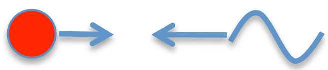
UHECR Propagation + Related Physics (~25 mins)

Topics

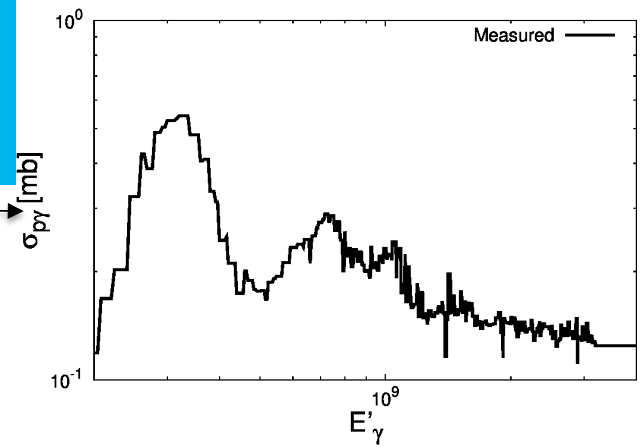
- Cosmic ray interactions with background radiation fields
- Extragalactic cosmic ray source distribution
- Secondary particles and cascades
- From where?...clues from the first pevatron detected at the Galactic center

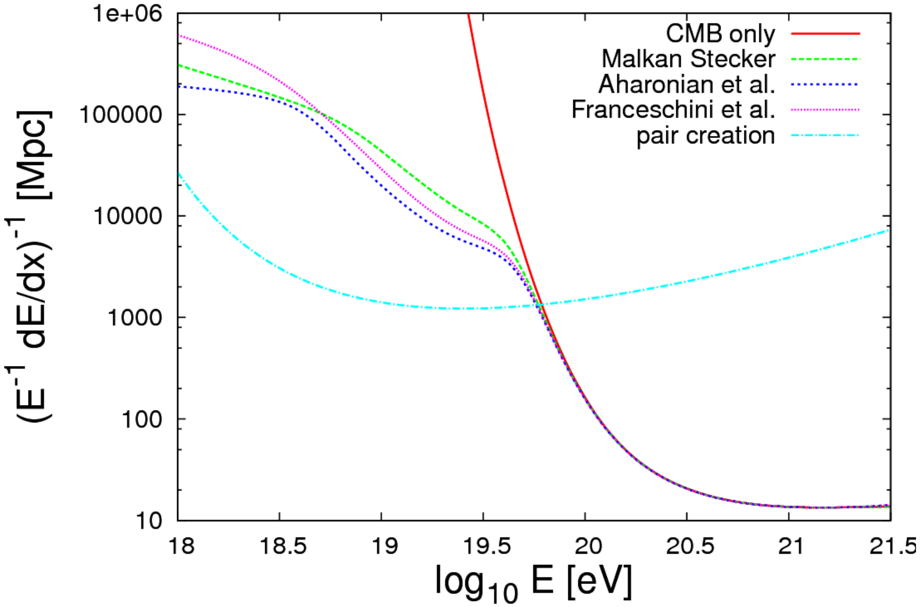
Cosmic Ray Proton

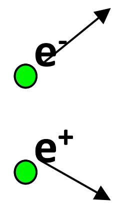


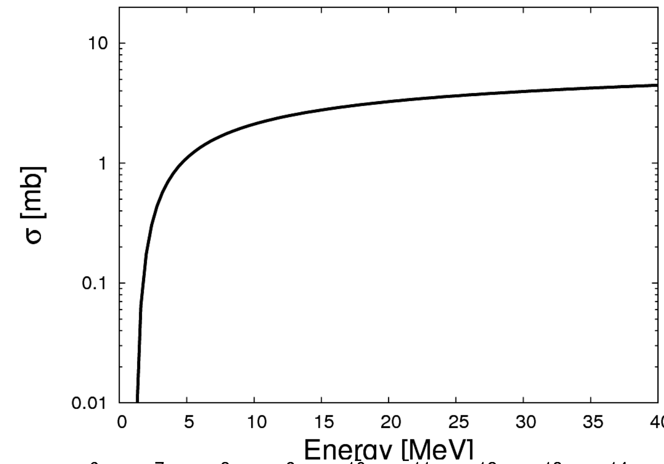
p γ

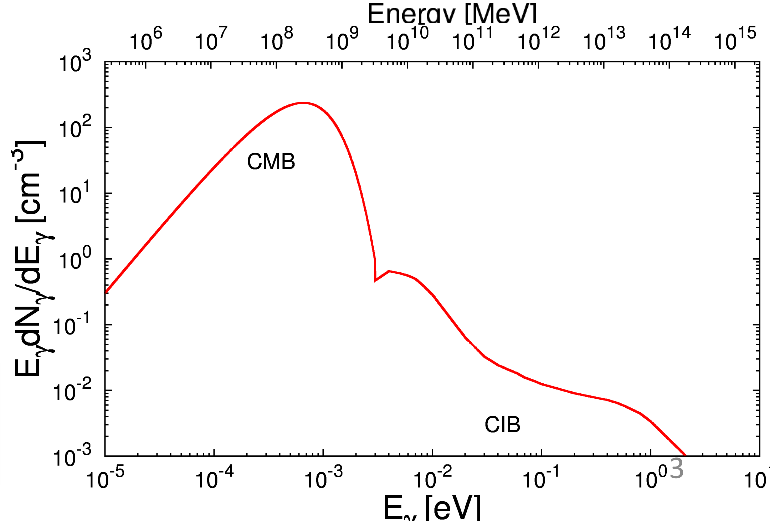
π





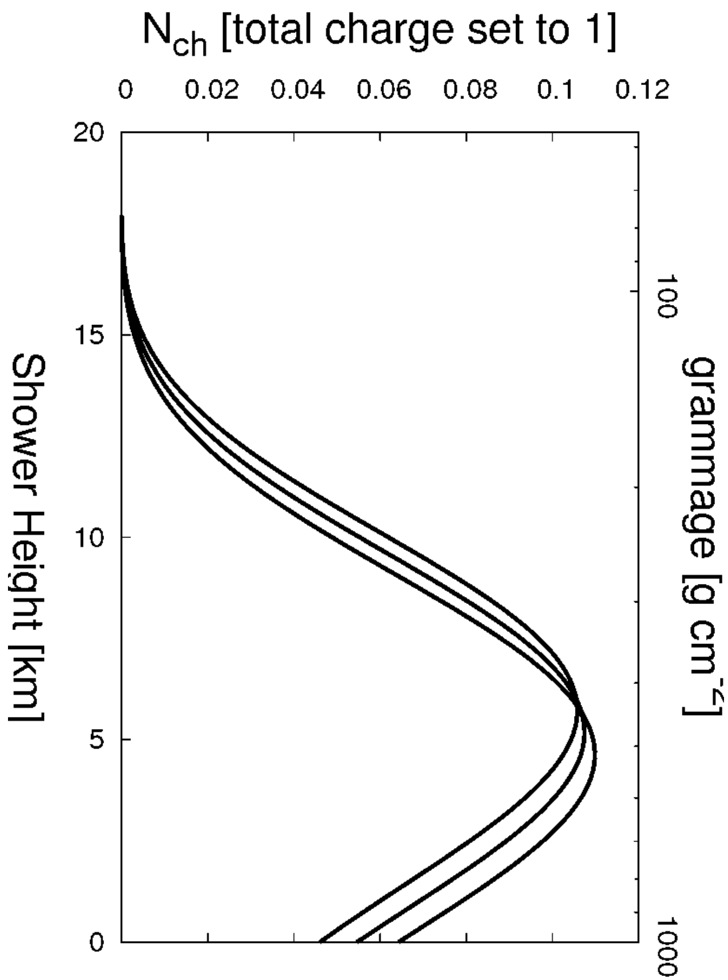


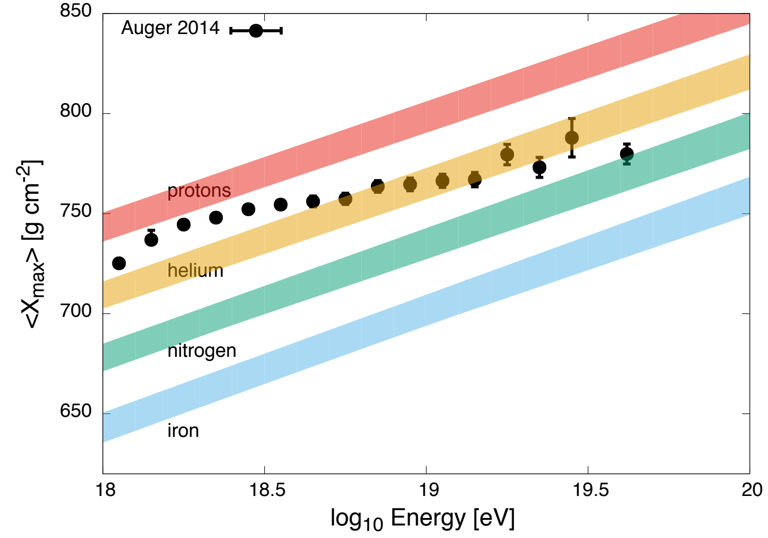


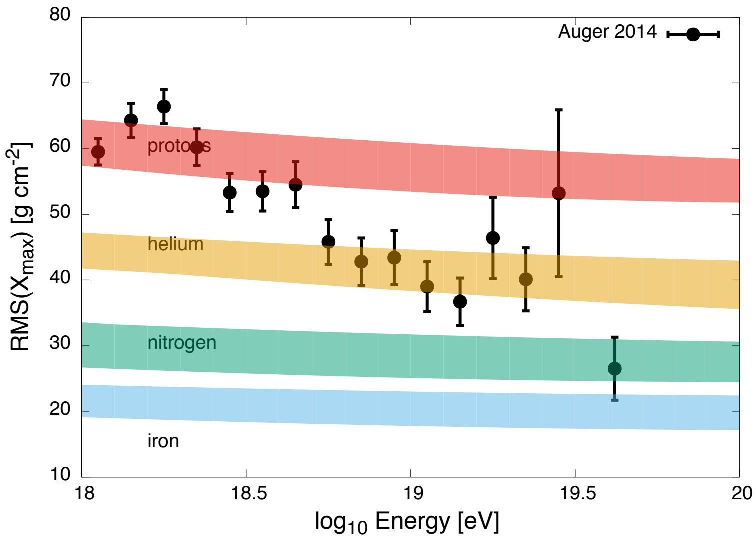


$$\mathbf{R} = \frac{2\mathbf{m_p^2}}{\mathbf{E_p^2}} \int \frac{1}{\epsilon^2} \frac{\mathbf{dN_\gamma}}{\mathbf{d}\epsilon} \int_0^{4\mathbf{E_p}\epsilon/\mathbf{m_p}} \mathbf{k_{p\gamma}}\epsilon' \sigma_{\mathbf{p}\gamma}(\mathbf{E_p}, \epsilon')\mathbf{d}\epsilon'$$

Composition- Consider Nuclei?



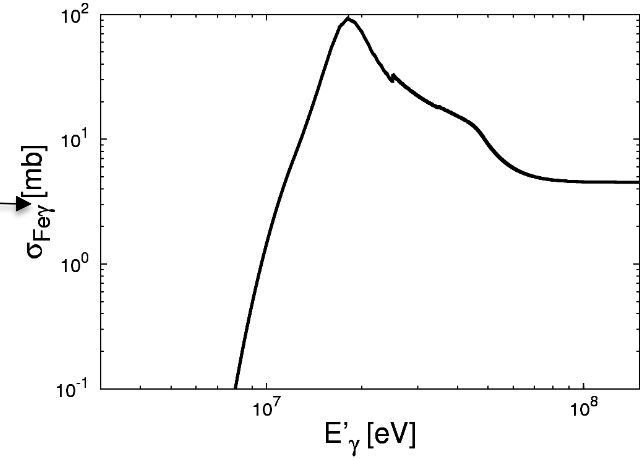


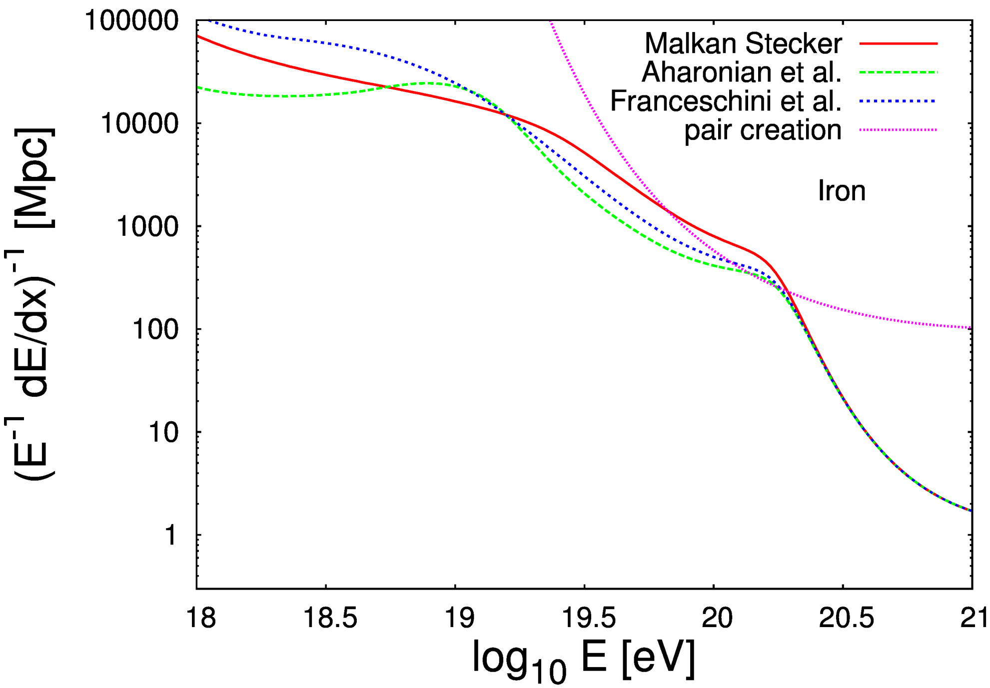


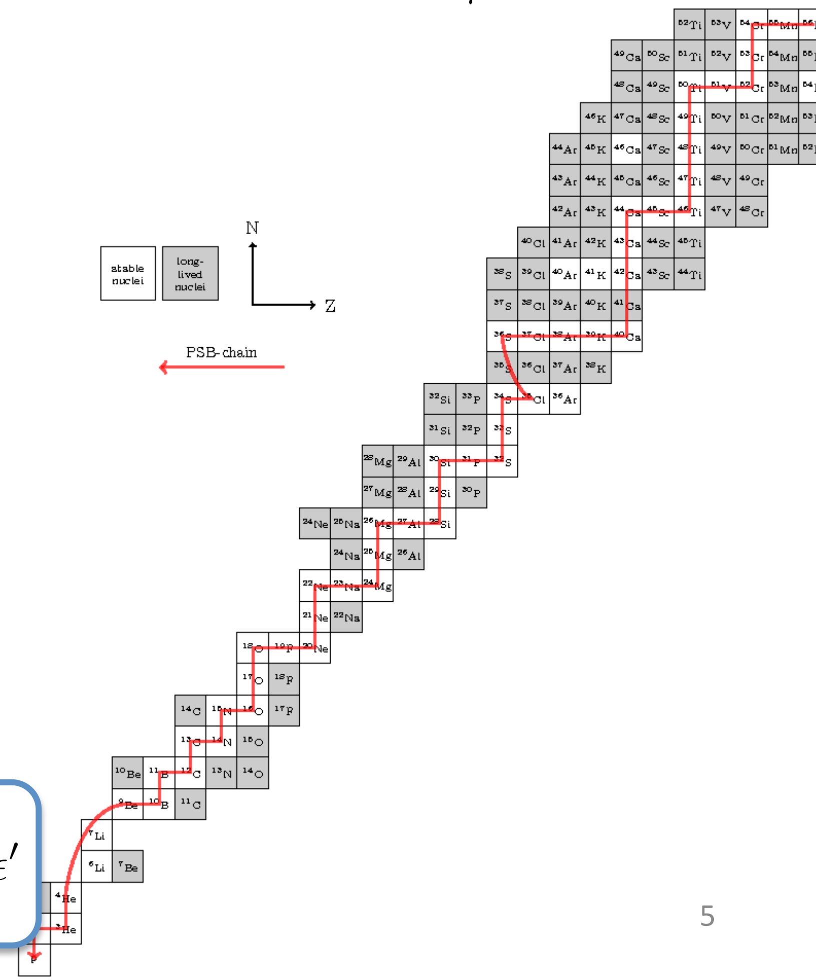
DESY.

Cosmic Ray Nuclei

N γ p





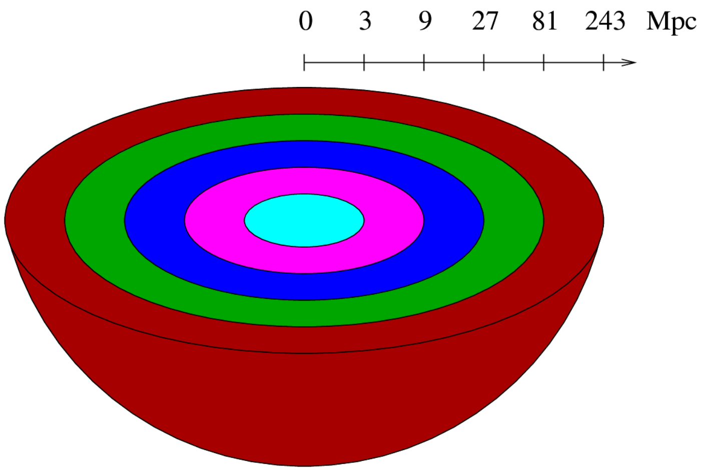


$$\mathbf{R = \frac{2m_N^2}{E_N^2} \int \frac{1}{\epsilon^2} \frac{dN_\gamma}{d\epsilon} \int_0^{4E_N\epsilon/m_N} k_{N\gamma}\epsilon' \sigma_{N\gamma}(E_N, \epsilon') d\epsilon'}$$

Assumptions on Source Population

$$\frac{dN}{dV_C} \propto (1+z)^n$$

$$z < z_{max}$$



$$n = -6,\ -3,\ 0,\ 3$$

$$\frac{dN}{dE} \propto E^{-\alpha} \exp[-E/E_{Z,max}]$$

$$E_{Z,max} = (Z/26) \times E_{Fe,max}$$

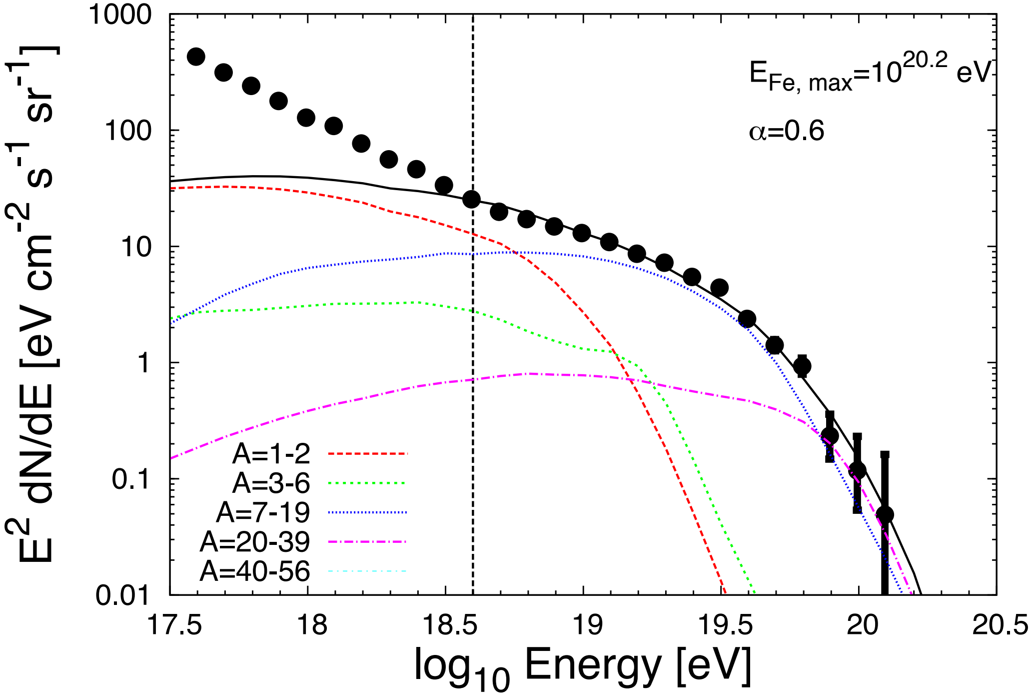
Note- magnetic field horizon effects are neglected in the following. This amounts to assuming: $d_s < (ct_H \lambda_{scat})^{1/2}$
ie. the source distribution may be approximated to be spatially continuous (also note, presence of t_H term comes from temporally continuous assumption)

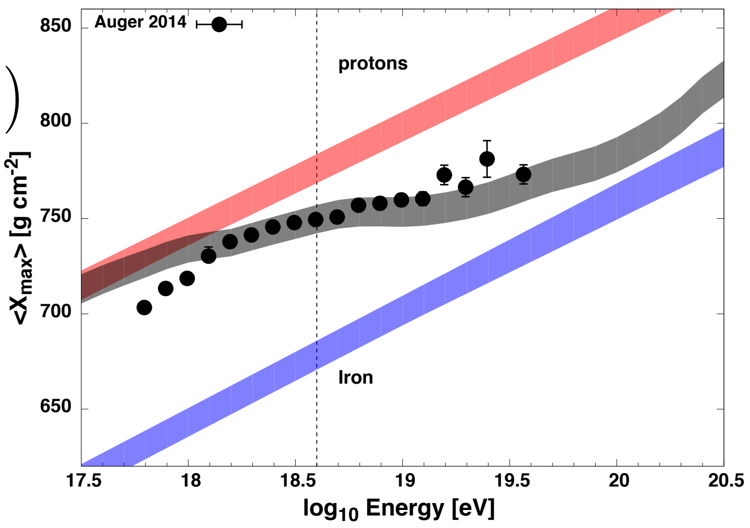
DESY.

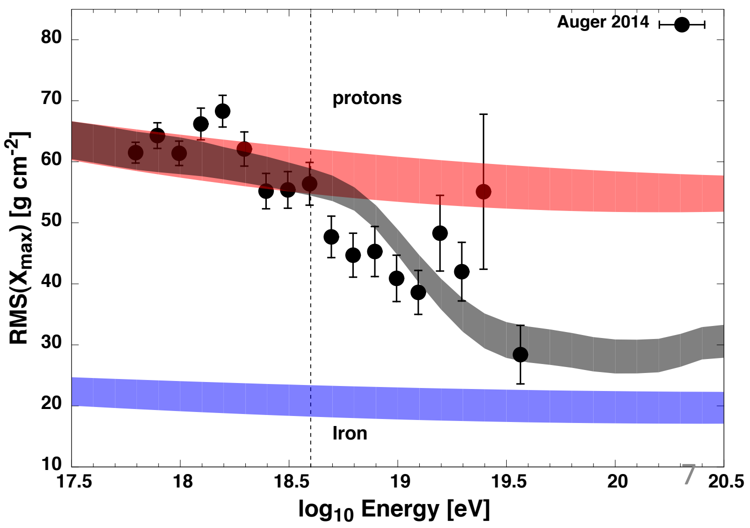
MCMC Likelihood Scan: Spectral + Composition Fits

$$\mathbf{L(f_p, f_{He}, f_N, f_{Si}, E_{max}, \alpha) \propto \exp(-\chi^2/2)}$$

n=3 evolution result





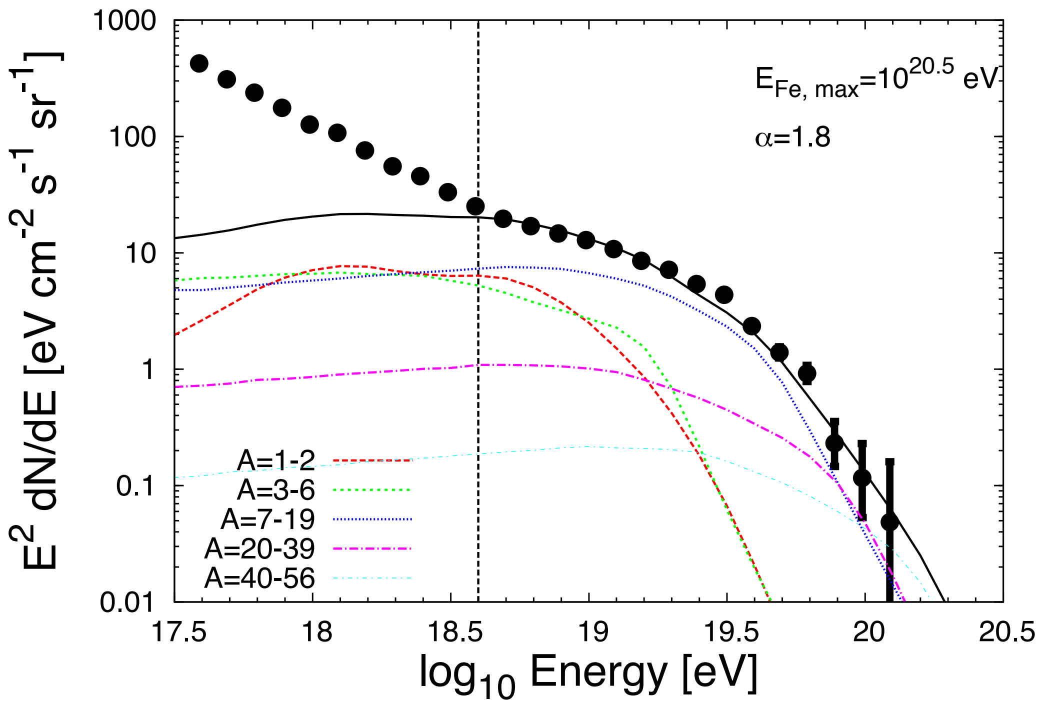


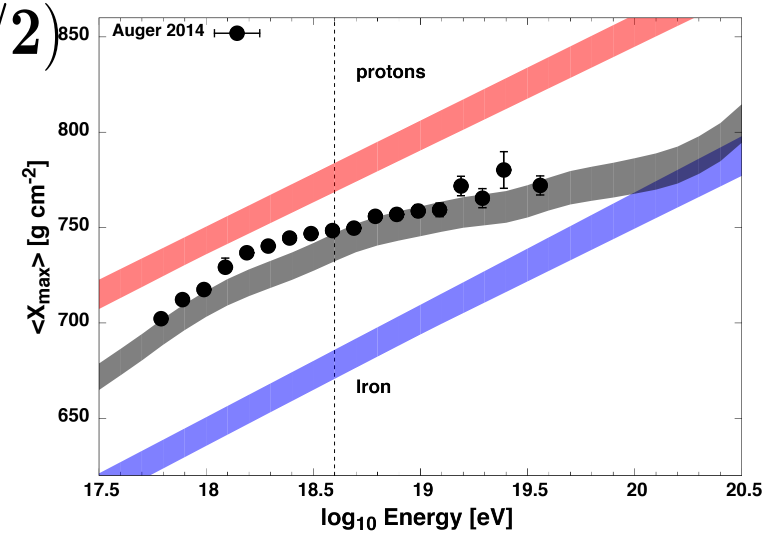
DESY.

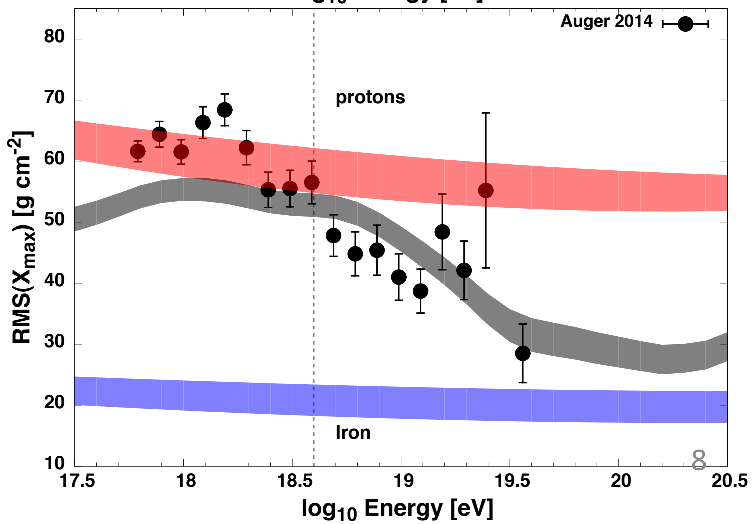
MCMC Likelihood Scan: “Soft” Spectra Solutions

$$\mathbf{L}(\mathbf{f_p}, \mathbf{f_{He}}, \mathbf{f_N}, \mathbf{f_{Si}}, \mathbf{E_{max}}, \alpha) \propto \exp(-\chi^2/2)$$

n=-6 evolution result







DESY.

MCMC Results Table

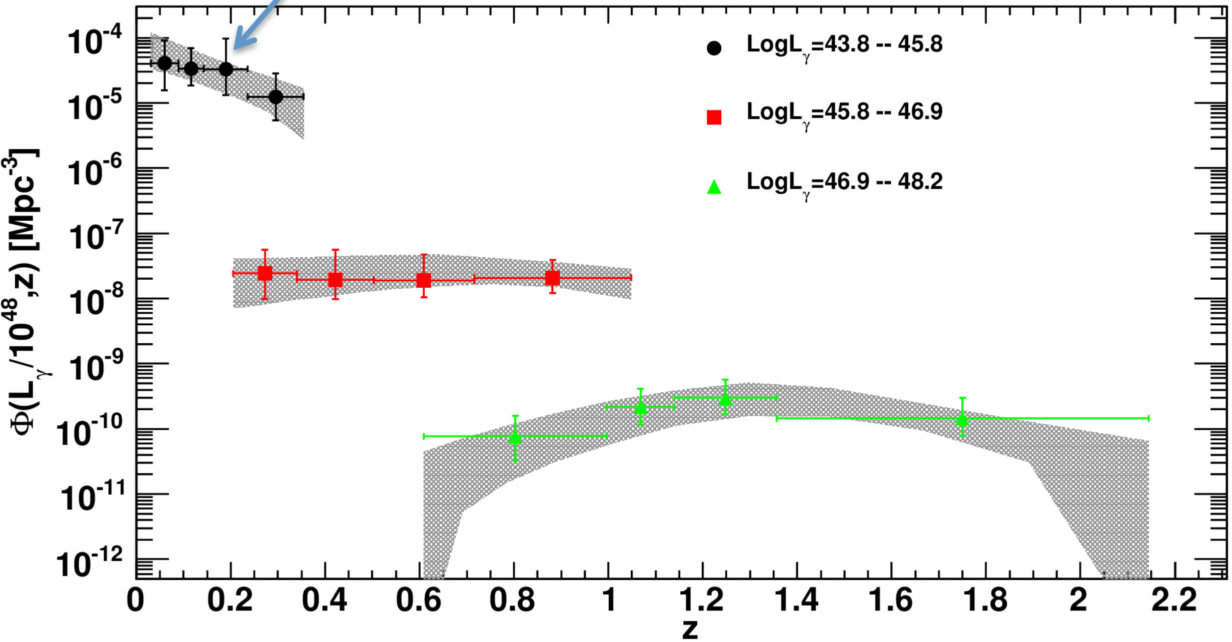
Parameter	$n=-6$ Best-fit Value	$n=-6$ Posterior Mean & Standard Deviation	$n=-3$ Best-fit Value	$n=-3$ Posterior Mean & Standard Deviation	$n=0$ Best-fit Value	$n=0$ Posterior Mean & Standard Deviation	$n=3$ Best-fit Value	$n=3$ Posterior Mean & Standard Deviation
f_p	0.03	0.14 ± 0.12	0.08	0.15 ± 0.13	0.17	0.17 ± 0.16	0.19	0.20 ± 0.16
f_{He}	0.50	0.21 ± 0.17	0.42	0.17 ± 0.16	0.53	0.20 ± 0.17	0.32	0.23 ± 0.20
f_{N}	0.40	0.50 ± 0.18	0.42	0.51 ± 0.19	0.29	0.47 ± 0.19	0.43	0.45 ± 0.21
f_{Si}	0.06	0.11 ± 0.12	0.08	0.12 ± 0.13	0.0	0.11 ± 0.12	0.06	0.078 ± 0.086
f_{Fe}	0.01	0.052 ± 0.039	0.0	0.053 ± 0.042	0.01	0.050 ± 0.038	0.0	0.044 ± 0.034
α	1.8	1.83 ± 0.31	1.6	1.67 ± 0.36	1.1	1.33 ± 0.41	0.6	0.64 ± 0.44
$\log_{10}\left(\frac{E_{\mathrm{Fe,max}}}{\mathrm{eV}}\right)$	20.5	20.55 ± 0.26	20.5	20.52 ± 0.27	20.2	20.38 ± 0.25	20.2	20.16 ± 0.18

Flatter spectra preferred for negative source evolution

Hard spectra preferred for source evolution following that of the SFR

High Spectral Peaked Blazar Evolution

n=-6 evolution result

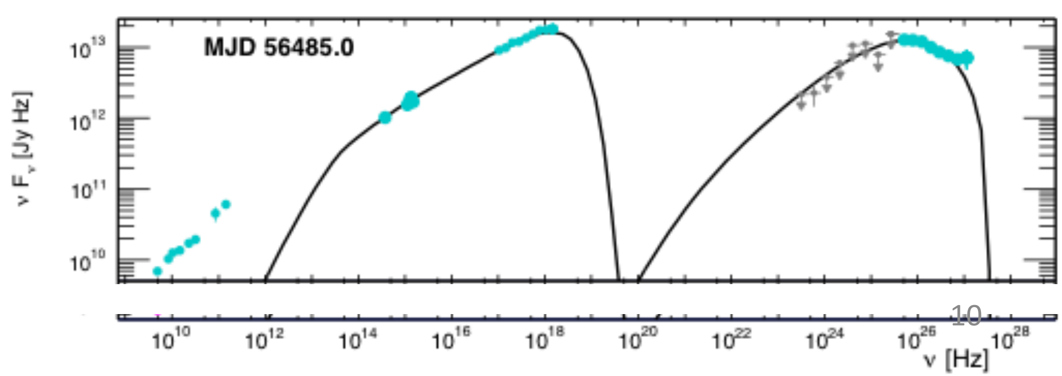


- Reminder:
Blazar -> BL Lac (FR1) -> HSP

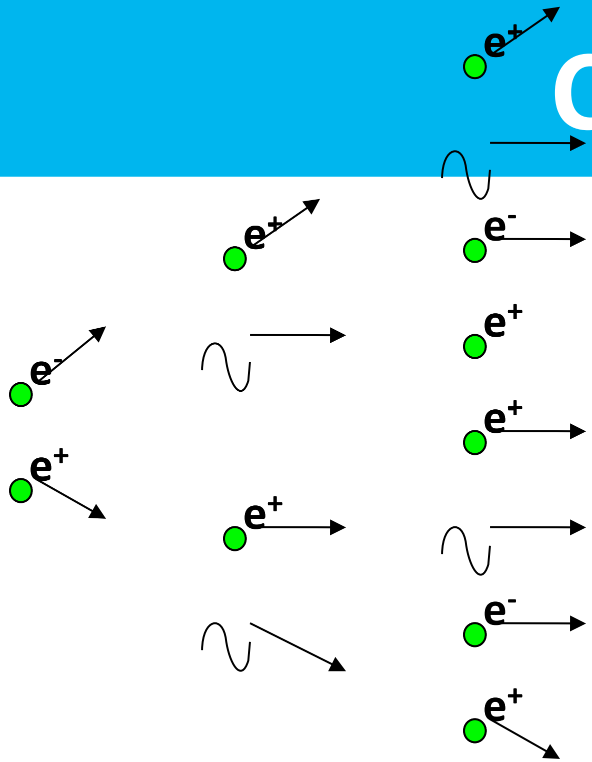
- Supports idea that FSRQ (gas accreting) AGN evolve into BL Lac (gas starved) AGN

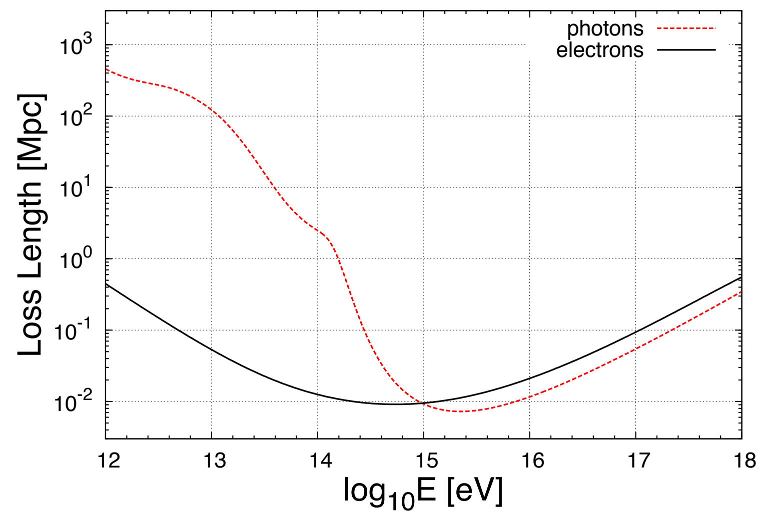
From astro-ph/1310.0006 (Ajello et al. 2014)

Archetypal HSP example Mrk 501

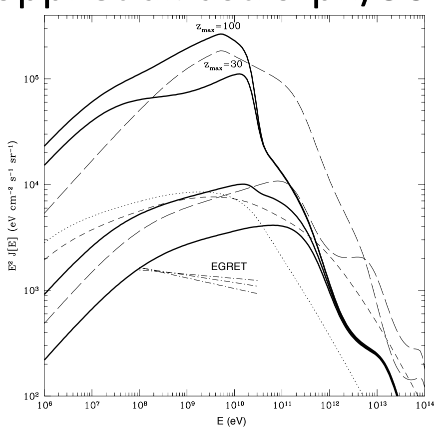


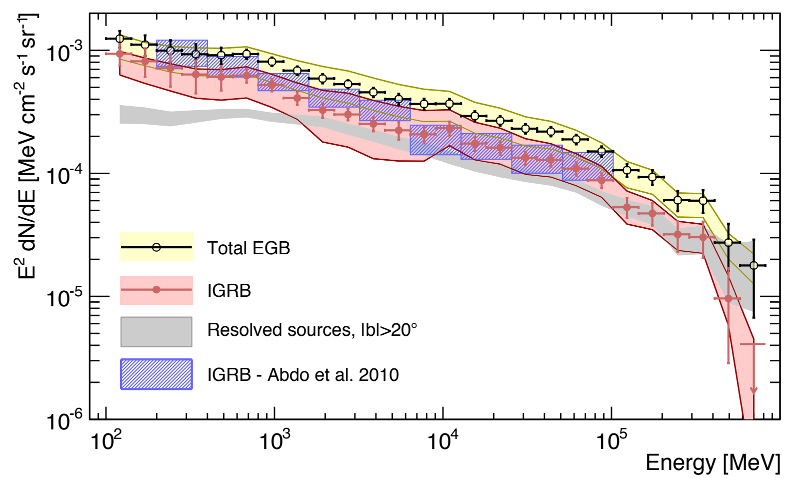
Cascade Spectra + the IGRB





From Coppi et al. astro-ph/**9610176**





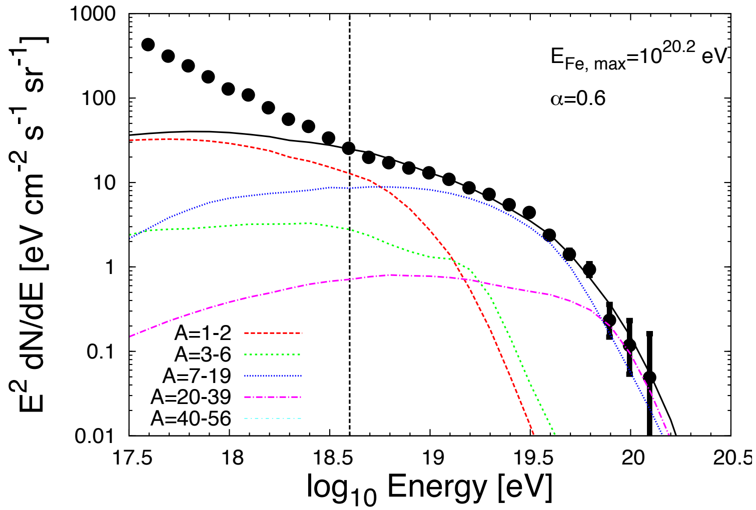
Regardless of where the energy is injected (ie independent of source z), the arriving flux possesses a ~universal shape

DESY.

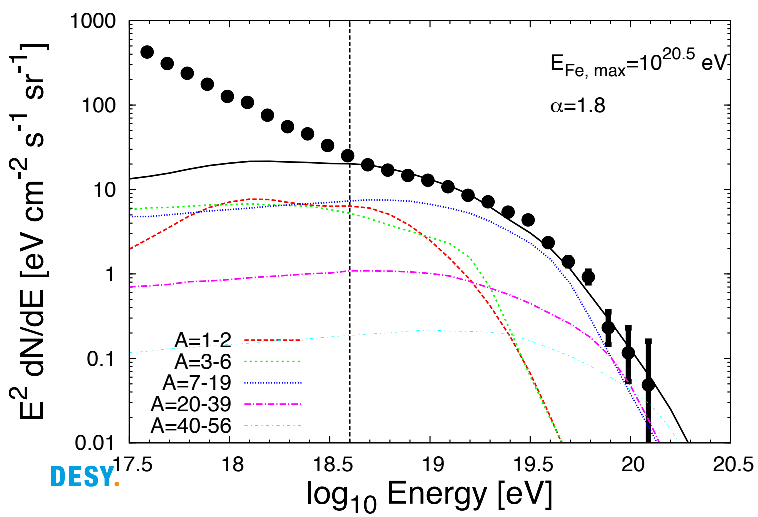
11

Secondary (Guaranteed) Gamma-Ray Fluxes From >$10^{18.6}$eV UHECR Component

n=3 evolution result



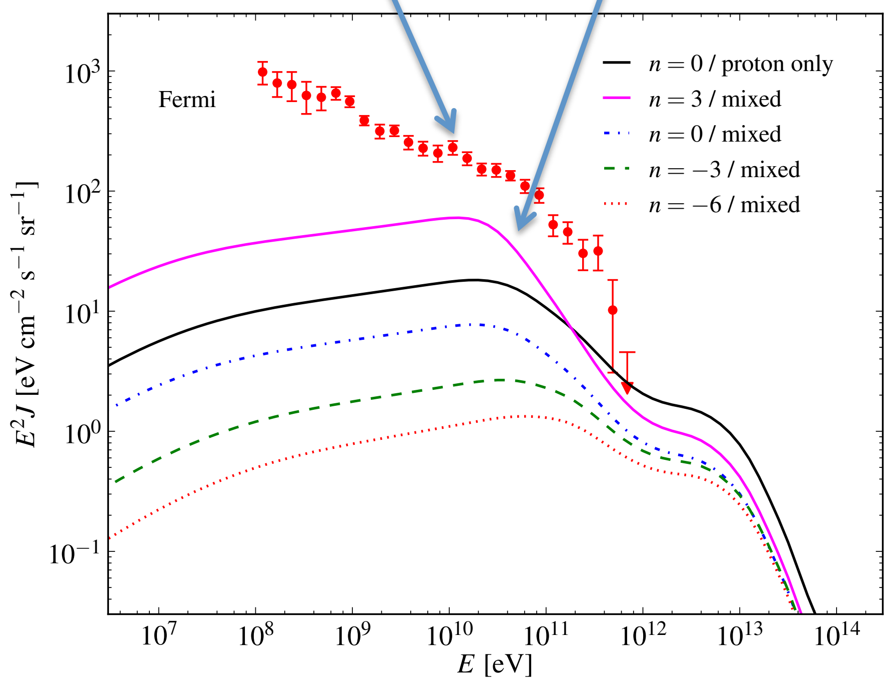
n=-6 evolution result



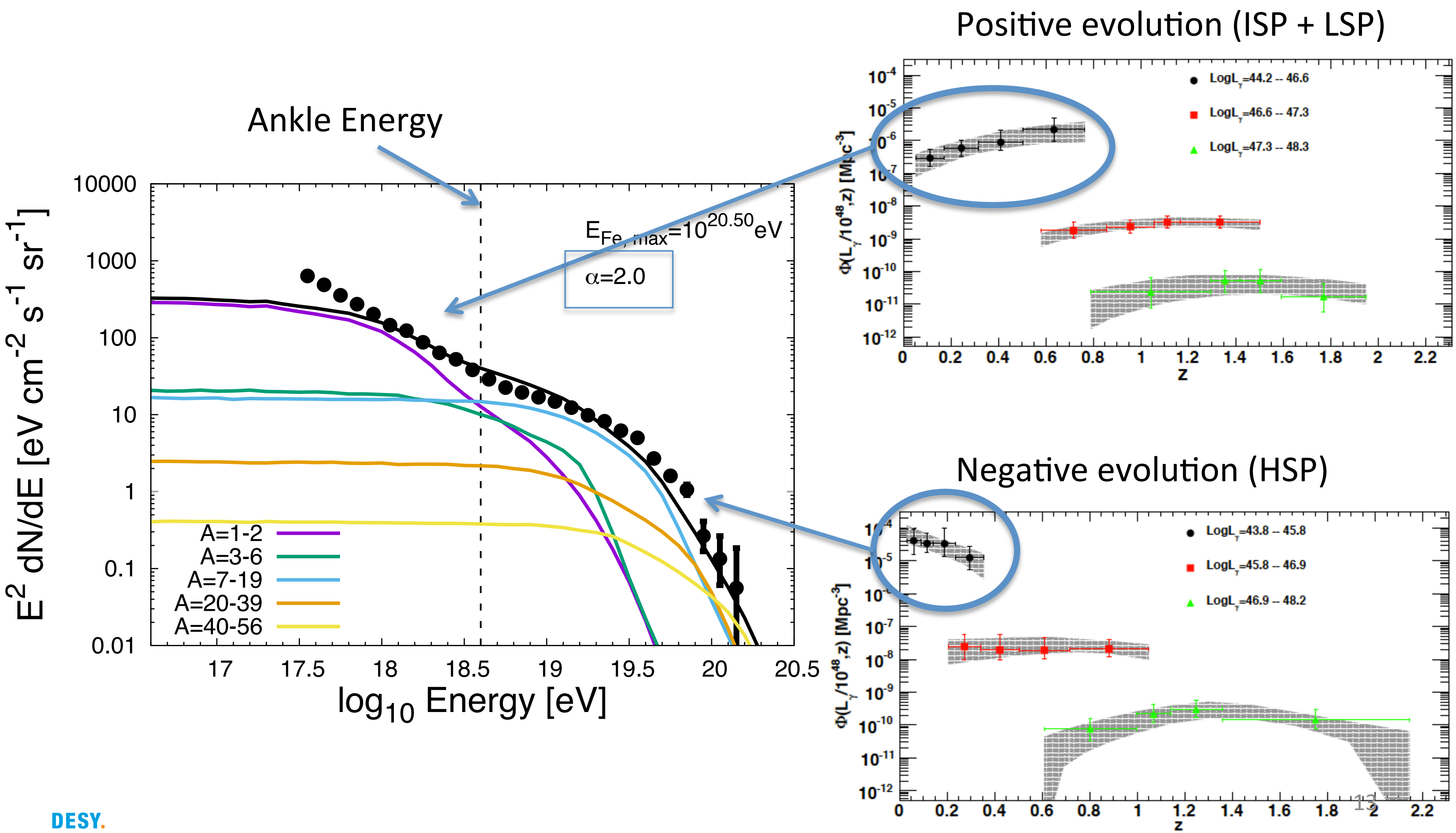
DESY.

IGRB (EGB with resolved points sources removed)

n=3 to -6 evolution scenarios give rise to between **40%** and **12%** of Fermi limit

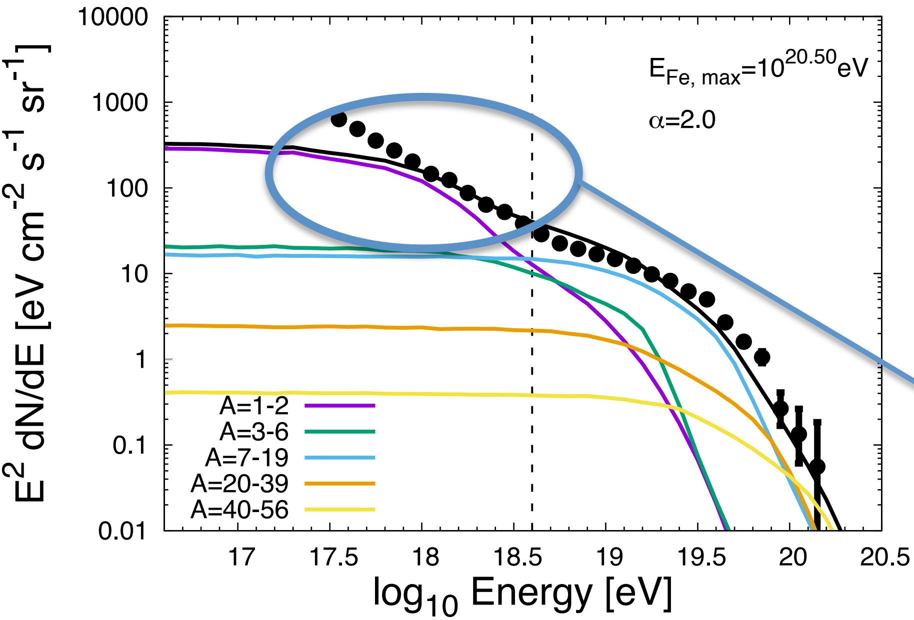


Does a Separate Class of Extragalactic Source Dominate at Sub-Ankle Energies?

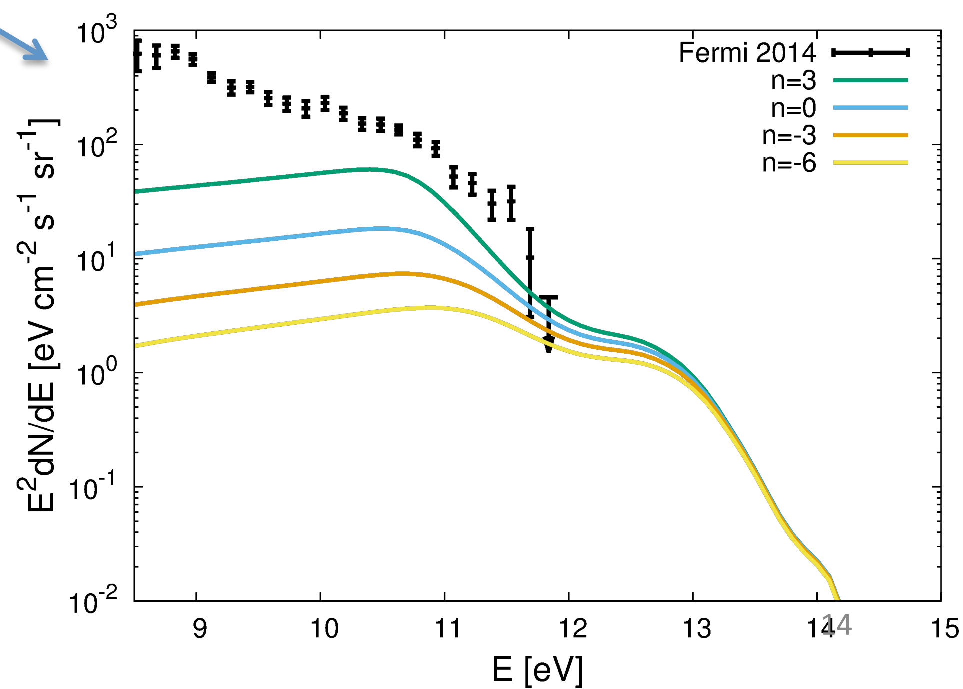


DESY.

Cascade Contribution from Second Source Population

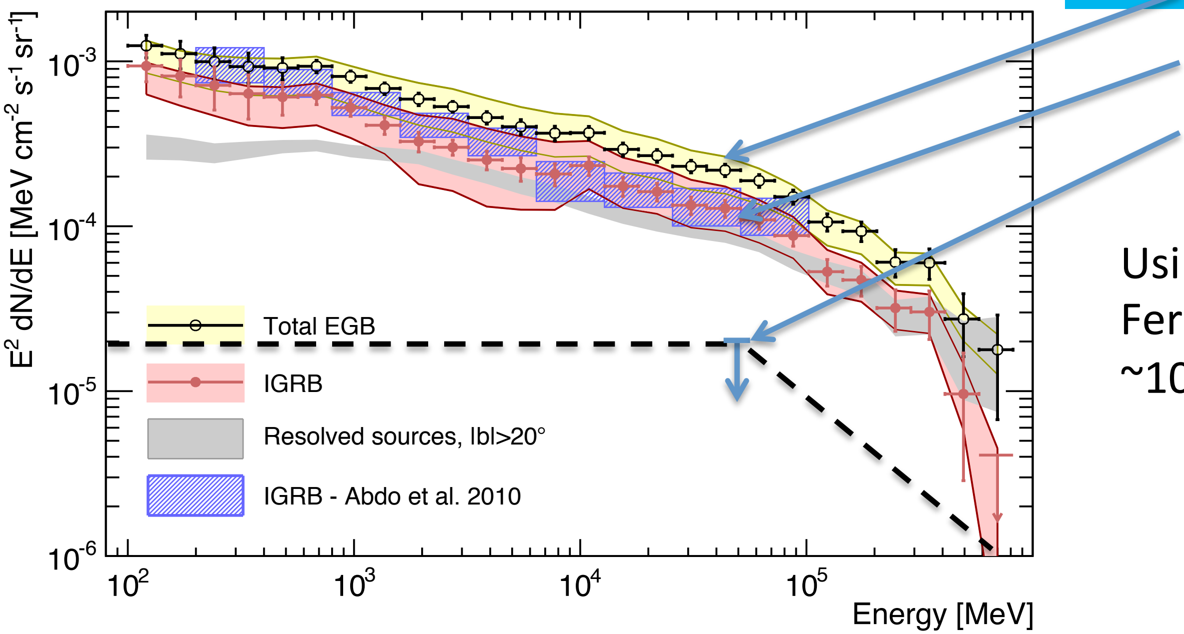


n=3 to -6 evolution scenarios give rise to between **100%** and **40%** of Fermi limit



DESY.

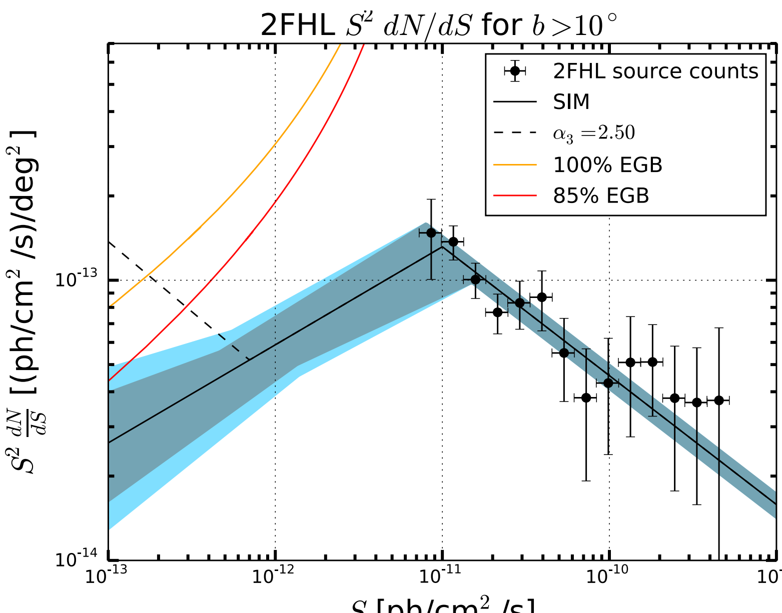
The Isotropic Gamma-Ray Background



Using Photon Fluctuation Analysis, the Fermi collaboration pushed a factor of ~10 below the 2FHL sensitivity

$$\frac{\mathbf{dN}}{\mathbf{dS}} \propto \mathbf{S}^{-\alpha}$$

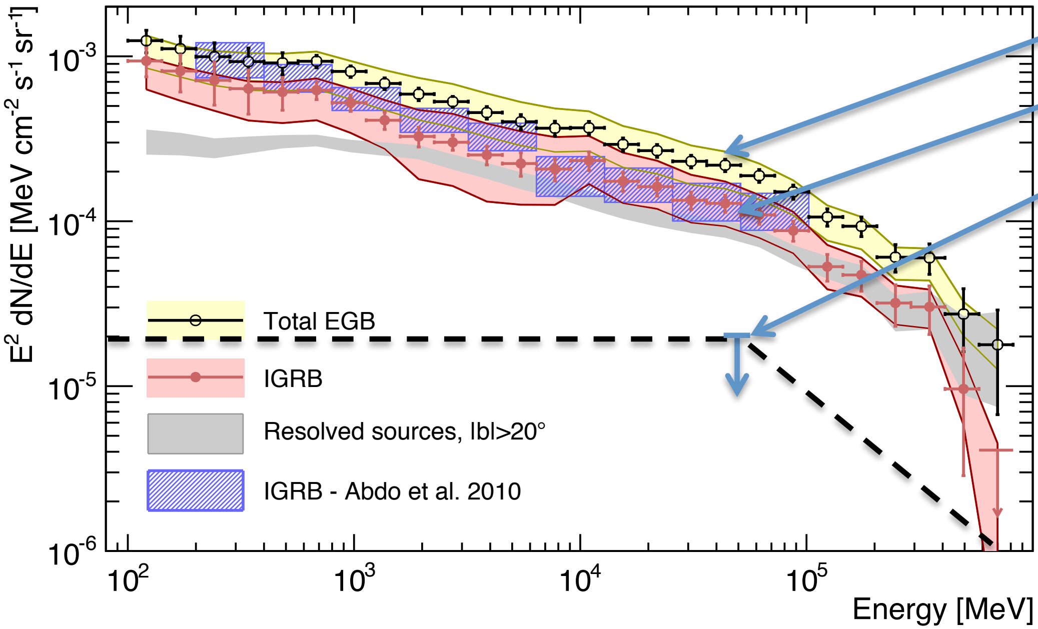
$$\mathbf{I} = \int \mathbf{S}\frac{\mathbf{dN}}{\mathbf{dS}}\mathbf{dS}$$



"Our analysis permits us to estimate that point sources, and in particular blazars, explain almost the totality (86^{+16}_{-14} %) of the >50 GeV EGB."

Fermi Collaboration (2015)- astro-ph/1511.00693

The Isotropic Gamma-Ray Background



Lat. Cut + Gal. Foreground Removal

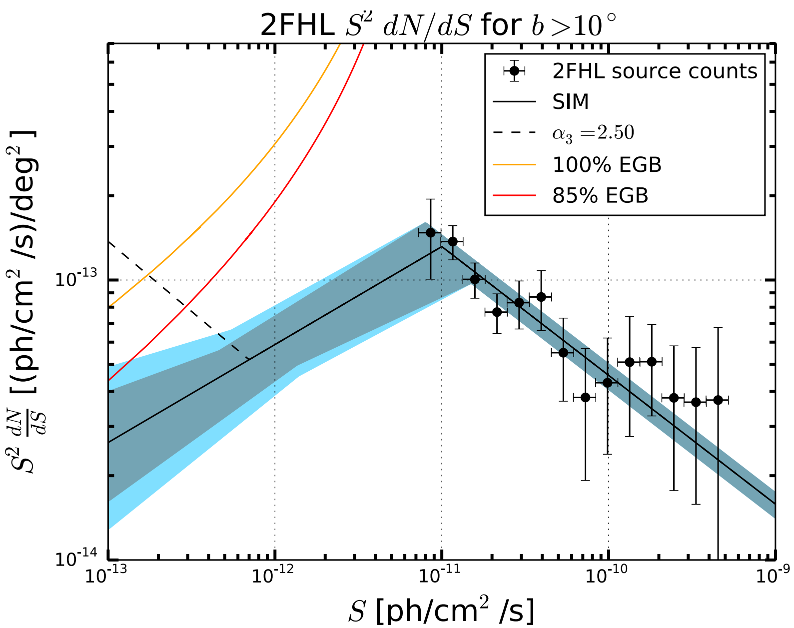
....+ Removal of Res. Blazars

....+ Removal of Unres. Blazars

Using Photon Fluctuation Analysis, the Fermi collaboration pushed a factor of ~10 below the 2FHL sensitivity

$$\frac{\mathbf{dN}}{\mathbf{dS}} \propto \mathbf{S}^{-\alpha}$$

$$\mathbf{I} = \int \mathbf{S}\frac{\mathbf{dN}}{\mathbf{dS}}\mathbf{dS}$$



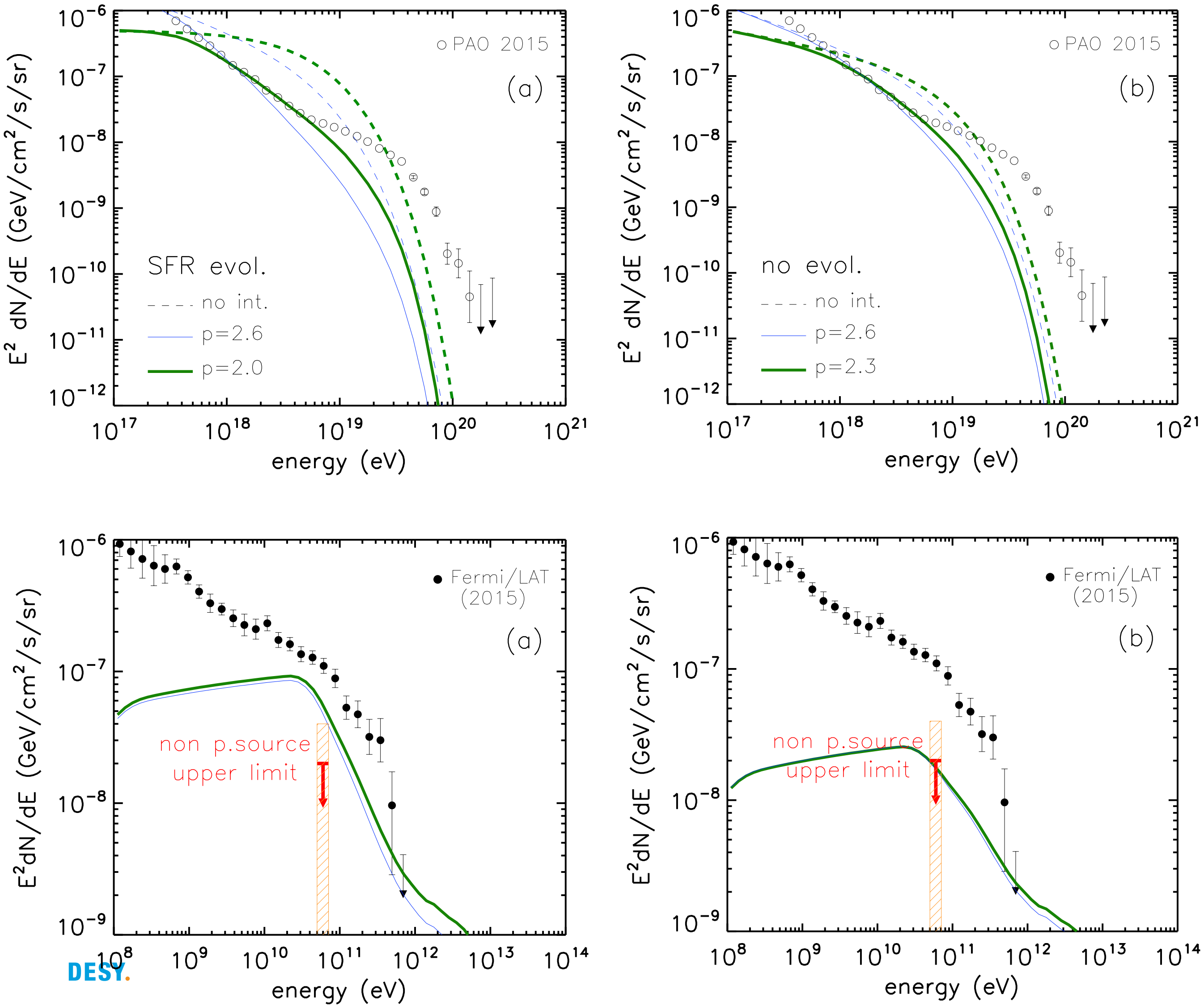
A repeat of this analysis by other groups have given: 68^{+9}_{-8}% and 81^{+52}_{-19}%

Lisanti + (2016) 1606.04101,
Zechlin + (2016), 1605.04256

The Origin of Protons Below the Ankle

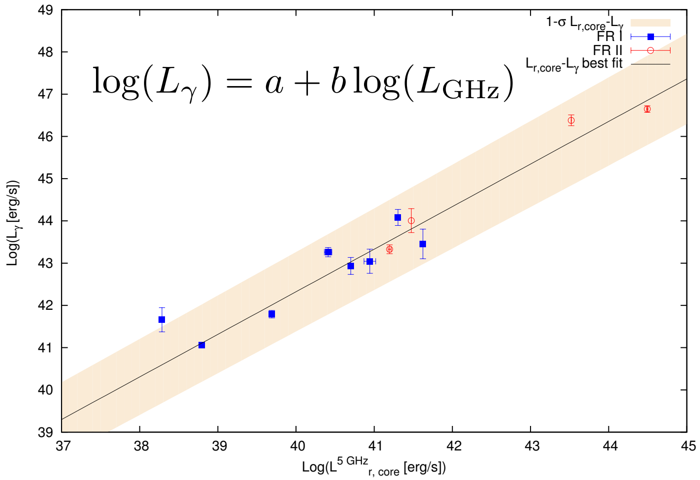
SFR evolution scenario

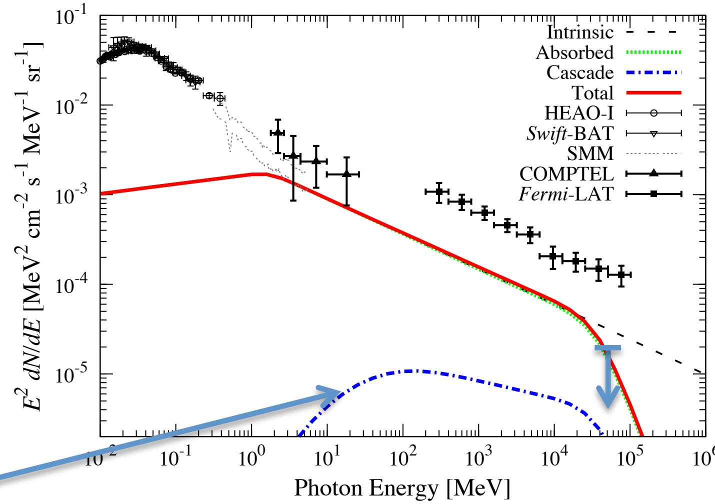
no evolution scenario



Note- IGRB contribution from cascade losses rather independent of source spectra

.....and Radio Galaxy Contributions Still Not Removed

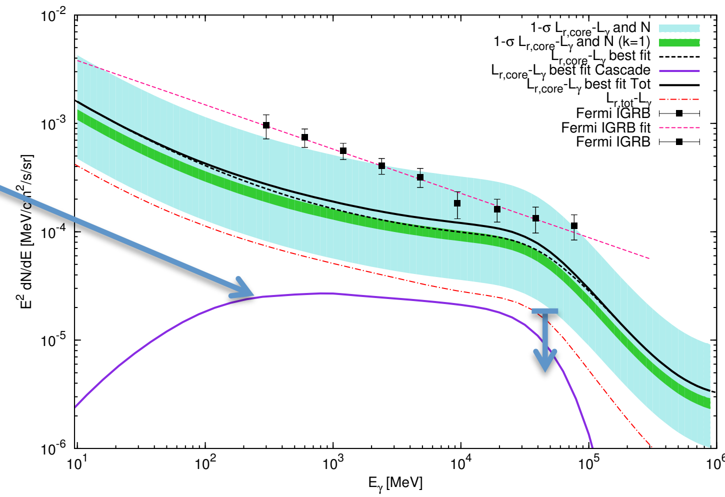




From astro-ph/1103.3946 (Inoue et al. 2011)

Note level of AGN gamma-ray generated cascades

Radio Galaxy contributions are estimated to make up a significant fraction of the remaining IGRB.

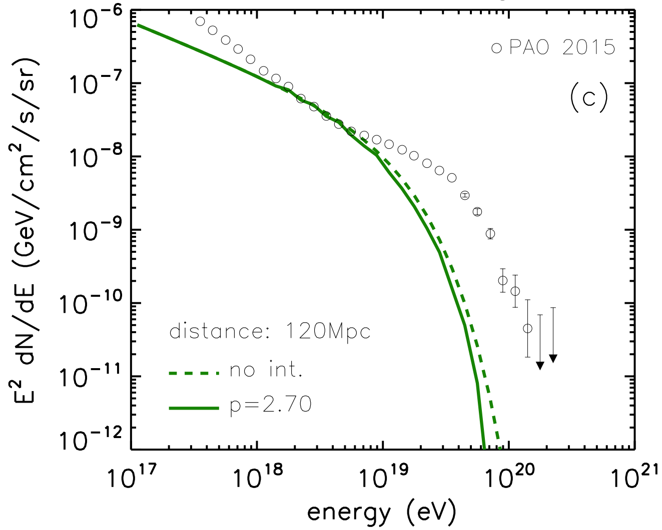


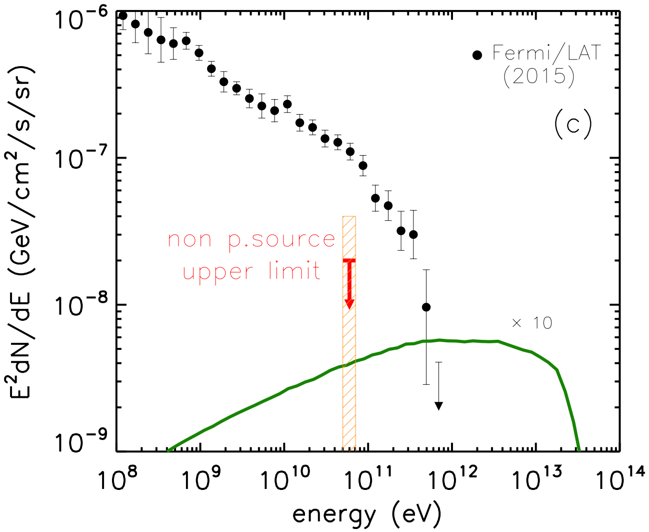
From astro-ph/1304.0908 (Di Mauro et al. 2013)

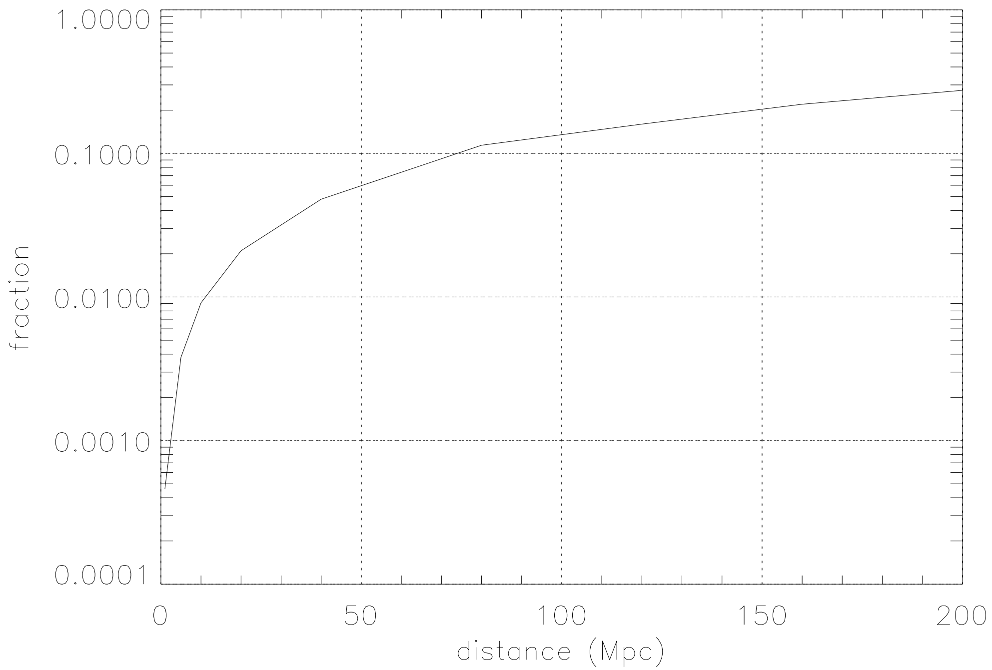
DESY.

The Origin of Protons Below the Ankle

Sources at 120 Mpc







If only 1% of EGB comes from sub-ankle UHECR (present limit is 14%), we will be forced to look extremely locally for their sources

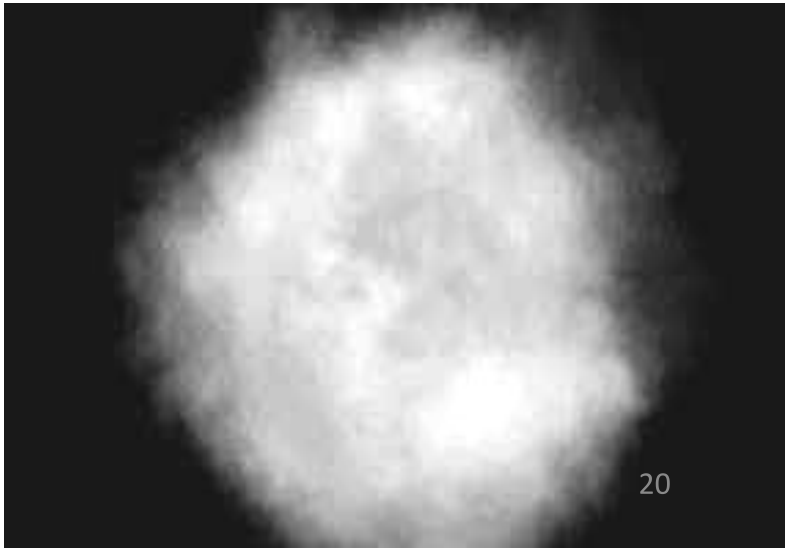
An Alternative Interpretation of the Negative Source Evolution Result

At high energies, the negative evolution scenarios help resolve both:

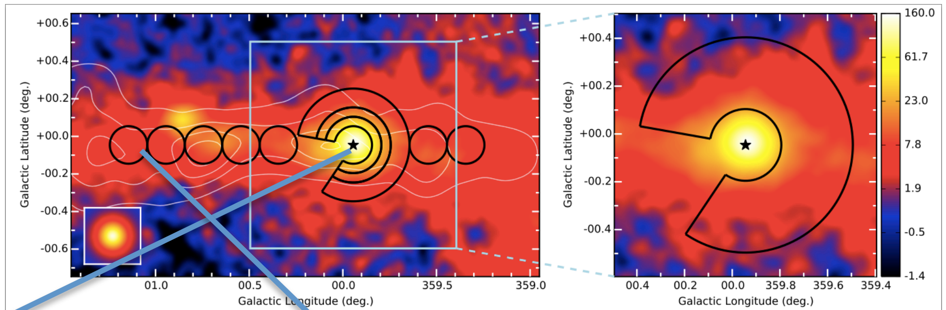
- "hard spectrum"
- "IGRB over-production"

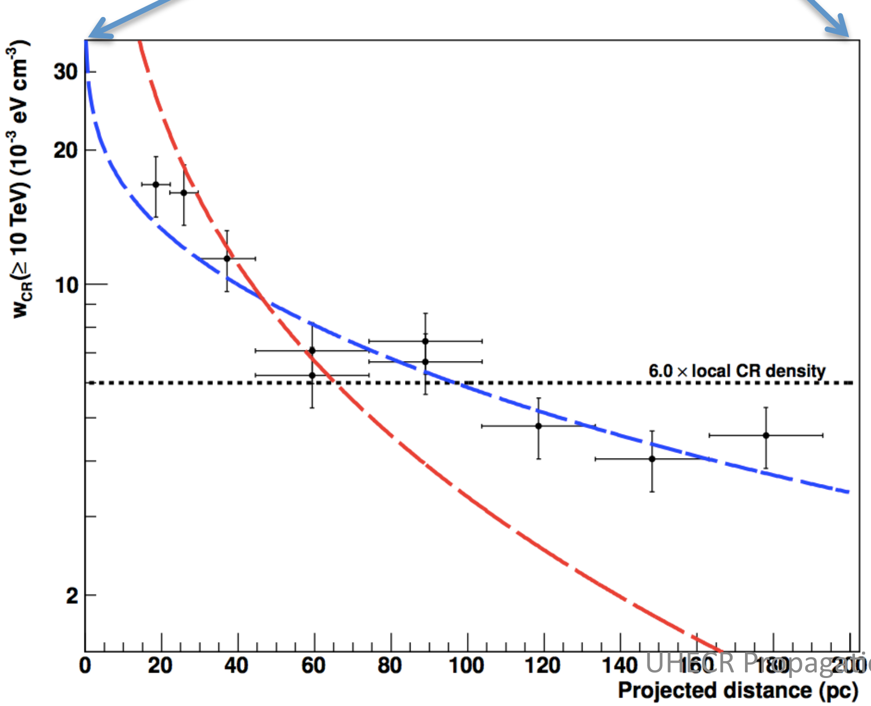
problems.

Alternatively, these scenarios may simply be encapsulating the fact that we've a local dominant source and our local value for UHECR is well above the "sea level"!



From Where?





Recall that the diffusive propagator is

$$\mathbf{G(r,t) \propto \frac{e^{(-r^2/(4Dt))}}{(4\pi Dt)^{3/2}}}$$

Steady State Spectrum Flux from Source is

$$\mathbf{n \propto 1/Dr}$$

Particle Acceleration in Centers of Galaxies (within the Central Molecular Zone)

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^2}$$

$$\mathbf{t_{diff.}} = \frac{\mathbf{R^2}}{\eta \mathbf{c R_{lar}}}$$

Maximum energy
(Hillas criterion)

$$\mathbf{R_{lar}} = \frac{\beta}{\eta}\mathbf{R}$$

$$\mathbf{R_{lar}(E, B)} = \left(\frac{\mathbf{E}}{\mathbf{1\ PeV}}\right)\left(\frac{\mathbf{100\ \mu G}}{\mathbf{B}}\right)\mathbf{0.01\ pc}$$

Conclusions

- A negative source evolution allows for an $\mathbf{E^{-2}}$ type spectra to explain CR above the ankle (such an evolution is observed for the HBL blazars)

- The positive evolution of a separate source class, can account for sub Ankle extragalactic cosmic rays (which again allow an $\mathbf{E^{-2}}$ type spectra for this component)

- A new estimation of the diffuse gamma-ray background limit excludes positive evolution scenarios for these cosmic rays.

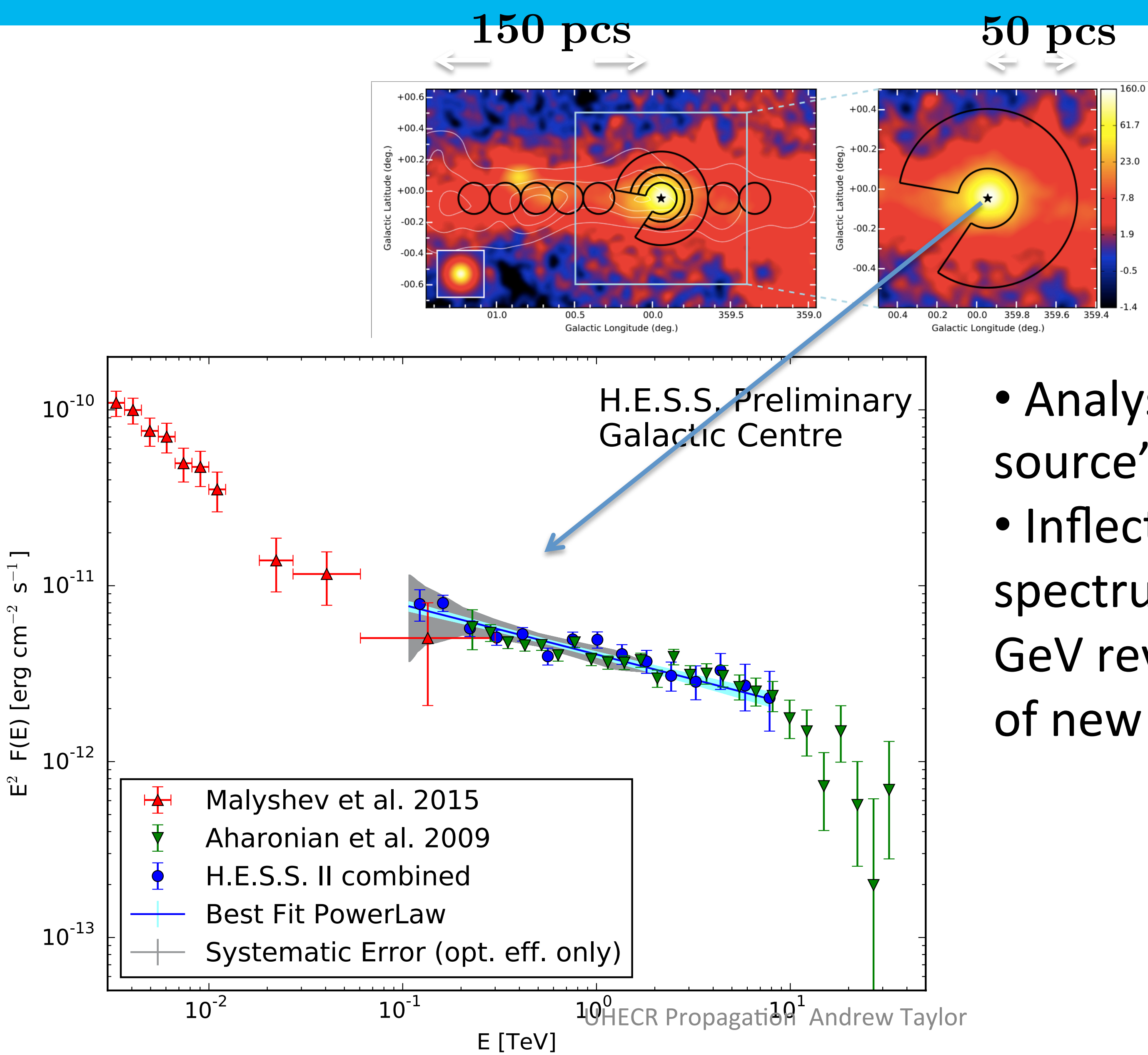
- New diffuse gamma-ray background limits are challenging for both positive and no-evolution scenarios which account for sub-Ankle extragalactic protons

- These results suggest that UHECR exist in a local fog, with the value locally being well above the “sea level”.

- An “understanding” of UHECR sources is possible through an understanding of AGN gamma-ray emission at very high energies!

Extra Slides

From Where?



- Analysis of Sgr A* 'point source' at Galactic center
- Inflection evident in spectrum around 100 GeV revealing presence of new hard component