Variability Patterns in Inhomogeneous Jets with Particle Diffusion and Localized Acceleration

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Recent Results in Astrophysics
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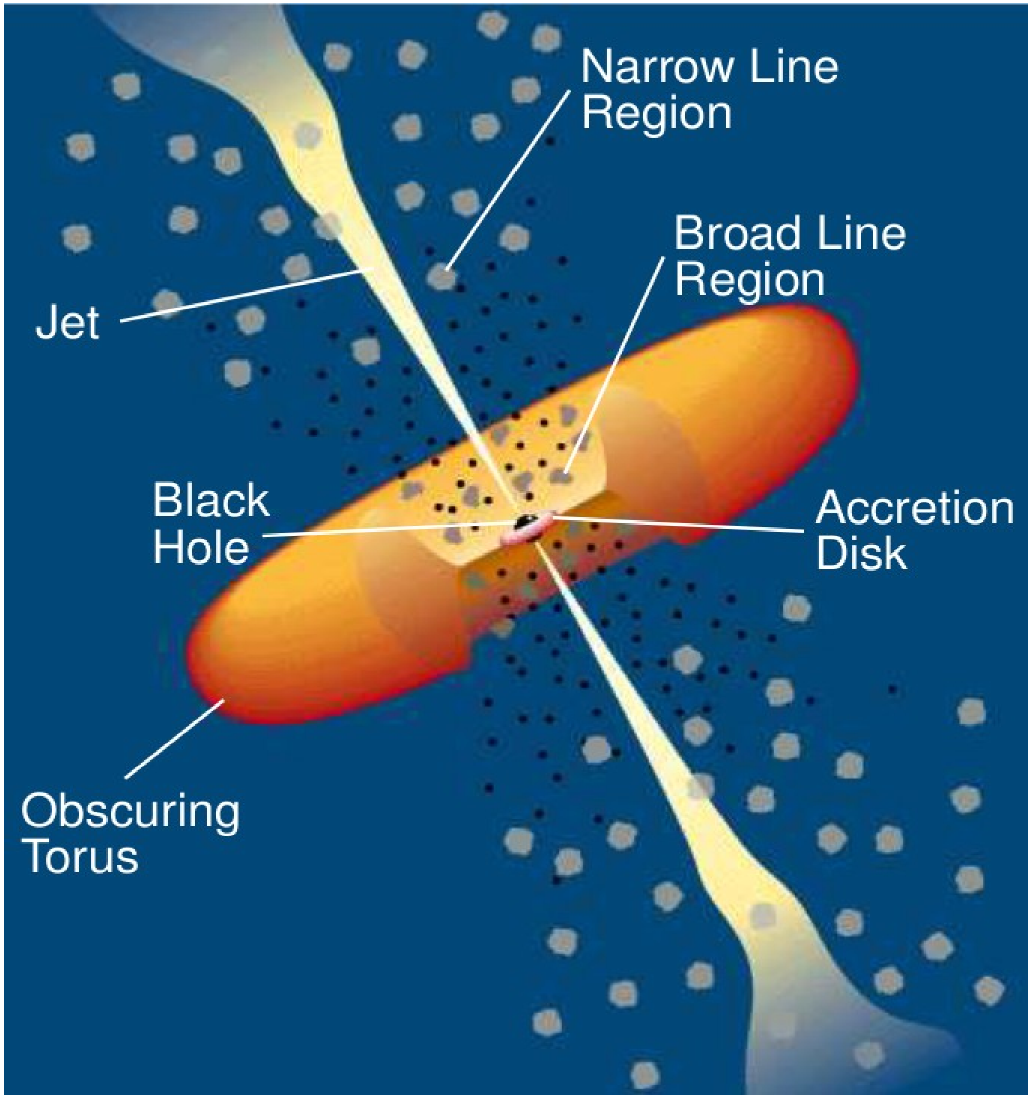
Outline

- Introduction and model setup
- Steady State Spectrum
- Variability Analysis

Active Galactic Nucleus (AGN)



(Credit: Urry & Padovani)

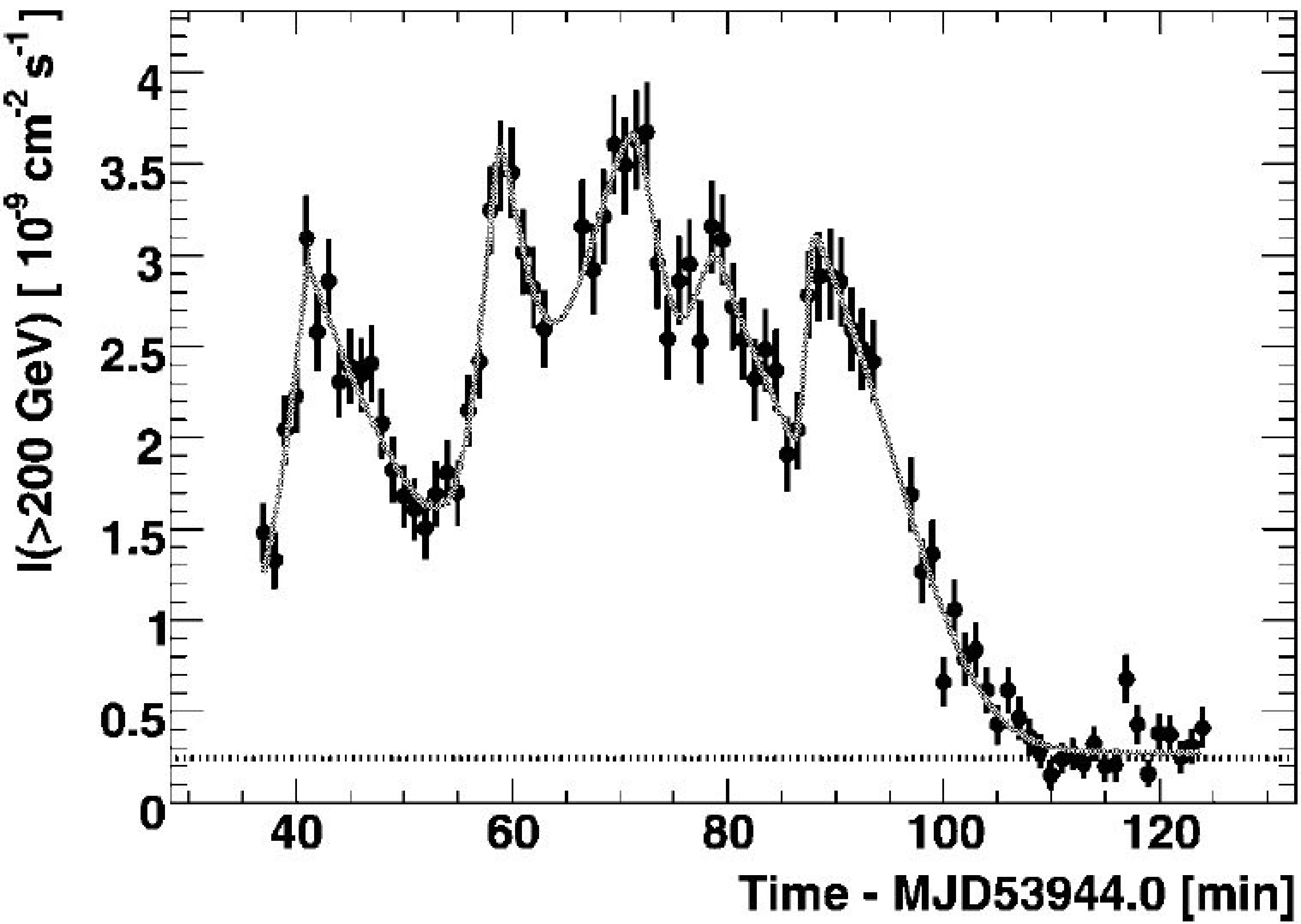
Jet moving relativistically

Blazars: Along the Jet

Observation

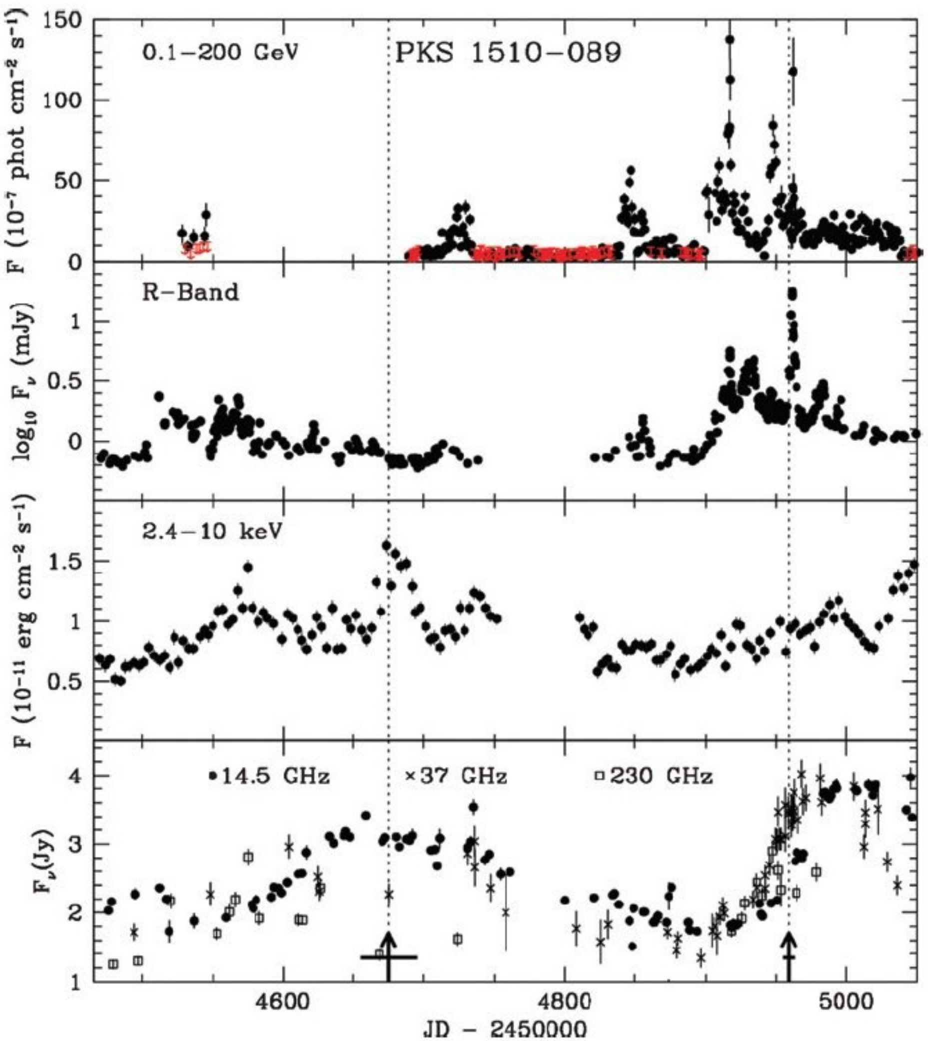
Ultra-fast flares

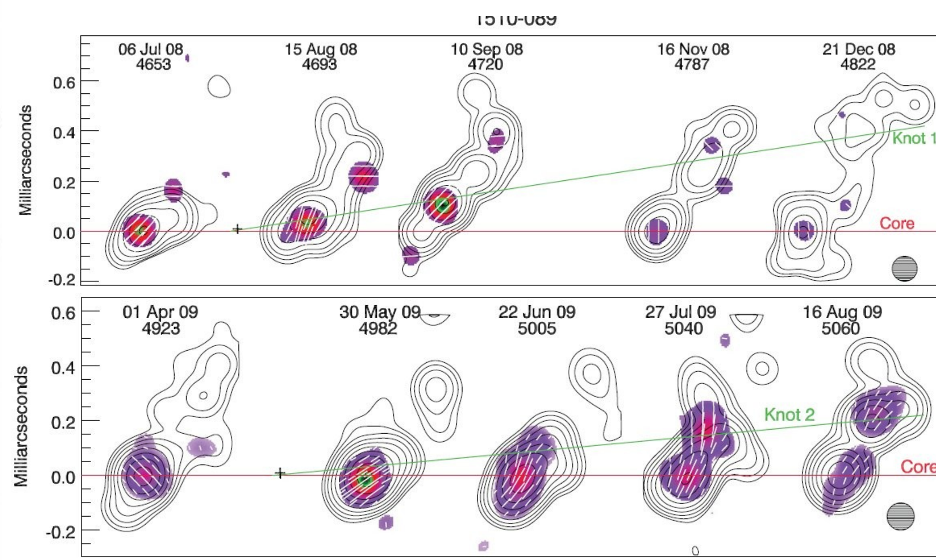
– small emission region (10^{-4} pc)



(PKS 2155-304, Aharonian et al. 2007)

Coincidence of flares and radio events
- far away emission region (~ pc scale)

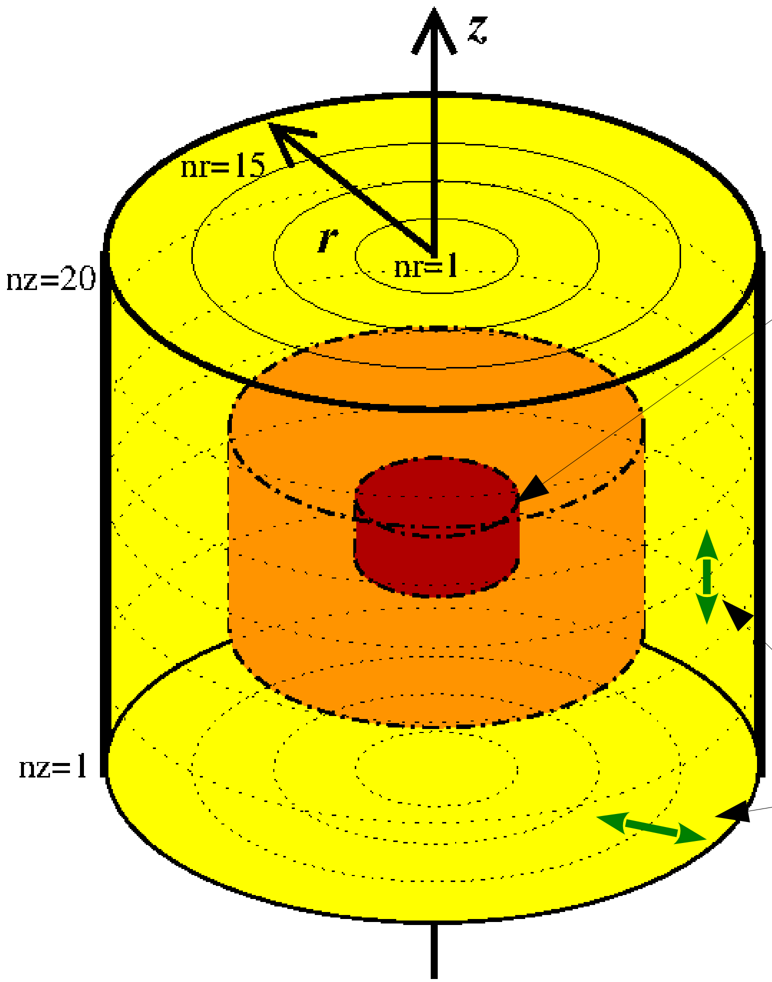




(PKS 1510-089, Marscher et al. 2010)

Our model

Sketch of the 2D cylindrical geometry



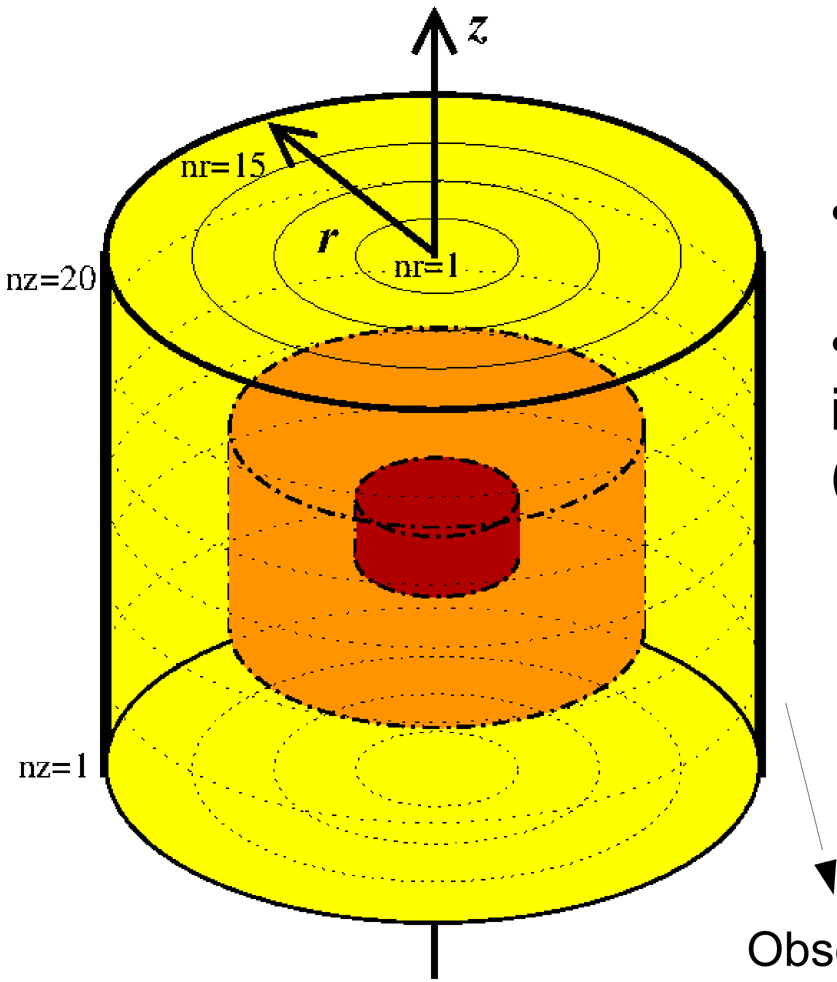
2nd order Fermi Acceleration
Through the continuity equation:

$$\frac{\partial n(\gamma,\mathbf{r},t)}{\partial t} = -\frac{\partial}{\partial\gamma}\left[n(\gamma,\mathbf{r},t)\dot{\gamma}(\gamma,\mathbf{r},t)\right] + \frac{\partial}{\partial\gamma}\left[D(\gamma,\mathbf{r},t)\frac{\partial n(\gamma,\mathbf{r},t)}{\partial\gamma}\right] + Q(\gamma,\mathbf{r},t) - \nabla\cdot\left[D_x(\gamma)\nabla n(\gamma,\mathbf{r},t)\right].$$

Spatial diffusion of particles

(Chen et al. 2011)

Radiation: Monte Carlo Comptonization



•Synchrotron radiation

•Synchrotron Self-Comptonization including light travel time effects (LTTEs)

Homogeneous magnetic field used in this study

Observer. Relativistic beaming

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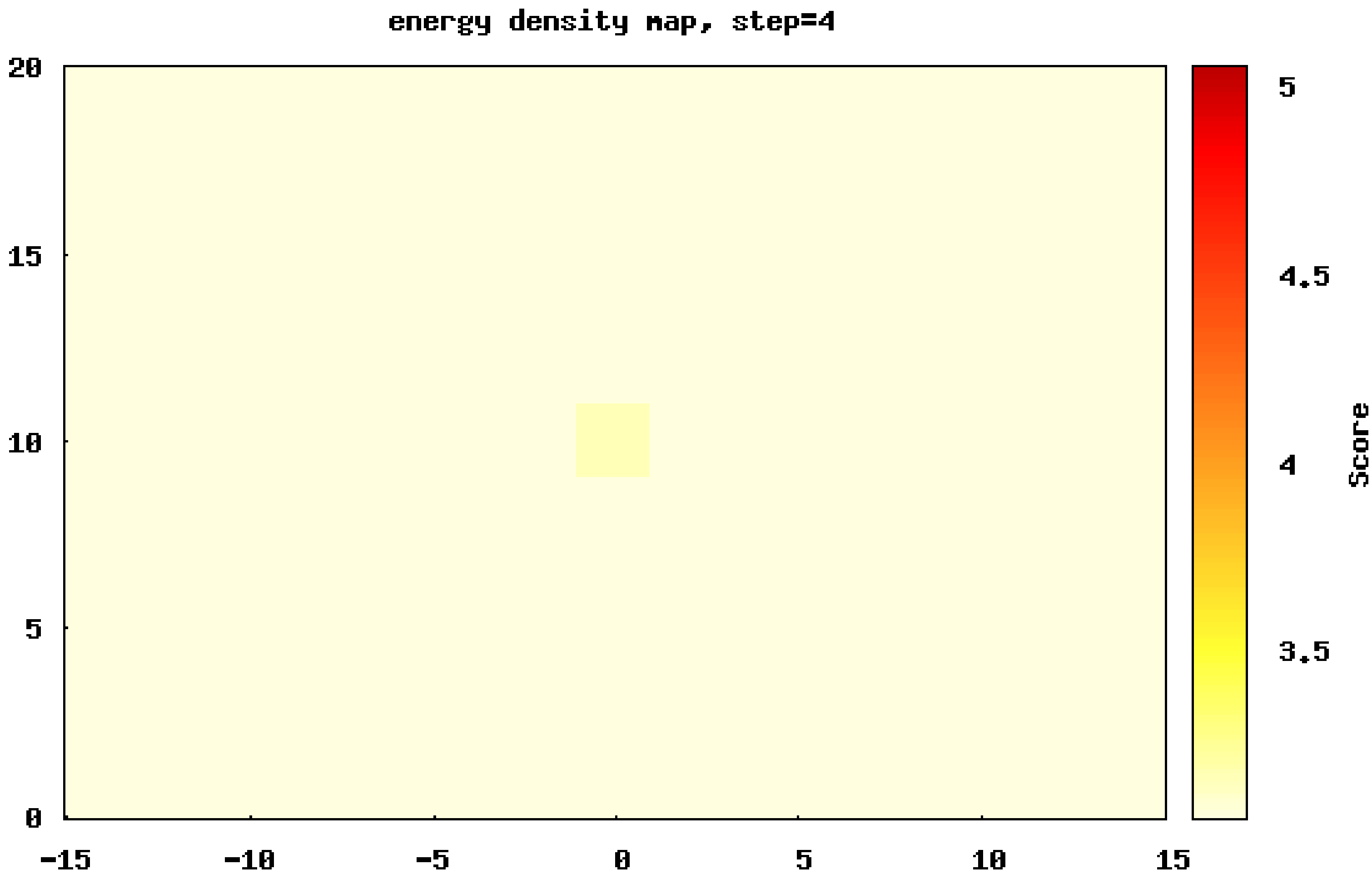
Steady State

Accelerator in the center

--Electron energy density map evolution

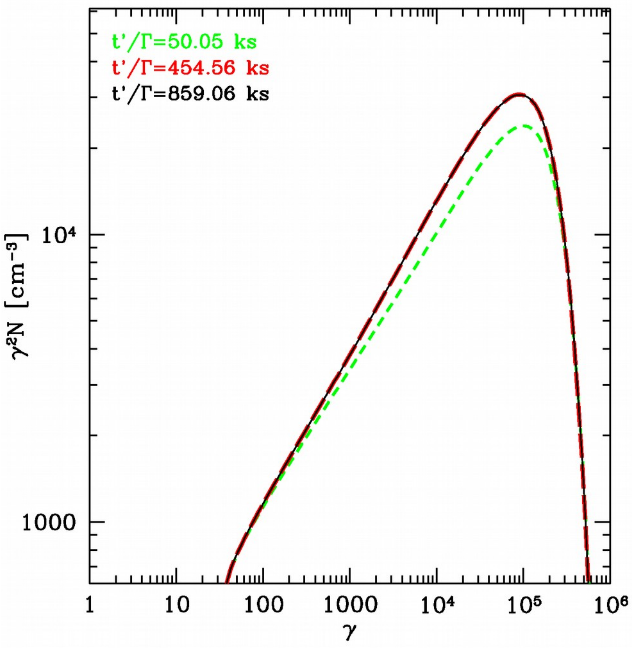
the acceleration region occupies 2x2 zones



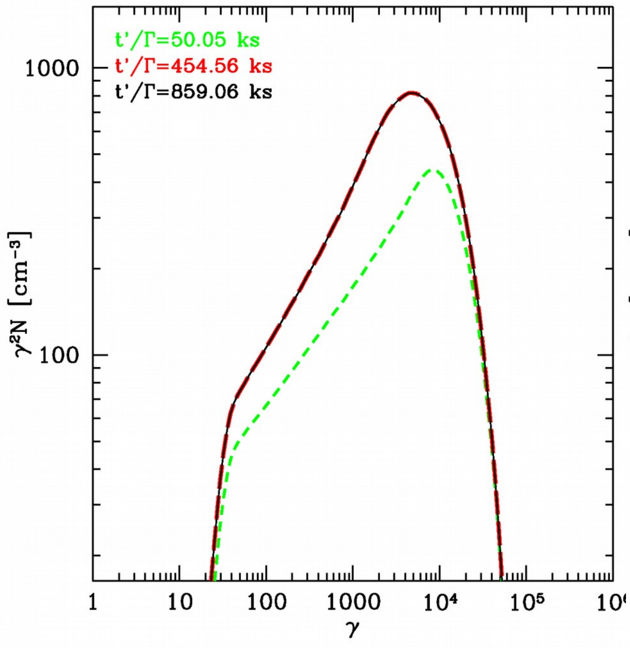
Accelerator in the center

--Electron energy distribution (EED) of individual cells

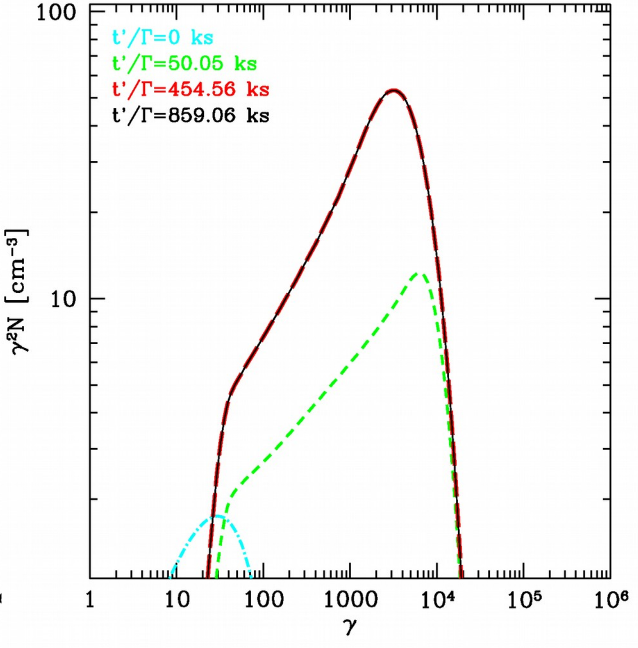
Inner cell



Mid cell



Outer cell

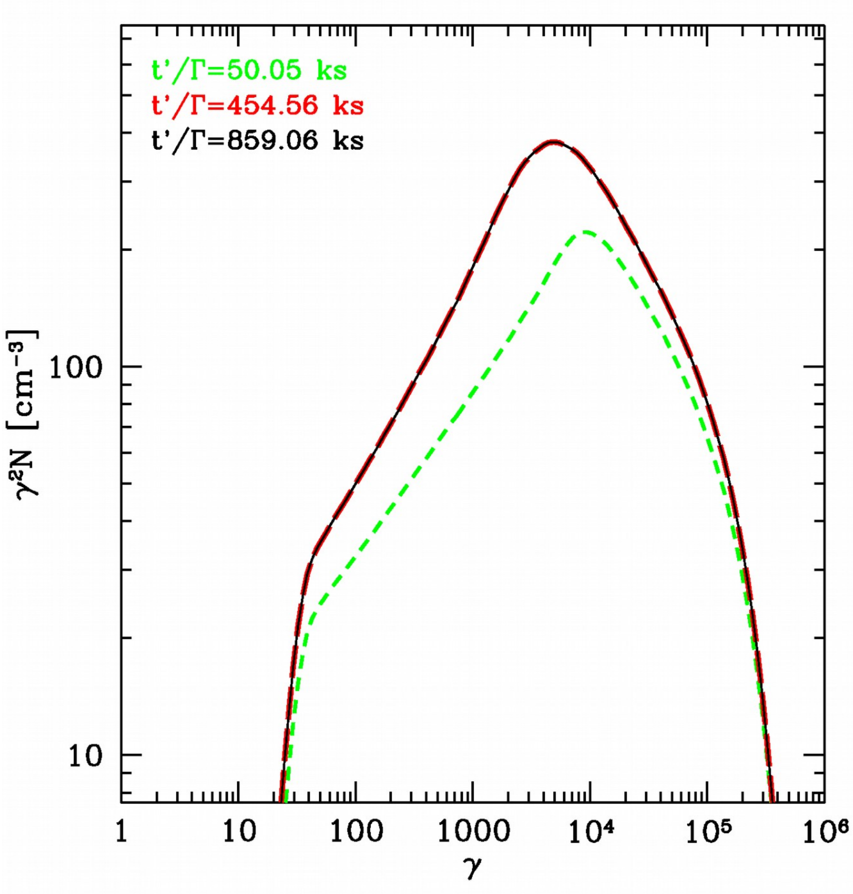


Steady State

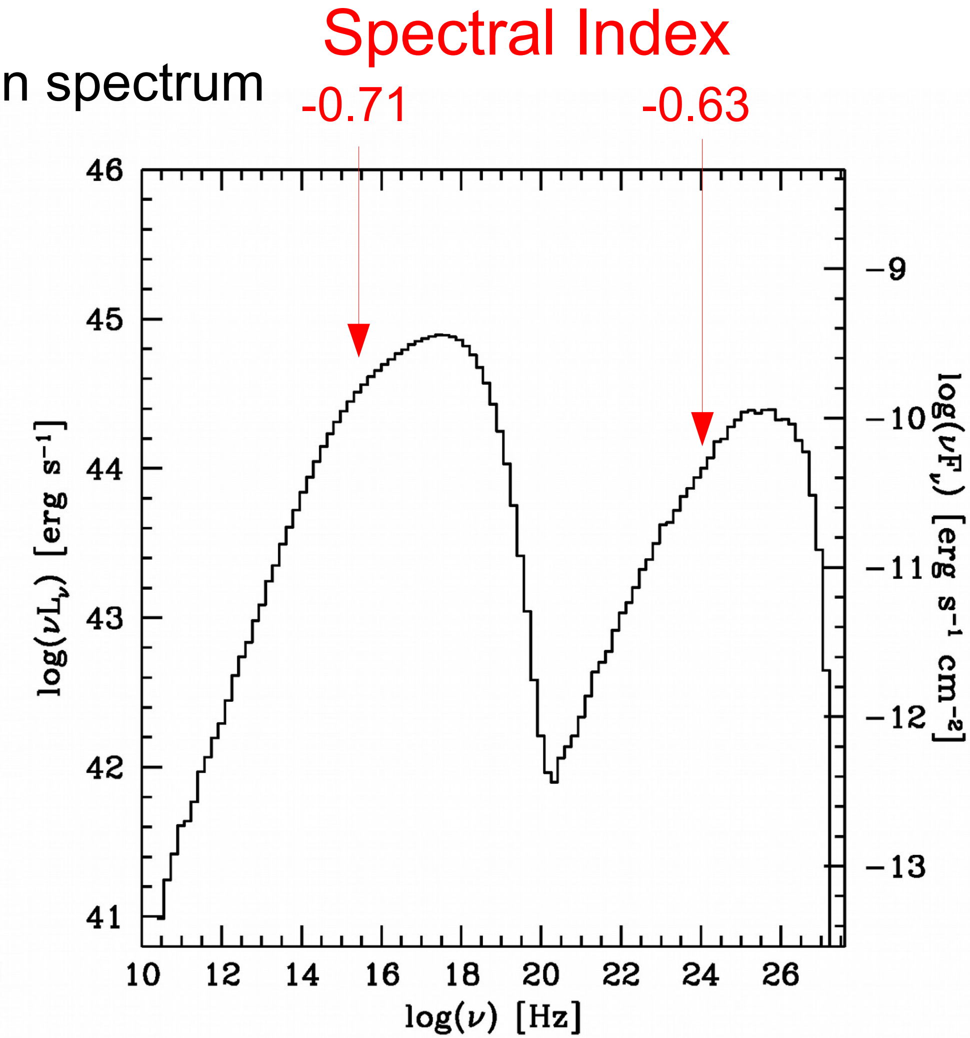
Accelerator in the center

--Total EED and SED

SSC spectrum harder than synchrotron spectrum



Total EED



SED

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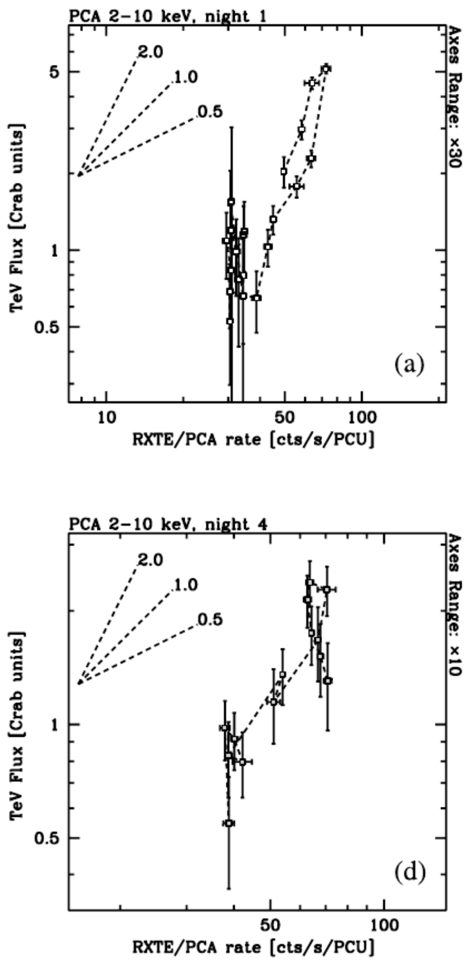
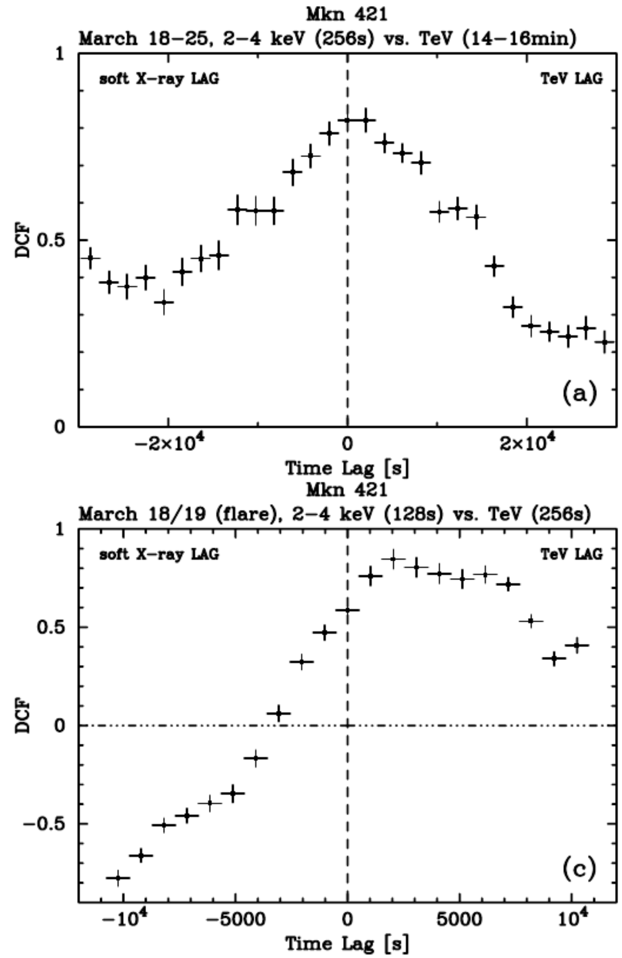
X-ray γ-ray Correlation





Amplitude: quadratic or linear?

Time: lag or no lag?

(Fossati et al. 2008)

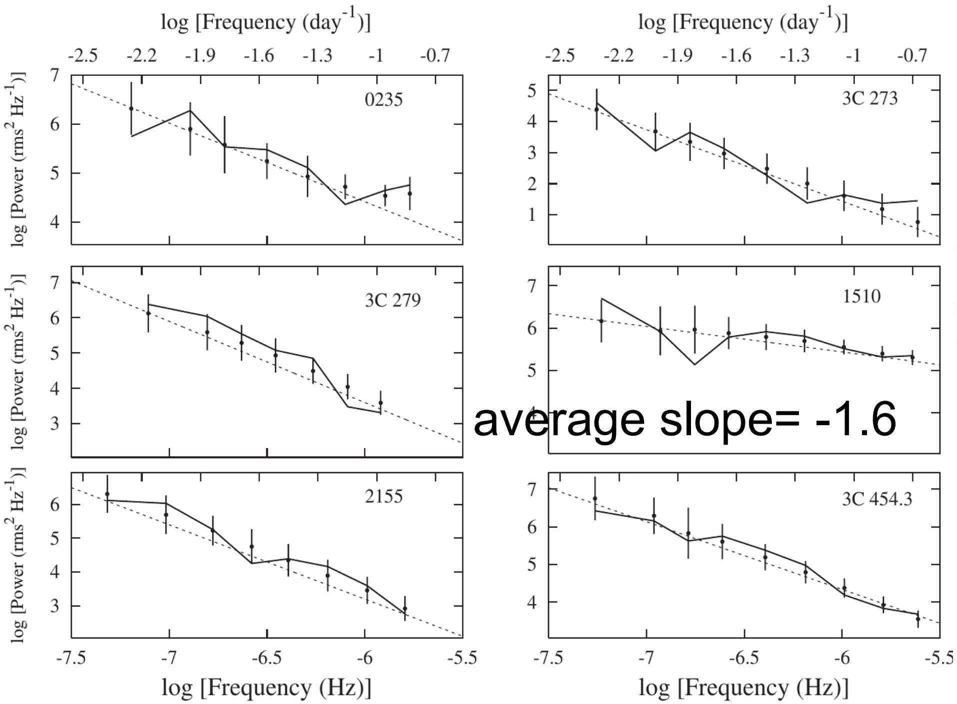
Observation

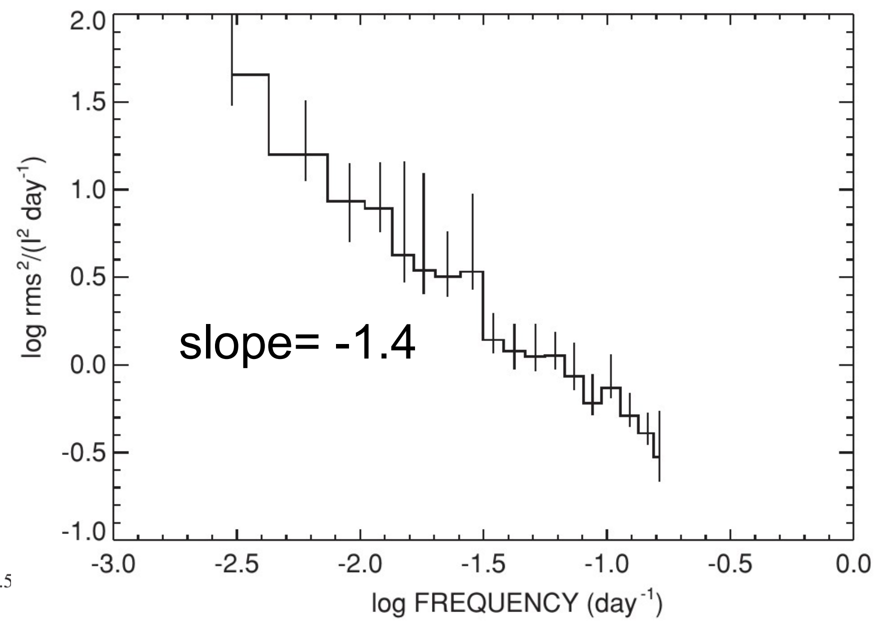
$$|F_N(\nu)|^2 = \left[\sum_{i=1}^{N} f(t_i)\cos(2\pi\nu t_i)\right]^2 + \left[\sum_{i=1}^{N} f(t_i)\sin(2\pi\nu t_i)\right]^2$$

Power Spectrum Density(PSD)

$$P(\nu) = \frac{2T}{\mu^2 N^2}|F_N(\nu)|^2$$

Power-law without any break





Optical PSD

(Chatterjee et al. 2012)

Average Fermi PSD,
for 9 brightest FSRQs

(Abdo et al. 2010)

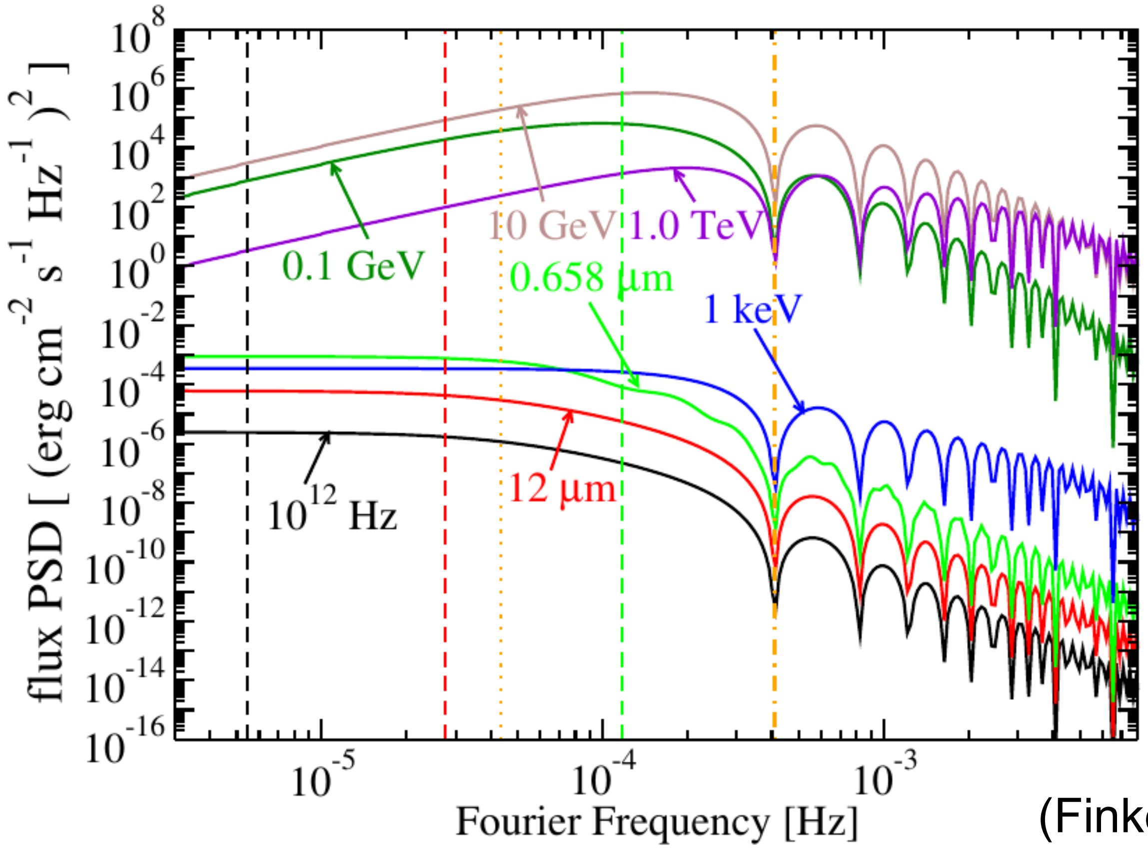
Existing model

Fourier Transform of the Fokker-Planck equation

$$\frac{\partial N_e}{\partial t} + \frac{\partial}{\partial \gamma}[\dot{\gamma}(\gamma,t)N_e(\gamma;t)] + \frac{N_e(\gamma;t)}{t_{\rm esc}(\gamma,t)} = Q(\gamma,t)$$

$$\Downarrow$$

$$-2\pi i f \tilde{N}_e(\gamma,f) + \frac{\partial}{\partial \gamma}[\dot{\gamma}(\gamma)\tilde{N}_e(\gamma,f)] + \frac{\tilde{N}_e(\gamma,f)}{t_{\rm esc}(\gamma)} = \tilde{Q}(\gamma,f)$$



$S(\gamma, f) \propto f^{-a}$ (f < $1/t_{cool}$)

$S(\gamma, f) \propto f^{-(a+2)}$ (f > $1/t_{cool}$)

$S(\gamma, f) \propto f^{-a}$ Synchrotron

$S(\gamma, f) \propto f^{-(a+2)}$ SSC

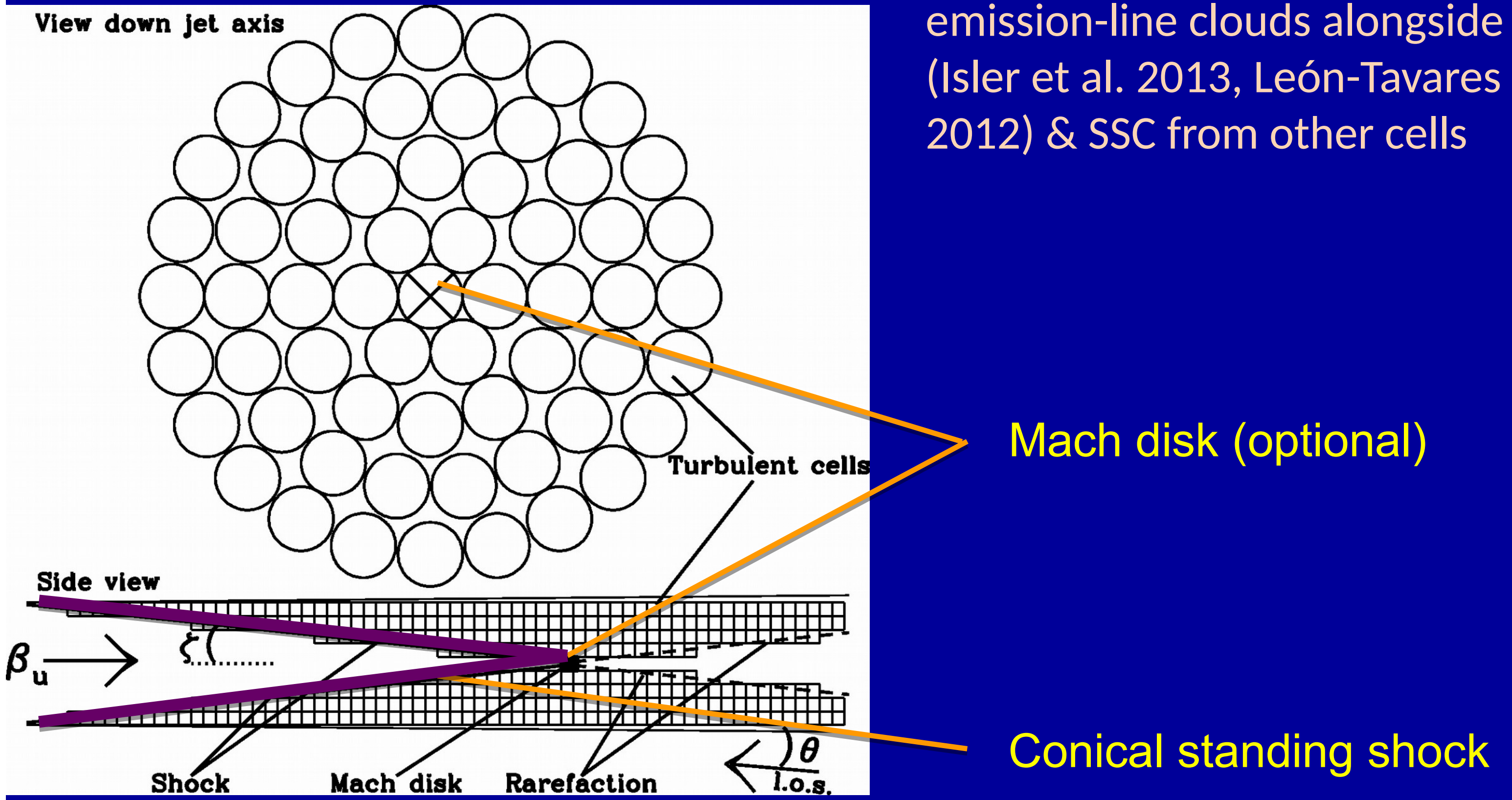
(Finke & Becker 2014)

Existing model

Turbulent Extreme Multi-zone (TEMZ) Model (Marscher 2014, ApJ)

Many (e.g., 169) turbulent cells across jet cross-section, each followed after crossing shock, where e⁻s are energized & Compton scatter seed photons from dusty torus & Mach disk*; each cell has its own uniform magnetic field selected randomly from turbulent power spectrum + its own e⁻ population

*Plan to add seed photons from emission-line clouds alongside the jet (Isler et al. 2013, León-Tavares et al. 2012) & SSC from other cells

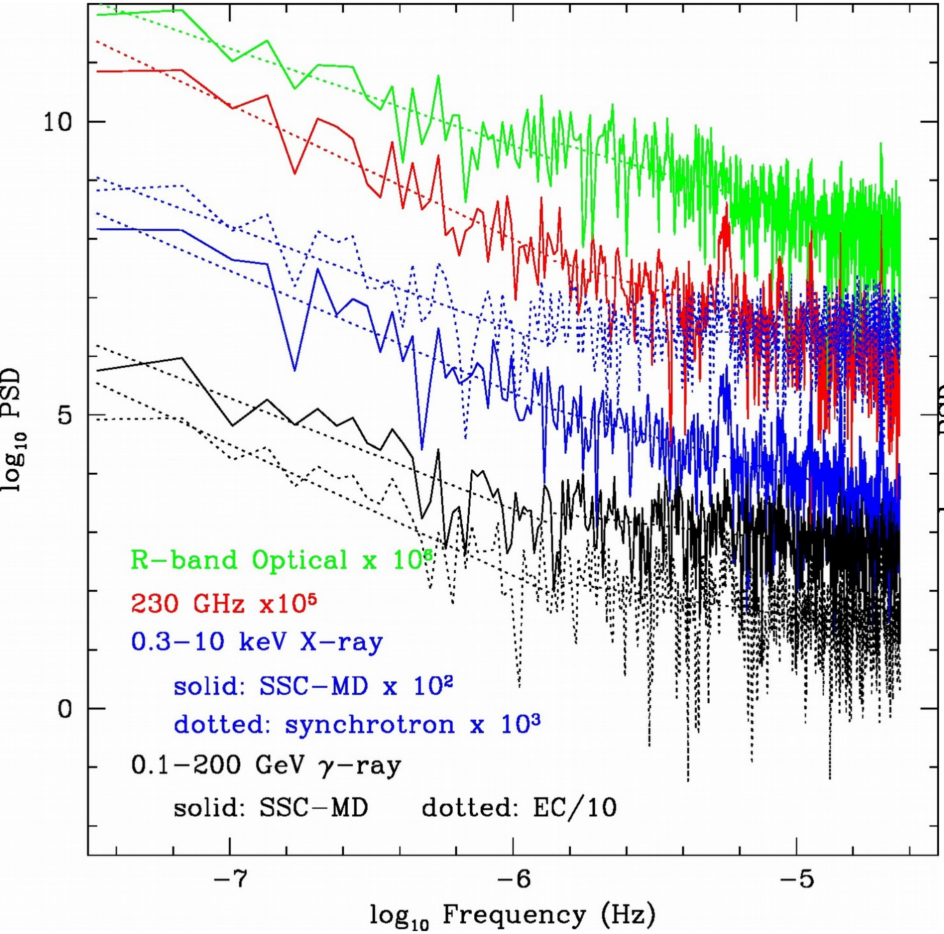


(talk by Alan Marscher 2015)

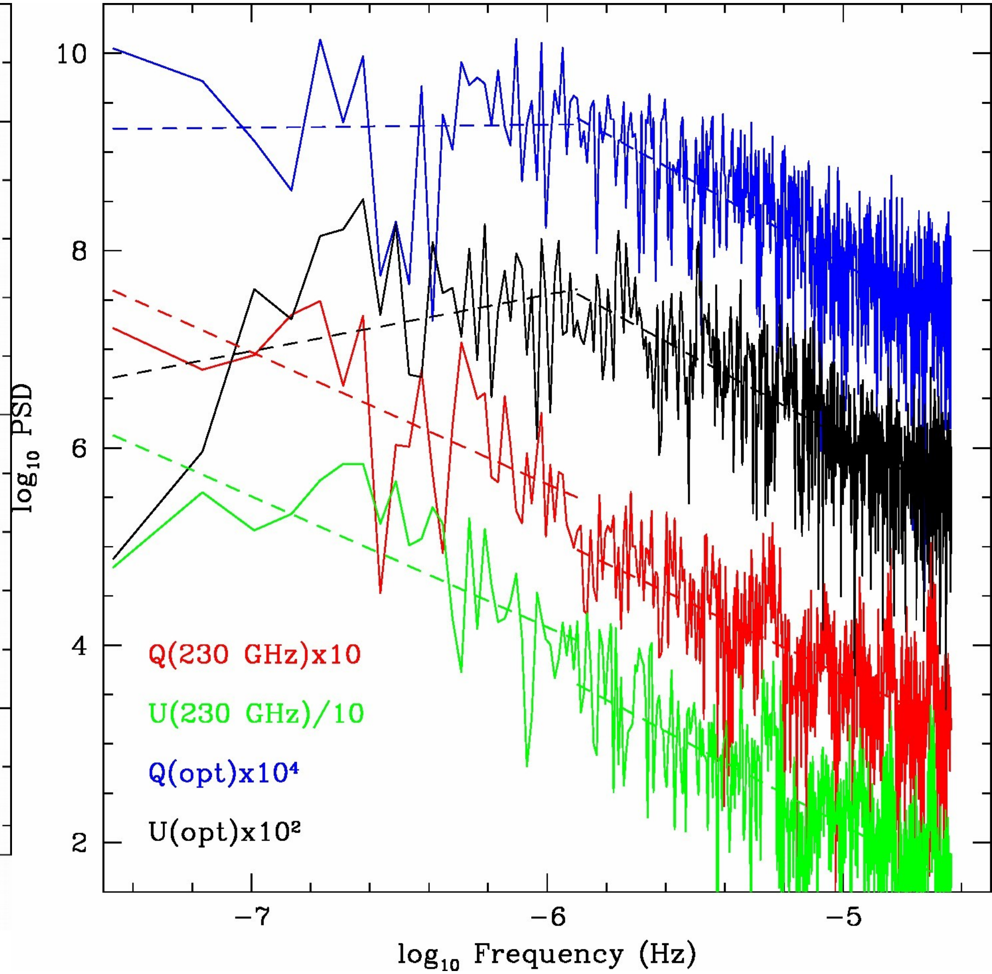
Existing model

Power Spectra of Polarization Variations of Simulation

Flux Power spectrum slope -1.6 to -2.3 on long time-scales (low variational frequencies), flattens on shorter time-scales



Stokes parameters: Power spectrum slope ~ -1.6 on short time-scales (high variational frequencies), flattens on longer time-scales

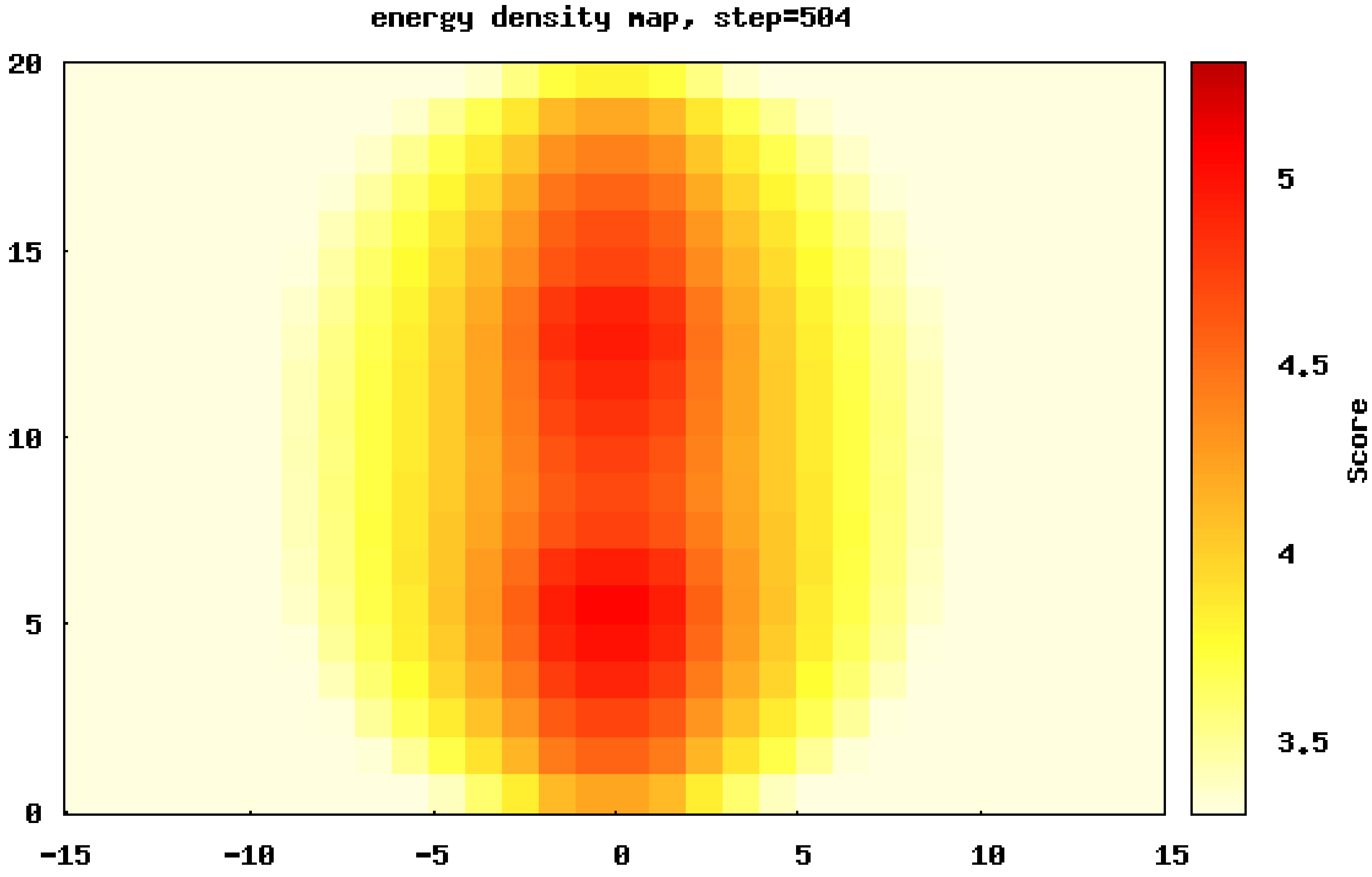


(talk by Alan Marscher 2015)

Break frequency higher for more turbulent fiel

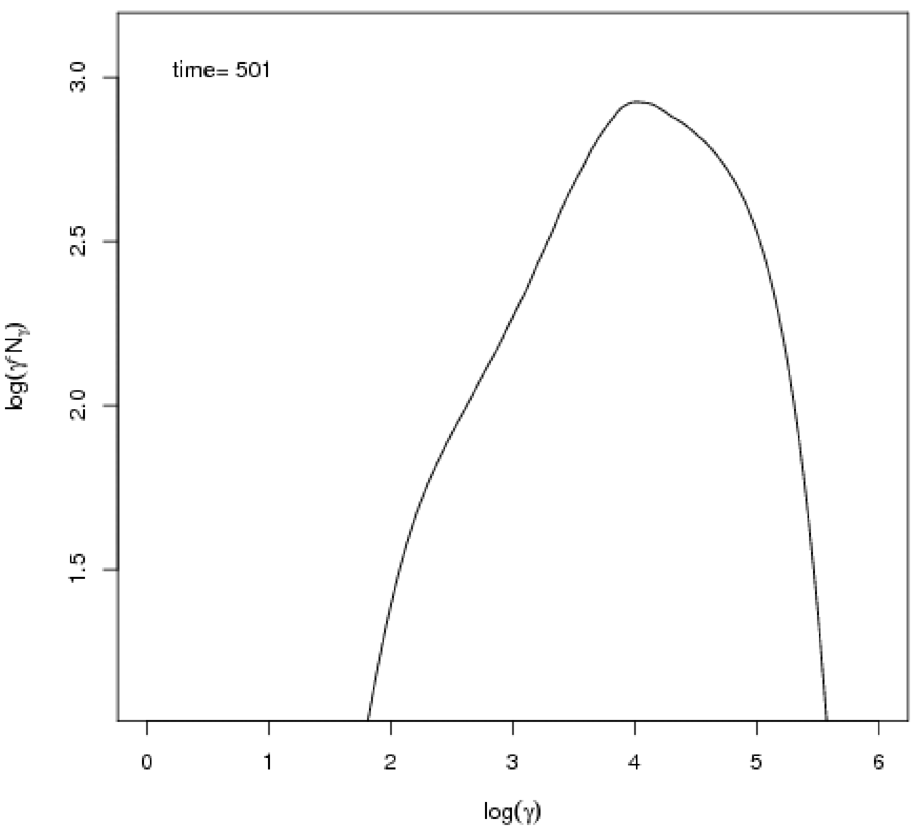
Random Acceleration along the spine

--Electron energy density map evolution

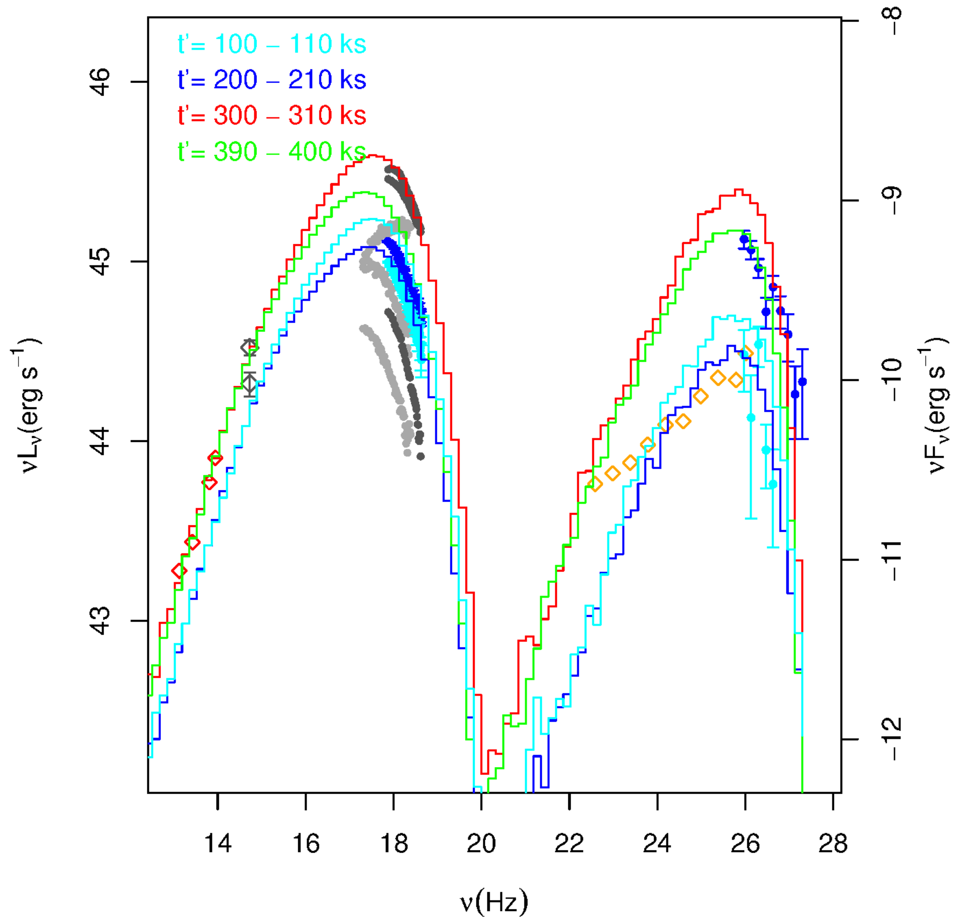


Random Acceleration along the spine

– EED and SED

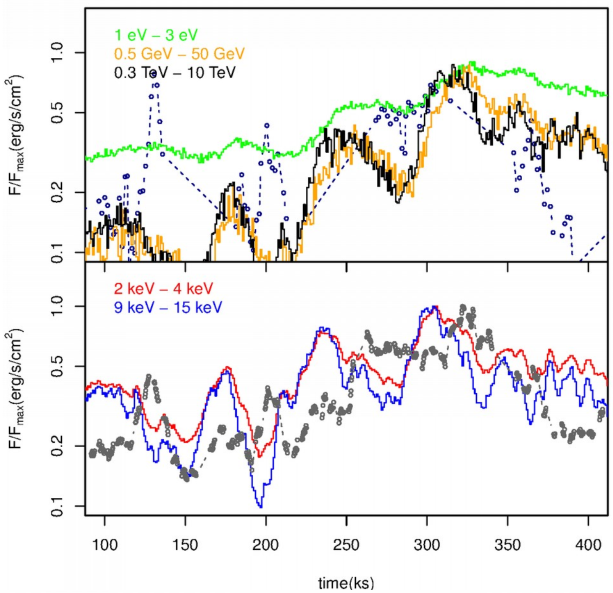


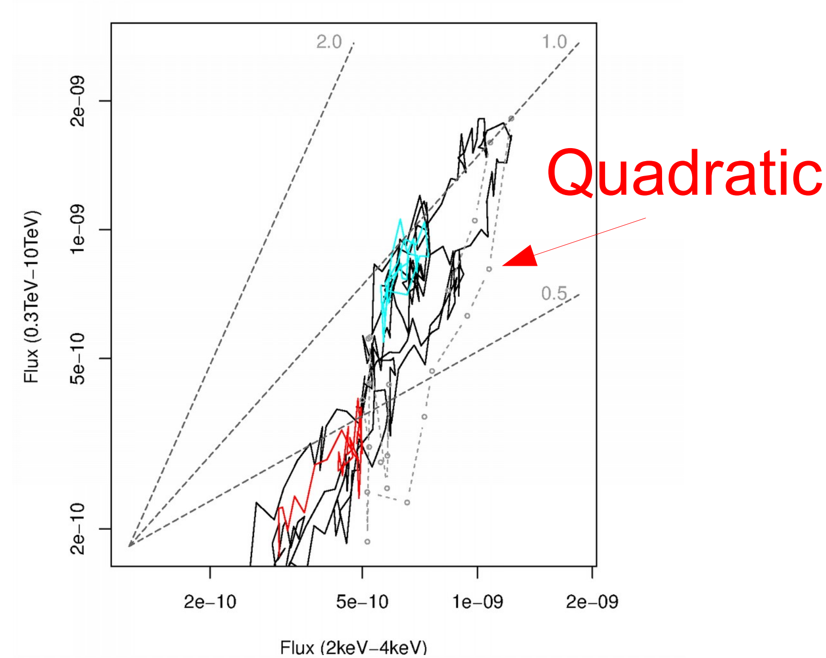
EED

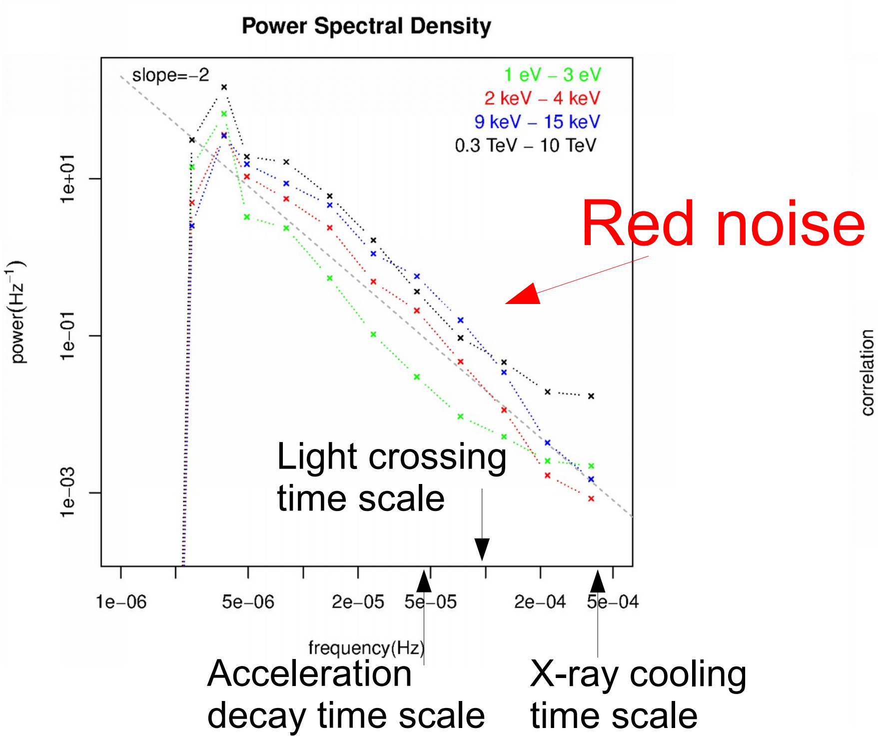


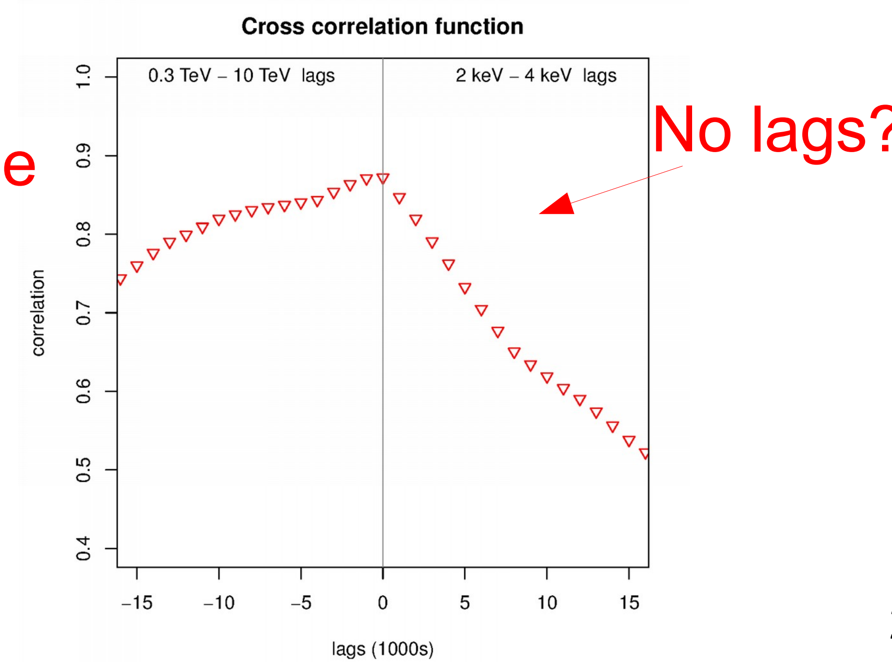
SED

Random acceleration

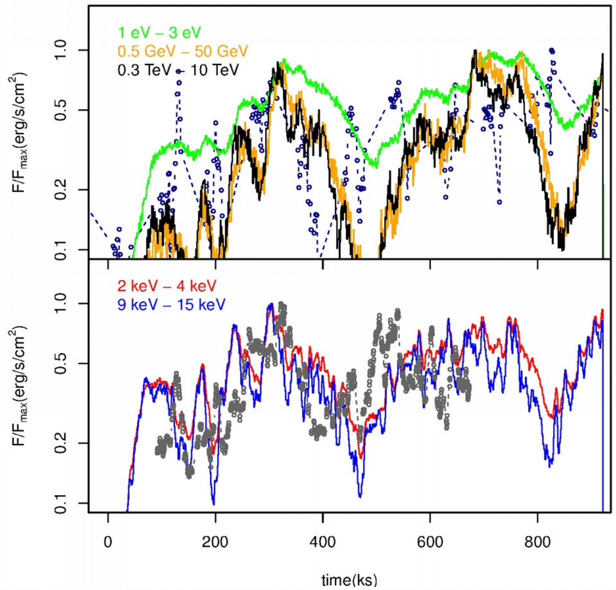


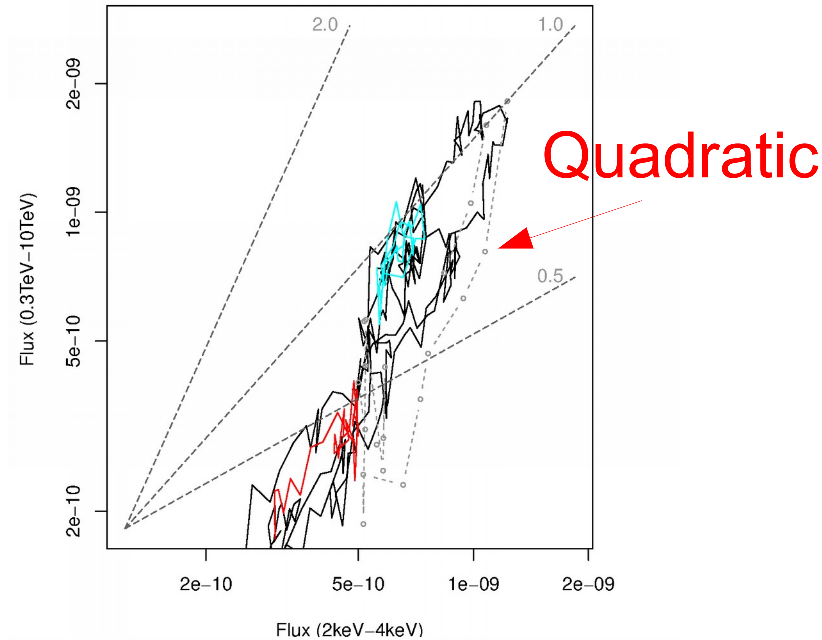


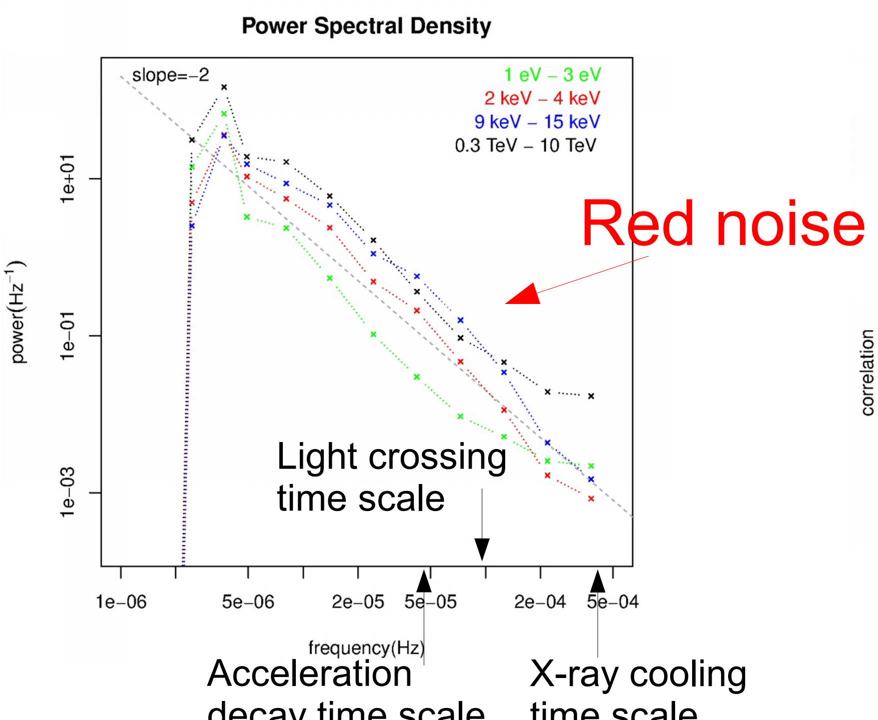


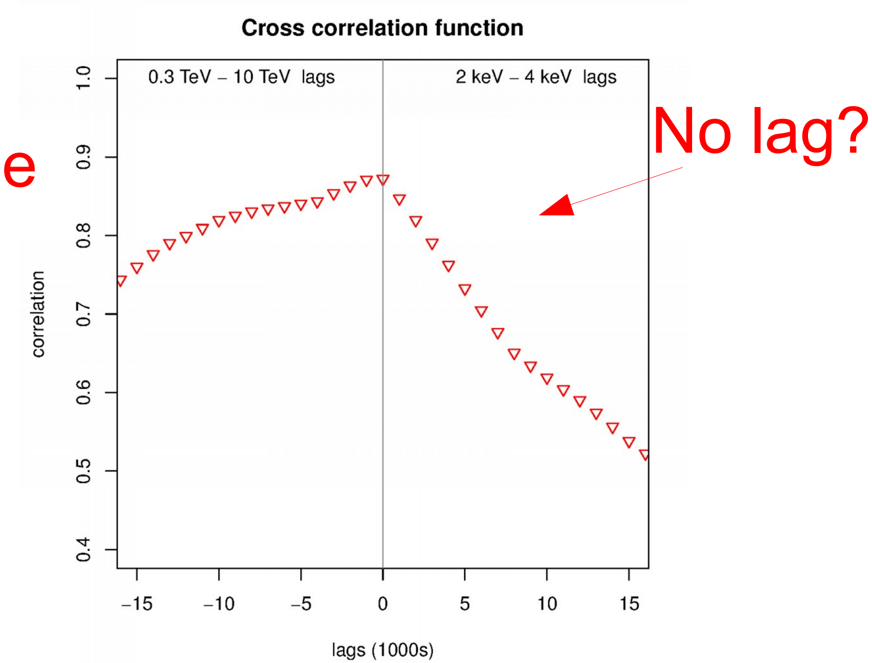


Random acceleration









Assumptions

1. Simulation length $T'/\Gamma = 9 \times 10^5$ ks;

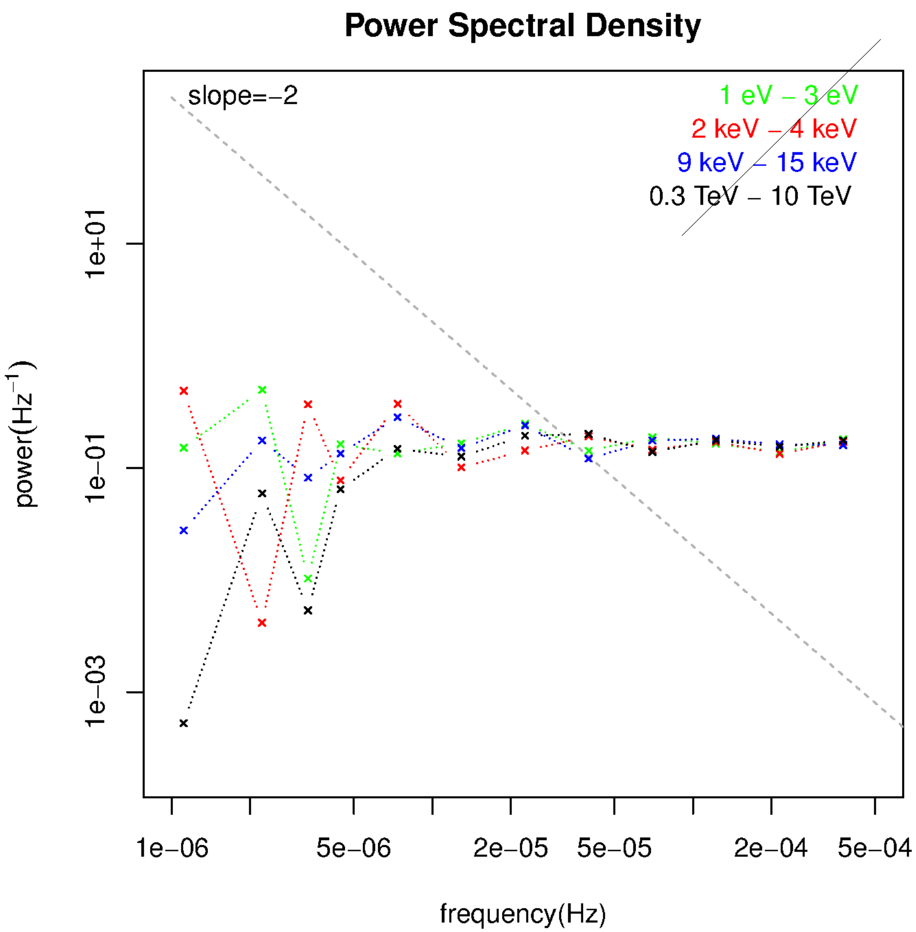
2. Every time step (0.5ks) each cell has 7% chance for additional acceleration (accumulating);

3. Acceleration decay on time scale of $t'/\Gamma = 20$ ks;

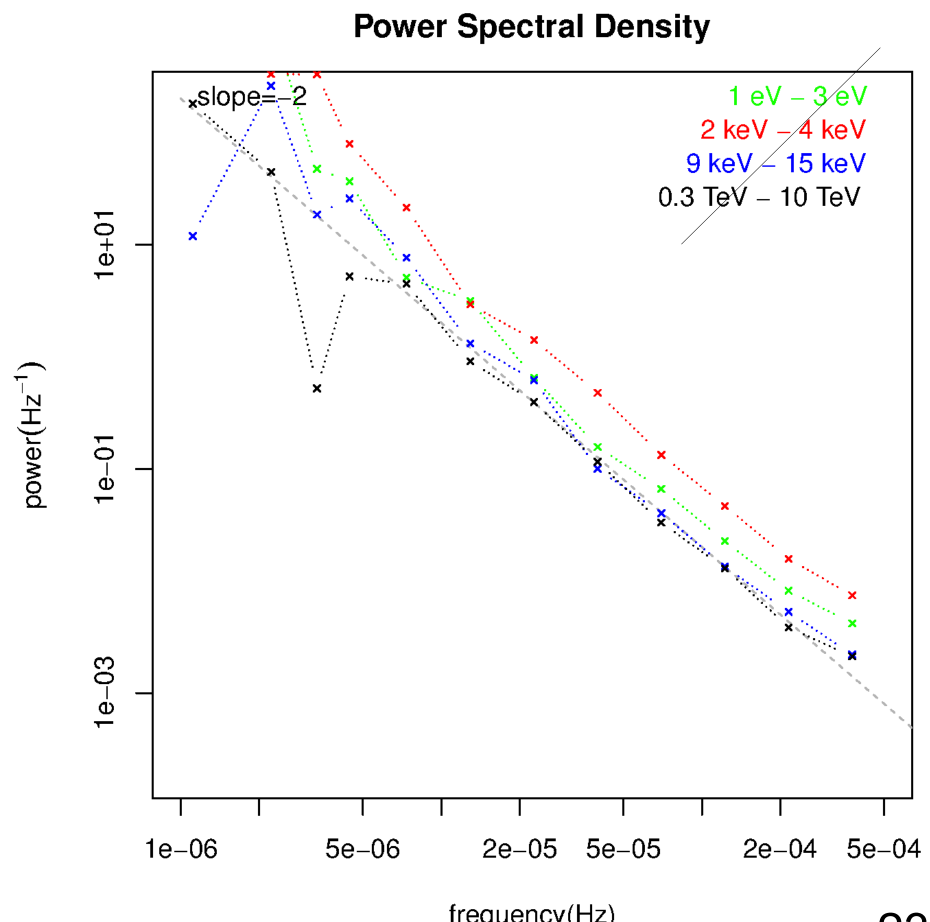
4. Particle injection (at $\gamma = 33$) increases with acceleration rate.

White Noise vs. Red Noise

F_t = random(-0.5,0.5)

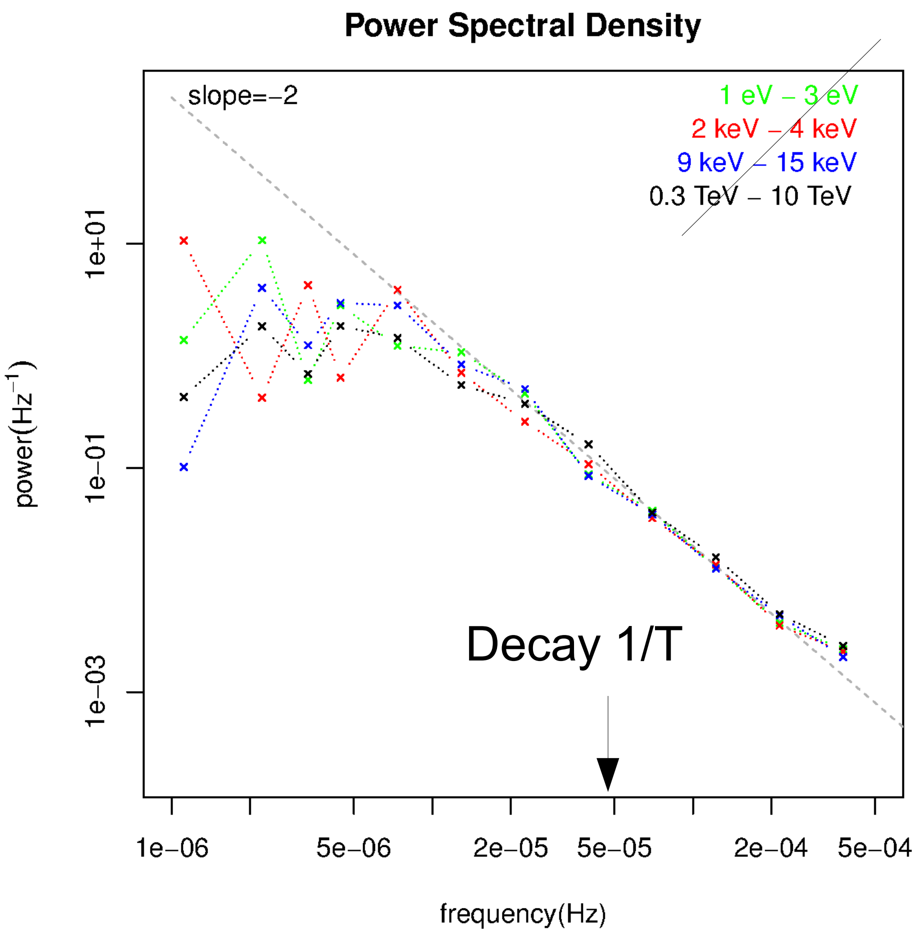


$F_{t+1} = F_t$ + random(-0.1,0.1)

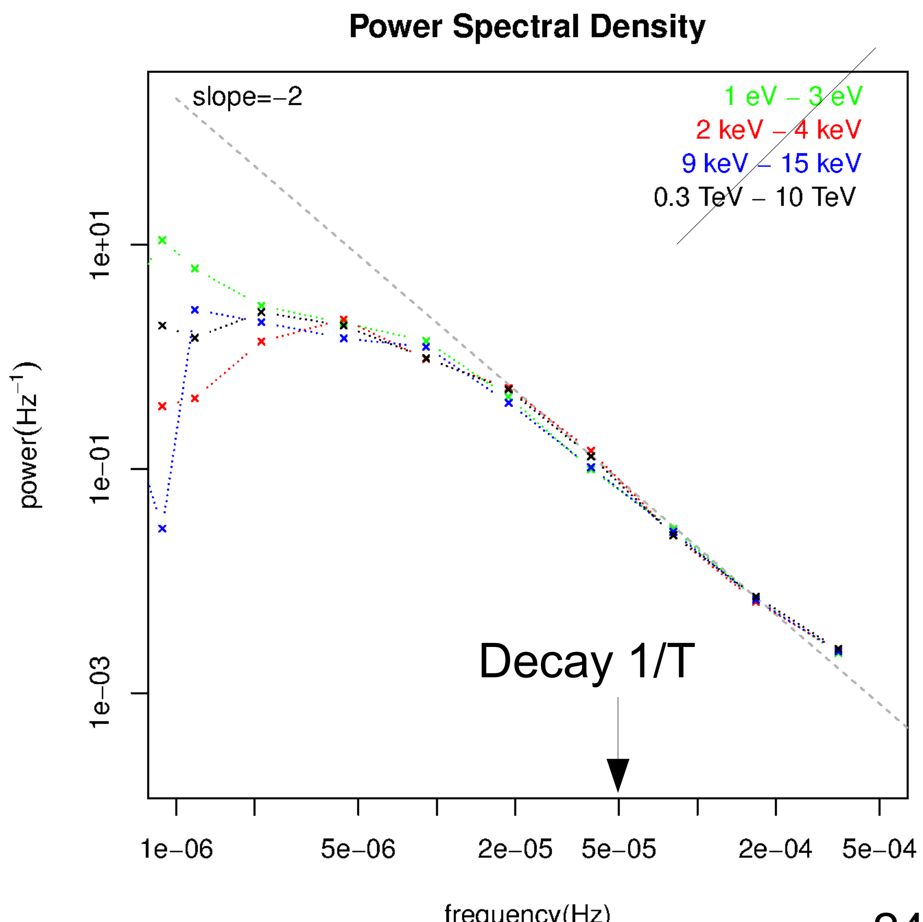


PSD with break

$F_{t+1}=F_t * \exp(-\Delta t/T)+\text{random}(-0.1,0.1)$



Longer data sample



3.5 Ms long simulation

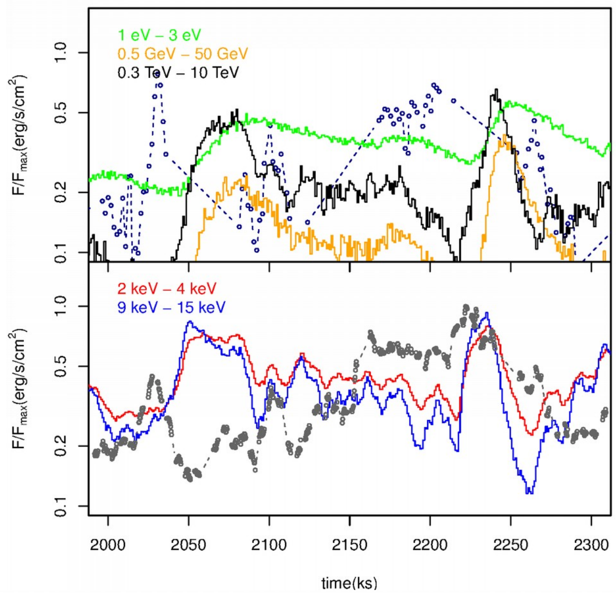
1. Simulation length T '/Γ=~~$9x10^5$~~ $3.5x10^6$s;

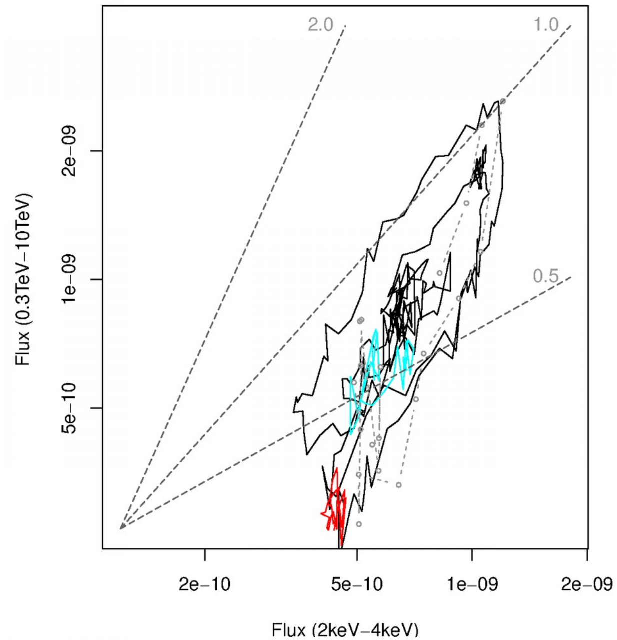
2. Every time step (0.5ks) each cell has 7% chance for additional acceleration (accumulating);

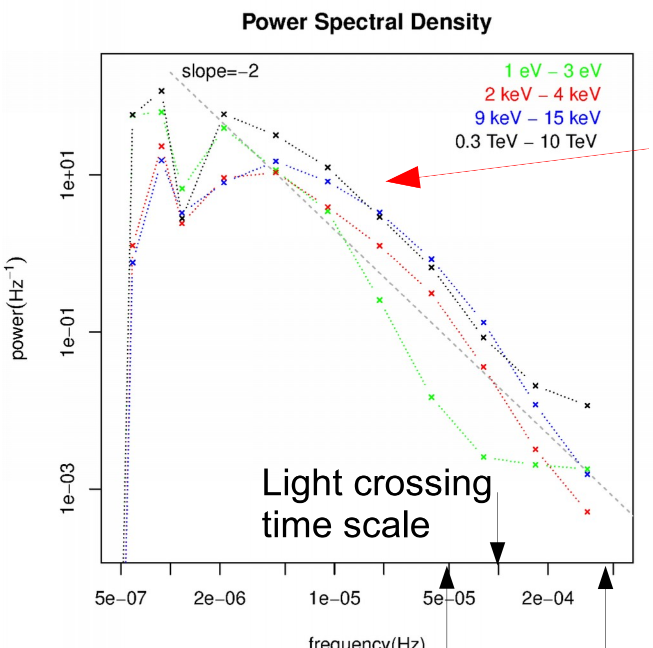
3. Acceleration decay on time scale of t'/Γ= 20 ks;

4. Particle injection (at γ=33) increases with acceleration rate;

3.5 Ms long simulation



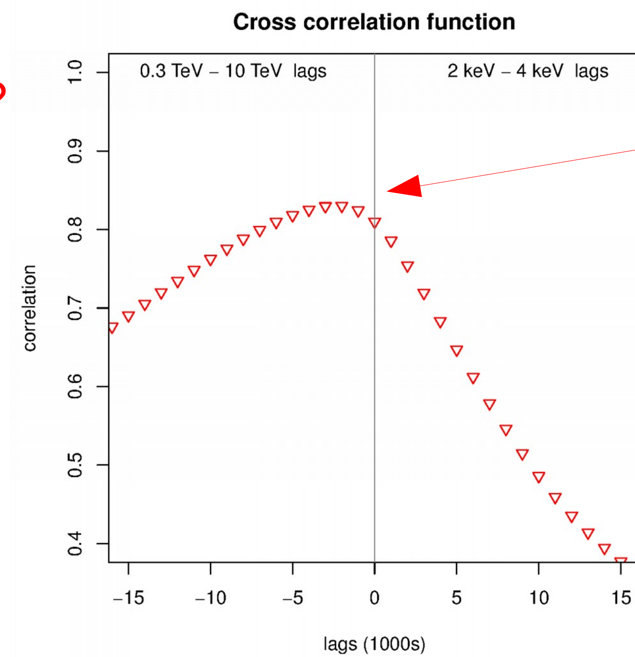




Is there a break?

Acceleration decay time scale

X-ray cooling time scale



γ-ray lags

Higher acceleration frequency

1. Simulation length $T'/\Gamma = 9 \times 10^5$ ks.

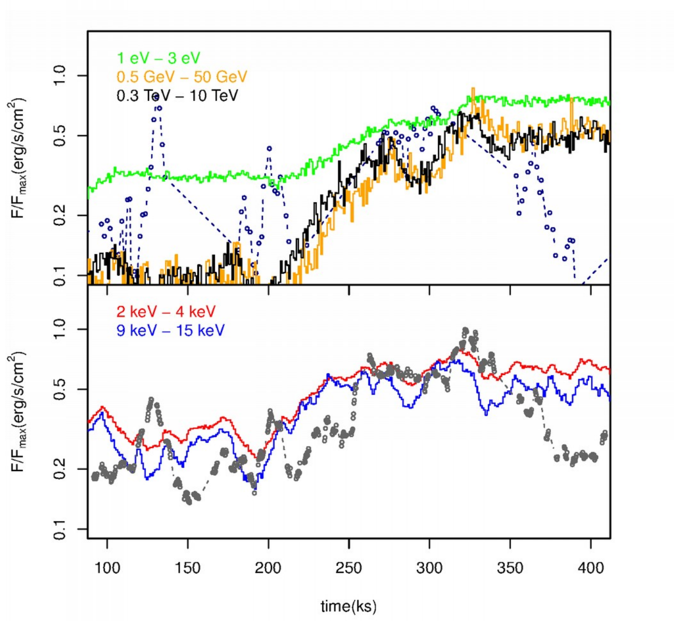
2. Every time step (0.5ks) each cell has ~~7%~~ 14% chance for additional acceleration (accumulating);

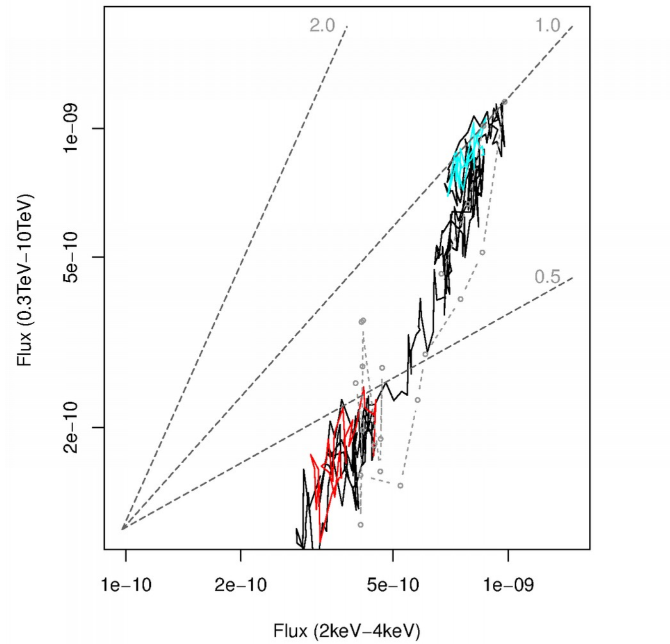
3. Acceleration decay on time scale of $t'/\Gamma = 20$ ks;

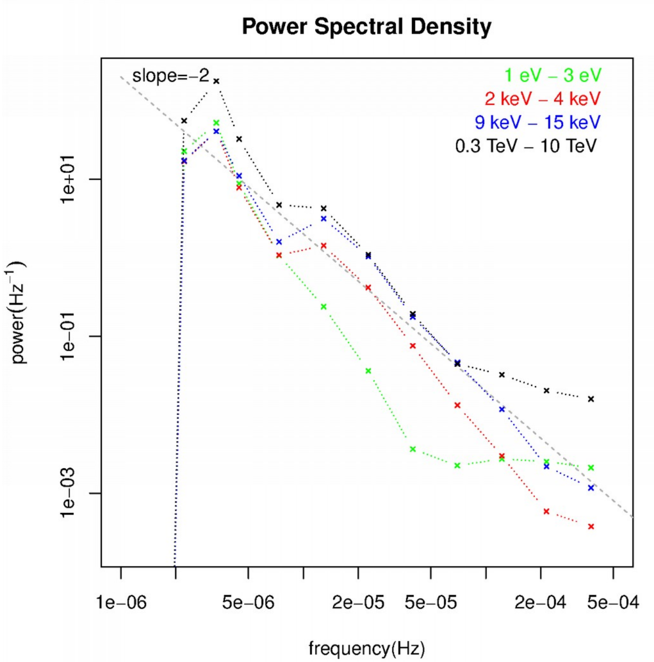
4. Particle injection (at $\gamma = 33$) increases with acceleration rate;

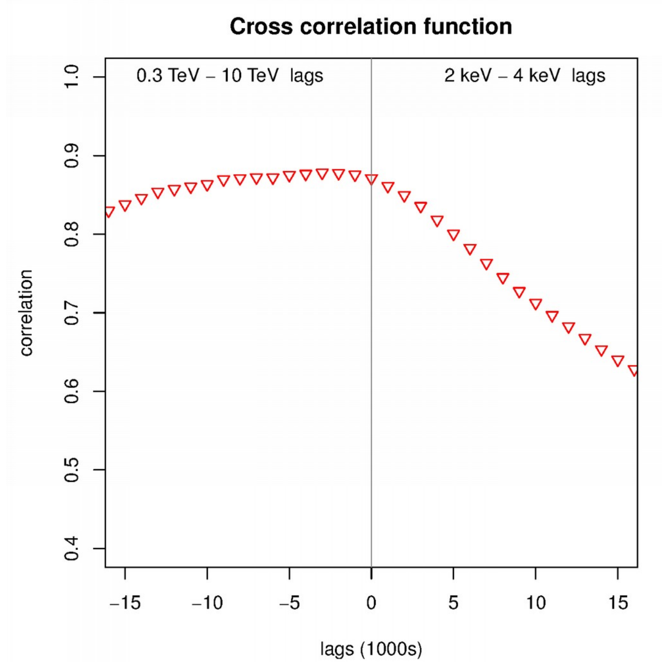
Higher acceleration frequency

No significant change









Slower Acceleration decay

1. Simulation length $T'/\Gamma=9\times10^5$ ks;

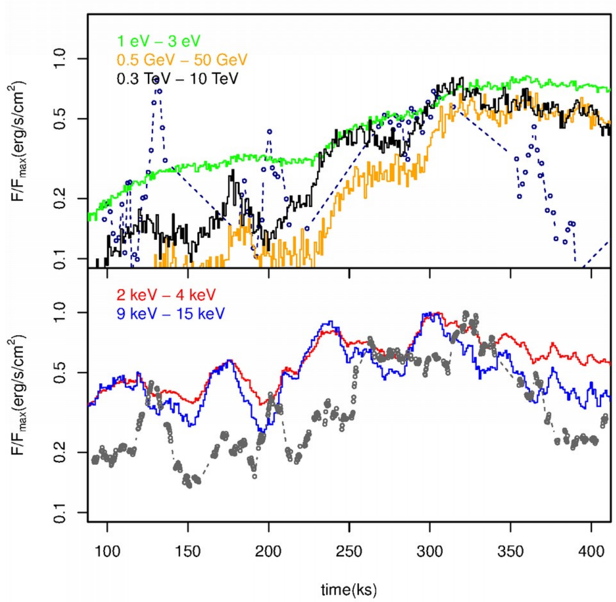
2. Every time step (0.5ks) each cell has 7% chance for additional acceleration (accumulating);

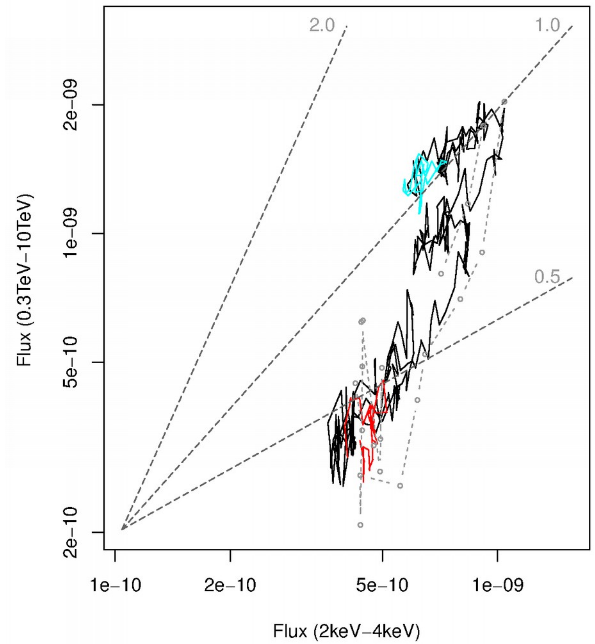
3. Acceleration decay on time scale of $t'/\Gamma=$ ~~20~~ 40ks;

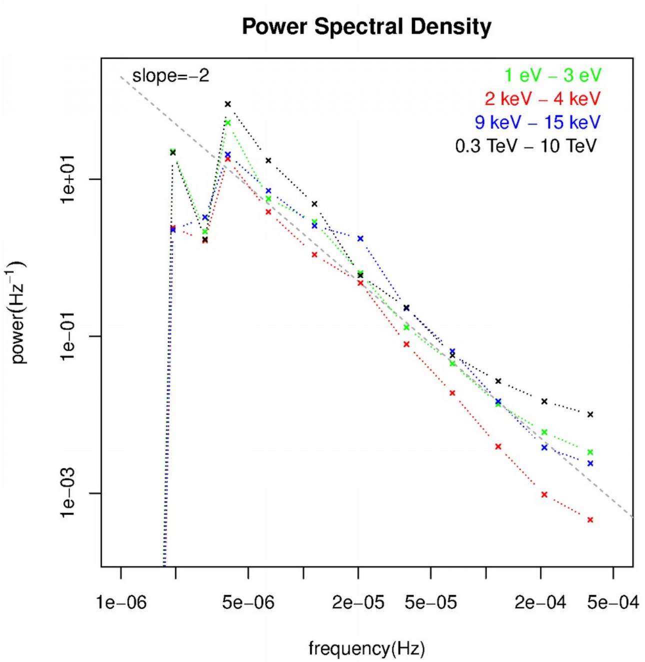
4. Particle injection (at $\gamma=33$) increases with acceleration rate.

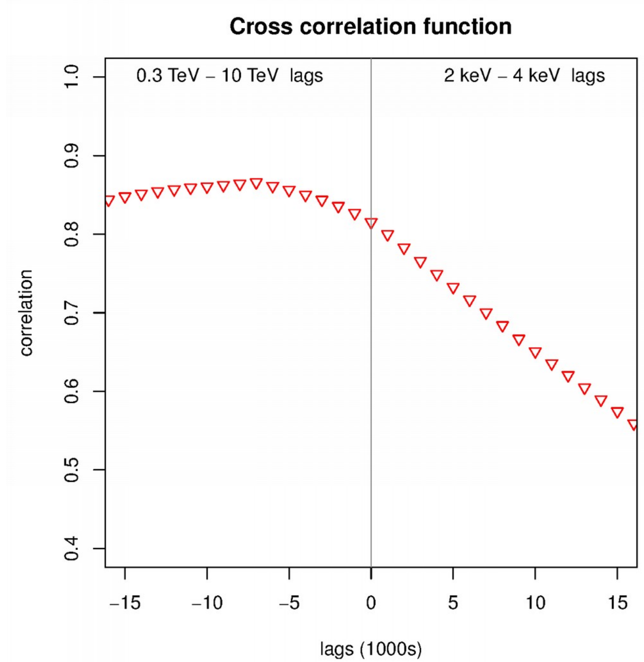
Slower Acceleration decay

No significant change









No injection variation

1. Simulation length T '/Γ=9x10^5 ks;

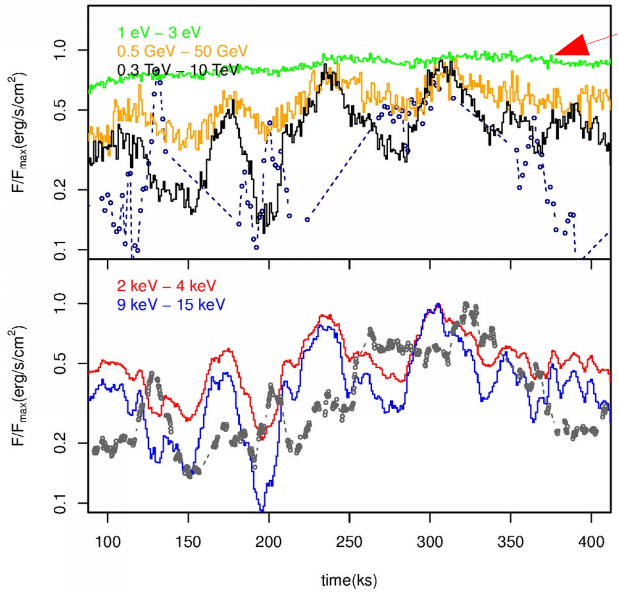
2. Every time step (0.5ks) each cell has 7% chance for additional acceleration (accumulating);

3. Acceleration decay on time scale of t'/Γ= 20 ks;

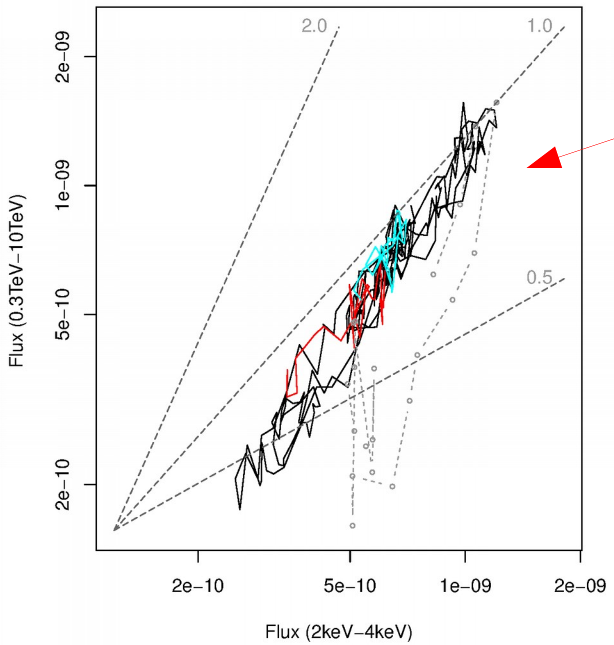
4. Particle injection (at γ=33) ~~increases~~ does not increase with acceleration rate.

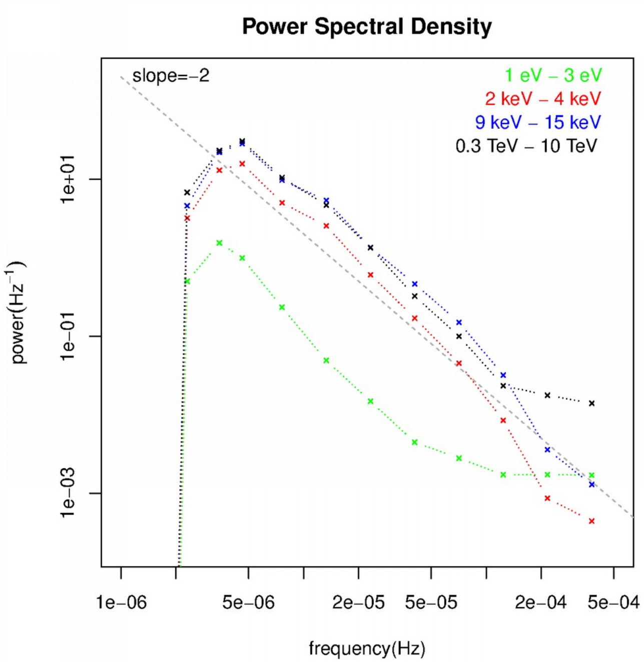
No injection variation

little optical variability

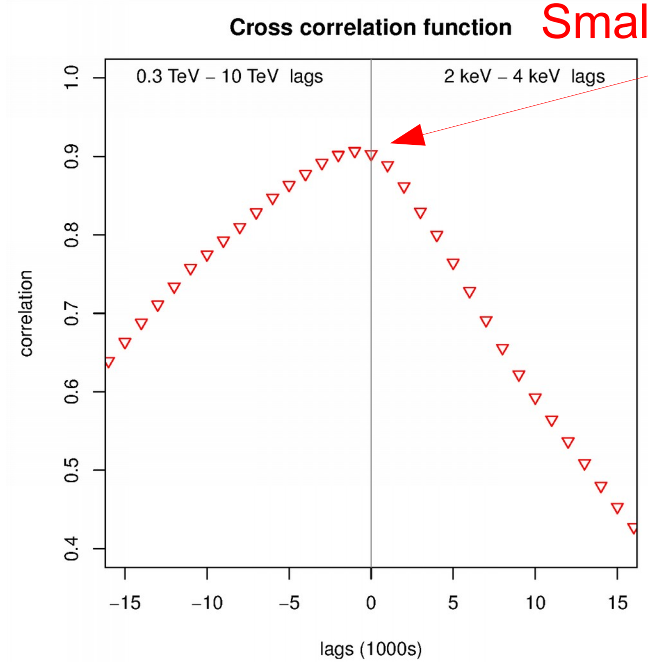


Linear





Small lag, LTTE?



Summary

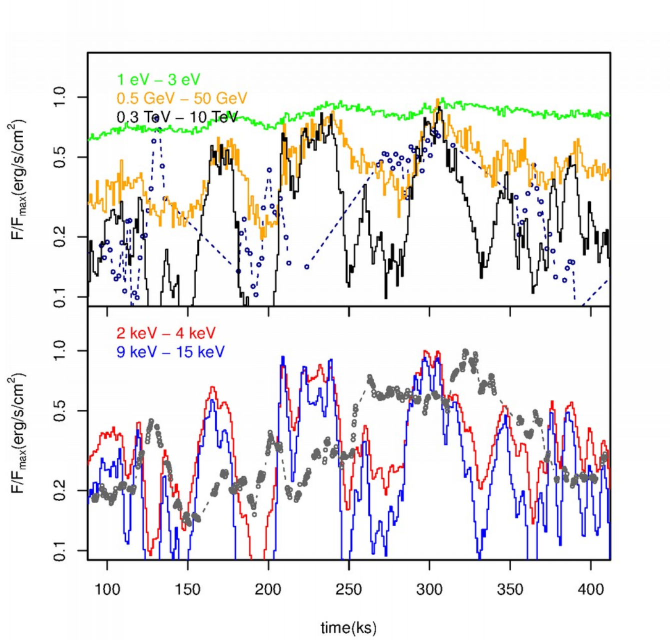
- Random acceleration produces light curves that qualitatively resemble the observed light curves in blazars;

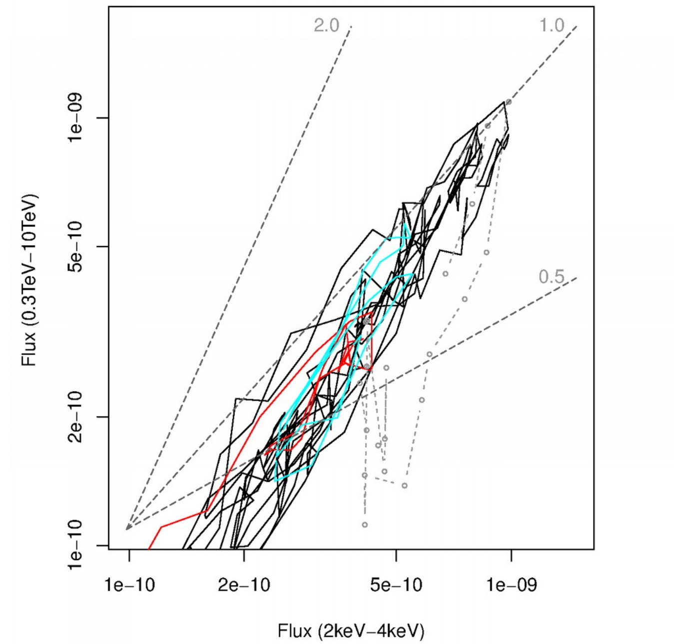
- PSD appears to be featureless red noise;

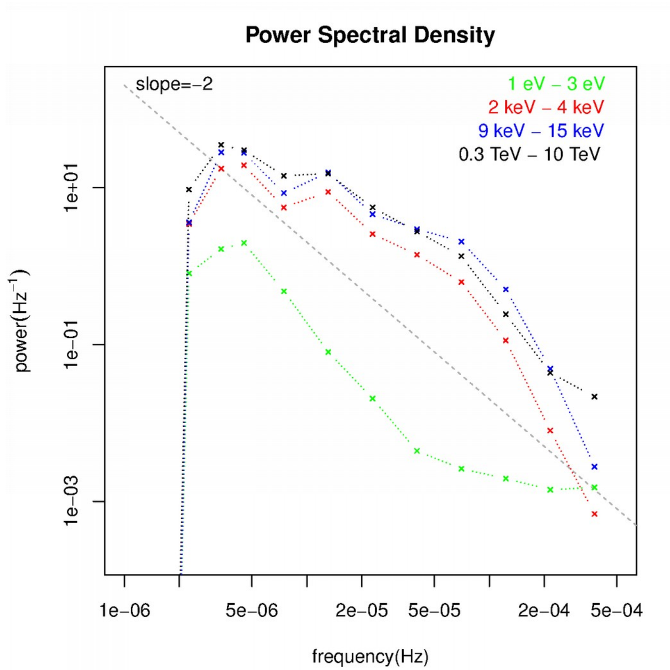
- The amplitude relation between synchrotron and IC flux is dependent on the variability in lower energy bands;

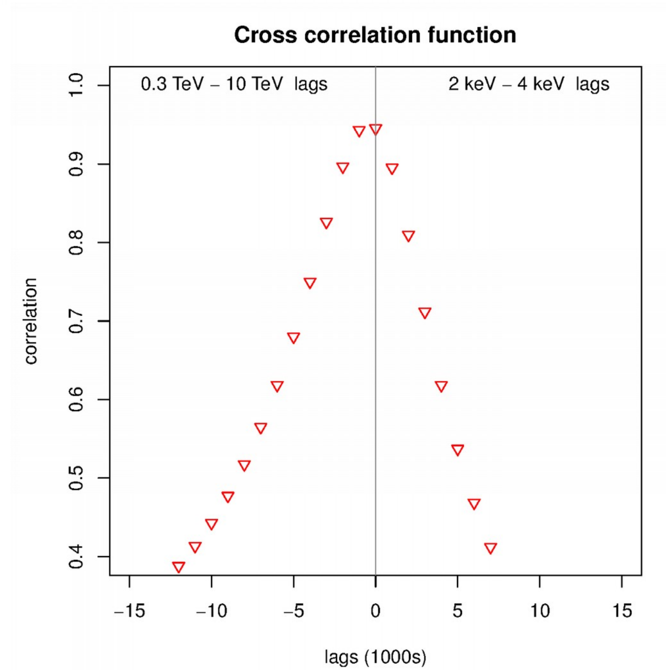
- Variation in IC generally lags those in synchrotron.

No injection variation, acceleration varies in $T'/\Gamma=5$ ks

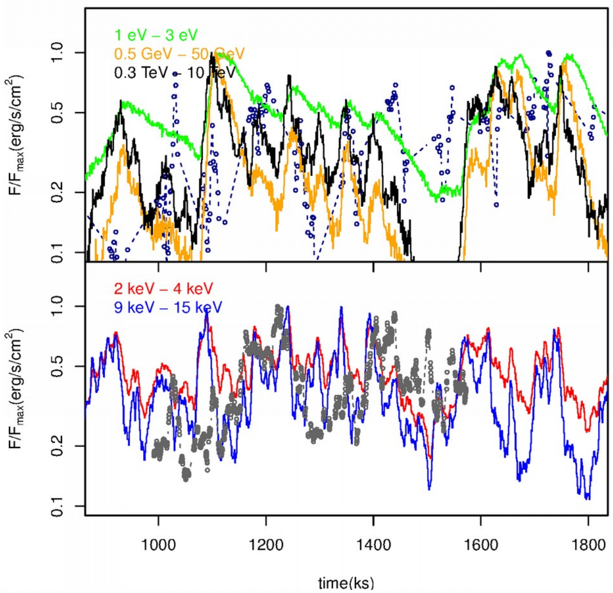


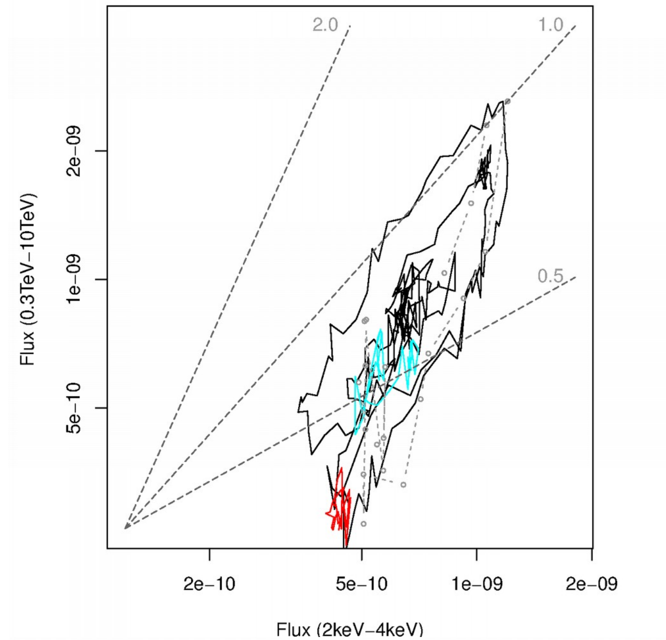


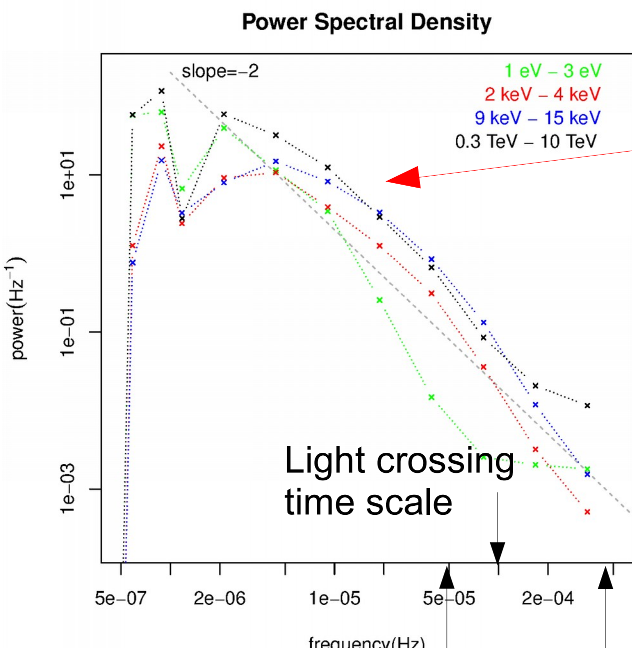




3.5 Ms long simulation



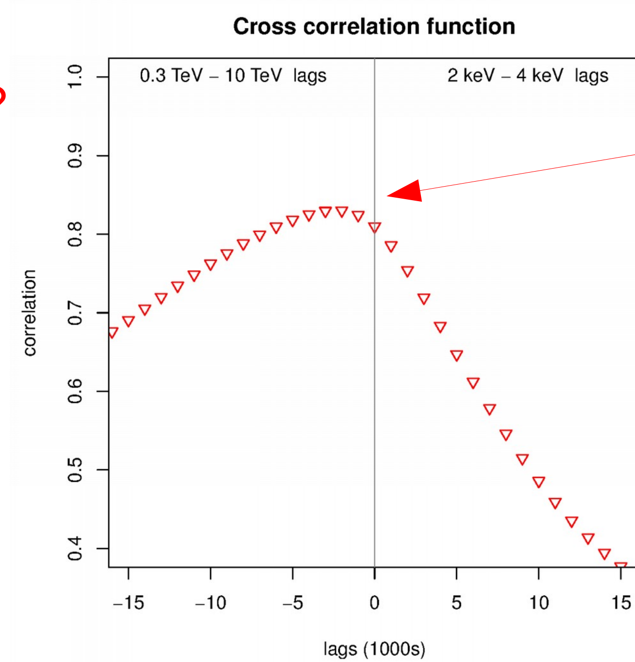




Is there a break?

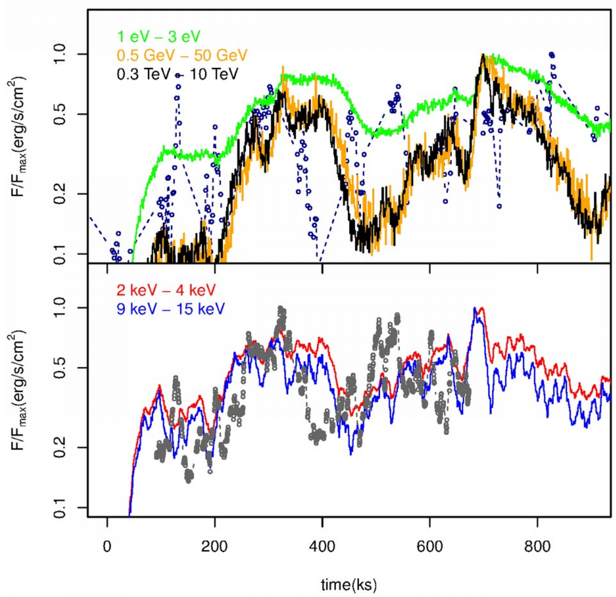
Acceleration decay time scale

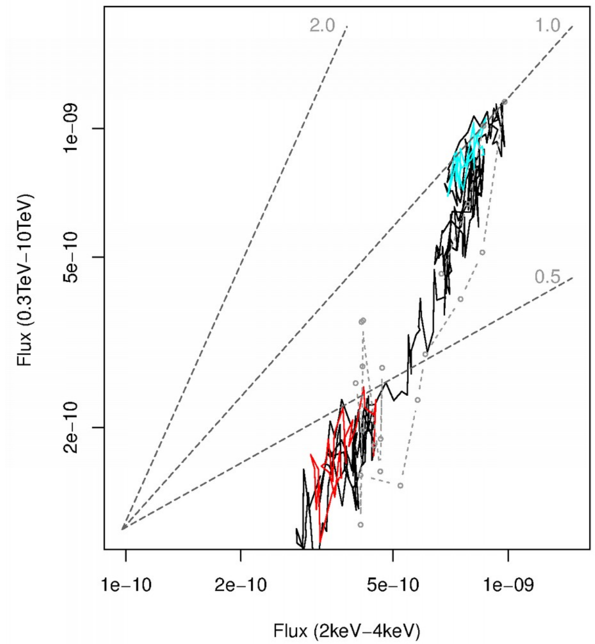
X-ray cooling time scale

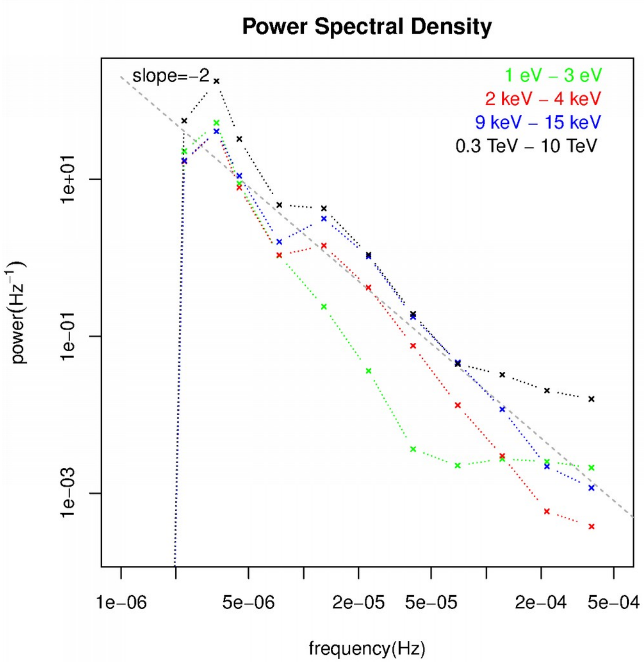


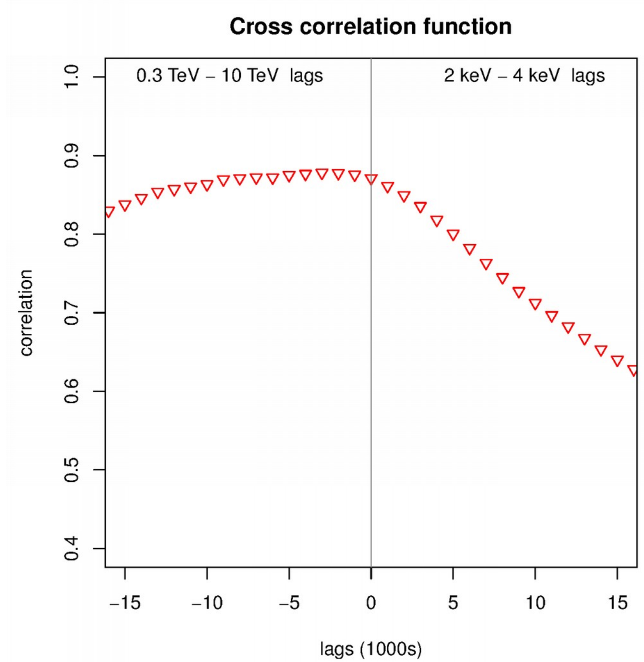
γ-ray lags

Higher acceleration frequency









Slower Acceleration decay