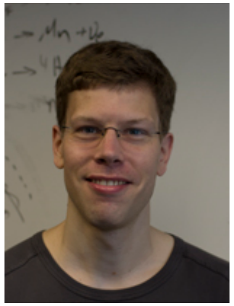
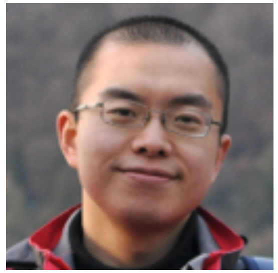
Extragalactic Cosmic Rays above the Iron Knee



Markus Ahlers

Dan Hooper

Felix Aharonian



Ruoyu Liu

Based on:

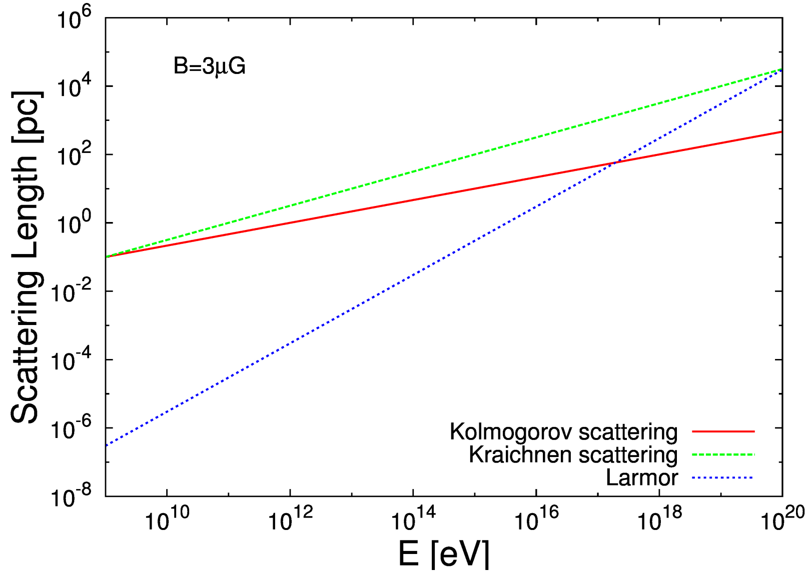
“Indications of Negative Evolution for the Sources of the Highest Energy Cosmic Rays”, **Phys.Rev. D92 (2015) 6, 063011 [**astro-ph/**1505.06090]**

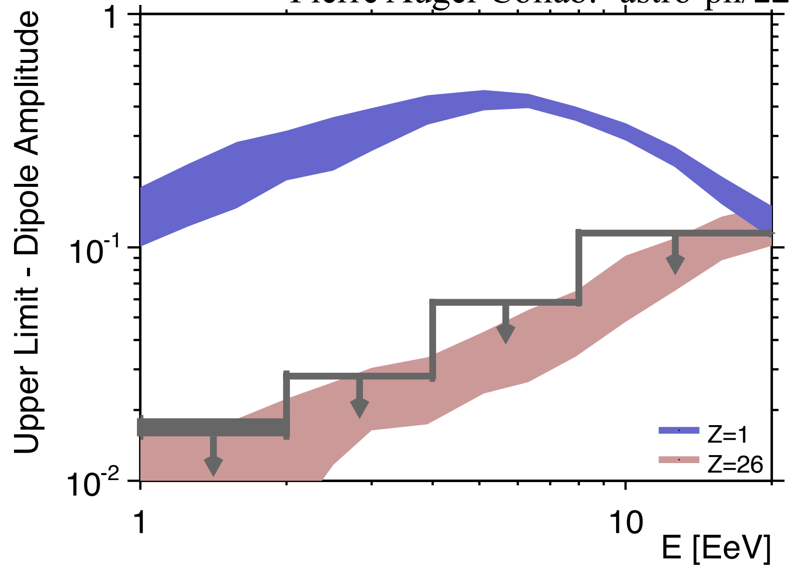
“Evidence for a Local "Fog" of Sub-Ankle UHECR”, **Phys.Rev.D94 (2016) 4, 043008 [**astro-ph/**1603.03223]**

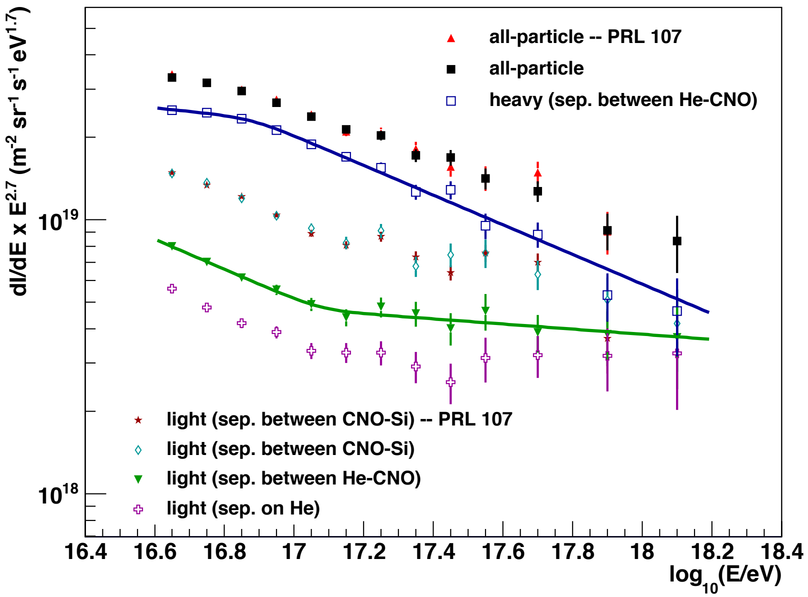
Andrew Taylor

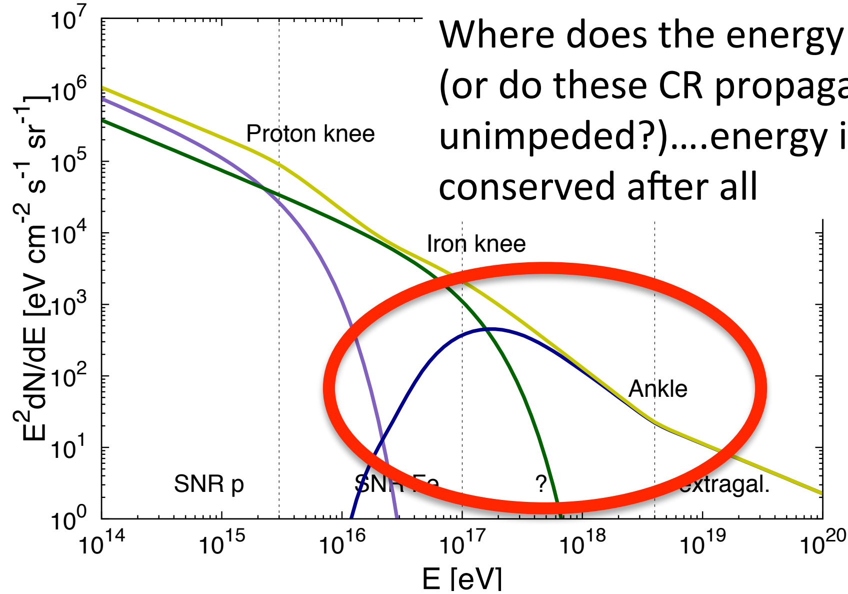
Transition Energy Probes

Anisotropy constraint:
Giacinti et al.- astro-ph/**1112.5599**
Pierre Auger Collab.- astro-ph/**1212.3083**







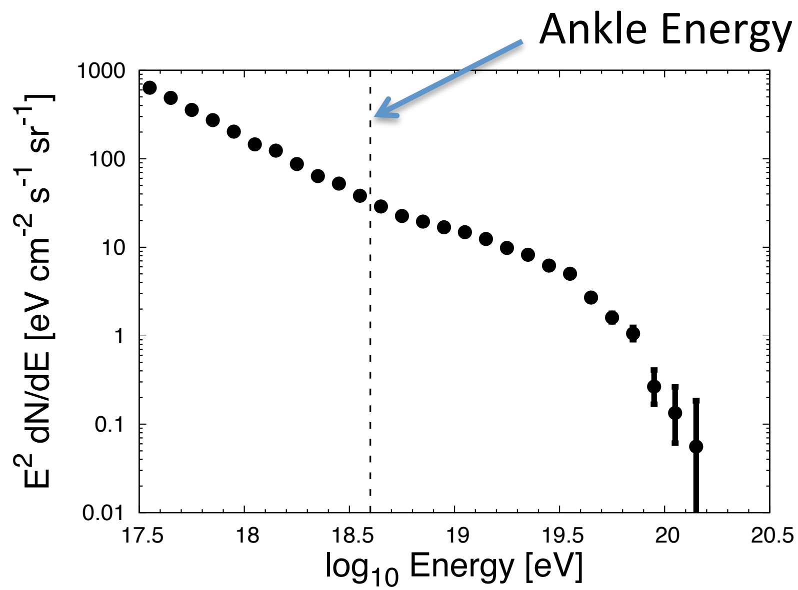


Where does the energy flux go?
(or do these CR propagate unimpeded?)....energy is conserved after all

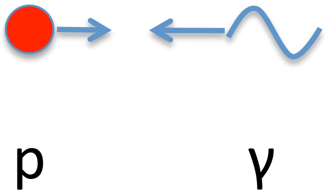
Why Consider Super-Ankle CR to Understand the Galactic/Extragalactic Transition?

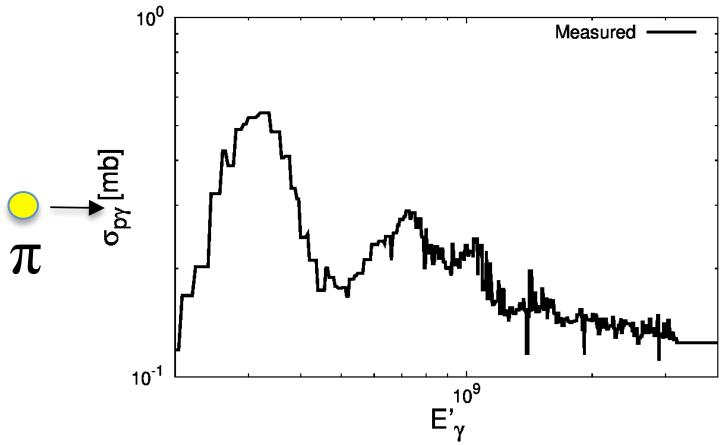
- Since the ankle feature appears at an energy of ~$10^{18.6}$ eV, a new extragalactic source class is presumed to begin to dominate here (in the first instance)

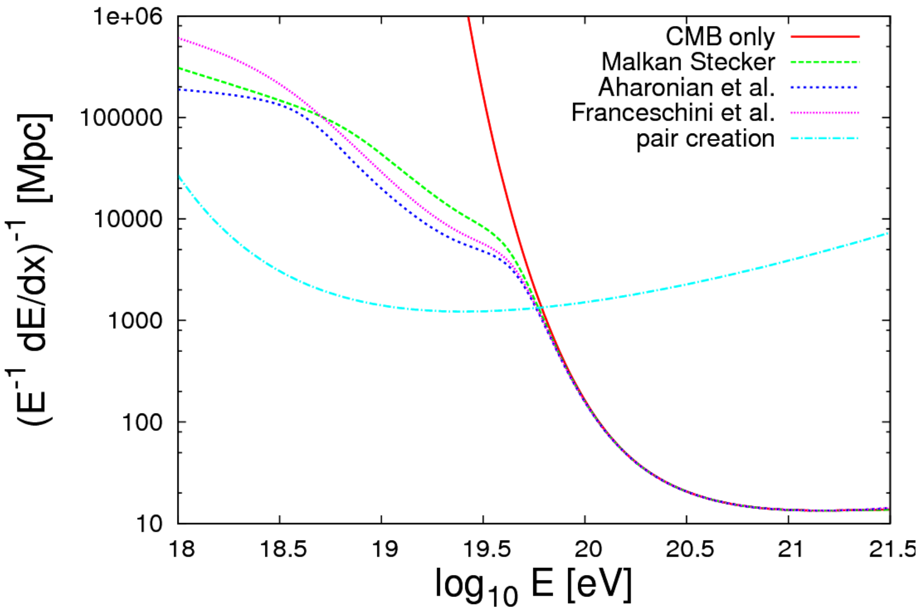
- Information obtained from investigations into the super-ankle sources may provide new insights into Galactic-Extragalactic transition energy

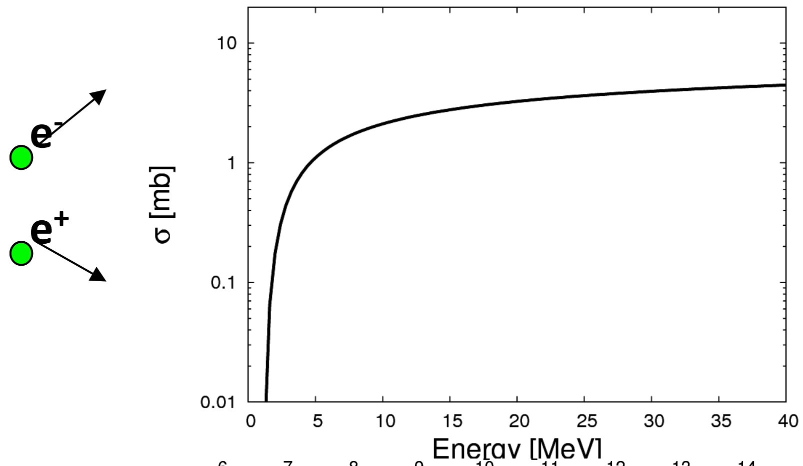


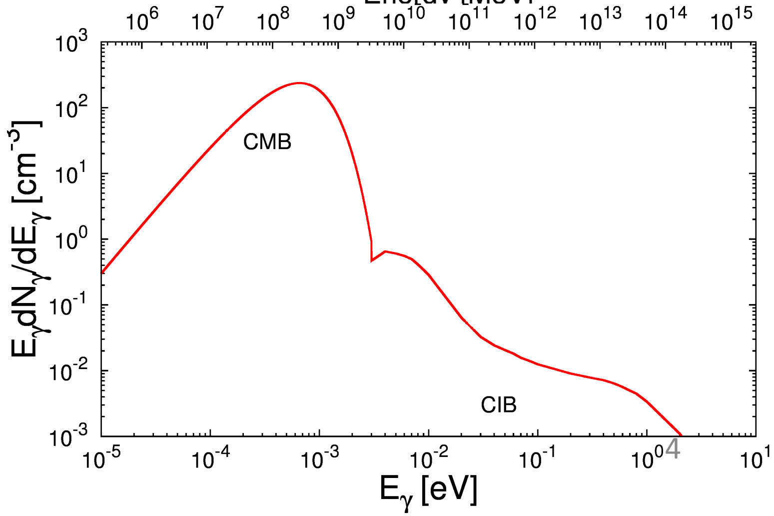
Cosmic Ray Proton Interactions





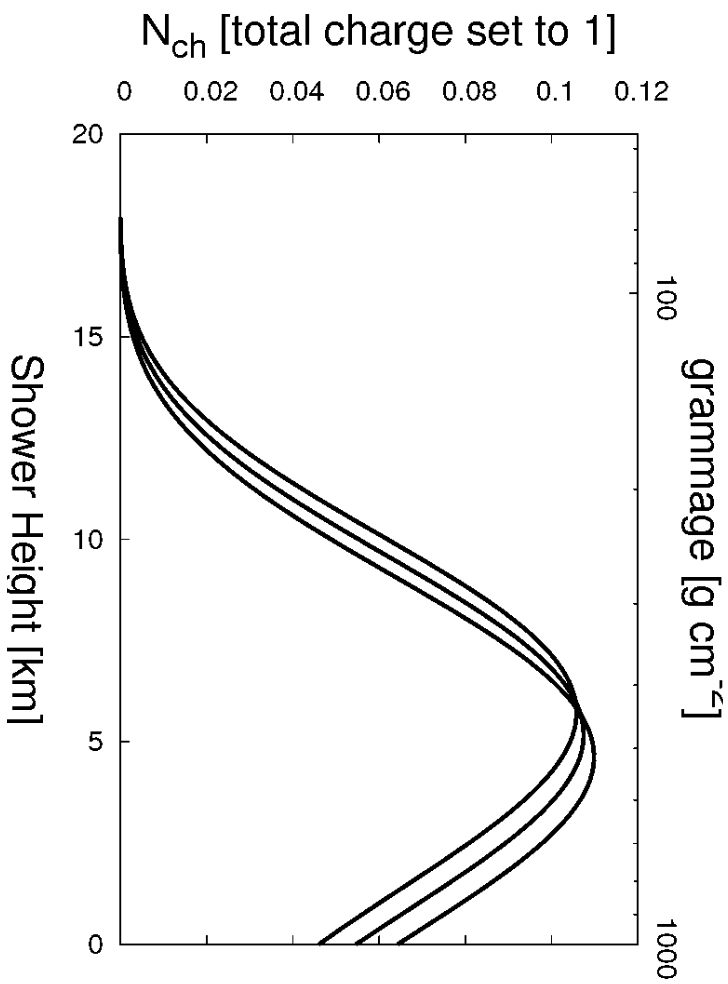


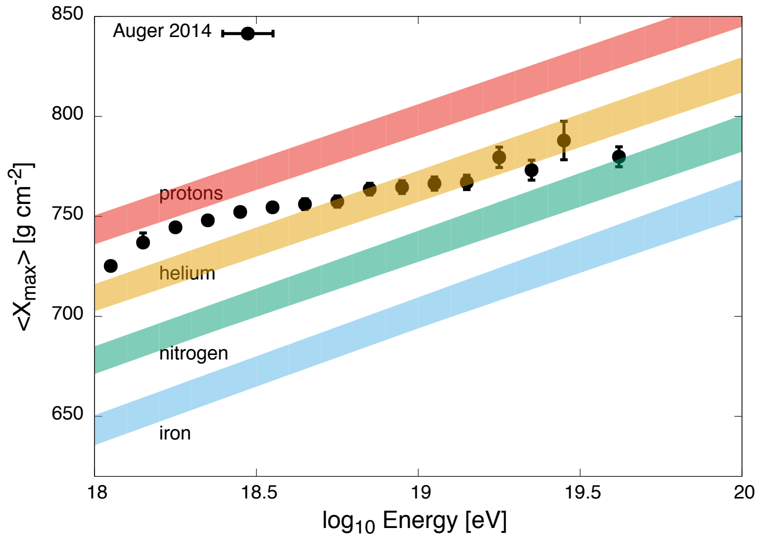


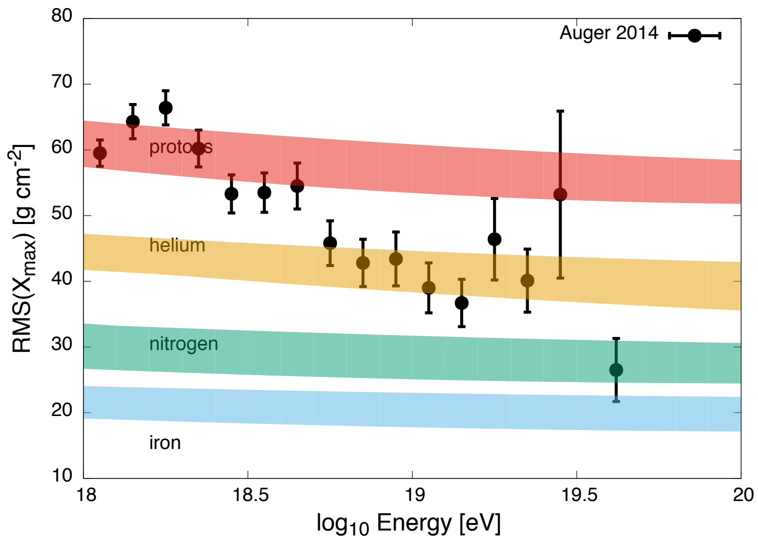


$$\mathbf{R} = \frac{2m_p^2}{E_p^2}\int \frac{1}{\epsilon^2}\frac{dN_\gamma}{d\epsilon}\int_0^{4E_p\epsilon/m_p} k_{p\gamma}\epsilon'\sigma_{p\gamma}(E_p,\epsilon')d\epsilon'$$

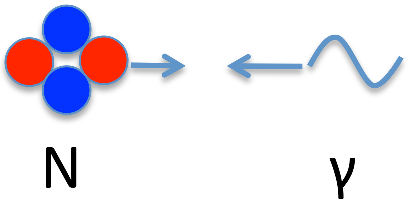
Composition- Consider Nuclei?

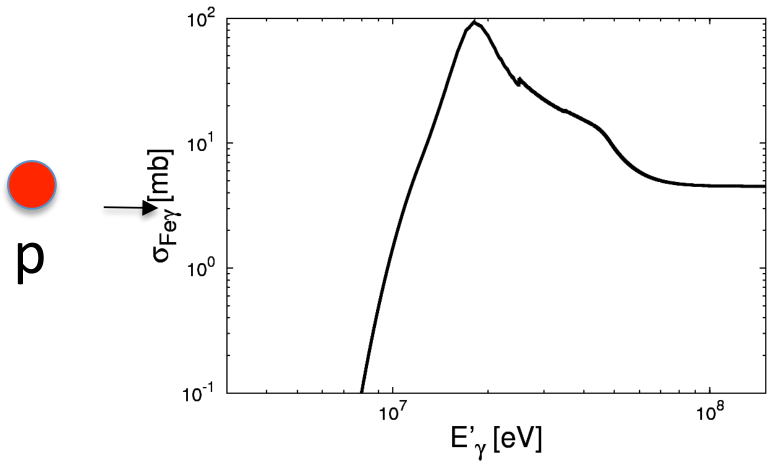


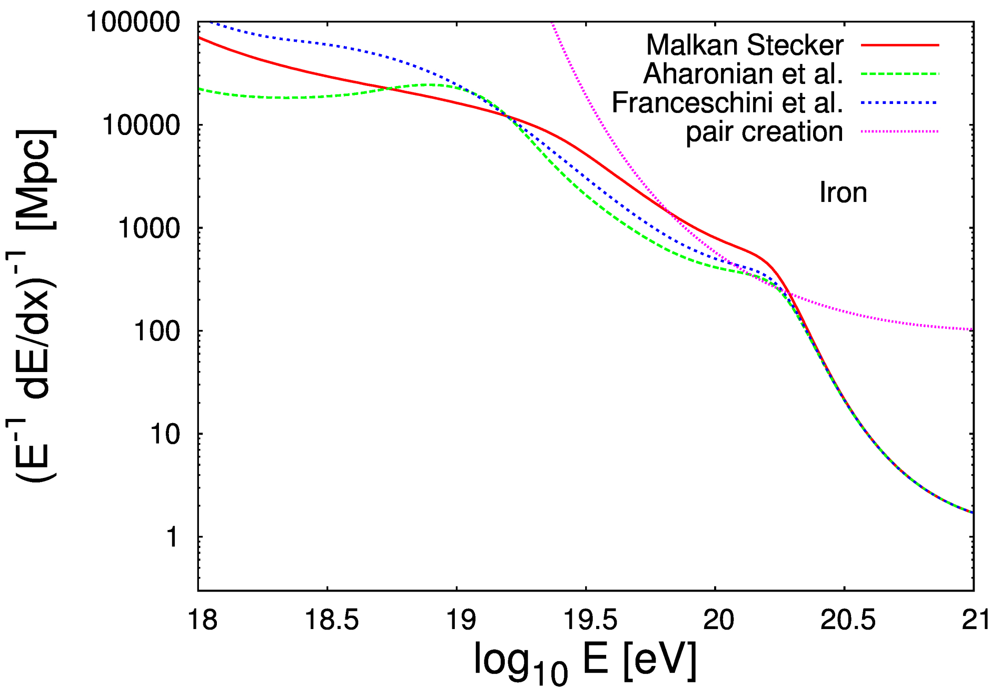


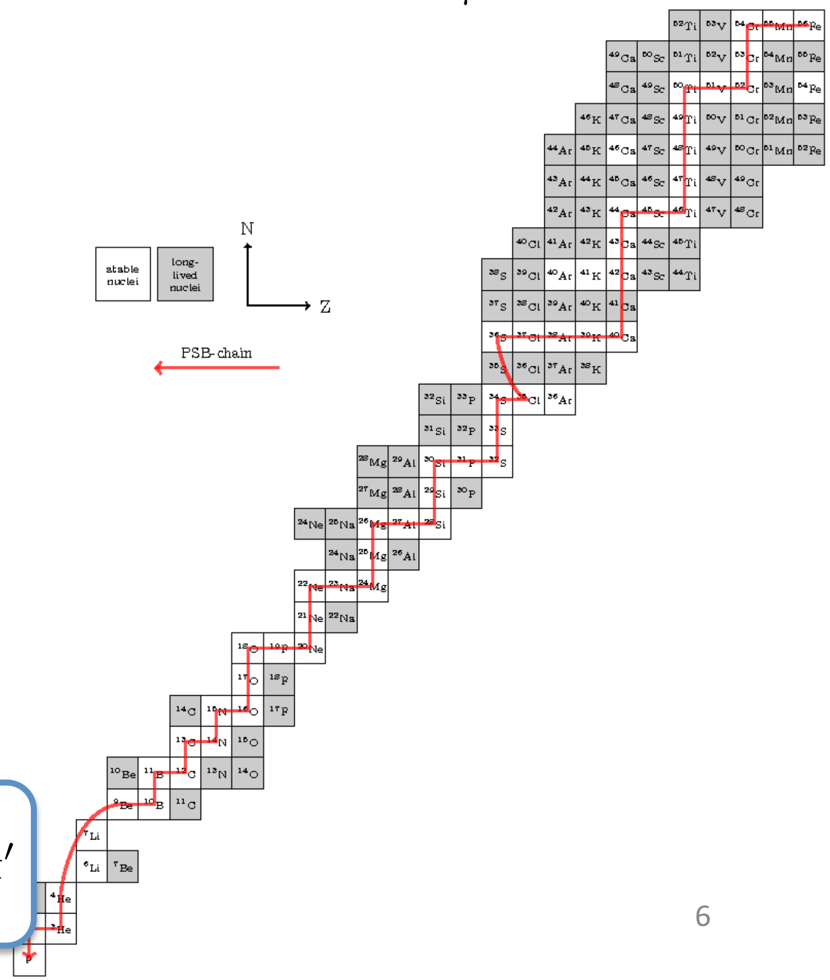


Cosmic Ray Nuclei Interactions







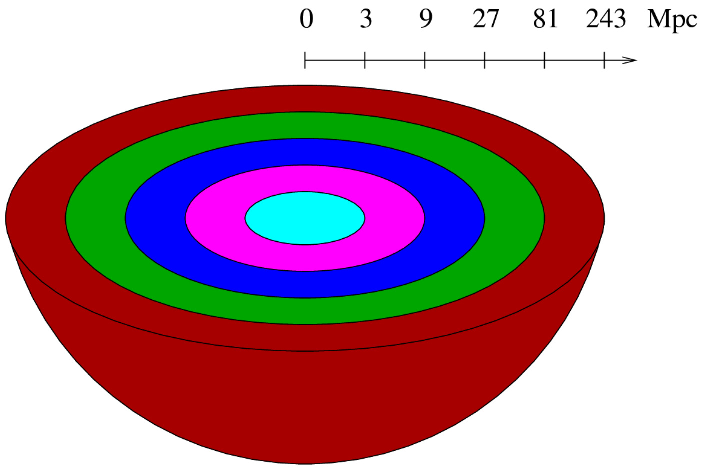


$$\mathbf{R = \frac{2m_N^2}{E_N^2}\int \frac{1}{\epsilon^2}\frac{dN_\gamma}{d\epsilon}\int_0^{4E_N\epsilon/m_N} k_{N\gamma}\epsilon'\sigma_{N\gamma}(E_N,\epsilon')d\epsilon'}$$

Assumptions on Source Population

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

$$z < z_{max}$$



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

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

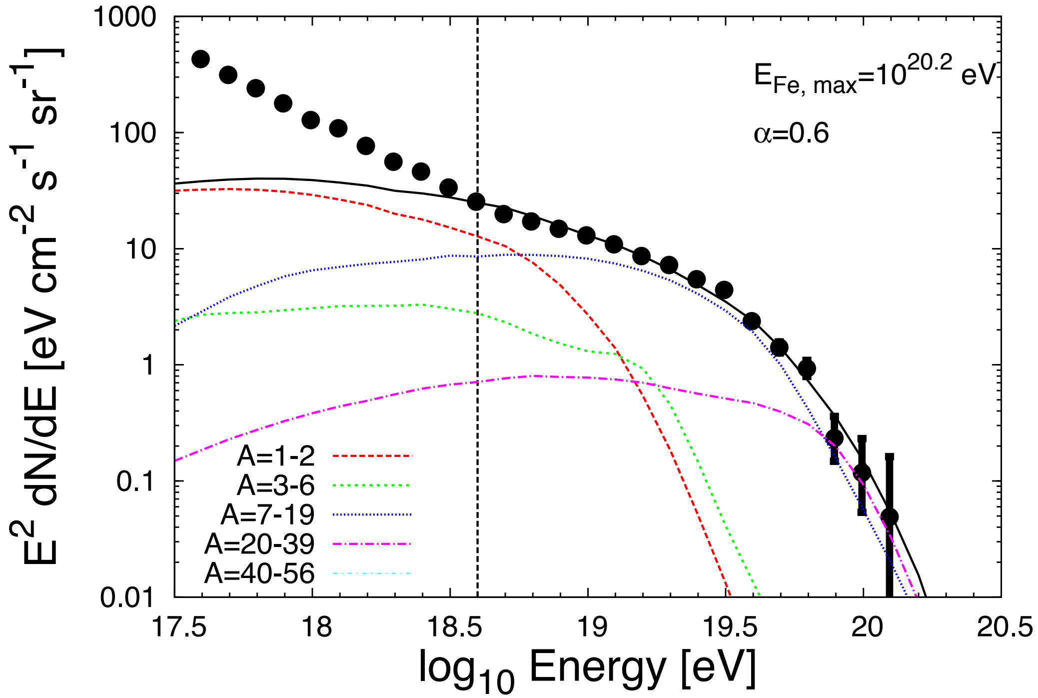
$$E_{Z,max} = (Z/26) \times E_{Fe,max}$$

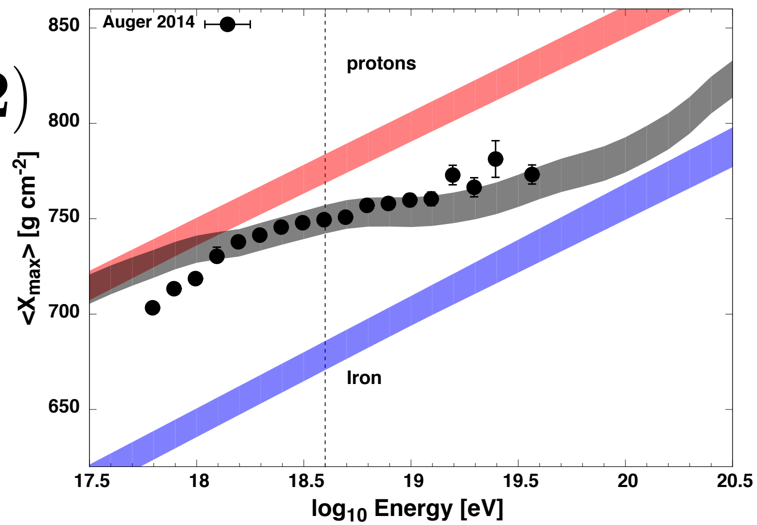
Note- magnetic field horizon effects are neglected in the following. This amounts to assuming: $d_s < (ct_H \lambda_{scat})^{1/2}$
ie. the source distribution may be approximated to be spatially continuous (also note, presence of t_H term comes from temporally continuous assumption)

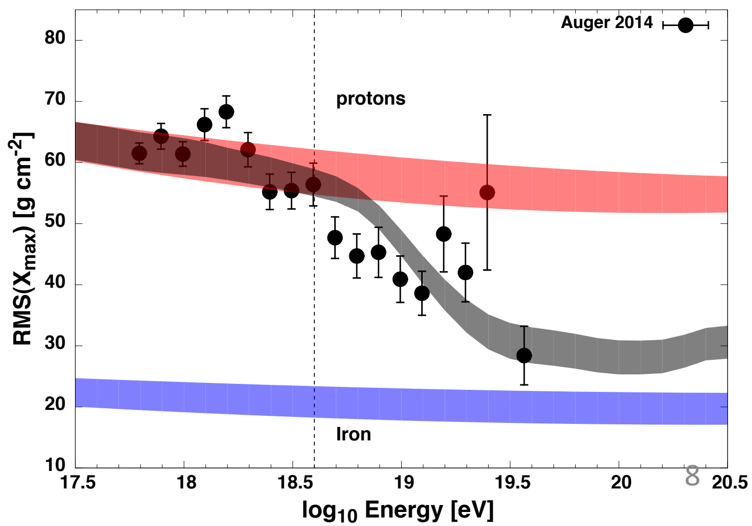
MCMC Likelihood Scan: Spectral + Composition Fits

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

n=3 evolution result



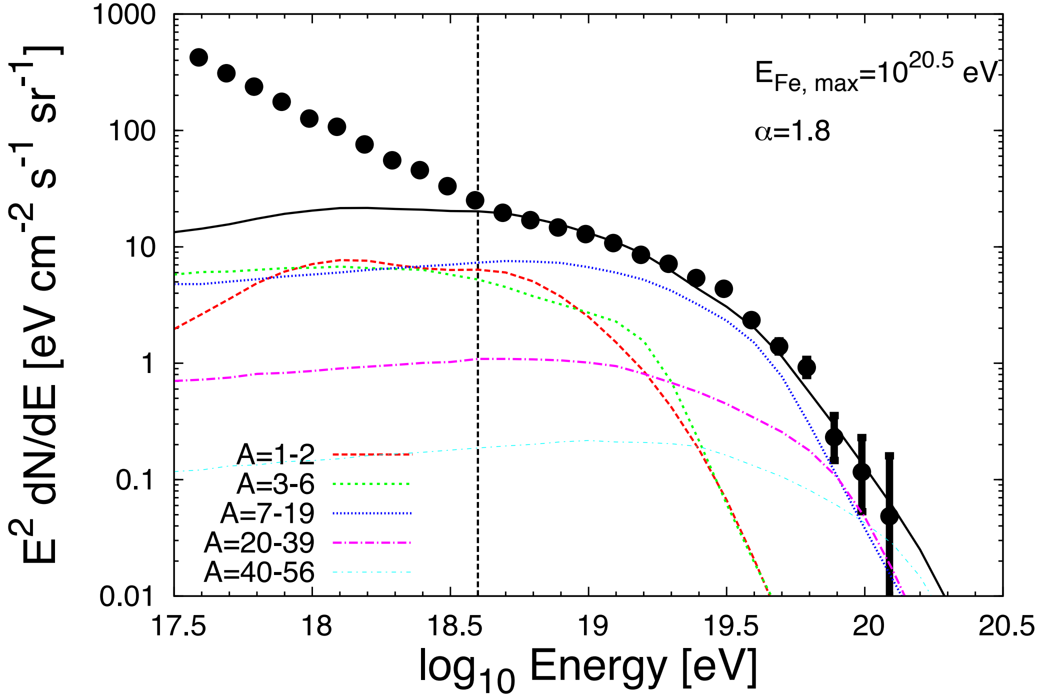


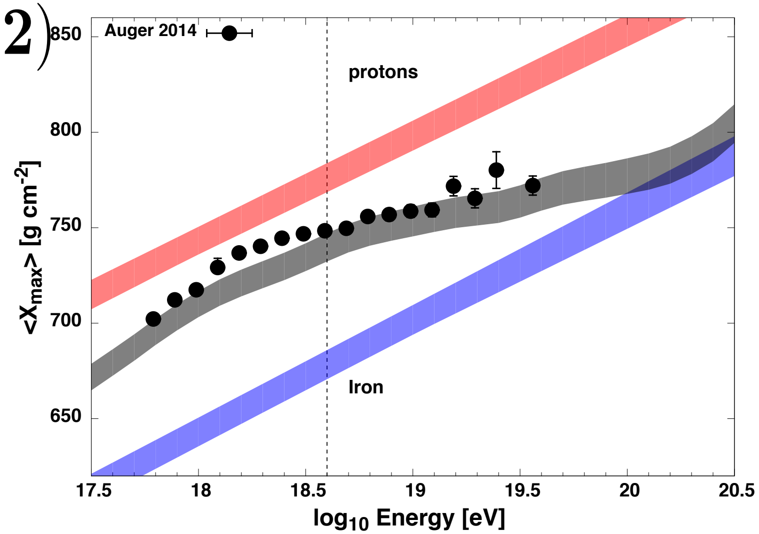


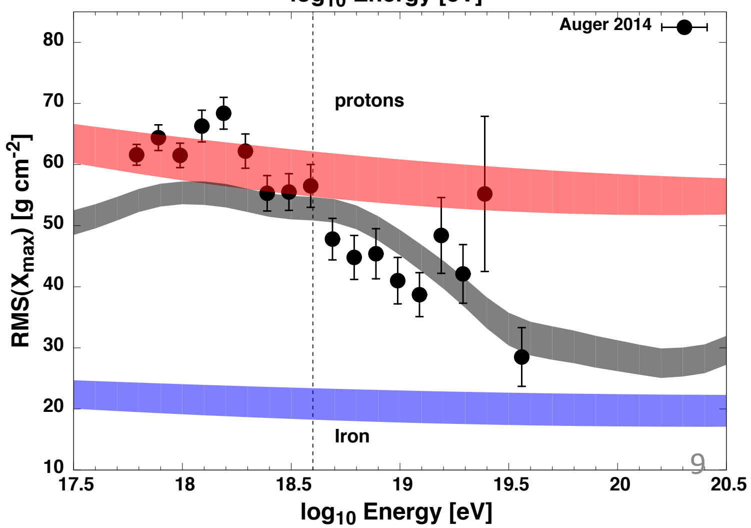
MCMC Likelihood Scan: "Soft" Spectra Solutions

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

n=-6 evolution result







MCMC Results Table

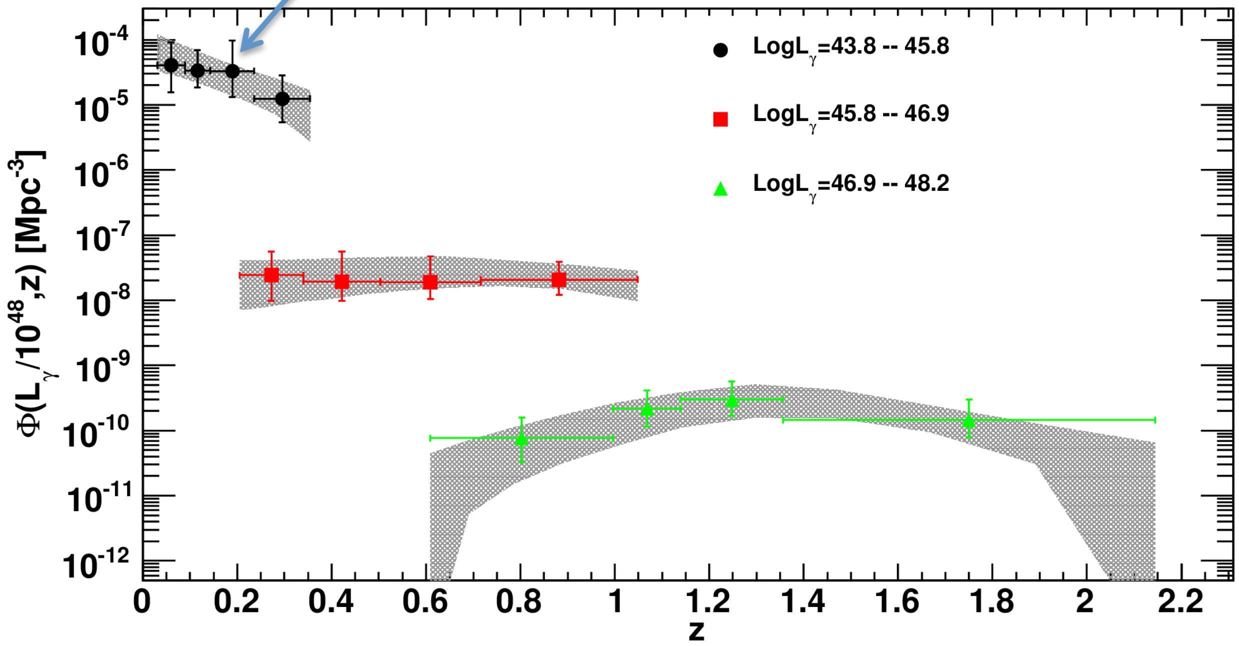
Parameter	$n=-6$		$n=-3$		$n=0$		$n=3$	
	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation
f_p	0.03	0.14 ± 0.12	0.08	0.15 ± 0.13	0.17	0.17 ± 0.16	0.19	0.20 ± 0.16
$f_{\rm He}$	0.50	0.21 ± 0.17	0.42	0.17 ± 0.16	0.53	0.20 ± 0.17	0.32	0.23 ± 0.20
$f_{\rm N}$	0.40	0.50 ± 0.18	0.42	0.51 ± 0.19	0.29	0.47 ± 0.19	0.43	0.45 ± 0.21
$f_{\rm Si}$	0.06	0.11 ± 0.12	0.08	0.12 ± 0.13	0.0	0.11 ± 0.12	0.06	0.078 ± 0.086
$f_{\rm Fe}$	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
$\log_{10}\left(\frac{E_{\rm Fe,max}}{\rm eV}\right)$	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

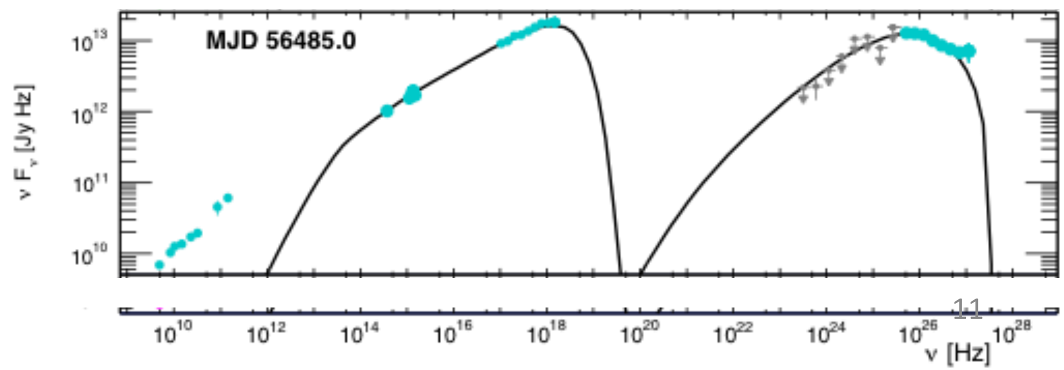


From astro-ph/1310.0006 (Ajello et al. 2014)

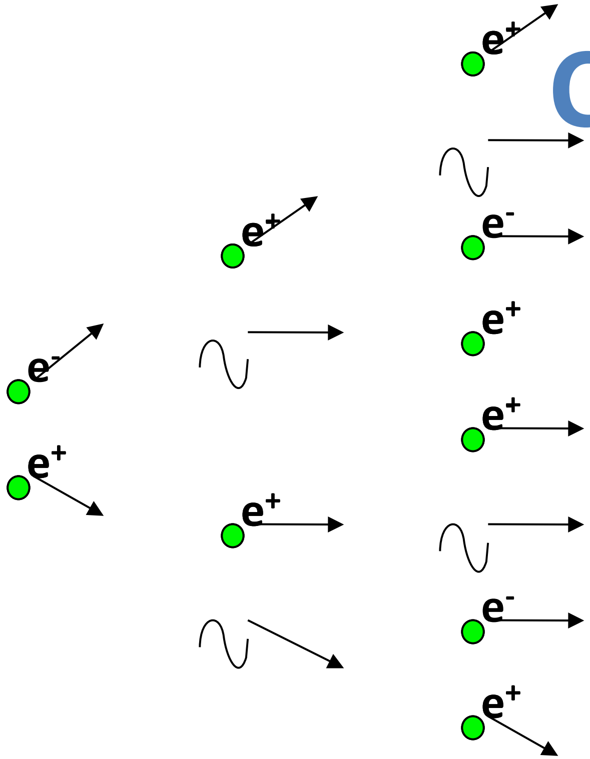
•Reminder:
Blazar -> BL Lac (FR1) -> HSP

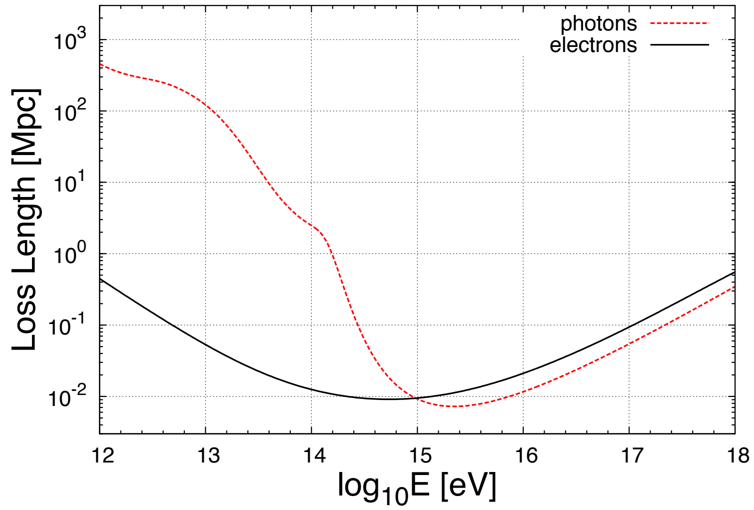
•Supports idea that FSRQ (gas accreting) AGN evolve into BL Lac (gas starved) AGN

Archetypal HSP example Mrk 501

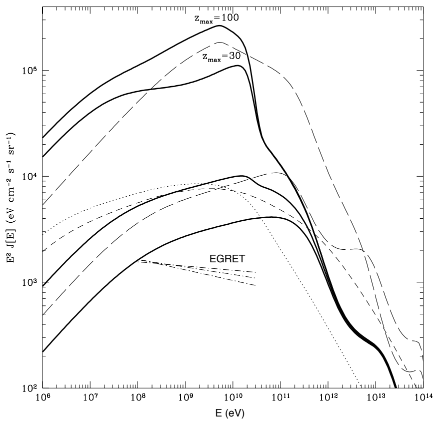


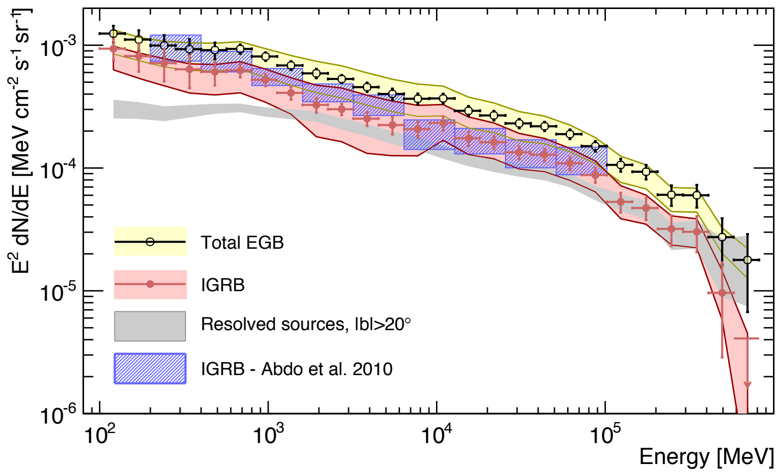
Cascade Spectra + the IGRB





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



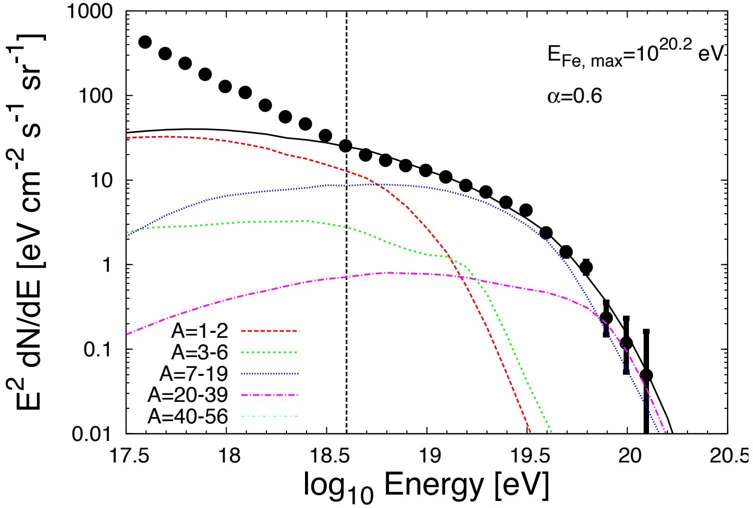


Regardless of where the energy is injected (ie independent of source z), the arriving flux possesses a ~universal shape

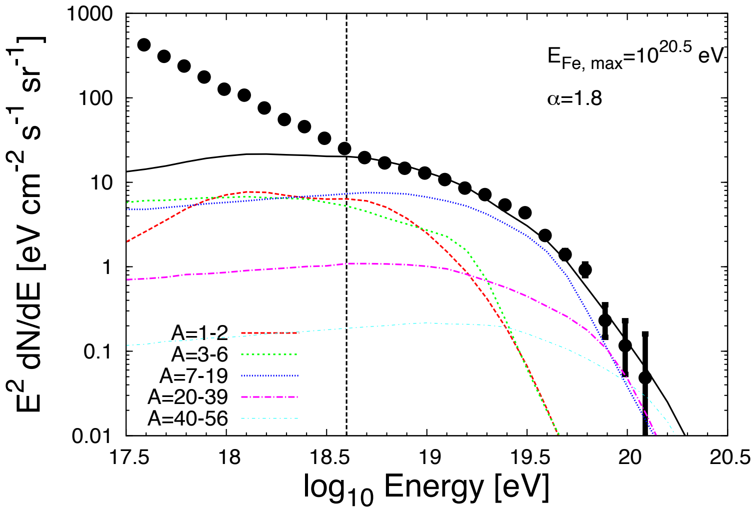
12

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

n=3 evolution result

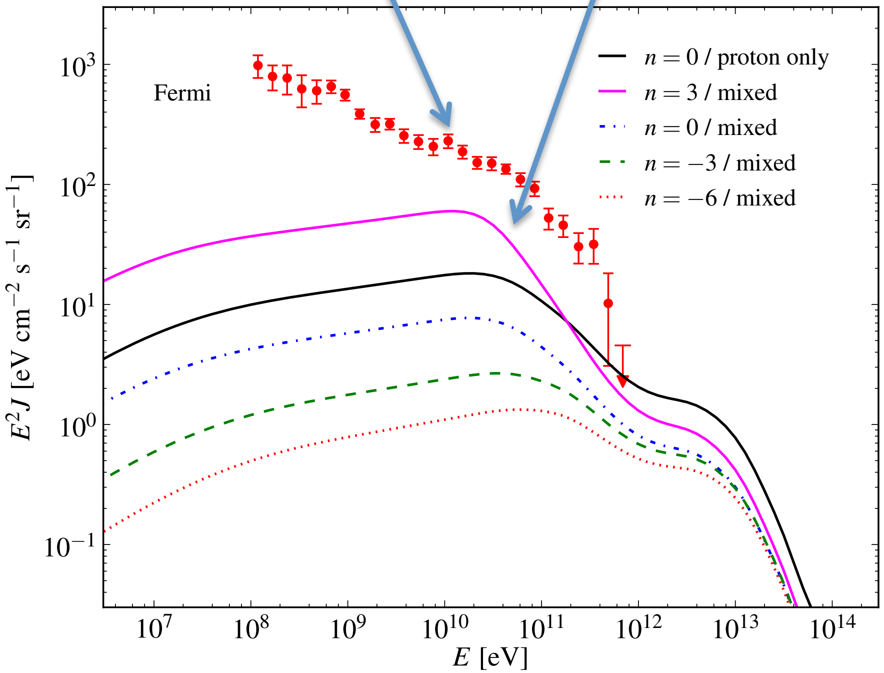


n=-6 evolution result

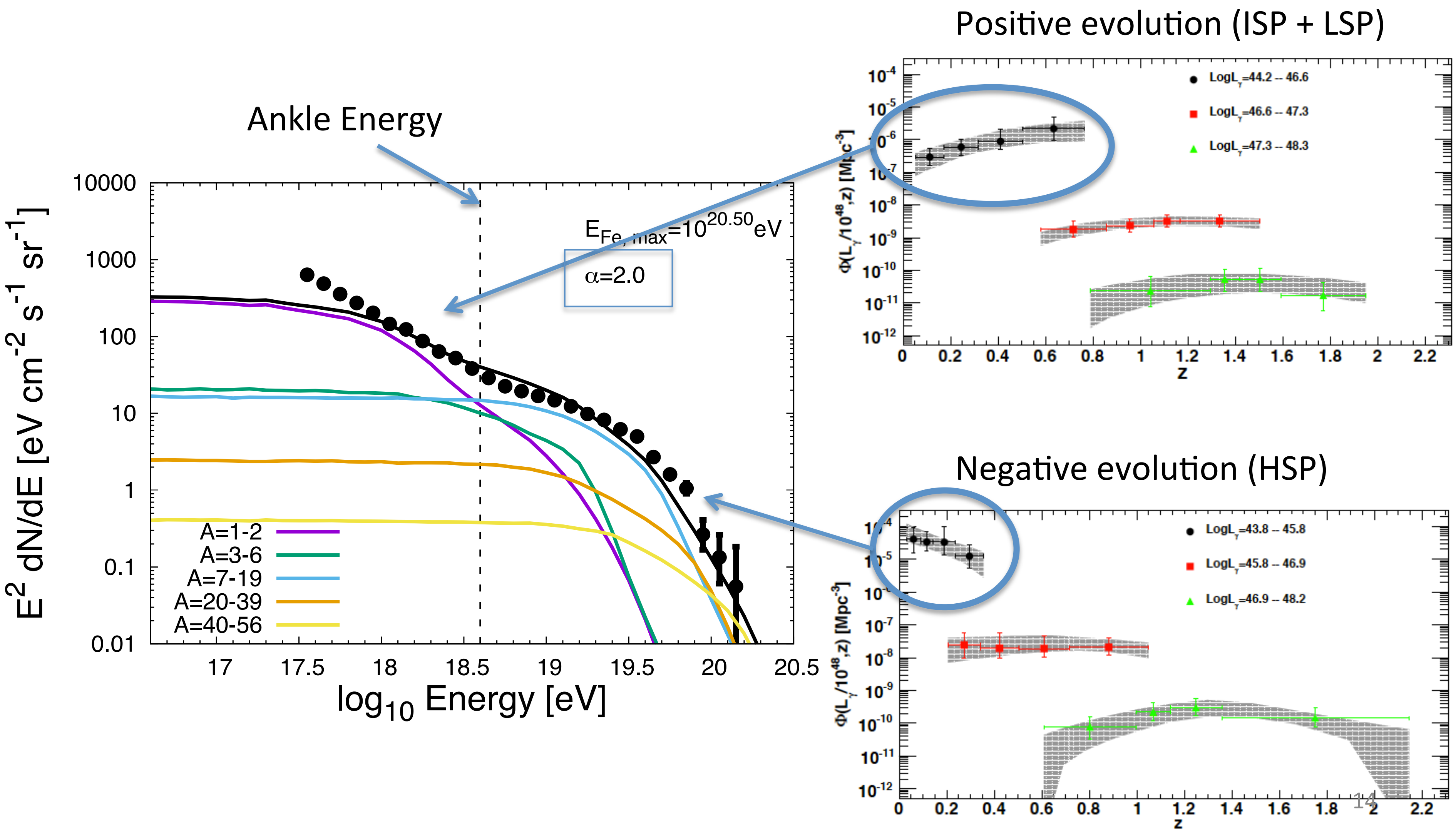


IGRB (EGB with resolved points sources removed)

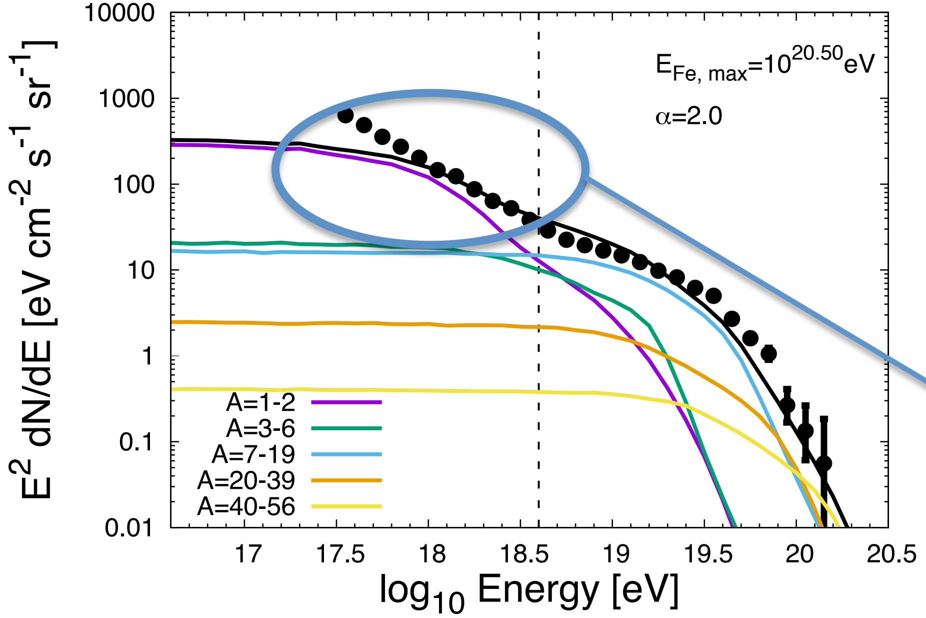
n=3 to -6 evolution scenarios give rise to between **40%** and **12%** of Fermi limit



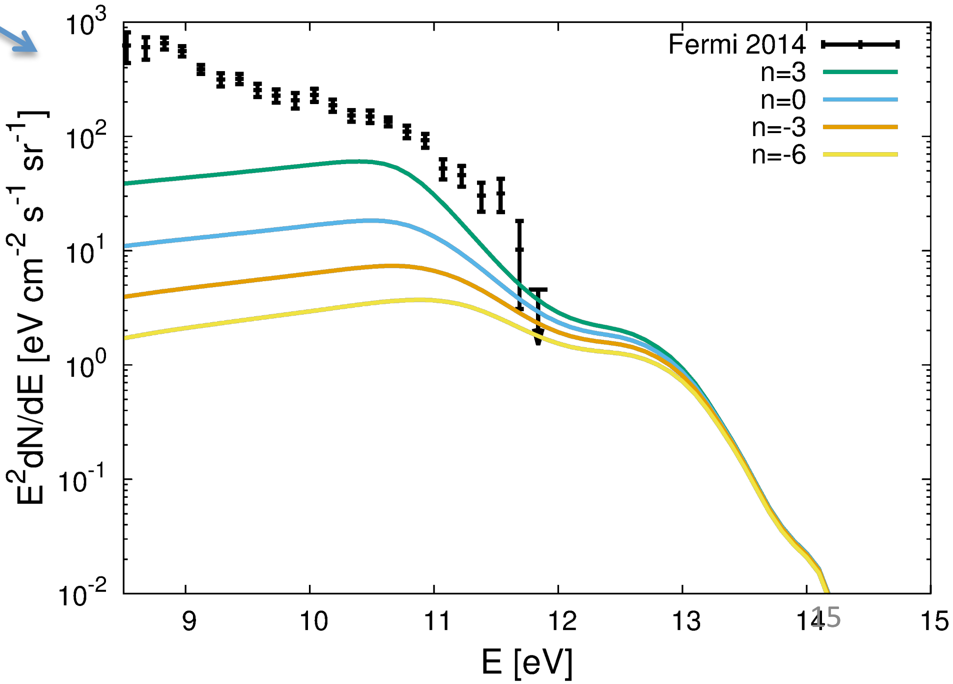
Does a Separate Class of Extragalactic Source Dominate at Sub-Ankle Energies?



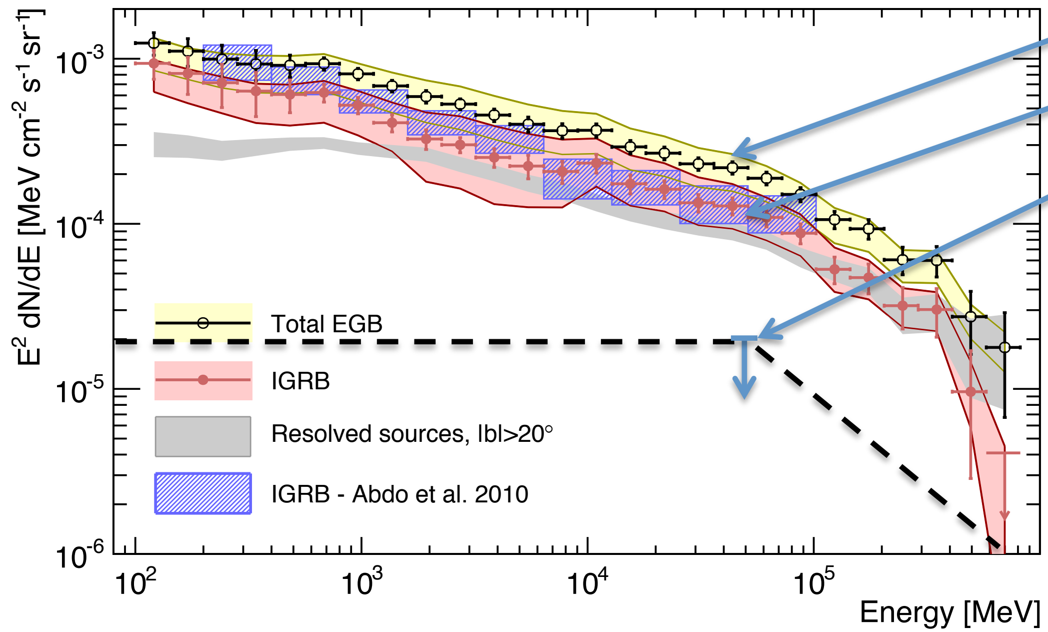
Cascade Contribution from Second Source Population



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



The Isotropic Gamma-Ray Background



Lat. Cut + Gal. Foreground Removal

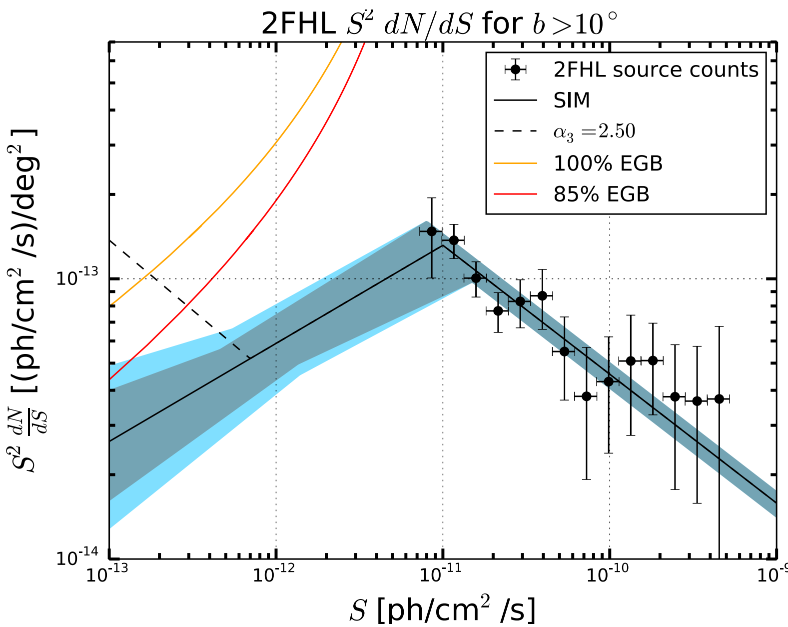
….+ Removal of Res. Blazars

….+ Removal of Unres. Blazars

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

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

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

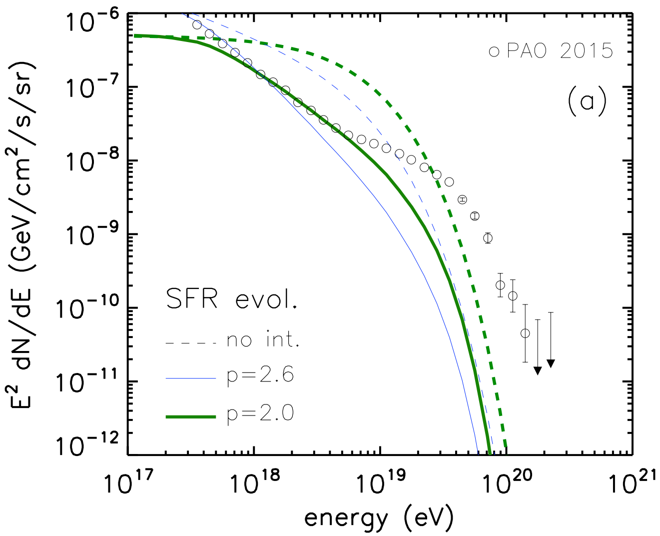


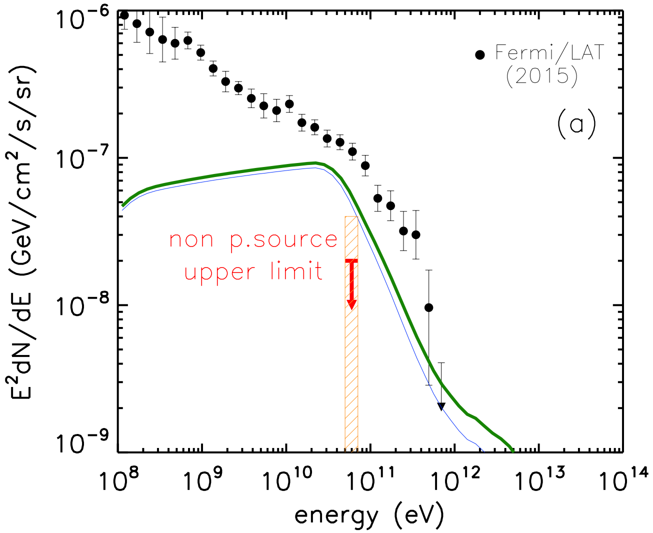
“Our analysis permits us to estimate that point sources, and in particular blazars, explain almost the totality (86^{+16}_{-14} %) of the >50 GeV EGB.”

Fermi Collaboration (2015)- astro-ph/1511.00693

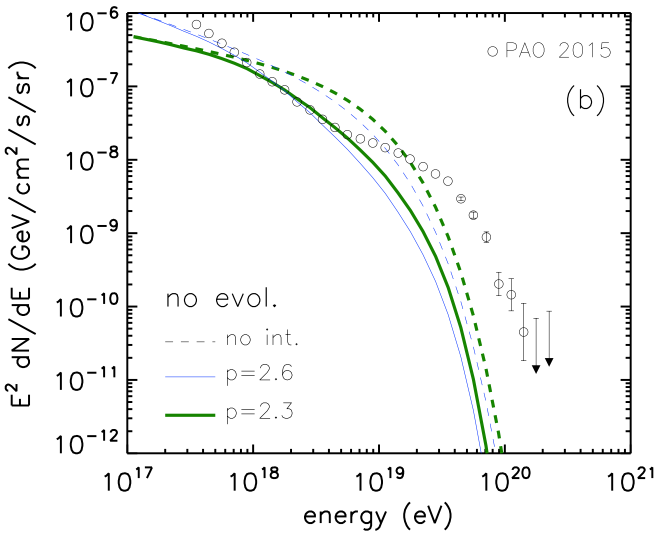
The Origin of Protons Below the Ankle

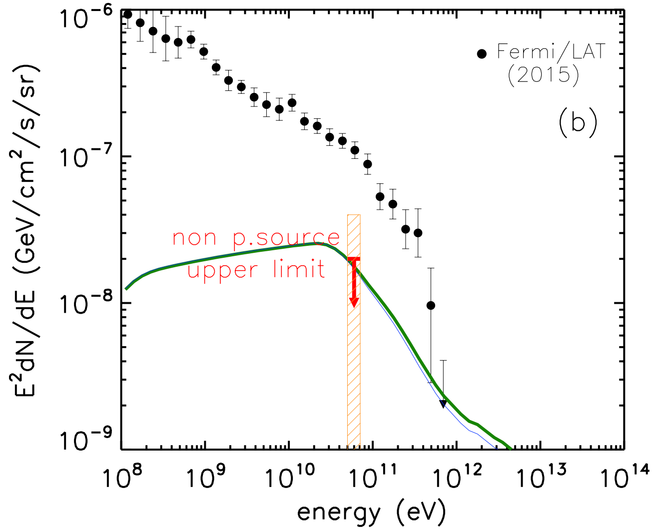
SFR evolution scenario





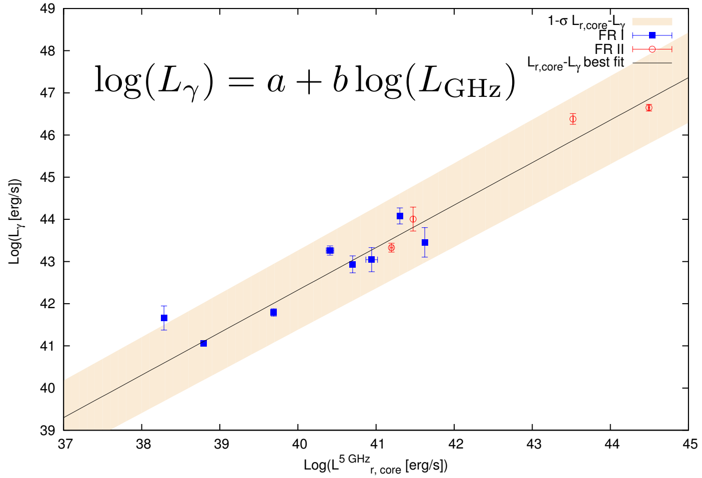
no evolution scenario

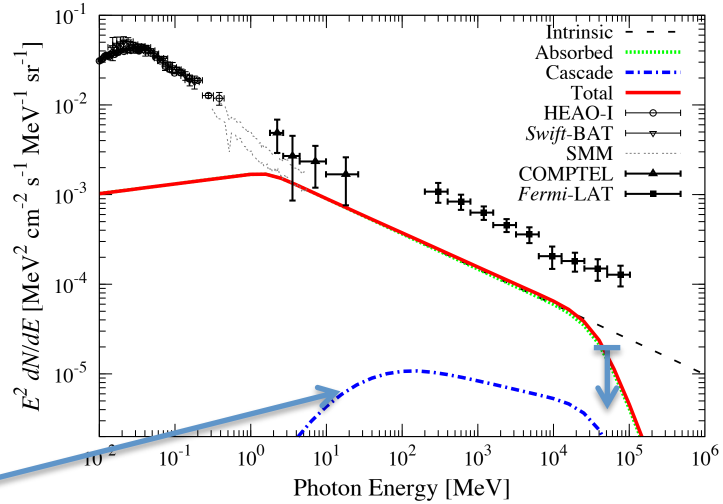




Note- IGRB contribution from cascade losses rather independent of source spectra

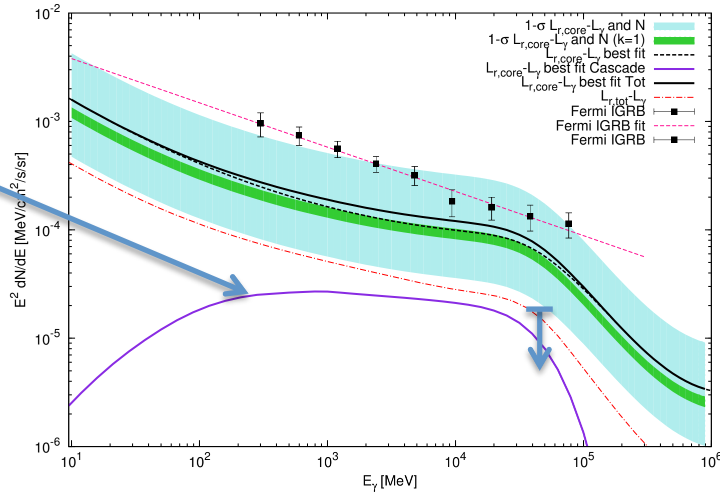
.....and Radio Galaxy Contributions Still Not Removed





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

Note level of AGN gamma-ray generated cascades

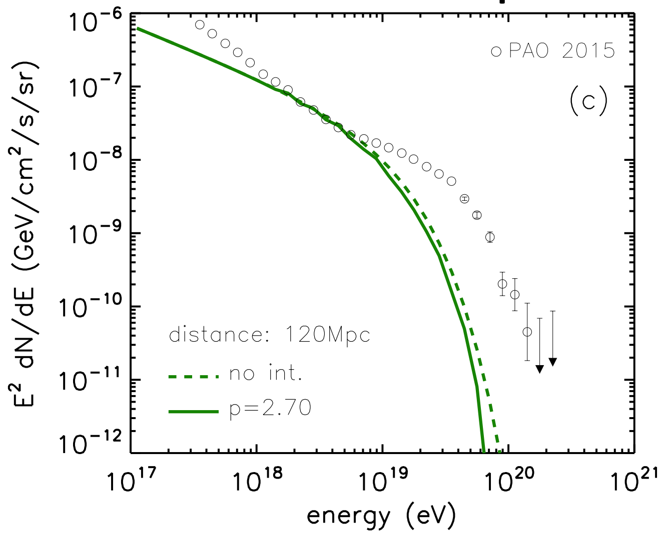


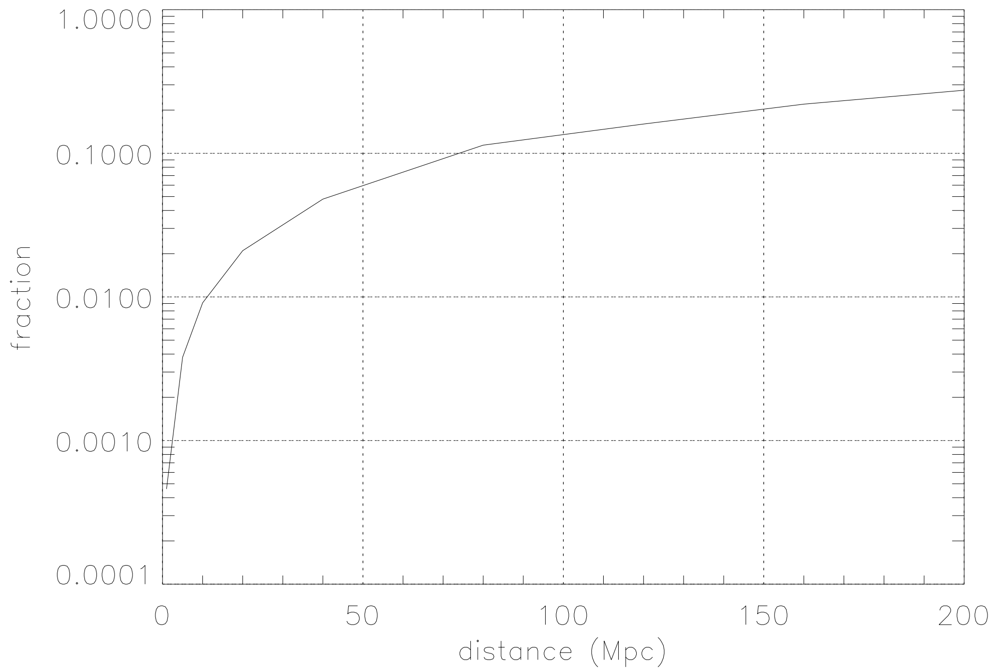
Radio Galaxy contributions are estimated to make up a significant fraction of the remaining IGRB.

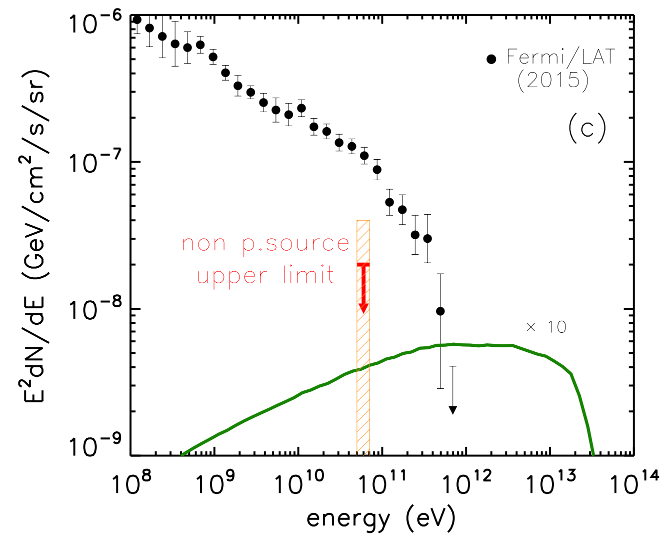
From astro-ph/1304.0908 (Di Mauro et al. 2013)

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

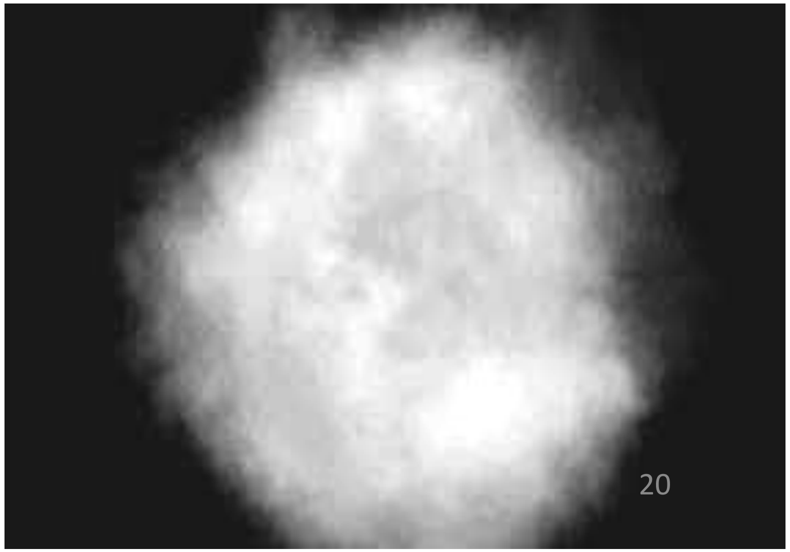
An Alternative Interpretation of the Negative Source Evolution Result

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"!

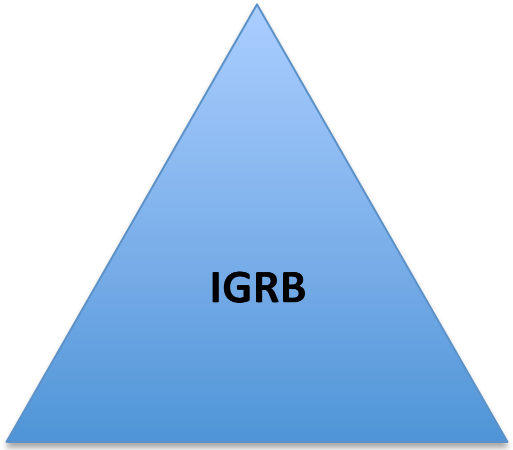


Conclusions

- 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!

The Promise of the IGRB

AGN Gamma-Rays Sources (Blazars + Radio Galaxies)



UHECR Propagation

PeV Neutrino Sources ($\pi^{+/-/0}$)

Each of these sectors wants to dominate the diffuse gamma-ray background....understanding this background holds huge potential for understanding these sectors.

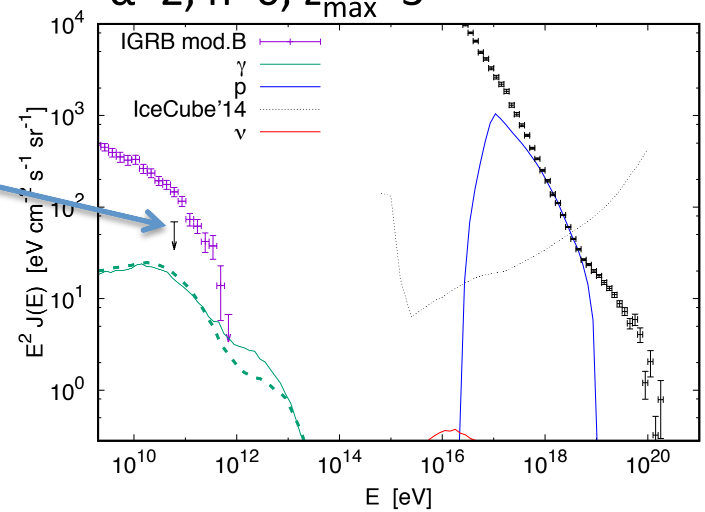
Future Directions for IGRB Studies......TeV Bright AGN cascade and radio galaxy contributions

The Level of the Constraint(s)

From Berezinsky et al. (2016)-
astro-ph/1606.09293

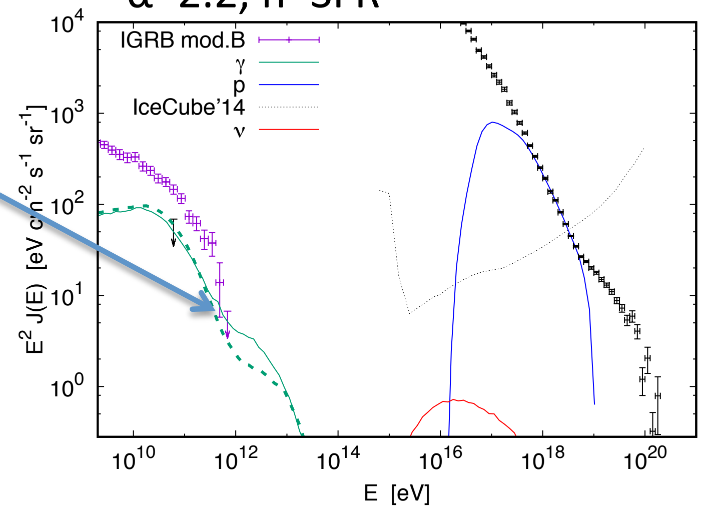
Note considerable difference in position of upper limit!...
“A contradiction with Ref. [31] is mainly explained by using of model B for galactic contribution in the Fermi LAT experiment. ”

α=2, n=0, z_{max}=3

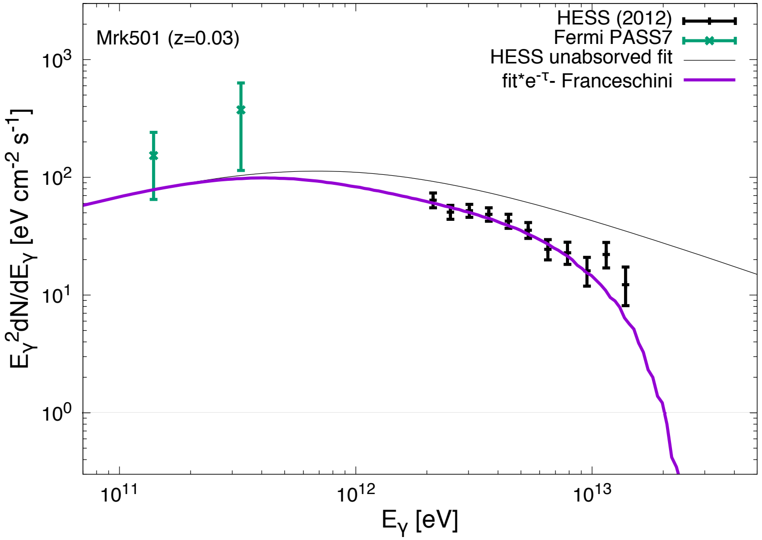


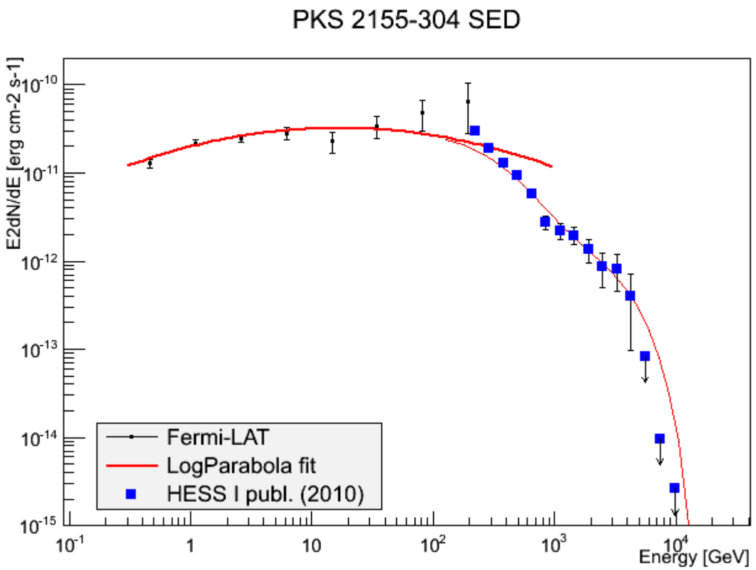
Attention is drawn to level of highest energy upper limit.

α=2.2, n=SFR



Why Conservative?.....Cascade Contributions from TeV Photons

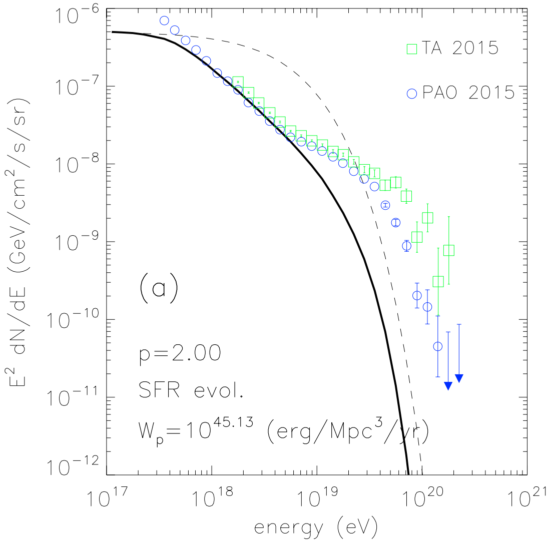


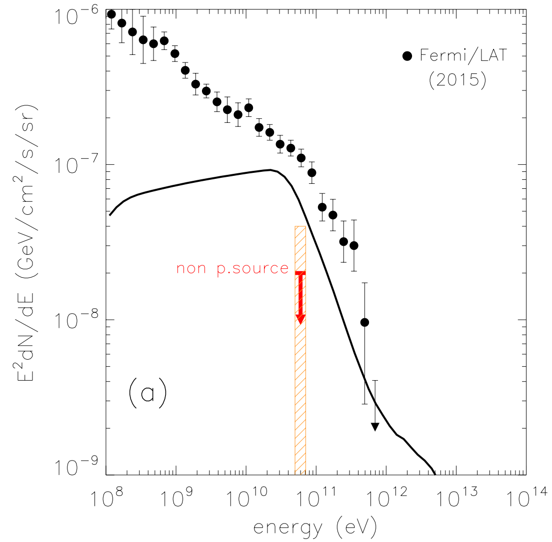


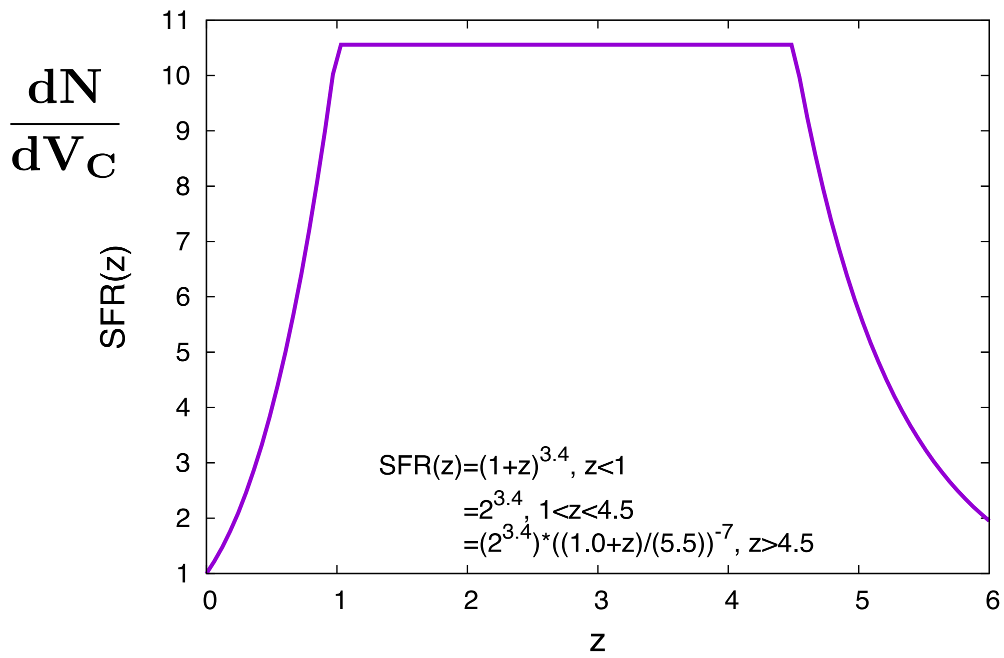
Only takes ~100 such objects to produce 100% of the EGB

The Origin of Protons Below the Ankle

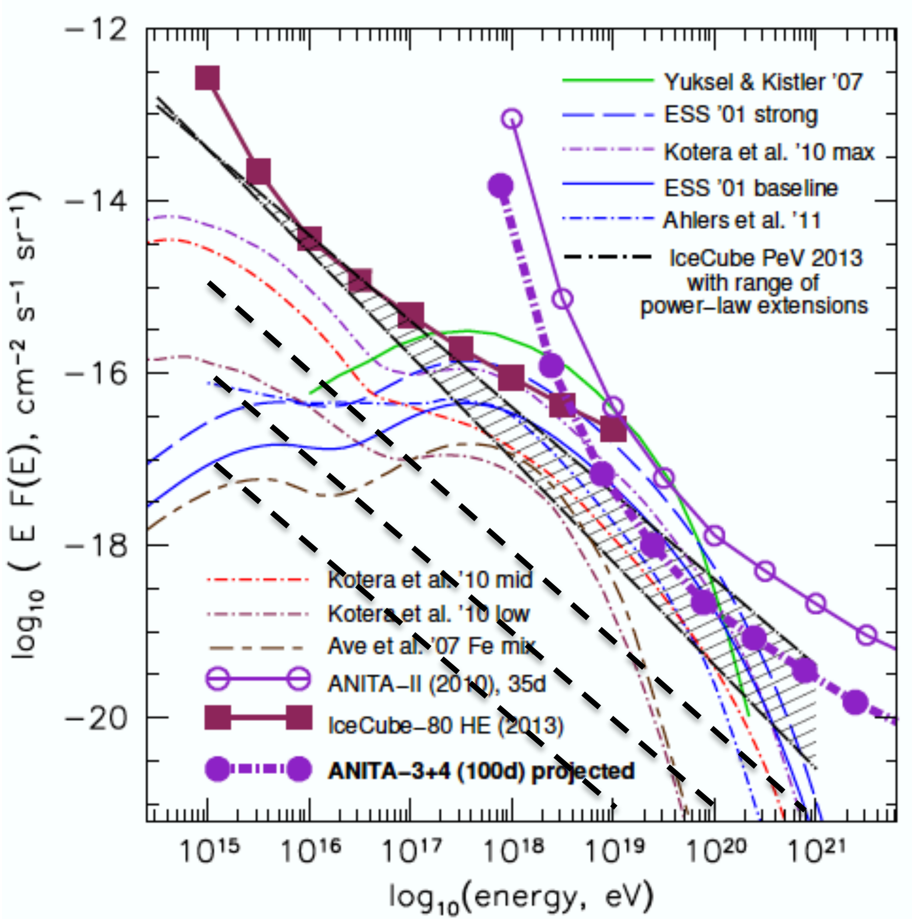
SFR evolution scenario

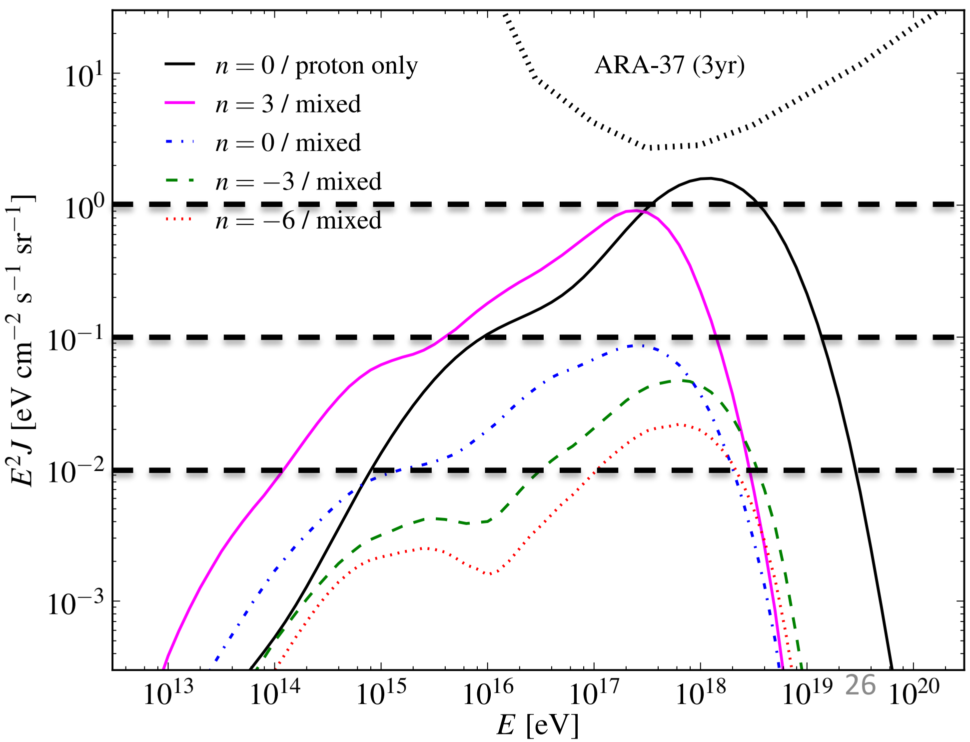






Secondary Neutrino Fluxes

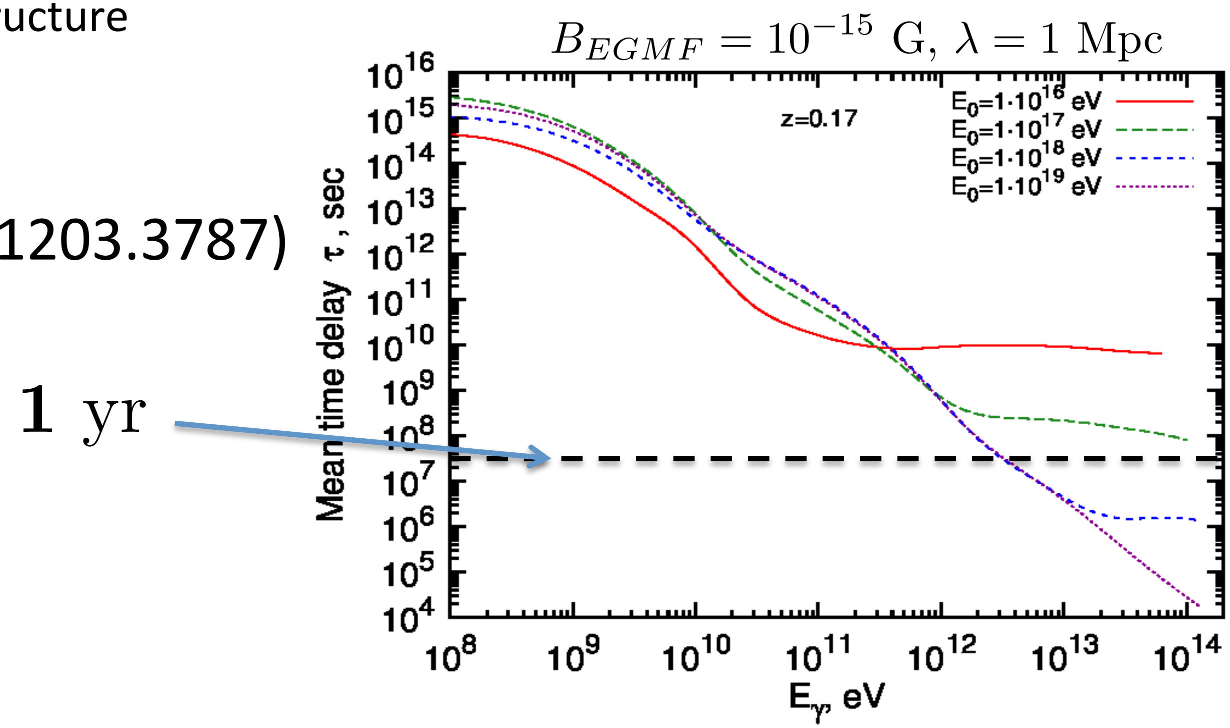




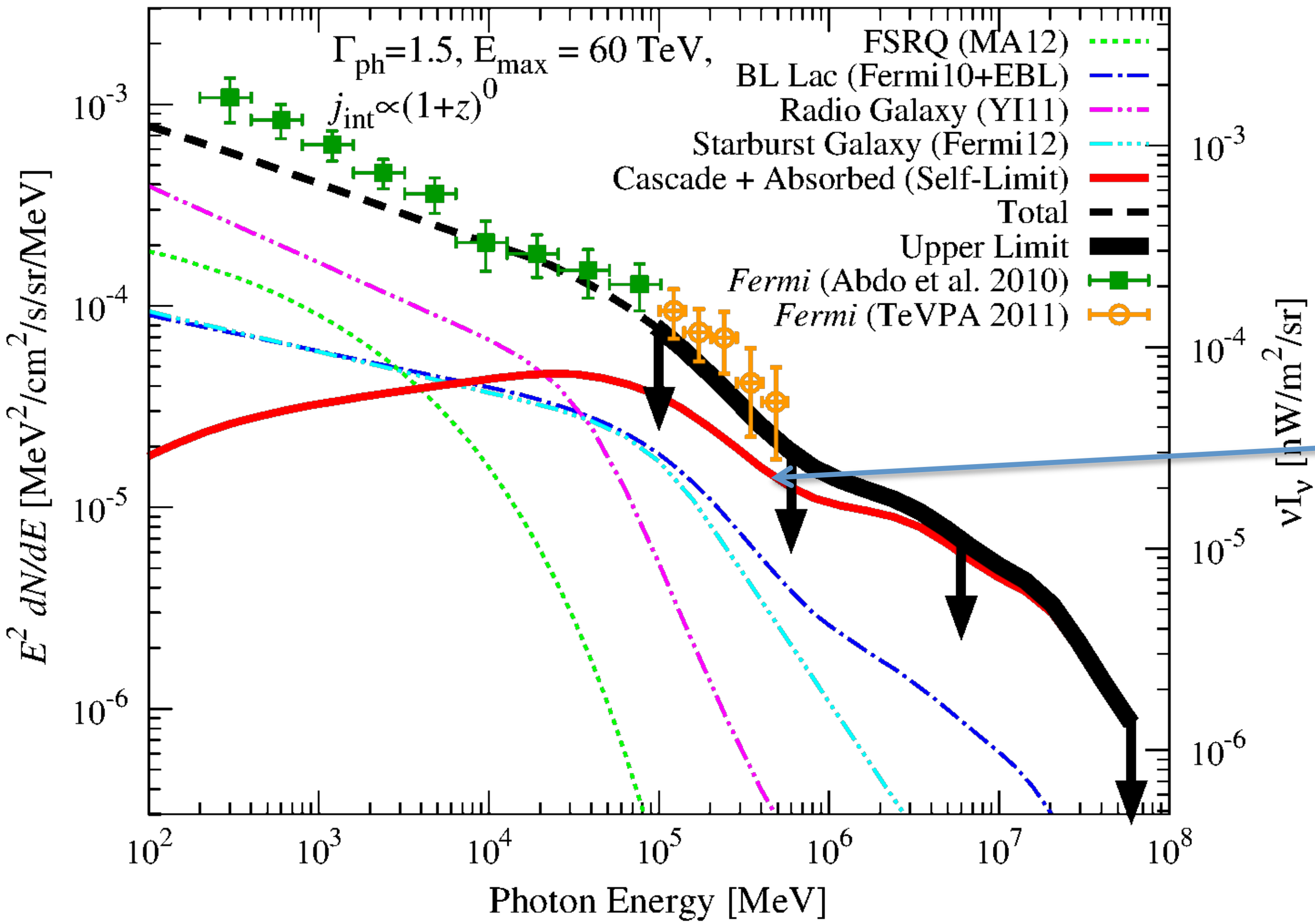
Proton Fed Blazar Emission Model

- Kusenko & Essey have spearheaded the suggestion that some TeV blazars are powered through proton losses in the presence of weak (10^{-15} G) extragalactic magnetic fields
- If this is the case, some subset of the component of resolved/ unresolved blazars should not be removed from the EGB
- However these blazars would not be expected to show short time-scale variability structure

Prosekin et al. (astro-ph/1203.3787)



Cascade Contribution Limit

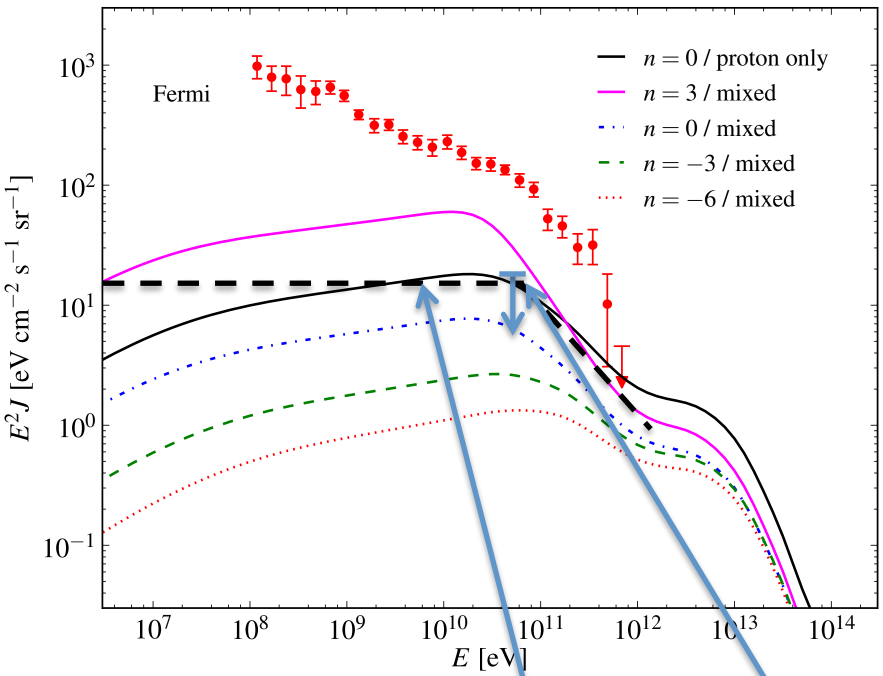


Limit on Cascade Component is around 40% of Fermi limit

Constraints also placed on evolution of contributors to cascade component

From astro-ph/1206.2923 (Inoue et al. 2012)

Revised Cascade Contribution Constraint



nuclei above $10^{18.6}$ eV

The n=3 scenario sits in conflict with this new constraint.

conservative flux upper limit at 50 GeV from astro-ph/1603.03223, Liu et al.

differential cascade limit taken from astro-ph/1511.00688, Bechtol et al.

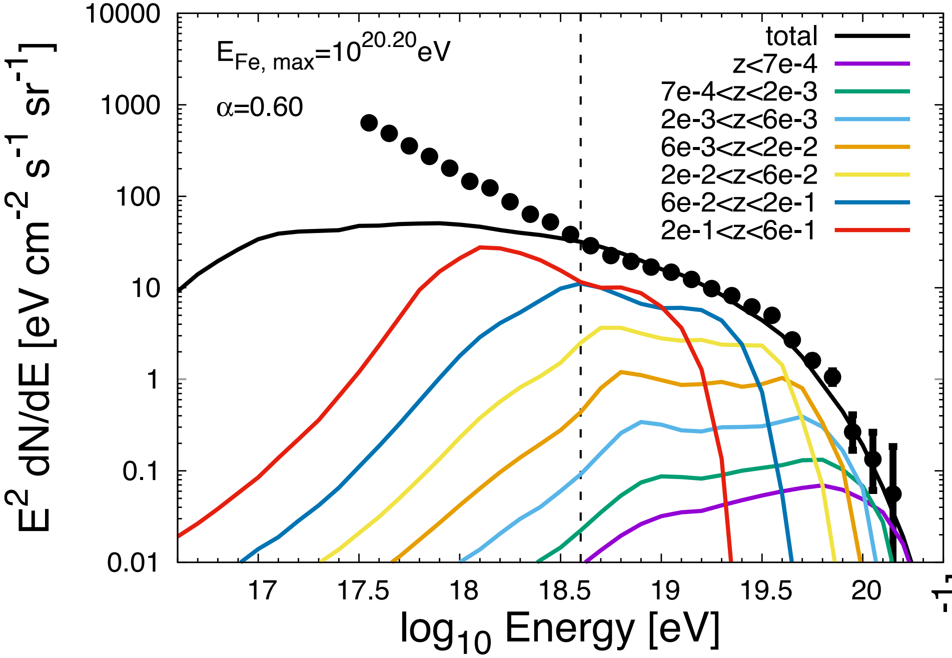
Similar Evolution Observed for Non-Blazar AGN?

Radio Loud AGN are suggested to have positive evolution (n=2) up to z=0.5, followed by negative evolution (n=-4) beyond this.

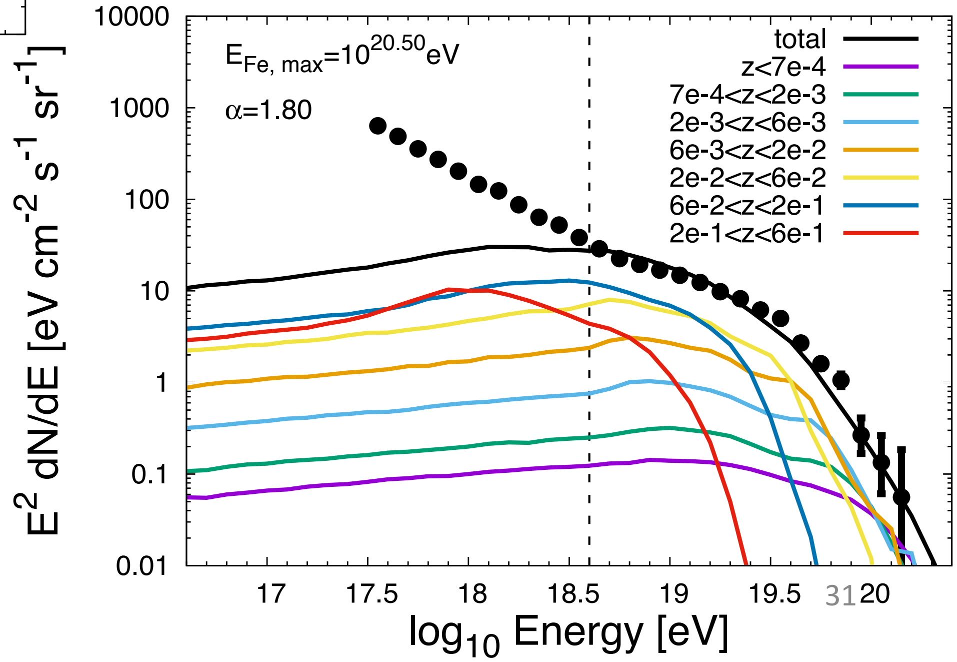
From astro-ph/1506.06554 (Padovani et al. 2015)

Source Redshifts Contributing to Arriving Flux

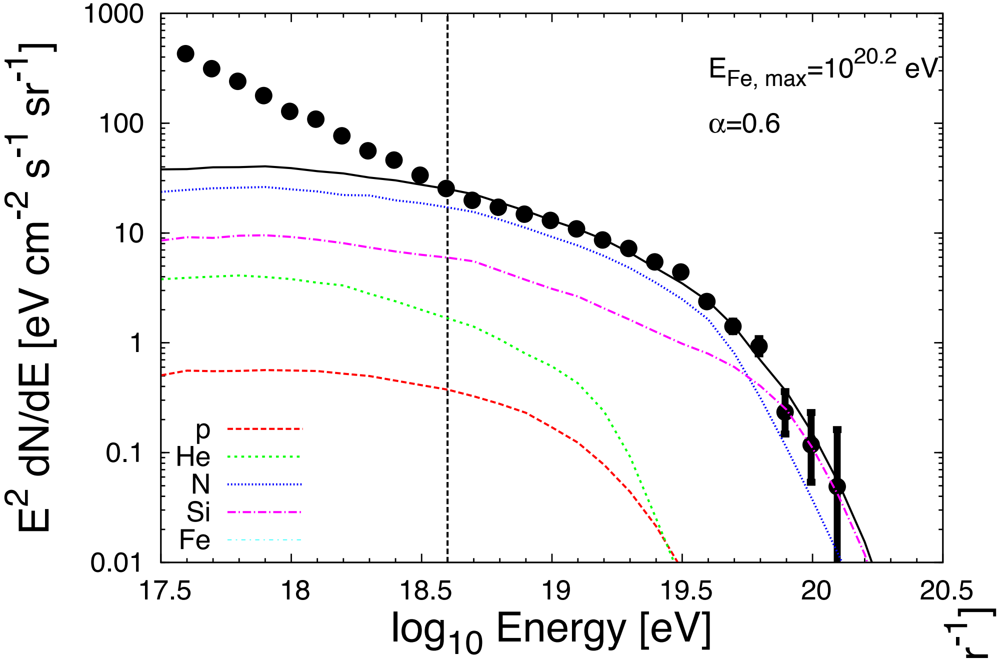
n=3 evolution

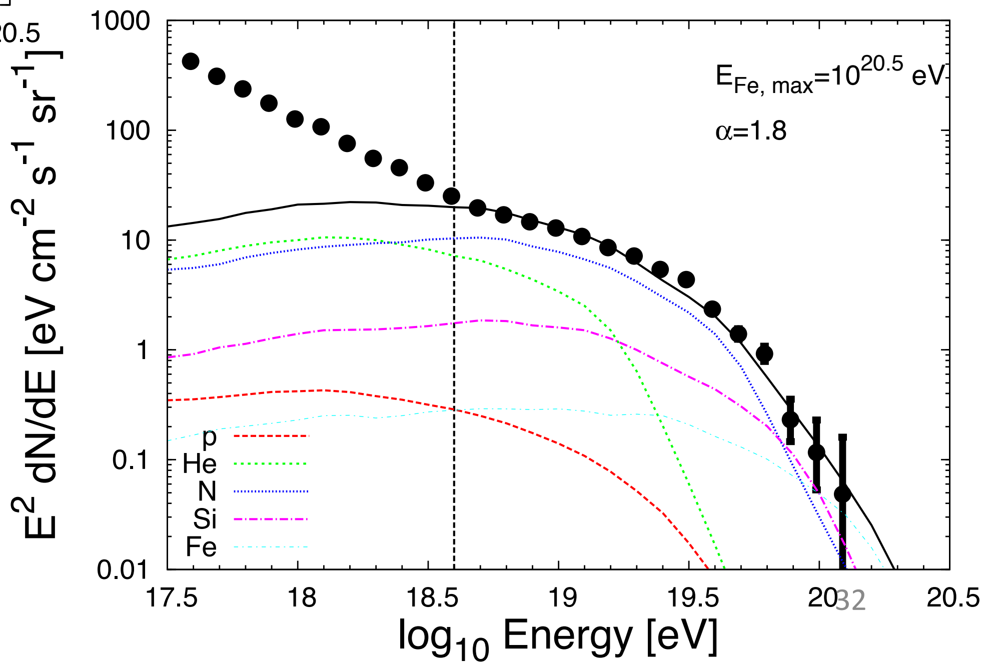


n=-6 evolution



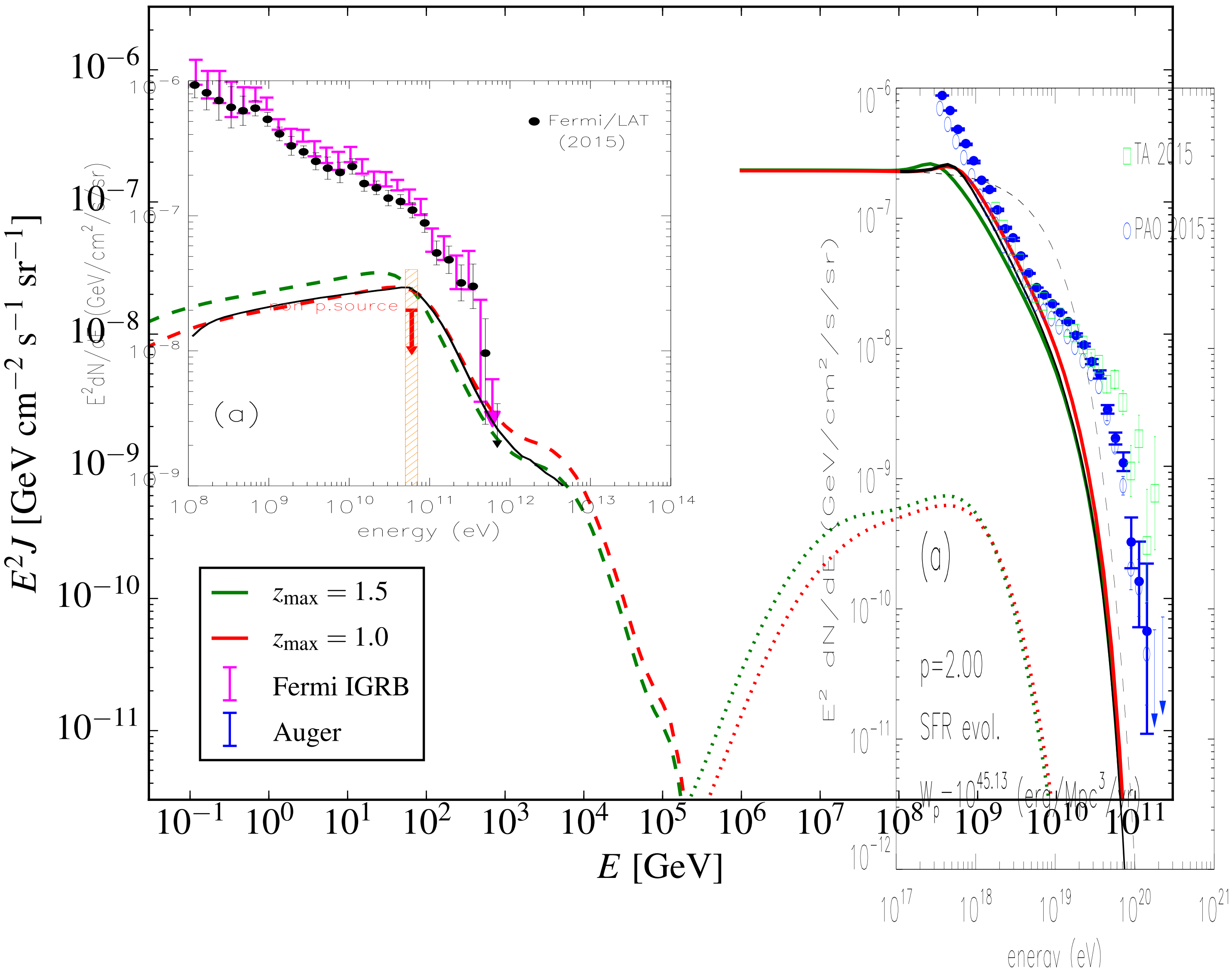
Injection Species Contributing to Arriving Flux





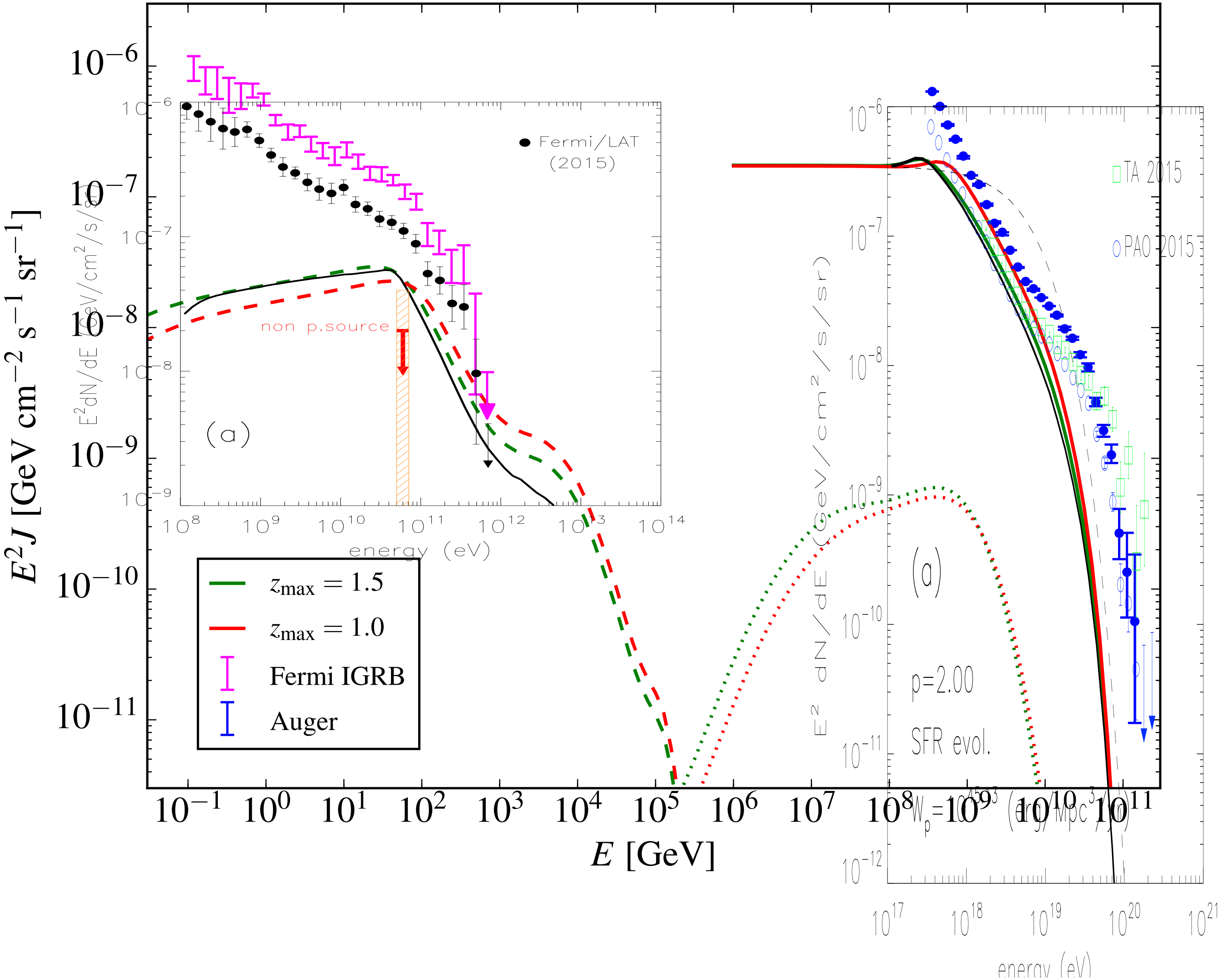
Comparison with Other Kinetic Equation Solver (MA)

$(1+z)^3$ evolution
zmax=1

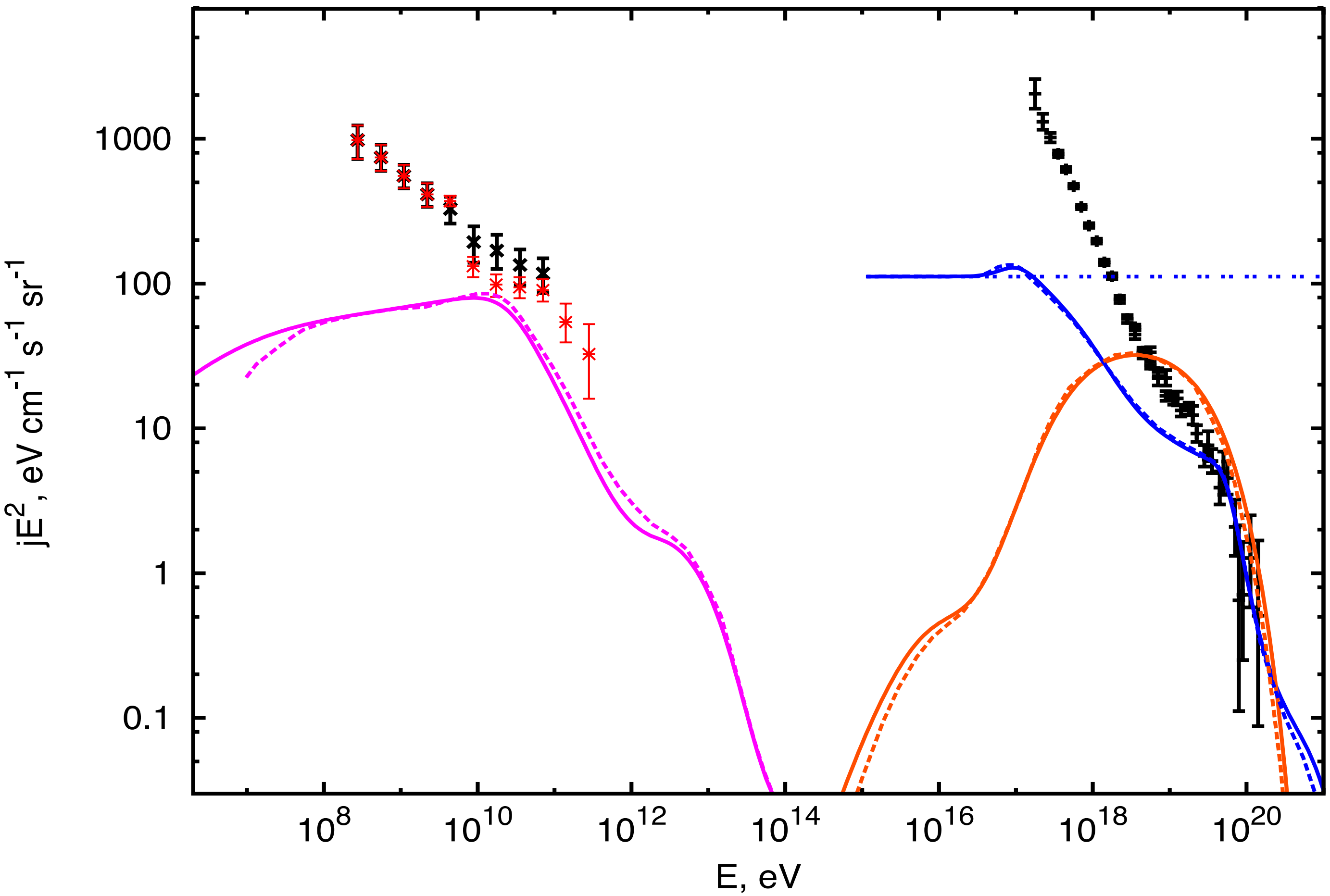


Comparison with Other Kinetic Equation Solver (MA)

$(1+z)^3$ evolution
zmax=1.5



Other Cross-Checks



A comparison is shown between the kinetic equation solver of Markus Ahlers and Oleg Kalashev

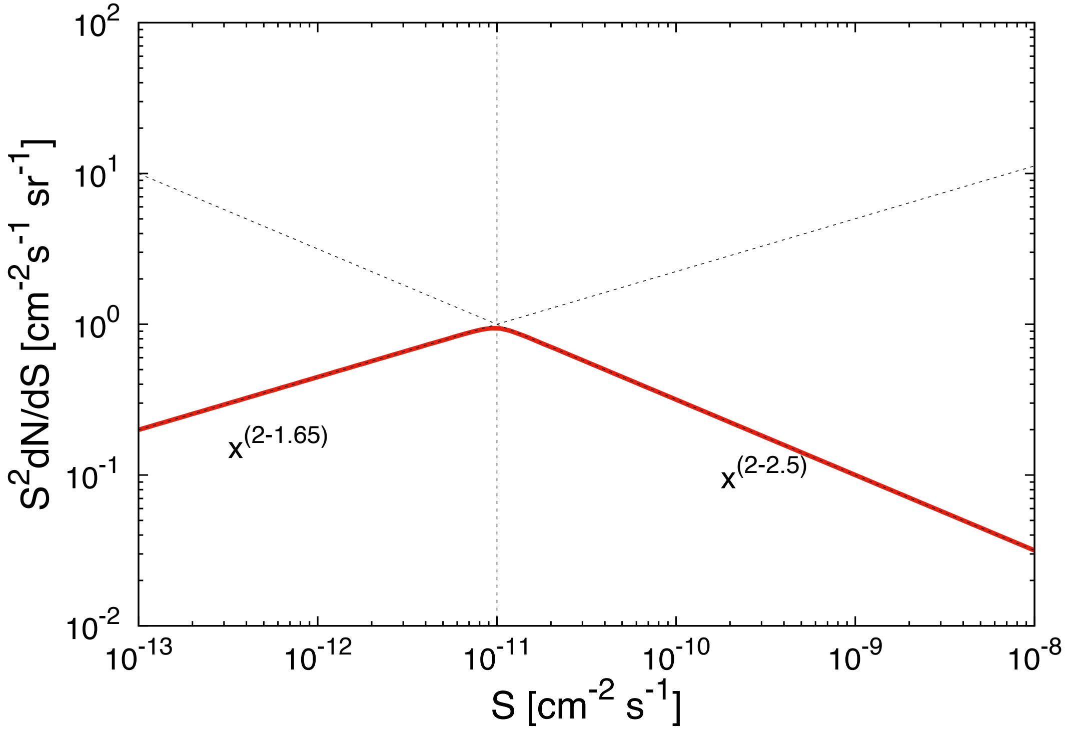
Gelmini et al. astro-ph/**1107.1672**

General Problem for Cascade Contribution?

Fermi Collaboration (2015)- astro-ph/1511.00693

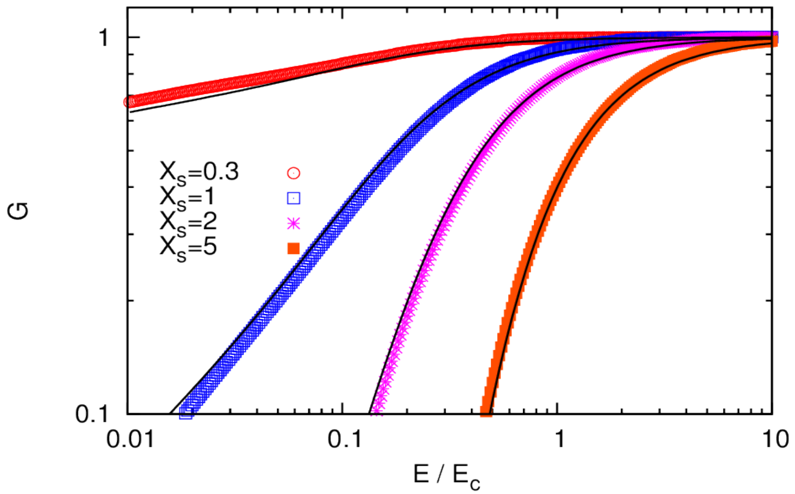
$$\frac{\mathbf{dN}}{\mathbf{dS}} \propto \mathbf{S}^{-\alpha}$$

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



"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."

Hard Spectra Problem



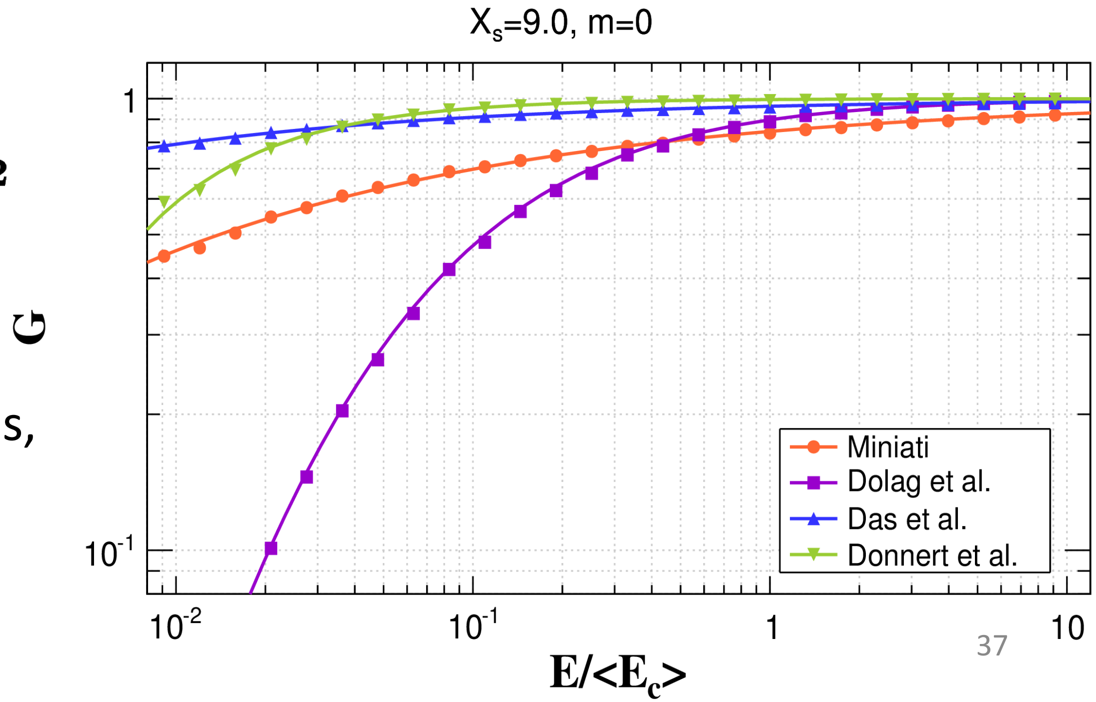
Magnetic horizon suppression suggested to resolve "hardness" issue, Mollerach et al. astro-ph/1305.6519

	Miniati	Dolag *et al.*	Das *et al.*	Donnert *et al.*
$\langle B \rangle$ [G]	1.8×10^{-8}	5.5×10^{-11}	1.2×10^{-9}	6.3×10^{-11}
B_{rms} [G]	1.7×10^{-7}	1.5×10^{-8}	5.7×10^{-8}	1.7×10^{-8}

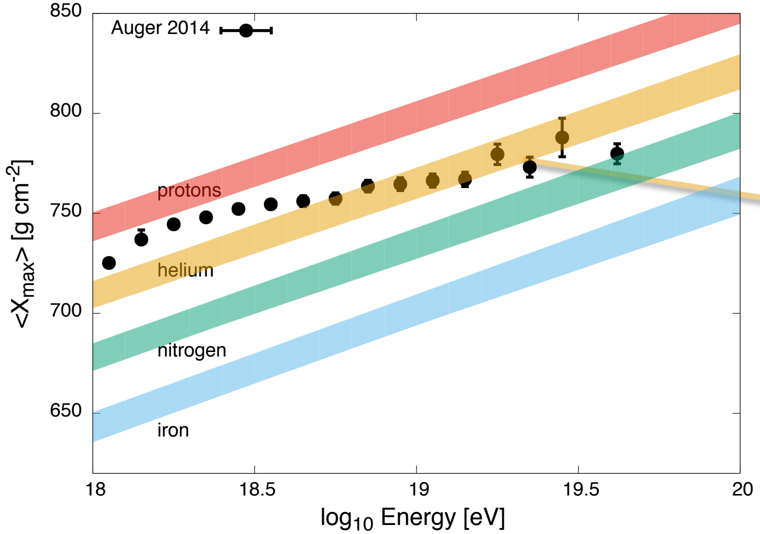
$$X_s = \frac{d_s}{(ct_H l_c)^{1/2}}$$

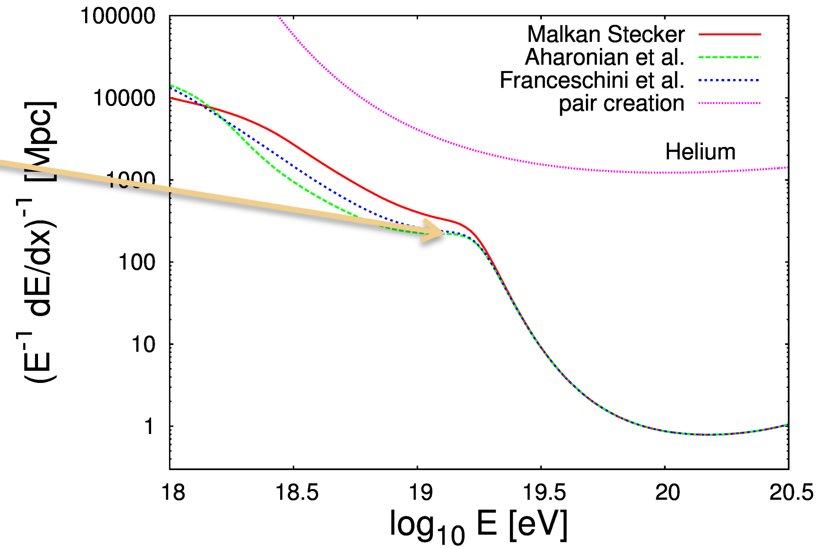
$$= 0.1 \left(\frac{d_s}{10\ \text{Mpc}}\right)\left(\frac{1\ \text{Mpc}}{l_c}\right)^{1/2}$$

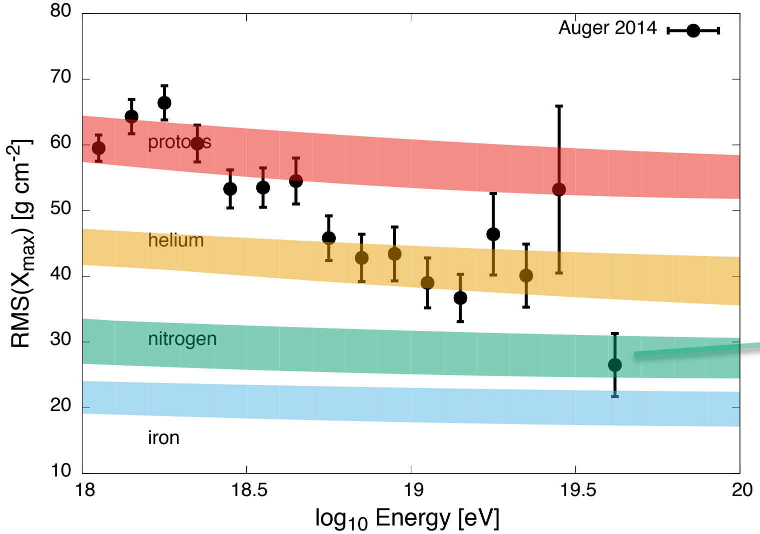
"Realistic" field structures/strengths, however, don't provide sufficient suppression, Alves Batista et al. astro-ph/1407.6150

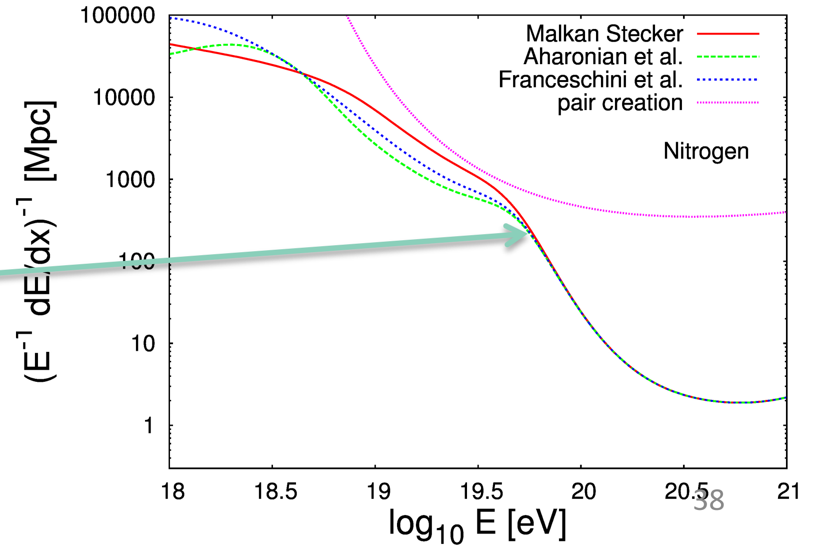


Sources of Cosmic Ray Nuclei Must be Nearby

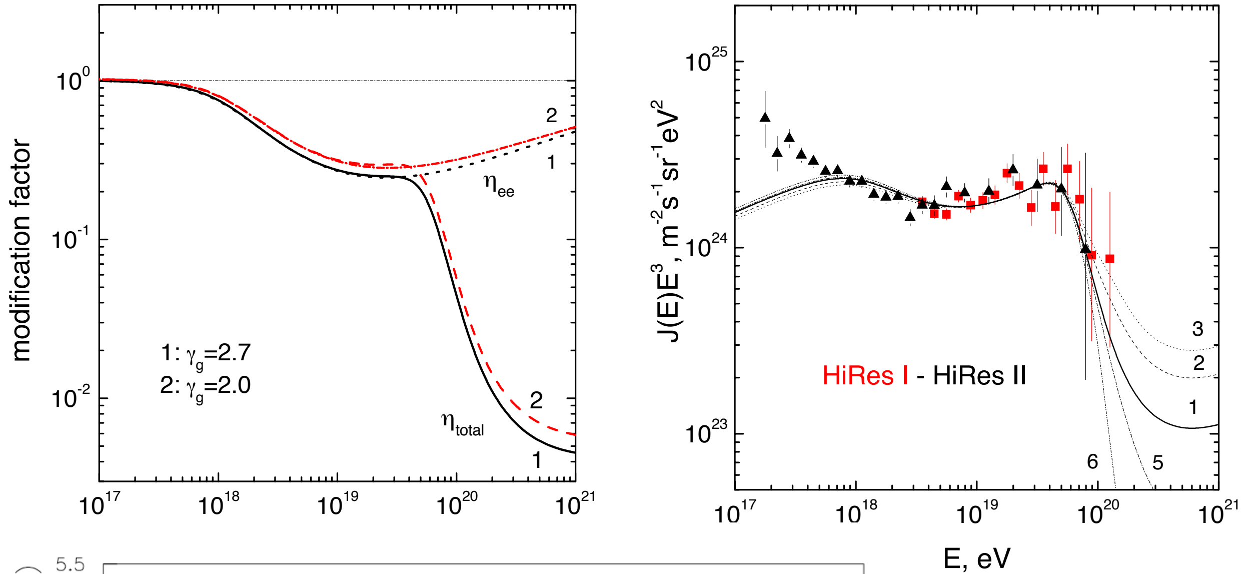




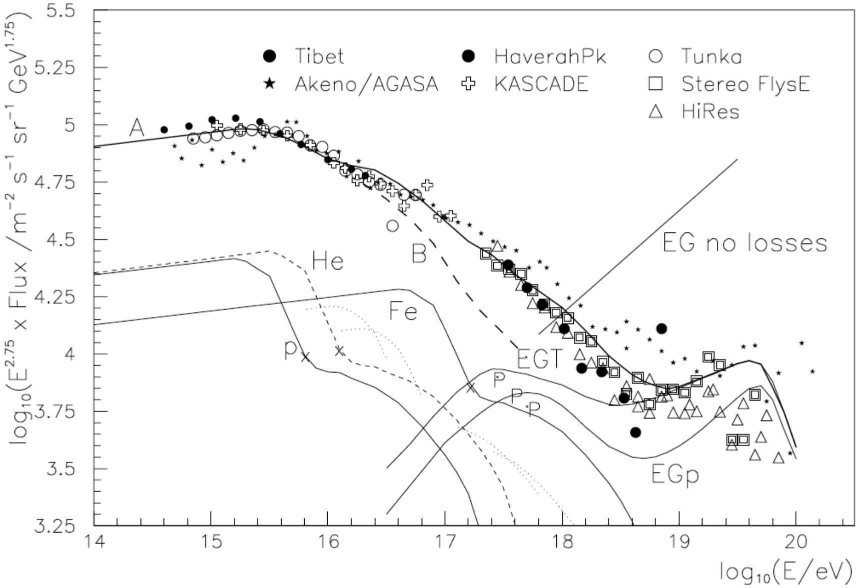




Historical Debate about the Nature of the Ankle Feature



From Berezinsky et al. (2006)
astro-ph/**0204357**
"Dip Model"



From Hillas et al. (2004)
SKA Conf. Proceedings

What's changed since then? In which direction do the scales now tip towards?