HEPRO meeting 2023 | Institut d'Astrophysique de Paris | October 25, 2023 | Paris, France

Magnetar Eruptions and Electromagnetic Fireworks

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Magnetar Eruptions and Electromagnetic Fireworks

Motivation

Magnetars and their transients

Warm-up

High energy emission from the Crab

Magnetospheric eruptions

Instabilities of the magnetar magnetosphere

arXiv:2302.07273

Fast Radio Bursts

Compressed reconnection beyond the light cylinder

arXiv:2203.04320

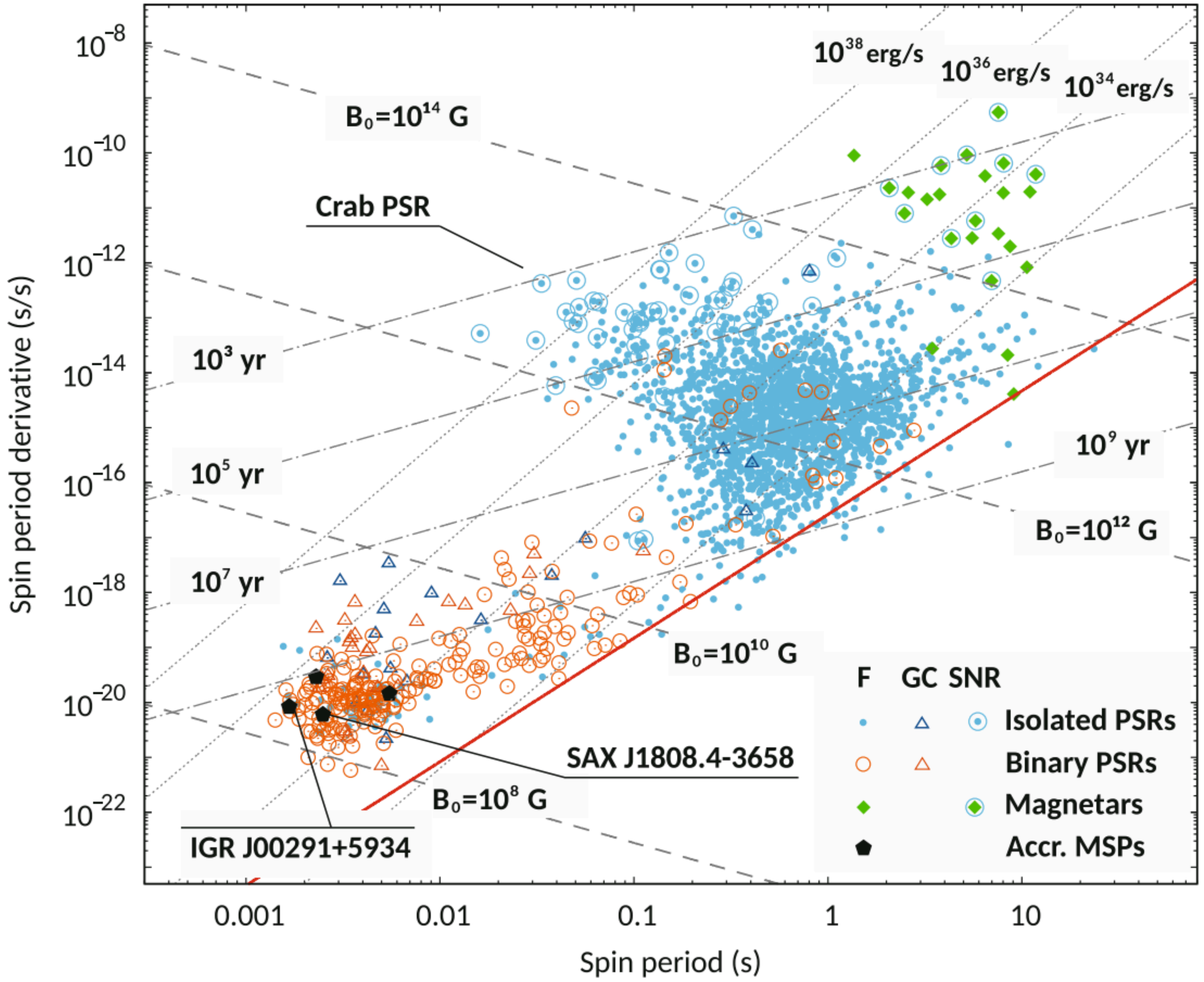
Non-eruptions shine

Safety First: Flux tube (in)stability

arXiv: coming soon

Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods



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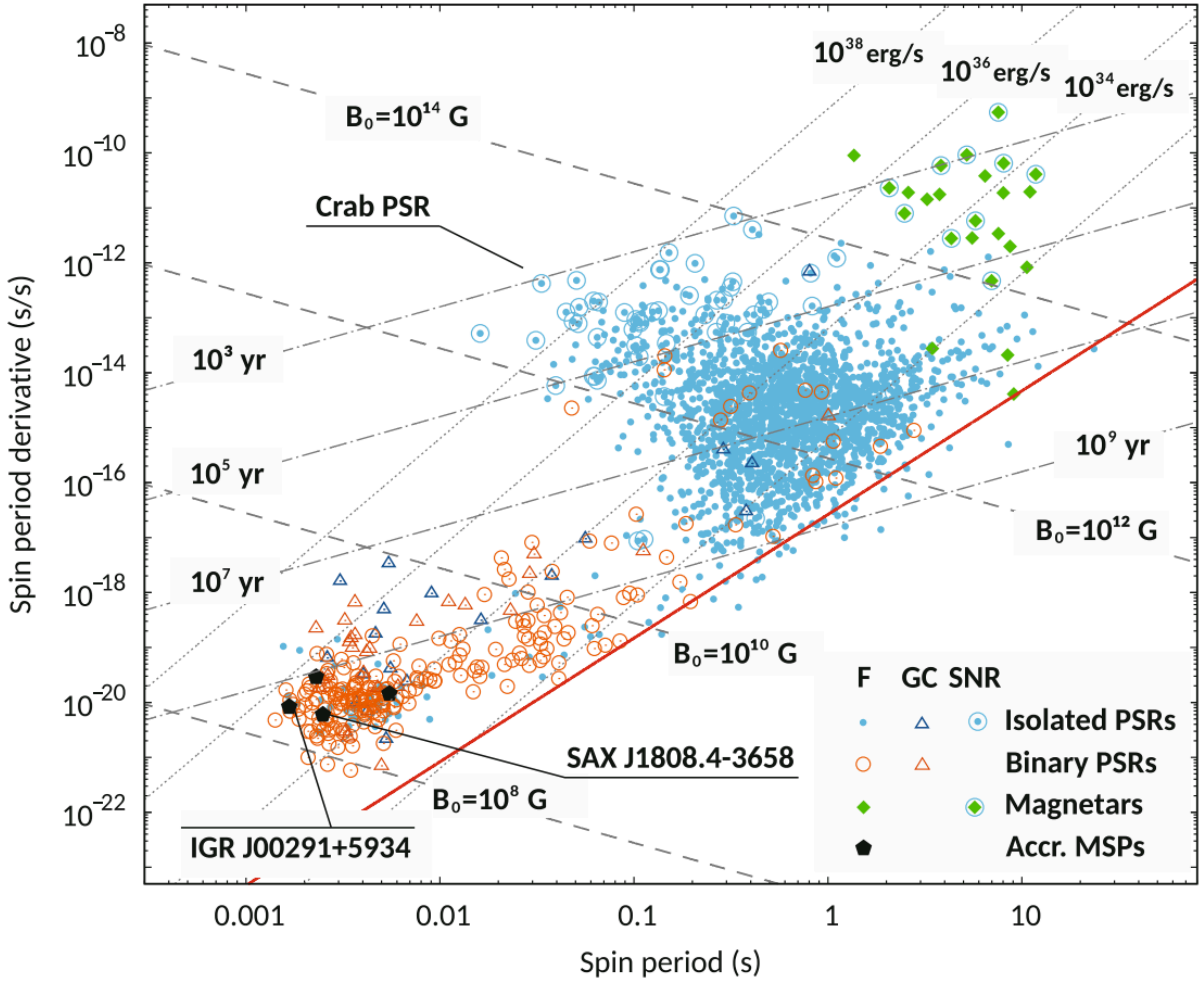
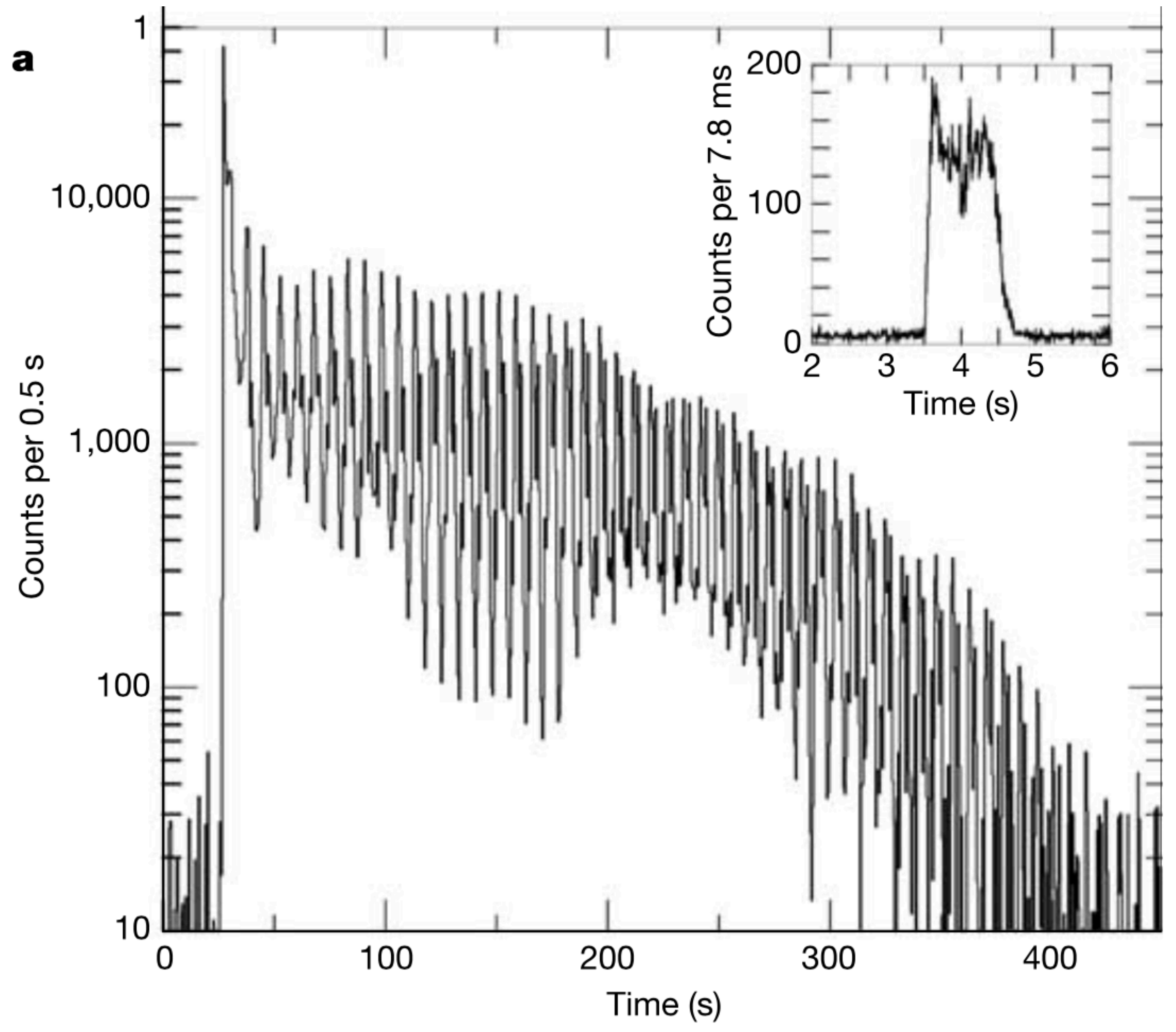


Rich set of X-ray giant flares and outbursts



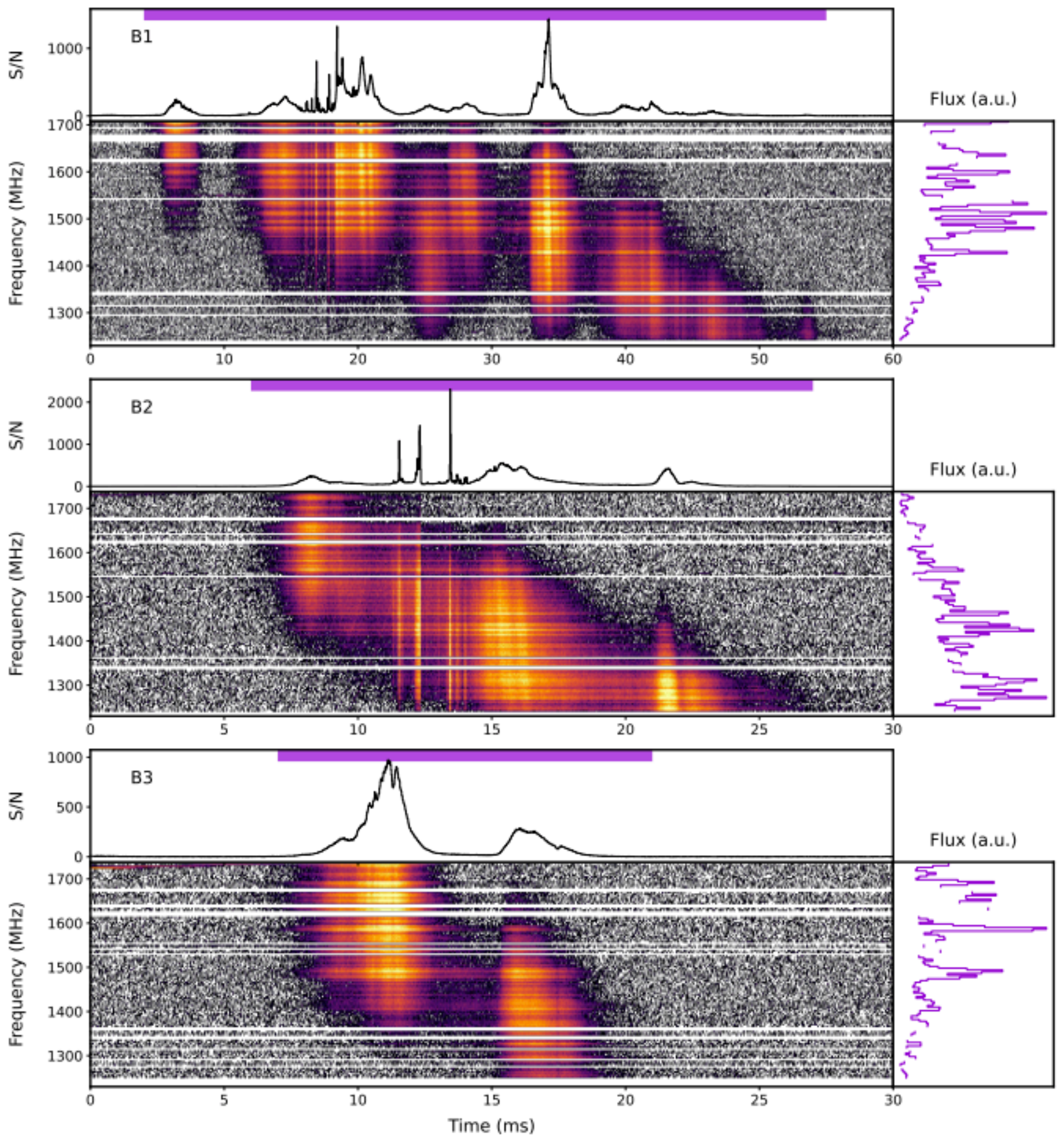
What makes them?

Di Salvo et al. (2021); Hurley et al. (2005); Ravi et al. (2023)

Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods

Are FRBs coming from magnetars? At least some.



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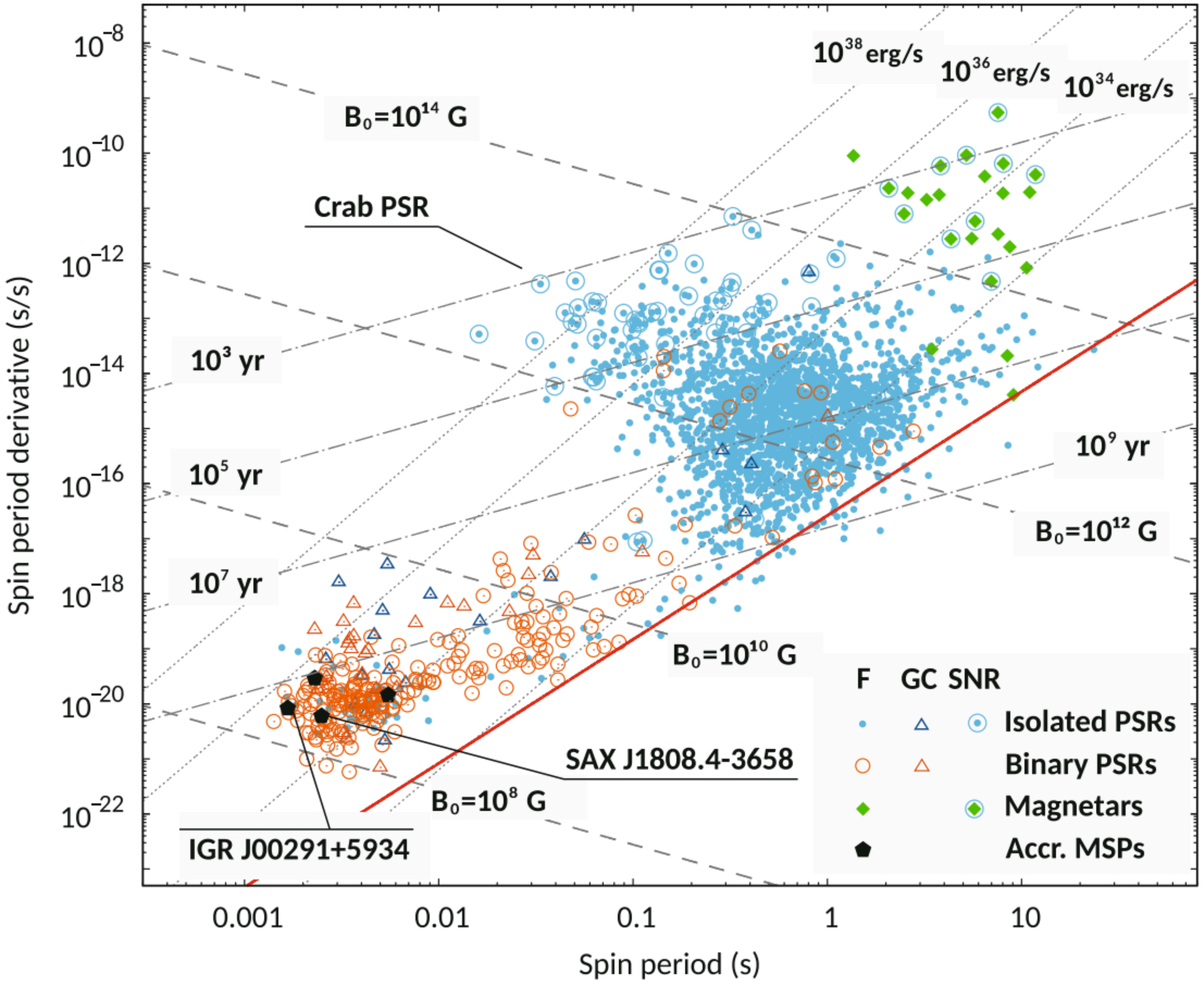
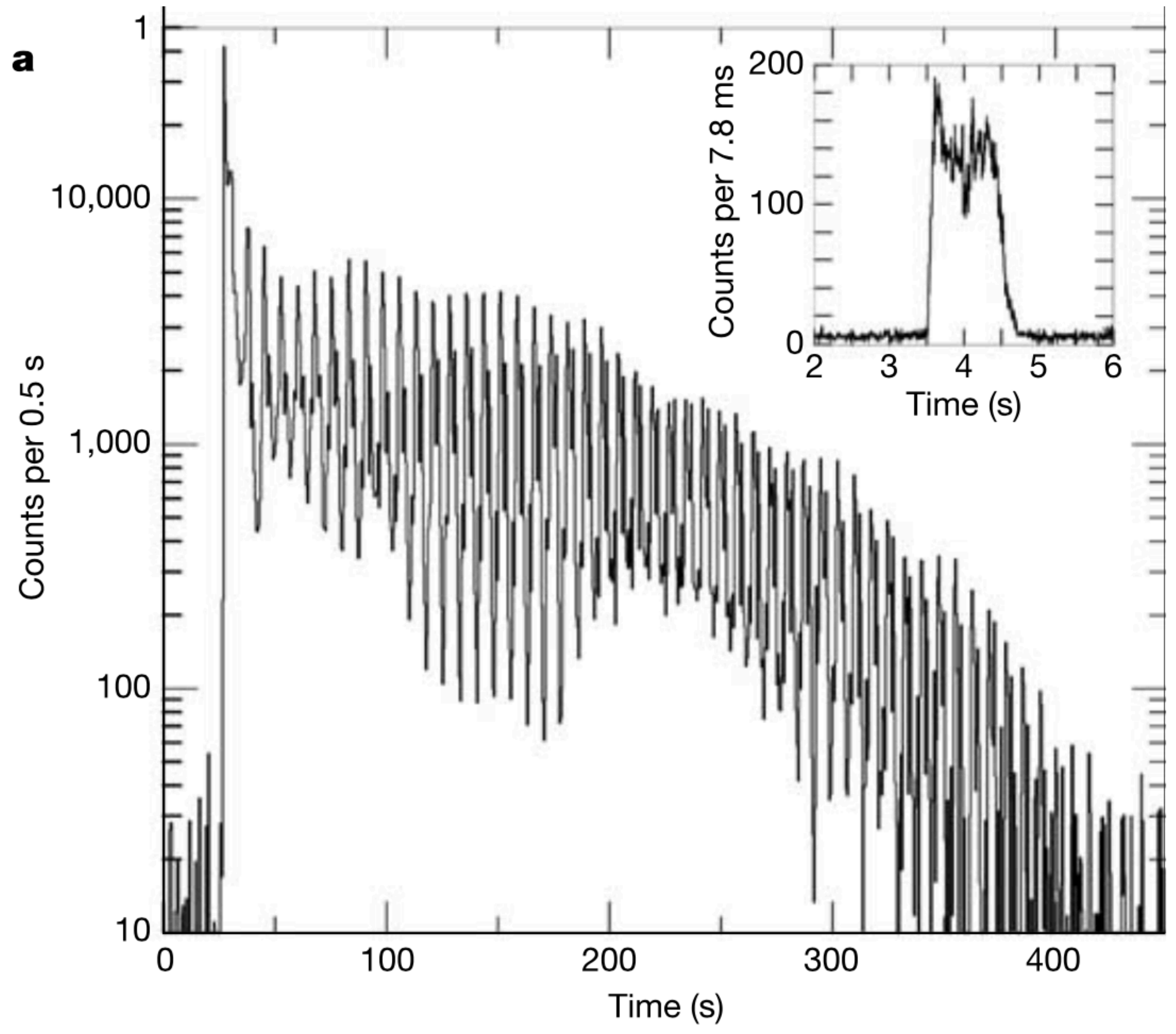


Rich set of X-ray giant flares and outbursts



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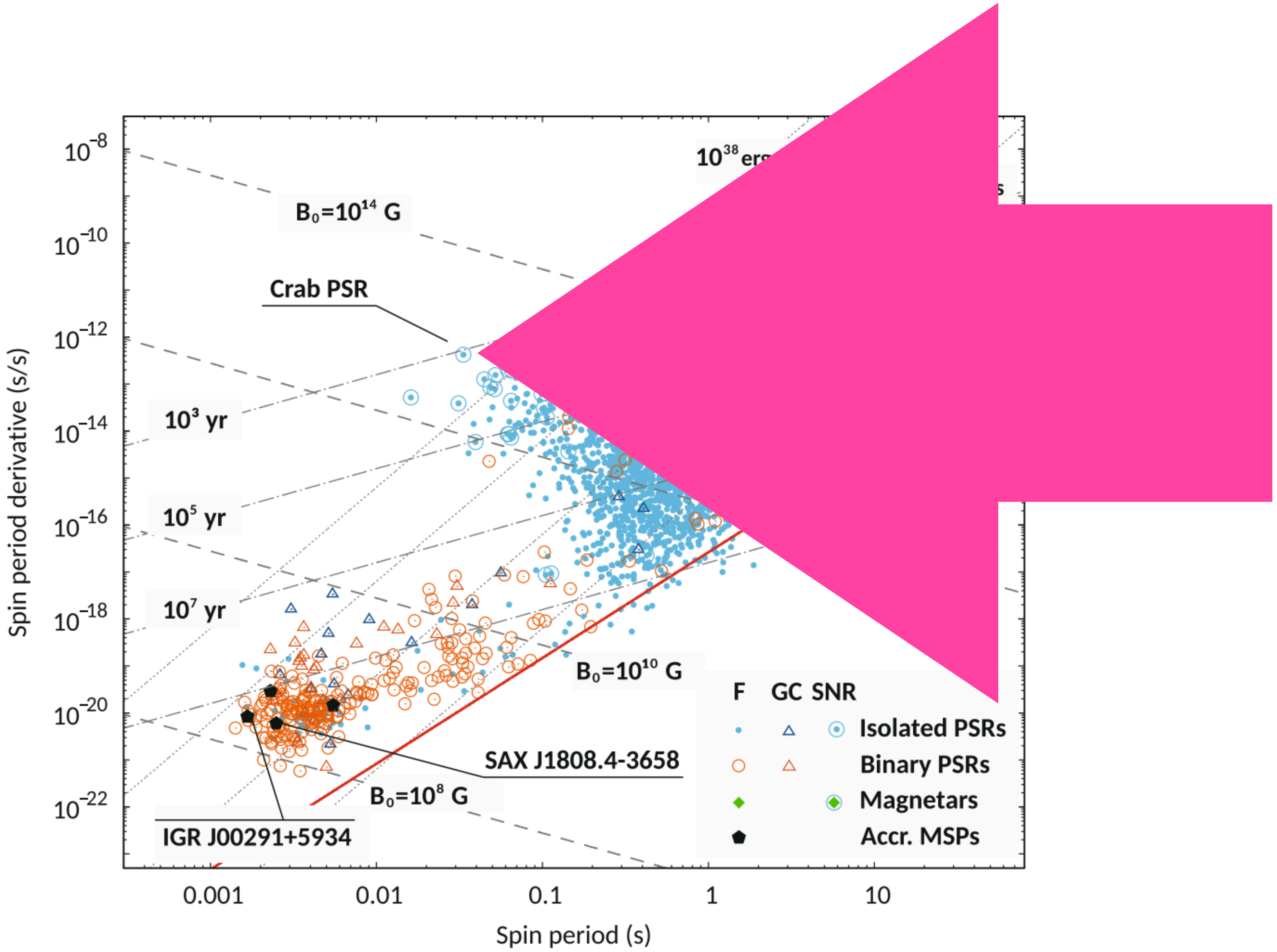
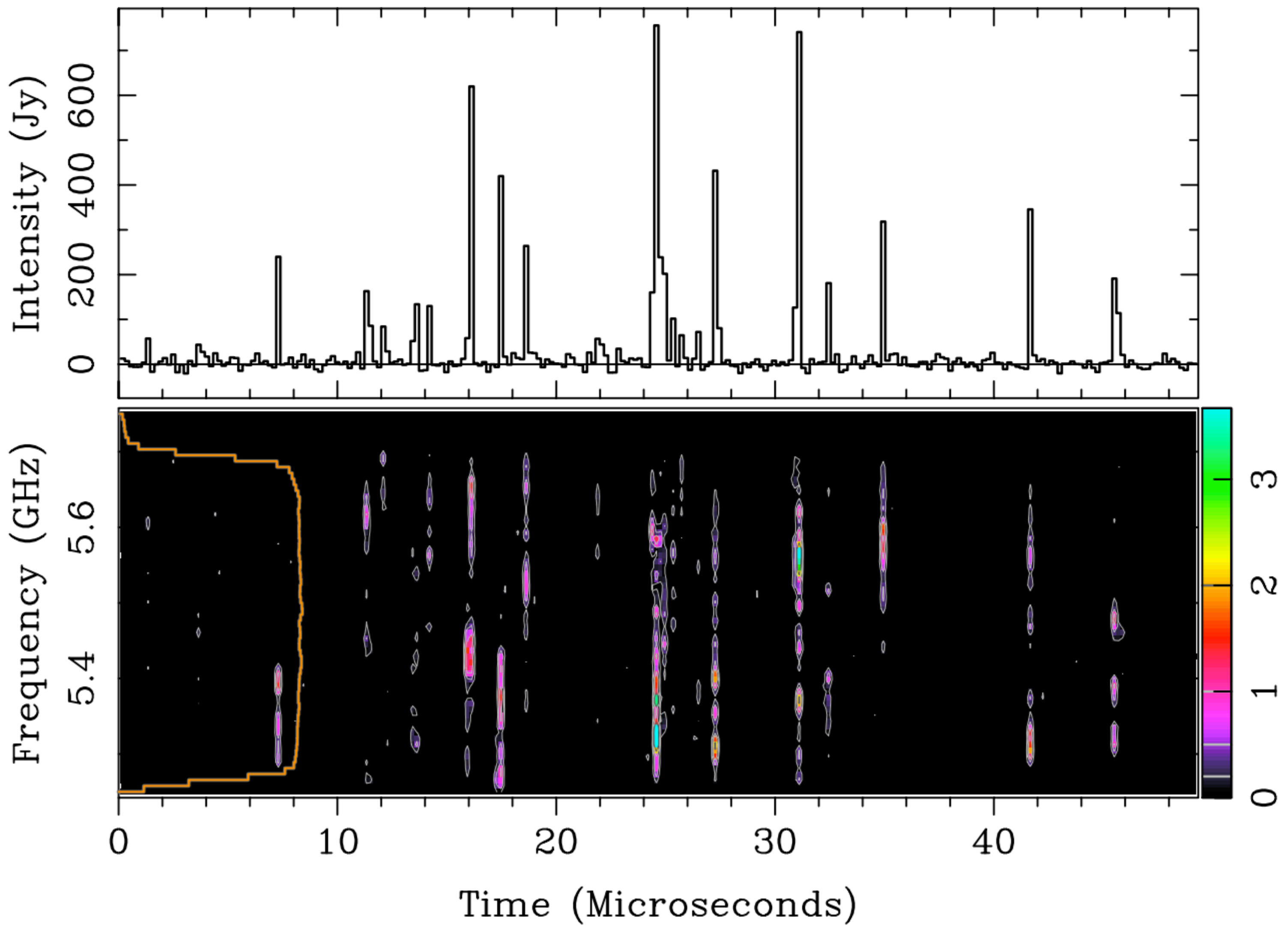


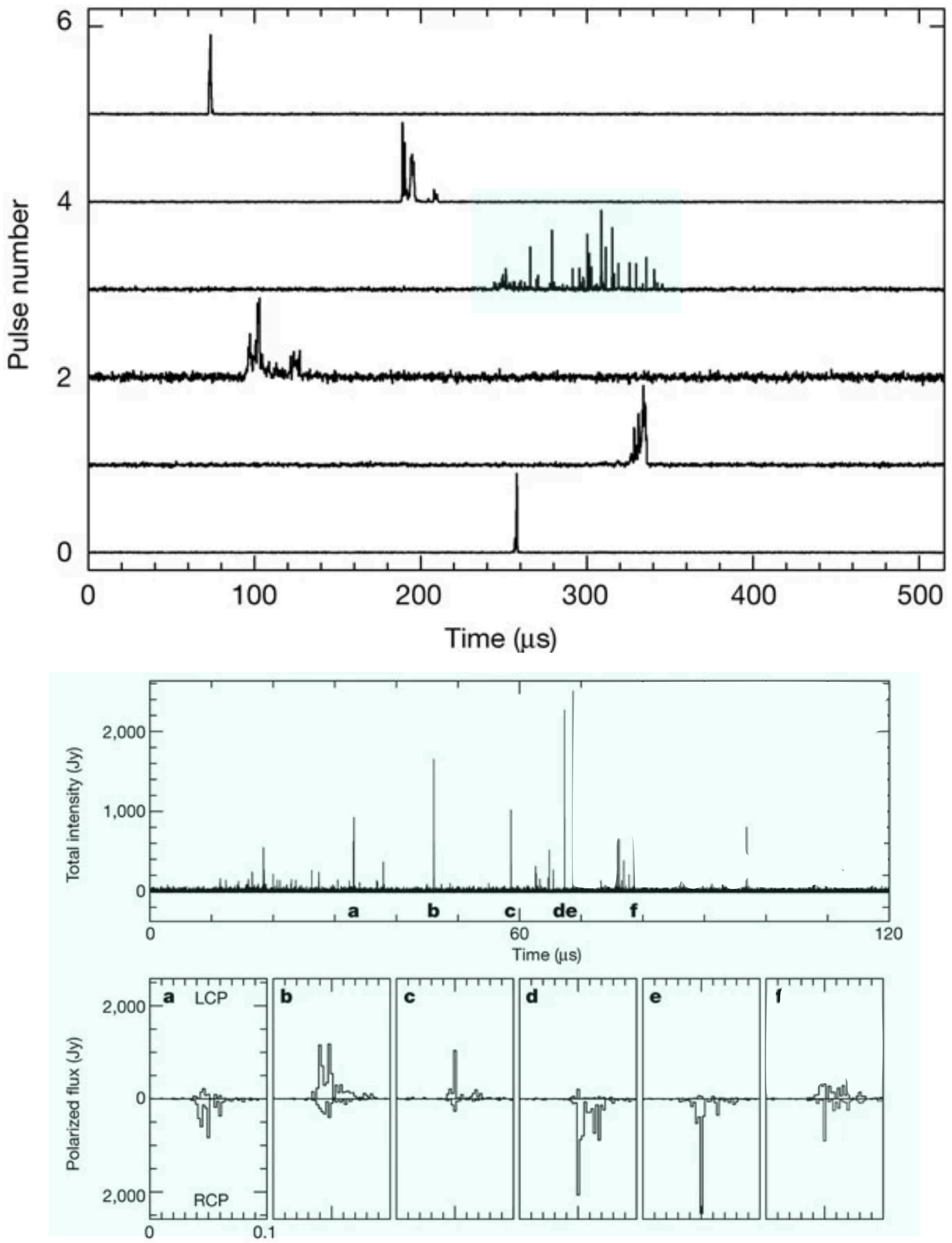
Coherent high energy signals from the Crab

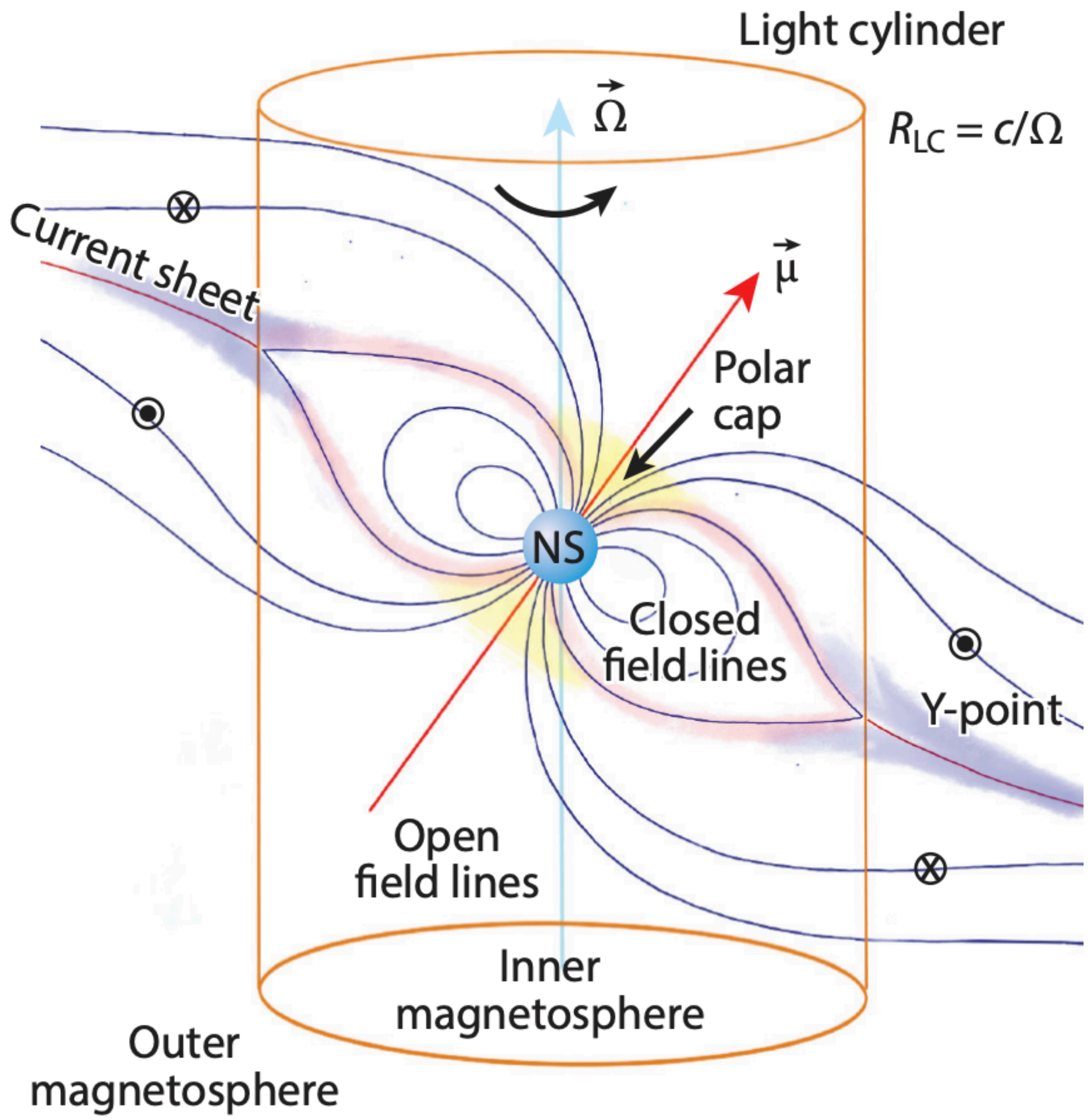
Non-phased giant pulses and nano-shots hint efficient magnetic energy tapping

Observations (nano-shots)



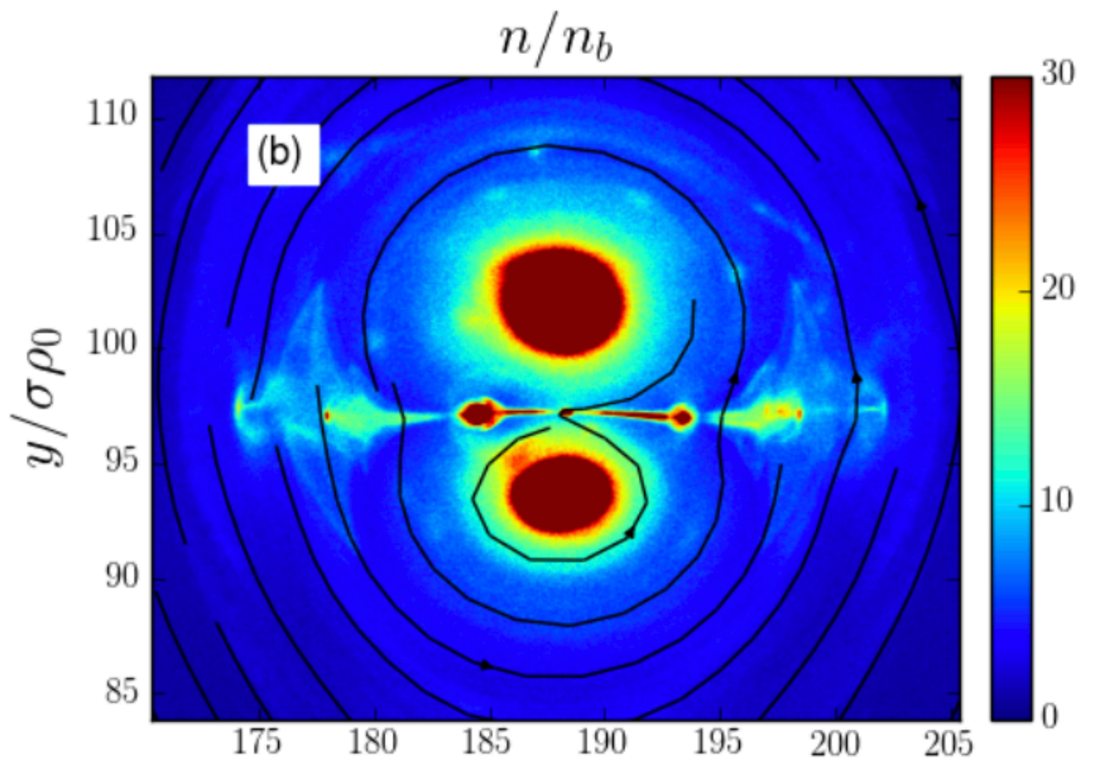
Observations (giant pulses and nano-shots)

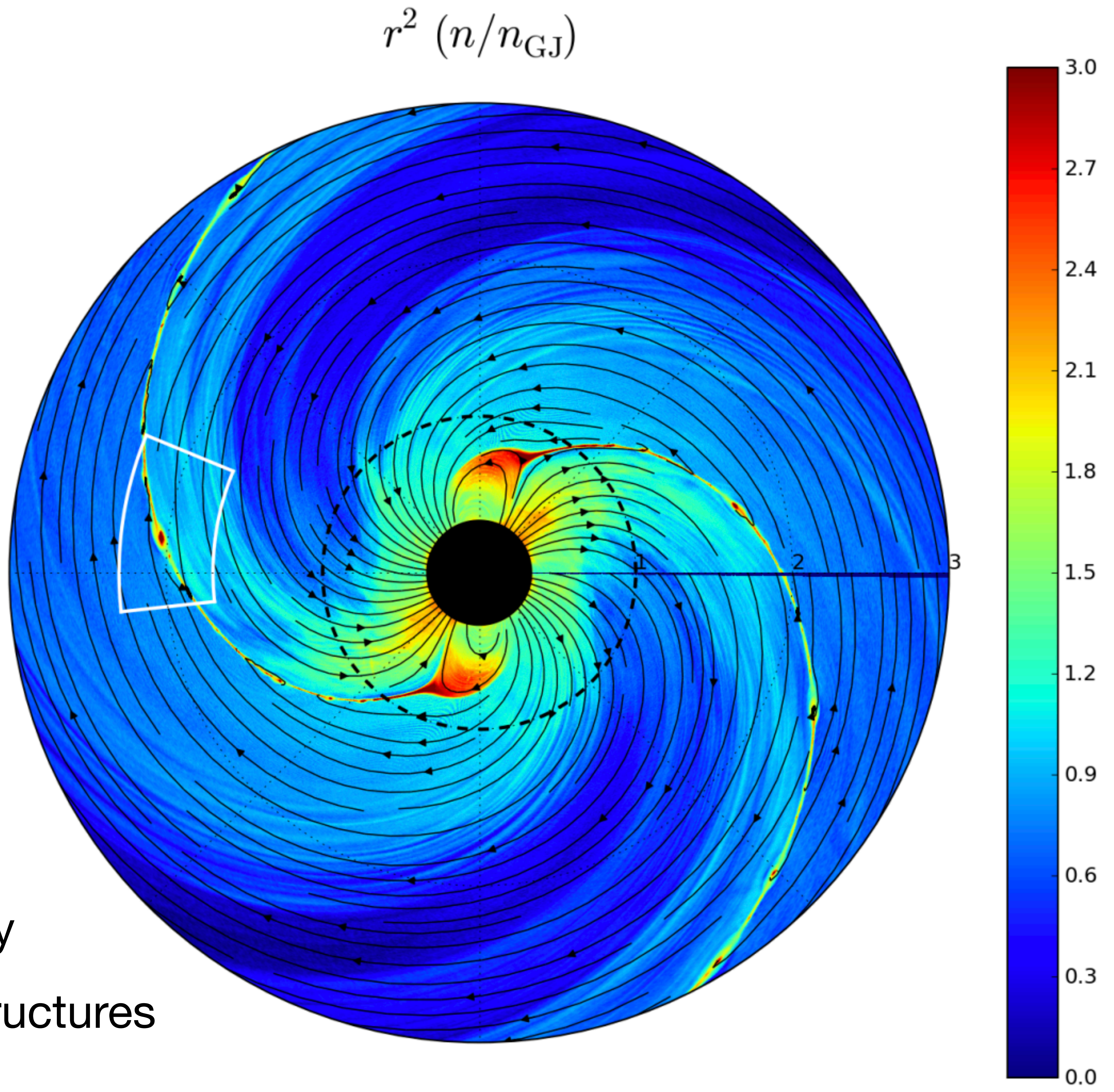


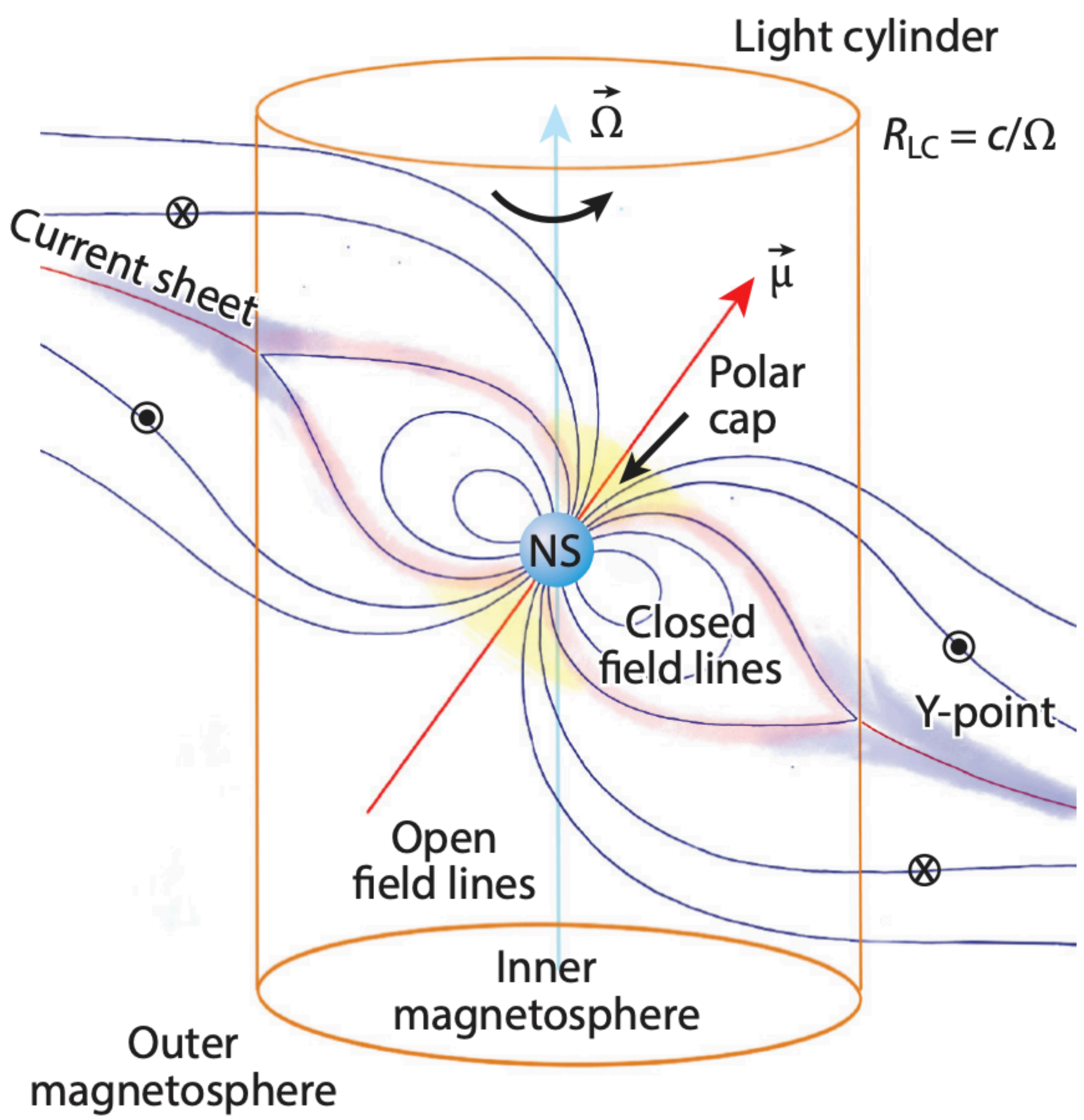


Plasmoid mergers as short duration ‘shots’

Currents of secondary reconnection layers induce high-frequency fast waves







Fast waves injected by **merging magnetic islands** (plasmoids) may explain this time and frequency structures with $S_{\rm fast} \sim 10^{-4} B_0^2$.

Philippov et al. (2019)

Plasmoid mergers as short duration 'shots'

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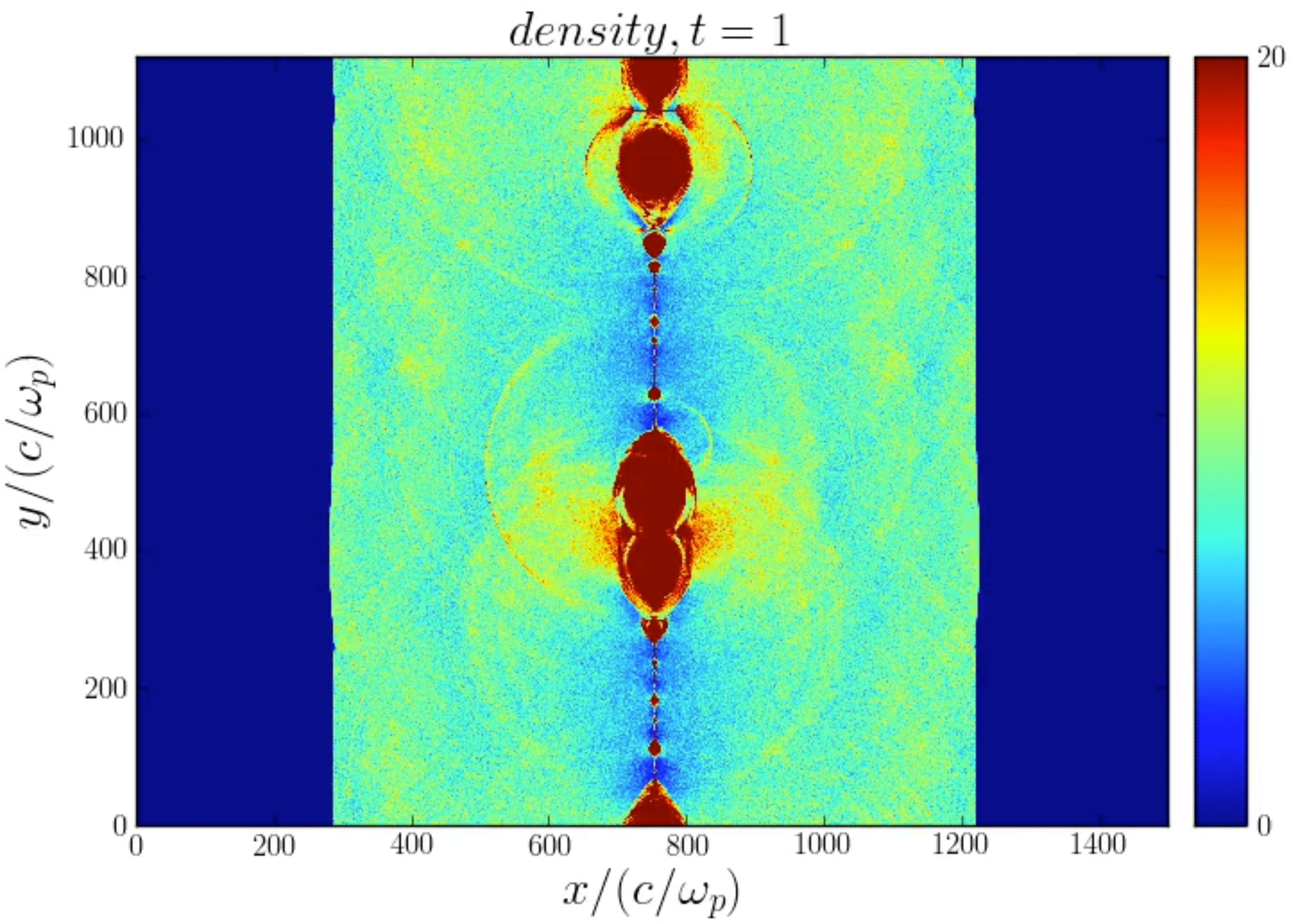

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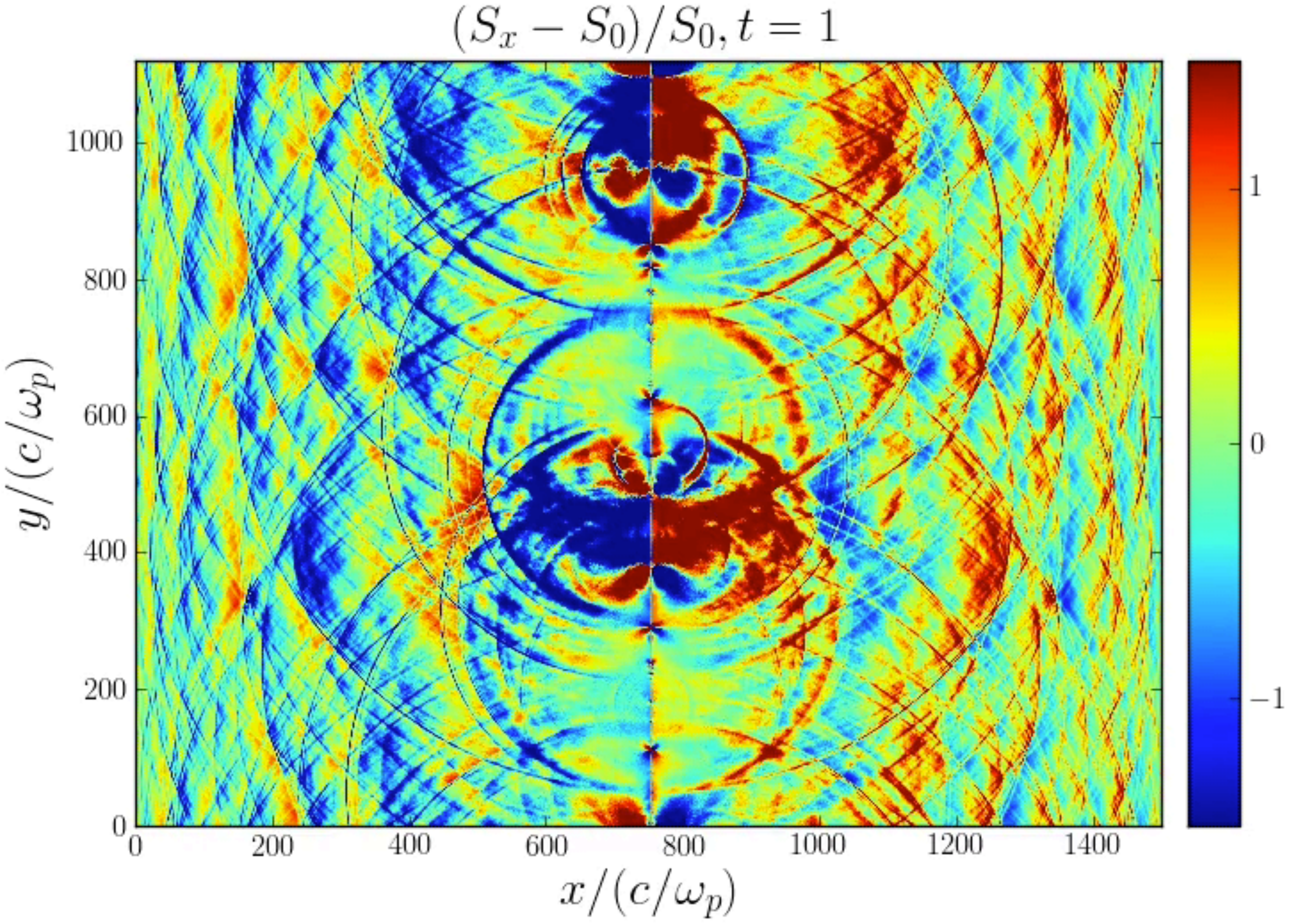
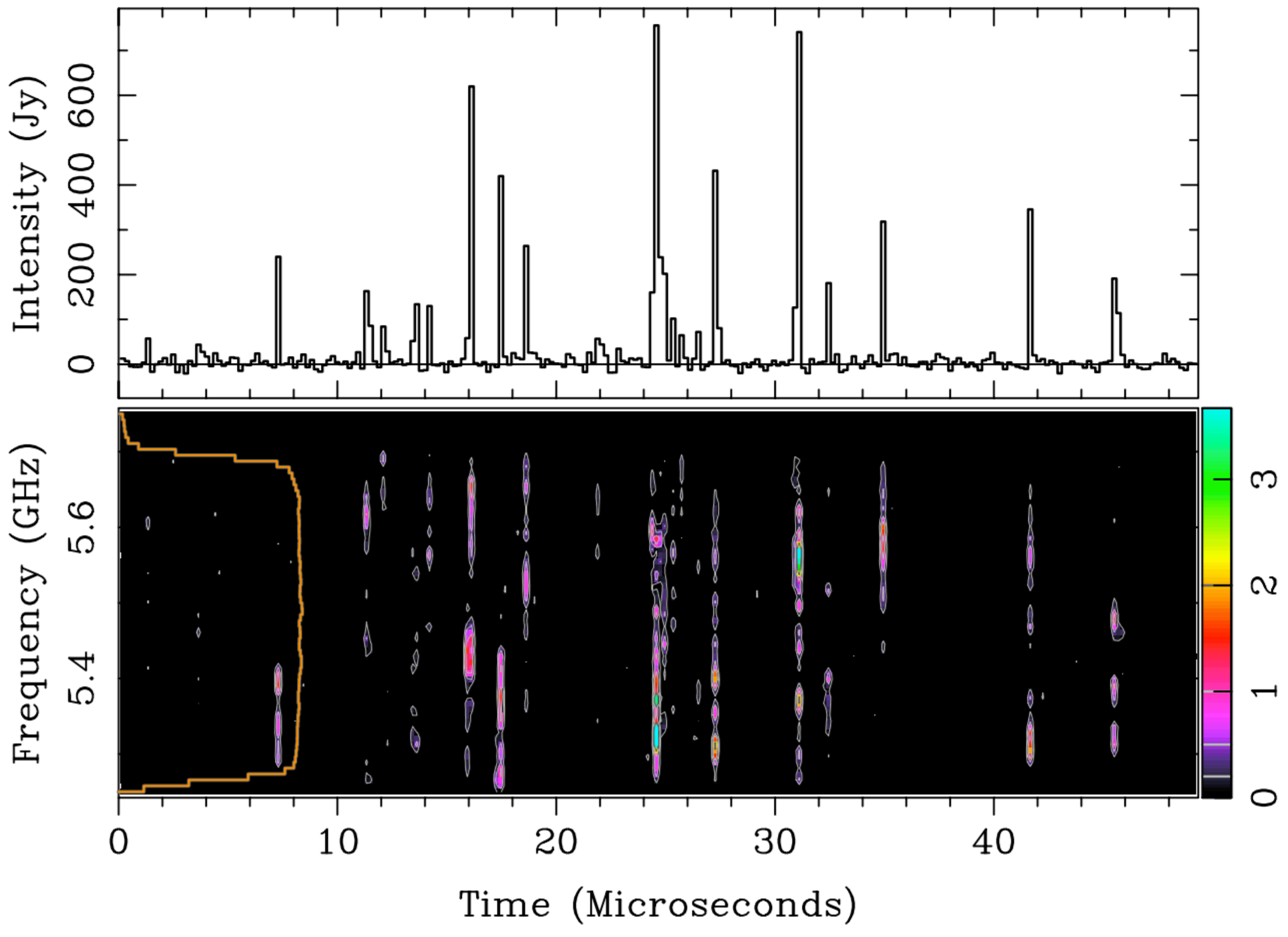


Eilek & Hankins (2016); Lyubarsky (2020); Philippov et al. (2019)

Radio emission from reconnection

Frequency estimates for pulsar nano shots

Observations (nano-shots)



The **frequency of the outgoing waves**

is given by $\nu = \frac{c}{\xi a'}\Gamma$

a': reconnection layer size

ξ: ratio of plasmoid size to reconnection layer thickness size (10-100)

Γ: boost into current sheet rest frame

For the **Crab** one finds nanosecond pulses with

$a' \sim 1$ meter $\xi \sim 10 - 100$, $\Gamma = 10 - 100$ } $\nu \sim 0.03 - 3$ GHz

An approximate current sheet width follows from

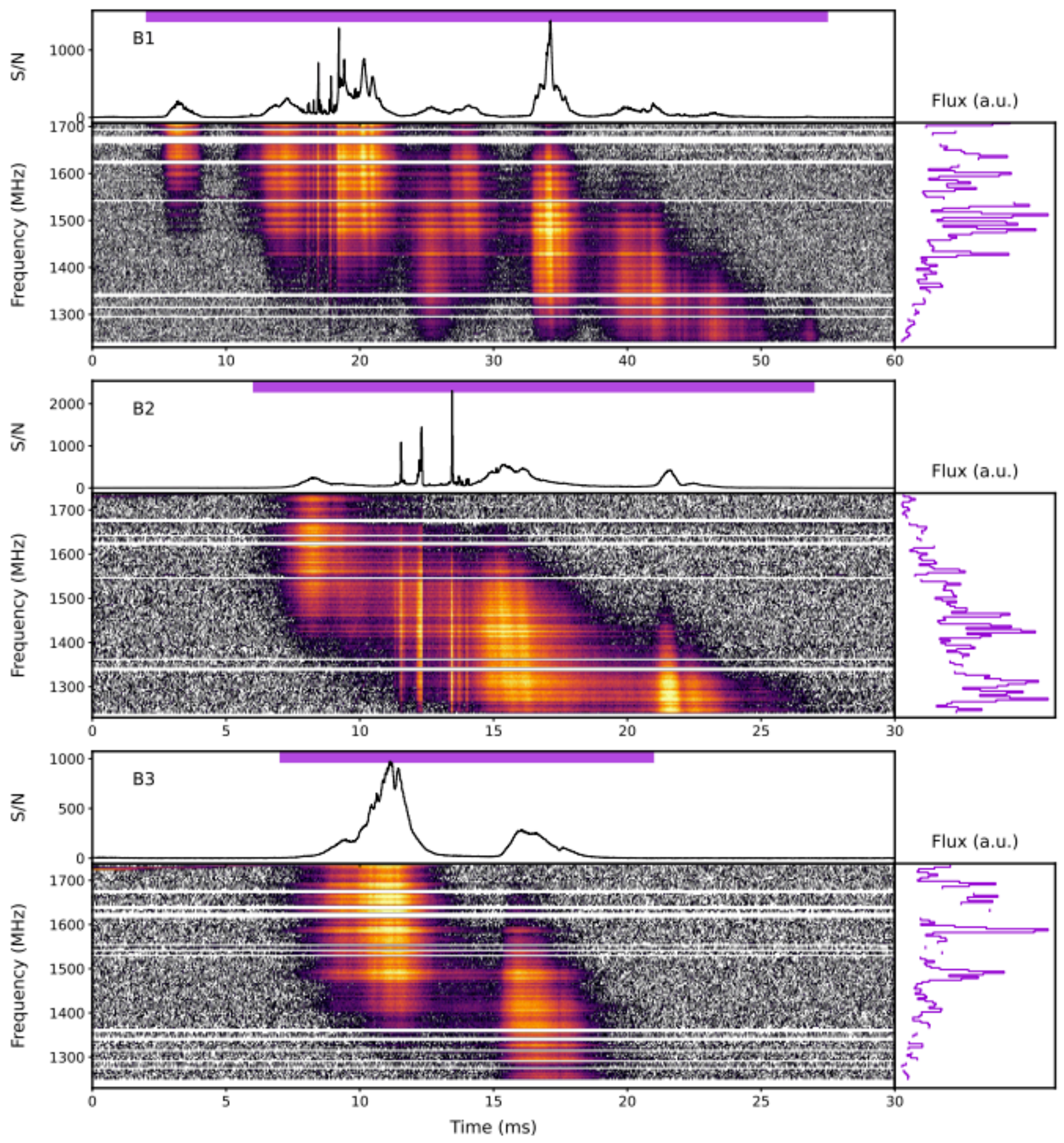
$$a' \sim r_e^{-1/2}\left(\frac{c}{\omega_B}\right)^{3/2} = 1.3\left(\frac{B}{10^6 G}\right)^{-3/2} m$$

For **Vela** the parameter range is already different: $a' \sim 100$ meters

Radio emission from reconnection

What about FRBs from magnetars?

Observations (FRBs)



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a': reconnection layer size
ξ: ratio of plasmoid size to reconnection layer thickness size (10-100)
Γ: boost into current sheet rest frame

For $P \sim 1s$ rotators we find

$a' \sim 1.4 \times 10^3$ meters
$\xi \sim 10 - 100$
$\Gamma = 100$

} $\nu \sim 0.2 - 2$ MHz

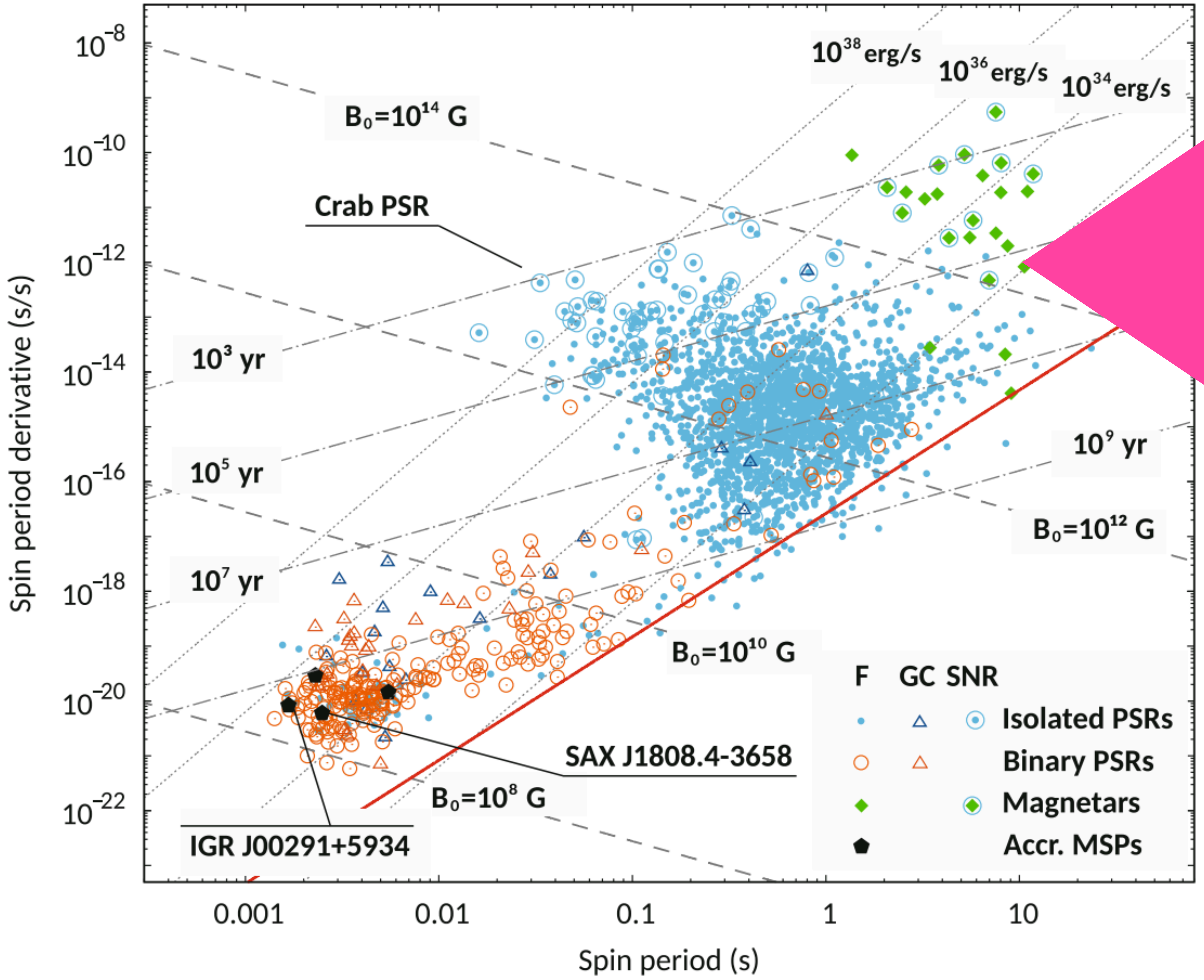
AND we need **millisecond duration wave-packets**!

How do we get waves with FRB duration and frequency?

Di Salvo et al. (2021)

Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods

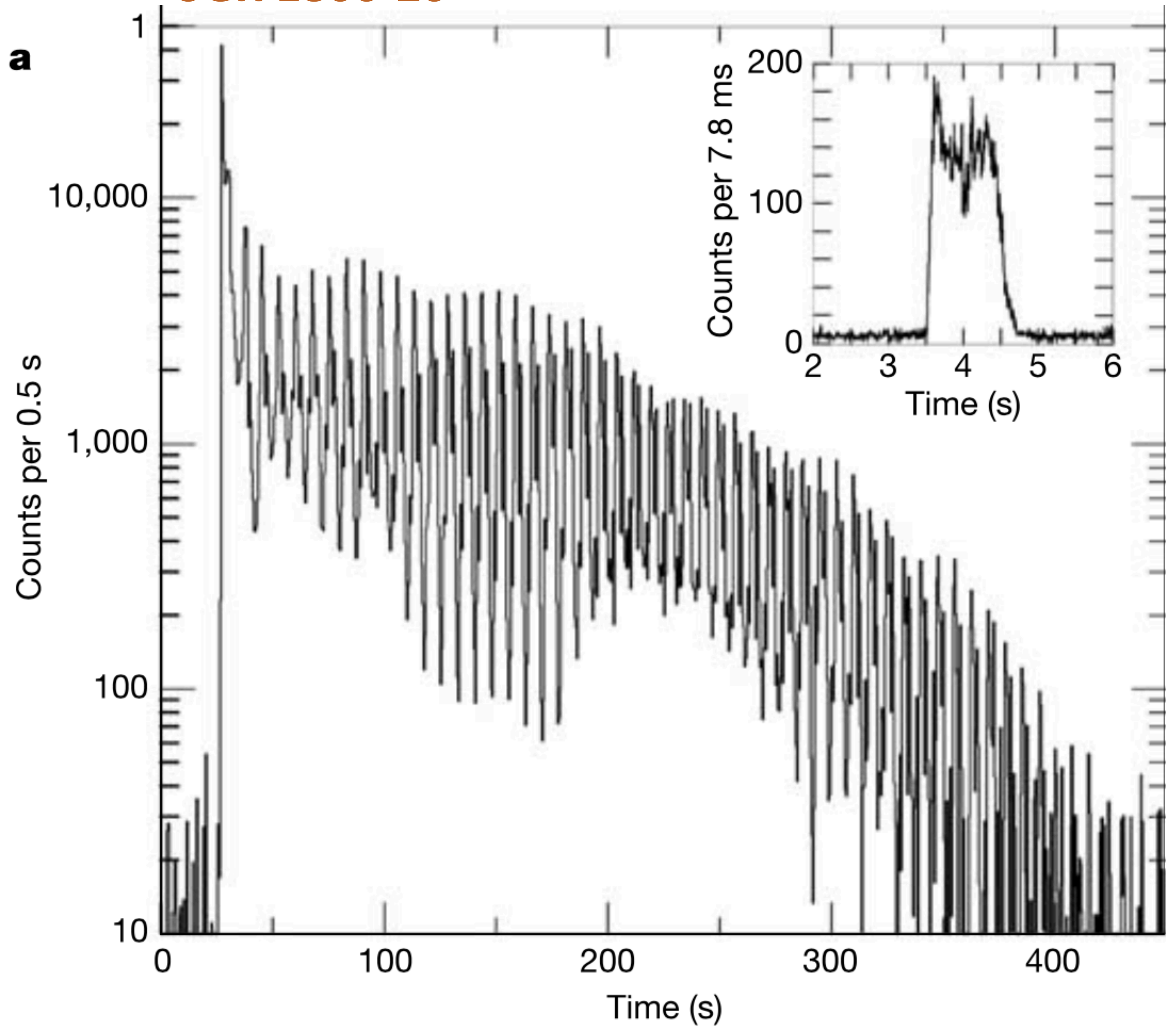


One thing we know about magnetars:

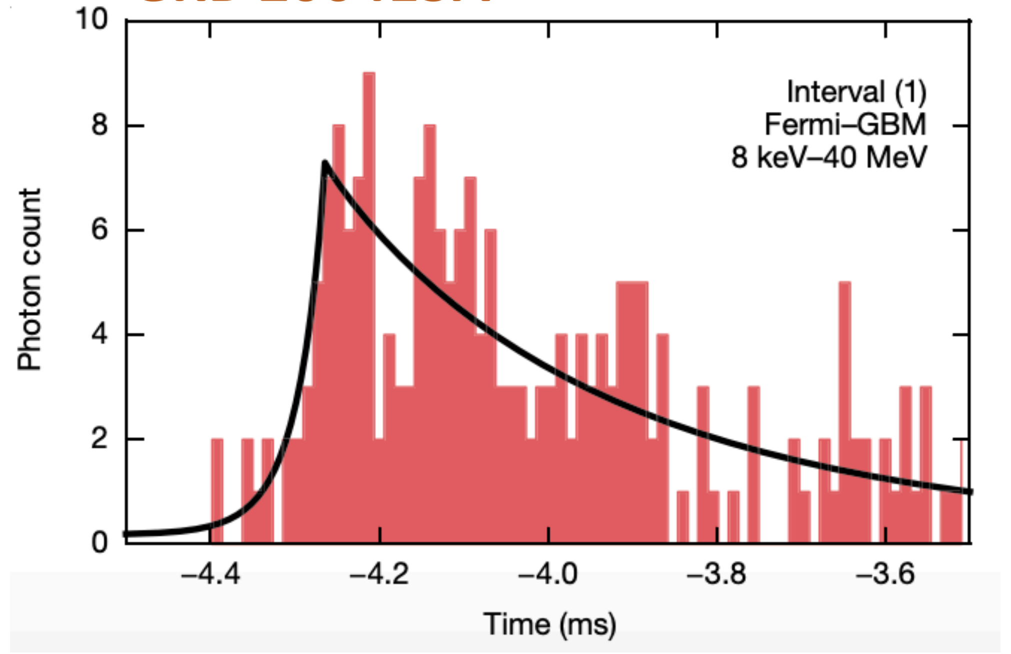
They flare! A lot..

Observations (Giant Flares)

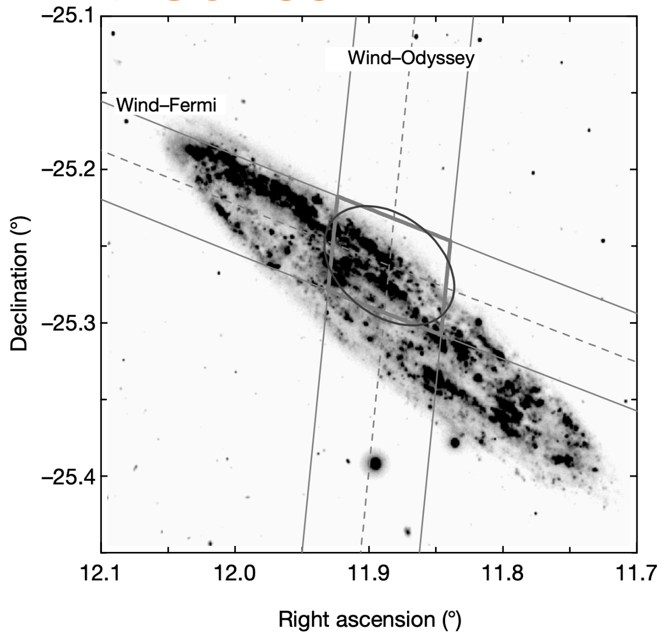
SGR 1806-20



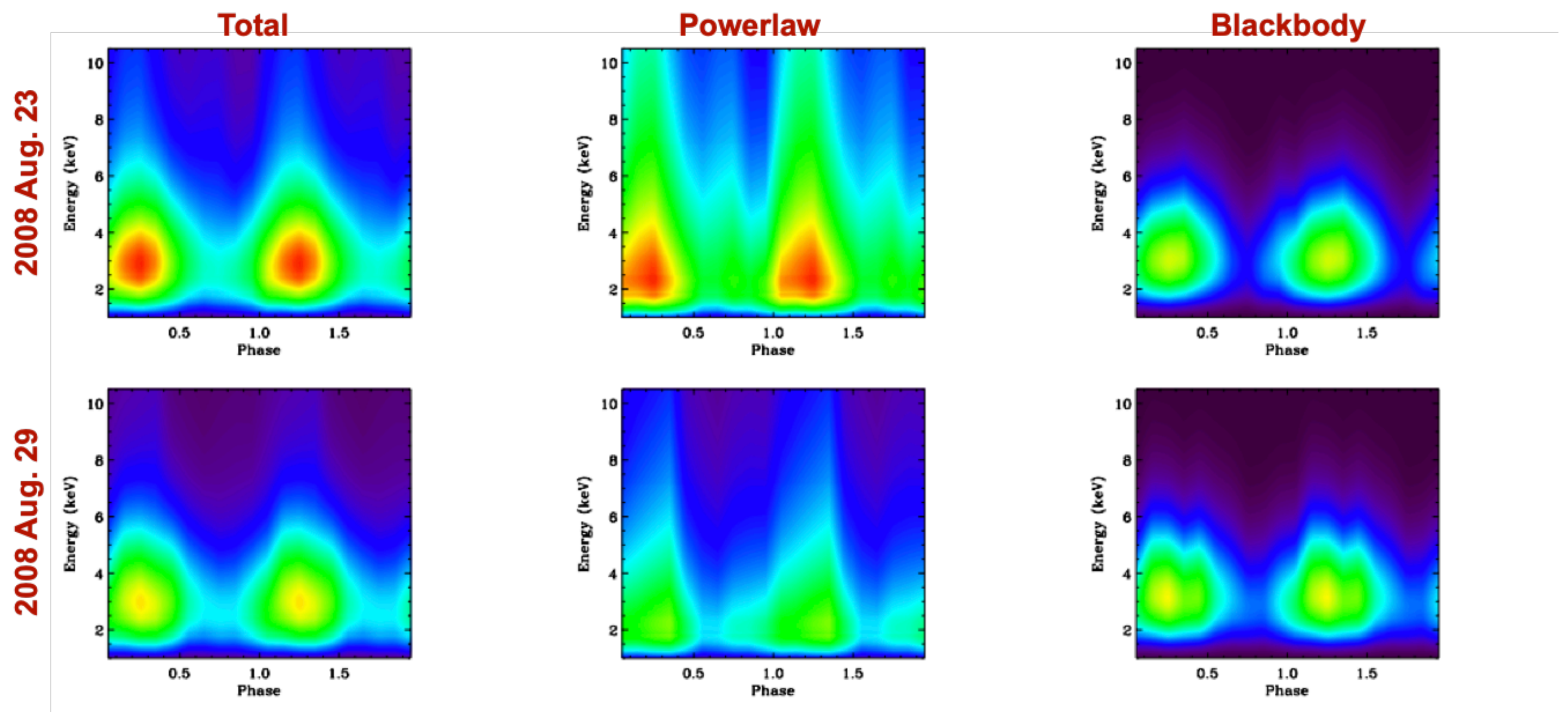
GRB 200415A

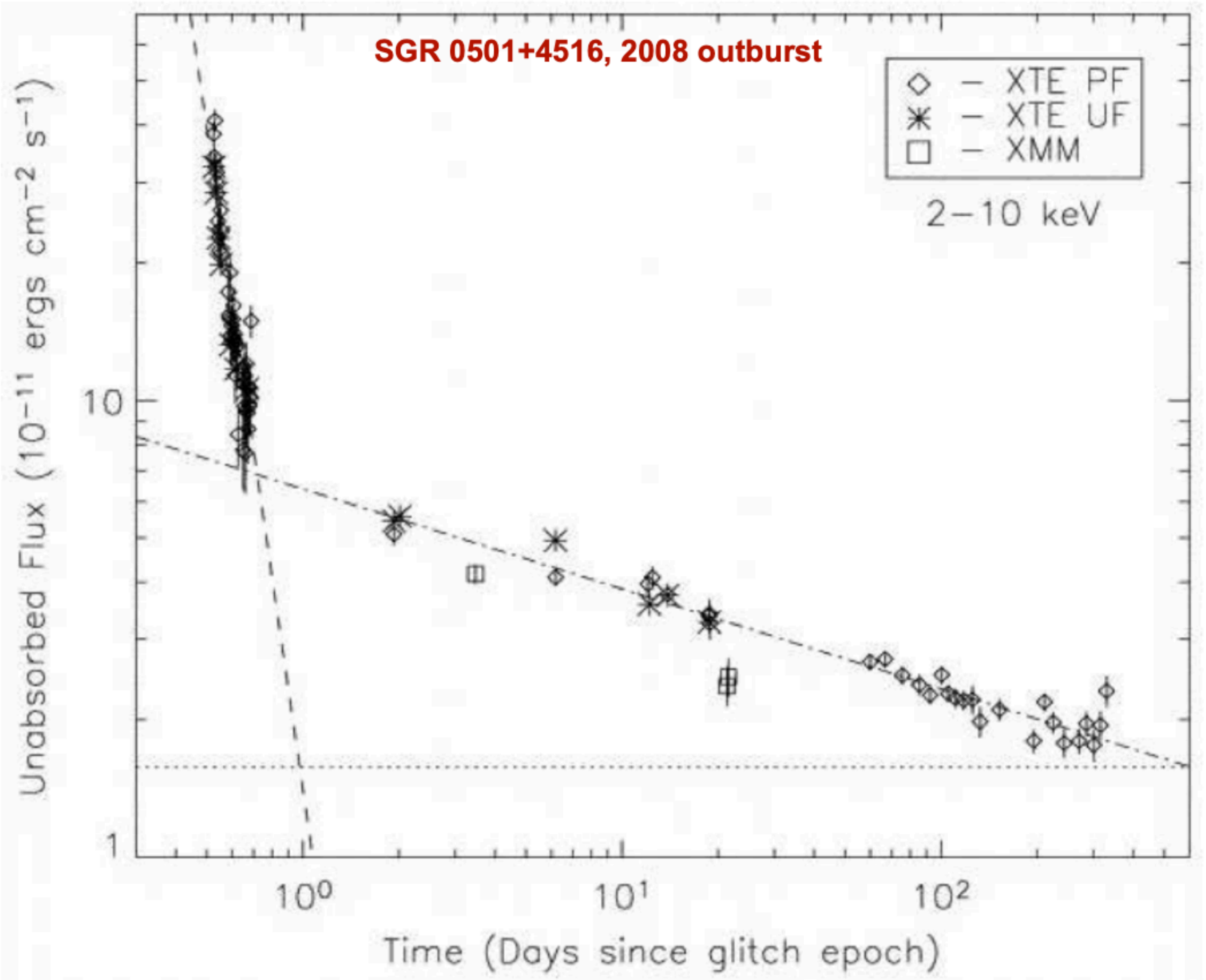


NGC 253

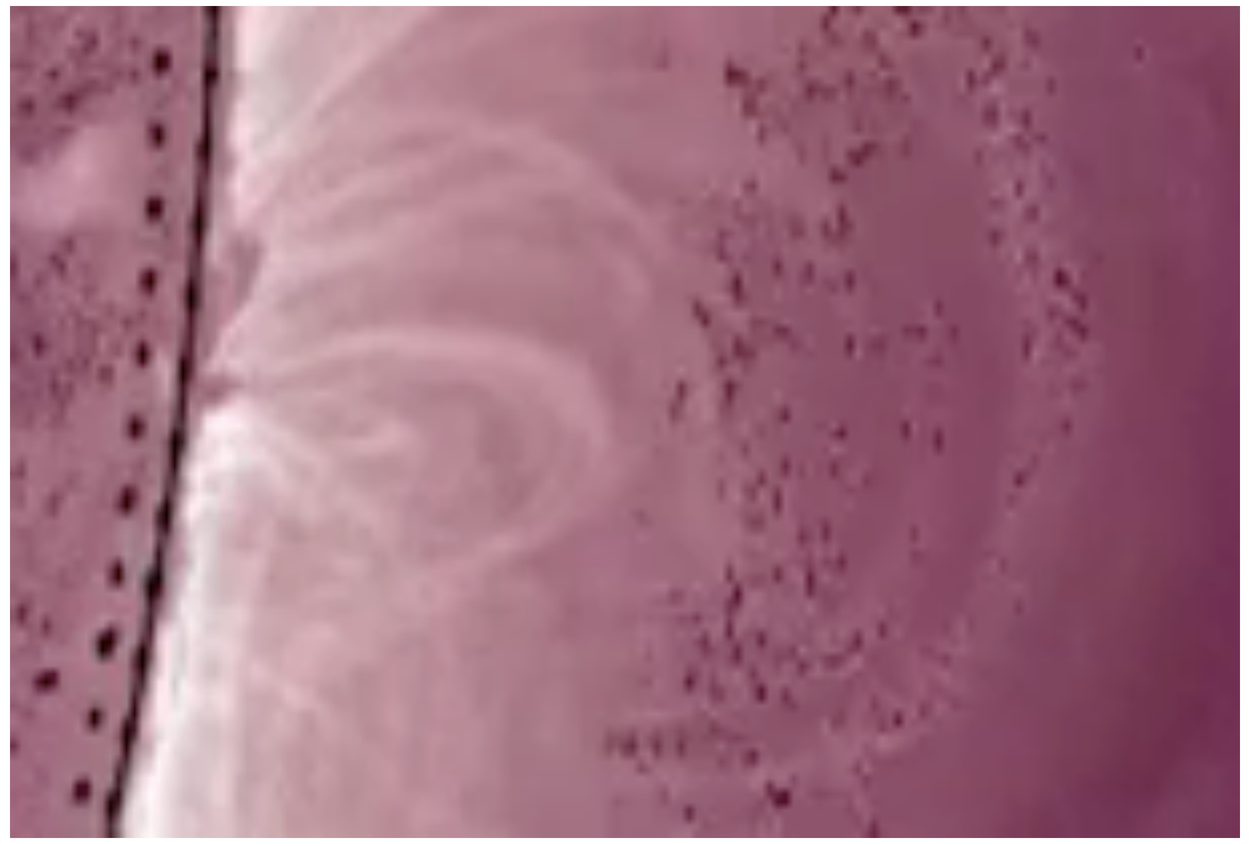


Observations (Outbursts)





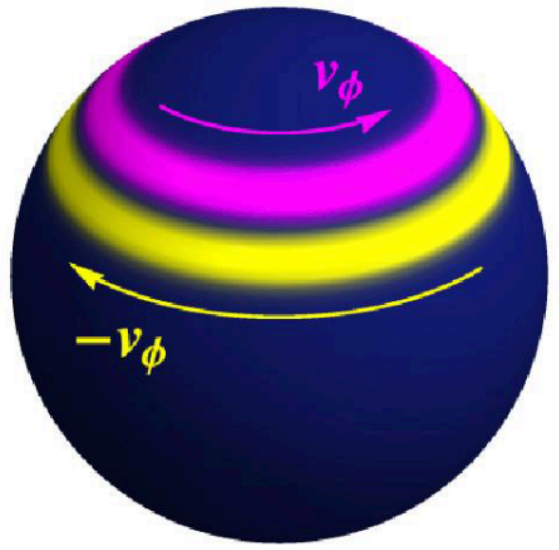
The Sun in extreme ultraviolet



Can there be an analogy to the Sun's CMEs?

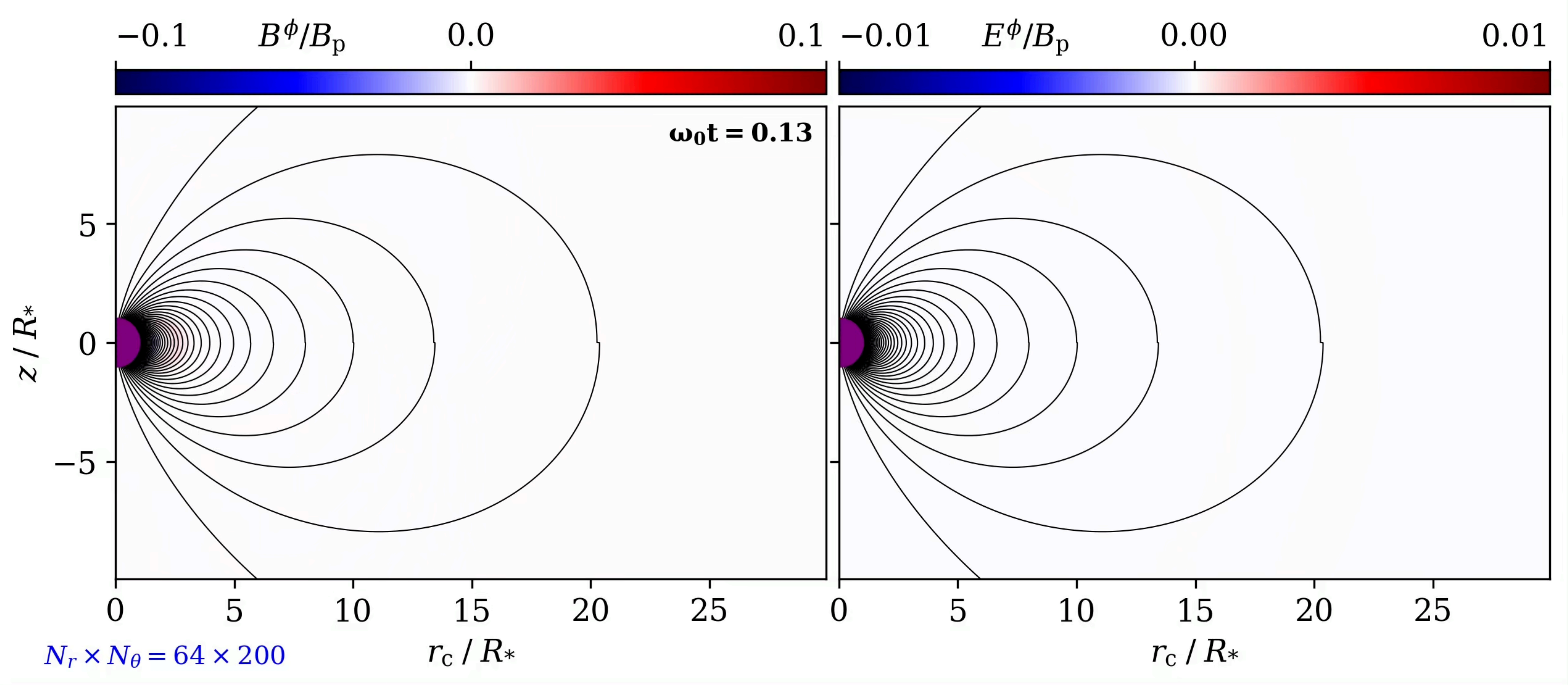
Giant-Flare-like energy dissipation in 2D

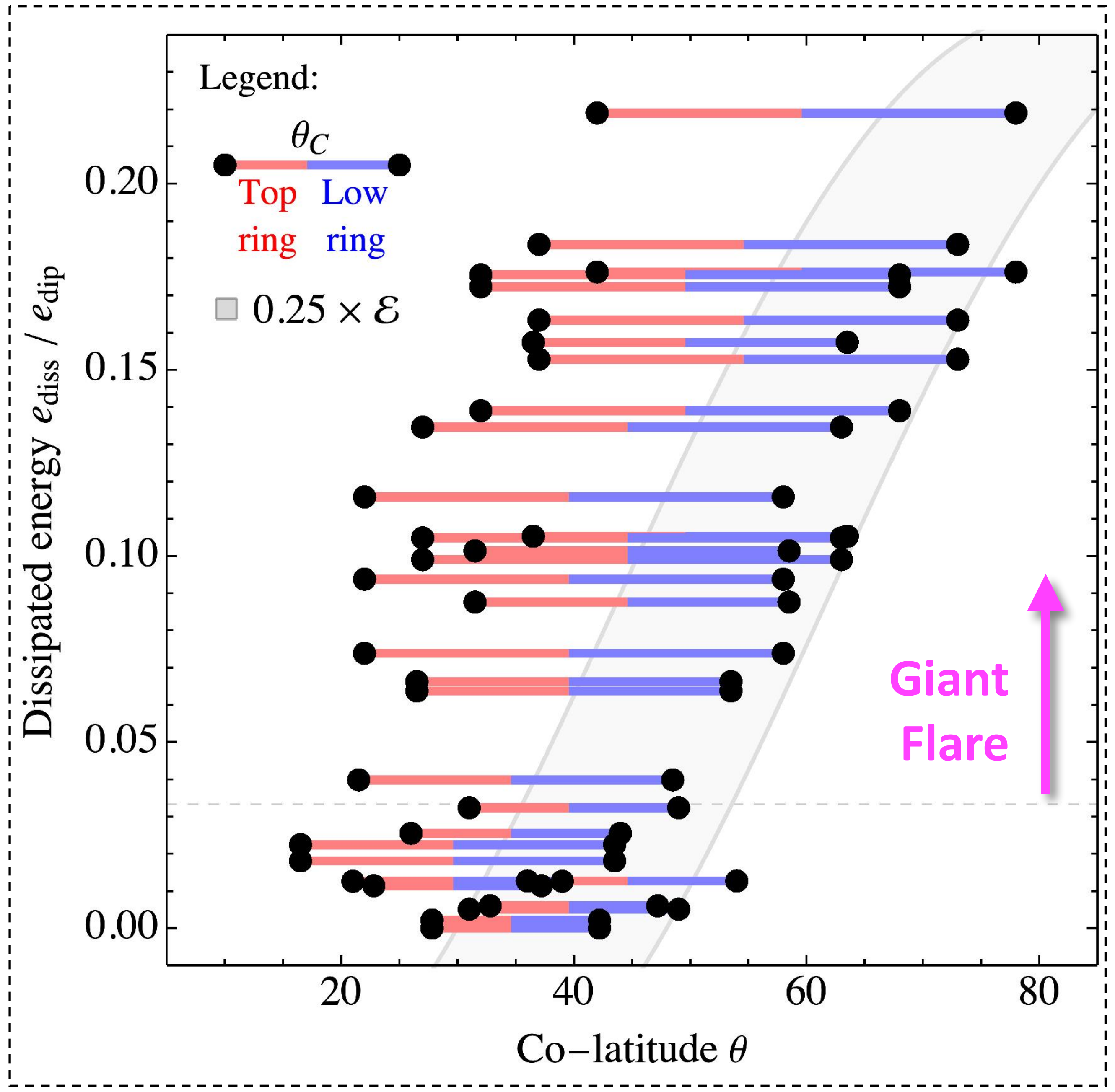
Axisymmetric eruptions commonly drive powerful magnetospheric dissipation



We study **32 force-free axisymmetric eruptions** and their dissipated energy beyond the critical twist.

Coronal flux ejections in analogy to the Sun's CMEs, see also recent work by Sharma et al. (2023).

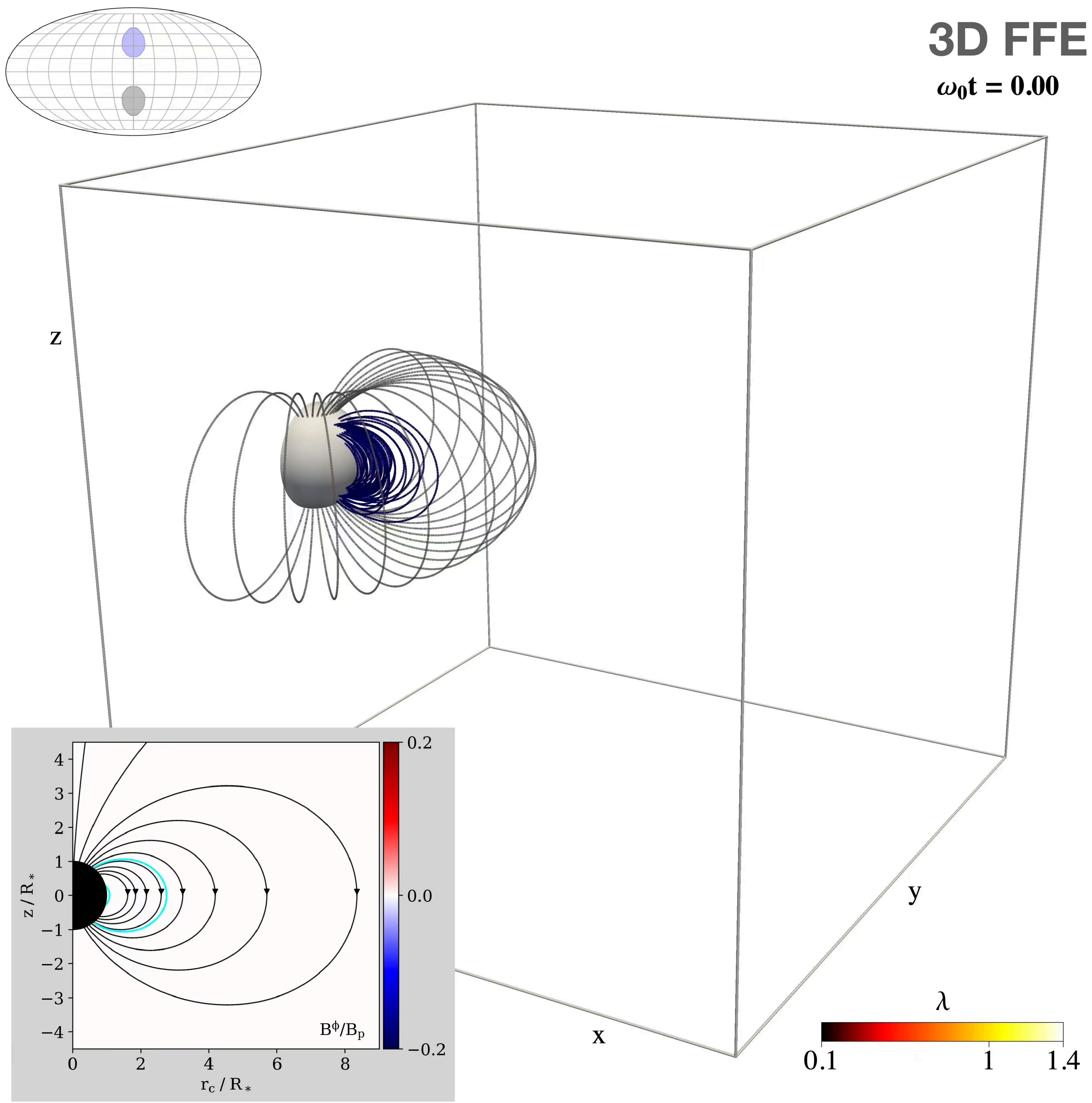




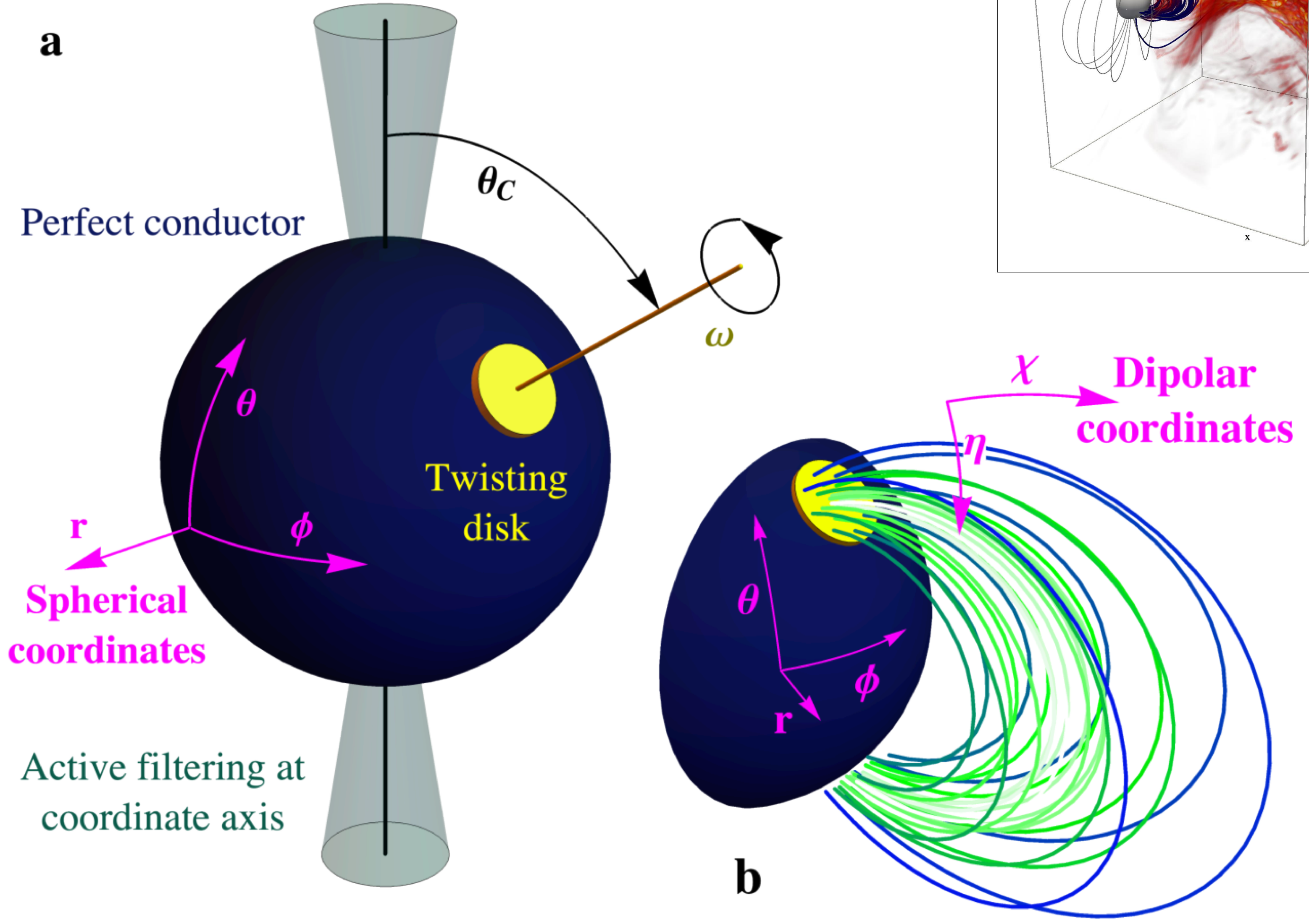
Twisted 2D magnetospheres will eventually open up. But how will 3D structures change the flare energy and dynamics?

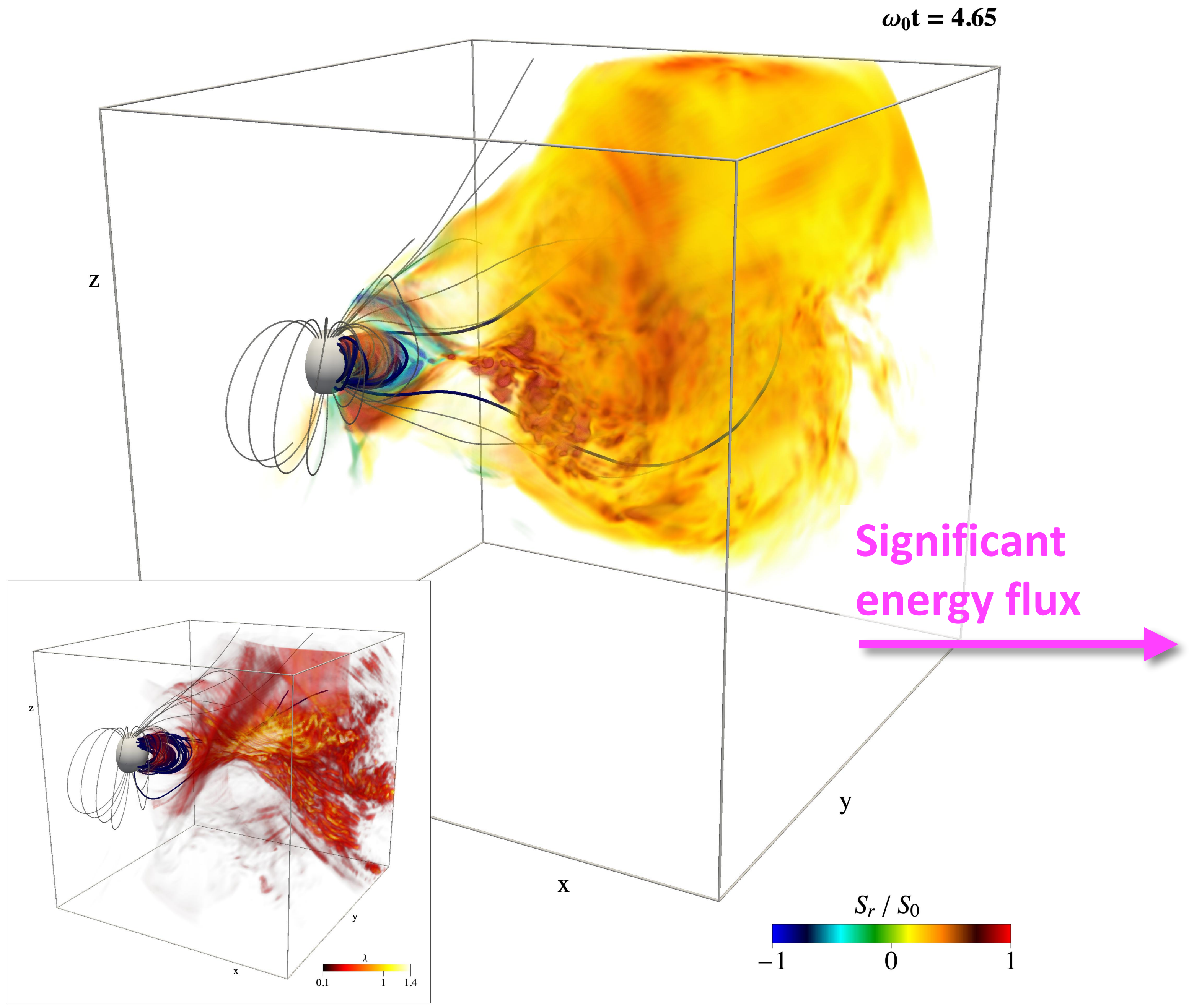
Everything bursts everywhere all at once

Global eruptions generate outflows to the outer magnetosphere



Each instability event **dissipates a fraction of the twist energy**. in our models up to 0.1% of the dipole energy, or $10^{41} - 10^{43}$erg.

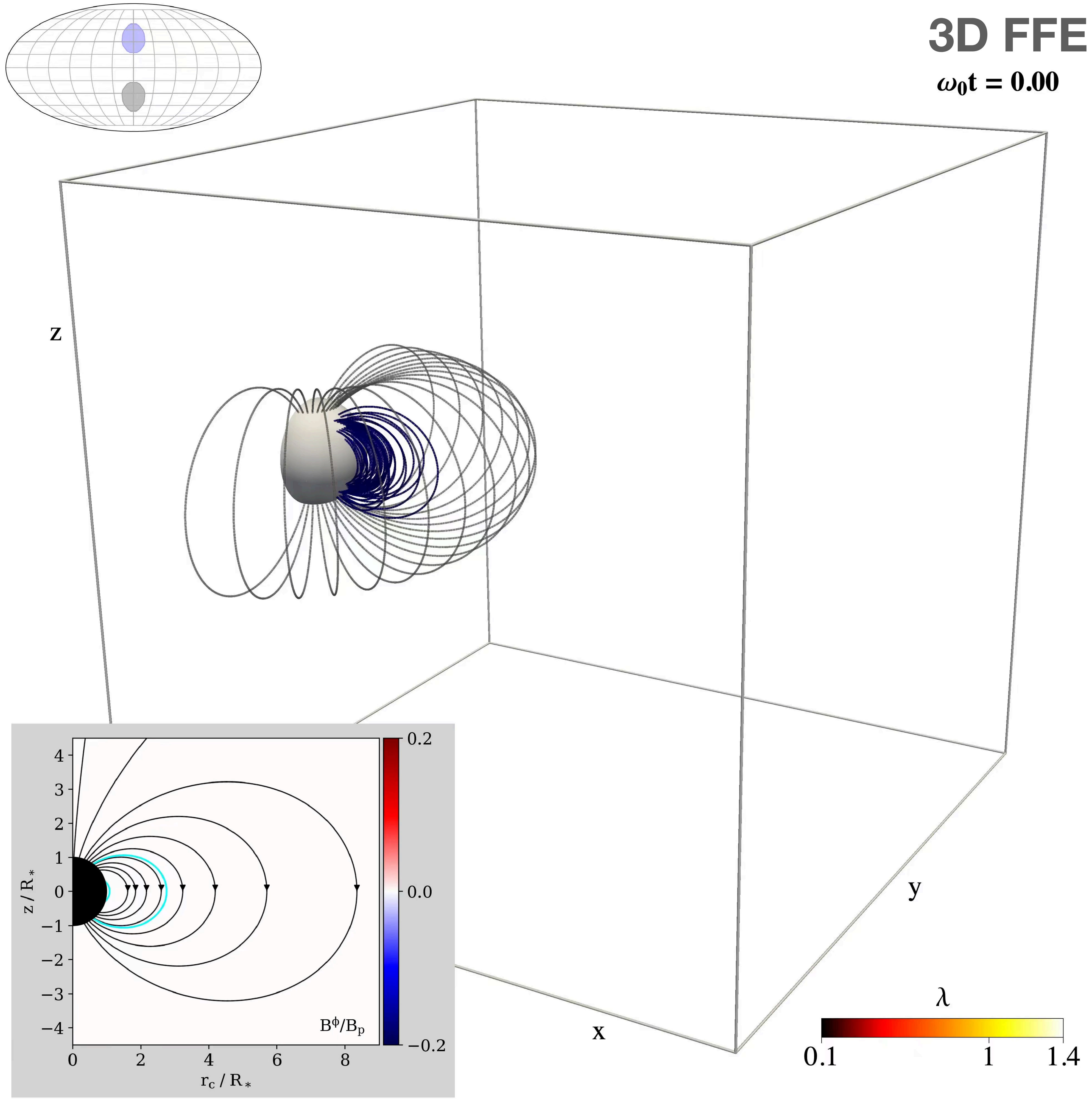




Global eruptions can inject energy to the outer magnetosphere.

Everything bursts everywhere all at once

Global eruptions generate outflows to the outer magnetosphere



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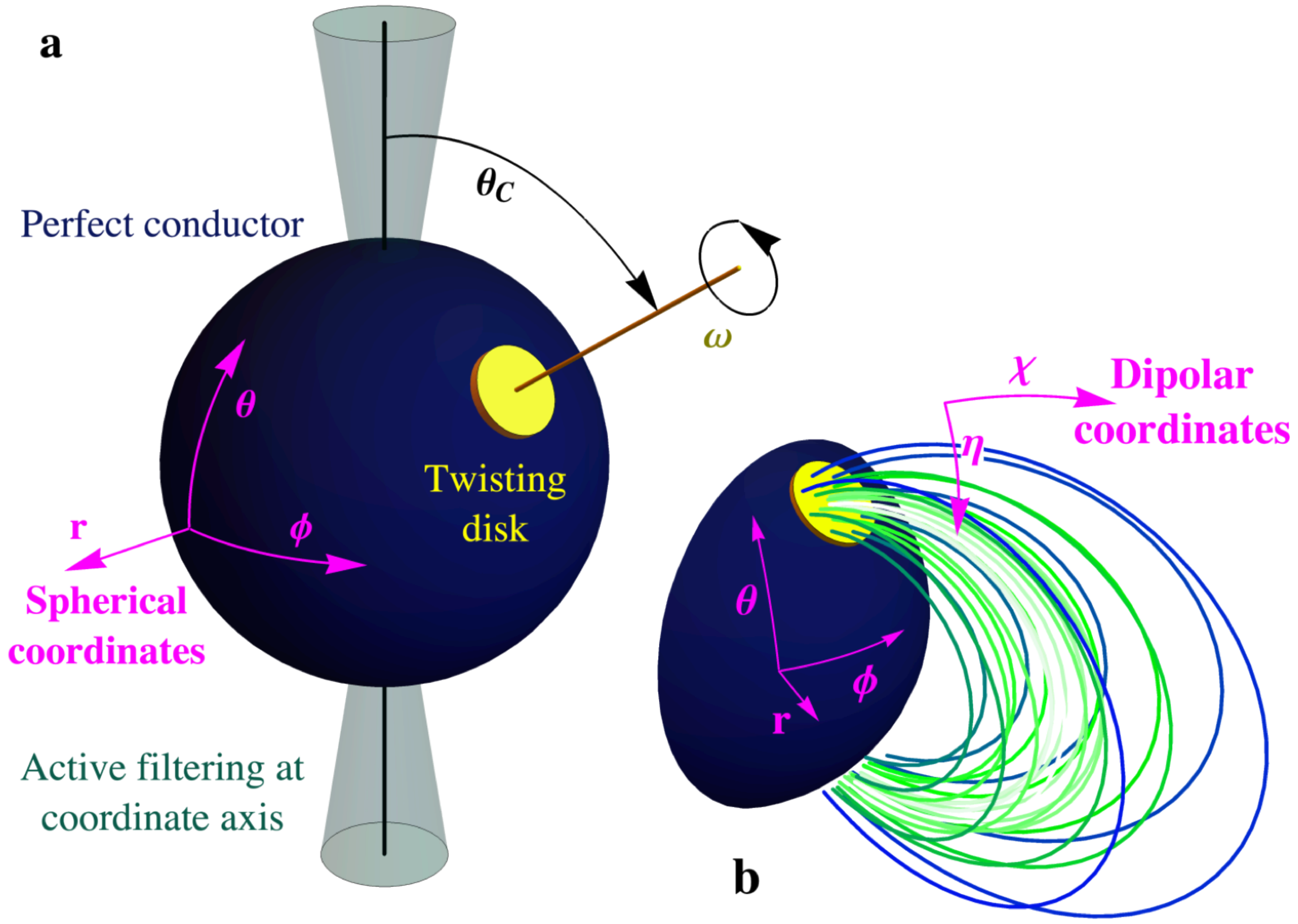
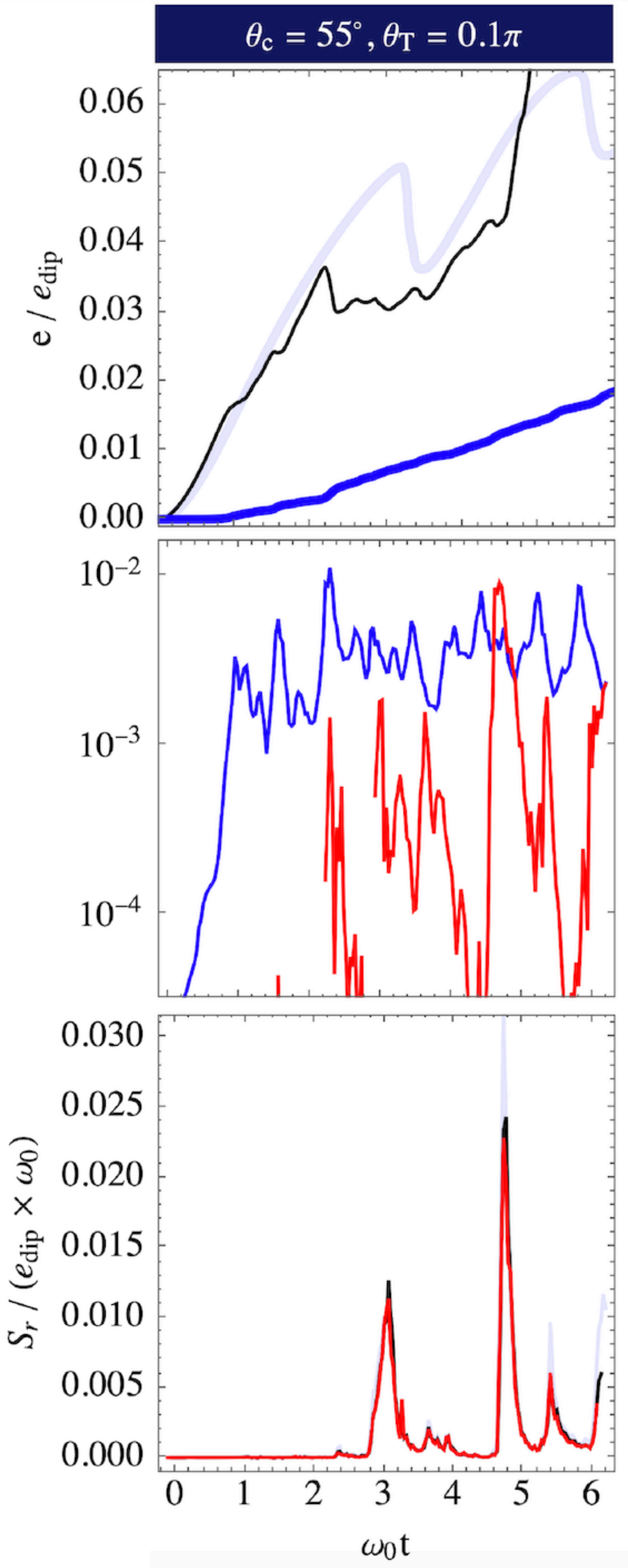
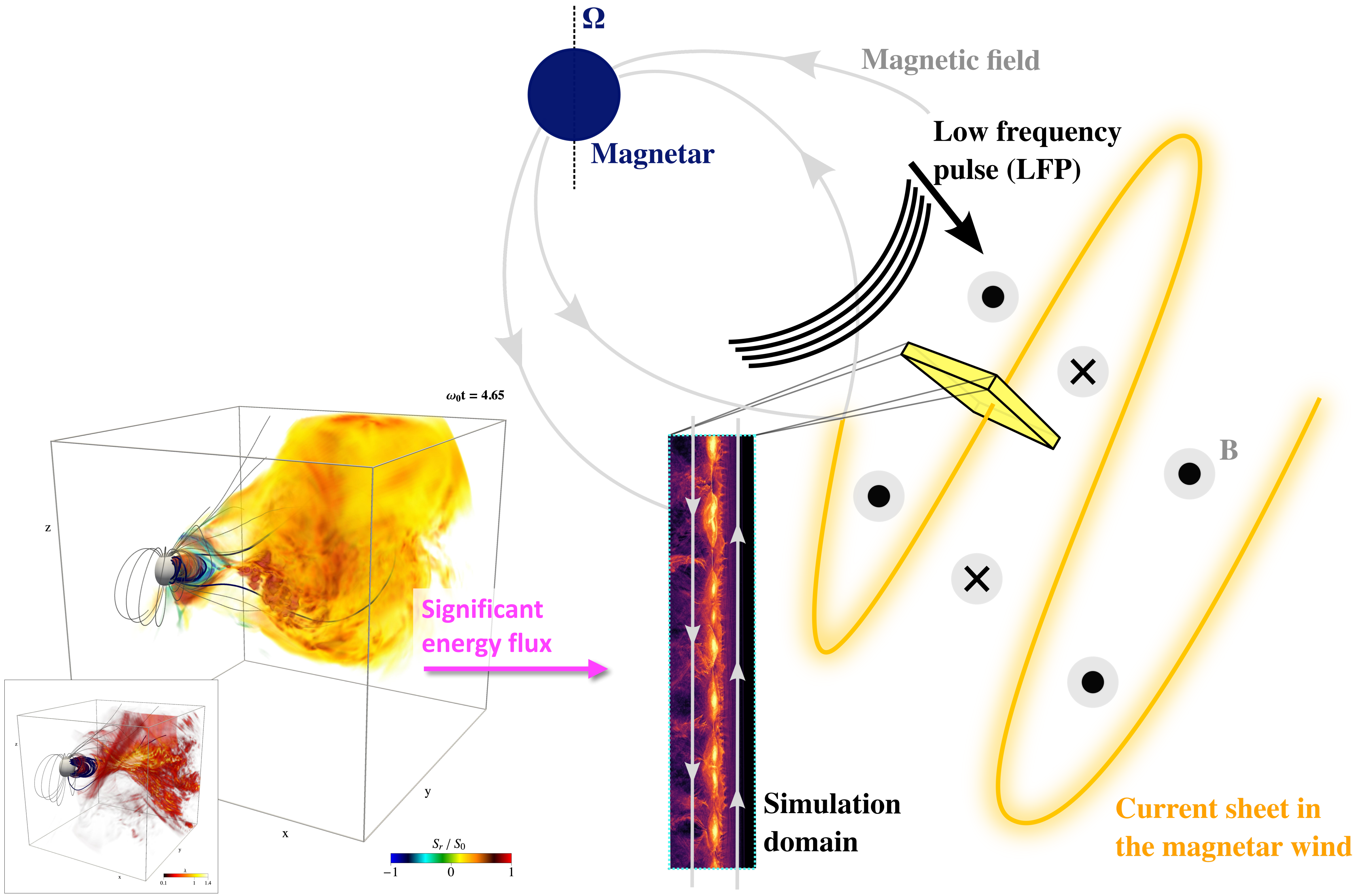




The reconnection mediated FRB model

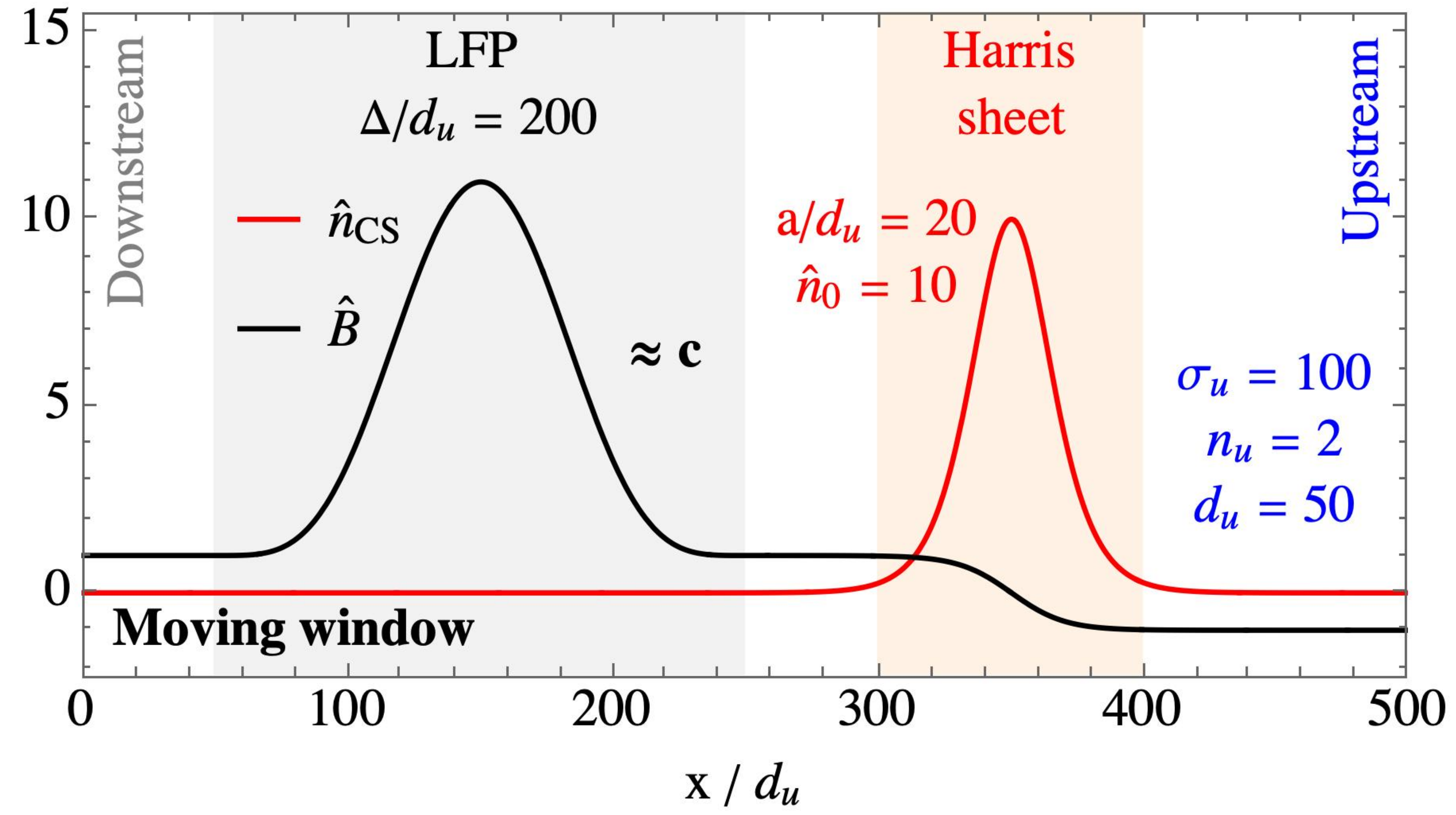
One viable alternative to the much discussed shock model



2D relativistic particle-in-cell (PIC) simulations with **Tristan-v2**.

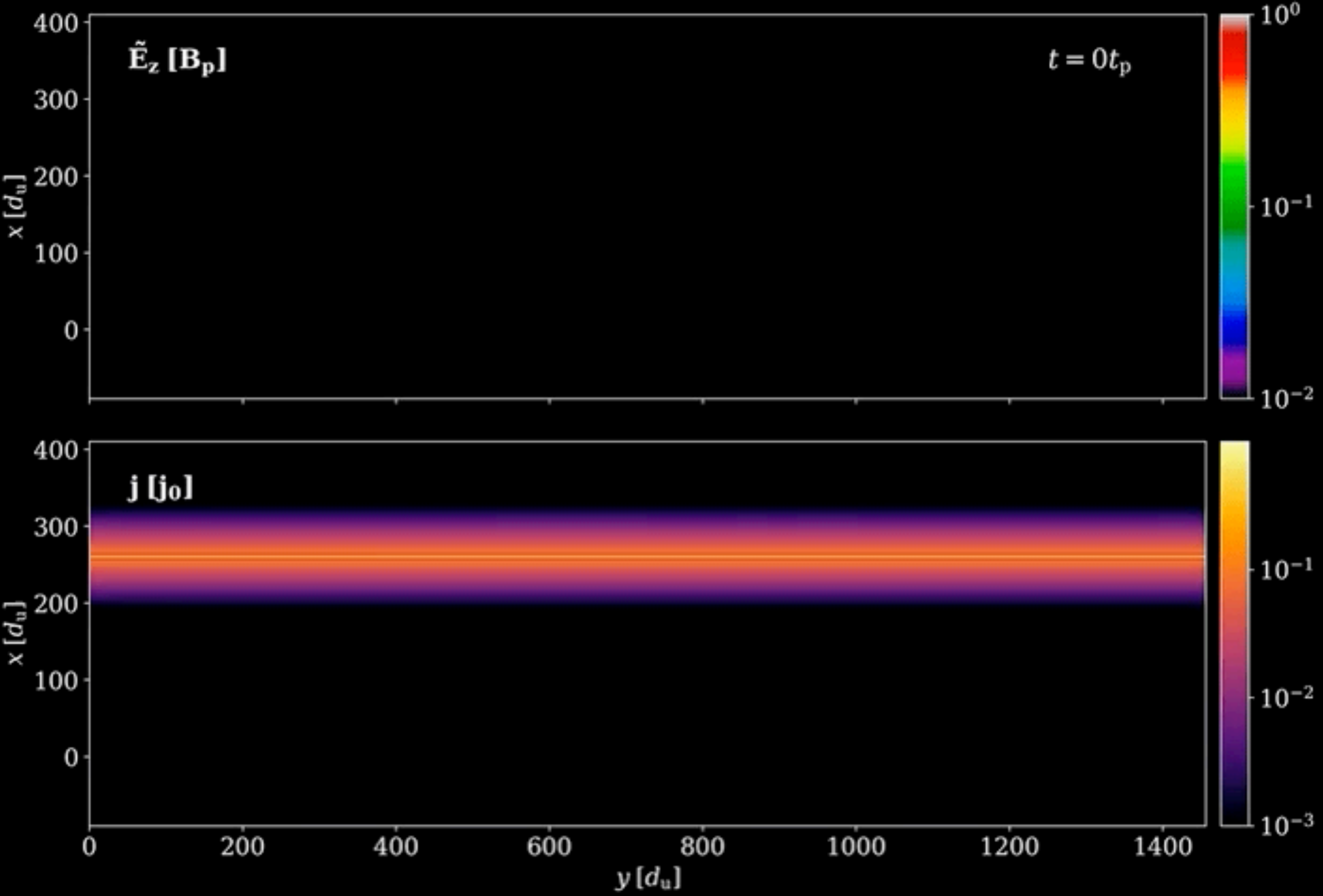
A macroscopic low-frequency **fast magnetosonic pulse** interacts with a **Harris sheet**. The simulation window moves with the speed of light:

MareNostrum (3k CPUs); **Frontera** (18k CPUs)



Electrodynamic fireworks

Plasmoid mergers induce a high-frequency fast wave signature



Conversion of magnetic energy to radio waves

The reconnection rate dictates interaction energetics

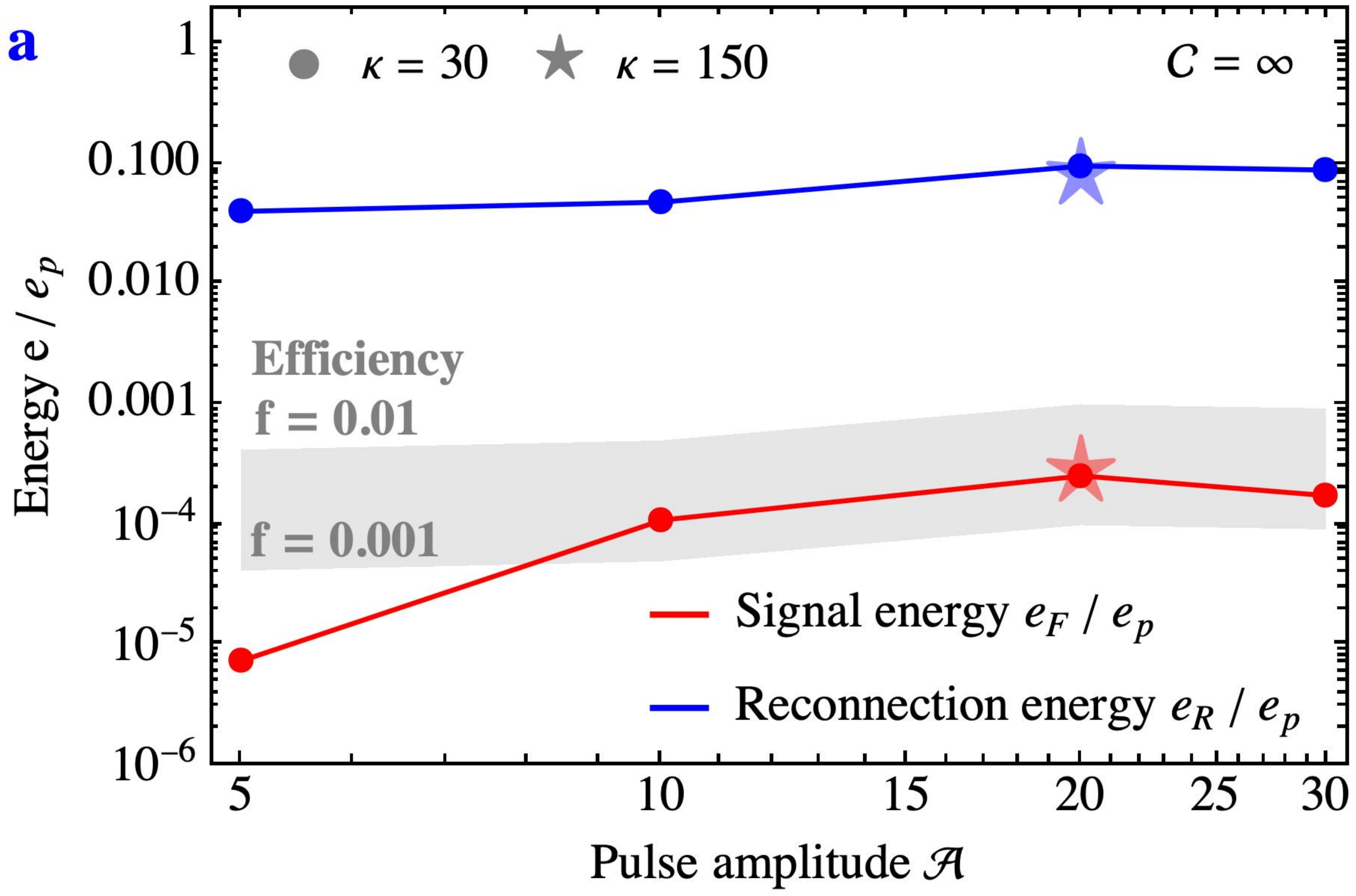
Our simulation setup is an **INFINITE system**, the reconnected energy has to reflect this:

$$e_{\rm R} \sim \beta_{\rm rec} \frac{1}{2\pi} \hat{B}_{\rm p}^2 B_{\rm u}^2 L_y \Delta \approx 2\beta_{\rm rec} e_{\rm p}$$

Twice pulse energy

$$e_{\rm R}/e_{\rm p} \sim 2\beta_{\rm rec}$$

Only depends on the **reconnection rate** (with a factor determined by the pulse shape)!



This result **compares well** to Philippov et al. (2019) for nano shots without compression, who find $S_{\rm fast} \sim 10^{-4} B_0^2$.

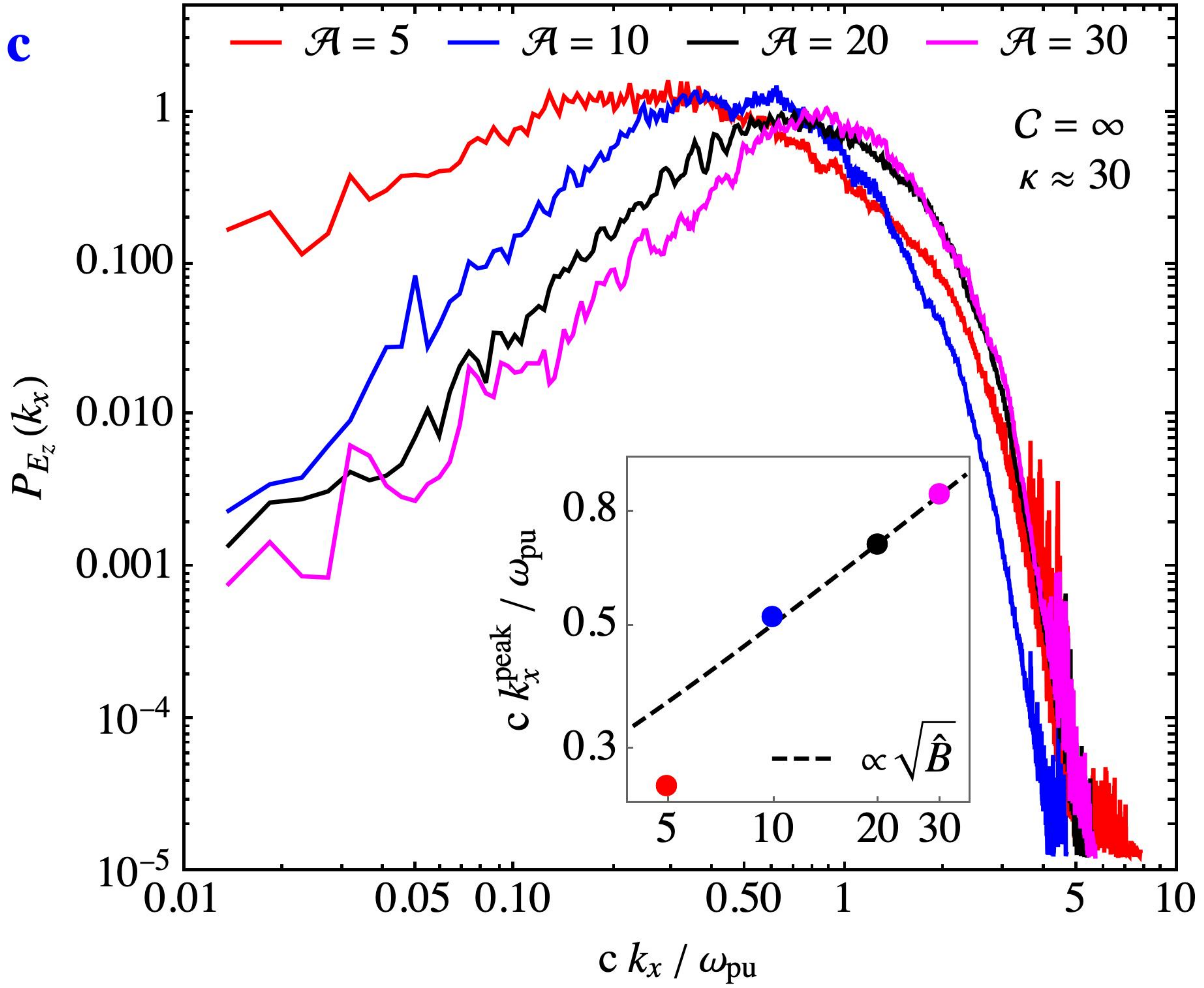
With **conversion rate** we can estimate:

For magnetospheric models we expect GHz bursts with luminosities of

$$L_b = 10^{42} \left(\frac{L_{\rm p}}{10^{47} erg\ s^{-1}}\right)^{1/2} \left(\frac{B_*}{10^{15} G}\right) \left(\frac{1s}{P}\right) \left(\frac{1ms}{\tau}\right) erg\ s^{-1}$$

The pulse amplitude shifts the spectral peak

High-frequency fast waves depend on background of merger dynamics



Increased field compression **shifts the spectra to higher frequencies**.

We analyze the frequency of the outgoing high-frequency fast waves along the (outwards pointing) propagation direction of the incident fms pulse. In the limit of **NO** synchrotron **cooling**, we expect

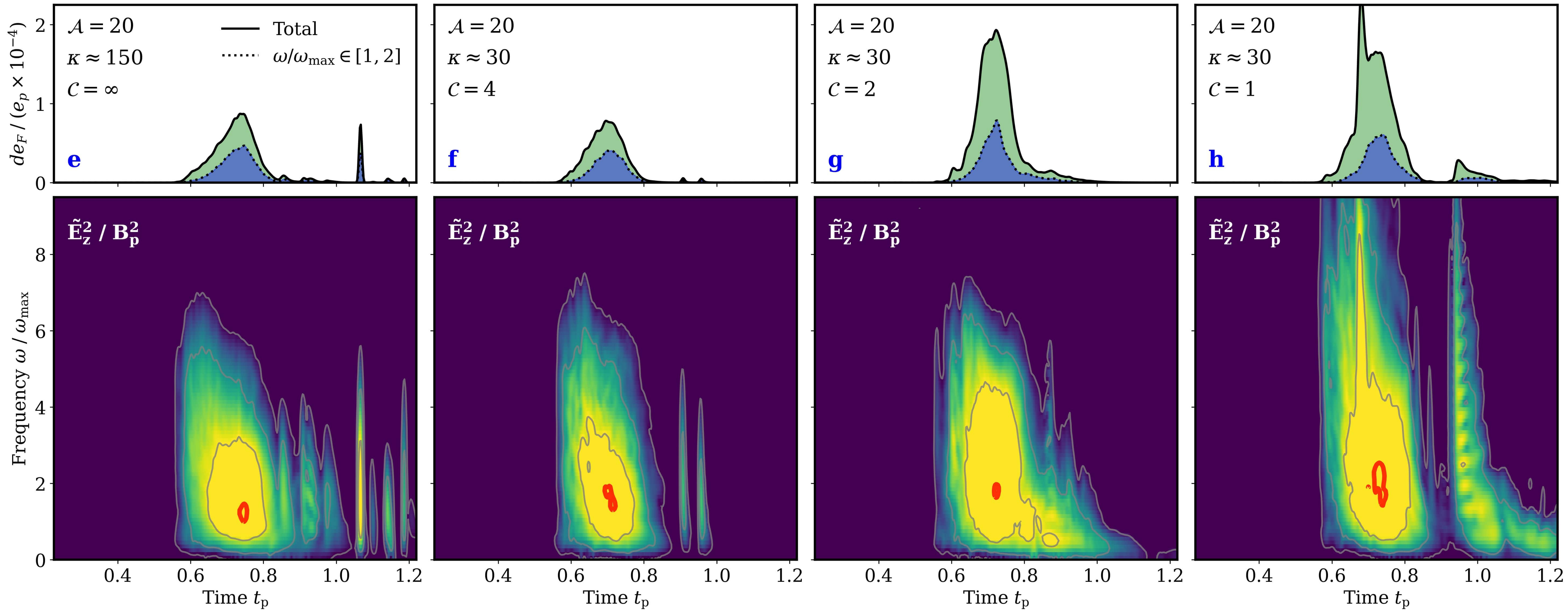
$$\nu = \frac{1}{\pi \xi \zeta} \frac{c}{\rho_{Lu}} \gamma_p \propto \hat{B}_p^{1/2}$$

Direct fit: $\xi\zeta \sim 90$

Dynamical spectra of the induced FMS waves

Compression and cooling boost the wave frequency to FRB range

Reference — Cooling strength



Plasmoid size

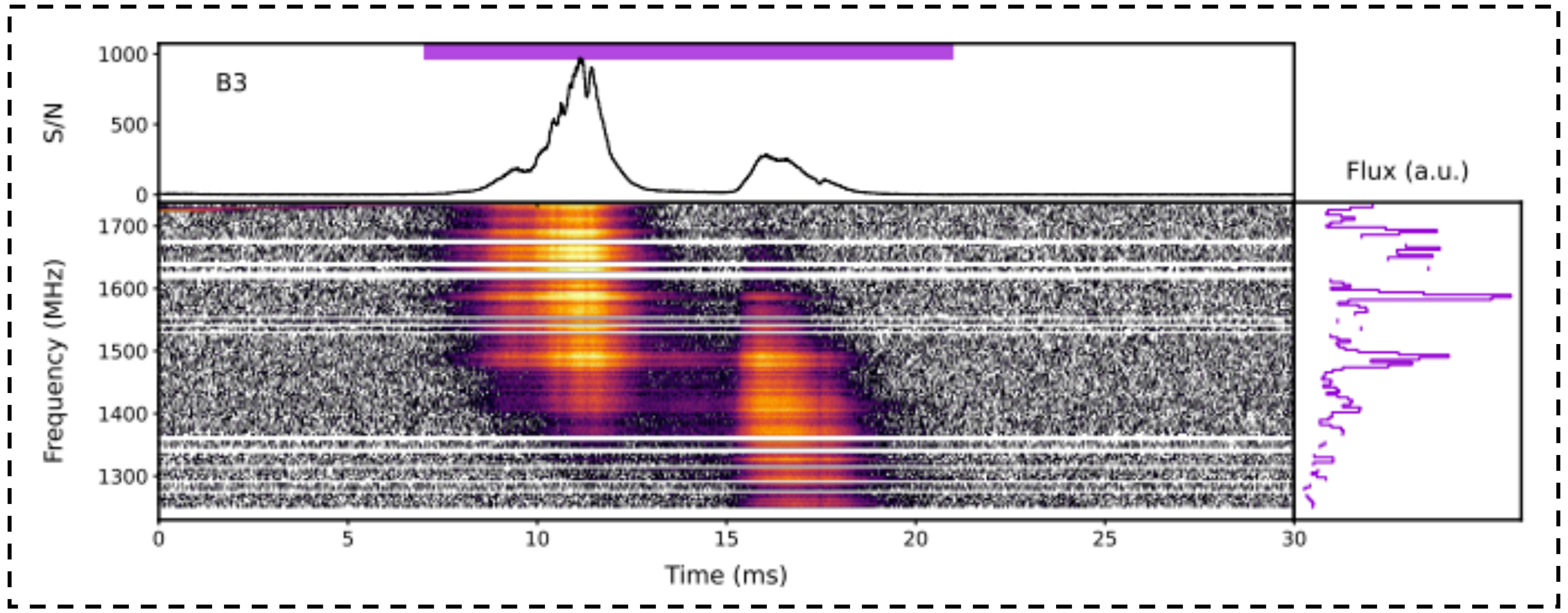
Wave frequency

$$\nu = \frac{c}{\xi\pi}\frac{1}{a'}\Gamma_{pulse} \approx \frac{1}{\pi\xi\zeta}\frac{\omega_B}{\langle\gamma\rangle}$$

Stronger synchrotron cooling **shifts spectra to higher frequencies**:

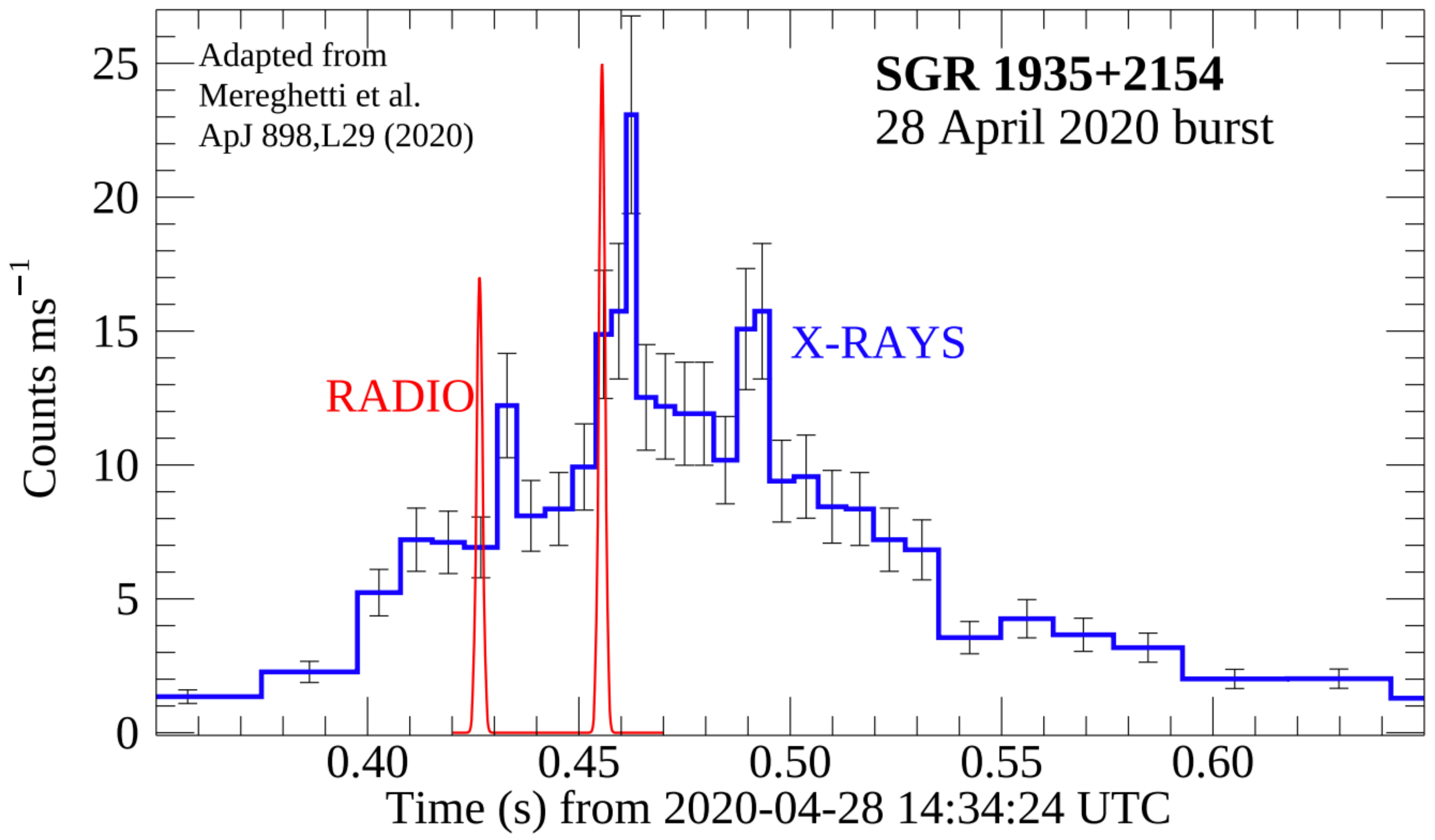
$$\nu \approx 1 \times \left(\frac{L_b}{10^{42} erg\ s^{-1}}\right)^{5/4} \left(\frac{10^{15}G}{B_*}\right) \left(\frac{1s}{P}\right)^{3/4} \left(\frac{0.1}{\beta_{rec}}\right)^{1/2} \left(\frac{100}{\xi\zeta}\right) \left(\frac{\tau}{1ms}\right)^{5/4} \text{GHz}$$

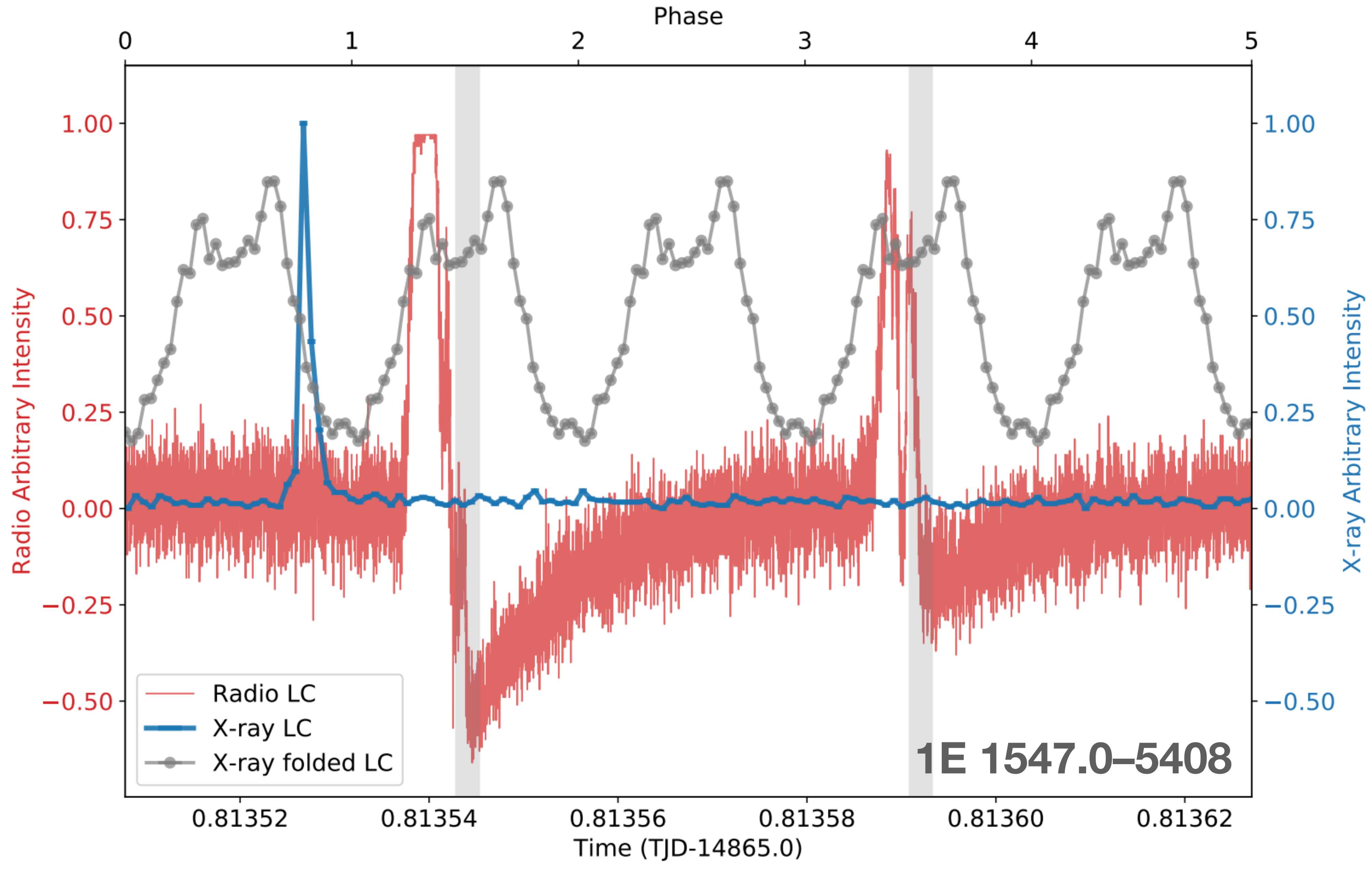
Plasmoid mergers naturally induce a **scale hierarchy**.



At least one magnetar flares and bursts

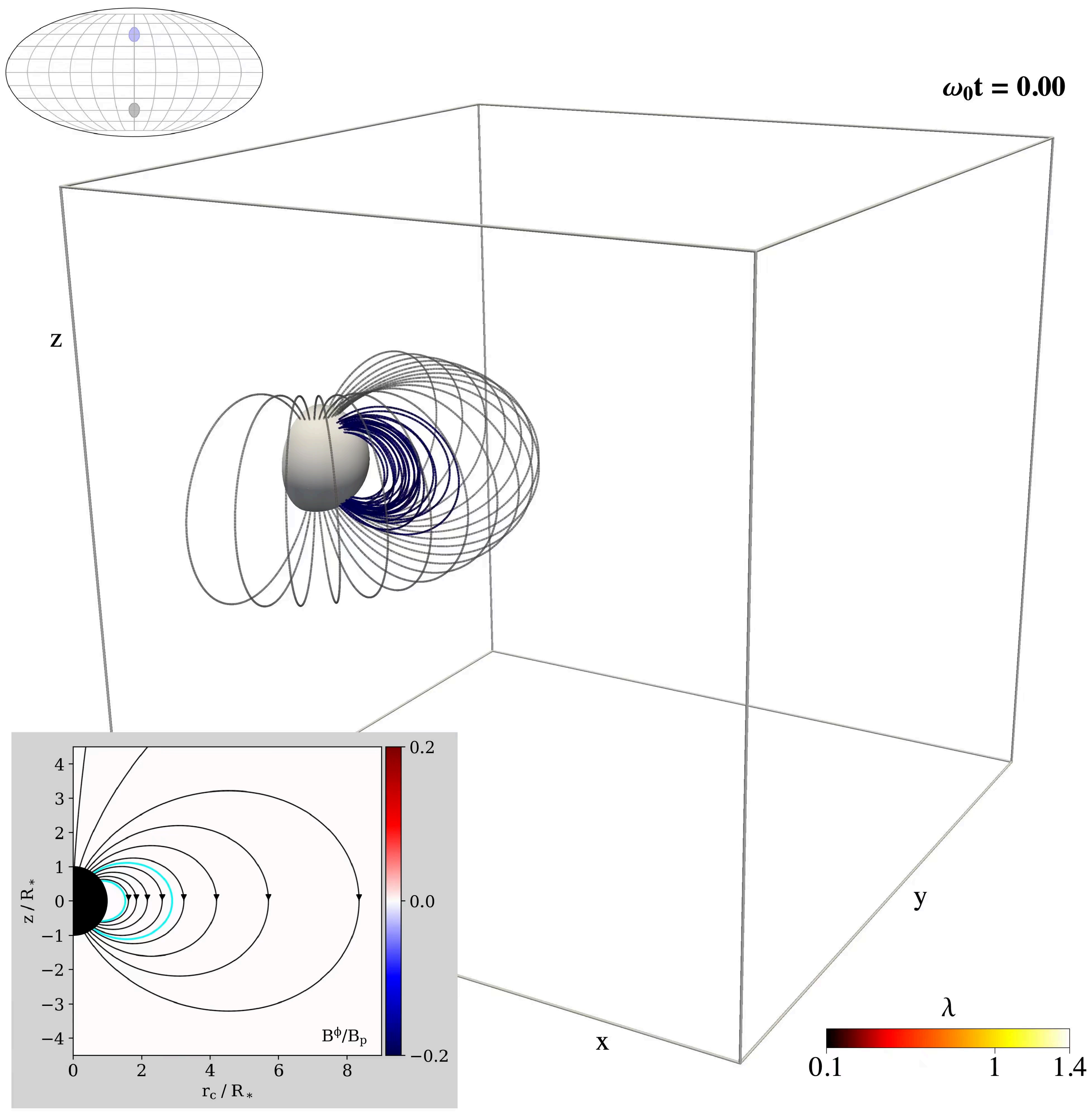
Compression and cooling boost the wave frequency to FRB range



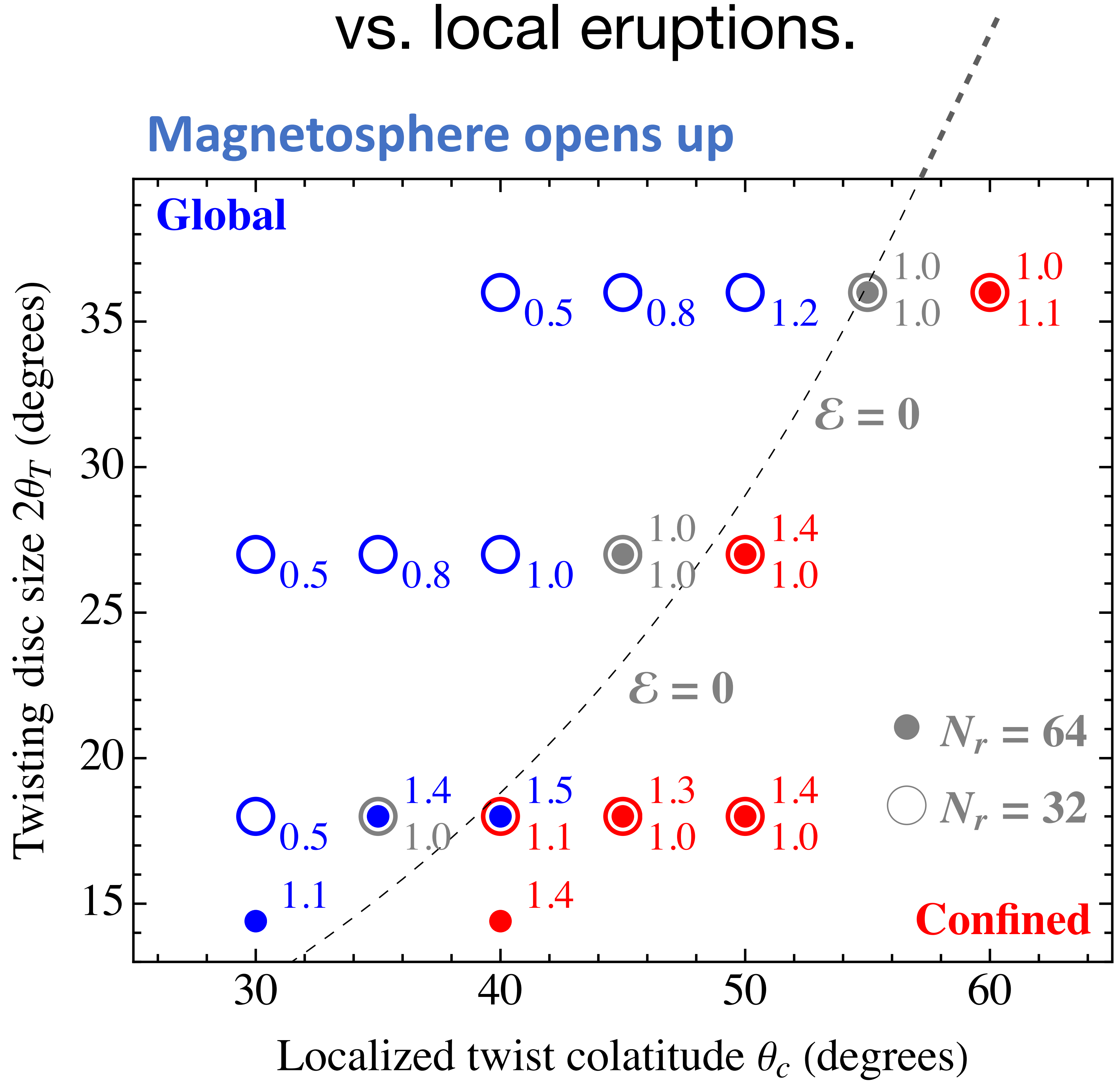


Everything bursts everywhere all at once

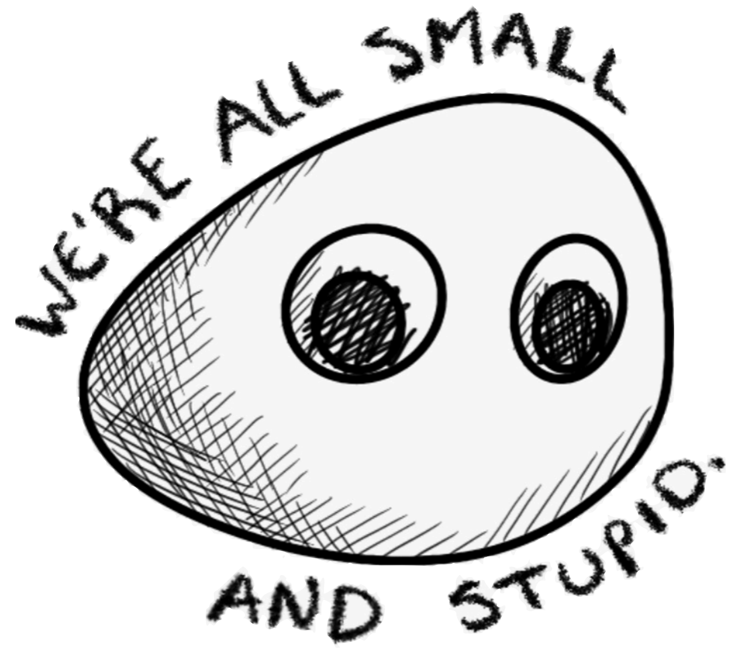
A new magnetospheric instability to explain faint(er) X-ray bursts



Magnetic pressure balance
a simple criterion for global vs. local eruptions.



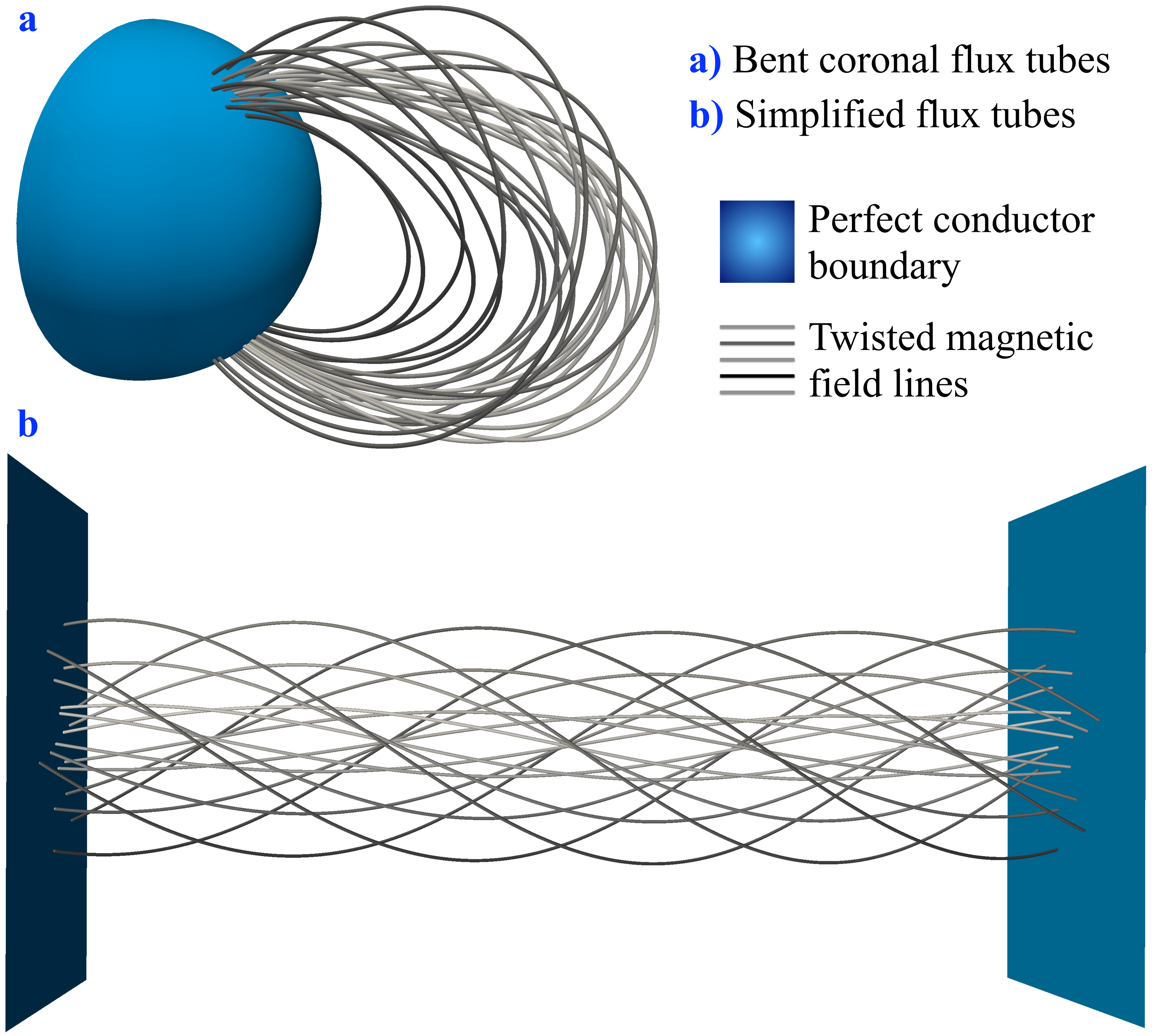
Kink-like local dissipation



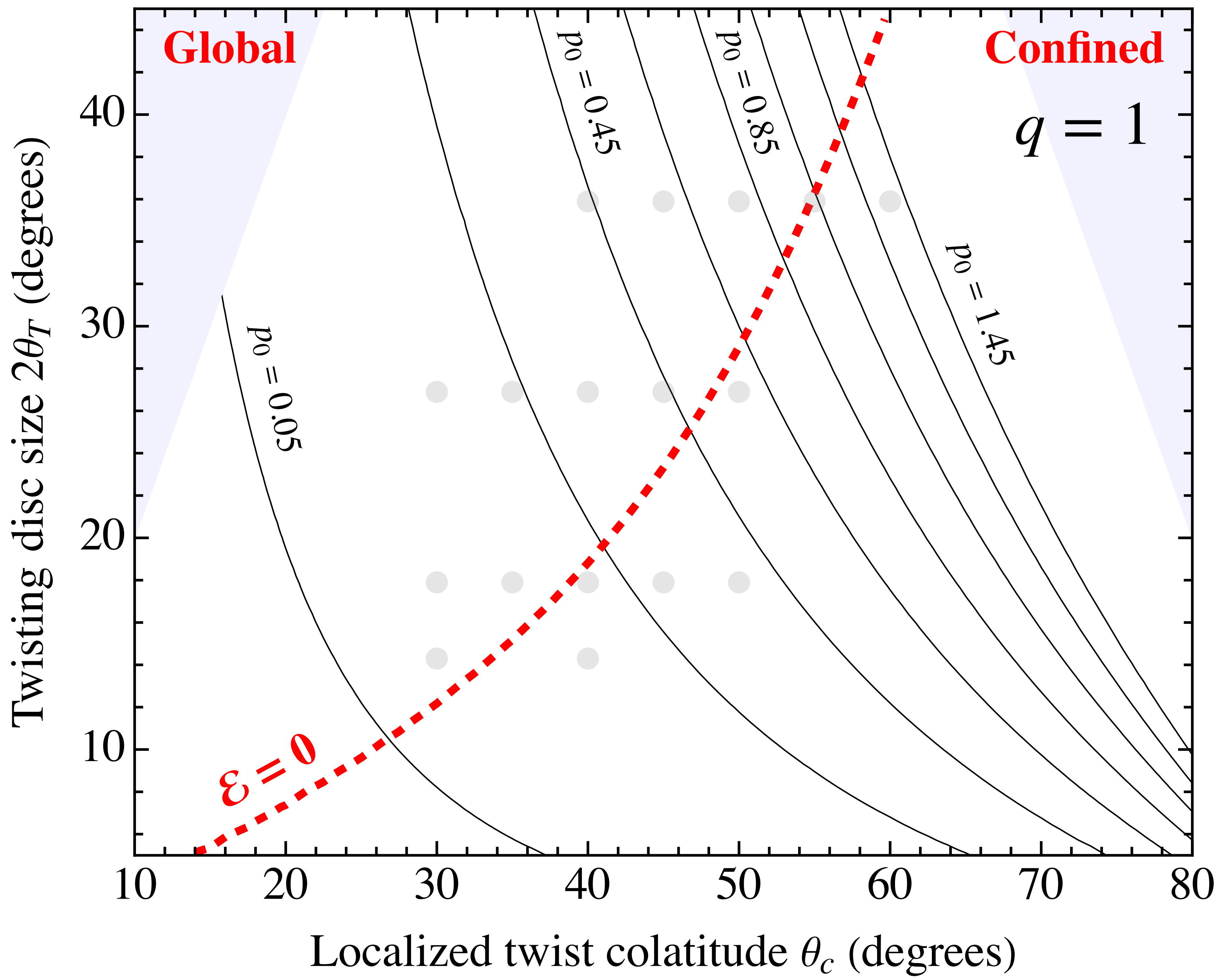
When do confined flux tubes become unstable and how exactly?

Safety first: Line tied flux tubes don't just erupt

Critical twist is for kink, but higher order modes can outrun this



Safety factor: $q \equiv \frac{2\pi r_0}{Lp}$ Inverse pitch: $p = \frac{B_\phi}{B_z}$



Safety first: Line tied flux tubes don’t just erupt

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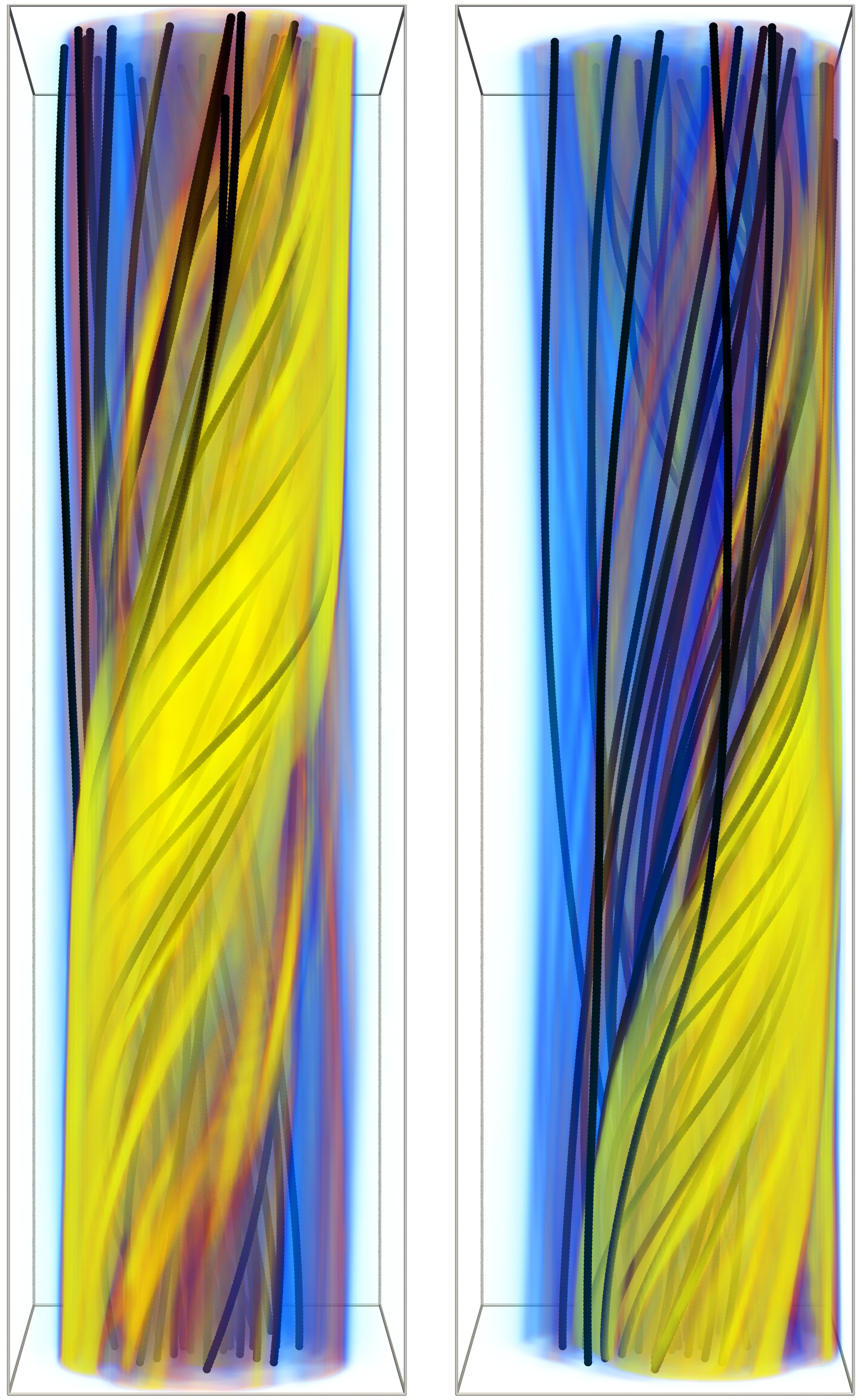
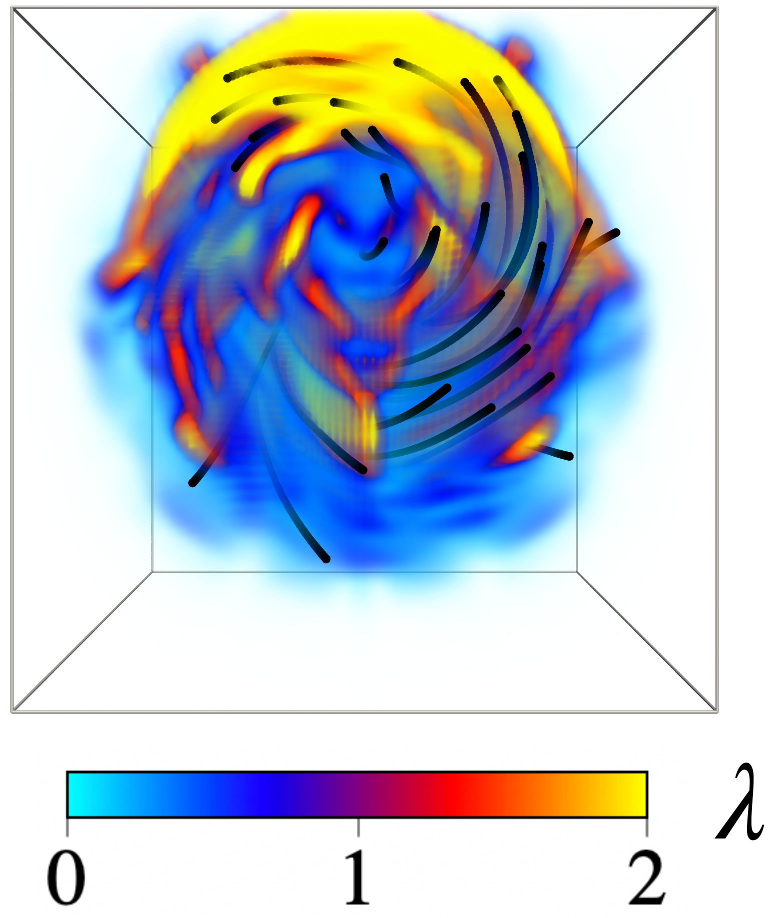
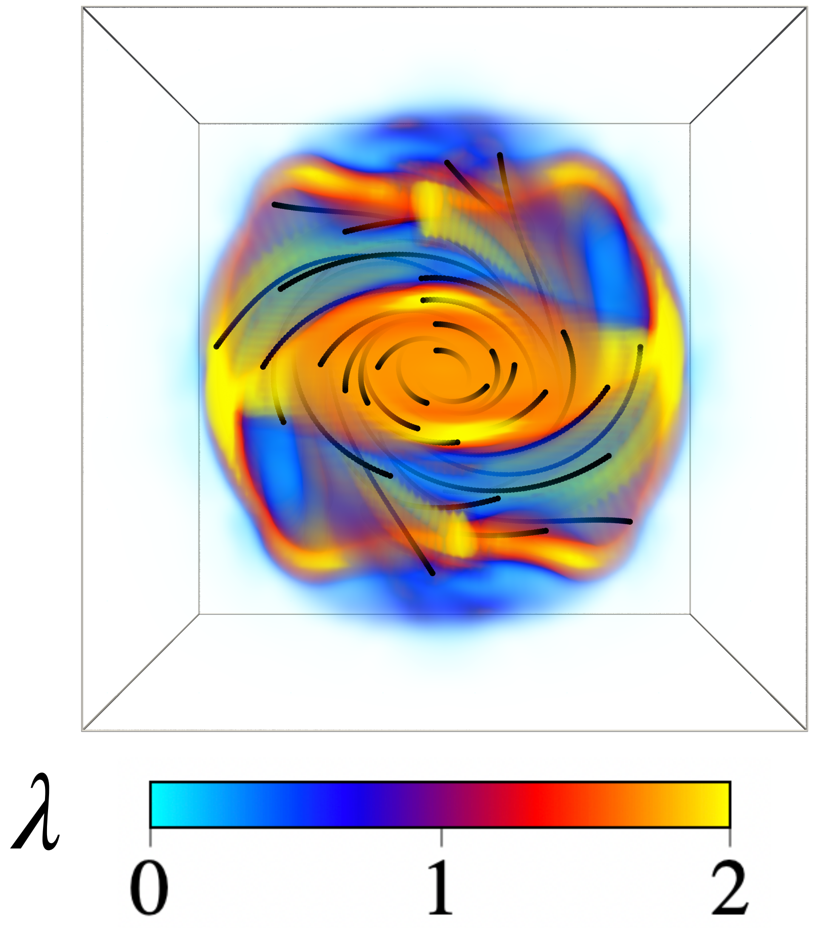
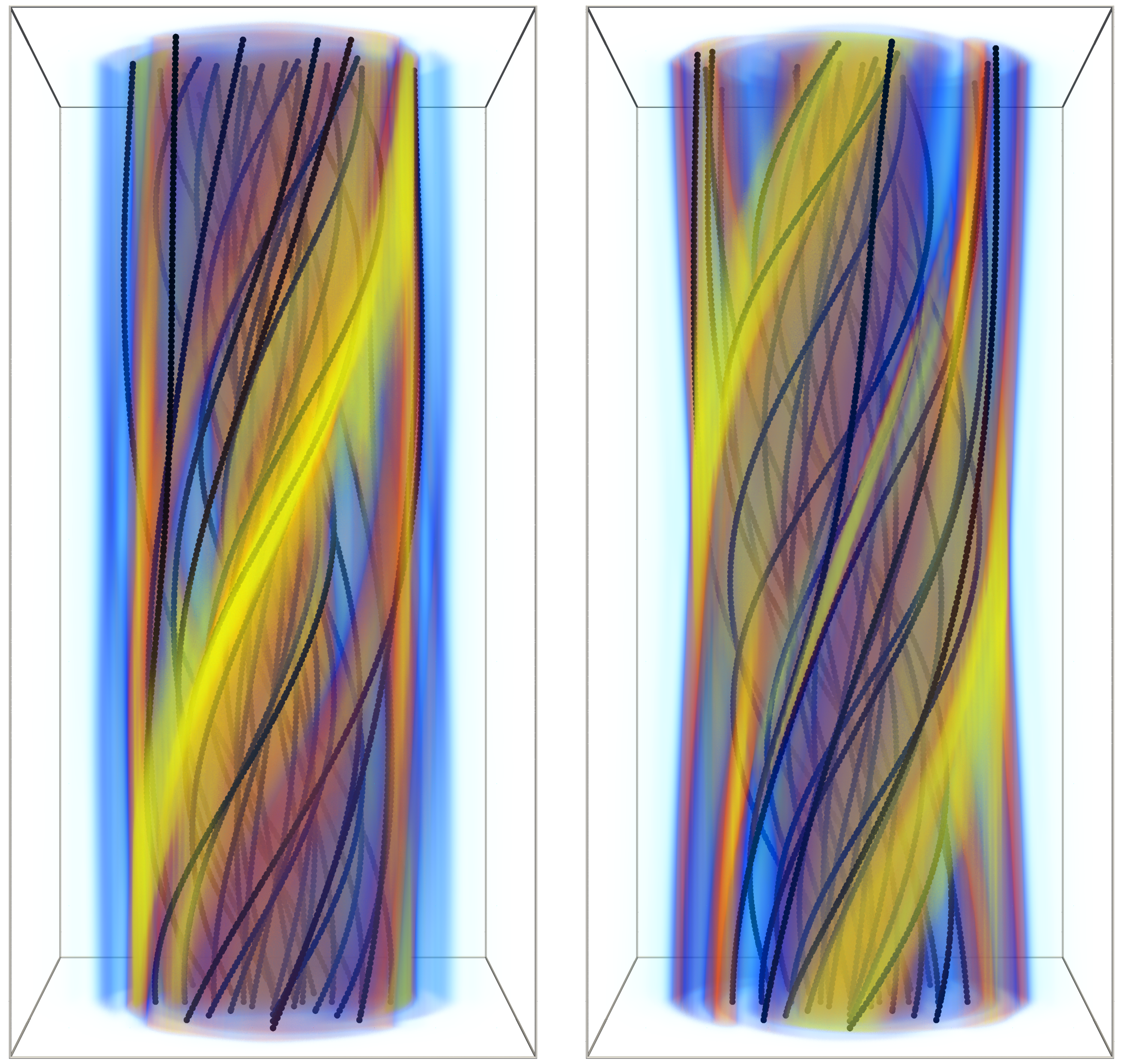


Magnetic-field-aligned
force-free current



Kink





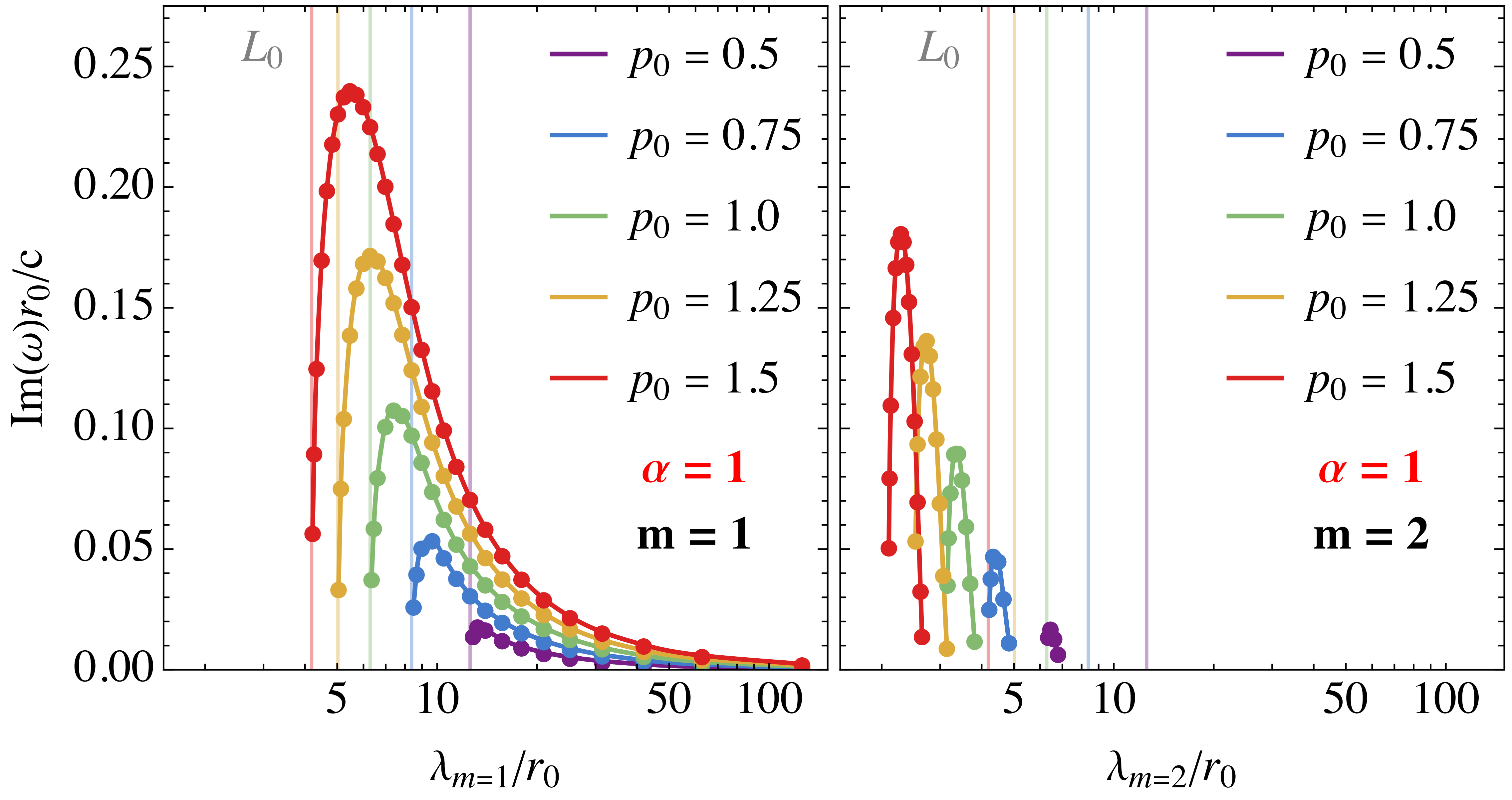
Fluting

Rugg et al. (soon)

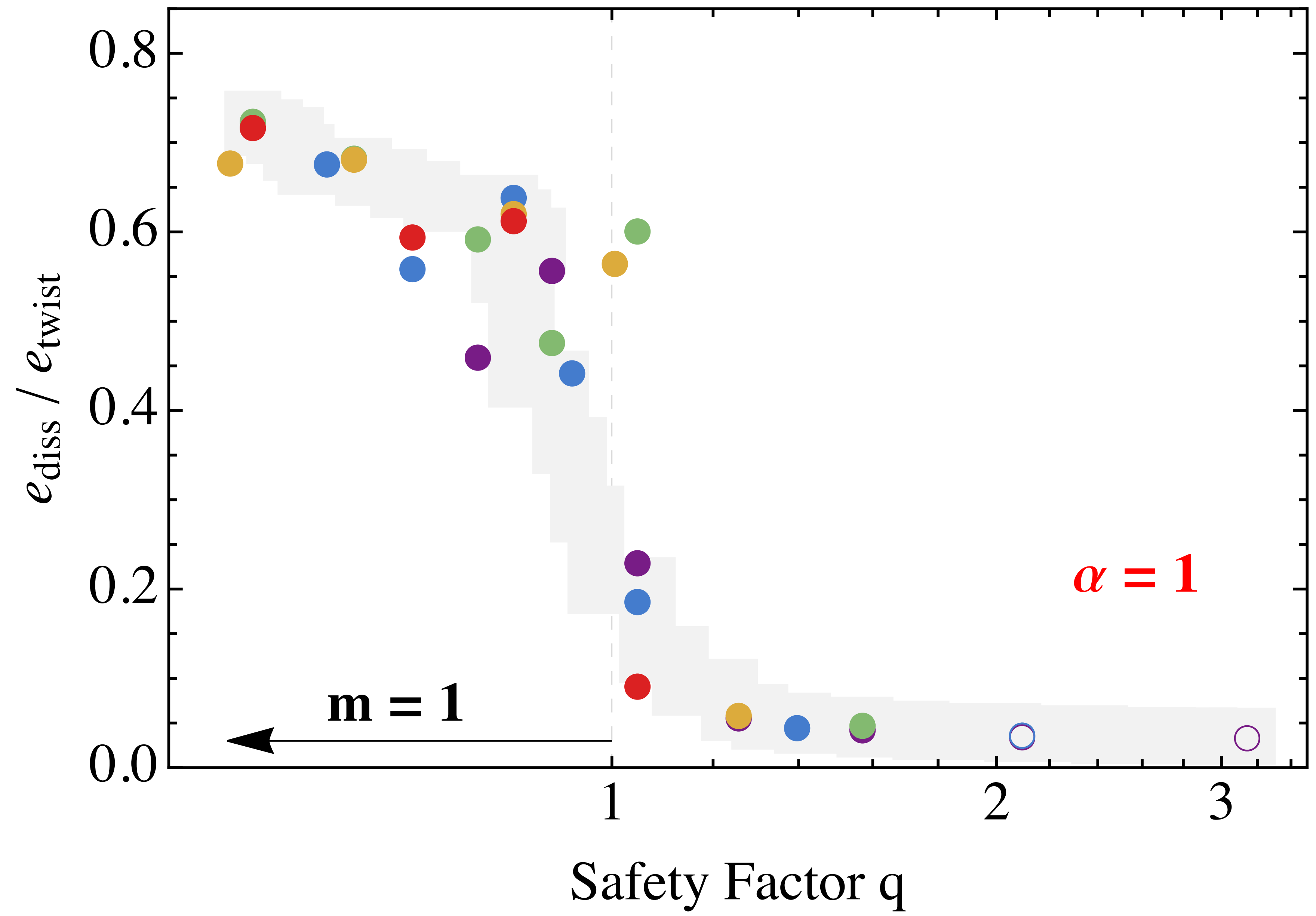
Fluting dissipates less, but can trigger kink

Rich dynamics at critical safety makes twisting velocity important

Growth rates of m = 1 and m = 2 modes

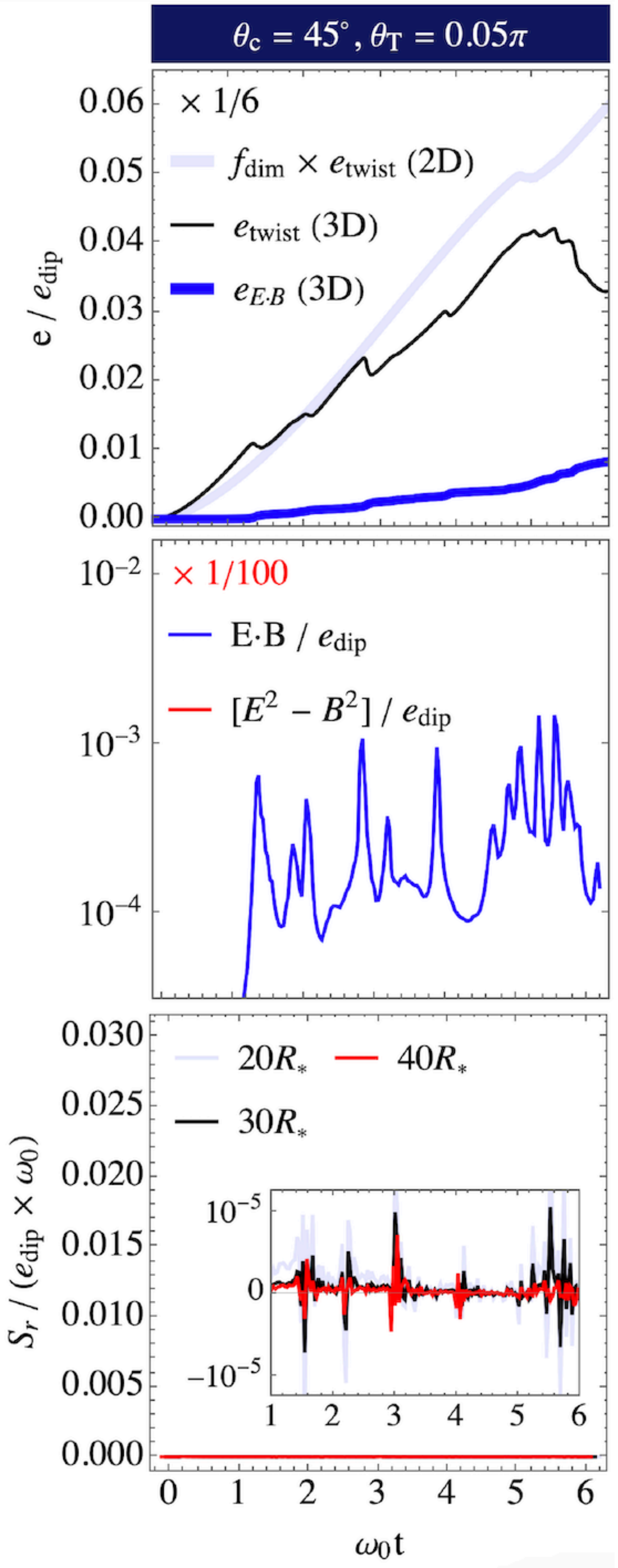


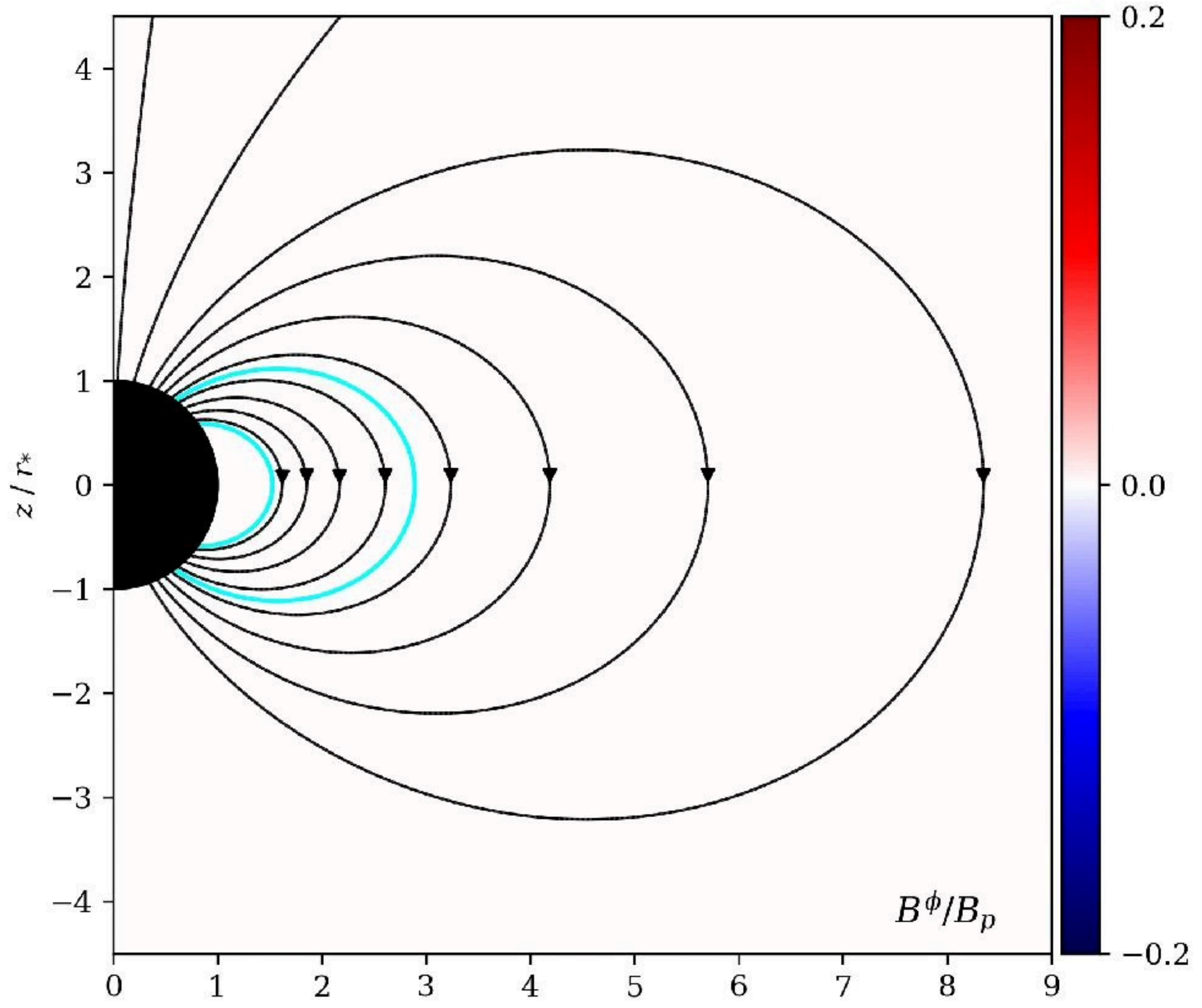
Energy dissipation during instability

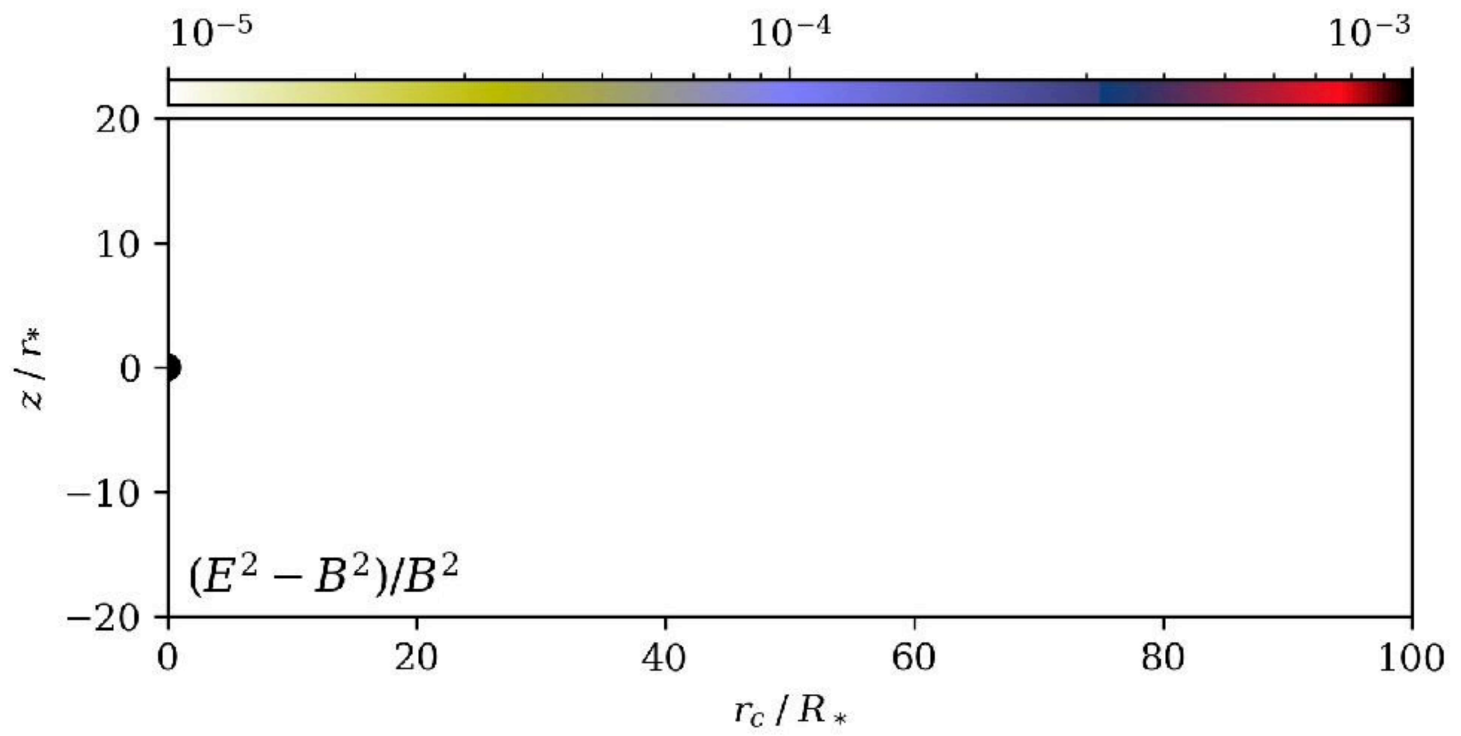


Kink eruption: Energy transport and dissipation

Fast magnetosonic waves are seeded in the inner magnetosphere

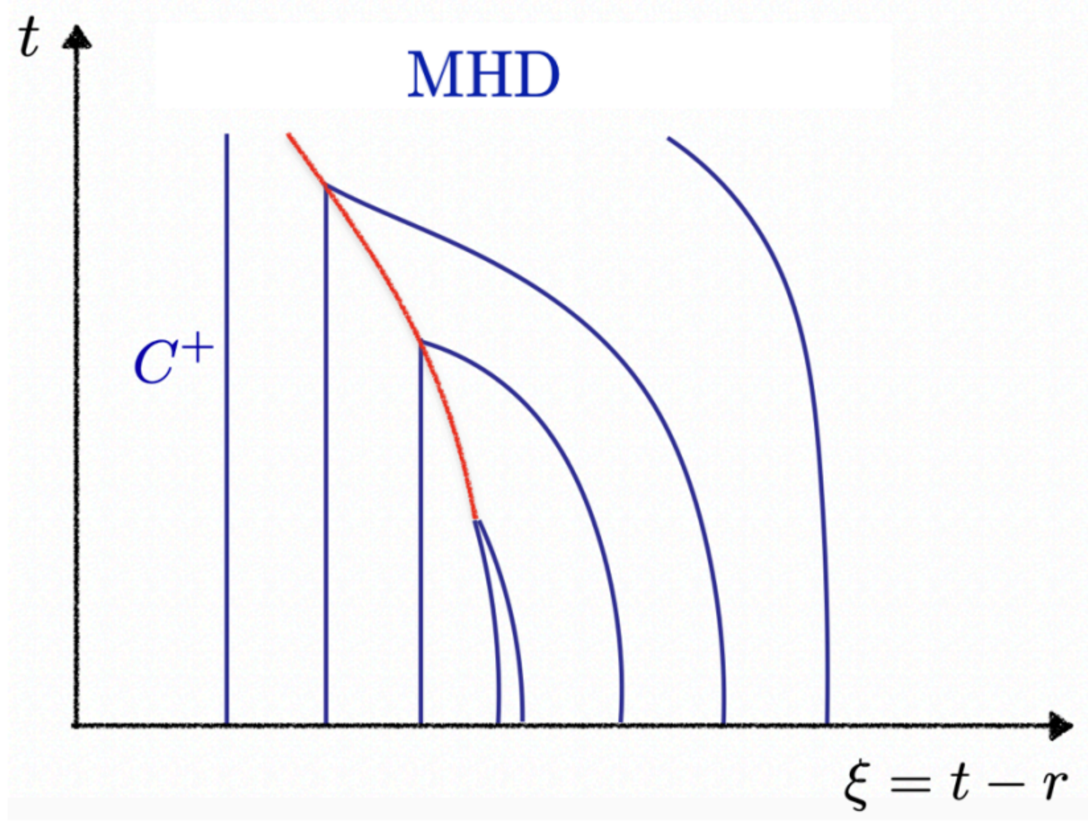


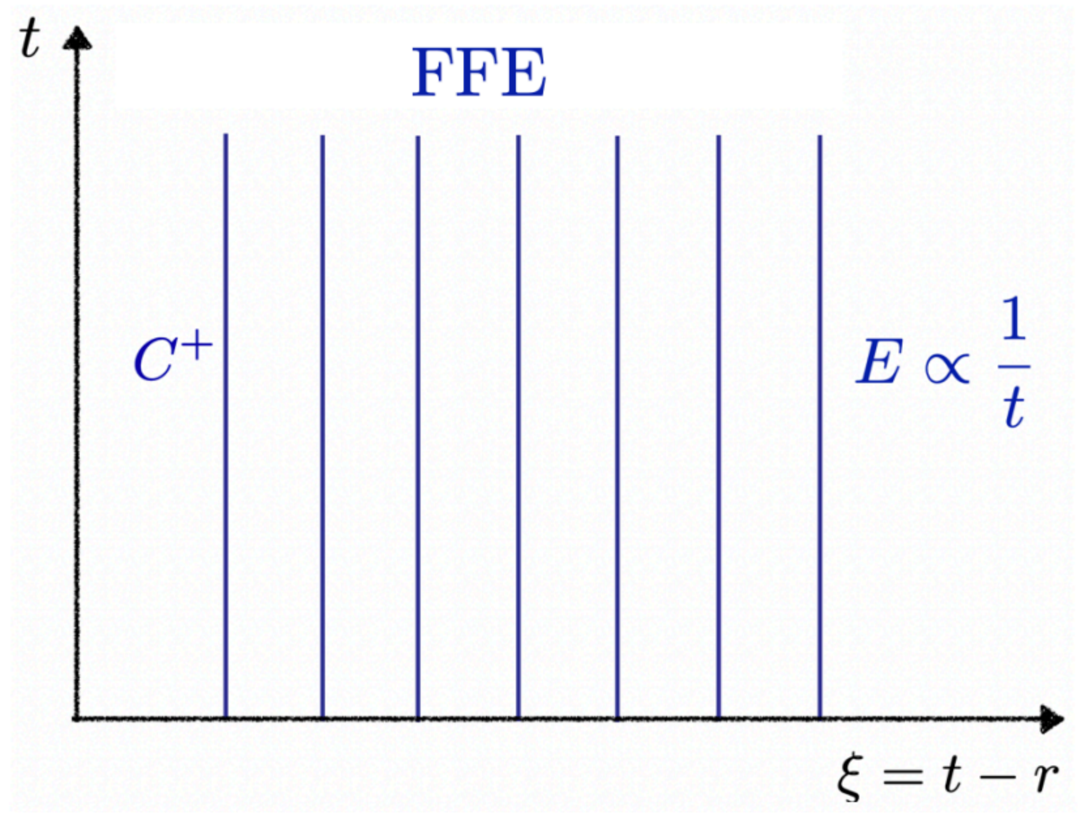




Kink events can seed **high frequency fast magnetosonic waves** that become electrically dominated at $80 - 100R_*$.

Shocks in the inner magnetosphere could generate additional X-ray emission.





Electric zones can alter characteristics and generate shocks.

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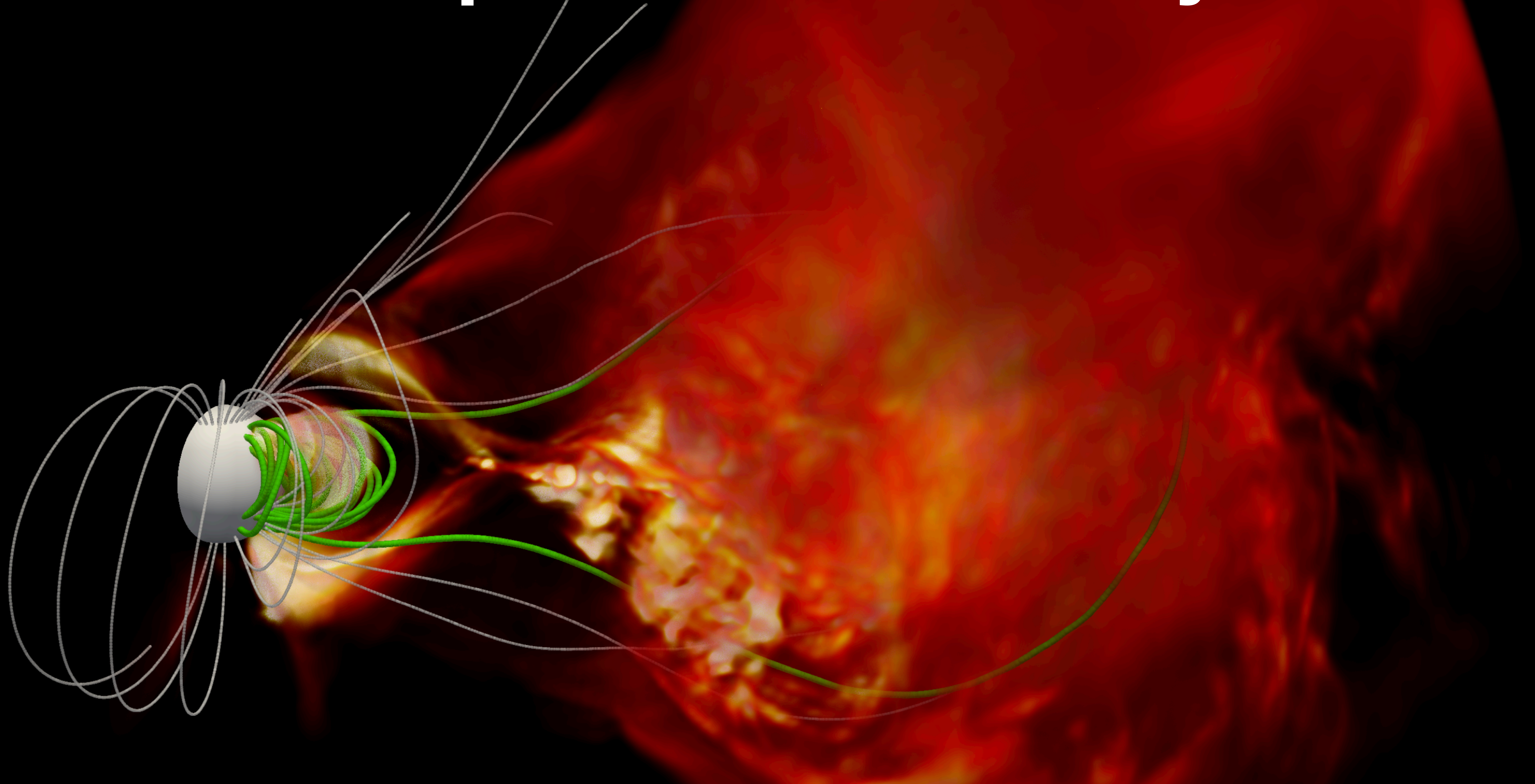
Discuss. Criticize. Explain. Ask. Thank you.



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