Nonthermal particle acceleration in (electron-positron) relativistic plasmas: shocks vs reconnection

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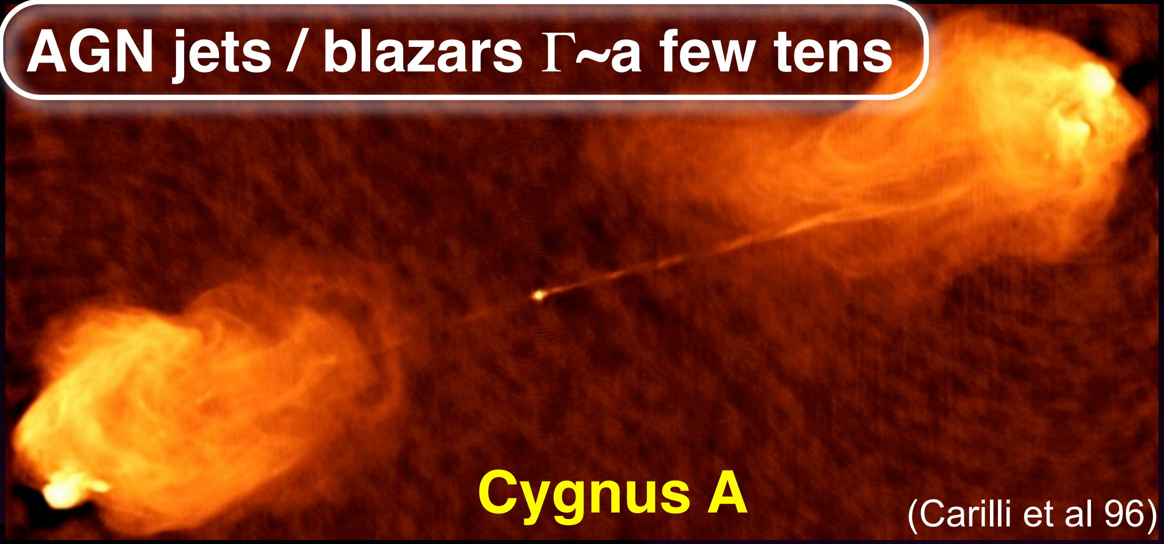
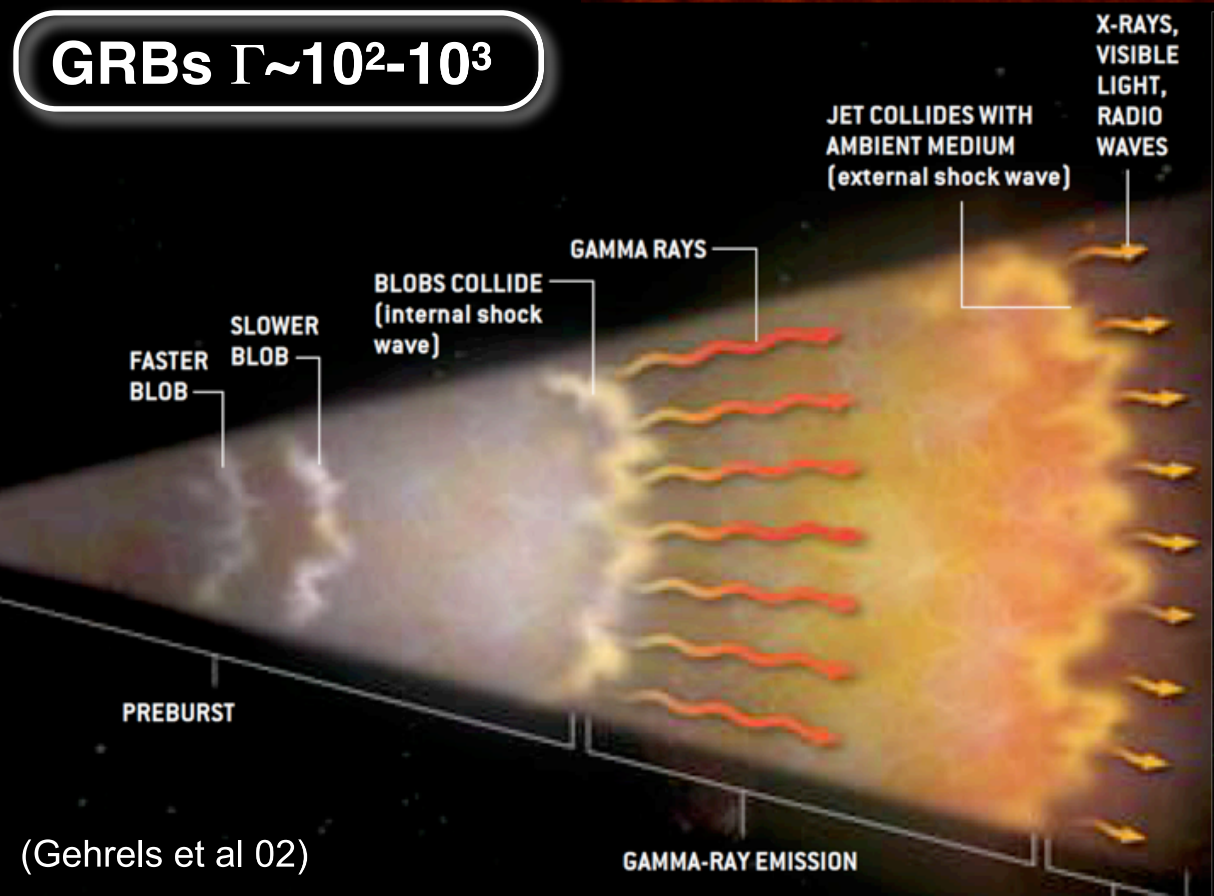
Relativistic flows in astrophysics

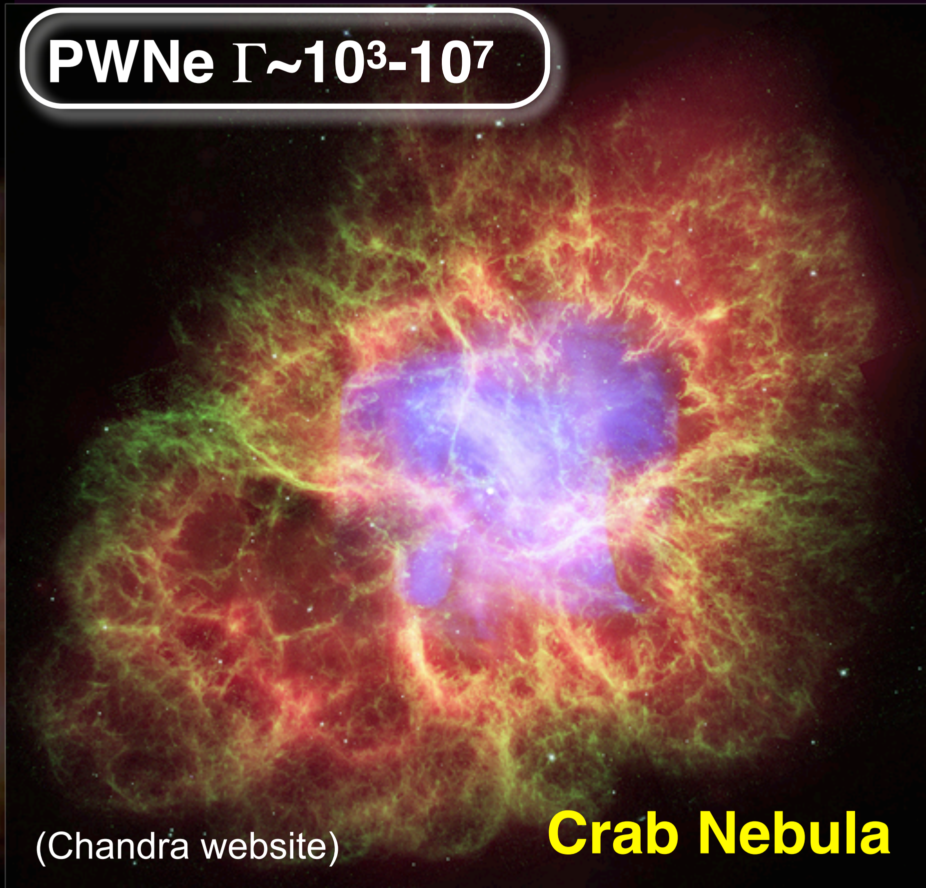
AGN jets / blazars Γ~a few tens



GRBs Γ~10^2-10^3

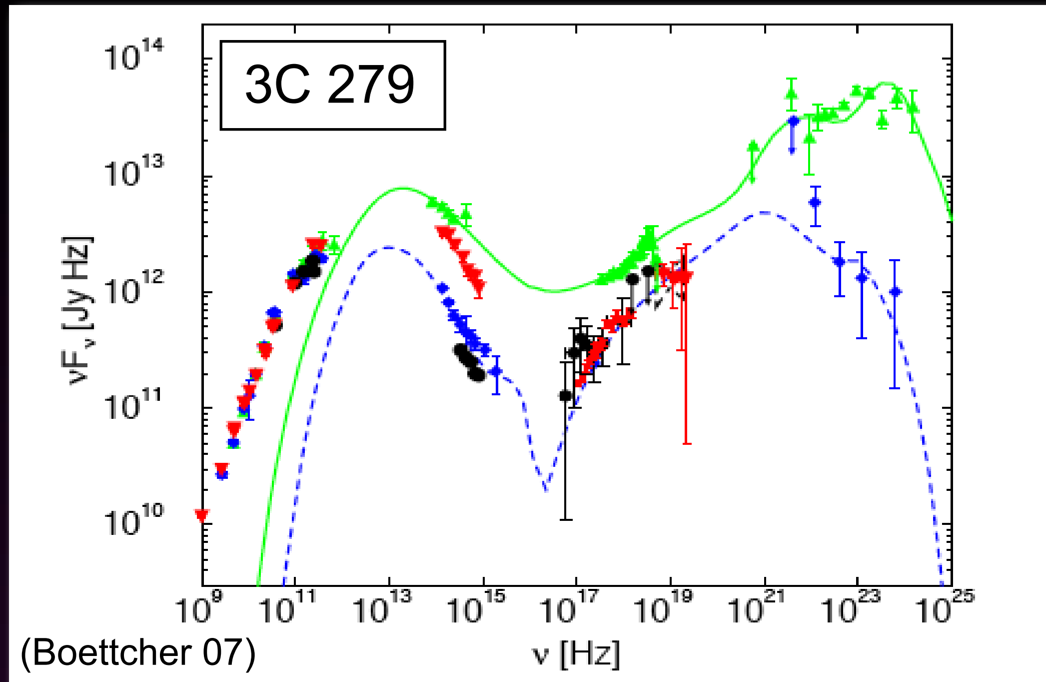


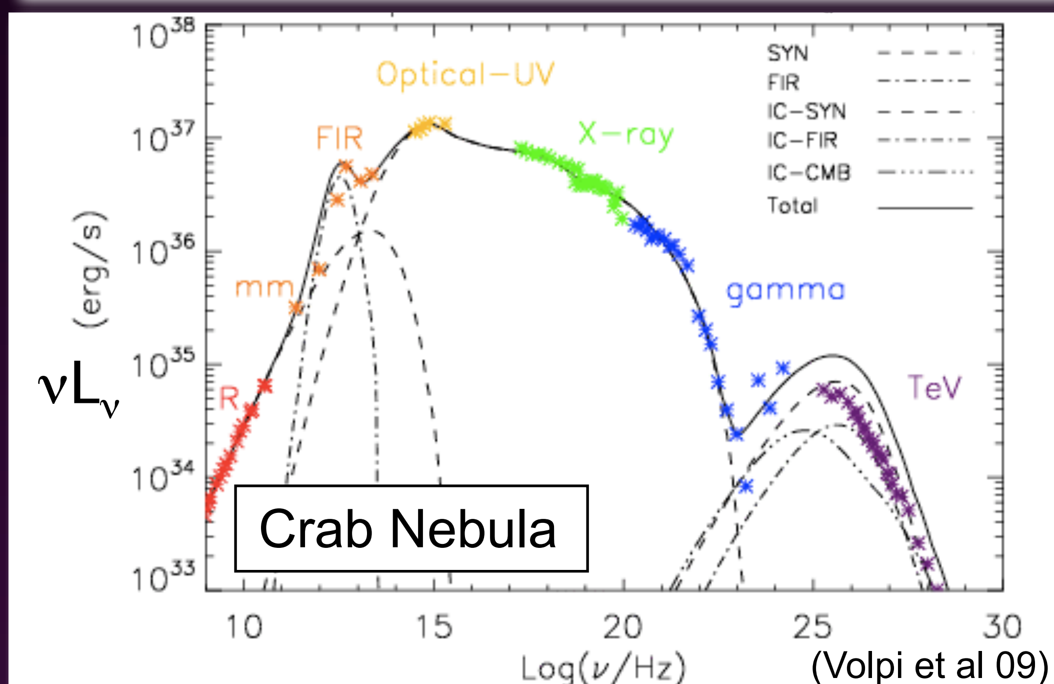
PWNe Γ~10^3-10^7



The astrophysical “exhausts”

Extended radiation spectra



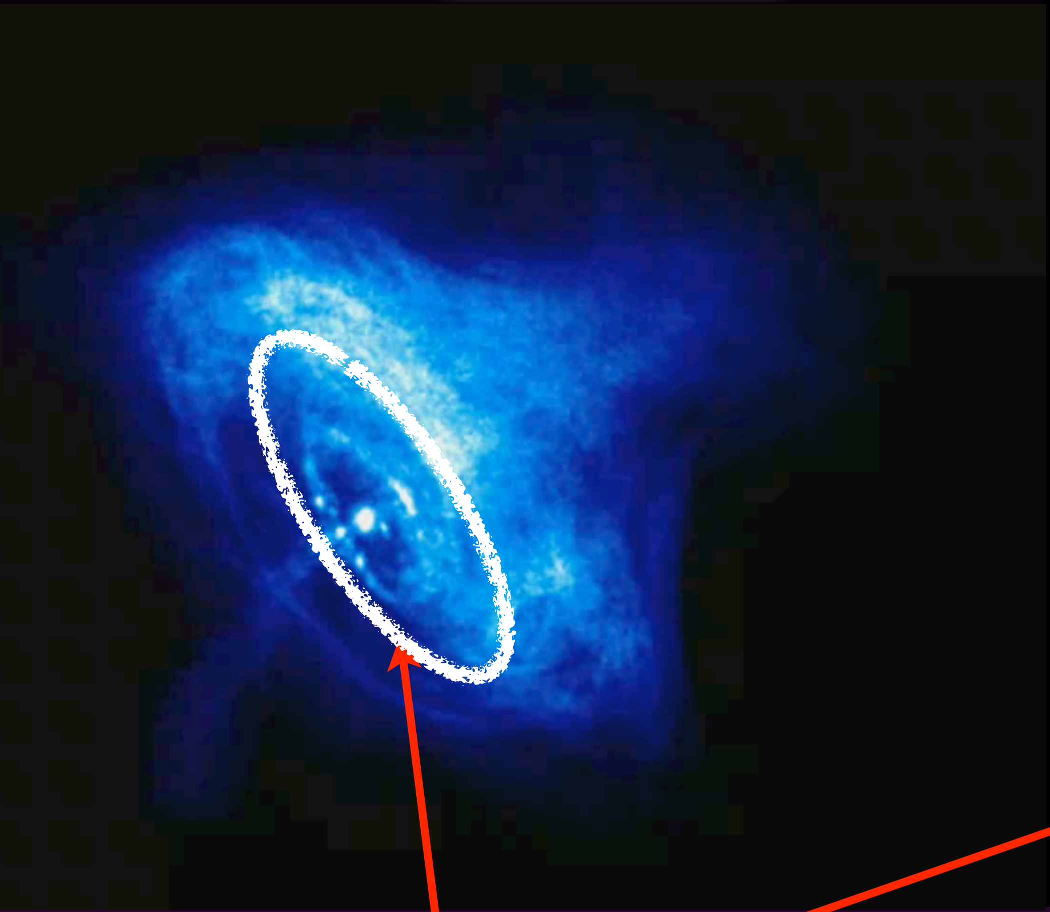


Extended power-law distributions of the emitting particles:

$$\frac{dn}{d\gamma} \propto \gamma^{-p}$$

The astrophysical "engines"

Crab Nebula



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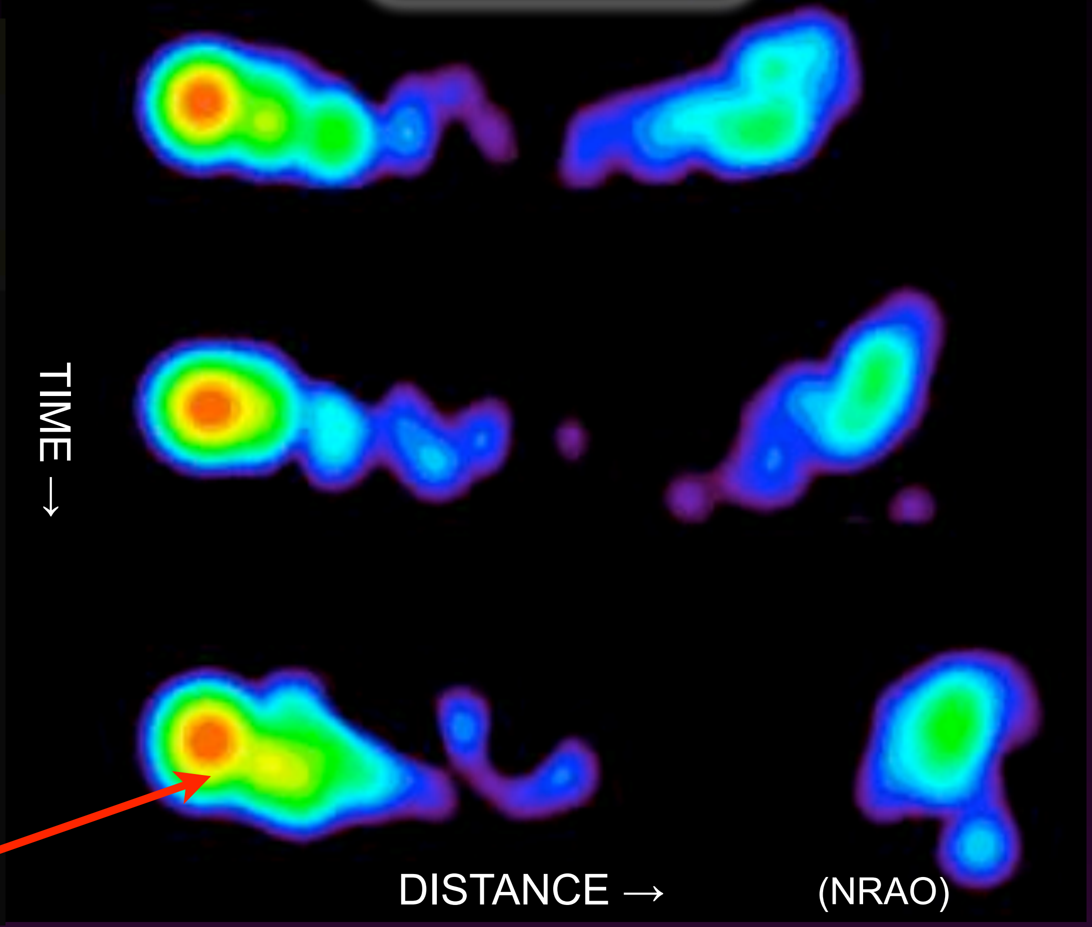
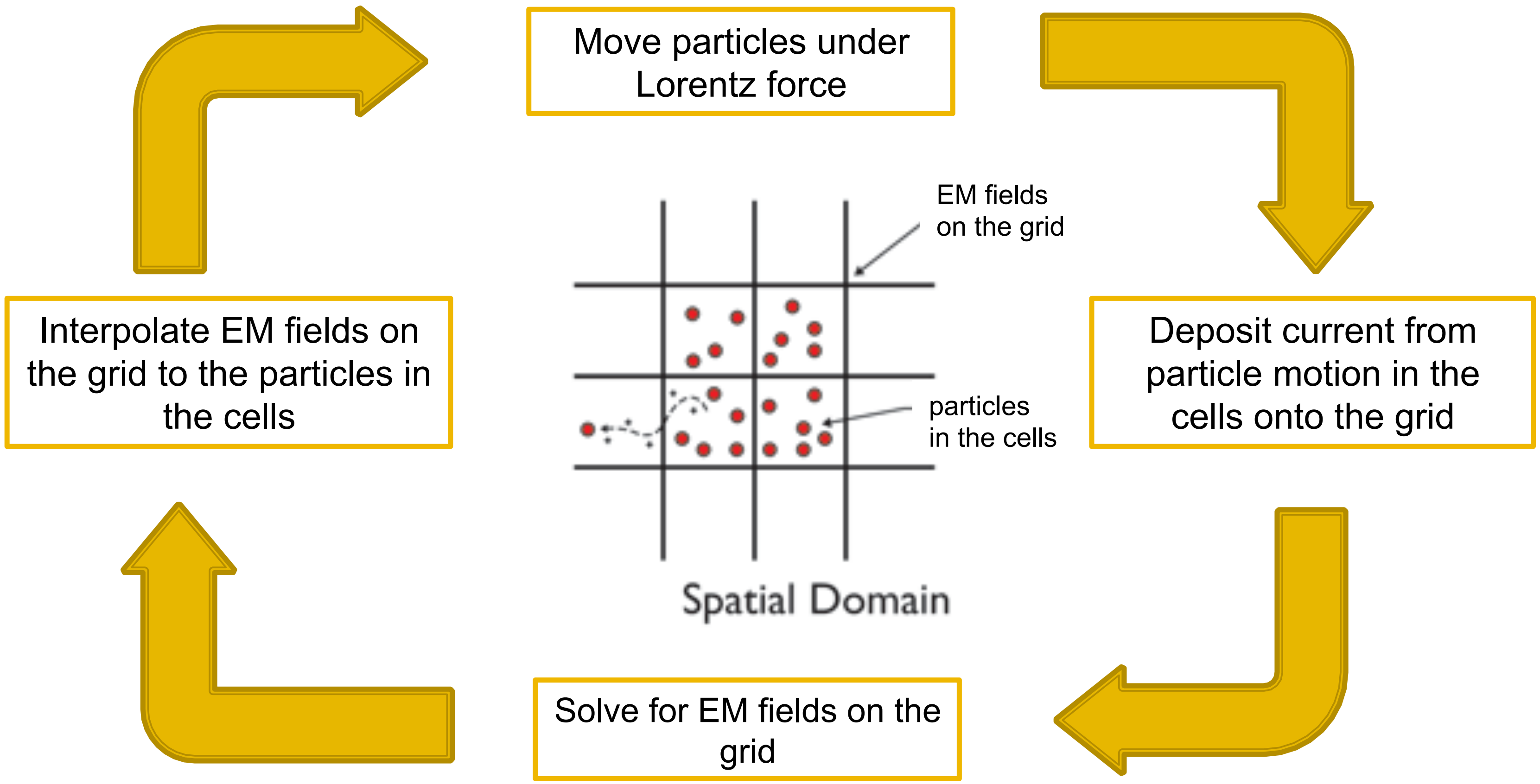


Dissipation Sites: Shocks or Reconnection?

The PIC method



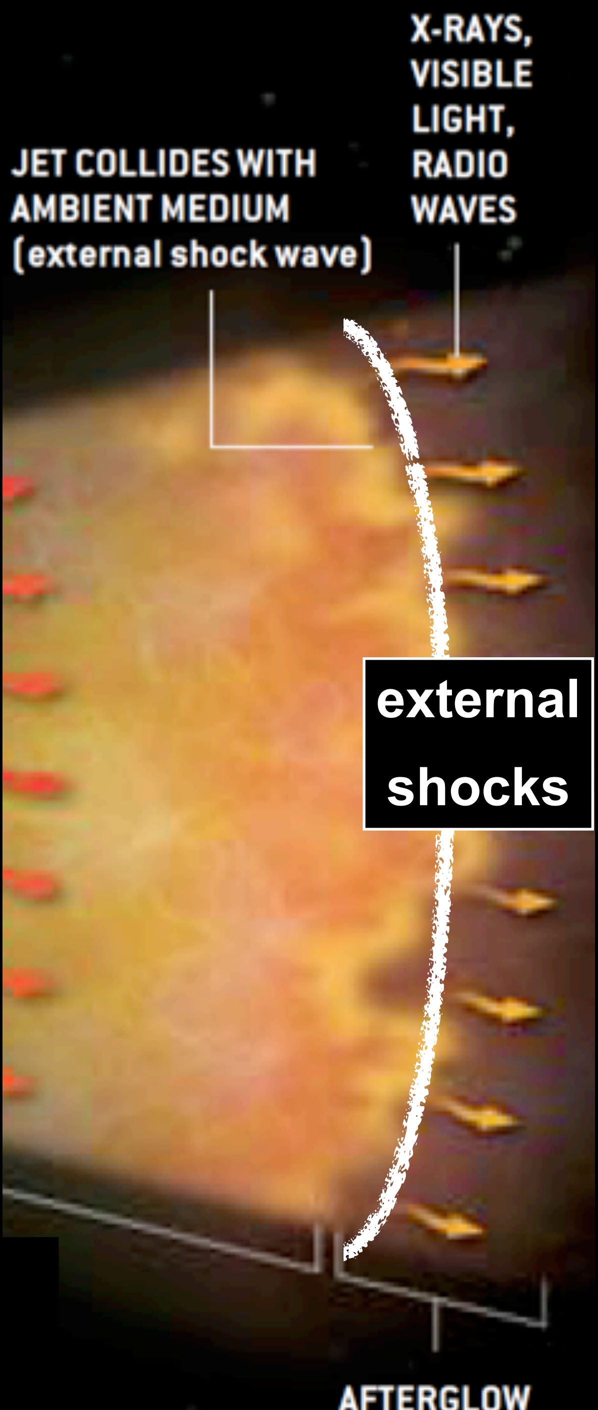
No approximations, full plasma physics of ions and electrons

Tiny length-scales (c/ω_p) and time-scales (ω_p^{-1}) need to be resolved: $\omega_p = \sqrt{\frac{4\pi n e^2}{m}}$

➔ huge simulations, limited time coverage

- Relativistic 3D e.m. PIC code TRISTAN-MP (Buneman 93, Spitkovsky 05, LS+ 13)

Relativistic shocks



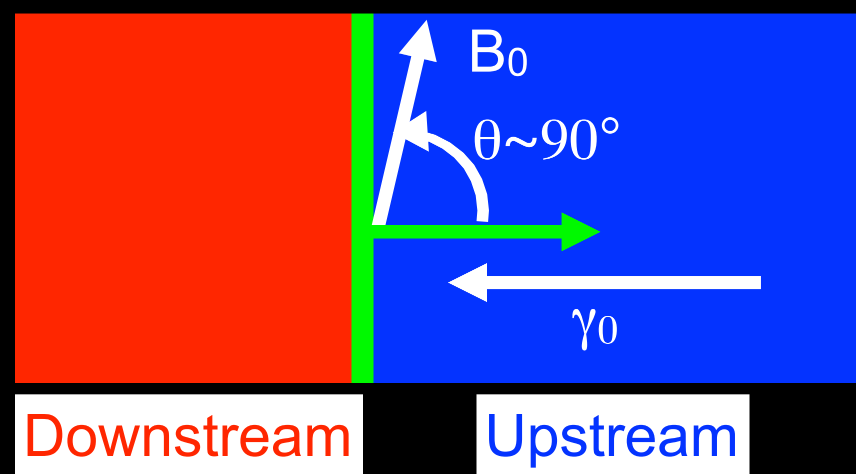
(Gehrels et al 02)

Gamma-ray burst external shocks:

- γ_0~a few hundreds
- weakly magnetized: $\sigma \sim 10^{-9}$

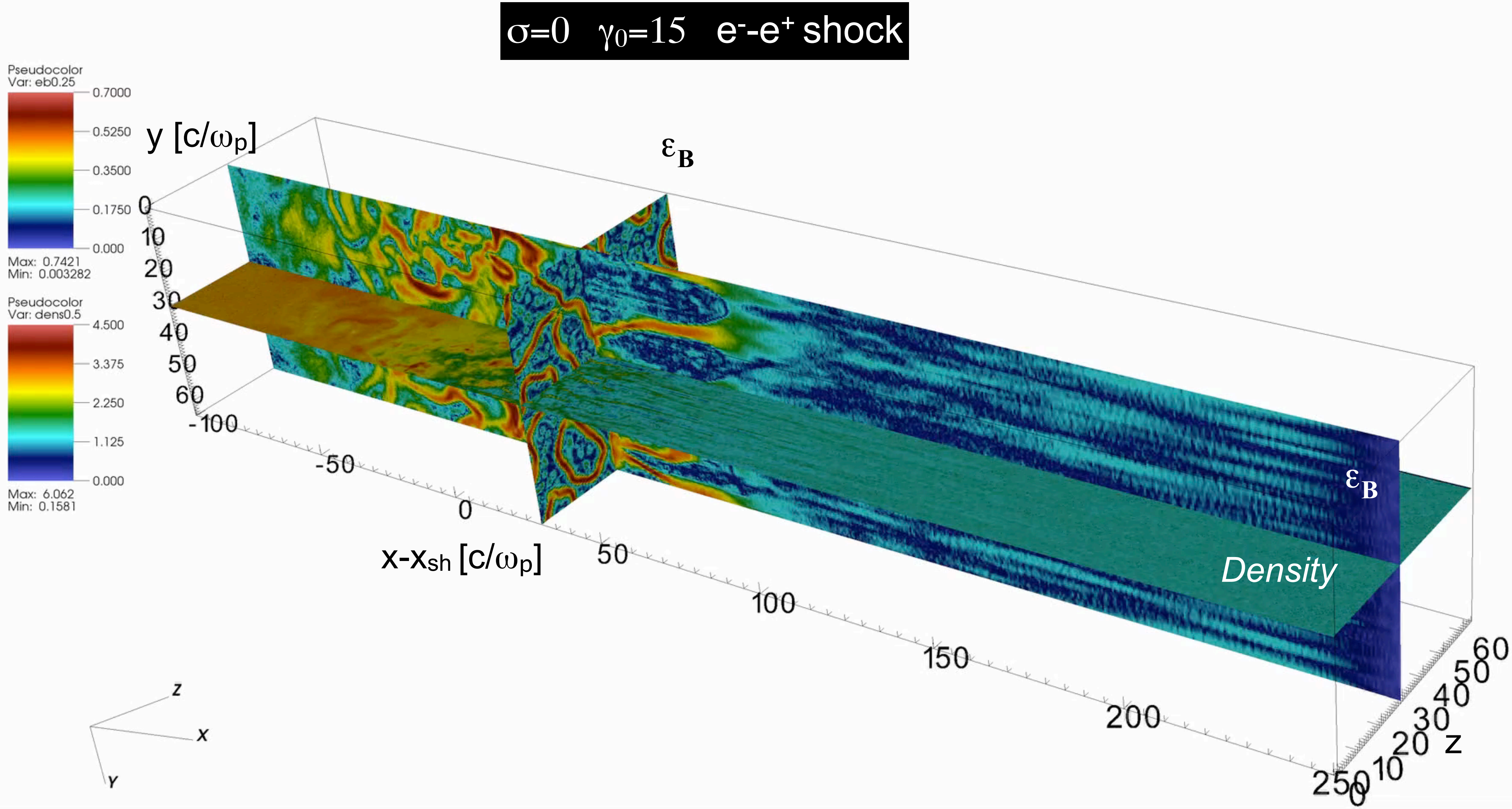
$$\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$$

- quasi-perpendicular shocks



Low-σ shocks are filamentary

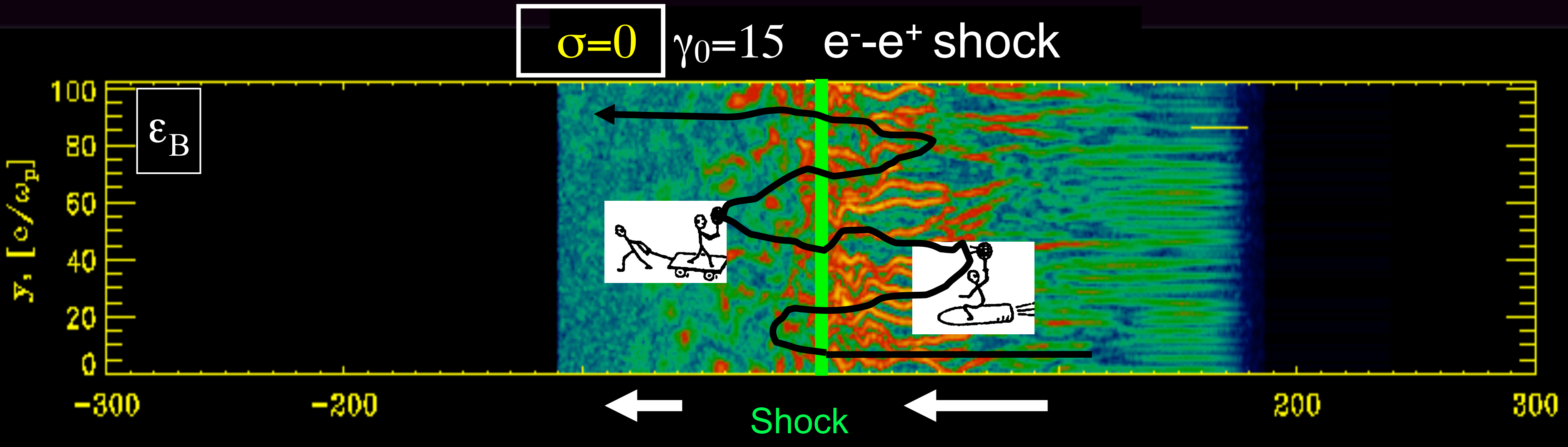
Mediated by the filamentation (Weibel) instability, that generates small-scale sub-equipartition magnetic fields.



(LS et al. 13)

The Fermi process in low-σ shocks

Particle acceleration via the Fermi process in self-generated turbulence, for initially unmagnetized (i.e., $\sigma=0$) or weakly magnetized flows.

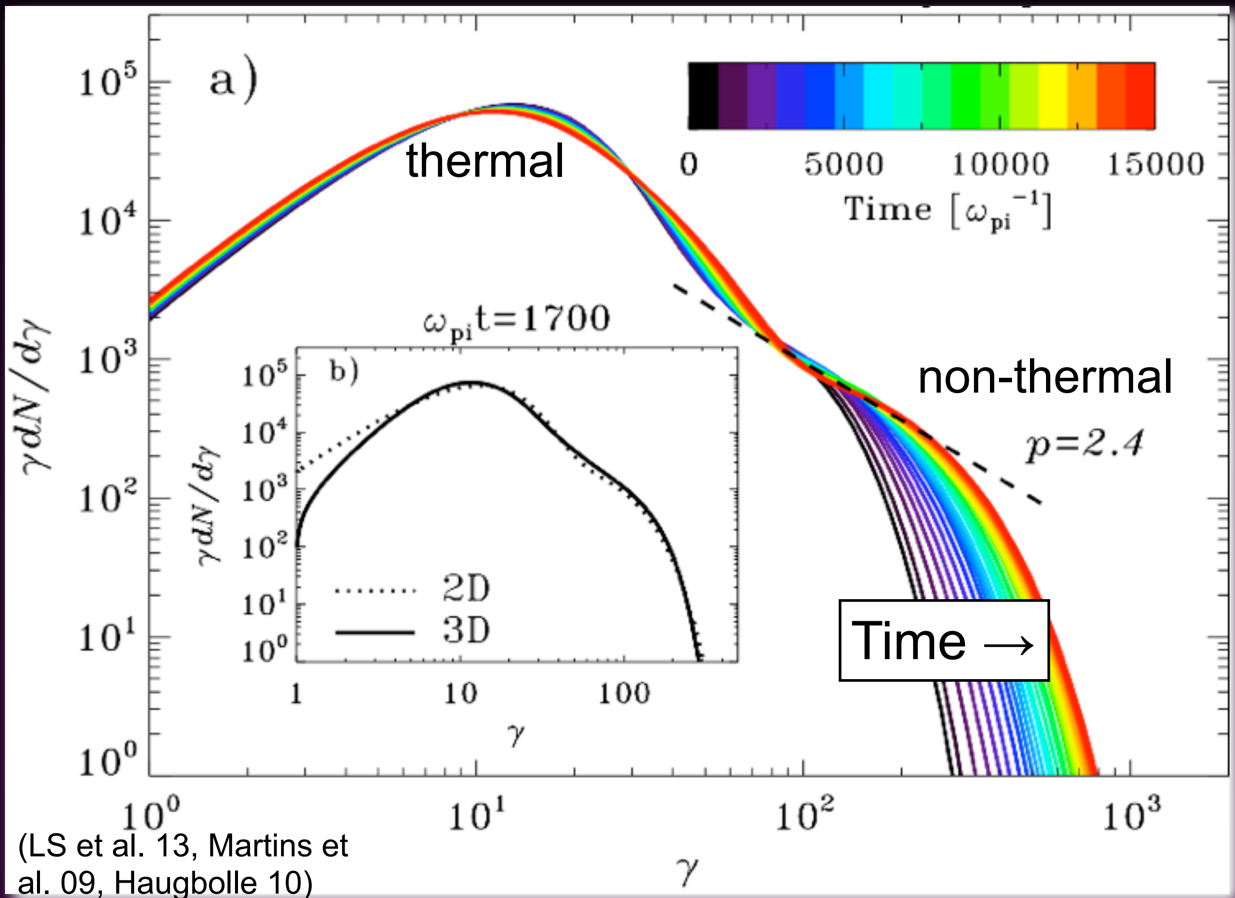


Low-σ shocks are efficient but slow

The nonthermal tail has slope p=2.4±0.1 and contains ~1% of particles and ~10% of energy.

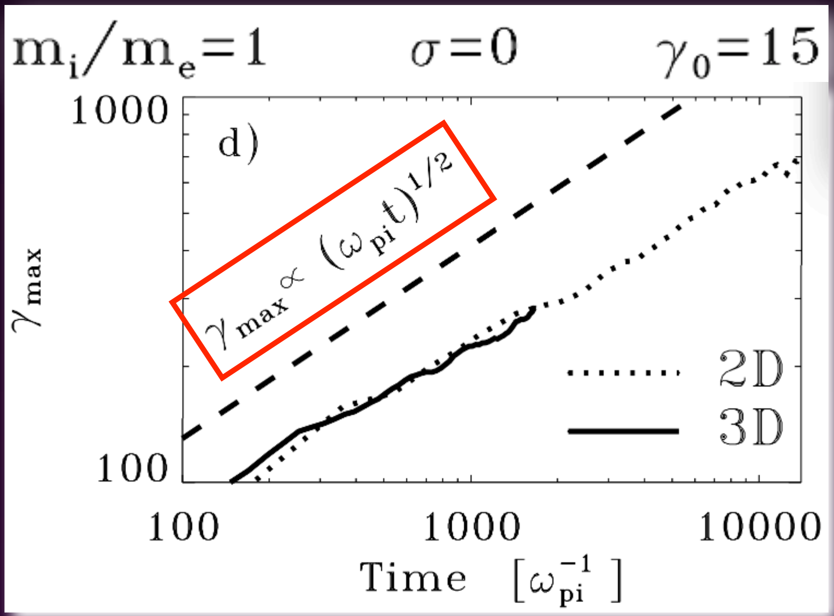
By scattering off small-scale Weibel turbulence, the maximum energy grows as $\gamma_{max} \propto t^{1/2}$.

Instead, most models of particle acceleration in shocks assume $\gamma_{max} \propto t$ (Bohm scaling).



(LS et al. 13, Martins et al. 09, Haugbolle 10)

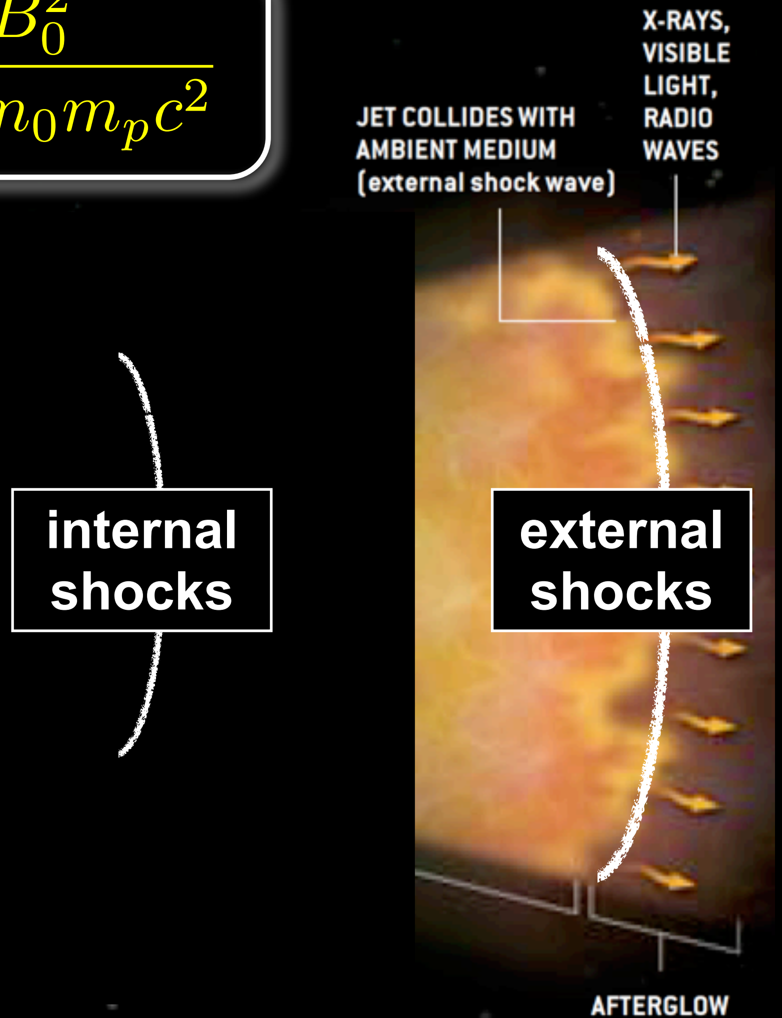
$$\gamma_{max} \simeq 0.5\,\gamma_0\,(\omega_{pi}t)^{1/2}$$



Conclusions are the same in 2D and 3D, for electron-positron and electron-ion plasmas

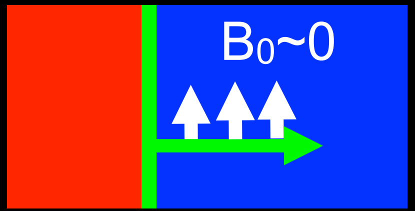
External vs internal shocks

$$\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$$



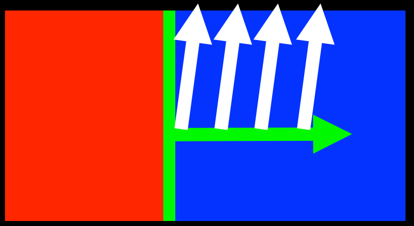
Gamma-ray burst external shocks:

- γ_0~a few hundreds
- quasi-perpendicular shocks
- $\sigma \sim 10^{-9}$



Internal shocks in blazars and gamma-ray burst jets:

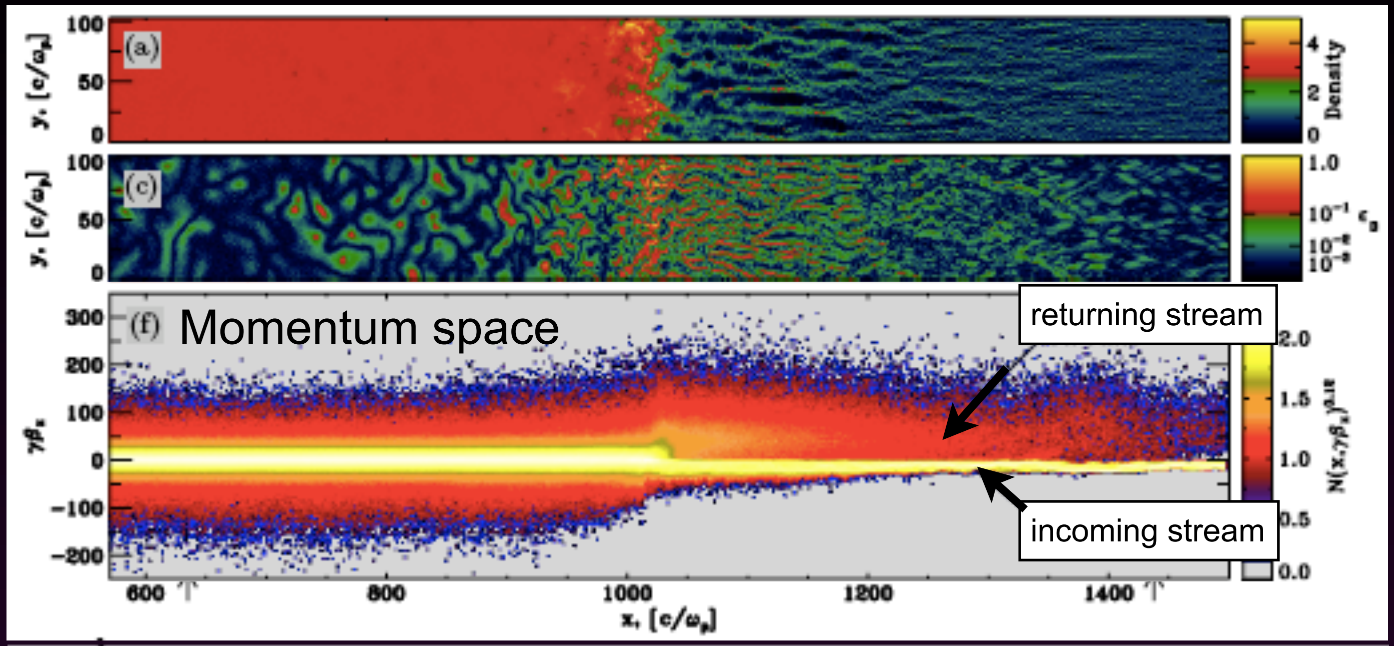
- γ_0~a few
- quasi-perpendicular shocks
- $\sigma \sim 0.01 - 0.1$



Low-σ vs high-σ shocks

- Low-σ shocks: returning particles → oblique & filamentation instabilities

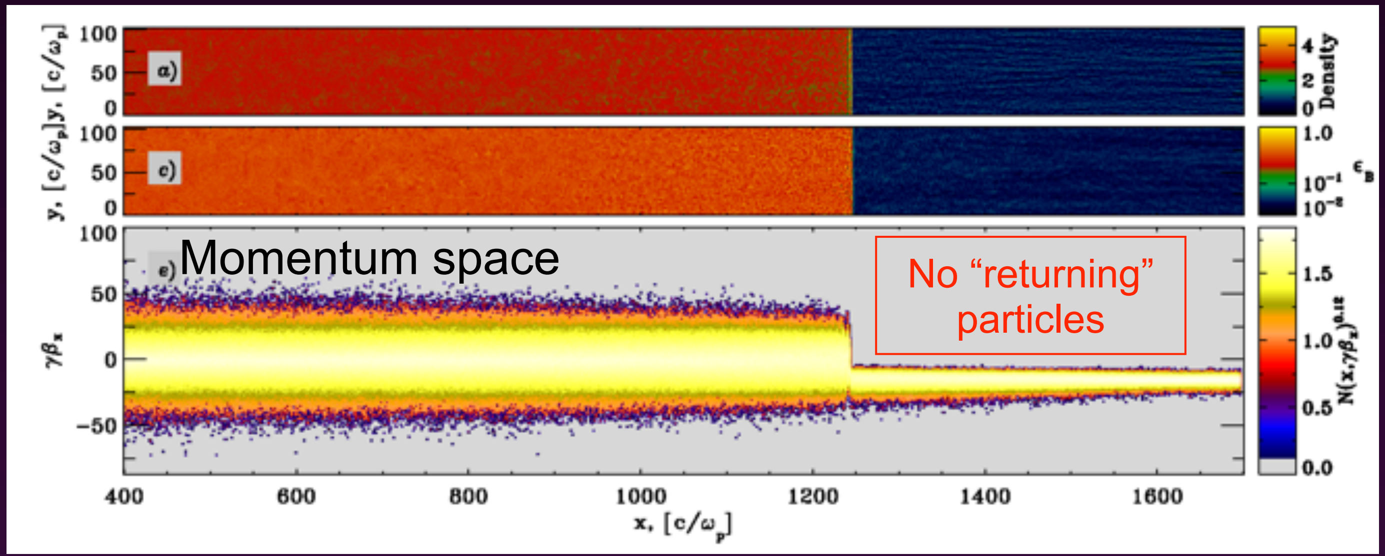
$\sigma=0$
$\gamma_0=15$
e^--e^+



(LS et al 13)

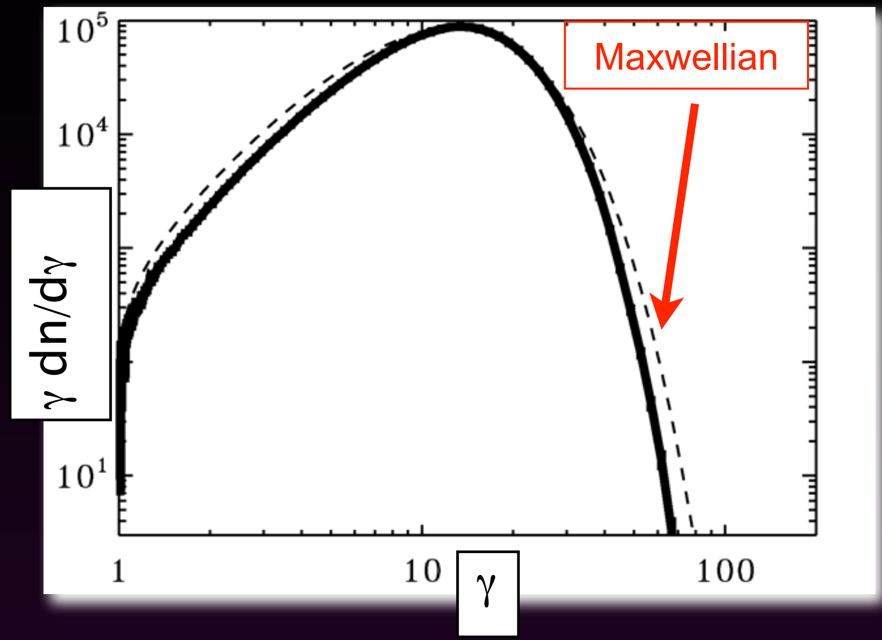
- High-σ shocks: no returning particles → no turbulence

$\sigma=0.1$
perp shock
$\gamma_0=15$
e^--e^+



(LS & Spitkovsky 11)

Shocks: no turbulence → no acceleration

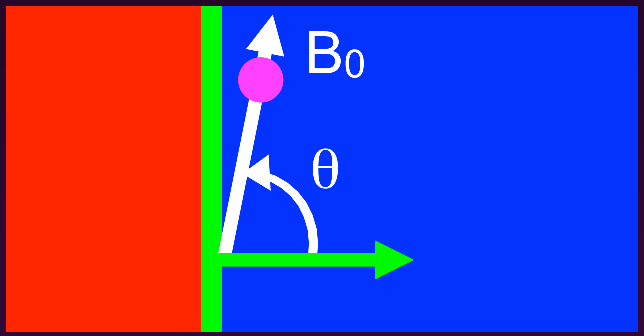


(LS+ 13, LS & Spitkovsky 09,11)

No "returning" particles → No self-generated turbulence

No self-generated turbulence → No particle acceleration

Strongly magnetized ($\sigma > 10^{-3}$) quasi-perp $\gamma_0 \gg 1$ shocks are poor particle accelerators:



σ is large → particles slide along field lines

θ is large → particles cannot outrun the shock

unless v>c ("superluminal" shock)

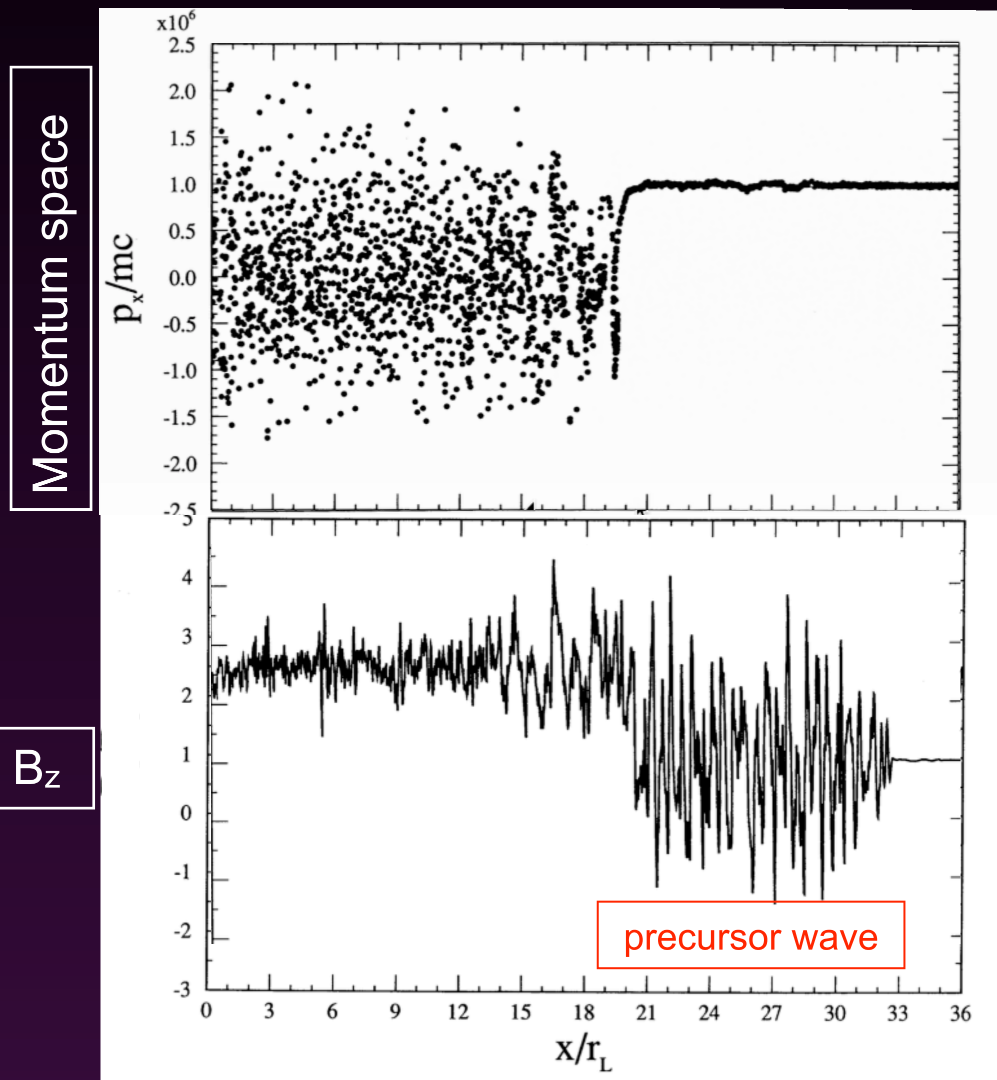
→ Fermi acceleration is generally suppressed

Is this the end for relativistic magnetized quasi-perp pair shocks?

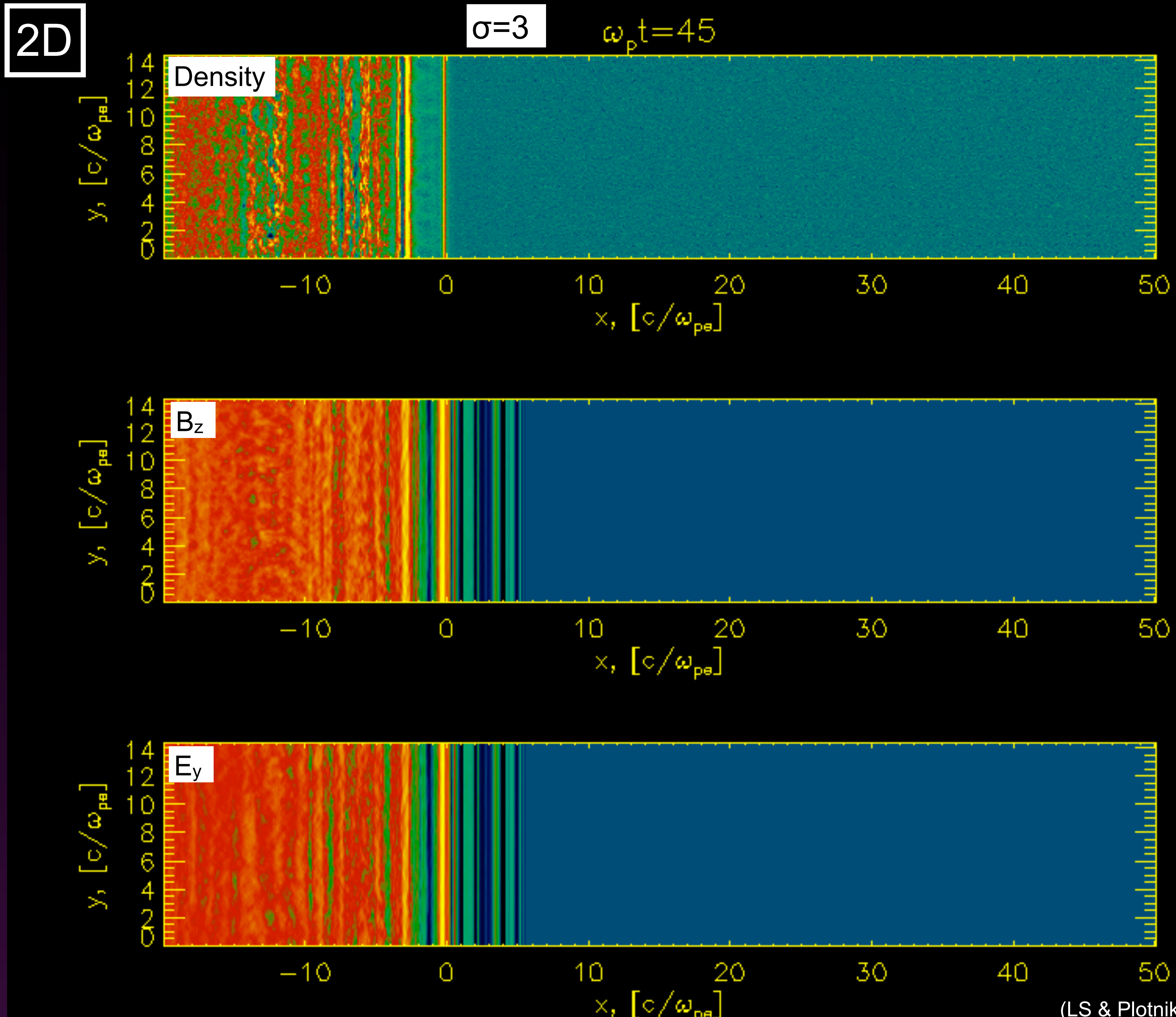
(1) Pretty much, as regard to particle acceleration.

(2) But, they radiate a semi-coherent precursor of electromagnetic waves into the pre-shock medium, via the synchrotron maser instability.

1D results



(Gallant + 92)



(LS & Plotnikov 17, in prep)

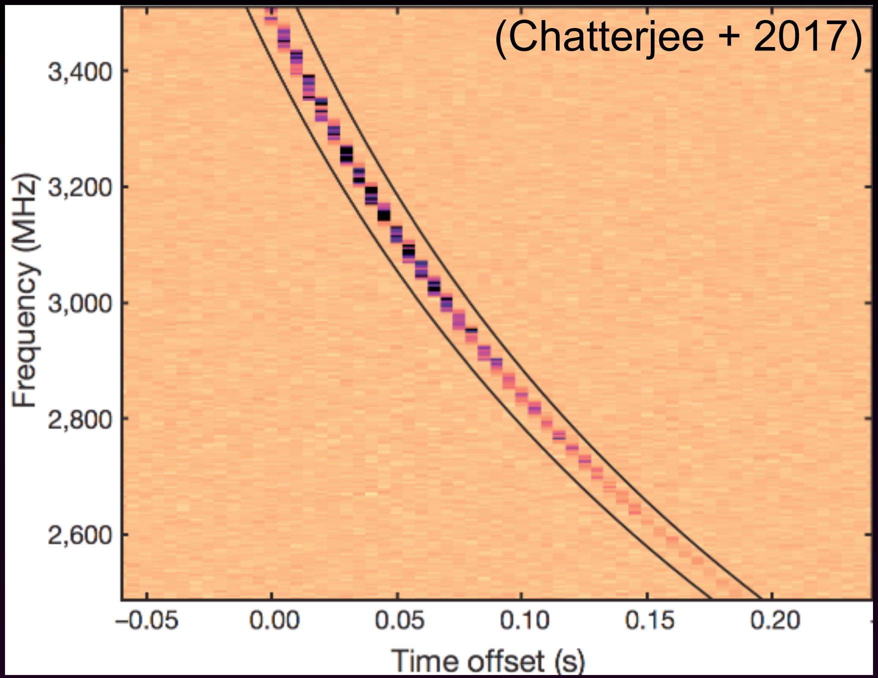
Fast radio bursts (FRBs)

(1) Bursts of ~ms duration in the GHz band.

(2) Cosmological (large dispersion measures) → extreme brightness temperature.

(3) Repeating (so, not a cataclysmic event).

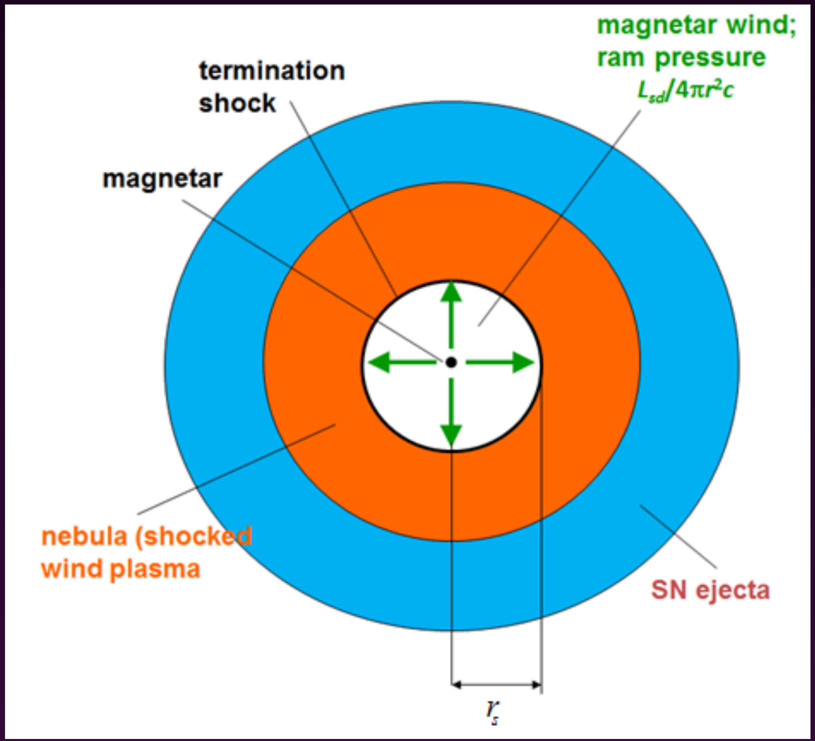
(4) Localized (in star-forming galaxies).



A model for FRBs:

A magnetic pulse in the magnetar wind is decelerated at a strong relativistic shock.

This generates the FRB via the synchrotron maser instability.

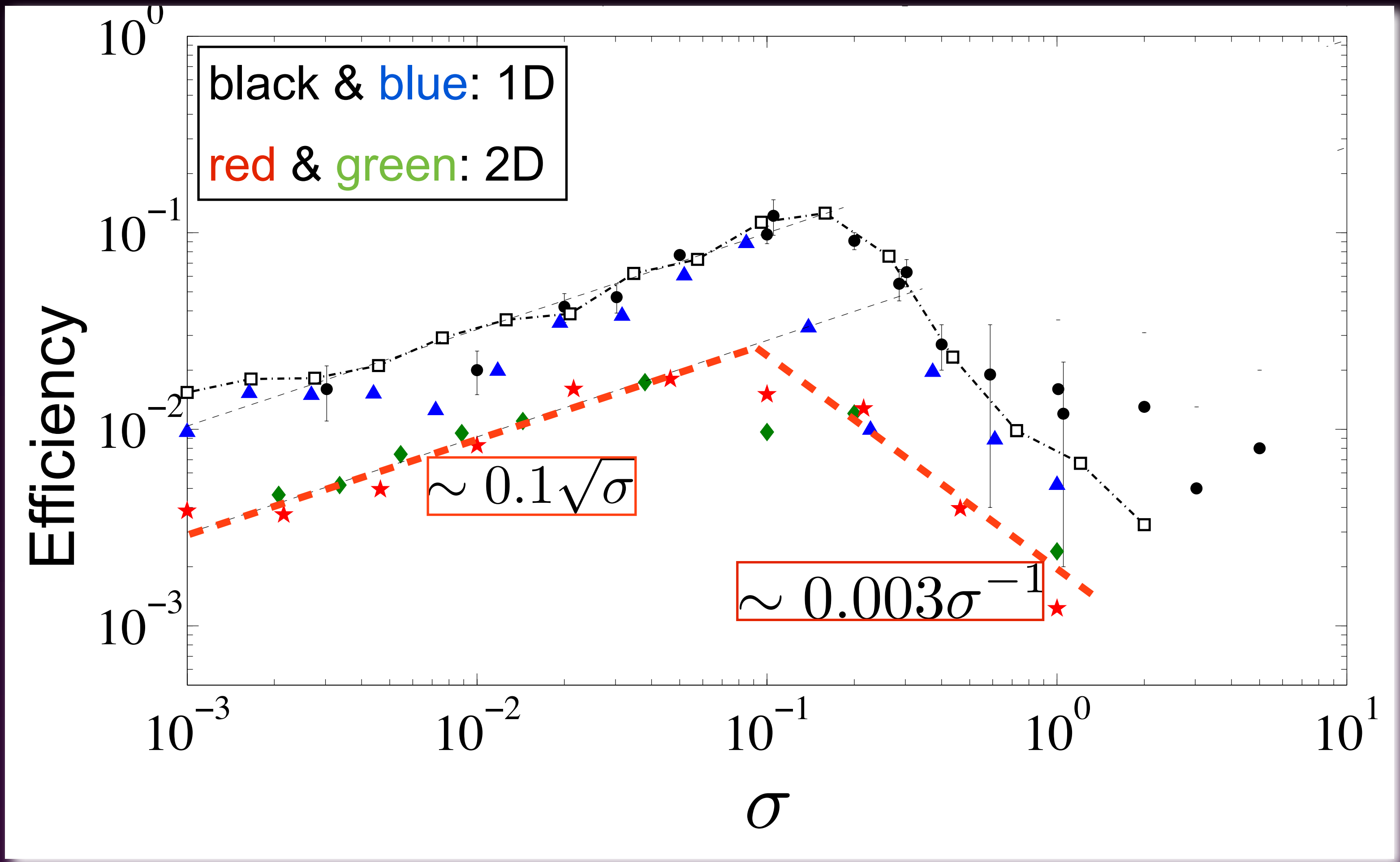


The synchrotron maser for FRBs

- The precursor emission is steady in time in 1D, 2D and 3D.

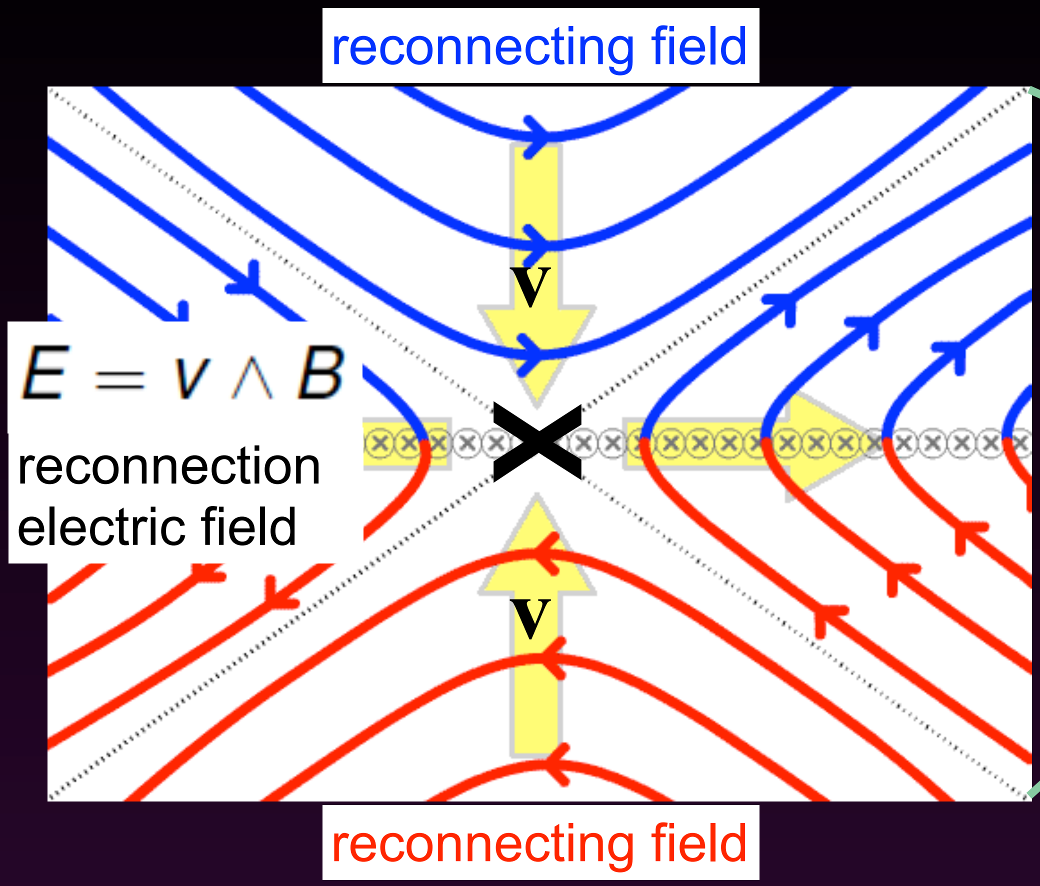
- The spectrum is strongly peaked at the Larmor frequency.

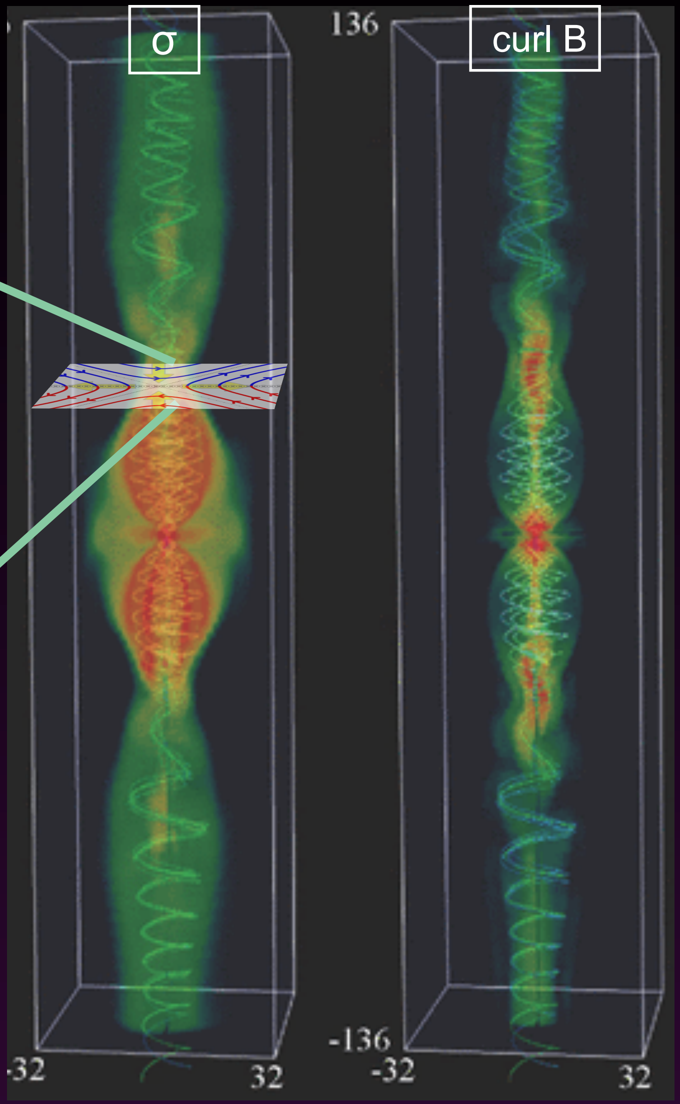
- In 2D and 3D, the efficiency of the synchrotron maser emission is smaller than in 1D by a factor of ~ 3.



(LS & Plotnikov 17, in prep)

Relativistic magnetic reconnection





(Bromberg & Tchekhovskoy 15)

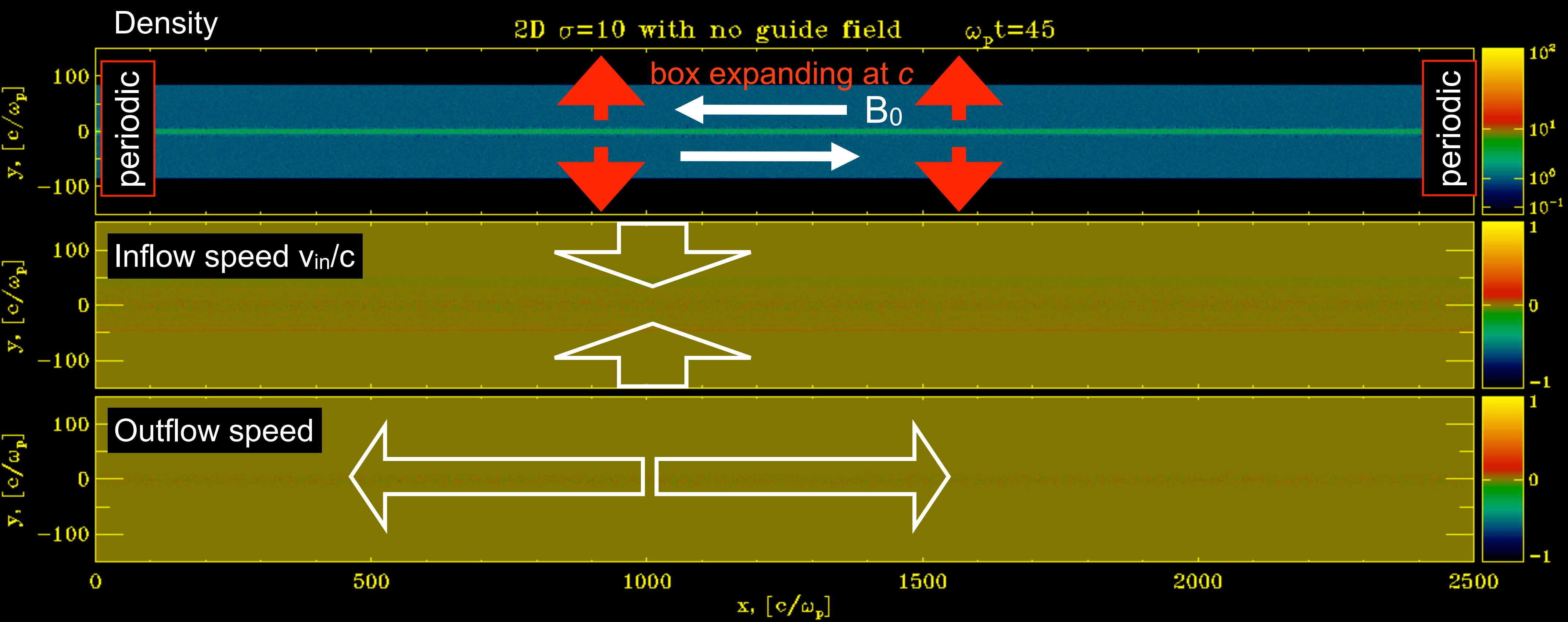
Relativistic Reconnection

$$\sigma = \frac{B_0^2}{4\pi n_0 m_p c^2} \gg 1 \qquad v_A \sim c$$

Dynamics and particle spectrum

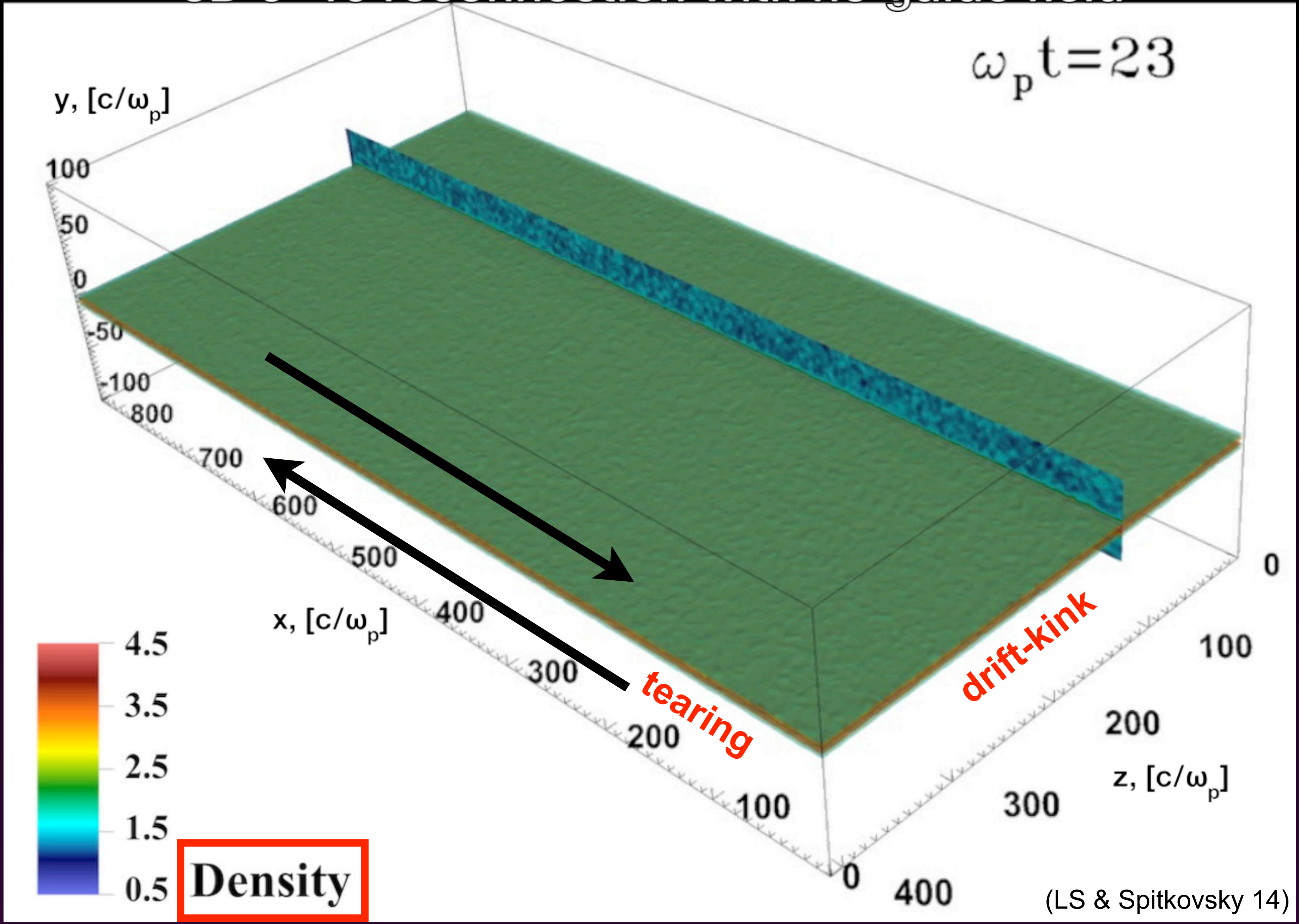
Inflows and outflows

2D PIC simulation of $\sigma=10$ electron-positron reconnection



- Inflow into the layer is non-relativistic, at v_{in} ~ 0.1 c (Lyutikov & Uzdensky 03, Lyubarsky 05).
- Outflow from the X-points is ultra-relativistic, reaching the Alfven speed $v_A = c\sqrt{\frac{\sigma}{1+\sigma}}$

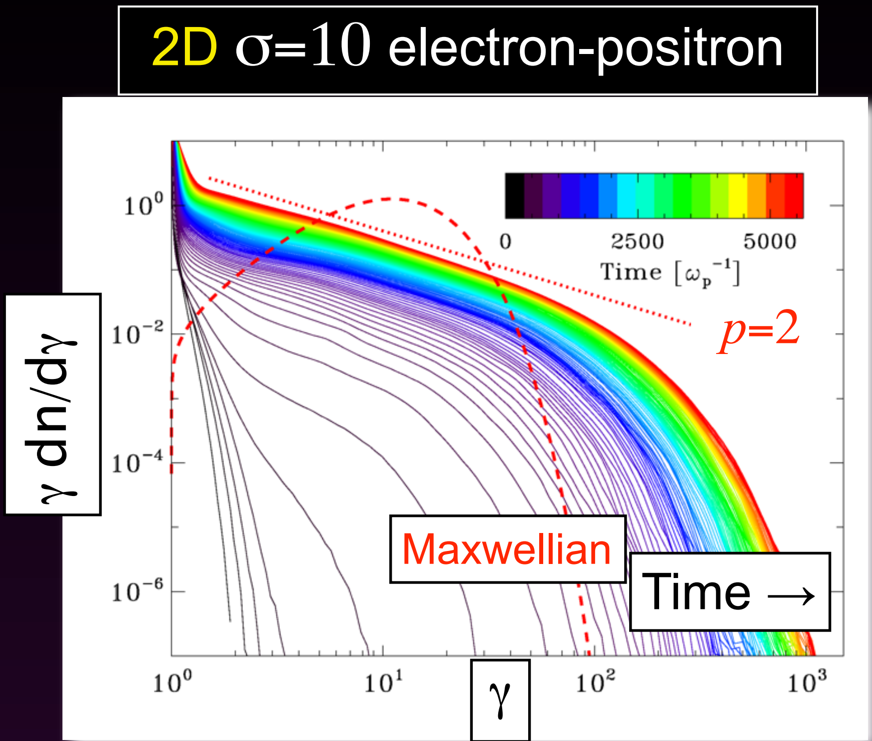
3D σ=10 reconnection with no guide field

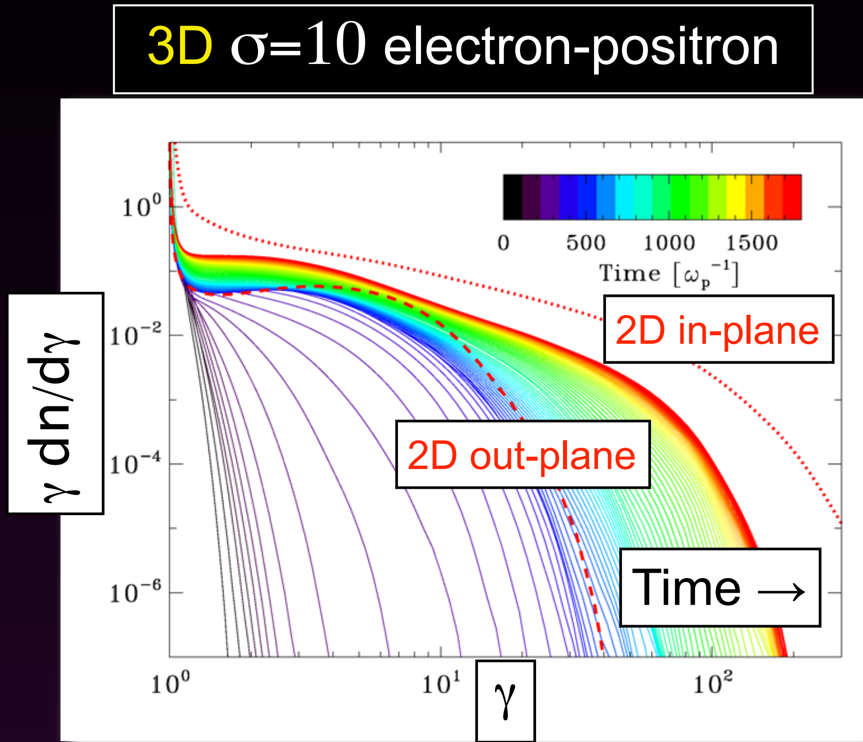


- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

The particle energy spectrum

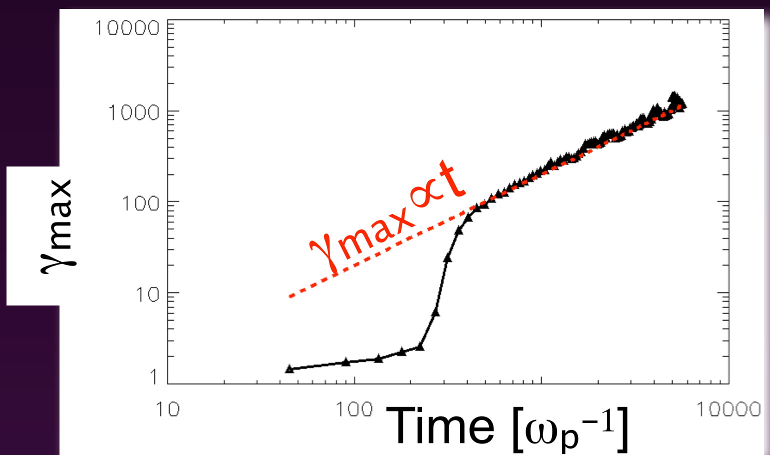
- At late times, the particle spectrum approaches a power law $dn/d\gamma \propto \gamma^{-p}$

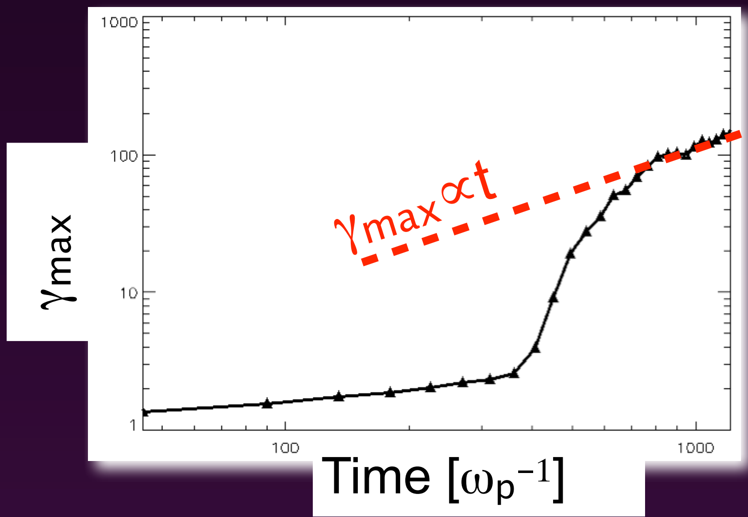




(LS & Spitkovsky 14)

- The max energy grows linearly with time, if the evolution is not artificially inhibited by the boundaries.

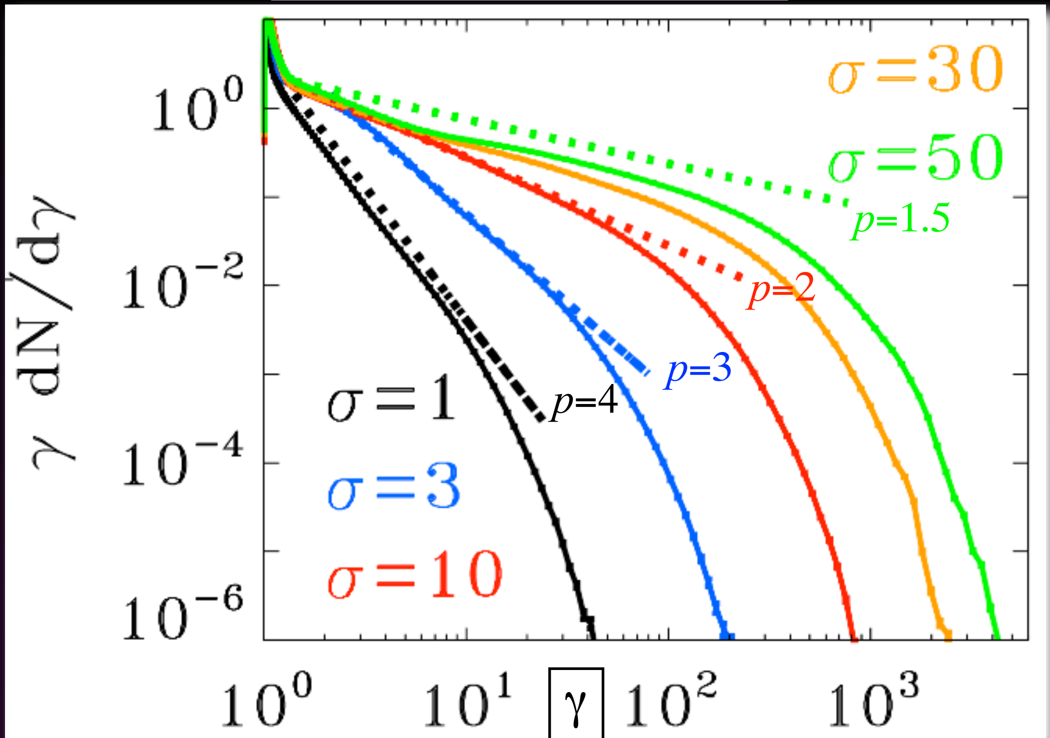




(LS & Spitkovsky 14)

The power-law slope

2D electron-positron



(LS & Spitkovsky 14, also Melzani+14, Guo+14,15, Werner+16)

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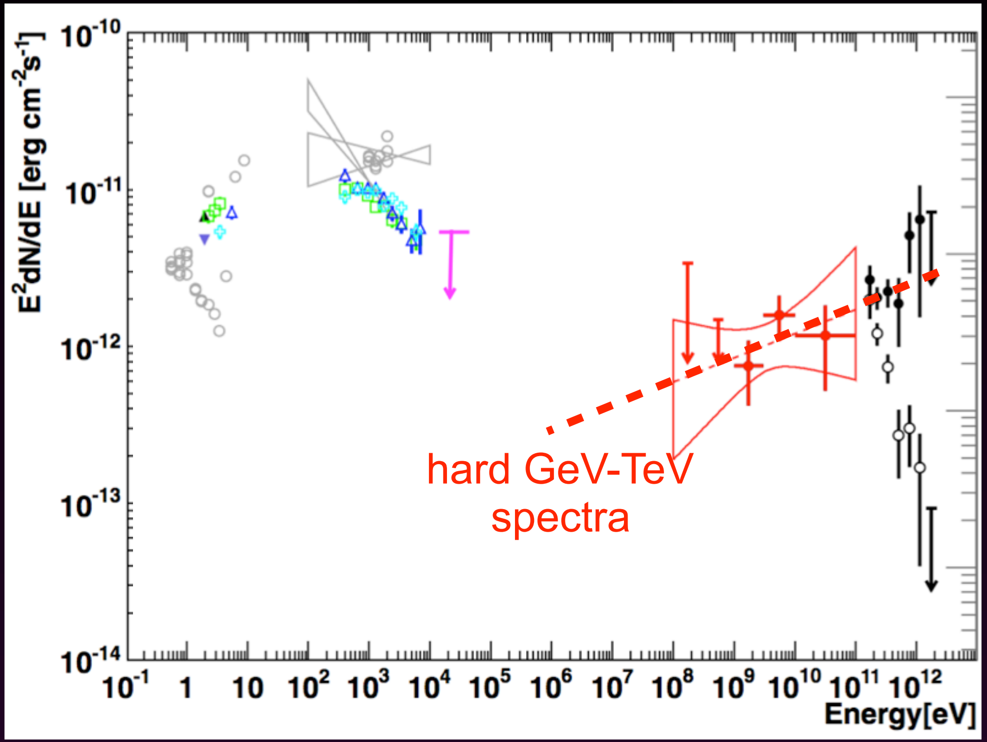


The power-law slope of relativistic reconnection is *not* universal.

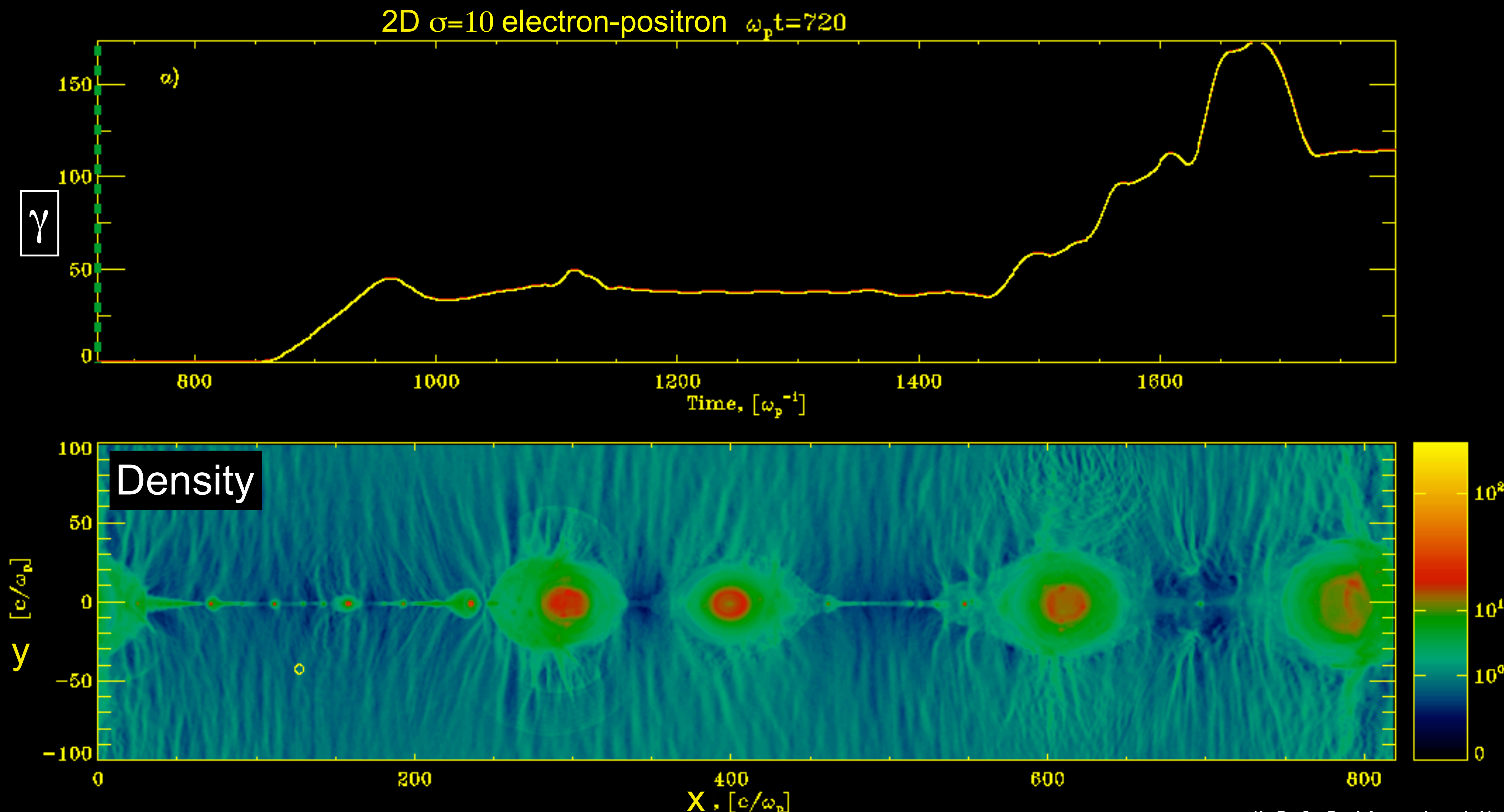
The slope is harder for higher magnetizations.

In blazars, the emitting particles have a variety of power-law slopes, sometimes with a hard slope:

$$\frac{dn}{d\gamma} \propto \gamma^{-p} \qquad p \lesssim 2$$

Particle acceleration mechanism

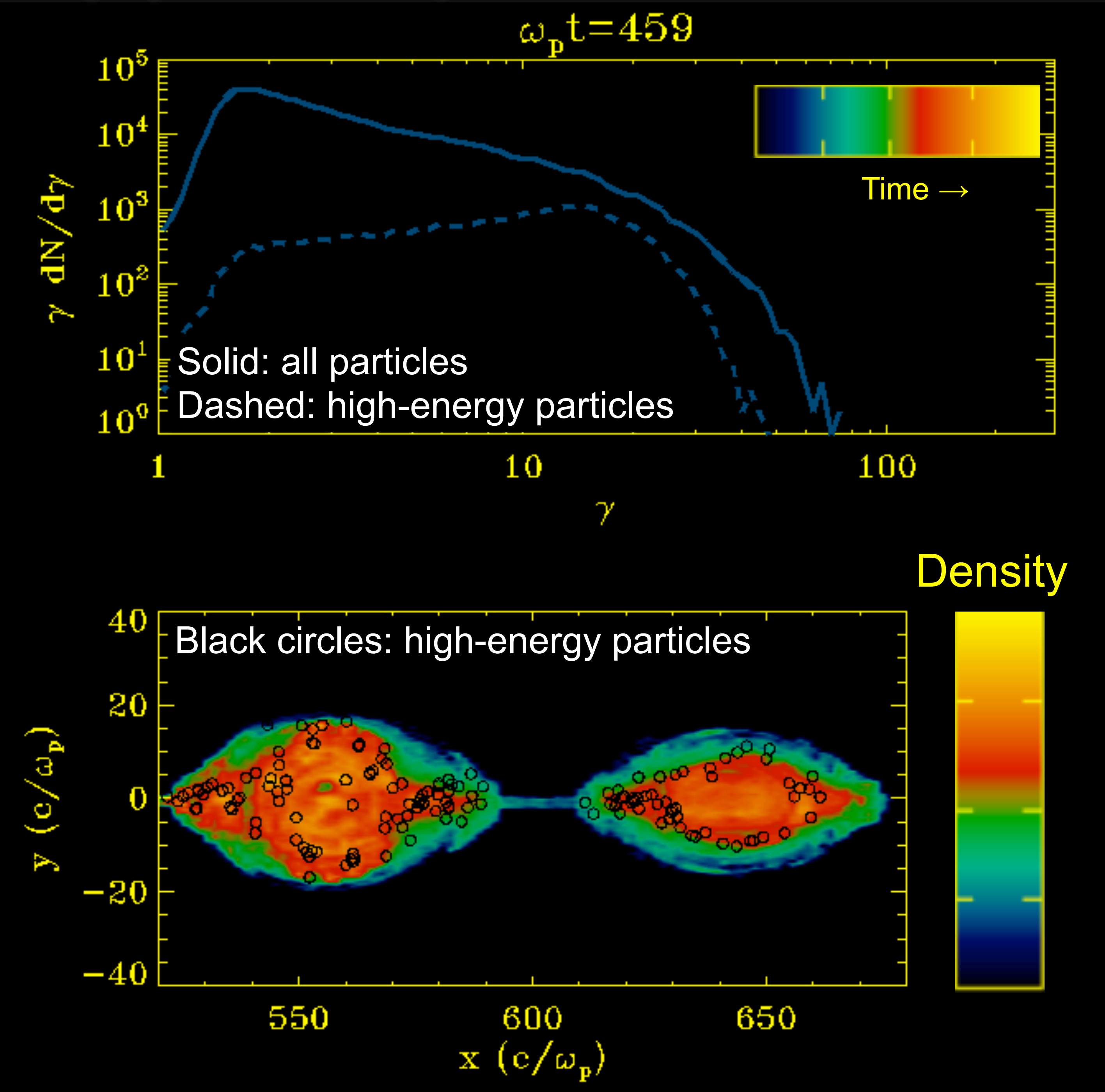
The highest energy particles



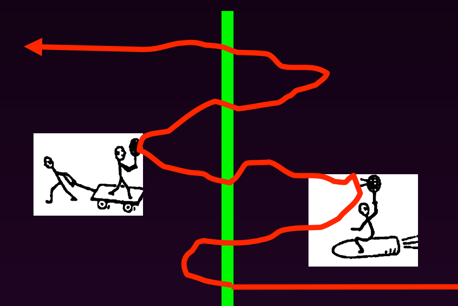
(LS & Spitkovsky 14)

Two acceleration phases: (a) at the X-point; (b) in between merging islands

(b) Fermi process in between islands

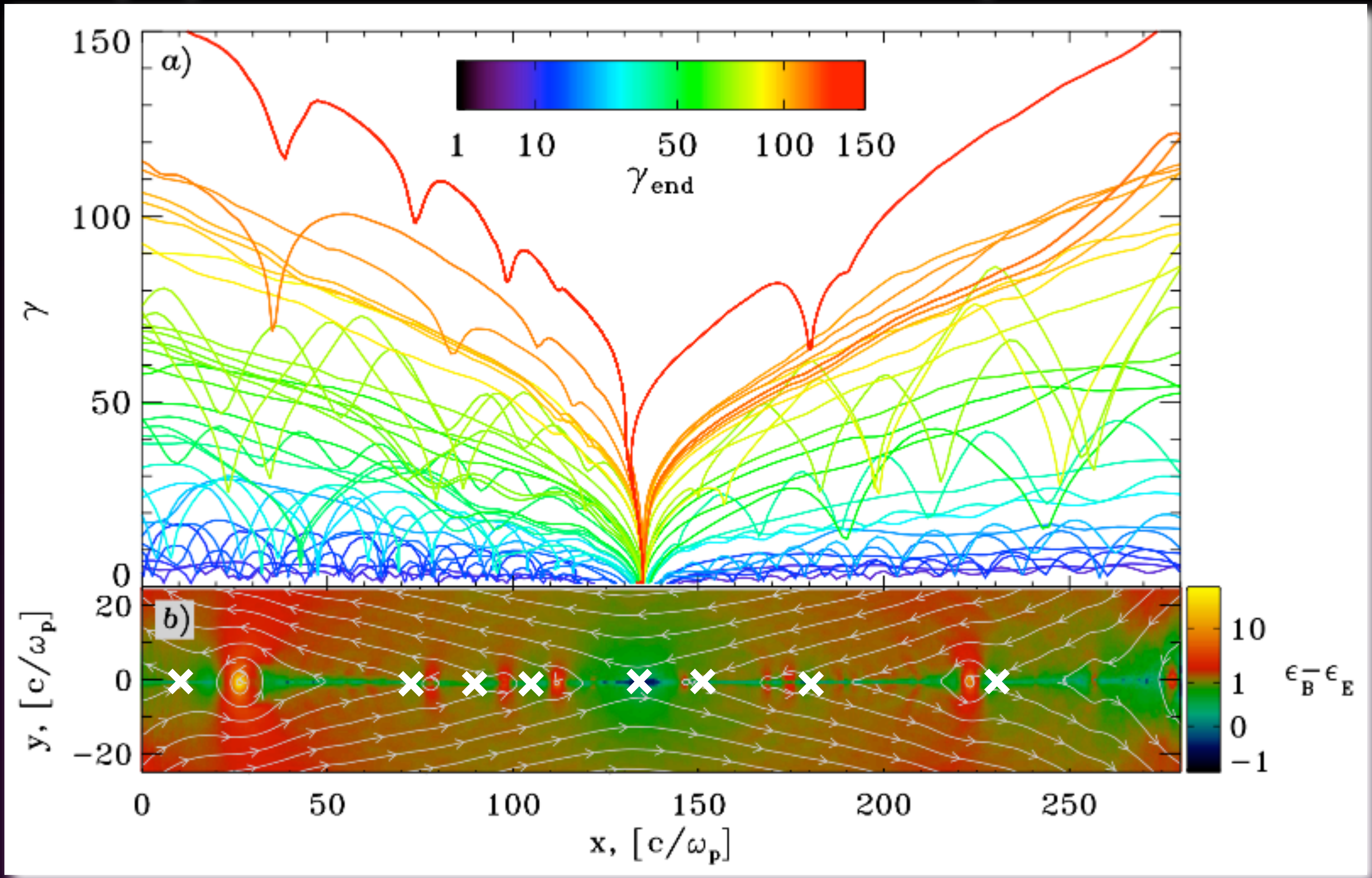


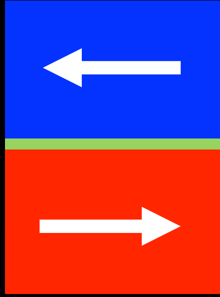
- The particles are accelerated by a Fermi-like process in between merging islands (Guo+14, Nalewajko+15).



- Island merging is essential to shift up the spectral cutoff energy.
- In the Fermi process, the rich get richer. But how do they get rich in the first place?

(a) Acceleration at X-points

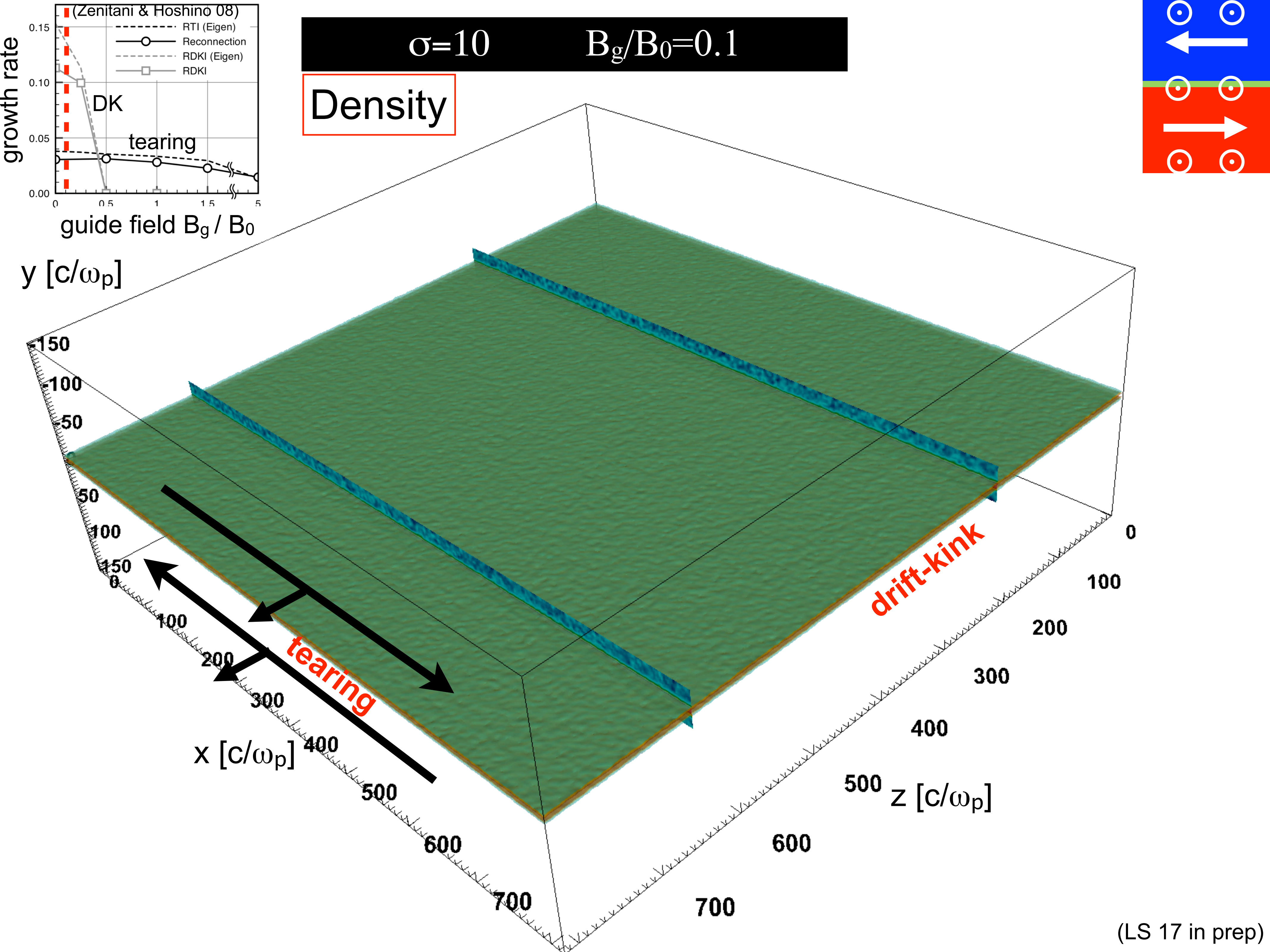


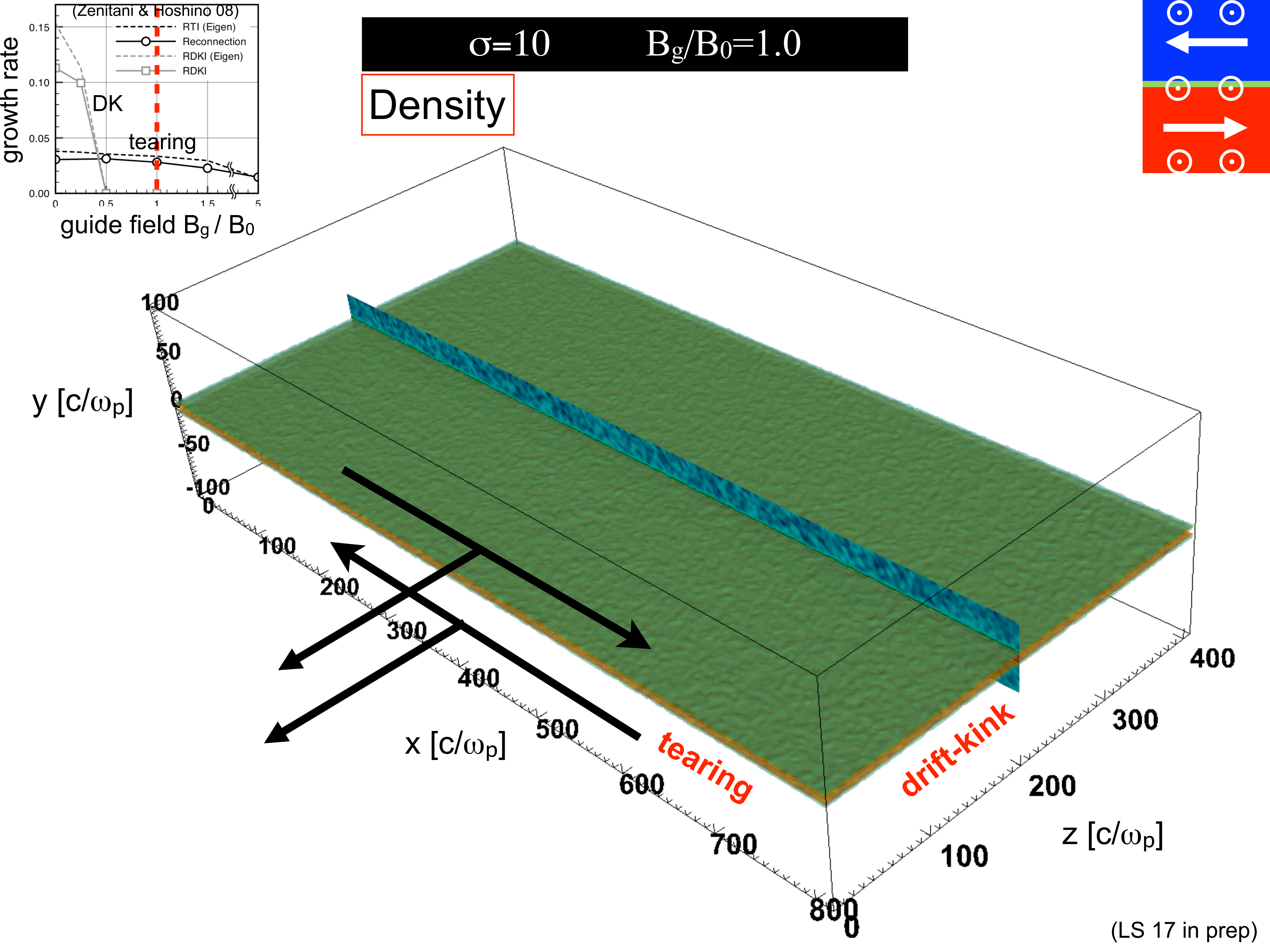


(LS & Spitkovsky 14)

- In cold plasmas, the particles are tied to field lines and they go through X-points.
- The particles are accelerated by the reconnection electric field at the X-points (Zenitani & Hoshino 01). The energy gain can vary, depending on where the particles interact with the sheet.
- The same physics operates at the main X-point and in secondary X-points.

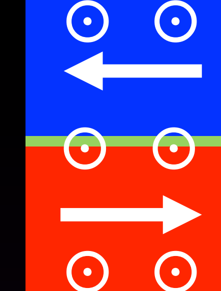
Dependence on the guide field


σ=10 Bg/B0=0.1
Density
(Zenitani & Hoshino 08)
growth rate
0.15
0.10
0.05
0.00
RTI (Eigen)
Reconnection
RDKI (Eigen)
RDKI
DK
tearing
0
0.5
1
1.5
5
guide field Bg / B0
y [c/ωp]
-150
-100
-50
50
100
150
x [c/ωp]
0
100
200
300
400
500
600
700
z [c/ωp]
0
100
200
300
400
500
600
700
tearing
drift-kink
(LS 17 in prep)

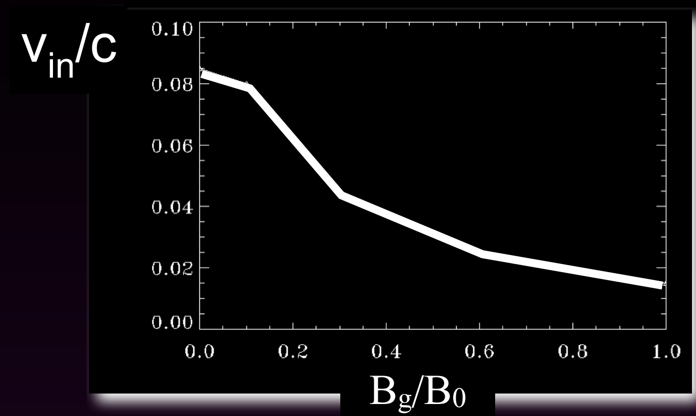


σ=10 Bg/B0=1.0
Density
(Zenitani & Hoshino 08)
RTI (Eigen)
Reconnection
RDKI (Eigen)
RDKI
DK
tearing
growth rate
guide field Bg / B0
y [c/ωp]
x [c/ωp]
z [c/ωp]
tearing
drift-kink
(LS 17 in prep)

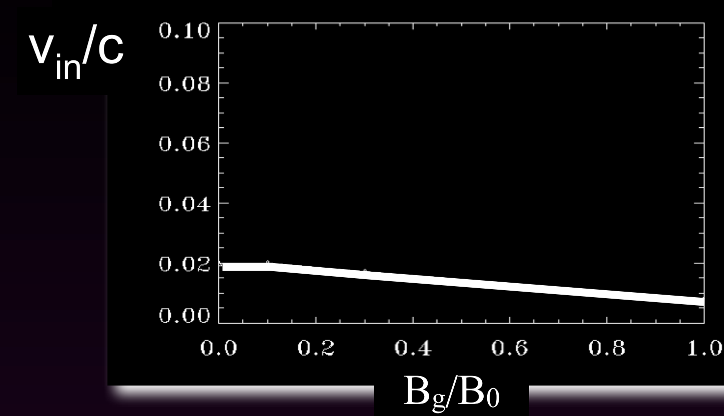
Dependence on the guide field

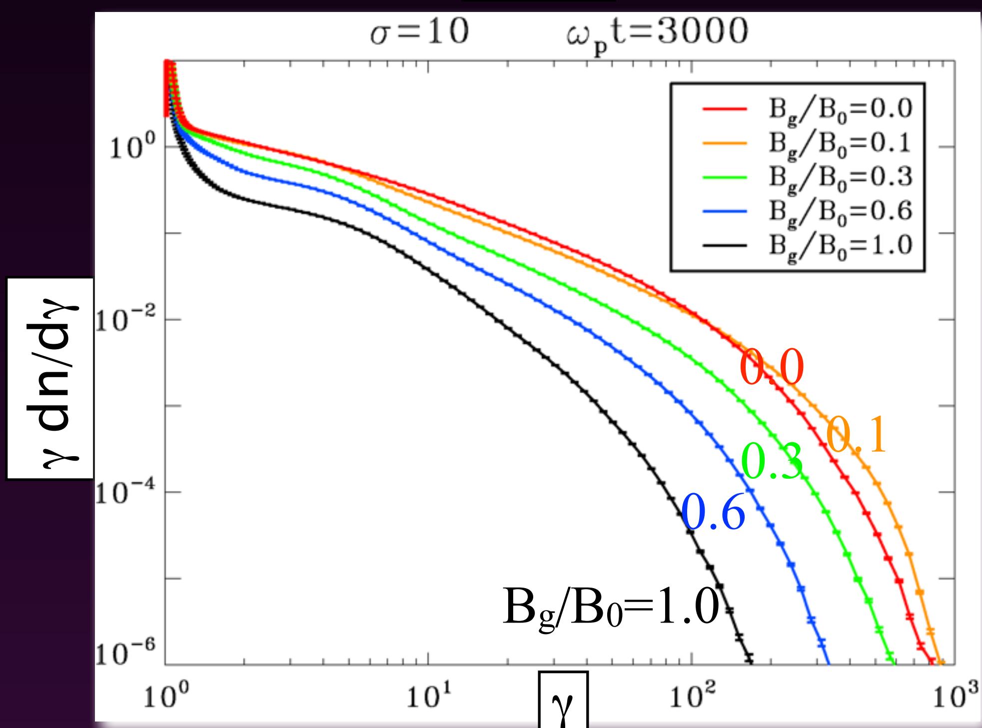


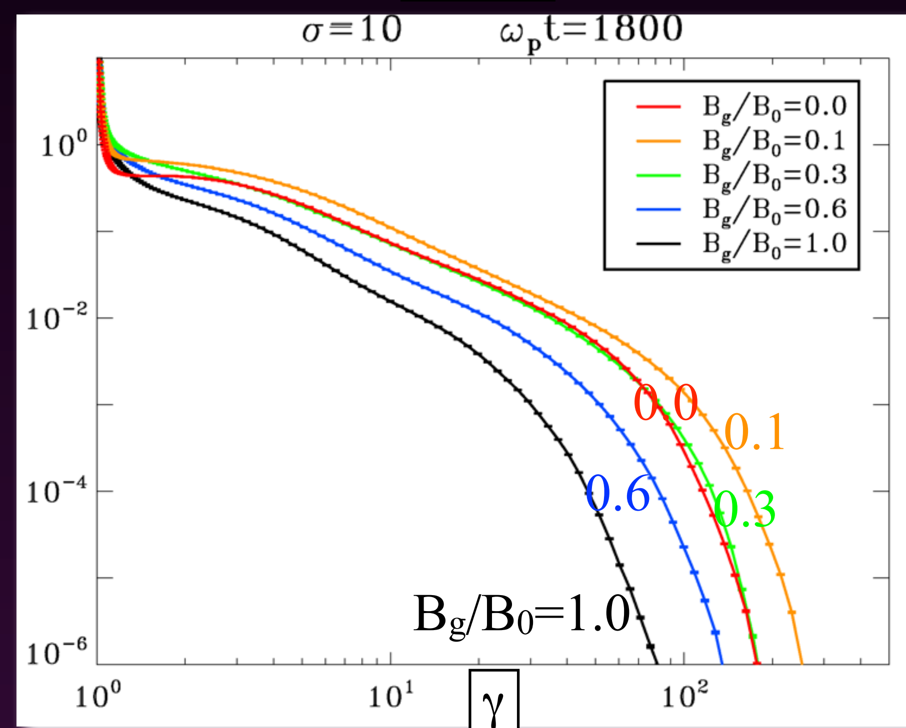
2D $\sigma=10$ electron-positron



3D $\sigma=10$ electron-positron





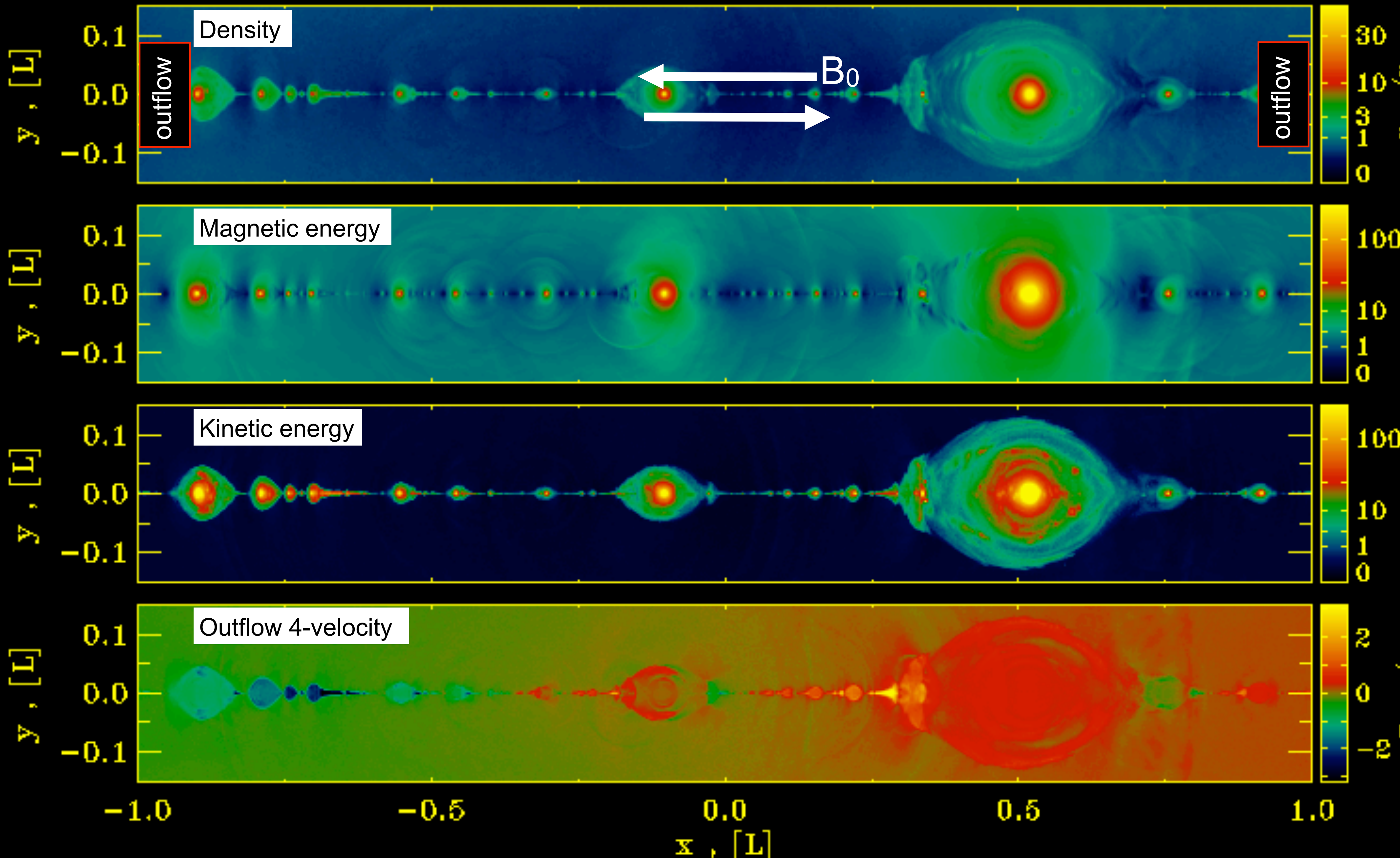


For stronger guide fields, the normalization and the maximum energy are smaller, because the reconnection electric field (and so, the reconnection rate) are smaller.

Plasmoids in reconnection layers

Plasmoids in reconnection layers

electron-positron $\sigma=10$ $ct_{lab}/L=7.7$ $L\sim1600\ c/\omega_p$

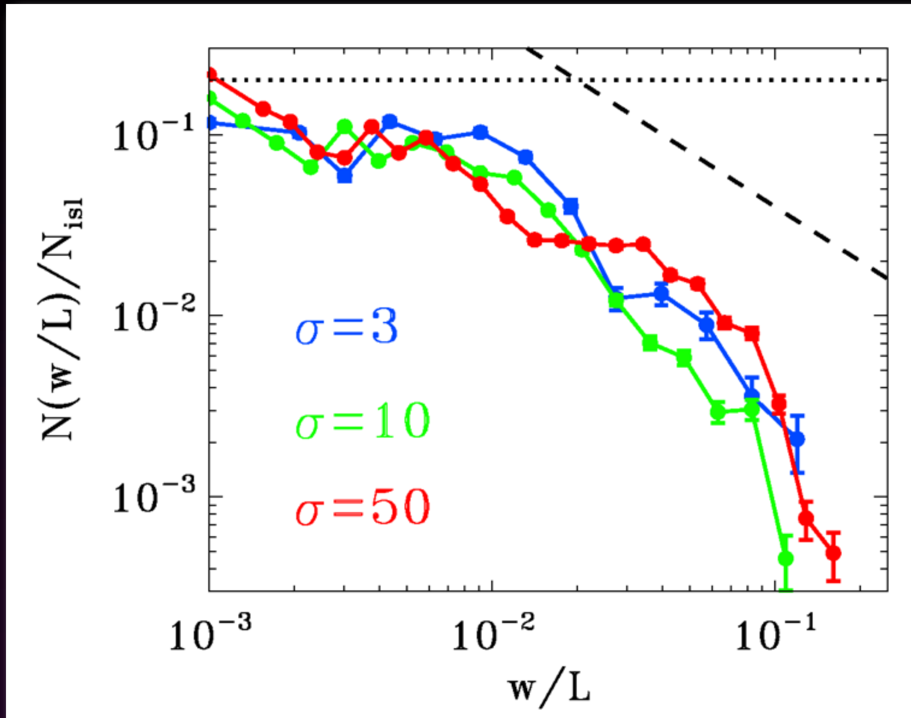


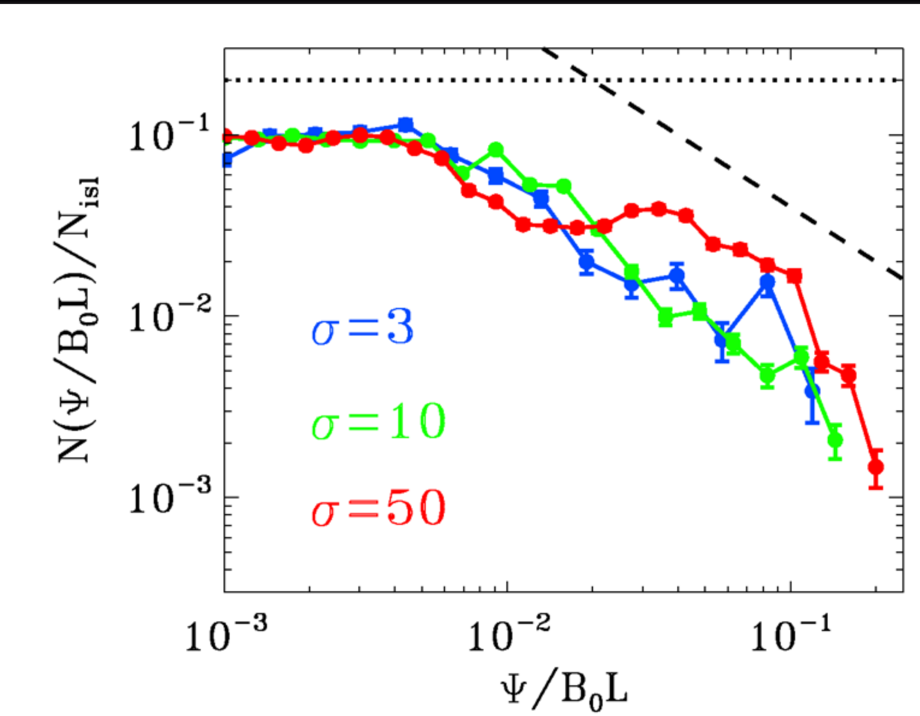
(LS, Giannios & Petropoulou 16)

Plasmoid statistics

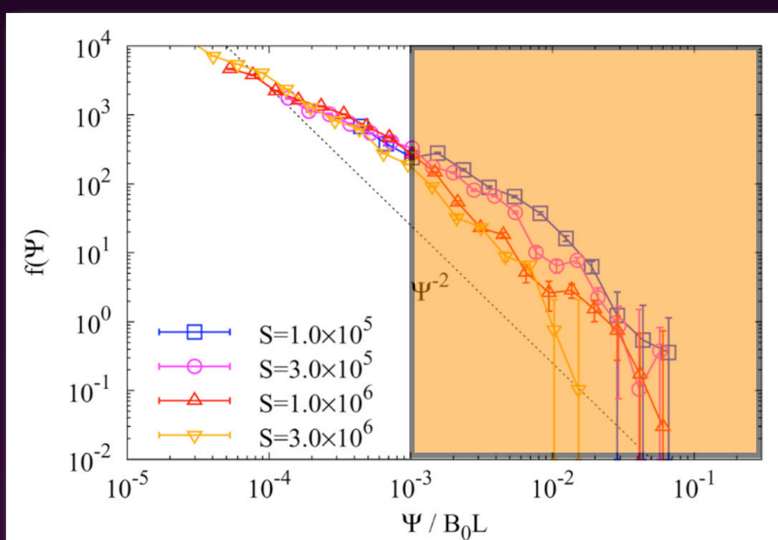
Cumulative distribution of size

Cumulative distribution of magnetic flux

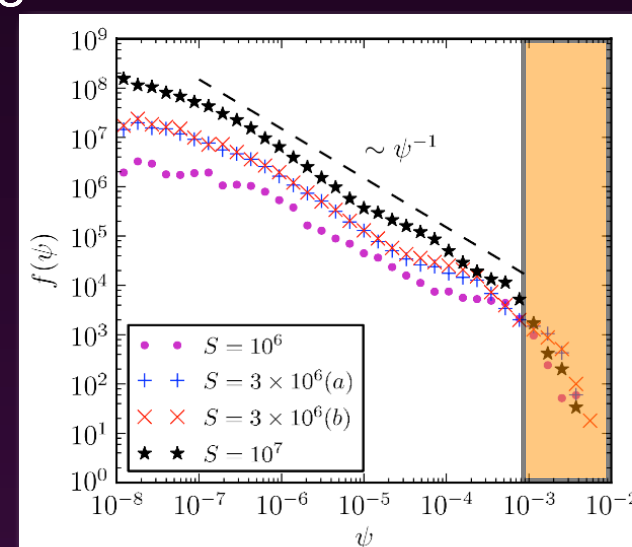




Differential distributions of magnetic flux

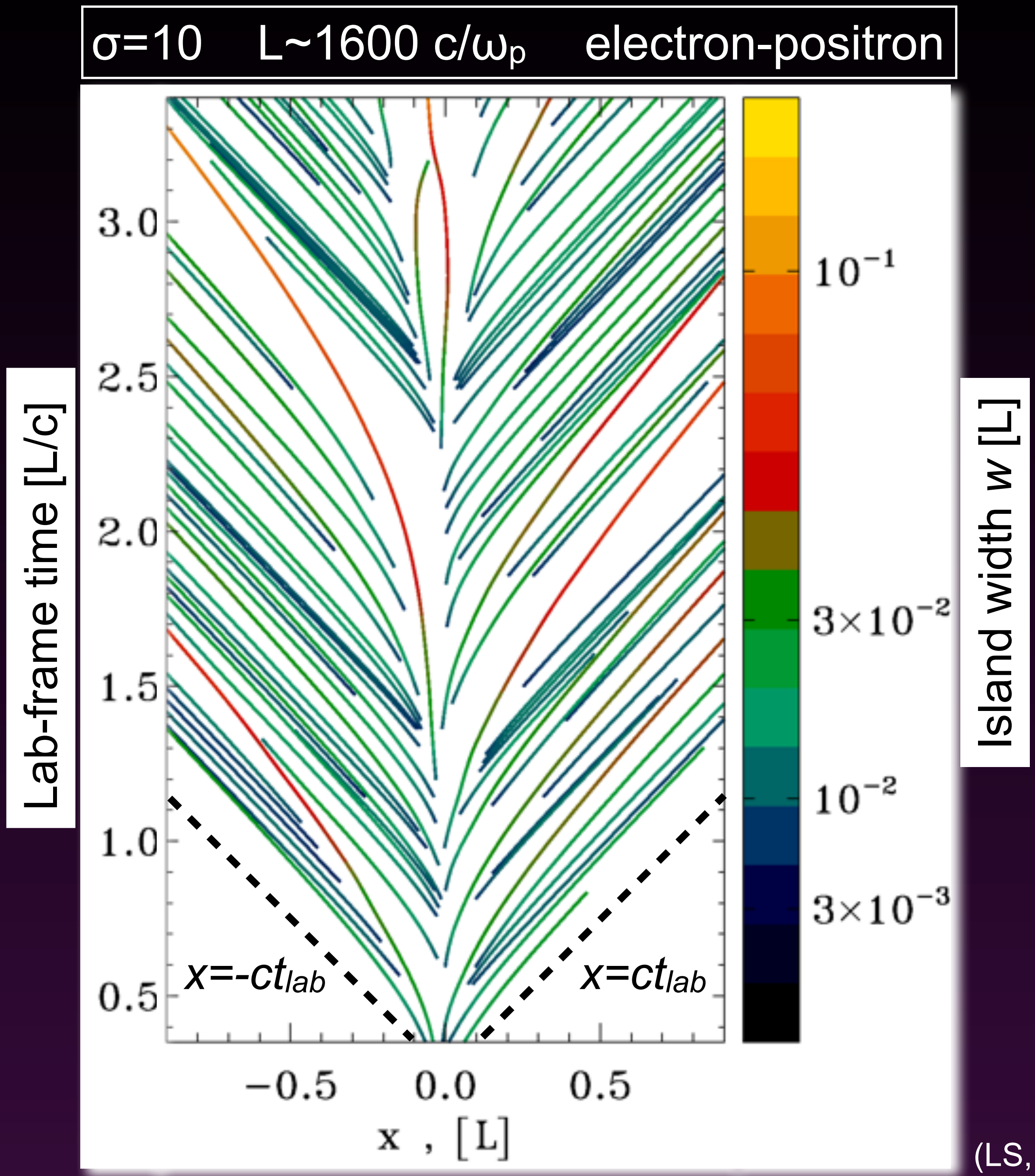


(Loureiro+12)



(Huang+12)

Plasmoid space-time tracks



We can follow individual plasmoids in space and time.

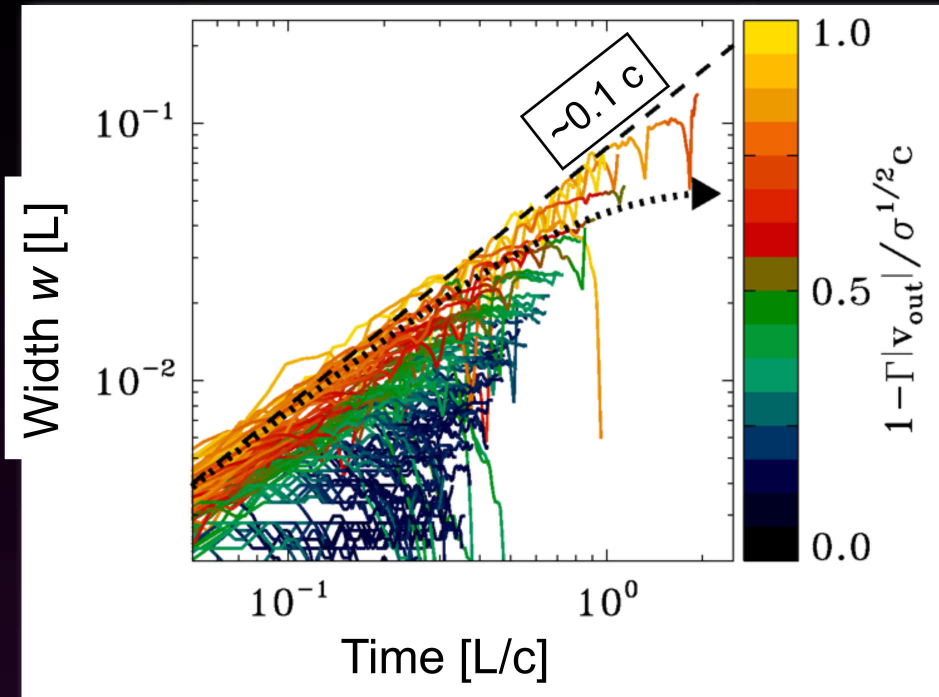
First they grow, then they go:

- First, they grow in the center at non-relativistic speeds.
- Then, they accelerate outwards approaching the Alfven speed ~ *c*.

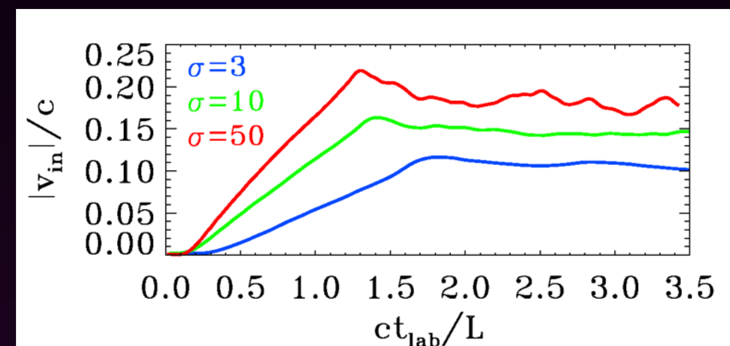
(LS, Giannios & Petropoulou 16)

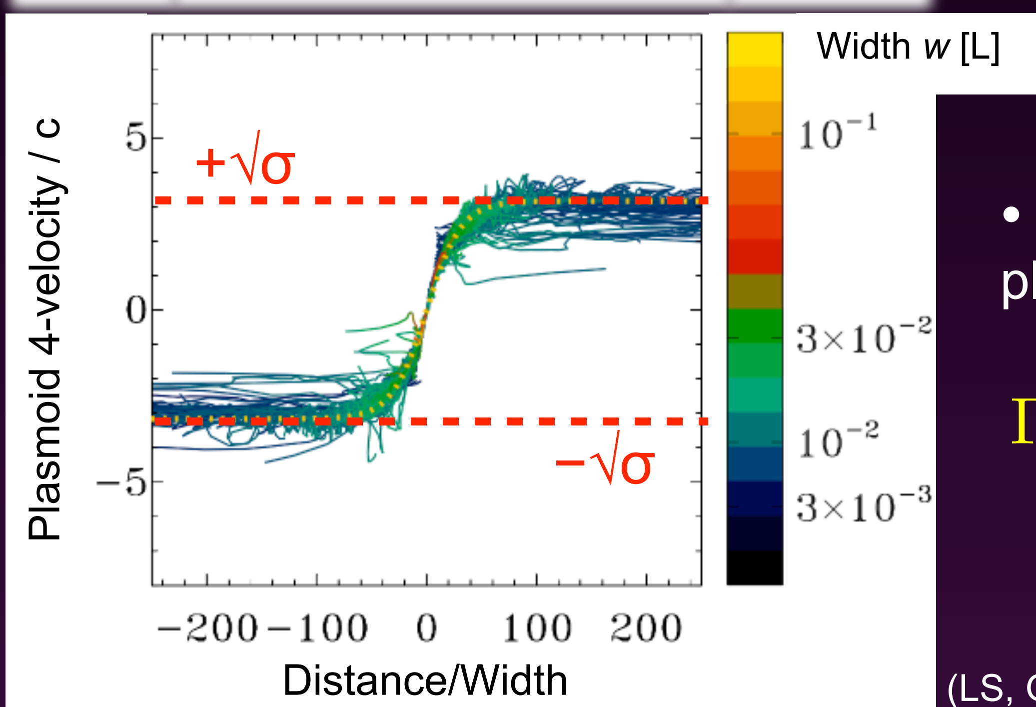
First they grow, then they go

σ=10 electron-positron



- The plasmoid width *w* grows in the plasmoid rest-frame at a constant rate of ~0.1 c (~ reconnection inflow speed), weakly dependent on the magnetization.





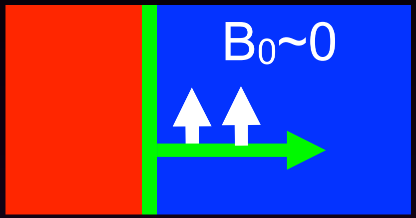
- Universal relation for the plasmoid acceleration:

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

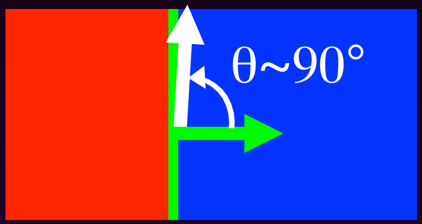
(LS, Giannios & Petropoulou 16)

Summary

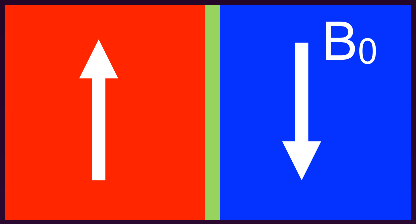
Nonthermal particle acceleration in relativistic shocks and reconnection:



• External shocks in GRBs: Weakly magnetized ($\sigma<10^{-3}$) shocks can be efficient particle accelerators (~1% by number, ~10% by energy). The maximum energy grows slowly, as $\gamma_{max} \propto t^{1/2}$.



• Internal shocks in blazars and GRB jets: Since they are significantly magnetized ($\sigma>10^{-3}$) and quasi-perpendicular, they are poor particle accelerators.



• Magnetic reconnection in magnetically-dominated flows ($\sigma \gg 1$) is fast and efficient in 2D and 3D, can produce non-thermal populations with a power-law slope between -4 and -1, and results in rough energy equipartition between particles and fields. It is a promising source of extreme time variability.