UHECR Propagation + Related Physics

Andrew Taylor

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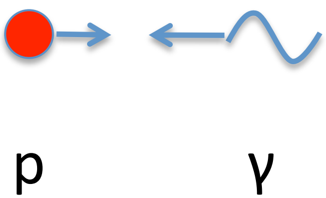
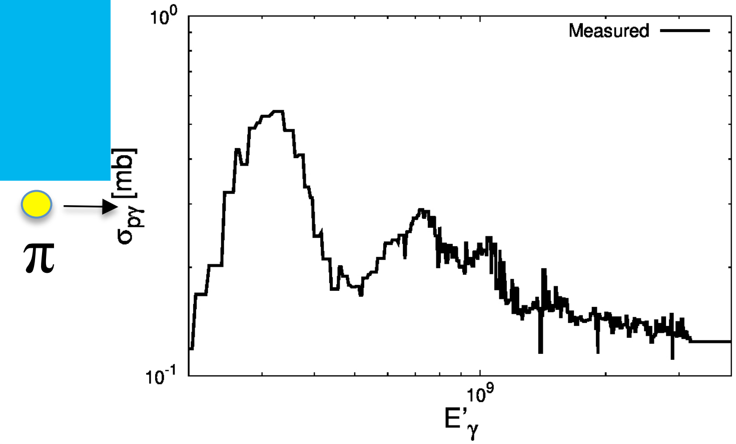
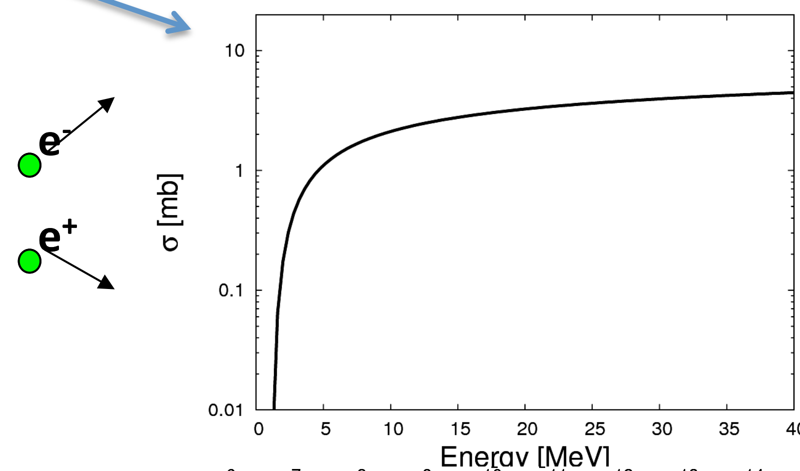
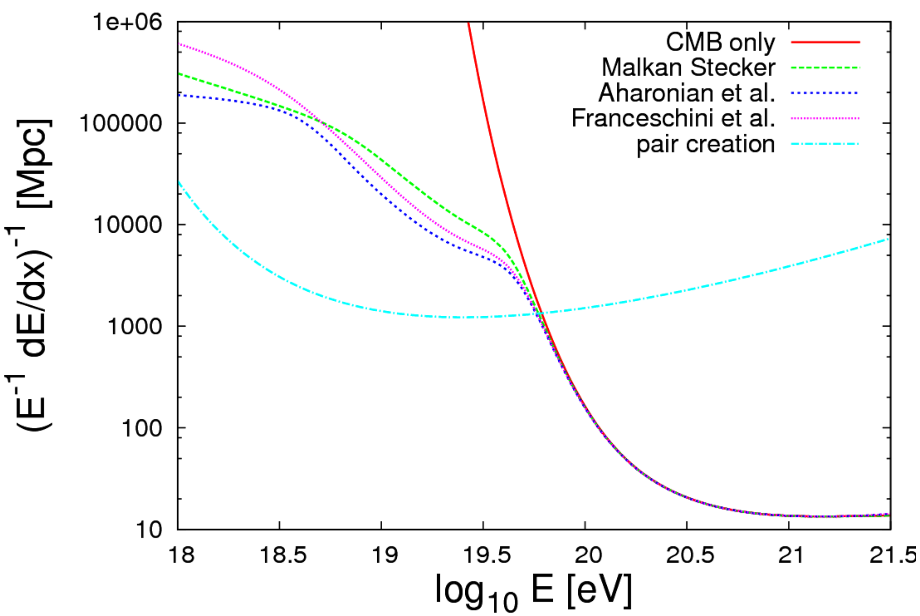
Cosmic Ray Interactions

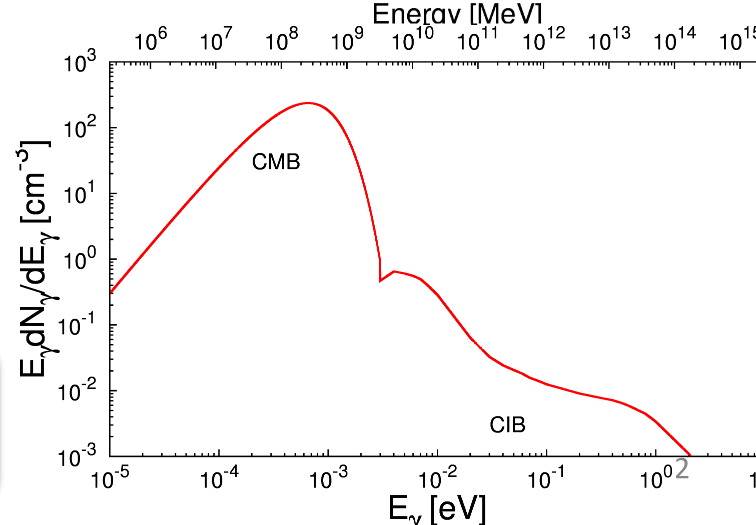


Most important energy losses



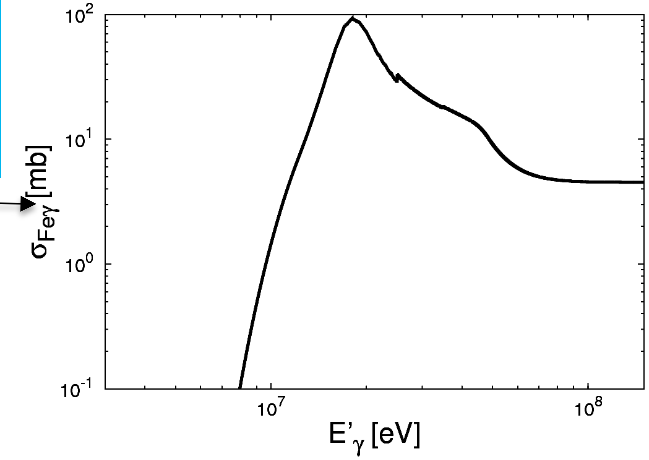


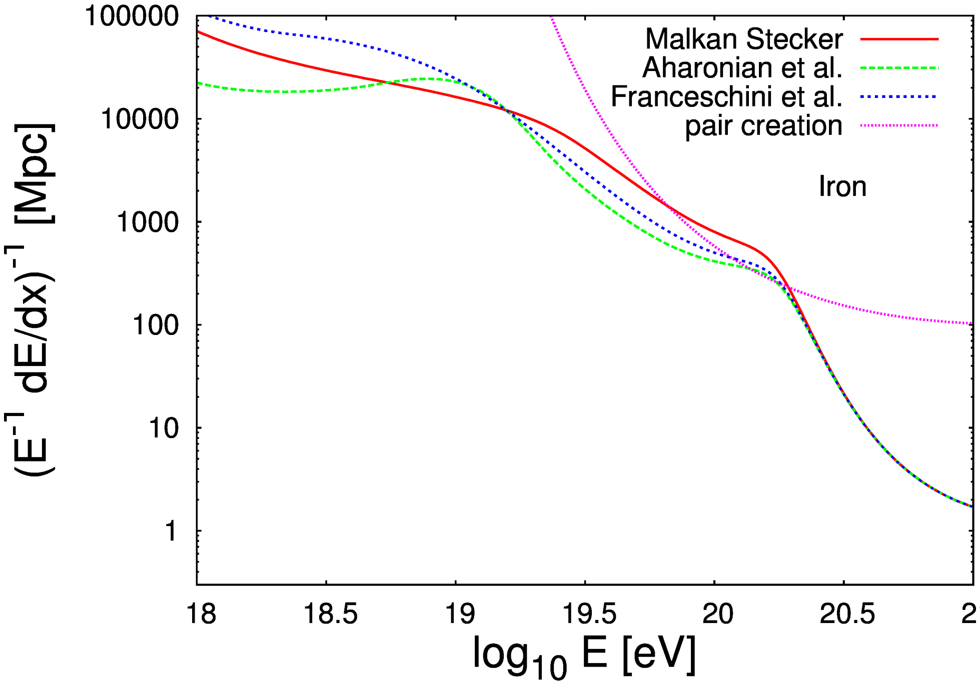


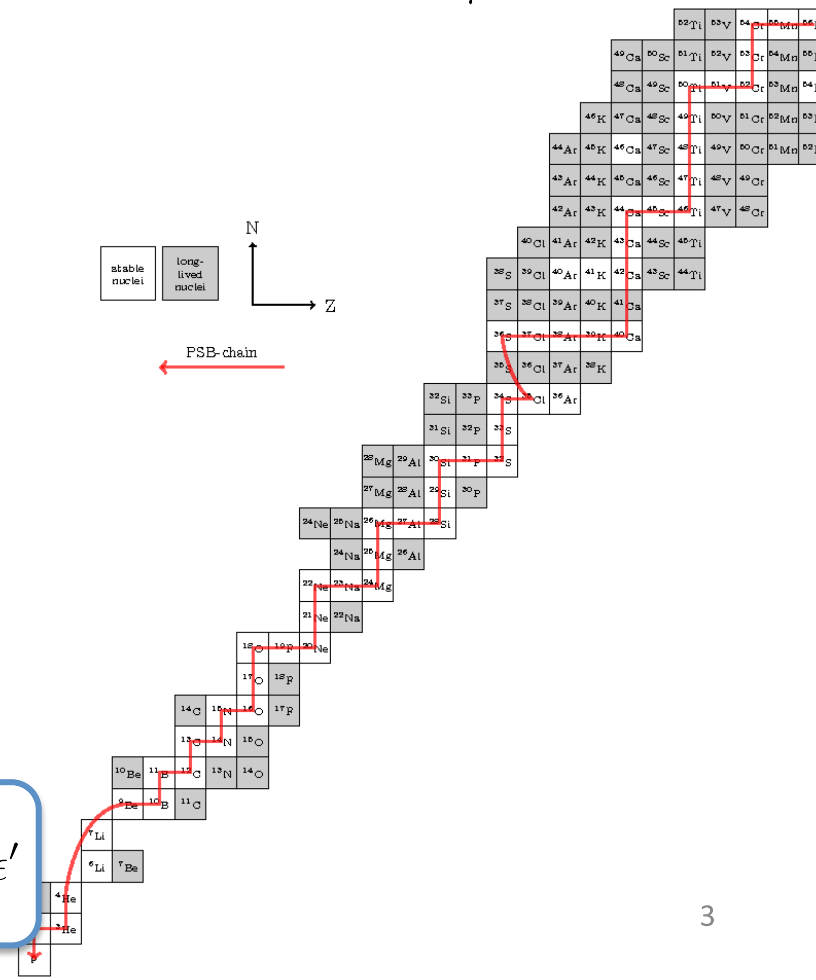


$$\mathbf{R} = \frac{2m_p^2}{E_p^2}\int \frac{1}{\epsilon^2}\frac{dN_\gamma}{d\epsilon}\int_0^{4E_p\epsilon/m_p} k_{p\gamma}\epsilon'\sigma_{p\gamma}(E_p,\epsilon')d\epsilon'$$

Cosmic Ray Interactions





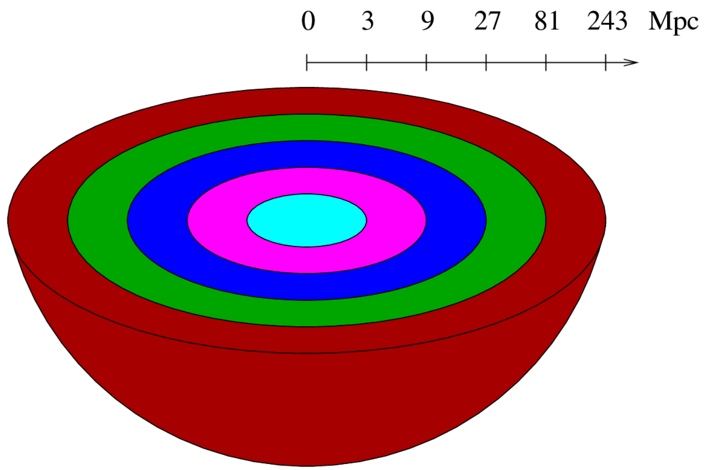


$$R = \frac{2m_N^2}{E_N^2}\int \frac{1}{\epsilon^2}\frac{dN_\gamma}{d\epsilon}\int_0^{4E_N\epsilon/m_N} k_{N\gamma}\epsilon'\sigma_{N\gamma}(E_N,\epsilon')d\epsilon'$$

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)

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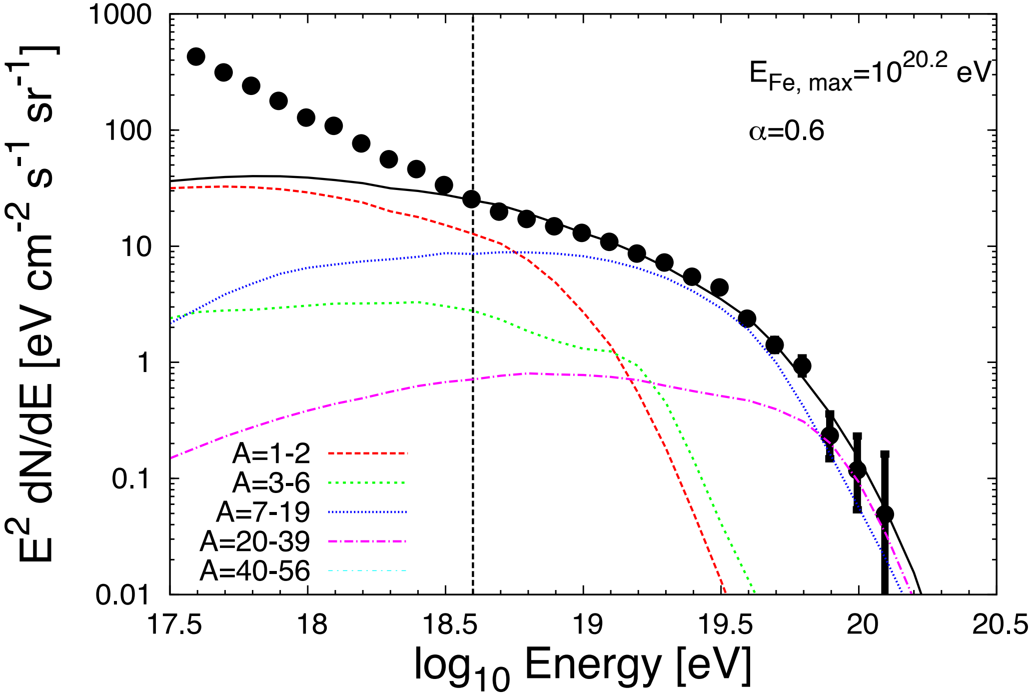
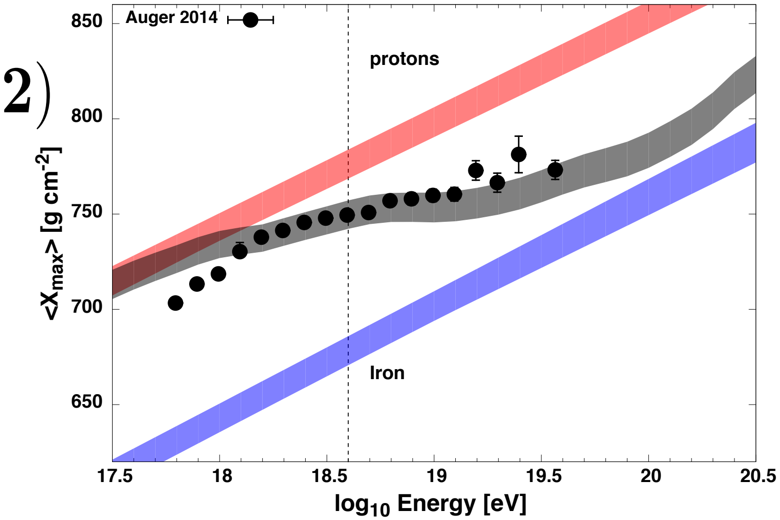
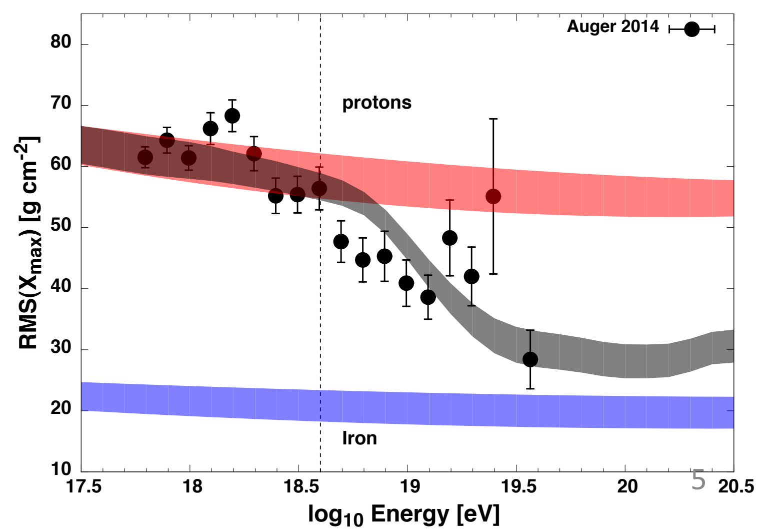
MCMC Likelihood Scan: Spectral + Composition Fits

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

n=3 evolution result







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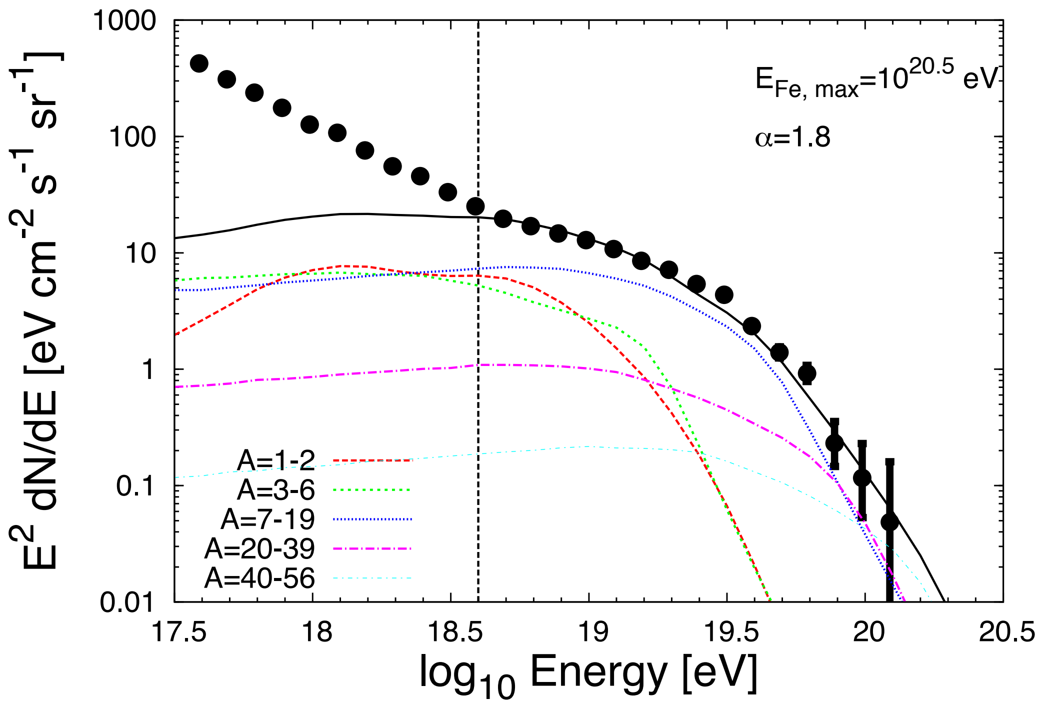
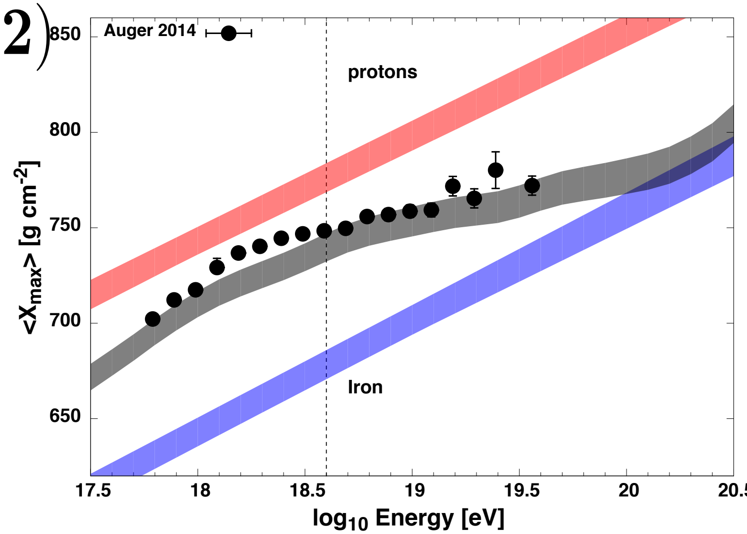
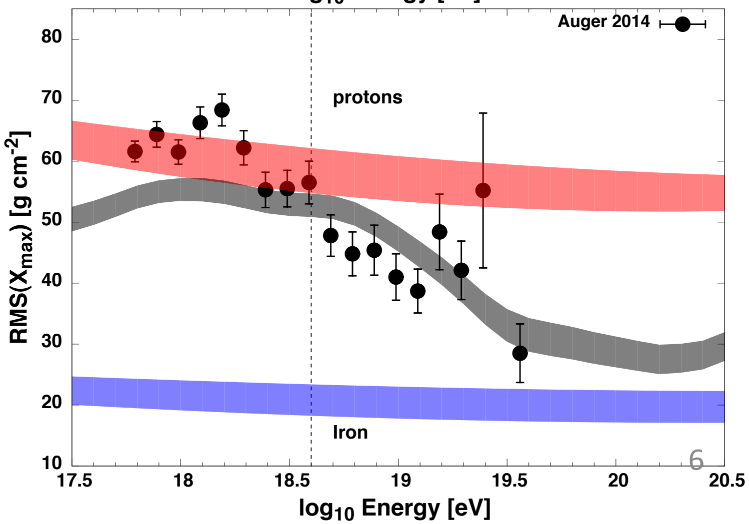
MCMC Likelihood Scan: “Soft” Spectra Solutions

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

n=-6 evolution result







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MCMC Results Table

Similar conclusion arrives to by others (eg. ADD REF. TO KAMPERT ET AL.)

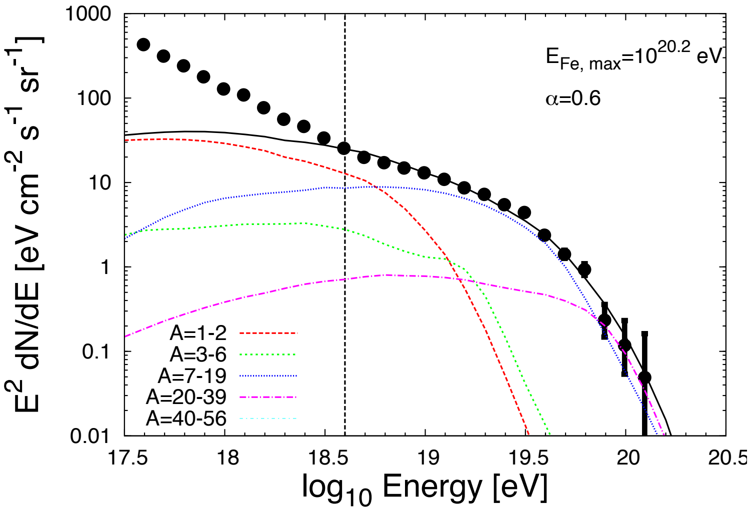
Parameter	$n=-6$		$n=-3$		$n=0$		$n=3$	
	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation	Best-fit Value	Posterior Mean & Standard Deviation
f_p	0.03	0.14 ± 0.12	0.08	0.15 ± 0.13	0.17	0.17 ± 0.16	0.19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

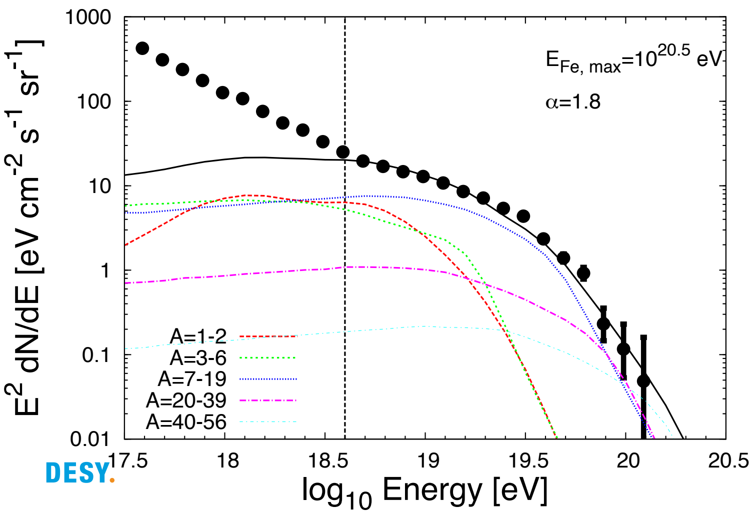
Hard spectra preferred for source evolution following that of the SFR

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

n=3 evolution result

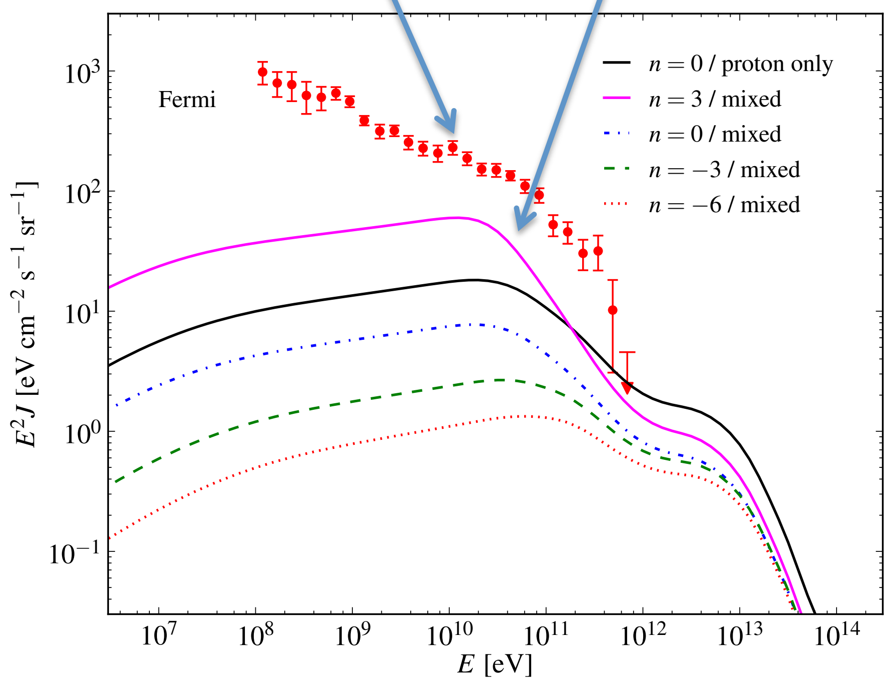


n=-6 evolution result



IGRB (EGB with resolved points sources removed)

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



Taylor et al. 2015 (1505.06090)

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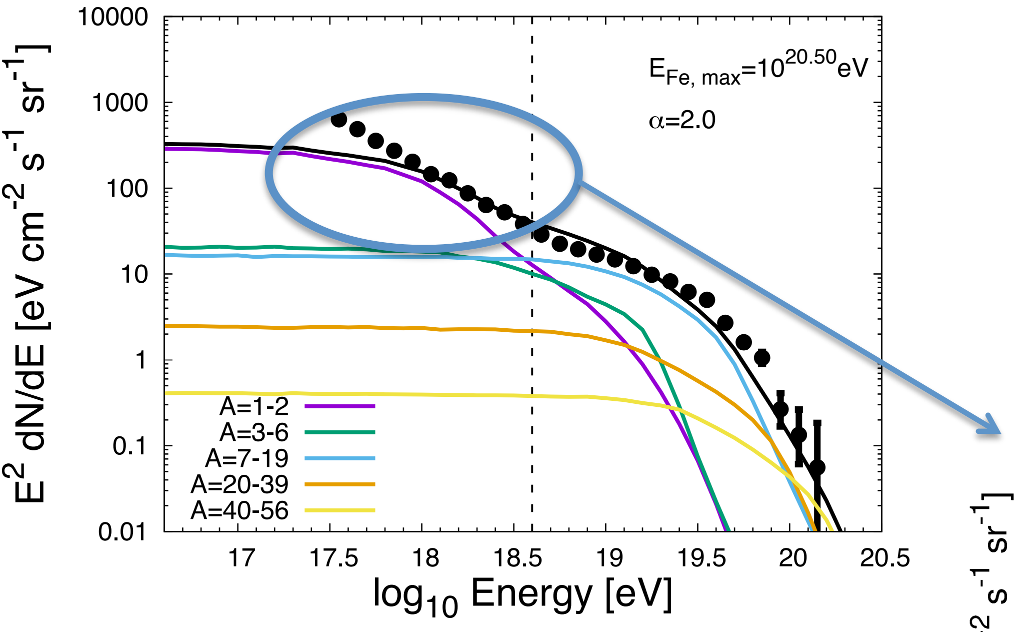
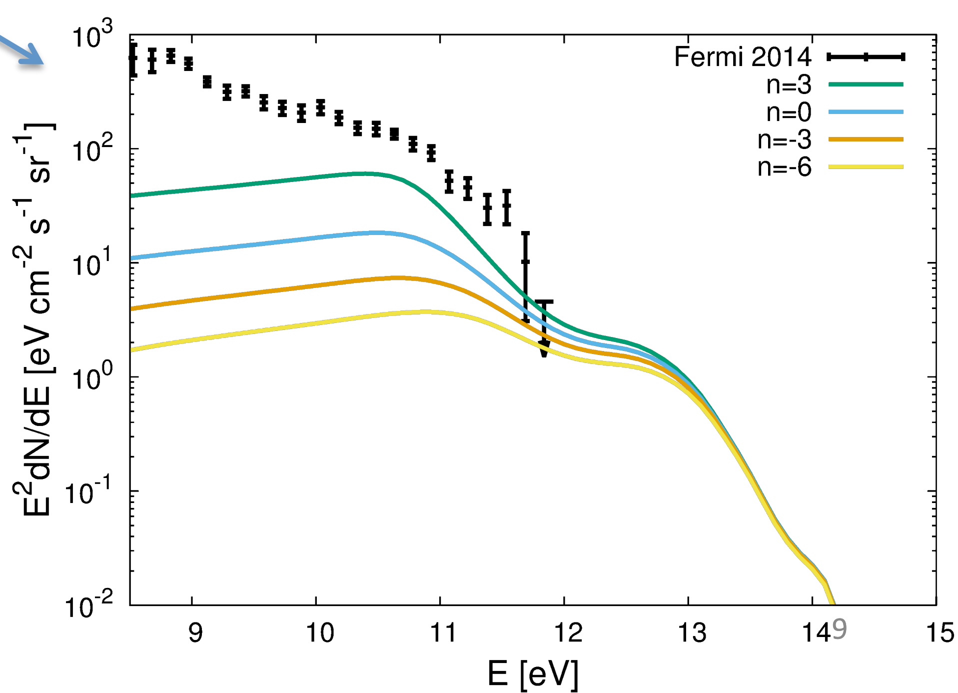
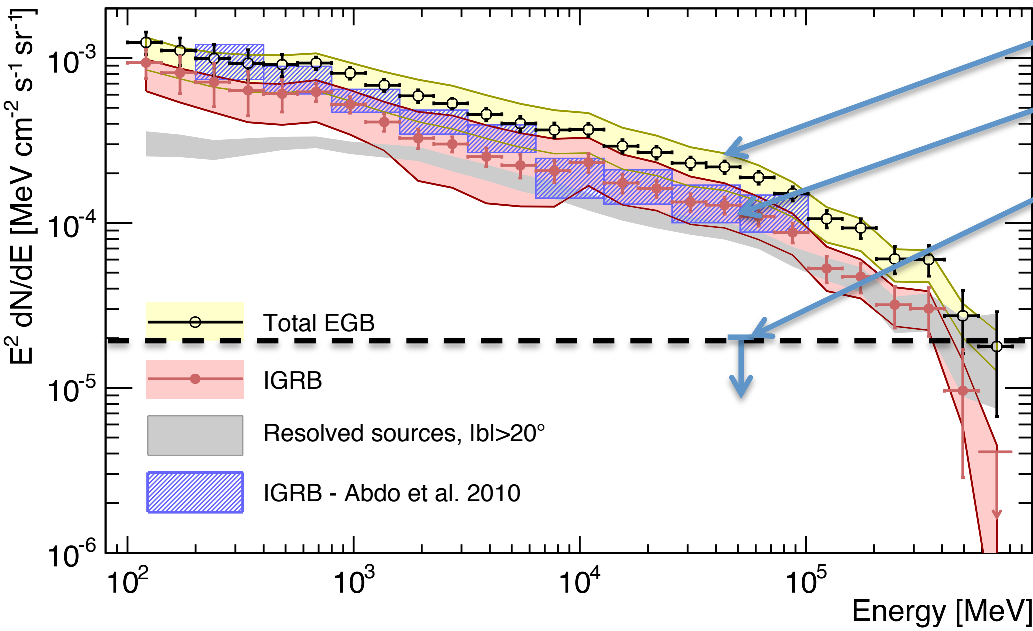
Dominant Source at Sub-Ankle Energies



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

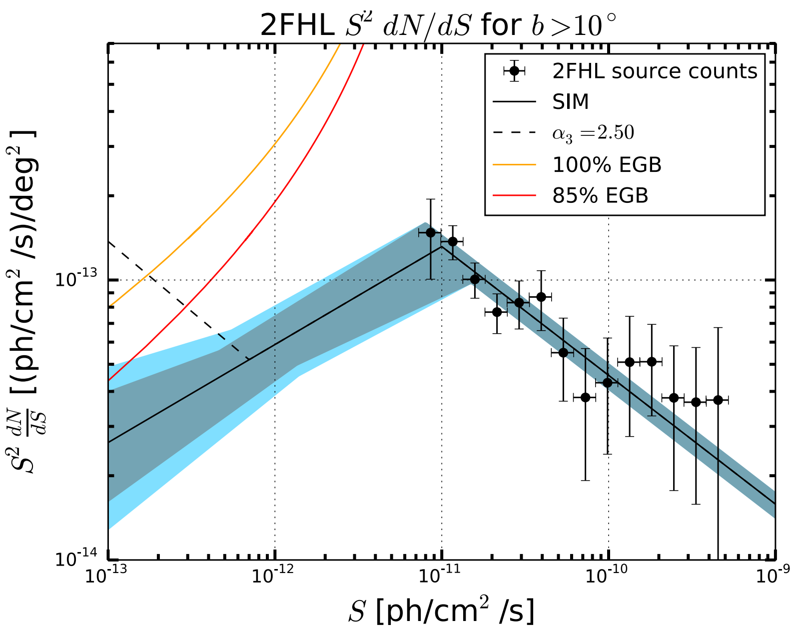
….+ Removal of Res. Blazars

….+ Removal of Unres. Blazars

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

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

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



Blazars explain in totality 86^{+16}_{-14} % of the >50 GeV EGB

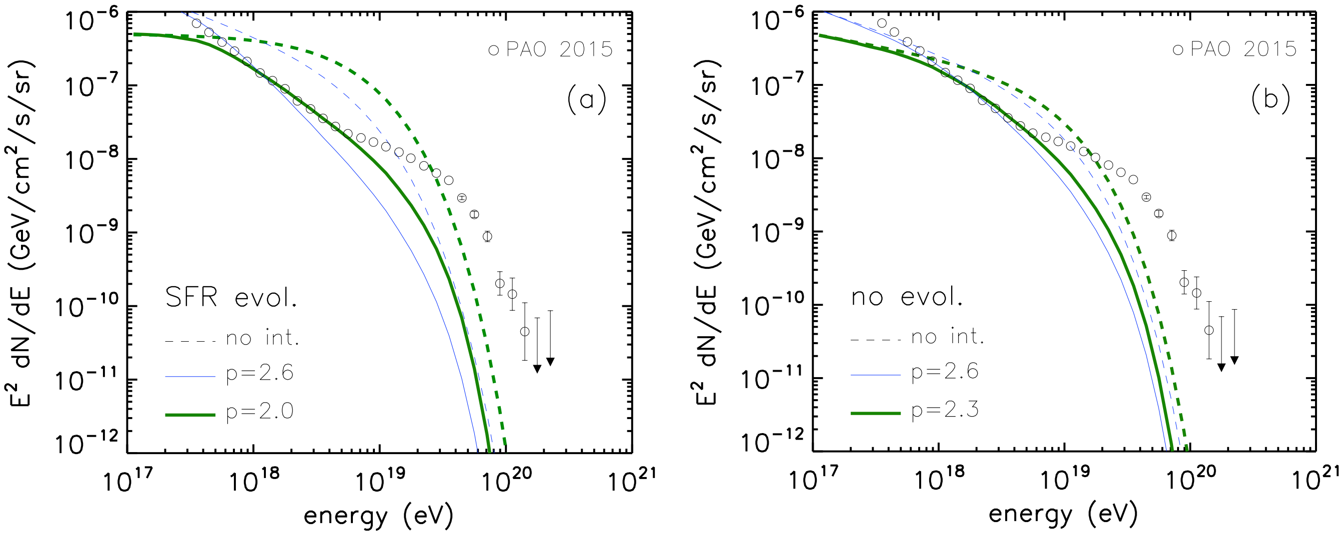
A repeat of this analysis by other groups have given: 68^{+9}_{-8}% and 81^{+52}_{-19}%

Lisanti et al. 2016 (1606.04101)
Zechlin et al. 2016 (1605.04256)

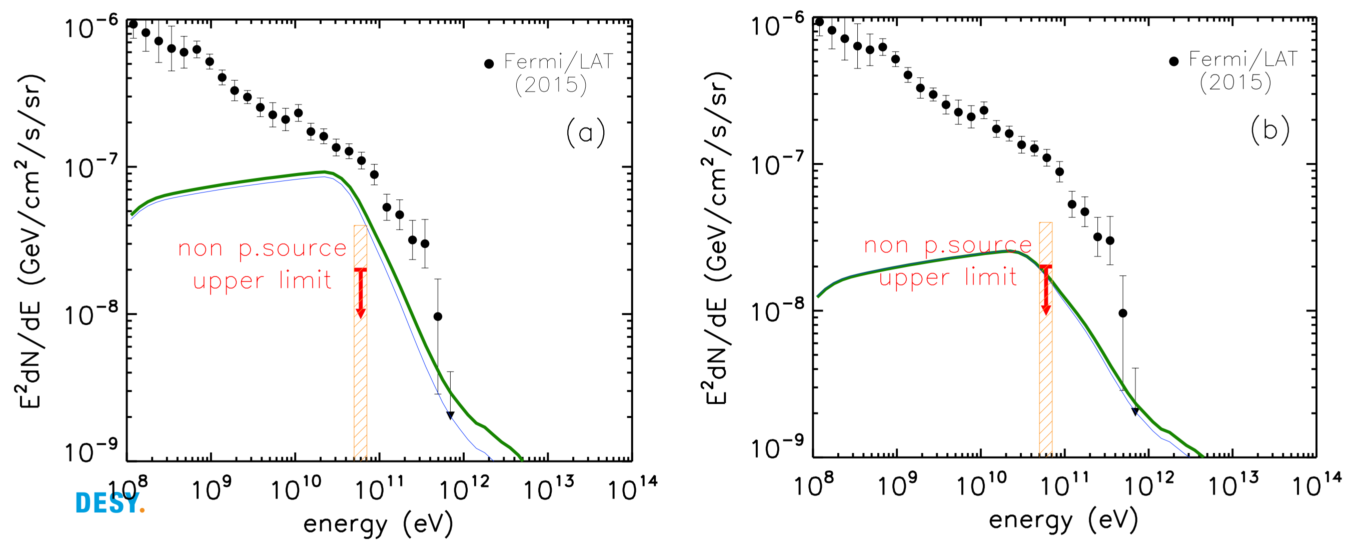
The Origin of Protons Above the Second Knee

SFR evolution scenario

no evolution scenario



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



Liu et al. 2016 (1603.03223)

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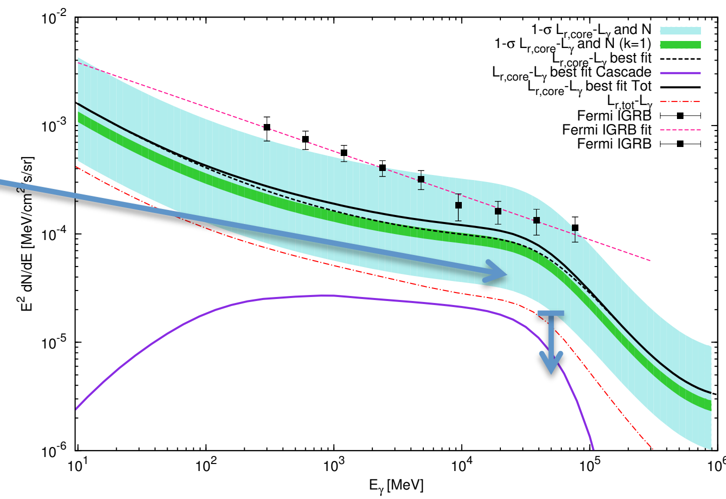
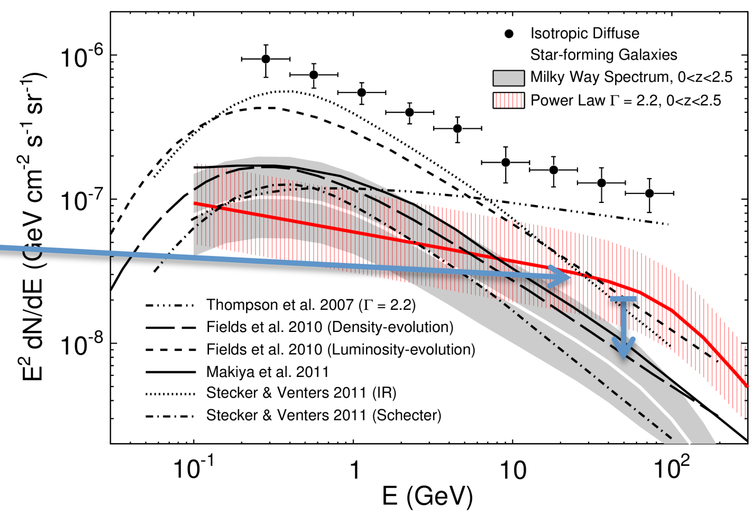
Still Non-Blazar & Starburst Galaxy Contributions Not Removed

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



Di Mauro et al. 2013 (1304.0908)

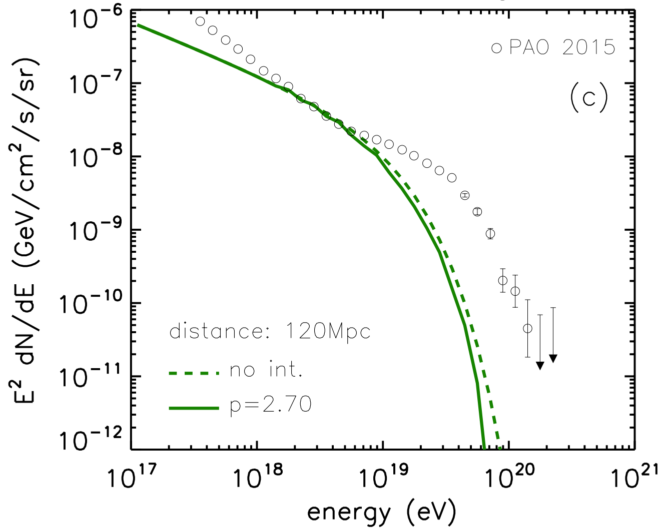
Contribution from lower energy (< 10 PeV) CRs in starburst galaxies

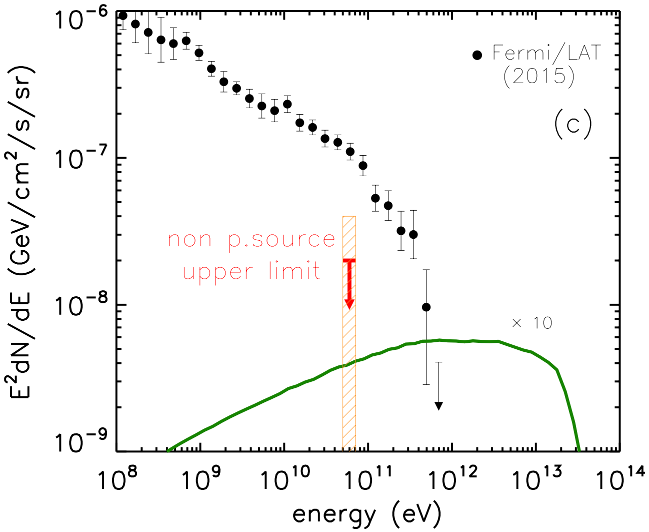


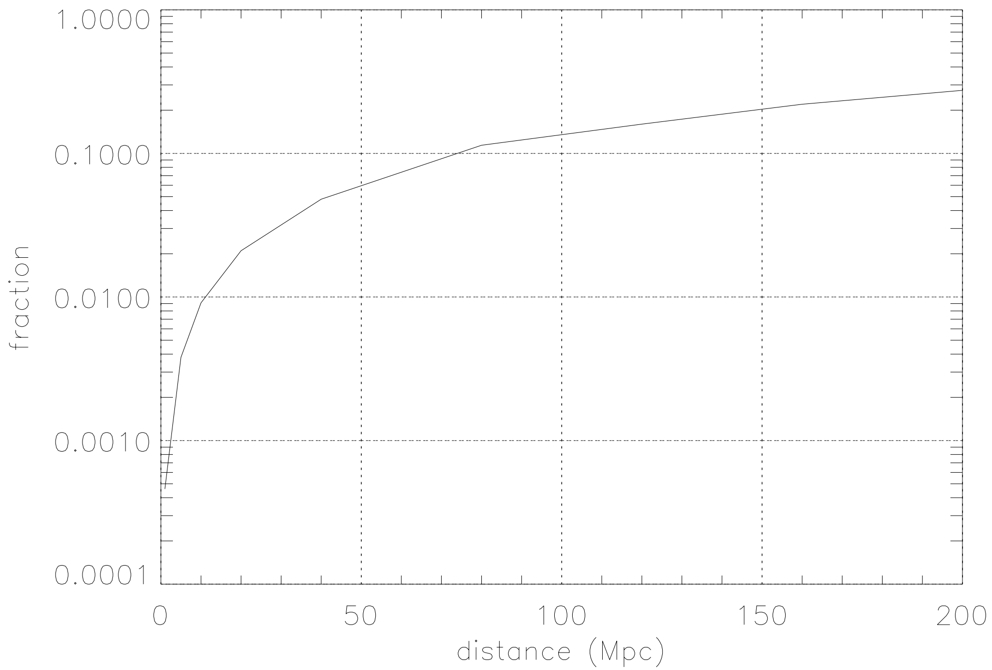
Ackermann et al. 2012 (1206.1346)

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

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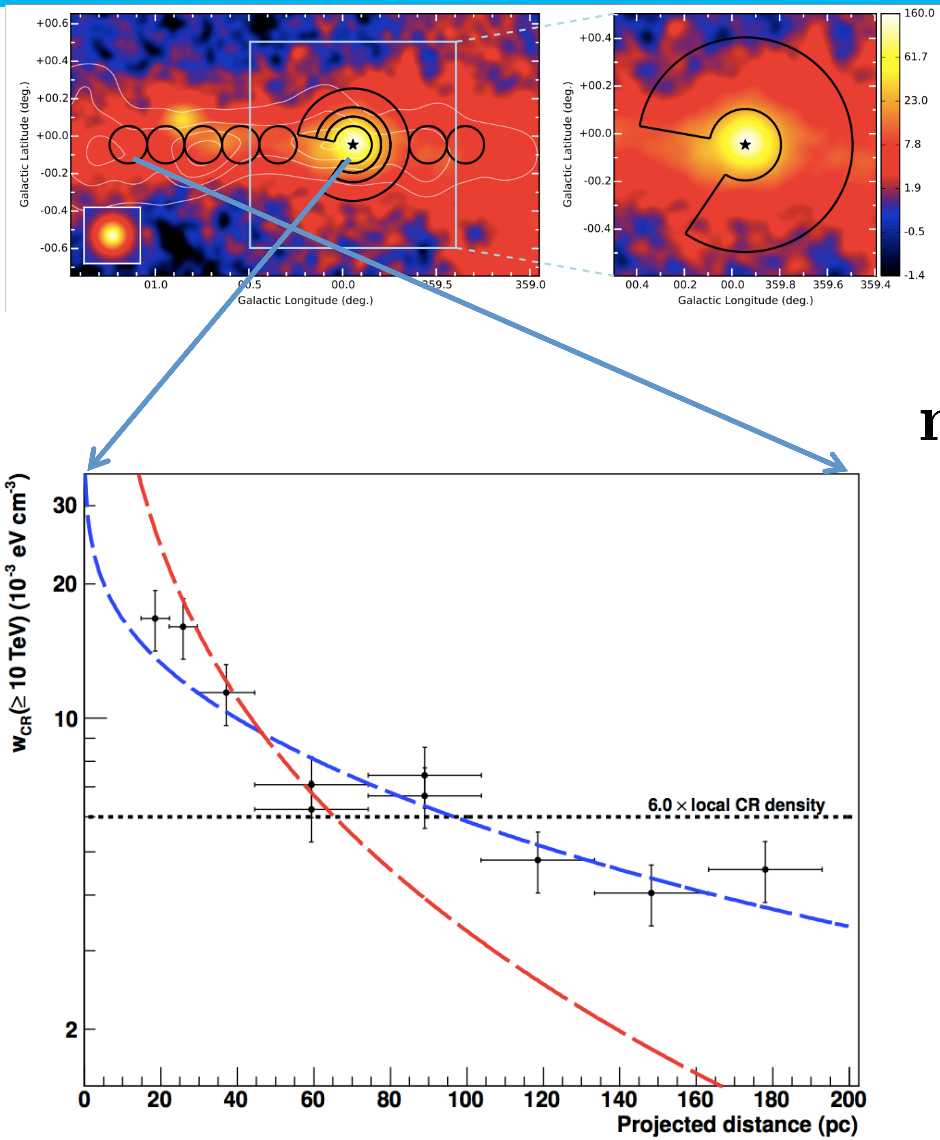
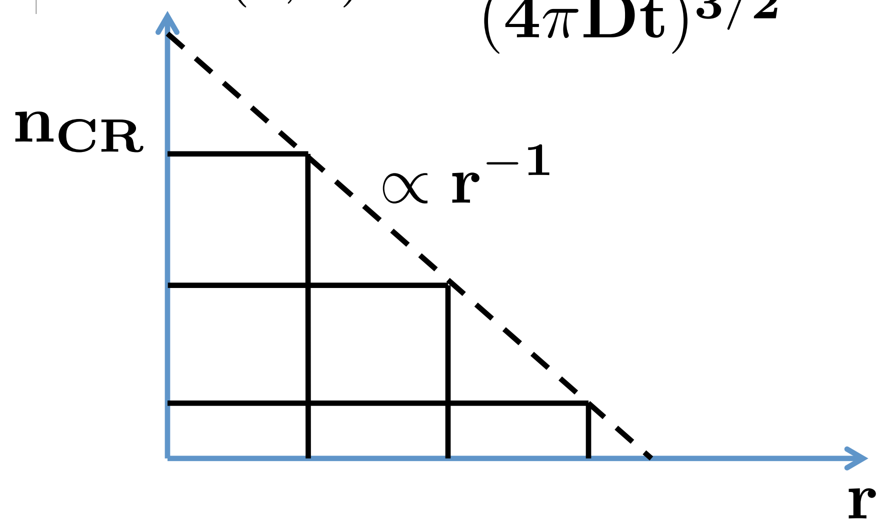
Source of Cosmic Rays Below the Ankle?



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

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

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Abramowski et al. 2016 (1603.07730)

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

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

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

Maximum energy
(Hillas criterion)

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

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

Note however **Eichler et al. 2016 (1604.05721)**

Example Candidate Local Sources

HESS- New Results from Cen A!

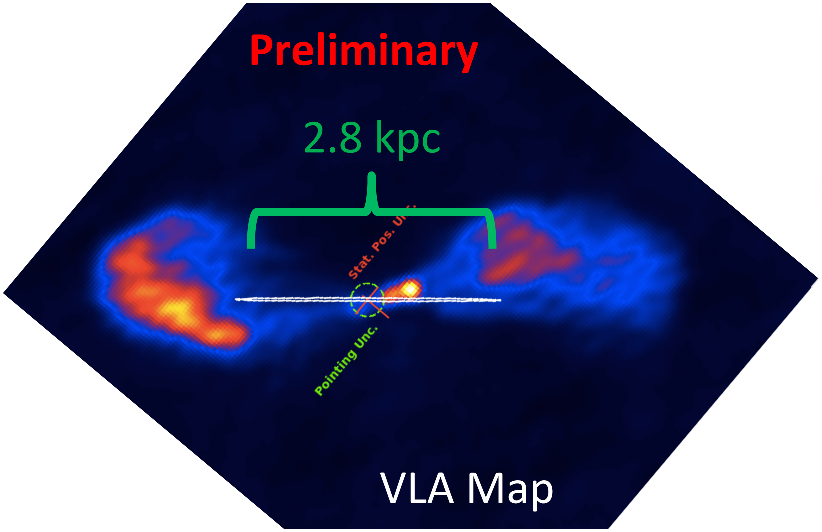
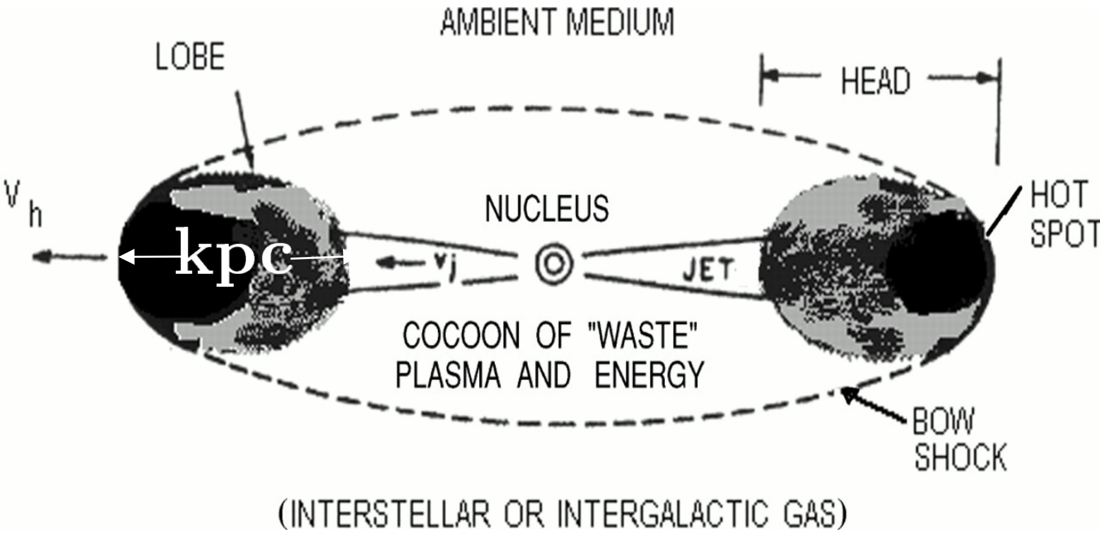


Diagram taken from Ferrari -1998



$$\mathbf{B_{sc} \approx 30\ \mu G}$$

$$\mathbf{R_{Lar}(10^{18}eV\ p) \approx 30\ pc}$$

For $\beta_{\mathbf{scat.}} \approx \mathbf{10^{-1}}$

$$\mathbf{E_{max} \approx 10^{18}eV}$$

$$\mathbf{t_{acc} \approx 0.1\ Myr}$$

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O'Sullivan et al 2009 (0903.1259)

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GW/EM170817 as an Efficient Accelerator

What can we learn from MWL measurements?

Acceleration within remnant timescale constraint (t_{acc}< 100 days)

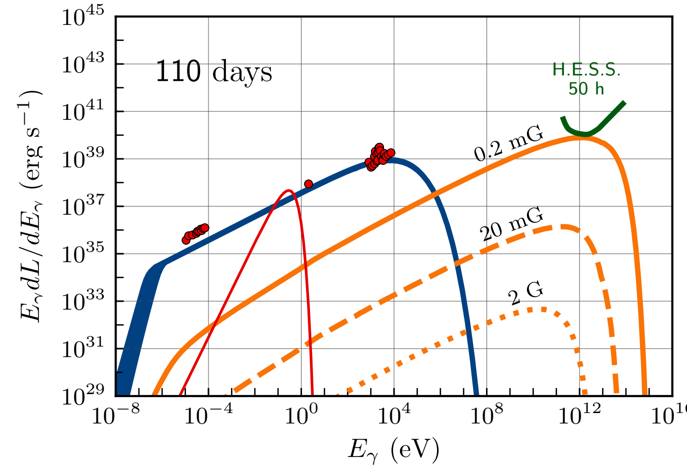
$$\mathbf{B > 0.02\ mG}$$

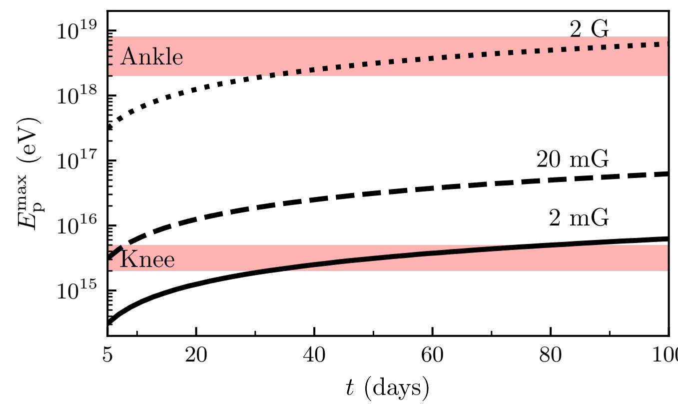
Absence of break in synchrotron emission spectrum up to X-ray energies constraint

$$\mathbf{B < 2\ mG}$$

…alternatively, synchrotron emitting electrons may be always "fresh", or the injection spectrum from the source may be very hard and the electrons observed cooled

synchrotron Inverse Compton





Kimura et al. 2018 (1807.03290) **Rogrigues et al. 2018 (1806.01624)**

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Conclusions

- A negative source evolution allows for an $\mathbf{E^{-2}}$ type spectra to explain CR above the ankle (eg. the evolution observed for 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 sub-ankle cosmic rays.
- Other sources of the diffuse gamma-ray background remain to be removed- UHECR can only be a small contributor to this background
- New input on the candidates for CR sources below the ankle are coming from recent non-thermal observations of the local Universe!

Extra Slides

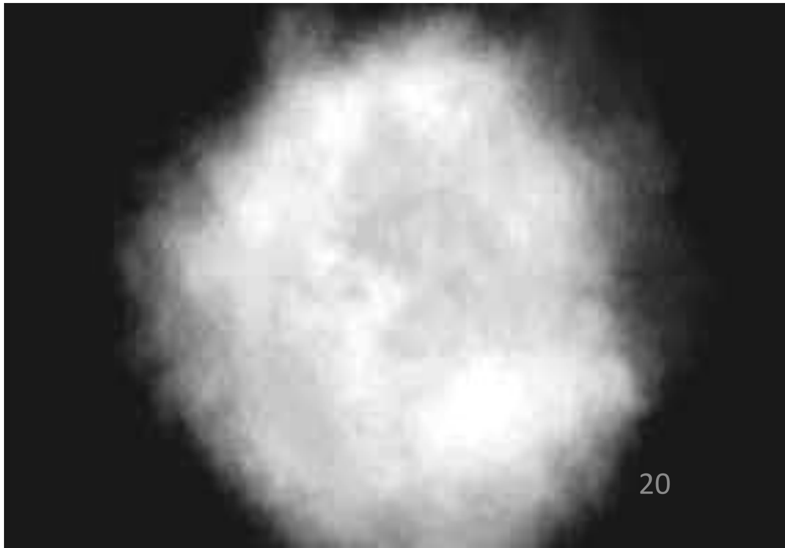
An Alternative Interpretation of the Negative Source Evolution Result

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

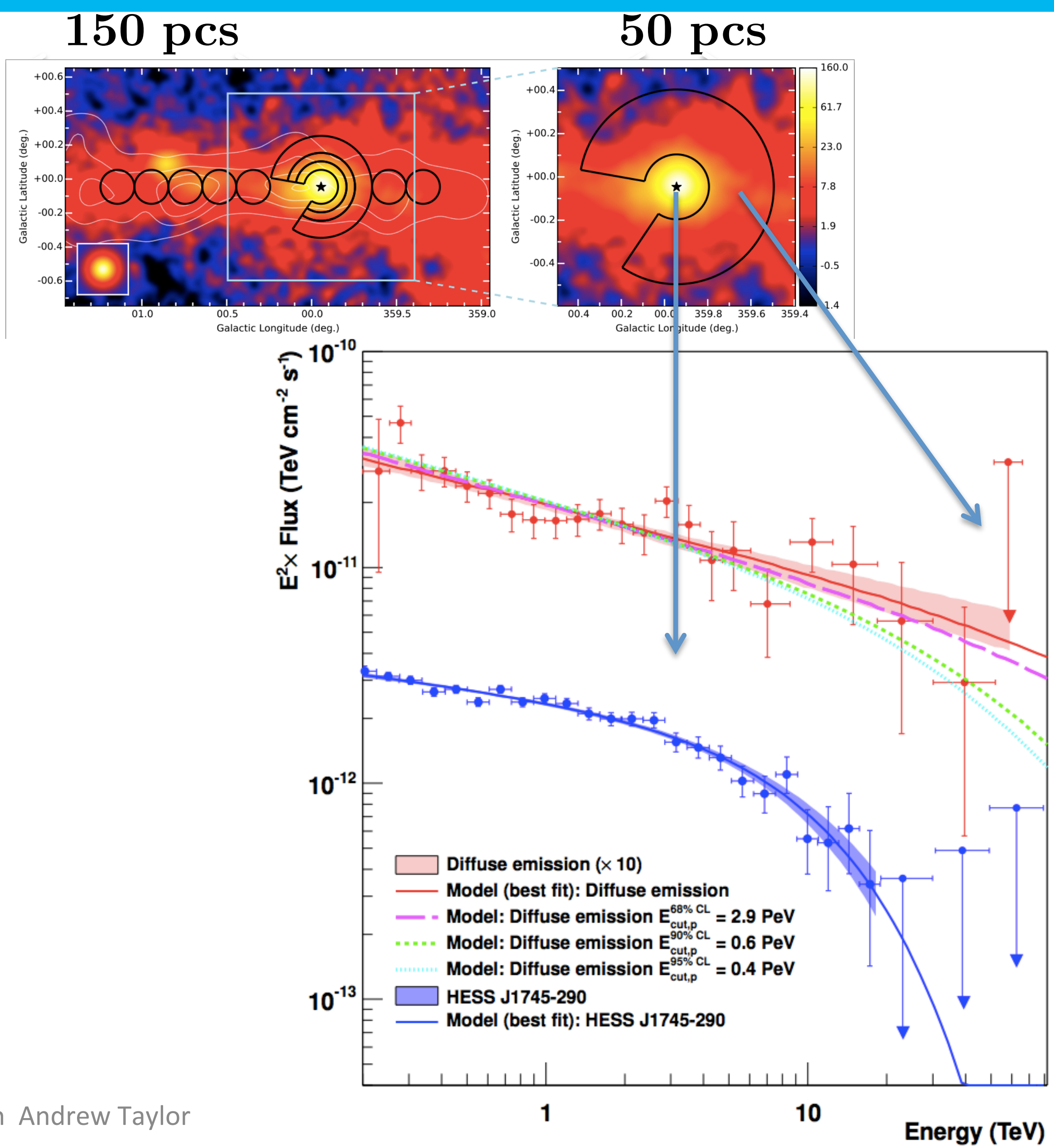
- "hard spectrum"
- "IGRB over-production"

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"!



Galactic Center Pevatron



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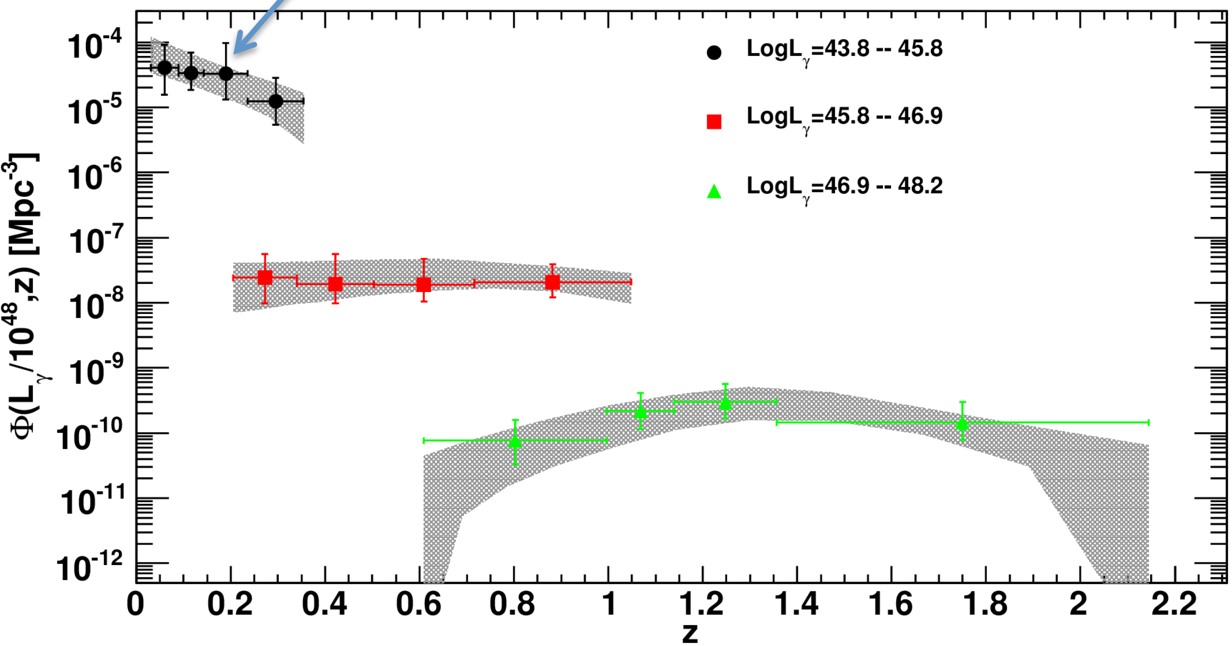
High Spectral Peaked Blazar Evolution

n=-6 evolution result

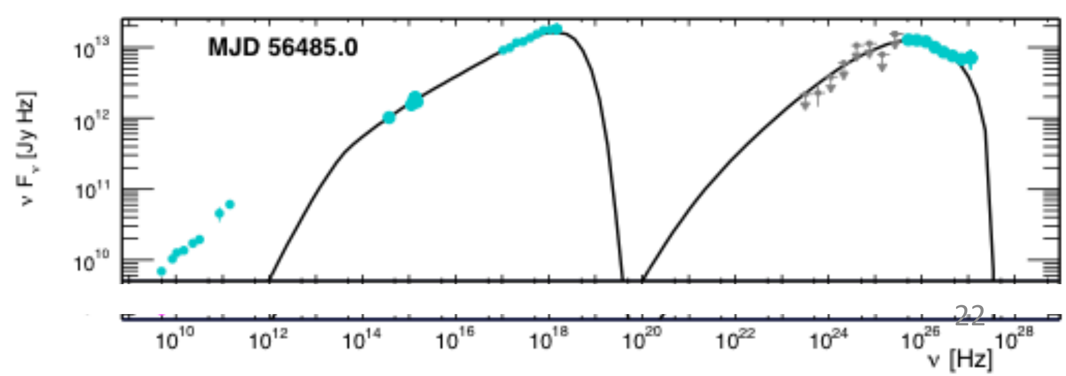


From astro-ph/1310.0006 (Ajello et al. 2014)

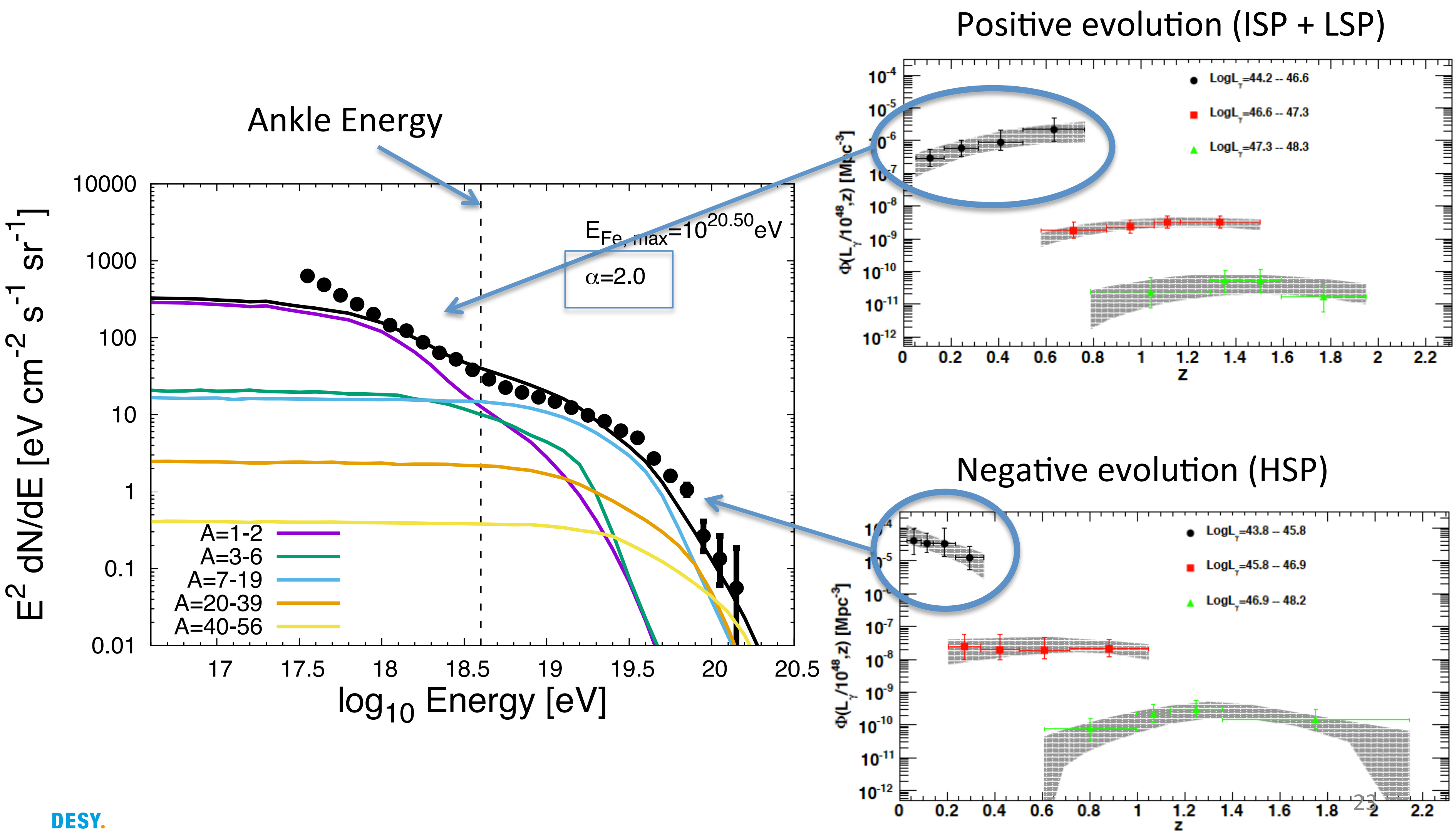
- Reminder:
Blazar -> BL Lac (FR1) -> HSP

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

Archetypal HSP example Mrk 501



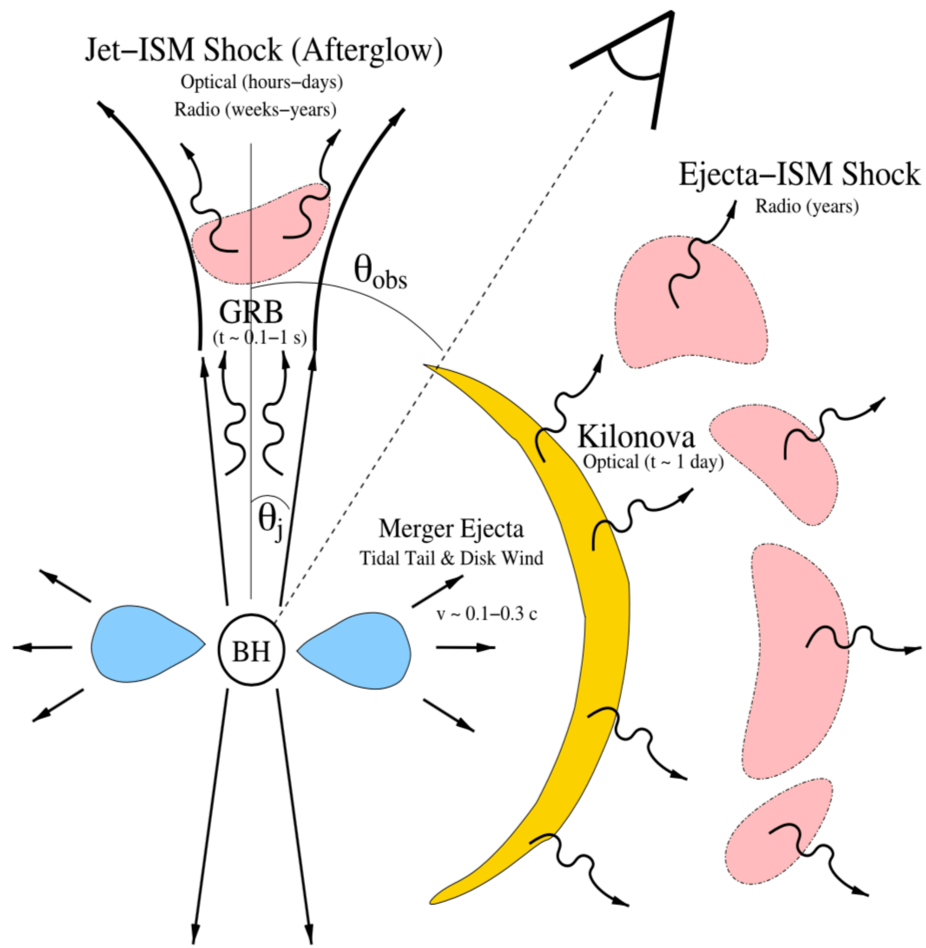
Does a Separate Class of Extragalactic Source Dominate at Sub-Ankle Energies?



Binary neutron-star mergers

Expected electromagnetic emission

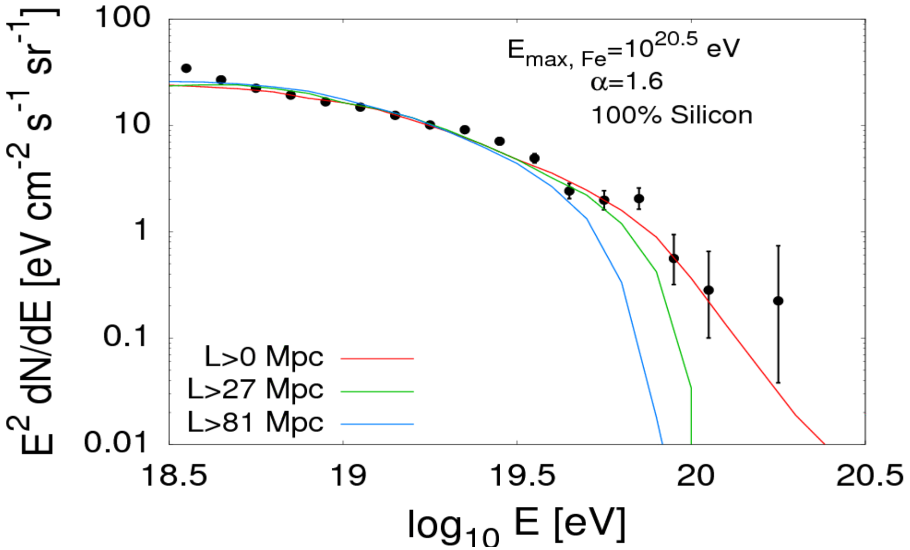
- First proof that Binary NS mergers are progenitors of short GRBs
- Jet emission
  - Internal shocks in jet
  - → particle acceleration
  - Hard X-ray and soft gamma-ray production
  - Timescales of (0.1 – 2) seconds
- Merger Ejecta- gives rise to late time (10-150 day) non-thermal emission



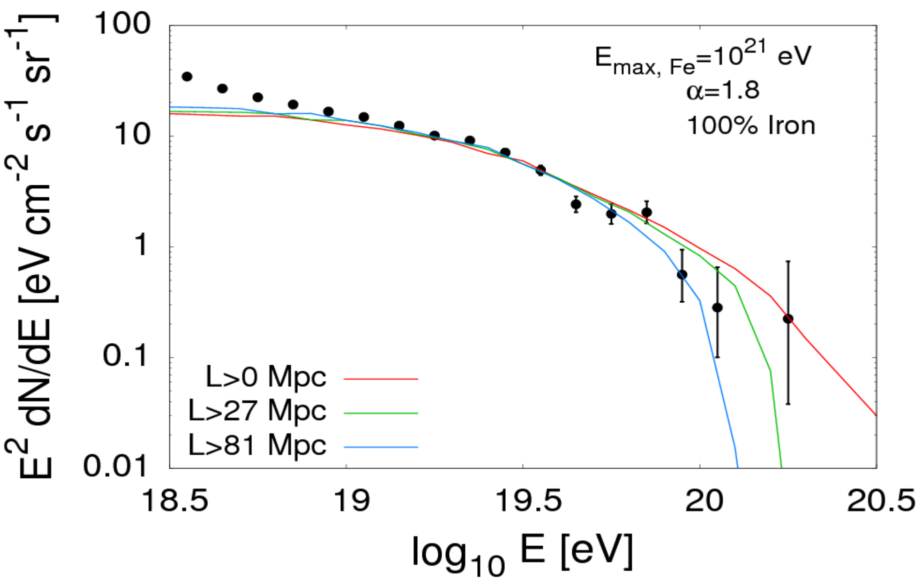
(Baiotti & Rezzolla 2017, pre-GW170817)

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)

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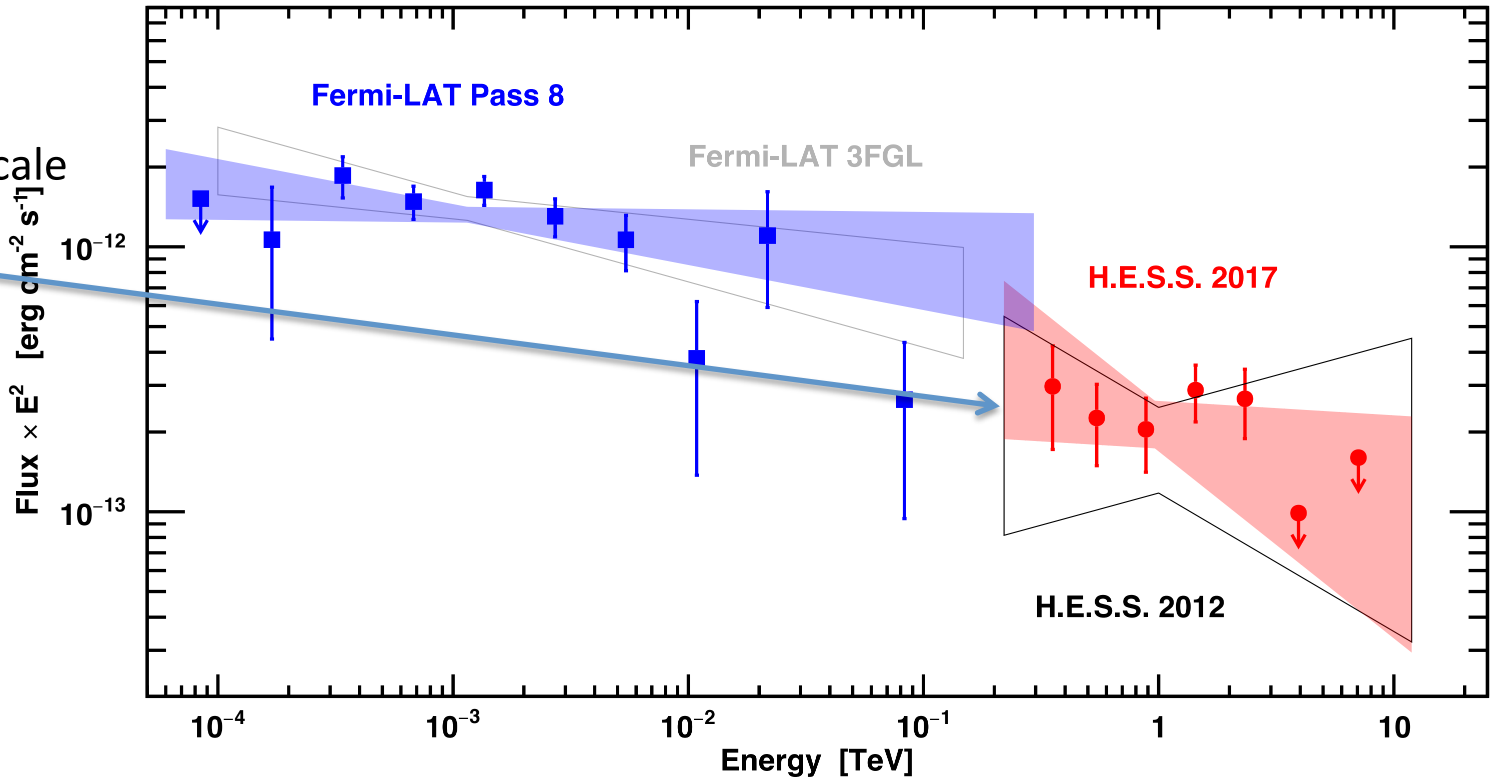
NGC 253: Gamma-Ray Spectrum

Gamma-Ray Spectral Coverage- very good energy information

$$L_\gamma(\mathrm{GeV}) \approx 10^{40}\ \mathrm{erg\ s^{-1}}$$

Could be larger scale diffuse emission missed



Do cosmic ray protons dump all their energy within the source, or are some fraction of them able to escape?

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