Revisiting the high-energy cutoff of accelerated particles in relativistic magnetic reconnection

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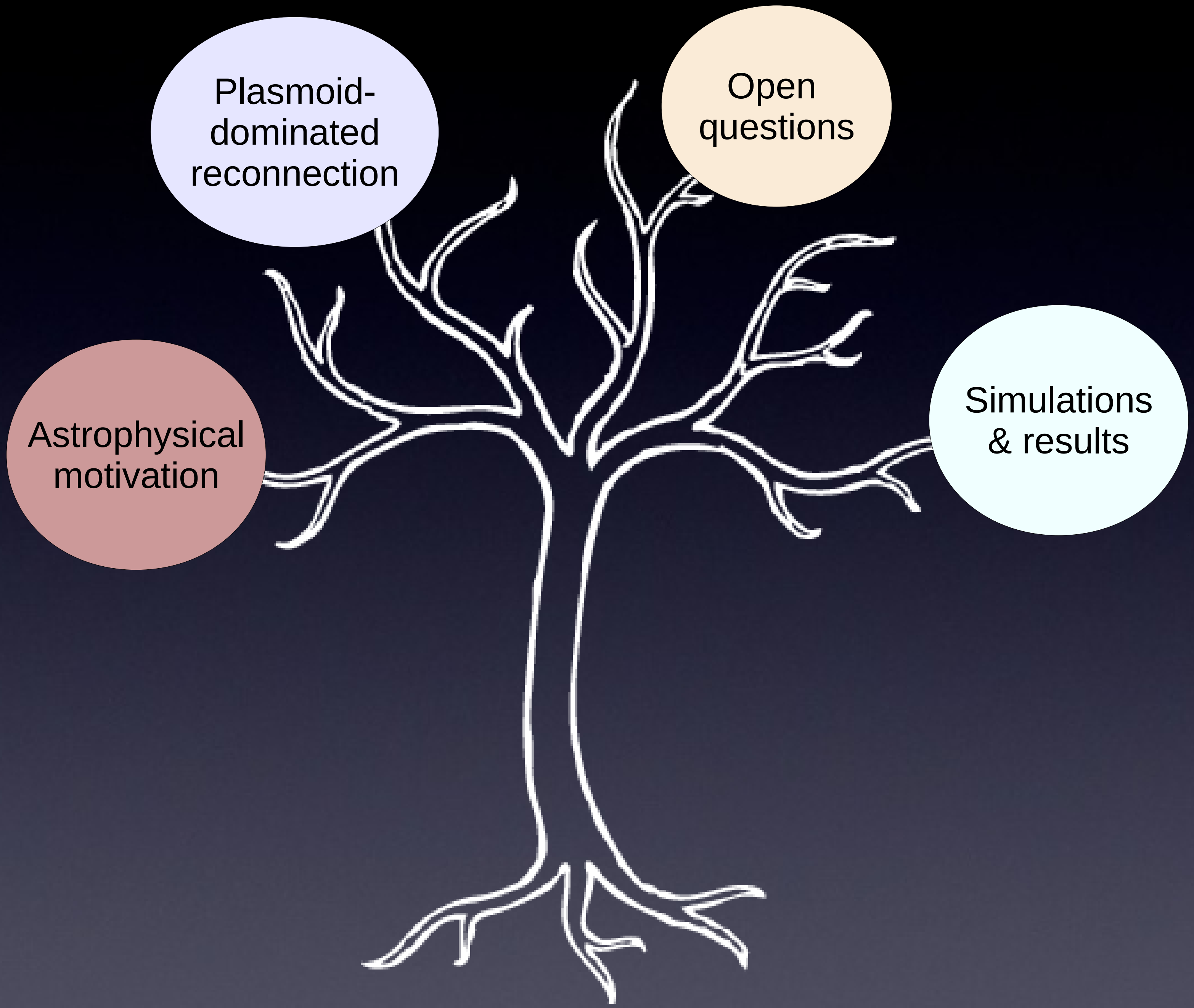
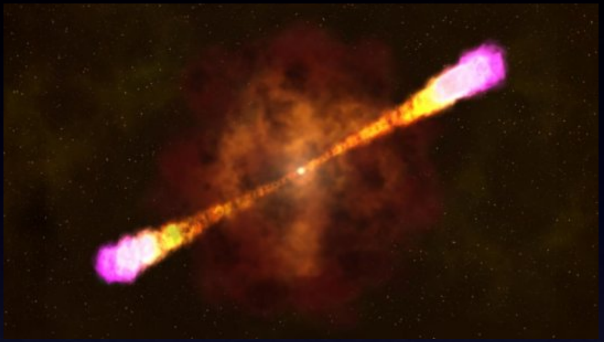
3rd Workshop on Relativistic Plasma Astrophysics, Purdue University


Plasmoid-
dominated
reconnection
Open
questions
Astrophysical
motivation
Simulations
& results

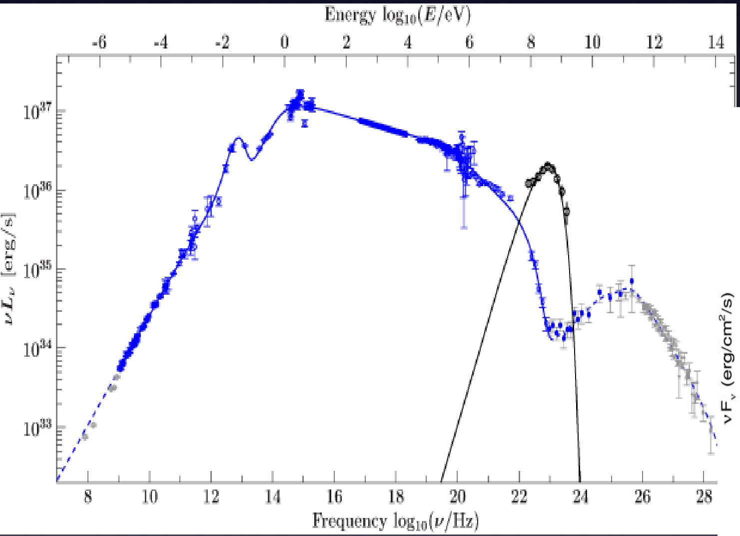
Non-thermal broadband radiation

From PWNe ...

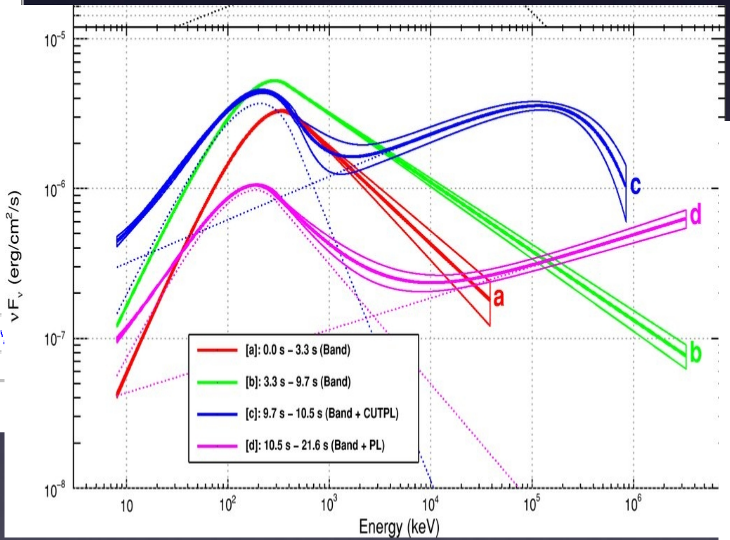


to GRBs …

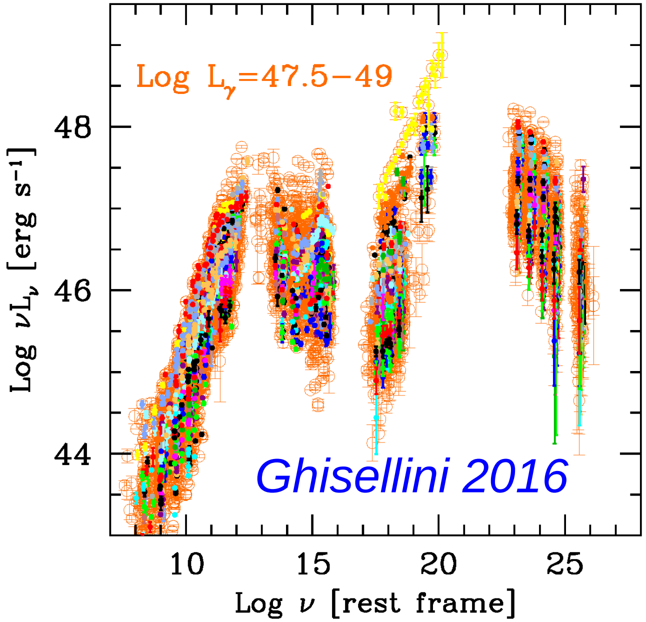
to jetted AGN.



Lyutikov 2014



Ackermann+ 2011



Ghisellini 2016

Energy dissipation

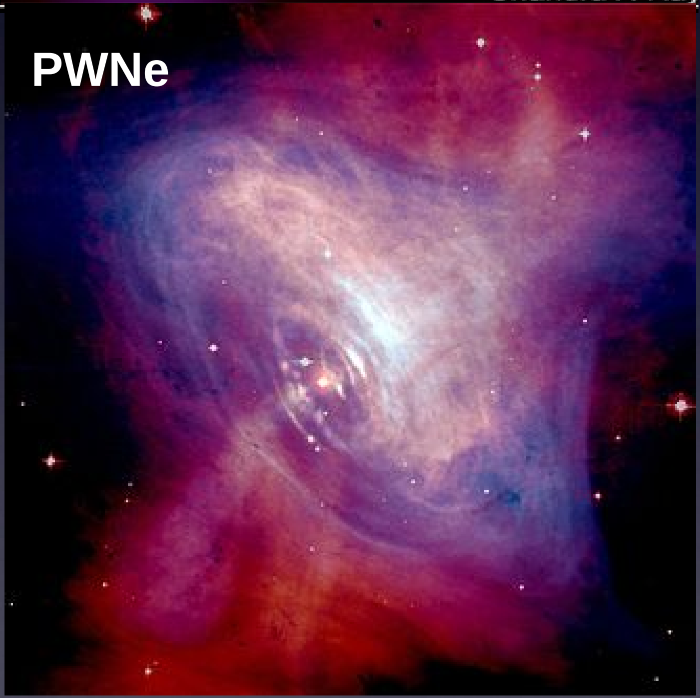
Energy reservoir: kinetic

- Kelvin-Helmholtz instabilities
- Shocks

$$\sigma = \frac{B_0^2}{4\pi n_0 m c^2} \gtrsim 1$$

Energy reservoir: magnetic

- Current-driven kink instability
- Magnetic reconnection
- Magneto-luminescence



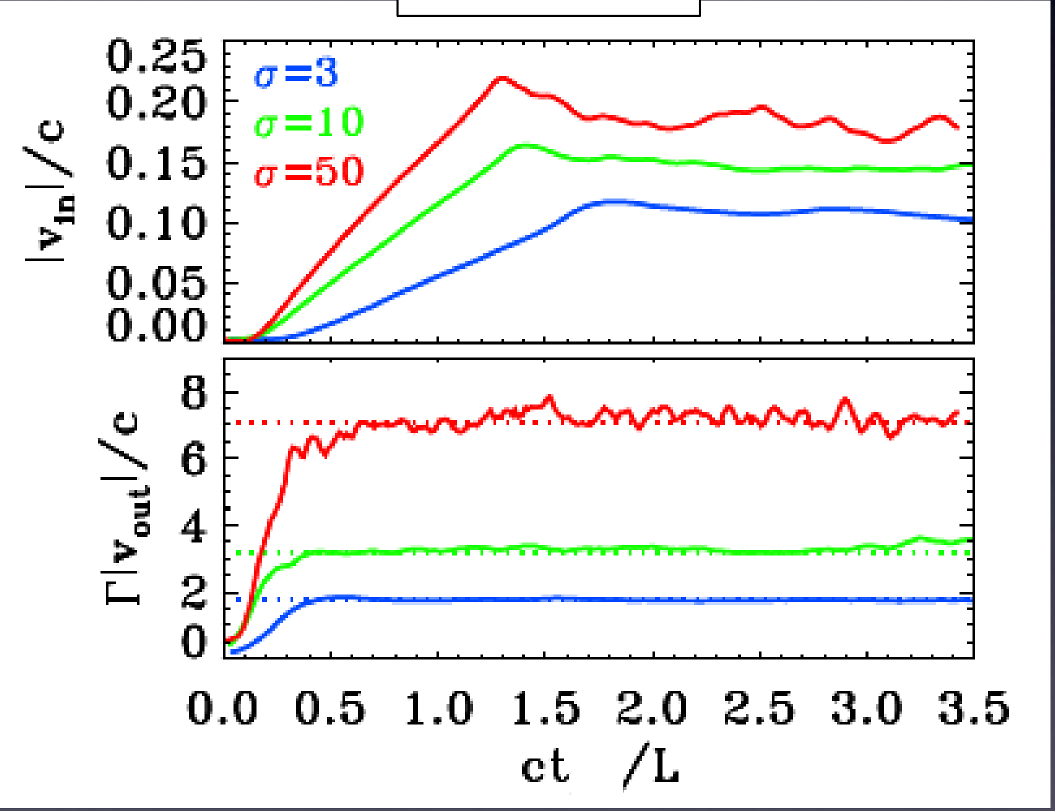
Plasmoid-dominated reconnection

Zenitani & Hoshino 2001, Loureiro+2007, Bhattacharjee+2009, Uzdensky+2010, Loureiro+2012, Guo+2014; 2015, Sironi & Spitkovsky 2014; Nalewajko+2015; Kagan+2015 (for review); Sironi+2015; Werner+2016, Sironi+2016 and many more …

What makes plasmoid-dominated reconnection appealing?

- Fast dissipation
- Fast bulk motion
- Efficient dissipation
- Non-thermal particle distributions
- σ-dependent power-law slopes

Pair plasma



Sironi, Giannios, Petropoulou, 2016

Plasmoid-dominated reconnection

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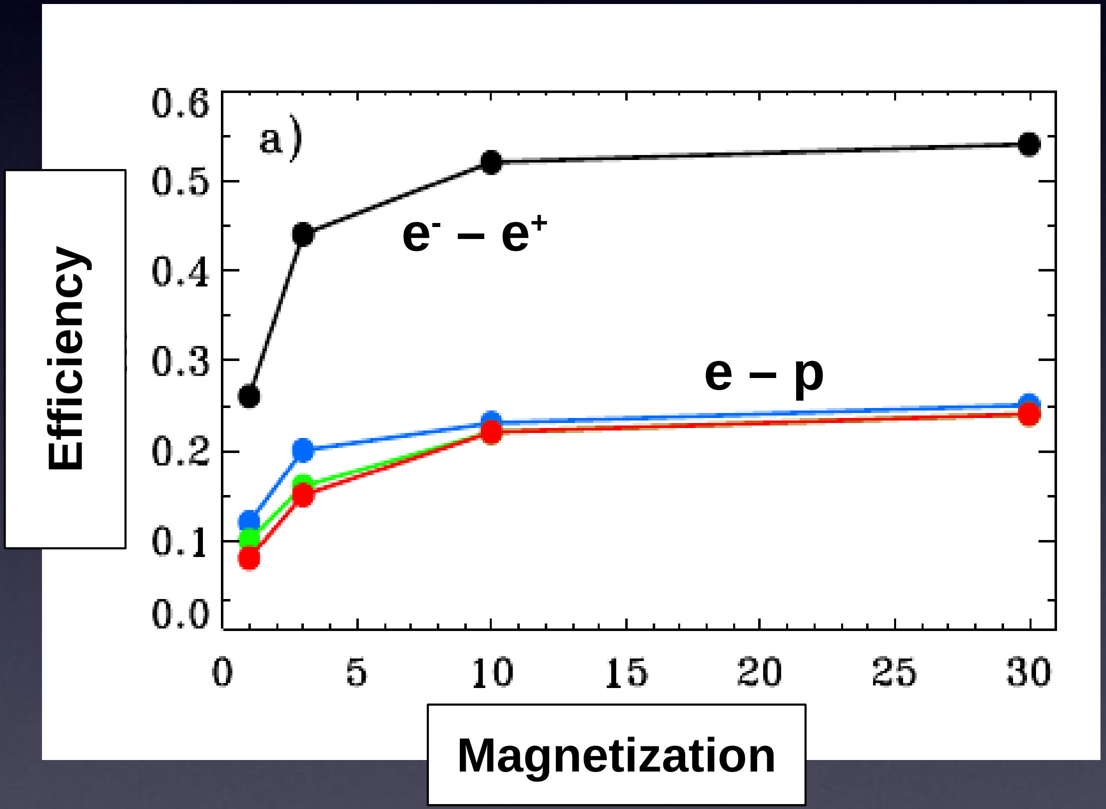

Sironi, Petropoulou, Giannios 2015

Plasmoid-dominated reconnection

Zenitani & Hoshino 2001, Loureiro+2007, Bhattacharjee+2009, Uzdensky+2010, Loureiro+2012, Guo+2014; 2015, Sironi & Spitkovsky 2014; Nalewajko+2015; Kagan+2015 (for review); Sironi+2015; Werner+2016, Sironi+2016 and many more …

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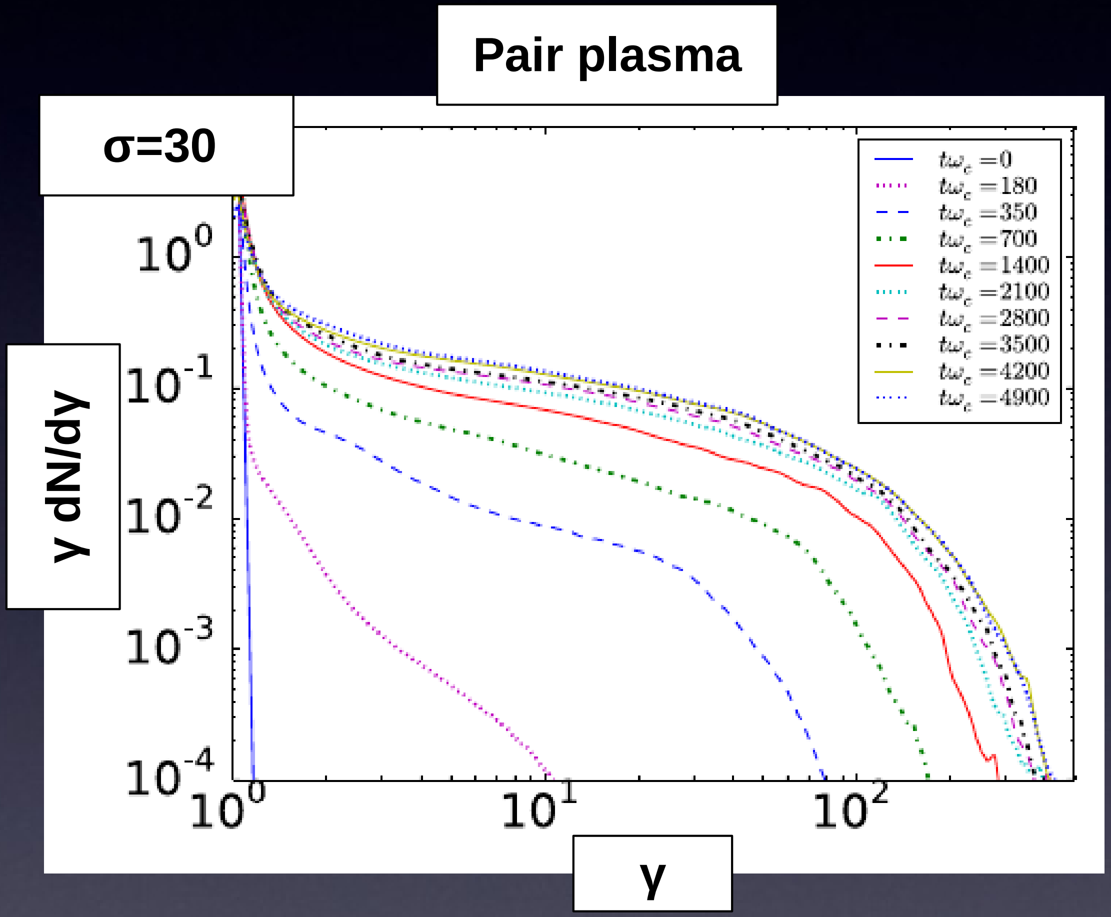

Werner, Uzdensky+2016

Plasmoid-dominated reconnection

Zenitani & Hoshino 2001, Loureiro+2007, Bhattacharjee+2009, Uzdensky+2010, Loureiro+2012, Guo+2014; 2015, Sironi & Spitkovsky 2014; Nalewajko+2015; Kagan+2015 (for review); Sironi+2015; Werner+2016, Sironi+2016 and many more …

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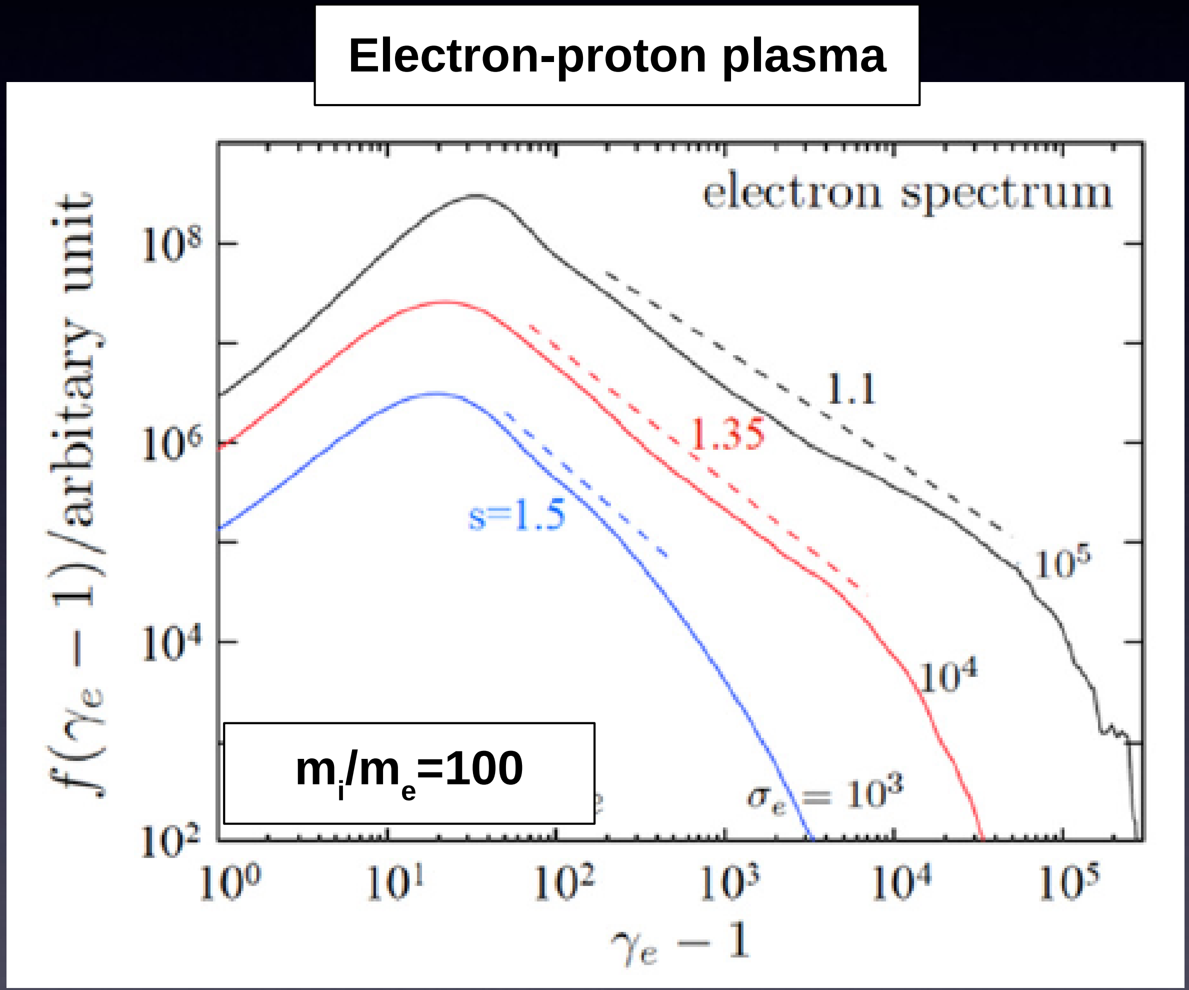
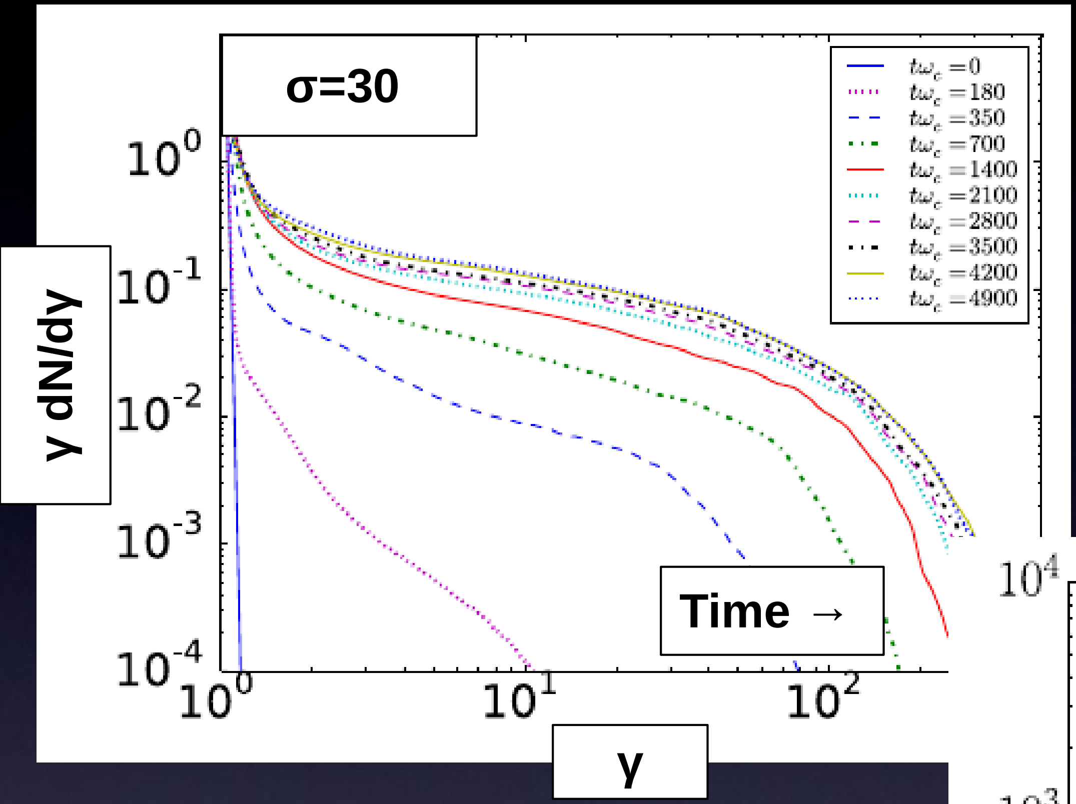


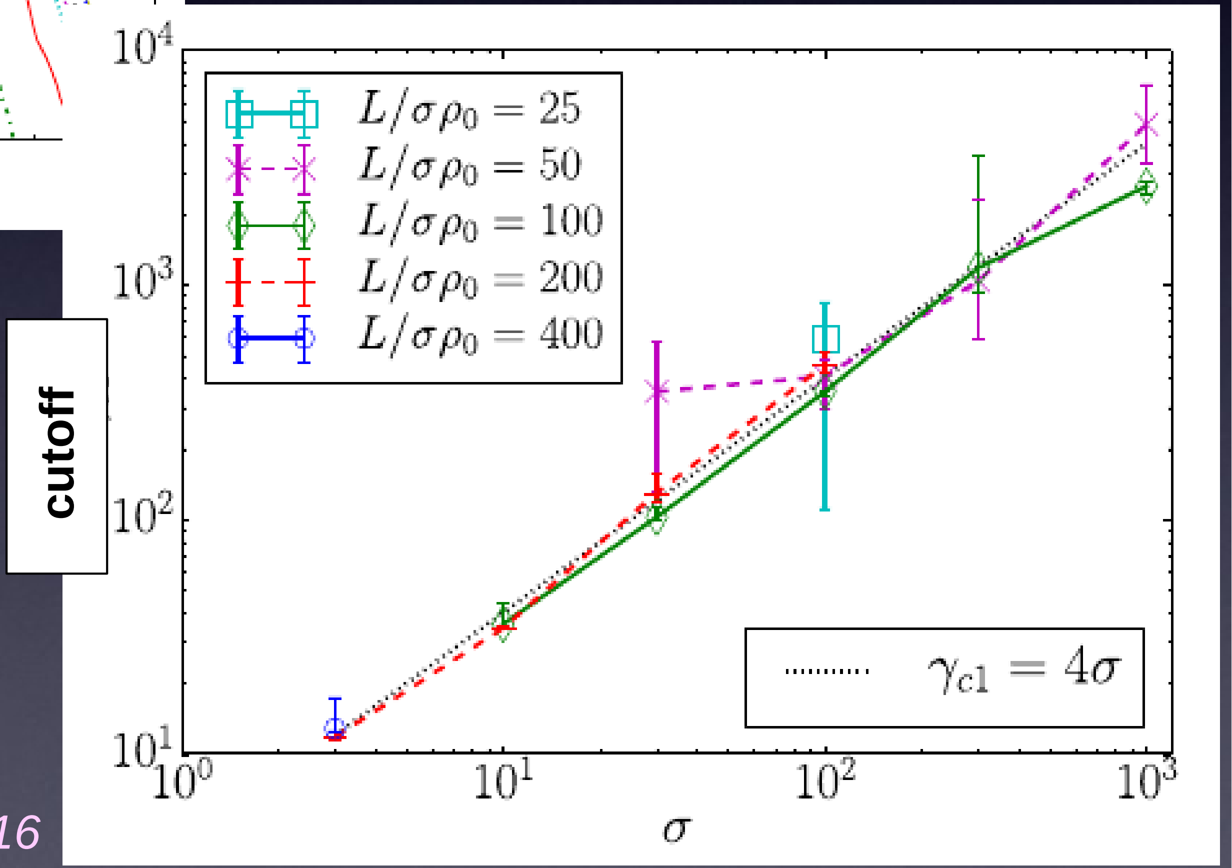
Guo+2016

The extent of the power law (1)



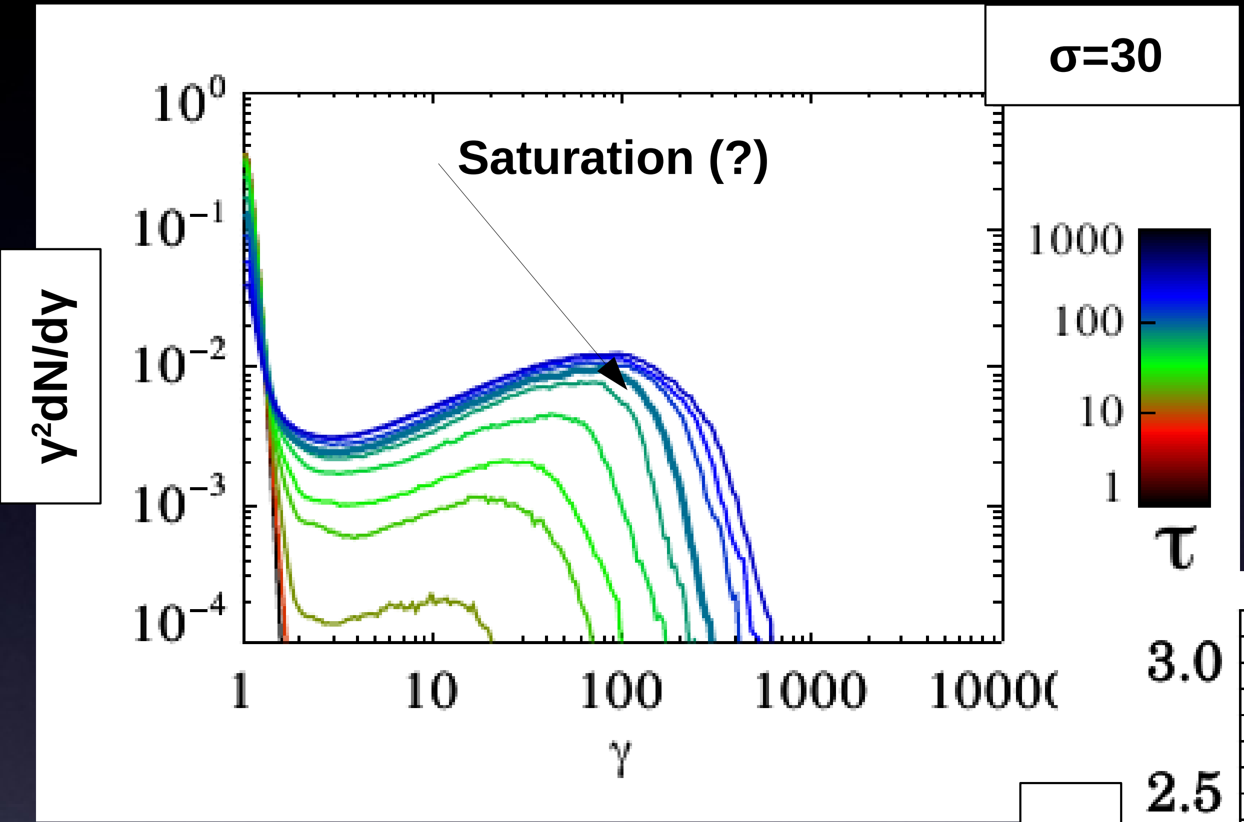
$$\frac{dN}{d\gamma} \propto \gamma^{-p} \exp[-\gamma/\gamma_c - (\gamma/\gamma_{c2})^2]$$

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



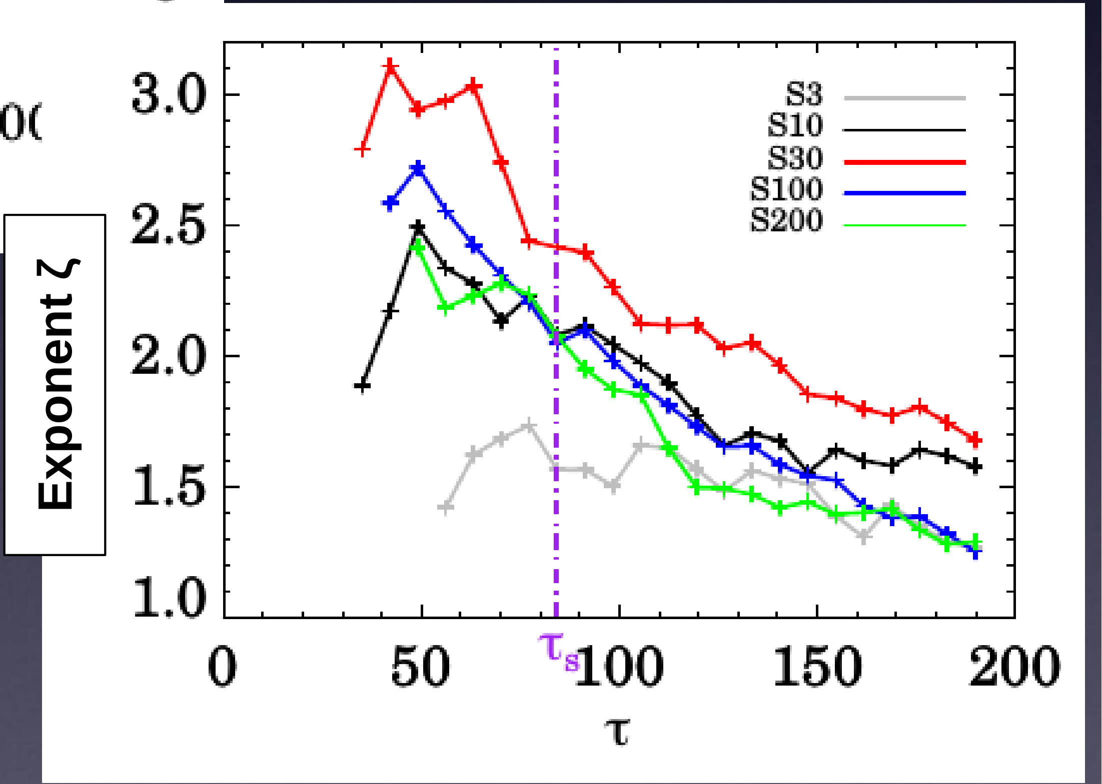
Werner, Uzdensky+2016

The extent of the power law (2)



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

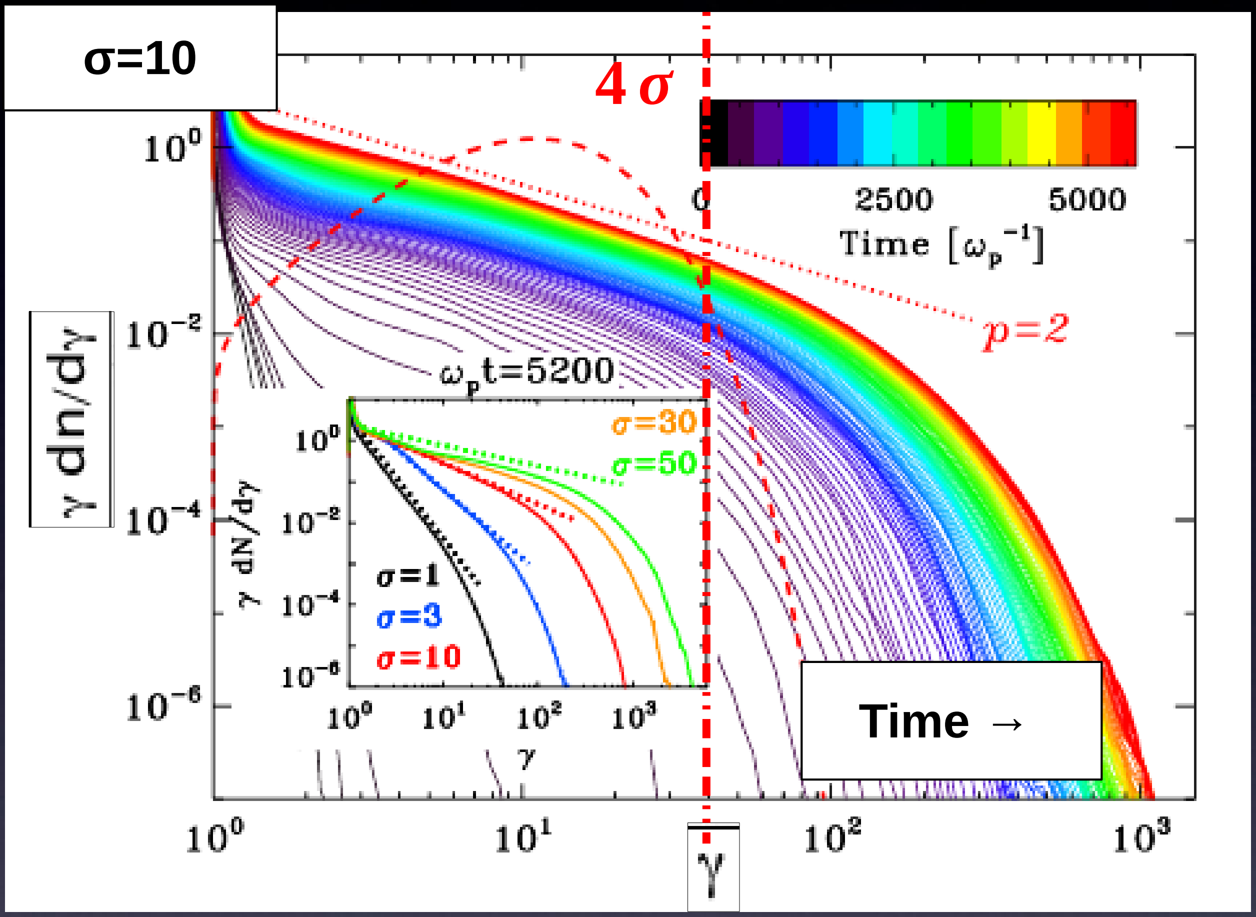
$cutoff: \gamma_c \sim 4\sigma$



Kagan, Nakar, Piran 2018

Open questions

Is the 4σ cutoff a strict limit?



Sironi & Spitkovsky 2014

How does the cutoff evolve with time?

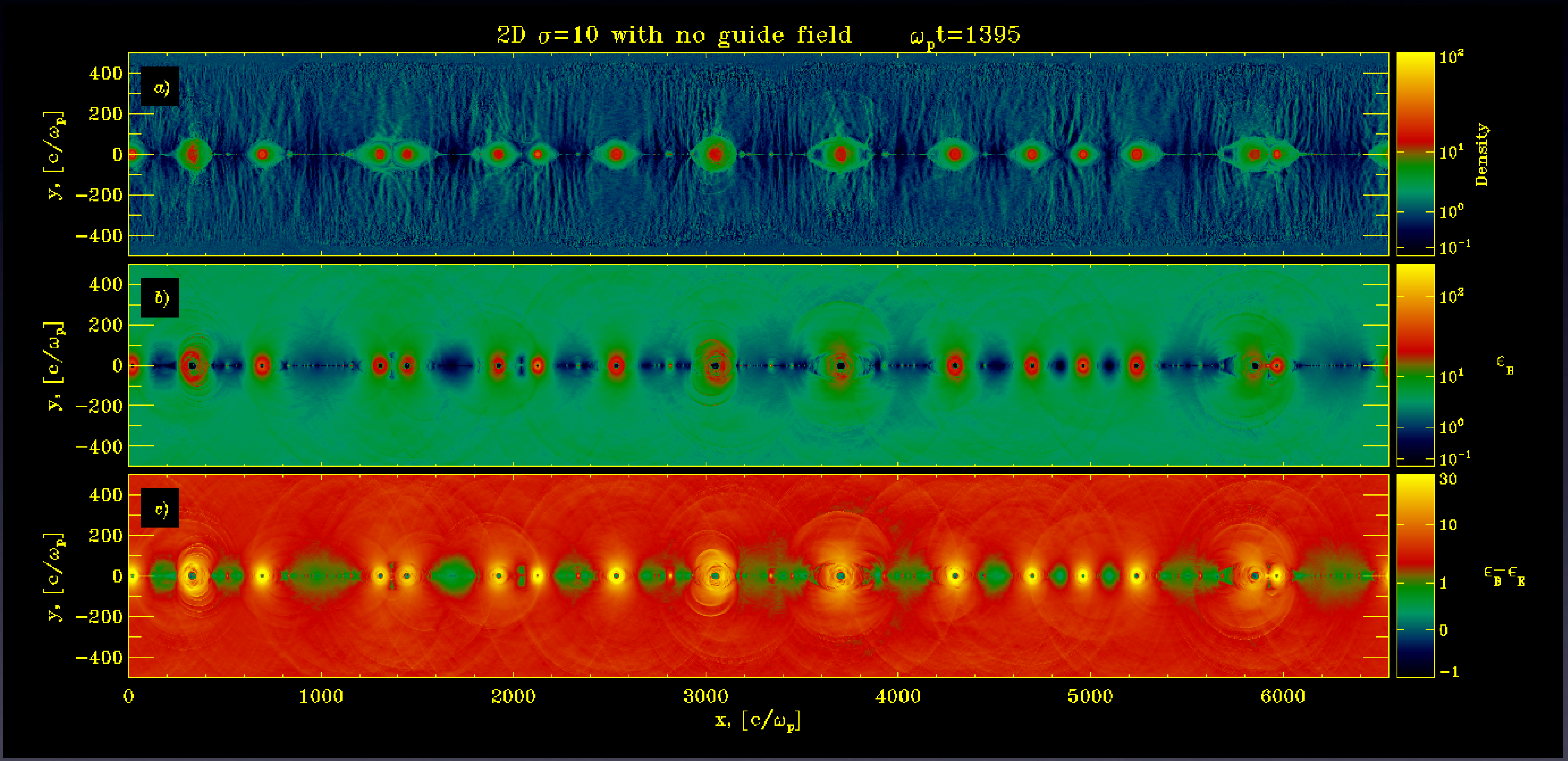
Where do the most energetic particles get accelerated?

Simulations with periodic BC

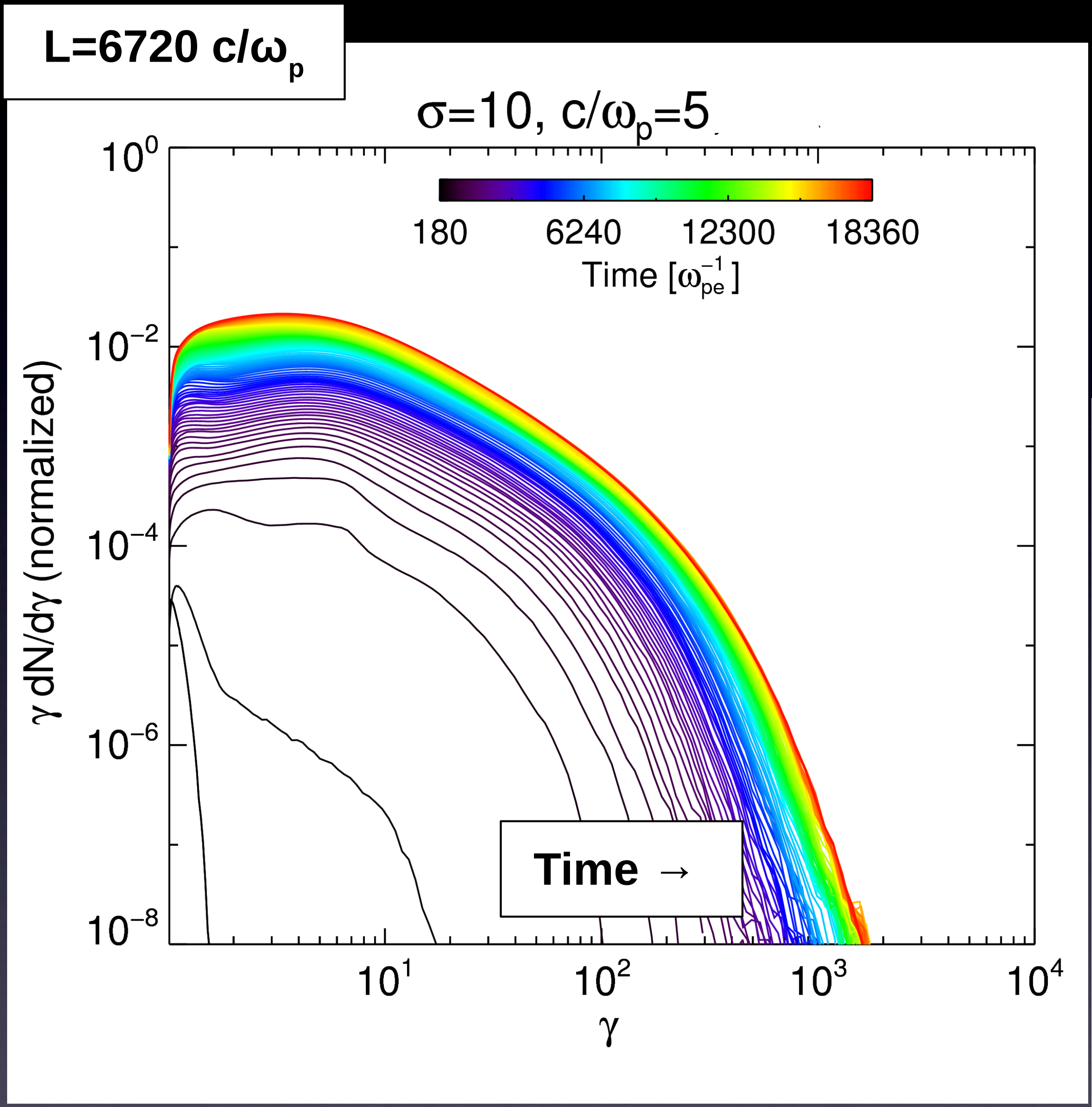
σ	c/ω_p [cells]	L [c/ω_p]	L [$r_{L,\,hot}$]*	Duration [$1/\omega_p$]
10	5	1680	531	3375
10	5	3360	1062	13500
10	5	6720	2125	18360
10	5	13440	4250	27000
10	10	1680	531	3375
10	10	3360	1062	6750
50	5	1680	237.5	3375
50	5	3360	475	6750
50	5	6720	950	13500
50	5	13440	1900	27000

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

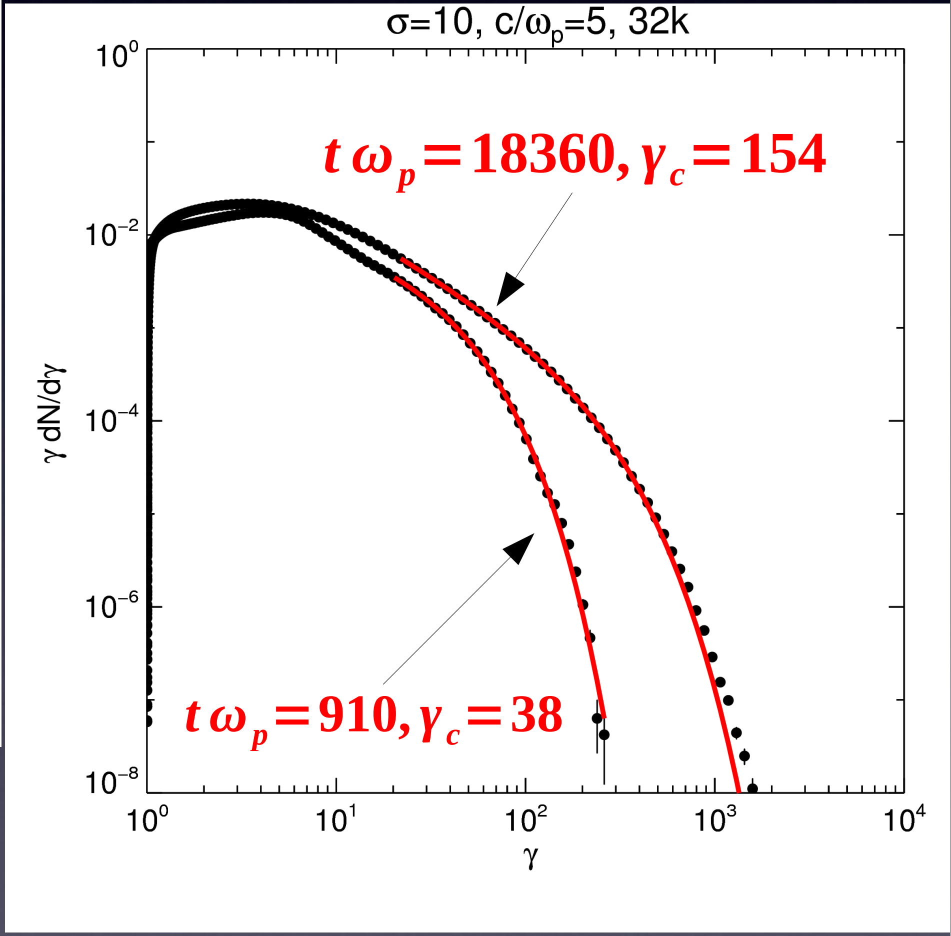
Evolution of the layer



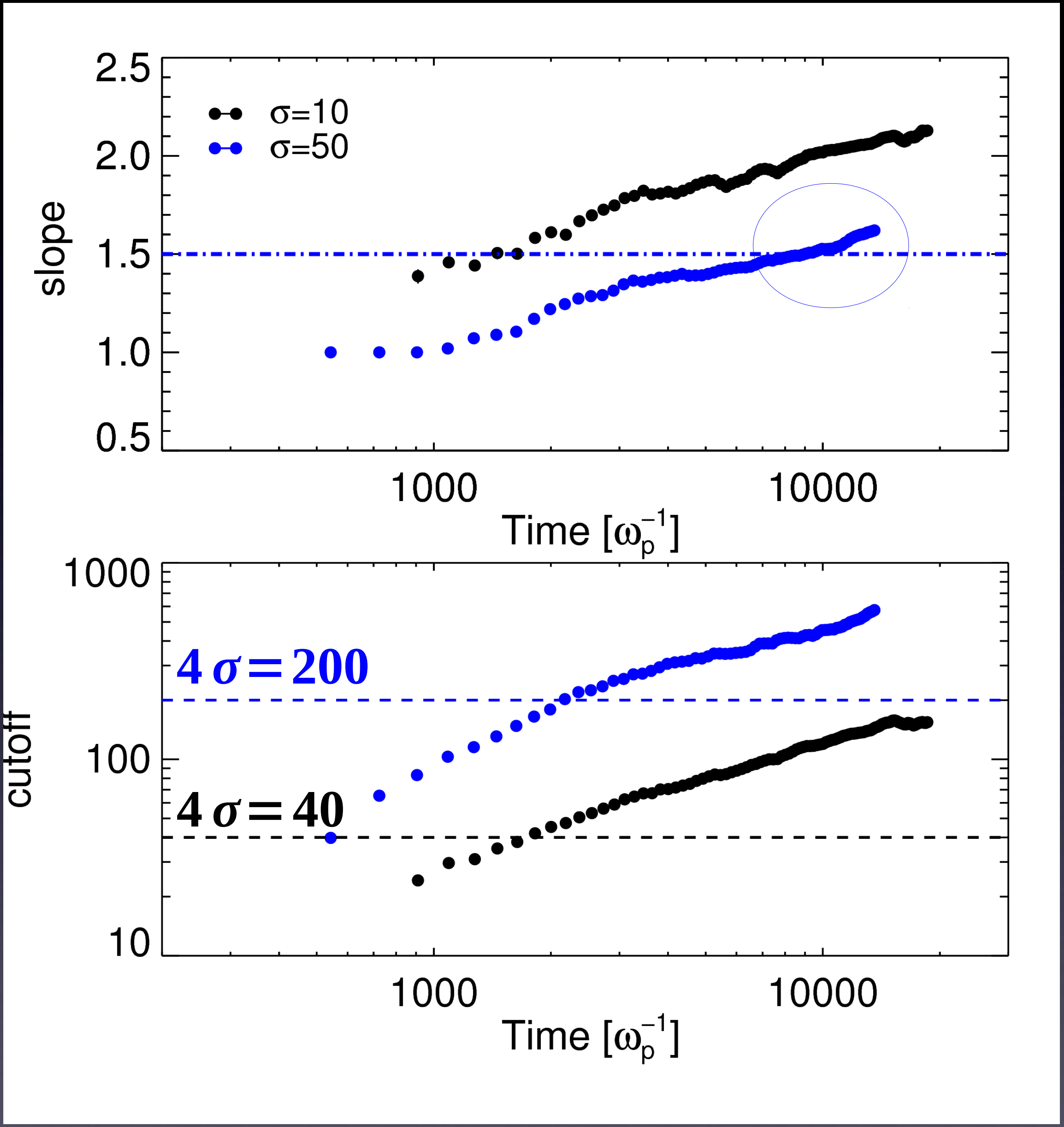
Particle distribution fitting



$$\frac{dN}{d\gamma} \propto \gamma^{-p} \exp[-\gamma/\gamma_c], \gamma > 20$$



Evolution of slope & cutoff

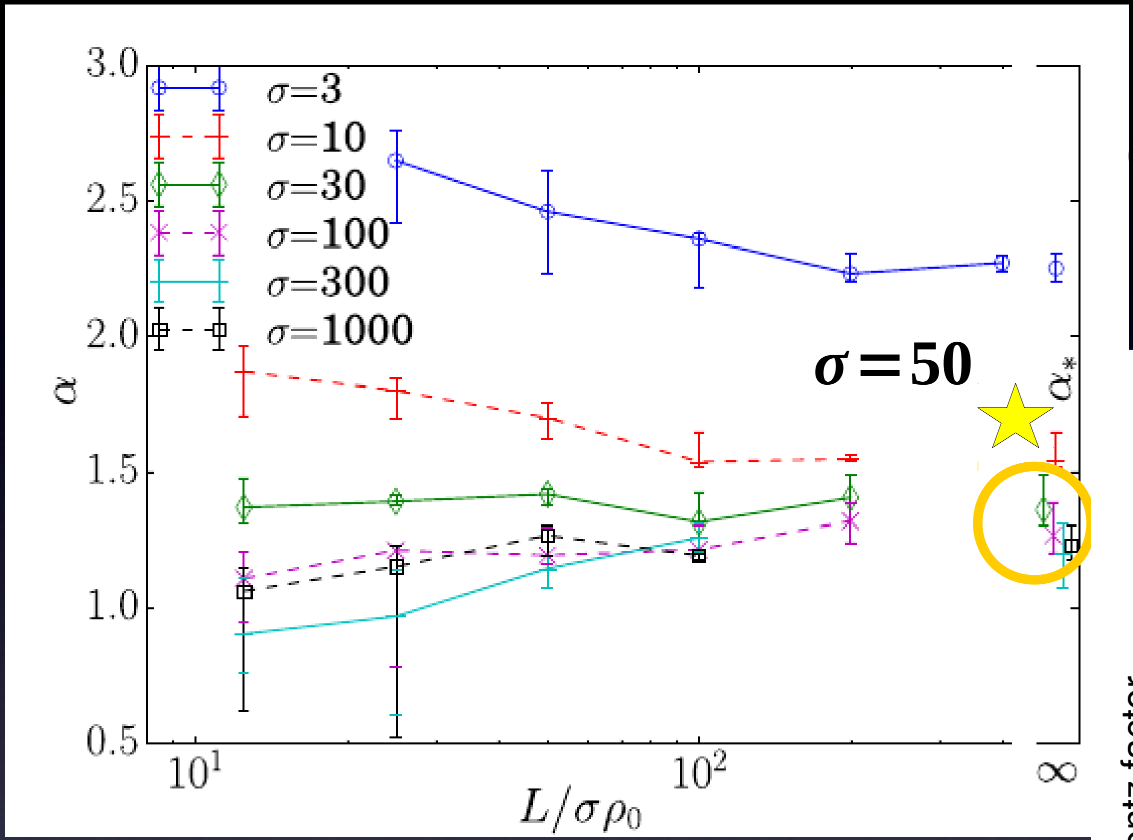


Hint for softening

The cutoff clearly exceeds the 4σ value regardless of σ

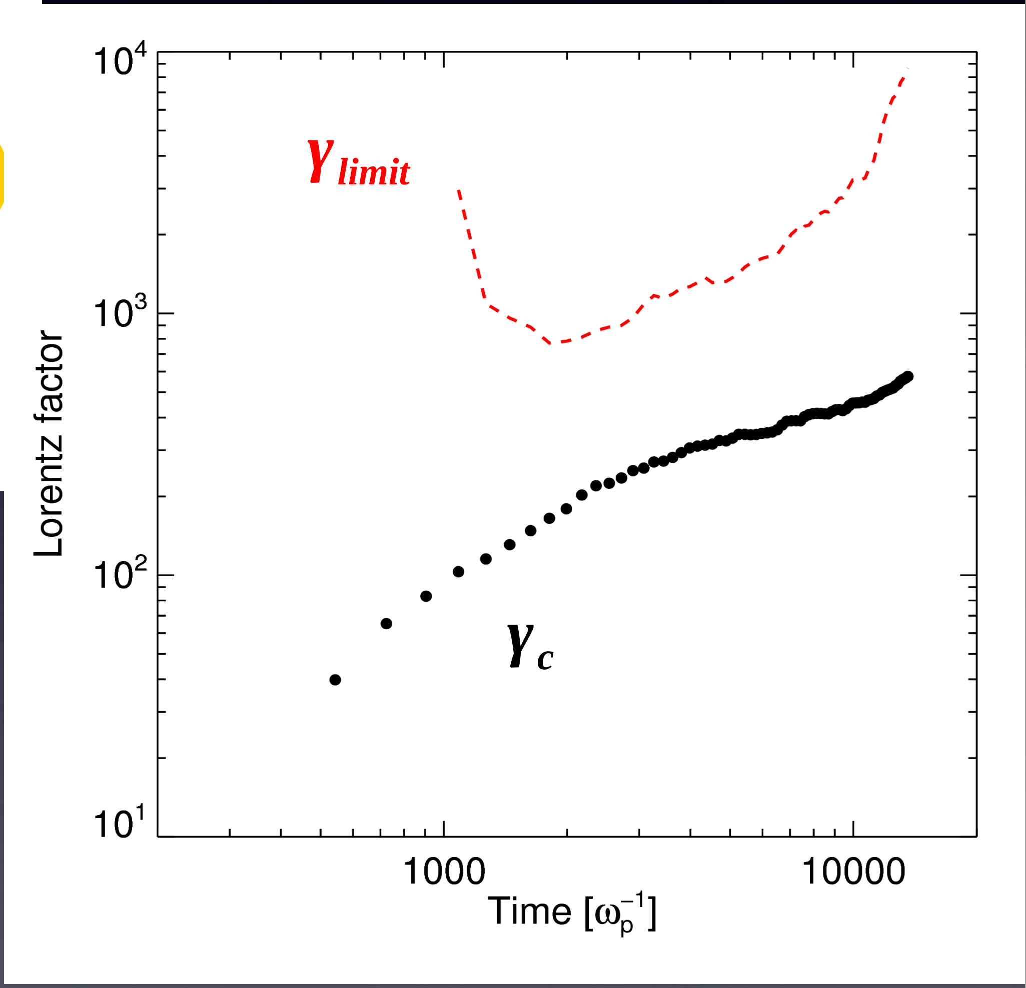
Click here

Energy crisis for σ >> 1 ?

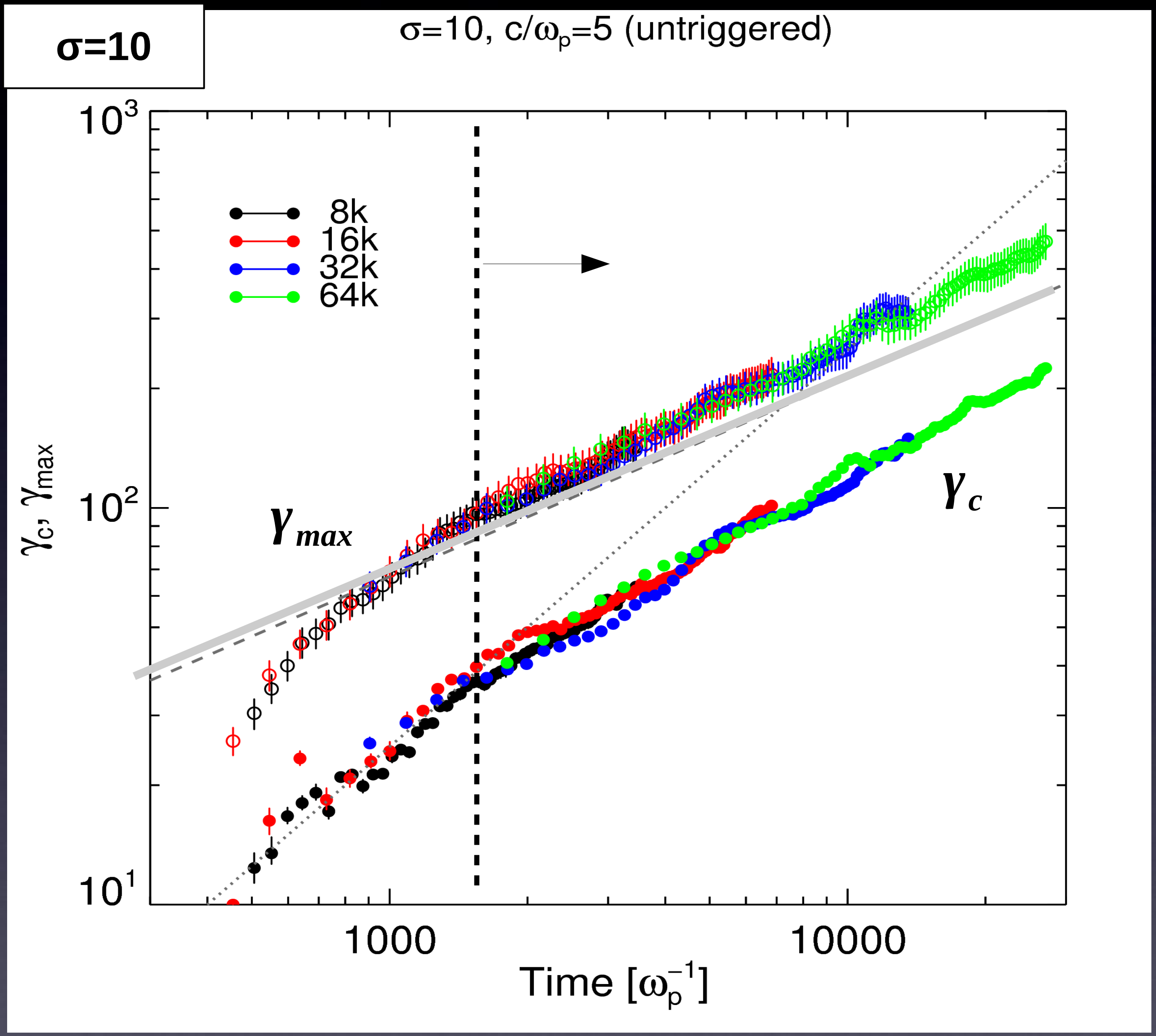


Werner, Uzdensky+2016

$\gamma_{limit} \sim [(\sigma+1)(2-p)/(p-1)]^{1/(2-p)}$



System's size



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

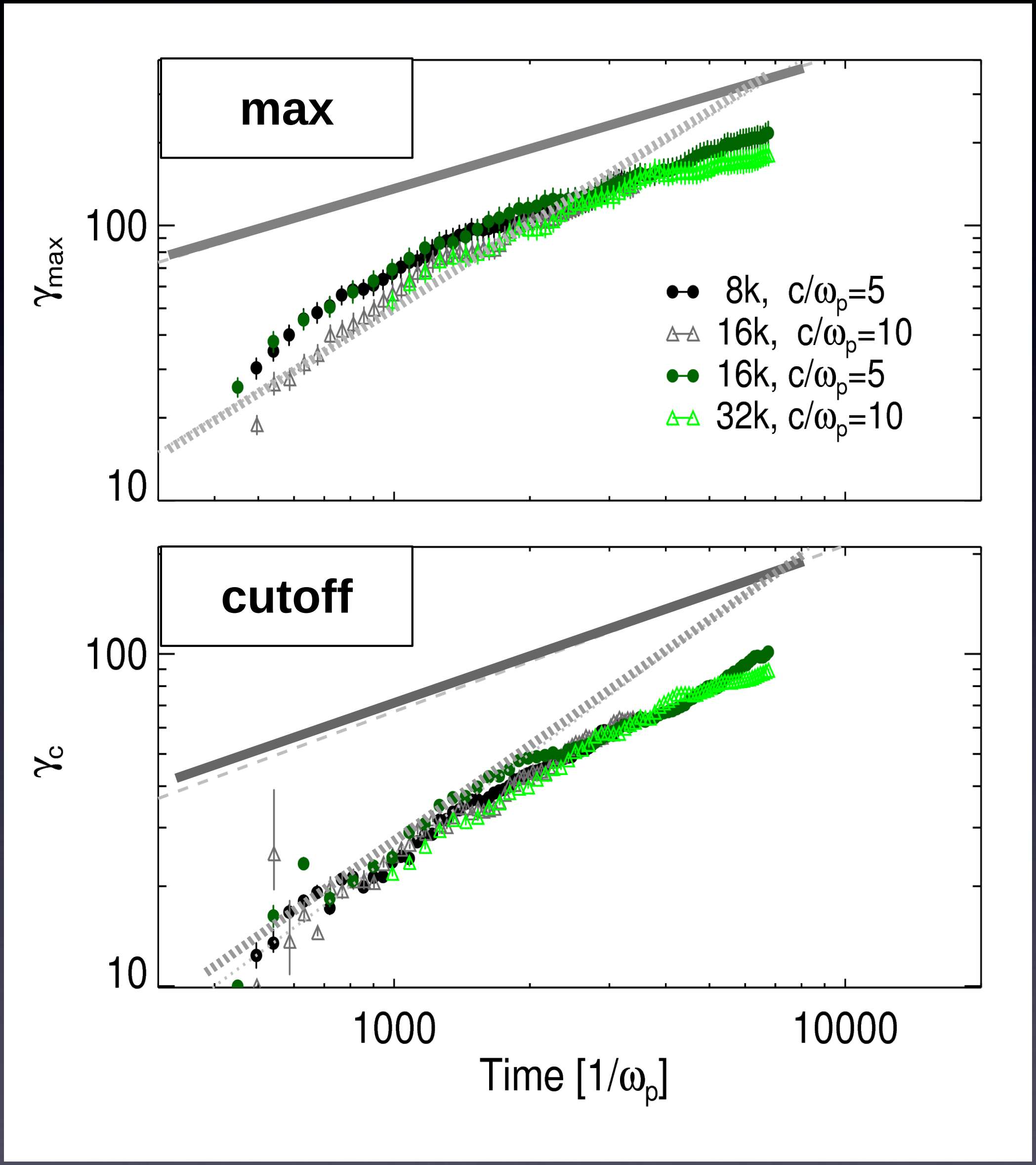
$$\gamma_{max} \approx \frac{\int d\gamma\, \gamma^{n+1} \frac{dN}{d\gamma}}{\int d\gamma\, \gamma^{n} \frac{dN}{d\gamma}}$$

Sub-linear evolution of cutoff & max energy with time?

Click here

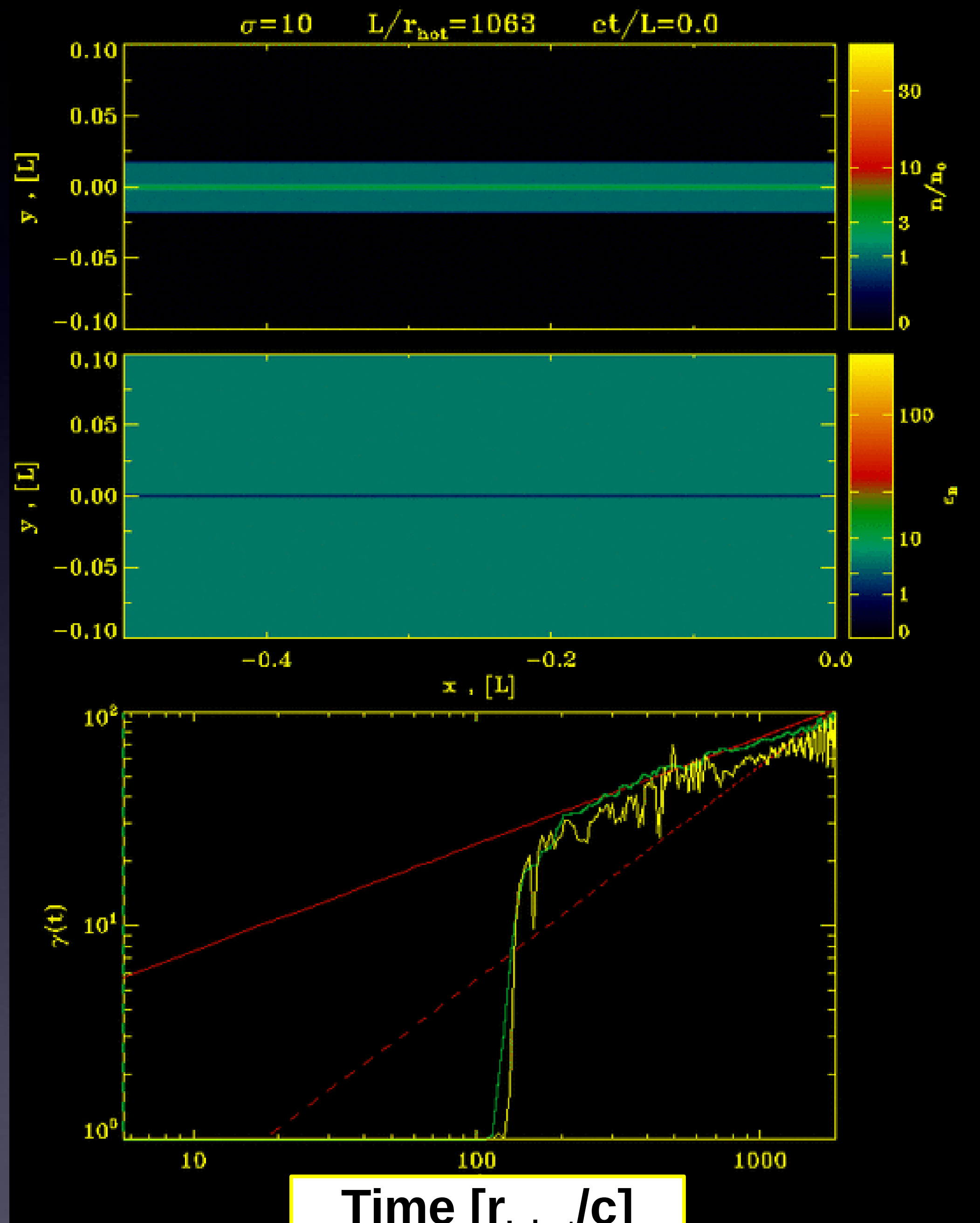
Resolution

Same box size in skin depths



WORK IN PROGRESS

Tracking particles



Density

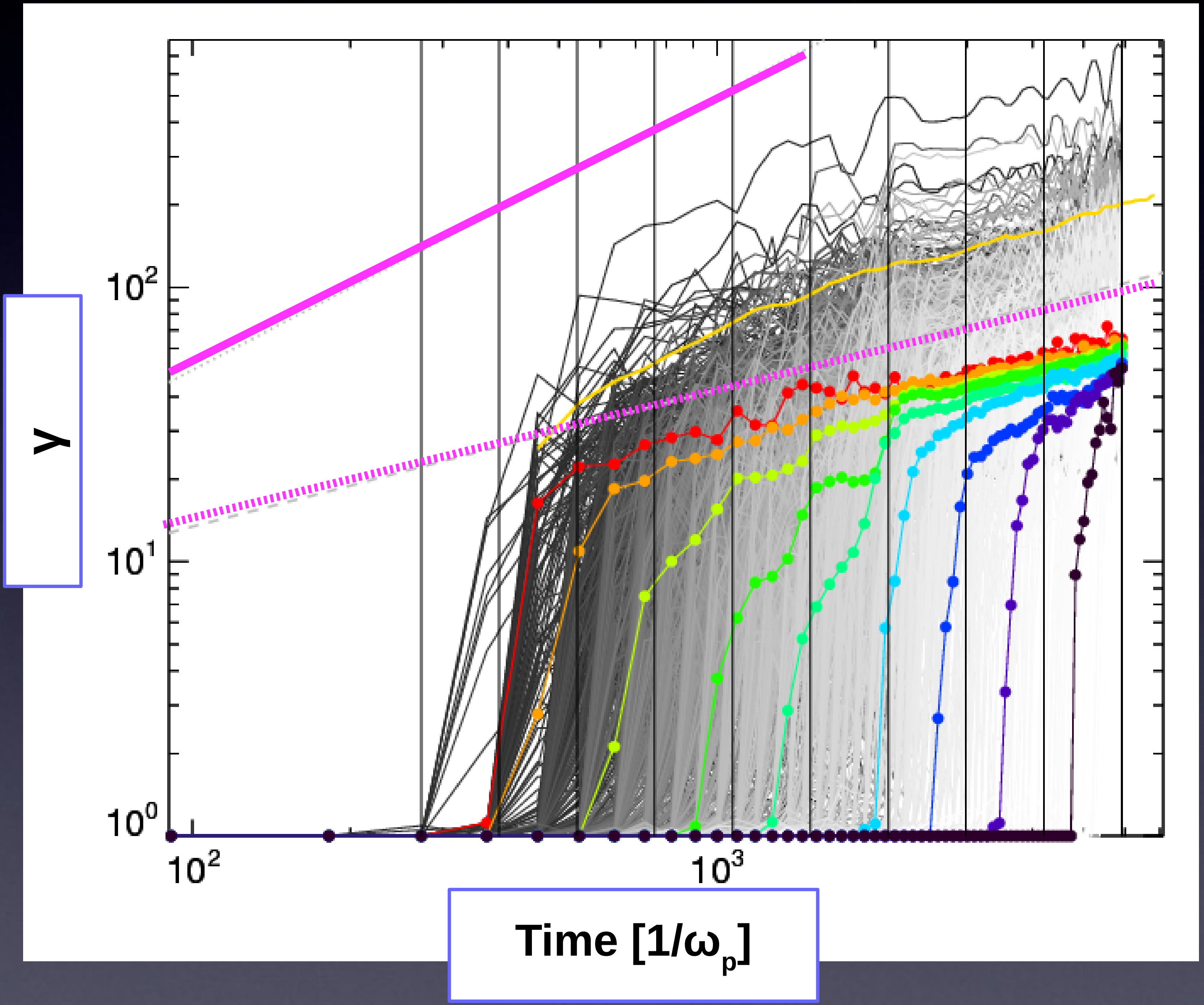
Magnetic energy

Lorentz factor

Time [$r_{L,hot}/c$]

Energy evolution of particles

Sub-linear evolution of particle energy with time



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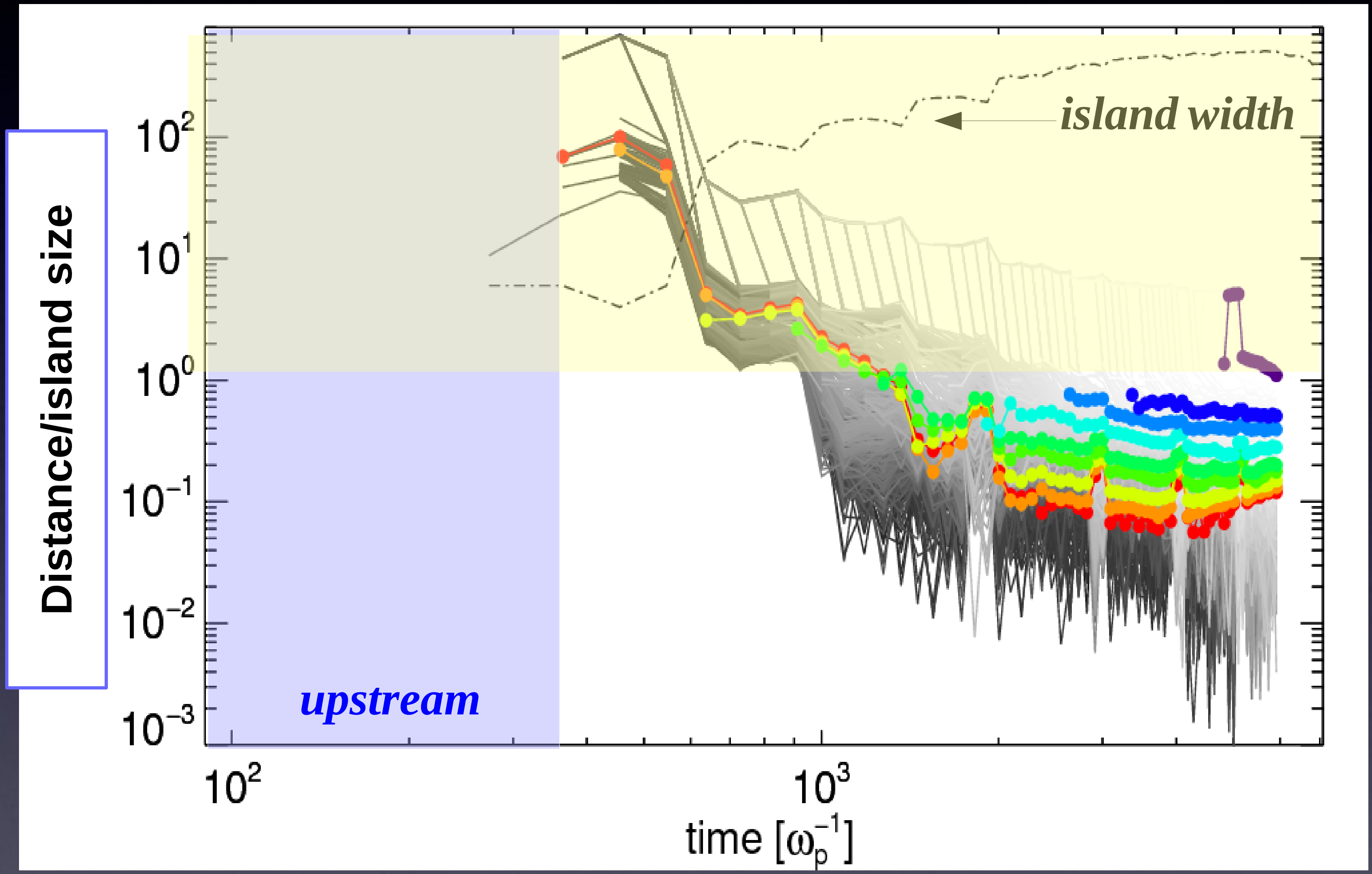
Distance from island's core

Particles confined close to the core region



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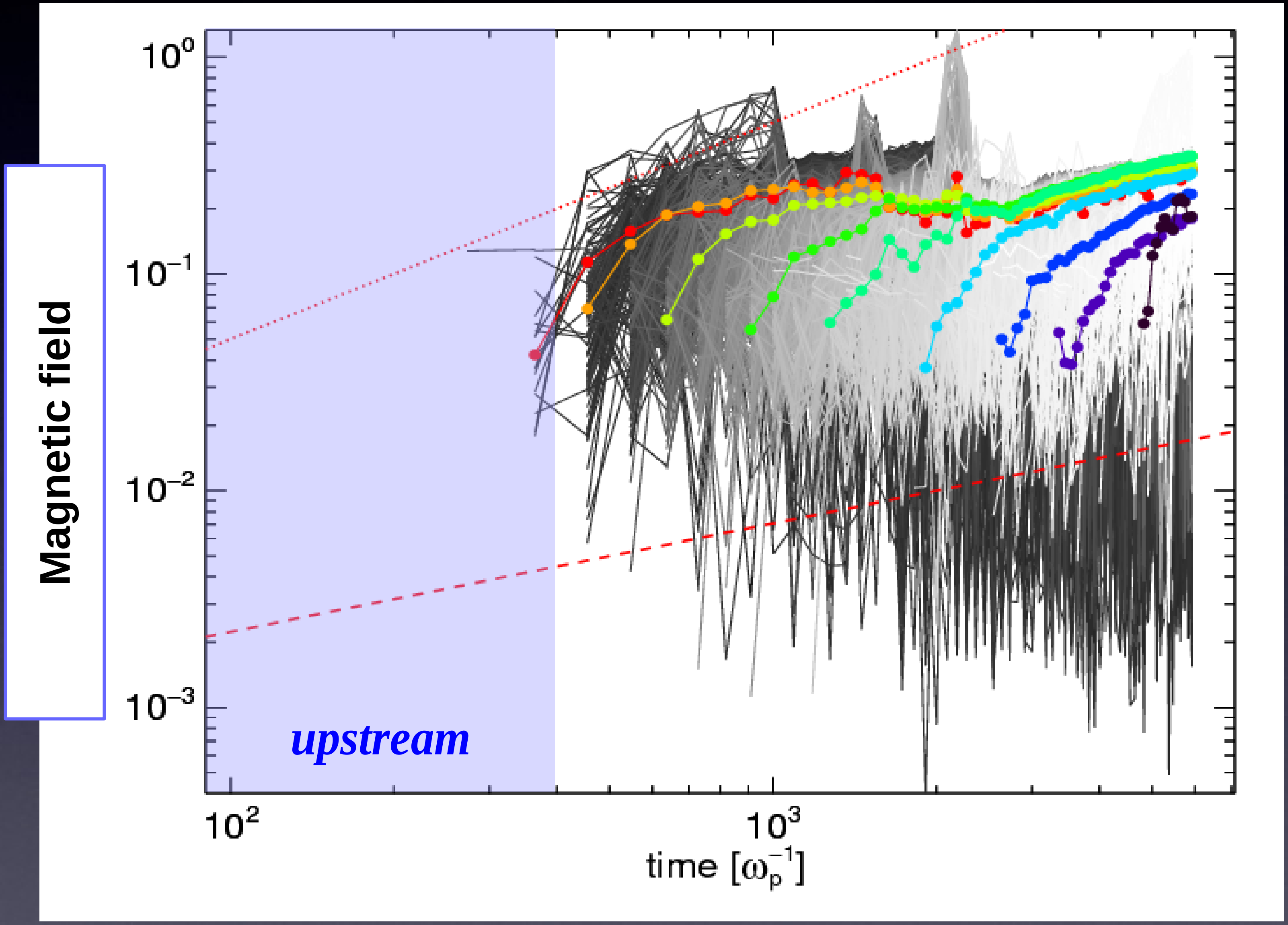
Magnetic field along trajectory

Particles experience stronger B-fields



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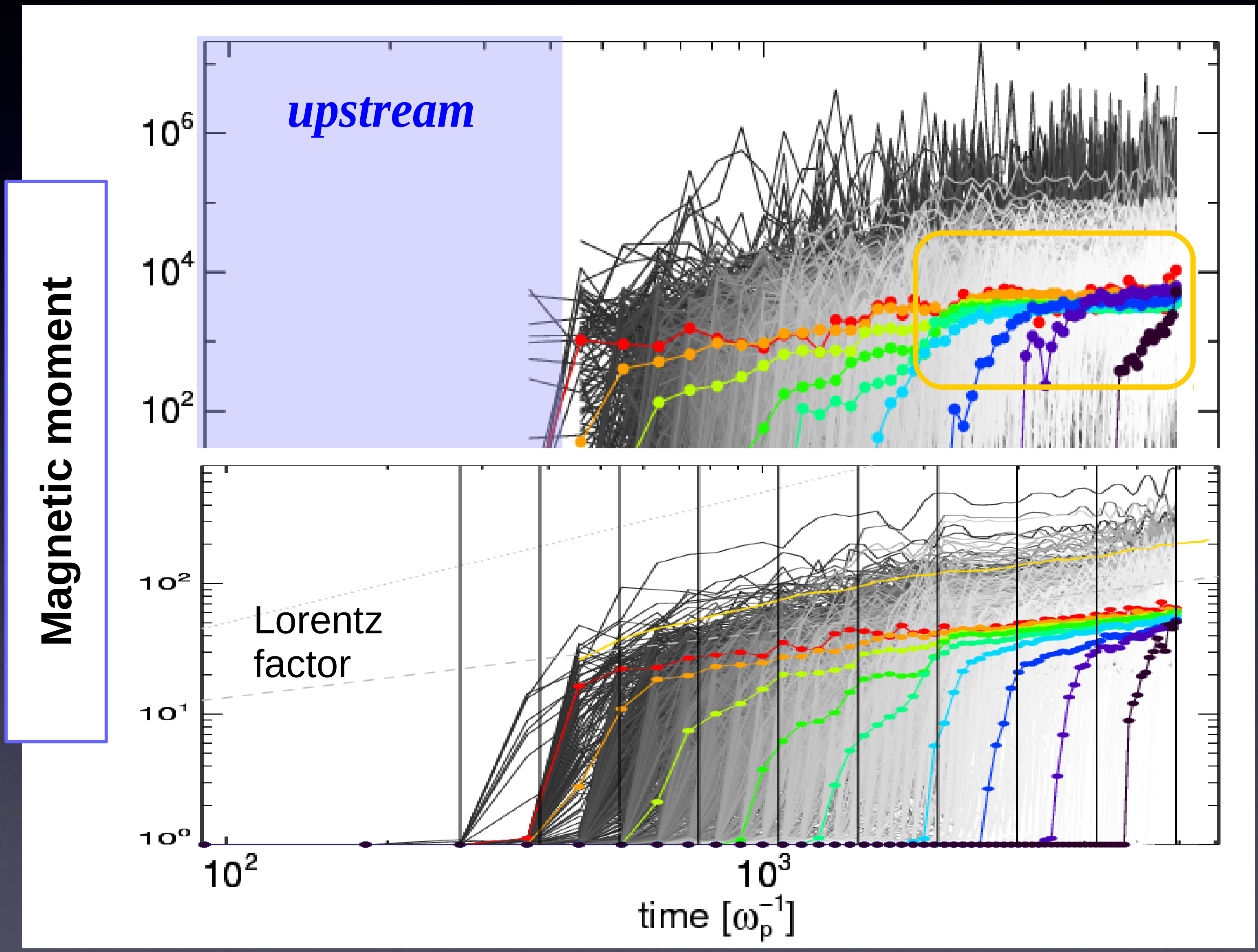
Particle magnetic moment

Magnetic moment at late times becomes ~constant



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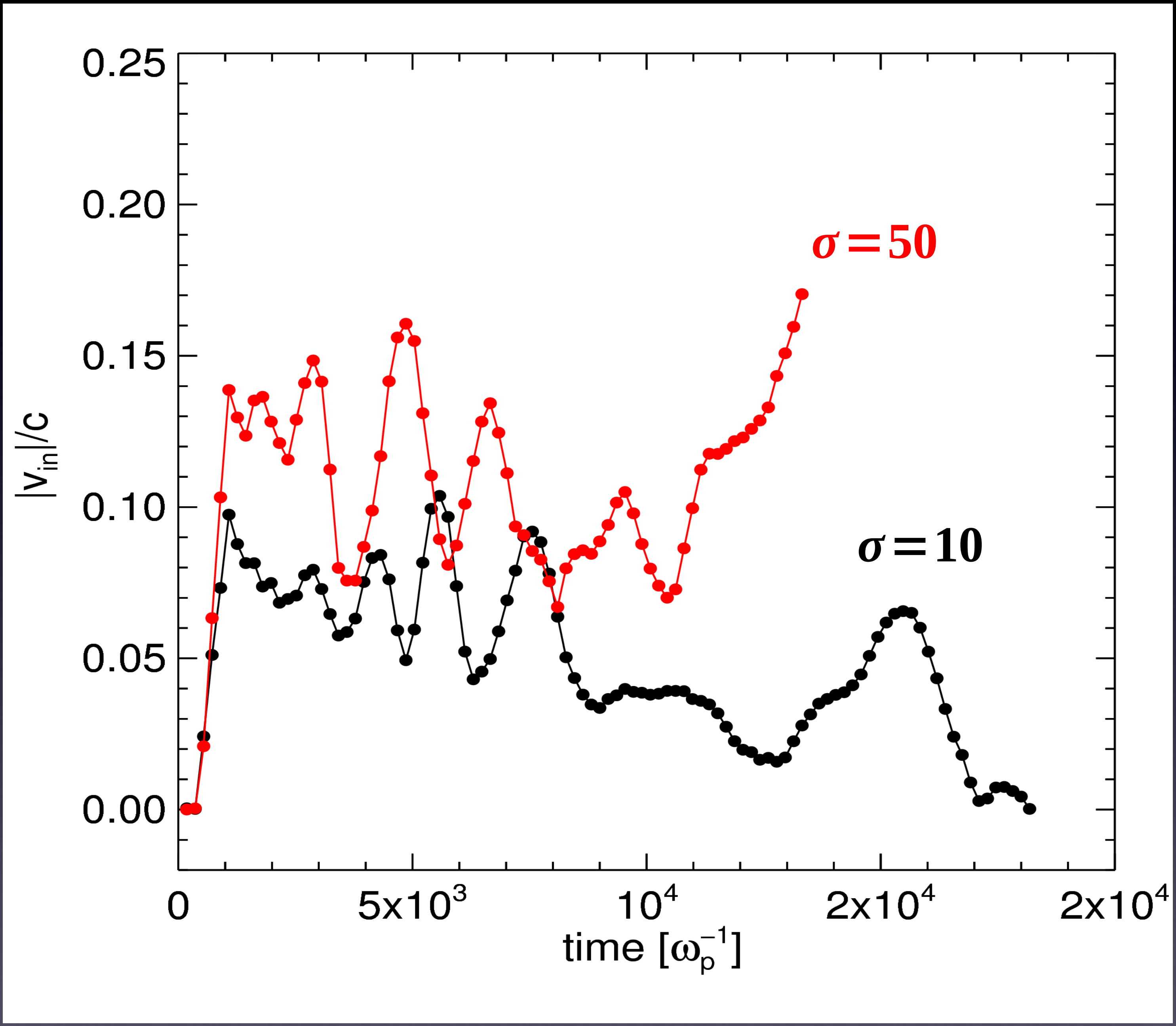
Conclusions

- The cutoff Lorentz factor increases beyond the 4σ limit, if the simulation domain is large enough and reconnection is sustained.
- This holds for 2D simulations with either periodic or outflow BC.
- The power law softens slowly with time for σ=50. No energy crisis.
- The cutoff of the distribution increases as $(\mathrm{time})^{1/2}$ after it has exceeded the ~4σ value.
- The energy of individual particles also increases as $(\mathrm{time})^{1/2}$, while they are being trapped close to the core of big islands.
- What controls particle acceleration in this case?

Thank you!

Back-up slides

Reconnection rate



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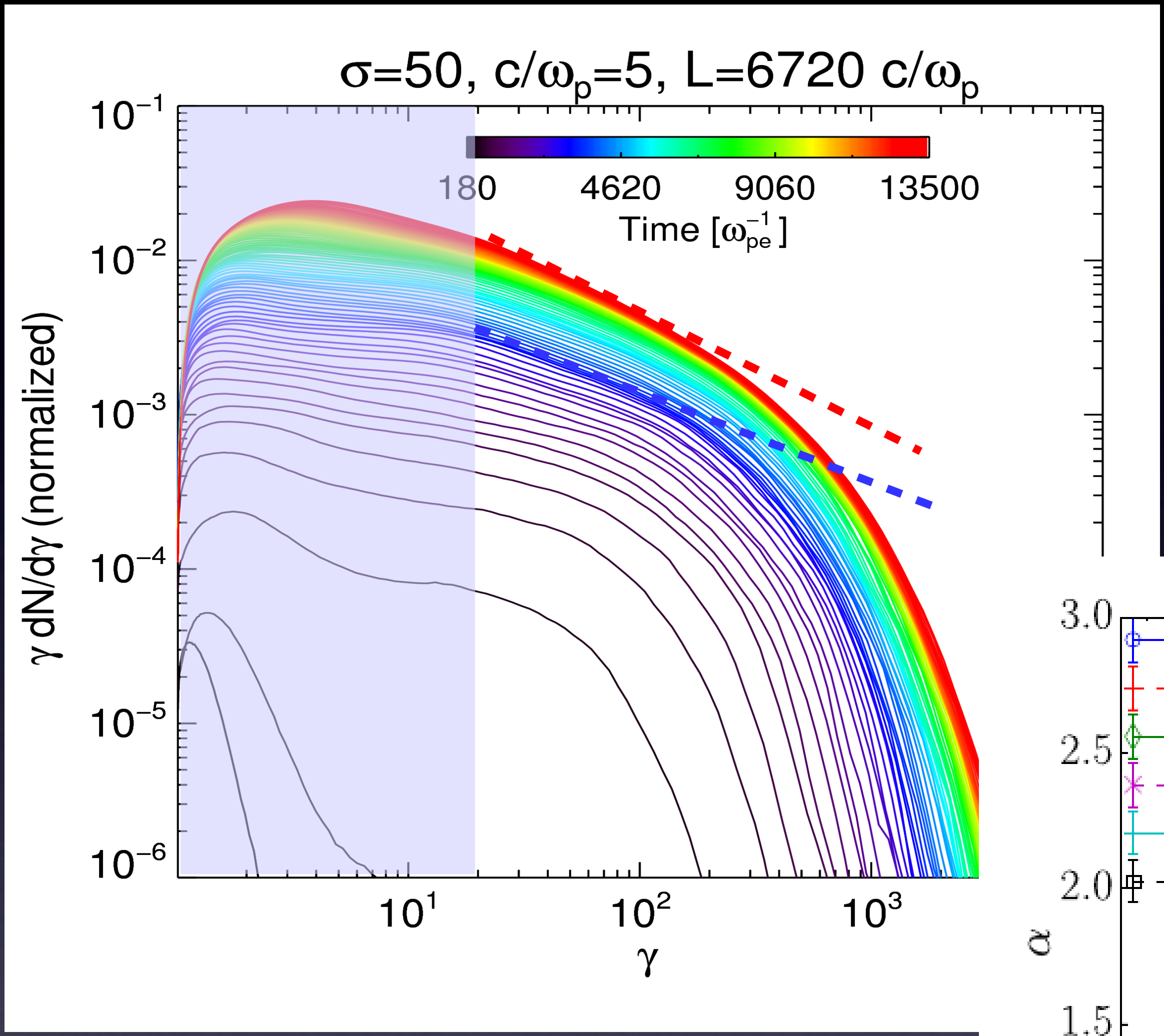
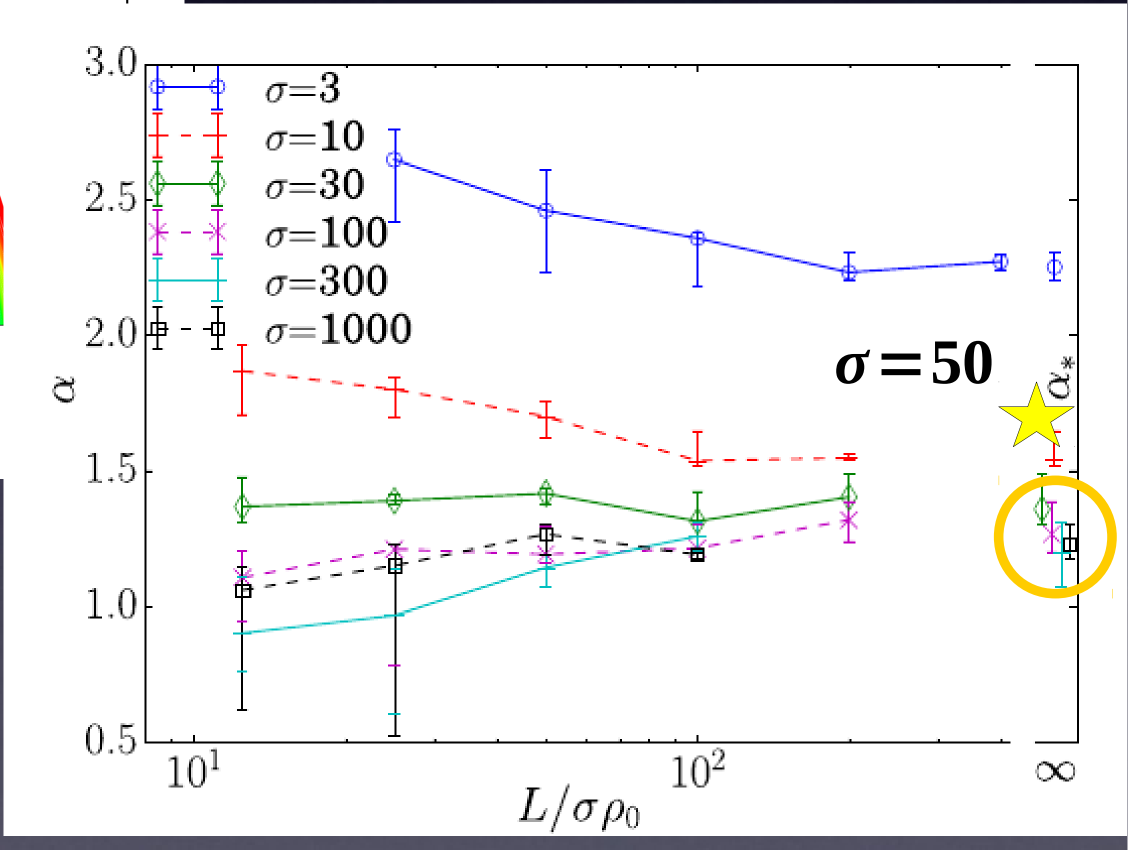
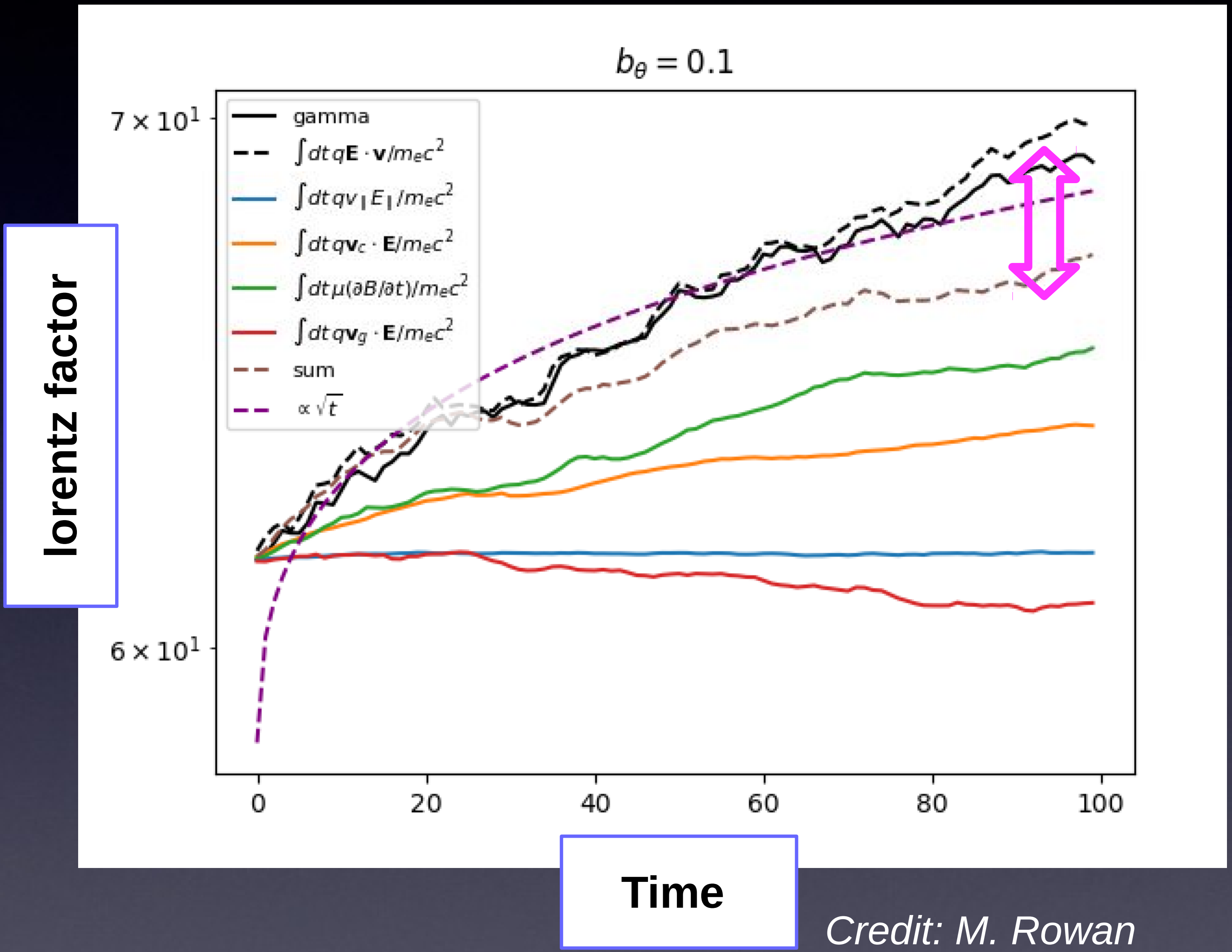
Energy crisis for σ >> 1 ?



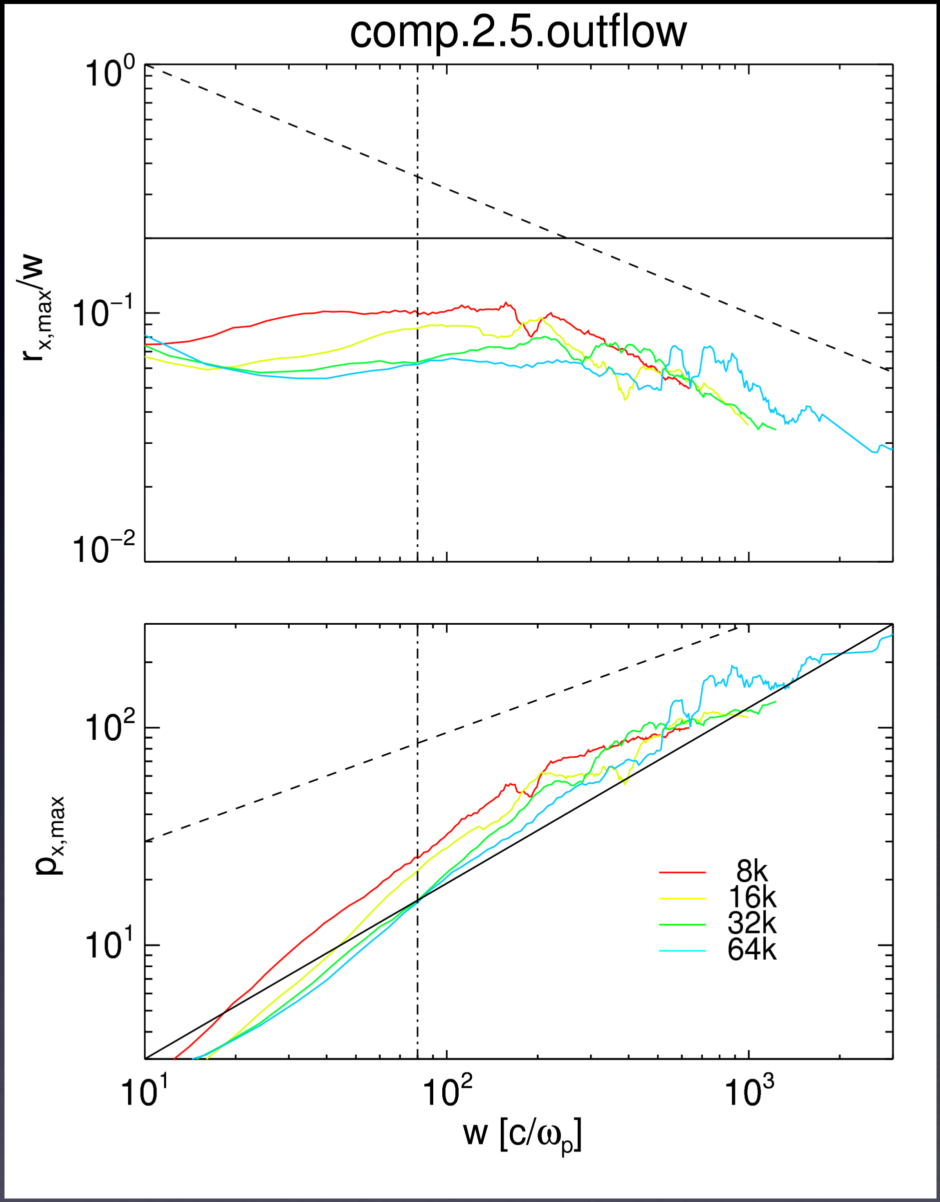


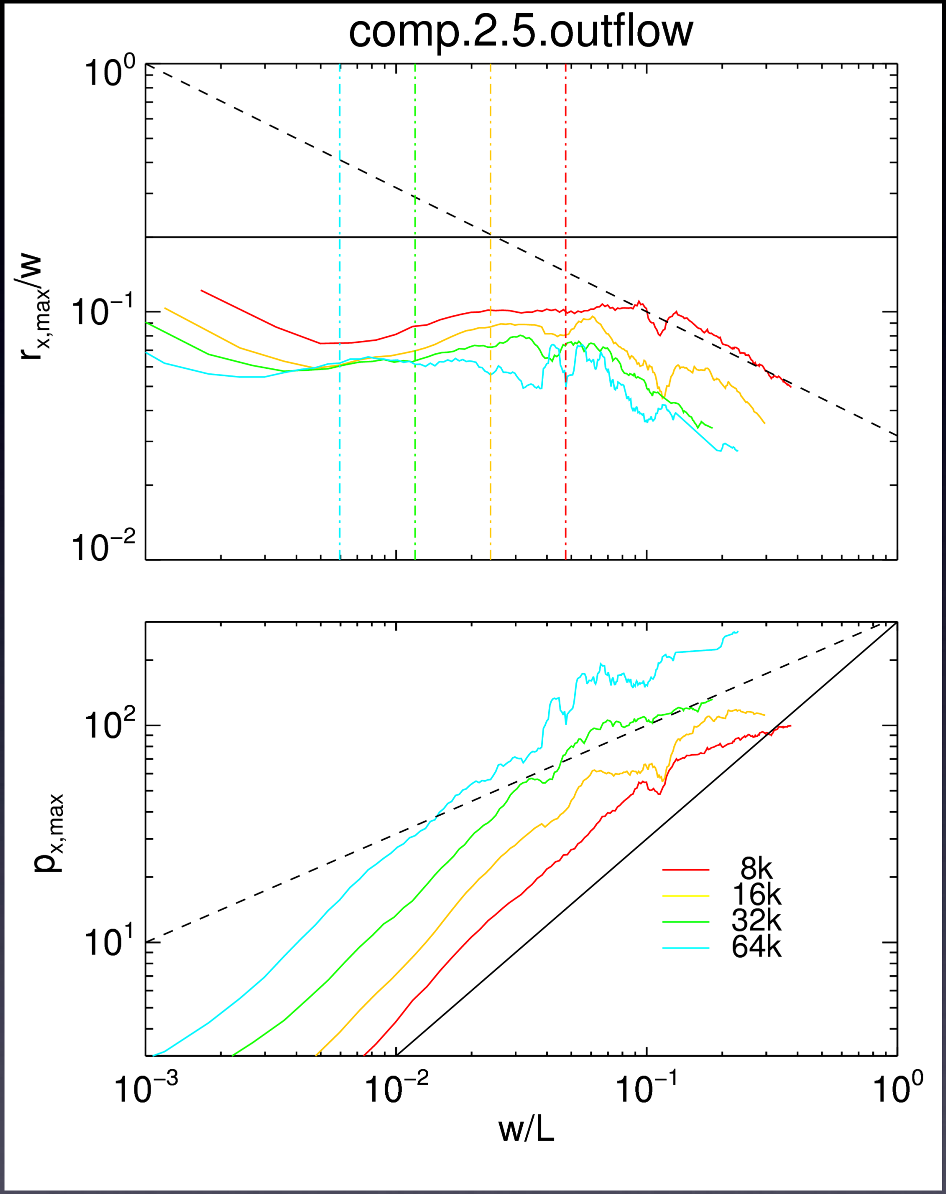
Tracking particle acceleration



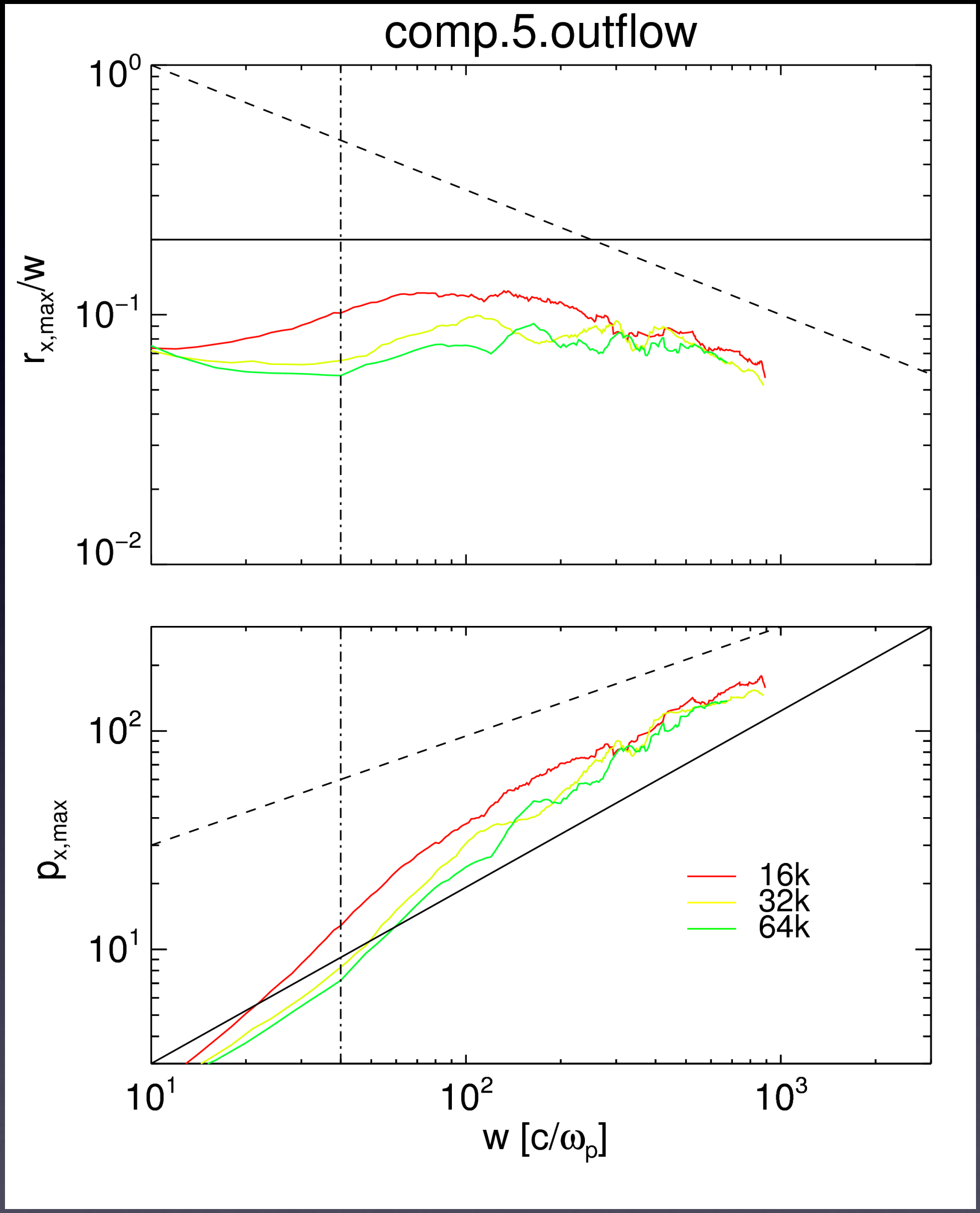
Credit: M. Rowan

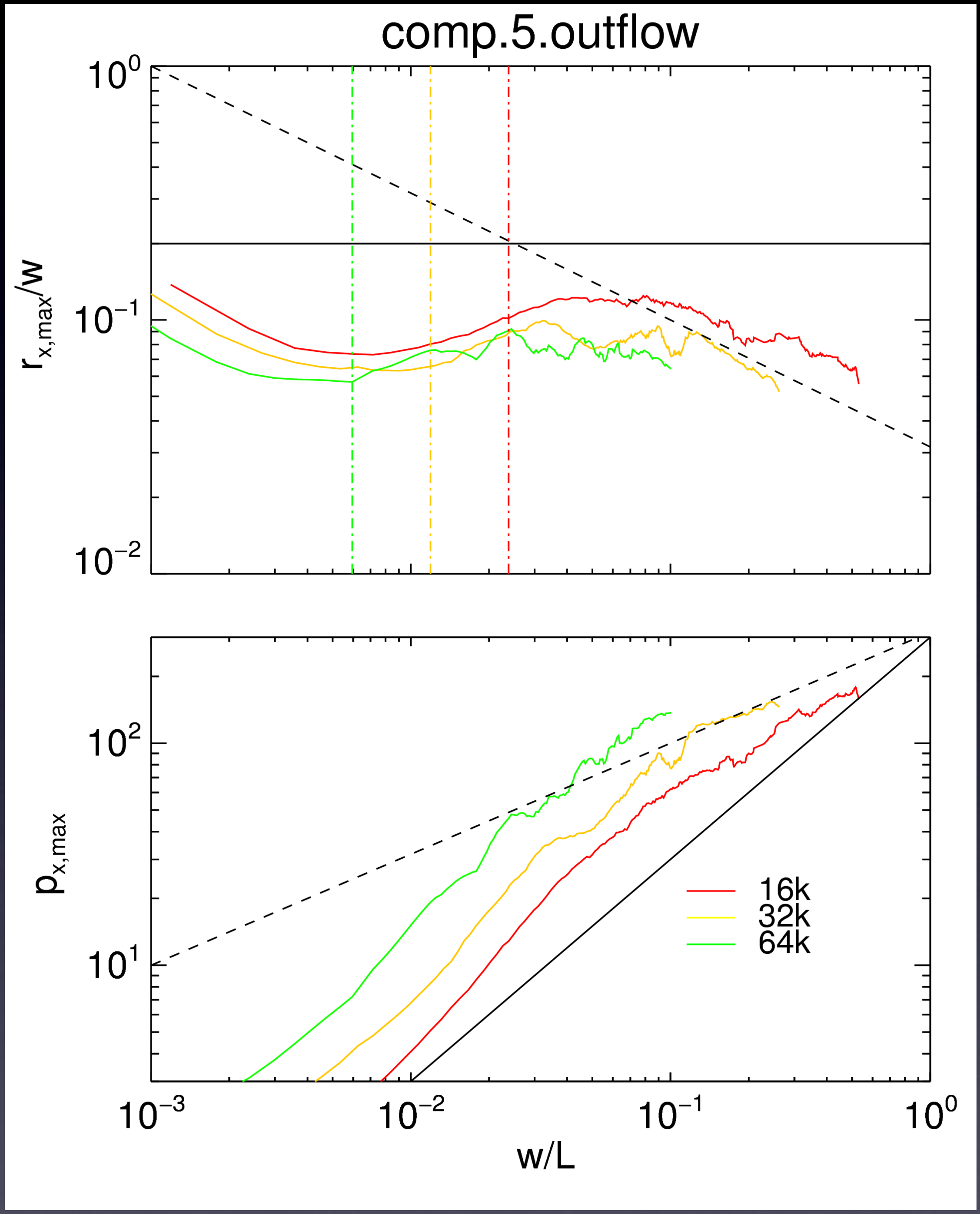
Larmor radius vs island size (1)



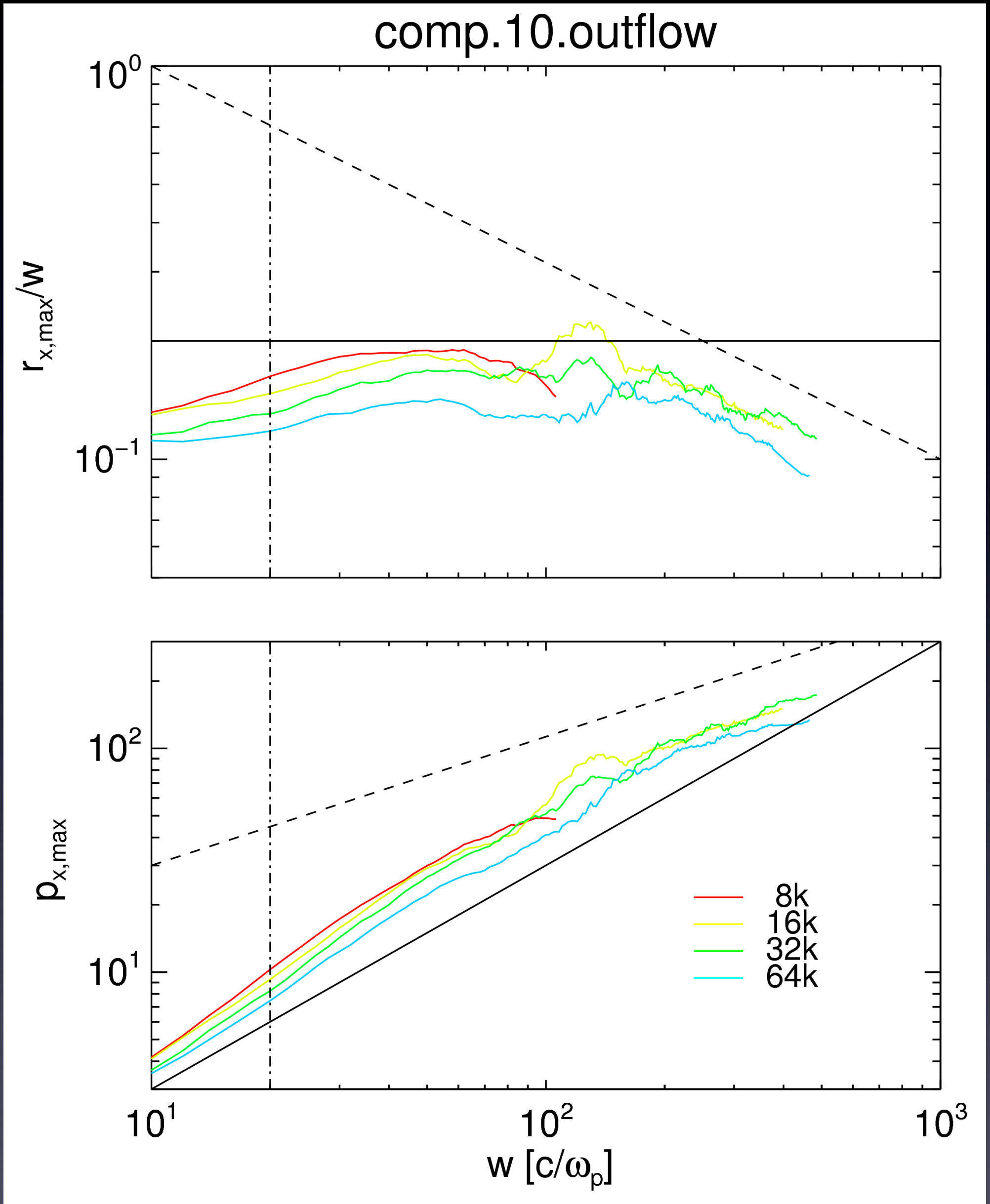


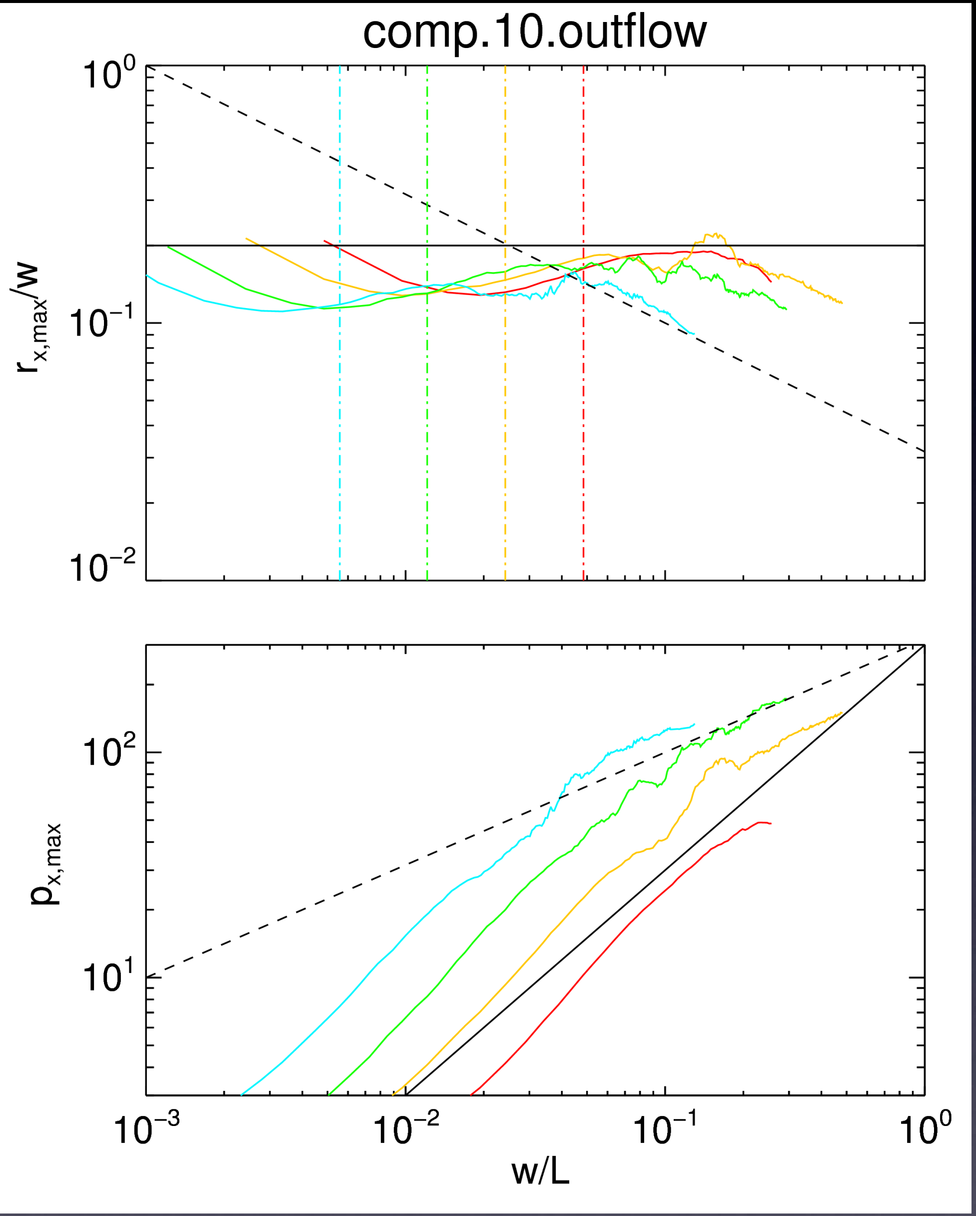
Larmor radius vs island size (2)





Larmor radius vs island size (3)





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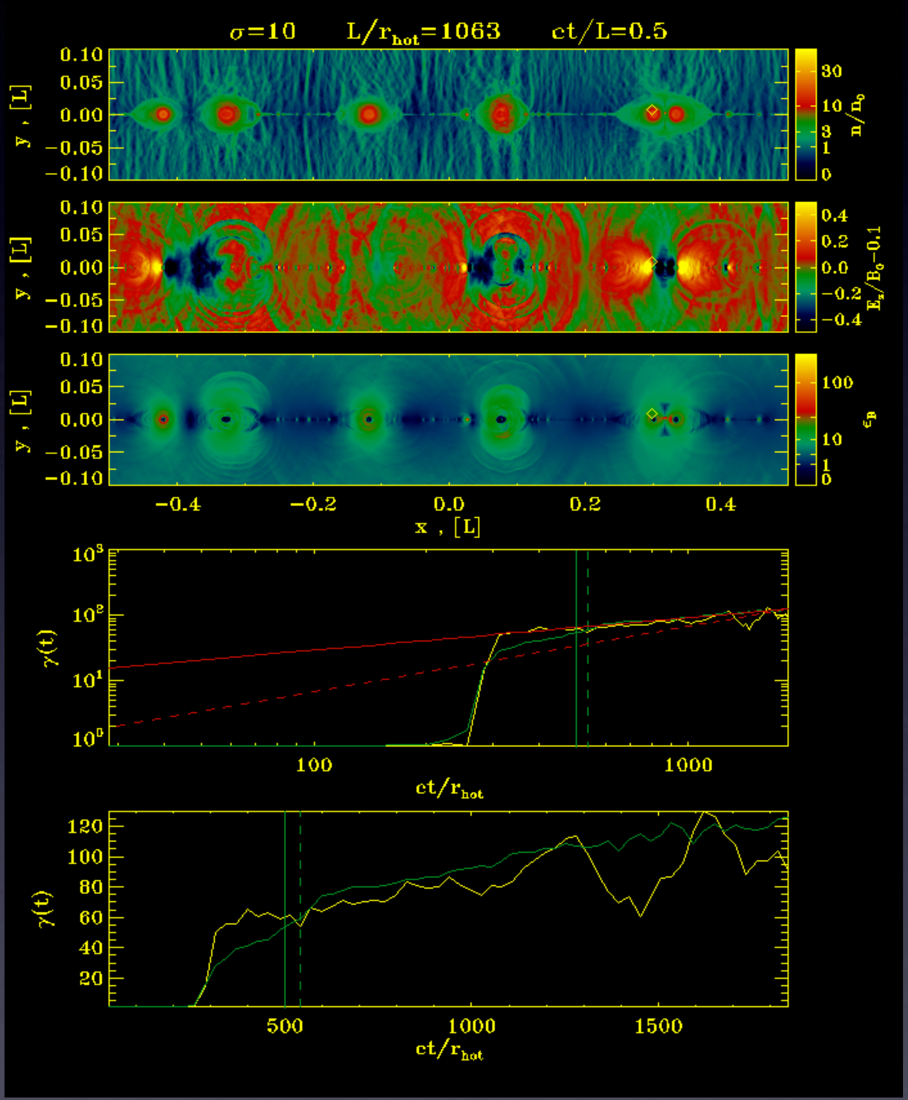
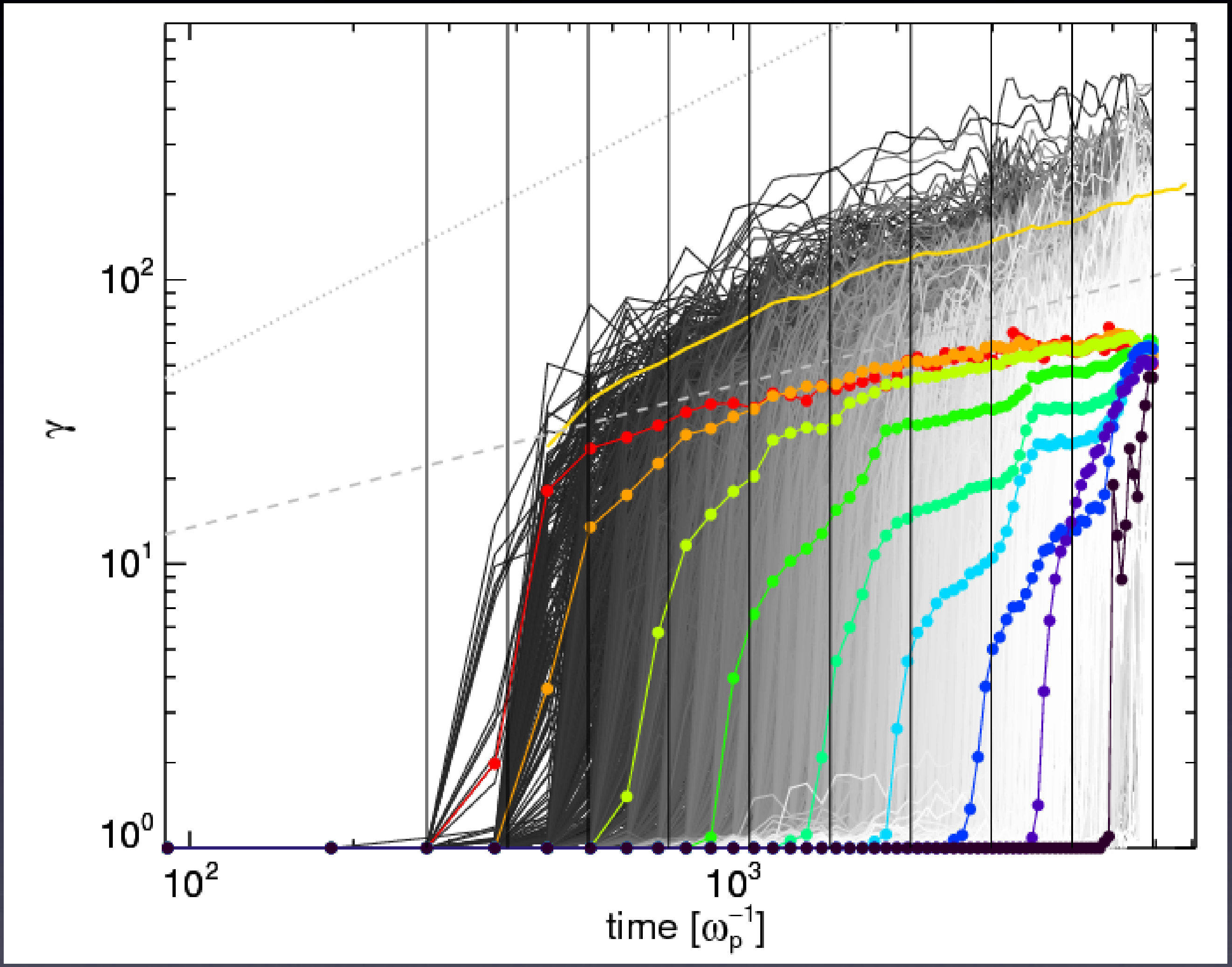
Tracking particles (2)



Energy evolution of particles (2)



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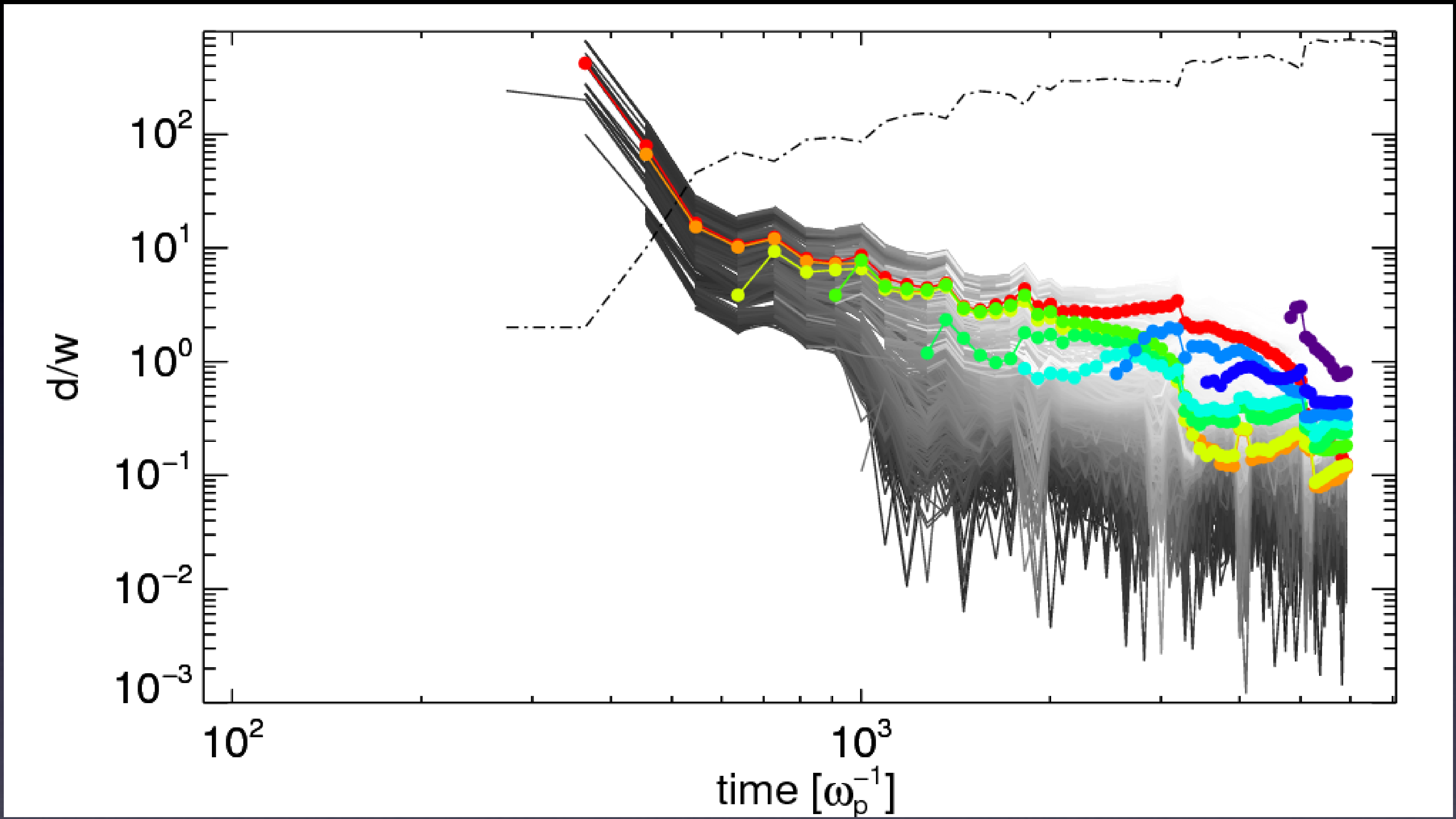
Distance from island's core (2)



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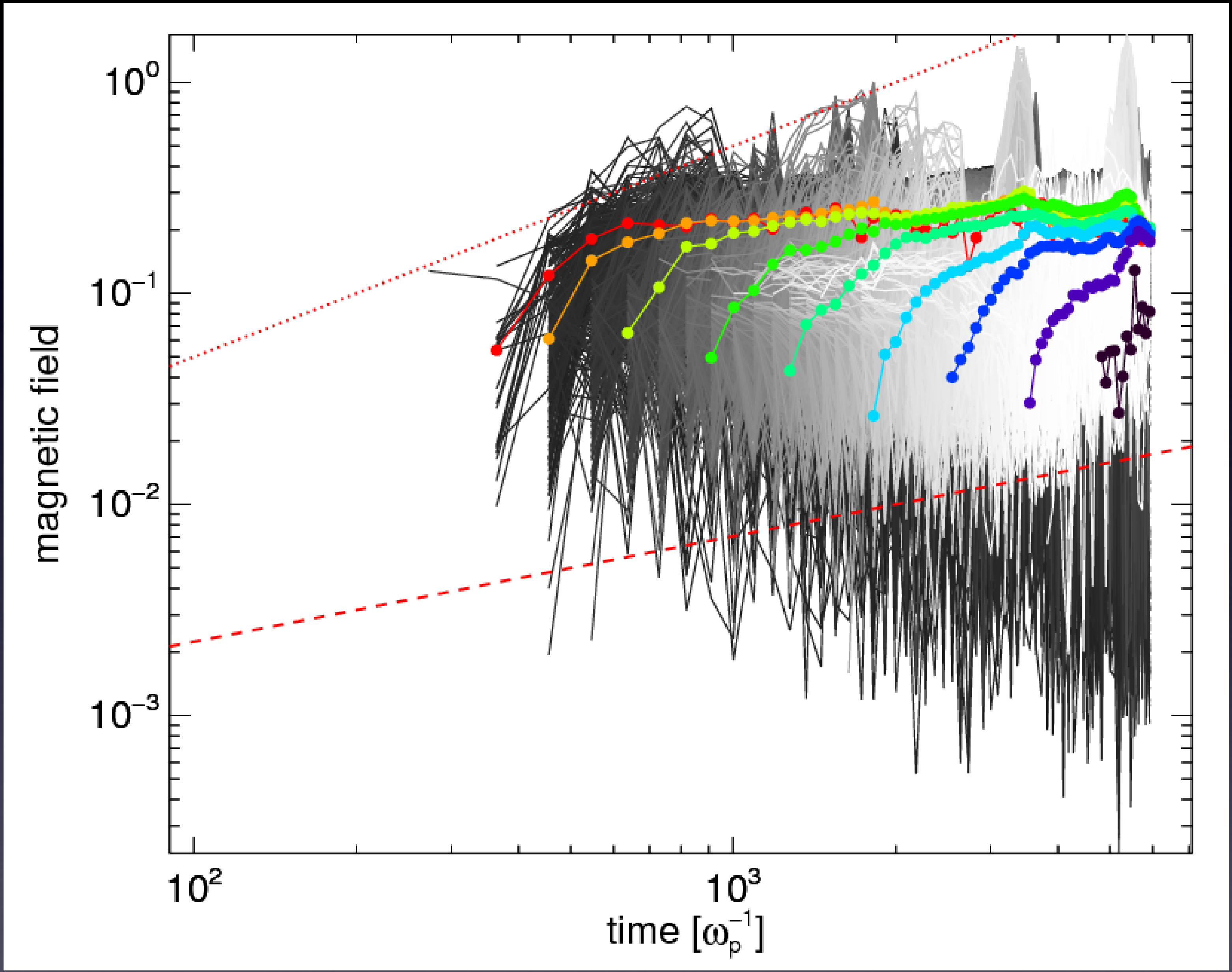
Magnetic field along trajectory (2)



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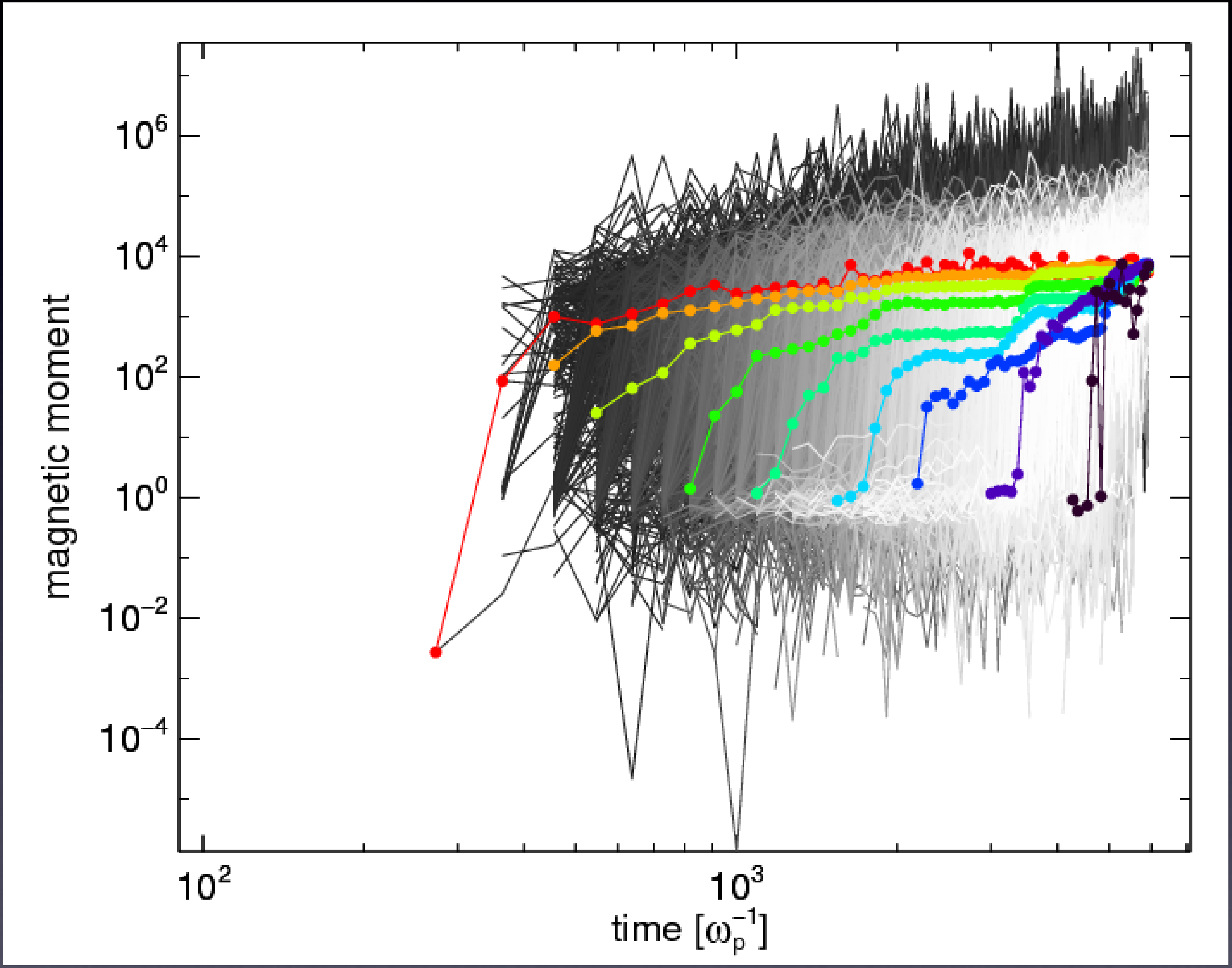
Particle magnetic moment (2)



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