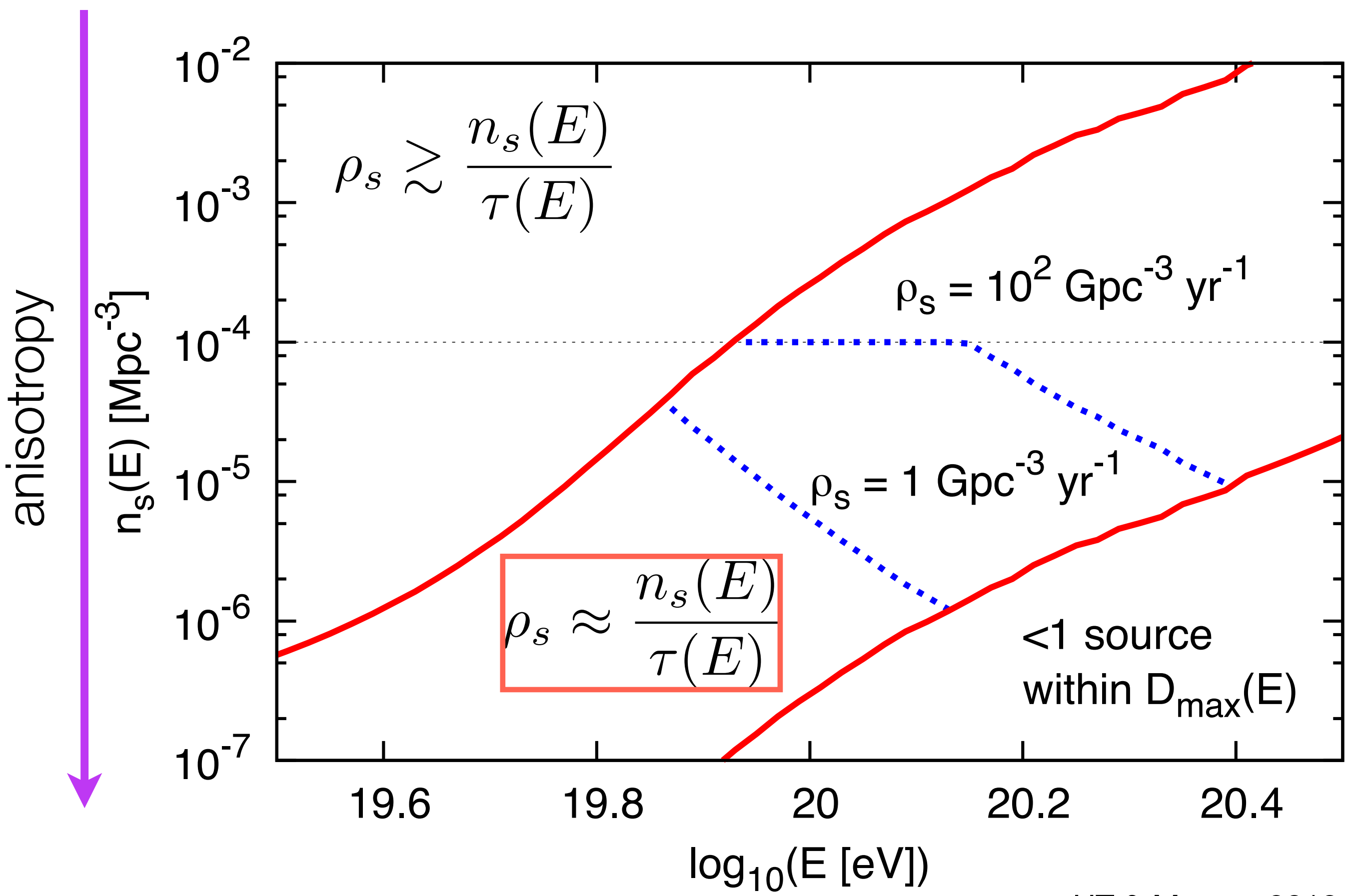
Observational features are different among energies.



- ✓ Arrival time is delayed, and depends on energies.
- ✓ Intrinsic burst duration < apparent CR-burst duration
- ✓ Apparent duration also depends on energies.

Apparent Source Number Density of UHECRs

A stronger anisotropy appears at higher energies
(even without considering the GZK mechanism).



HT & Murase 2012

Higher energy CRs

Shorter apparent duration

↓

Smaller probability to observe a UHECR burst

↓

Smaller number of “point source”-like features

↓ + GZK mechanism

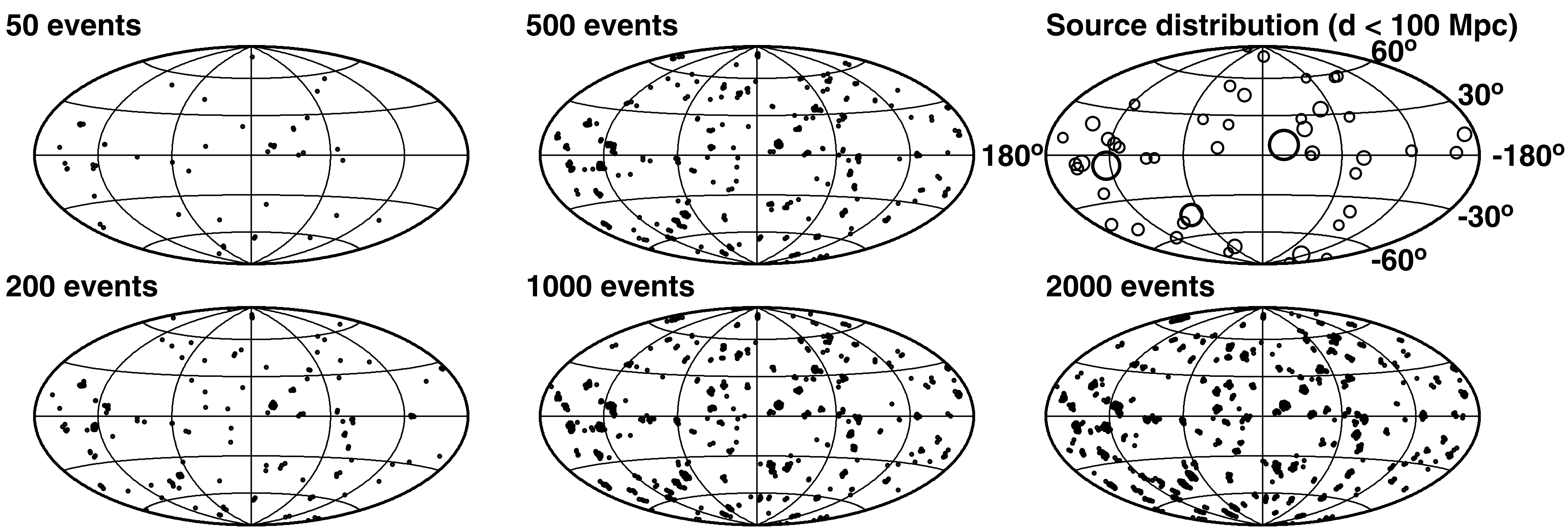
Stronger anisotropy (smaller n_s(E))

The dependence of n_s(E) is evidence of transient generation of UHECRs.

n_s(E) should be estimated in at least two energy ranges.

Evolution of anisotropy

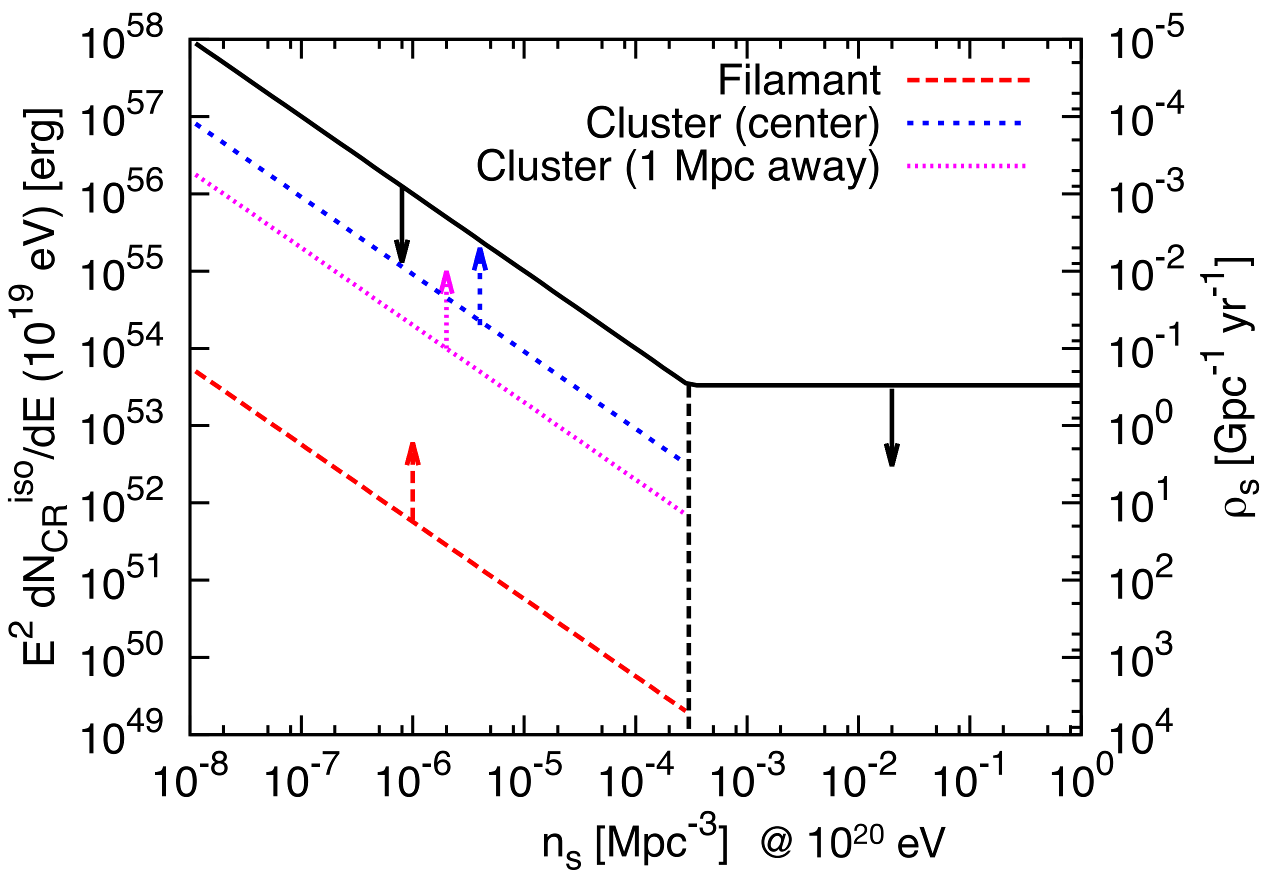
$E_p > 6 \times 10^{19}$ eV, $n_s = 10^{-5}$ Mpc^{-3}



HT & Sato 2008

Constraints on ρs and Energy Budget

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



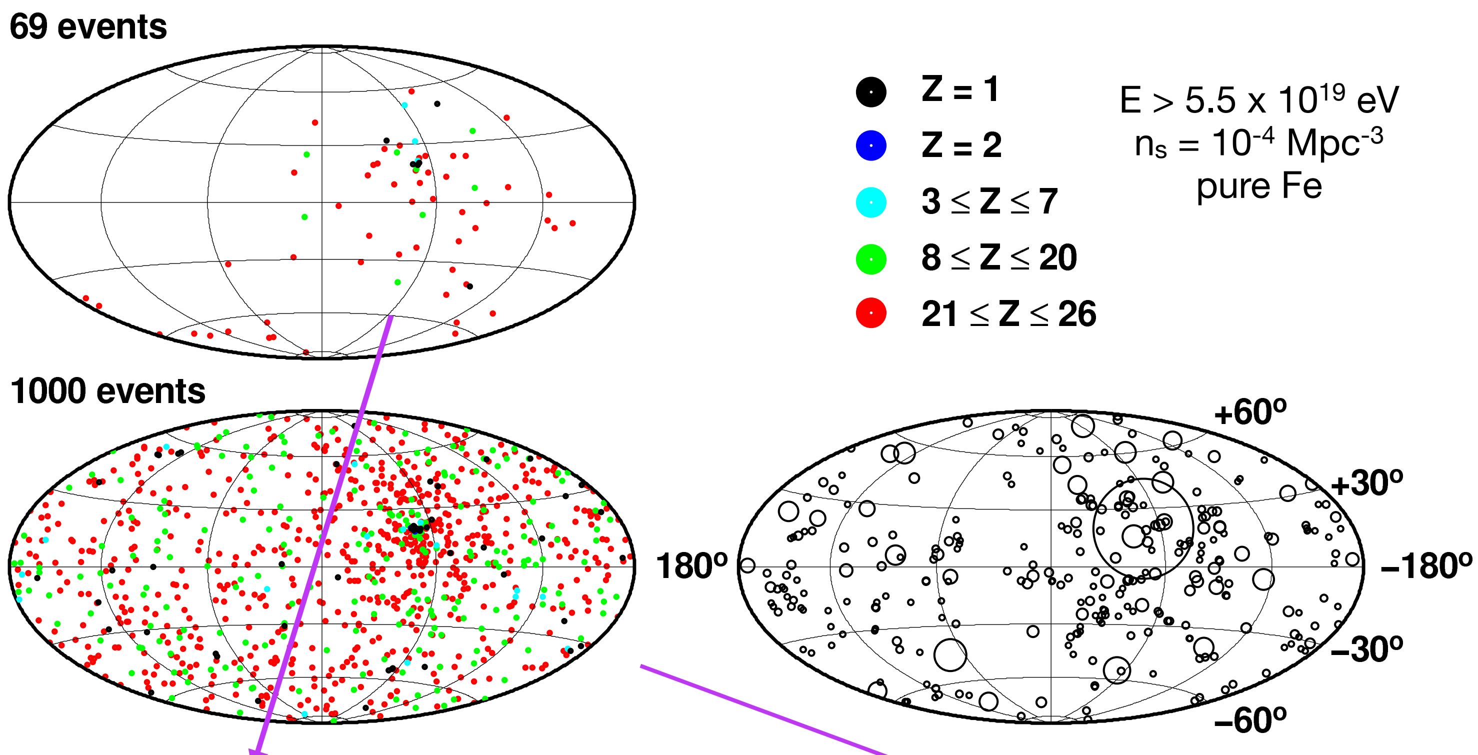
HT & Murase 2012

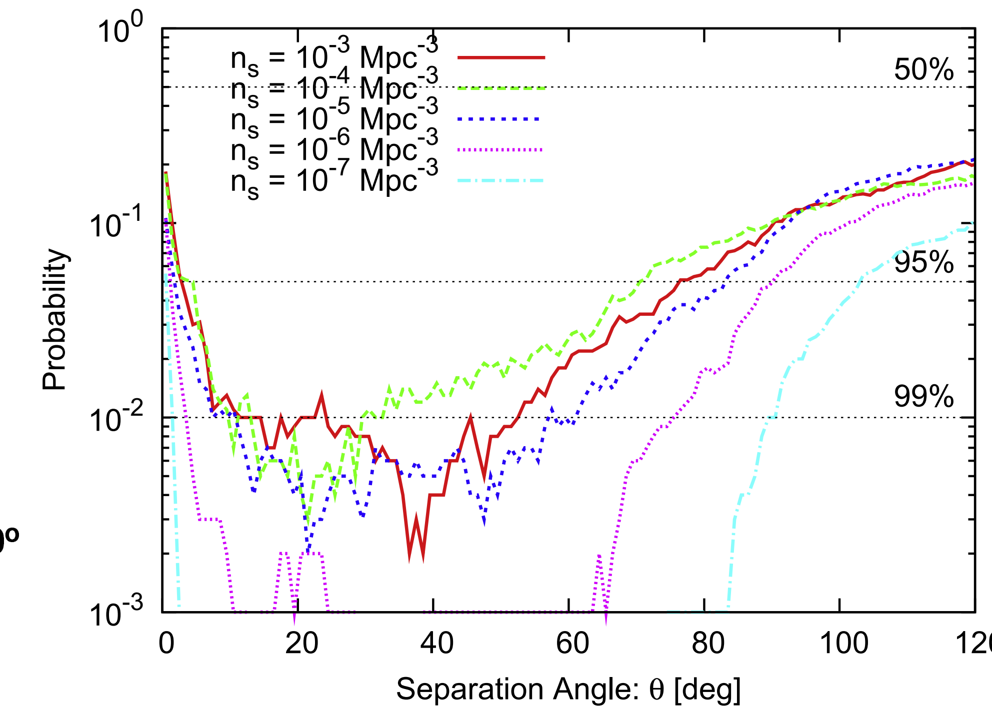
- τ_{min} : GMF, EGMF surrounding sources
- τ_{max} : GMF, EGMF surrounding sources, IGMF

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

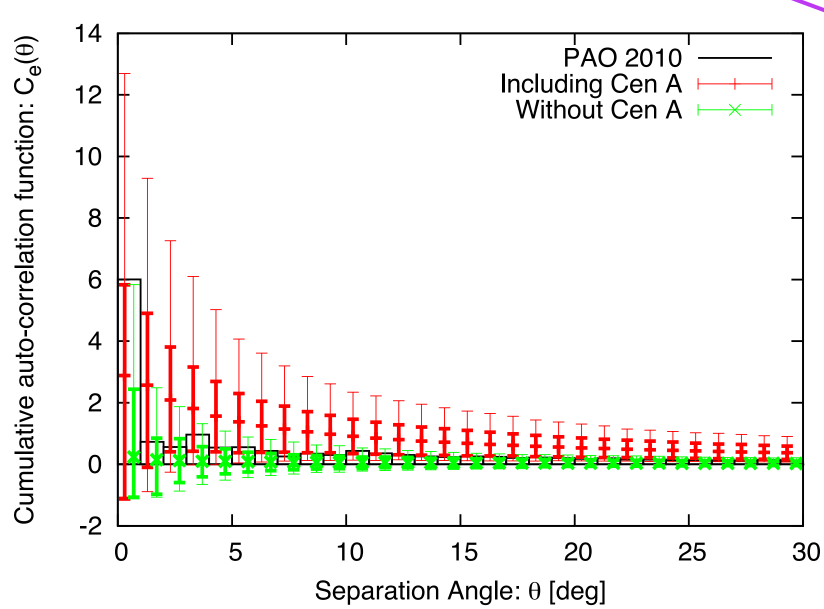
$n_s(E)$ from huge UHECR experiments and $\tau(E)$ from understanding cosmic magnetic fields allows us to constrain transient UHECR sources by comparing their restricted properties with parameters of known astrophysical objects.

Anisotropy in a heavy-nuclei-dominated case





HT, Inoue, Yamamoto 2012



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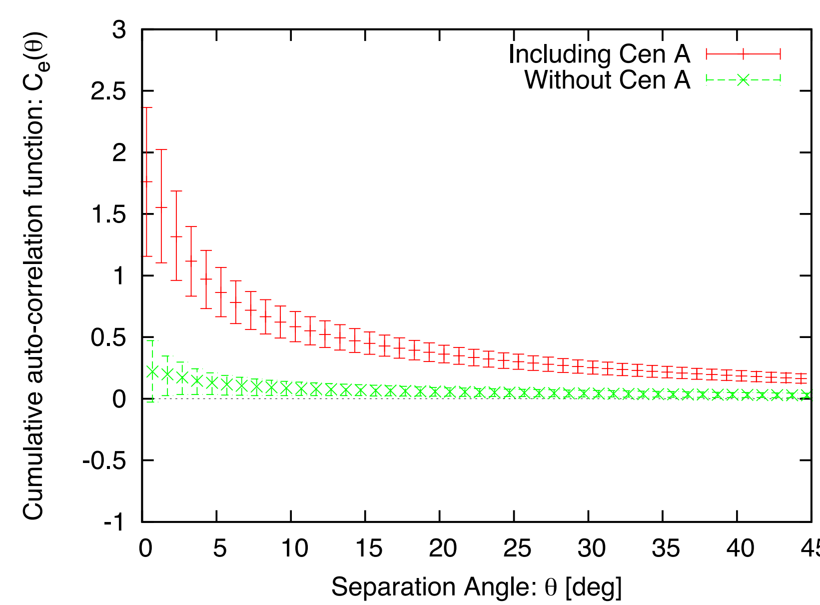


HT, Inoue, Yamamoto 2012

Anisotropy studies may be doable in the future.

Summary

- The origin of ultra-high-energy cosmic rays is still unknown, but some hints have appeared in their arrival distribution.

- Anisotropy indicates source number density: $n_s \sim 10^{-4}$ Mpc^{-3} for steady sources in the cases of light composition / weakly magnetized universe. This value is much larger than blazars, radio galaxies, and clusters of galaxies.

- An anisotropy study in narrow consecutive energy bins can reveal the transient generation of UHECRs.

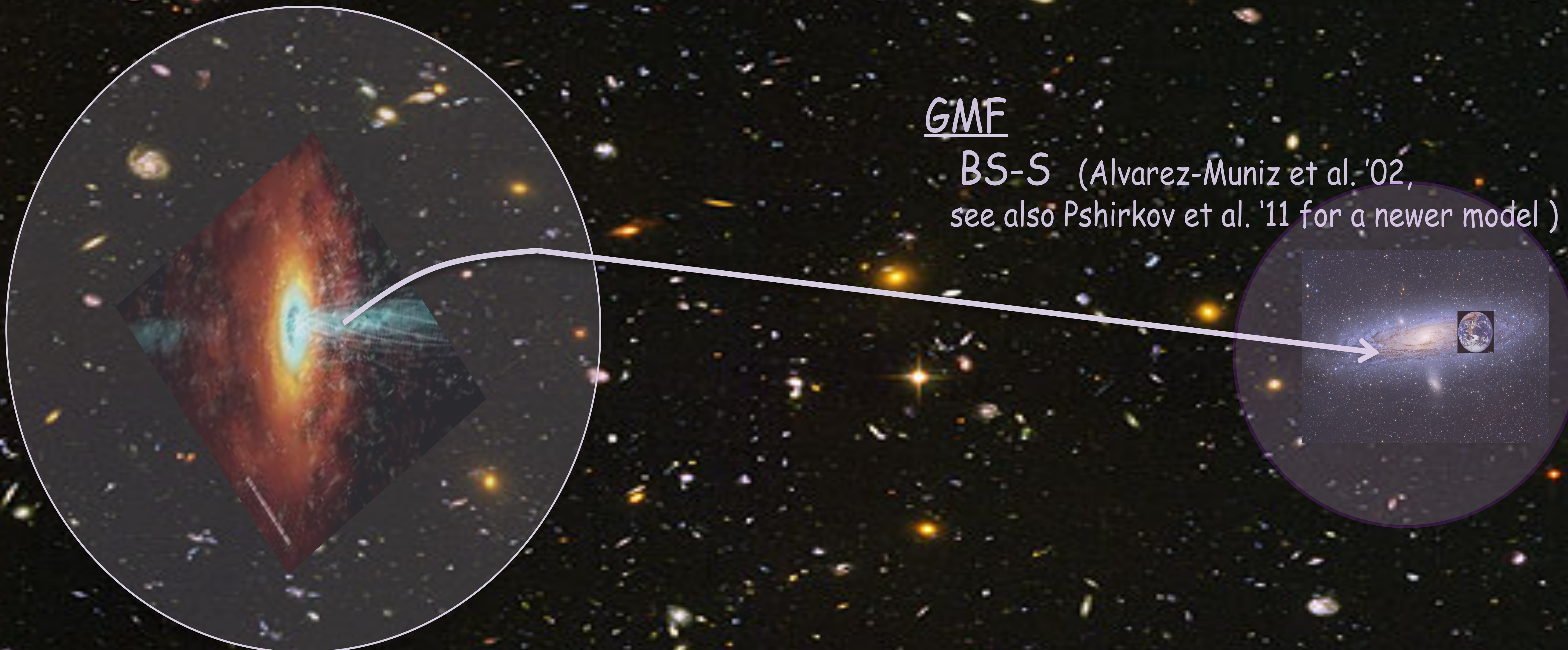
- Conservative estimation of the UHECR generation rate and related energy output can be achieved by independent studies on extragalactic magnetic fields.

Filament

$B \sim 10$ nG (e.g., Ryu et al. '08),
assuming turbulence with $\lambda_c \sim 100$ kpc

GMF

BS-S (Alvarez-Muniz et al. '02,
see also Pshirkov et al. '11 for a newer model)



Cluster

$B \sim 1\ \mu$G, β-model +
turbulence with $\lambda_c \sim$
100 kpc (e.g., de Marco et al. '06),

Void

$B\, \lambda_c^{1/2} < (10\ \mathrm{nG})\,(1\ \mathrm{Mpc})^{1/2}$ (e.g., Ryu et al. '98, Blasi et al. '99)
$B > 10^{-17 \sim -18}$ G (e.g., Dolag et al. '11, Dermer et al. '11,
Takahashi et al. '12, see also Ando & Kusenko '10 and Neronov et al. '11)

HT & Murase (2011)