PIC simulations of relativistic magnetic reconnection

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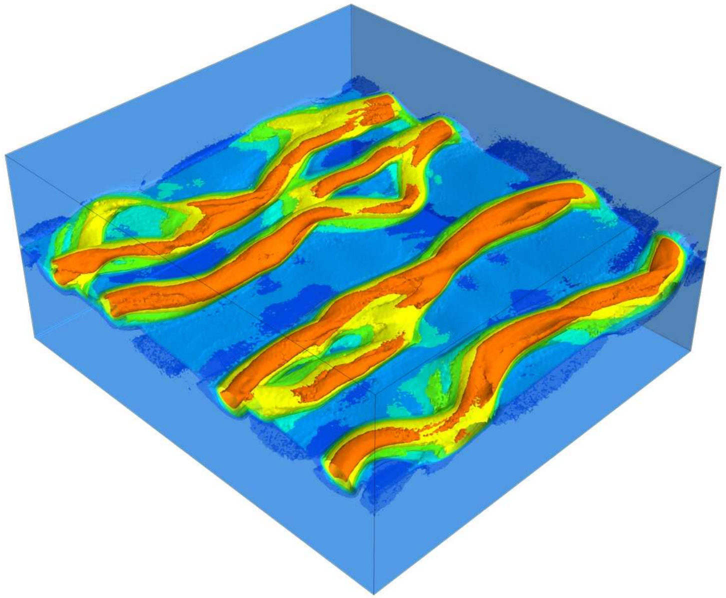

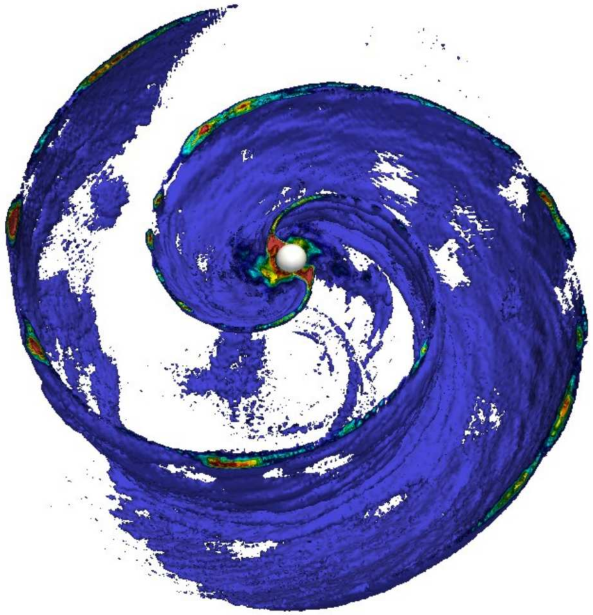

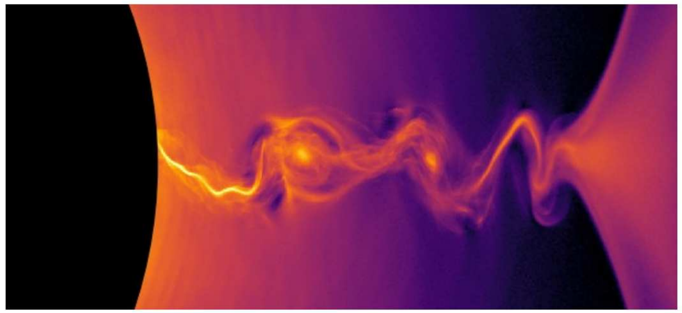

Simulating the evolution and emission of relativistic outflows, Meudon, November 28-29, 2019

Relativistic magnetic reconnection

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

Relativistic reconnection: $\sigma >\sim 1$

Relativistic Alfvén speed $V_A = c\sqrt{\frac{\sigma}{1+\sigma}} \approx c$

Dissipation of magnetic energy => relativistic particles !

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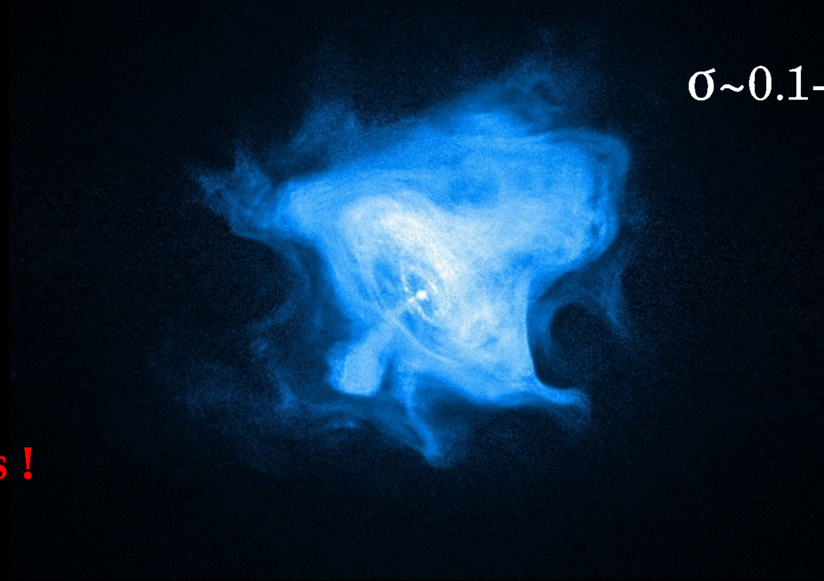
Possible astrophysical applications:

Pulsar Wind Nebulae (Crab flares)



$\sigma \sim 0.1\text{-}1$

Relativistic magnetic reconnection

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Relativistic reconnection: σ>~1

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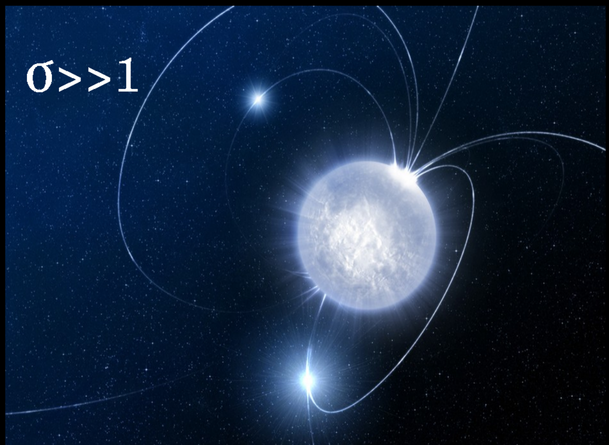
σ~0.1-1

Relativistic magnetospheres

(pulsars, magnetars, Kerr black holes)



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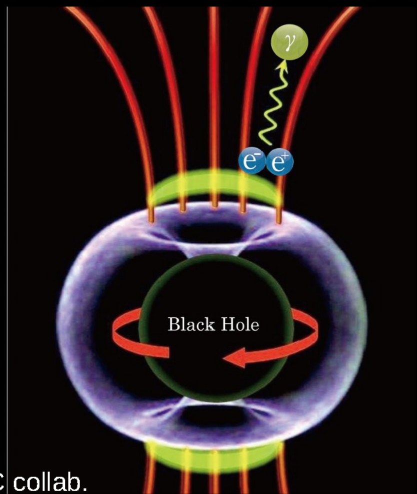

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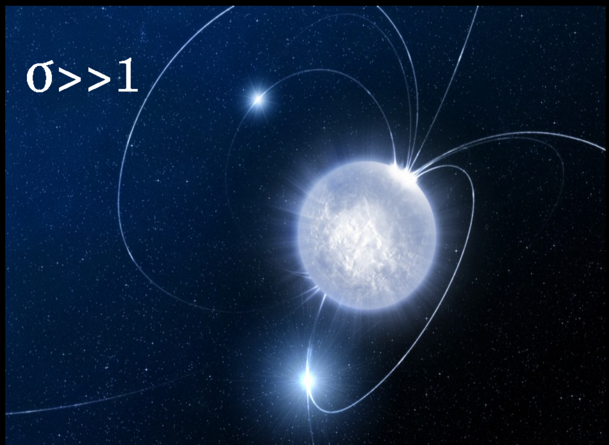

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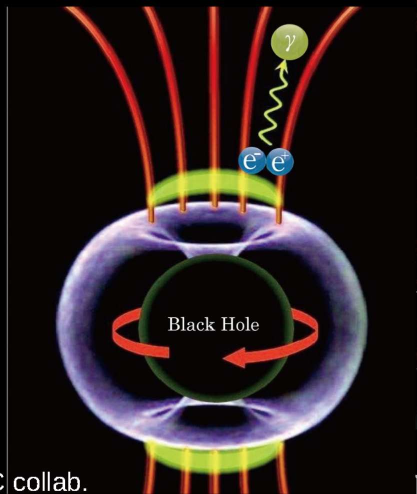

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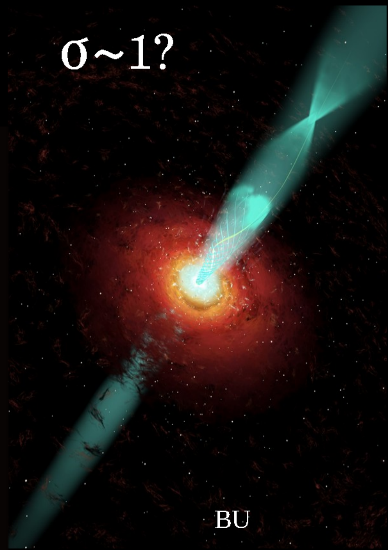
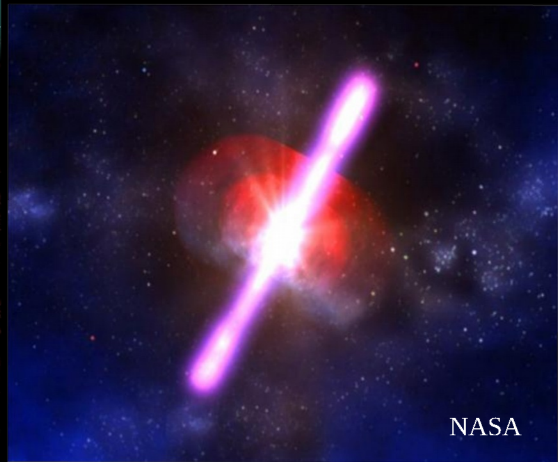
Possible astrophysical applications:

Pulsar Wind Nebulae (Crab flares)



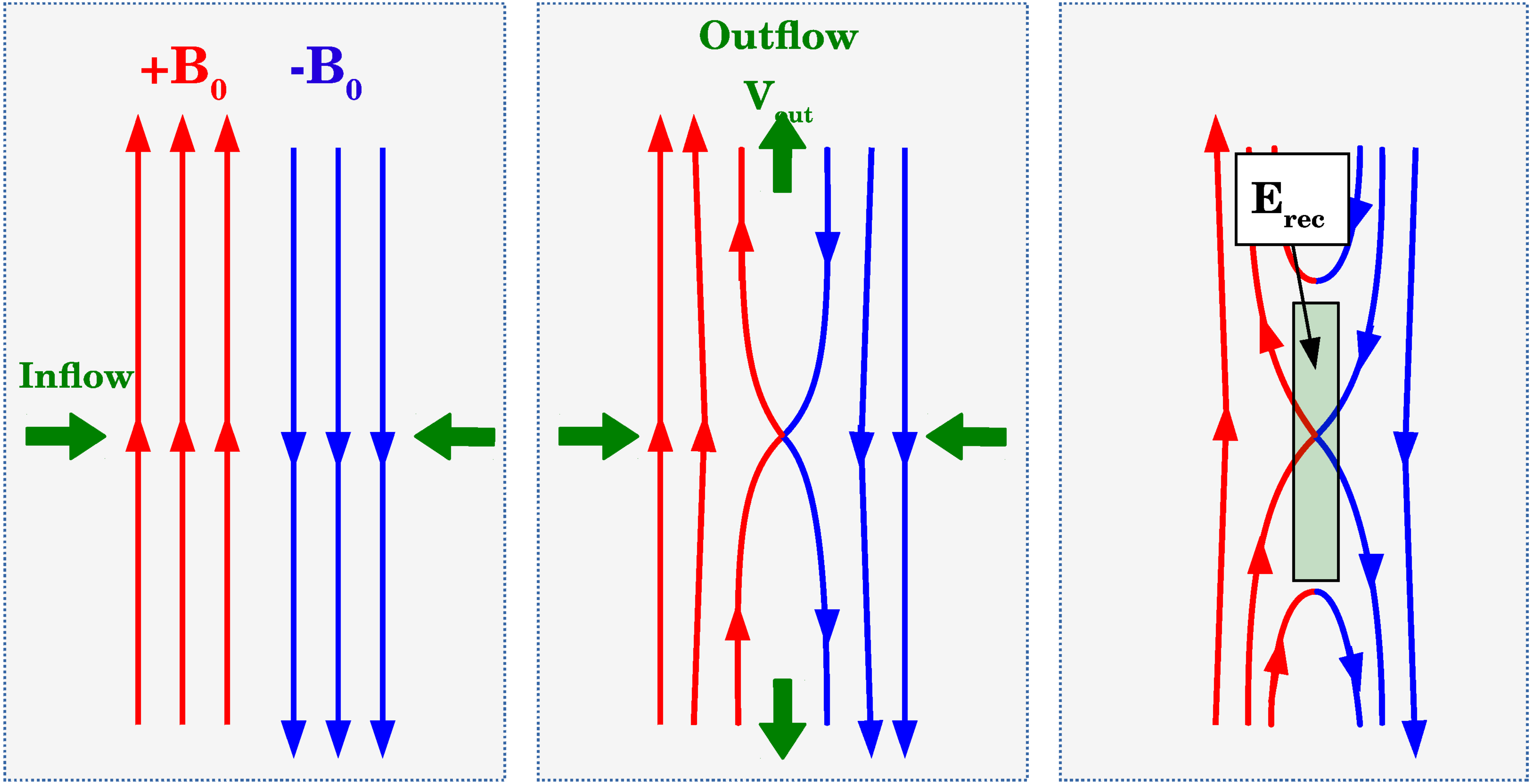
Relativistic jets



Gamma-ray burst
(prompt?)

Reconnection : A change of magnetic topology

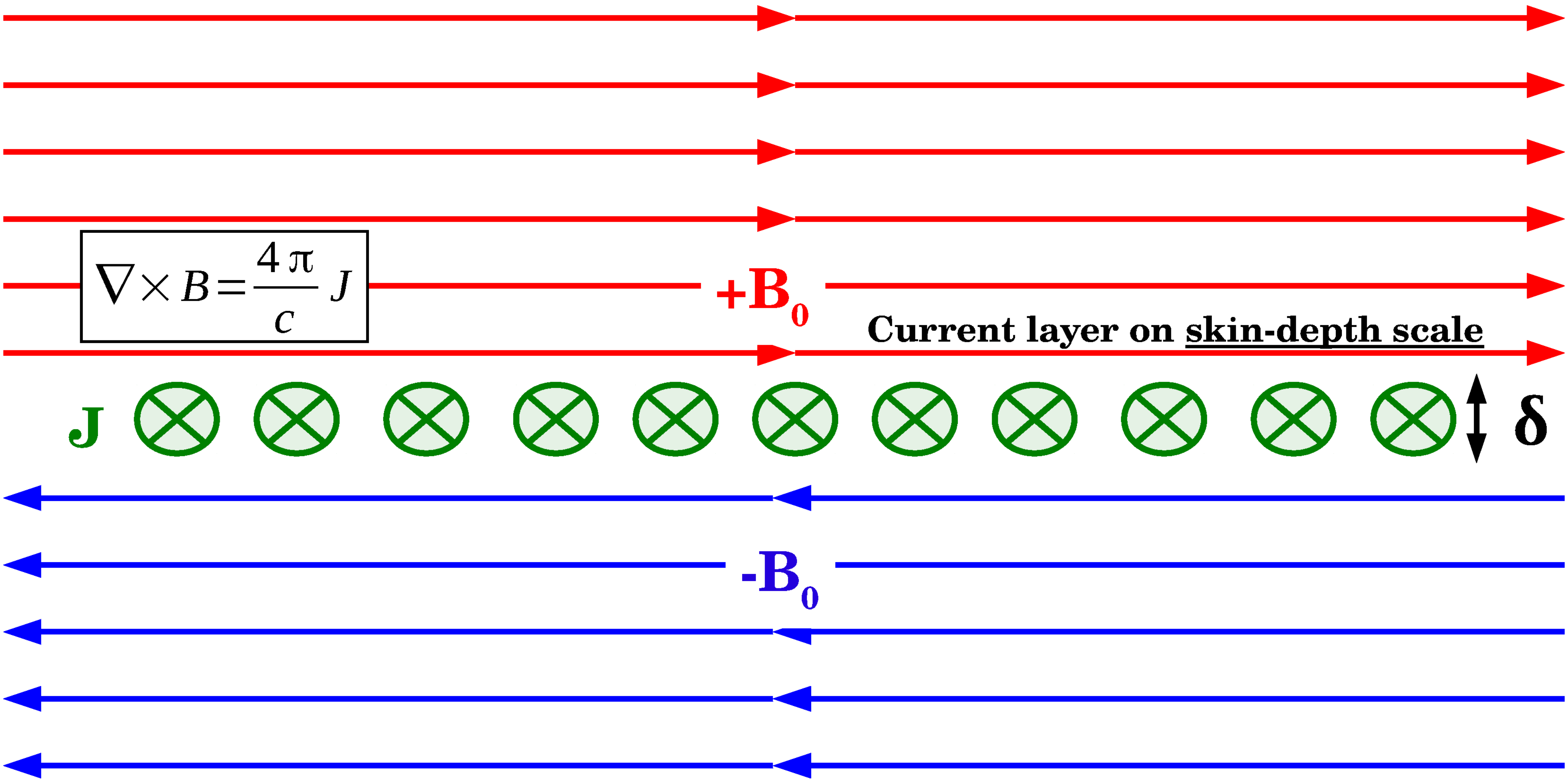
[See reviews by Zweibel & Yamada, 2009, Kagan et al. 2015]



How fast does reconnection proceed? **Reconnection rate: $\beta_{rec}=V_{in}/V_{out}$**

Magnetic energy => Plasma kinetic energy (heating+non-thermal particles)

Usual PIC setup: The Harris sheet

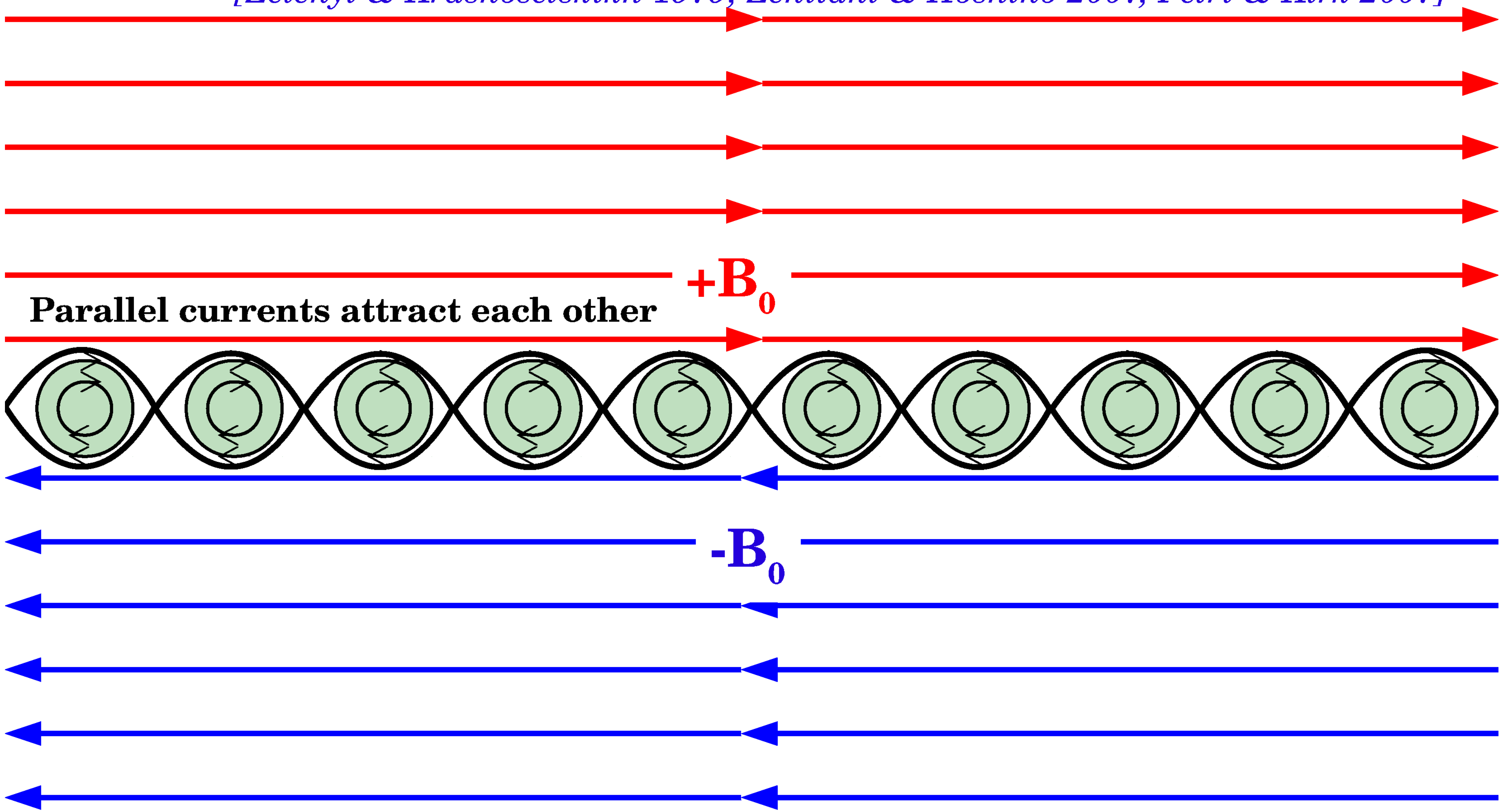


Other setup investigated :

- « **Force-Free** » current sheet (e.g., *Guo et al. 2015*)
- « **ABC** » equilibrium setup **see Journal club** (*Nalewajko+2016 ; Lyutikov+2016*)

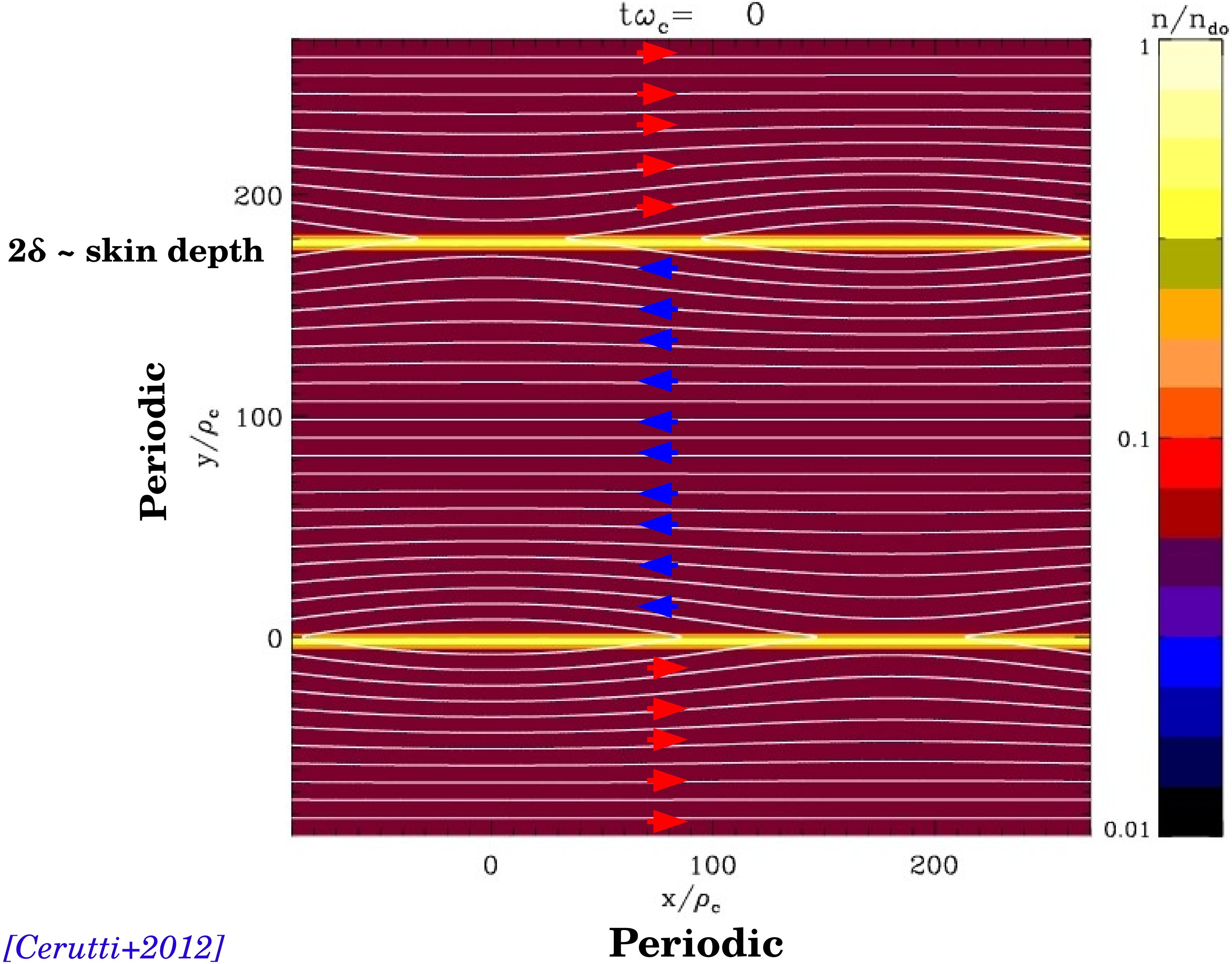
A long thin current sheet is **tearing** unstable

[Zelenyi & Krasnoselskikh 1979, Zenitani & Hoshino 2007, Pétri & Kirk 2007]



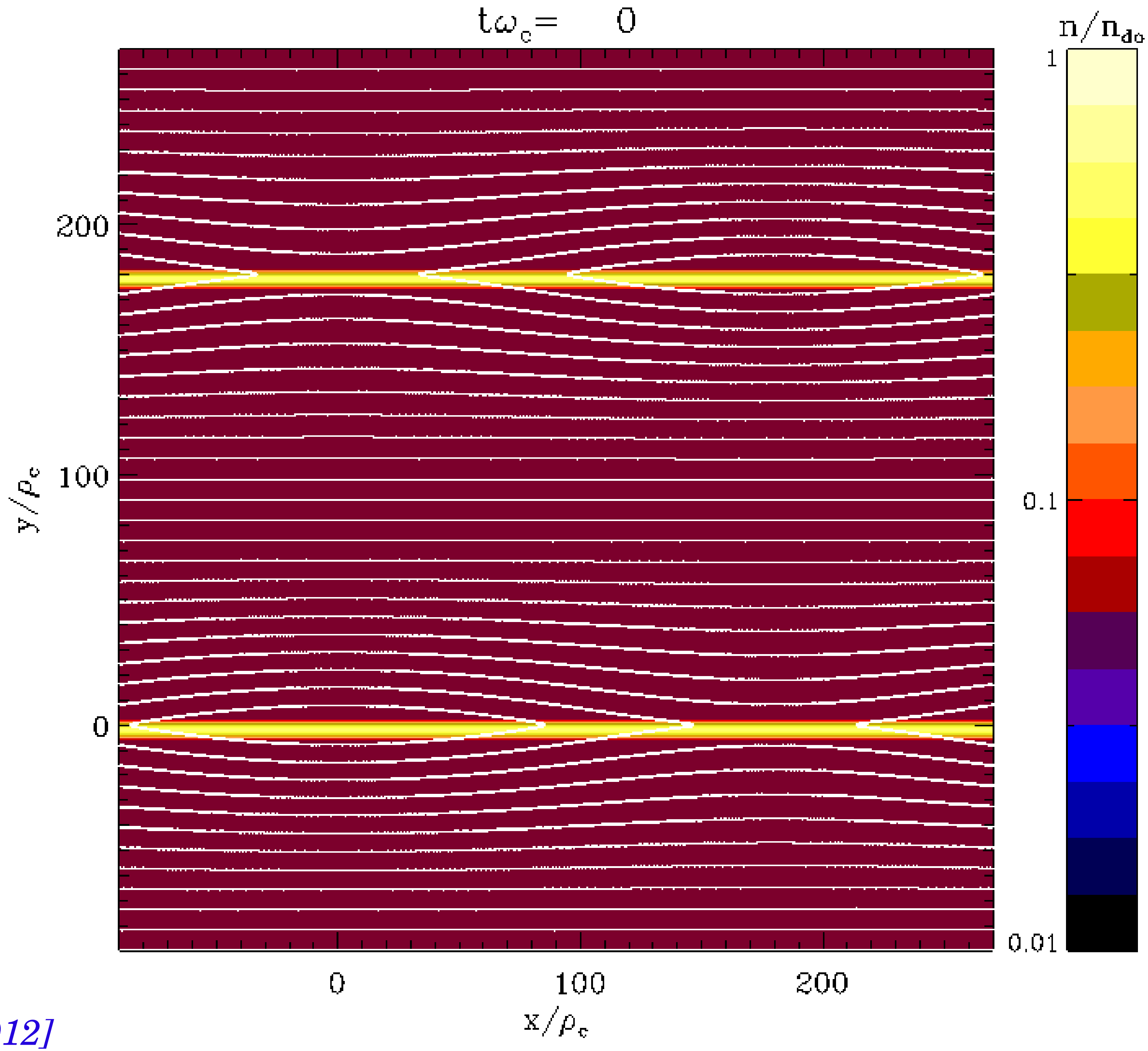
Mediate fast reconnection and non-thermal particle acceleration

2D PIC simulation



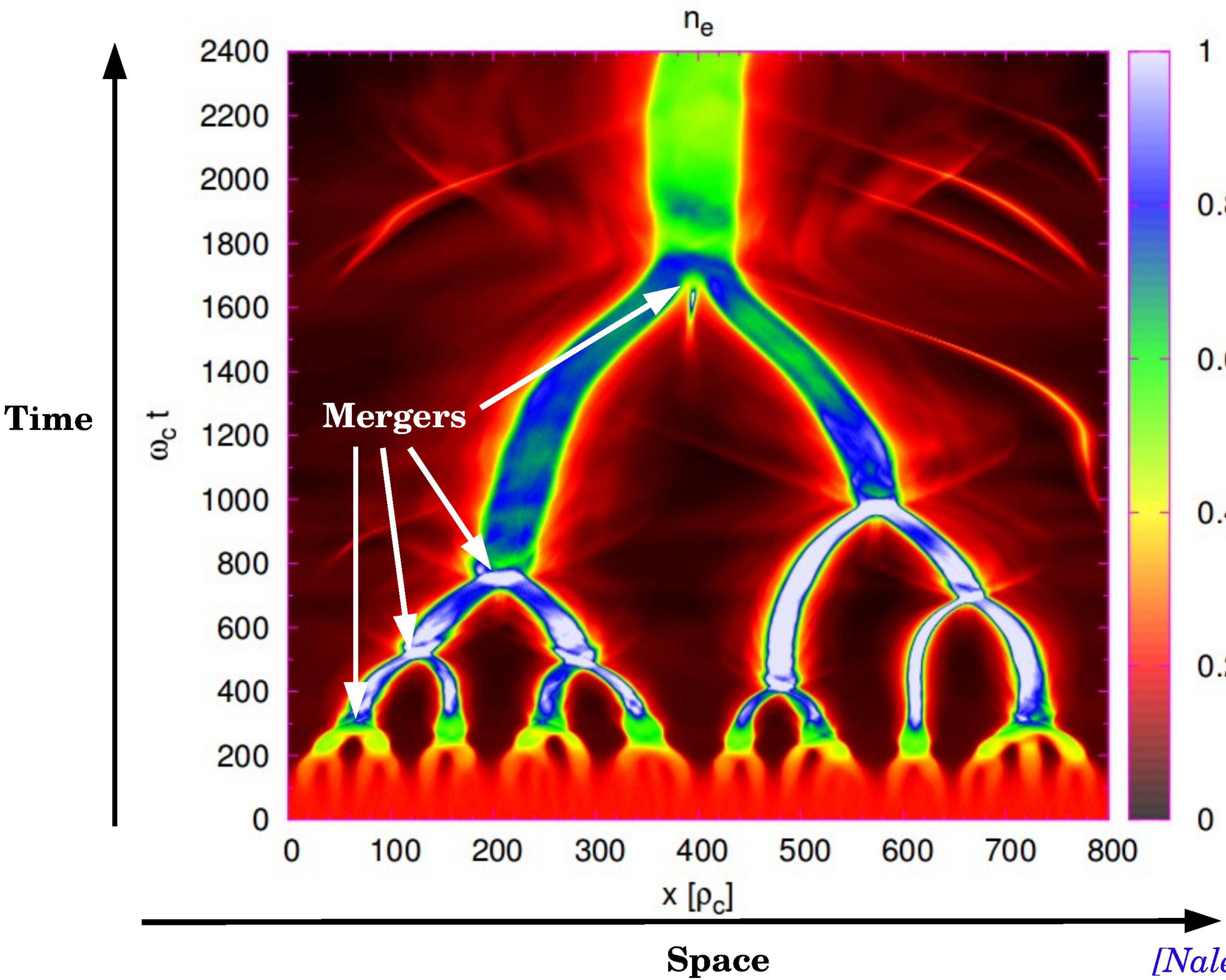
[Cerutti+2012]

2D PIC simulation



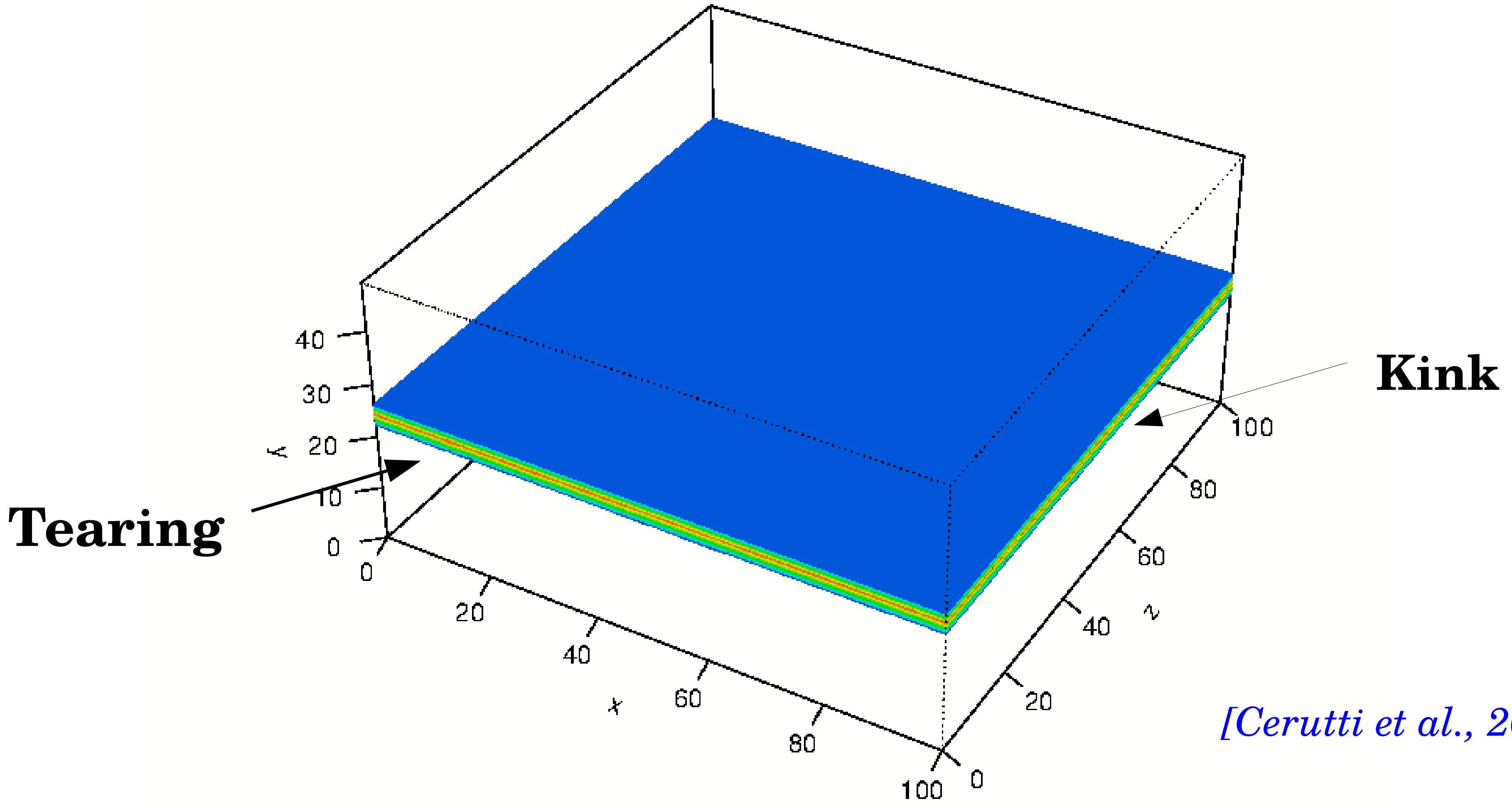
[Cerutti+2012]

Space-time diagram: a sequence of mergers



[Nalewajko+2015]

3D evolution



[Cerutti et al., 2014a]

The kink dominates the early stages of the layer...

... but the tearing controls the later evolution, so that 3D ≈ 2D !

=> Non-thermal particle acceleration still efficient in 3D without guide field

[Sironi & Spitkovsky 2014, Werner & Uzdensky 2017]

The flow velocity structure

Outflow velocity

Relativistic at high σ

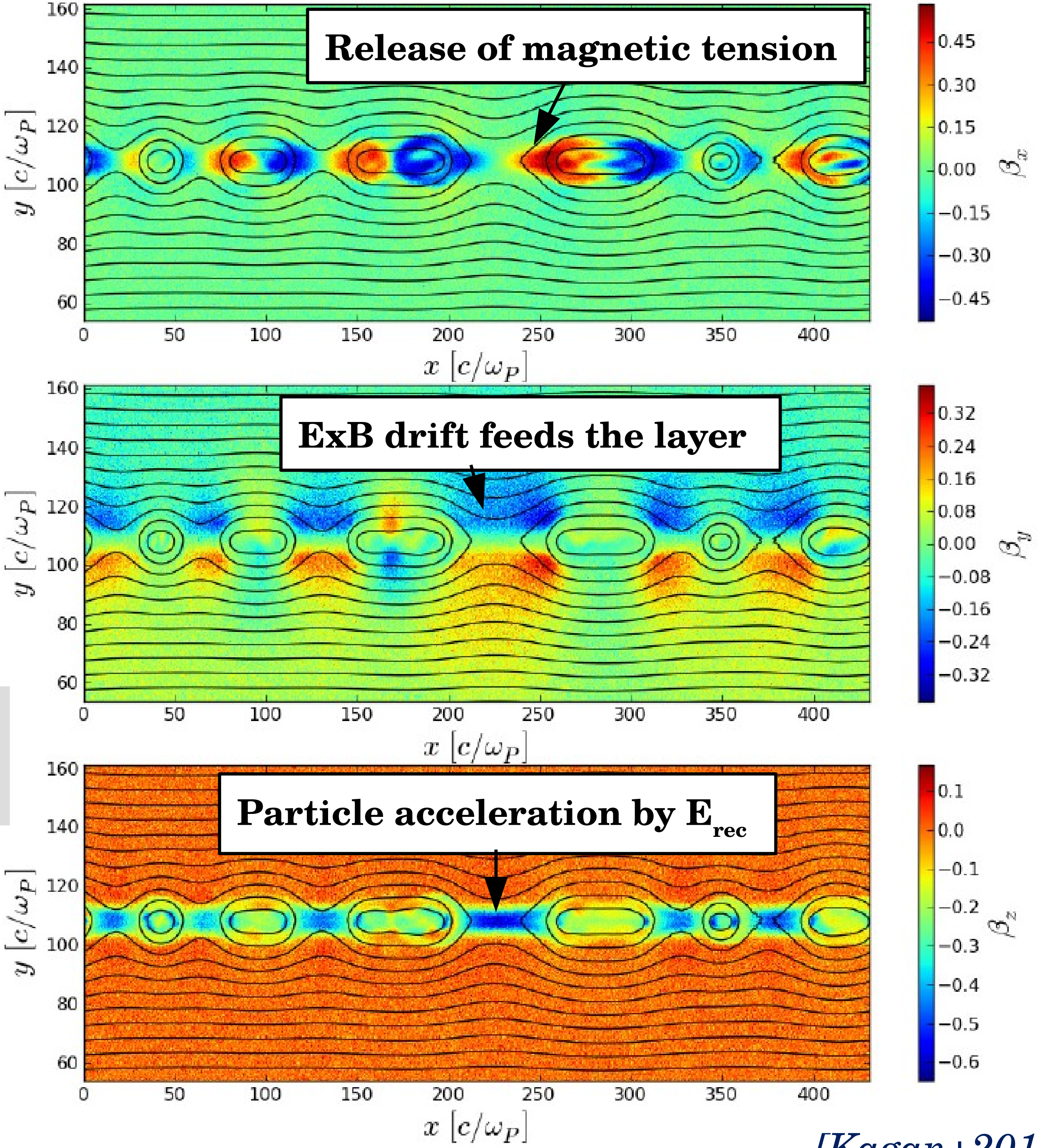
Inflow velocity

Reconnection rate **~0.1-0.2**

Relativistic reconnection is **fast**!

And **efficient**: ~50% dissipation

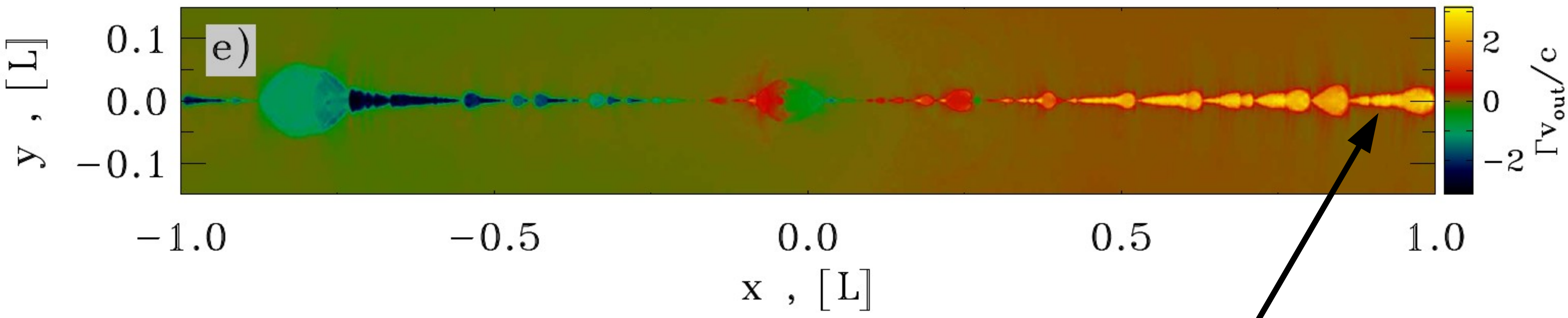
Out-of-plane velocity

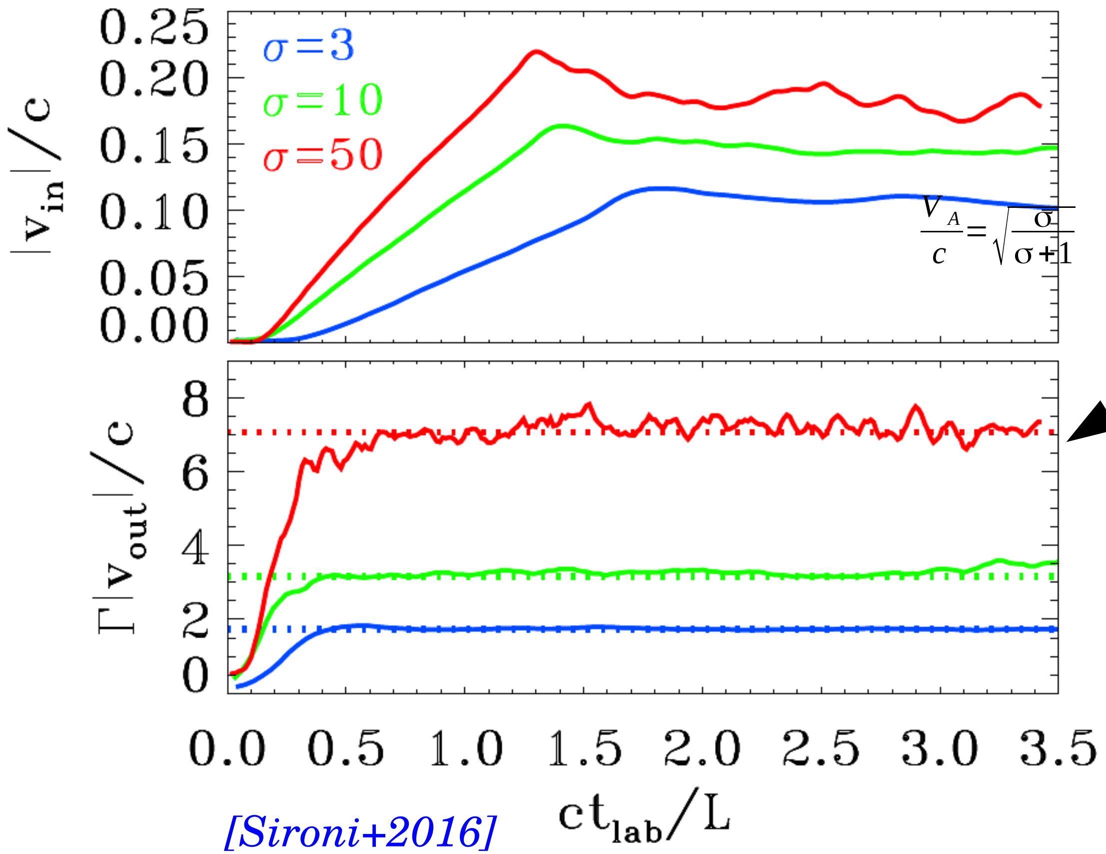


[Kagan+2015]

Relativistic bulk flows

Large box with open boundaries





[Sironi+2016]

Terminal velocity of reconnection outflow is **ultra-relativistic for σ>>1.**

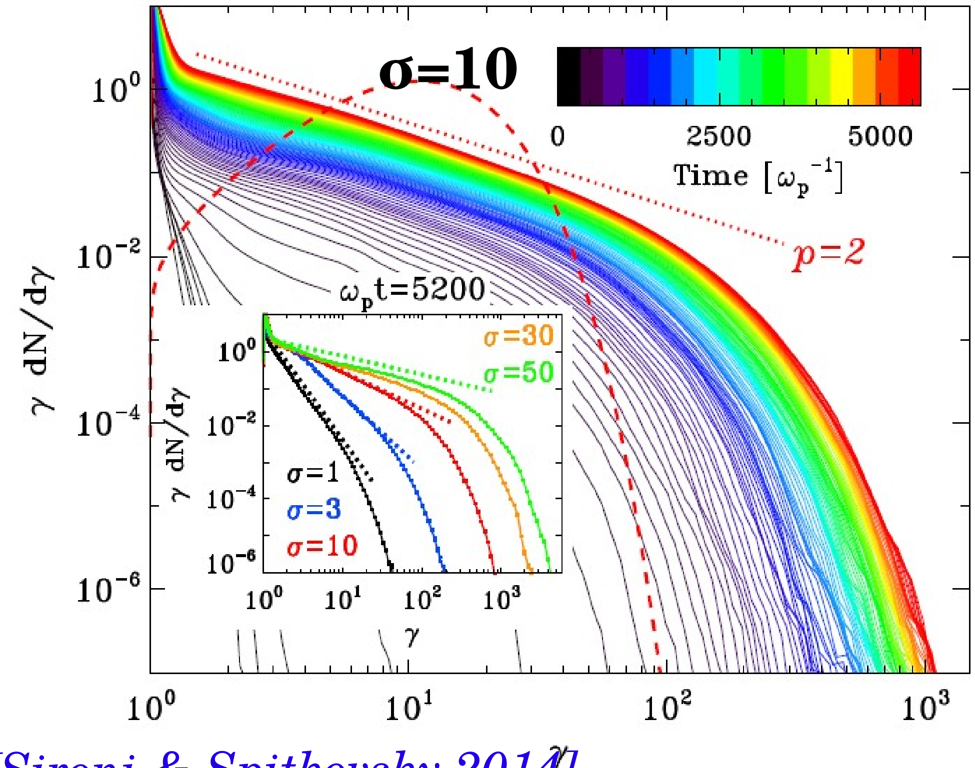
Scales as the Alfvén speed :

$$\boxed{\frac{V_A}{c} = \sqrt{\frac{\sigma}{\sigma+1}} \rightarrow \Gamma \approx \sqrt{\sigma}}$$

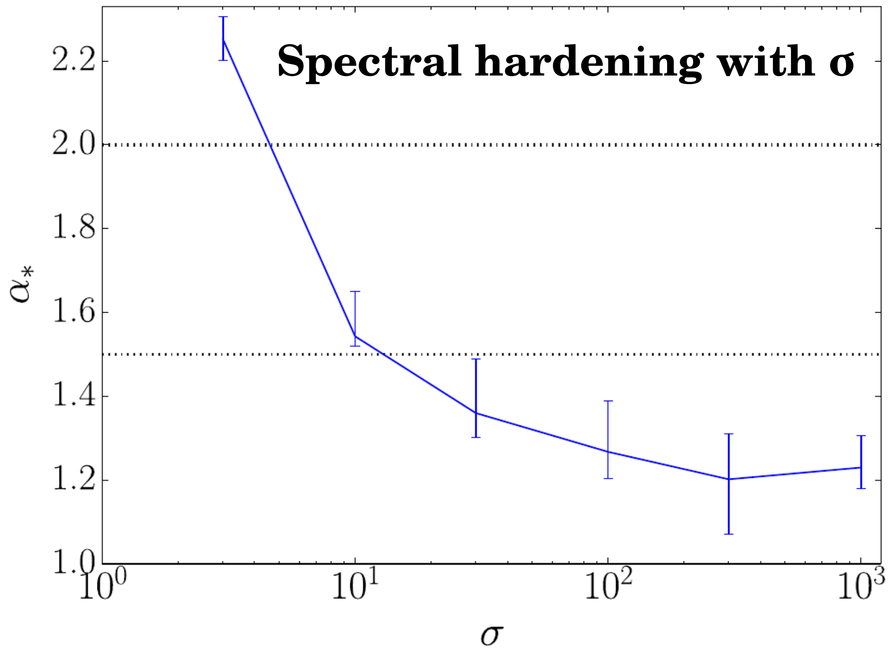
[Lyubarsky 2005]

Efficient particle acceleration

[Zenitani & Hoshino; Jaroschek et al.; Bessho & Bhattacharjee; Pétri & Lyubarsky; Sironi & Spitkovsky; Liu et al., Cerutti et al.; Kagan et al., Guo et al., Werner et al.]



[Sironi & Spitkovsky 2014]



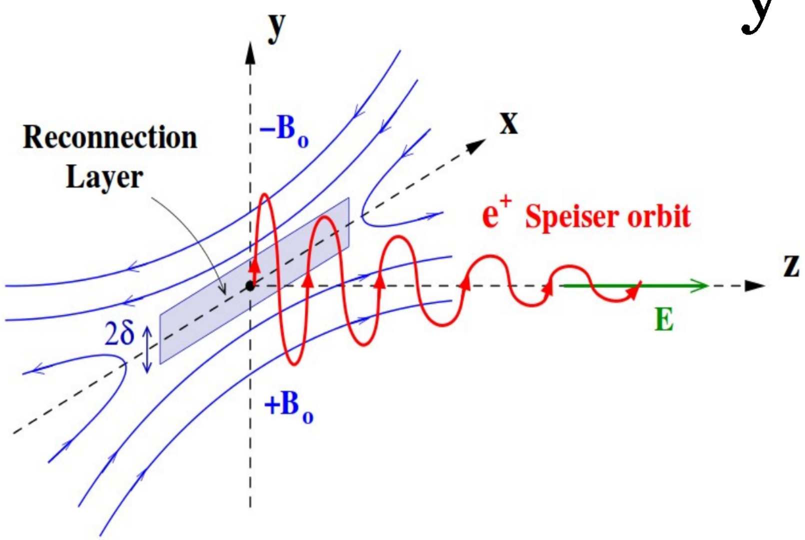
[Werner + 2016]

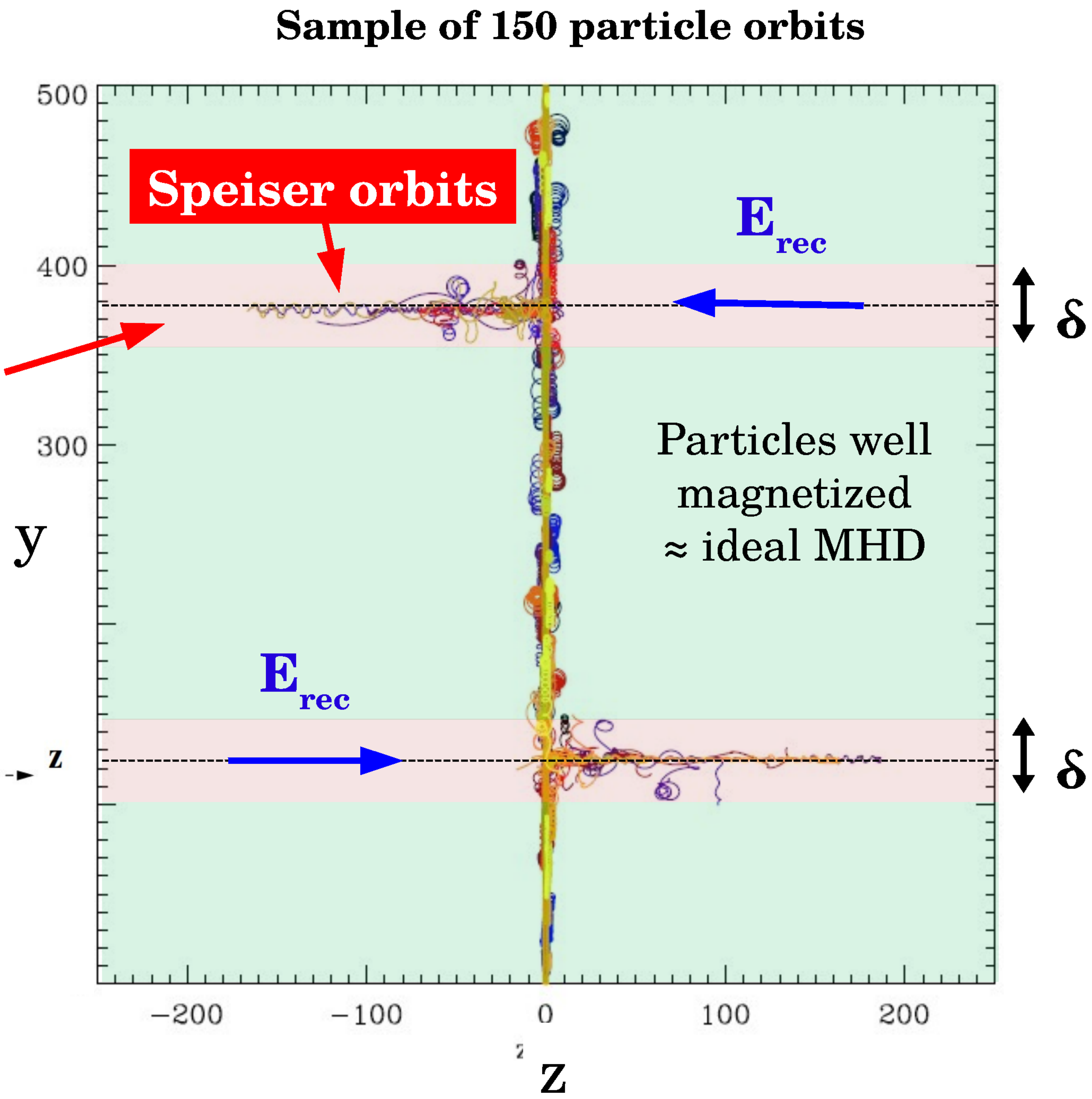
Non-thermal particle acceleration is **efficient** for **highly magnetized plasmas** (σ>>1), need for **large computational box** and **late time evolution** of the system. **Hard** distributions at large sigmas.

Physical origin of the spectra still debated and poorly understood.

Particle acceleration at X-points

Particles' beam
E>B, non-ideal MHD!
=> Linear accelerator

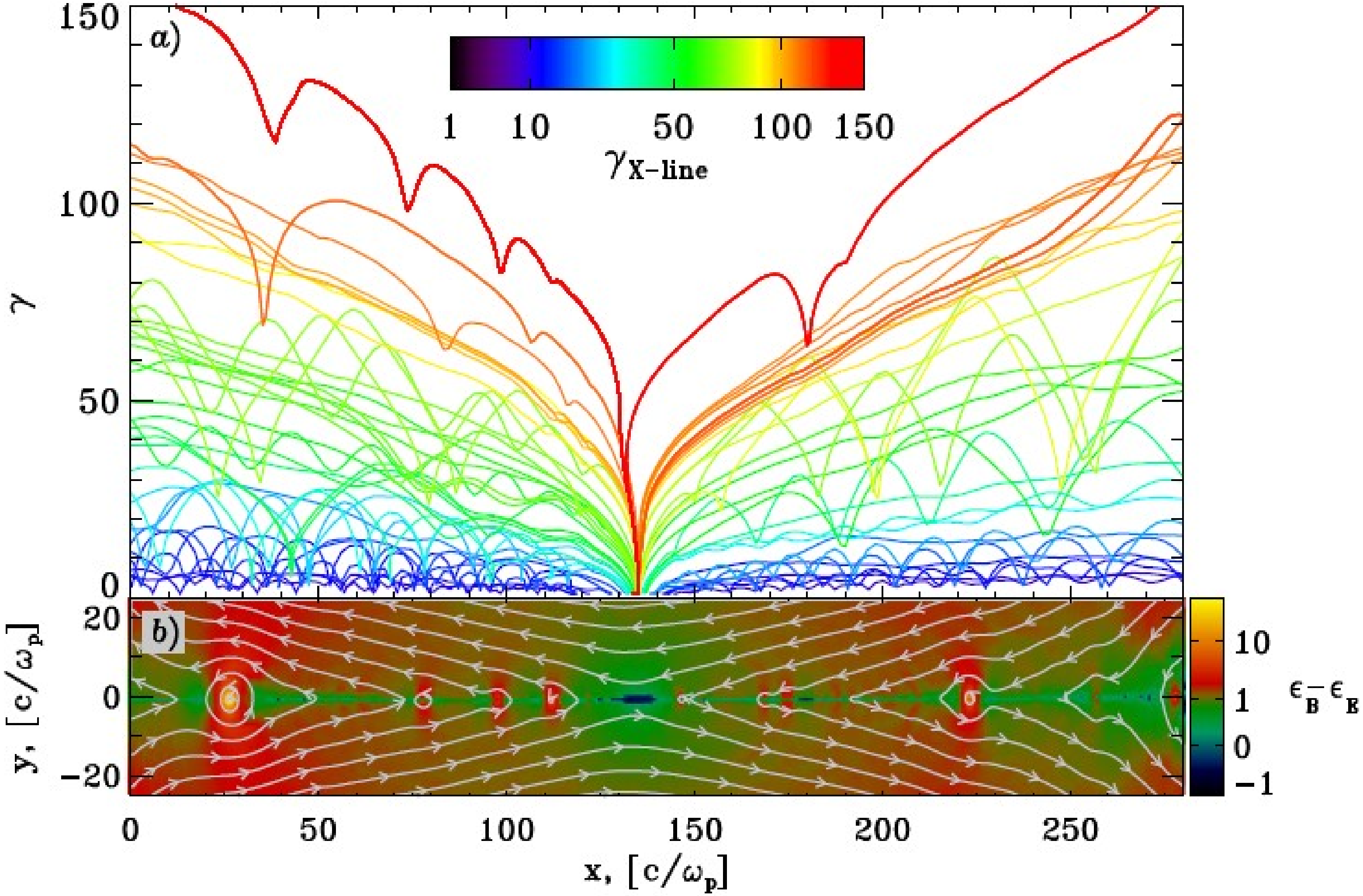




[Cerutti+2013]

Particle acceleration at X-points

[Sironi & Spitkovsky 2014]

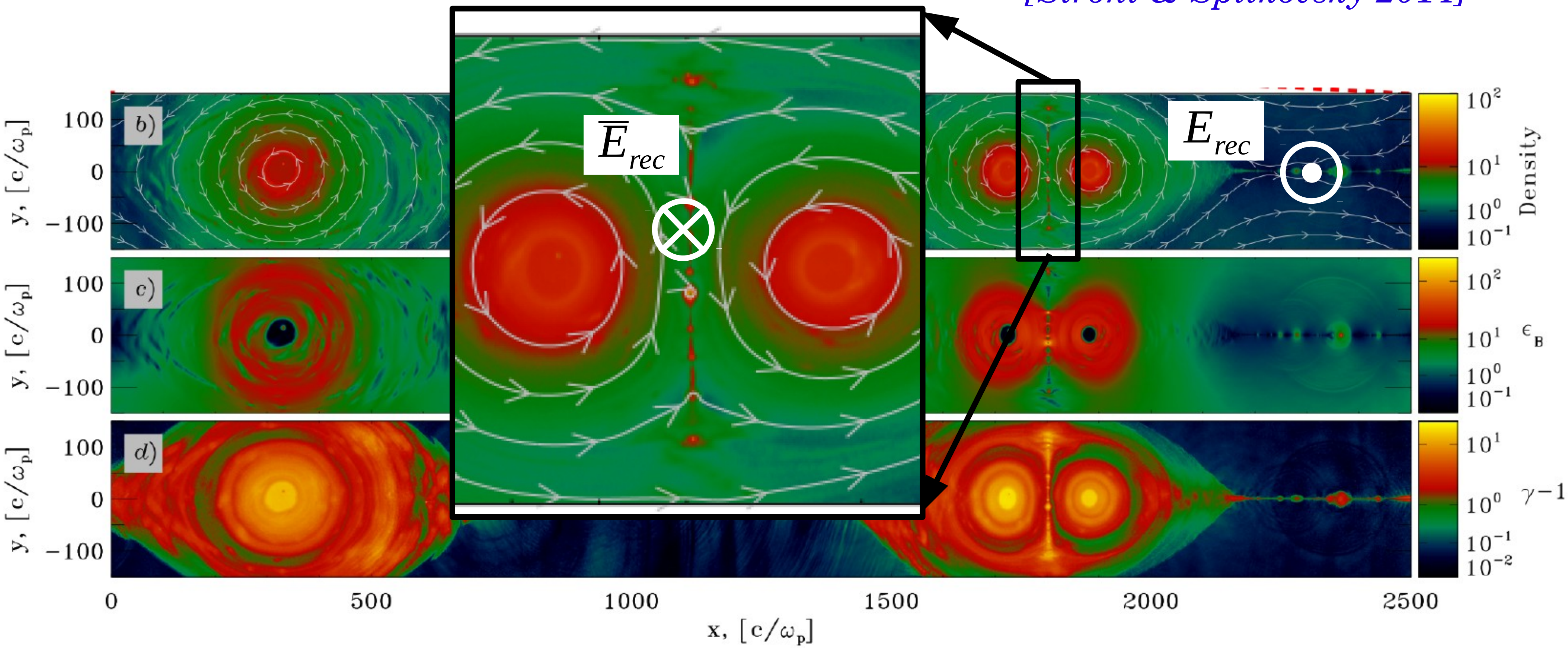


[see also Larrabee et al. 2003 ; Bessho & Bhattacharjee 2012]

The final particle **energy gain** depends how close from the **X-point** they are injected, leads to a **wide distribution** in energy.

Plasmoid mergers

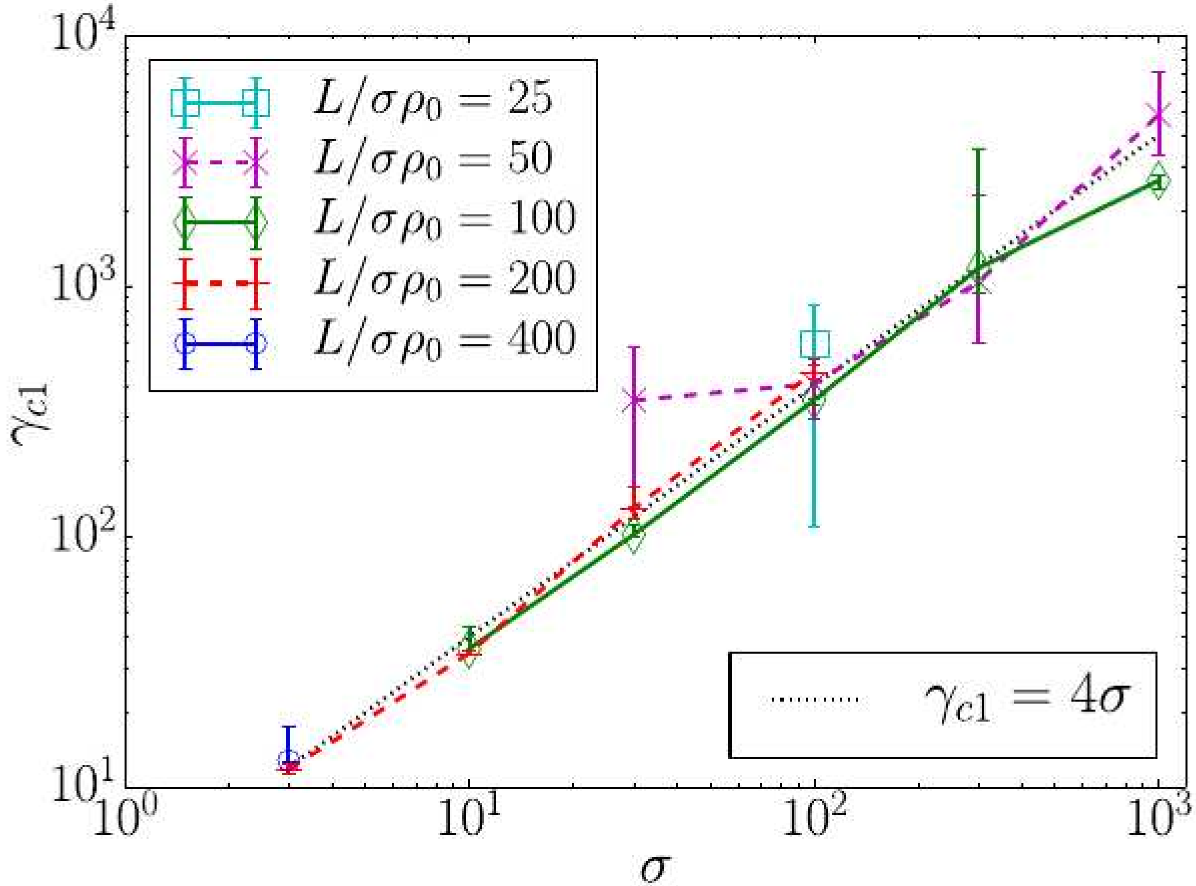
[Sironi & Spitkovsky 2014]



[See also Oka et al. 2010 (non relativistic)]

Extra particle acceleration by the "**anti-reconnection electric field"** between merging islands: increase the maximum energy.

Saturation of the maximum energy?



[Werner + 2016]

$$f(\gamma) \sim \gamma^{-\alpha} \exp(-\gamma/\gamma_{c1})$$

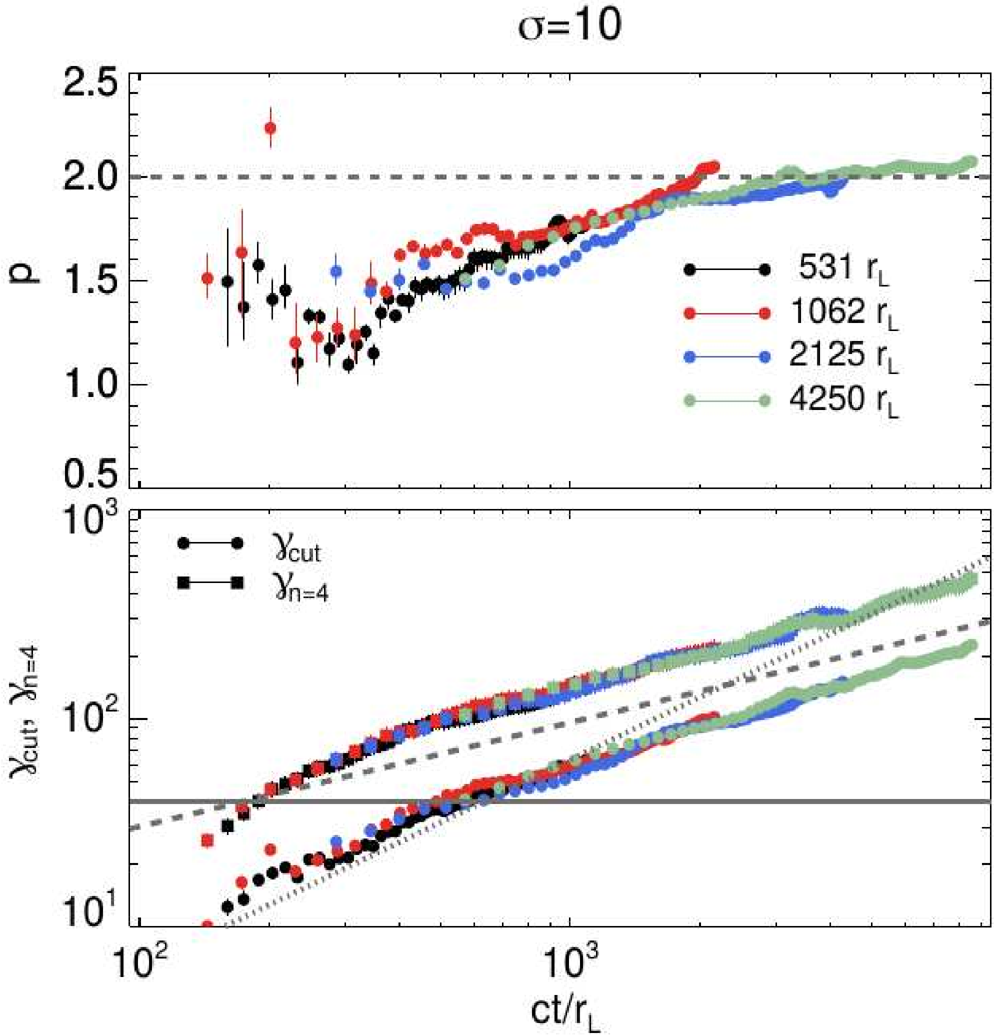
Spectral fitting shows a saturation of $\gamma_{max} \sim 4\sigma$!

Limits set by energetic constraints because hard spectra (<2)

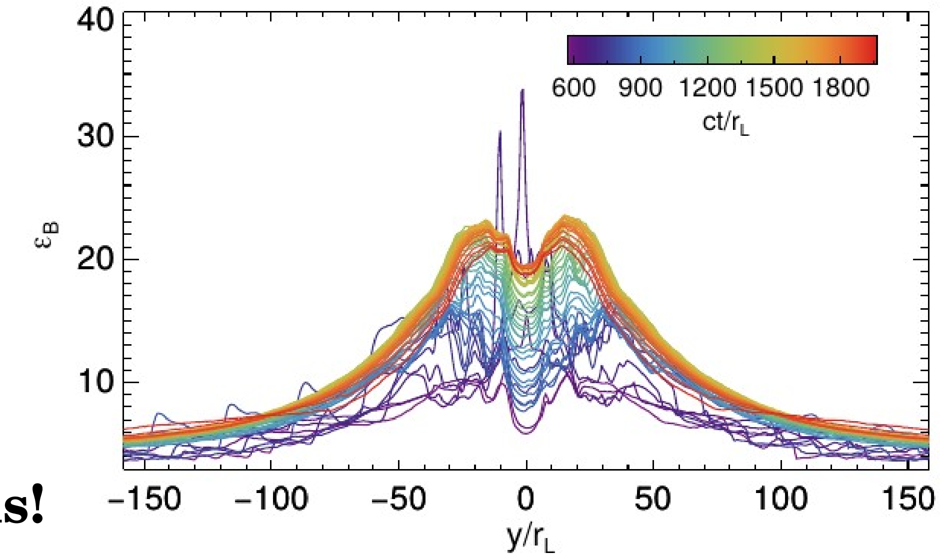
=> Bad news for astrophysical applications where σ rarely very large

Saturation of the maximum energy?

[Petropoulou & Sironi + 2018]



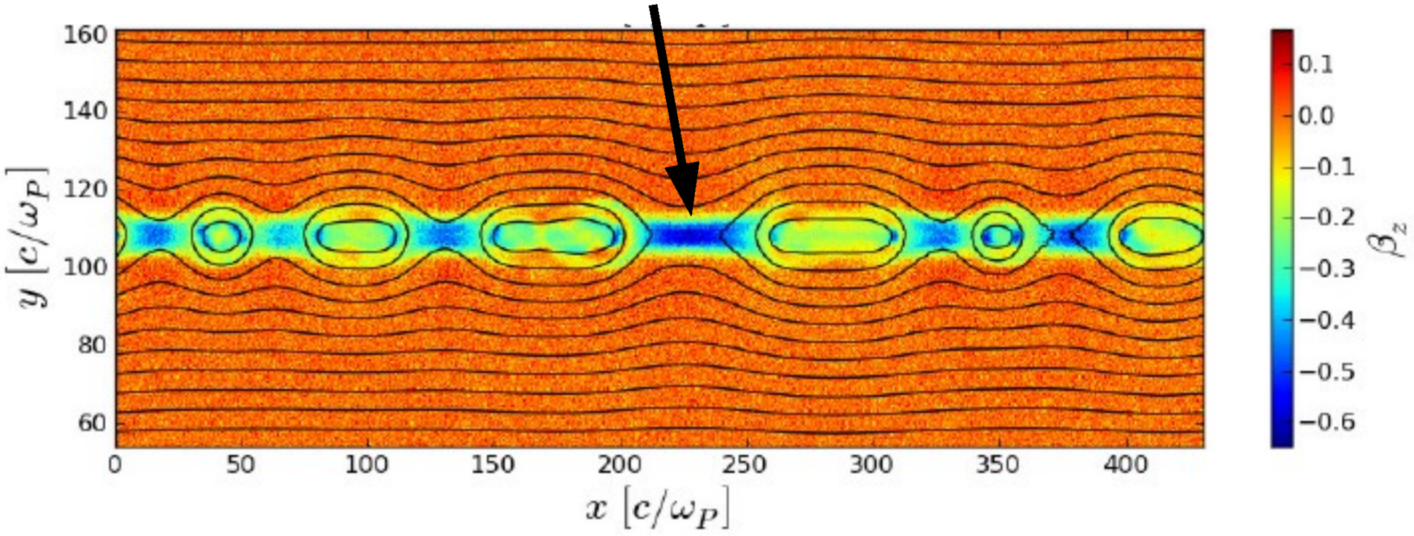
- Spectral **steepening** with time
- Maximum energy first grows as: $\boxed{\gamma_{max} \propto t}$, and then slowly as $\boxed{\gamma_{max} \propto t^{1/2}}$
- Slow energy gain within large magnetic islands where B field increases with time



Good news for astrophysical applications!

Are PIC simulations essential after all?

… At X-points yes! Fast acceleration by $E_{//}$

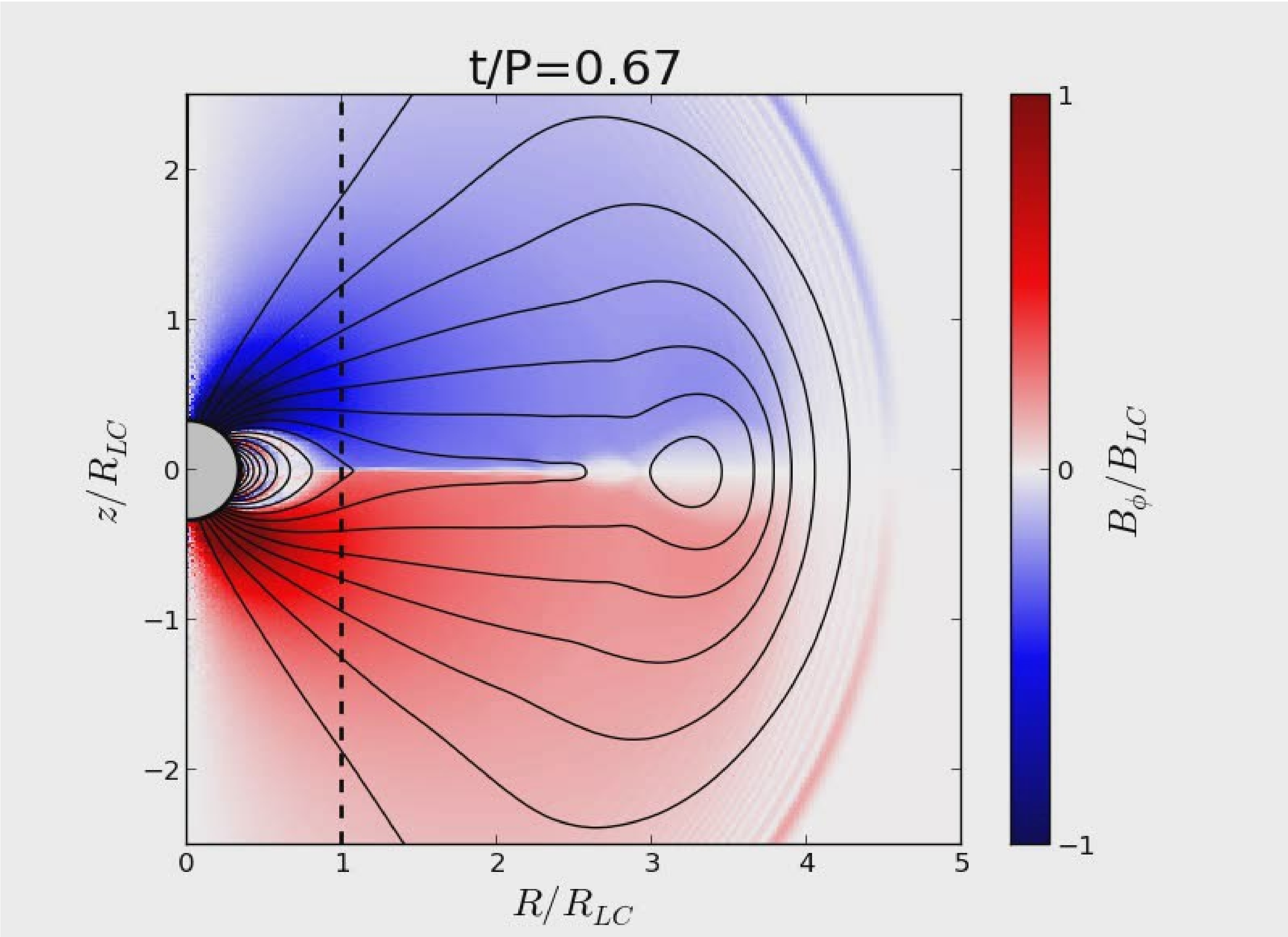


… but if max energy dominated by slow MHD process, X-point acceleration only injection mechanism.

=> Ironically, my feeling is that future progress could be done with resistive MHD simulations with test particles with a larger scale separation.

[see e.g., Mignone et al. 2018]

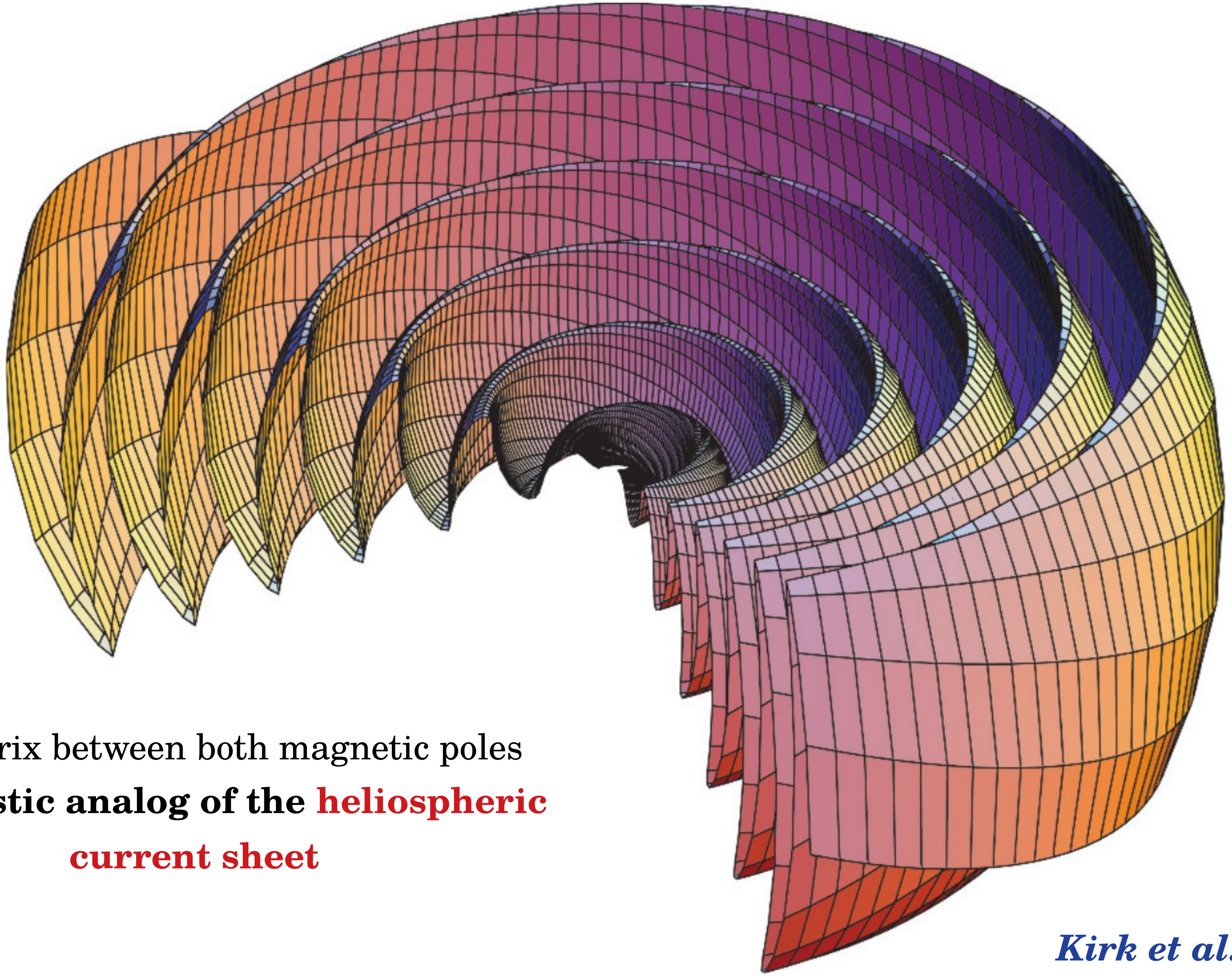
Reconnection in pulsar magnetospheres



[Cerutti+2015]

Equatorial current sheet of an inclined rotator

Bogovalov 1999



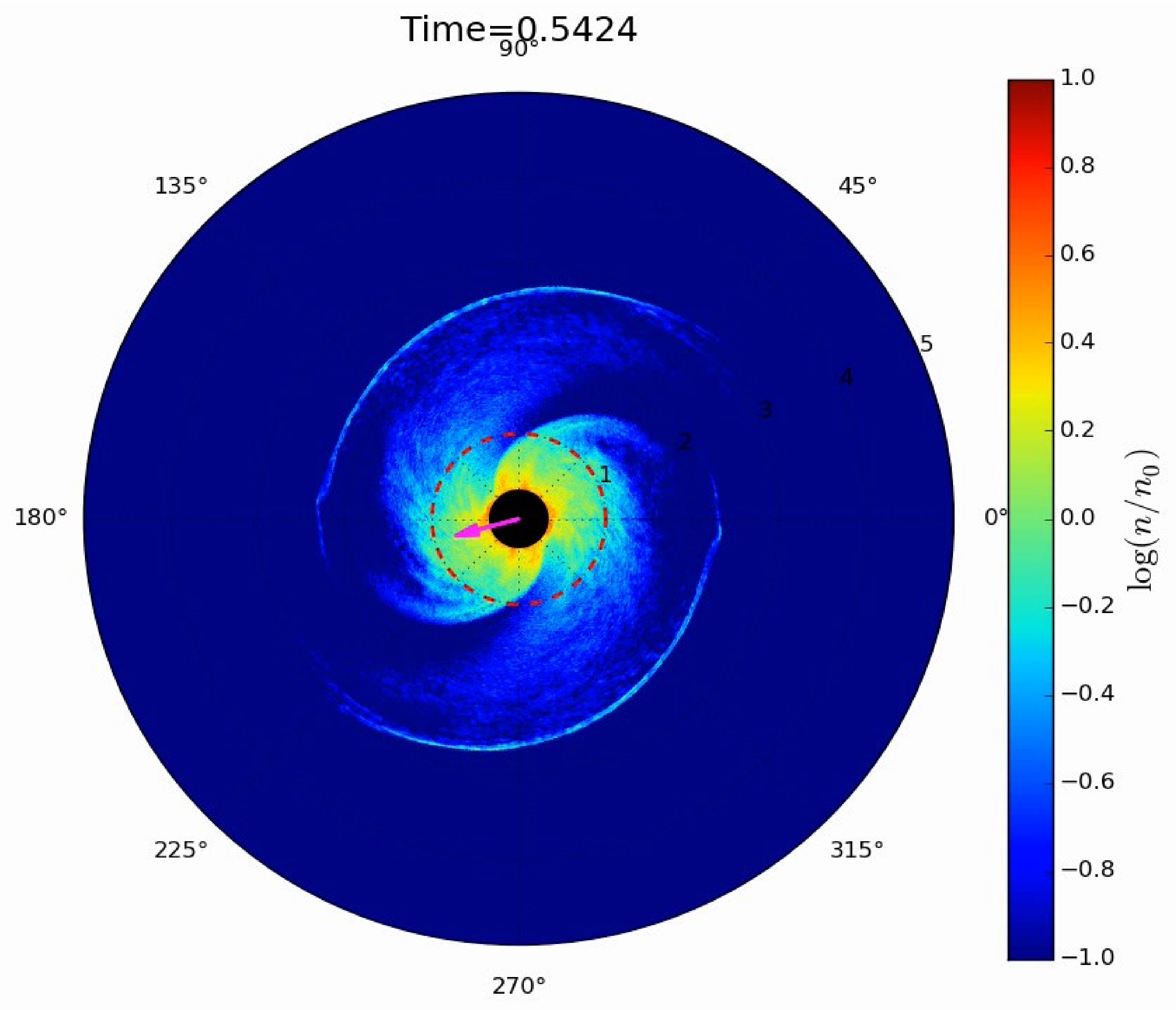
Separatrix between both magnetic poles

Relativistic analog of the heliospheric current sheet

Kirk et al. 2009

View in the equatorial plane

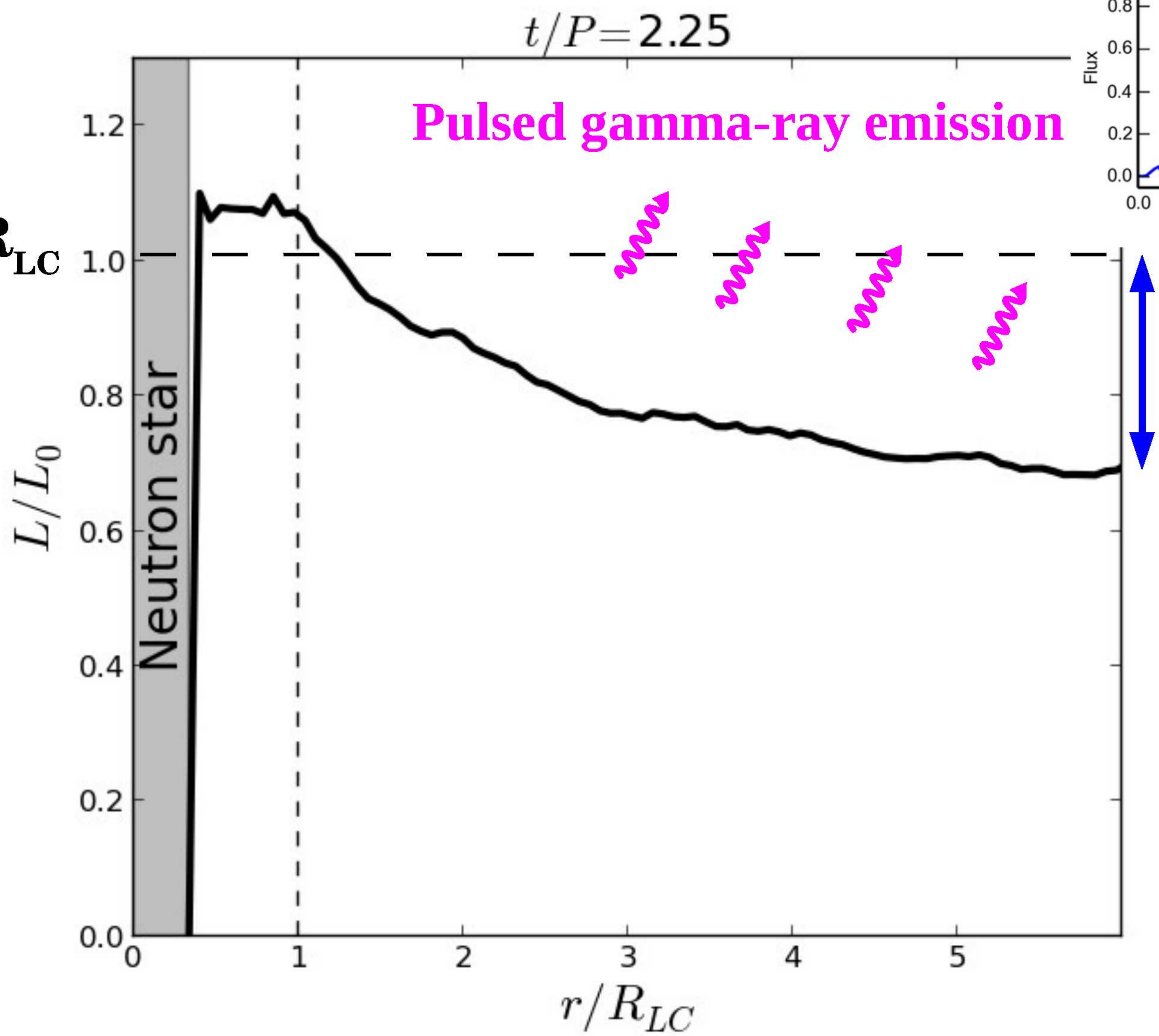
Cerutti & Philippov 2017

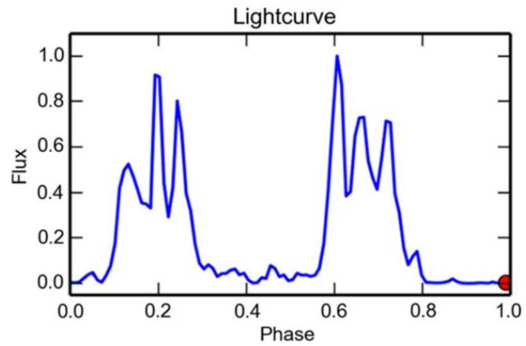


Pulsar spin down and dissipation

Force-free

$L_0 = cB_*^2 R_*^6 / 4R_{LC}$





~30% drop

[Cerutti+2015]

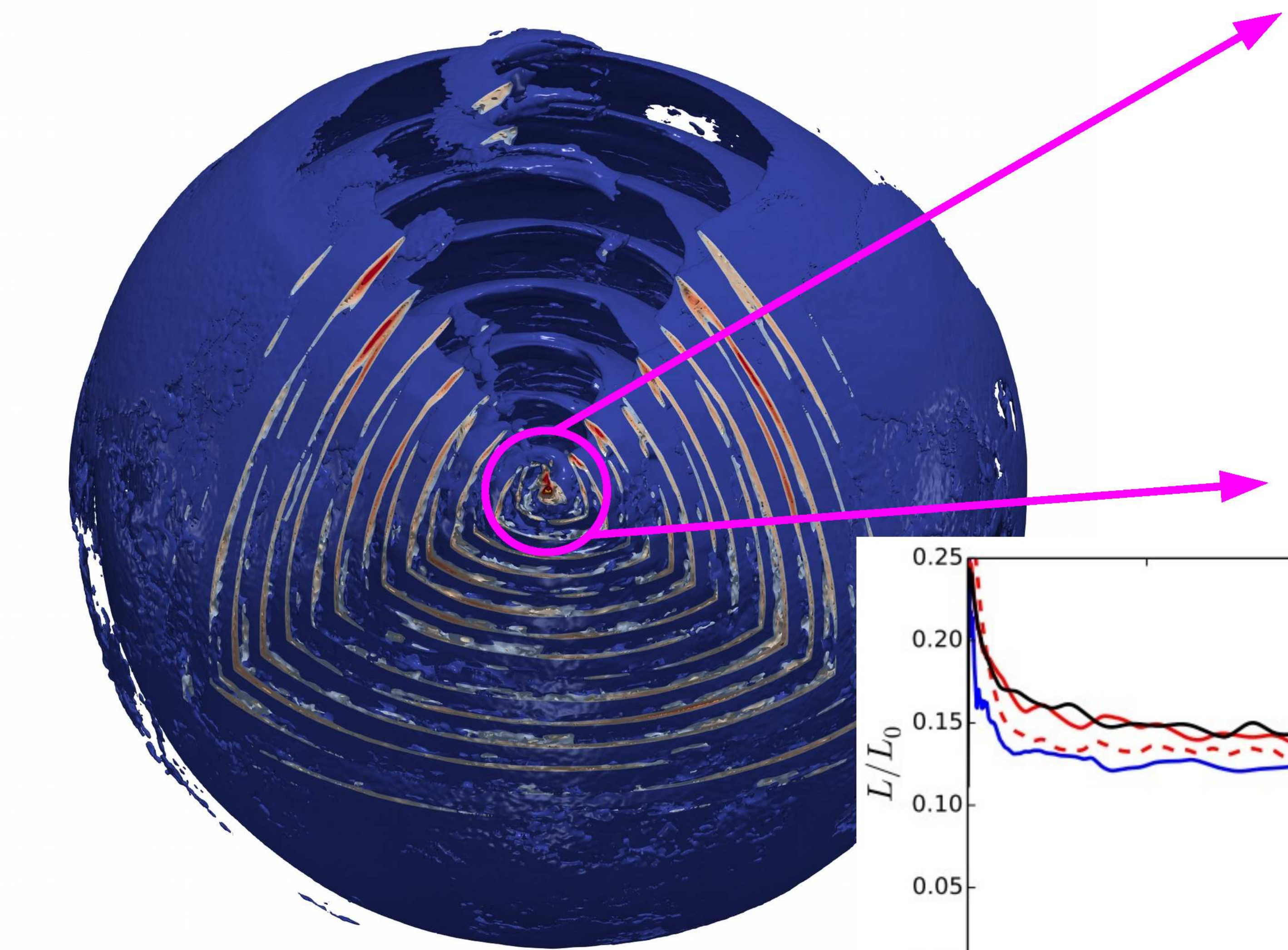
Significant dissipation within a few R_{LC}!

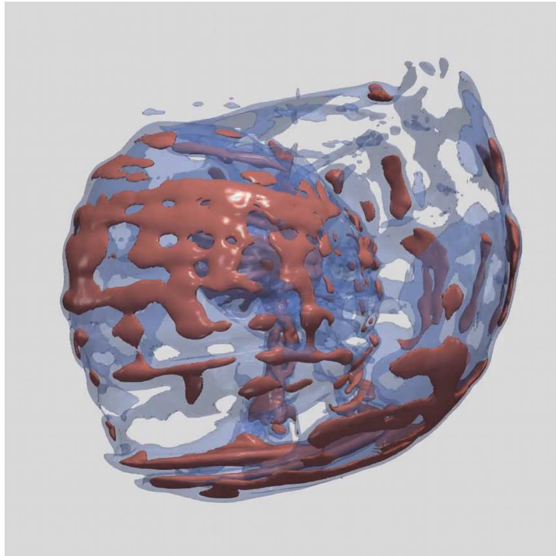
=> Energy transferred to energetic particles and radiation!

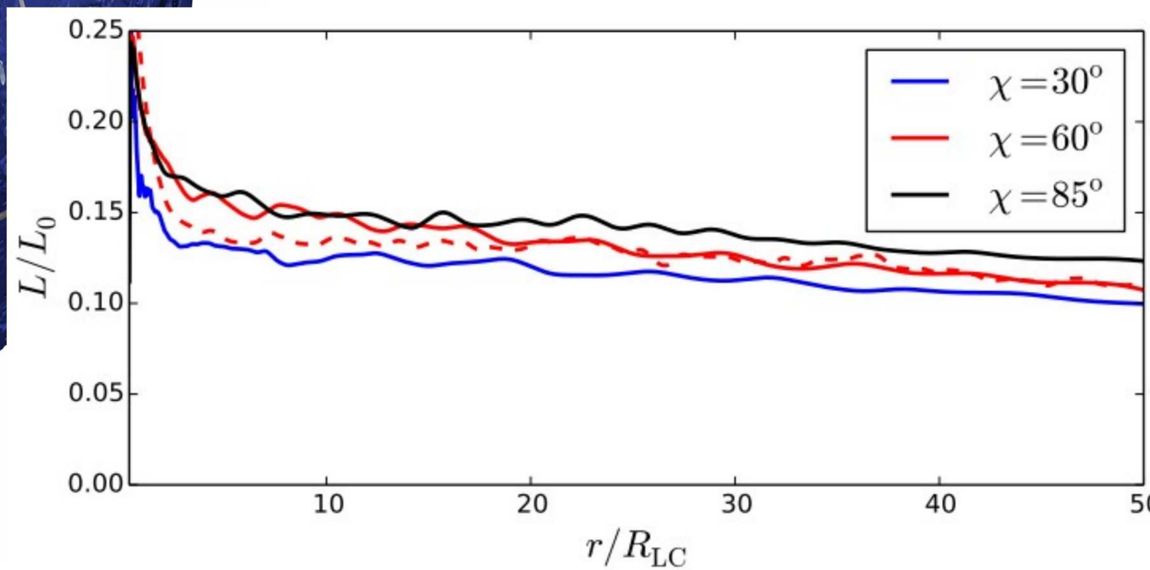
The FROMTON project

Magnetic reconnection and particle acceleration proceeds in the wind

=> Complete dissipation before the termination shock



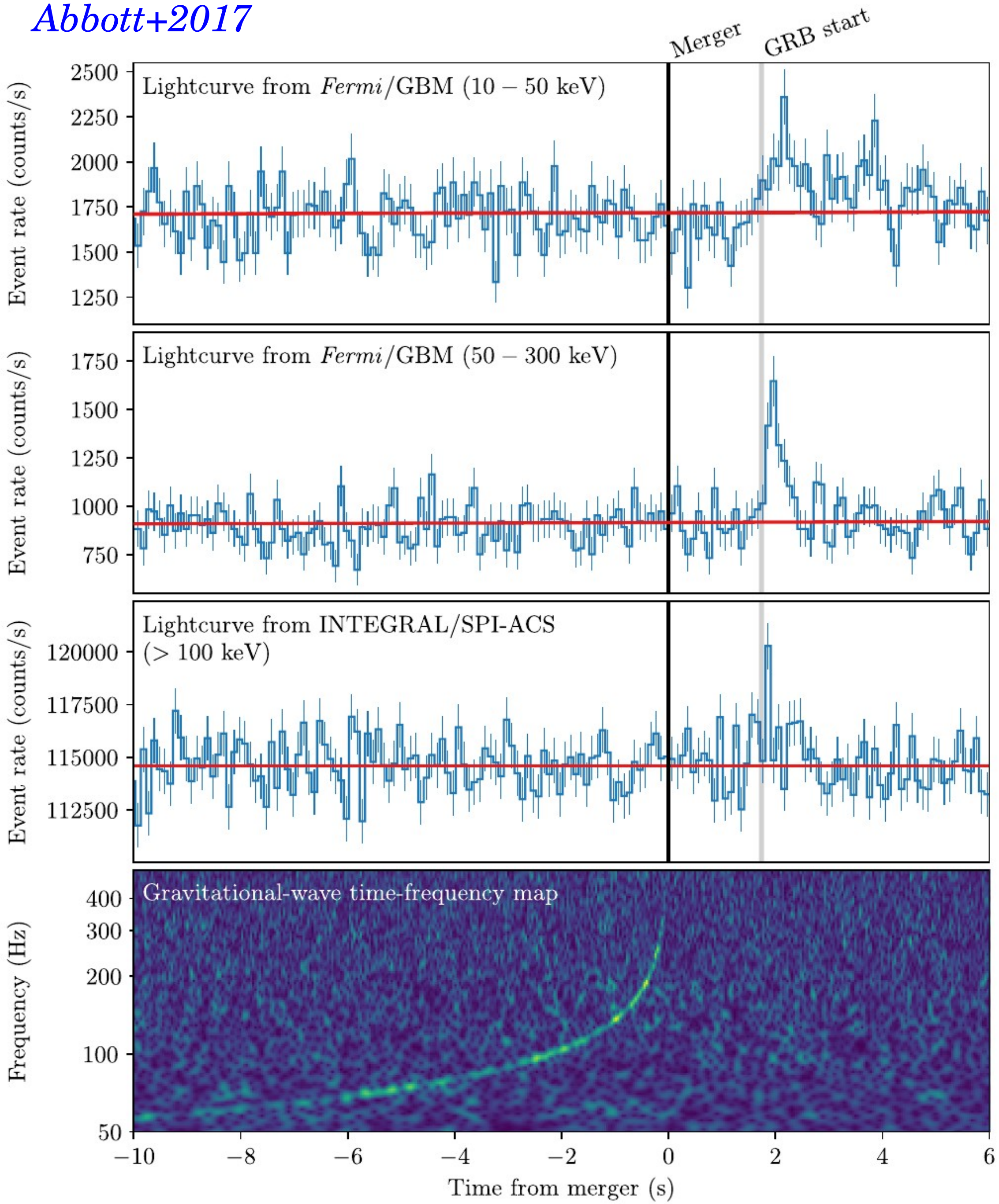


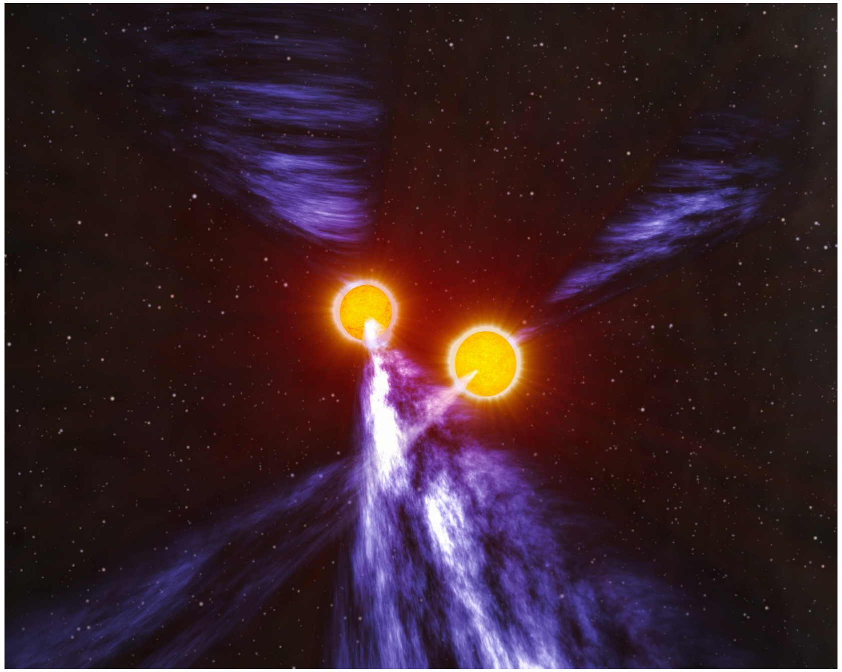


[Cerutti, Philippov & Dubus in prep]

Merging binary pulsar

Abbott+2017

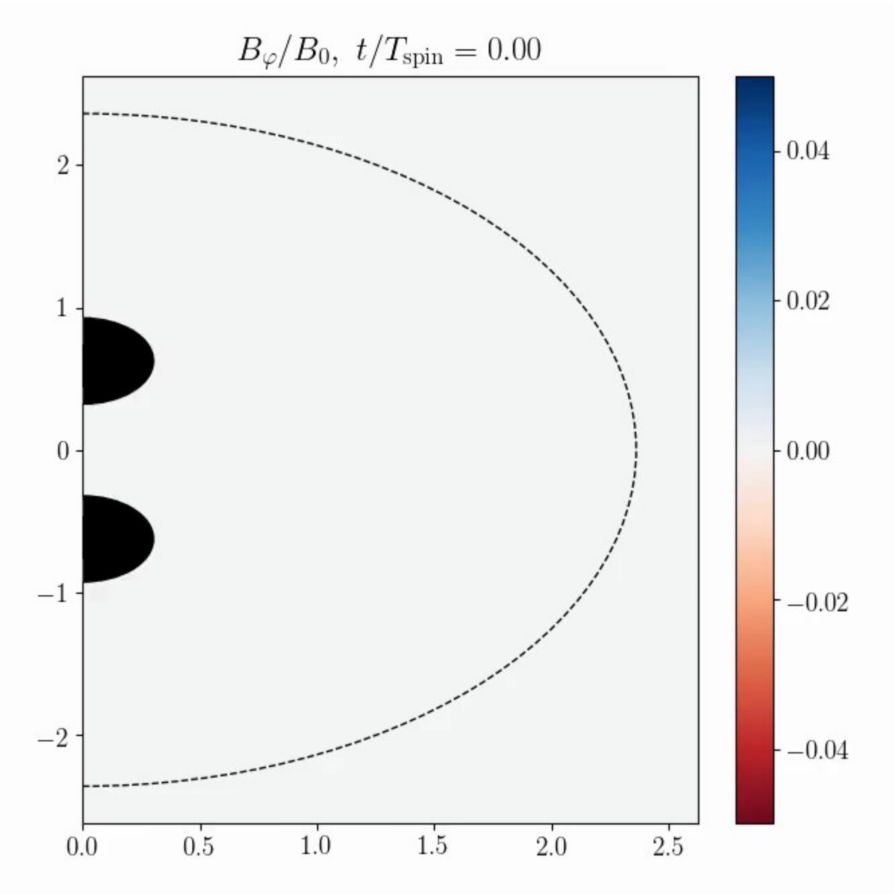




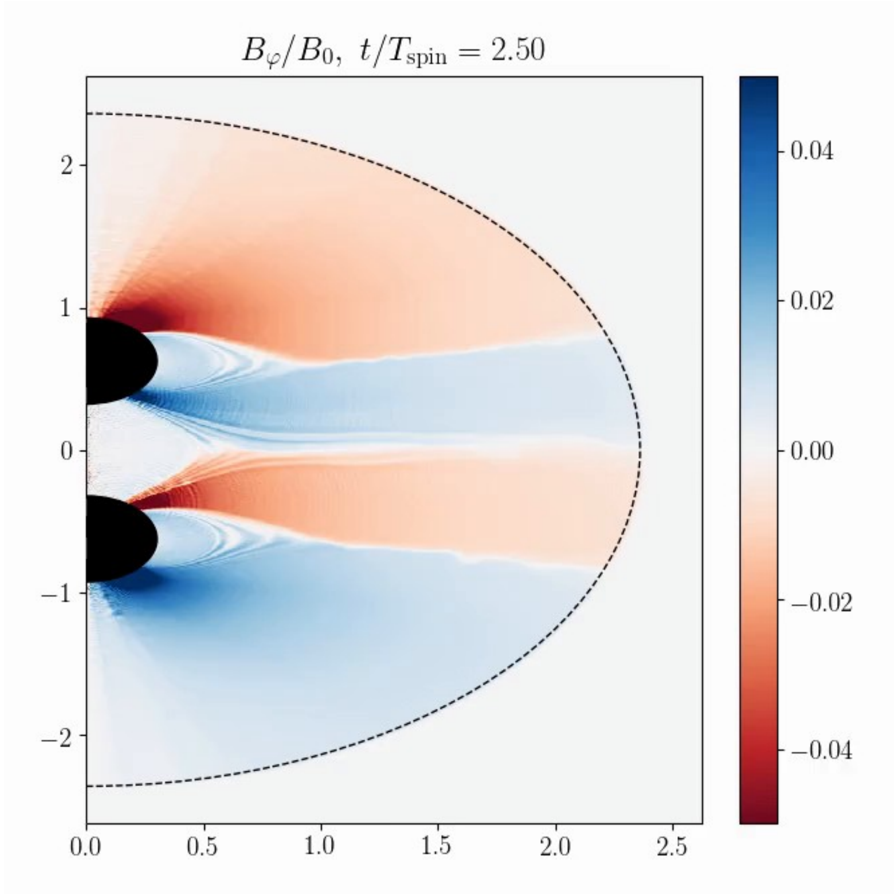
Interacting magnetospheres: an electromagnetic precursor to merging neutron star?

Merging binary pulsar: PIC simulations

Establishement of the magnetospheres



Inspiral begins

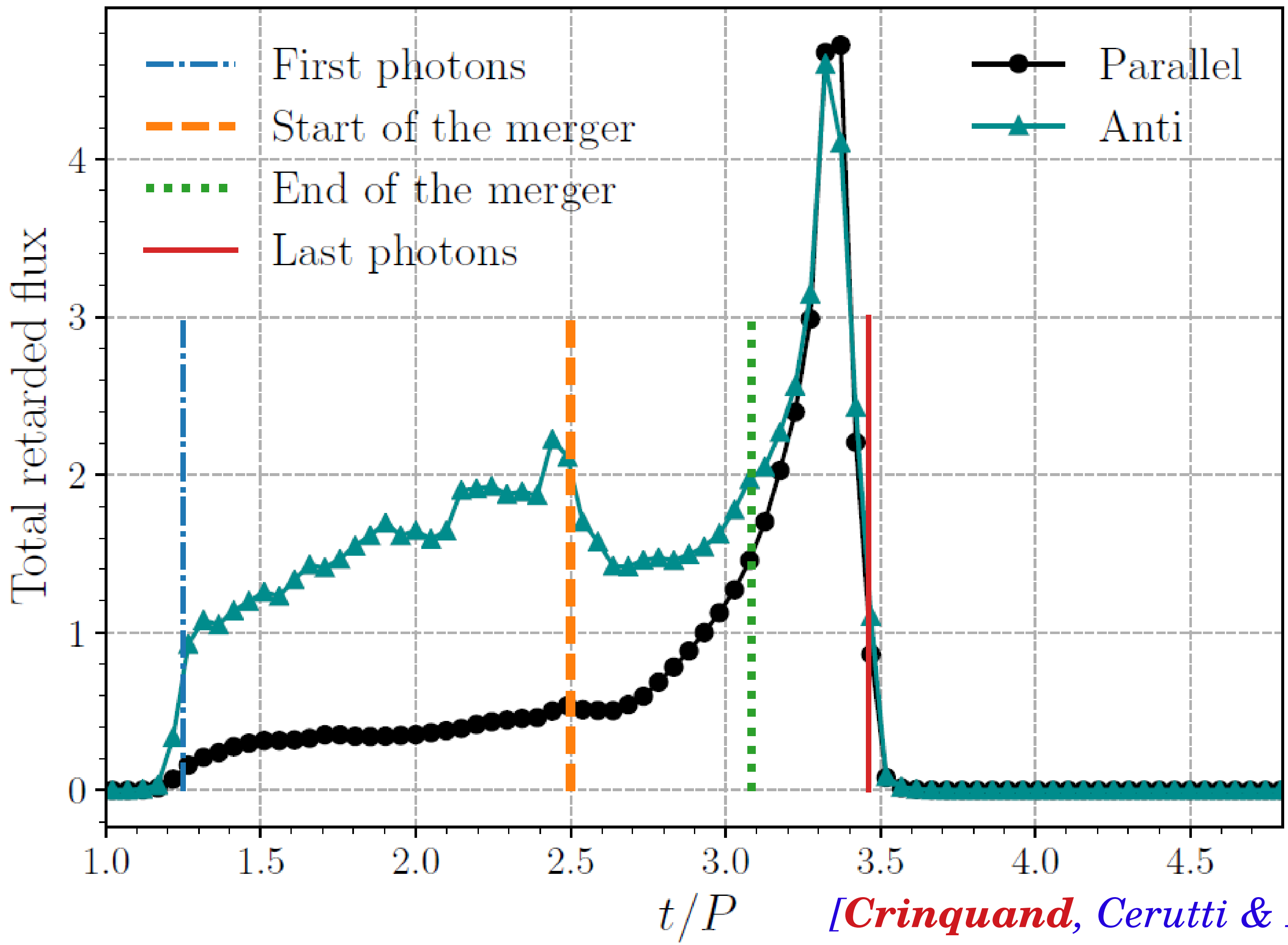


[Crinquand, Cerutti & Dubus 2018]

Driven reconnection in the inspiral phase. Reconnection of the poloidal field

=> Strong magnification of dissipation

A detectable precursor?

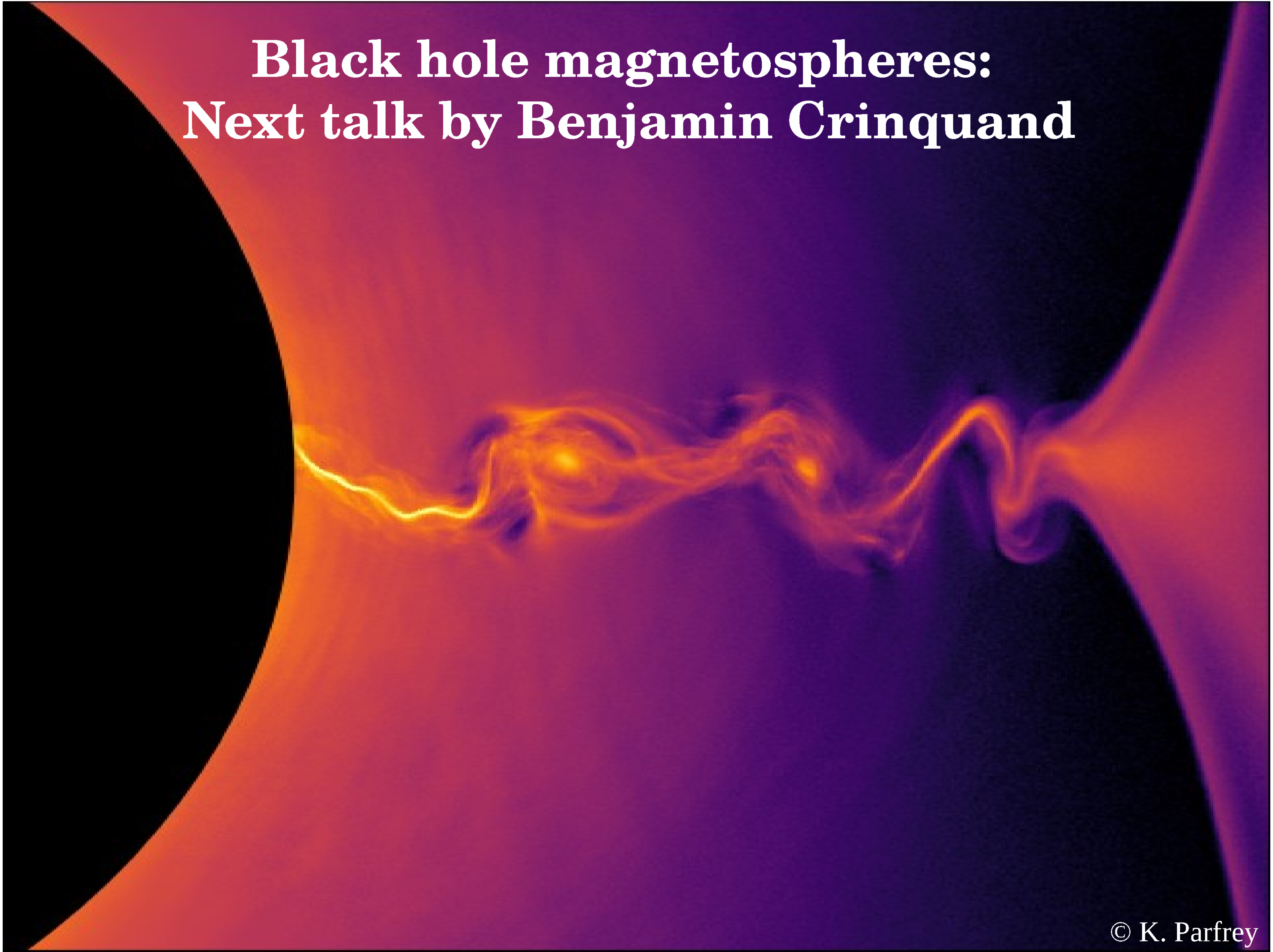


[**Crinquand**, *Cerutti & Dubus 2018*]

2 orders of magnitude gamma-ray luminosity increase during the inspiral !

Still **too weak to be detected.** Go to 3D + orbital motion.

Could produce a (non-repeating) fast radio burst ?


Black hole magnetospheres:
Next talk by Benjamin Crinquand
© K. Parfrey

Summary relativistic reconnection

- **Fast**, acceleration scales **linearly with time**, to be compared with shocks diffusive time ($t^{1/2}$).

- Is **efficient** for **highly magnetized** plasmas, $\sigma >> 1$. Works well where shocks fail.

- **Non-thermal** particle spectrum typically **harder than 2,** and **saturation of γ_{max}~σ**

- But **slower acceleration** and **spectral steepening** at large timescales
=> Does γ_{max} saturate? We may consider hybrid simulations to go further (resistive MHD + test particles)

- Applications to **AGN jets**, **PWN**, **pulsars & black hole magnetospheres**. Gamma-ray flares in blazars and Crab could be a direct demonstration of relativistic reconnection.