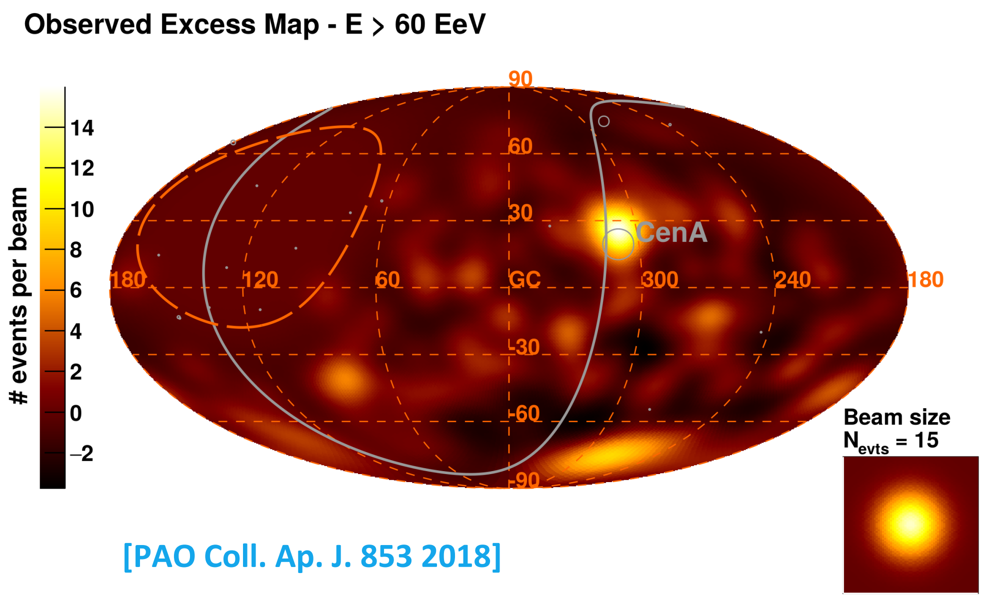
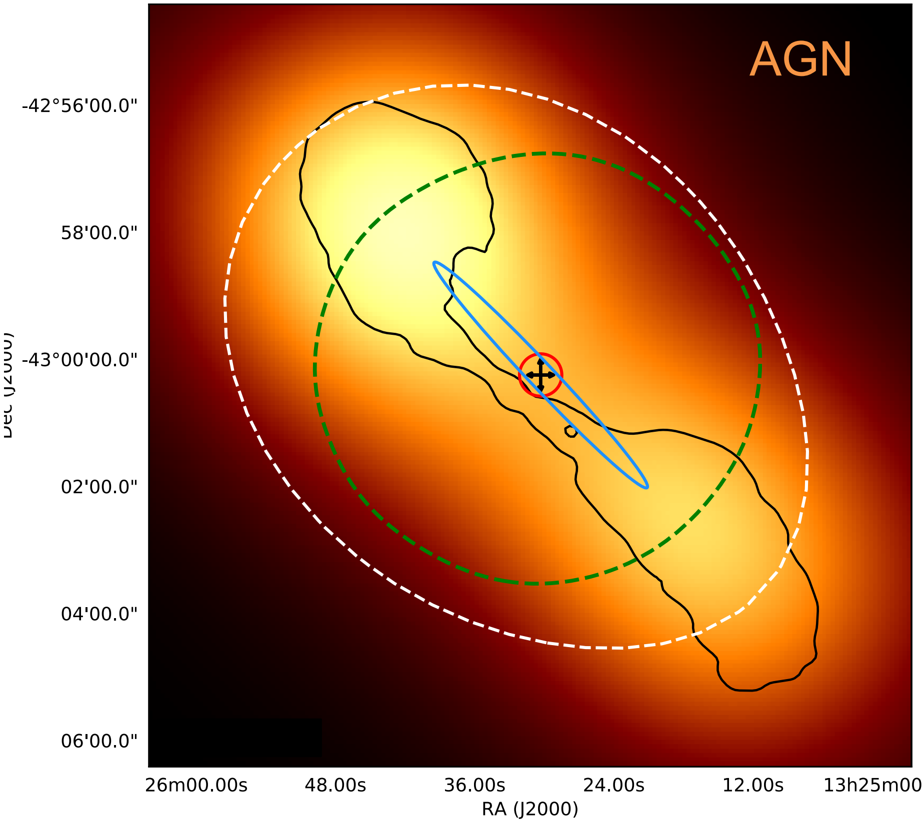
Particle Acceleration in the Jets of Cen A

Auger UHECR Data

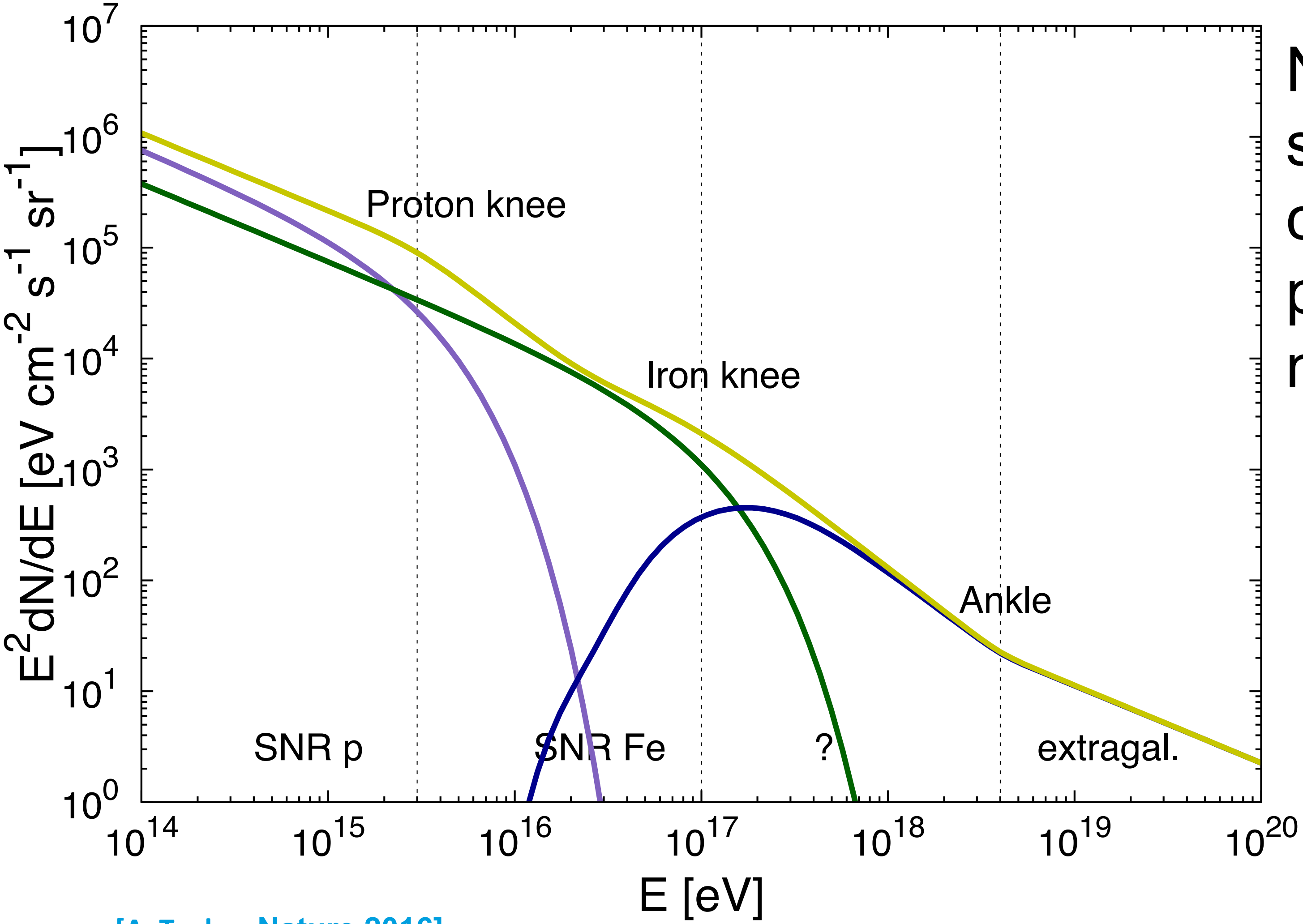


[PAO Coll. Ap. J. 853 2018]



[HESS- F. Rieger, A. Taylor, et al., Nature 2020]

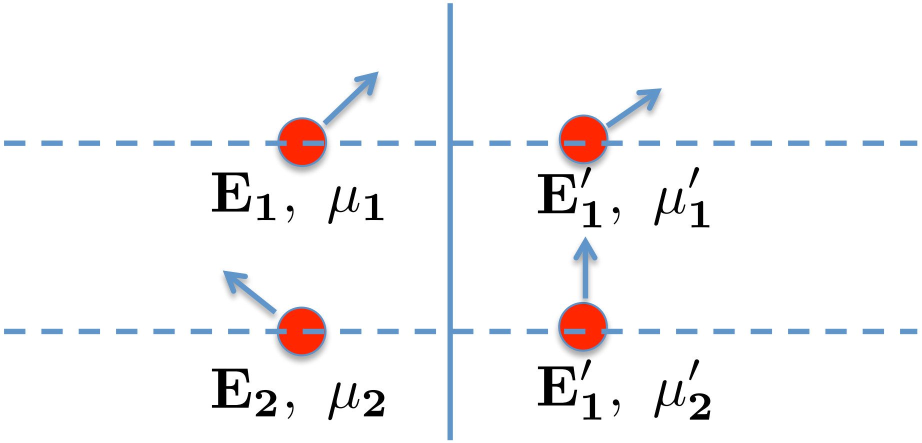
The Challenge: The Existence of Ultra High Energy Cosmic Rays



Note- spectrum composed of protons and nuclei

[A. Taylor, Nature 2016]

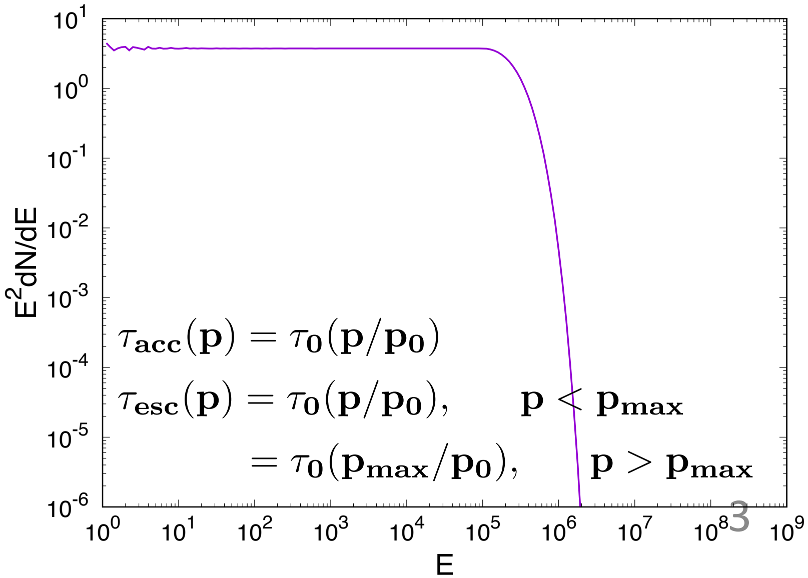
Particle Acceleration and Magnetic Turbulence



- Shifting of μ_1' to μ_2' is caused by magnetic turbulence, rate described by scattering time, which in Larmor time units is described by **η**
- Scattering agent velocity **β** dictates energy gain each crossing cycle

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

Note- shock acceleration isn't the only acceleration mechanism on the block!

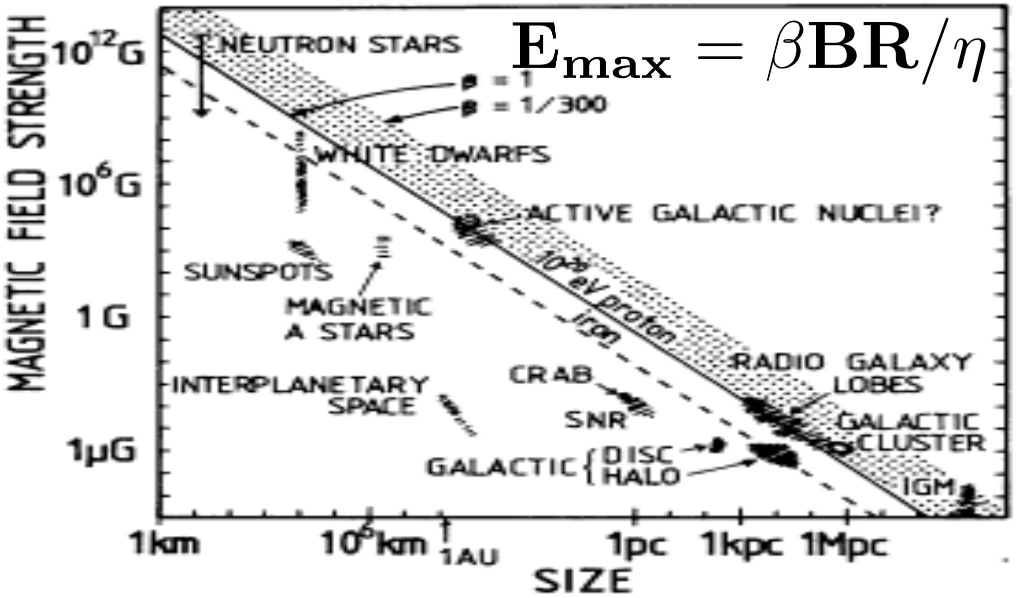


Cosmic Ray Source Requirements

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

$$\mathbf{t_{esc.}} = \frac{\mathbf{R}}{\mathbf{c}\beta}$$

[AM Hillas (1984)]



$$\mathbf{E_{max}} = \beta \mathbf{B}\mathbf{R}/\eta$$

[Norman et al. (1995)]

$$\mathbf{L_B} = \mathbf{U_B}\mathbf{4}\pi\mathbf{R^2 c}$$

Under the assumption of equipartition of energy between kinetic energy and magnetic field:

$$\mathbf{L_0} > \mathbf{3} \times \mathbf{10^{42}} \frac{\mathbf{1}}{\beta^{\mathbf{2}}} \left(\frac{\mathbf{E_p}}{\mathbf{3} \times \mathbf{10^{18}}\ \mathrm{eV}} \right)^{\mathbf{2}} \mathrm{erg\ s^{-1}}$$

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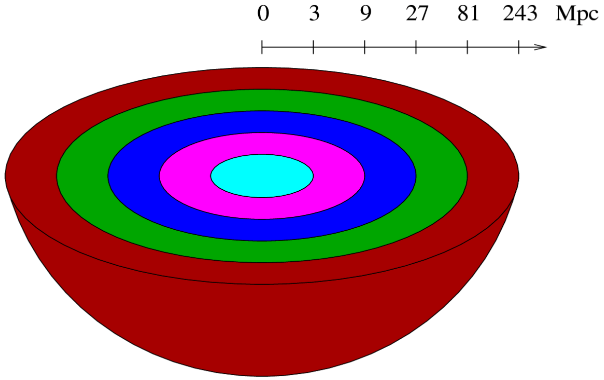
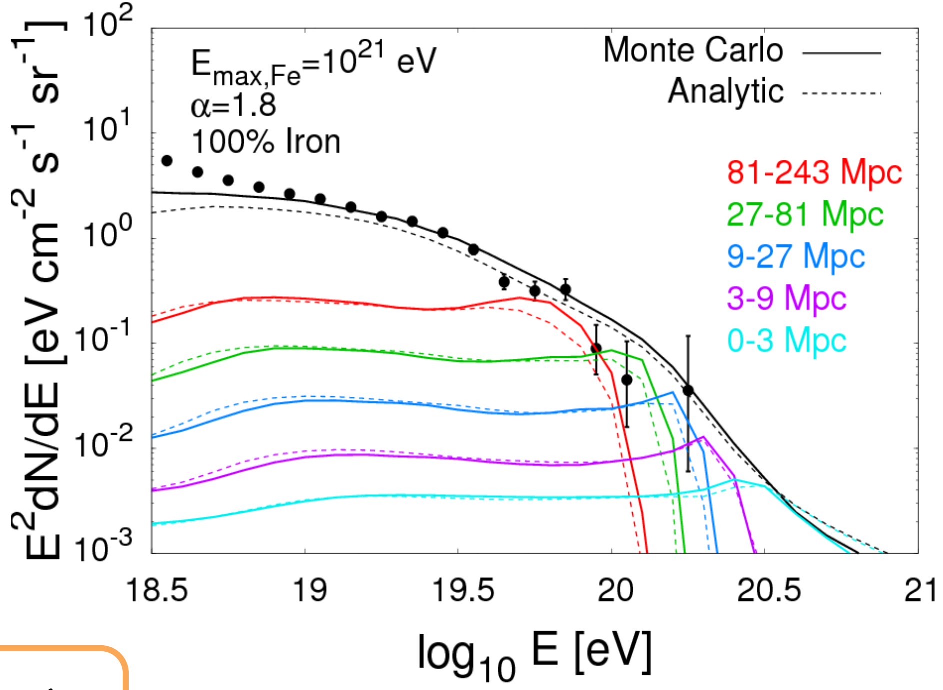
Local Scales Effect Highest Energies

(logarithmic scale)



$$d_{\mathrm{GZK}} \sim 100\ \mathrm{Mpc}$$



[A. Taylor et al., PRD (2011)]

[R. Lang and A. Taylor PRD (2020)]

$$\boxed{\mathcal{L}_0 \approx 4 \times 10^{44}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}}$$

[E. Waxman, Ap. J. 452 (1995)]

$$\begin{aligned} \mathcal{L}_0 &\approx L_0 n_0 \\ &\approx E_0 \dot{n}_0 \end{aligned} \quad \Rightarrow \quad \begin{aligned} n_0 &\sim 10^{-5}\ \mathrm{Mpc^{-3}} \\ \dot{n}_0 &\sim 10^{-6}\ \mathrm{Mpc^{-3}\ yr^{-1}} \end{aligned}$$

Only AGN and GRB appears to satisfy these requirements as the sources of extragalactic cosmic rays

Electron Acceleration with Cooling

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

$$\mathbf{t_{cool}} = \frac{\mathbf{9}}{\mathbf{8}\pi\alpha}\left(\frac{\mathbf{U_{Bcrit}}}{\mathbf{U_B}}\right)\left(\frac{\mathbf{h}}{\mathbf{E_e}}\right)$$

$$\mathbf{B_{crit}} = \mathbf{4} \times \mathbf{10^{13}G}$$

$$\mathbf{E_e^{max}} = \left(\frac{\eta^{\mathbf{-1/2}}}{\alpha^{\mathbf{1/2}}(\mathbf{B}/\mathbf{B_{crit}})^{\mathbf{1/2}}}\right)\mathbf{m_e c^2}$$

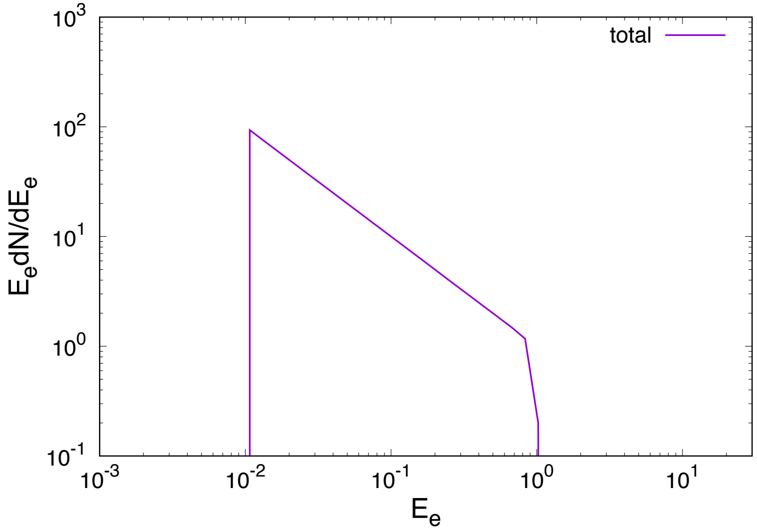
Maximum synchrotron energy tells us how efficient accelerator is!

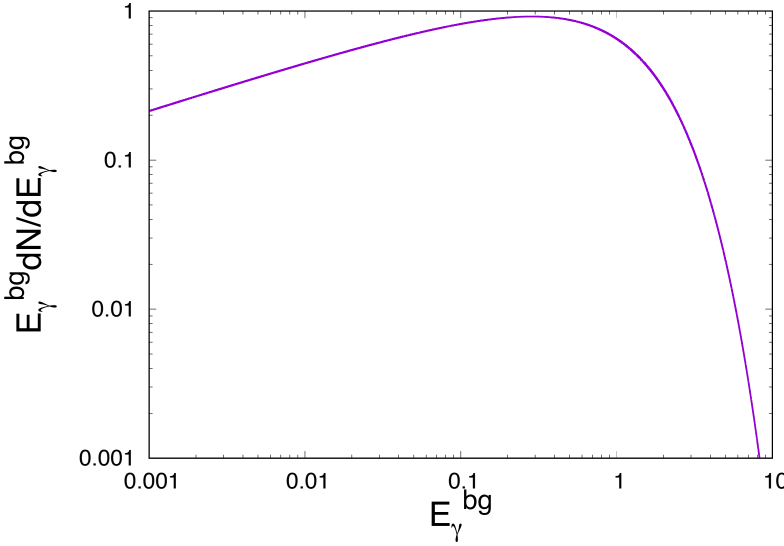
$$\mathbf{E_\gamma^{sync}} \approx \frac{\mathbf{9}}{\mathbf{4}}\eta^{\mathbf{-1}}\beta^{\mathbf{2}}\frac{\mathbf{m_e}}{\alpha}$$

→

Where do synchrotron cutoffs for AGN sit in energy?

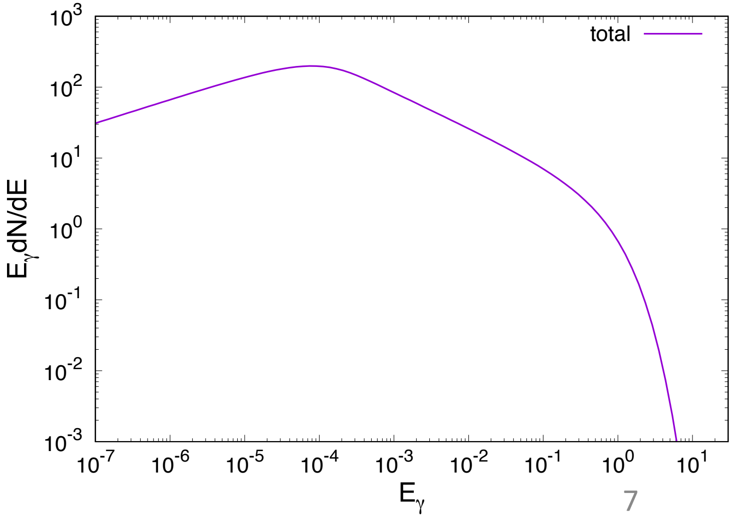
The Cutoff Region-
Synchrotron Emission Example



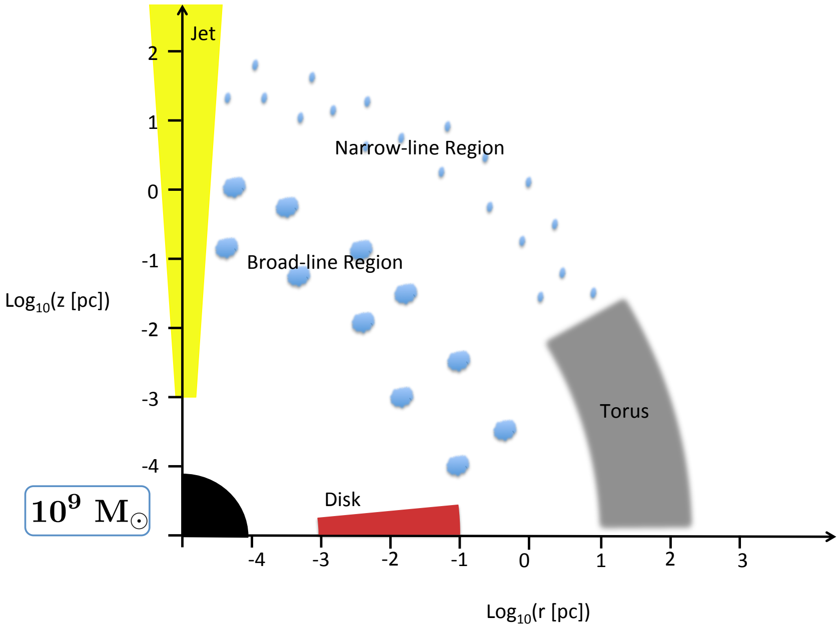


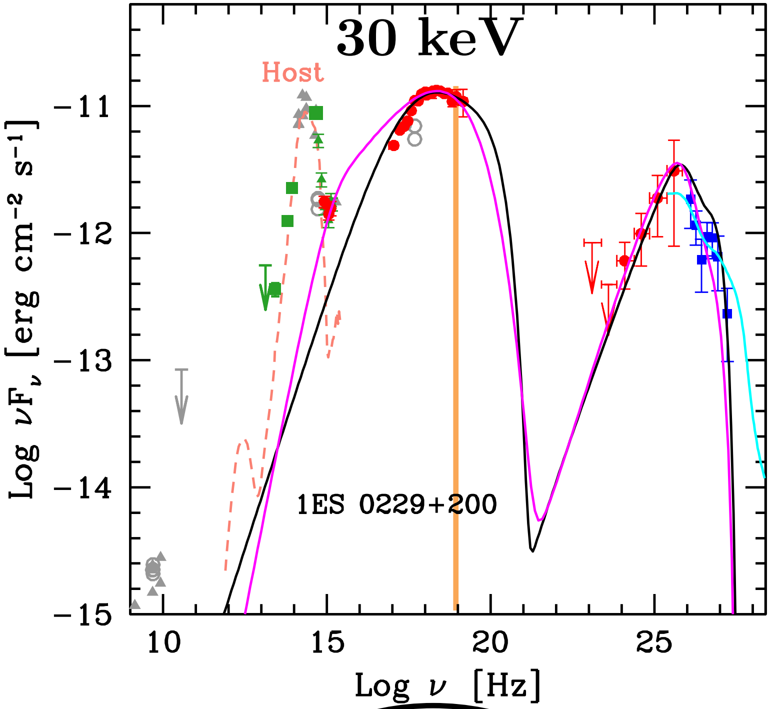
$$\mathbf{E}_\gamma = \gamma_\mathbf{e}^\mathbf{2}\left(\frac{\mathbf{B}}{\mathbf{B}_\mathrm{crit}}\right)\mathbf{m_e}$$

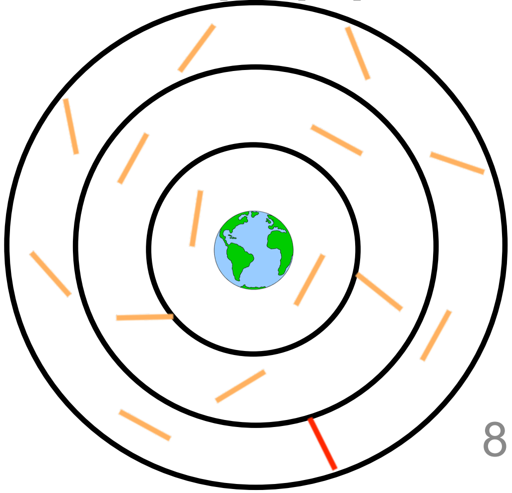
$$E_\gamma \frac{dN}{dE_\gamma}_{tot} = \int \left(\frac{E_\gamma}{E_e^2}\right)\frac{dN}{dE_\gamma}\left(\frac{E_\gamma}{E_e^2}\right)E_e\frac{dN}{dE_e}dE_e$$



Most Promising AGN (Blazars)
Extragalactic Cosmic Ray Source Candidates

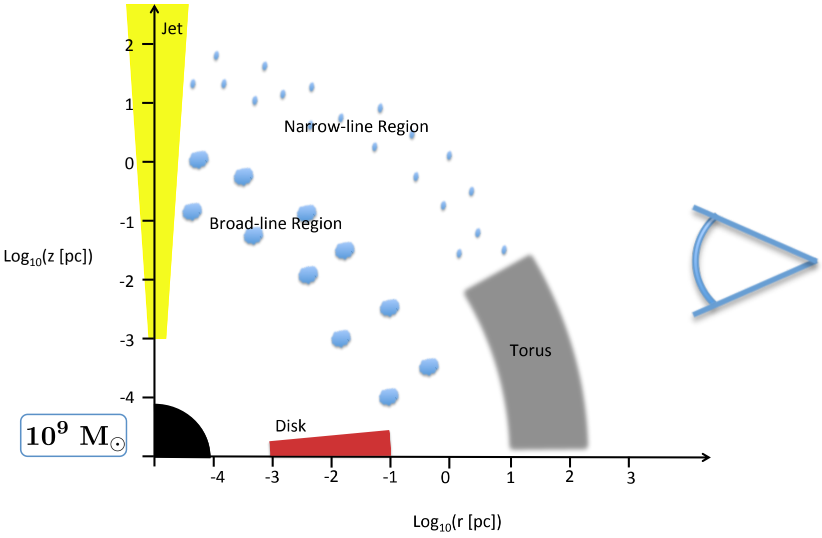




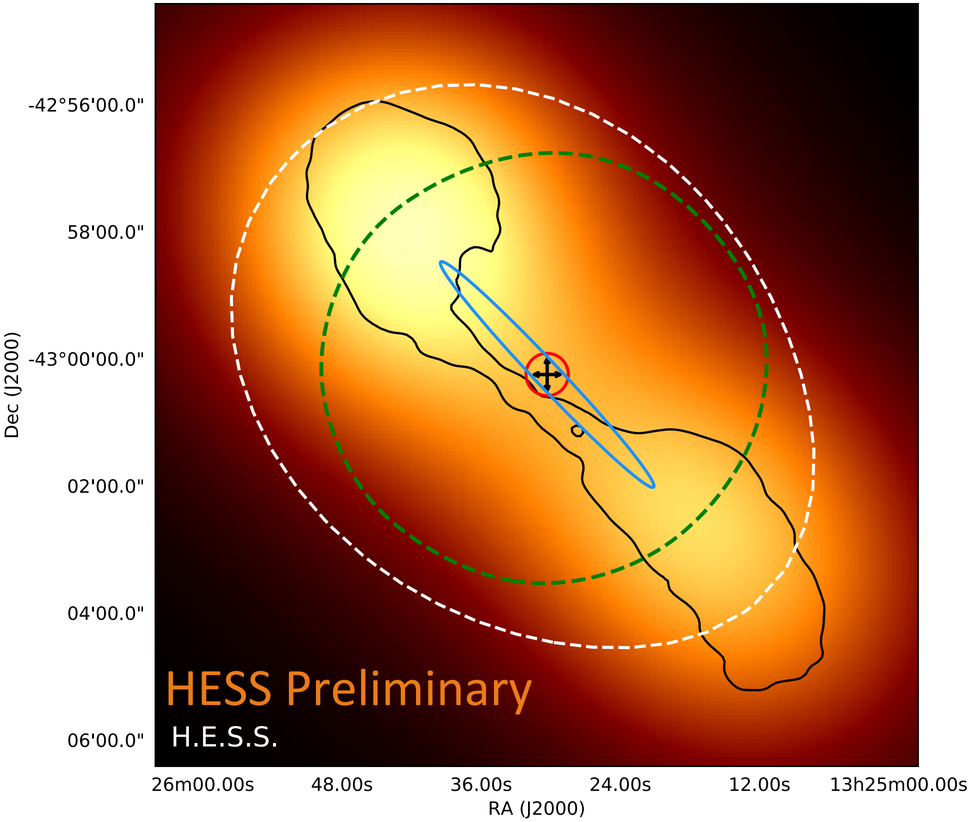


[J. Biteau, E. Pueschel, A. Taylor, et al., Nature Astronomy 2020]

Centaurus A - VHE Extension



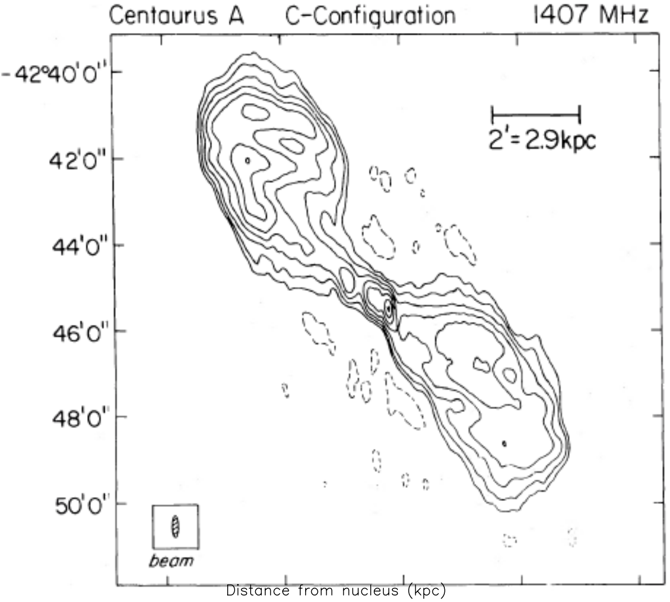
HESS Detected Extension on ~2kpc scale

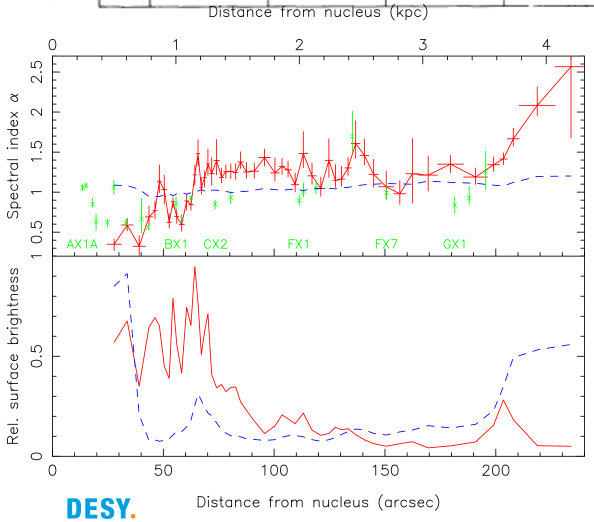


[HESS- F. Rieger, A. Taylor, et al., Nature]

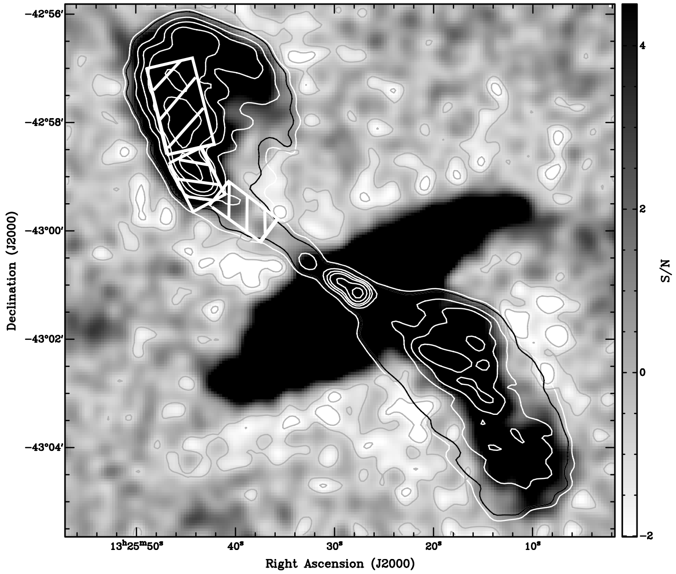
Centaurus A's Inner Jet- A Cosmic Lab

[J. Burns et al., ApJ (1983)]





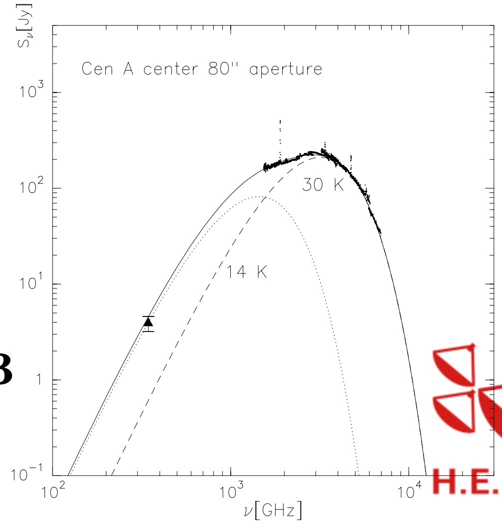
[A. Weiss et al., A&A (2008)]



$$B_{eq} = 60\ \mu G$$

$$U_B \approx 10\ \mathrm{eV\ cm^{-3}}$$

$$U_{IR} \approx 10\ \mathrm{eV\ cm^{-3}}$$

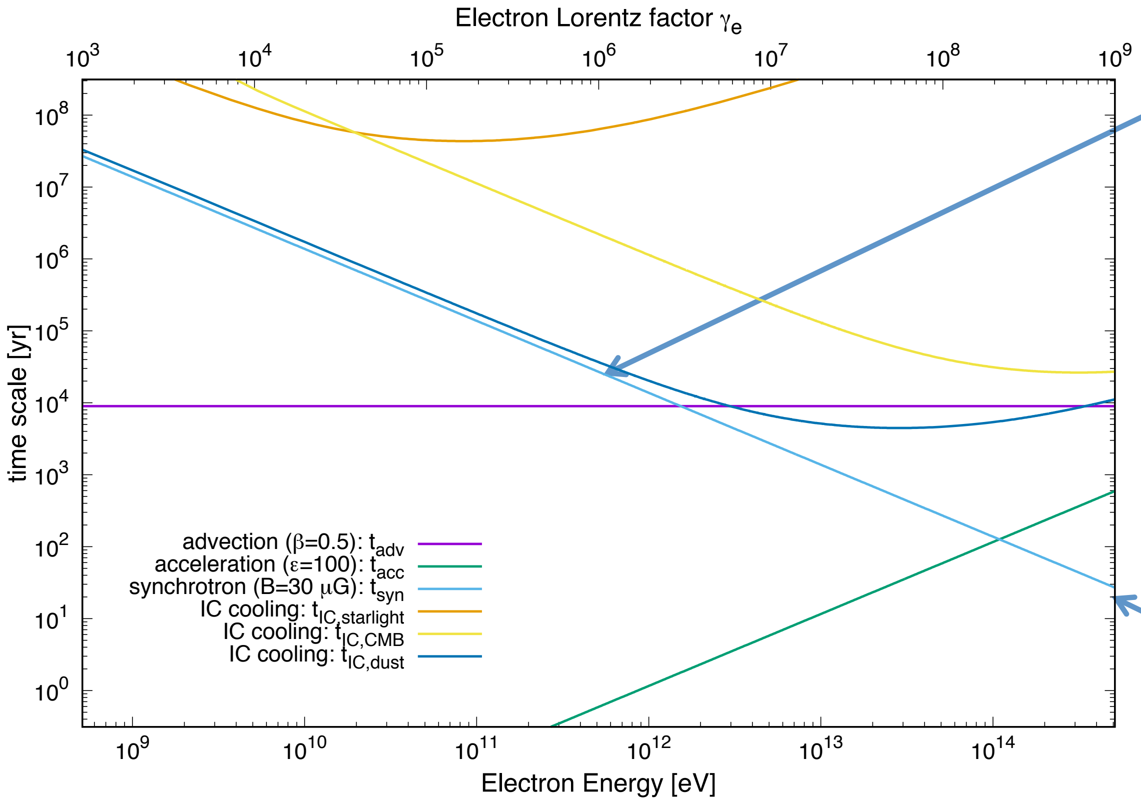


Andrew Taylor

DESY.

H.E.S.S.

Transport & Cooling Times of Electrons in Cen A's Jets



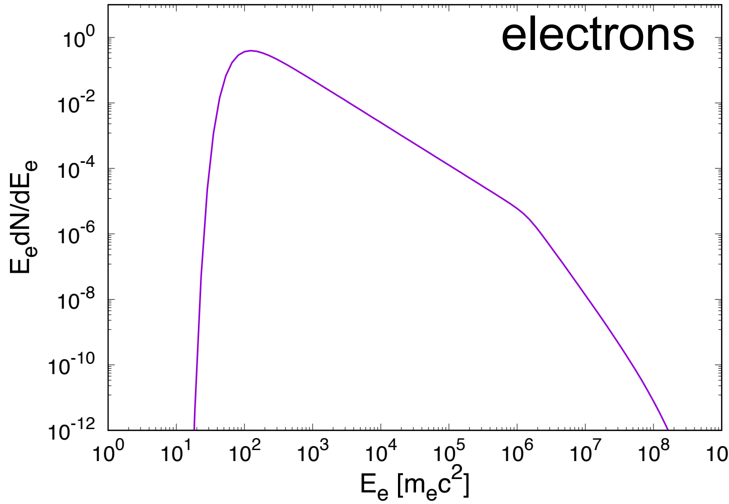
Synchrotron cooling dominates

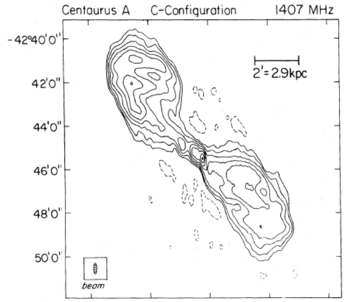
Cooling time becomes shorter than advection time

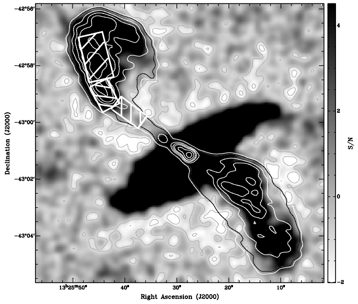
Electrons accelerated to 0.1 PeV energies

$$\cancel{\frac{\partial \mathbf{n}}{\partial \mathbf{t}}} = \nabla_{\mathbf{p}} \cdot \left[\frac{\mathbf{p}}{\tau_{\mathbf{loss}}(\mathbf{p})}\mathbf{n}\right] - \frac{\mathbf{n}}{\tau_{\mathbf{esc}}(\mathbf{p})} + \mathbf{Q}$$

Distinguishing Cen A’s Nucleus and Inner Jet SED



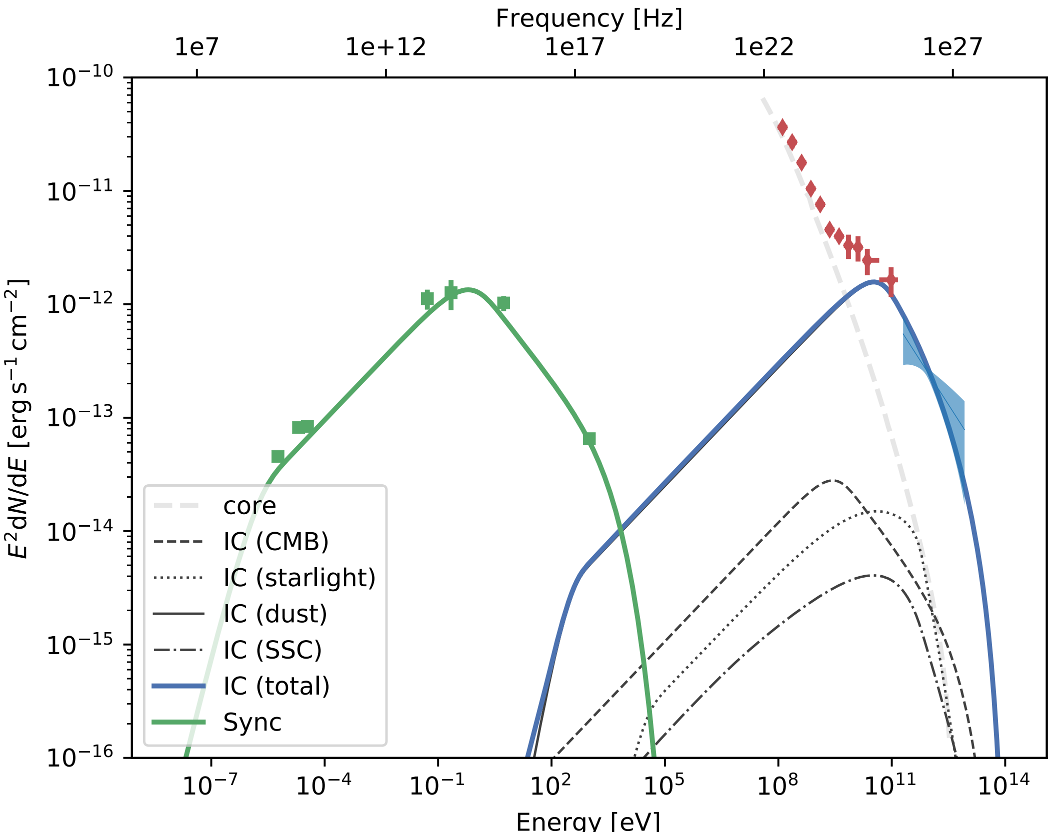




$$\eta = \frac{1}{{\Gamma_e^{max}}^2 (B/B_{crit})\alpha}$$

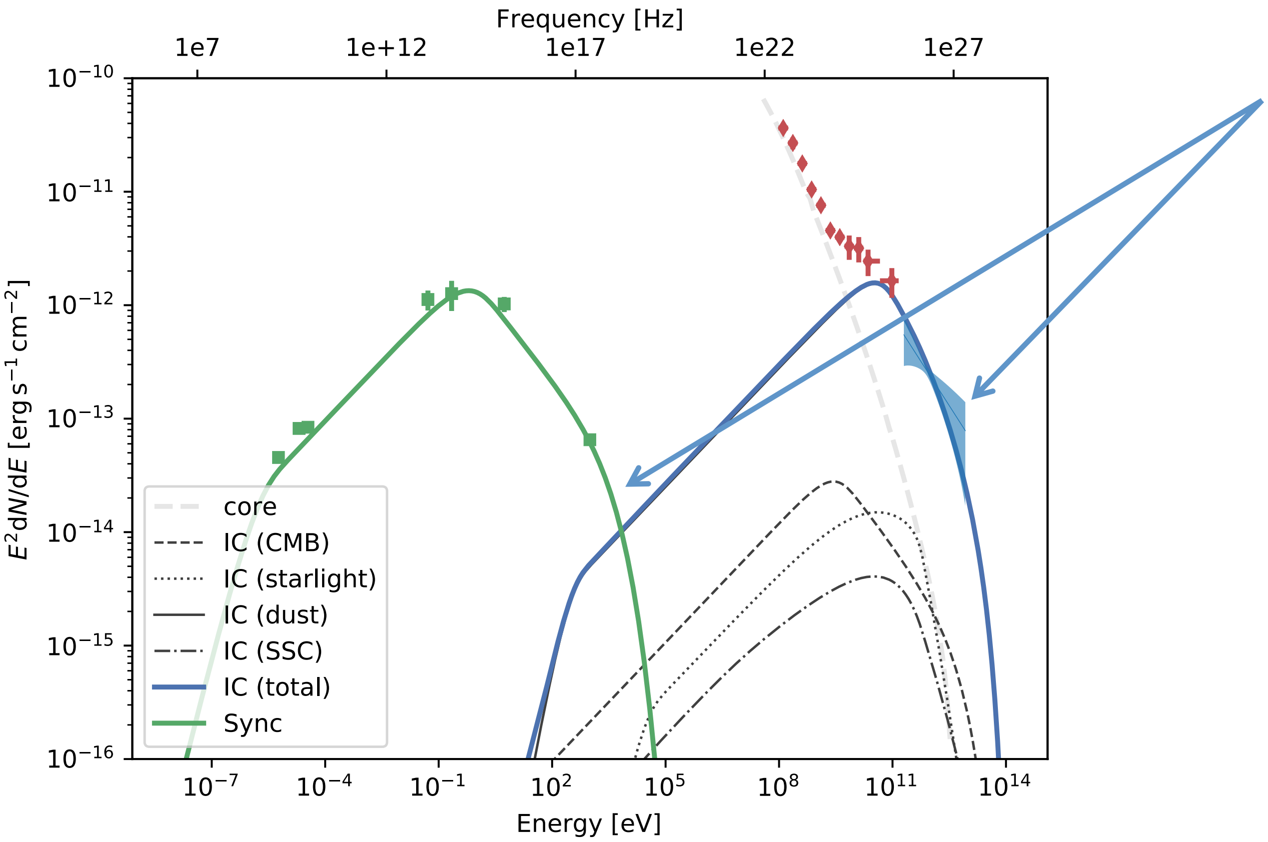
$$\approx 10^4 \left(\frac{10^8}{\Gamma_e^{max}}\right)^2 \left(\frac{20\mu G}{B}\right)$$

[HESS- F. Rieger, A. Taylor, et al., Nature 2020]



DESY.

Important Pending Questions to be Answered

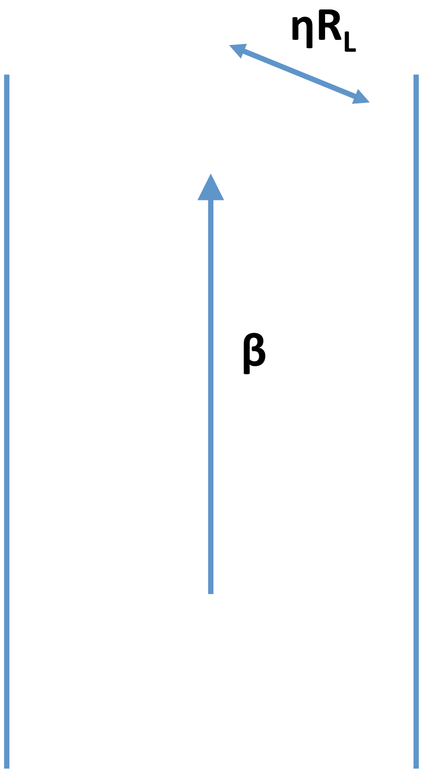


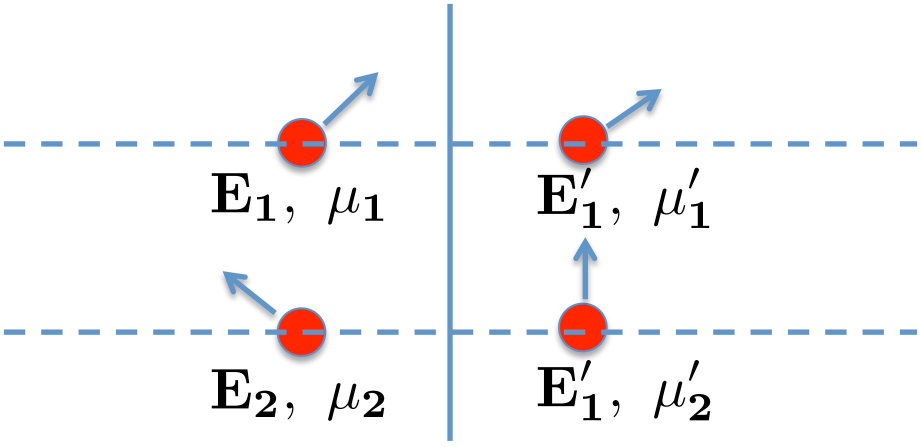
Where does energy of synchrotron & IC spectra occur?

How does B-field strength vary along the jet on larger scales?

Variation of target photons on larger scales?

Keep It Simple- Shear Flow with Random Isotropic Scattering

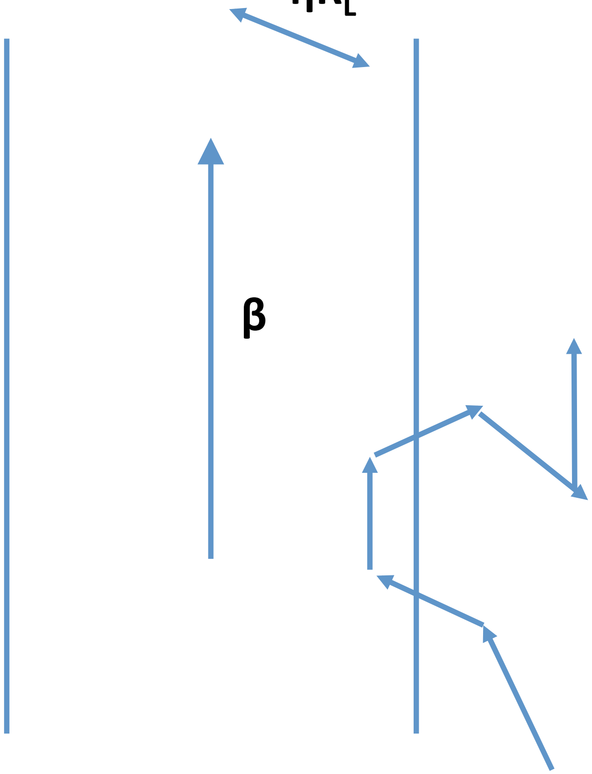




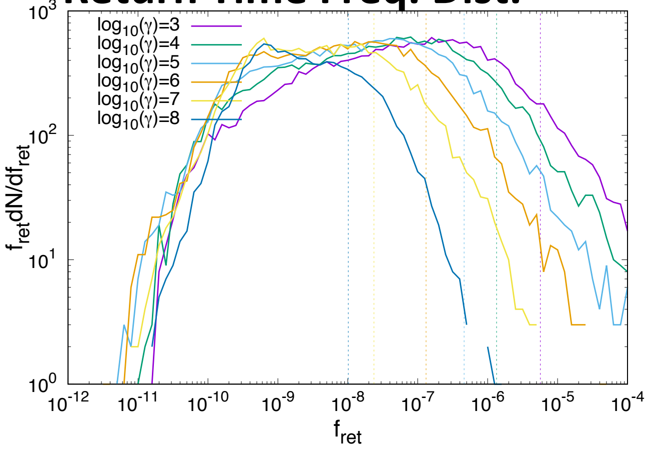
$$\lambda_{\mathbf{scatt}} = \eta \mathbf{R}_{\mathbf{lar}}$$

$$\epsilon_{\mathbf{boost}} = \frac{\mathbf{E_2}}{\mathbf{E_1}} = \left(\frac{\mathbf{1} + \beta\mu_{\mathbf{1}}}{\mathbf{1} + \beta\mu_{\mathbf{2}}}\right)$$

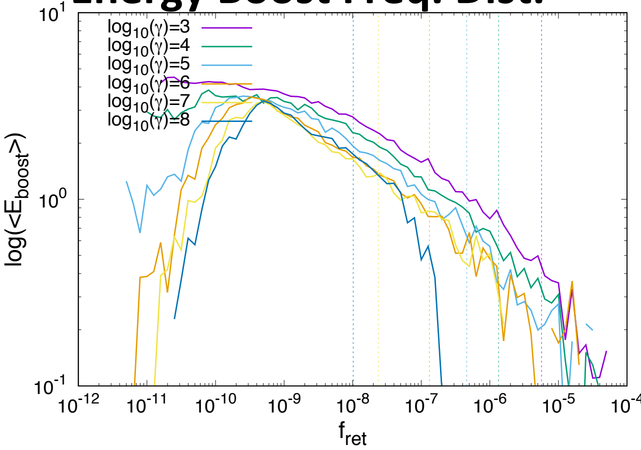
Keep It Simple- Shear Flow with Random Isotropic Scattering



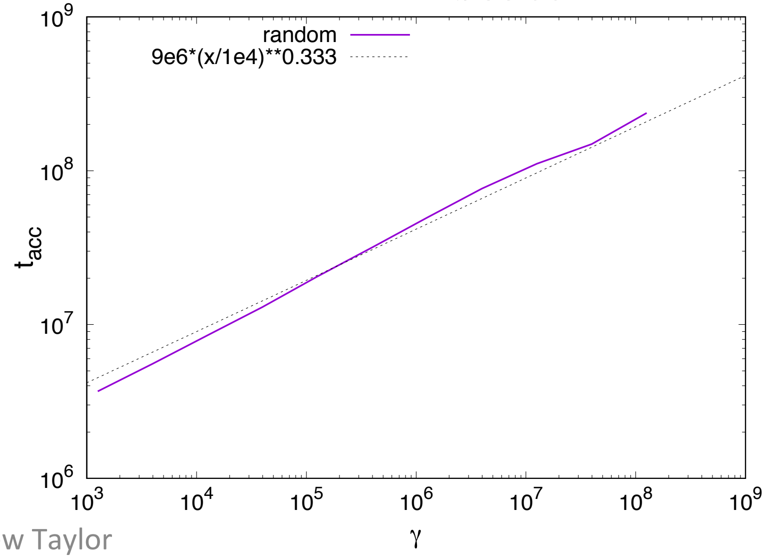
Return Time Freq. Dist.



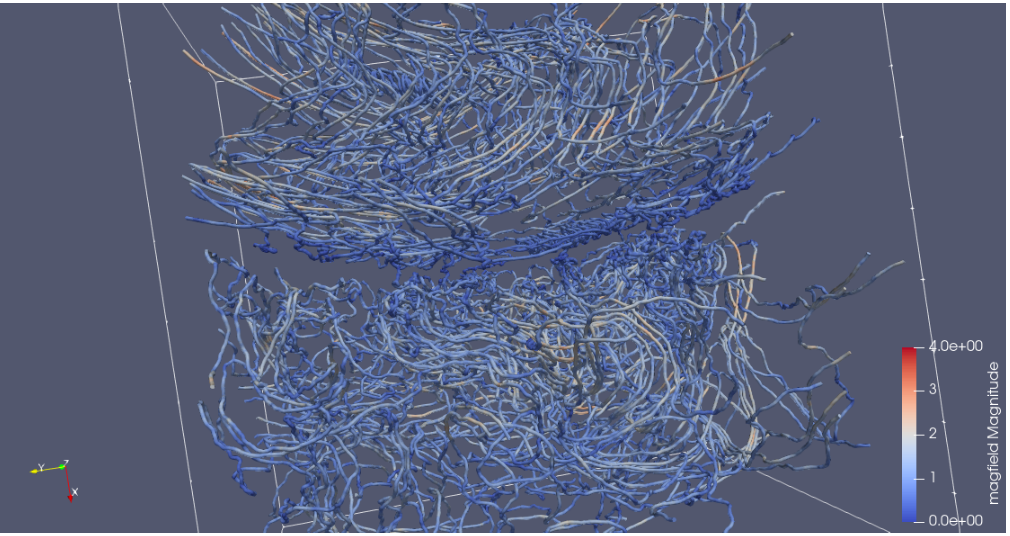
Energy Boost Freq. Dist.



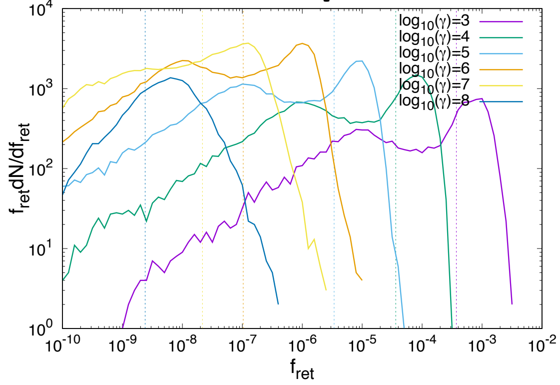
$$\lambda_{\mathbf{scatt}} \propto \mathbf{E^{1/3}}$$



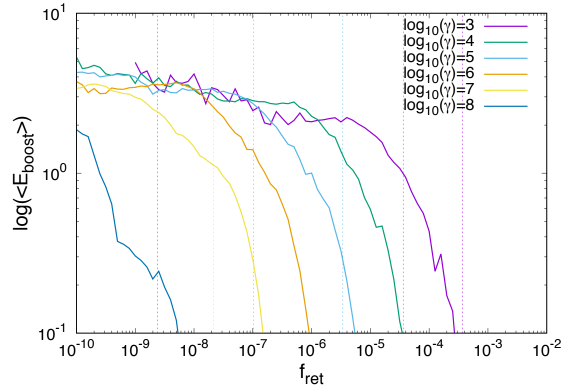
Consideration of a Scenario with an Actual B-Field Realisation

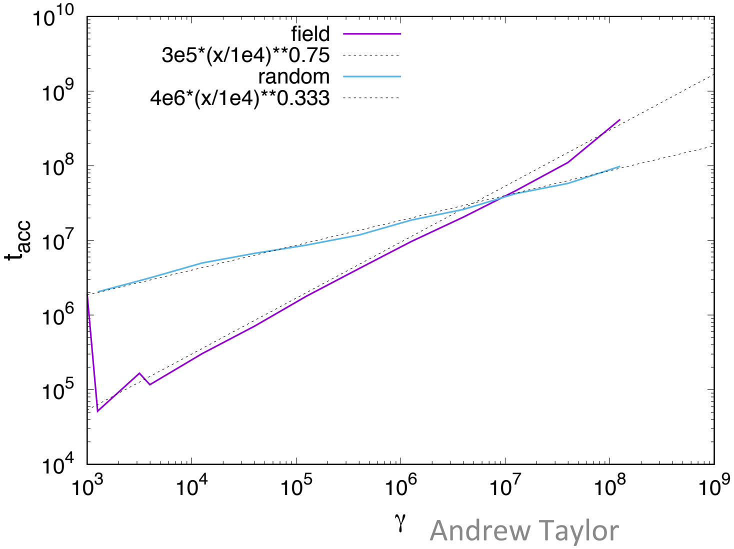


Return Time Freq. Dist.



Energy Boost Freq. Dist.





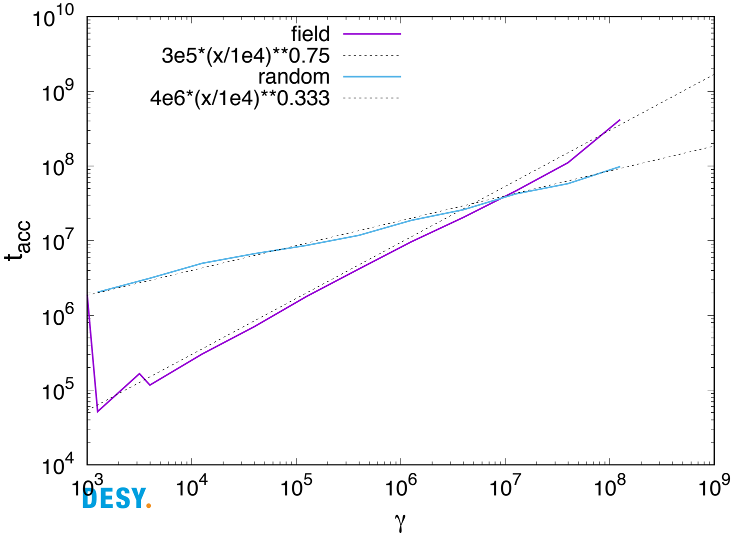
Dissecting Cen A's Acceleration Sites

Acceleration on kpc scales:

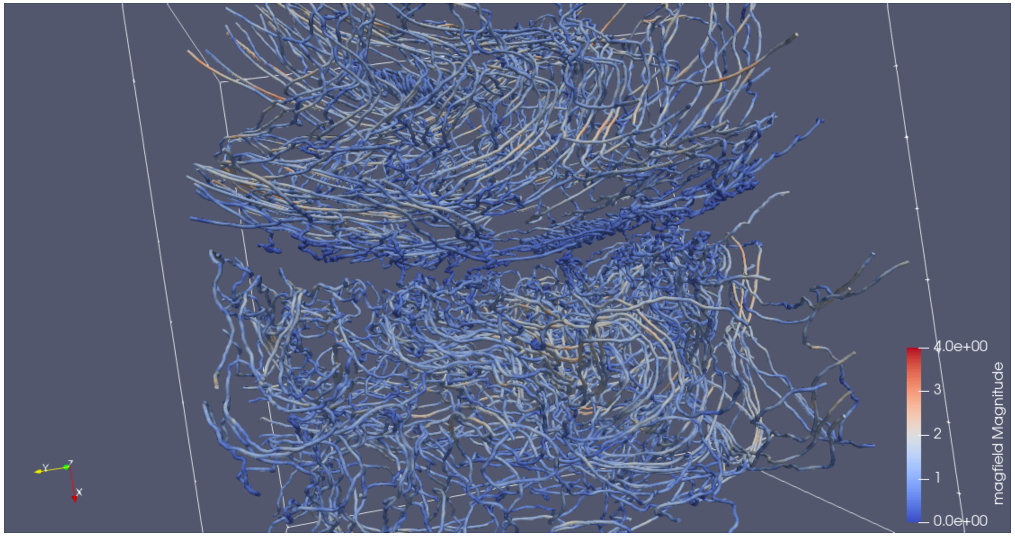
$$\boxed{\mathbf{E_{max}} = \beta \mathbf{BR}/\eta}$$

$$\beta_{\mathbf{scat.}} \approx \mathbf{0.5}, \quad \eta \approx \mathbf{10^4}$$

$$\boxed{\mathbf{E}_{\max} \approx \mathbf{10^{15} eV}}$$



Acceleration on larger scales:



[S. O'Sullivan, A. Taylor, B. Reville in prep.]

Energy dependence of acceleration time may only approach the Bohm level (η~1) at the highest energies

$$\boxed{\begin{gathered}\mathbf{E}_{\max} \approx \mathbf{10^{18} eV} \\ \mathbf{t}_{\mathrm{acc}} \approx \mathbf{0.1\ Myr}\end{gathered}}$$

Looking to the Future

Next 10 years

General VHE efforts to probe UHECR source- determine the cutoff position of electrons accelerated by candidate UHECR sources. Additionally, probing the growth in small scale anisotropy at >60 EeV energies.

Tools needed to accomplish this

For local AGN, this amounts to filling in the observational MeV gap (**new instrument needed**), and pushing to higher energies in the VHE bands (**CTA**) where the synchrotron and IC cutoff in the spectrum sit

More broadly still

Determining the synchrotron cutoff of other UHECR candidates (eg. GRB) should be a major observational focus

Conclusion

- UHECR acceleration candidates force a consideration of local (mildly) relativistic accelerators

- Synchrotron emission from local AGN and GRB can tell us directly how efficient these sources operate as cosmic ray accelerators

- The nearest AGN candidate (Cen A) serves as a cosmic laboratory. We have now moved beyond hand picking magnetic field stregnths/radiation fields. This allows an indirect probe of the efficiency

UHE Cosmic Ray Dipole

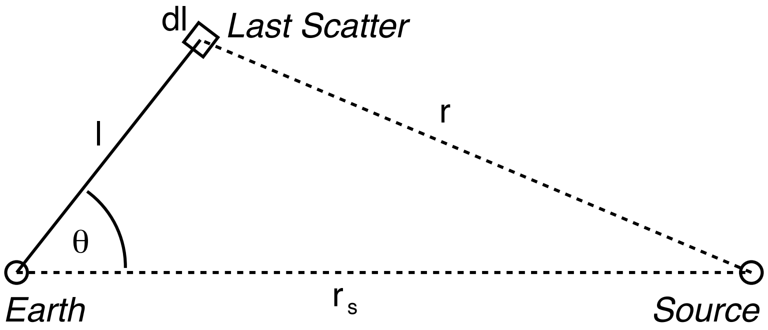
$$\boxed{\frac{\partial \mathbf{n}}{\partial \mathbf{t}} = \mathbf{D}\nabla^2\mathbf{n} + \mathbf{Q}}$$

$$\mathbf{n} = \frac{\partial \mathbf{N}}{\partial^3 \mathbf{r}} = \int_0^\infty \frac{\mathbf{e}^{-\mathbf{x}^2/(4\mathbf{D}\mathbf{t})}}{(4\pi \mathbf{D}\mathbf{t})^{3/2}} \frac{\mathbf{d}\mathbf{t}}{\tau}$$

$$\mathbf{n} = \frac{1}{4\pi \mathbf{D}\mathbf{r}} \propto \frac{1}{\lambda_{\mathbf{scatt}}\mathbf{r}}$$

UHE Cosmic Ray Dipole

$$\frac{\partial \mathbf{N}}{\partial \cos\theta} \propto \int \frac{\mathbf{e}^{-\mathbf{l}/\lambda_{\mathbf{scatt}}}}{\mathbf{r}(\mathbf{l})}\mathbf{dl}$$



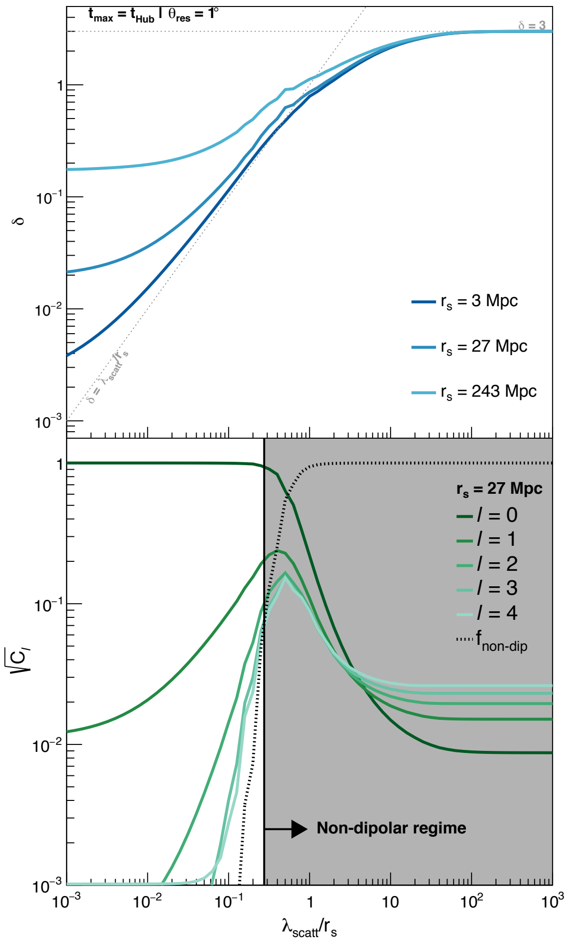
$$\approx \frac{\lambda_{\mathbf{scatt}}}{\mathbf{r}(\mathbf{l})} = \frac{\lambda_{\mathbf{scatt}}}{\mathbf{r_s}}\left(\mathbf{1} + \frac{\lambda_{\mathbf{scatt}}}{\mathbf{r_s}}\cos\theta\right)$$

$$\propto \mathbf{1} + \delta\cos\theta$$

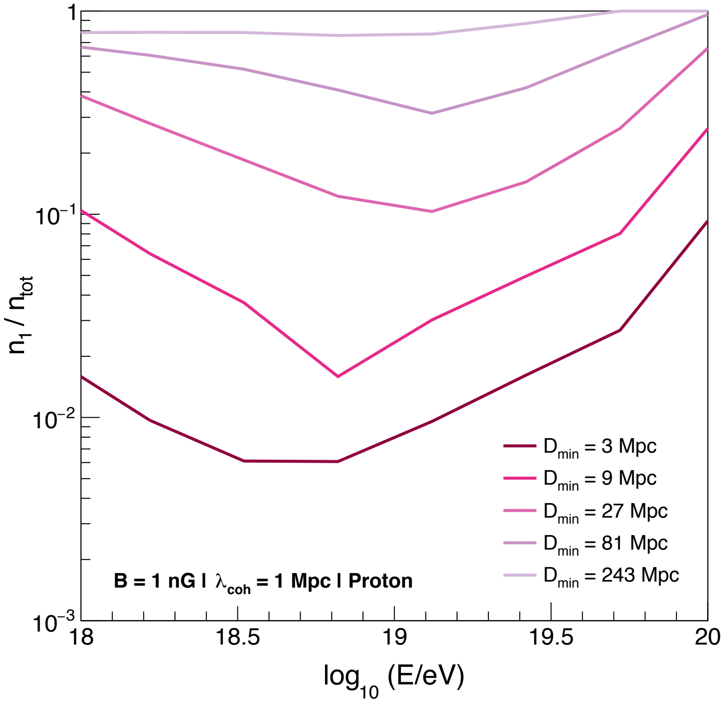
$$\boxed{\delta = \frac{\lambda_{\mathbf{scatt}}}{\mathbf{r_s}}}$$

UHE Cosmic Ray Dipole

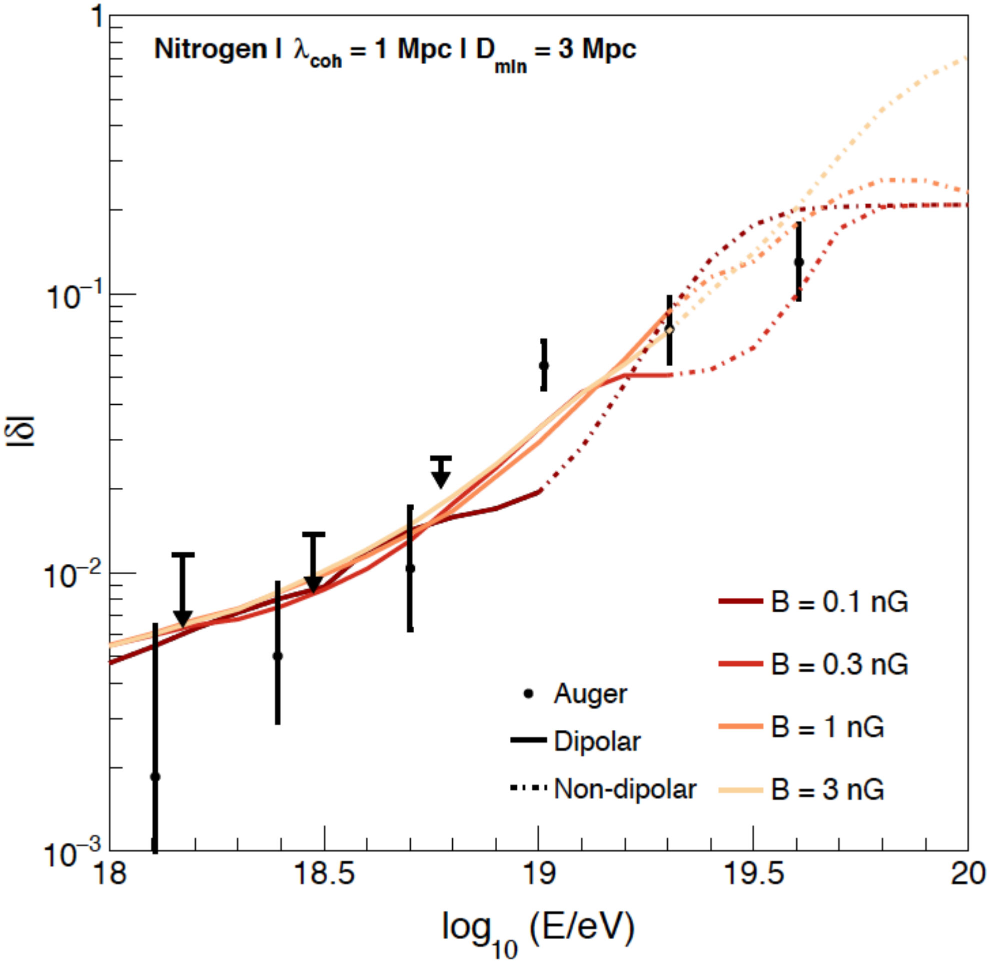
Dipole driven by nearest by source, and diluted by more distance sources



$$\delta = \frac{\lambda_{\mathbf{scatt}}}{\mathbf{r_s}}$$



UHECR Dipole- Energy Dependence



- Dipole from nearest sources grows linearly with λ_{scatt} (for nearby sources steady-state approximation holds)
- Contribution of nearest source to total flux decays as $1/\lambda_{scatt}$
- At highest energies, harmonic power migrates to multi-pole terms….have the Auger collaboration seen this already?

Particle Acceleration in AGN

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

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

Maximum energy
(Hillas criterion)

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

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

AM Hillas (1984)

Particle Acceleration with Cooling

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

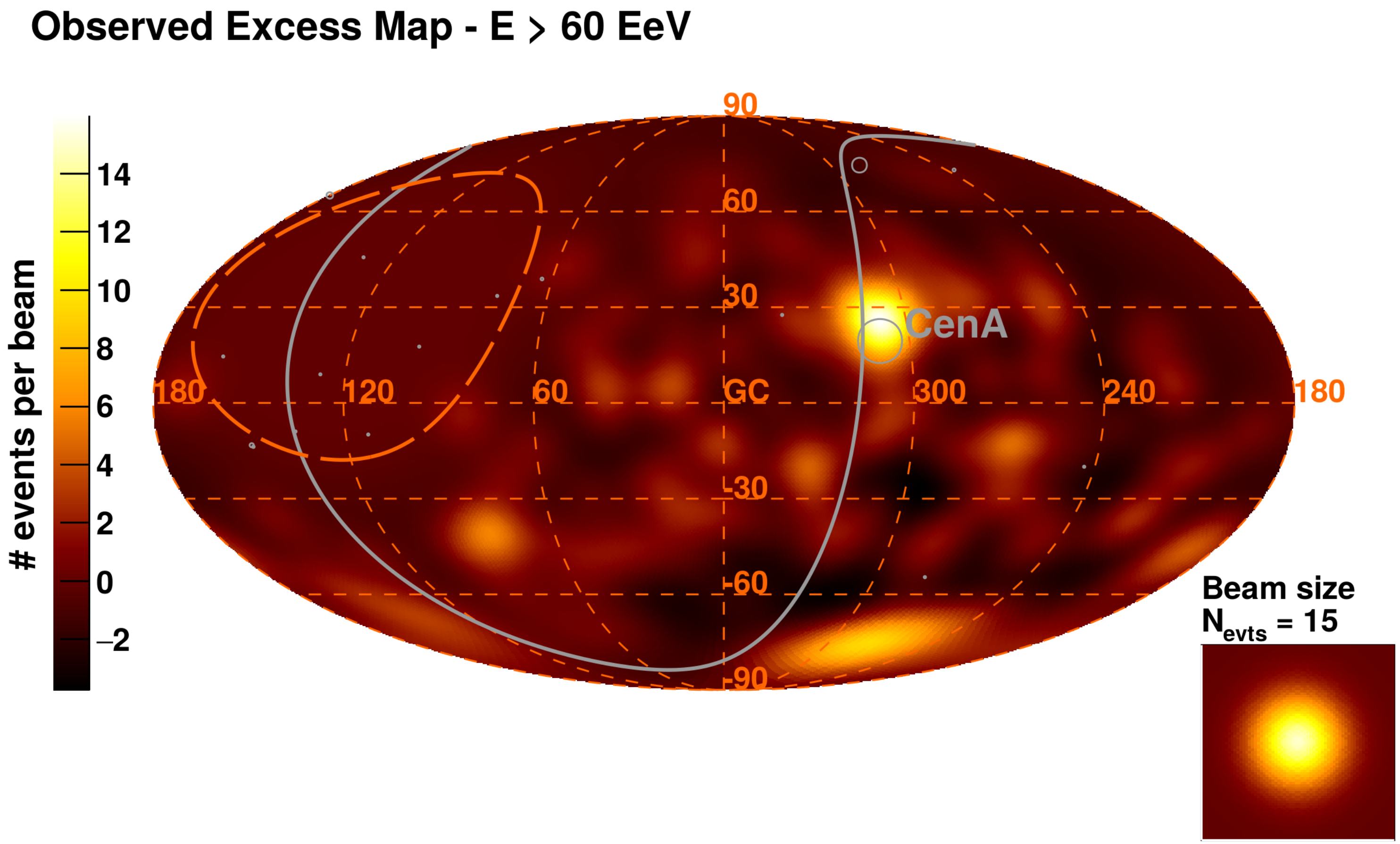
$$\mathbf{t_{cool}} = \frac{\mathbf{9}}{\mathbf{8}\pi\alpha}\left(\frac{\mathbf{m_e}}{\mathbf{E_\gamma^{sync}}}\right)\mathbf{t_{lar}}$$

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

Maximum synchrotron energy tells us how efficient accelerator is!

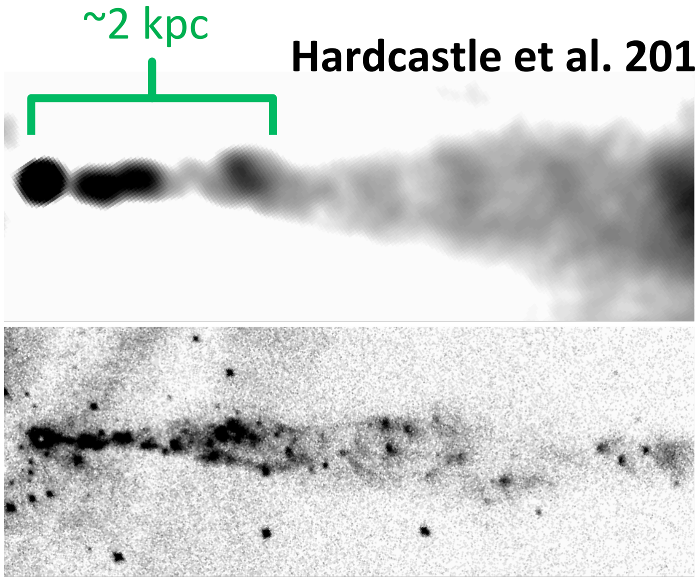
$$\eta < \mathbf{10^3}$$

Can We See UHECR Sources Directly?



PAO Coll. 2018 (1801.06160)

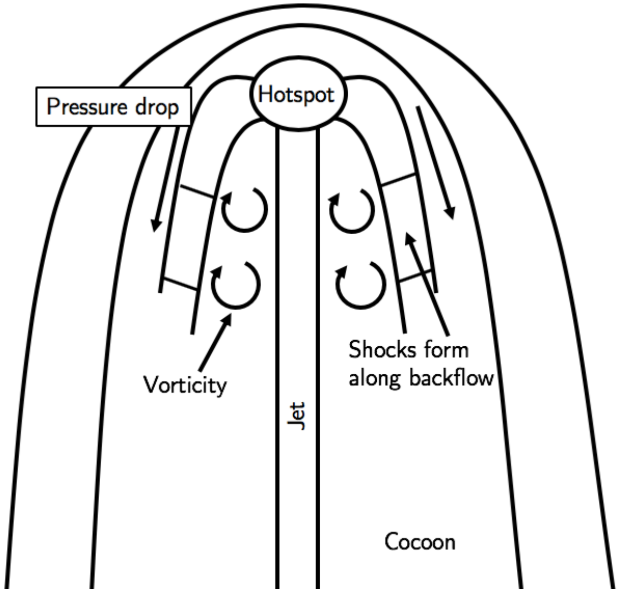
Example Candidate Local Source



Hardcastle et al. 2011 (1103.1744)

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

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



Matthews et al. 2019 (1902.10382)

Maximum energy (Hillas criterion)

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

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

$$\boxed{\mathrm{E_{max}} \approx 10^{15}\mathrm{eV}}$$

$$\boxed{\begin{array}{l}\mathrm{E_{max}} \approx 10^{18}\mathrm{eV} \\ \mathrm{t_{acc}} \approx 0.1\ \mathrm{Myr}\end{array}}$$

O'Sullivan et al. 2009 (0903.1259)