Numerical Study of Propagation of UHECR

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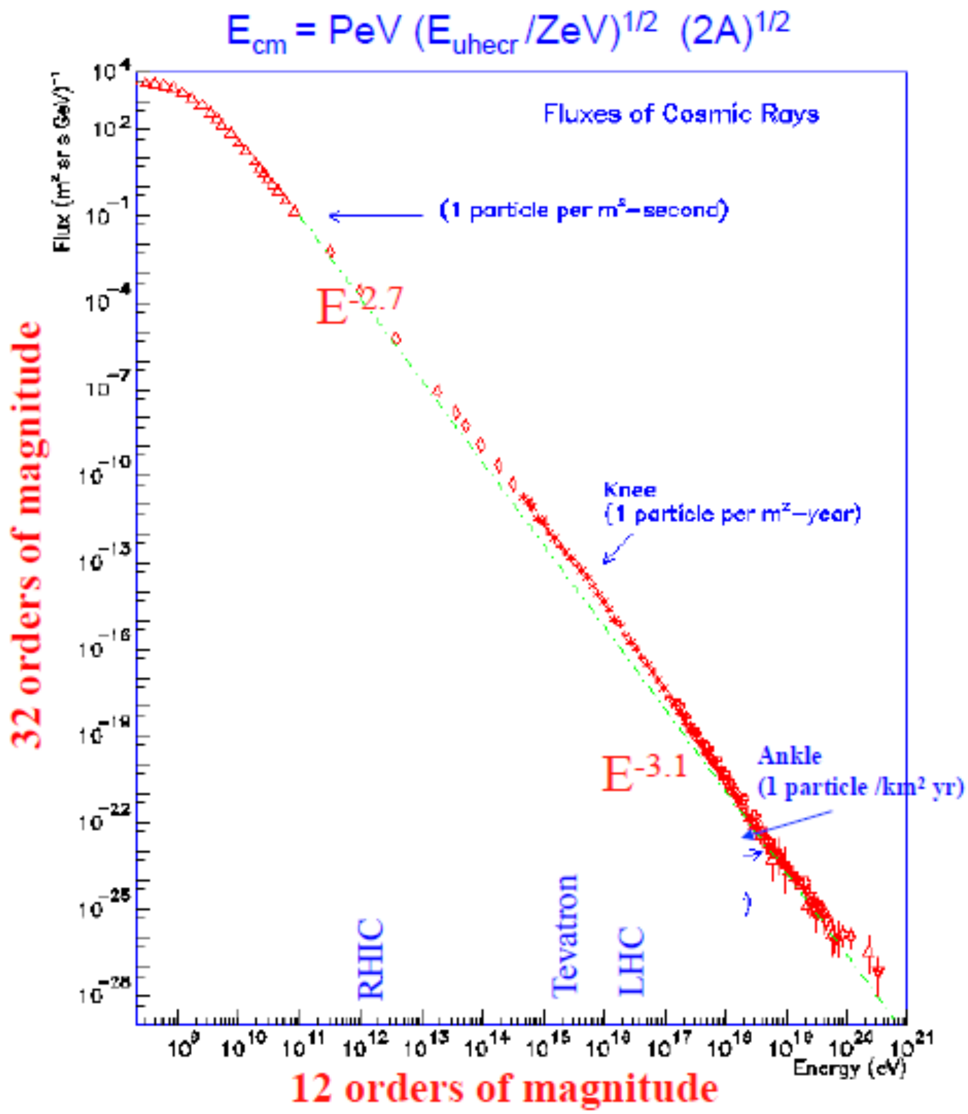
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Moorea, French Polynesia, 10th Sep 2011

§ Introduction

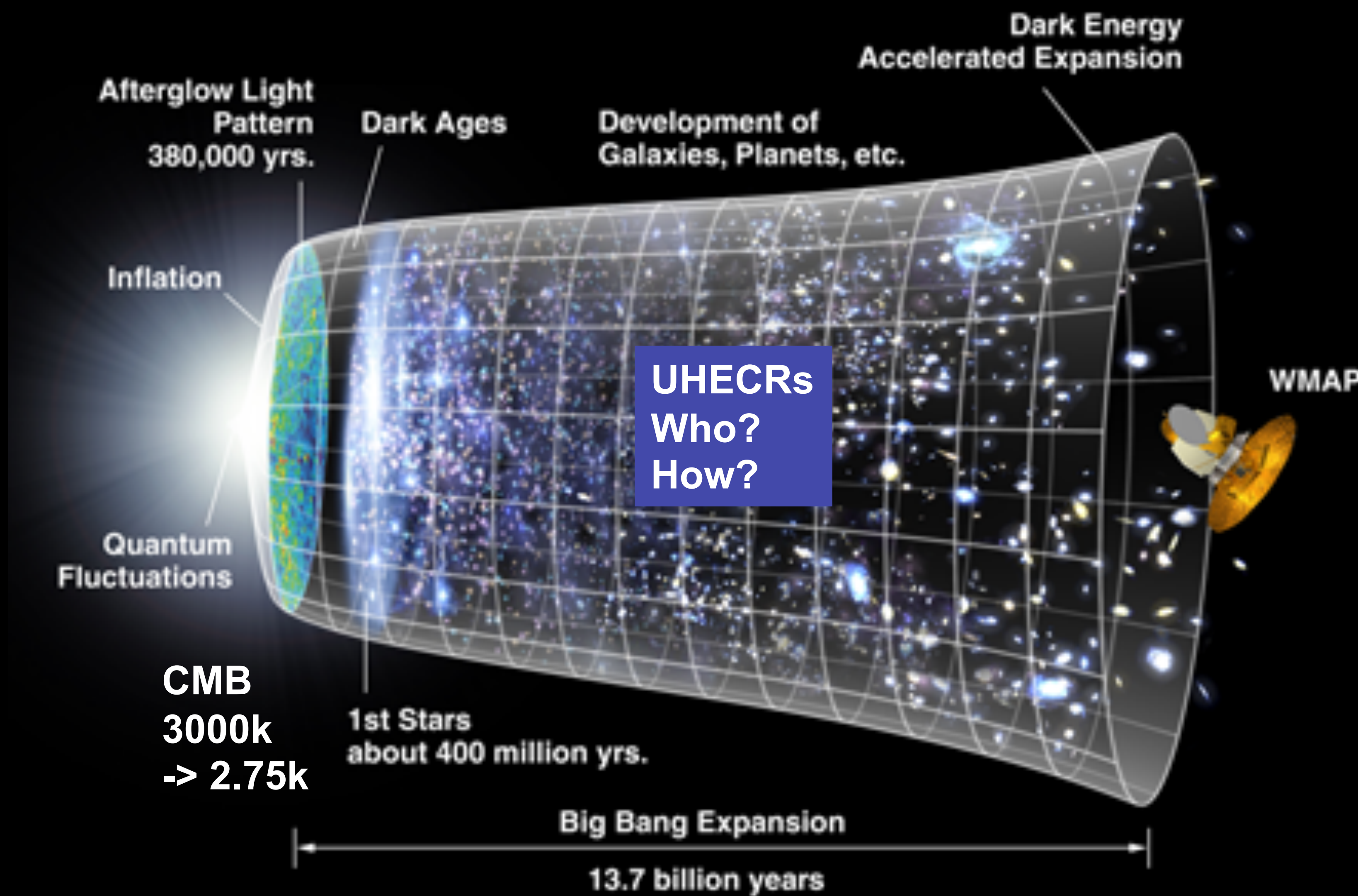
Mysteries of UHECRs



Energy Spectrum of Cosmic-Rays @Earth

- What are the sources of UHECRs?
- How large is the highest energy of CRs in the universe?
- How are UHECRs produced?

History of the Universe



Active Galactic Nuclei

Centaurus A

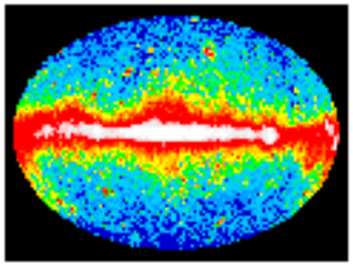
11million light years.
= 3.4Mpc.

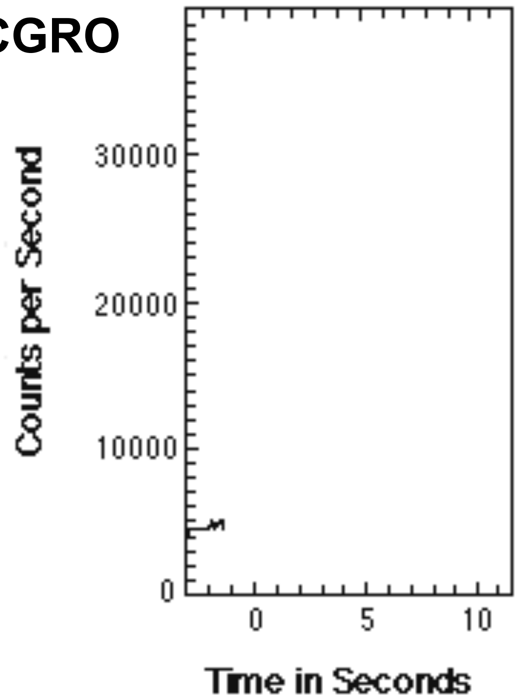
Chandra X-ray Image

Jet: 13,000 light years.

Gamma-Ray Bursts

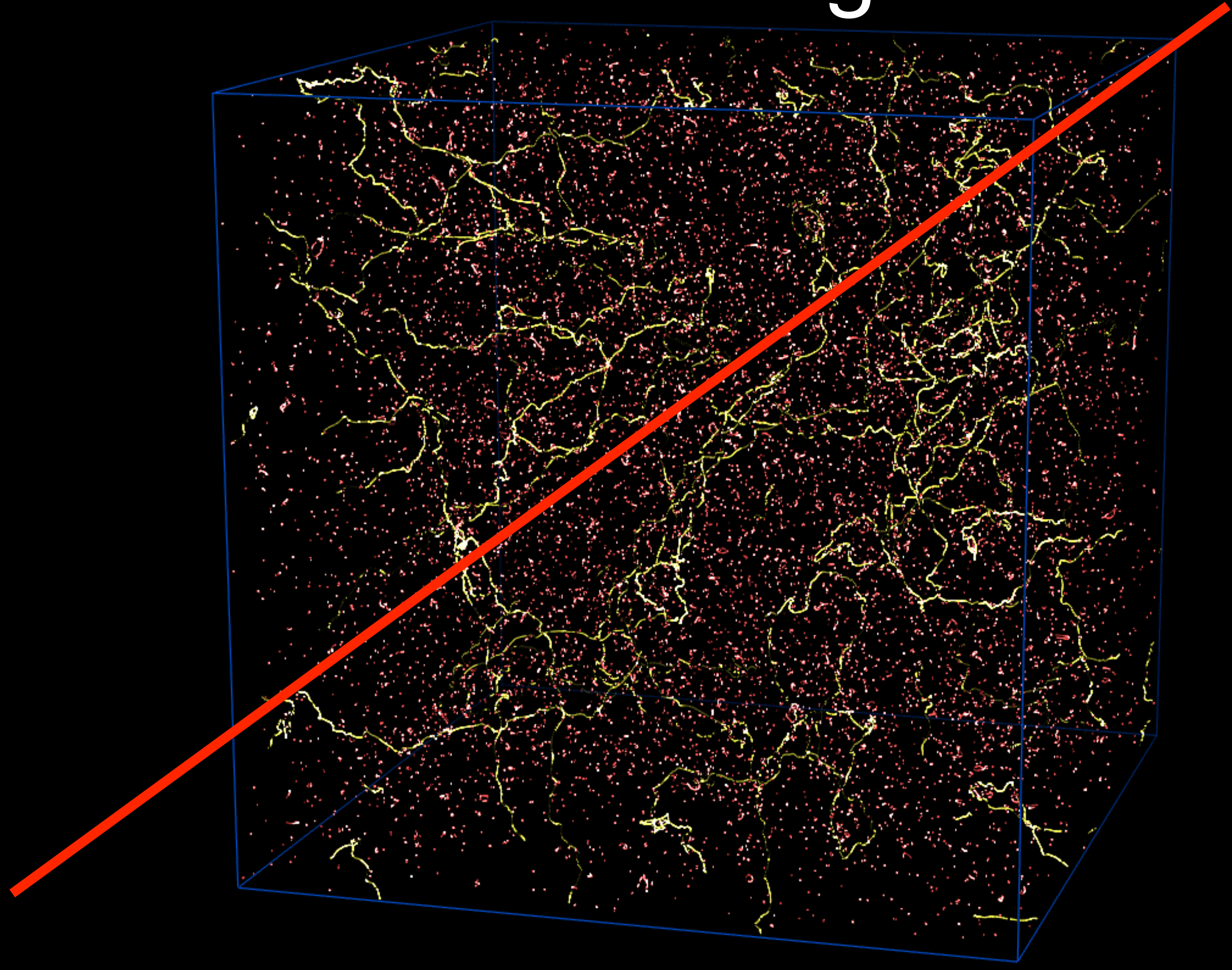
Hard X-ray by CGRO





From NASA’s HP.
(Imagination)

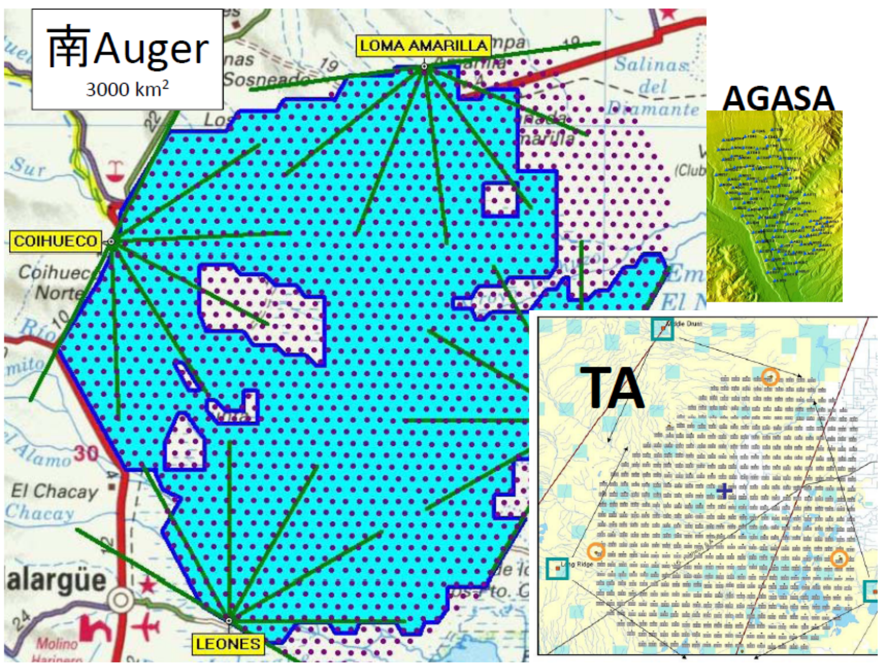
Cosmic Strings?

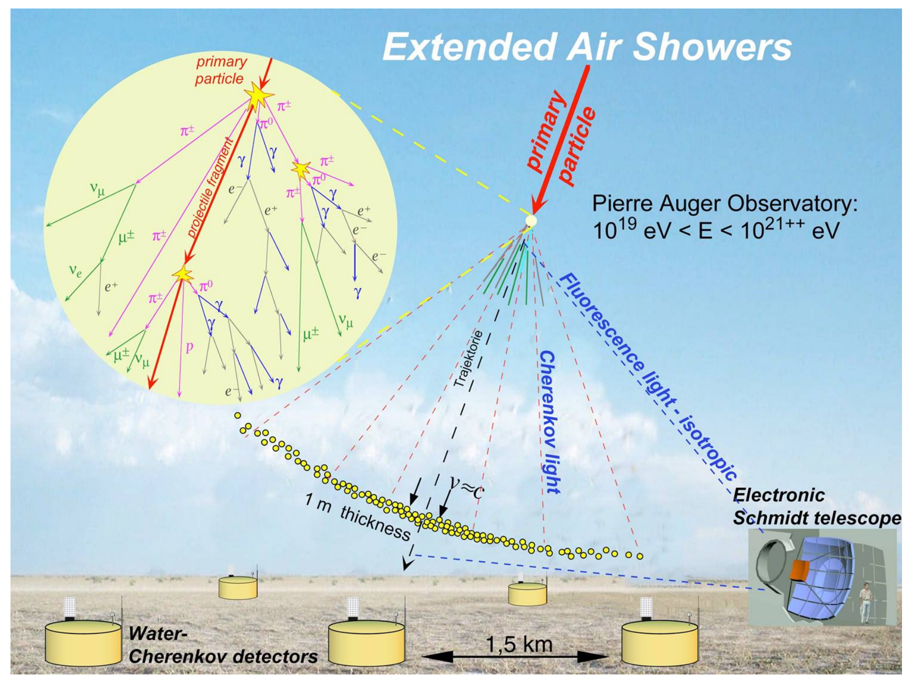


§ Current Status of Observations

Pierre Auger Observatory (PAO) 2004-

- @ Mendoza, Argentina
- Two independent techniques:
  Ground array of 1660 water-Cherenkov detectors (SDs).
  27fluorescence telescopes (FDs).
- 3000km^2





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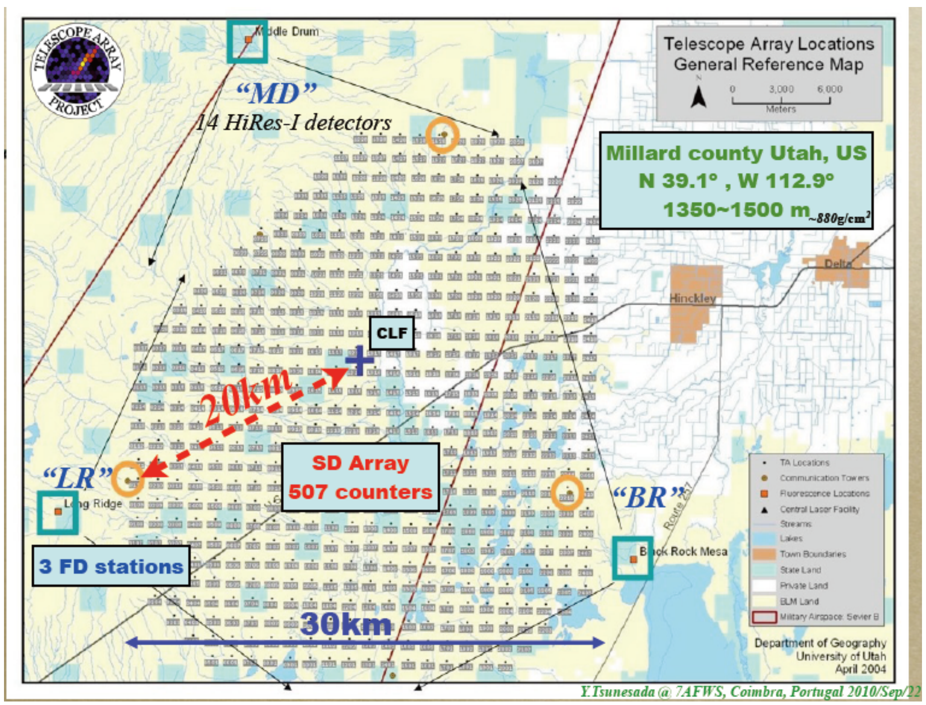
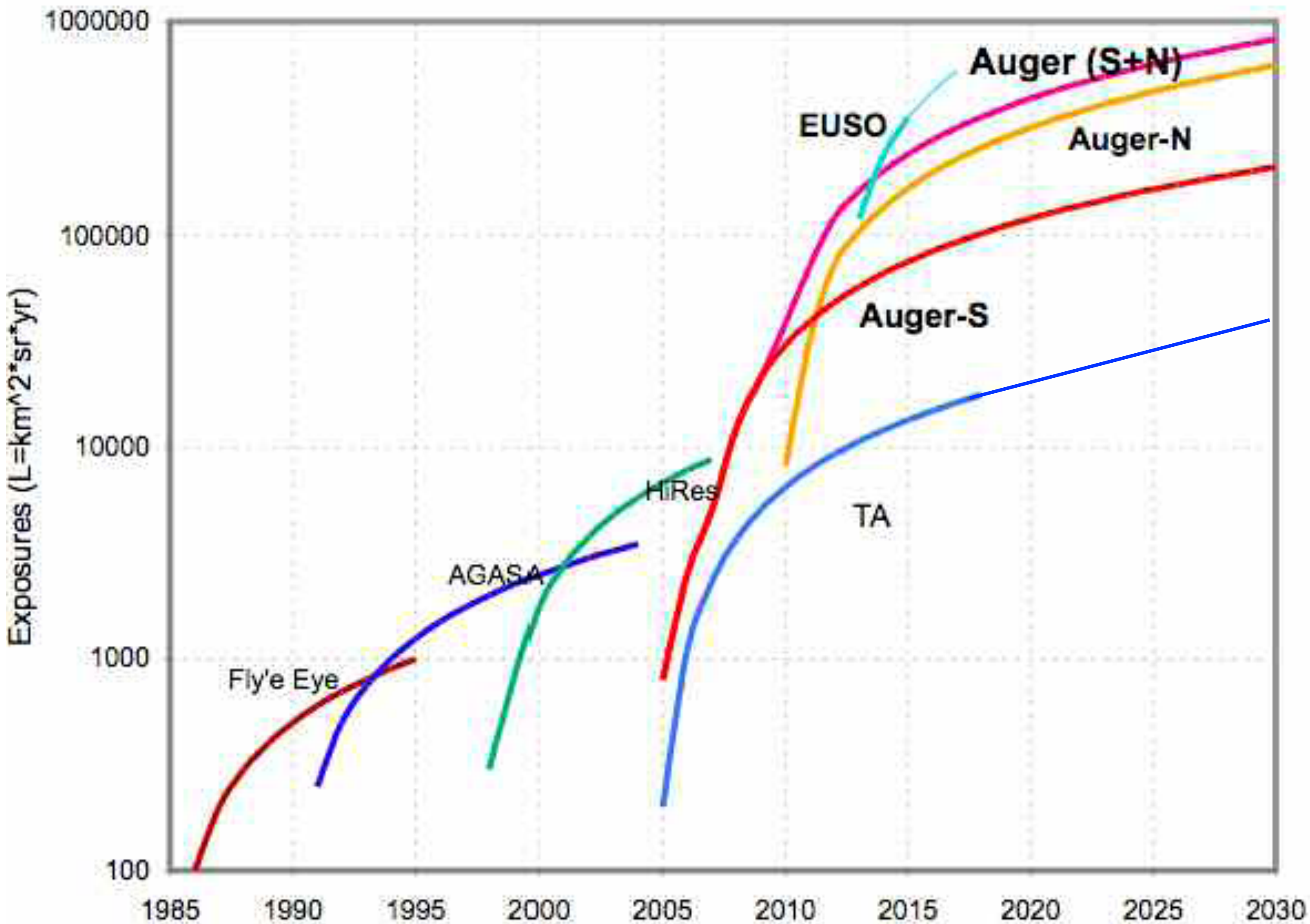
Telescope Array (2008-)

- @Utah, USA. Collaboration between AGASA and HiRes.
- 507 surface detectors (SD)
- 38 fluorescence telescopes (FDs).
- 680 km^2



Comparison of Exporsures



Three Key Points

- Spectrum: Are sources really extra-galactic, and in nearby Universe?
- Arrival Direction: Clue to identify sources.
- Composition: Source Properties.

Spectrum: GZK Cutoff (1)

- Penzias and Wilson 1964 : First Discovery of CMB.
- Greisen 1996, Zatsepin and Kuz'min 1966. Theory of GZK cut-off.

Cosmic Microwave Background by WMAP （from NASA HP）

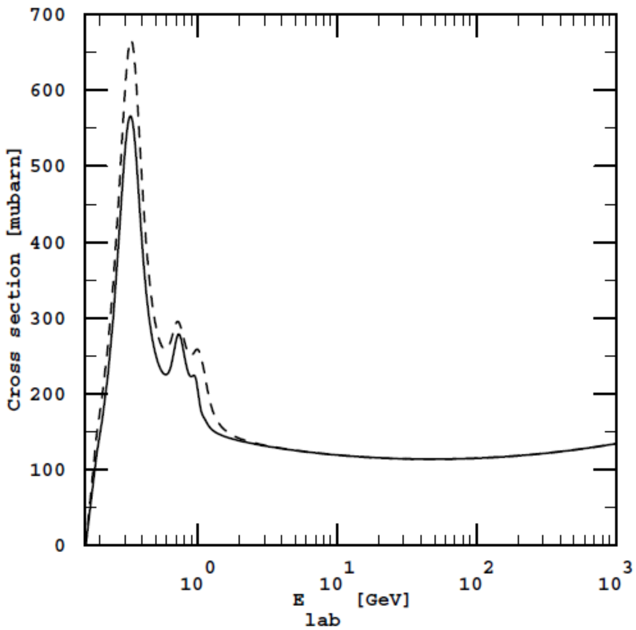
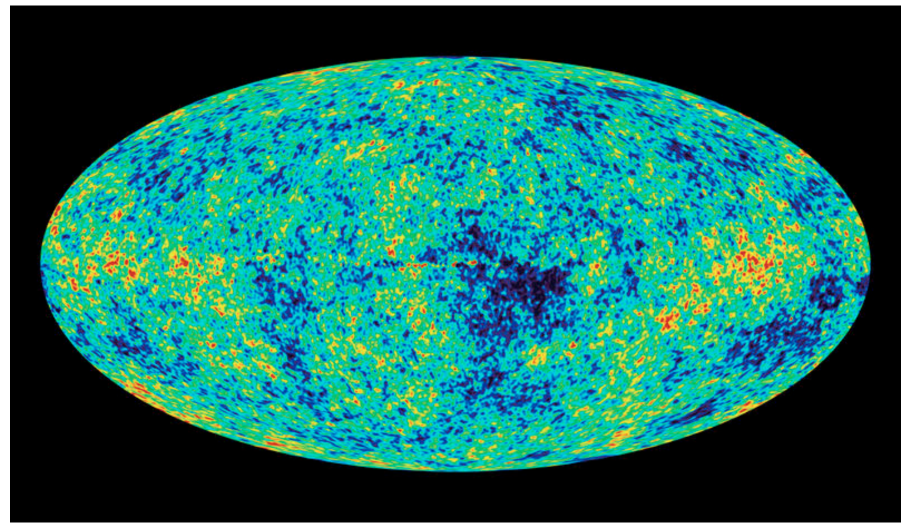


Figure 8: The total photo-pion production cross section for protons (solid line) and neutrons (dashed line) as a function of the photon energy in the nucleon rest frame, $E_{\rm lab}$.



Cross Section for Photo-pion production

3K＝2.5^-4 eV
Lorentz transformation with
Γ= 5*10^11 makes it 1.25^8 eV = 125MeV ～Pion's mass＝140MeV
Energy loss length is about 50Mpc.

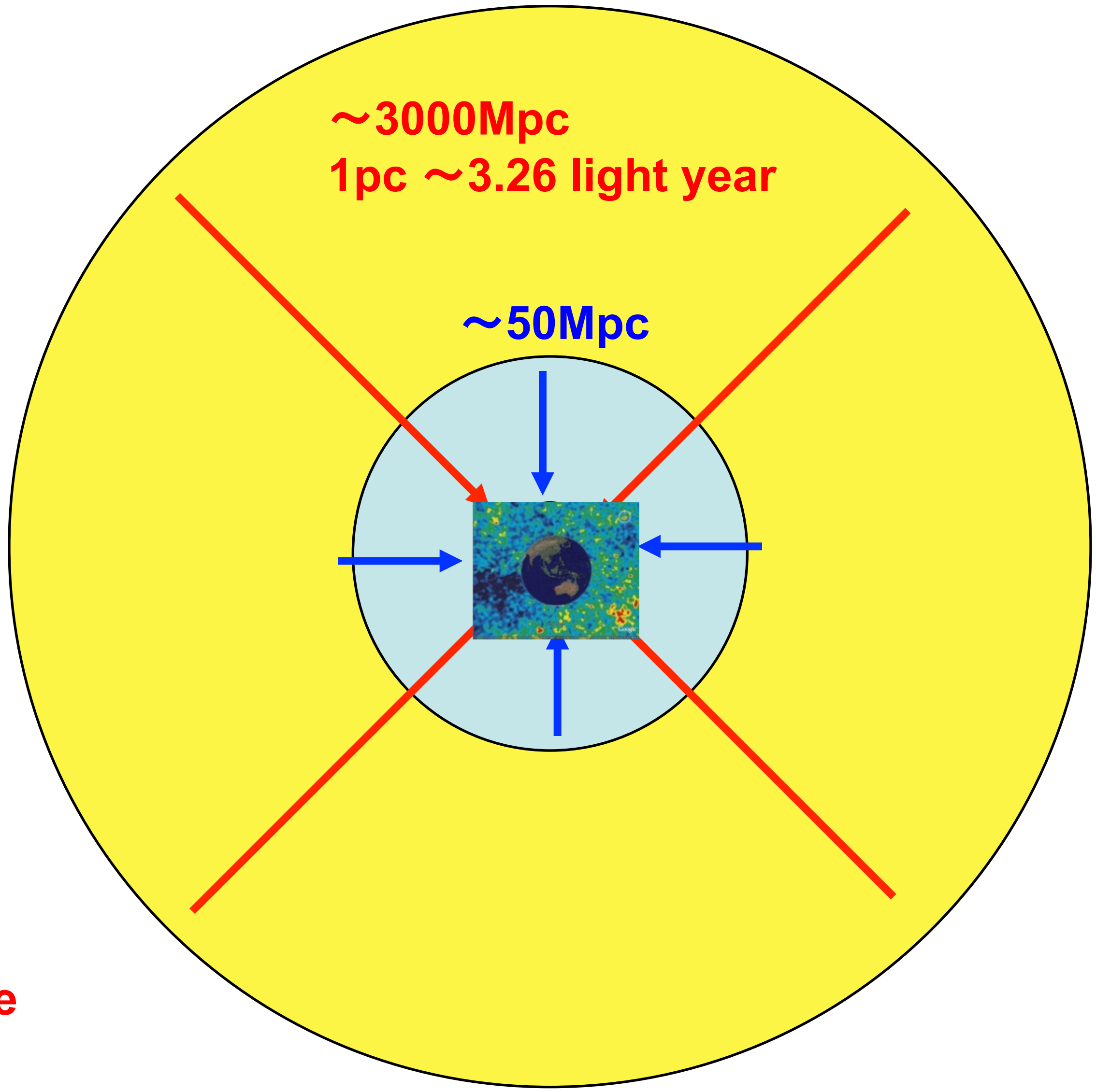
GZK Cutoff (2)

Center: The Earth

Light Blue Region:
The region from where UHECRs can reach to the Earth.

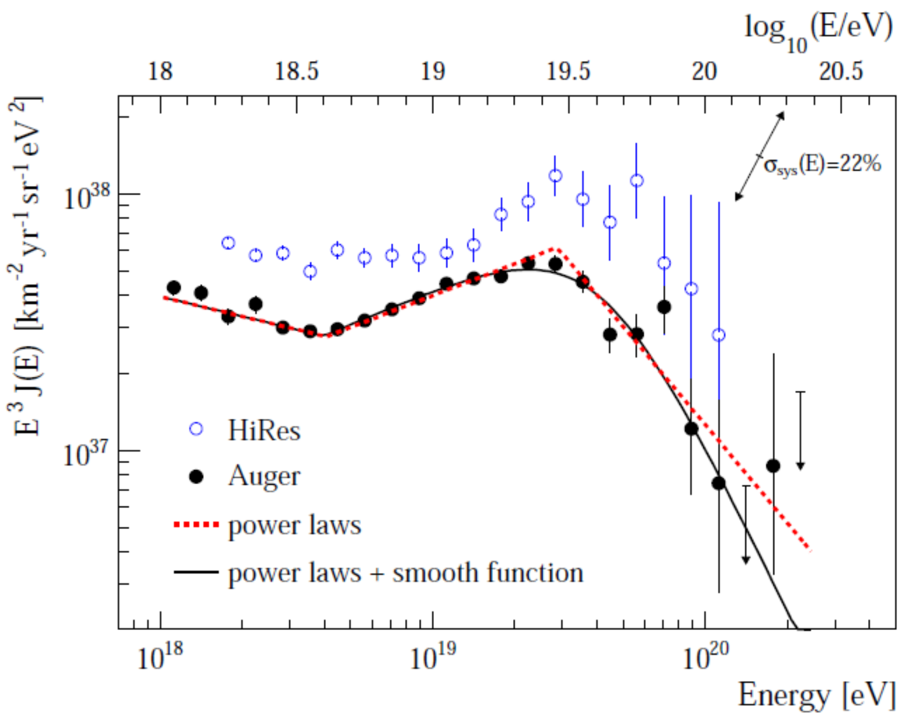
Yellow Region (including the light Blue region):
The region where CRs below 10^20eV can reach to the Earth.

If GZK cutoff is confirmed, the Sources should be extra-galactic And sources of UHECRs should be Within GZK sphere (～50Mpc).

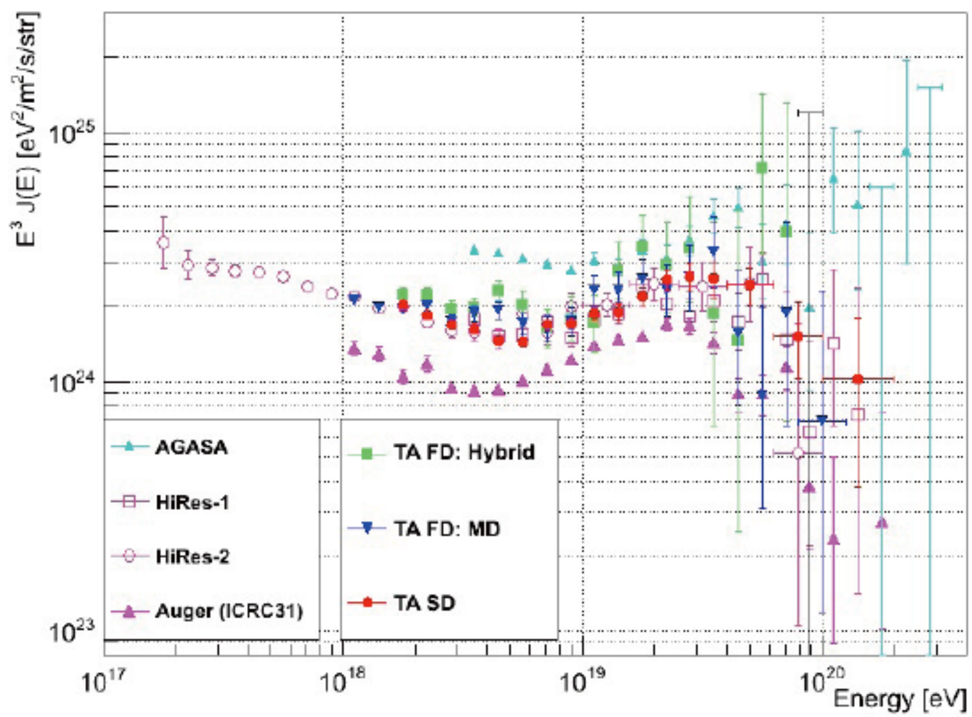


Energy Spectrum of UHECRs

The flux suppression is seen at GZK-cut off energy scale.

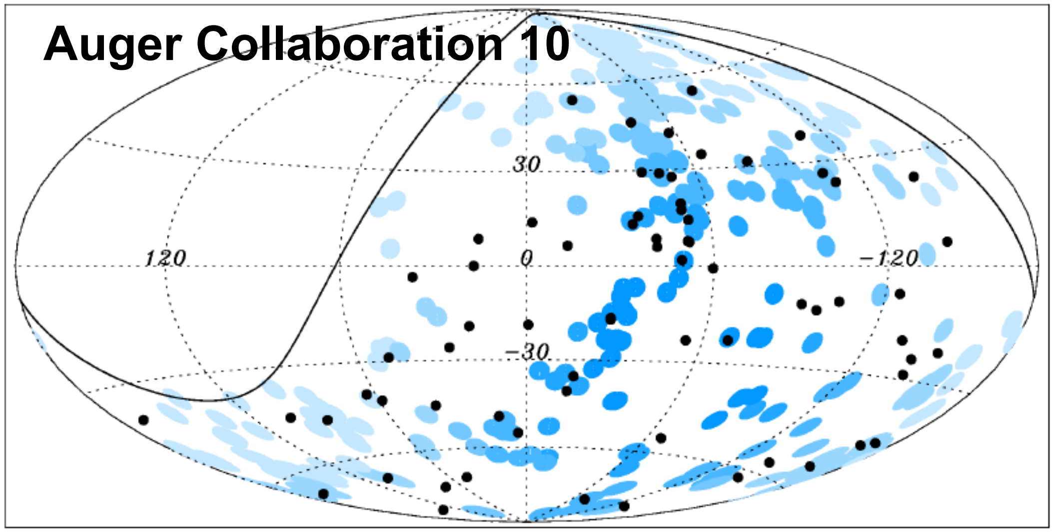


Auger Collaboration 10
More than 20 sigma.

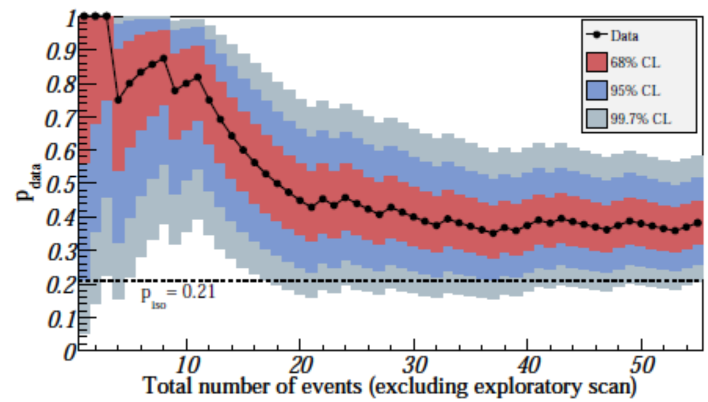


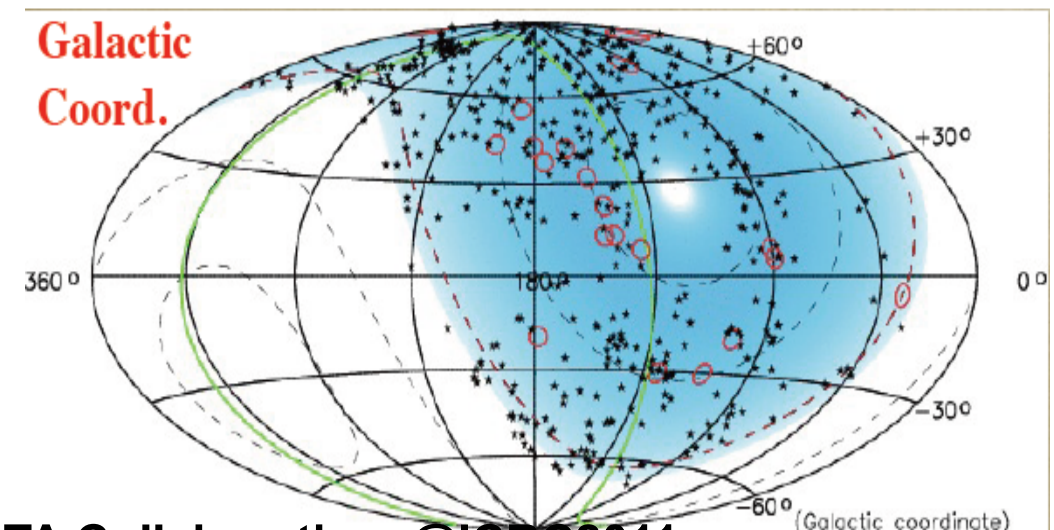
TA Collaboration 11 @ICRC2011
3.9 sigma.

Arrival Direction

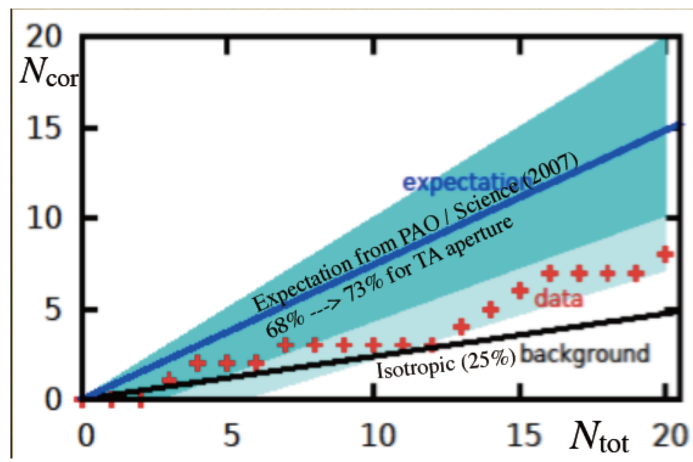


Black: 69 events (> 55EeV).
Blue: Nearby AGNs (<75Mpc)





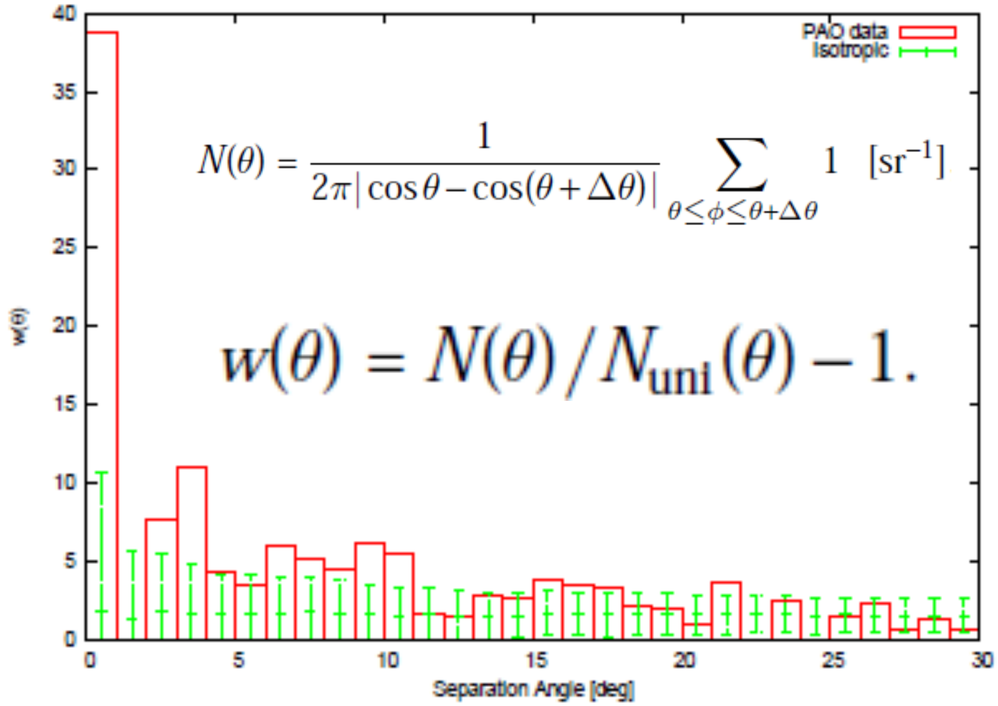
Red: 20 events (>57EeV).
Black: Nearby AGNs (<75Mpc)



TA Collaboration @ICRC2011

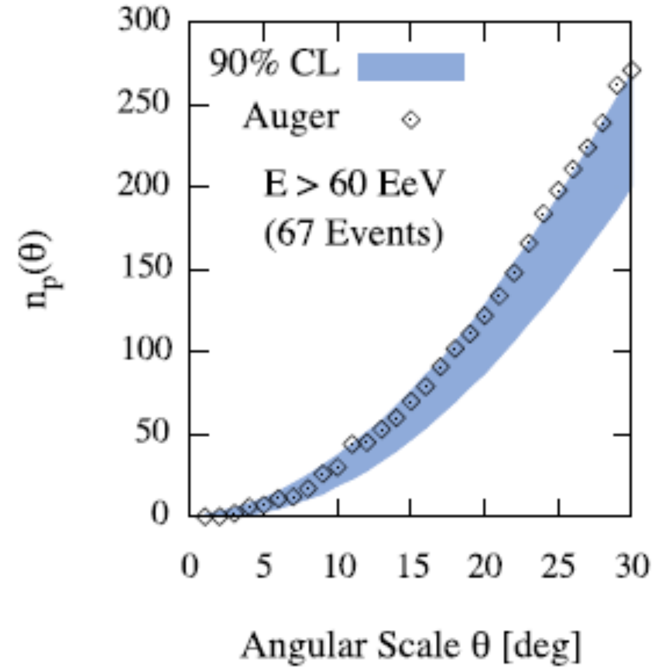
Anisotropy in Small Scale?

Takami et al. 2009



Autocorrelation of PAO's 27 events With E>57EeV.

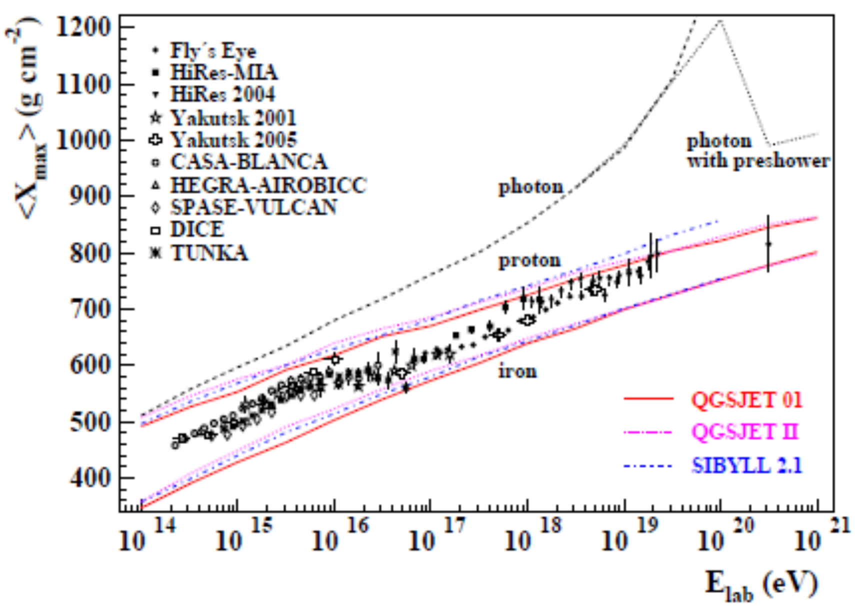
Auger Collaboration@ICRC2011



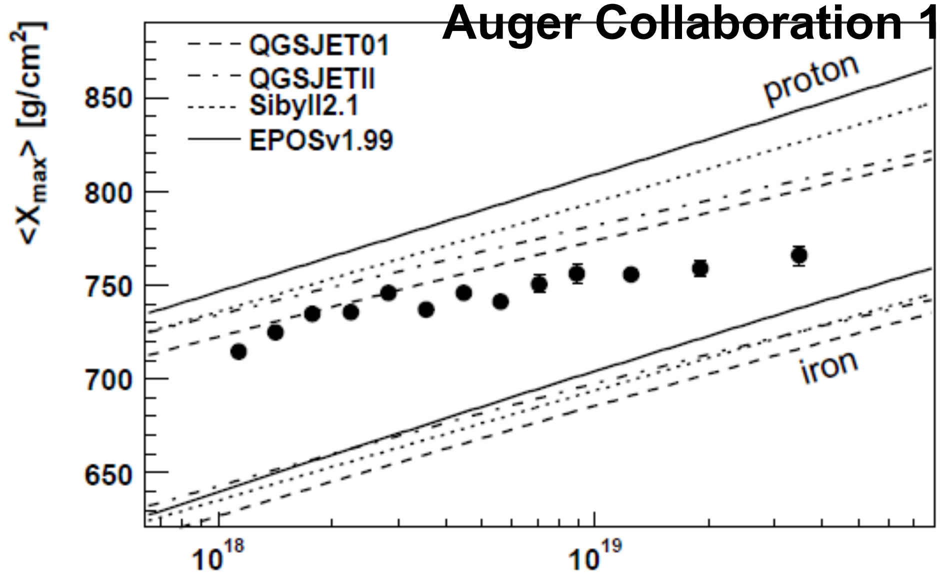
$$n_p(\theta) = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \Theta\left(\theta - \theta_{ij}\right)$$

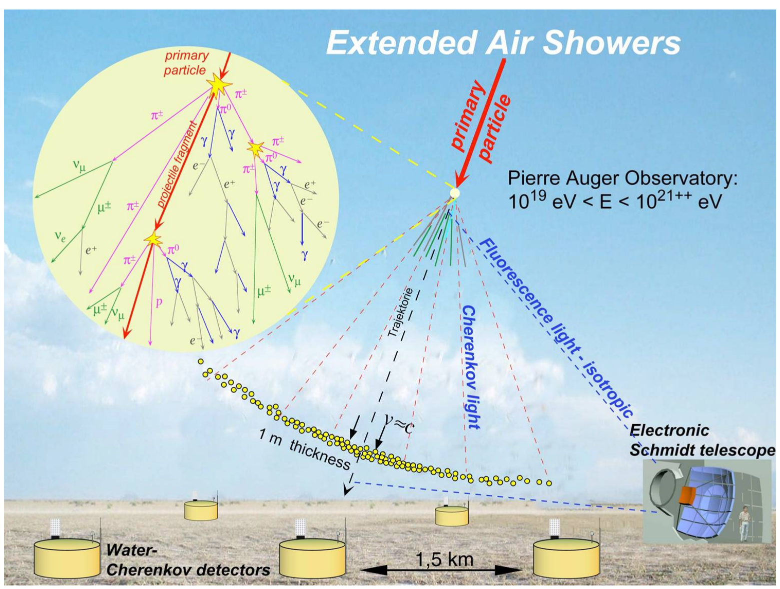
Cumulative number of Pairs within θ.
Shaded area is the 90%CL for Isotropic distribution.

UHECRs are Charged Particles

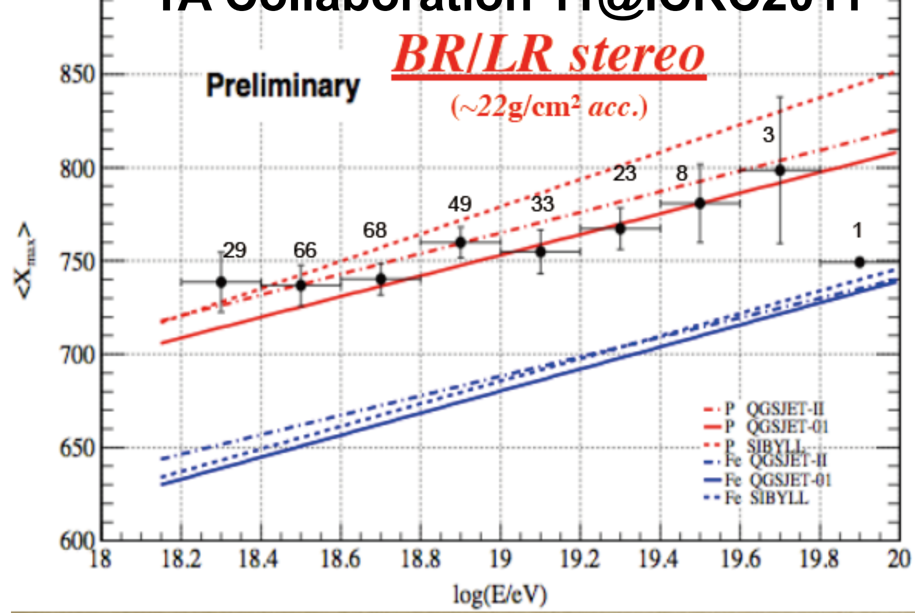


Auger Collaboration 10





TA Collaboration 11@ICRC2011



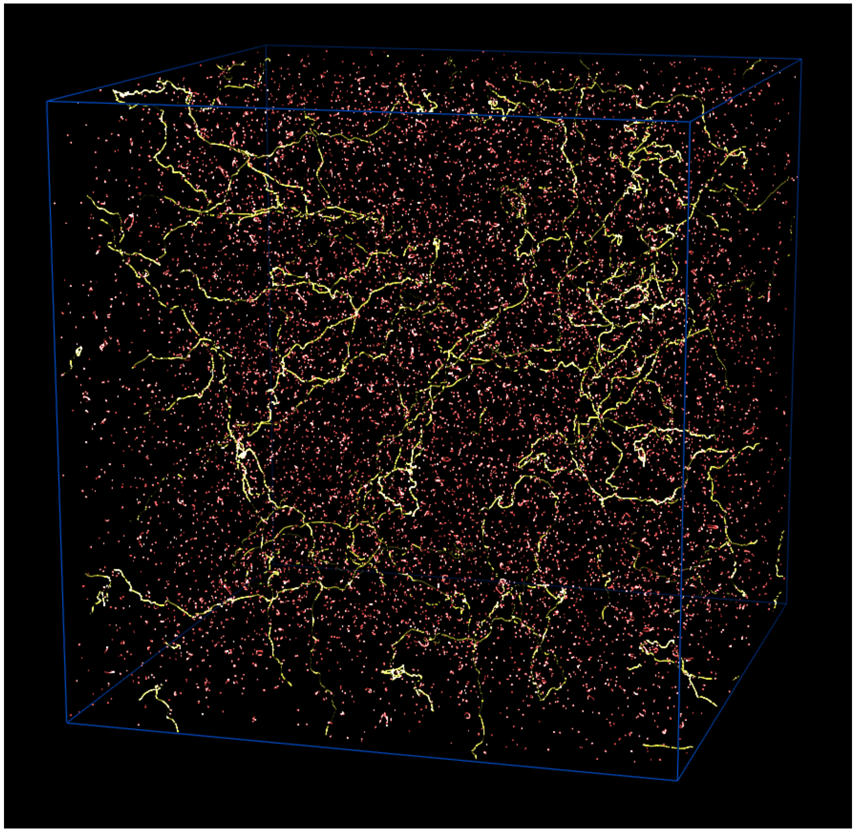
Current Status of Observations

- Cut-off @GZK energy has been confirmed.
- Arrival Directions: No source is identified.
  Correlation with AGN?
  Anisotropy in small scale?
- Composition: Hadronic. Proton or Fe?

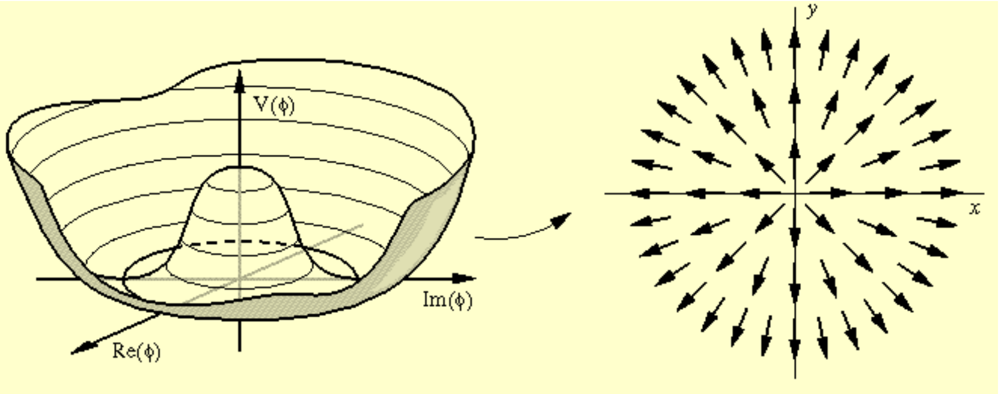
§ Top-down Scenario, or Bottom Up Scenario?

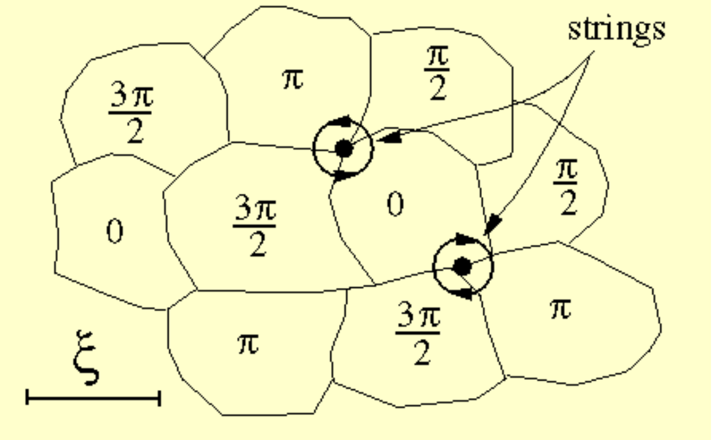
Top-down Scenario？

- Long-lived, super-heavy particles?
- Cosmological Defect?



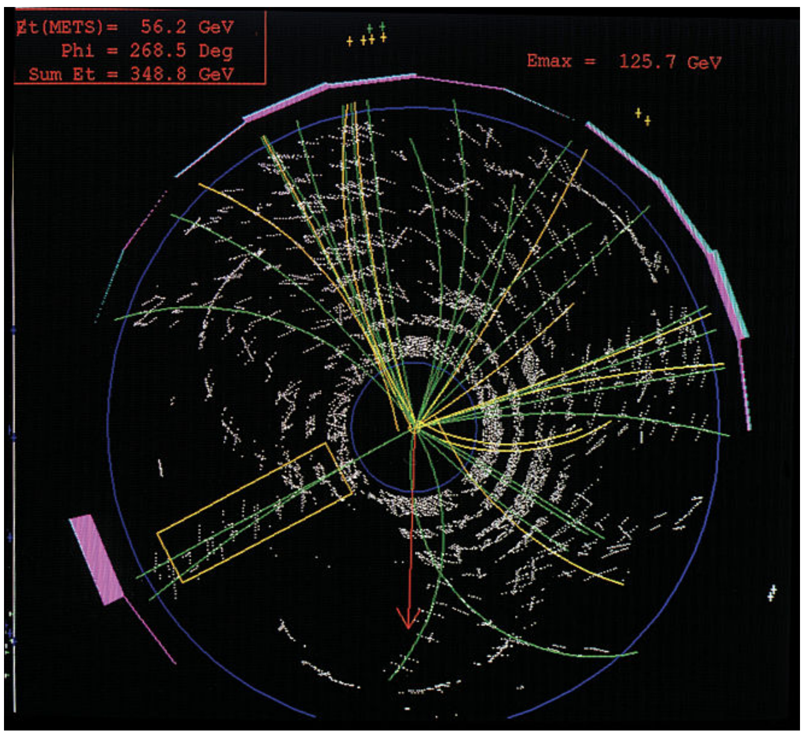
Simulation of Cosmic String
(Cambridge Cosmology Group HP)



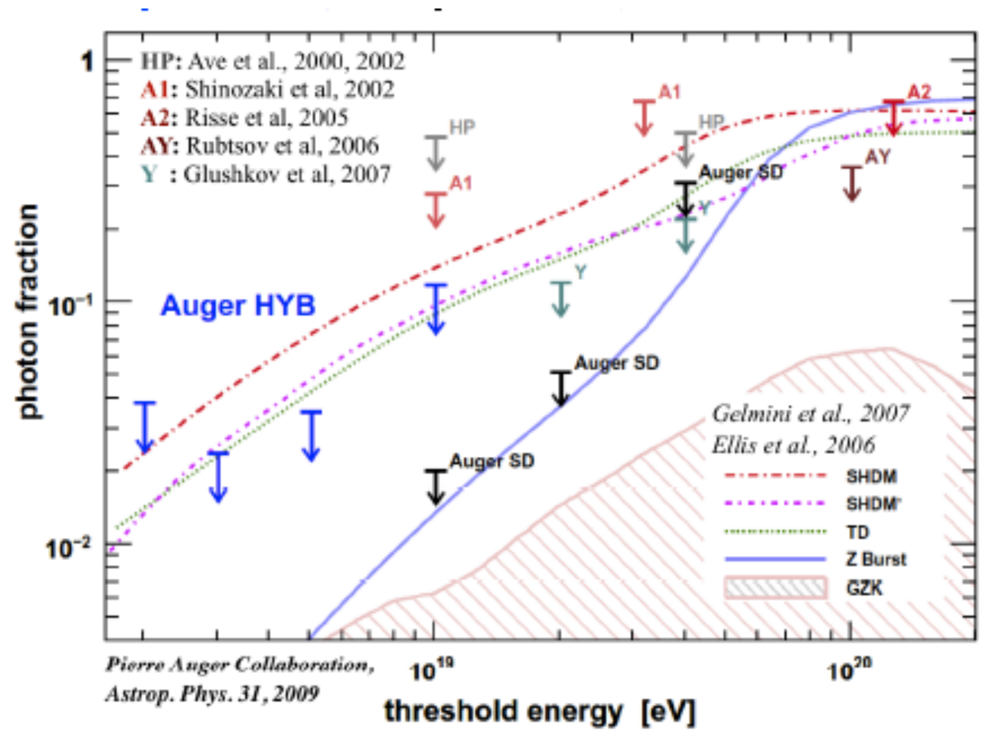


Decay of Super-heavy particles/Cosmic Strings

- (N-quark+N-lepton) are assumed to be born.
- They Cascade.
- Resulting Particles are mainly Gamma-Rays and Neutrinos.

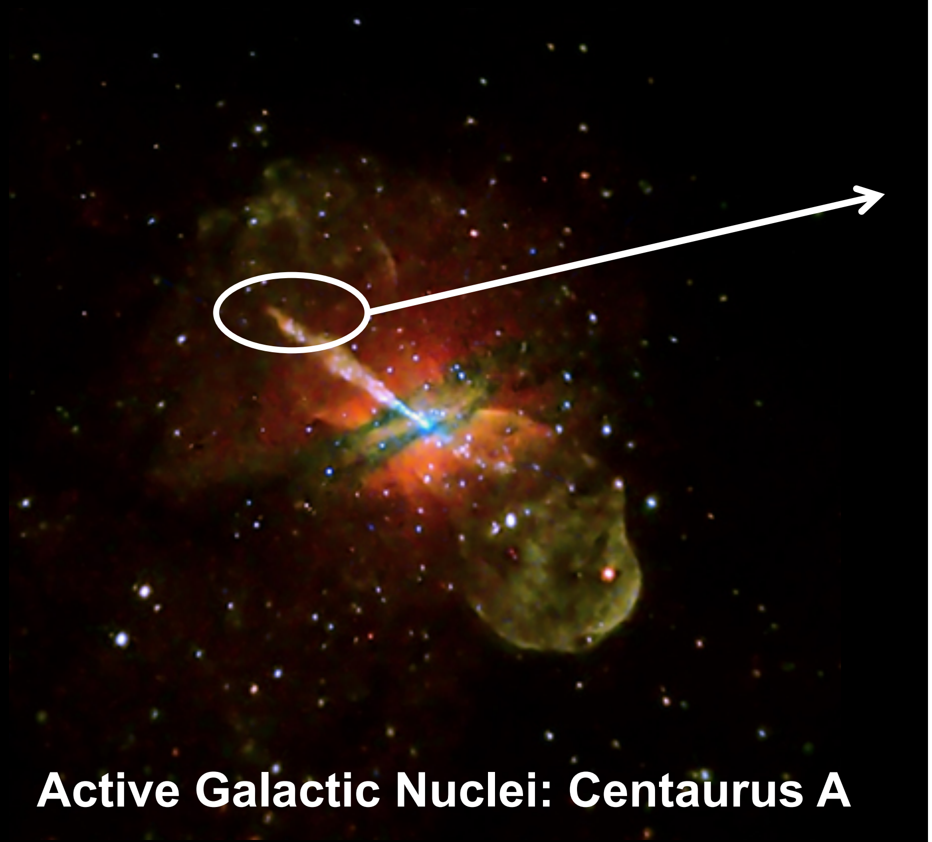


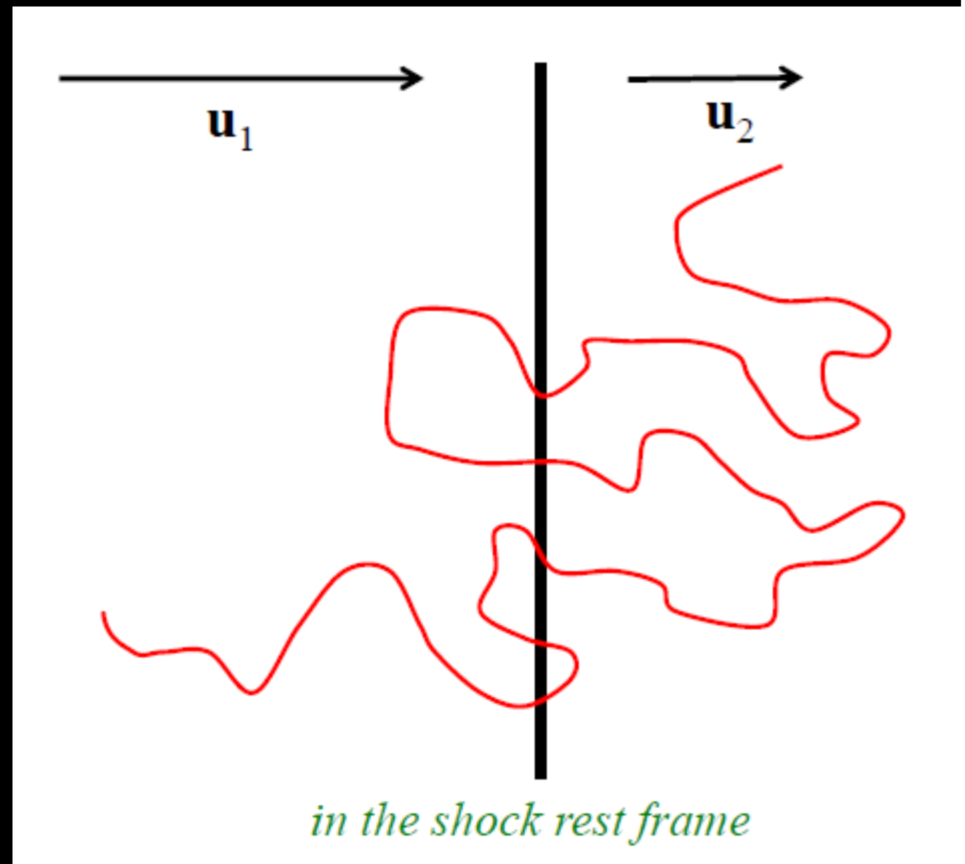
Jets from Top-quark and anti-top quark (by Tevatron).



Fraction of primary photons (from PAO collaboration, ICRC 2011)

Charged Particle Acceleration at Shocks (AGNs, GRBs,…)





Bottom-Up Scenario

Top-down or Bottom-up

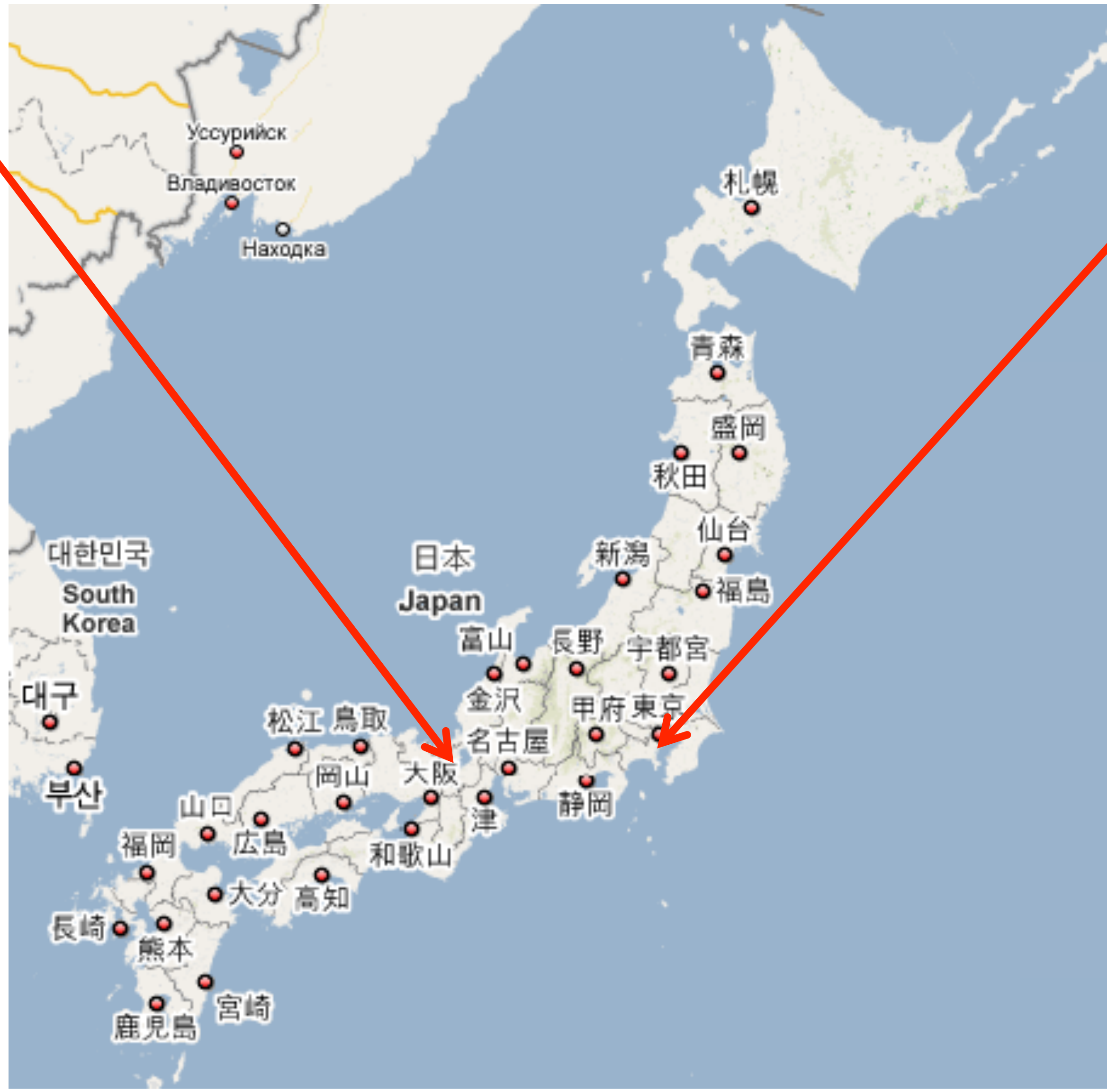
- Composition study tells us that UHECRs are hadronic.
- Fraction of UHE-Photons is limited.
- Top-down scenarios are being constrained by these observations.
- Bottom-up scenario is favored.

Hiro: From Tokyo to Kyoto.

Kyoto
京都

7years ago,
I have moved
To Kyoto
As an
Associate
Professor
Of Yukawa
Institute,
Kyoto Univ.

I was a visiting
Scholar of
KIPAC
(Mar.2006 –
Mar.2007).



Tokyo
東京

I was born
And grew
Up here.

I was a
Graduate
Student,
PosDoc,
and
assistant
Professor
Of the Univ.
Of Tokyo.


靜御前

My Boss in Tokyo was…

Mon. Not. R. astr. Soc. (1981) **195**, 467–479

First-order phase transition of a vacuum and the expansion of the Universe

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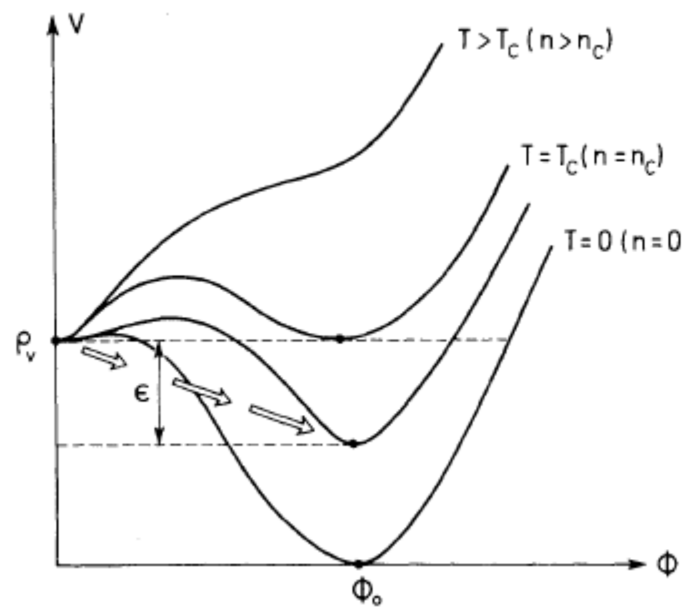
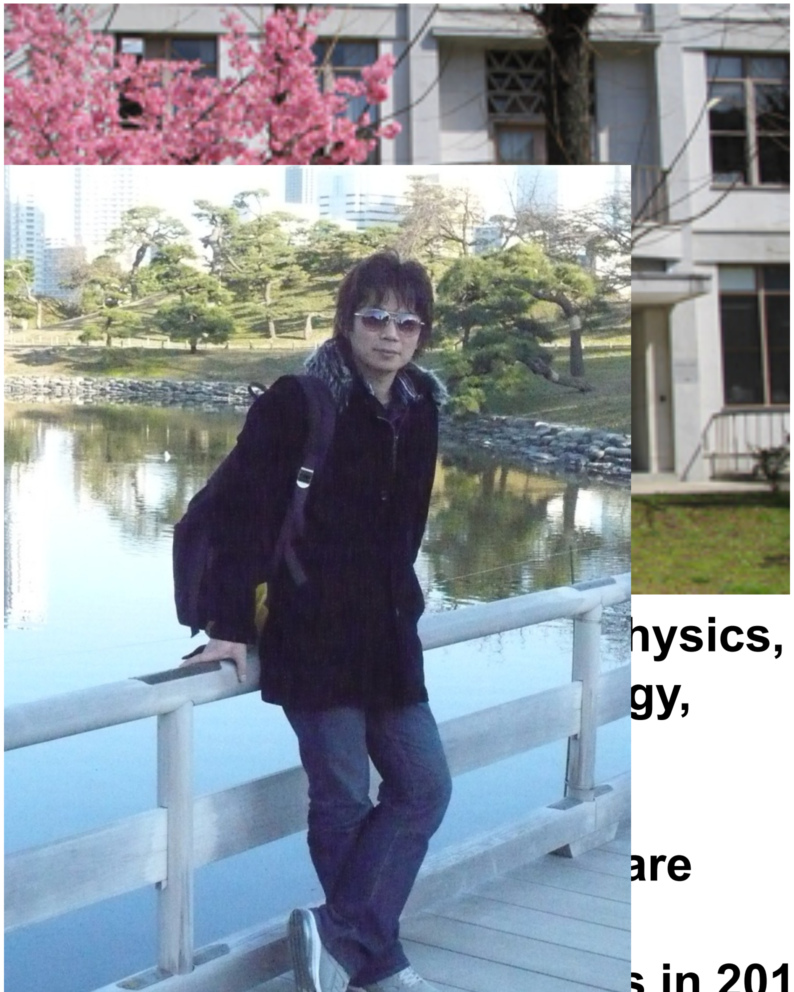
Received 1980 September 9; in original form 1980 February 21



Yukawa Institute for Theoretical Physics (YITP), Kyoto University (1953-)



hysics,
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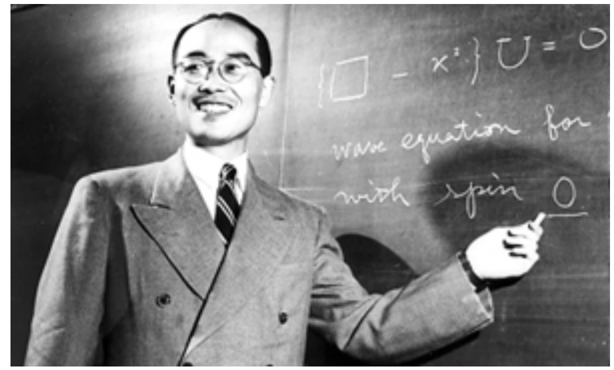
are
s in 2010.

Prof. Nagataki (20XX)



Prof. Yukawa (1949)

Prof. Masukawa (2008)

§ Hunting the Sources of UHECRs, How?

Why is it difficult to identify the sources of UHECRs?

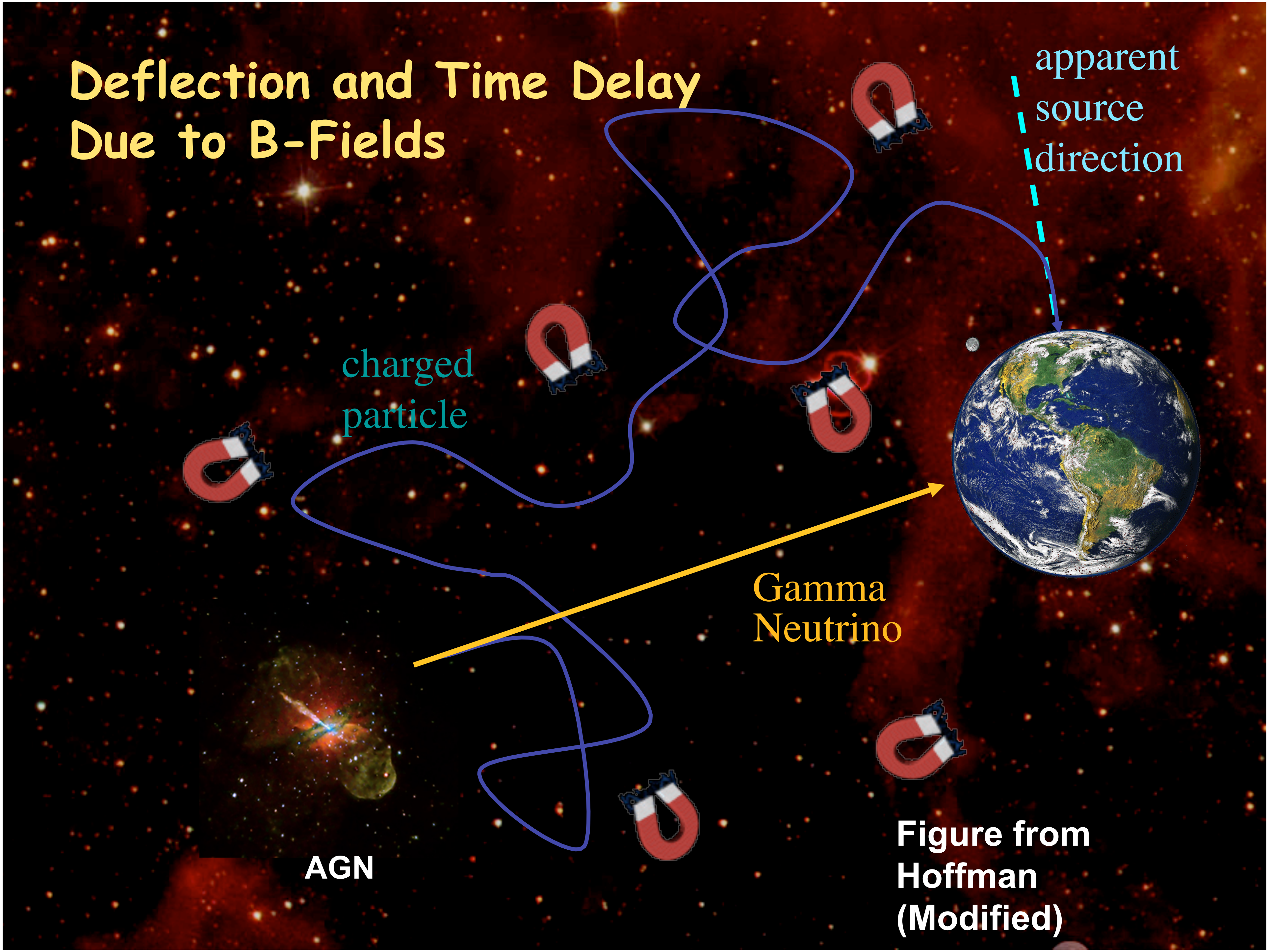
- This is because the trajectories of UHECRs are bent by magnetic fields.
- This also makes time delay (e.g. GRBs).

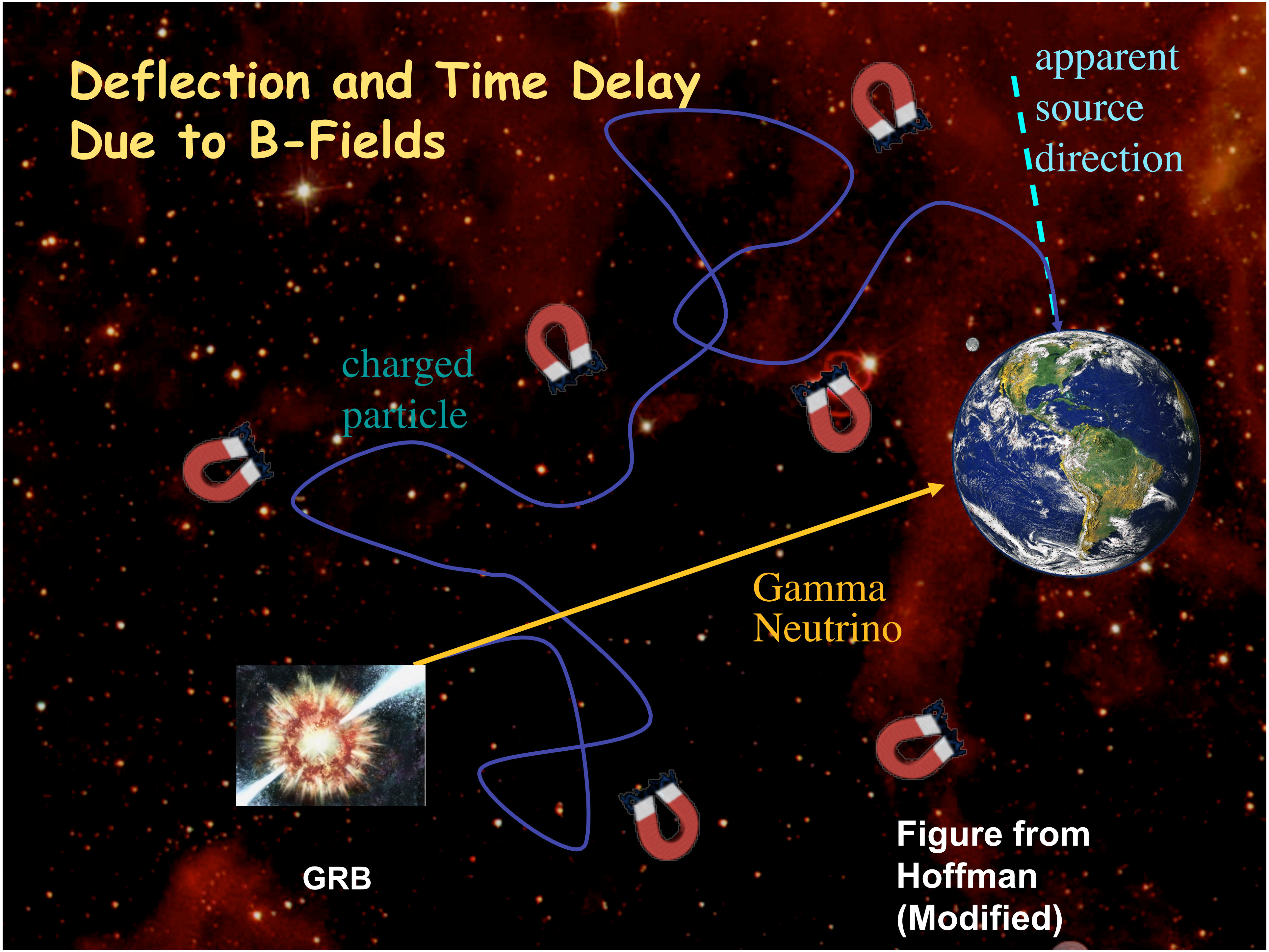
$$\theta(E,d) \simeq \frac{(2dl_c/9)^{1/2}}{r_g} \simeq 0.8^\circ\, q \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)$$

Q: Charge

$$\tau(E,d) \simeq d\theta(E,d)^2/4 \simeq 1.5\times 10^3\, q^2 \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-2} \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{2} \left(\frac{l_c}{1\,\mathrm{Mpc}}\right) \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)^{2} \mathrm{yr}$$

e.g. Bhattacharjee 00; Kashti and Waxman 08; Kotera and Lemoine 08

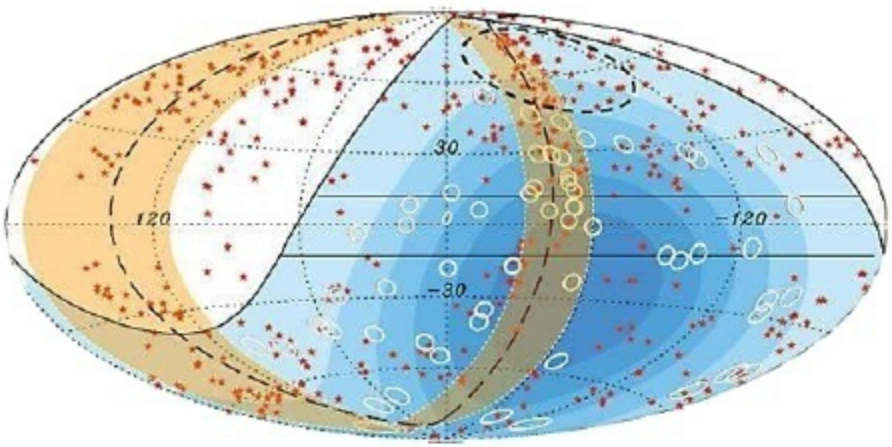

Deflection and Time Delay
Due to B-Fields
apparent
source
direction
charged
particle
Gamma
Neutrino
AGN
Figure from
Hoffman
(Modified)

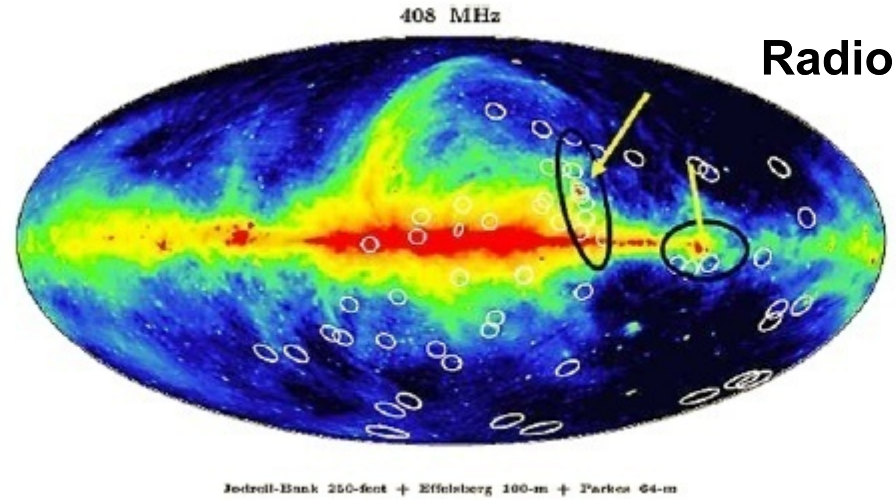

Deflection and Time Delay
Due to B-Fields
apparent
source
direction
charged
particle
Gamma
Neutrino
GRB
Figure from
Hoffman
(Modified)

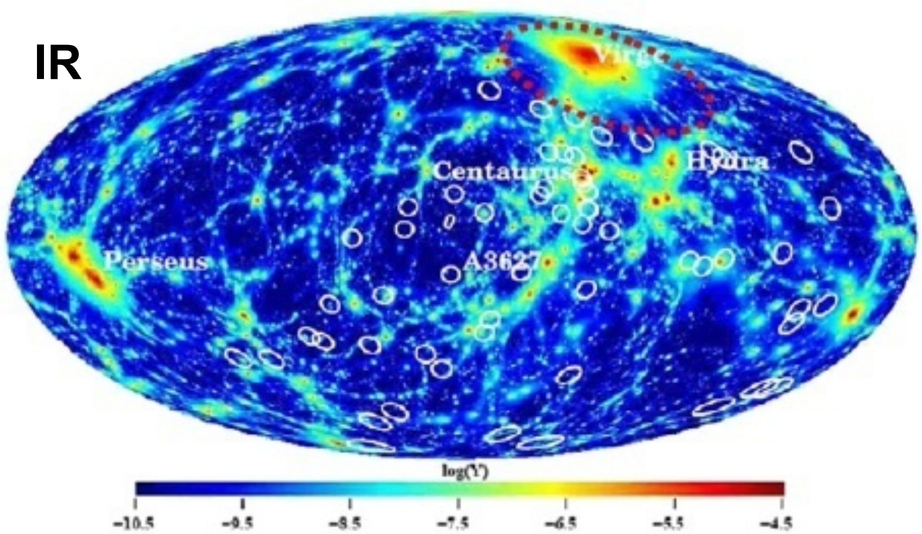
What can we do to identify the sources of UHECRs?

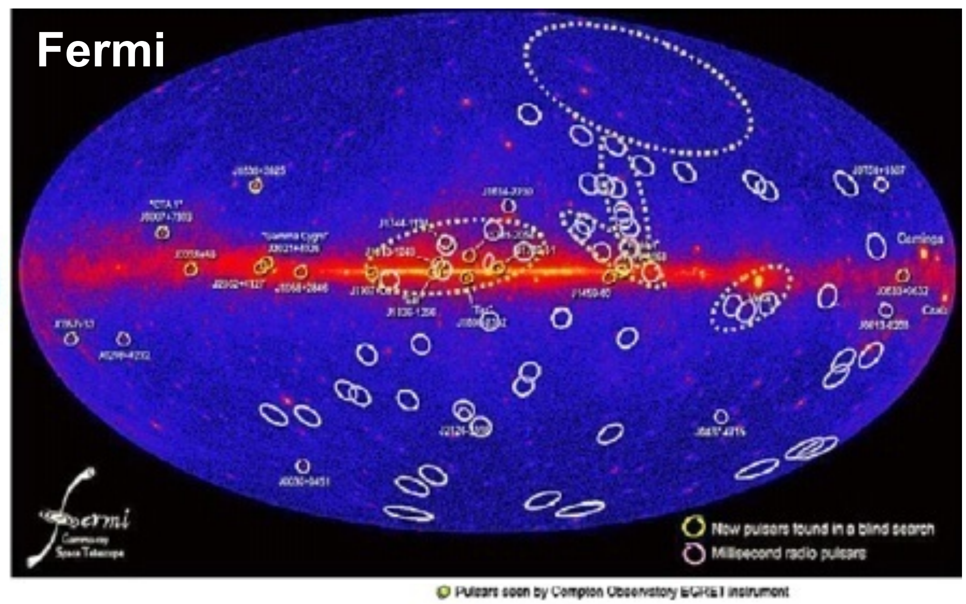
- More Observations. Higher Statistics.
- Simulations of Propagation of UHECRs and comparison with the observations (Making Templates).
- Secondaries Produced in the sources (gamma-rays and neutrinos).

1. Simulations of Propagation of UHECRs: Which Distributions are Similar?

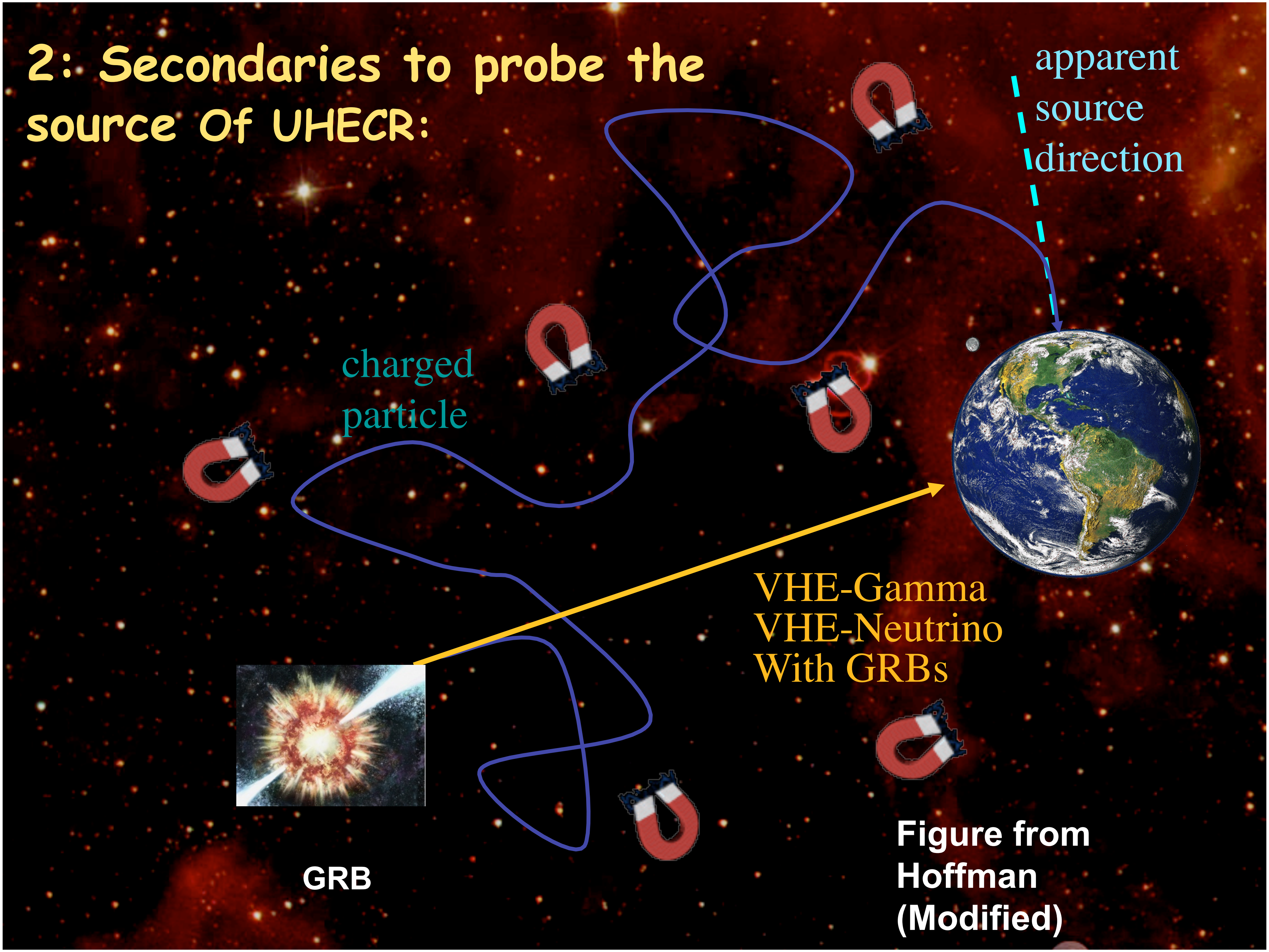








Figures from D.Fargion

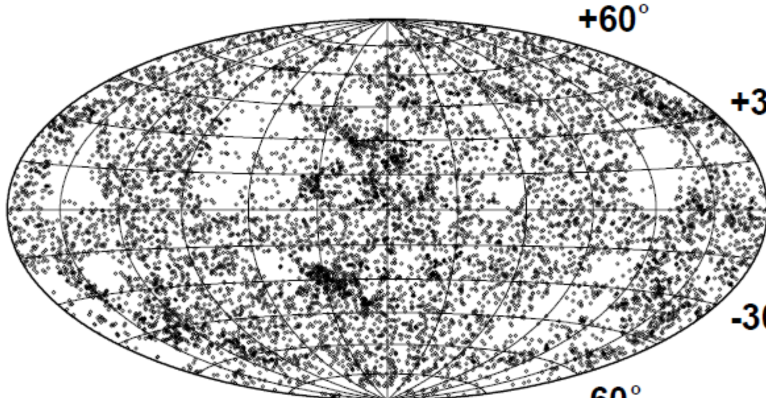

2: Secondaries to probe the source Of UHECR:
apparent source direction
charged particle
VHE-Gamma
VHE-Neutrino
With GRBs
GRB
Figure from Hoffman (Modified)

§ Simulations of Propagation of UHECRs

Ref.
Yoshiguchi, S.N. Tsubaki, Sato ApJ 586 (2003) 1211
Yoshiguchi, S.N. Sato *ApJ* 592 (2003) 311
Yoshiguchi, S.N. Sato *ApJ* 596 (2003) 1044
Yoshiguchi, S.N. Sato *ApJ 607* (2003) 840
Yoshiguchi, S.N. Sato *ApJ* 614 (2004) 43

Simulations of Propagation of UHECRs

Ref. Yoshiguchi, S.N. Tsubaki, Sato 2003; Yoshiguchi, S.N. Sato 2003a,b,c,2004



Distribution of nearby Galaxies (from ORS galaxy Catalog)

$$\langle B^2(k)\rangle \propto k^{n_H} \text{ for } 2\pi/l_c \le k \le 2\pi/l_{cut}$$

$$n_H = -11/3,\ l_{cut} = 1/8 \times l_c$$

Gaussian random field with Zero mean and a power-law Spectrum for ICM.

Protons

$$p + \gamma_{CMB} \to p + e^+ + e^-$$

$$p + \gamma_{CMB} \to N + \text{pions}$$

UHECRs are assumed to be Protons.

$$B(r_{||},\phi) = B_0 \left(\frac{R_\oplus}{r_{||}}\right) \cos\left(\phi - \beta \ln \frac{r_{||}}{r_0}\right)$$

$$|B(r_{||},\phi,z)| = |B(r_{||},\phi)| \begin{cases} \exp(-z): & |z| \le 0.5 \text{ kpc} \\ \exp(\frac{-3}{8})\ \exp(\frac{-z}{4}): & |z| > 0.5 \text{ kpc} \end{cases}$$

$$B_0 = 4.4\ \mu\text{G},\ r_0 = 10.55 \text{ kpc and } \beta = 1/\tan p = -5.67.$$

$$B_x = -3\mu_G \sin\theta \cos\theta \cos\varphi/r^3,$$

$$B_y = -3\mu_G \sin\theta \cos\theta \sin\varphi/r^3,$$

$$B_z = \mu_G(1 - 3\cos^2\theta)/r^3, \qquad \mu_G \sim 184.2\ \mu\text{G kpc}^3$$

Disk Component: BSS
Halo Component: Dipole
Random Fields.

Energy Spectrum and Auto-correlation function

Ref. Yoshiguchi, S.N. Tsubaki, Sato 2003; Yoshiguchi, S.N. Sato 2003a,b,c,2004

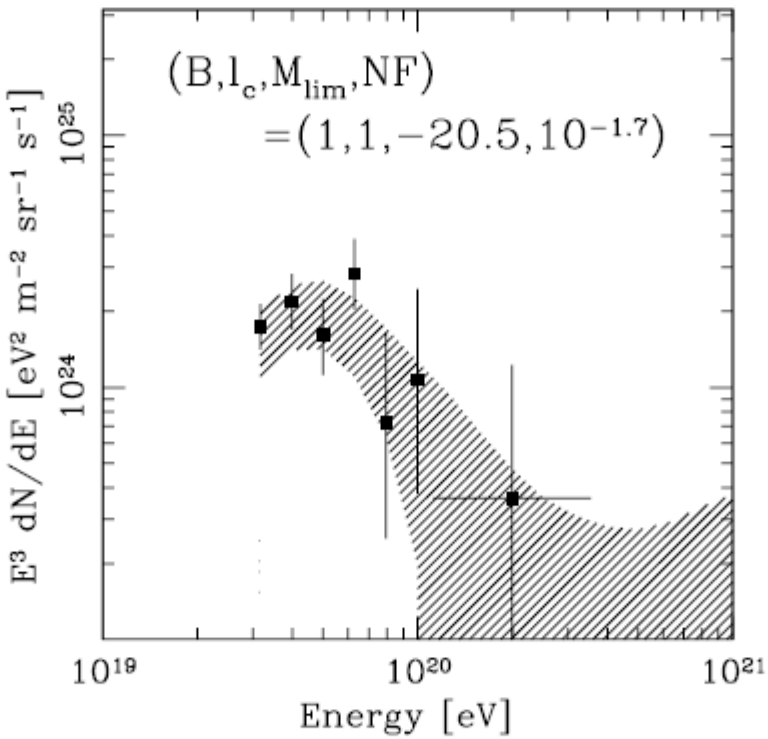
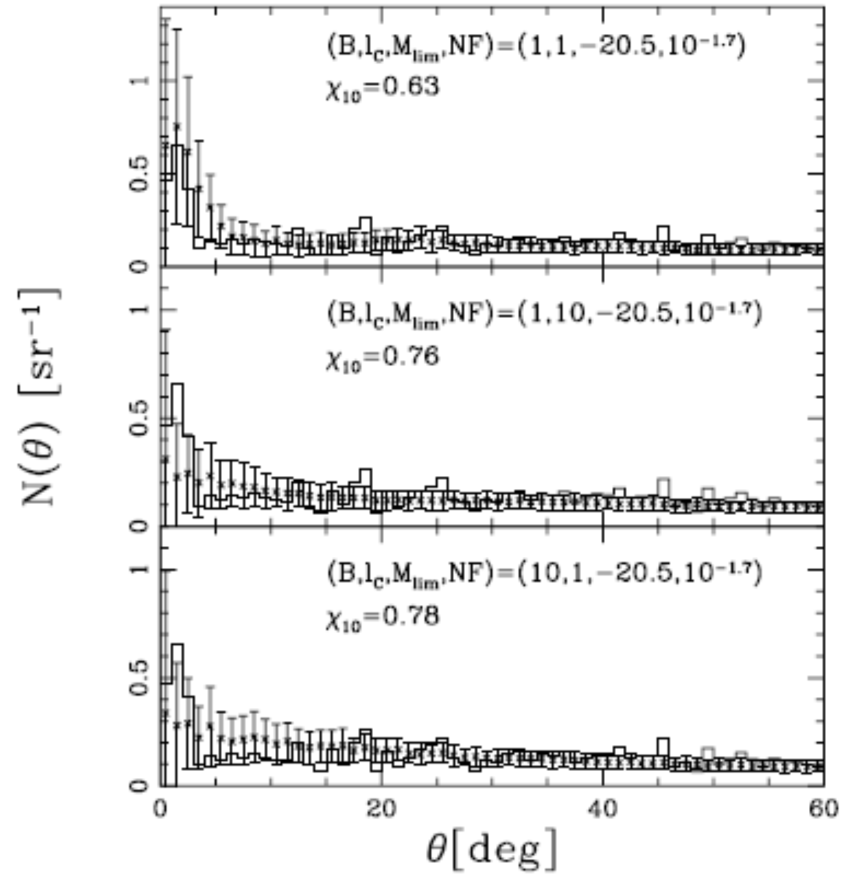


FIG. 22.—Energy spectra predicted by sources selected from the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ in the case of $(B, l_c, {\rm NF}) = (1, 1, -20.5, 10^{-1.7})$. NF represents the number fraction of selected UHECR sources to all ORS galaxies ($M_{\rm lim} < -20.5$). They are fitted to the data of the HiRes I detector (*squares and error bars*). The shaded regions represent 1 σ error due to the source selection from our ORS sample.



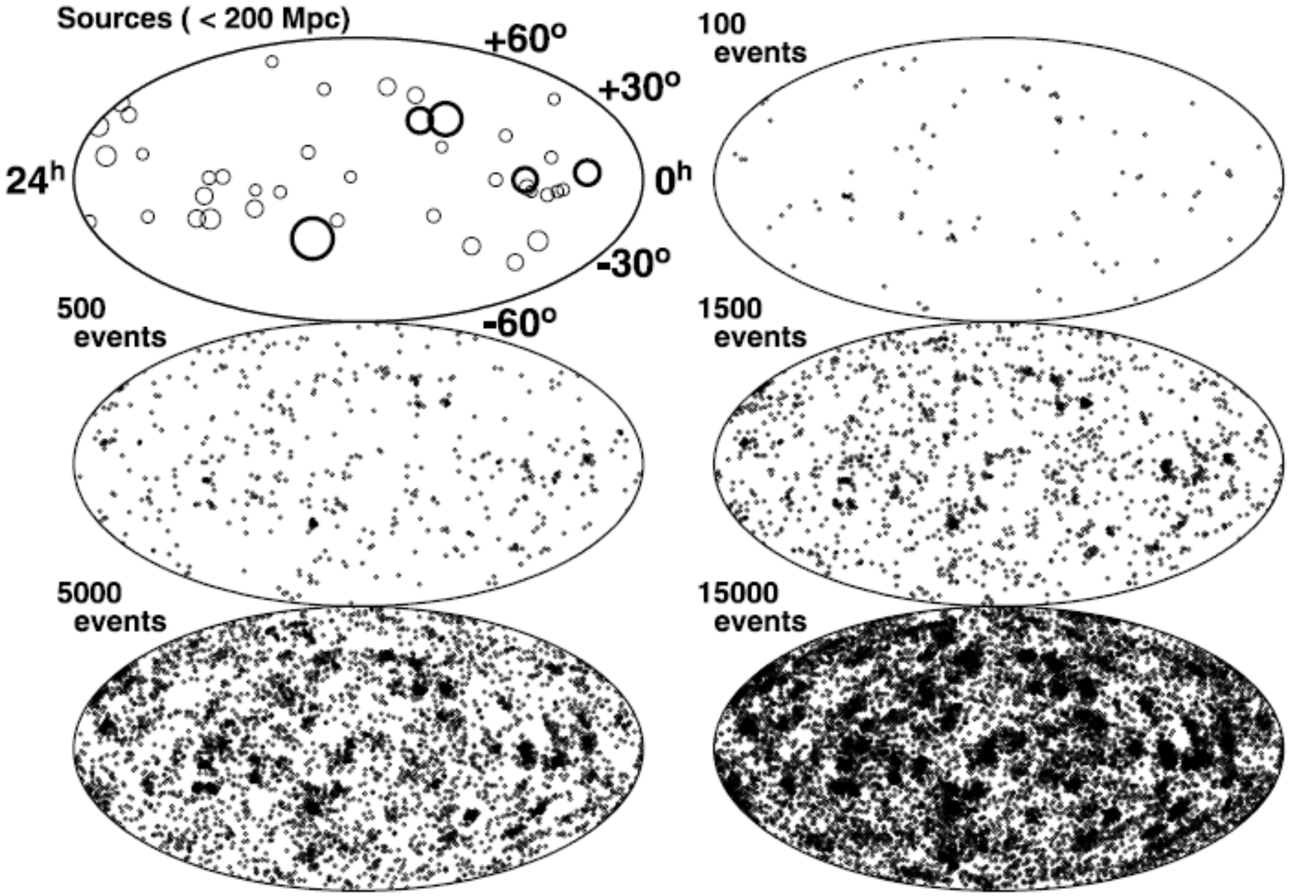
$$N(\theta) = \frac{1}{2\pi|\cos\theta - \cos(\theta+\Delta\theta)|} \sum_{\theta \le \phi \le \theta+\Delta\theta} 1 \ [{\rm sr}^{-1}],$$

Hatched region: Simulation.
Dots: Observations (HiRes)

Dots with error bars: Simulation.
Histgrams: Observations (AGASA)

An Example of Arrival Distribution of UHECRs

Yoshiguchi, S.N. Sato *ApJ* 592 (2003) 311



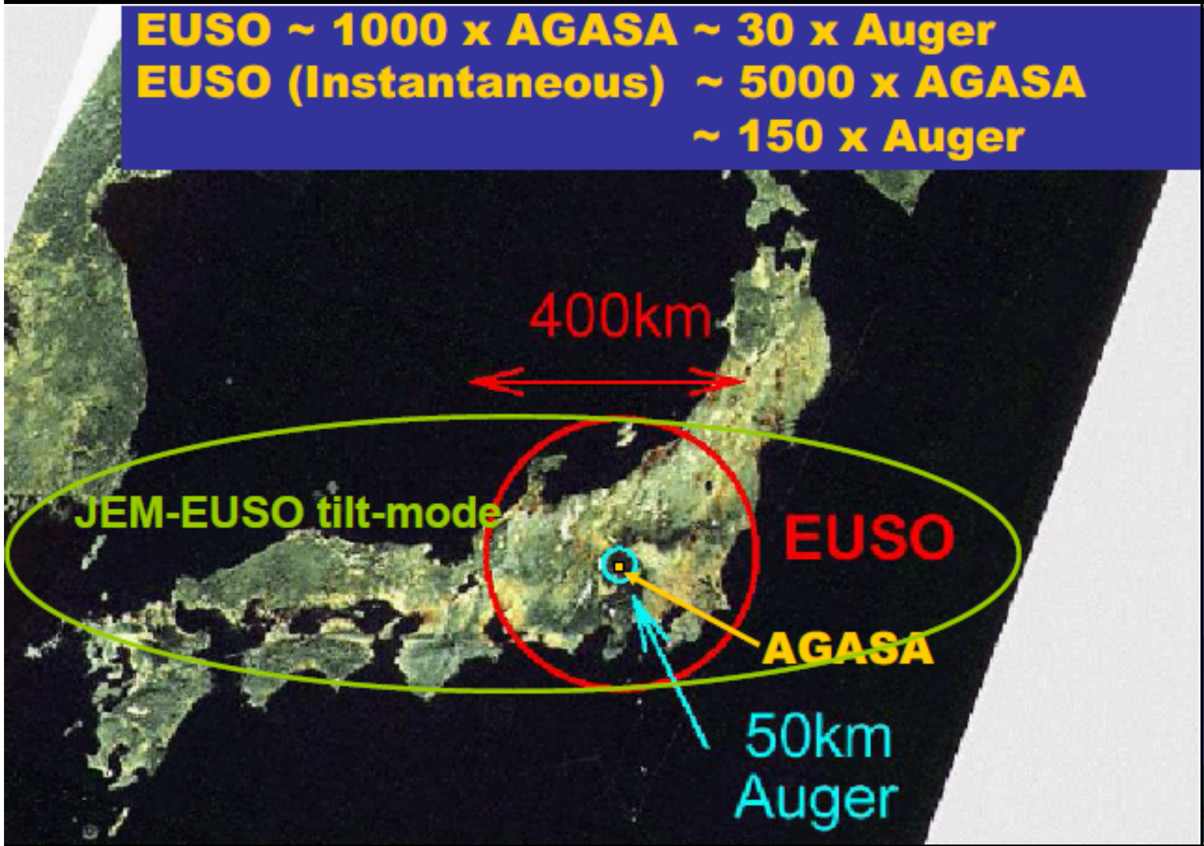
E > 4×10^{19} eV

Clear correlation Will be seen between UHECRs and Matter Distribution.

c.f.
102 events with E>4*10^19eV are Found by Auger (Auger collabora-Tion 2009).

FIG. 3.—Arrival directions of UHECRs above 4×10^{19} eV predicted by a specific source scenario when 1/50 of the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ are selected as UHECR sources. Distribution of selected sources within 200 Mpc is also shown as circles of radius inversely proportional to their distances. Only the sources within 100 Mpc are shown with bold circles.

One of Future Directions: JEM-EUSO



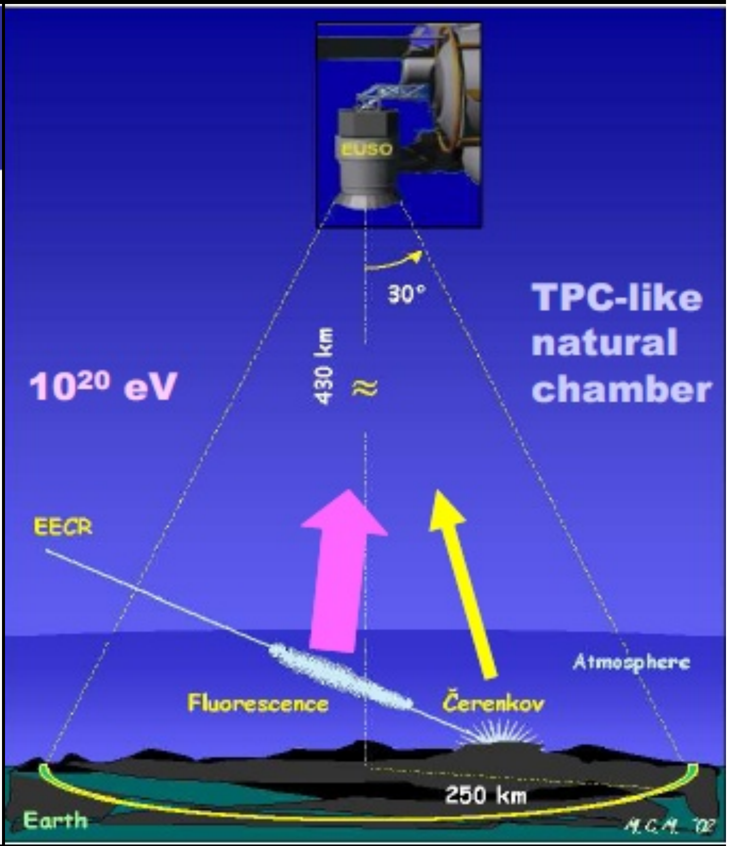


Figure from M. Bertaina, (Cris2008, Salina)

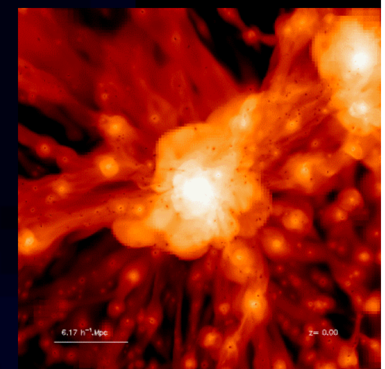
Other approaches: Extension of South Auger, Auger Next, Raido Experiments, Next generation of Telescope Array, …

§ Toward More Realistic Simulations: 1. UHECRs in a Galaxy Cluster

Ref.
Kotera, Allard, Murase, Aoi, Dubois, Pierog, S.N.
ApJ 707 370 (2009)

UHECRs in and from Clusters of Galaxies

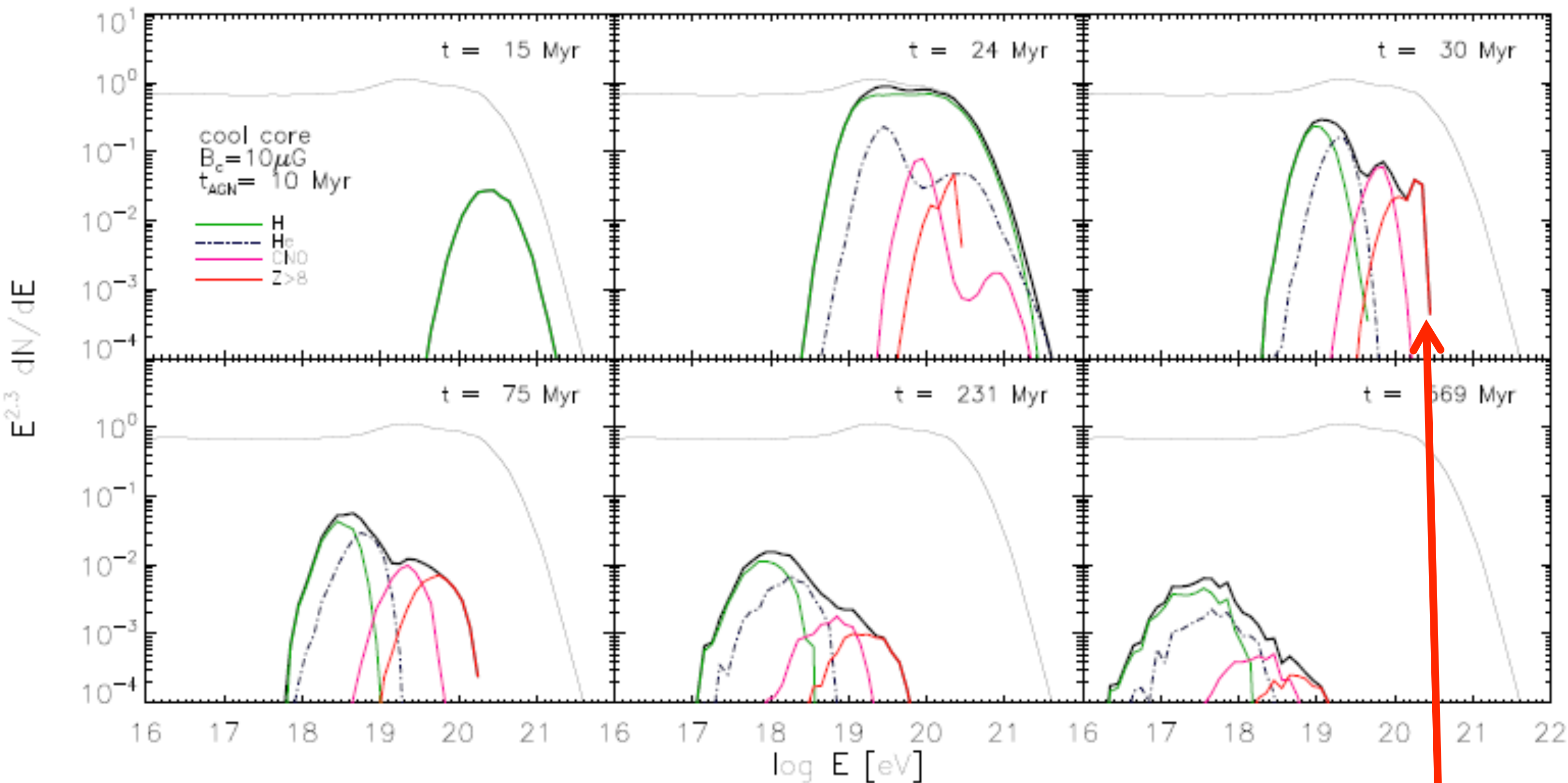
Kotera, Allard, Murase, Aoi, Dubois, Pierog, S.N. ApJ (2009)



Red : Temperature
Blue: Density

Formation of Clusters of Galaxies

Cosmic-Ray Afterglow



The life-time of the source (AGN) is set to be 10Myr.
Light and energetic elements comes first, and
Heavy and low-energy components come our later
(Cosmic Ray Afterglow) (Note that the composition of UHECRs).

Future Direction: Collaboration with Ryu's Group

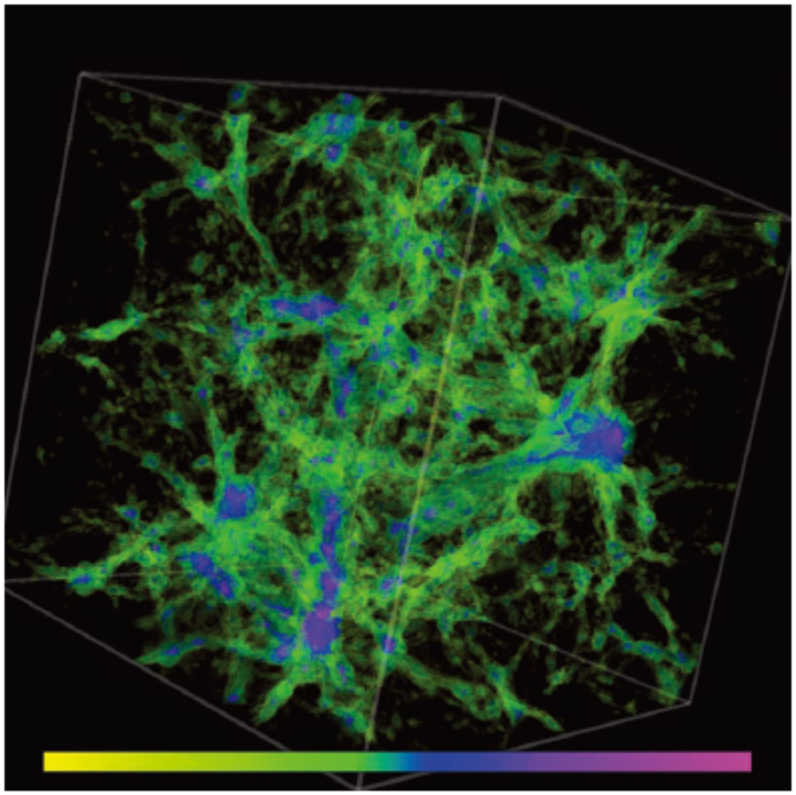
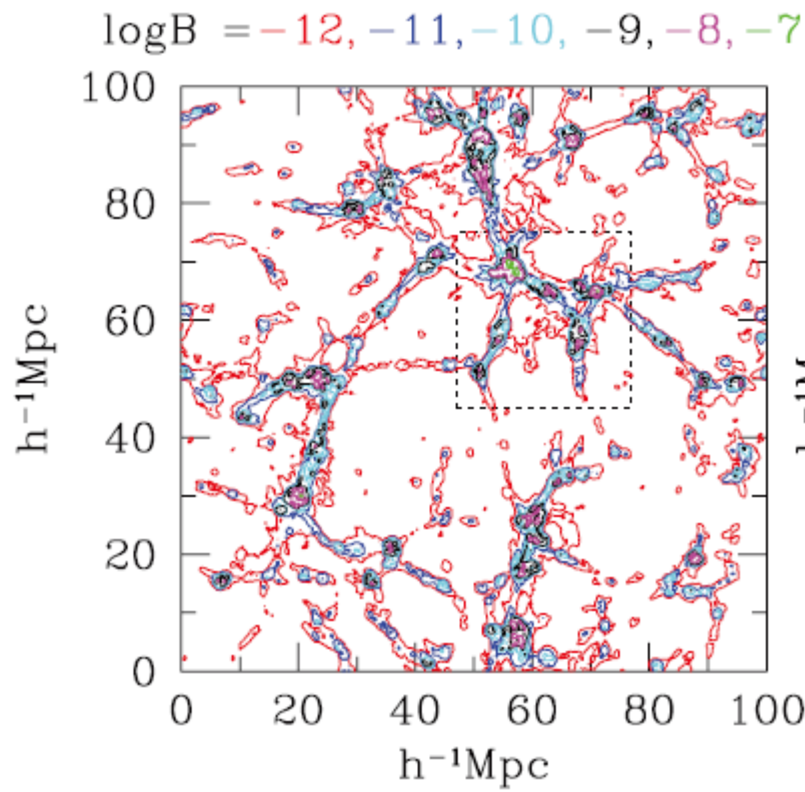


Fig. 4. Volume-rendering image showing the logarithmically scaled magnetic field strength at $z = 0$ in the whole computational box of (100 h^{-1} Mpc)^3 volume. Color codes the magnetic field strength from 0.1 nG (yellow) to 10 μG (magenta). The colors were chosen so that clusters and groups show as magenta and blue and filaments as green.



Das, Kang, Ryu Cho ApJ 08

Ryu, Kang, Cho, Das Science 08

§ Toward More Realistic Simulations:
2. VHECRs in Our Galaxy

Ref.
Calvez, Kusenko, S.N. PRL 105 091101 (2010)

If GRBs happened in Milky Way every 10^5 years…

- As in the case of a galaxy cluster, protons will escape easier than iron.

$$t_D \sim \frac{R^2}{D} \sim 10^8 \mathrm{yr} \left(\frac{R}{10\ \mathrm{kpc}}\right)^2 \left(\frac{26}{Z}\ \frac{10^{19}\ \mathrm{eV}}{E}\right)^2$$

- But in this case, the Earth is in Milky Way.

- So, we should observe UHE-Nuclei more than UHE-protons.

Calculated Flux and Anisotropy with Composition

Calvez, Kusenko, S.N. PRL 105 091101 (2010)

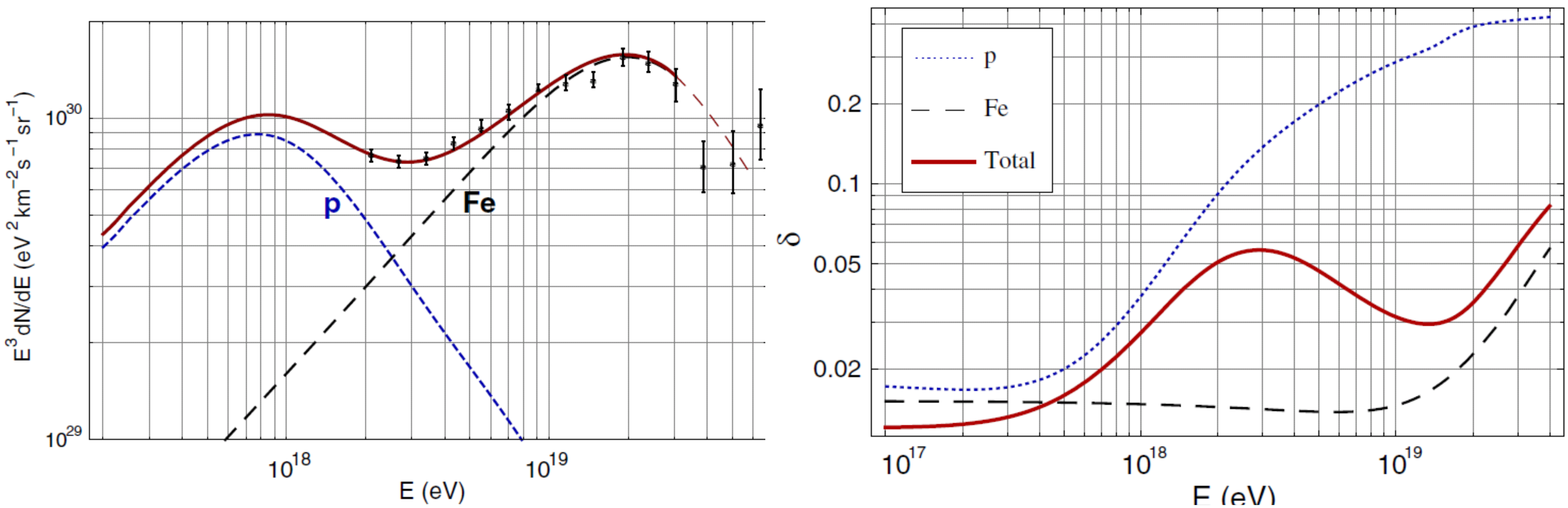
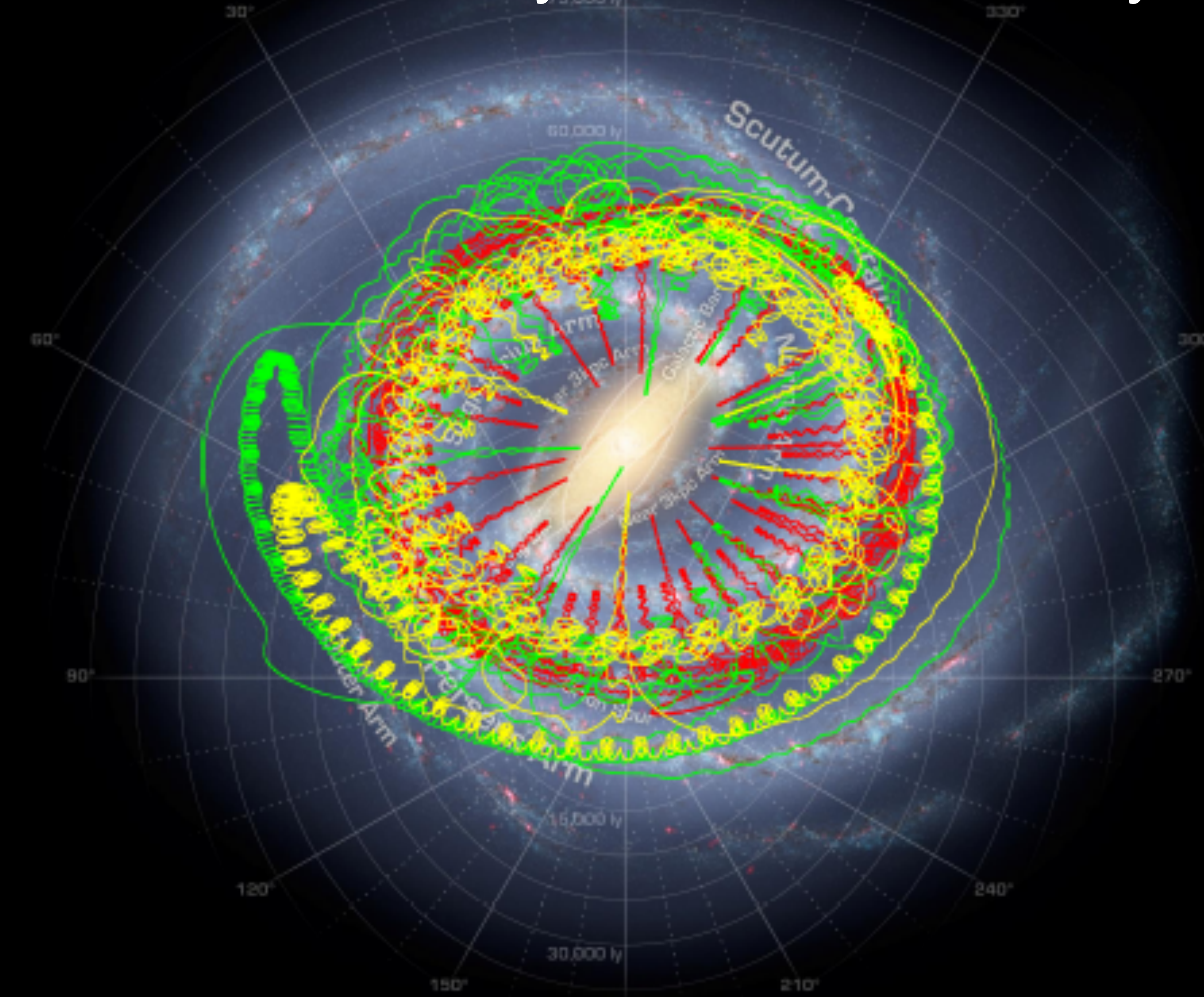


FIG. 1 (color online). Predicted UHECR spectra, assuming that the sources produce 90% protons and 10% iron, with identical spectra $\propto E^{-2.3}$, and that the source distribution traces the distribution of stars in the Galaxy. We used samples of 10^3 GRBs at random locations with time intervals of 10^5 years. The magnetic field was assumed to be 4 μG, coherent over $l_0 =$ 0.2 kpc domains, $\delta_1 = 0.3$, $\delta_2 = 0$. The overall power and the iron fraction were adjusted to fit the PAO data points [24]

$$\delta(E) \equiv \frac{J_{\text{max}} - J_{\text{min}}}{J_{\text{max}} + J_{\text{min}}}$$

$$D_i(E) = \begin{cases} D_0\left(\frac{E}{E_{0,i}}\right)^{\delta_1}, & E \le E_{0,i}, \\ D_0\left(\frac{E}{E_{0,i}}\right)^{(2-\delta_2)}, & E > E_{0,i}. \end{cases}$$

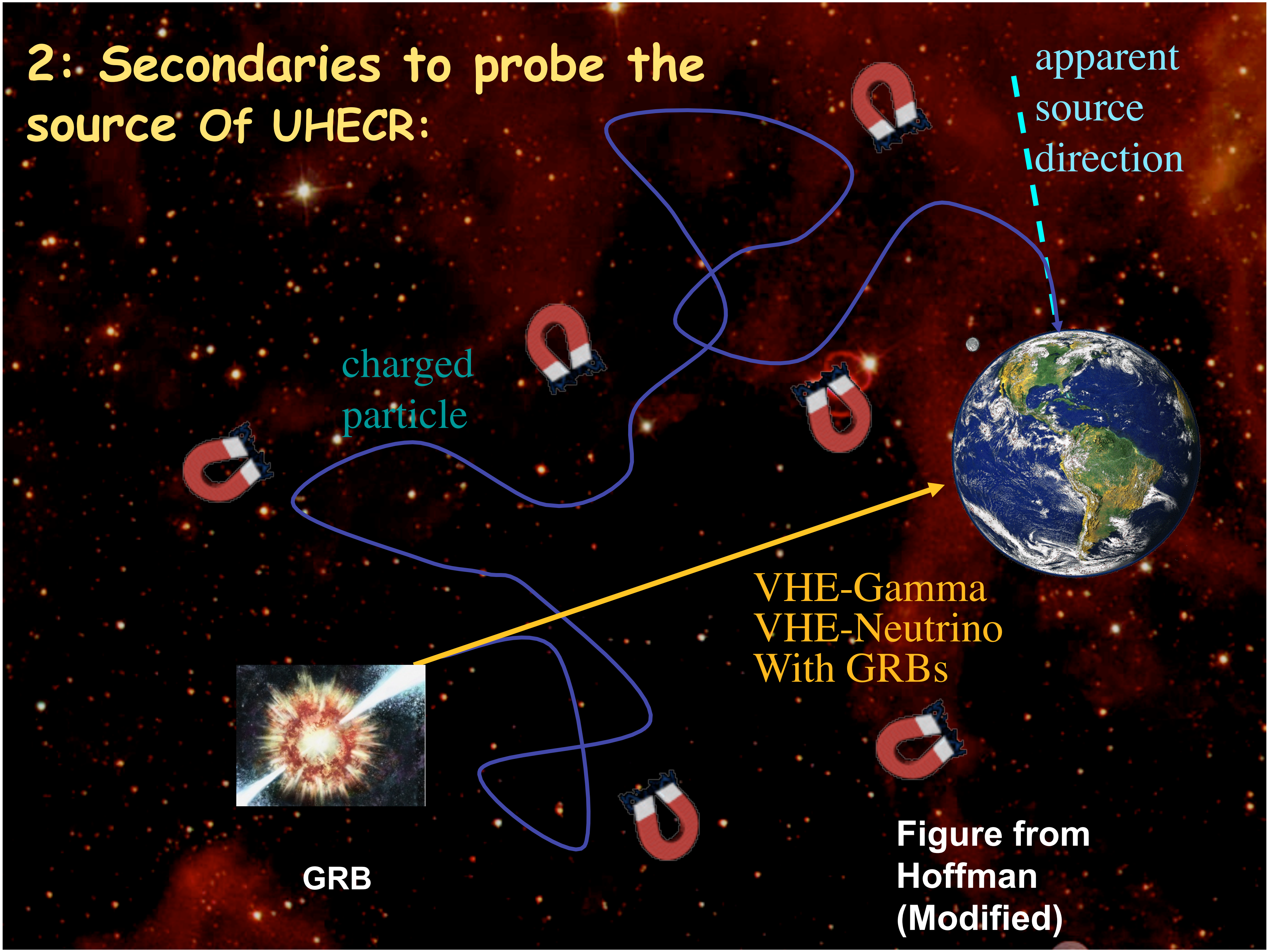
Our Future Direction: Numerical Propagation of VHE-Nuclei Produced by Past GRBs in Milky Way



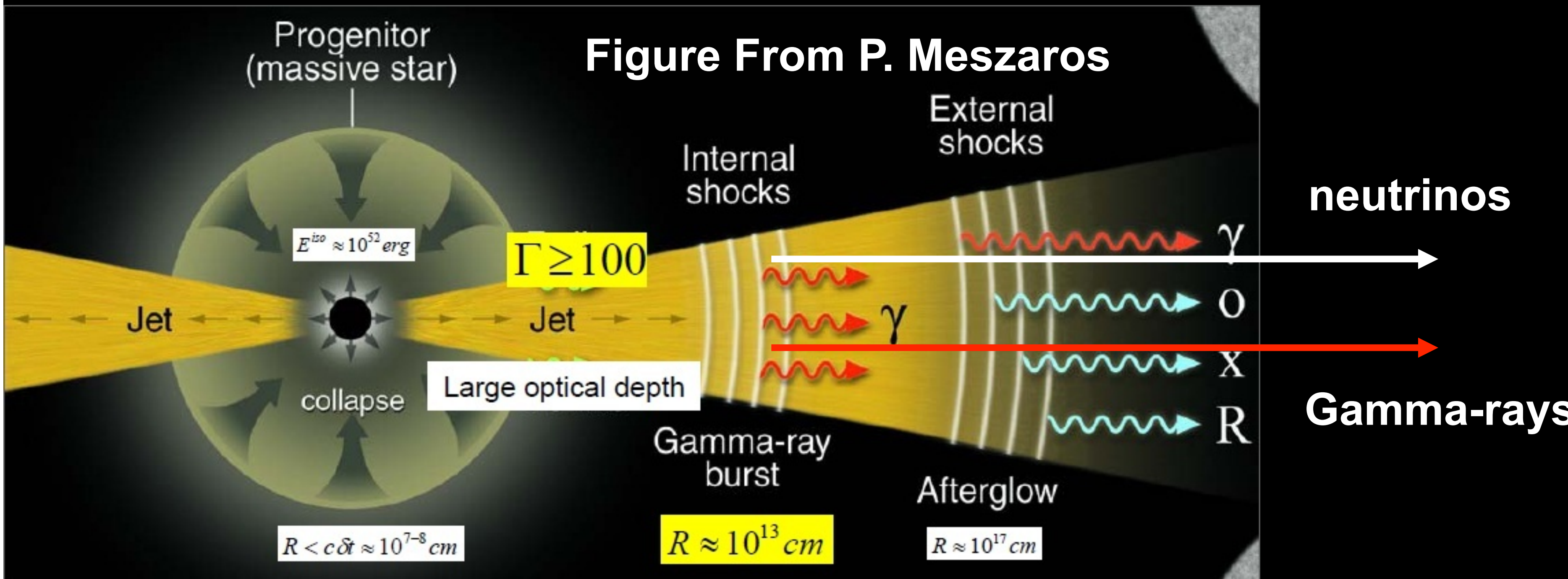
Van Vliet, Scholten, S.N., Kusenko, Calvez, He and Wang.

§ Secondaries: VHE Neutrinos from Gamma-Ray Bursts

Ref.
Murase and S.N. PRD, 73 063002 (2006)
Murase and S.N. PRL, 97 051101 (2006)


2: Secondaries to probe the source Of UHECR:
apparent source direction
charged particle
VHE-Gamma
VHE-Neutrino
With GRBs
GRB
Figure from Hoffman (Modified)

Gamma-rays and Neutrinos do not suffer from the bending effect by magnetic fields

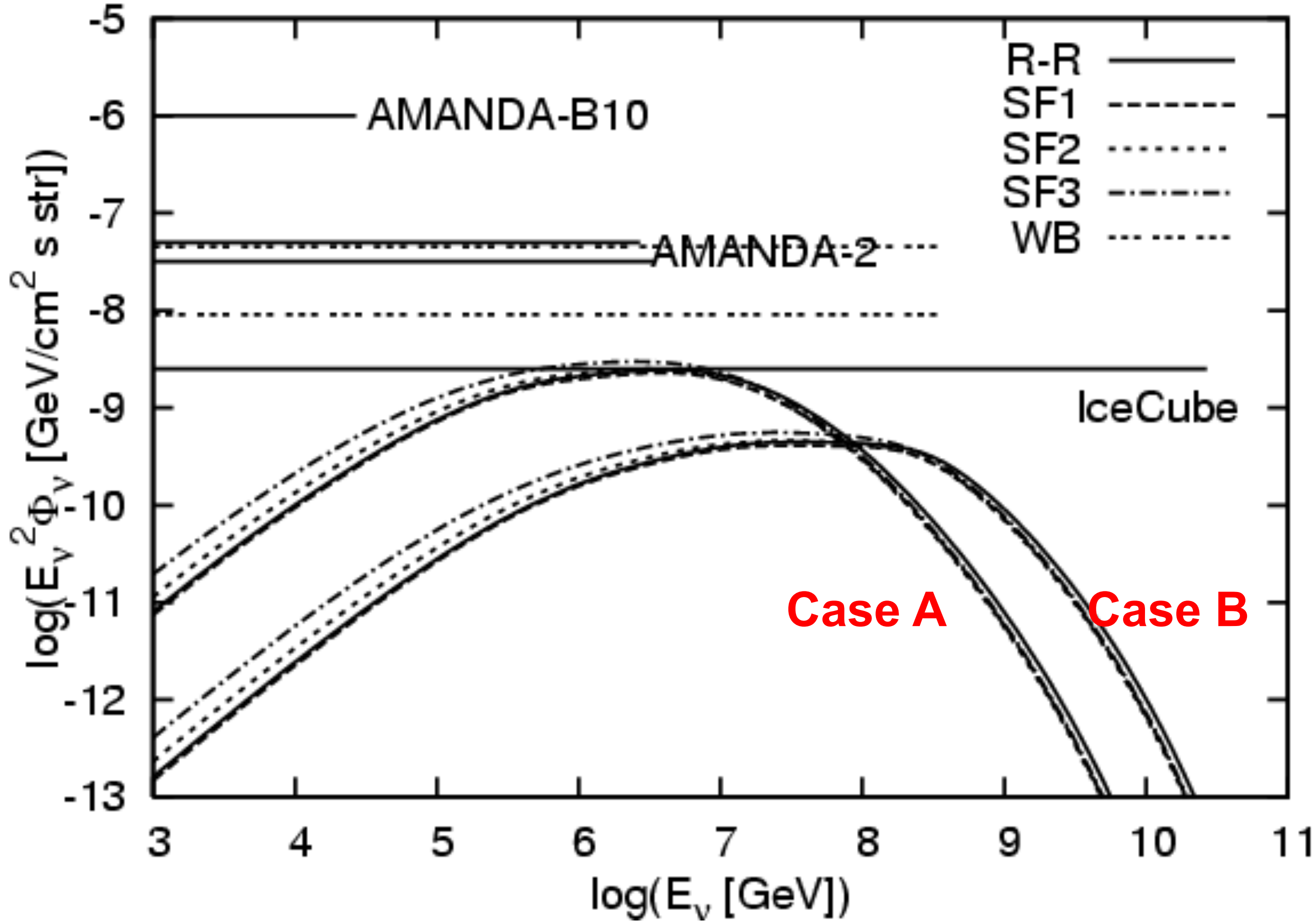


Time Correlation and Special Correlation.

e.g. Murase, Ioka, S.N., Nakamura (2007)

GRB Diffuse Neutrino Background

Murase & S.N., PRD, 063002 (2006)

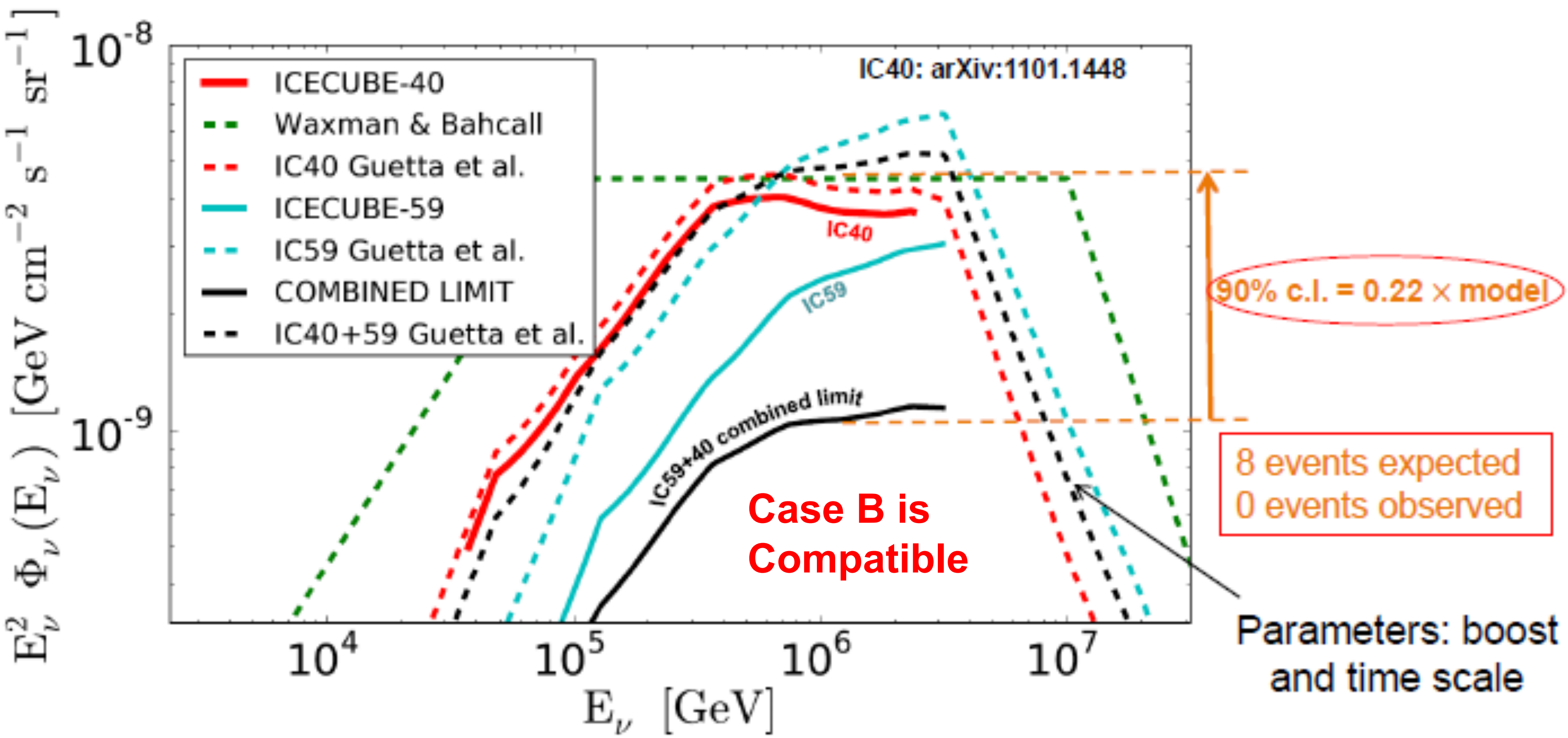


Upper lines: Small Radius, Lower lines: Large Radius

Event rates@ IceCube:
Case A: 17 events per yr, Case B: 1.5 events per yr.

Limits on GRB-Neutrino by IC40,59

ICRC 2011



IceCube is starting to draw a severe constraint on the modeling of UHE-Neutrinos from GRBs. However, more sensitivity is necessary to detect UHE-Neutrinos.

- Summary

Summary

- Simulations of propagation of UHECRs from nearby luminous galaxies: More than 1000 events will tell us the source distribution of UHECRs (if composition is proton).
- Trapping effects by B-field in clusters of galaxies may play an important role for the composition of UHECRs (Cosmic Ray Afterglow).
- Past GRBs in Milky Way may contribute to UHECRs (at least, for UHECRs less than GZK cut-off). Transition from proton to Fe is simply and reasonably explained by this scenario.
- Secondary particles produced at sources are powerful tools to determine the origins of UHECRs.

Thank You Very Much！！

2011.Sep.09@Moorea.