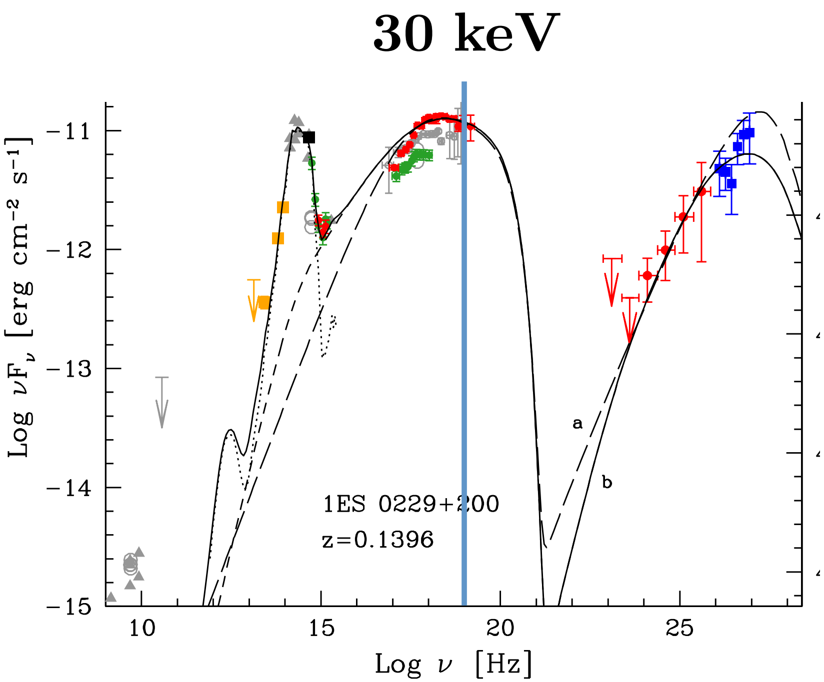
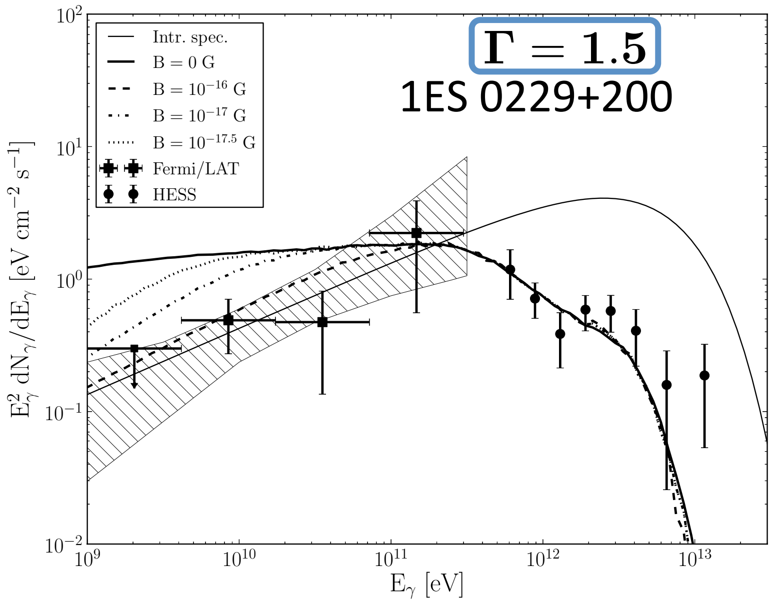
(Extreme) HBLs (+ Misaligned Versions) as UHECR Sources



Costamante et al. (1711.06282)



Vovk et al. (1112.2534)

Andrew Taylor

Particle Acceleration in AGN

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

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

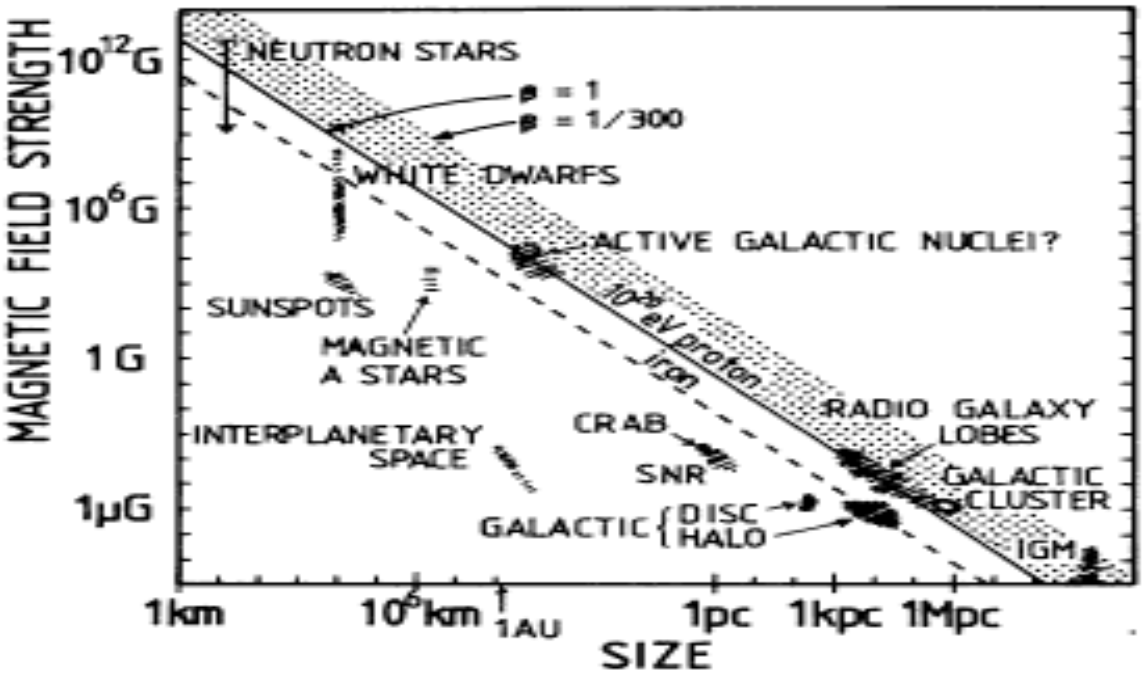
Maximum energy
(Hillas criterion)

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

$$\mathbf{R_{lar}}(\mathbf{E}, \mathbf{B}) = \left(\frac{\mathbf{E}}{\mathbf{10\ EeV}} \right) \left(\frac{\mathbf{1\ mG}}{\mathbf{B}} \right) \mathbf{10\ pc}$$

AM Hillas (1984)

Compactness of UHECR Sources: Proton/Nuclei Synchrotron Losses



$\eta \approx 1$ assumed in above plot

Andrew Taylor

AM Hillas (1984)

Particle Acceleration with Cooling

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

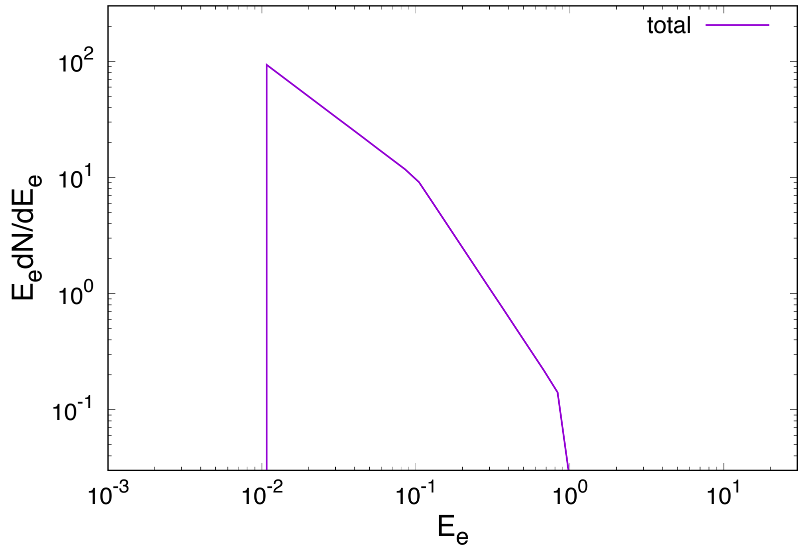
$$\mathbf{t_{cool}} = \frac{\mathbf{9}}{\mathbf{8}\pi\alpha}\left(\frac{\mathbf{m_e}}{\mathbf{E}_{\gamma}^{\mathbf{sync}}}\right)\mathbf{t_{lar}}$$

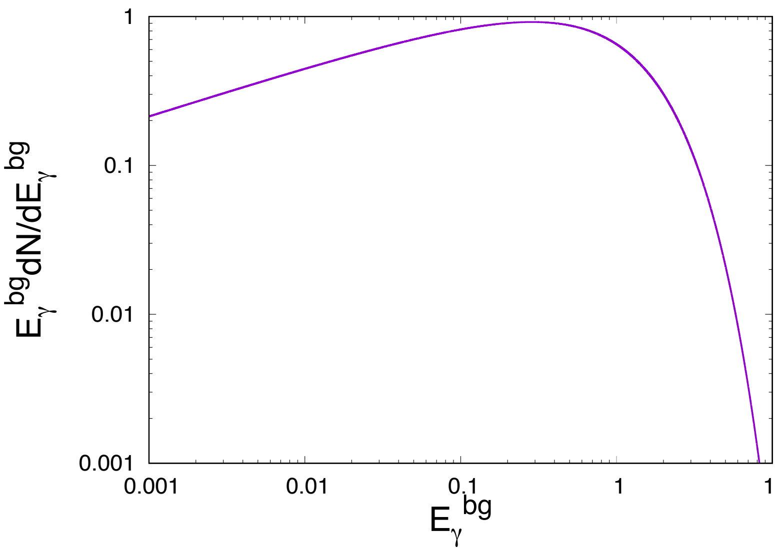
$$\mathbf{E}_{\gamma}^{\mathbf{sync}} \approx \frac{\mathbf{9}}{\mathbf{4}}\eta^{-\mathbf{1}}\beta^{\mathbf{2}}\frac{\mathbf{m_e}}{\alpha}$$

Maximum synchrotron energy tells us how efficient accelerator is!

$$\eta < \mathbf{10^3}$$

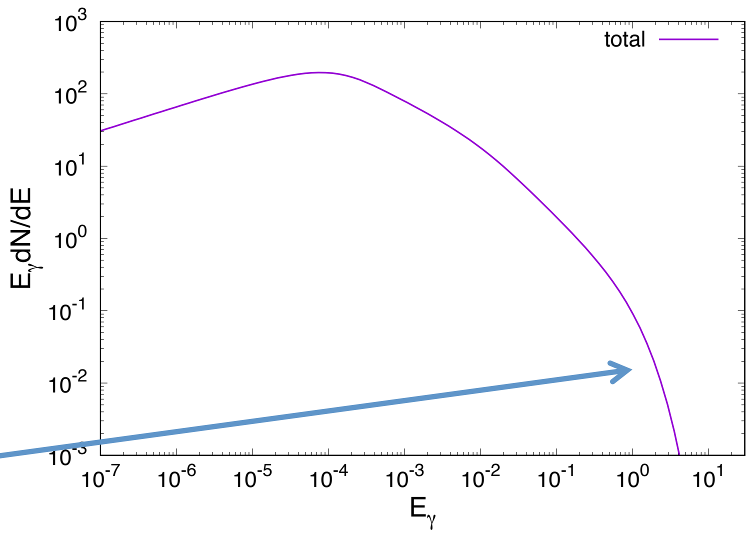
Future Probes- Cutoff Region





$$\mathbf{E}_\gamma = \gamma_\mathbf{e}^\mathbf{2}\left(\frac{\mathbf{B}}{\mathbf{B}_\mathrm{crit}}\right)\mathbf{m_e}$$

$$E_\gamma \frac{dN}{dE_\gamma}_{tot} = \int \left(\frac{E_\gamma}{E_e^2}\right)\frac{dN}{dE_\gamma}\left(\frac{E_\gamma}{E_e^2}\right) E_e \frac{dN}{dE_e} dE_e$$

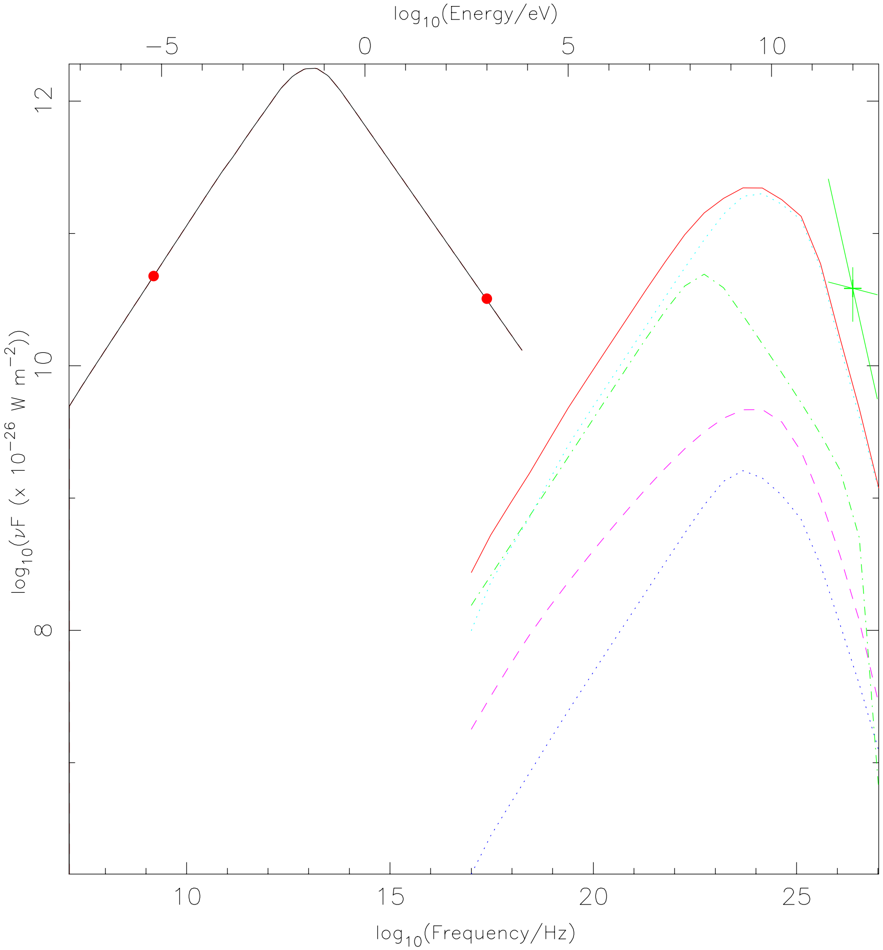


Possibility to probe cutoff region

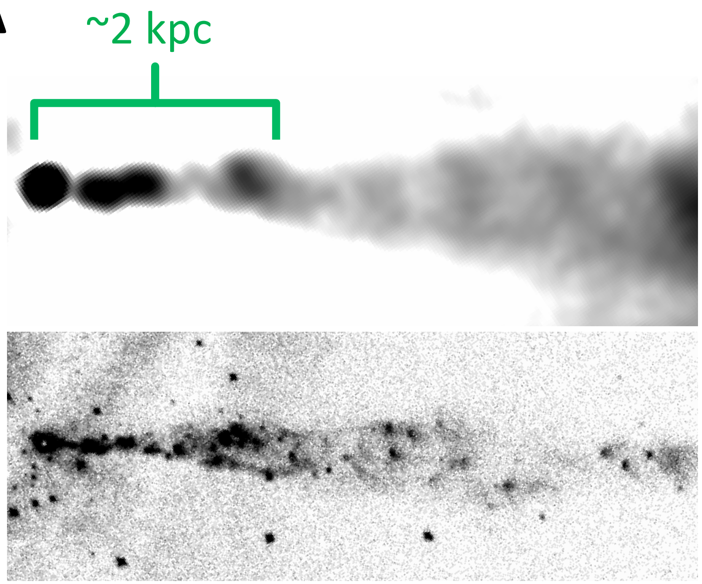
Emission Site?

Where are the misaligned (X)HBLs?

Hardcastle et al. (1103.1744)



Cen A



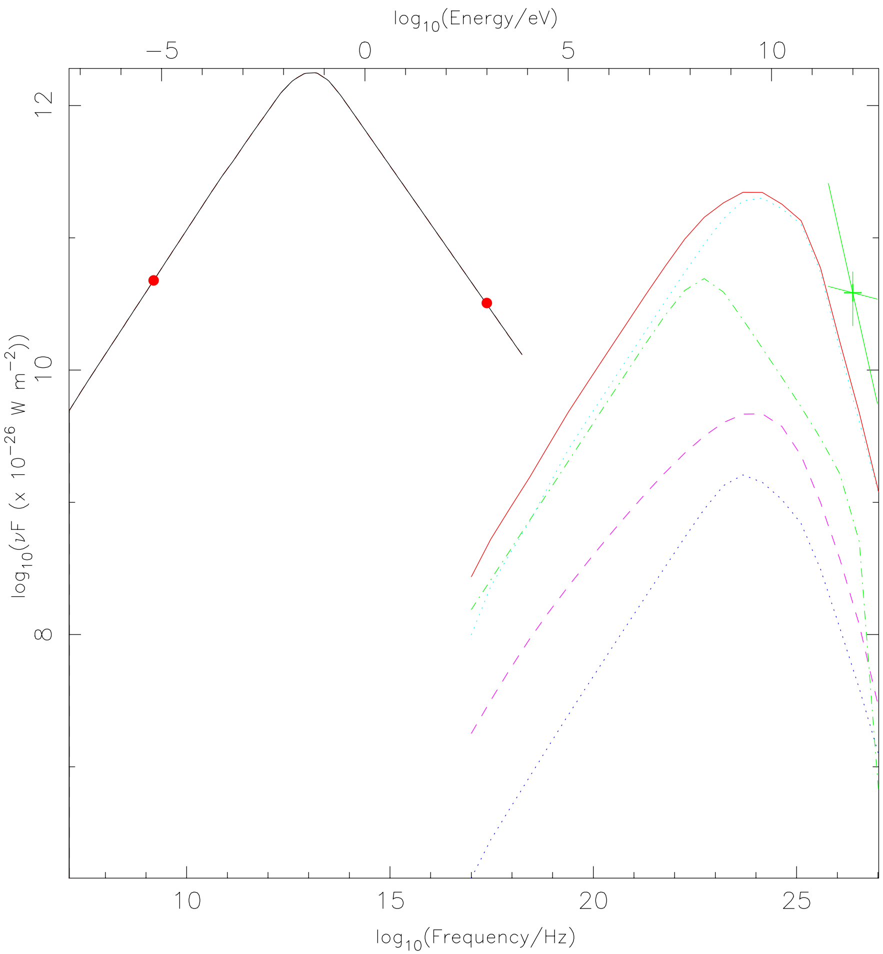
DESY.

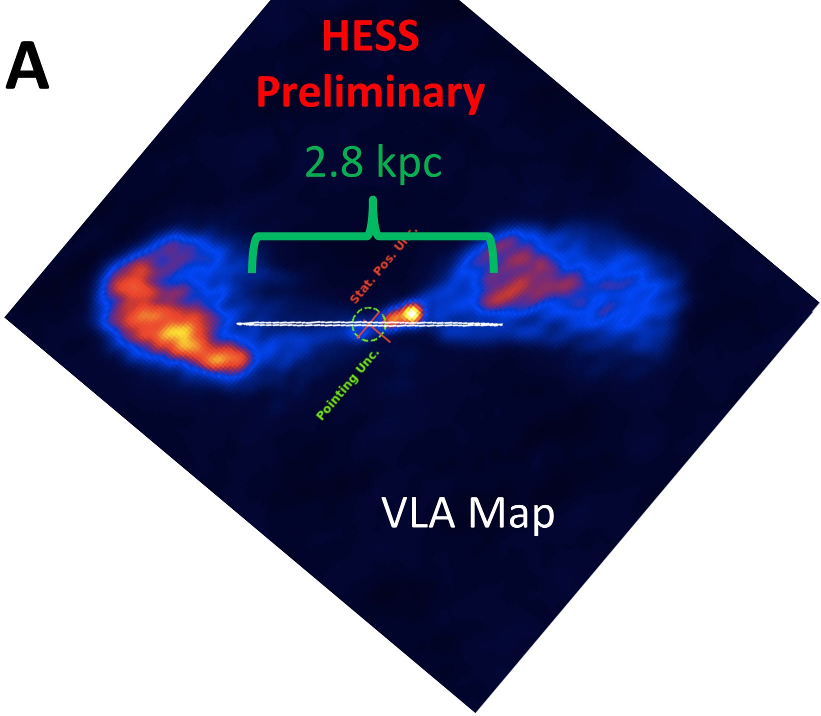
Emission Site?

Cen A

Where are the misaligned (X)HBLs?

Hardcastle et al. (1103.1744)

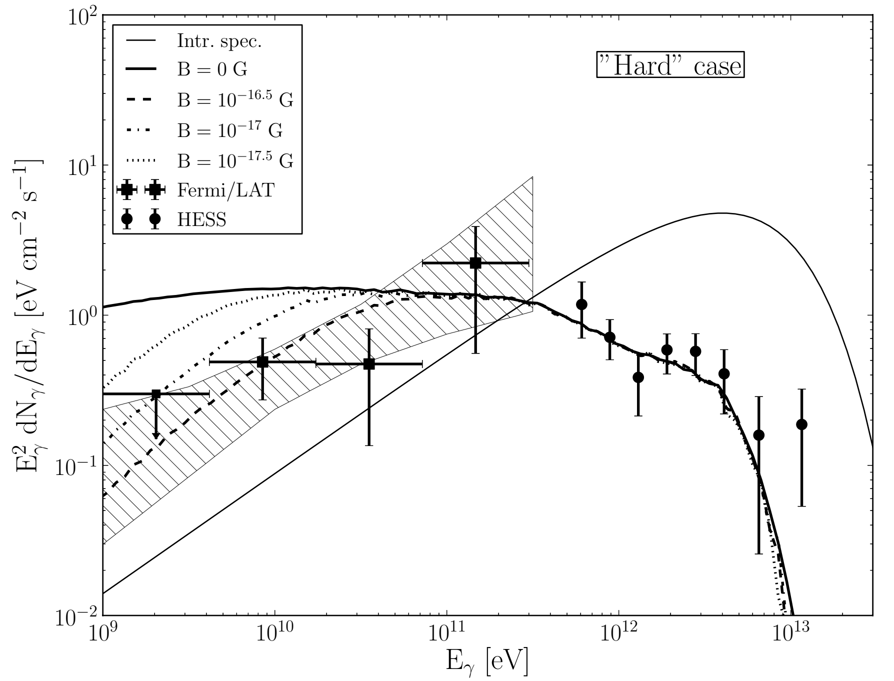




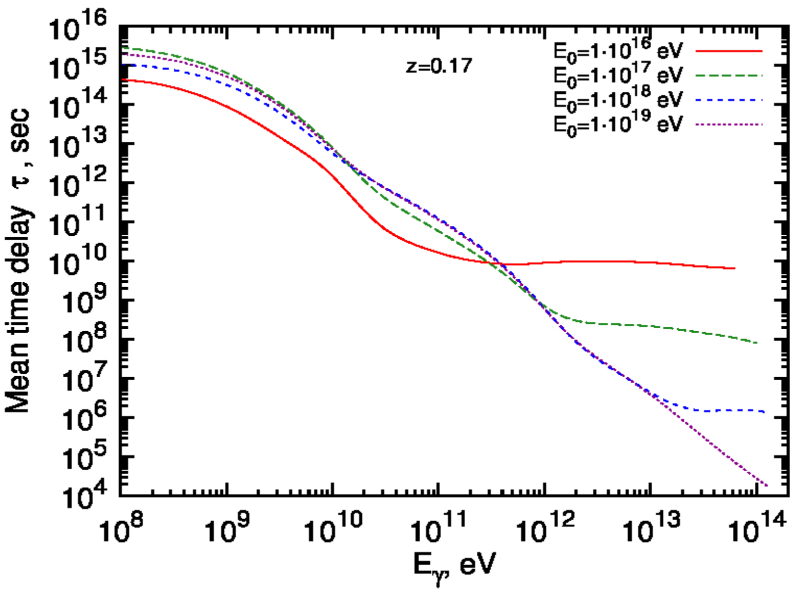
DESY.

Future Probes- Temporal Structure

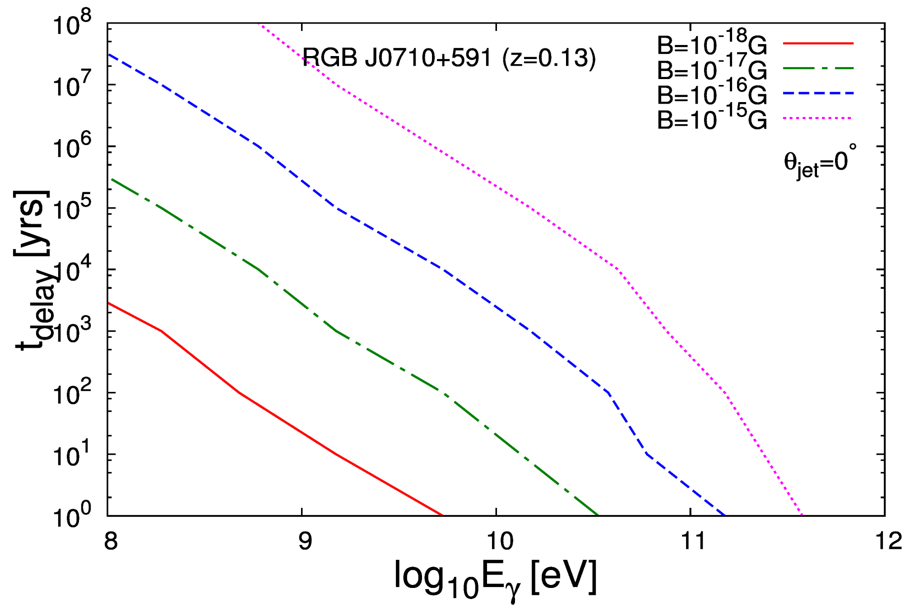
Possibility that emission comes from much higher energy emission (potentially from proton losses……)



Prosekin et al. (1203.3787)



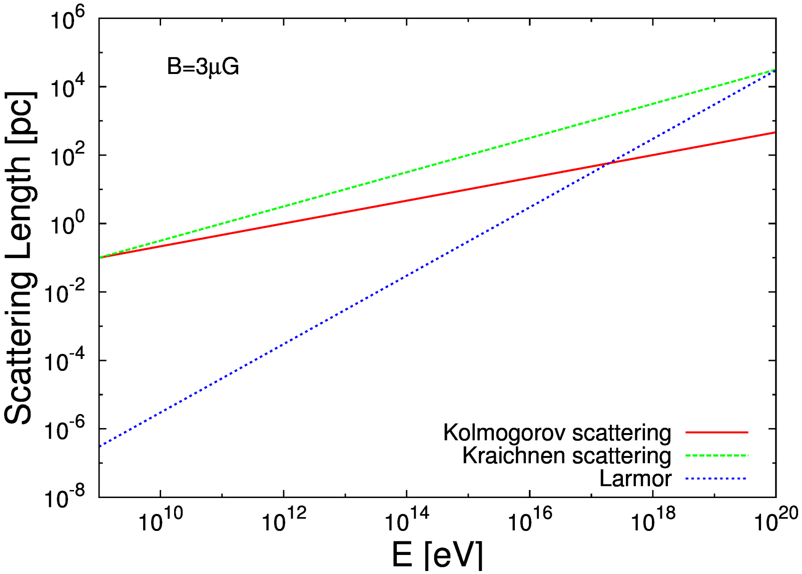
Taylor et al. (1101.0932)

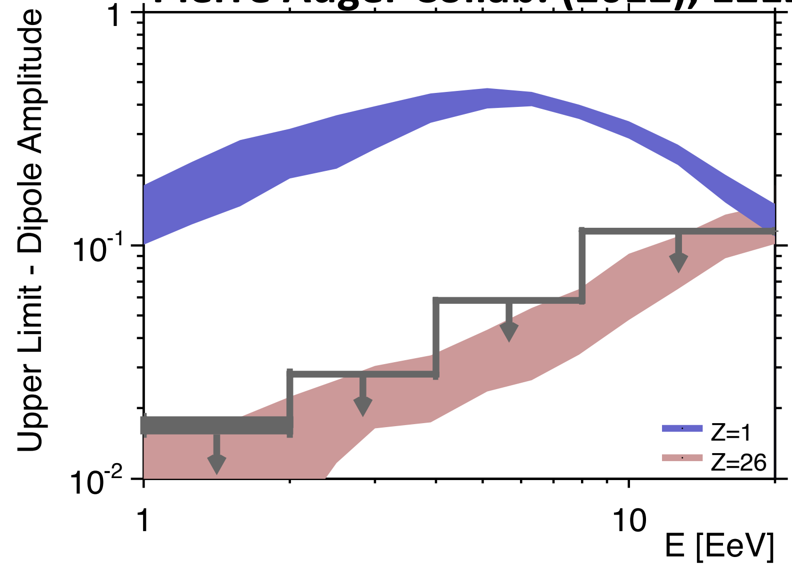


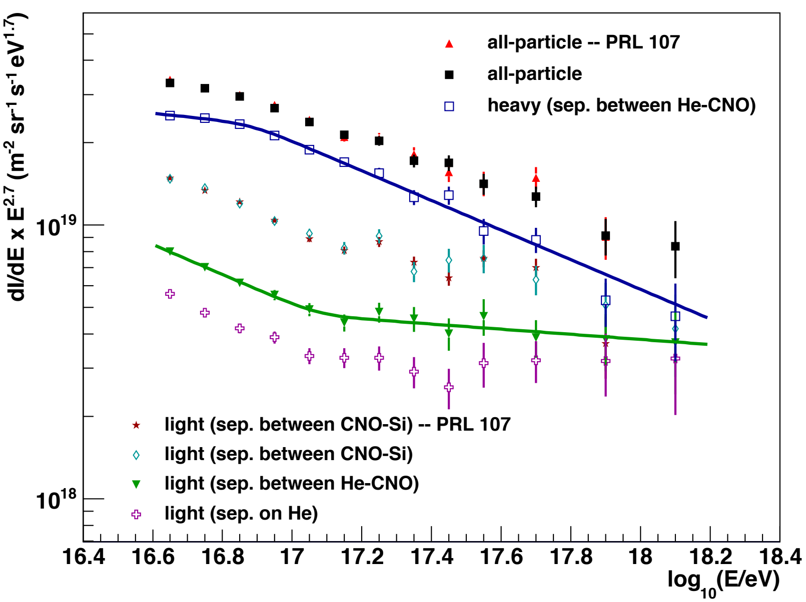
Transition Energy Probes

Anisotropy constraint: **Giacinti et al. (2011), 1112.5599**

Pierre Auger Collab. (2012), 1212.3083



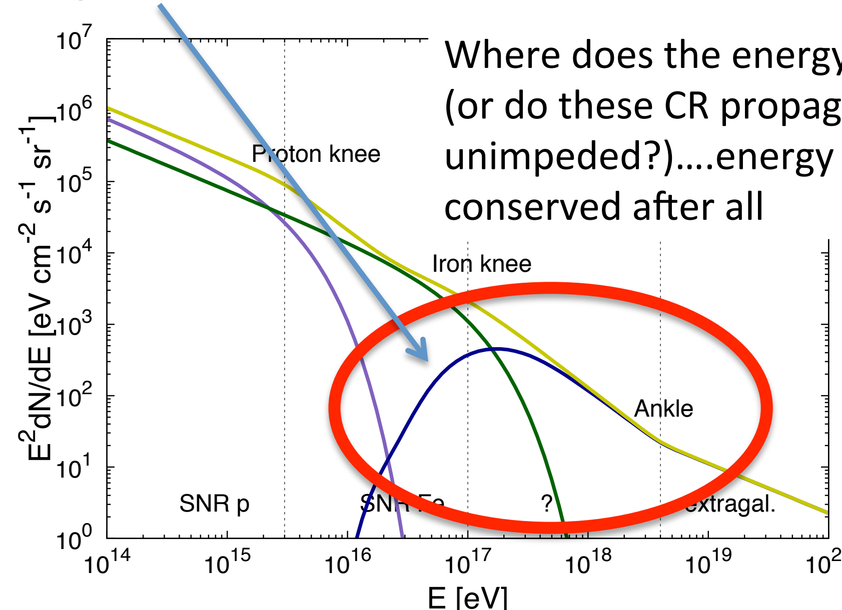




Kascade-Grande Coll. (2013), 1304.7114

Magnetic horizon effect

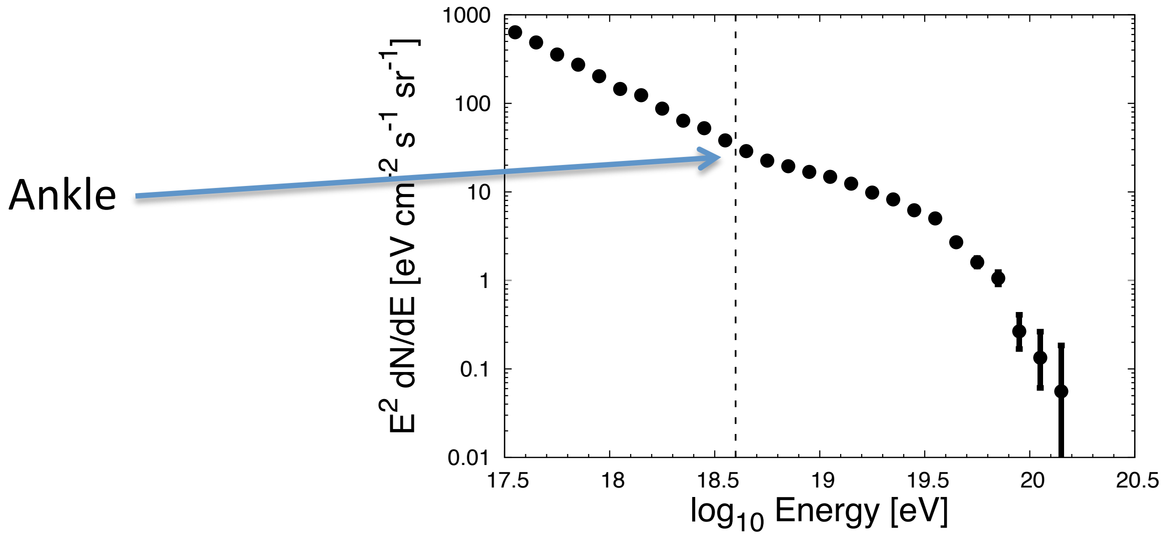
Where does the energy flux go? (or do these CR propagate unimpeded?)....energy is conserved after all



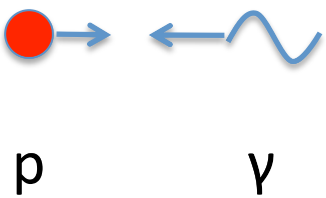
Why Consider UHECR to Understand the Galactic/Extragalactic Transition?

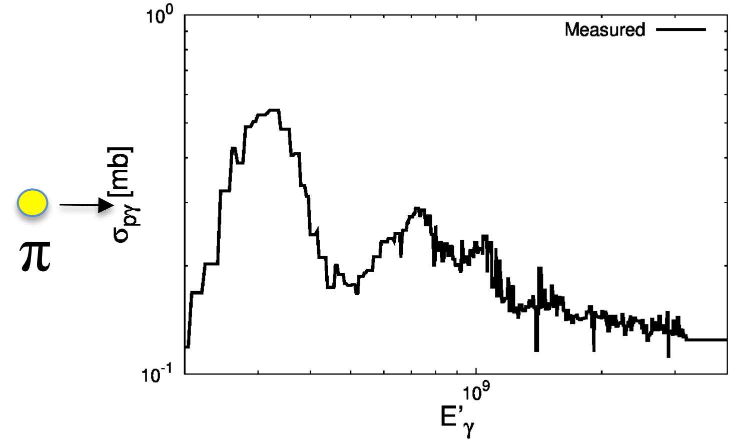
- Since the ankle feature appears at an energy of ~$10^{18.6}$ eV, a new extragalactic source class is presumed to begin to dominate here (in the first instance)

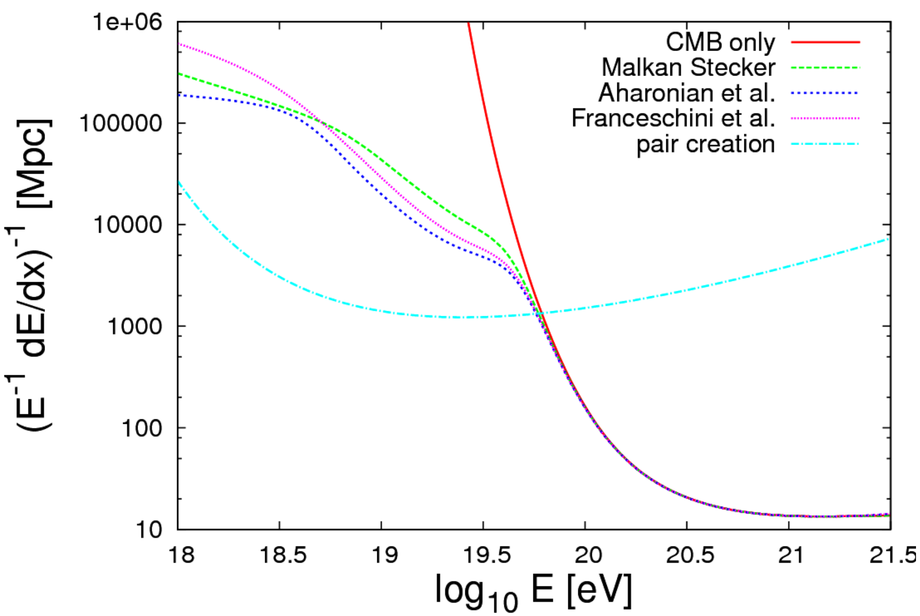
- Information obtained about this source class from investigations into the UHECR sources may provide new insights into Galactic-Extragalactic transition energy

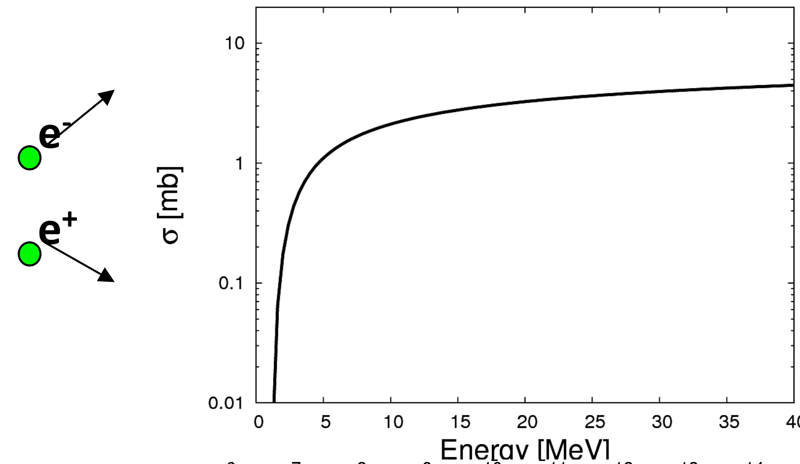


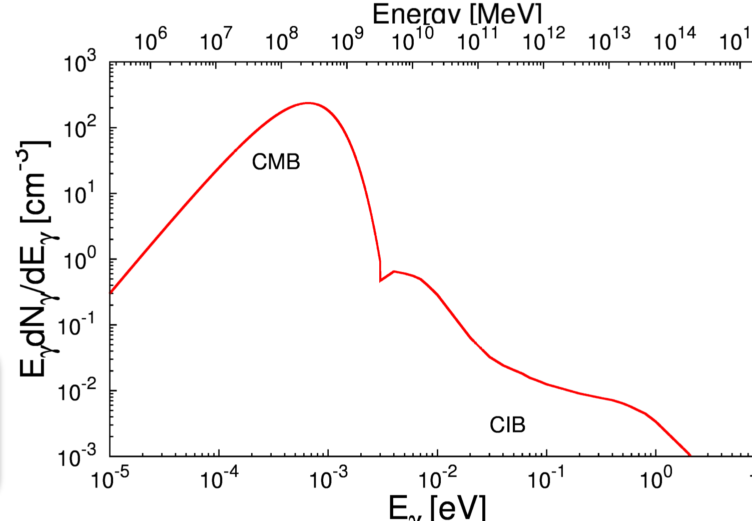
Cosmic Ray Proton Interactions





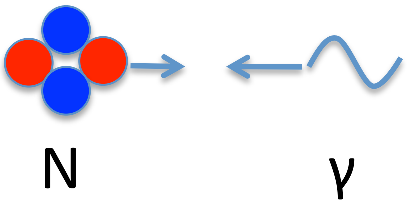


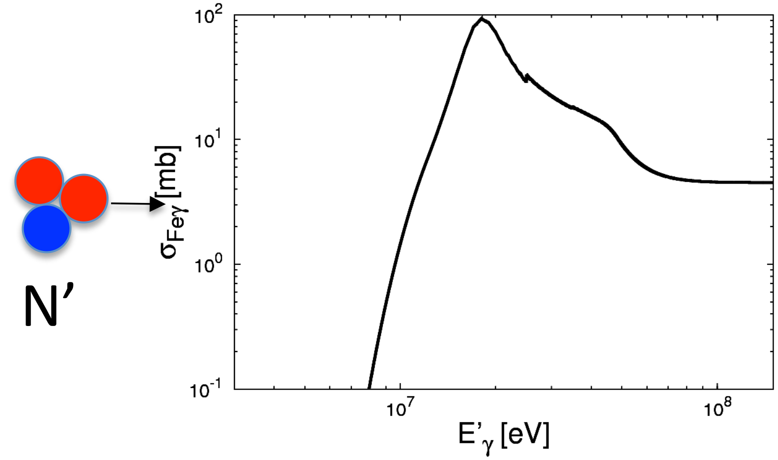


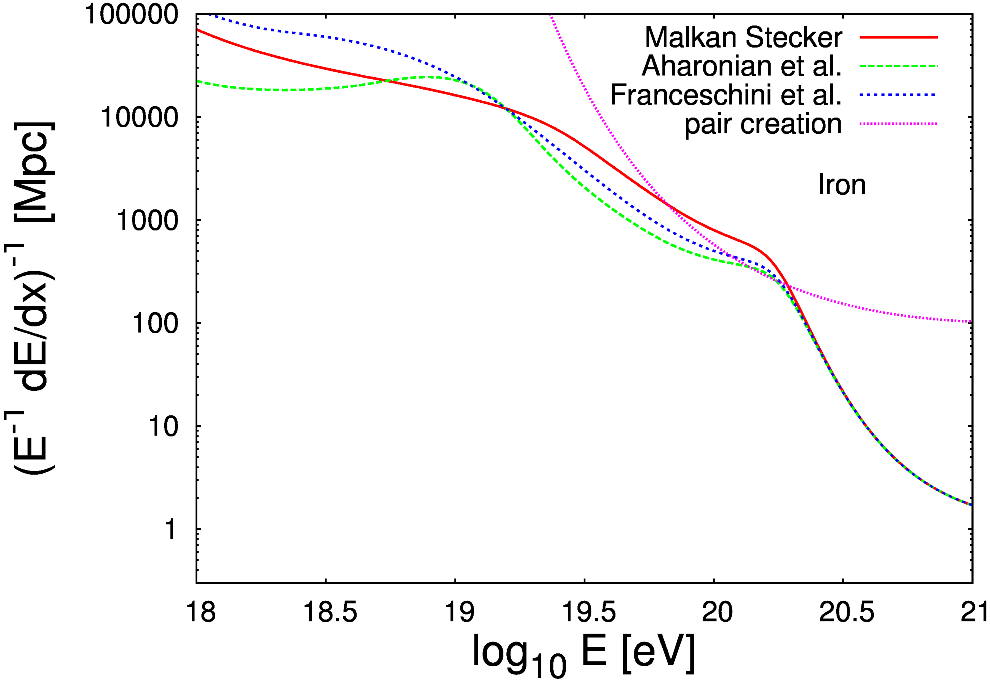


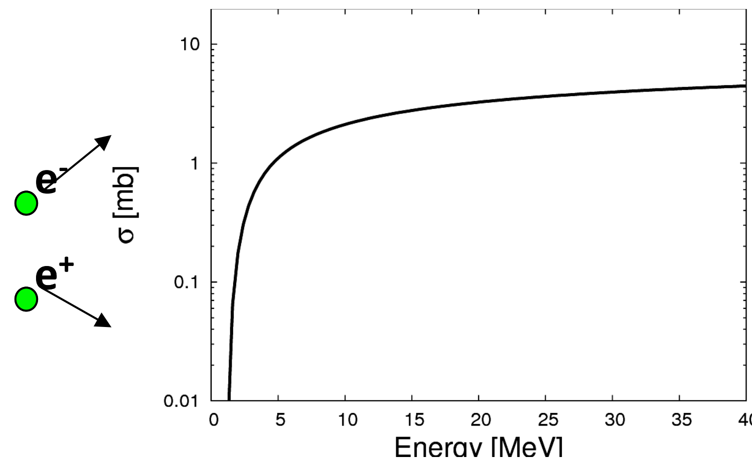
$$\mathbf{R} = \frac{2\mathbf{m_p^2}}{\mathbf{E_p^2}} \int \frac{1}{\epsilon^2} \frac{\mathbf{dN_\gamma}}{\mathbf{d}\epsilon} \int_0^{4\mathbf{E_p}\epsilon/\mathbf{m_p}} \mathbf{k_{p\gamma}}\epsilon' \sigma_{\mathbf{p}\gamma}(\mathbf{E_p}, \epsilon')\mathbf{d}\epsilon'$$

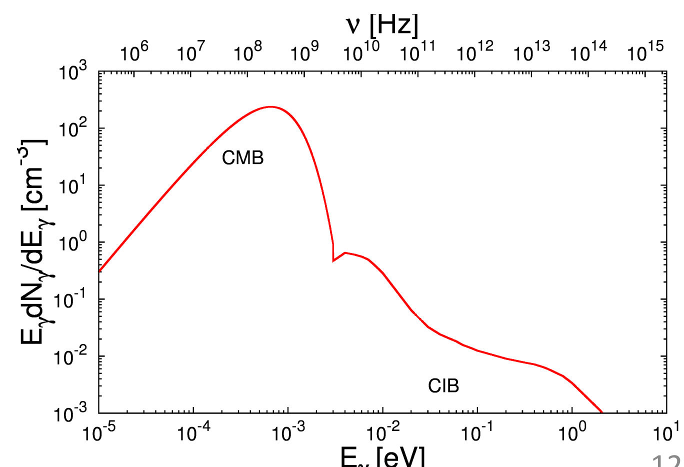
Cosmic Ray Nuclei Interactions











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

Assumptions on Source Population

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

$$z < z_{max}$$

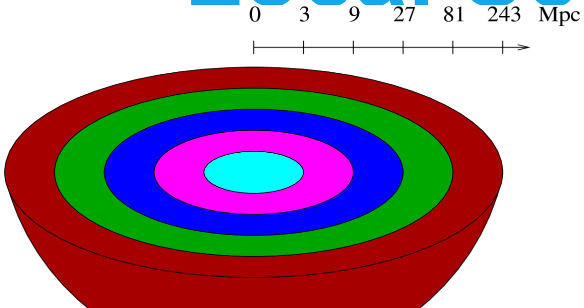
$$n = -6,\ -3,\ 0,\ 3$$

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

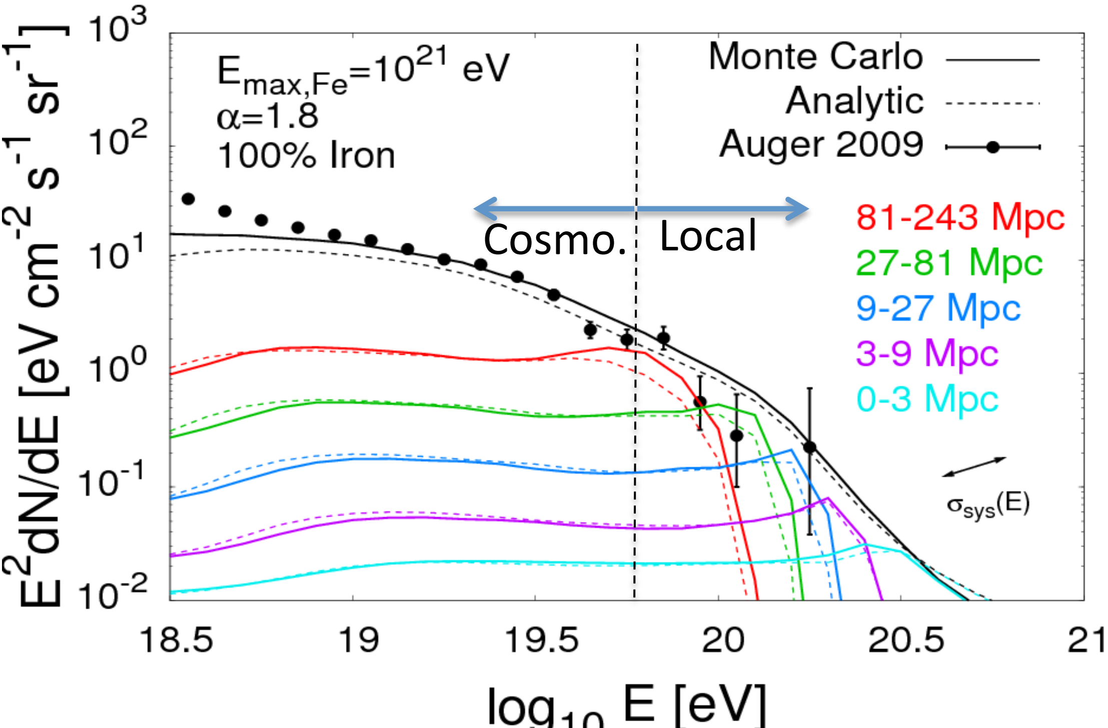
$$E_{Z,max} = (Z/26) \times E_{Fe,max}$$

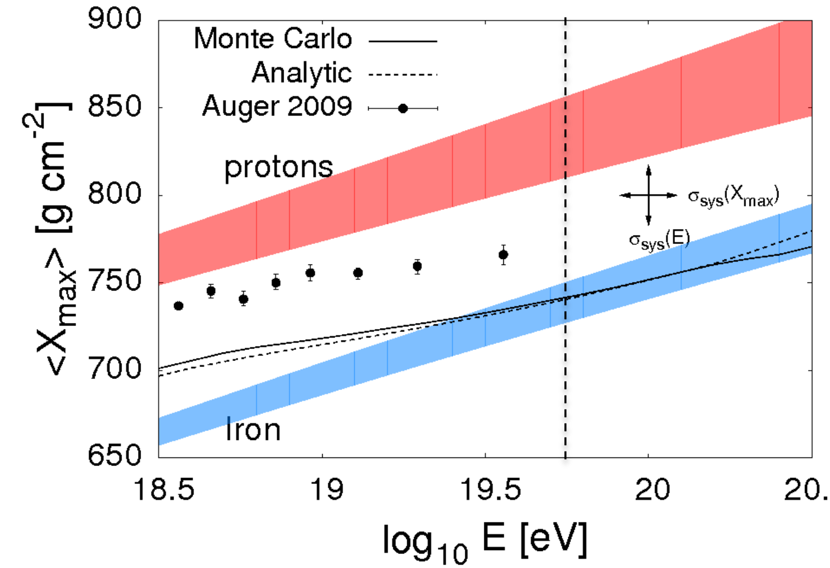
Note- magnetic field horizon effects are neglected in the following. This amounts to assuming: $d_s < (ct_H \lambda_{scat})^{1/2}$
ie. the source distribution may be approximated to be spatially continuous (also note, presence of t_H term comes from temporally continuous assumption)

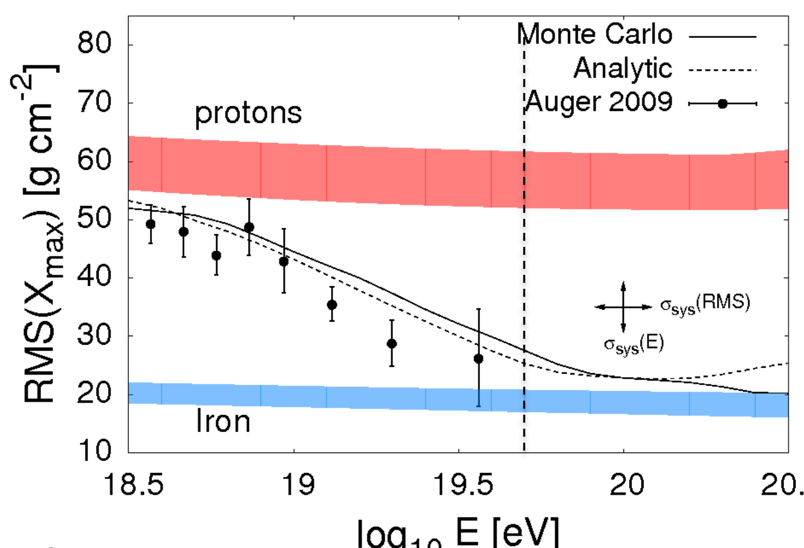
Local Scales Effect Highest Energies: Analytic Treatments



$$f_q(t) = \sum_{n=q}^{m} \frac{\tau_q \tau_n^{m-q-1}}{\prod_{p=q}^{m} (\tau_n - \tau_p)} e^{\frac{-t}{\tau_n}} f_n(0)$$



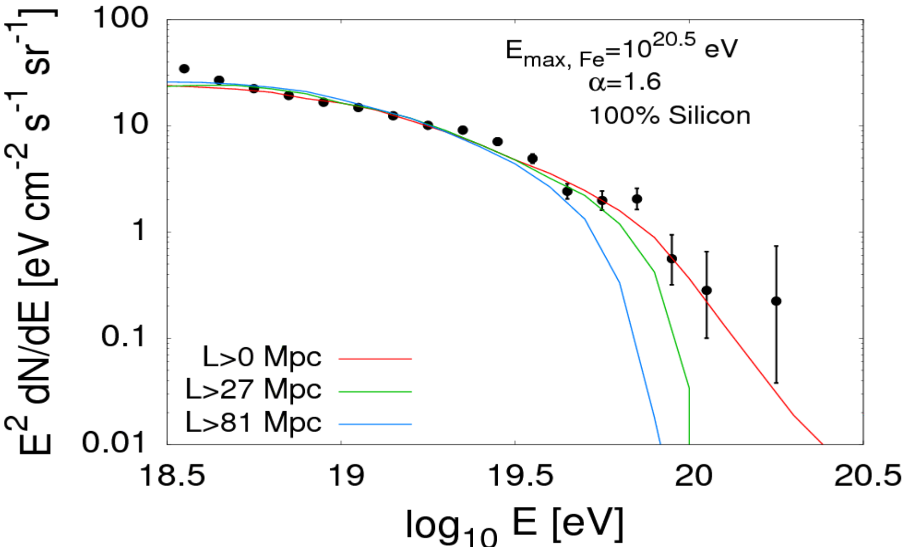




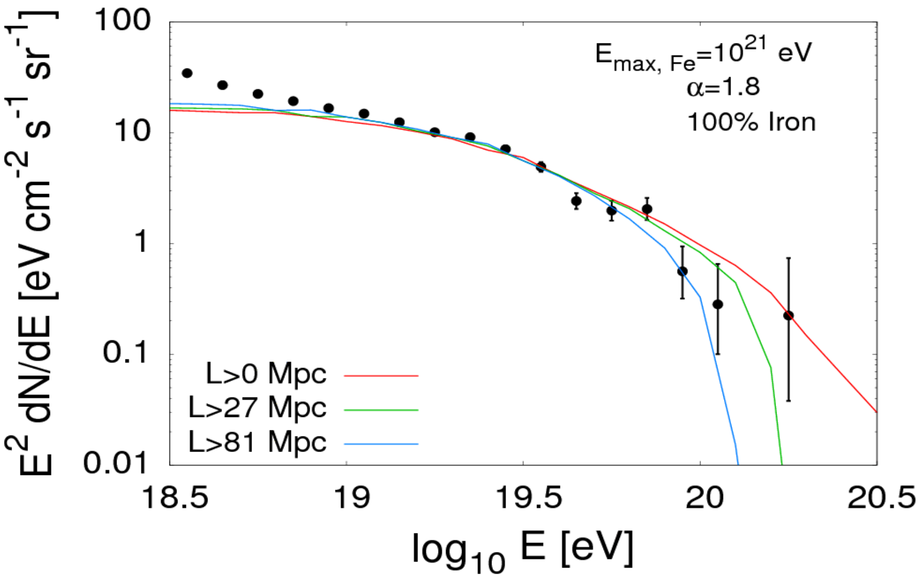
Hooper et al. (2008), 0802.1538 **Aloisio et al. (2013) 1006.2484**

How Far is the Nearest Source?

Silicon- L<60 Mpc



Iron- L<80 Mpc



De Marco et al. (2006), 0603615

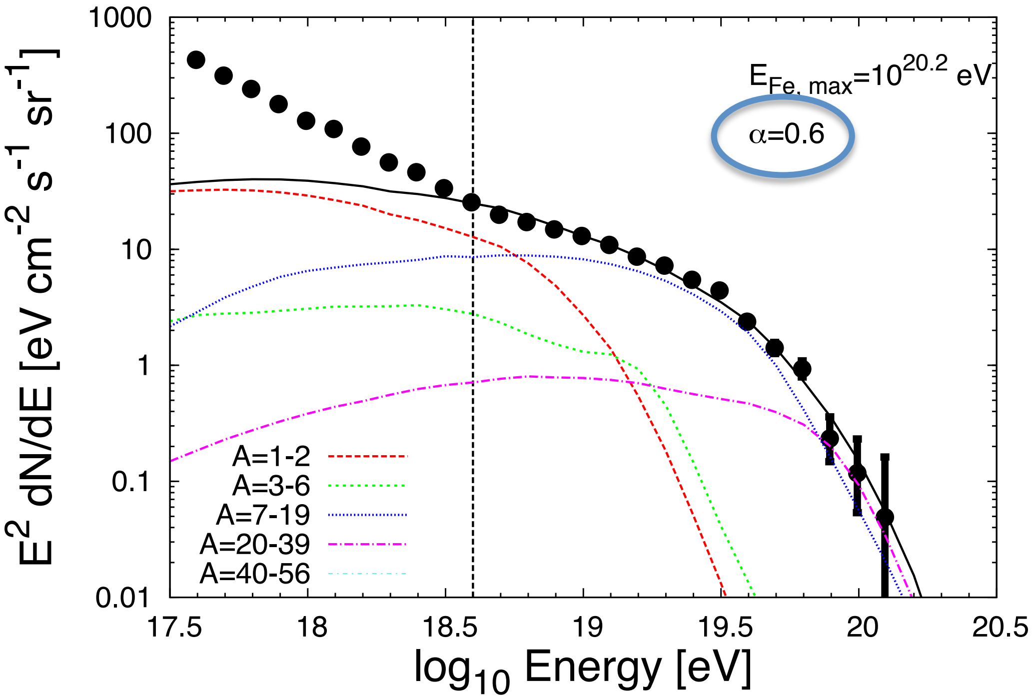
Taylor et al. (2011), 1107.2055

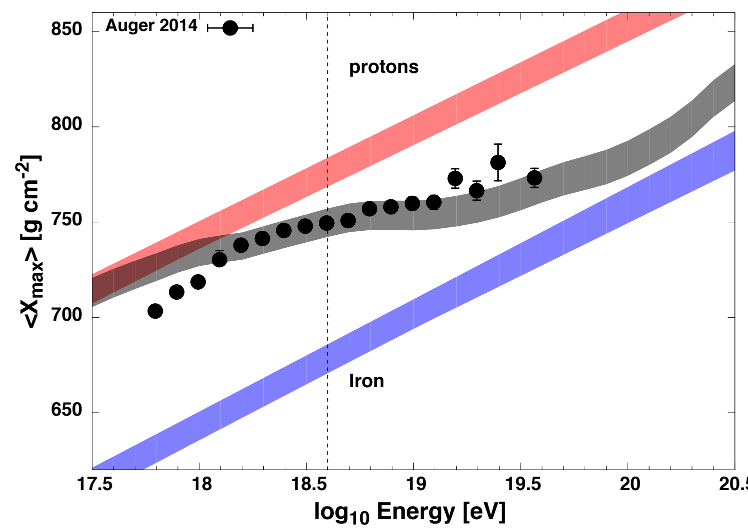
Fargion et al. (2015), 1412.1573

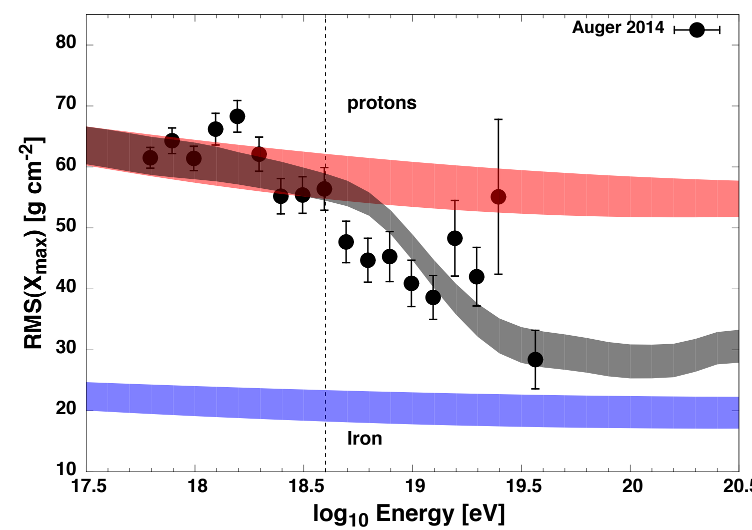
MCMC Likelihood Scan: Spectral + Composition Fits

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

n=3 evolution result





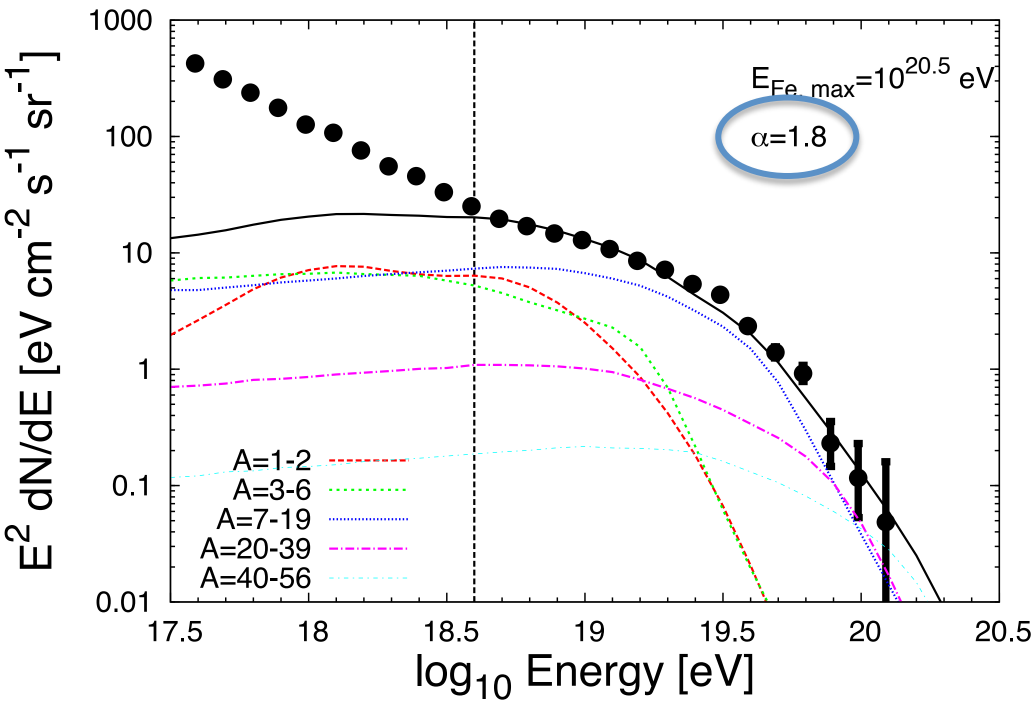


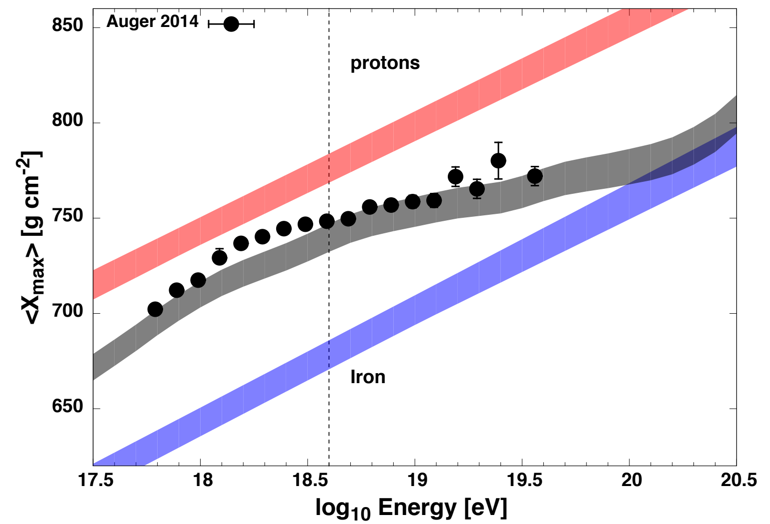
Taylor et al. (2015), 1505.06090
Aloisio et al. (2014), 1312.7459
Di Matteo et al. (2015), ICRC 2015
Zirakashvili et al. (2017), 1701.00820

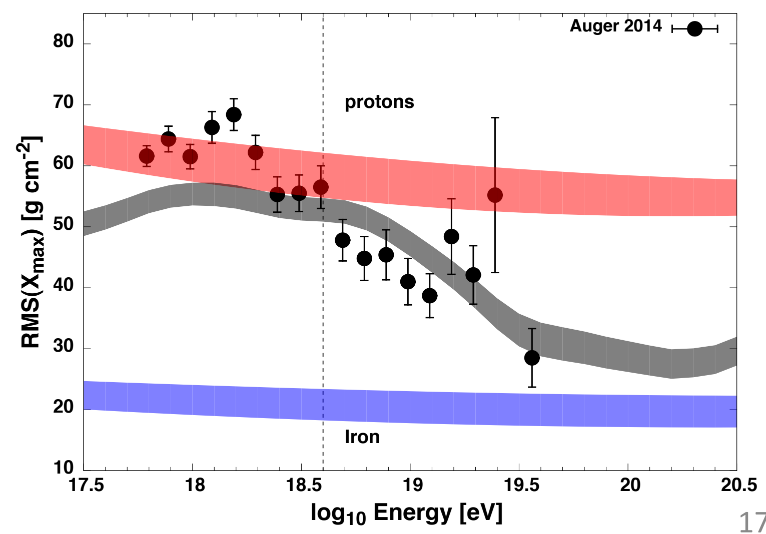
MCMC Likelihood Scan: Soft Spectra Solutions

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

n=-6 evolution result







Taylor et al. (2015), 1505.06090

MCMC Results Table

Taylor et al. (2015), 1505.06090

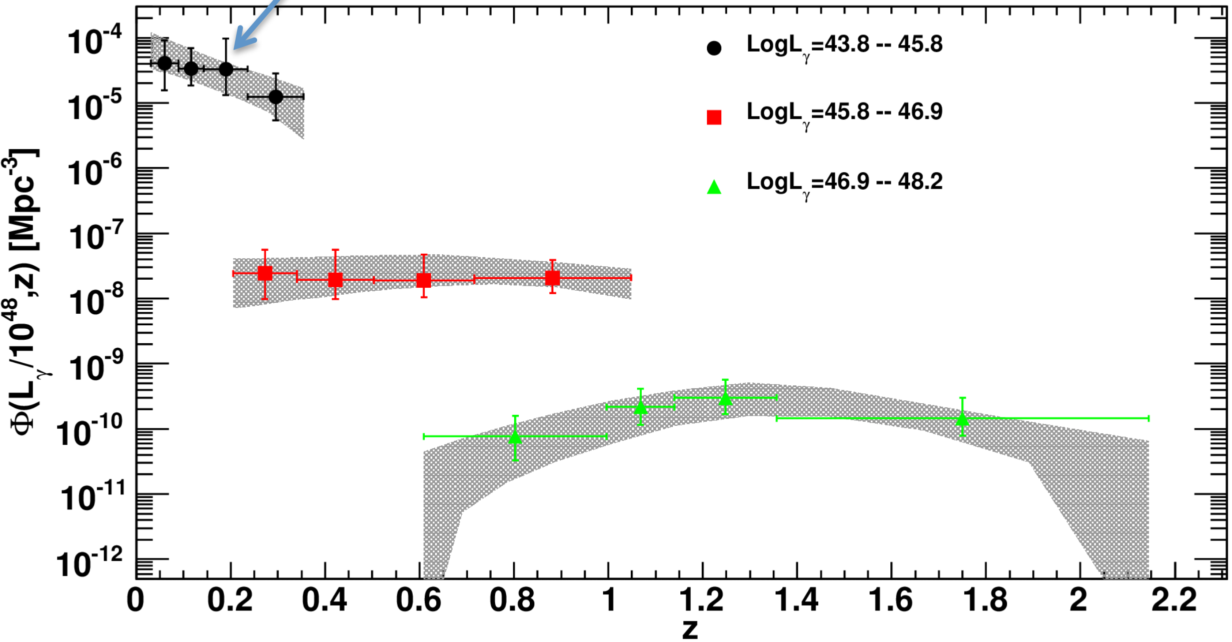
Parameter	$n=-6$		$n=-3$		$n=0$		$n=3$	
	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation
f_p	0.03	0.14 ± 0.12	0.08	0.15 ± 0.13	0.17	0.17 ± 0.16	0.19	0.20 ± 0.16
f_{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



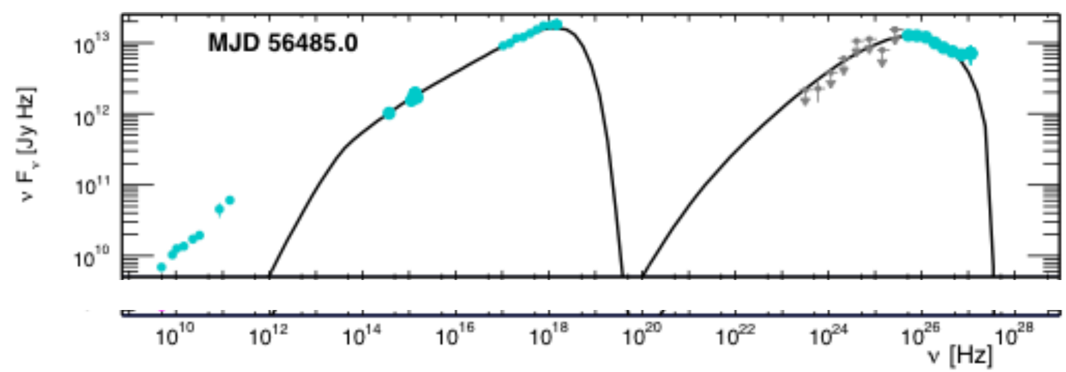
- Reminder:
Blazar -> BL Lac (FR1) -> HSP

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

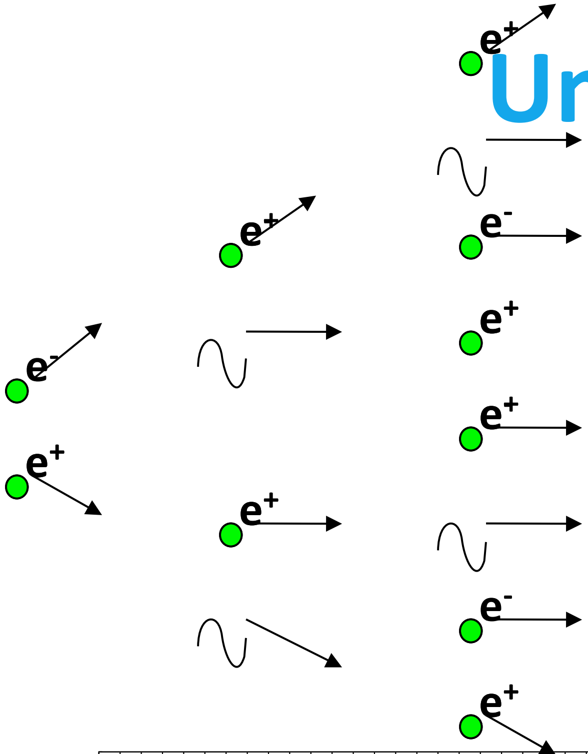
Ajello et al. (2014), 1310.0006

Ueda et al. (2003), 0308140

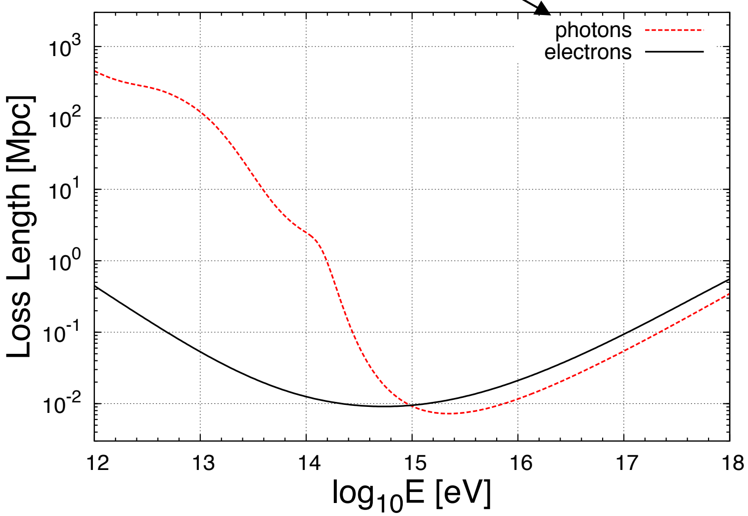
Archetypal HSP example Mrk 501

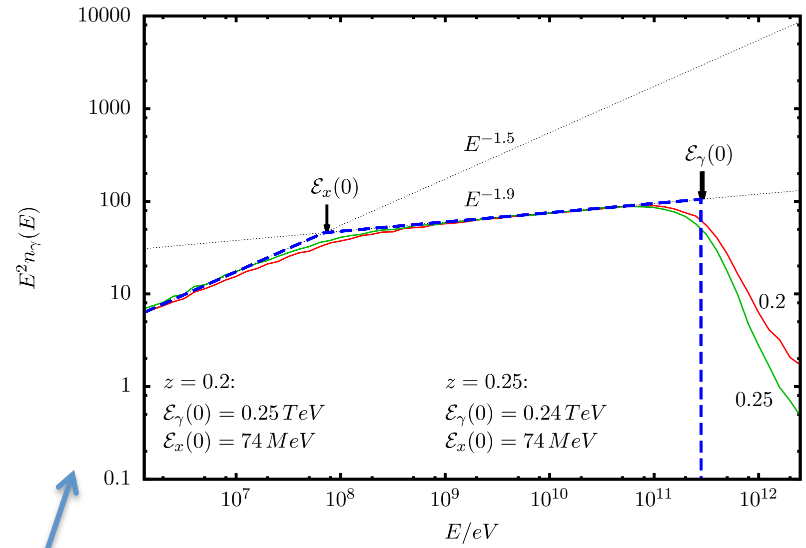


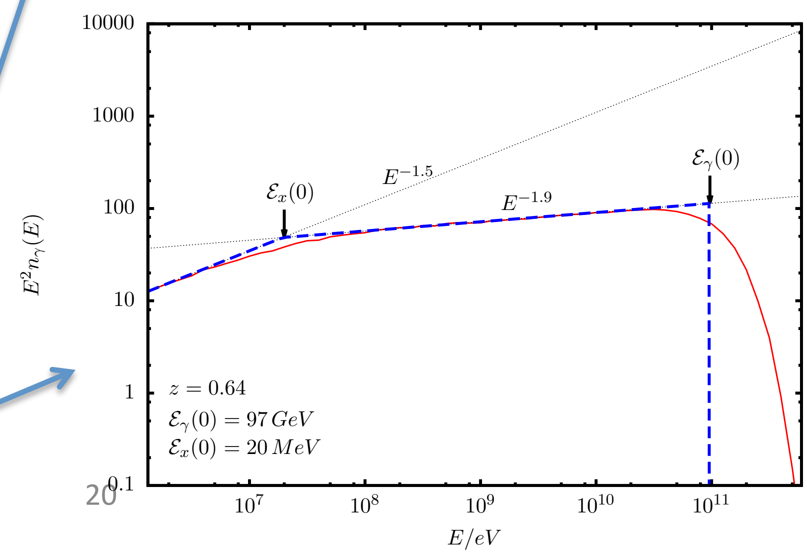
Universality of Cascade Spectra



Wolfendale et al. (1976) Coppi et al. (1997), 9610176
Berezinsky et al. (2016), 1603.03989



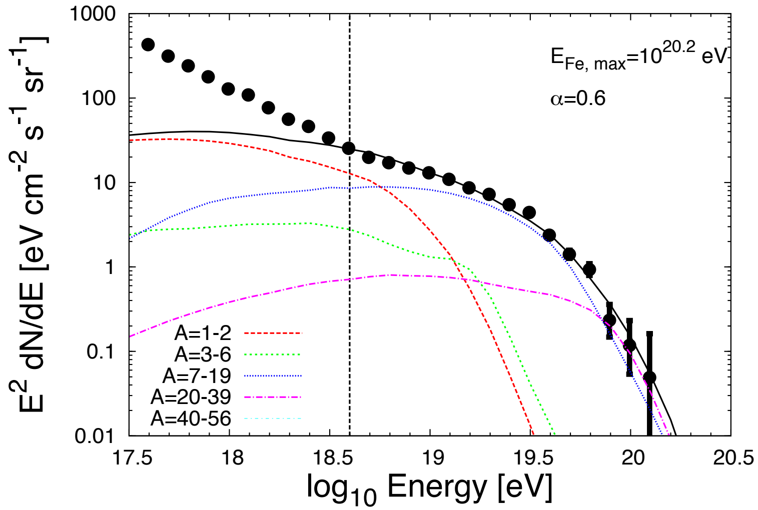




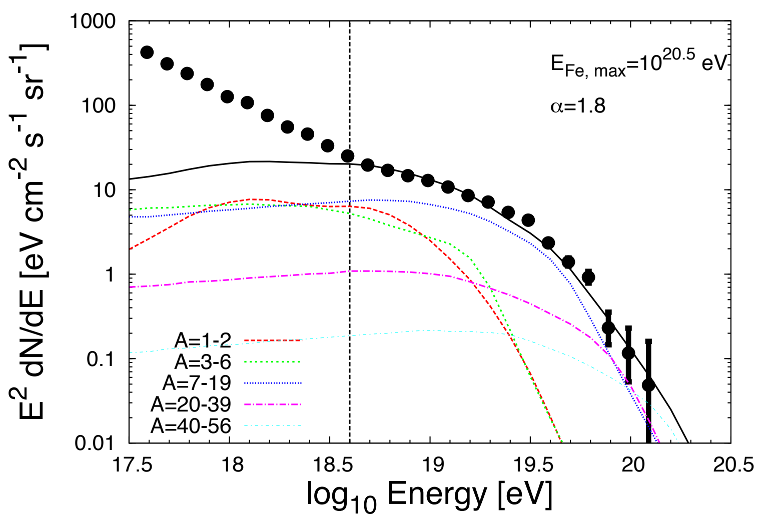
Regardless of where the energy is injected (ie independent of source z), the arriving flux possesses a universal shape

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

n=3 evolution result

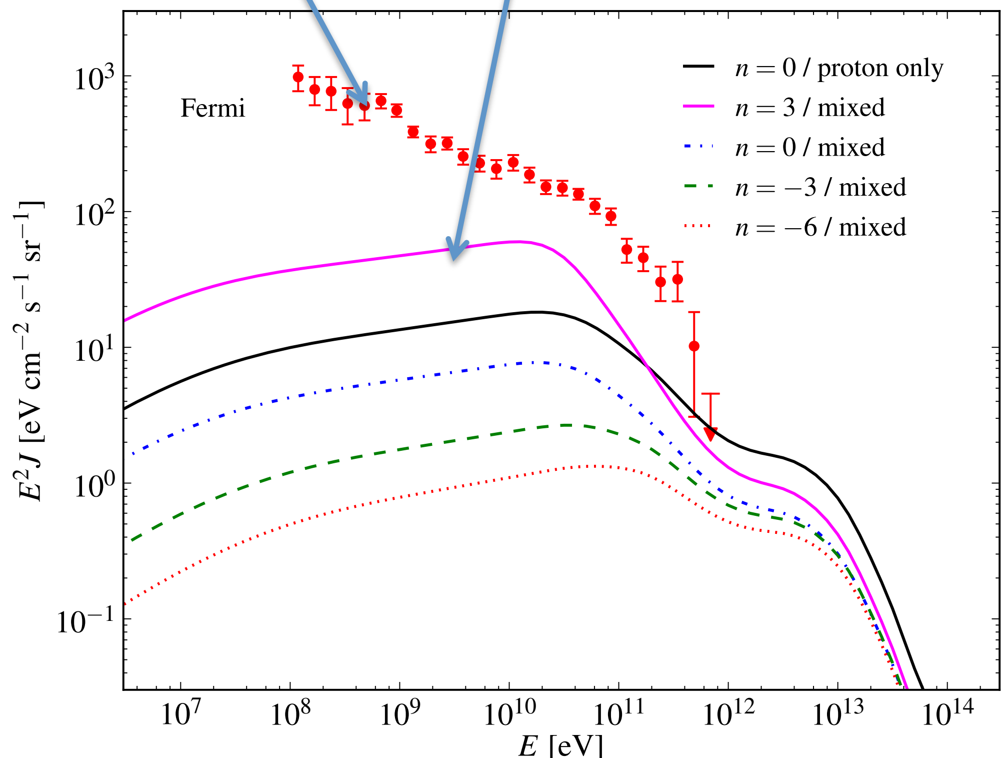


n=-6 evolution result



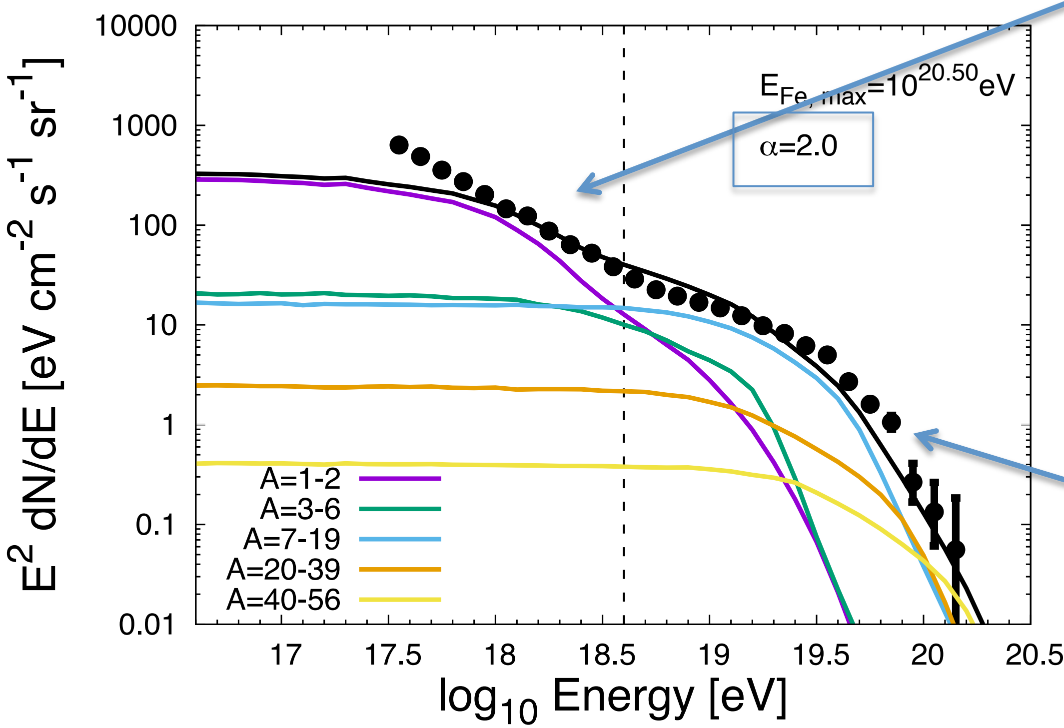
IGRB (EGB with resolved points sources removed)

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

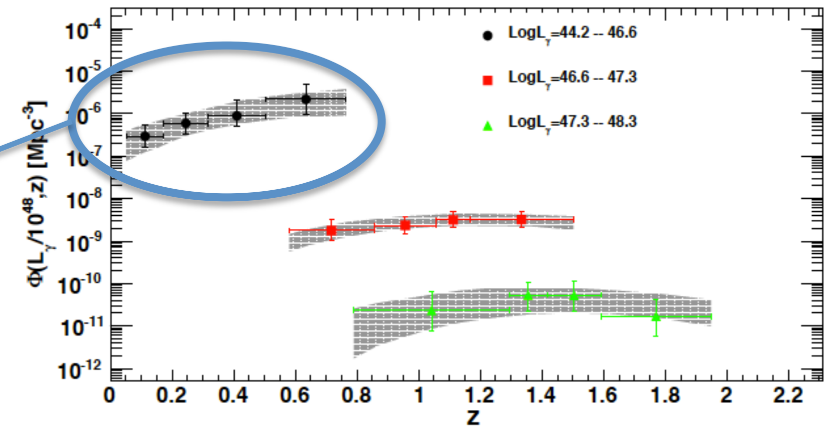


A similar conclusion is reached by **Gavish et al. (2016), 1603.04074**

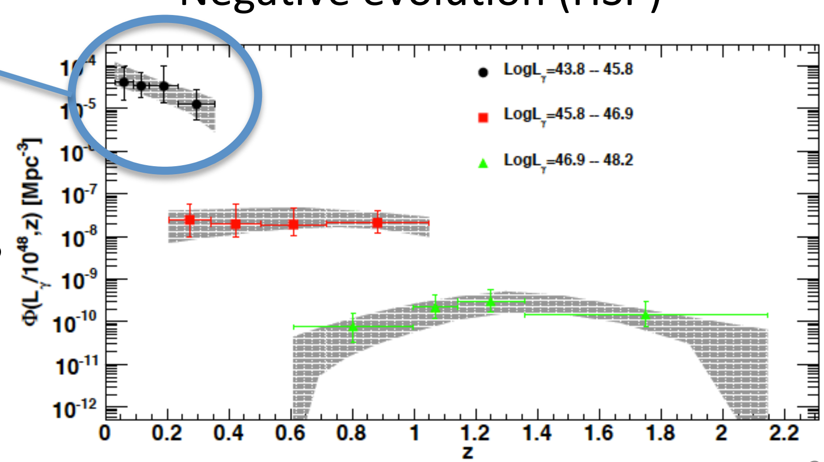
Does a Separate Class of Extragalactic Source Dominate Below the Ankle?



Positive evolution (ISP + LSP)

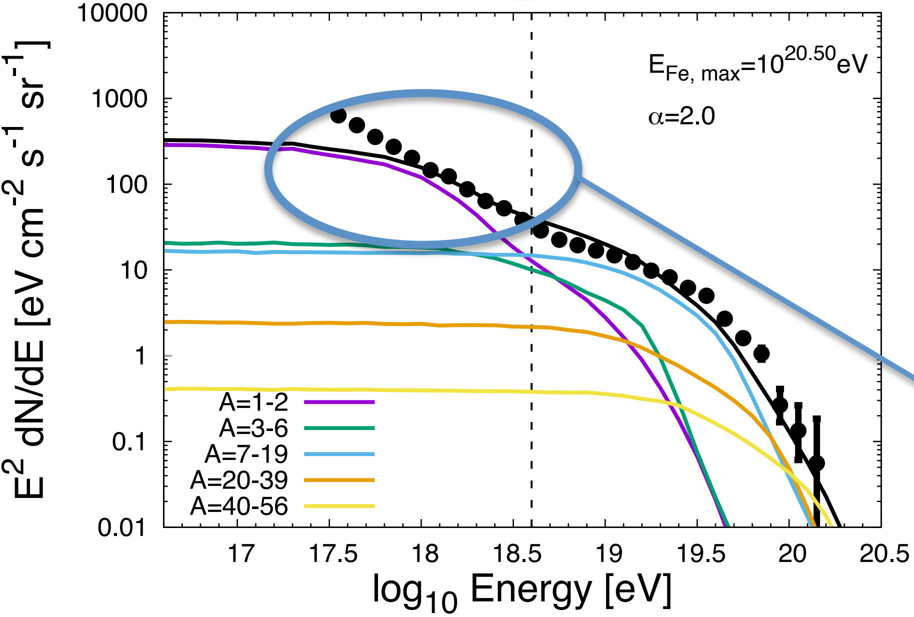


Negative evolution (HSP)

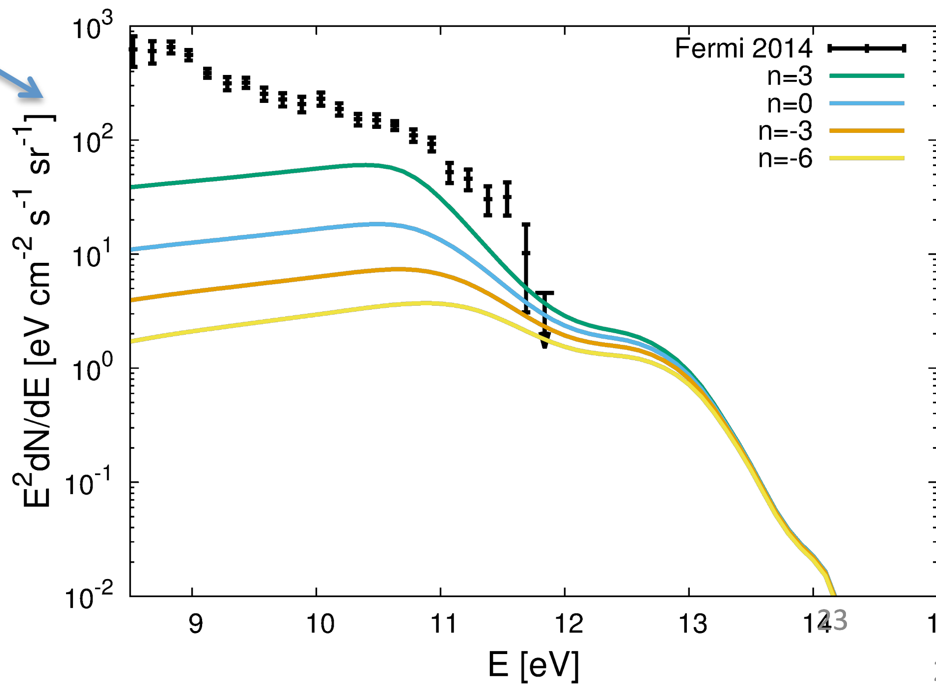


Cascade Contribution from the Postulated Sub-Ankle Populated

Ankle Energy

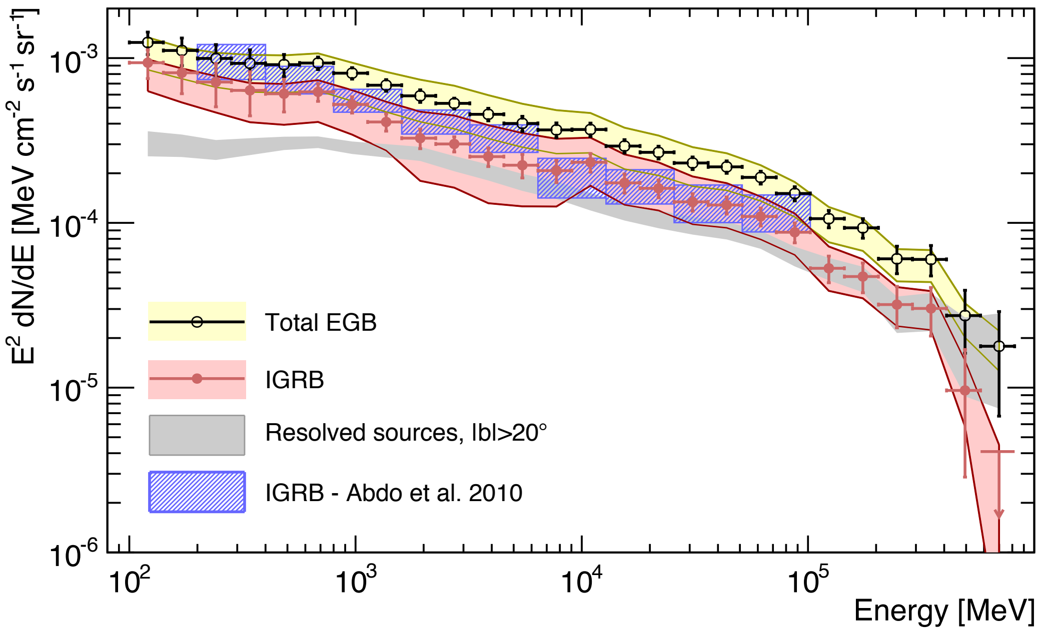


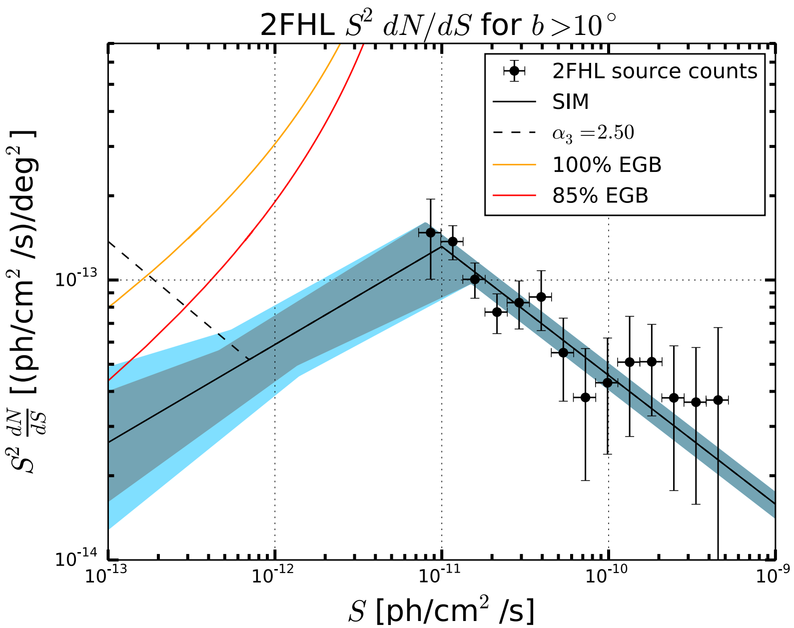
n=3 to -6 evolution scenarios give rise to between **100%** and **40%** of Fermi limit



Giacinti et al. (2015), 1502.01608
Taylor et al. (2015), 1505.06090

General Problem for Cascade Contribution?





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

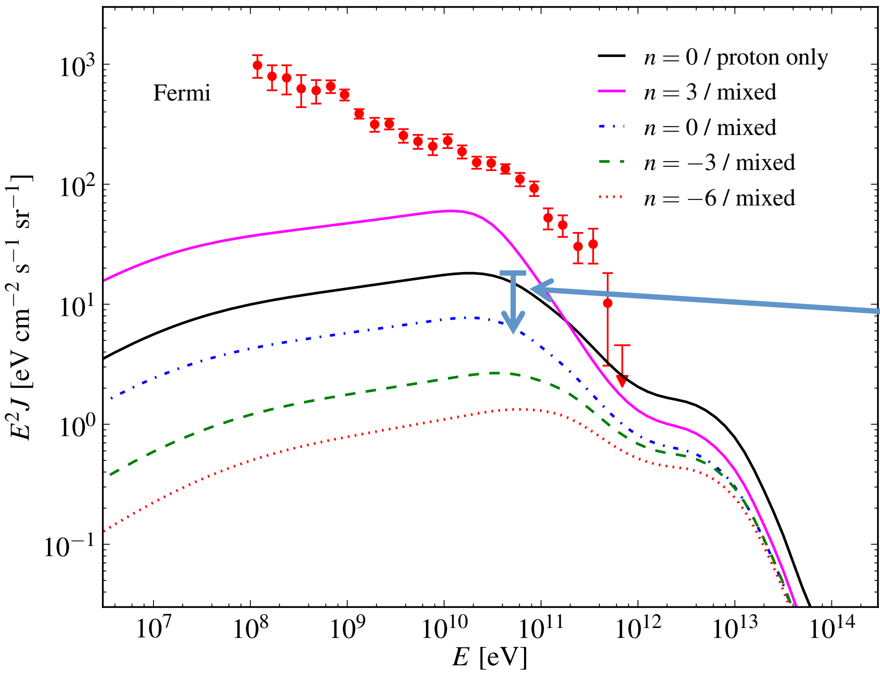
$$\frac{\mathbf{dN}}{\mathbf{dS}} \propto \mathbf{S}^{-\alpha}$$

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

"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 Coll. (2015), 1511.00693

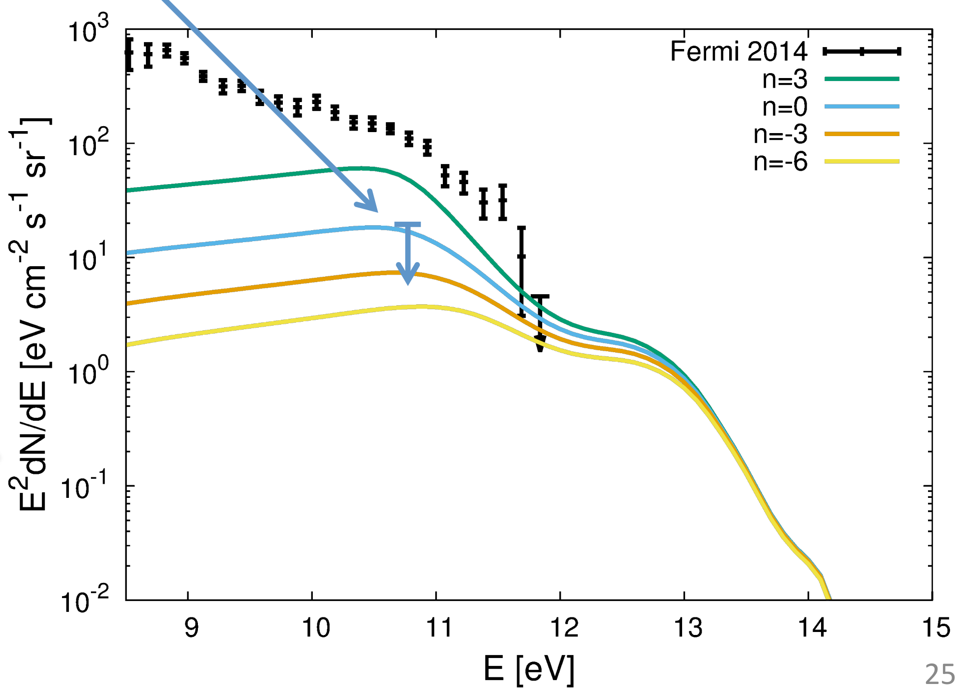
Cascade Contributions from Sources Above + Below the Ankle



nuclei above $10^{18.6}$ eV

conservative flux upper limit at 50 GeV

Liu et al. (2016), 1603.0322)

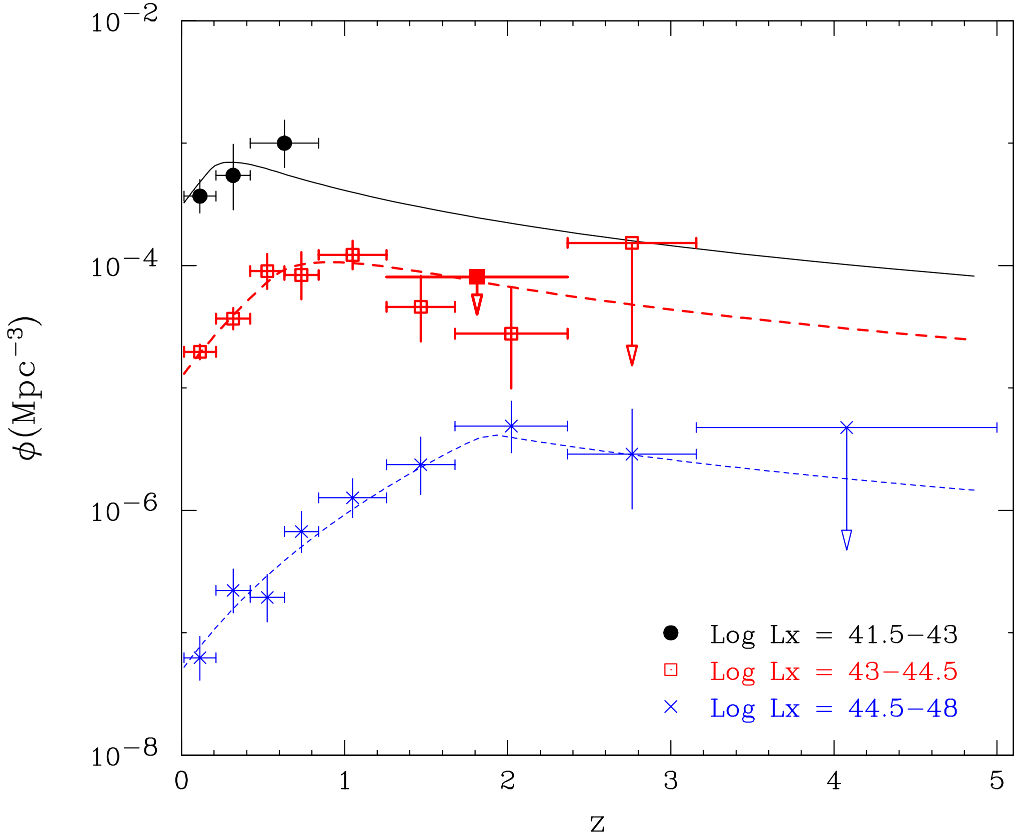


protons and nuclei below $10^{18.6}$ eV

Conclusions

- **(Extreme) HBL blazars** promote themselves as efficient particle accelerators via their high energy synchrotron emission
- **Local sources**, < 80 Mpc, must exist! Where are the misaligned (extreme) HBL counterparts?
- Lower energy UHECR and GeV gamma-rays provide a complimentary probe of the **cosmological source distribution**
- 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)
- New diffuse gamma-ray background limits are **challenging for both positive and no-evolution scenarios** which account for sub Ankle extragalactic protons
- An "understanding" of UHECR sources is possible through an understanding of AGN gamma-ray emission at very high energies!

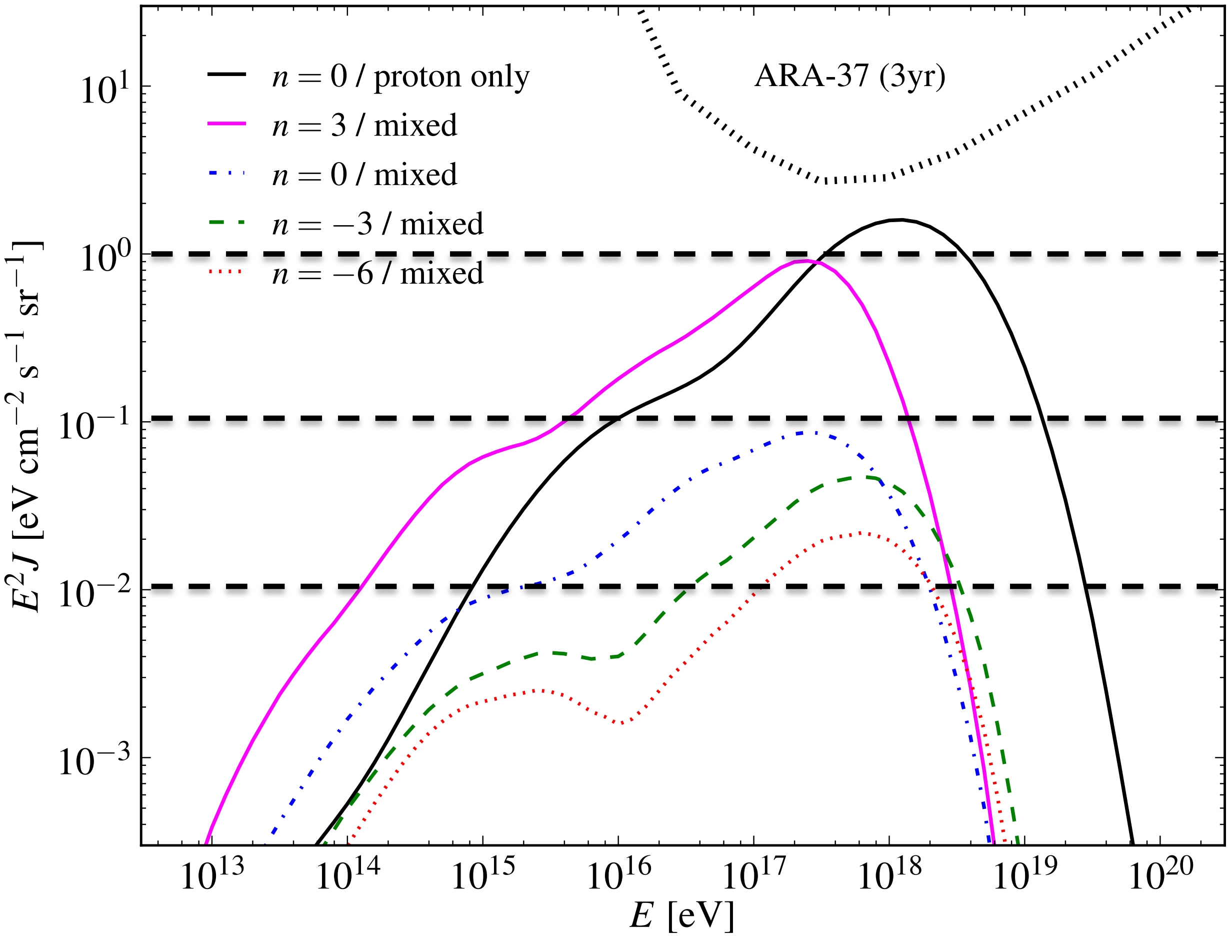
Hard X-Ray Source Evolution



In a similar manner to BL Lac blazars, the low luminosity hard X-ray sources (Seyferts) have also been suggested to indicate a negative evolution with redshift

Ueda et al. (2003), 0308140

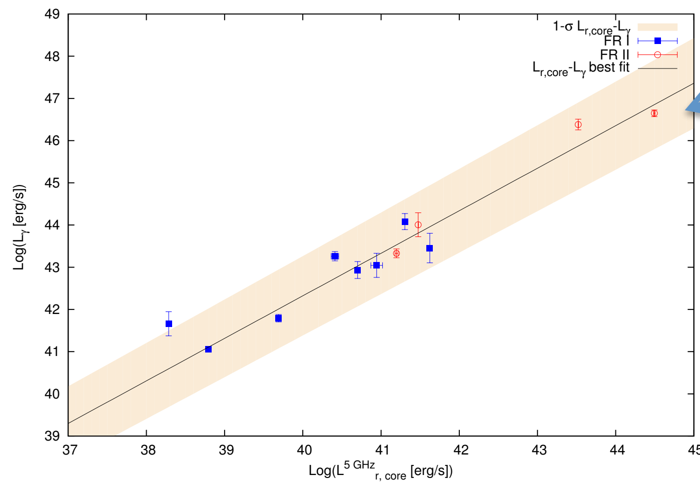
Secondary Neutrino Fluxes



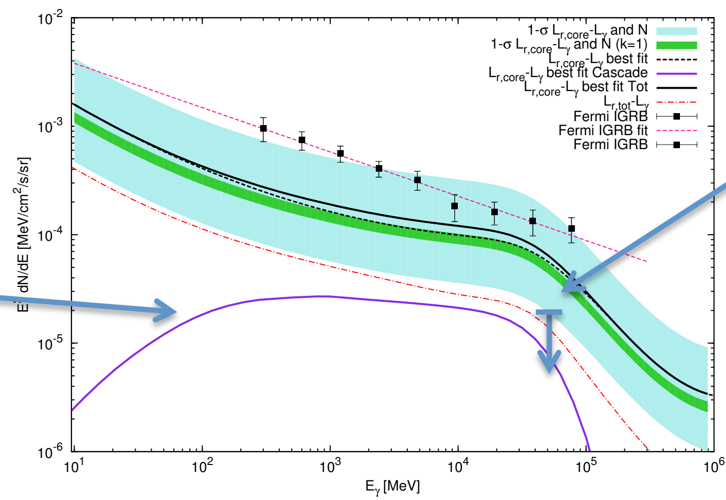
Taylor et al. (2015), 1505.06090

Globus et al. (2017), 1703.04158

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



Radio vs Gamma-Ray correlation



Note level of AGN gamma-ray generated cascades

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

Di Mauro et al. (2013), 1304.0908
Inoue et al. (2011), 1103.3946

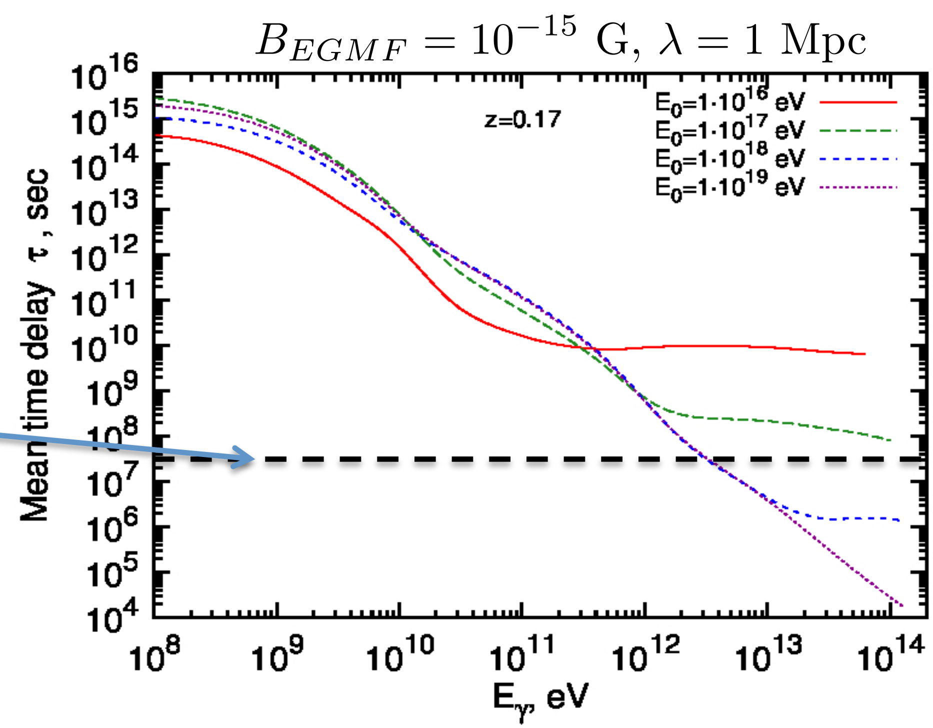
DESY.

Proton Fed Blazar Emission Model

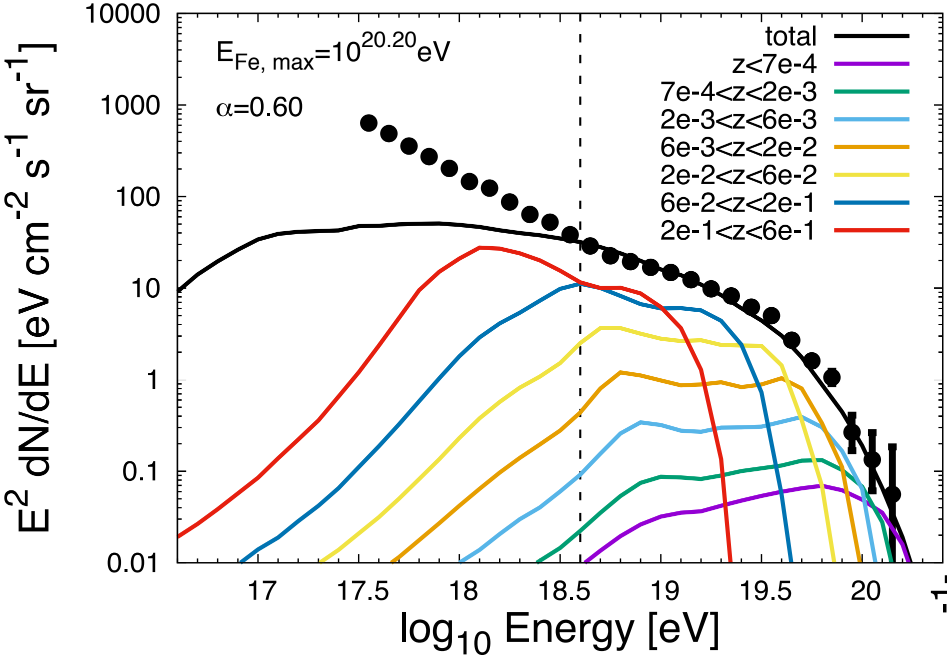
- Kusenko & Essey have spearheaded the suggestion that some TeV blazars are powered through proton losses in the presence of weak (10^{-15} G) extragalactic magnetic fields
- If this is the case, some subset of the component of resolved/unresolved blazars should not be removed from the EGB
- However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

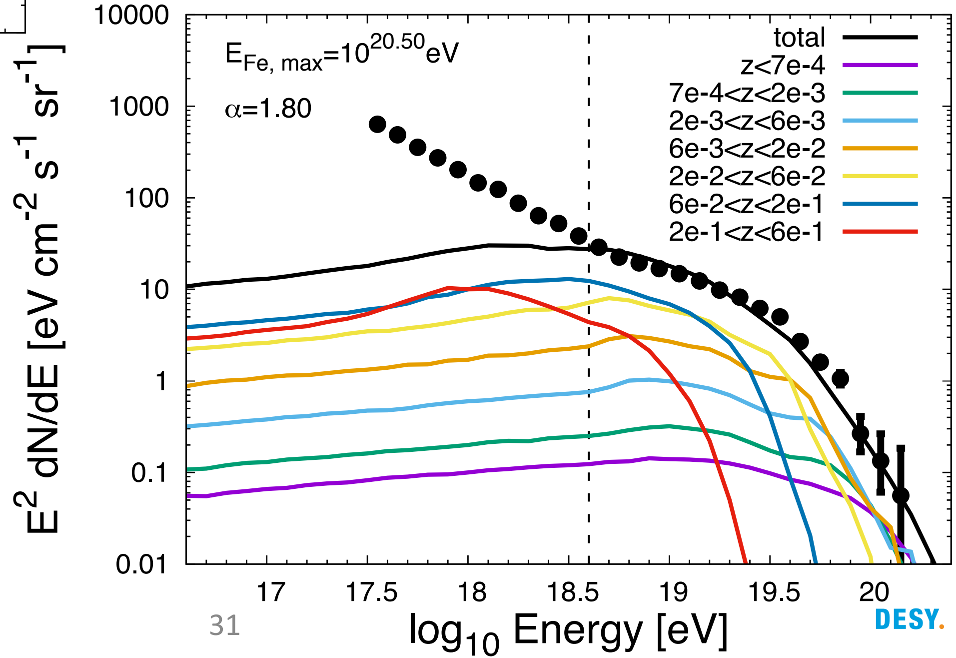
Prosekin et al. (2012), 1203.3787

1 yr



Source Redshifts Contributing to Arriving Flux



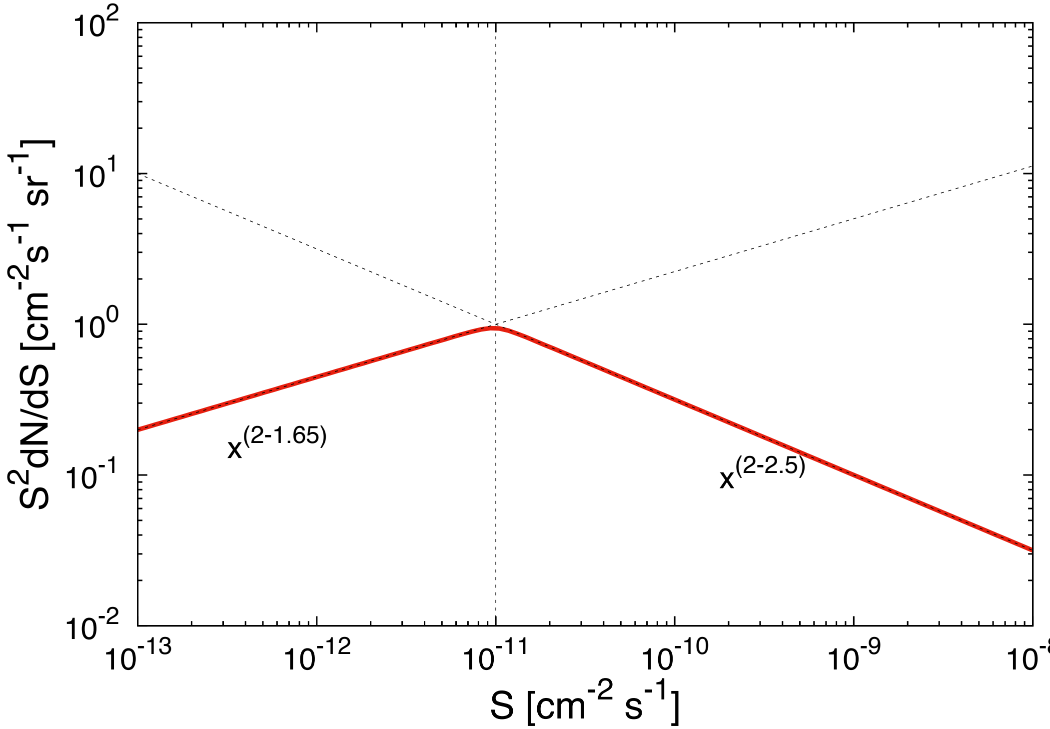


General Problem for Cascade Contribution?

Fermi Collaboration (2015)- astro-ph/1511.00693

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

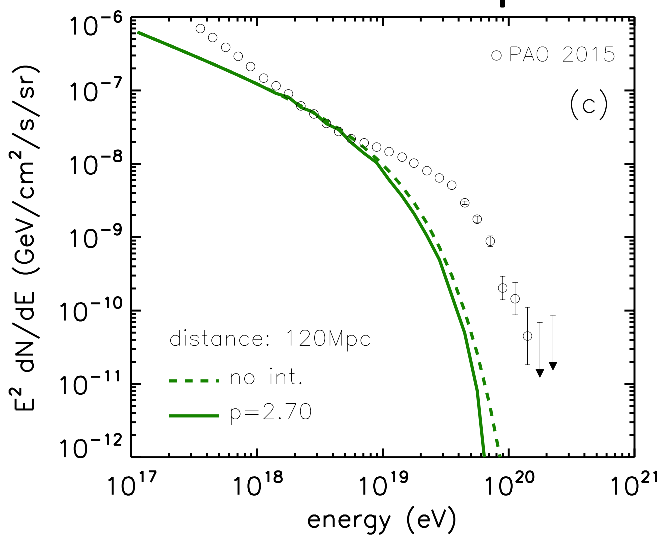
$$\mathbf{I} = \int \mathbf{S} \frac{\mathbf{dN}}{\mathbf{dS}} \mathbf{dS}$$

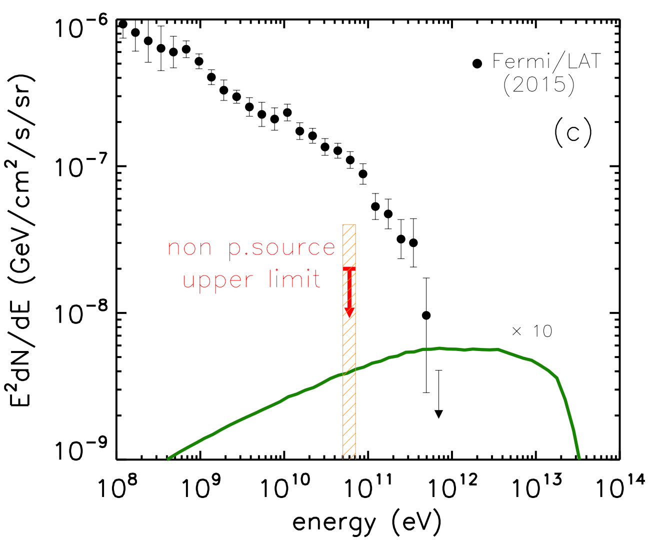


"Our analysis permits us to estimate that point sources, and in particular blazars, explain almost the totality (86^{+16}_{-14} %) of the >50 GeV EGB."

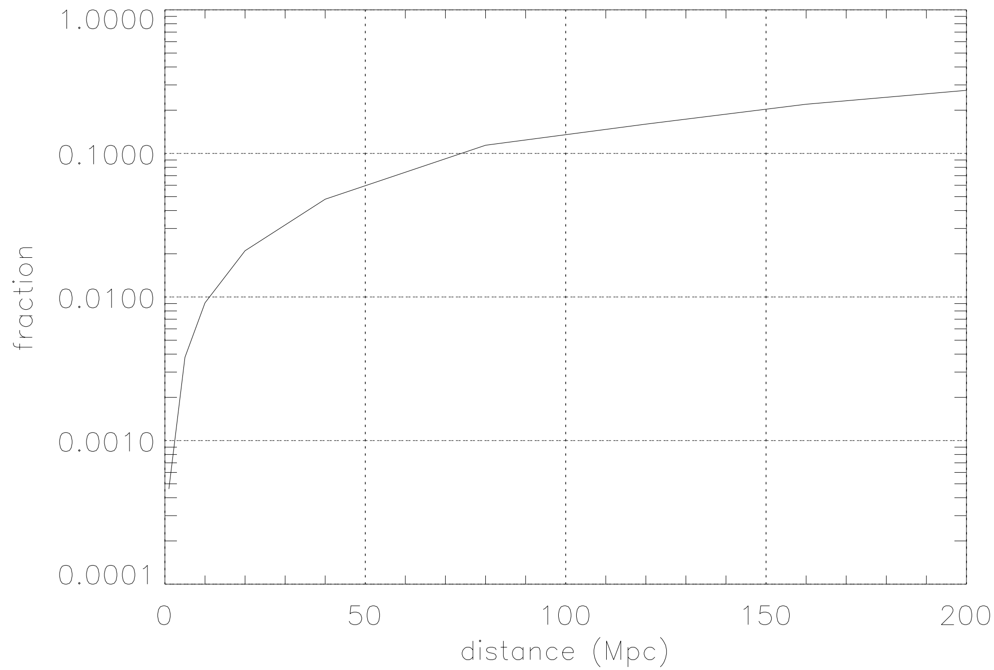
The Origin of Protons Below the Ankle

Sources at 120 Mpc





Liu et al. (2016), 1603.03223

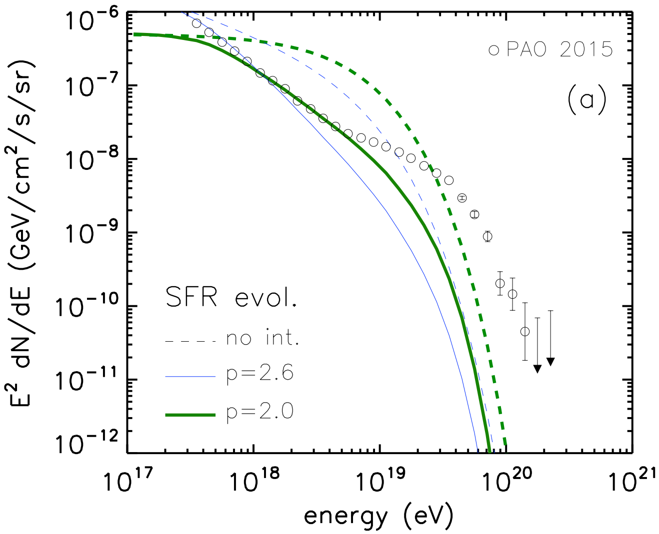


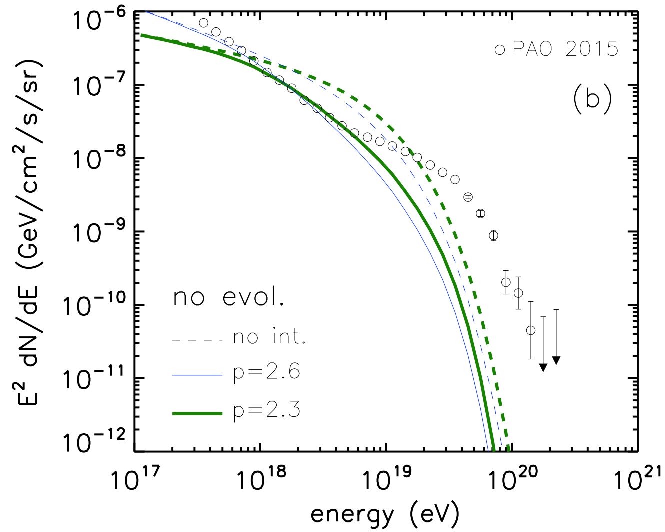
If only 1% of EGB comes from sub-ankle UHECR (present limit is 14%), we will be forced to look extremely locally for their sources

The Origin of Protons Below the Ankle

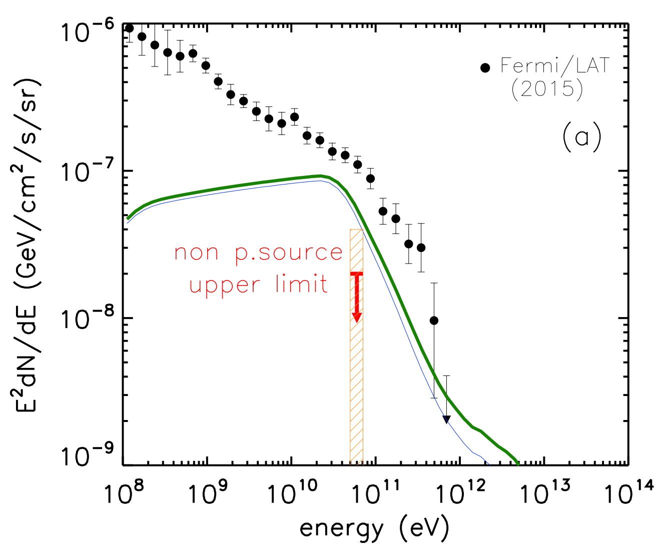
SFR evolution scenario

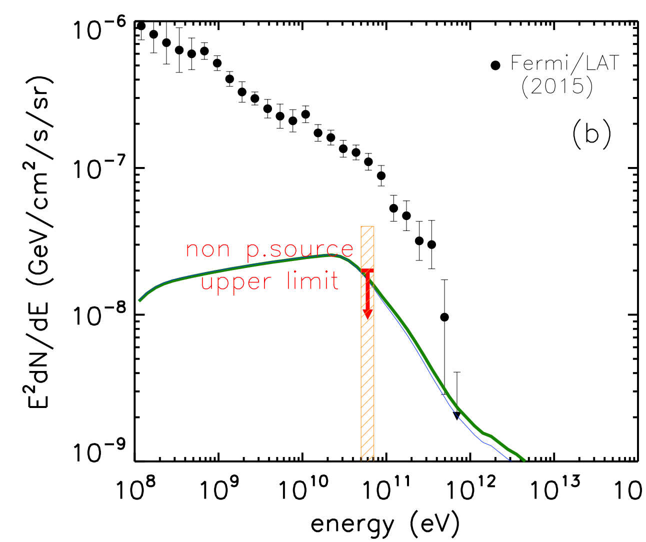
no evolution scenario





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





Liu et al. (2016), 1603.03223

Decerprit et al. (2011), 1107.3722

Gelmini et al. (2012), 1107.1672

An Alternative Interpretation of the Negative Source Evolution Result

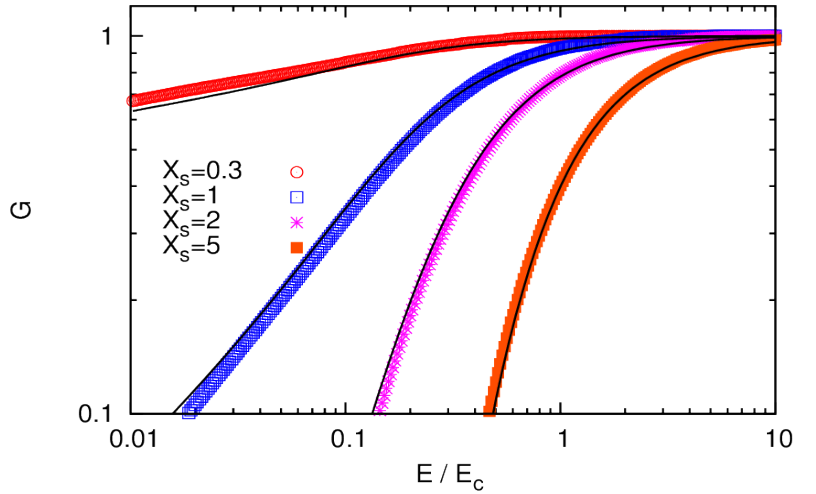
At high energies, the negative evolution scenarios help resolve both:

- "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"!

Hard Spectra Problem



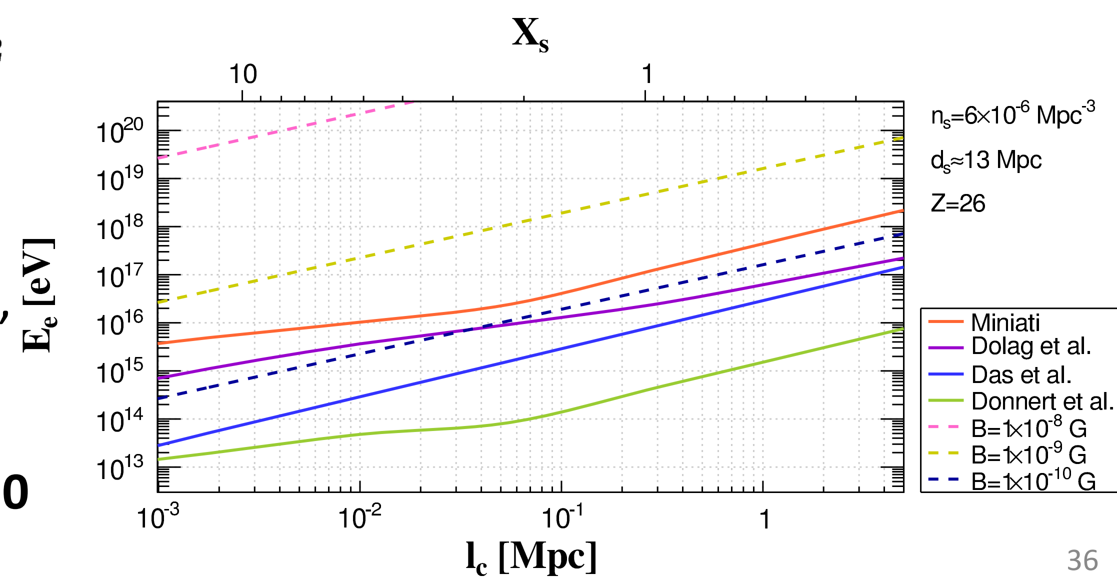
Magnetic horizon suppression suggested to resolve "hardness" issue,
Mollerach et al. (2013), 1305.6519

	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}

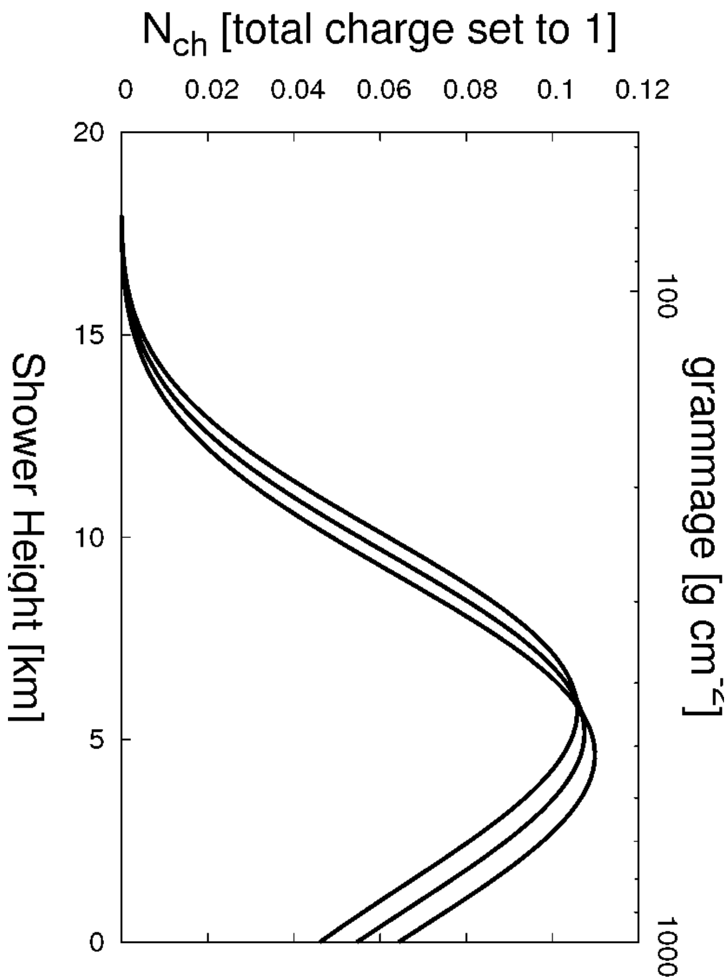
$$X_s = \frac{d_s}{(ct_H l_c)^{1/2}}$$

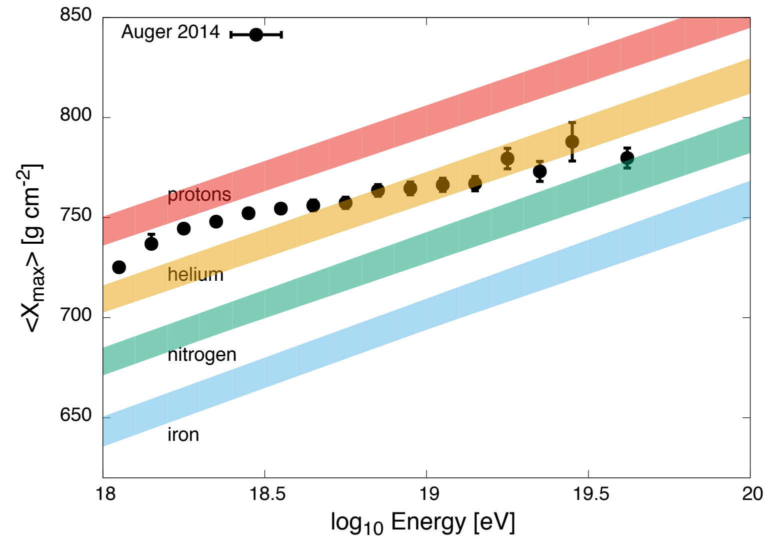
$$= 0.1 \left(\frac{d_s}{10\ \mathrm{Mpc}}\right)\left(\frac{1\ \mathrm{Mpc}}{l_c}\right)^{1/2}$$

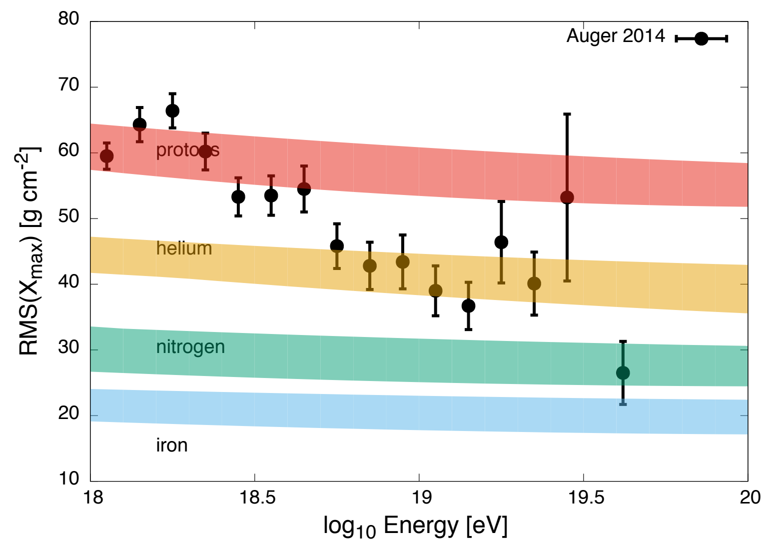
"Realistic" field structures/strengths, however, don't provide sufficient suppression,
Alves Batista et al. (2014), 1407.6150



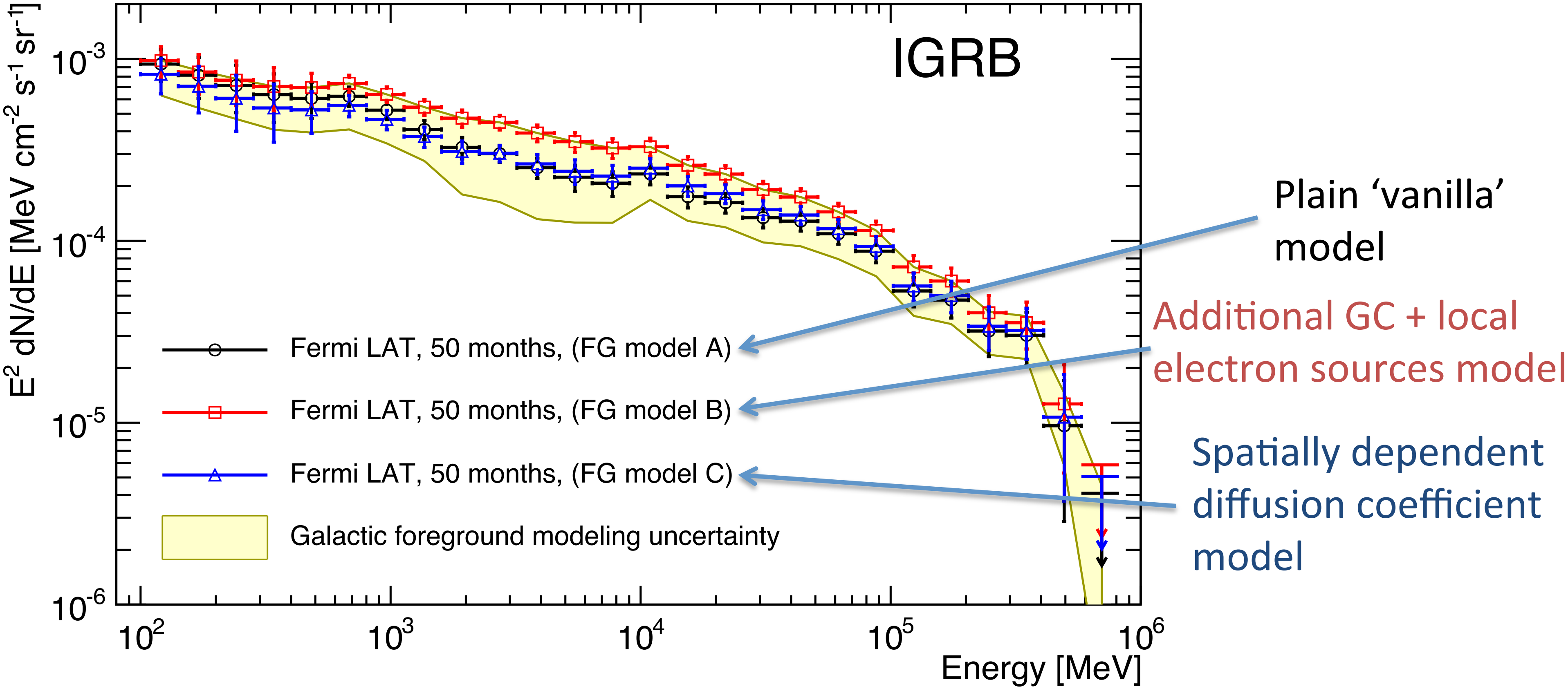
Composition- Consider Nuclei?







The Importance of the Galactic Diffuse Emission



Berezinsky et al. (2016), 1606.09293

Globus et al. (2017), 1703.04158