PIC simulations of resonant scattering in magnetar magnetospheres

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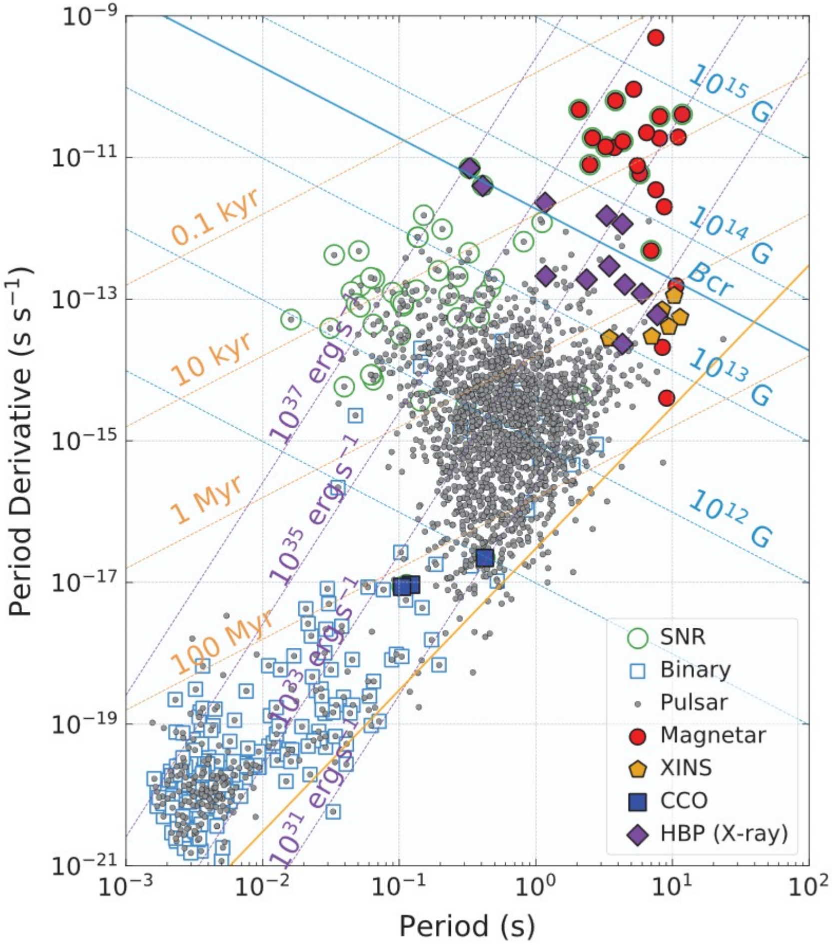
SF2A – Atelier ASNum

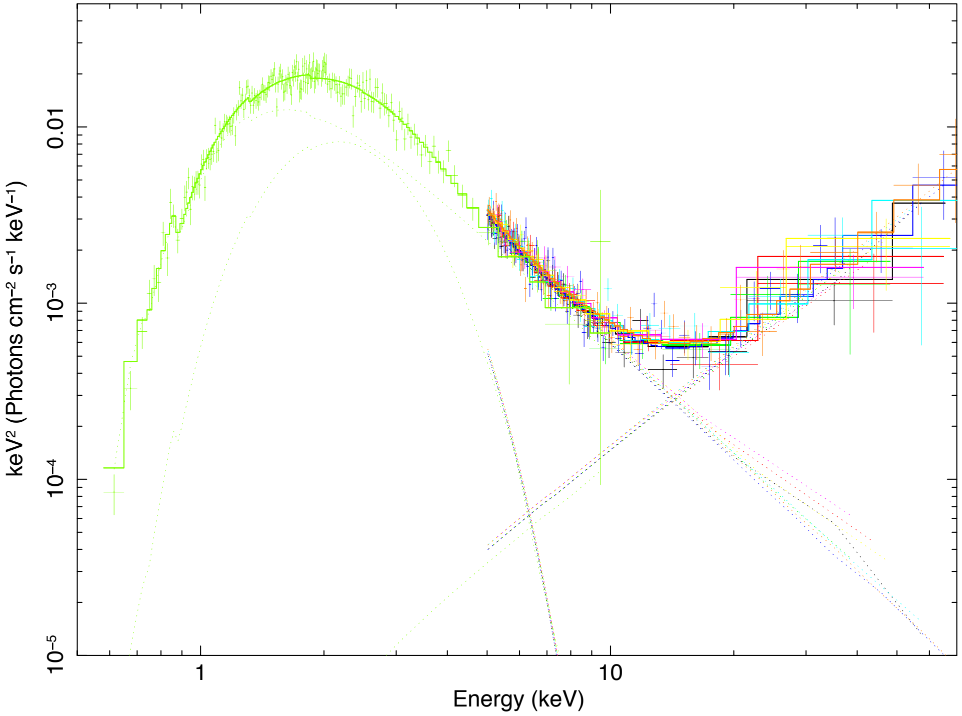
Magnetars: slow highly magnetized neutron stars



[Teruaki et al 2019]

Magnetars: Persistent X-ray emission

Magnetar 1E 2259+586



[Vogel et al. 2014]

Magnetars: Persistent X-ray emission

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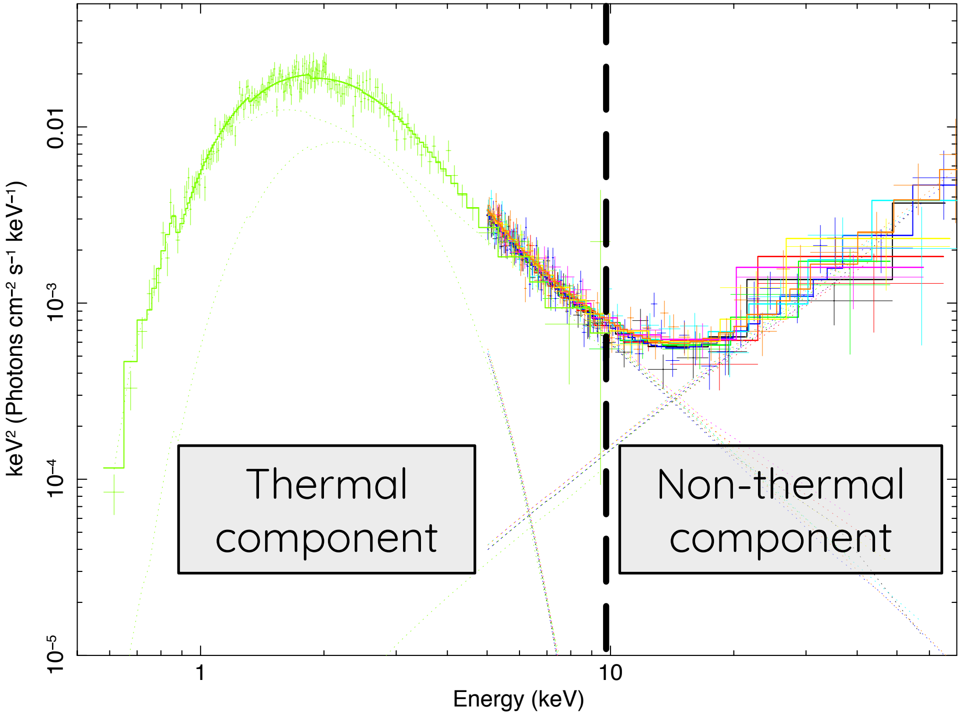
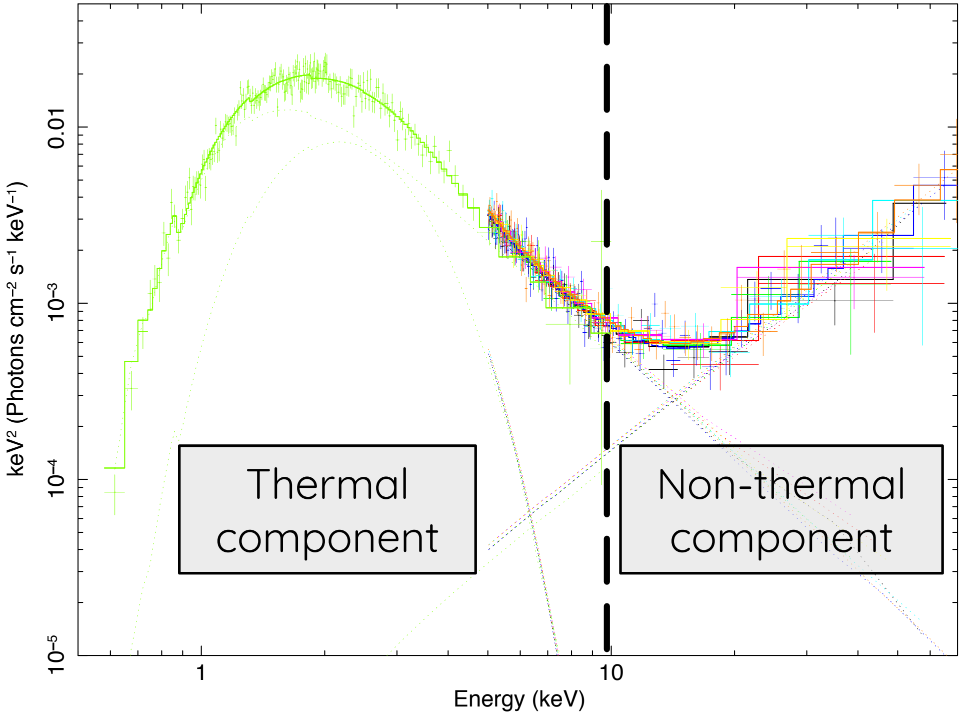


[Vogel et al. 2014]

Main questions

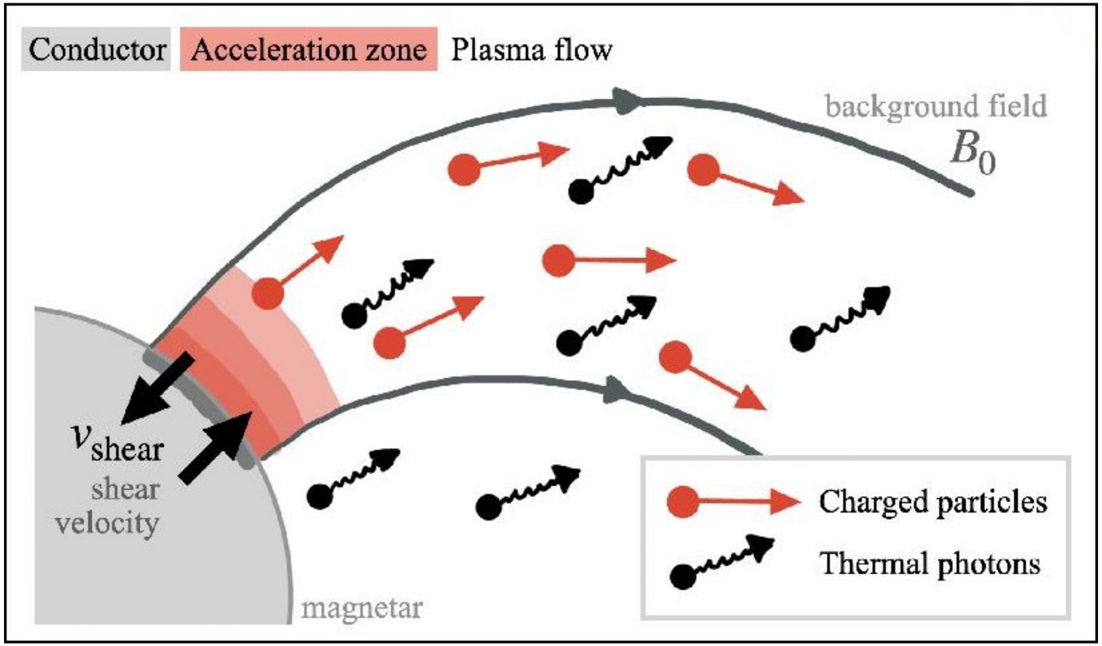
Magnetar 1E 2259+586



[Vogel et al. 2014]

- Explain the hard X-ray spectrum
- How do magnetar magnetospheres fill with plasma?

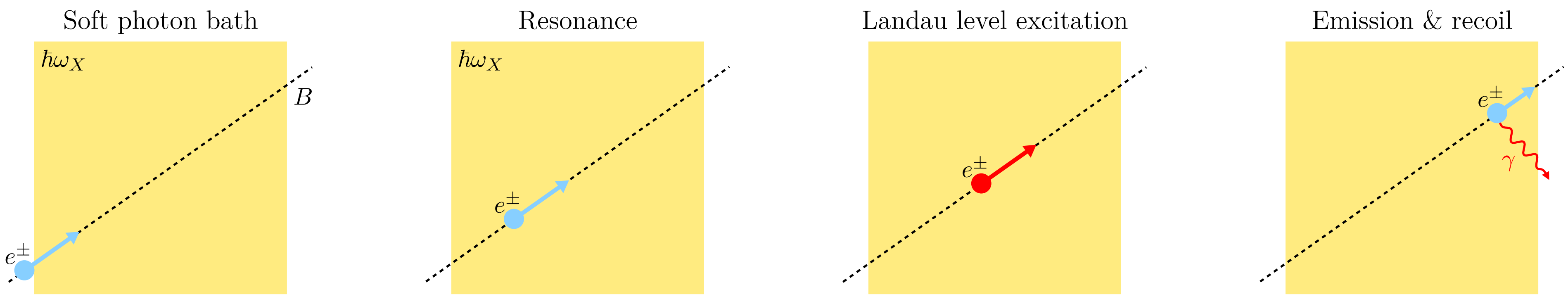
Filling the magnetosphere



Resonant Inverse Compton Scattering

$\widetilde{\omega}_X$ Photon energy

ω_B gyro-frequency



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

$\widetilde{\omega}_X = \omega_B$

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

$\widetilde{E}_{e^{\pm}} = \widetilde{E}_B - \widetilde{E}_{\gamma}$

- Faith of photon depends on its energy (escape **OR** pair production)

- Several frame boosting and interpolation required for each particles

Resonant Inverse Compton Scattering: numerical implementation

Number of scatterings per unit time

$$\dot{N}_{\rm sc} = c \int {\rm d}\Omega \int {\rm d}\omega \, \frac{I_\omega}{c\hbar\omega} \tilde{\sigma}_{\rm res}$$

I_ω Planck's law

$\tilde{\sigma}_{\rm res}$ Resonant scattering cross section

Two region prescription

$$\frac{B}{B_{\rm QED}} \approx 0.063 \left(\frac{E_X}{1 {\rm keV}} \right)$$

$$p_{\rm sc} = \dot{N}_{\rm sc} \, \Delta t$$

$$\mathcal{F} = \dot{N}_{\rm sc} \Delta P$$

Numerical implementation

Scattering kernel

Probabilistic approach

Photon emission + splitting

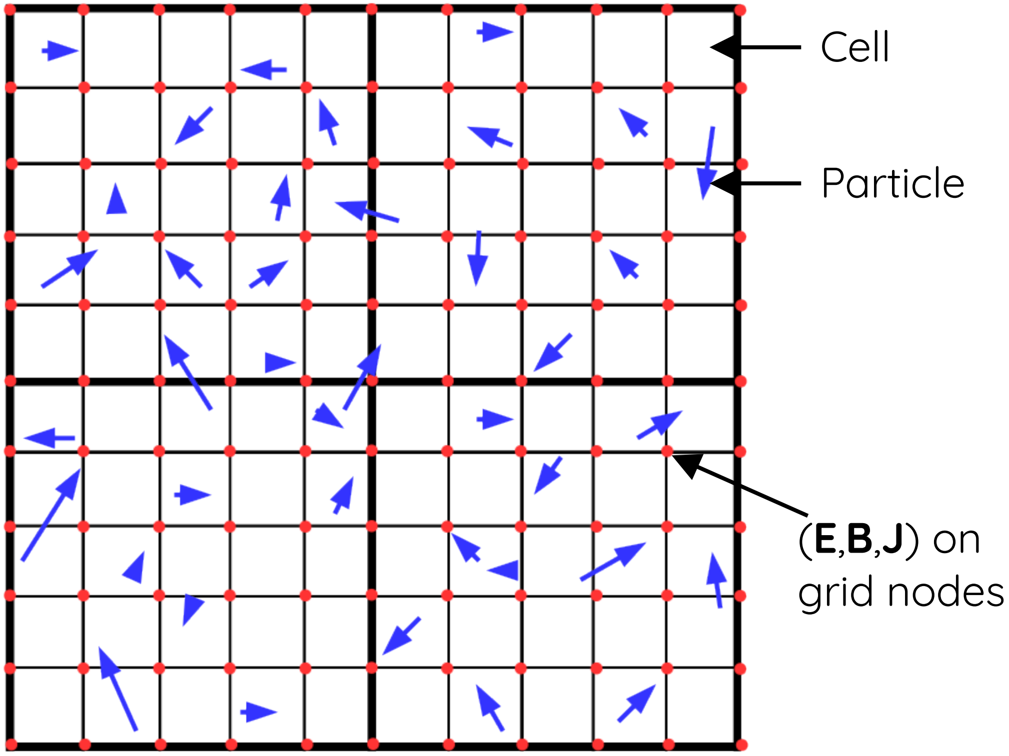
Continuous drag kernel

Semi-implicit approach

External force for particles

Cooling timescale

Particle-in-cell simulations



Particles: continuous space Fields: grid

Entity GPU-PIC code using Kokkos

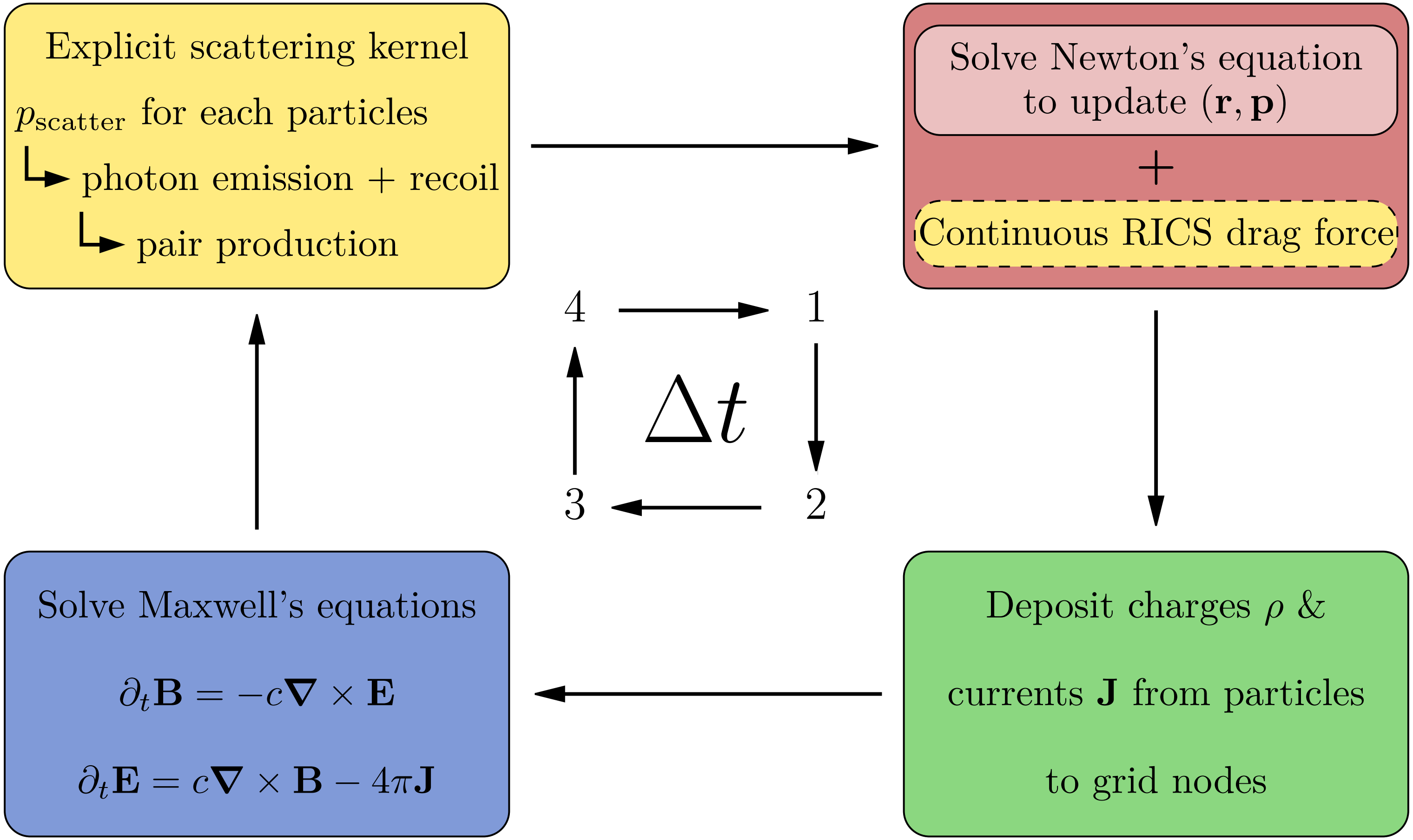
Open source: github.com/entity-toolkit/entity

2nd order in time and space (FDTD + staggered field)

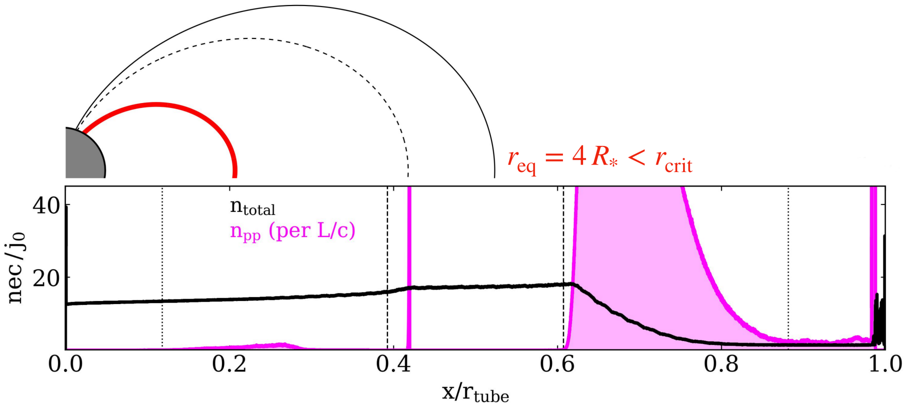
Critical length scale = electron skin-depth

$$d_e = \sqrt{\frac{m_e c^2}{4\pi n e^2}} > \min\left(\Delta_{\rm grid}\right)$$

Modified Particle-in-Cell loop

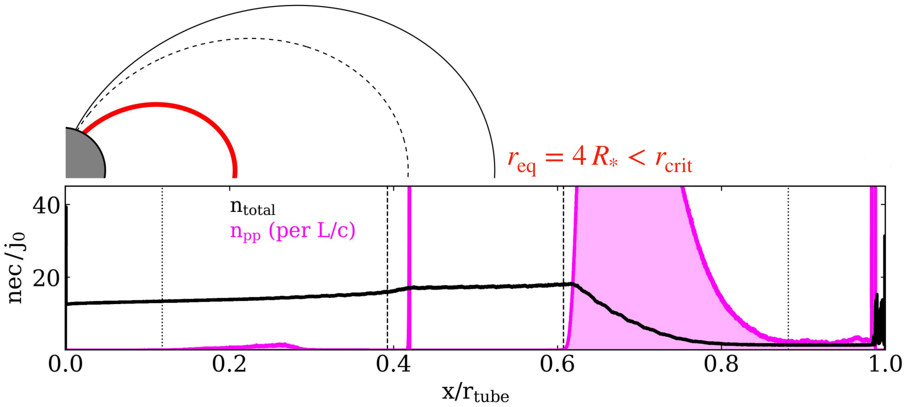


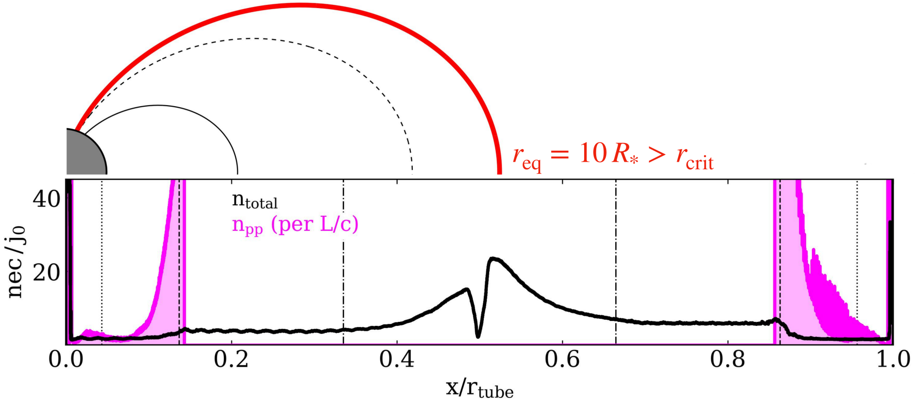
1D simulations



Mahlman et al. (in prep)

1D simulations





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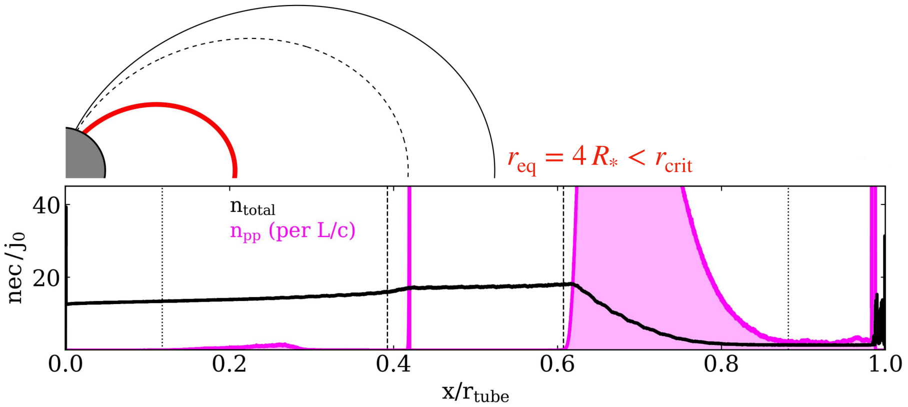

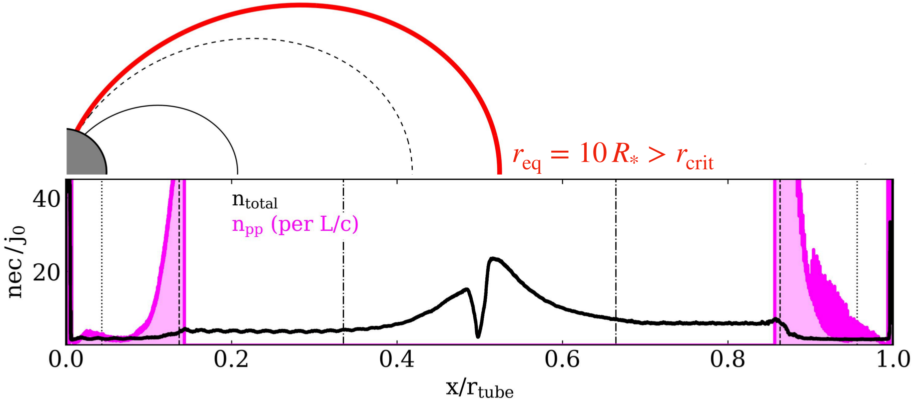

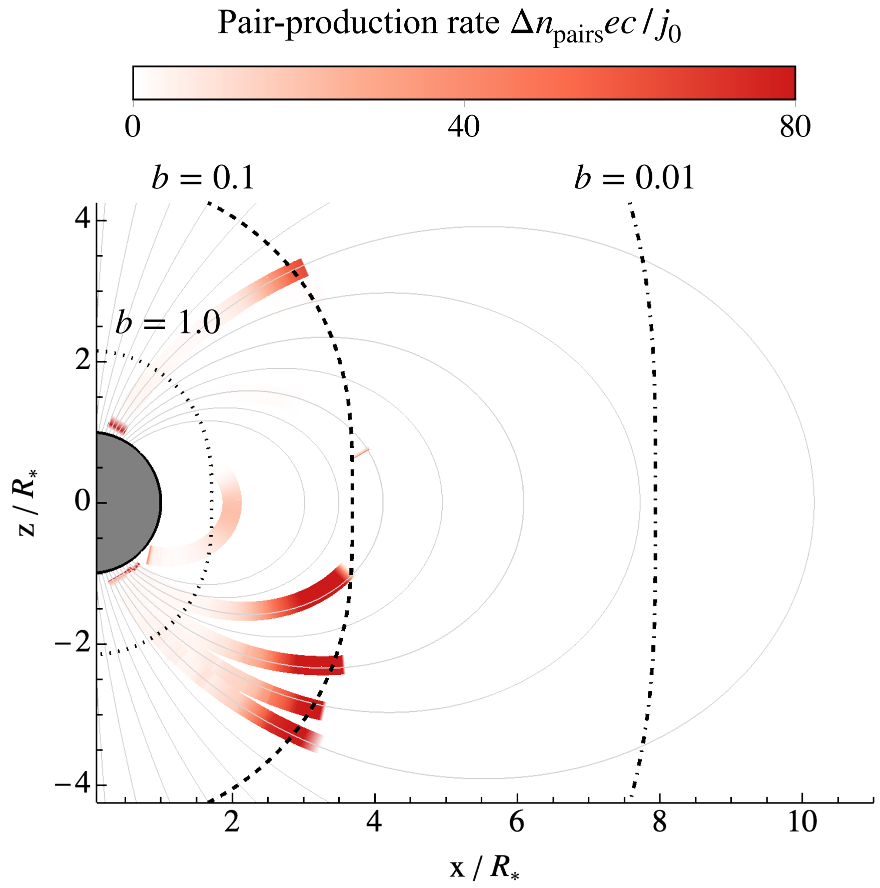

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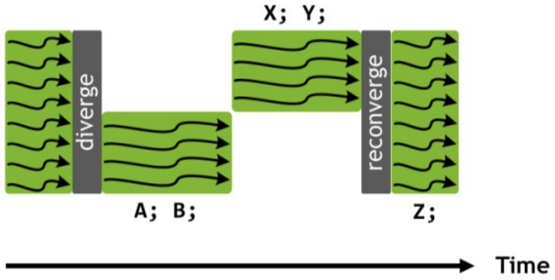
Warp divergence

Example of warp divergence

```
if (threadIdx.x < 4) {
    A;
    B;
} else {
    X;
    Y;
}
Z;
```

[Nvidia wiki]



- kernel is compute-bound
- current warp divergence small
- pre-check loop can be unproductive

Divergence work from student **Brigid O'Donnell**

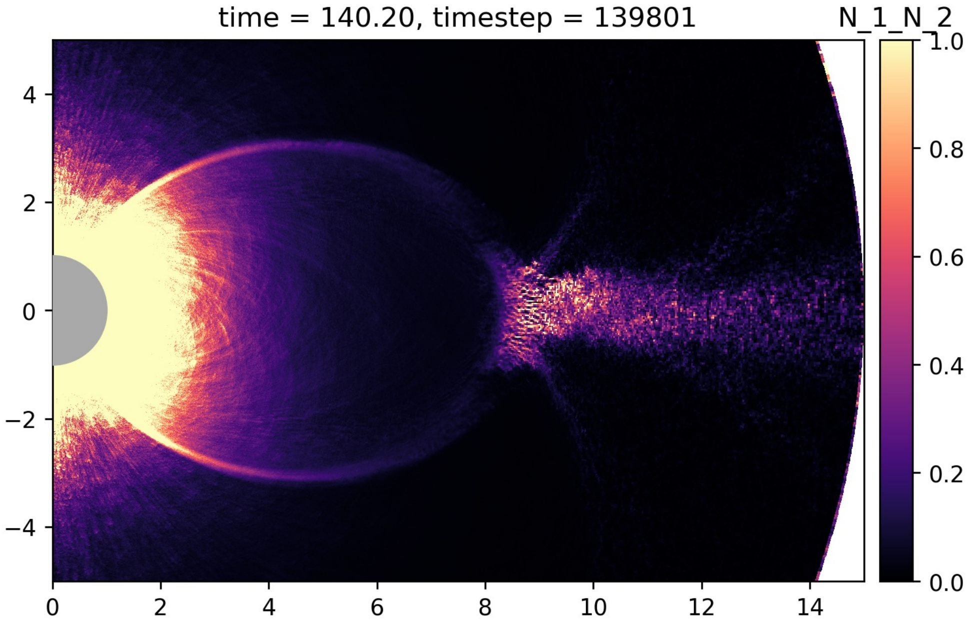
Loop over **N** particles Full scattering kernel	Loop over **N** particles Pre-check conditions **N → N'**
	Loop over **N'** particles Scattering kernel (No divergence)

Conclusions

- Numerical implementation of RICS:
  - scattering → explicit
  - drag force → semi-implicit

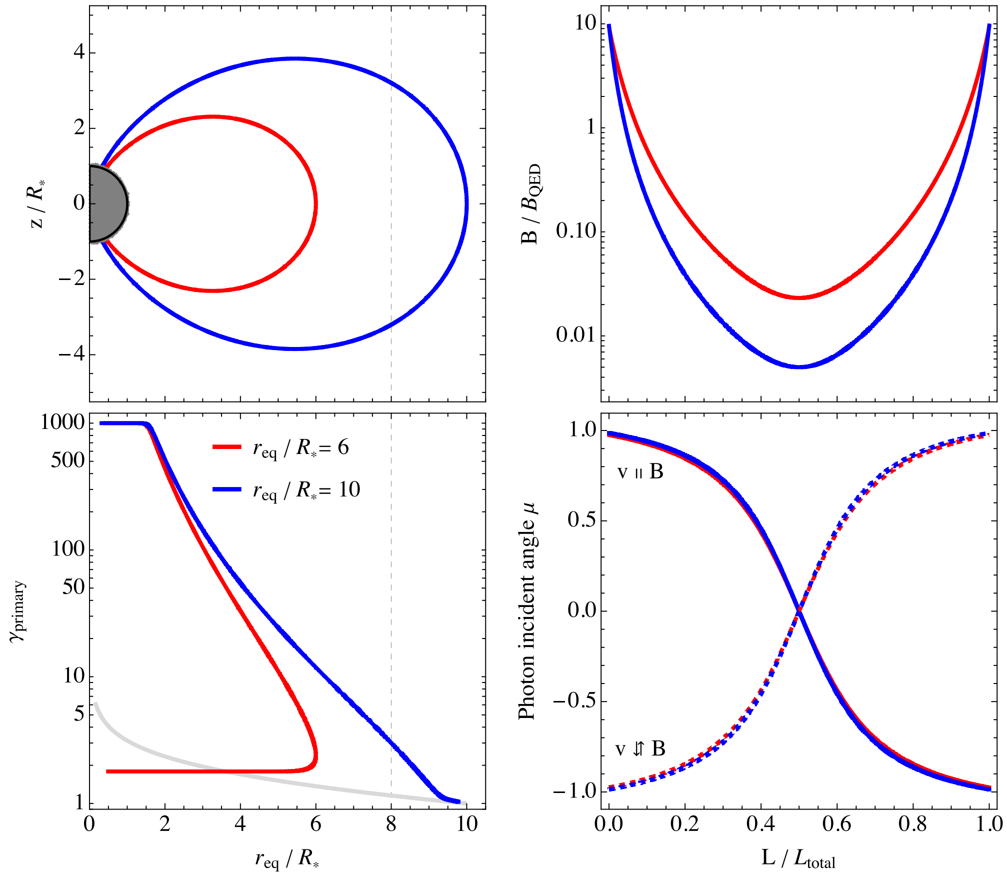
- 1D simulations results:
  - magnetar circuit can ignite from RICS
  - asymmetric gaps
  - cooling timescale = crux
  - high resolution required at equator

- 2D simulations early stage:
  - implementation done
  - warp divergence is weak
  - first global run last week



Thank you

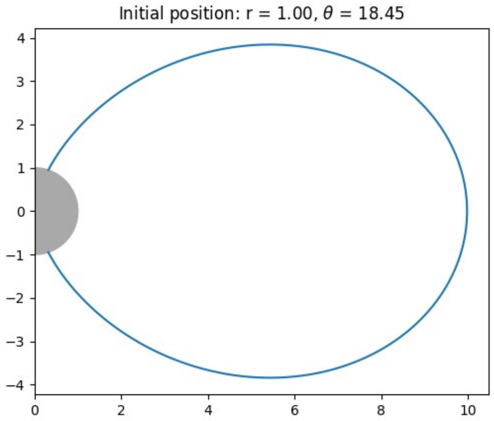
RICS process for different field lines

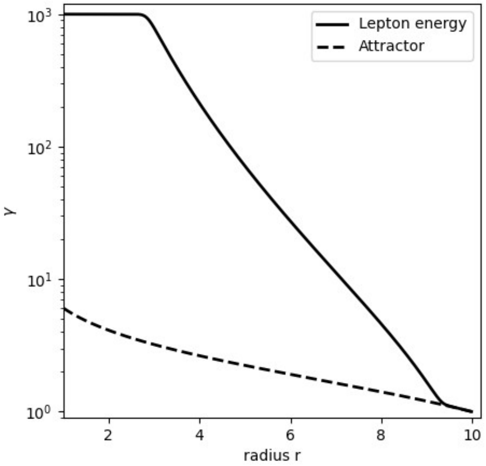


Drag force integration

Numerical integration along field line:

$$\frac{d\,p(l)}{dt} = \mathcal{F}(l) = \left(\frac{r_e m_e c^2}{4^2}\right) \frac{\gamma\,(\mu-\beta)}{r^2} \frac{\left(\frac{B/B_{\mathrm{QED}}}{\gamma(1-\beta\mu)}\right)^3}{\exp\left(\frac{B/B_{\mathrm{QED}}}{\gamma(1-\beta\mu)T_0}\right)-1}$$





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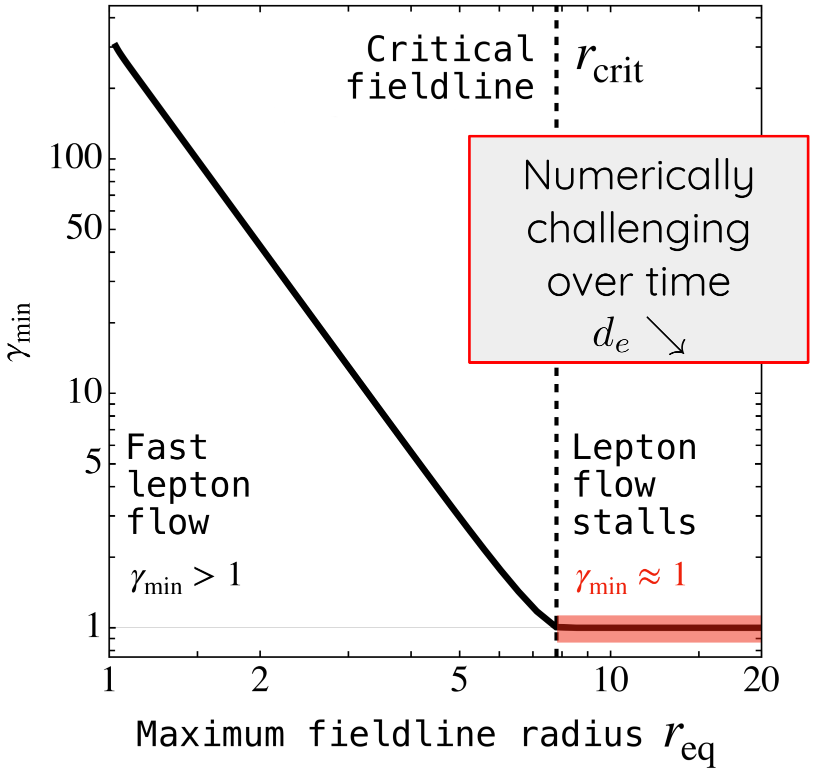
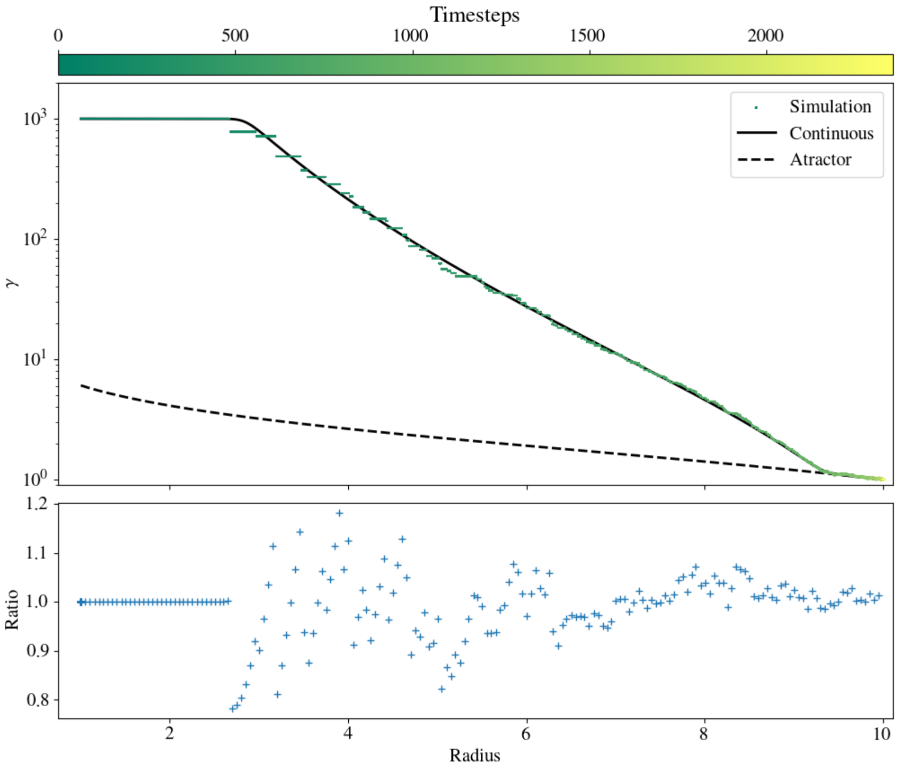


Kernel validation

Scattering Kernel



Radiative drag force