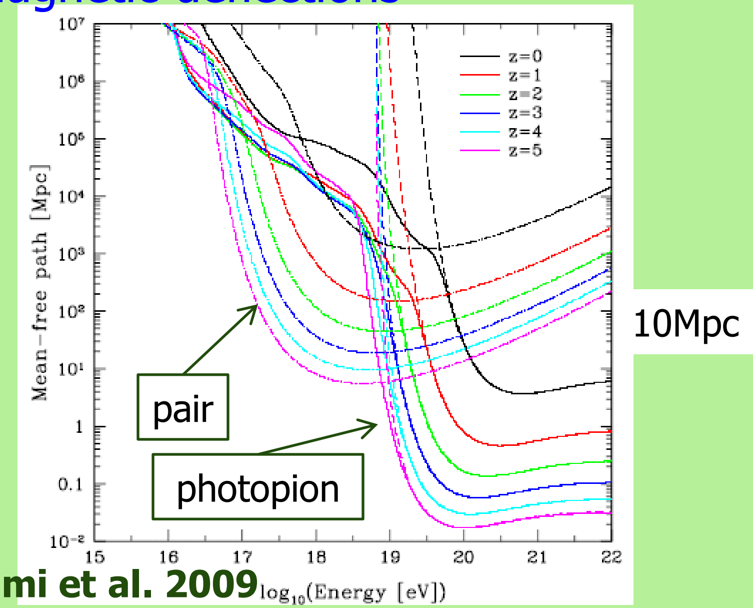
Interactions during propagation to the Earth

Interactions

- Bethe-Heitler pair creation
  $p\gamma \rightarrow pe^+e^-$ ($E_p>10^{16}$eV for CMB)
- Photopion production
  $p\gamma \rightarrow p\pi^0, n\pi^+$ ($E_p>7\times10^{19}$eV :CMB)
- Photodisintegration (for Nuclei)
  $N\gamma \rightarrow (N-1)p,(N-1)n$
- Adiabatic energy-loss
  $dE/dt=-H_0[\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}E$
- Magnetic deflections



Takami et al. 2009

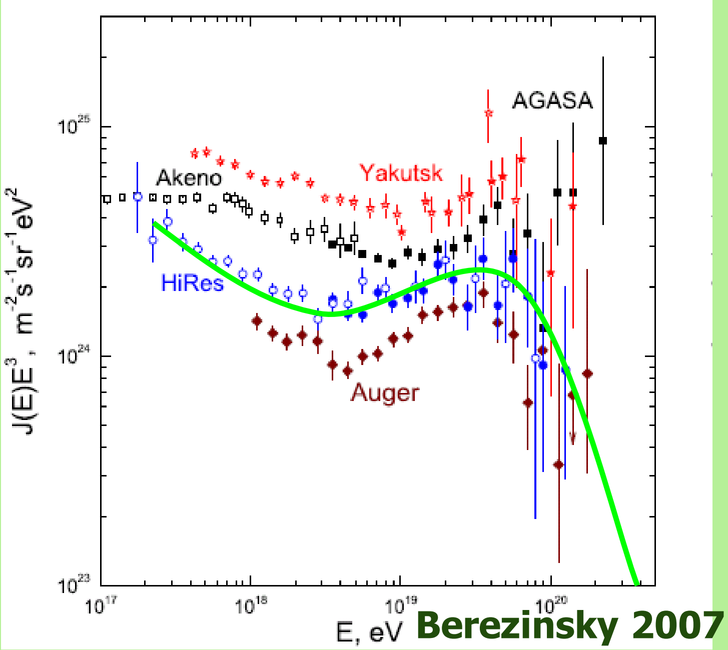
GZK mechanism

photopion production

- ✓ l_{att}~10Mpc @ z=0
- ✓ ~30% of E_p is lost per reaction

Predictions are :

1. a spectral cutoff @~7×10^{19}eV
2. The origin of the highest energy cosmic rays is within ~50Mpc.



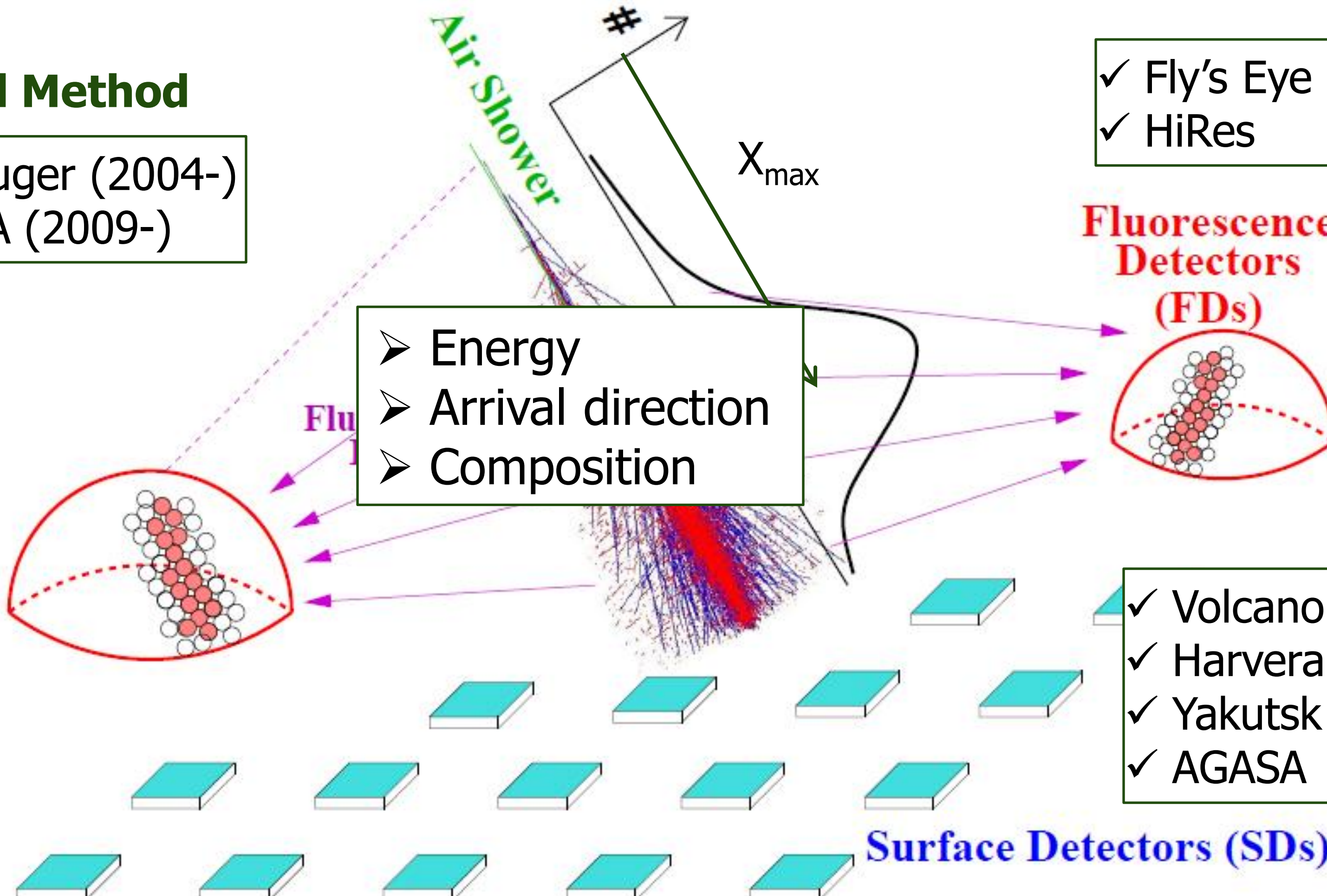
Berezinsky 2007

Detection of UHECRs

UHECRs are indirectly detected through the properties of extensive air showers.

Hybrid Method

- ✓ Auger (2004-)
- ✓ TA (2009-)



- ➢ Energy
- ➢ Arrival direction
- ➢ Composition

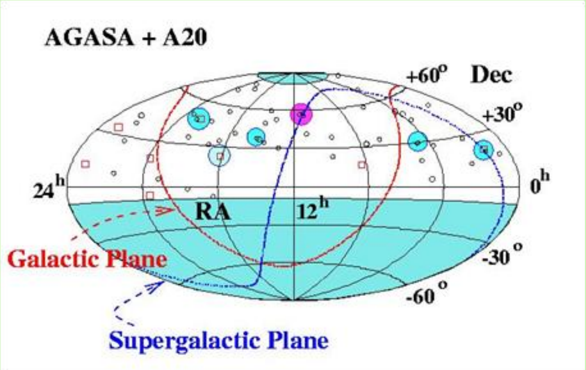
- ✓ Fly's Eye
- ✓ HiRes

- ✓ Volcano Launch
- ✓ Harverah park
- ✓ Yakutsk
- ✓ AGASA

M.Takeda's presentation 2008

UHECR Arrival Distribution

AGASA

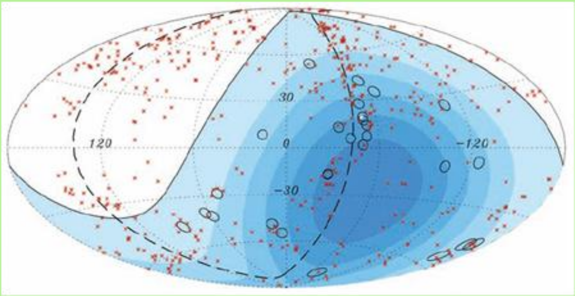


Takeda et al. 1999

- Ground-based detector
- Exposure~1300 km^2 sr
- Akeno (Japan)
- Ang. Resolution ~ 2°
- Ene. Resolution ~ 30%
- E>4x10^{19}eV 57 events

- Small-scale anisotropy
- Super-GZK events

Pierre Auger (PAO)

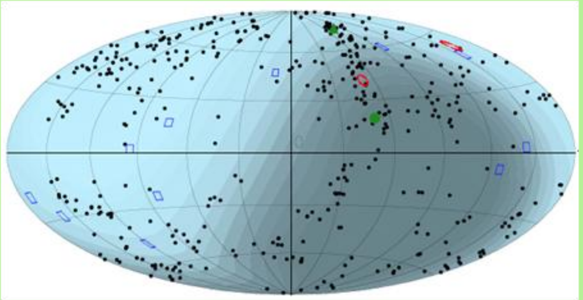


Abraham et al. 2008

- Hybrid detector
- Exposure~9000 km^2 sr
- Pampa Amarilla (Argentina)
- Ang. Resolution ~ 1°
- Ene. Resolution ~ 22%
- E>5.7x10^{19}eV, 27 events

- Small-scale anisotropy
- Correlation with AGNs
- GZK steepening

HiRes



Abbasi et al. 2008

- Fluorescence detector
- Exposure<850 km^2 sr
- Utah (USA)
- Ang. Resolution ~ 0.8°
- Ene. Resolution ~ 30%
- E>5.6x10^{19}eV, 13 events

- No small-scale anisotropy
- No Super-GZK events
- No Correlation

Abstract of this talk

<u>Question</u>

➢ What is really the origin of UHECRs?

UHECRs themselves and their secondary neutrinos are used for probes.

➢ Anisotropic distribution of arriving UHECRs indicates the local number density of UHECR sources of $10^{-4\pm1}\mathrm{Mpc}^{-3}$, which is much larger than the number density of several plausible source candidates.

➢ Estimating upper/lower bounds of bursting UHECR sources as

$$0.1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1} \lesssim \rho_0 \lesssim (60-3000)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

➢ Cosmogenic neutrinos enable us to obtain information on not only the origin of cosmic rays above the spectral knee but also UHECR sources at high-redshift universe (z~1).

Index

1. Introduction (~20min)
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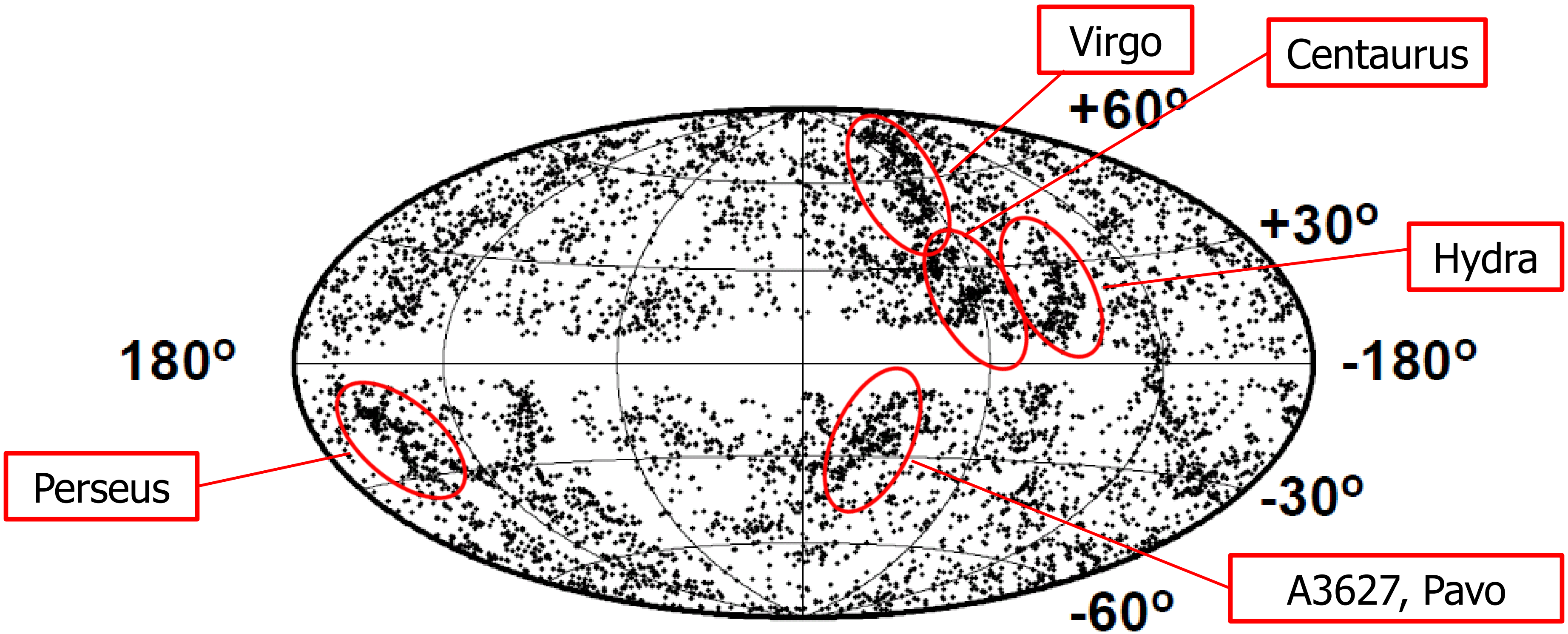
Nearby Universe (<100Mpc)

Nearby universe is highly structured.



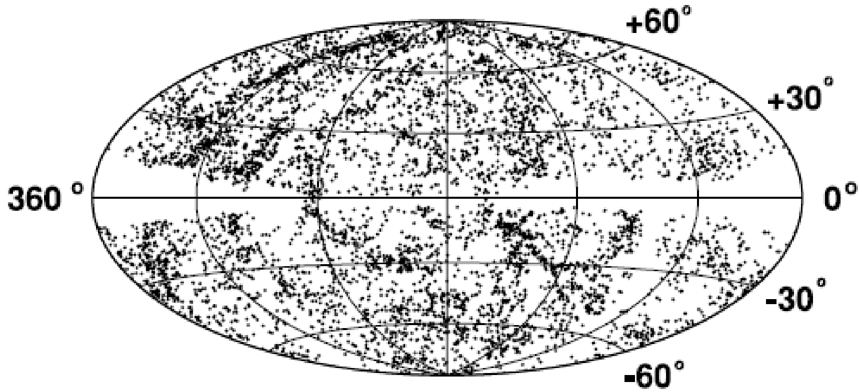
Saunders et al. 2000

Astrophysical Sources ➔ LSS structure is important

Source Model

d>100Mpc → isotropic

IRAS catalog



Luminosity function

$$\Phi(L) = \phi_* \left(\frac{L}{L_*}\right)^{1-\alpha} \exp\left\{ -\frac{1}{2\sigma^2} \left[\log\left(1 + \frac{L}{L_*}\right) \right]^2 \right\}$$

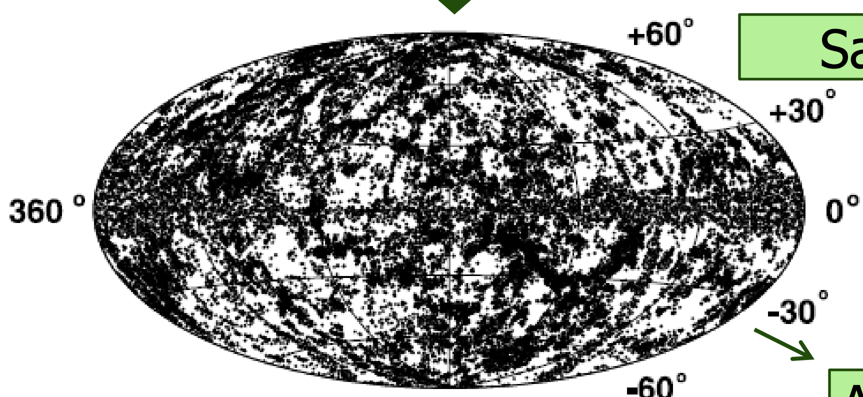
Selection function

$$\phi(r) = \frac{\int_{L_{\min(r)}}^{\infty} dL\, \Phi(L)}{\int_0^{\infty} dL\, \Phi(L)}$$

Modified IRAS catalog

$$\bar{n}(r)\phi(r)^{-1}$$

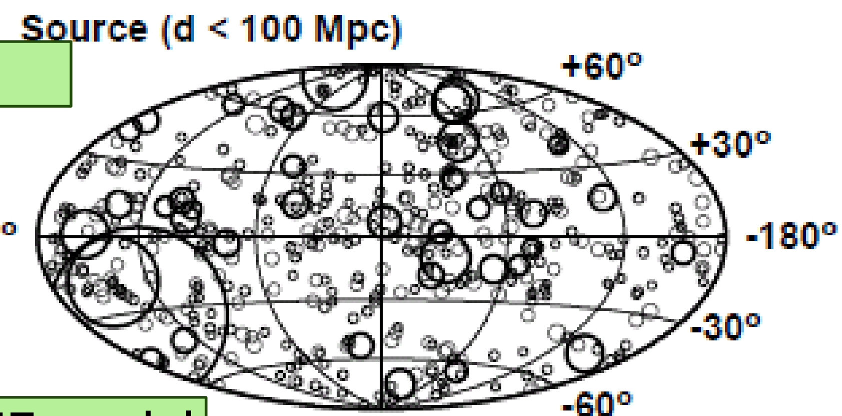
$$\frac{4\pi}{3} l(r)^3 n(r) = 1$$



Sampling

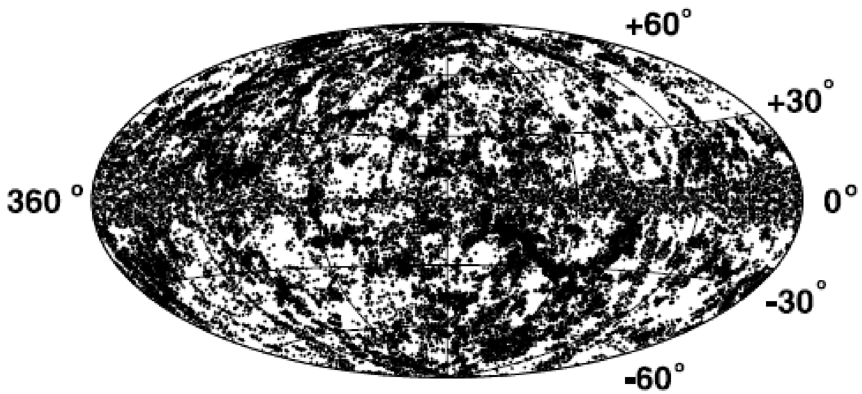
Also IGMF model

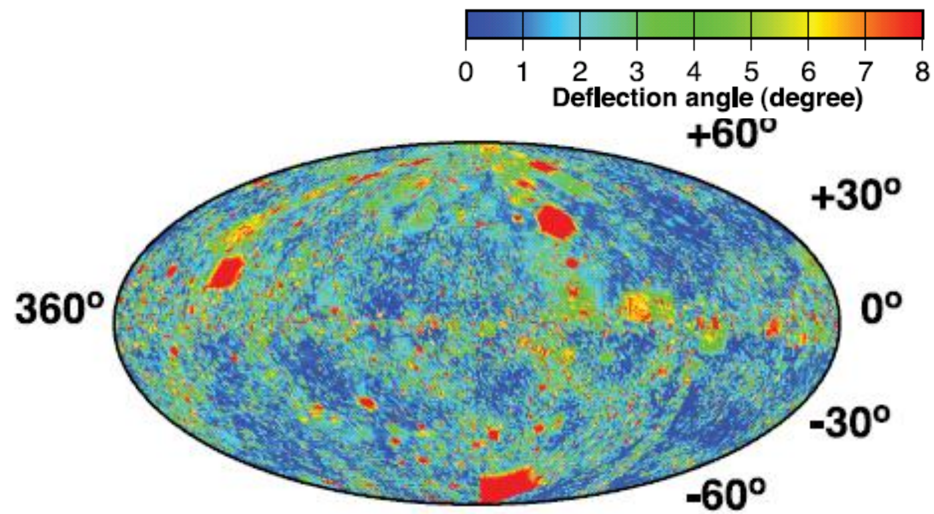
Source distribution



Our IGMF model

Constructed from the IRAS PSCz catalog of galaxies

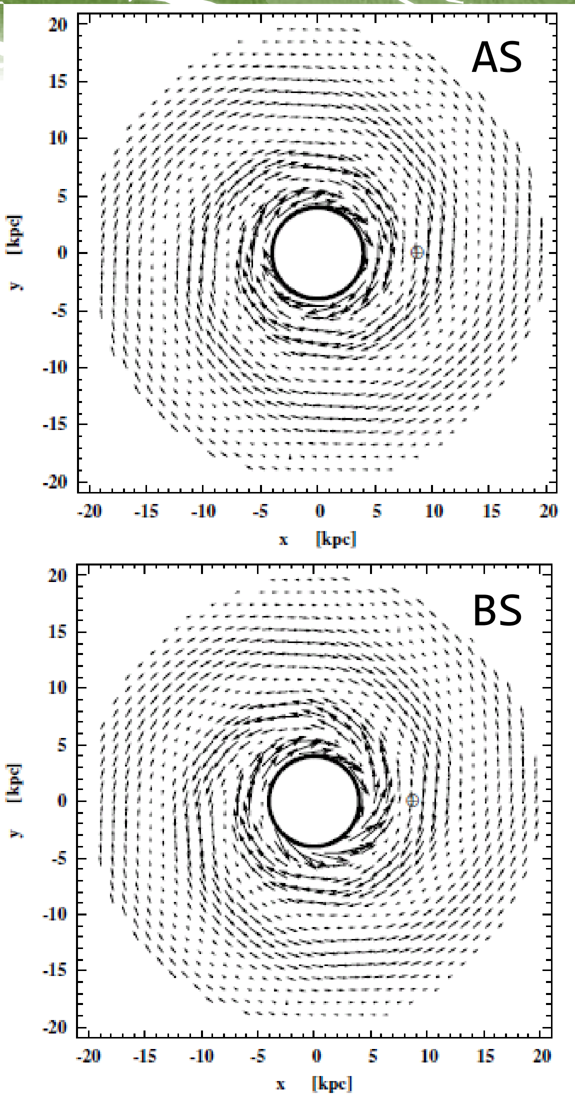




HT, Yoshiguchi, Sato 2006

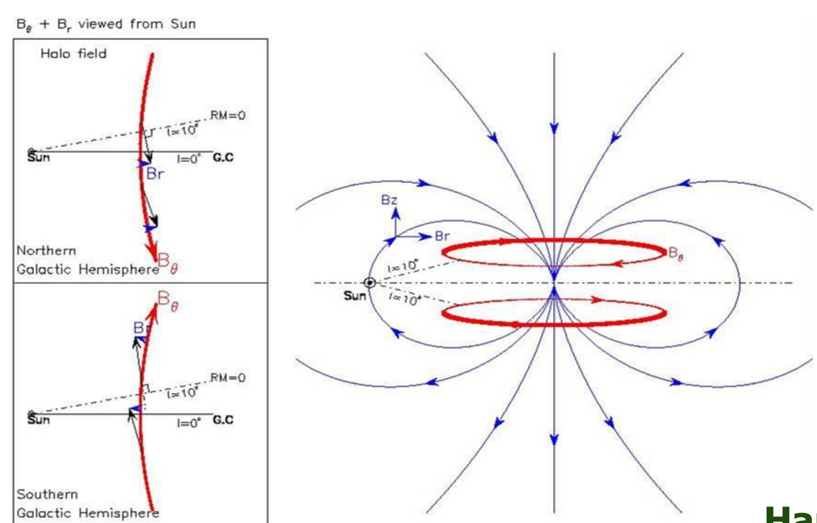
- Observed structure is reflected
- $B \propto \rho^{2/3}$, normalized at Virgo cluster, as B=0.0, 0.1, 0.4, 1.0μG
- Assuming isotropic distribution of galaxies in the IRAS mask
- d>100Mpc → uniform turbulent field with 1nG

Galactic Magnetic Field



Alvarez-Muniz & Stanev 2006

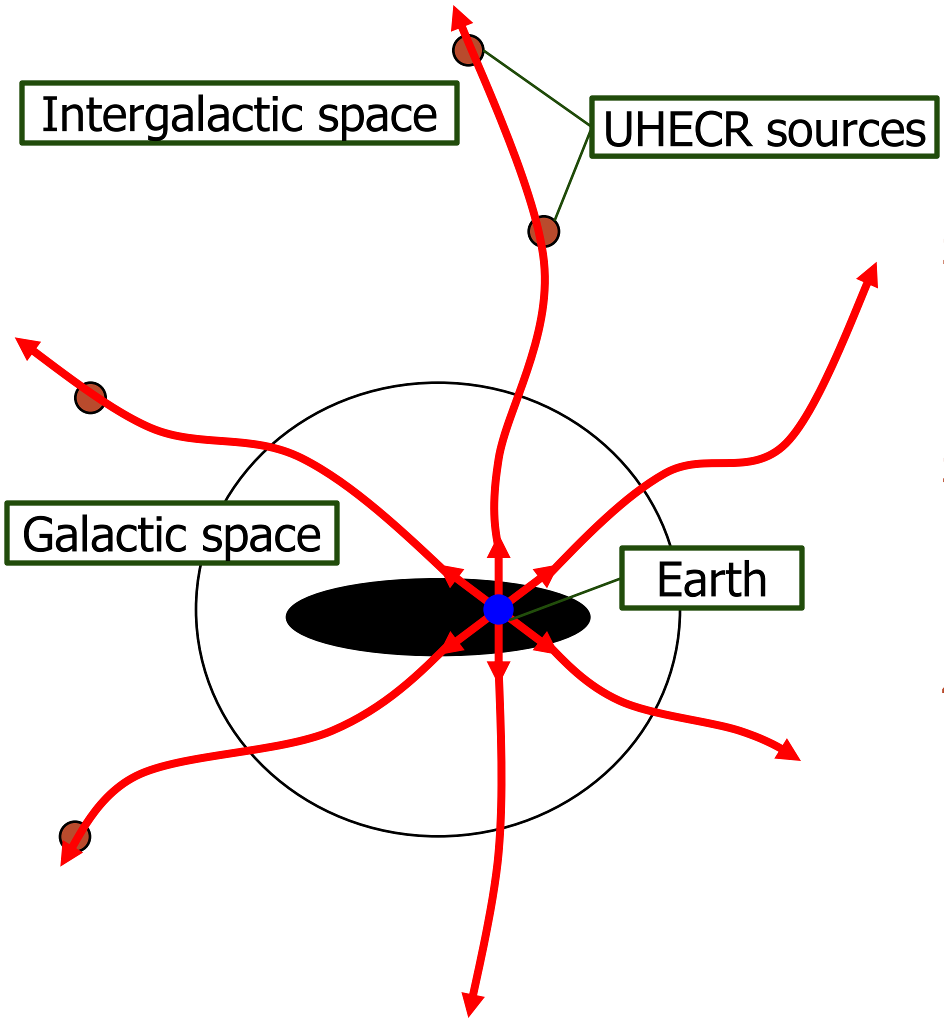
- Magnetic field is Galactic disk
  - ✓ Axisymmetric (AS) / Bisymmetric (BS)
  - ✓ BS has field reversals, while AS does not.
- Magnetic field in Galactic halo: much less known
  - ✓ Spiral field with exponential decay in the z direction
  - ✓ Classified by parity about Galactic plane: symmetric(S) or anti-symmetric (A)
  - ✓ A dipole field at Galactic center is also assumed.



Han 2002

A calculation method

Emitted cosmic rays rarely reach the Earth in simulation due to magnetic deflections.



1. Many particles (2,500,000)with charges of -1 are ejected isotropically from the earth, and calculated their trajectories.
2. If a trajectory passes a source, the particle has a certain contribution shown below to the "real" – positive arriving – CRs.
3. We regard the contribution factor of each CR as the probability that the CR is a "real" event observed at the earth.
4. We select trajectories corresponding to the probabilities.

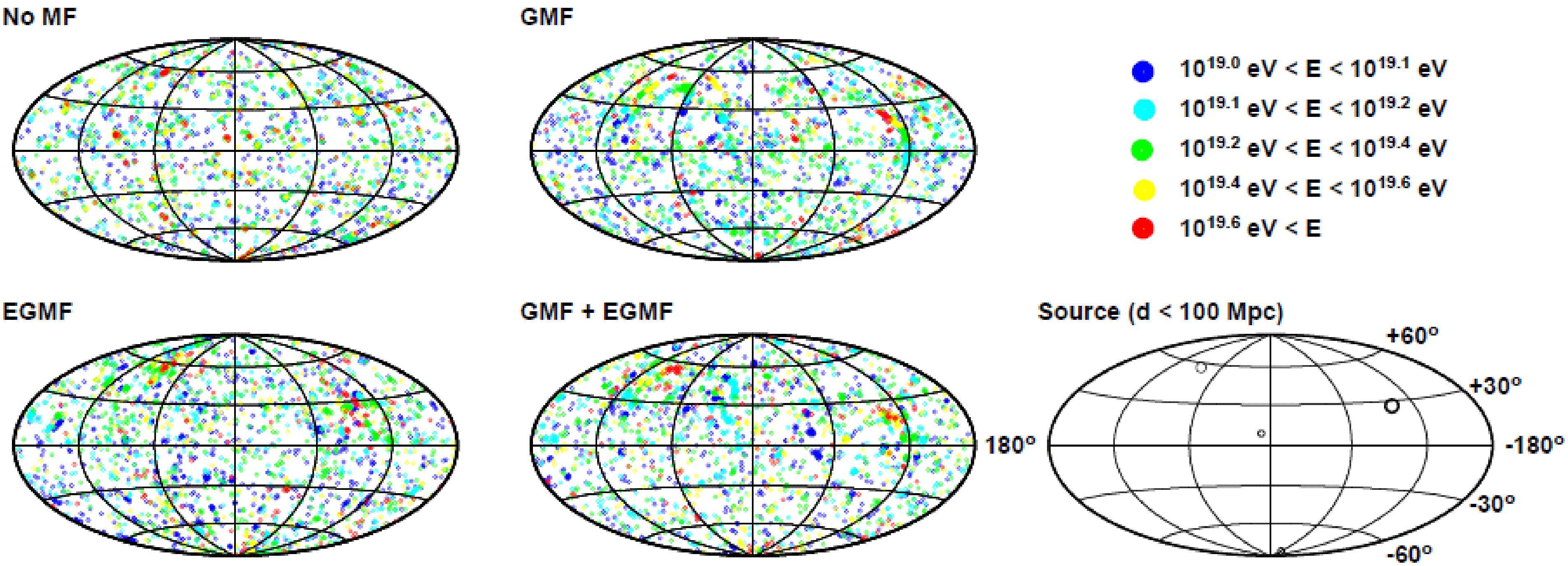
$$P_{\mathrm{selec}}(E,j) \propto \sum_i \frac{1}{(1+z_{i,j})d_{i,j}^2} \boxed{\frac{dN/dE_g(d_{i,j},E_g^i)}{E^{-1.0}}} \frac{dE_g}{dE}$$

$\propto E^{-2.6}$

HT, Yoshiguchi, Sato 2006

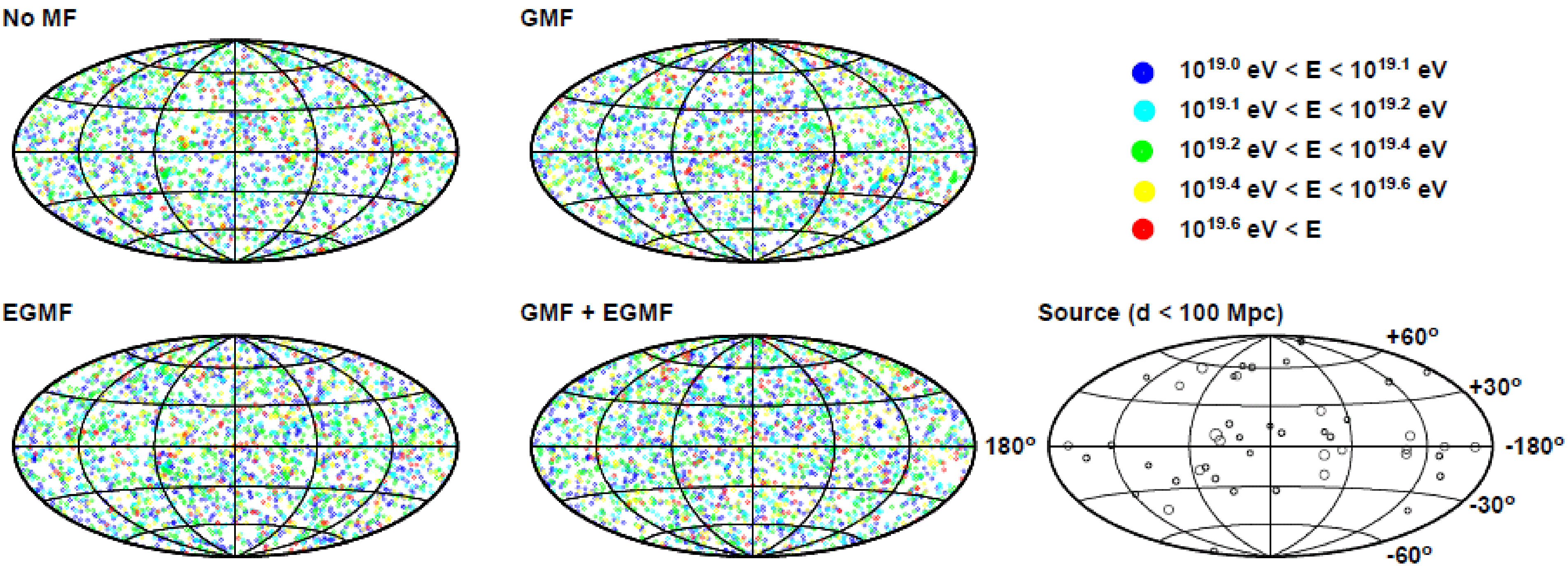
An example of UHECR arrival distribution

$\sim 10^{-6} Mpc^{-3}$



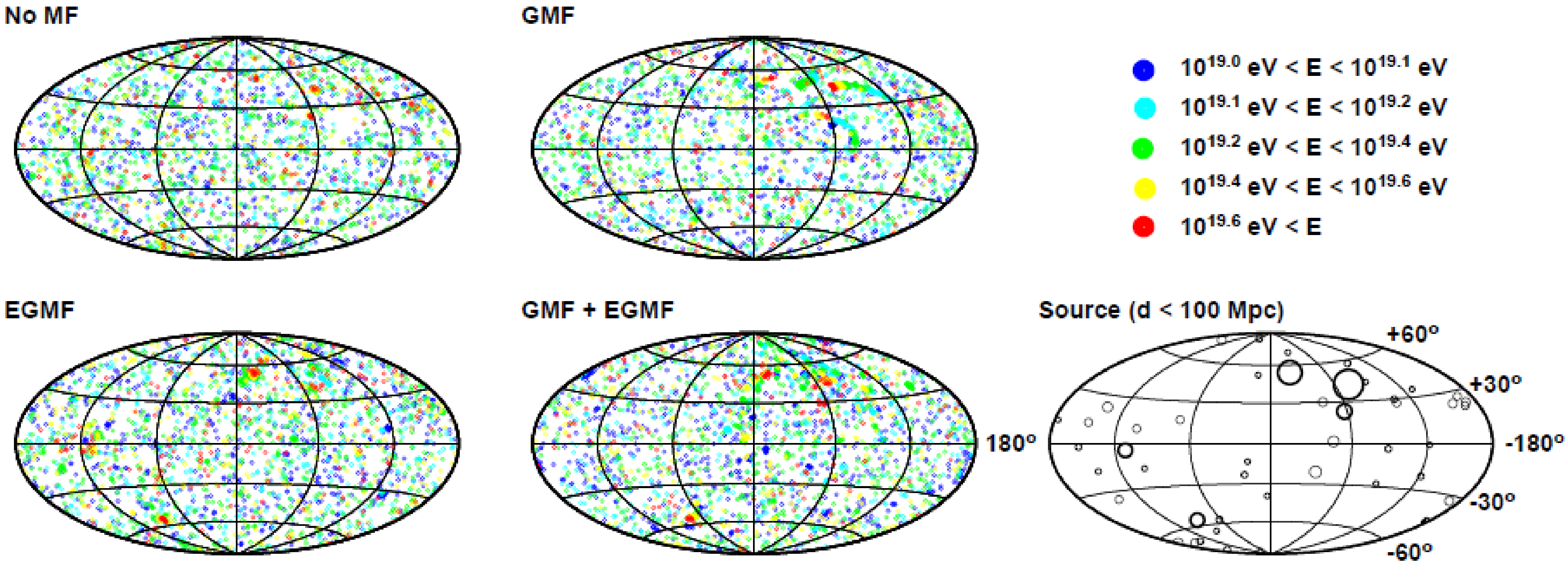
An example of UHECR arrival distribution

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



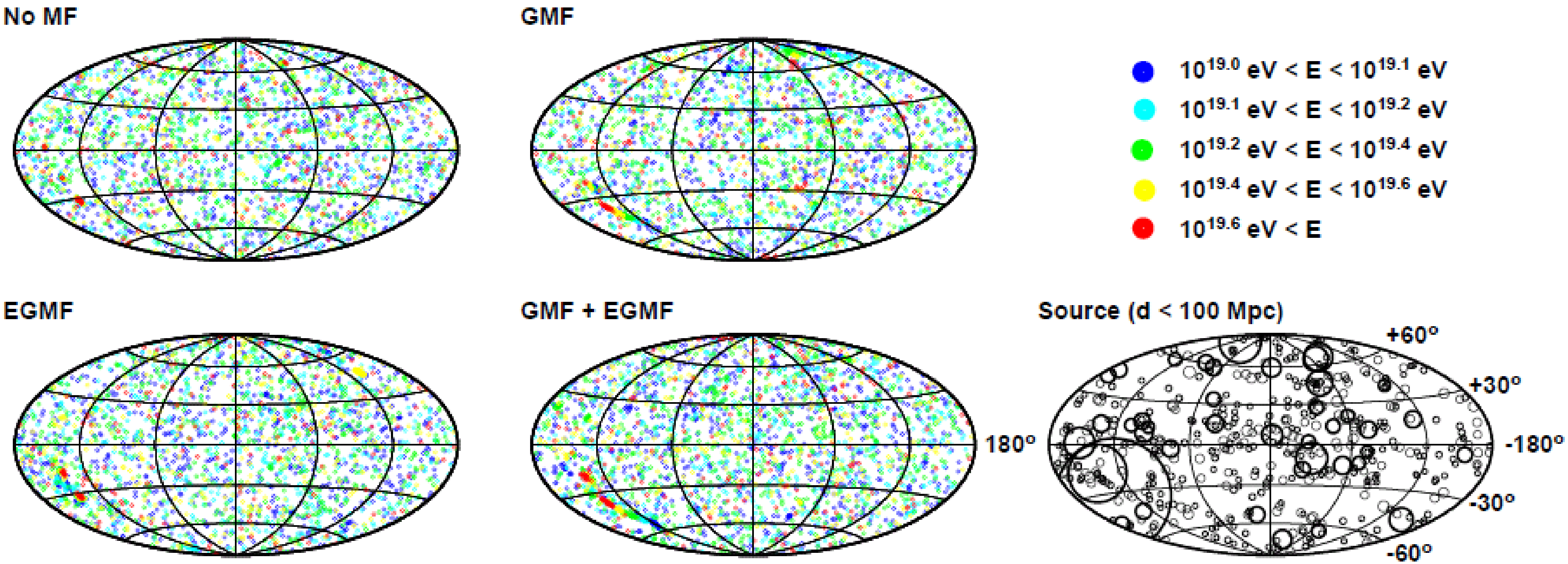
An example of UHECR arrival distribution

$\sim 10^{-5}\mathrm{Mpc}^{-3}$



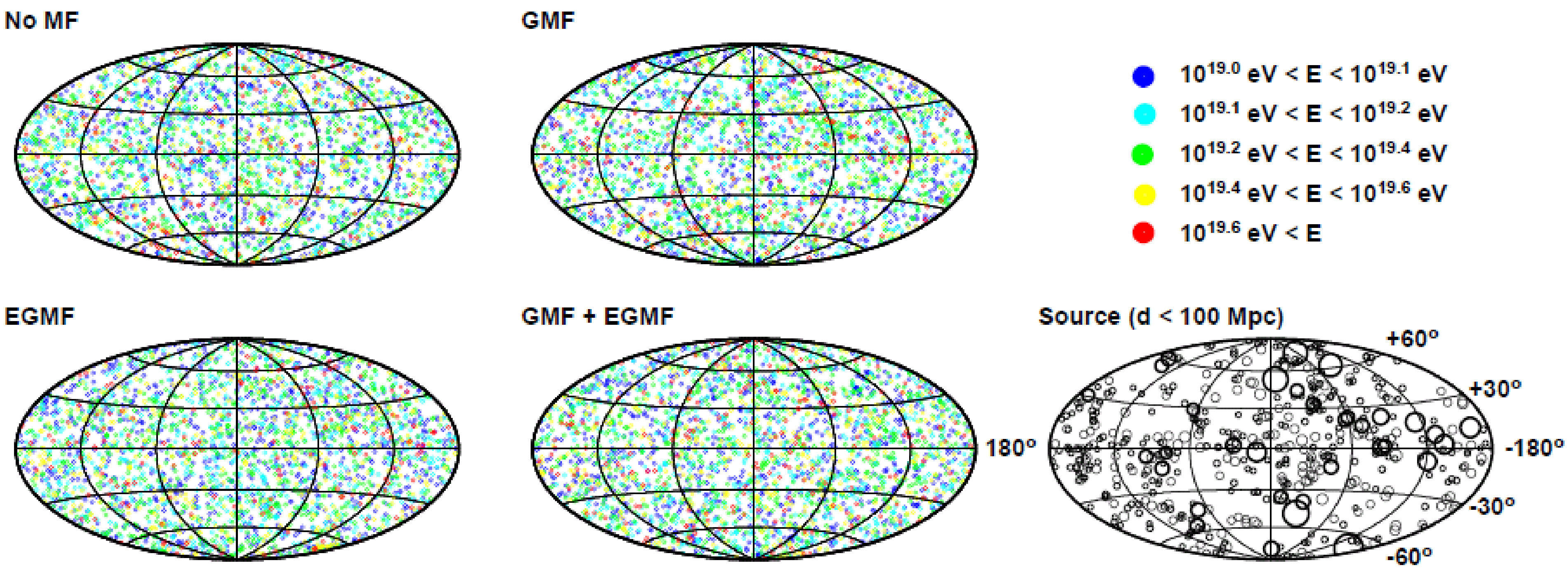
An example of UHECR arrival distribution

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



An example of UHECR arrival distribution

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

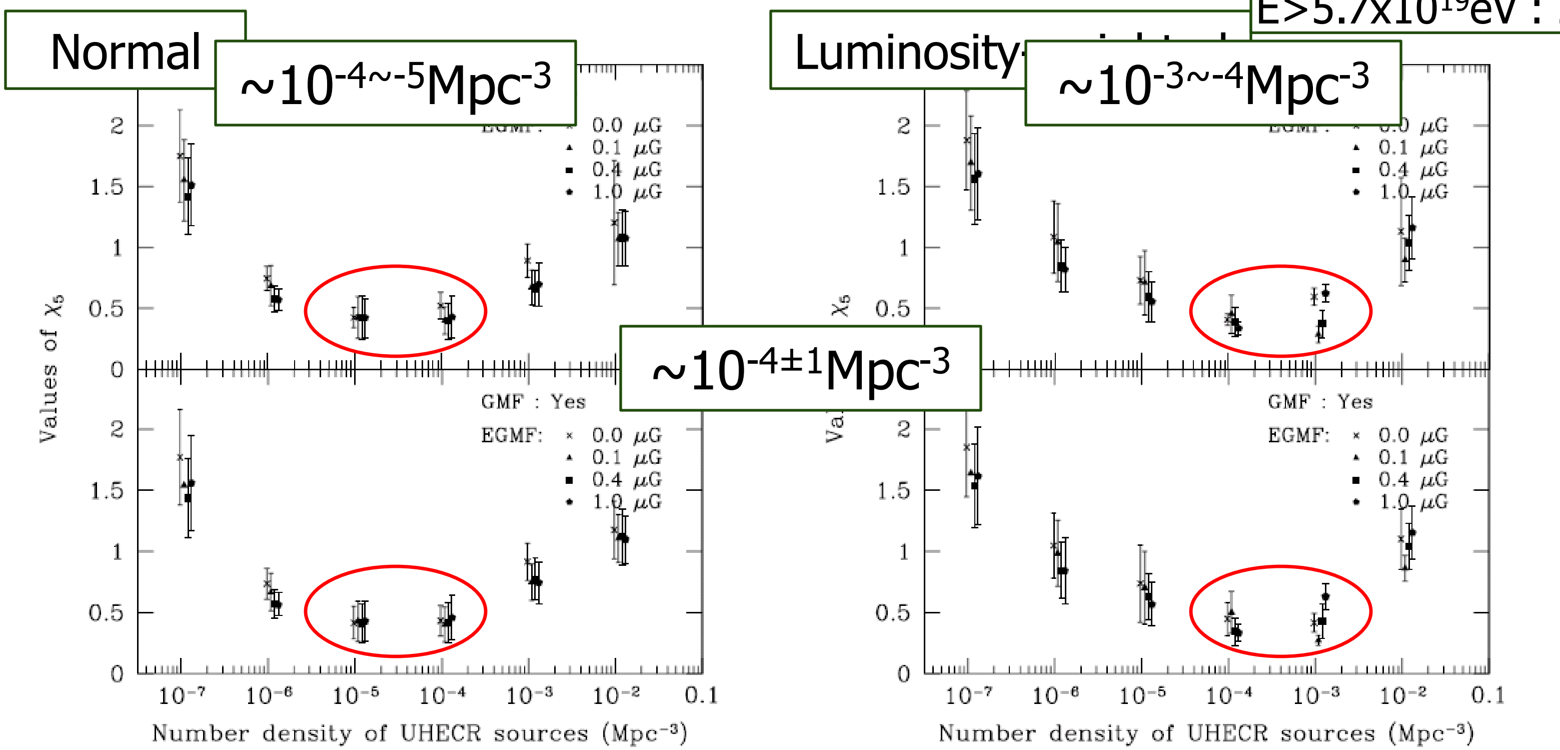


UHECR Source Number density (PAO)

Auto-correlation function : a statistic for finding anisotropy in UHECR distribution

$$w(\theta) = \frac{1}{2\pi\,|\cos\theta - \cos(\theta+\Delta\theta)|} \sum_{\theta \le \phi \le \theta+\Delta\theta} 1\,[\mathrm{sr}^{-1}] \quad \chi_{\theta_{\max}} = \frac{1}{N_{\mathrm{bin}}} \sqrt{\sum_{n=0}^{N_{\mathrm{bin}}-1} \frac{[w(\theta_n) - w_{\mathrm{obs}}(\theta_n)]^2}{\sigma(\theta_n)^2}}$$

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



HT & Sato 2008

Comparison with n_s of known objects

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

appropriate

too small

subdominant contribution

Several specific types of AGNs or GRBs

Index

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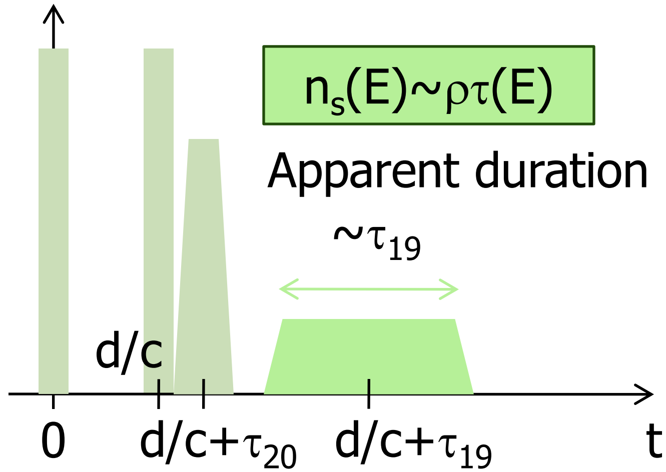
Transient Activity for UHECR generation?

Apparent n_s depends on the energy of arriving cosmic rays



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

Setup

- uniform IGMF (1nG), GMF
  - GMF → lower bound
  - IGMF+GMF → upper bound

Required rate

$$0.1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1} \lesssim \rho_0 \lesssim (60-3000)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

Required energy output

$$(0.3-20)\times 10^{50}\,\mathrm{ergs} \lesssim \tilde{\mathcal{E}}^{\mathrm{iso}}_{\mathrm{HECR}} \lesssim 10^{54}\,\mathrm{ergs}$$

Source	Typical Rate ρ_0 [$\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$]
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

Index

1. Introduction (~20min)
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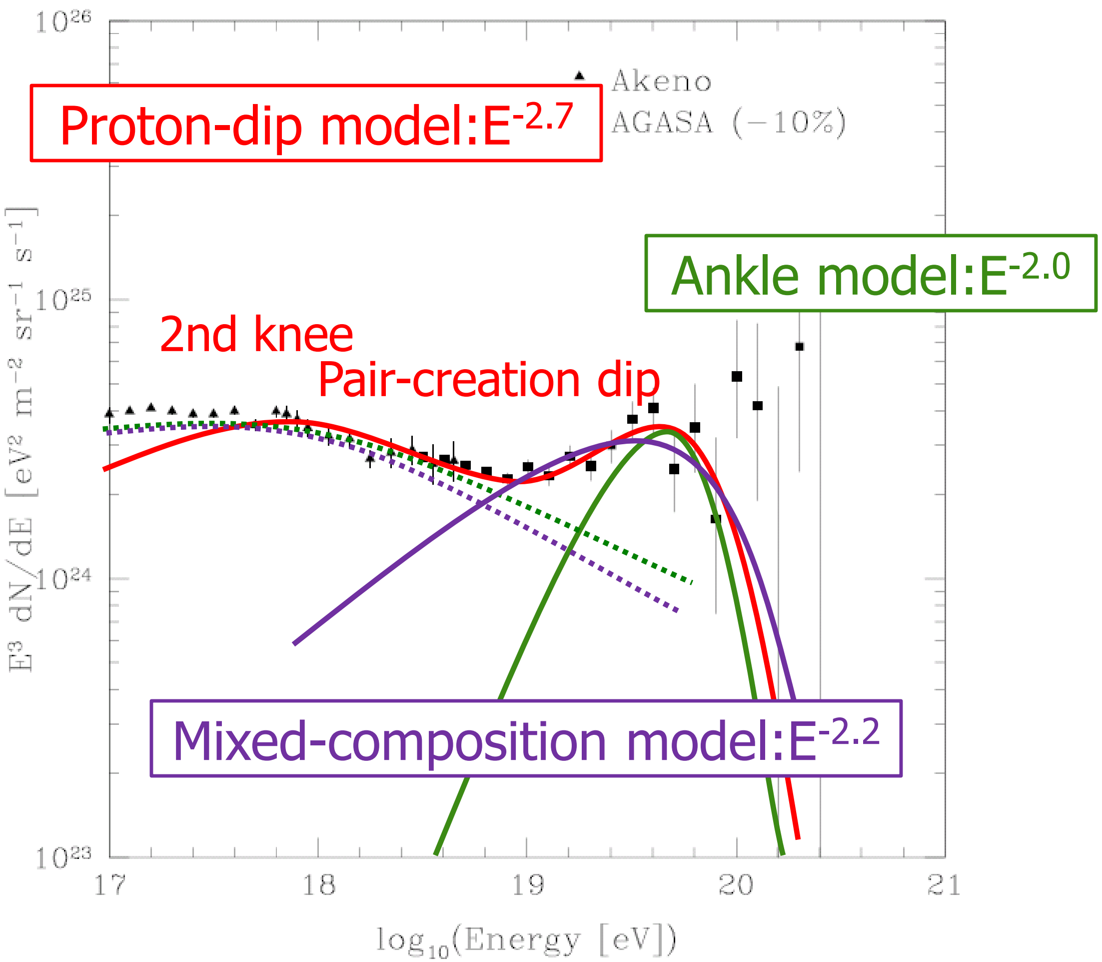
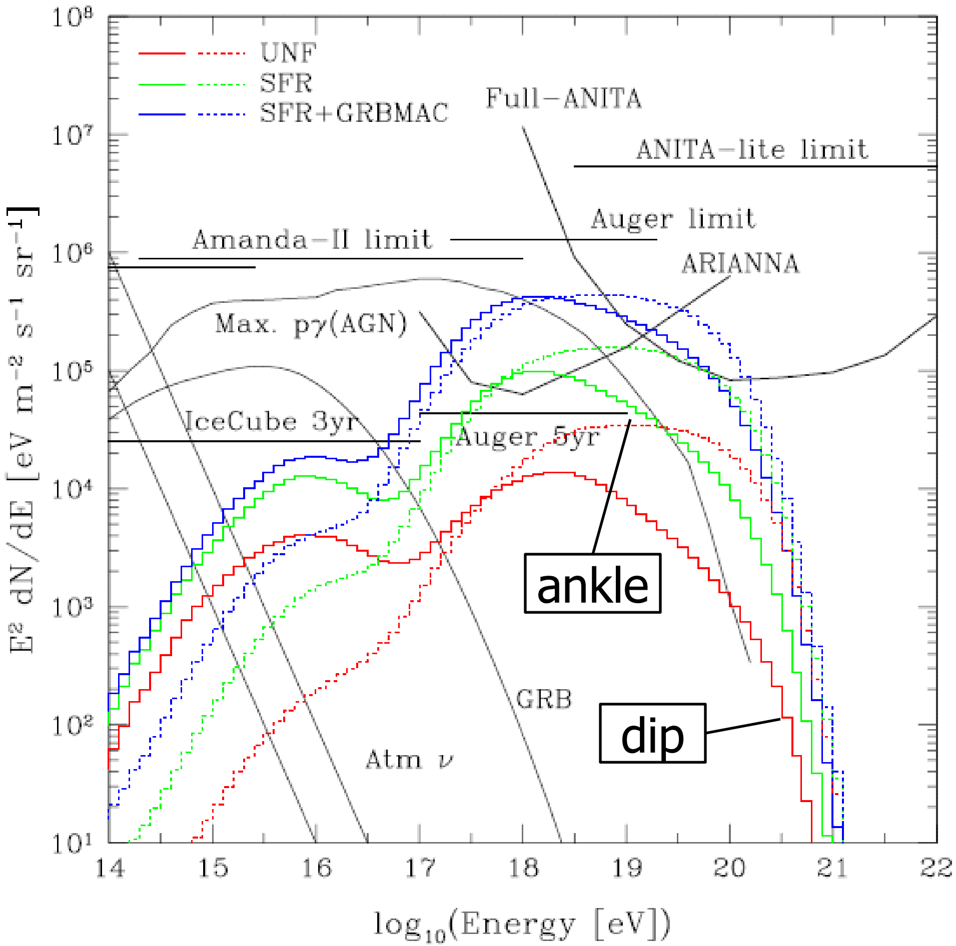
3. Constraining the Rate of Transient UHECR Sources
4. Secondary Neutrinos
5. Conclusion

Transition from GCRs to EGCRs

Which is a better scenario?



Neutrino Fluxes



HT, Murase, Nagataki & Sato 2009

Setup for calculations

- IGMF is neglected.
- considering up to z~5.
- UHECR sources are uniformly distributed with some cosmological evolution models

- Neutrino fluxes in both scenarios are obviously different.
  - peak at ~10^{16}eV for dip scenario
  - Larger flux at ~10^{20}eV for ankle scenario
- Neutrino flux also depends on cosmological evolution of UHECR sources
  - Flux at ~10^{18}eV is a good probe which is independent of the transition scenarios
- Detectability is realistic!

Conclusion

➢ We simulate the arrival distribution of the highest energy protons. The simulated results are compared to observed ones, and we obtain several constraints on the nature of the sources of the highest energy cosmic rays.

➢ We estimate the fluxes of cosmogenic neutrinos.

➢ Anisotropic distribution of arriving UHECRs indicates the local number density of UHECR sources of $10^{-4\pm1}\mathrm{Mpc}^{-3}$, which is much larger than the number densities of blazars and FR2 radio galaxies.

➢ Estimating upper/lower bounds of bursting UHECR sources as

$$0.1\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1} \lesssim \rho_0 \lesssim (60 - 3000)\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

$$(0.3 - 20) \times 10^{50}\,\mathrm{ergs} \lesssim \tilde{\mathcal{E}}_{\mathrm{HECR}}^{\mathrm{iso}} \lesssim 10^{54}\,\mathrm{ergs}$$

➢ Cosmogenic neutrinos enable us to obtain information on not only the origin of cosmic rays above the spectral knee but also UHECR sources at high-redshift universe.