APCTP Focus Program on Recent Developments in Neutrino Physics and Astroparticle Physics (In memory of Prof. Benjamin W. Lee)

Ultra-High Energy Cosmic Rays and Cosmogenic Neutrinos

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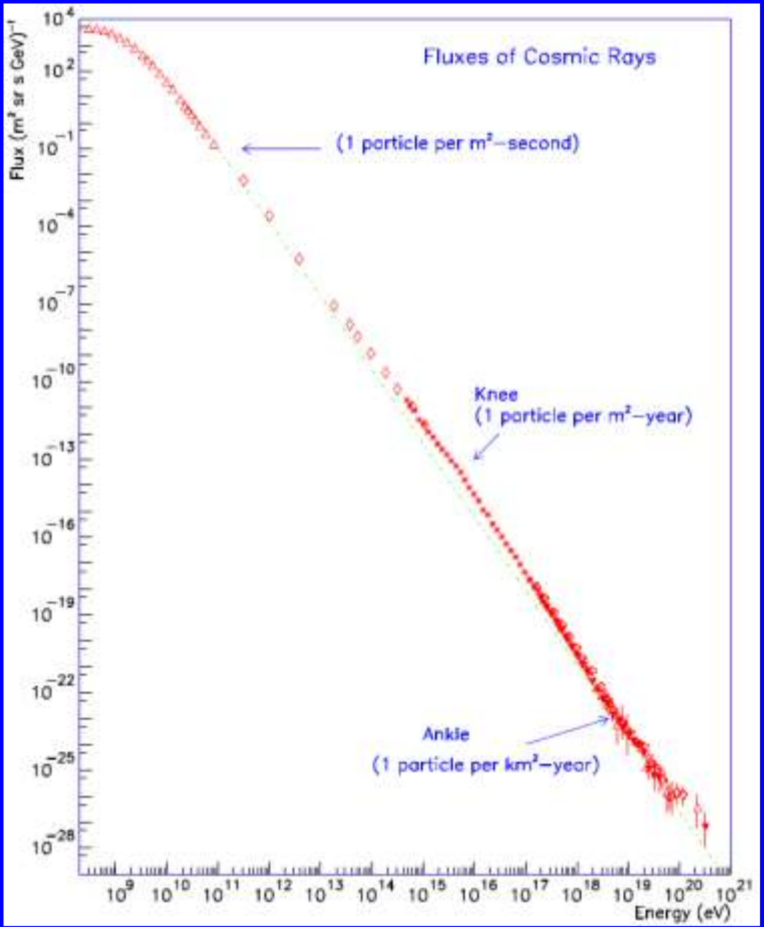
25th June 2009, APCTP, Korea

§ Introduction

What are Ultra-High Energy Cosmic Rays (UHECRs)？

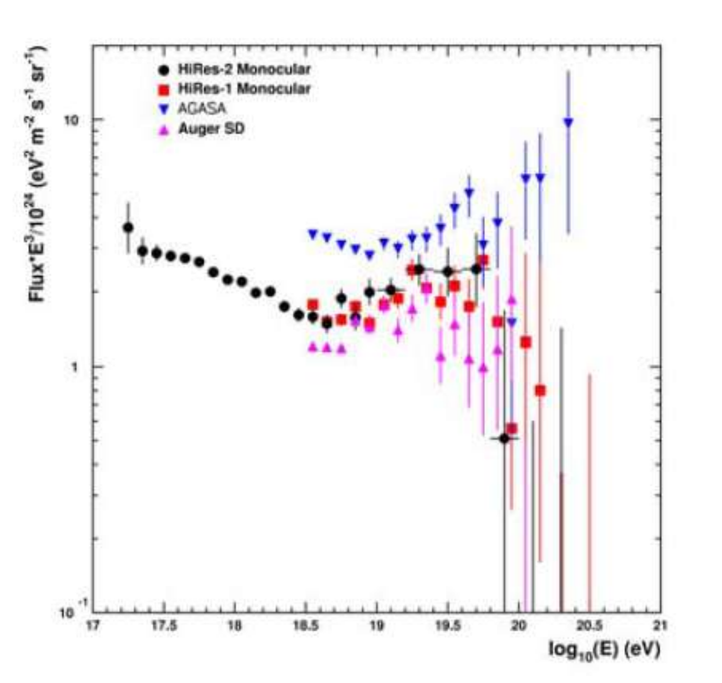


Energy Spectrum of Cosmic-Rays coming to the Earth (from sub-GEV to 10^20 eV).

What are the sources of UHECRs?

How large is the highest energy of CRs in the universe?

How are UHECRs produced?



Sokolsky and Thomson 07

GZK Cutoff (1)

- UHECRs with 10ˆ20eV interact with Cosmic Microwave Background (CMB) and lose their energy. Thus there should be a cutoff of the energy spectrum of CRs around 10^20eV（Greisen 1996, Zatsepin and Kuz'min 1966）.

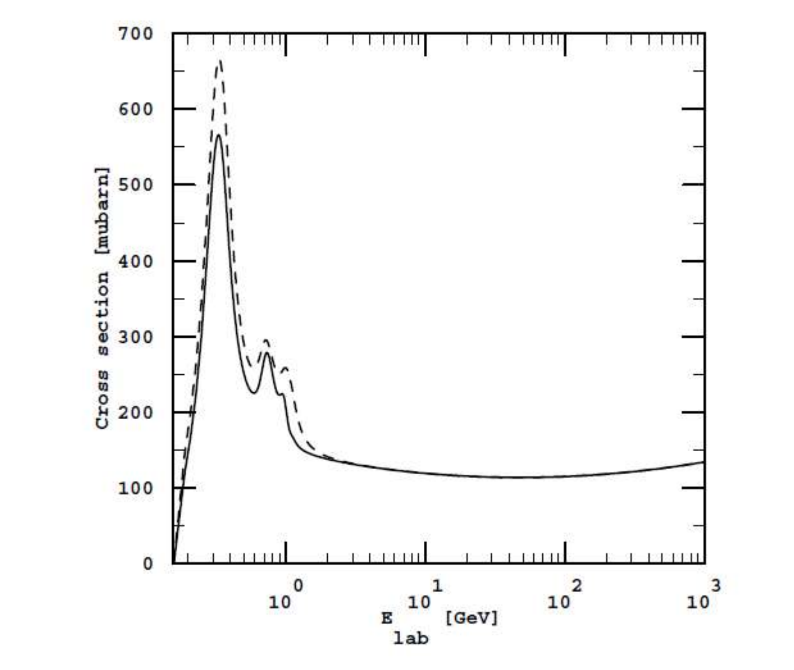
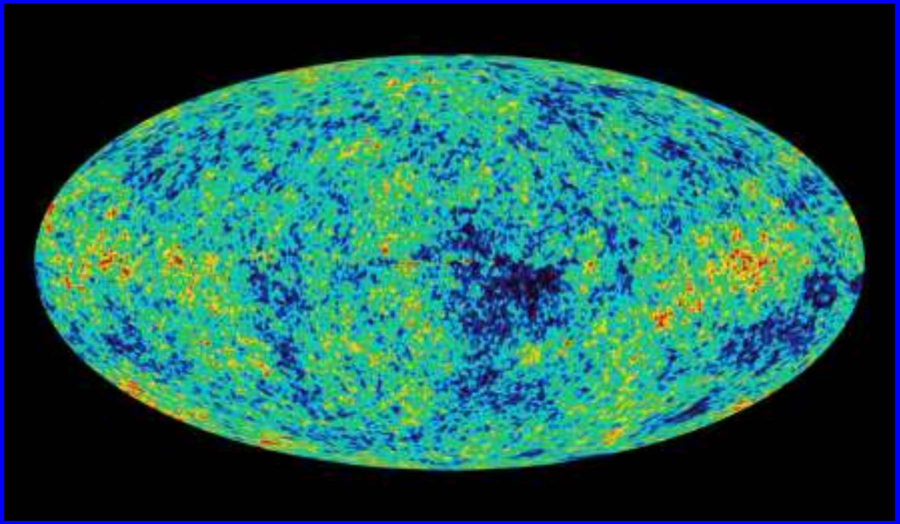


Figure 8: The total photo-pion production cross section for protons (solid line) and neutrons (dashed line) as a function of the photon energy in the nucleon rest frame, E_{lab}.

Cross Section for Photo-pion production



Cosmic Microwave Background by WMAP（from NASA HP）

3K＝2.5^-4 eV
Lorentz transformation with Γ= 5*10^11 makes it 1.25^8 eV = 125MeV ～Pion's mass＝140MeV

GZK Cutoff (2)

Center：The Earth

Light Blue　Region：　The region from where UHECRs with 10^20 eV can reach to the Earth.

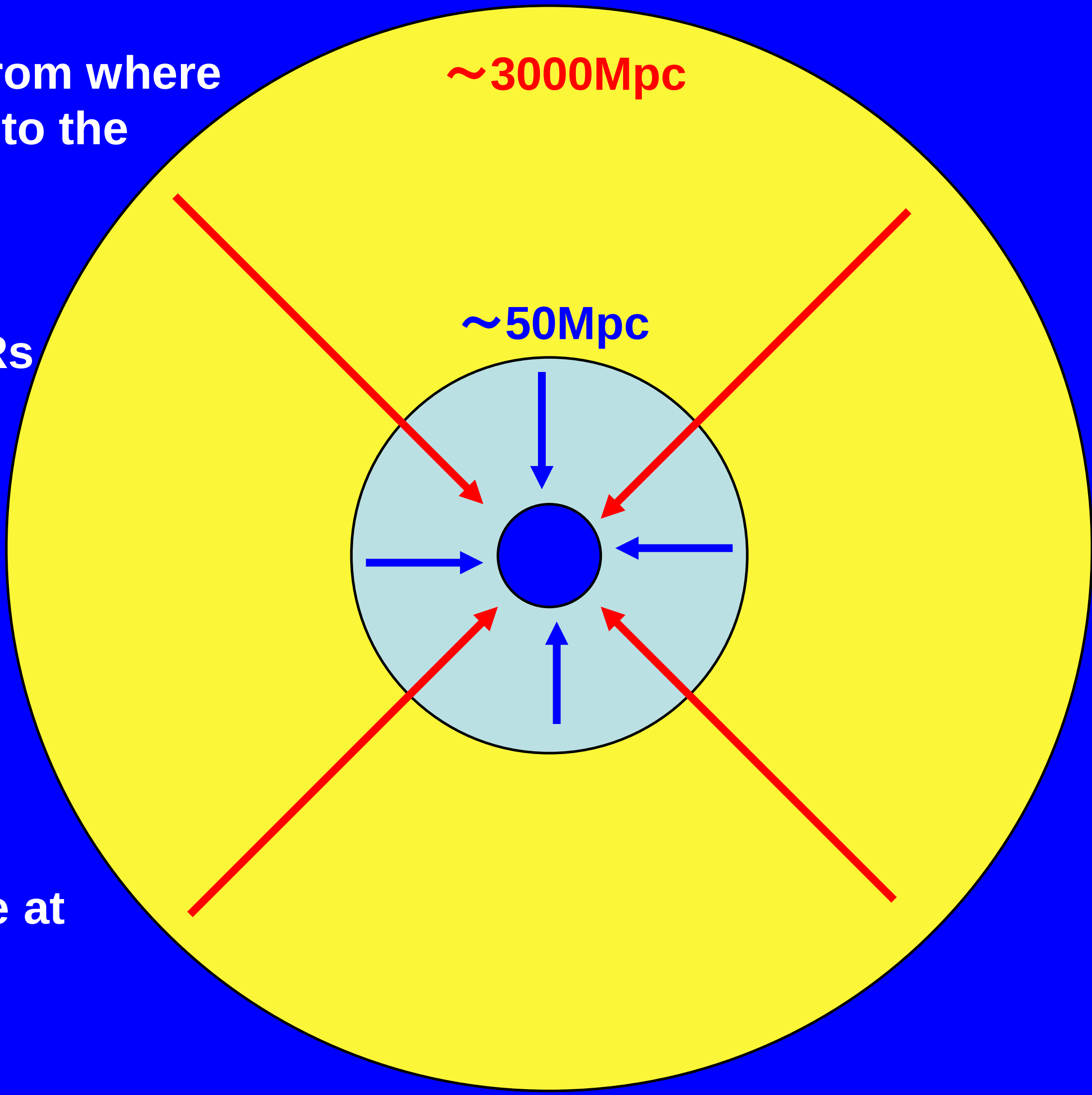
Yellow Region (including the light Blue region)：The region where CRs below10^20eV can reach to the Earth.

Even if UHECRs are produced At every region in the universe, Only UHECRs in the light blue Region can arrive at the Earth.

↓

The amount of UHECRs that arrive at the Earth becomes relatively low.

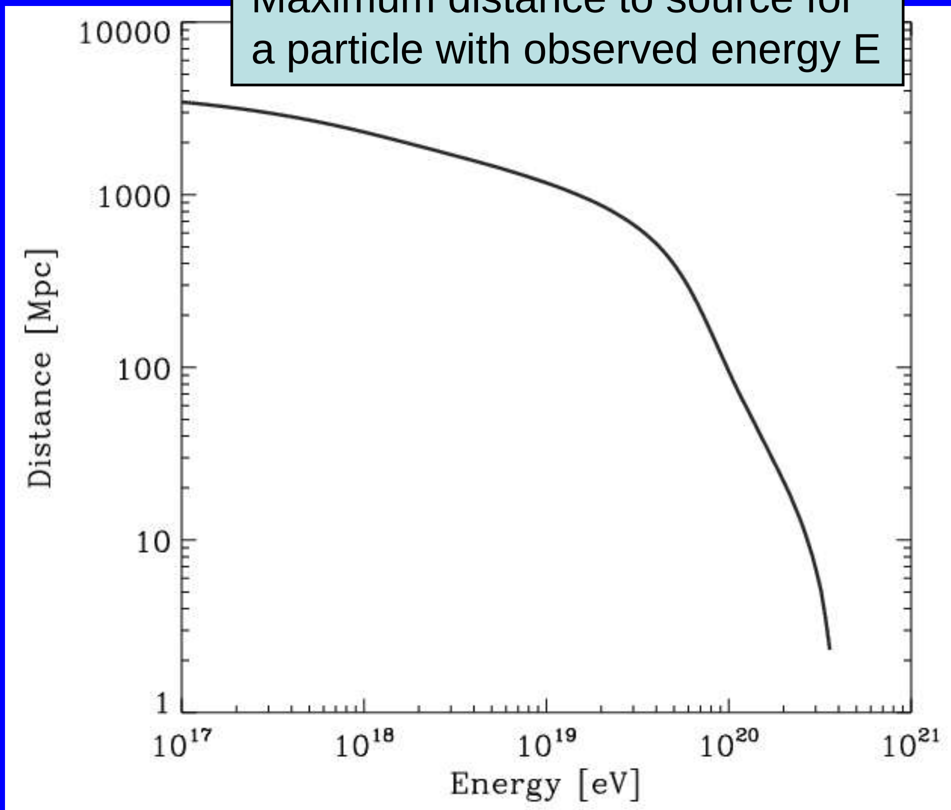
↓



The energy spectrum of CRs should have a cut off at ～10^20eV（GZK Cutoff）.

First report on GZK cutoff

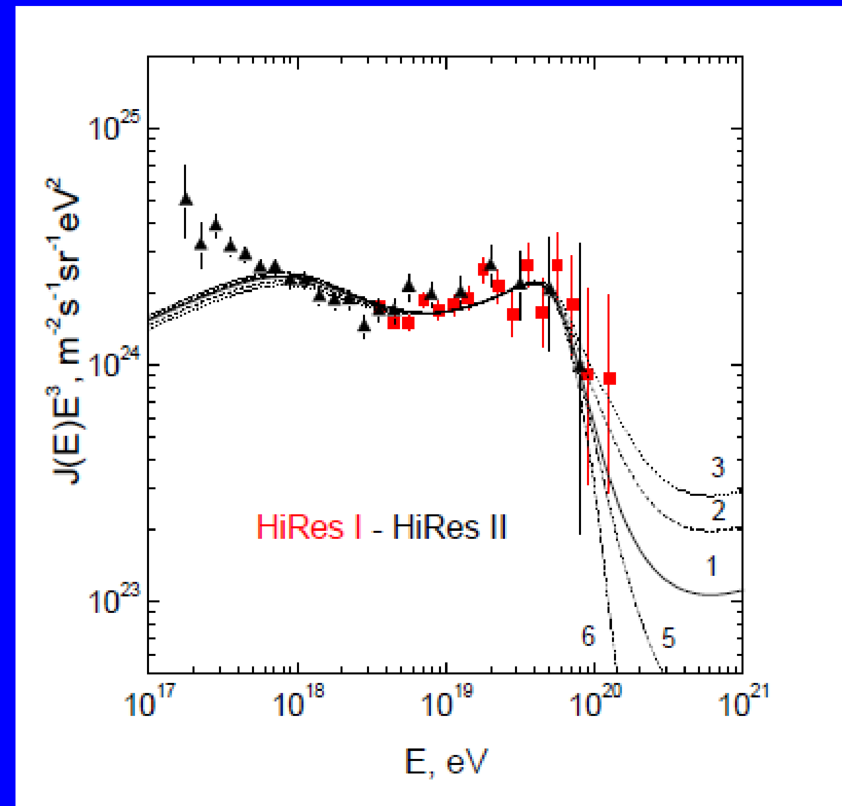
Maximum distance to source for a particle with observed energy E



Protons

$$p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-}$$

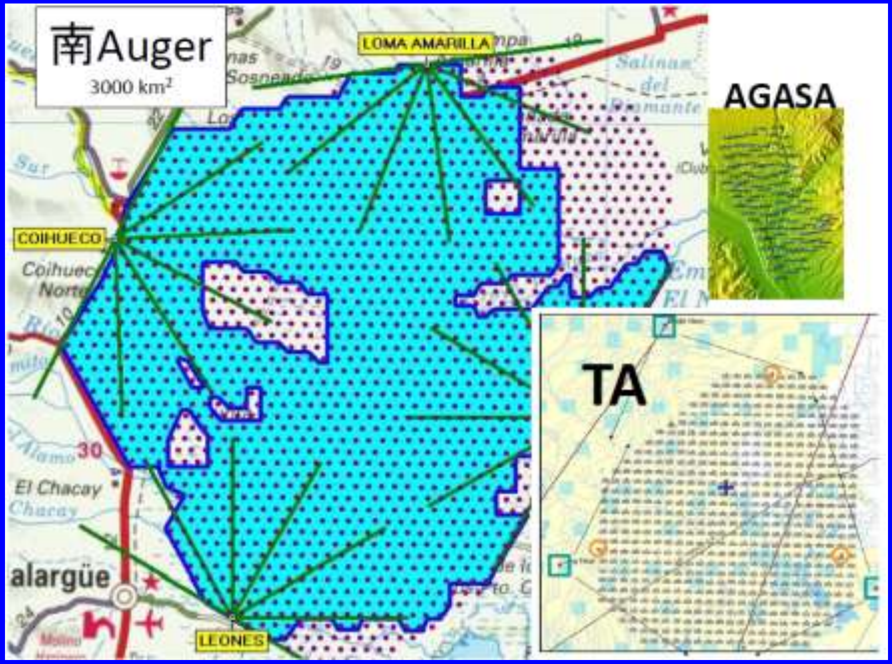
$$p + \gamma_{\mathrm{CMB}} \rightarrow N + \mathrm{pions}$$

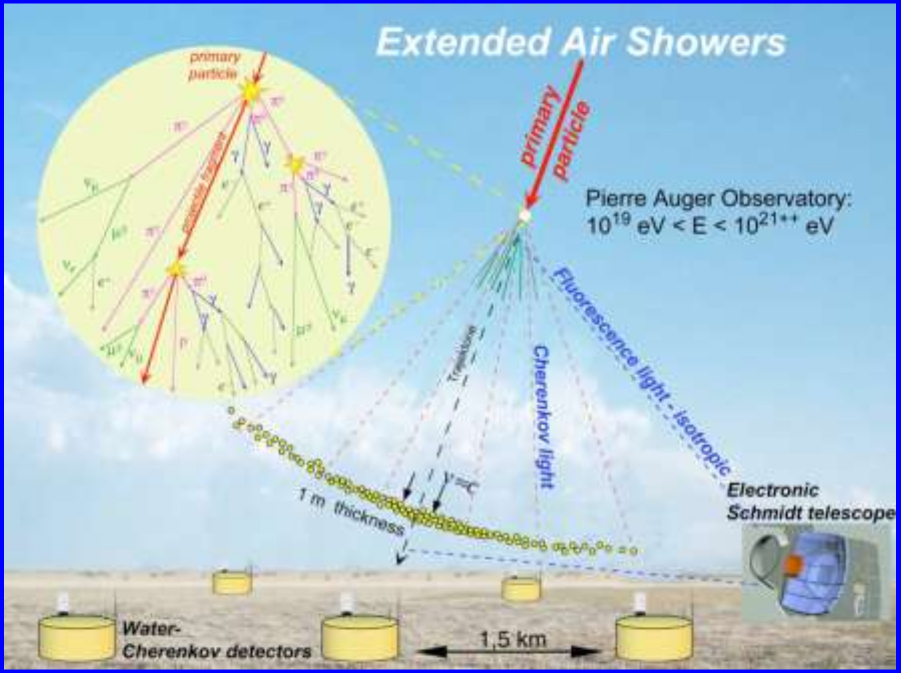


GZK cutoff seen by HiRes
Abbasi et al. 2008

Pierre Auger Observatory (PAO)

- Two independent techniques are used at the PAO to study extensive air showers created by ultra-high energy cosmic rays, a ground array of more than 1600 water-Cherenkov detectors (SDs) and a set of 24 fluorescence telescopes (FDs).
- Exposure (km^2 sr yr) of SDs is the biggest in the world.

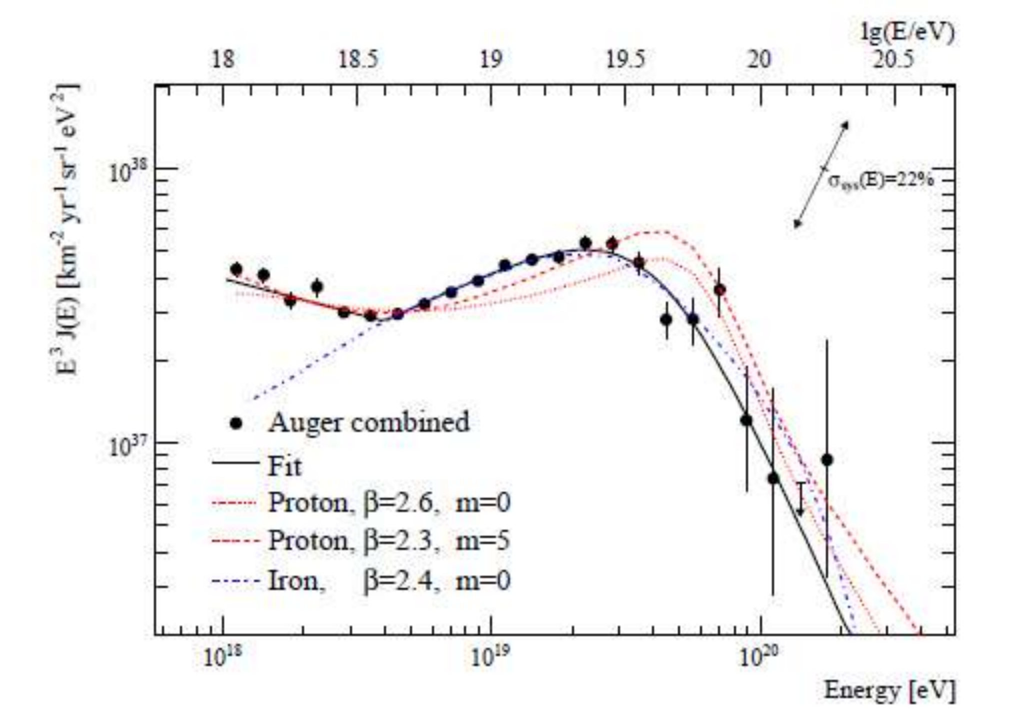


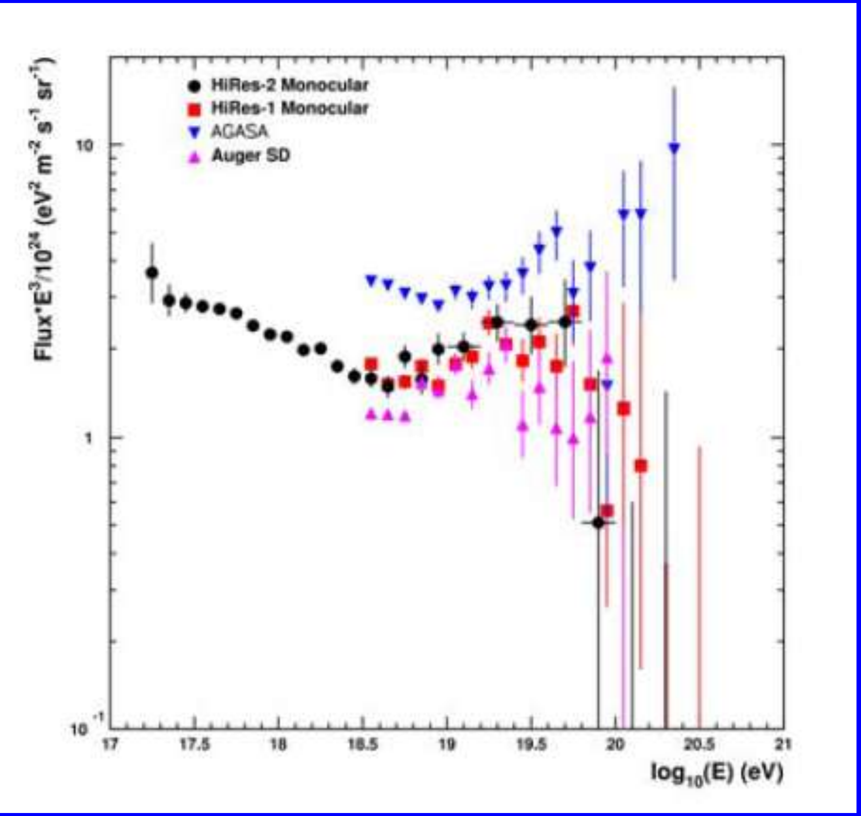


(Armenguad 05)

Energy Spectrum of UHECRs

The flux suppression is seen at GZK-cut off energy Scale (c.f. HiRes and AGASA).





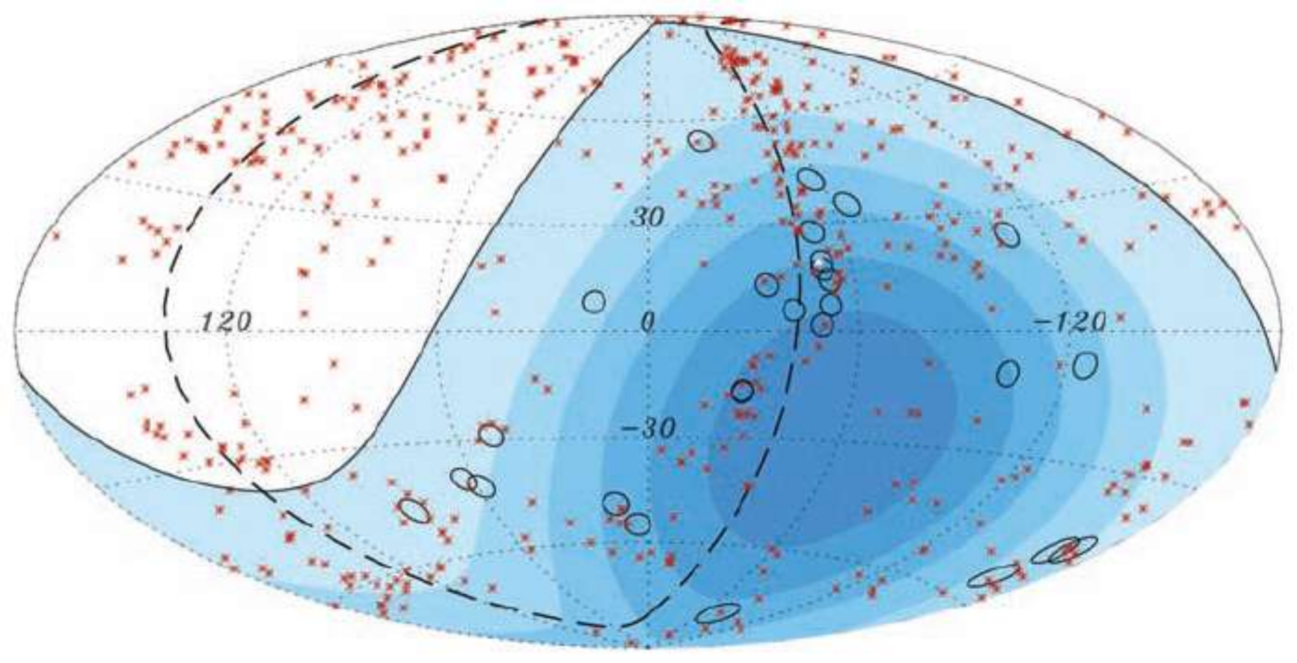
Auger Collaboration 09

Sokolsky and Thomson 07

Correlation between the arrival directions of UHECR and the positions of nearby AGNs

(Pierre Auger Collaboration 2007)

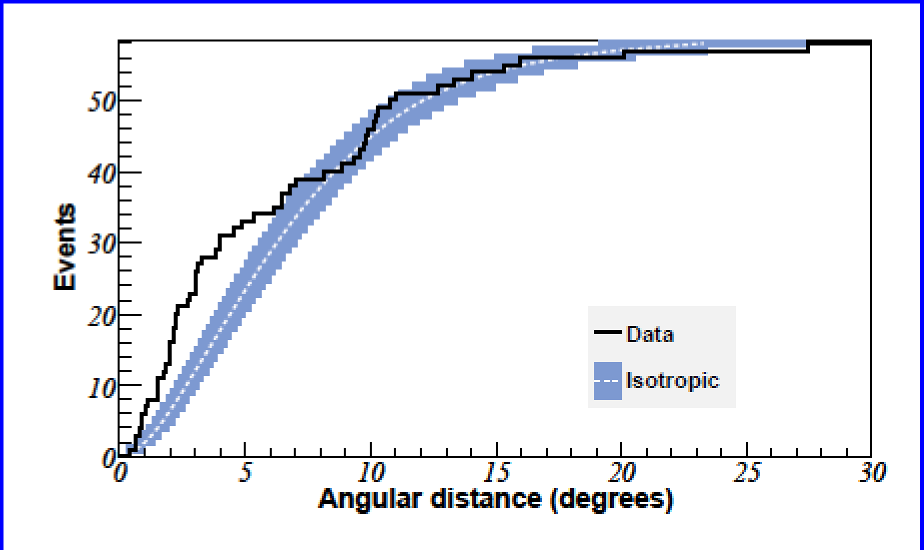
Asterisks：nearby AGNs
White：CenA
Circles： UHECR
Dashed lines：Super-galactic Plane
Solid line：Boundary of the observation area.
Contour: Exposure



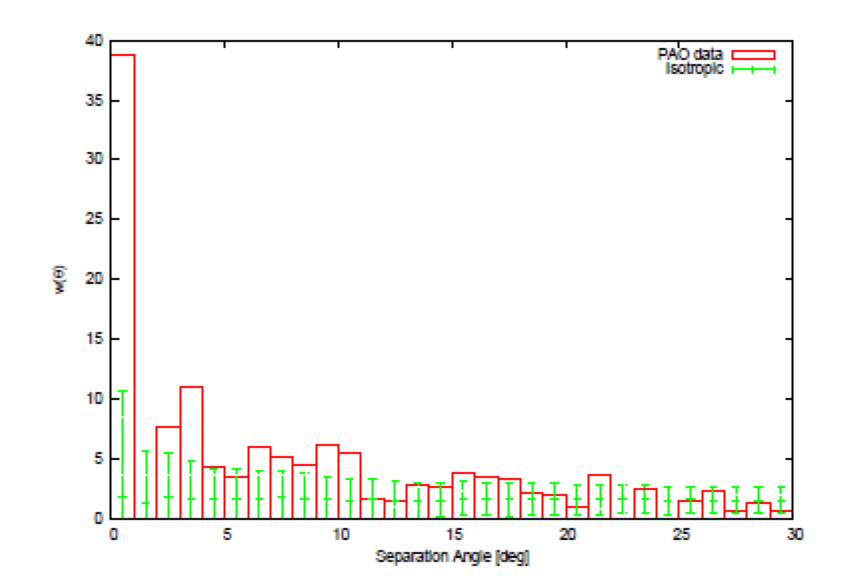
- Correlation with nearby AGNs (D<75Mpc)?
  E>57EeV, δ=3.1^{o} **27events**
- Correlation with the super-galactic plane？
- Several events from Cen A?
- No excess from Virgo (M87).

See also HiRes Results.
e,g, Abbasi+ 08

Cross-correlation and Auto-correlation



Cross-correlation
The distribution of angular Separation between the 58 events With E>55EeV and the closest AGN in the VCV catalog within 75Mpc (Auger collaboration 09).



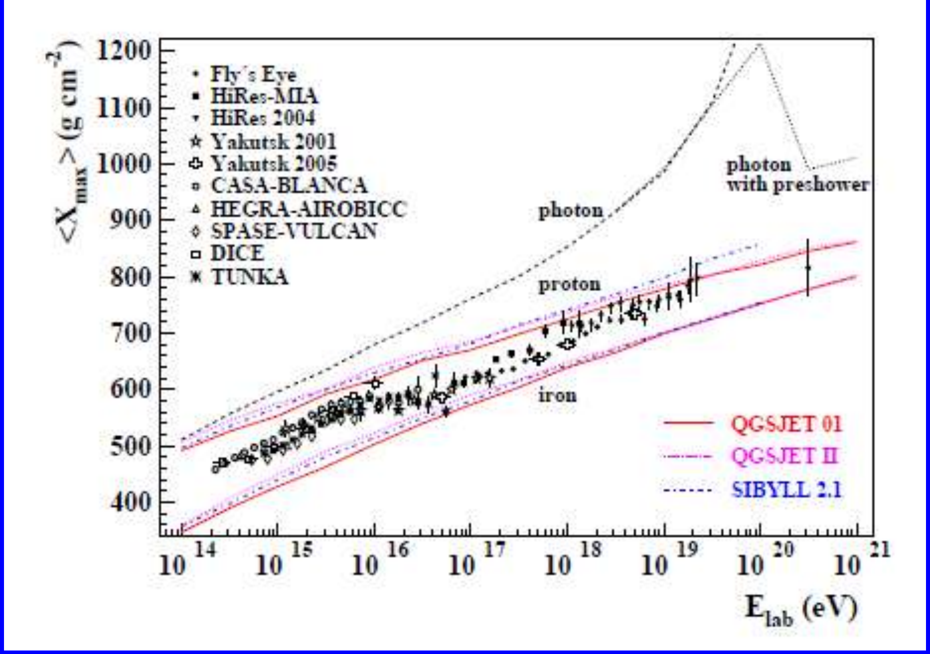
Auto-correlation
Autocorrelation of PAO's 27 events With E>57EeV (Takami et al. 2009).

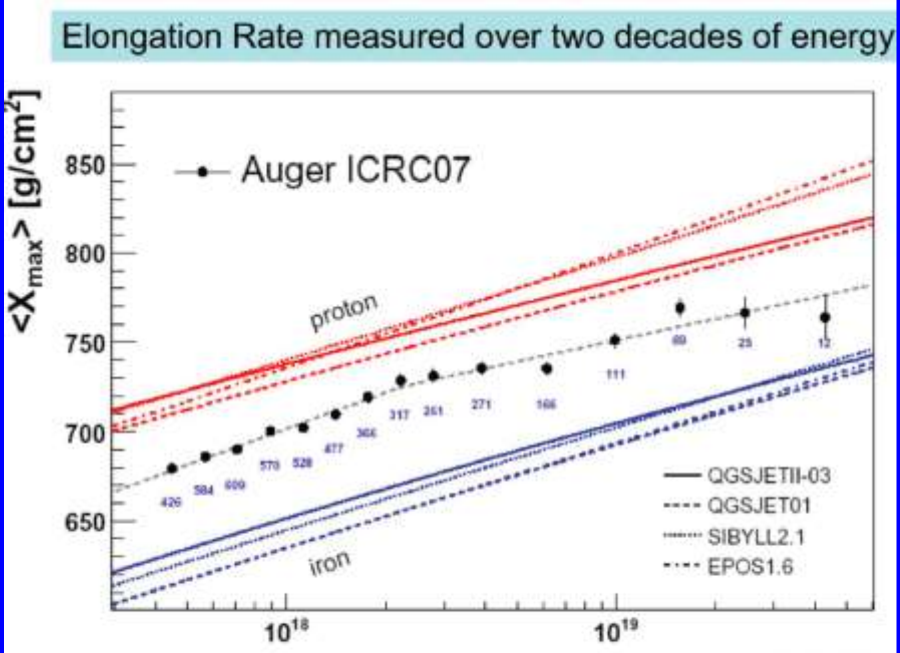
$$N(\theta) = \frac{1}{2\pi|\cos\theta - \cos(\theta+\Delta\theta)|} \sum_{\theta\le\phi\le\theta+\Delta\theta} 1 \ [\mathrm{sr}^{-1}],$$

Composition of UHECRs

Past experiments

Auger **Abraham+07**

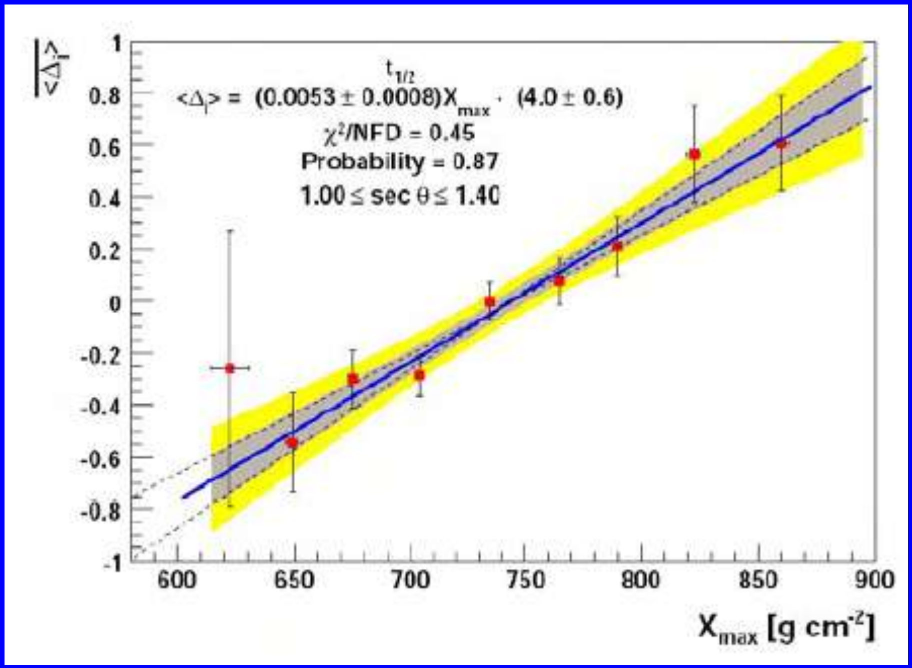


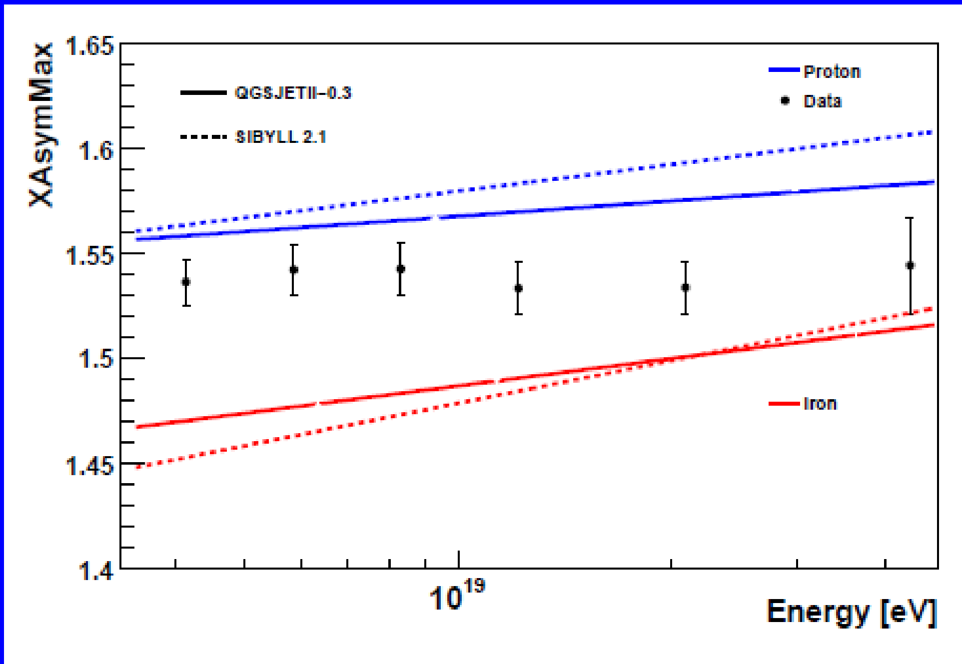


An upper limit of 16% (at 95% c.l.) is derived for the photon fraction in cosmic rays with energies greater than 10^{19} eV, based on observations of the depth of shower

This result favors the bottom-up scenario.
Consistency with the arrival direction?

Shower Asymmetry (Auger collaboration 2009)





Left Figure:

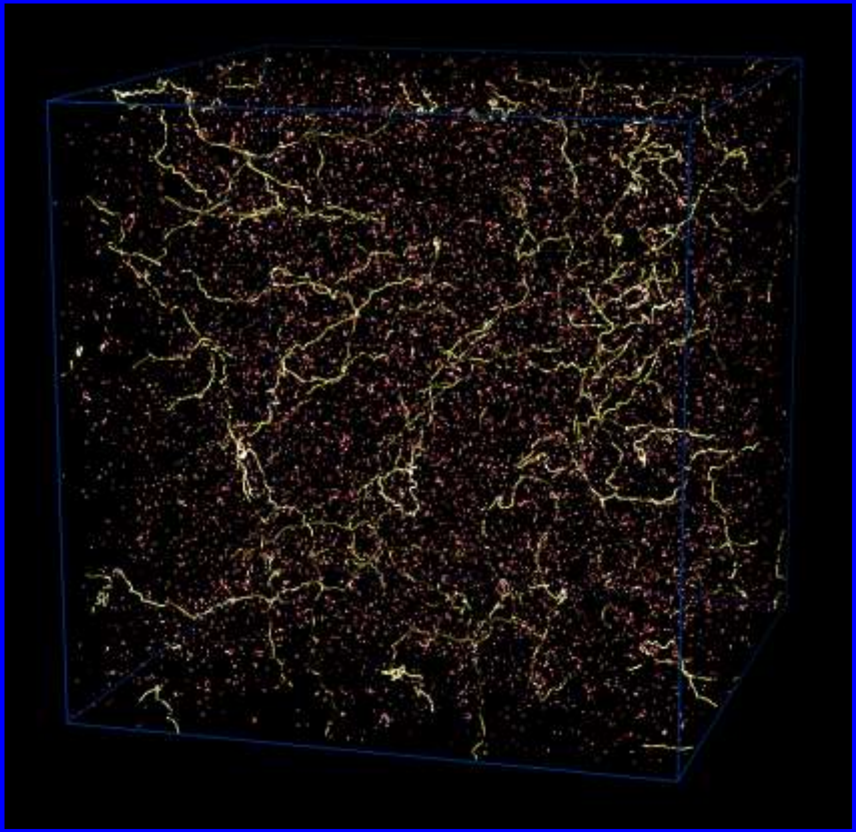
Fig. 3. The average $< \Delta_i >$ as a function of X_{max} for selected hybrid events. A correlation is found which is parameterised with a linear fit. The shaded areas show the estimated uncertainty (one and two σ), obtained by fluctuating each point randomly within the measured error bar and repeating the fitting procedure.

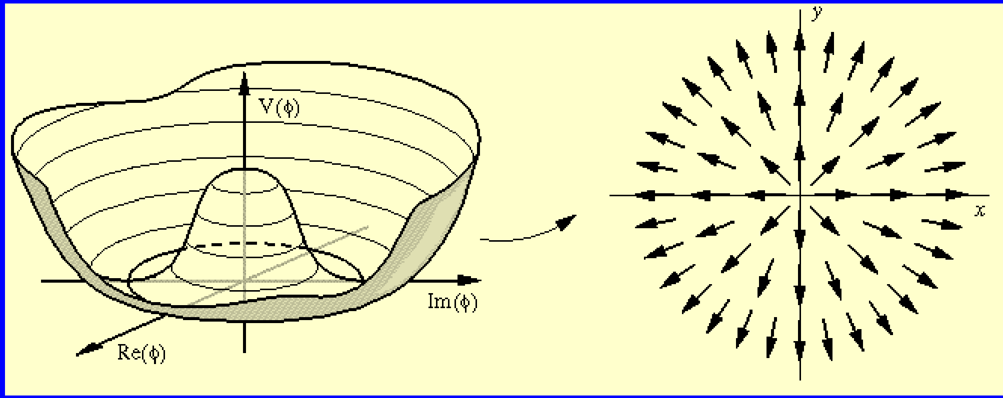
Right Figure:

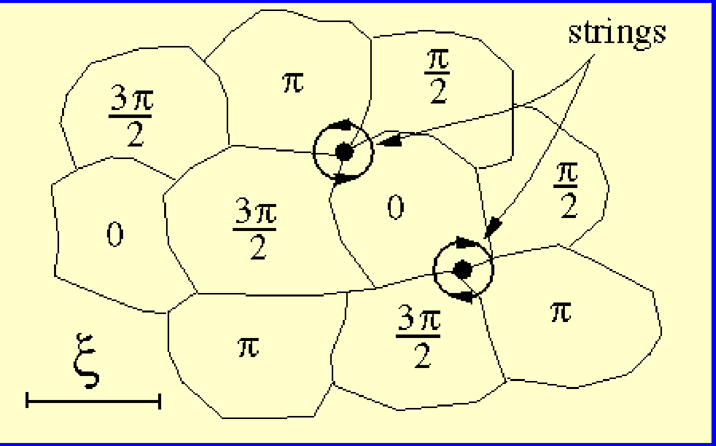
Fig. 5. Position of maximum asymmetry vs. primary energy for different models and primaries. Lines correspond to fitted distributions of MC samples for proton (blue) and iron (red) primaries.

Top-down Scenario？

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





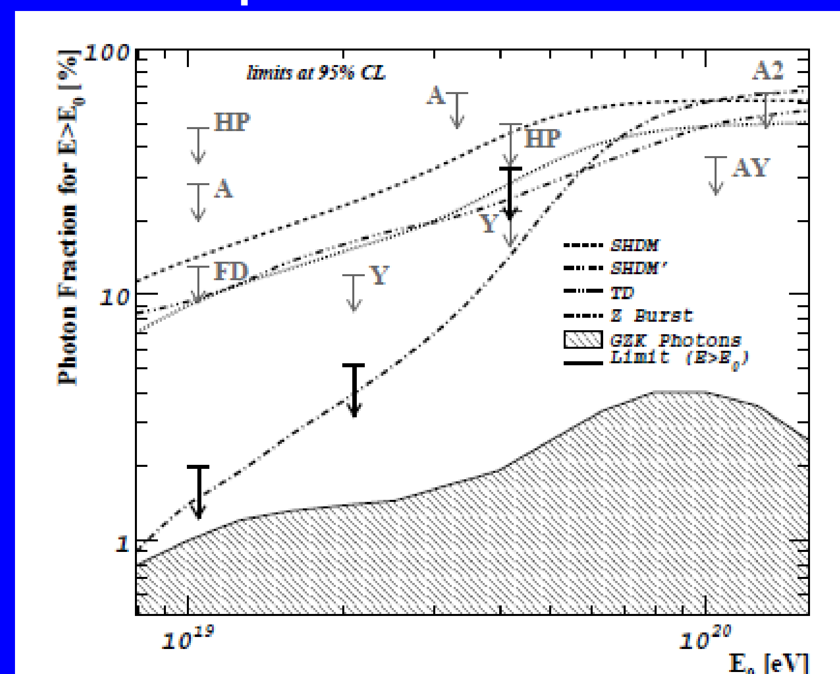


Simulation of Cosmic String (Cambridge Cosmology Group HP)

Decay of Super-heavy particles/Cosmic String

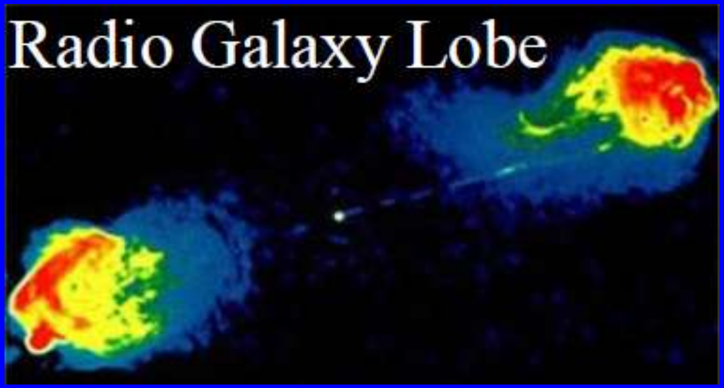
- (N-quark+N-lepton) are assumed to be born. N:Free Parameter.
- Every quark and lepton has the same energy (equi-partition).
- Simulation of the cascades.

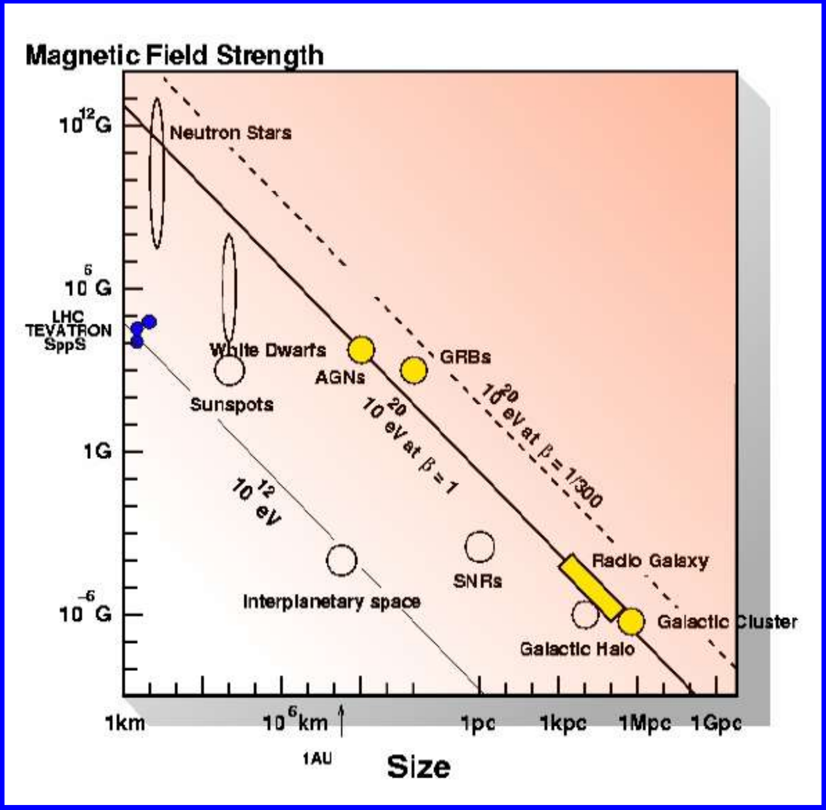
Huge amount of mesons are produced. The resulting components are dominated By photons, neutrinos, and e+e-. Thus, gamma-rays and/or neutrinos are Favored for UHECRs as long as the Top-down Scenario is adopted.



Upper: Jets from Top-quark and anti-top quark (by Tevatron). Right: Fraction of primary photons (from PAO collaboration, 2008)

Candidates of the Sources of UHECRs





Why is it difficult to find the sources of UHECRs?

- The sources should be near from the Earth (<50Mpc). However, the sources are not confirmed with high significance level yet.
- This is because the trajectories of UHECRs bend 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

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

Bhattacharjee 2000

Origin of cosmic radiation ?

Note:
This is the case of Low-energy CRs.

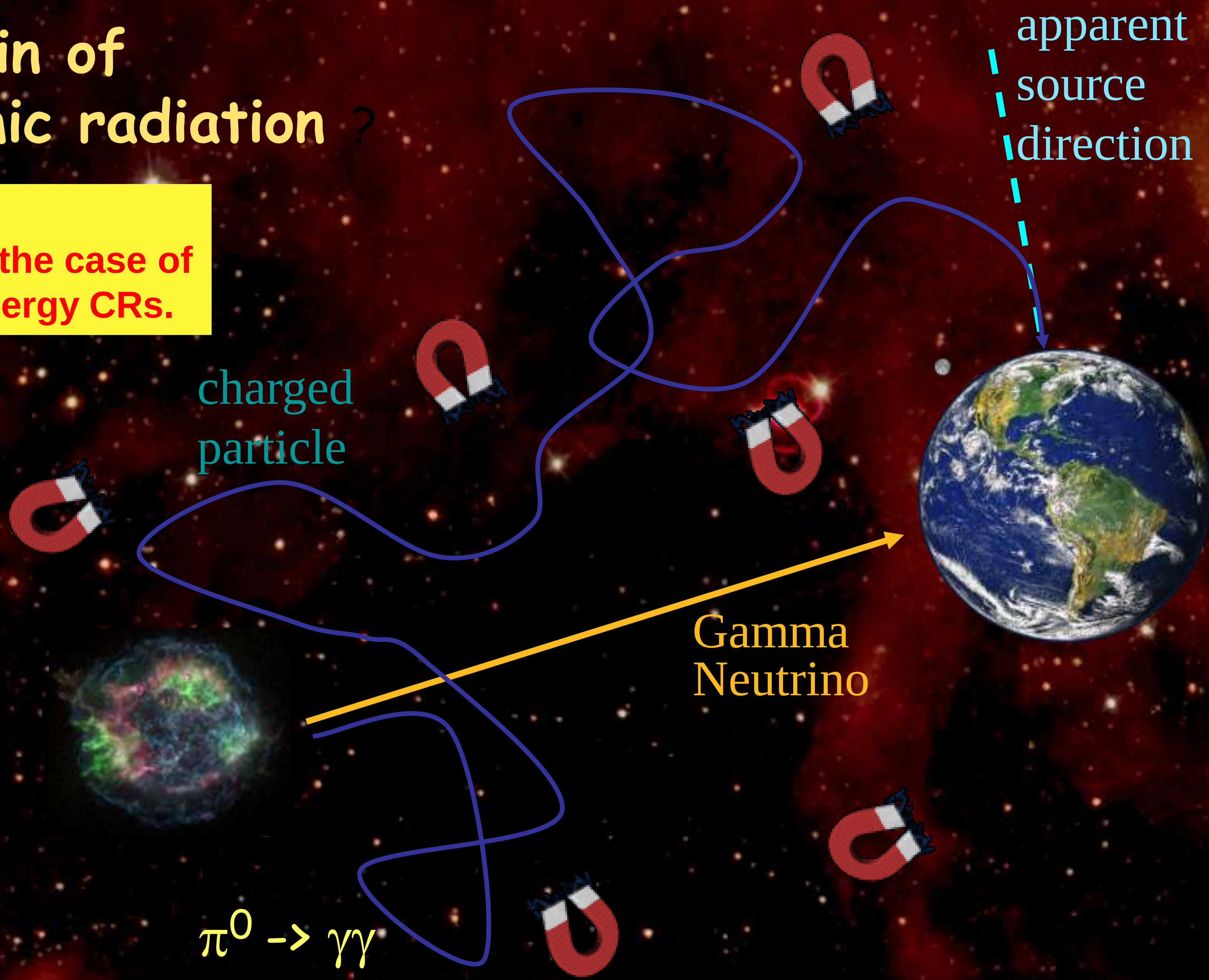
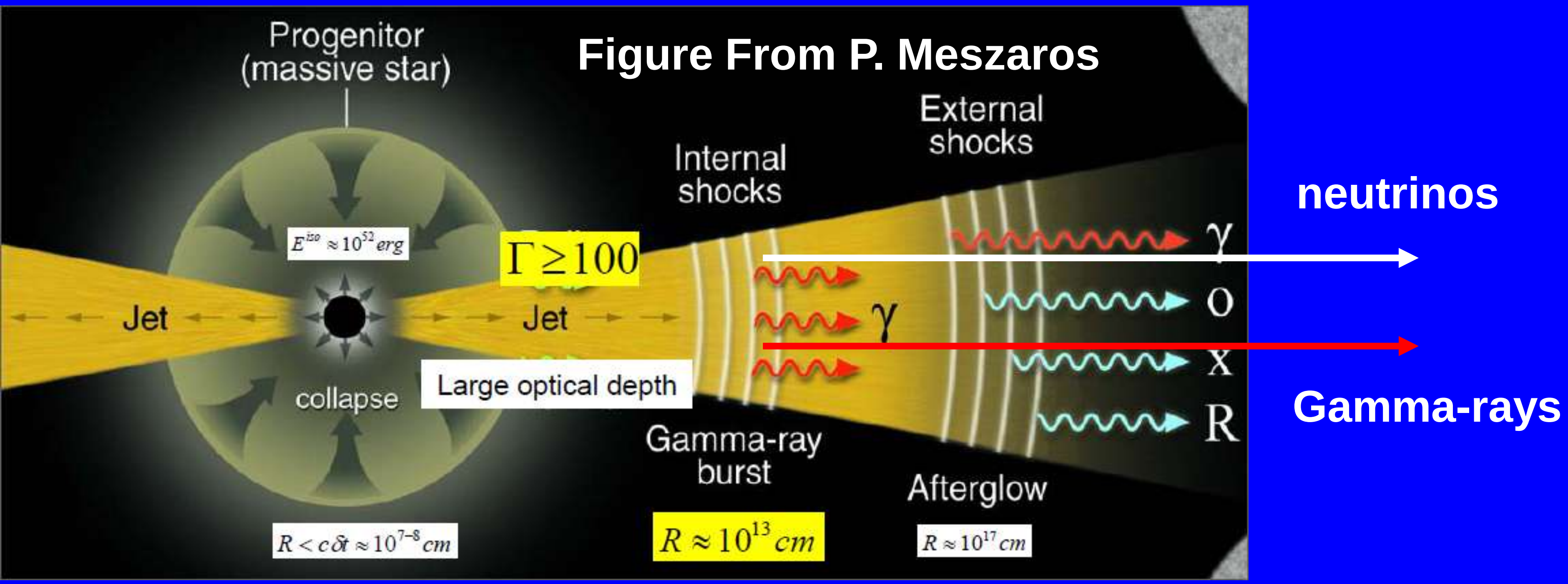


Figure from Hoffman

What can we do to identify the sources of UHECRs?

- Simulations of Propagation of UHECRs and comparison with the observations (some source models are assumed as well as magnetic fields in the universe).
- Observations of secondaries (gamma-rays and/or neutrinos).

Gamma-rays and Neutrinos do not suffer from magnetic fields



High energy neutrinos from a GRB correlate with the GRB.
High energy gamma-rays from a GRB also correlate with the GRB,
Although the mean-free path of high-energy gamma-rays is short.

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

§ Simulations of Propagation of UHECRs

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

Simulations of Propagation of UHECRs

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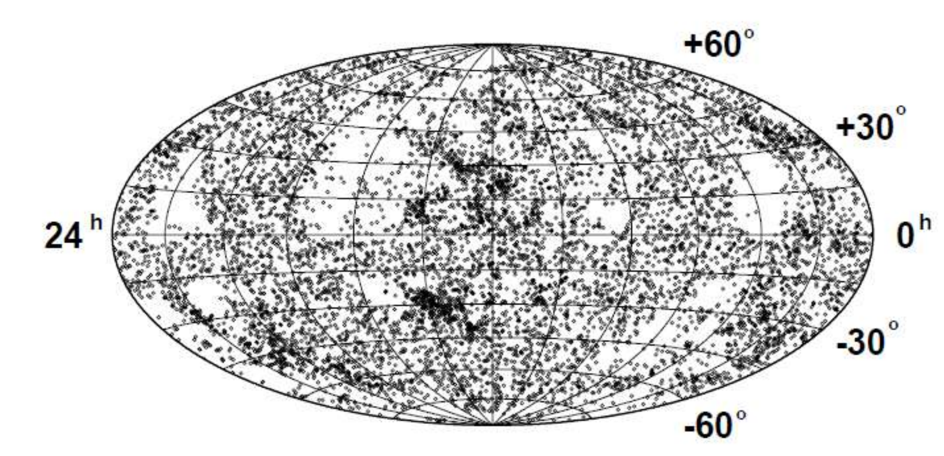


Distribution of nearby Galaxies (from ORS galaxy Catalog)

Protons

$$p + \gamma_{\mathrm{CMB}} \rightarrow p + e^+ + e^-$$

$$p + \gamma_{\mathrm{CMB}} \rightarrow N + \mathrm{pions}$$

UHECRs are assumed to be Protons.

$$\langle B^2(k) \rangle \propto k^{n_{\mathrm{H}}} \text{ for } 2\pi/l_c \leq k \leq 2\pi/l_{\mathrm{cut}}$$

$$n_{\mathrm{H}} = -11/3, \quad l_{\mathrm{cut}} = 1/8 \times l_c$$

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

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

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

$$B_z = \mu_G (1 - 3\cos^2\theta) / r^3,$$

$$\mu_G \sim 184.2 \ \mu\mathrm{G\ kpc}^3$$

Dipole field with random field For the Milky Way

Energy Spectrum and Auto-correlation function

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

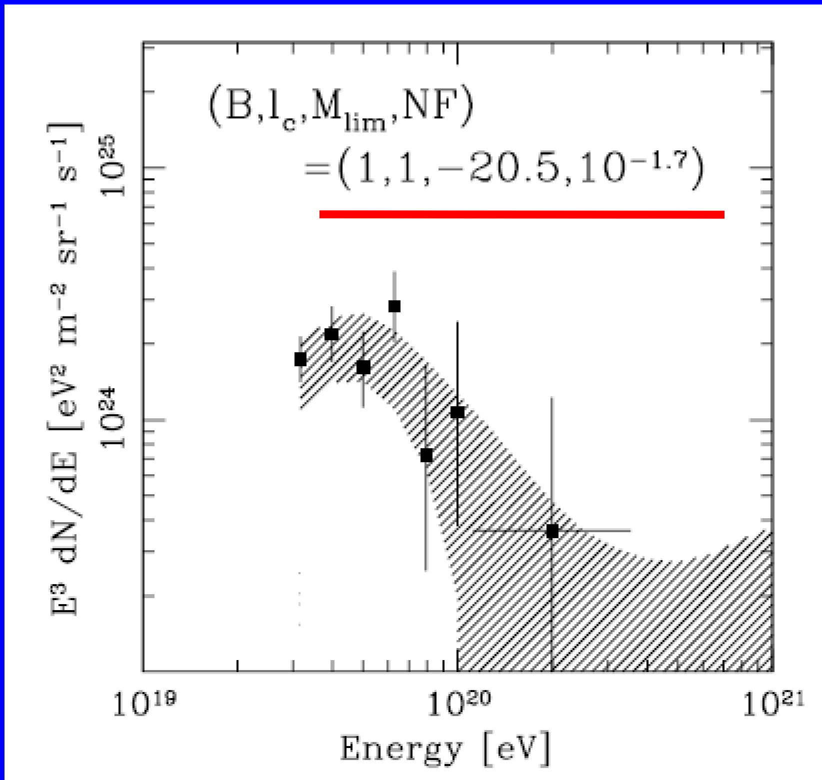
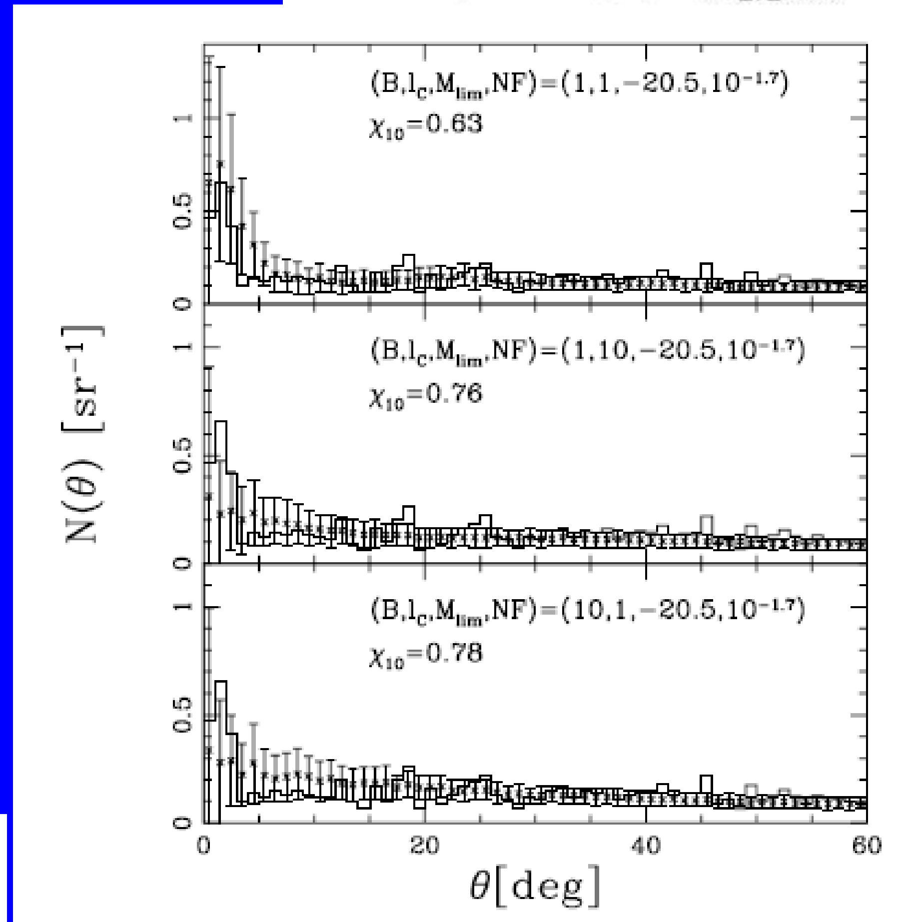


FIG. 22.—Energy spectra predicted by sources selected from the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ in the case of $(B, l_c, \mathrm{NF}) = (1, 1, -20.5, 10^{-1.7})$. NF represents the number fraction of selected UHECR sources to all ORS galaxies ($M_{\rm lim} < -20.5$). They are fitted 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.



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

Hatched region: Simulation.
Dots: Observations (HiRes)

An Example of Arrival Distribution of UHECRs

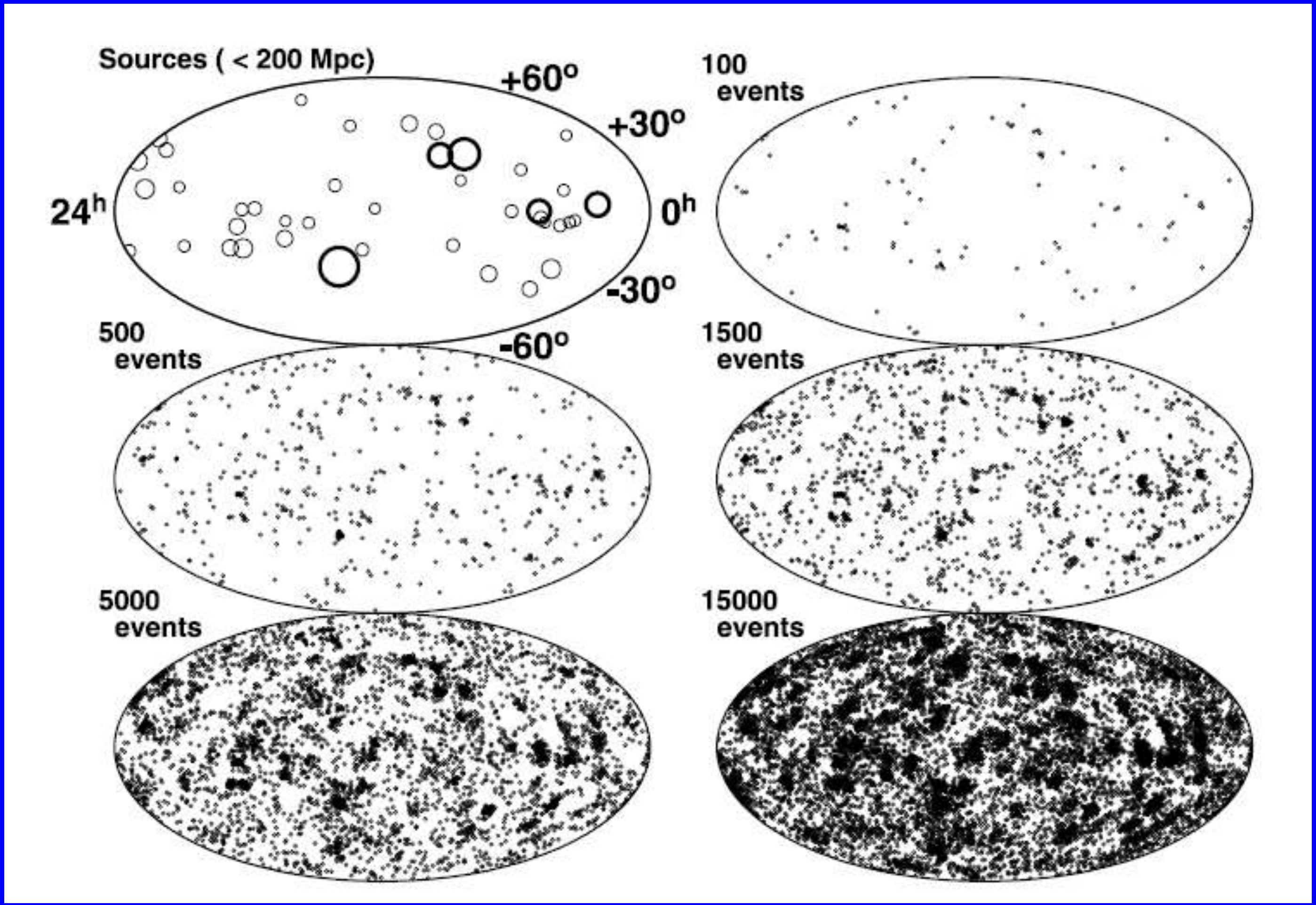
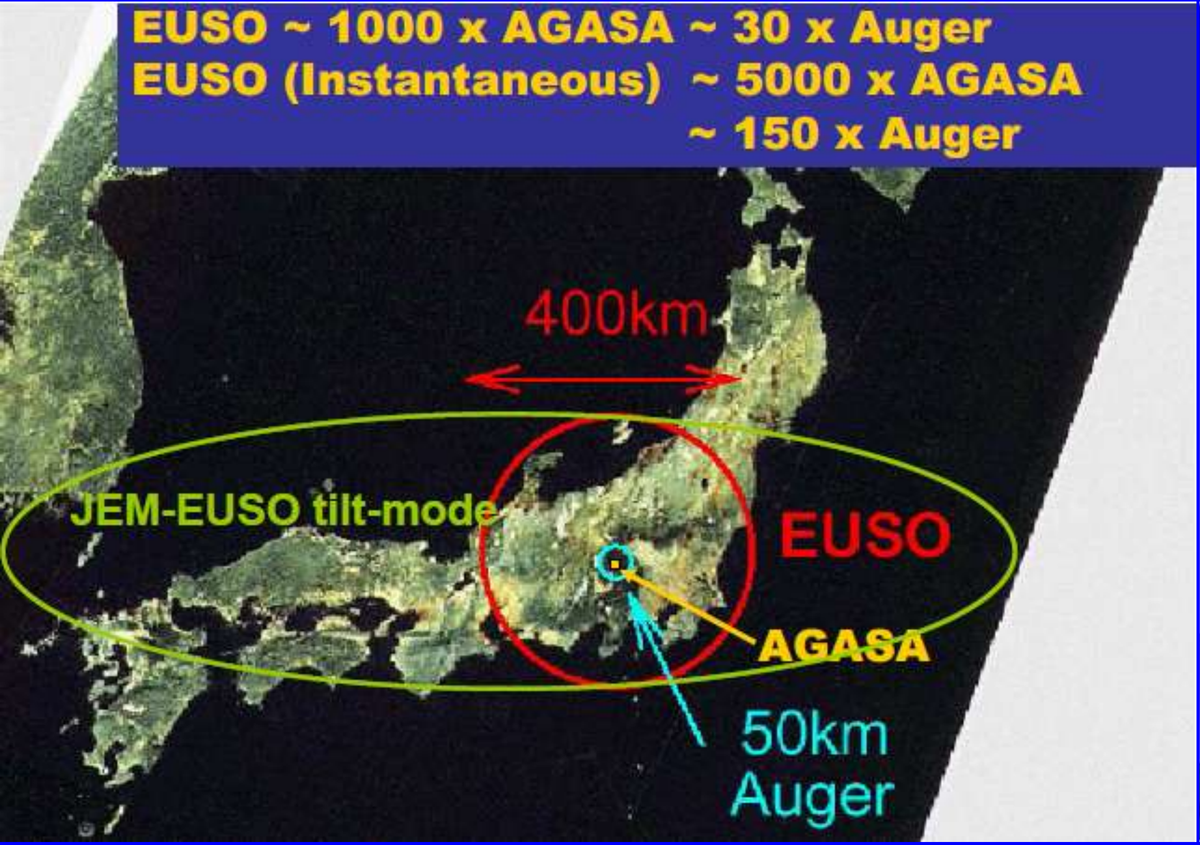


Fig. 3.—Arrival directions of UHECRs above 4×10^{19} eV predicted by a specific source scenario when 1/50 of the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ are selected as UHECR sources. Distribution of selected sources within 200 Mpc is also shown as circles of radius inversely proportional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

Arrival distribution Will be correlated With matter distribution.

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

JEM-EUSO



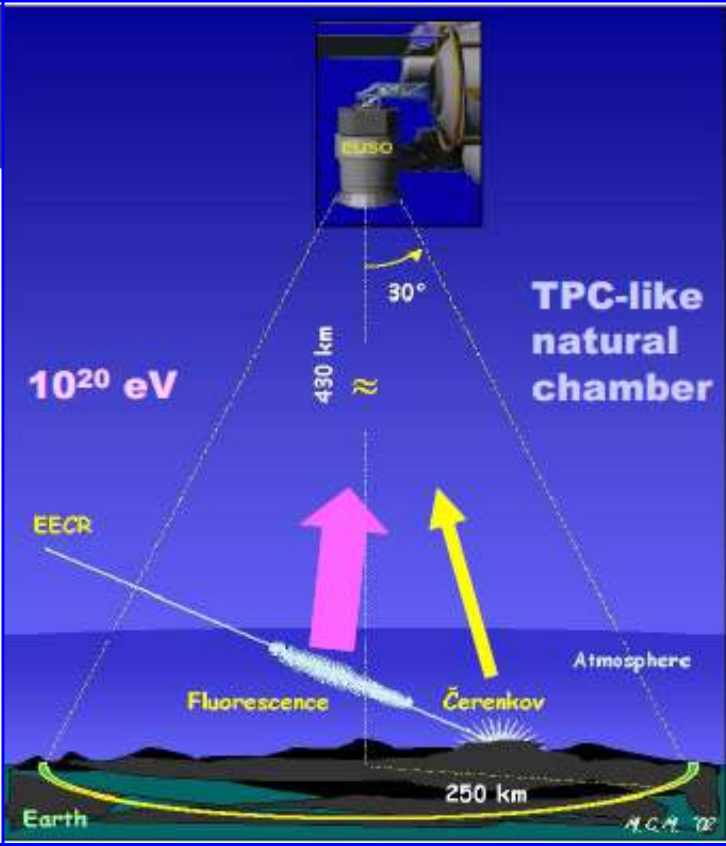
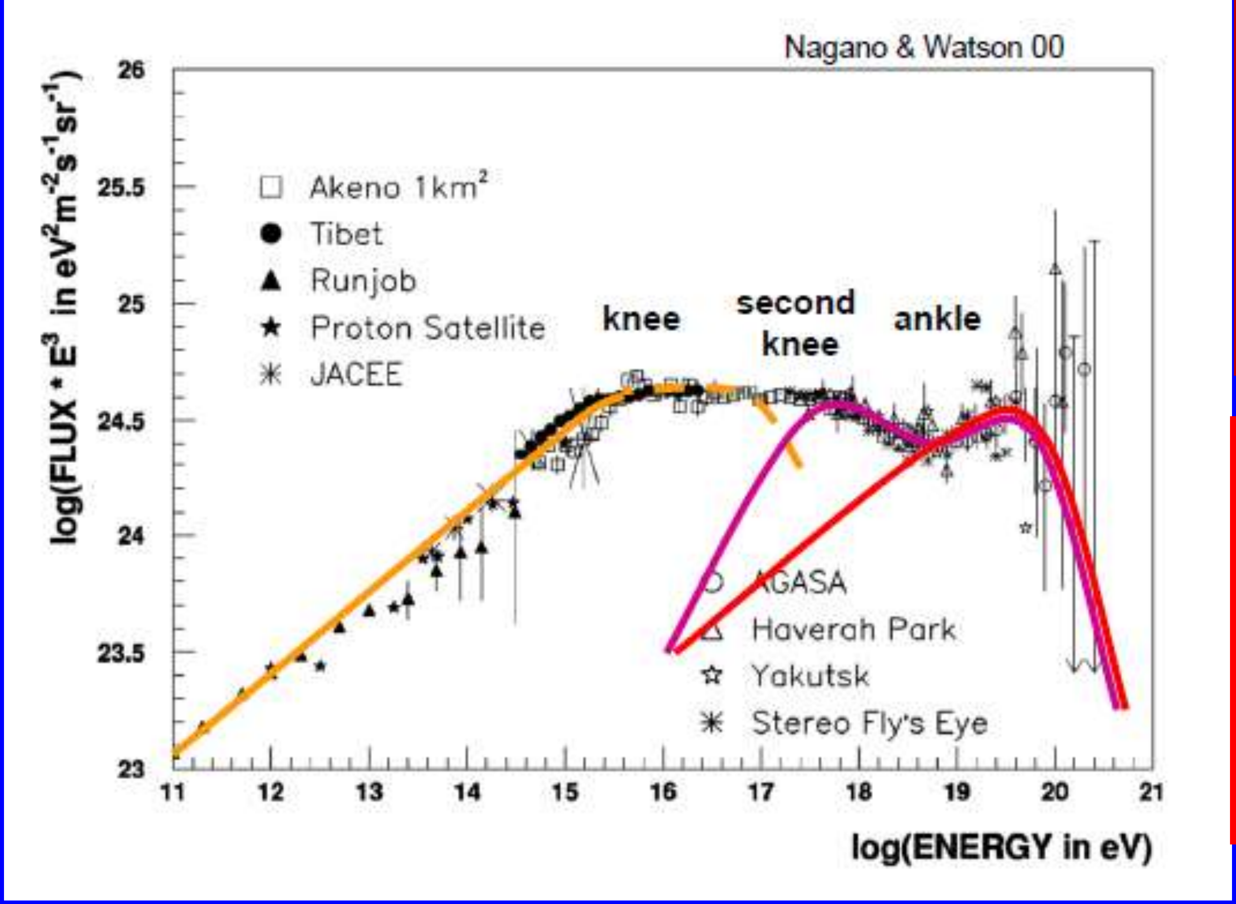


Figure from M. Bertaina, (Cris2008, Salina)

The instantaneous aperture of JEM-EUSO is larger than that of Pierre Auger Observatory by a factor of 50 – 250 (from JEM-EUSO HP).

§ Cosmogenic Neutrinos

Transition from Galactic to Extragalactic component: Cosmogenic neutrinos



second knee at 10^{18} eV: a controversial feature. Does it represent the emergence of the UHECR component? (Berezinsky et al.)

ankle at 10^{19} eV: emergence of the UHECR component ? What about cosmic rays between 10^{17} eV and 10^{19} eV?

From M. Lemoine

$$p + \gamma \rightarrow \Delta \rightarrow n + \pi^{+} \qquad \kappa_p \sim 0.2$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu$$

Spectrum of resulting neutrinos (cosmogenic neutrinos) will tell us Which scenario is correct.

Cosmogenic Neutrinos and Sensitivities of Detectors

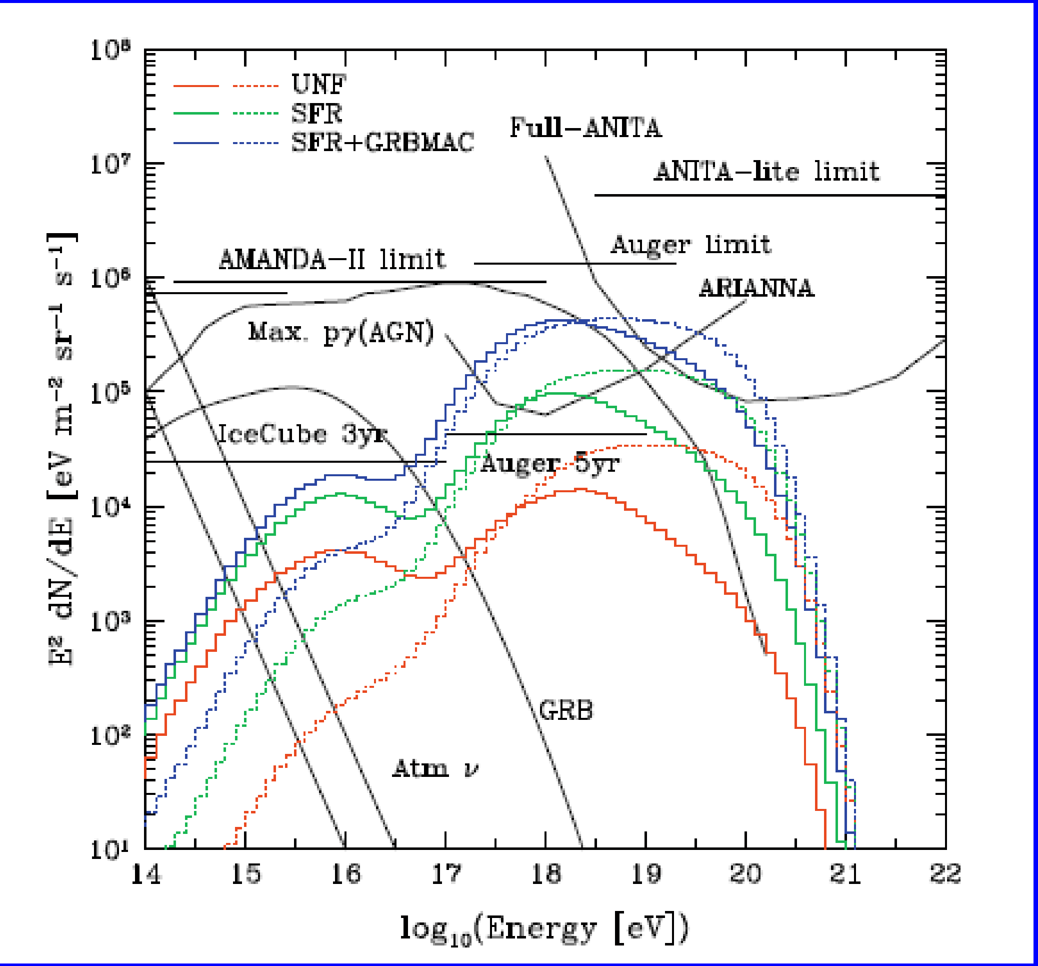
UHECRS: from nearby sources
Cosmogenic Neutrinos:
From the whole universe

$$f_{\rm SFR}(z) \propto \begin{cases} (1+z)^{3.5} & (z < 1.2) \\ (1+z)^{-1.2} & (1.2 < z) \end{cases}.$$

$$f_{\rm GRB}(z) \propto (1+z)^{1.4} f_{\rm SFR}(z)$$

Solid lines: Proton-dip scenario
Dotted lines: Ankle-transition scenario

Neutrinos below 10^16eV Is coming from the interactions Against IR/UV photons rather than CMB.



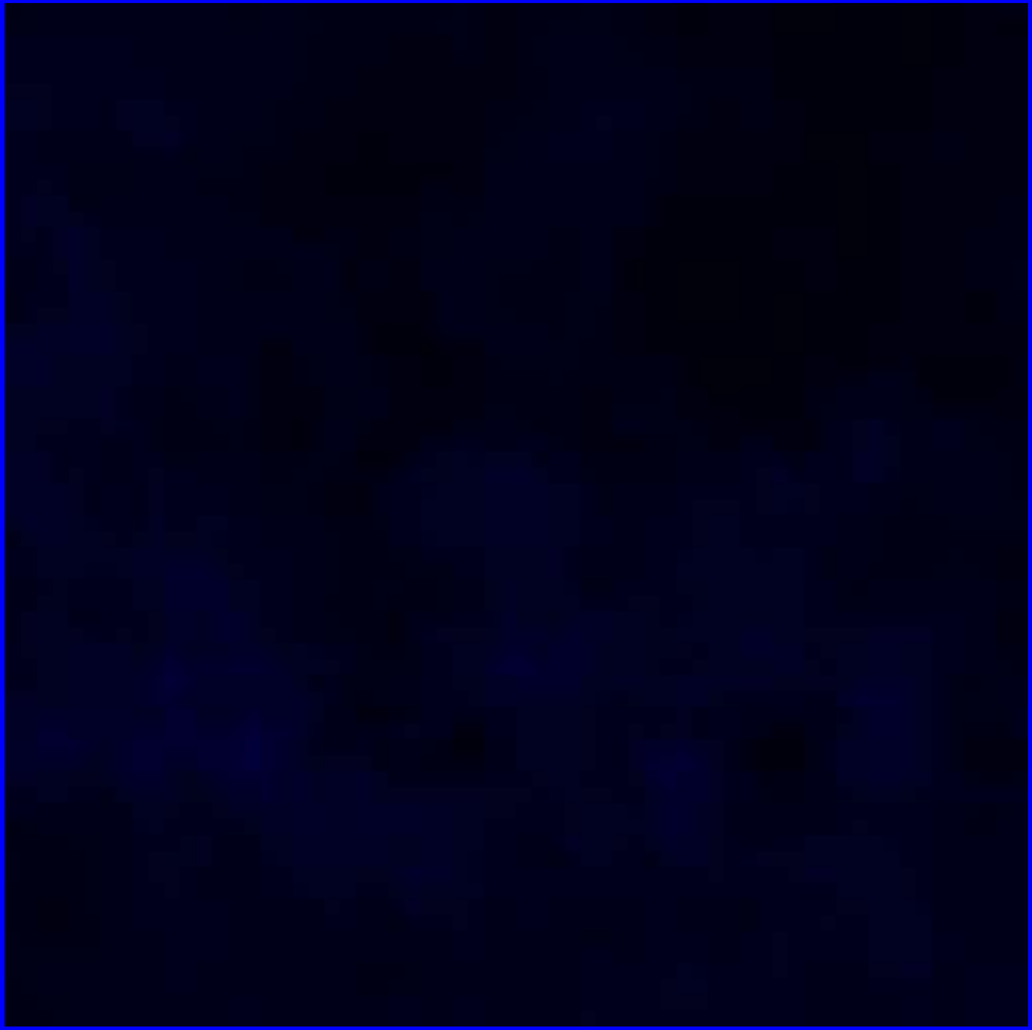
Flux of Cosmogenic Neutrinos for each Flavor (Takami, Murase, S.N., Sato 2009)

§ UHECRs in a Cluster of Galaxies

Kotera, Allard, Murase, Aoi, Dobois, Pierog, SN, 2009, in preparation （Preliminary Results）.

Propagation of UHECRs in CGs

Kotera, Allard, Murase, Aoi, Dobois, Pierog, SN, 2009, in preparation.



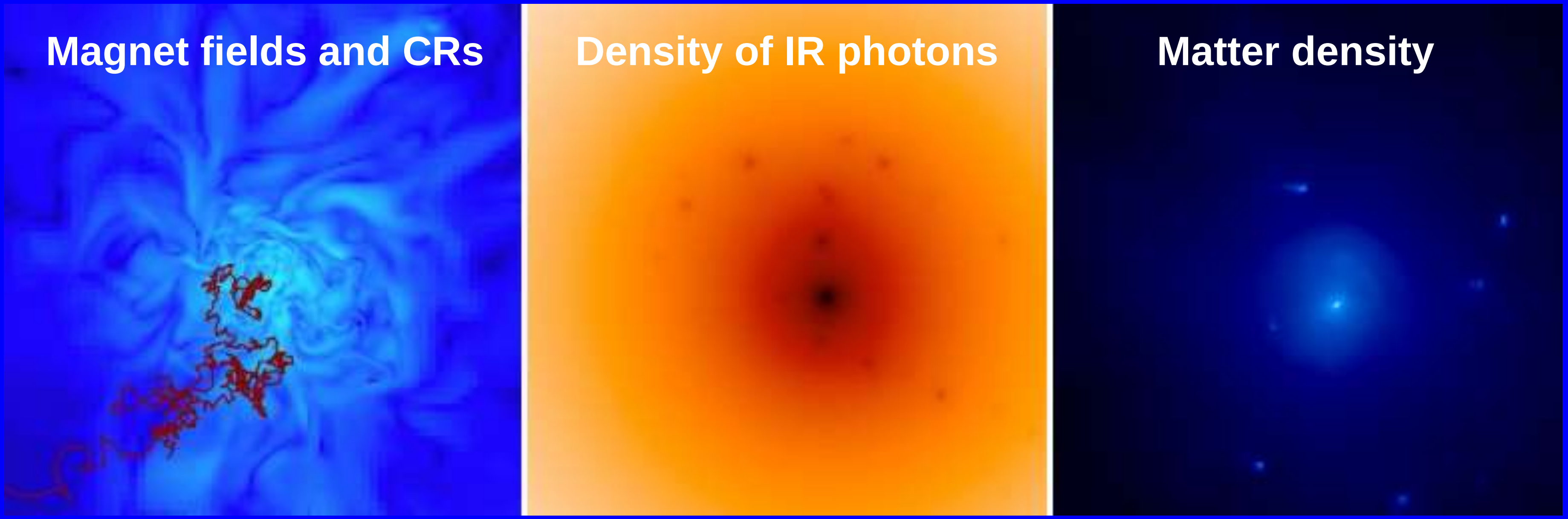
Matter in the Universe clusters Gravitationally.

In the cluster of galaxies (CGs), Matter density is high as well as the Number density of the Possible sources of UHECRs such as AGNs and GRBs.

CGs themselves are a possible candidate of UHECRs.

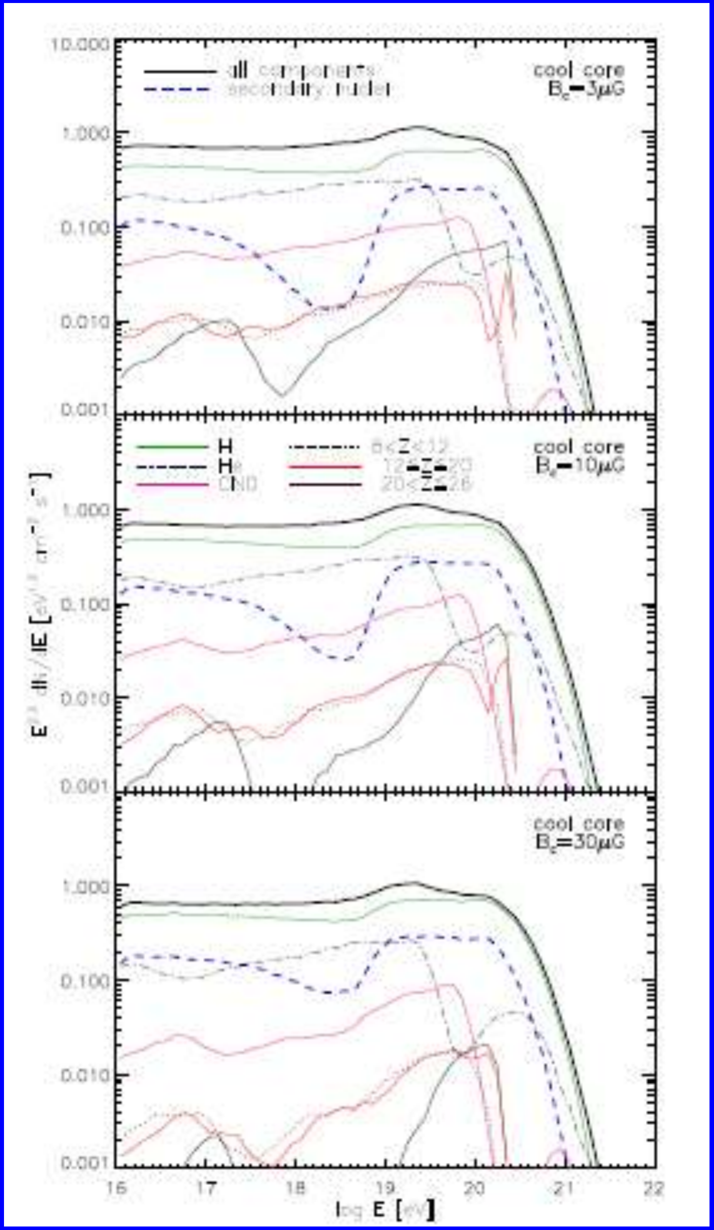
Thus, we should consider the Propagation of UHECRs in CGs Taking into account the fact that Density of The target photons/gas Is high in CGs.

Propagation of UHECRs in CGs



CRs are injected at the center (e.g. M87 in Virgo Cluster). Propagation of VHECRs are solved taking account of Photo-disintegration of nuclei, pion-production (targets Are background photons and protons). Strength of magnetic fields is normalized at the center. Solar metallicity is assumed for the initial compositions of VHECRs.

Continuous Injection Model



The energy injection rate is set to be 10^44 Erg/s (c.f. the luminosity of AGNs is in the Range of 10^43-10^44 erg/s).

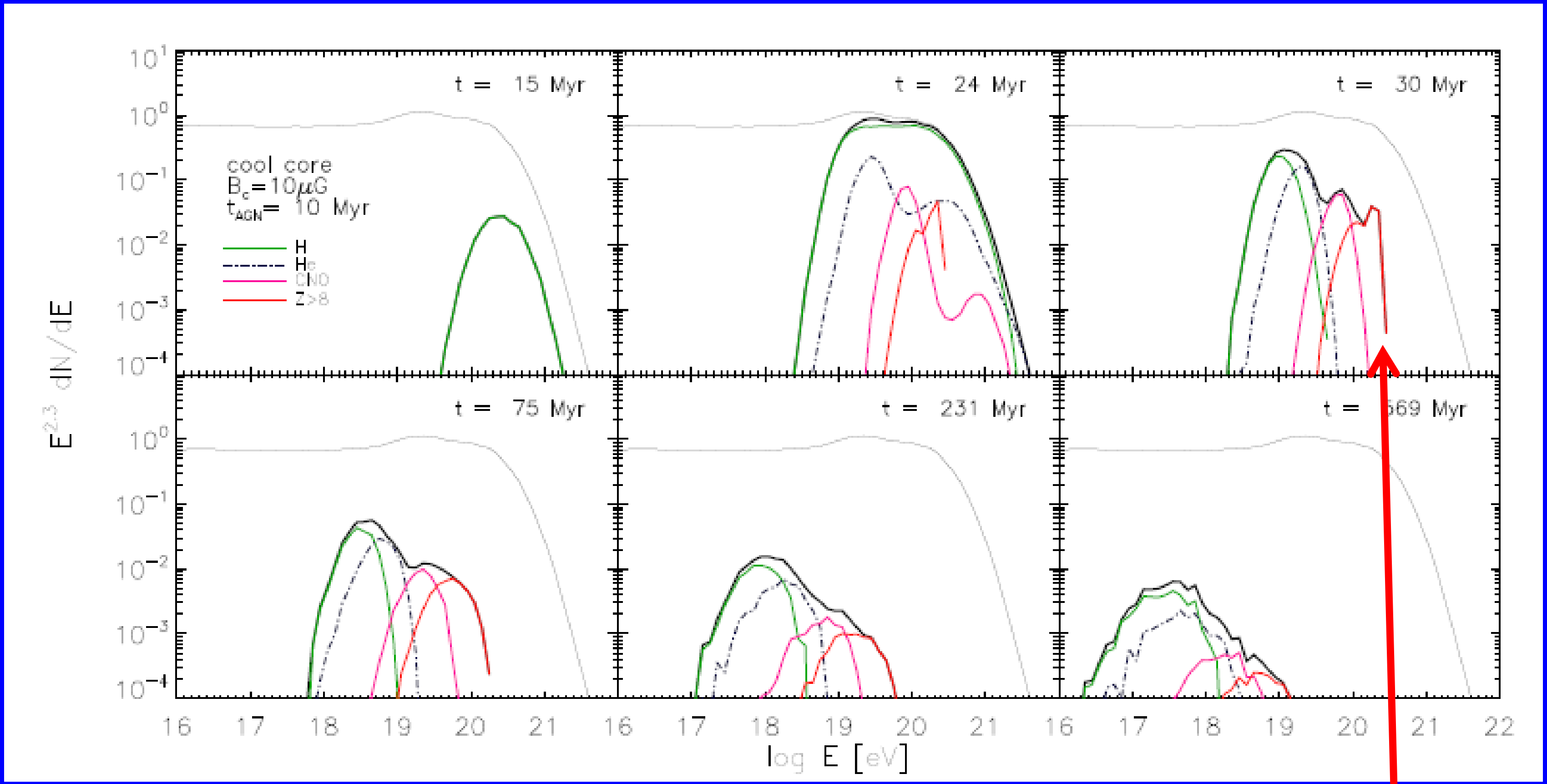
The injection spectral index is chosen to be 2.3.

Figures: the resulting composition when CRs are coming out from the CGs.

Contributions from photons and gas can be seen clearly.

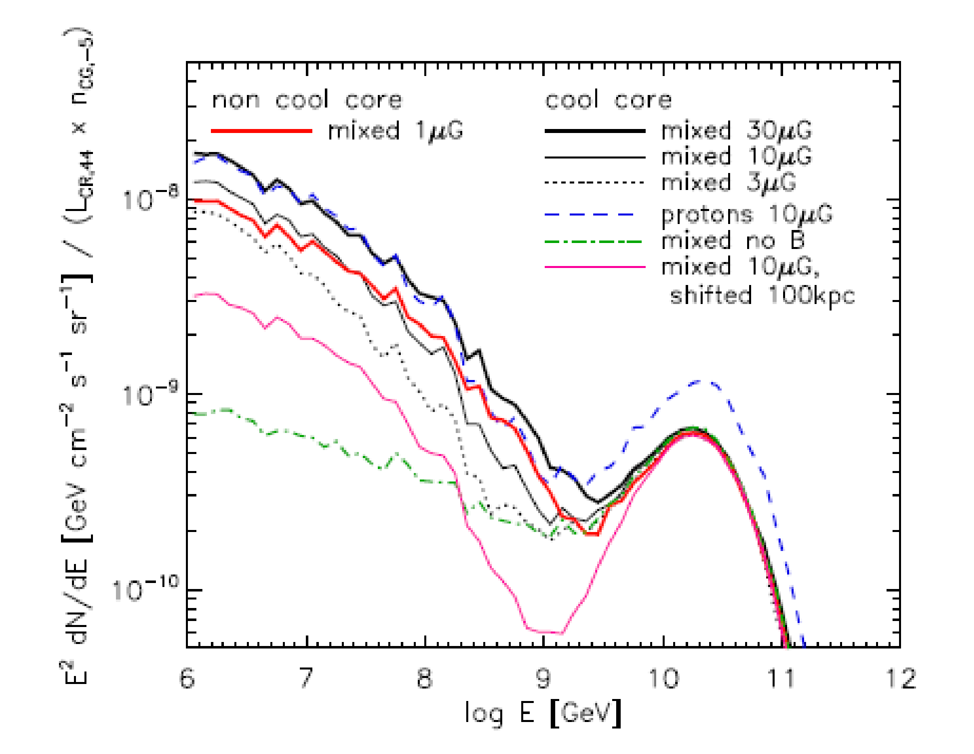
Heavy elements (such as iron) are suppressed for high-energy region.

The 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).

Neutrino Background



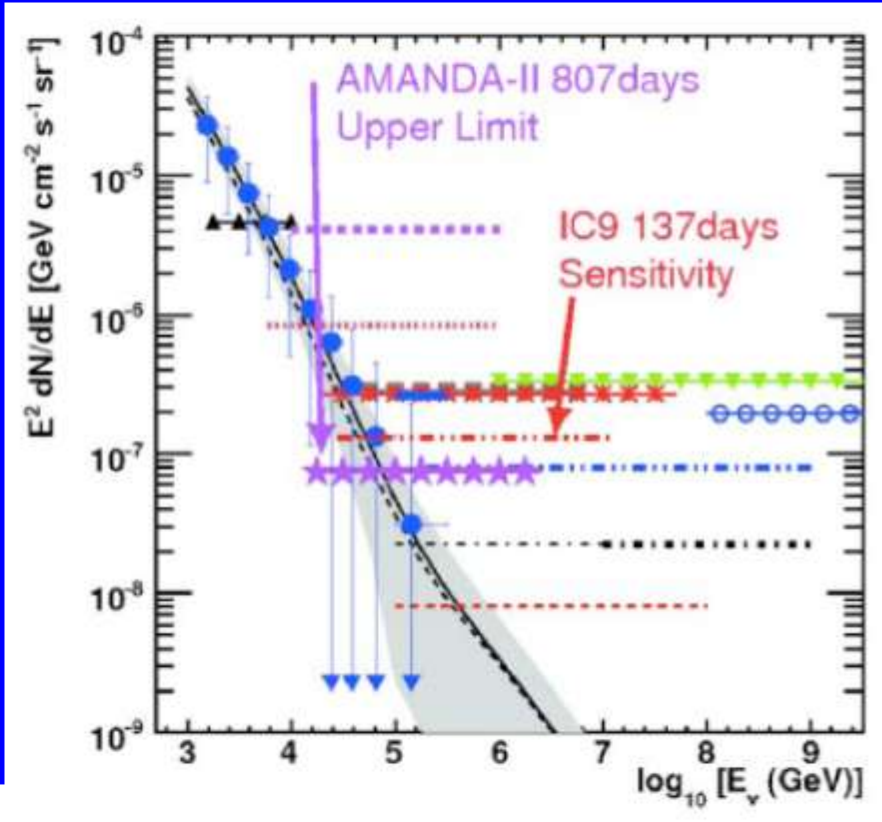


FIG. 11.— Diffuse neutrino fluxes obtained with galaxy cluster density $n_{GC} = 10^{-5}$ Mpc^{-3} and AGN cosmic ray luminosity $L_{cr} = 10^{44}$ erg/s. A mixed composition is injected at the centre of the non cool core cluster with $B_c = 1\mu$G (red thick solid), and in cool core clusters with $B_c = 30\mu$G (black thick solid), $B_c = 10\mu$G (black thin solid), $B_c = 3\mu$G (black dotted) and without magnetic field (green dash dotted). We also present the cases of a pure proton injection at the centre and a mixed composition injected at 100 kpc from the centre (blue long dashed) of a cool core cluster of $B_c = 10\mu$G. The pink solid line is the neutrino flux obtained for a mixed composition injected at 100 kpc from the center of a cool core cluster of $B_c = 10$ μG.

Summary

- Load map to identify the source of UHECRs are..
- Simulations of Propagation of UHECRs themselves.
- Detecting Secondaries (gamma-rays and/or neutrinos).

감사합니다
カムサハムニダ