Title: Modeling X-ray emission in radiation-rich magnetar magnetospheres

Speakers: Jens Mahlmann

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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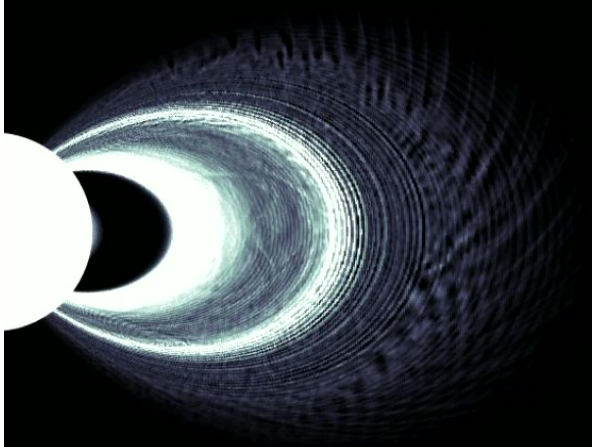
Abstract:

Neutron star magnetospheres are a source of abundant X-ray activity. They have transients observed in different bands, like the fast radio burst (FRB) and associated hard X-ray flare from the Galactic magnetar SGR 1935+2154. We present global models for magnetar X-ray emission, including a landmark first-principle radiative particle-in-cell simulation of the twisted magnetar magnetosphere with the GPU-PIC code Entity. In one scenario, plasma particles accelerated by surface-motion-induced discharges interact resonantly with thermal background photons. Our GPU-accelerated particle-in-cell simulations track up-scattered high-energy photons that drive secondary pair production and ignite a magnetospheric circuit that persistently generates X-rays. We divulge the plasma properties of such a magnetospheric circuit, including densities and velocities, and give an outlook on alternative ignition scenarios for persistent magnetar X-ray emission.

Modeling X-ray emission in radiation-rich magnetar magnetospheres

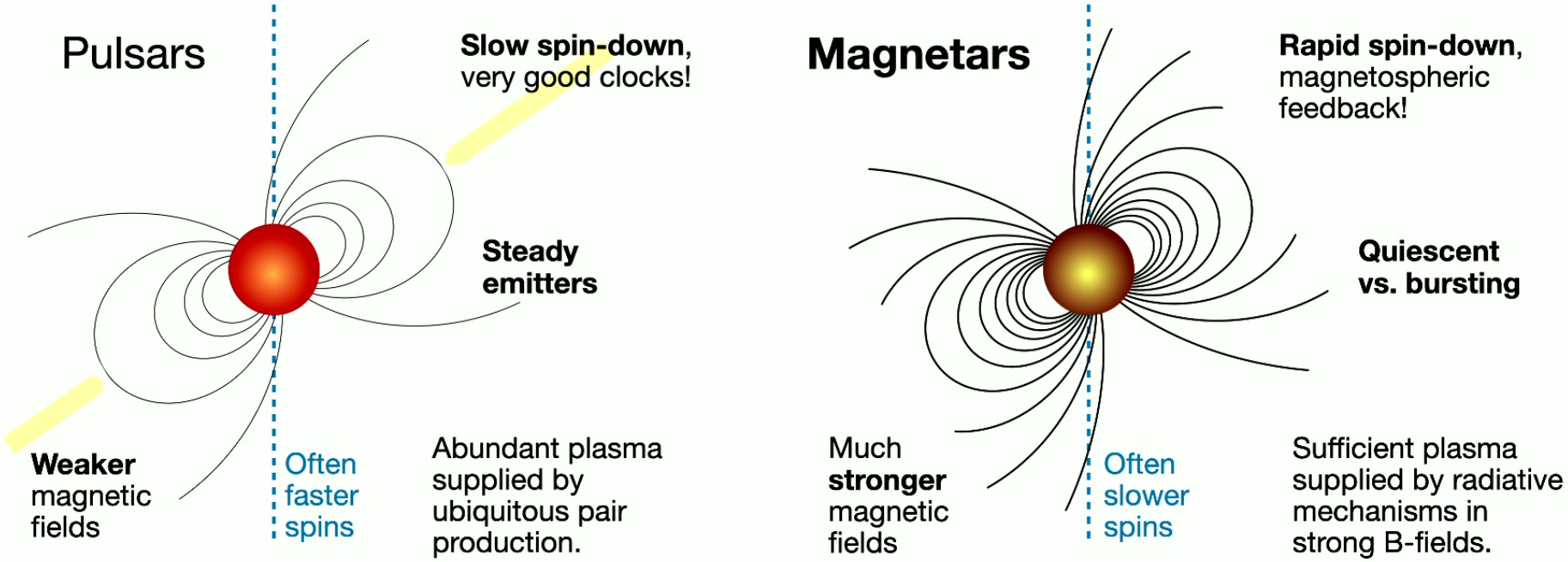


Jens Mahlmann (Dartmouth College)

with Alexander Philippov, Muni Zhou, Hayk Hakobyan, Andrei Beloborodov, Lorenzo Sironi, and Alexander Chernoglazov

Magnetars are unique plasma labs

Strong magnets with energetic X-ray and radio emission

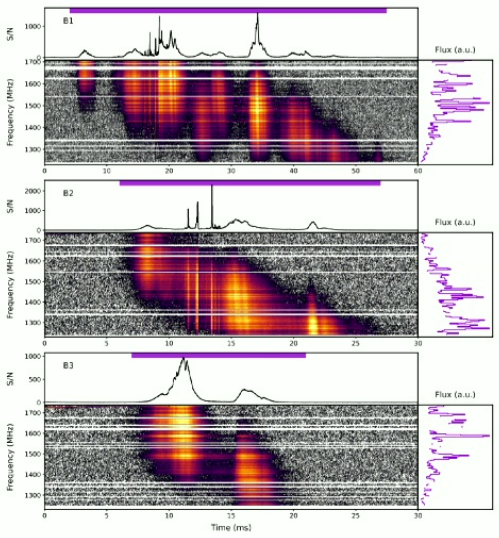


Di Salvo et al. (2021); Hurley et al. (2005); Ravi et al. (2023)

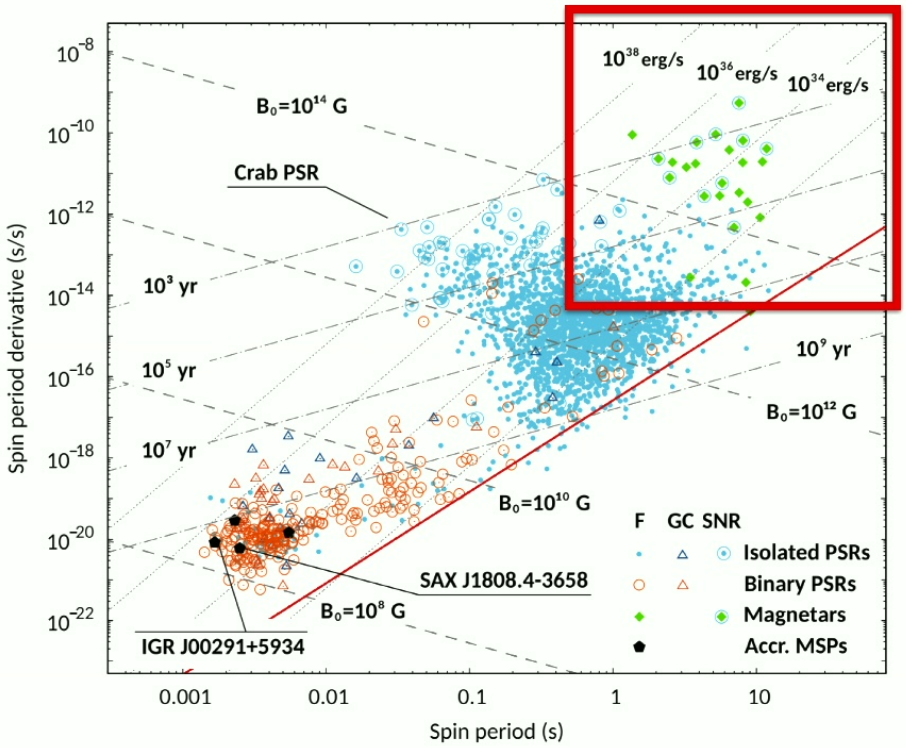
Magnetars and their transients

Bursty young ultra-magnetized neutron stars with long periods

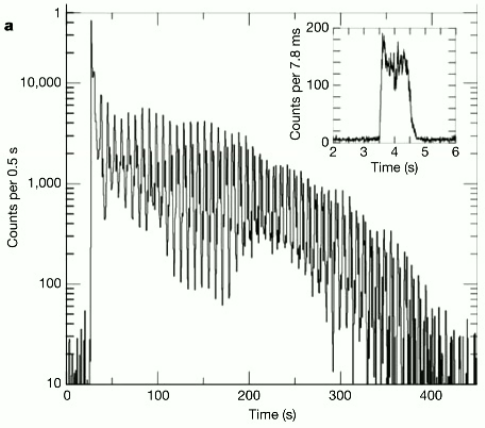
Are FRBs coming from magnetars? At least some.



What makes them?



Rich set of X-ray bursts and activity

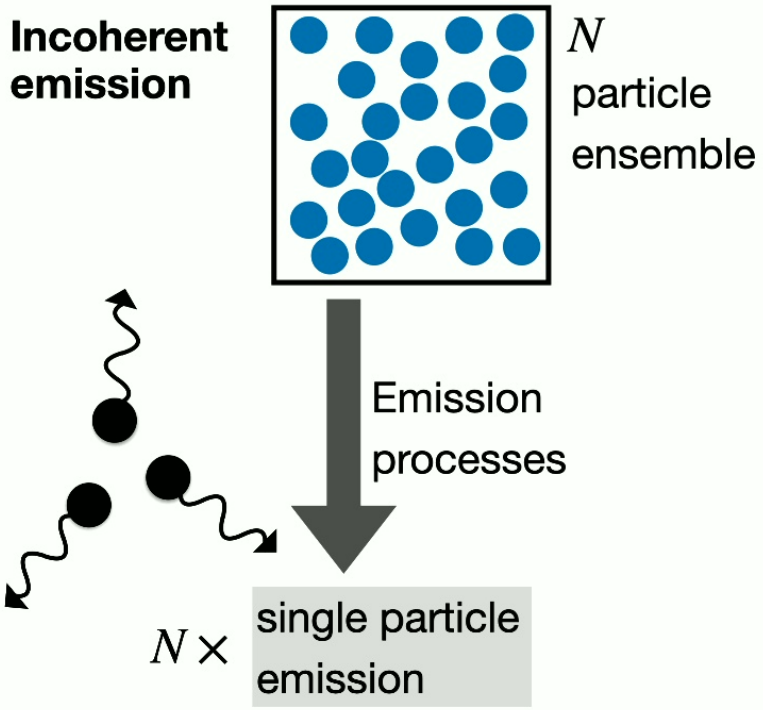


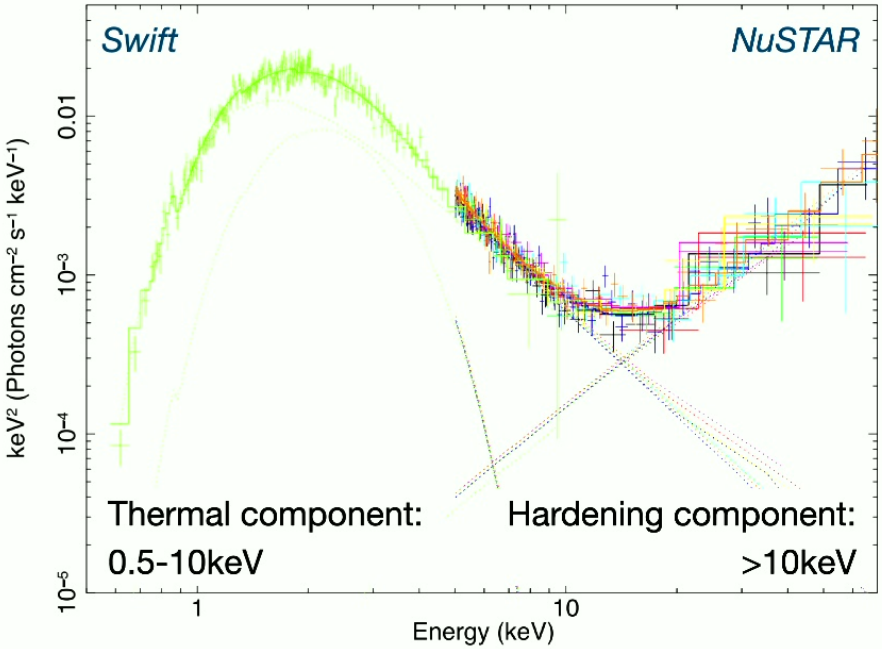
What makes them?

References: Vogel et al. (2014)

Persistent magnetar emission

Energetic photons via incoherent radiation processes





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

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

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

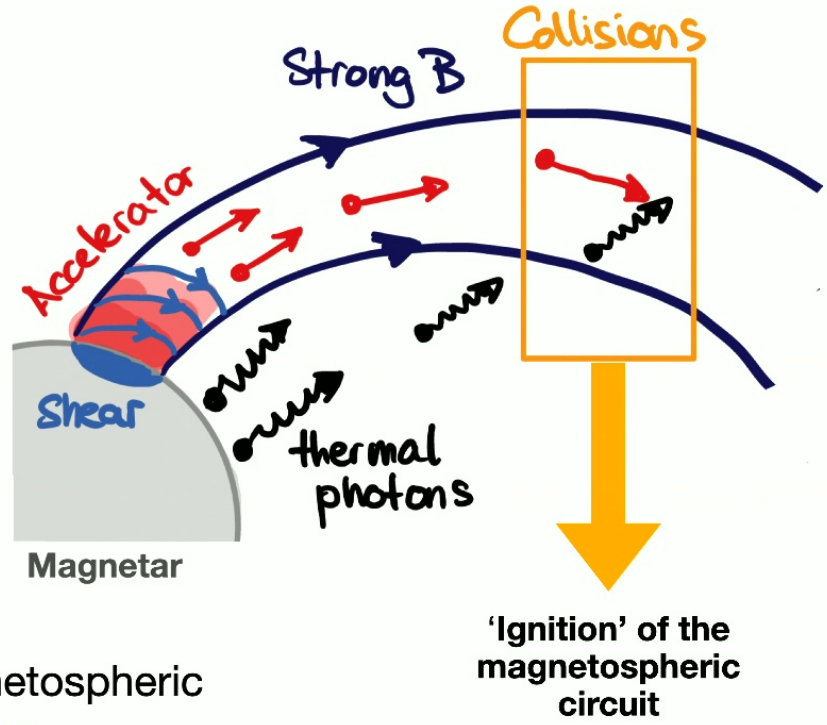
The plasma supply of magnetar magnetospheres

Providing the first fully consistent QED-PIC description

Q: How do magnetar magnetospheres fill with plasma?

Localized potentials accelerate particles in discharges.

Large-scale potentials drive twist dissipation.

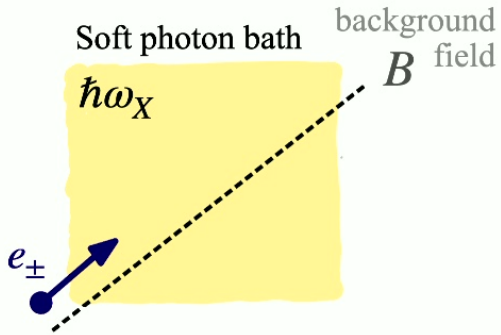


Nobody ever modeled a global non-linear magnetospheric model of the **extreme QED-plasma interactions**.

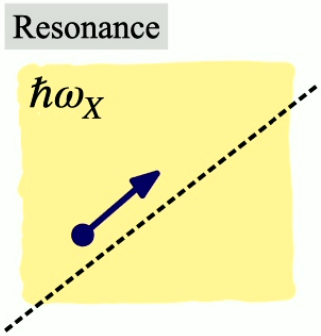
References: Beloborodov & Thompson (2007)

Pair production in ultra-magnetized plasmas

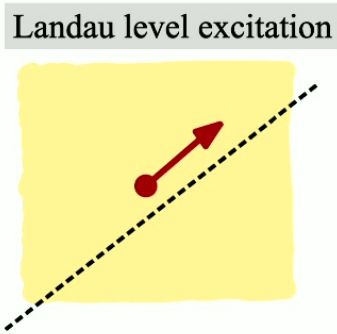
Fast leptons at Landau resonance: de-excitation photons pair-produce



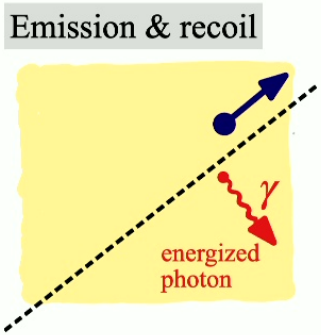
$$B \gtrsim B_{\rm QED} \approx 4.4 \times 10^{13}\,{\rm G}$$



$$\tilde{\omega}_X = \tilde{\omega}_B$$



$$\frac{\tilde{E}_B}{m_e c^2} = \left(1 + \frac{2\tilde{B}}{B_{\rm QED}}\right)^{1/2}$$



$$\tilde{E}_{e_\pm} = \tilde{E}_B - \tilde{E}_\gamma$$

Energetic photons pair produce

References: Beloborodov & Thompson (2007)

Radiative kinetics of the magnetar circuit

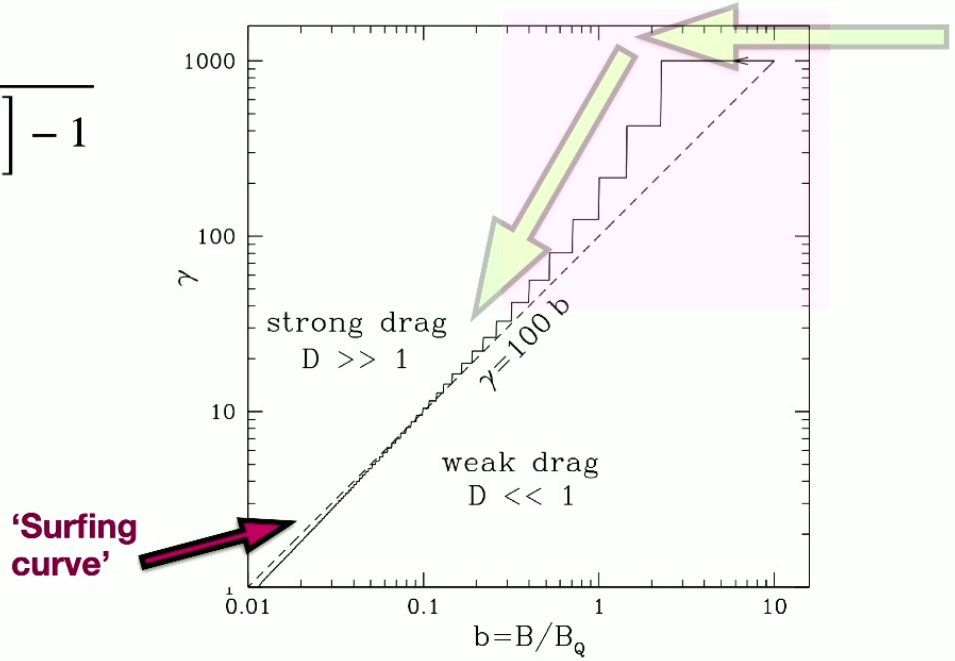
Acceleration and deceleration with sufficient pair production

Scattering rate:

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

Resonance condition:

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

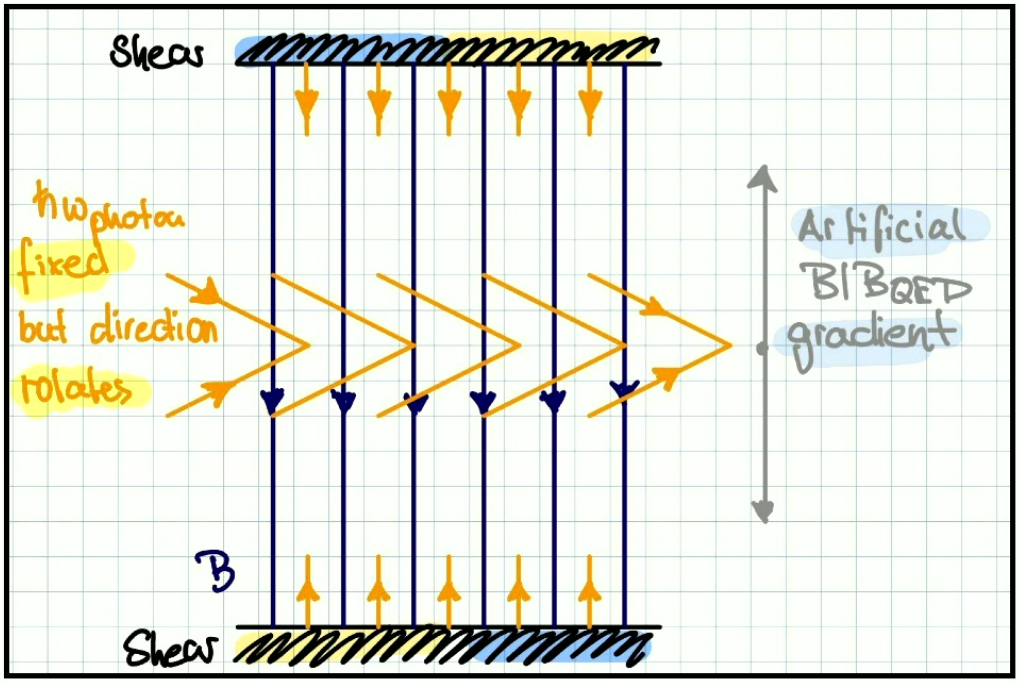


References: Beloborodov & Thompson (2007)

Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

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

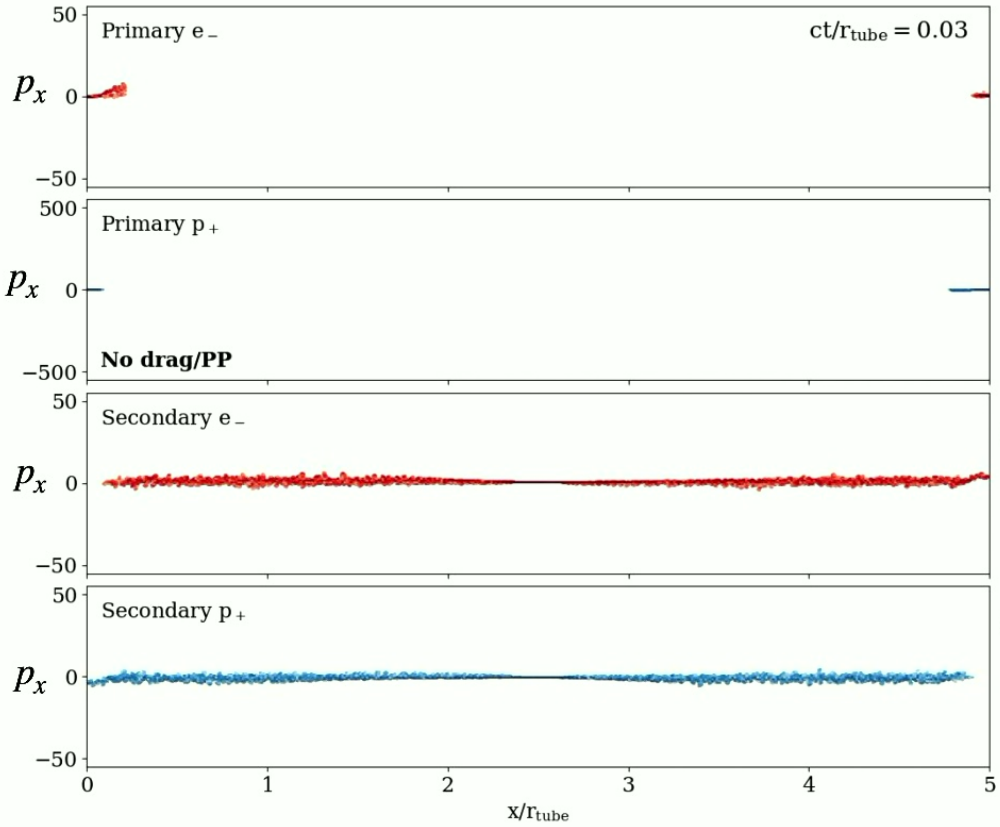


We use a scattering kernel that sees a different magnetic field and an artificial photon bath.

In 1D we use an external current j_0.

Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production



Primary electrons

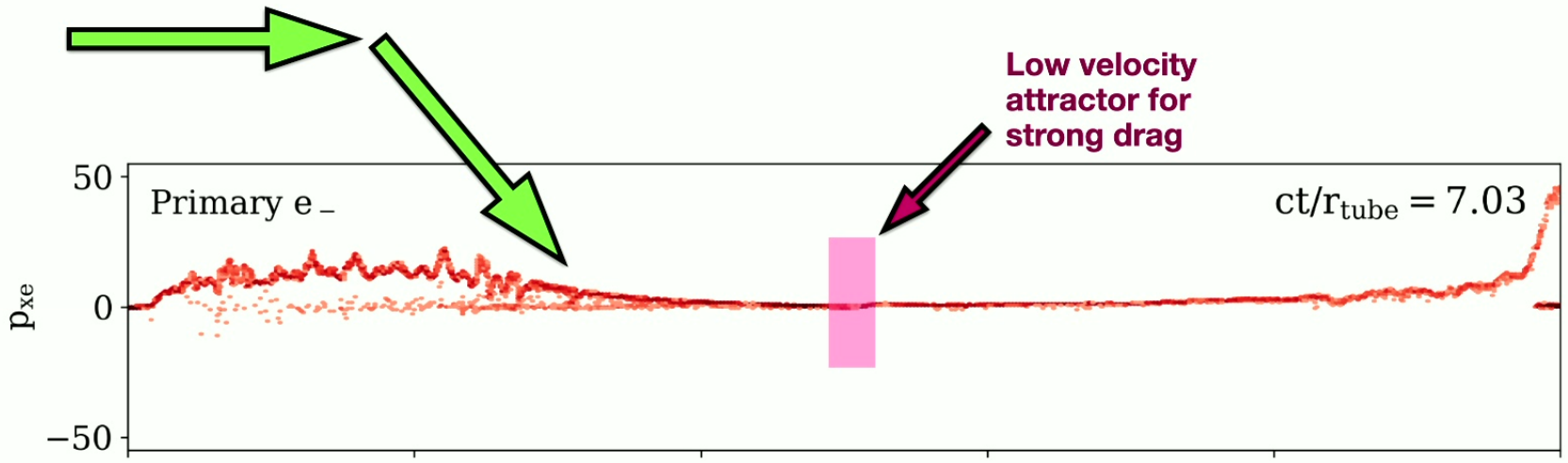
Primary positrons (fake ions)

Secondary electrons

Secondary positrons

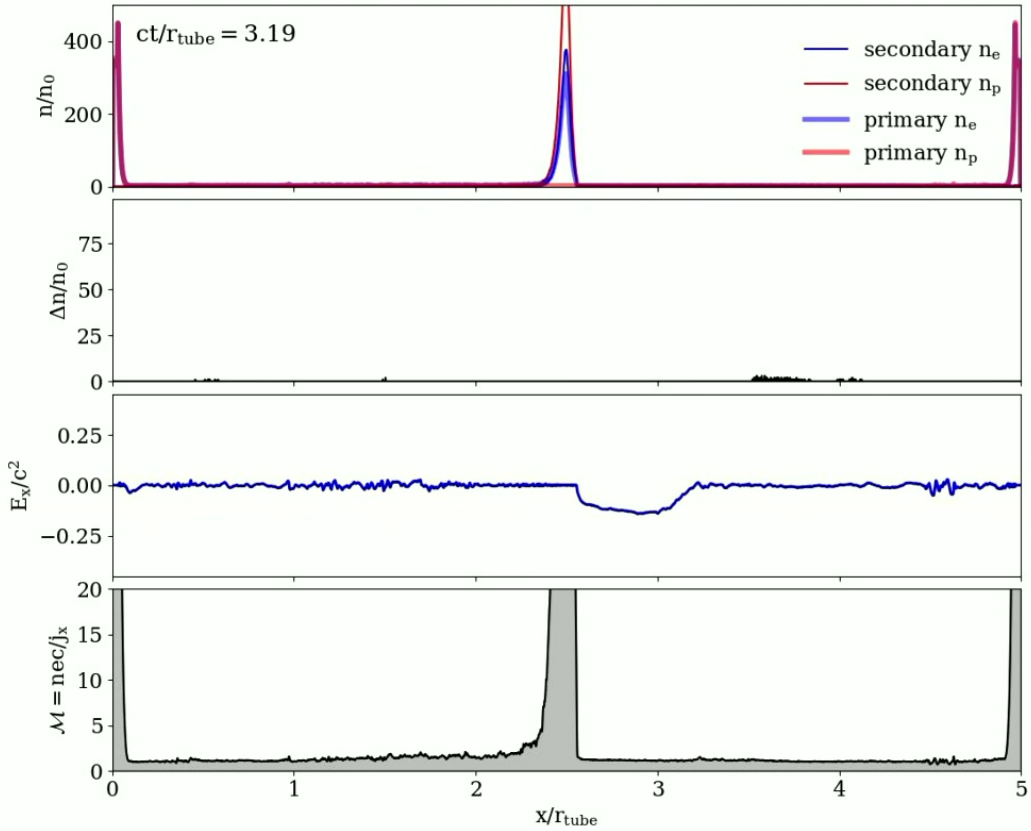
Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production



Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production



Density

Pair creation rate

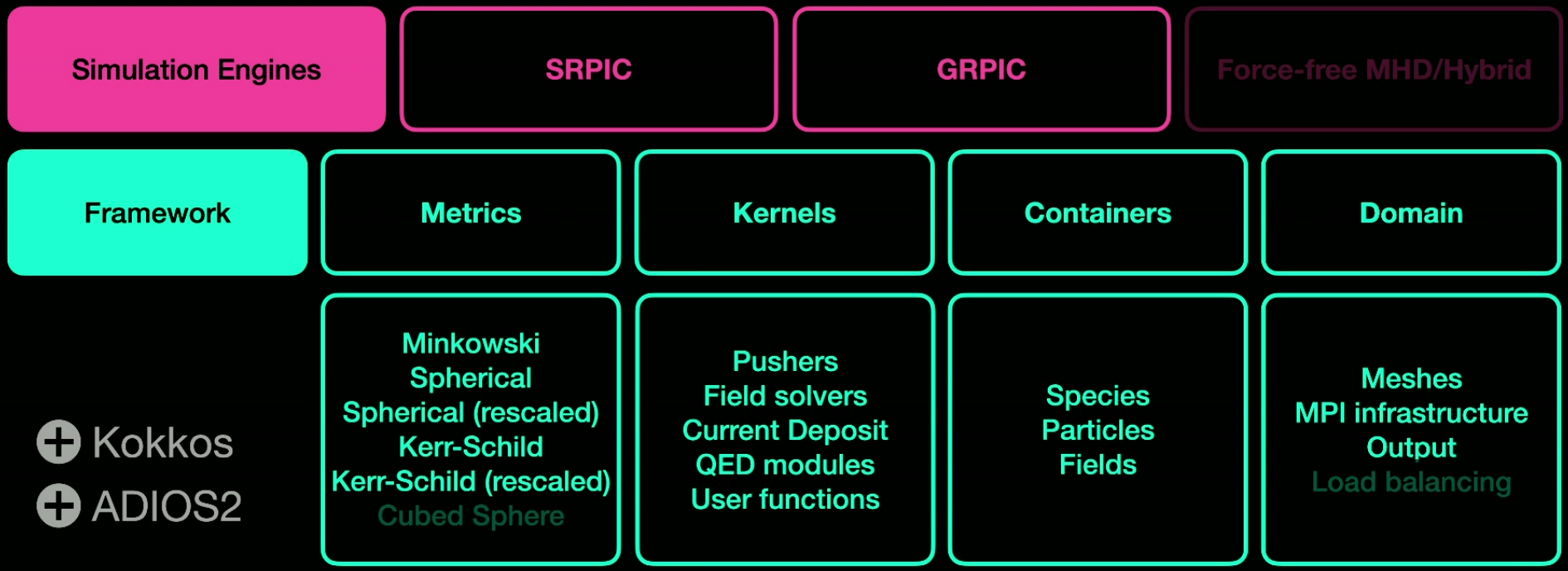
Parallel electric fields

Drive magnetospheric dissipation.

Multiplicity

Entity is templated for versatility

One framework supports various plasma physics applications

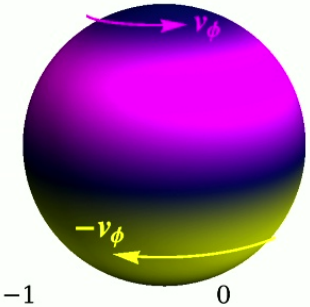


The entity framework is compiled, the user only interfaces a problem generator!

Work in progress

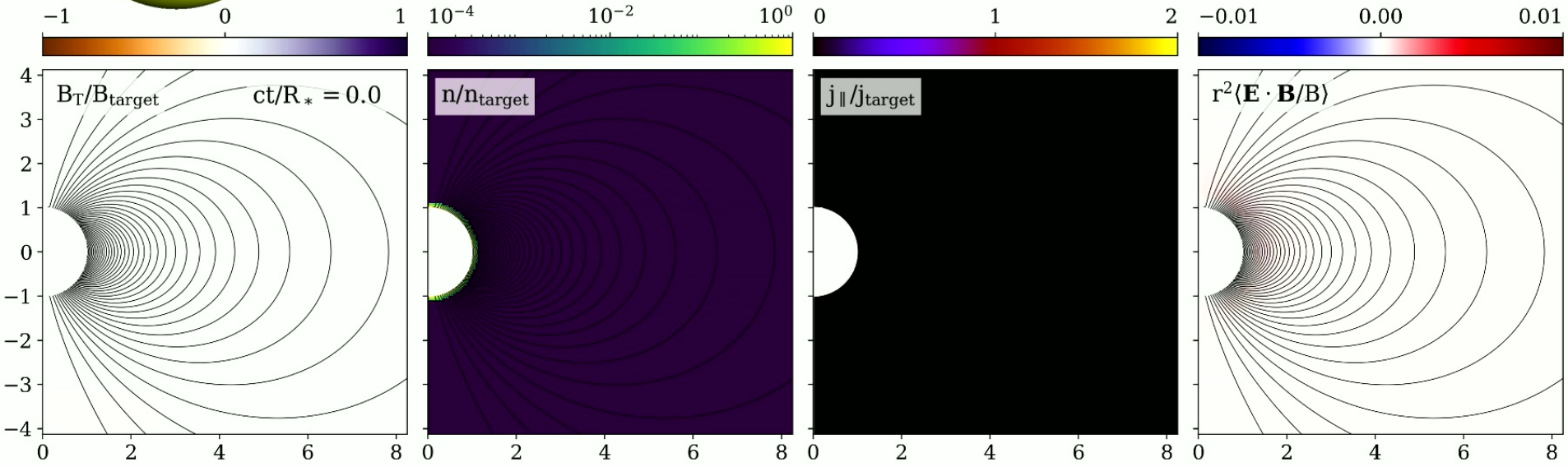
First first-principle models of magnetar plasma

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.



Work in progress

First first-principle models of magnetar plasma

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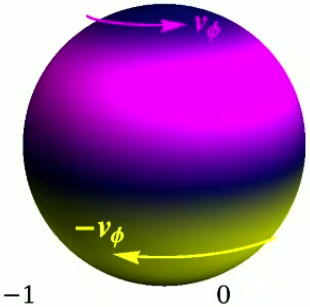

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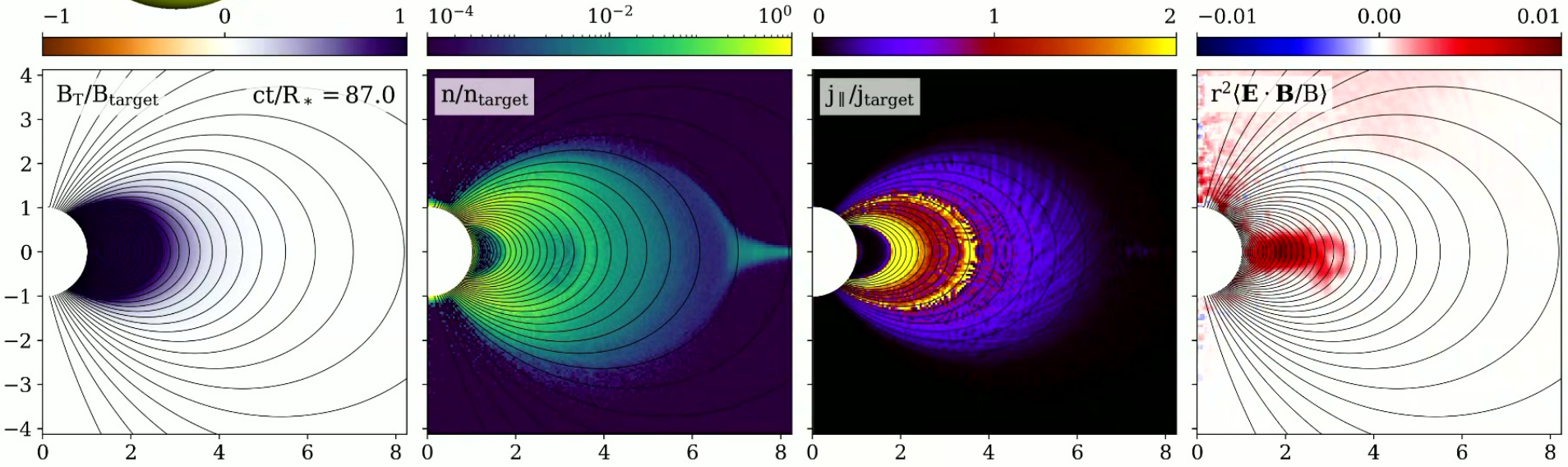


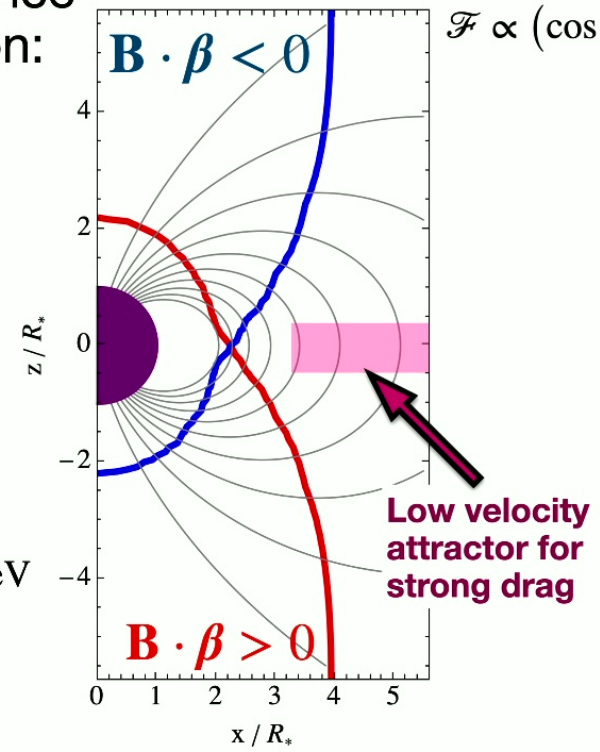
References: Beloborodov & Thompson (2007)

Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

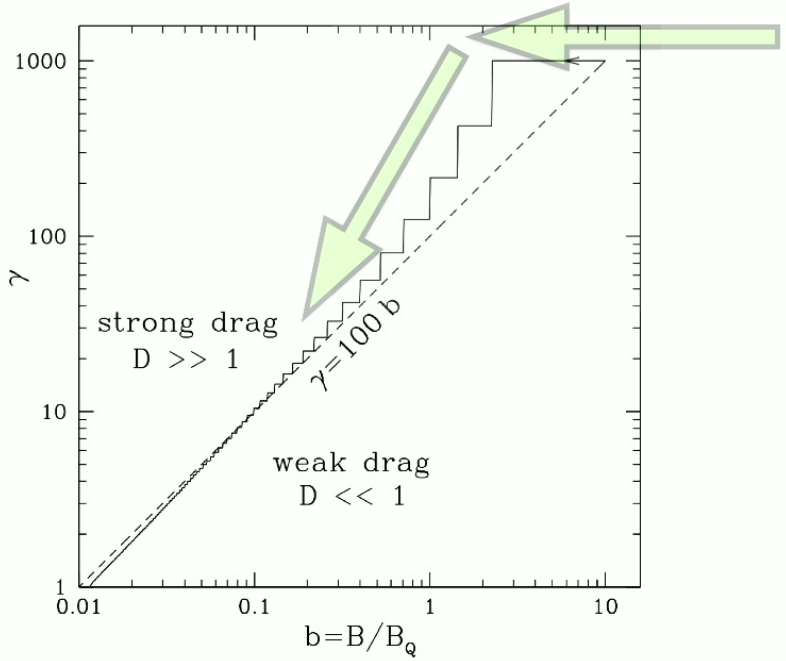
Resonance condition:

$\mathcal{F} \propto (\cos\theta - \beta)$



$E_{\rm ph} = 8\,{\rm keV}$

$\gamma = 30$

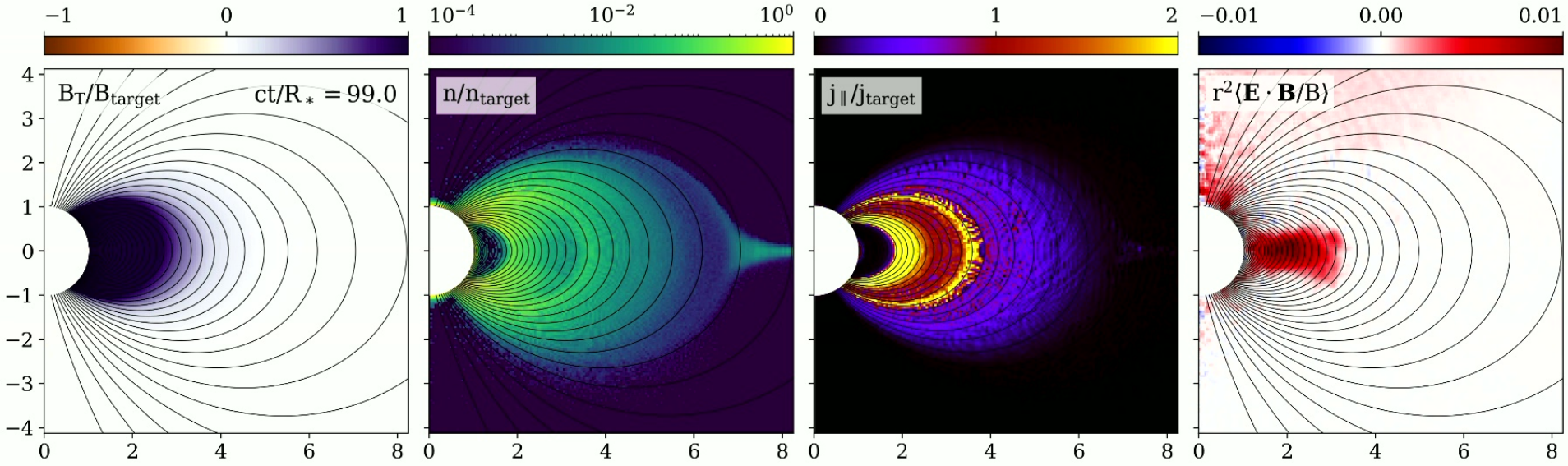


Work in progress

First first-principle models of magnetar plasma

Resonant scattering, different photon polarization and pair production

Q: What about scale separation?



References: Beloborodov & Thompson (2007)

Radiative kinetics of the magnetar circuit

Acceleration and deceleration with sufficient pair production

From reference without radiation:

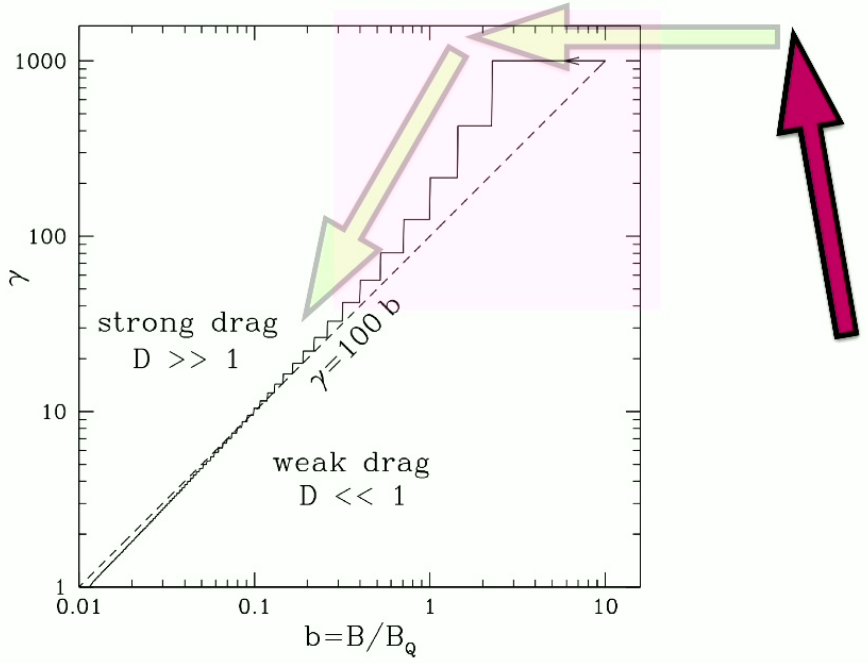
Double layer potential

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

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

L_0 : Layer length

d_0 : Fiducial skindepth



Modeling X-ray emission in radiation-rich magnetar magnetospheres

1. On the verge of simulating the first self-consistent magnetar circuit that explains radiation in the equilibrium state from first principles.

   > This is very exciting, with lots of fundamental physics.

2. We find equilibrium states with different circuit manifestations throughout the magnetosphere.

   > Scale separation will allow physical AND realistic models.

3. Let's discuss how creating reliable numerical models is far more challenging than polished slides might suggest!

   > Shoutout to collaboration.