Propagation of Ultra-high-energy Cosmic Rays

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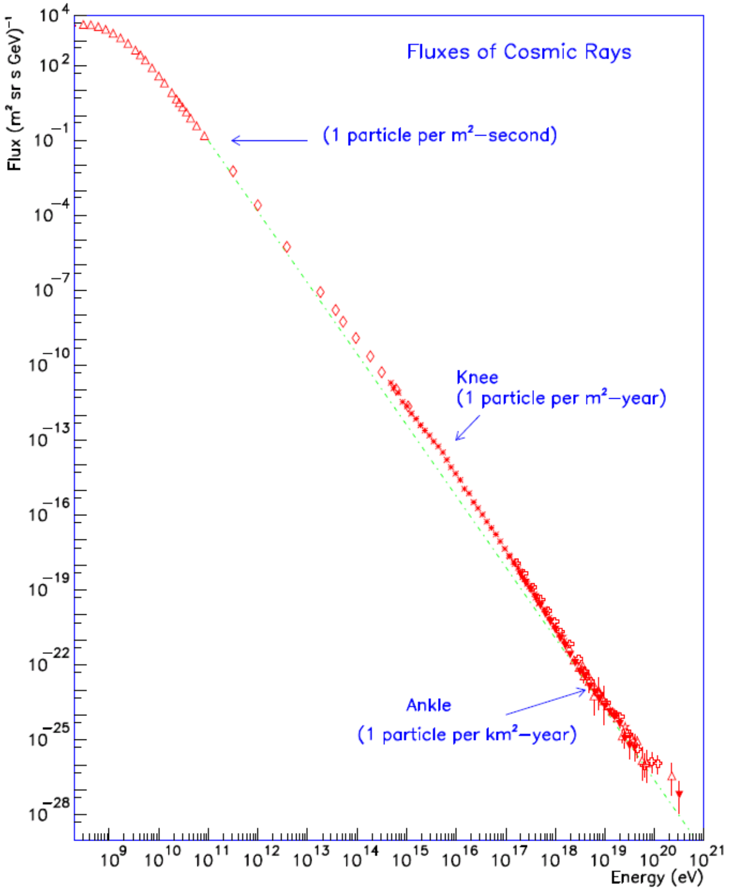
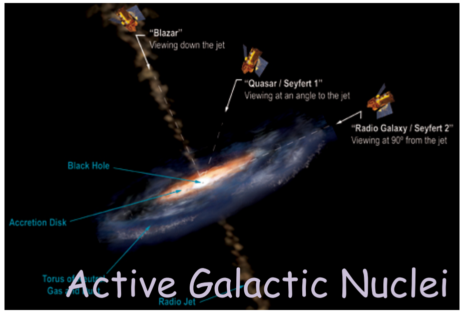
Ultra-high-energy Cosmic Rays

One of the biggest mysteries in modern astrophysics



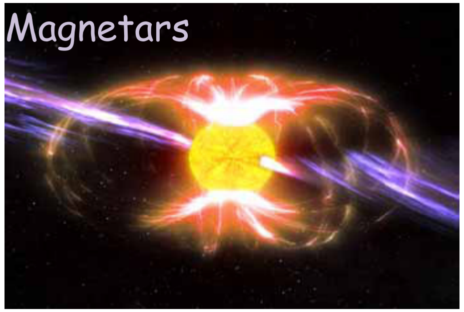
Bhattacharjee & Sigl (2000)

<u>Plausible Sources</u> ~ extragalactic sources
only extreme environments in the Universe



- Active galaxies with rel. jets
- Largest energy budgets

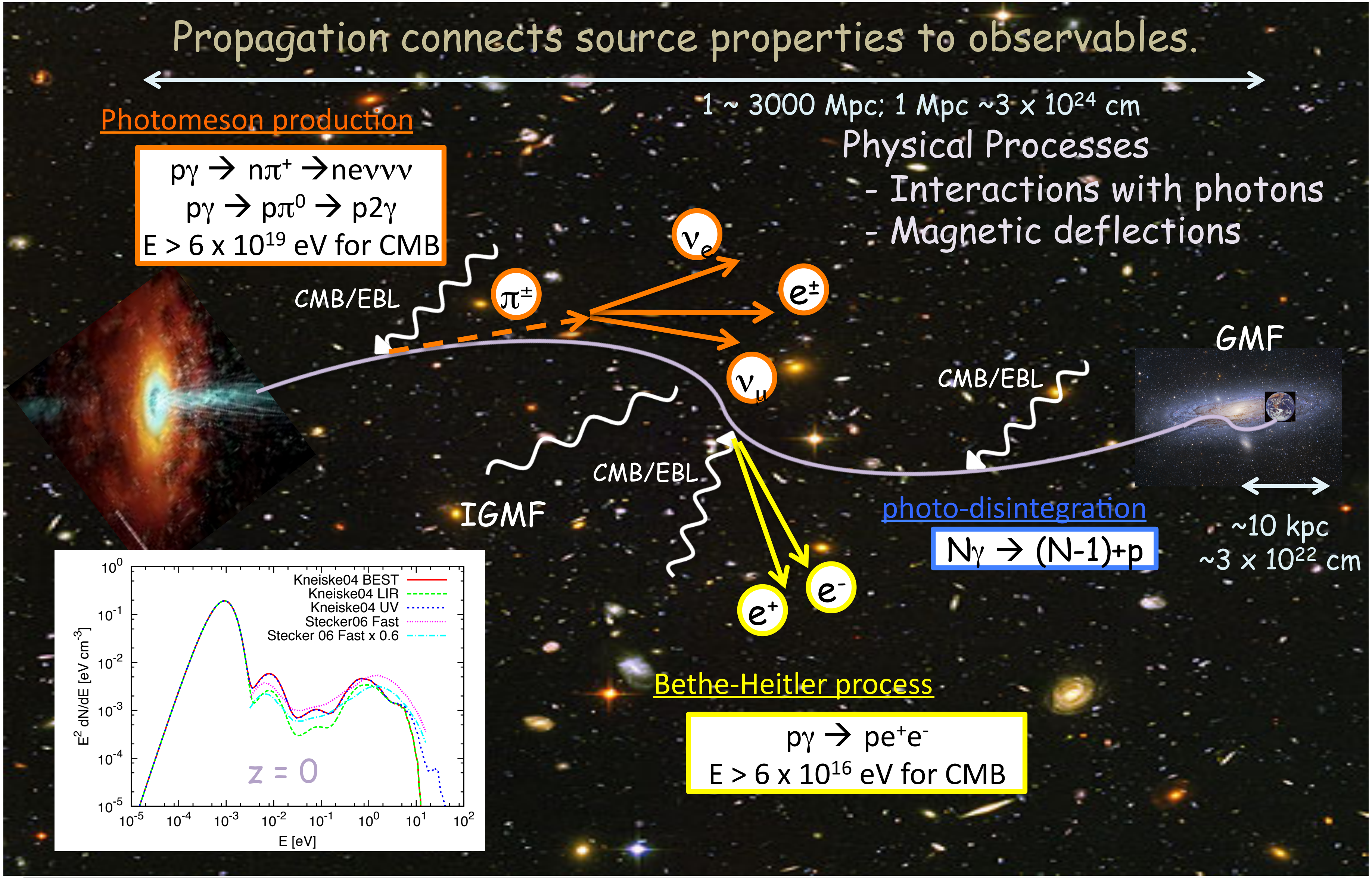
- Hypernova / NS-NS merger
- Most energetic bursts



- Strongly magnetized neutron stars (NSs)
- Strongest magnets

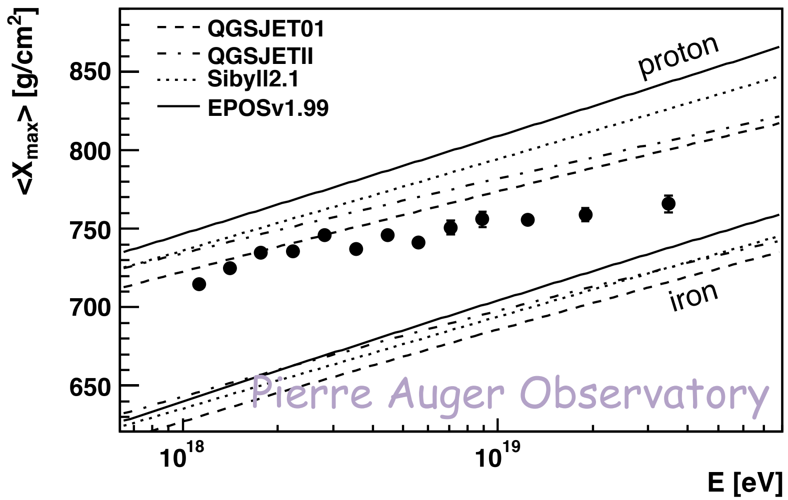
- Largest structures

Physics on UHECR Propagation

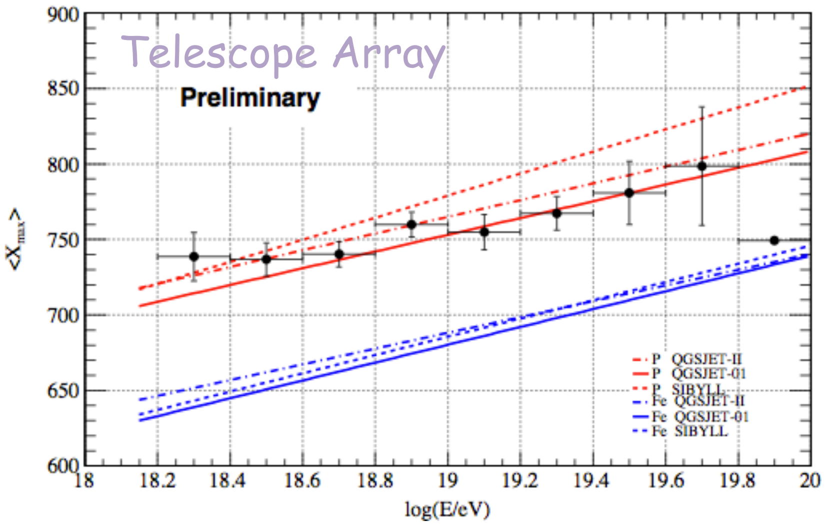


UHECR Composition

UHECR composition is a controversial issue at present.



Abraham et al. (2010)



TA Collaboration (2011)

Composition seems to change light to heavy nuclei gradually.

Almost protons even at the highest energies (since the last point consists of just one event, so it could be interpreted as a fluctuation.)

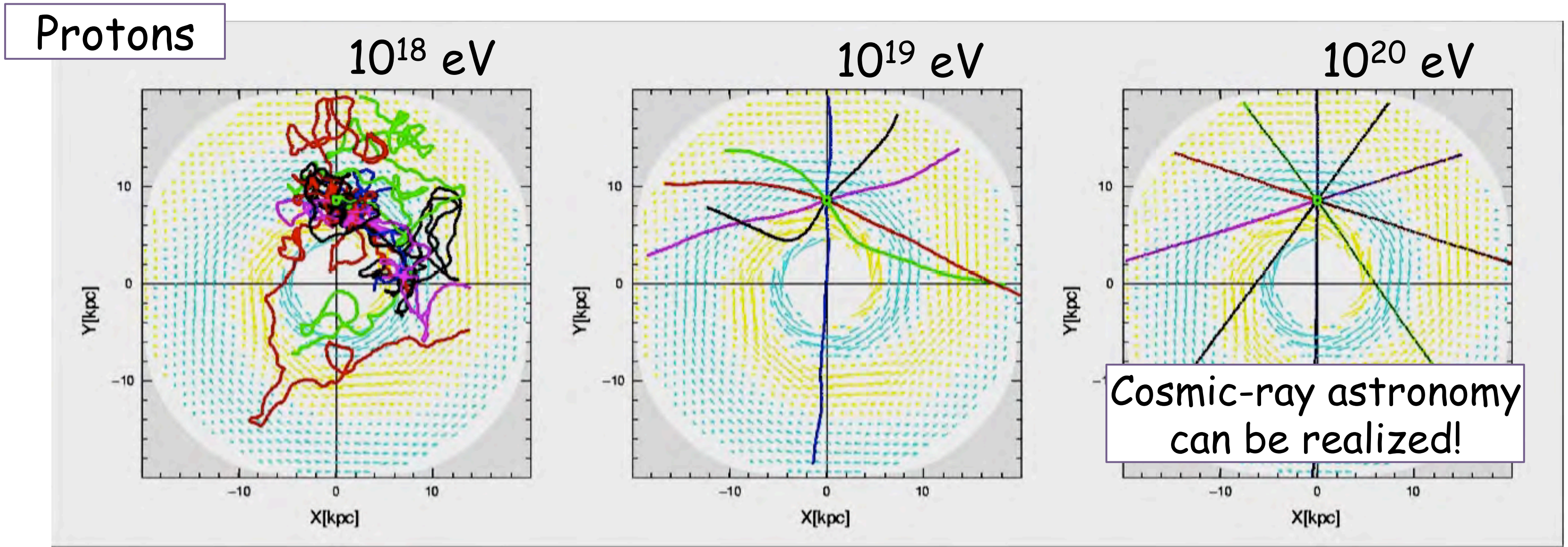
Possibilities

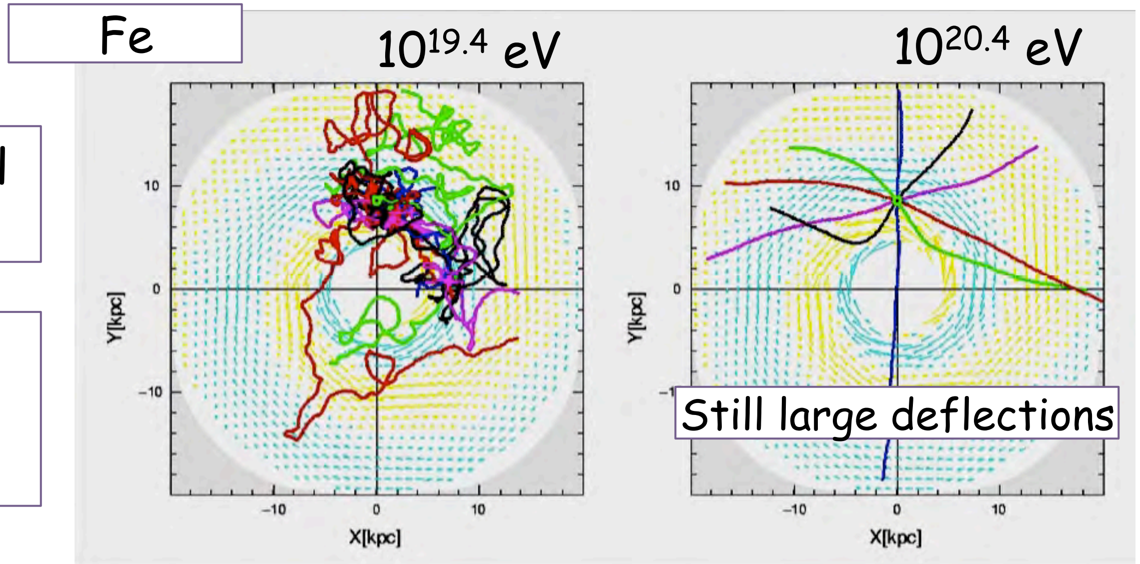
- ✓ Due to methods to estimate X_{max}?
- ✓ Astronomical difference between northern and southern sky?

Uncertainty on hadronic interaction models changes interpretations.

→ LHCf, …

Deflection by the Galactic Magnetic Field

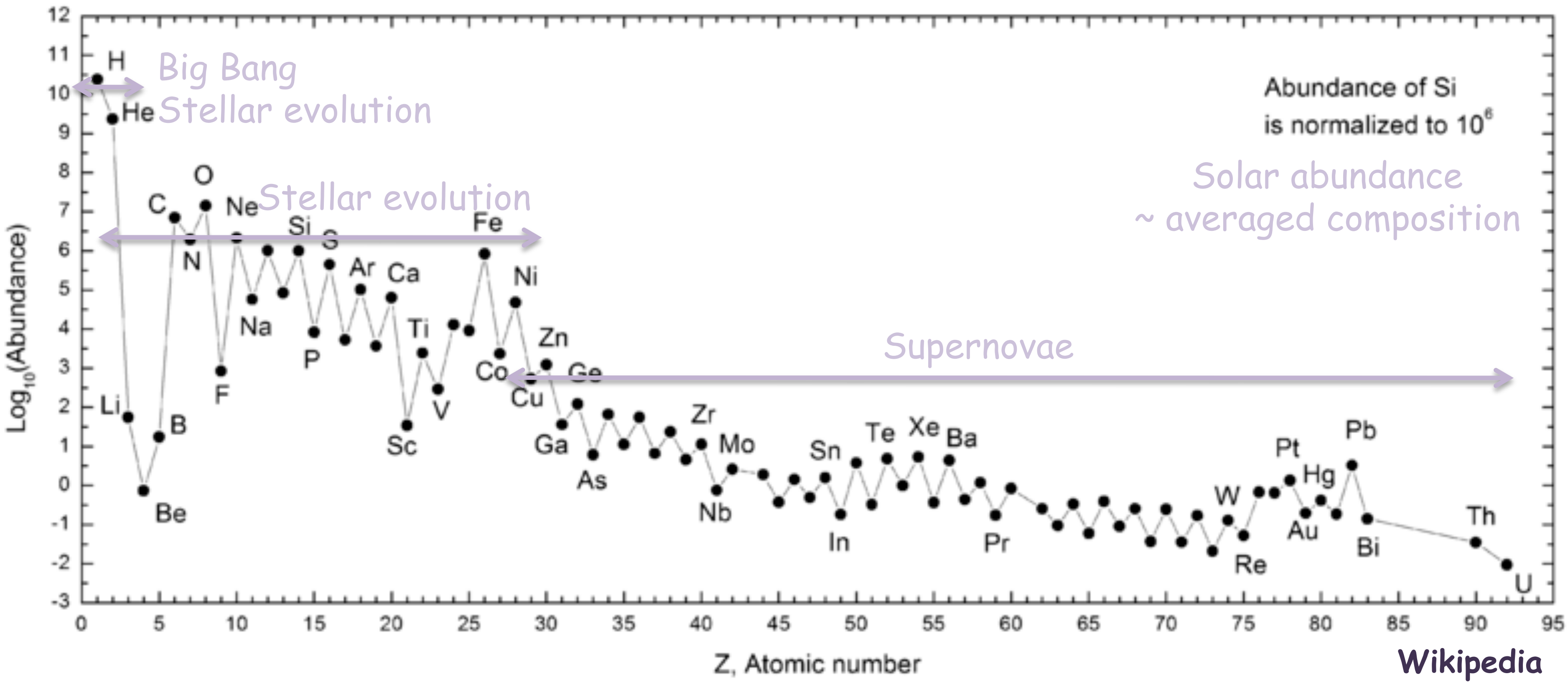




UHECR composition is crucial for cosmic-ray astronomy!

Cosmic-ray astronomy is one of the motivations for propagation studies.

Cosmic Abundance

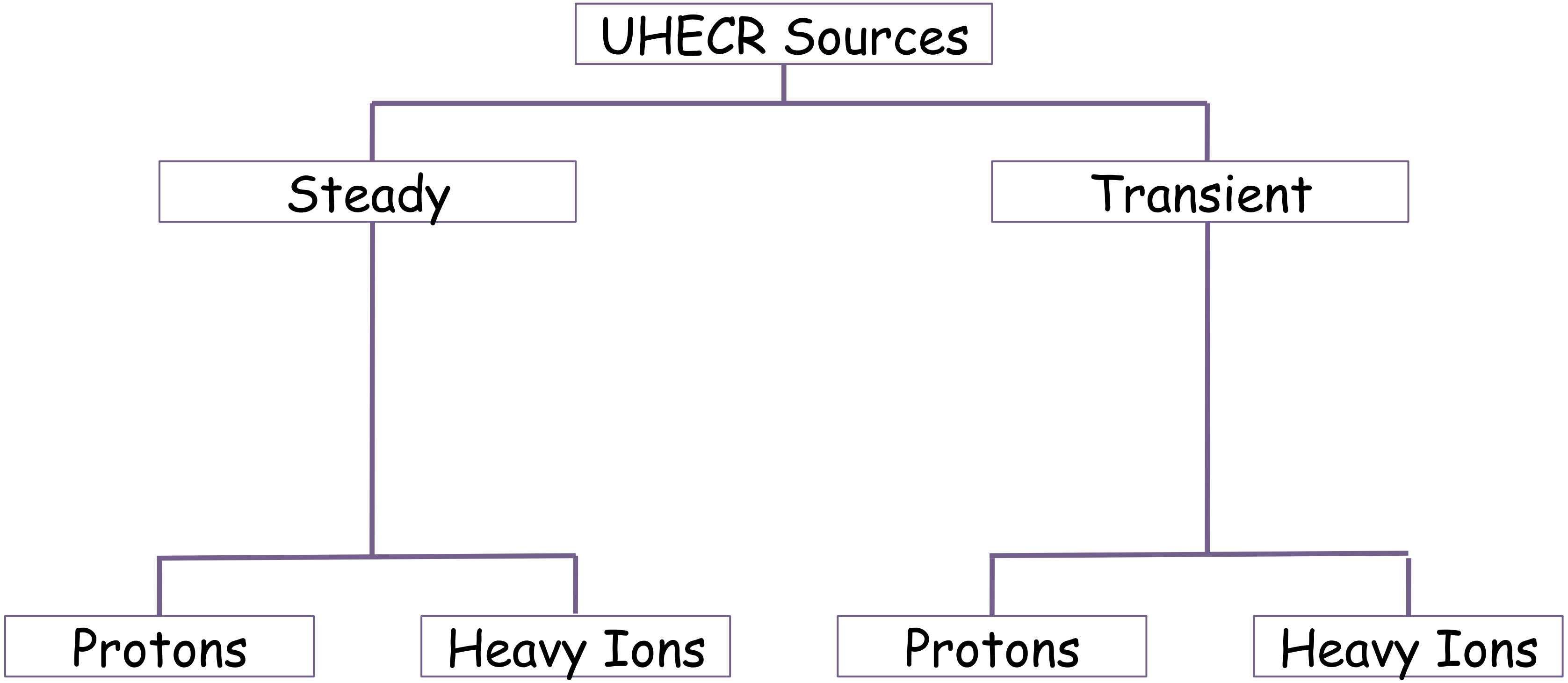


Wikipedia

How is the composition of UHECRs?
→ Cosmic-ray composition implies the environment of sources.

The composition gradually changes via interactions with ambient matter/photons.
→ propagation studies

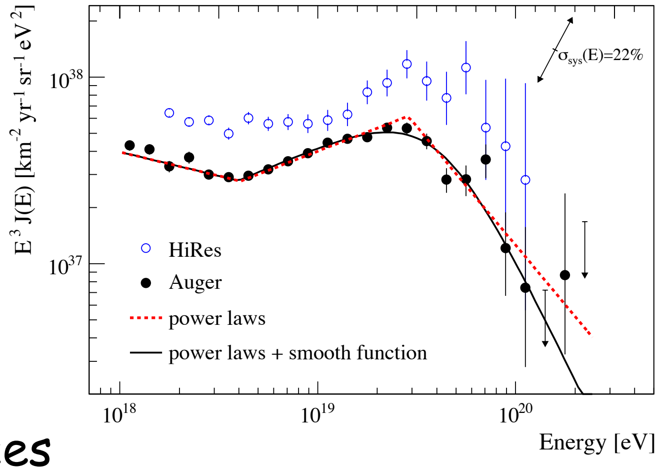
UHECR Source Candidate Classes



Other Motivations of Propagation Studies

Spectrum

- ✓ Required energy budget ~ 10^{44} erg Mpc^{-3} yr^{-1}
- ✓ How are source spectra?
- ✓ What composition explains the spectra?



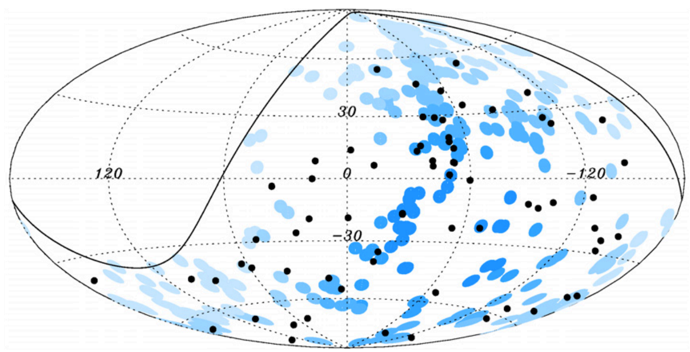
Abraham et al. (2010)

Arrival Directions

- ✓ Where are UHECR sources? (astronomy)
- ✓ Statistical Properties → Constraints on sources

Secondary neutrinos / γ-rays

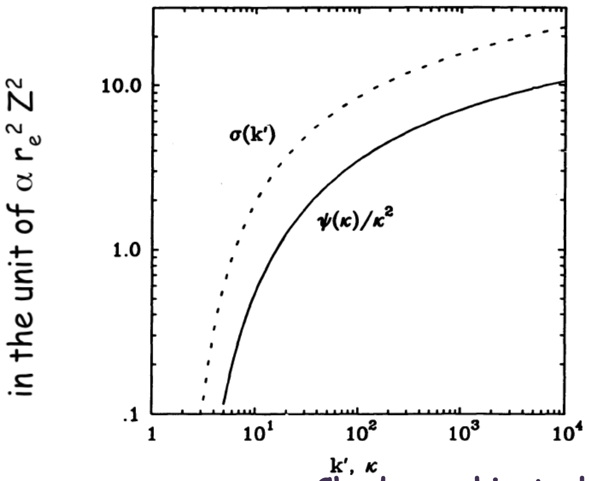
- ✓ Diffuse background flux
  - ✓ cosmic history of UHECR sources
  - ✓ GCR/EGCR transition **HT et al. (2009)**
- ✓ Diffuse γ-rays could be a foreground of possible dark matter annihilation signals



Abreu et al. (2010)

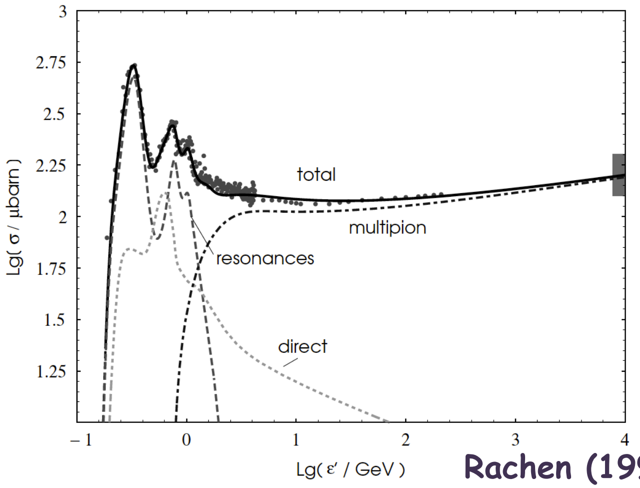
Interactions of Protons

Bethe-Heitler process ($p\gamma \rightarrow pe^+e^-$)



Chodorowski et al. (1992)

Photomeson production



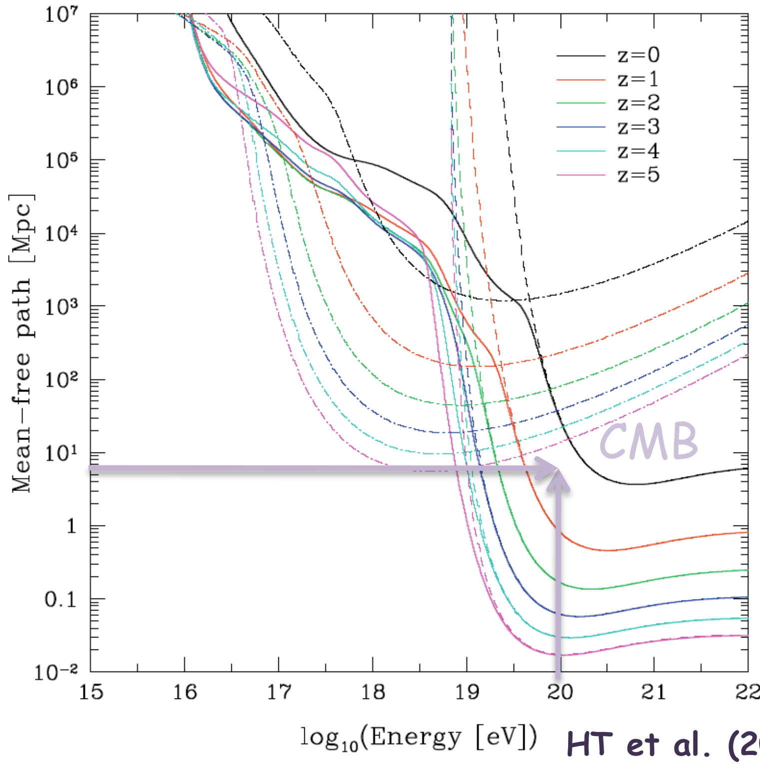
Rachen (1996)

Main target:

cosmic microwave background photons (~ 10^{-3} eV)

→ Interactions during propagation are described by physics confirmed in laboratories (if the Lorentz invariance is conserved).

Mean free paths / attenuation lengths

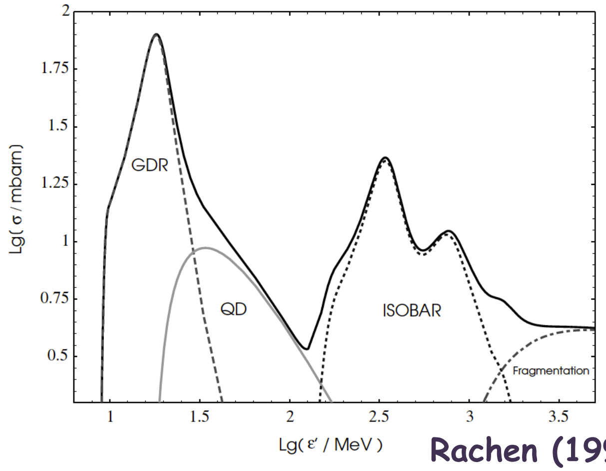


HT et al. (2009)

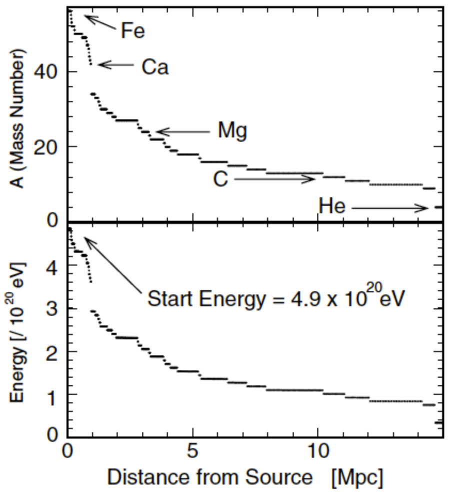
Interactions of Heavy Nuclei

Bethe-Heitler process ($N\gamma \rightarrow Ne^{+}e^{-}$)

Photo-disintegration



Rachen (1996)

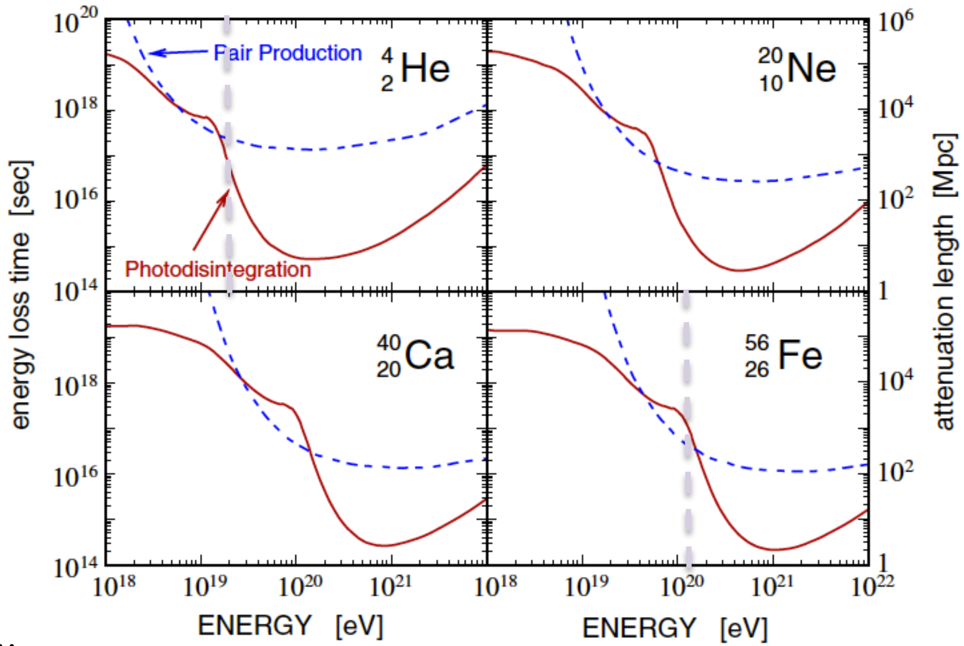


Yamamoto et al. (2004)

Fate of a Fe nucleus

A nucleus is gradually disintegrated.

Energy-loss timescale

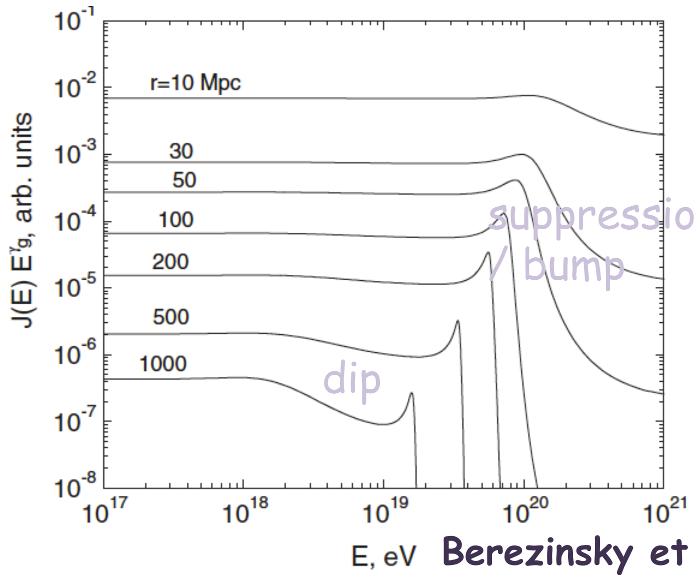


Yamamoto et al. (2004)

The energy of sharp decrease of energy-loss timescale depends on nuclear species.

A spectral shape is different among dominant nuclear species.

Spectral Shape



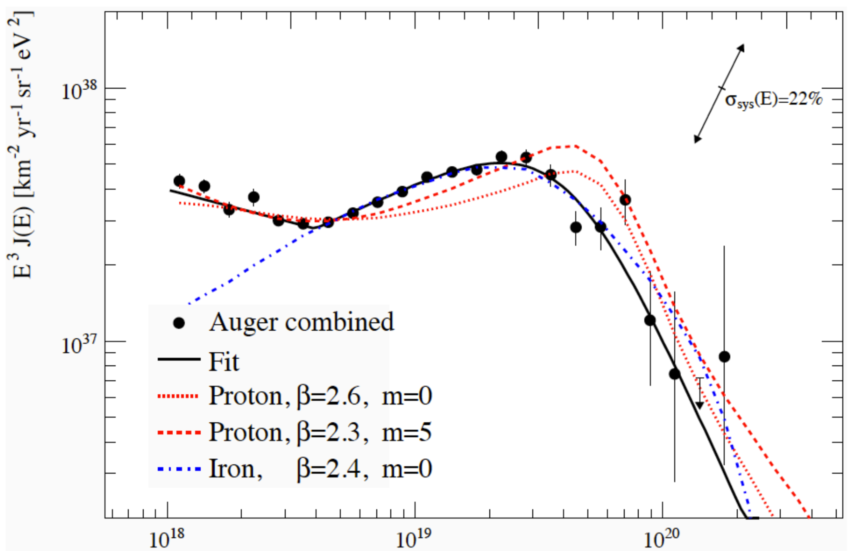
Berezinsky et al. (2006)

From a source

- ✓ CMB photons suppress flux above 10^{20} eV within ~100Mpc (GZK mechanism)
- ✓ Bethe-Heitler process makes a spectral bump for cosmologically distant (~ its attenuation length) sources.

Total spectrum

- ✓ Features mentioned above appear because it is superposition of individual source spectra
- ✓ Ion dominated composition produces the spectrum above the ankle too, but Fe should be dominated because of the threshold of photo-disintegration.

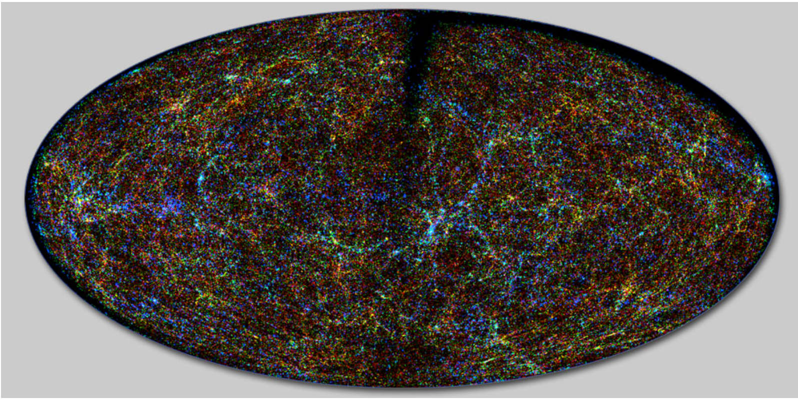


The Pierre Auger Collaboration (2009)

Intergalactic Magnetic Field

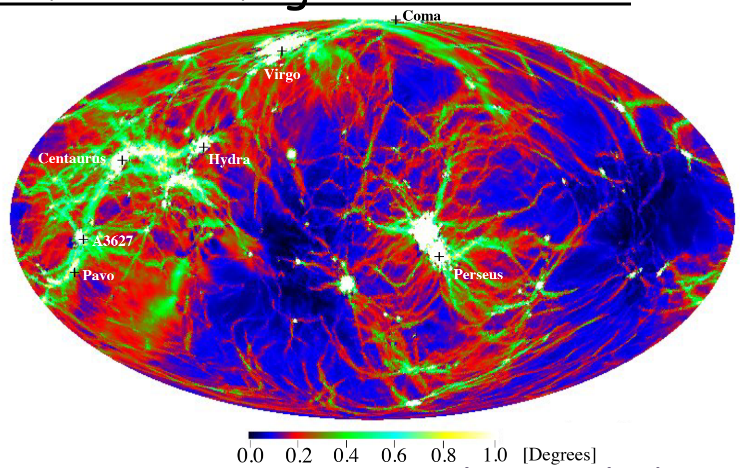
Local matter is distributed with structures.

Galaxies in local Universe



(2MASS Showcase)

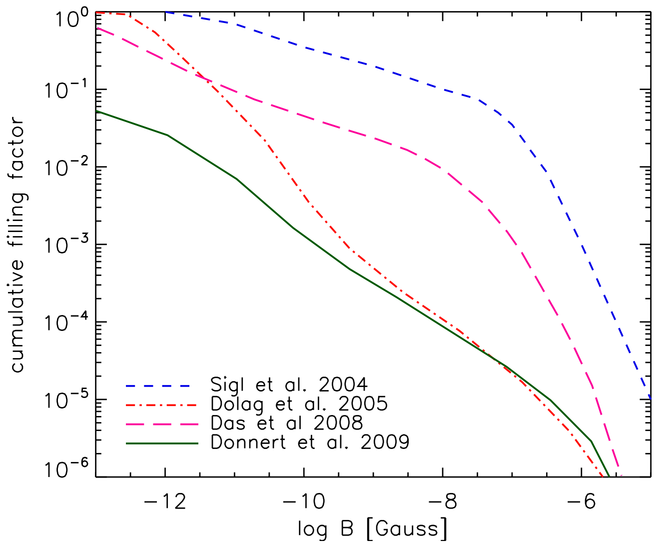
A simulated magnetic stucture



Dolag et al. (2005)

Magnetic fields are also structured commonly in simulations, but their results depend on the modeling of magnetic field amplification.

Future magnetic field surveys will increase our knowledge of IGMF.

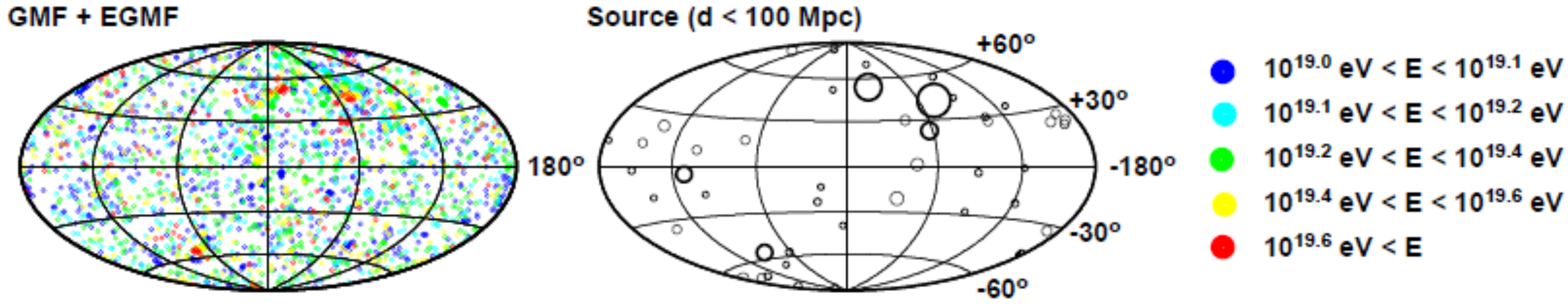


Kotera & Olinto (2011)

Arrival Distribution of UHE protons

Simulations taking GMF / EGMF, source distribution following an observed galaxy distribution

$E_p > 10^{19}$ eV, $n_s=10^{-5}$Mpc^{-3}, D_{max}=1Gpc
$E_{max}=10^{21}$ eV, 3000 evts, steady



HT, Yoshiguchi, Sato (2006)

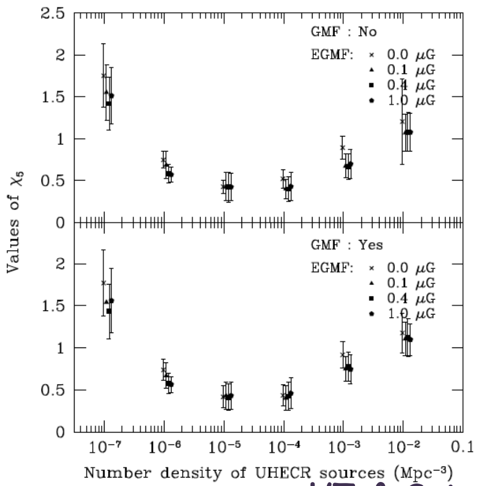
✓ Event clusters point out the location of nearby sources

✓ This simulated the first Auger data (1672 evts @ E>10^{19} eV). In the data, such strong anisotropy was not be found. So, the number density of sources should be larger than 10^{-5} Mpc^{-3}.

Implications to UHECR Sources

Reproducibility of anisotropy can constrain UHECR sources

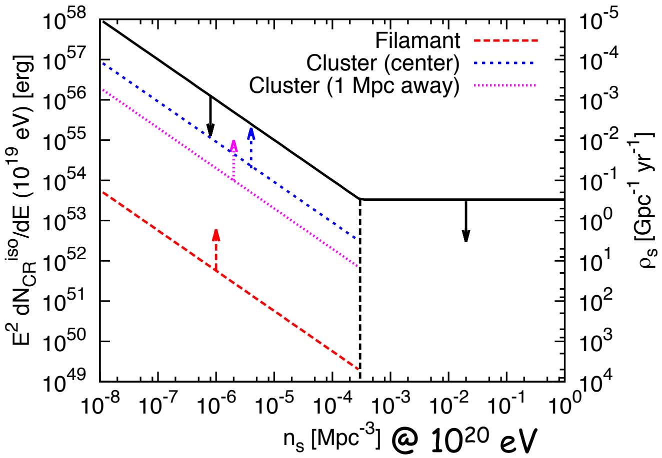
Steady Sources



HT & Sato (2009)

Objects	n_s [Mpc^{-3}]
Bright galaxy	1.3×10^{-2}
Seyfert galaxy	1.25×10^{-2}
Dead Quasar	5×10^{-4}
Fanaroff-Riley 1	8×10^{-5}
Colliding galaxies	7×10^{-7}
BL Lac objects	3×10^{-7}
Fanaroff-Riley 2	3×10^{-8}

Transient Sources



HT & Murase (2011)

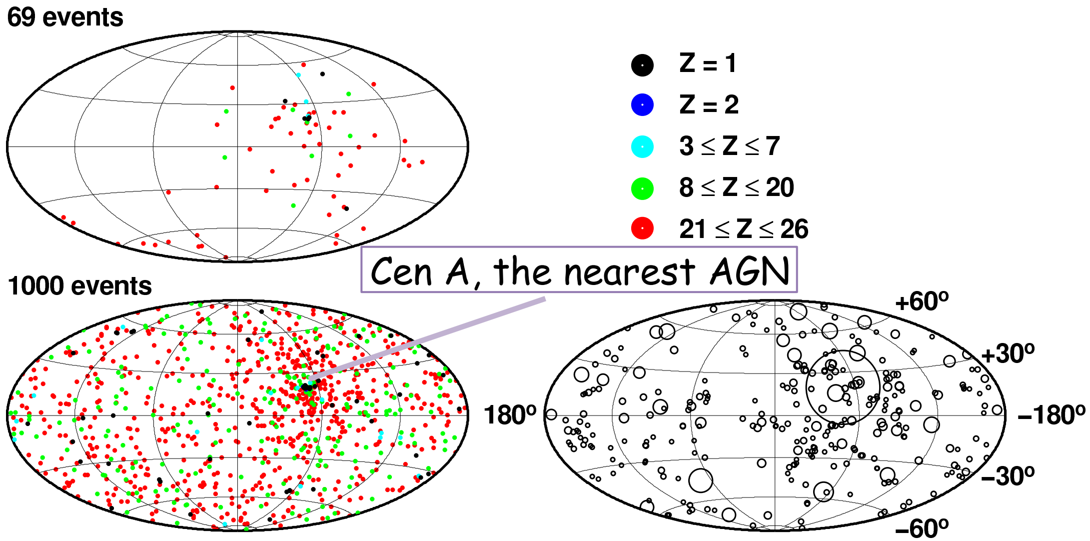
Source	Typical Rate ρ_0 [$Gpc^{-3}\,yr^{-1}$]
HL GRB	~ 0.1
LL GRB	~ 400
Hypernovae	~ 2000
Magnetar	~ 12000
Giant Magnetar Flare	~ 10000
Giant AGN Flare	~ 1000
SNe Ibc	~ 20000
Core Collapse SNe	120000

Murase & HT (2009)

Arrival Distribution of UHE Nuclei

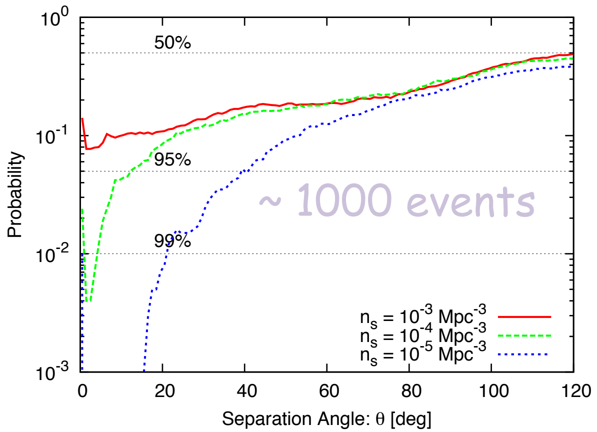
Consider a pure Fe case ~ unrealistic, but a conservative case ~

$E_{Fe} > 10^{19.75}$eV, $n_s = 10^{-4}$Mpc^{-3}
$E_{max} = 10^{21.5}$eV, steady



HT, Inoue, Yamamoto, in prep.

- ✓ Nearby sources could produce anisotropy.
- ✓ Secondary protons are a good indicator of sources.



HT, Inoue, Yamamoto, in prep.

Statistical analysis

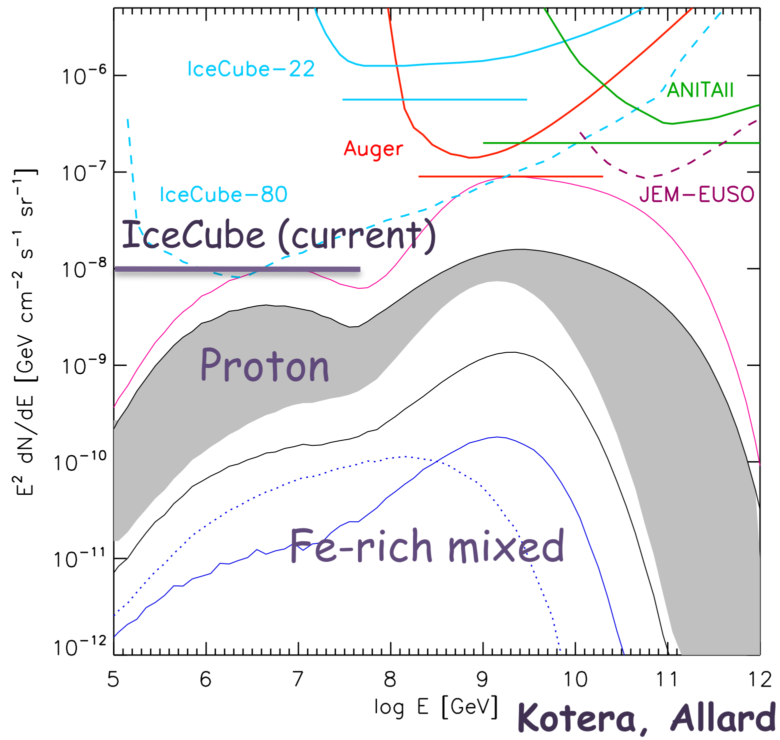
Probability that UHECR arrival distribution is consistent with isotropy.

⇩

Anisotropy can be observed if $n_s > 10^{-4}$ Mpc^{-3}.

Cosmogenic Neutrinos

Secondary neutrinos of UHECRs



- ✓ Background neutrino flux (i.e., summation of all the neutrinos produced by UHECRs in the Universe.
- ✓ The flux reflects the cosmic history of UHECR sources (sources at z~1 dominantly contribute).
- ✓ The neutrino flux is much lower for mixed composition than that for pure proton composition (→ indicator of composition).

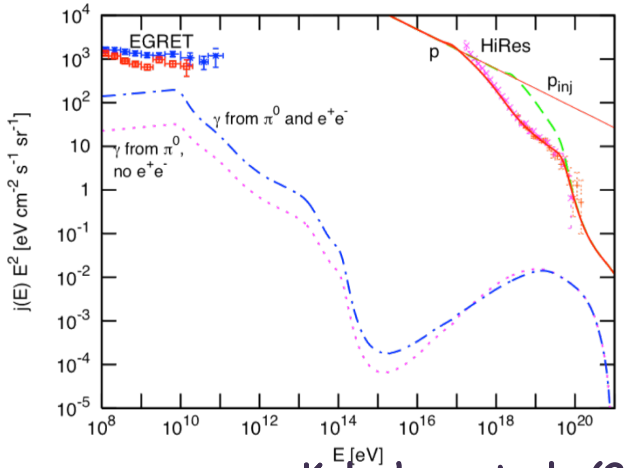
Kotera, Allard, Olinto (2011), see also HT et al. (2009)

Detection of cosmogenic neutrinos is still a challenging topic, but it has enough benefit.

Cosmogenic γ-rays

Secondary γ-rays of UHECRs

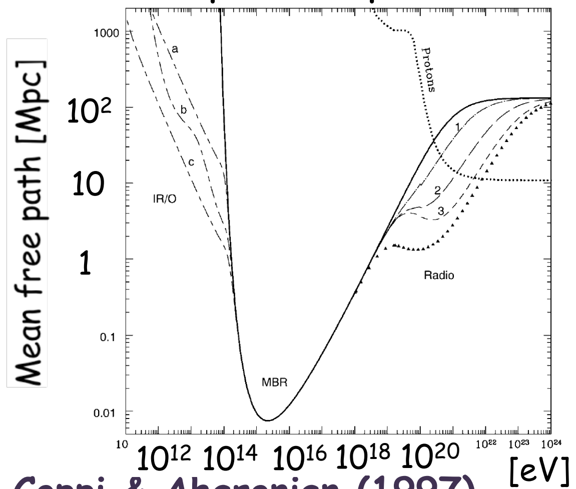
Diffuse γ-ray flux



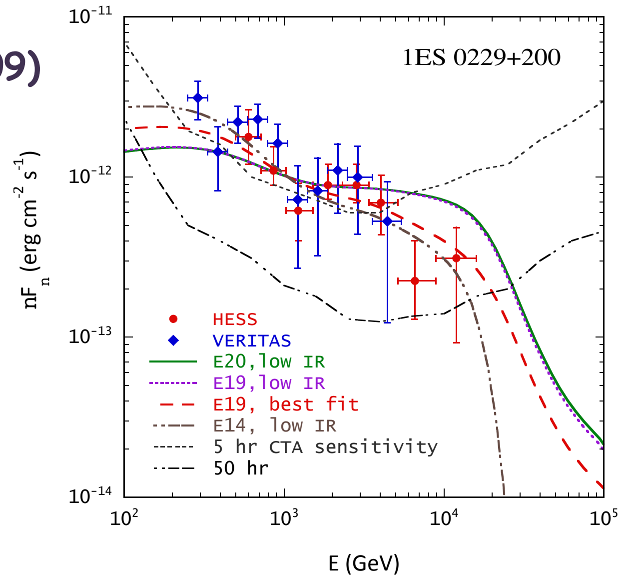
Kalashev et al. (2009)

- ✓ Same as cosmogenic neutrinos, but γ-rays
- ✓ EM cascade during propagation (inverse Compton scattering & pair creation with CMB photons)
- ✓ Contributions of individual sources already appeared? e.g., Essey et al. (2010)

Mean free path of photons



Coppi & Aharonian (1997)



Murase, Dermer, HT, Migliori (2011)

UHE γ-rays are another option, and could be a smoking-gun for nearby UHECR sources.

e.g., Murase (2009)

Summary

- Propagation process connects source properties with observables.

- The determination of UHECR composition is essential to identify unknown sources and to understand the nature of UHECR sources.

- Secondary neutrinos / γ-rays play complementary roles to approach UHECR sources

Galactic Magnetic Field

Faraday rotation measurements well constrain the structure of GMF, but there is still uncertainty.

Galactic plane

axisymmetric (AS) / bisymmetric (BS)

Sofue & Fujimoto (1983), Stanev (1997)

Halo

exponential decay with ~kpc

e.g., Sun et al. (2010)

Asymmetric (A-) / Symmetric (S-)

Turbulent field

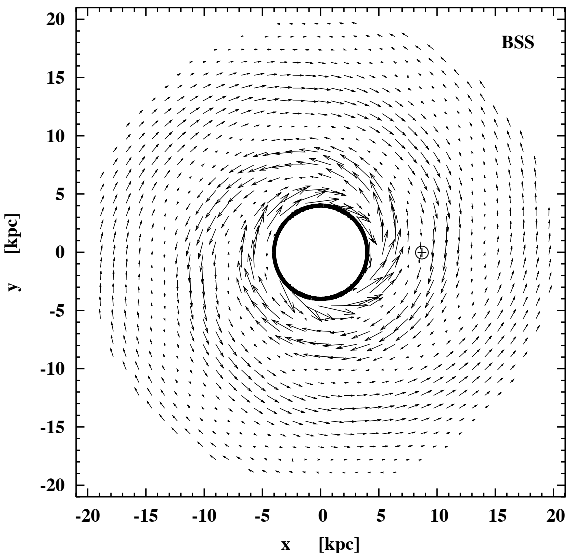
0.5-2 times as large as coherent components

Beck (2000)

z-component

evidence of B_z near the solar system

dipole? (no direct evidence)

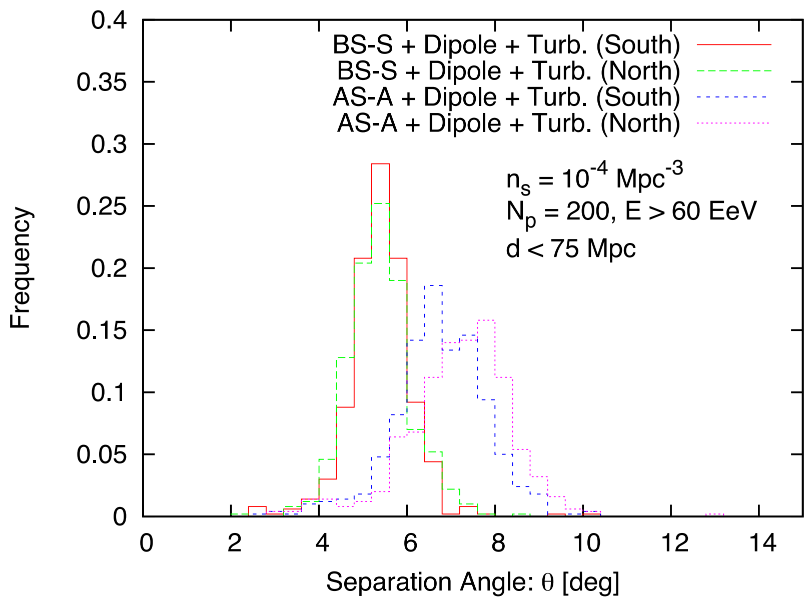


Alvarez-Muniz & Stanev (2006)

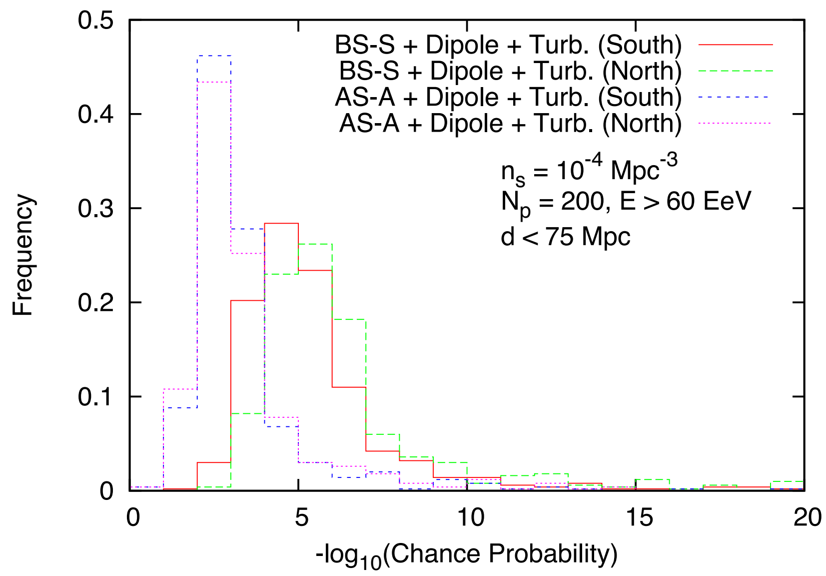
Correlation between Sources and UHECRs

$E_p > 6 \times 10^{19}$ eV, $n_s = 10^{-4} Mpc^{-3}$
$E_{max} = 10^{21}$ eV, 200 evts, steady

<u>Angle where the correlation is maximized.</u>



<u>Significance</u>



HT & Sato (2010)