Long-term evolution of the particle energy spectrum in relativistic magnetic reconnection

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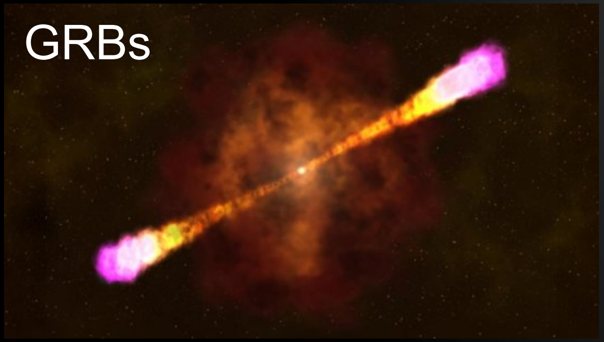
Magnetic Reconnection in Space, Solar, Astrophysical, and Laboratory Plasmas (MR2018)

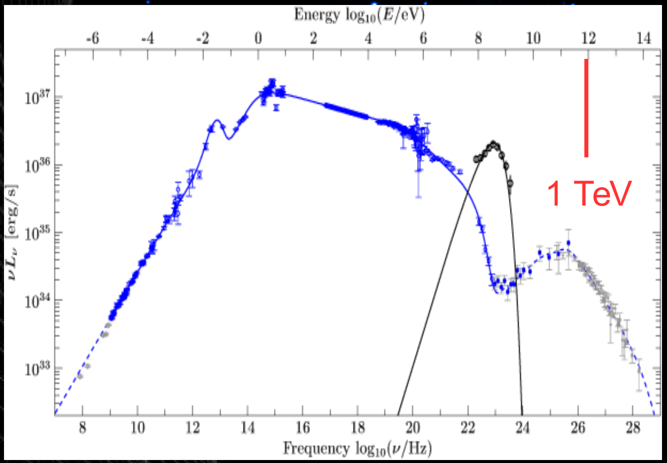
Astrophysical motivation

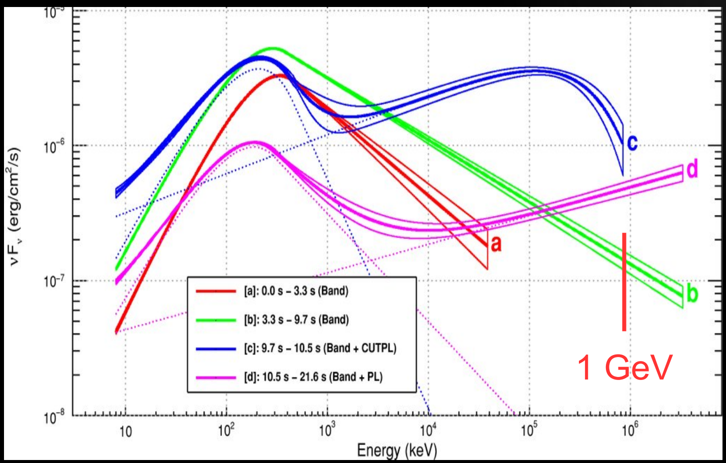
Simulations & results

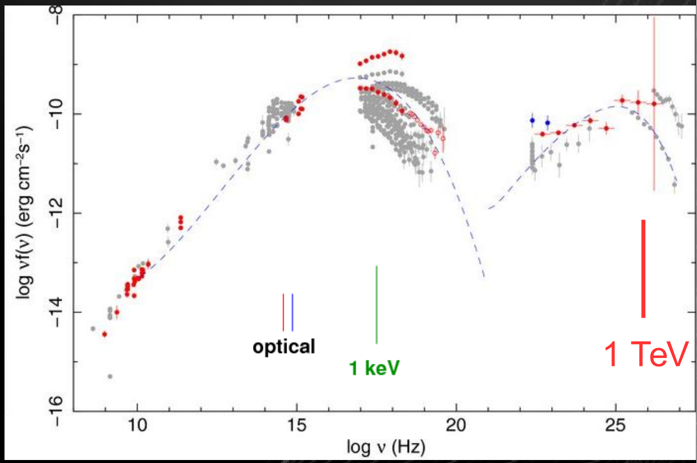
Open questions

Non-thermal broadband radiation





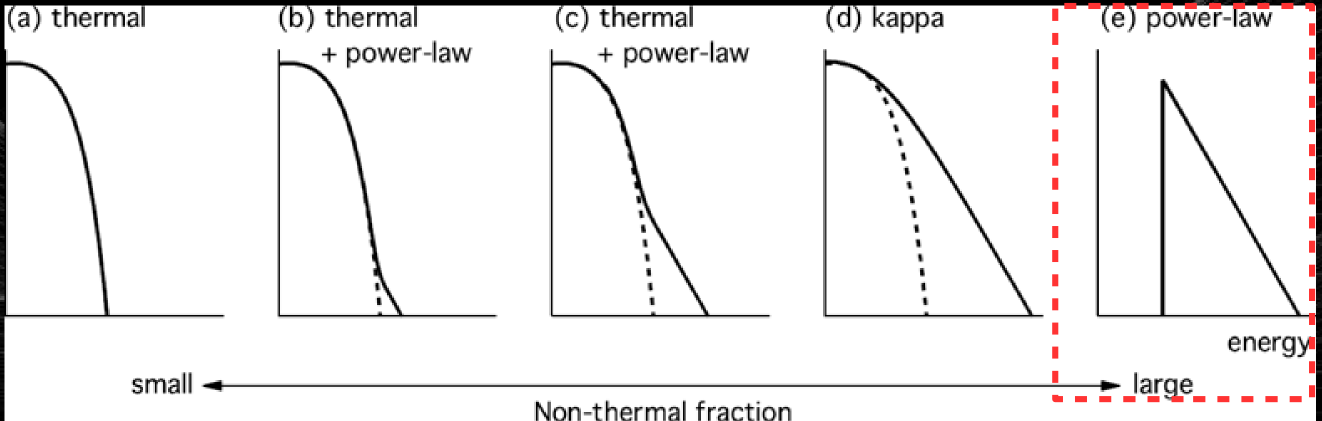




Lyutikov 2014

Ackermann+2011

Abdo+2010

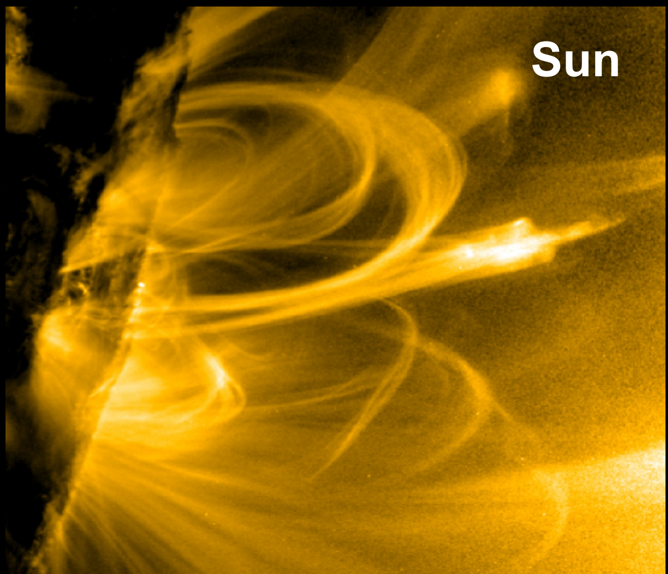


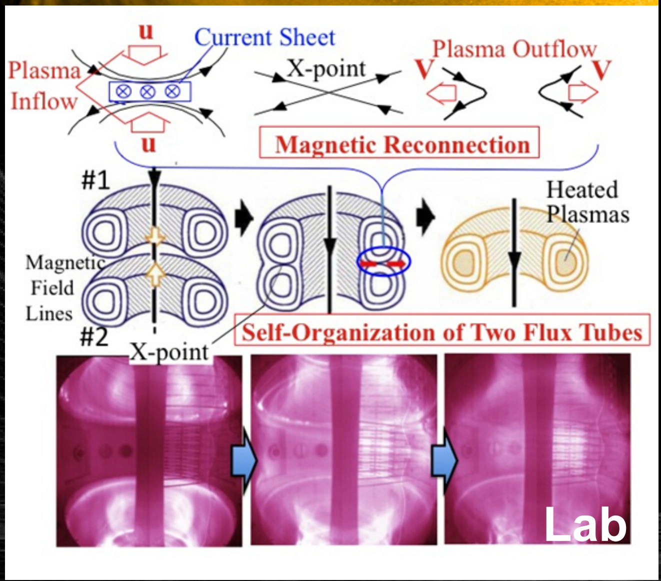
Oka+2018

Regimes of magnetic reconnection

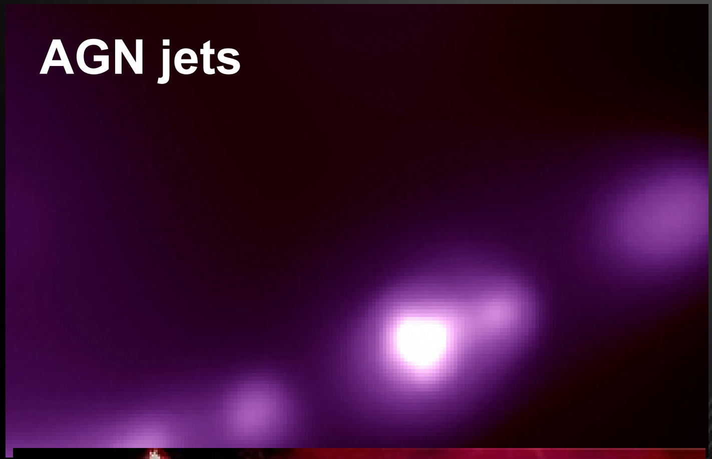
$$\sigma = \frac{B_0^2}{4\pi n_0 m c^2}$$

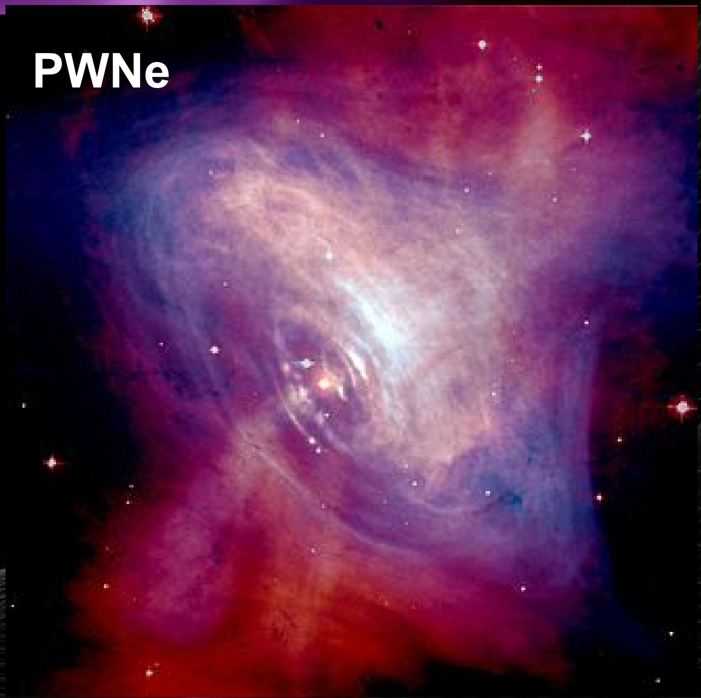
$\sigma \ll 1$ → $\sigma \gg 1$





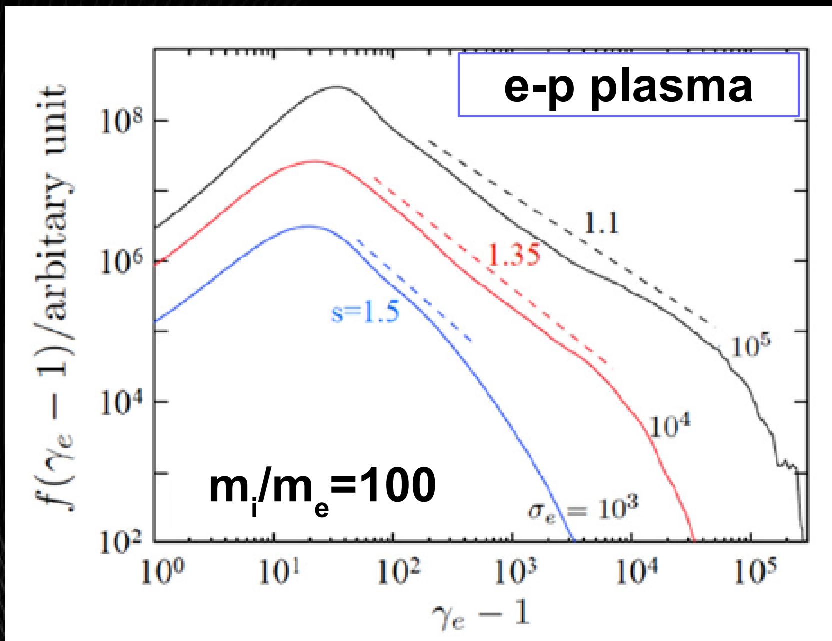
Non-relativistic reconnection



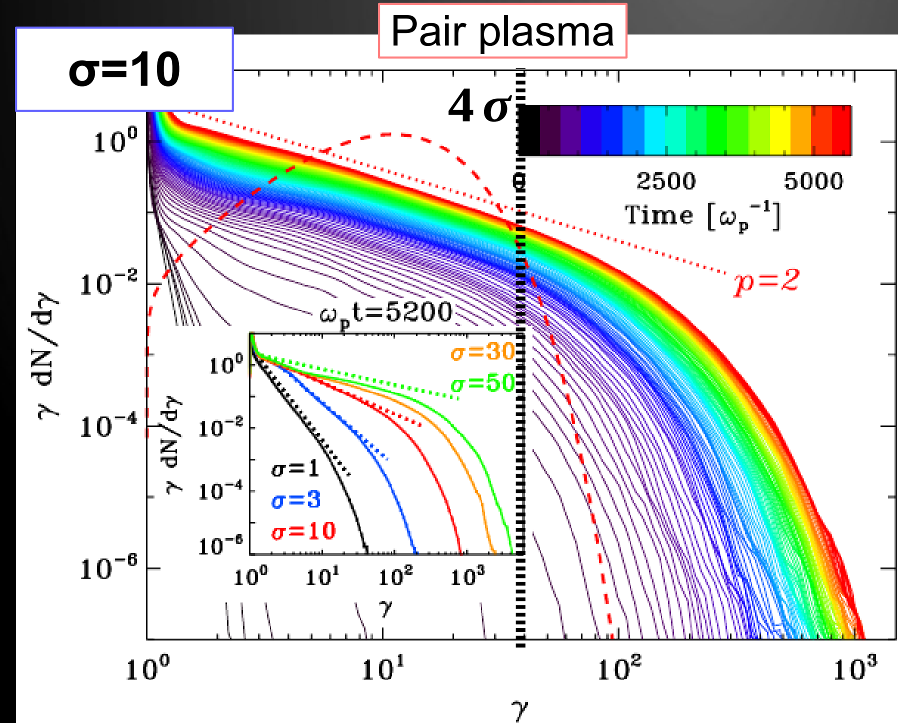


Relativistic reconnection

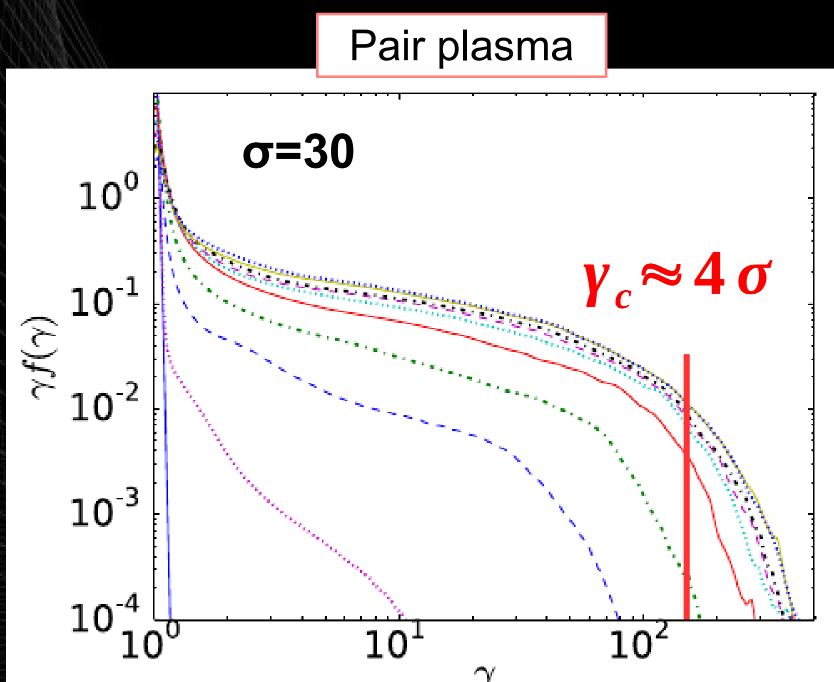
Non-thermal particle distributions



Guo+2016



Sironi & Spitkovsky 2014



Werner+2016

$$\frac{dN}{d\gamma} \propto \gamma^{-p} \exp[-\gamma/\gamma_{cut}]$$

Power-law slope
(σ-dependent)

High-energy
cutoff

Open questions

What is the long-term evolution of the particle distribution?

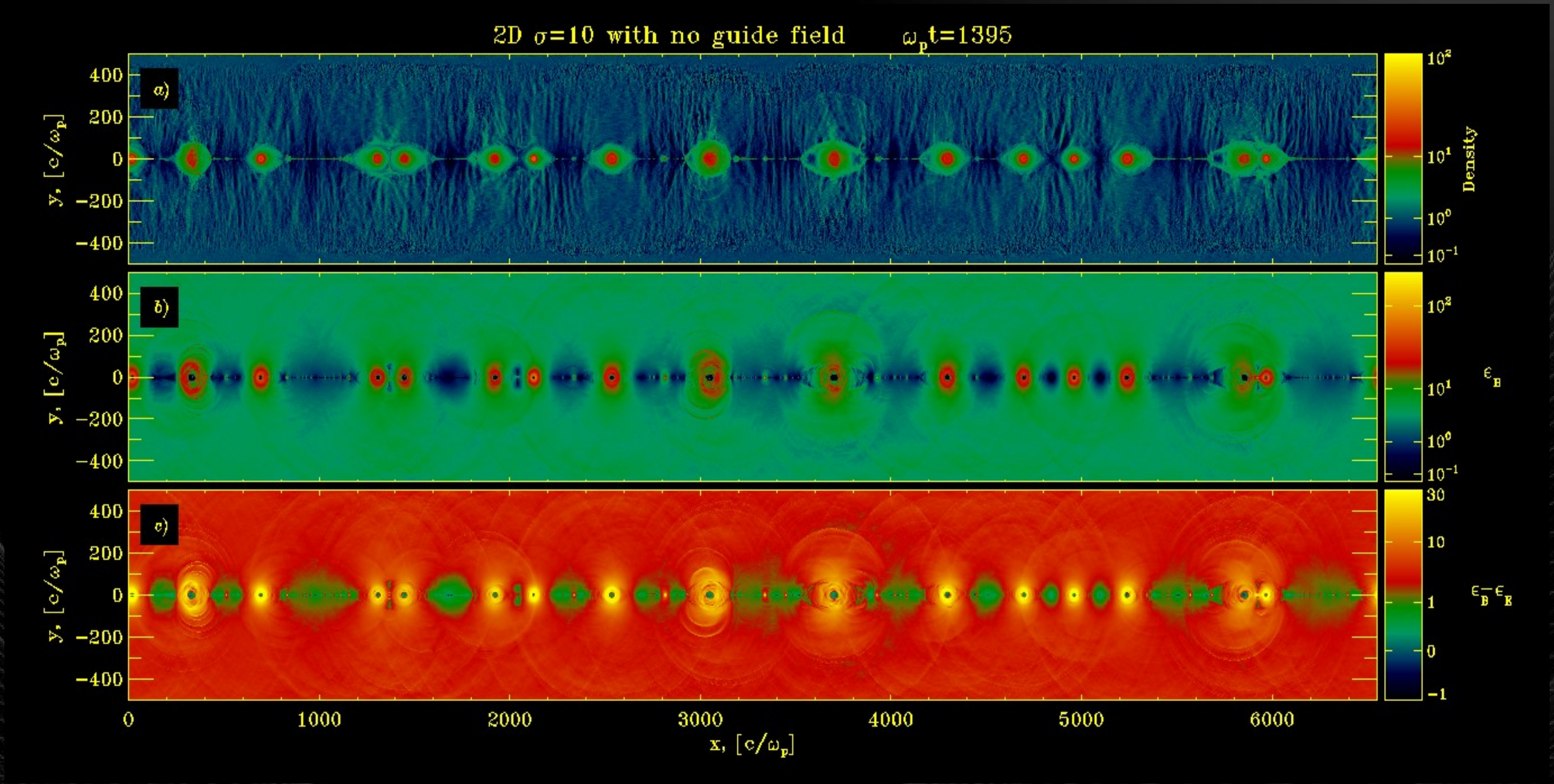
Does the high-energy cutoff saturate at 4σ ?
(Werner+2016; Kagan+2018)

How do energetic particles get accelerated?

Simulations

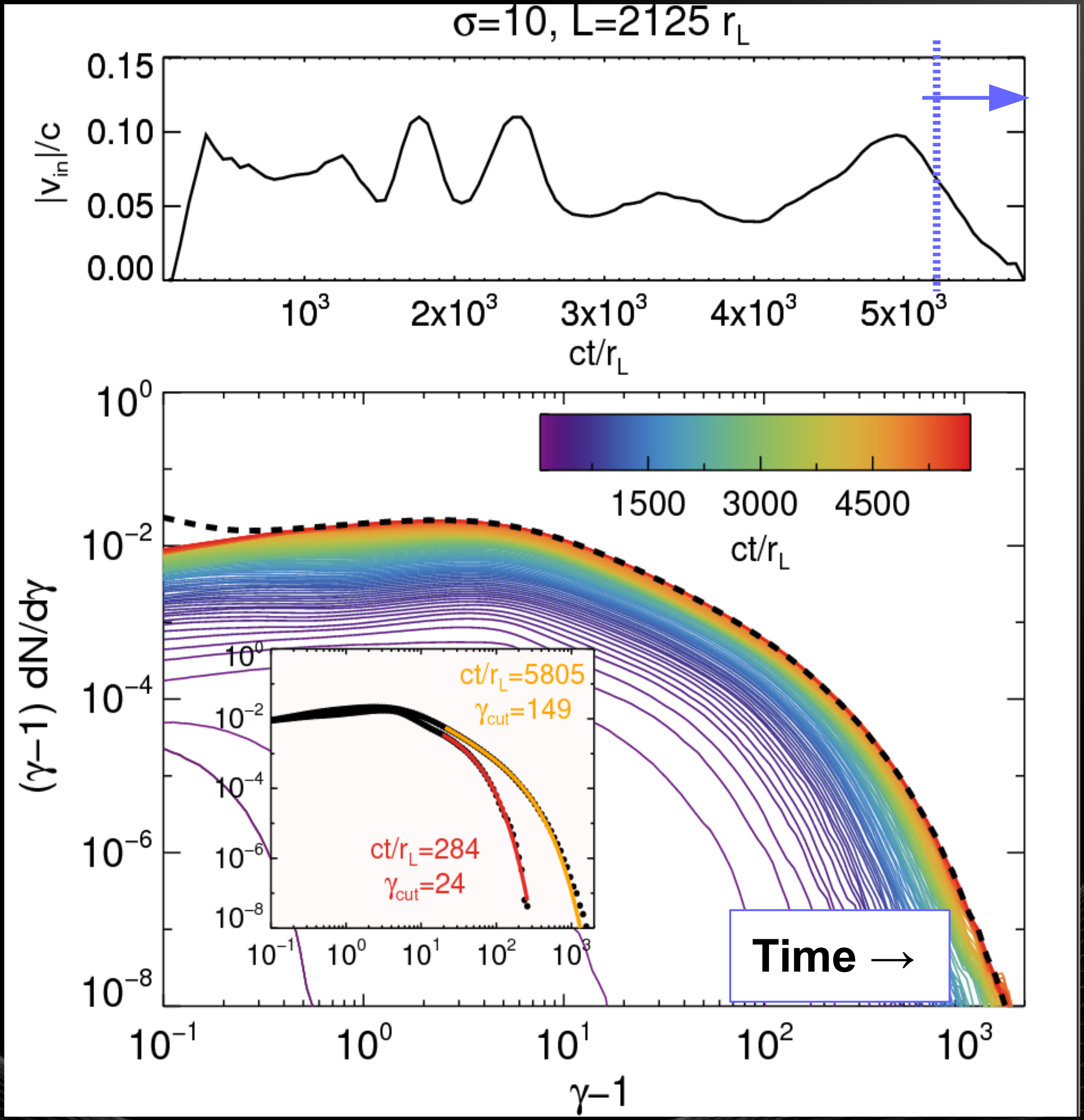
Click here

- 2D PIC simulations of anti-parallel reconnection in pair plasma
- Code: TRISTAN-MP (*Buneman 1993*, *Spitkovsky 2005, Sironi +2013*)
- Boundary conditions: Periodic in x-direction, receding injector in y-direction
- Different physical parameters (magnetization, upstream temperature, current sheet thickness)
- Different box sizes $\left(500-4250\, r_L,\, r_L=\sqrt{\sigma}\, c/\omega_p\right)$



MP & Sironi 2018, sub. (arXiv:1808.00966)

Particle distribution fitting

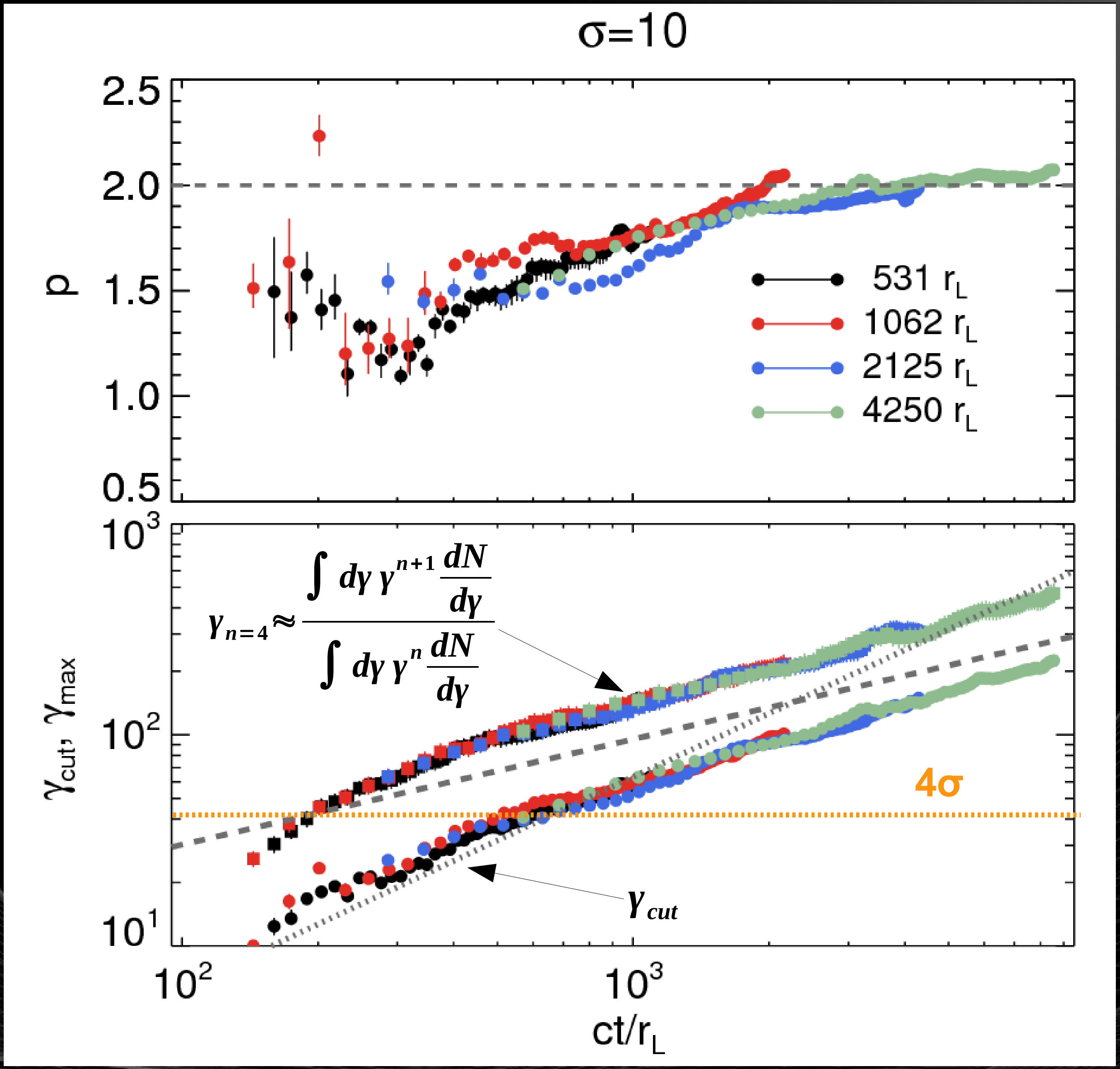


One large plasmoid in the domain →

Reconnection will shut off

Click here

Evolution of slope & cutoff



$$\frac{dN}{d\gamma} \propto \gamma^{-p} e^{-\gamma/\gamma_{cut}}$$

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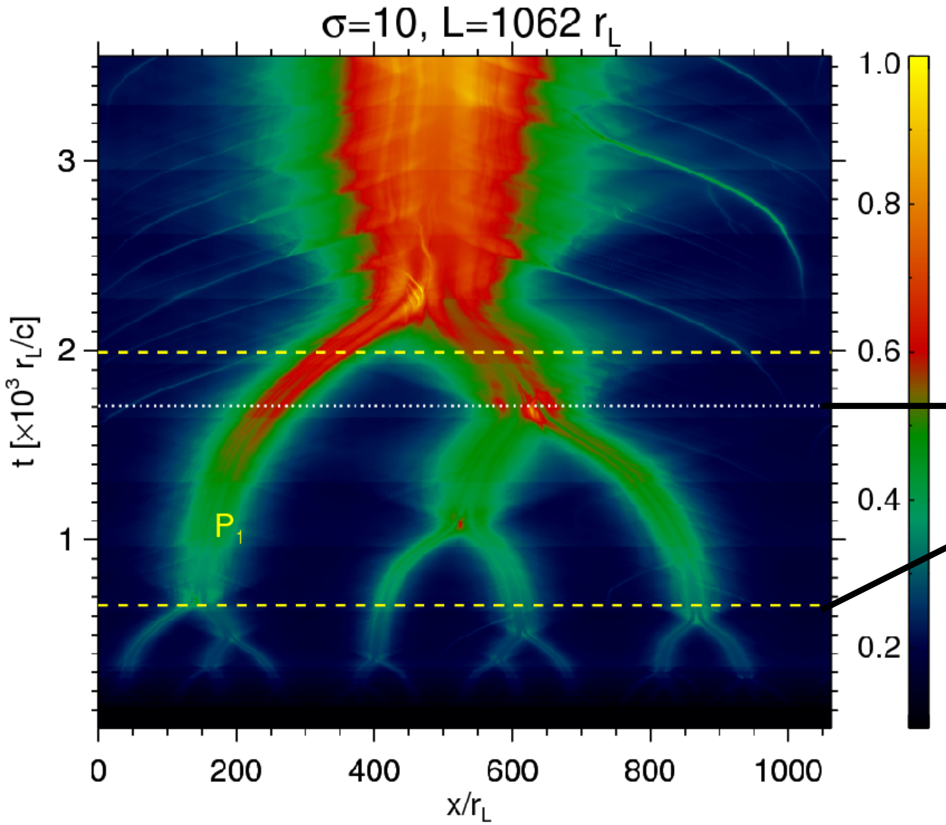
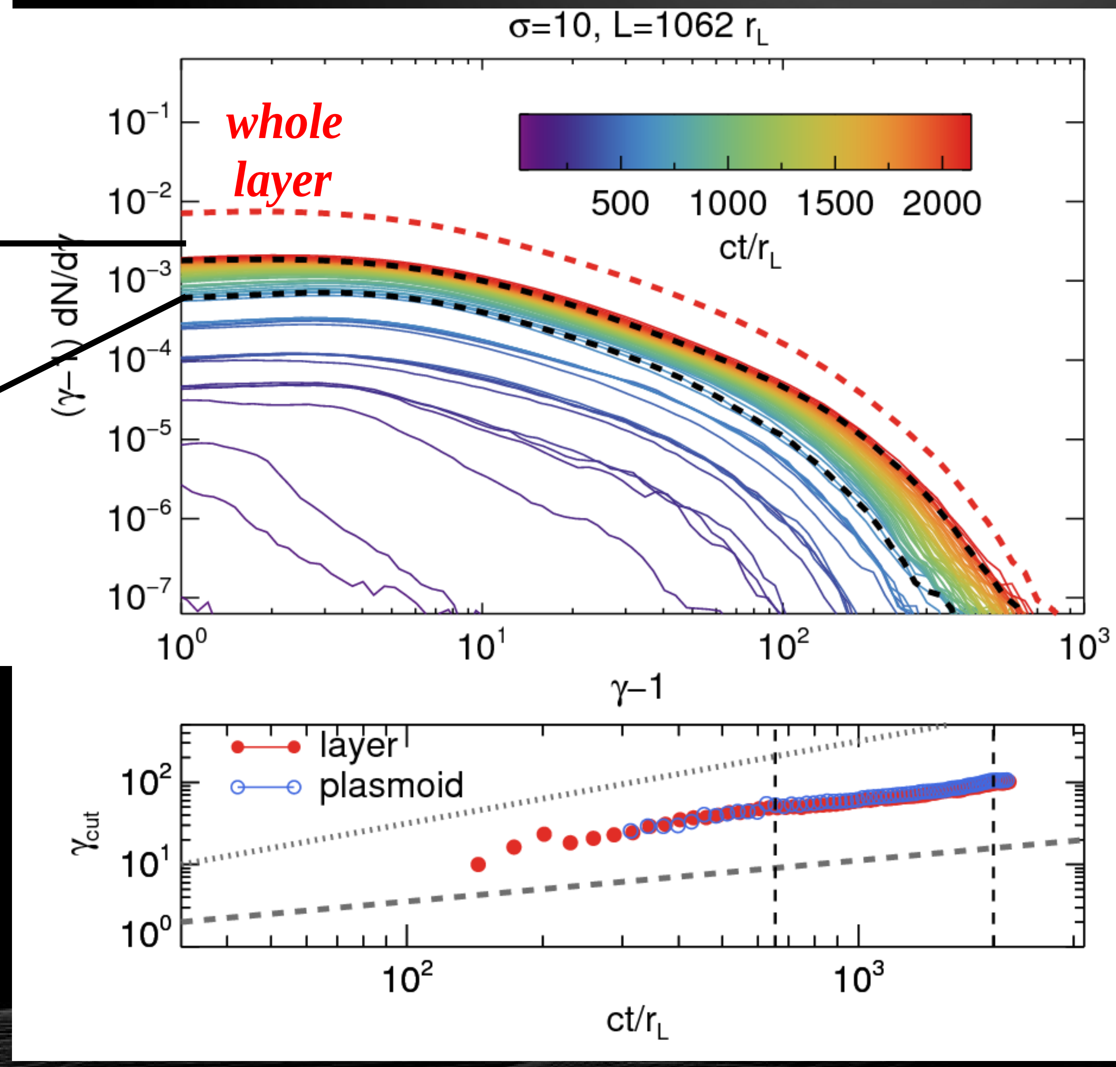
Spectrum of an "isolated" plasmoid

Time-position plot of layer





Similar spectral evolution of layer & isolated plasmoid

Plasmoid "tomography"

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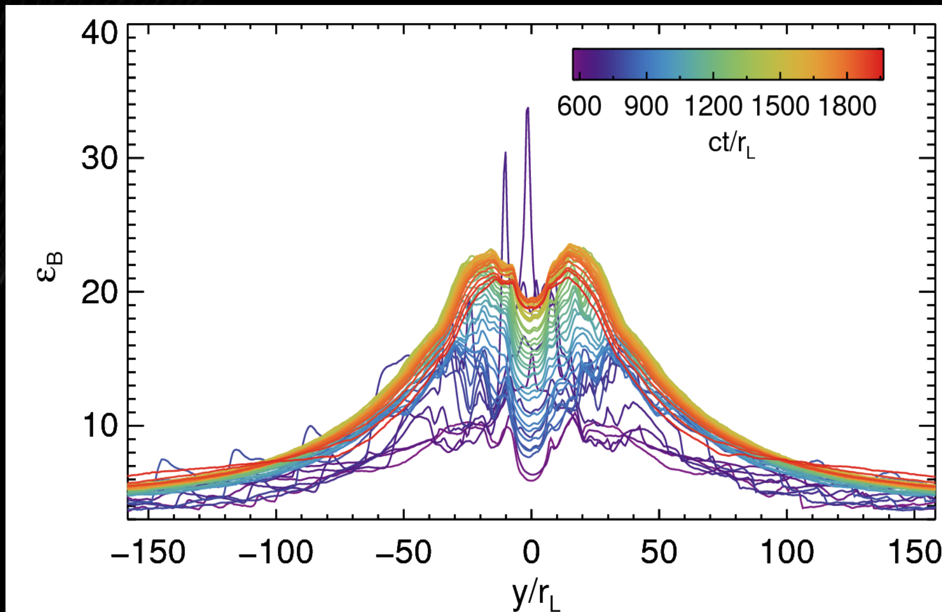
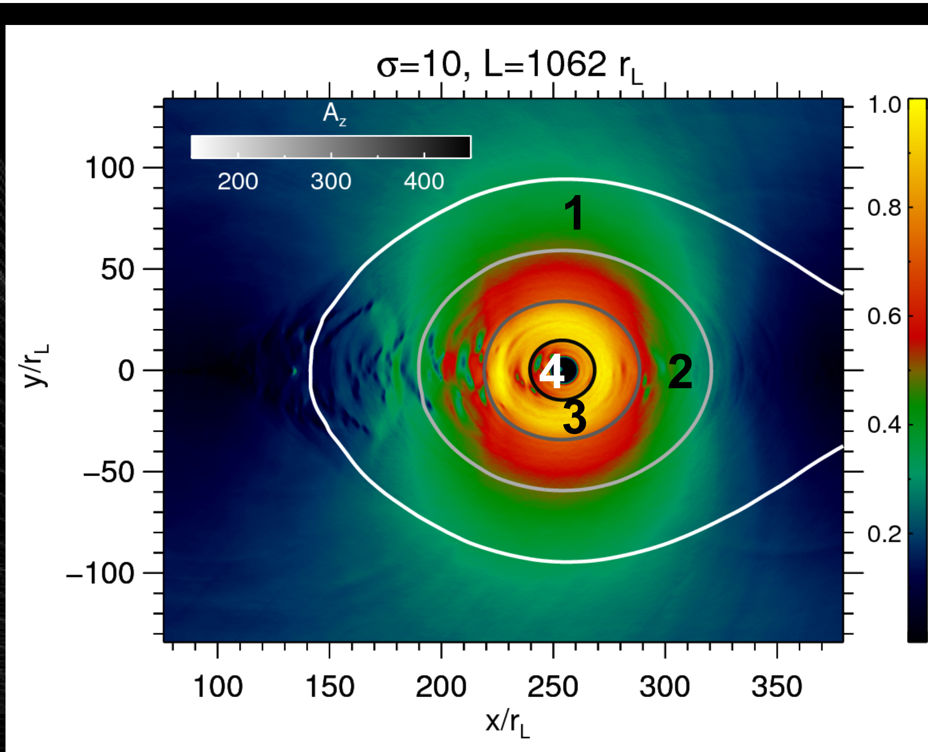
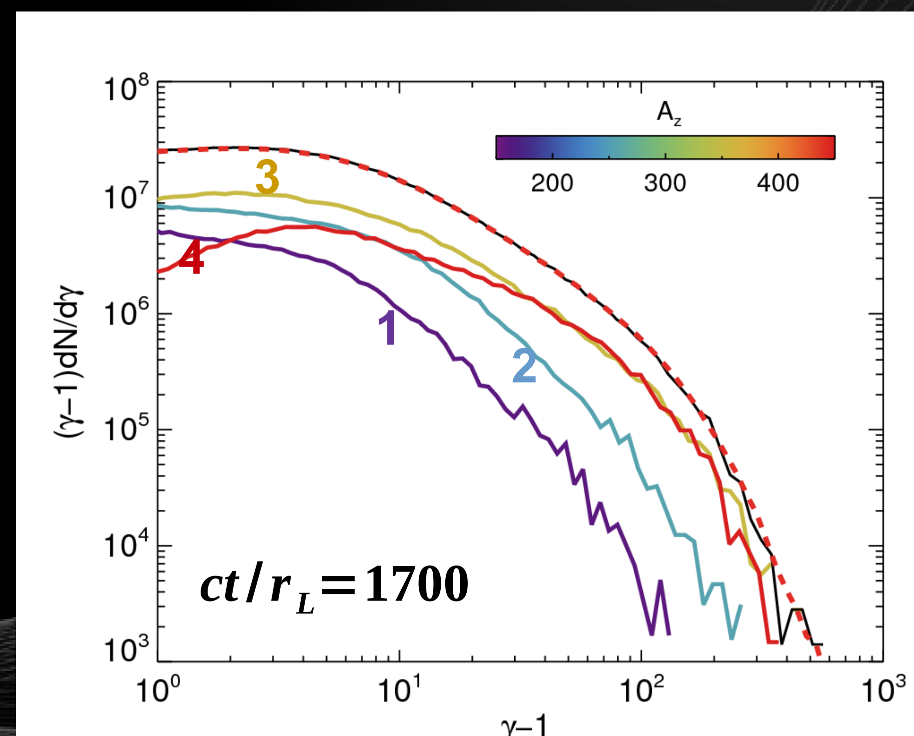


Particles controlling the cutoff reside in a magnetized ring



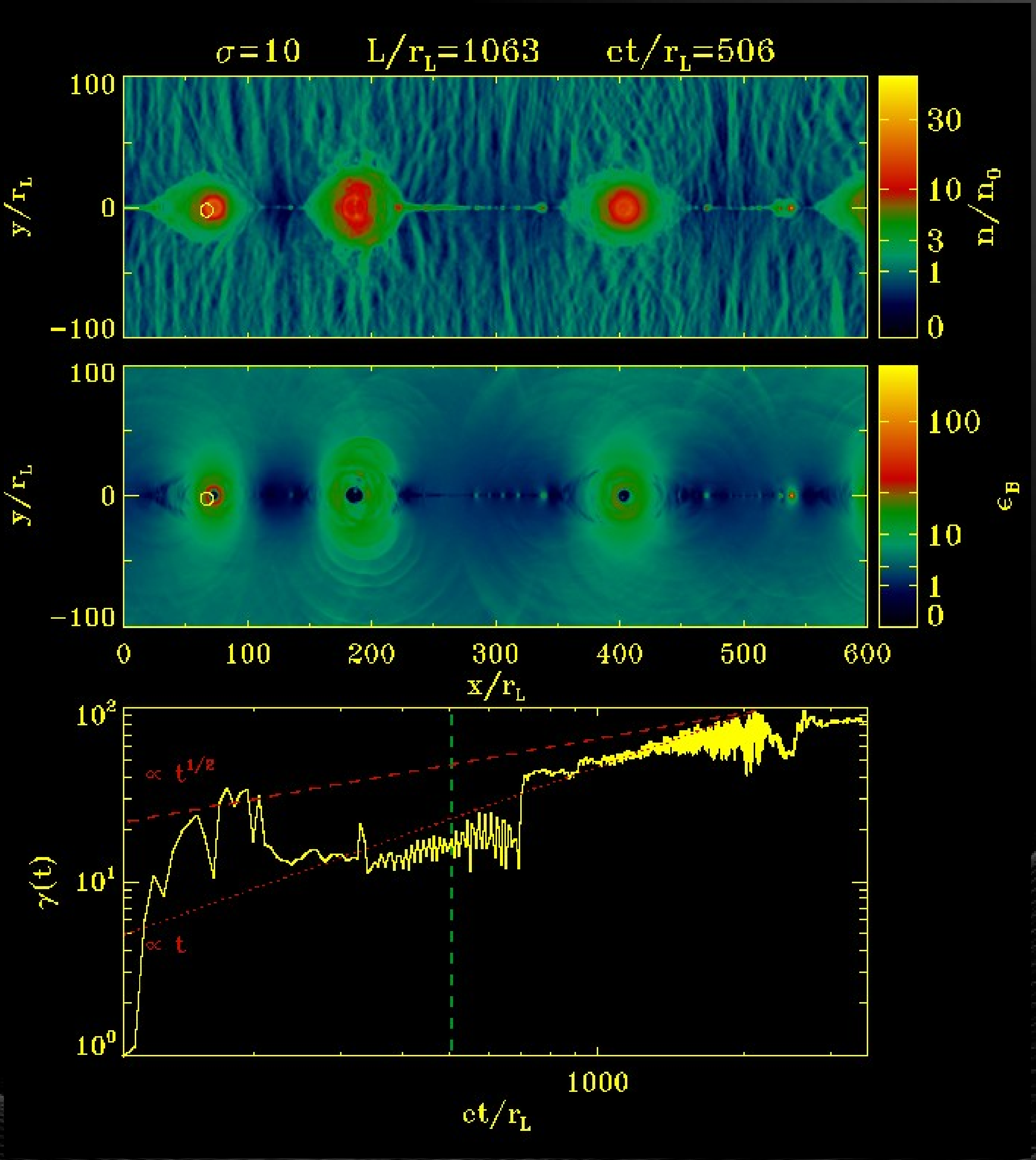


Particle tracking - 1

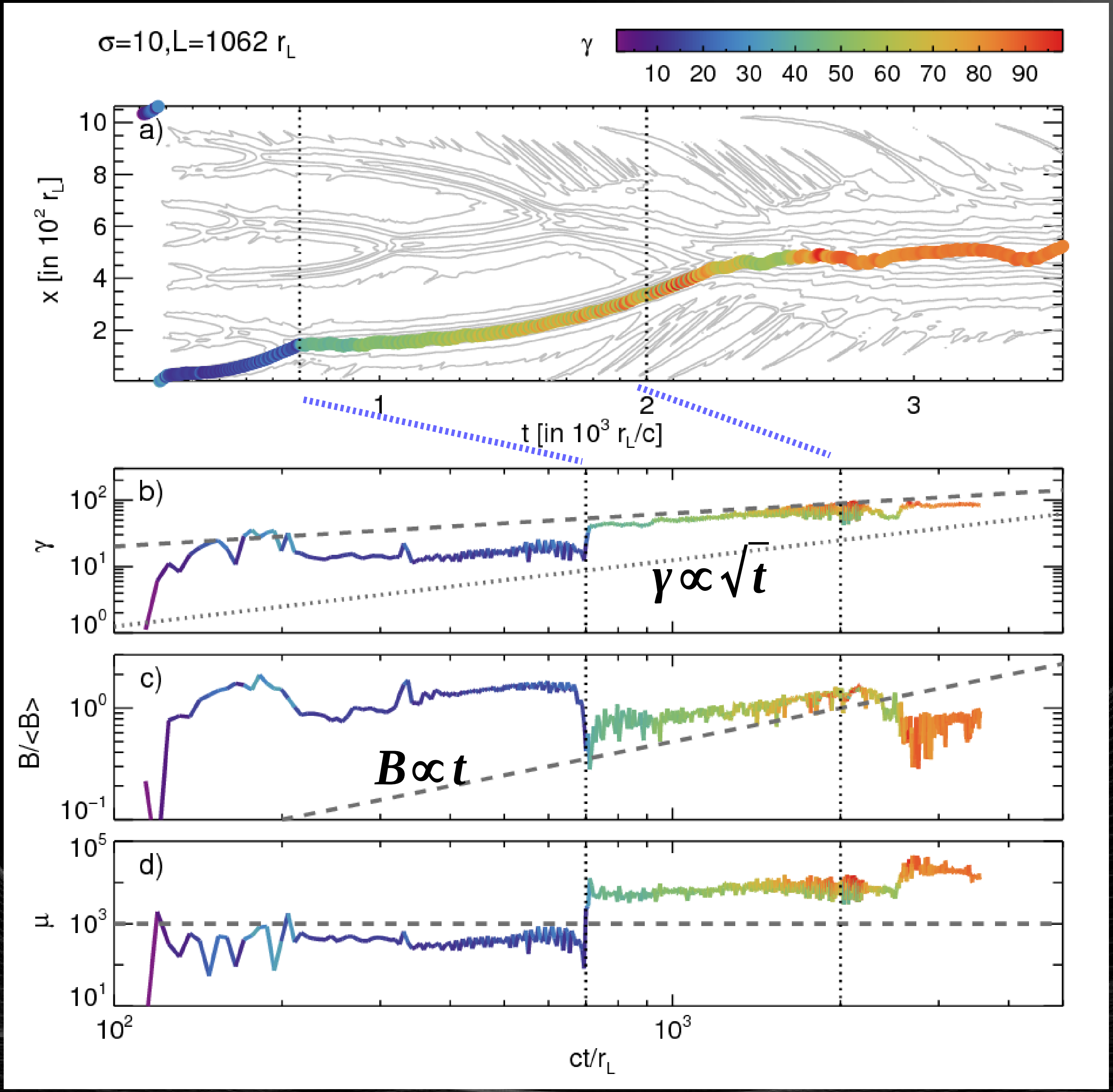
n/n_0

ε_B

γ

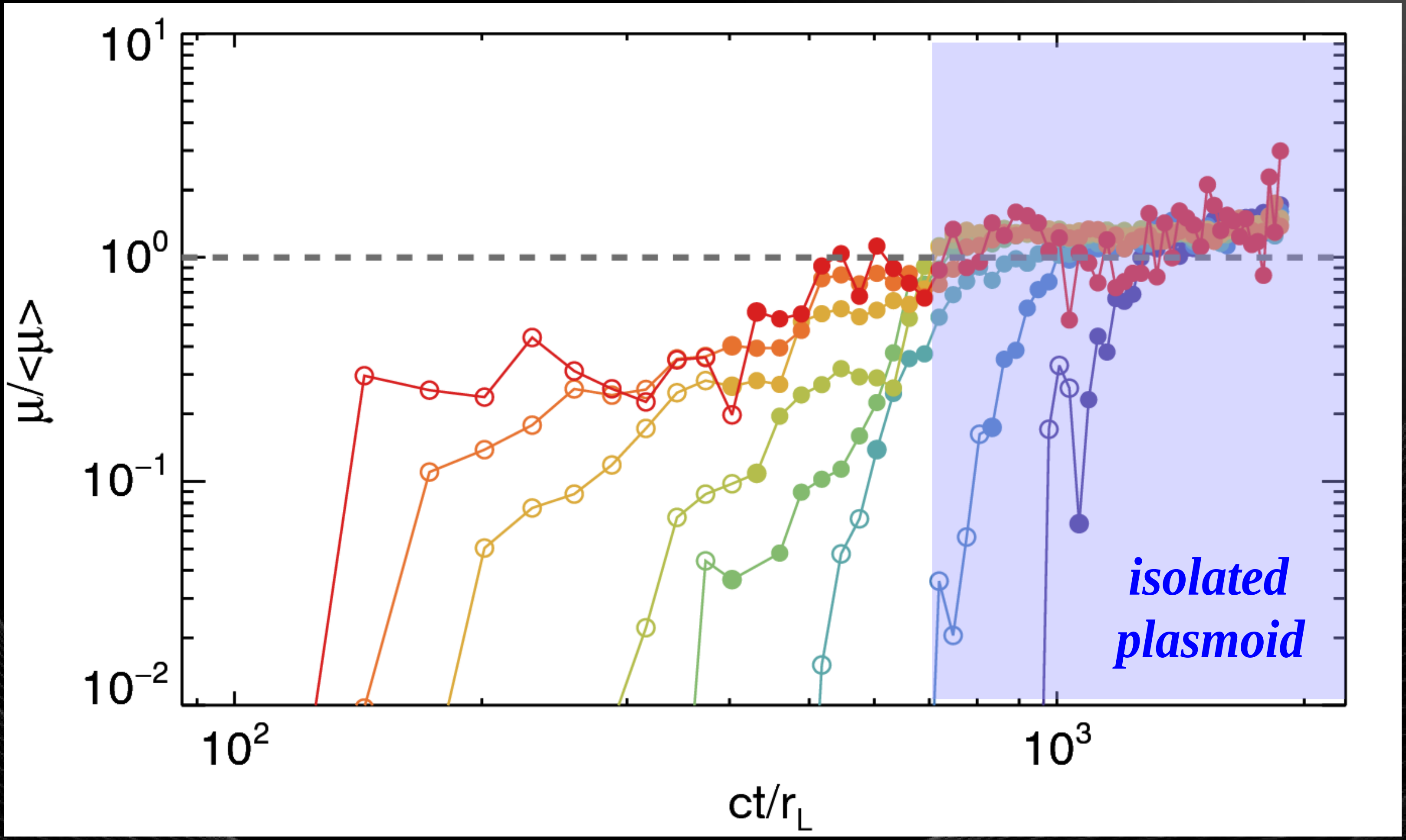


Particle tracking - 2



Particle magnetic moment

Magnetic moment in isolated phase is ~ constant



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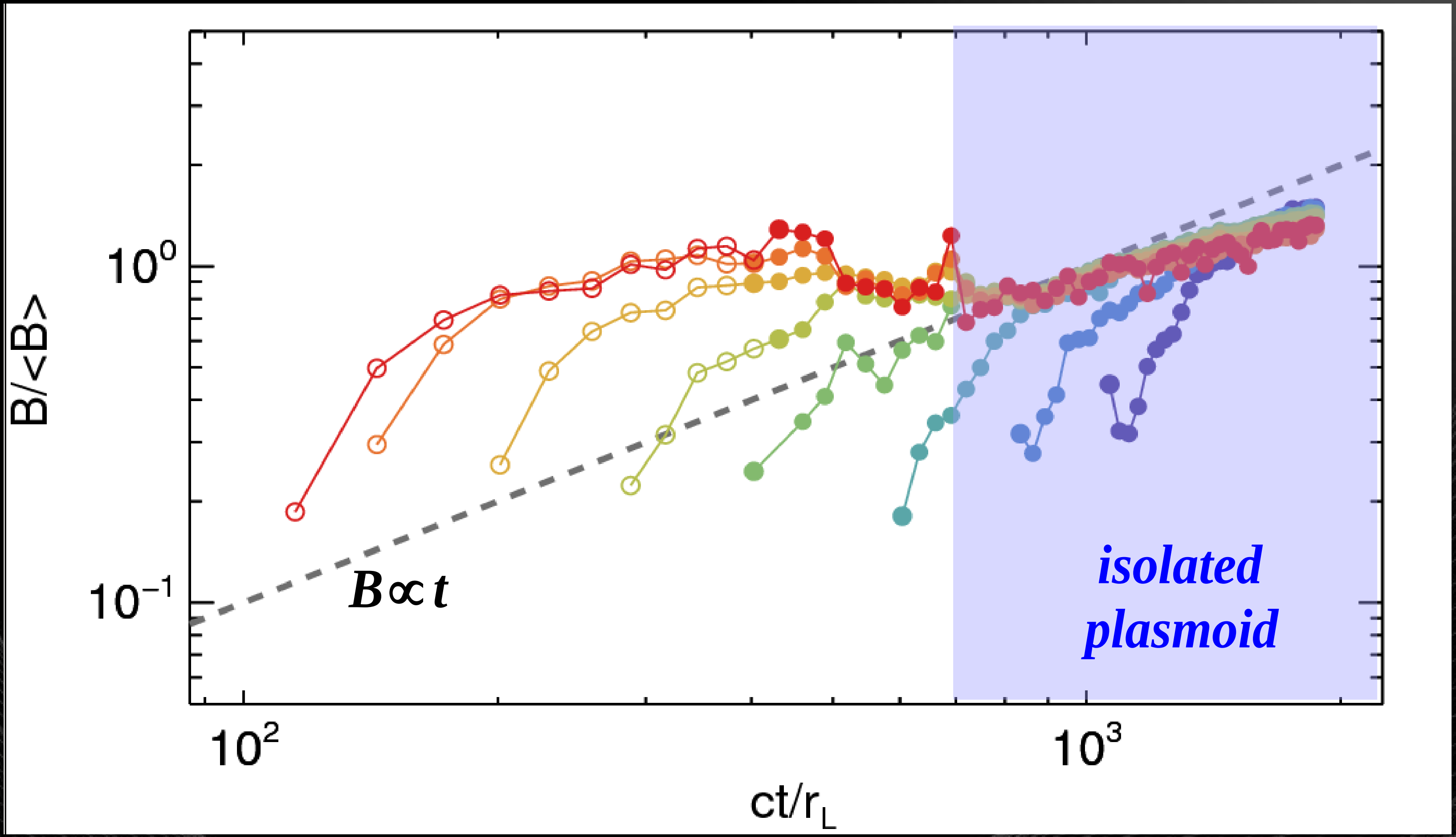
Magnetic field along trajectory

Particles experience stronger B-fields



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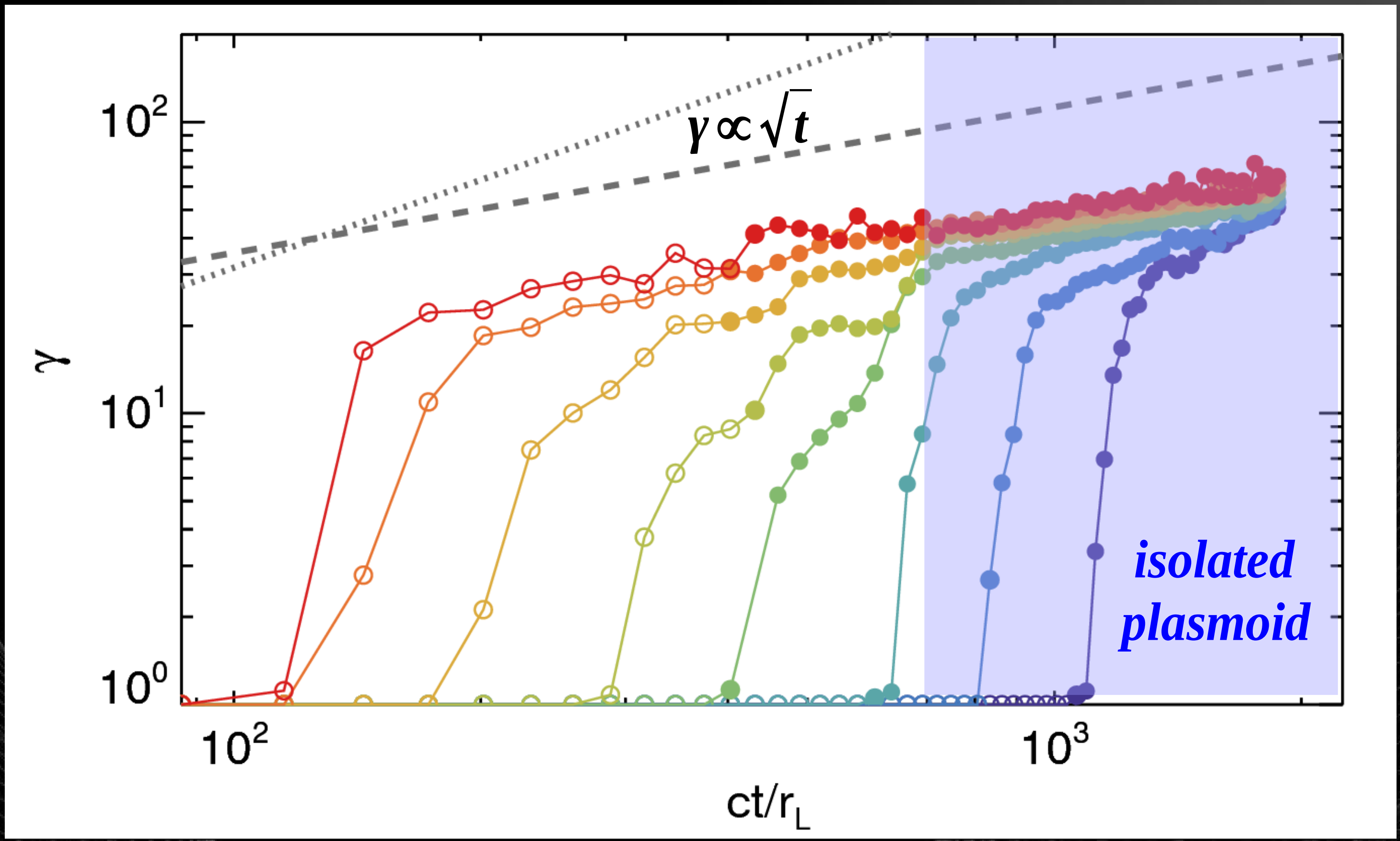
Energy evolution of particles

Sub-linear evolution of particle energy with time



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Summary

The high-energy cutoff increases beyond 4σ, if box size is large & reconnection stays active.

The high-energy cutoff increases as $t^{1/2}$ after it exceeds the ~4σ value.

Particles controlling the cutoff reside in a magnetized ring around the core.

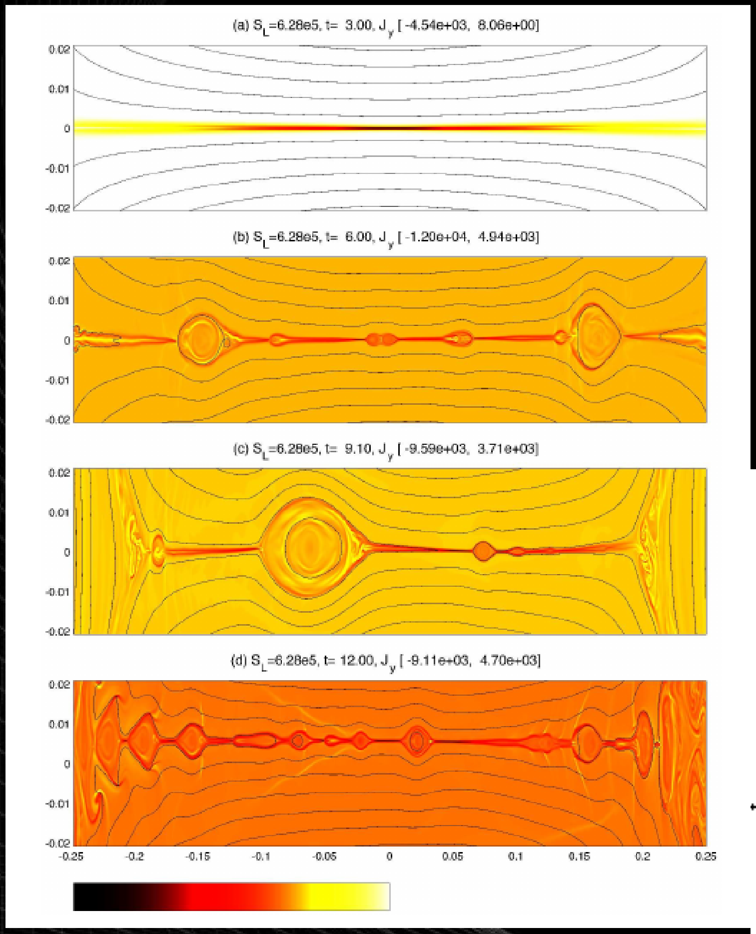
Particles gain energy due to local B increase in plasmoids & conservation of magnetic moment.

Thank you!

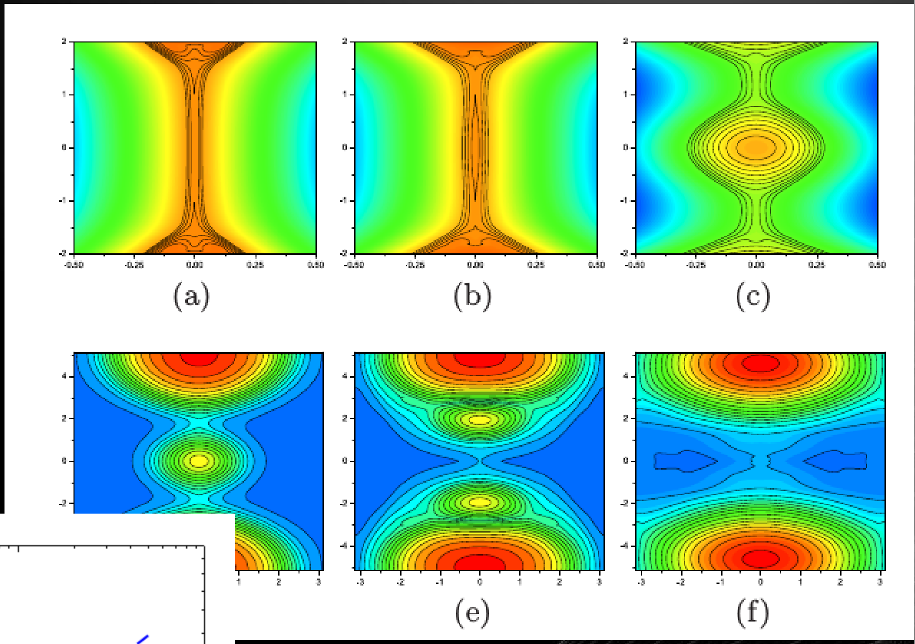
Back-up slides

Plasmoid-dominated reconnection

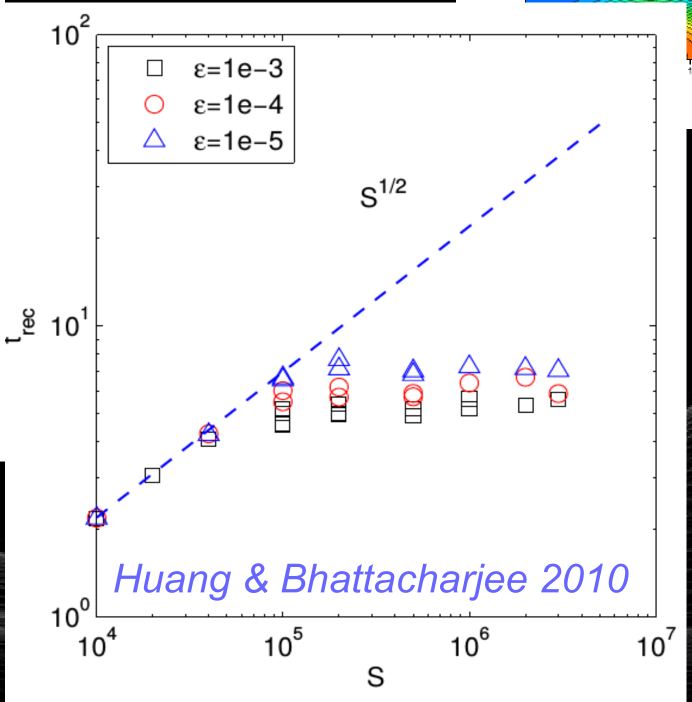
Zenitani & Hoshino 2001, Loureiro+2005; 2007, Bhattacharjee+2009, Uzdensky+2010, Loureiro+2012, Guo+2014; 2015, Sironi & Spitkovsky 2014; Nalewajko+2015; Sironi+2015; Werner+2016, Sironi+2016 ...



Bhattacharjee+2009



Loureiro+2005

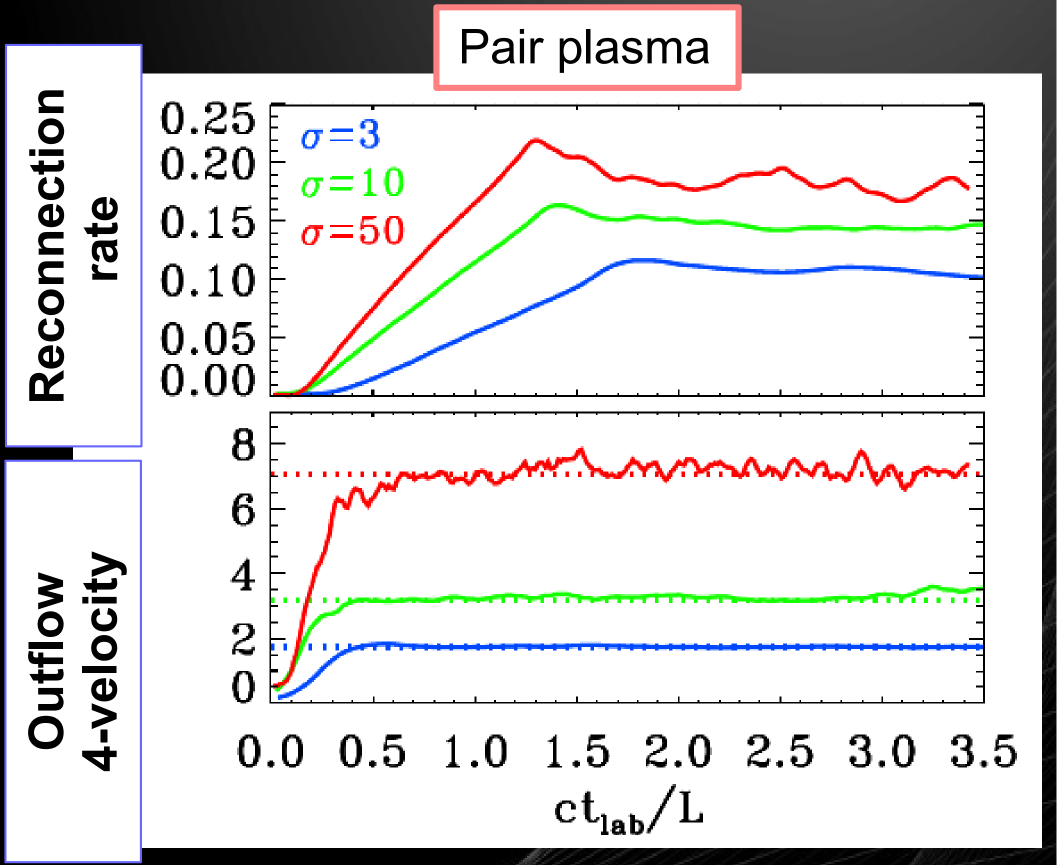


Reconnection time independent of Lundquist number

What makes plasmoid-dominated reconnection appealing for astrophysical applications?

Fast dissipation

Fast bulk plasma motion



Sironi, Giannios, MP 2016

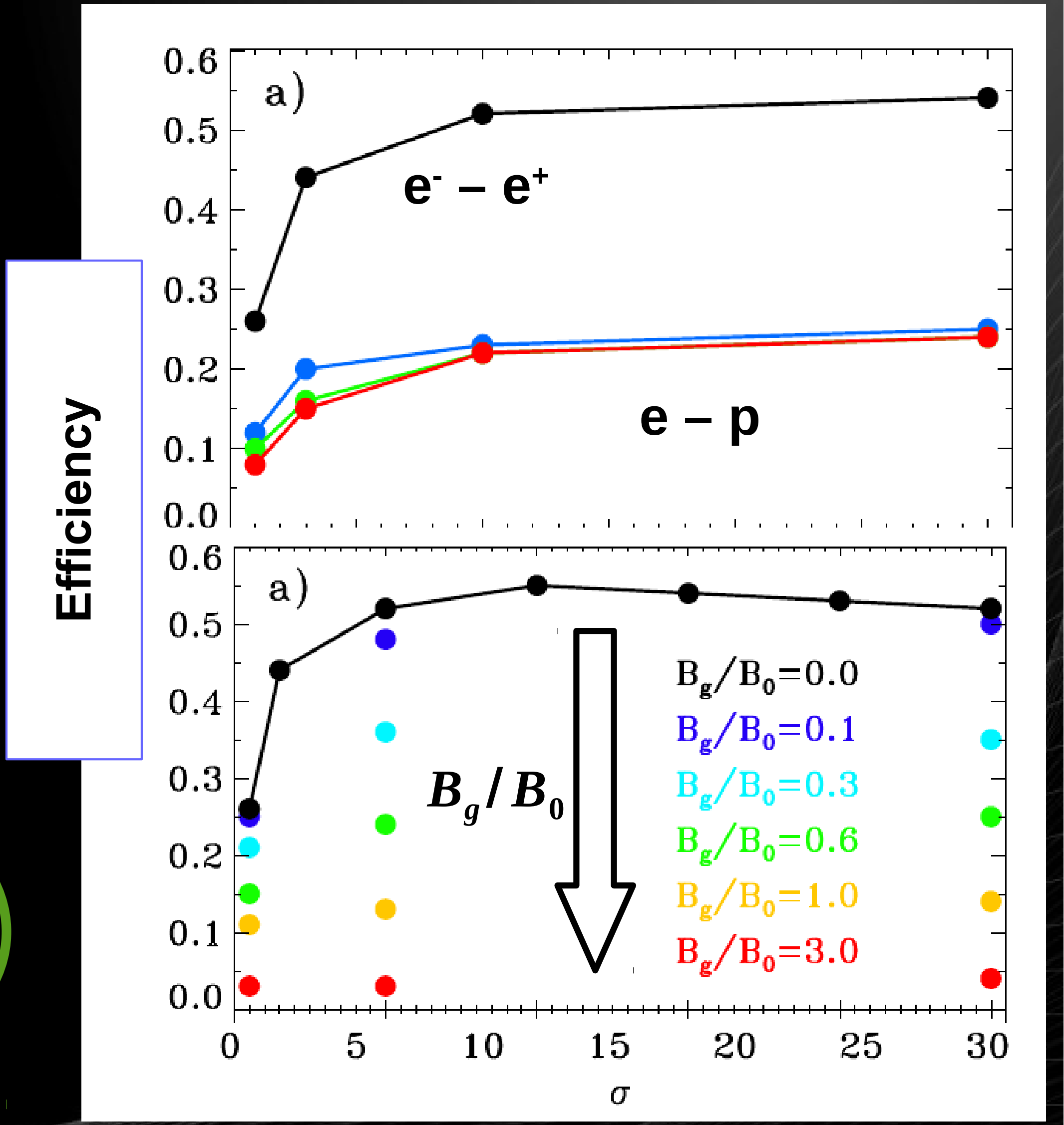
What makes plasmoid-dominated reconnection appealing for astrophysical applications?

Efficient dissipation

***Efficiency*:**

$$f_{rec} = \frac{\sum_i \int_{V_i} U_e \, dV_i}{\sum_i \int_{V_i} \left(e + \rho c^2 + U_B\right) dV_i}$$

Efficiency depends on guide field



Sironi, MP, Giannios 2015
(see also Werner+2017)

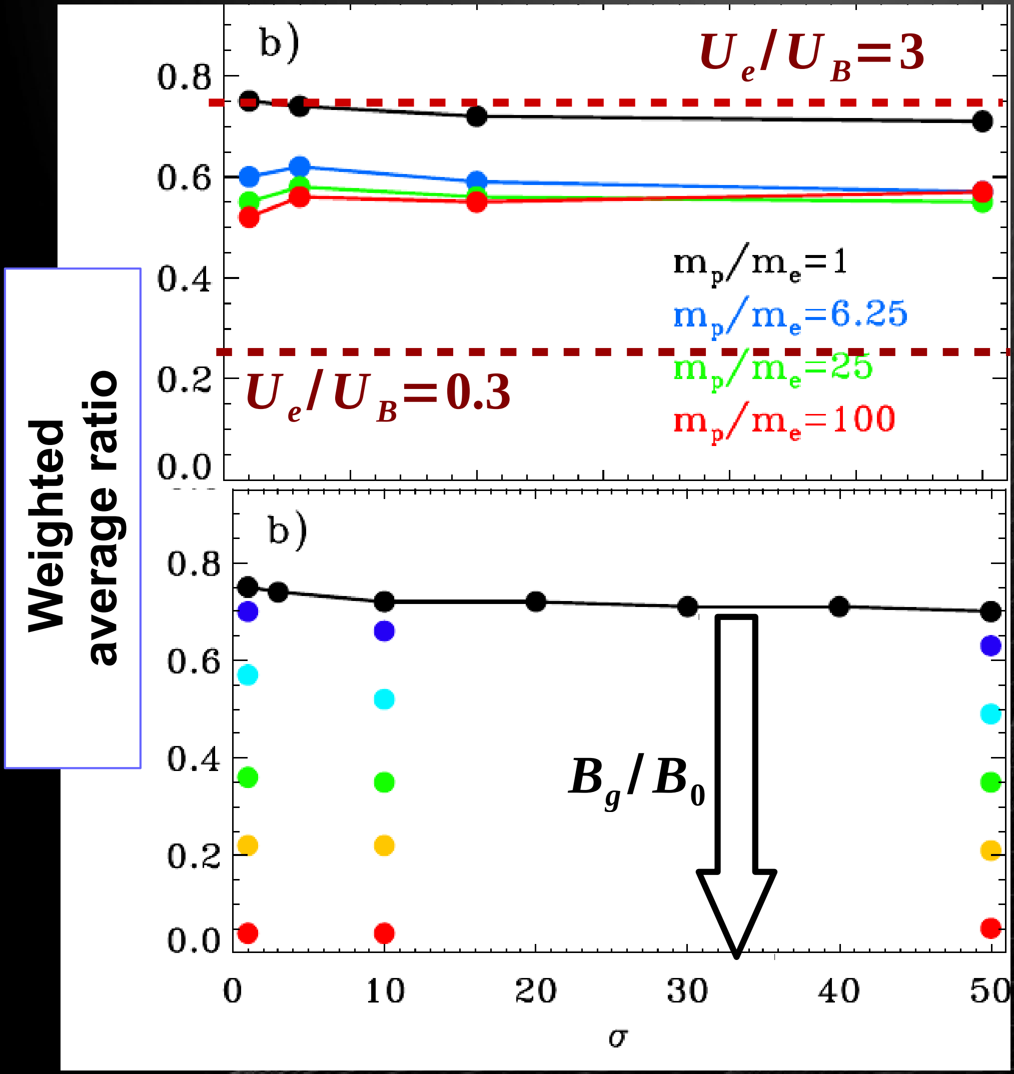
What makes plasmoid-dominated reconnection appealing for astrophysical applications?

Rough energy equipartition

Weighted average energy density ratio:

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

$U_B \gg U_e$ for strong guide fields



Sironi, MP, Giannios 2015

Simulations with periodic BC

σ	c/ω_p [cells]	L [c/ω_p]	L [$r_{L,\,hot}$]*	Duration [$1/\omega_p$]
10	5	1680	531	3375
10	5	3360	1062	13500
10	5	6720	2125	18360
10	5	13440	4250	27000
10	10	1680	531	3375
10	10	3360	1062	6750
50	5	1680	237.5	3375
50	5	3360	475	6750
50	5	6720	950	13500
50	5	13440	1900	27000

Click here

$$Note: r_{L,hot} = \sqrt{\sigma}\, c/\omega_p$$

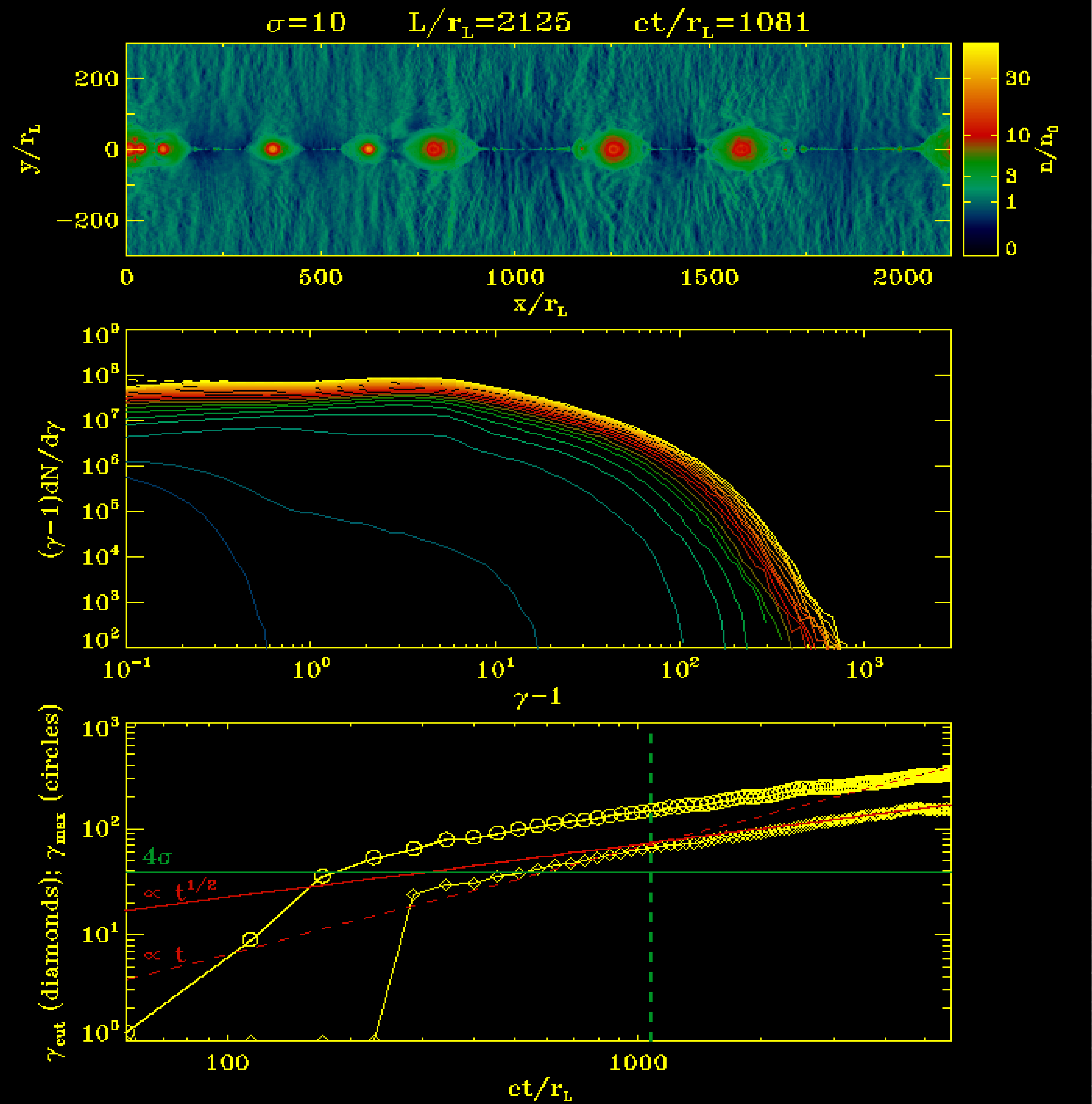
Combined view of layer & particle spectrum

$$y/r_L$$

$$(\gamma-1)\frac{dN}{d\gamma}$$

$$\frac{dN}{d\gamma}\propto\gamma^{-p}e^{-\gamma/\gamma_{cut}}$$

$$\gamma_{cut},\gamma_{n=4}\approx\frac{\int d\gamma\,\gamma^{n+1}\frac{dN}{d\gamma}}{\int d\gamma\,\gamma^{n}\frac{dN}{d\gamma}}$$



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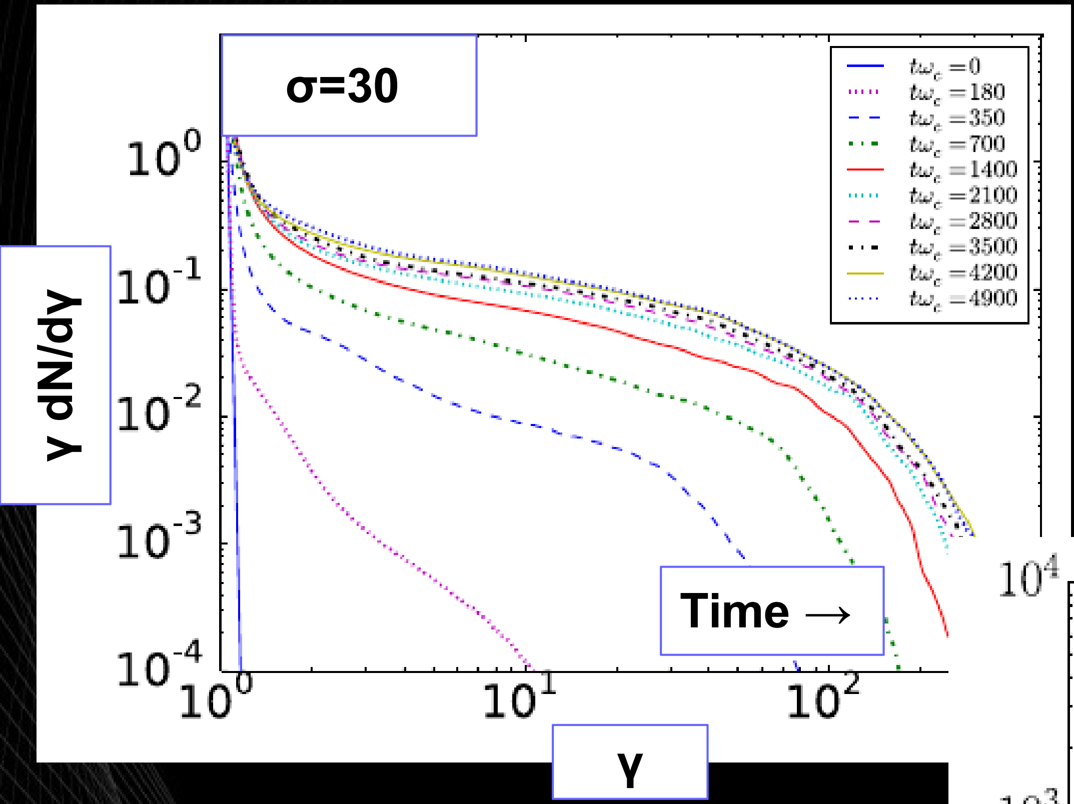
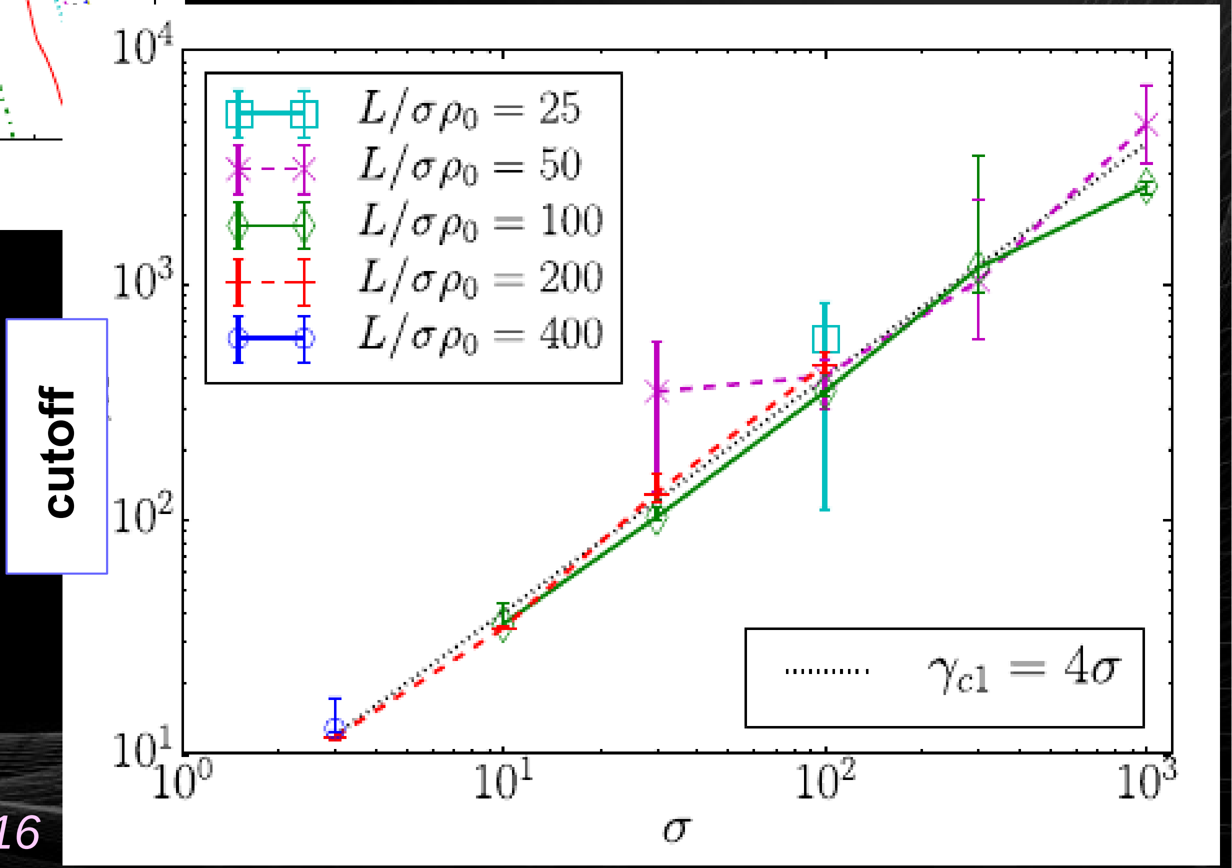
The extent of the power law (1)



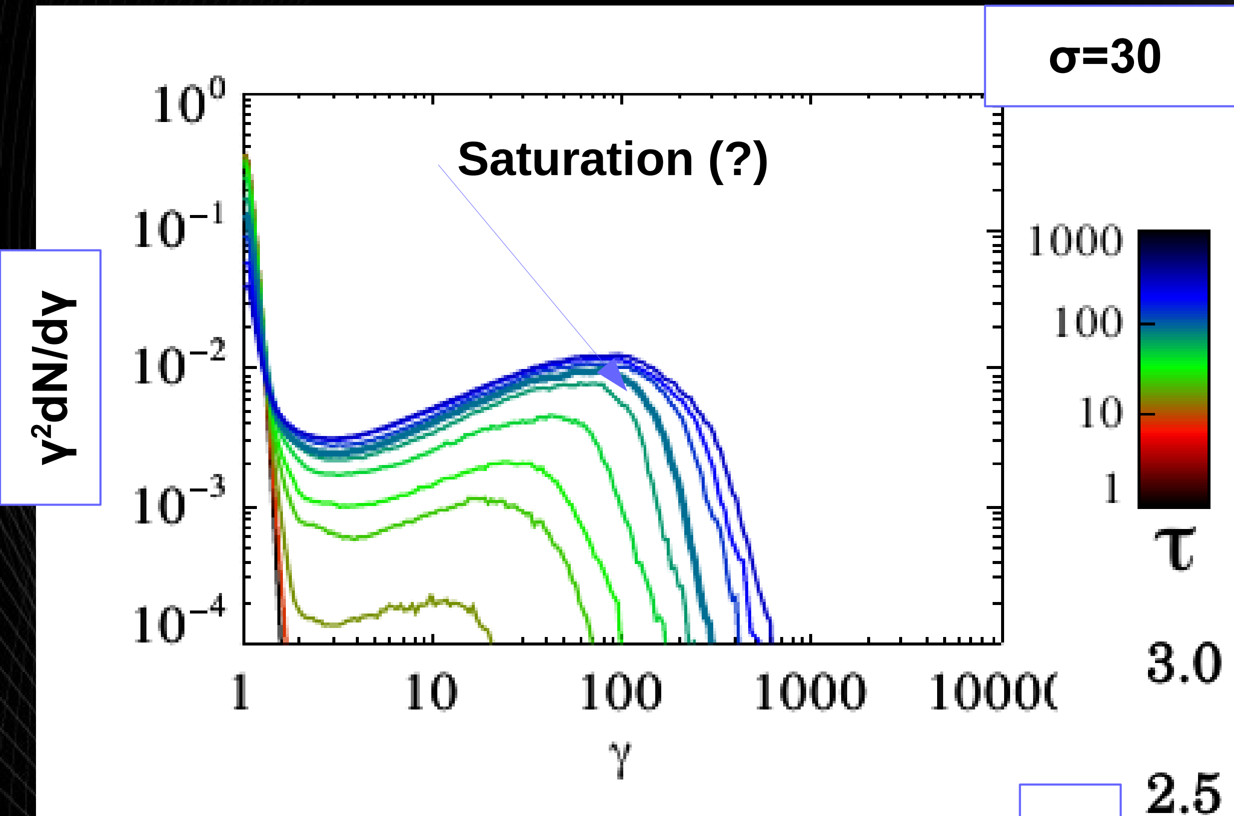
$$\frac{dN}{d\gamma} \propto \gamma^{-p} \exp\left[-\gamma/\gamma_c - (\gamma/\gamma_{c2})^2\right]$$

$$cutoff: \gamma_c \sim 4\sigma$$



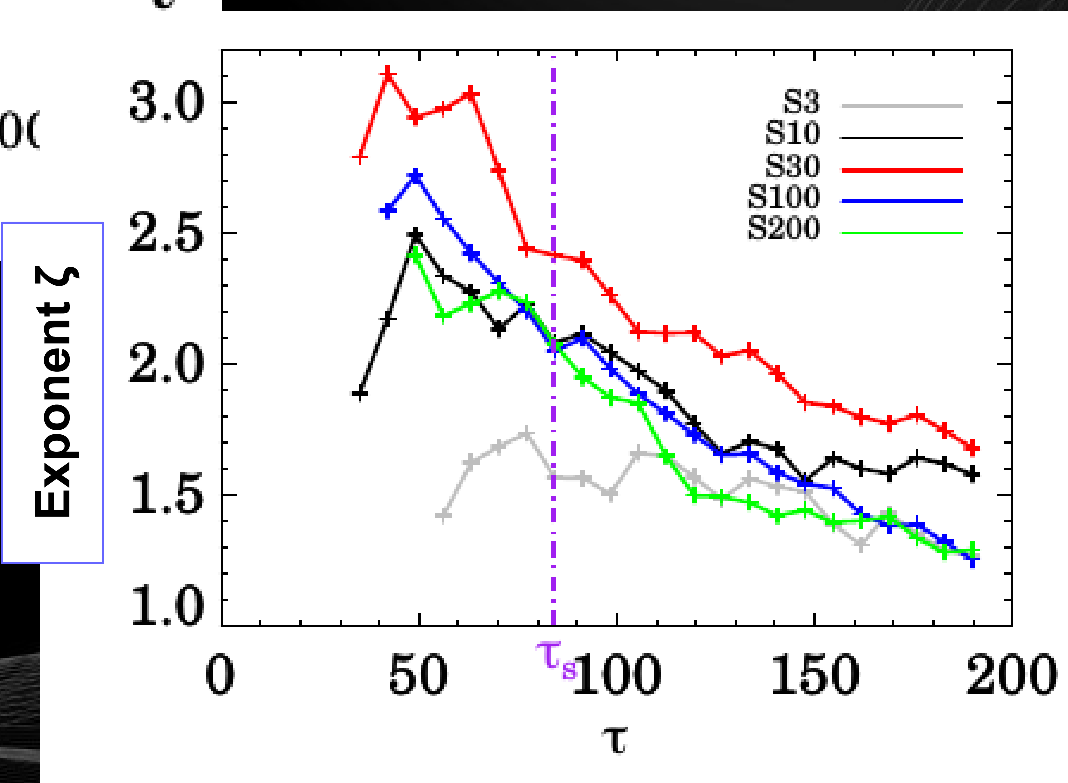
Werner, Uzdensky+2016

The extent of the power law (2)



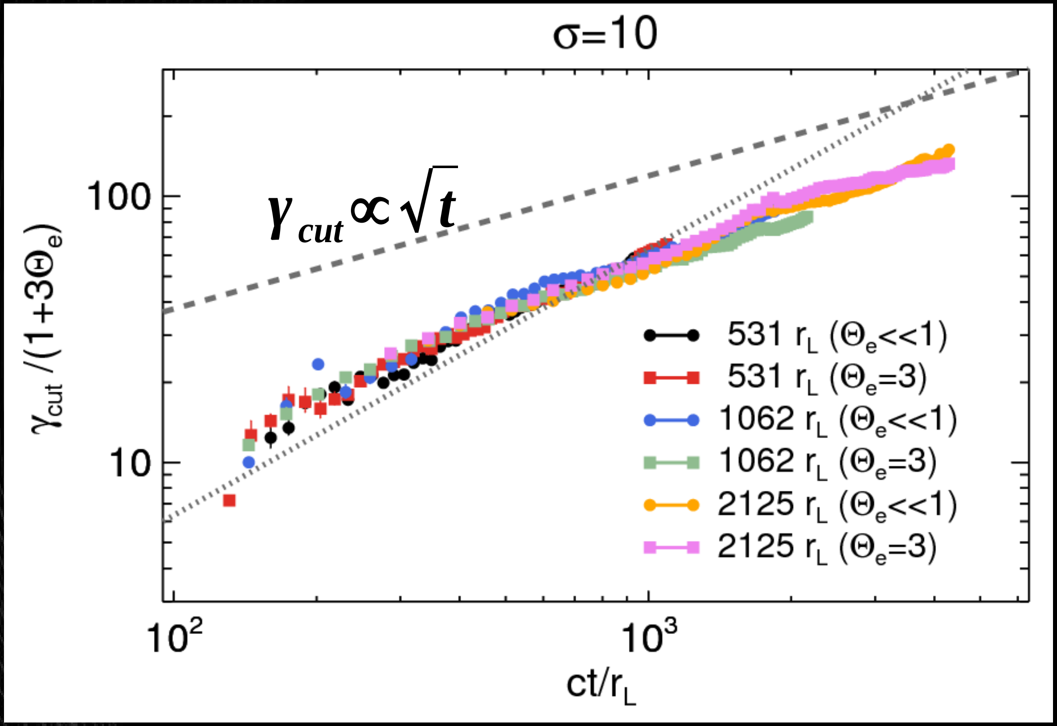
$$\frac{dN}{d\gamma} \propto \gamma^{-p} \exp\left[-(\gamma/\gamma_c)^{\zeta}\right]$$

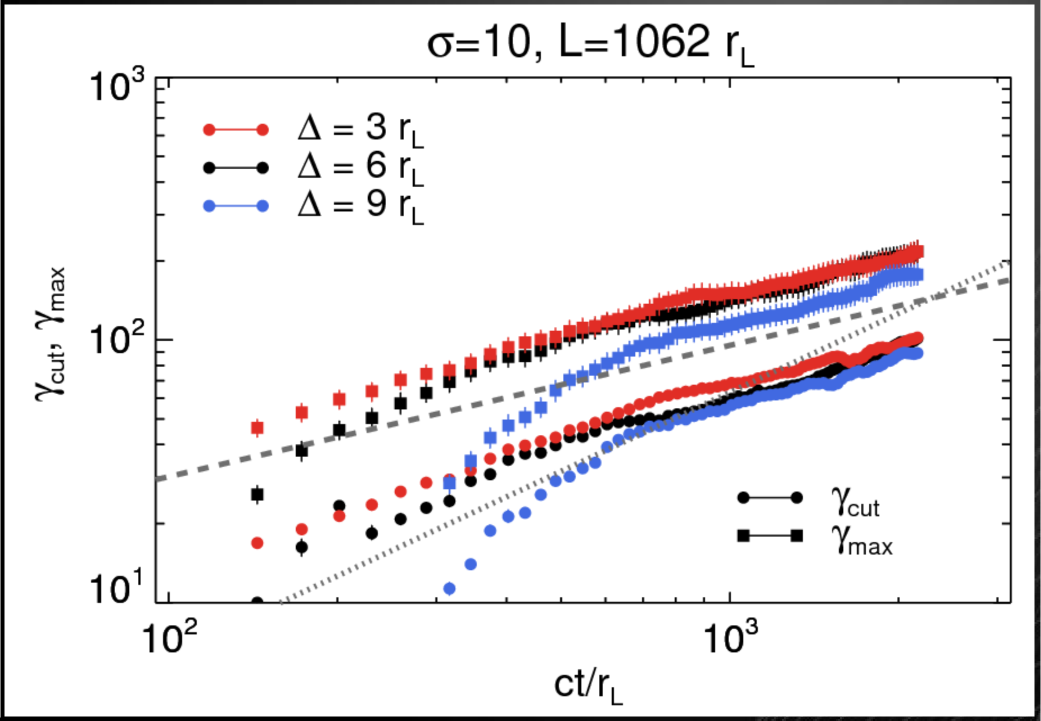
$$cutoff: \gamma_c \sim 4\sigma$$



Kagan, Nakar, Piran 2018

Effects of physical parameters





Late-time evolution of cutoff is independent of current sheet thickness

Similar evolution of cutoff for different upstream temperatures

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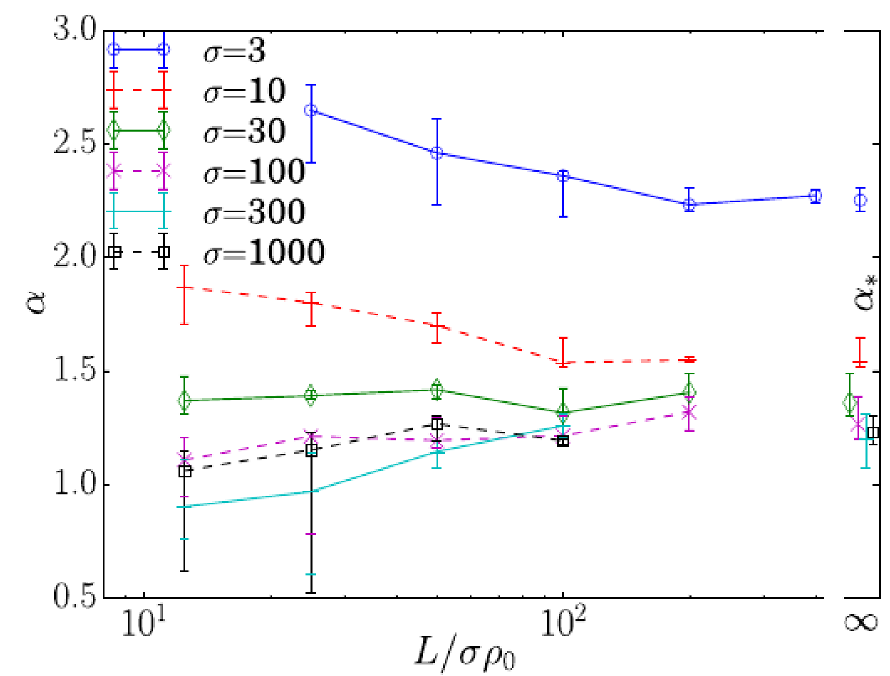
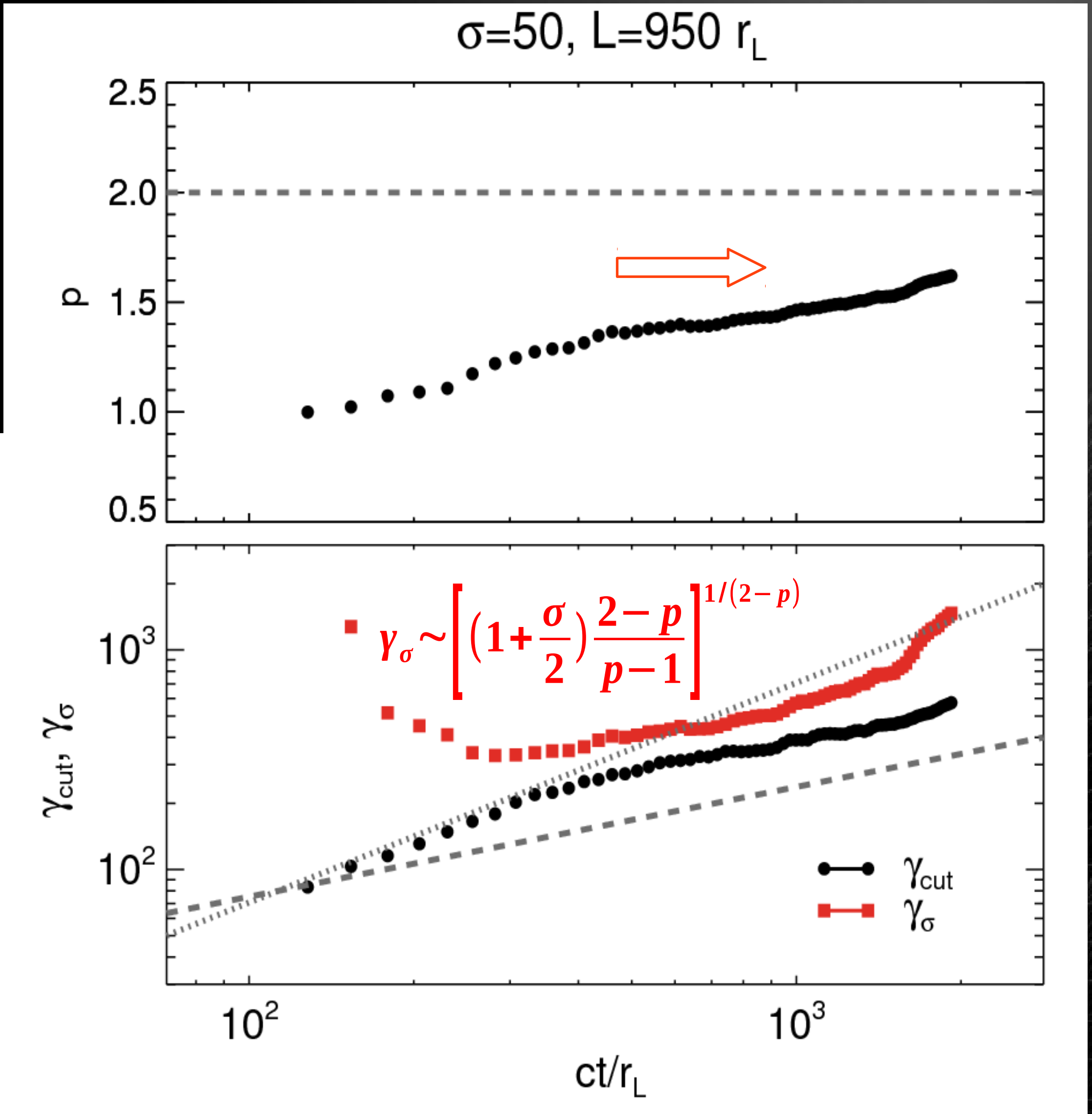
Energy crisis for σ >> 1 ?

Hints of spectral softening over time





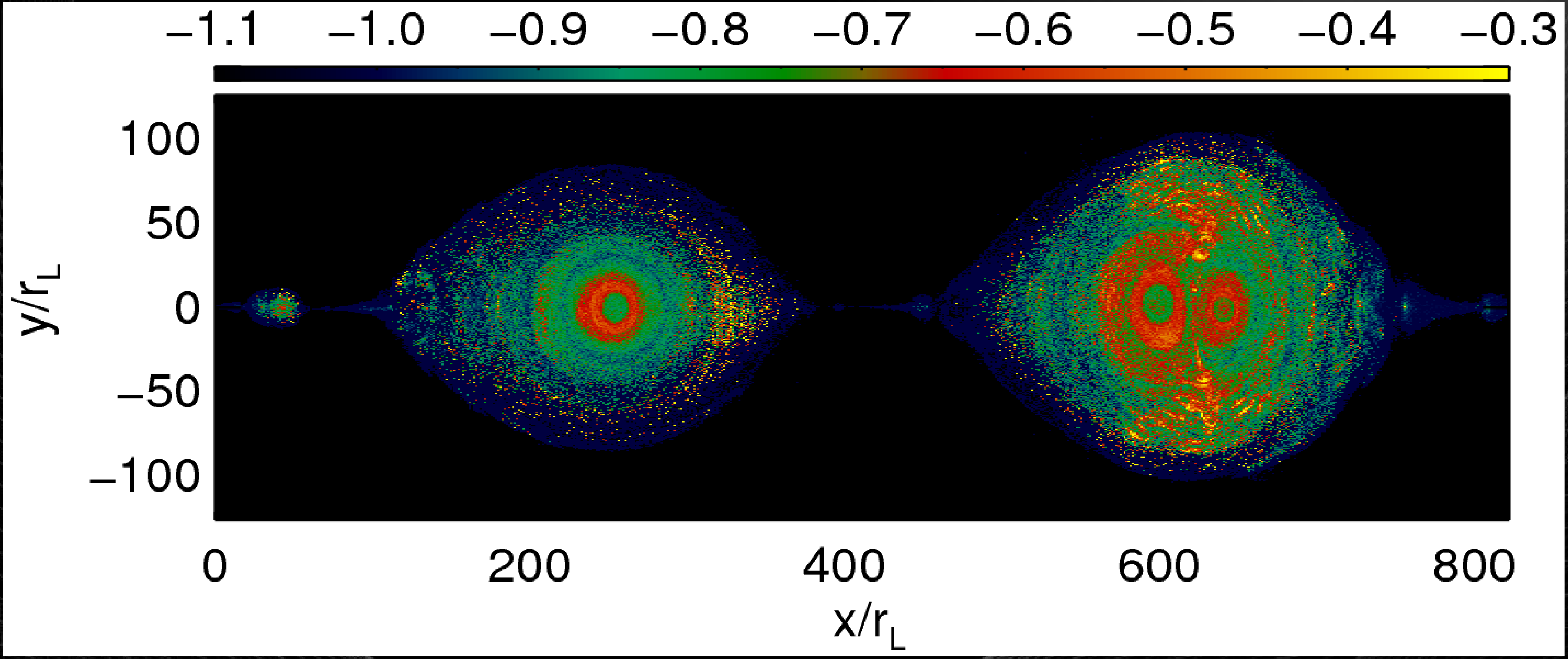
Werner+2016

Hardness ratio

$$N_s = N(5 \leq \gamma \leq 25)$$

$$HR = \frac{N_h - N_s}{N_s + N_h}$$

$$N_h = N(25 \leq \gamma \leq 250)$$



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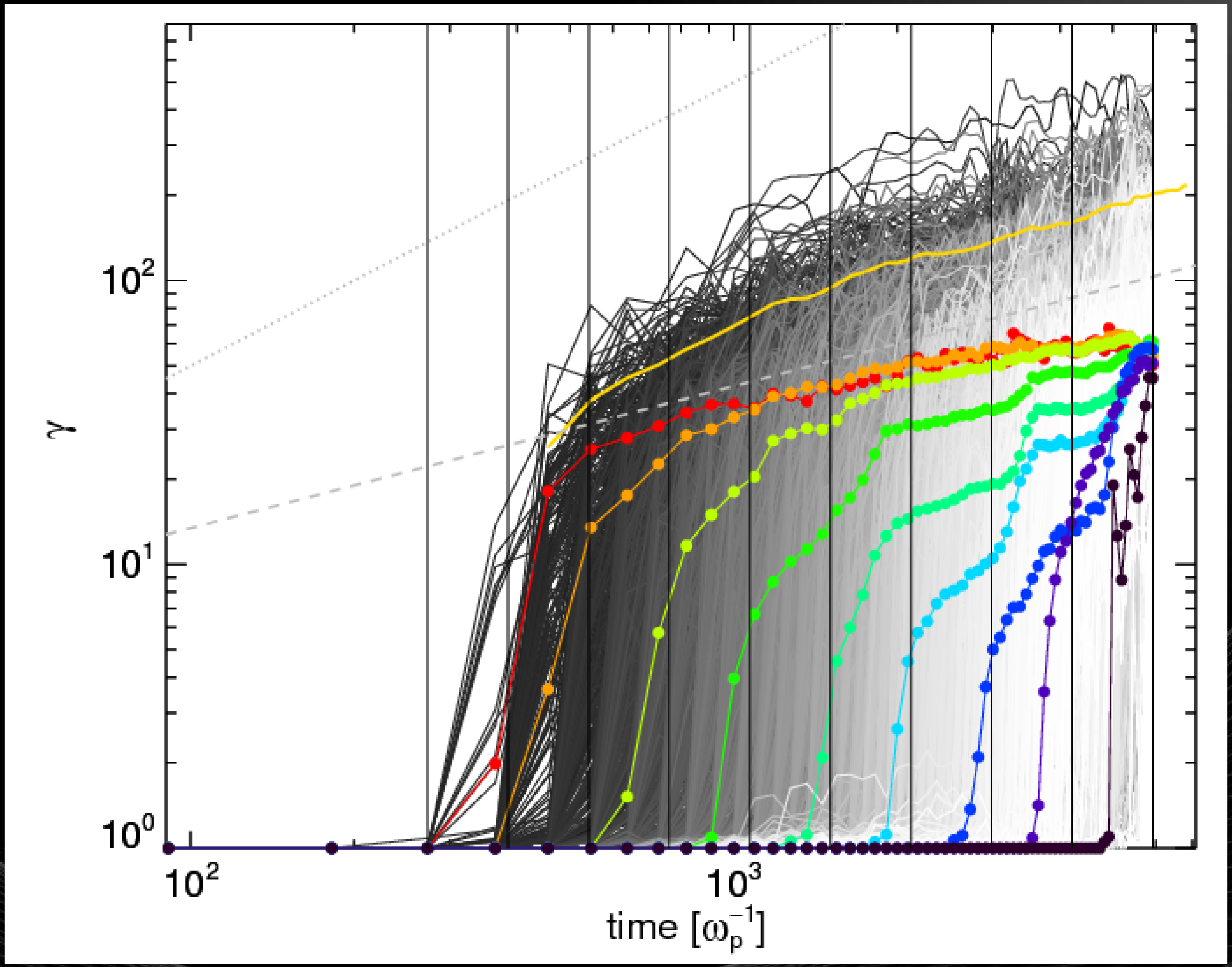
Energy evolution of particles (2)



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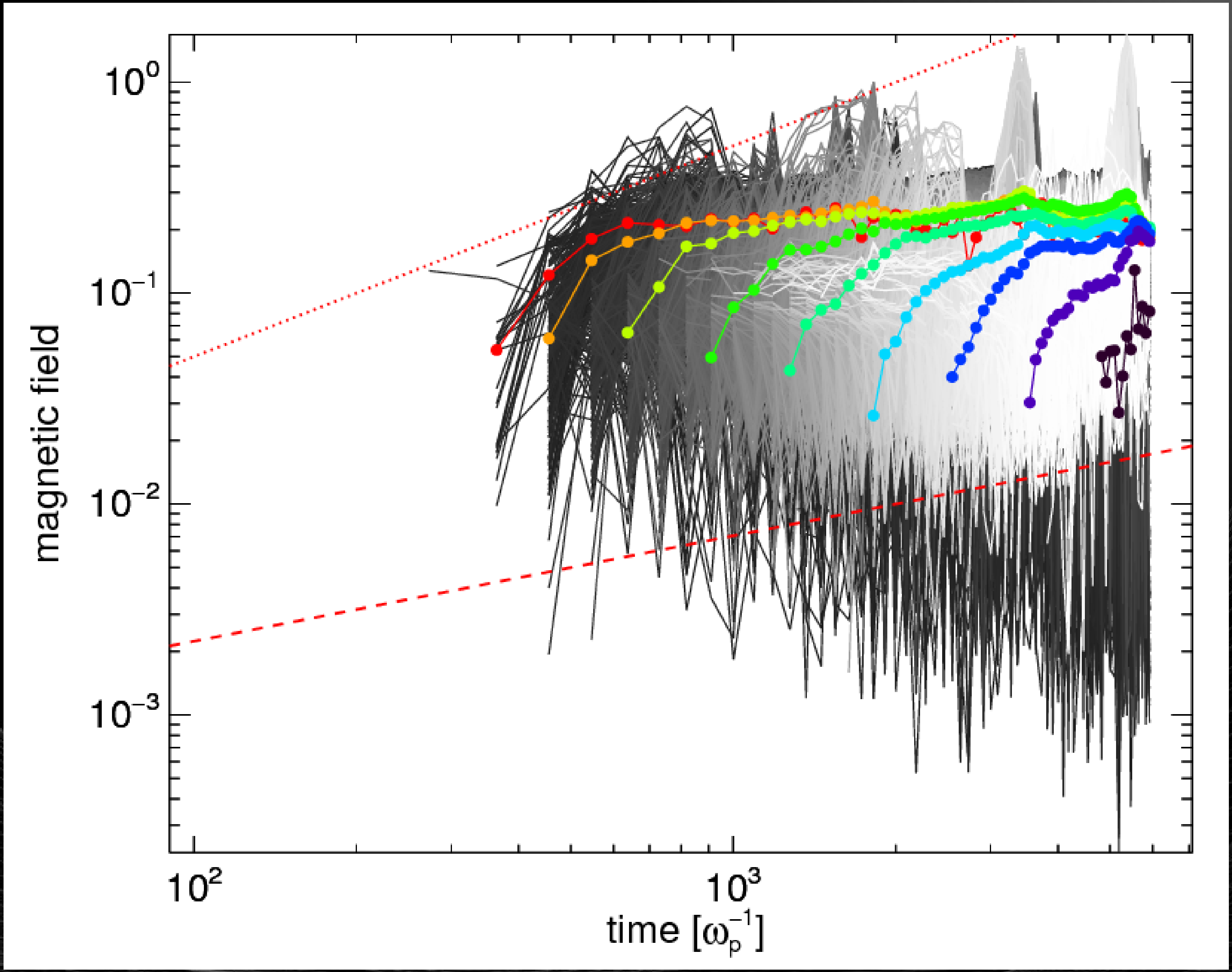
Magnetic field along trajectory (2)



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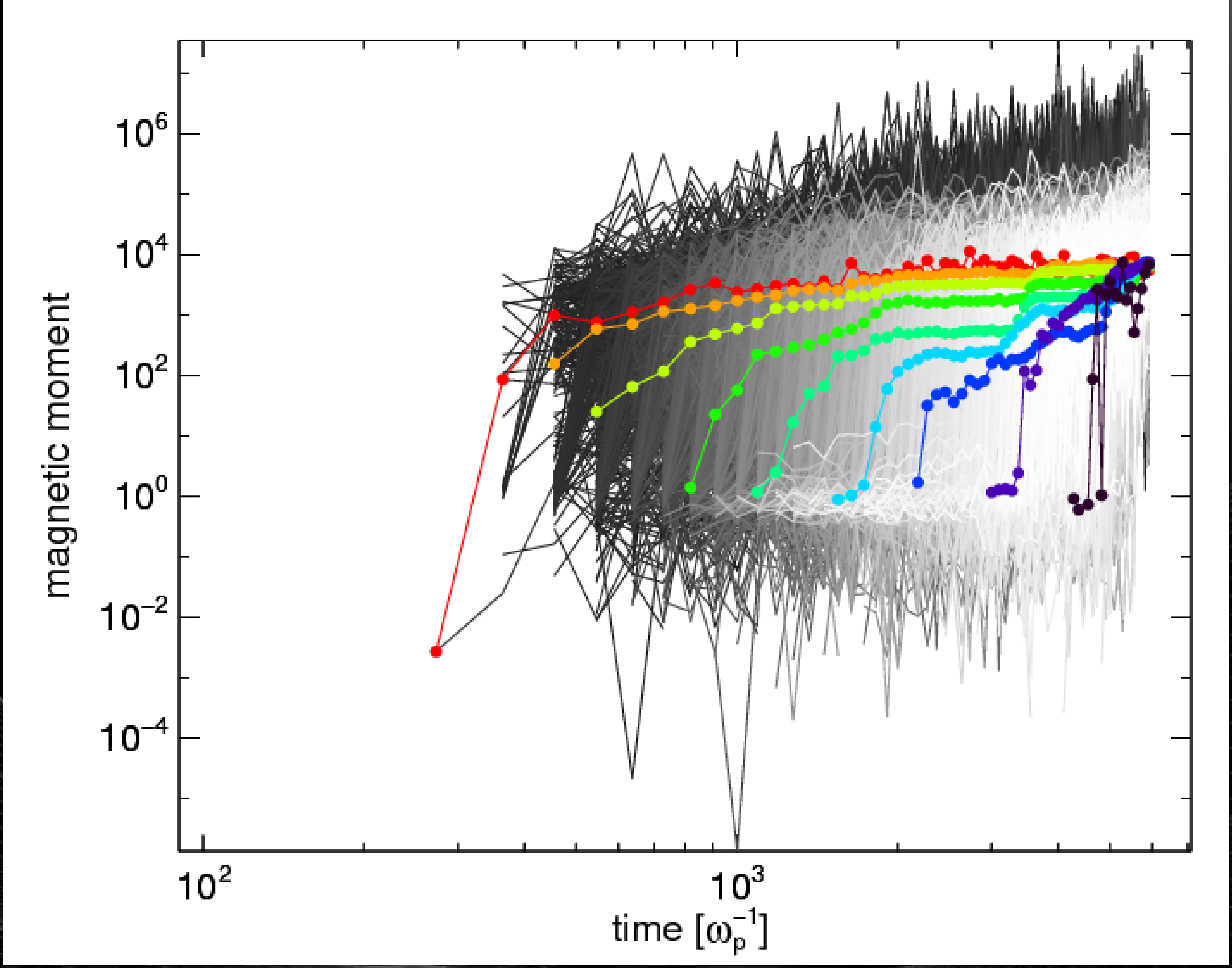
Particle magnetic moment (2)



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