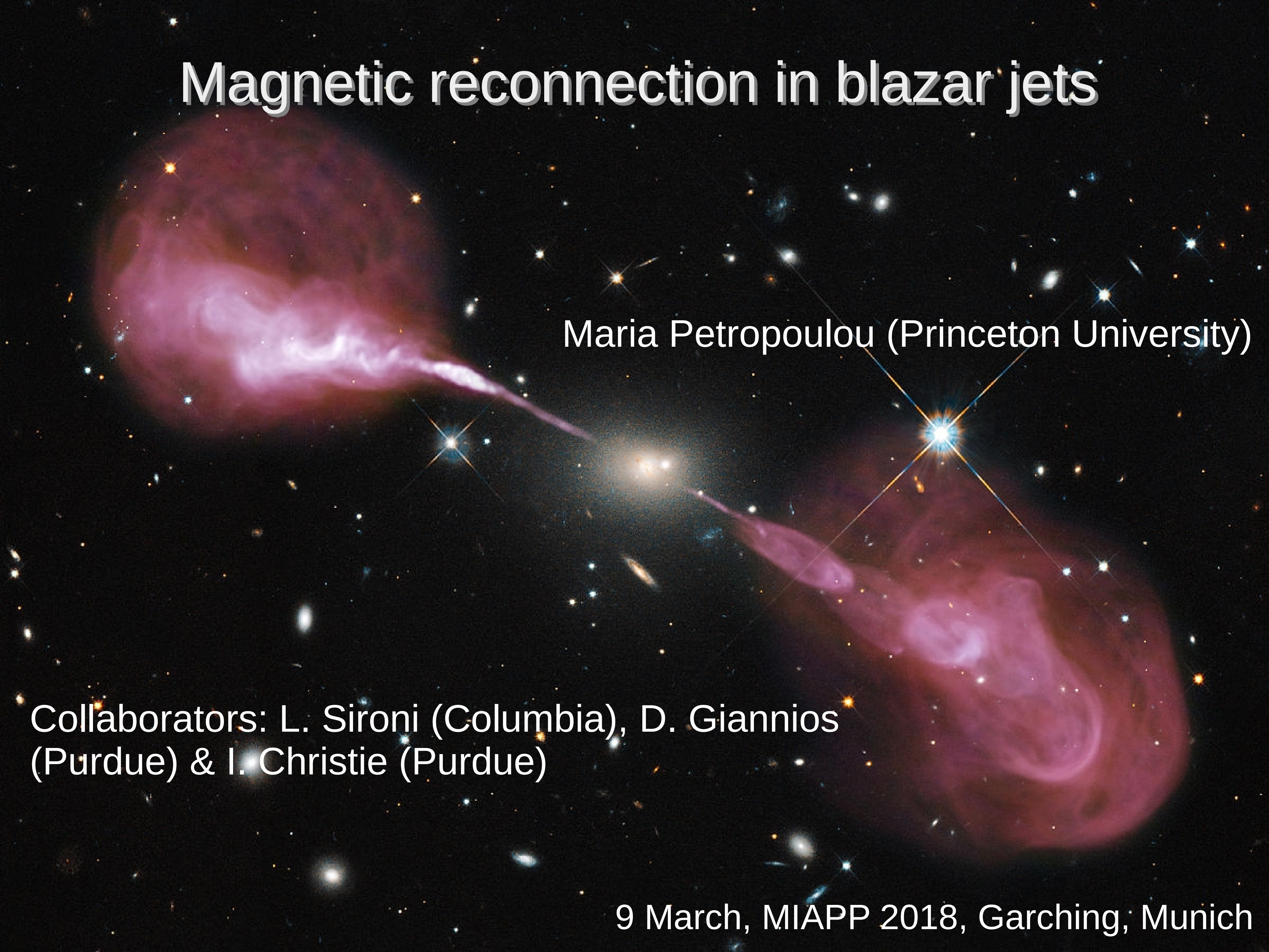
Magnetic reconnection in blazar jets



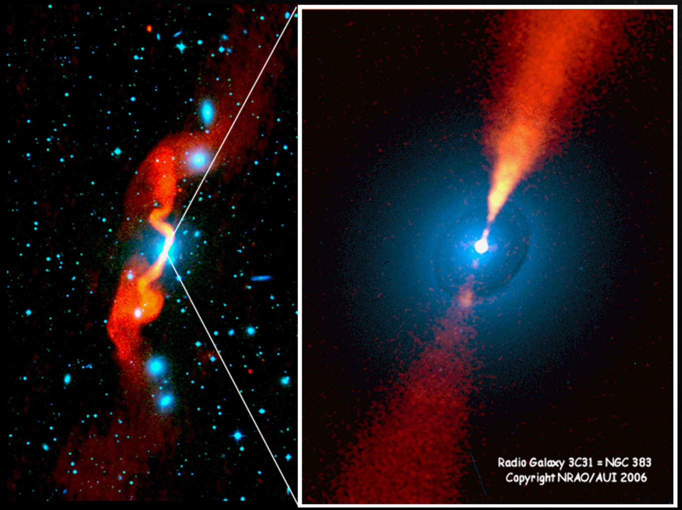
Maria Petropoulou (Princeton University)

Collaborators: L. Sironi (Columbia), D. Giannios (Purdue) & I. Christie (Purdue)

9 March, MIAPP 2018, Garching, Munich

AGN: a reminder

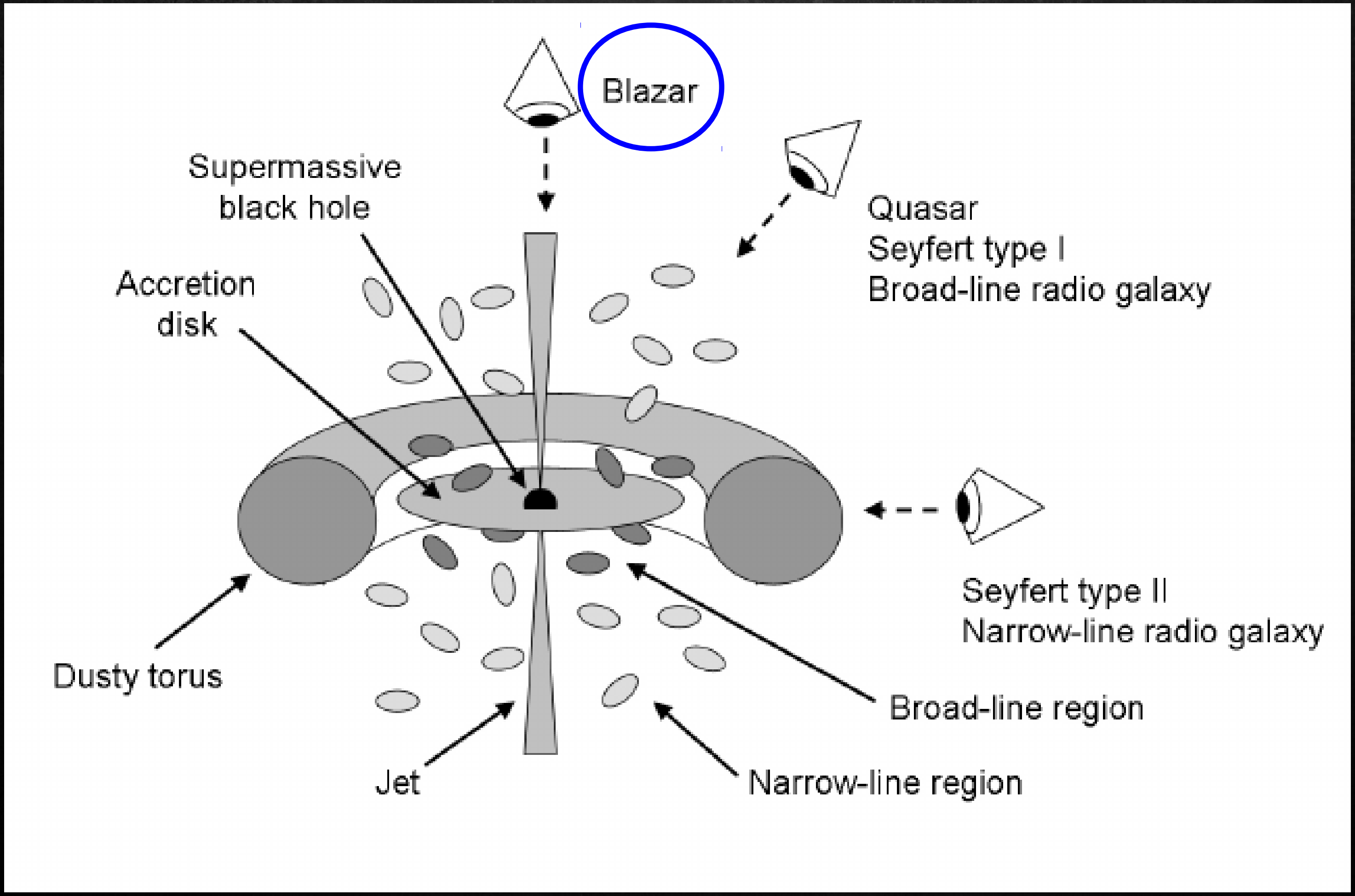
- Compact, variable bright core
- Central engine: massive black hole ($M_{BH} \sim 10^6 - 10^{10}\, M_{sun}$)
- Radiation from core dominates the emission from galaxy (star light)
- Radiation= thermal from accretion flow + non-thermal from relativistic jet (when this is present)



For a recent review, see Padovani+2017, A&ARv

Blazars: AGN jets viewed face-on

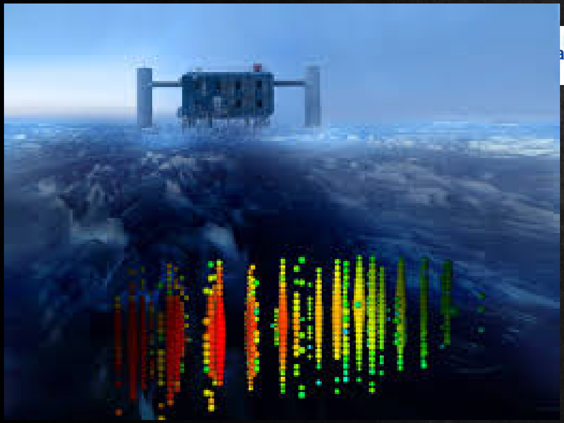
Blazar radiation dominated by the jet



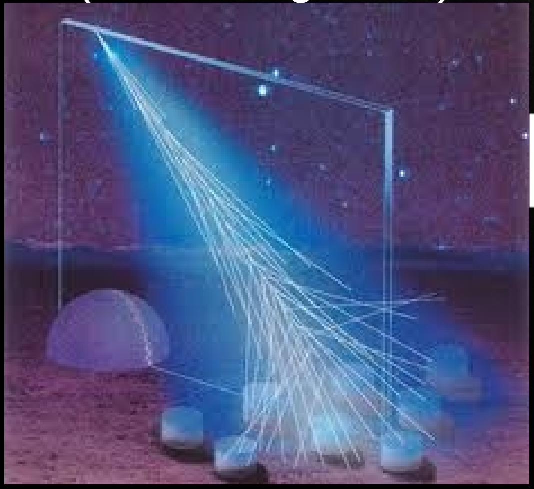
Urry & Padovani 1995

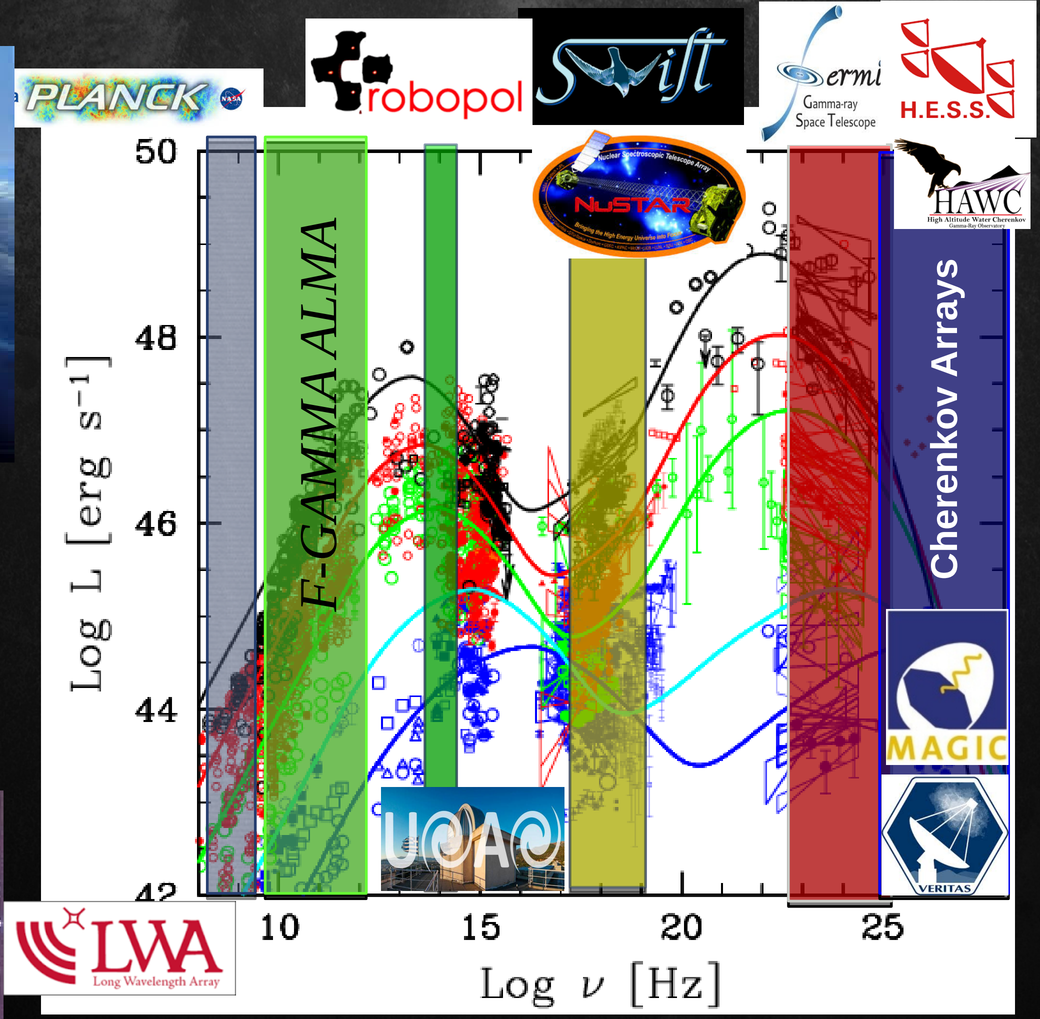
Blazars are multi-wavelength emitters

Neutrinos
(IceCube, ANTARES)



Cosmic Rays
(Pierre Auger, TA)



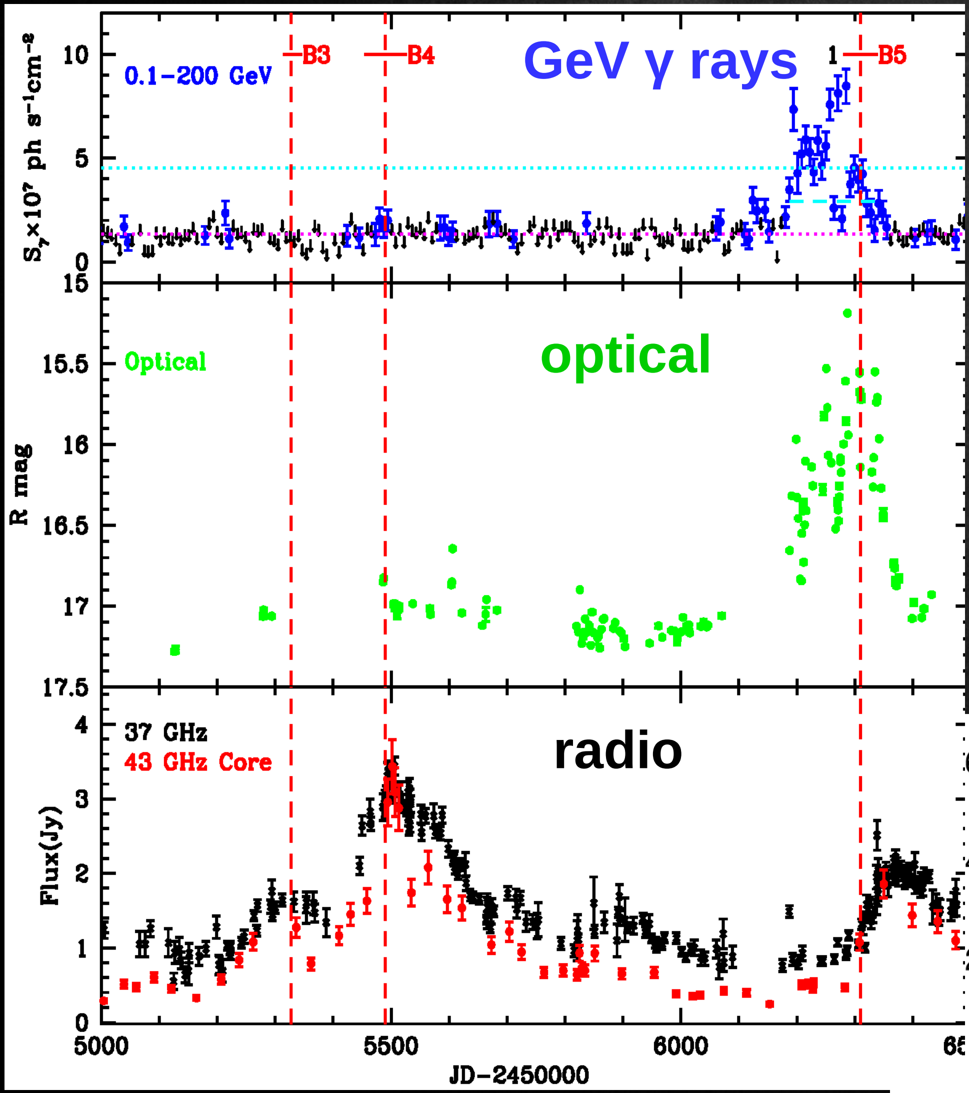


Fossati et al. 1998

Future
Cherenkov
Array

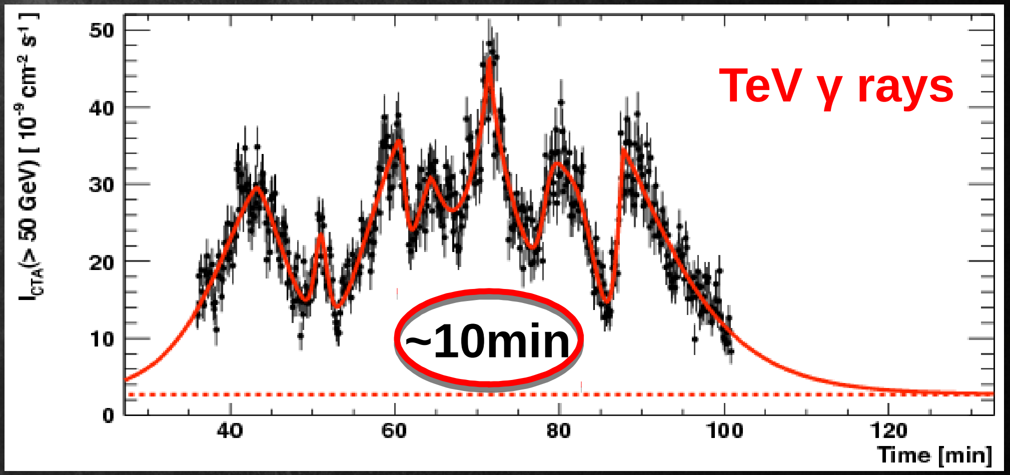
Blazars are variable on many timescales

From months ...



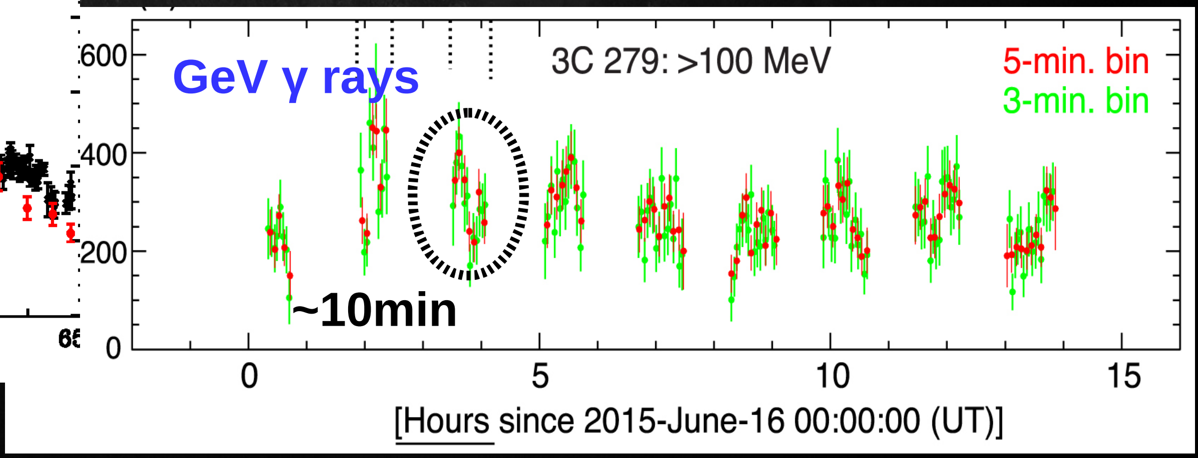
Jorstad & Marscher 2016

... to minutes !

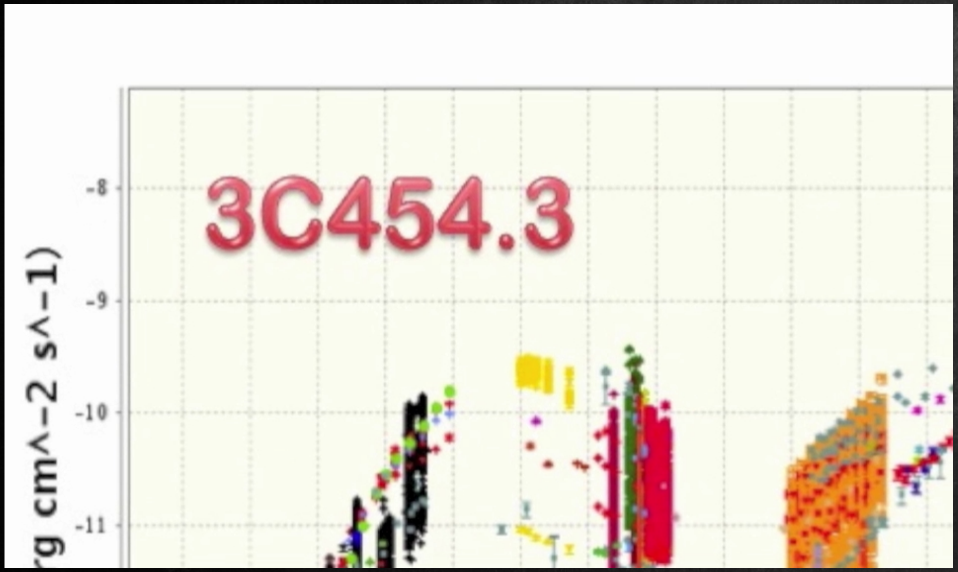


Aharonian et al. 2007

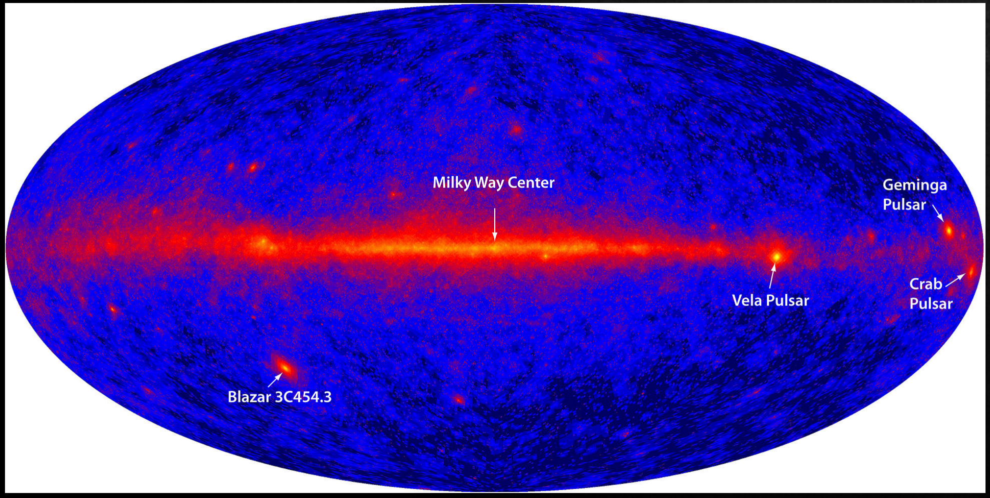
Fermi-LAT collaboration 2016



An example: 3C 454.3



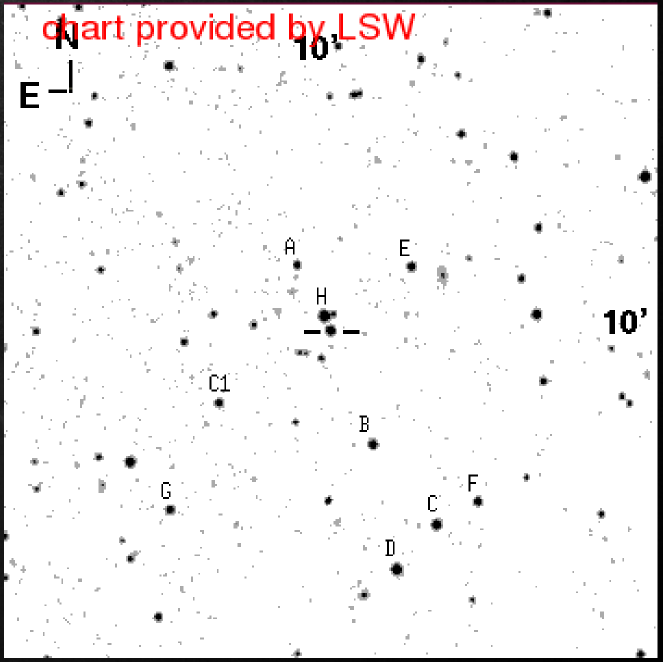
Giommi 2015, JHEA; https://tools.asdc.asi.it/SED/



Coordinates

α= 22:53:57.7479, δ = +16:08:53.560 (2000)

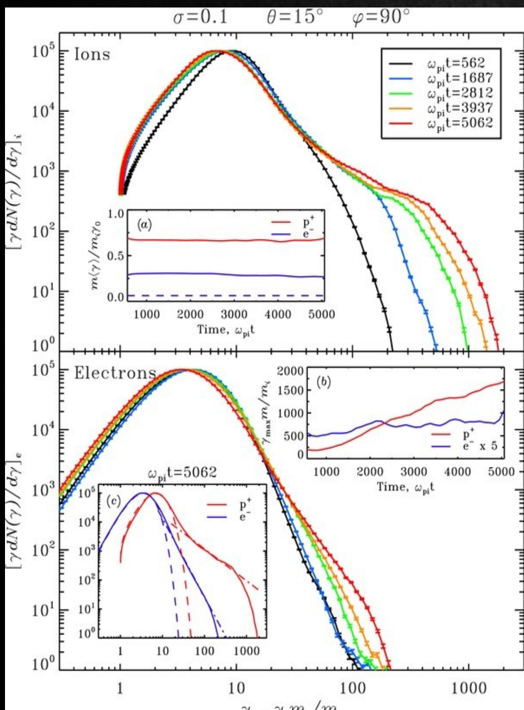
z = 0.85900



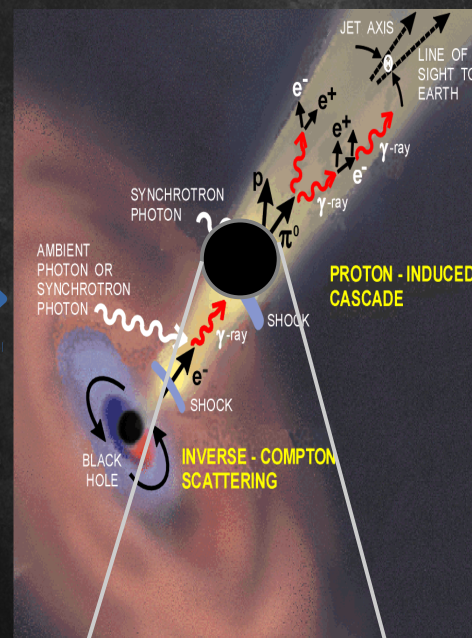
Landessternwarte Heidelberg-Königstuhl

Status of blazar modeling

Particle acceleration



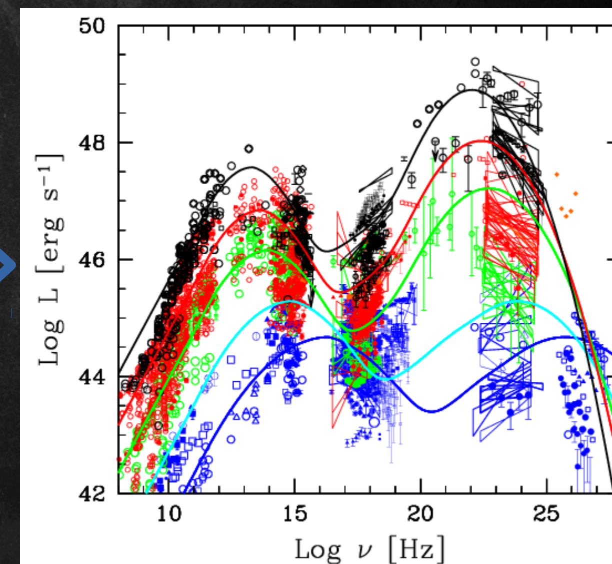
Injection of particles



"The blob"

Radiative processes

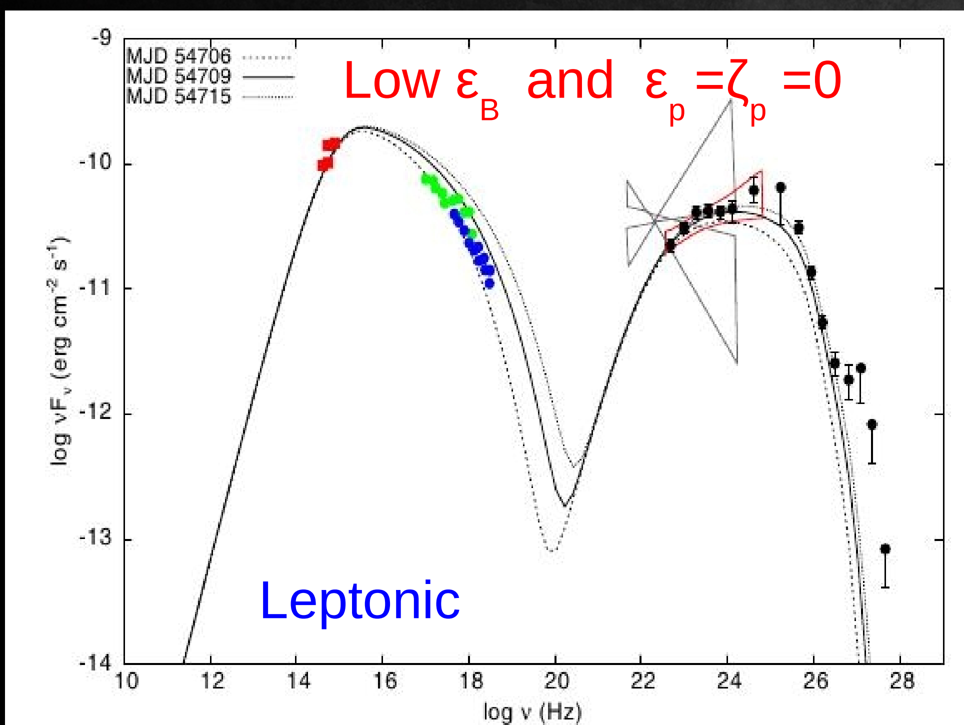
Photon spectrum

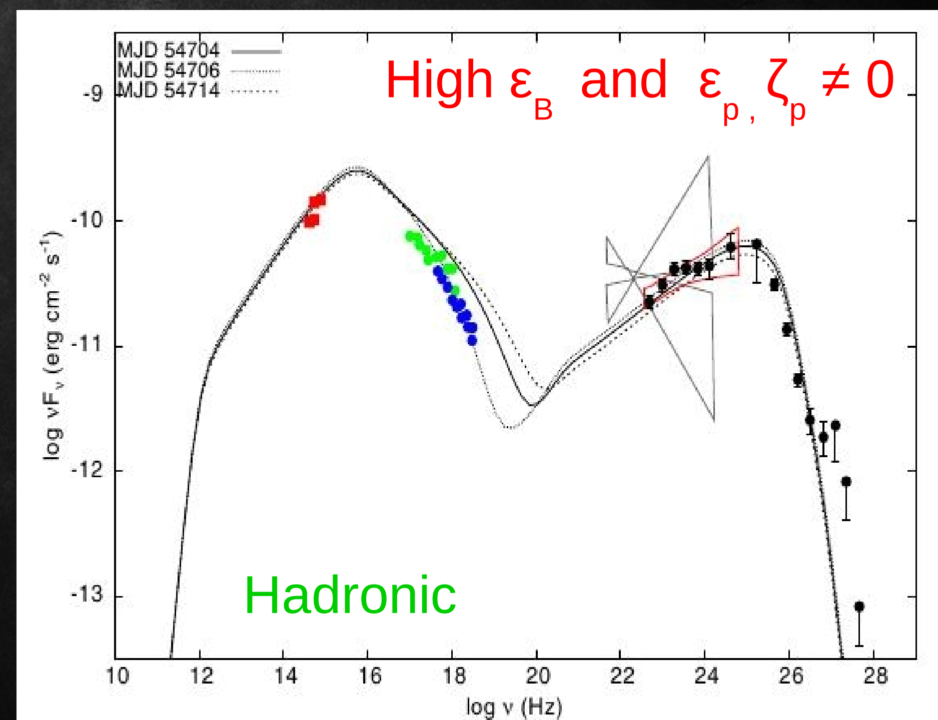


Parametrizing our ignorance

- ζ_e (ζ_p) : fraction of electrons (protons) in the non-thermal tail of the distribution
- ε_e (ε_p) : fraction of jet flow energy in relativistic electrons (protons)
- ε_B : fraction of jet flow energy in magnetic fields

PKS 2155-304



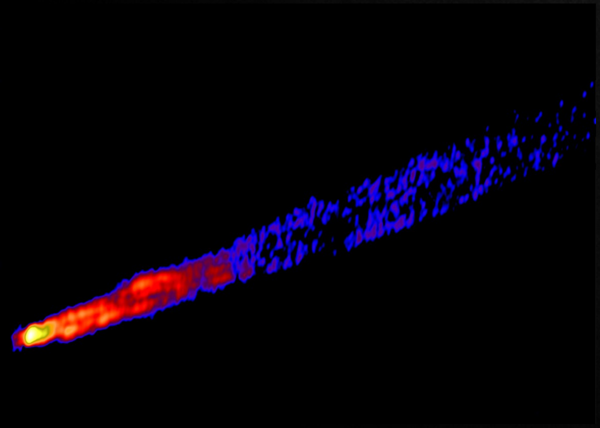
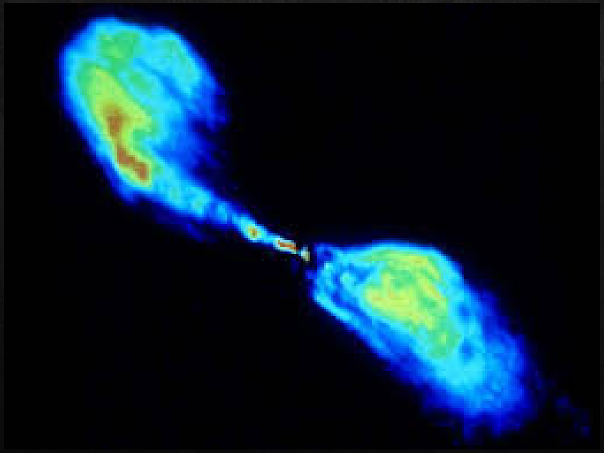
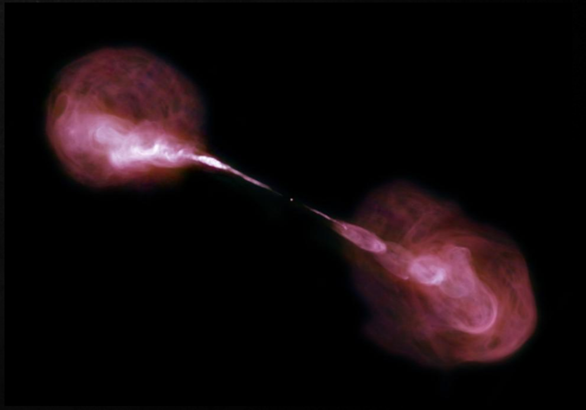


Petropoulou M, 2014, A&A

Which model materializes in blazars?

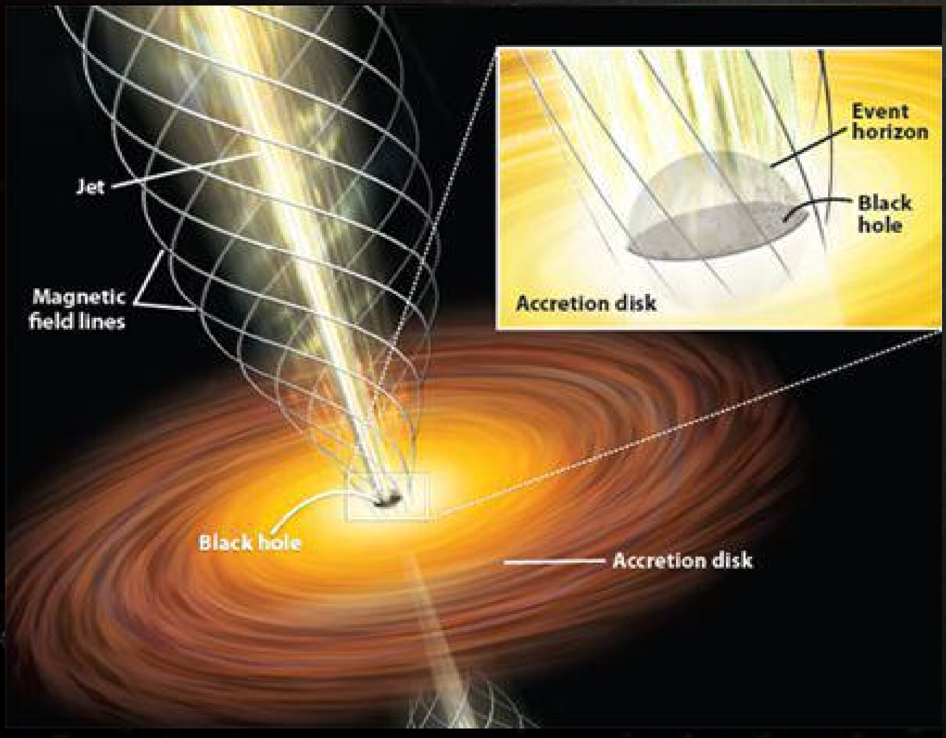
Puzzling questions

- How is the jet energy converted to radiation?
- Are the radiating particles electrons or protons? How can we tell?
- Where and how are particles accelerated ?

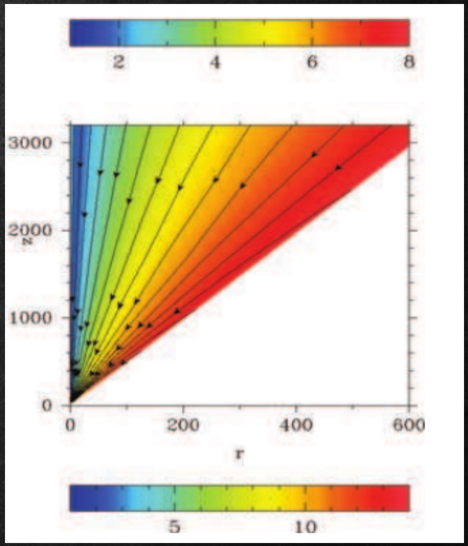




The paradigm of jet formation

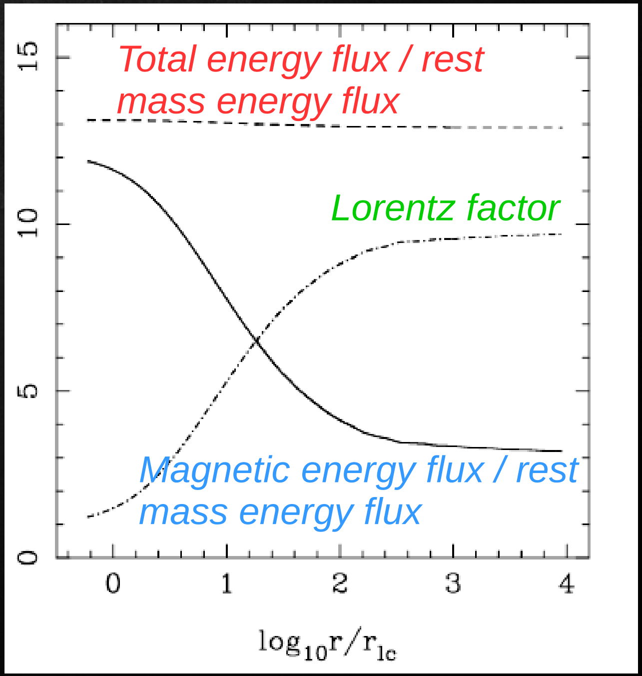
Jet acceleration over a range of scales (~0.001- 0.1 pc) *(e.g. Vlahakis & Koenigl 2004, Komissarov+2007)*



Blandford & Znajek 1977; Begelman & Li 1992; Meier et al. 2001; Koide et al. 2001; Komissarov, Lyubarsky, McKinney, Tchekhovskoy +++



Lorentz factor Γ

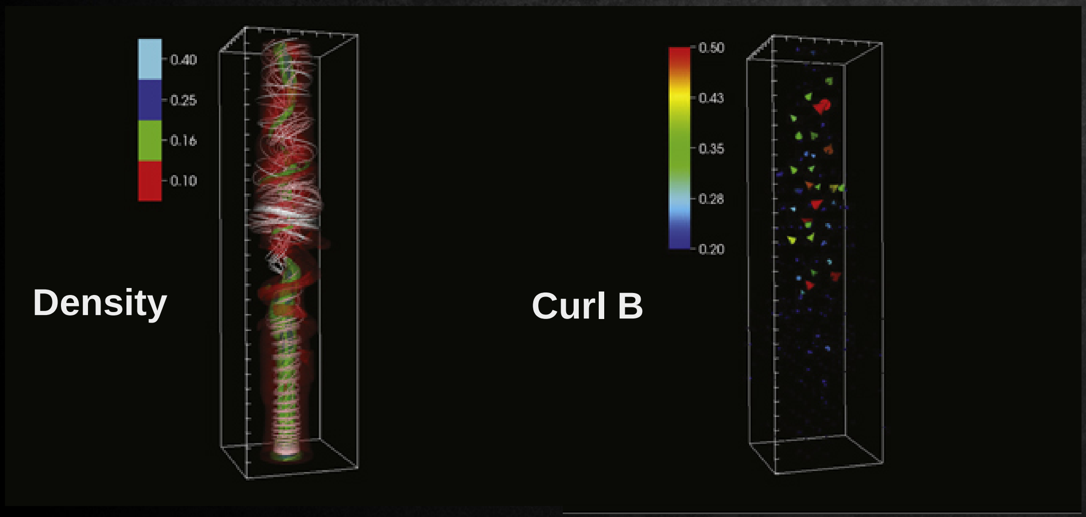


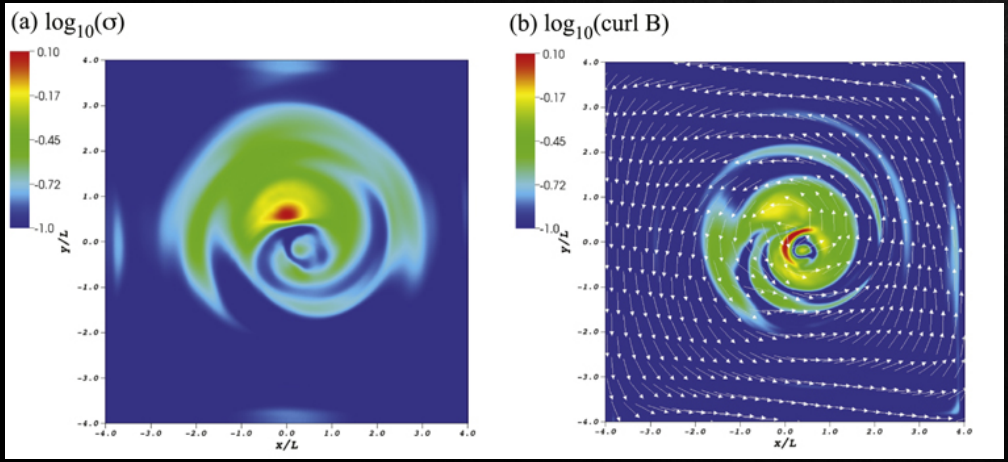
Komissarov et al. 2007

Jet dissipation

Energy reservoir: magnetic

- Current driven kink instability
- Magnetic reconnection

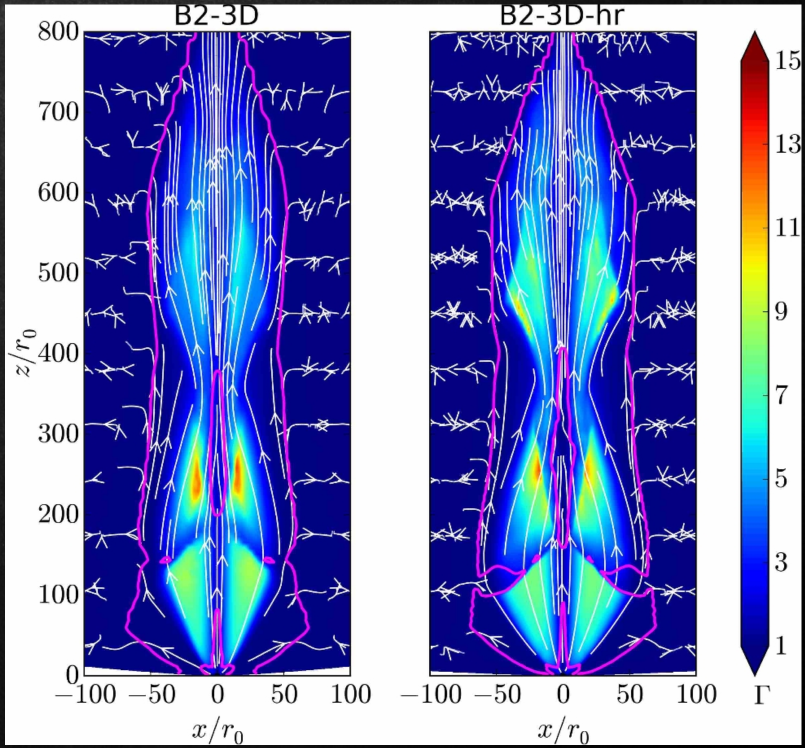




Singh + 2016

Energy reservoir: kinetic

- Kelvin-Helmholtz instabilities
- Shocks



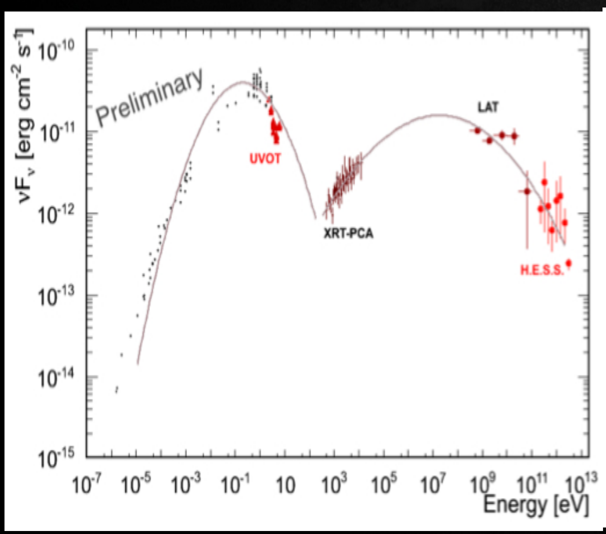
Barniol-Duran+2017

Facts from blazar observations

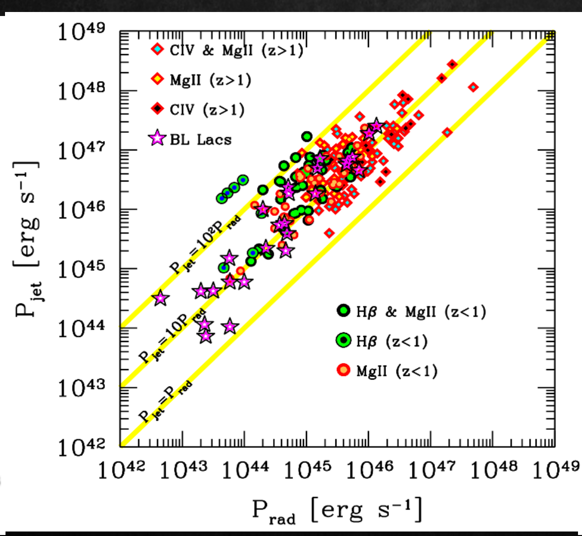
* Extended power-law energy distributions of radiating particles

* Radiative power is ~ 1%-10% of jet power → efficient energy dissipation

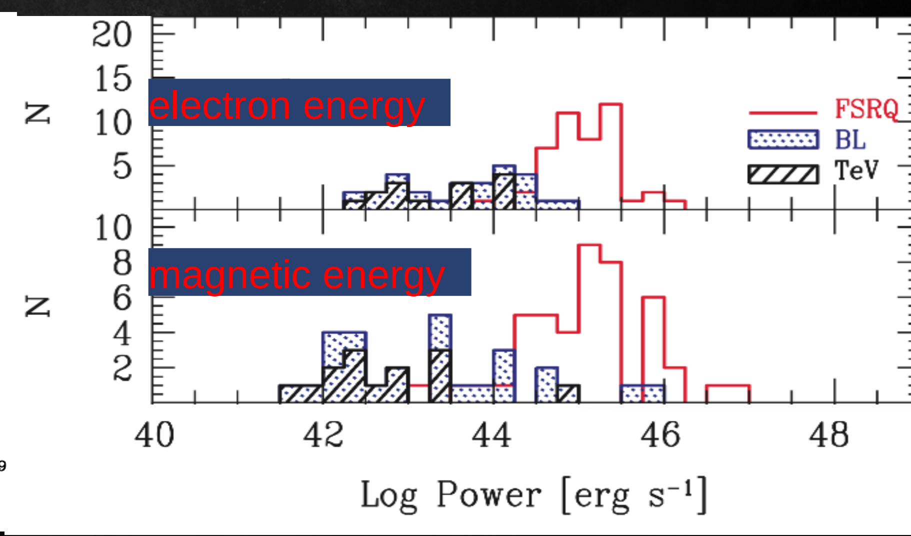
* Rough energy equipartition between radiating particles & magnetic fields



HESS collaboration 2011

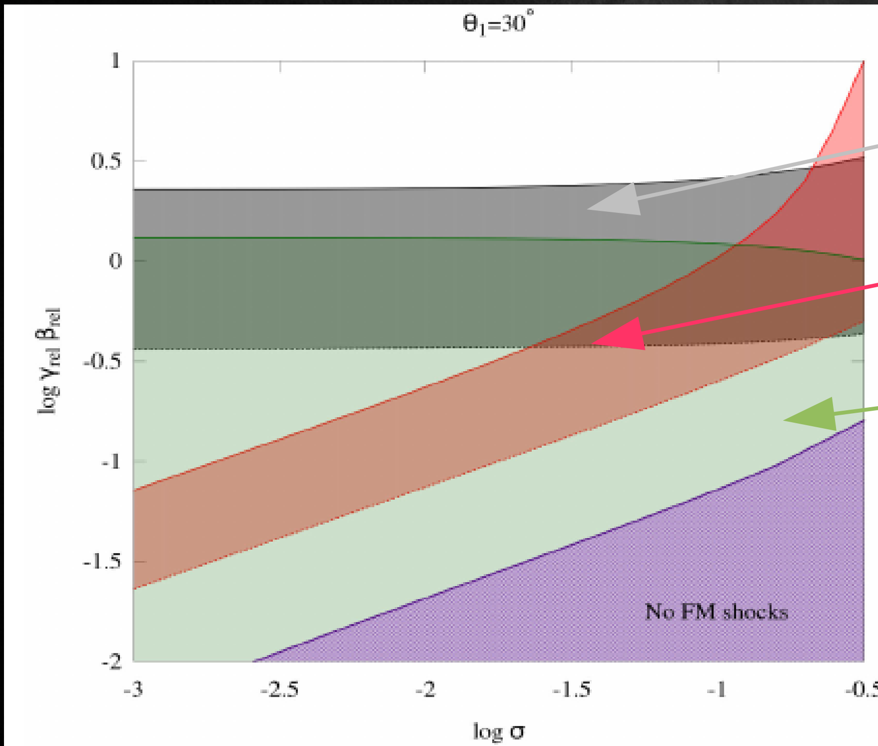


Ghisellini et al. 2014



Celotti & Ghisellini 2008

Constraints on shock dissipation scenarios



Relative 4-velocity

Plasma magnetization

Dissipation efficiency

Equipartition between pairs & magnetic field

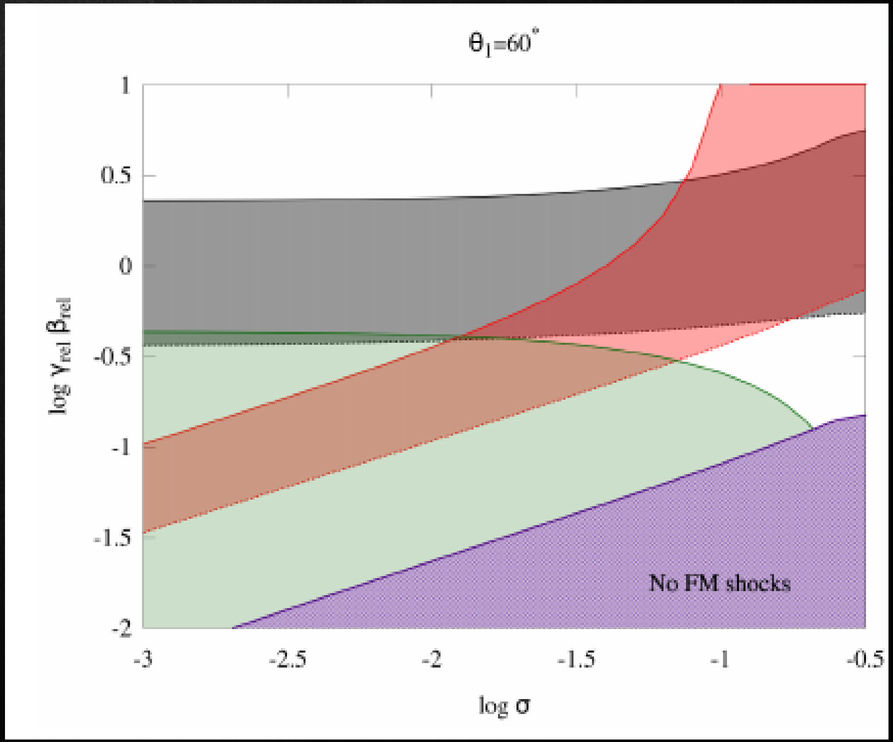
Sub-luminal shocks

$$\cos\theta_1 < v_1/c$$

$$\sigma = \frac{B_0^2}{4\pi n_0 m c^2}$$

$$\sigma = \frac{B_0^2}{4\pi n_0 h}$$

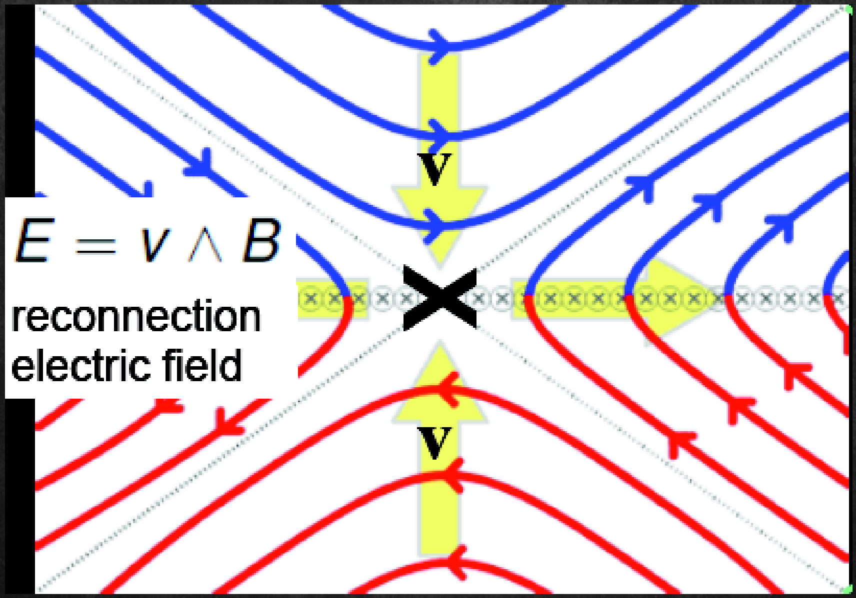
$$h = m \langle \gamma \rangle c^2 + \frac{p}{n}$$



Sironi, Petropoulou, Giannios 2015

Magnetic reconnection

Reconnecting magnetic field

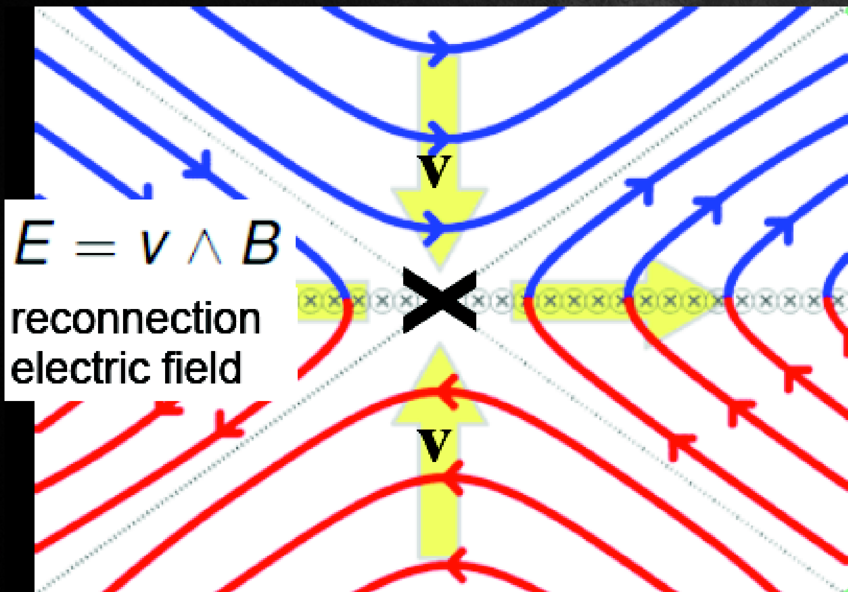


Reconnecting magnetic field

- Magnetized plasma enters the reconnection region
- Plasma leaves the reconnection region at the Alfvén speed
- Magnetic energy is transformed to heat, bulk plasma motion and accelerated particles

Magnetic reconnection

Reconnecting magnetic field



Reconnecting magnetic field

* Magnetized plasma enters the reconnection region

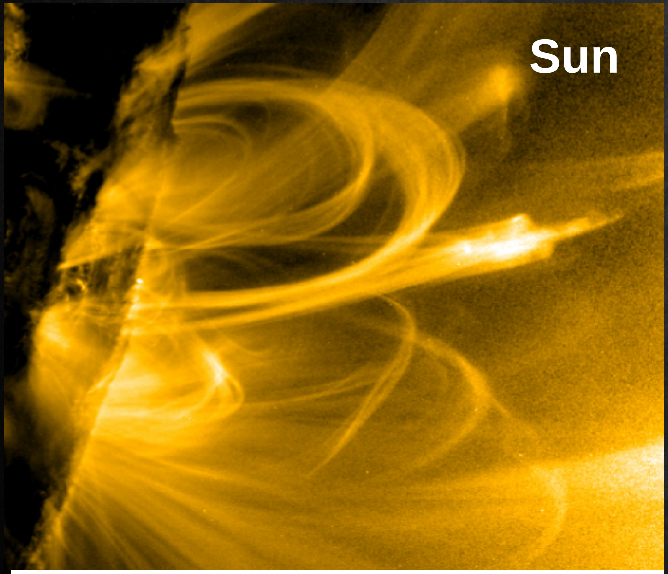
* Plasma leaves the reconnection region at the Alfvén speed

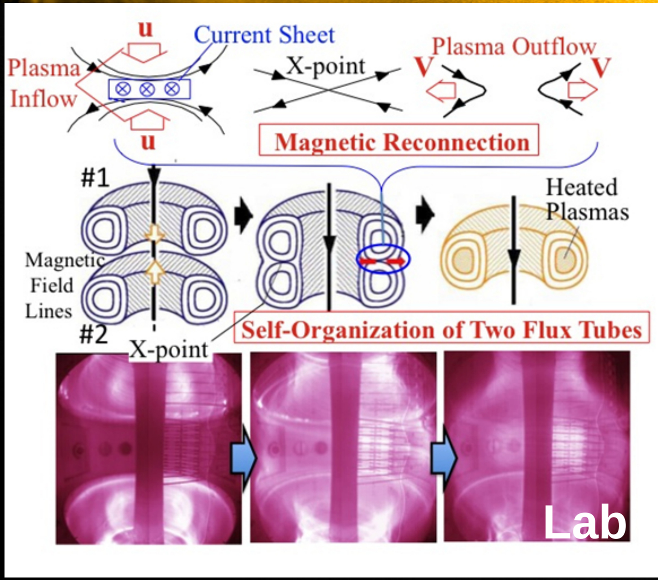
* Magnetic energy is transformed to heat, bulk plasma motion and accelerated particles

Regimes of magnetic reconnection

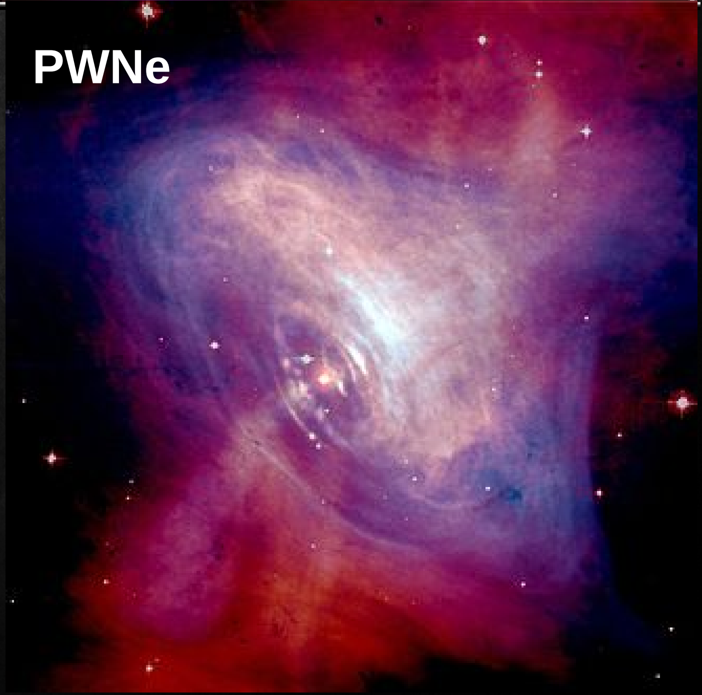
$$\sigma = \frac{B_0^2}{4\pi n_0 m c^2}$$

$\sigma \ll 1$ → $\sigma \gg 1$





Non-relativistic reconnection



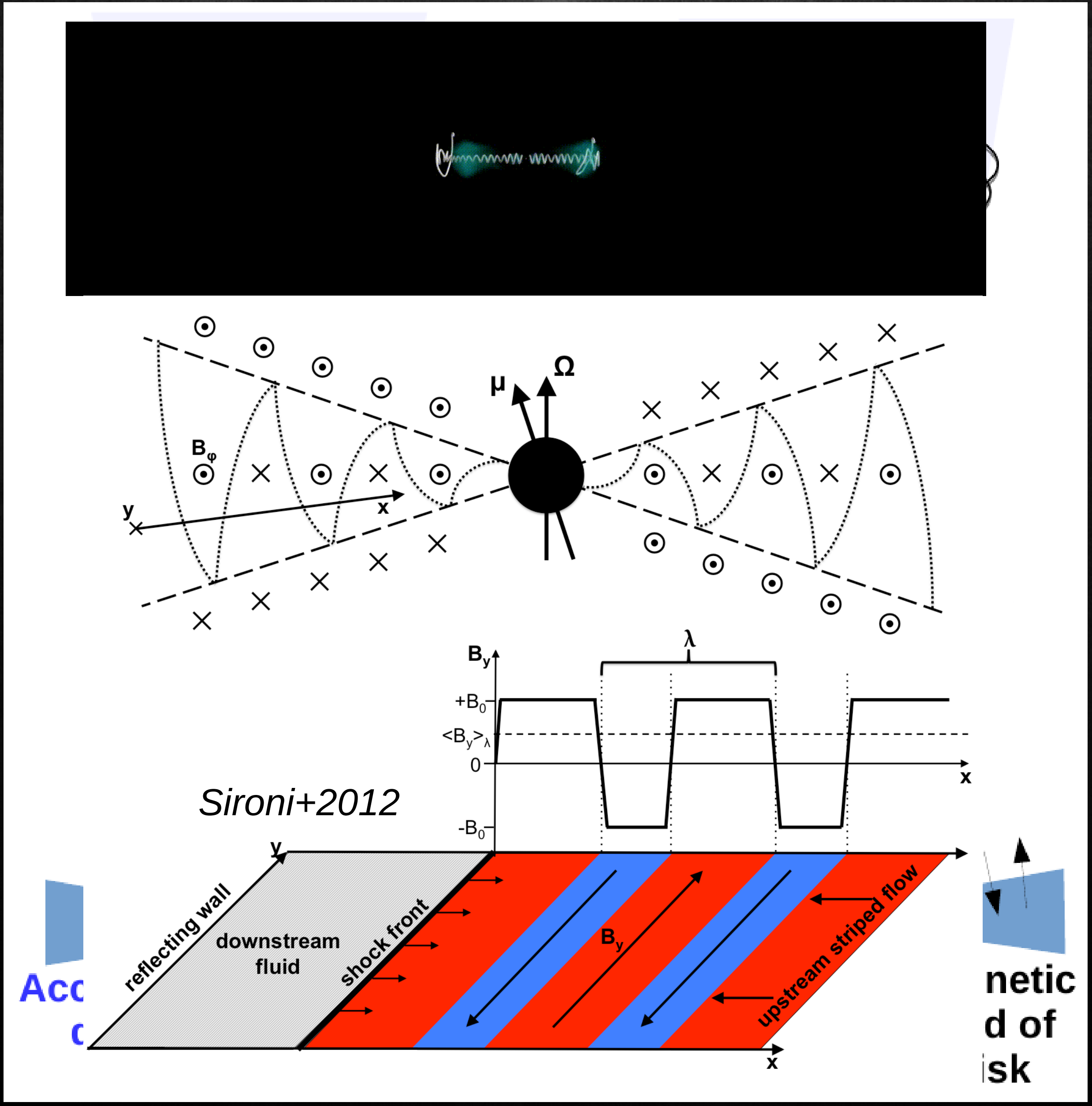
Relativistic reconnection

Triggering reconnection in jets

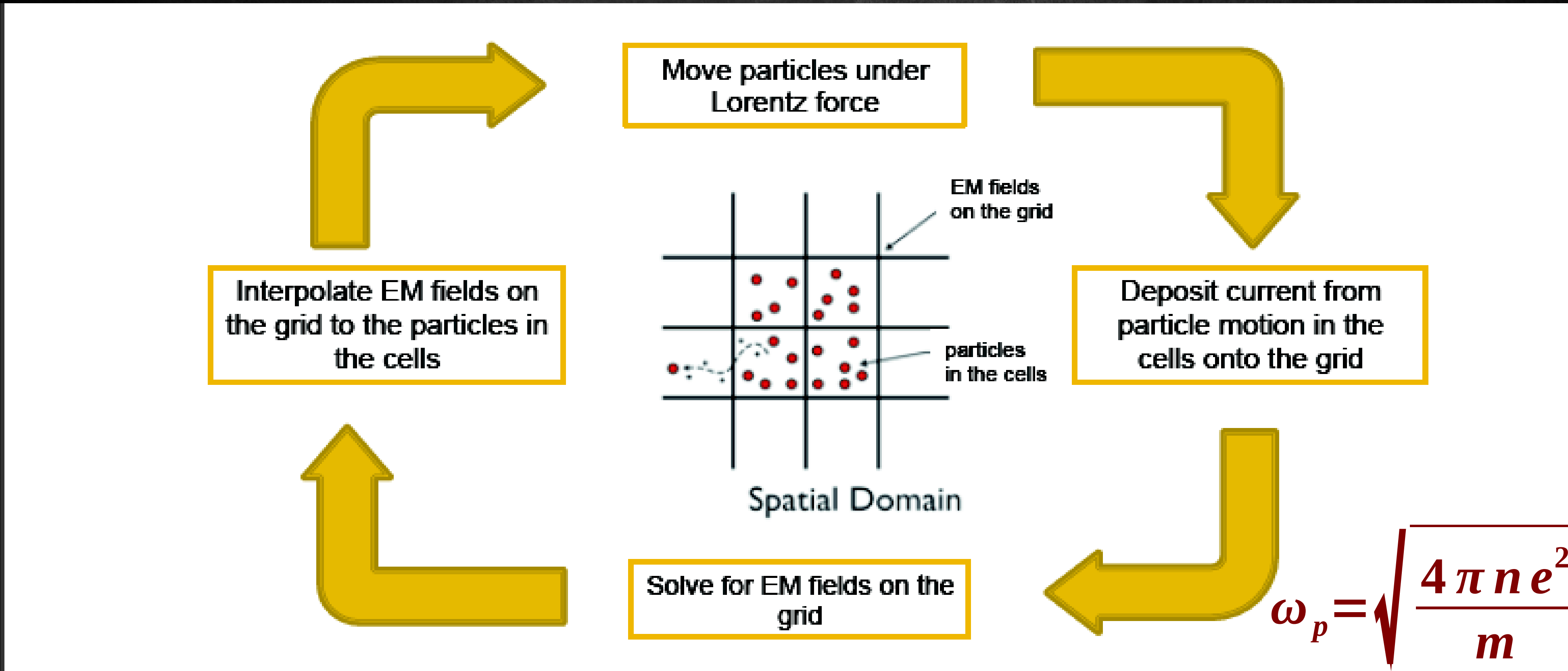
(e.g. Eichler 1993; Begelman 1998; Giannios & Spruit 2006; McKinney + 2009; Porth & Komissarov 2015; Parfrey, Giannios, Beloborodov 2015; Barniol-Duran + 2017)

Global MHD instability

Alternating magnetic field



Particle-in-Cell simulations



$$\omega_p = \sqrt{\frac{4\pi n e^2}{m}}$$

- No approximations; full plasma physics of ions and electrons
- Tiny length scales (c/ω_p) and timescales (ω_p^{-1}) need to be resolved → expensive simulations → limited time coverage + spatial domains
- 3D PIC code TRISTAN-MP *(Buneman 1993; Spitkovsky 2005; Sironi+2013)*

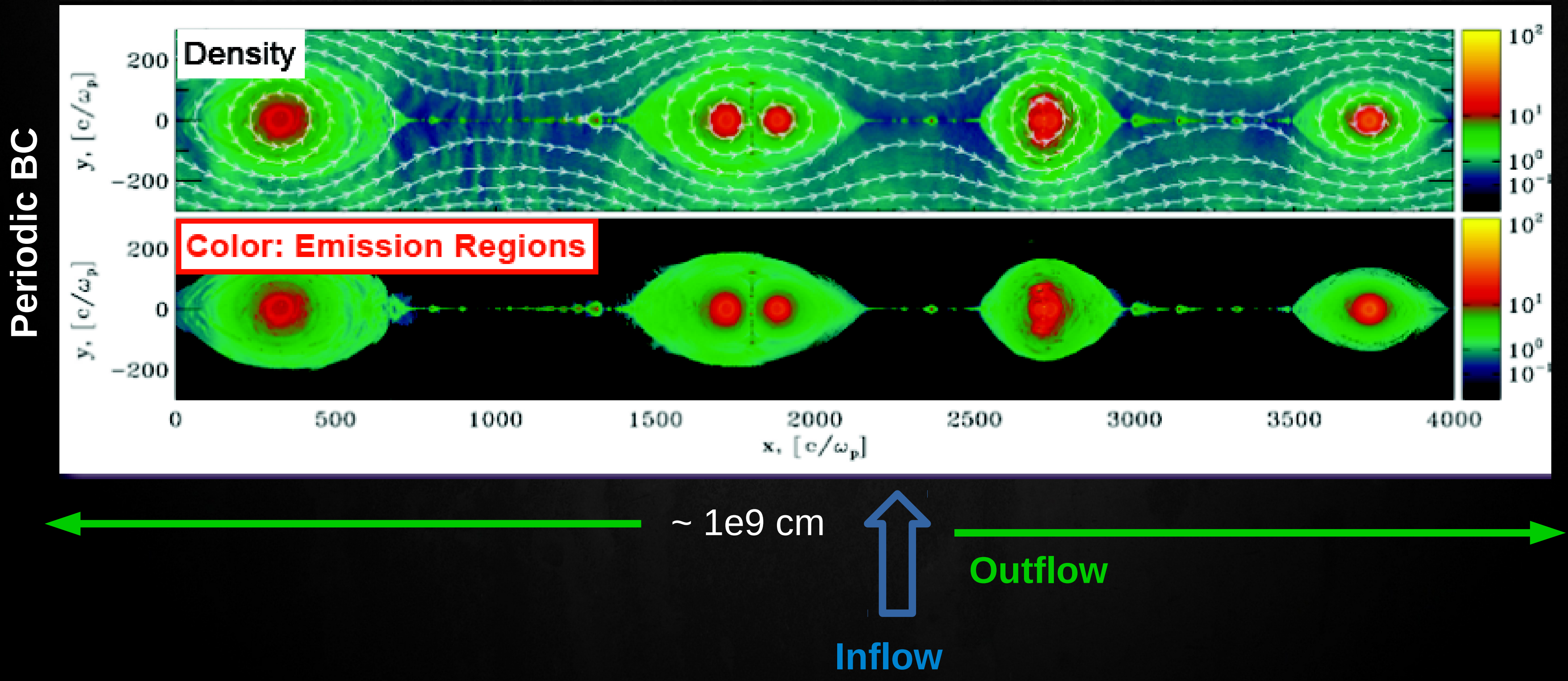
Magnetic reconnection in blazar jets

- General requirements of the process: efficiency, particle spectra etc.
- Properties of the plasmoids: acceleration, growth etc.
- Statistics of the plasmoid chain (e.g. size distribution)
- Radiation from a single plasmoid
- Radiation from the plasmoid chain

Plasmoid-dominated reconnection

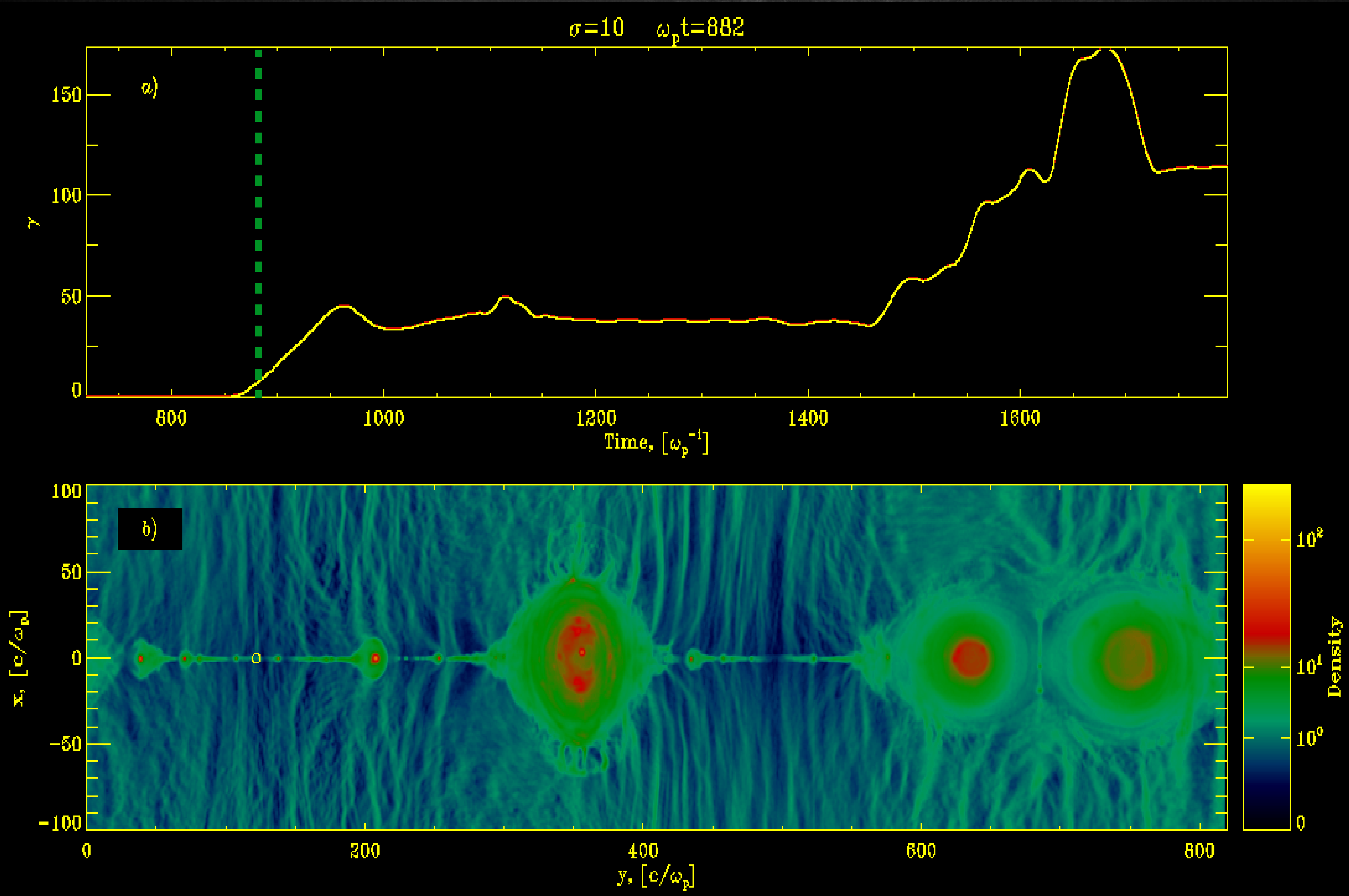
Zenitani & Hoshino 2001, Loureiro+2007, Bhattarjee+2009, Uzdensky+2010, Loureiro+2012, Guo+2014; 2015, Sironi & Spitkovsky 2014; Kagan+2015 (for review); Sironi, Petropoulou, Giannios 2015; Werner+2016, Sironi, Giannios, Petropoulou 2016+++

2D PIC simulation of σ=10 electron-positron reconnection



Sironi, Petropoulou, Giannios 2015

Particle acceleration



Periodic

Periodic

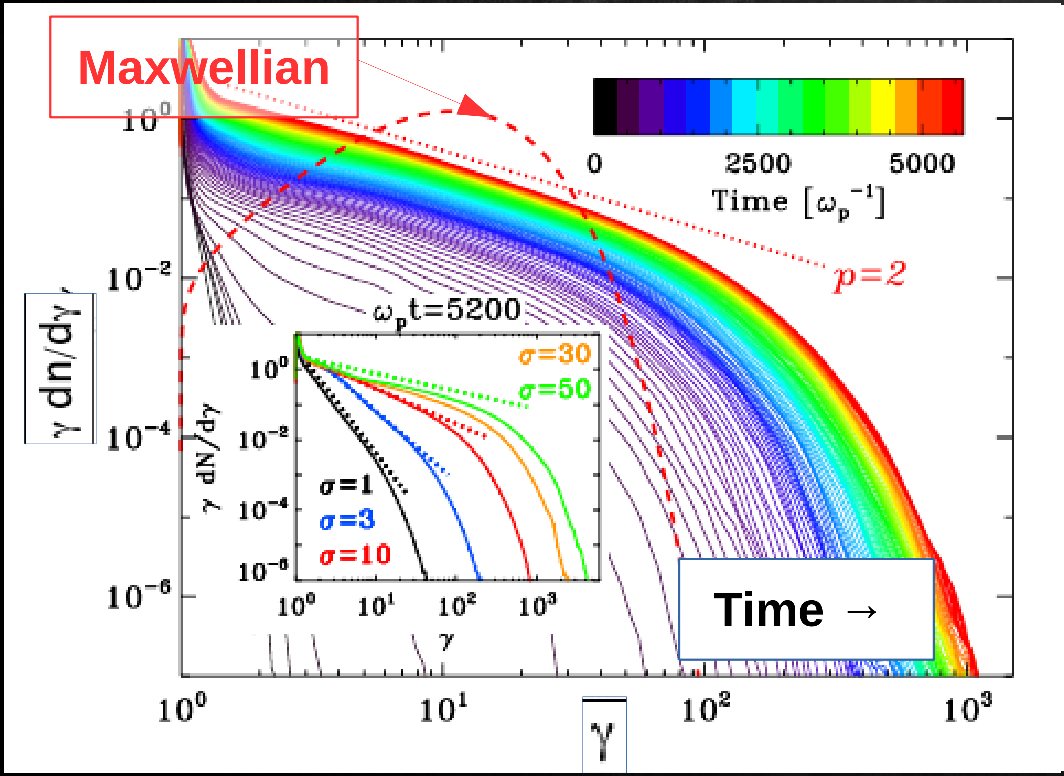
$$c/\omega_p = \sqrt{\frac{mc^2}{4\pi n e^2}}$$

Sironi, Petropoulou, Giannios 2015

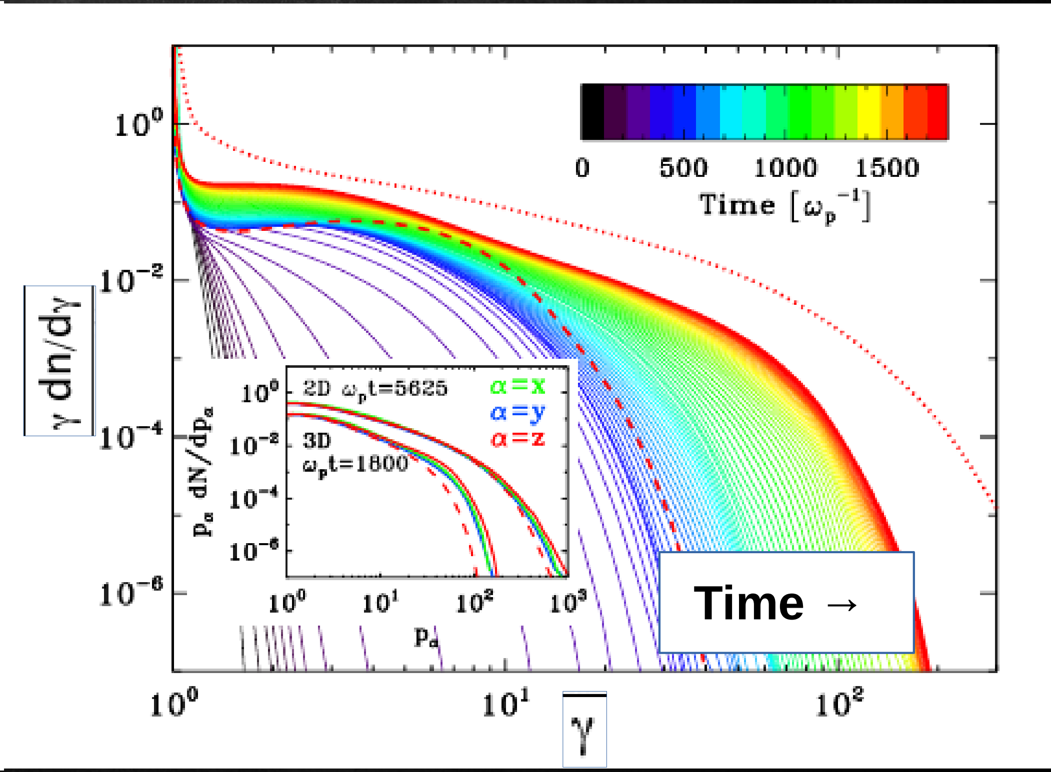
Particle energy distributions

Simulation of σ=10 electron-positron reconnection

2D



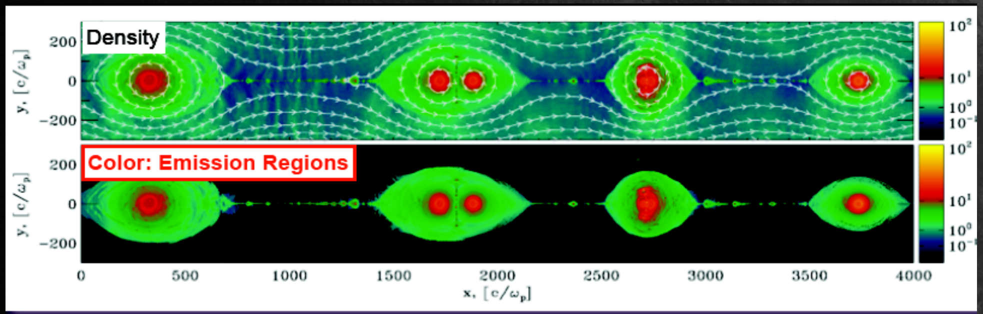
3D



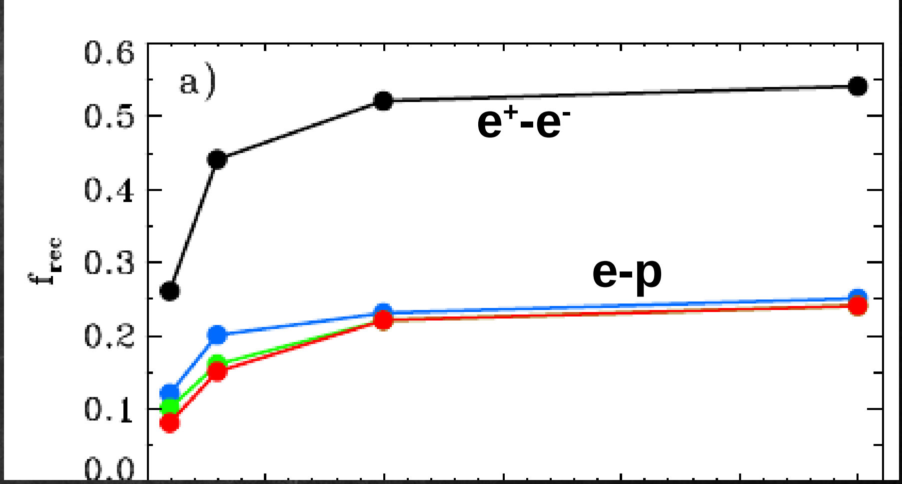
Sironi & Spitkovsky 2014

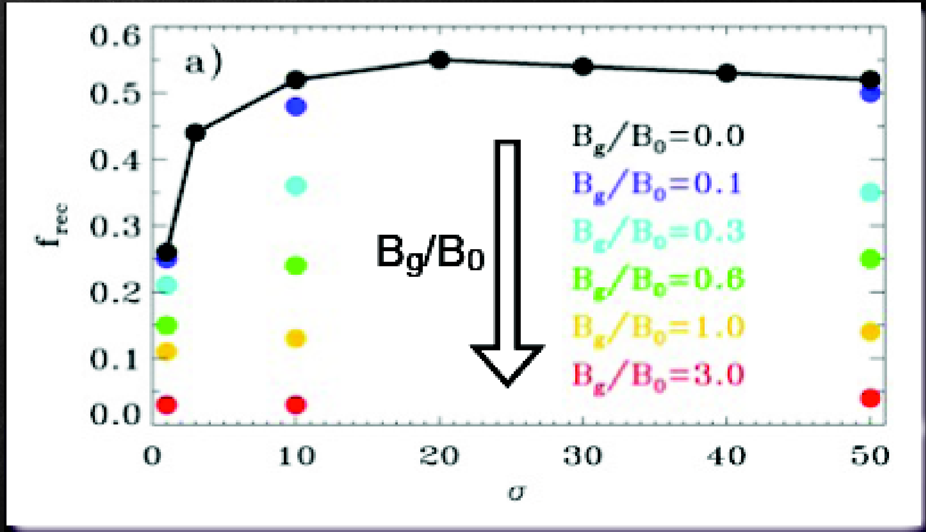
- Higher σ produces harder (p<2) particle spectra *(see also Guo+2014, 2015; Werner+2016)*
- The maximum energy increases LINEARLY* with time, if it is not inhibited by the boundaries

Dissipation efficiency



Sironi, Petropoulou, Giannios 2015



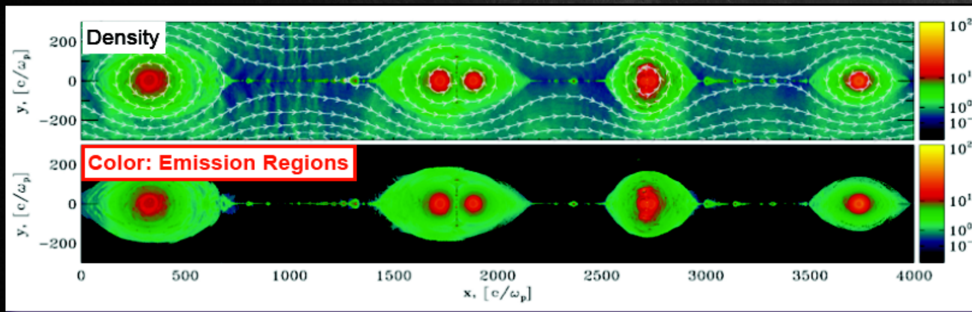


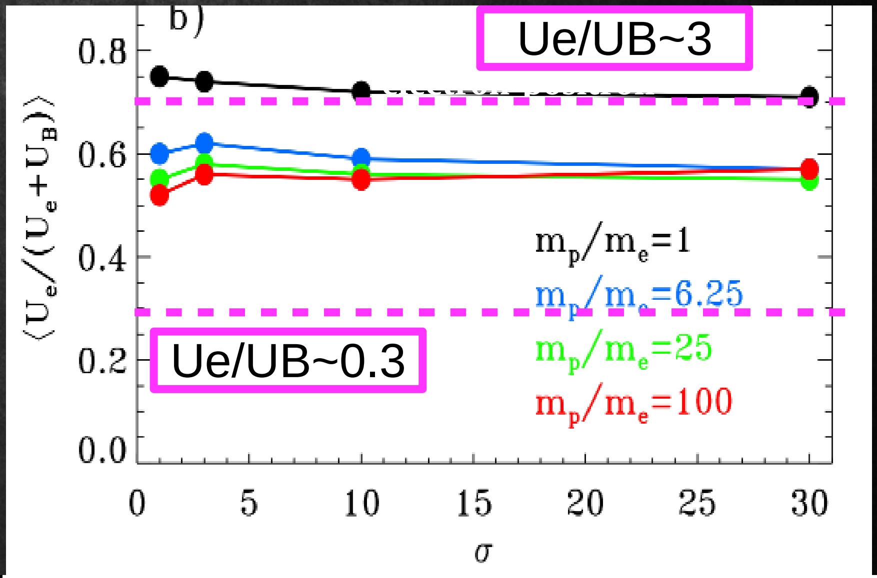
Efficiency

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

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

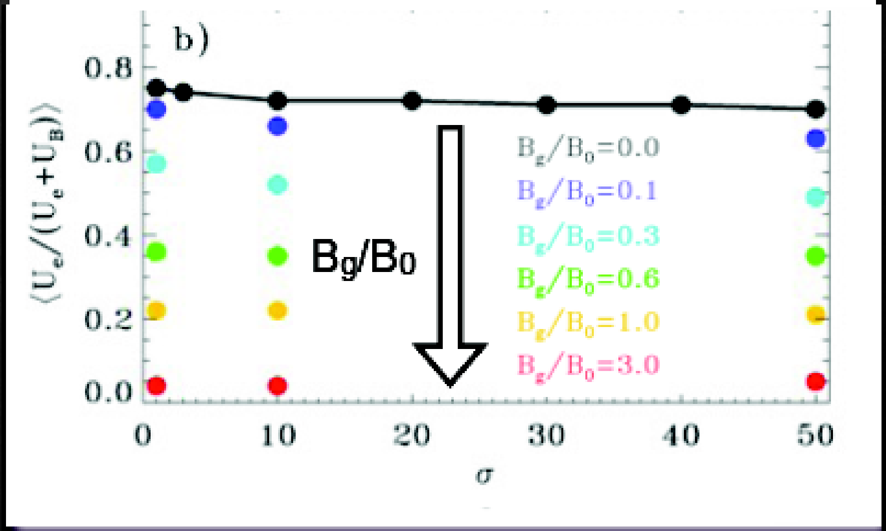
Energy equipartition





Weighted average of the ratio

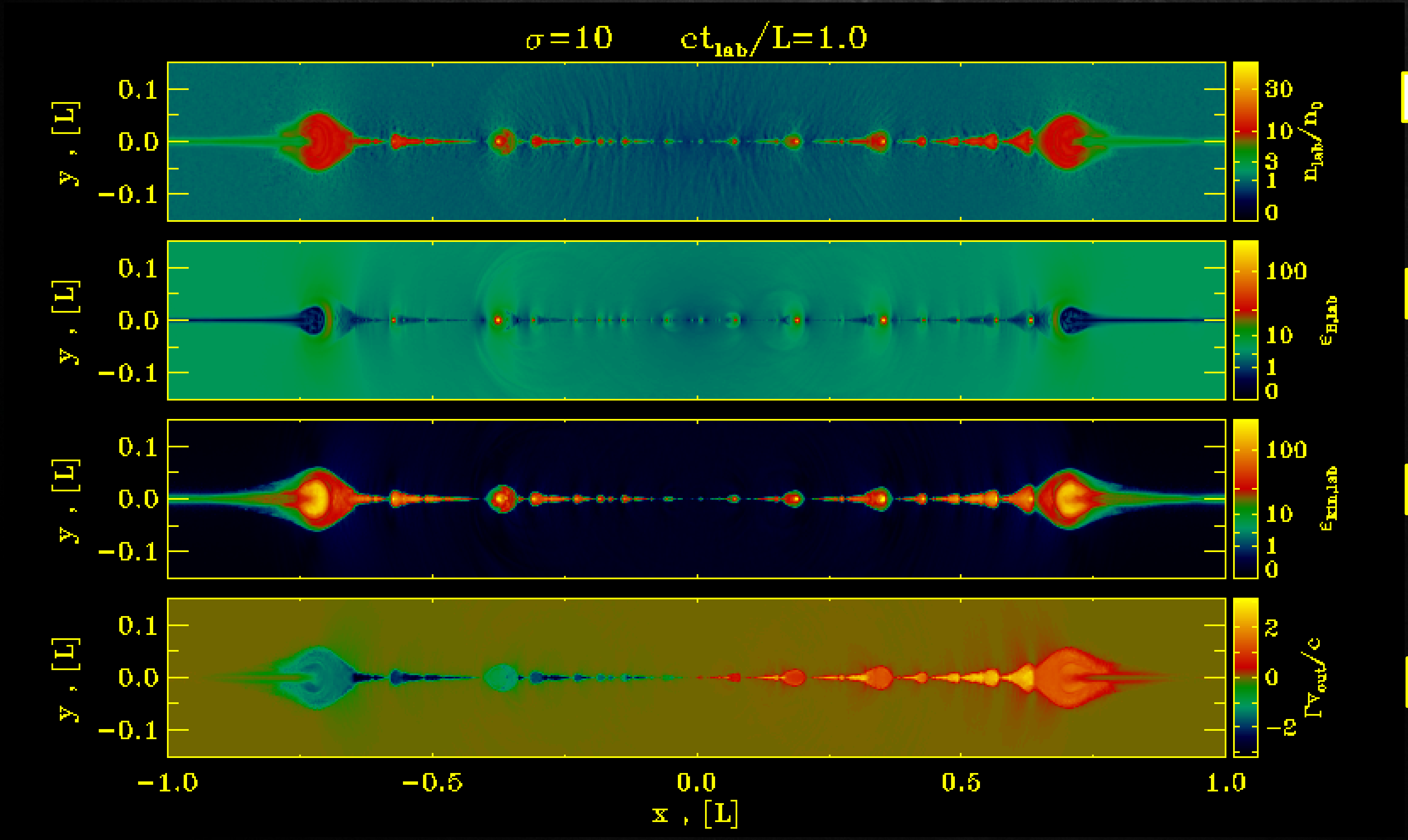
$$\left\langle \frac{U_e}{U_e + U_B} \right\rangle \equiv \frac{\sum_i \int_{V_i} U_e \frac{U_e}{U_e+U_B} dV_i}{\sum_i \int_{V_i} U_e dV_i}$$



- rough energy equipartition between particles and magnetic fields in plasmoids
- for strong guide fields then UB >> Ue in the plasmoids

Plasmoids in reconnection layers

2D PIC simulations of relativistic magnetic reconnection in pair plasma



Density

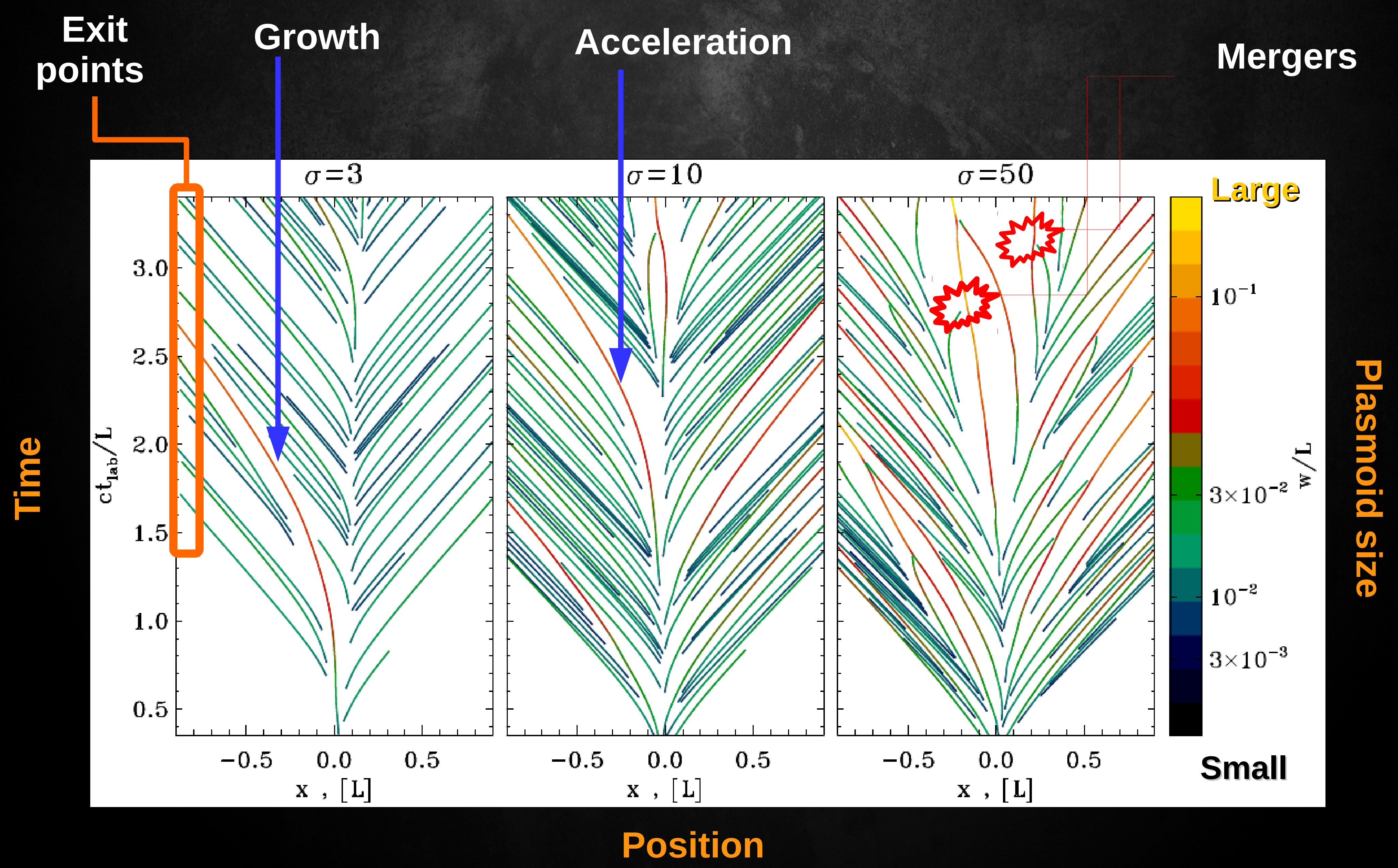
Magnetic energy

Kinetic energy

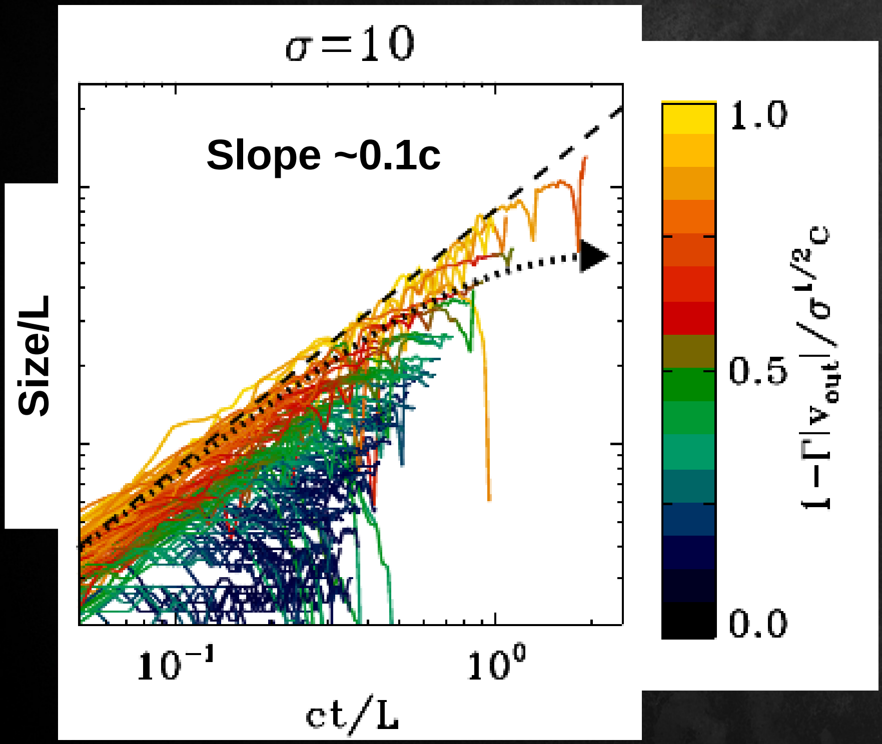
4-velocity

Sironi, Giannios, Petropoulou 2016

The plasmoid tree of life

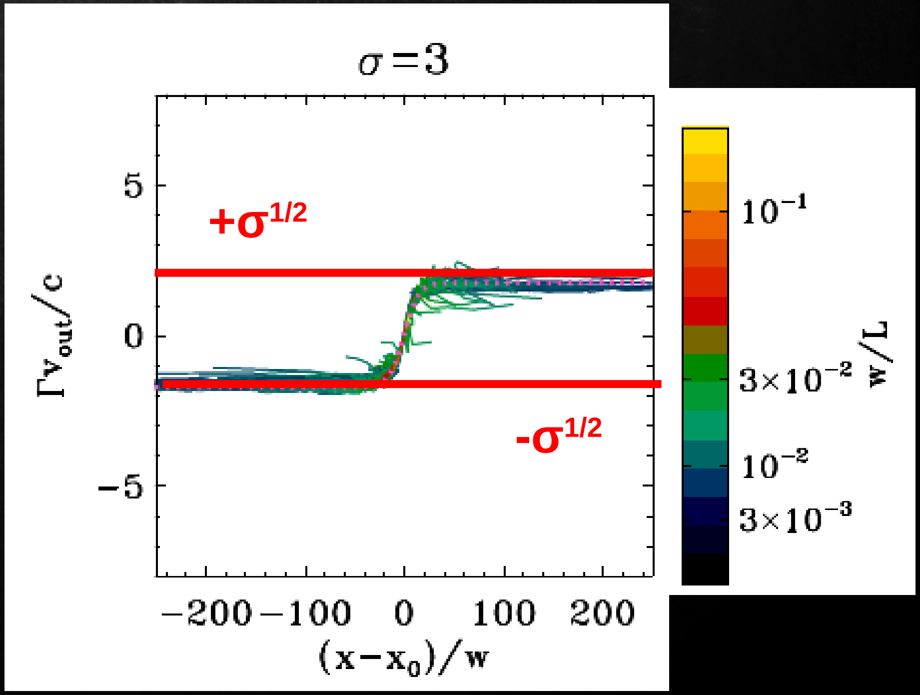


Plasmoid growth & acceleration



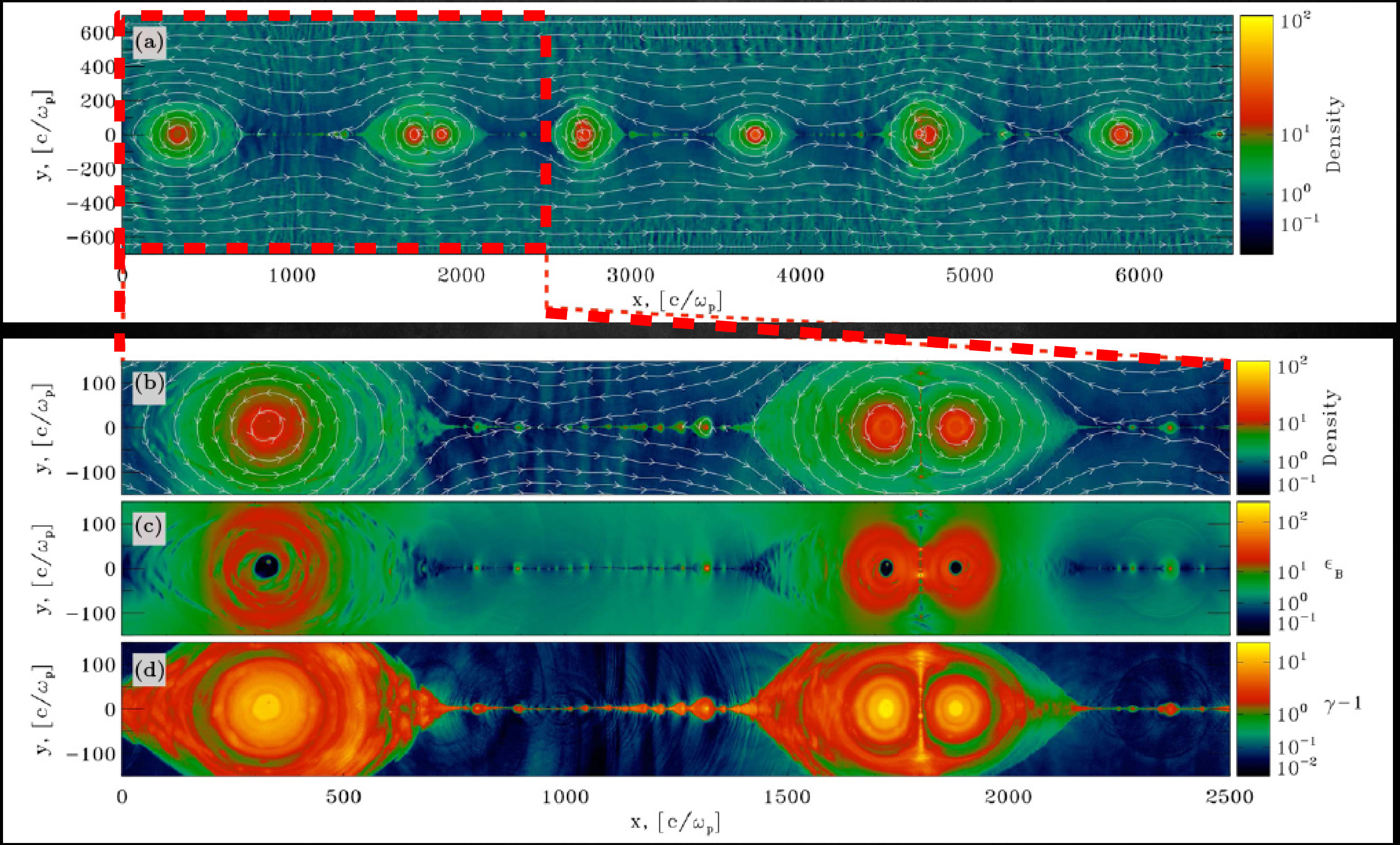
- The plasmoid size grows with constant rate ~0.1 c (as measured in its rest frame)
- The growth rate depends weakly on the magnetization

$$\frac{\Gamma\, v_{out}}{c} \approx \sqrt{\sigma}\,\tanh\left(\frac{0.1\,x}{\sqrt{\sigma}\,w}\right)$$



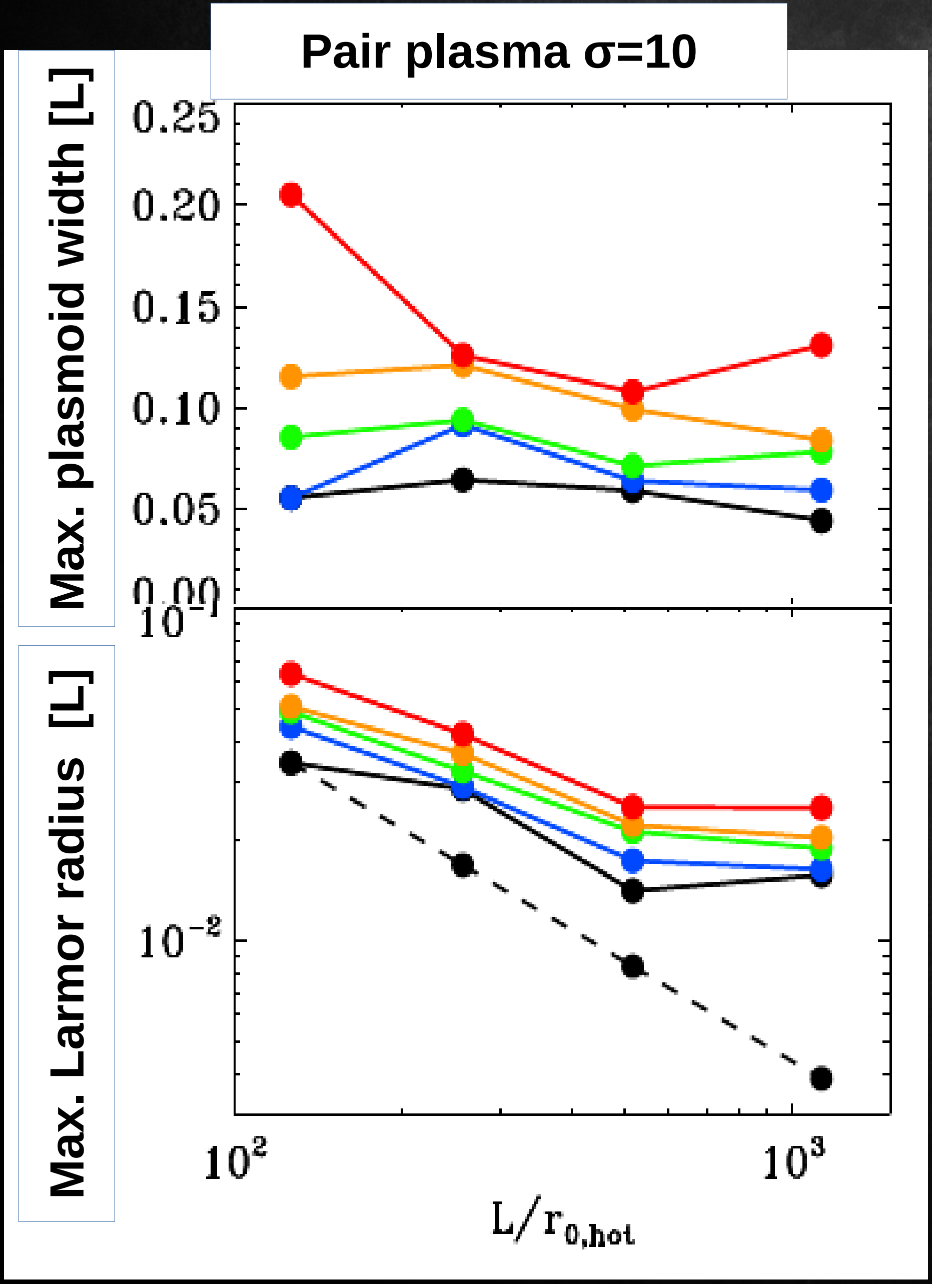
- “Universal” acceleration profile due to magnetic forces
- Smaller plasmoids are faster
- Biggest plasmoids move with non-relativistic speeds

Self-similarity



Sironi & Spitkovsky 2014; Sironi, Petropoulou, Giannios 2015

Scalings with the system size

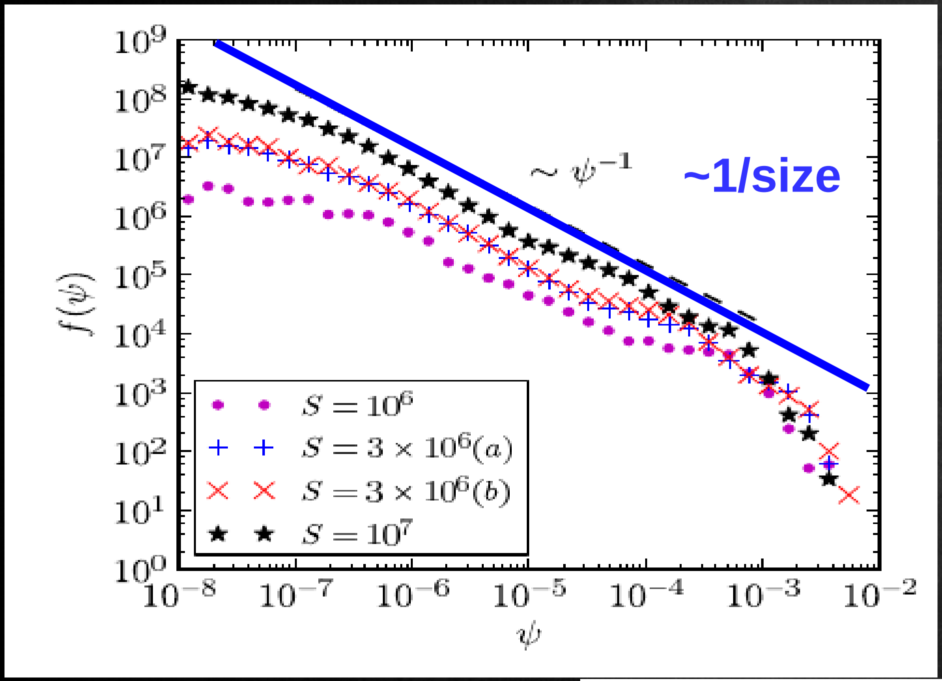


$$r_{L,hot} = \sigma \frac{m_e c^2}{eB_0} = \sqrt{\sigma} \frac{c}{\omega_p}$$

- The max. plasmoid size is always a fraction (~10%-20%) of the layer's length
- The max. Larmor radius is a constant fraction (~3%-5%) of the layer's length
- This holds for large enough systems: L >> $r_{L, hot}$
- Scalings can be used to extrapolate to larger systems

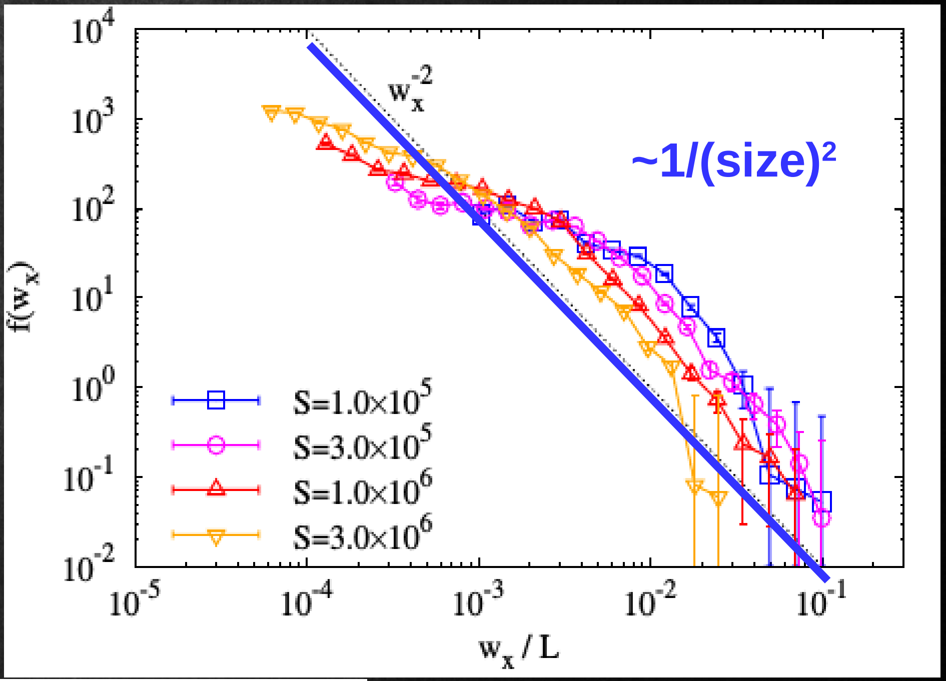
Plasmoid distributions

(Huang et al 2012, 2013)



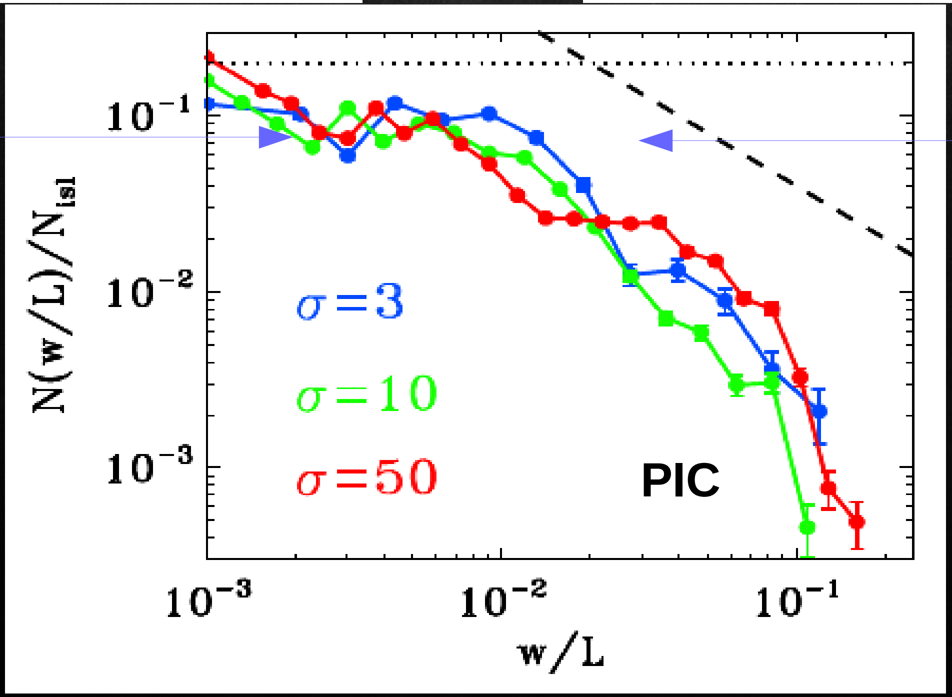
OR

(Uzdensky et al 2010; Loureiro et al 2011)



~1/size

~1/(size)²



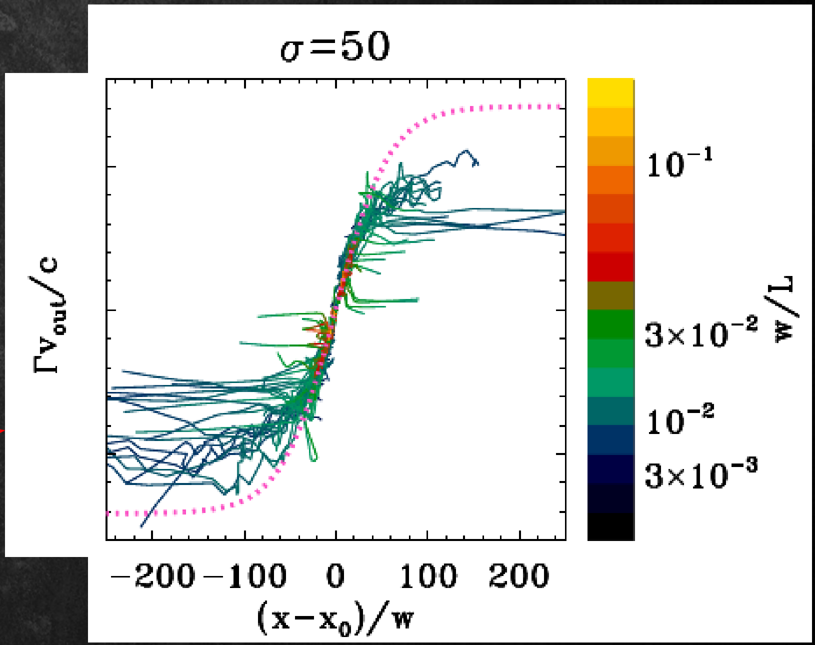
How do we understand PIC results ?

Sironi et al 2016

A Monte-Carlo approach

* Mimics the plasmoid dynamics as obtained from 2D PIC simulations

* Study many realizations of the layer



Included processes are:

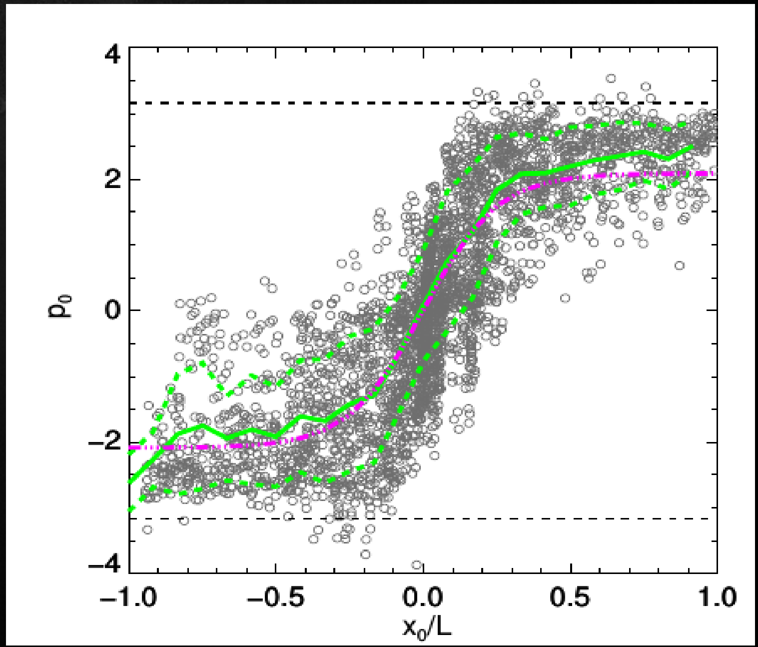
* Plasmoid acceleration NEW

* Plasmoid growth & suppression NEW

* Size & position-dependent initial 4-vel NEW

* Plasmoid mergers

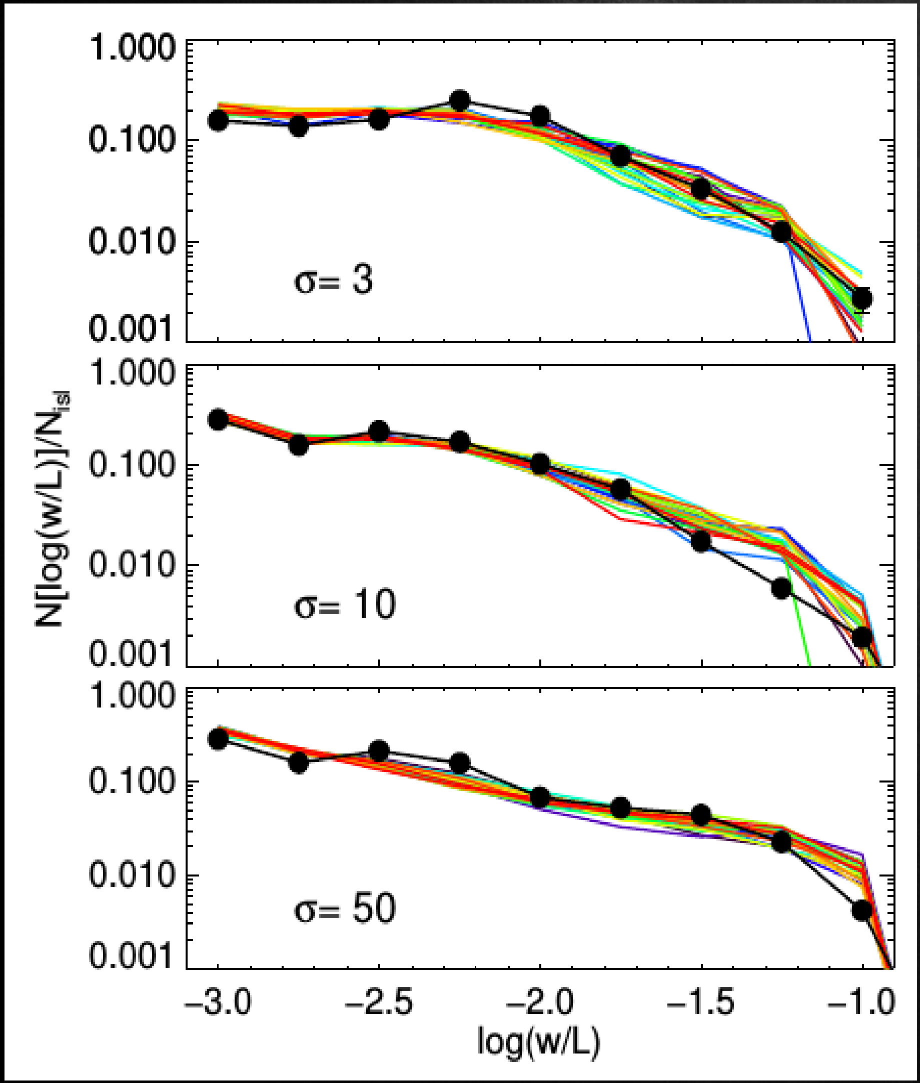
* Plasmoid advection



Petropoulou+2018

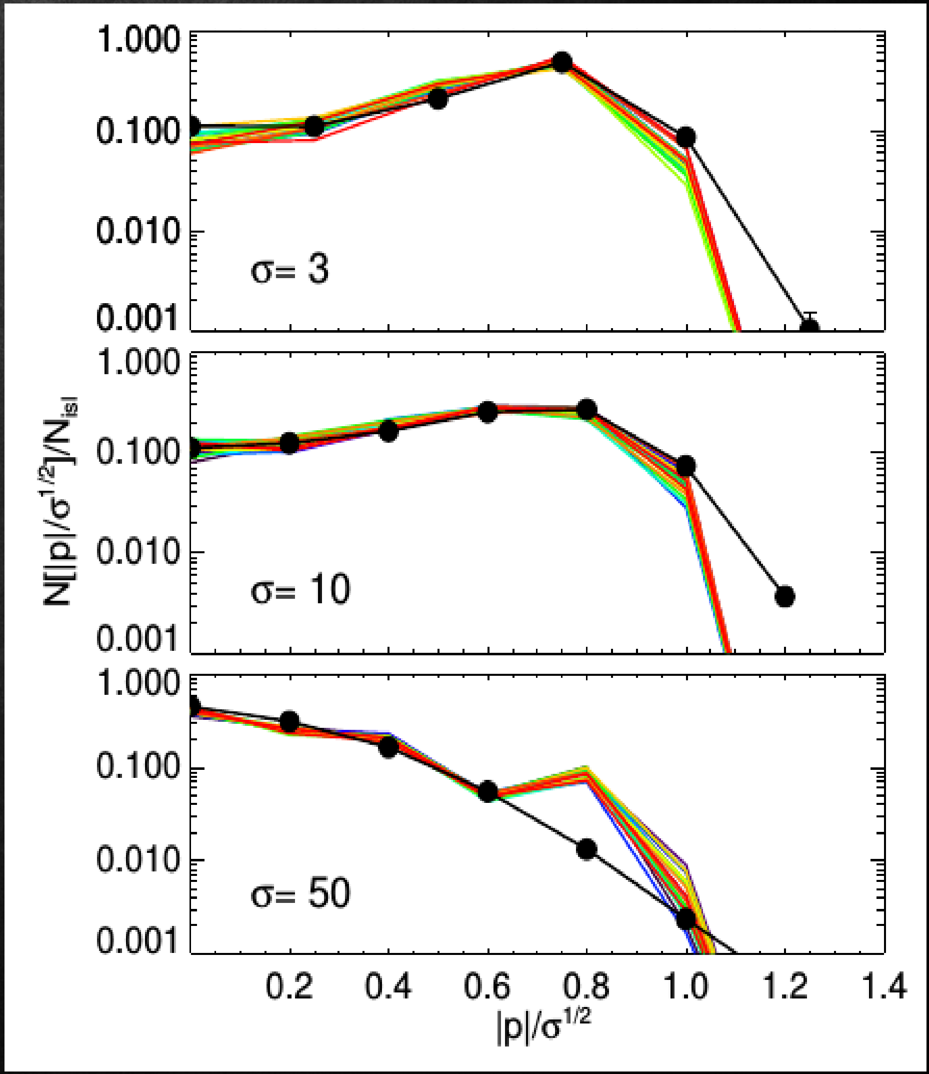
Comparison to PIC results

"Benchmarked"



Distribution of sizes

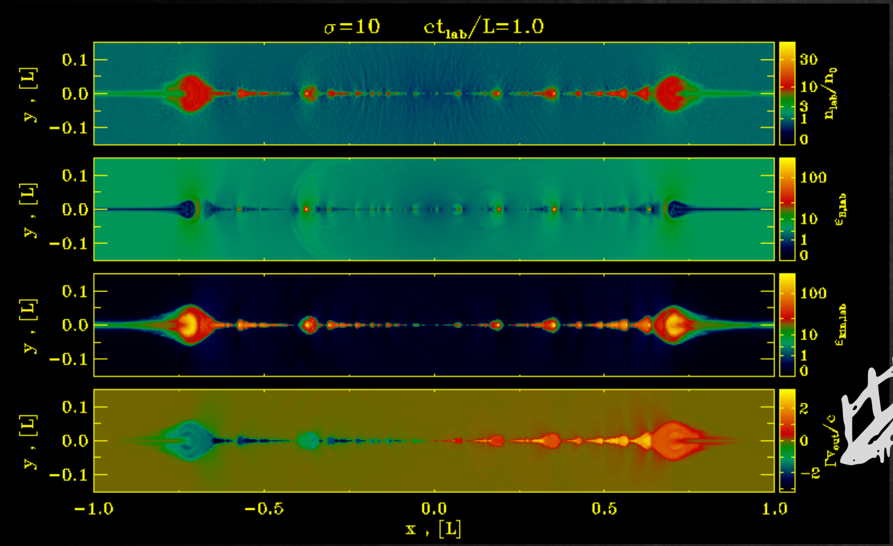
"Predicted"



Distribution of 4-velocities

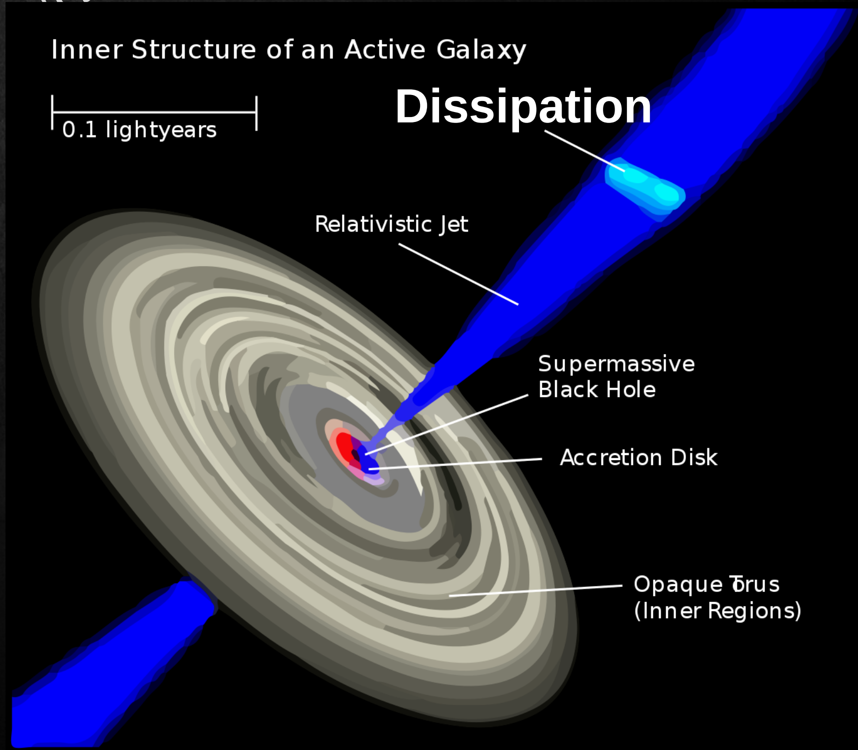
Petropoulou+2018

From microscoPIC to large scales

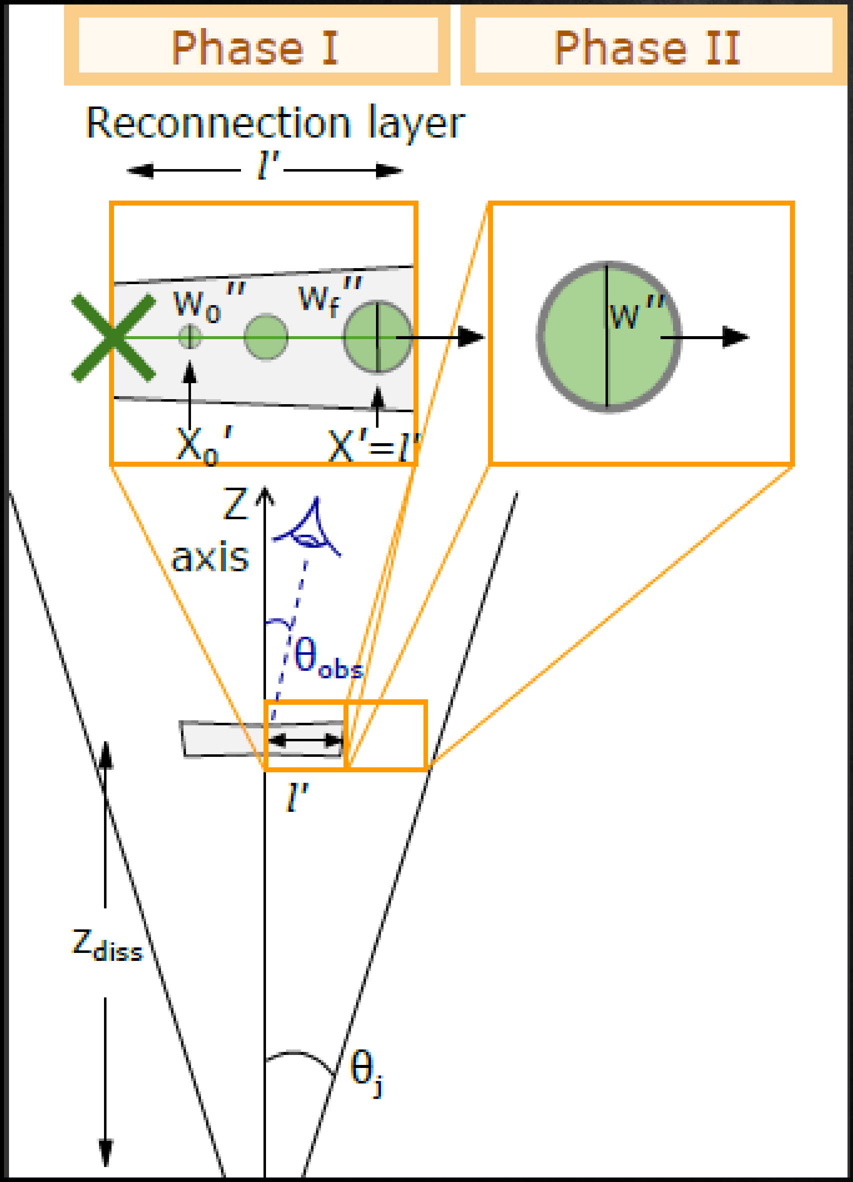


Self-similarity

Extrapolation to large scales



Radiation from a single plasmoid

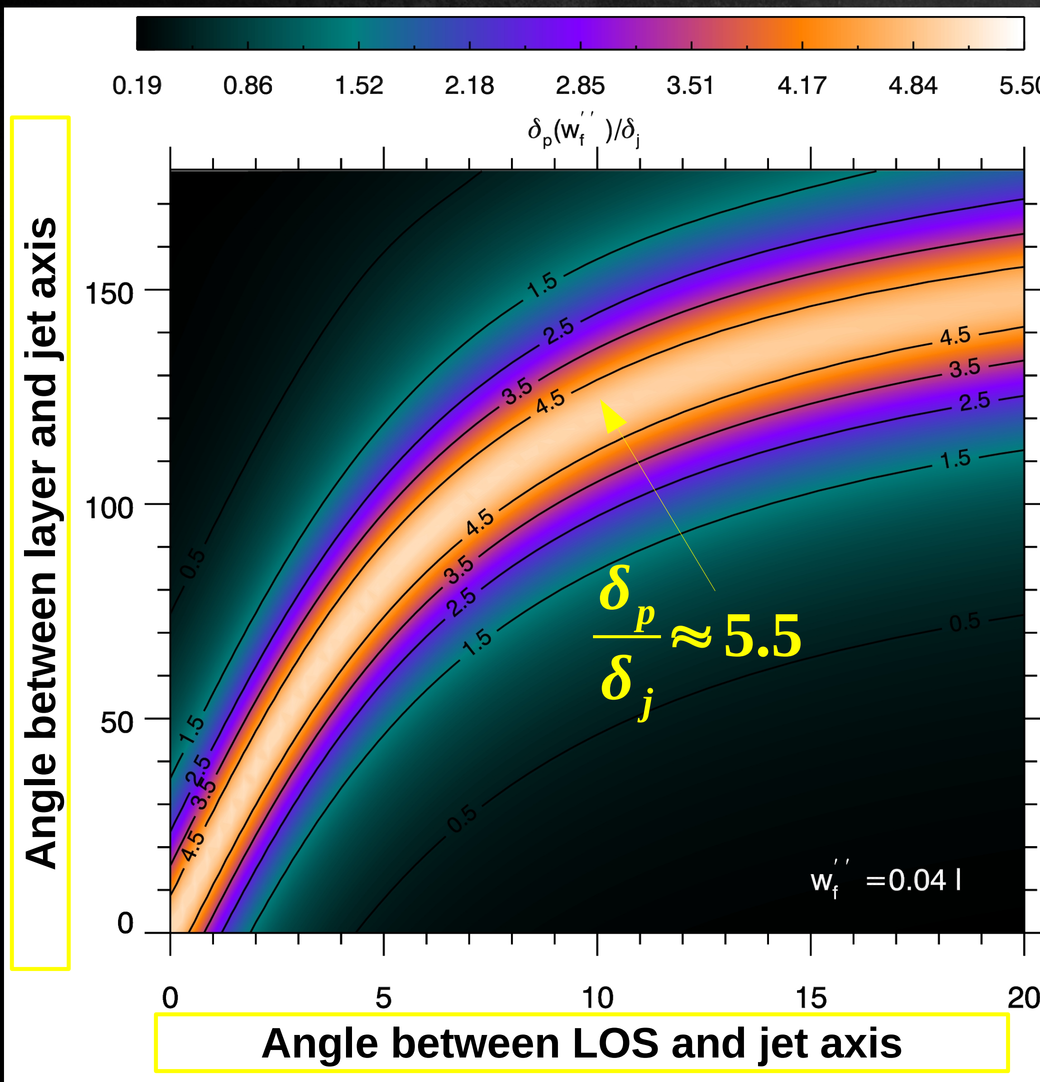


- Plasmoids are quasi-spherical structures
- Plasmoid growth depends on σ.
- Plasmoids accelerate while smaller.
- Smaller plasmoids → faster
- Larger plasmoids → slower
- Particle density & B-field ~ constant
- Particle distribution ~ isotropic in larger plasmoids

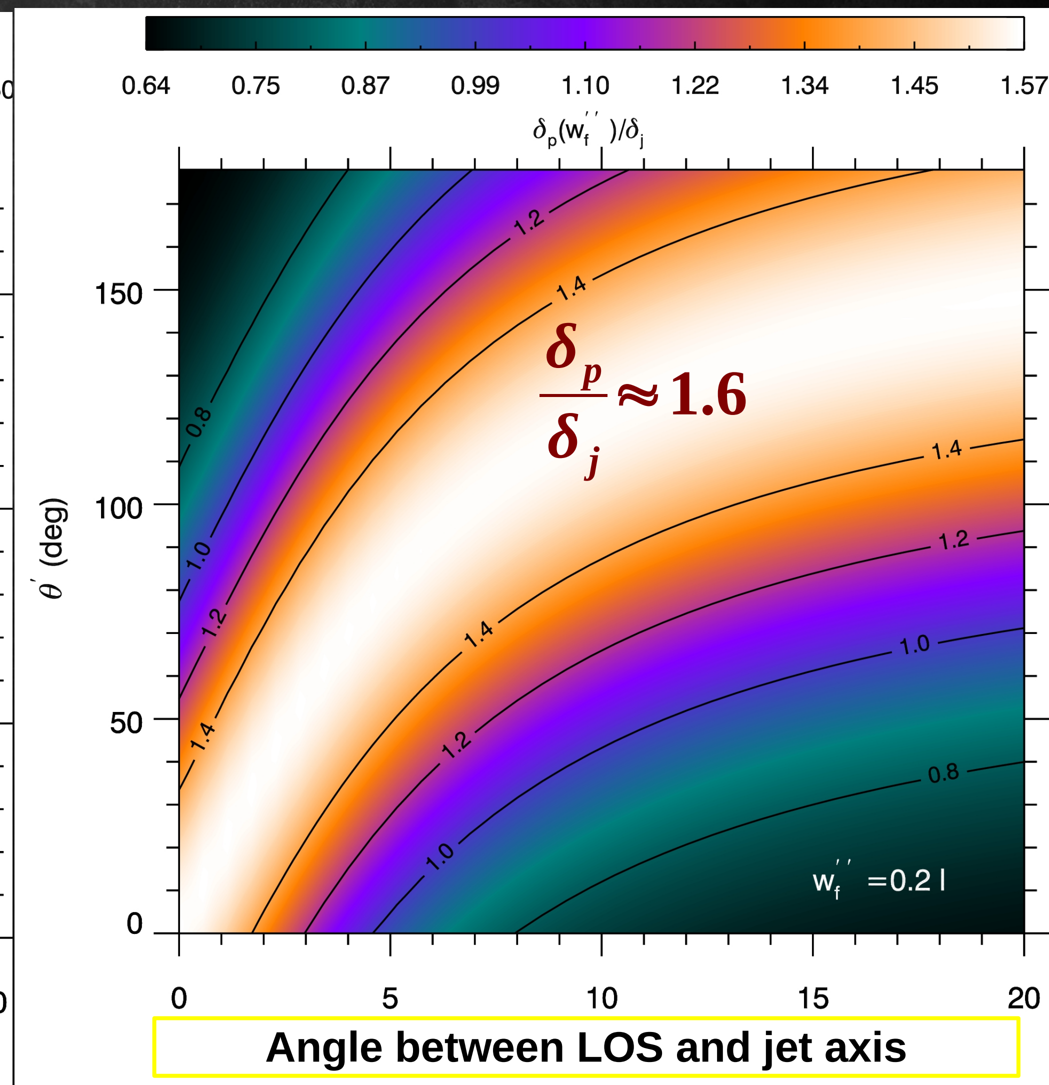
Doppler factor

$$\delta_p = \frac{1}{\Gamma_p\left(1 - \beta_p \cos\omega\right)} \Big/ \delta_j = \frac{1}{\Gamma_j\left(1 - \beta_j \cos\theta_{obs}\right)}$$

Small & Fast



Large & Slow



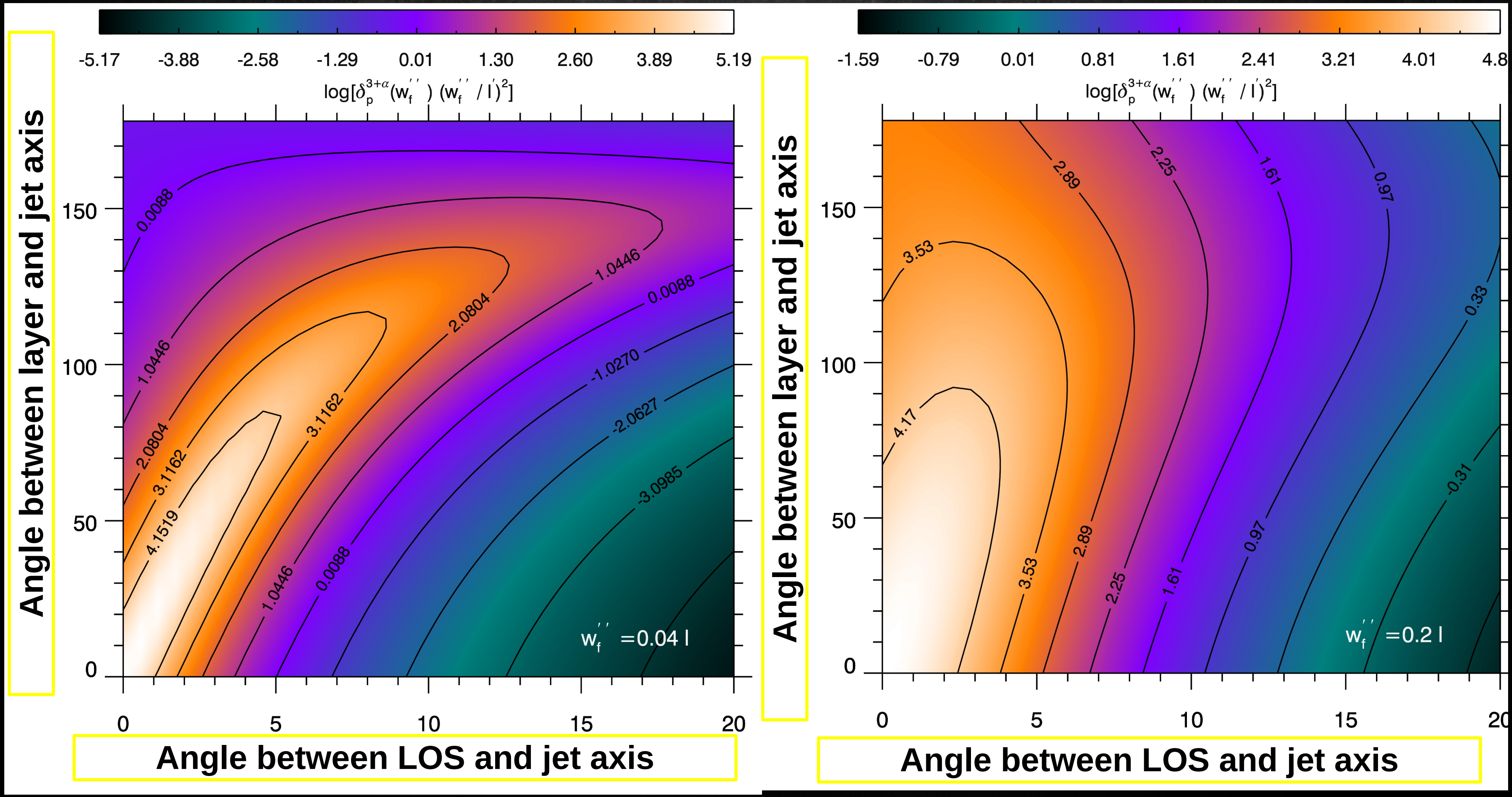
Peak Flare Luminosity

Luminosity depends on:

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

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

Small & Fast **Large & Slow**



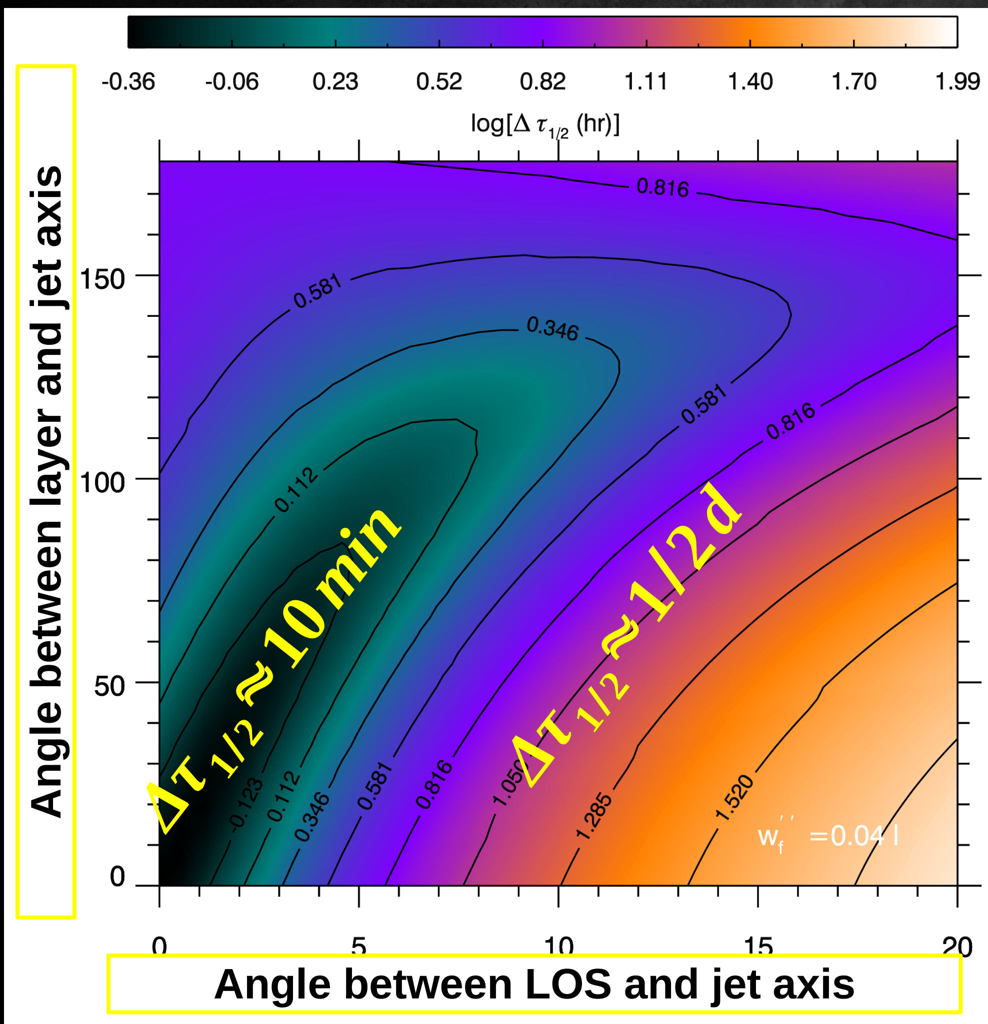
Flux-doubling timescale

It depends on:

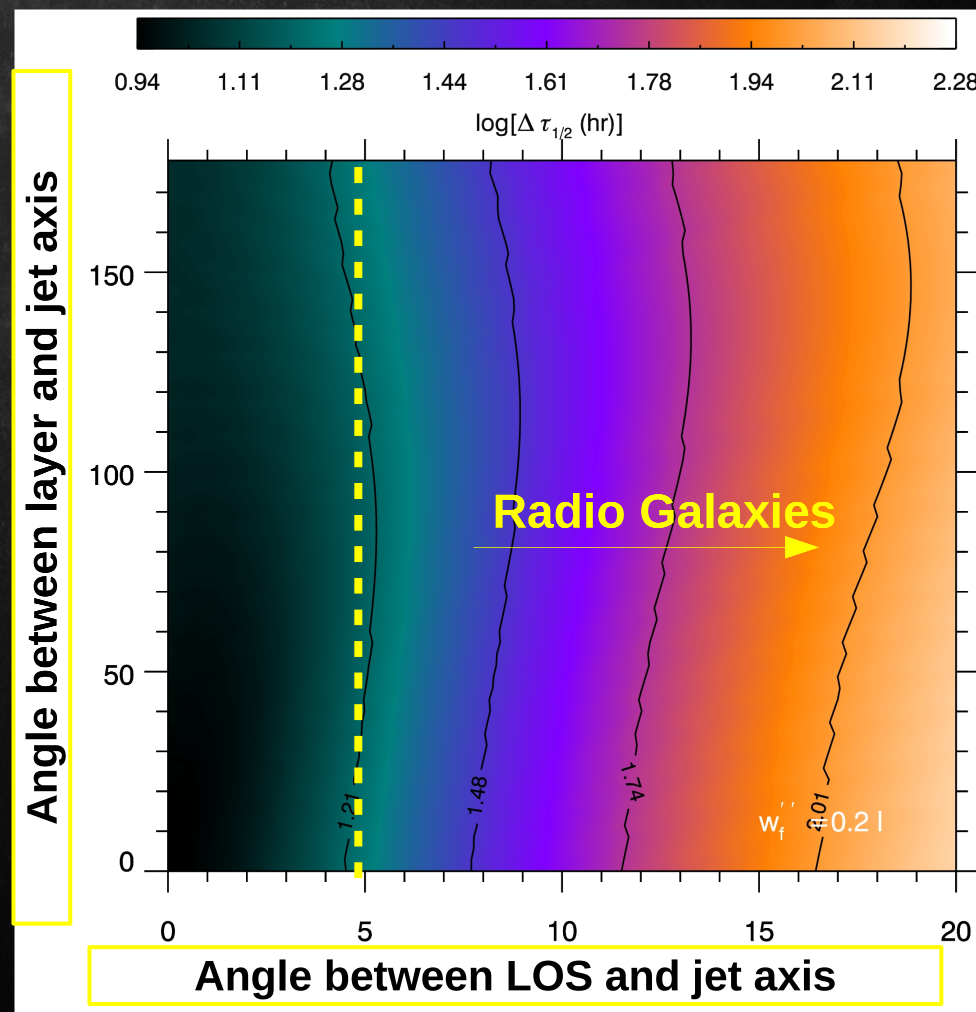
- Acceleration profile of plasmoid
- Final Doppler factor

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

Small & Fast



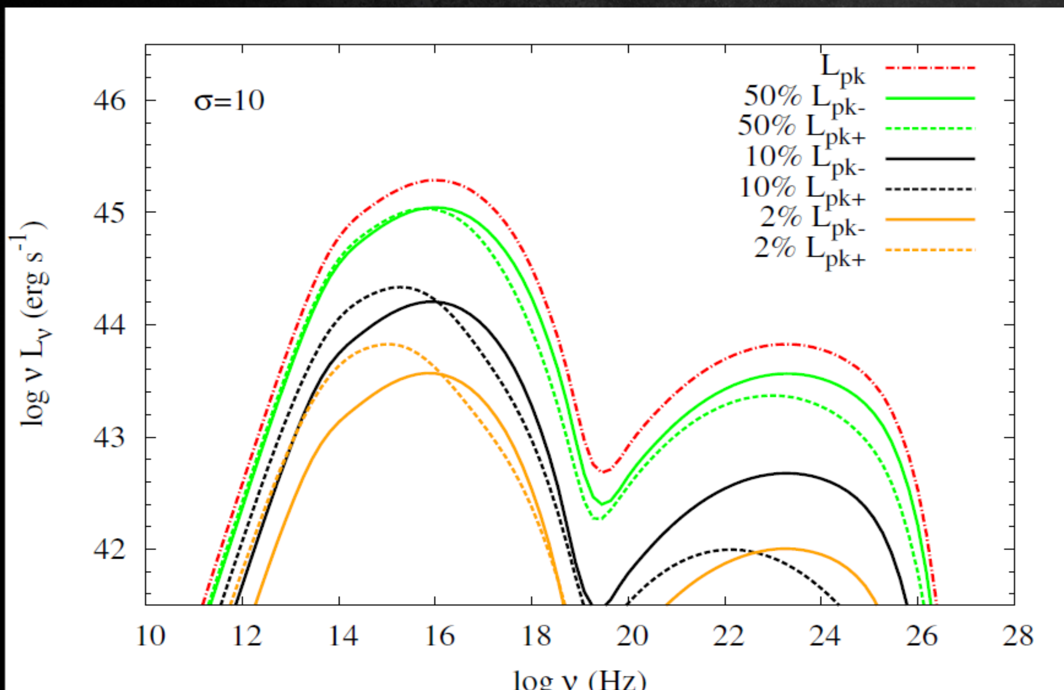
Large & Slow



Radiation from a single plasmoid

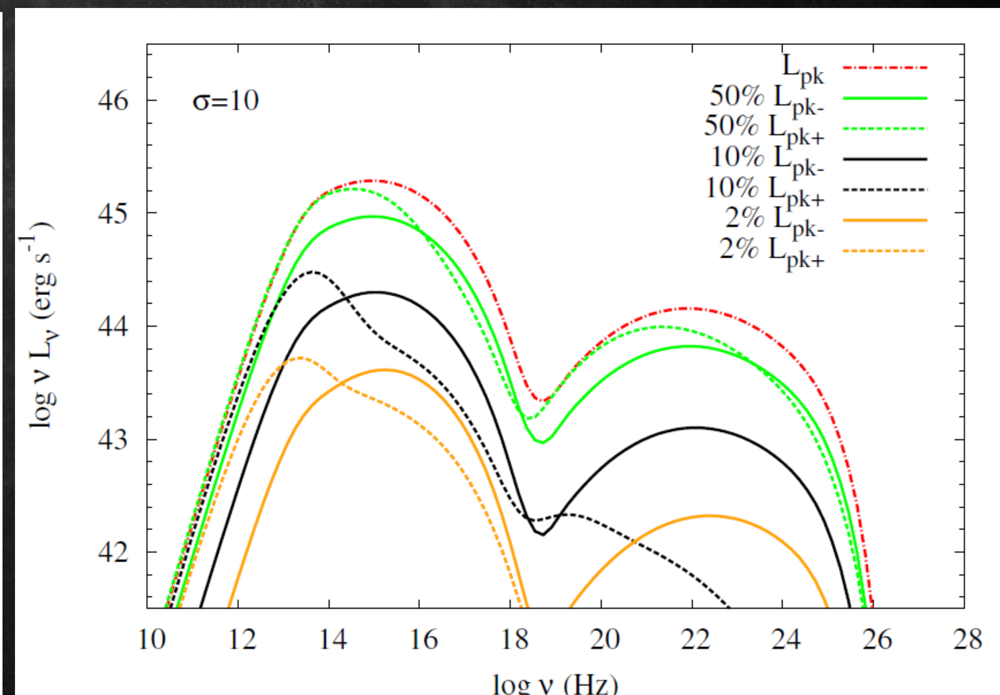
Benchmarked with PIC: plasmoid growth & acceleration, properties of accelerated particles

Small & Fast



Minute-scale duration!

Large & Slow



Hour-scale duration

Peak luminosity ~ size^2 * Doppler^4

Duration ~ size / Doppler

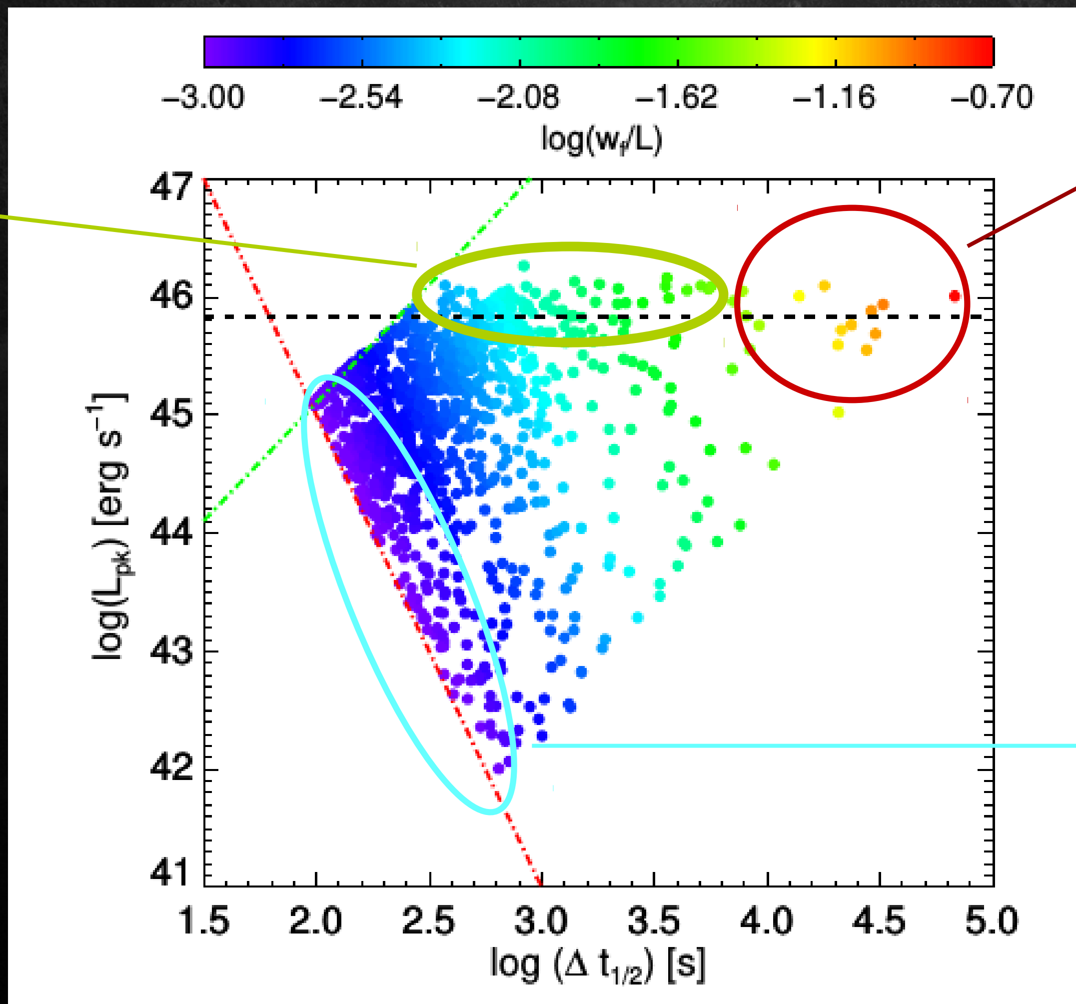
Petropoulou, Giannios & Sironi 2016

Statistics of flares

Estimates for a single plasmoid ➕ Plasmoid chain statistics

- Several luminous flares
- Range of durations
- Range of sizes

Peak flare luminosity



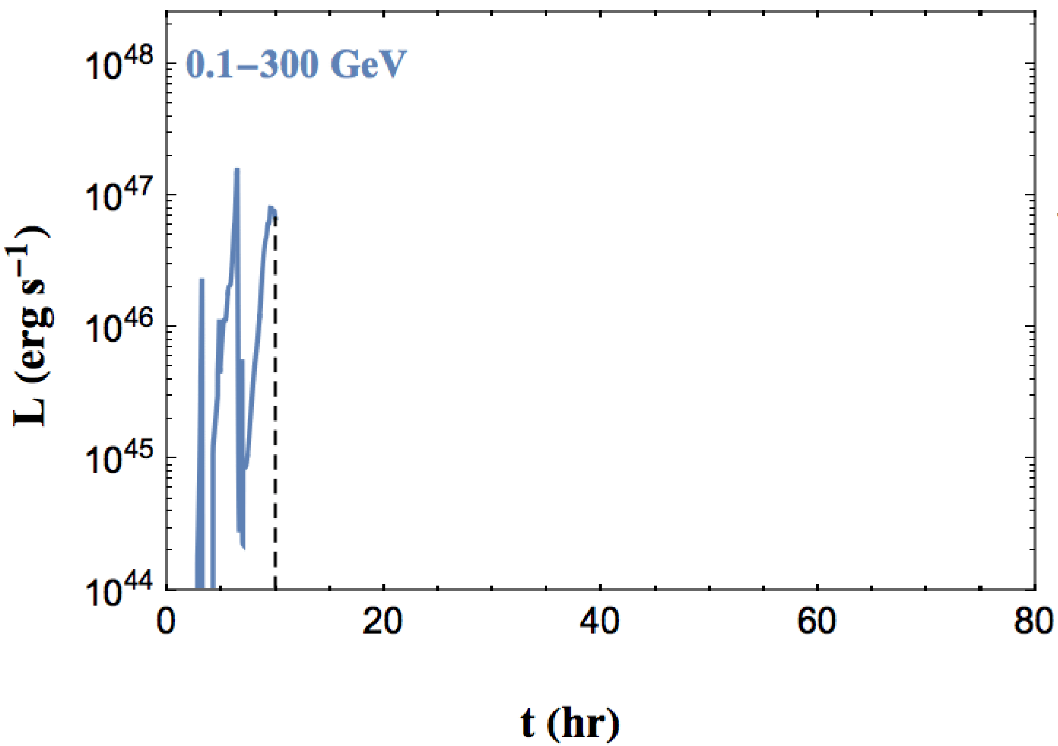
Flare duration

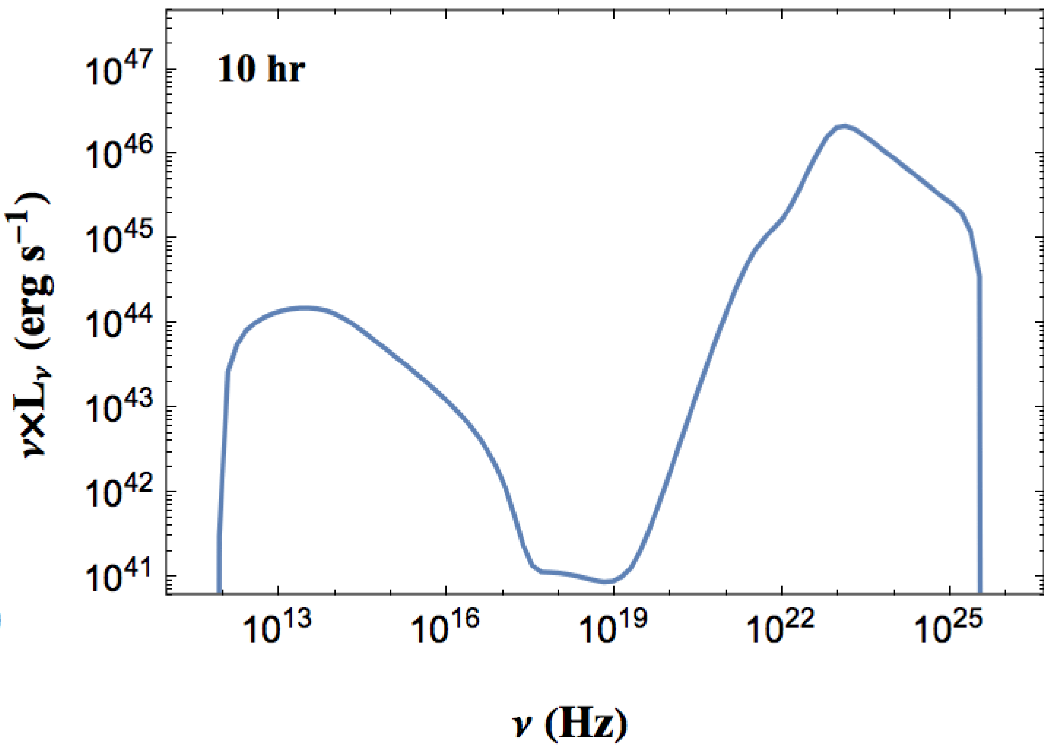
- Few luminous & long flares
  - Powered by “monster” plasmoids
- Numerous low-luminosity & short flares
  - Powered by the smallest plasmoids

Radiation from the whole layer

GeV light curve

Multi-wavelength spectrum





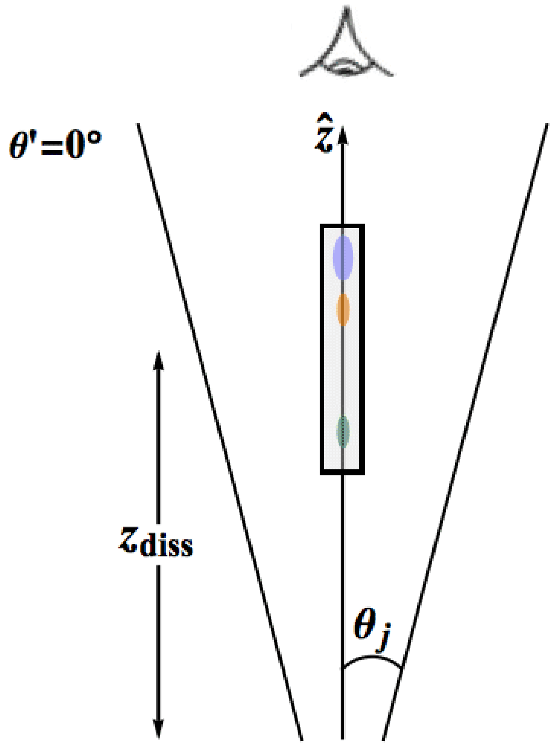
Time [hr]

Frequency [Hz]

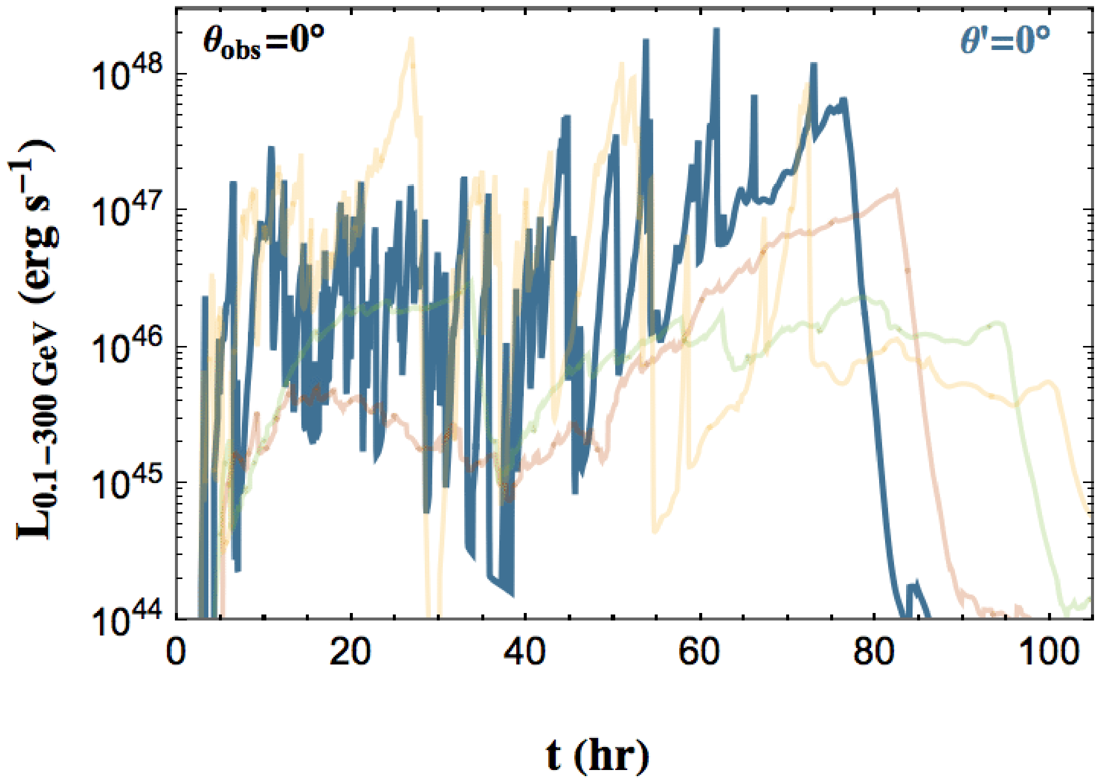
(Christie, Petropoulou+, in prep.)

Orientation of the layer

Layer in Jet



GeV light curve



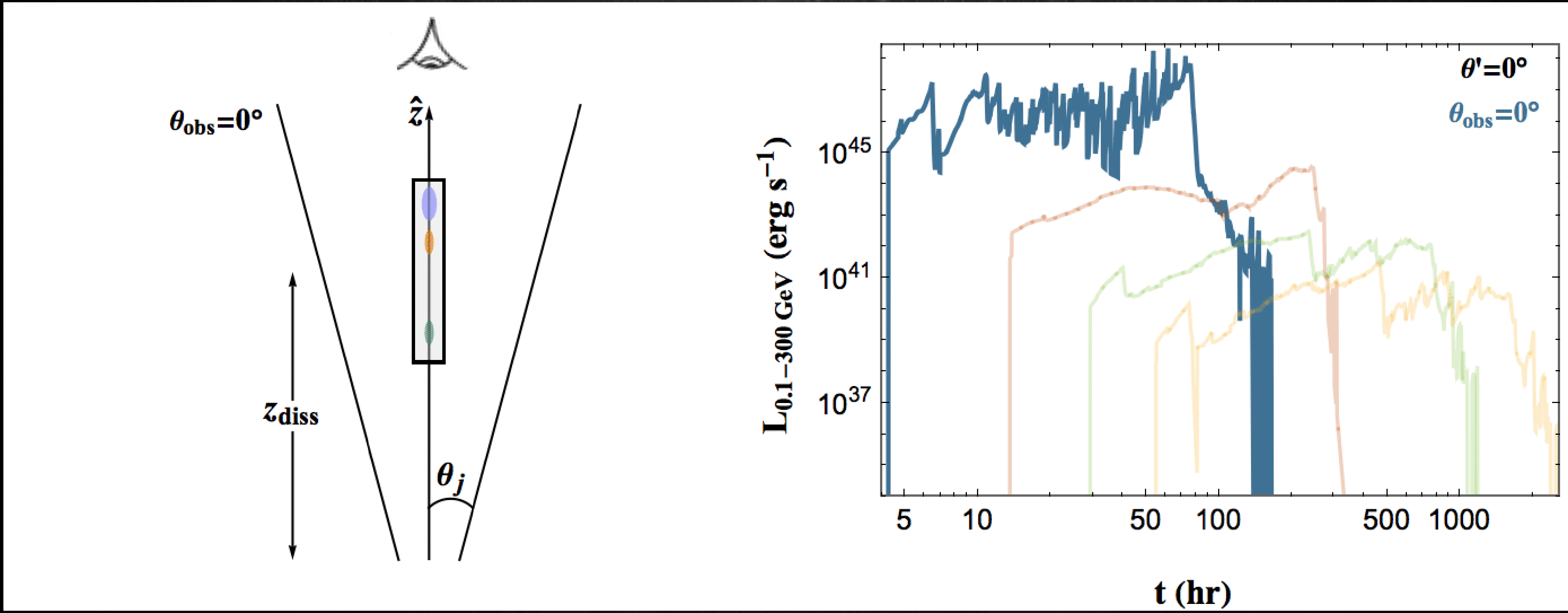
Time [hr]

(Christie, Petropoulou+, in prep.)

Observer's angle

Layer in Jet

GeV light curve



Time [hr]

Open issues...

Reconnection in 3-D

* What are the statistical properties of the plasmoid chain?
* What is the geometry of the emitting regions?
* What about polarization signatures?

Location of dissipation region

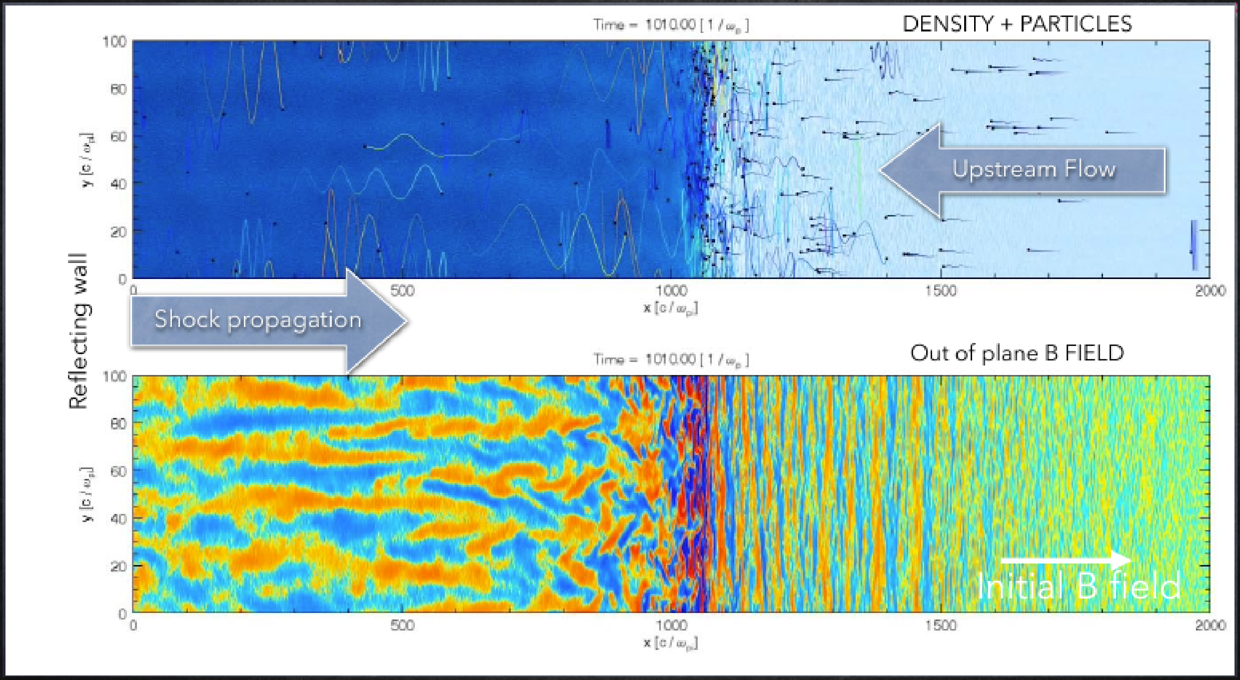
* Where in the jet does the dissipation take place?
* What is the local plasma magnetization, guide field etc?
* Do we expect one or multiple reconnection layers?
* What happens to the plasmoids after they are advected from the layers?
* Is there a connection between gamma-ray and radio flares?

Plasma composition & collisions

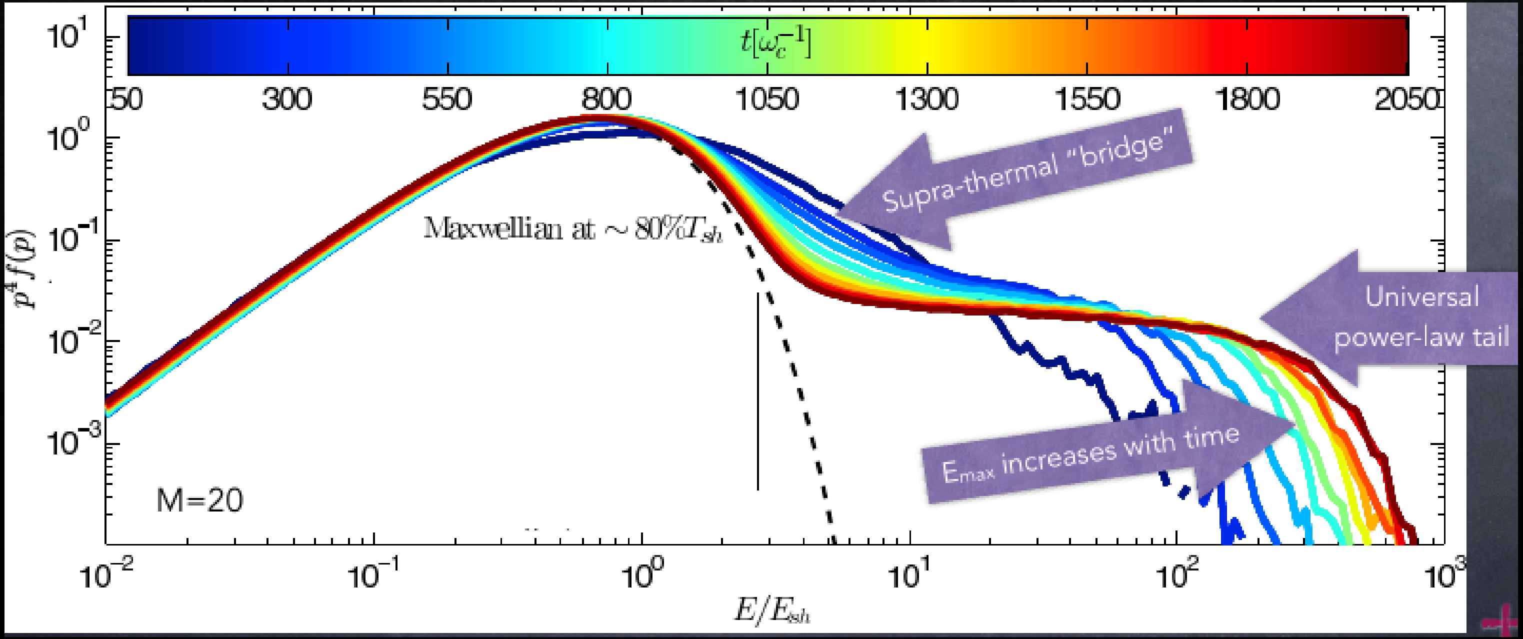
* Are the accelerated particle distributions affected by the composition of the plasma?
* Are the dynamics of the reconnection (especially in 3D) change when different particle species are included?
* Can we implement photo-hadronic interactions in PIC???

Back-up slides

Non-relativistic magnetized shocks

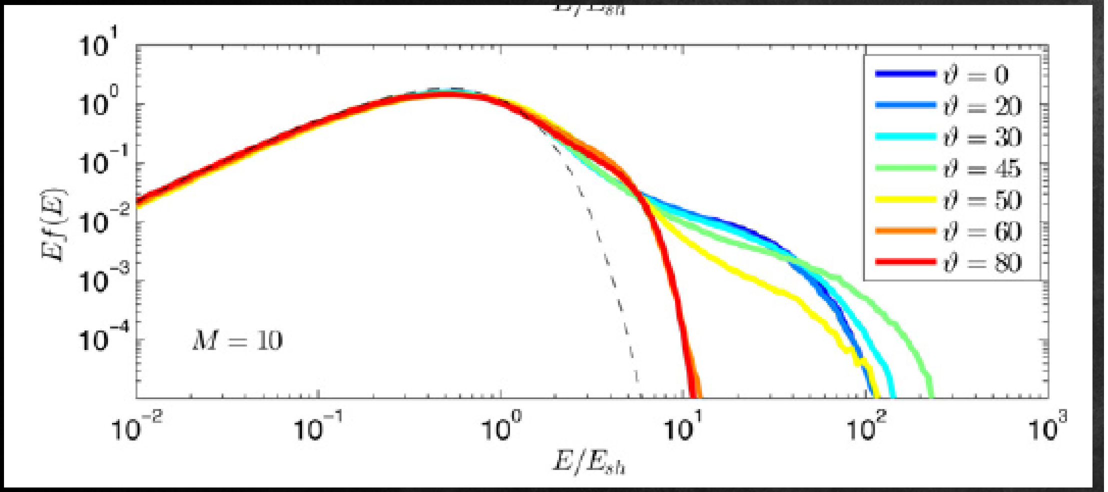


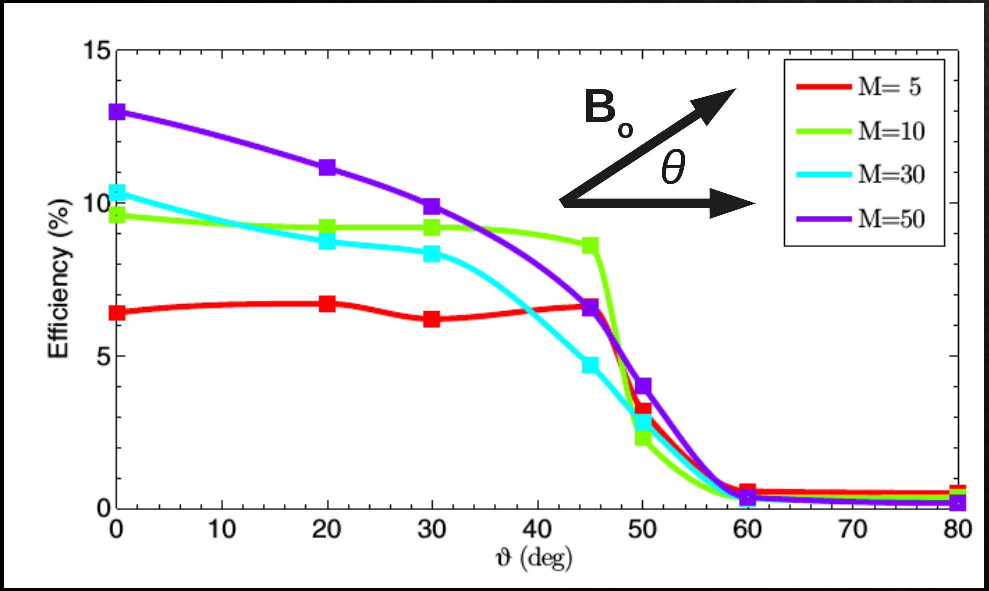
Downstream spectrum

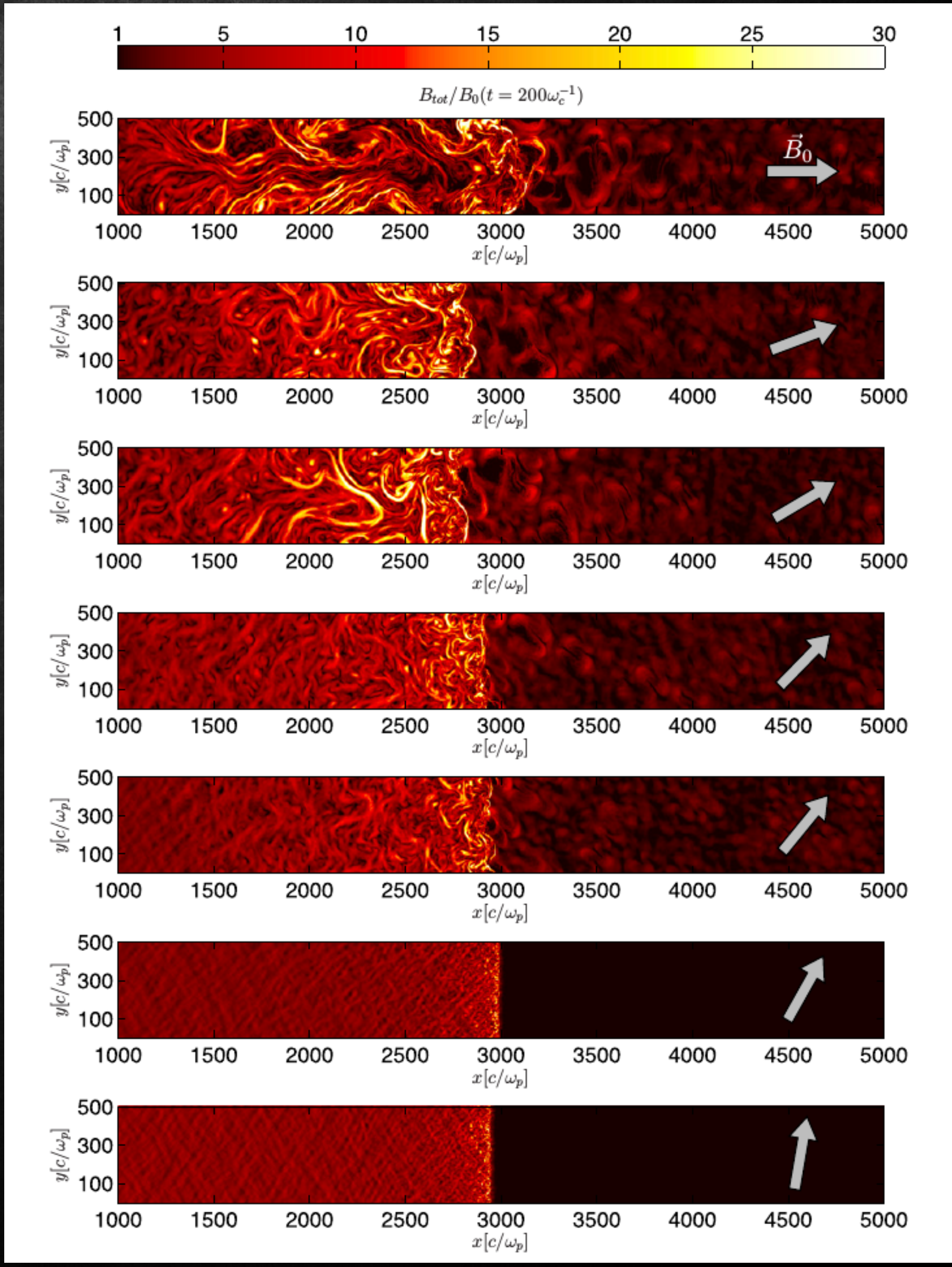


Caprioli & Spitkovsky 2014

Parallel vs oblique shocks

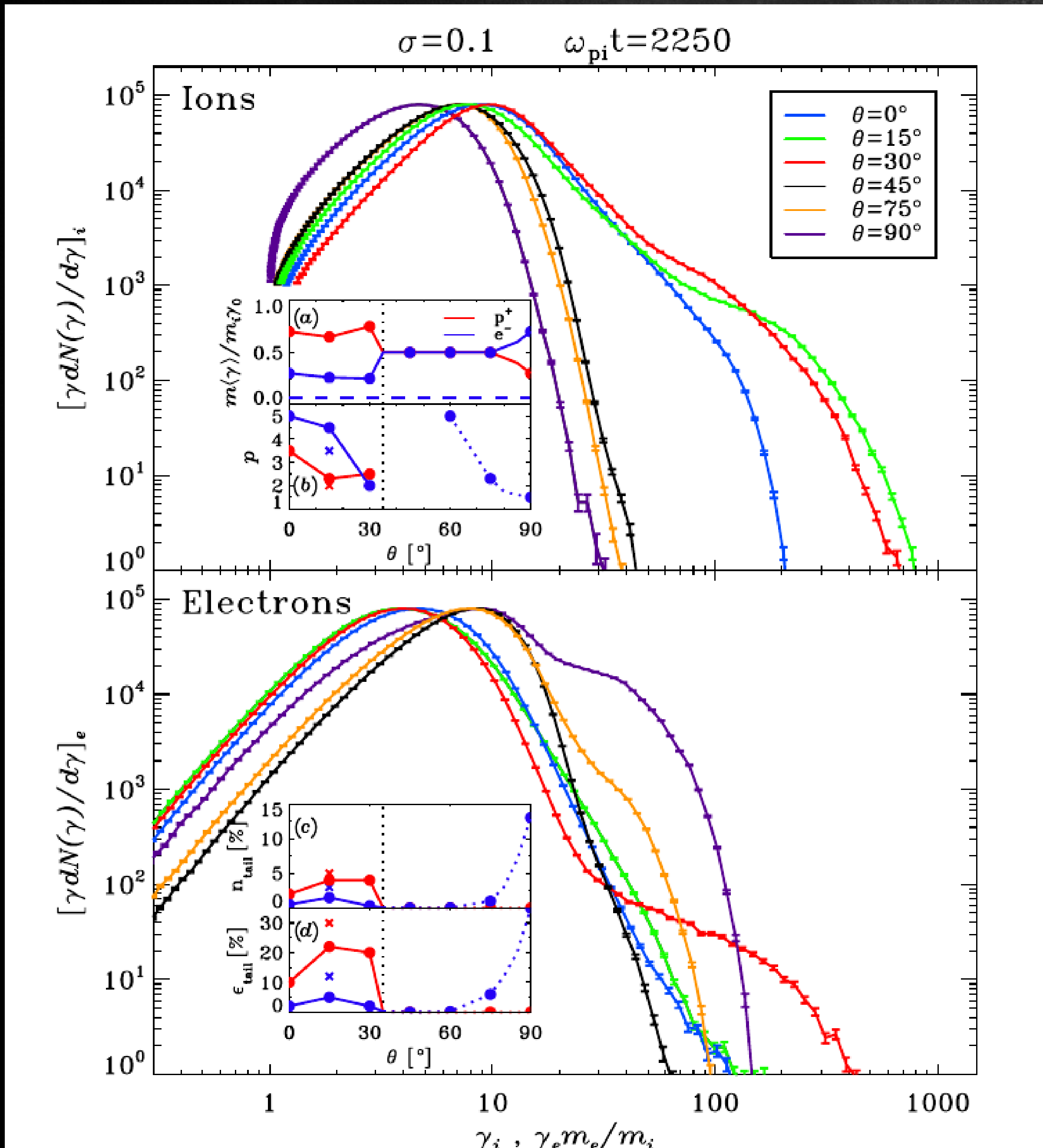




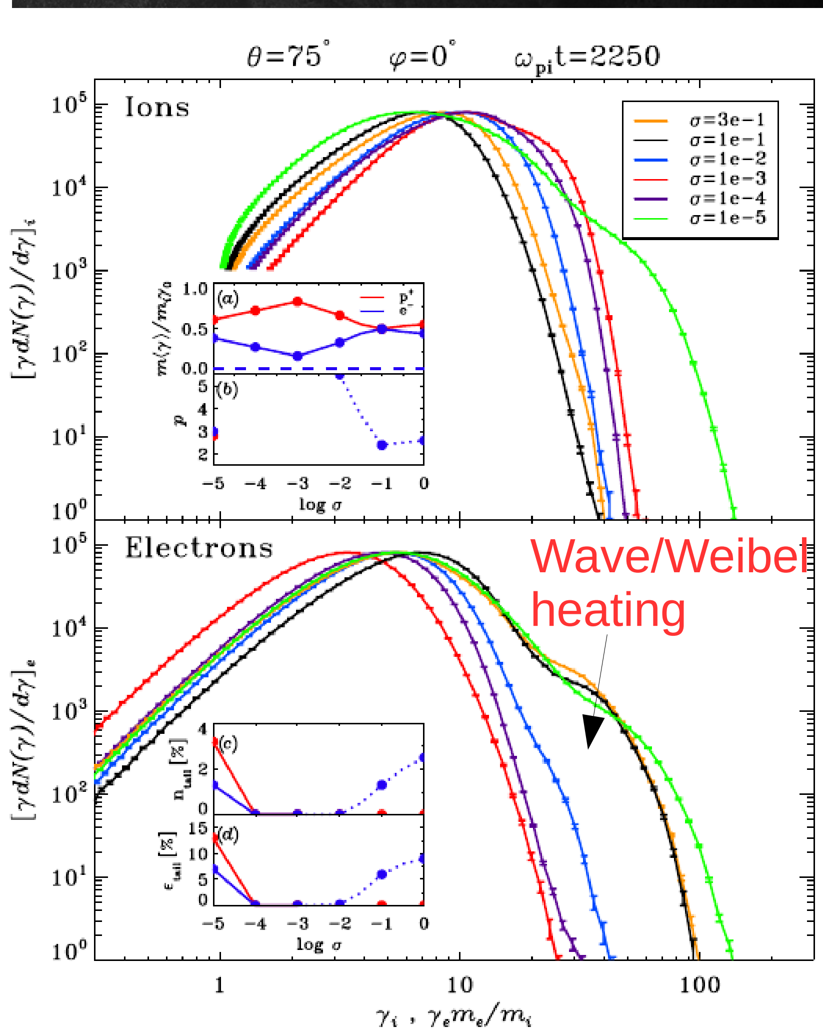


Caprioli & Spitkovsky 2014

Relativistic magnetized shocks

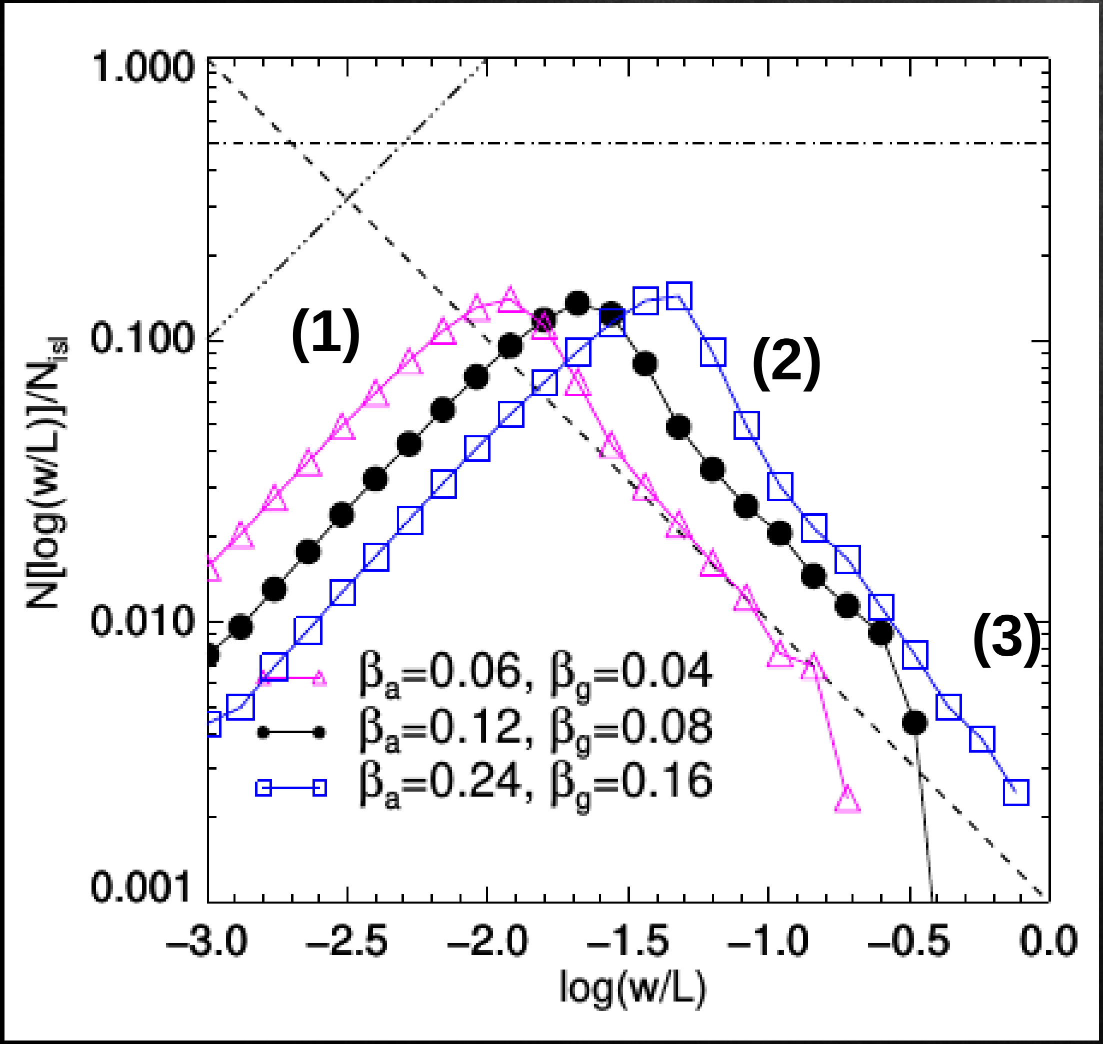


Suppression of particle acceleration for super-luminal oblique shocks *(e.g. Kirk & Heaven 1987, Begelman & Kirk 1990; Sironi & Spitkovsky 2009)*



Sironi & Spitkovsky 2011

Plasmoid acceleration



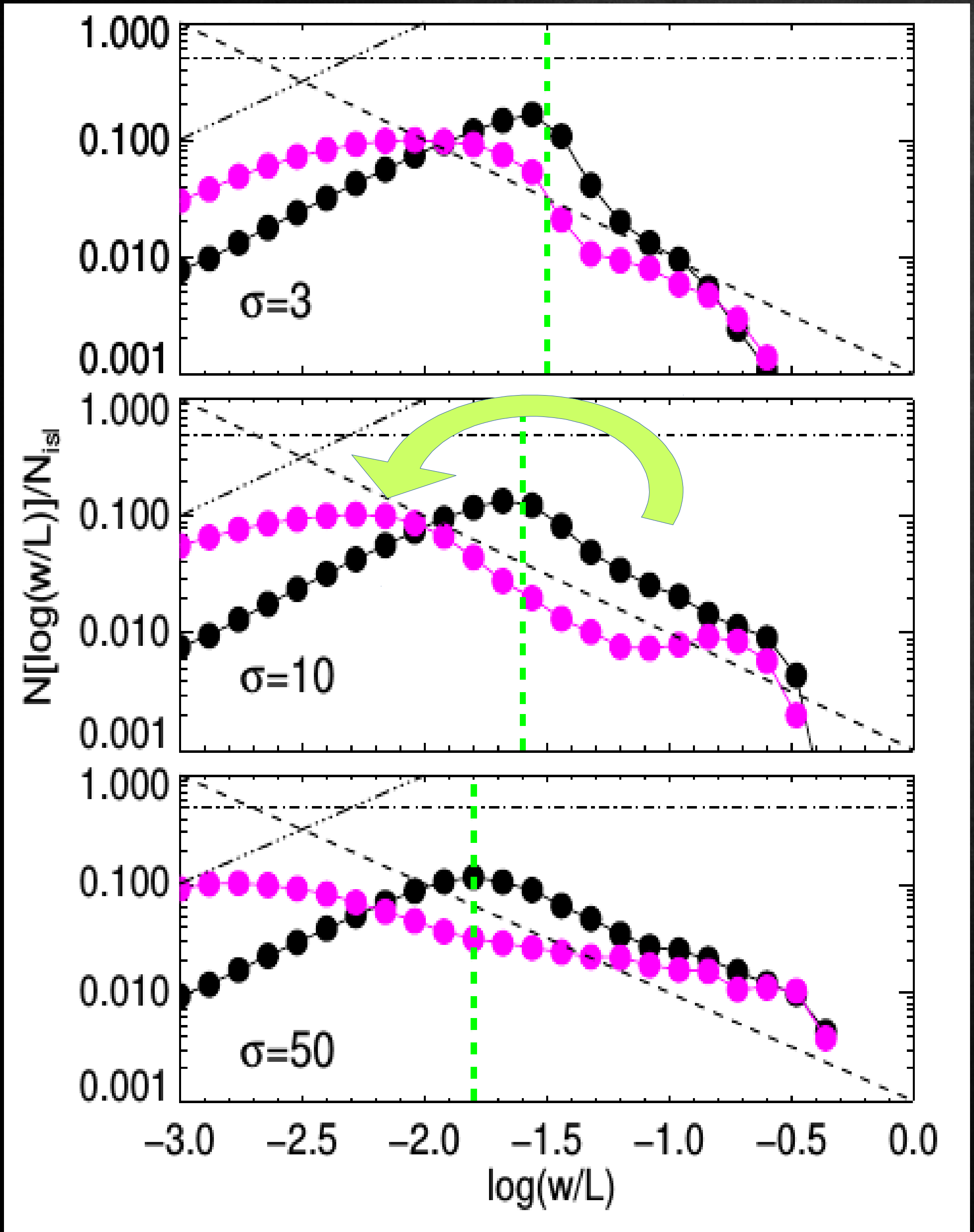
(1) Plasmoids moving with the Alfven speed (relativistic)

(2) Accelerating plasmoids (mildly relativistic)

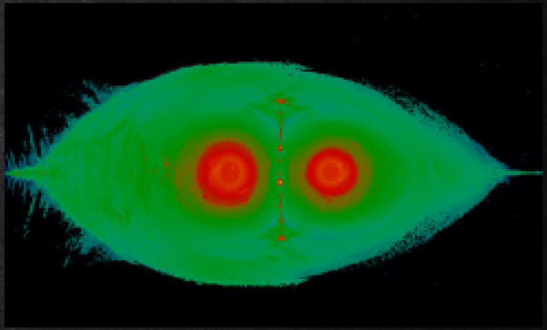
The slope depends on the ratio of acceleration-to-growth rates

(3) Plasmoids with constant speed (Non-relativistic)

Plasmoid mergers

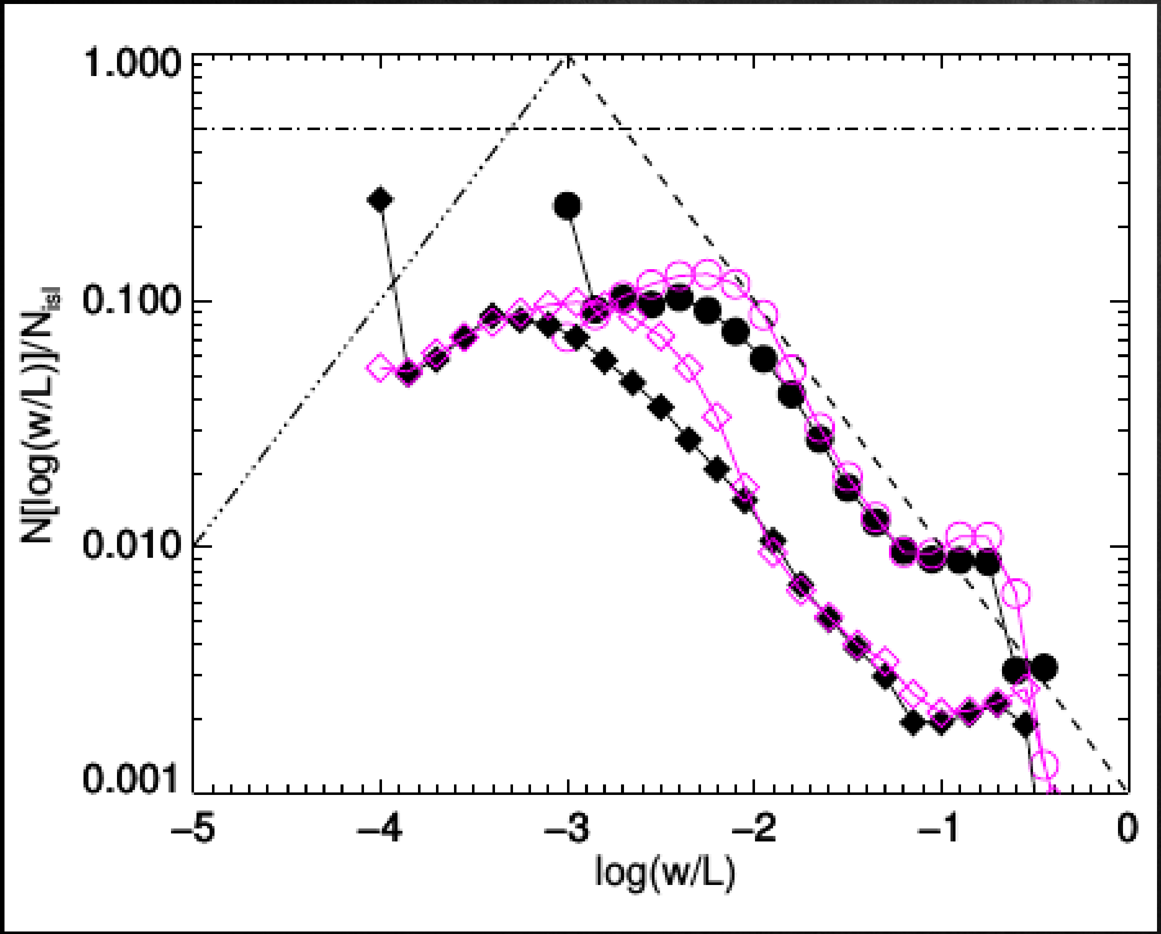


- Loss process for plasmoids
- Smallest plasmoid of the merging pair is absorbed

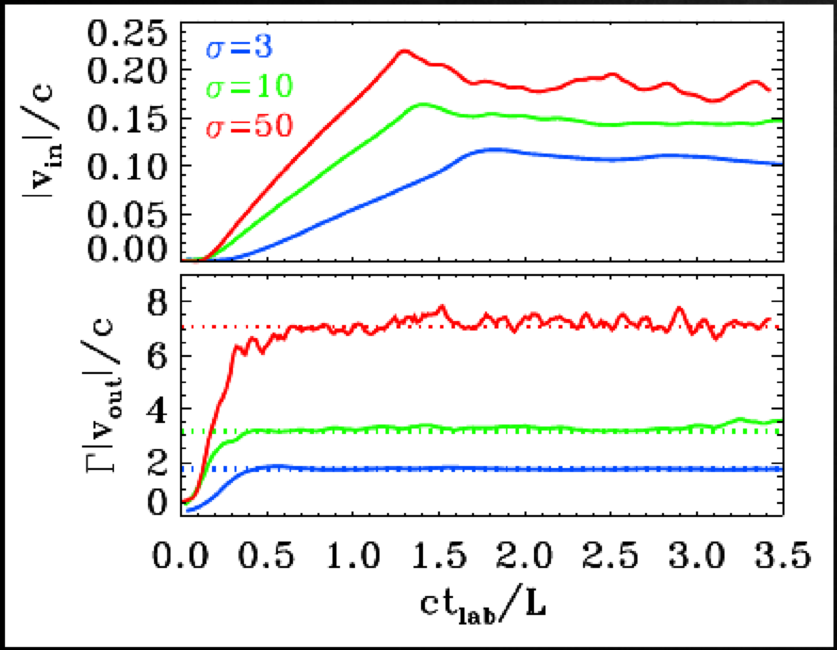


- Redistribution in sizes
- Fewer plasmoids with medium sizes
- More plasmoids with small sizes
- The slope of the soft power law is retained

Size of the system



- Power-law formation
- From small sizes (few plasma skin depths) to large sizes (10%-30% of layer's length)
- Power-law slope is the same



σ=3
σ=10
σ=50
0.25
0.20
0.15
0.10
0.05
0.00
|v_in|/c
8
6
4
2
0
Γ|v_out|/c
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
ct_lab/L