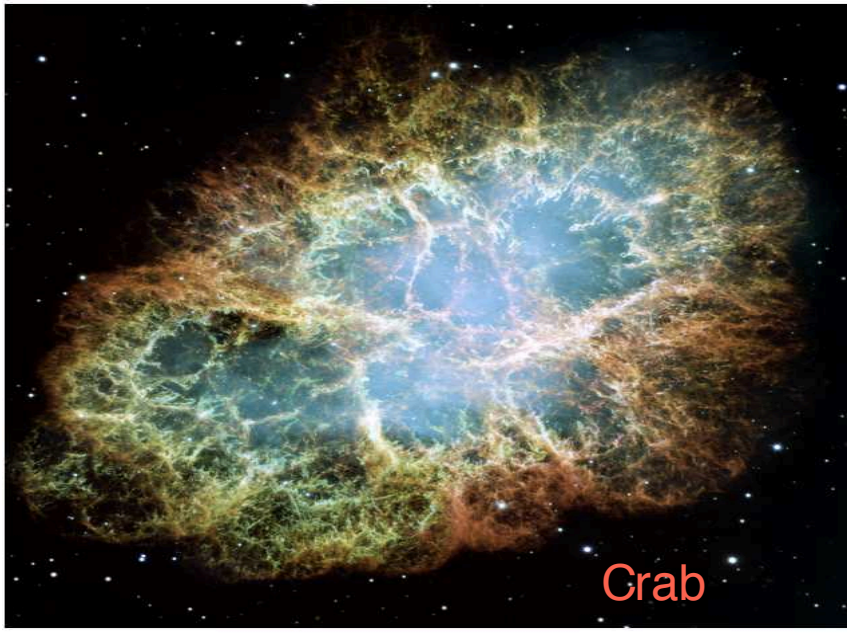
Cosmic Rays

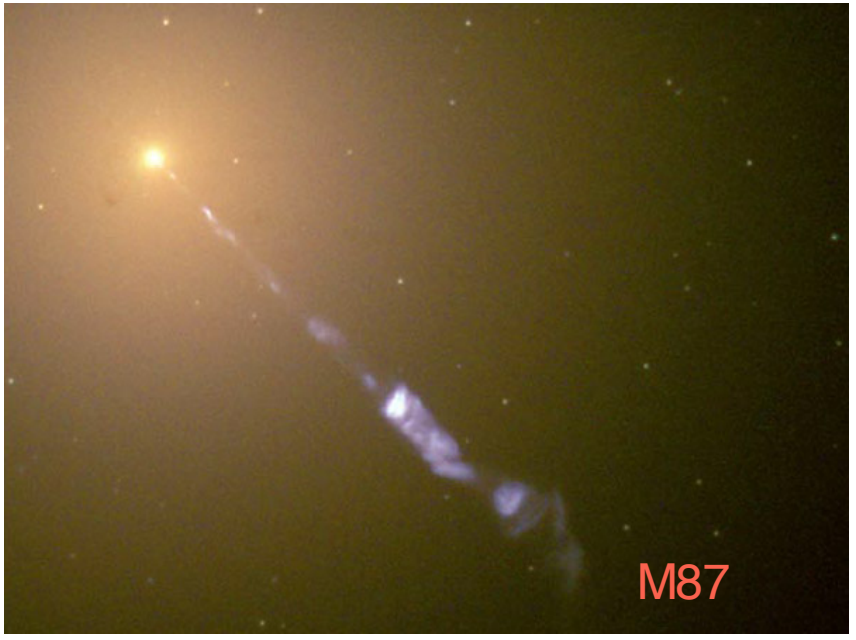
I. Tkachev

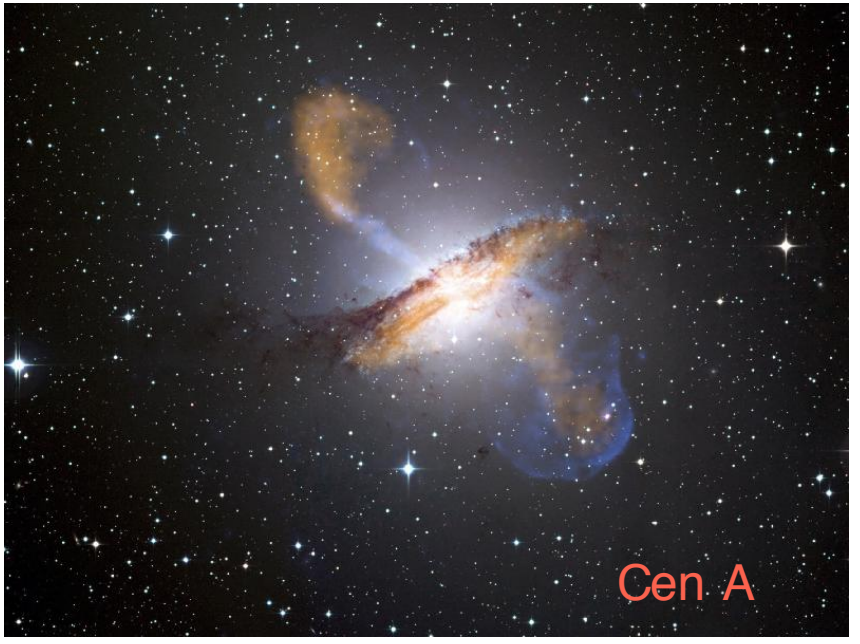
Institute for Nuclear Research, Moscow

1 June 2012, Blois

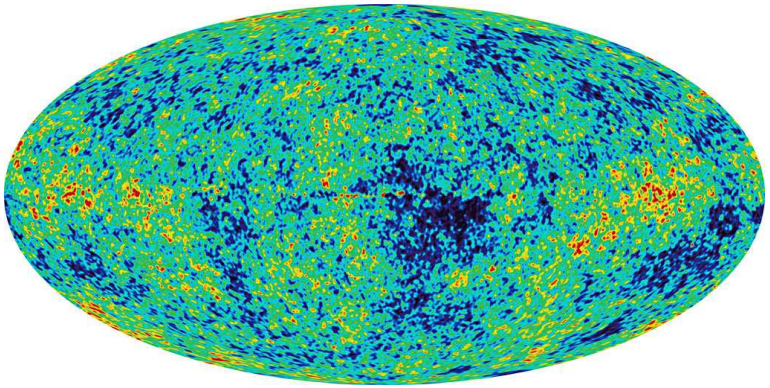
Quest for cosmic ray sources.



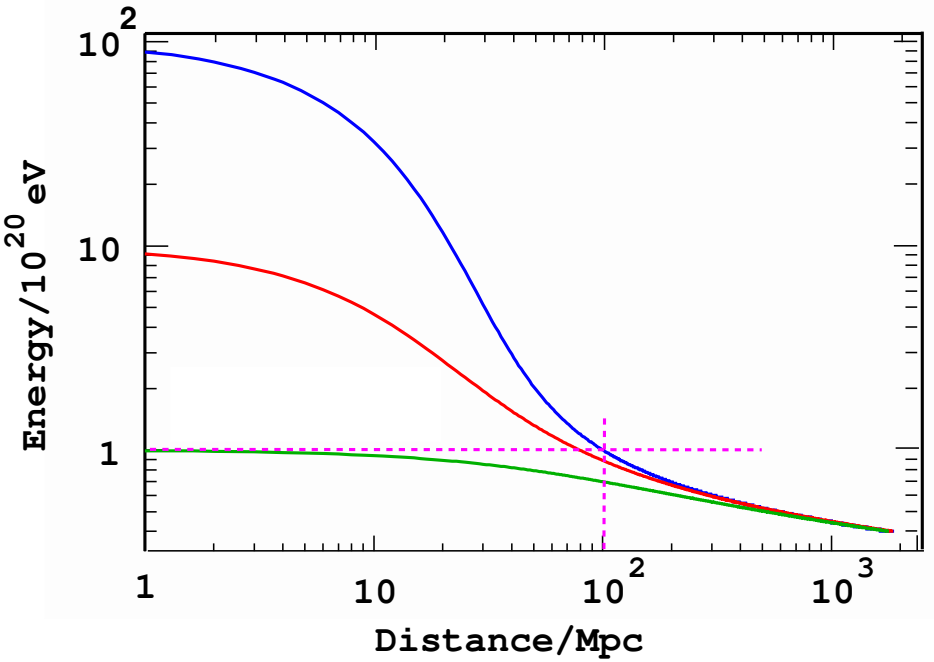


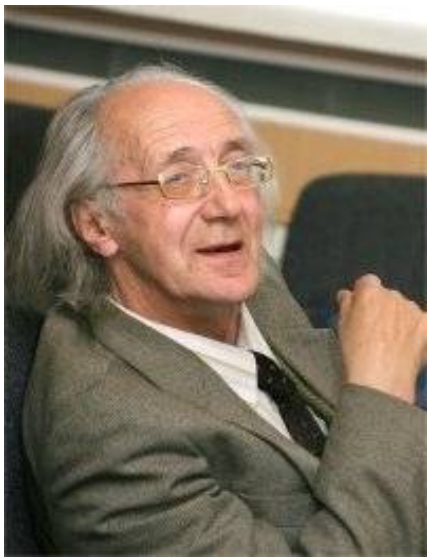


Greisen-Zatsepin-Kuzmin Effect



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





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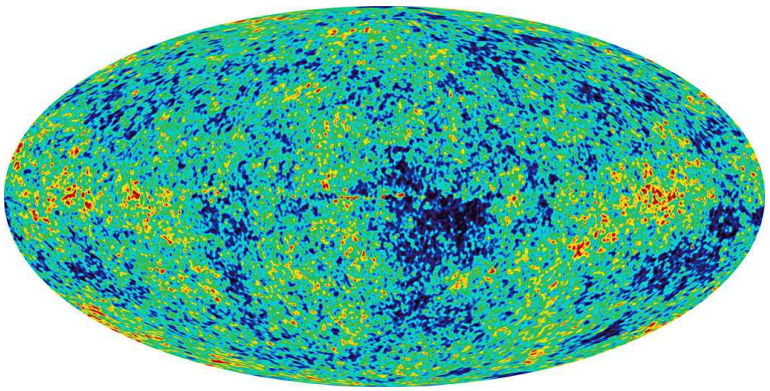
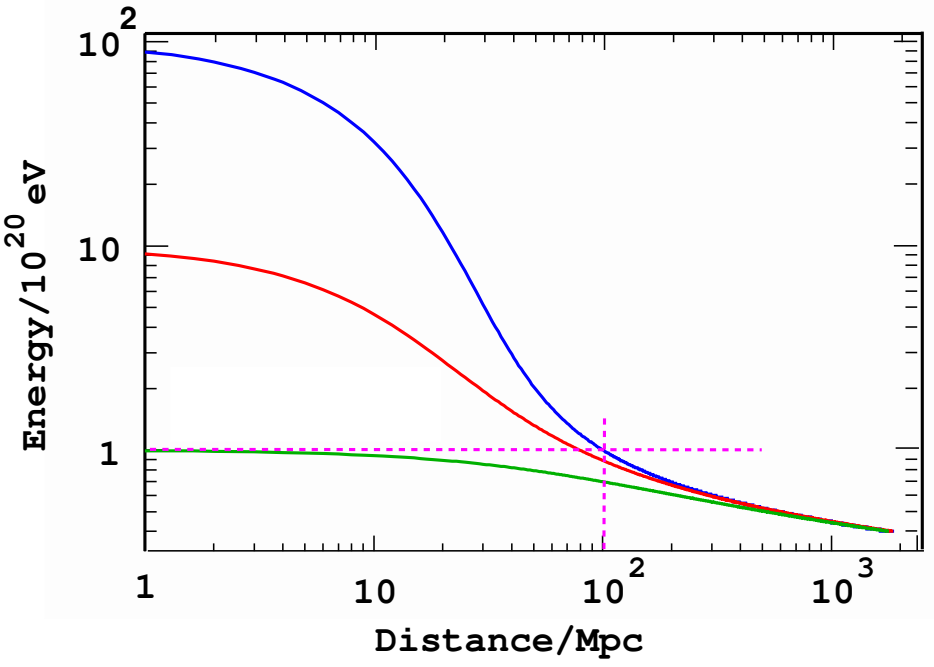
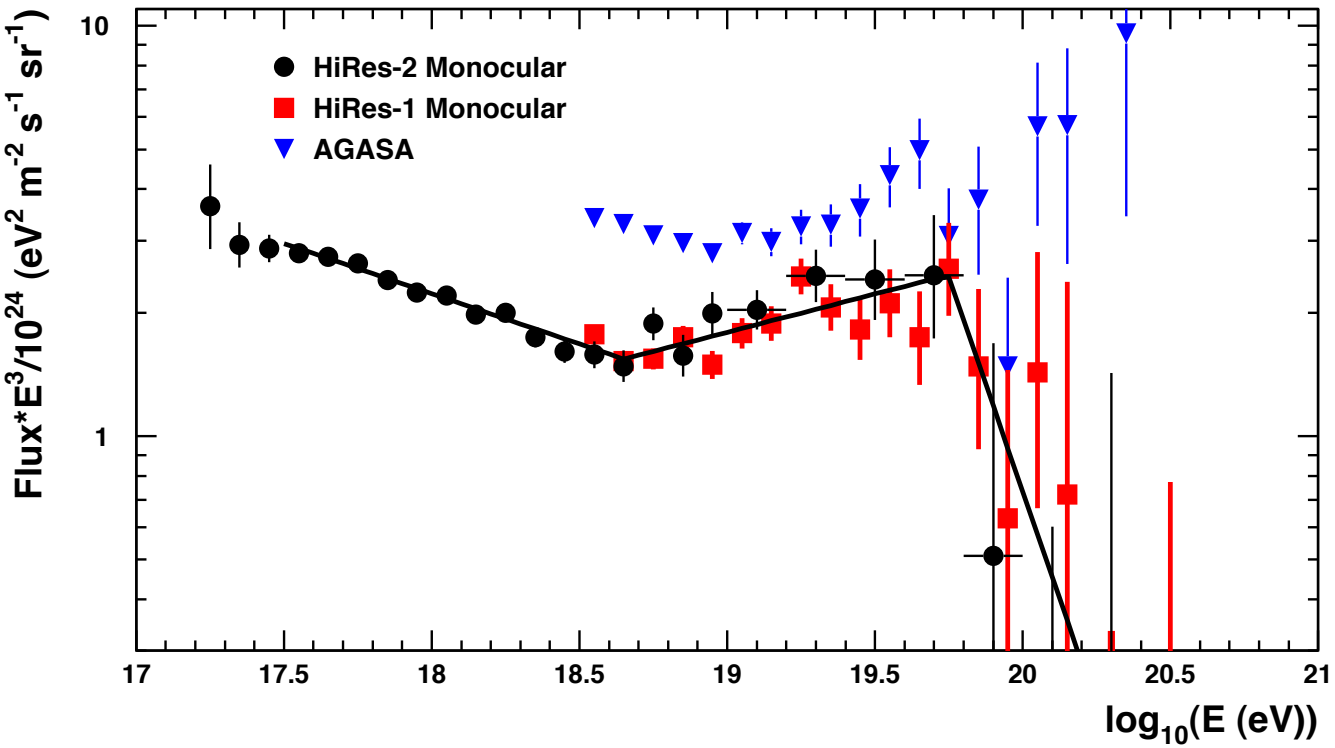


$$p + \gamma_{\mathrm{CMB}} \rightarrow N + \pi$$



- CR detected at $E > 10^{20}\ \mathrm{eV}$ should originate within $R < 100\ \mathrm{Mpc}$. This also leads to a cut off in the spectrum.
- Universe is inhomogeneous at these scales.
- If CR are protons, deflections in magnetic fields are expected to be small.
  Charged particle astronomy should be possible and we should see sources.

Greisen-Zatsepin-Kuzmin Cut-off



- No cut-off in the AGASA data.
  (AGASA was an array of surface detectors (SD))

  AGASA collaboration (2003)

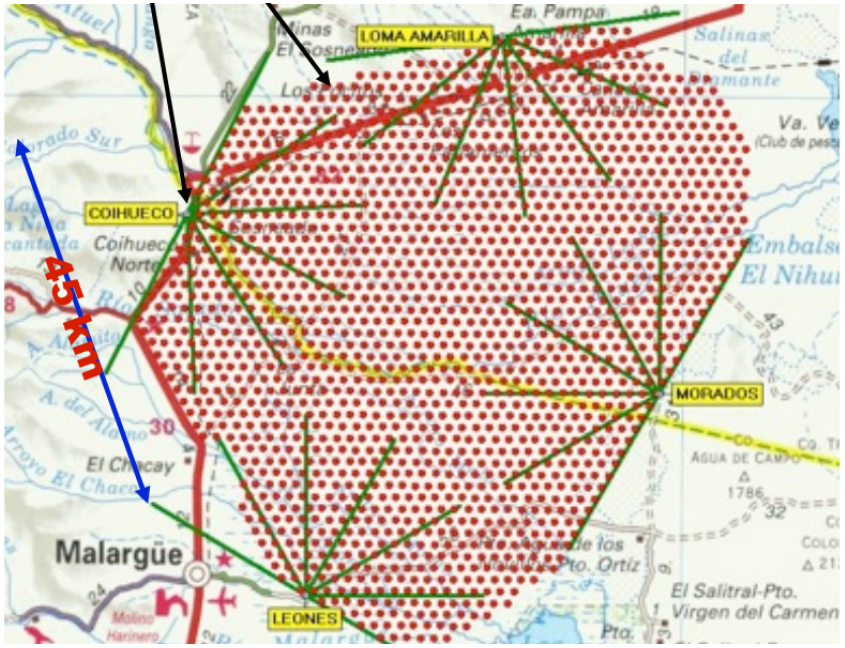
- HiRes announced observation of the GZK.
  (HiRes was an observatory of fluorescent light detectors (FD))

  HiRes collaboration (2007)

New generation of CR observatories

PAO

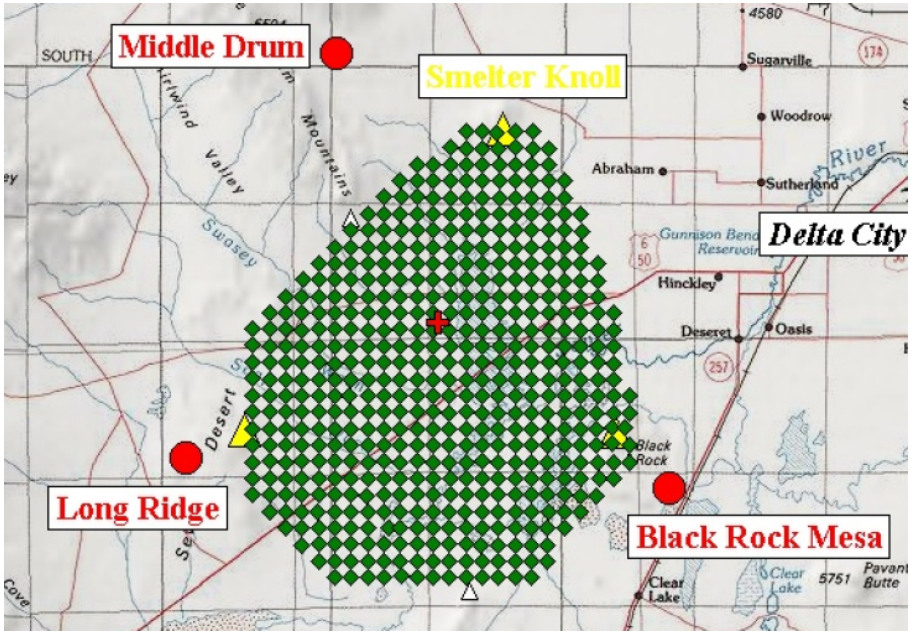
(Hybrid, Southern hemisphere)



- 1600 SD's
  1.5 km spacing, 3000 km^2
- 4 FD's

Telescope Array

(Hybrid, Northern hemisphere)



- 507 SD's
  1.2 km spacing, 700 km^2
- 3 FD's

New generation of CR observatories

PAO

- Water tanks

Telescope Array

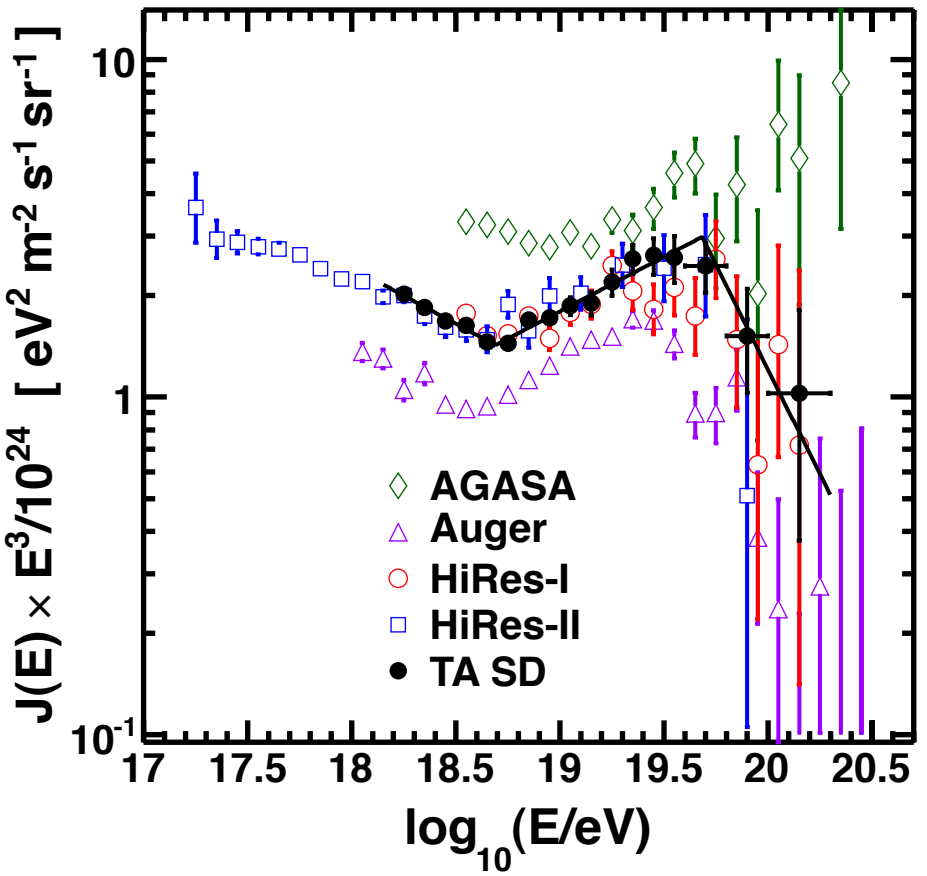
- 3 m^2 scintillators

Cut-off is firmly established

Telescope Array SD spectrum

TA collaboration, arXiv:1205.5067

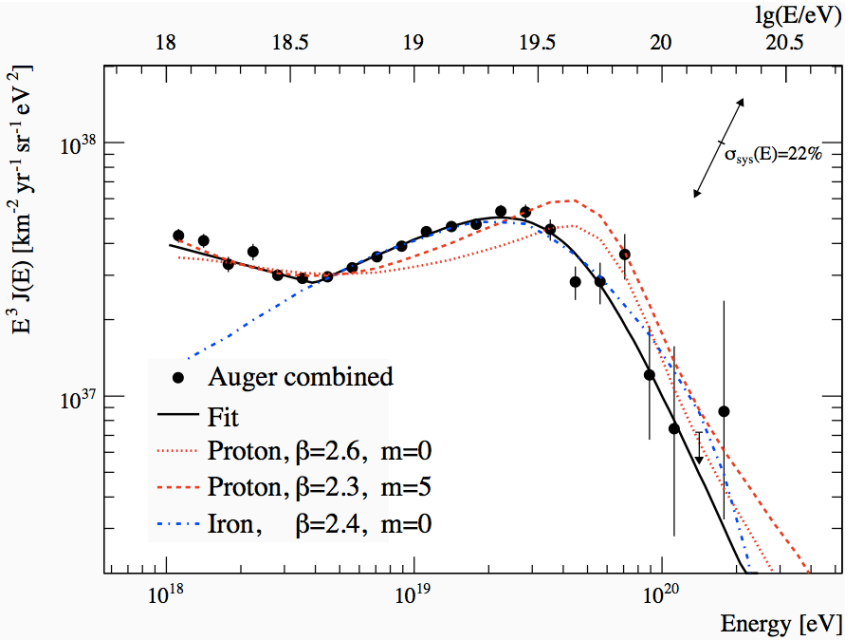
See also G. Thomson, this conference

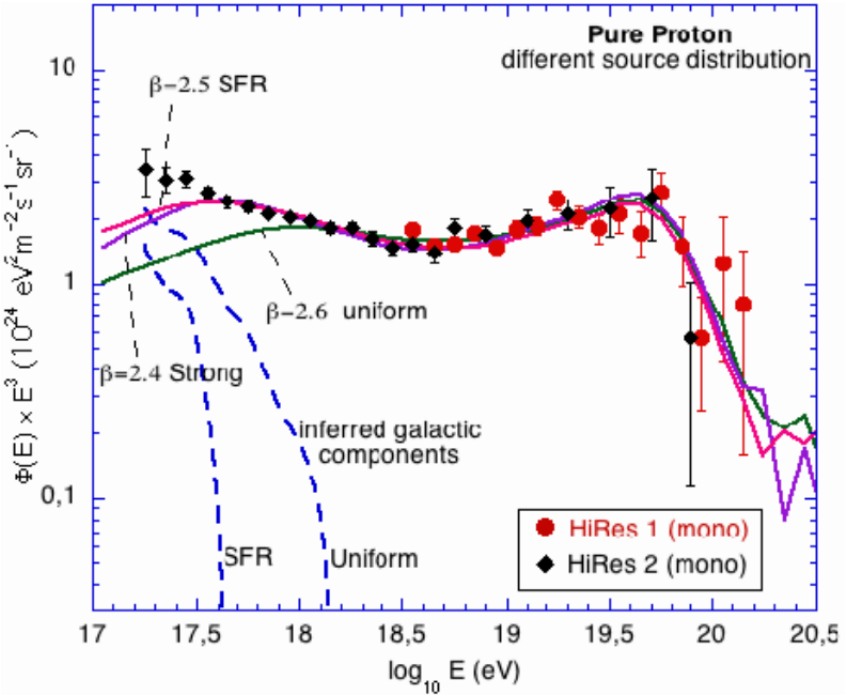


Note: TA is using the same type of SDs as were employed by AGASA

Theoretical modeling

$$J_{source} \propto E^{-\beta}(1+z)^{m}$$





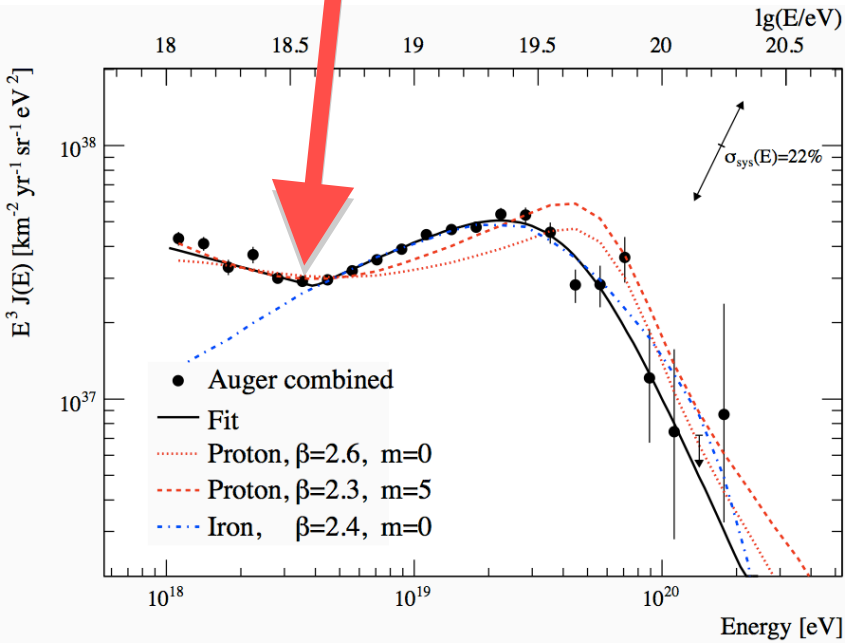
PAO spectrum fitted by Fe primaries
Auger collaboration, ICRC 2009

HiRes spectrum fitted by proton primaries
Berezinsky, Gazizov, Grigorieva (2005)

Dramatically different conclusions at face value ...

Theoretical modeling

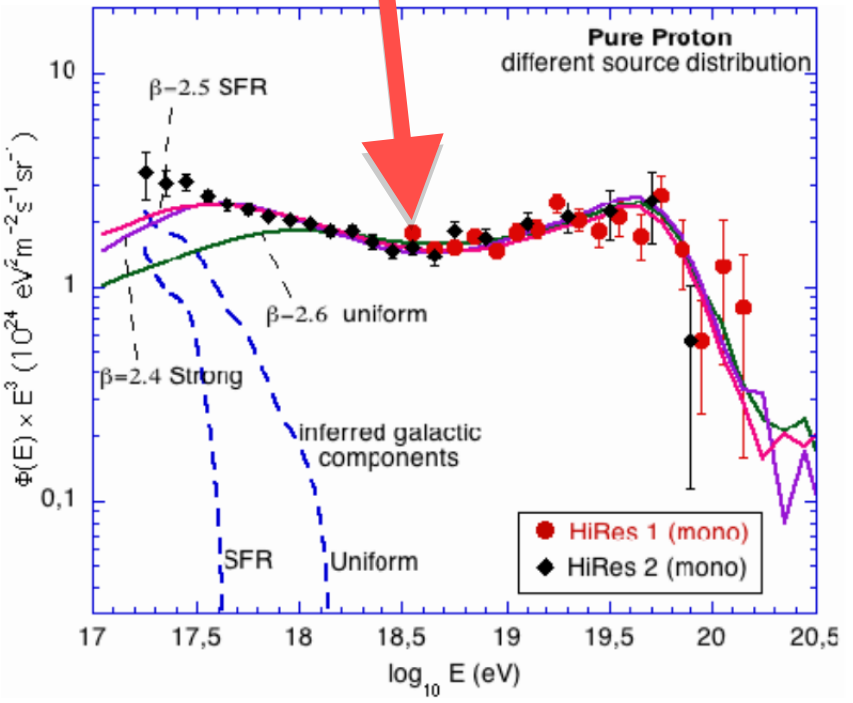
Galactic to Extragalactic



PAO spectrum fitted by Fe primaries

Auger collaboration, ICRC 2009

e^+e^-



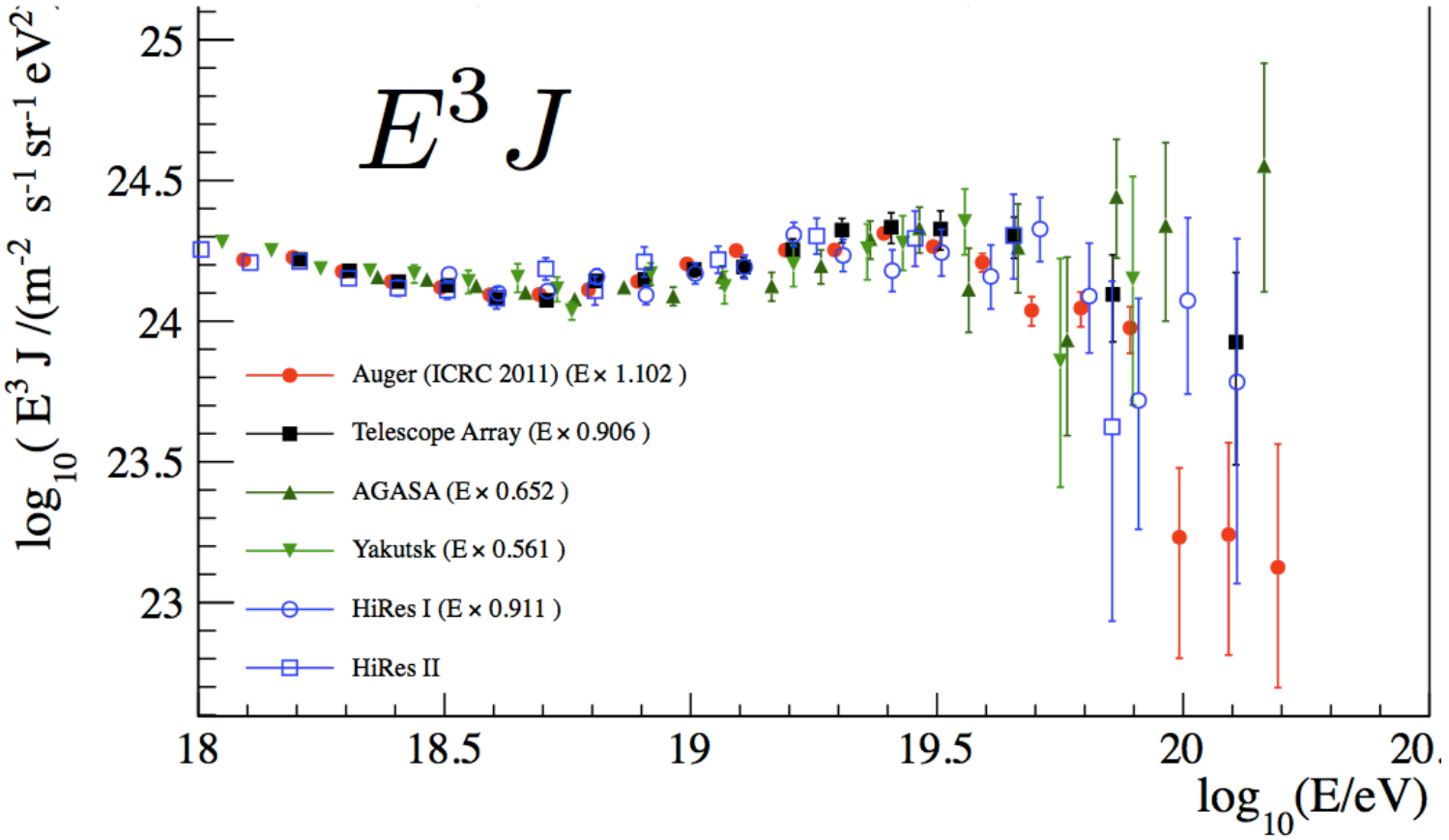
HiRes spectrum fitted by proton primaries

Berezinsky, Gazizov, Grigorieva (2005)

Dramatically different conclusions at face value ...

Spectra comparison

Working Group, UHECR2012



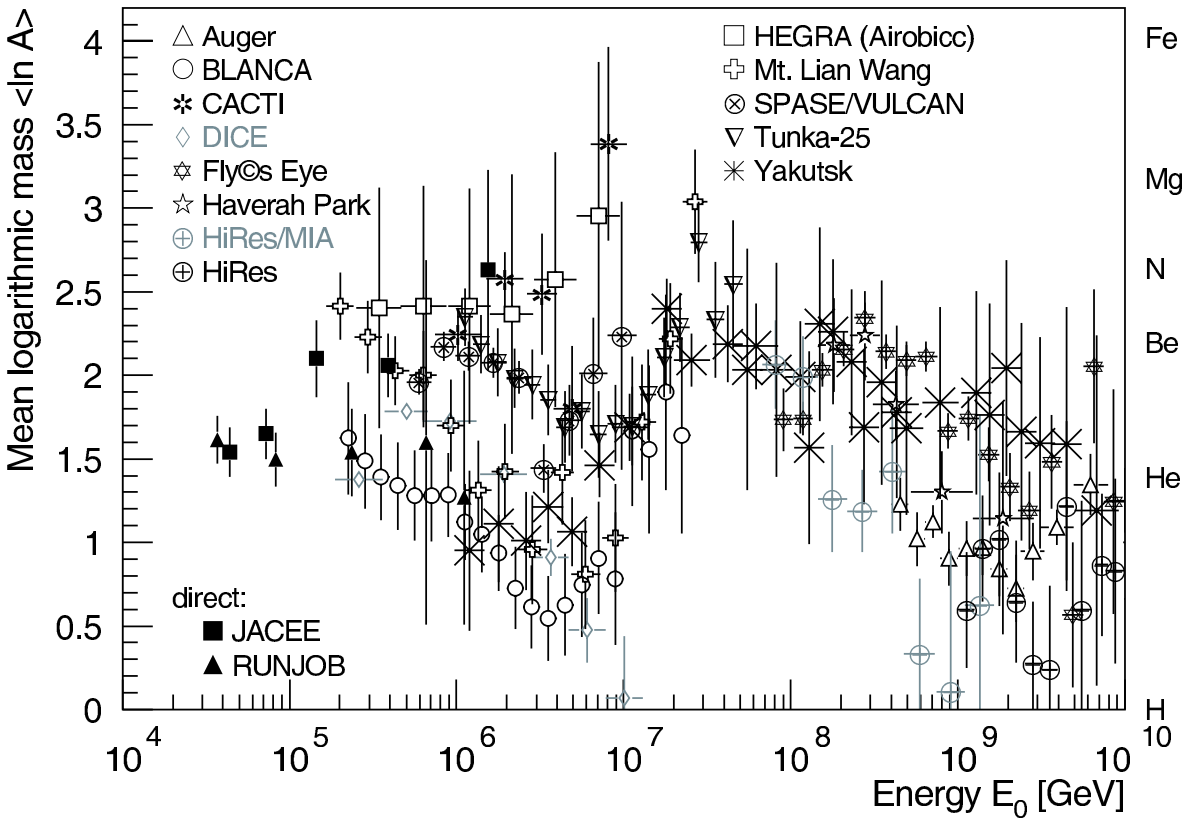
After indicated constant energy shift

- **Auger/HiRes/TA** are in agreement within systematic uncertainties
- At $E < 40$ EeV all spectra match

True energy scale is still unknown, but may be the dip position reveals it?

CR composition

Intermediate energies:



All experiments agree on light composition at

$$E \sim E_{\mathrm{ankle}}$$

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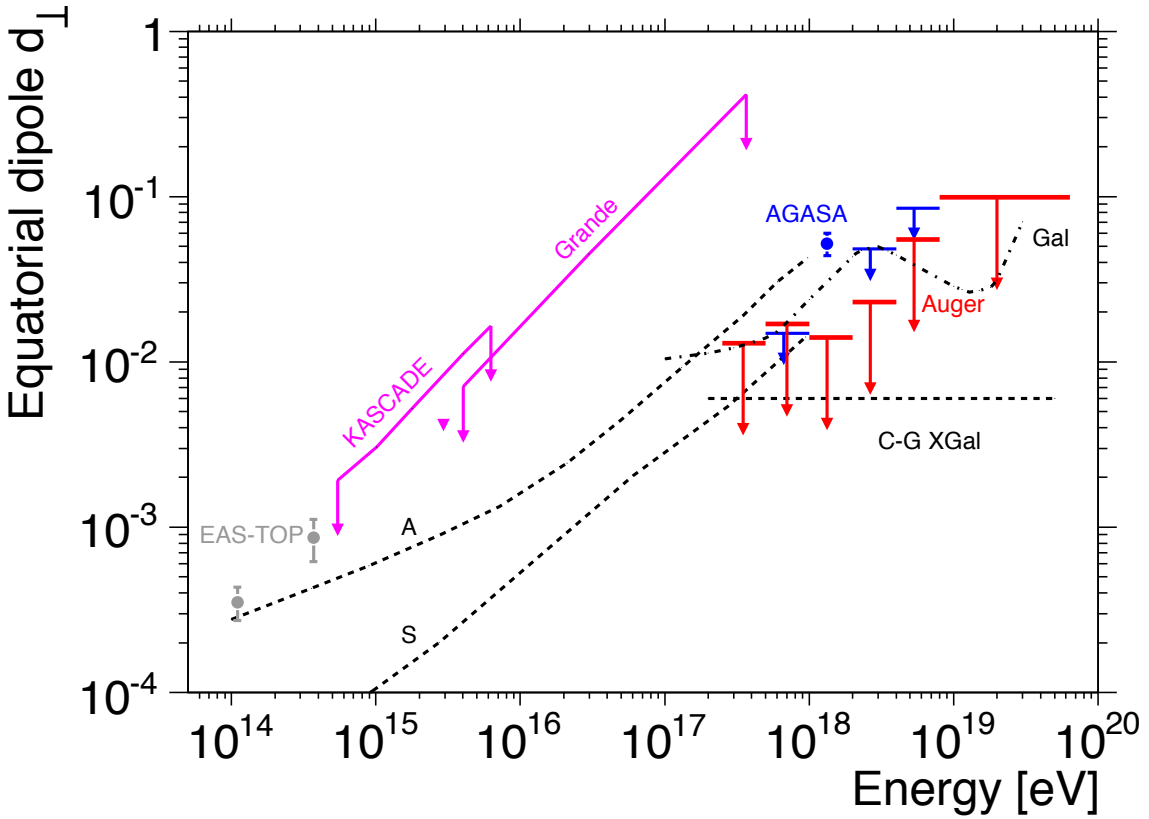
Bluemer et al, Prog.Part.Nucl.Phys. 63 (2009) 293

Upper limits on the dipole

Anisotropy amplitude of the first harmonic in RA

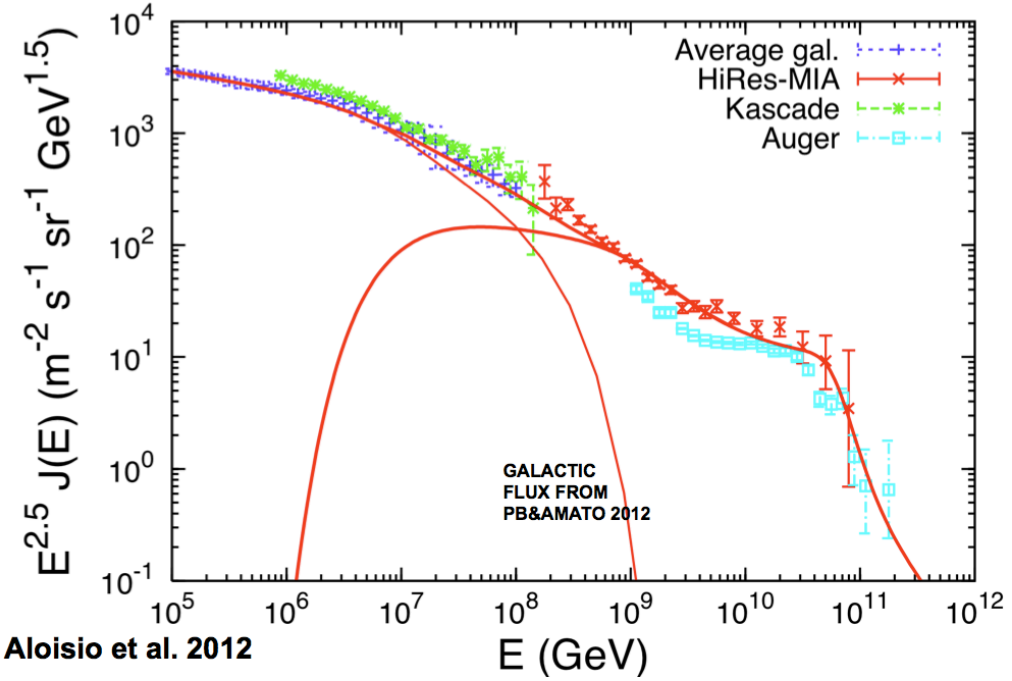


Galactic protons or light nuclei at $E \sim E_{\mathrm{ankle}}$ are excluded by anisotropy.

Giacinti et al, arXiv:1112.5599

PAO, Astropart.Phys. 34 (2011) 627

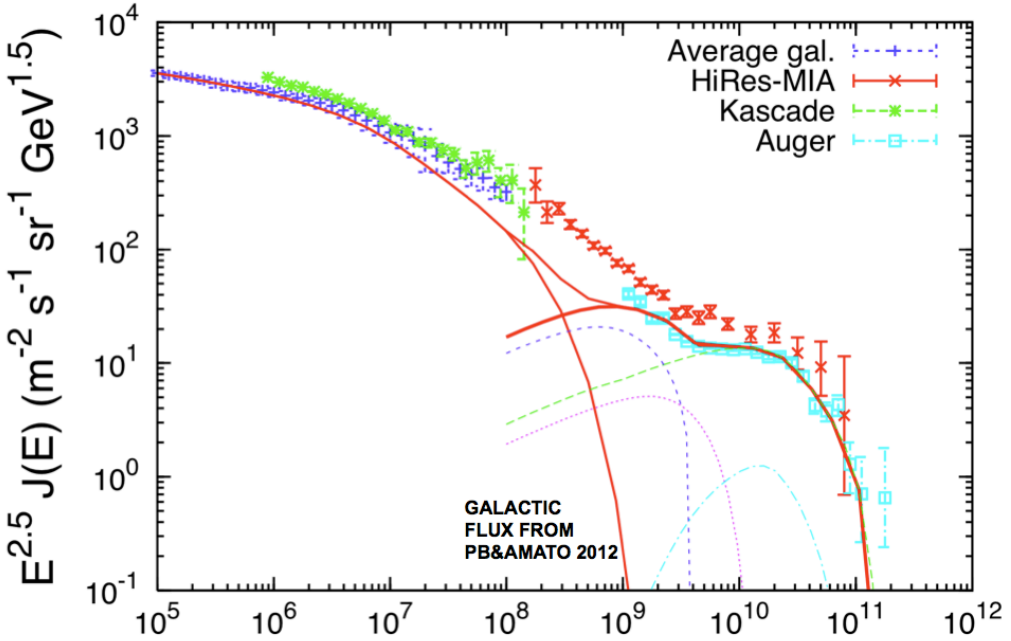
Galactic to Extragalactic transition



Aloisio et al. 2012

At highest energies

HiRes fitted by proton primaries



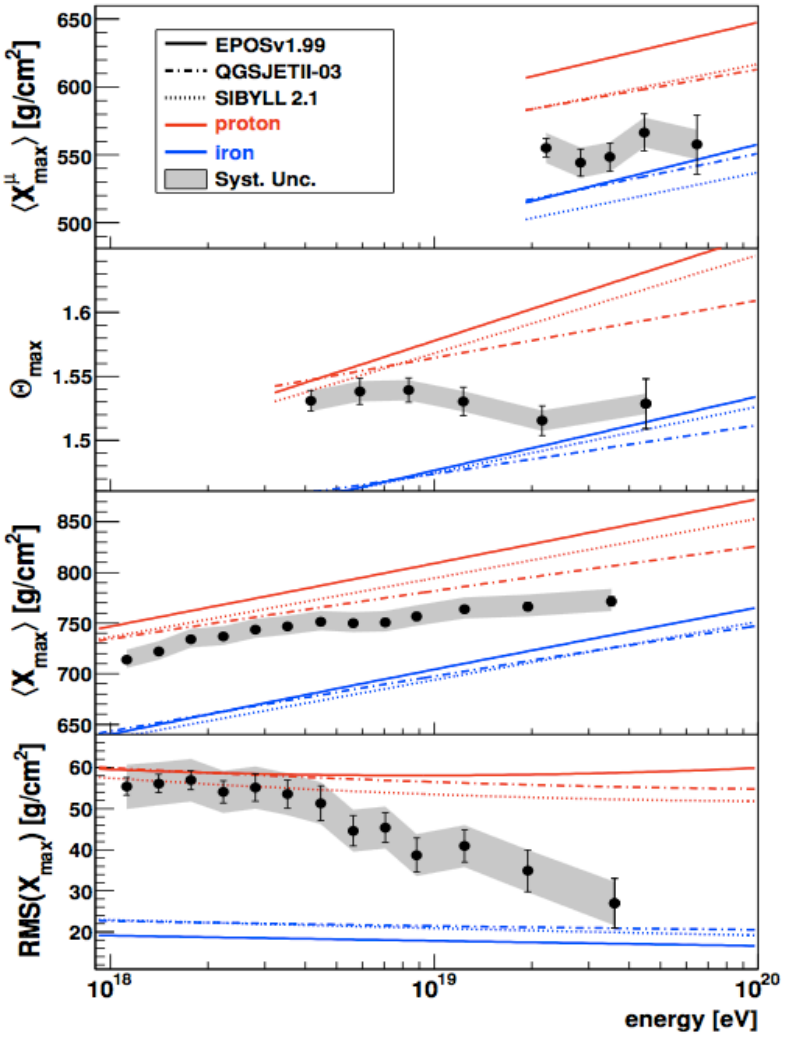
PAO fitted by mixed composition

We cannot use dip position to calibrate energy yet.

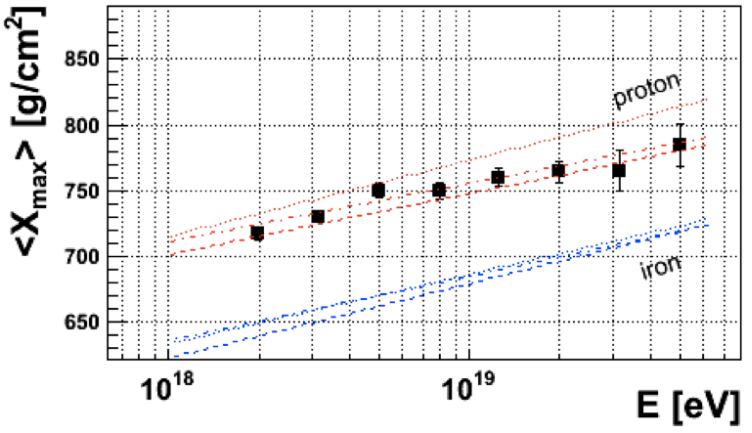
CR composition

At highest energies:

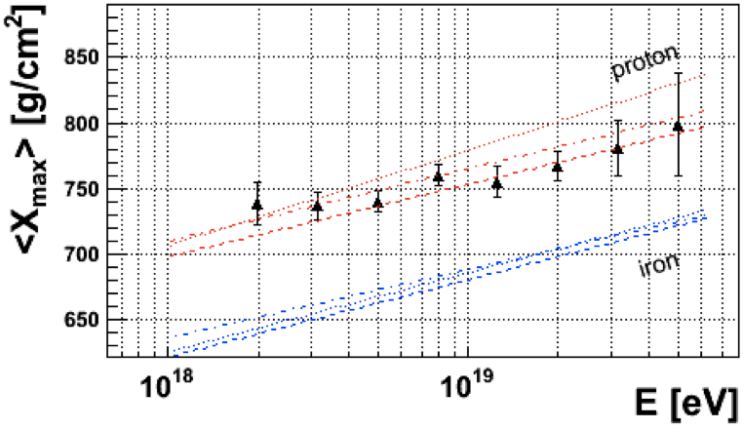
PAO - heavy nuclei



HiRes- protons

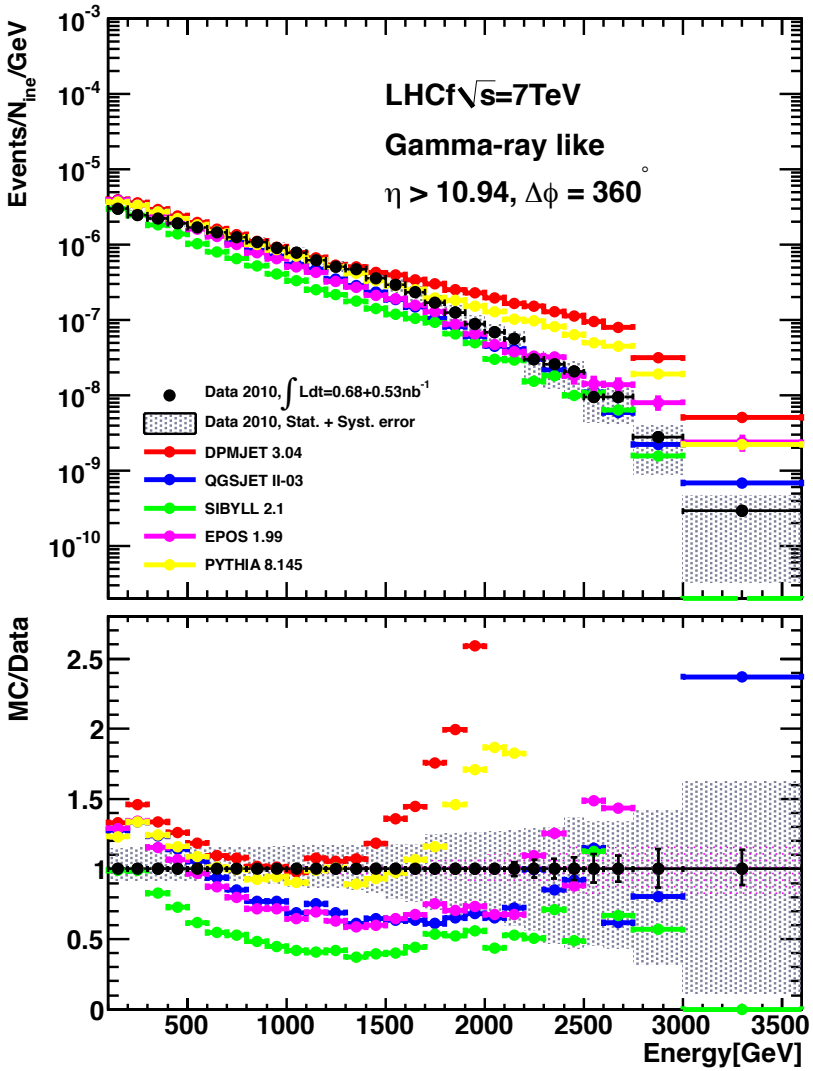


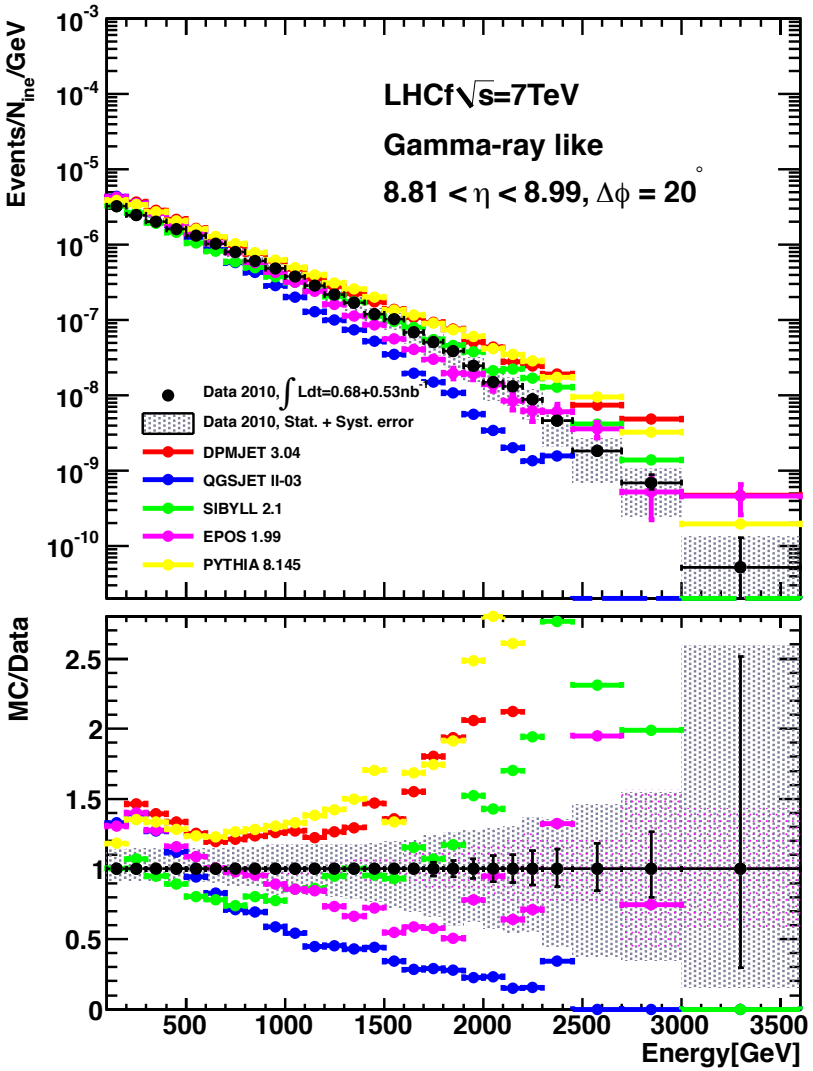
TA- protons



LHCf

Spectra of single γ showers at $\sqrt{s} = 7\ \mathrm{TeV}$ and MC predictions.



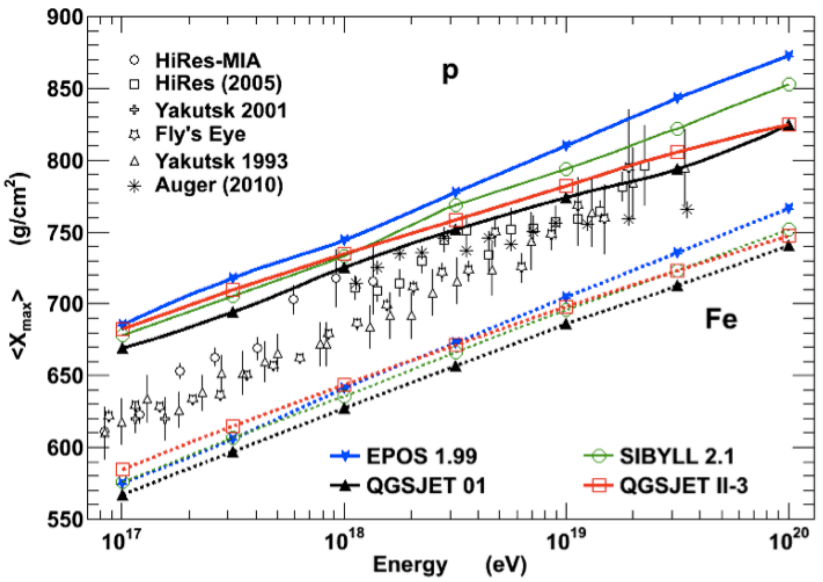


None of the original models perfectly agree with data.

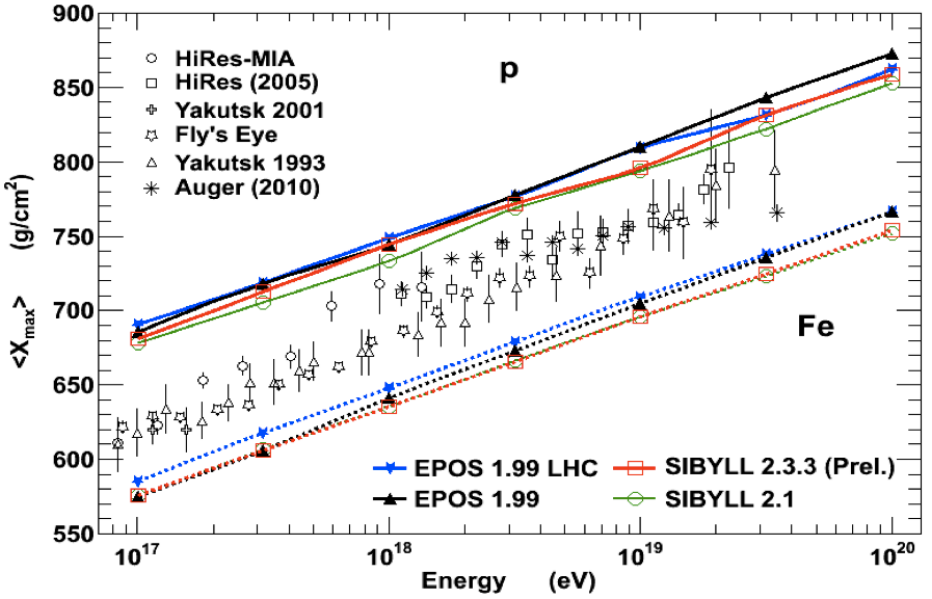
LHCf, Phys.Lett. B703 (2011) 128

EAS with Re-tuned CR Models

Before LHC



With LHC



Cross section and multiplicity fixed at 7 TeV

Pierog, UHECR2012

November 9, 2007

"Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

Anisotropy of the UHECR sky

AGN < 71 Mpc (VC catalogue)

Shading level: exposure

Cen A

30

0

-30

120

-120

Super Galactic Plane

Prob. chance correlation =21%

circles of 3.1° radius centered at UHECR arrival direction

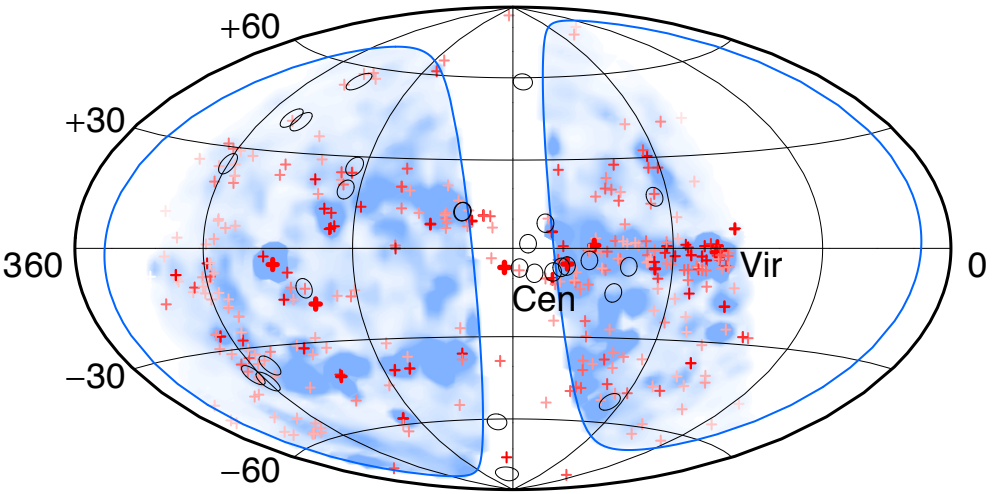
27 events E> $5.7 \cdot 10^{19}$ eV

Angular resolution < 1°

AGNs is not the only interpretation

Tensions within AGN interpretation:

- Signal is not consistent with the hypothesis; Virgo problem.
- Chemical composition - Fe but should be p.
- Local AGNs are weak.
- No signal in HiRes.



Gorbunov, Tinyakov, I.T., Troitsky, arXiv:0711.4060, arXiv:0804.1088
Fargion, arXiv:0801.0227

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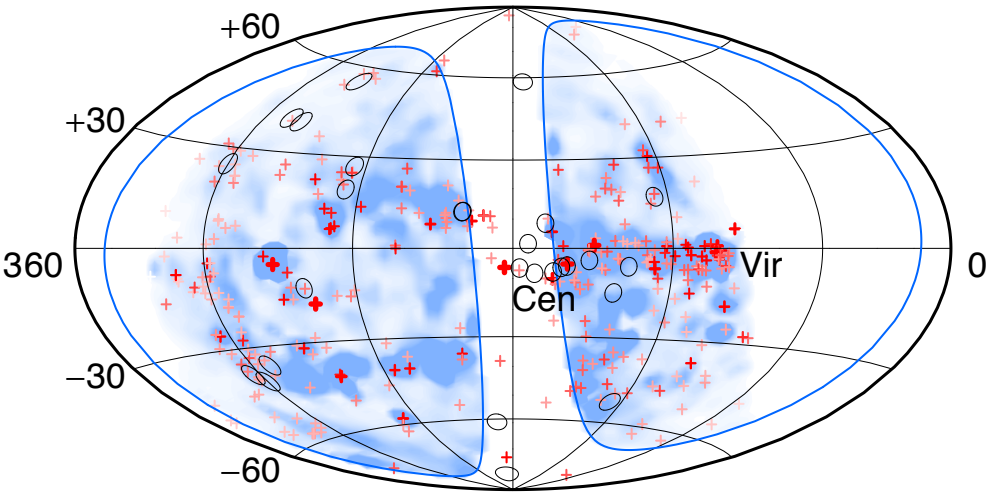
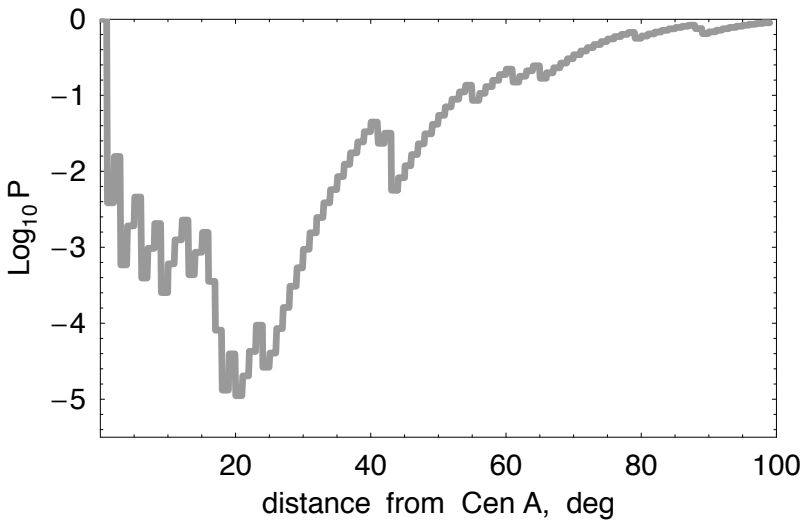




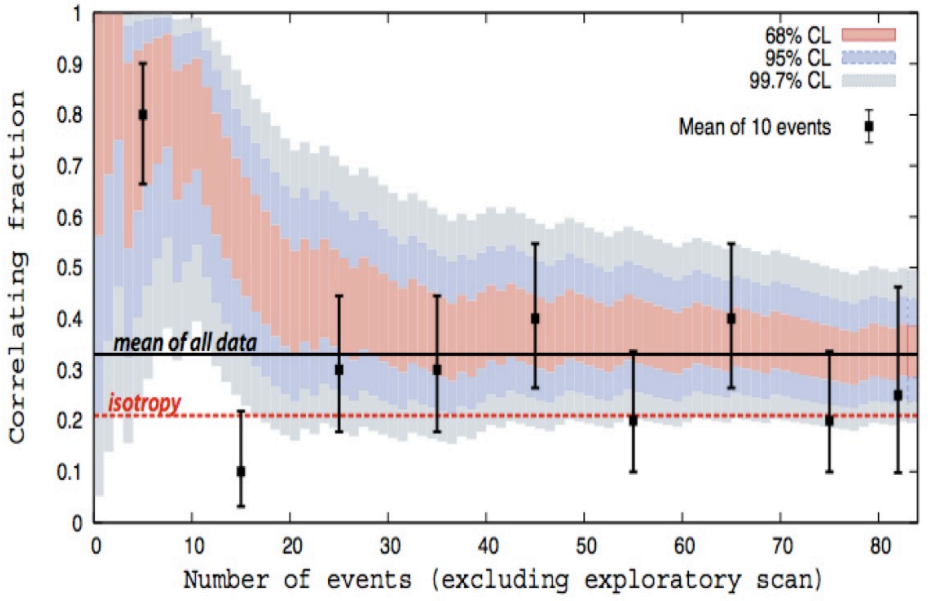
- Cen A is the closest radiogalaxy by chance projected on LSS
- It is outside of HiRes field of view

This provides an alternative explanation for the Auger signal.

Gorbunov, Tinyakov, I.T., Troitsky, arXiv:0711.4060, arXiv:0804.1088
Fargion, arXiv:0801.0227

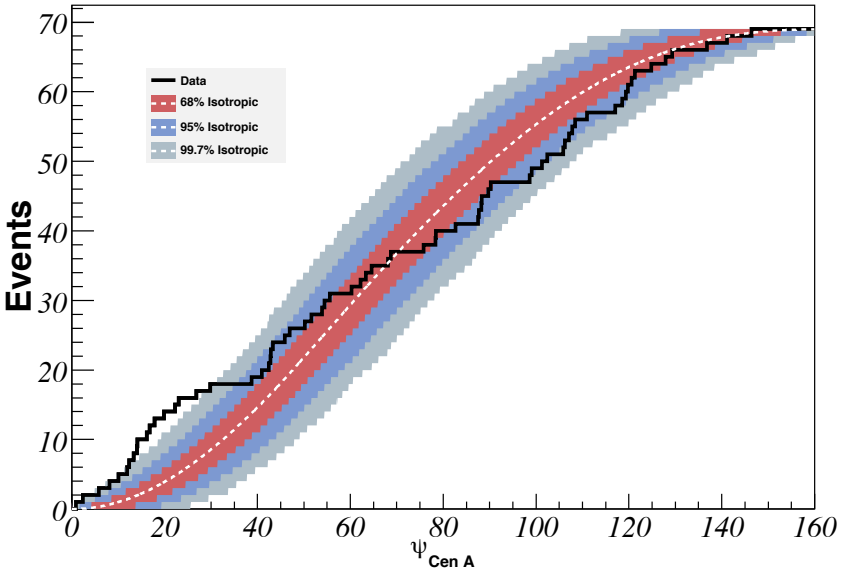
Evolution of the signal in Auger data

AGN



AGN signal became weaker

Cen A



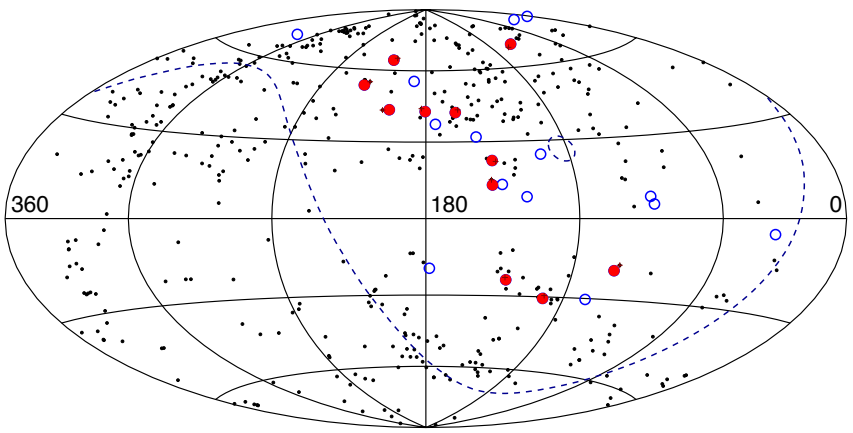
Cen A signal persists

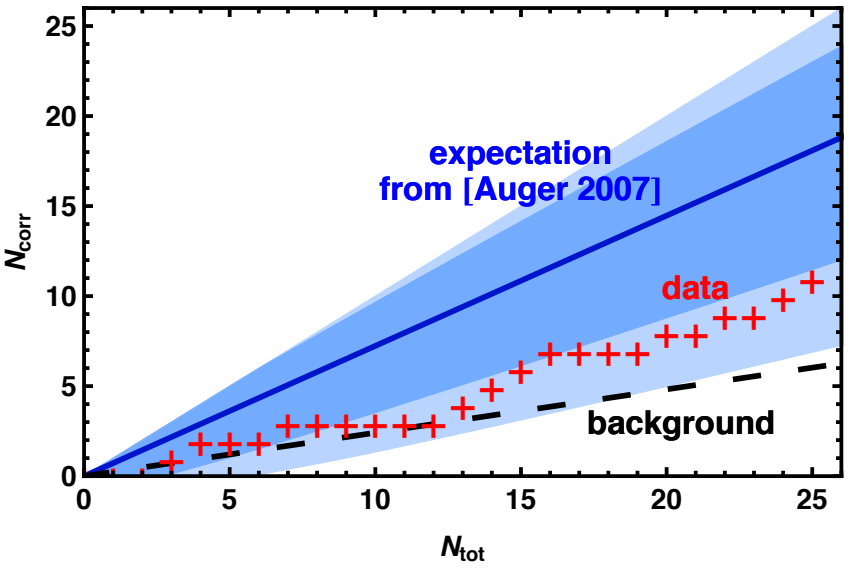
Virgo paucity persists

PAO, ICRC 2011

Search for AGN signal in Telescope Array data

'Blind' test of AGN hypothesis



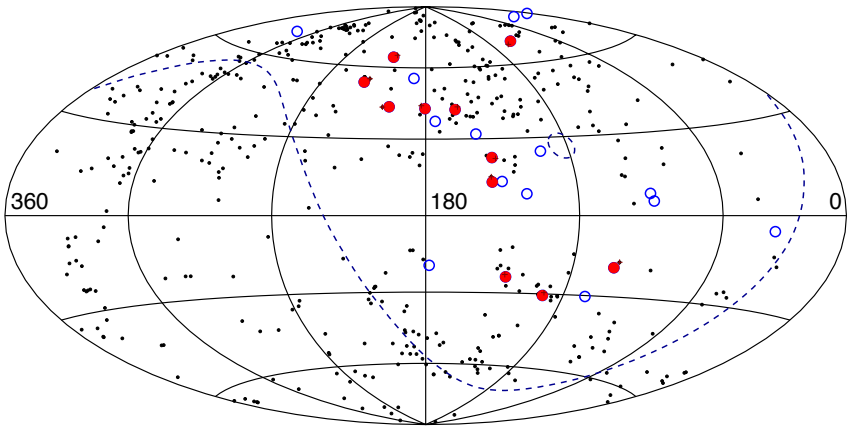


Original Auger AGN hypothesis is not supported by TA data.

TA collaboration, arXiv:1205.5984

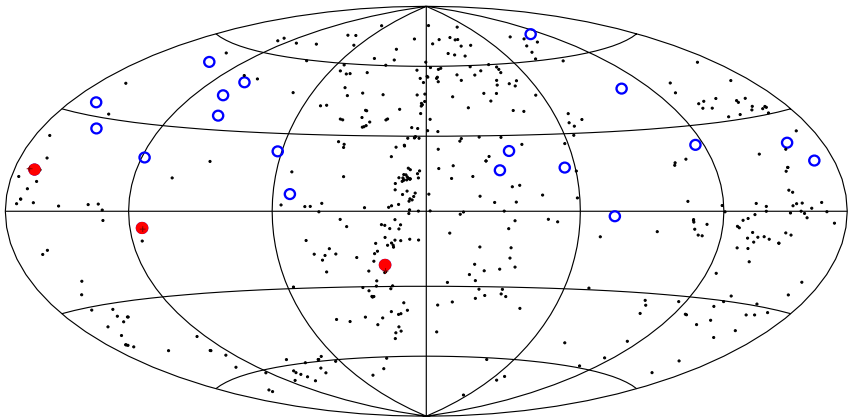
Test of AGN hypothesis in Northern Hemisphere

Telescope Array



TA collaboration, arXiv:1205.5984

AGASA+Yakutsk+HiRes
@ common energy scale

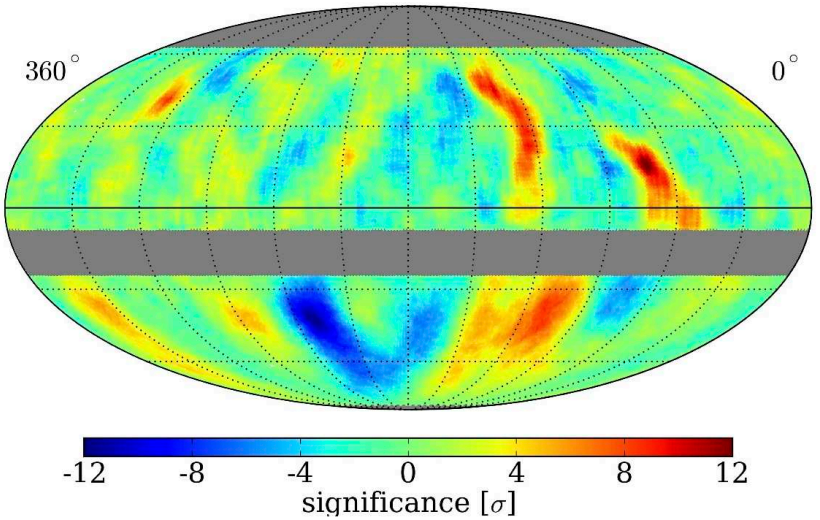


Rubtsov et al, JETP Lett. 95 (2012) 569

Original Auger AGN hypothesis is not supported.

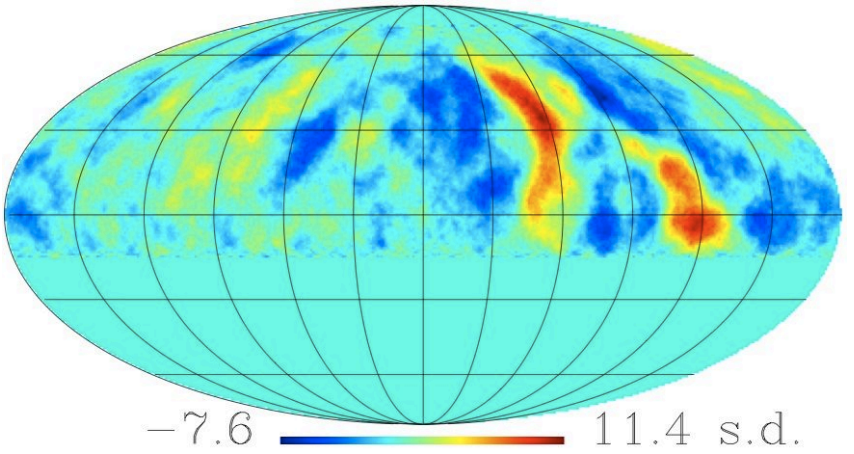
Puzzling anisotropy (of hadronic CRs) at low energy

Flux variations at the level of a few 10^{-4}



1 TeV, Milagro, PRL 101,221101

20 TeV, IceCube, arxiv:1105.2326



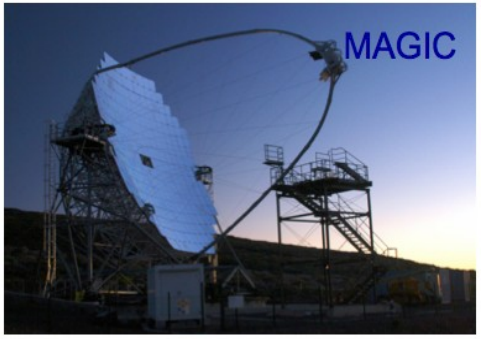
2 TeV, ARGO-YBJ, arxiv:1010.4401

Interpretational problems:

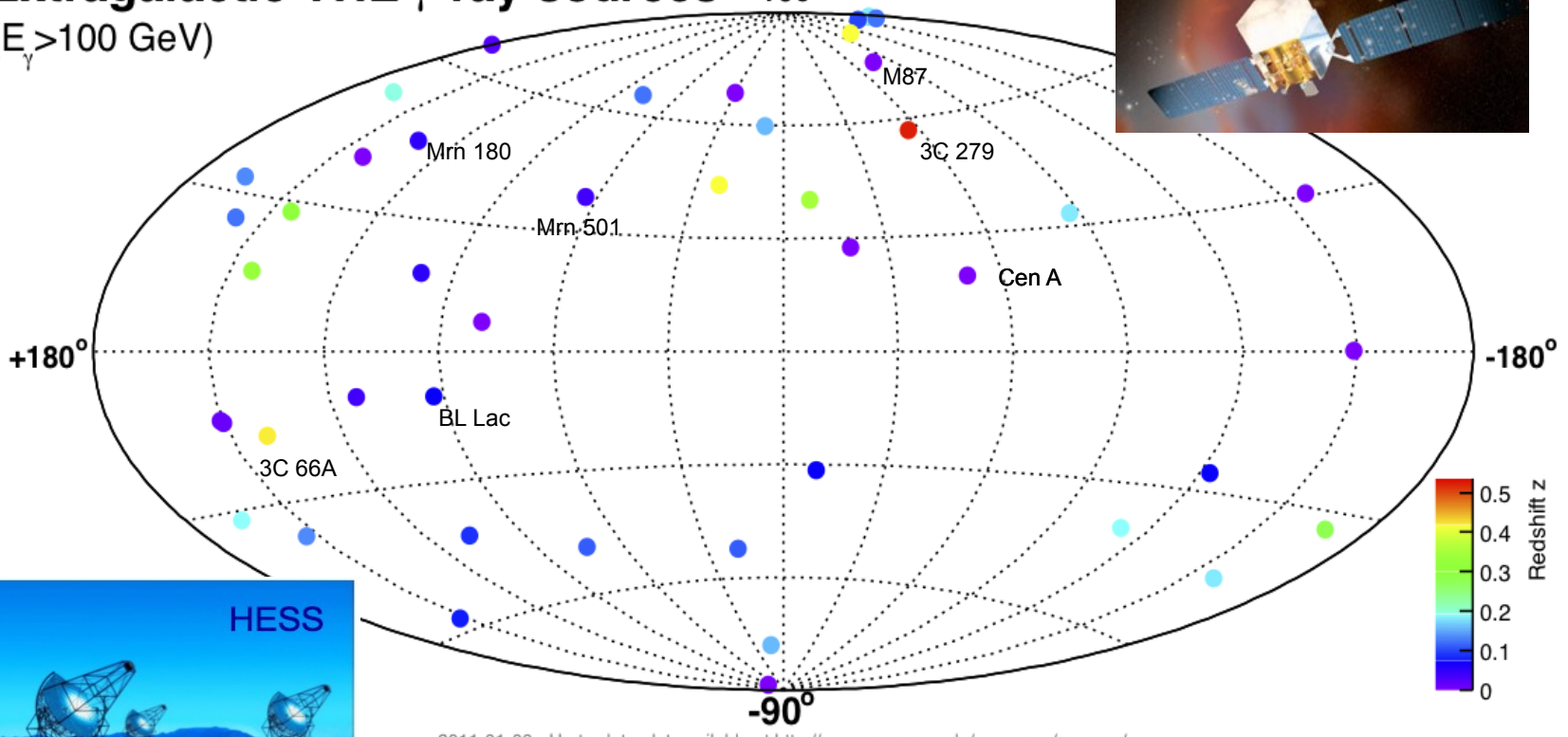
- Larmor radius of a 10 TeV proton in a 2μG magnetic field is 0.005 pc.
- Decay length of 10 TeV neutron is 0.1 pc

No compelling explanation found yet.

Gamma astronomy



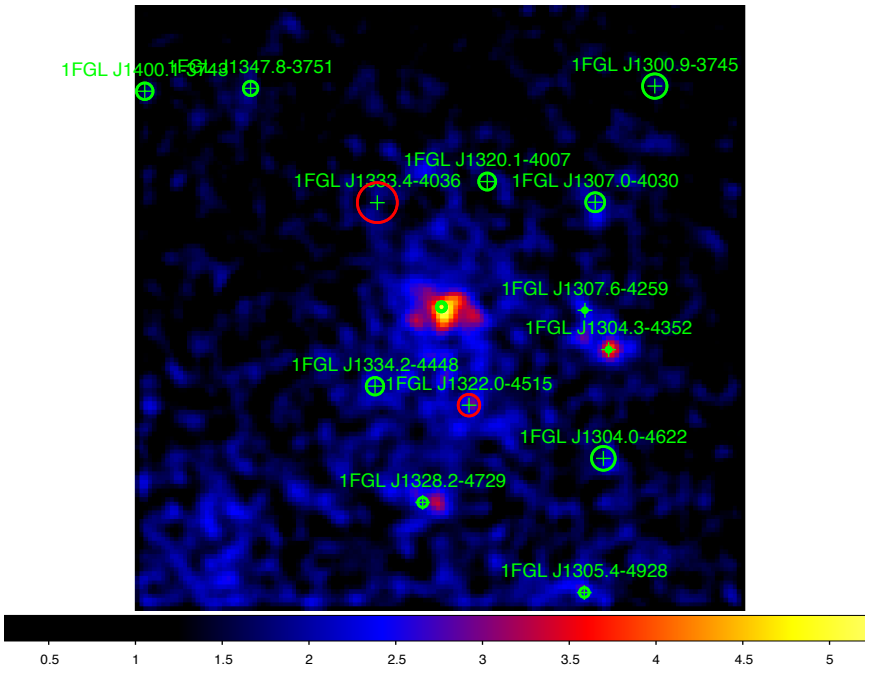
Extragalactic VHE γ-ray sources
(E_γ>100 GeV)

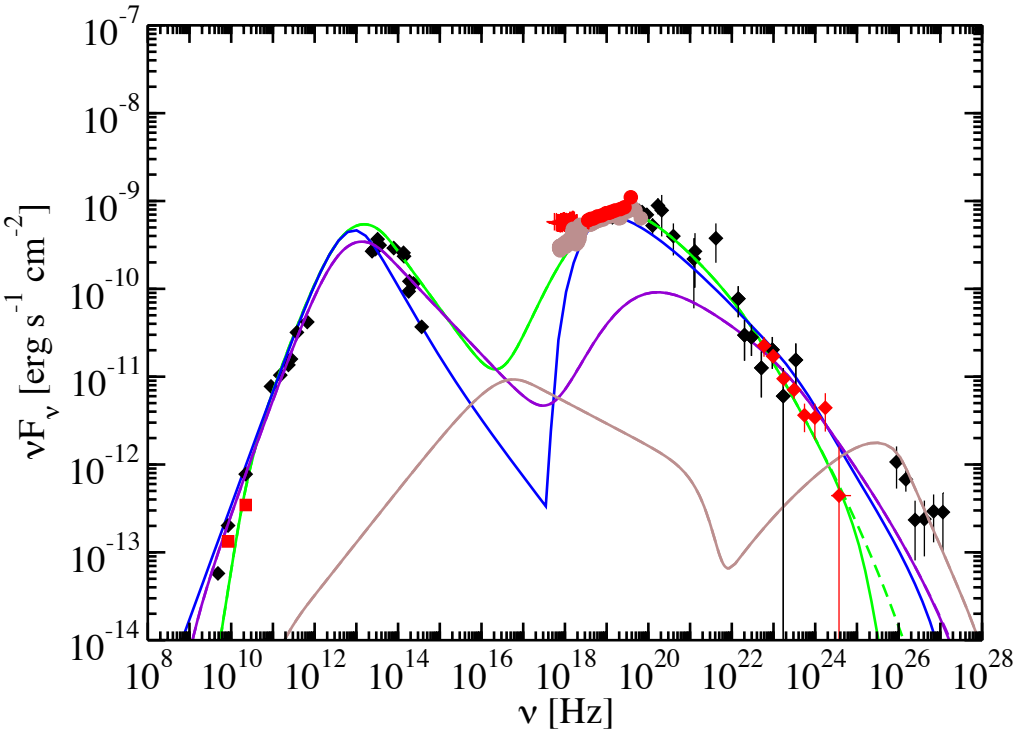


2011-01-08 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

46 Sources

Fermi Lat study of Cen A





Red diamonds: Fermi-LAT data

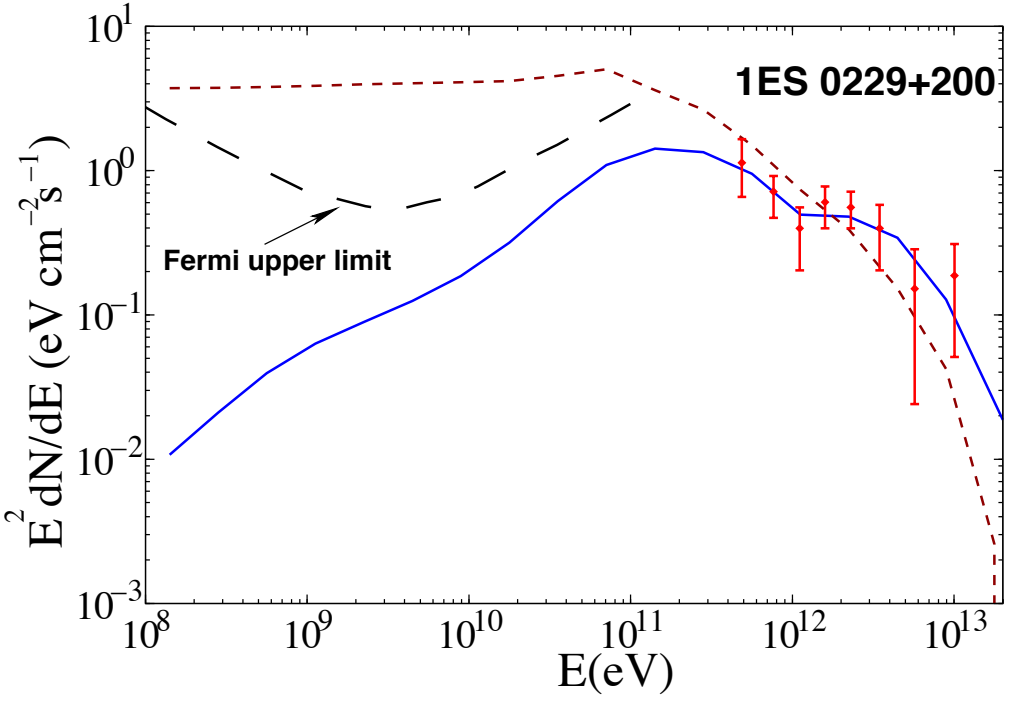
Single zone SSC model explains multiwavelength SED, except for the HESS data.

It is unlikely that protons can be accelerated to energies above 4×10^{19} eV, although this is possible for heavier ions.

Fermi collaboration, ApJ 719 (2010) 1433

Electromagnetic Cascades and TeV γ-Rays

Universe is not transparent to TeV radiation $\gamma\gamma \rightarrow e^+e^-$. Resulting cascades overproduce GeV γ-ray, not observed by Fermi LAT. Why?



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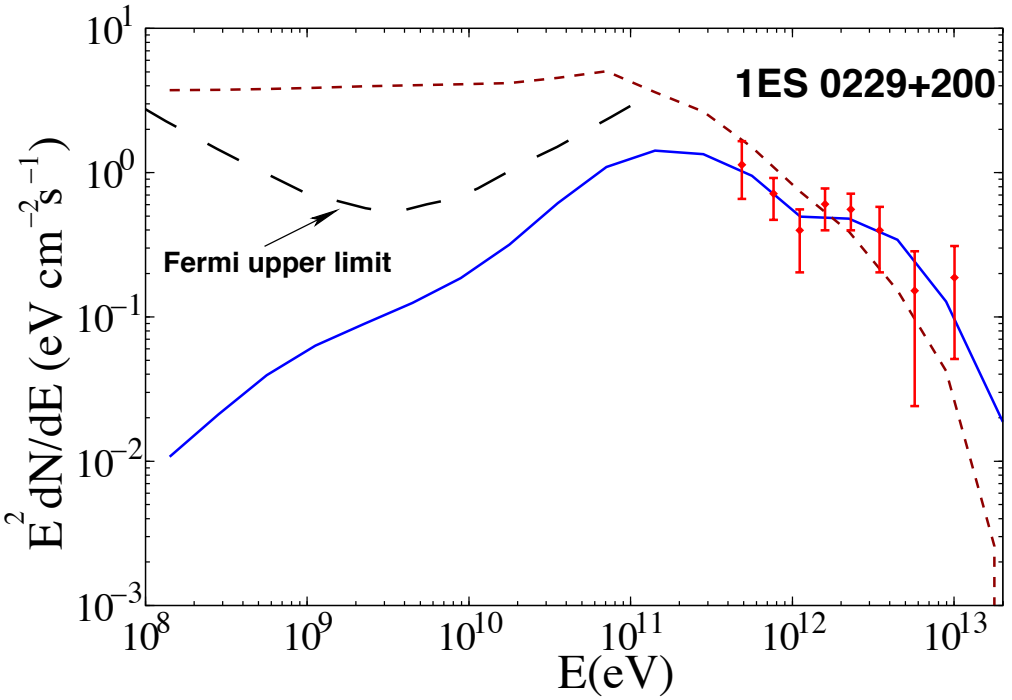


Solution 1:

Magnetic fields $\mathbf{B} > \mathbf{10^{-17}\ G}$ sufficiently disperse GeV γ-ray cascades.

Neronov, Vovk, Science 328 (2010) 73

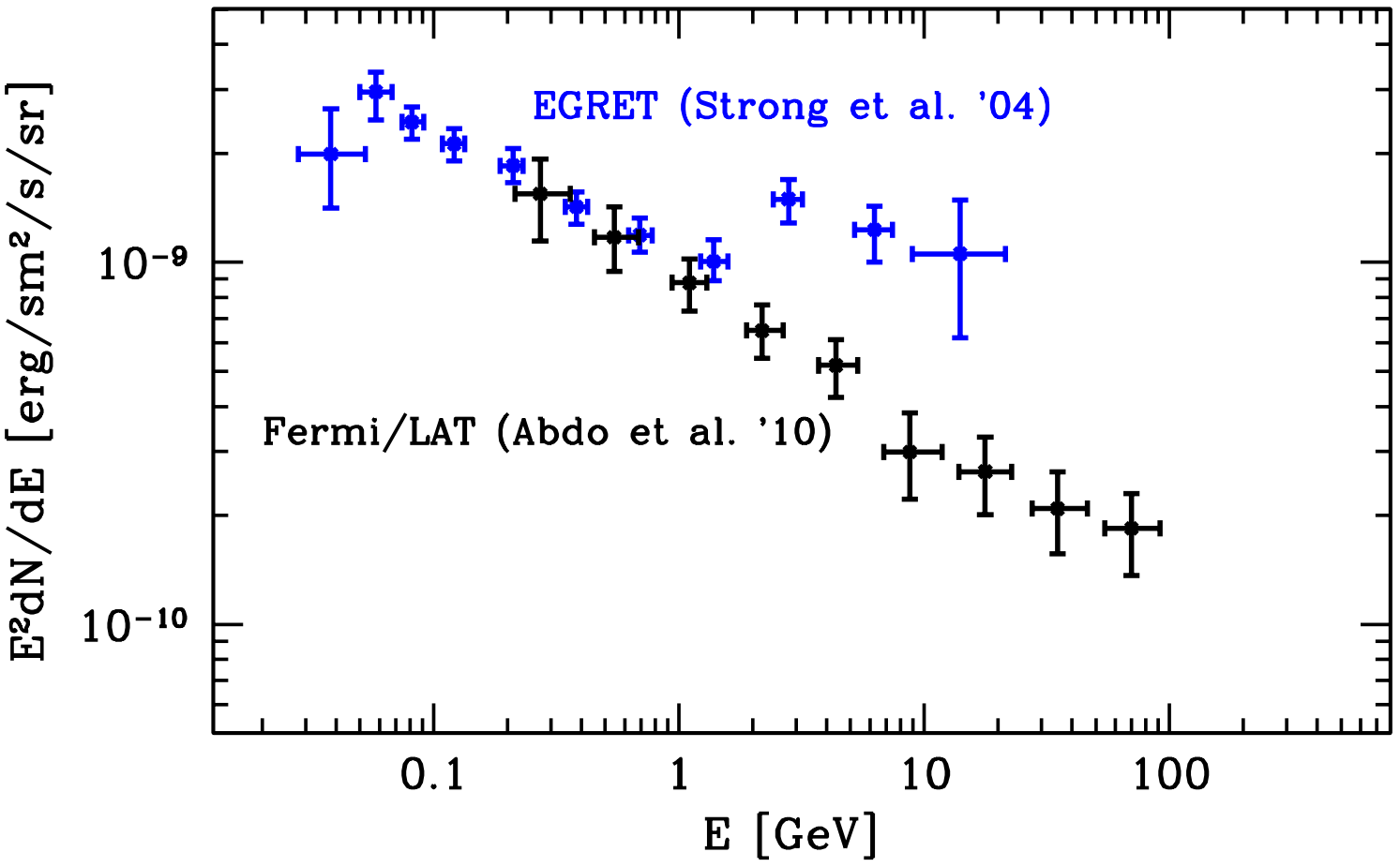
Solution 2:

UHE protons produce TeV γ-ray continuously en-route from source.

Requires $\mathbf{B} < \mathbf{10^{-14}\ G}$.

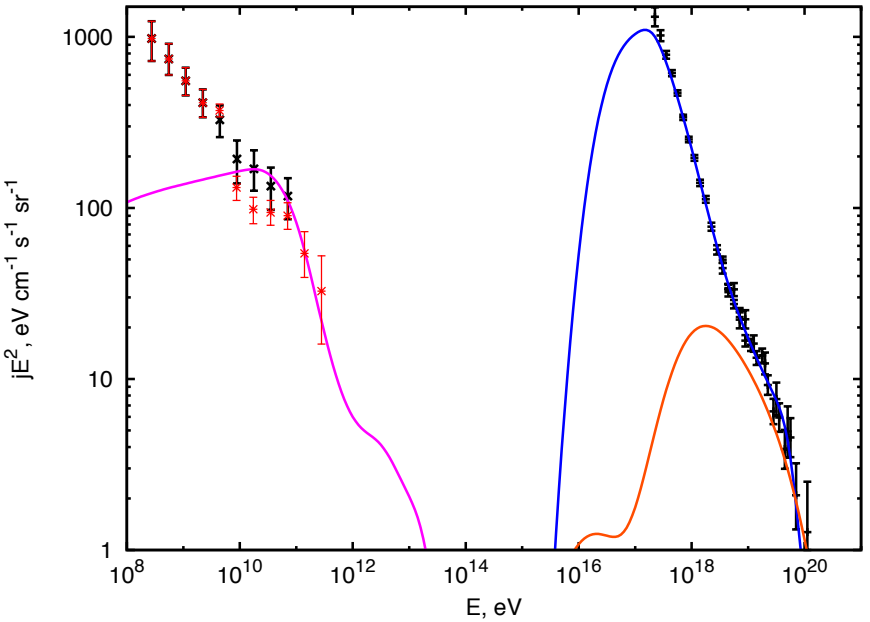
Essey et al, ApJ. 731 (2011) 51

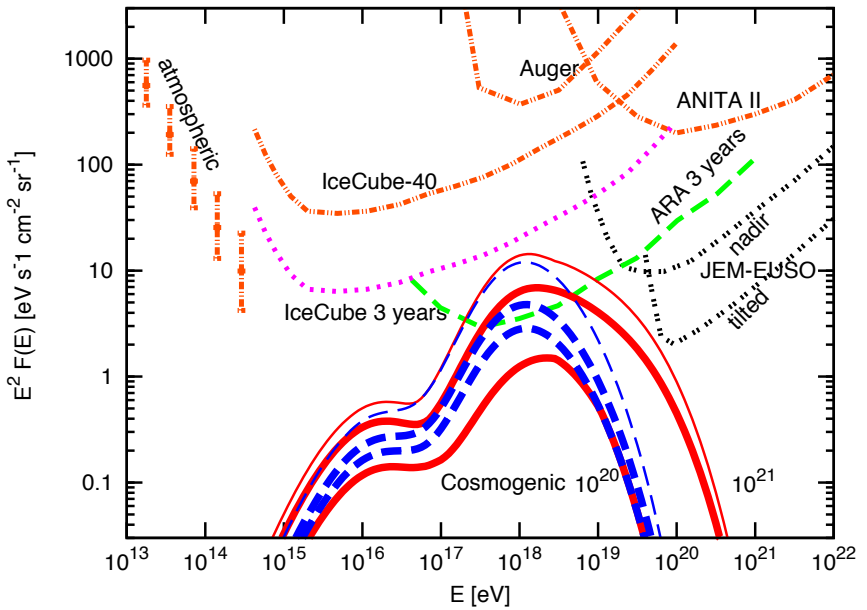
Extragalactic γ-ray background



UHECR and extragalactic γ-ray background

UHE primary p and secondary γ and GZK ν



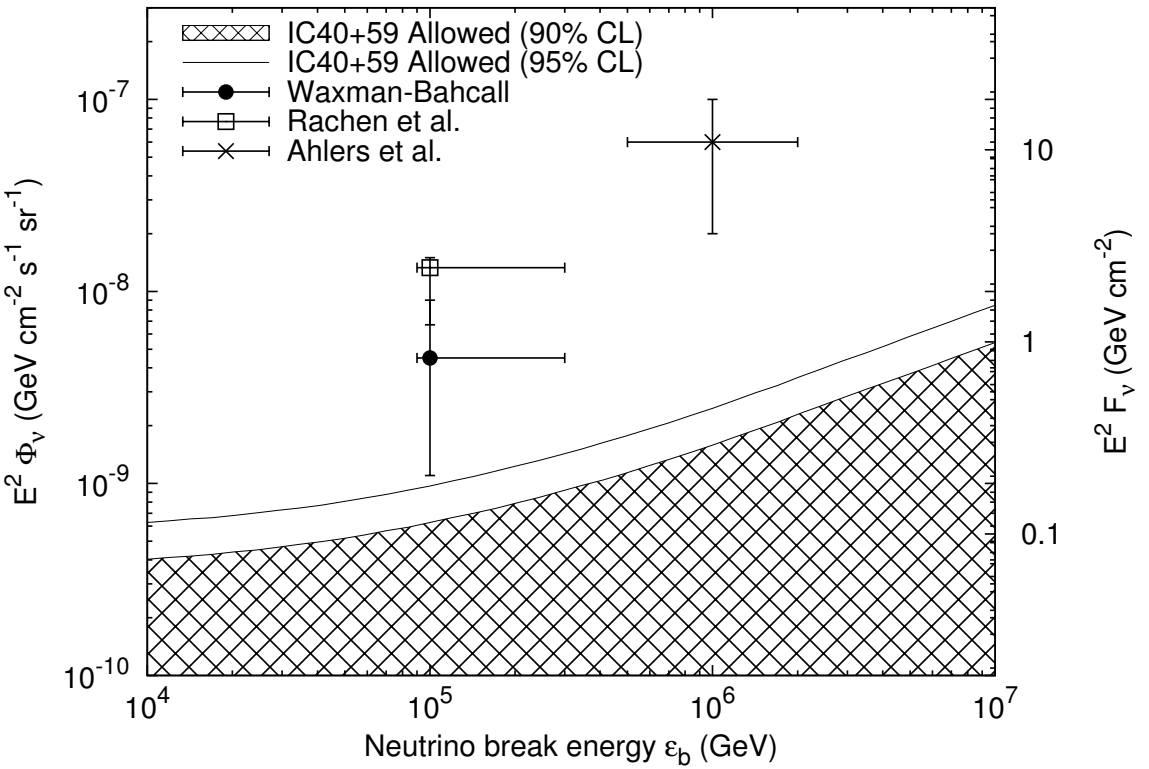


Limits on source properties are emerging.
Injection spectrum $\beta > 2.4$ and evolution parameter $m < 4$.
Revised upper bounds for GZK neutrino.

Gelmini, Kalashev, Semikoz, JCAP 1201 (2012) 044 , see also
Berezinsky et al, Phys. Lett. B 695 (2011) 13
Ahlers at al, Astropart. Phys. 34 (2010) 106

GRB models of UHECR are in problem

Neutrino flux for cosmic ray normalized models



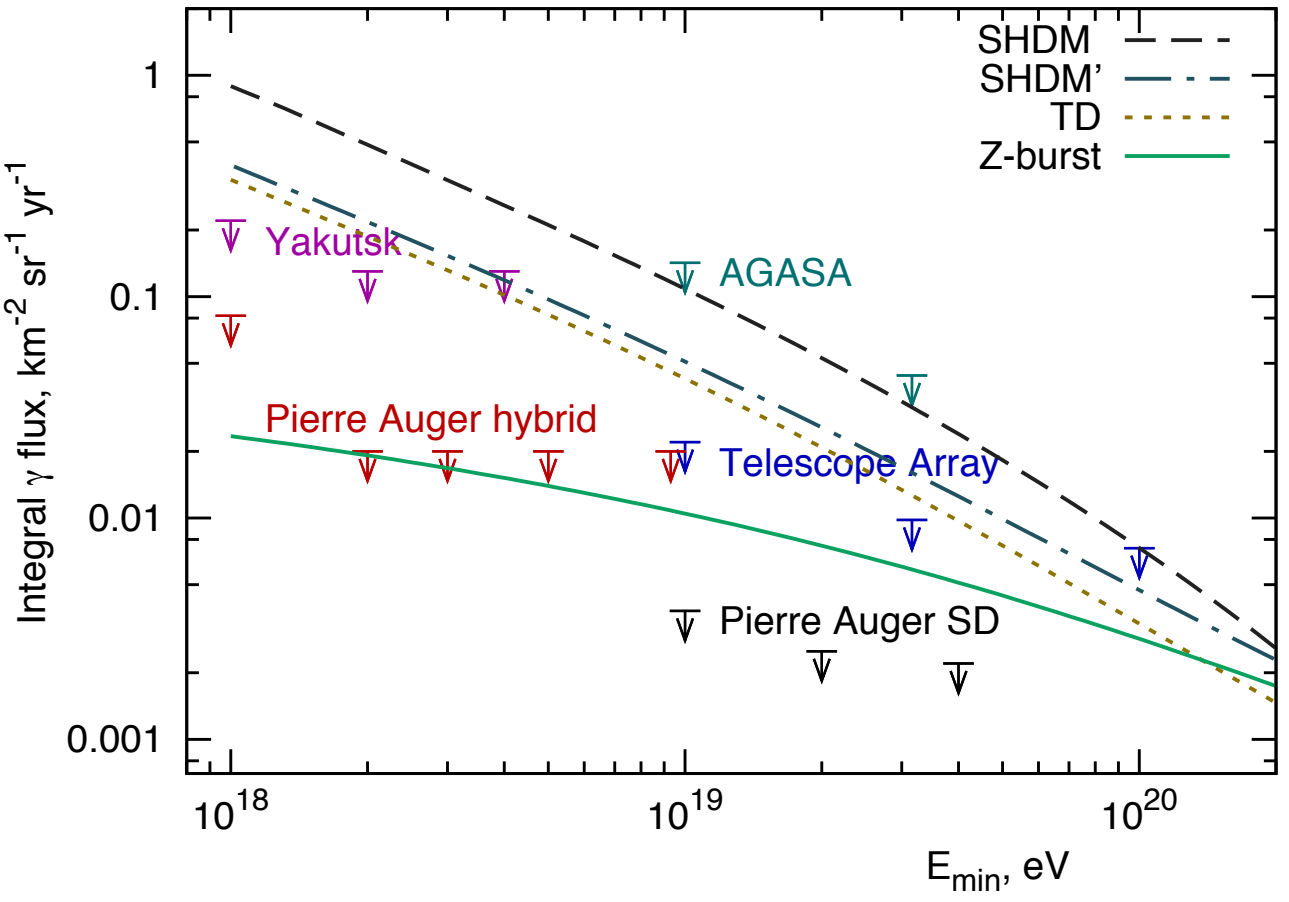
Derived using tight constraint on spatial and temporal coincidence of ν with a γ-ray burst.

GRBs are not the only sources of cosmic rays

IceCube, Nature 484 (2012) 351

See also D. Williams, this conference

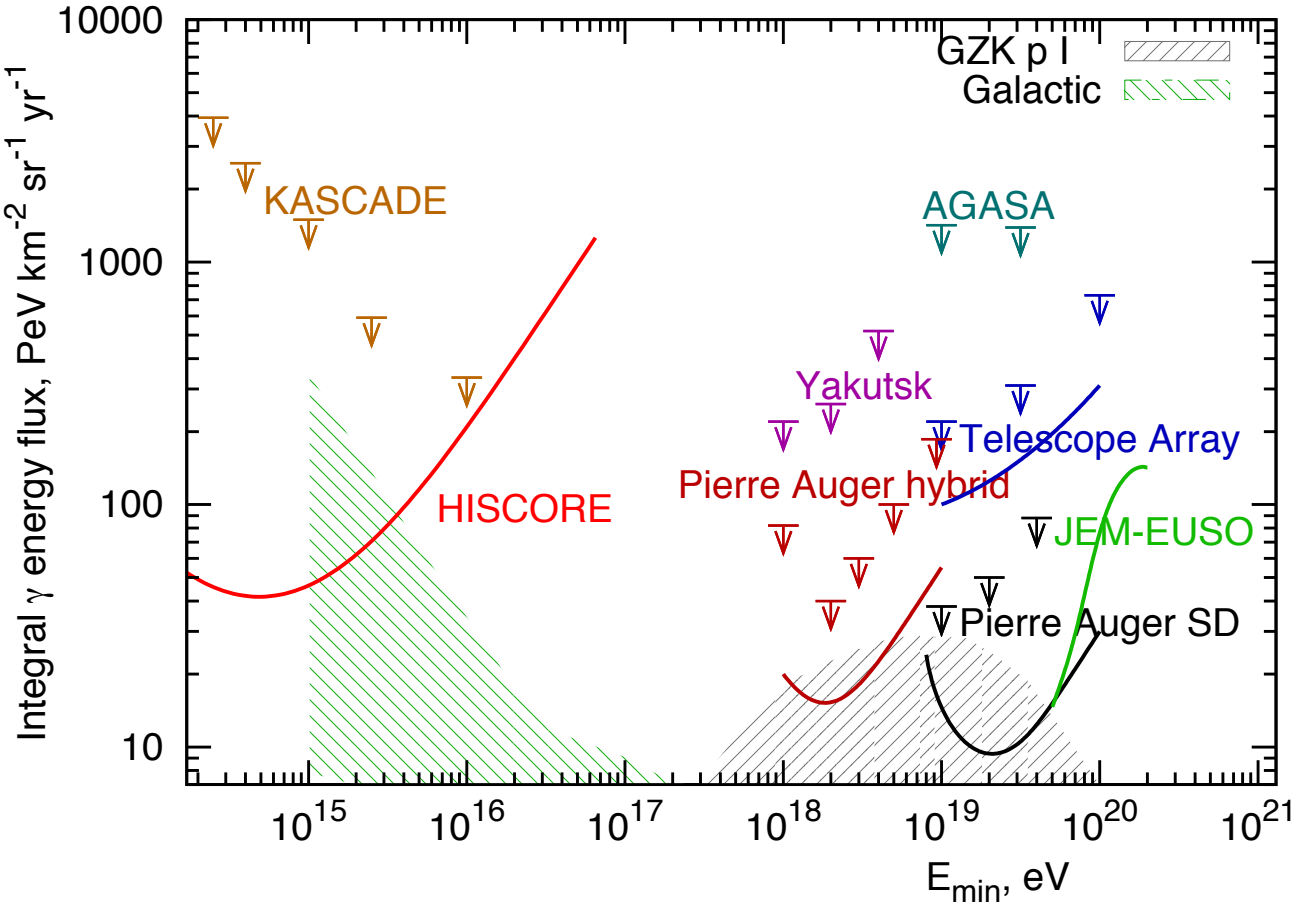
Search for UHE photons



Limits on photon flux. Exotic models ruled out.

Multimessenger WG, UHECR2012

Search for UHE photons



Limits on photon flux and projected sensitivities.

Multimessenger WG, UHECR2012

Conclusions

- Greisen-Zatsepin-Kuzmin cut-off
  - The cut-off is firmly established, it's nature is under study
- Cosmic ray composition
  - Protons or Heavy Nuclei?
  - Disagreement between PAO and HiRes/TA is not understood yet
  - What are the fractions of photons and neutrino?
- Cosmic ray sources and anisotropy
  - Large number of new γ-ray sources detected by H.E.S.S., MAGIC, VERITAS and Fermi
  - Anisotropy of TeV CR confirmed by ARGO/YBJ and IceCube
  - Is local population of AGNs relevant for UHECR?
  - GRBs are out of favour
  - Is charged particle astronomy possible?
- Shower development
  - New physics?
  - LHC data are streaming and should improve understanding