# Radiative signatures of magnetic reconnection in blazar jets

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Understanding Blazars Through Multiwavelength Variability
Stanford University
08/29/2019

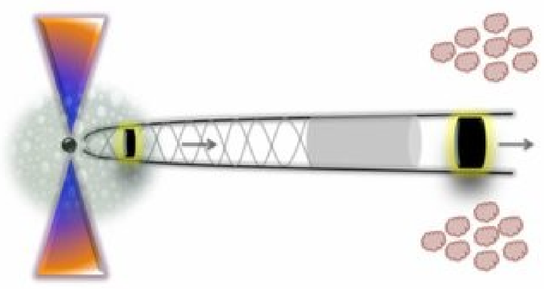
# Main ingredients

1. Dissipation

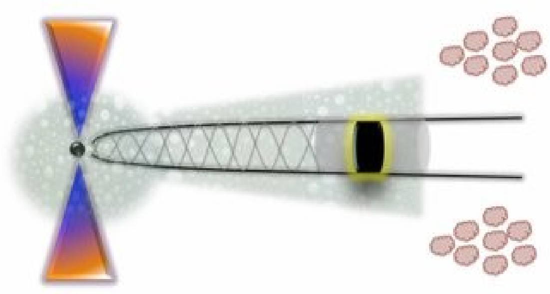
- Close vs. far from SMBH
- Magnetic- vs. kinetic-dominated jet
- Structured vs. uniform jet
- Continuous vs. localized

2. Radiation

- Radiating particle species
- Radiation processes
- Properties of accelerated particle distributions



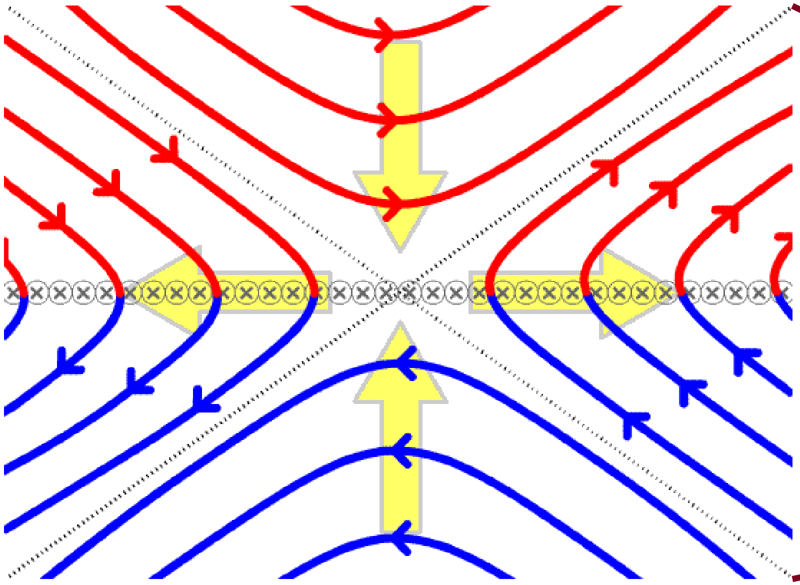
*Leon-Tavares et al. 2014*



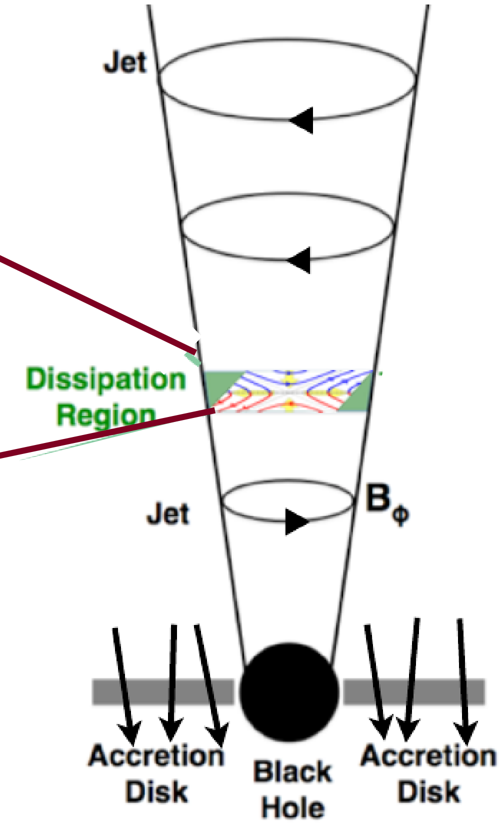
3. Polarization

# Magnetic reconnection

Reconnecting B-field



Reconnecting B-field

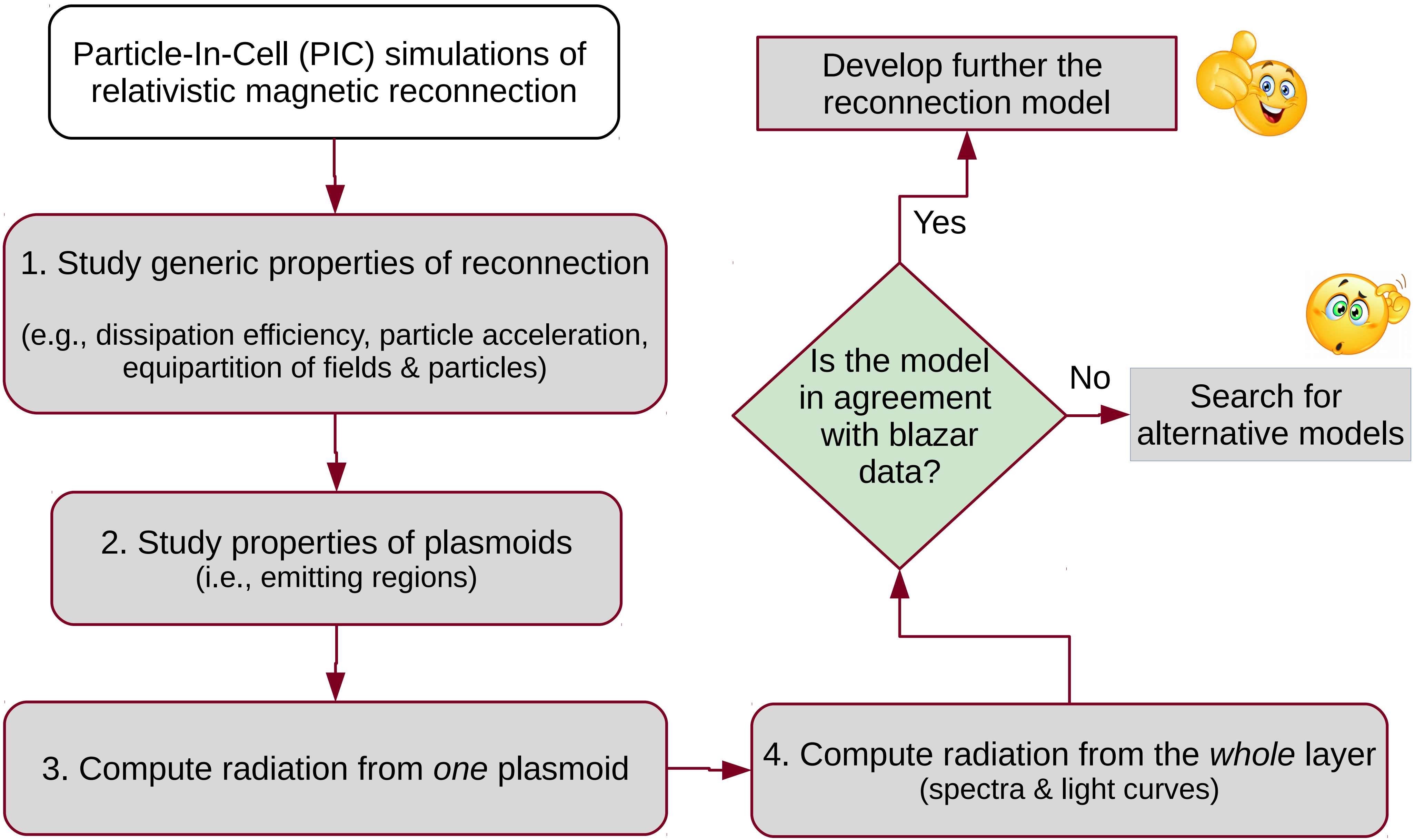



- Changes in the topology of the magnetic field
- Dissipation of magnetic energy
- Transformation into heat, bulk plasma kinetic energy and non-thermal particle energy

- Magnetic kink instability at jet interior
  - Striped wind structure of jet

*(e.g. Romanova & Lovelace 1992; Eichler 1993; Begelman 1998; Giannios & Spruit 2006; McKinney & Uzdensky 2012, Yuan et al. 2016; **Blandford+2017 (review);** Alves et al. 2018; Giannios & Uzdensky 2019)*

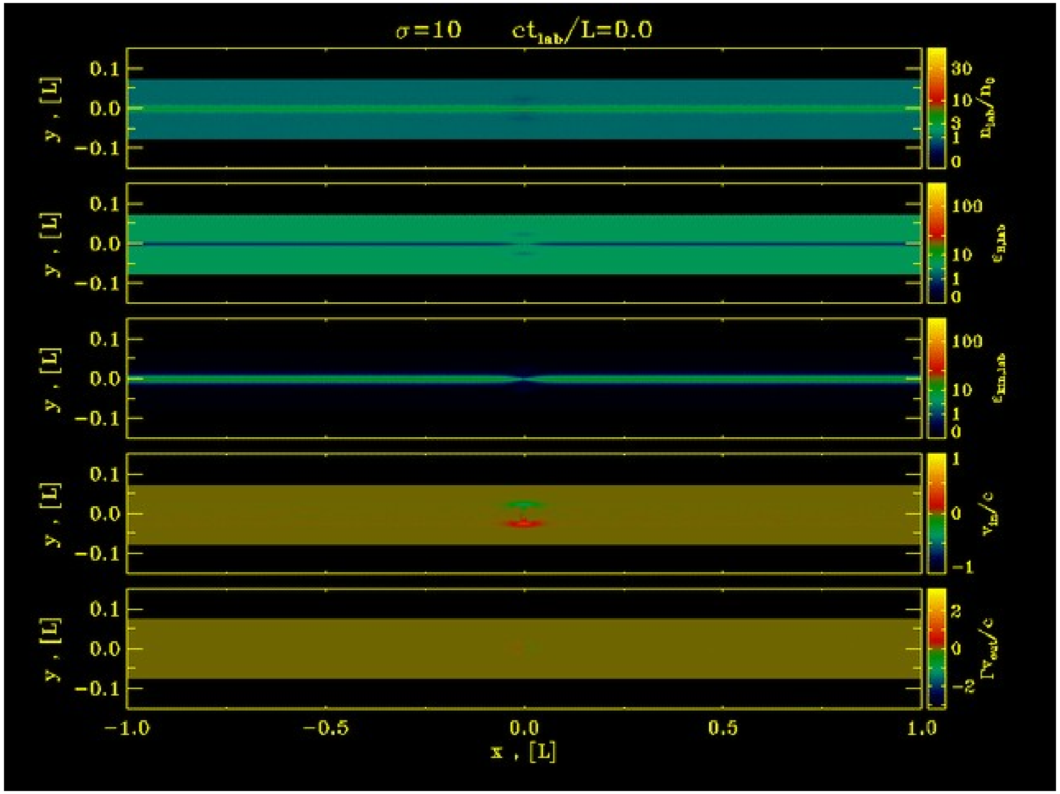
# A radiative model of magnetic reconnection



# Reconnection dynamics, energetics, and particle energy spectrum

# Appearance of the reconnection layer

2D PIC simulations in electron-positron plasma with σ=10




Density

Magnetic energy

Kinetic energy

Inflow rate

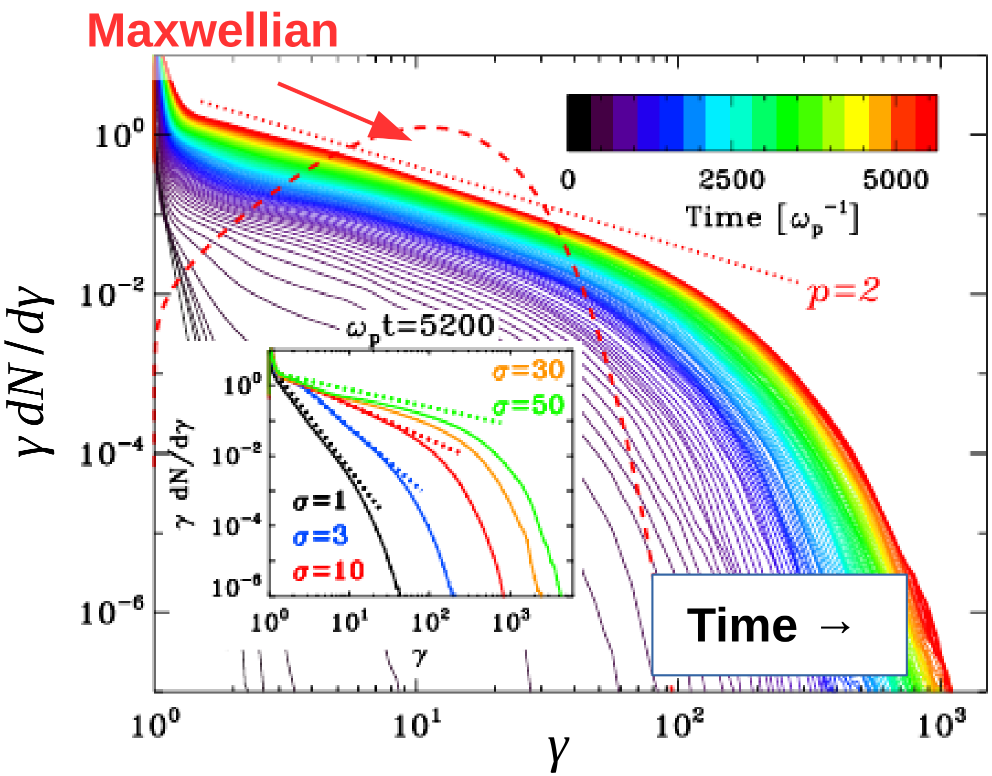
4-velocity

*Sironi, Giannios, Petropoulou 2016*

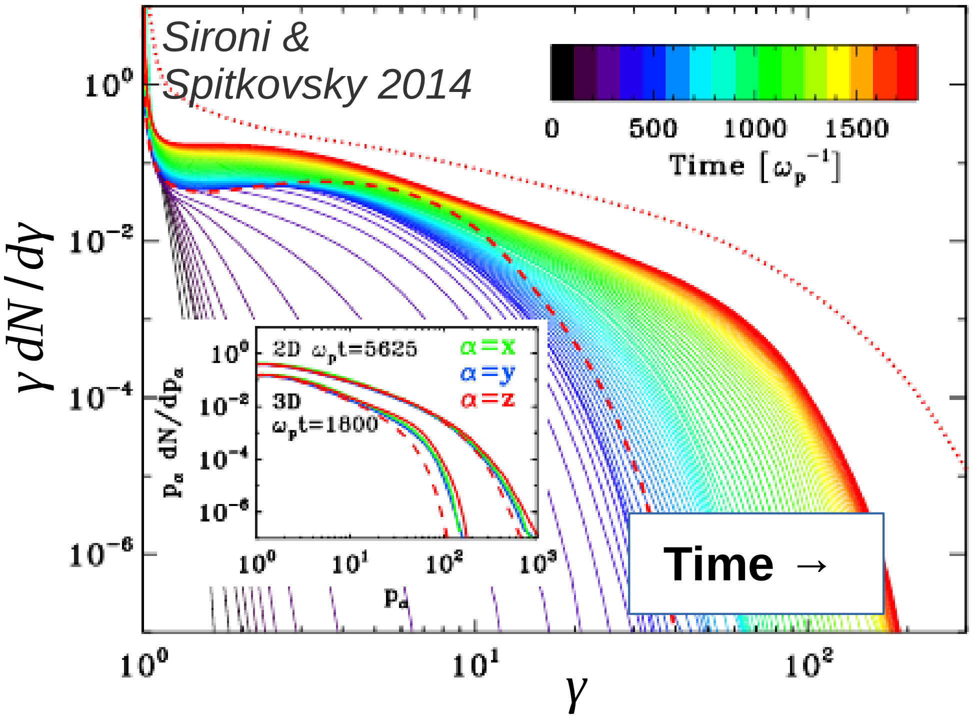
- Inflow into the layer is non-relativistic, $|v_{\rm in}|/c \sim 0.10$ *(Lyutikov & Uzdensky 03, Lyubarsky 05)*
- Outflow from the X-points is relativistic, reaching the Alfvén speed, $v_A/c = \sqrt{\sigma/(\sigma+1)}$
- Current sheet breaks into a series of magnetic islands or plasmoids *(e.g. Loureiro+07, Bhattacharjee+09, Uzdensky+10, Huang & Bhattacharjee 12).*

# Particle energy spectrum

**2D** σ=10 electron-positron

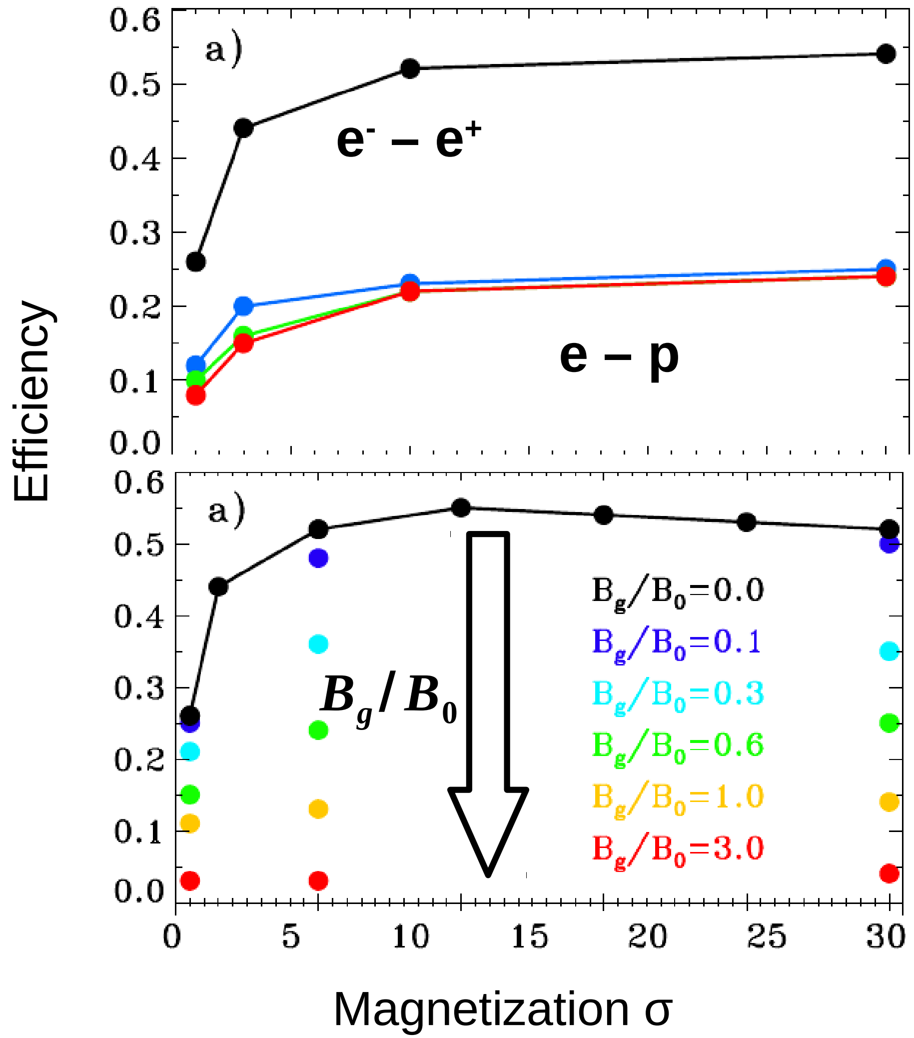



**3D** σ=10 electron-positron




- Higher σ produces harder (p<2) particle spectra. *(Sironi & Spitkovsky 2014; Guo+2014, 2015; Werner+2016)*
- The maximum energy increases with time, if it is not inhibited by the boundaries. *(Sironi & Spitkovsky 2014; Petropoulou & Sironi 2018)*

# Energy dissipation efficiency



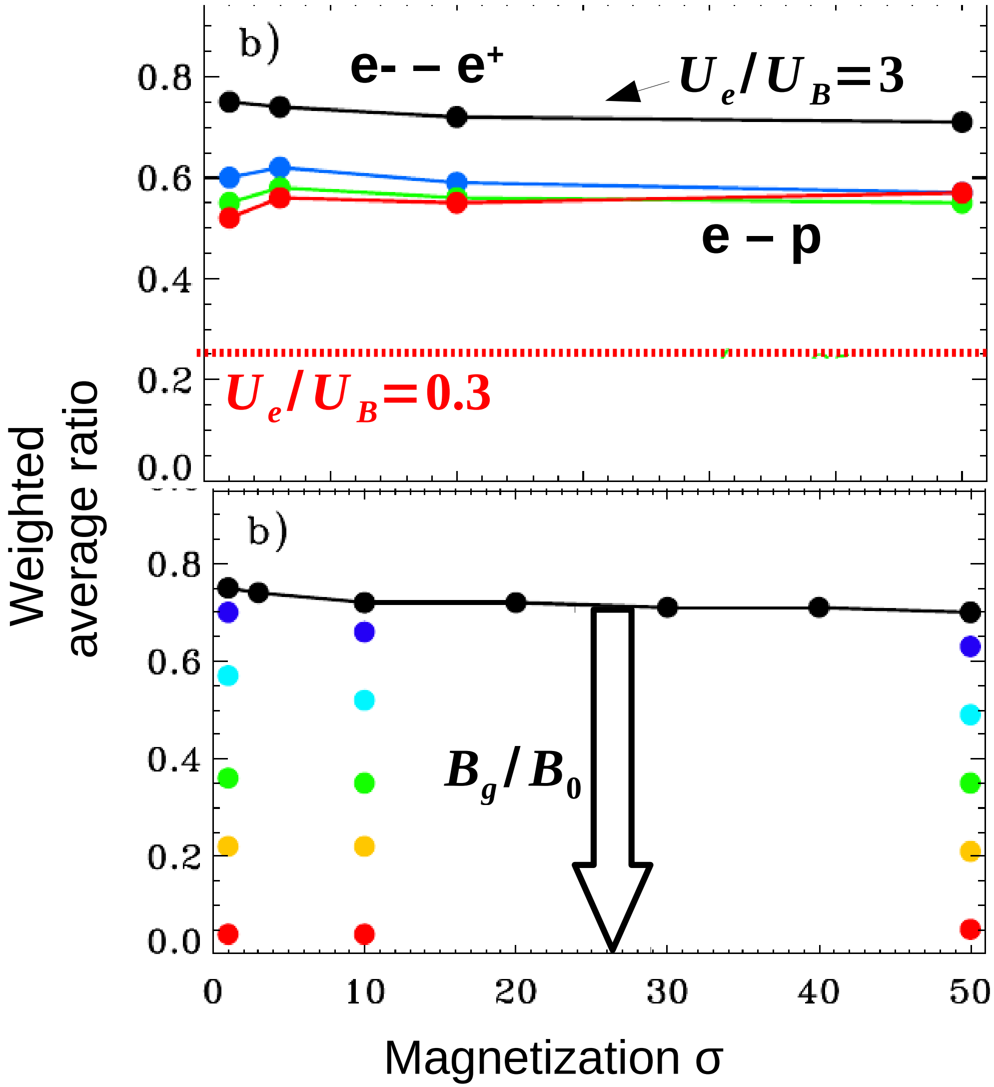

**Efficiency:**

$$f_{\rm rec} \equiv \frac{\sum_i \int_{V_i} U_{\rm e} {\rm d}V_i}{\sum_i \int_{V_i} (e + \rho c^2 + U_{\rm B})\, {\rm d}V_i}$$

- Reconstruction transfers ~ 50% of the flow energy (electron-positron plasmas) or ~ 25% (electron-proton) to radiating particles.
- Efficiency decreases with increasing guide field.

*Sironi, Petropoulou, Giannios 2015 (see also Werner+2017)*

# Energy equipartition



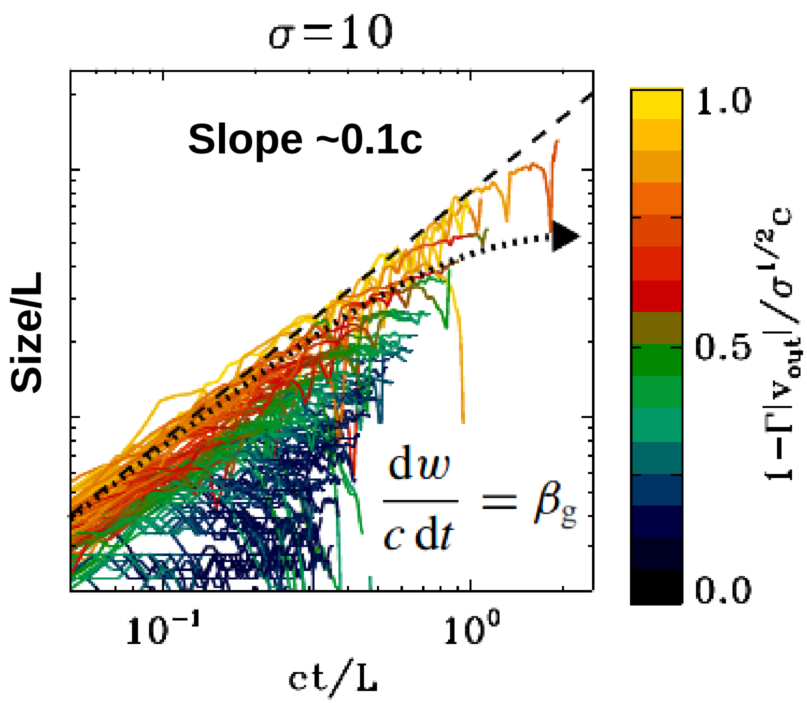

**Weighted average energy density ratio:**

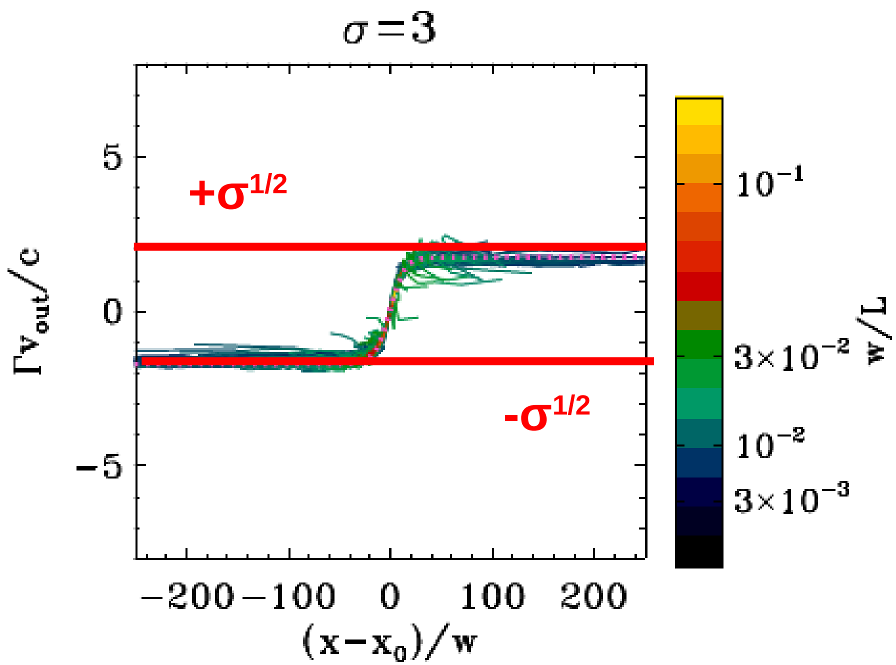
$$\left\langle \frac{U_\mathrm{e}}{U_\mathrm{e}+U_\mathrm{B}} \right\rangle \equiv \frac{\sum_i \int_{V_i} U_\mathrm{e} \frac{U_\mathrm{e}}{U_\mathrm{e}+U_\mathrm{B}} \mathrm{d}V_i}{\sum_i \int_{V_i} U_\mathrm{e} \mathrm{d}V_i}$$

- Rough energy equipartition in plasmoids: *even if the upstream plasma is strongly magnetized, the"effective" σ~1 within plasmoids.*
- $U_e >> U_B$ is not expected.
- $U_B >> U_e$ for strong guide fields.

*Sironi, Petropoulou, Giannios 2015*

# Plasmoid growth & acceleration




- The plasmoid size grows with constant rate $\beta_g$~0.1 (in its rest frame).
- The growth rate depends weakly on the magnetization σ.

*Sironi, Giannios, Petropoulou 2016*

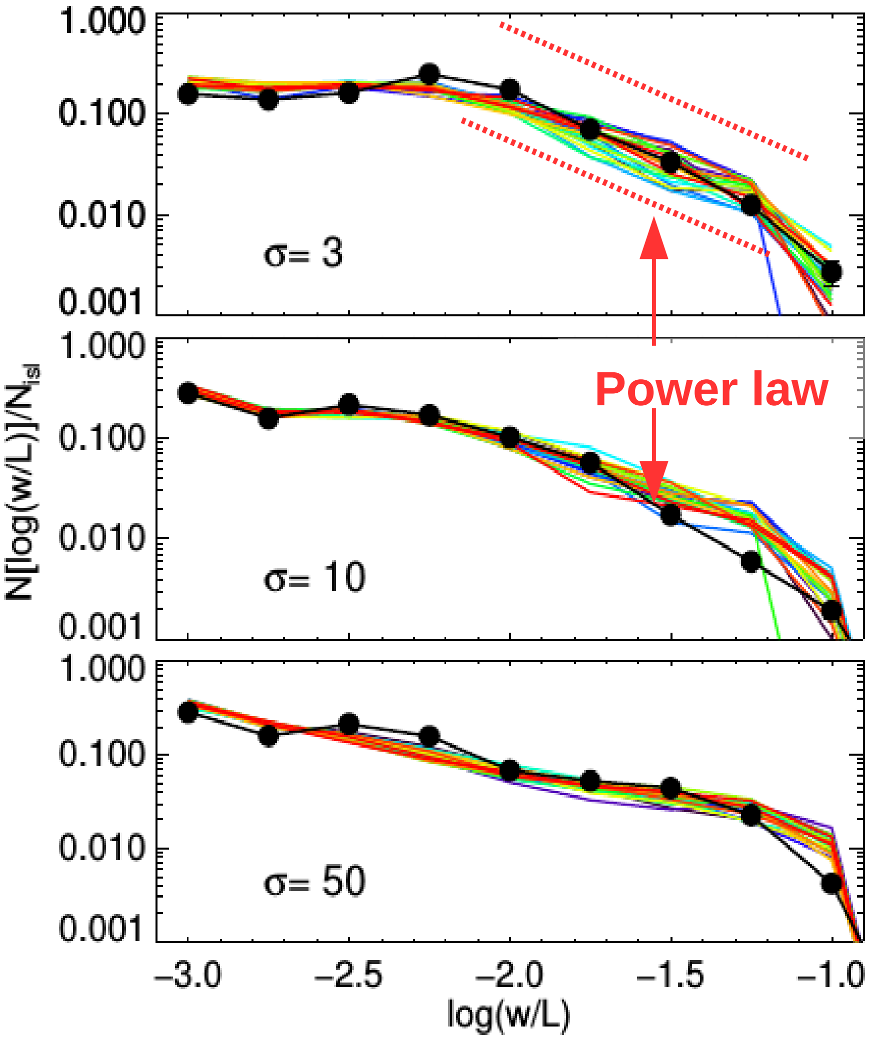
- “Universal” acceleration profile due to magnetic forces:

$$\Gamma \frac{v_{\rm out}}{c} \simeq \sqrt{\sigma}\tanh\left(\frac{\beta_{\rm acc}}{\sqrt{\sigma}}\frac{x-x_0}{w}\right)$$

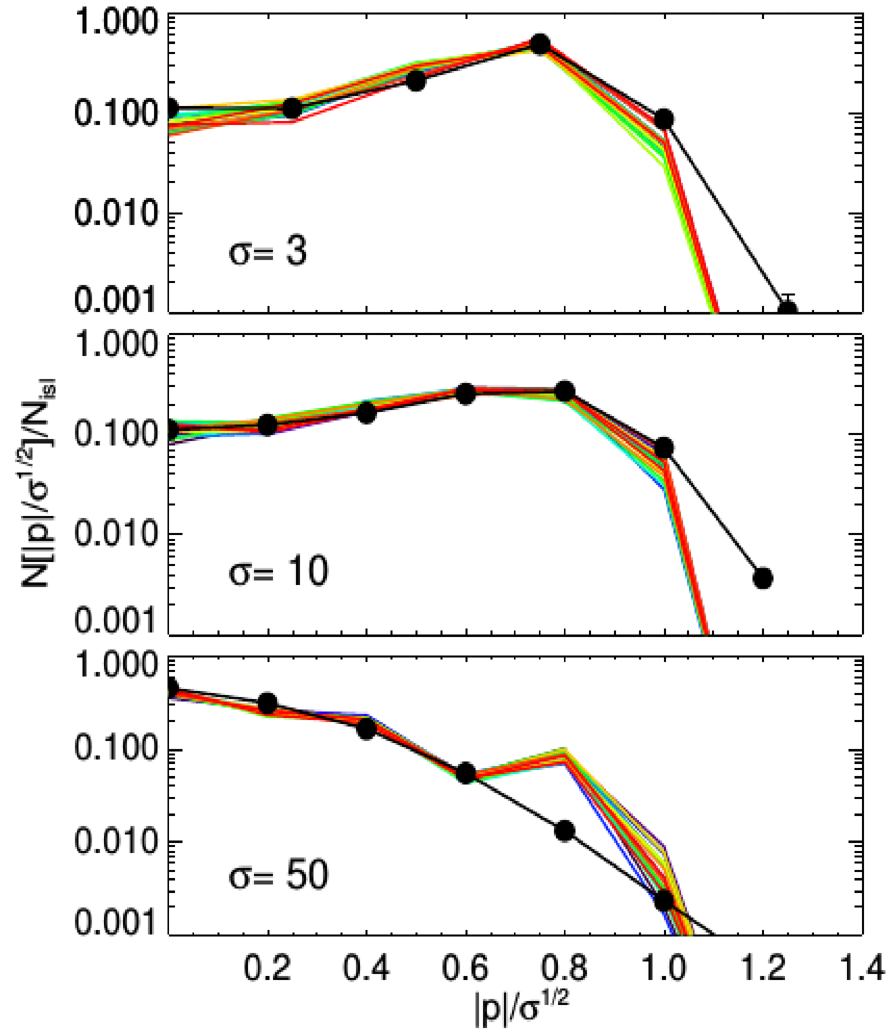
- Small plasmoids are relativistic.
- Biggest plasmoids move with non-relativistic speeds.

# Plasmoid statistics

Distribution of sizes




Distribution of 4-velocities

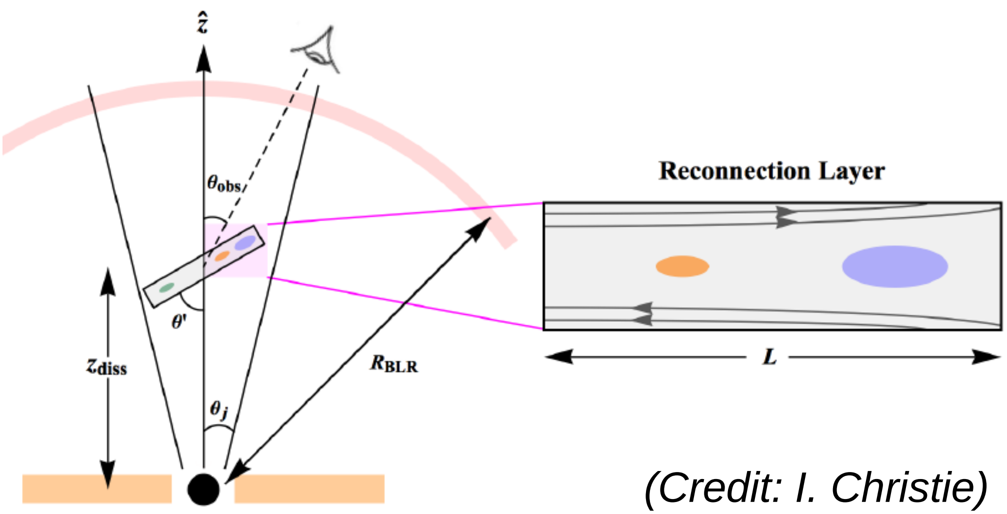



*Petropoulou, Christie, Sironi, Giannios 2018*

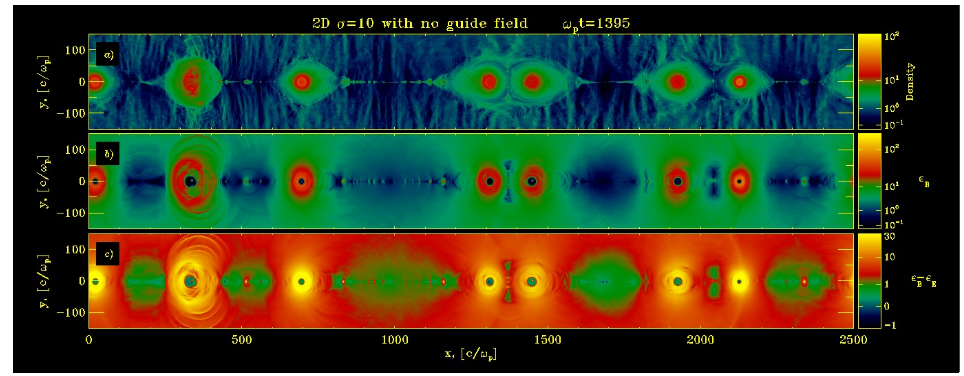
- Slope of power-law size distribution depends on plasmoid growth & acceleration rates.
- 4-velocity distribution depends on σ.

# Radiative signatures from plasmoids

# The radiative model




(Credit: I. Christie)




- Use 2D PIC of magnetic reconnection to benchmark:

  i. the particle energy spectrum (slope, minimum, maximum energies),
  ii. the growth rate of emitting regions,
  iii. the ratio of electron-to-magnetic energy density, and
  iv. the Doppler factor of emitting regions.

- Vary free parameters to produce generic blazar spectra:

  i. magnetic field strength and magnetization σ,
  ii. length & orientation of the layer,
  iii. pair multiplicity,
  iv. jet's bulk Lorentz factor, and
  v. external radiation fields.

# Emission from a single plasmoid

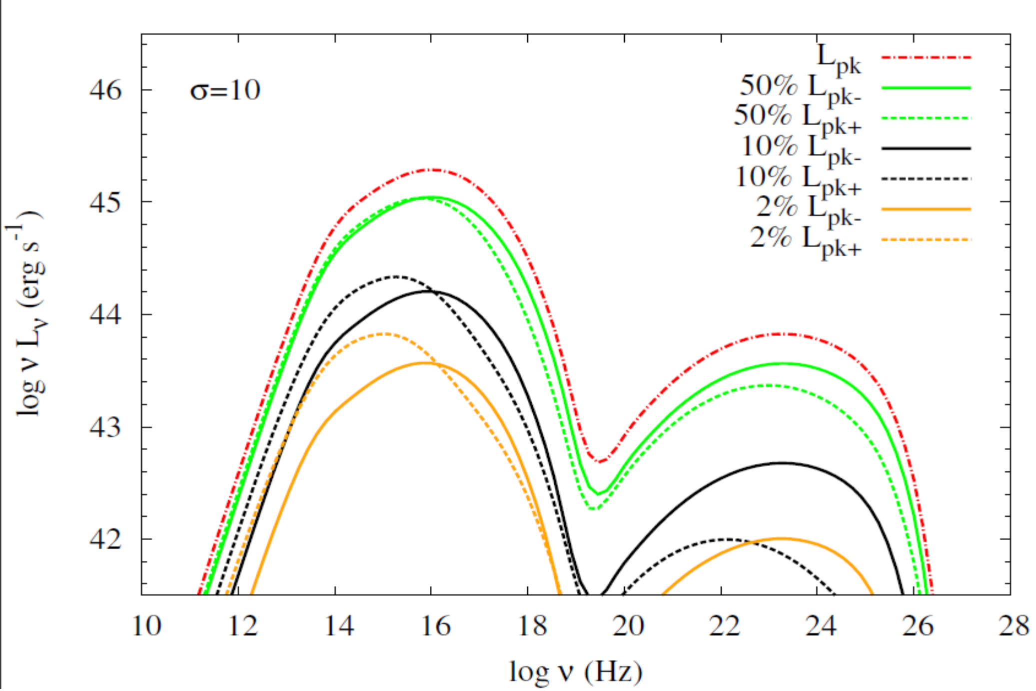
Each plasmoid produces a flare of characteristic duration and flux

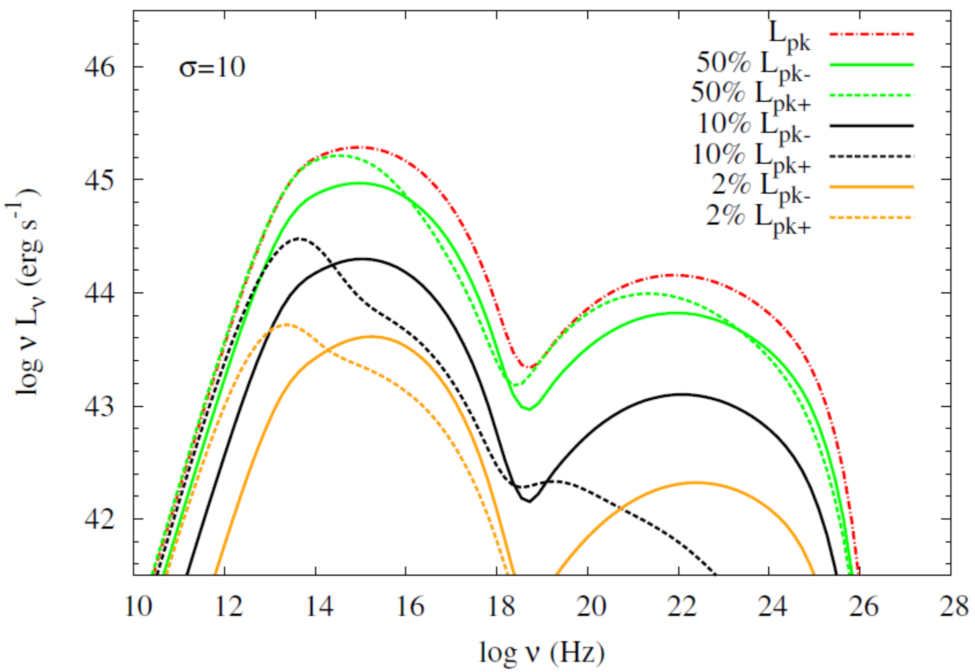
$$\Delta t_{1/2} \approx \frac{w_p}{\beta_g c\, \delta_p}$$

$$L_{pk} \approx \frac{f_{rec} L_j}{8 R^2 c\, \beta_j \Gamma_j^2} \beta_g c\, w_p^2 \delta_p^4$$

Small & fast → Minute-scale flare

Large & slow → Hour-scale flare

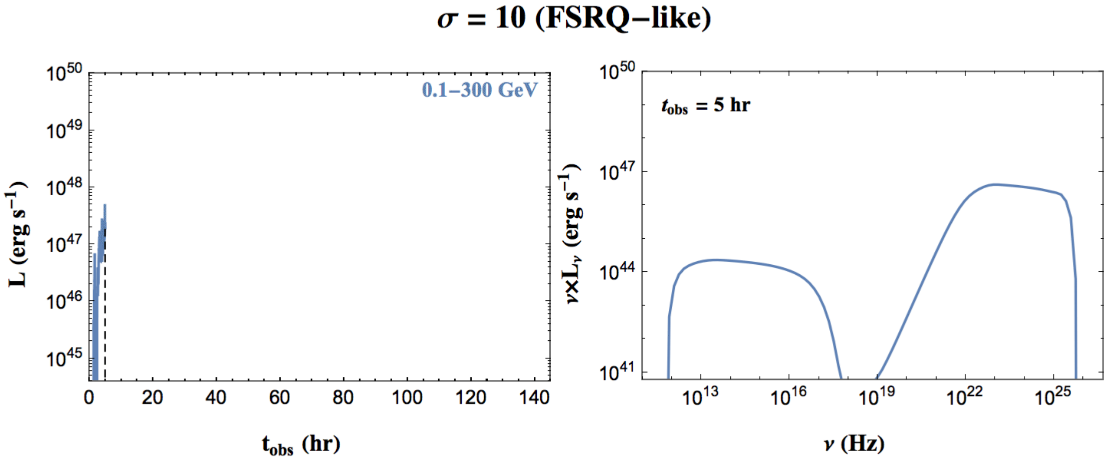


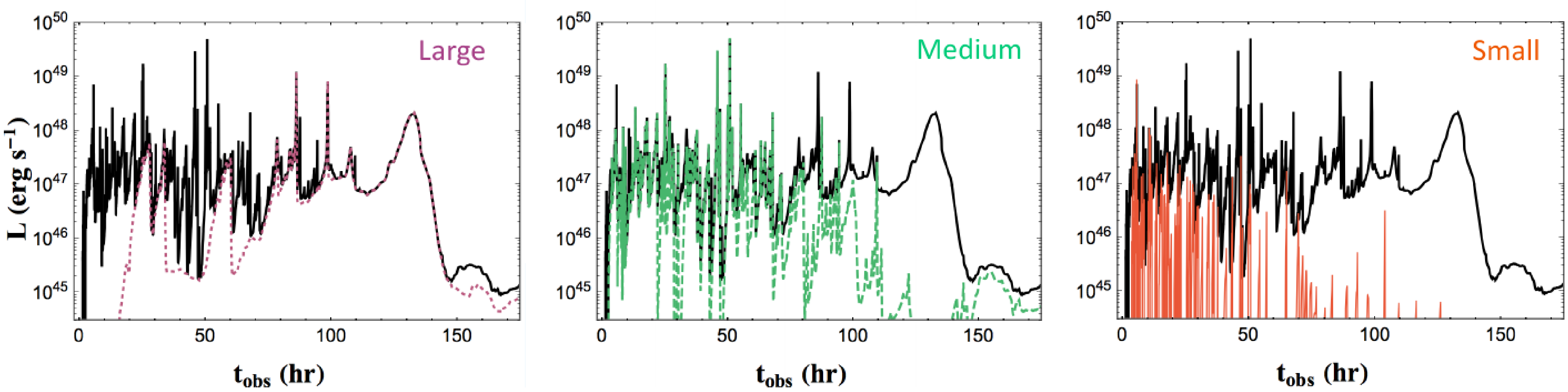

*Petropoulou, Giannios & Sironi 2016*

# Emission from the whole layer

Each reconnection event produces a chain of plasmoids with power-law size distribution

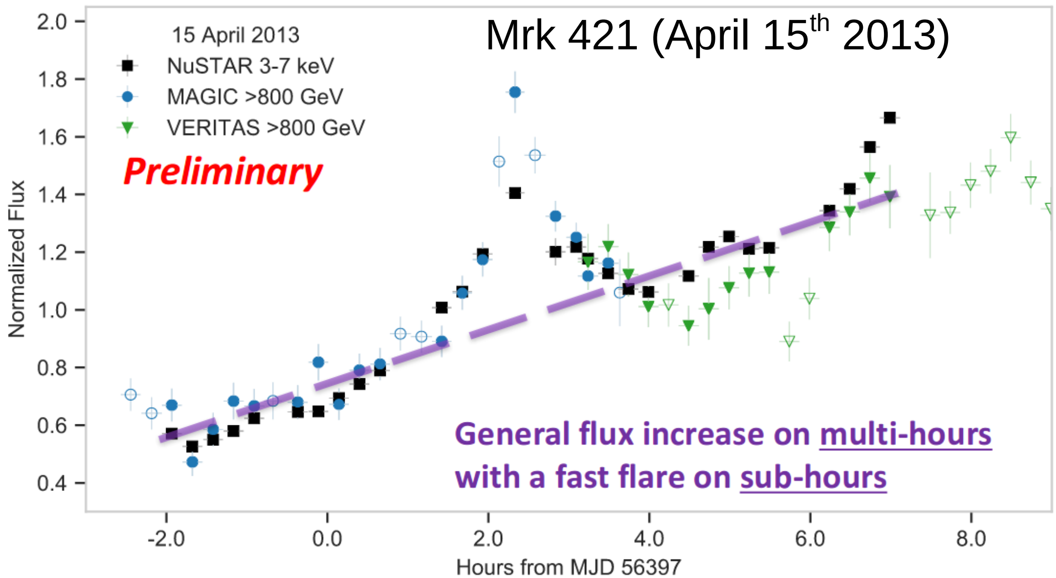


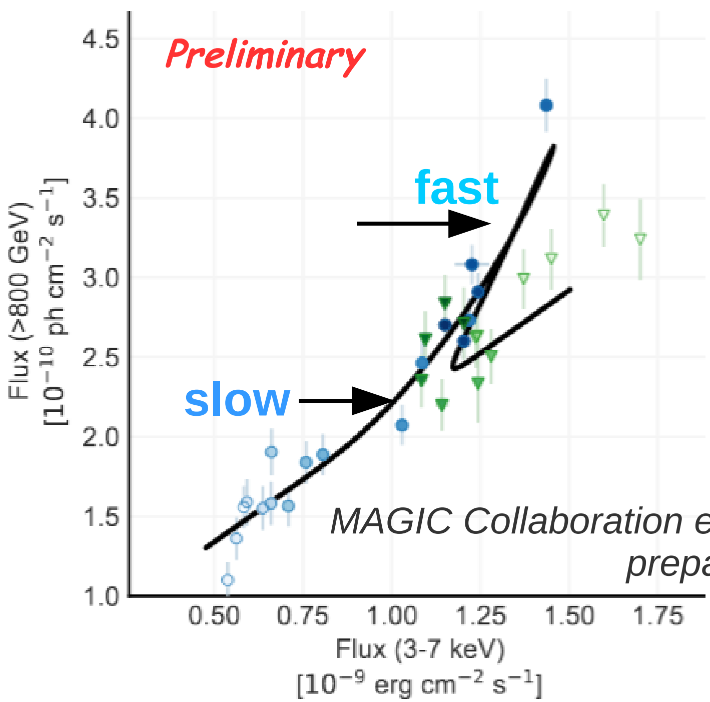

*Christie et al. 2019*




- Fast flares on top of slowly evolving envelope *(Giannios 2013)*.
- Physical model for multi-timescale variability in jets.

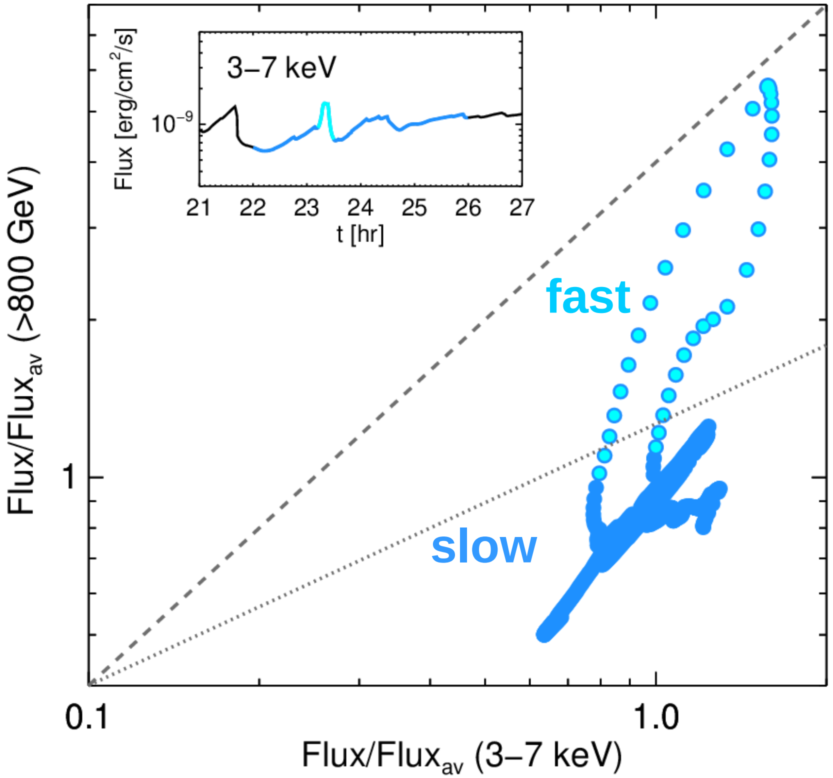
# Flux-flux correlations




*MAGIC Collaboration et al., in preparation.*

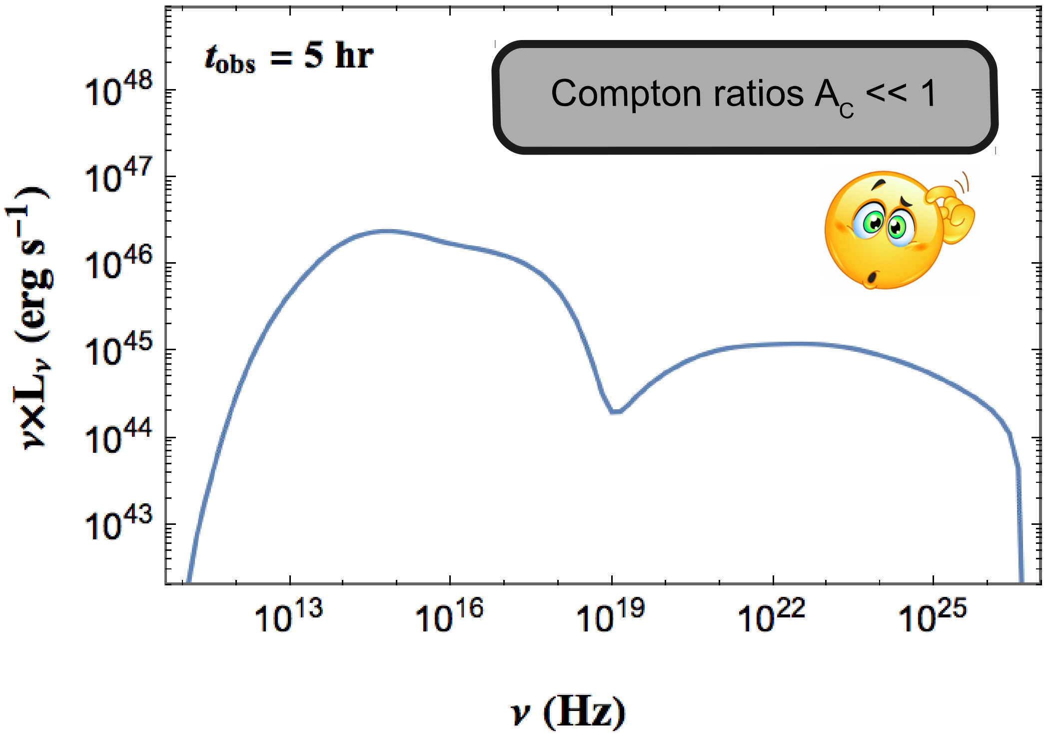
BL Lac-like source (σ=10)



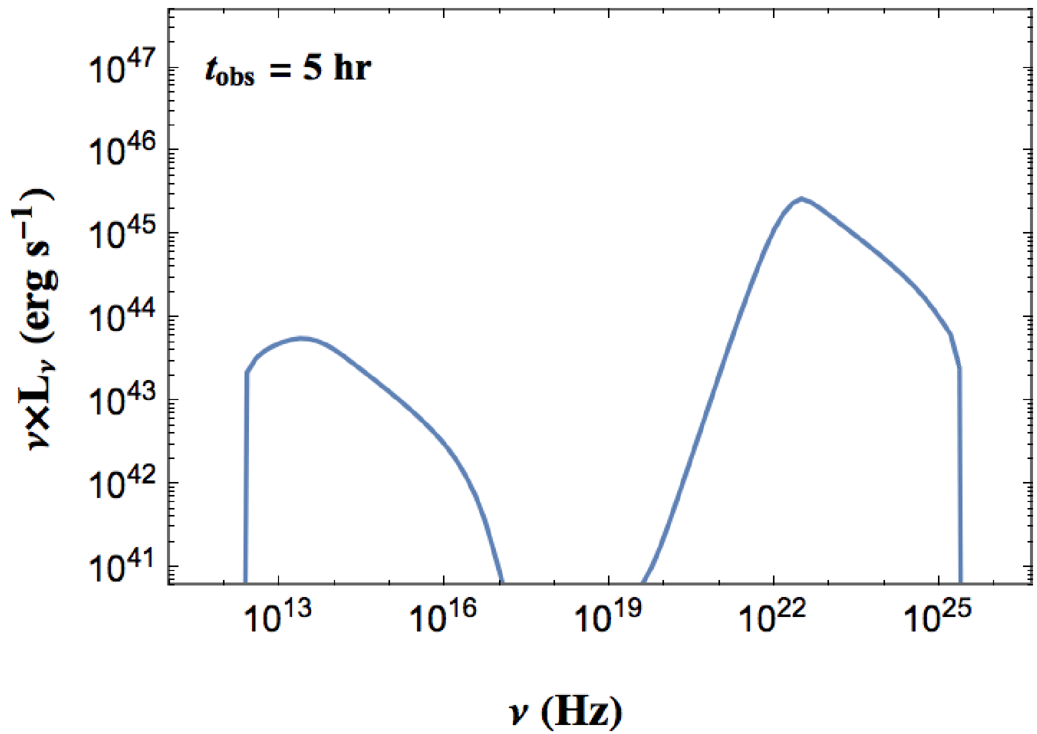

- Fast flares on top of slowly evolving envelope *(Giannios 2013, Christie et al. 2019)*.
- Different spectral variability of fast & slow components.

# BL Lac objects and FSRQs

(BL Lac)




(FSRQ)



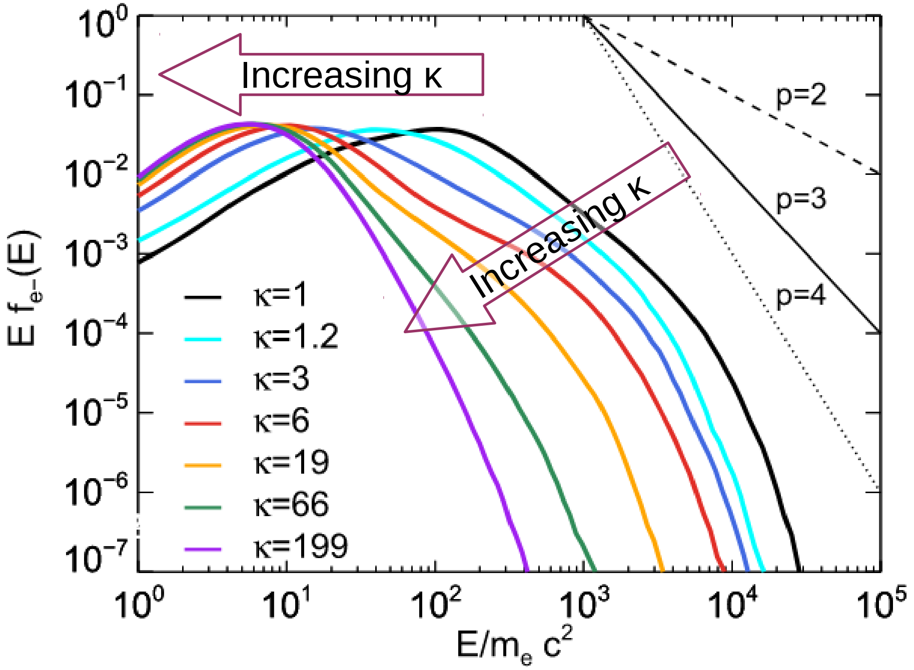

- Different plasma magnetization $\sigma$ → power-law index of electron distribution
- Different pair multiplicities → $\gamma_{min}$ for soft PL ($\gamma_{max}$ for hard PL)
- Luminosity of broad line region → strength of external Compton

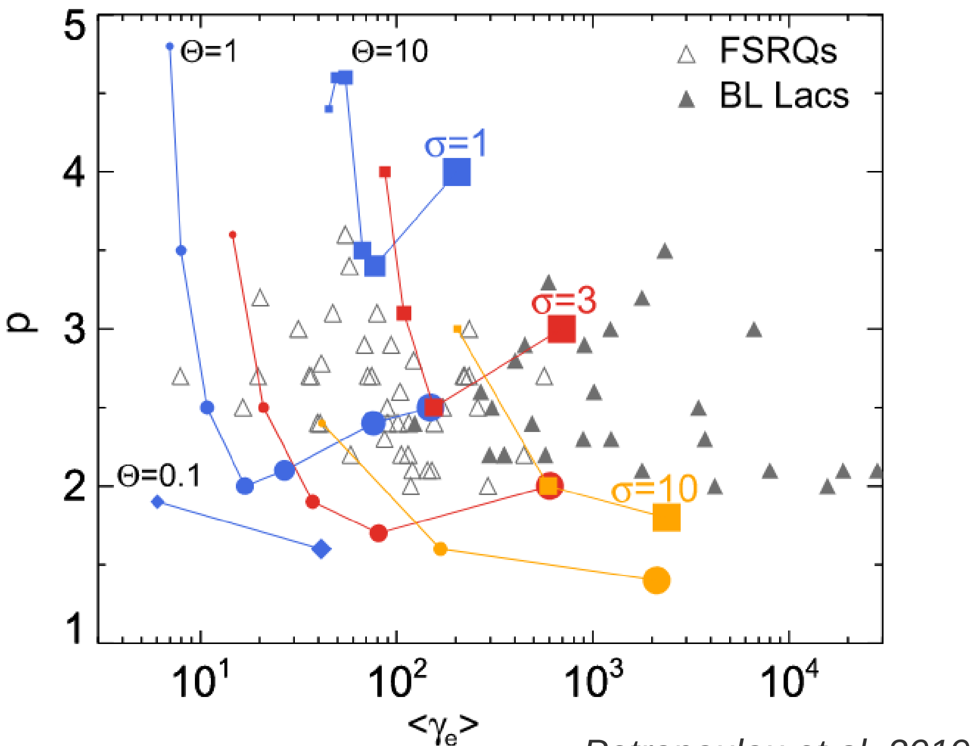
Not yet demonstrated with PIC

# Effects of pair multiplicity

First 2D PIC simulations in electron-positron-proton plasmas with

σ=1, 3,10, $\Theta_e$=0.1, 1, 10 and pair multiplicity κ=1-199




*Petropoulou et al. 2019*

Empirical scaling of mean lepton Lorentz factor on physical parameters:

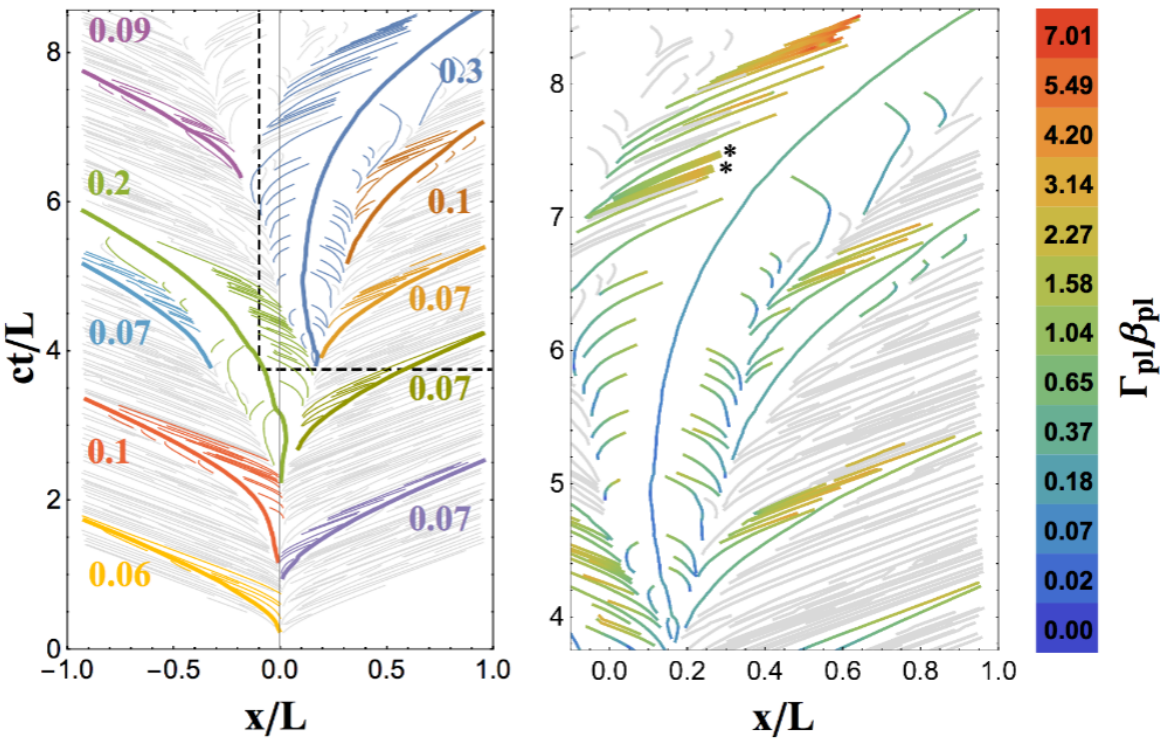
$$\langle \gamma_e - 1 \rangle \approx \sqrt{\sigma}\,(1 + 4\Theta_e)\left(1 + \frac{\sigma_{e,h}}{30}\right)$$

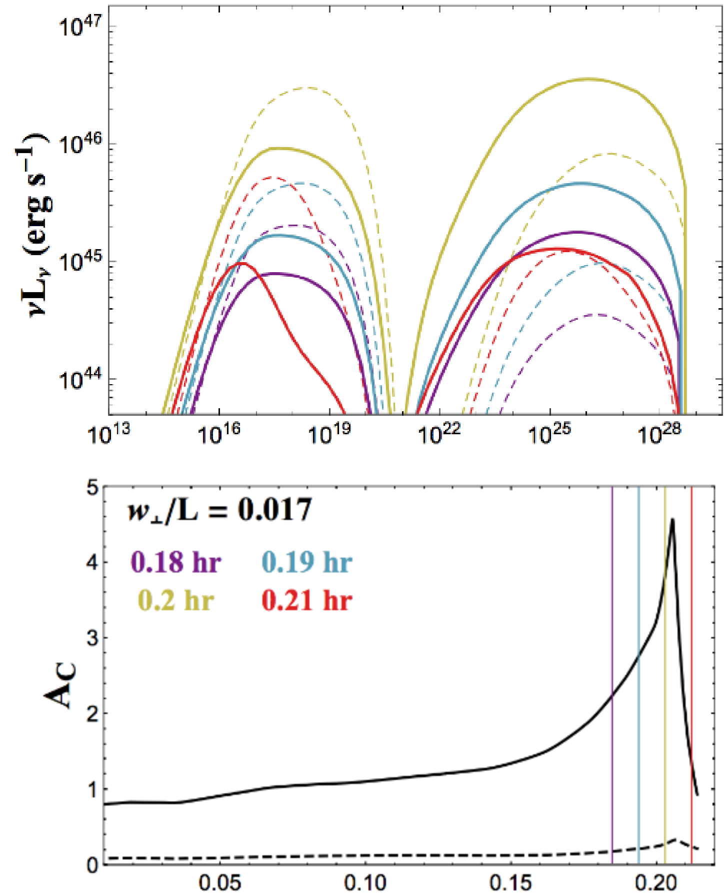
magnetization of pairs defined with enthalpy

- Higher κ → softer power laws
- Higher κ → lower mean lepton energy
- Larger σ → harder power laws

# Inter-plasmoid Compton scattering

Time-position diagram of layer (σ=10)




*Christie et al. 2019, MNRAS submitted (arXiv:1908.02764)*

- Large plasmoids can provide extra seed photons for Compton scattering.
- Inter-plasmoid Compton scattering (IPCS) is important for a large fraction of plasmoids in layer.
- IPCS in BL Lacs can explain $A_C$~ 1-5 without requiring particle-dominated emitting regions!

# Fake *Fermi* light curves from reconnection

*Meyer, Petropoulou,Christie, in prep.*

Our method:

i. Select a real FSRQ and a random time window.

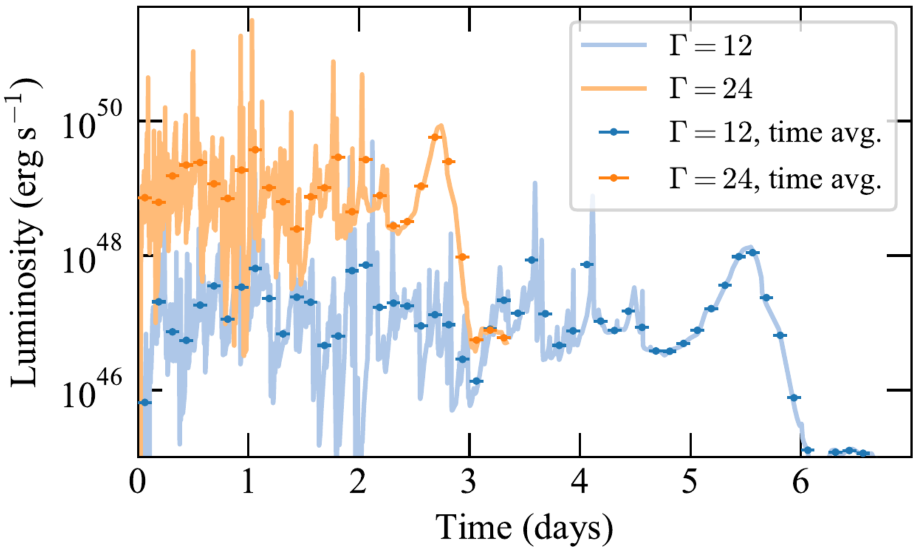
ii. Conduct standard *Fermi* analysis of optimizing source parameters in a given ROI, and build a light curve (with fixed temporal binning).

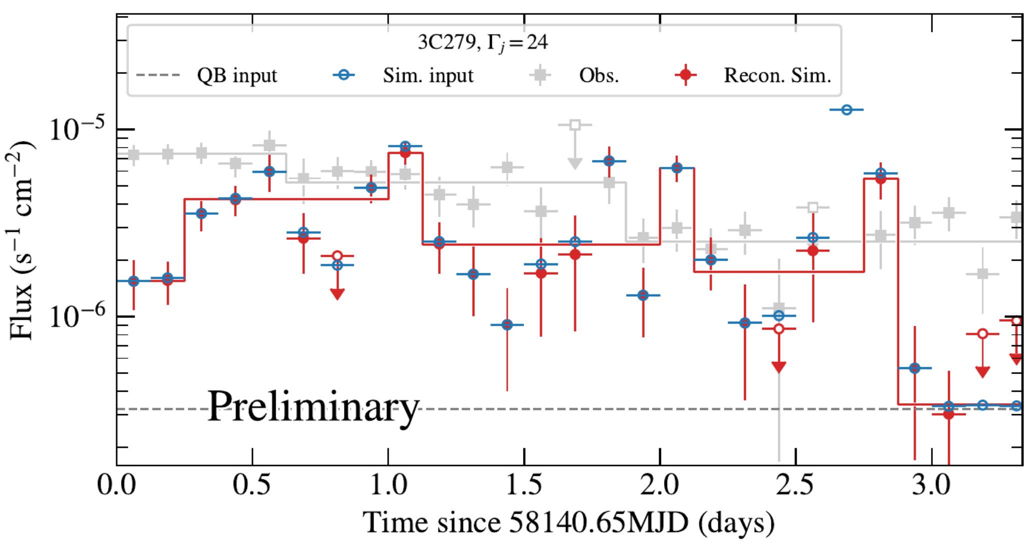
iii. For each time bin, replace the central source by the prediction of our “vanilla” blazar model, add a baseline flux, and simulate the modified ROI.

iv. Conduct a standard *Fermi* analysis on the simulated ROI and reconstruct the source light curve.

Our goal:

i. Test which (if any) features of the model light curves are retained in a *Fermi*-LAT observation.



# Summary

**Magnetic reconnection:**

- is an efficient dissipation process.
- produces extended non-thermal particle energy spectra.
- leads to the generation of many plasmoids, aka emitting regions.
- can produce multi-wavelength non-thermal emission.
- can produce variable emission on multiple timescales.
- offers a physical framework for jet emission.

# Future directions

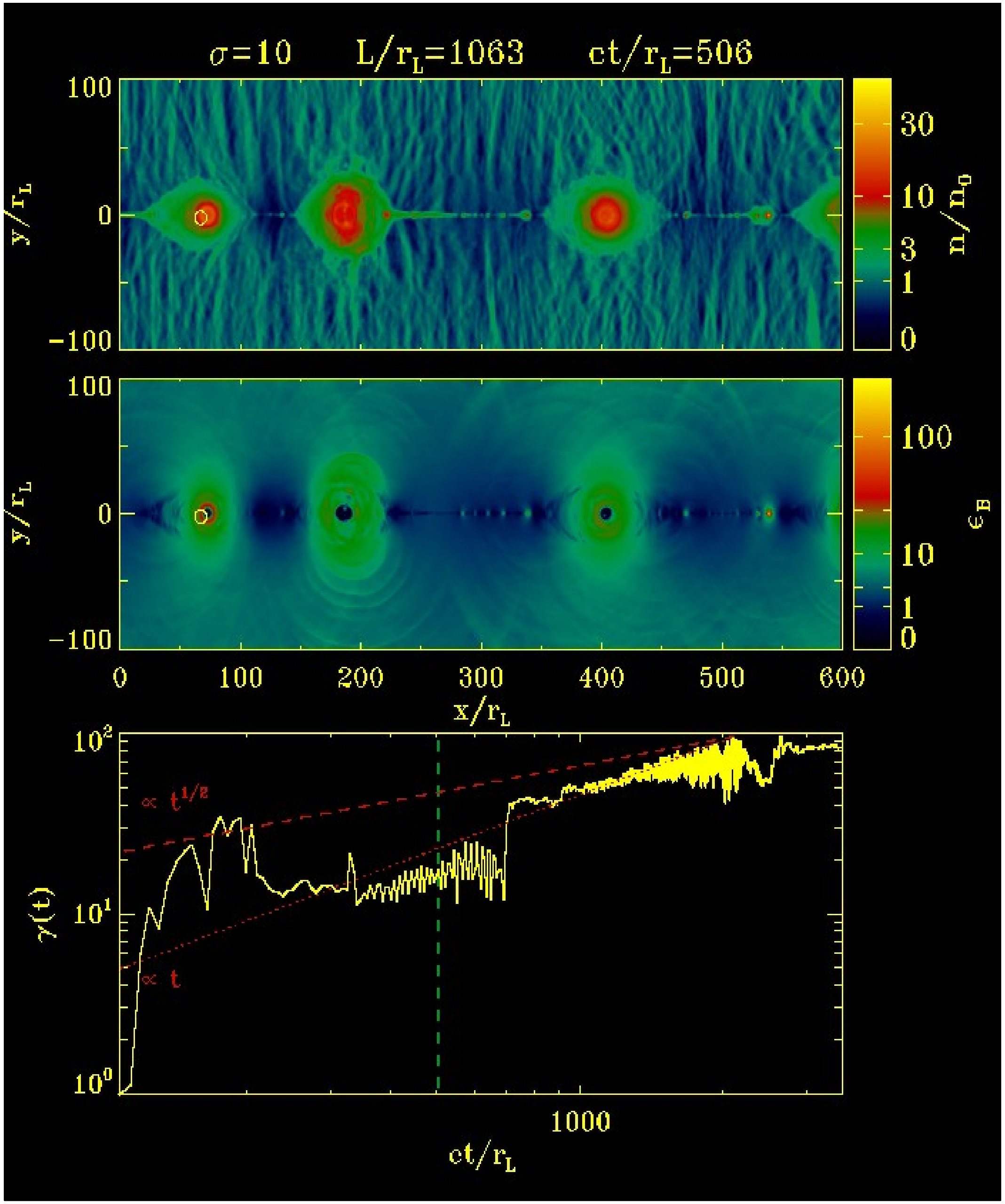
- Systematic study of flare statistics: flux distributions, power spectral density, flux-flux correlations.
- Neutrino emission from reconnection layers.
- Connection to large-scale jet properties: Where? How? Guide field?

**THANK YOU!**

# Back-up slides

# Plasmoid compression: a slow acceleration process

**2D** σ=10 electron-positron




**Plasma Density**

**Magnetic energy density**

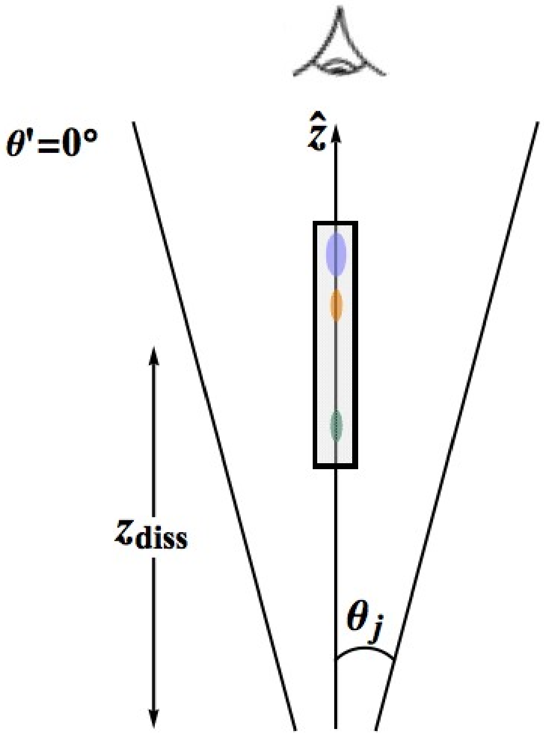
**Particle Lorentz factor**

- Acceleration within plasmoids
- Plasmoid compression and magnetic moment conservation

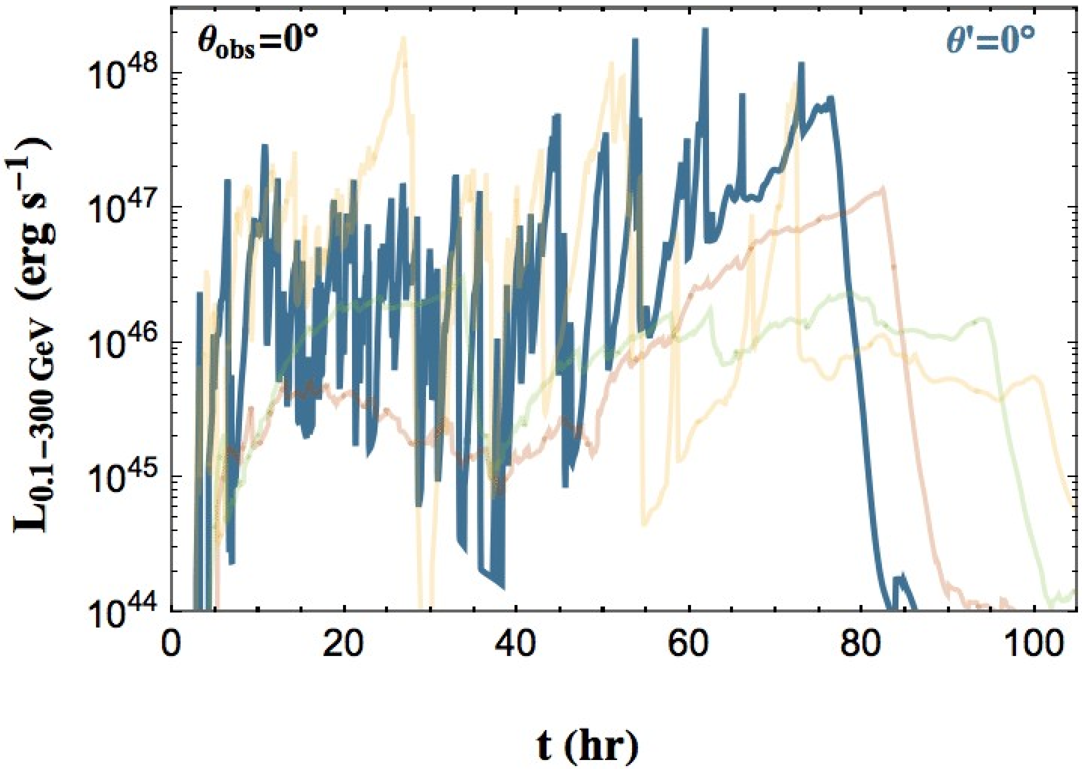
*Petropoulou & Sironi 2018*

# Effects of layer's orientation

Layer in Jet



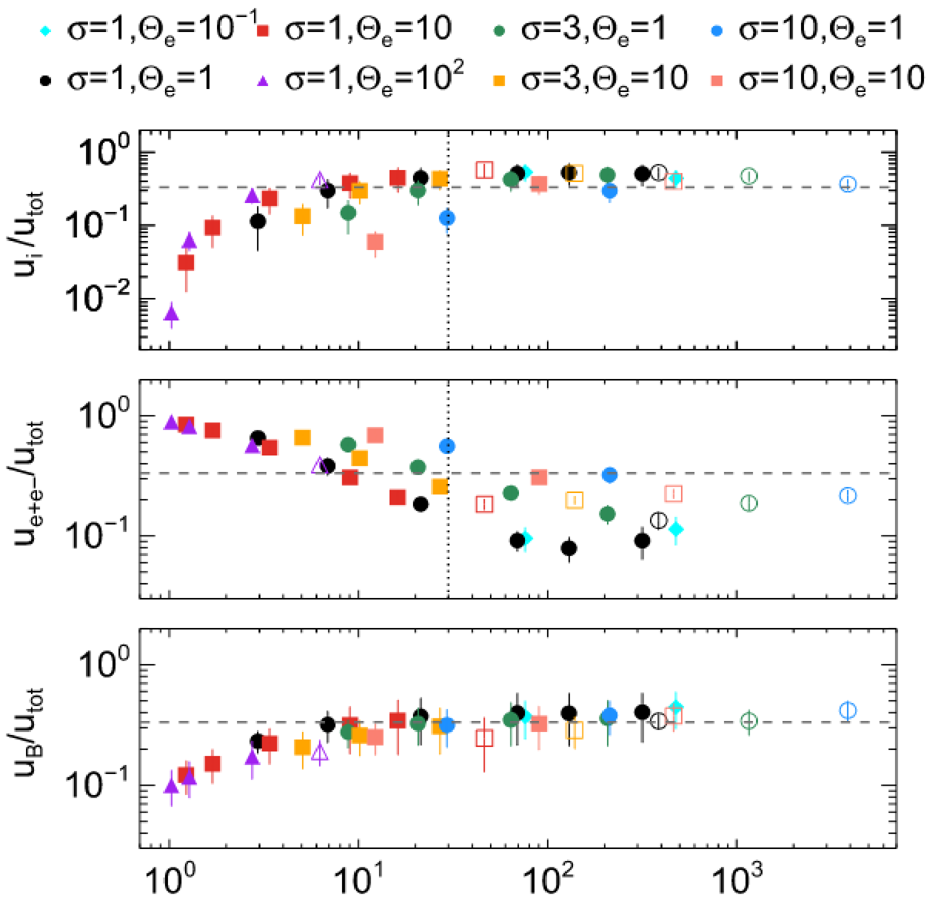

GeV light curve



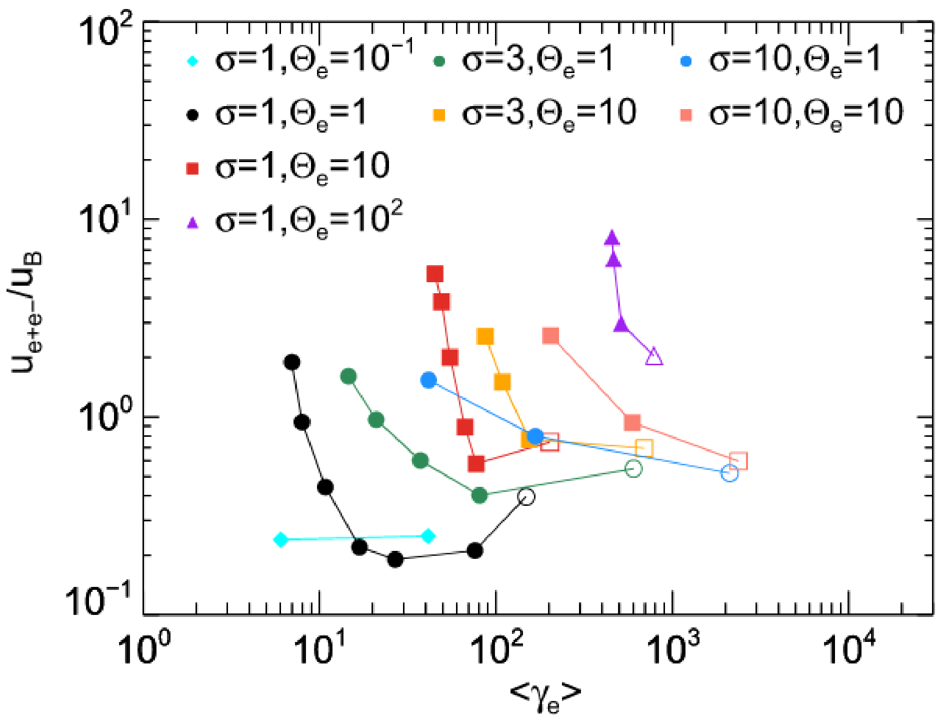

Time [hr]

*Christie et al. 2019*

# Energy equipartition in pair-proton reconnection

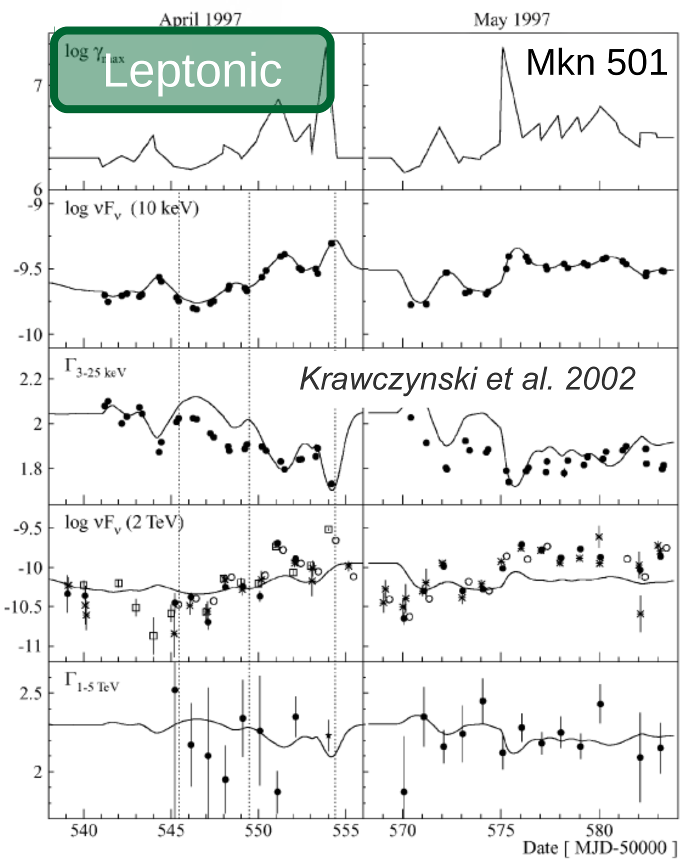


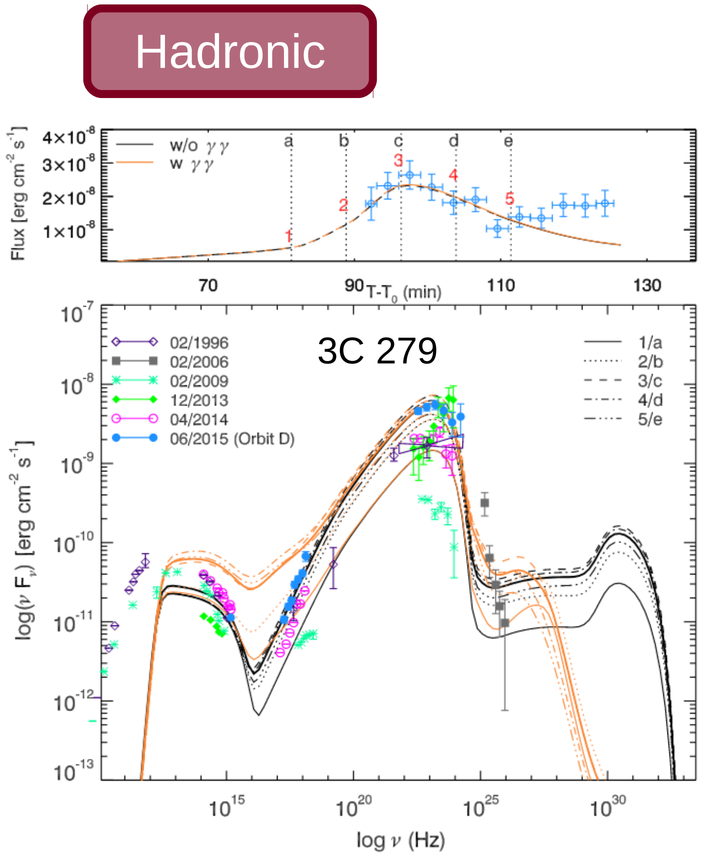

Pair-plasma magnetization defined with enthalpy ($\sigma_{e,h}$)

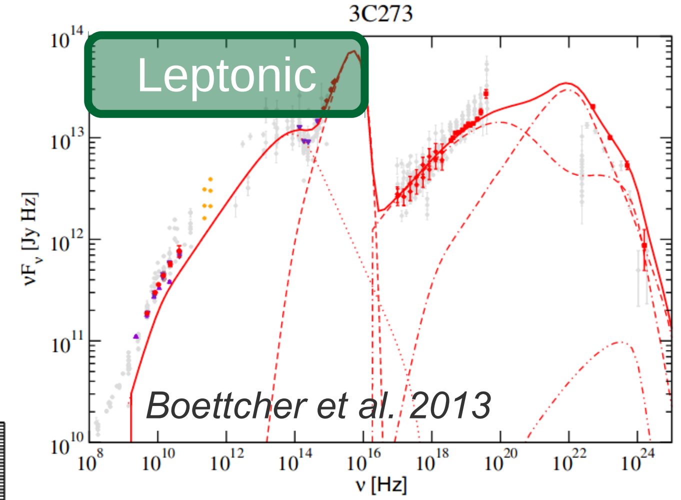


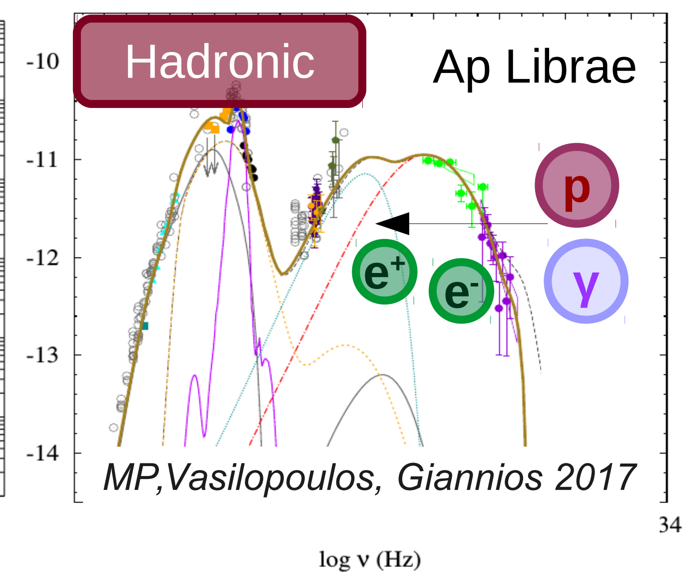
# Standard blazar SED modeling

- Both models describe equally well steady-state & time-resolved photon spectra.
- The models imply different physical conditions for the radiation zone.



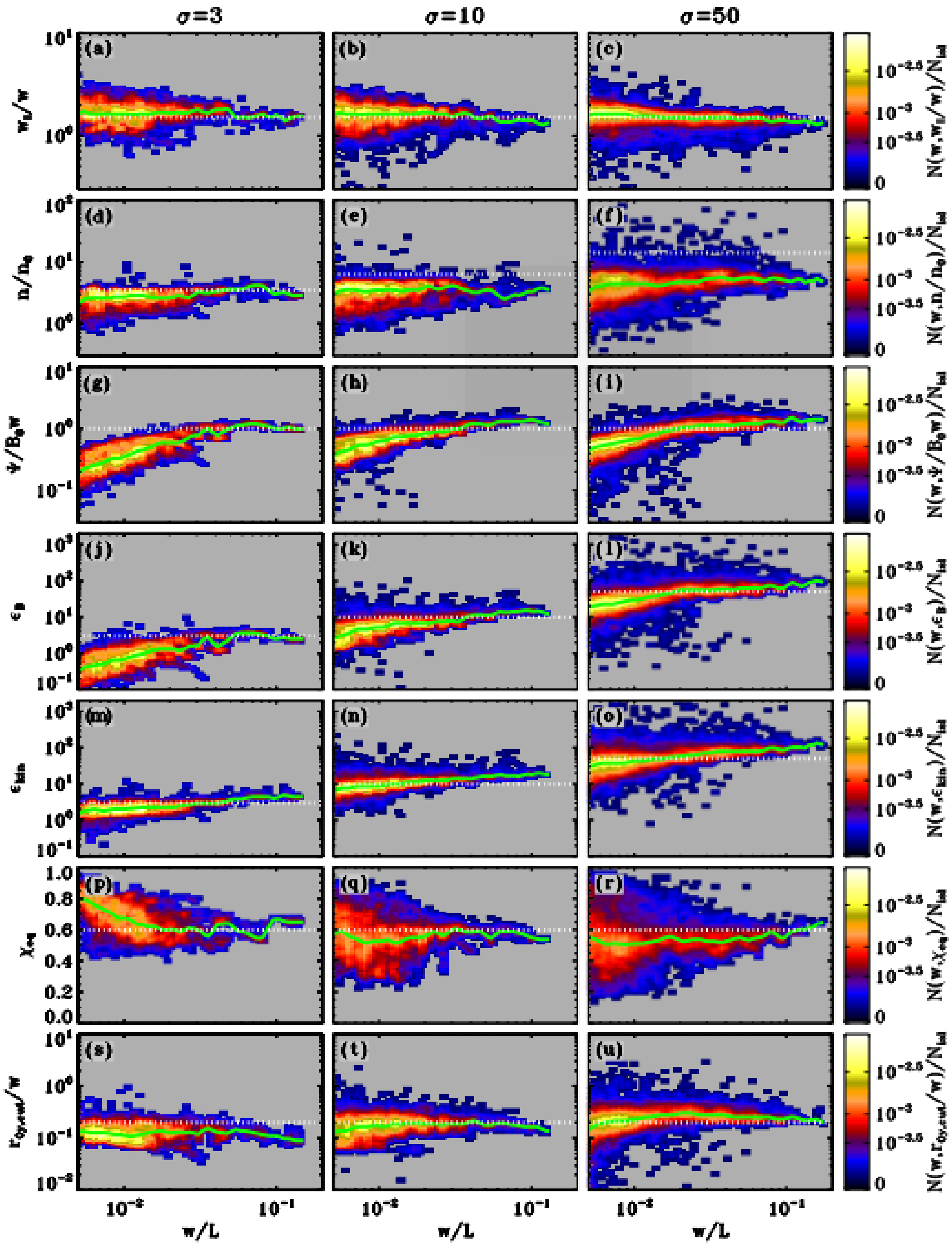






***Modeling studies***: *Krawczynski et al. 2002; Ghisellini et al. 2010; Boettcher et al. 2013; Potter & Cotter 2013; Dimitrakoudis, MP, Mastichiadis 2014; MP 2014; MP, Dimitrikoudis et al. 2015; Cerruti et al. 2015; Diltz, Boettcher & Fossati 2015; Gao et al. 2017; MP, Nalewajko et al. 2017; Cerruti et al. 2017 +++*



σ=3
σ=10
σ=50
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
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w/L