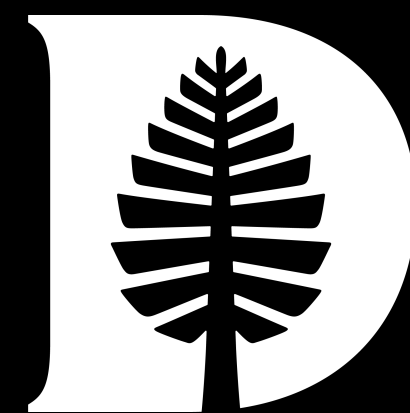


Extreme plasma processes around compact objects

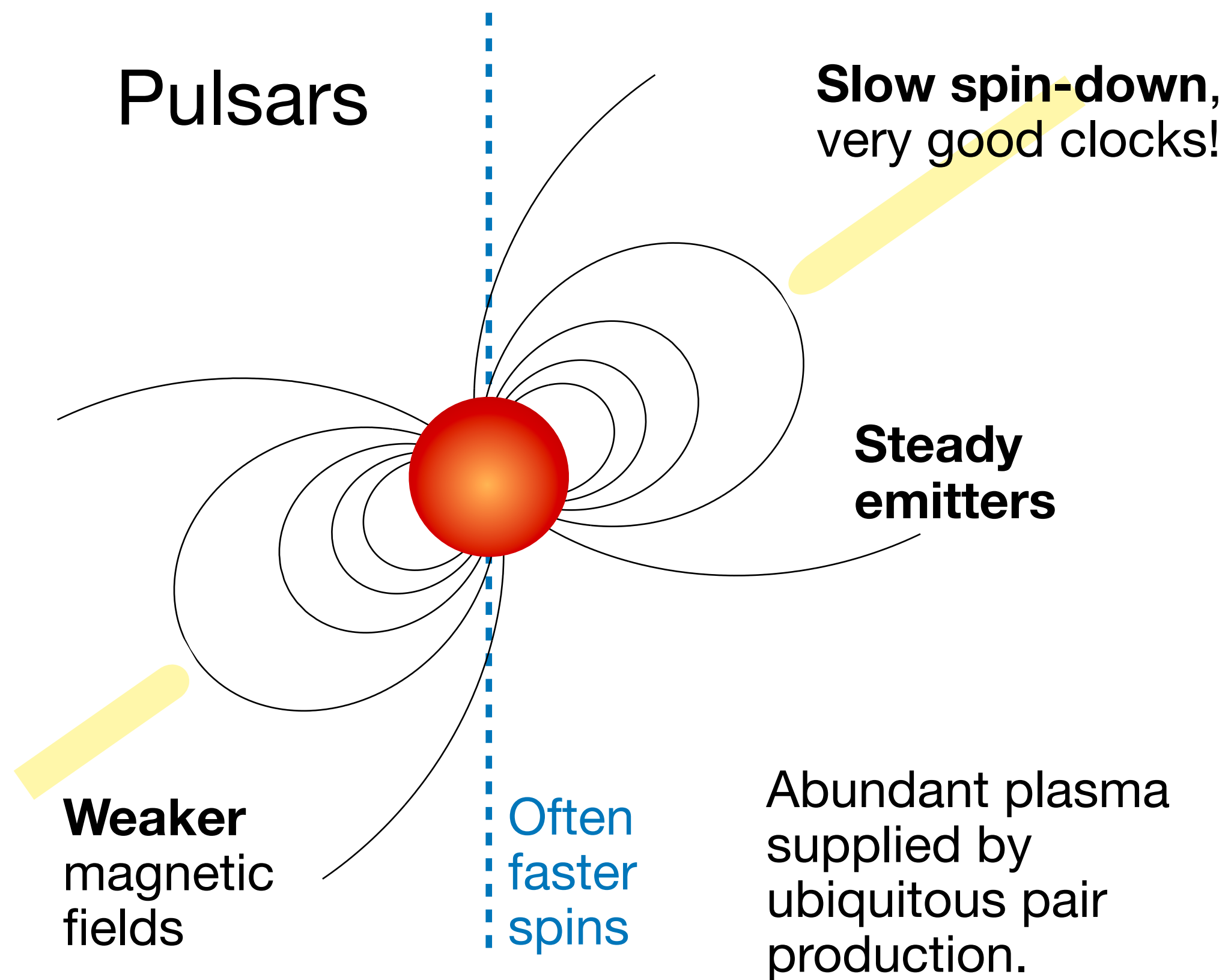
Jens Mahlmann, Dartmouth College



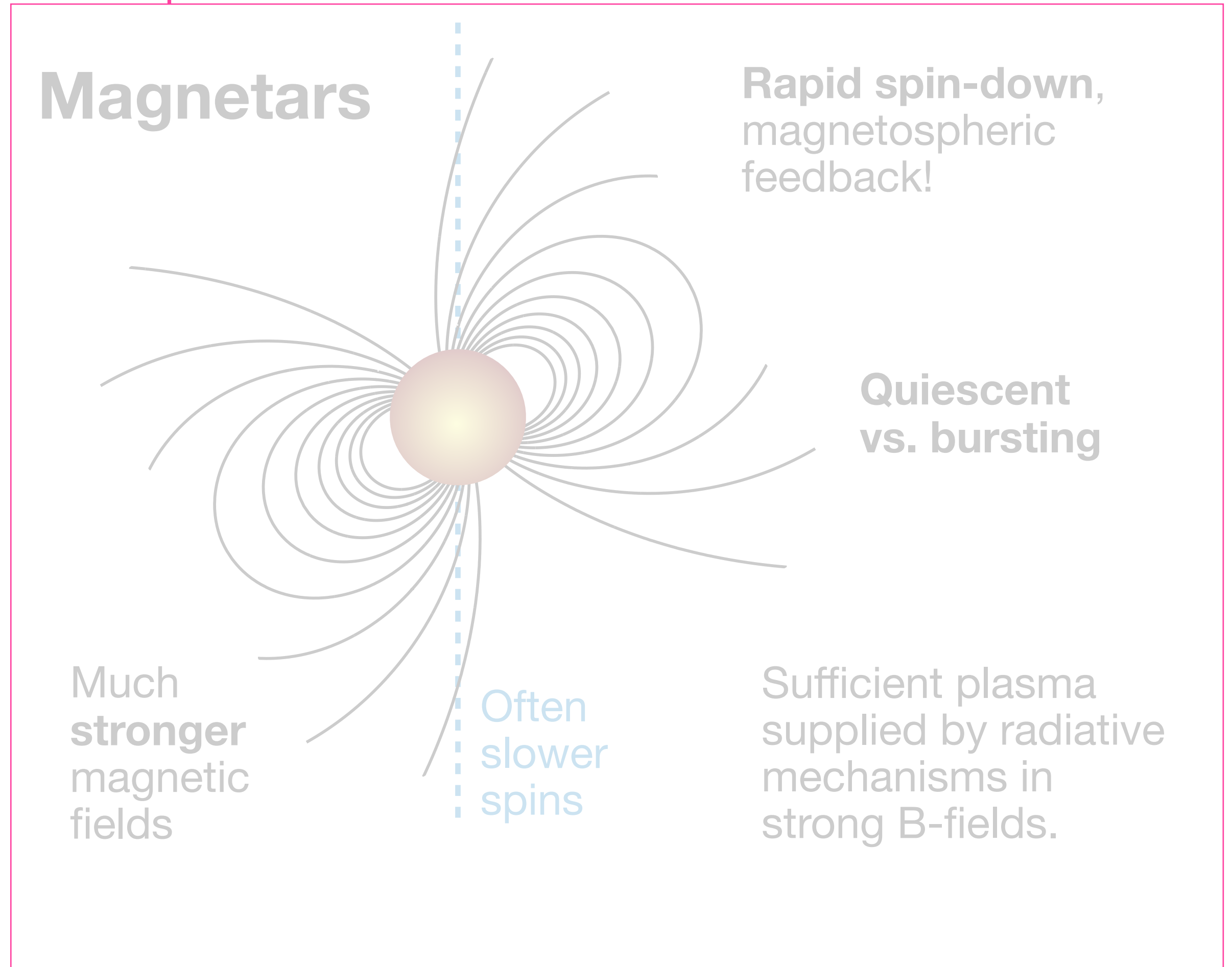
with Alexander Philippov, Andrei Beloborodov, Muni Zhou, Hayk Hakobyan,
Lorenzo Sironi, Xinyu Li, Miguel Á. Aloy, and Alexander Chernoglazov

Neutron stars are unique plasma labs

Strong magnets with energetic X-ray and radio emission



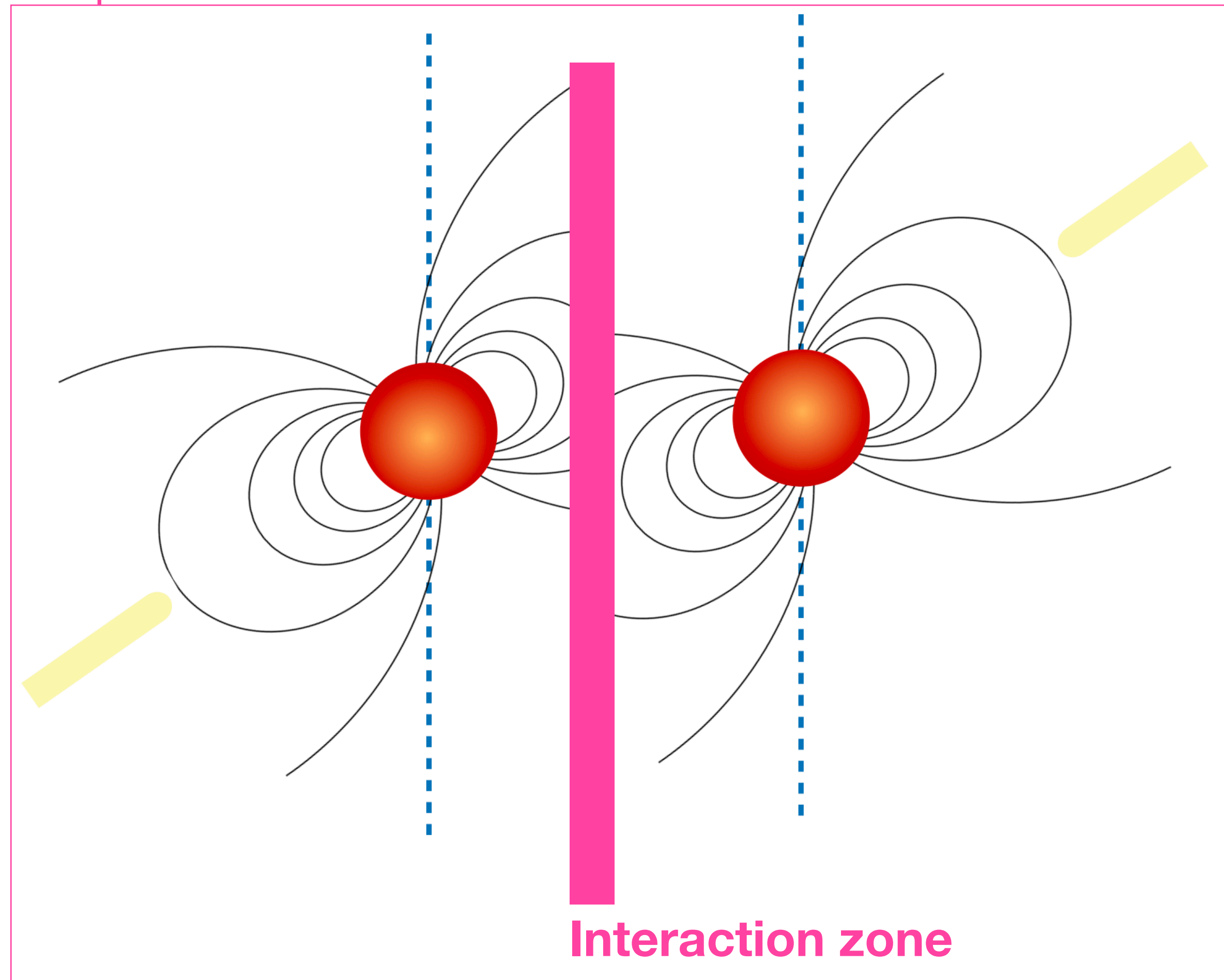
second part of this talk



Binaries interact with their environments

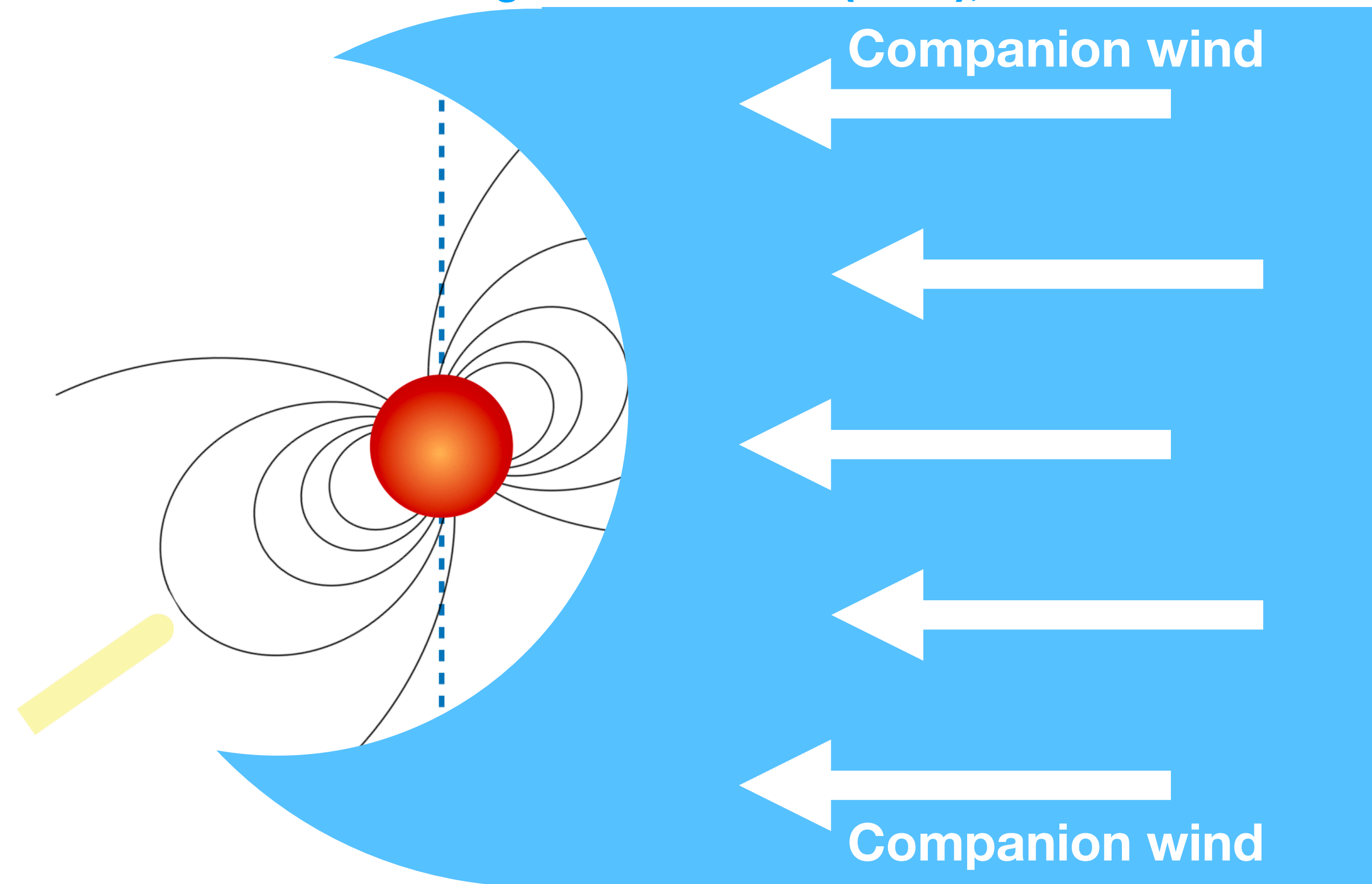
(Radiative?) dynamics of magnetospheric and wind interactions

first part of this talk



Binary neutron stars

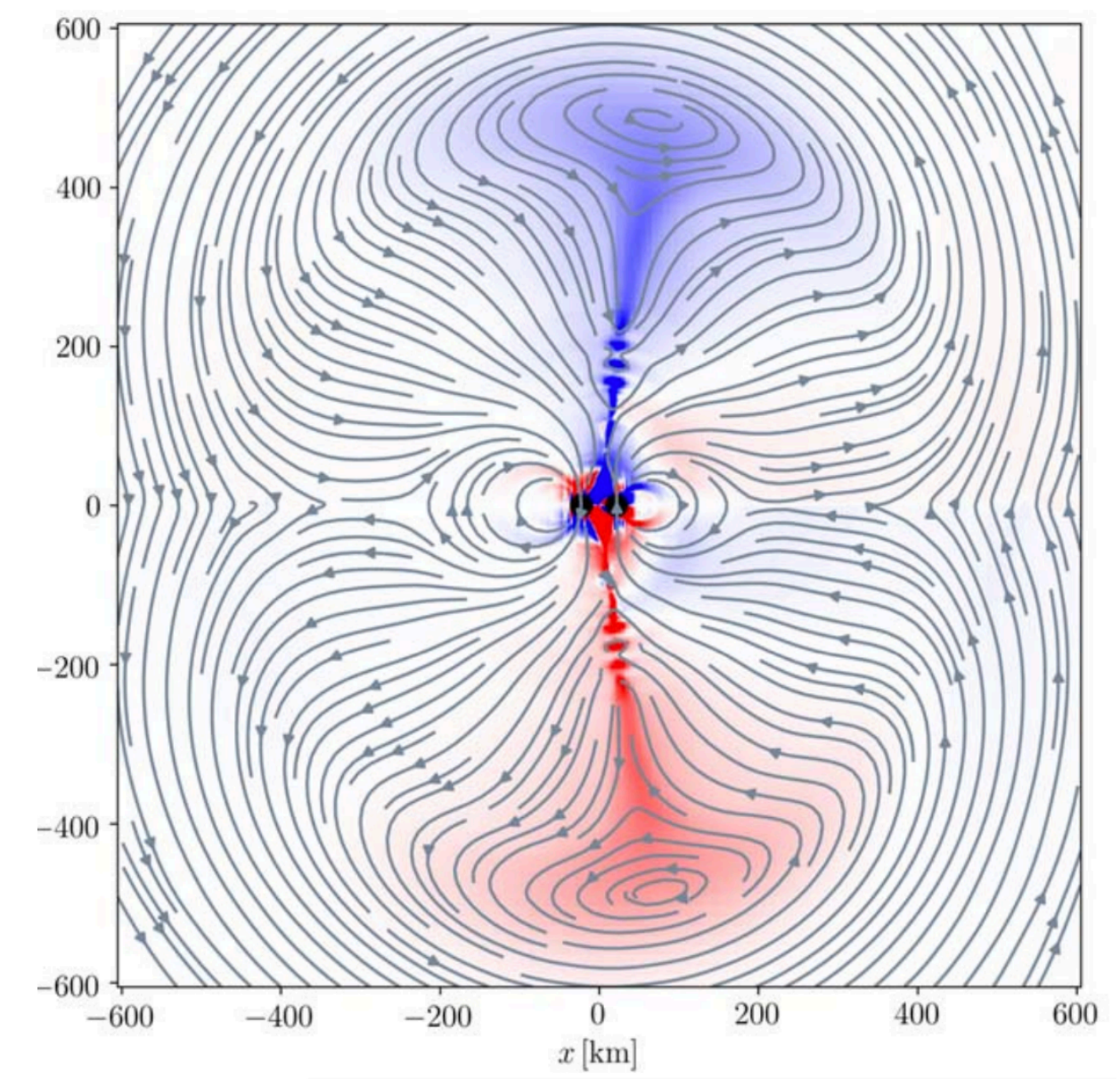
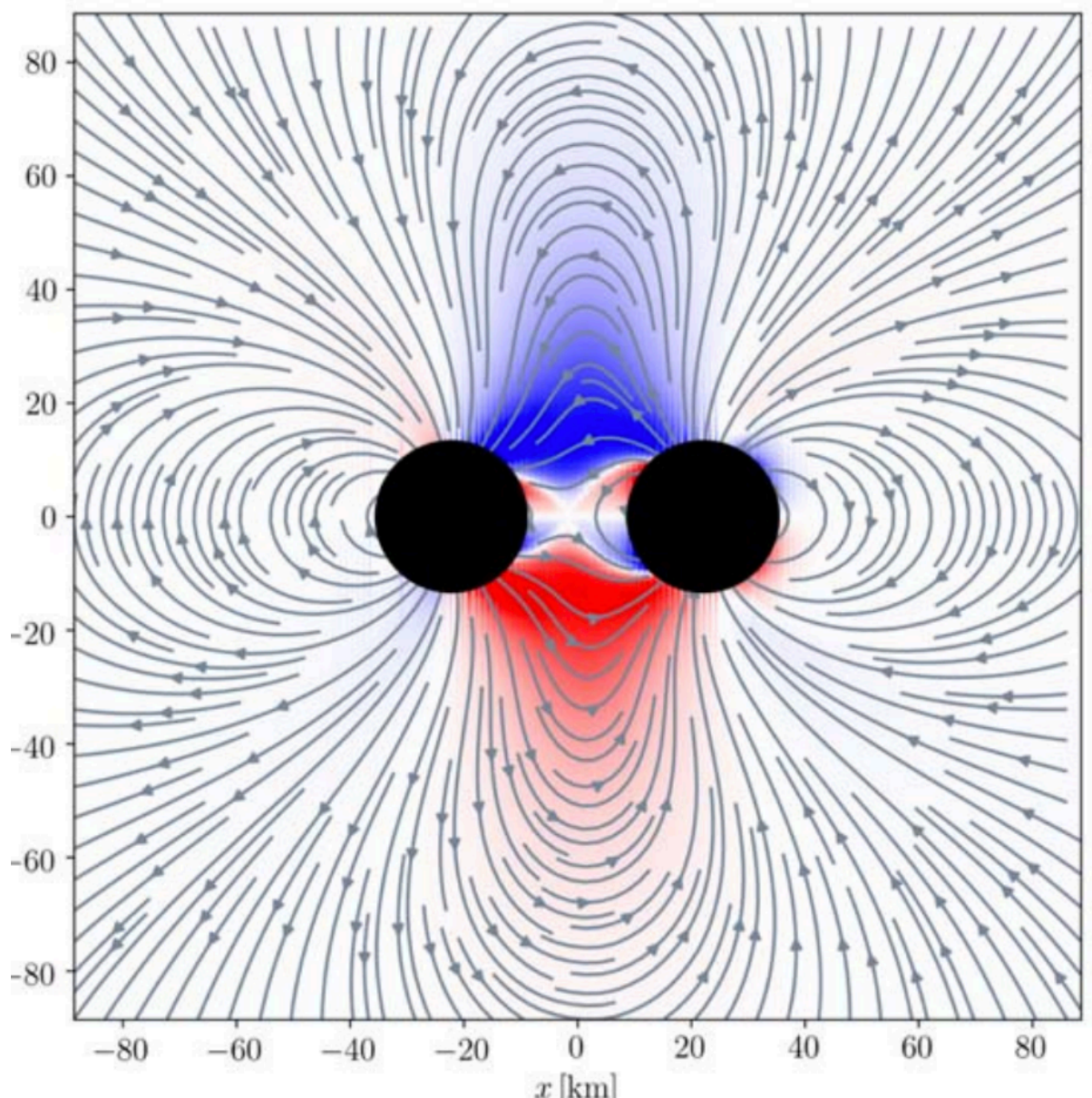
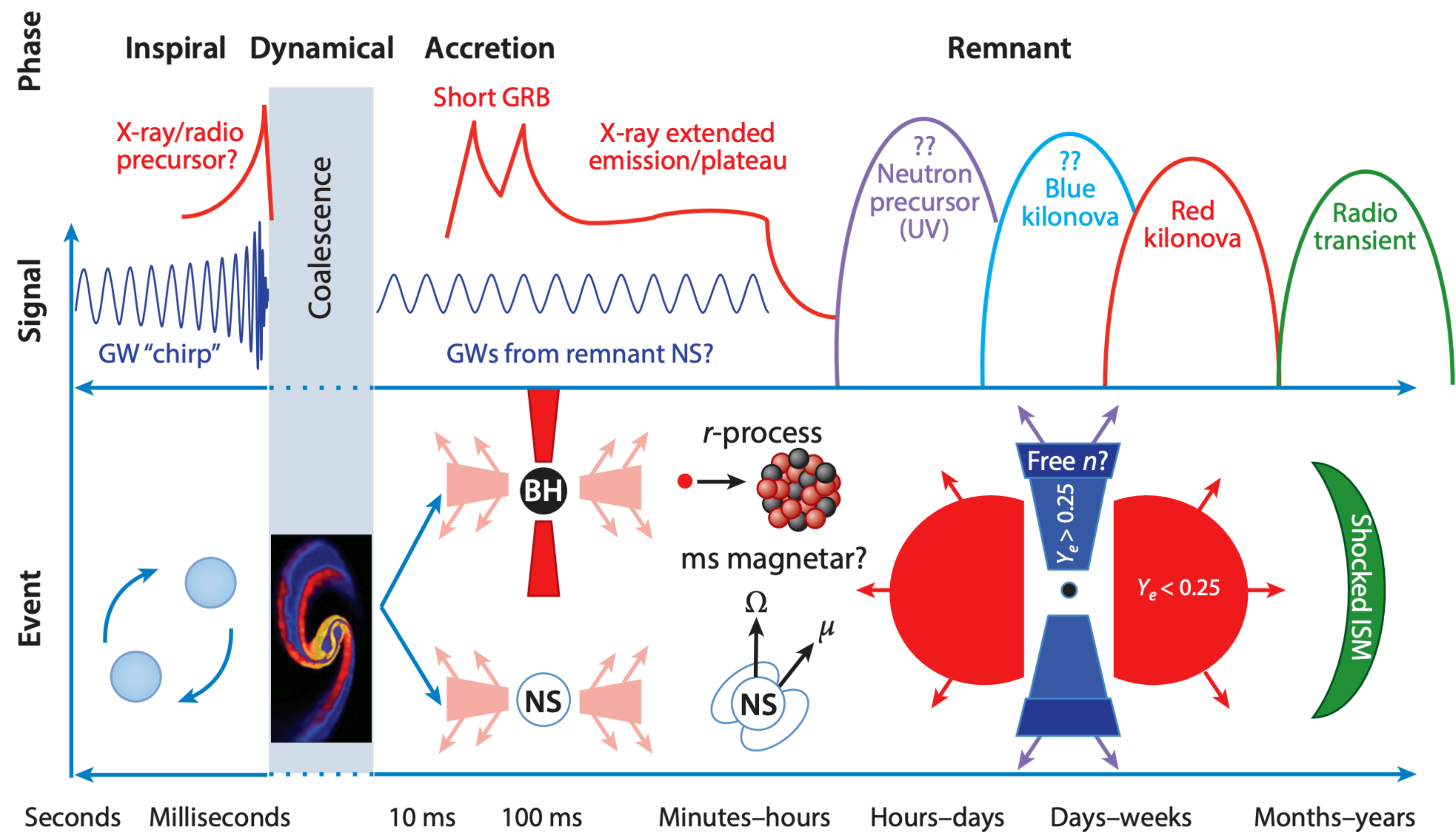
Jorge Cortés et al. (2024); arXiv:2404.03700



Yici Zhong et al. (2024); arXiv:2407.04941

Puzzling neutron star mergers

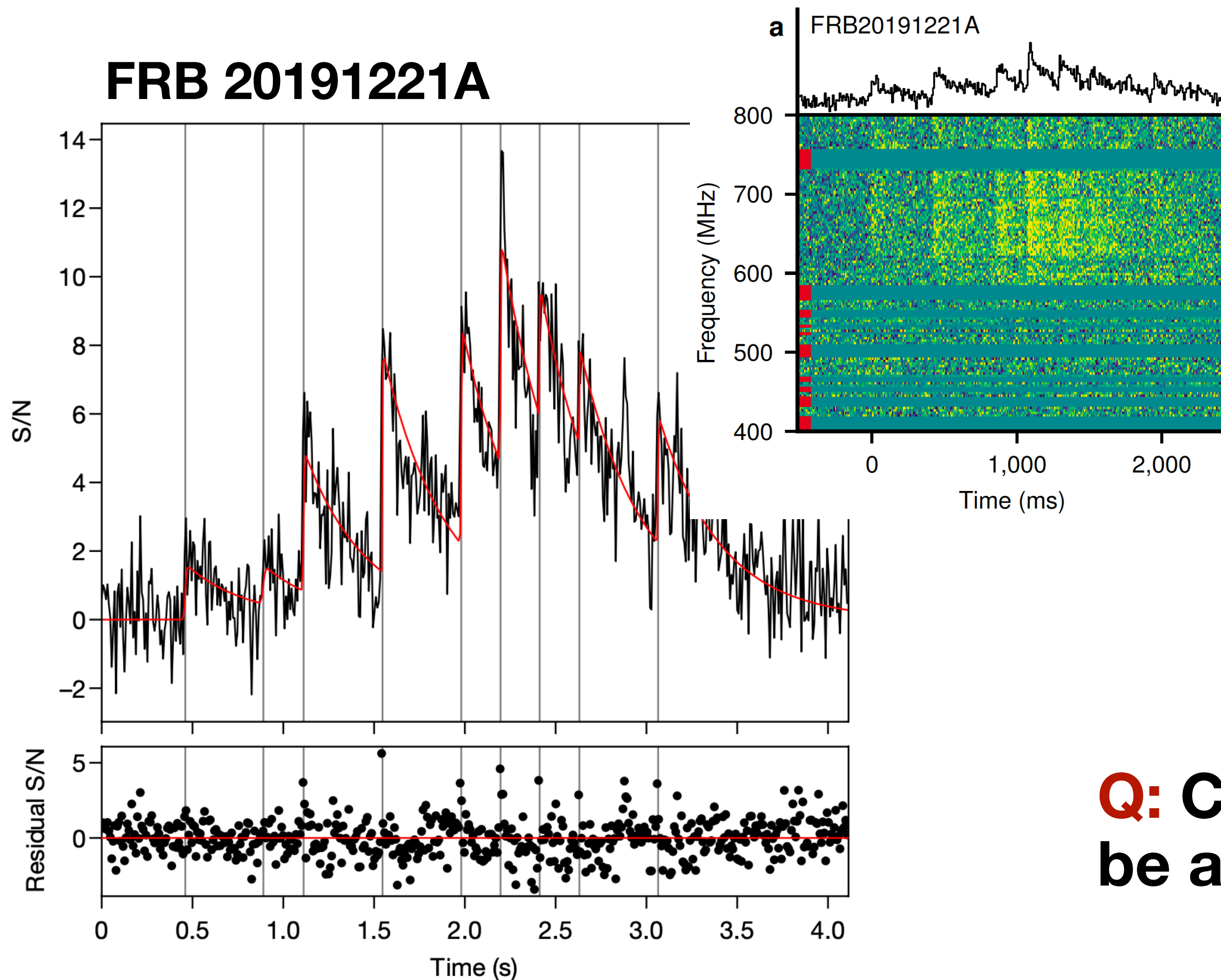
Pre-merger for localization and plasma state



First models of electromagnetic precursors for **anti-aligned fields**

Some FRBs have periodic structures

‘Heartbeat’ FRBs could be the link to systems with periodicity



- First FRB observed with several burst fronts within one signal train
- FRB 20191221A has a somewhat large DM
- No notable frequency drift between different components
- Significant swings of the polarization angle

Q: Could neutron star binary systems be a source of such events?

Electromagnetic precursor models are ‘stuck’

Precursor X-ray emission may not be observable from far away

Simplified model:

Magnetic
instabilities



Energy release



Hard X-rays /
soft γ -rays

$$E_{\text{tot}} \approx 5 \times 10^{43} \text{ erg}$$
$$t_{\text{GRB}} \approx 1 - 10 \text{ ms}$$

But

X-ray bursts of that luminosity are hard to observe from far away. No merger association yet.

Alternative

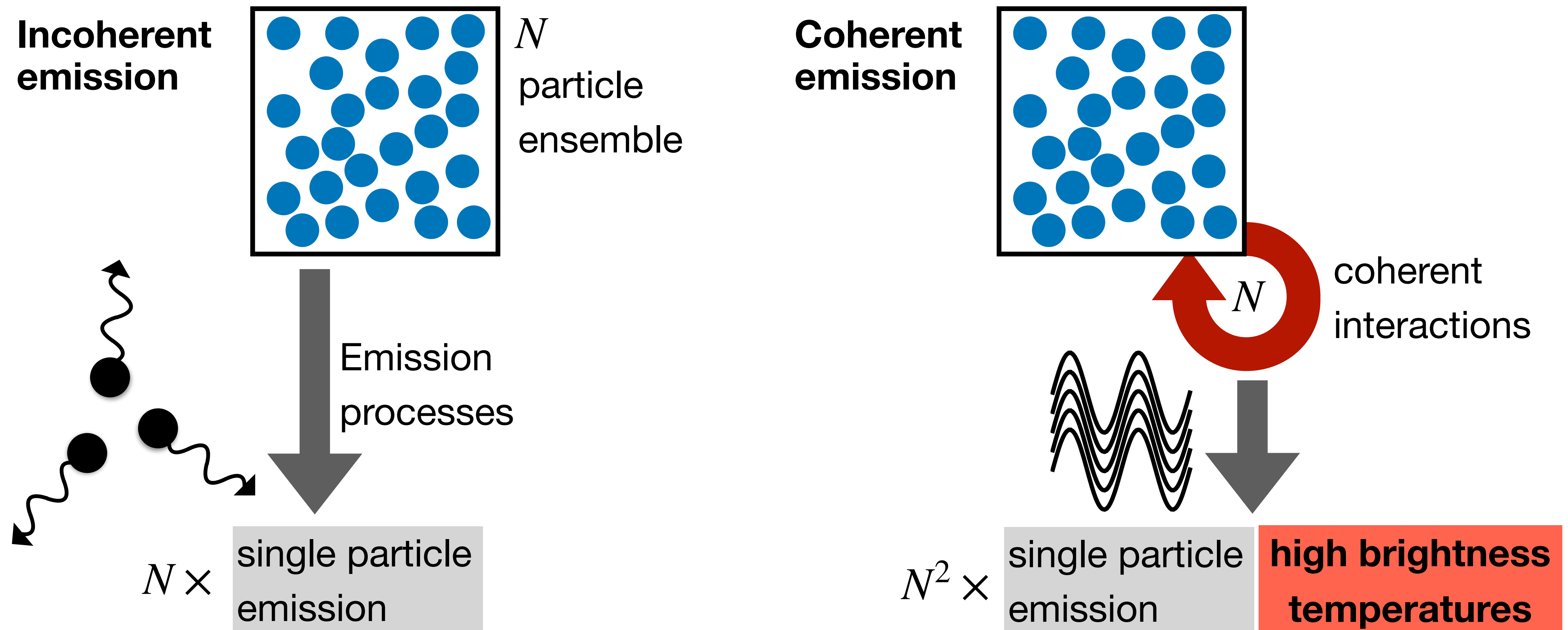
Coherent radio emission, as
Fast Radio Bursts (FRBs)

Population: ~1% of FRBs
could be binary mergers.

Q: How are these
FRBs generated?

Radiation injection in plasmas

Coherent processes boost brightness temperature

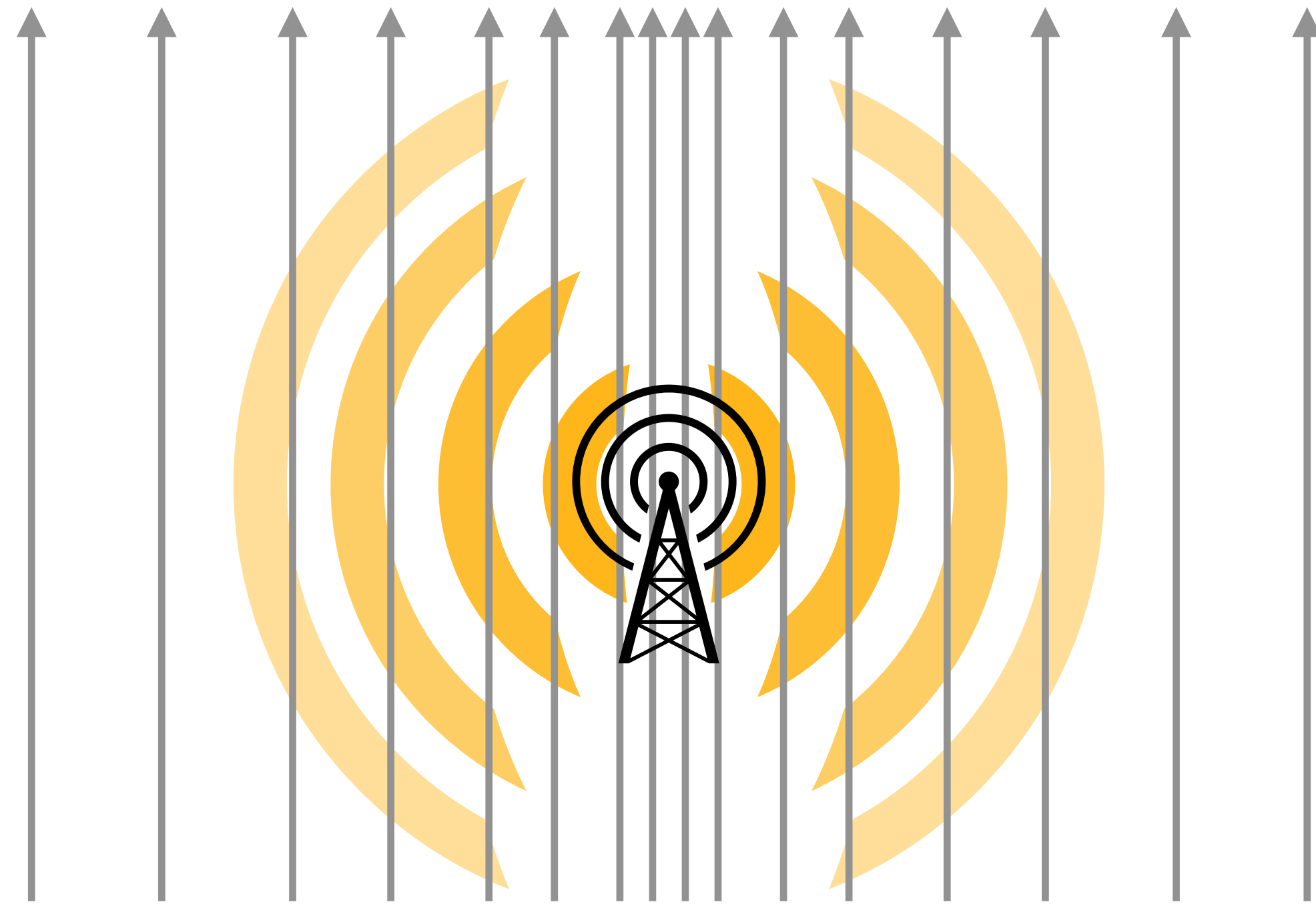


Non-linear growth of fast magnetosonic waves

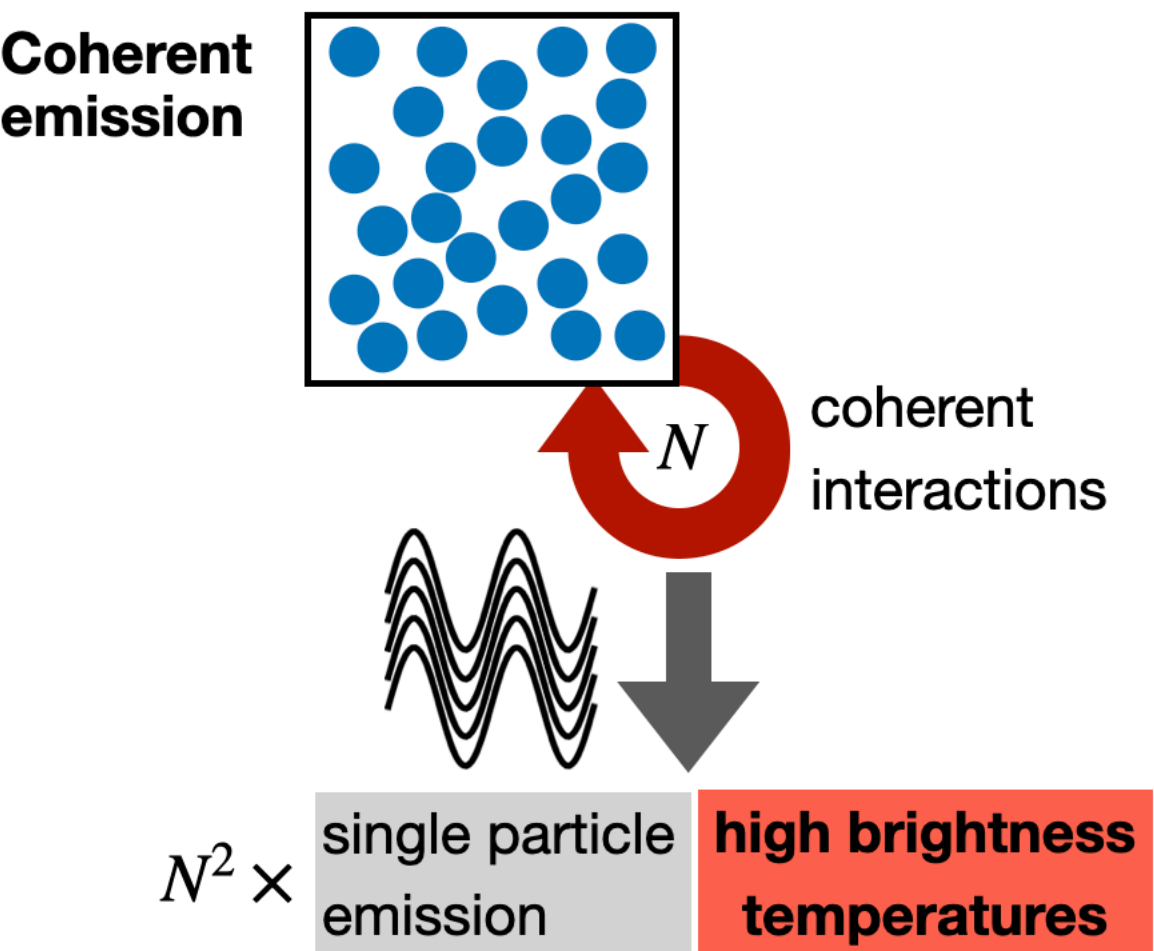
High-magnetization FMS waves cross field lines of varying strengths

Q: What is the relative wave amplitude?

FMS wave amplitude: $\delta B_{\text{FMS}} \propto r^{-1}$



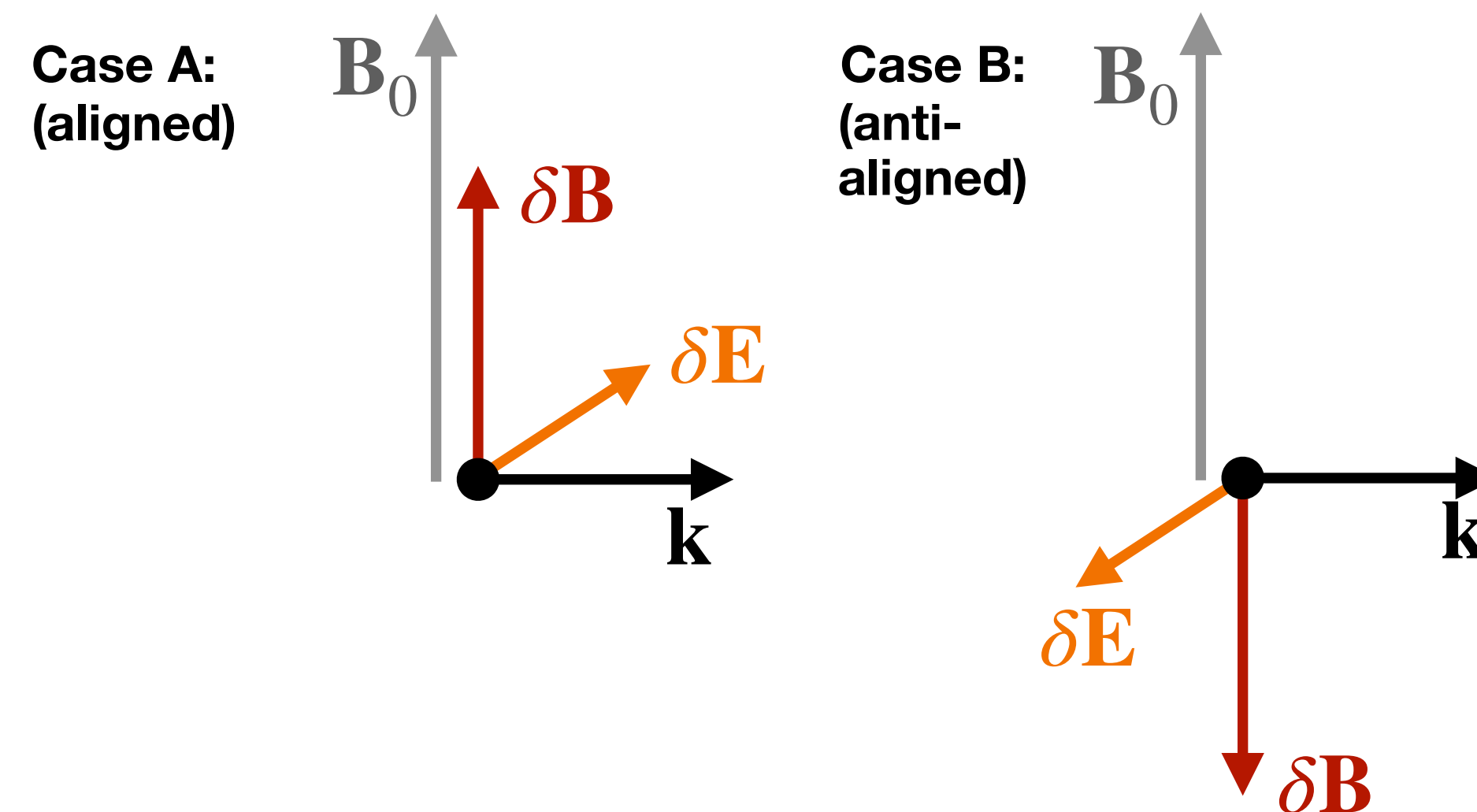
Background field decay: $B_0 \propto x^\nu$



Non-linear growth of fast magnetosonic waves

High-magnetization FMS waves cross field lines of varying strengths

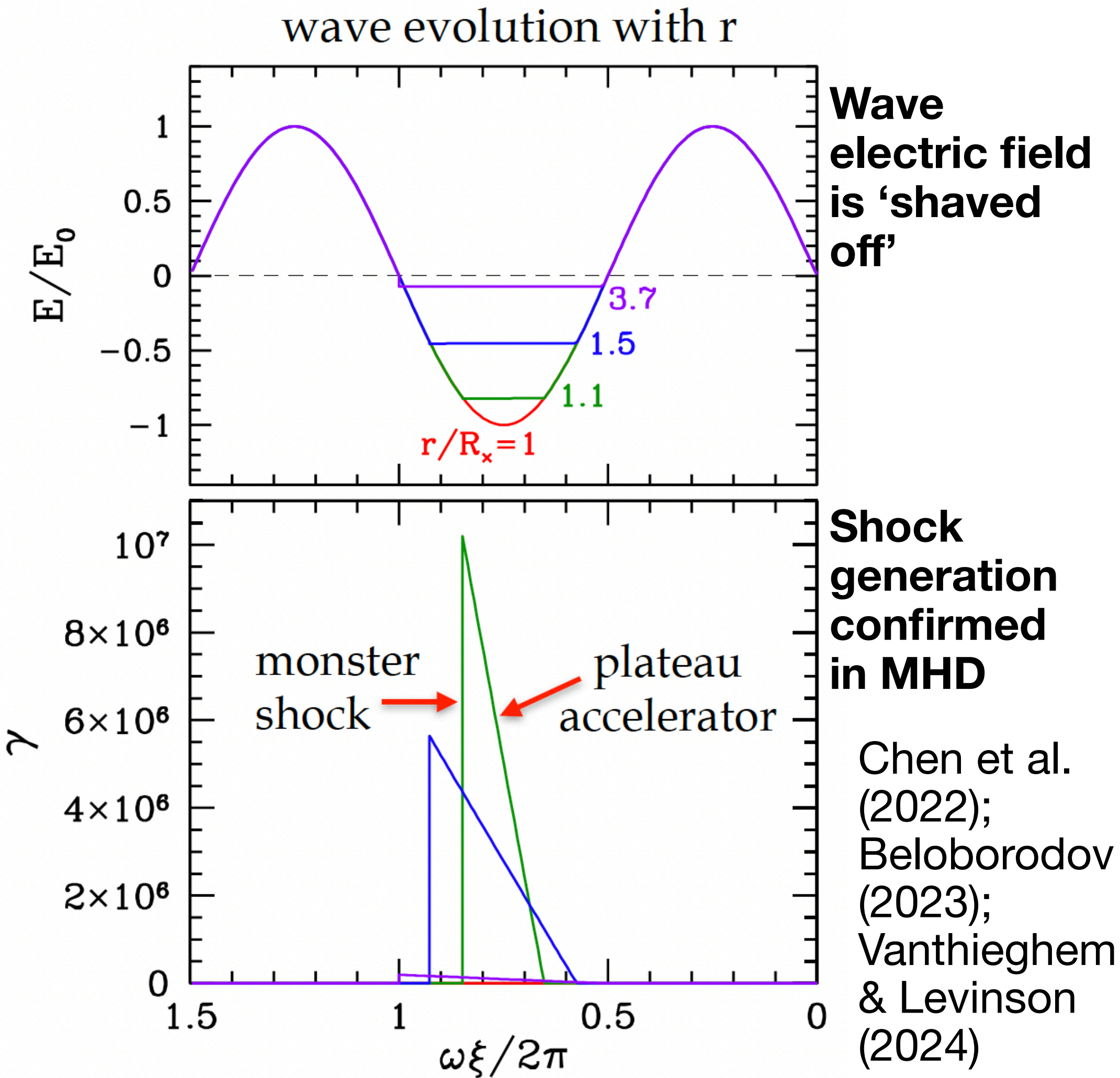
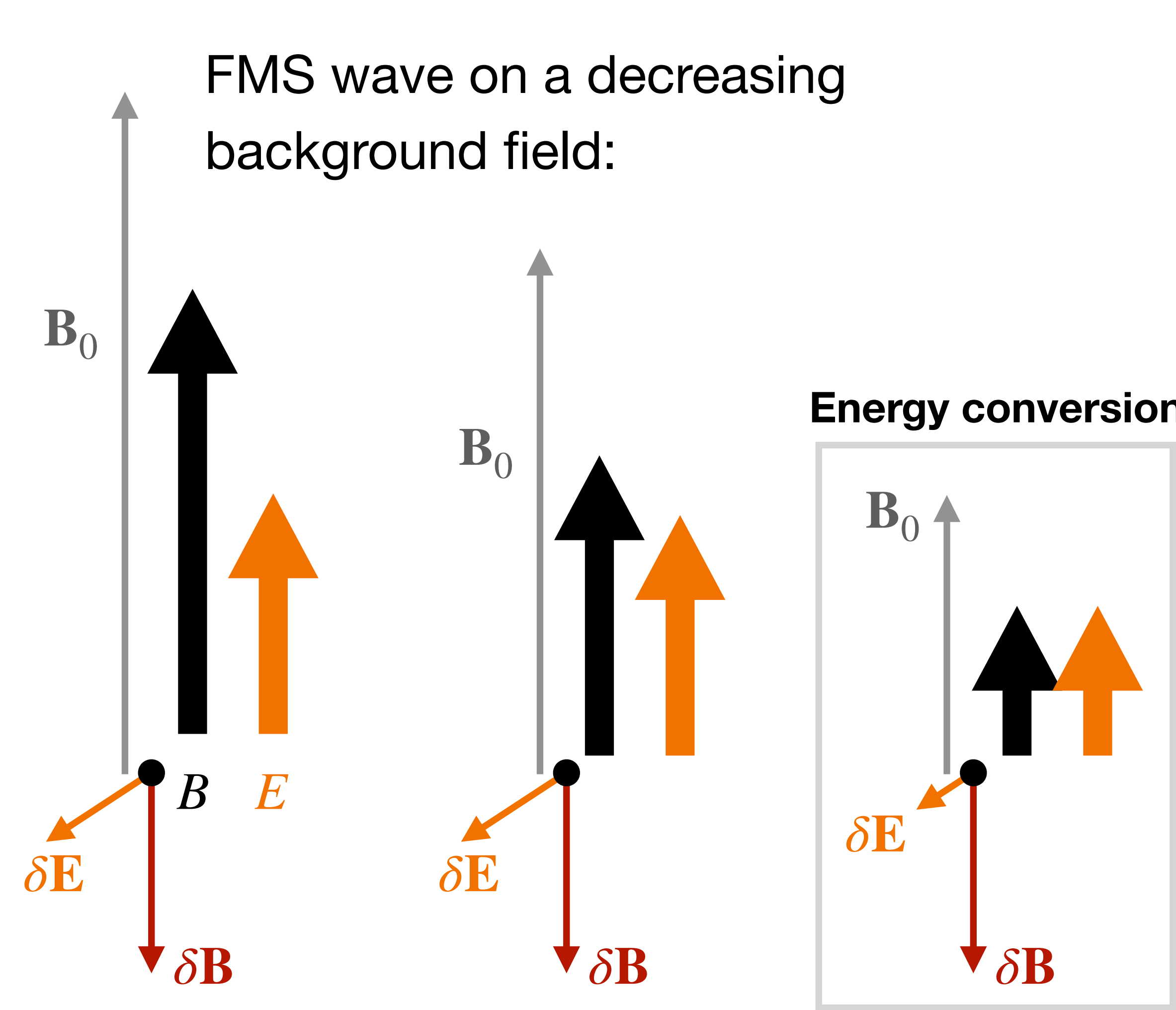
- Force-free fast magnetosonic (FMS) waves have dispersion $\omega = \pm |\mathbf{k}|$
- Exemplary wave fields for $\mathbf{k} \perp \mathbf{B}_0$:



Case B can develop $E > B$.

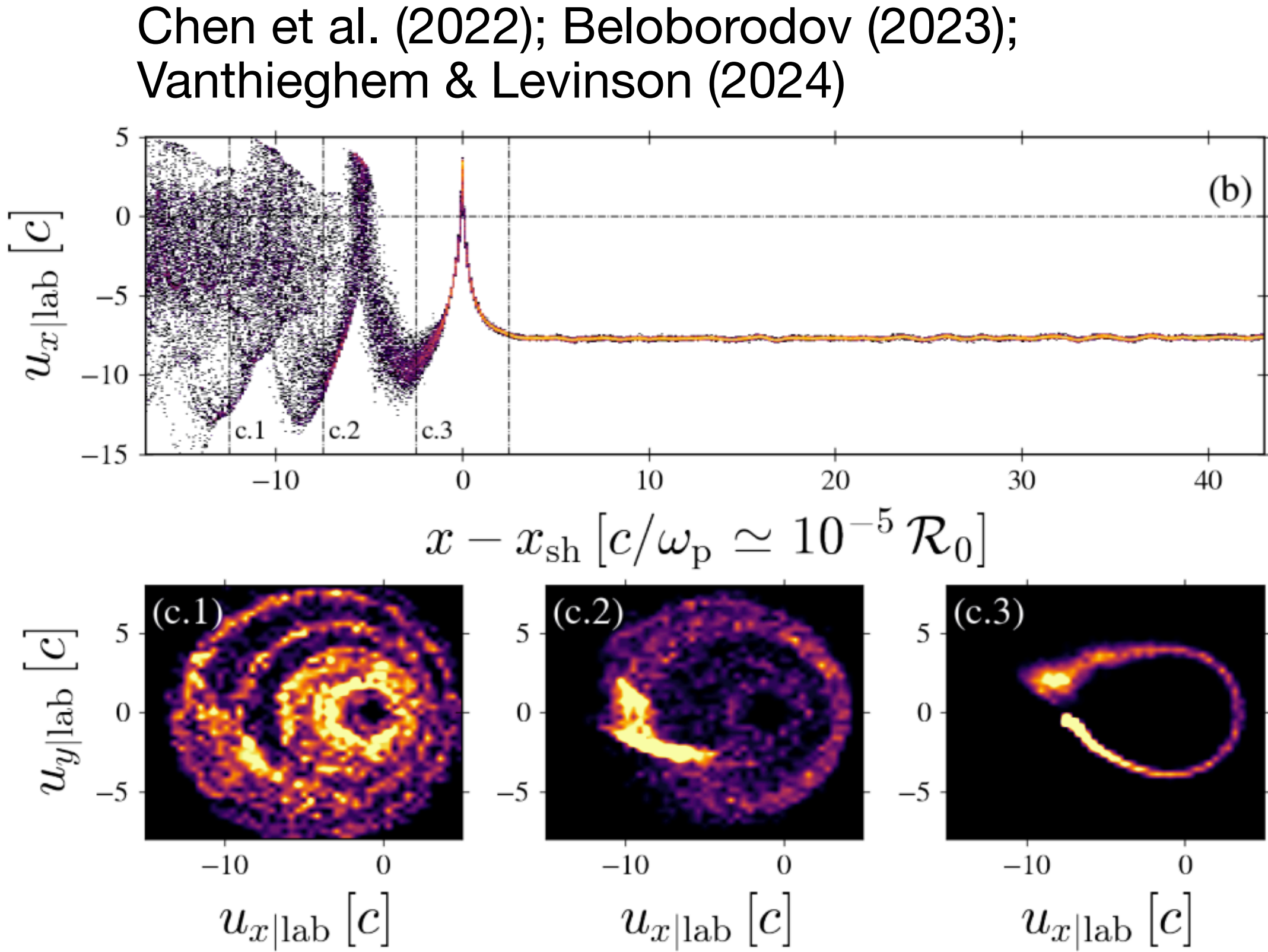
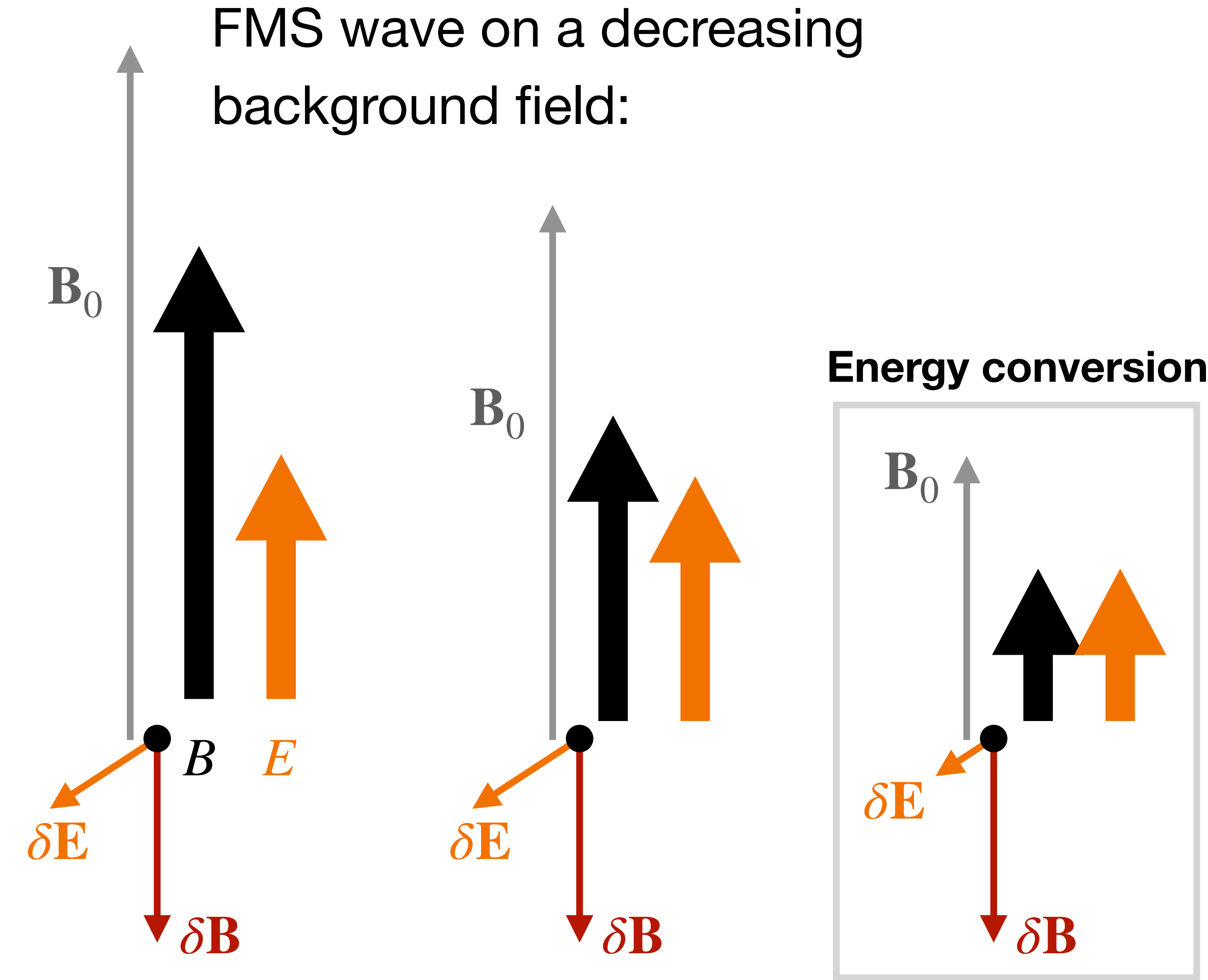
Monster shocks and particle acceleration

Waves close to electric dominance dissipate energy efficiently



Monster shocks and particle acceleration

Waves close to electric dominance dissipate energy efficiently

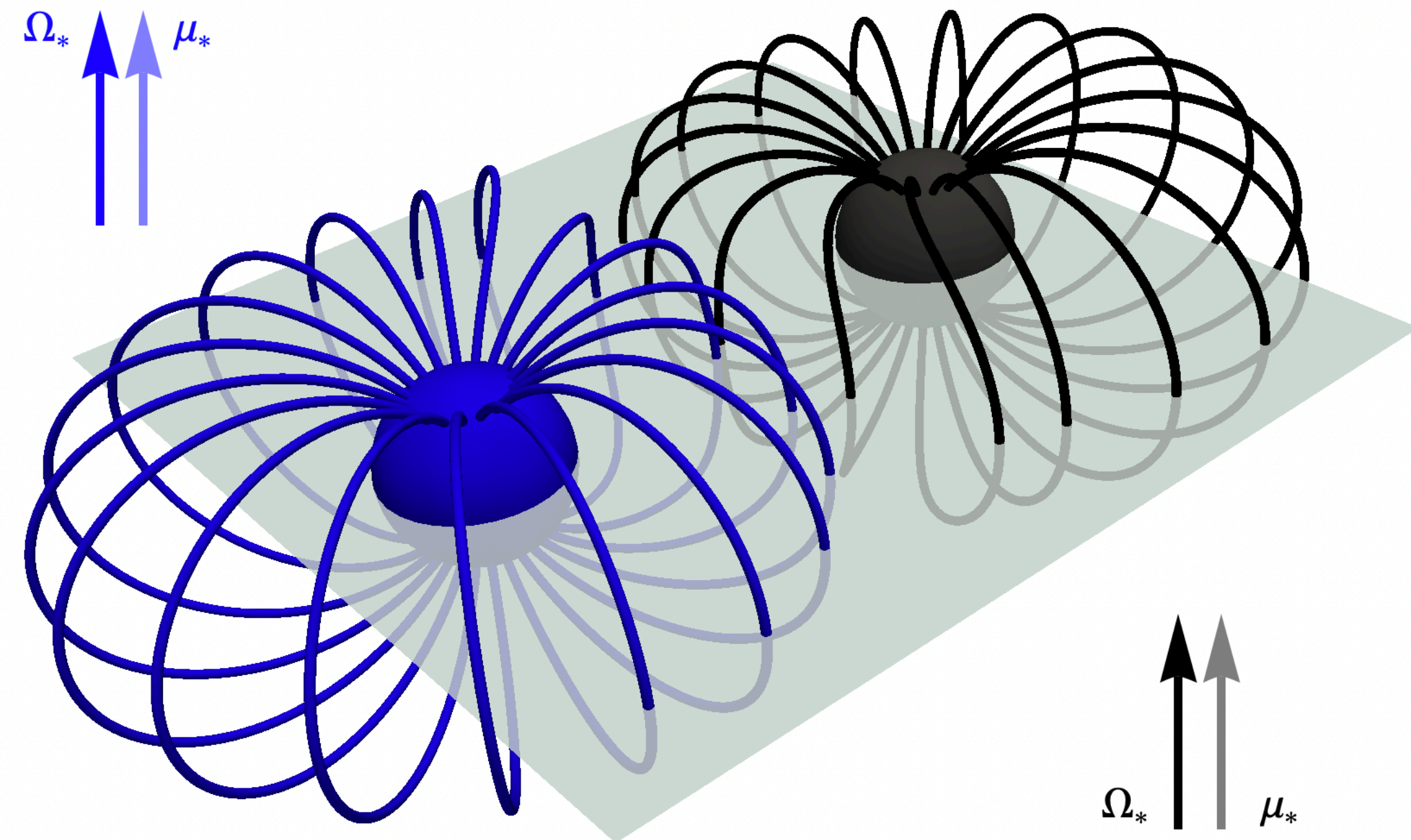
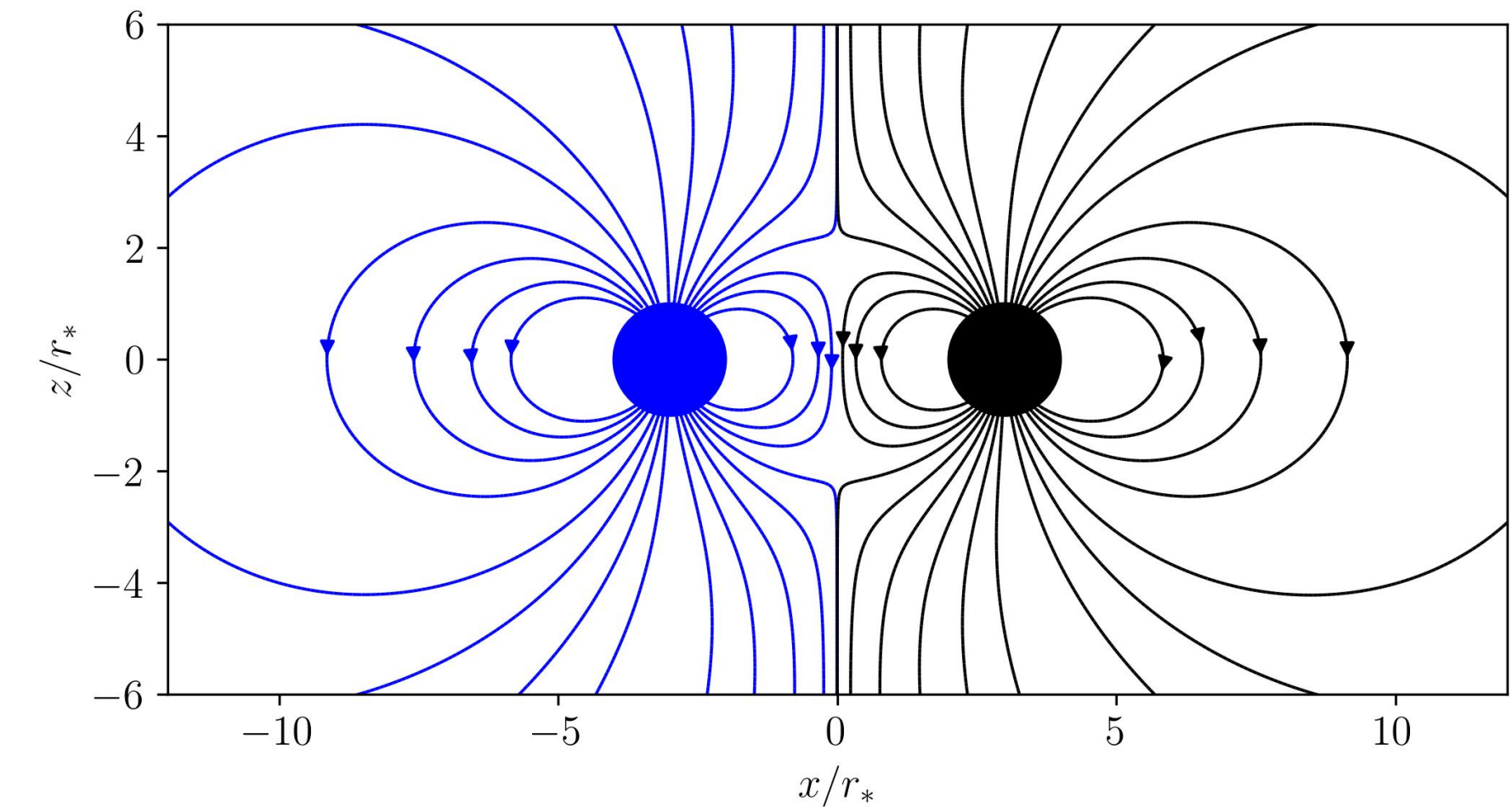
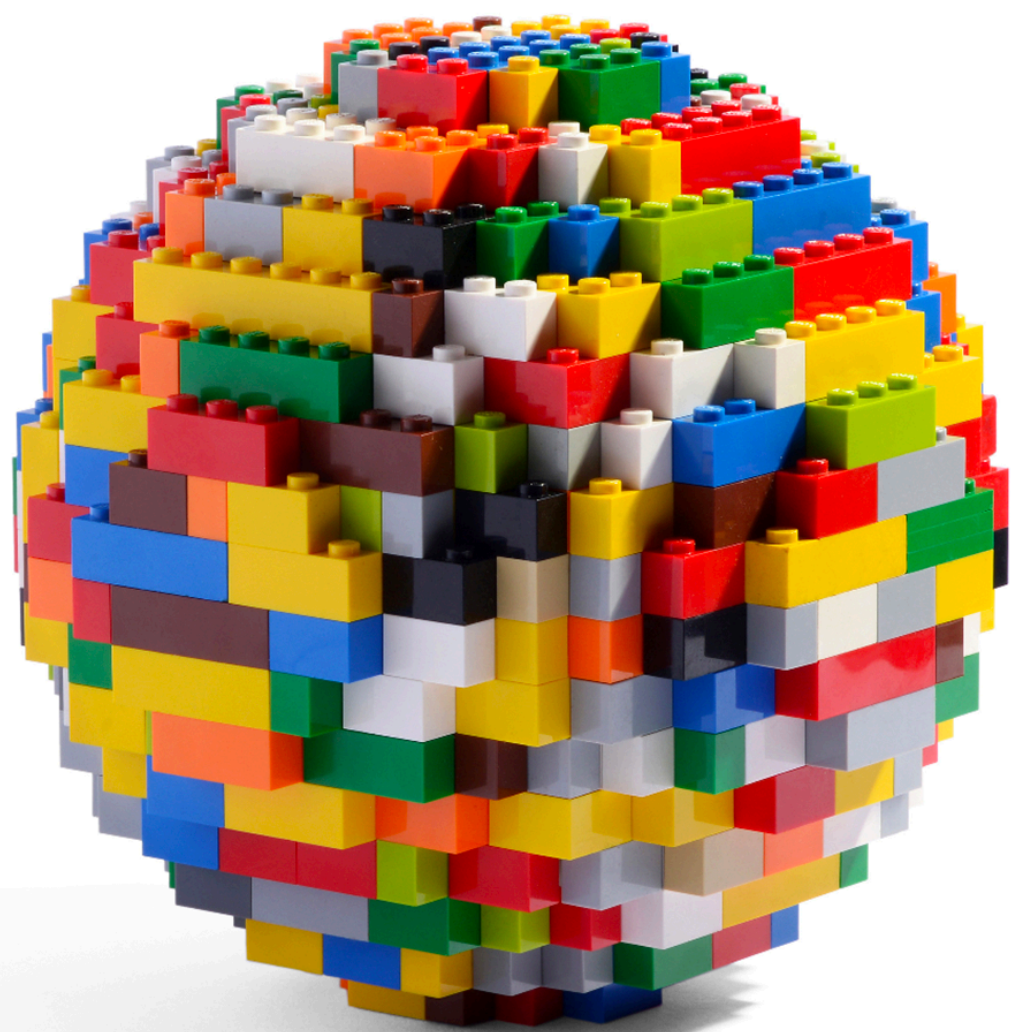


Numerical setup of the binary system

Two 'neutron stars' on a Cartesian mesh

We use **two perfectly conducting spheres** on a Cartesian mesh

- Magnetic fields are initially dipolar
 - Surface electric fields correspond to the neutron star rotation
 - Binary separation: $6r_*$
 - Light cylinder: $r_{LC} = 20r_*$
- r_* : Stellar radius
- Simplifications:** No orbital motion, wind zone unresolved, spin choice



Modeling global magnetar magnetospheres

Force-free limit of ideal MHD tracks large scale magnetic dynamics

Force-free electrodynamics (FFE): the **zero-inertia limit** of relativistic **ideal magnetohydrodynamics** (fluid description of collisional magnetized plasma).

Momentum Equation

$$\rho \mathbf{E} + \mathbf{J} \times \mathbf{B} = \cancel{\frac{d(n\mathbf{v})}{dt}} + \cancel{\text{pressure}}$$

$$\partial_t (\mathbf{E} \cdot \mathbf{B}) = 0$$

$$+$$

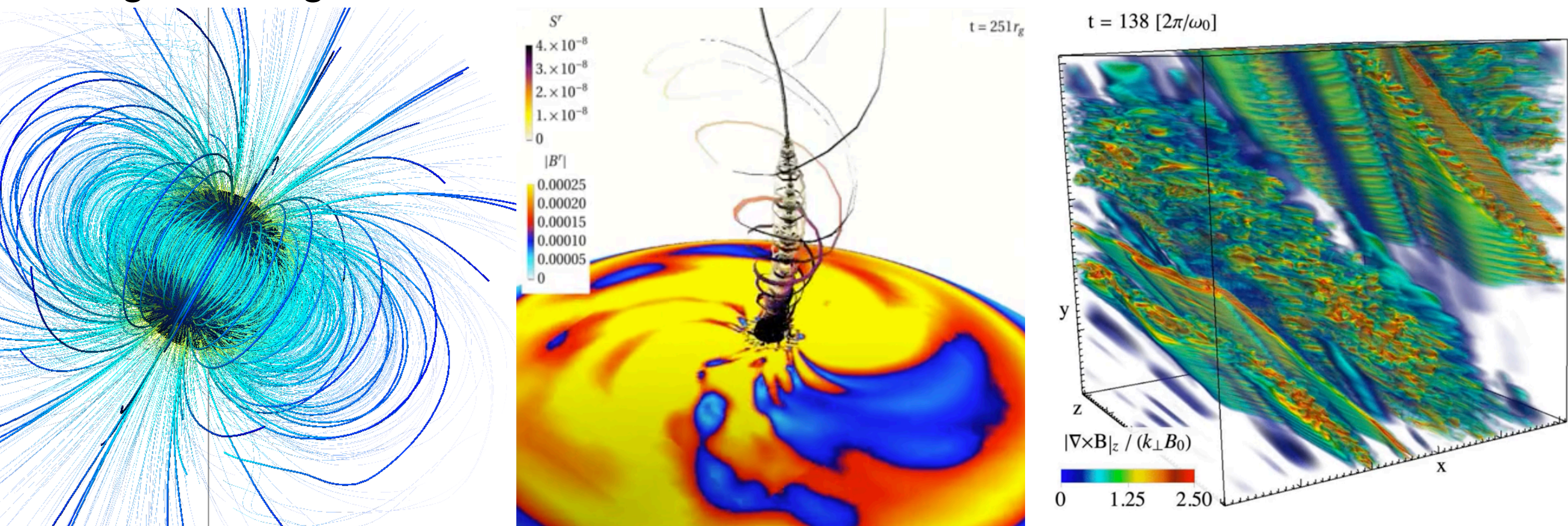
Maxwells Equations

Ideal fields

Predicts **flows of electromagnetic energy** BUT NOT particle acceleration, plasma supply, non thermal radiation.

✓ Good for identifying dissipation regions and limits.

Our high-order general relativistic FFE code on the Einstein Toolkit infrastructure:



NS magnetospheres

Black hole jets

Plasma fundamentals

Interacting magnetospheres

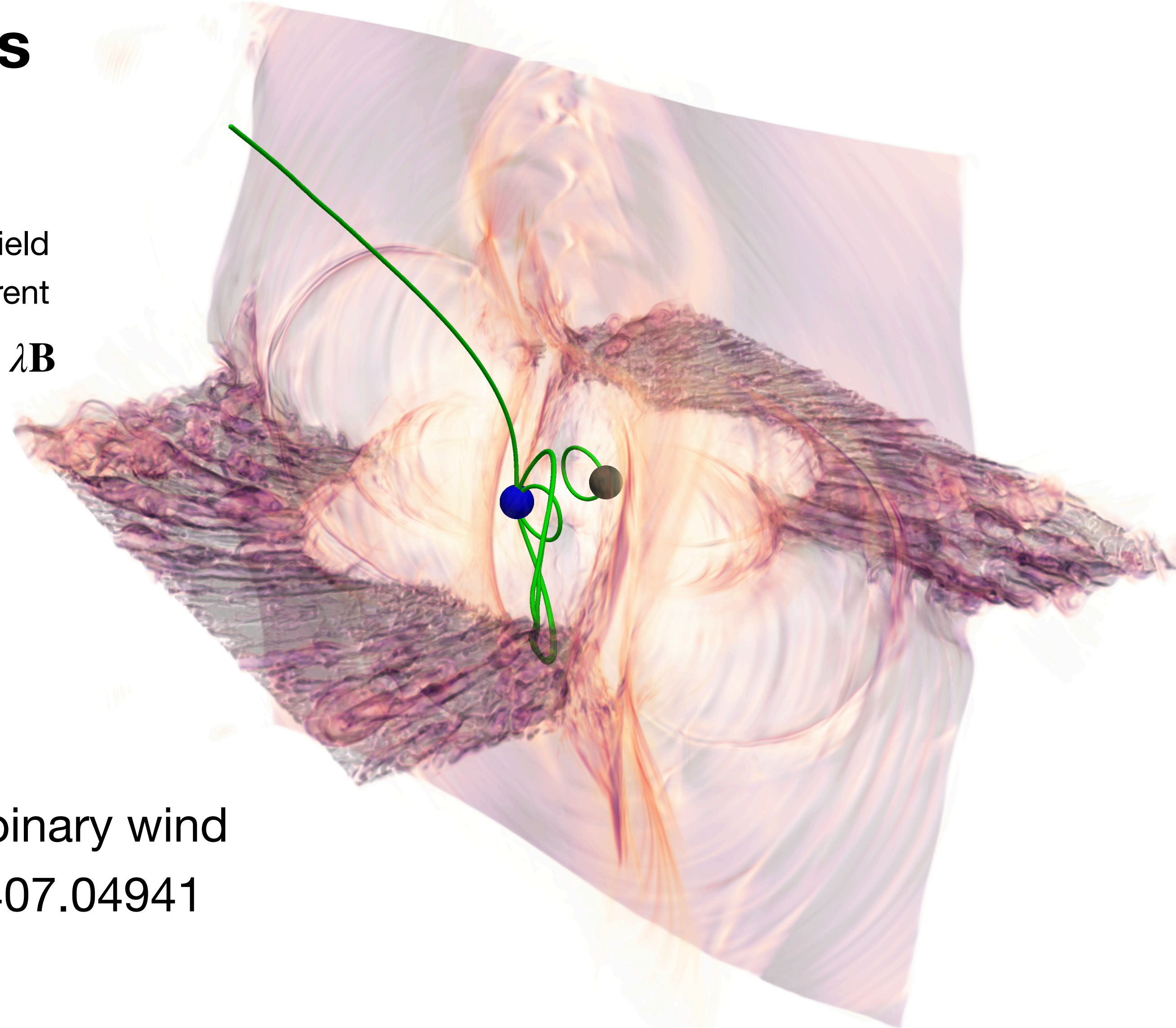
Close look at field line dynamics

magnetic-field
aligned current

$$\mathbf{j}_{\parallel} = \lambda \mathbf{B}$$

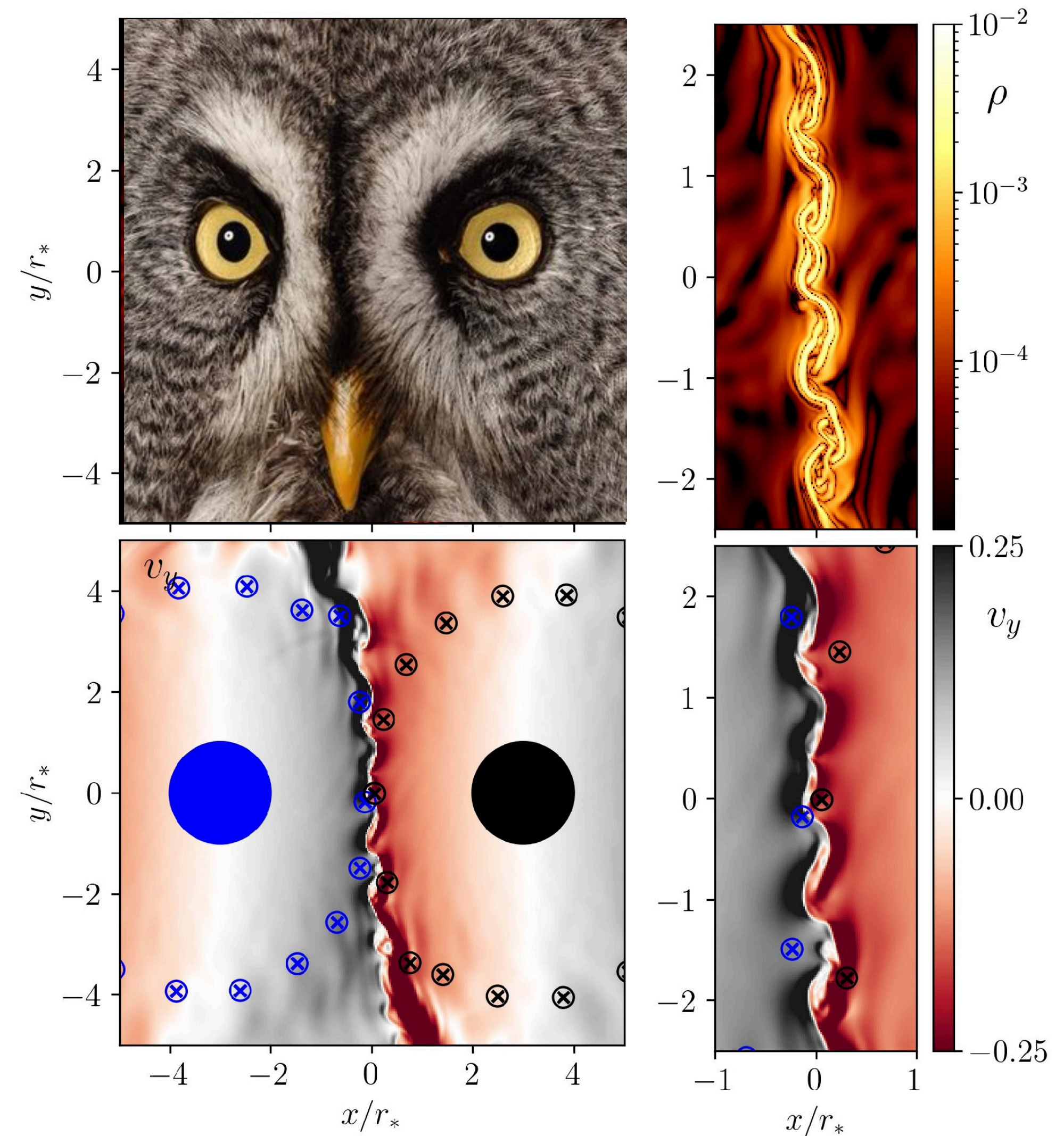
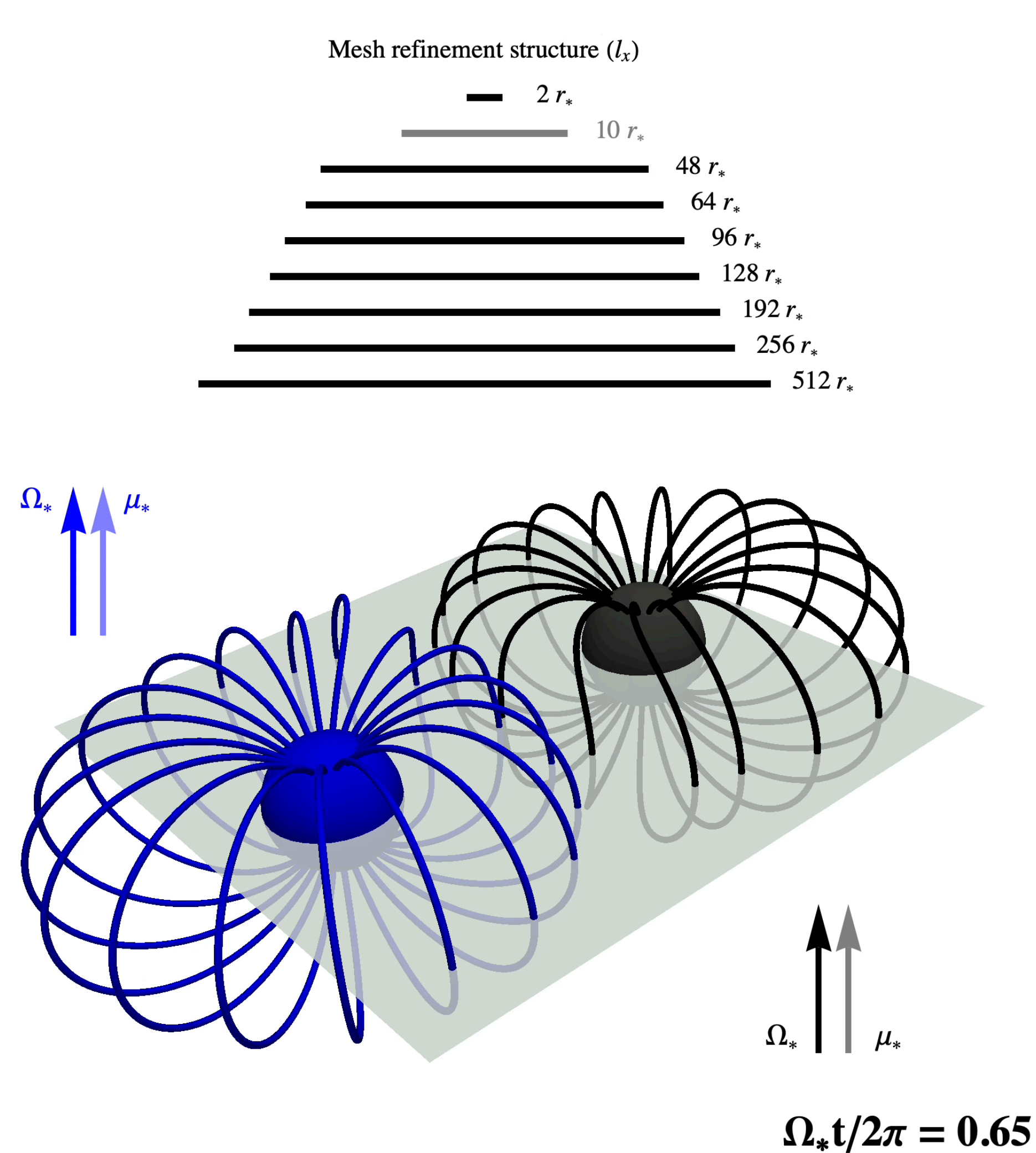
We distinguish **two phases**: Compression
and decompression.

More about compressed magnetospheres in binary wind
interactions: Yici **Zhong et al. (2024)**; arXiv:2407.04941



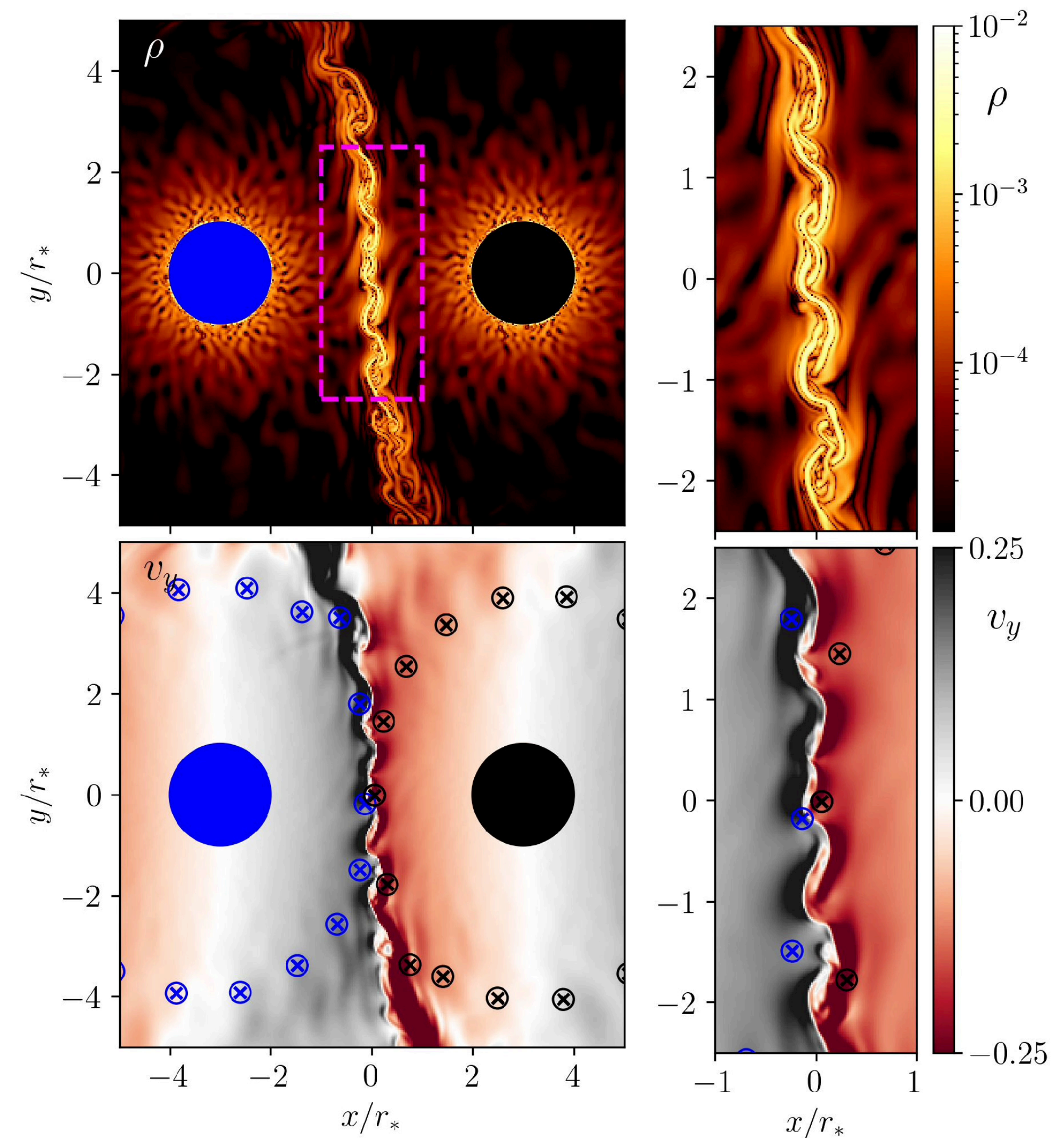
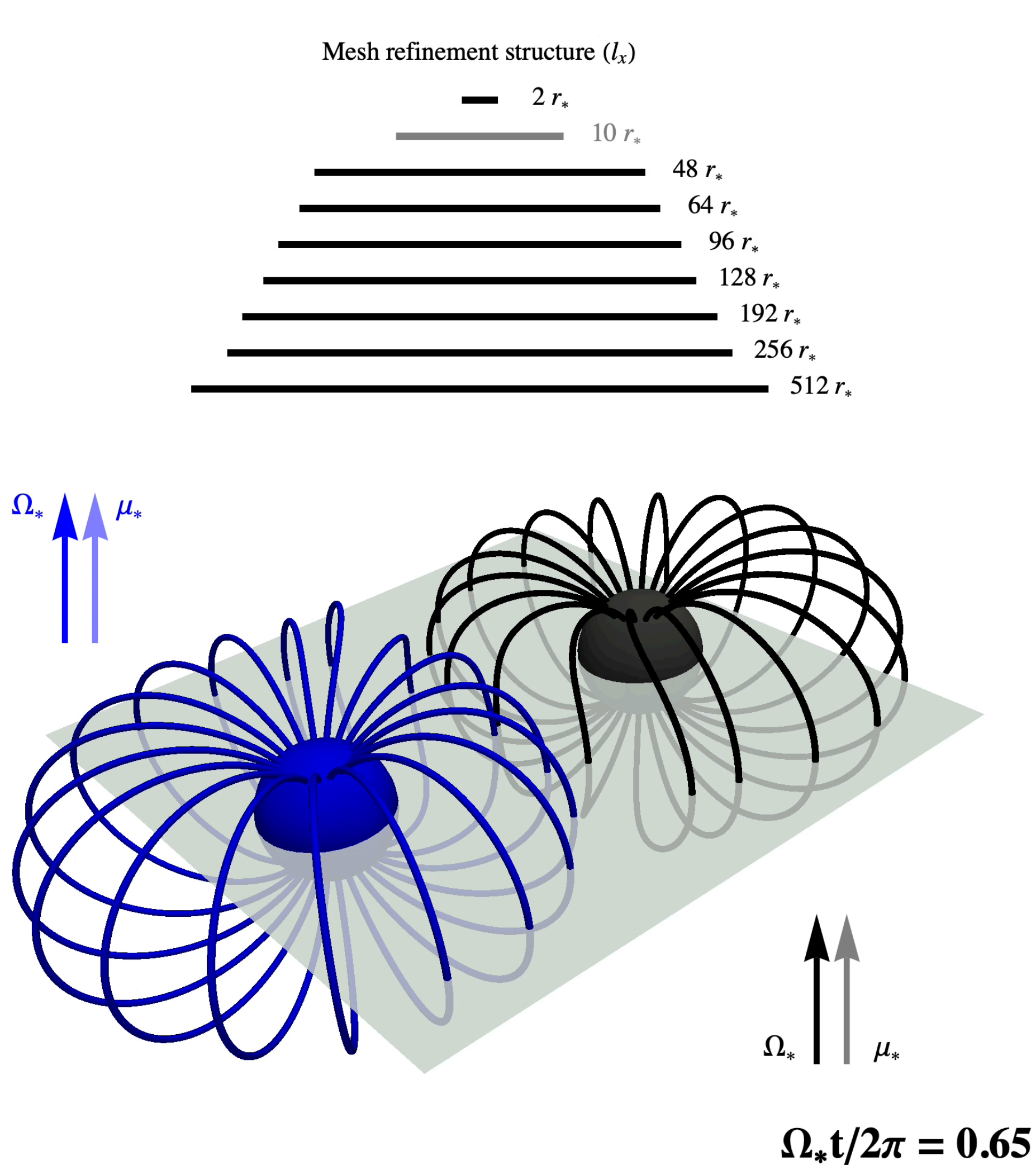
Development of the KH layer in the binary system

KH drag on magnetic field lines in the inner interaction region



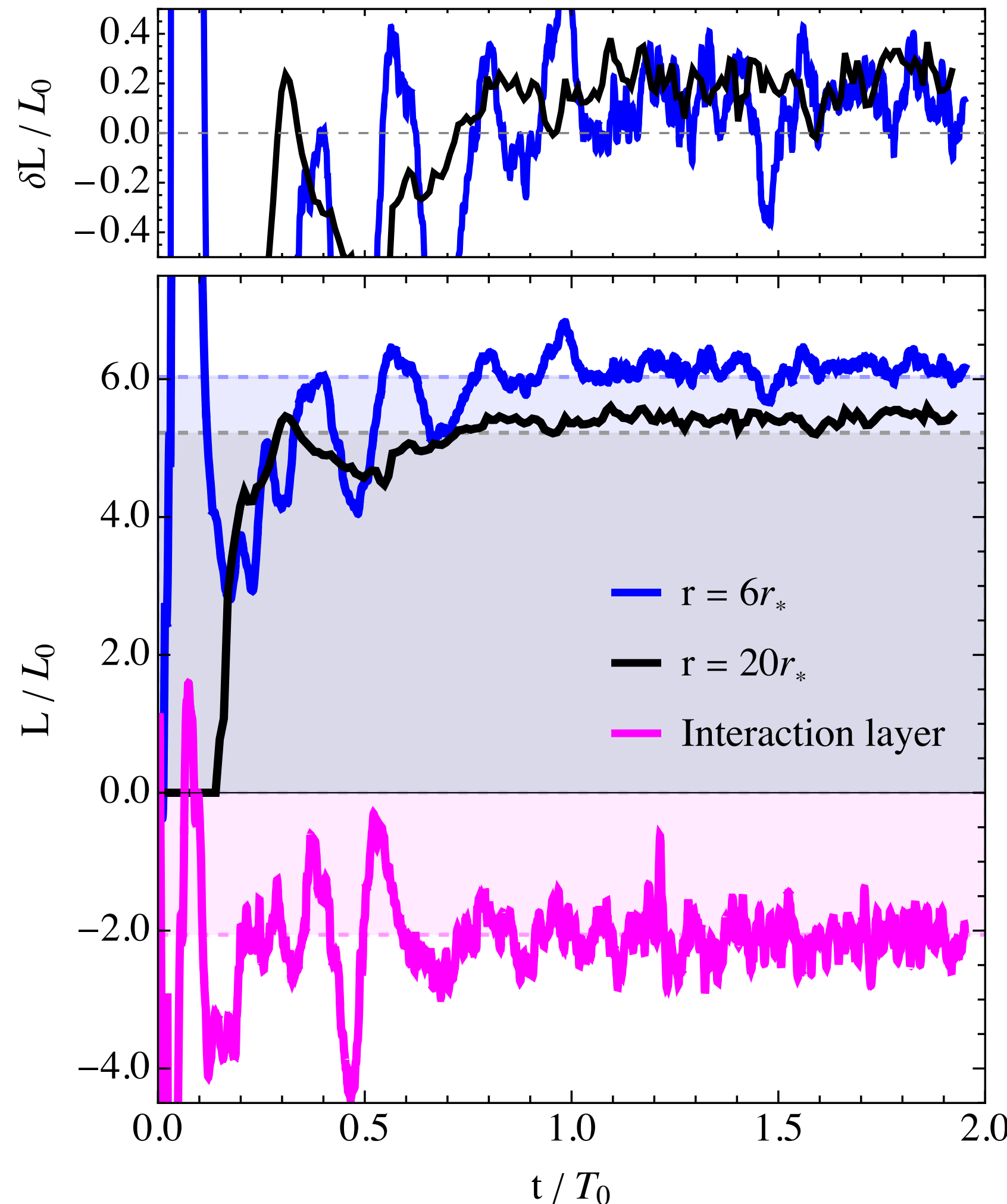
Development of the KH layer in the binary system

KH drag on magnetic field lines in the inner interaction region



Dissipation in the inner KH layer is significant

Energetics for aligned pulsar magnetospheres



Poynting flux variation
around field-averaged
contribution

Outgoing Poynting flux

Energy dissipated in
inner KH layer

- Compressed magnetospheres have a higher spin-down luminosity compared to isolated pulsars
- Dissipation in the KH layer reaches up to 40% of the spin-down luminosity
- Likely 5-10% of energy carried by outgoing FMS waves.

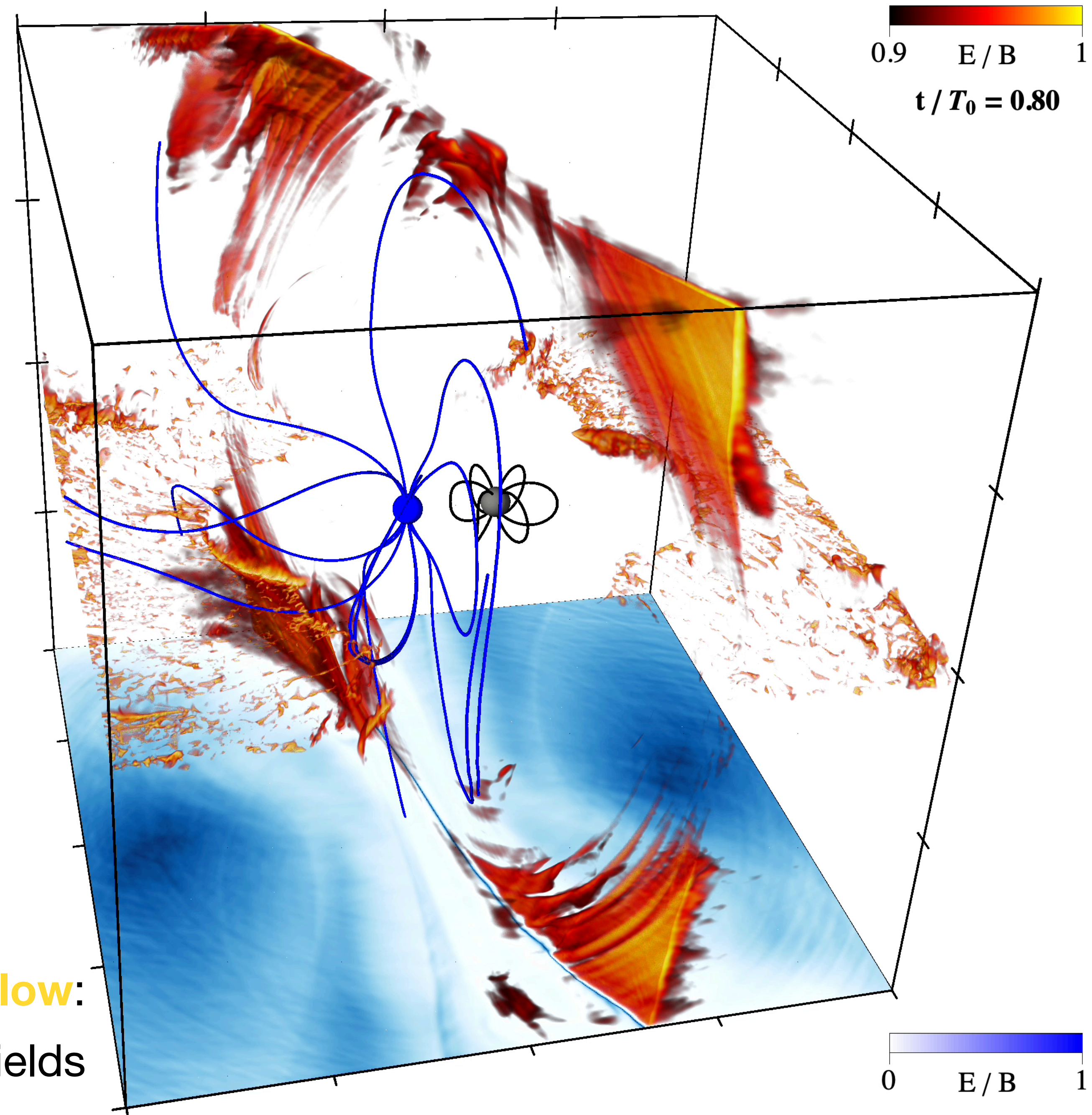
$$L_0 = \frac{\mu_*^2 \Omega_*^4}{c^3} = 4.7 \times 10^{36} \text{erg/s} \left(\frac{B_*}{10^{10} \text{G}} \right)^2 \left(\frac{r_*}{10^6 \text{cm}} \right)^2 \left(\frac{\Omega_* r_* / c}{0.05} \right)^4$$

Electric dynamics

Ubiquitous fast magnetosonic waves with low amplitudes

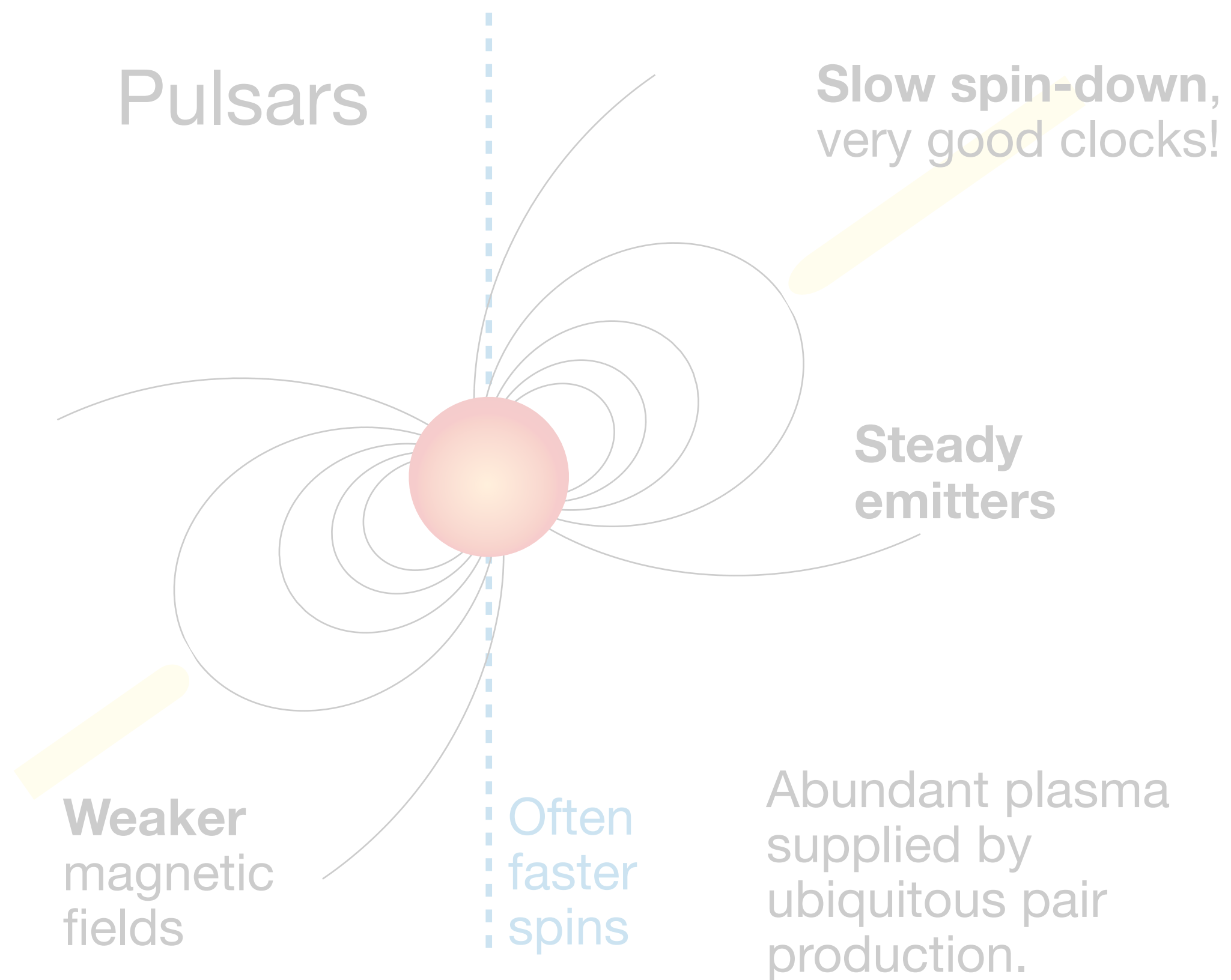
- Significant electric fields in the interaction layer current sheet
- Concentric structures in the electric field strength hint presence of **fast magnetosonic waves** (low amplitudes)
- Some surface waves in the interaction layer develop large amplitudes

Red/Yellow:
strong electric fields



Magnetars are unique plasma labs

Strong magnets with energetic X-ray and radio emission



second part of this talk

Magnetars

Rapid spin-down, magnetospheric feedback!

Quiescent vs. bursting

Much **stronger** magnetic fields

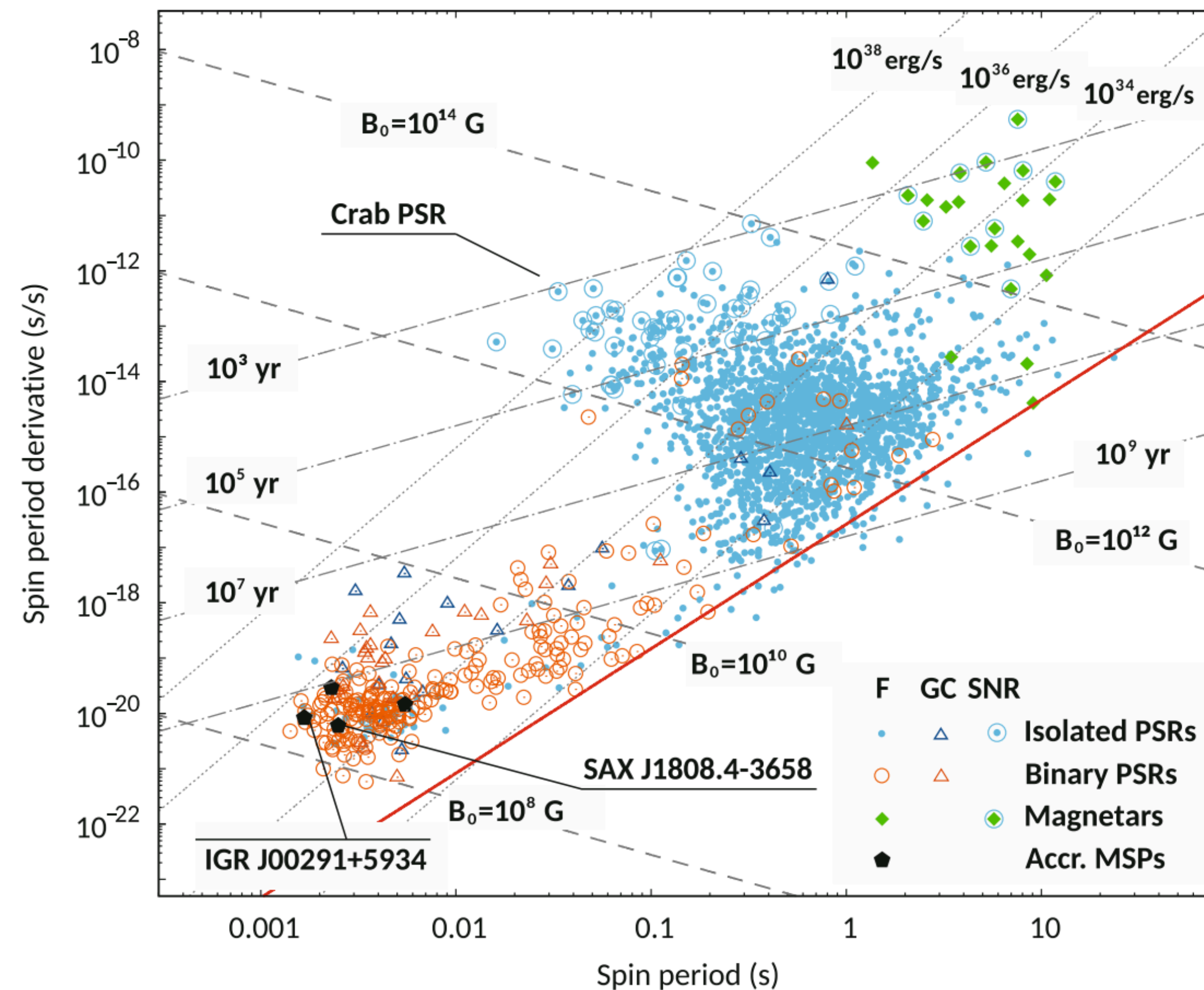
Often **slower** spins

Sufficient plasma supplied by radiative mechanisms in strong B-fields.

The diagram shows a central brown sphere representing the magnetar, with a blue dashed line indicating its axis of rotation. Concentric black lines represent the magnetic field. The text 'Magnetars' is in the top left, 'Rapid spin-down, magnetospheric feedback!' is in the top right, 'Quiescent vs. bursting' is in the middle right, 'Often slower spins' is in the bottom right, 'Much stronger magnetic fields' is in the bottom left, and 'Sufficient plasma supplied by radiative mechanisms in strong B-fields.' is in the bottom center.

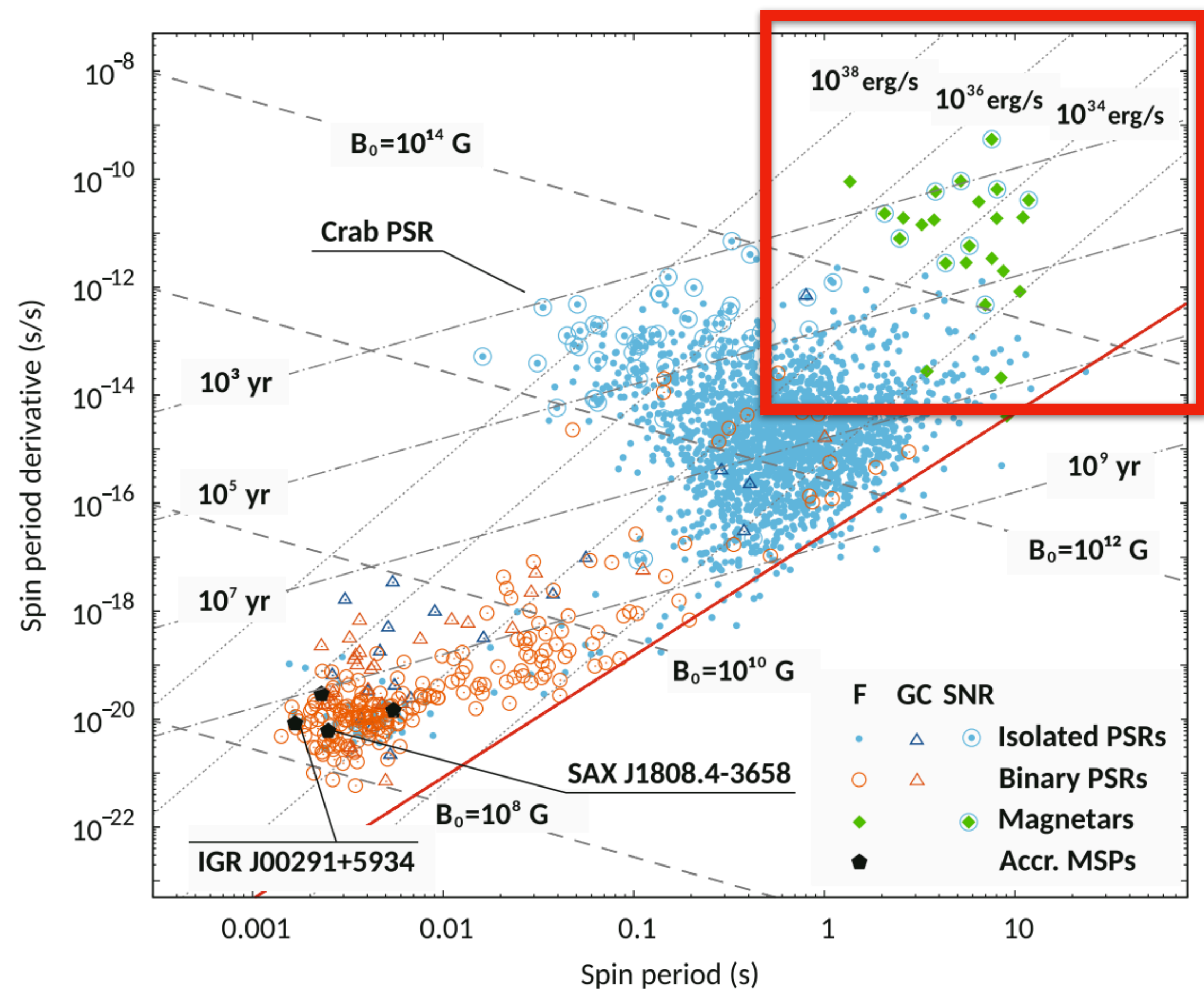
Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods

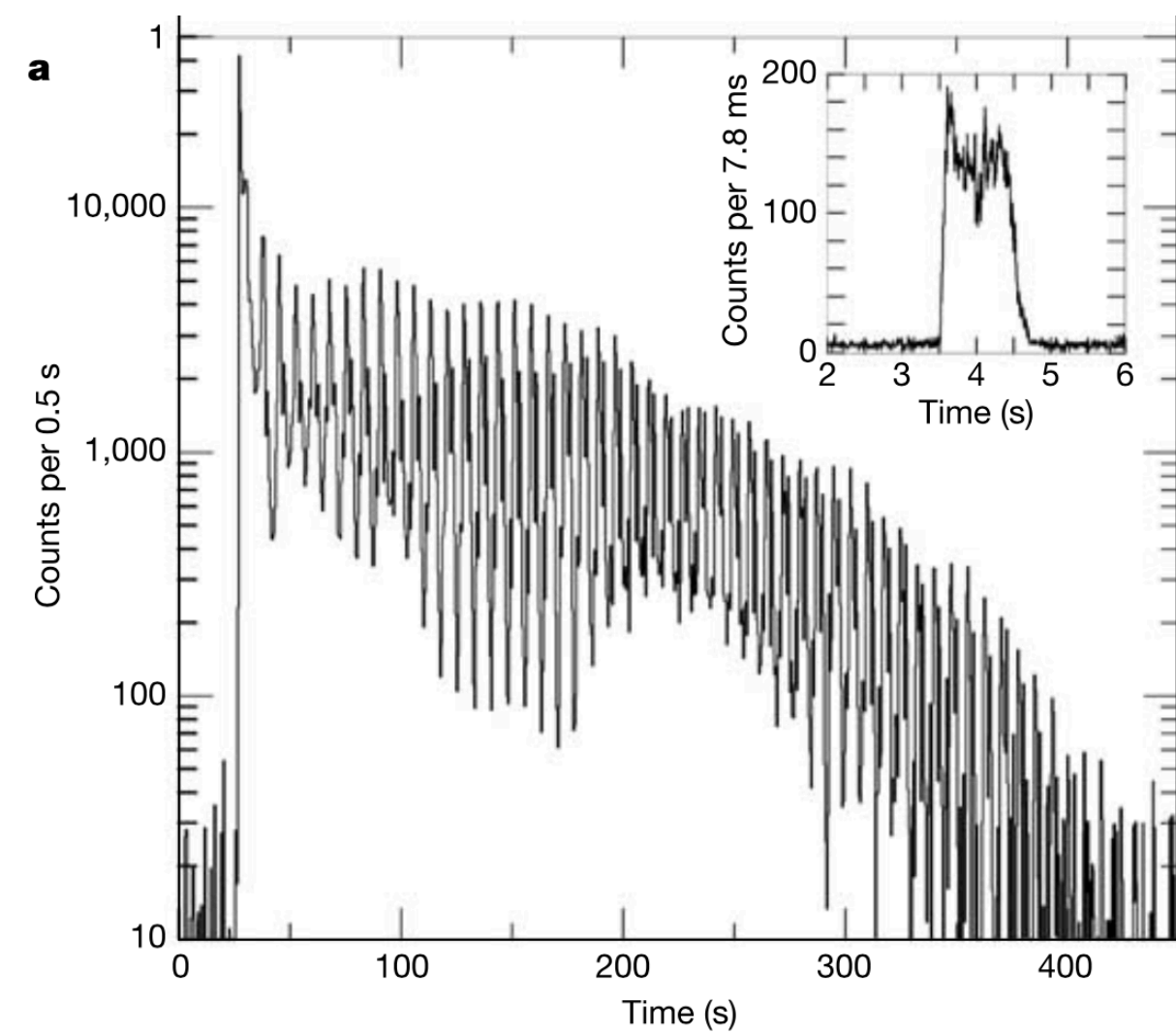


Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods



Rich set of X-ray
bursts and activity

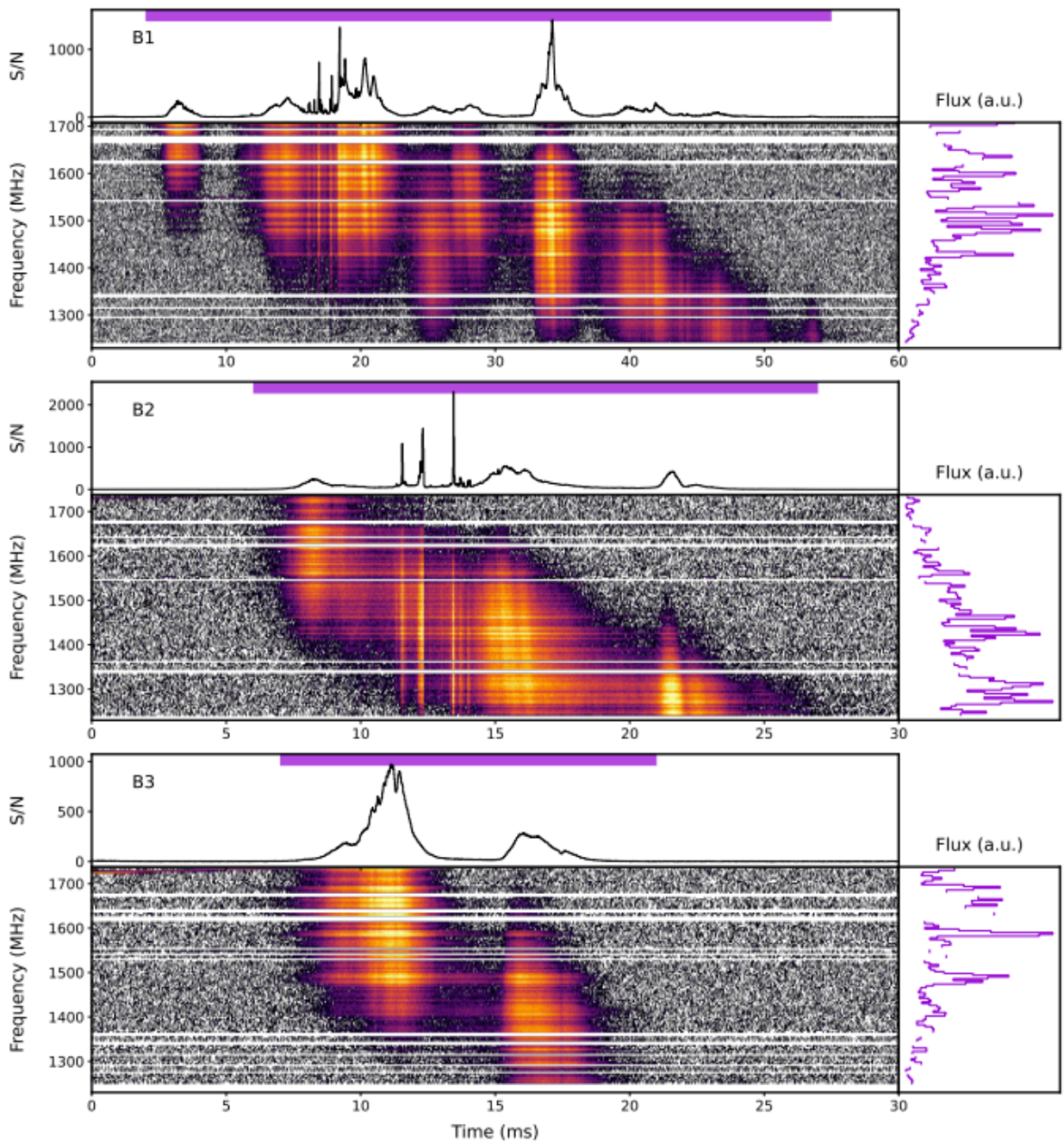


What makes them?

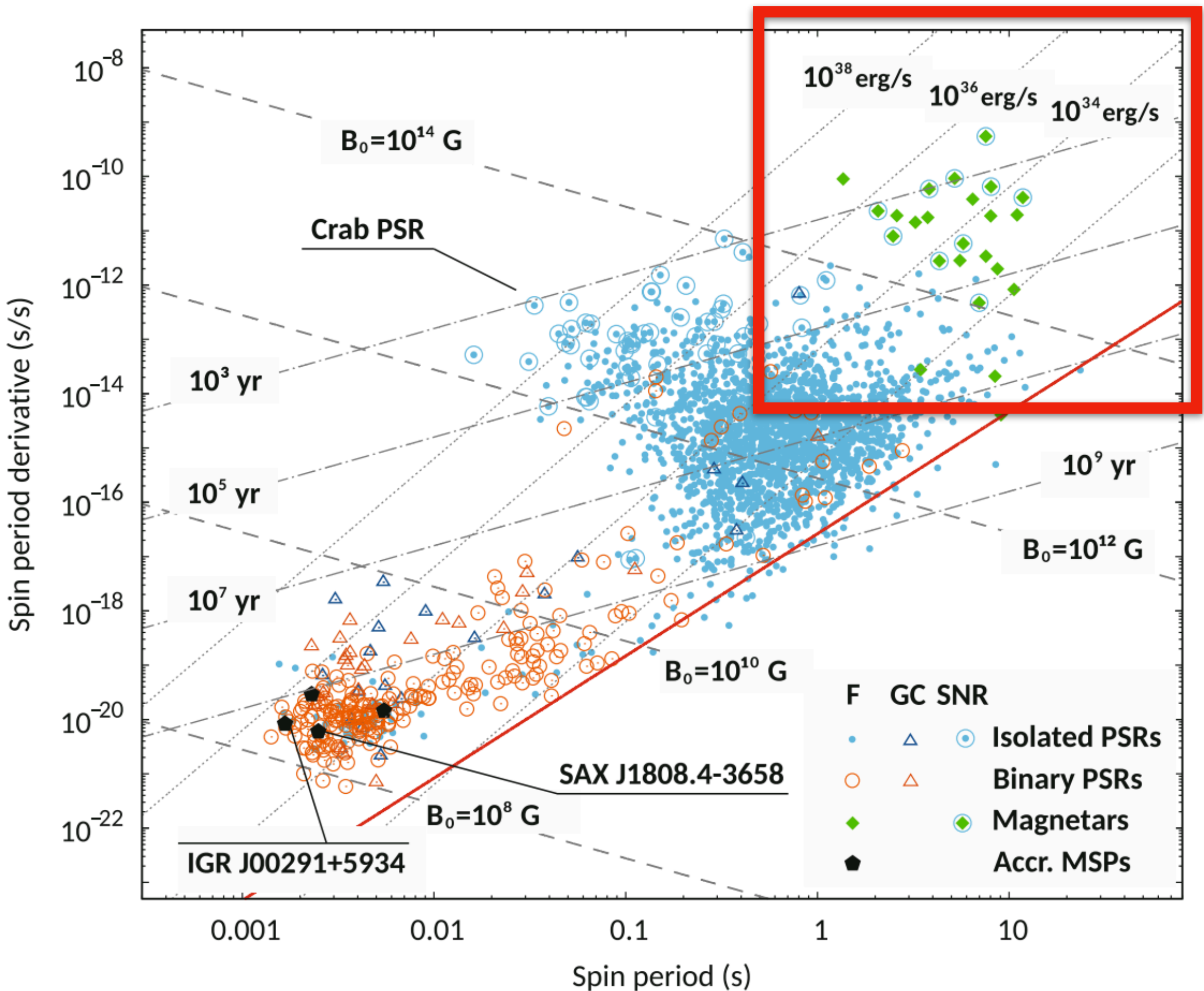
Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods

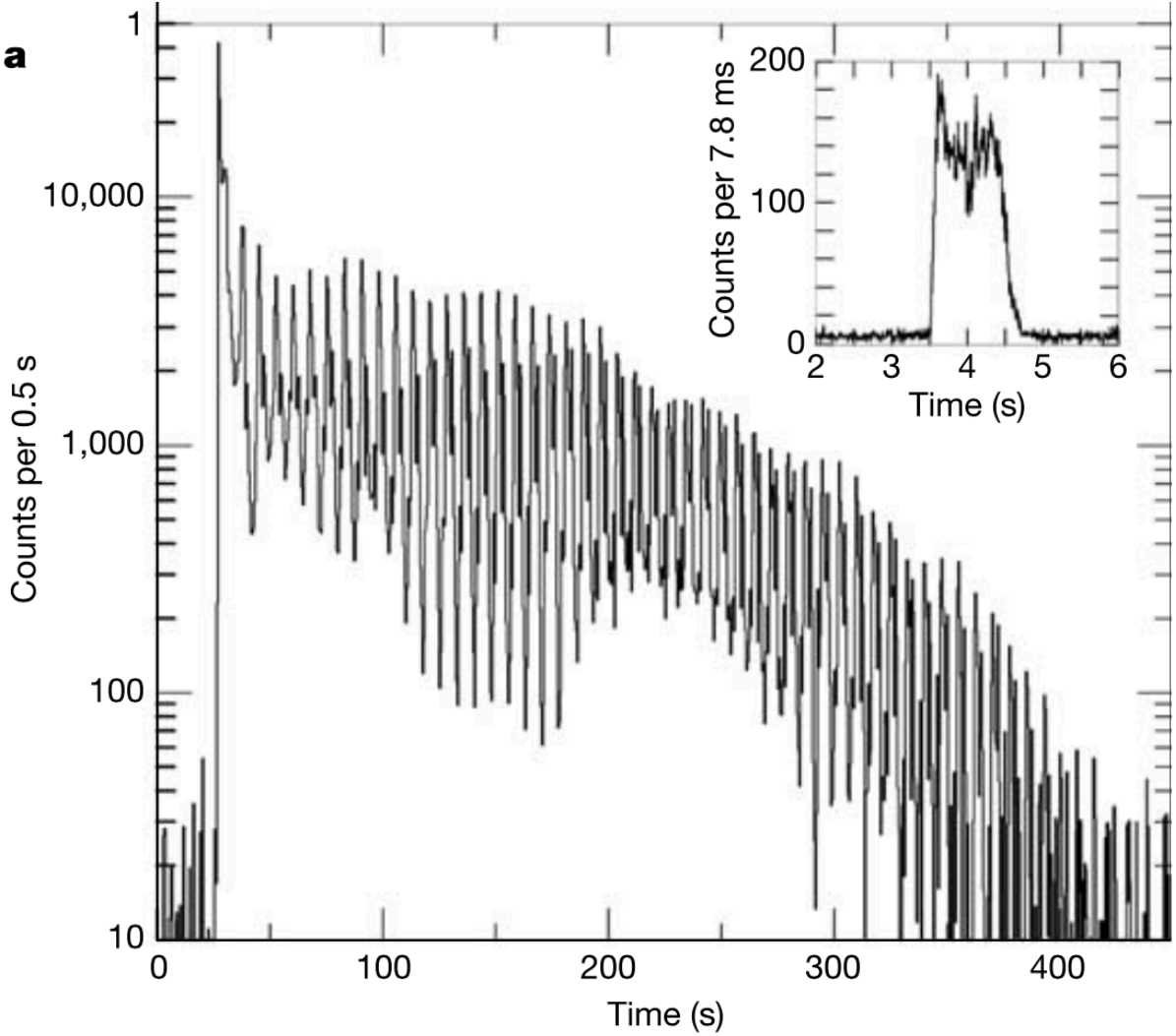
Are FRBs coming from magnetars? At least some.



What makes them?



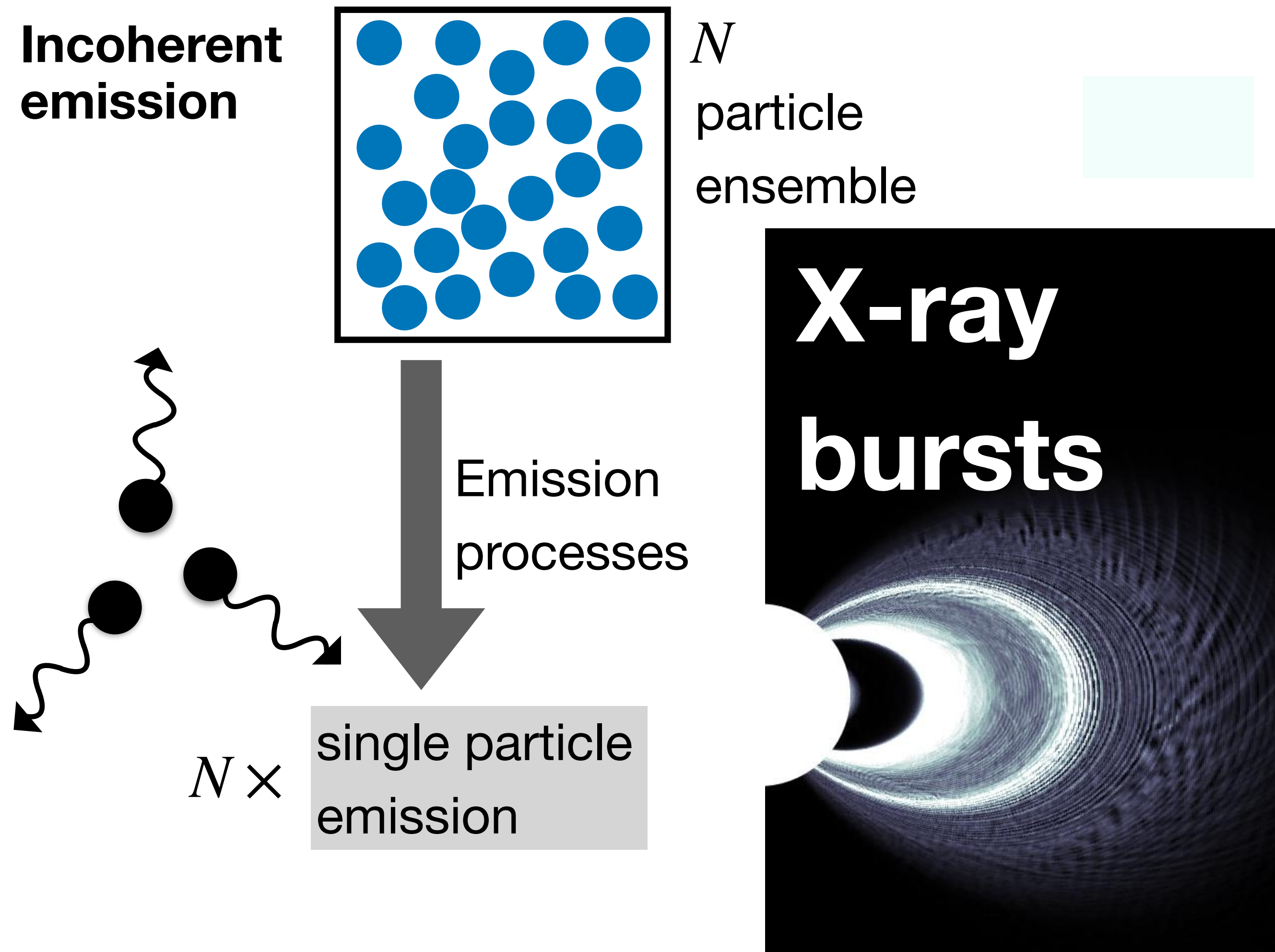
Rich set of X-ray bursts and activity



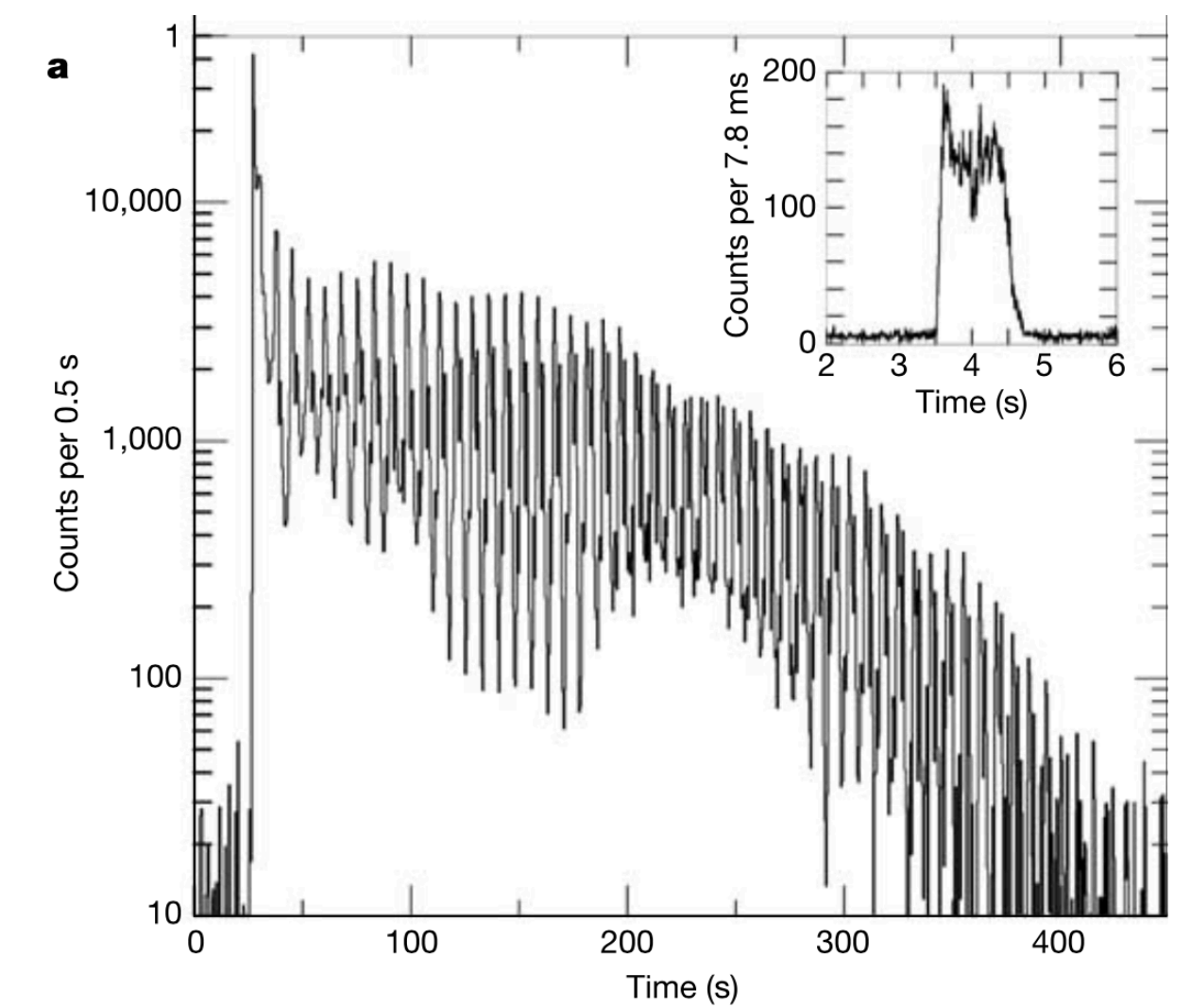
What makes them?

Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods



Rich set of X-ray bursts and activity



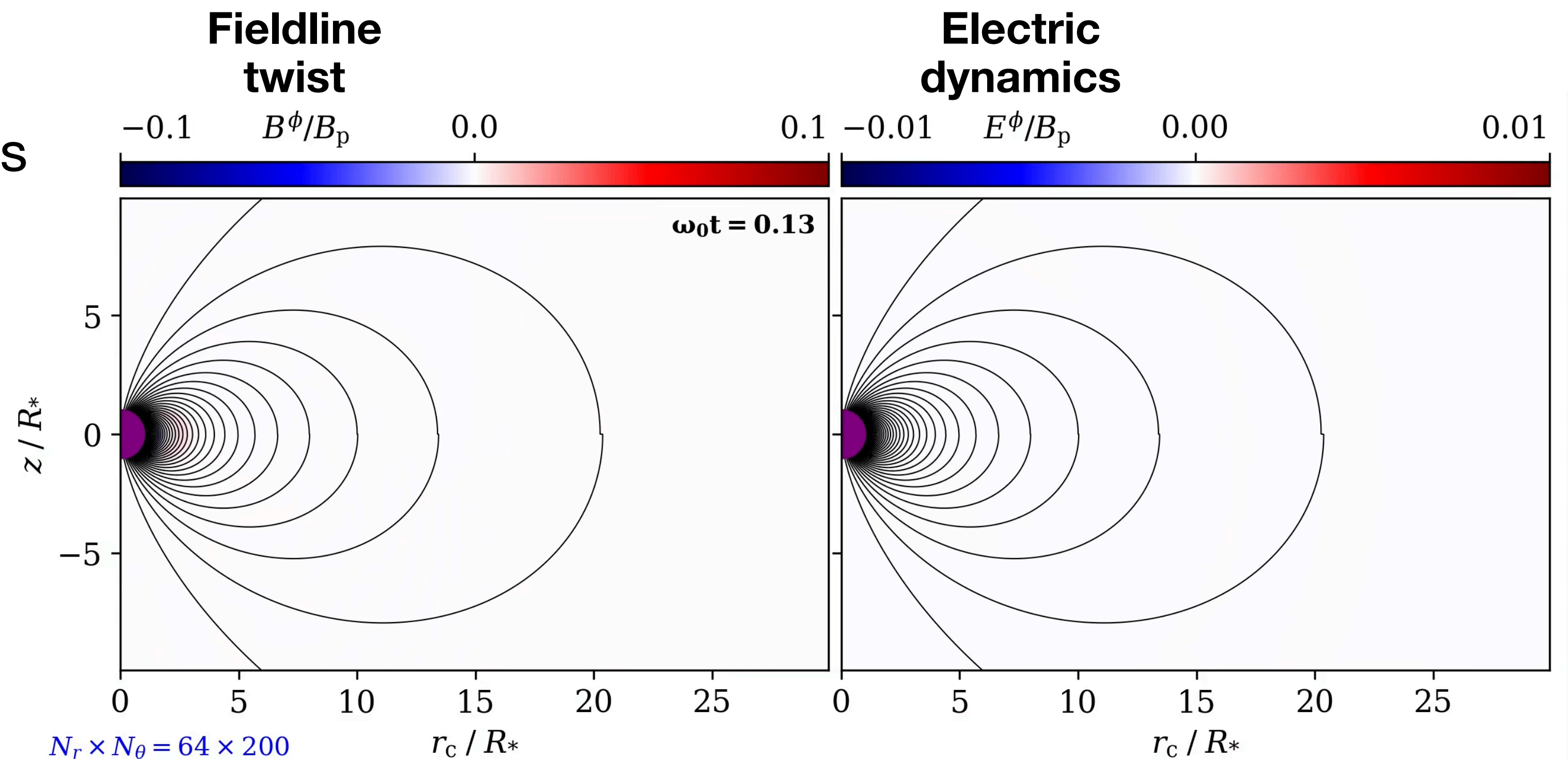
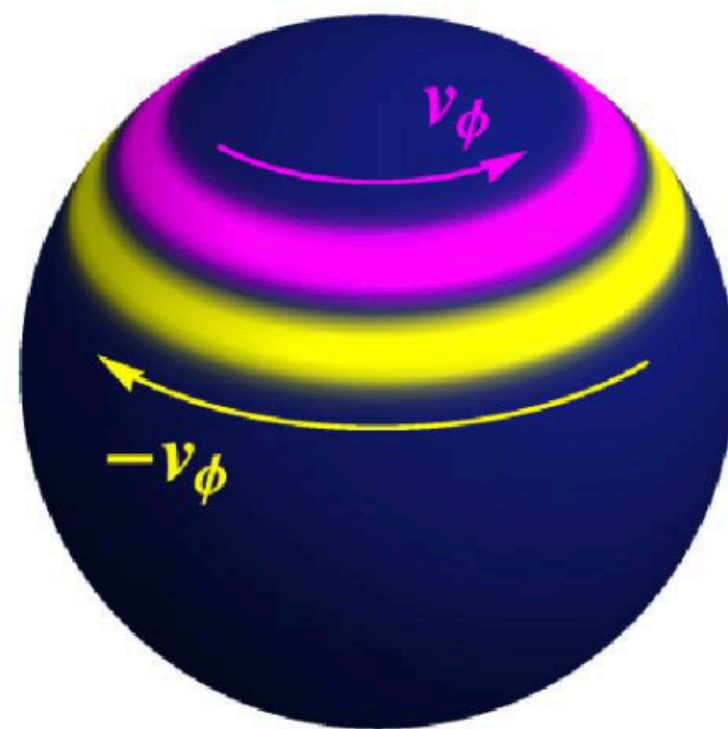
What makes them?

Axisymmetric shears can power giant flares

Eruptions happen on large scales, sometimes resembling CMEs

Shearing 2D dipolar magnetic

fields by moving field lines across the magnetar surface in axisymmetry:

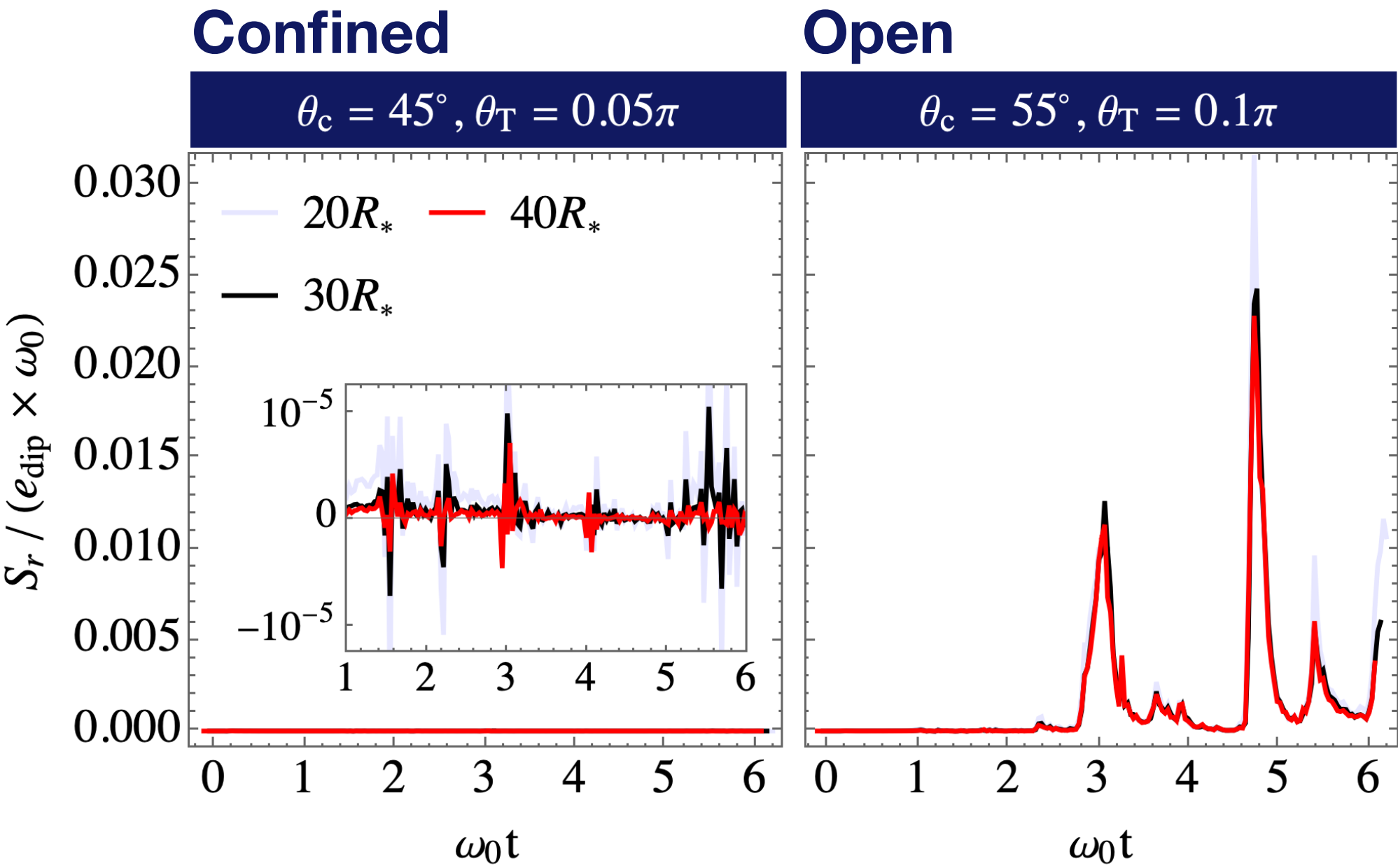


Q: What does this magnetic field look like?

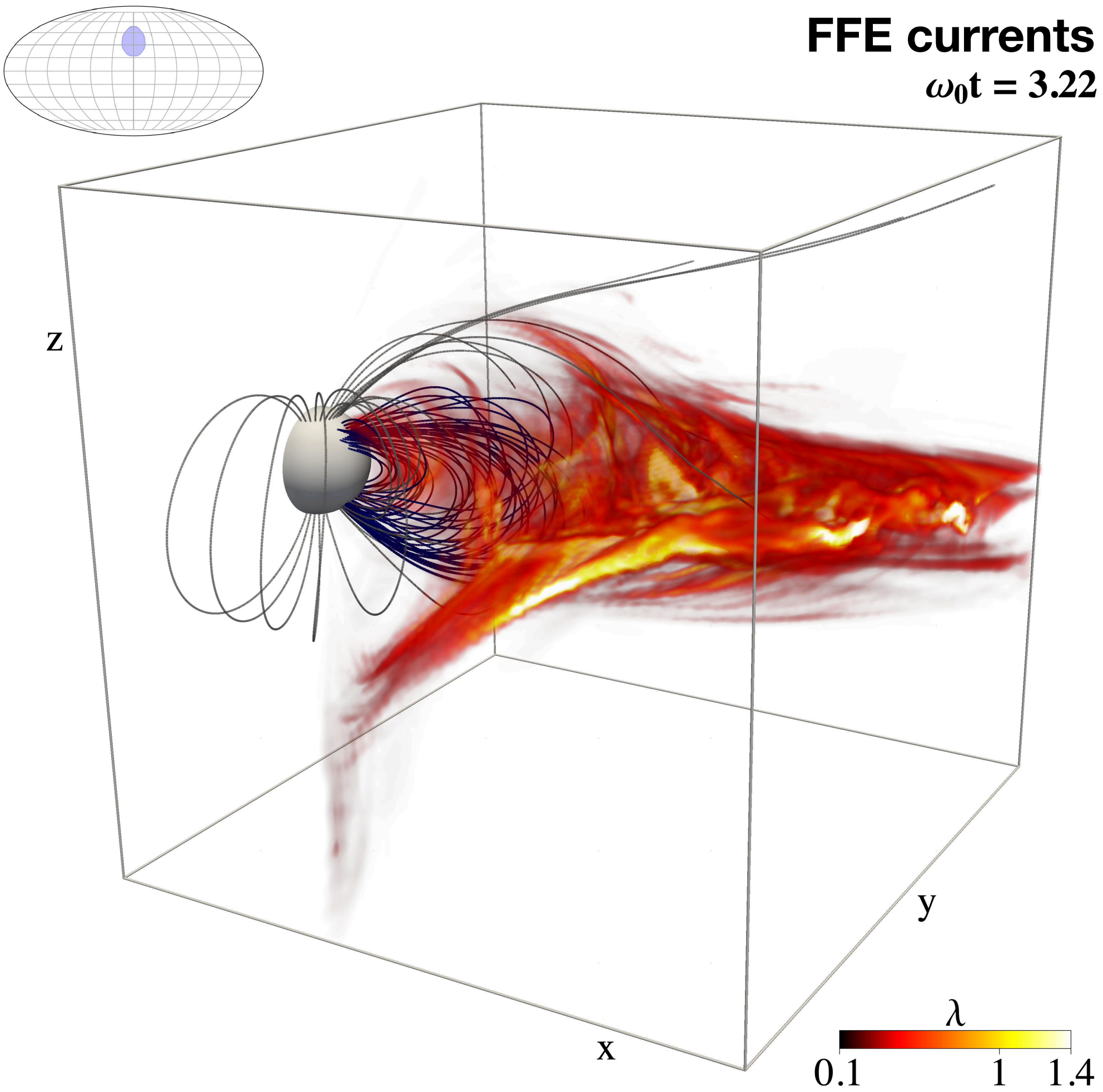
Large flux tubes can open up the magnetosphere

Global current sheets dissipate energy on global scales

Outflowing electromagnetic energy:



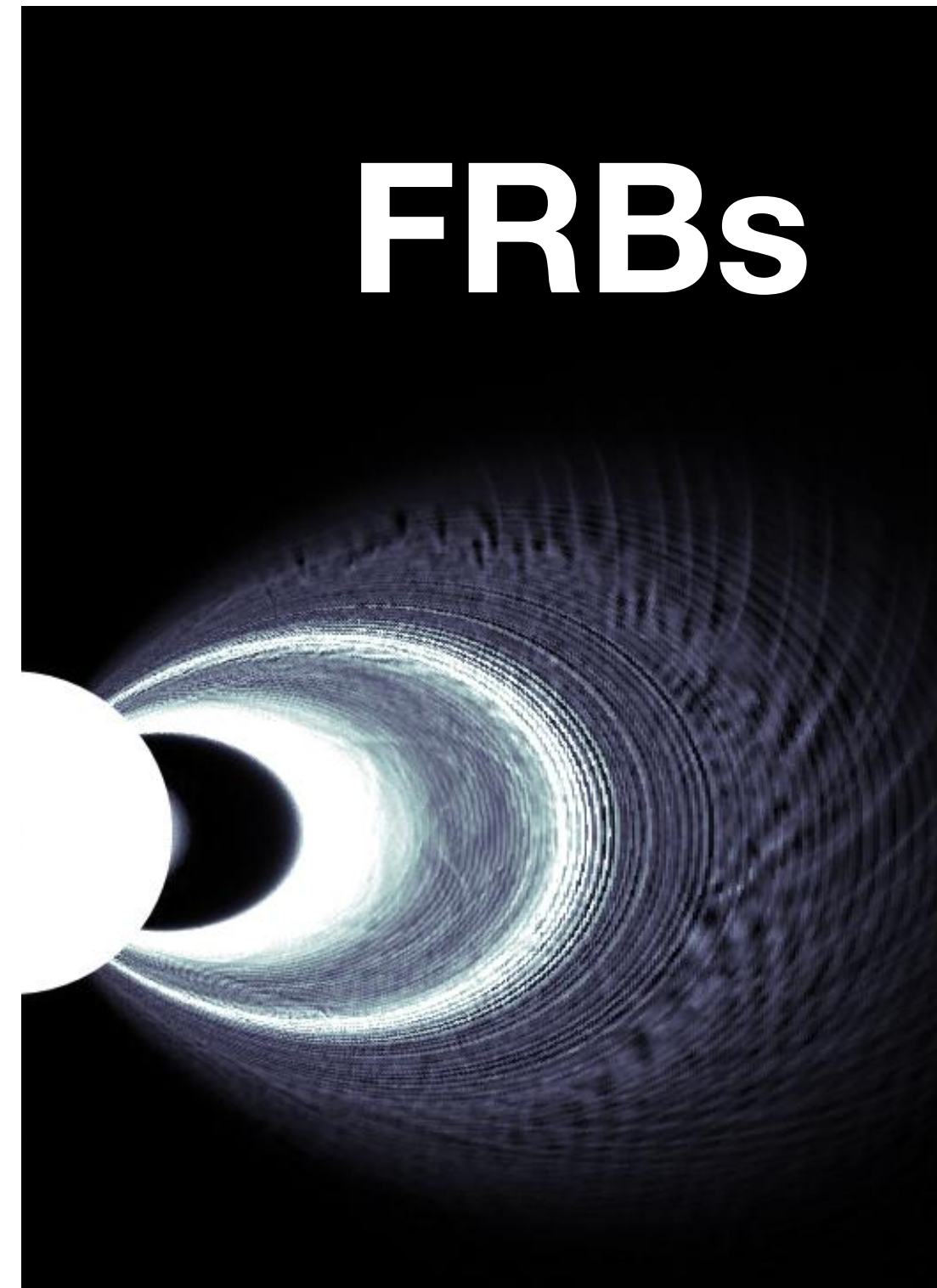
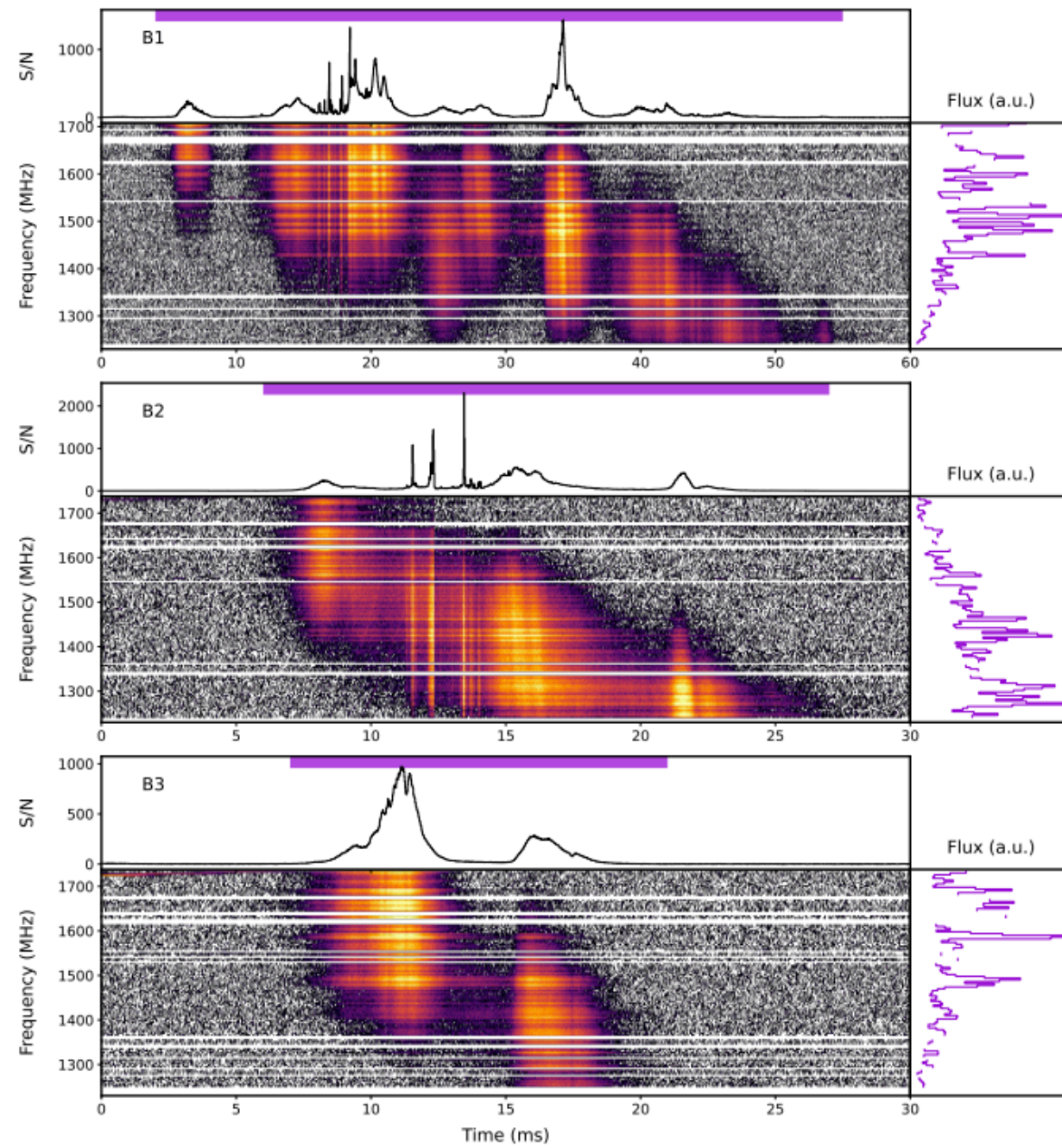
$$L_X \approx 10^{41} - 10^{43} \text{ erg/s}$$



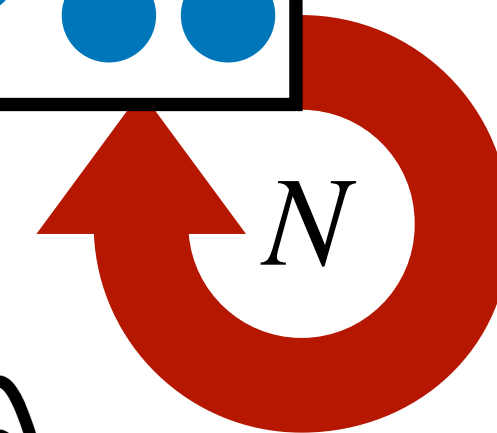
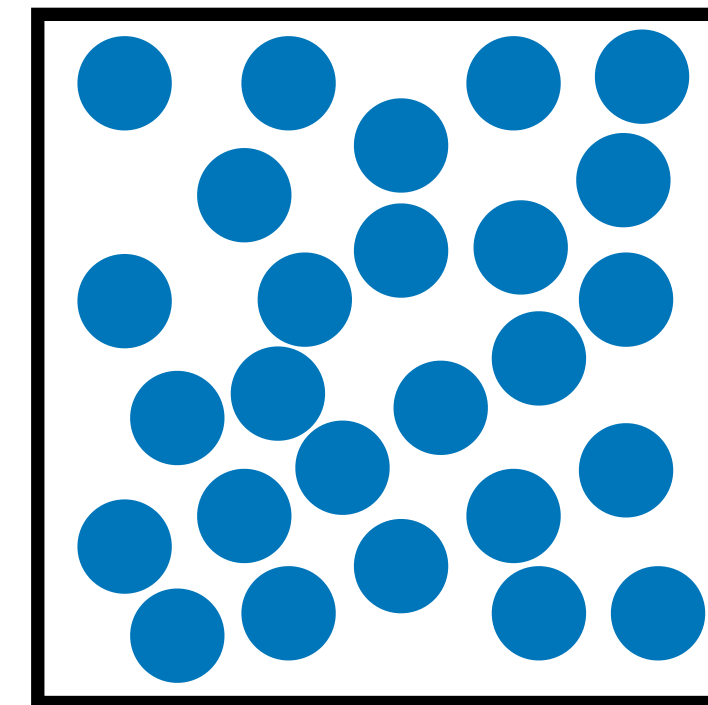
Magnetars and their transients

Coherent emission processes to burst brightness temperature

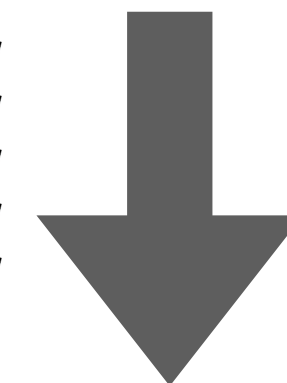
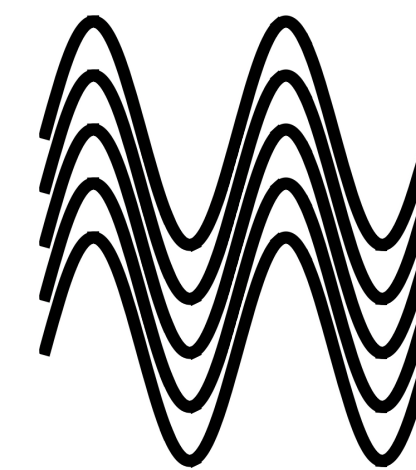
Are FRBs coming from magnetars? At least some.



Coherent
emission



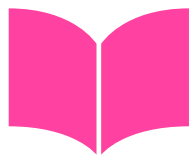
coherent
interactions



$$N^2 \times$$

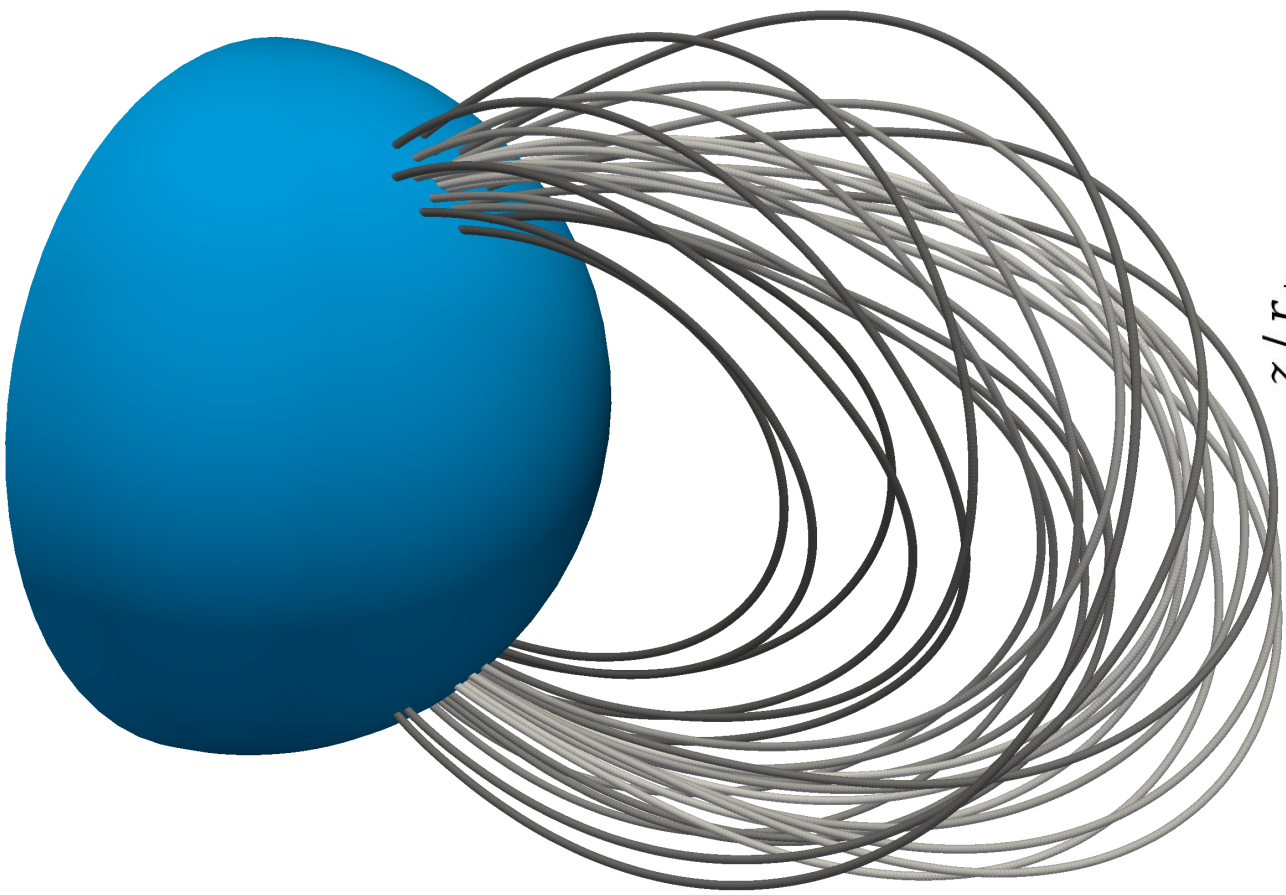
single particle
emission

**high brightness
temperatures**



3D helical instabilities can seed fainter bursts

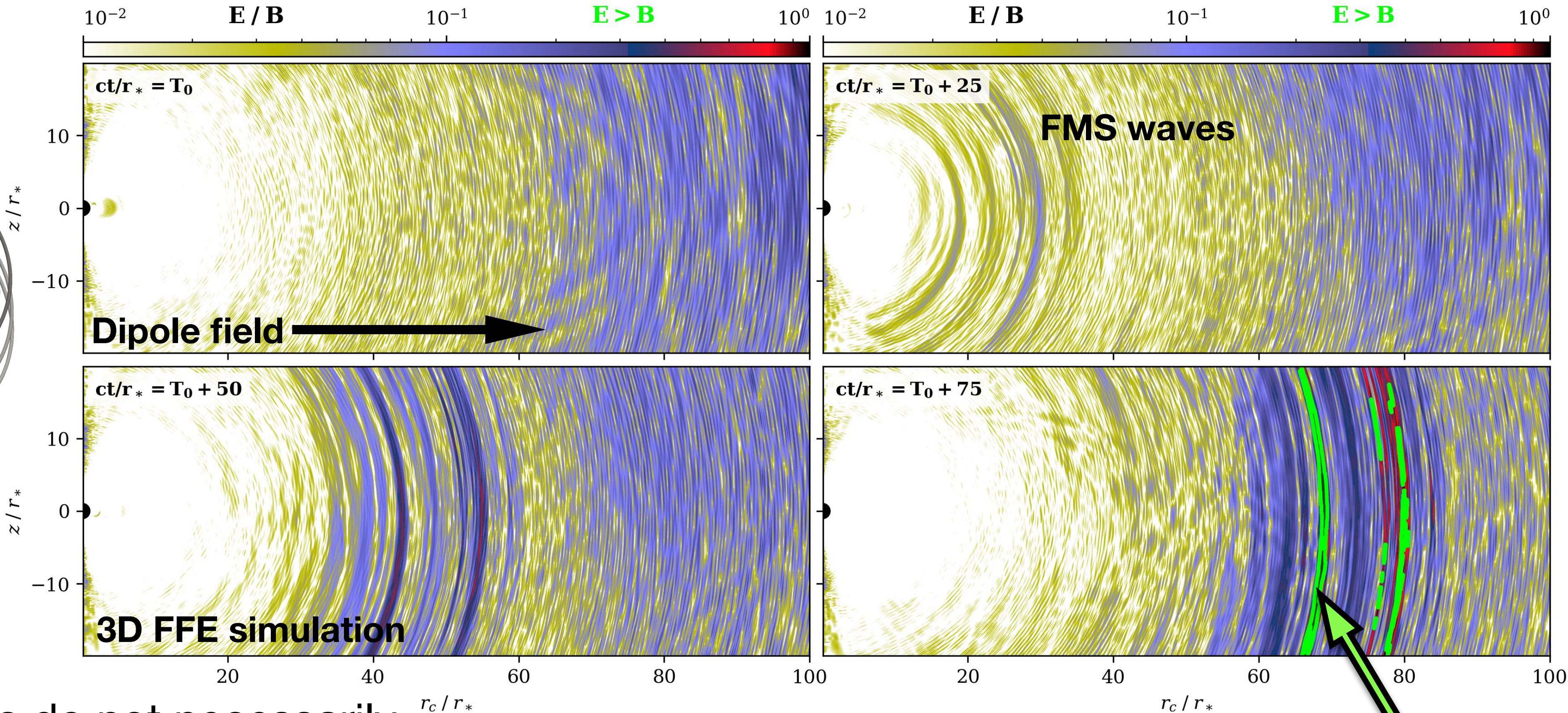
Kink-unstable flux tubes seed fast waves that develop E-zones



A kinking flux tube in the inner magnetosphere generates FMS waves.

But: Large scale eruptions do not necessarily generate FMS waves.

(see also Sharma et al. 2023)

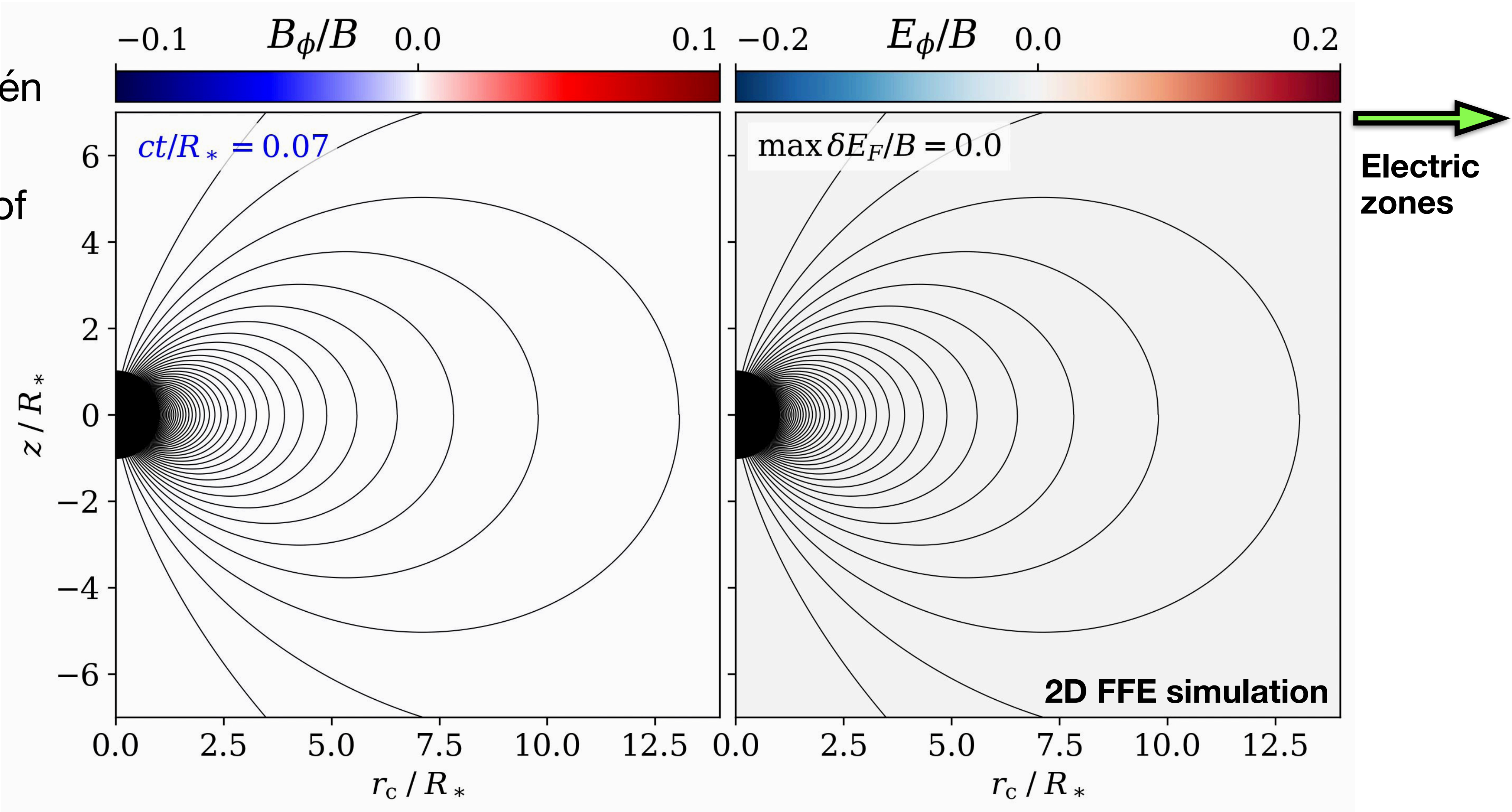
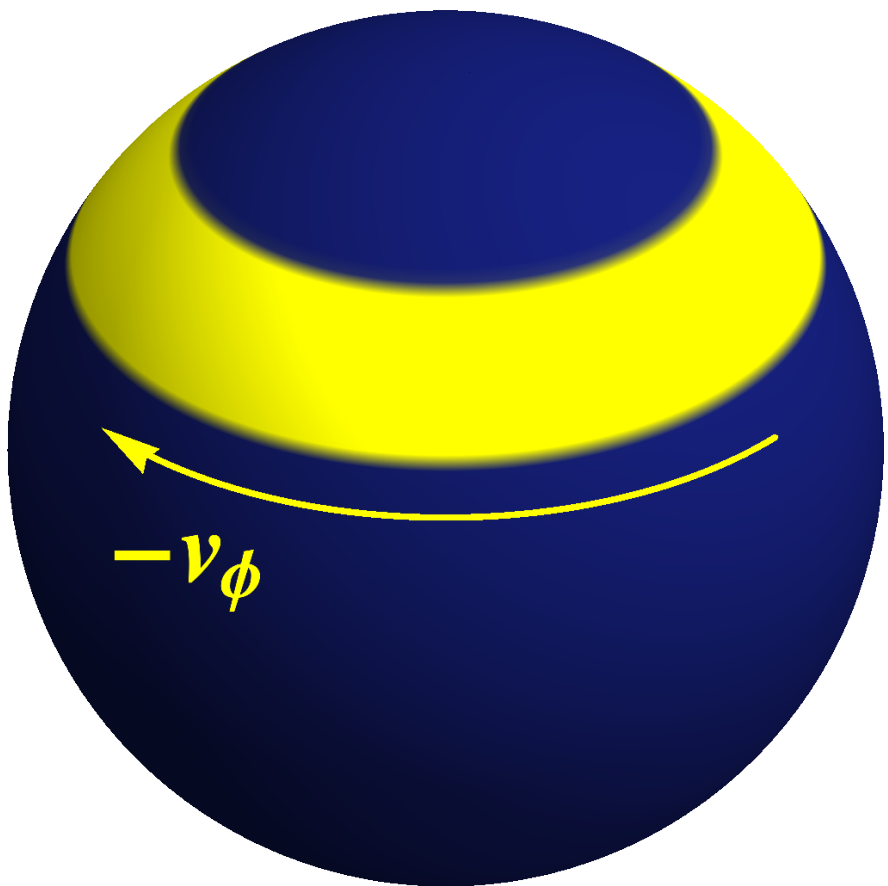


Electric zones

Alfvén waves mode-convert at curved fields

Surface motions can seed fast waves that develop E-zones

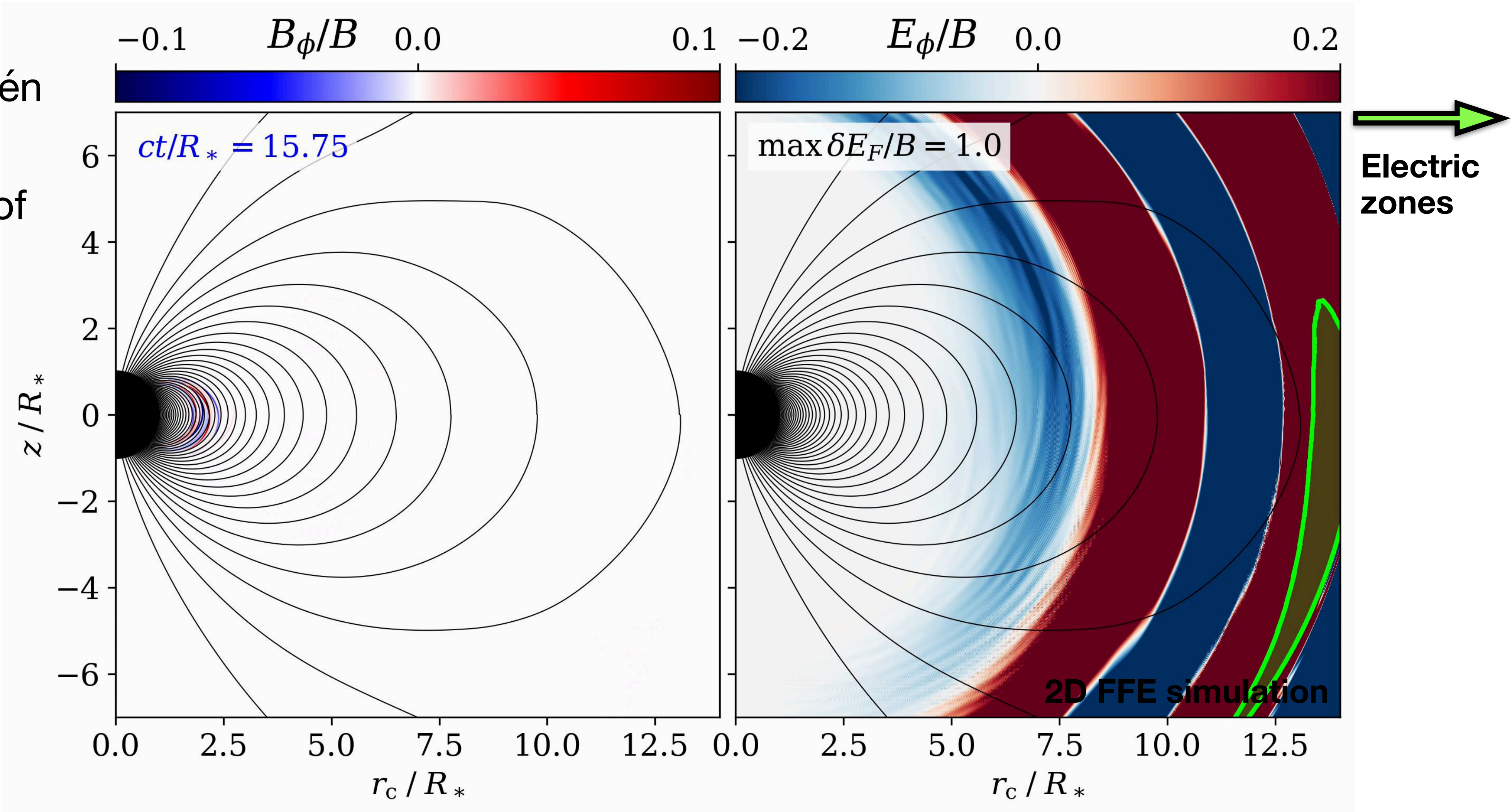
A low amplitude Alfvén wave generates several generations of FMS waves — of varying frequency!



Alfvén waves mode-convert at curved fields

Surface motions can seed fast waves that develop E-zones

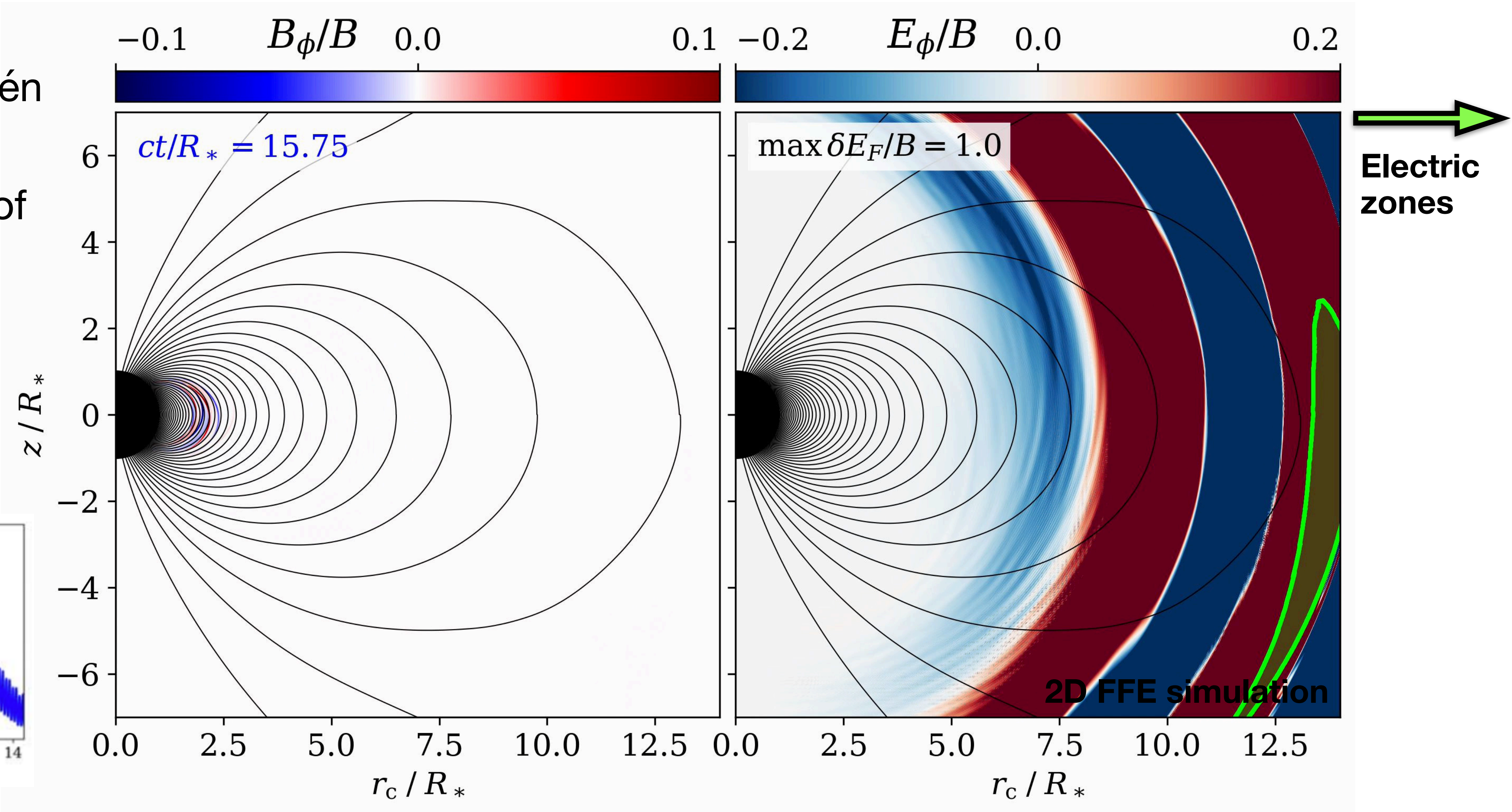
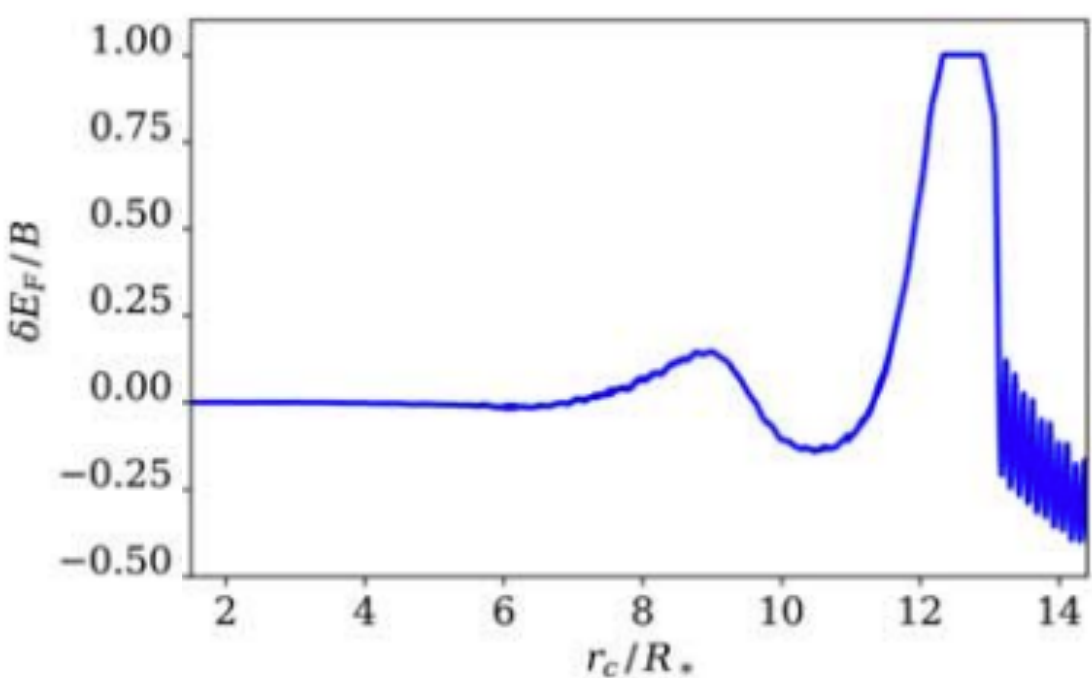
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Alfvén waves mode-convert at curved fields

Surface motions can seed fast waves that develop E-zones

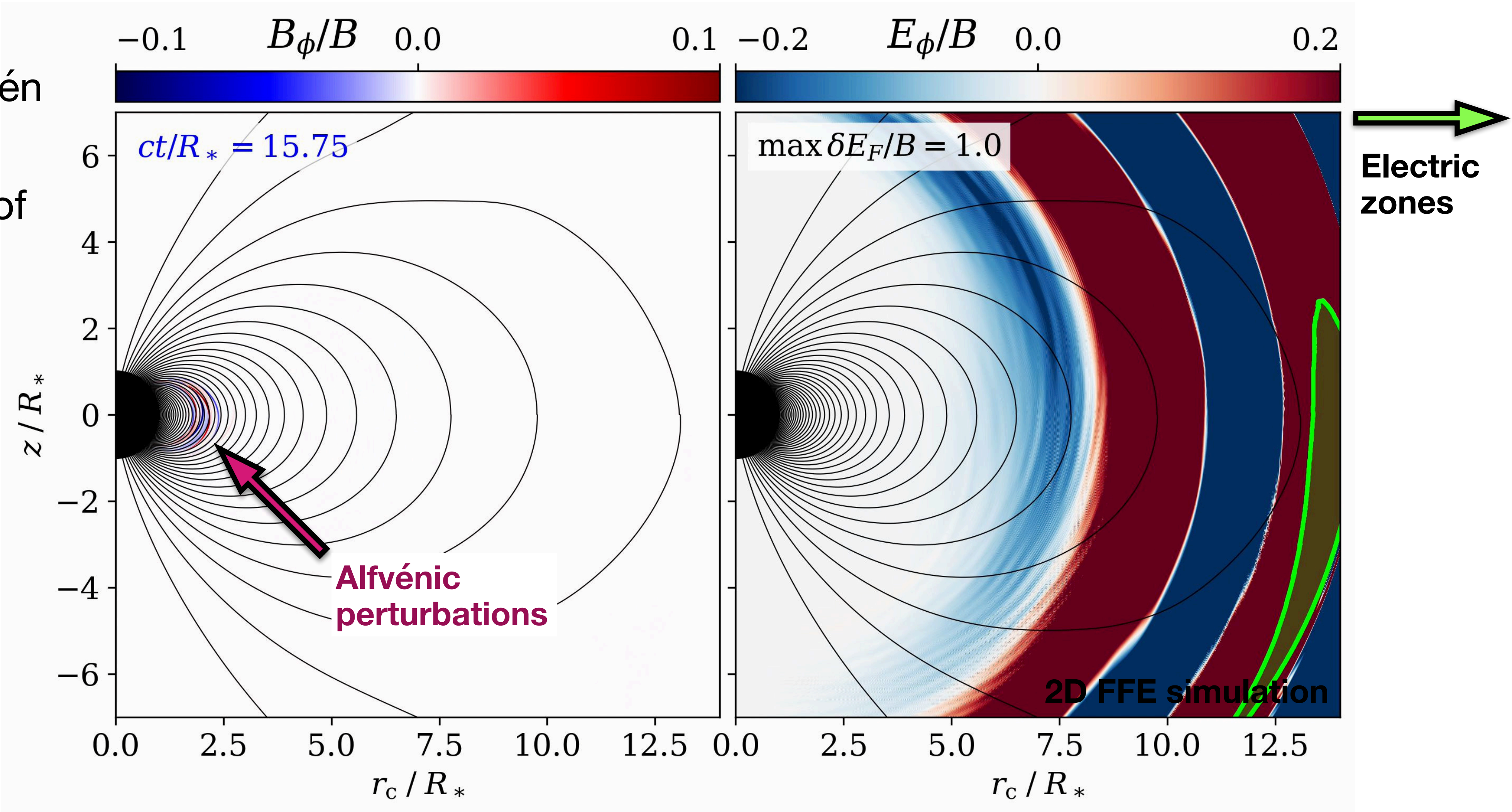
A low amplitude Alfvén wave generates several generations of FMS waves — of varying frequency!



Alfvén waves mode-convert at curved fields

Surface motions can seed fast waves that develop E-zones

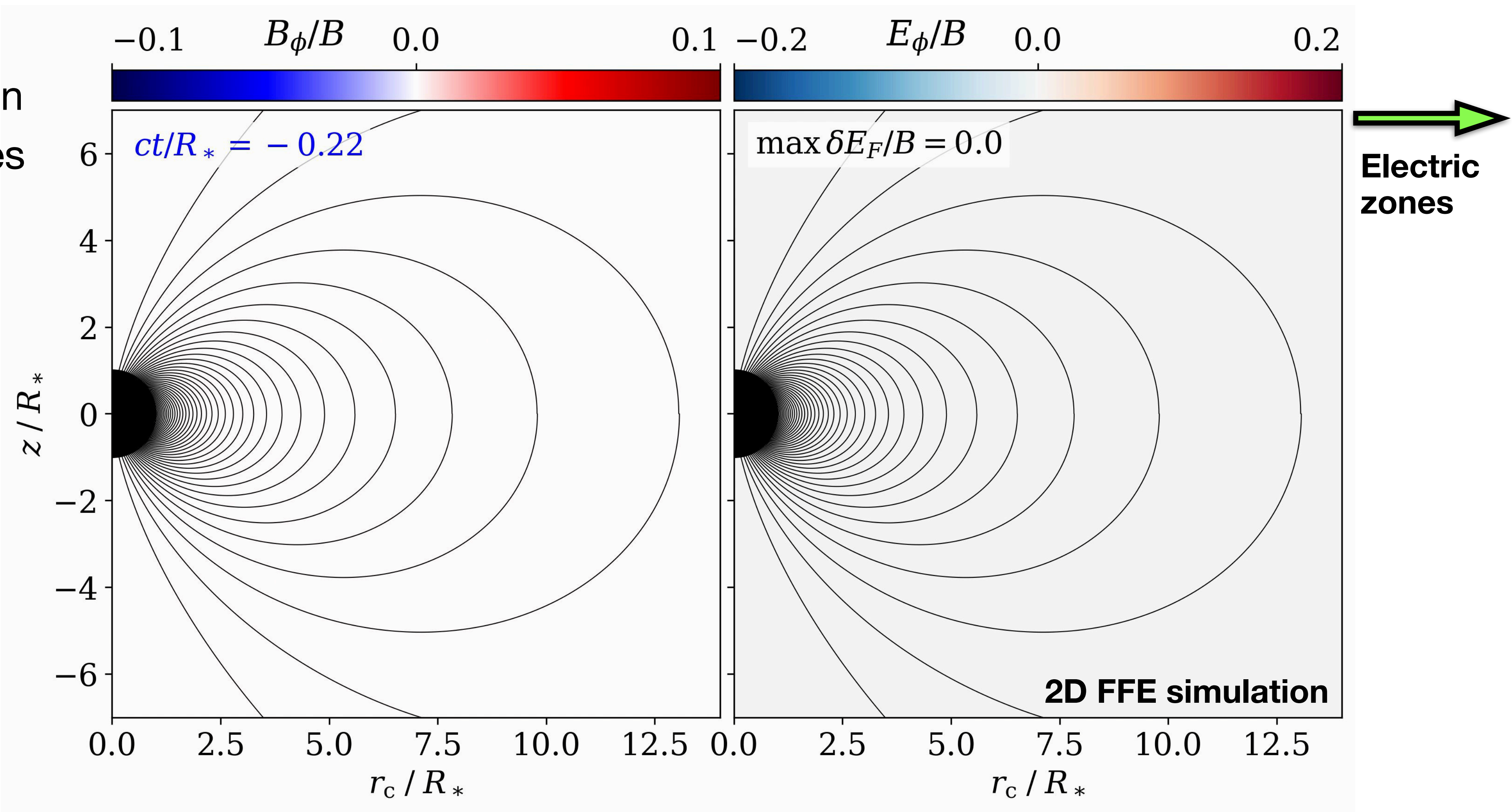
A low amplitude Alfvén wave generates several generations of FMS waves — of varying frequency!



Alfvén wave interactions add an FMS channel

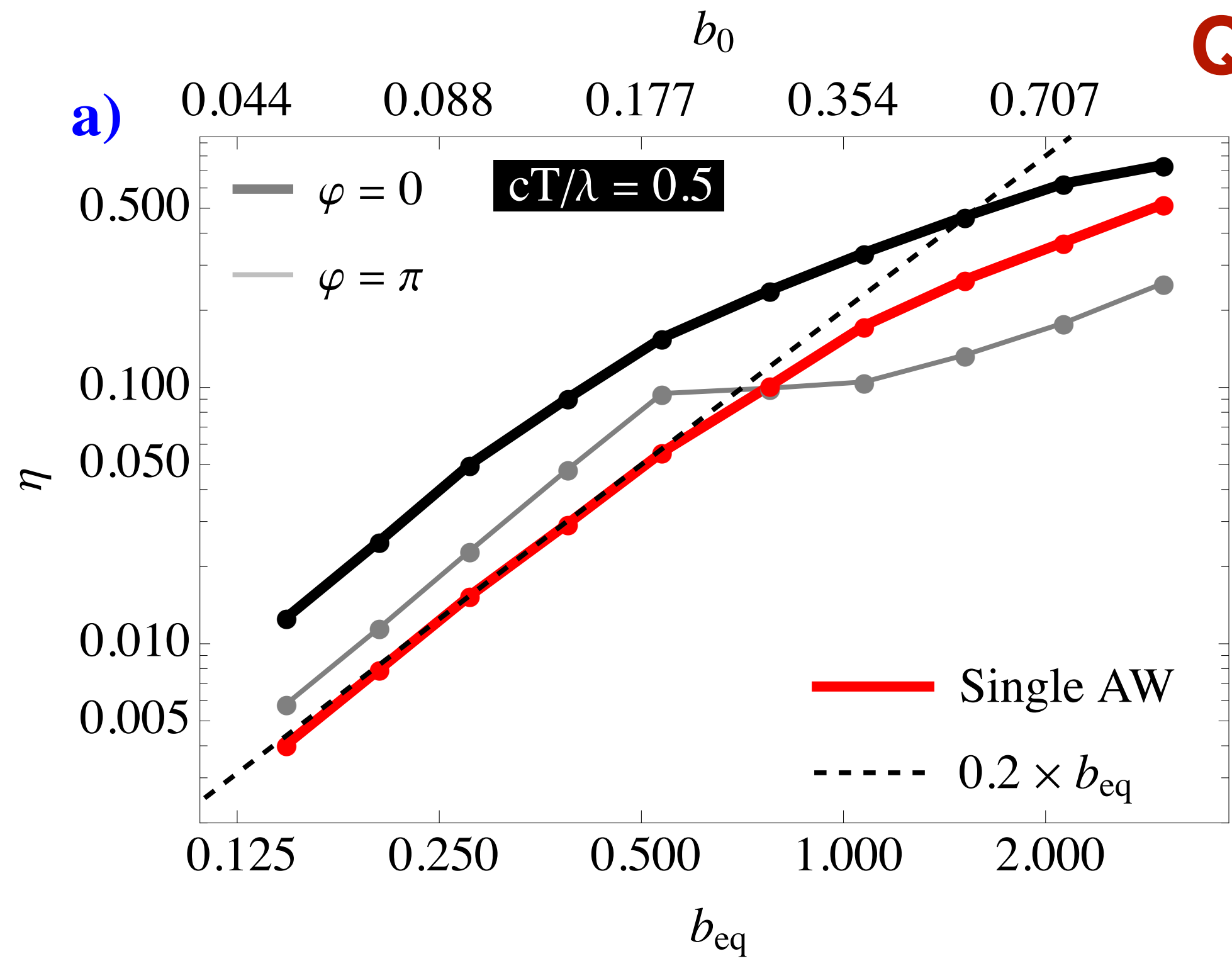
Depending on seed wave properties, FMS efficiency is enhanced

Two waves injected in both magnetospheres interact in the equatorial region.



Alfvén wave interactions add an FMS channel

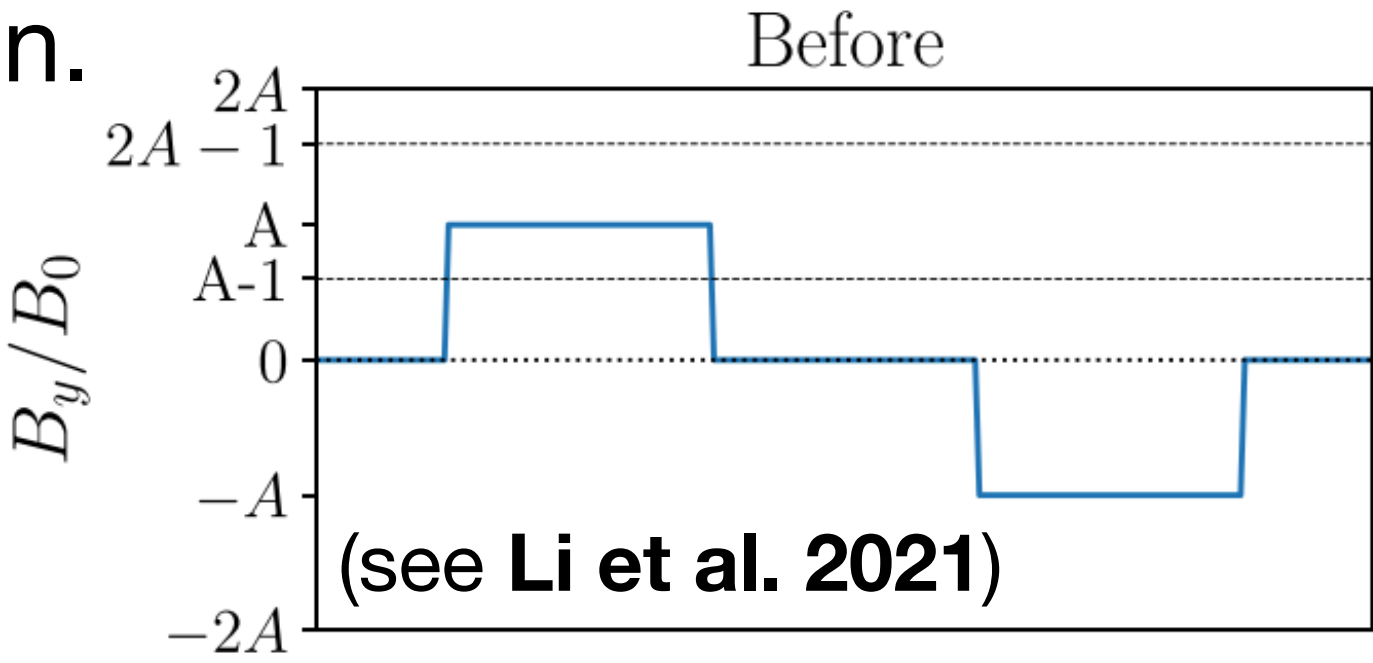
Depending on seed wave properties, FMS efficiency is enhanced



Q: What effect do wave interactions have?

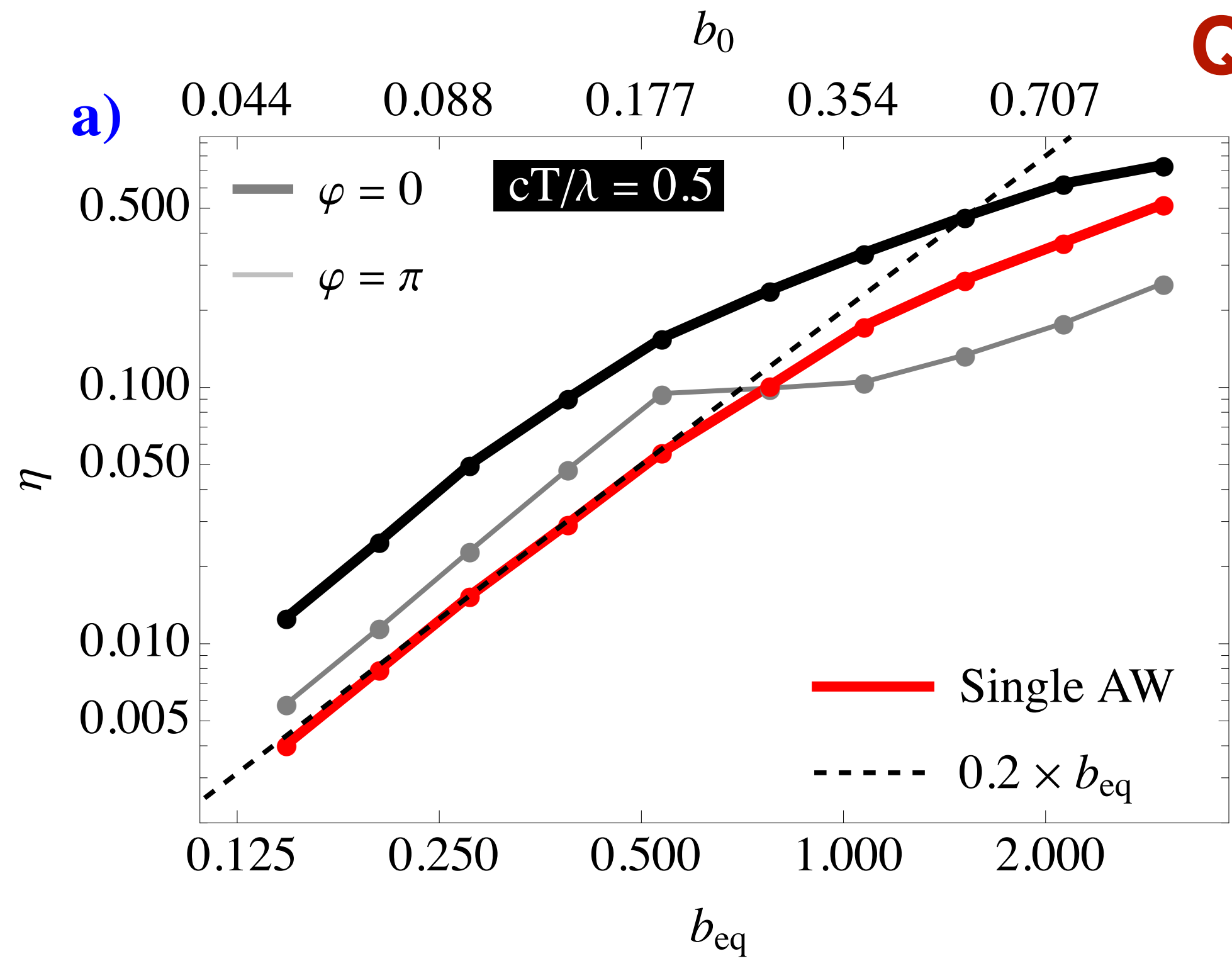
2D simulations suggests that **fast wave injection can be enhanced** for favorable primary waves.

Strong primary waves can develop electric zones during their interaction.



Alfvén wave interactions add an FMS channel

Depending on seed wave properties, FMS efficiency is enhanced

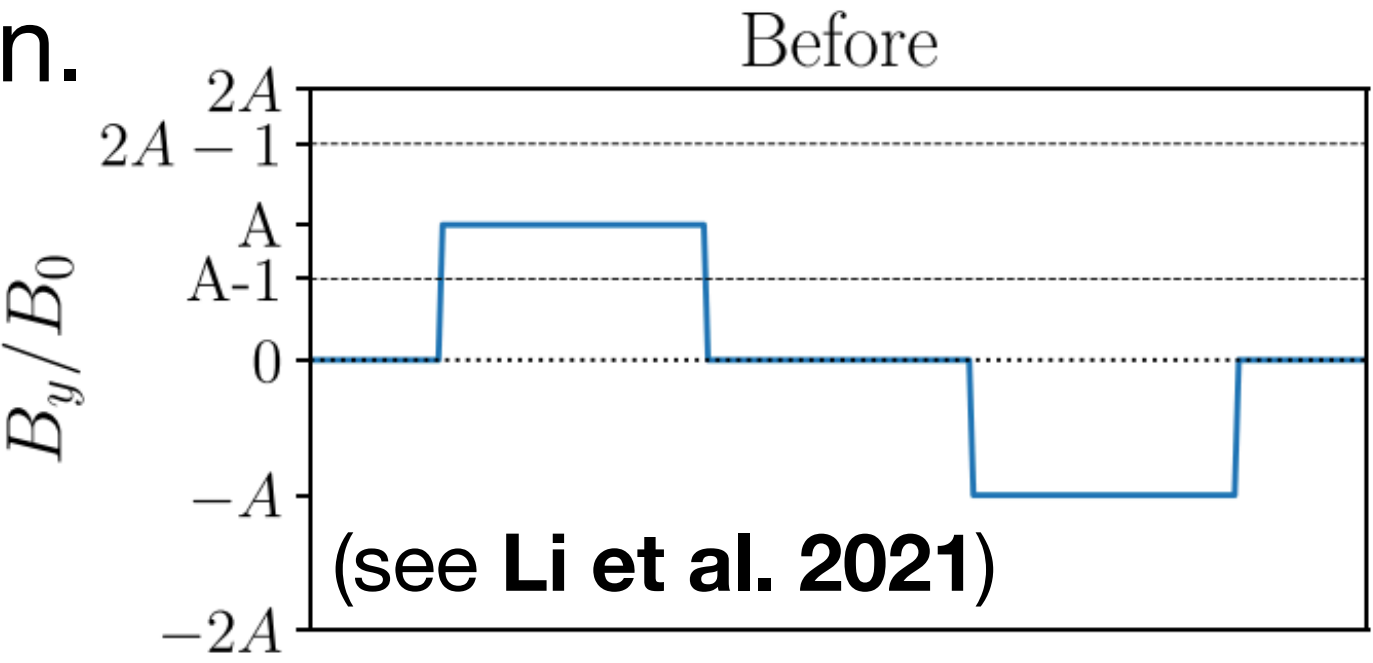


Q: What effect do wave interactions have?

3D will be required to answer this!

2D simulations suggests that **fast wave injection can be enhanced** for favorable primary waves.

Strong primary waves can develop electric zones during their interaction.

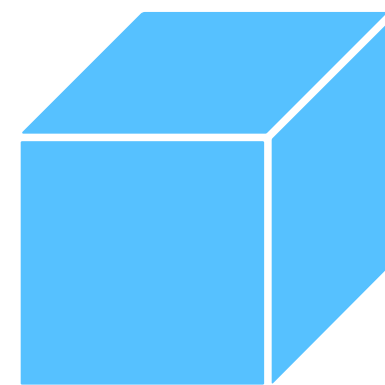


FRBs escape from inner magnetosphere

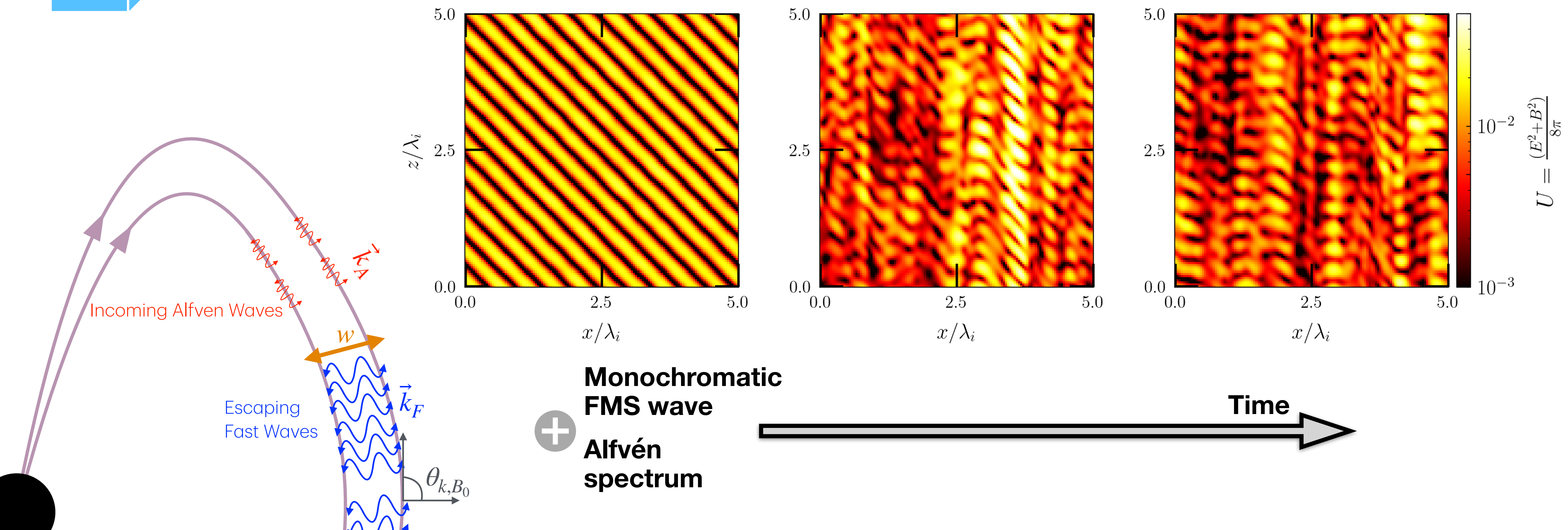
Modeling FRB propagation as force-free weak turbulence



Siddhant Solanki

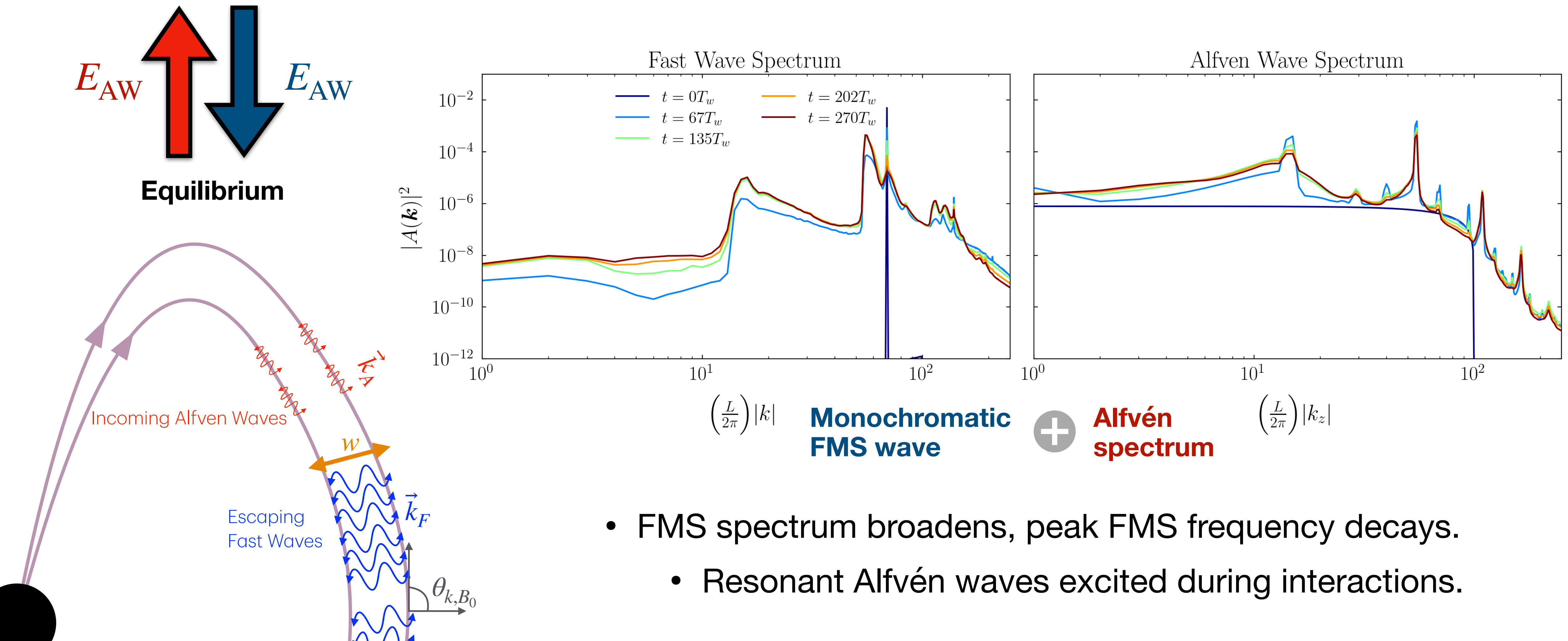


3D simulations of a **local** setup—we initialize relevant modes and let them interact during many dynamics times.



FRBs escape from inner magnetosphere

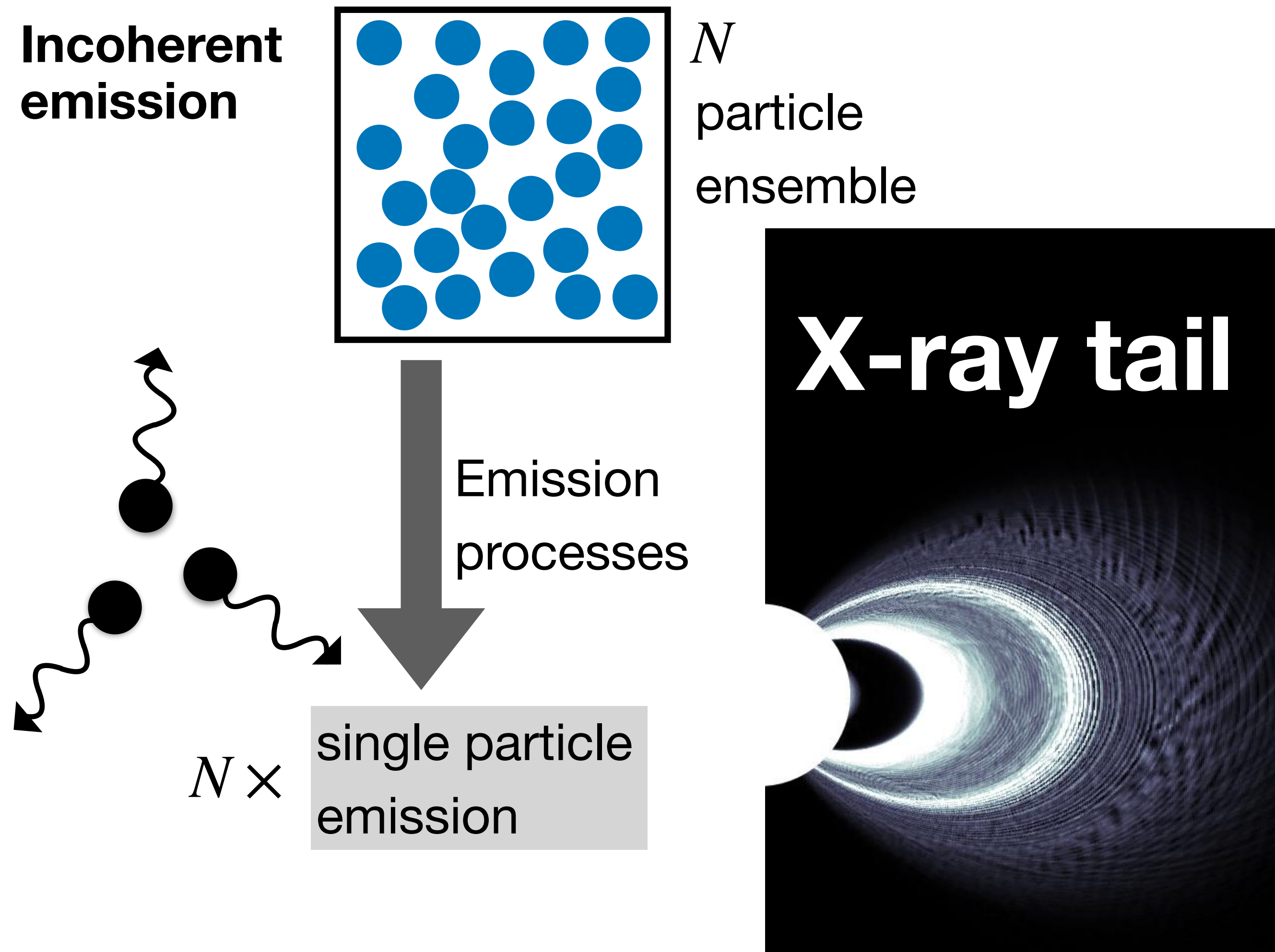
Modeling FRB propagation as force-free weak turbulence



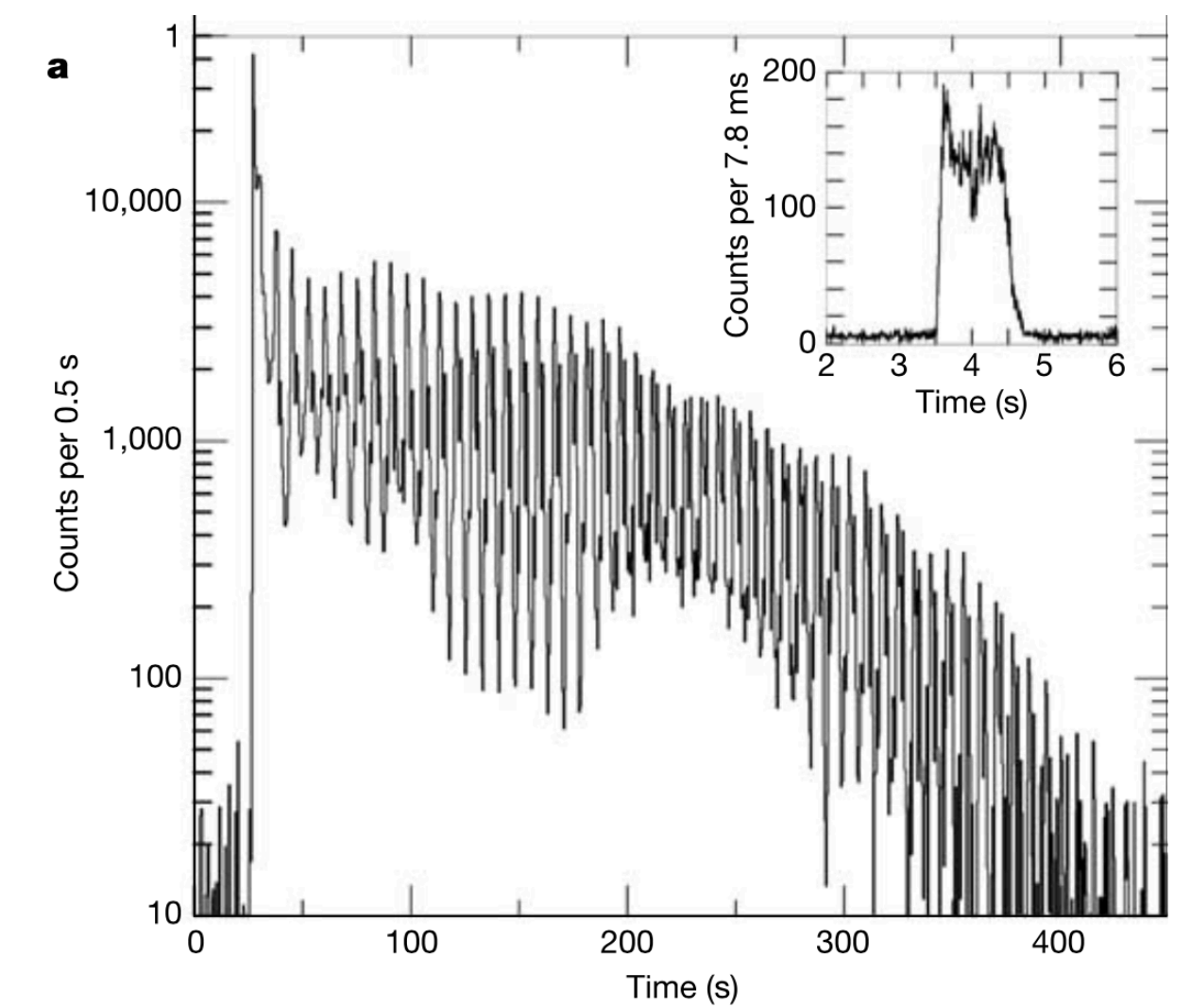
- FMS spectrum broadens, peak FMS frequency decays.
- Resonant Alfvén waves excited during interactions.

Magnetars and their persistent emission

Where does plasma in magnetar magnetospheres come from?

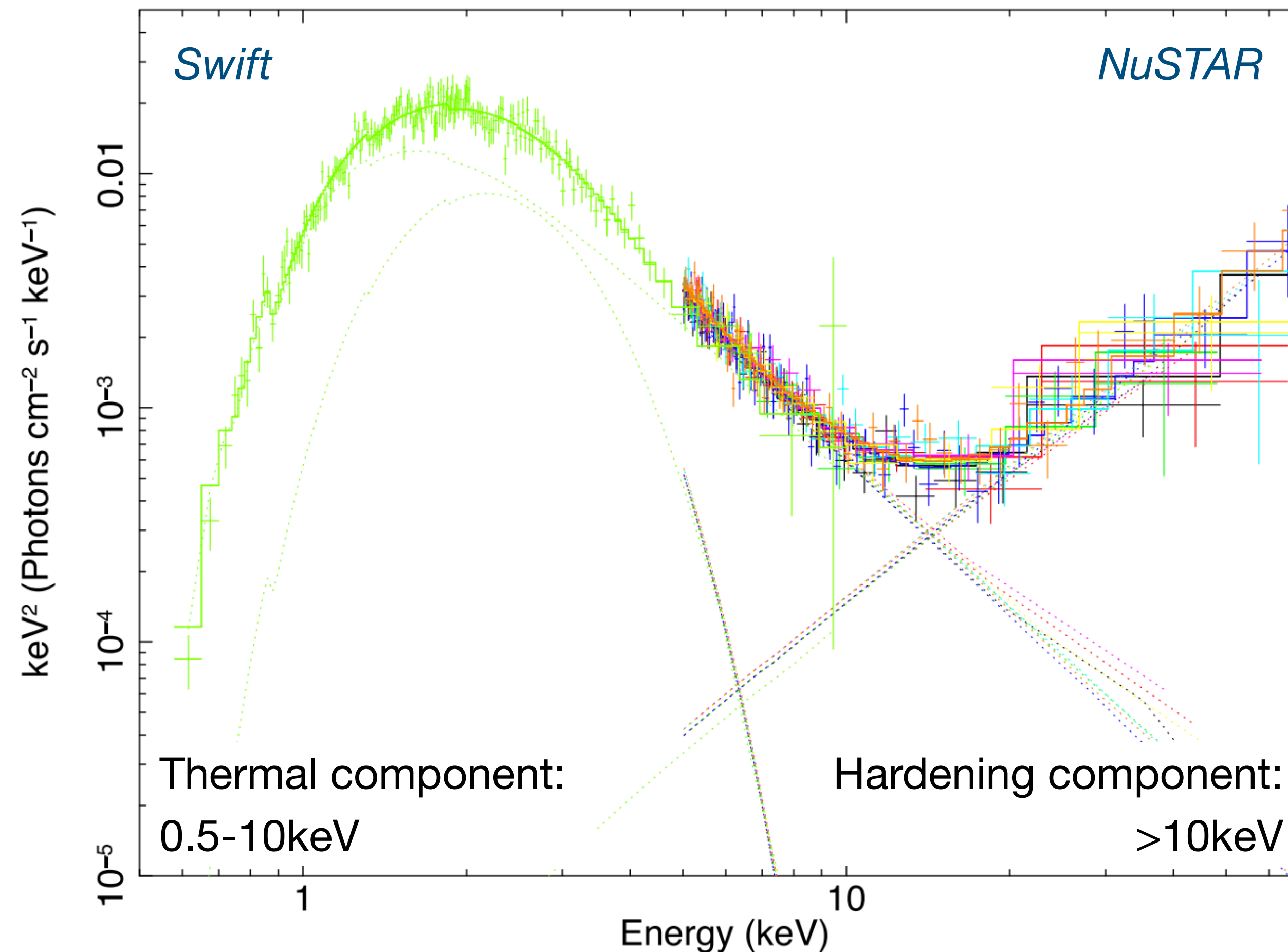


Rich set of X-ray
bursts and activity



We want to explain hard X-ray spectra

Understand magnetar magnetospheres from persistent emission

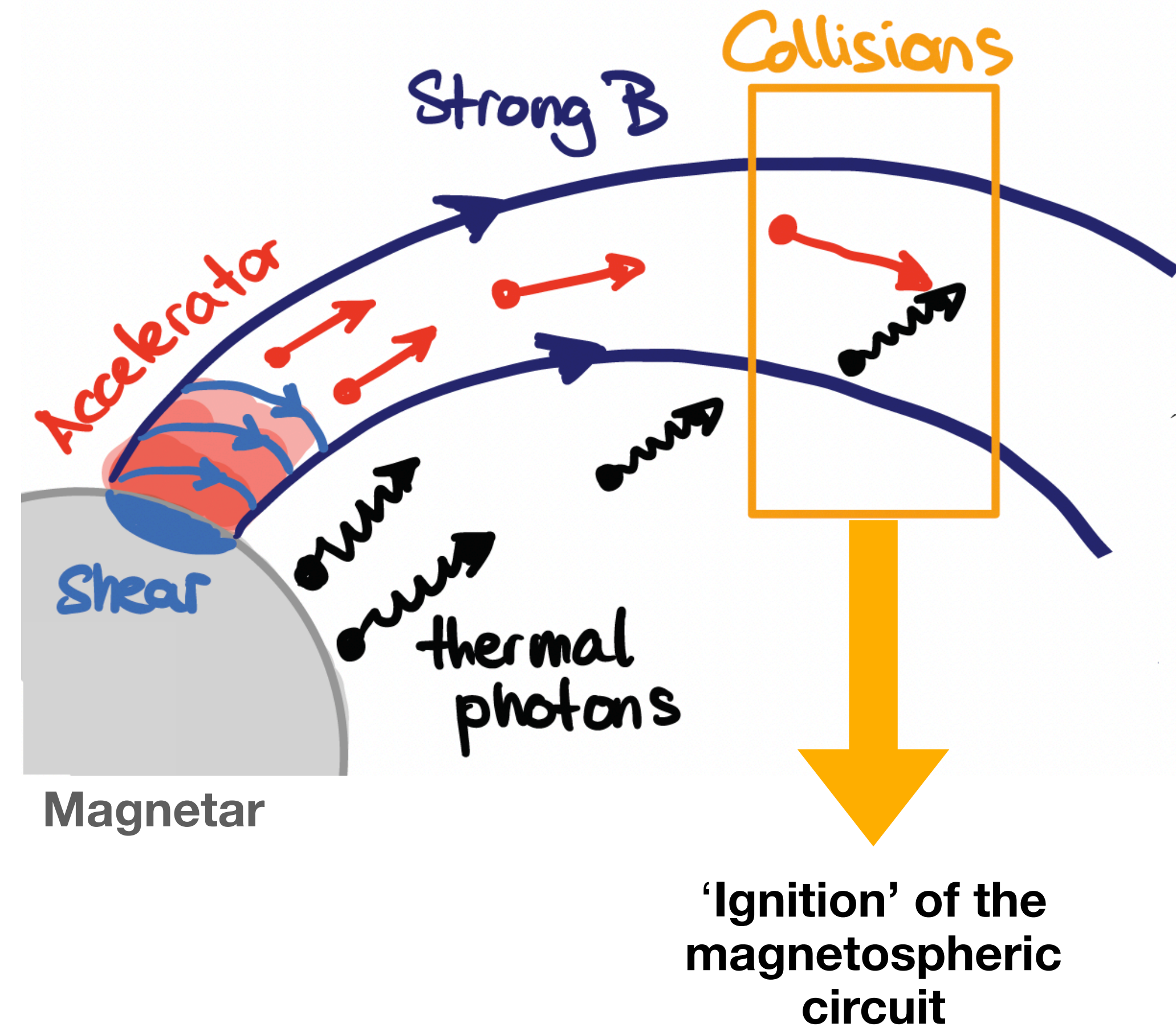


The plasma supply of magnetar magnetospheres

Providing the first fully consistent QED-PIC description

Q: How do magnetar magnetospheres fill with plasma?

Nobody ever modeled a global non-linear magnetospheric model of the **extreme QED-plasma interactions**.



$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}$$

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Magnetospheric twist has to be **supported by a current.**

$$\mathbf{J}_s = q_s \times n_s \times v_s$$

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Twist induced current Is regulated by **balancing plasma density and velocity.**

Depends on
acceleration kinetics
and QED reactions!

$\mathbf{J}_s$

=

$q_s \times n_s \times v_s$

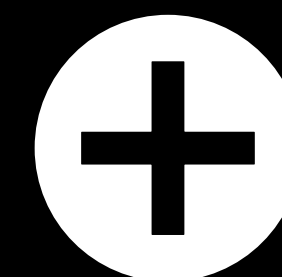
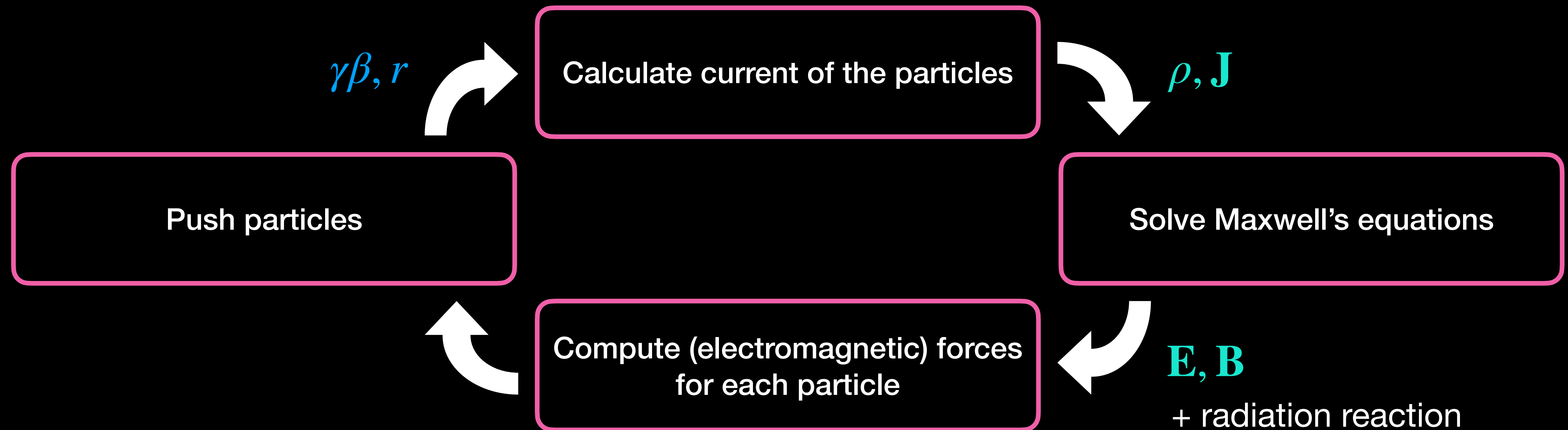
Twist induced current

Is regulated by

balancing plasma
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Capturing collisionless plasma kinetics

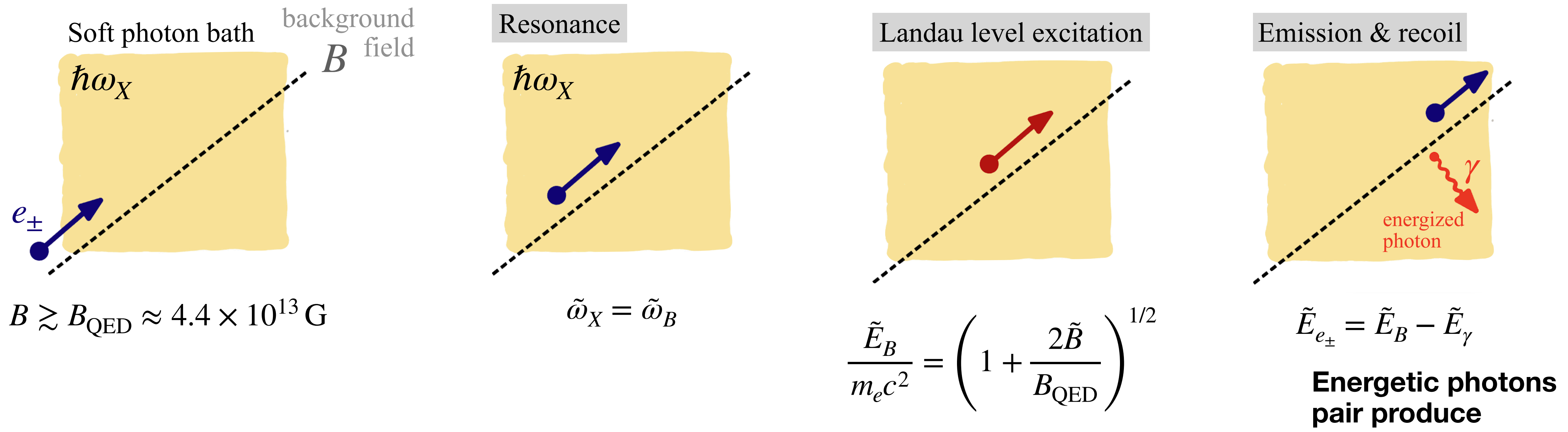
Particle-in-cell (PIC) simulations for first-principle plasma dynamics



Additional modifications for extreme plasma densities and velocities.

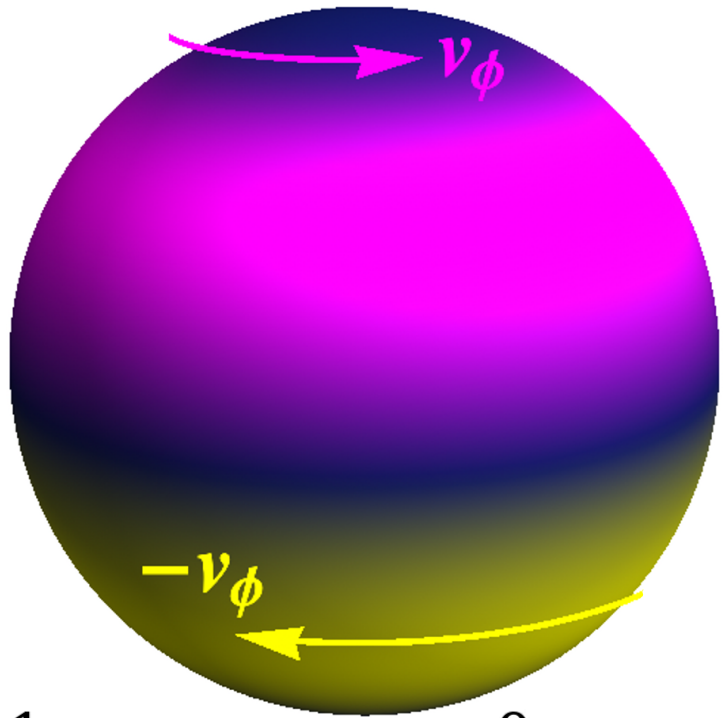
Pair production in ultra-magnetized plasmas

Fast leptons at Landau resonance: de-excitation photons pair-produce

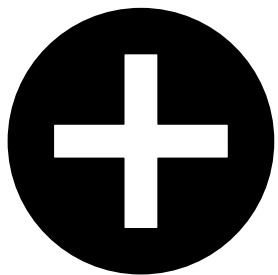


First first-principle models of magnetar plasma

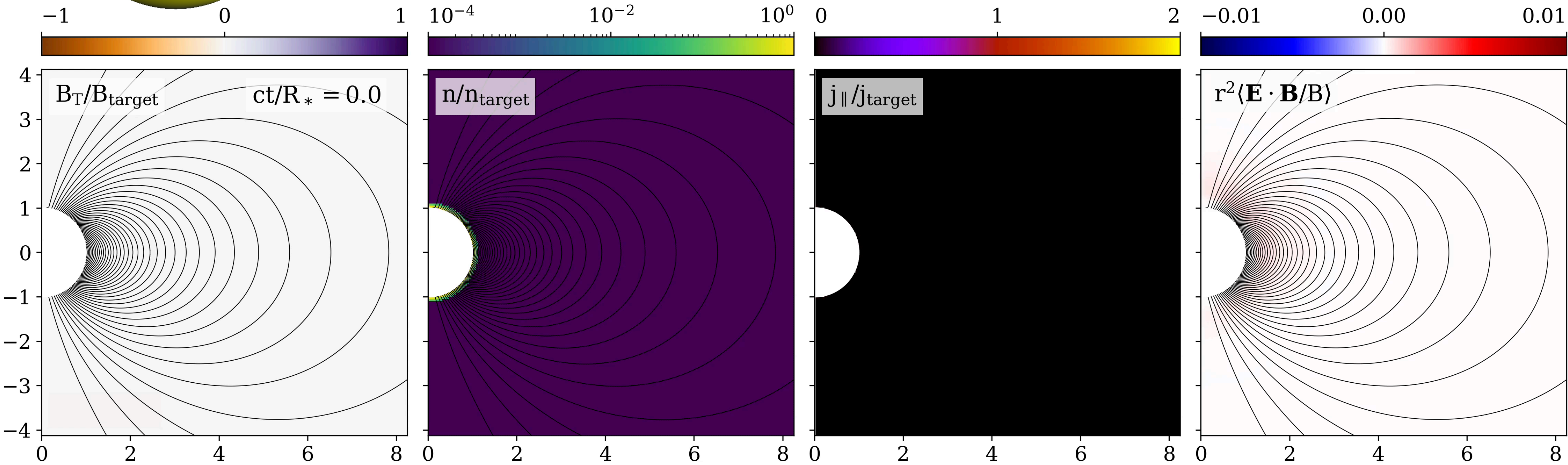
Resonant scattering, different photon polarization and pair production



Shearing a dipole field by moving field lines across the magnetar surface in axisymmetry.

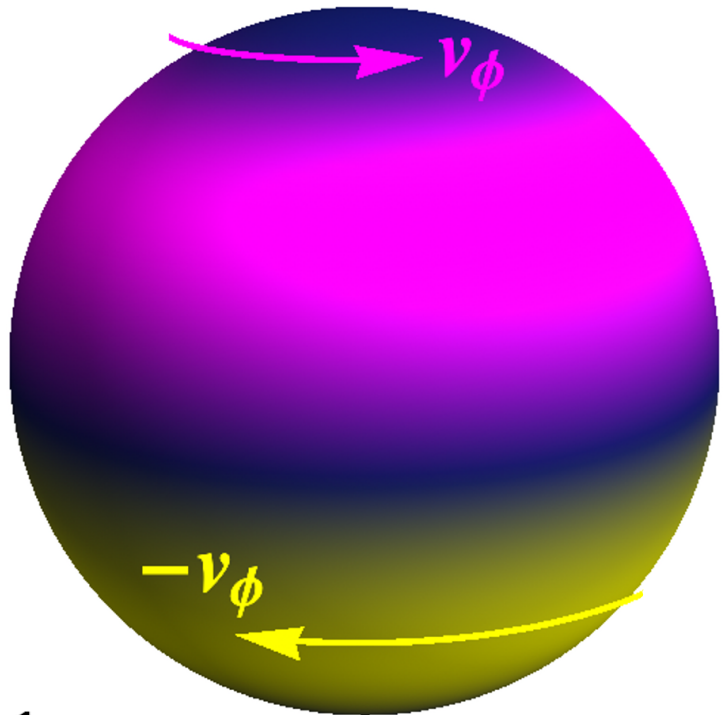


Resonant scattering of **2 keV** thermal photons.

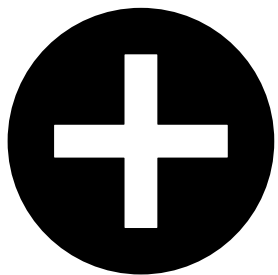


First first-principle models of magnetar plasma

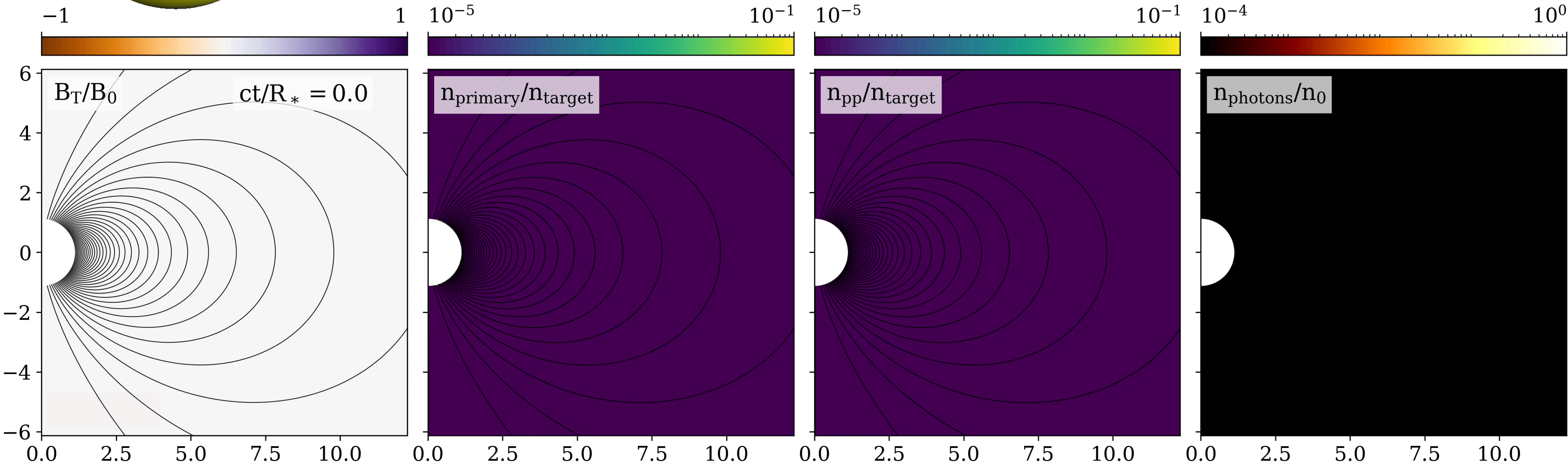
Resonant scattering, different photon polarization and pair production



Shearing a dipole field by moving field lines across the magnetar surface in axisymmetry.



Resonant scattering of **2 keV** thermal photons.



Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

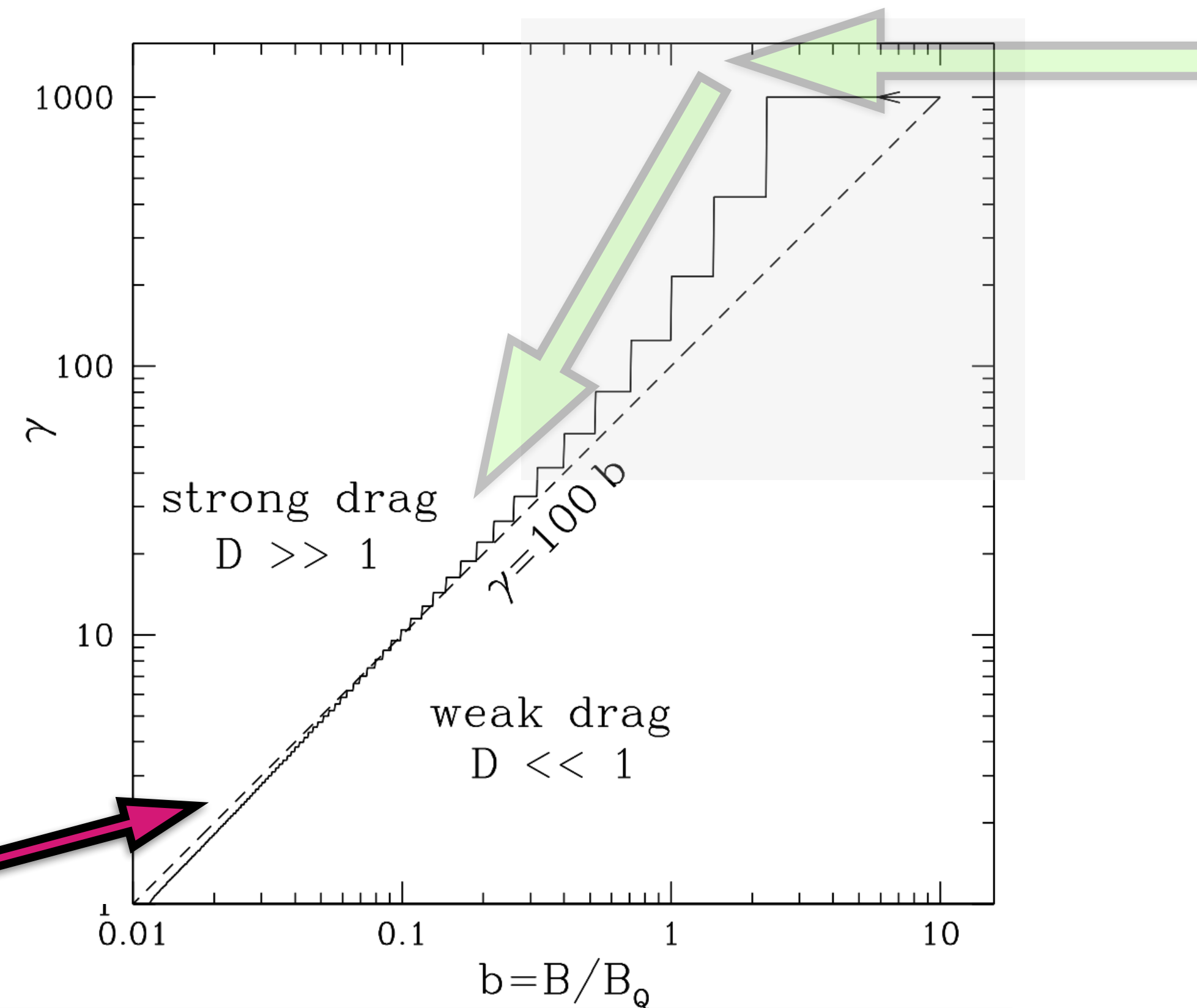
Scattering rate:

$$\dot{N}_{\text{sc}} = \frac{\pi r_e c}{\lambda^2 \gamma} \int d\Omega \left[\frac{\hbar \omega_X}{m_e c^2} \right]^2 \frac{1}{\exp \left[\frac{\hbar \omega_X}{k_B T} \right] - 1}$$

Resonance condition:

$$\omega_X = \frac{\tilde{\omega}_X}{\gamma(1 - \beta\mu)} = \frac{B/B_{\text{QED}}}{\gamma(1 - \beta\mu)} \frac{m_e c^2}{\hbar}$$

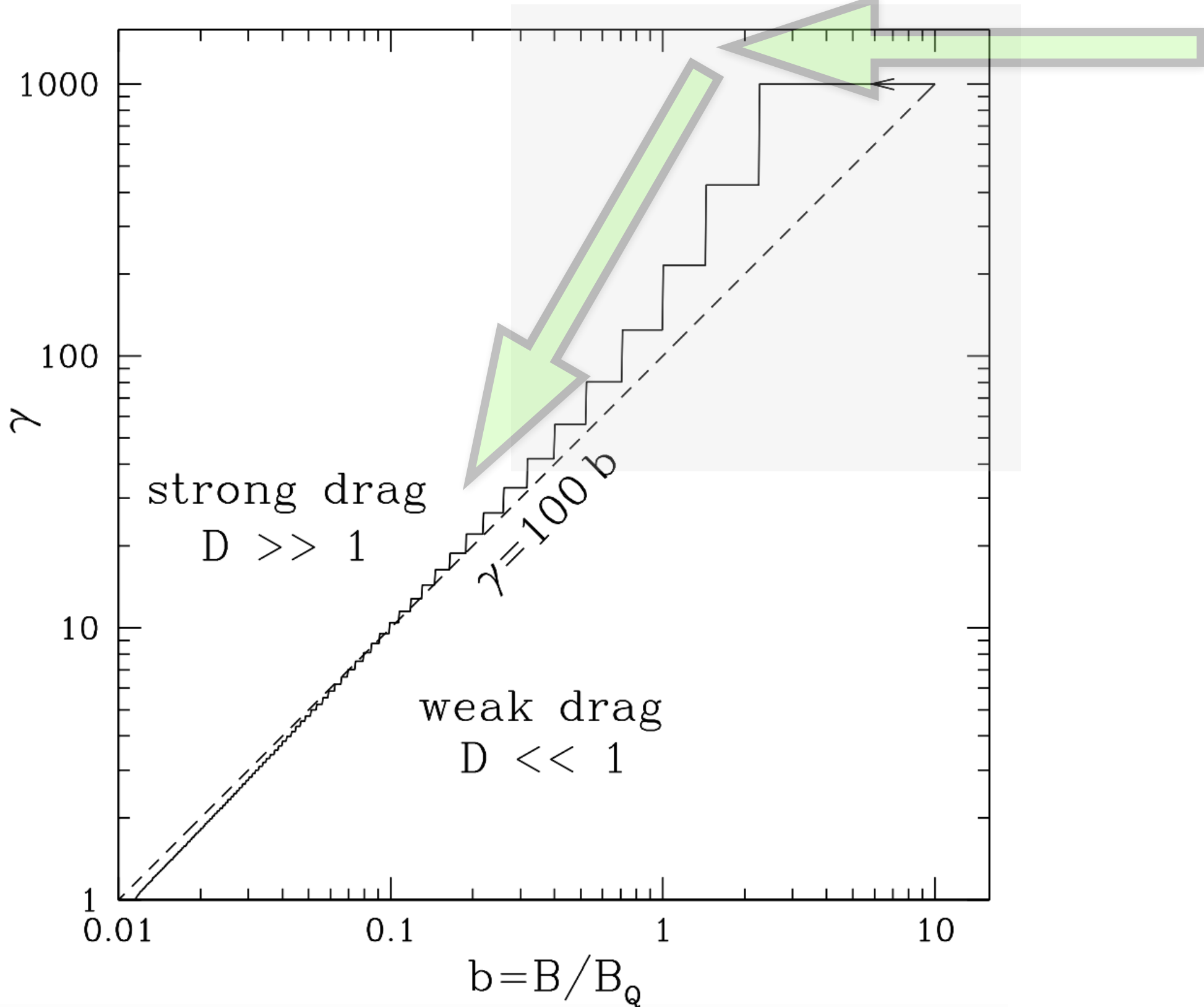
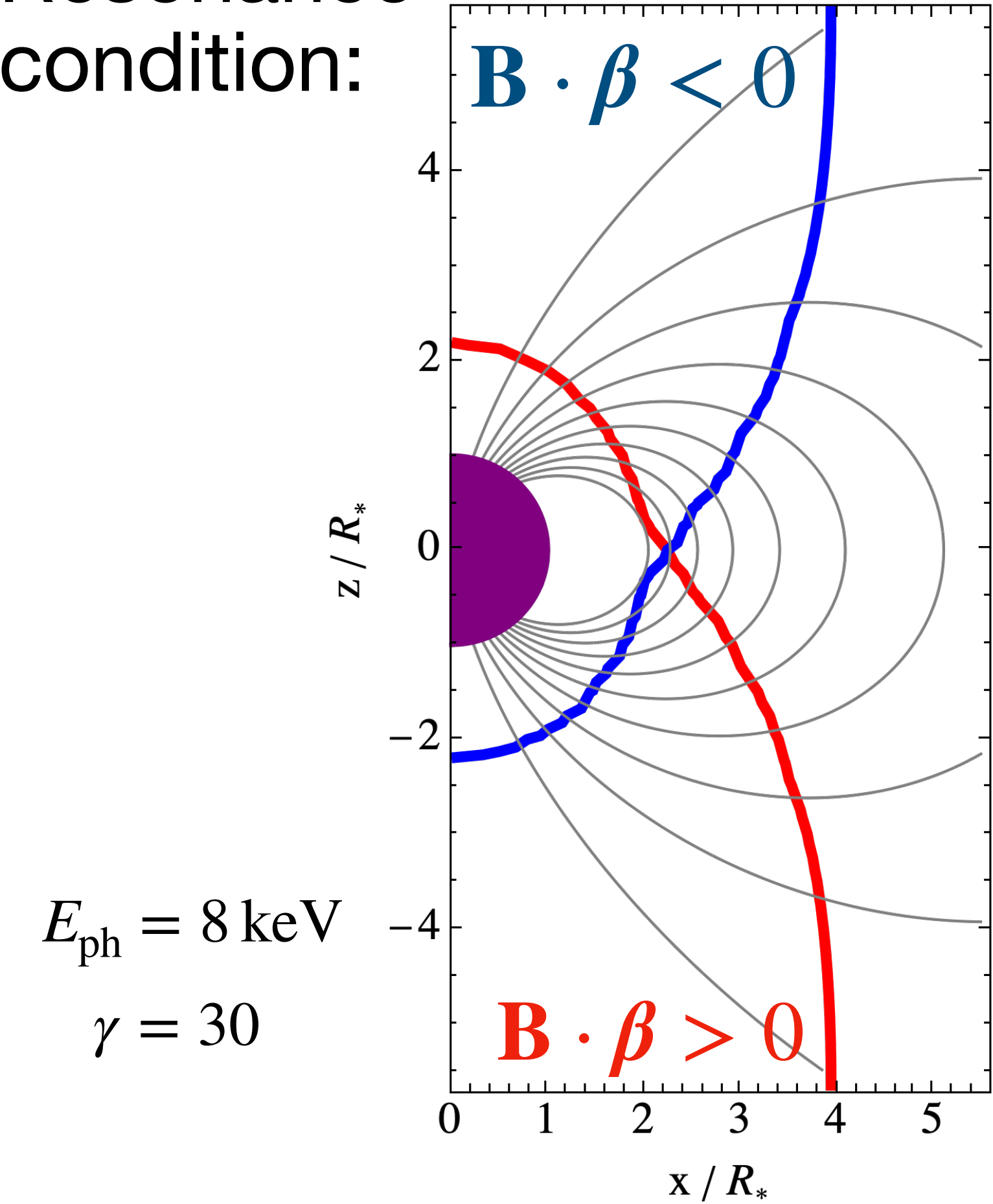
**'Surfing
curve'**



Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

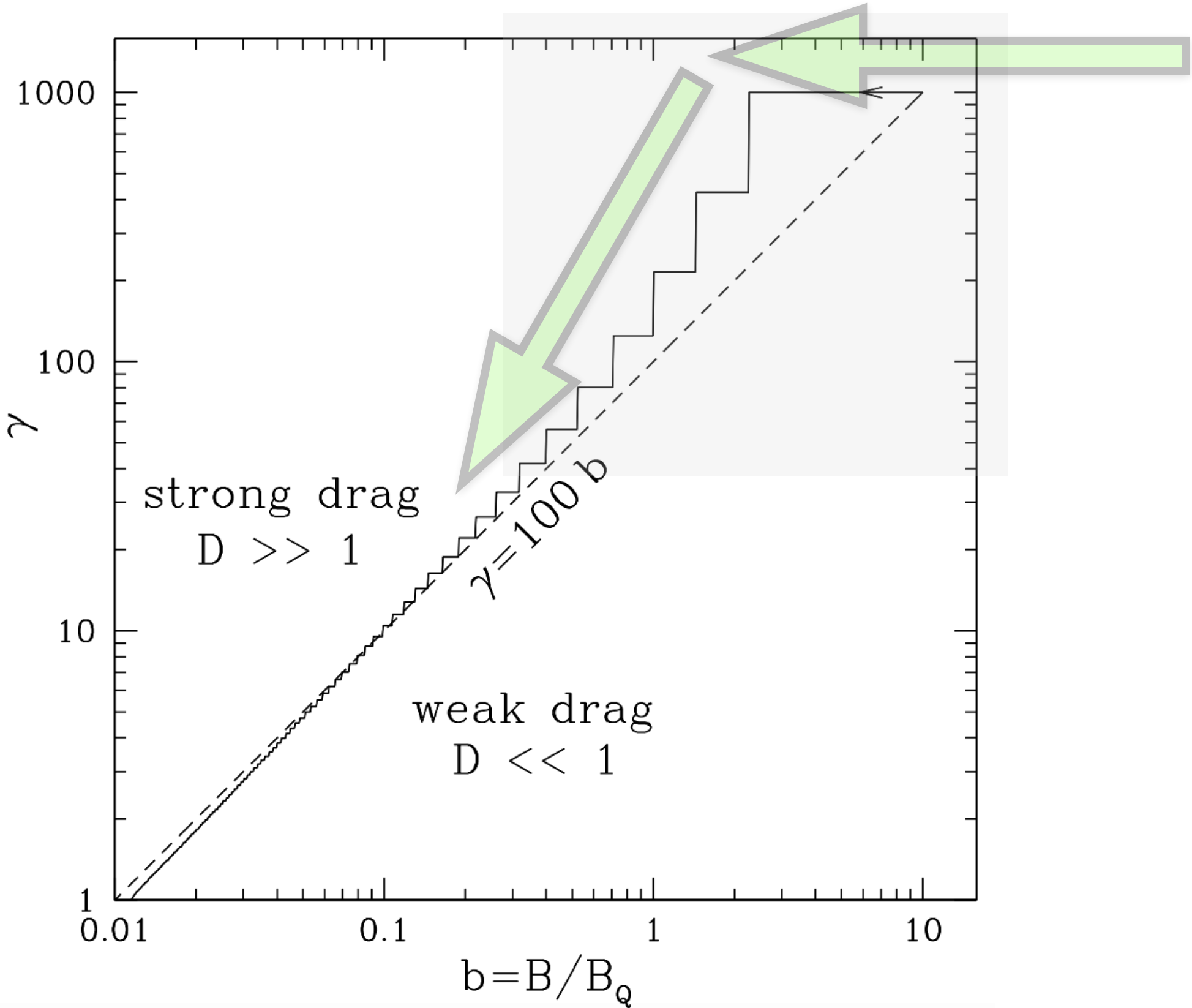
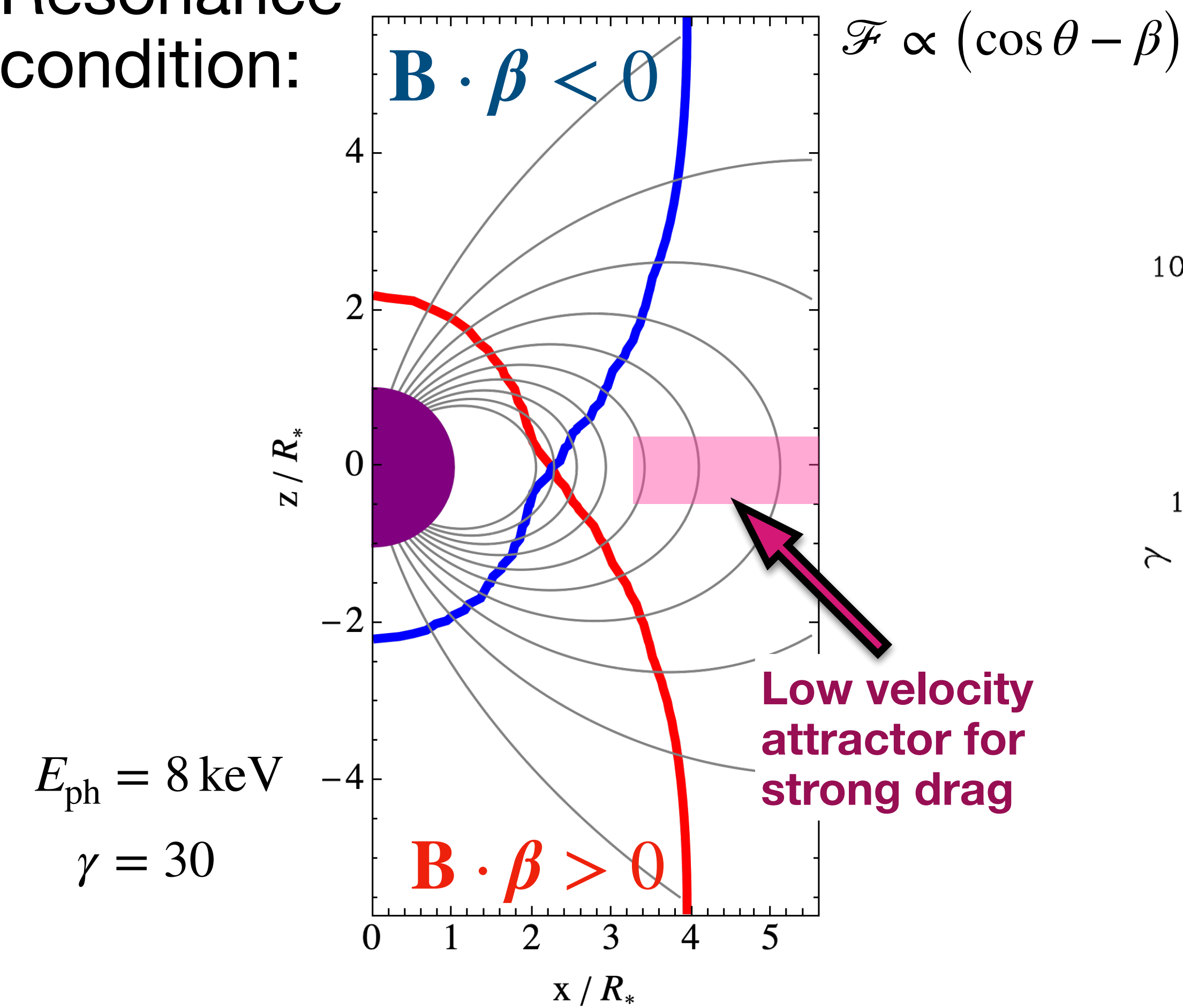
Resonance
condition:



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Acceleration and deceleration with sufficient pair production

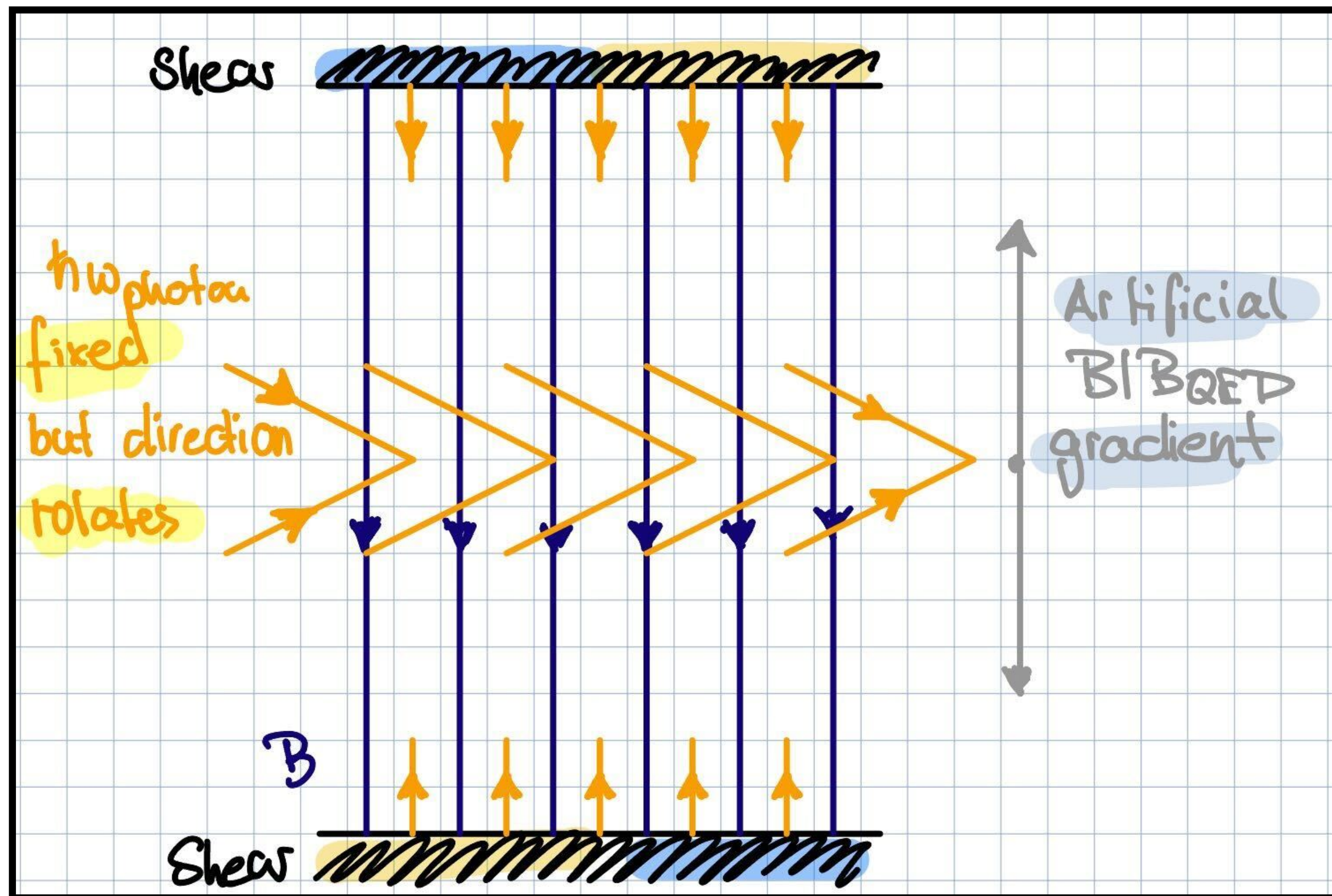
Resonance condition:



Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

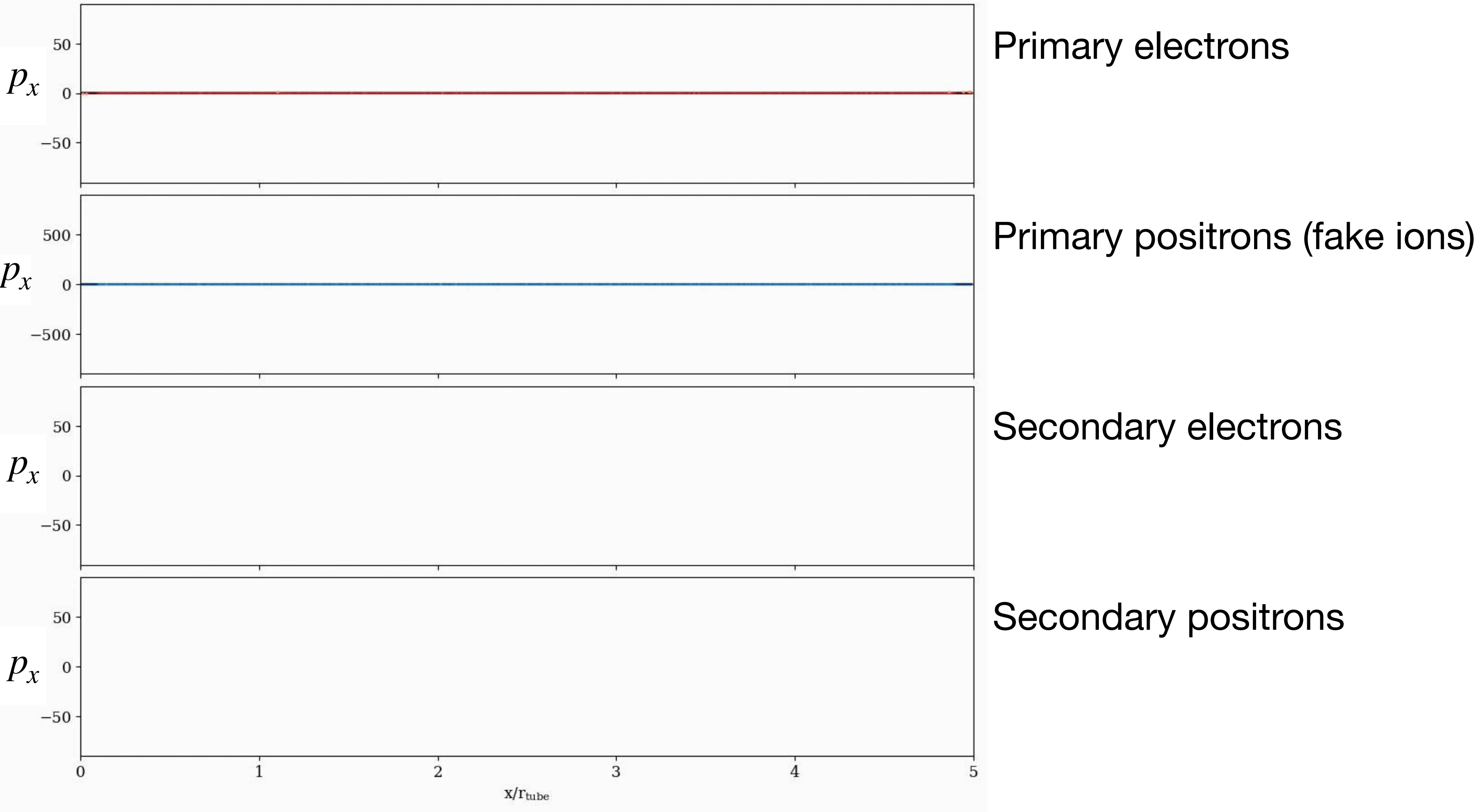
1D toy model set-up or faking physics for efficiently



We use a scattering kernel that sees a different magnetic field and an artificial photon bath.

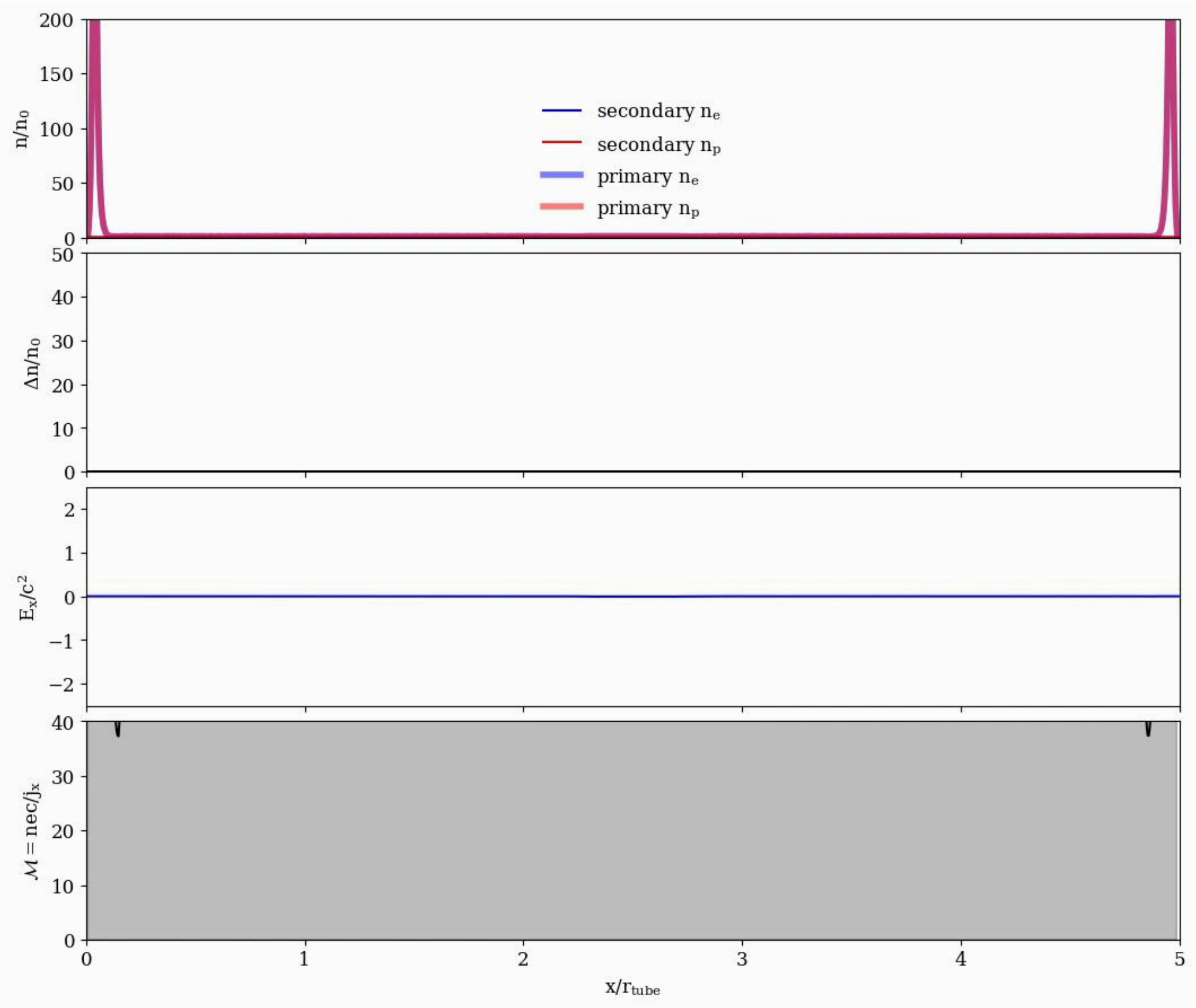
Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production



Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production



Density

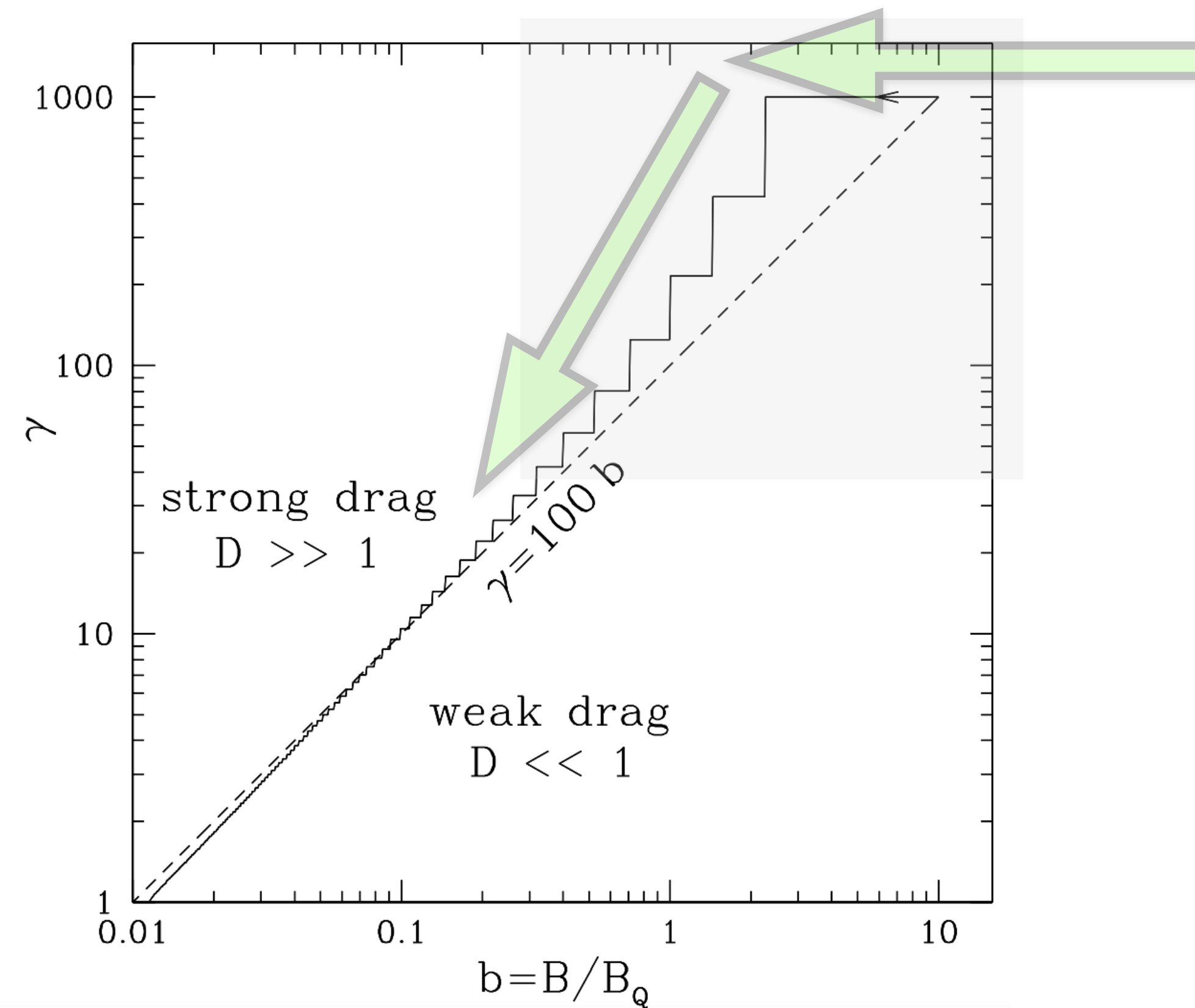
Pair creation rate

Parallel electric fields

Multiplicity

Radiative kinetics of the magnetar circuit

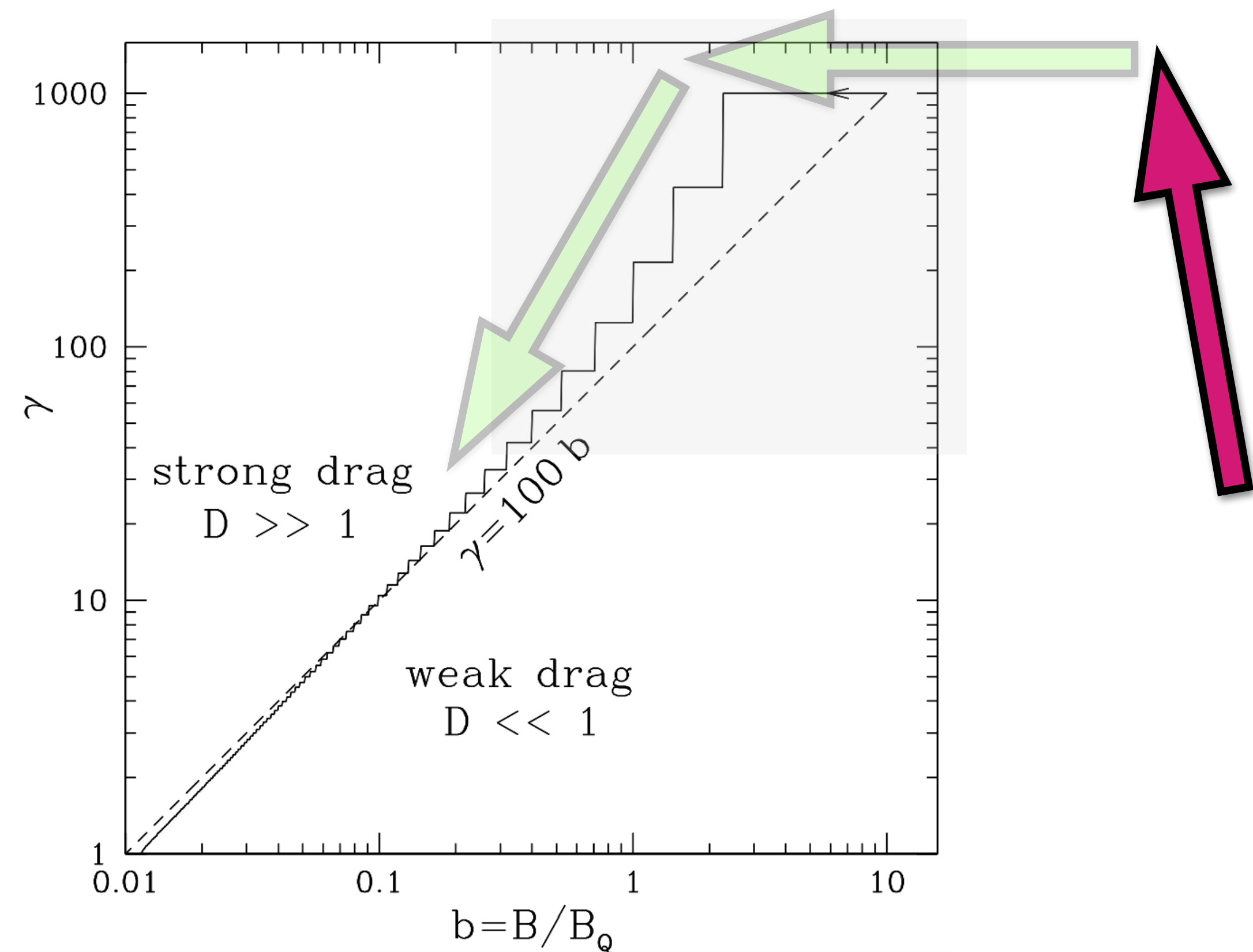
Acceleration and deceleration with sufficient pair production



Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

Q: How to make γ large?



Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

From reference without radiation:

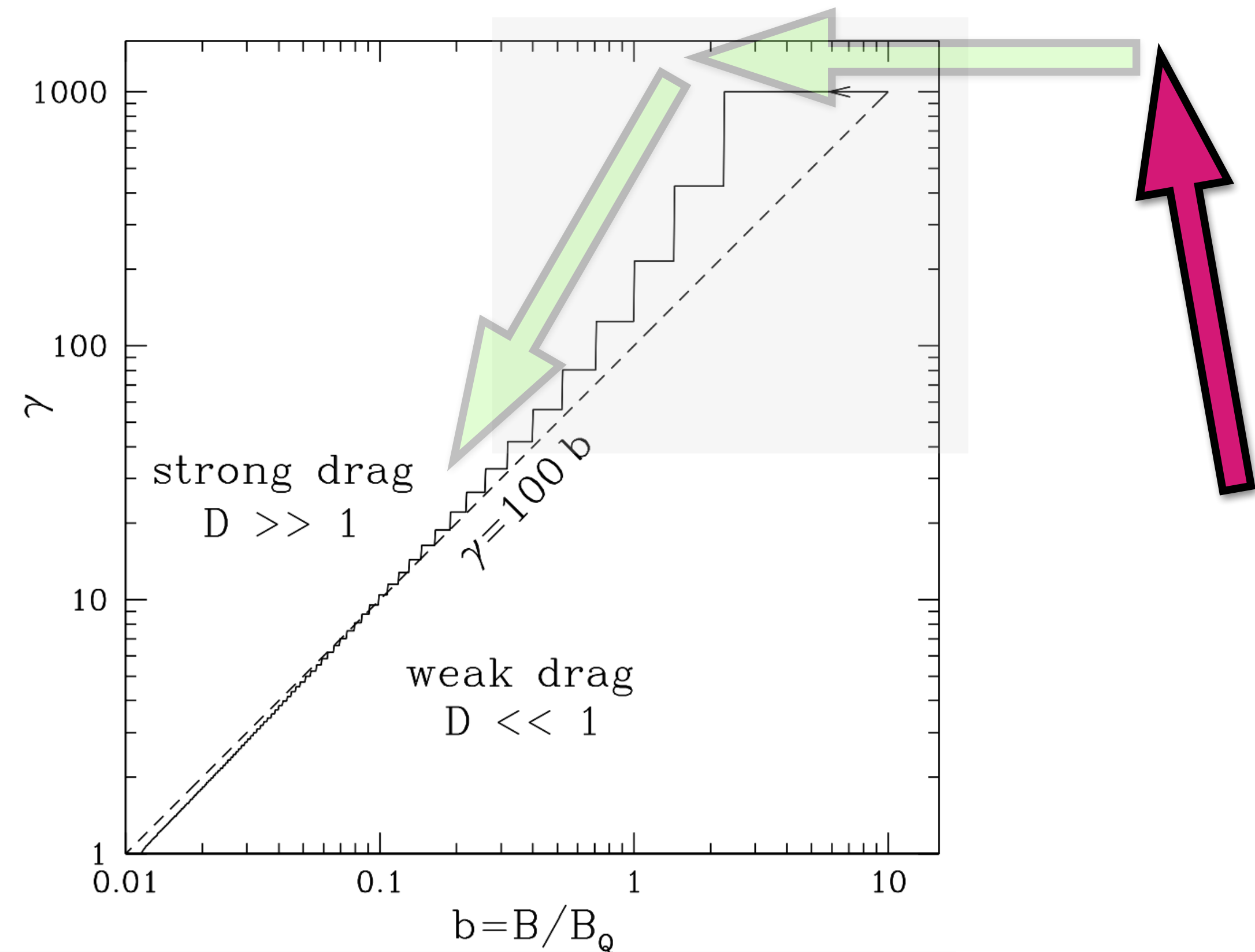
Double layer potential

$$\gamma_{\text{circuit}} = V_{\text{circuit}} \left(\frac{e}{m_e c^2} \right)$$

$$\approx \frac{L_0}{d_0} \left(\frac{j}{n_0 e c} \right)^{1/2}$$

L_0 : Layer length

d_0 : Fiducial skindepth

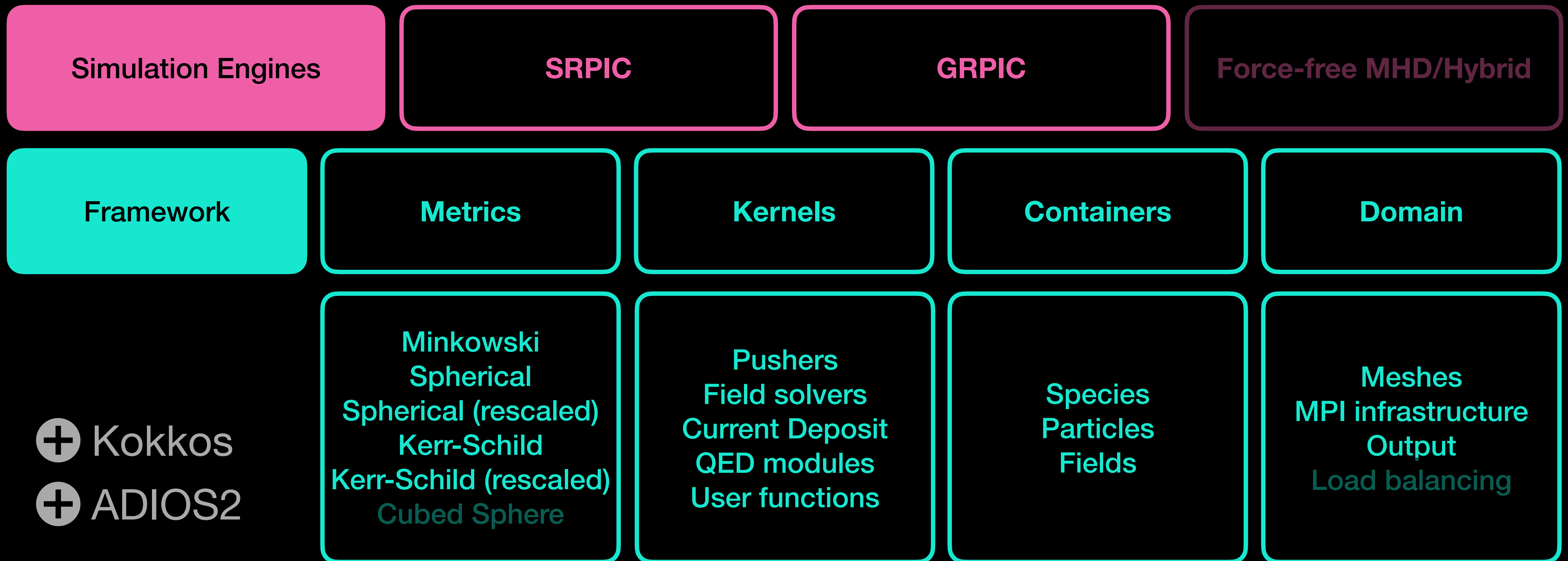


Extreme plasma processes around compact objects

1. We differentiate coherent and incoherent radiative plasma processes.
2. Magnetospheric and kinetic instabilities interact to produce burst dynamics through dissipative processes and radiation mechanisms.
3. We're developing a first-principles simulation of magnetar radiation in equilibrium, combin fundamental physics with circuit modeling.
4. Let's discuss how creating reliable models is far more challenging than our polished slides might suggest!

Entity is templated for versatility

One framework supports various plasma physics applications



The entity framework is compiled, the user only interfaces a problem generator!