Observable signatures of plasmoid-dominated magnetic reconnection in relativistic astrophysical plasmas

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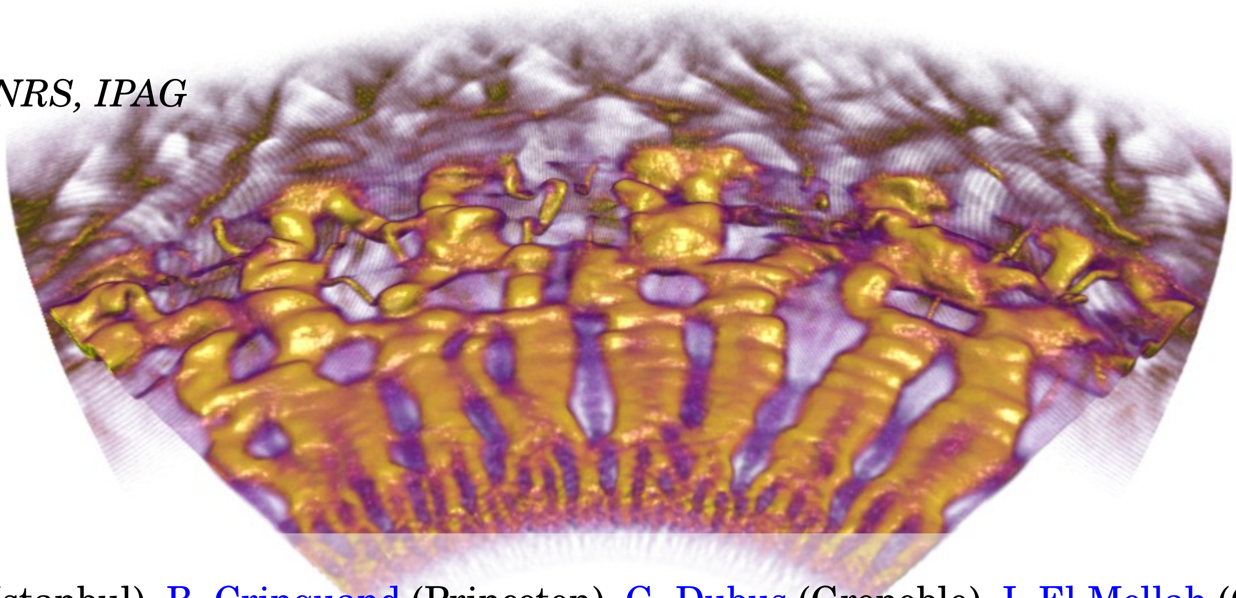
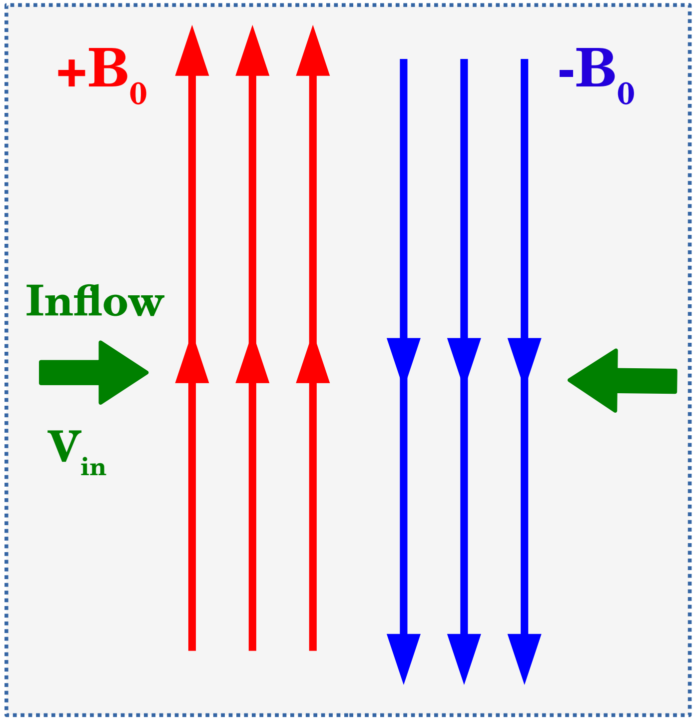


Collaborators :
I. C. Andaç (Grenoble & Istanbul), B. Crinquand (Princeton), G. Dubus (Grenoble), I. El Mellah (Grenoble), K. Y. Ekşi (Istanbul), G. Giacinti (Heidelberg), K. Parfrey (Dublin), A. Philippov (Maryland).

SF2A 2022, 7-10 juin, Besançon.

Reconnection : A change of magnetic topology

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



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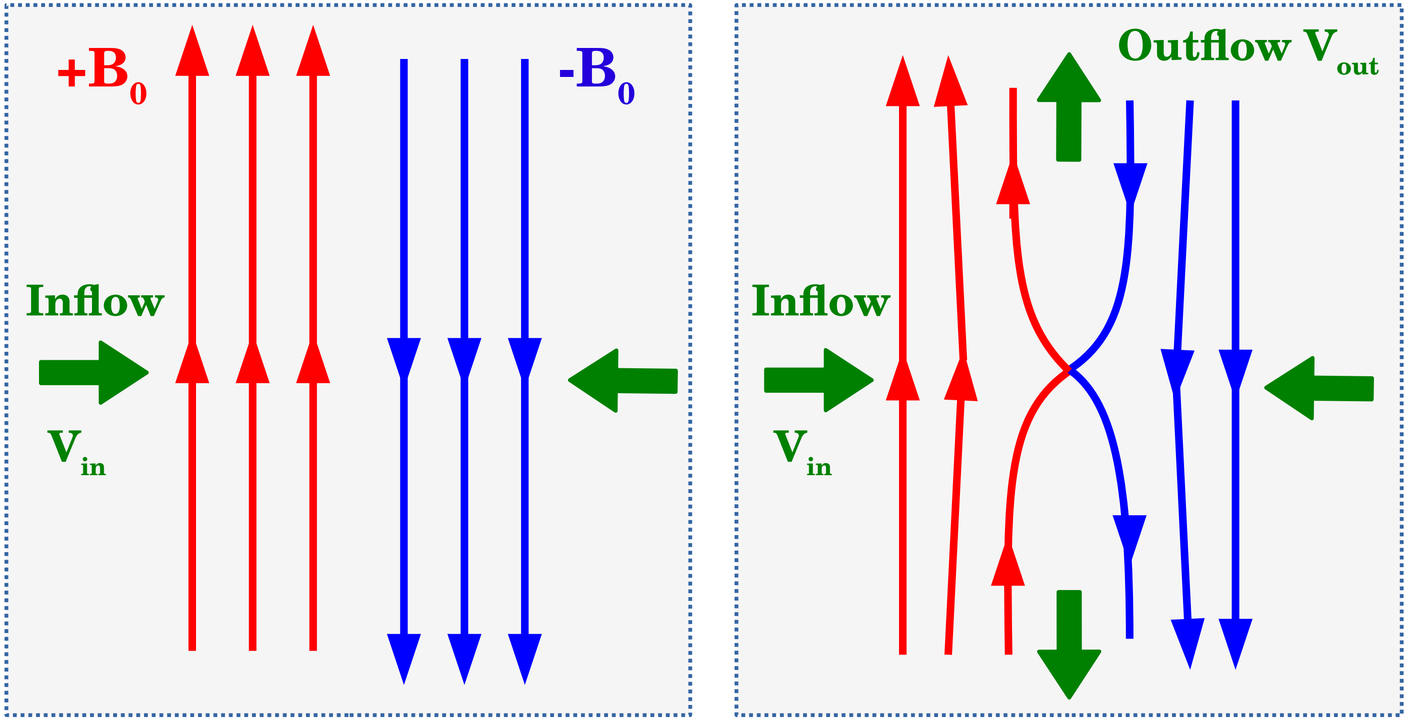

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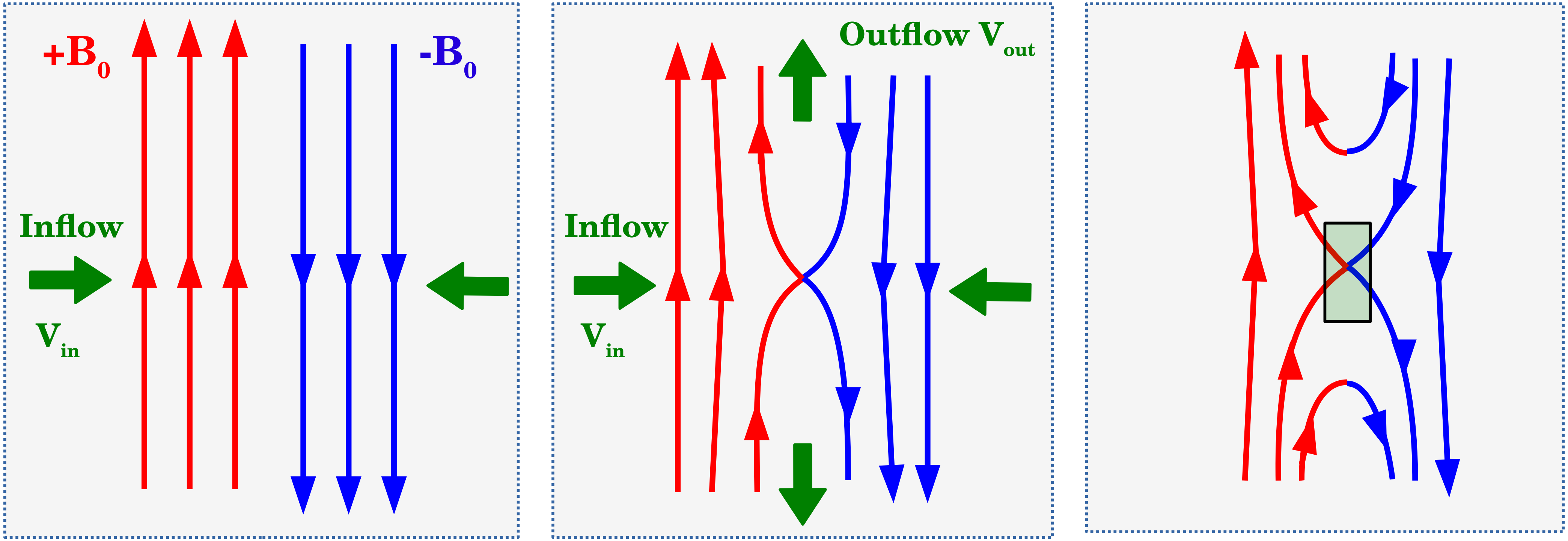

How fast does reconnection proceed? **Reconnection rate: $\beta_{rec}=V_{in}/V_{out}$**

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

Relativistic reconnection at work

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

Relativistic reconnection: σ>~1

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

Dissipation of magnetic energy => relativistic particles !

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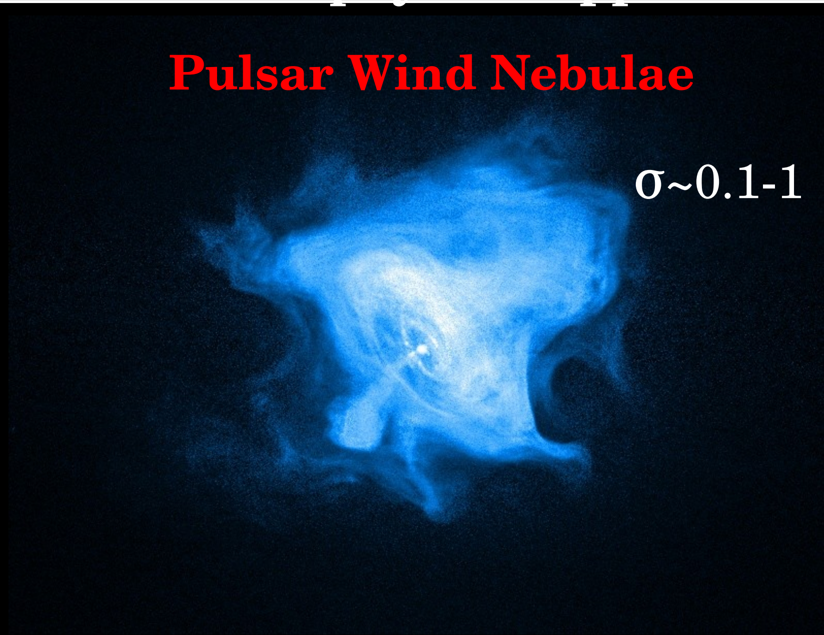
Possible astrophysical applications:



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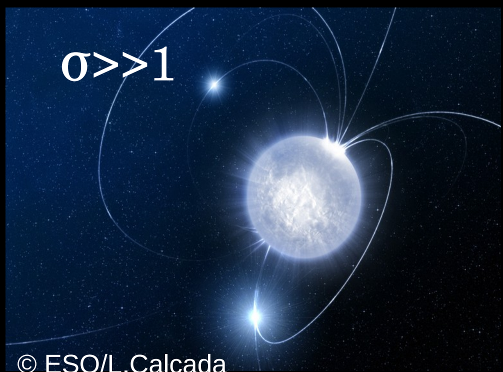
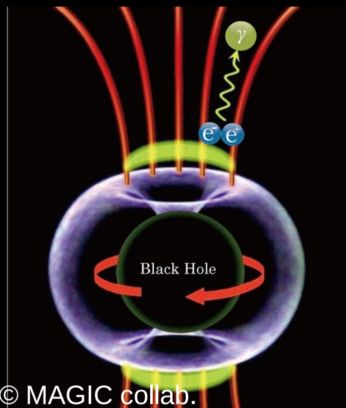
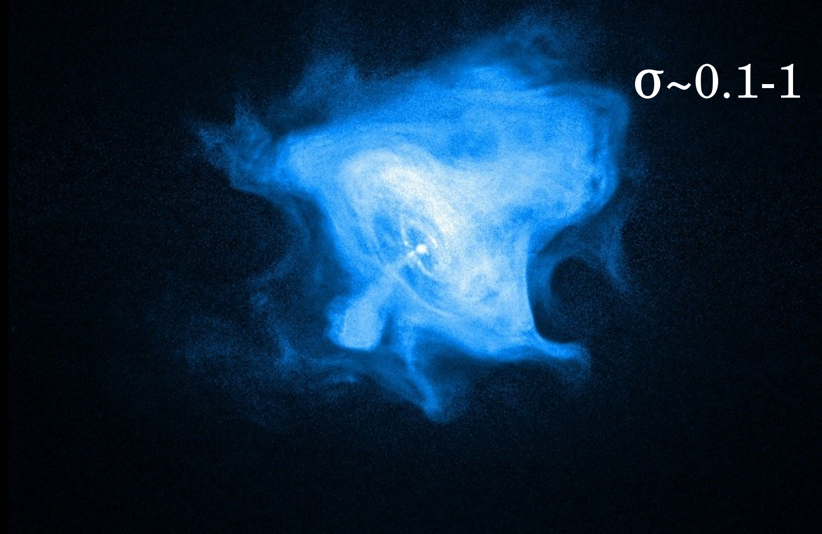
Pulsars, BH magnetospheres





Possible astrophysical applications:

Pulsar Wind Nebulae



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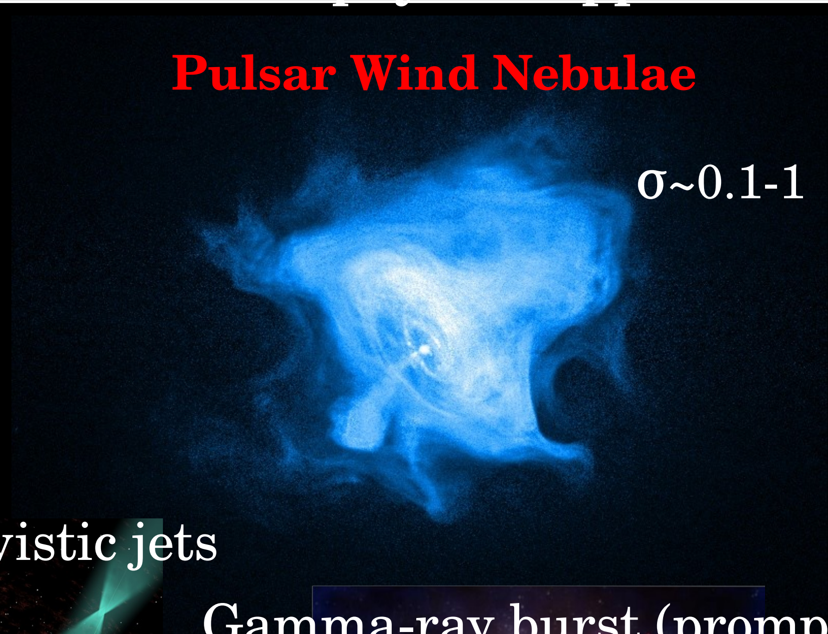

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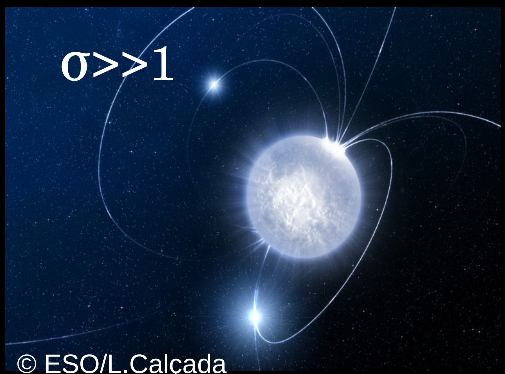
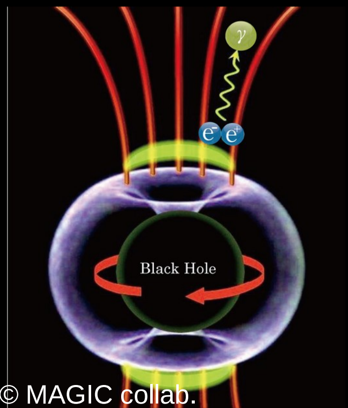
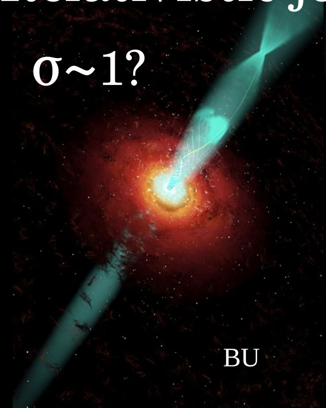
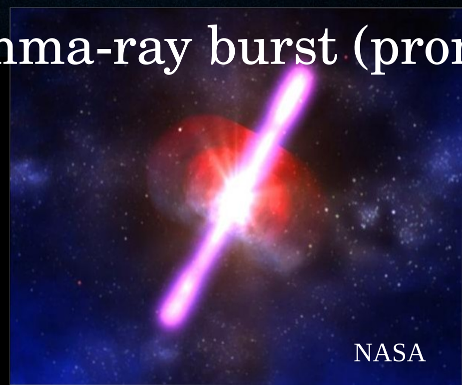




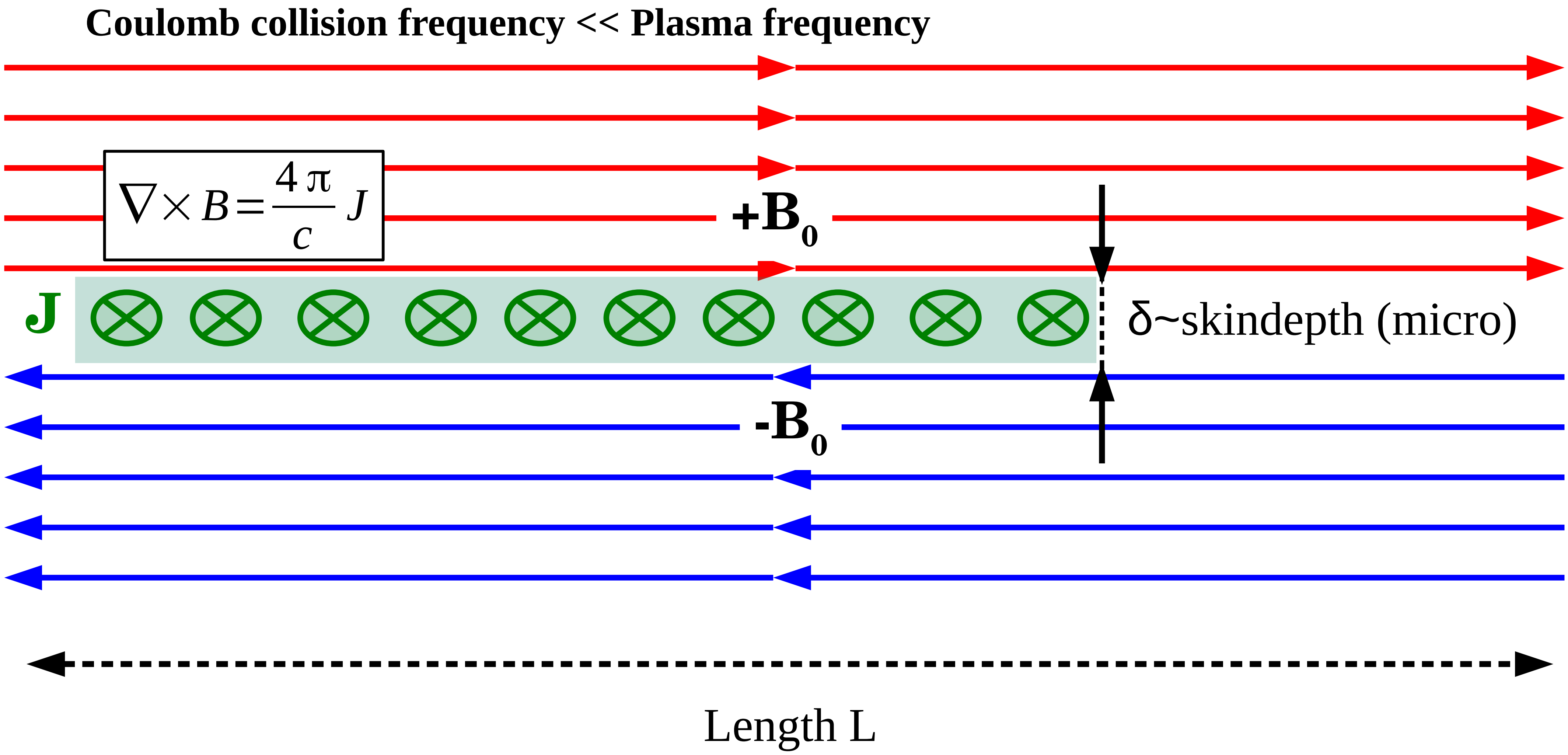
Relativistic jets



Gamma-ray burst (prompt?)

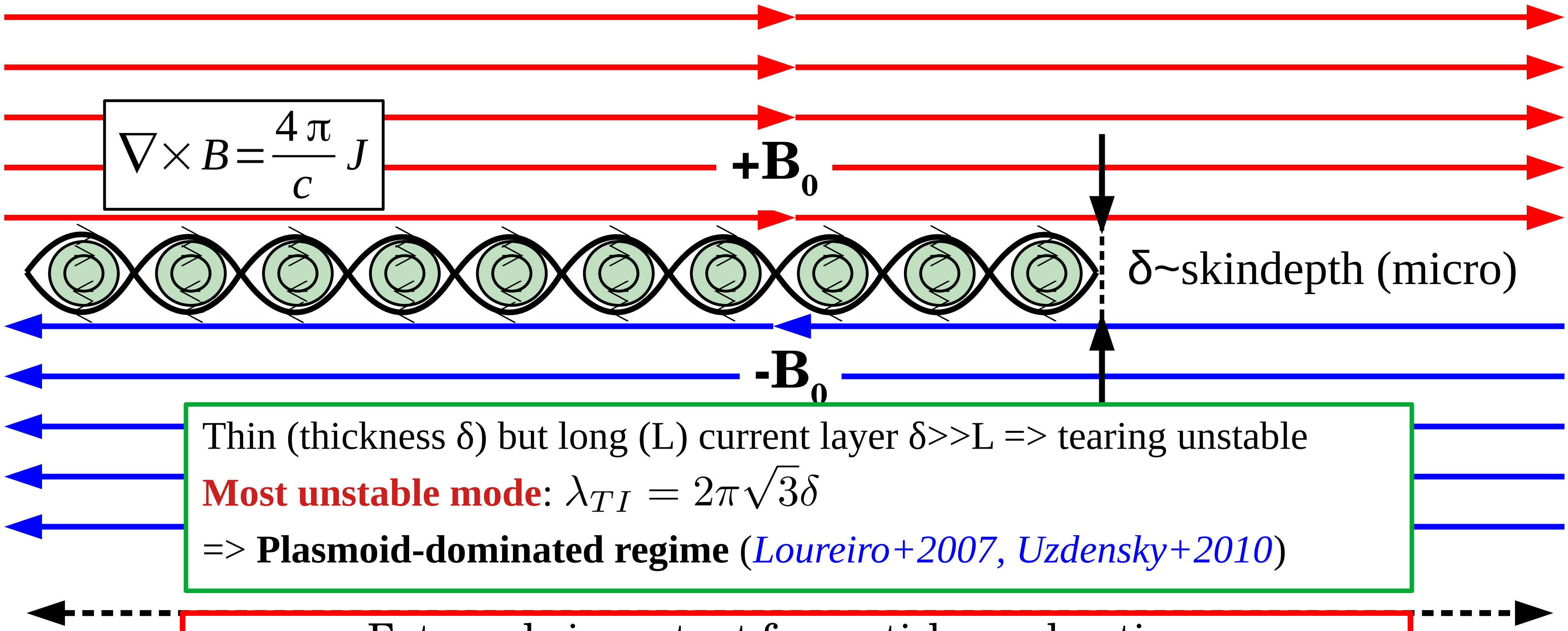


Collisionless reconnection layer



A long thin current sheet is tearing unstable

[Zelenyi & Krasnoselskikh 1979 ; Zenitani & Hoshino (2007) ; Pétri & Kirk 2007]



Thin (thickness δ) but long (L) current layer δ>>L => tearing unstable

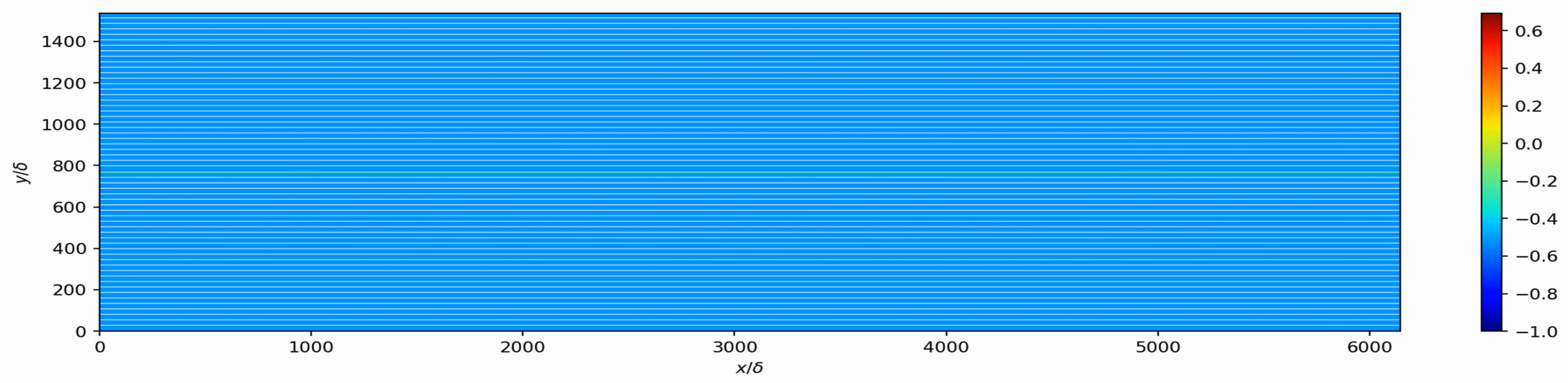
Most unstable mode: $\lambda_{TI} = 2\pi\sqrt{3}\delta$

=> **Plasmoid-dominated regime** (*Loureiro+2007, Uzdensky+2010*)

Extremely important for particle acceleration :
Mediate fast reconnection and non-thermal particle acceleration

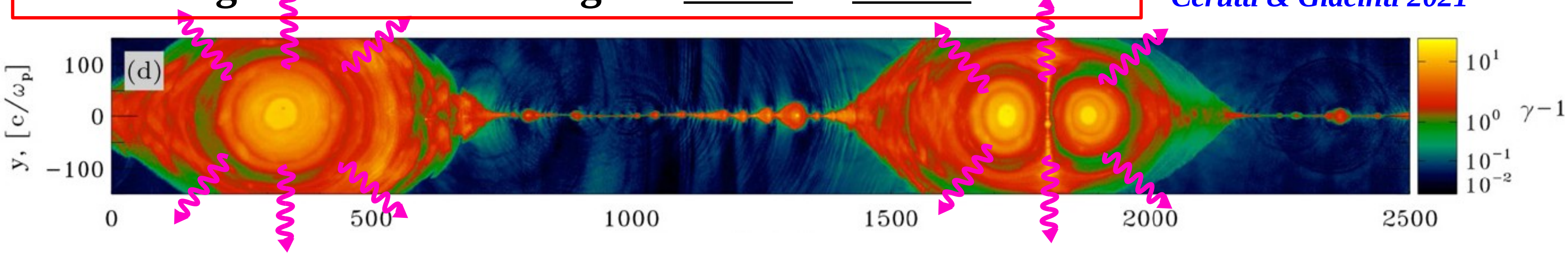
Reconnecting Harris layer (2D PIC simulation)

Inverse cascade : Hierarchical merging process



Plasmoid growth : Connecting the <u>micro</u> to <u>macro</u> scales ?

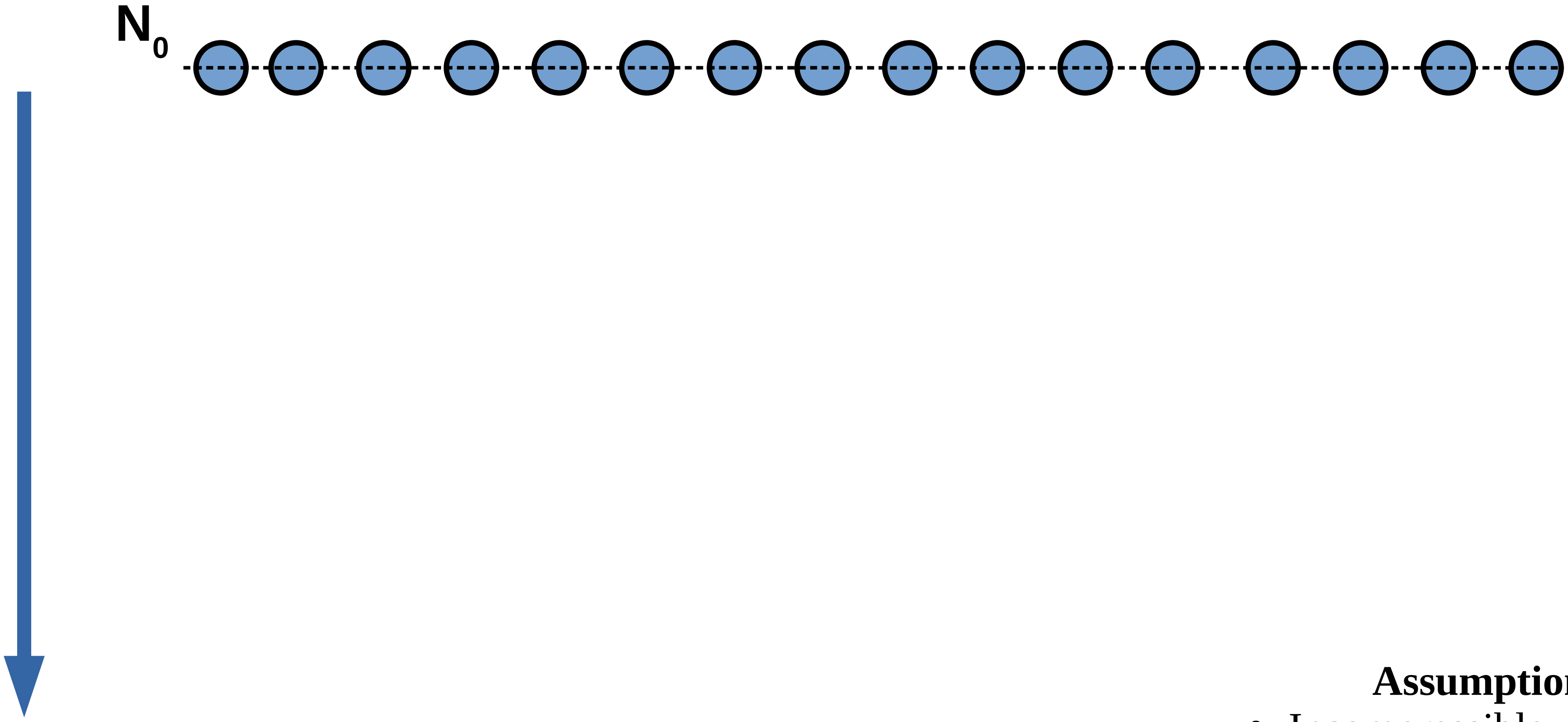
e.g., Loureiro+2012 ; Sironi+2016 ; Cerutti & Giacinti 2021



Large plasmoids concentrate energetic particles => observational signature ?

Hierarchical merging model

Zhou+2019



Assumptions:

- Incompressible
- Identical circular islands
- No secondary islands
- Constant reconnection rate

Hierarchical merging model

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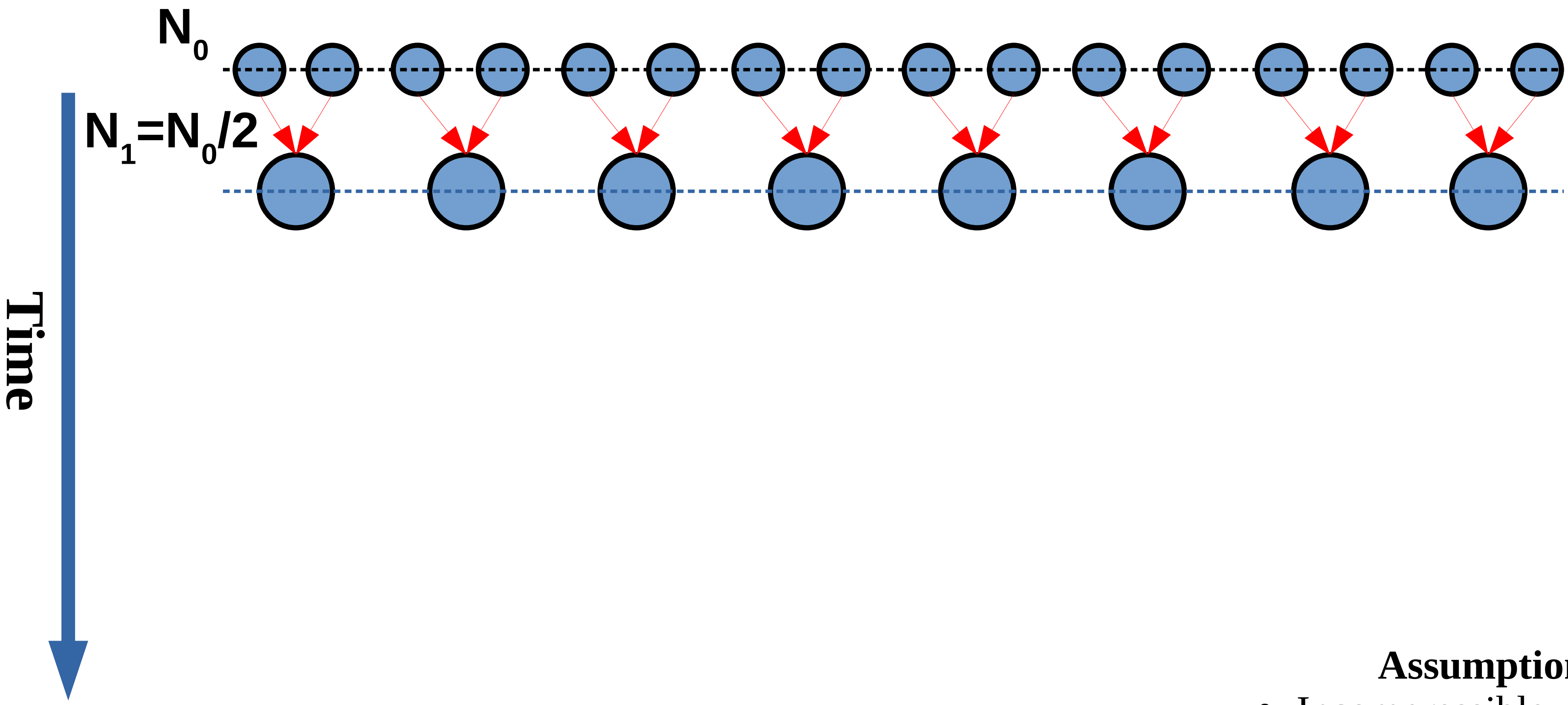

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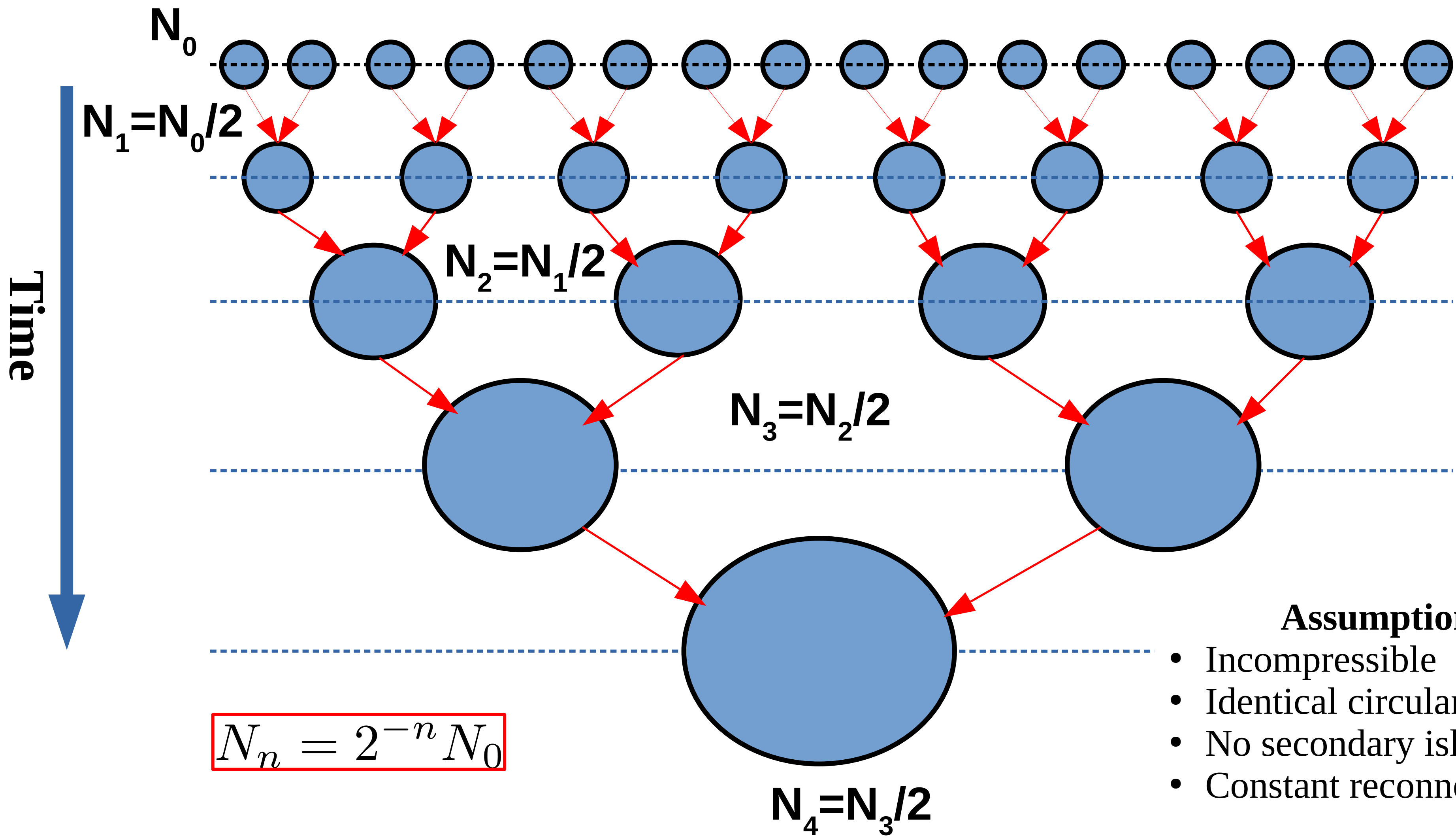

$$N_n = 2^{-n} N_0$$

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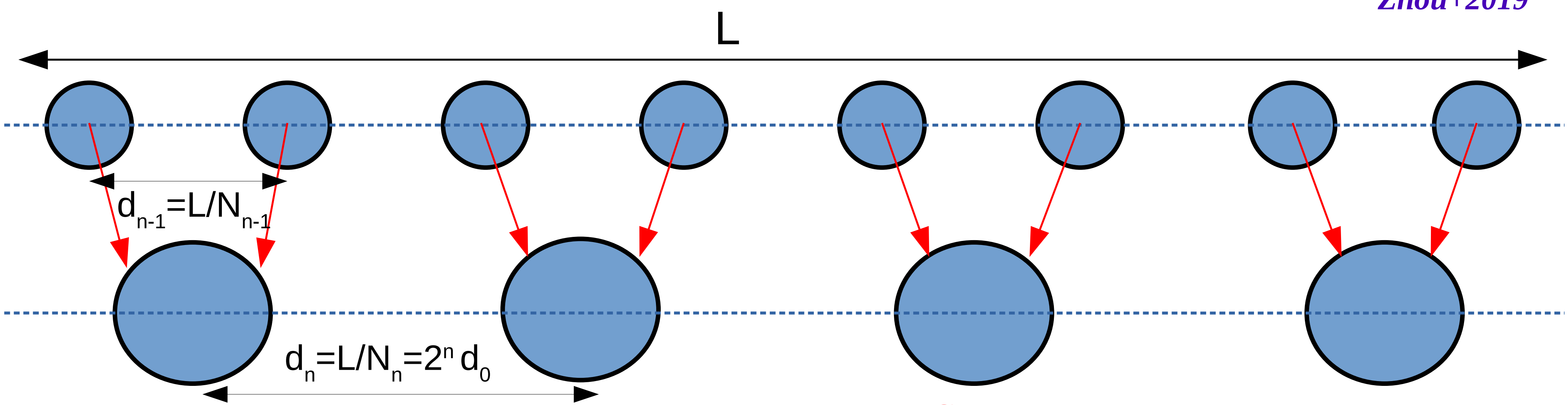
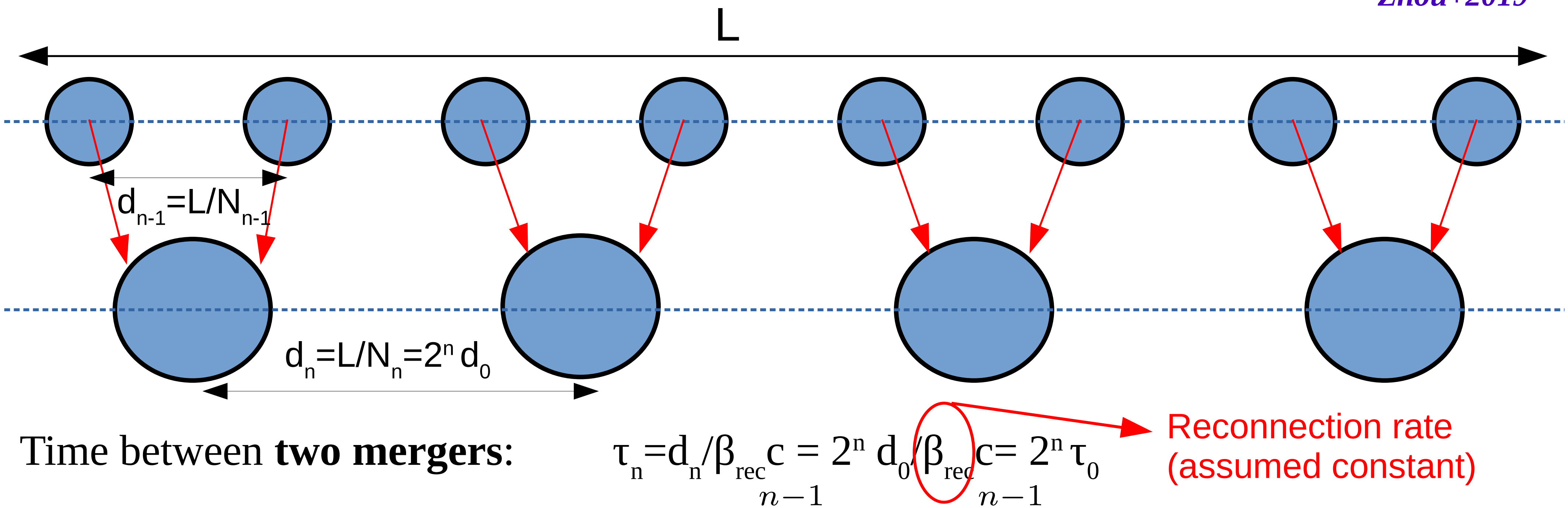


Time between **two mergers**: $\tau_n = d_n/\beta_{rec} c = 2^n d_0/\beta_{rec} c = 2^n \tau_0$

Reconnection rate (assumed constant)

Hierarchical merging model

Zhou+2019



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Total time to reach **generation n**: $t_n = \sum_{k=0}^{n-1} \tau_k = \tau_0 \sum_{k=0}^{n-1} 2^k = \tau_0(2^n - 1)$

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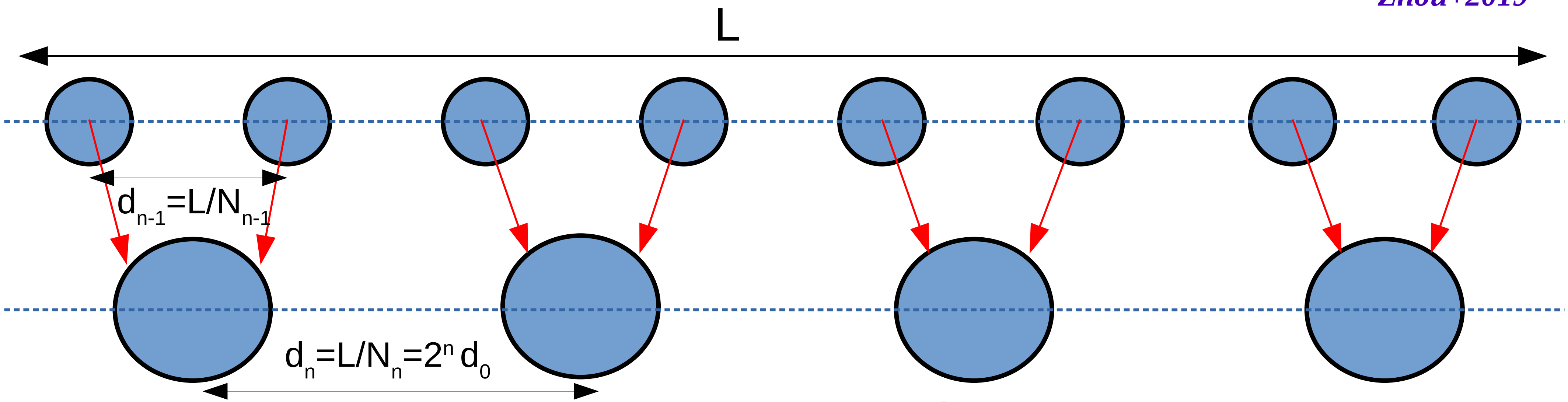

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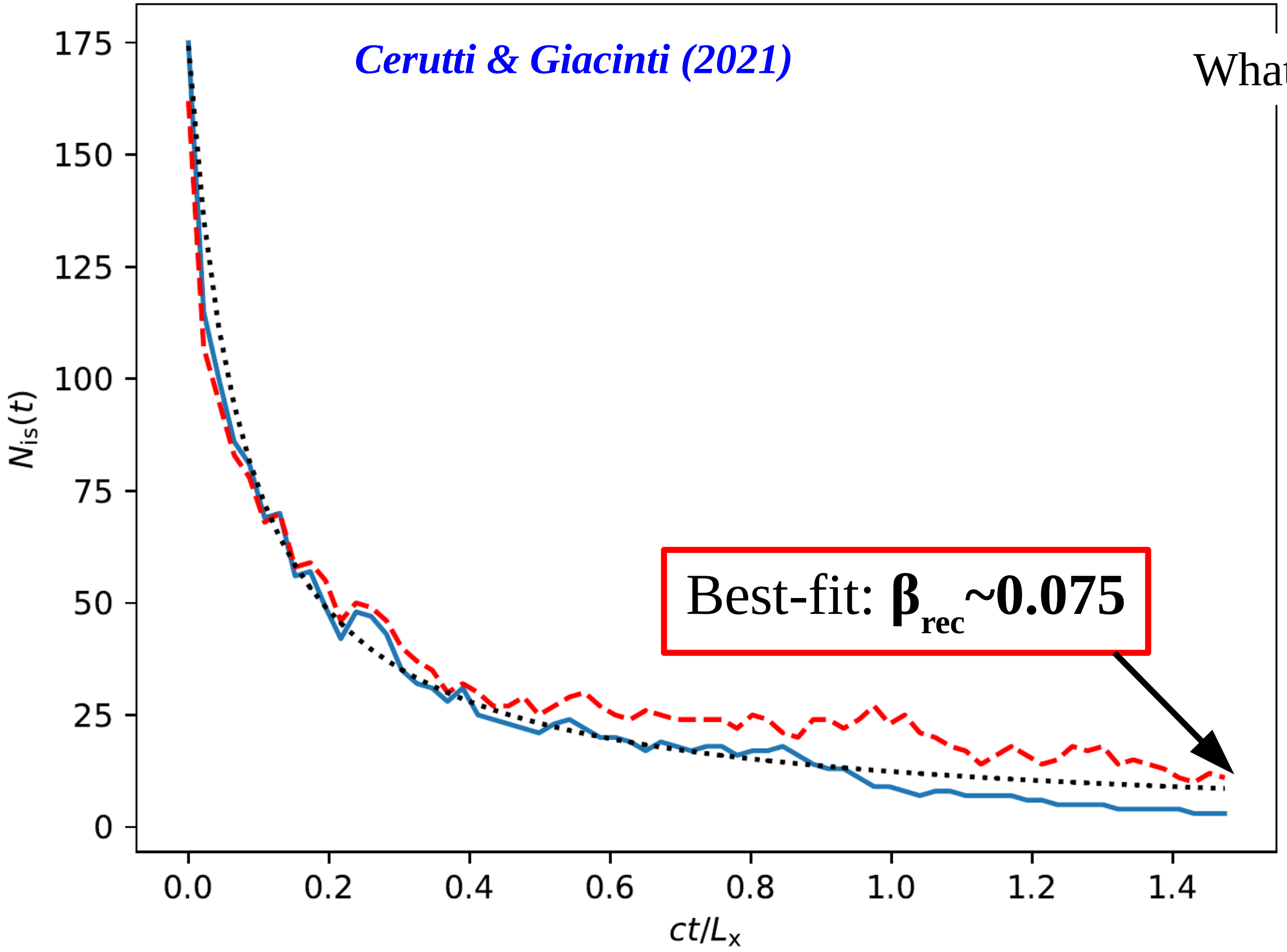
$$N_n = 2^{-n} N_0$$

$$N(\tilde{t}) = \frac{N_0}{1 + \tilde{t}} \qquad \tilde{t} = t/\tau_0$$

Putting the model to the test : Harris layer



What is the final number of giant plasmoids ?

$$N_{is}^{f} = \frac{N_0}{1 + t_{esc}/\tau_0}$$

Taking t_{esc}~L/c >> τ_0 gives :

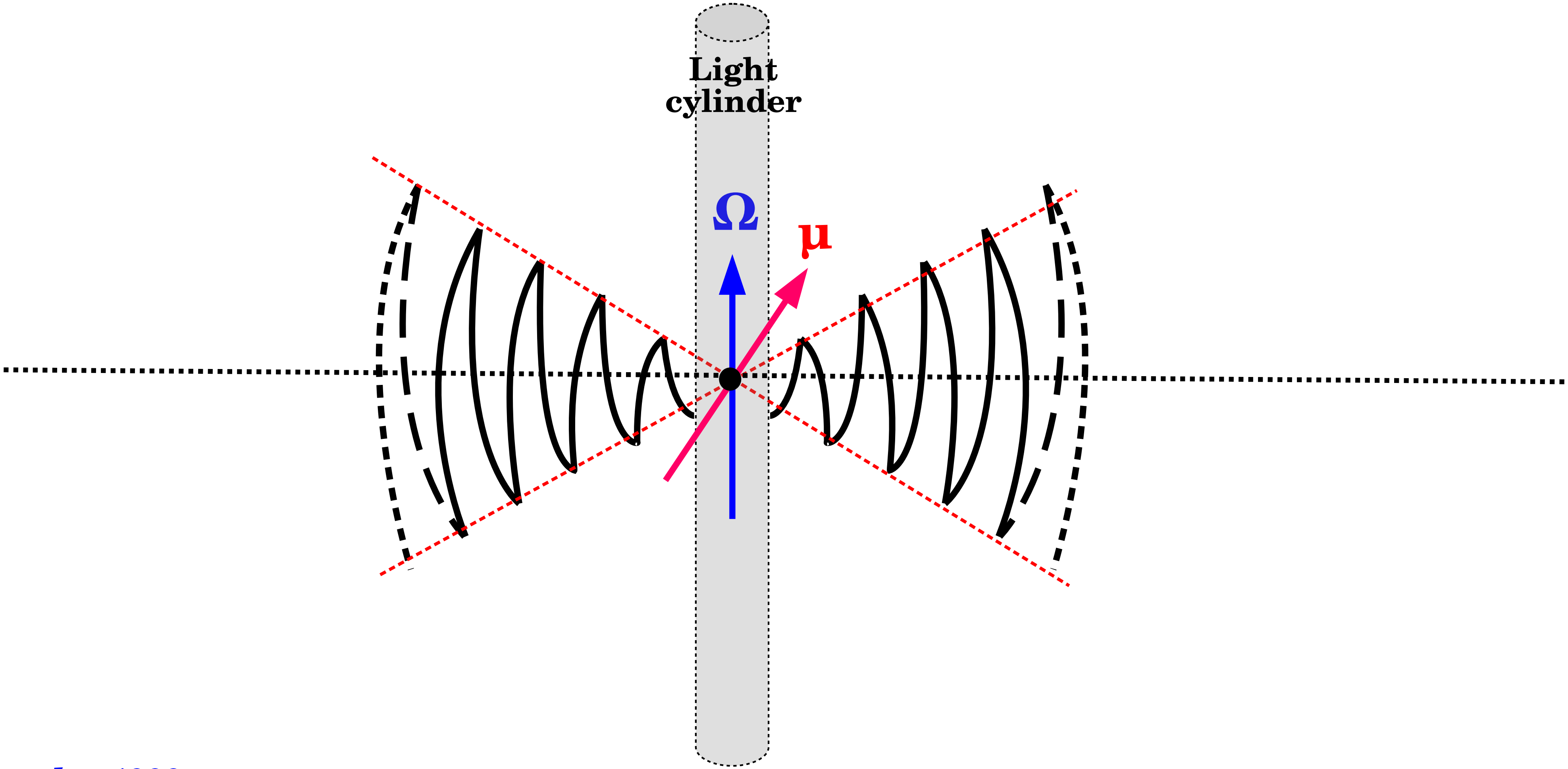
$N_f \sim 1/\beta_{rec}$

The reconnection rate is well constrained and is ~ **universal**

β_{rec}**~0.1**

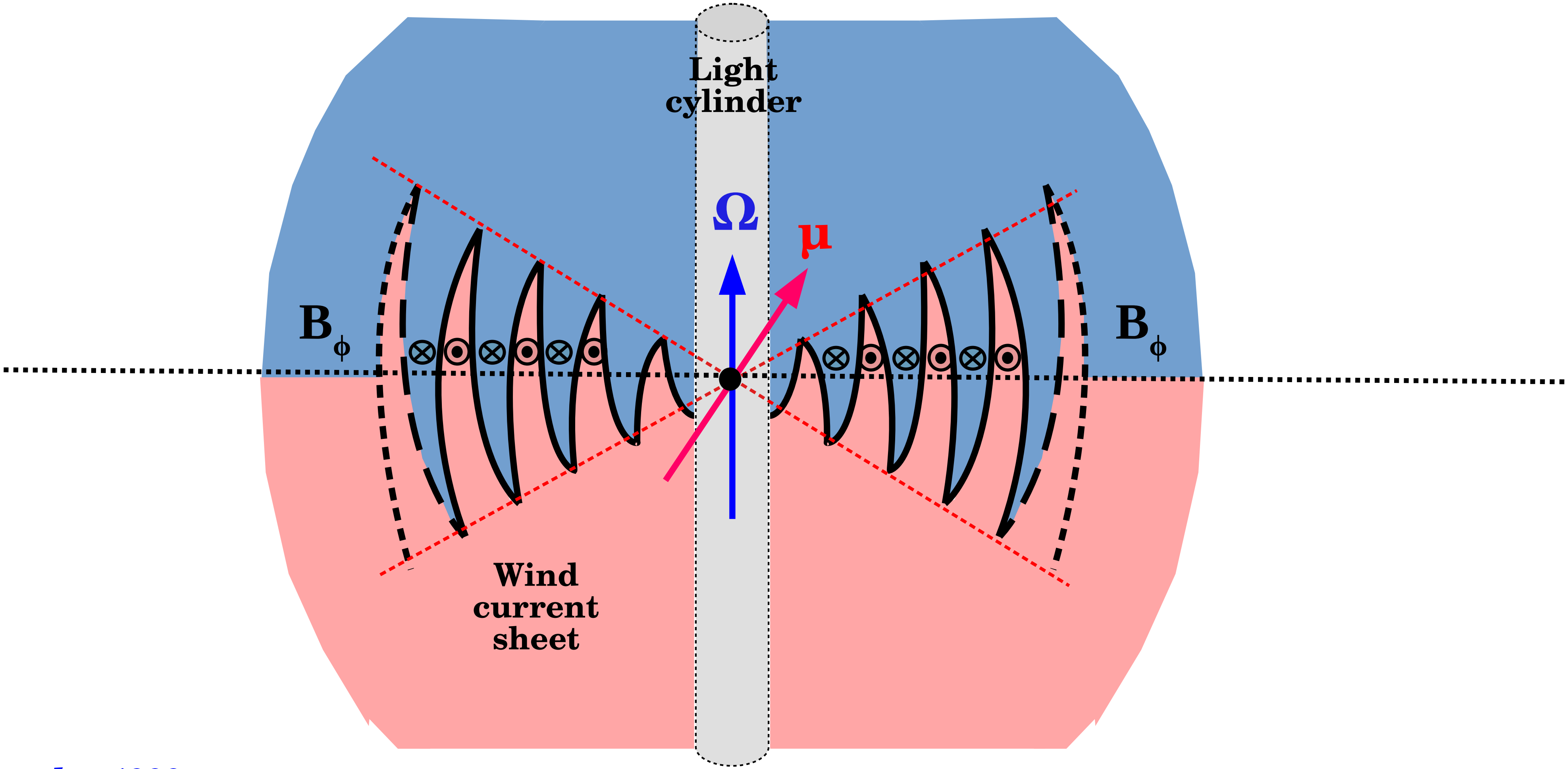
e.g., Werner et al. (2018)

Large-scale currents sheets in pulsars



Bogovalov 1999

Large-scale currents sheets in pulsars



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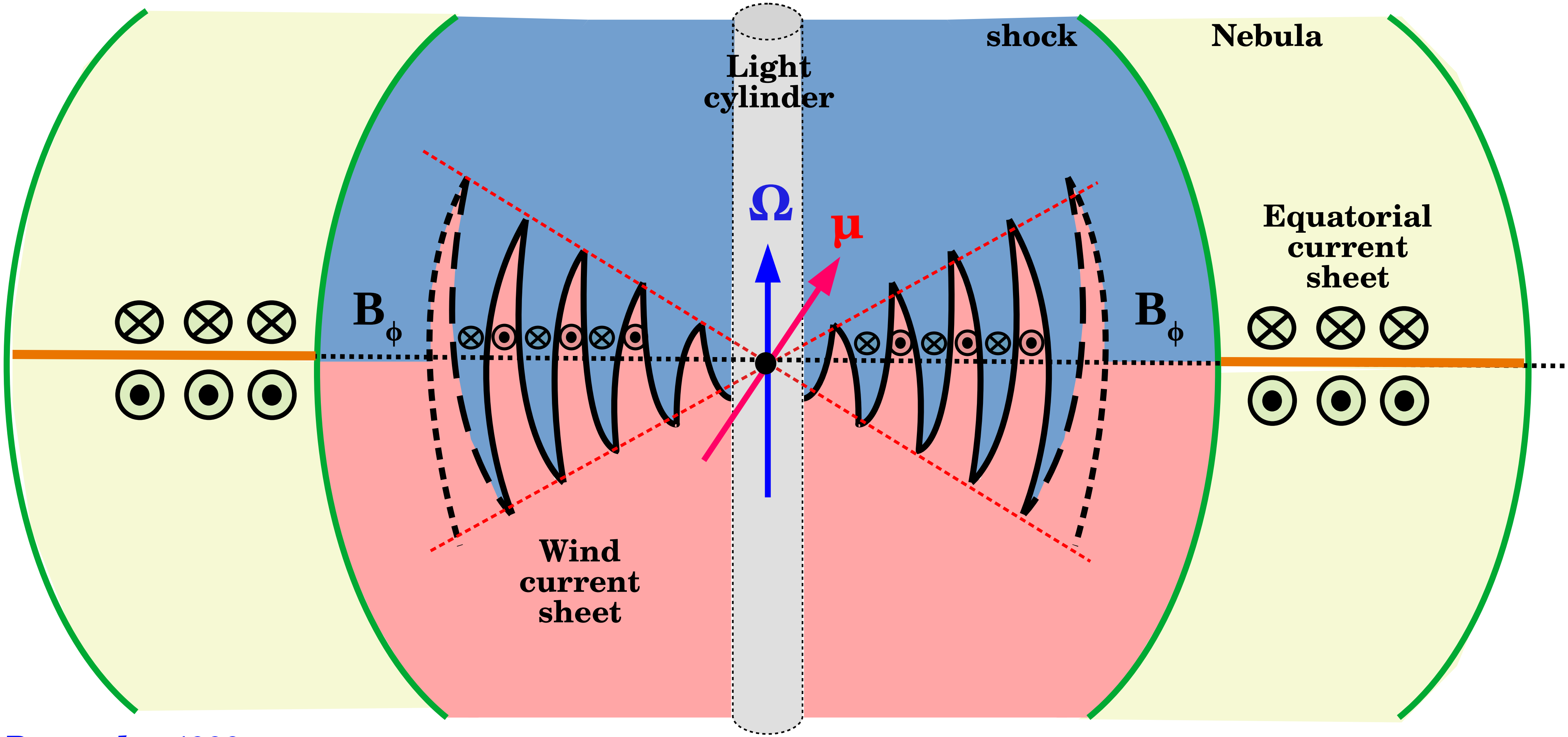


Bogovalov 1999

I. Pulsar wind current sheet

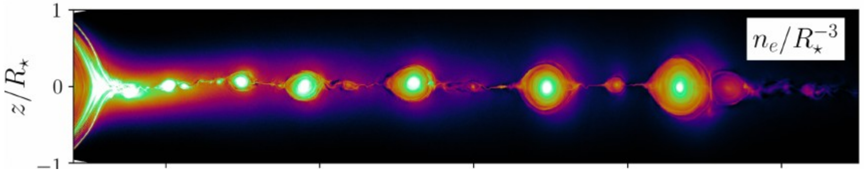
3D PIC simulations

Wind current sheet

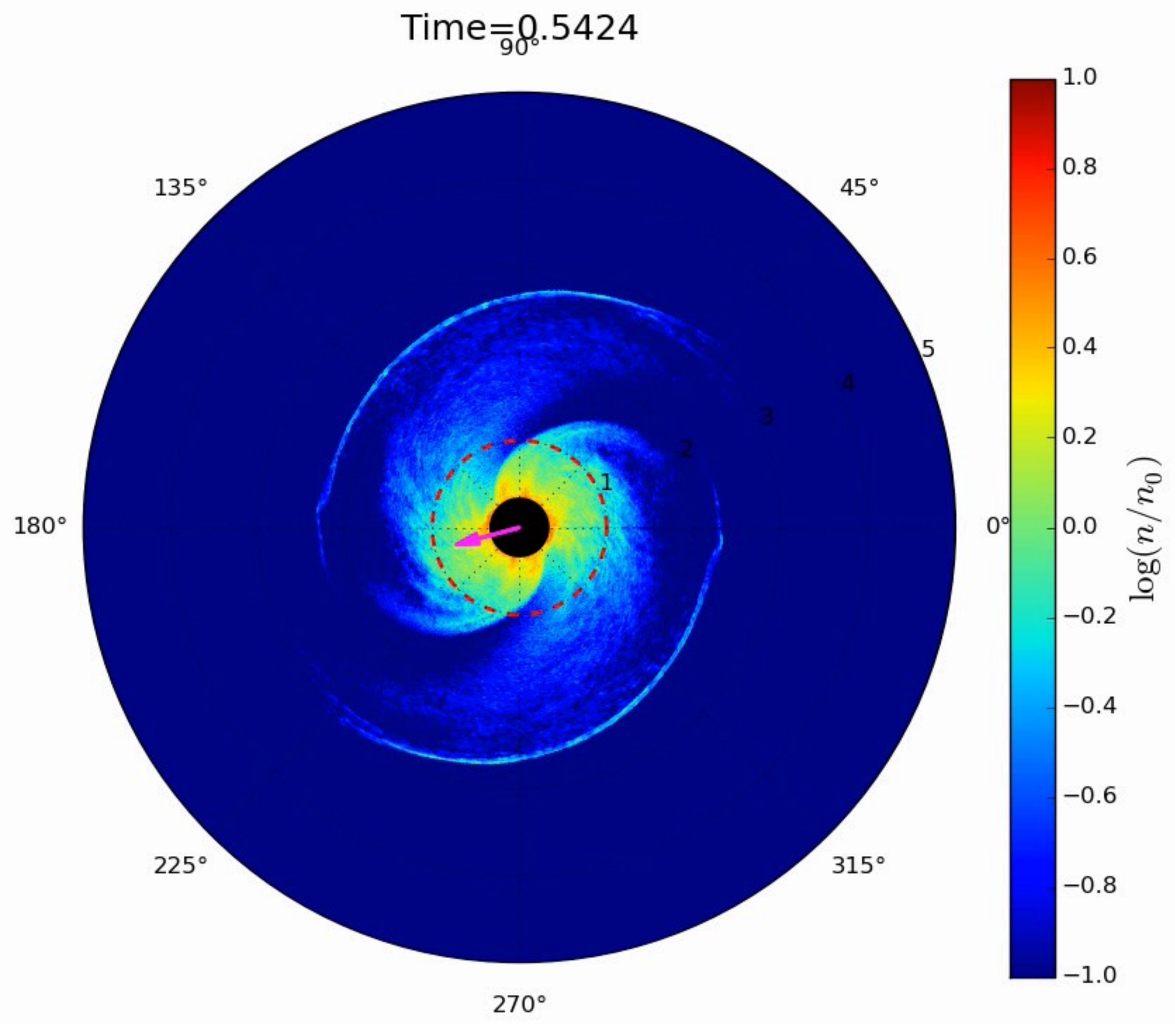
Tearing unstable !

e.g., Cerutti & Philippov 2017
Cerutti et al. 2020

Hu & Beloborodov 2022



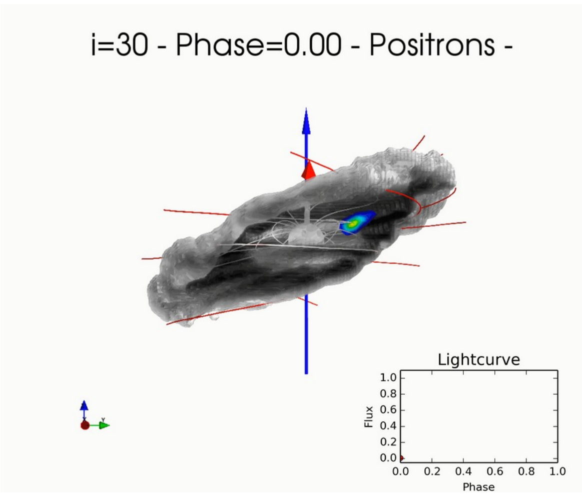
Equatorial cut

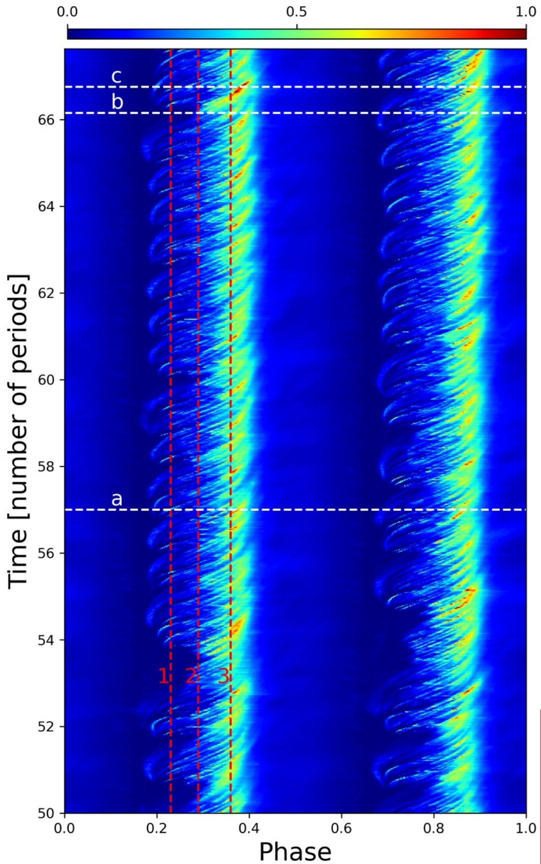


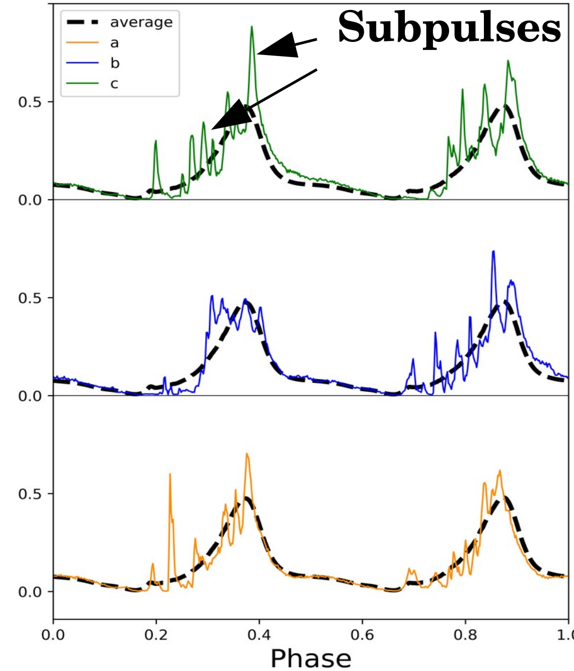
Cerutti & Philippov (2017); Andaç et al. (2022)

Subpulses induced by plasmoid formation

High-energy pulsed emission from the current sheet





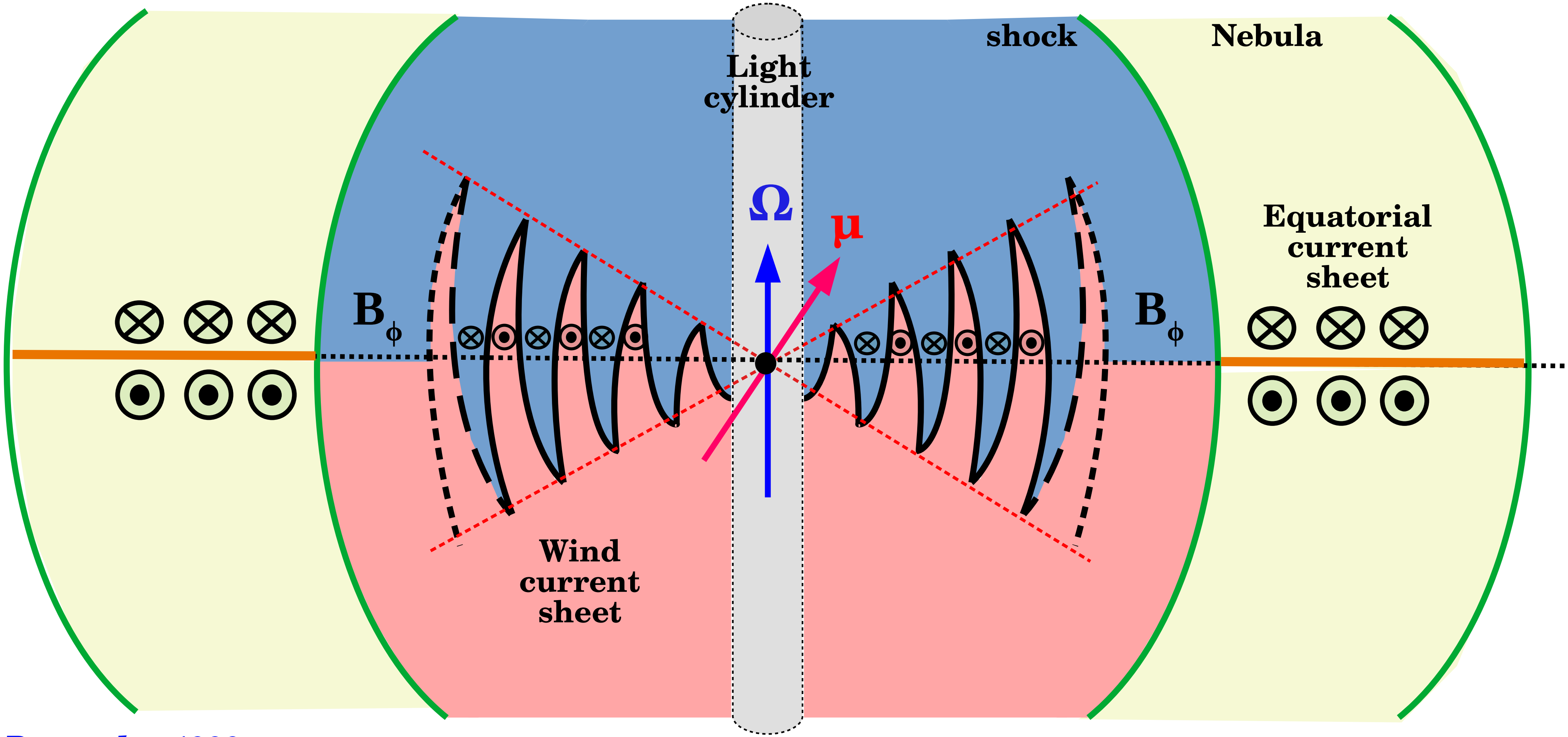


e.g., Lyubarskii (1996)
Cerutti et al. (2016)
Philippov & Spitkovsky 2018

- **Noise on the leading edge**
- **Number subpulse per pulse $1/\beta_{rec}$~10**
  => prediction for fast optical observations?

Andaç et al. 2022

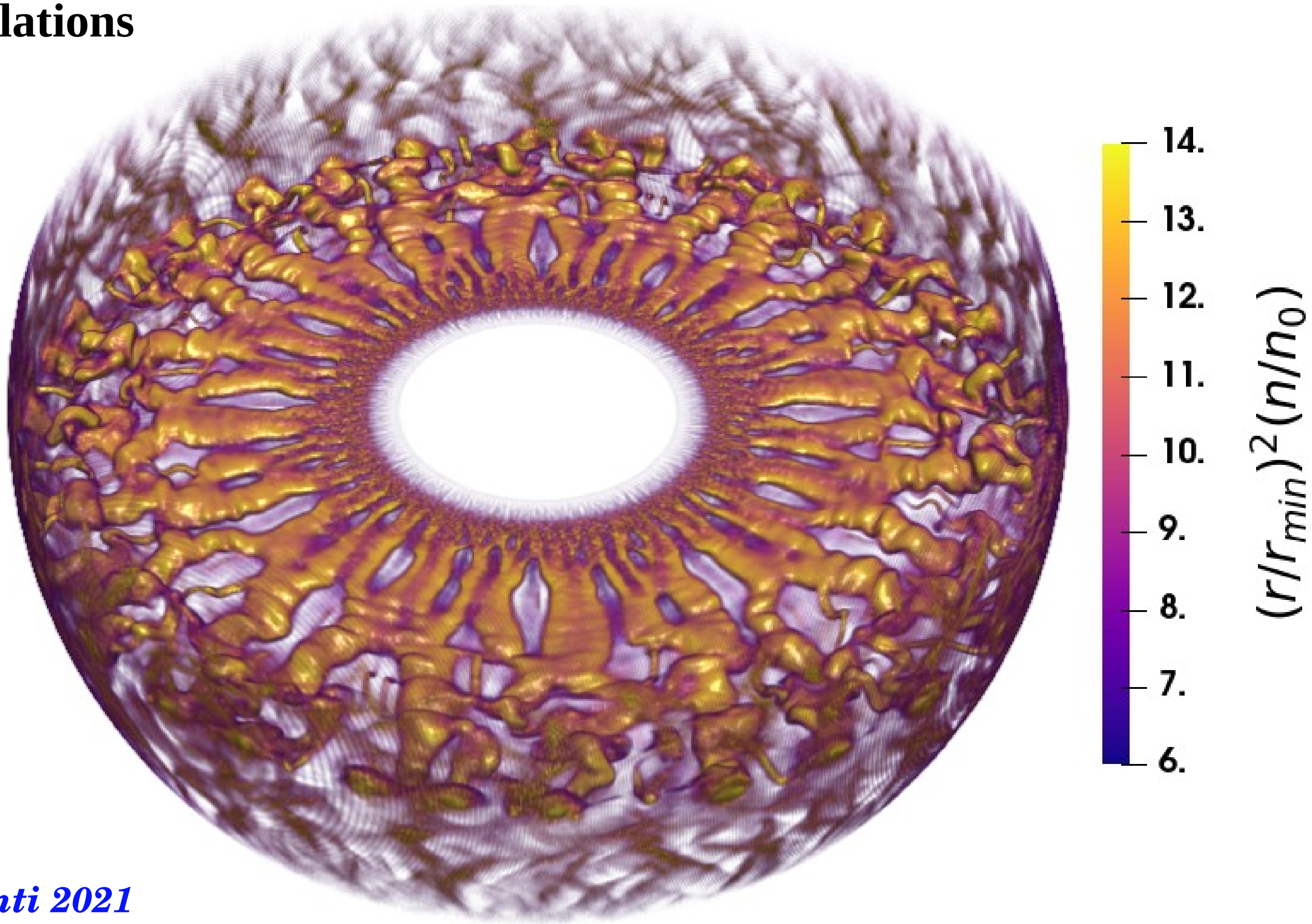
Large-scale currents sheets in pulsars



Bogovalov 1999

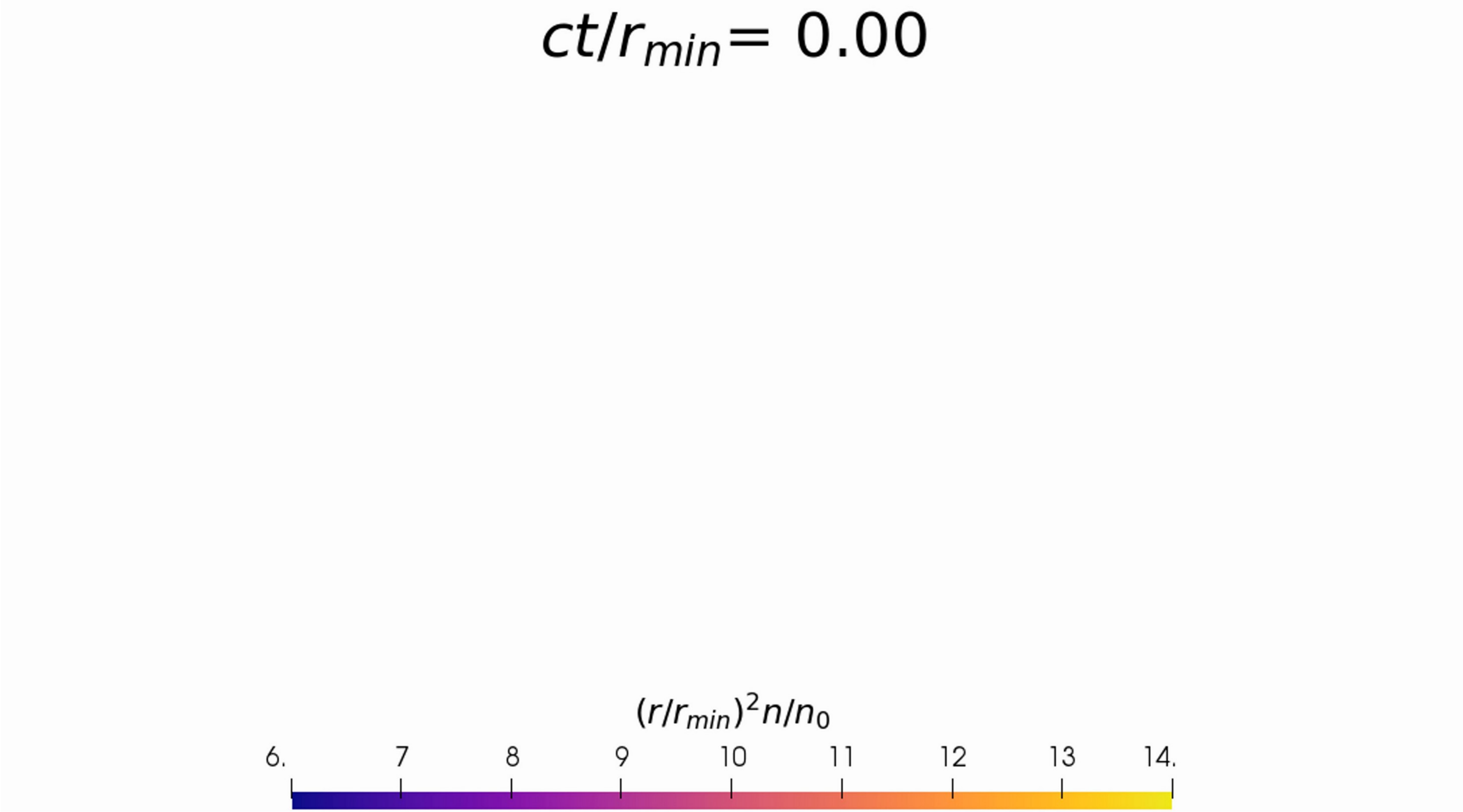
II. Pulsar wind nebula current sheet

3D PIC simulations



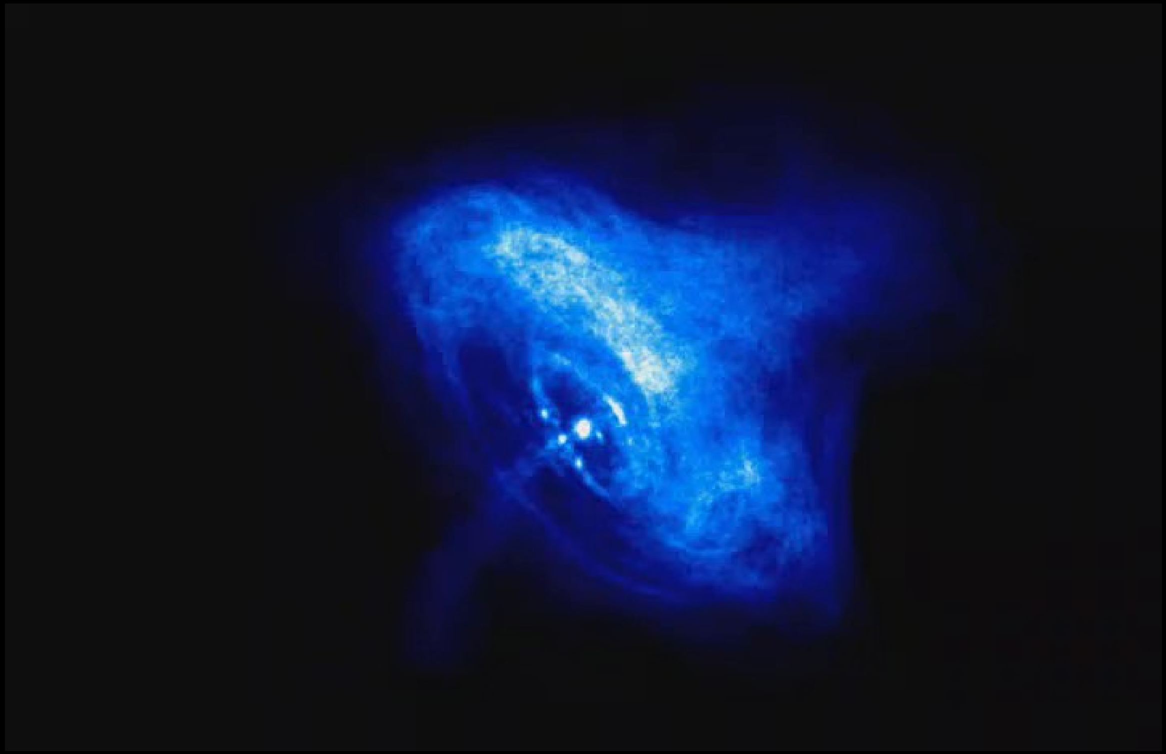
Cerutti & Giacinti 2021

Plasma density evolution



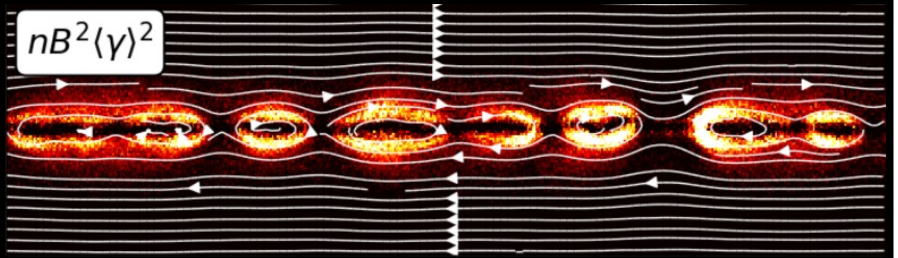
Origin of the Crab Nebula inner ring knots ?

Final number of islands : $N_f \approx \pi \beta_{\rm rec}^{-1} \approx 30 \beta_{\rm rec,0.1}^{-1} islands$

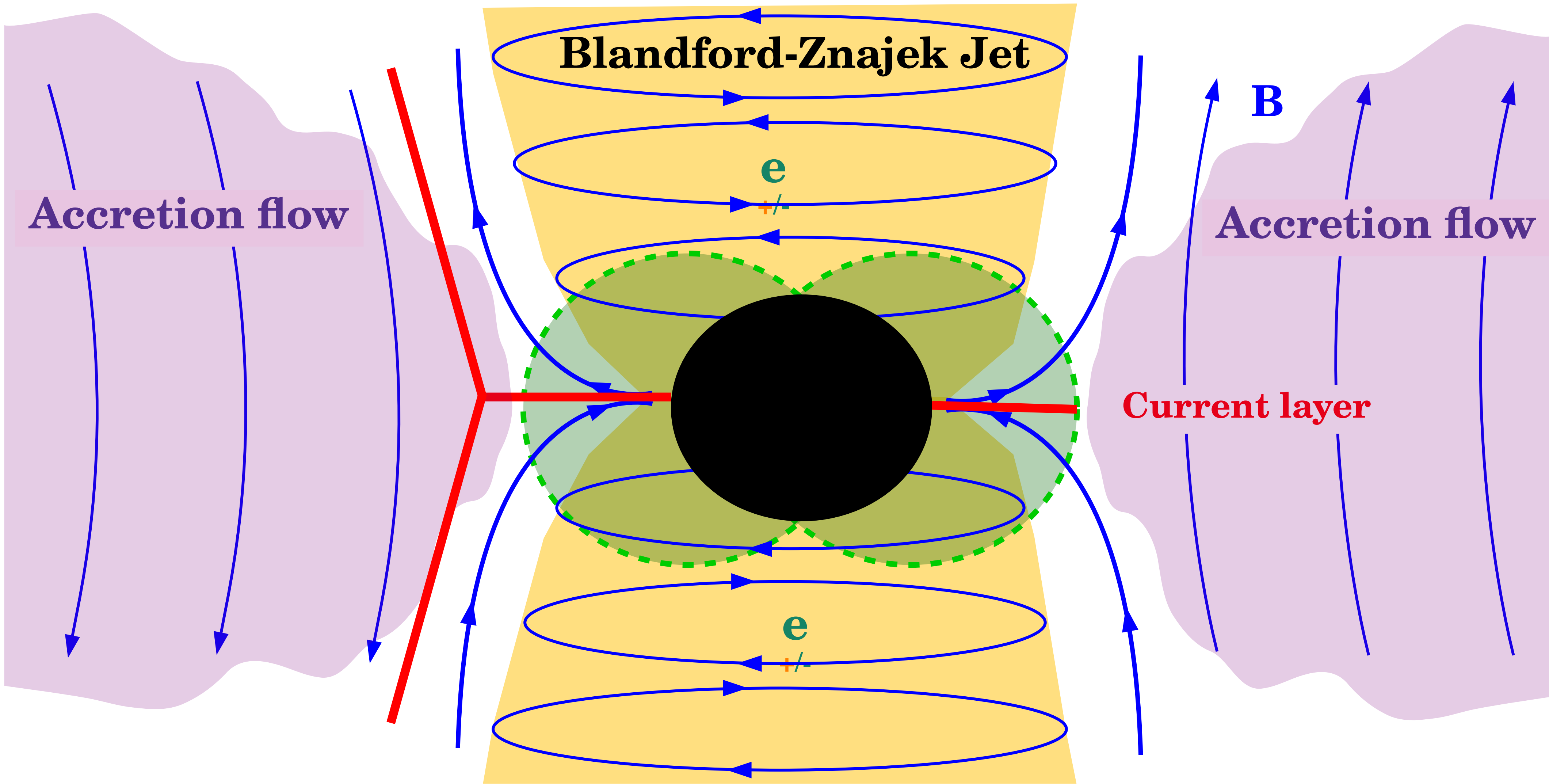


« The X-ray ring itself is composed of roughly <u>two dozen knots</u> that are highly variable but roughly stationary » [Hester 2008]

Simulated synchrotron power



III. Kerr black hole magnetospheres



3D GRPIC simulations

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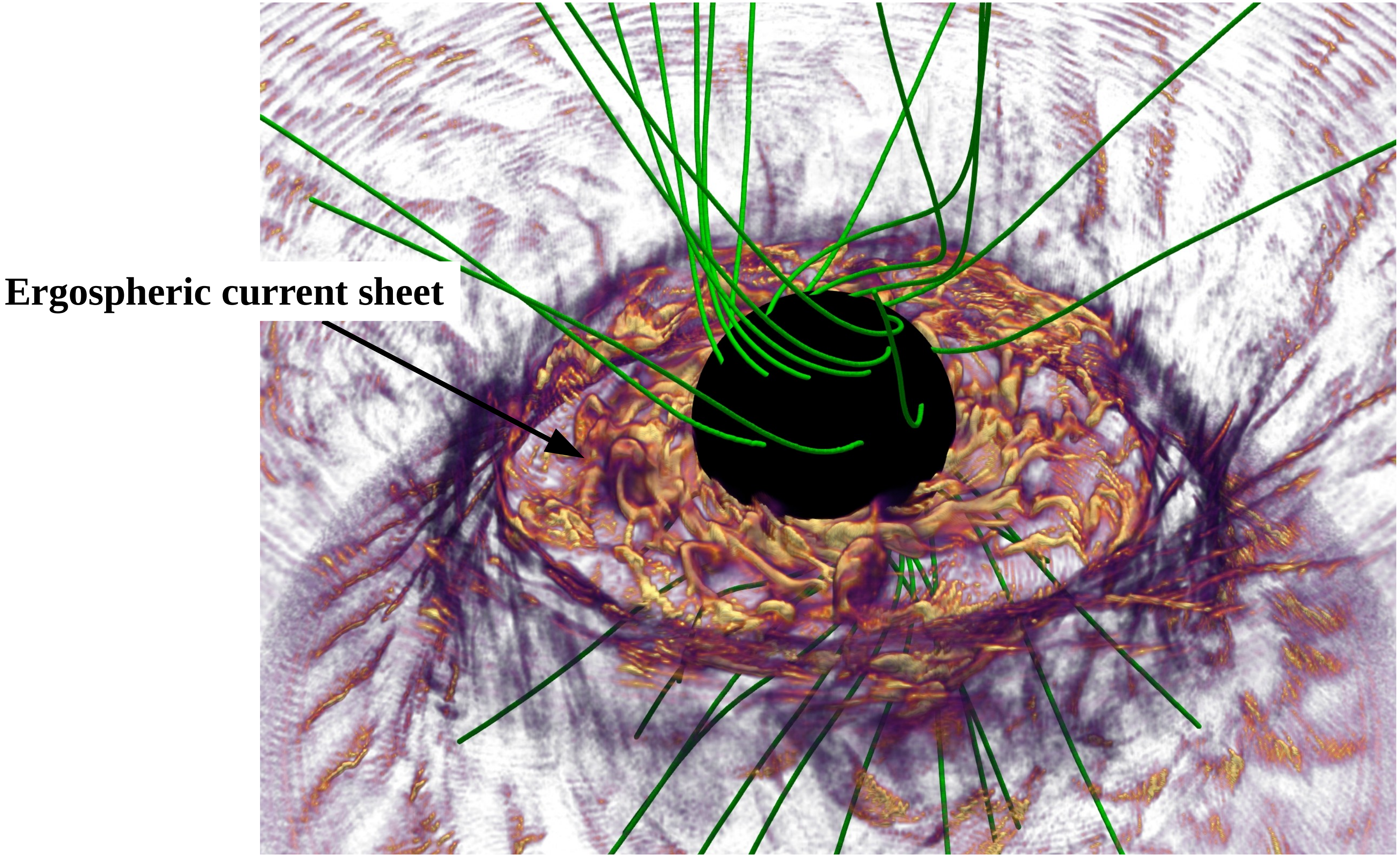
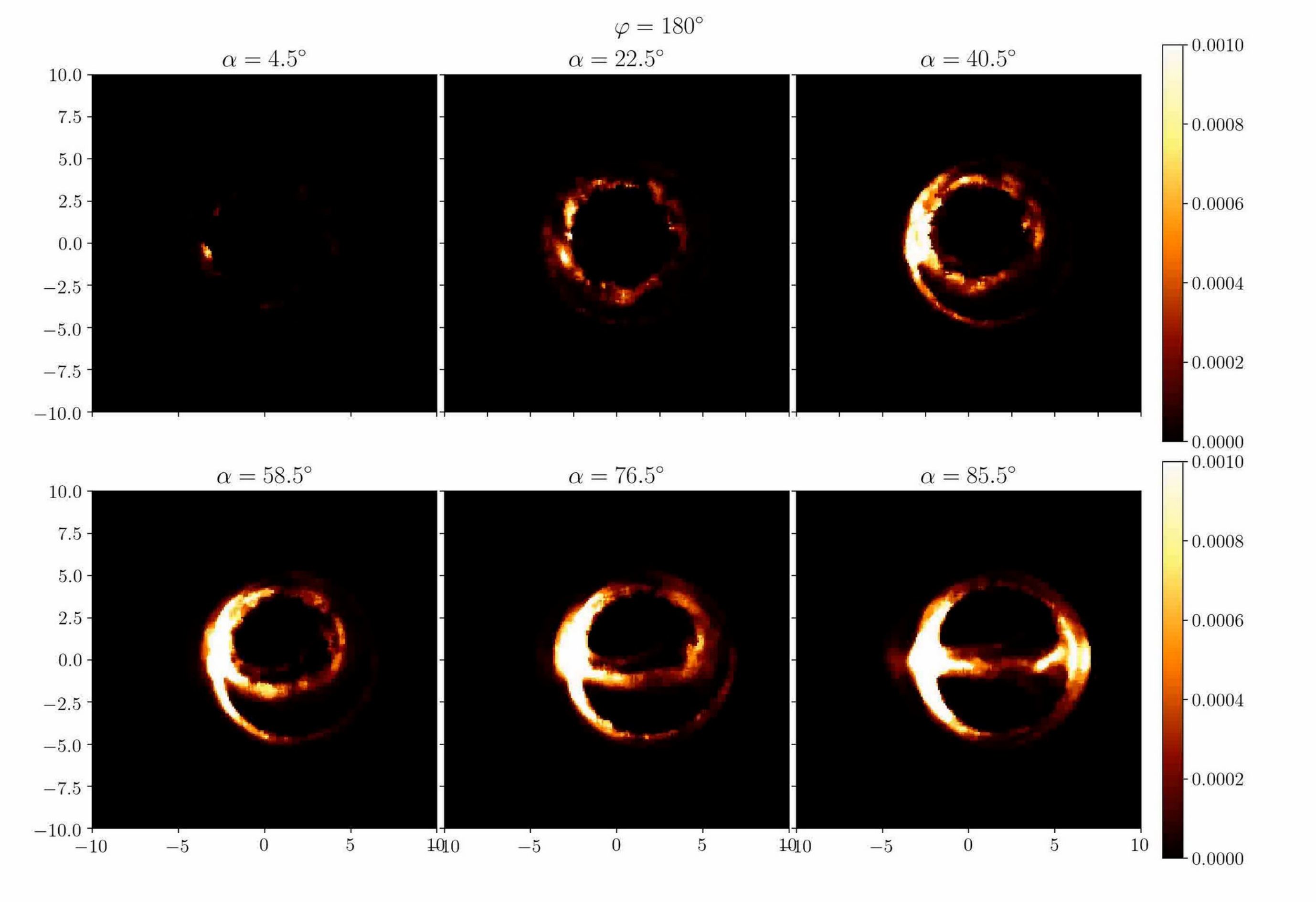
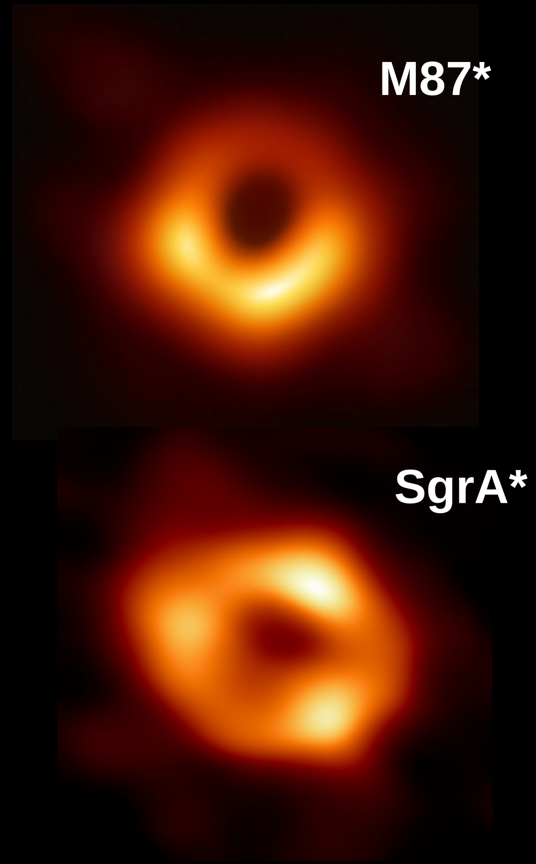


Spinning horizon-scale features : hot spots

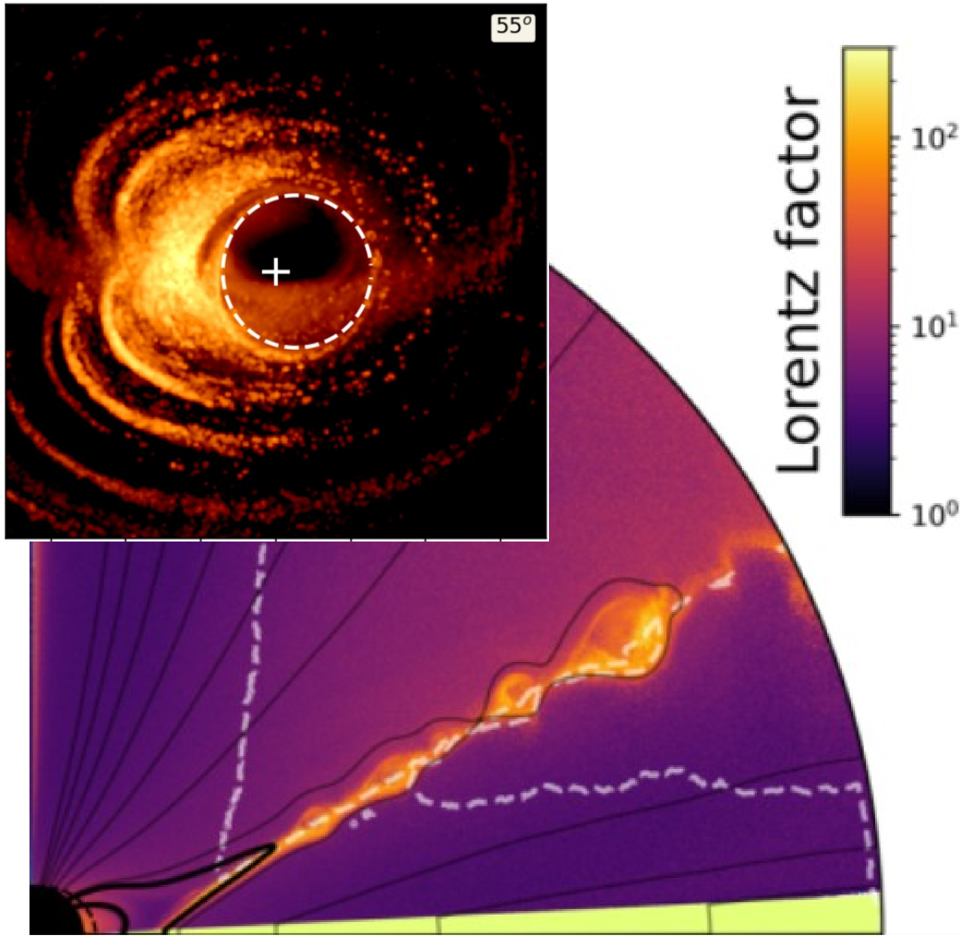


Prediction for future EHT observations ?

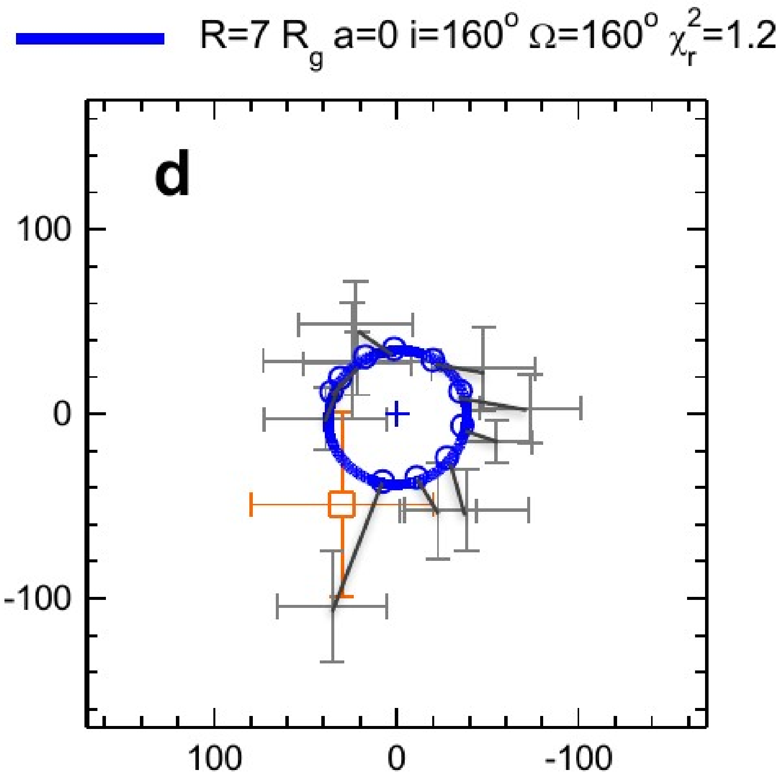


Crinquand et al. (2022)

Black hole coronal heating, SgrA* flare & hot spot ?



El Mellah et al. (2022)



Gravity collaboration (2018)
Aimar et al. 2022

Summary

- Relativistic reconnection is **fast** and **accelerates** particles
- Plasmoid formation & hierarchical merging process connects **micro** **to** **macro scales**
- **Giant plasmoids may be observables** where large-scale current sheets form : e.g., pulsars, pulsar wind nebulae, black hole magnetospheres

  => Reconnection smoking gun ?