The Abdus Salam
International Centre for Theoretical Physics

United Nations
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2246-19

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Multi-messenger signals and cosmic backgrounds

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Multimessengers in cosmic backgrounds

- **Multimessenger signals:** neutrinos, nuclei, photons, protons
- **Cosmic backgrounds:** CMB, EBL, GMF, IGMF

based on the work in collaboration with

Shin'ichiro Ando
John Beacom
Antoine Calvez
Warren Essey
Oleg Kalashev
Shigehiro Nagataki

Sources: AGN

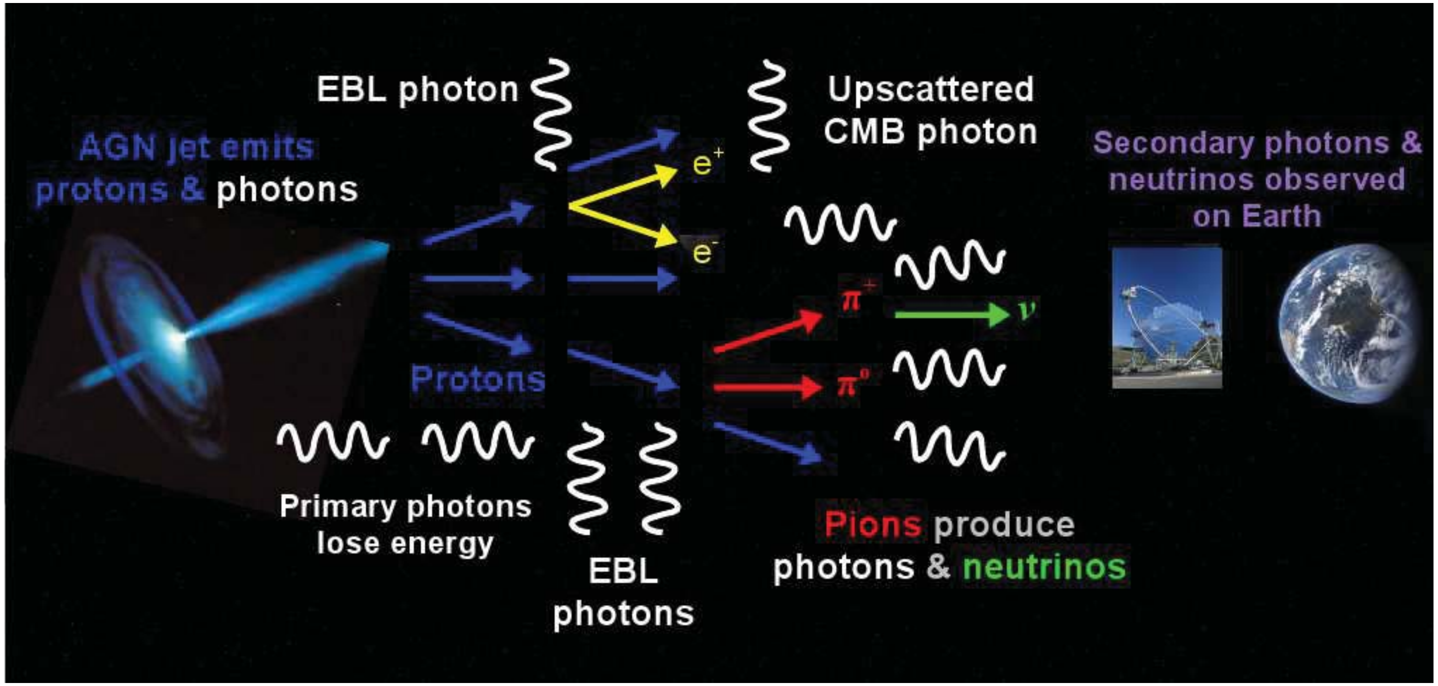
messengers: $\boldsymbol{\gamma, p, \nu}$, etc.
relevant backgrounds: **CMB, EBL**

Gamma-rays produced at the source can attenuate via pair production on EBL for TeV energies: expect **attenuation of TeV γ rays**.

Protons below GZK cutoff interact with EBL, CMB and produce γ rays via $p\gamma \to pe^+e^-, p\gamma \to p\pi^0$: expect **regeneration of TeV γ rays**
Photon backgrounds provide opacity/sink for the former, source for the latter.

What is the scaling of these effects with distance?

AGN produce both UHECR and photons



Unusual scaling

$$F_{\text{primary},\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\} \quad (1)$$

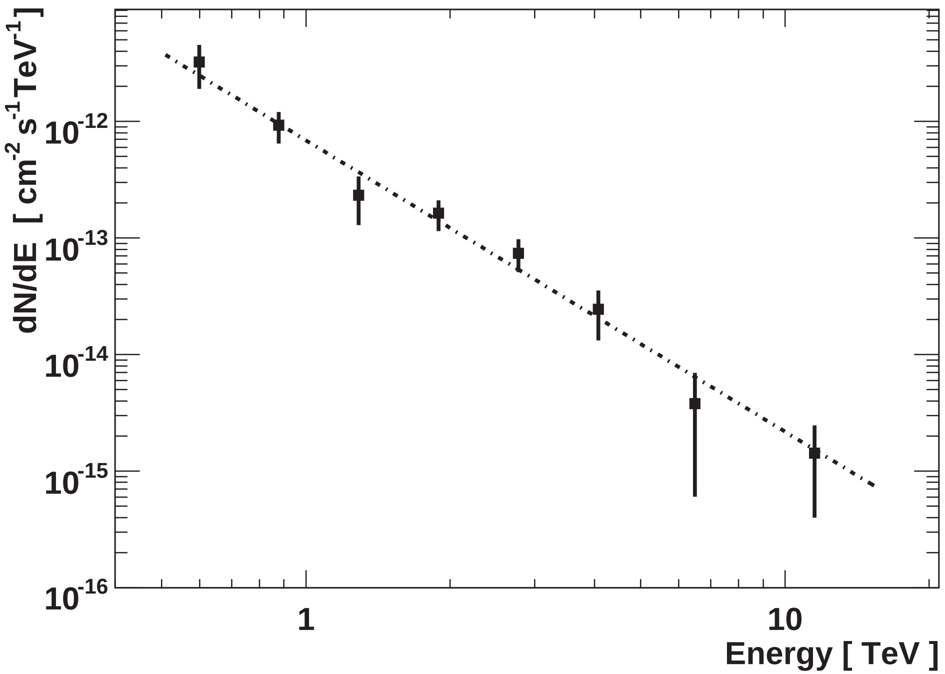
$$F_{\text{secondary},\gamma}(d) = \frac{p\lambda_\gamma}{4\pi d^2}\left[1-e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases} \quad (2)$$

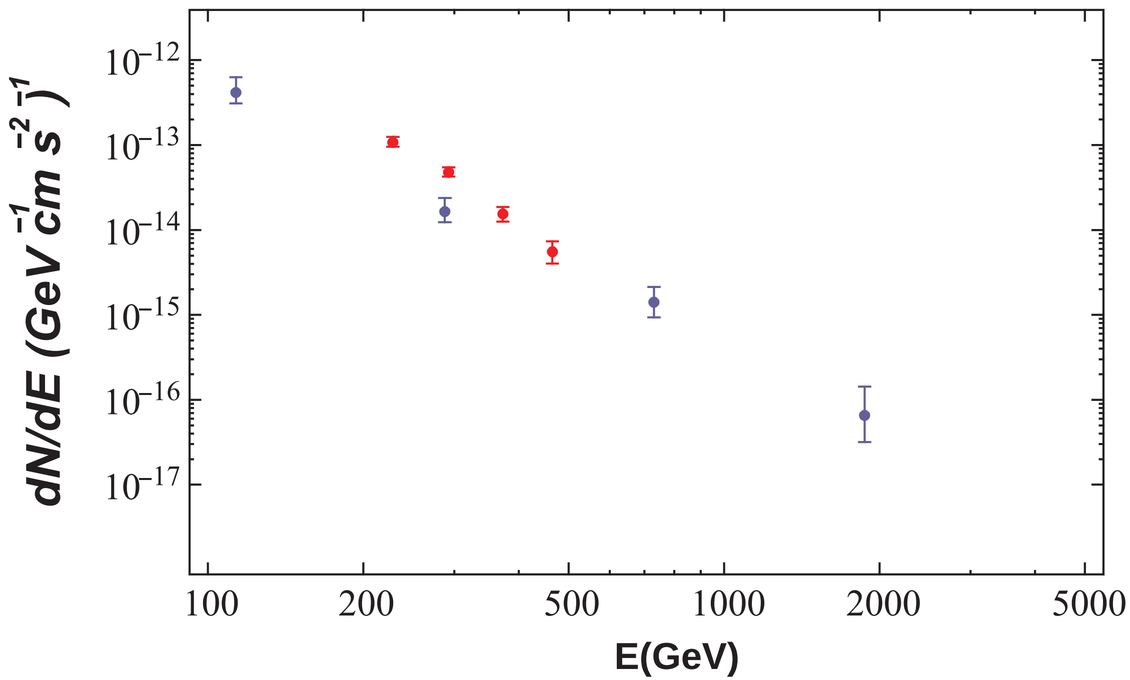
$$F_{\text{secondary},\nu}(d) \propto (F_{\text{protons}} \times d) \propto \frac{1}{d}. \quad (3)$$

For distant sources, secondary photons and neutrinos win

For *average* AGN at small distances, secondary photons are too few to detect **[Blasi *et al.*]**. However, selection effect: the sources seen at large distances are *not* average, they are *much brighter than average*.

Gamma-ray observations of distant blazars: 1ES 0229+200 ($z = 0.14$) and 3C66A ($z = 0.44$)





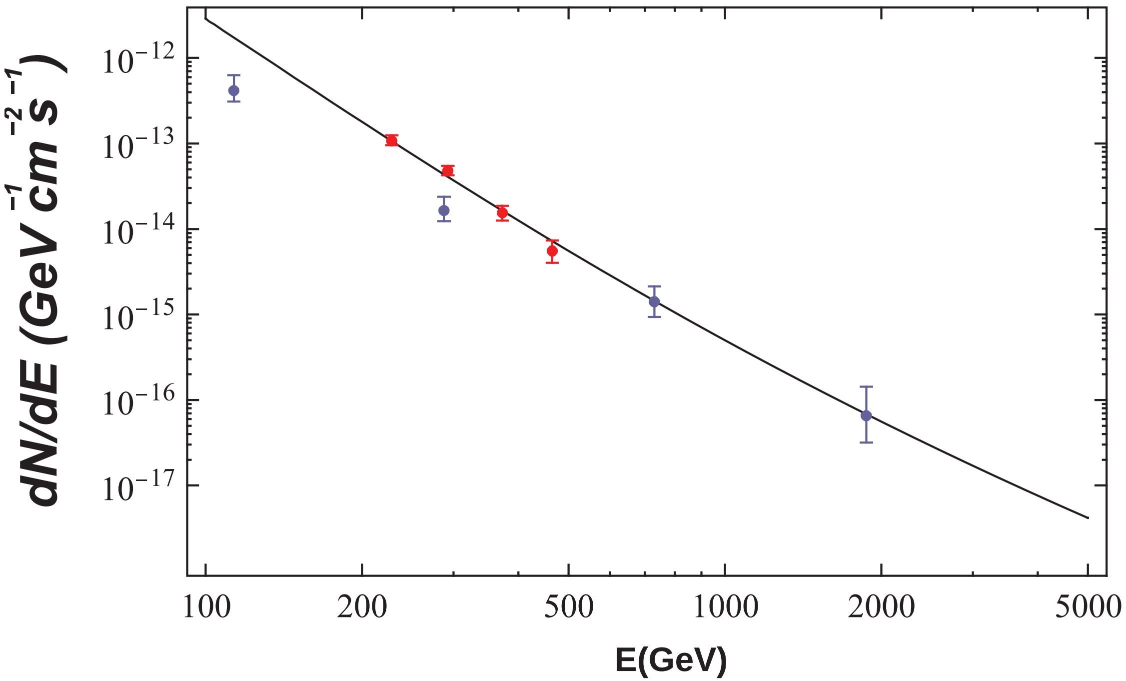
HESS (black), MAGIC (blue) and VERITAS (red) data points

Theory, e.g., Stecker, et al. (1992): *...“we predict a sharp cutoff between 0.1 and 1 TeV”*

The data: no signs of absorption due to $\gamma\gamma_{EBL} \to e^+e^-$

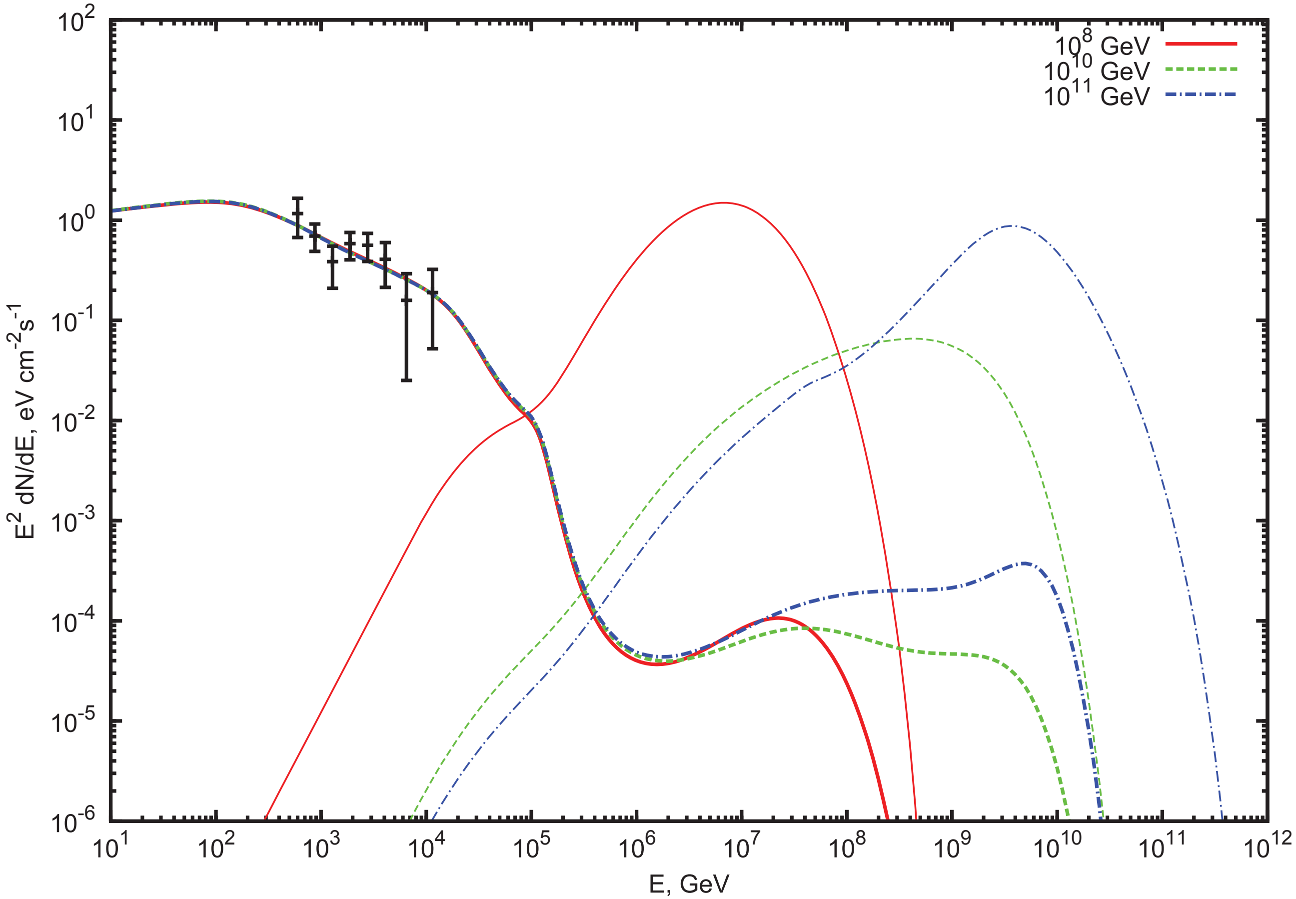
A one parameter fit, 3C66A

(parameter = power emitted in CR, subject to constraints)



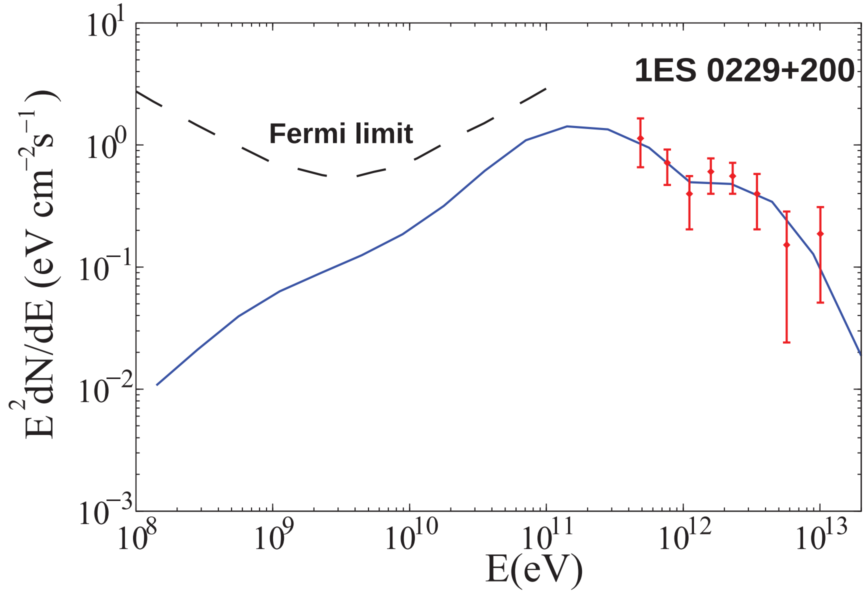
[Essey, AK, Astropart Phys. 33, 81 (2010)]

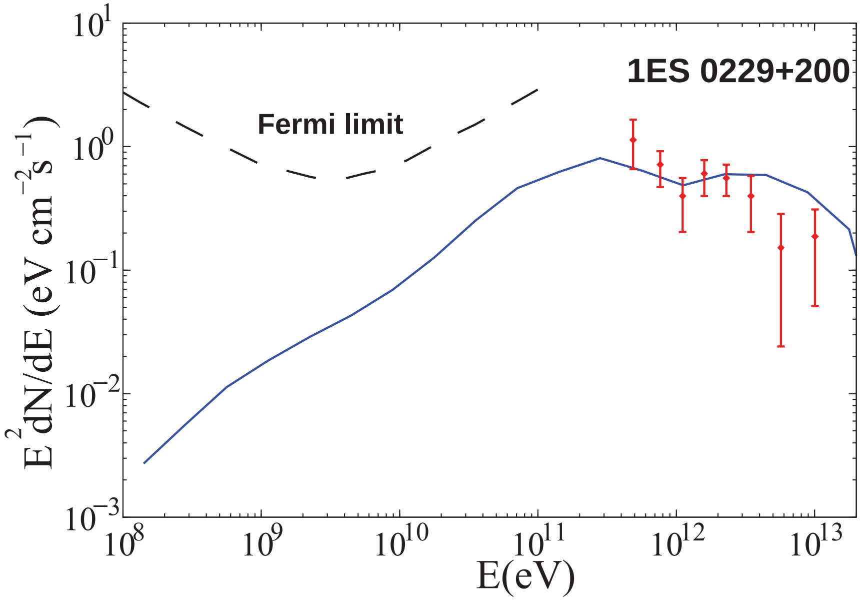
Secondary photons and neutrinos from 1ES0229+200 ($z = 0.14$)



[Essey, Kalashev, AK, Beacom, PRL 104, 141102 (2010)]

"Low" EBL (left), "high" EBL (right)

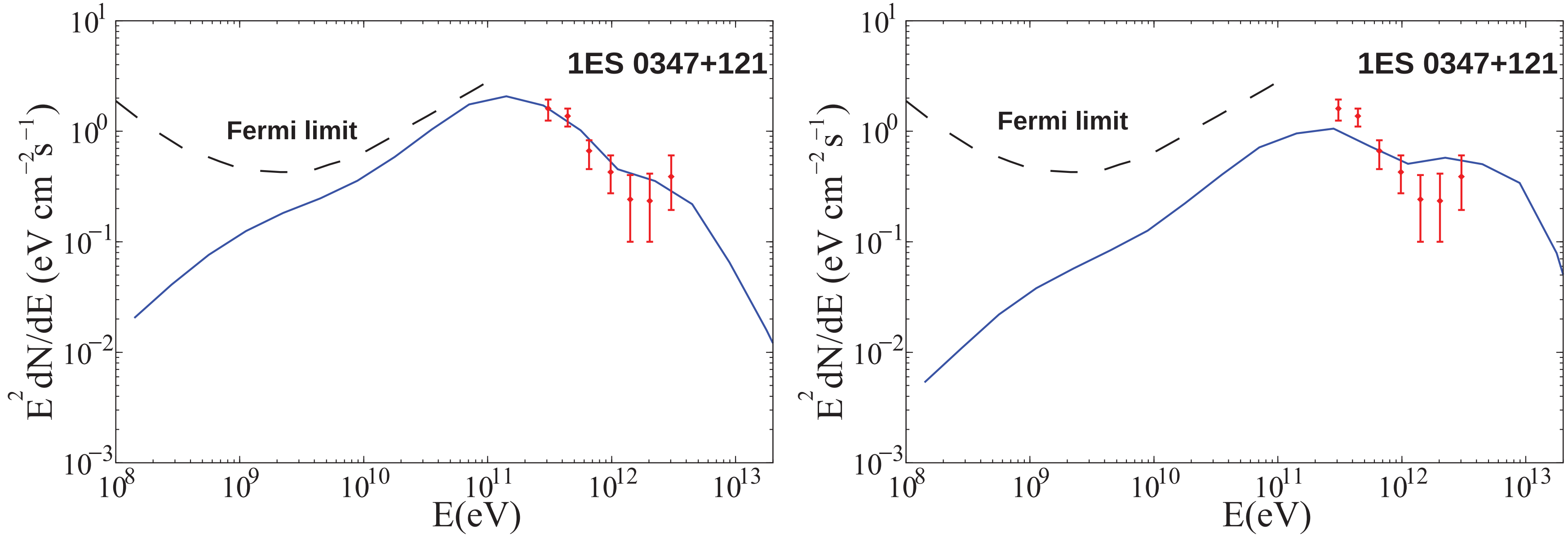




Both fit the data.

[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

"Low" EBL (left), "high" EBL (right)



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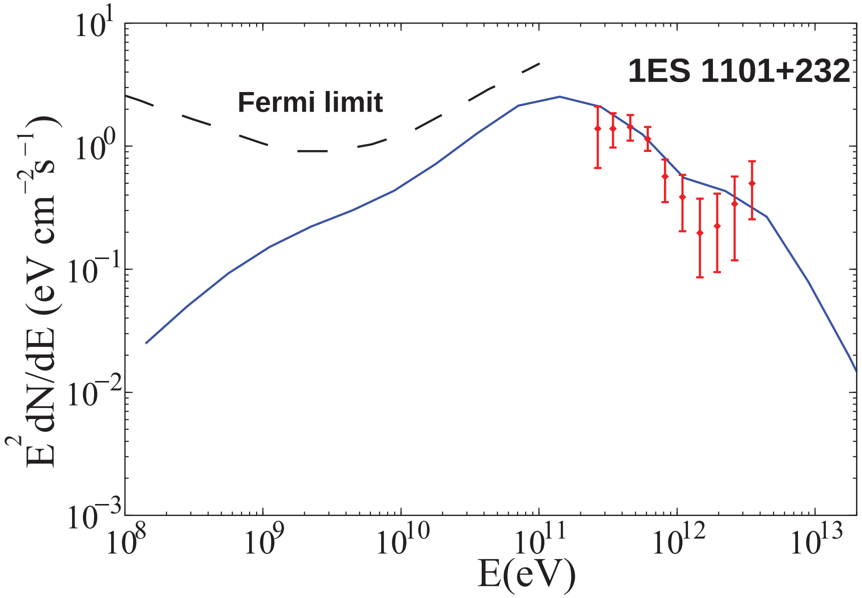
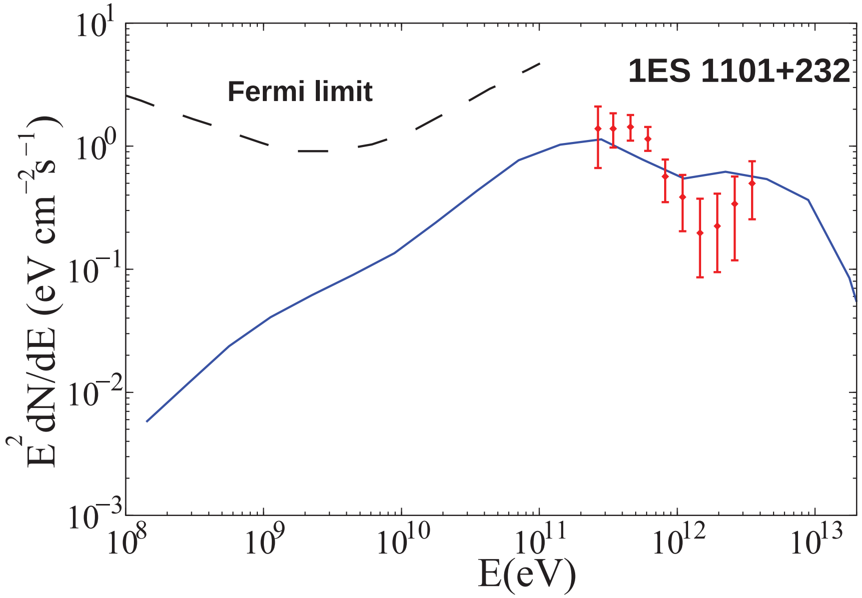
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

"Low" EBL (left), "high" EBL (right)





Both fit the data.

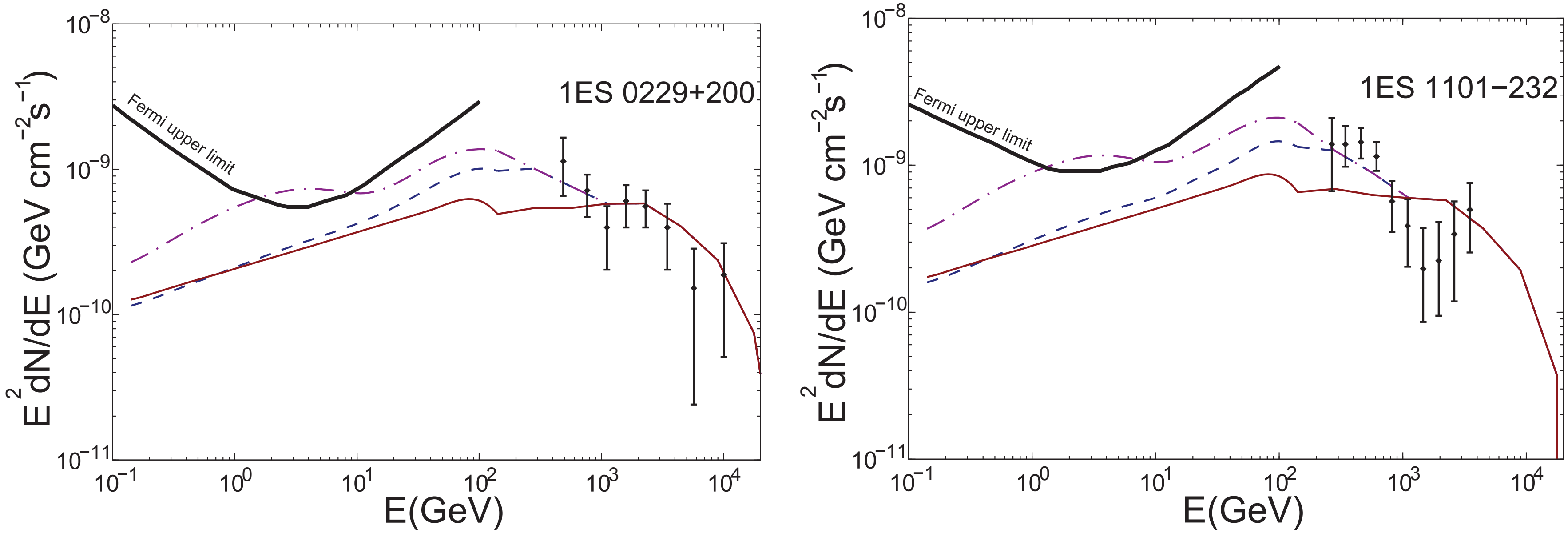
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

"Low" EBL vs "high" EBL

Source	Redshift	EBL Model	L_p , erg/s	$L_{p,\mathrm{iso}}$, erg/s	χ^2	DOF
1ES0229+200	0.14	Low	1.3×10^{43}	4.9×10^{45}	6.4	7
1ES0229+200	0.14	High	3.1×10^{43}	1.1×10^{46}	1.8	7
1ES0347-121	0.188	Low	2.7×10^{43}	1.0×10^{46}	16.1	6
1ES0347-121	0.188	High	5.2×10^{43}	1.9×10^{46}	3.4	6
1ES1101-232	0.186	Low	3.0×10^{43}	1.1×10^{46}	16.1	9
1ES1101-232	0.186	High	6.3×10^{43}	2.3×10^{46}	4.9	9

Here we have assumed $\theta_{jet} = 6^\circ$ (and $E_{\max} = 10^{11}$ GeV, $\alpha = 2$.)
[Essey, Kalashev, AK, Beacom, ApJ 731 (2011) 51]

IGMFs: spectra imply *femtogauss fields*



Spectra for $B = 10^{-18}$ G (upper, dash-dotted line), $B = 10^{-15}$ G (middle, dashed line), and B $= 10^{-13}$ G Spectral fits imply IGMF in the range of $\sim 10^{-15}$ G. [Essey, Ando, AK]

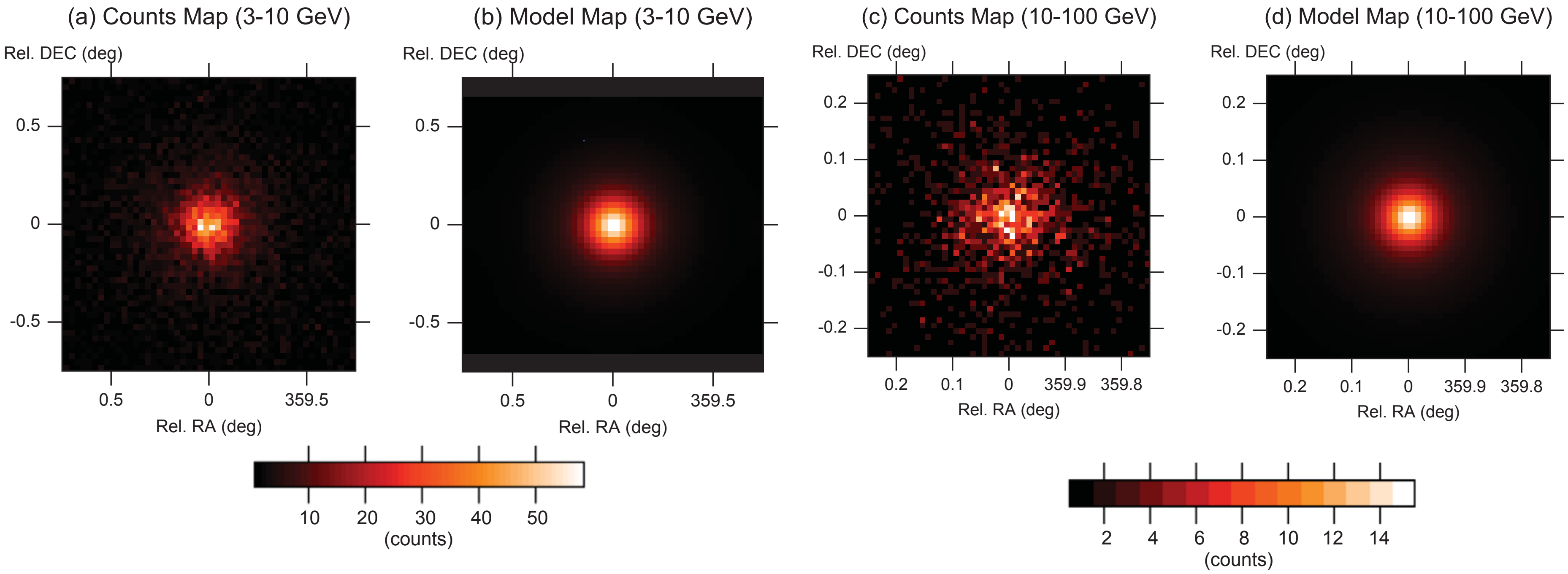
Spectra: $B \sim 10^{-15}$ Gauss

For line-of-sight interactions to explain the point sources, the IGMFs must be in the range:

$$\mathbf{1 \times 10^{-17}}\ \mathrm{G} < \boldsymbol{B} < \mathbf{3 \times 10^{-14}}\ \mathrm{G}$$

Halos: $B \sim 10^{-15}$ Gauss

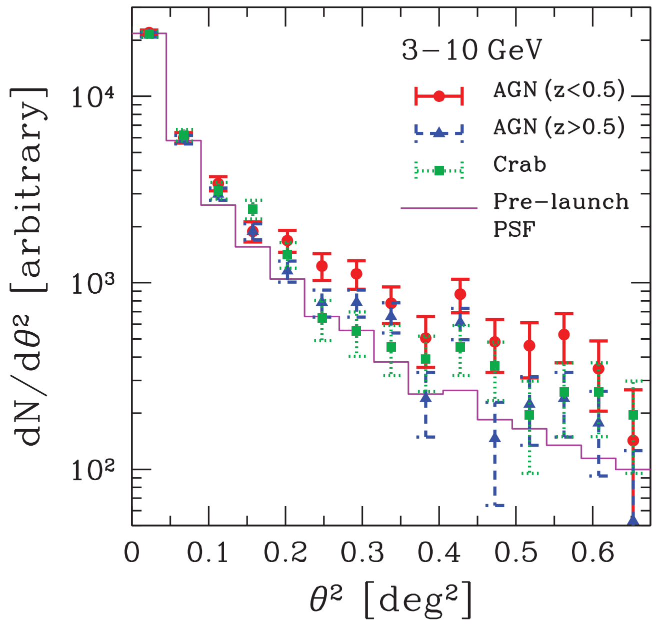
Intergalactic magnetic fields make the images of blazars diffuse. The halos observed in a composite image of 170 blazars (stacked).

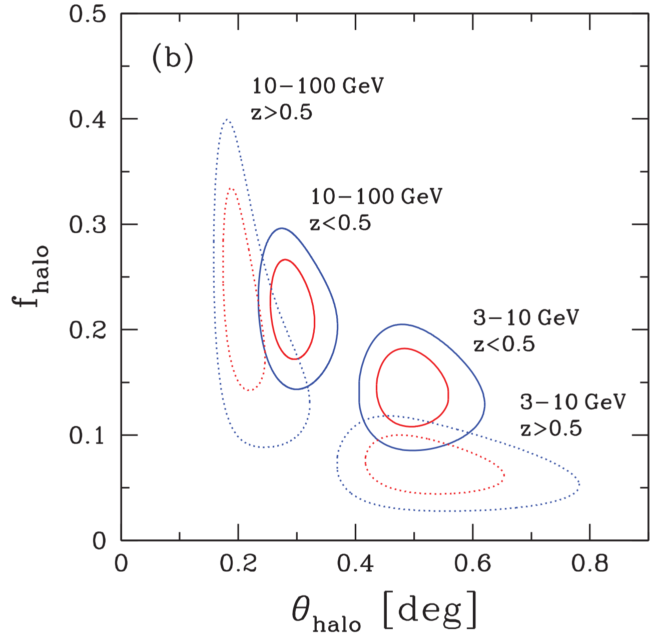


[Ando, AK, ApJ 722 L39 (2010)]

Halos: $B \sim 10^{-15}$ Gauss

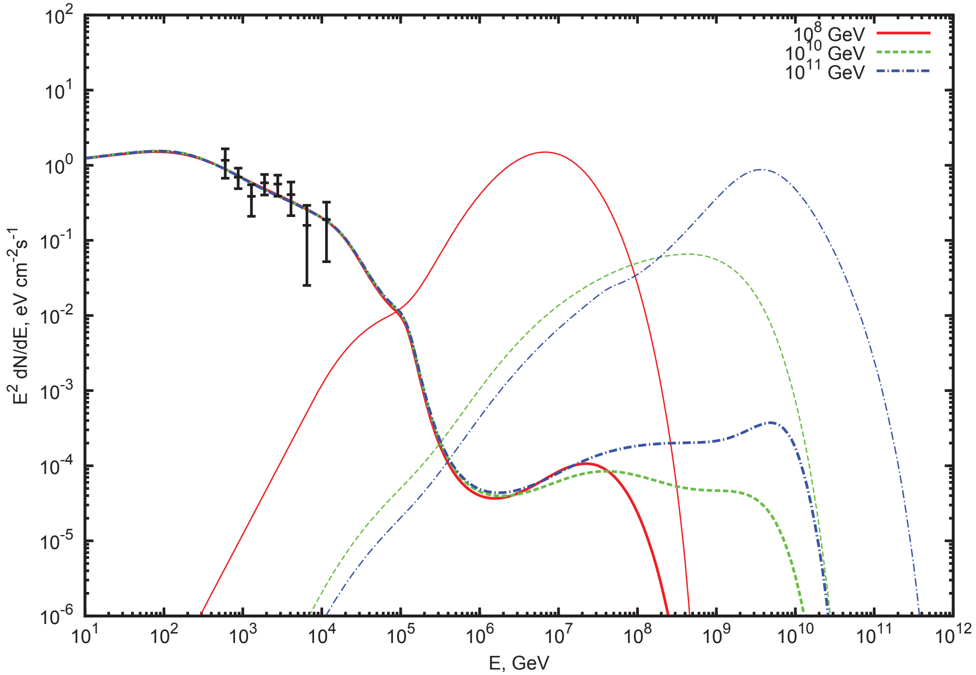
Both Fermi prelaunch calibrated PSF and the actual image of Crab puilsar were used for two alternative analyses. Redshift dependence inconsistent with instrumental effects. The halos around blazars imply 10^{-15} Gauss magnetic fields.

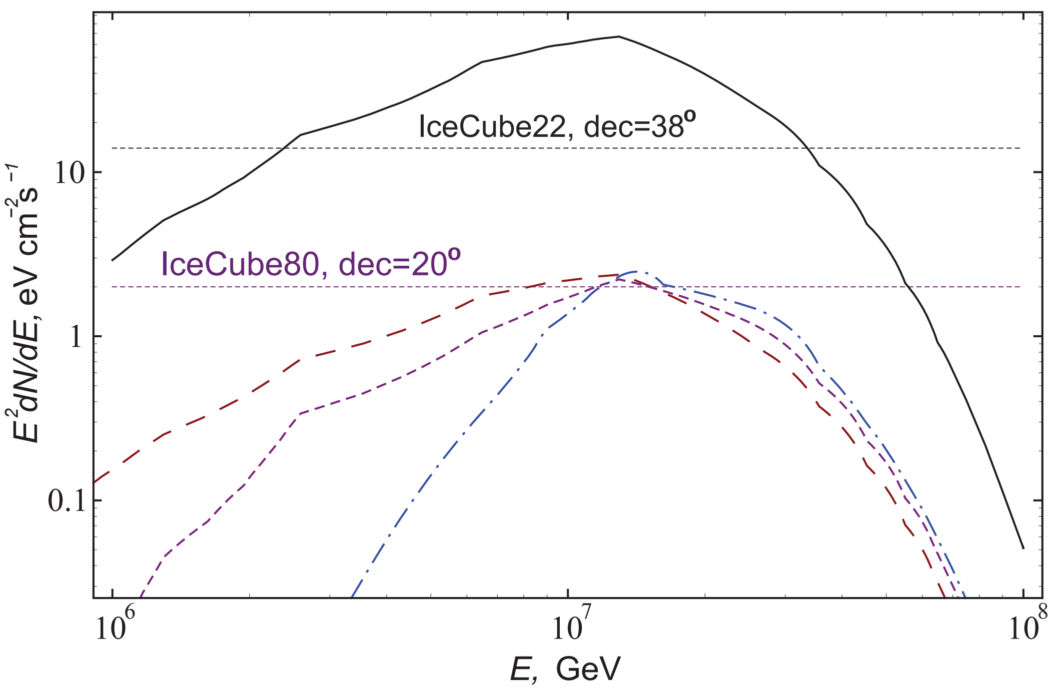




[Ando, AK, ApJ 722 L39 (2010)]

IceCube can see point sources...

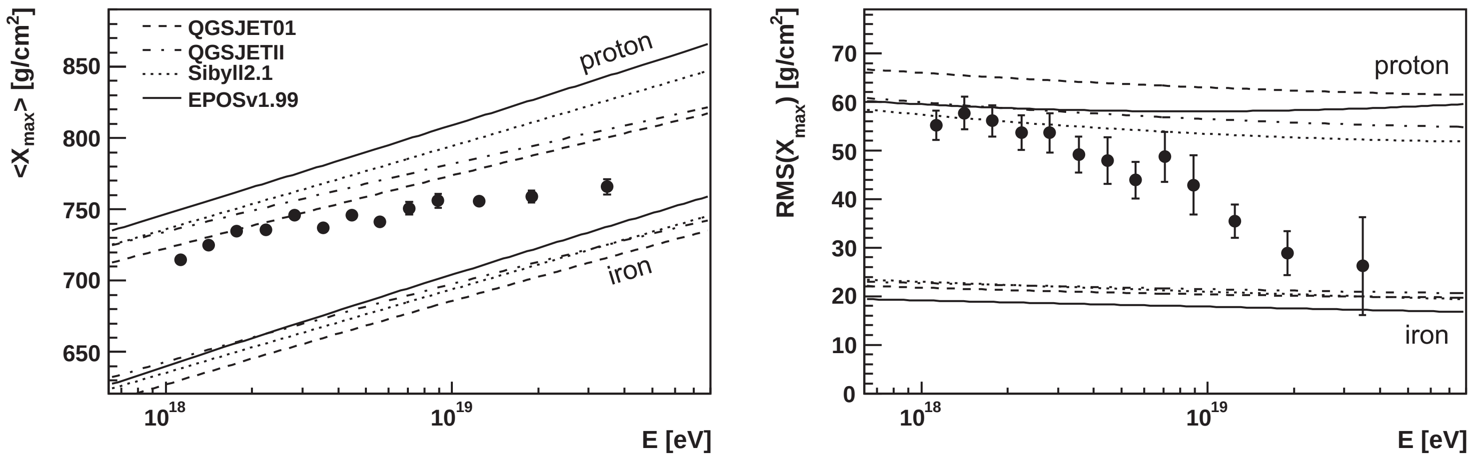




...but predictions are uncertain. For *optimistic* values of parameters, IceCube can see 1ES0229+200 (dashed lines, for 80 strings with 1 year exposure time), and Mrk421 or Mrk501 (solid line). **[Essey, Kalashev, AK, Beacom, PRL 104, 141102 (2010)]**

A recent result from Pierre Auger Observatory

energy-dependent chemical composition



Warning: corroborated by Yakutsk [A. V. Glushkov *et al.*, JETP Lett. **87**, 190 (2008)], but not by HiRes [Abbasi *et al.* Phys. Rev. Lett. **104**, 161101 (2010)]

Why should any source accelerate nuclei rather than protons at high energies??

[talk by Berezinsky]

UHECR

messengers: **nuclei (?)**, $\boldsymbol{p}$, $\boldsymbol{\nu}$, etc.
relevant backgrounds: **GMF, CMB**

Composition puzzle: contribution of Galactic sources?

It is hard to imagine an extragalactic source that accelerates selectively heavy nuclei. In fact, the opposite is expected from photodissociation of nuclei at the source.

If sources accelerate all the particles, can propagation effects alter the observed composition?

Yes, if the sources are **Galactic**.

Diffusion times for nuclei are longer than for protons of the same energy.

$$t_D \sim \frac{R^2}{D} \sim 10^7 \mathrm{yr} \left(\frac{R}{10\ \mathrm{kpc}} \right)^2 \left(\frac{Z}{26} \frac{10^{19}\,\mathrm{eV}}{E} \right)^2$$

Diffusion is also energy-dependent.

Galactic sources likely to exist... in the past

Long list of candidates (in possibly overlapping categories):

- GRBs
- hypernovae
- collapsars
- other unusual supernovae

Do these events occurred in our our own galaxy?

GRBs as sources in Milky Way Galaxy

- GRBs have been proposed as sources of *extragalactic* UHECRs [Vietri; Waxman; Dermer]
- Galactic GRBs have been considered as sources of UHECRs [Dermer *et al.*, Biermann *et al.*]
- Long GRBs: probably unusual supernova explosions. Short GRBs: probably mergers of compact stars.
- Both should have happened in our own Galaxy in the past, at a rate of one per $\mathbf{10^4 - 10^5}$ **years**.
- Past Galactic GRBs have been considered as the explanation of 511 keV line from the Galactic Center [Bertone, et al.; Parizot et al., Calvez, AK], as well as the electron excess of PAMELA/Fermi [Ioka; Calvez, AK]
- How long will the UHECRs diffuse in the Galactic magnetic fields, and how isotropic will they become? Depends on composition.

Transport equation (a simple exercise)

$$\frac{\partial n_i}{\partial t} - \vec{\nabla}(D_i \vec{\nabla} n_i) + \frac{\partial}{\partial E}(b_i n_i) =$$

$$Q_i(E, \vec{r}, t) + \sum_k \int P_{ik}(E, E')n_k(E')dE'.$$

For energies below GZK cutoff, neglect energy losses; consider just diffusion. For a pointlike source

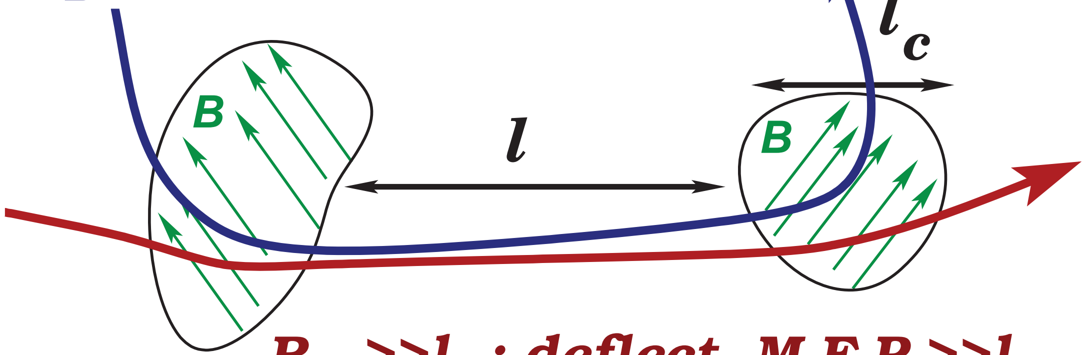
$$Q_i(E, \vec{r}, t) = \delta(\vec{r})Q_0 \left(\frac{E_0}{E}\right)^\gamma$$

the solution is

$$n_i(E, r) = \frac{Q_0}{4\pi r\, D_i(E)} \left(\frac{E_0}{E}\right)^\gamma.$$

Diffusion in two different regimes

$R_B \ll l_c$; deflect. M.F.P.=l



$R_B \gg l_c$; deflect. M.F.P.$\gg l$

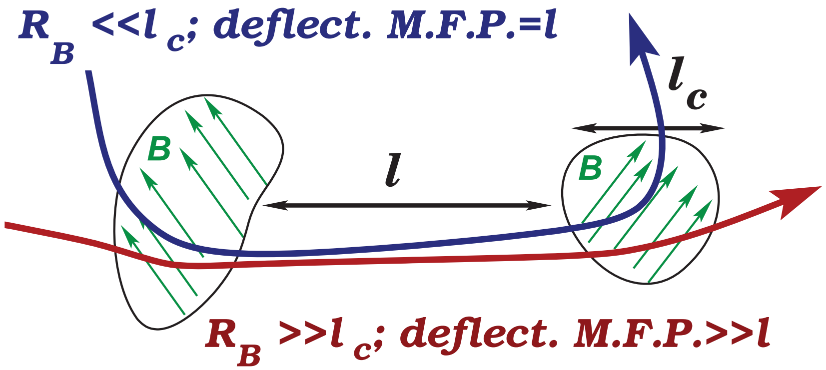
$D(E)=D_0=l/3$, for $E \ll E_0$

$D(E)=D_0(E/E_0)^2$, for $E \gg E_0$

critical energy, E_0: $R_B=l_c$

E_0 depends on Z of a nucleus.

Diffusion in two different regimes



D(E)=D₀=l/3, for E<<E₀

D(E)=D₀(E/E₀)², for E>>E₀

critical energy, E₀: R_B=l_c

$E_{0,i}$ depends on Z_i of a nucleus i.

Critical energy $E_{0,i}$, at which $R_{B,i} = l_c$, depends on Z_i

$$
\begin{aligned}
R_i &= \frac{E}{Bq_i} = l_0 \left(\frac{E}{E_{0,i}}\right), \quad \text{where} \\
E_{0,i} &= eBl_0 Z_i, \\
E_{0,i} &= Z_i \times 10^{18}\,\mathrm{eV} \\
&\quad \times \left(\frac{B}{3\times 10^{-6}\,\mathrm{G}}\right)\left(\frac{l_0}{0.3\,\mathrm{kpc}}\right)
\end{aligned}
$$

Diffusion in two different regimes:

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

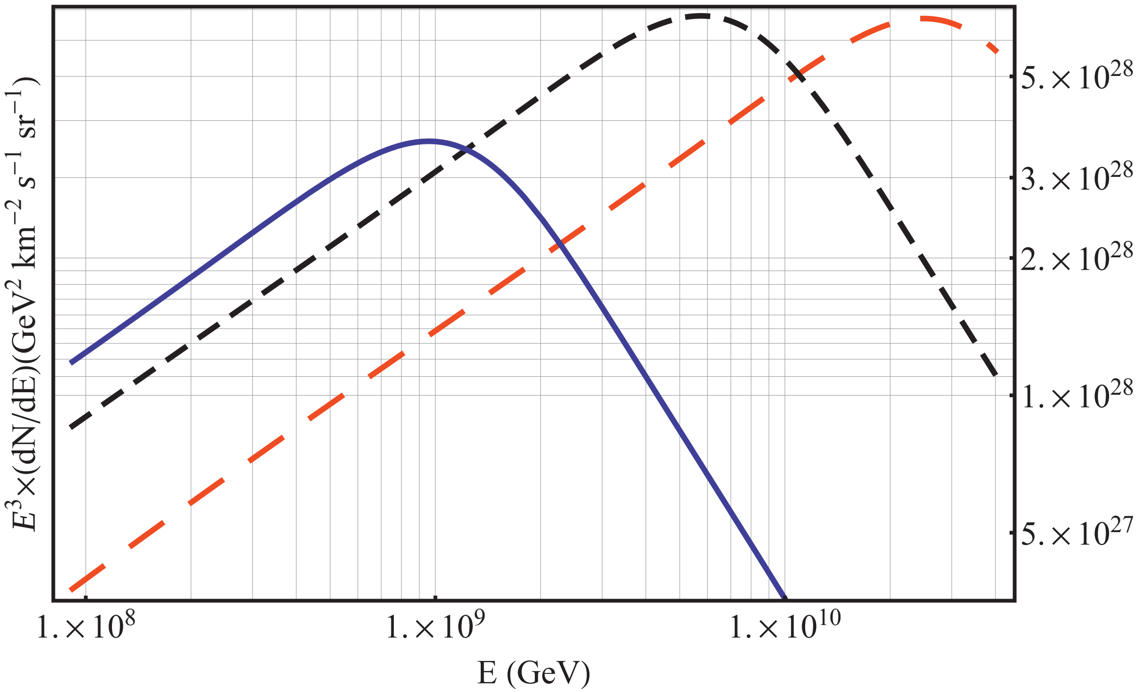
What about our solution?

$$n_i(E,r) = \frac{Q_0}{4\pi r\, D_i(E)} \left(\frac{E_0}{E}\right)^{\gamma}$$

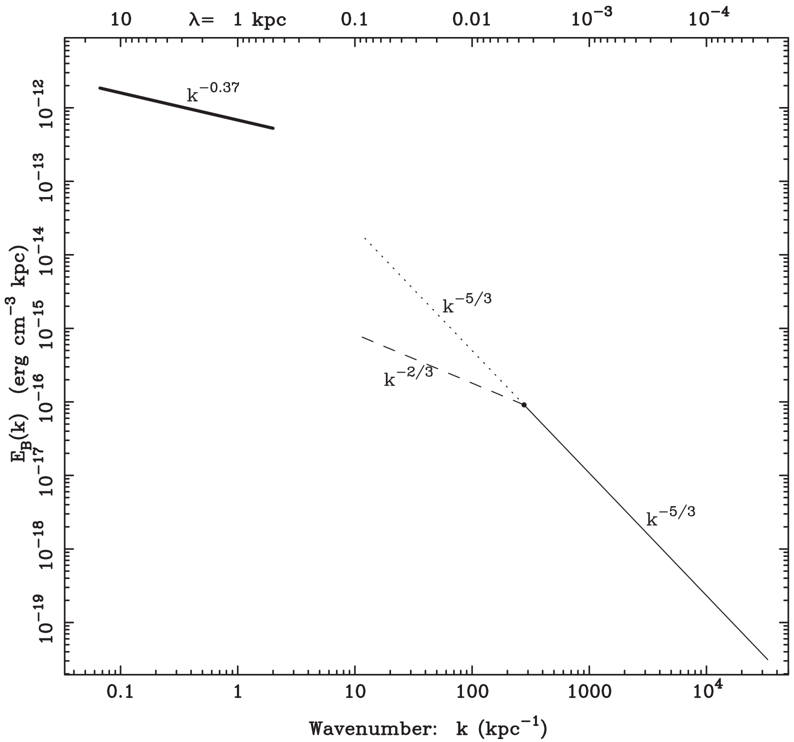
The spectral slope changes at $E \sim E_{0,i}$, and the flux drops dramatically because the particles escape from the galaxy. The flux drops for protons at lower energies than heavy nuclei.

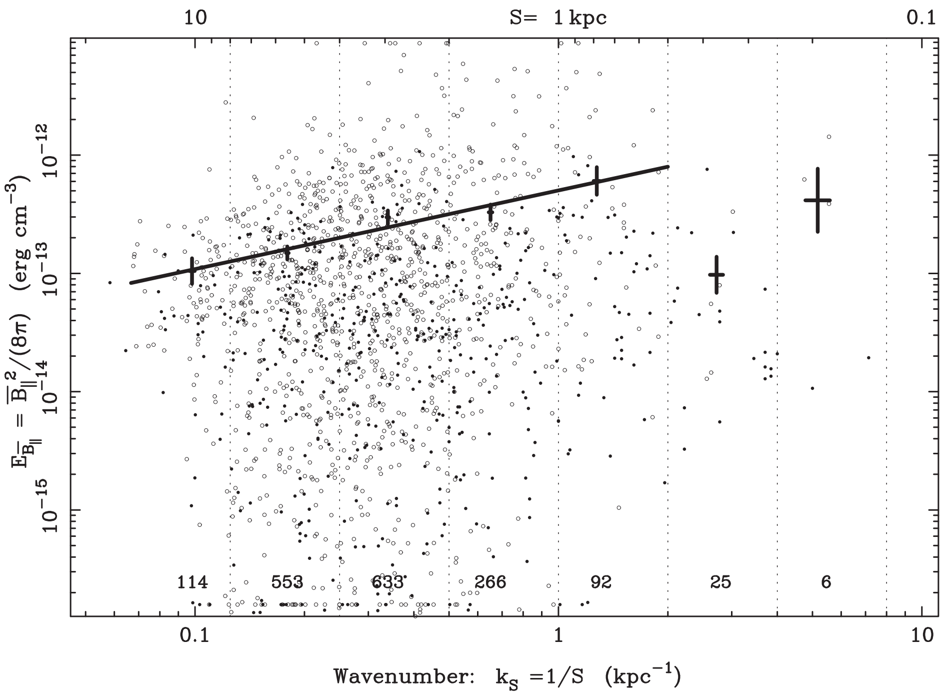
Energy-dependent composition due to diffusion

protons, C, Fe



Galactic magnetic fields

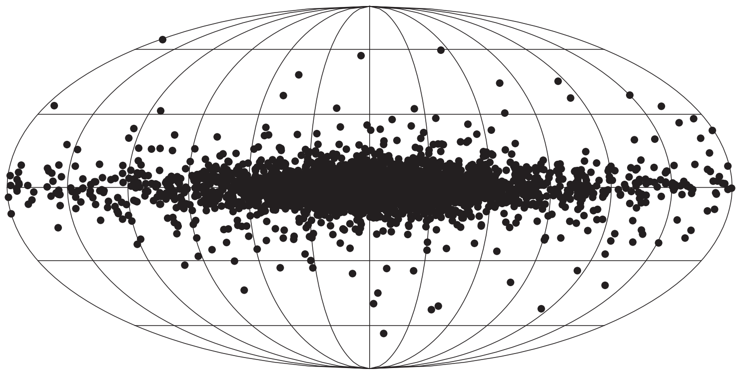




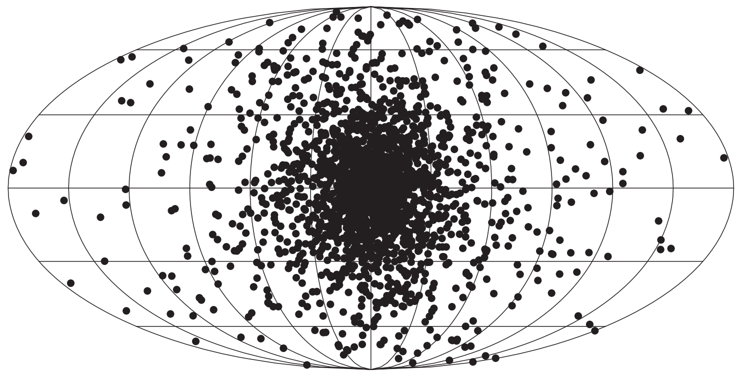
[Han, Ferriere, Manchester, ApJ, 610, 820 (2004)]

At each energy, probe new scale in the magnetic field power spectrum.

More realistic source distribution

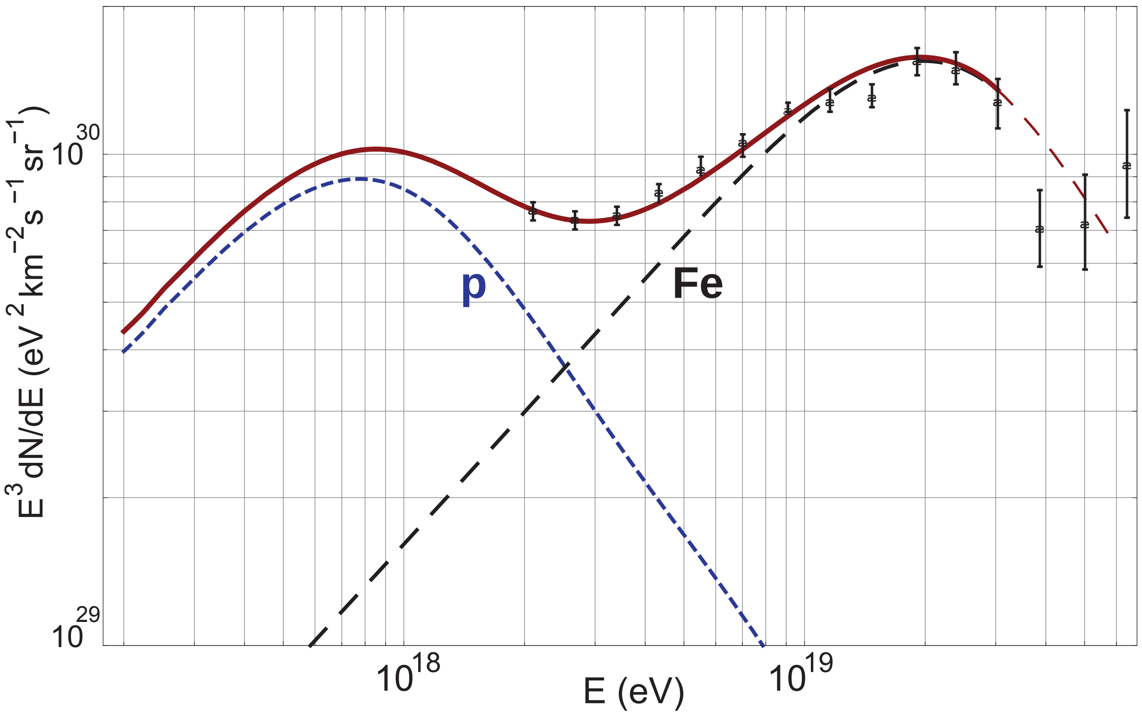


Supernovae or long GRBs, assuming they follow star counts [Bahcall et al.]



Short GRBs, based on observed distribution in other galaxies [Cui, Aoi, Nagataki]

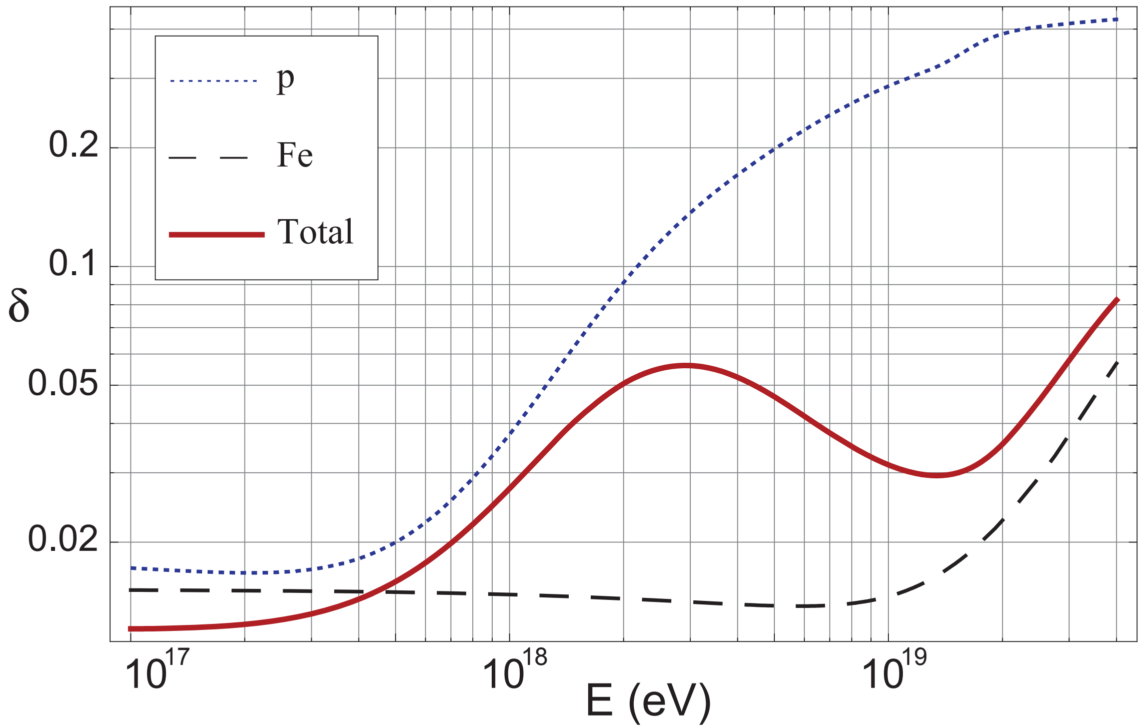
Comparison with Pierre Auger data



[Calvez, AK, Nagataki, PRL 105, 091101 (2010)]

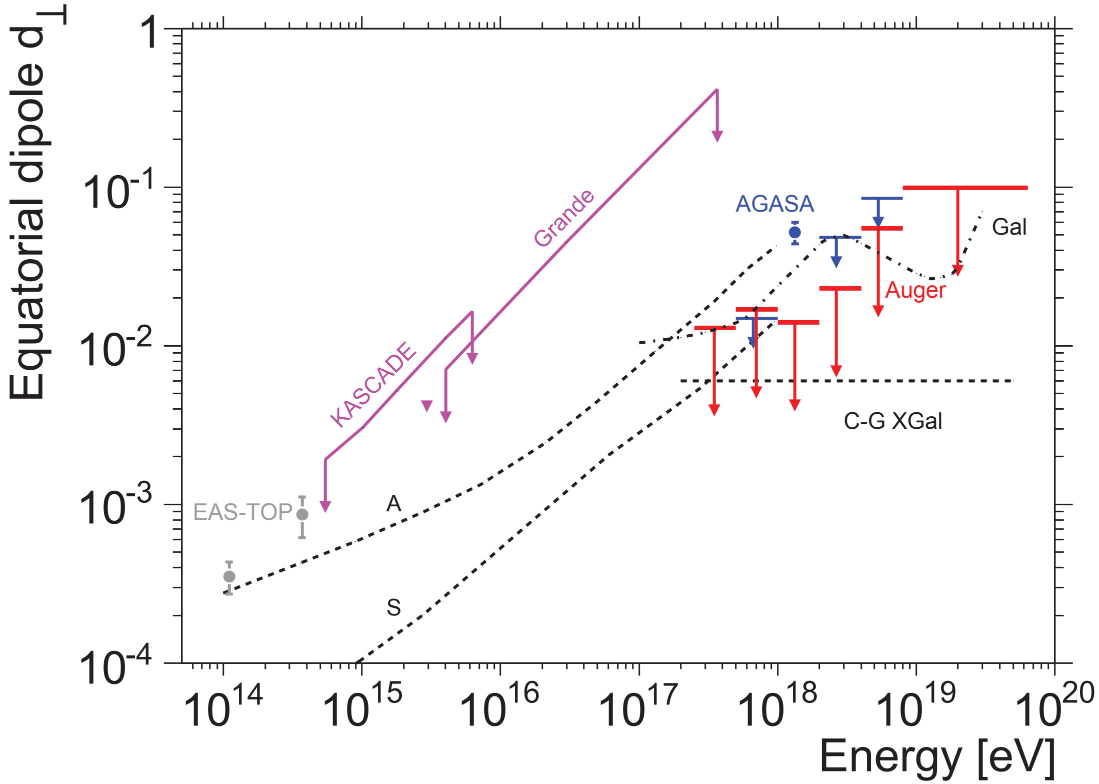
Energy required in UHECR($> 10^{19}$) is **only 10^{46} erg per GRB** (*cf.* 10^{51} erg for extragalactic GRB models).

Galactocentric anisotropy (sources follow stars)



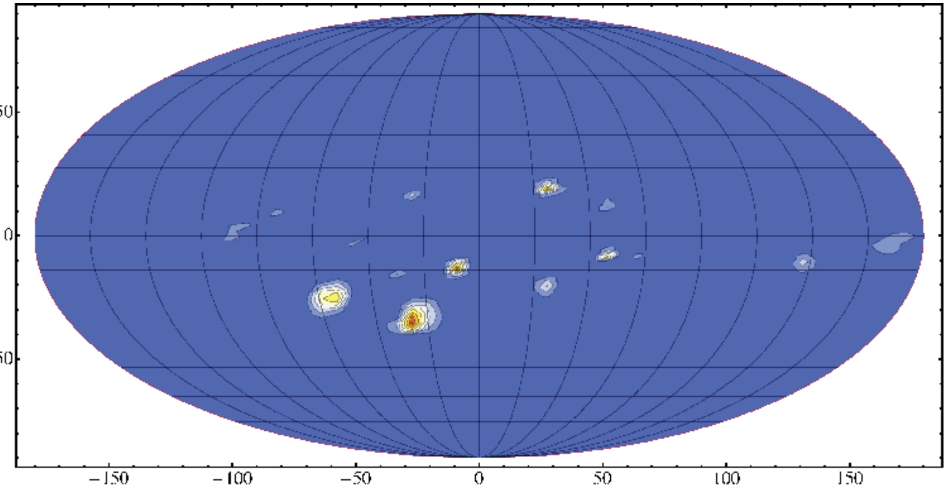
[Calvez, AK, Nagataki, PRL 105, 091101 (2010)]

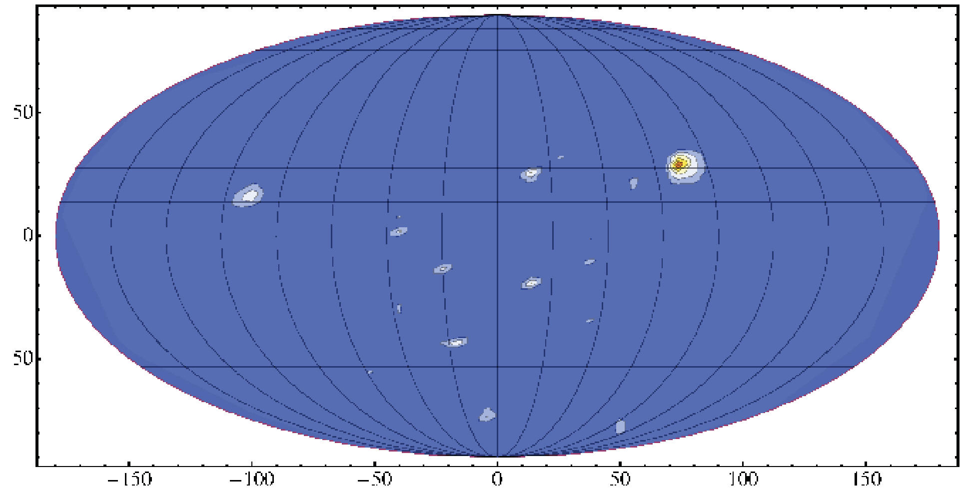
Pierre Auger limits



Clusters of events from recent/closest GRBs

supernovae/long GRBs **short GRBs**





In addition, extragalactic **protons** can show correlation with distant sources.

Conclusions

- nuclei at high energies $\Rightarrow$ galactic sources, probably unusual supernovae, hypernovae, GRBs
- AGN produce both cosmic rays and gamma rays $\Rightarrow$ secondary gamma rays should dominate the signals of distant sources
- photons – cosmic rays and neutrinos connection $\Rightarrow$ evidence for CR acceleration in AGN; need a holistic multi-messenger approach to AGN studies
- unusual scaling of sources with distance $\Rightarrow$ implications for future population studies

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