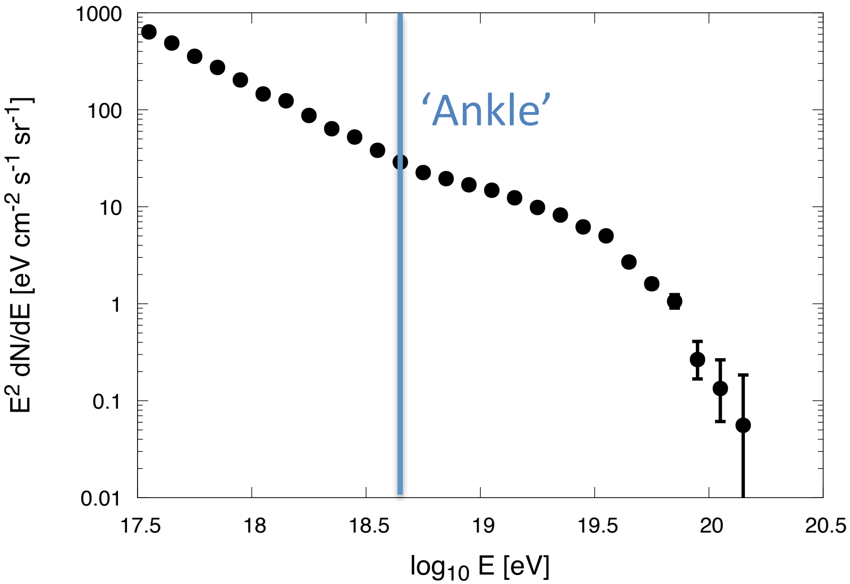
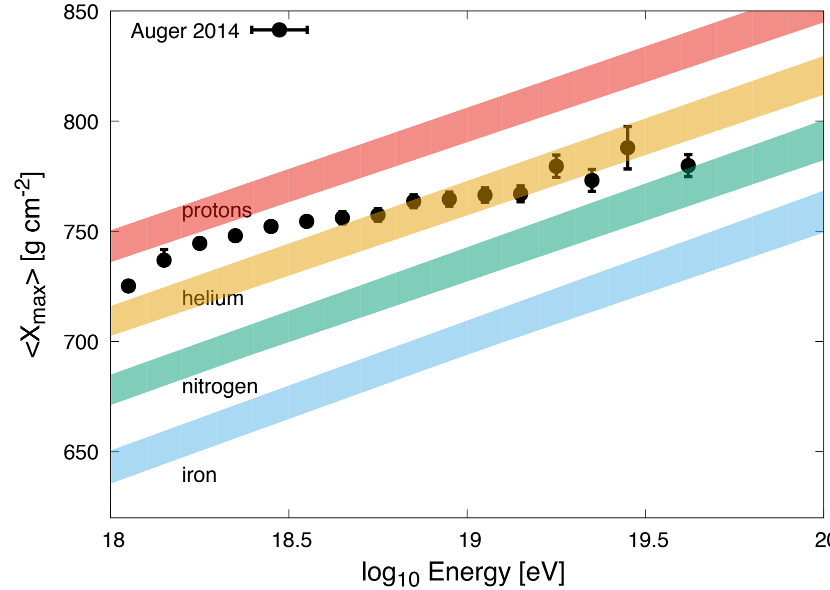
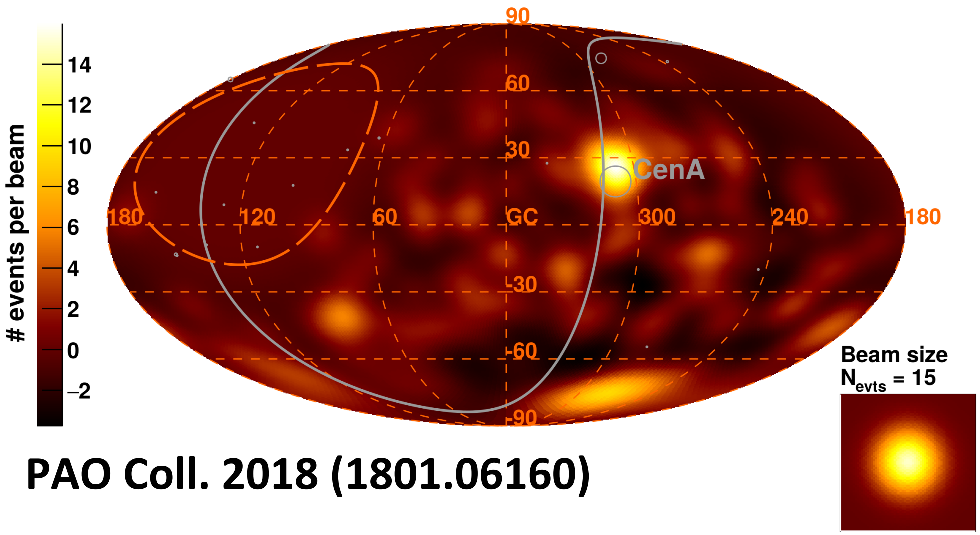
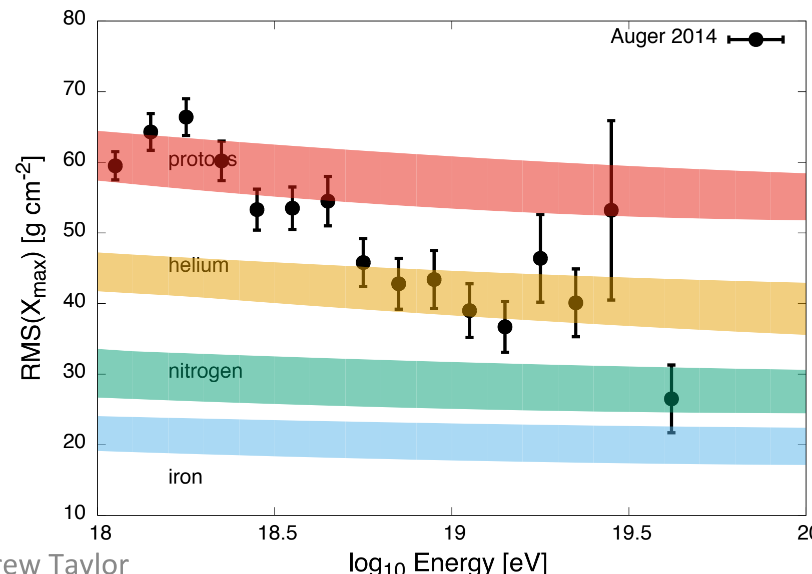
CTA as a Probe of Extragalactic CR Sources





Observed Excess Map - E > 60 EeV





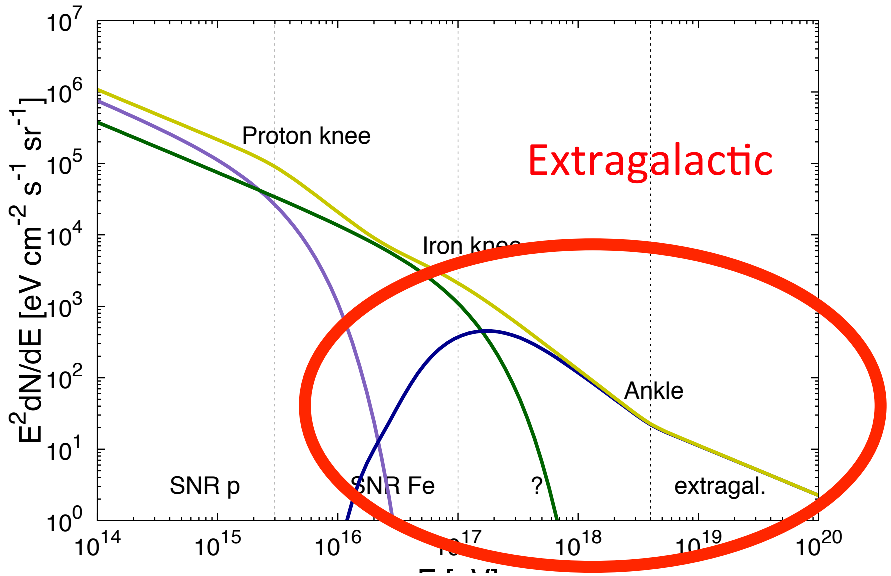
PAO Coll. 2018 (1801.06160)

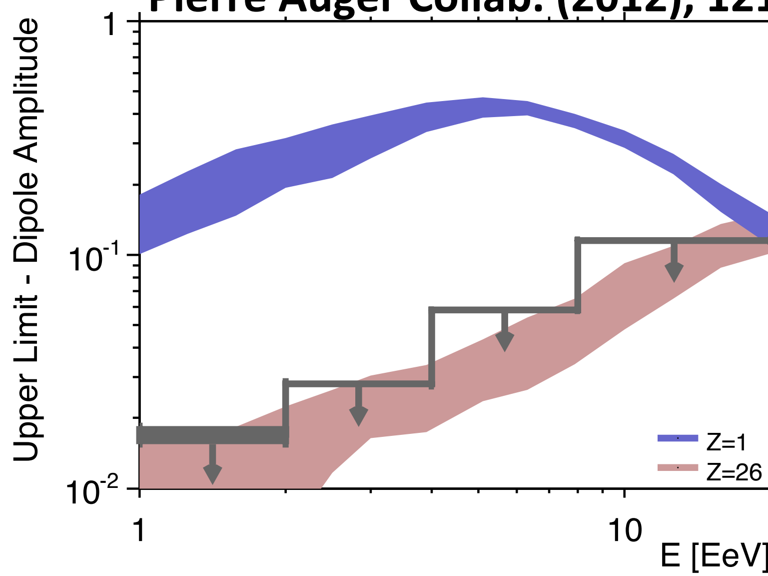
By Andrew Taylor

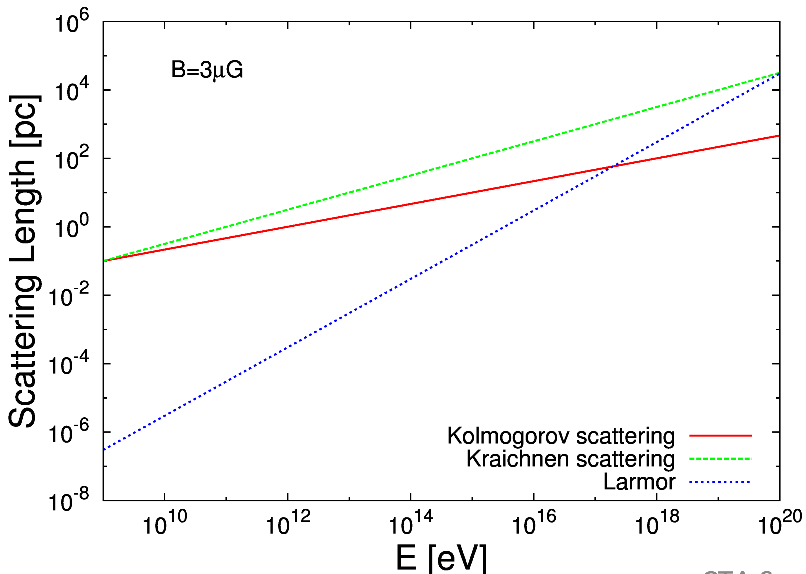
Where Does Extragalactic Begin?

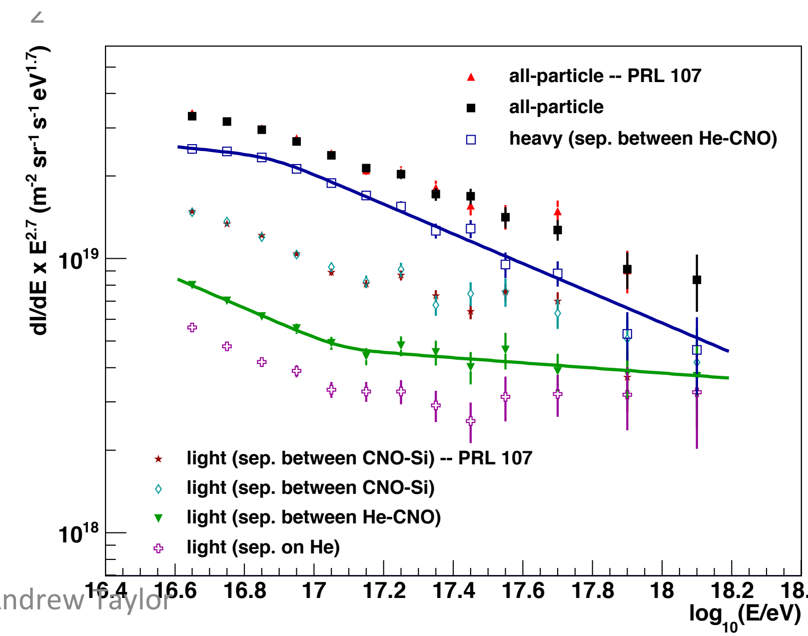
Anisotropy constraint: **Giacinti et al. (2011), 1112.5599**

Pierre Auger Collab. (2012), 1212.3083









Kascade-Grande Coll. (2013), 1304.7114

DESY.

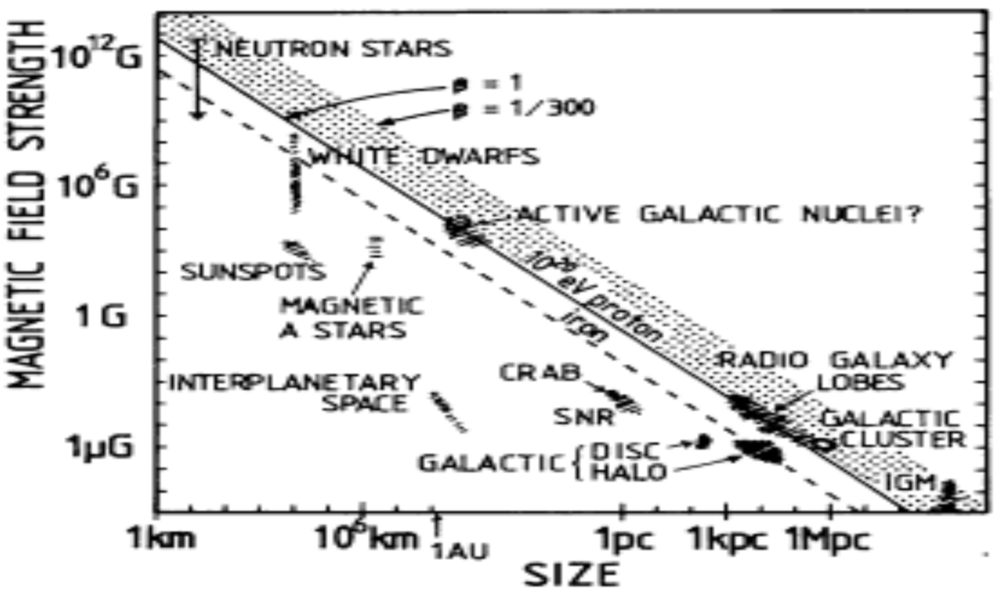
Candidate Sources- Basic Argument Hasn't Changed!

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

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

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

$\eta \approx 1$ assumed in plot below



AM Hillas (1984)

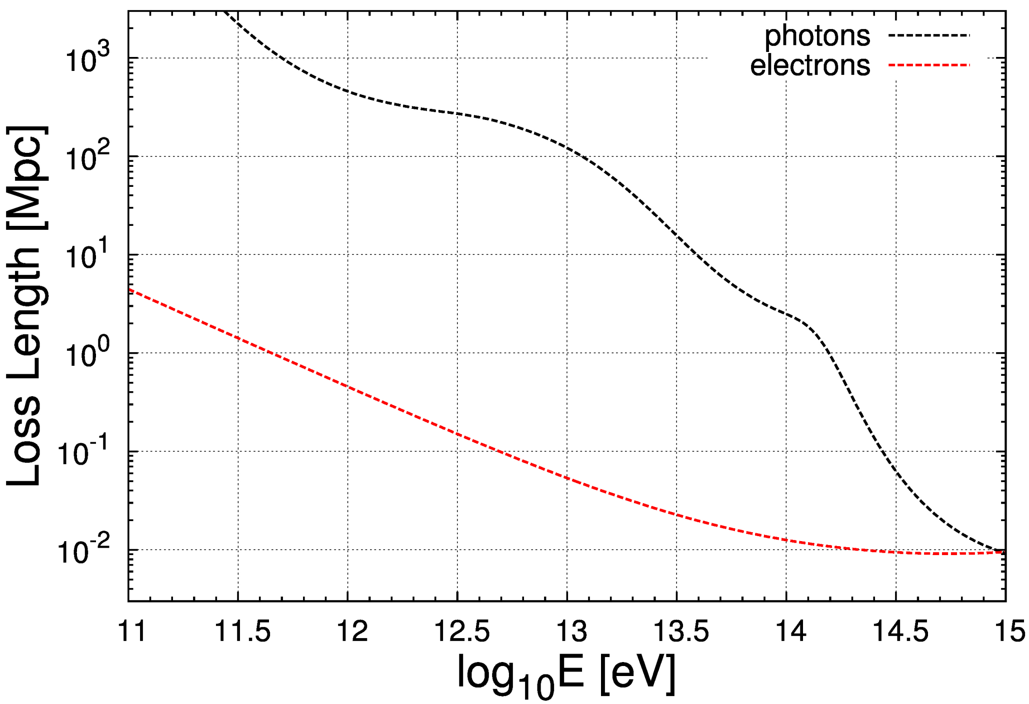
$$\mathbf{L} > \mathbf{3} \times \mathbf{10^{42}} \frac{\mathbf{1}}{\beta^2} \left(\frac{\mathbf{E_p}}{\mathbf{3} \times \mathbf{10^{18}}\ \mathrm{eV}} \right)^{\mathbf{2}} \mathrm{erg\ s^{-1}}$$

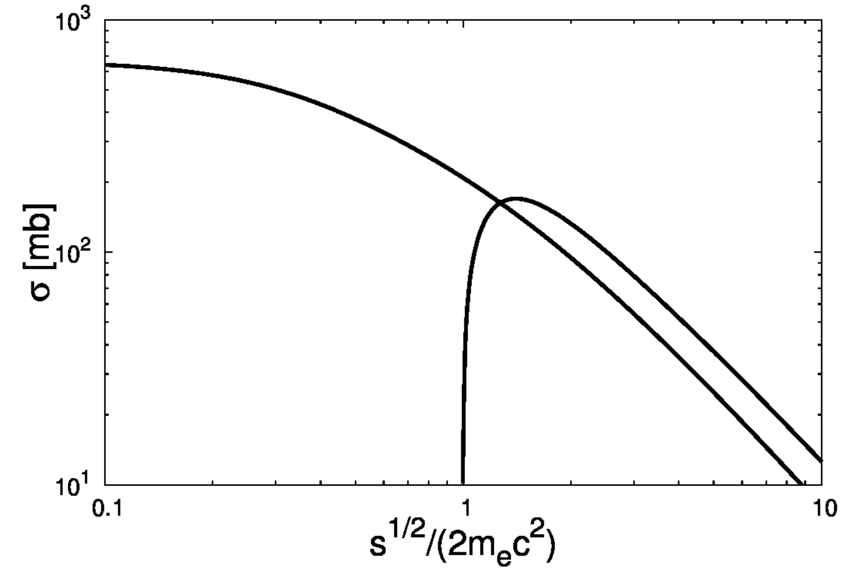
AGN

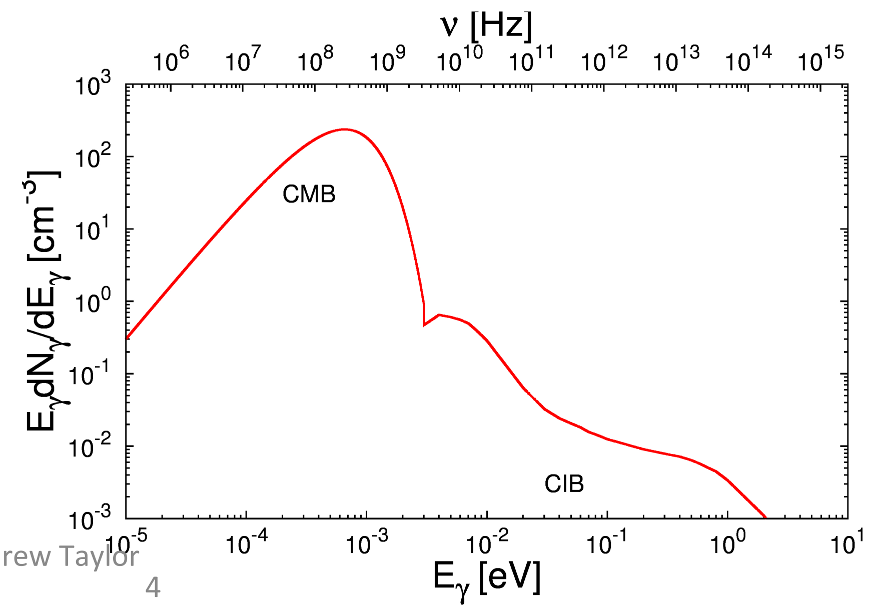
GRB

Norman et al. (1995)

Gamma-Ray Blazars (AGN) and the EBL

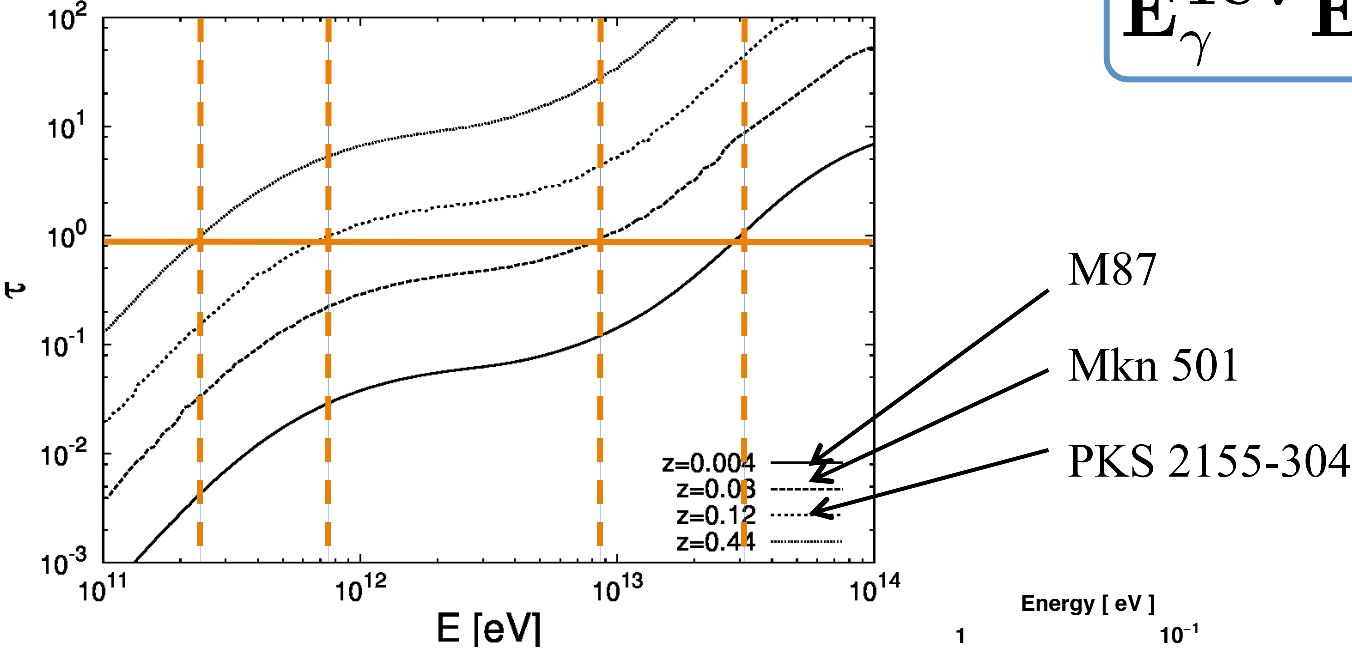


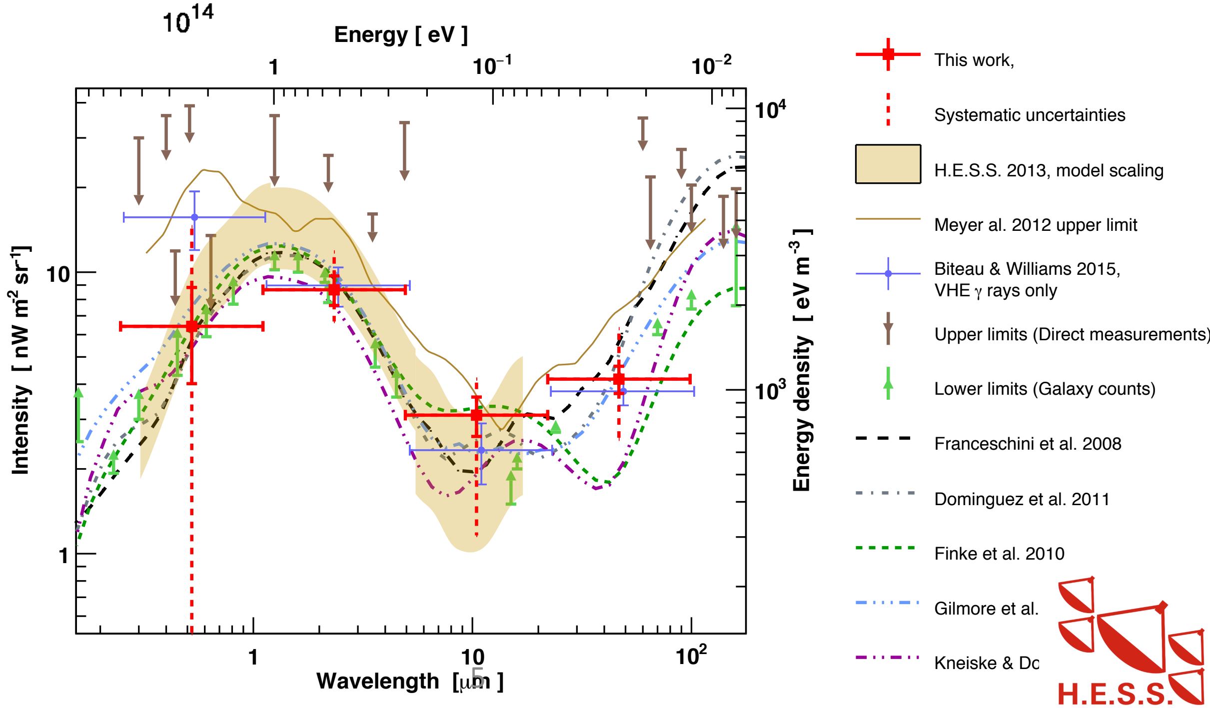




EBL Attenuation

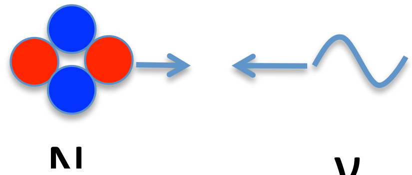
$$E_\gamma^{\mathrm{TeV}} E_\gamma^{\mathrm{eV}} \approx 1$$

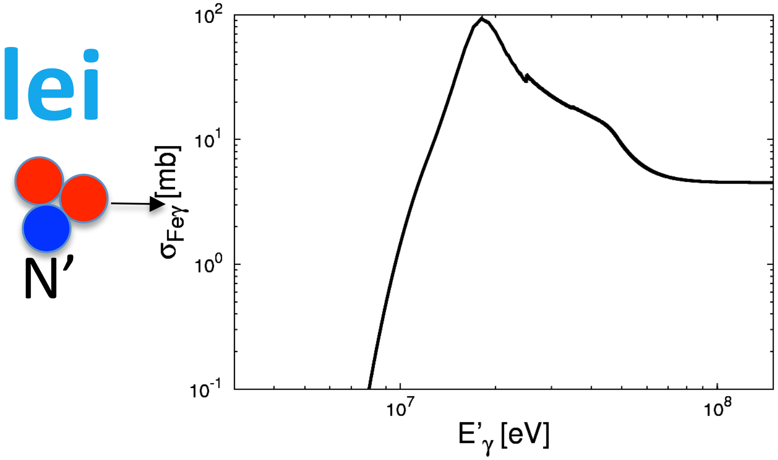




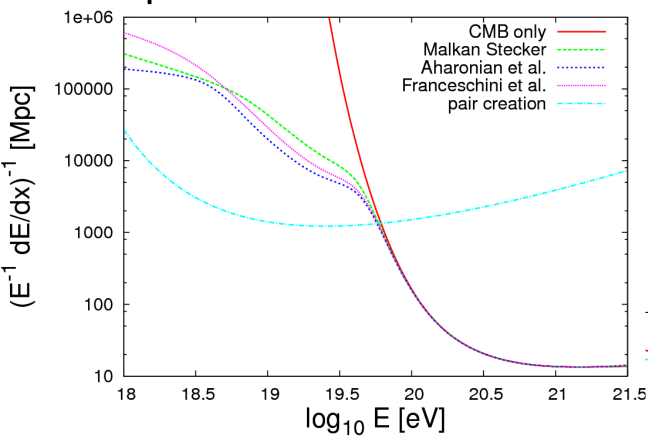
HESS Coll. A&A 606 (2017) A59

Cosmic Ray Proton/Nuclei Interactions

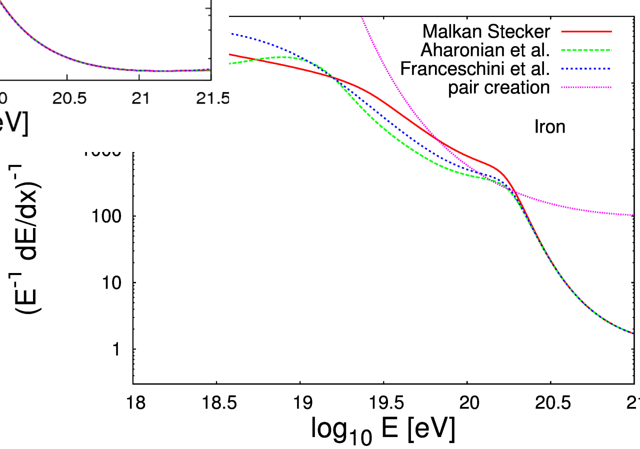


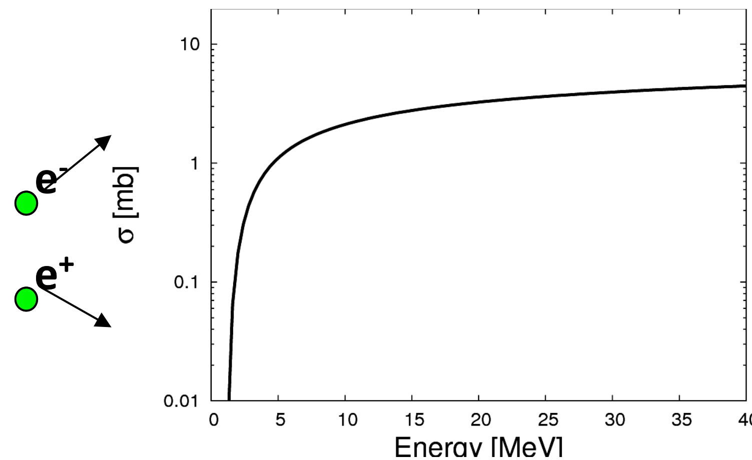


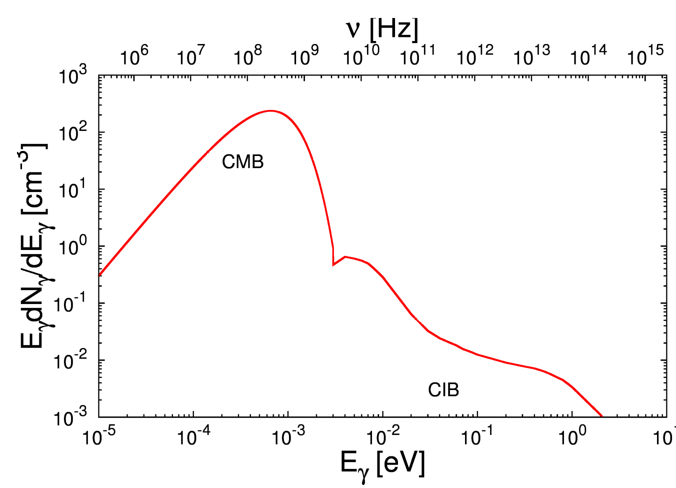
protons



iron

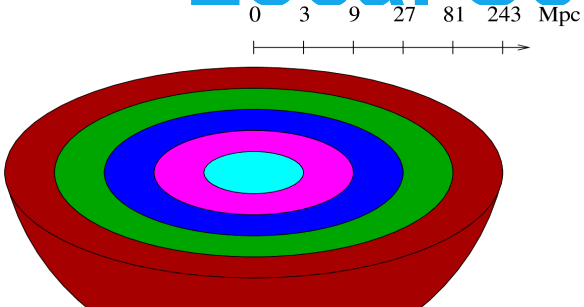




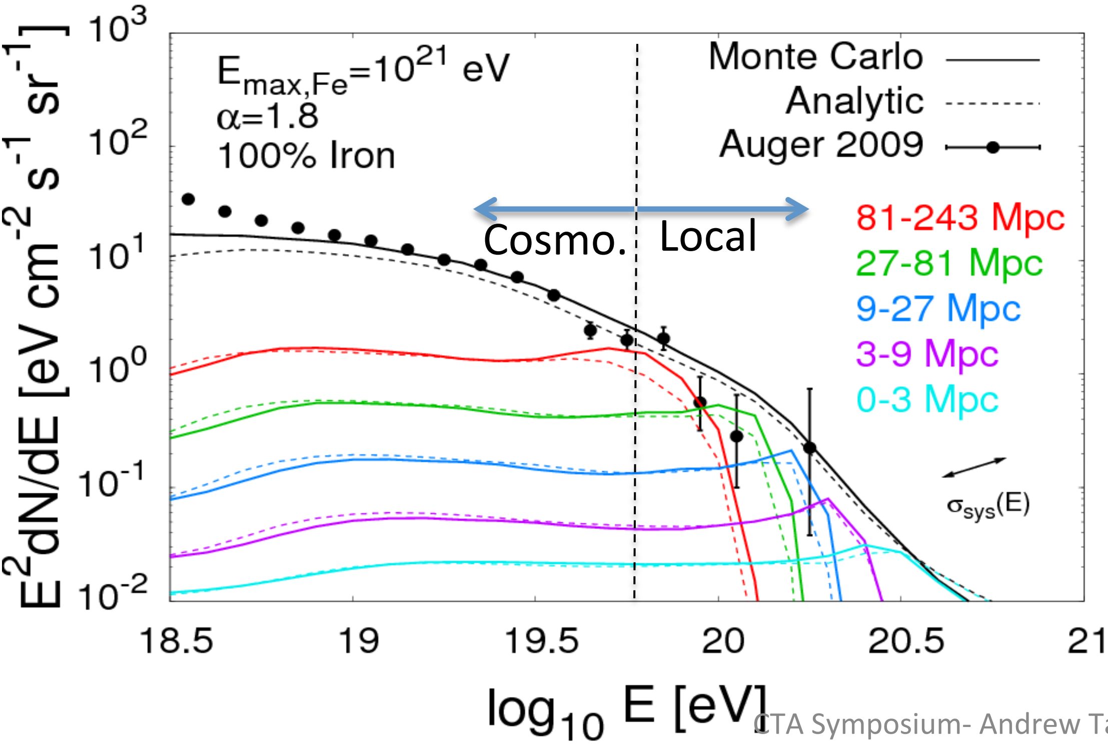


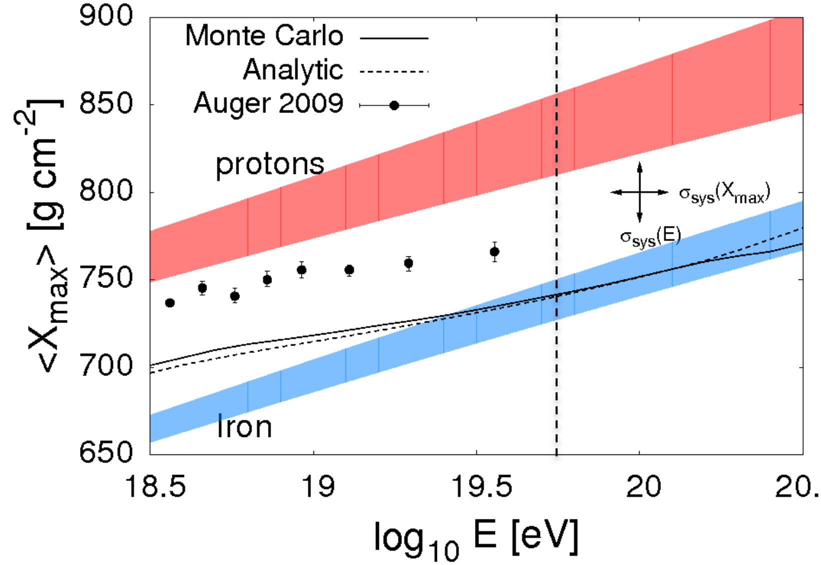
$$E_{CR}^{30PeV} E_{\gamma}^{eV} \approx A$$

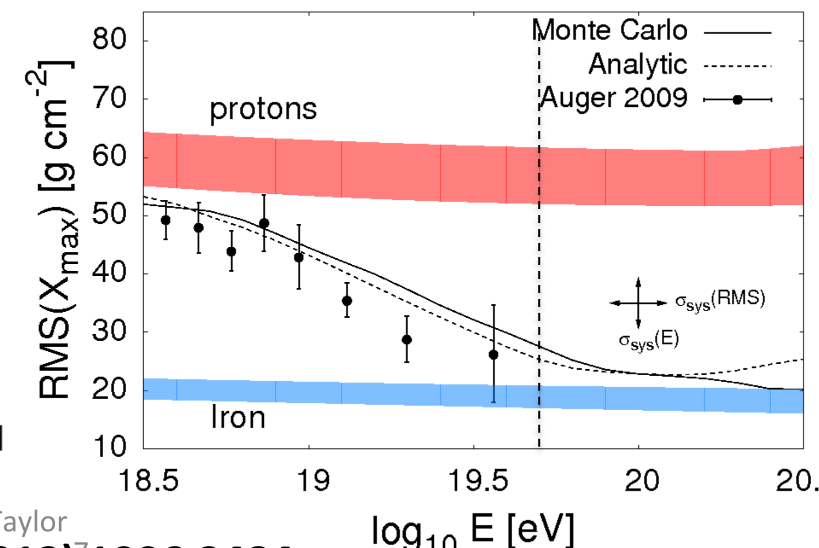
Local Scales Effect Highest Energies: Analytic Treatments



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



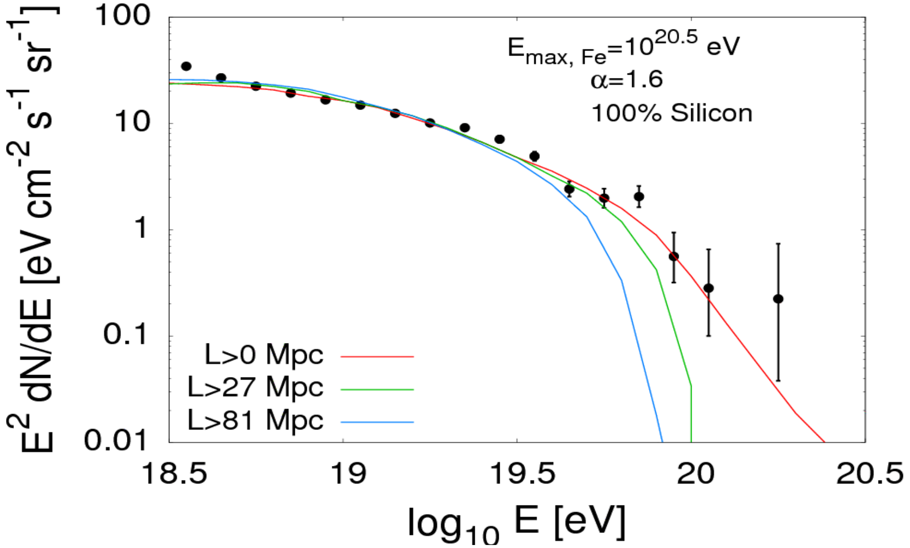




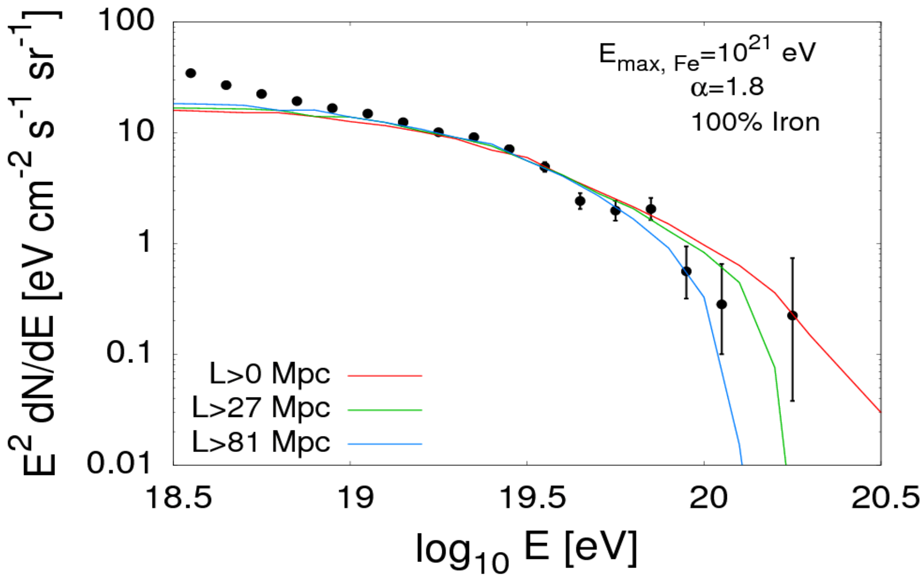
Hooper et al. (2008), 0802.1538 **Aloisio et al. (2013) 1006.2484**

How Far is the Nearest Source?

Silicon- L<60 Mpc



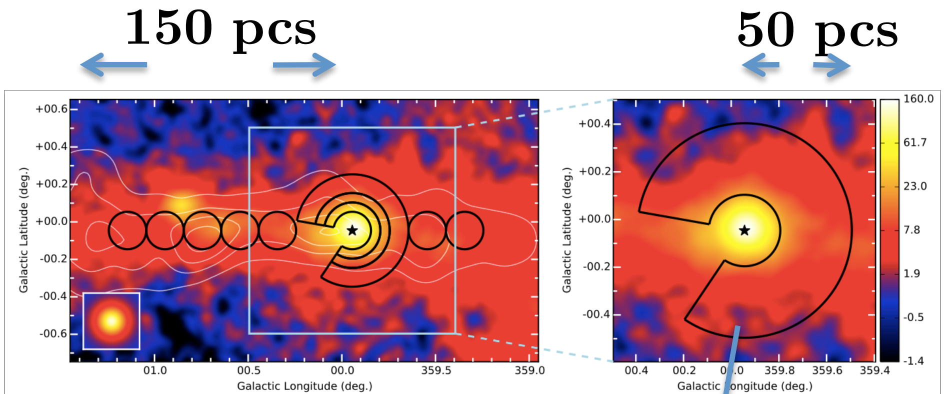
Iron- L<80 Mpc



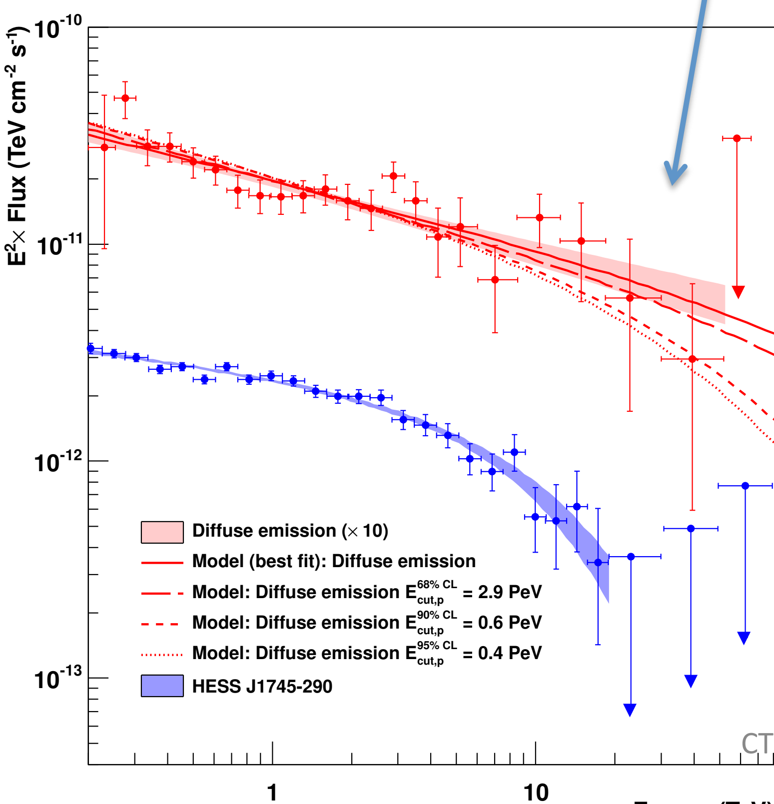
De Marco et al. (2006), 0603615
Taylor et al. (2011), 1107.2055
Fargion et al. (2015), 1412.1573

Galactic Center- Sgr A*

HESS Coll. Nature 531 (2016) 476



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



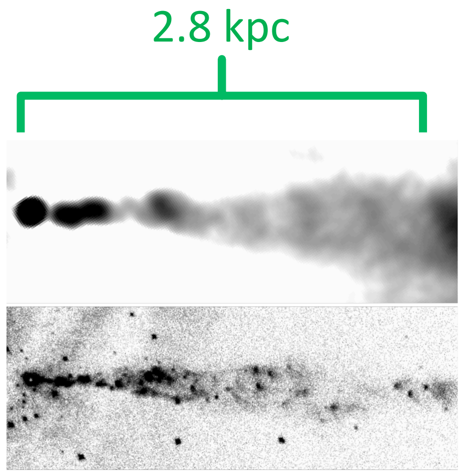
Further Questions:

1) Maximum energy of cosmic rays produced? (info from Auger)
2) Stability of the source Power?

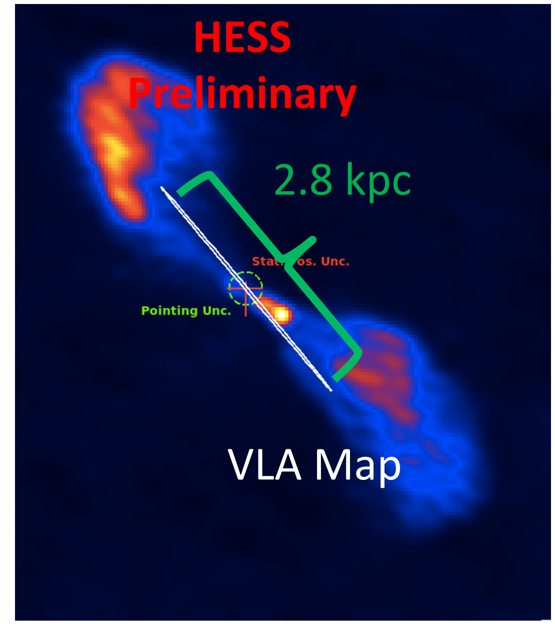
H.E.S.S.

Max Energy on Smaller Scales of Cen A?

Hardcastle et al. (1103.1744)



HESS Coll. TeVPa 2018



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

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

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

For $\beta_{\mathbf{scat.}} \approx \mathbf{10}^{-\mathbf{1}}, \ \eta \approx \mathbf{10}^{\mathbf{3}}$

Maximum energy (Hillas criterion)

$$\mathbf{E_{max}} \approx \mathbf{10}^{\mathbf{15}}\mathbf{eV}$$

Other (Local) Candidates- GRBs

New Information About sGRBs

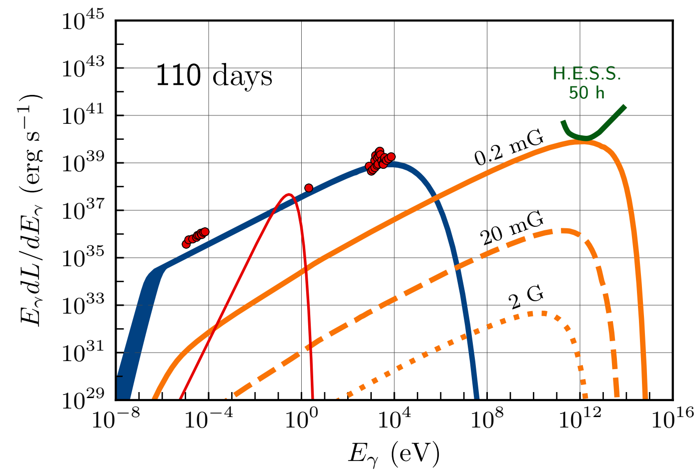
Acceleration within remnant timescale constraint (t_{acc}< 100 days)

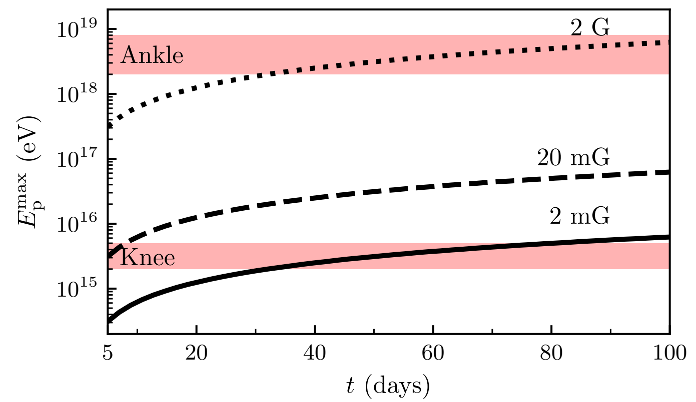
$$\mathbf{B > 0.02\ mG}$$

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

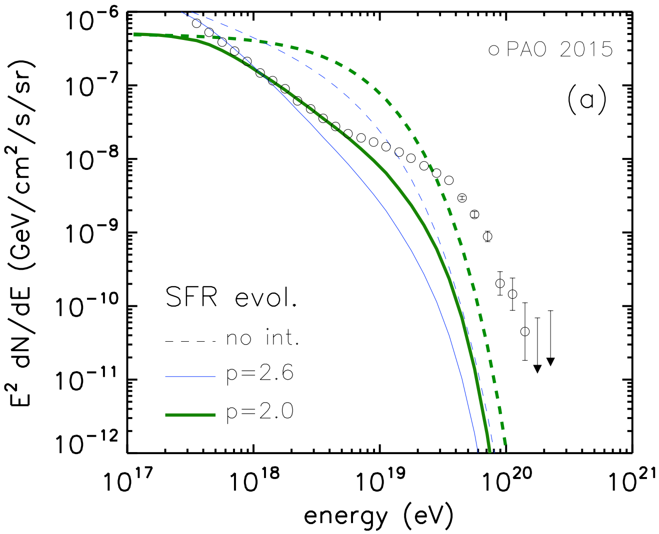


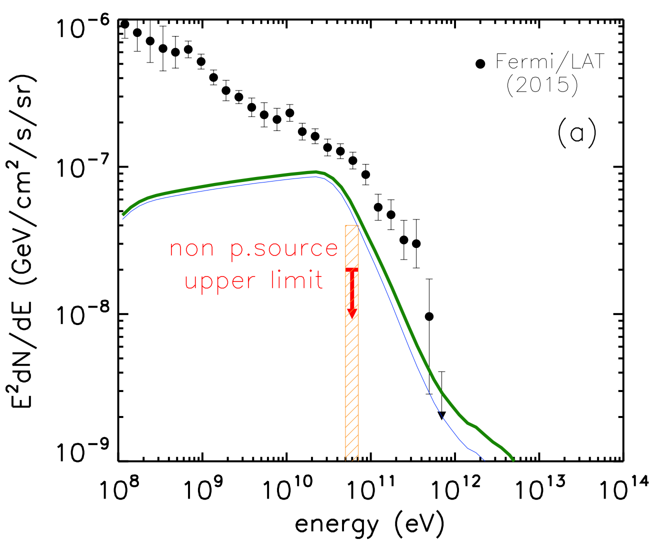


Kimura et al. 2018 (1807.03290) **Rogrigues et al. 2018 (1806.01624)**

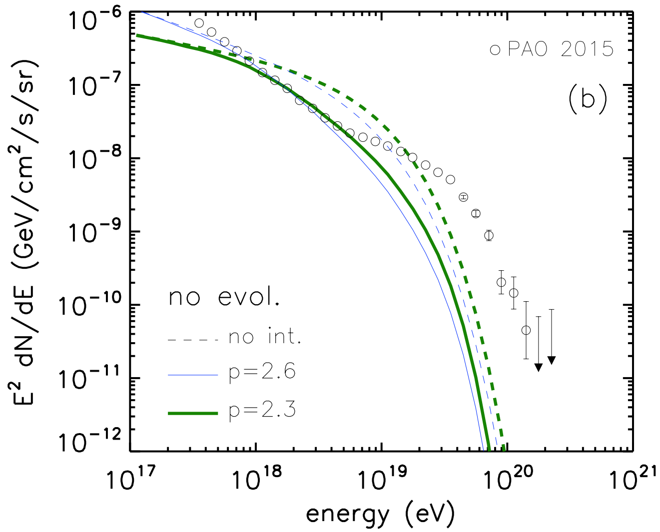
The Origin of Protons Below the Ankle

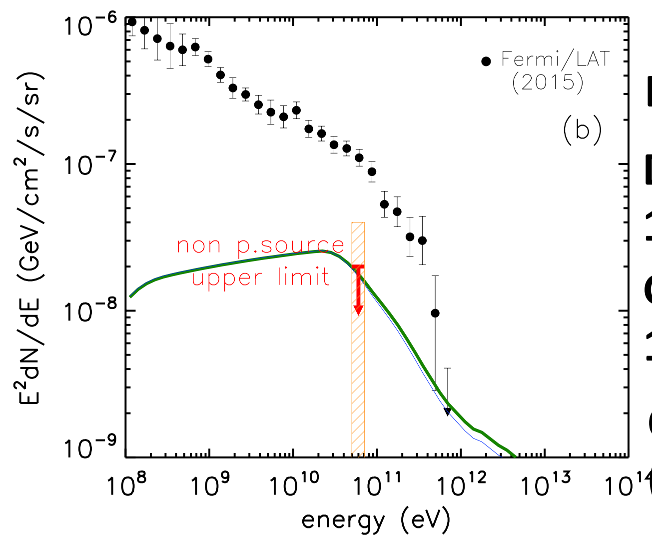
SFR evolution scenario





no evolution scenario





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

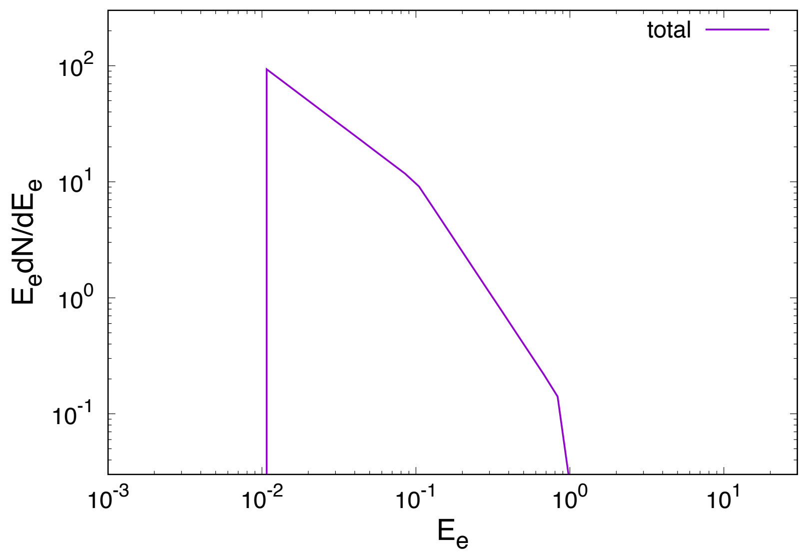
Liu et al. (2016), 1603.03223

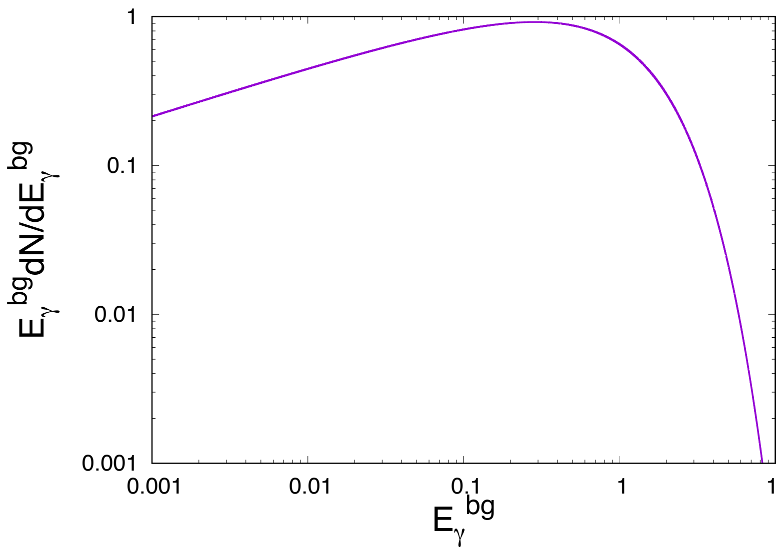
Decerprit et al. (2011), 1107.3722

Gelmini et al. (2012), 1107.1672

Crostron et al. 2019 (1801.10172)

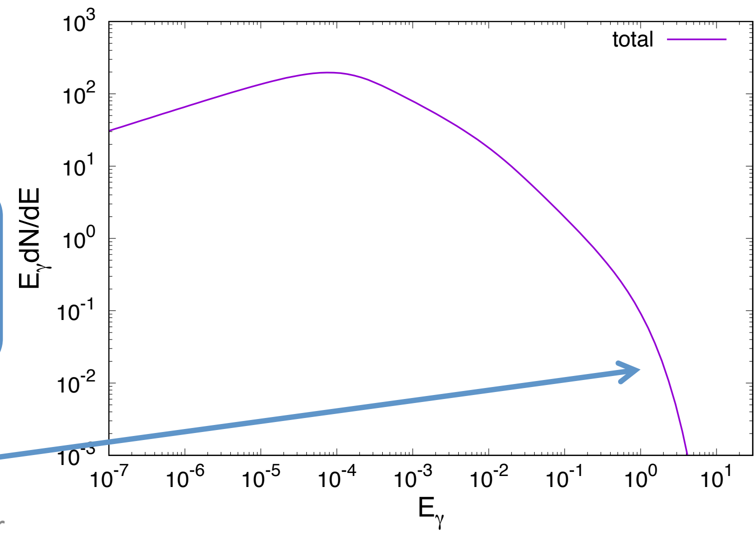
Future Probes- Cutoff Region





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

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



Possibility to probe cutoff region

Cut-off Generation- A Simple Case

- Bohm diffusion (**q=1**) + only escape results in simple exponential cutoff.
- Some simplifications to the transport equation:

$$\frac{\partial \mathbf{f}}{\partial \mathbf{t}} = \nabla_{\mathbf{p}} \cdot \left[(\mathbf{D_{pp}} \nabla_{\mathbf{p}} \mathbf{f}) - \frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})} \mathbf{f} \right] - \frac{\mathbf{f}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \frac{\mathbf{Q}}{\mathbf{p^2}}$$

Steady state

No losses

Delta injection

$$\frac{\partial^2 \mathbf{f}}{\partial \mathbf{p}^2} + \frac{\mathbf{3}}{\mathbf{p}} \frac{\partial \mathbf{f}}{\partial \mathbf{p}} - \left(\frac{\mathbf{1}}{\mathbf{D_0} \tau_{\mathbf{0}}} \right) \mathbf{f} = \delta(\mathbf{p})$$

Cutoff comes from balancing 1st and 3rd term → $\mathbf{f} \propto \mathbf{A} \mathbf{e}^{-\mathbf{p}/\mathbf{p}_\tau}$

$$\mathbf{q} = \mathbf{1}, \ \mathbf{r} = \mathbf{0}, \ \rightarrow \ \beta_{\mathbf{e}} = \mathbf{1}$$

Cut-off Shape- Emission Dependence

$$\frac{dN}{dE_e} \propto E_e^{-\Gamma} e^{-(E_e/E_{max})^{\beta_e}}$$

$$\frac{dN}{dE_\gamma} \propto E_\gamma^{-\Gamma} e^{-(E_\gamma/E_{max})^{\beta_\gamma}}$$

Recall generally, $\beta_e = 2 - q - r$

- Different emission processes dictate different relation between electrons and gamma rays

e.g.

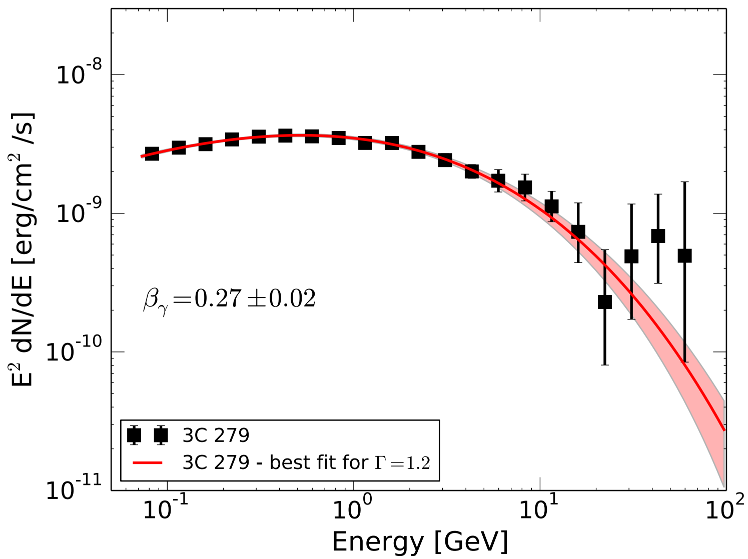
- Synchrotron/IC Thomson: $\beta_\gamma = \frac{\beta_e}{\beta_e + 2}$
- SSC: $\beta_\gamma = \frac{\beta_e}{\beta_e + 4}$
- IC (Klein Nishina) $\beta_\gamma = \beta_e$

Good measurement of gamma ray cut-off can give insight into the acceleration environment

Observation of Cut-offs in Gamma-ray Spectra

- 2nd Brightest AGN Flare-

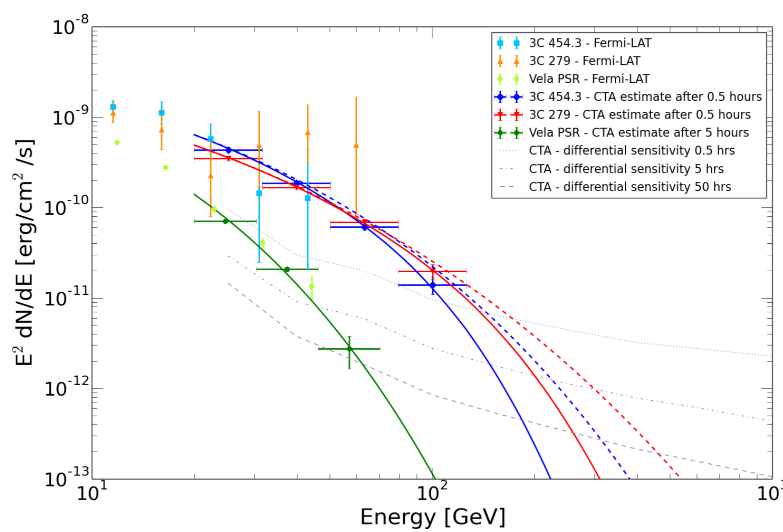
3C 279 June 2015



Parameter	$\Gamma = 1.2$
N [ph/cm^2/s/GeV]	$(2.8^{+0.8}_{-0.6})\ 10^{-4}$
Γ (fixed)	1.2
E_c [GeV]	$(8.4^{+6.6}_{-4.1})\ 10^{-3}$
β_γ	0.27 ± 0.02
E_s (fixed) [GeV]	

Values obtained on a 3 days integration
Note- X-ray observations during flare indicated that $\Gamma = 1.17 \pm 0.06$

Romoli et al., **Astropart.Phys. 88 38-45 (2017)**



Study using the expected CTA performance
Fermi data integrated over 3 days
Constraint on parameter at 10% level obtained during only 0.5 hr flare!

Fermi Gamma-ray Space Telescope

DESY.

Conclusion

- Nearby extragalactic cosmic ray sources must exist
- Further probe of the Galactic center still needed to understand nature and limitations of source
- The probe of nearby candidates is helping to put the pieces in place about how these accelerators operate
- The time domain holds key potential for probing sources, which CTA is particularly suited to take advantage of

A Simple Case (II)- q=1, only escape

- Rearranging the terms (and explicitly stating the dependences from p of the parameters):

$$\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_0 \frac{p}{p_0}\frac{\partial f}{\partial p}\right) - \frac{f}{\tau_{esc}(p)} = \delta(p), \qquad \tau_{esc}(p) \propto p^{-1}$$

$$\boxed{\frac{\partial^2 f}{\partial p^2} + \frac{3}{p}\frac{\partial f}{\partial p} - \left(\frac{1}{D_0 \tau_0}\right) f = \delta(p)}$$

Cutoff comes from balancing 1st and 3rd term → $f \propto A e^{-p/p_\tau}$

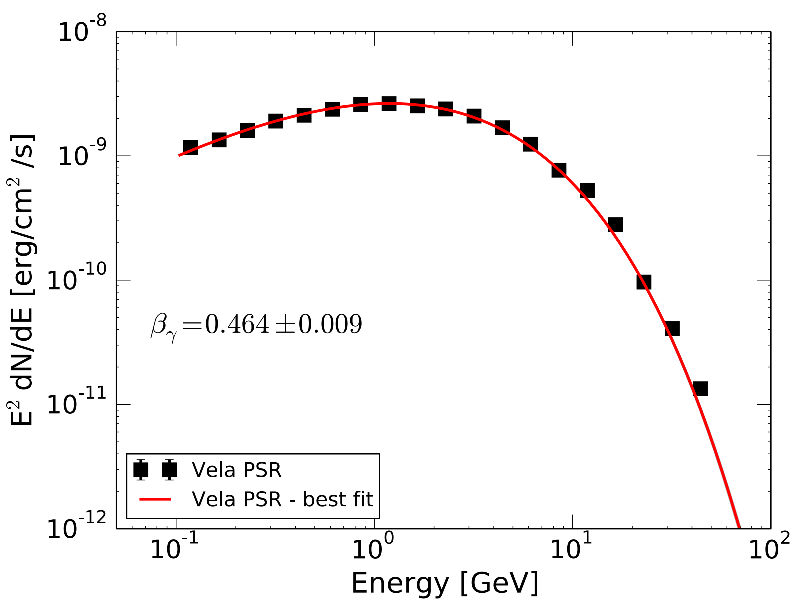
Recall generally, $\beta_e = 2 - q - r$

$$q = 1,\ r = 0,\ \rightarrow\ \beta_e = 1$$

(Note- energy losses for the $r = 0$ case will not alter this result)

Observation of Cut-offs in Gamma-ray Spectra

- Test case- Vela Pulsar (brightest source)



Romoli et al., **Astropart.Phys. 88 38-45 (2017)**

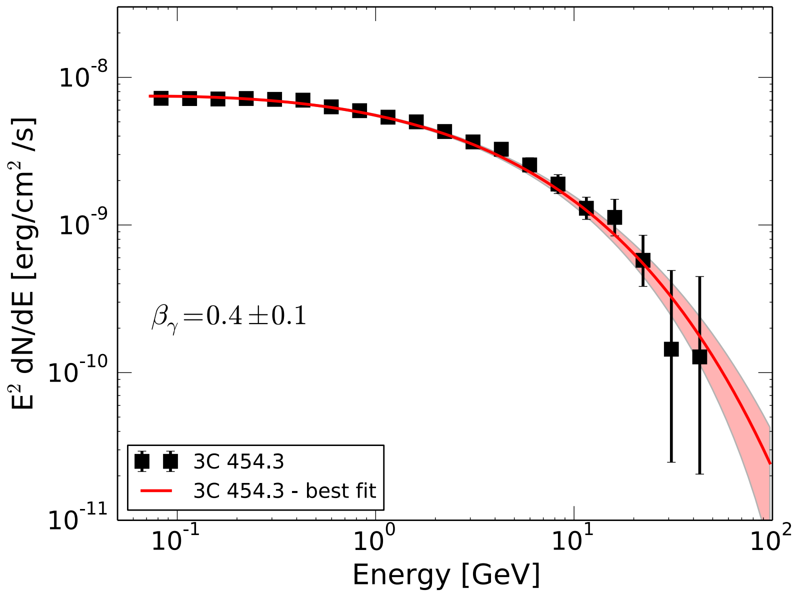
$$\frac{\mathbf{dN}}{\mathbf{dE}_\gamma} \propto \mathbf{E}_\gamma^{-\mathbf{\Gamma}} \mathbf{e}^{-(\mathbf{E}_\gamma/\mathbf{E}_{\max})^{\beta_\gamma}}$$

Parameter	Value
N [ph/cm^2/s/GeV]	$\left(1.39^{+0.12}_{-0.10}\right)\ 10^{-5}$
Γ	1.019 ± 0.011
E_c [GeV]	0.238 ± 0.016
β_γ	0.464 ± 0.009
E_s (fixed) [GeV]	0.83255

- Note- MCMC method used to explore 'good-fit' region. This has the benefit of being stable on the landscape being explored

Observation of Cut-offs in Gamma-ray Spectra

- Brightest AGN Flare- 3C 454 Nov 2010



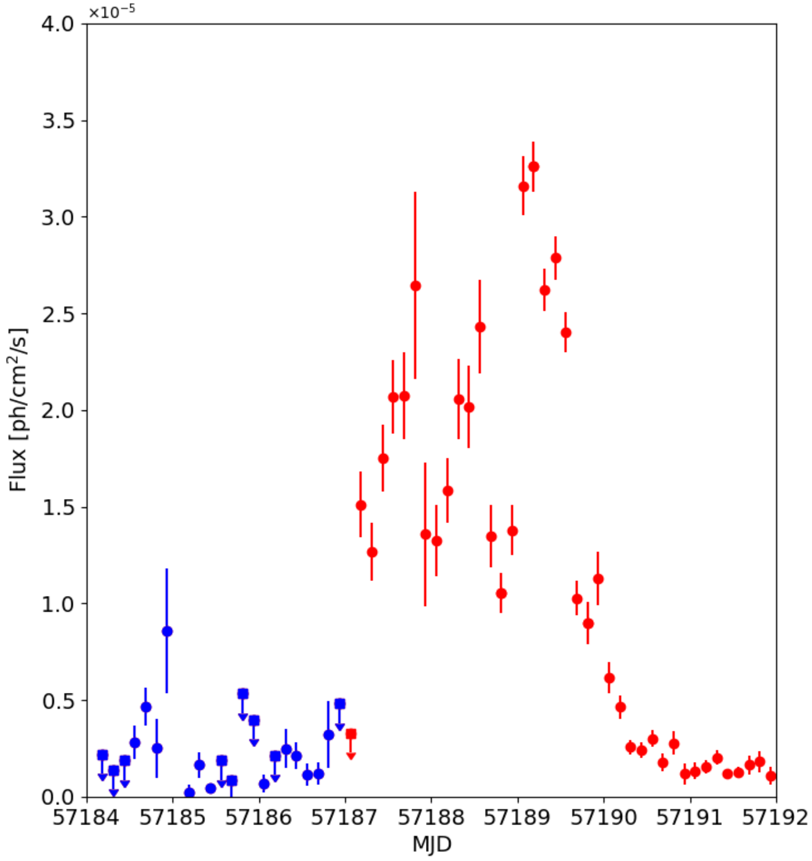
Romoli et al., **Astropart.Phys. 88 38-45 (2017)**

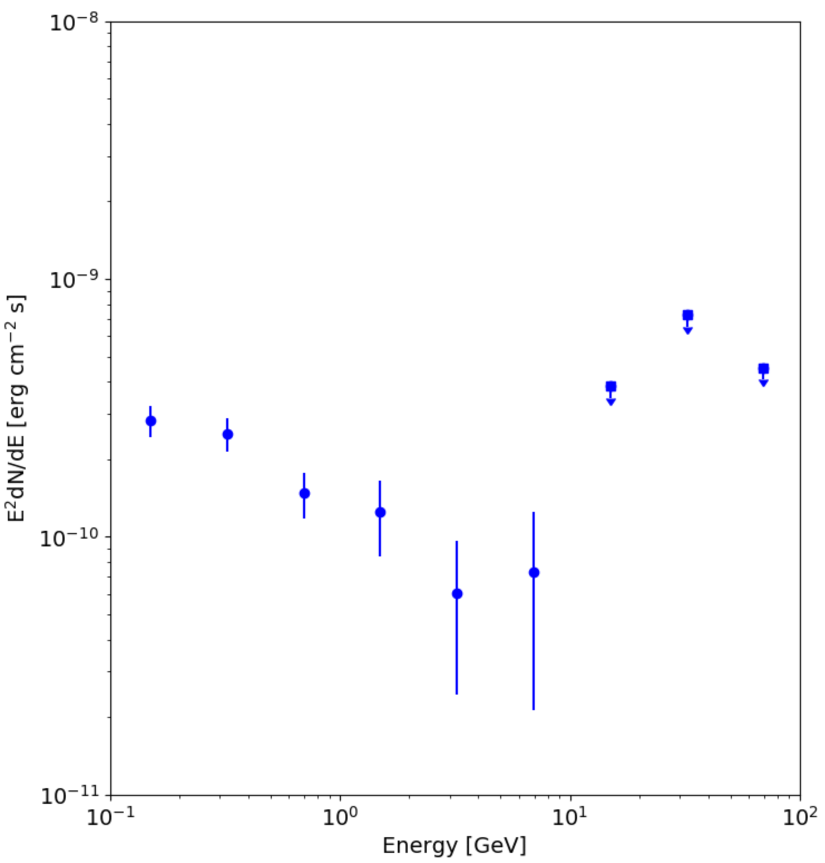
Parameter	Value
N [ph/cm^2/s/GeV]	$(4.7^{+3.9}_{-1.2})\,10^{-5}$
Γ	$1.87^{+0.08}_{-0.12}$
E_c [GeV]	$1.1^{+1.6}_{-0.9}$
β_γ	0.4 ± 0.1
E_s (fixed) [GeV]	0.41275

- Indicating a cut-off value of the primary particles around 1 GeV
- **Caveats:**
  - Values obtained on a 7 days integration (for statistics)
  - Spectrum variable during the flare -> superposition effects?

Fermi Gamma-ray Space Telescope

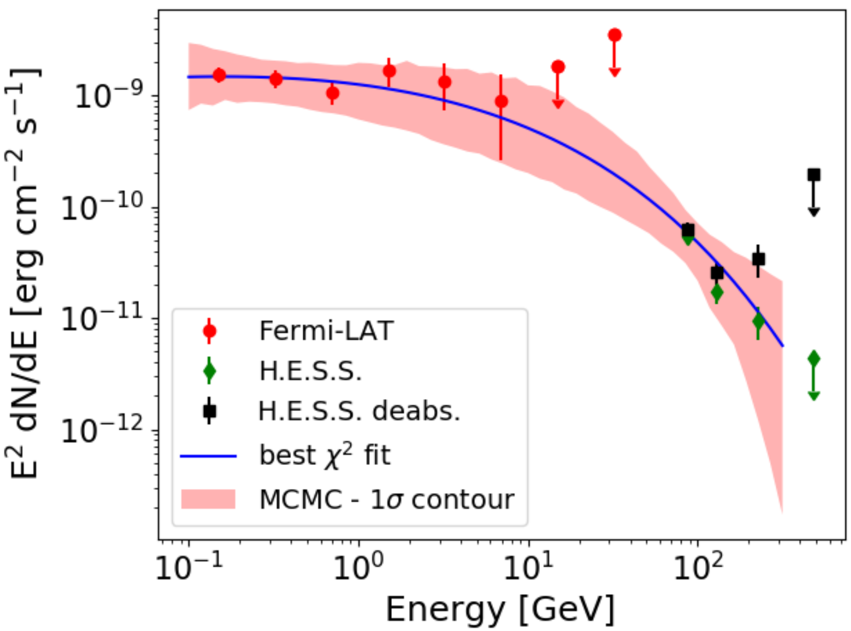
3C 279 June 2015 Flare-Temporal Evolution





DESY.

Can We Do Better Already? Fermi + H.E.S.S.II Fit

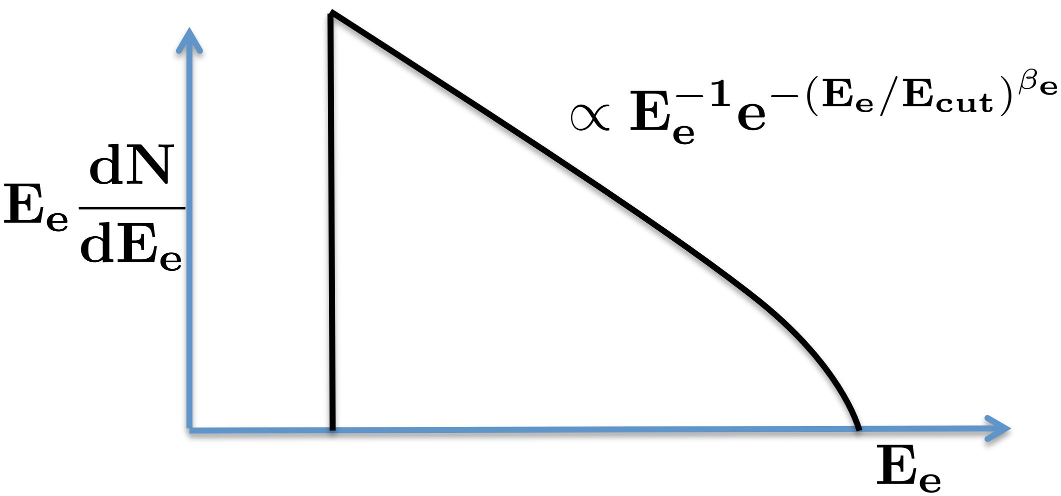


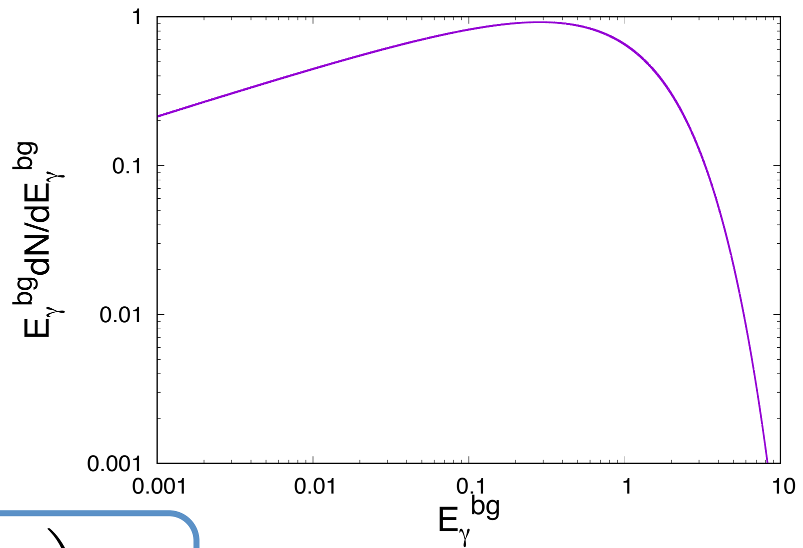
Parameter	MCMC fit
$\log_{10} N_0$ [ph/cm^2/s/GeV]	$(-4.75^{+0.91}_{-0.24}) \times 10^{-5}$
Γ	$(1.93^{+0.29}_{-0.41})$
$\log_{10} E_c$ [GeV]	$0.13^{+1.33}_{-2.82}$
β_γ	$0.34^{+0.32}_{-0.14}$

- Joint fit of Fermi-LAT data (9 hours centred on HESSII obs.) taken on night 2
- $\beta_\gamma = \mathbf{0.34^{+0.32}_{-0.14}}$

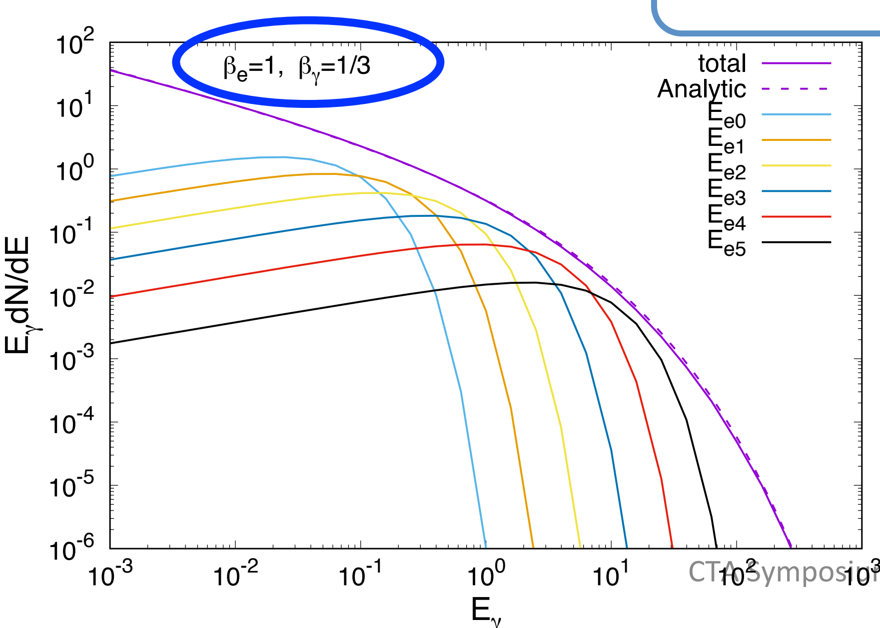
DESY.

Cut-off Shape- Electrons & Photons



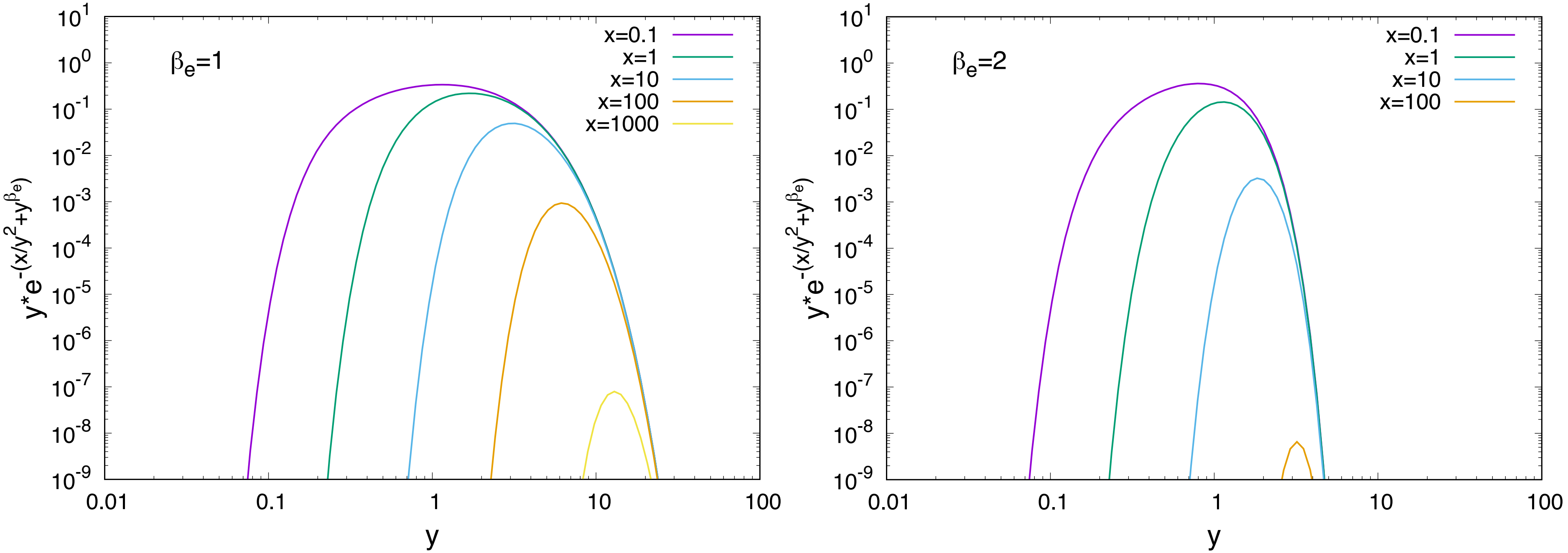


$$\mathbf{E_\gamma = \gamma_e^2 \left(\frac{B}{B_{crit}}\right) m_e}$$



$$\mathbf{f(x) = \int_0^\infty e^{-(x/y^2)} e^{-y^{\beta_e}} dy}$$

Integrand-



$$\mathbf{y^2}\left(\mathbf{y}^{\beta_\mathbf{e}} - \frac{\mathbf{1}}{\beta_\mathbf{e}}\right) = \frac{\mathbf{2x}}{\beta_\mathbf{e}}$$

$$\mathbf{y^2} \approx \left(\frac{\mathbf{2x}}{\beta_\mathbf{e}}\right)^{\frac{\mathbf{2}}{\beta_\mathbf{e}+\mathbf{2}}}$$

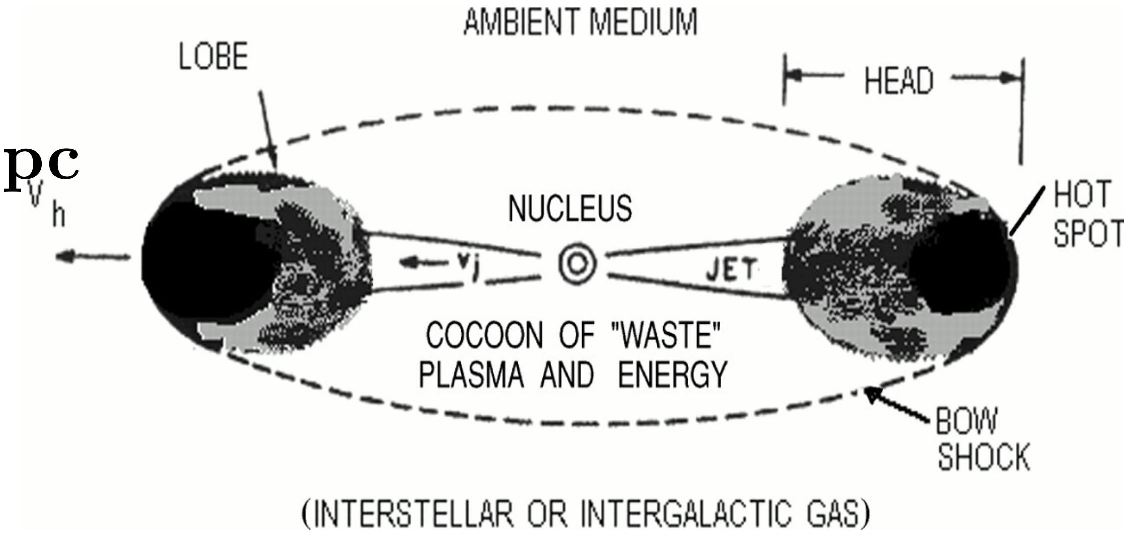
$$\frac{\mathbf{x}}{\mathbf{y^2}} \approx \mathbf{x}^{\frac{\beta_\mathbf{e}}{\beta_\mathbf{e}+\mathbf{2}}} \longrightarrow \qquad \beta_\gamma = \frac{\beta_\mathbf{e}}{\beta_\mathbf{e}+\mathbf{2}}$$

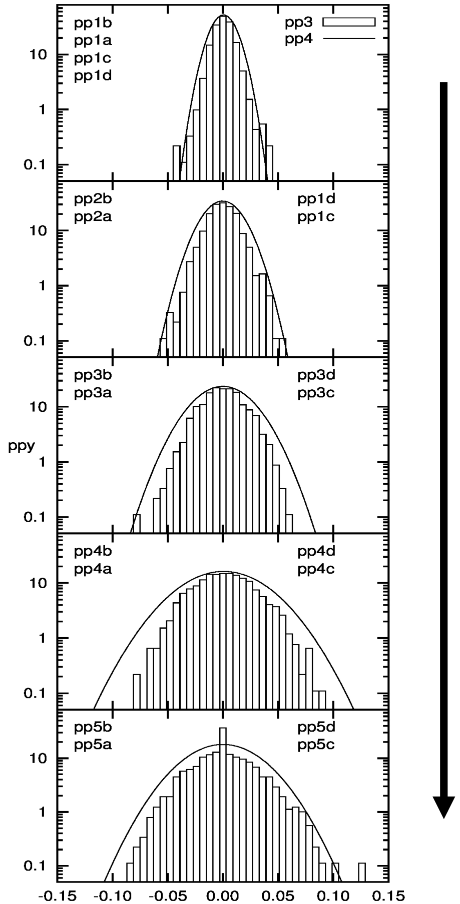
Further Acceleration Further Out?

$$\mathbf{R_{lar}} = \frac{\beta_{\mathbf{scat}}}{\eta}\mathbf{R}$$

$$\mathbf{R_{Lar}(10^{18}eV\ p) \approx 100\ pc}$$

Diagram taken from Ferrari -1998





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

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

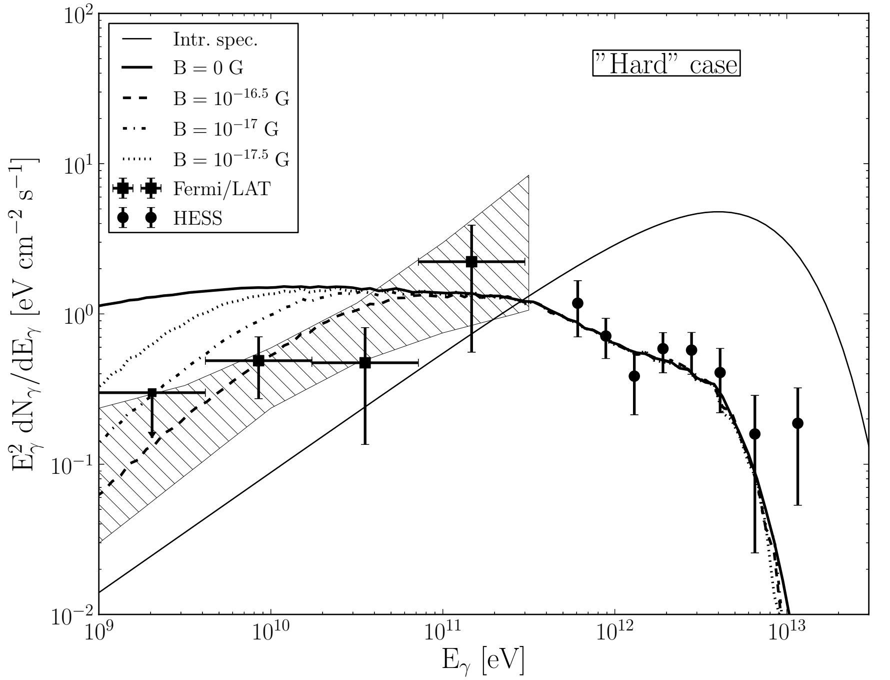
O'Sullivan et al. 2009 (0903.1259)

Matthews et al. 2019 (1902.10382)

Crostron et al. 2019 (1801.10172)

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)