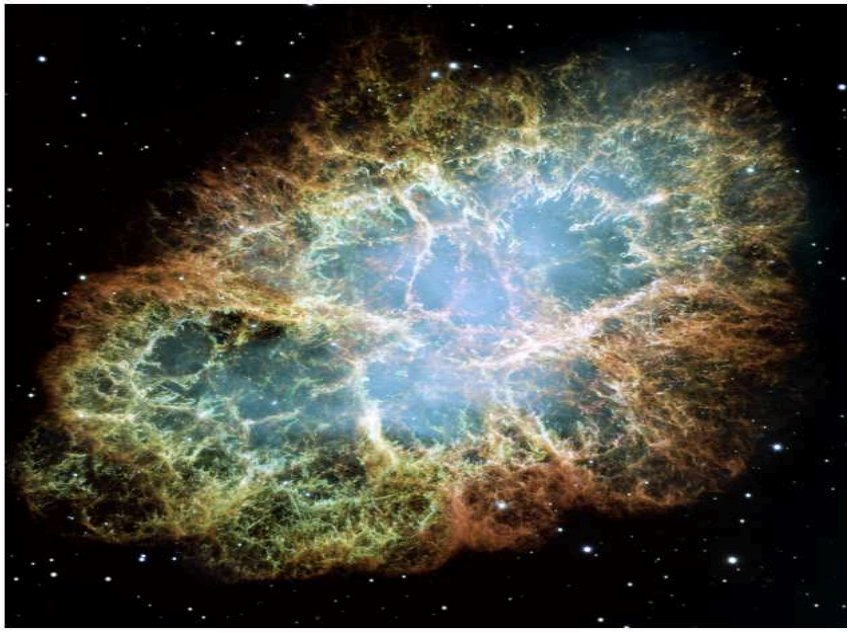
Cosmic Rays

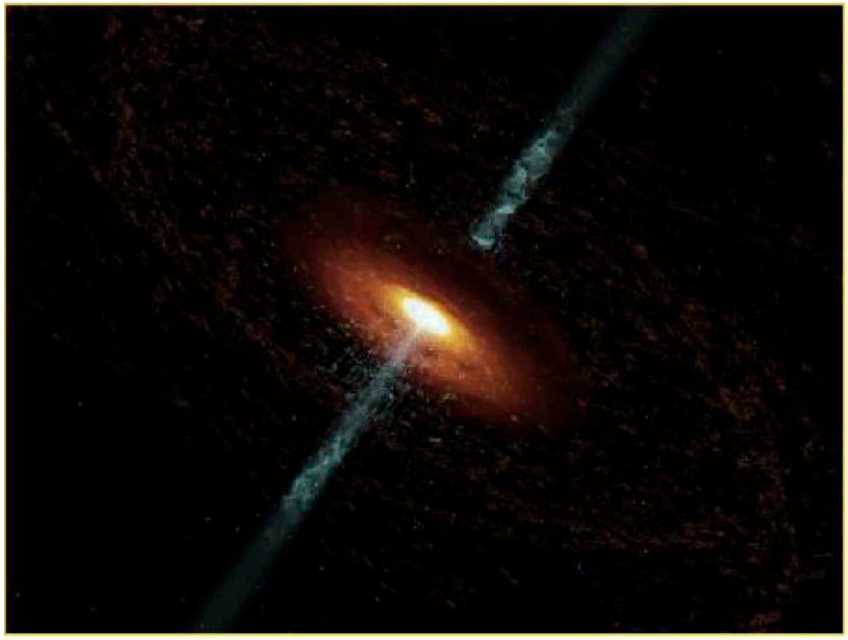
I. Tkachev

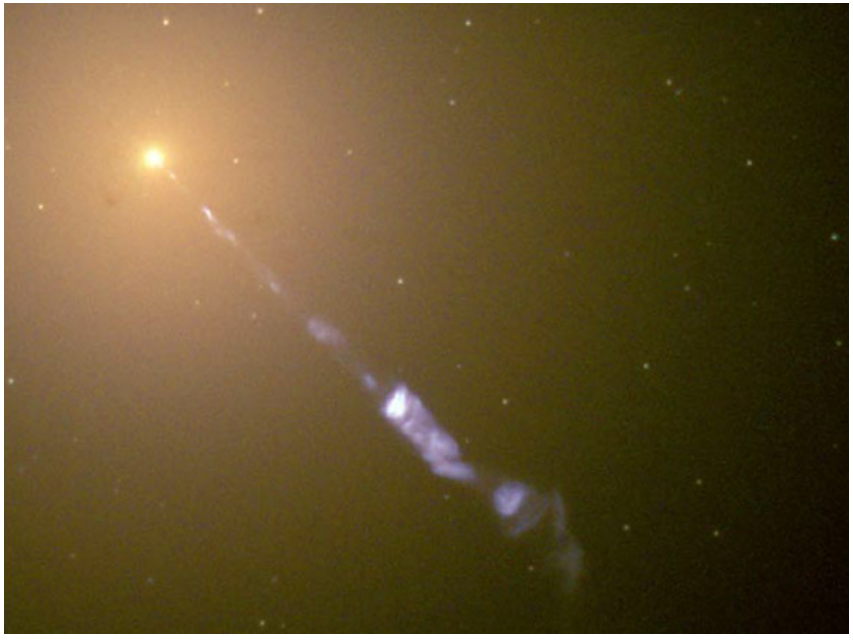
Institute for Nuclear Research, Moscow

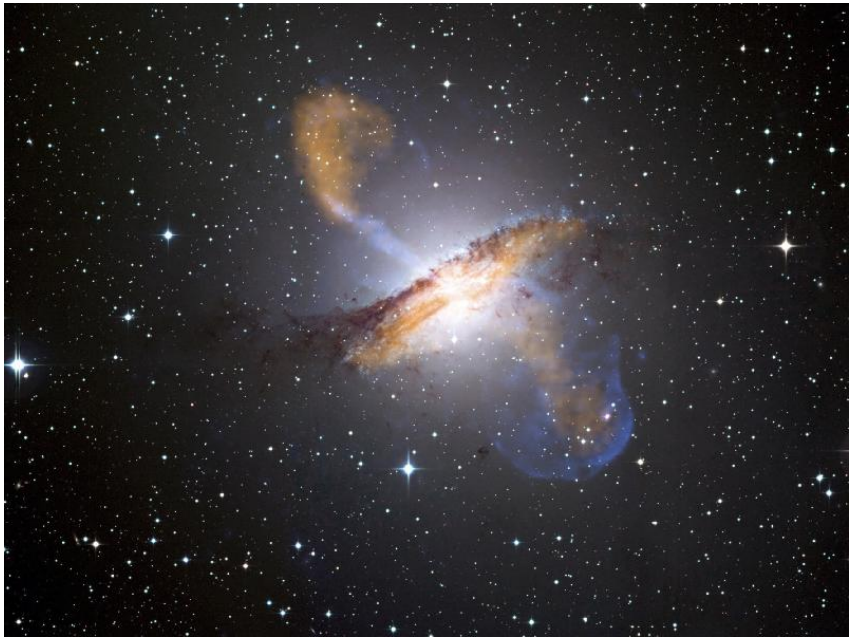
26 July 2011, Grenoble

Quest for cosmic ray sources.

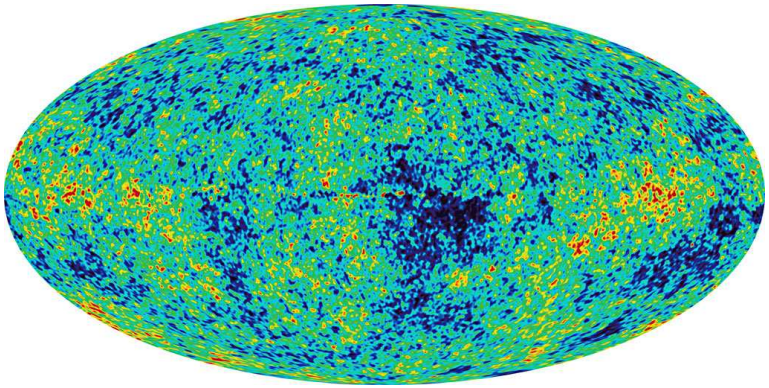




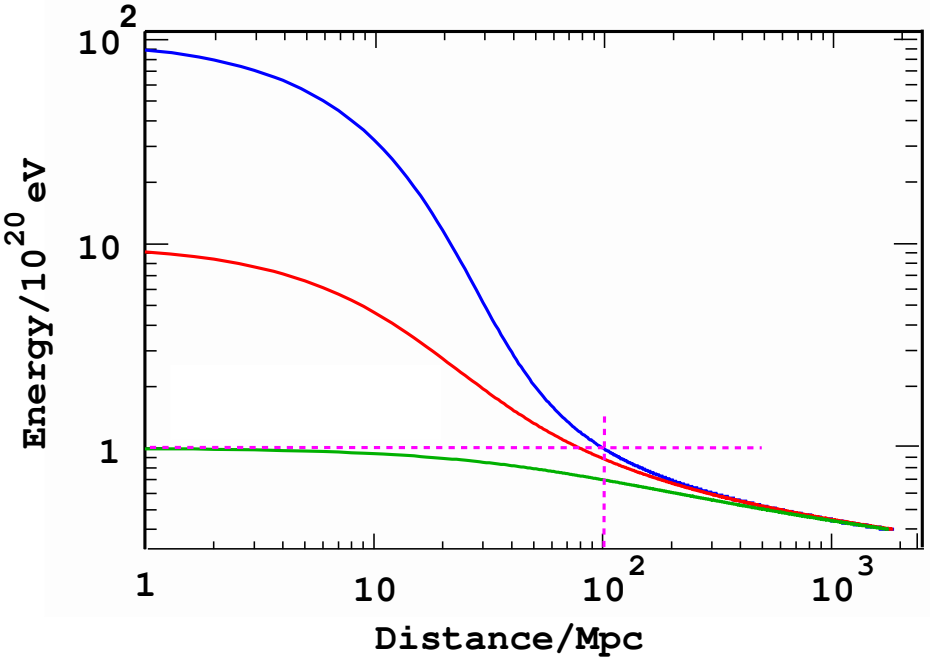


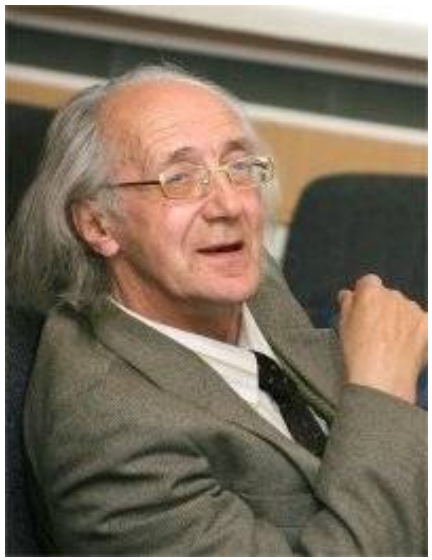


Greisen-Zatsepin-Kuzmin Effect

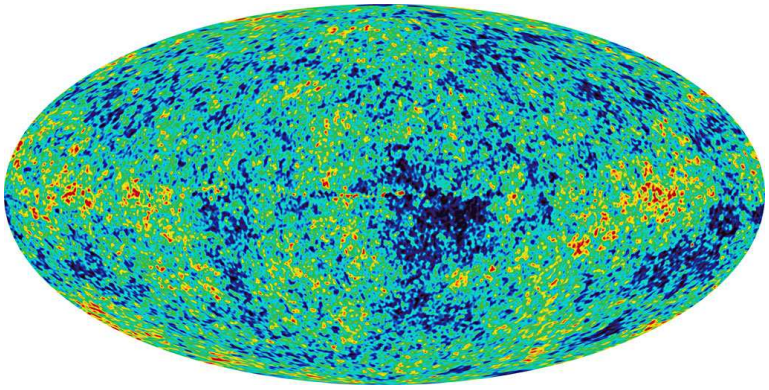


$$p + \gamma_{\mathrm{CMB}} \rightarrow N + \pi$$

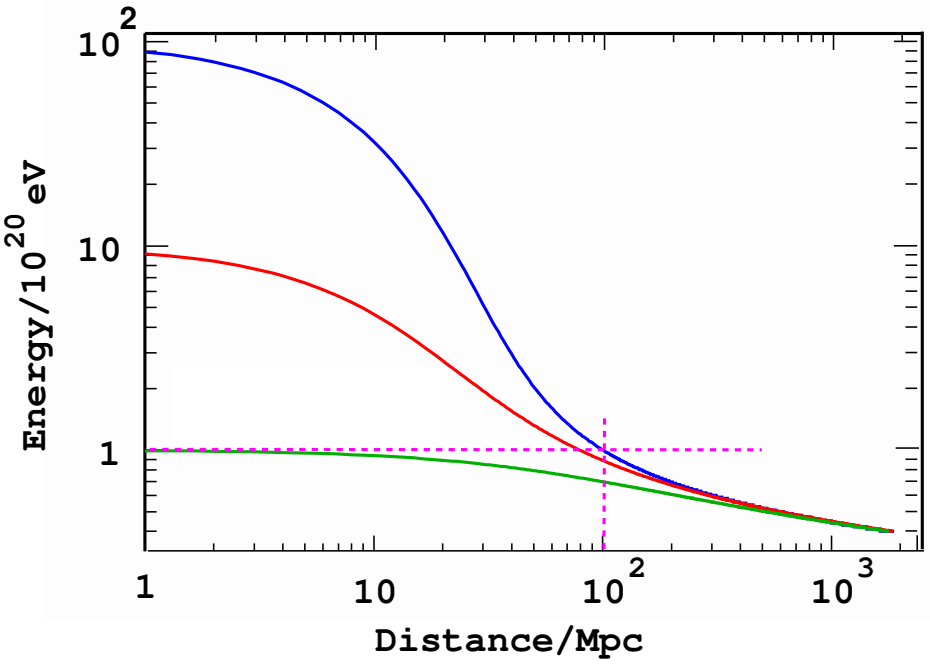




Greisen-Zatsepin-Kuzmin Effect

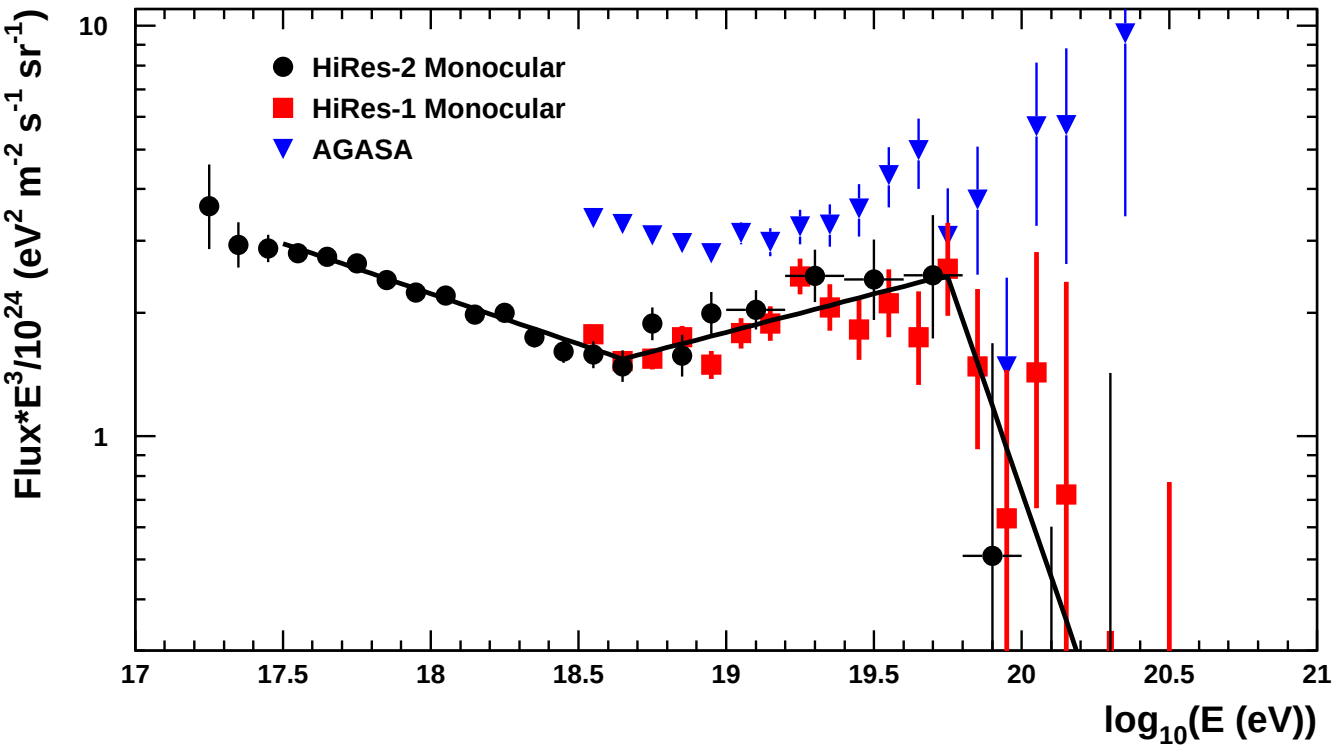


$$p + \gamma_{\mathrm{CMB}} \rightarrow N + \pi$$



- 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)

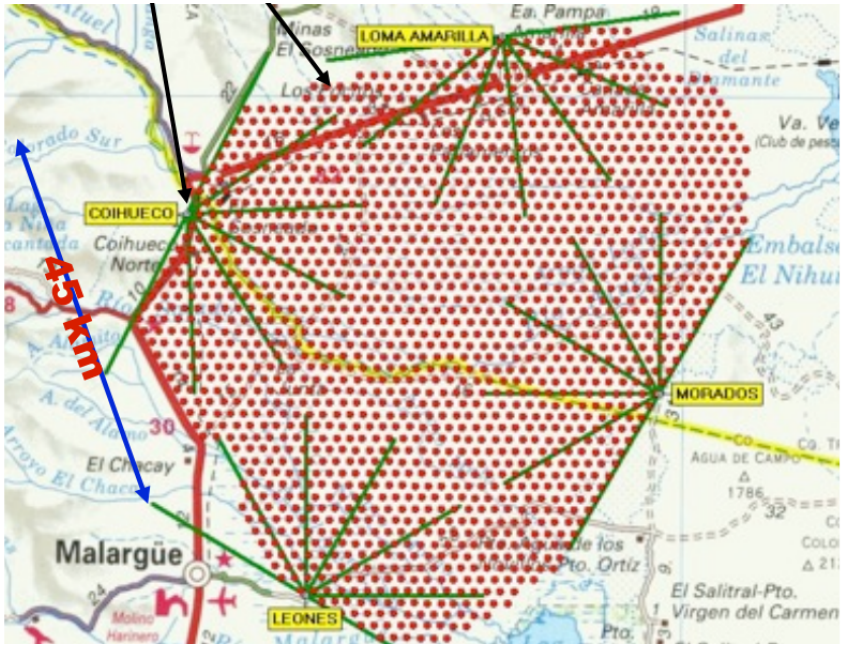
- HiRes announced observation of the GZK.
  (HiRes was an observatory of fluorescent light detectors (FD))

  HiRes collaboration (2007)

New generation of CR observatories

PAO

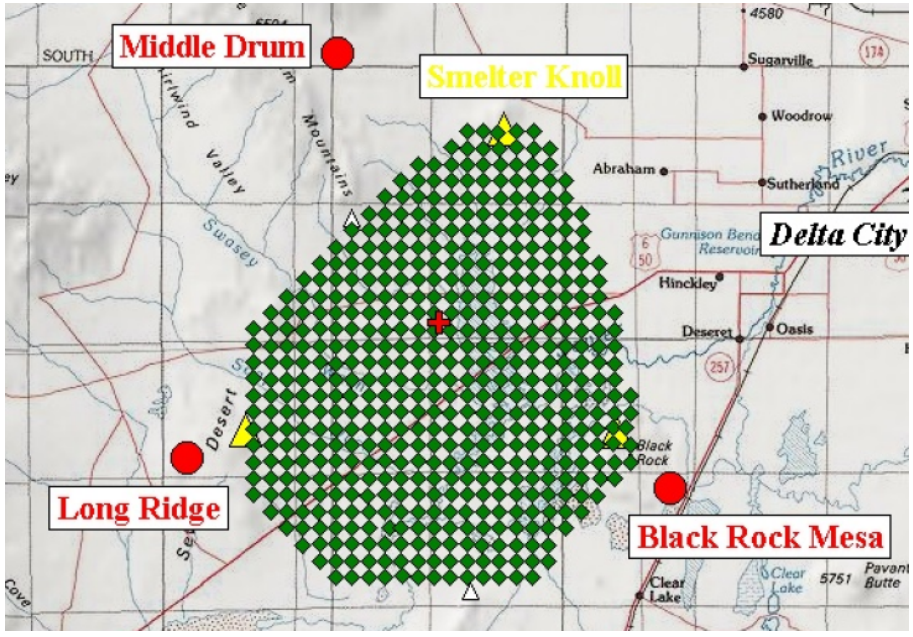
(Hybrid, Southern hemisphere)



- 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

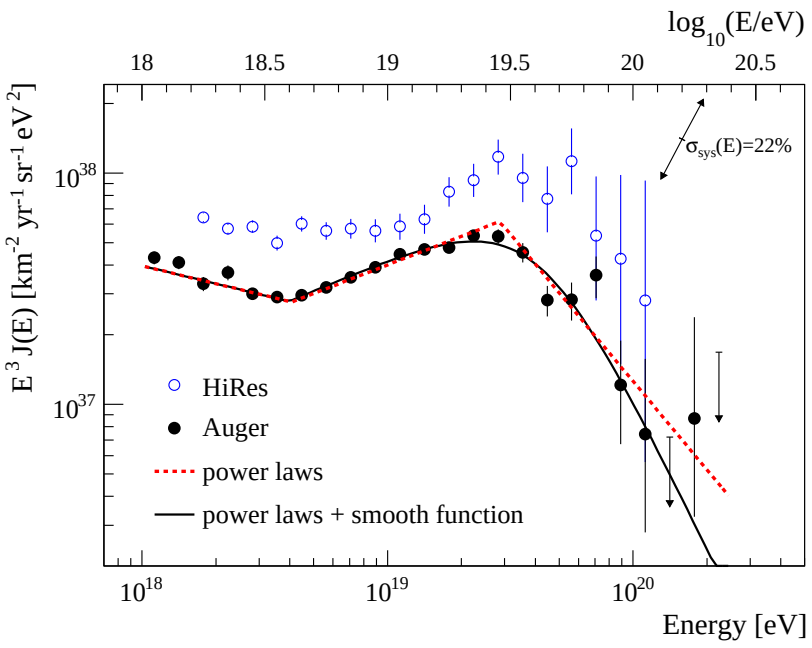
Telescope Array

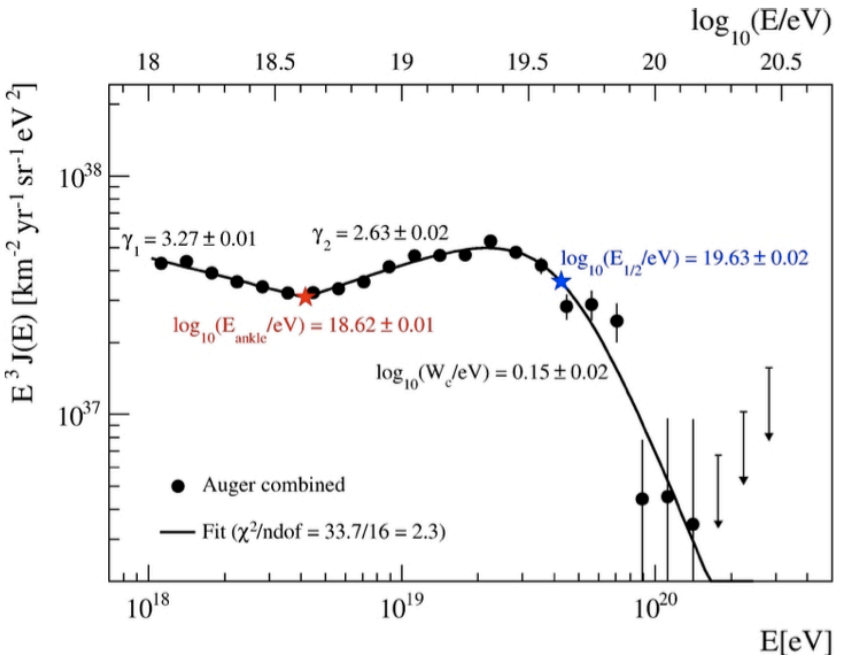
- 3 m^2 scintillators

Cut-off is firmly established

HiRes, 5.3σ, Phys.Rev.Lett. 100 (2008) 101101

PAO, 20σ, Phys.Lett. B 685 (2010) 239



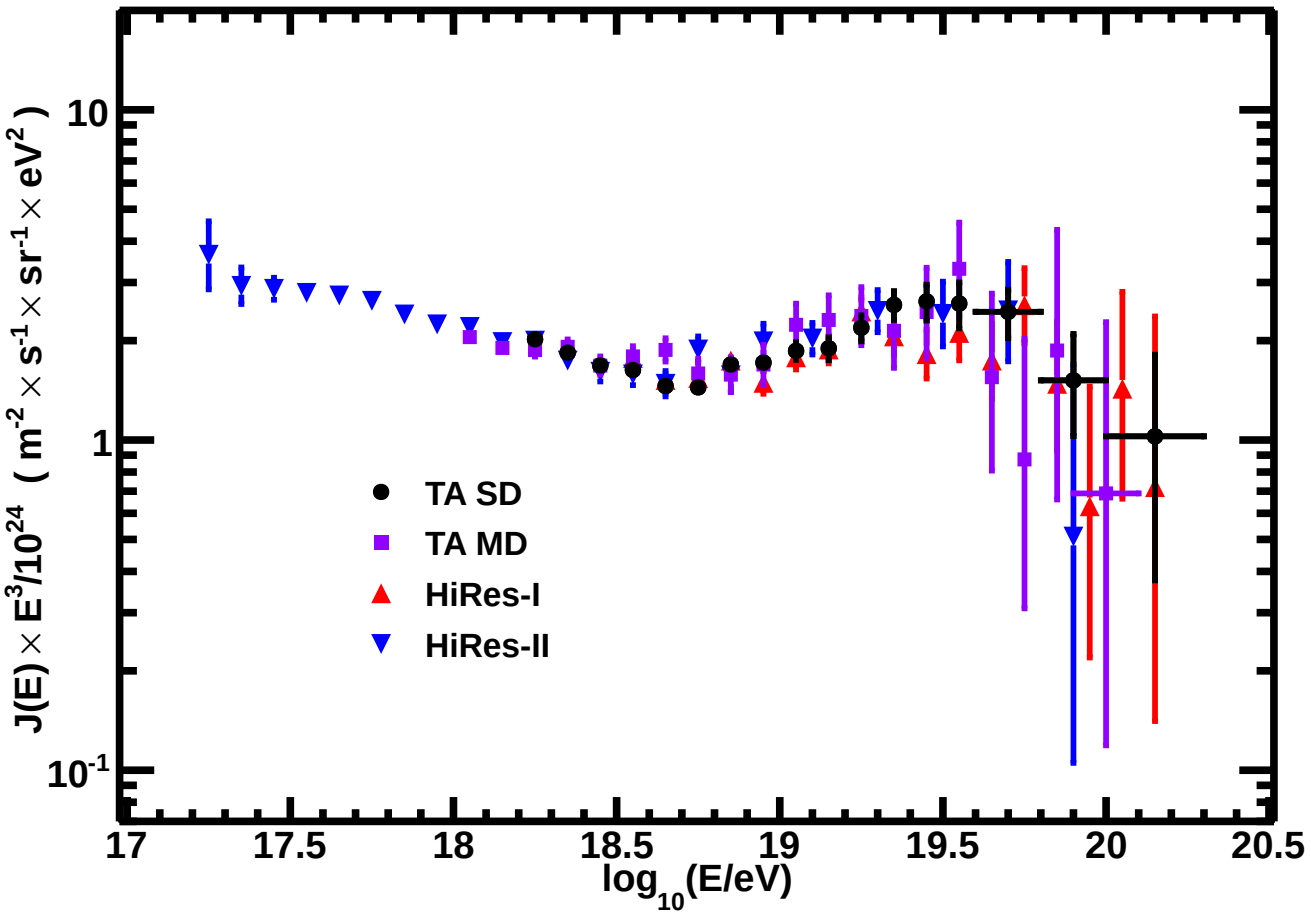


C. Berat (PAO, this conference)

Cut-off is firmly established

Telescope Array spectra

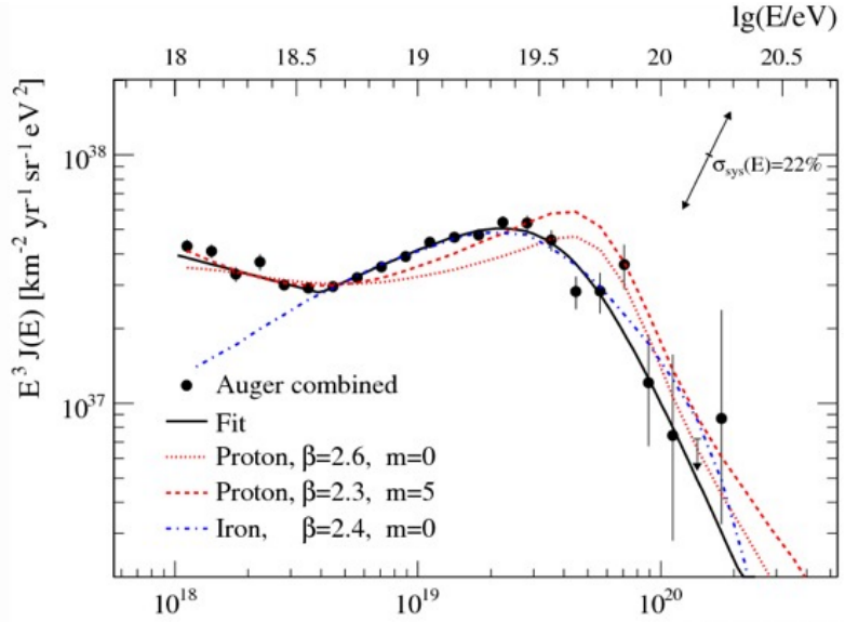
TA collaboration, 2011



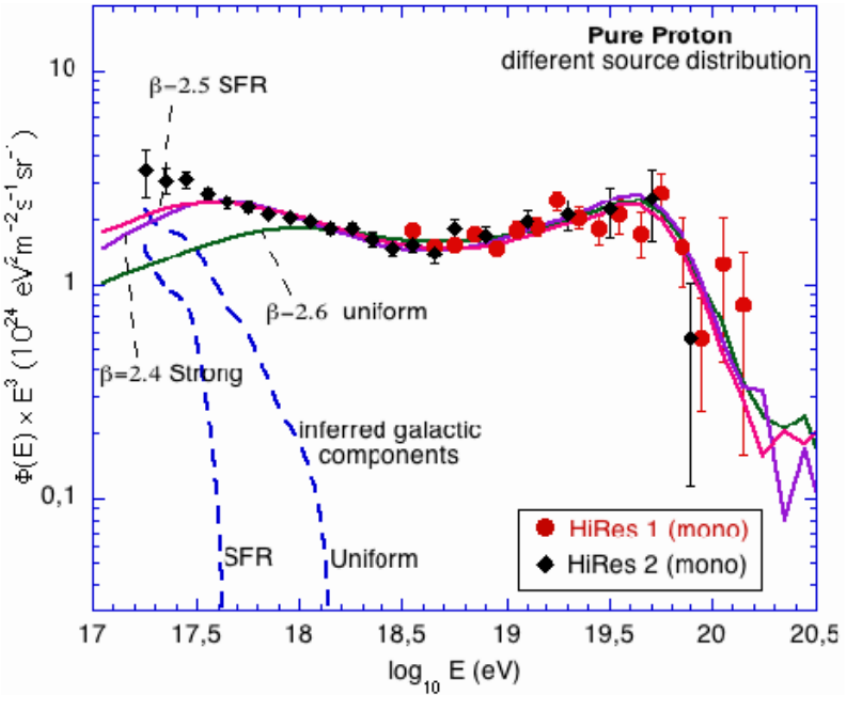
Note: TA is using the same type of SDs as were employed by AGASA

Theoretical modeling

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



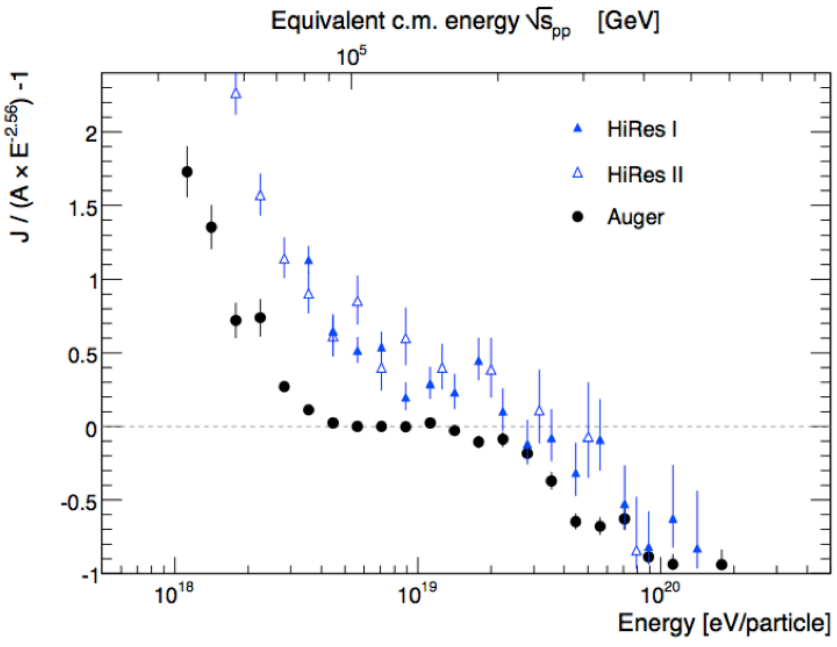
PAO spectrum fitted by Fe primaries
Auger collaboration, ICRC 2009

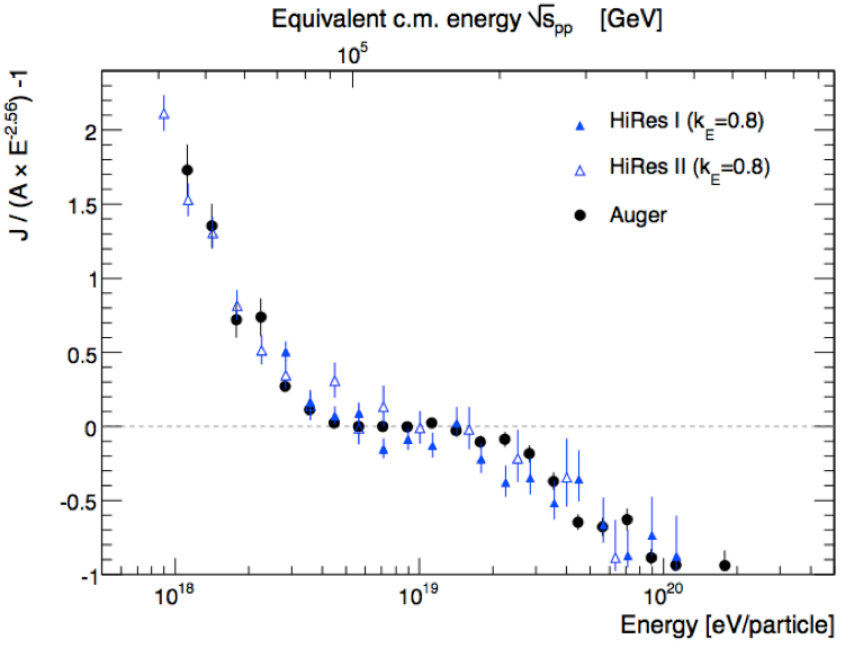


HiRes spectrum fitted by proton primaries
Berezinsky, Gazizov, Grigorieva (2005)

Dramatically different conclusions at face value ...

HiRes/Auger spectra comparison

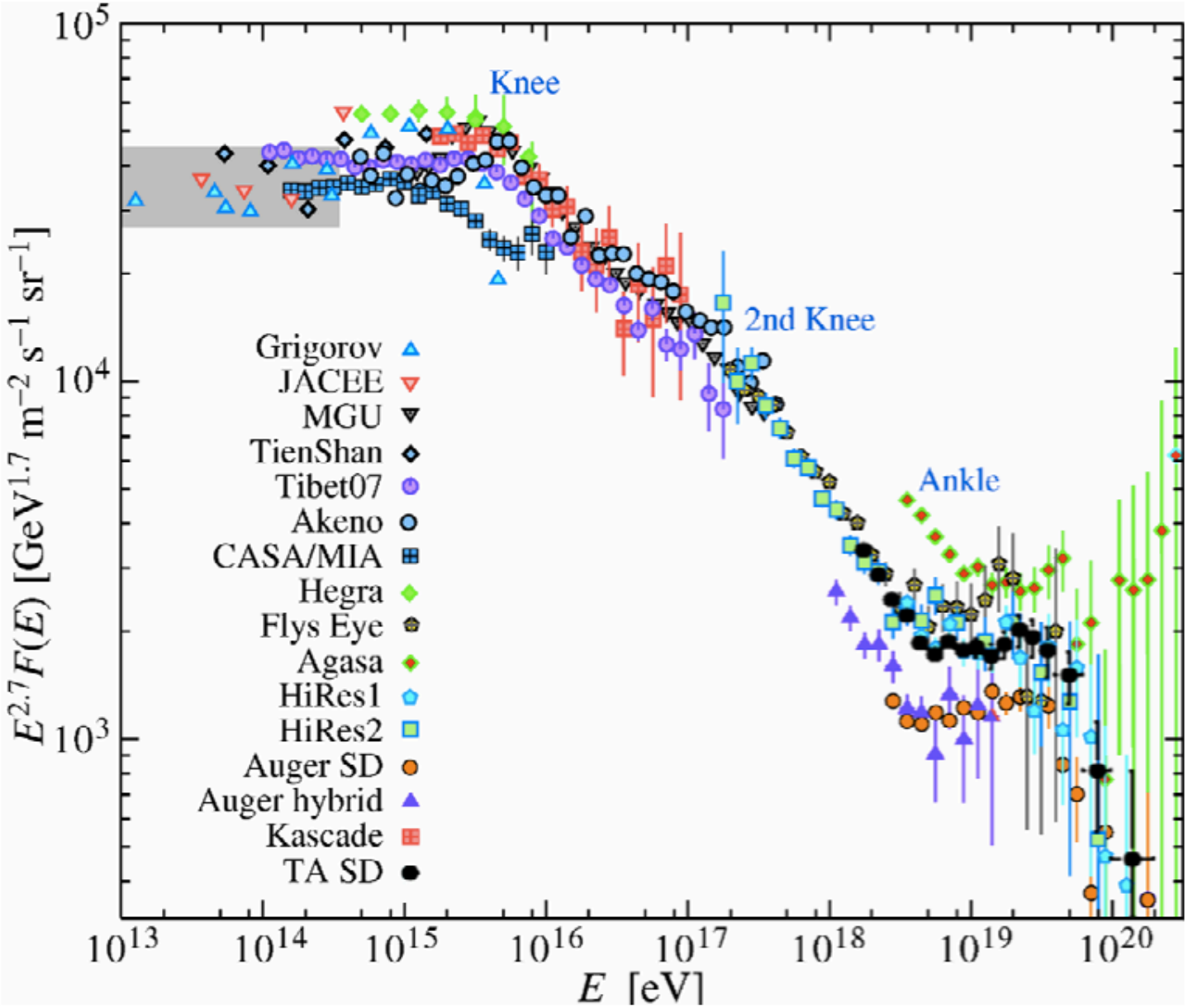




P. Sokolsky, 2010

However, spectra match after 20% shift in energy scale

Overall CR Spectrum

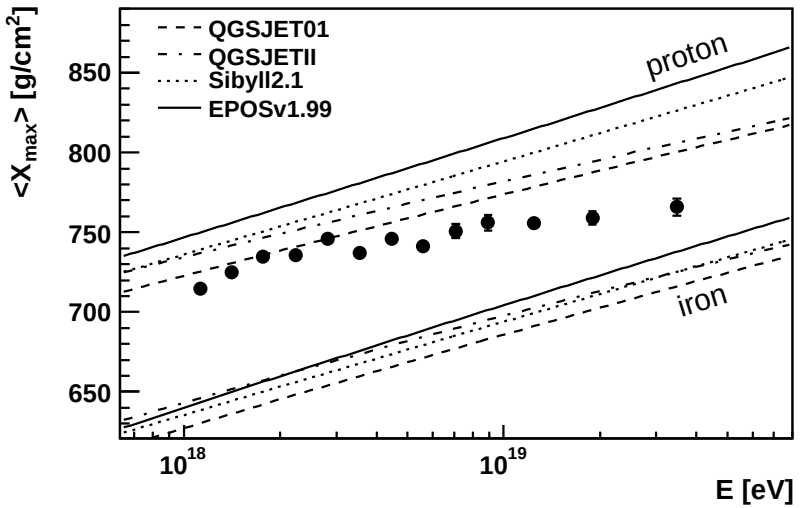


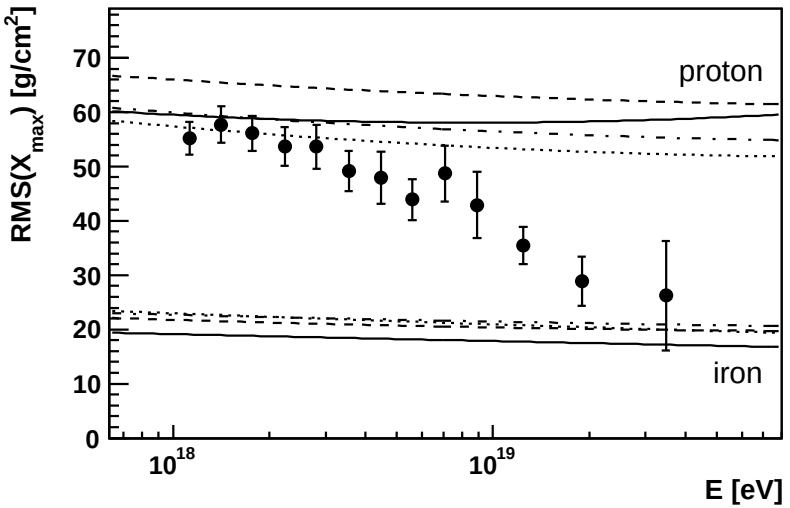
Gaisser, Stanev, PDG, 2010 + TA SD, 2011

Composition.

PAO - heavy nuclei

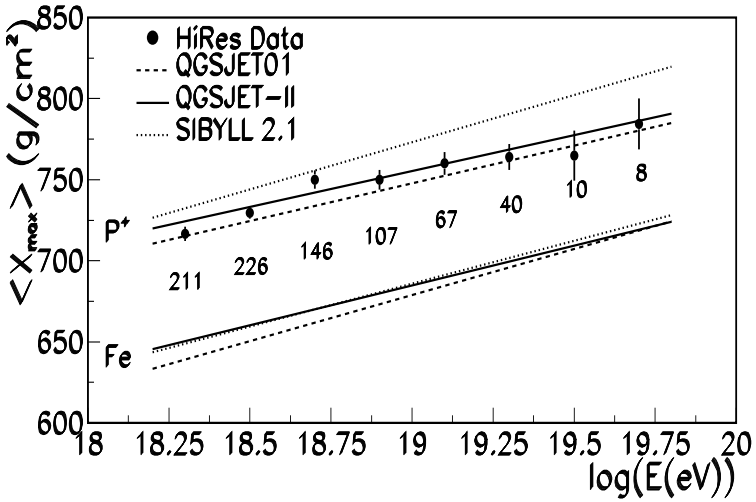
Phys. Rev. Lett. 104 (2010) 091101

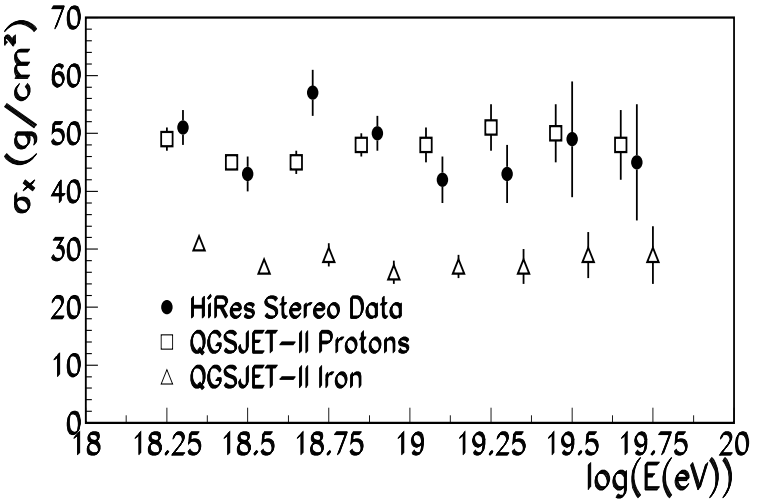




HiRes - protons

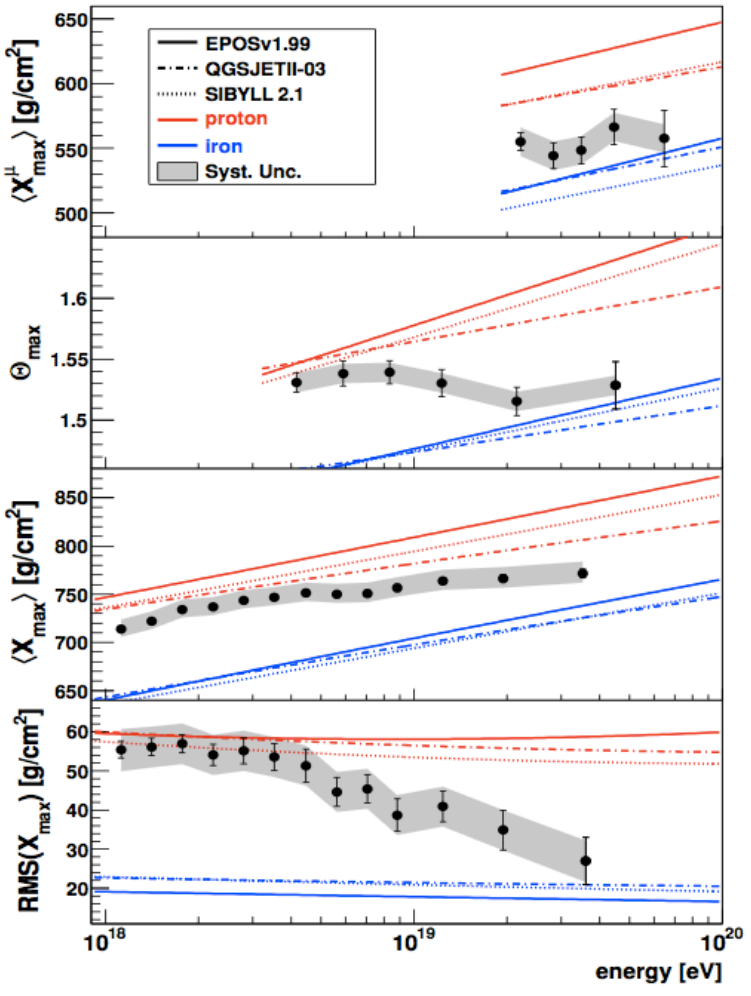
Phys. Rev. Lett. 104 (2010) 161101





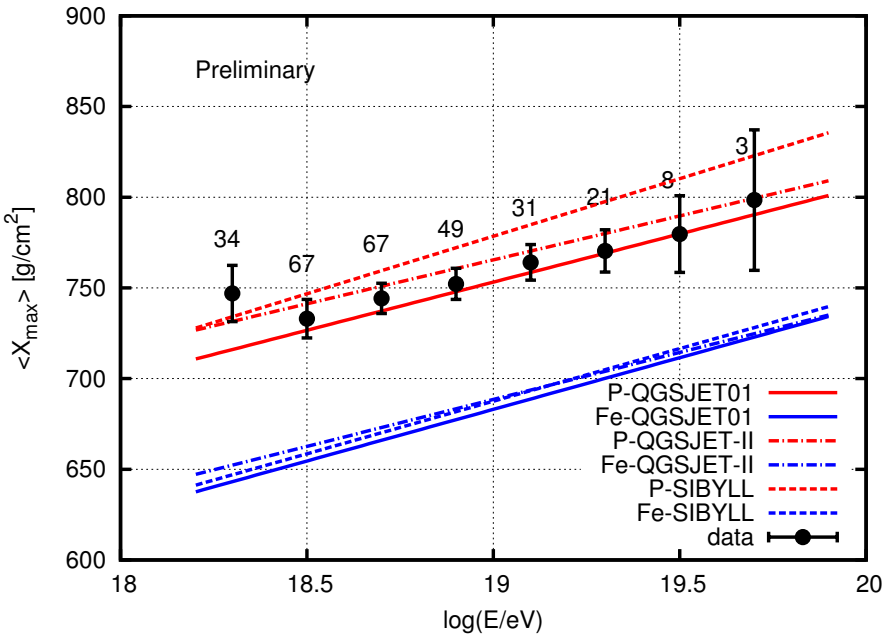
Composition. Latest results.

PAO - heavy nuclei



H. Wahlberg (PAO, this conference)

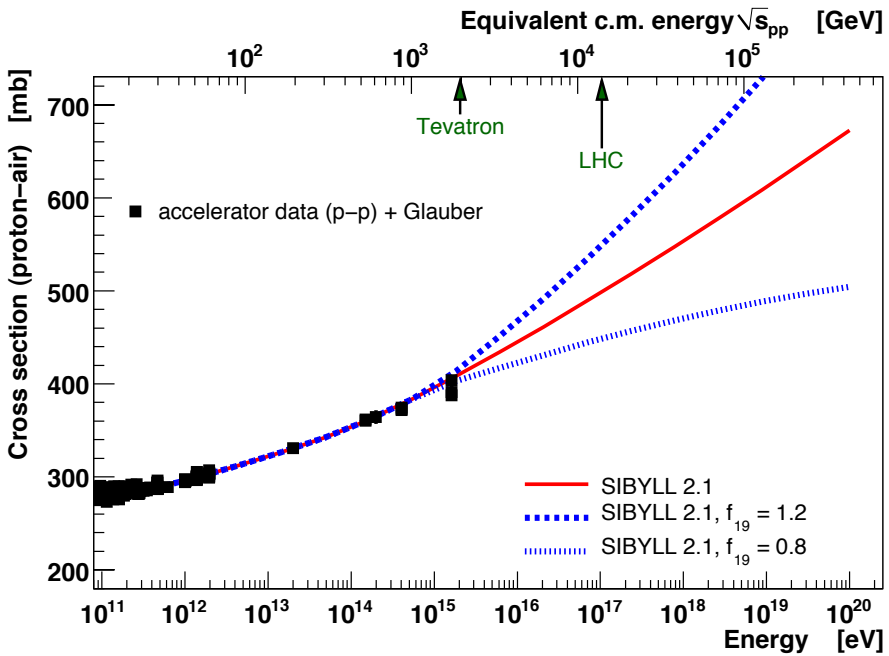
TA- protons



TA collaboration, 2010

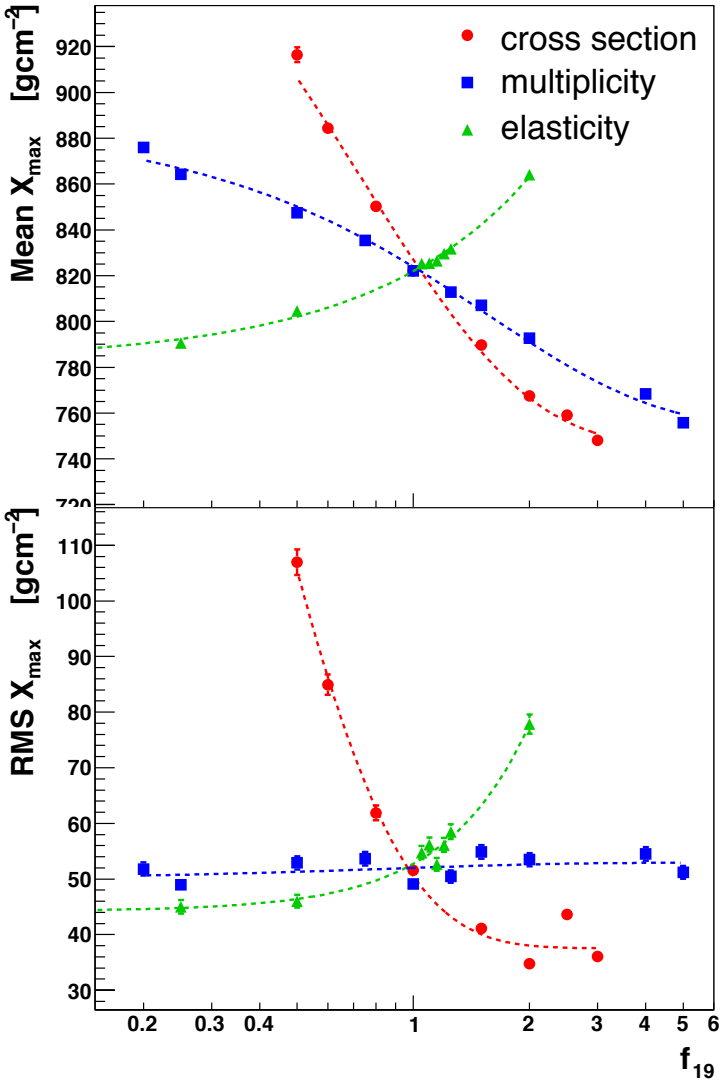
Composition

Do Auger data imply a new physics?



f_{19} re-scales properties of hadronic interactions.

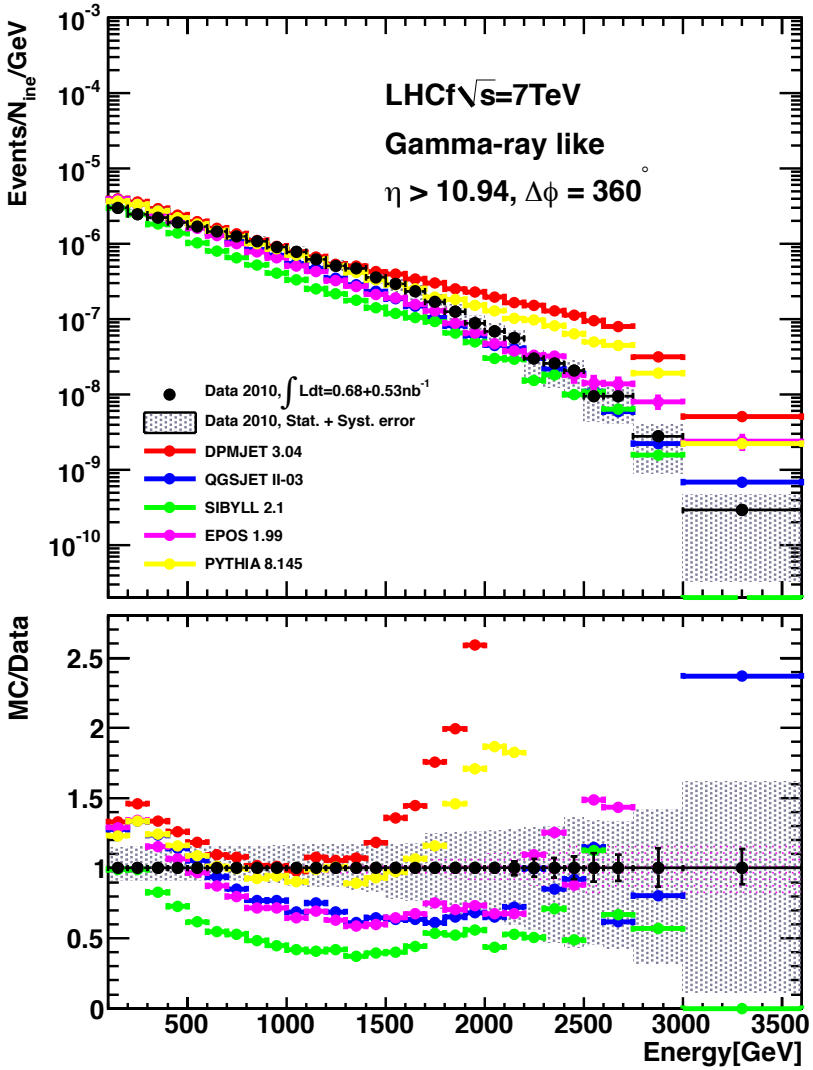
However, a new physics cannot explain the difference between PAO and HiRes/TA.
We need LHC data.

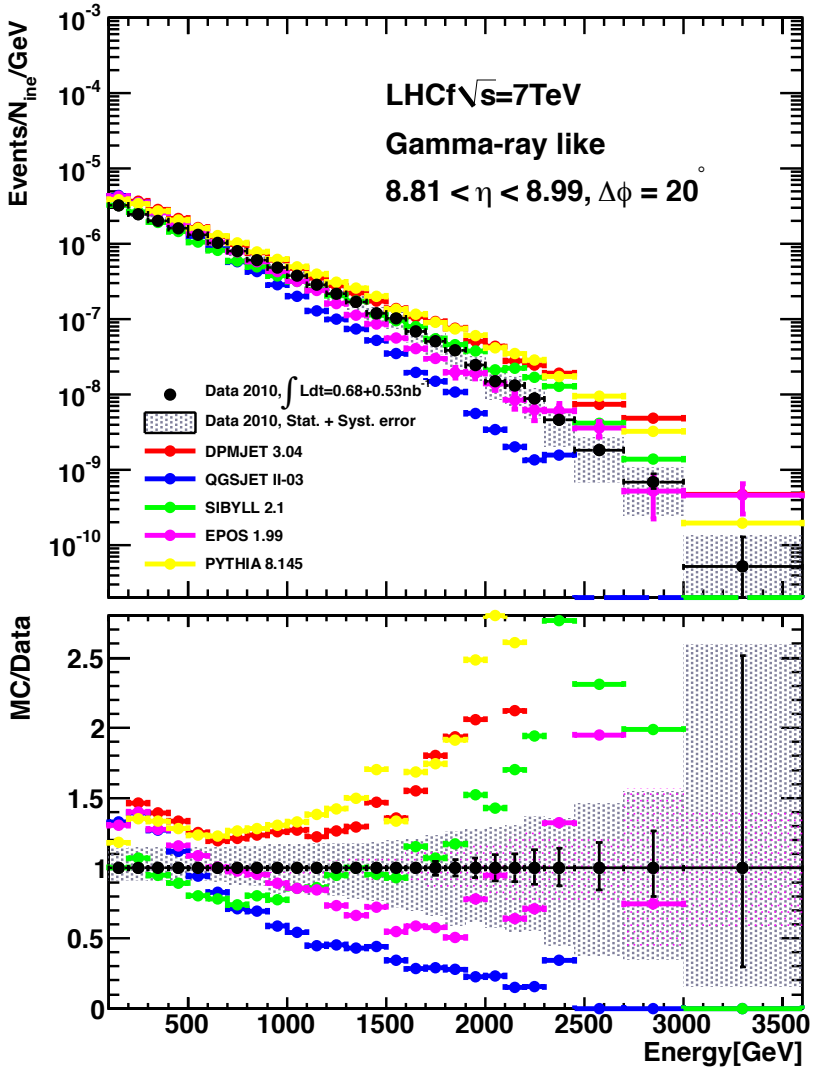


R. Ulrich at al, arvix:0906.0418

LHCf

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





None of the models perfectly agree with data.

LHCf, arXiv:1104.5294. See also A. Tricomi, this conference

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

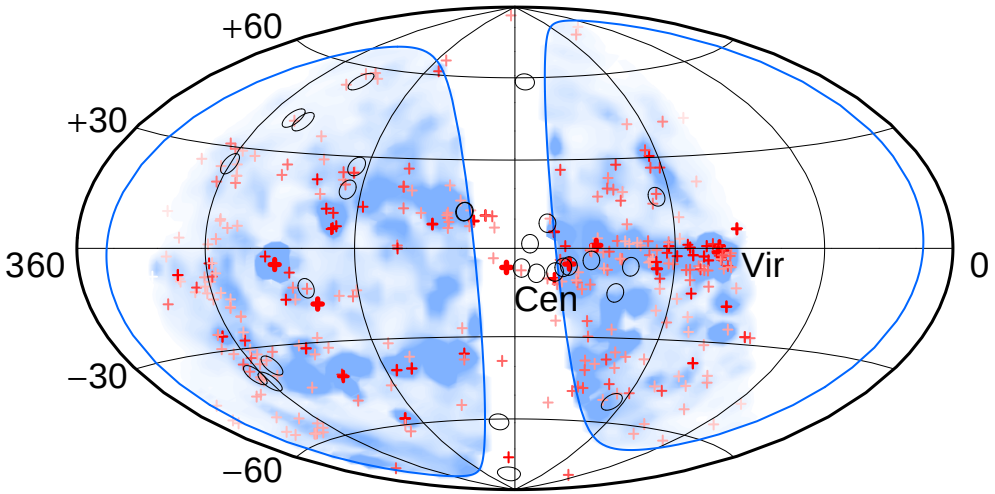
27 events E> $5.7 \cdot 10^{19}$ eV

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.

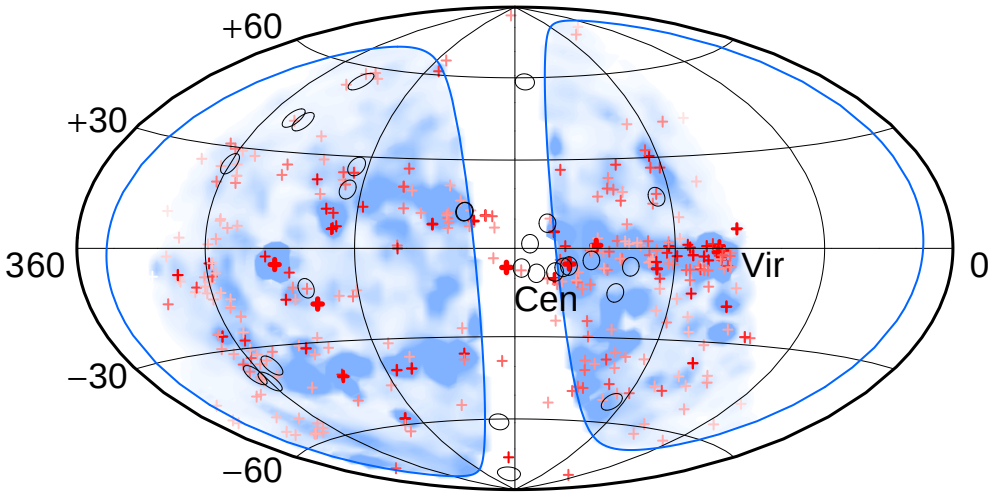


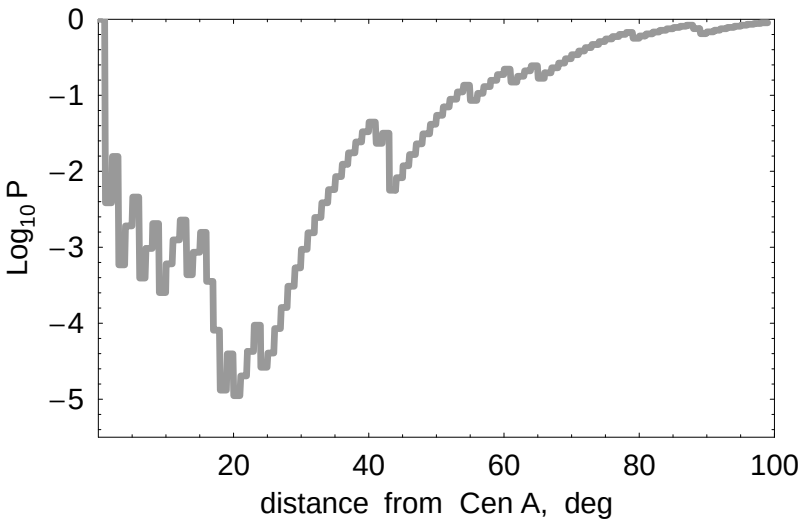
Gorbunov, Tinyakov, I.T., Troitsky, arXiv:0711.4060, arXiv:0804.1088
Fargion, arXiv:0801.0227

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.





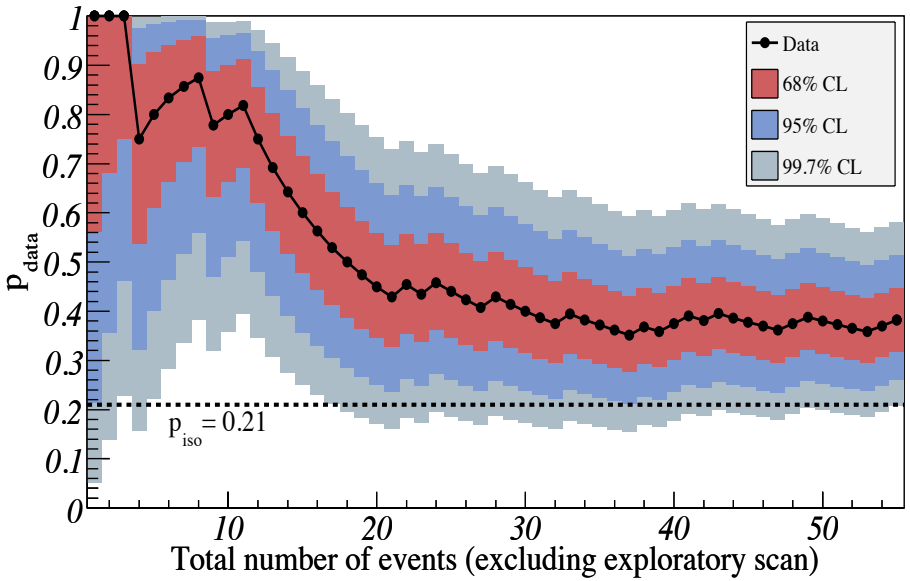
- Cen A is the closest radiogalaxy by chance projected on LSS
- It is outside of HiRes field of view

This provides an alternative explanation for the Auger signal.

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

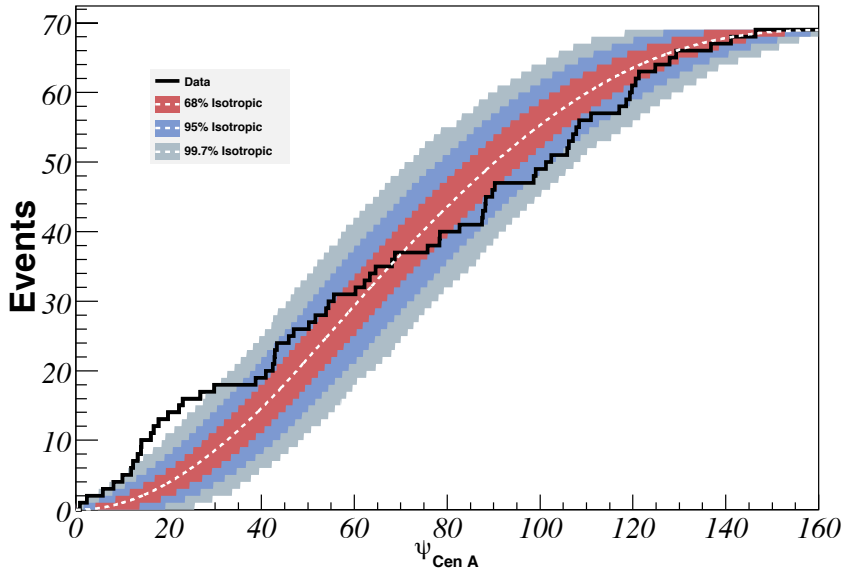
Evolution of the signal in Auger data

AGN



AGN signal became weaker

Cen A



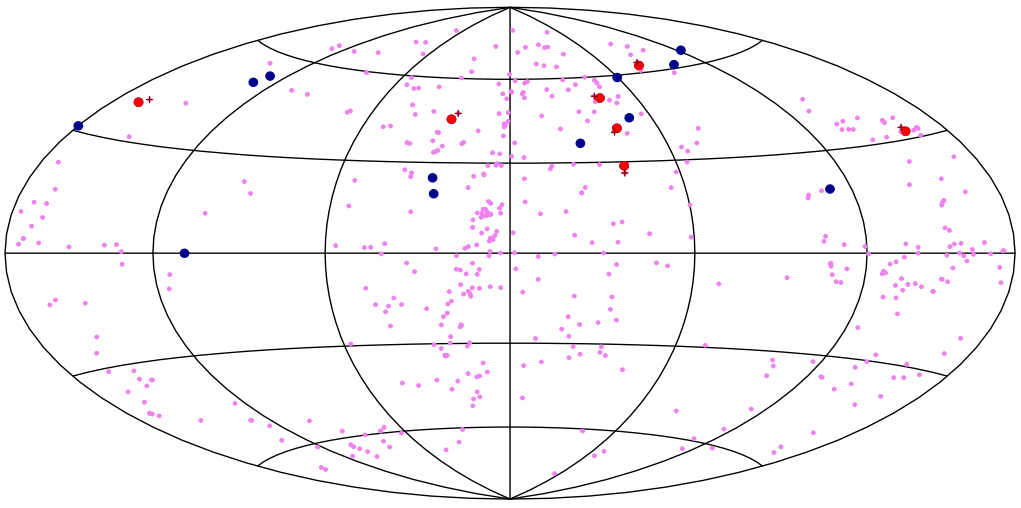
Cen A signal persists

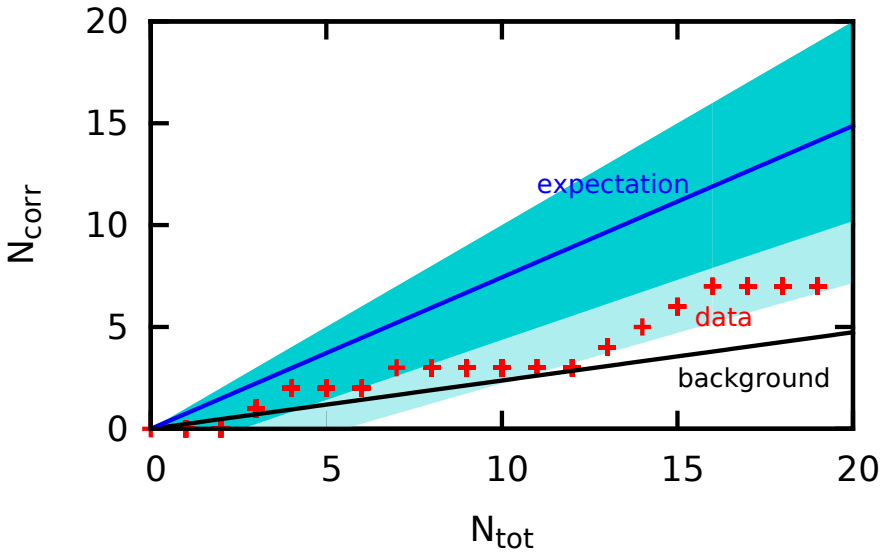
Virgo paucity persists

Auger collaboration, Astroparticle Phys. 34 (2010) 314

Search for AGN signal in Telescope Array data

'Blind' test of AGN hypothesis



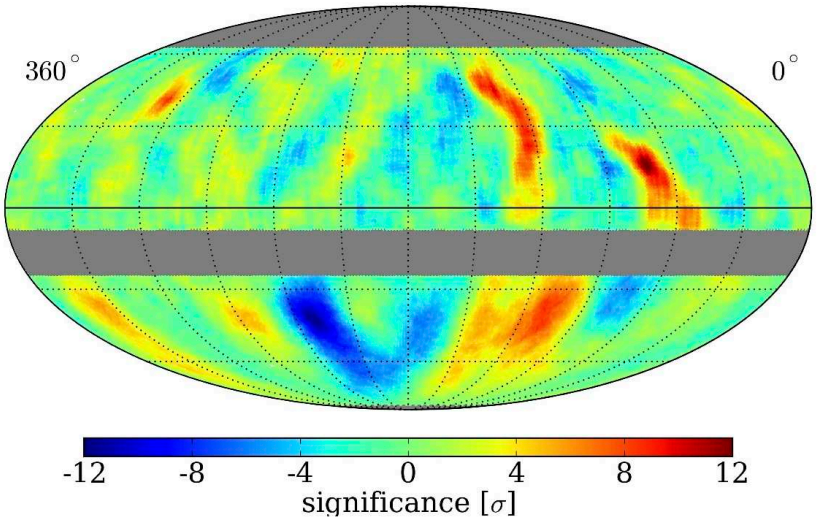


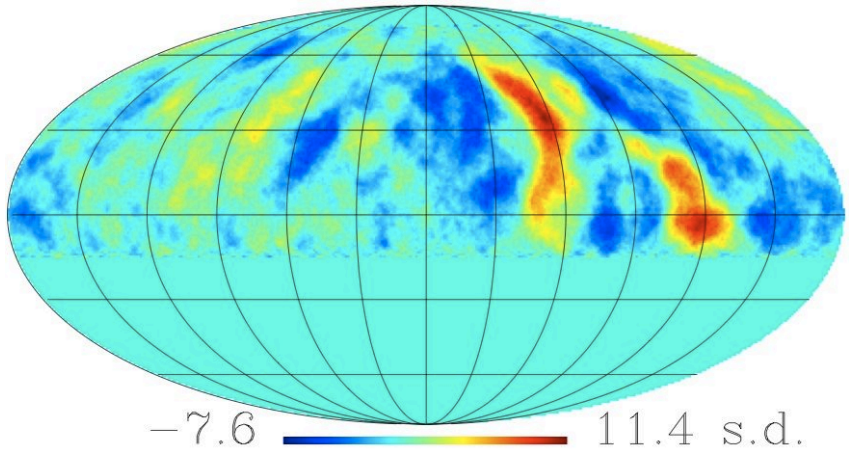
Auger AGN hypothesis is not supported by TA data.

TA collaboration, 2011

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

see also P. Camarri, this conference

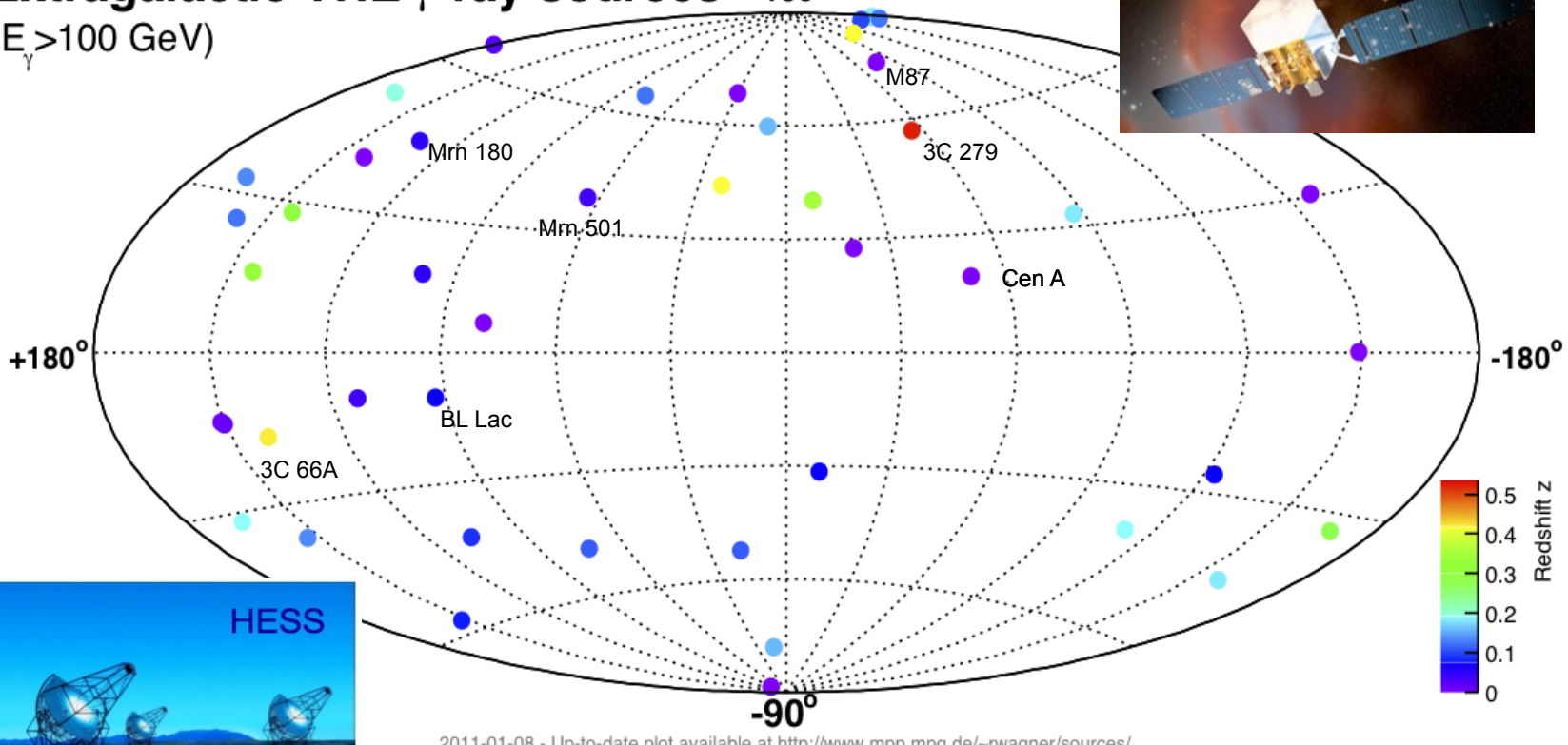
Interpretational problems:

- 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)

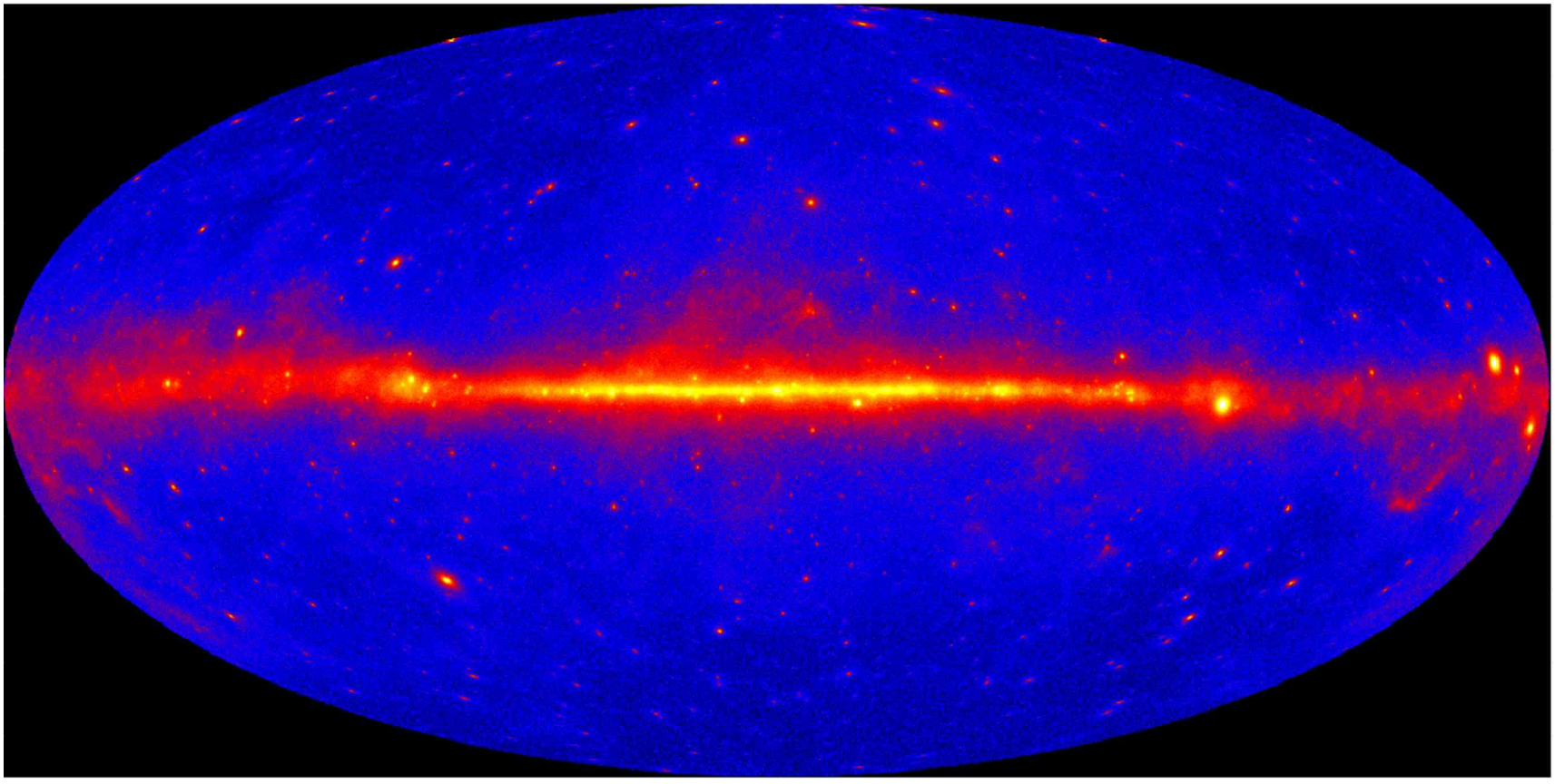


2011-01-08 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

46 Sources

Fermi Lat

The best ever view of the gamma-ray sky



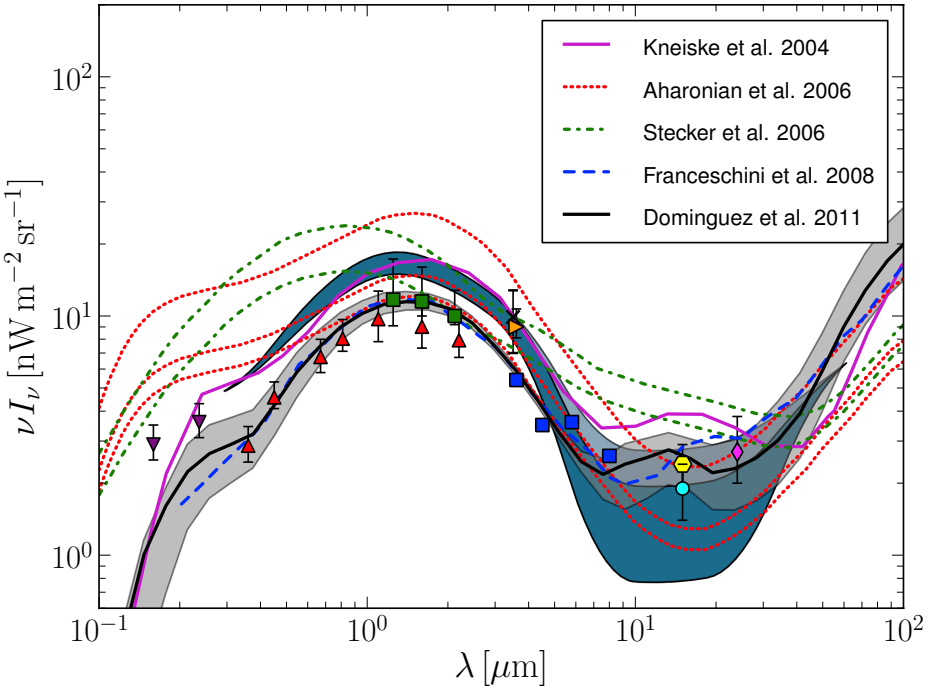
2 years of data, $E_\gamma > 200\ \mathrm{MeV}$

$> 10^3$ sources

$> 6 \cdot 10^8$ γ-rays

Resulting constraints on

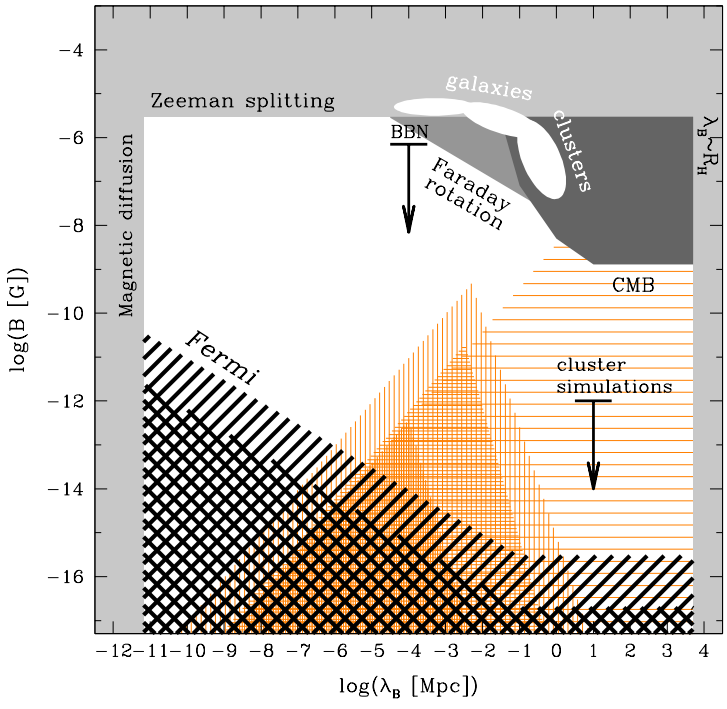
EBL



Derived from transparency of the Universe to TeV radiation $\gamma\gamma \rightarrow e^+e^-$

Orr, Krennrich, Dwek, arxiv:1101.3498

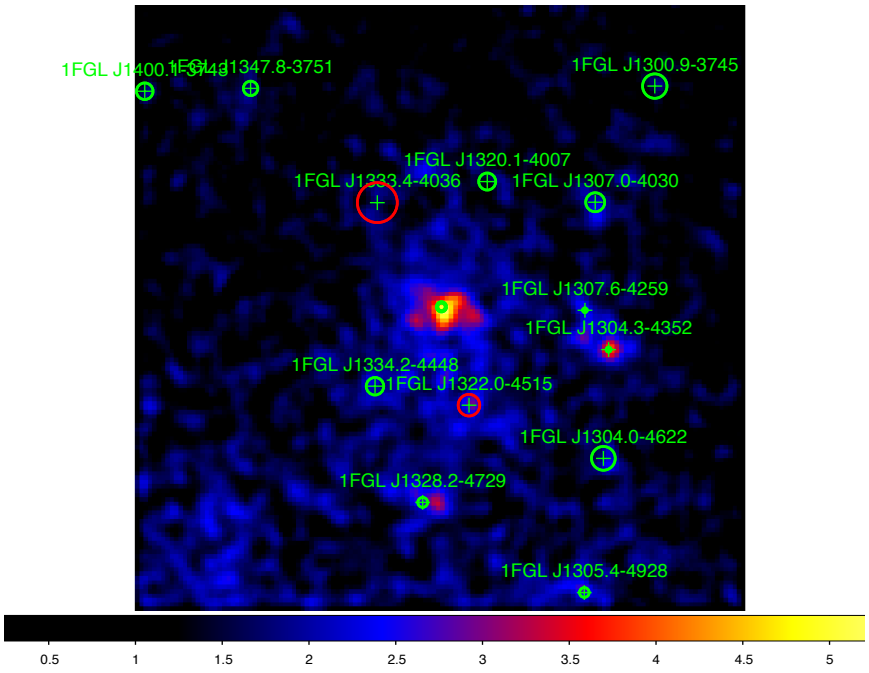
EGMF

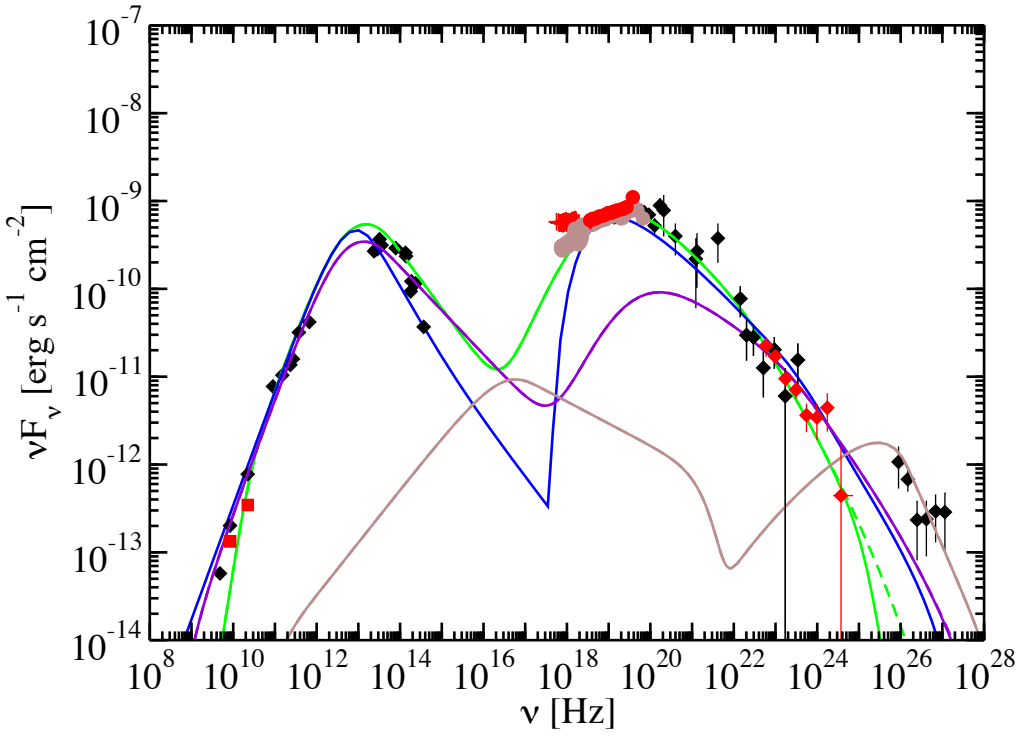


Derived from Fermi limits on cascade emission of HESS TeV blazars.

Neronov, Vovk, Science 328 (2010) 73

Fermi Lat study of Cen A





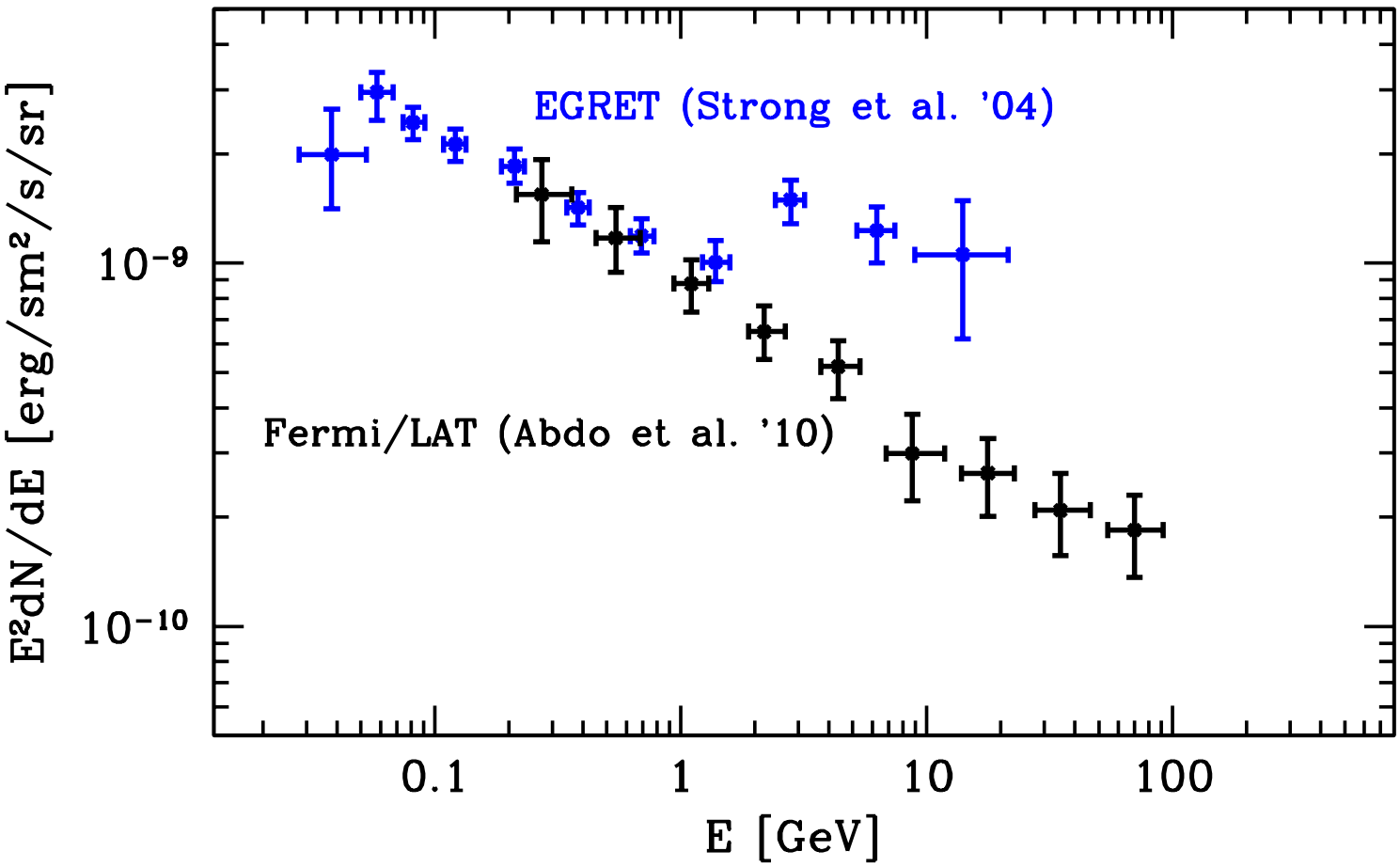
Red diamonds: Fermi-LAT data

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

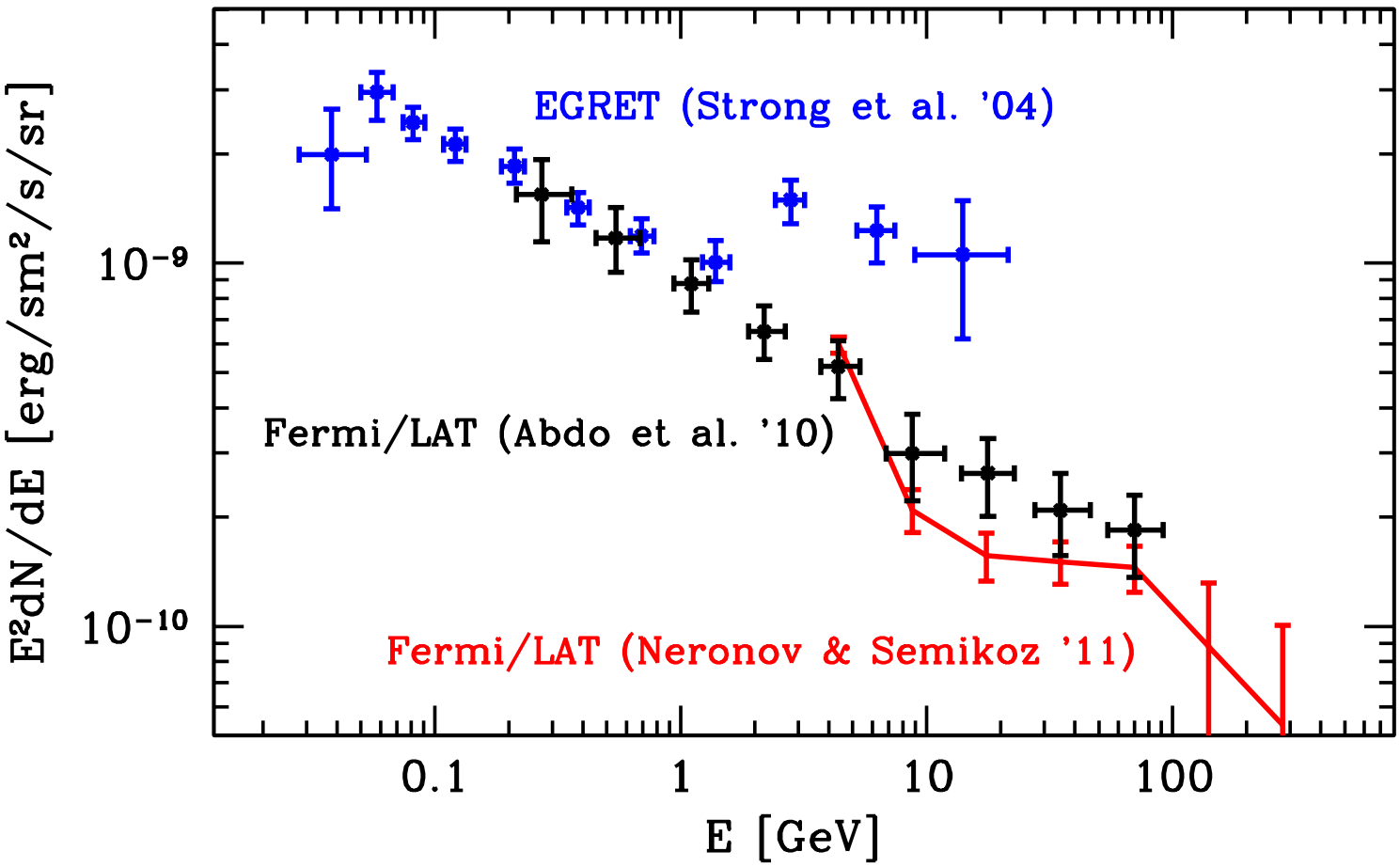
It is unlikely that protons can be accelerated to energies above 4×10^{19} eV, although this is possible for heavier ions.

Fermi collaboration, ApJ 719 (2010) 1433

Extragalactic γ-ray background

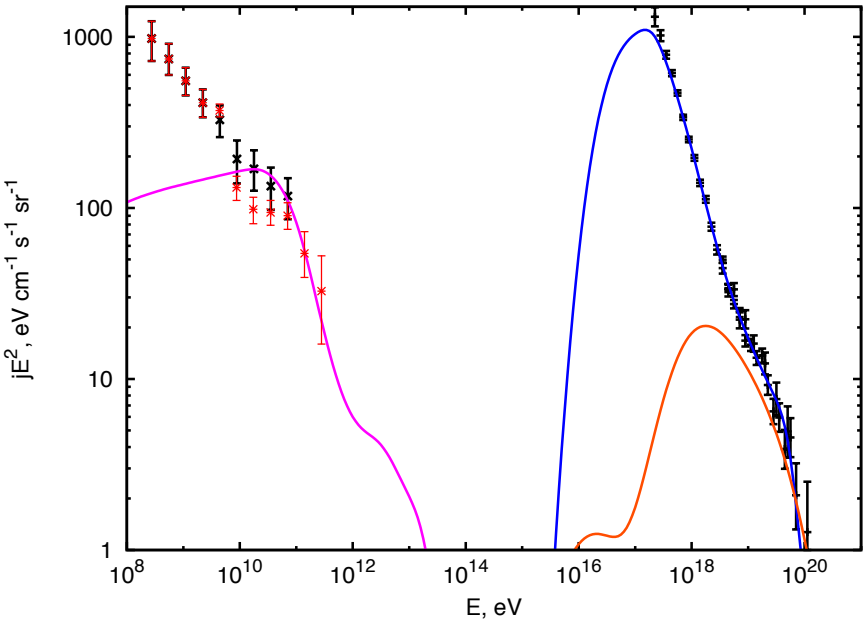


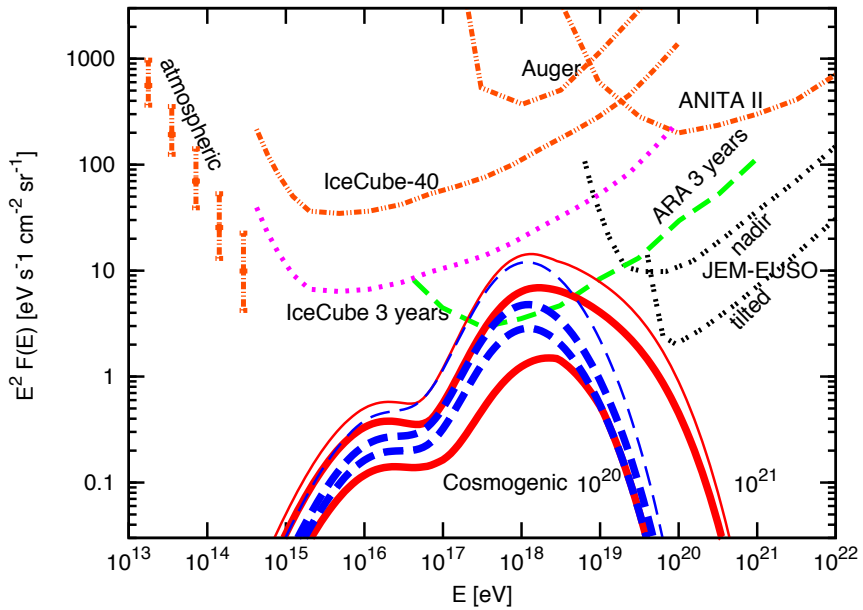
Extragalactic γ-ray background



UHECR and extragalactic γ-ray background

UHE primary p and secondary γ and GZK ν

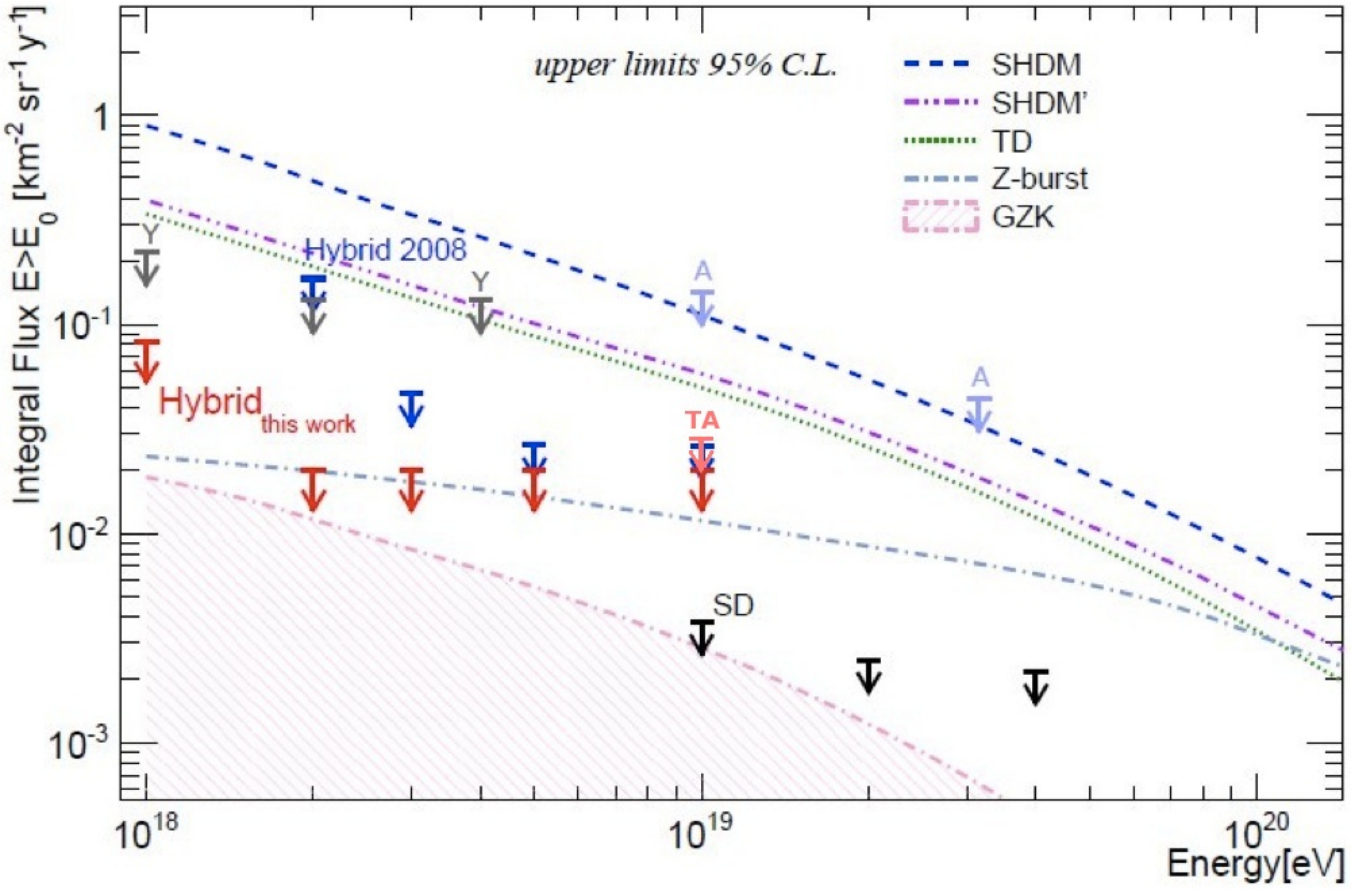




Limits on source properties are emerging.
Injection spectrum $\beta > 2.4$ and evolution parameter $m < 4$.
Revised upper bounds for GZK neutrino.

Gelmini, Kalashev, Semikoz, arxiv:1107.1672 , see also
Berezinsky et al, Phys. Lett. B 695 (2011) 13
Ahlers at al, Astropart. Phys. 34 (2010) 106

Search for UHE photons



Limits on photon flux obtained by PAO, AGASA, Yakutsk and TA.
Top Down models disfavored.

H. Wahlberg (PAO, this conference) + TA 2010 limit

Conclusions

- Greisen-Zatsepin-Kuzmin cut-off
  - The cut-off is firmly established
  - It's precise nature is under study
- Cosmic ray composition
  - Protons? Heavy Nuclei?
  - Origin of disagreement between PAO and HiRes, TA is not understood yet
  - What is the fraction of photons and neutrino?
- Cosmic ray sources and anisotropy
  - A huge number of new 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?
  - Is charged particle astronomy possible?
- Shower development
  - New physics?
  - LHC data are streaming and should improve understanding

Immediate future

AMS-2 detector is launched and since May 2011 collecting data on board of ISS.

B. Bertucci, this conference

Prospect

- AMS-2 detector is launched
- TUS (prototype of JEM- EUSO) scheduled for launch in 2011
- Low energy PAO and Telescope Array extensions
  - CR data in the LHC energy range
- Tunka-133 (dense EAS Cherenkov array) completed and collecting data. To be upgraded. HiSCORE.
- LHAASO (Large High Altitude Air Shower Observatory)
- CTA