PLASMOIDS IN RELATIVISTIC RECONNECTION: THE BLOBS OF BLAZAR EMISSION?

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in collaboration with

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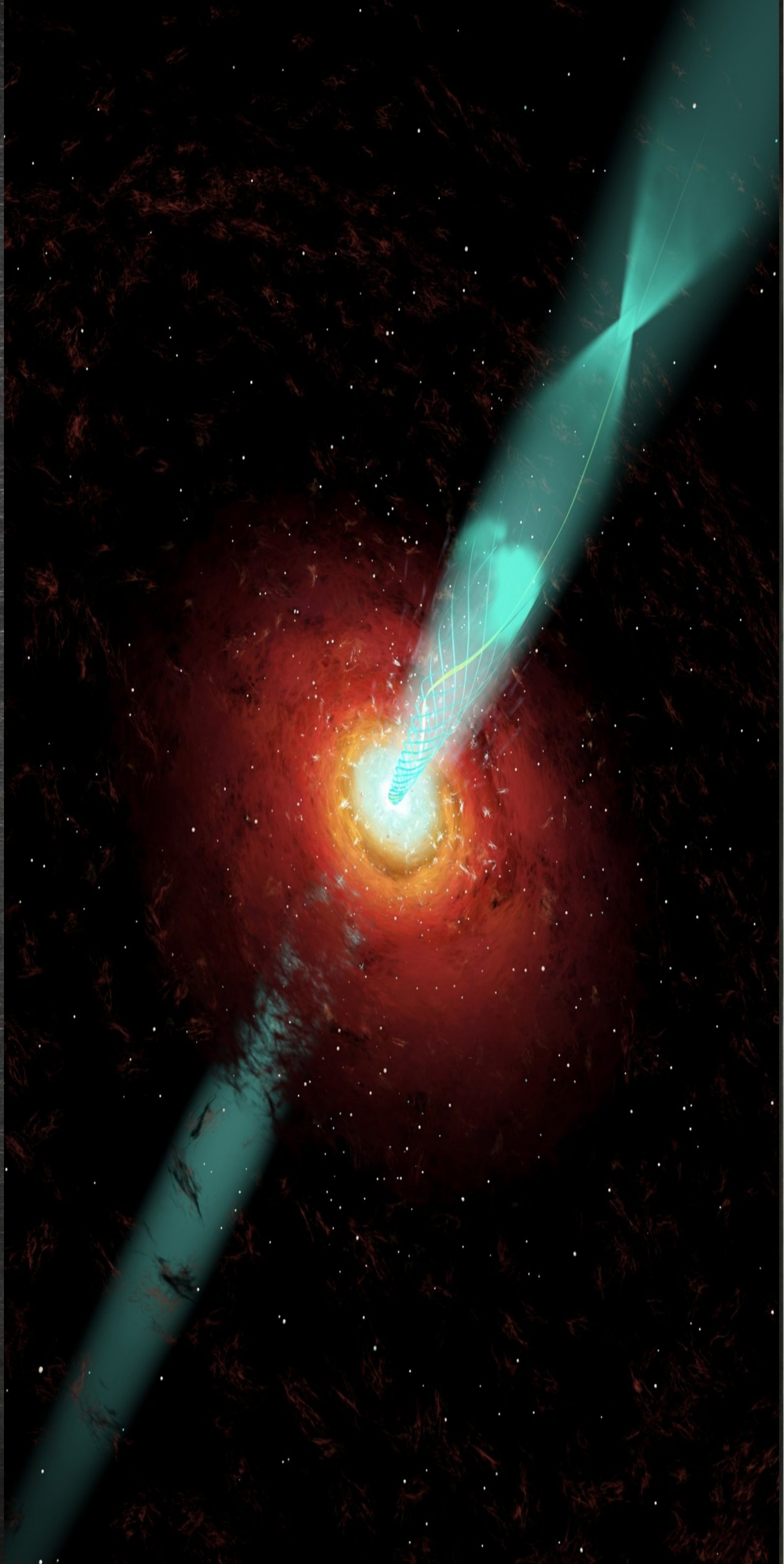
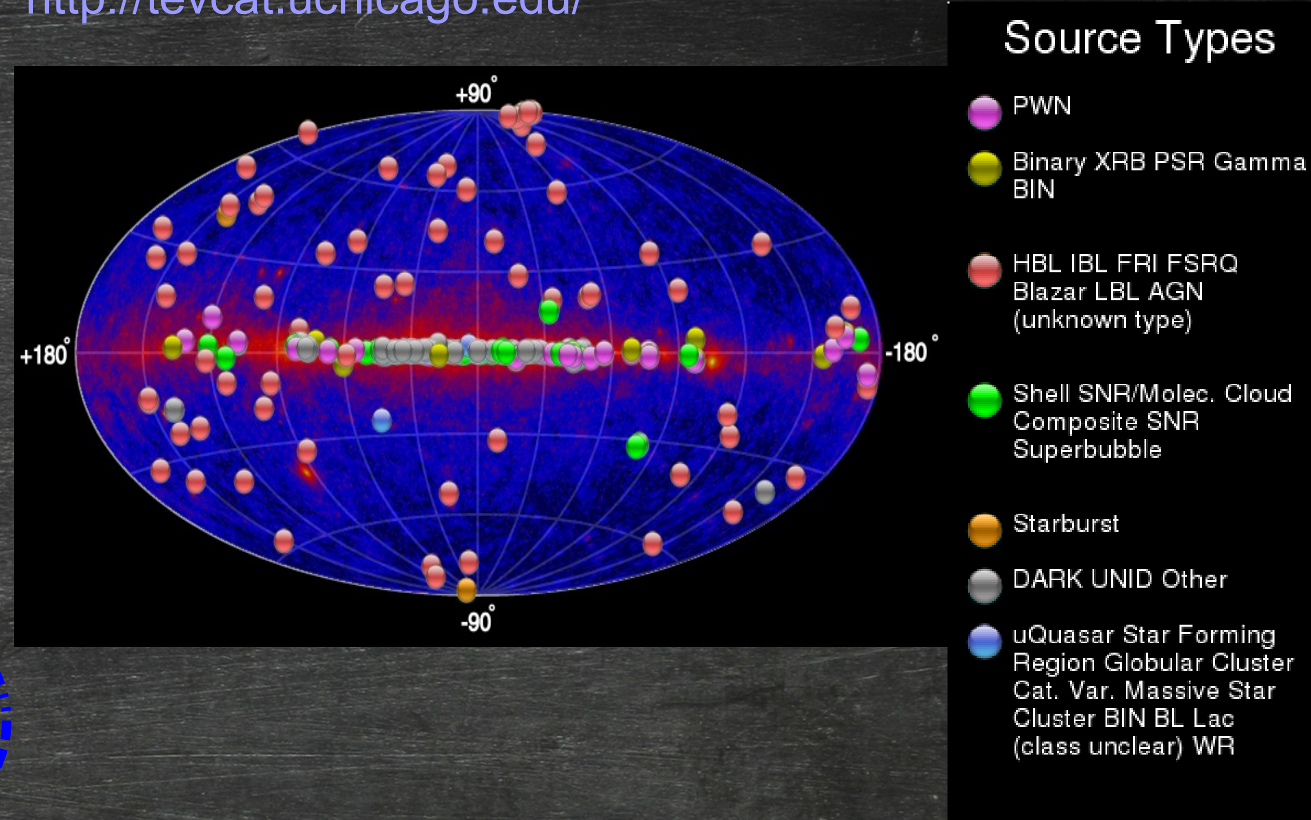
Outline

- Introduction to blazars
- Motivation
- Model setup
- Plasmoid-powered flares: timescales & spectra
- Future directions

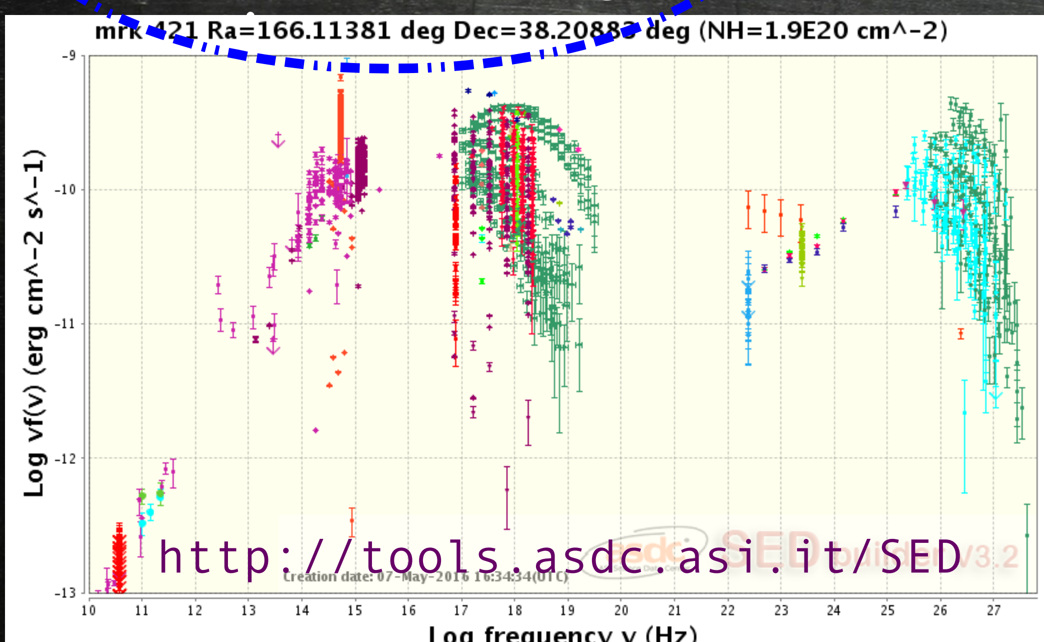


Blazars

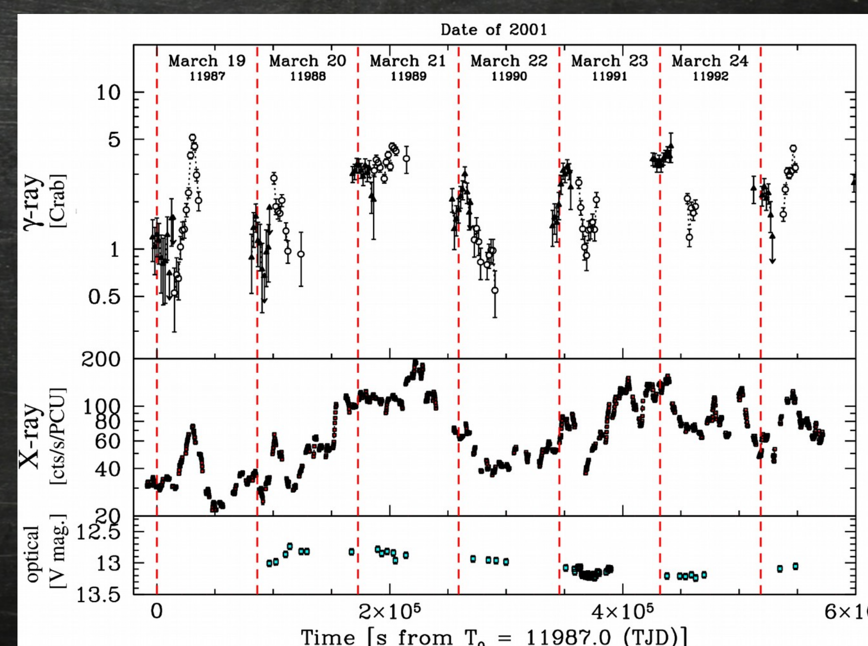
http://tevcat.uchicago.edu/



- Radio-loud AGN (< 5/% of all AGN)
- Superluminal motion
- GeV/TeV emitters
- "Double-hump" SED
- Short variability (min-hr) at high

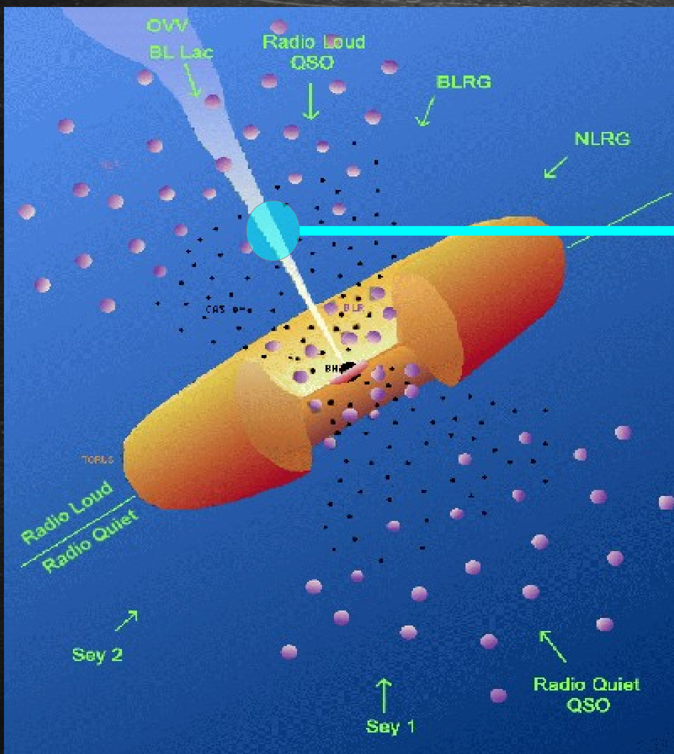


http://tools.asdc.asi.it/SED

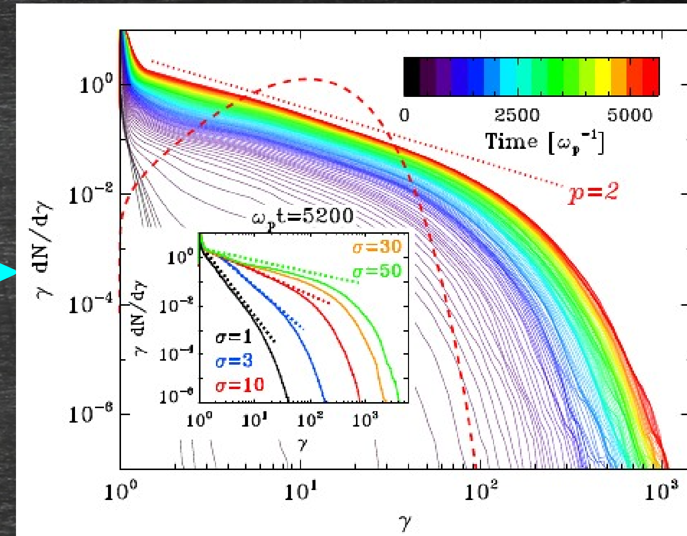


Motivation

Emitting region
Aka: The blob

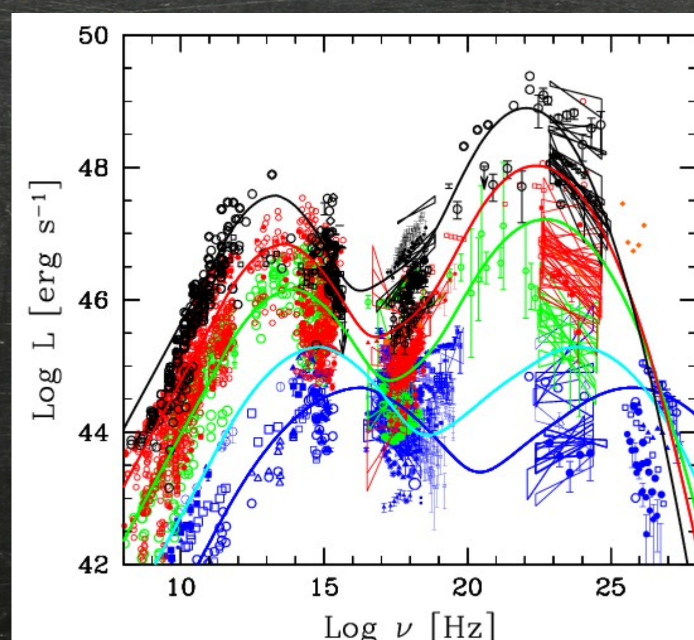


Relativistic particles



Sironi & Spitkovksy 2014

Photon emission



Fossati et al. (1998)

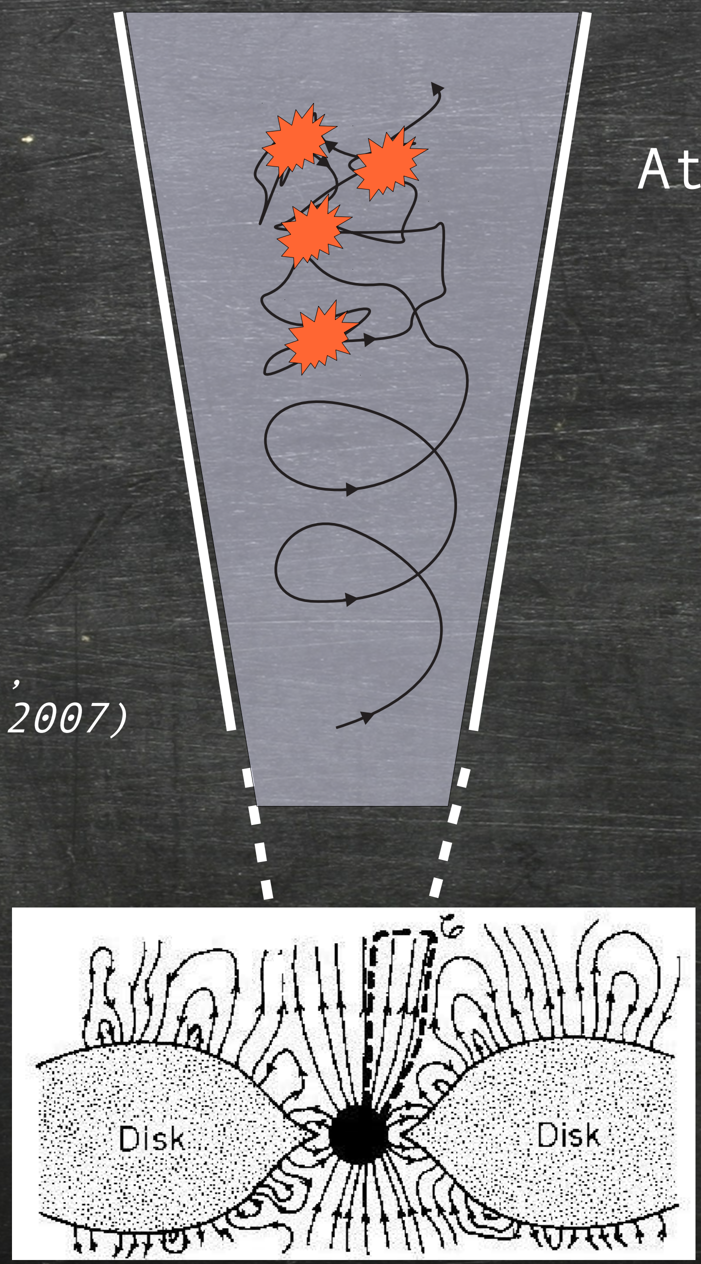
What is the physical origin of the "blob"?

Can we build an *ab initio* model for the blob and its emission?

Jet dissipation

Jet dissipation
(~ 0.1-1 pc)

At dissipation σ~1-10



Jet acceleration
(~0.001- 0.1 pc)
(e.g. Vlahakis & Koenigl, 2004; Komissarov et al. 2007)

Jet launching

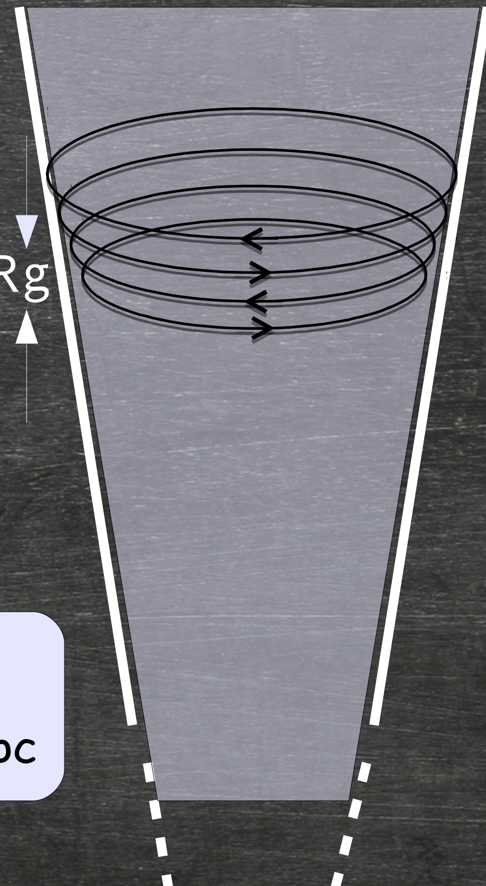
Initially σ >> 1

Magnetization σ

$$\sigma = \frac{B_0^2}{4\pi \rho c^2}$$

Jet dissipation

- The jet may contain field reversals with a scale ~100 Rg

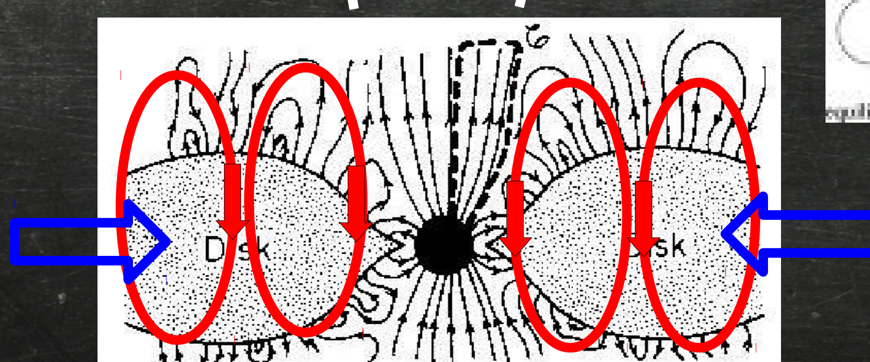


- Magnetic field lines may reconnect if: $t_{exp} \sim t_{rec}$

$$r_{diss} / \Gamma_j c \sim 100 \Gamma_j R_g / \varepsilon c$$

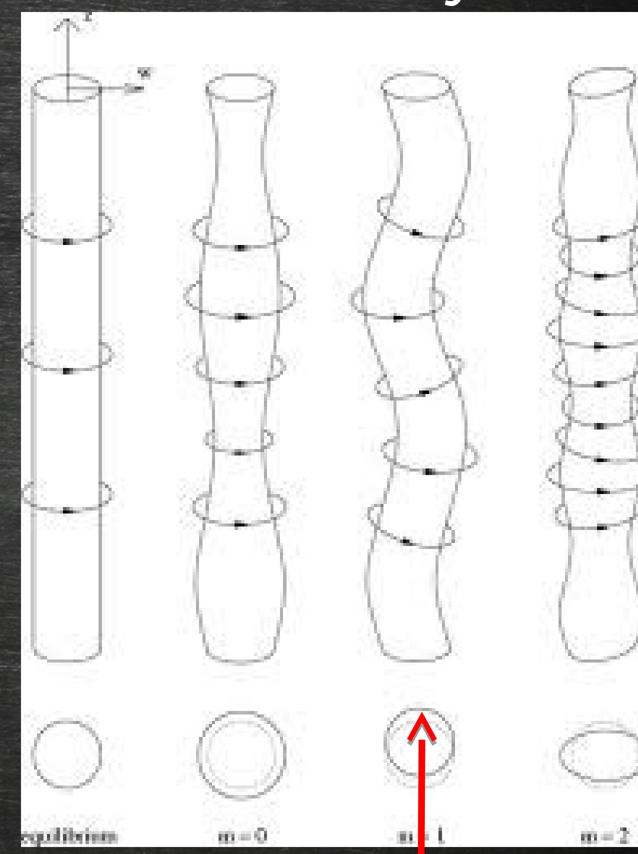
$$r_{diss} \sim \Gamma_j^2 100 R_g / \varepsilon \sim 1 M_8 \Gamma_{j,10}^2 \varepsilon_{-1}^{-1} \text{ pc}$$

$v_{rec} \sim \epsilon c \sim 0.1\ c$



Parfrey, Giannios, Beloborodov, 2015, MNRAS

Magnetized jets may be prone to the kink instability



kink instability

(e.g. Eichler 1993; Begelman 1998; Giannios & Spruit 2006; Porth & Komissarov 2015)

Magnetic reconnection

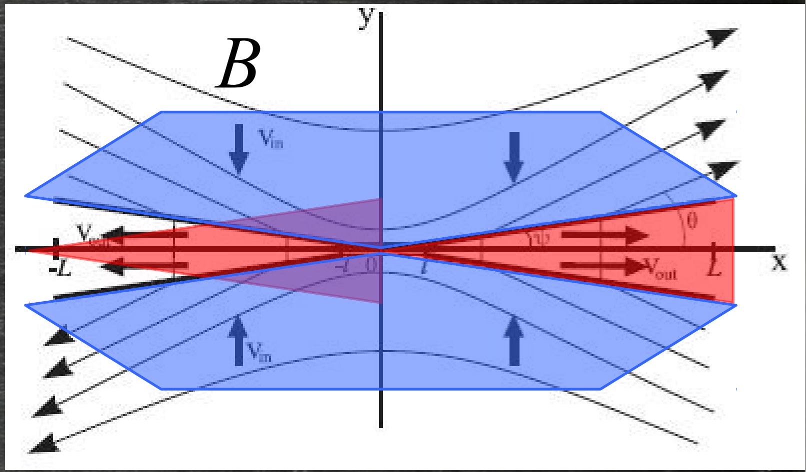
It converts magnetic energy into bulk motion, heat, energetic particles

1. Cold, magnetized plasma enters the reconnection region

2. Plasma leaves the reconnection region at the Alfvén speed $\Gamma_{out} \sim (1+\sigma)^{1/2} > 1$

3. Reconnected material contains energetic (non-thermal) particles

Petschek Reconnection (Lyubarsky 2005)

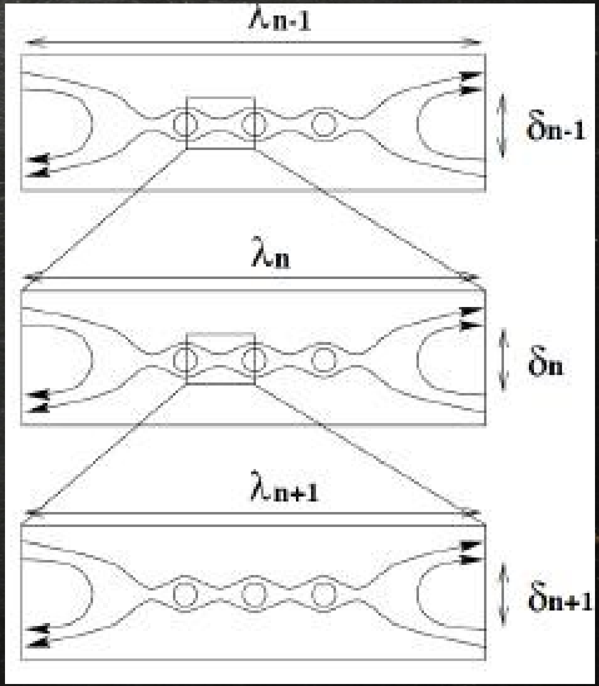


Plasmoid-dominated reconnection

1. Current sheet fragments to **plasmoids** (*Loureiro et al. 2007; Uzdensky et al. 2010; Loureiro et al. 2012 +*)

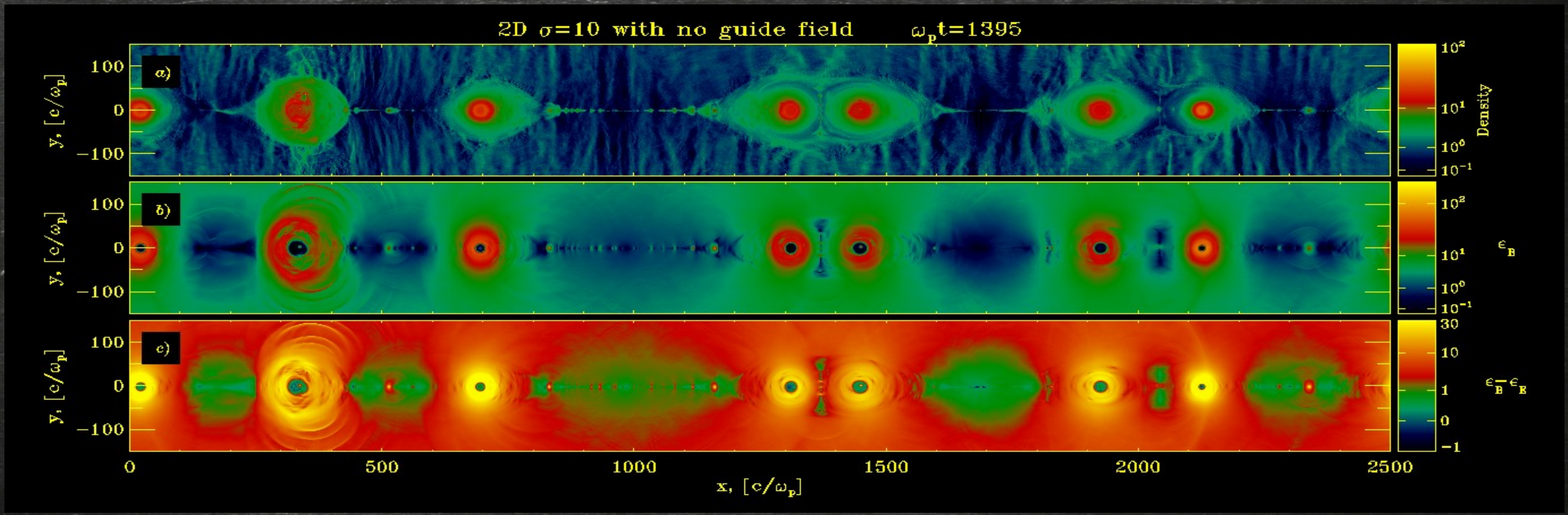
2. Plasmoids "grow" (merge) and leave the layer at Alfvén speed ~c

3. The largest plasmoids can power bright/ultrafast blazar flares (*e.g. Giannios et al. 2009; 2010; Giannios 2013*)



Plasmoid-dominated reconnection

(Zenitani & Hoshino 2001, Loureiro+2007, Bhattarjee+2009, Uzdensky+2010, Loureiro+2012, Guo+2014;2015, Sironi & Spitkovsky 2014, Werner+2016)

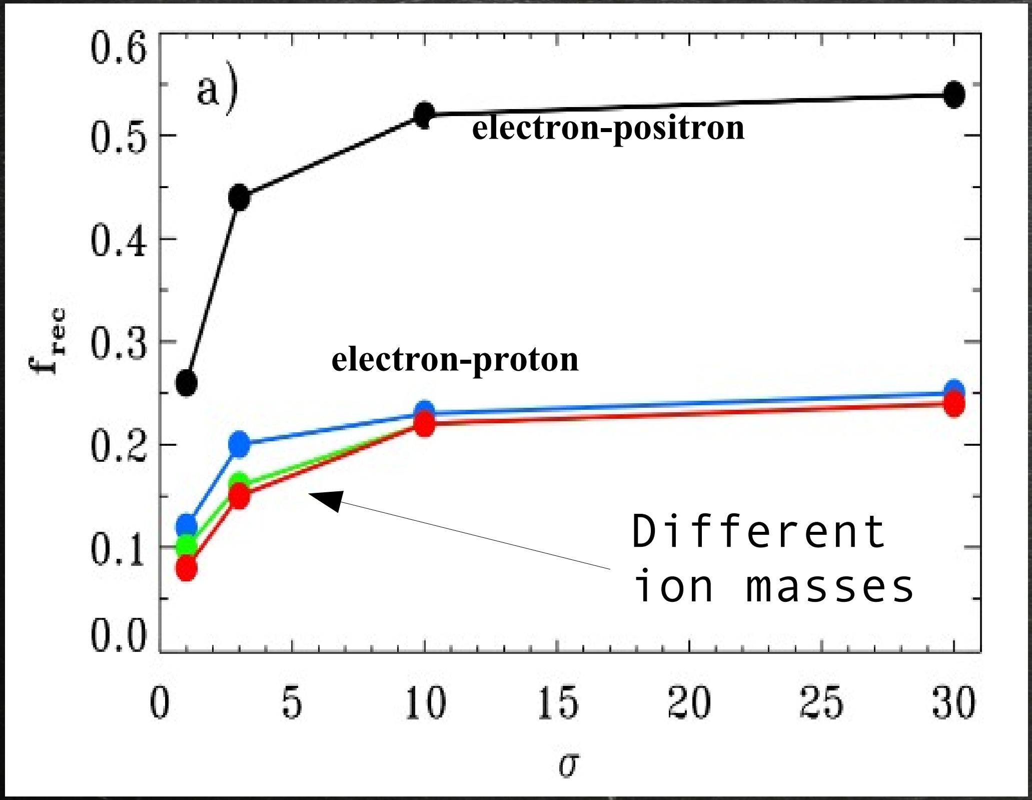


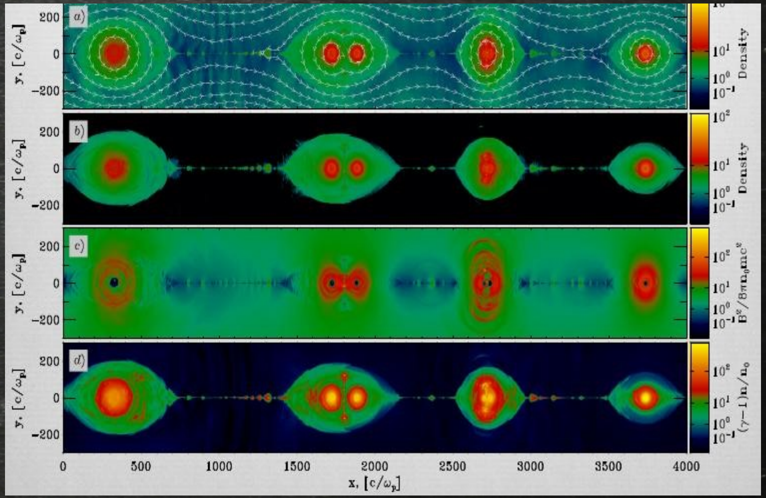
Why?

Efficiency

It transfers ~ 50% of the flow energy (electron-positron plasmas) or ~ 25% (electron-proton) to the emitting particles

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





Sironi, Petropoulou & Giannios 2015

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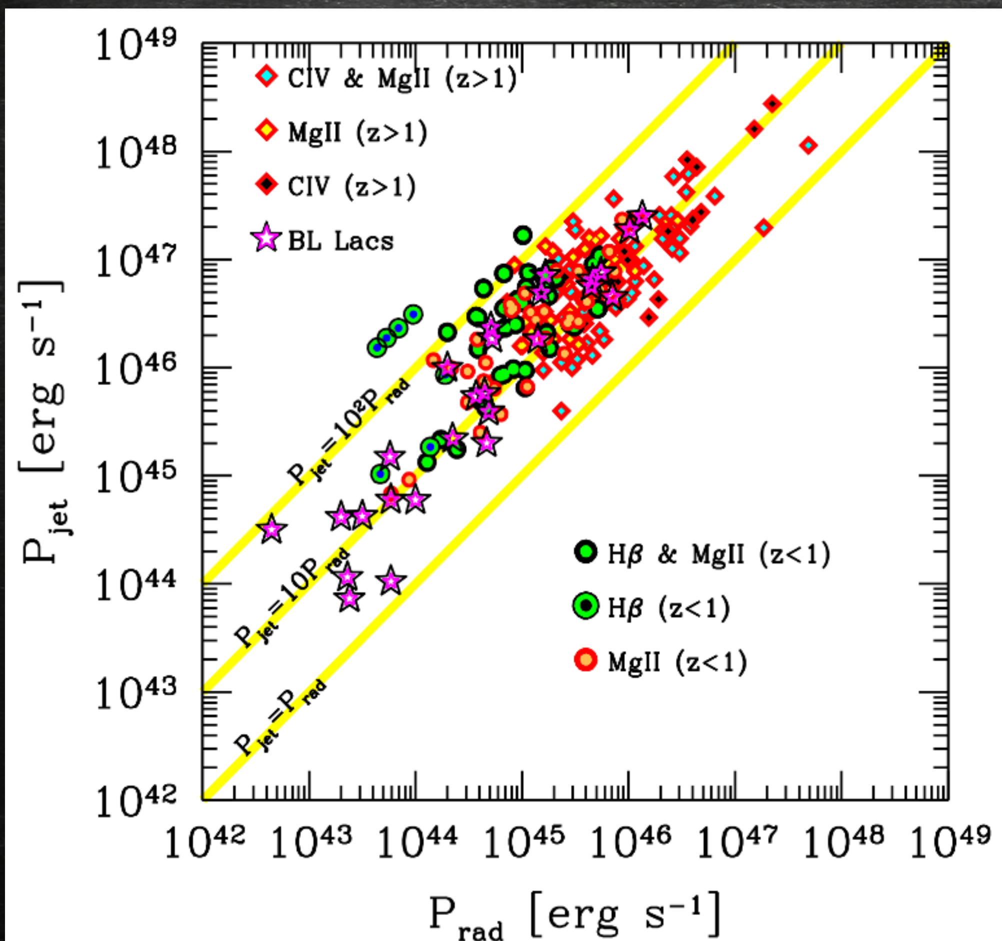

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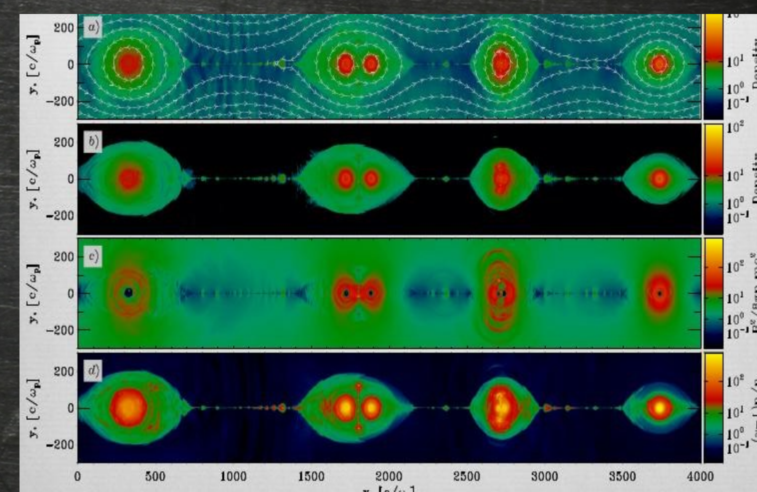
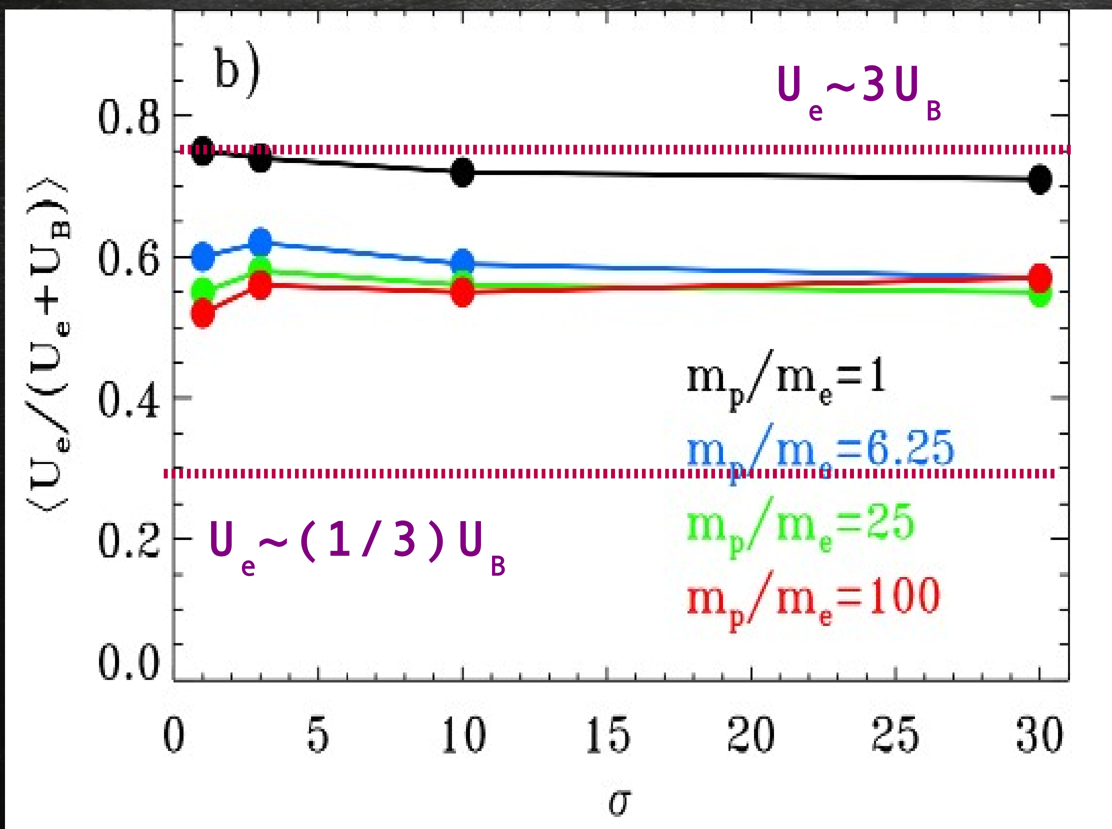


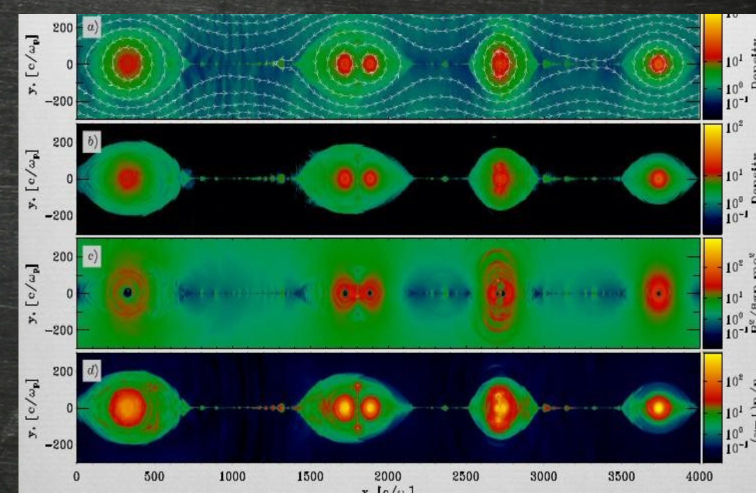
Ghisellini et al. 2014

Equipartition

It leads to rough equipartition between the particles and magnetic fields in the plasmoids

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





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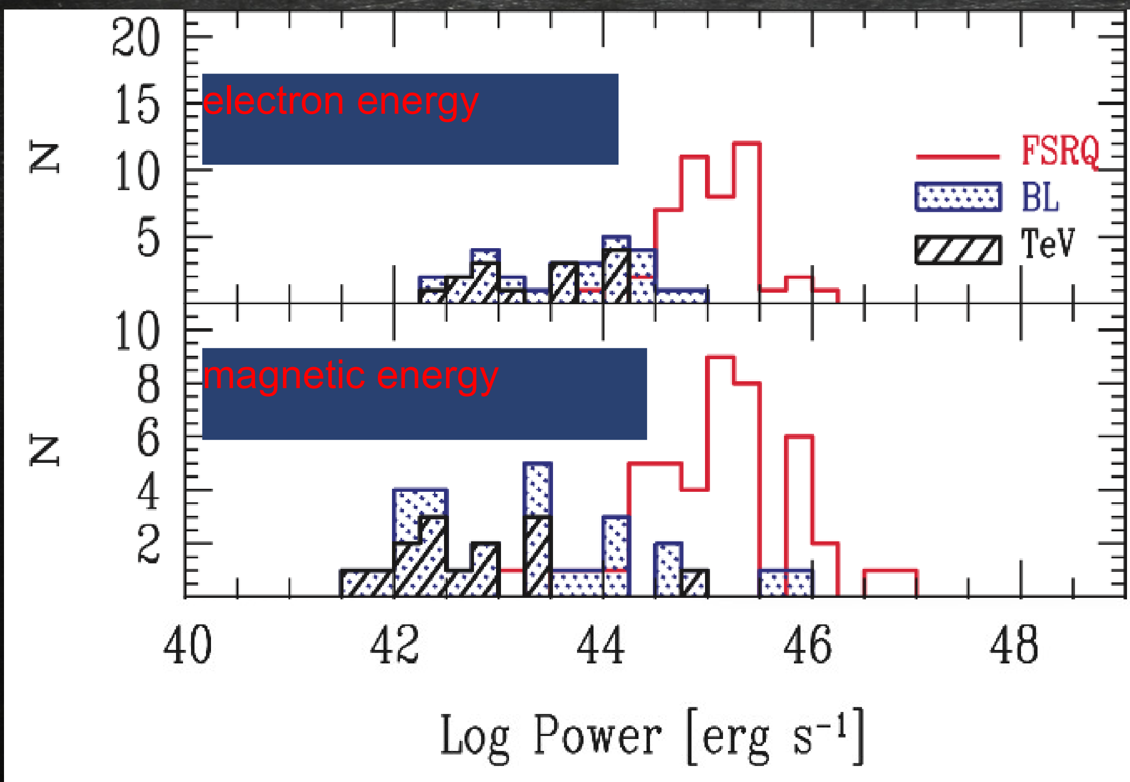
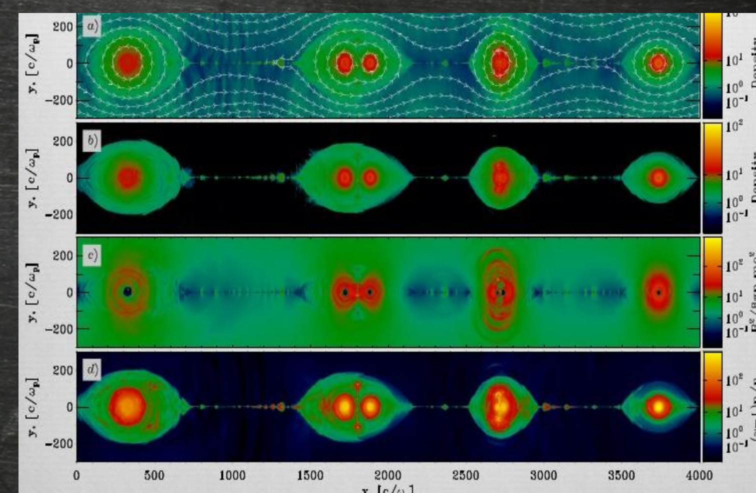
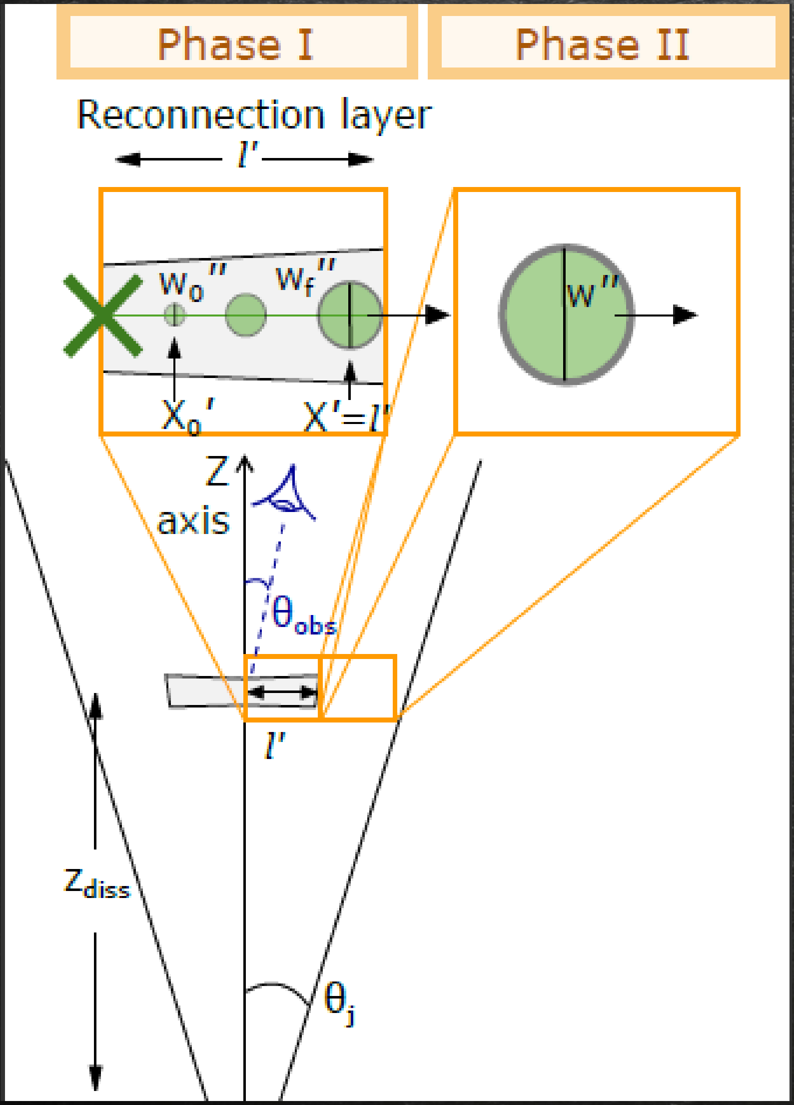




(Celotti & Ghisellini 2008)

A model for blazar flares

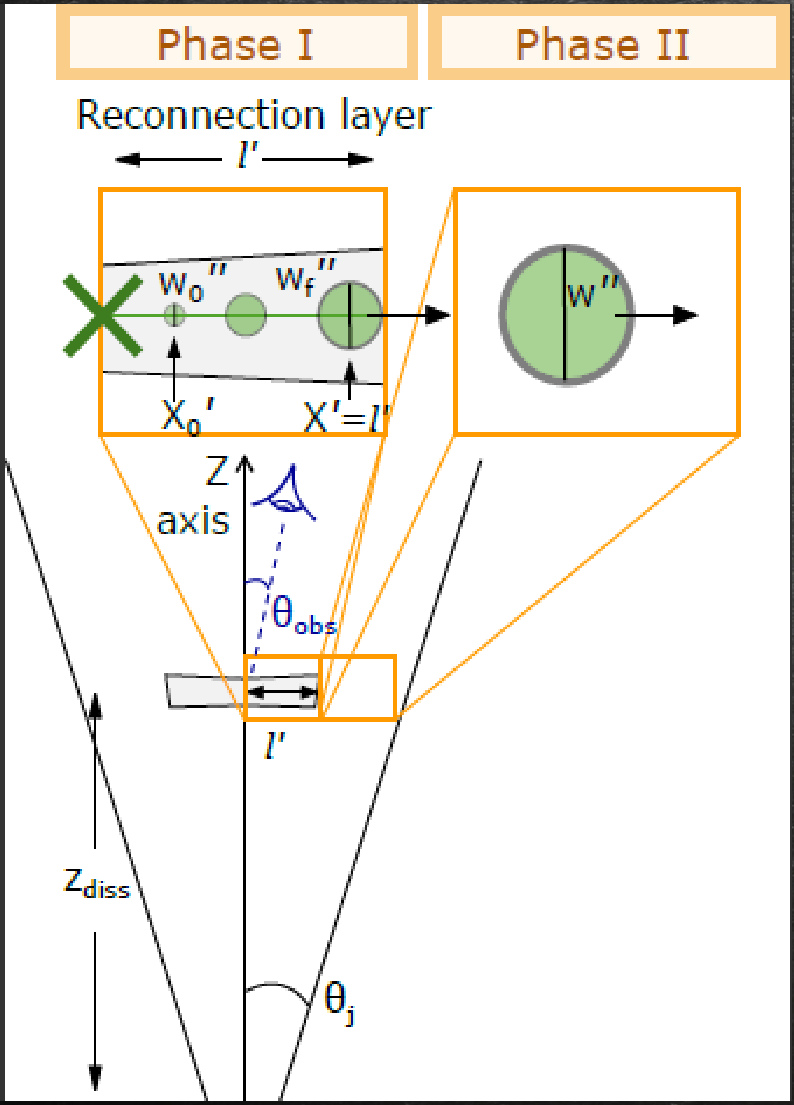
(Petropoulou, Giannios, Sironi 2016)



Phase I:

- Plasmoids are quasi-spherical structures
- Plasmoids grow through mergers and accumulate particles. Growth speed ~ 0.06c-0.12c for σ=3-50
- Plasmoids accelerate while smaller. Acceleration rate is ~0.12-0.15 independent of σ
- Comoving particle density & B-field ~ constant
- Particle distribution ~ isotropic in larger plasmoids

A model for blazar flares



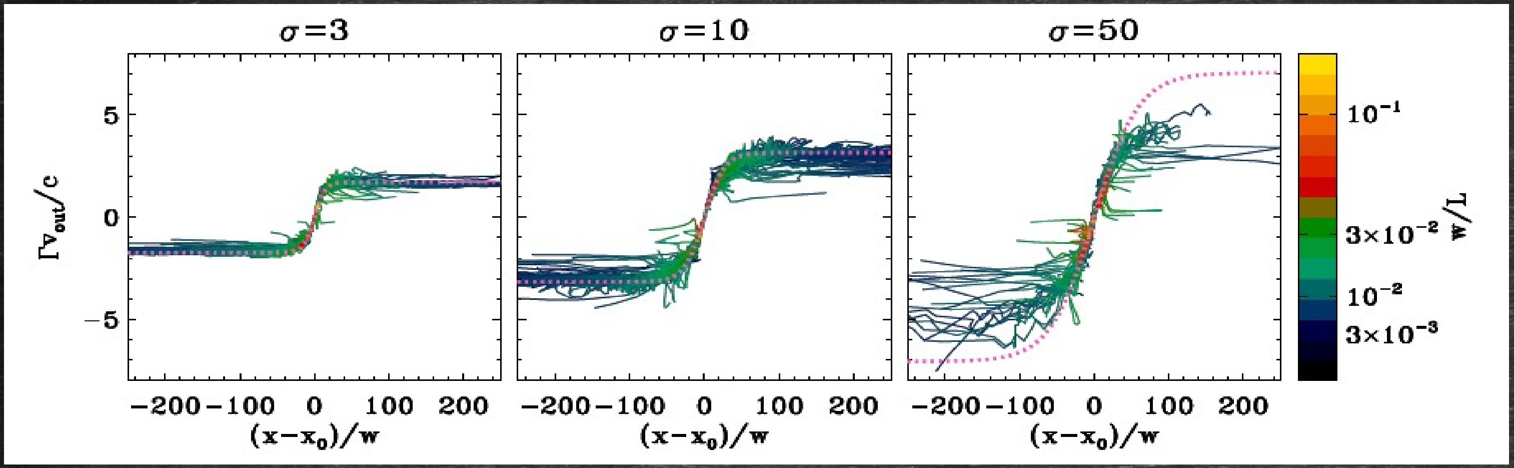
Phase II:

- Gradual cessation of accelerated particles
- Plasmoids expand due to e.g. an under-pressure outside the layer
- Comoving B-field decays

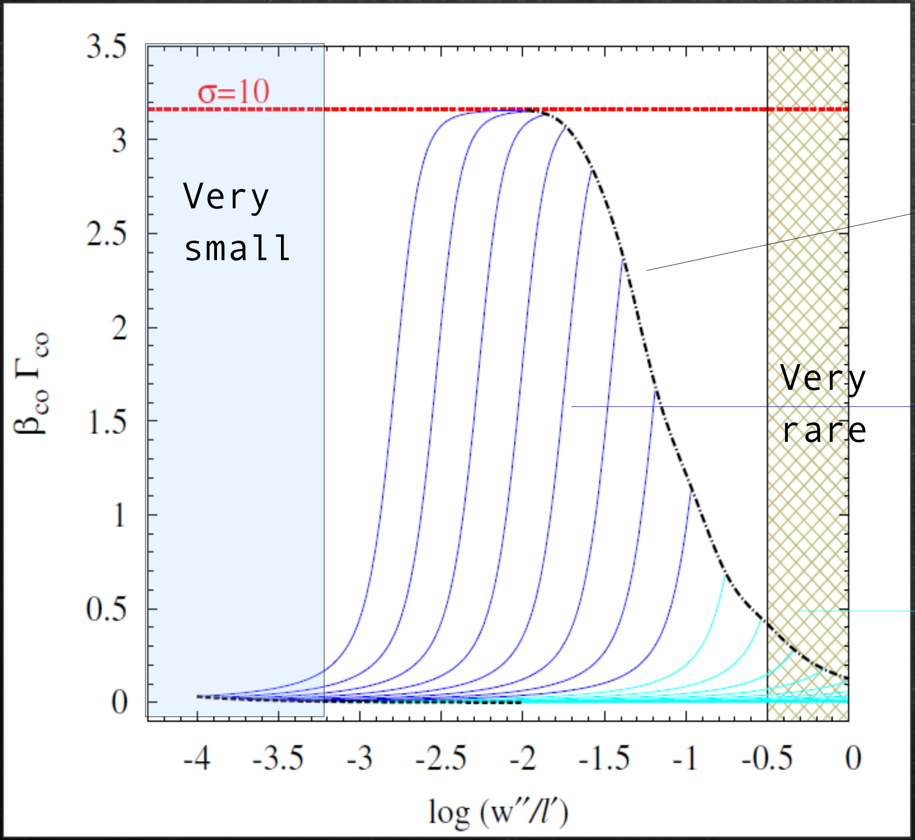
Phase II is poorly constrained from PIC simulations

Phase I is well constrained from PIC simulations.

Plasmoid momentum: an example



(Sironi, Giannios, Petropoulou 2016)



Exit (final)

Blue: small & relativistic

Cyan: large & non-relativistic

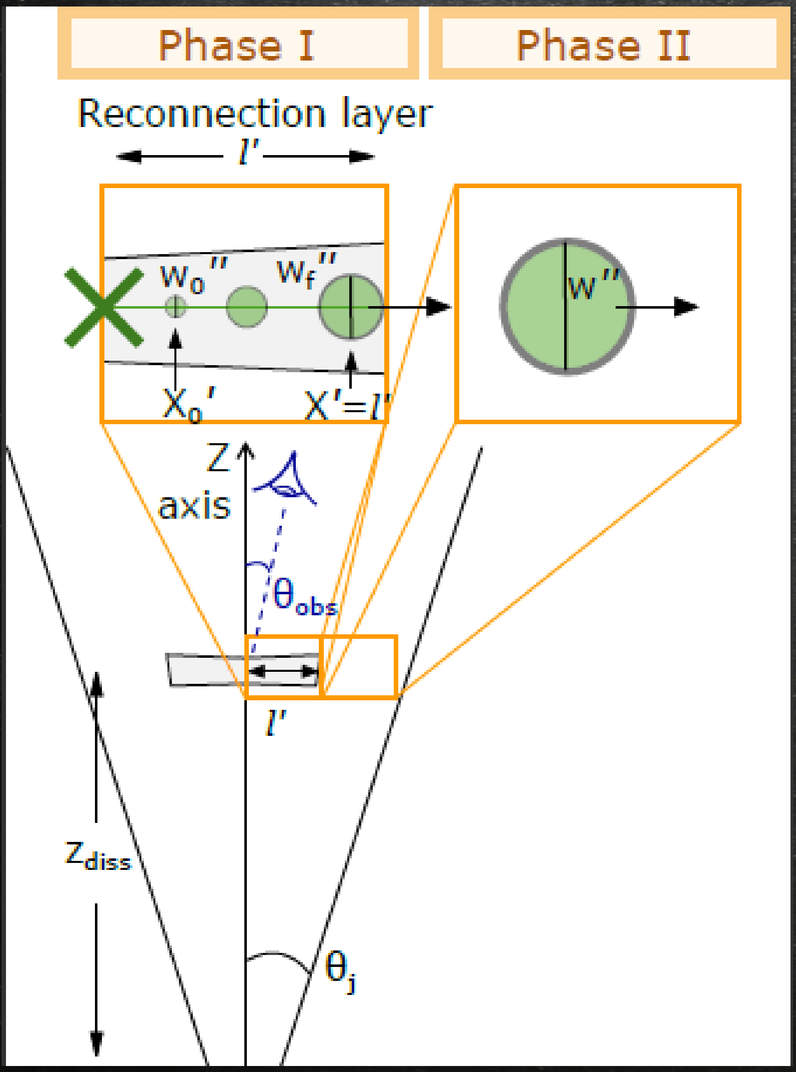
Doppler factor

Ratio δ_p / δ_j

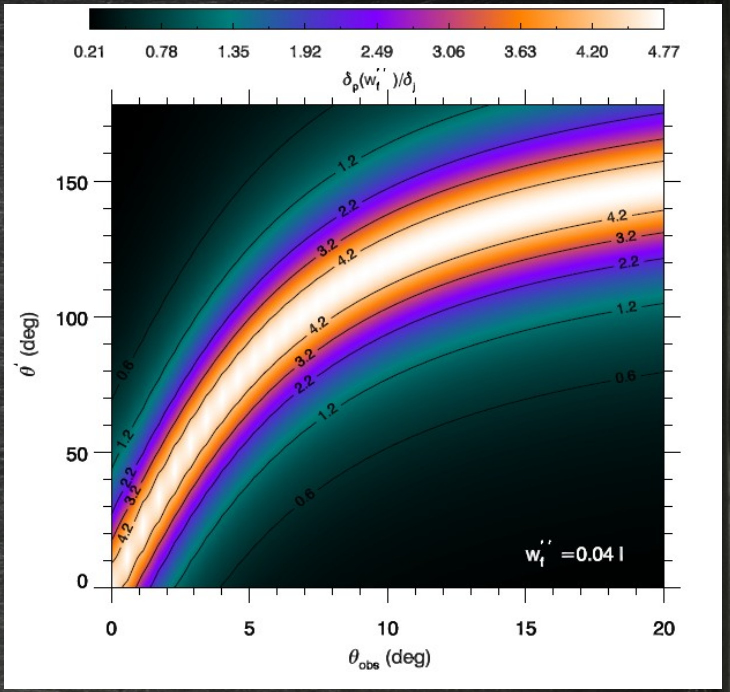
Plasmoid vs. Jet

$$\delta_p = \frac{1}{\Gamma_p \left(1 - \beta_p \cos\omega\right)}$$

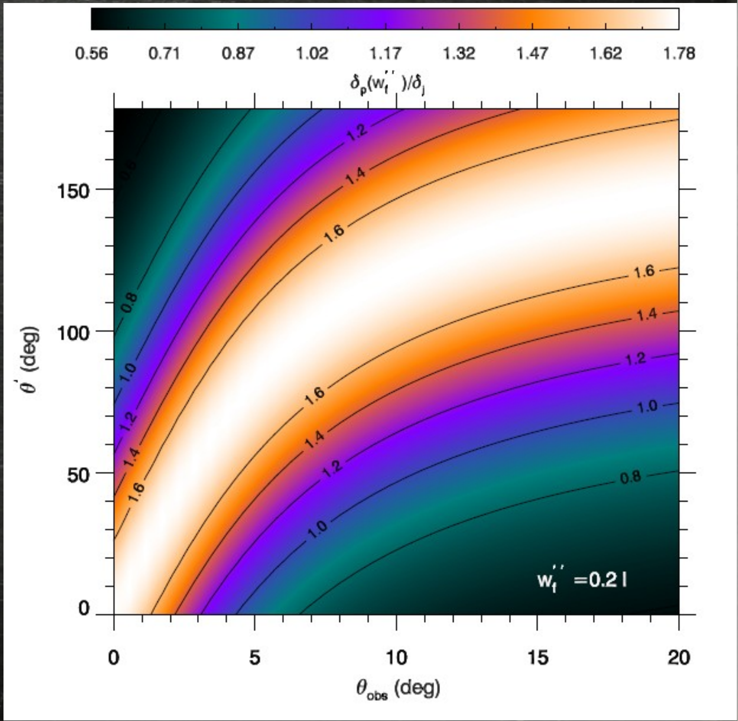
$$\delta_j = \frac{1}{\Gamma_j \left(1 - \beta_j \cos\theta_{obs}\right)}$$



Small & Fast →

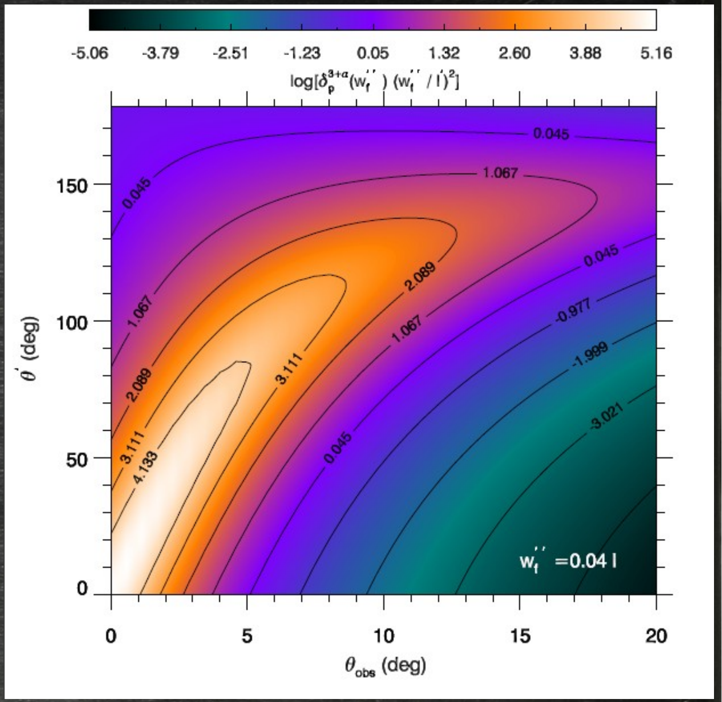


Large & Slow →



Peak luminosity

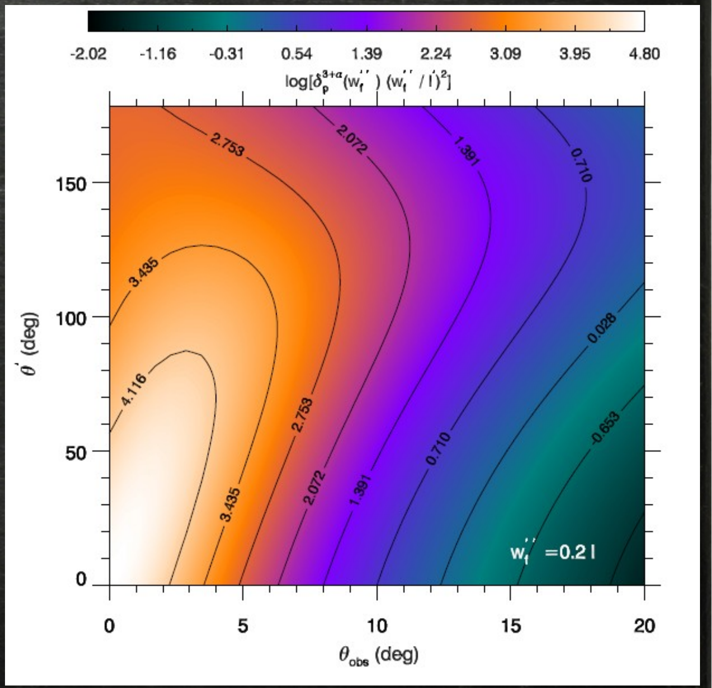
Small & Fast →



Luminosity depends on:

- Total number of radiating particles in the plasmoid
- Size w of the plasmoid
- Doppler factor of the plasmoid

Large & Slow →



Peak luminosity at end of Phase I:

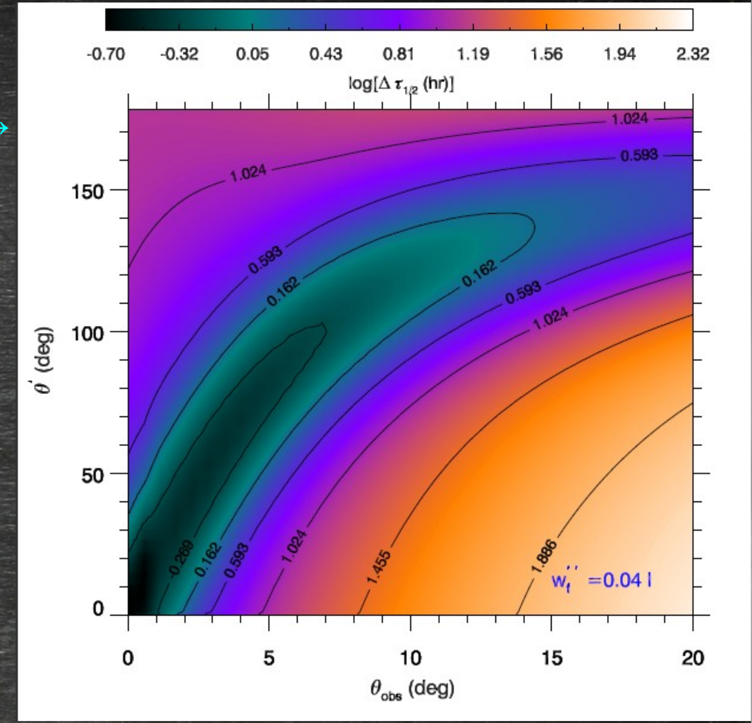
- Final size w_f of the plasmoid
- Final momentum (acceleration has been completed)

$$L^{\rm pk}(\nu) \propto \left[\delta_{\rm p}(w_{\rm f}'')\right]^{3+\alpha} w_{\rm f}''^{2}$$

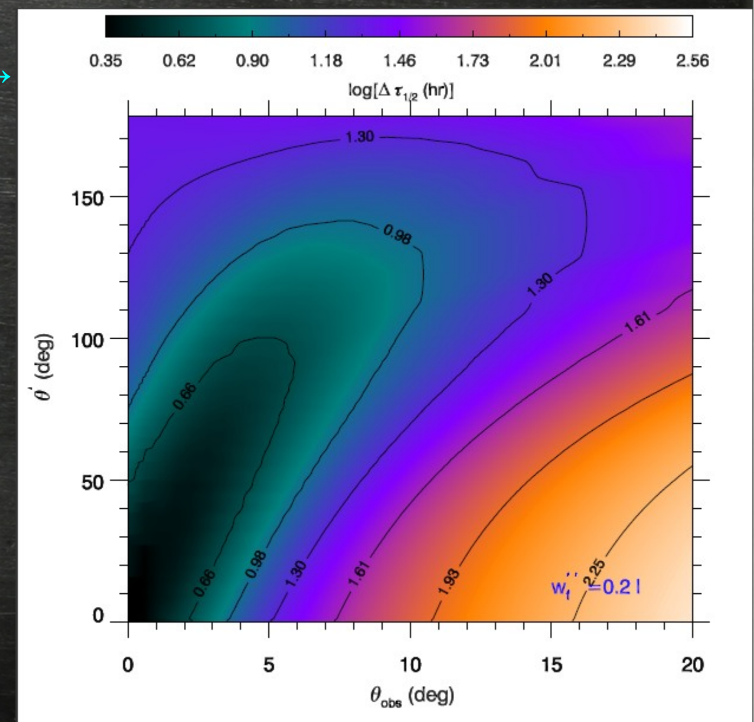
Flux-doubling timescale

$$\Delta\tau_{1/2}(1+z)^{-1} = \int_{w''_{1/2}}^{w''_{\rm f}} \frac{d\tilde{w}}{\delta_{\rm p}(X/\tilde{w})}$$

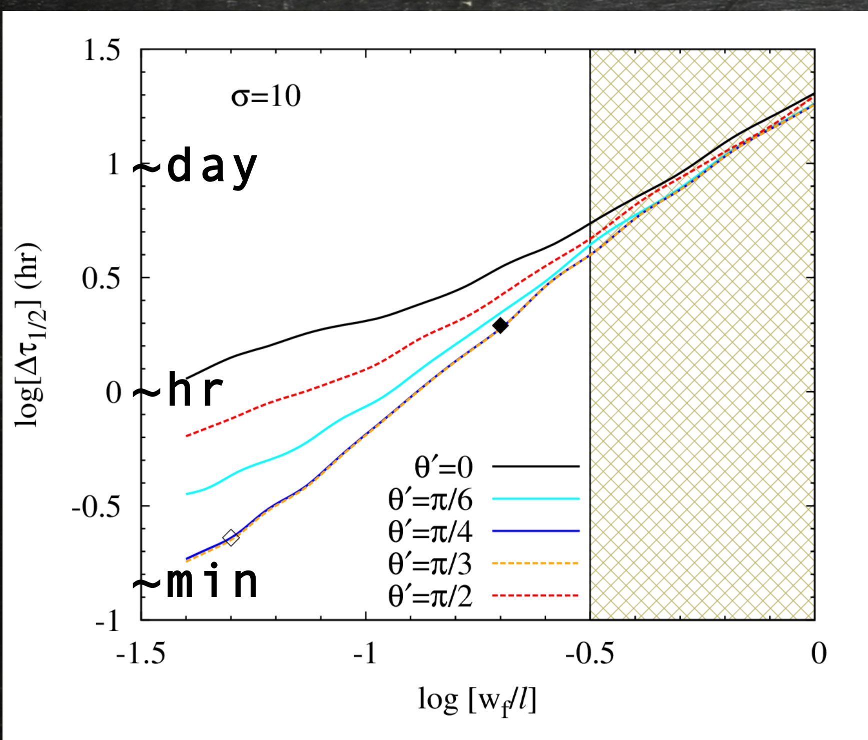
Small & Fast →



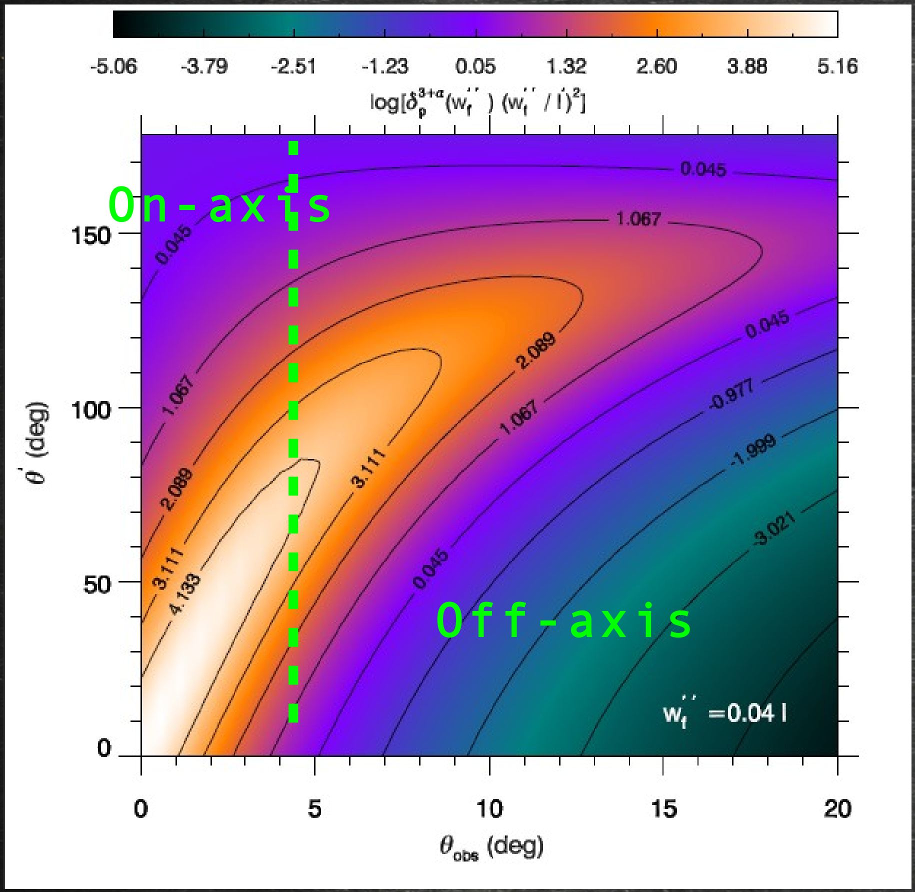
Large & Slow →

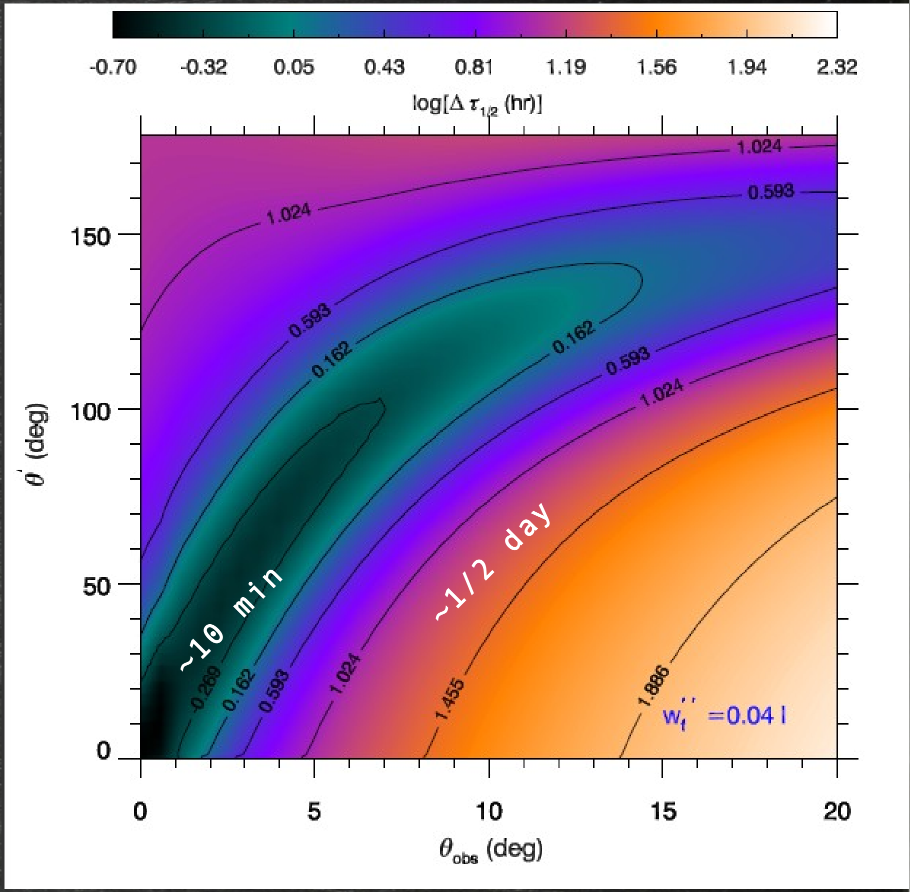


Fixed viewing angle



Peak luminosity vs. risetime



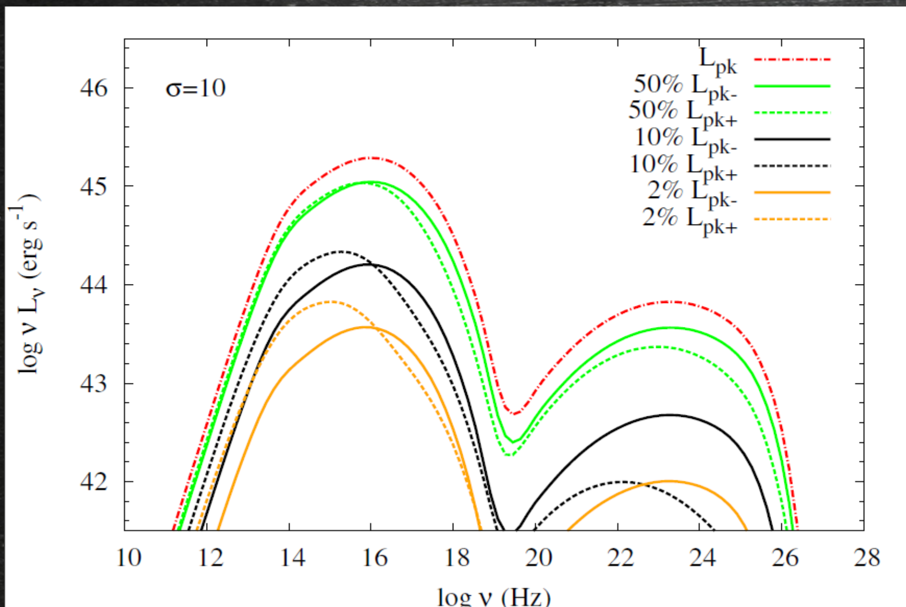


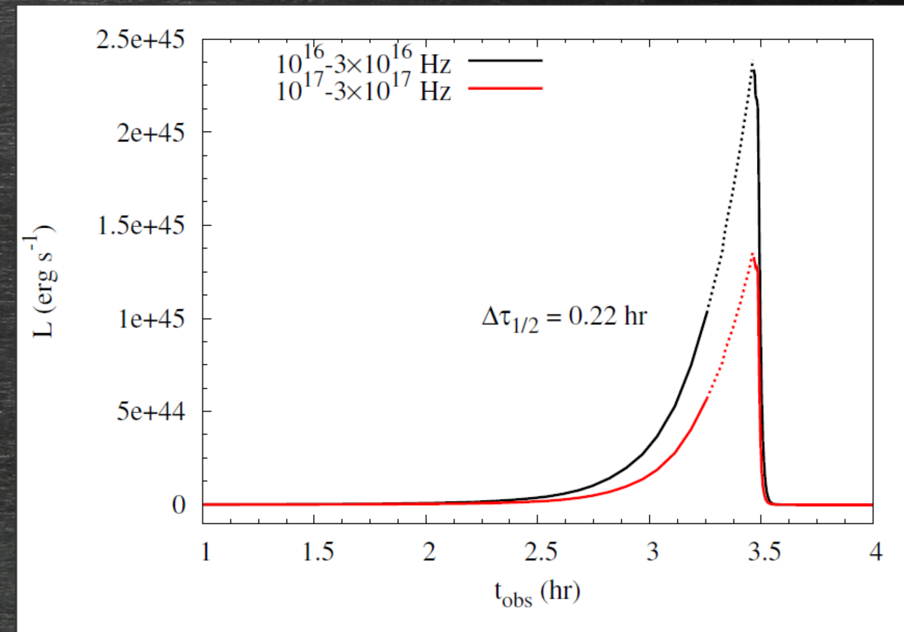
For a given plasmoid there is a clear anticorrelation between Lpk and $\Delta t_{1/2}$:

The brighest flares have the shortest $\Delta t_{1/2}$

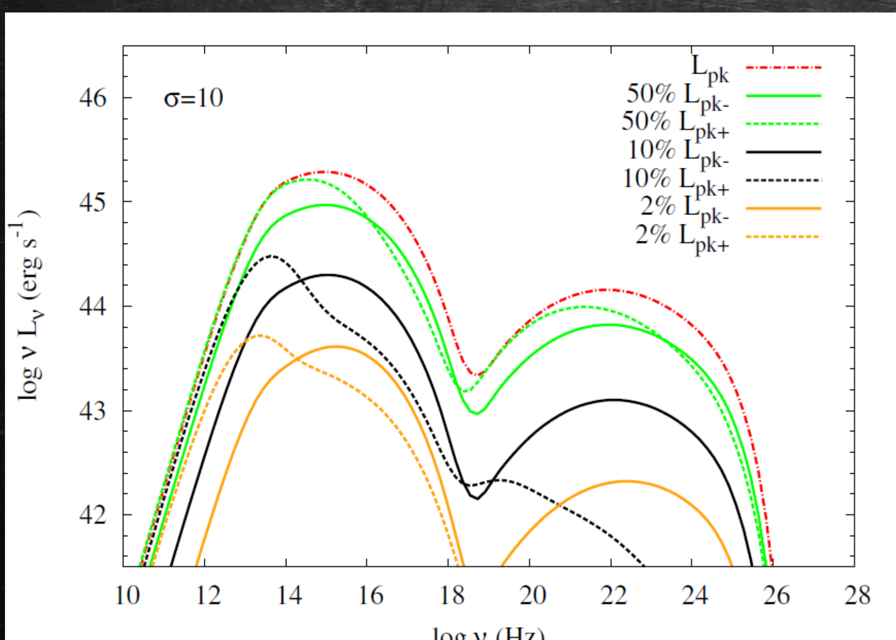
SED & light curves

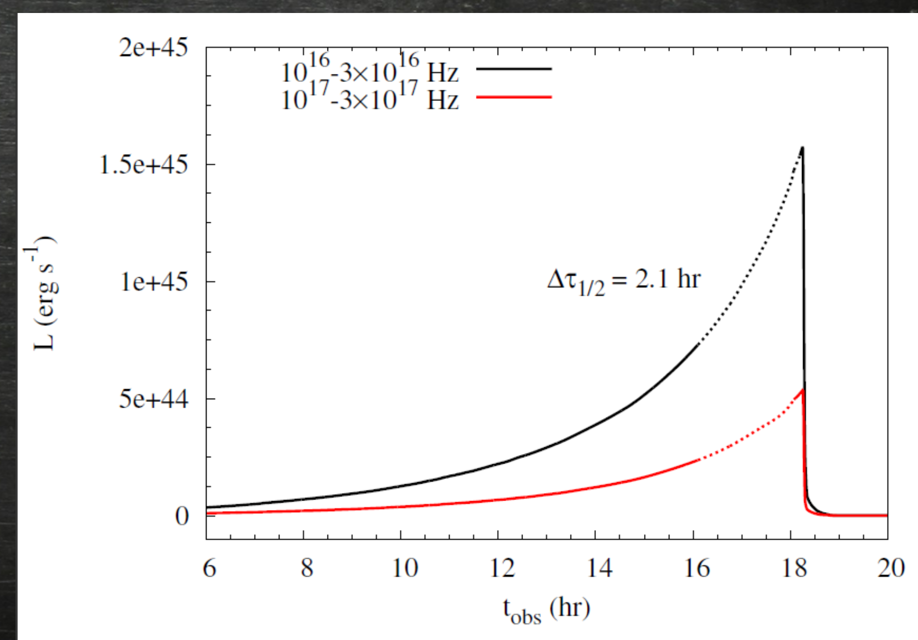
Small & Fast





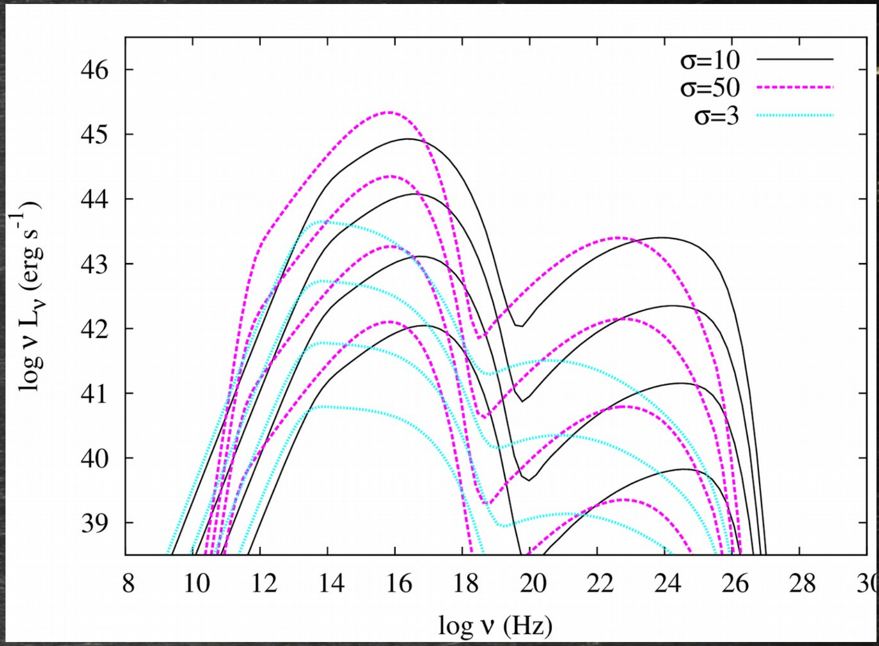
Large & Slow

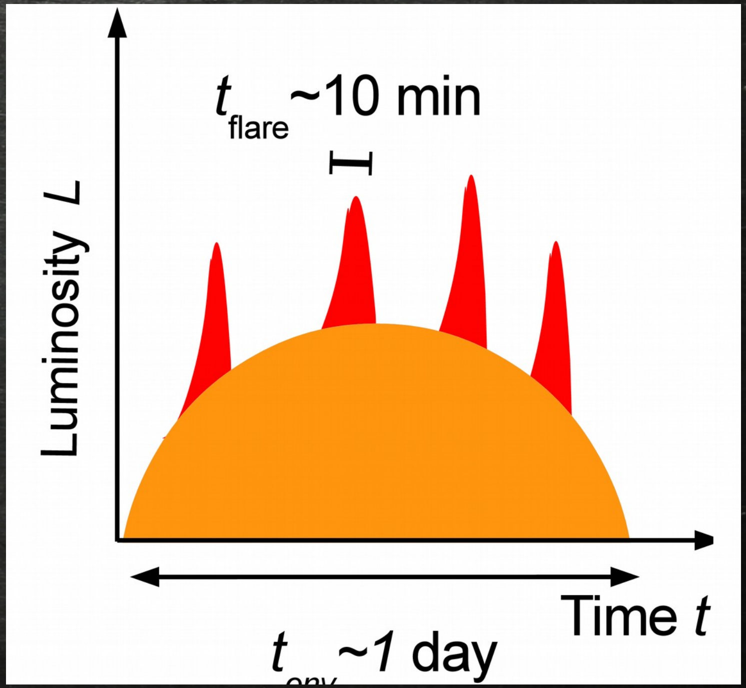




Future directions

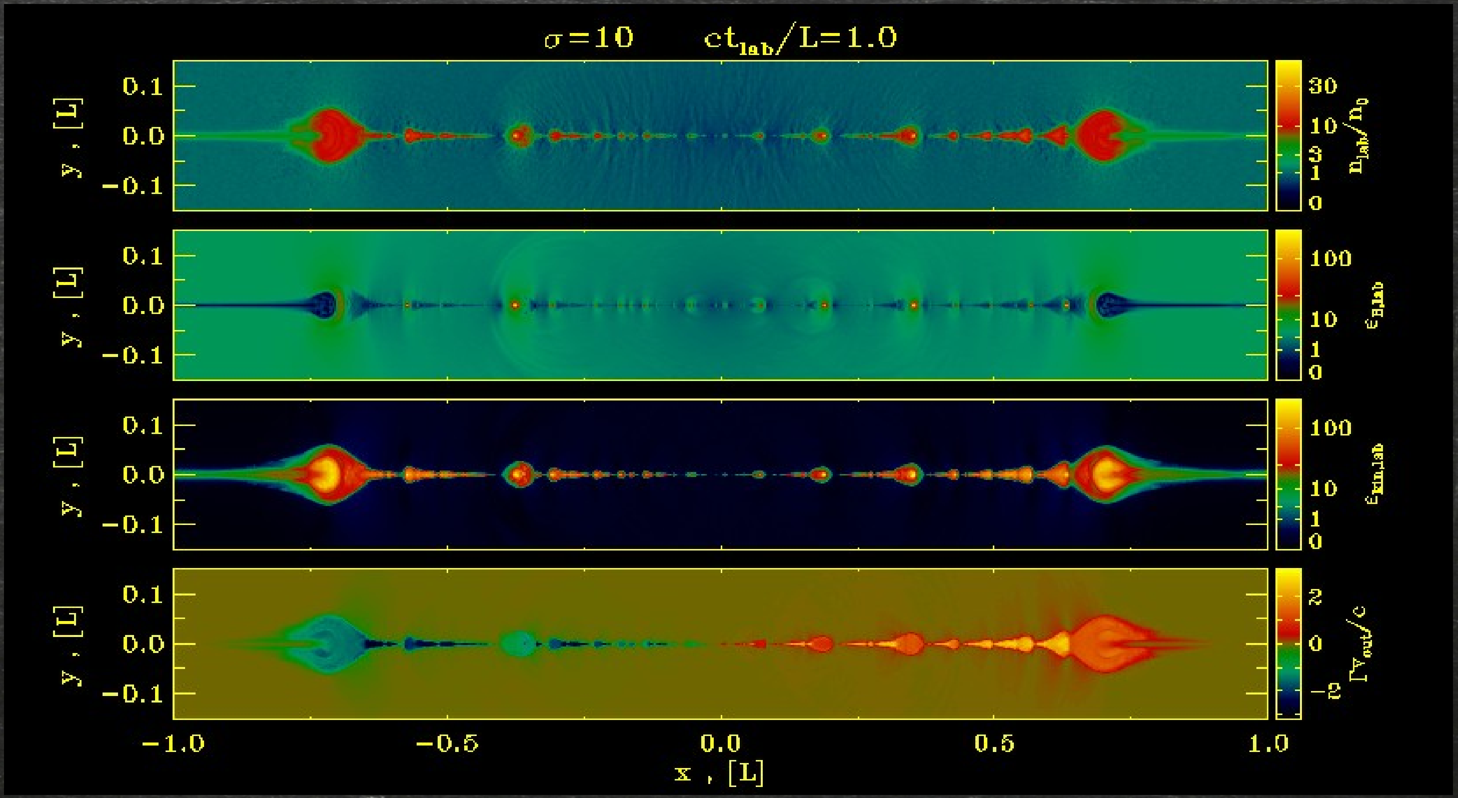
- Pair multiplicity in electron-proton plasma & SED morphology
- Compton scattering on external radiation fields & Compton dominance of flares
- Plasmoid chain & statistics of flares (e.g. recurrence of fast & bright flares)
- Connection to the large-scale properties: Where? Why?
- Radio “afterglow”: Radio flares following a gamma-ray flare?





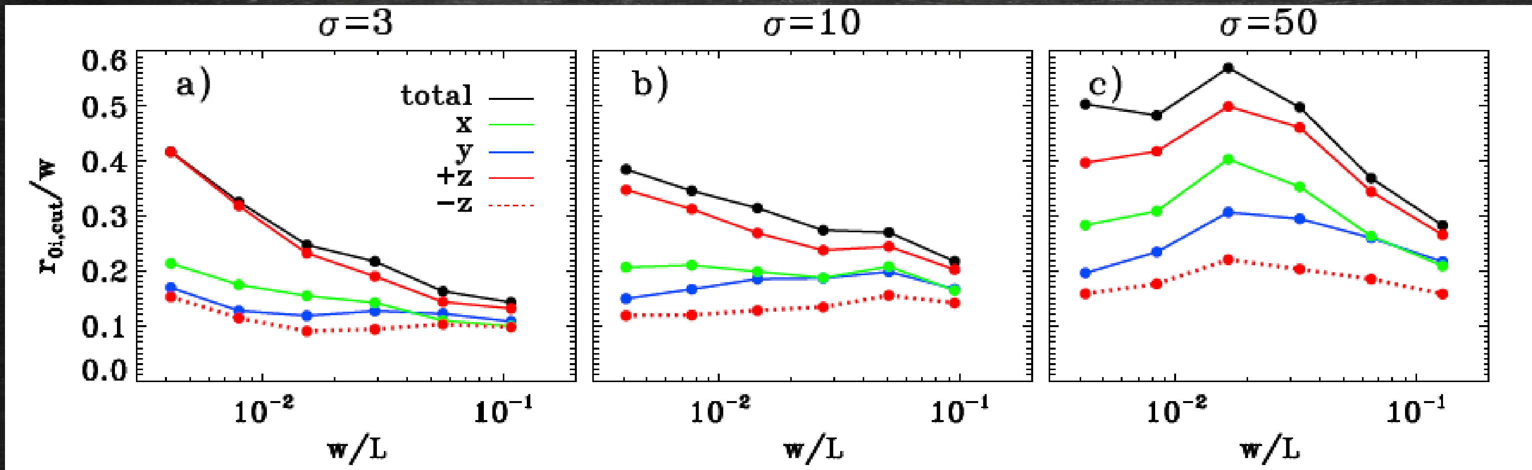
Thank you

Back-up slides

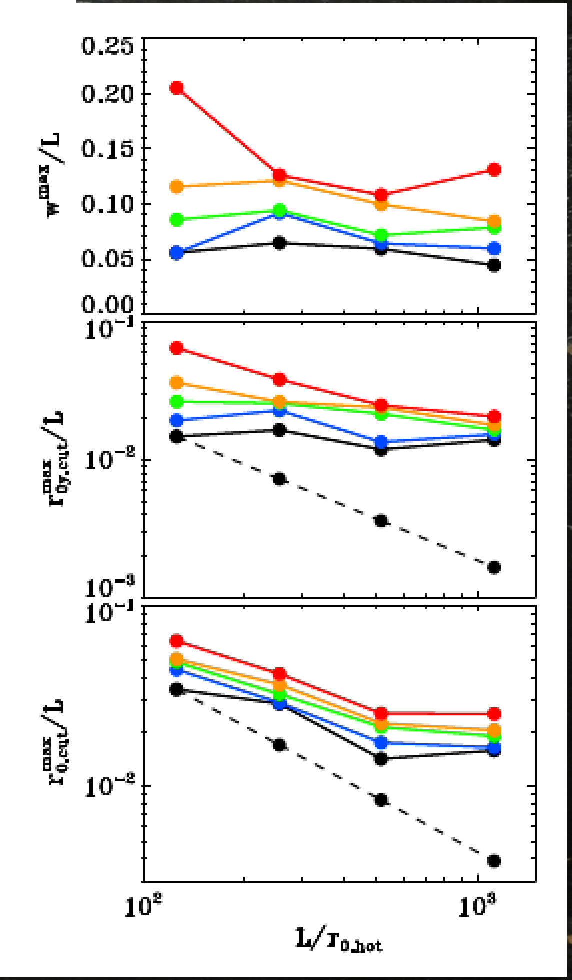


Credit: L. Sironi

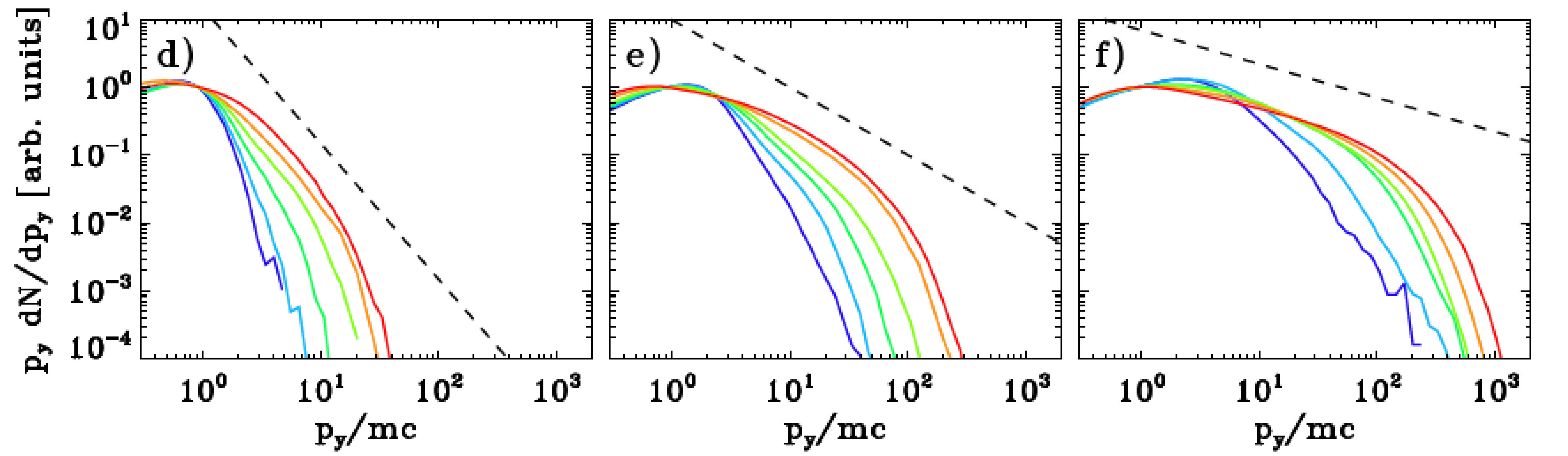
Particle anisotropy



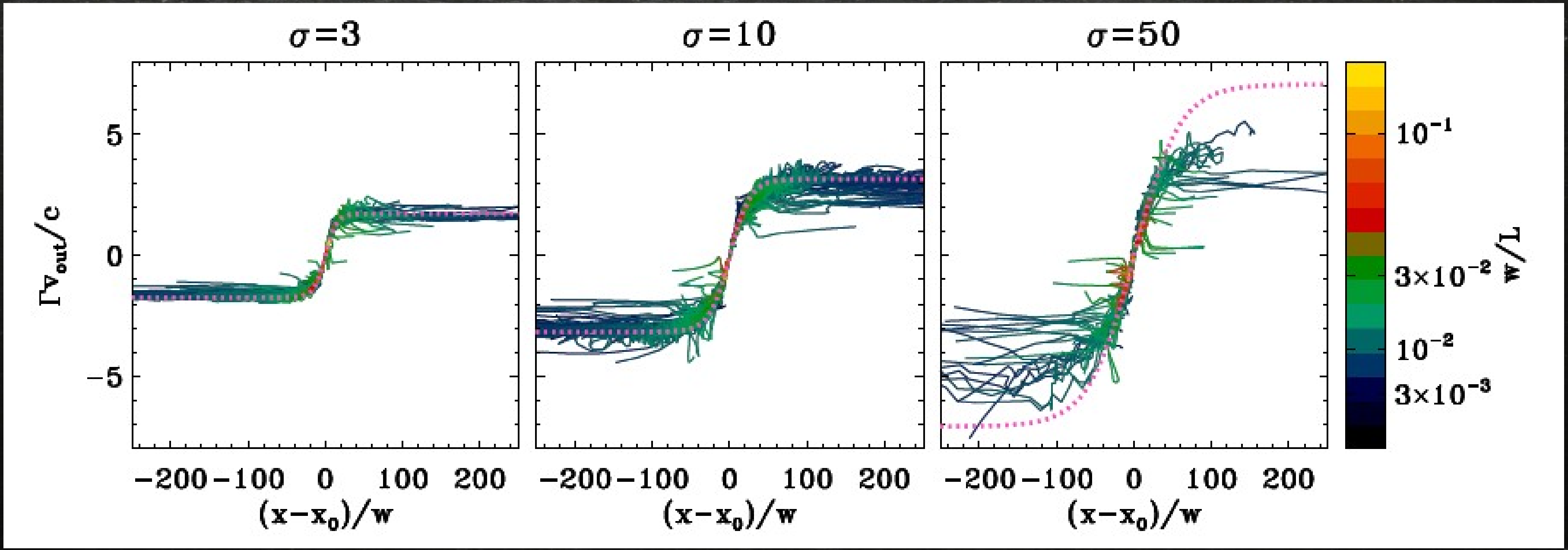
Dependence on system size →



Particle momentum (y-direction) spectrum



Plasmoid acceleration

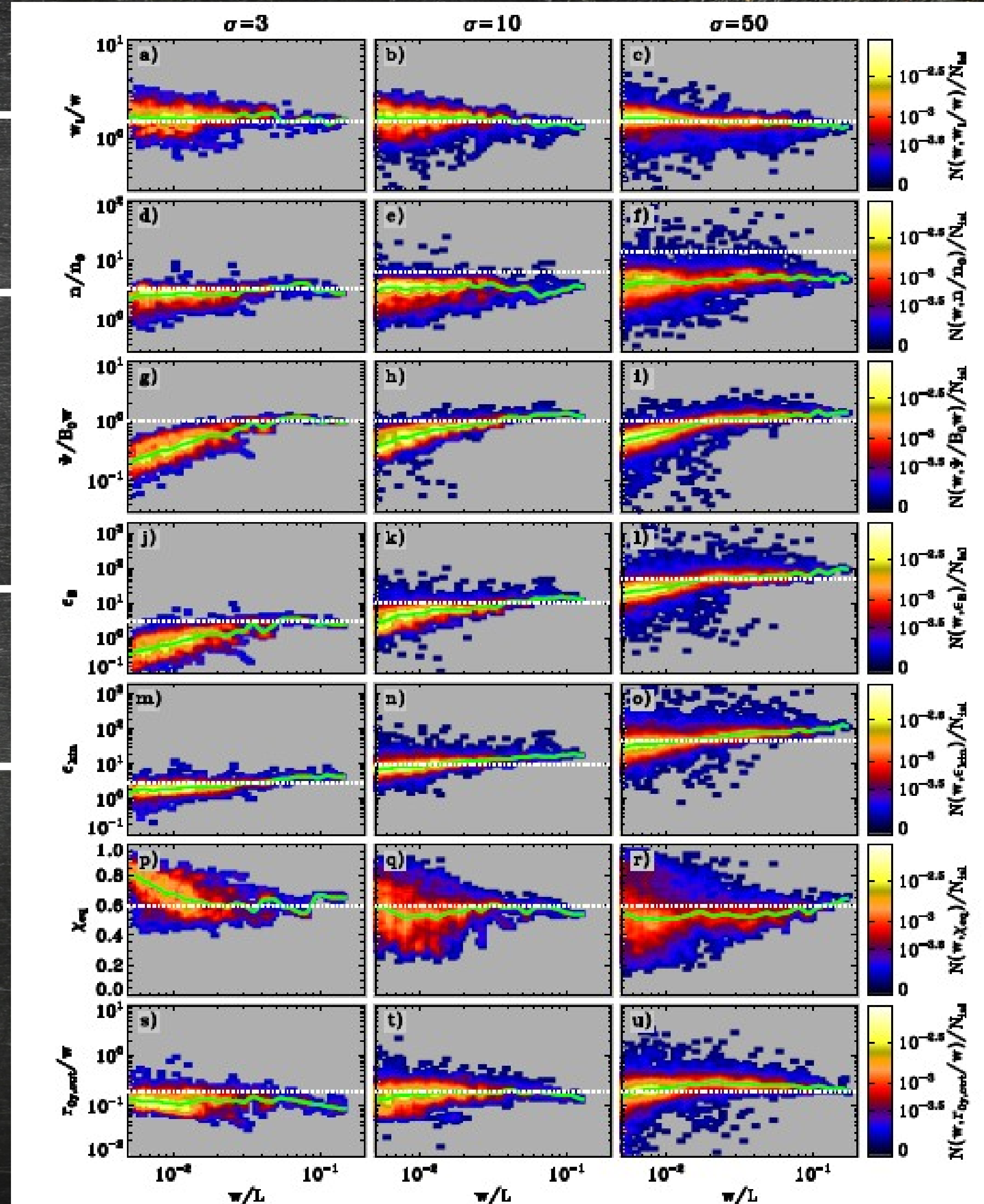


Ratio of w// to w

Particle number density

Magnetic energy fraction

Kinetic energy fraction



Sironi, Giannios & Petropoulou, 2016