Multi-messenger astrophysics with the Ultra-High Energy Cosmic Rays

Ultra High Energy \\ Cosmic Rays

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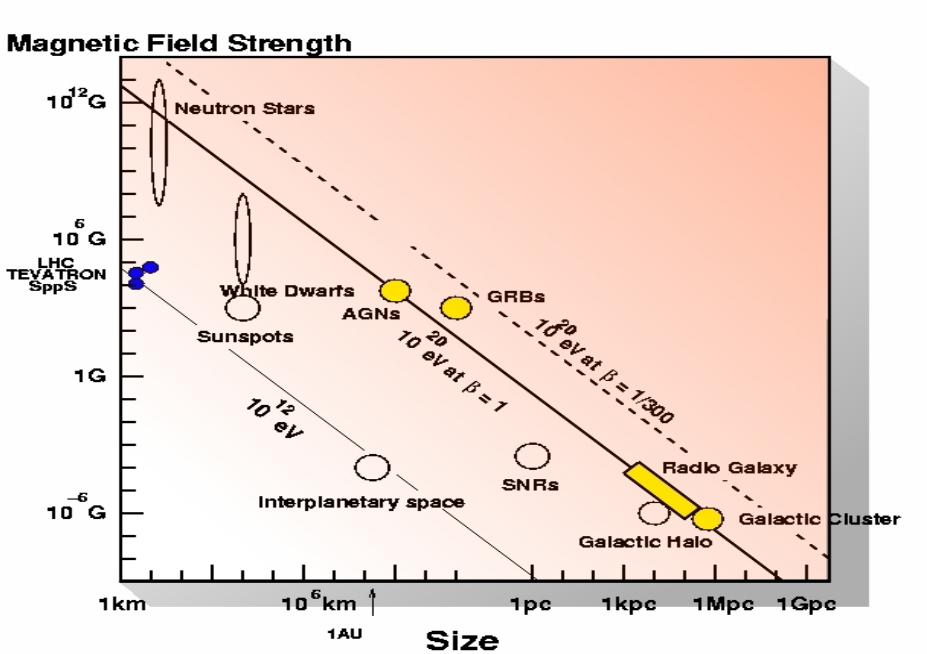
Overview:

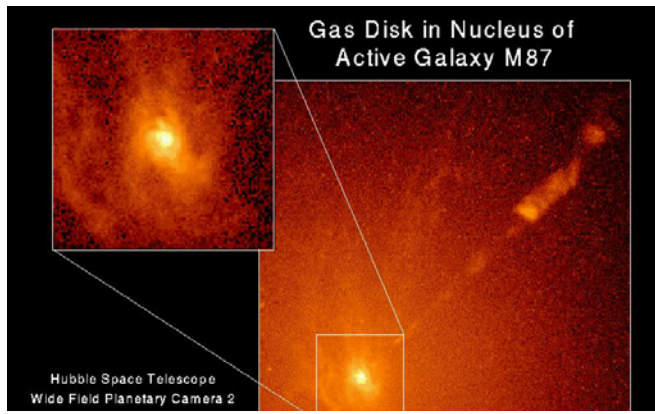
- *Introduction: UHECR spectrum and GZK cutoff*
- *UHECR arrival directions, their sources and galactic and extragalactic magnetic fields*
- *EGMF study with TeV telescopes.*
- *Secondary gamma-rays at energies E>10 EeV*
- *Secondary gamma-rays at GeV-TeV energies*
- *Cosmogenic neutrinos*
- *Multi-messenger observations with UHECR*
- *Conclusions*

INTRODUCTION: UHECR spectrum and GZK cutoff

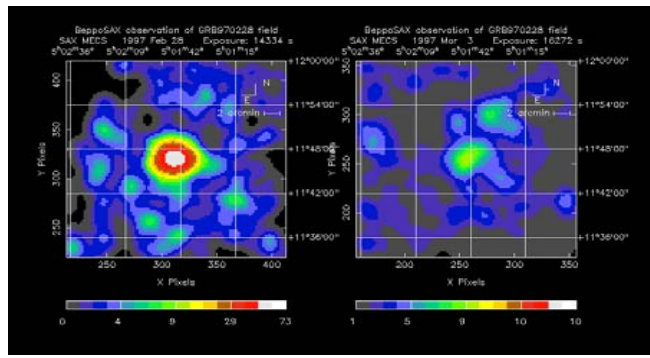
Acceleration of UHECR



A.G.N.



GRB

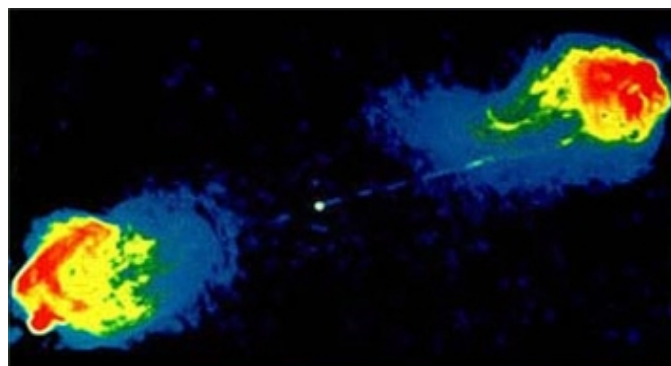


- Shock acceleration $1/E^{\alpha}$ $\alpha>=2$

  (talks by J.Aoi, A.Marcowich)
- Electric field acceleration line at E_{max}
- Converter acceleration can be both

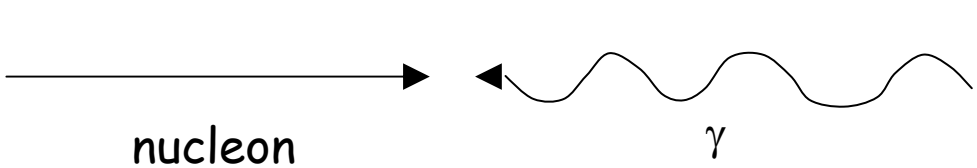
  (talk by V.Kocharovsky)

Radio Galaxy Lobe

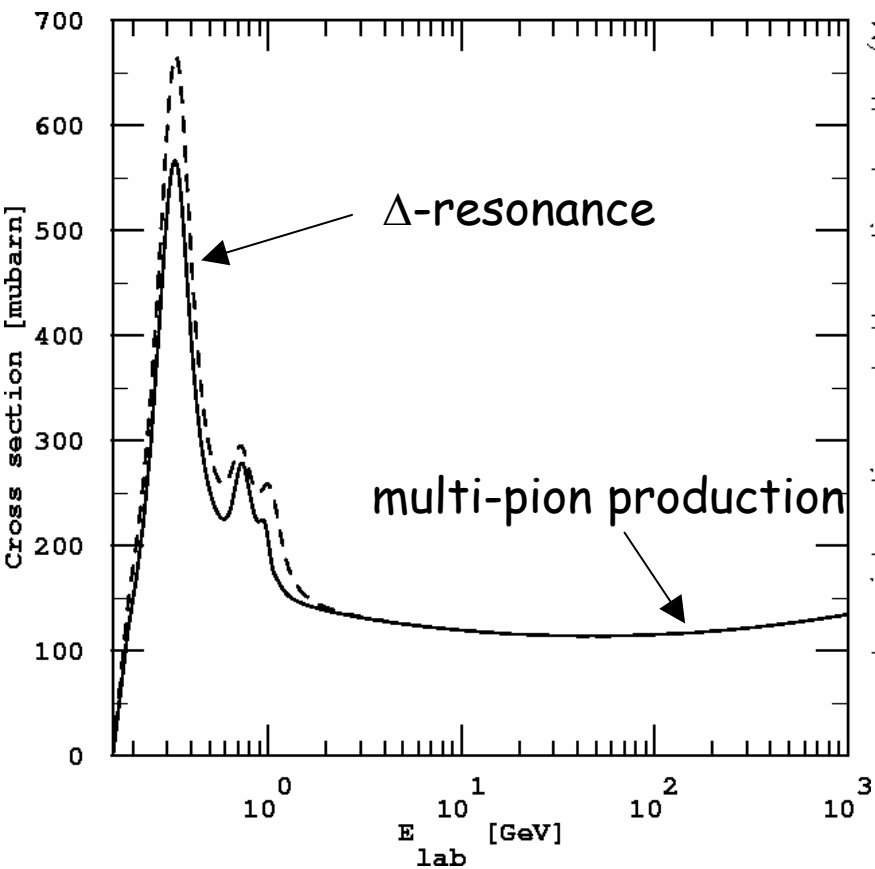


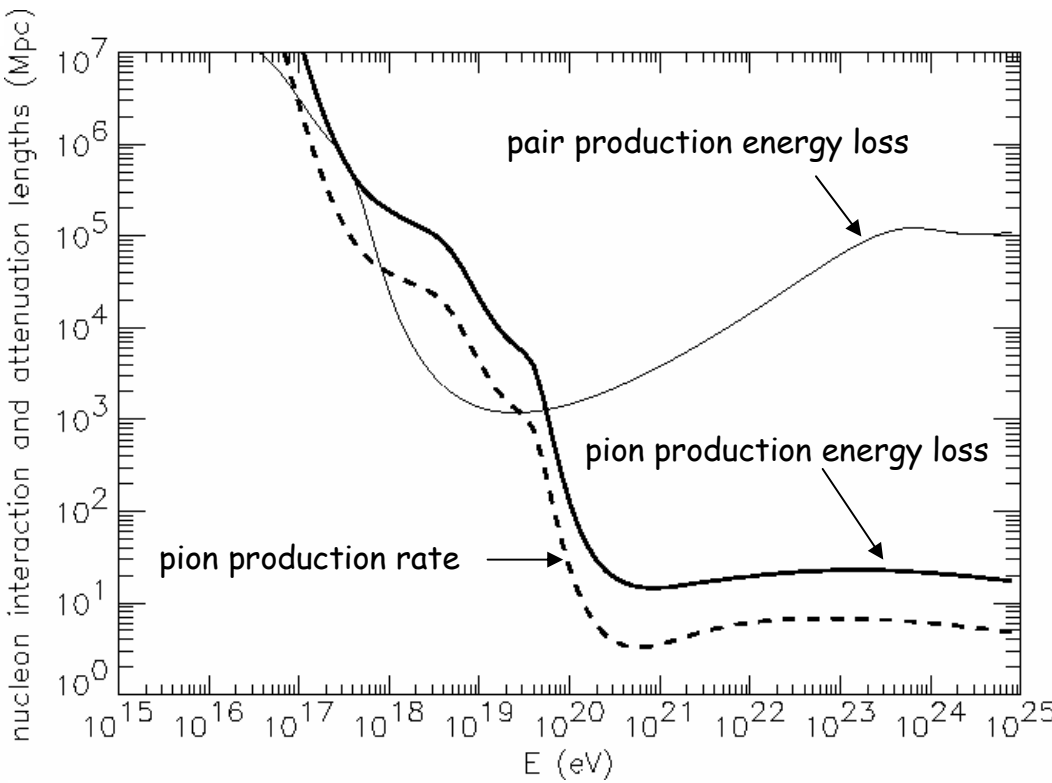
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



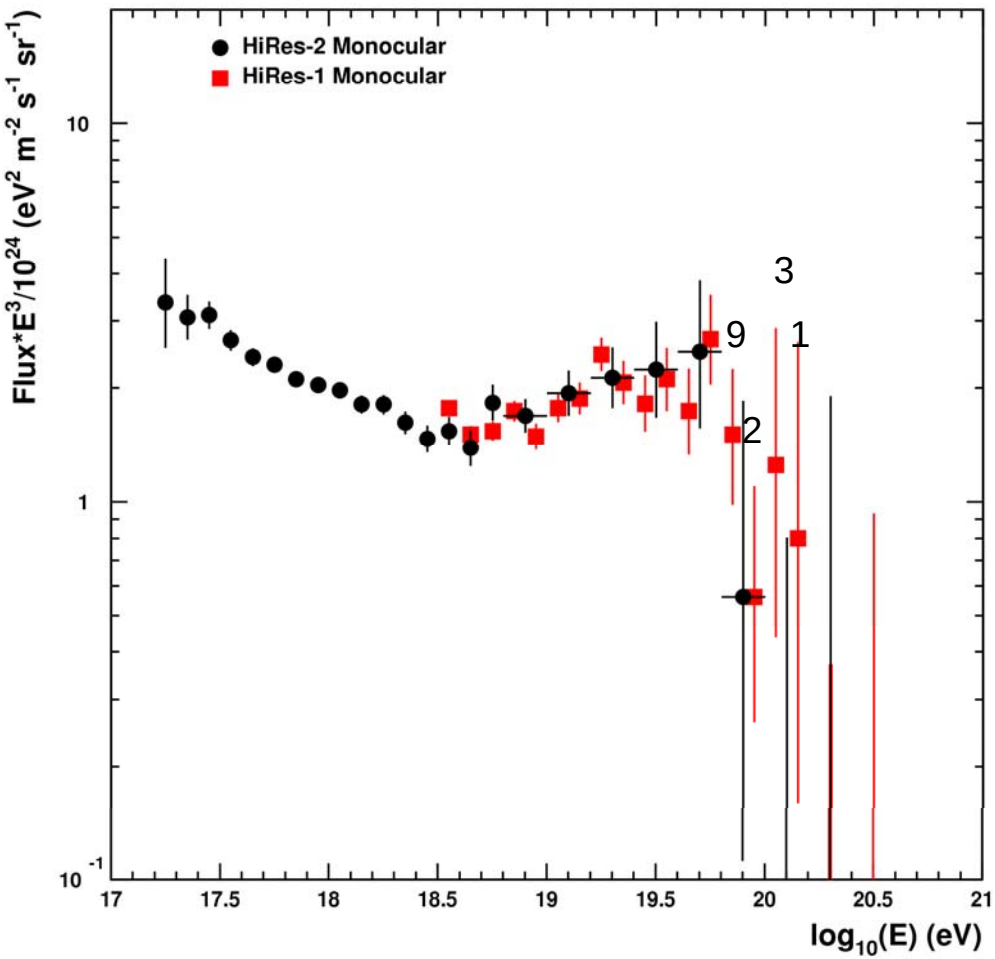
$$E_{\mathrm{th}} = \frac{2m_N m_\pi + m_\pi^{\,2}}{4\varepsilon} \approx 4\cdot 10^{19}\,\mathrm{eV}$$





⇒sources must be in cosmological backyard within 50-100 Mpc from Earth (compare to the Universe size ~ 5000 Mpc)

HiRes: cutoff in the spectrum



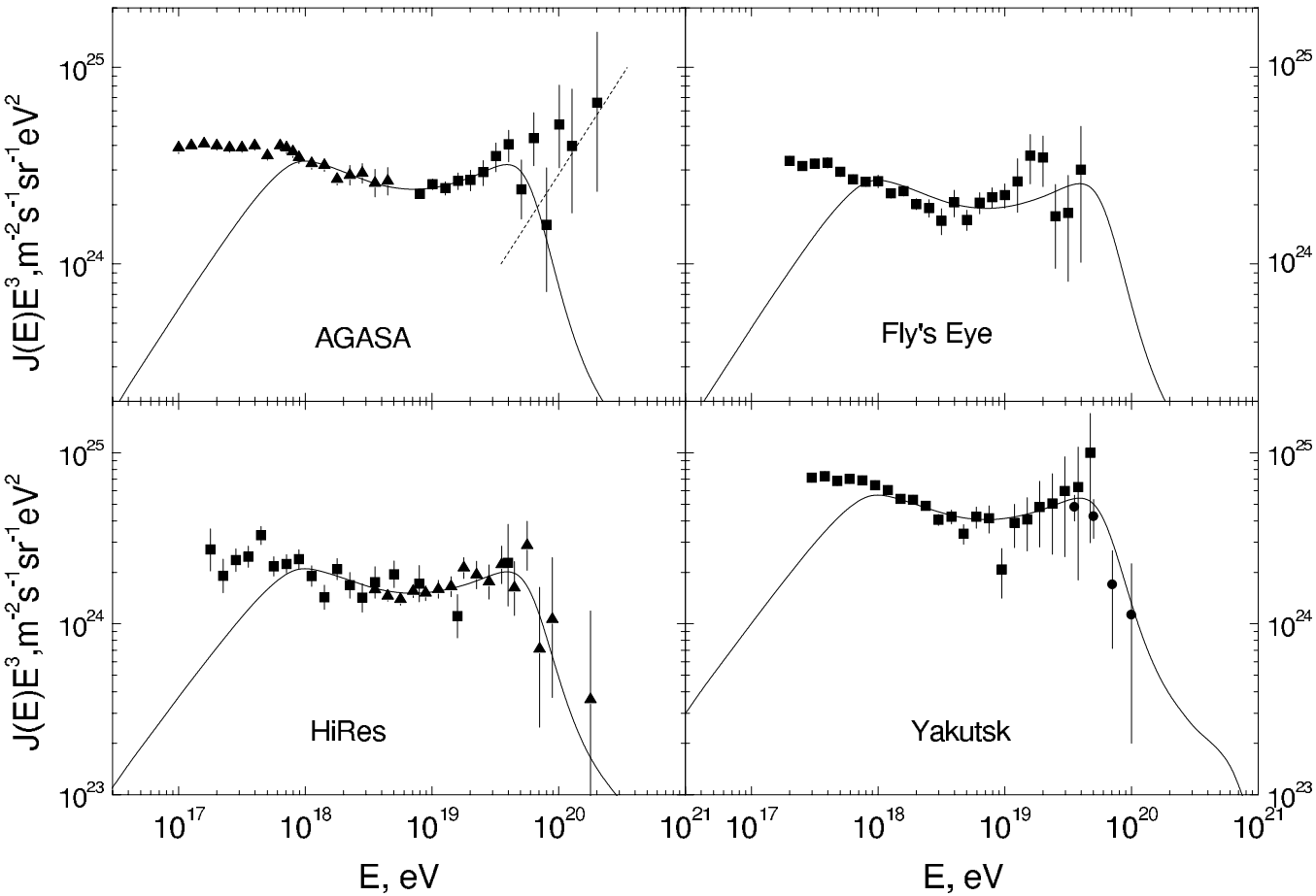
"GZK" Statistics

- Expect 42.8 events
- Observe 15 events
- ~ 5 σ

Bergman (ICRC-2005)

6σ

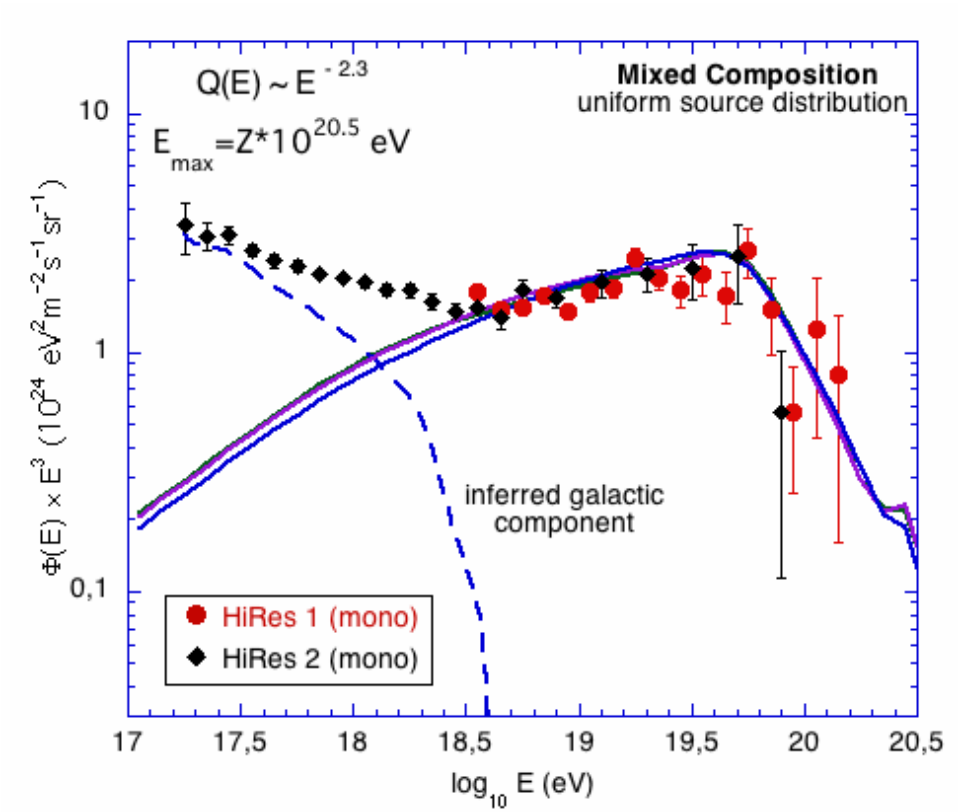
Protons can fit UHECR data



V.Berezinsky , astro-ph/0509069

problem: composition

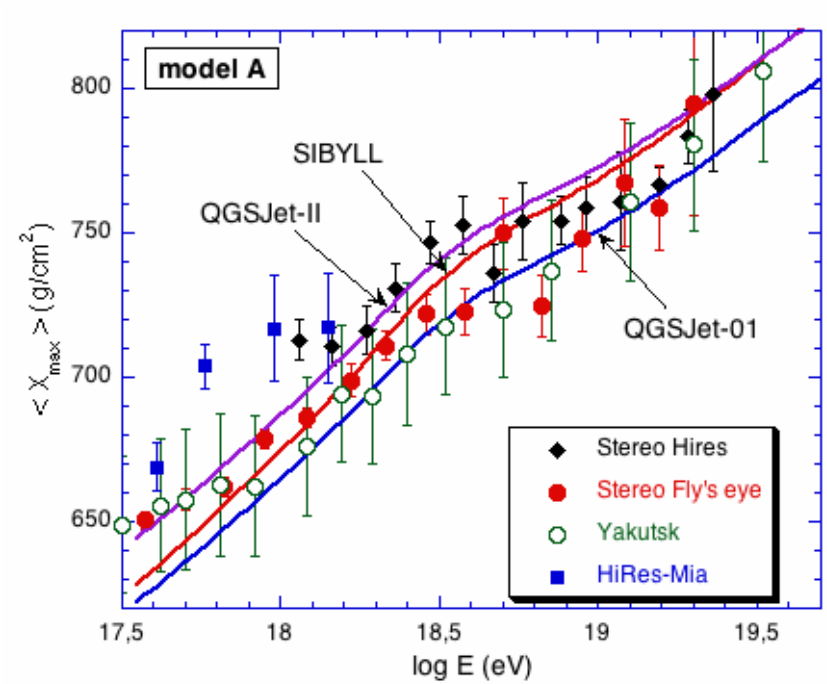
Mixed composition model

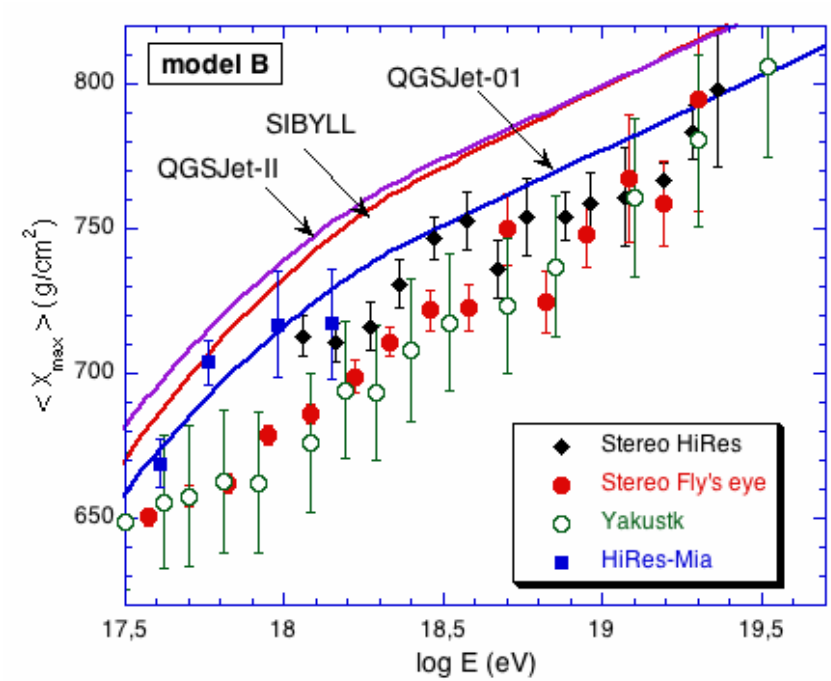


D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Potential problem: escape of the nuclei from the source (talk by A.Teylor)

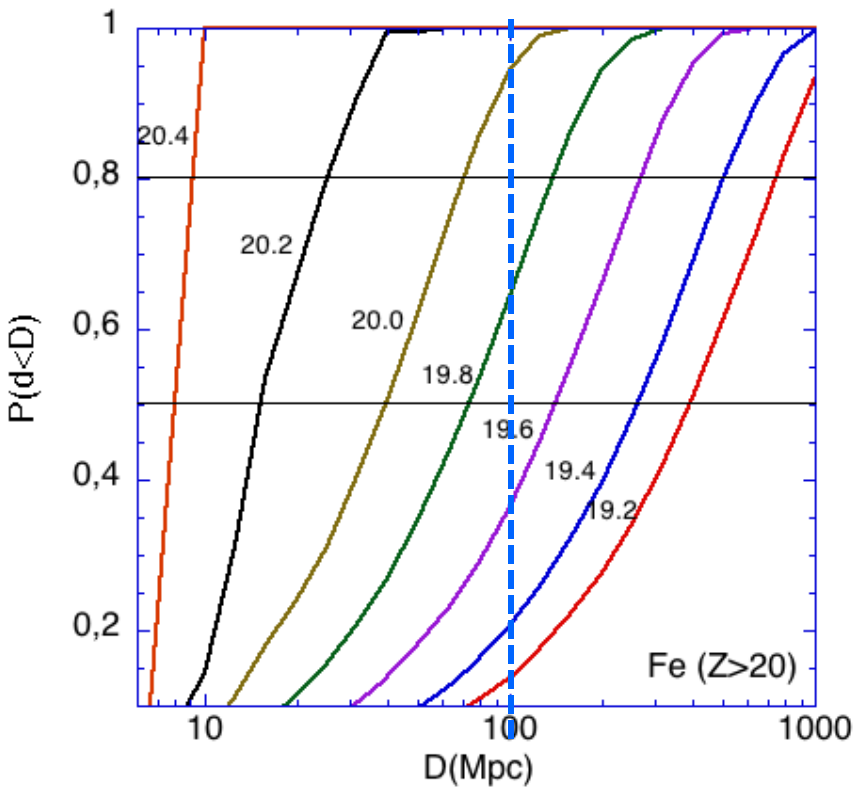
Mix model and pure protons versus composition





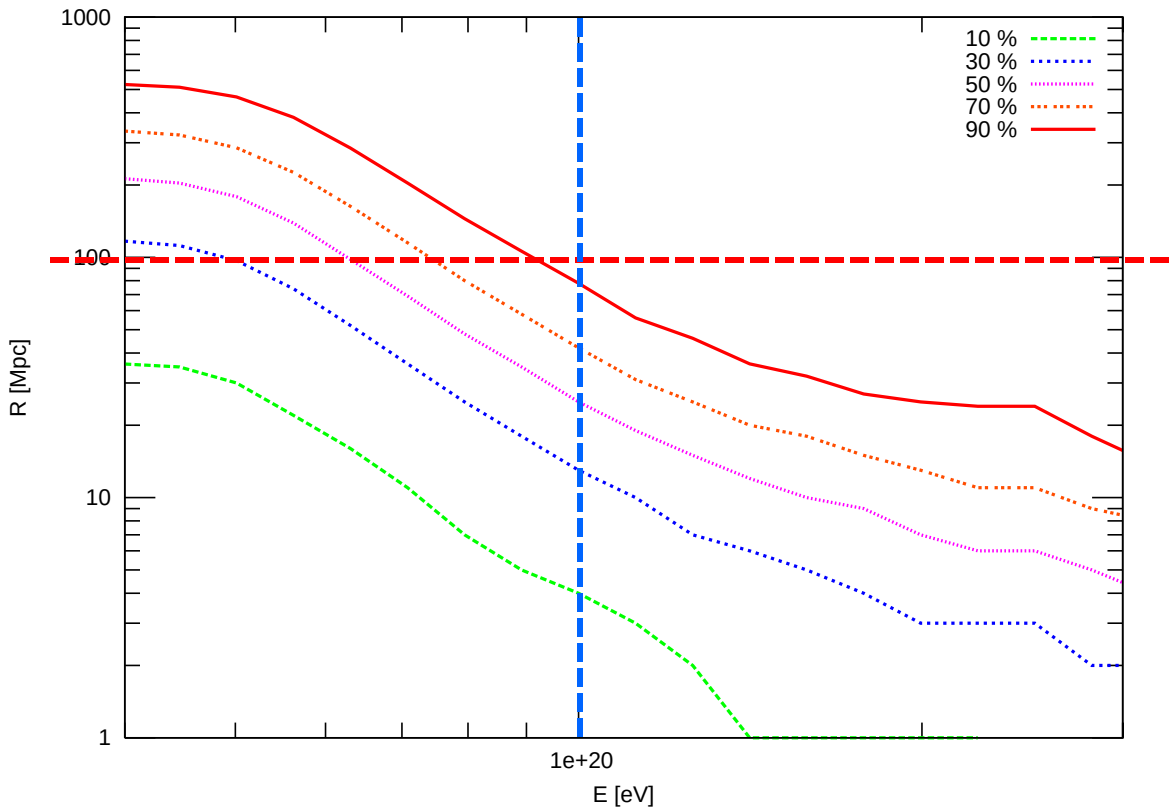
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Fraction of Fe



Simulation by D.Allard

Horizon for protons



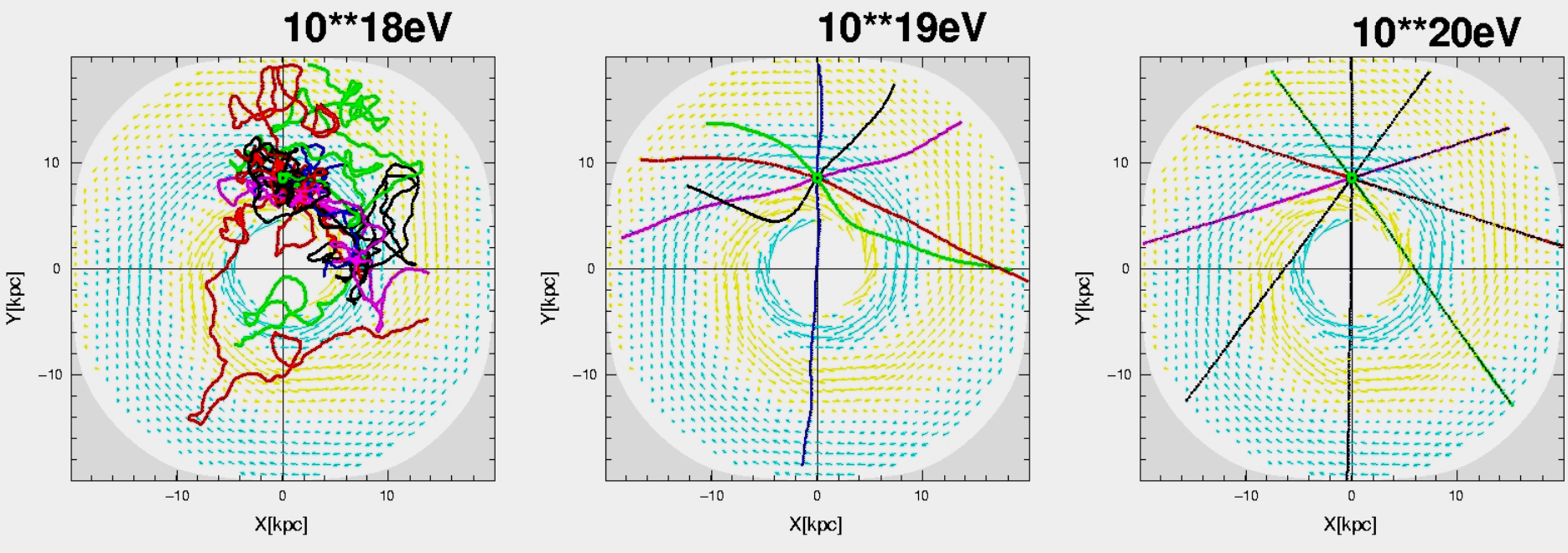
Simulation with SOPHIA, stochastic energy losses,

Assuming $\Delta E/E = 20\%$ event by event

Arrival directions of UHECR and magnetic fields.

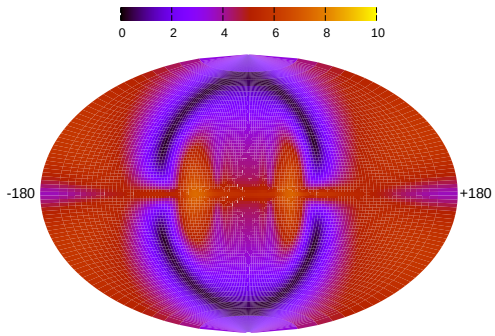
UHECR propagation in Milky Way

- Deflection angle ~ 1-2 degrees at 10^{20}eV for protons
  - Astronomy by hadronic particles?

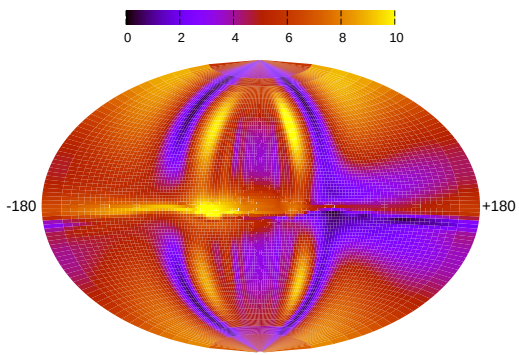


Uncertainty of GMF models

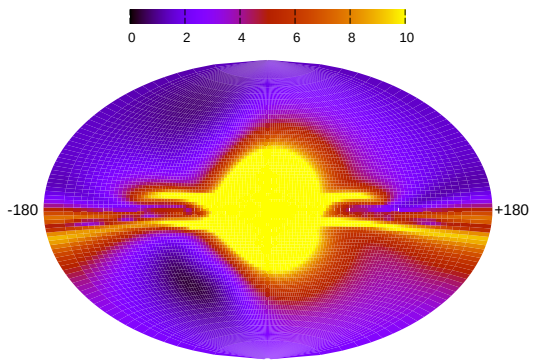
- From M.Kachelriess et al, astro-ph/0510444
- Protons with energy $4*10^{19}$ eV deflection in galactic magnetic field.



TT model



HMR model



PS model

Deflections by EGMF

By K.Dolag, D.Grasso, V.Springel, and I.Tkachev

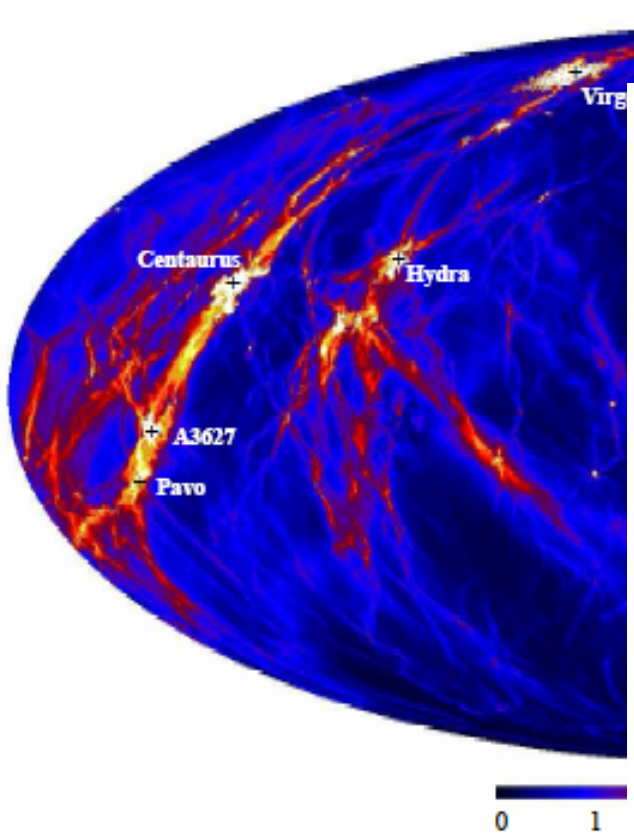


FIG. 1: Full sky map (area preserving projection) of c
scale. All structure within a radius of 107 Mpc aroun
with the galactic anti-center in the middle of the ma
corresponding halos in the simulation.

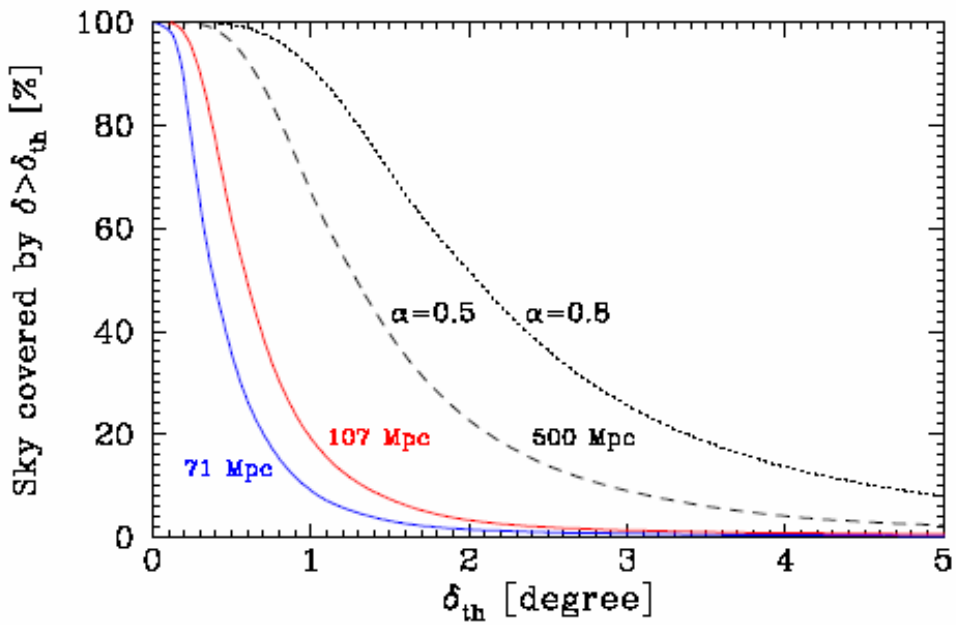
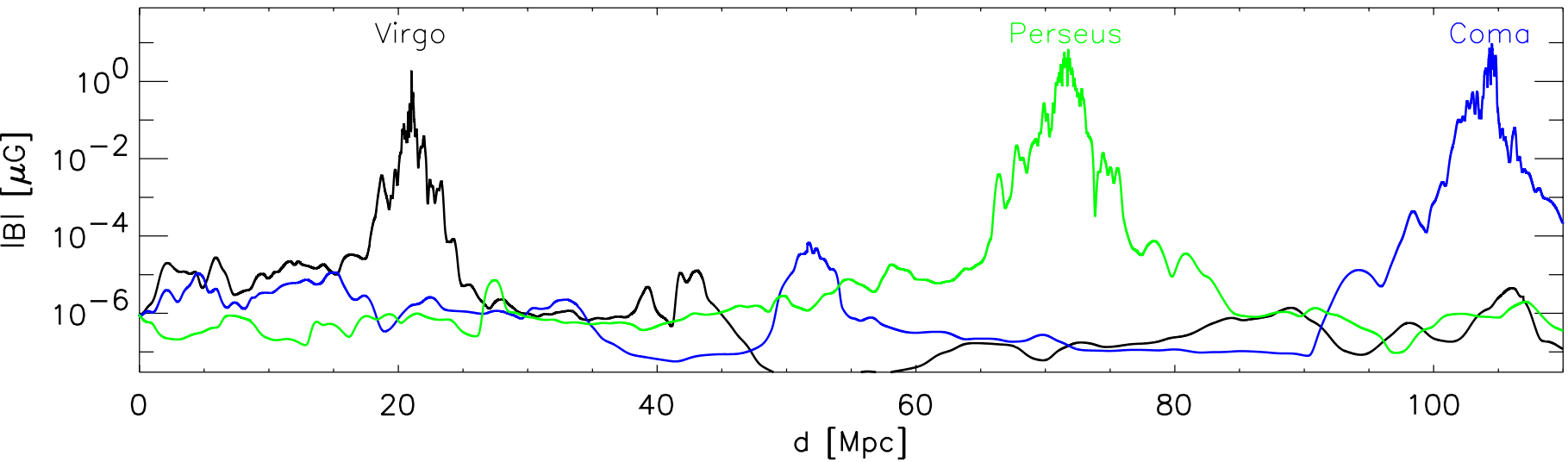


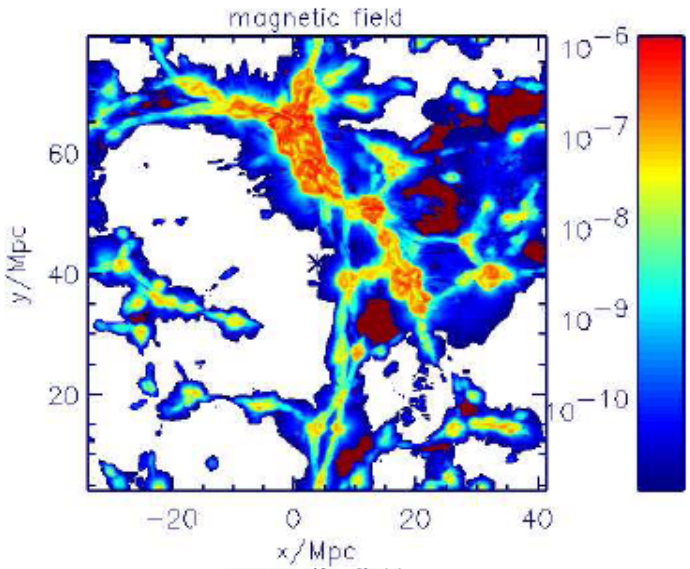
FIG. 2: Cumulative fraction of the sky with deflection angle larger than $\delta_{\rm th}$, for several values of propagation distance (solid lines). We also include an extrapolation to 500 Mpc, assuming self similarity with $\alpha = 0.5$ (dashed line) or $\alpha = 0.8$ (dotted line). The assumed UHECR energy for all lines is 4.0×10^{19} eV.

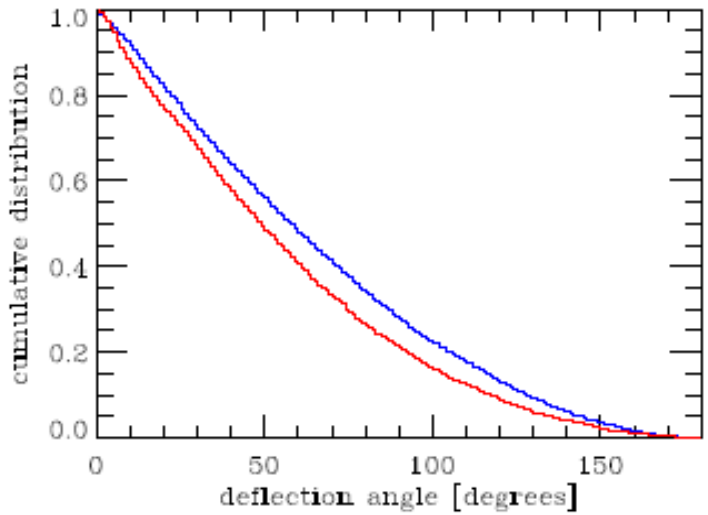
Magnetic field in several directions from Earth for constrained simulation

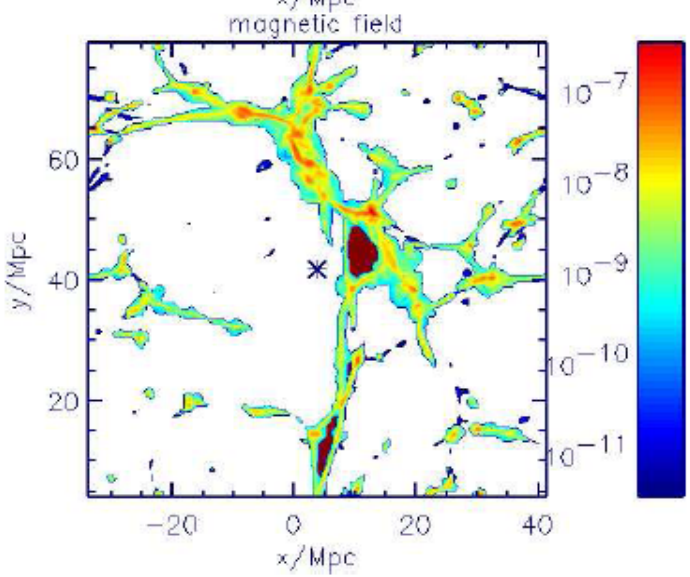


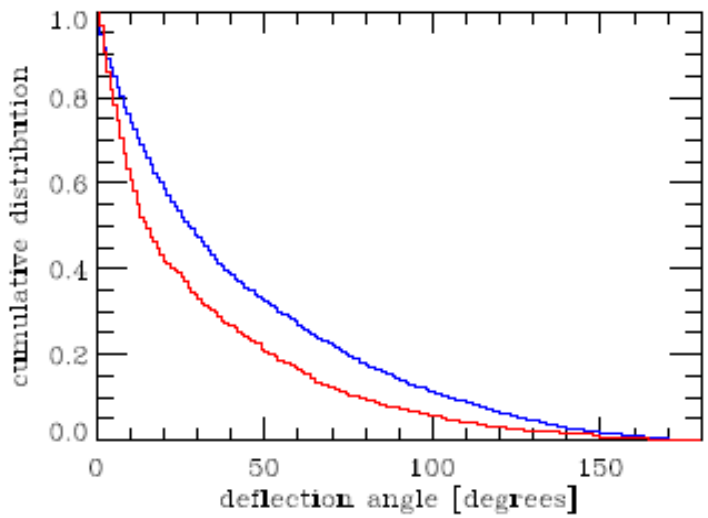
Dolag et al, astro-ph/0410419

EGMF by G. Sigl et al.

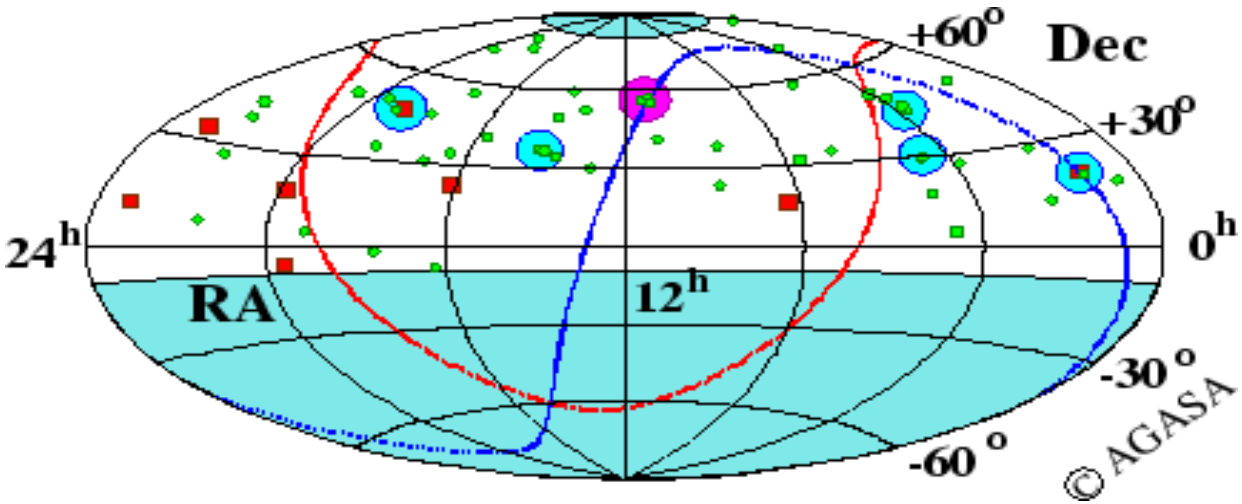






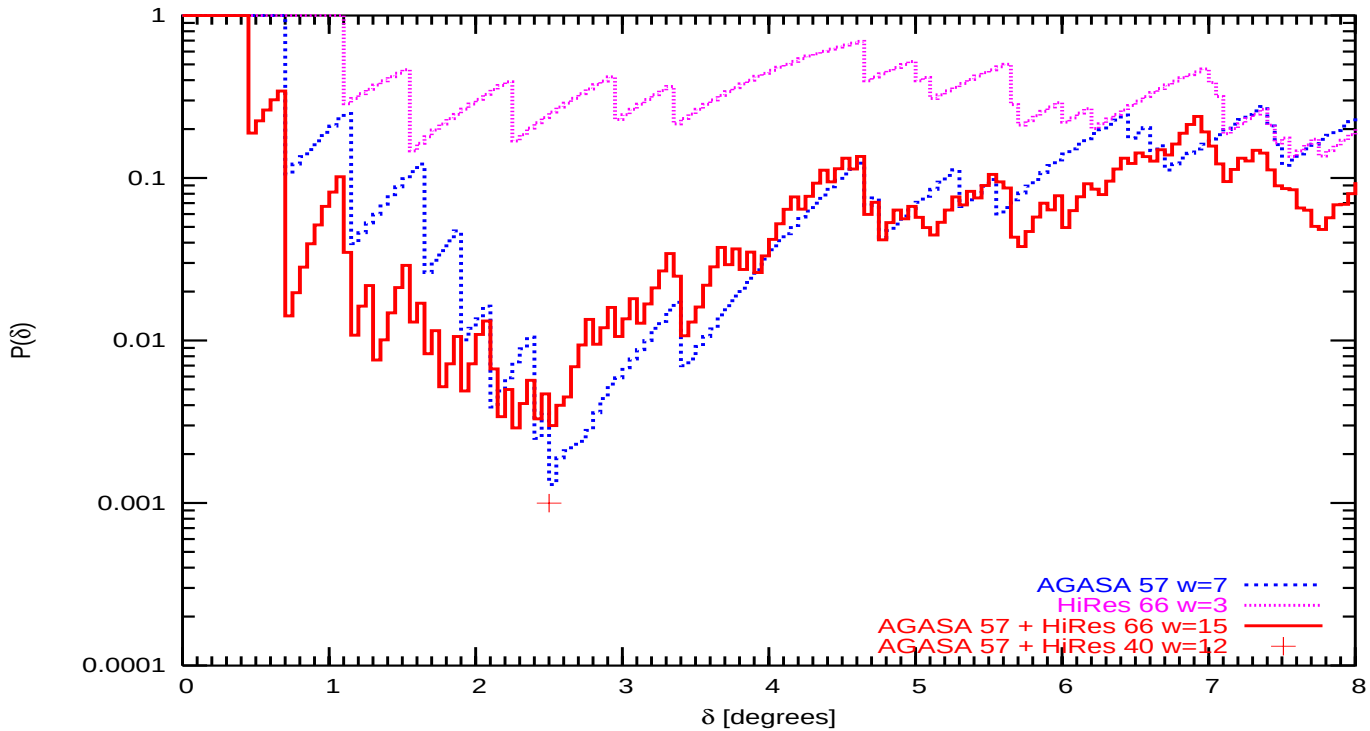


AGASA data $E > 4 \times 10^{19}$ eV ~60 events



Clusters -- are events which came from the same part of sky within given (usually small) angle from each other. Angle is 2.5 degrees for AGASA.

AGASA plus HiRes

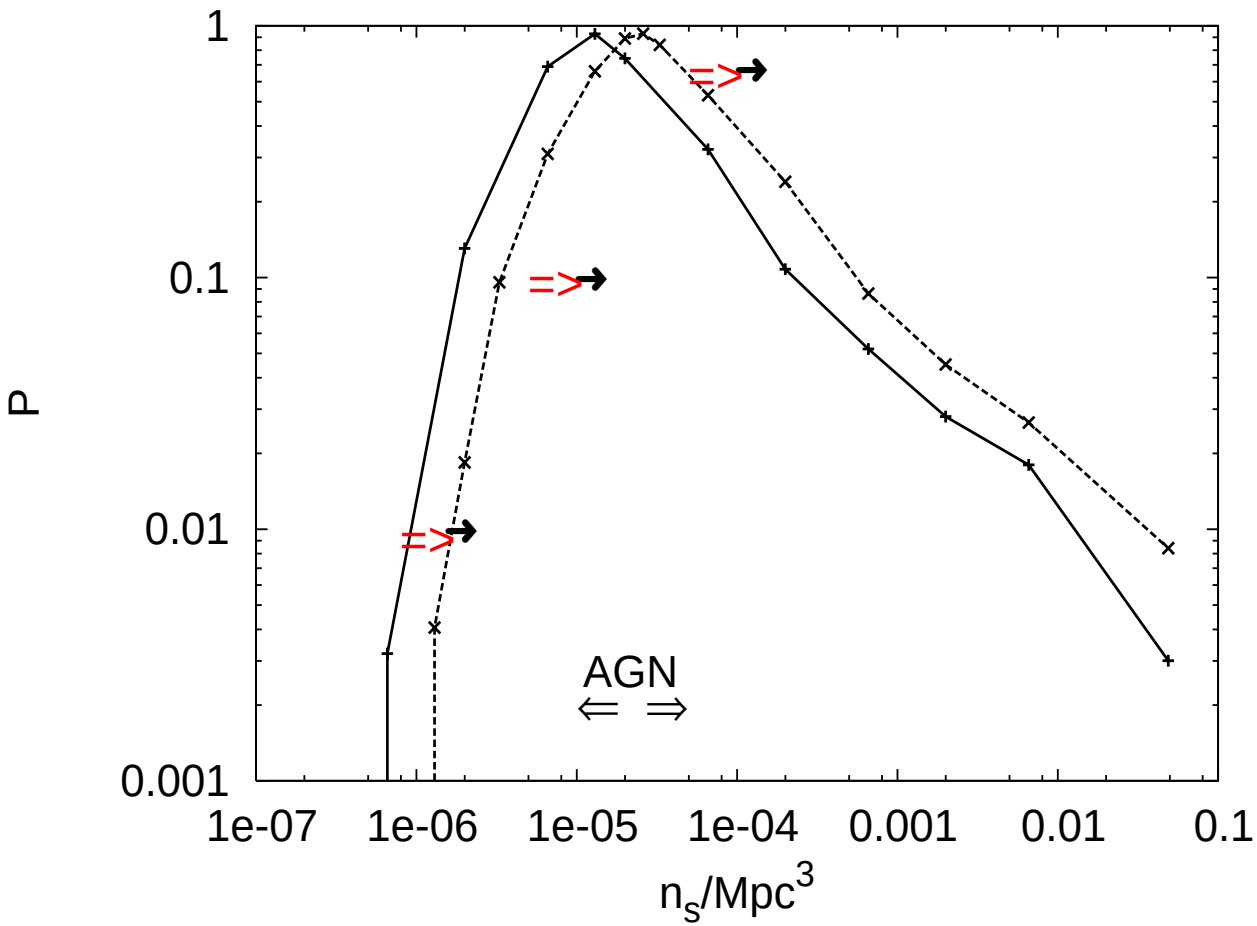


In AUGER at 2.5 degrees and E>30 EeV

5% excess 14/8.5 in 130 events – not significant

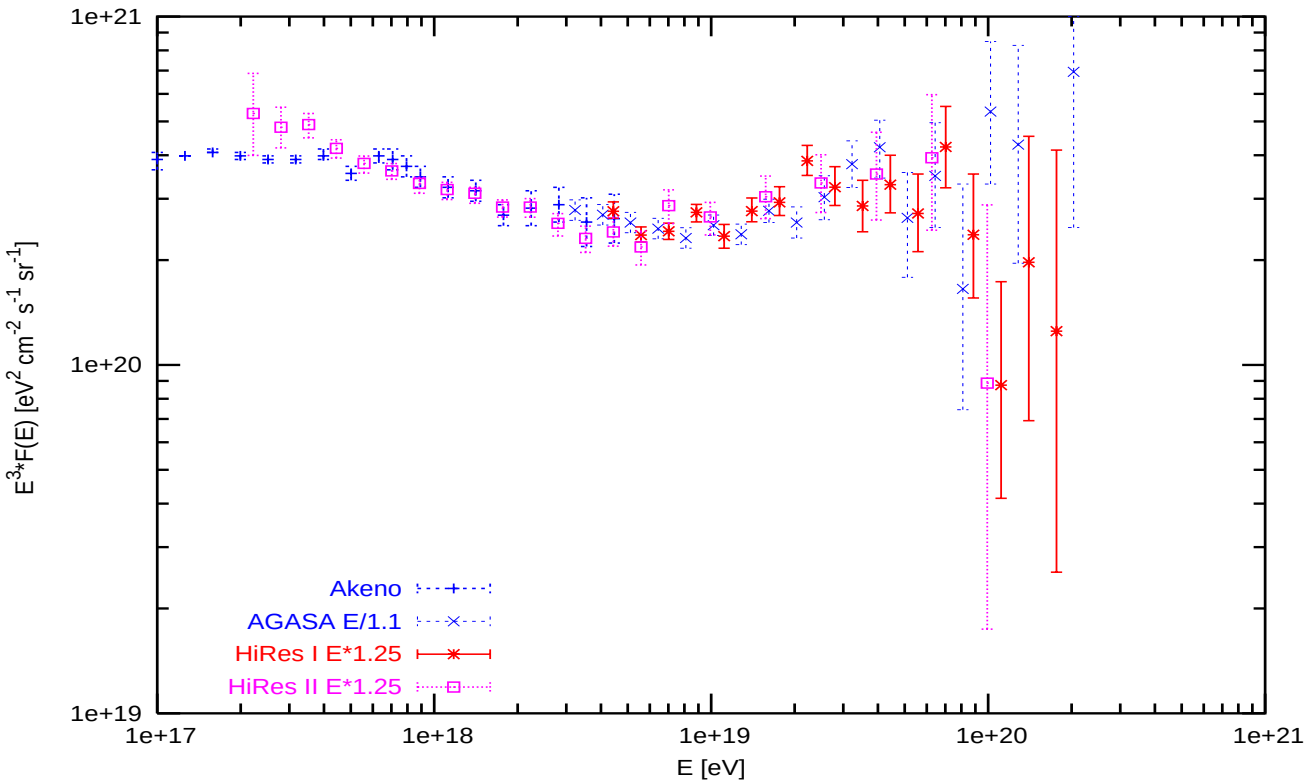
Pierre Auger Collaboration ICRC 2007

Density of UHECR sources from AGASA and HiRes data

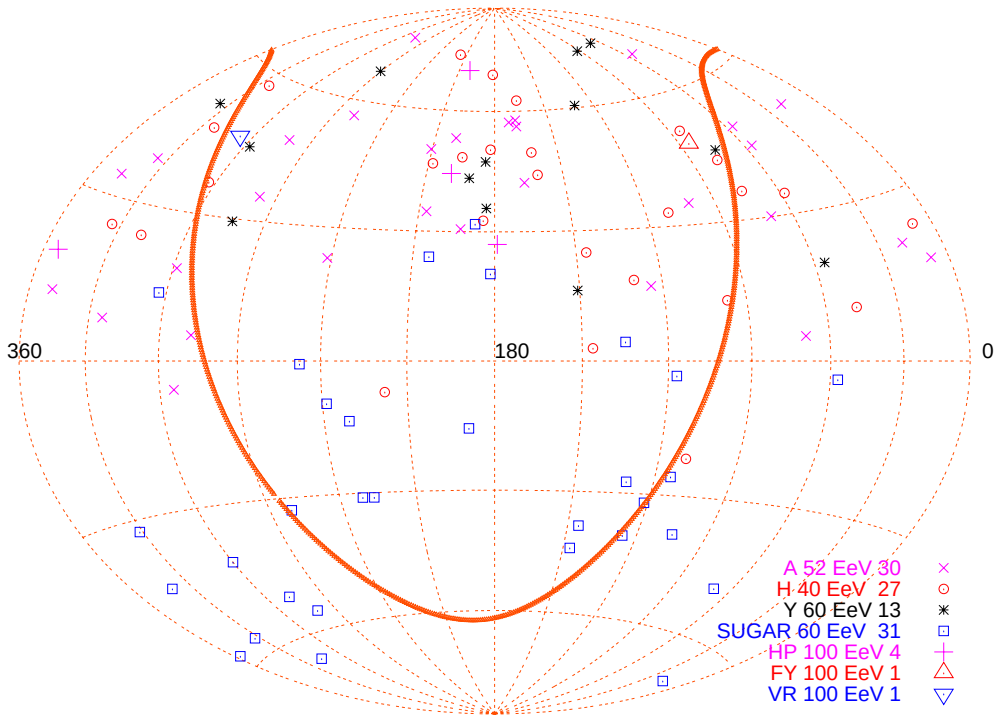


P.Blasi and de Marco 2003; M.Kachelriess and D.S., 2004

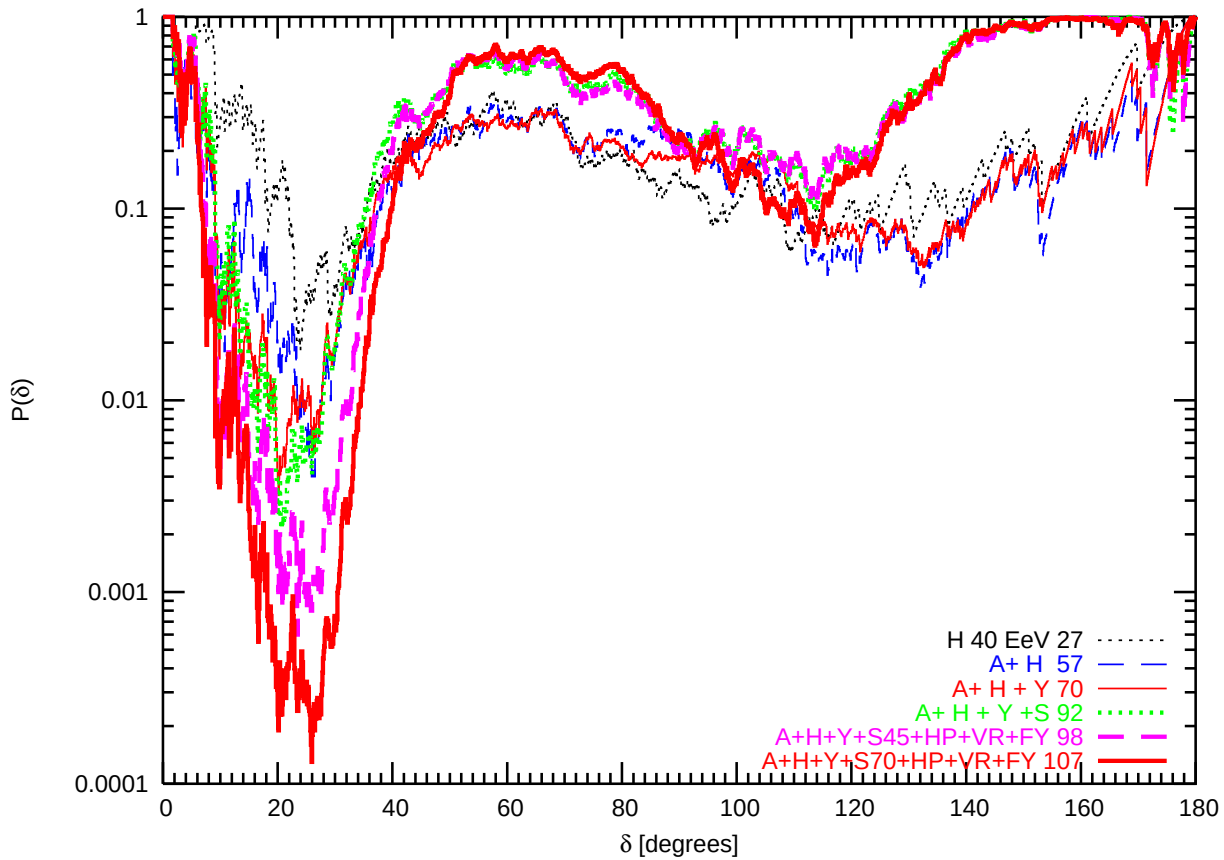
Global energy rescaling



Arrival directions for E>40 EeV in HiRes (E>52 EeV in AGASA)



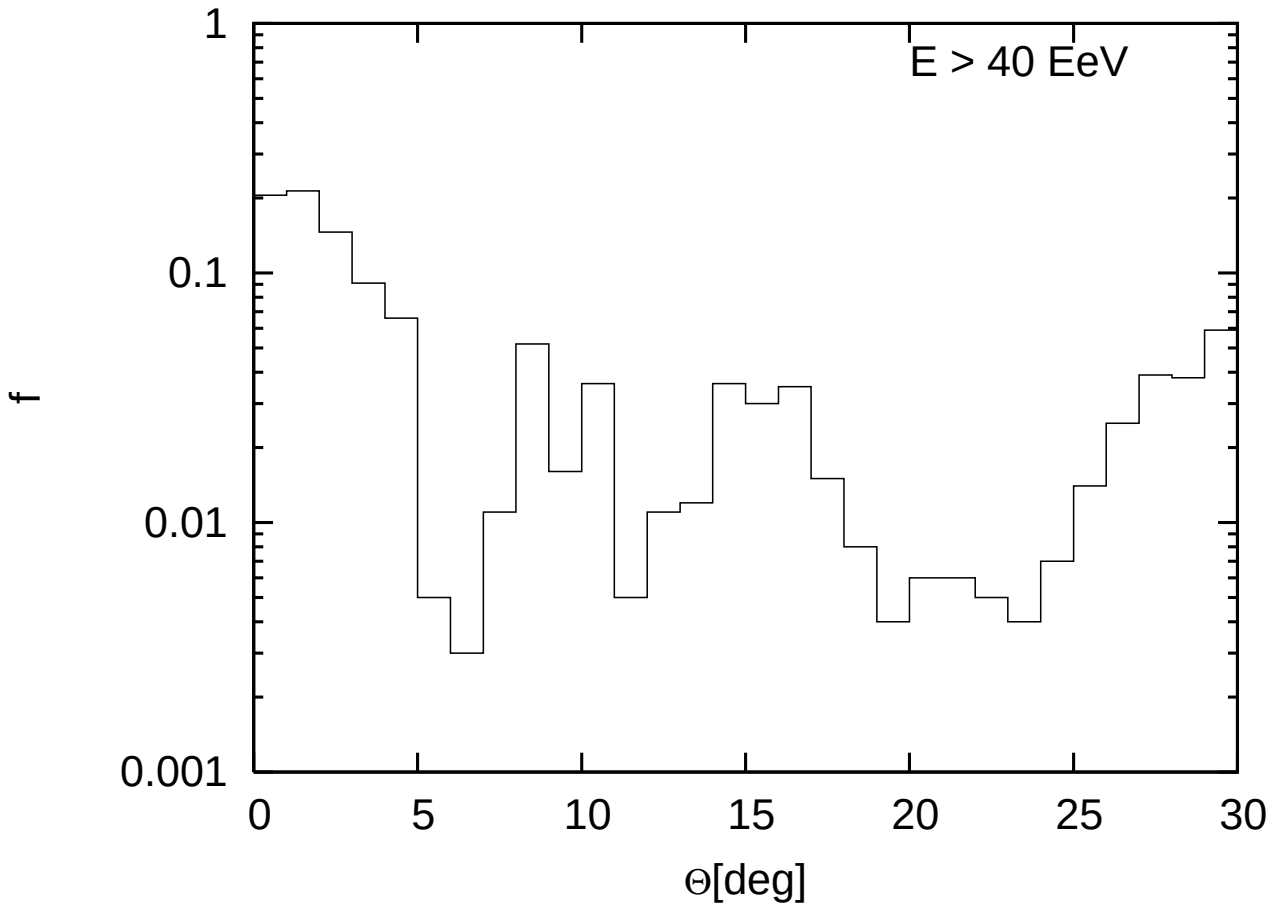
Probability of correlation



3 σ after penalty on angle

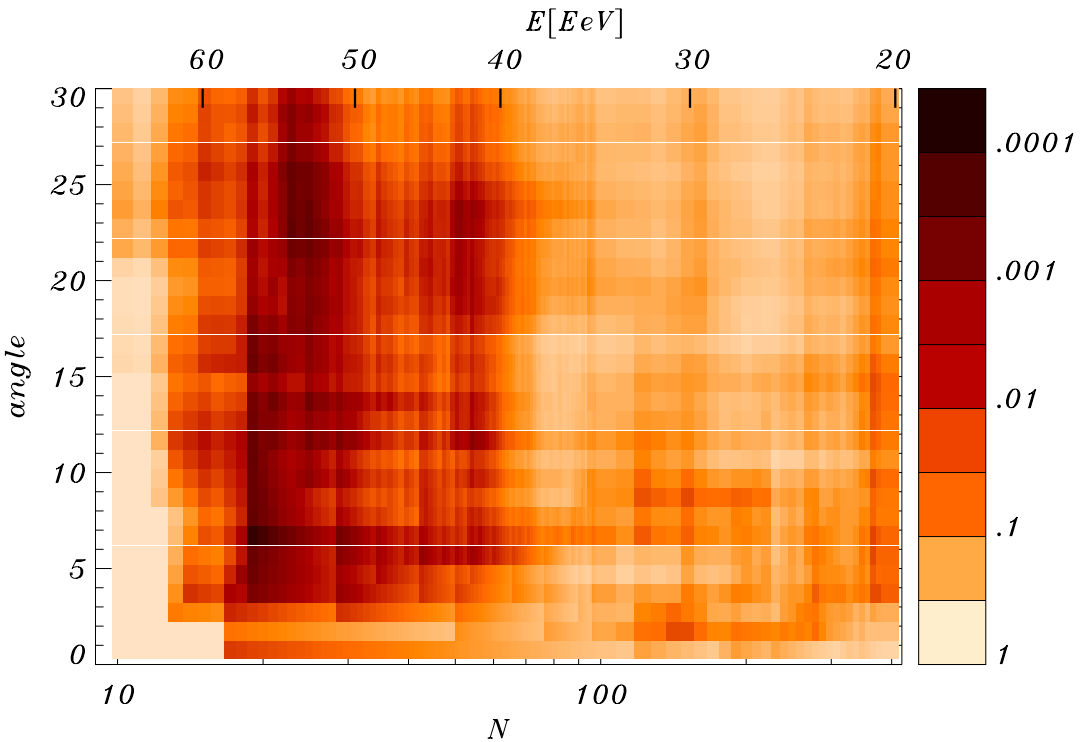
M.Kachelriess and D.S., astro-ph/0512498

Clustering signal in AUGER: 20-25 degree scales



~1-2 %, ~70 events, Pierre Auger Collaboration, ICRC 2007

Clustering signal in AUGER: scan



2% after scan and penalty at 7 and 23 degrees

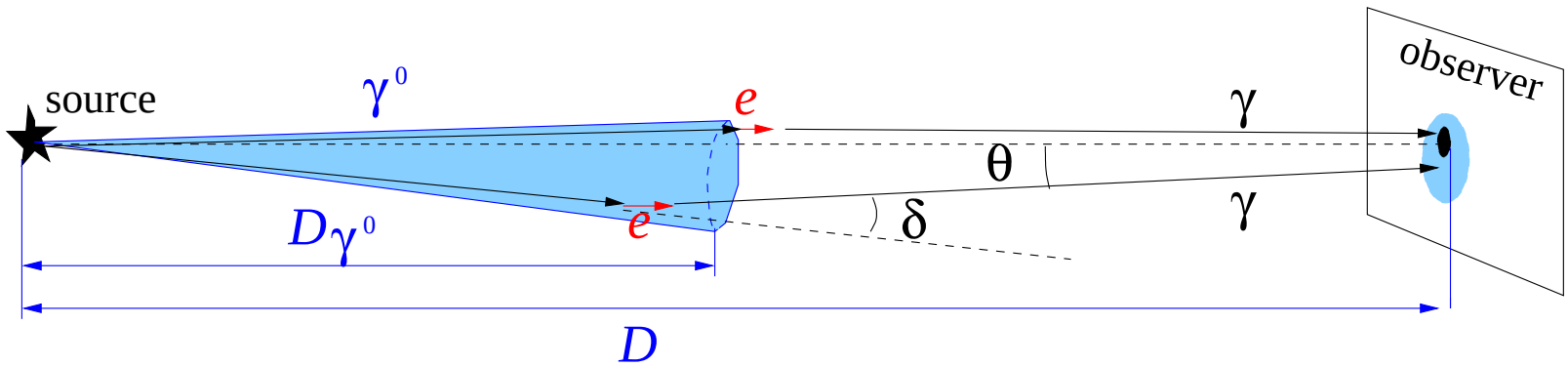
Pierre Auger Collaboration, ICRC 2007

Statistically limited at the moment.

If real, connection to LSS and EGMF

EGMF in voids and TeV telescopes

Production of secondary TeV photons



$$D_{\gamma_0} = \frac{1}{n_{\mathrm{IR}}\sigma_{PP}} \propto 15\,\mathrm{Mpc}\,\frac{40\,\mathrm{TeV}}{\mathrm{E}}\,\frac{10nW/(m^2 sr)}{(\nu F(\nu))_{IR}} \qquad D_{\gamma} = \frac{1}{n_{\mathrm{IR}}\sigma_{PP}} \propto 400\,\mathrm{Mpc}\,\frac{1\,\mathrm{TeV}}{\mathrm{E}}\,\frac{10nW/(m^2 sr)}{(\nu F(\nu))_{IR}}$$

$$\lambda_e = \frac{1}{n_{\mathrm{CMB}}\sigma_{ICS}} \sim 1\ \mathrm{kpc}$$

A.Neronov and D.S., astro-ph/0604607

Maximal magnetic field

- Maximal magnetic field can be found from the condition that highest energy photons which still can reach detector are not deflected outside of jet.

$$B_{\max} < 1.5 \cdot 10^{-12} G \sqrt{\frac{E_\gamma}{1\,\mathrm{TeV}}} \frac{\Theta_{jet}}{5^\circ}$$

$$\alpha = \frac{E_\gamma}{E_e} = 0.05 \sqrt{\frac{E_\gamma}{1\,\mathrm{TeV}}}$$

Minimal magnetic field

- Minimal magnetic field can be found from the condition that lowest energy photons can not be resolved from point source flux

$$B_{\min} > 8 \cdot 10^{-17} G \cdot \tau(\mathrm{E}_{\gamma_0}, \mathrm{z}) \cdot \frac{E_{th}}{100\,\mathrm{GeV}} \cdot \frac{PSF}{0.1^{\circ}}$$

GZK photons with E>10 EeV

Pion production

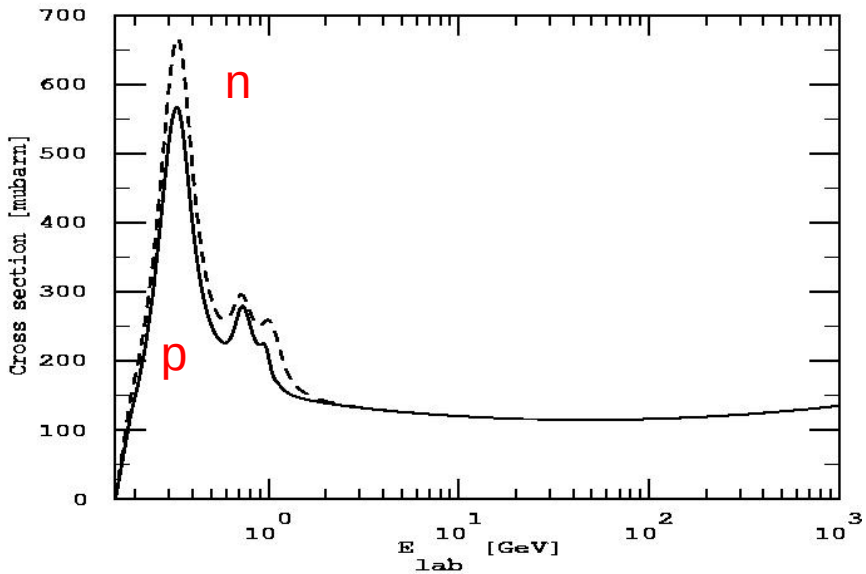
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

$$P + P_b \Rightarrow \sum \pi^i + \ldots$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^{\pm} \Rightarrow \mu^{\pm} + \nu_{\mu}$$

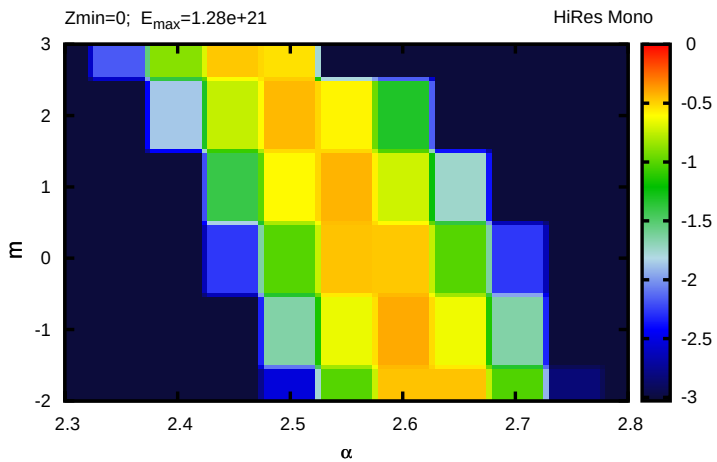
$$\mu^{\pm} \Rightarrow e^{\pm} + \bar{\nu}_e + \nu_{\mu}$$

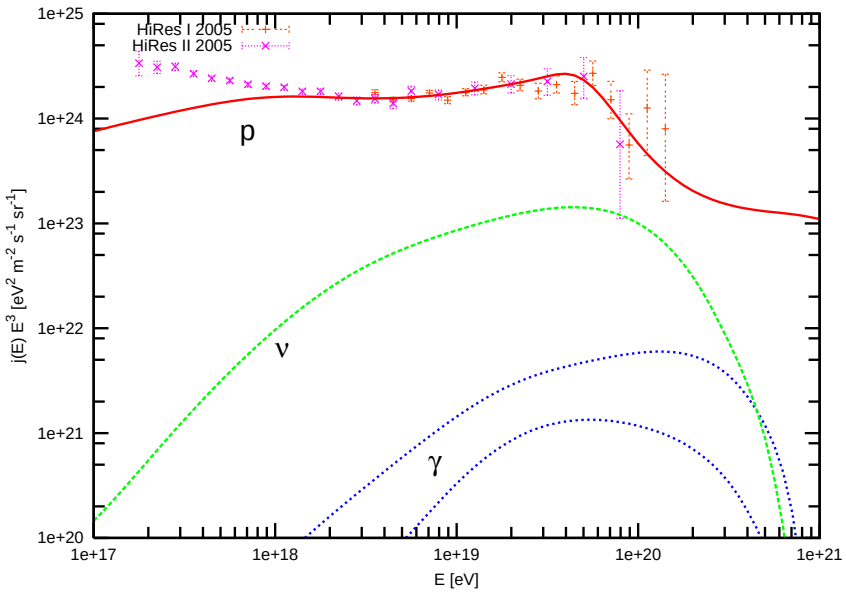


$$n \Rightarrow p + e^- + \bar{\nu}_e$$

Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_{\gamma}^{tot} \sim E_{\nu}^{tot}$

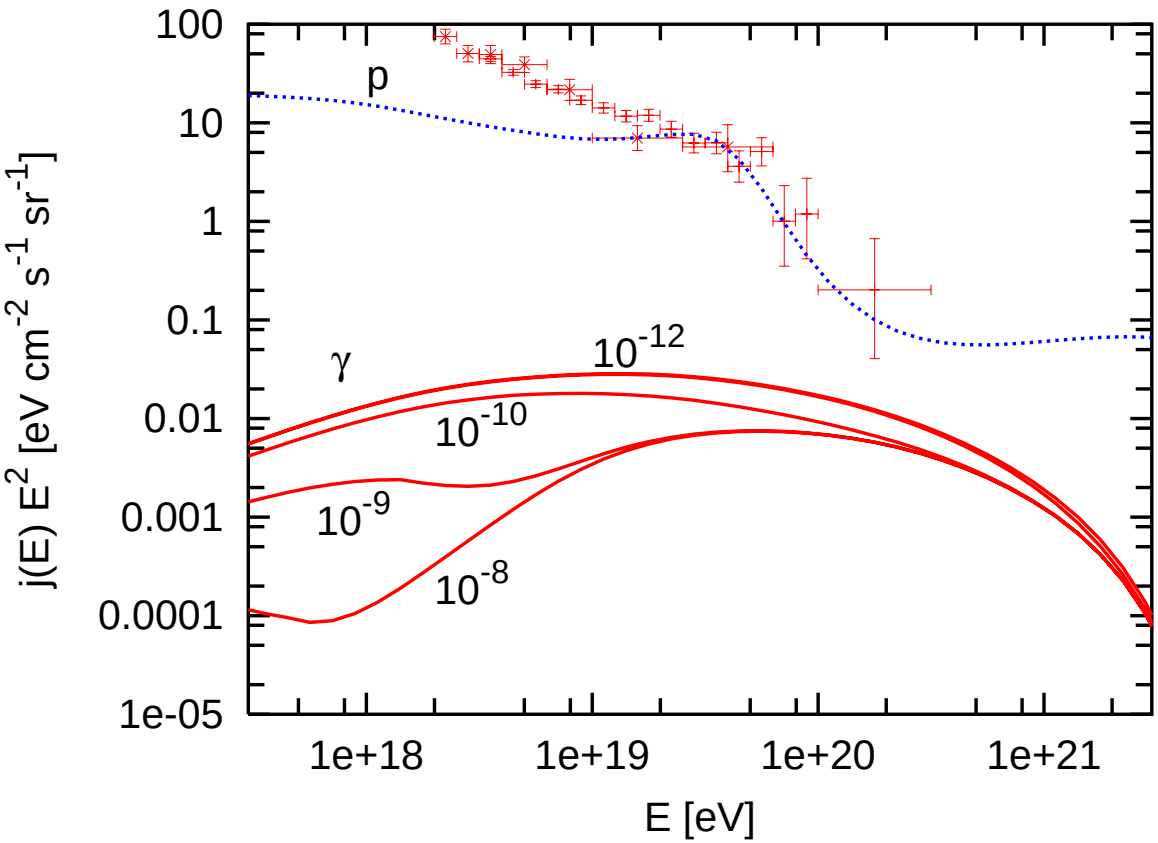
Secondary photons and neutrinos



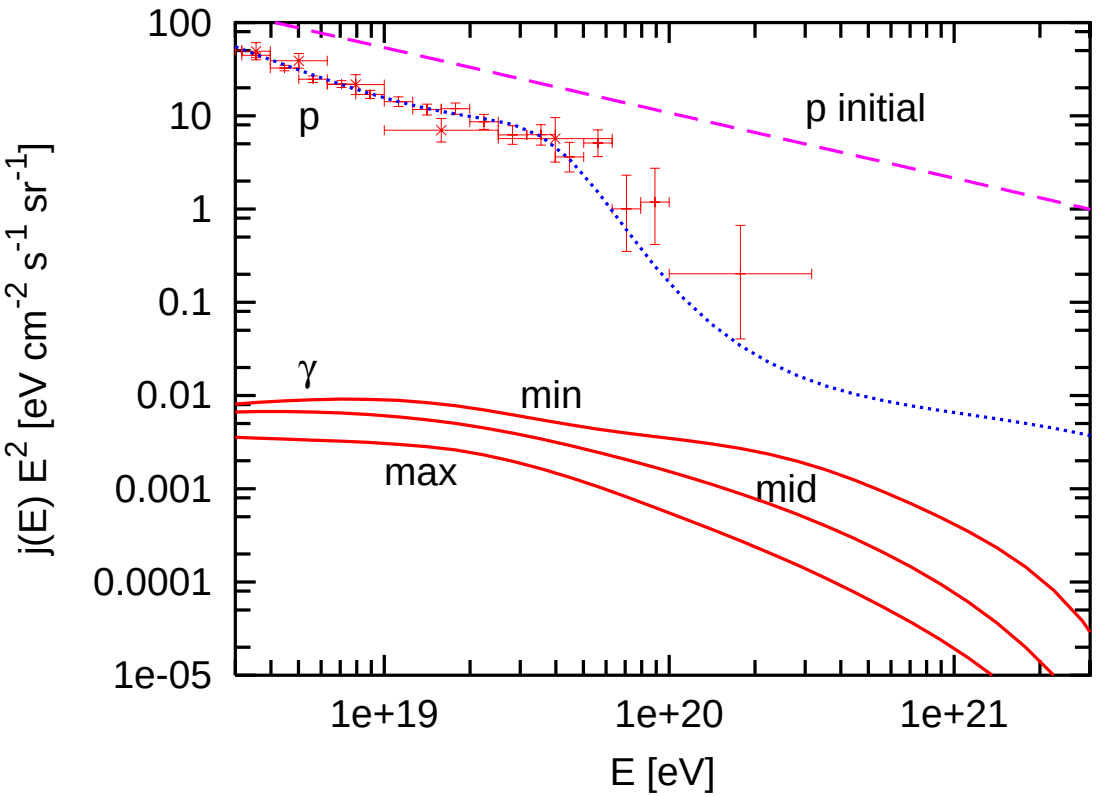


G.Gelmini, O.Kalashev and D.S., astro-ph/0702464

Average extragalactic magnetic field.

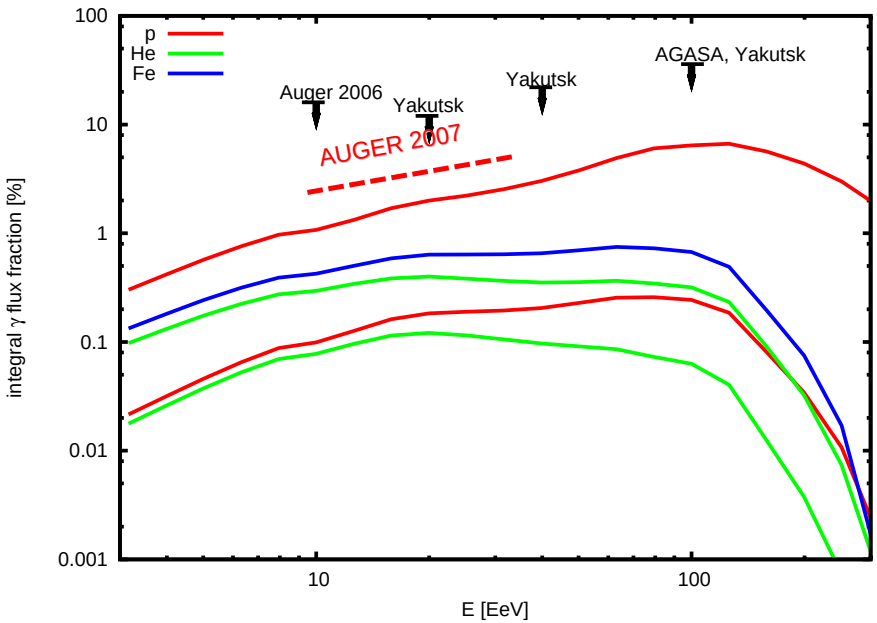


Radio background.

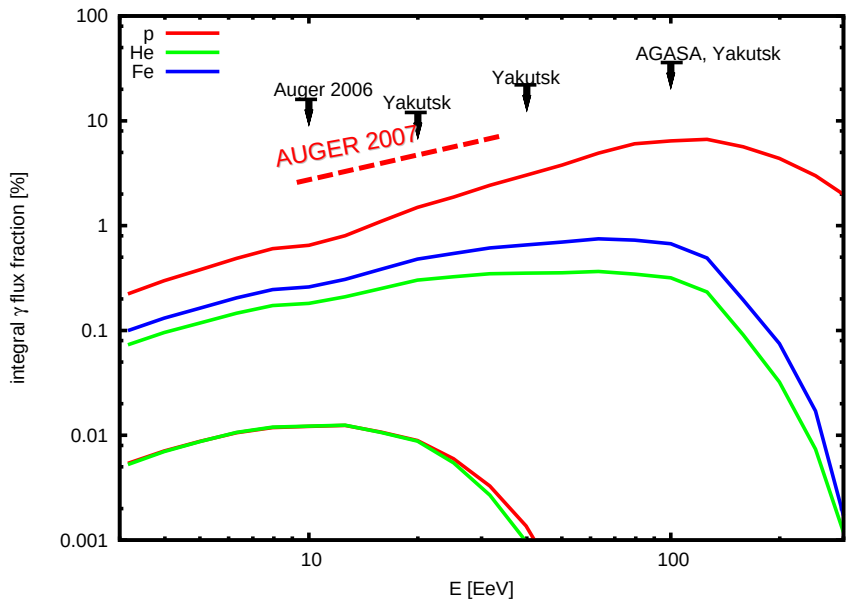


Sensitivity to fraction of photons

AGASA



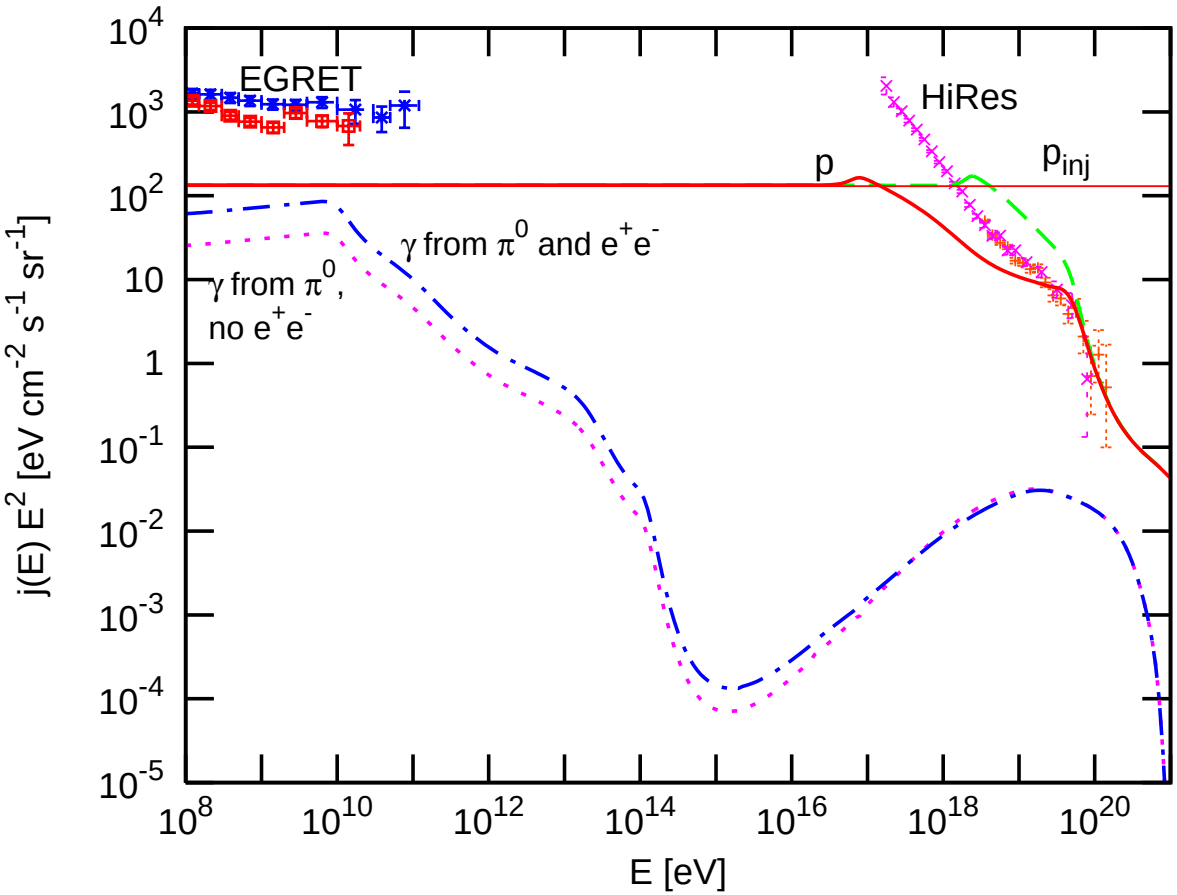
HiRes



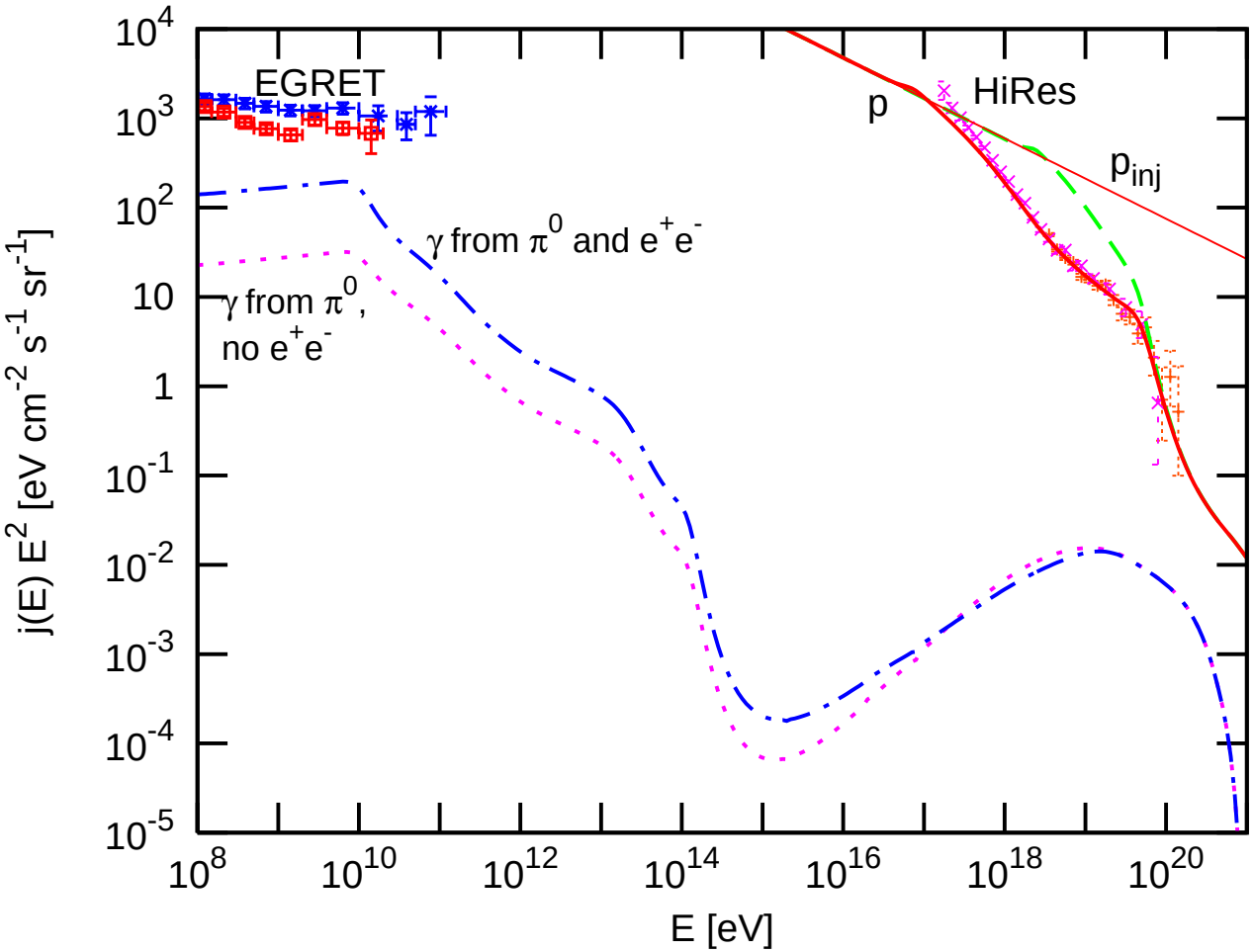
G.Gelmini, O.Kalashev and D.S., astro-ph/0706.2181

Cascade photons with GeV - TeV energies

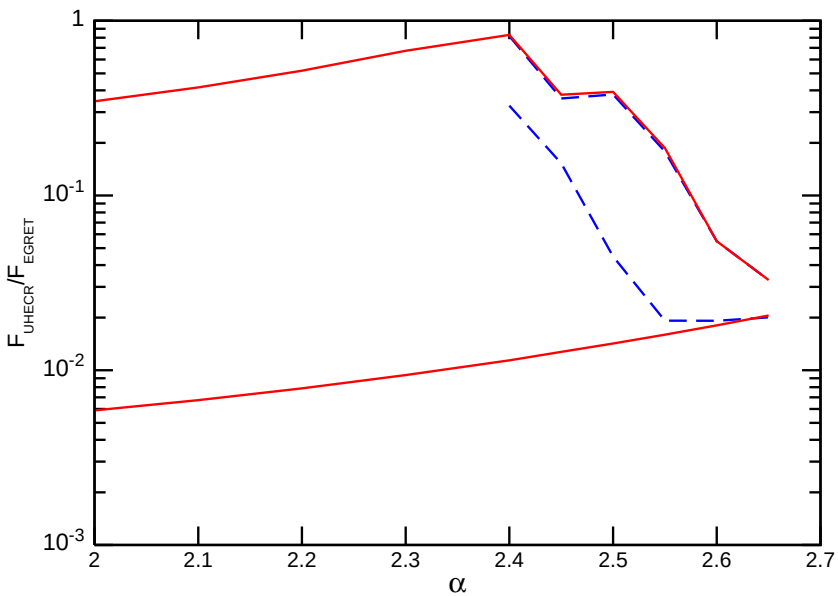
Cascade photons for $1/E^2$.

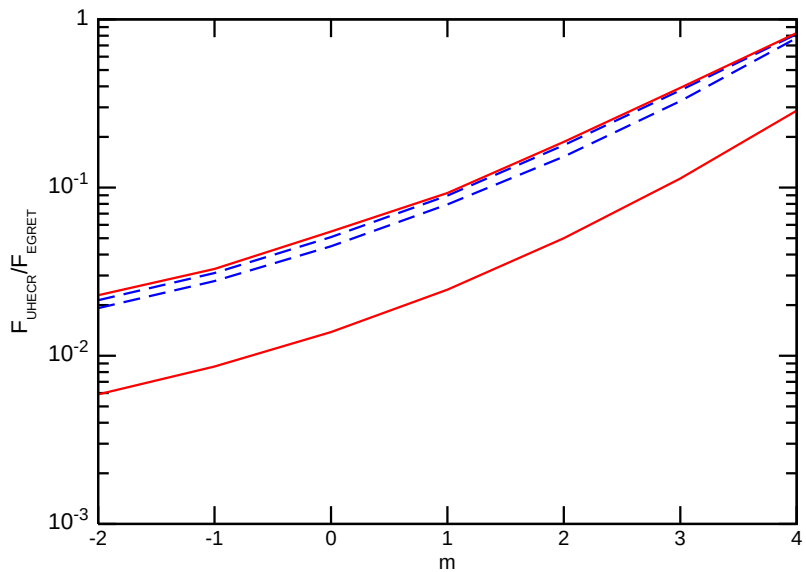


Cascade photons for $1/E^{2.5}$.

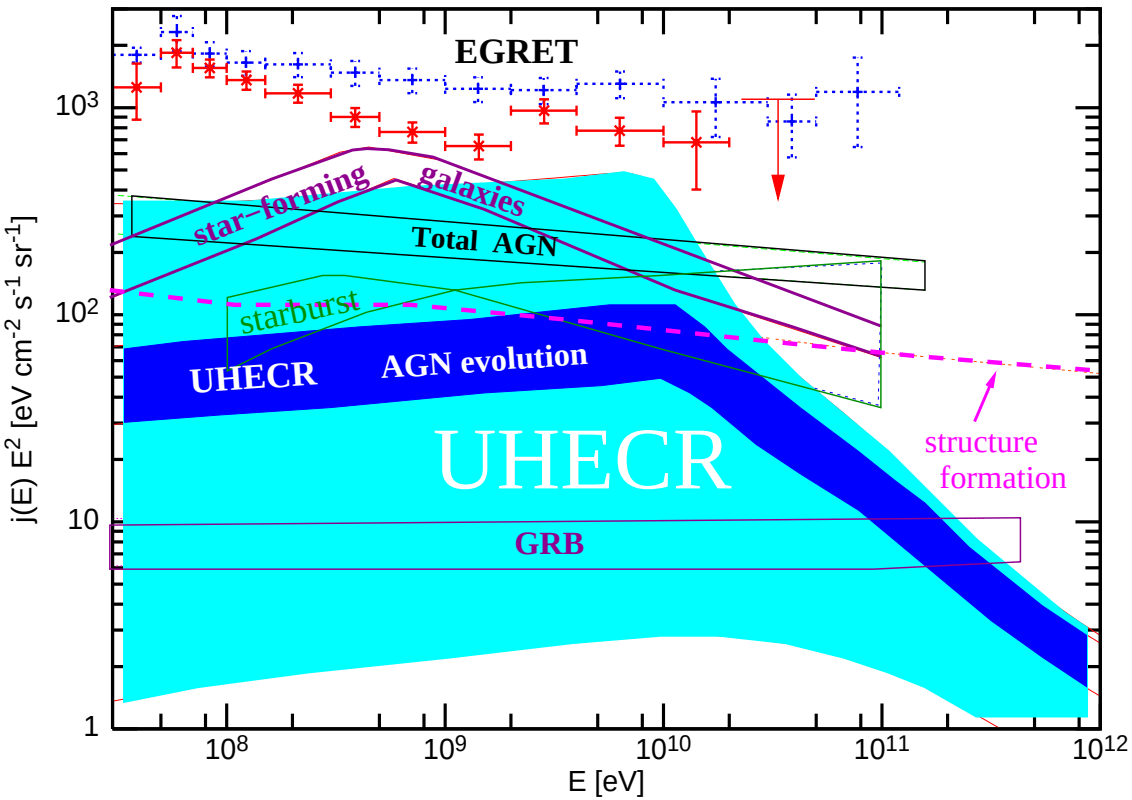


Contribution UHECR to EGRET diffuse background for different α and m.





Contribution of UHECR to EGRET



O.Kalashev , D.S. and G.Sigl, astro-ph/0704.2463

UHE neutrinos.

Pion production

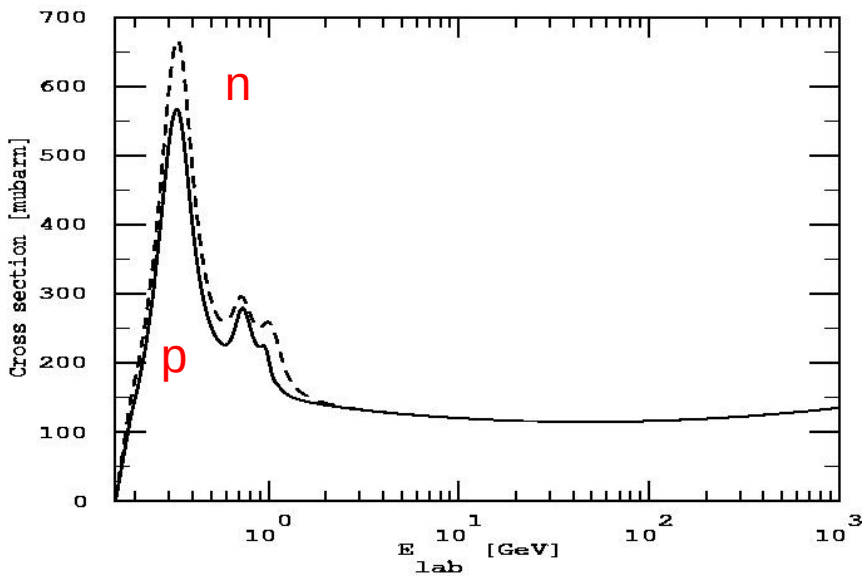
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^{\pm} \Rightarrow \mu^{\pm} + \nu_{\mu}$$

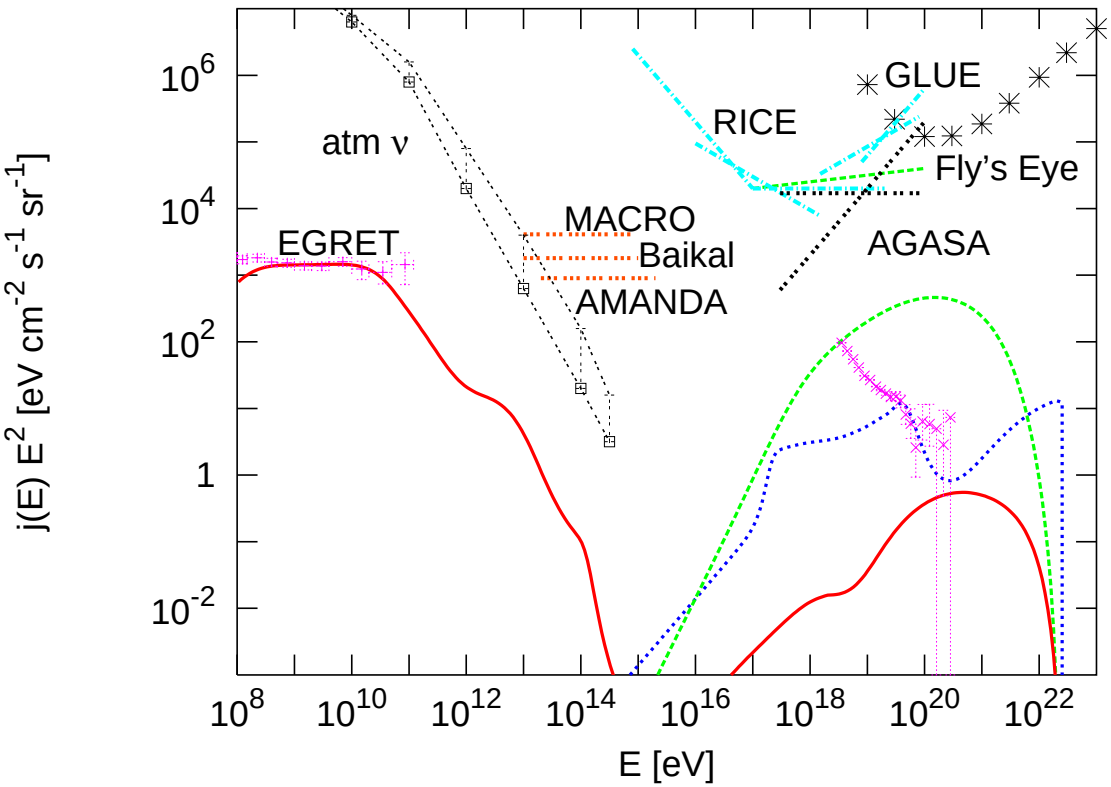
$$\mu^{\pm} \Rightarrow e^{\pm} + \bar{\nu}_e + \nu_{\mu}$$

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

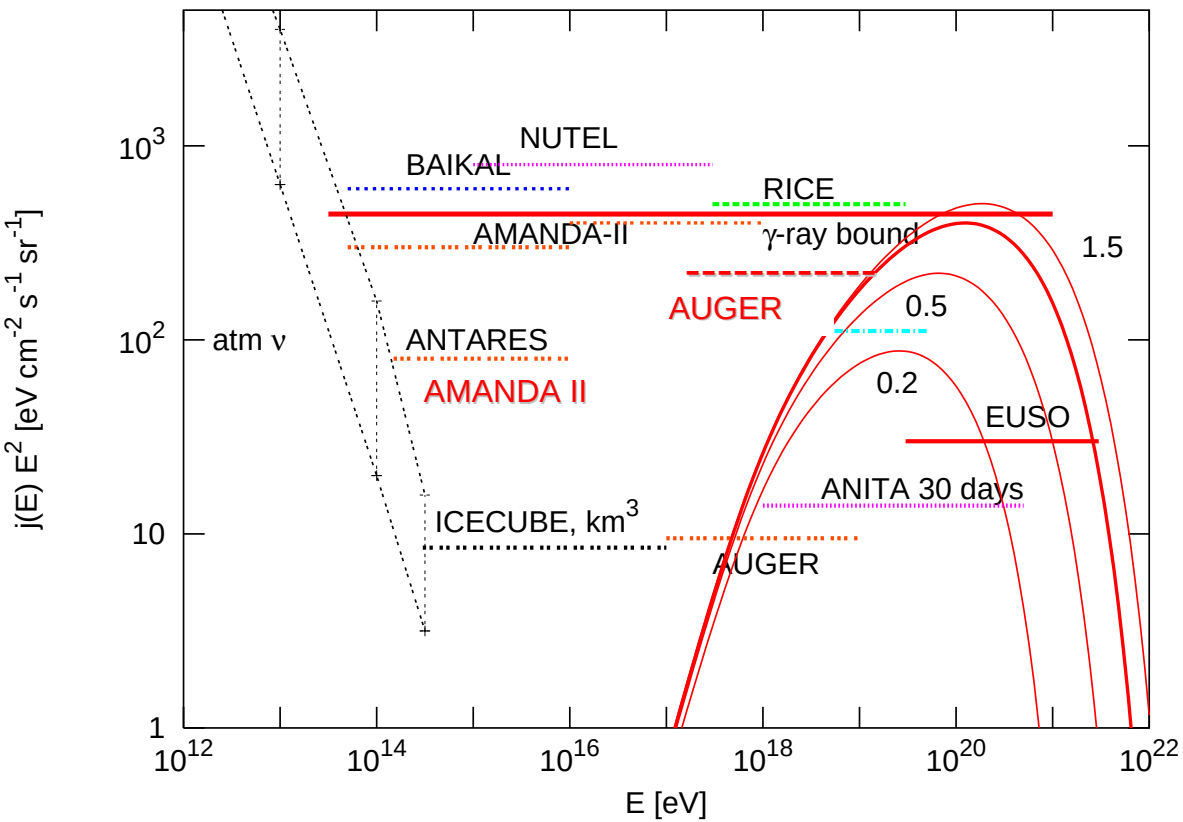


Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_{\gamma}^{tot} \sim E_{\nu}^{tot}$

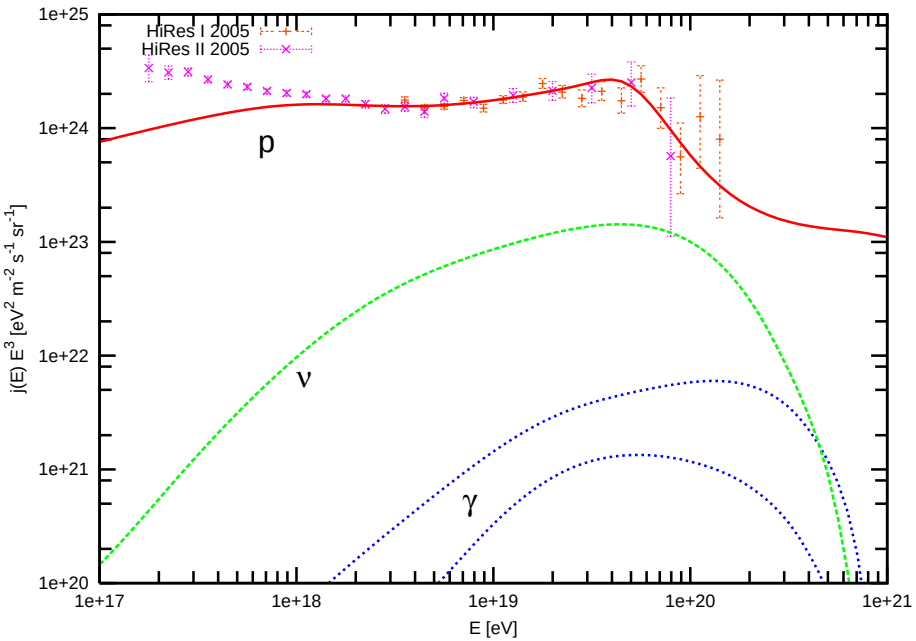
UHECR, gamma-ray and neutrino fluxes



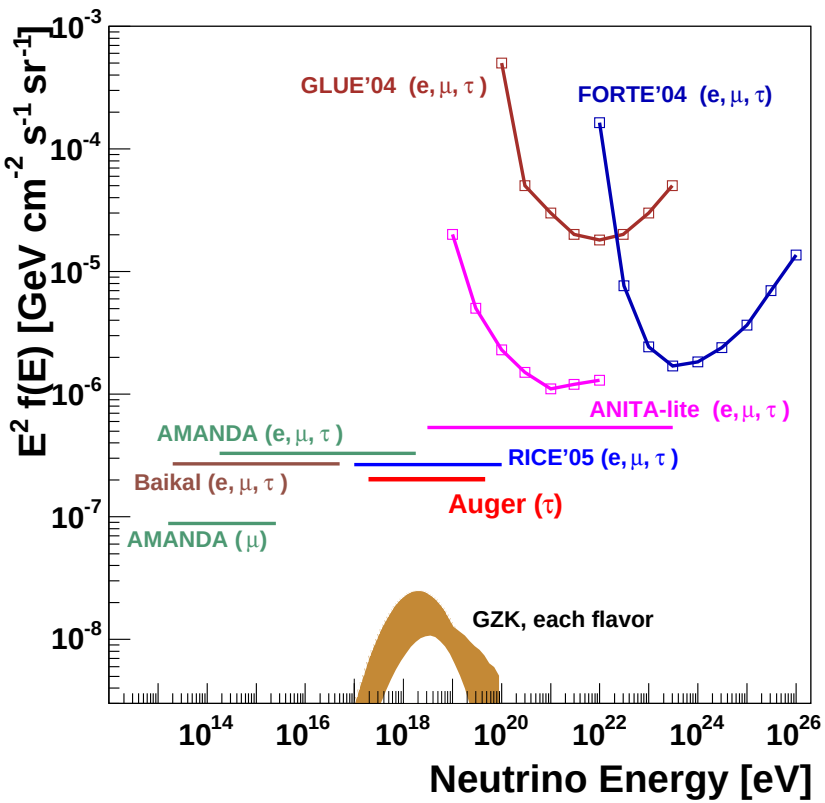
Present and future limits on neutrino flux



Secondary photons and neutrinos for $1/E^{2.7}$ protons

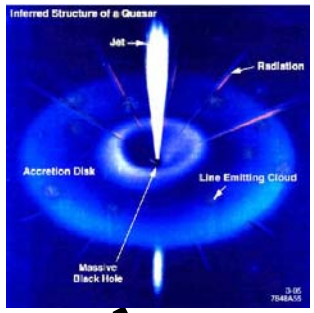


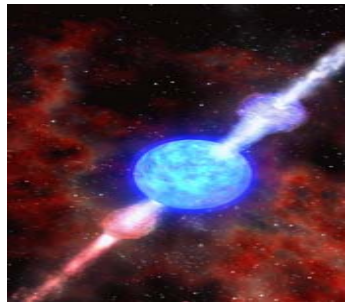
Limits on tau-neutrino fraction

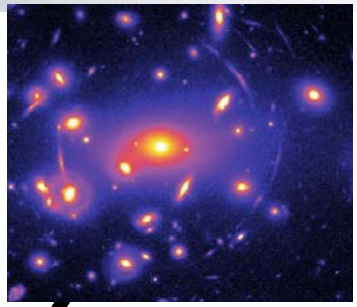


Pierre Auger Collaboration, ICRC 2007

Multi-messenger observations.







Acceleration

acceleration

Galactic magnetic field

Cosmic Rays $E < E_{GZK}$
Difficult to do astronomy

H. E. Electrons

$E > E_{GZK}$
Cosmic Rays
$z < 0.02$

Extragalactic magnetic field

Synch , I.C.

E.M. Cascades

Pion production
Neutron decay

X-Ray
Radio
$z \sim$ several

Gamma Rays
$z \sim$ several

H. E. Gamma Rays
$z < 0.2$

U.H.E. Gamma Rays
$z < 0.02$

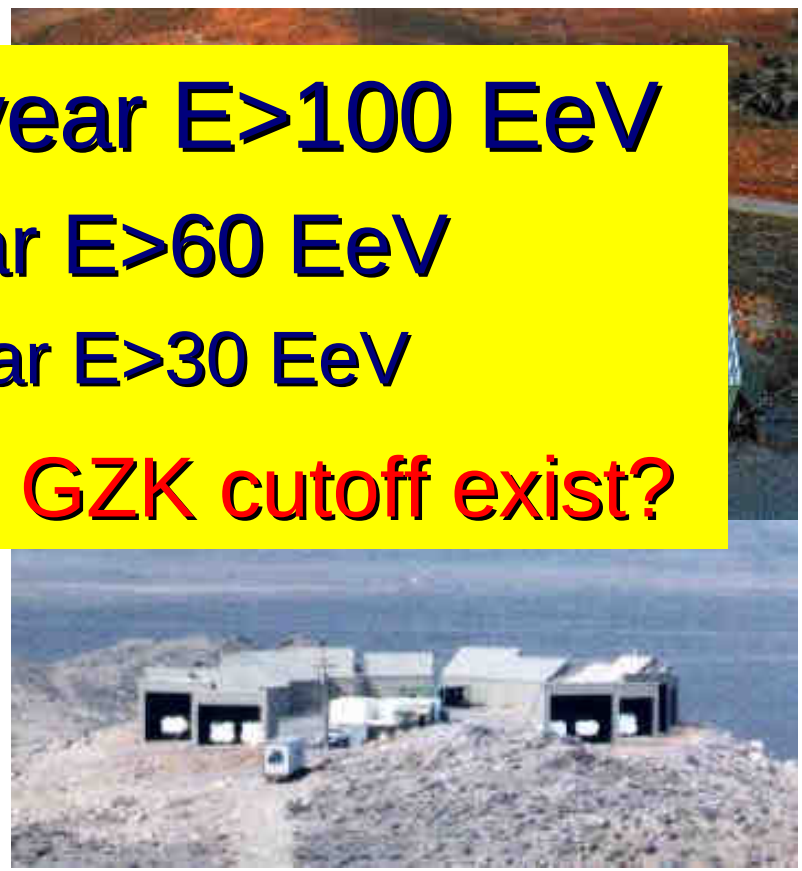
H. E. Neutrino
$z \sim$ several

Previous generation: AGASA, HiRes

AGASA ~100km^2
(closed in 2004)
111 scintillation detectors
27 muon detectors
~4M$ (~30 Scientists)

HiRes ~300km^{2}yr/yr
(closed in 2006)
HiRes-I, HiRes-II

~10M$ (~60 Scientists)



0.5-1 event/year E>100 EeV

3-5 events/year E>60 EeV

20-40 events/year E>30 EeV

Goal: check if GZK cutoff exist?

New Generation

TA (Utah Delta), Auger (Malargue)

Telescope Array ~800km2

10 events/year E>100 EeV

50 events/year E>60 EeV

400 events/year E>30 EeV

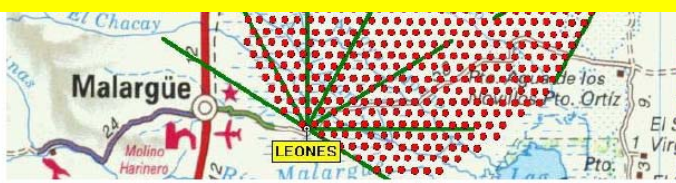
2007: !!! Cutoff confirmed !!!

Goal: establish UHECR sources.

Auger ~

1600 Wa
with 1.5k
4 Fluores

~50M$ (300 scientists)



Fluorescence Detectors
4 telescopes enclosures (``Eyes'')
6 telescopes per enclosure
24 telescopes total

Future Projects: Auger North, JEM-EUSO

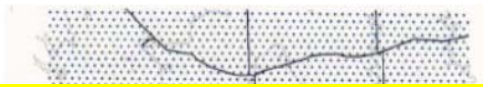
Auger North

~10,000km2 * (¾ π sr)

JEM-EUSO (~20% duty cycle)

Nadir mode ~40,000km2yr / yr for 2 years
Tilted mode ~200,000km2yr / yr for 3 years

Total ~680,000km2 yr ~2M km2 str yr



Northern Site

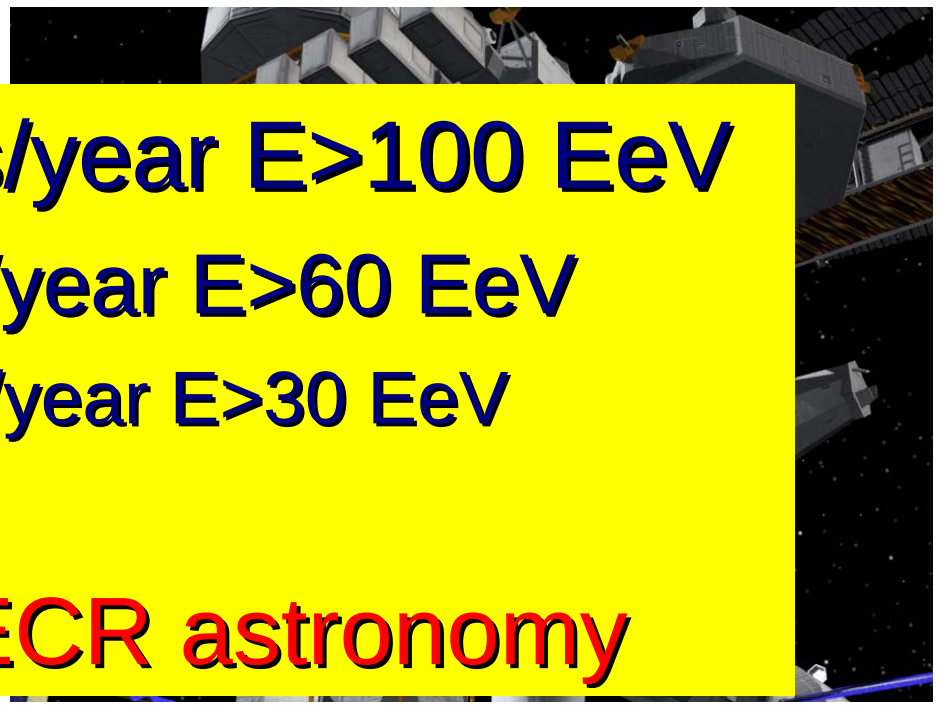
Southeastern Colo

Energy ≥ 10^{19} eV

1.6 km square grid

A single FD 30^0 x

Propose 10,000 km



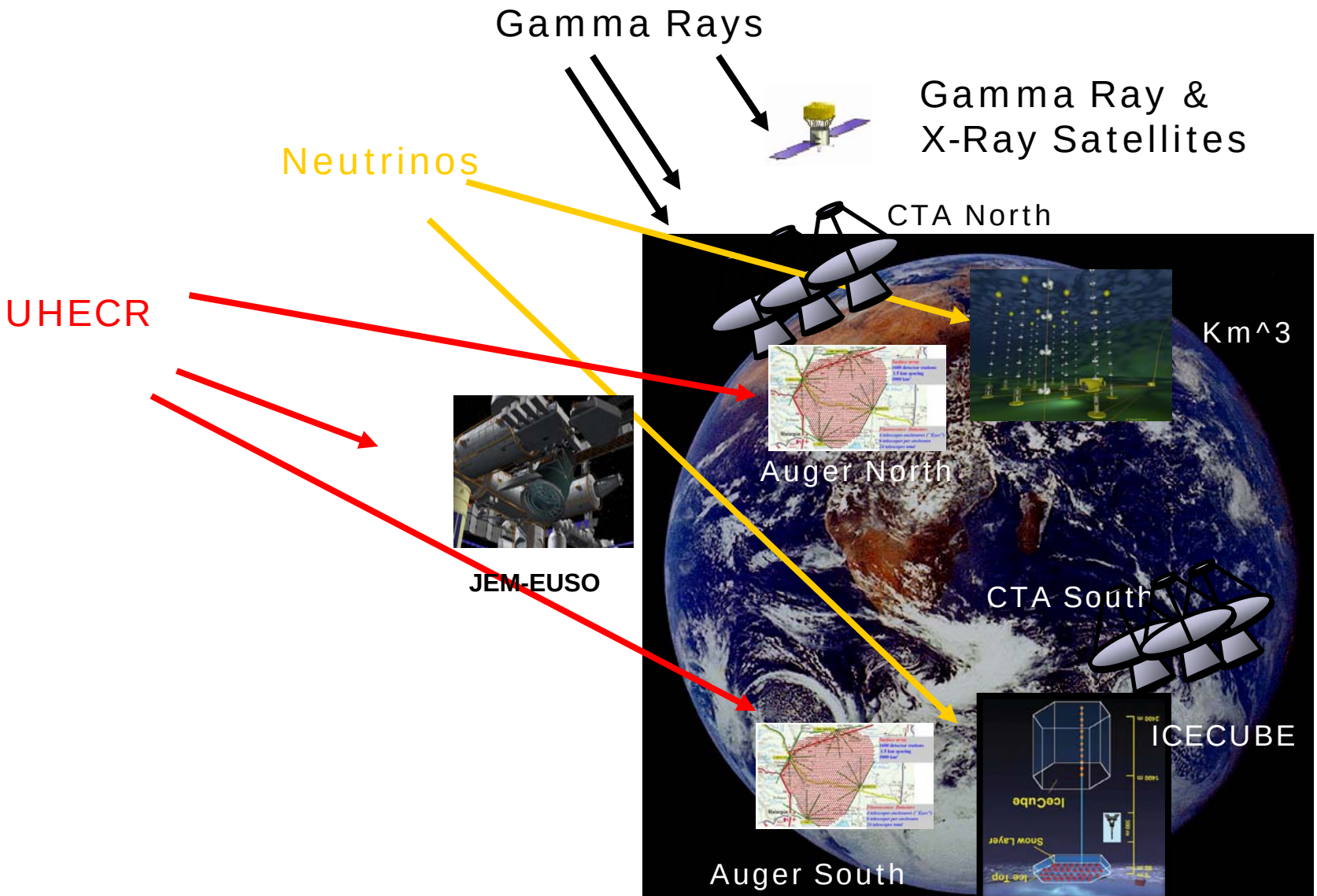
100-300 events/year E>100 EeV

500-1500 events/year E>60 EeV

4000-10000 events/year E>30 EeV

Goal: start UHECR astronomy

Multi-Messenger observation all-sky



Conclusions: status of UHECR

- Cutoff in UHECR spectrum exist. UHECR come from astrophysical sources. Open questions:
  - Cutoff from acceleration or/and cutoff from propagation.
  - Composition: protons or/and nuclei?
- Arrival directions anisotropy at few degree scales: connection to point sources and source density.
  - Density of sources is 10^{-5}-10^{-4} /Mpc^3
  - Magnetic fields, not a neutral particles
- Arrival directions anisotropy at 20-degree scales: connection to magnetic fields and LSS.
- Next step – find single sources or/and class of sources (!).
- A lot of astrophysics can be done: Galactic and extragalactic magnetic fields, individual sources of UHECR, acceleration mechanism, etc. Bigger detectors needed (Auger North, JEM-EUSO, etc.)!

Conclusion for Multi-Messenger observation with UHECRs

- Diffuse flux in GeV - TeV region from UHECR protons. Value of flux connected to evolution of UHECR sources. Point source flux from acceleration and propagation of UHECR.
- Diffuse fluxes of UHE photons and neutrinos due to cutoff
  - UHE photon flux 0.01-1% of cosmic ray flux
  - UHE diffuse neutrino flux uncertain due to unknown flux shape of protons after acceleration
- Establish UHECR Physics as Astrophysics
  - We need to identify classes of sources.
  - Then/same time we can identify some individual sources.
- Connection to the magnetic fields
  - Regular component of galactic field can be found, once brightest sources are established.
  - Extragalactic field require much larger statistics – future experiments.
  - EGMF models can be cross checked/ruled out by TeV telescopes