Implications to the Sources of Ultra-high-energy Cosmic Rays

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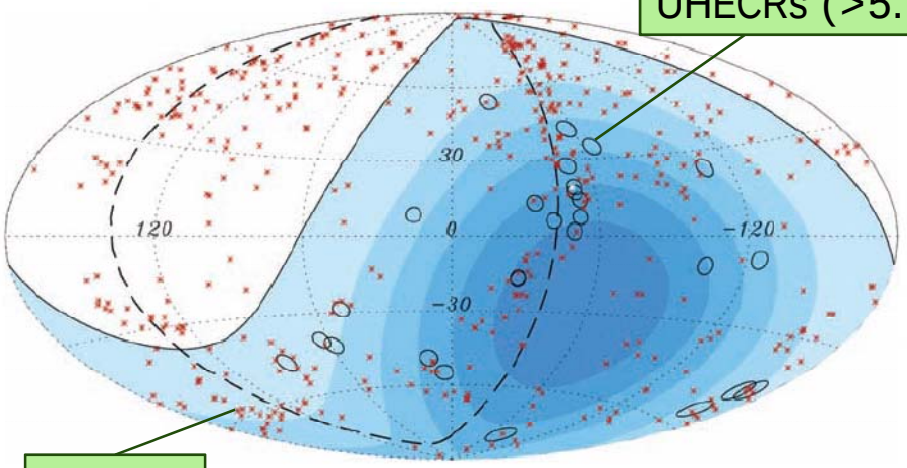
H. Takami & K. S[illegible] Astropart.Phys. in press (arXiv:0807.3442)

Motivation

Investigate UHECR sources based on the observed data of UHECR observatories

$E>10^{19}$eV



Abraham et al. 2007

- Correlation with AGNs
  - extragalactic sources
- Small-scale anisotropy
- Isotropy ($E>10^{19}$eV)

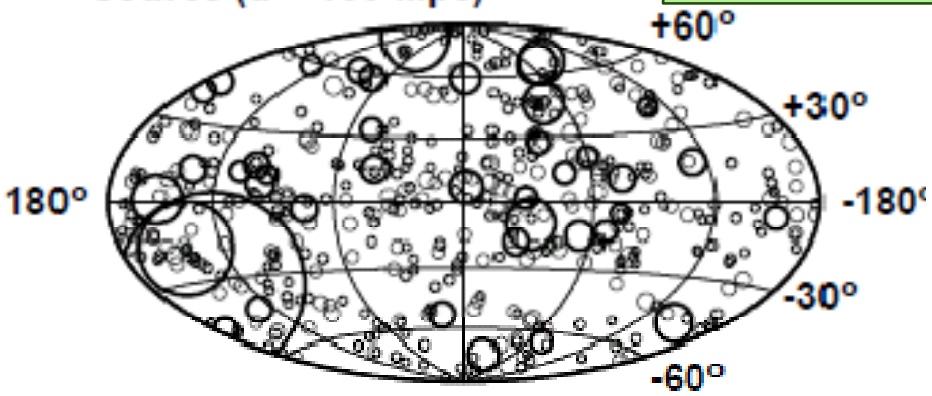
The arrival distribution has information on UHECR sources

Calculation

1. Simulate the arrival direction distribution of UHE protons for given source models taking into account Galactic and intergalactic magnetic fields

$n_s \sim 10^{-4}\mathrm{Mpc}^{-3}$, <1Gpc

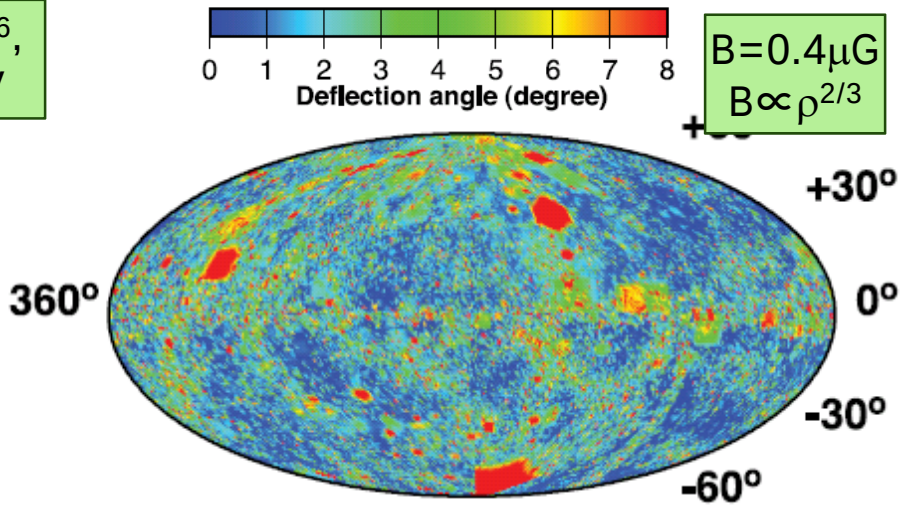
$dN/dE \propto E^{-2.6}$, $E_{max}=10^{22}$eV



Related to local LSS

$B=0.4\mu G$

$B \propto \rho^{2/3}$



GMF: spiral (BSS) + dipole

2. Compare the simulated arrival distribution with observed one

Auto-correlation function : a statistic to find anisotropy in UHECR distribution

$$w(\theta) = \frac{1}{2\pi\,|\cos\theta - \cos(\theta+\Delta\theta)|} \sum_{\theta \le \phi \le \theta+\Delta\theta} 1[\mathrm{sr}^{-1}]$$

UHECR Source Number density

$$\chi\theta_{\max} = \frac{1}{N_{\rm bin}}\sqrt{\sum_{n=0}^{N_{\rm bin}-1}\frac{[w(\theta_n)-w_{\rm obs}(\theta_n)]^2}{\sigma(\theta_n)^2}}$$

100 event generations per source distribution

$\theta_{max}=5^o$, $\Delta\theta=1^o$, $N_{bin}=5$

E>5.7x10^{19}eV : 27events

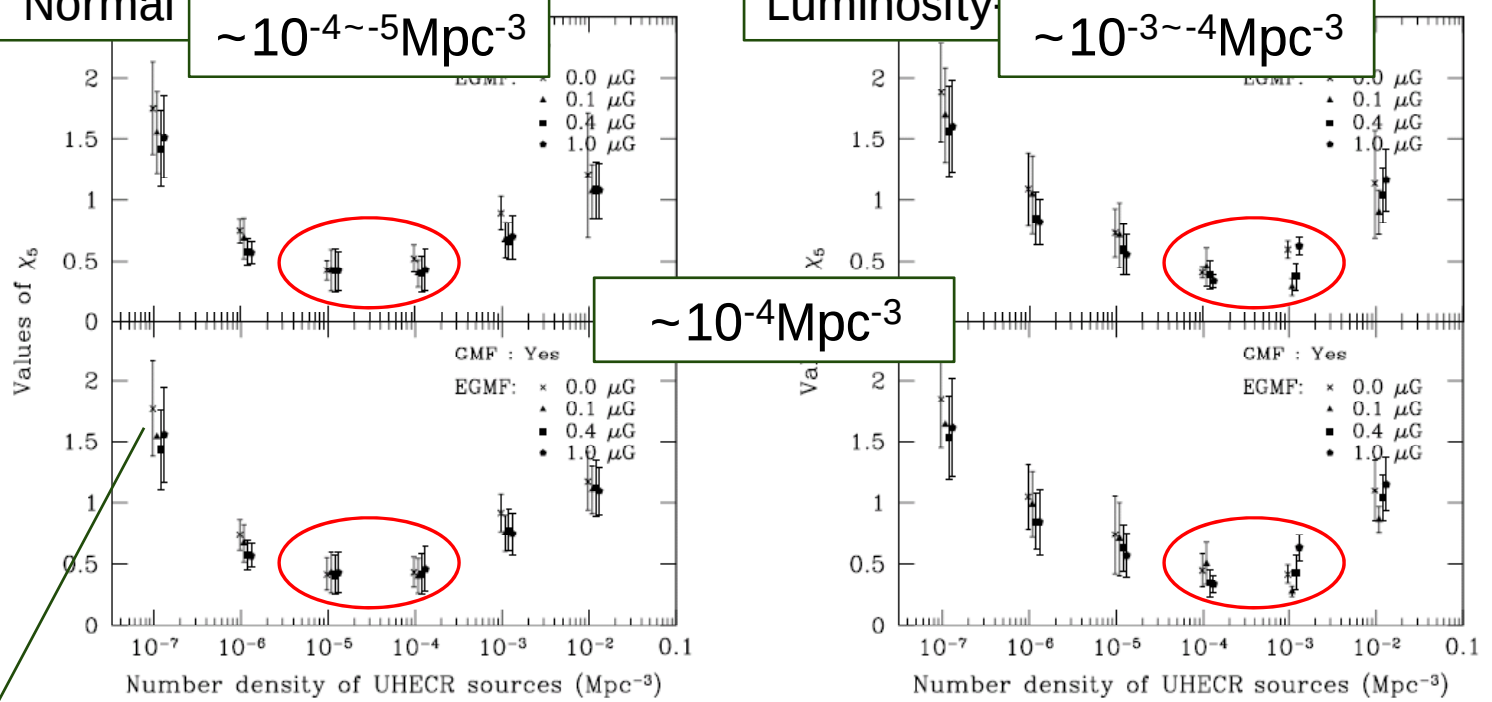
Normal

~10^{-4}~$^{-5}$Mpc^{-3}

Luminosity-

~10^{-3}~$^{-4}$Mpc^{-3}

~10^{-4}Mpc^{-3}



100 source distributions

HT & Sato 2008

Comparison with n_s of known objects

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

Objects	Number Density [Mpc^{-3}]	
Bright galaxy	1.3×10^{-2}	too many
Seyfert galaxy	1.25×10^{-2}	
GRB	1×10^{-4}	appropriate
Dead Quasar	5×10^{-4}	
Fanaroff-Reily 1	8×10^{-5}	
Bright quasers	1.4×10^{-6}	too small
Colliding galaxies	7×10^{-7}	subdominant contribution
BL Lac objects	3×10^{-7}	
Fanaroff-Reily 2	3×10^{-8}	

Several specific types of AGNs or GRBs

Another Population?

The constrained n_s cannot satisfy observed isotropy at around 10^{19}eV

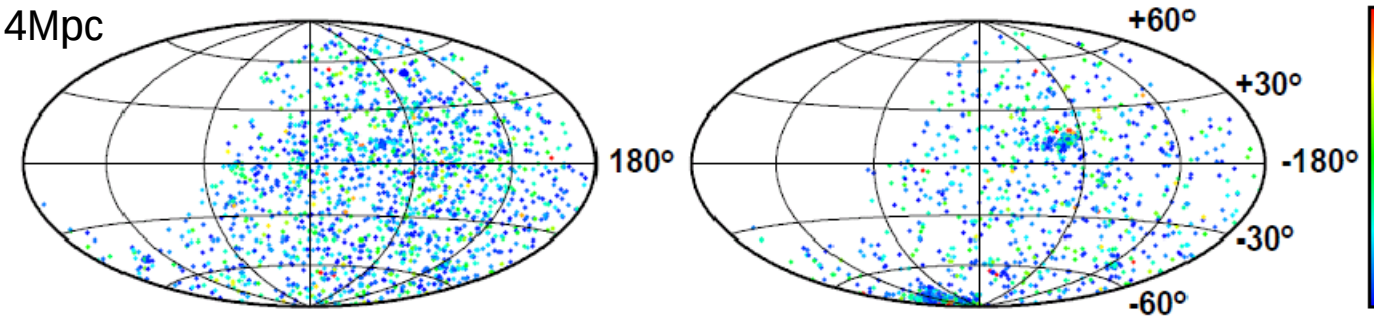
PAO: UHECR distribution above 10^{19}eV is consistent with isotropy with 95%C.L.

Normal: 10^{-3}Mpc^{-3}, B=0.4μG

Without d<5Mpc sources

All

CenA: d~3.4Mpc

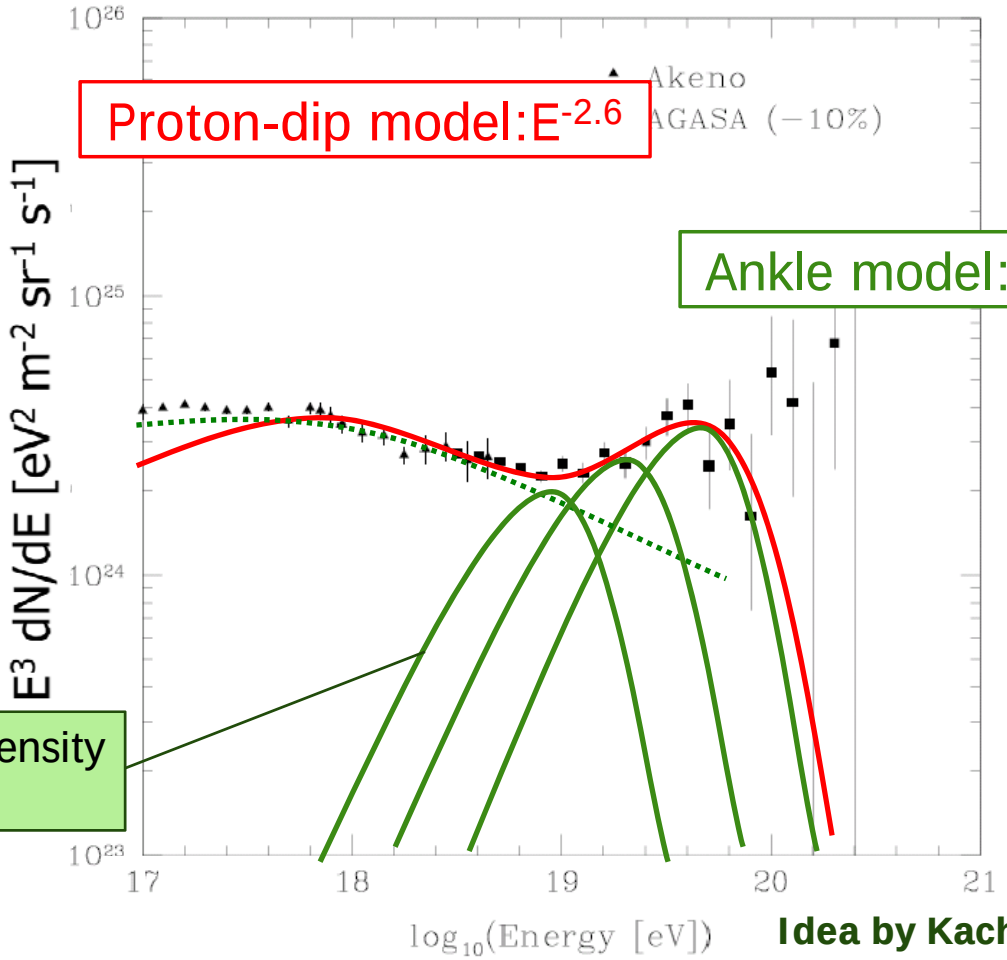


$B_{\rm IGMF}$	0.1 μG				0.4 μG			
$B_{\rm ran}$	0.0 nG		1.0 nG		0.0 nG		1.0 nG	
n_s [Mpc^{-3}]	2σ	3σ	2σ	3σ	2σ	3σ	2σ	3σ
10^{-2}	100(100)	100(100)	100(100)	100(100)	100(100)	100(100)	100(100)	100(100)
10^{-3}	5 (0)	54 (0)	33 (0)	79 (8)	7 (0)	34 (6)	34 (0)	73 (17)
10^{-4}	2 (0)	10 (0)	11 (0)	28 (0)	2 (0)	15 (0)	7 (0)	26 (0)

$10^{-2\sim-3}$Mpc^{-3} is required for the isotropy ➔ New source population!

HT & Sato 2008

Different E_{max}



Proton-dip model:$E^{-2.6}$

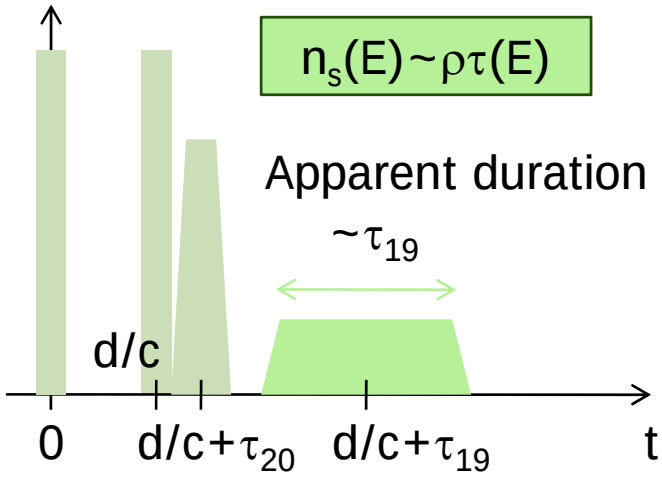
Ankle model:$E^{-2.0}$

Larger number density is required

Idea by Kachelriess & Semikoz 2005

Transient Activity for UHECR generation?

Apparent n_s depends on the energy of arriving cosmic rays



$$\tau(E,d) \simeq 1.5\times10^{5}\ Z^{2}\left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-2}\left(\frac{d}{100\ \mathrm{Mpc}}\right)^{2}\left(\frac{l_c}{1\ \mathrm{Mpc}}\right)\left(\frac{B}{1\ \mathrm{nG}}\right)^{2}\ \mathrm{yr}$$

$\tau_{19}/\tau_{19.8} \sim (10^{19}\mathrm{eV}/10^{19.8}\mathrm{eV})^{-2} \sim 10^{1.6}$

The discrepancy is reproduced.

Indirect evidence for transient generation?

Summary

- The observed anisotropy at the highest energy leads to $n_s \sim 10^{-4}\mathrm{Mpc}^{-3}$.
  - The estimated n_s implies that FR II galaxies are not mainly contribute to the observed flux of UHECRs.
  - The constrained n_s is comparable with the number density of FR I galaxies.
- The observed isotropy at 10^{19}eV cannot be reproduced by source models constrained by the anisotropy. Sources within 5 Mpc inevitably generate strong anisotropy.
- The isotropy implies
  - Another source population ($n_s \sim 10^{-2\sim-3}\mathrm{Mpc}^{-3}$, $E_{max} \sim 10^{19}$eV)
  - Sources with different E_{max} ($dN/dE \propto E^{-2.0}$)
  - Transient activity of UHECR generation