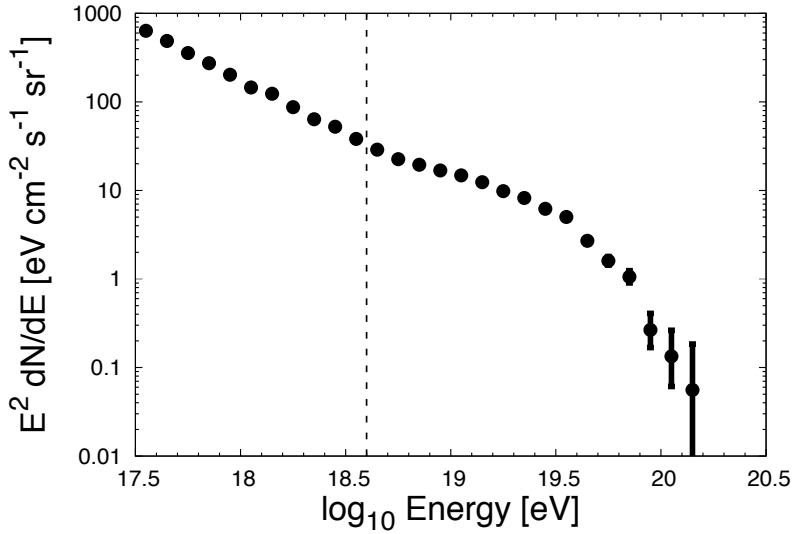
Extragalactic Cosmic Rays in the Knee to Ankle Region

Why Consider UHECR?

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

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



Assumptions on Source Population

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

$$z < z_{max}$$

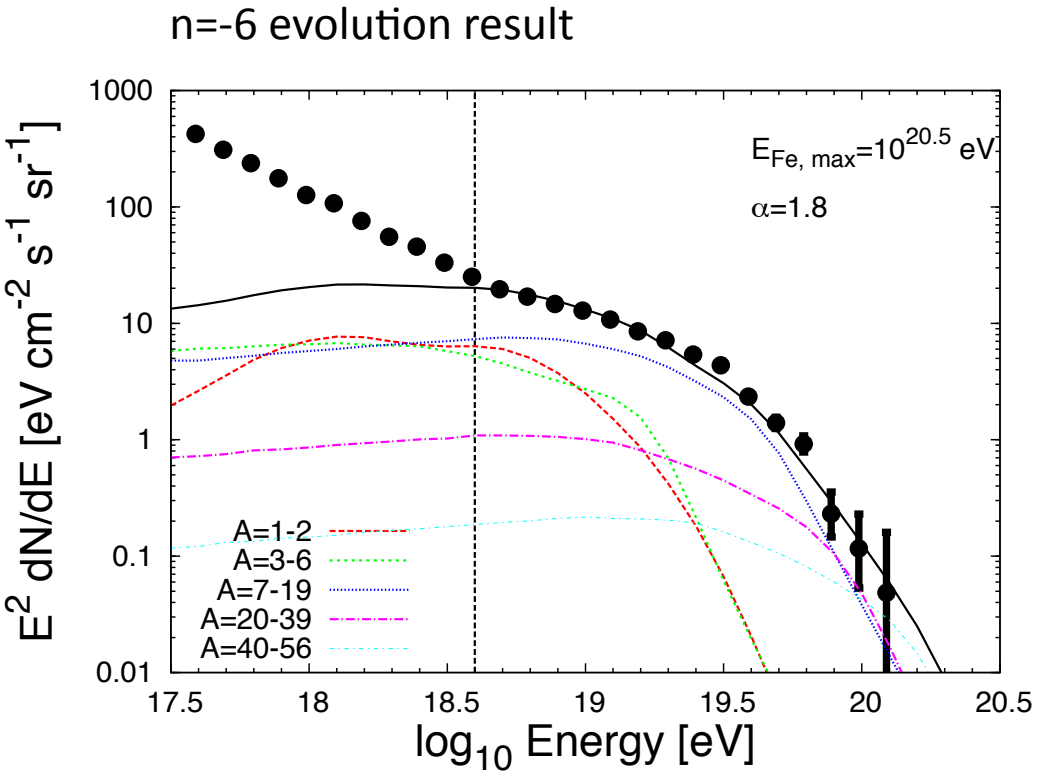
$$n = -6,\ -3,\ 0,\ 3$$

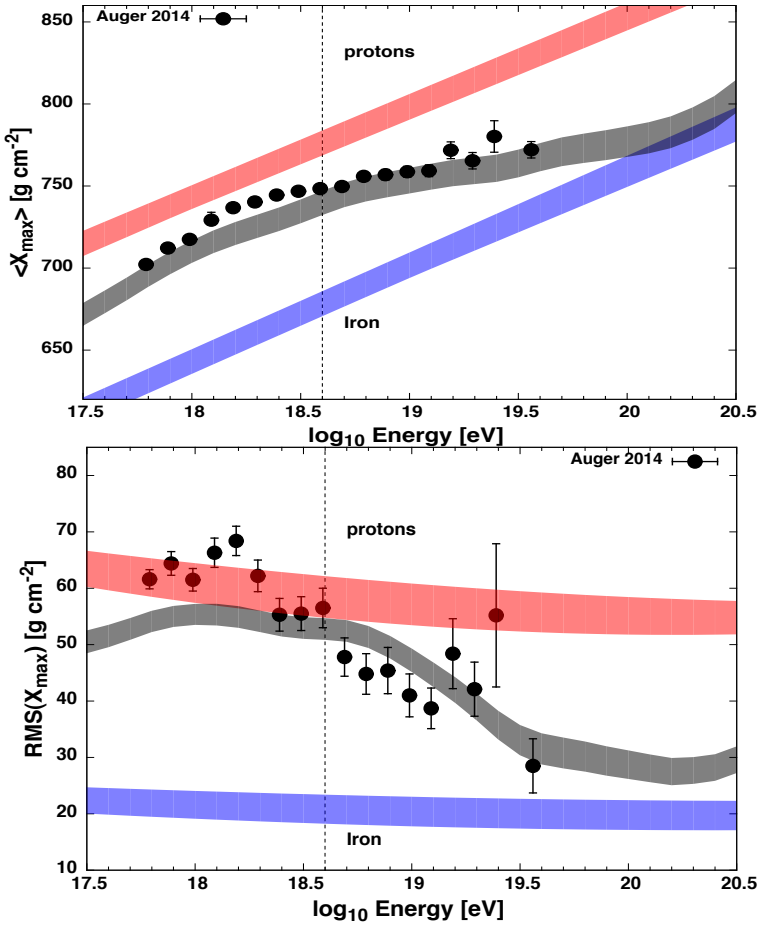
$$\frac{dN}{dE} \propto E^{-\alpha} \exp[-E/E_{Z,max}]$$

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

MCMC Likelihood Scan: Spectral + Composition Fits

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





MCMC Results Table

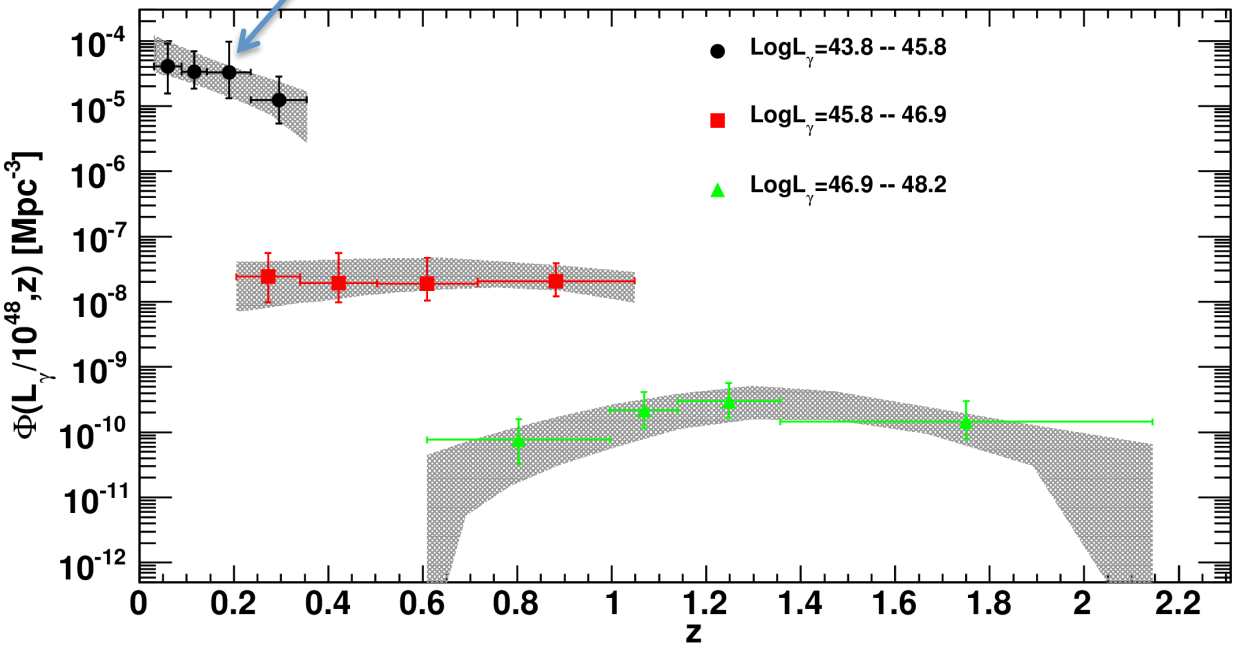
Parameter	$n = -6$		$n = -3$		$n = 0$		$n = 3$	
	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation
f_p	0.03	0.14 ± 0.12	0.08	0.15 ± 0.13	0.17	0.17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

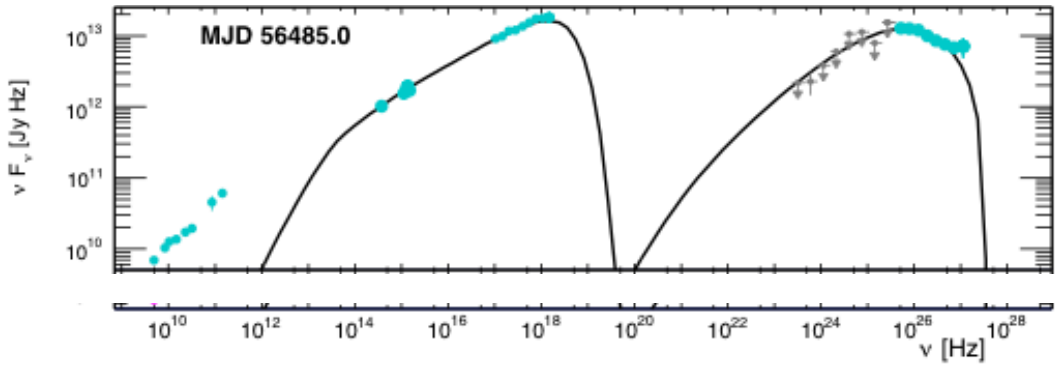


From astro-ph/1310.0006 (Ajello et al. 2014)

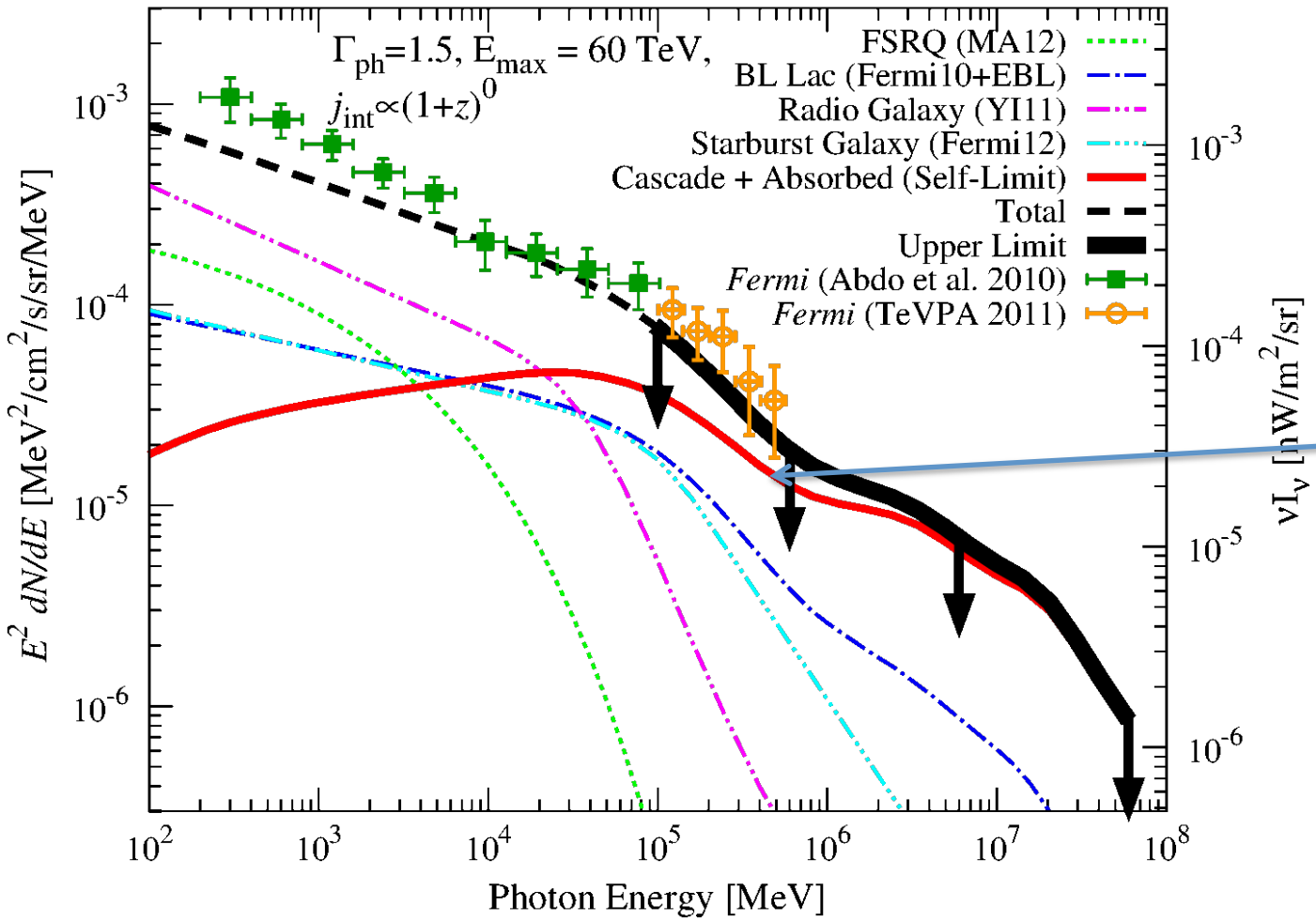
•Reminder:
Blazar -> BL Lac (FR1) -> HSP

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

Archetypal HSP example Mrk 501



Cascade Contribution Limit

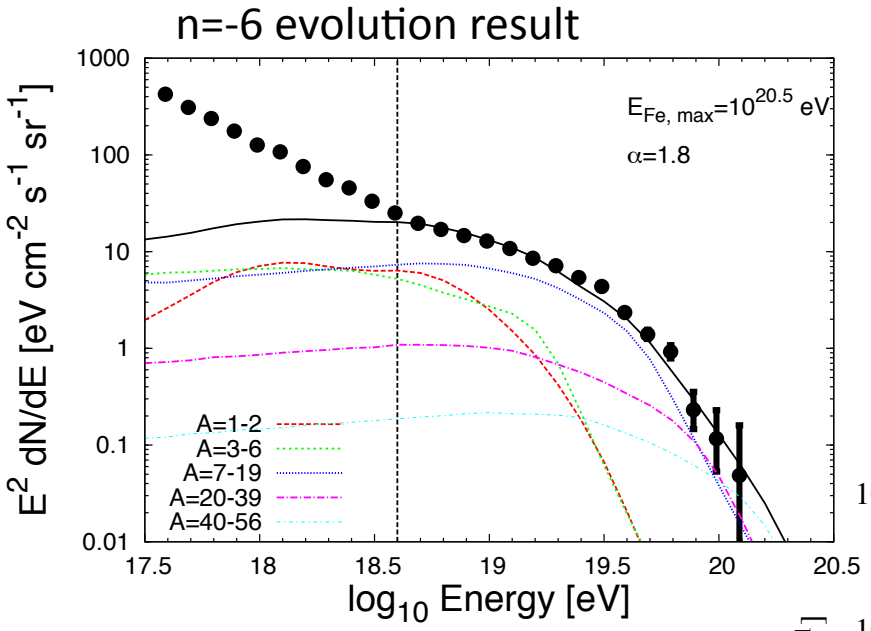


Limit on Cascade Component is around 40% of Fermi limit

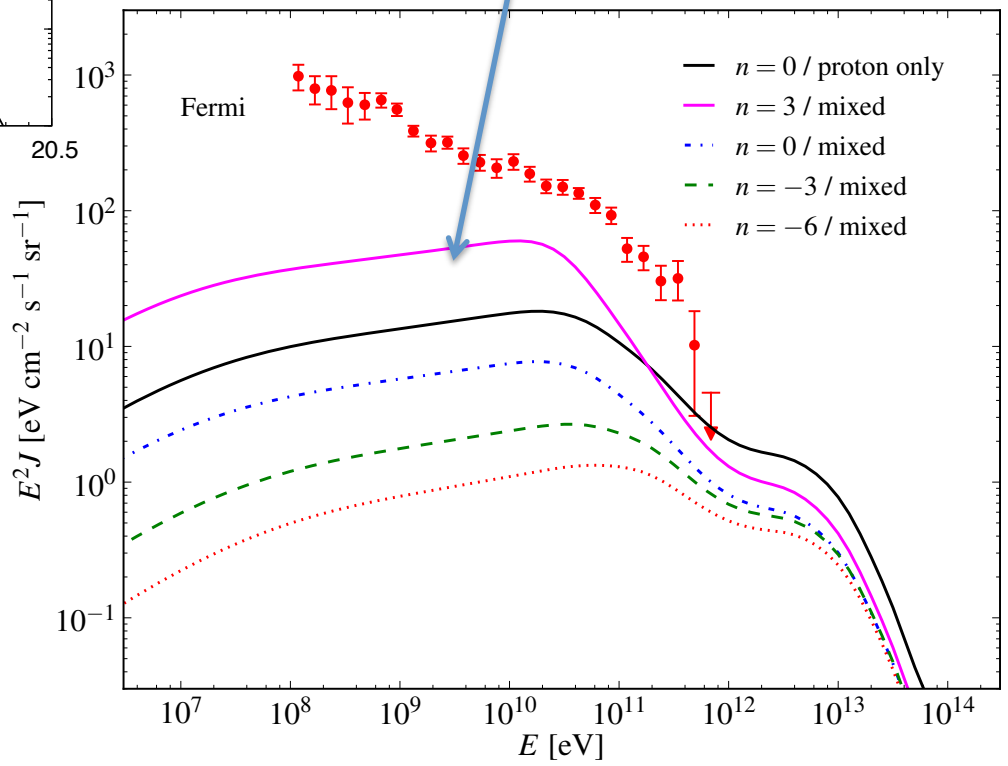
Constraints also placed on evolution of contributors to cascade component

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

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

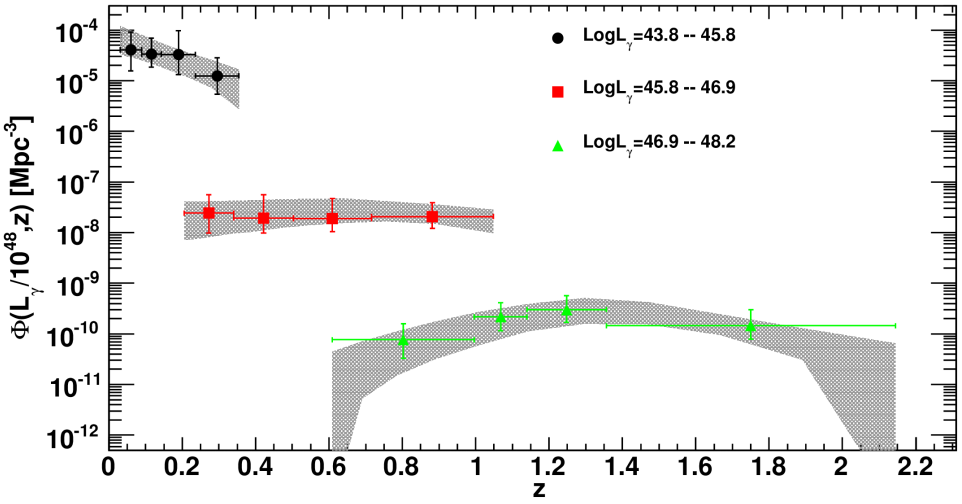


n=3 to -6 evolution scenarios give rise to between **40%** and **12%** of Fermi limit

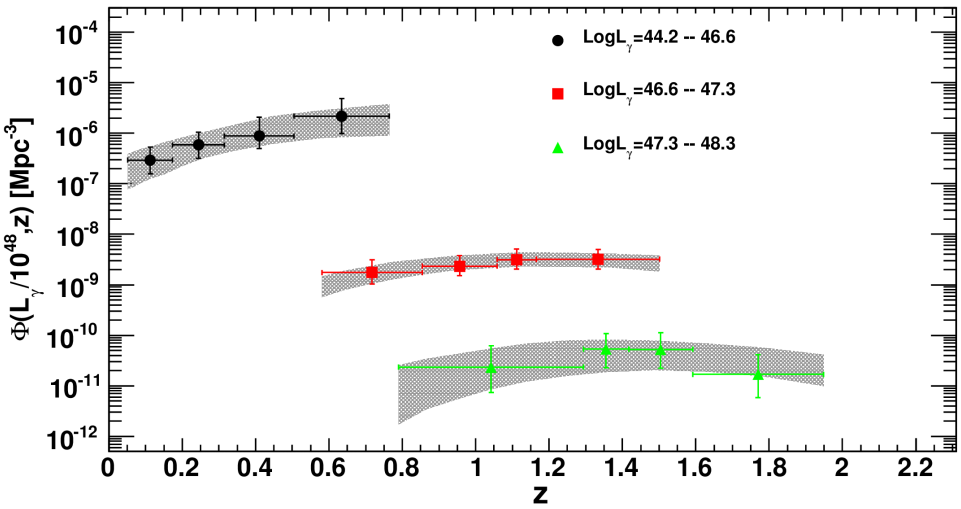


What About the Contribution from Other FR1 AGN (LSP + ISP)?

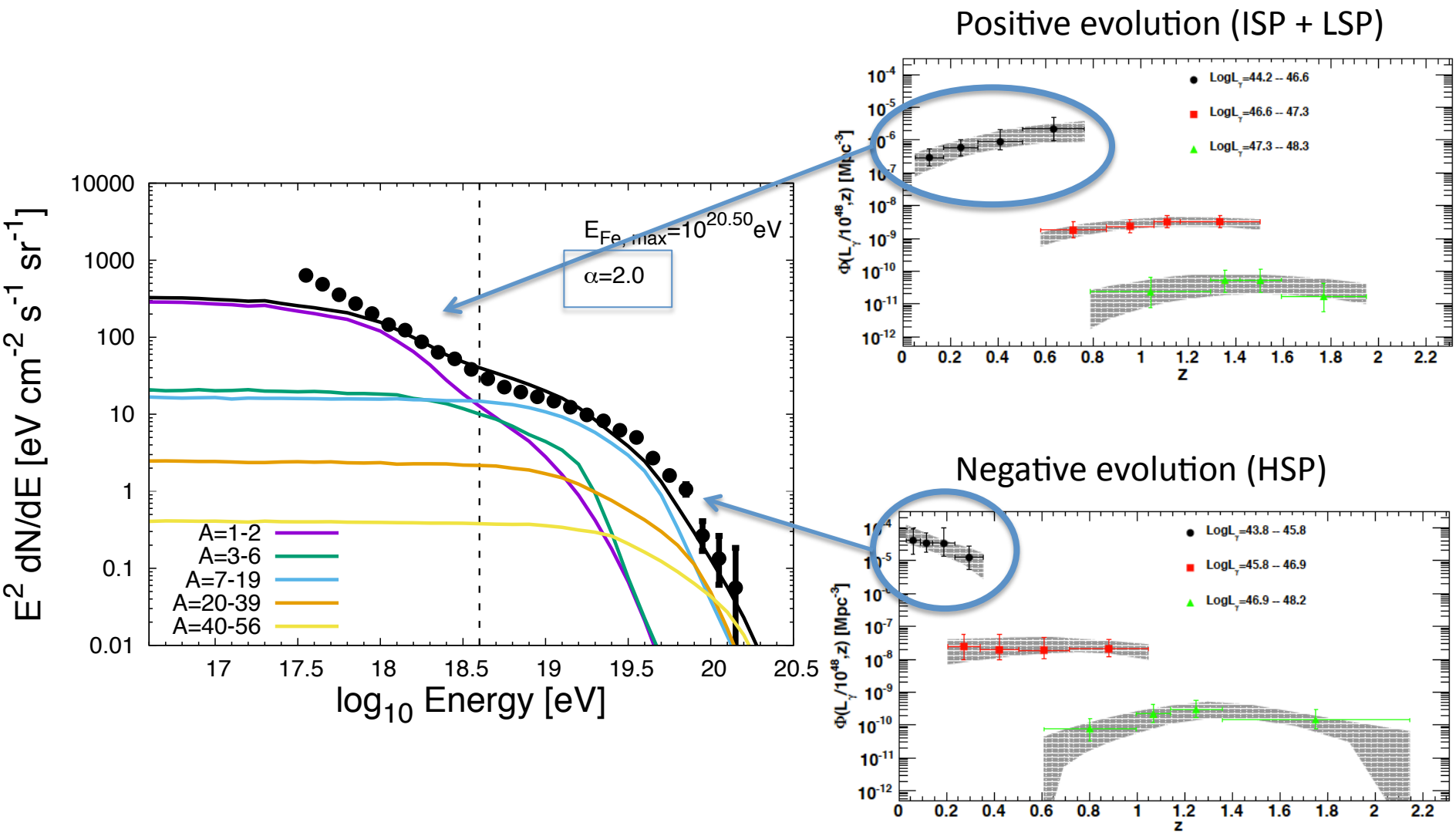
HSP AGN



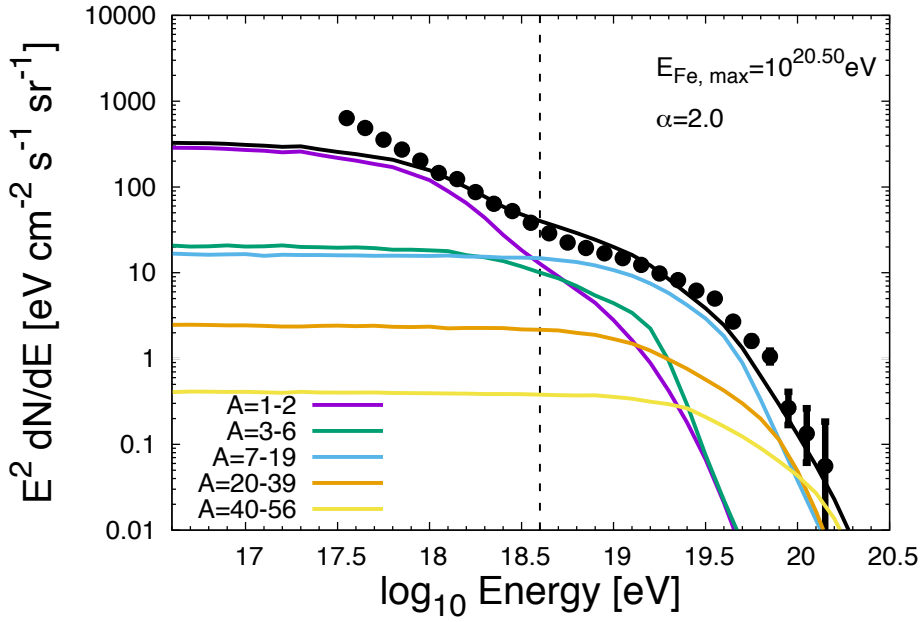
ISP + LSP AGN



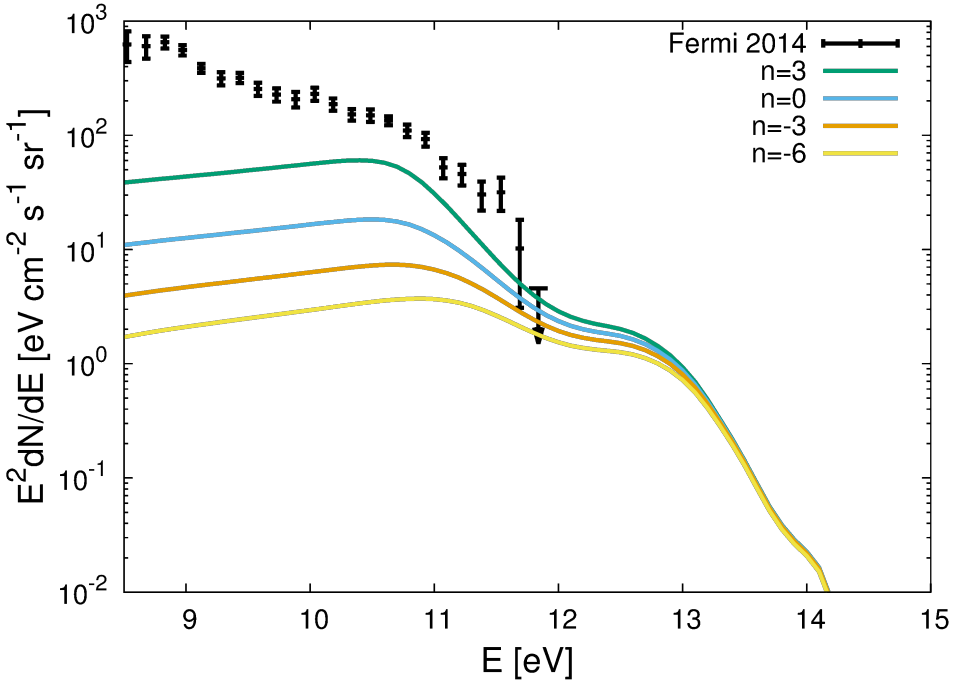
Does a Separate Class of Extragalactic Source Dominate at Lower Energies?



Cascade Contribution from Second Source Population



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



Conclusions

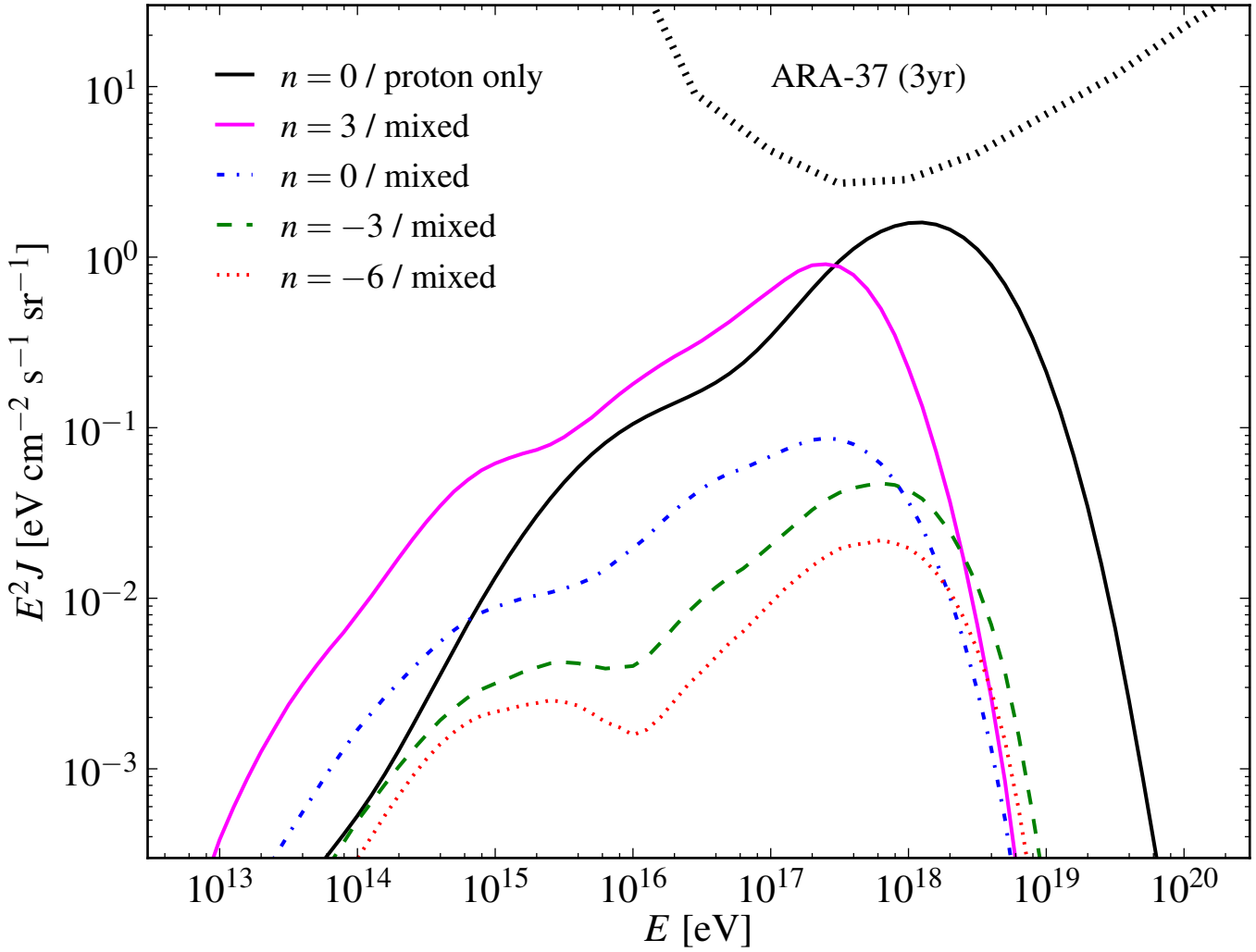
- Source distributions of certain classes of blazars (HSP) are observed to possess a negative evolution
- Such an evolution would explain how the extragalactic background flux level is not violated by HSP blazars
- A negative source evolution allows for $\mathbf{E^{-2}}$ type spectra to explain the highest energy particles
- The positive evolution of other blazar classes (ISP + LSP or FRSQ), would give rise to lower energy extragalactic cosmic rays (which again allow an $\mathbf{E^{-2}}$ type spectra for this component)

Similar Evolution Observed for Non-Blazar AGN?

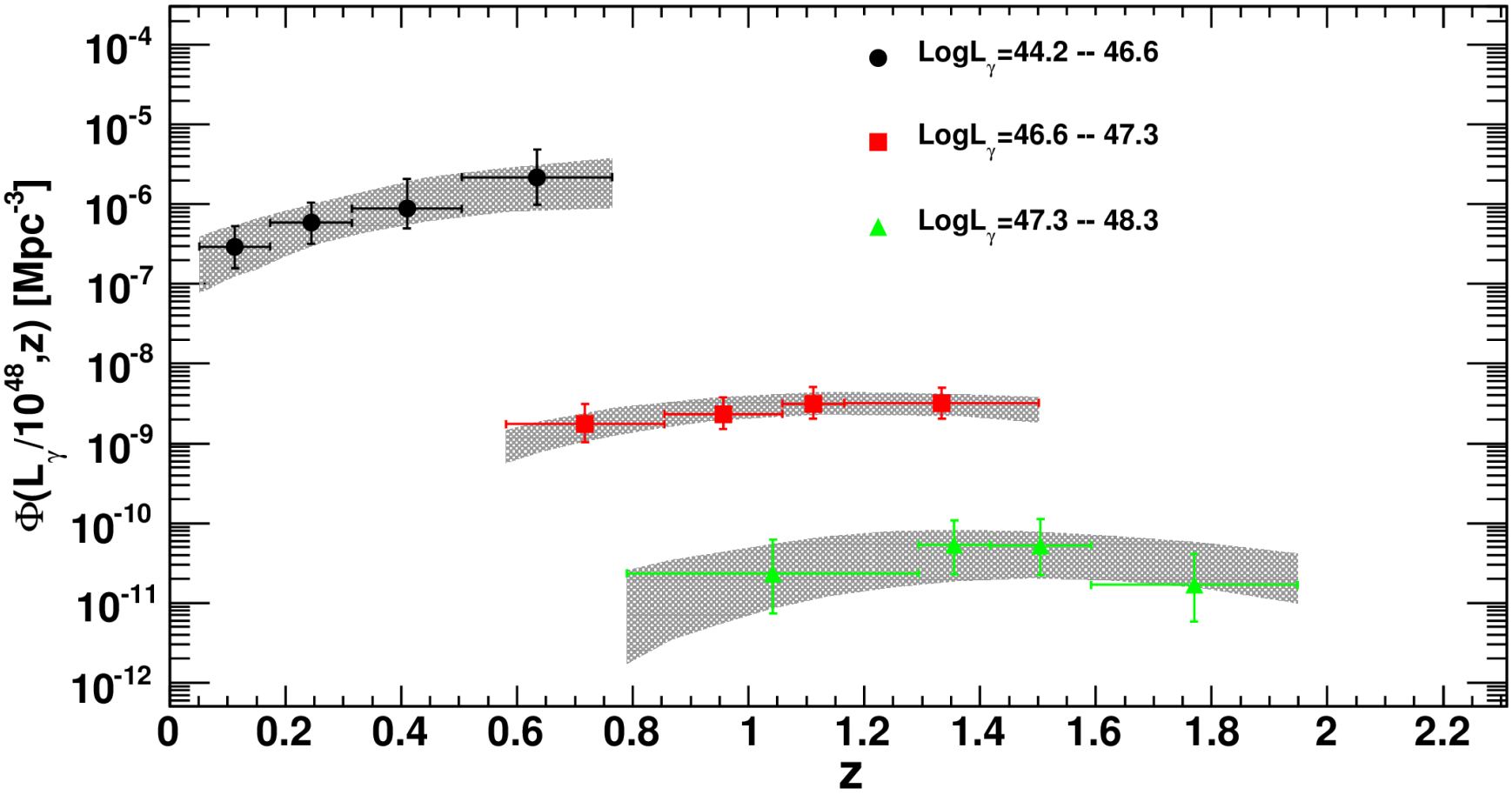
Radio Loud AGN are suggested to have positive evolution (n=2) up to z=0.5, followed by negative evolution (n=-4) beyond this.

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

Secondary Neutrino Fluxes

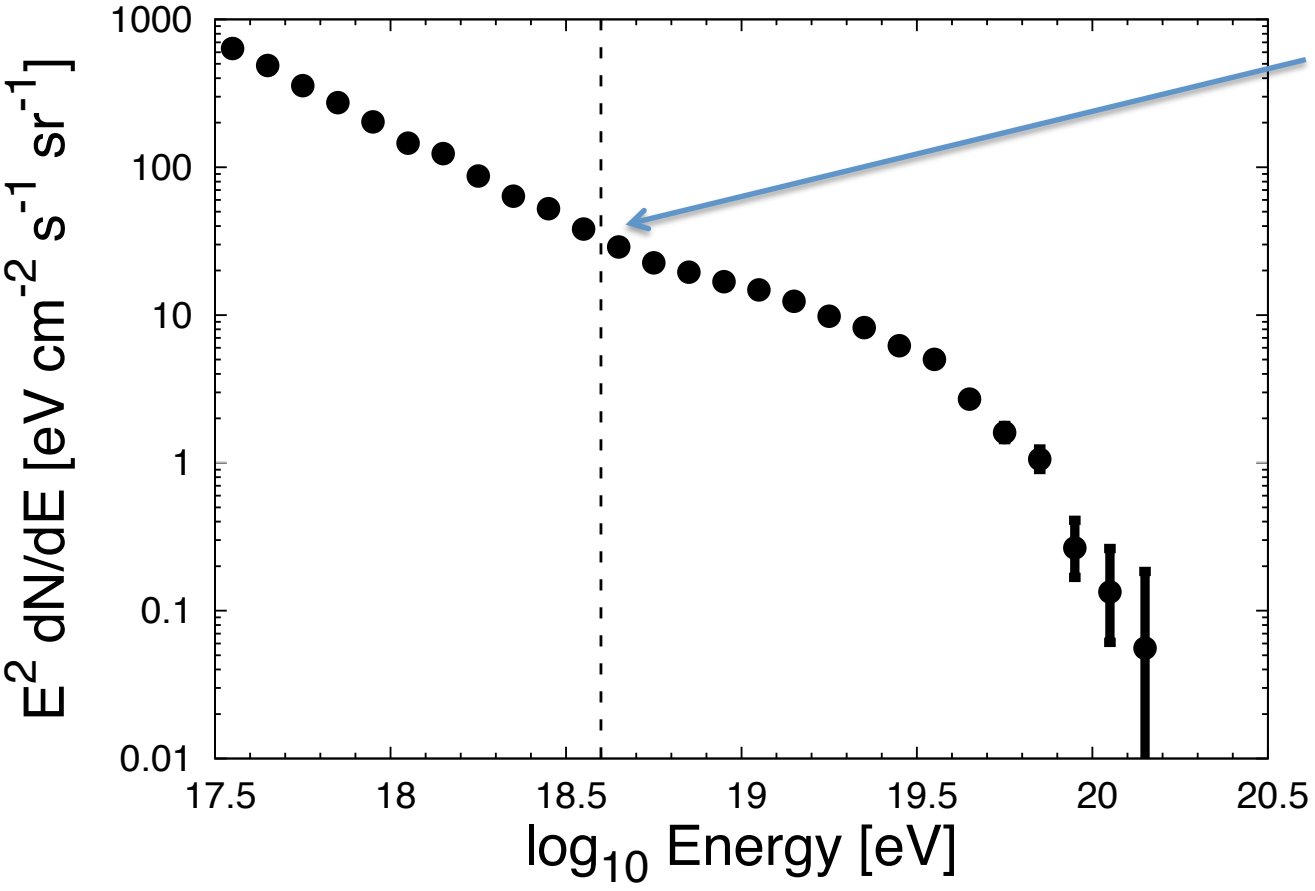


Intermediate/Low Spectral Peaked Blazar Evolution



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

At What Energy Is The Ankle?



A new component in the arriving cosmic ray spectrum is apparent above an energy of ~$10^{18.5}$ eV