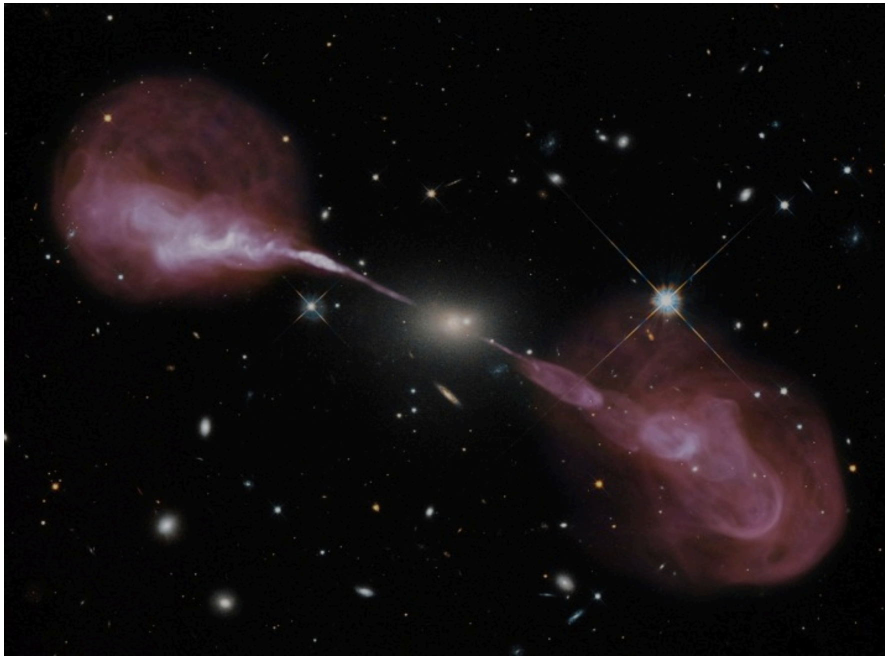
Particle Acceleration in Variable Jets



Andrew Taylor & James Matthews

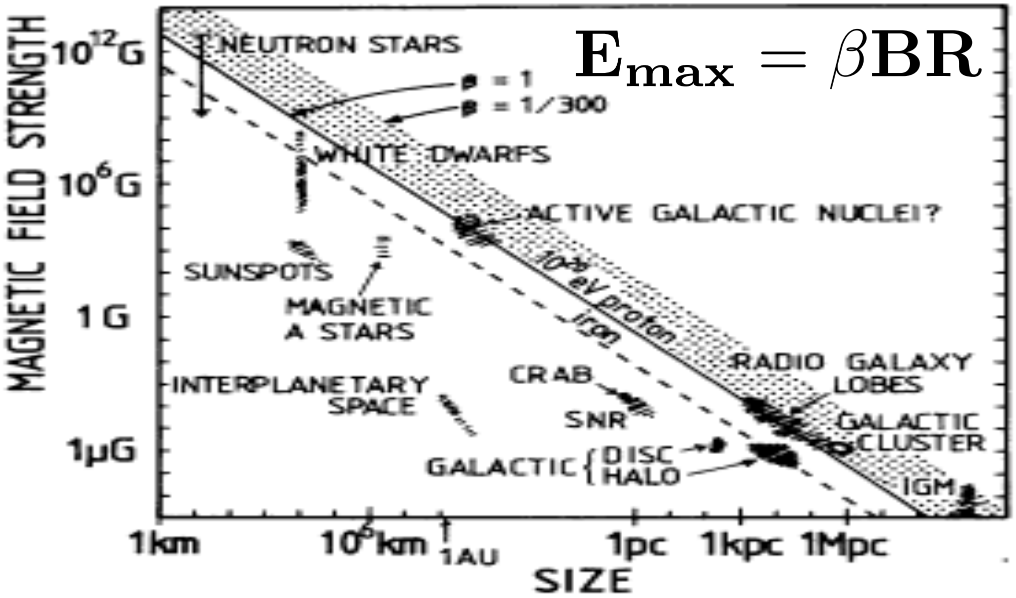
DESY.

Cosmic Ray Source Requirements

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

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

[AM Hillas (1984)]



$$E_{max} = \beta B R$$

[Norman et al. (1995)]

$$L_B = U_B 4\pi R^2 \beta c$$

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

$$L_{KE} > 10^{43} \frac{1}{\beta} \left(\frac{E_p}{10^{19}\ \mathrm{eV}} \right)^2 \ \mathrm{erg\ s^{-1}}$$

AGN Flickering

Observations of blazar, X-ray binary, + local AGN observations indicate that being noisy is not perculiar.

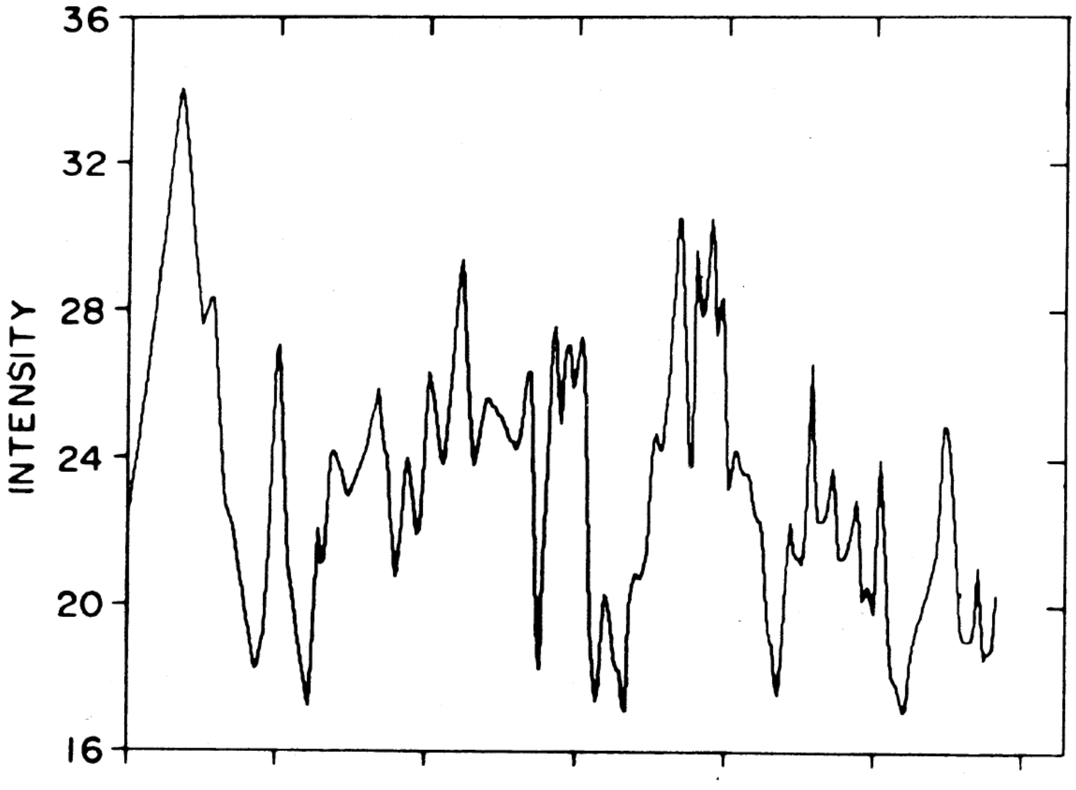
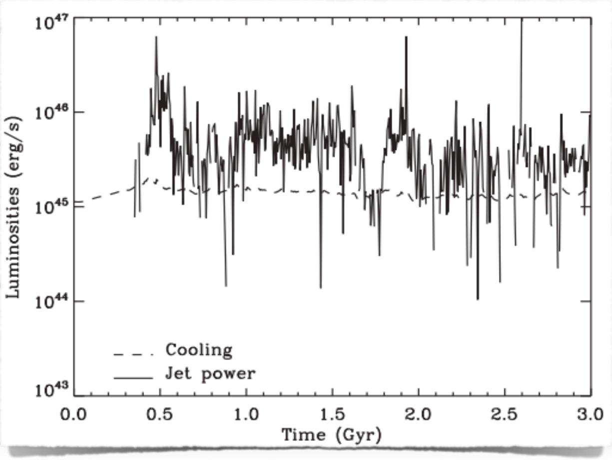


FIGURE 1 Light curve of the quasar 3C273 over a period of 80 years, from 1887 to 1967. The data of Kunkel[11] is here plotted by hundred-day averages; the ordinate is in arbitrary intensity units. (Reproduced from Fahlmann and Ulrych[6]).

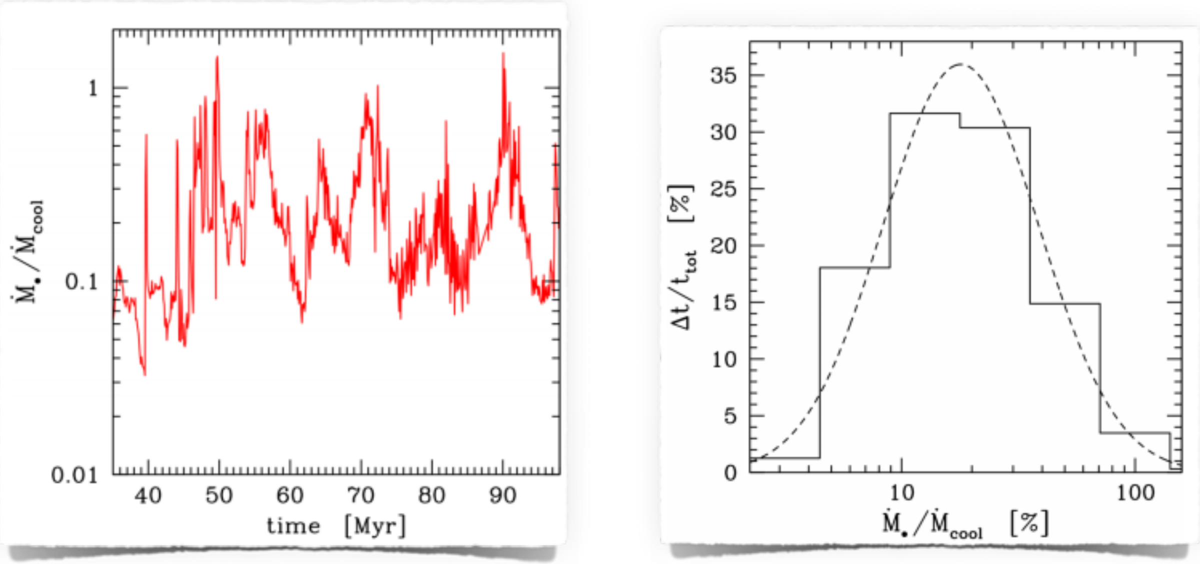
The Role Played By AGN Flickering

A number of simulations of AGN fuelling suggest the large-scale accretion rate follows a log-normal distribution with a flicker noise power spectrum!

Yang & Reynolds 2016



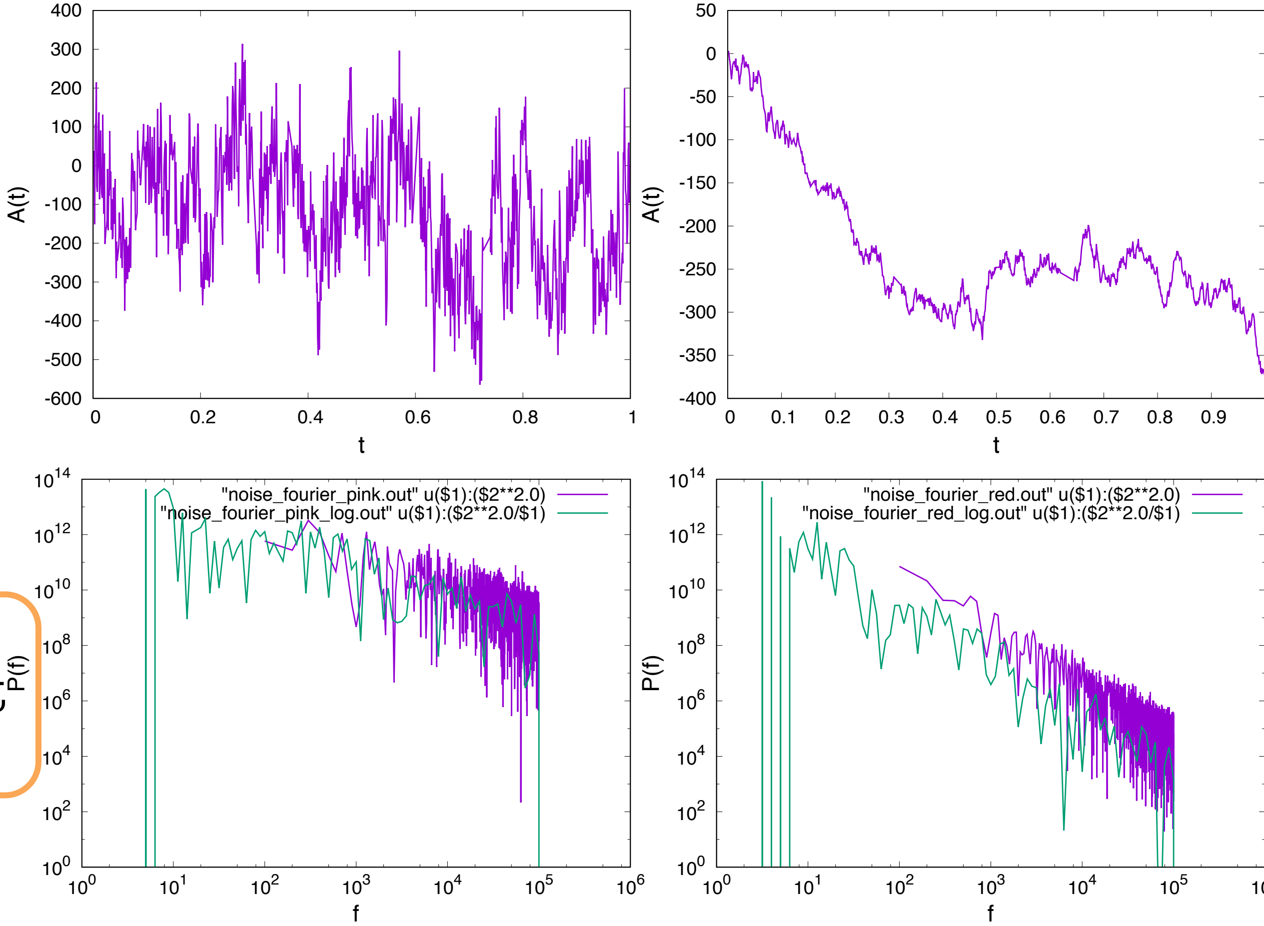
Gaspari et al. 2016



Characterising Noise

Pink/Flicker

Red



$$\mathbf{G(f)} = \int \mathbf{A(t)e^{ift}dt}$$

$$\mathbf{P(f)} = |\mathbf{G(f)}|^{\mathbf{2}}$$

$$\mathbf{P(f)} \propto \mathbf{f}^{-\beta}$$

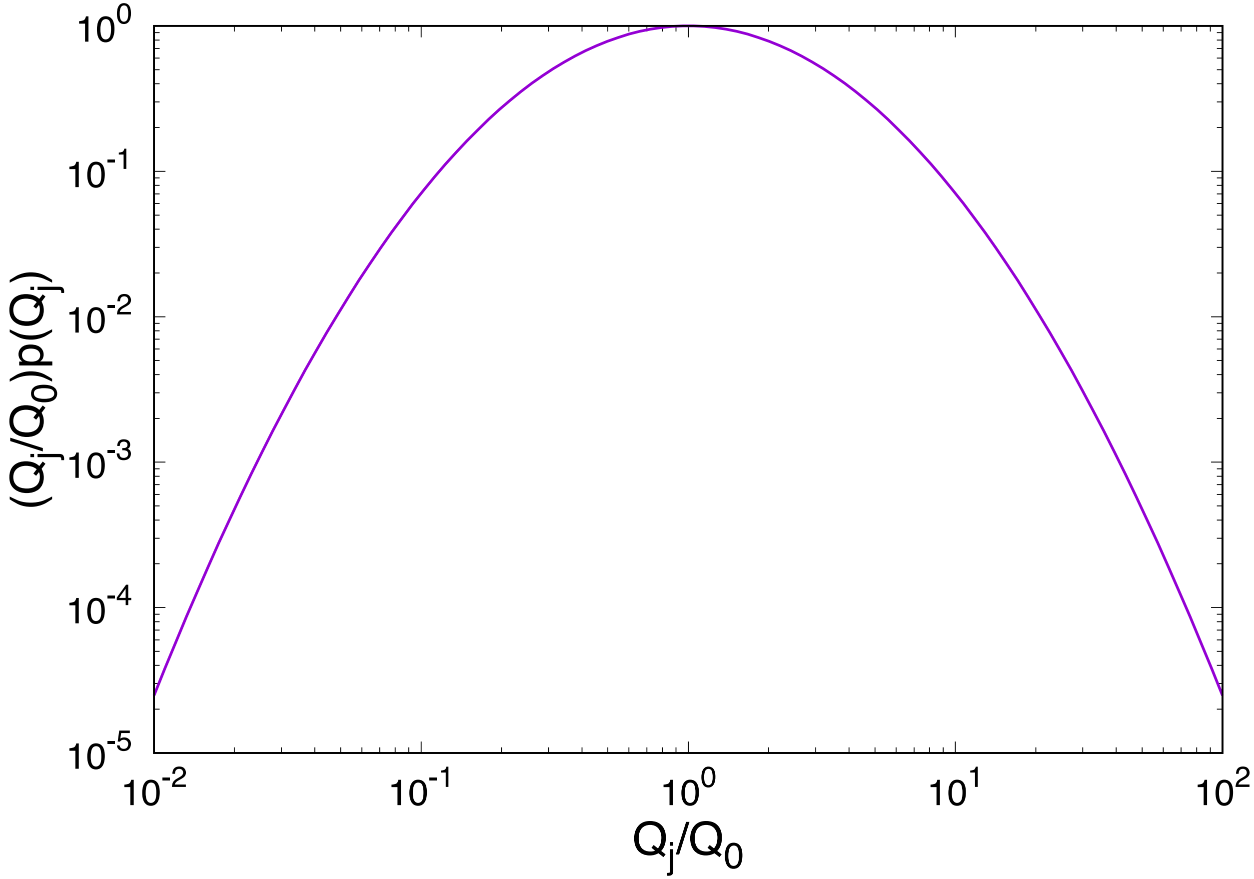
← Power Spectrum Density

$$\beta = \mathbf{1}$$

$$\beta = \mathbf{2}$$

Noise Amplitude Distribution (PDF)

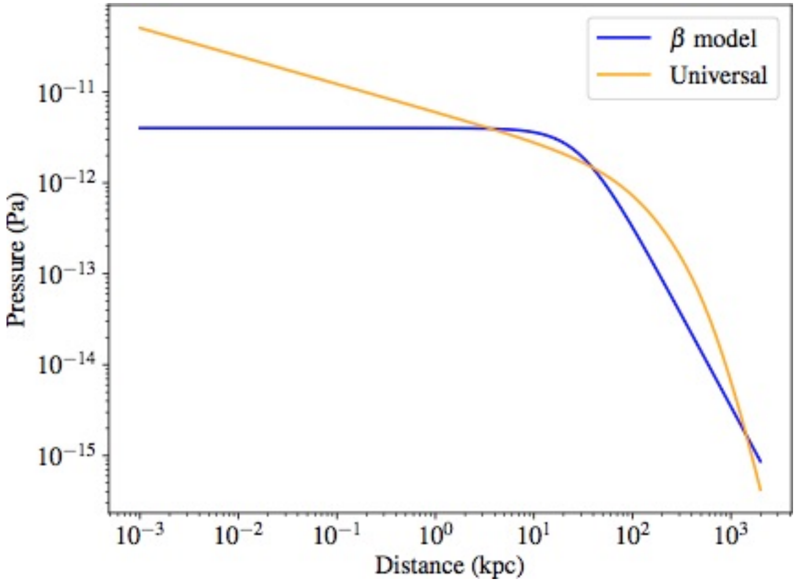
$$(\mathbf{Q_j}/\mathbf{Q_0})\mathbf{p}(\mathbf{Q_j}) = \frac{\mathbf{e}^{-\ln(\mathbf{Q_j}/\mathbf{Q_0})^2/2\sigma^2}}{\sqrt{2\pi\sigma^2}}$$



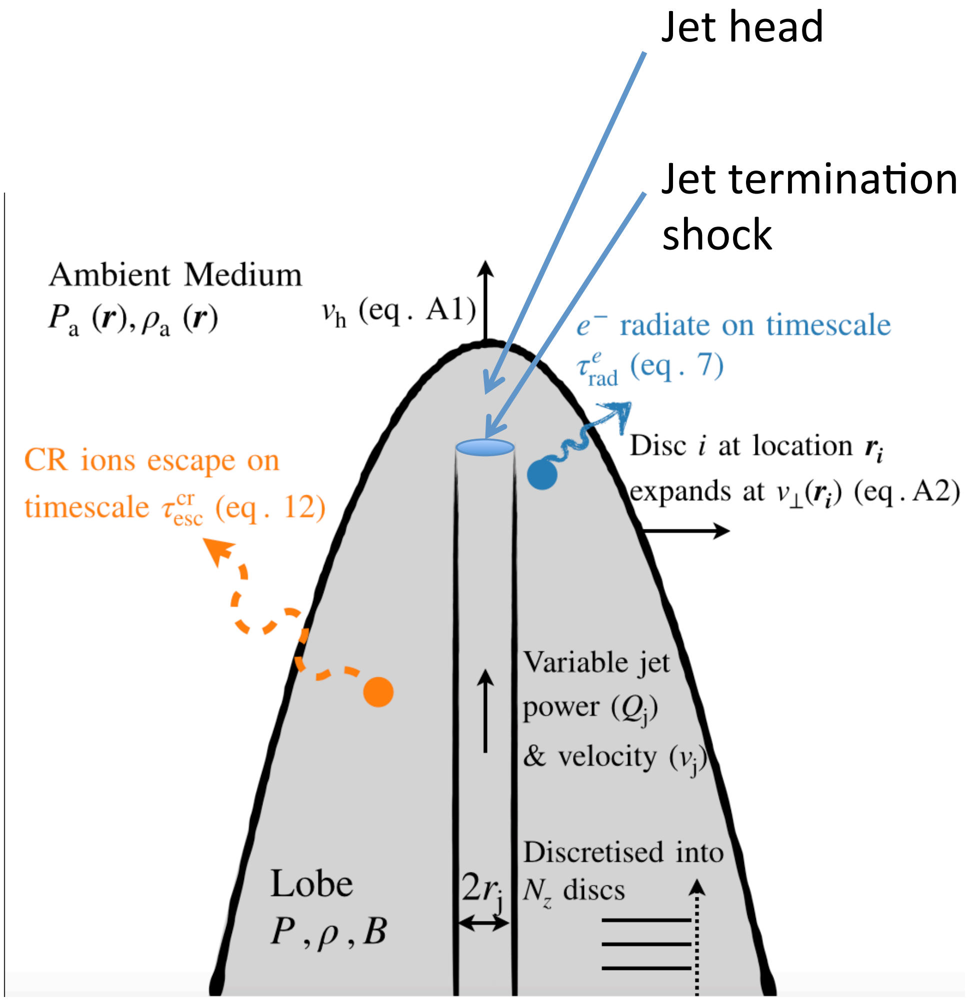
Particle Acceleration in Flickering Jets

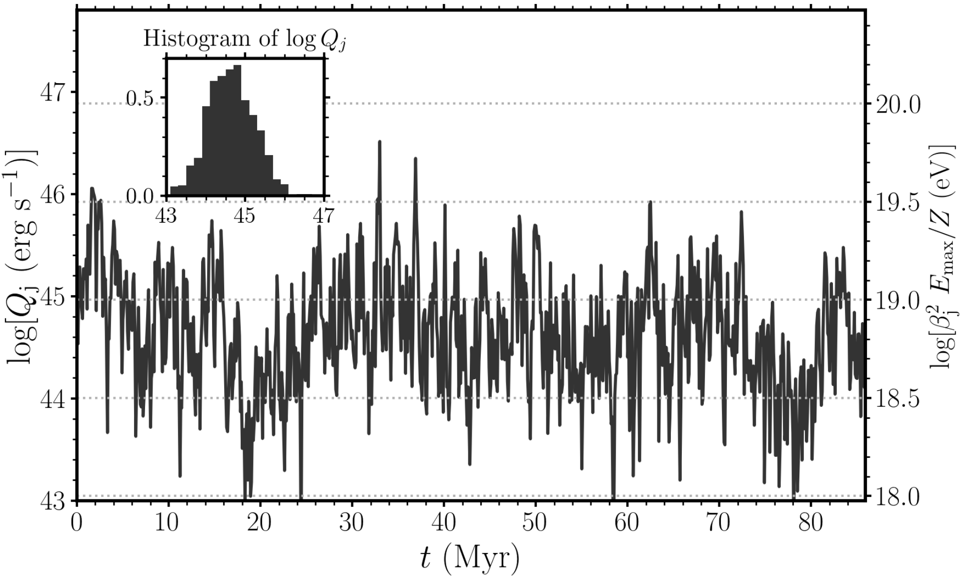
We developed a reduced model of a jet inflated lobe, keeping track of particle acceleration/cooling (inspired by previous efforts- eg. Hardcastle 2018)

Pressure profile external medium

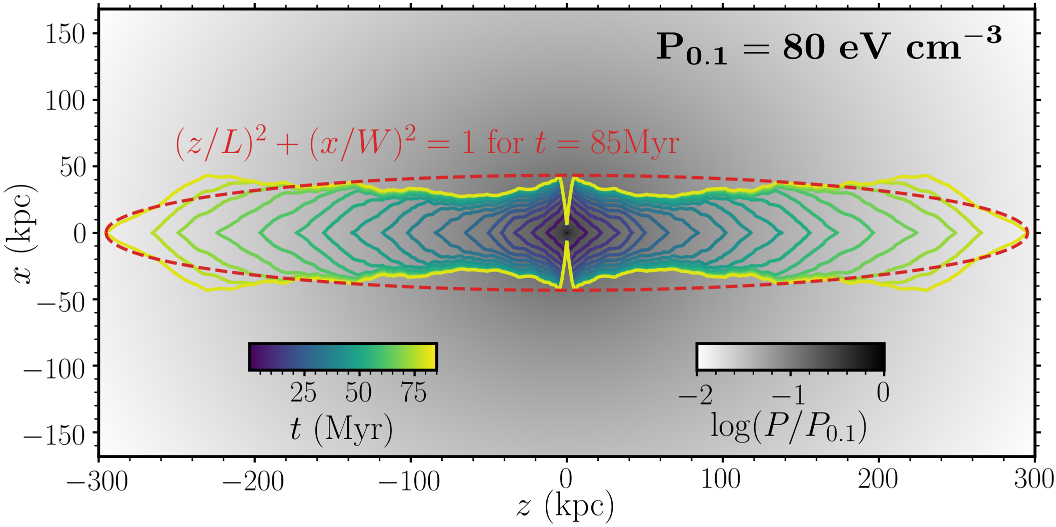


[1 Pa -> 6x10^{12} eV cm^{-3}]





Jet Inflated Cocoon Model



Assumptions:

- Jet termination shock is acceleration site
- Accelerated particles diffuse subsequently diffuse isotropically through homogeneous volume
- Diffusion throughout the cocoon volume is at the Bohm level

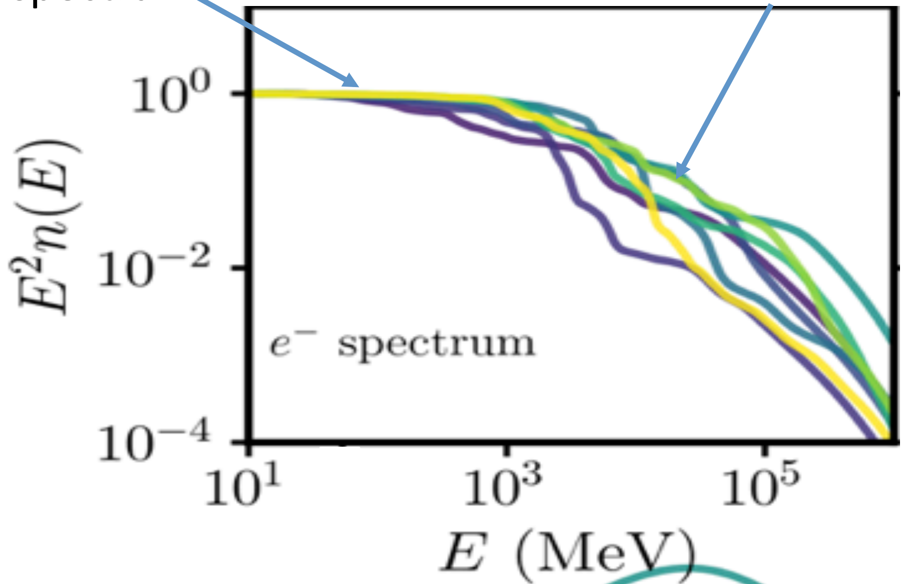
The Electron Spectrum

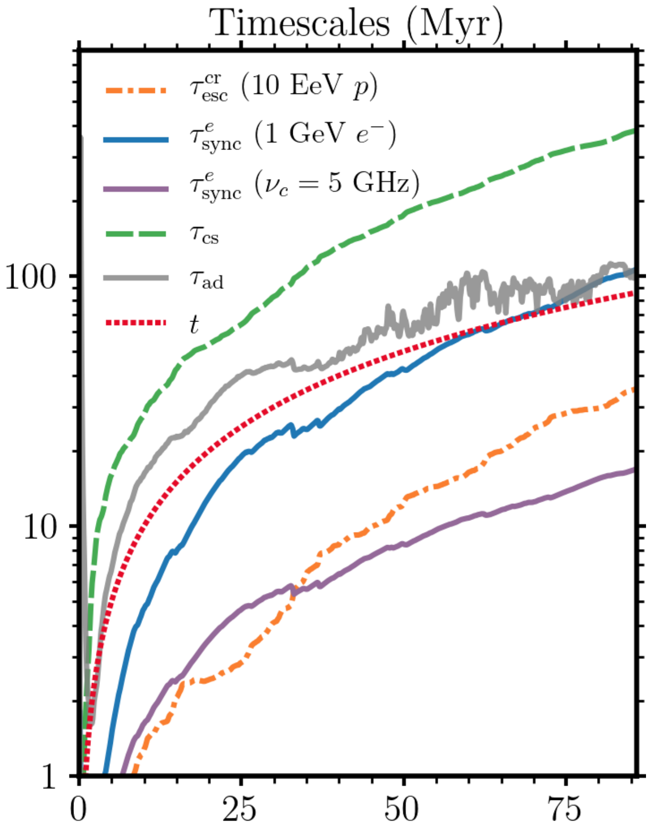
$$\frac{\partial \mathbf{n}(\mathbf{p})}{\partial \mathbf{t}} = \frac{\partial}{\partial \mathbf{p}}\left[\mathbf{p}\left(\frac{\mathbf{1}}{\tau_{\mathbf{sync}}(\mathbf{p})}+\frac{\mathbf{1}}{\tau_{\mathbf{adi}}}\right)\mathbf{n}(\mathbf{p})\right]+\mathbf{Q}(\mathbf{p},\mathbf{t})$$

$$\frac{\mathbf{dn}}{\mathbf{dp}}_{\mathbf{ss}} = \int \mathbf{Q}(\mathbf{p},\mathbf{t})\mathbf{G}(\mathbf{p},\mathbf{t})\mathbf{dt}$$

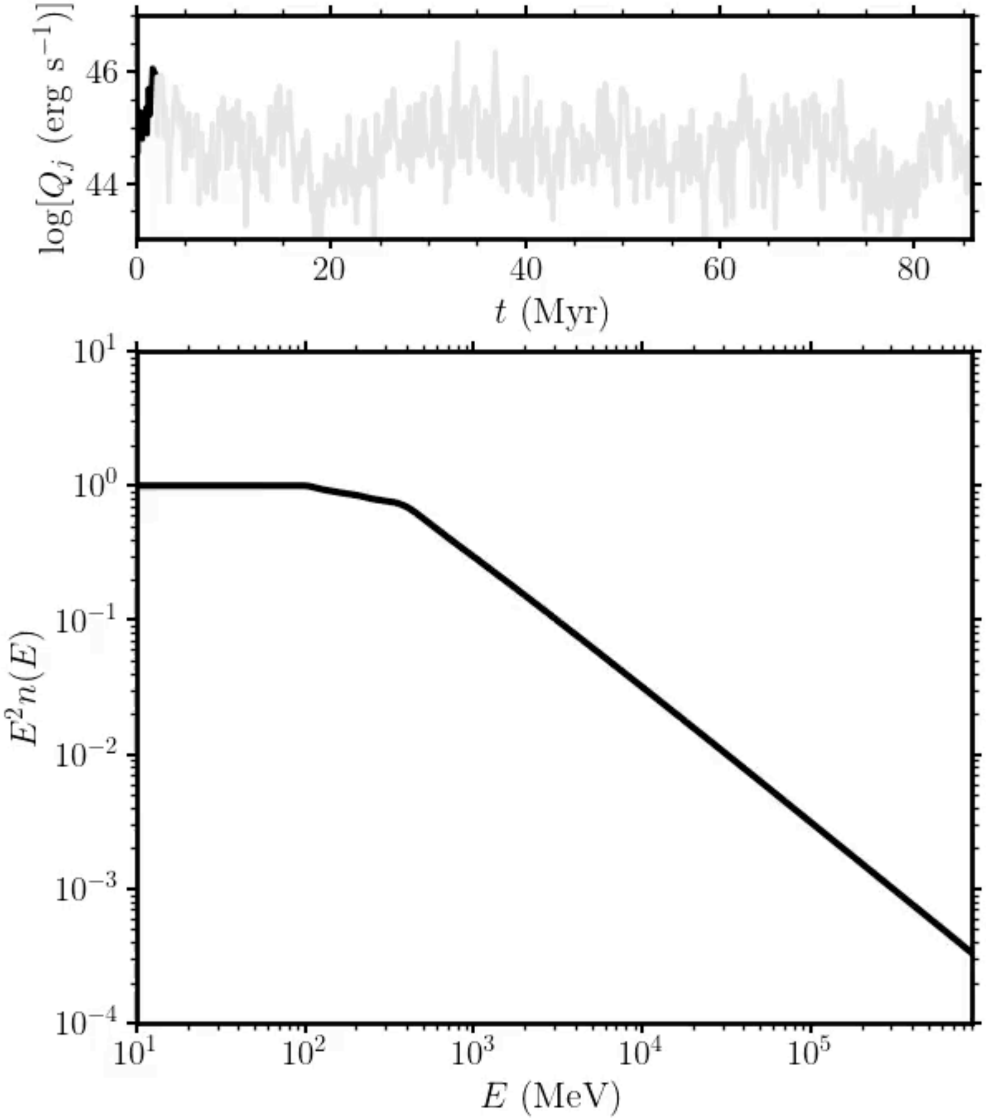
~time limited/adiabatic losses shaped spectra

~steady state via synchrotron cooling





The Electron Spectrum



Proxy Electrons with Cooling Times Comparable to the UHECR Escape Times

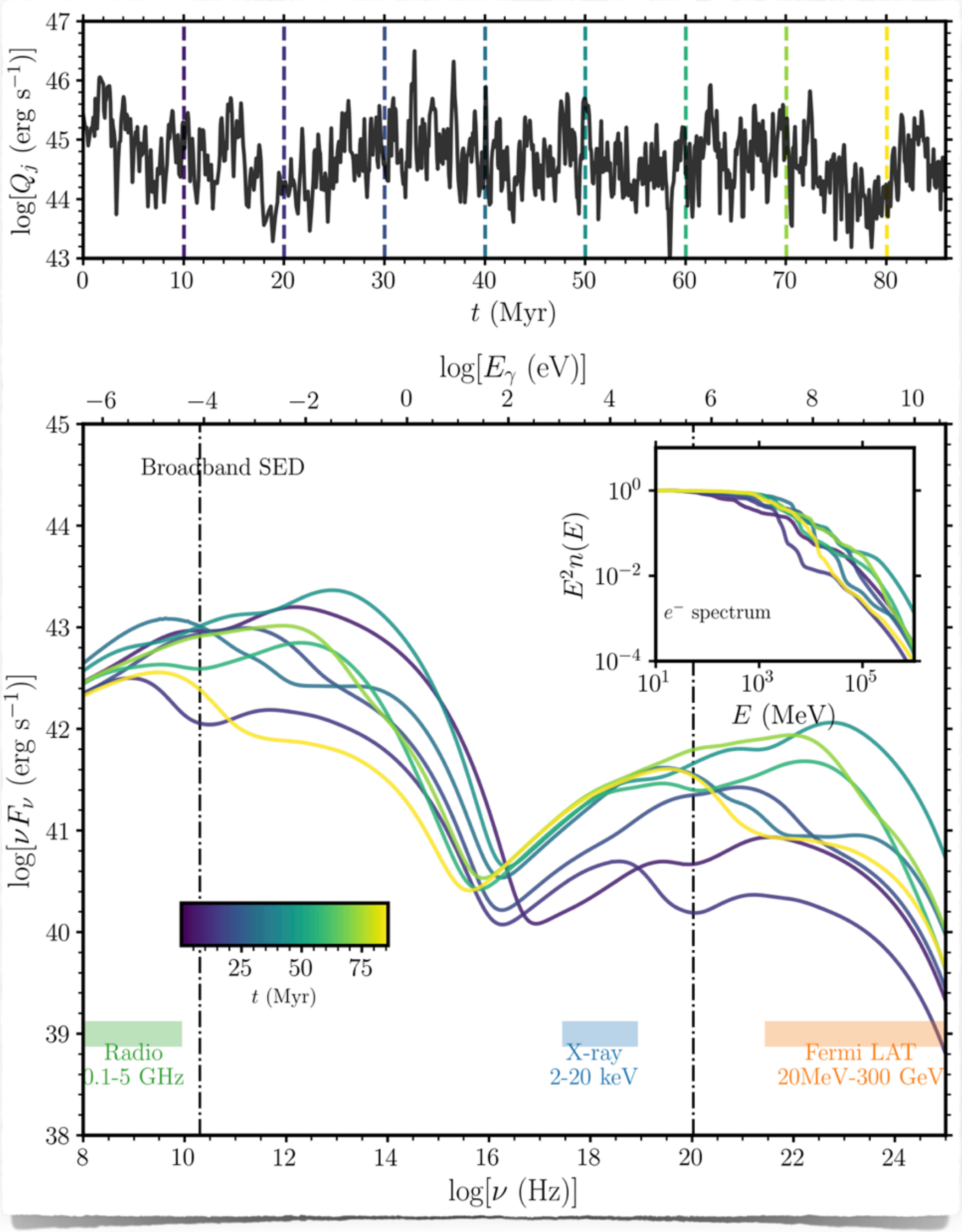
$$\tau^{\mathbf{p}}_{\mathbf{esc}} = \mathbf{9.05}\ \mathrm{Myr}\left(\frac{\mathbf{L}_{\mathrm{esc}}}{\mathbf{100}\ \mathrm{kpc}}\right)^{\mathbf{2}}\left(\frac{\mathbf{D}_{\mathbf{B}}}{\mathbf{D}}\right)\left(\frac{\mathbf{E/Ze}}{\mathbf{10\ EV}}\right)^{-\mathbf{1}}\left(\frac{\mathbf{B}}{\mathbf{10}\mu\mathrm{G}}\right)$$

$$\tau^{\mathbf{e}}_{\mathrm{sync}} = \mathbf{10}\ \left(\frac{\mathbf{10}\mu\mathbf{G}}{\mathbf{B}}\right)^{\mathbf{2}}\left(\frac{\mathbf{10\ GeV}}{\mathbf{E_e}}\right)\ \mathbf{Myrs}$$

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

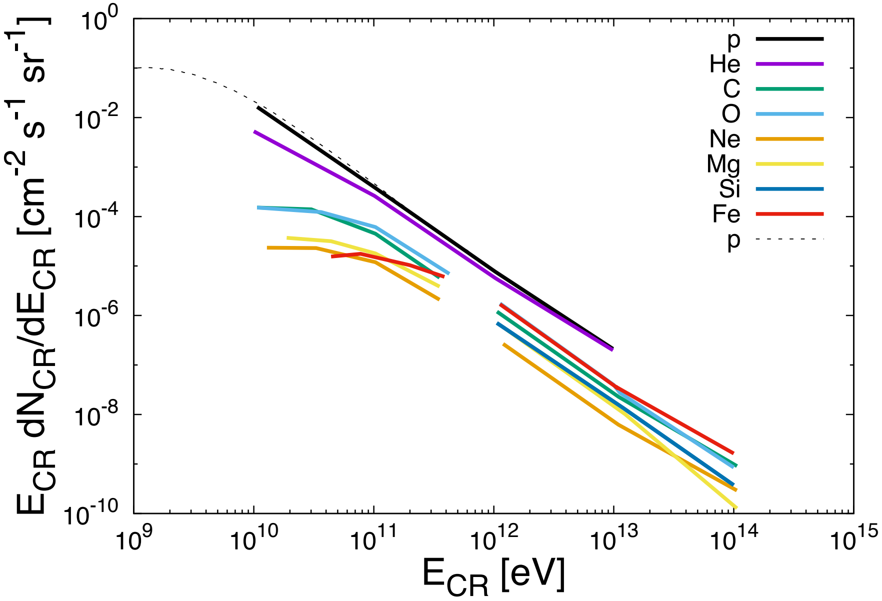
$$\nu_{\mathrm{proxy}} \approx \mathbf{20}\ \mathrm{GHz}\left(\frac{\mathbf{E/Ze}}{\mathbf{10EV}}\right)^{\mathbf{2}}\left(\frac{\mathbf{L}_{\mathrm{esc}}}{\mathbf{100}\ \mathrm{kpc}}\right)^{-\mathbf{4}}\left(\frac{\mathbf{D}_{\mathrm{esc}}}{\mathbf{D_B}}\right)^{\mathbf{2}}\left(\frac{\mathbf{B}}{\mathbf{10}\ \mu\mathrm{G}}\right)^{-\mathbf{5}}$$

Radiative Signatures from Accelerated Electrons



The msynchro code used here has been made publicly available at `https://github.com/jhmatthews/msynchro`

Proton/Nuclei Injection Spectra



$\mathbf{f}_{\odot}$

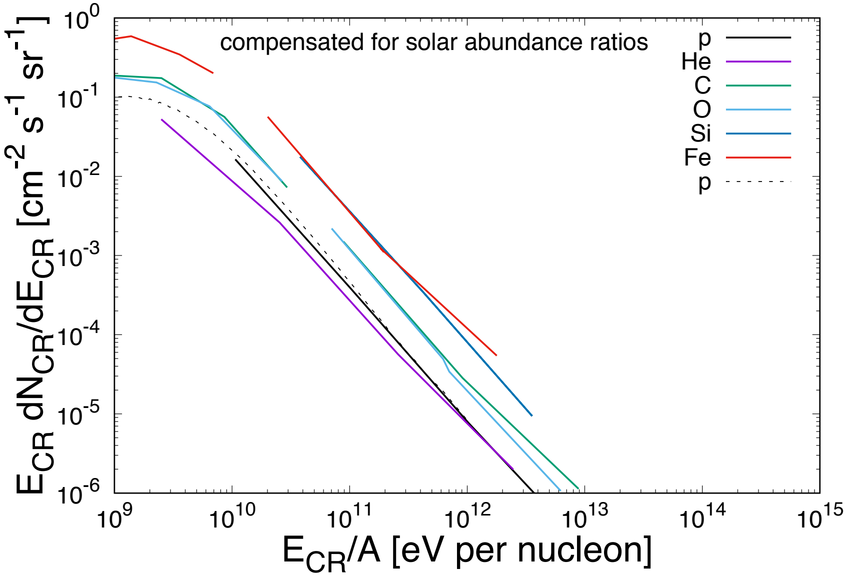
$$\boxed{\frac{\mathbf{dN_A}}{\mathbf{dE}} = \mathbf{Z^2 A^{p-2} f_{\odot}} \left(\frac{\mathbf{E}}{\mathbf{E_0}}\right)^{\mathbf{-p}}}$$

$\mathbf{f}_{\odot}$

solar system abundance ratios

	proton	He	C	O	Si	Fe
x_i	1.0	0.1	0.0004	0.0008	0.00003	0.00003

Low Energy CR Composition Consideration



solar system abundance ratios

	proton	He	C	O	Si	Fe
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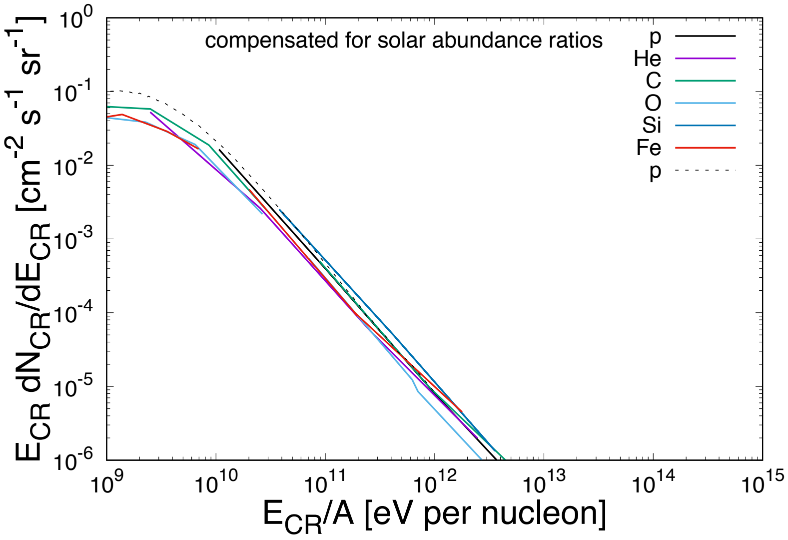


$$\mathbf{E_A \frac{dN_A}{dE_A}\left(\frac{E_A}{A}\right) = f_A E_p \frac{dN_p}{dE_p}(E_p)}$$

$$\mathbf{f_A = \frac{Z^2}{A} f_\odot}$$

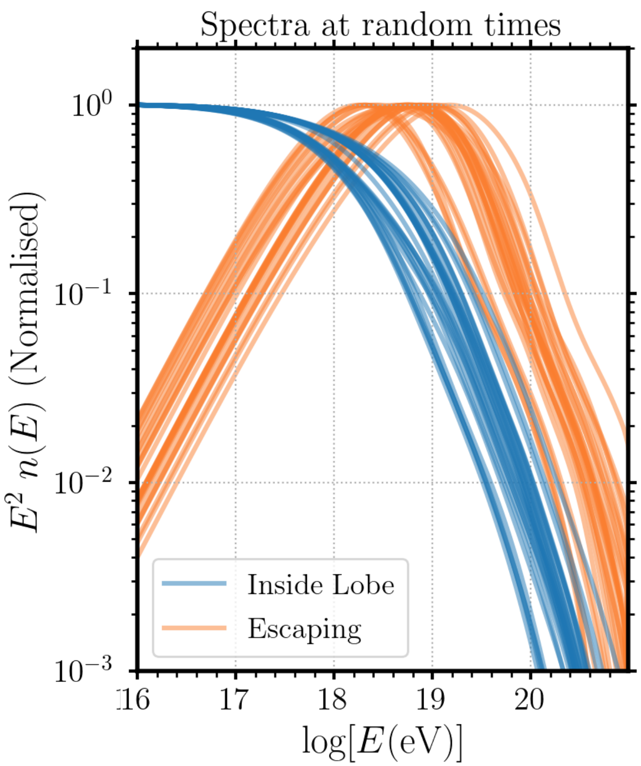
Wykes et al. (2018) 1706.08229

Caprioli et al. (2018) 1704.08252

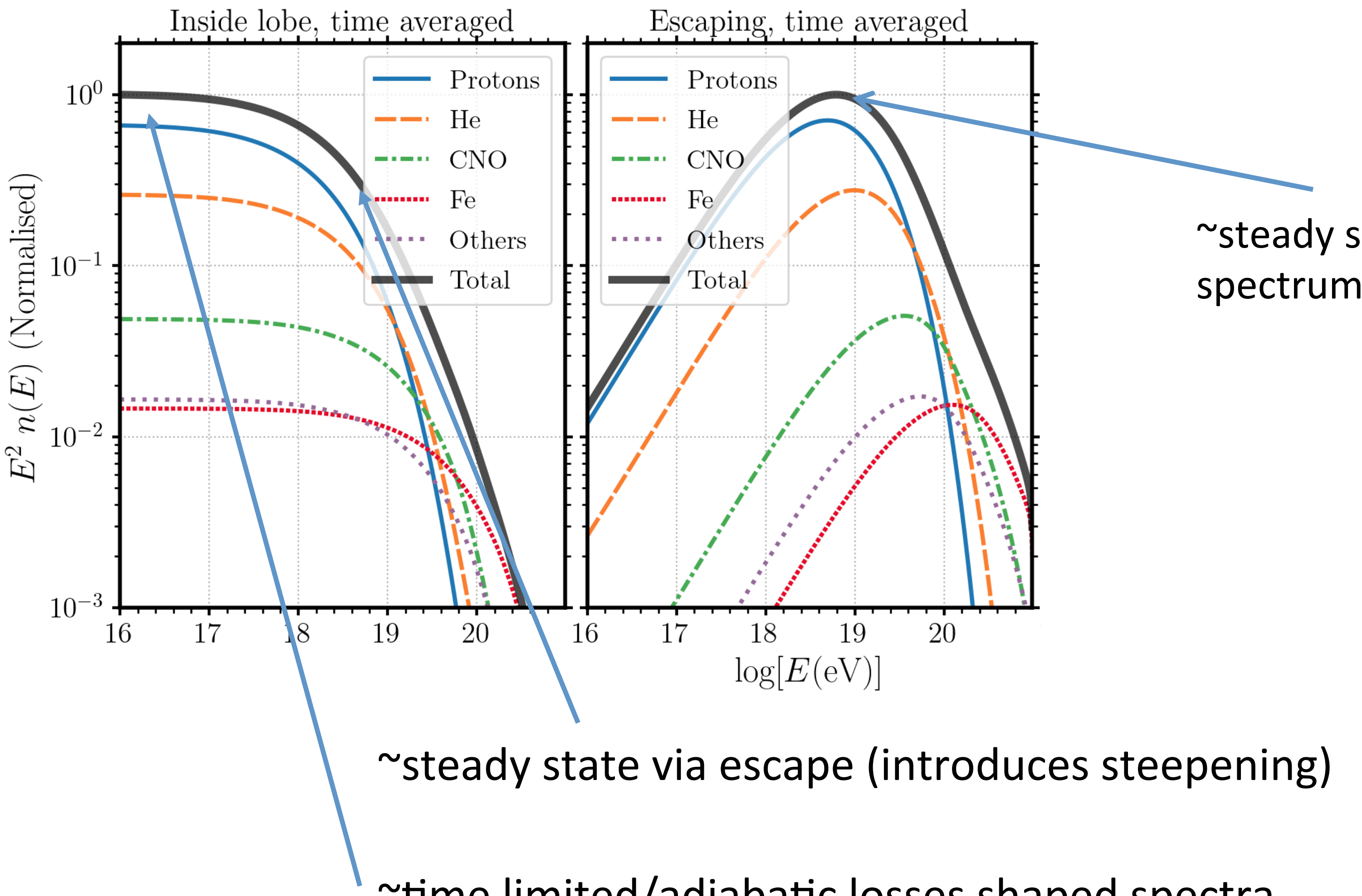
The Hadronic Spectrum

$$\frac{\partial \mathbf{n}(\mathbf{p})}{\partial \mathbf{t}} = \mathbf{Q}(\mathbf{p},\mathbf{t}) - \frac{\mathbf{n}(\mathbf{p})}{\tau_{\mathbf{esc}}(\mathbf{p})} - \frac{\mathbf{n}(\mathbf{p})}{\tau_{\mathbf{loss}}} - \frac{\mathbf{n}(\mathbf{p})}{\tau_{\mathbf{adi}}}$$

$$\frac{\mathbf{dn}}{\mathbf{dp}}_{\mathbf{ss}} = \int \mathbf{Q}(\mathbf{p},\mathbf{t})\mathbf{G}(\mathbf{p},\mathbf{t})\mathbf{dt}$$



The Proton/Nuclei Steady-State Spectra Inside/Outside Source



~steady state escape spectrum

~steady state via escape (introduces steepening)

~time limited/adiabatic losses shaped spectra

DESY.

The Shape of the UHECR Cutoff Produced by a Flickering Source

- Instantaneous maximum cosmic ray energy dependent on jet power

$$\boxed{\mathbf{E_{max} = 10^{19} \left(\frac{\beta Q_j}{10^{43}\ erg\ s^{-1}} \right)^{1/2} eV}}$$

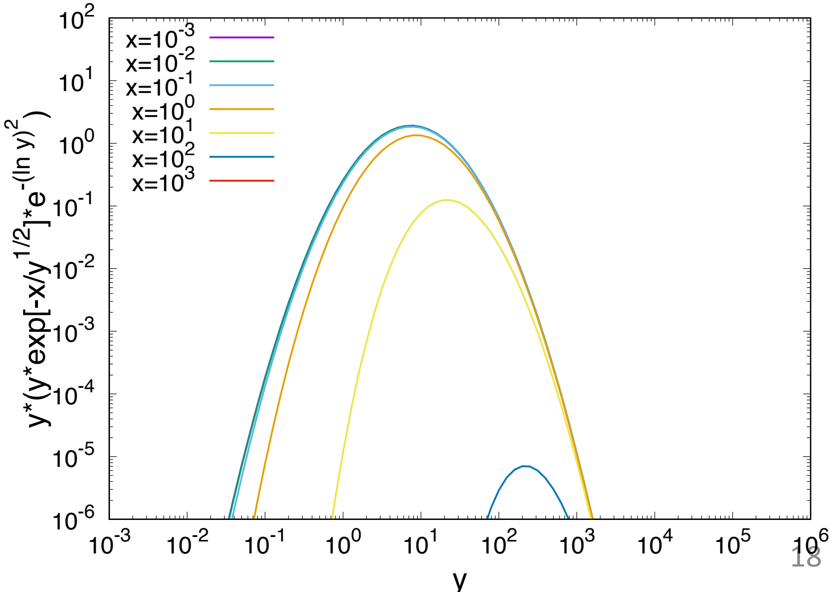
The Shape of the UHECR Cutoff Produced by a Flickering Source

$$\mathbf{n}(\mathbf{E}) \propto \mathbf{E}^{-\mathbf{p}} \int_{\mathbf{0}}^{\infty} \mathbf{Q}_{\mathrm{j}}(\mathbf{t})\ \exp\left[-\frac{\mathbf{E}}{\mathbf{E}_{\mathbf{k}}}\sqrt{\frac{\mathbf{Q}_{\mathbf{0}}}{\beta_{\mathbf{j}}\mathbf{Q}_{\mathrm{j}}(\mathbf{t})}}\right] \mathbf{dt}$$

$$\mathbf{f}(\mathbf{x},\mathbf{Q}_{\mathbf{0}}) = \int \mathbf{y}\mathbf{e}^{\left[-\frac{\mathbf{x}}{\sqrt{\mathbf{y}\mathbf{Q}_{\mathbf{0}}}}-\frac{(\ln\mathbf{y})^{\mathbf{2}}}{\mathbf{2}\sigma^{\mathbf{2}}}\right]}\mathbf{d}\ln\mathbf{y}$$

Method- approximate integral as value at peak of integrand.

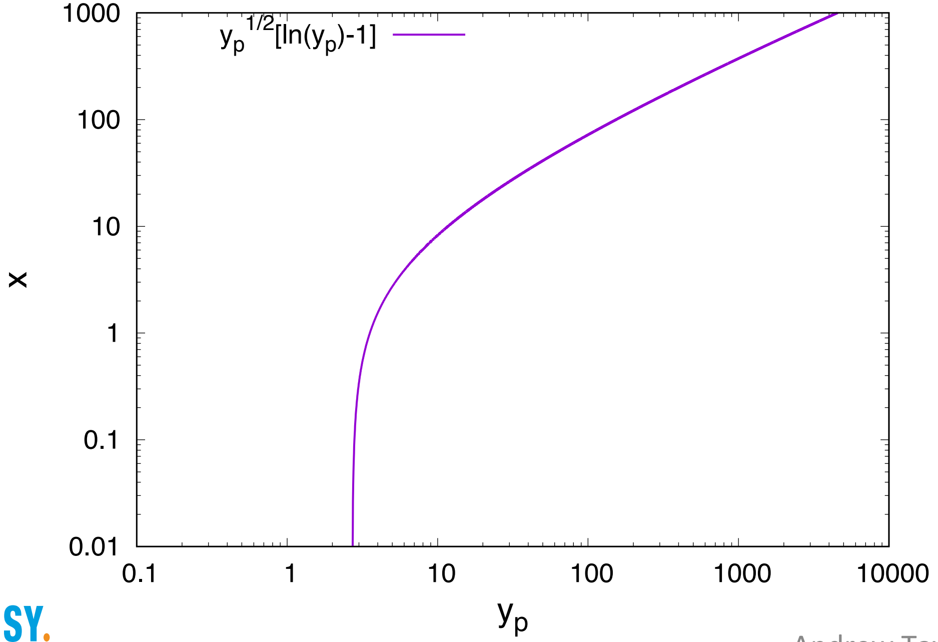
$$\mathbf{f}(\mathbf{x},\mathbf{Q}_{\mathbf{0}}) \approx \mathbf{y}_{\mathbf{p}}\mathbf{e}^{\left[-\frac{\mathbf{x}}{\sqrt{\mathbf{y}_{\mathbf{p}}\mathbf{Q}_{\mathbf{0}}}}-\frac{(\ln\mathbf{y}_{\mathbf{p}})^{\mathbf{2}}}{\mathbf{2}\sigma^{\mathbf{2}}}\right]}$$

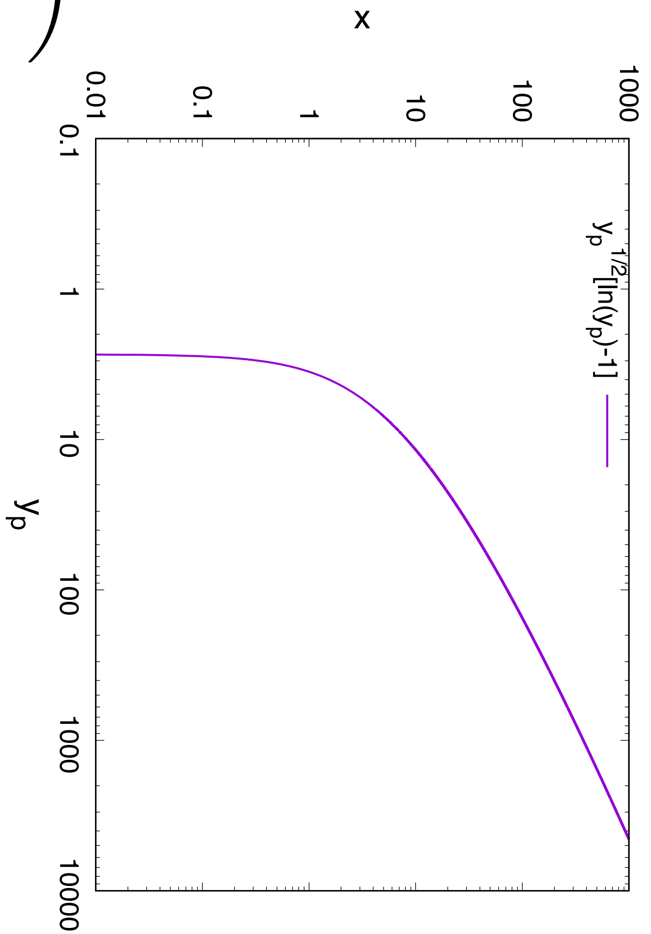


The Shape of the UHECR Cutoff Produced by a Flickering Source

Peak occurs at: $$\mathbf{x = 2y_p^{1/2}\left(\frac{\ln y_p}{\sigma^2} - 1\right)}$$

First a bit of insight:

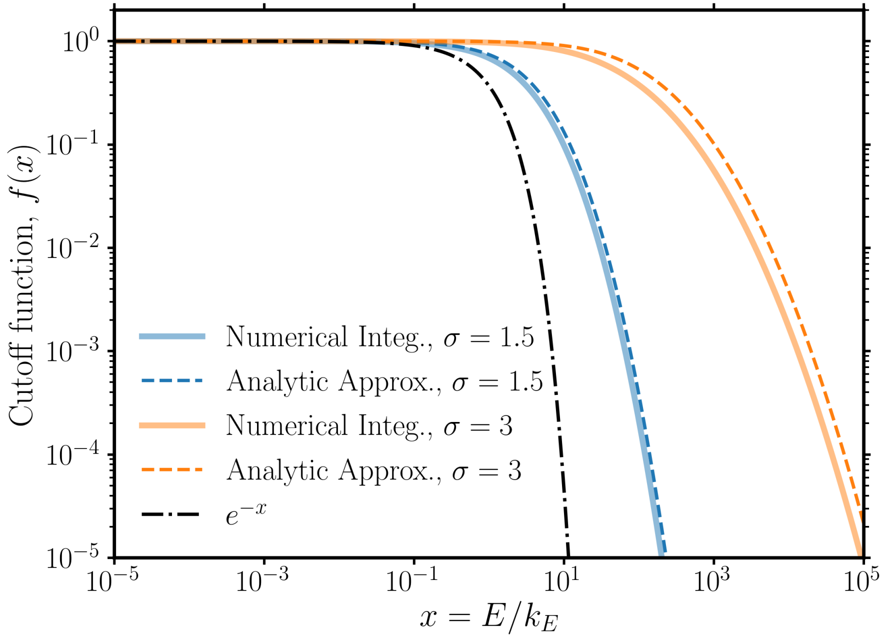




The Shape of the UHECR Cutoff Produced by a Flickering Source

Inversions of relation: $$\mathbf{x} = \mathbf{2y_p^{1/2}}\left(\frac{\ln \mathbf{y_p}}{\boldsymbol{\sigma^2}} - \mathbf{1}\right)$$

$$\mathbf{y_p}(\mathbf{x},\sigma) = \left(\frac{\boldsymbol{\sigma^2}\mathbf{x}/\mathbf{4}}{\mathbf{W}(\mathbf{e}^{-\boldsymbol{\sigma^2}/\mathbf{2}}\boldsymbol{\sigma^2}\mathbf{x}/\mathbf{4})}\right)$$ where $$\mathbf{W}(\mathbf{z})\mathbf{e}^{\mathbf{W}(\mathbf{z})} = \mathbf{z}$$



Conclusion

- Simple AGN model developed to investigated the effect jet variability has on non-thermal signatures

- Electron and UHECR luminosities track jet power with a response set by cooling/escape time

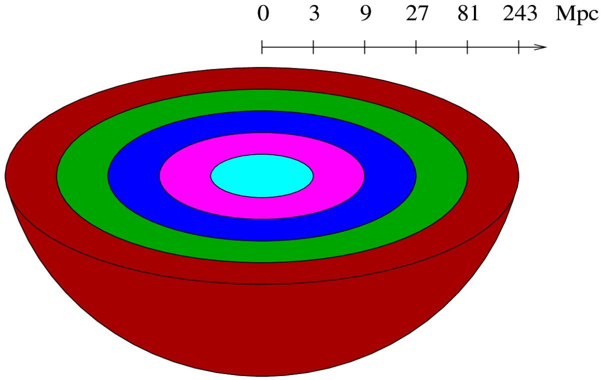
- Proxy electrons are noted, capable of probing source activity level on the relevant timescale for present UHECR escape

- Variation in power causes variation in both the resultant shape of the spectral break and cut-off features

Extra Slides

Local Scales Effect Highest Energies

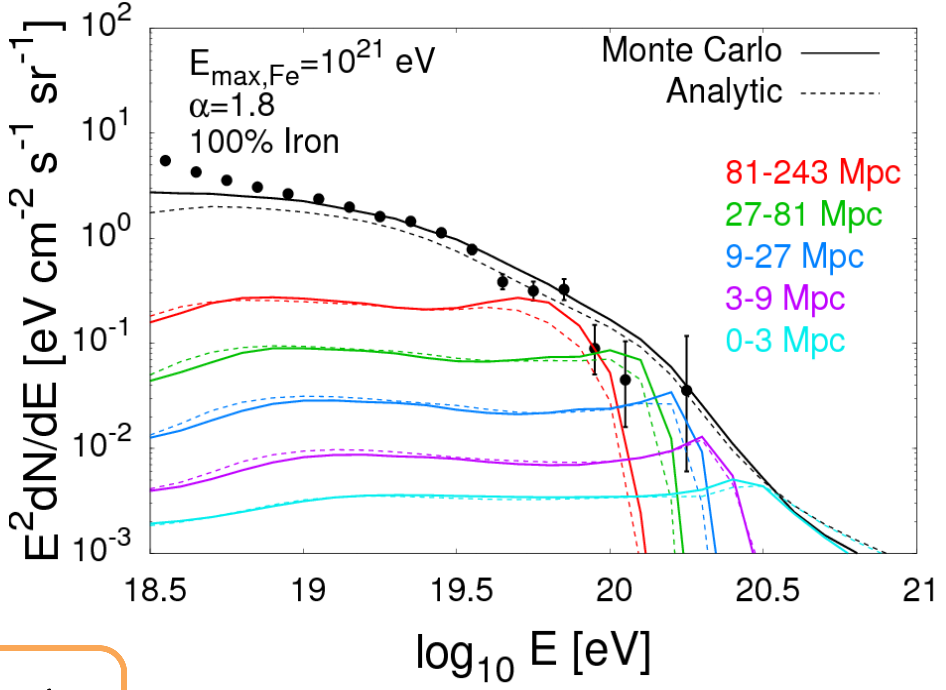
(logarithmic scale)



[A. Taylor et al., Phys Rev D (2011)]

[R. Lang and A. Taylor in prep.]

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



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

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

$$\mathcal{L}_0 \approx \mathrm{L_0 n_0}$$
$$\approx \mathrm{E_0 \dot{n}_0}$$

$$\Rightarrow$$

$$\mathrm{n_0} \sim 10^{-5}\ \mathrm{Mpc^{-3}}$$
$$\mathrm{\dot{n}_0} \sim 10^{-6}\ \mathrm{Mpc^{-3}\ yr^{-1}}$$

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

Electron Cooling Timescale

$$\tau^{\mathbf{e}}_{\mathrm{sync}} = \frac{\mathbf{9}}{\mathbf{4}\alpha}\left(\frac{\mathbf{B}_{\mathrm{crit}}}{\mathbf{B}}\right)^{\mathbf{2}}\frac{\hbar}{\gamma_{\mathbf{e}}\mathbf{m}_{\mathbf{e}}\mathbf{c}^{\mathbf{2}}}$$

$$= \mathbf{100}\ \left(\frac{\mathbf{10}\mu\mathbf{G}}{\mathbf{B}}\right)^{\mathbf{2}}\left(\frac{\mathbf{GeV}}{\mathbf{E}_{\mathbf{e}}}\right)\ \mathbf{Myrs}$$

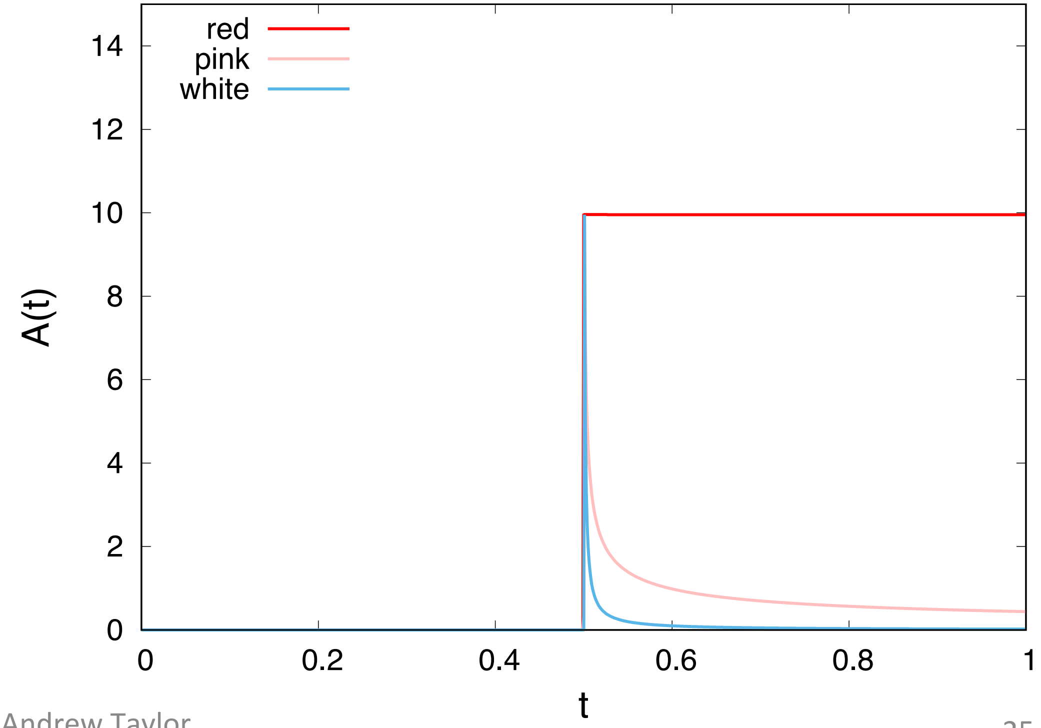
Noise Production

$$\frac{\partial \mathbf{A}}{\partial \mathbf{t}} = \overset{\text{driver}}{\overset{\downarrow}{\mathbf{rand}}} - \underset{\text{response}}{\underset{\uparrow}{\mathbf{bA^n}}}$$

Impulse response

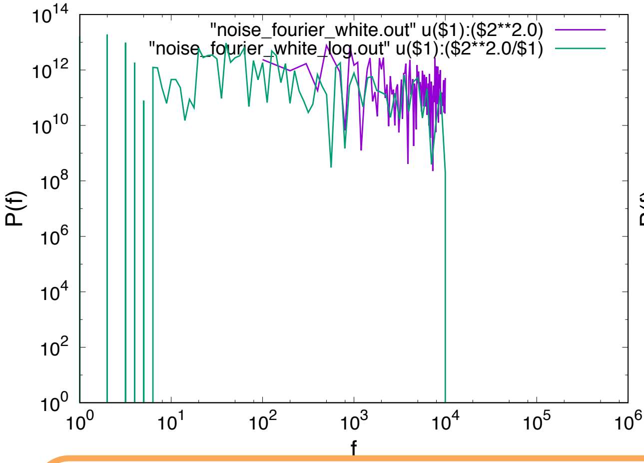
$$\mathbf{A(t)} = \theta(\mathbf{t})\mathbf{t}^{-\alpha}$$

$$\boxed{\begin{aligned}\mathbf{G(f)} &= \int \mathbf{A(t)e^{ift}dt} \\ &= \mathbf{\Gamma(\alpha+1)f^{\alpha-1}}\end{aligned}}$$

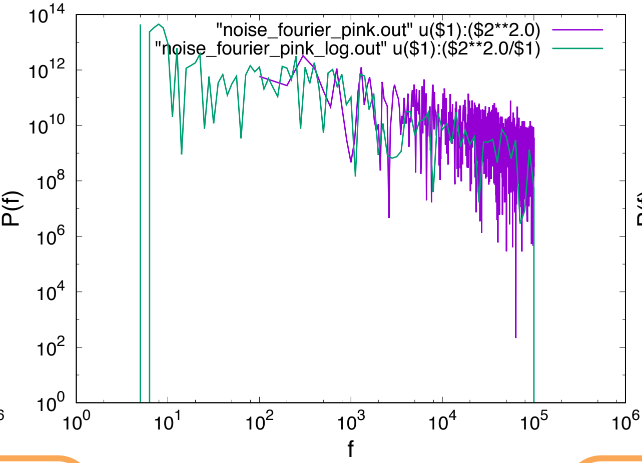


Noise Frequency Distribution (PSD)

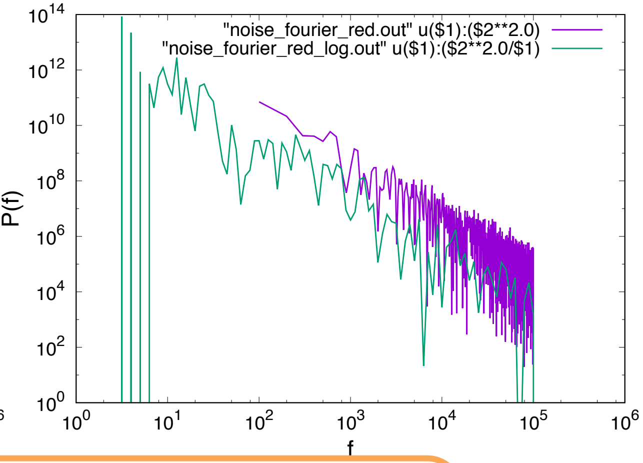
White



Pink/Flicker



Red



$$\mathbf{G(f) = \int A(t)e^{ift}dt}$$

$$\mathbf{P(f) = |G(f)|^2}$$

$$\mathbf{P(f) \propto f^{-\beta}}$$

← Power Spectrum Density

$$\beta = \mathbf{0}$$

$$\beta = \mathbf{1}$$

$$\beta = \mathbf{2}$$

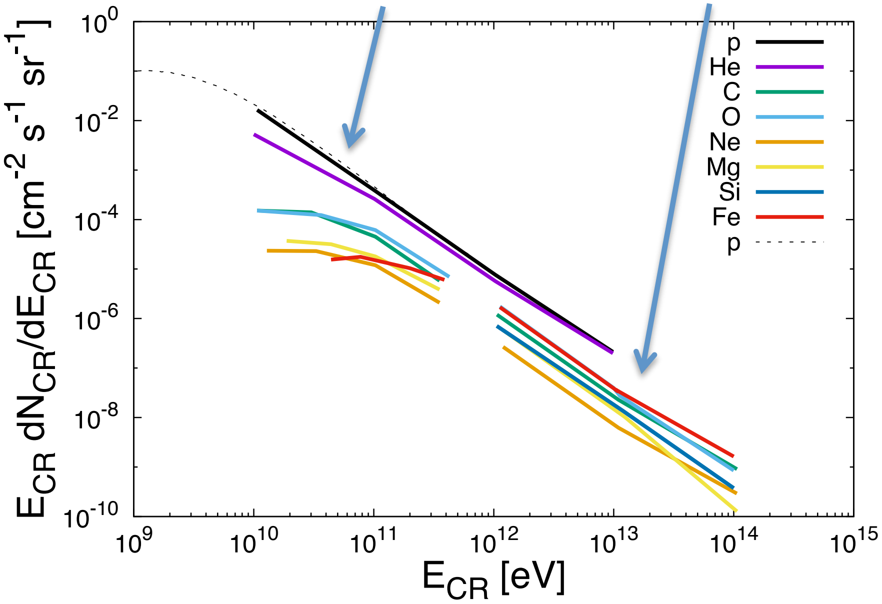
Injection Ratio of Nuclear Species-Motivation

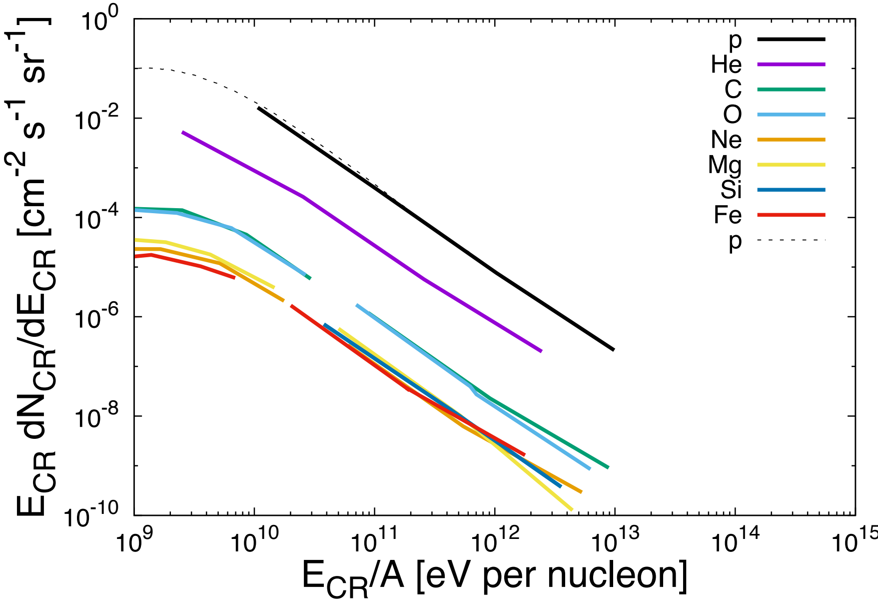
composition ratios of CR at 10~GeV per nucleon

	proton	He	C	O	Si	Fe
x_i	1.0	0.04	0.001	0.001	0.0002	0.0002

ATIC data

CREAM data





Proton Spectra