Title: Magnetar Eruptions and Electromagnetic Fireworks

Speakers: Jens Mahlmann

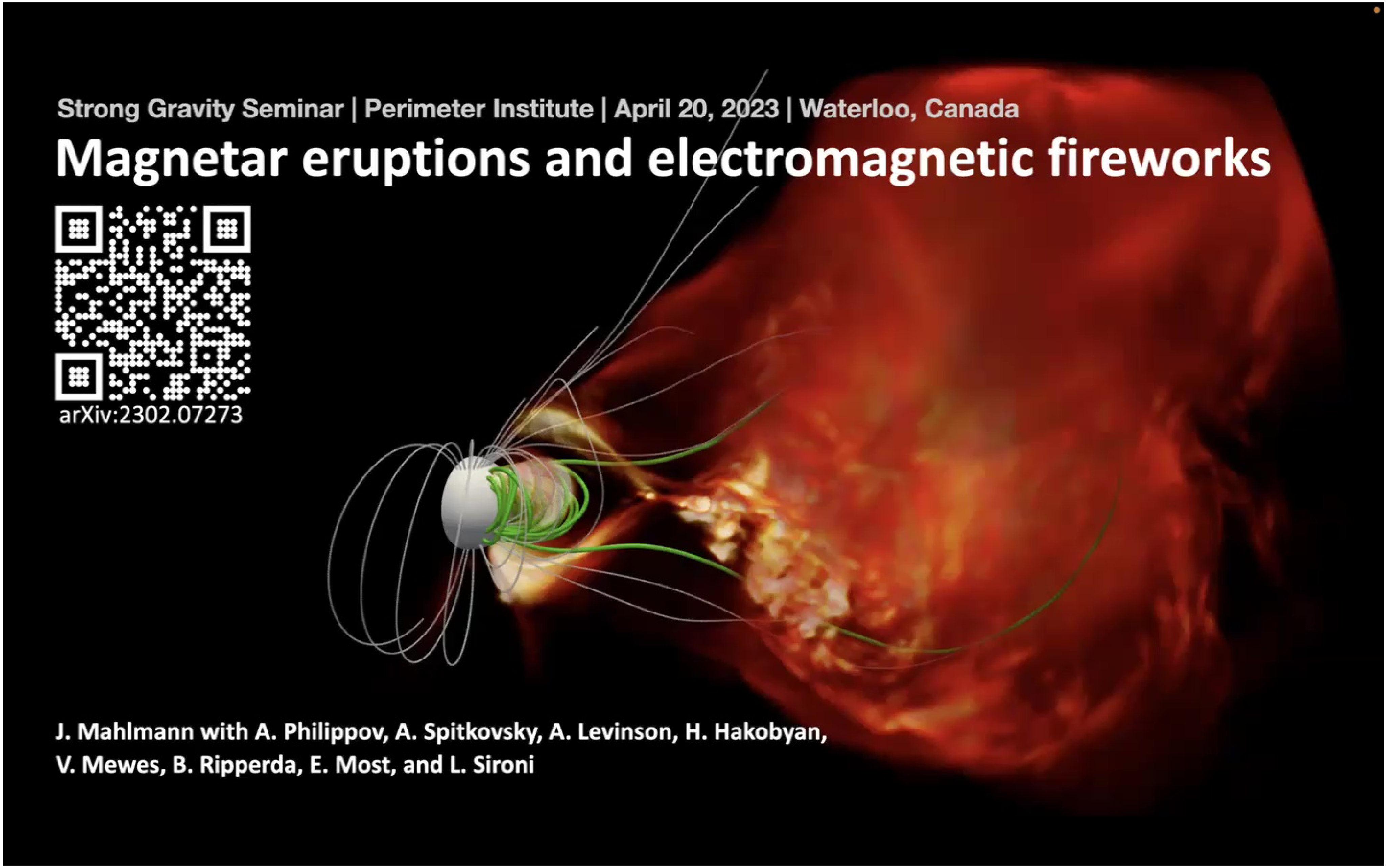
Series: Strong Gravity

Date: April 20, 2023 - 1:00 PM

URL: https://pirsa.org/23040134

Abstract: Highly magnetized neutron stars are a source of extreme transients observed in different bands, like the fast radio burst (FRB) and associated hard X-ray burst from the Galactic magnetar SGR 1935+2154. The origin of such outbursts, hard X-rays on the one hand and millisecond duration FRBs on the other hand, is still unknown. We present a global model for various kinds of such magnetar outbursting activities. Crustal surface motions are expected to twist the inner magnetar magnetosphere by shifting the frozen-in footpoints of magnetic field lines. We discuss criteria for the development of various instabilities of 3D twisted flux bundles in the force-free dipolar magnetospheres and compare their energetic properties to observations of magnetar X-ray flares. We then review a recently developed FRB generation mechanism in the outer magnetosphere of a magnetar. The strong magnetic pulse induced by a magnetar flare collides with the current sheet of the magnetar wind, compresses and fragments it into a self-similar chain of magnetic islands. Time-dependent plasma currents created during their collisions produce relatively narrow-band GHz emission with luminosities sufficient to explain bright extragalactic FRBs.

Zoom ink: https://pitp.zoom.us/j/96469987183?pwd=N1UzVkh6RGZUeWV6TFZJLzk0M3VWZz09



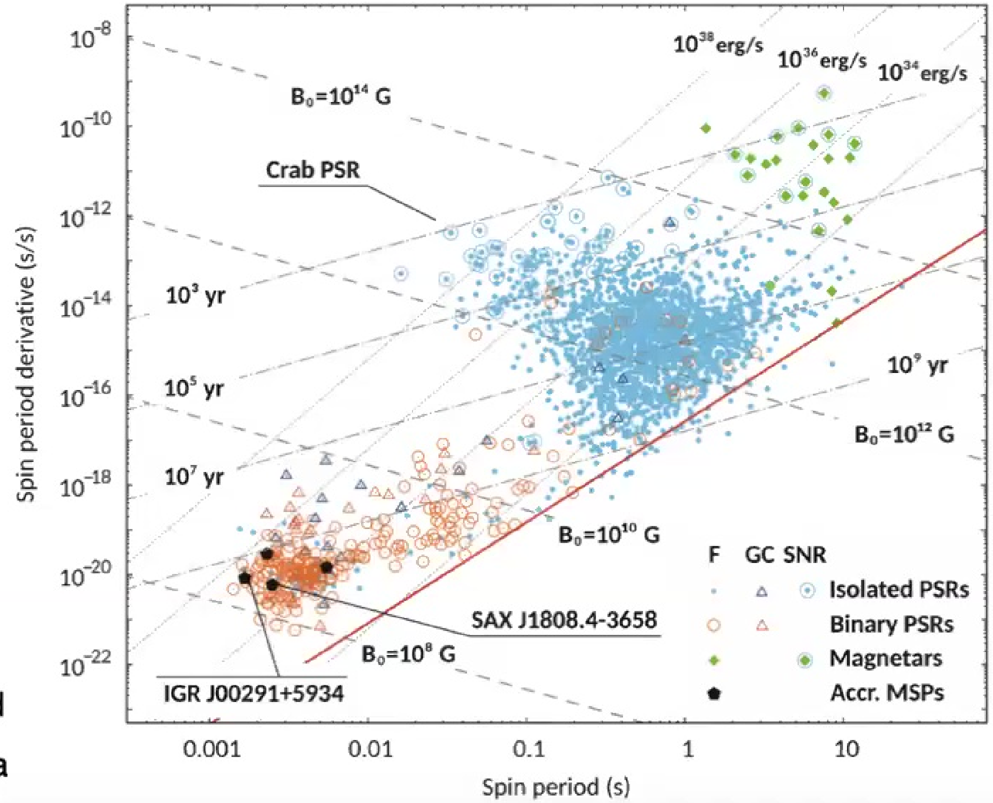
Strong Gravity Seminar | Perimeter Institute | April 20, 2023 | Waterloo, Canada
Magnetar eruptions and electromagnetic fireworks
arXiv:2302.07273
J. Mahlmann with A. Philippov, A. Spitkovsky, A. Levinson, H. Hakobyan,
V. Mewes, B. Ripperda, E. Most, and L. Sironi

Di Salvo et al. (2021)

Observations

Magnetars: Rapidly spinning neutron stars

- X-ray pulsations in the **range of 2-12s** (with exceptions)
- **X-ray bursting** often lead to the discovery of the object
- Spin-down time-scales of a few thousand years
- **Spin-down luminosity** typically smaller than persistent X-ray luminosity, but with some exceptions and possible connection to **transient radio emission**
- Spin-down rates imply **magnetic fields** of $B \gtrsim 10^{14}$ G
- Despite the small range in period (derivative), the **quiescent X-ray luminosity spans many orders of magnitude**, fainter objects have more bursting activity
- **Blackbody-like** spectrum in the softer X-rays, at higher energies with **spectral hardening or inversion**
- Some **fast radio bursts (FRBs)** are magnetar associated
- **Exotic candidates** exist do not match all of these criteria



Modeling and simulation

Relativistic force-free electrodynamics

Using Maxwell's equations as a tool to understand magnetic topology

Force-free electrodynamics: Vanishing inertia limit of relativistic ideal MHD **or** infinite conductivity, zero inertia limit of relativistic resistive MHD.

A. No non-ideal electric fields, i.e. $\mathbf{E} \cdot \mathbf{B} = 0$

B. Magnetic dominance, i.e. $\mathbf{E}^2 - \mathbf{B}^2 < 0$

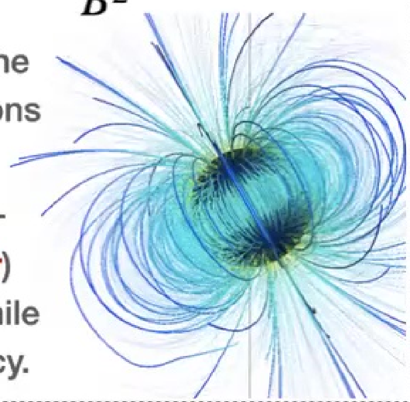
Einstein Toolkit FFE

Mahlmann et al. (2020a, b); Mahlmann & Aloy (2021)

Uses the **force-free current**

$$\mathbf{J} = q\frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{\mathbf{B}\cdot(\nabla\times\mathbf{B}) - \mathbf{E}\cdot(\nabla\times\mathbf{E})}{B^2}\mathbf{B}$$

and **algebraic corrections** to the electric field to restore conditions [**A**] and [**B**]. Evolves charge density q **conservatively**. High-order reconstruction (**7th order**) reduces numerical diffusion while maintaining dispersion accuracy.

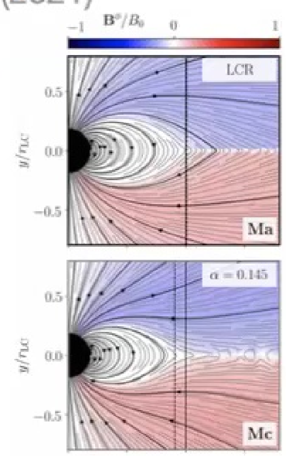


Optimized spherical meshes (3D)

Mewes et al. (2020); Mahlmann & Aloy (2021)

Well-calibrated divergence cleaning: Ensuring $\nabla \cdot \mathbf{B} = 0$ and $\nabla \cdot \mathbf{E} = \rho$ while controlling (numerical) diffusion at resistive layers.

Active filtering to ease the axis problem: Fourier filters along the toroidal direction with aggressive noise canceling close to the axis.



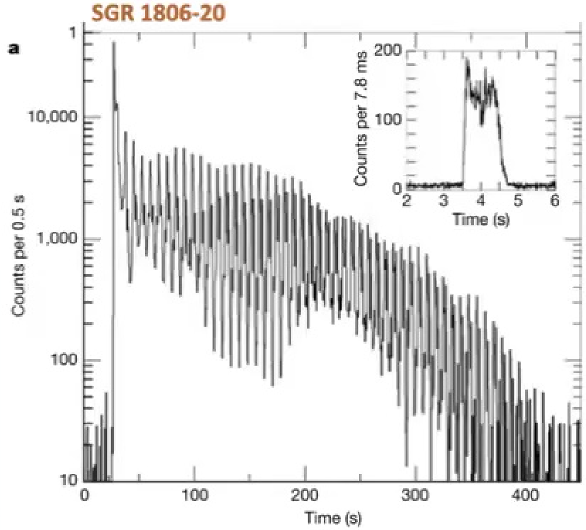
Enable 3D spherical simulations with the same tilmestep than 2D!

Giant-Flare-like energy dissipation in 2D

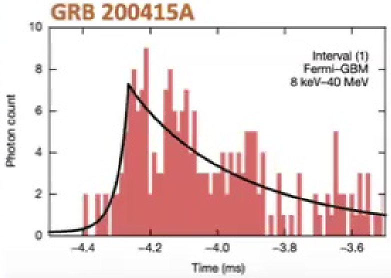
Axisymmetric eruptions commonly drive powerful magnetospheric dissipation

Observations

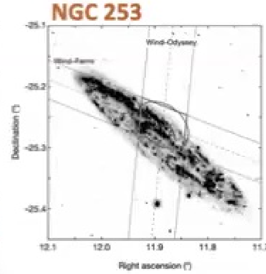
SGR 1806-20



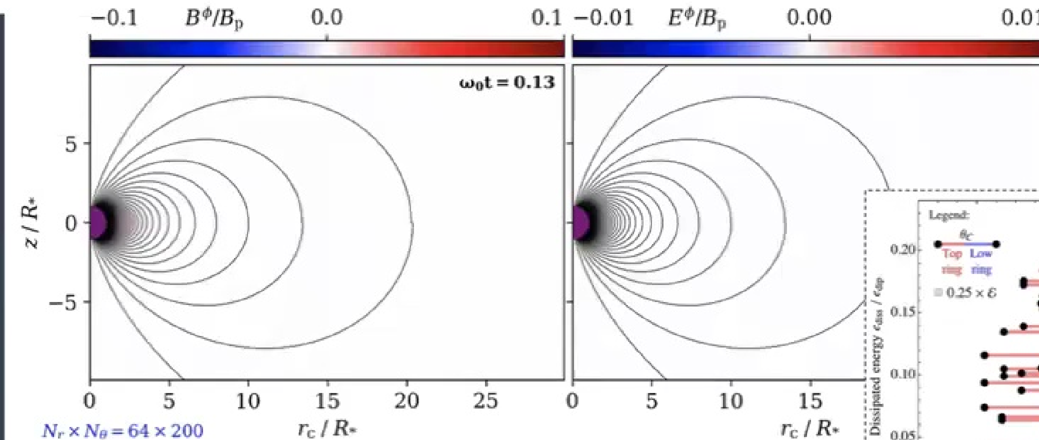
GRB 200415A

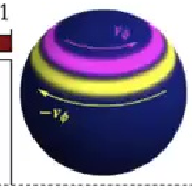


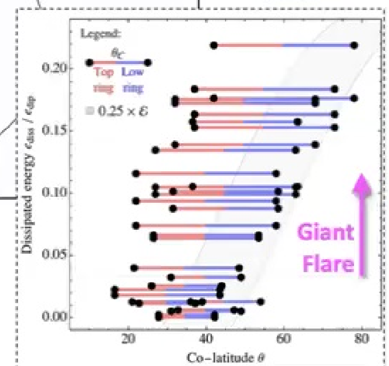
NGC 253



Modeling and simulation







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

The Sun in extreme ultraviolet

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

Analogy to the Sun's CMEs, see also recent work by **Sharma et al. (2023, arXiv:2302.08848)**

Roberts et al. (2021); Svinkin et al. (2021); Hurley et al. (2005)

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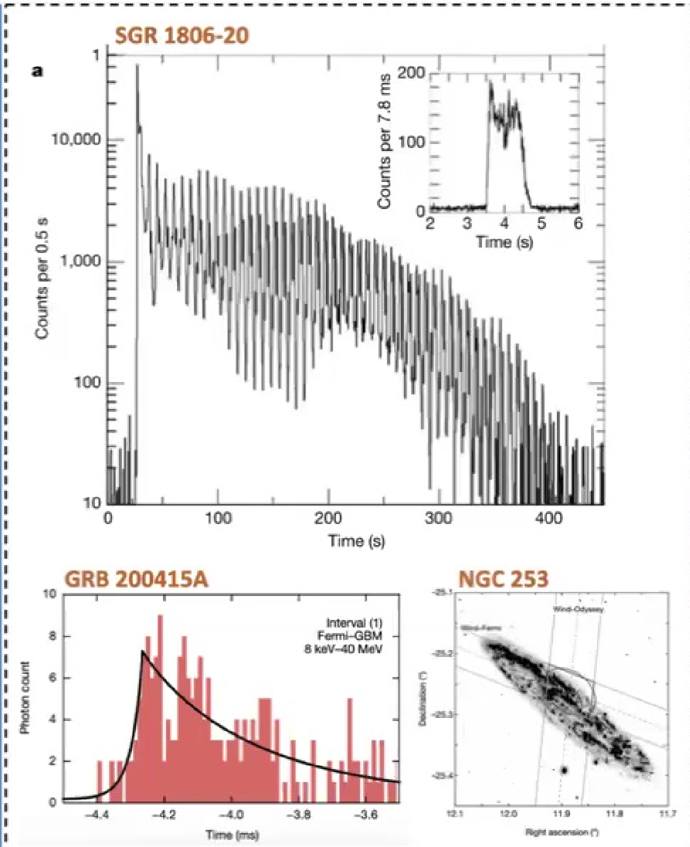

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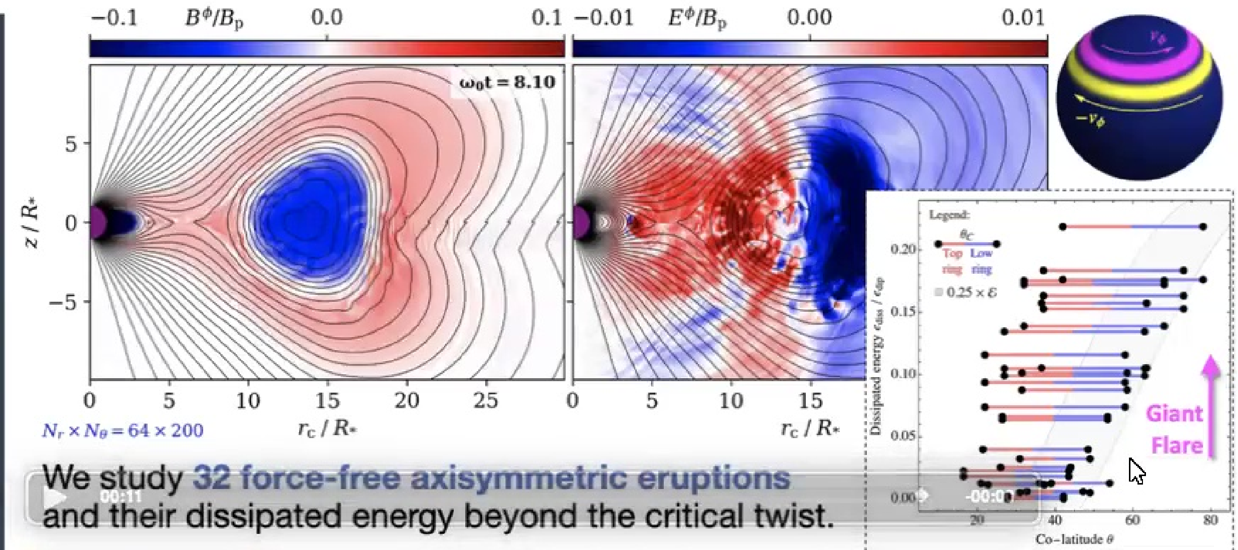

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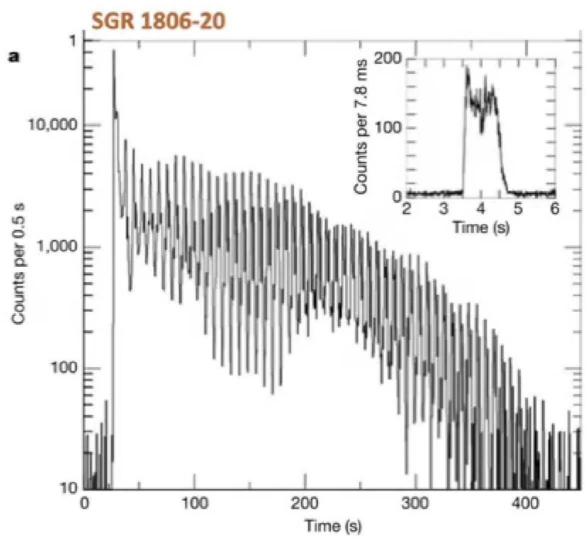

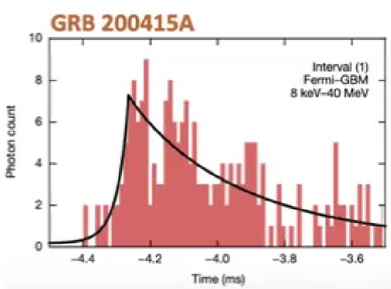

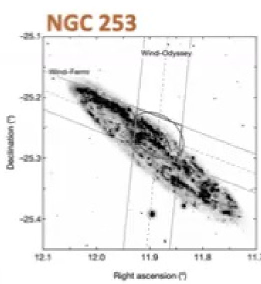

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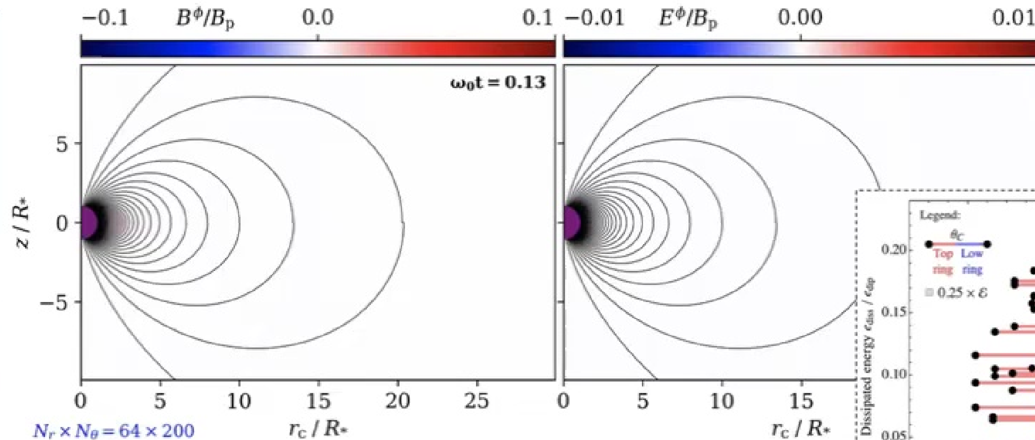

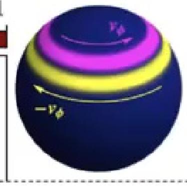

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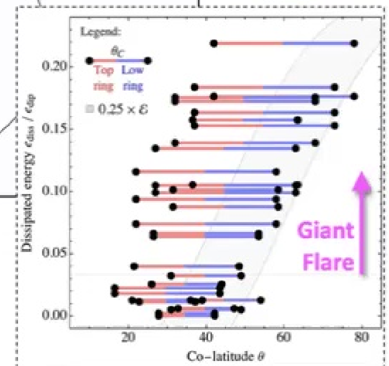

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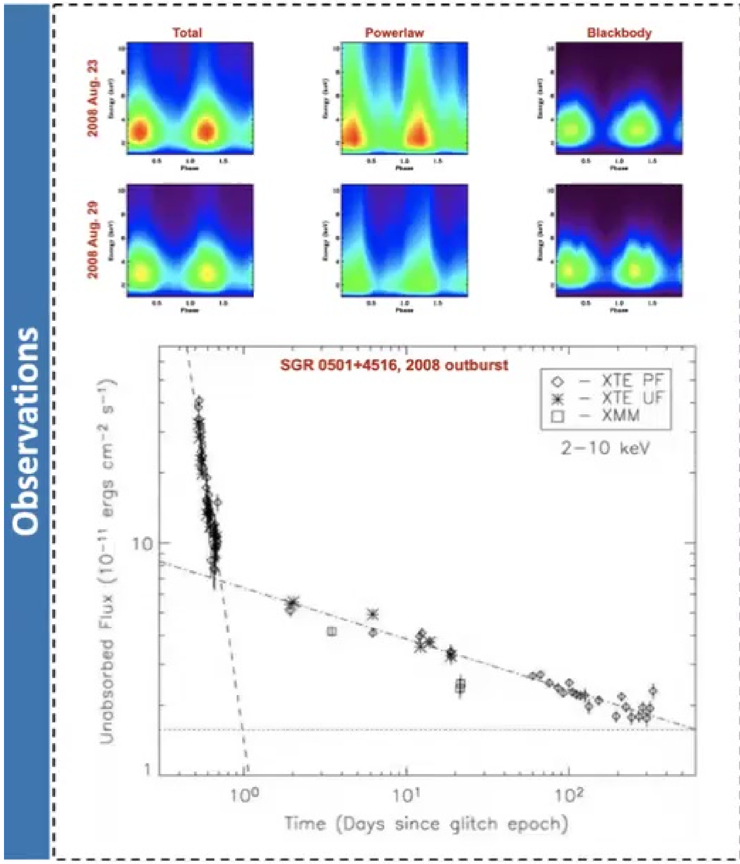
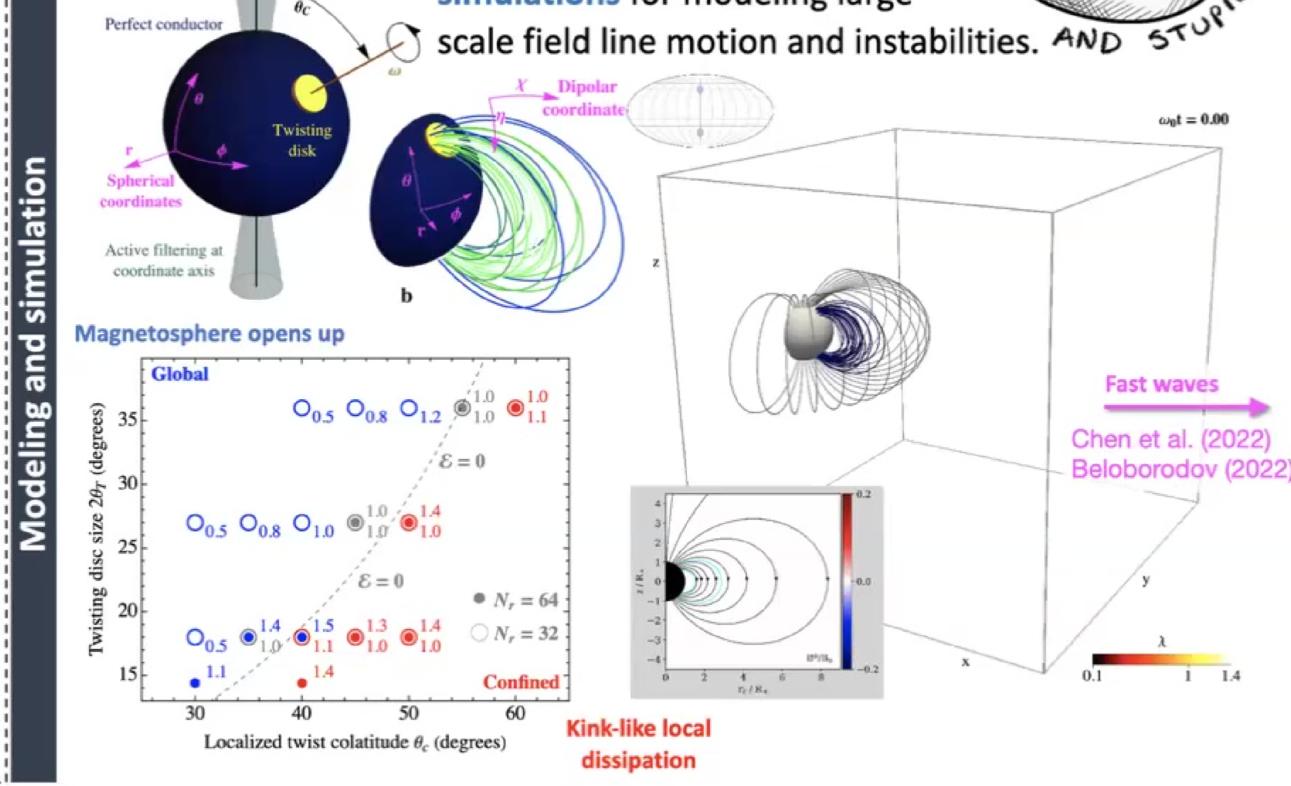
Woods et al. (2004); Rea & Esposito (2011)

Everything bursts everywhere all at once

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

High-order 3D **force-free (MHD) simulations** for modeling large-scale field line motion and instabilities.

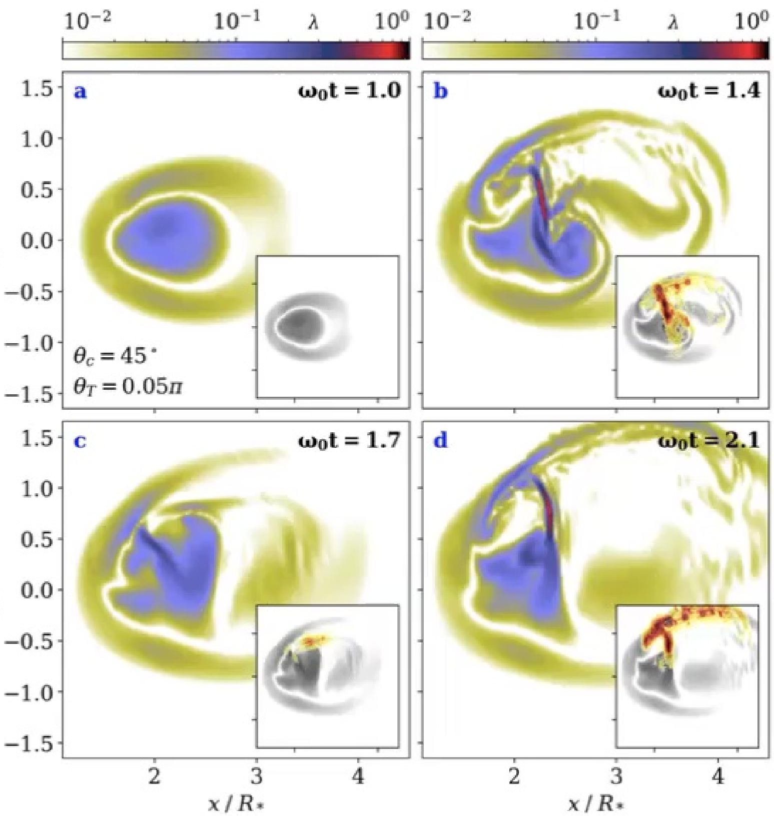




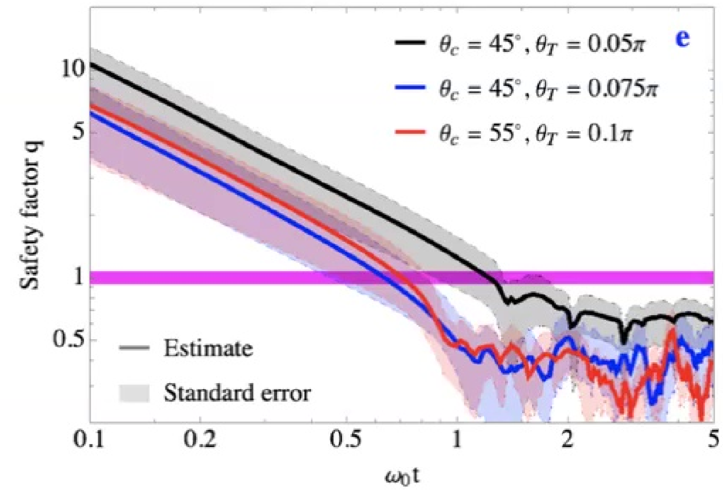
Modeling and simulation

Energy release after saturation of parallel currents

Current sheets form along the flux tube but decay after dissipation event



Stressed flux tubes release magnetic energy when they become unstable ($q \lesssim 1$). Kink-like instabilities confined to inner magnetosphere produce current sheets along the flux tube and release magnetic energy.



λ : Parallel current

R : Curvature radius

$$B_T = \frac{I}{2\pi r_0} = \frac{r_0 j_{\parallel}}{2}$$

$$\Rightarrow \; q \equiv \frac{r_0}{R}\frac{B_{\parallel}}{B_T} \approx \frac{2}{R\lambda}$$

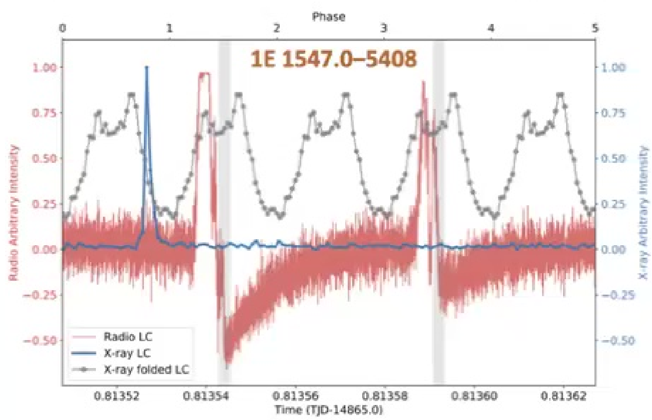
All cases become unstable, but how do they dissipate?

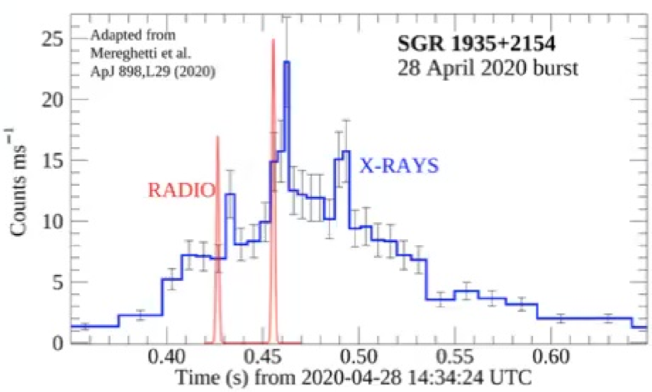
See also current student project with Natalie Rugg **(in prep.)**

Everything bursts everywhere all at once

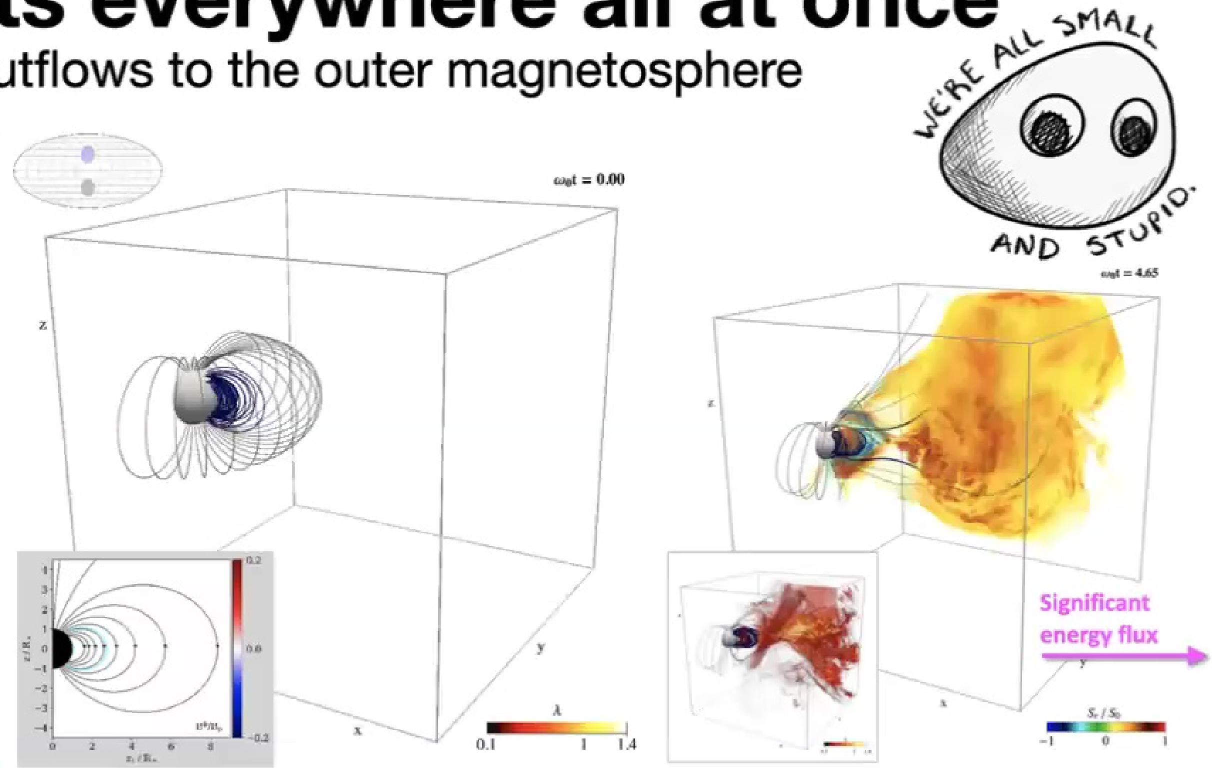
Global eruptions generate outflows to the outer magnetosphere

Observations





Modeling and simulation



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 inject energy to the outer magnetosphere.

Israel et al. (2022); Petroff et al. (2022)

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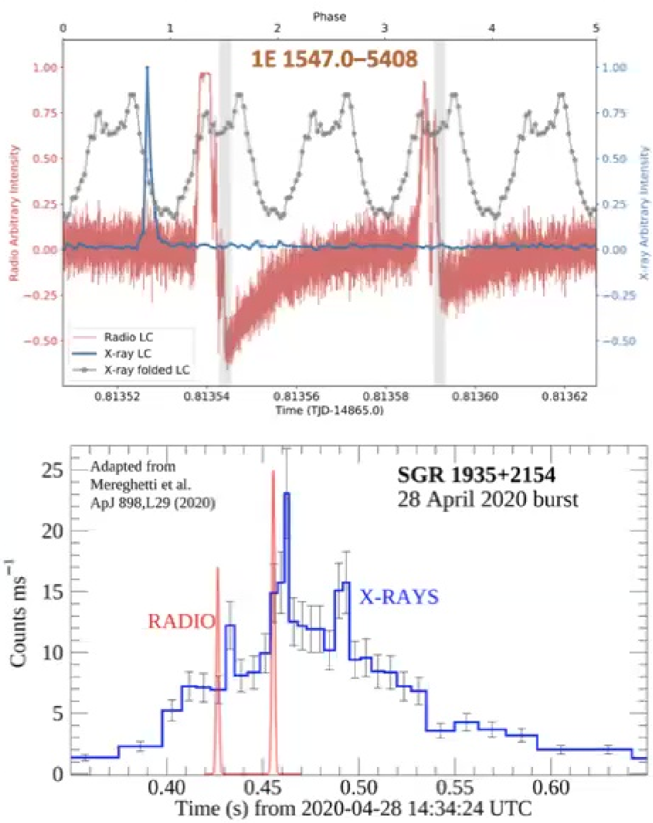

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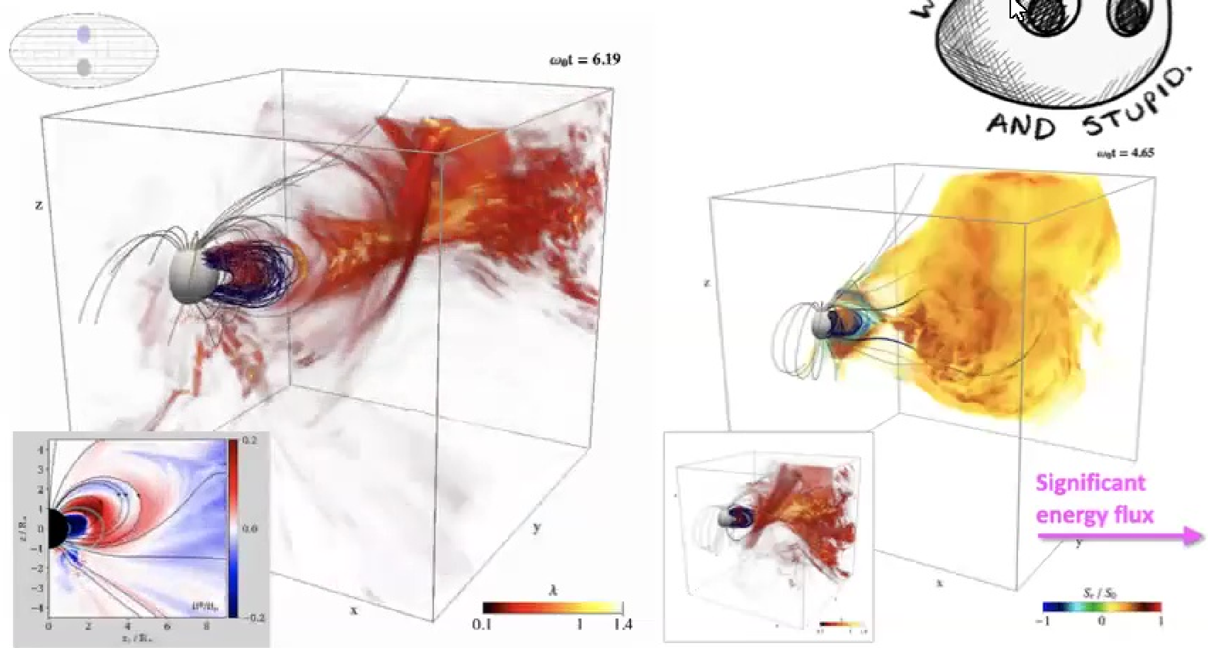

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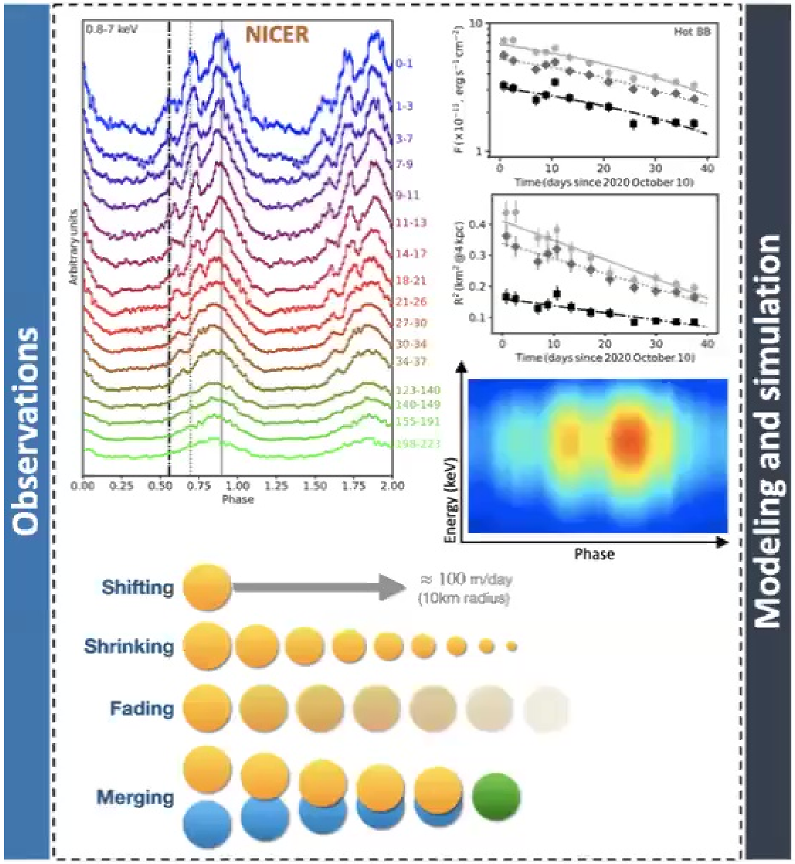
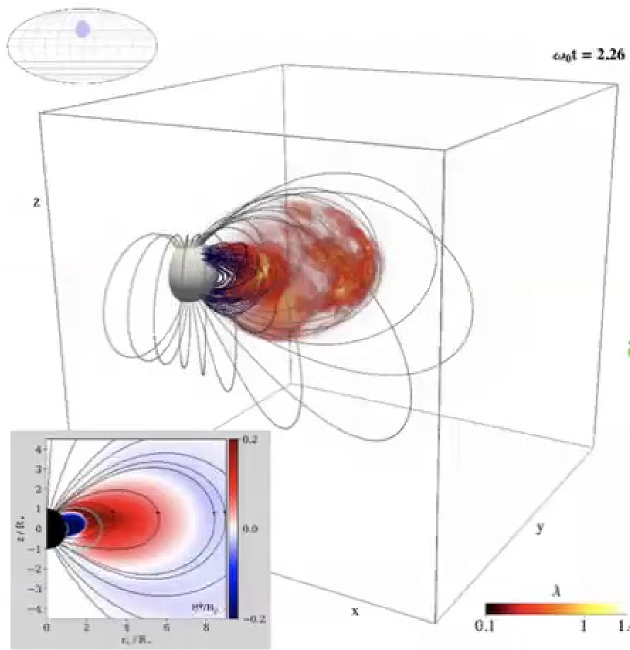
Younes et al. (2022); Beloborodov (2013), Thompson & Kostenko (2020)

How to make our models more realistic?

Crust coupling, magnetospheric plasma generation and radiative transfer

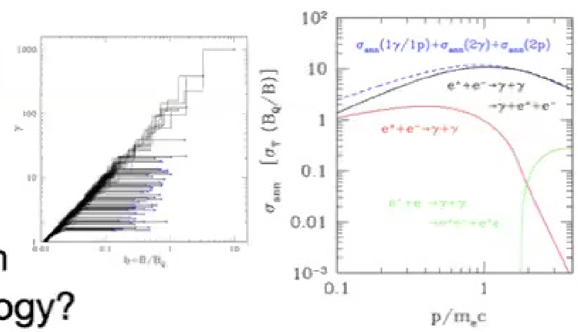




What is the most **realistic crust dynamics**, and how does it couple to the magnetosphere?

Realistic crust motion could allow for more energetic bursts.

What is the **plasma dynamics** in the magnetosphere?

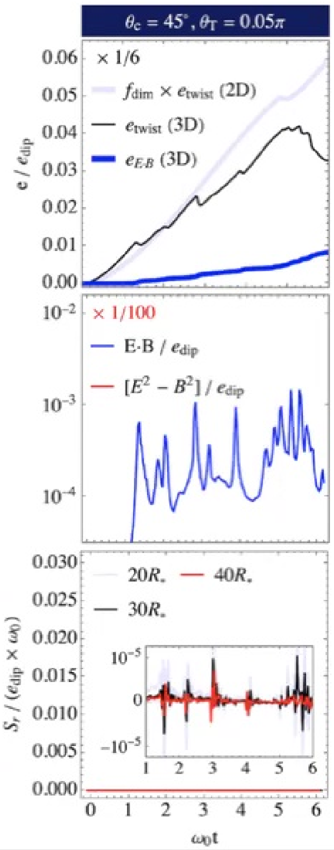


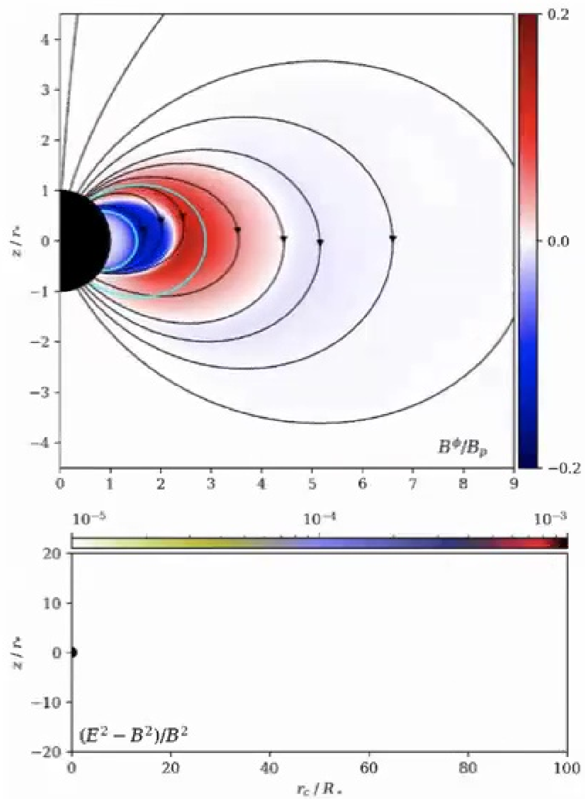
How does the **magnetospheric equilibrium** change after the eruption events? How **stable** is the new topology?

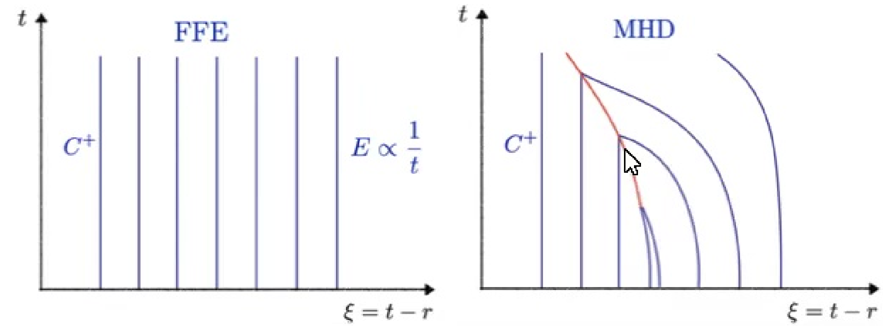
Chen et al. (2022), Beloborodov (2022)

Kink eruption: Energy transport and dissipation

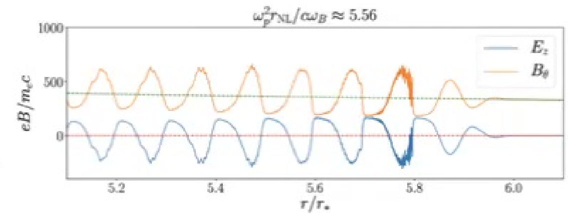
Fast magneto sonic waves are seeded in the inner magnetosphere







Electric zones can alter characteristics and generate shocks.



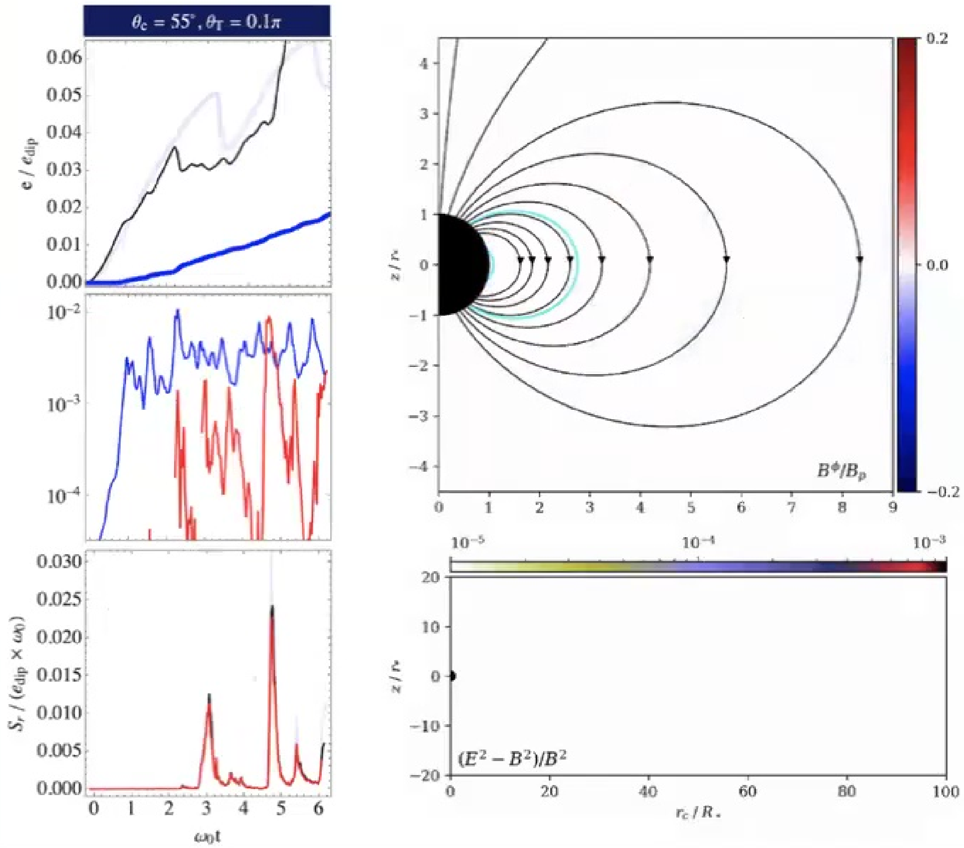
Kink events can seed **high frequency fast magnetosonic waves** that become electrically dominated at $80 - 100R_*$.

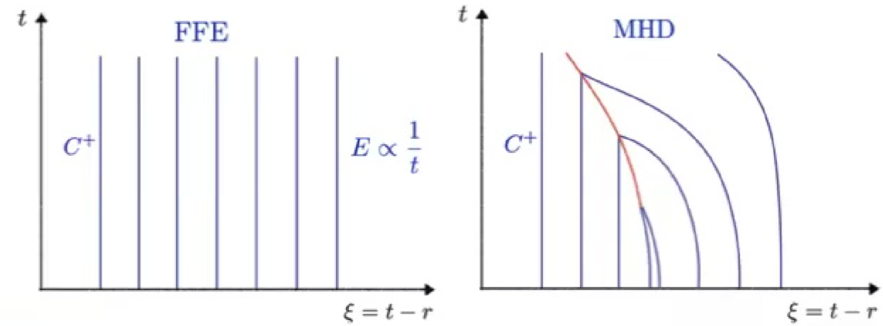
Shocks in the inner magnetosphere could generate additional X-ray emission.

Chen et al. (2022), Beloborodov (2022)

Global eruption: Energy transport and dissipation

Non-linear structures are ejected, stable outward propagation





Non-linear magnetic structures propagate outwards as an assembly of modes, they do not develop electric zones and show no significant dissipation.

Global eruption events can perturb the outer magnetosphere while shining in the X-rays during the field line instability.

Global magnetospheric eruptions could seed FRBs in the outer magnetosphere.

Modeling and simulation

Chen et al. (2022), Beloborodov (2022)

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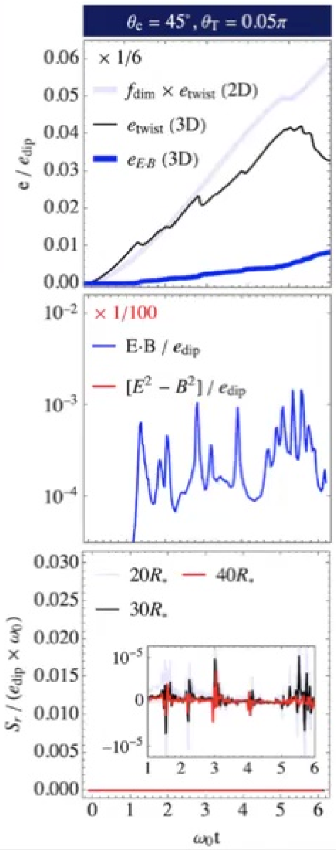

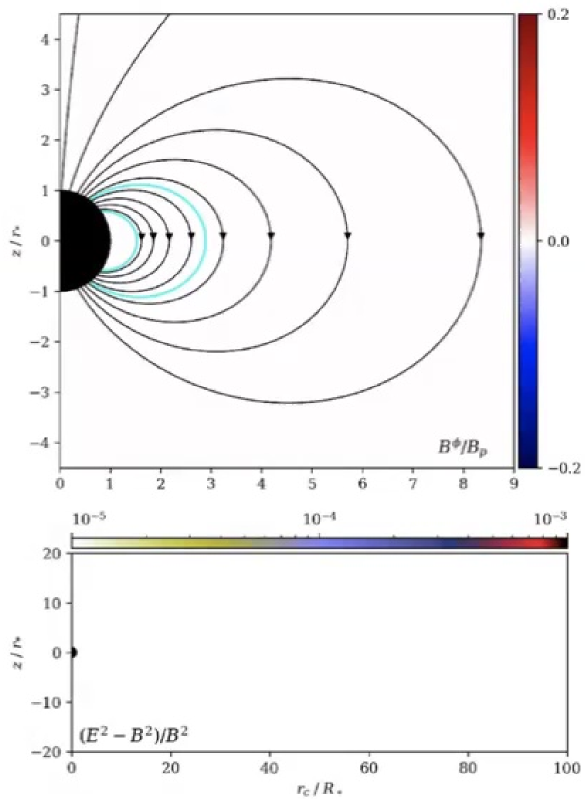

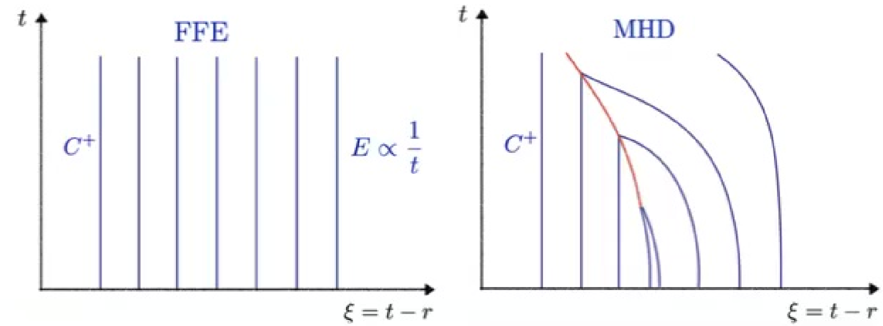

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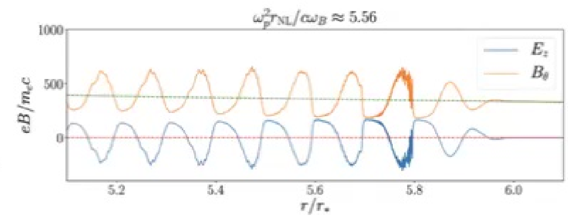

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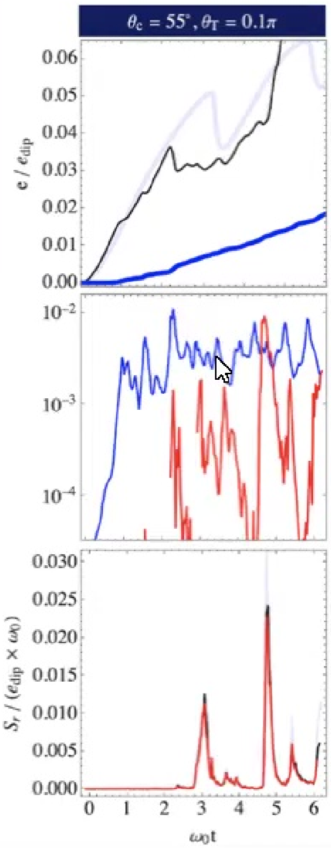

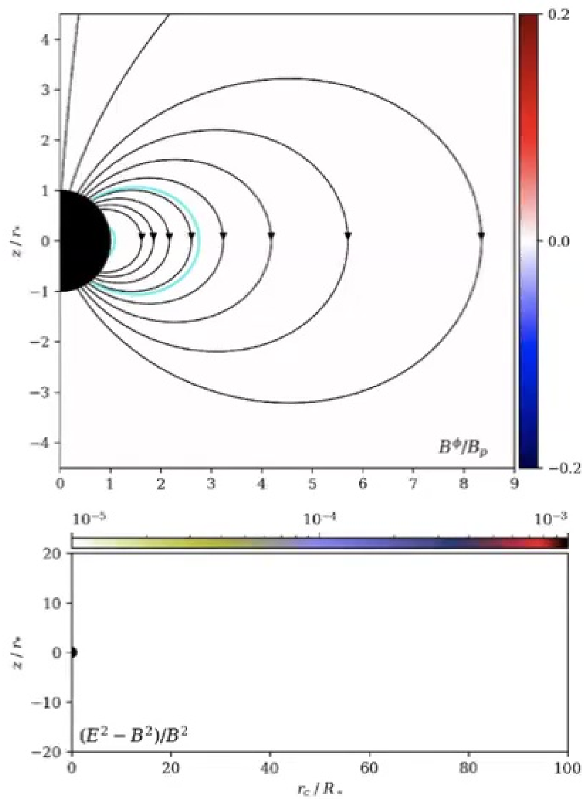

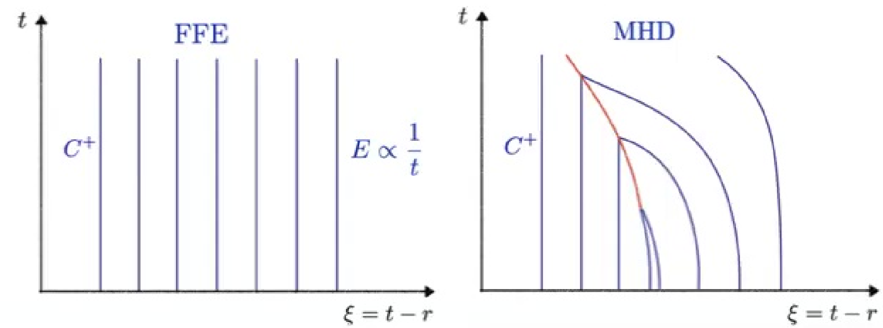

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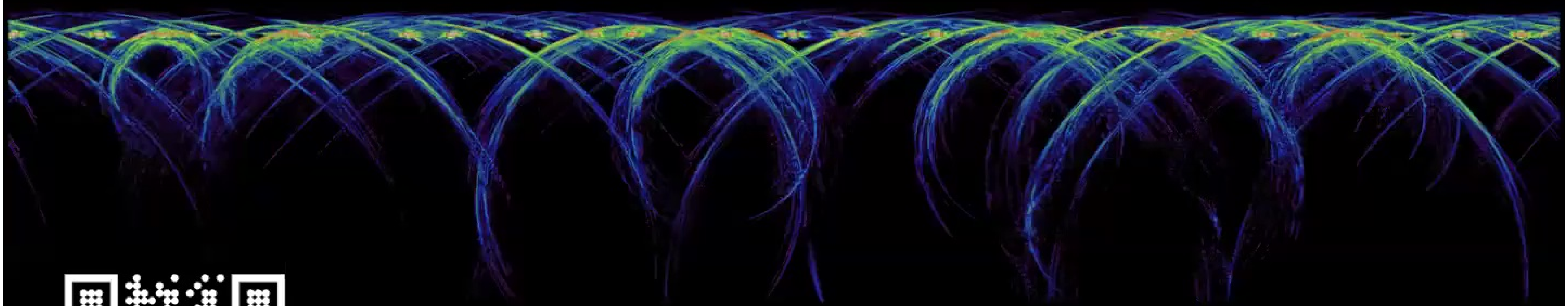
Strong Gravity Seminar | Perimeter Institute | April 20, 2023 | Waterloo, Canada

Magnetar eruptions and electromagnetic fireworks



arXiv:2203.04320

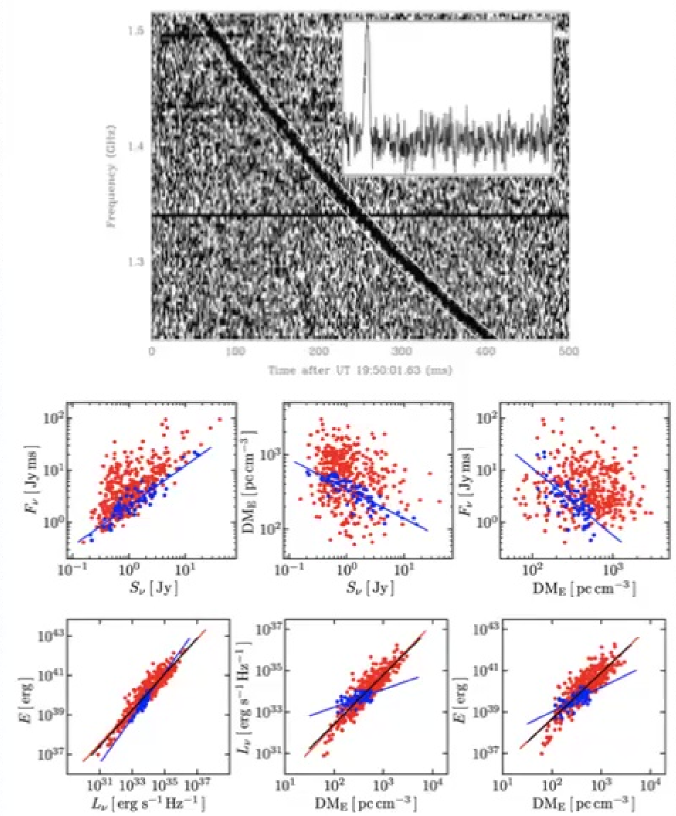
J. Mahlmann with A. Philippov, A. Spitkovsky, A. Levinson, H. Hakobyan,
V. Mewes, B. Ripperda, E. Most, and L. Sironi

Lorimer et al. (2007); Lyubarsky (2020); Guo and Wei (2022)

The reconnection mediated FRB model

One viable alternative to the much discussed shock model

Observations

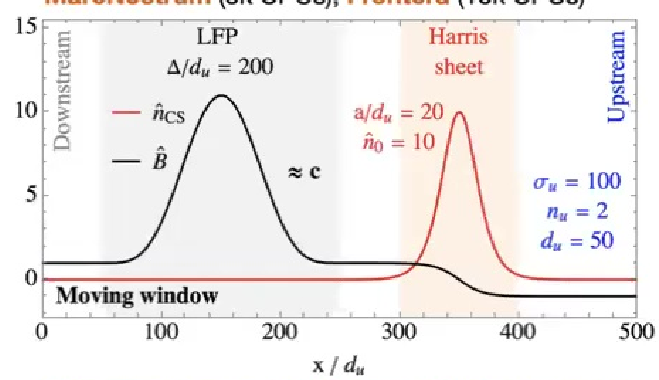


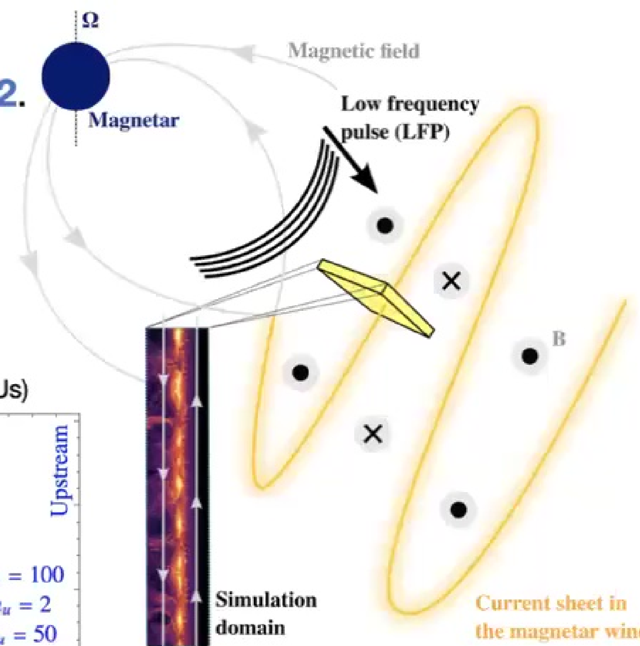
Modeling and simulation

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)

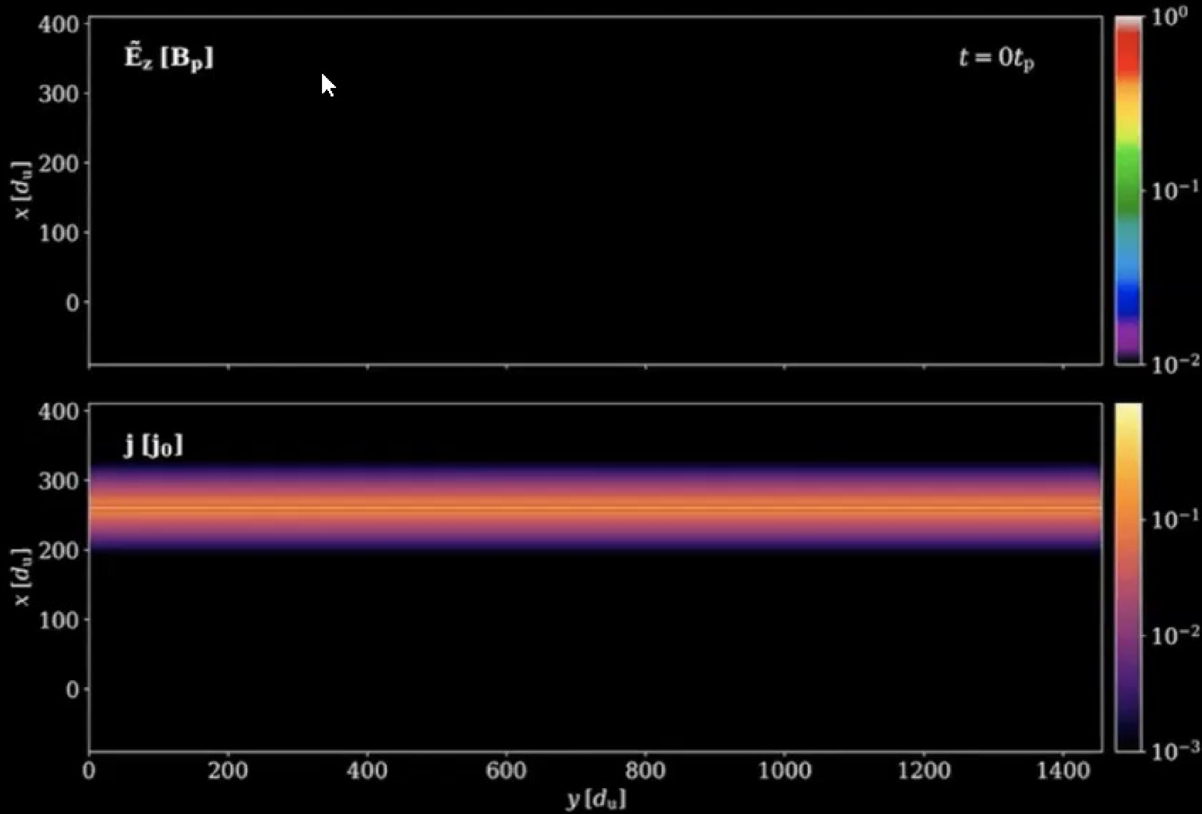




Compressed plasmoid mergers inject high frequency waves.

Electrodynamic fireworks

Plasmoid mergers induce a high-frequency fast wave signature



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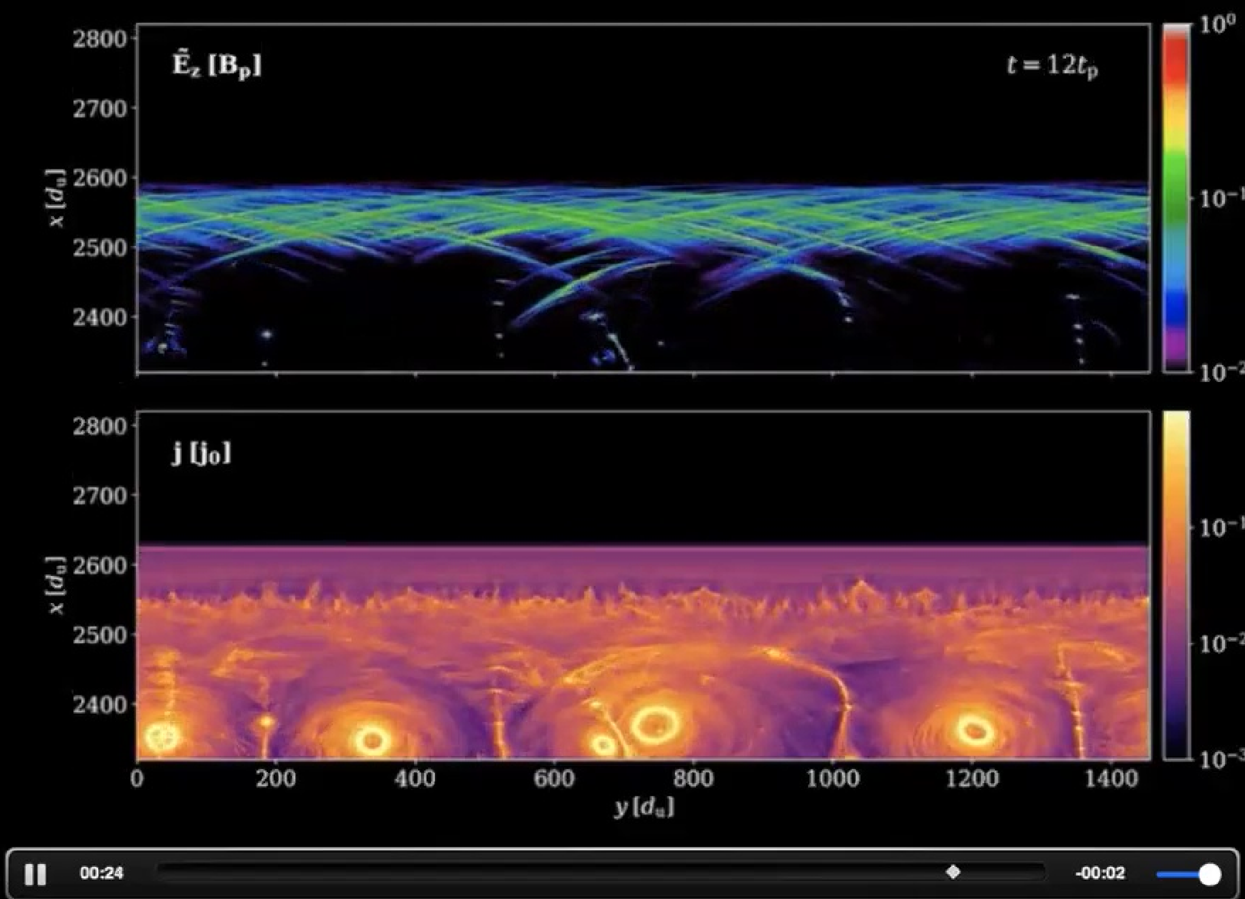
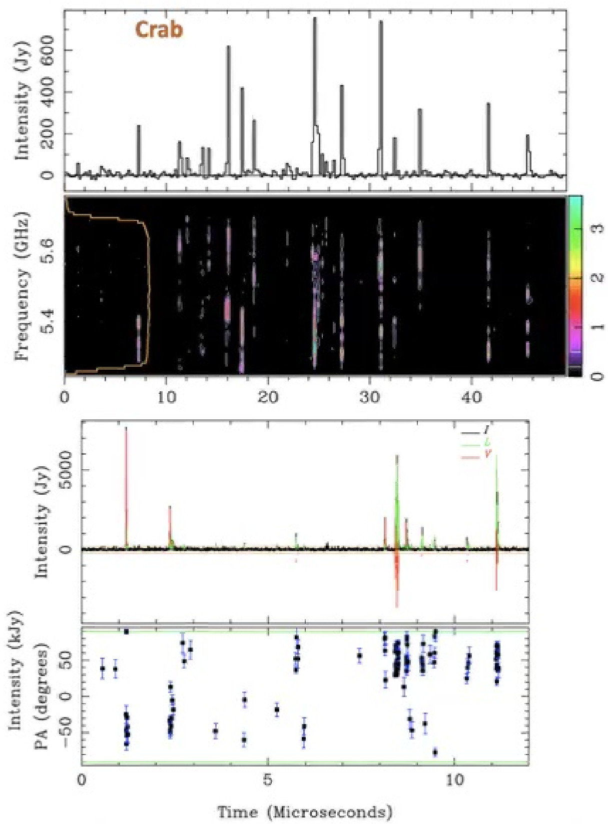


Eilek & Hankins (2016); Philippov et al. (2019)

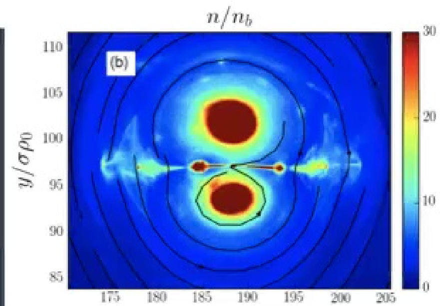
Plasmoid mergers as short duration 'shots'

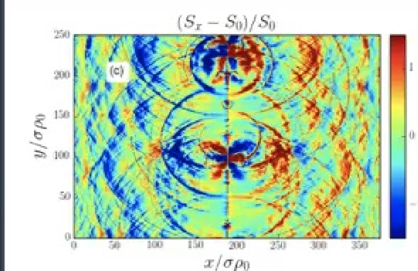
Currents of secondary reconnection layers induce high-frequency fast waves

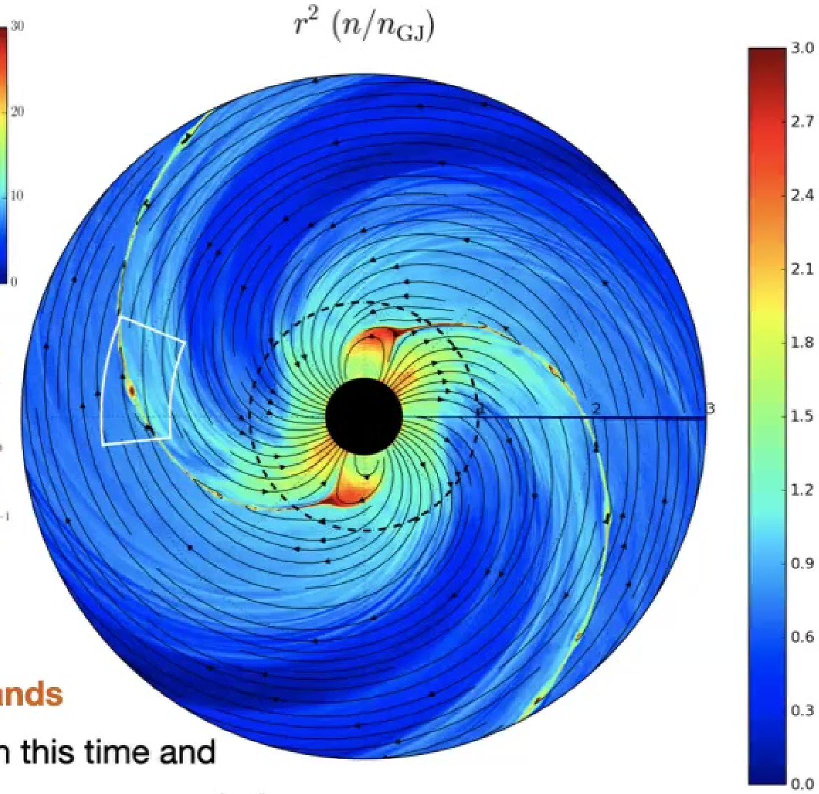
Observations



Modeling and simulation







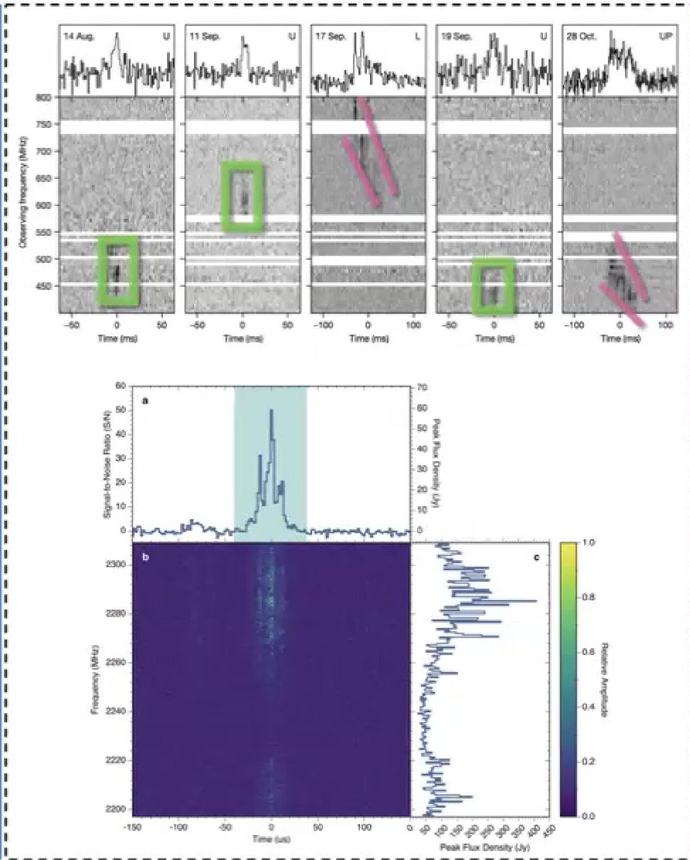
Fast waves injected by **merging magnetic islands** (plasmoids) may explain this time and frequency structures with $S_{\rm fast} \sim 10^{-4} B_0^2$.

Chime/FRB Collaboration (2019); Majid et al. (2021)

Dynamical spectra of the induced FMS waves

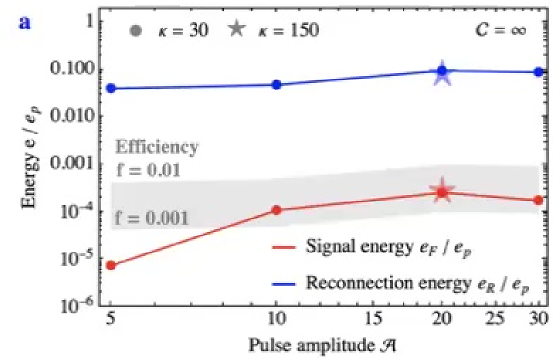
Compression and cooling boost the wave frequency to FRB range

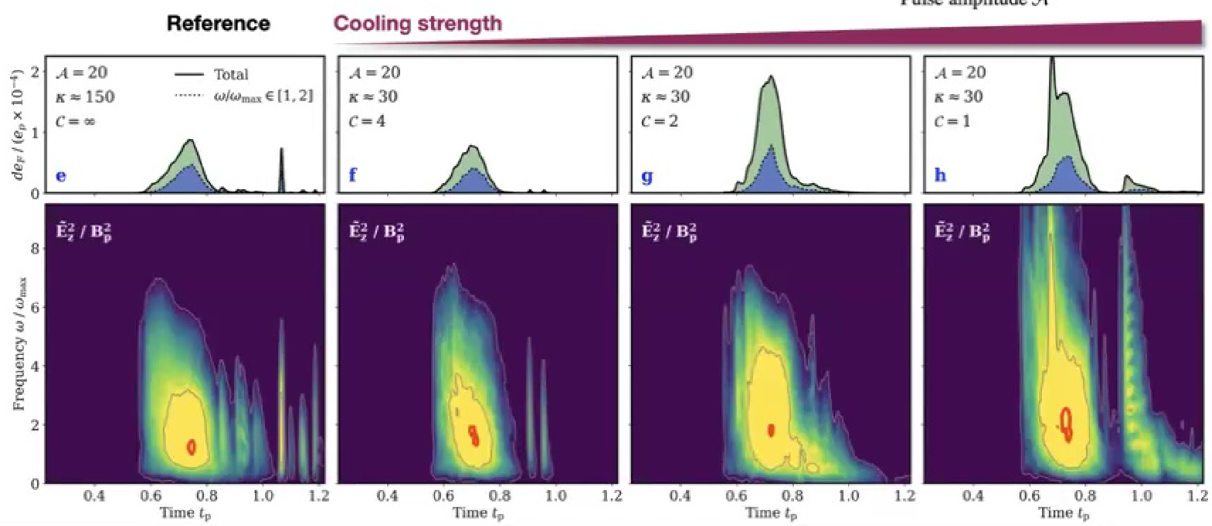
Observations



Modeling and simulation

0.1% of the reconnected energy is injected into **high-frequency waves**. Increased field compression or stronger synchrotron cooling **shifts the spectra to higher frequencies**. A significant part of the induced FMS waves is in higher energy bands.



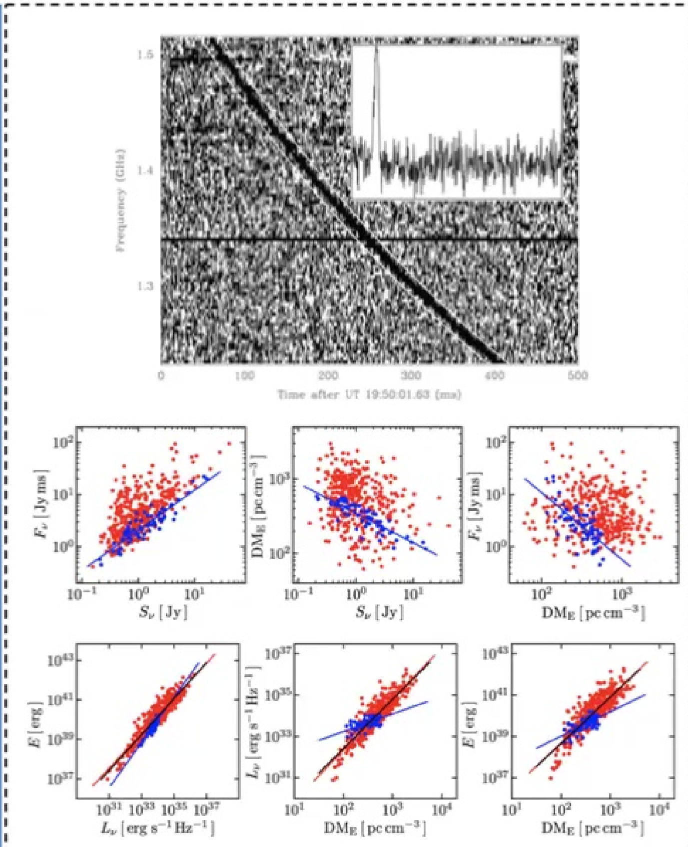


Lorimer et al. (2007); Lyubarsky (2020); Guo and Wei (2022)

The reconnection mediated FRB model

One viable alternative to the much discussed shock model

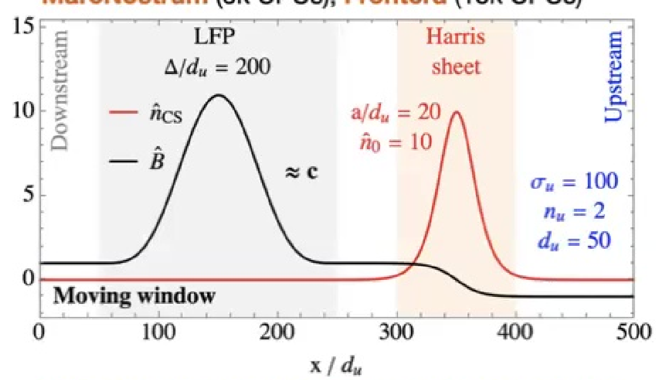
Observations

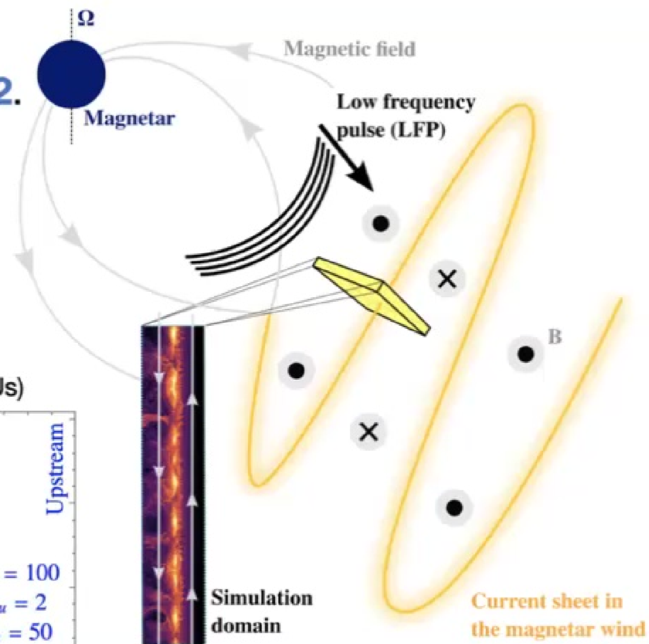


Modeling and simulation

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)



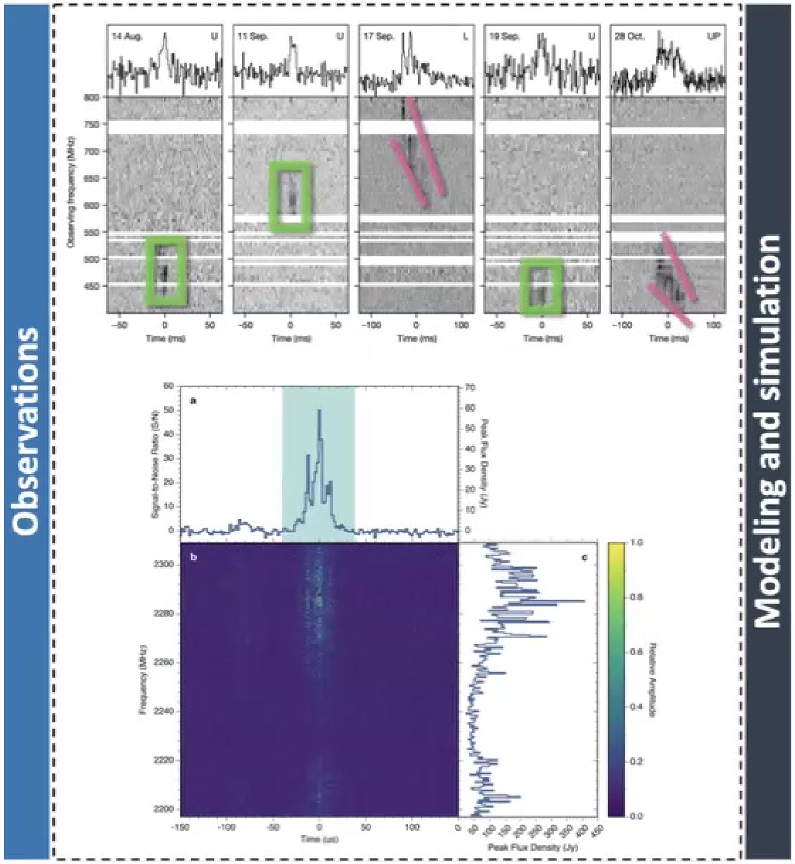


Compressed plasmoid mergers inject high frequency waves.

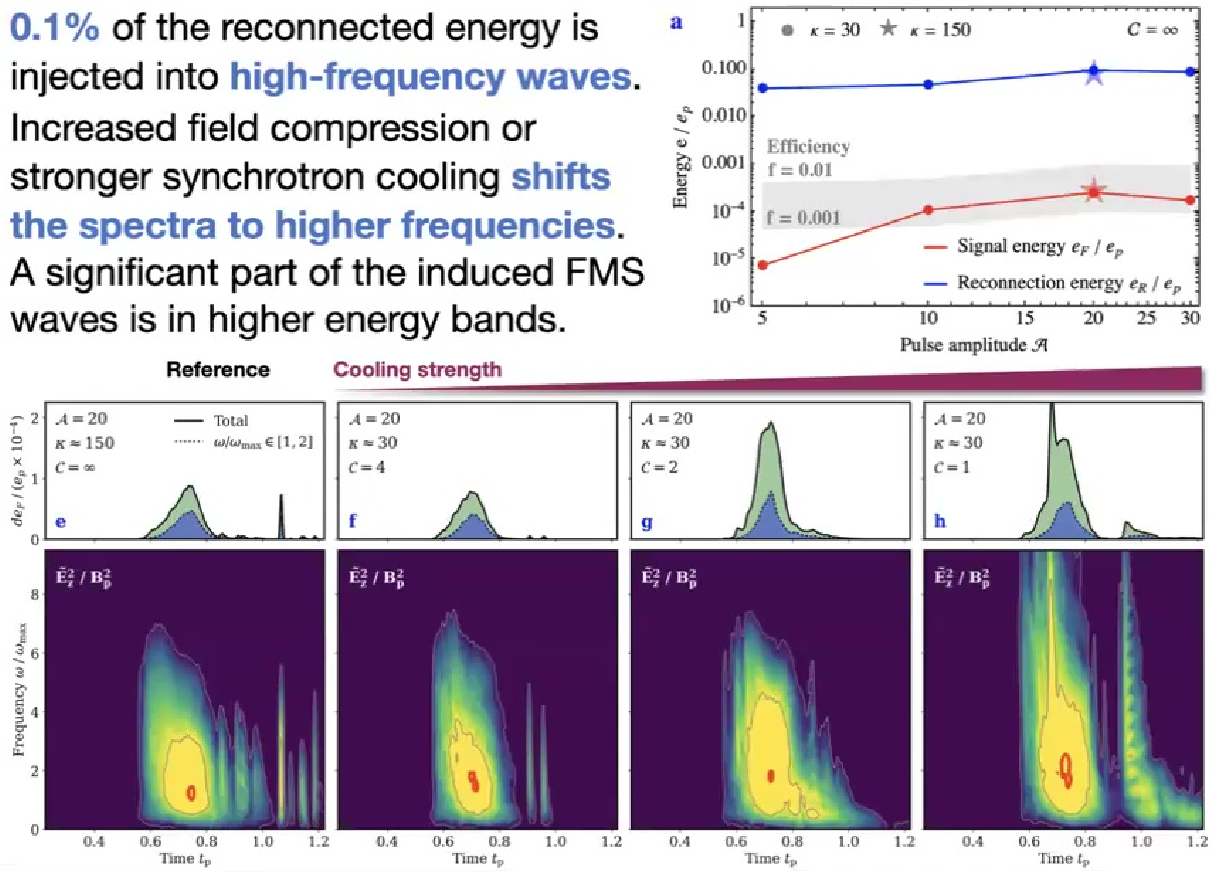
Chime/FRB Collaboration (2019); Majid et al. (2021)

Dynamical spectra of the induced FMS waves

Compression and cooling boost the wave frequency to FRB range



0.1% of the reconnected energy is injected into **high-frequency waves**. Increased field compression or stronger synchrotron cooling **shifts the spectra to higher frequencies**. A significant part of the induced FMS waves is in higher energy bands.



$e_{\rm dip} \approx 3 \times 10^{47} \left(\frac{B_*}{10^{15}{\rm G}}\right)^2 \left(\frac{R_*}{10{\rm km}}\right)^3$ erg

Our take on low(er) luminosity X-ray bursts

3D dynamics in the magnetar magnetosphere allow rich phenomenology

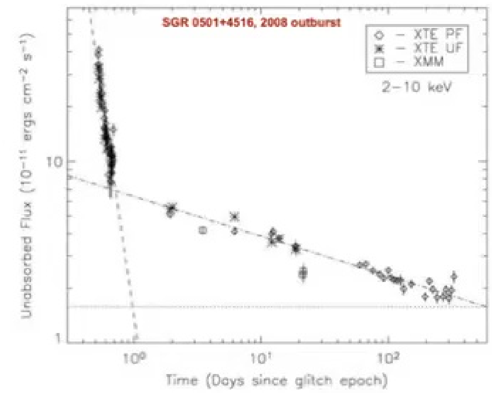
X-ray bursts

- Eruption models for giant flare events require to tap a sheared configuration with magnetic energy $e_{\rm twist} \gtrsim 4 \times 10^{46} \approx 0.13 \times e_{\rm dip}$.
- Before the first eruption, disk-like shearing only induce small twist energies $e_{\rm twist} \lesssim 0.025 \times e_{\rm dip}$ for deeply buried flux tubes.
- Several eruption events with subsequent injection are required to reach giant flare-like 'freeable' energy in the magnetosphere.
- Kink events seed short-wavelength fast magnetosonic waves that develop electric zones (possible monster shocks)

FRBs

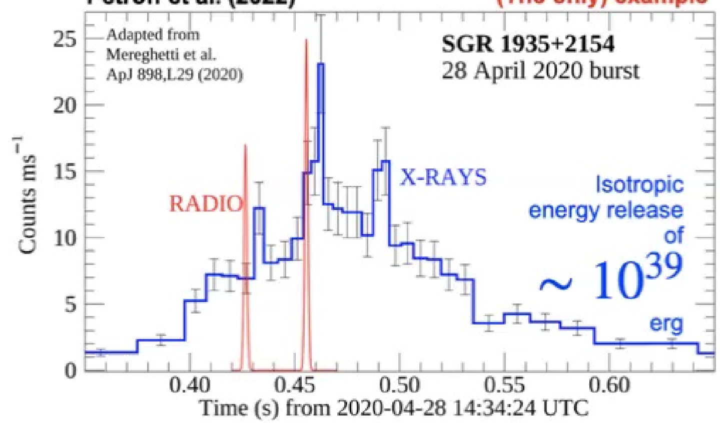
- In our naive scenarios, all flux tube instabilities shine in X-rays. Some of them inject energetic magnetic structures that propagate to the outer magnetosphere. These could power FRBs,

Magnetospheric instabilities can have a global impact!



Petroff et al. (2022)

(The only) example



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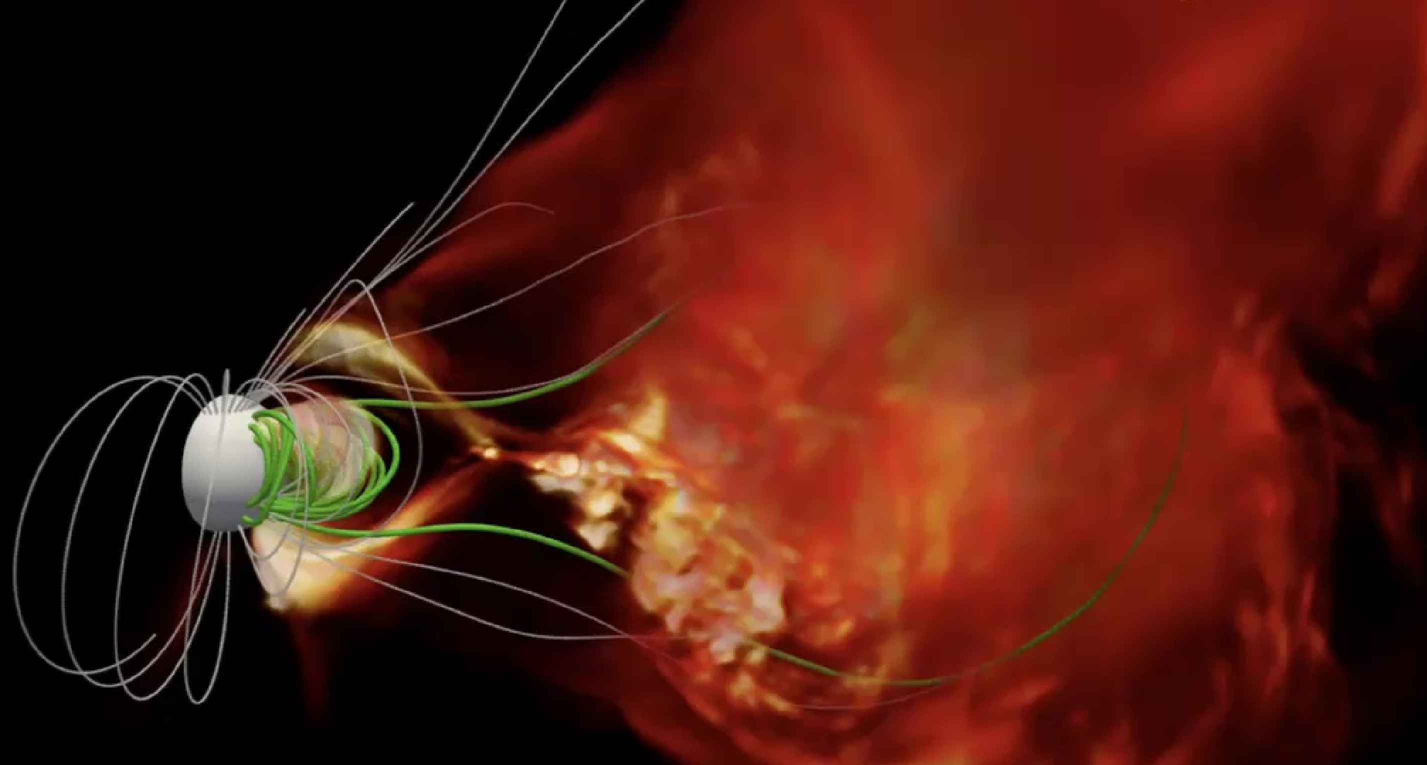
Discuss. Criticize. Explain. Ask. Thank you.

arXiv:2302.07273

arXiv:2203.04320



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V. Mewes, B. Ripperda, E. Most, and L. Sironi