Fast dissipation of magnetic energy near compact objects

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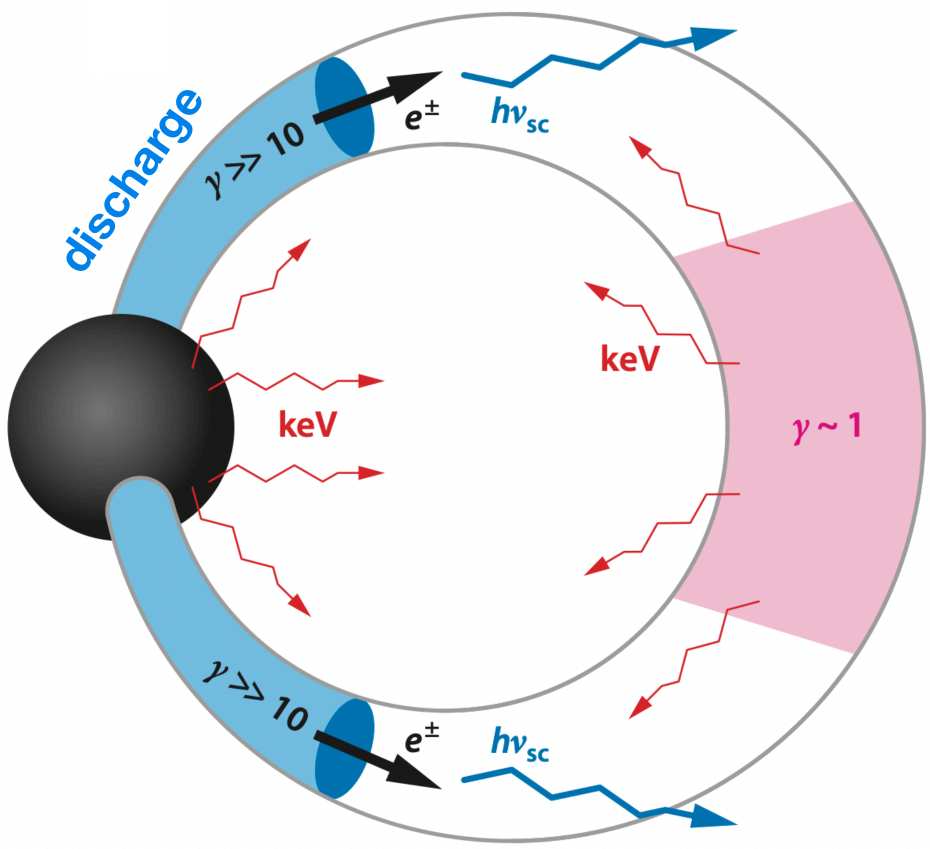
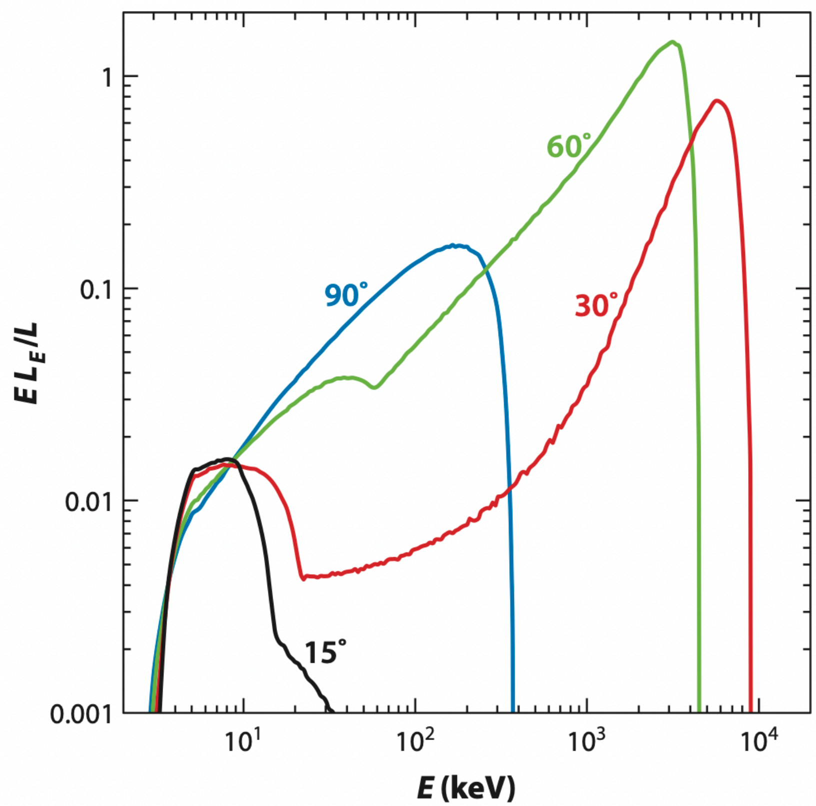
Daniel Groselj, Joonas Nattila, Lorenzo Sironi, Navin Sridhar, Yalie Yuan

Magnetars: twisted magnetospheres emit hard X-rays (slow dissipation)





AB 2013

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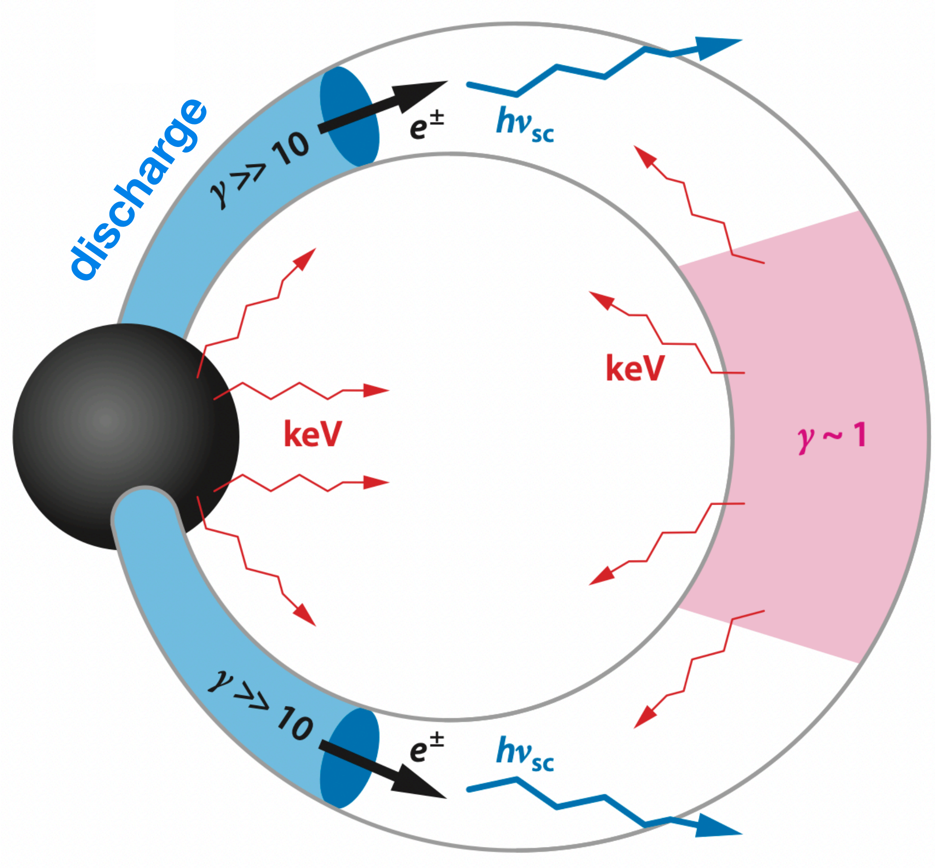
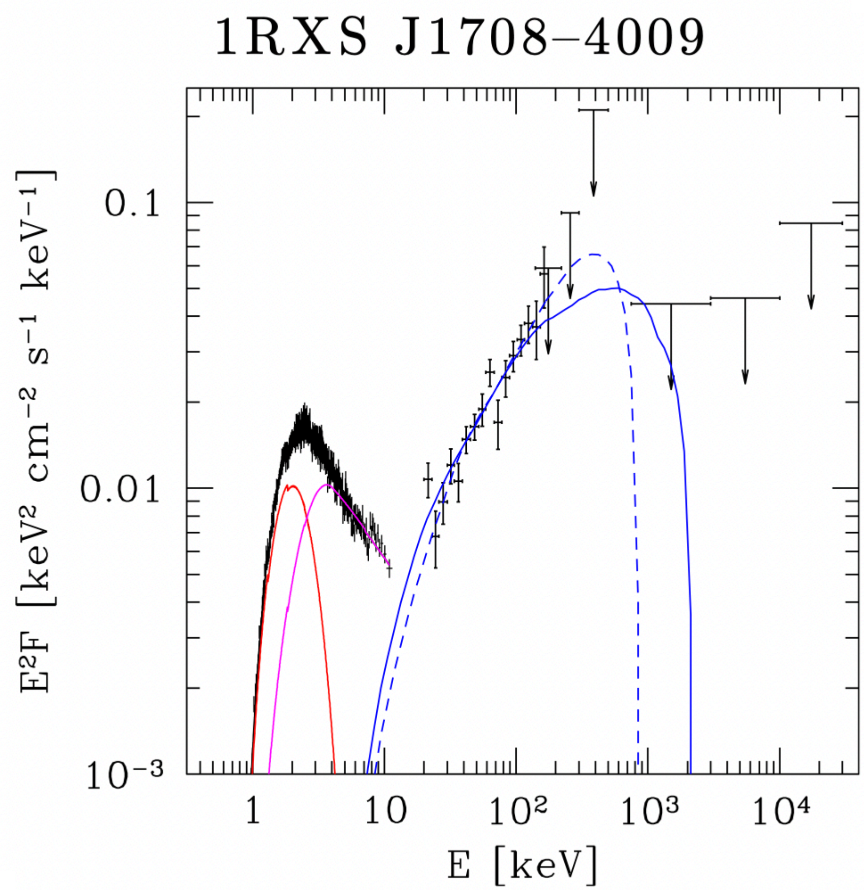
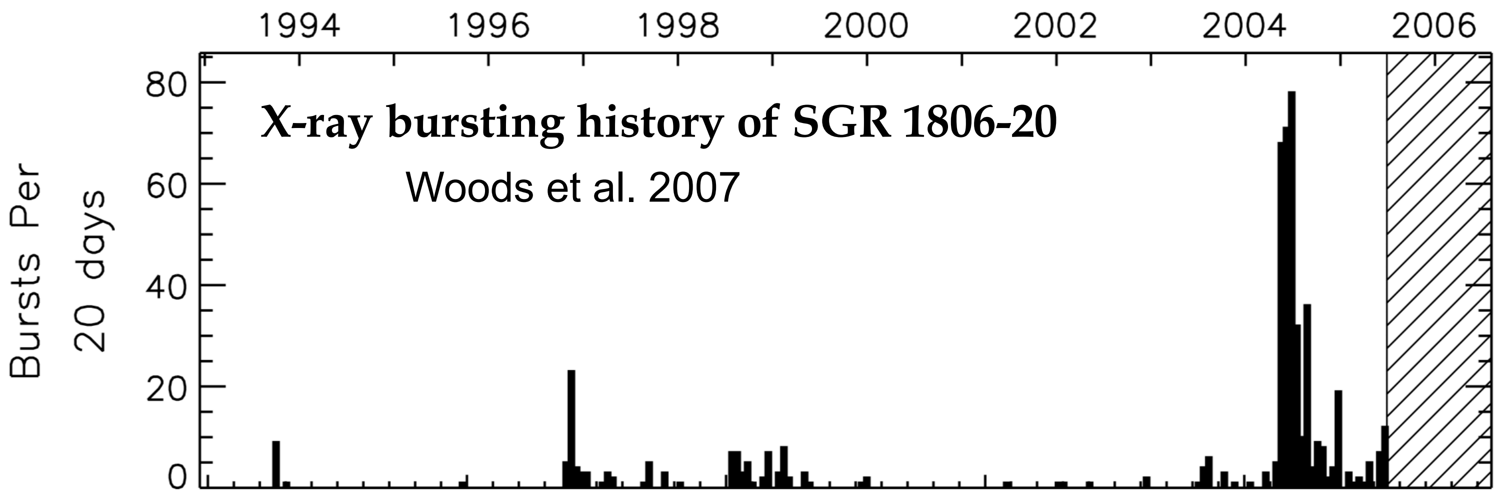




Hascoet, AB, den Hartog 2014

Magnetars produce bright bursts (fast dissipation)



burst durations
~ 0.1 s

luminosities
$10^{41} - 10^{47}$ erg/s

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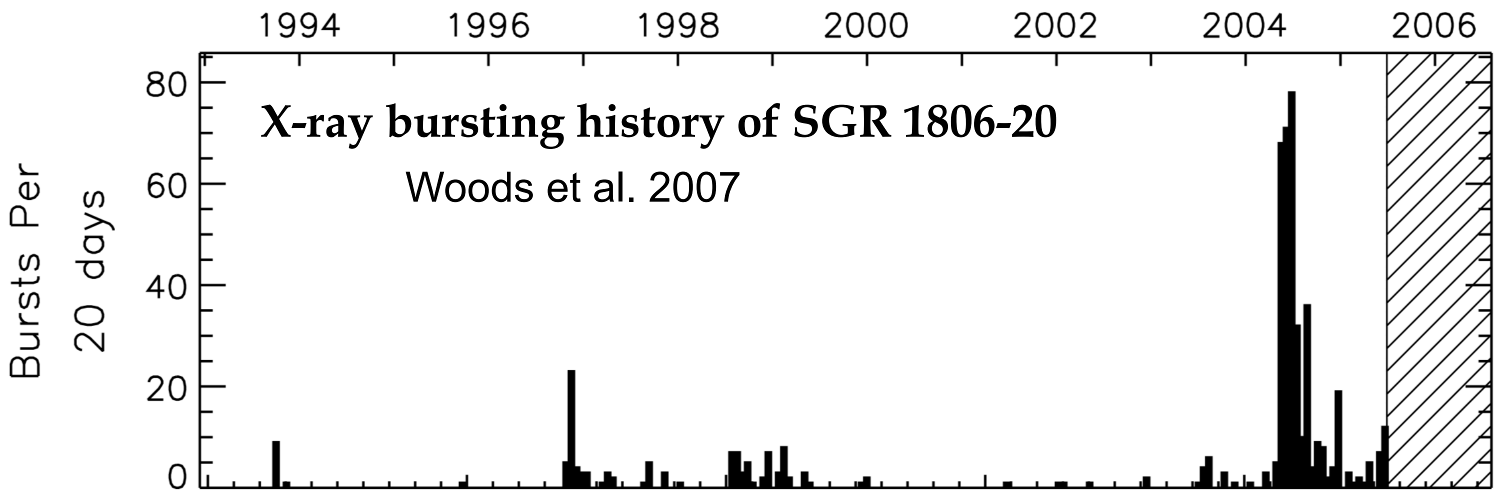

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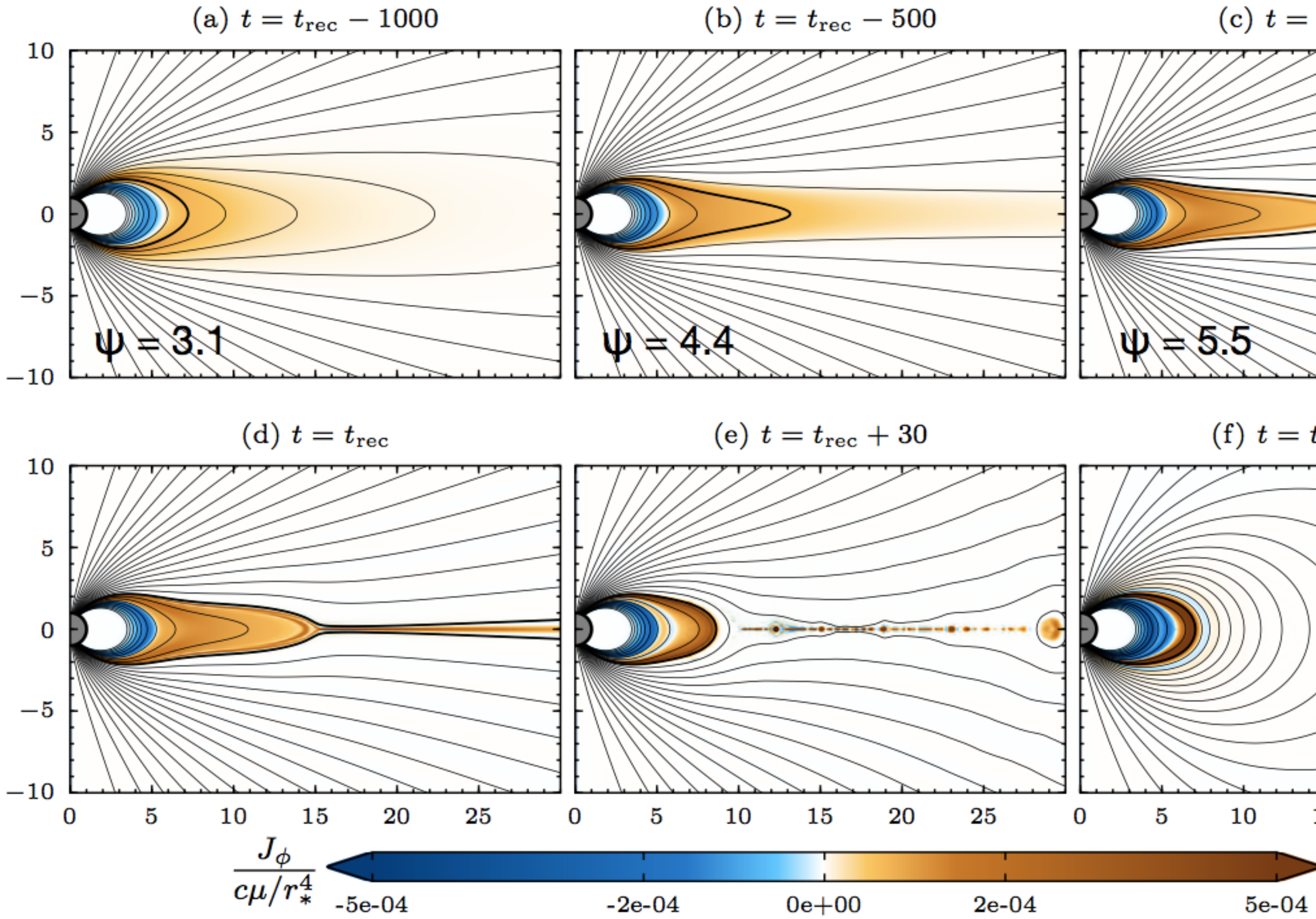
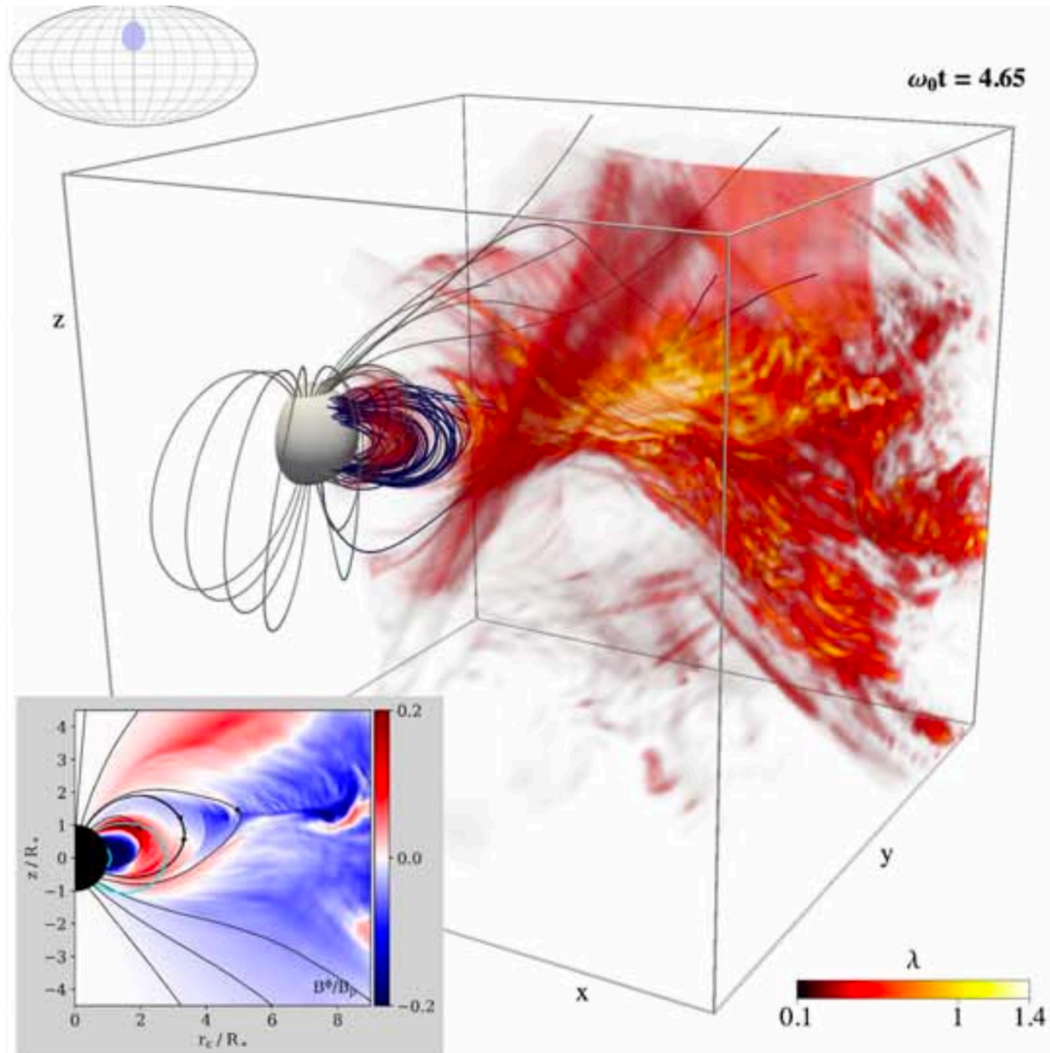
Mechanisms:

1. Short-lived Alfvenic turbulence (excited by quakes) — Thompson, Duncan 1995
2. Magnetic reconnection (over-twisted magnetosphere) — Parfrey, AB, Hui 2013; Yuan et al. 2020
3. Two strong Alfven waves collide, annihilating each other — Li, AB, Sironi 2021
4. Magnetosonic perturbations form monster radiative shocks — AB 2023

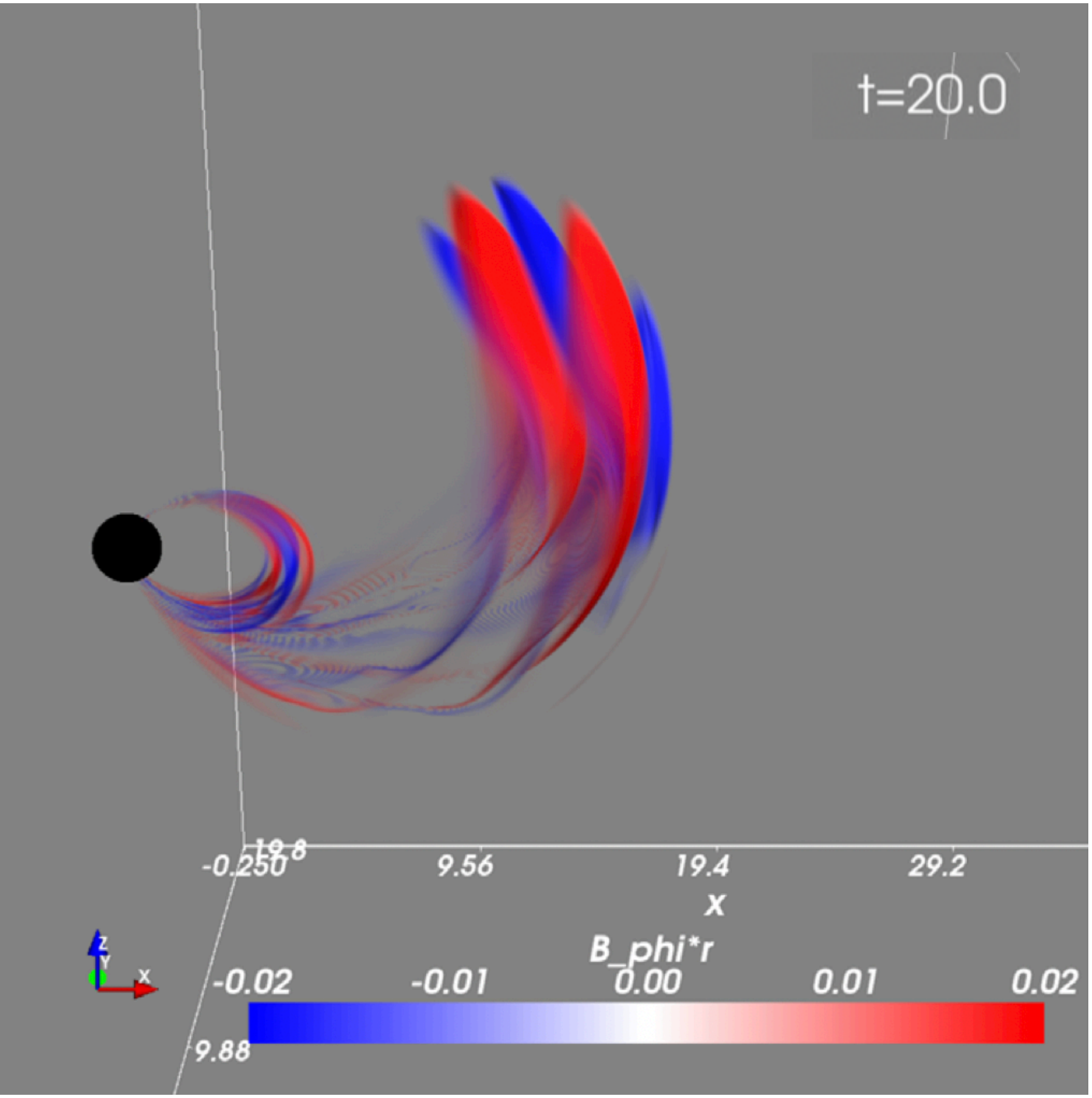
Loss of magnetic equilibrium and reconnection



Parfrey, AB, Hui 2013

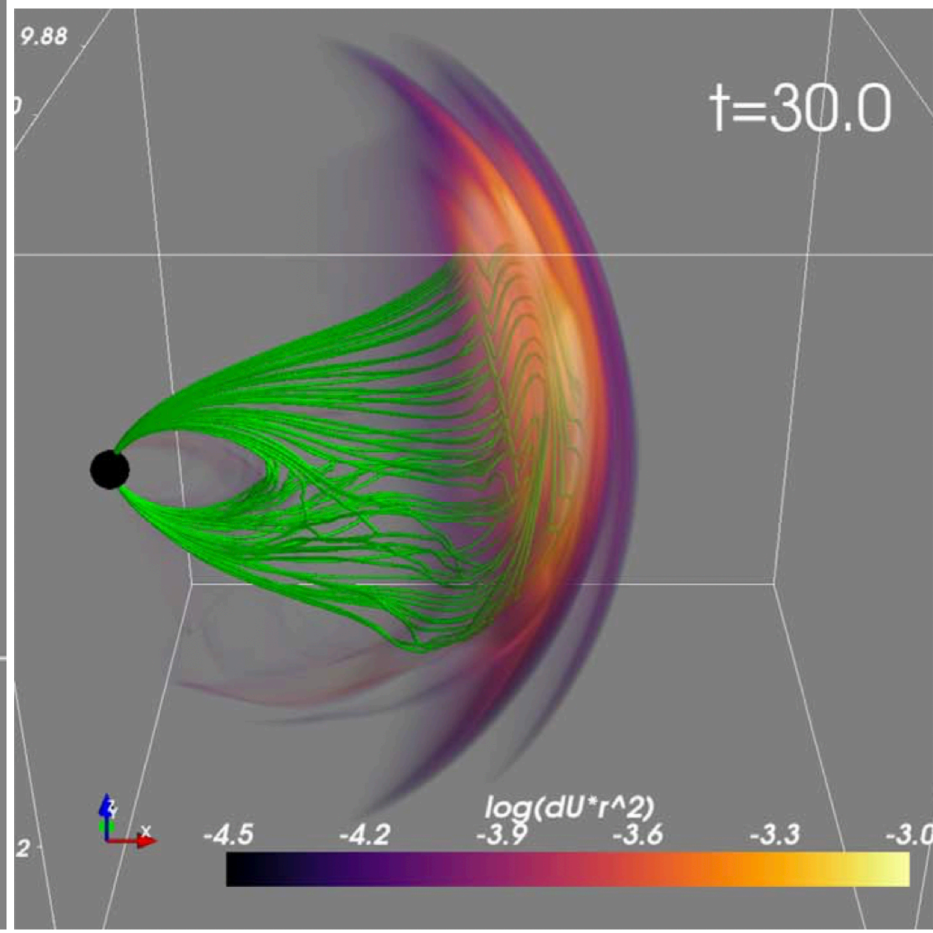


Mahlmann et al. 2023



Nonlinear Alfven wave from a quake

Yuan et al. 2022

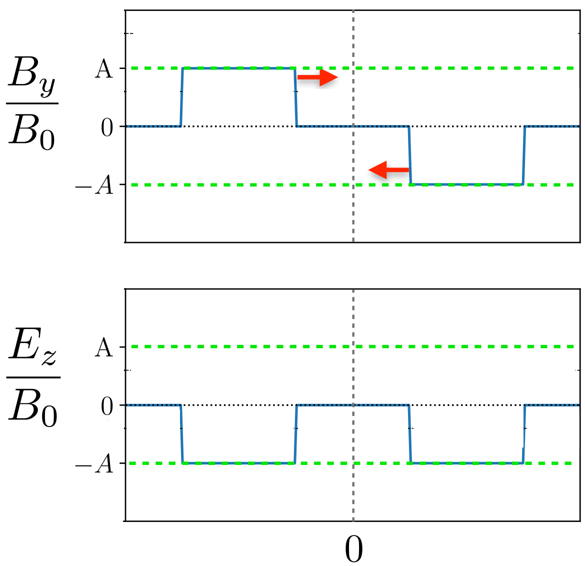


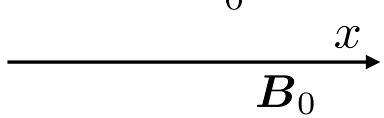
Collision of two strong Alfven waves

$\boldsymbol{B} = (B_0, B_y, 0)$

$\boldsymbol{E} = (0\,,\,0\,,\,E_z)$

$A \equiv \frac{\delta B}{B_0} = \frac{\max B_y}{B_x}$





$A > 1/2$

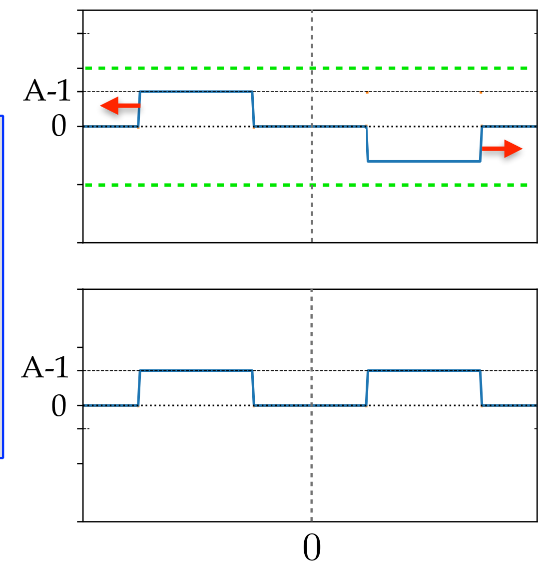
$\underline{x = 0}$:

$B_y = 0$

$|E_z| = B_0$

$\Rightarrow$ reflection with amplitude |A-1|

after collision

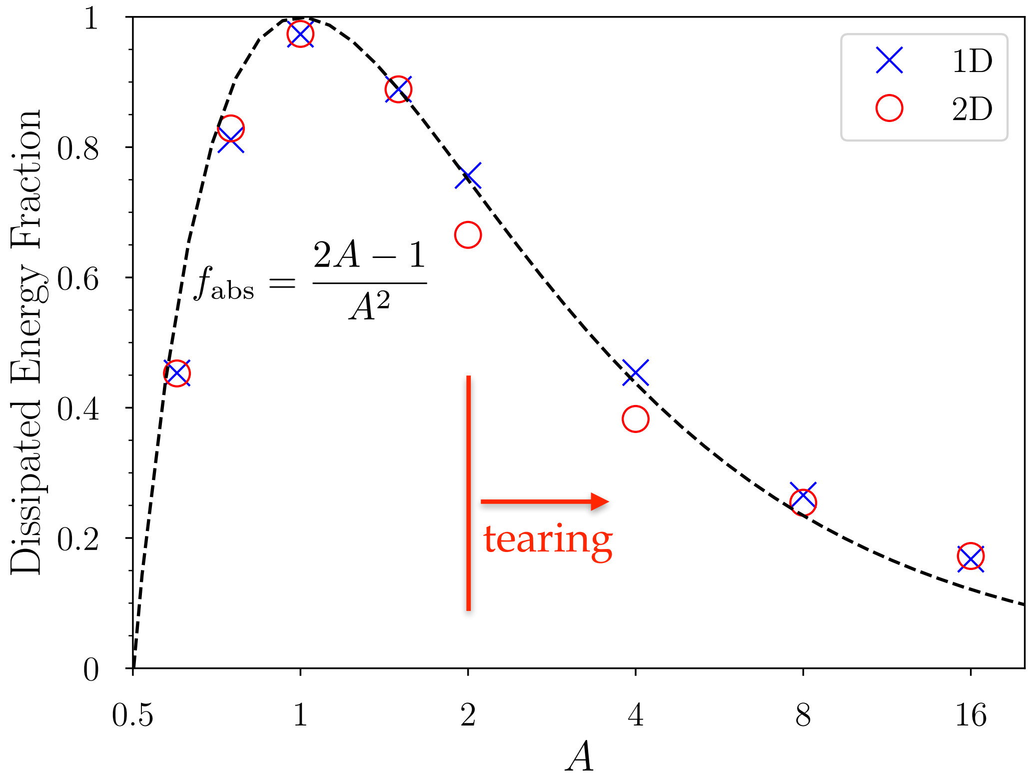


absorbed energy fraction:

$$f_{\rm abs} = 1 - \frac{(A-1)^2}{A^2} = \frac{2A-1}{A^2}$$

Li, AB, Sironi 2021

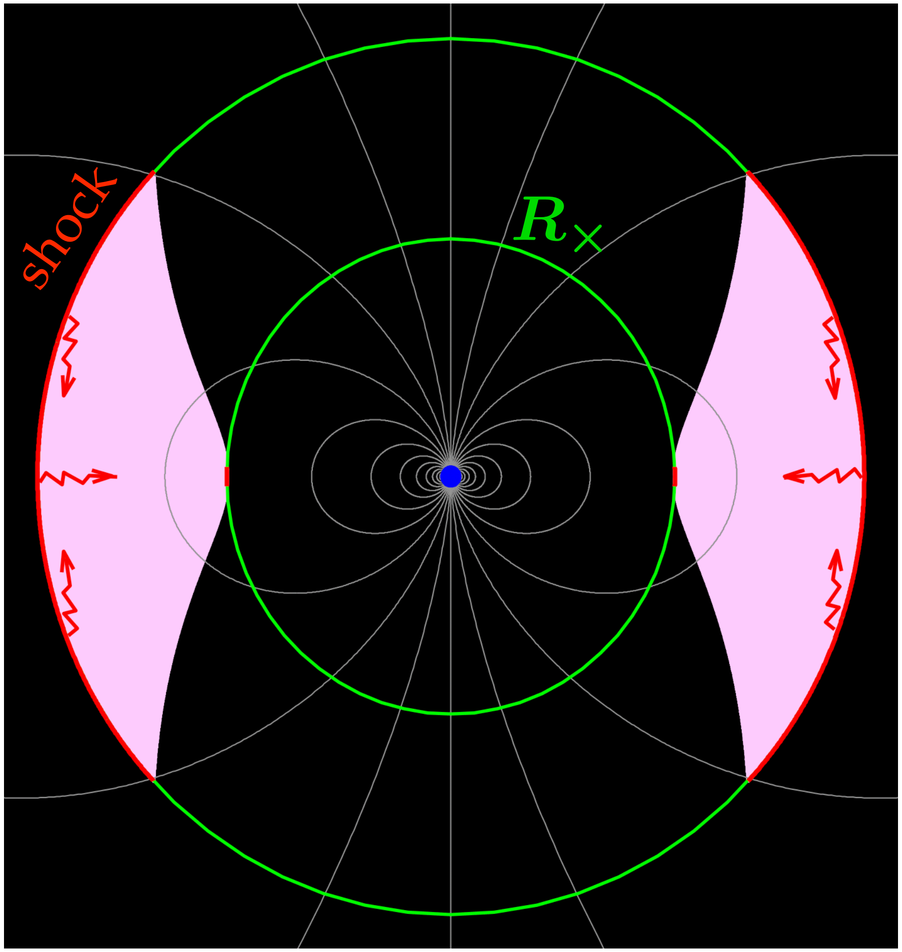
Alfven wave collision: PIC simulations



$\sigma = 20$

Li, AB, Sironi 2021

Magntesonic waves steepen into monster radiative shocks



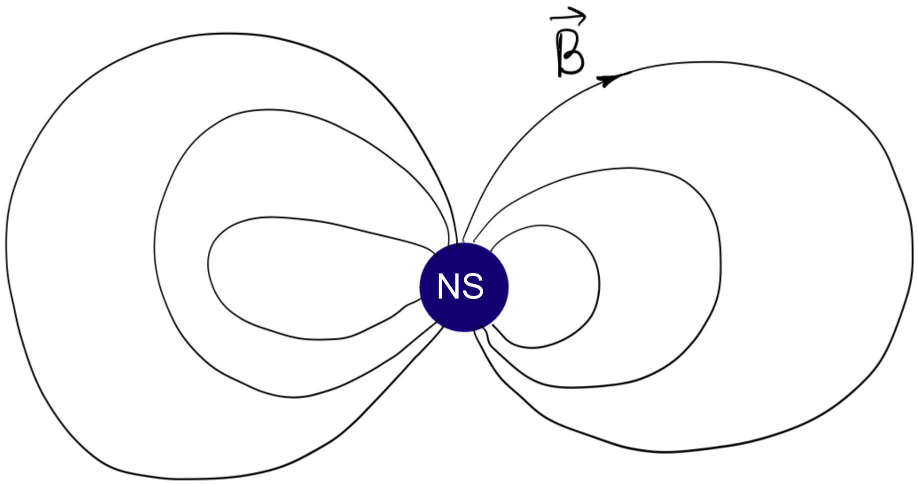
plasma acceleration in the wave
where $E^2 - B^2$ approaches zero

Lorentz factor $\gamma \sim \dfrac{c\,\sigma_{\rm bg}}{\omega R_\times}$

particles crossing the shock
emit curvature gamma-rays

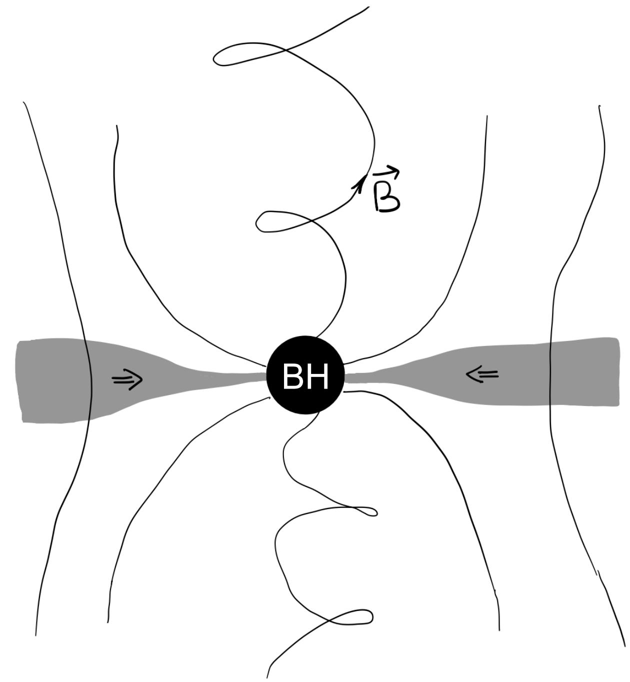
gamma-rays convert to e+- pairs
=> **e+- fireball**

AB 2023, Chen et al. 2023



Neutron stars hold long-lived ulstrastrong magnetic fields

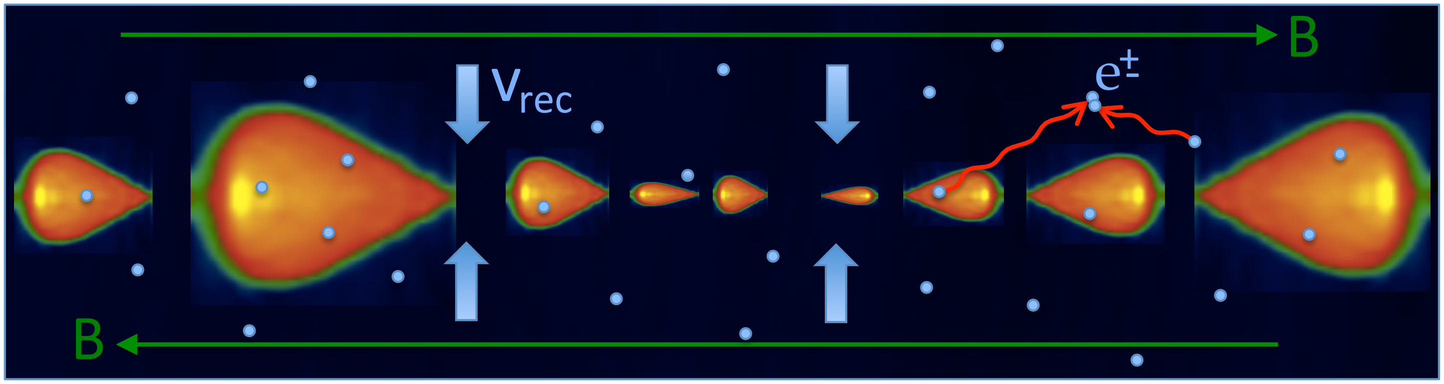
— extreme magnetization, stable fields with occasional instabilities and fast dissipation



Black holes have externally imposed magnetic fields (brought by accretion)

— lower magnetization, variable, with persistent fast dissipation

Radiative magnetic reconnection near BH and NS



AB 2017

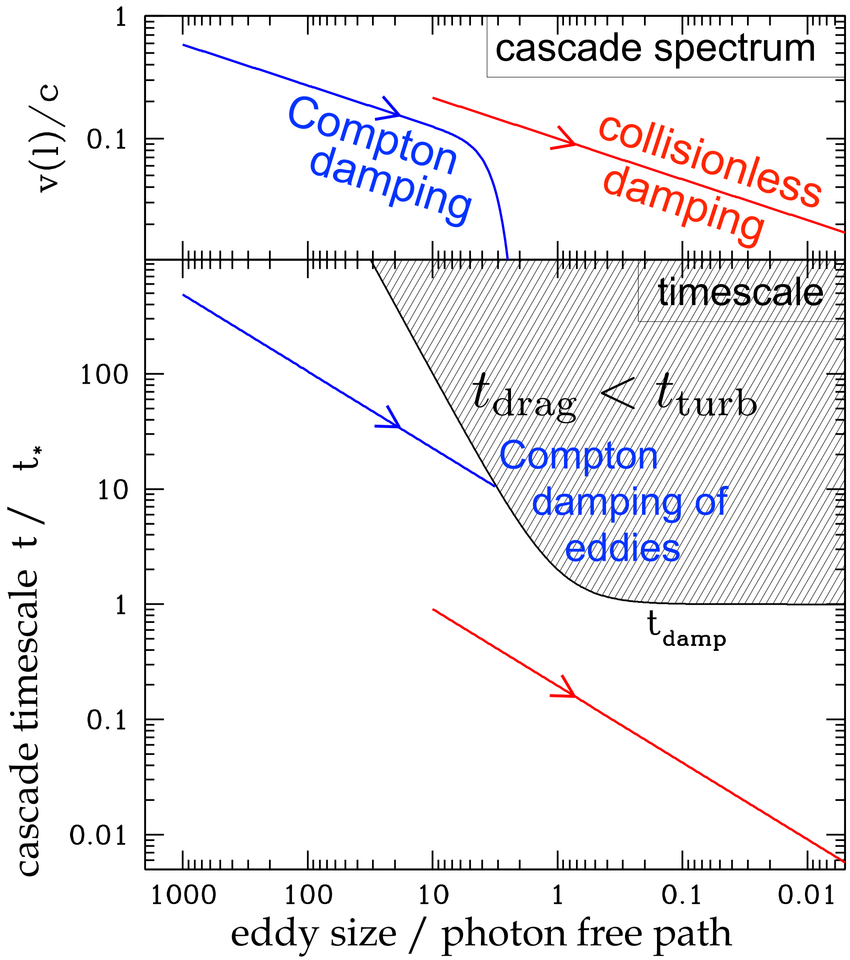
- Compton cooling keeps most of the plasma cold
- Magnetic stresses pull plasmoids through radiation drag

Dissipation: photon upscattering by the moving cold plasmoids (photon viscosity)

Similar dissipation mechanism operates in turbulent cascades

Turbulent cascade in optically thick plasma

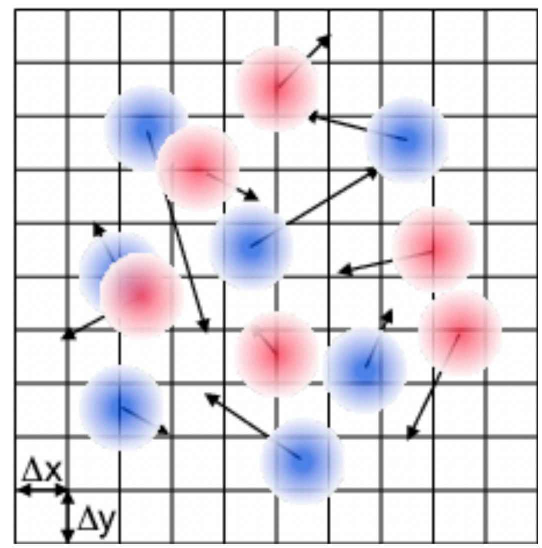
Zrake, AB, Lundman 2019



First-principles numerical experiments

dissipation by magnetic reconnection or turbulence cascades

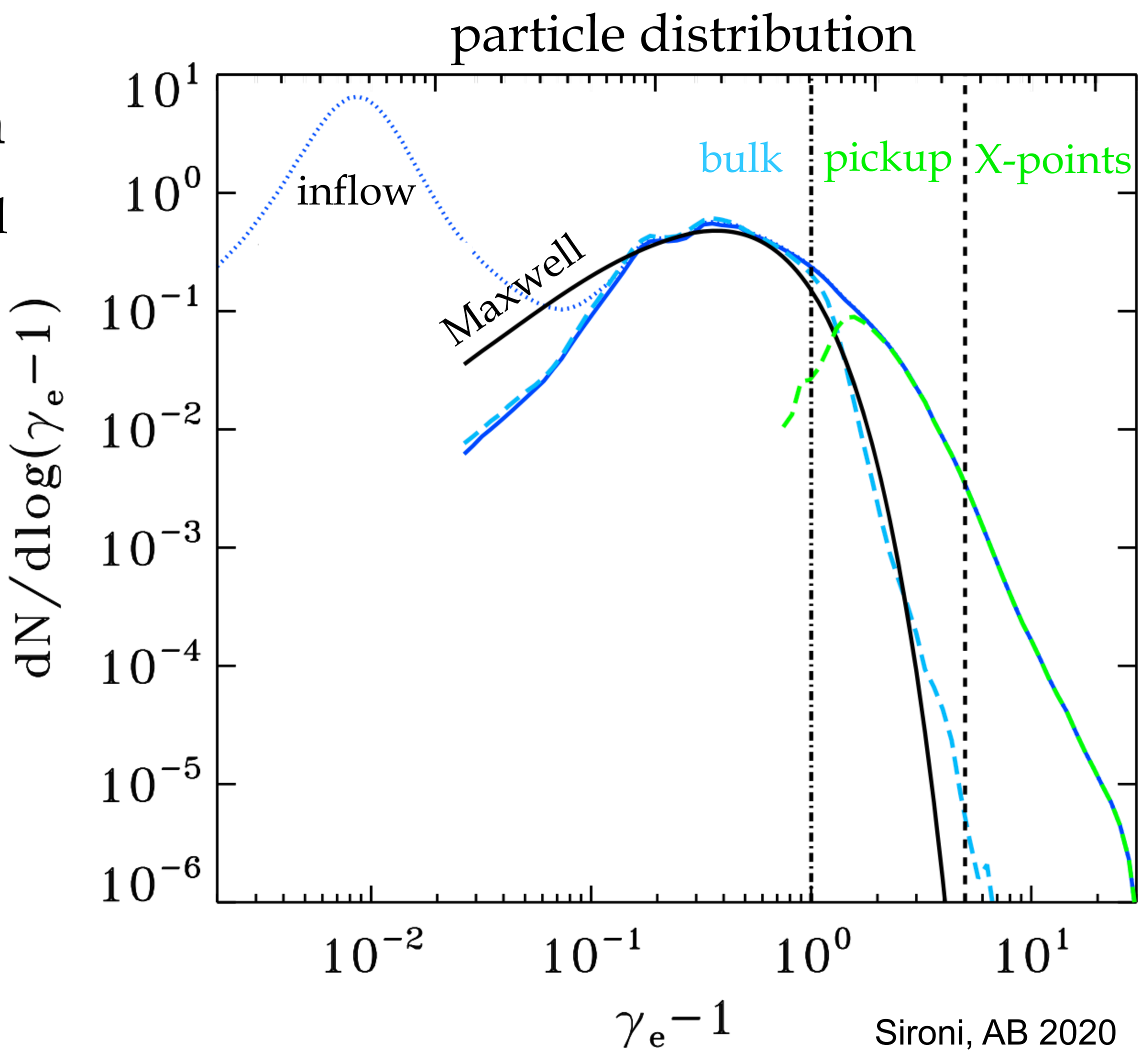
Method: “particle-in-cell” (PIC)
evolves self-consistently plasma particles and electromagnetic field



Radiative reconnection

in a magnetically dominated corona ($\sigma = 10$)

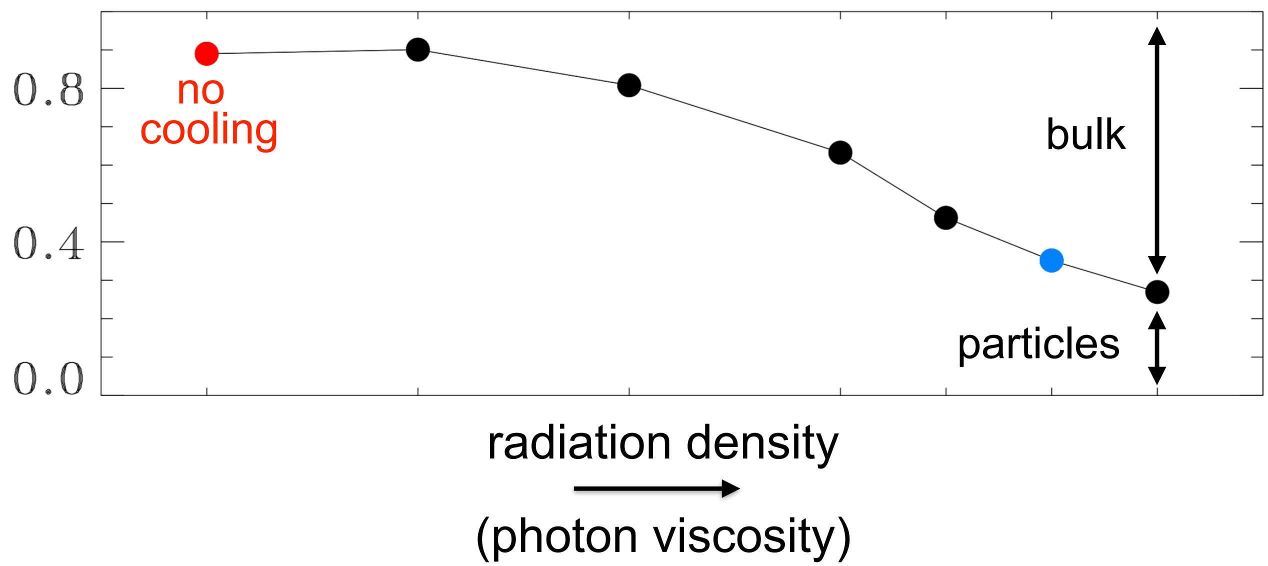
kinetic (PIC) simulation with fixed background radiation exerting Compton drag



Sironi, AB 2020

Partitioning of reconnection power:

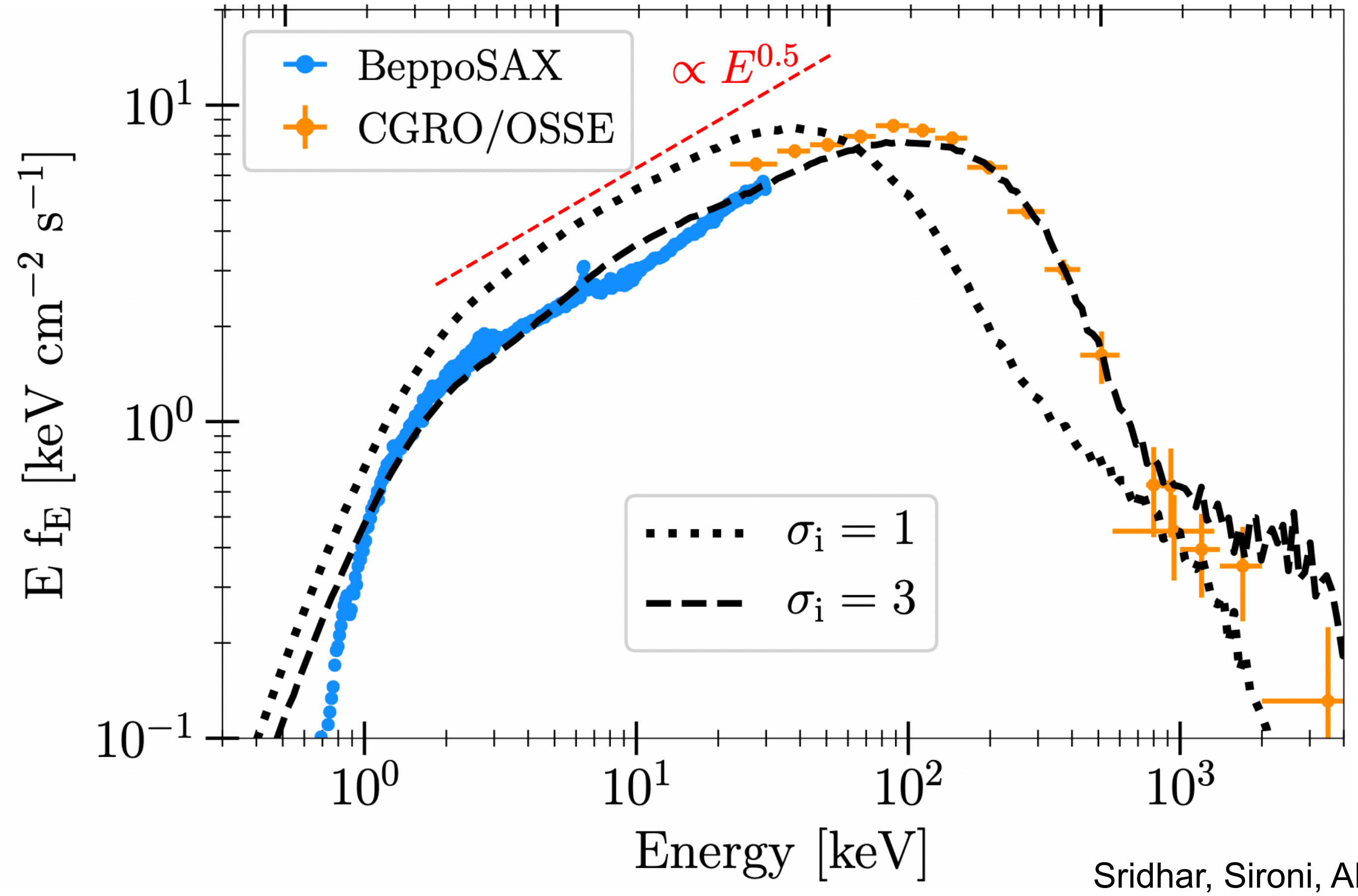
individual particle heating vs. hydro (bulk) motions



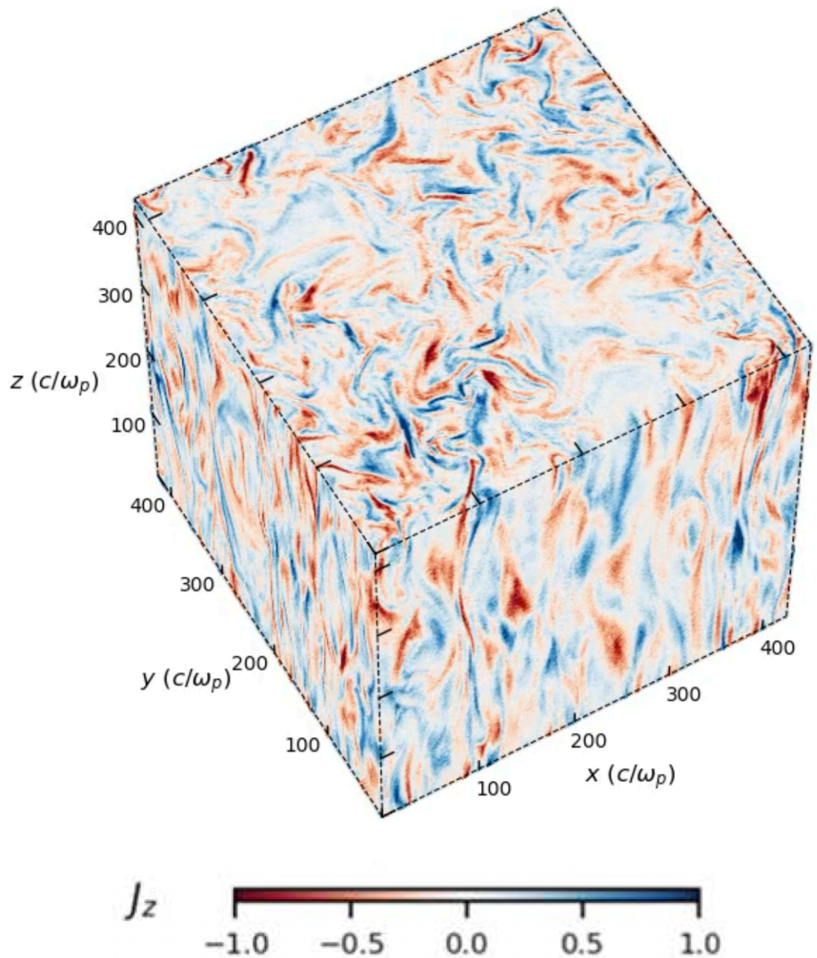
~80% of energy is dissipated through drag on bulk motions

Sironi & AB 2020

Post-processing radiative transfer: comparison with Cyg X-1



Sridhar, Sironi, AB 2022



Radiative turbulent cascade

in a magnetically dominated plasma ($\sigma = 10$)

– losses suppress diffusive particle acceleration

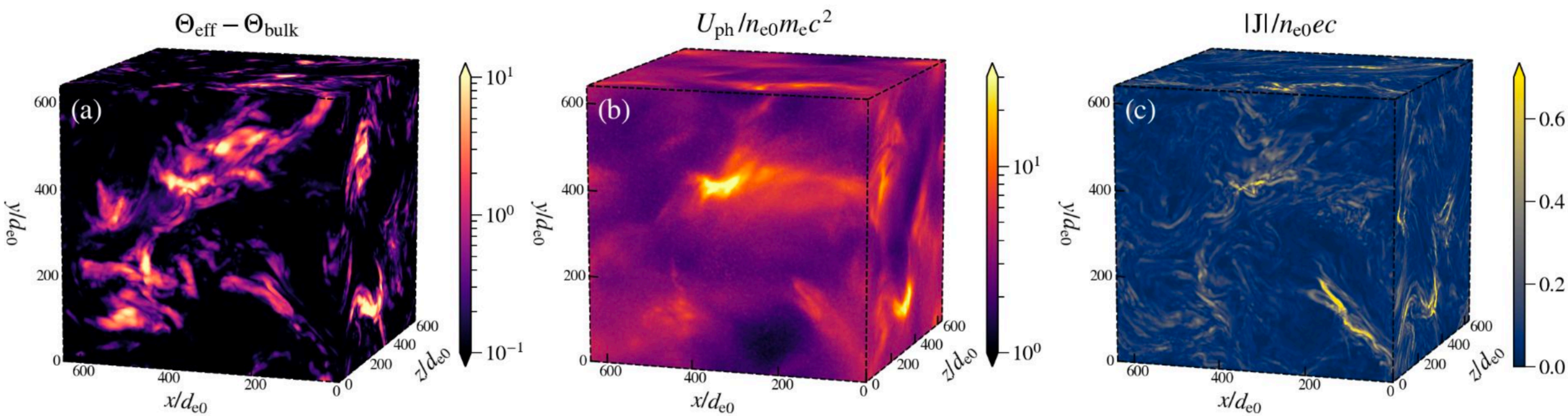
– plasma stays cool

– Compton drag on turbulent fluid motions

Nattila & AB 2021

Turbulent plasma (PIC) + radiative transfer in real time

Groselj et al. 2023



box size / plasma skin depth = 640

grid: 1280 x 1280 x 1280

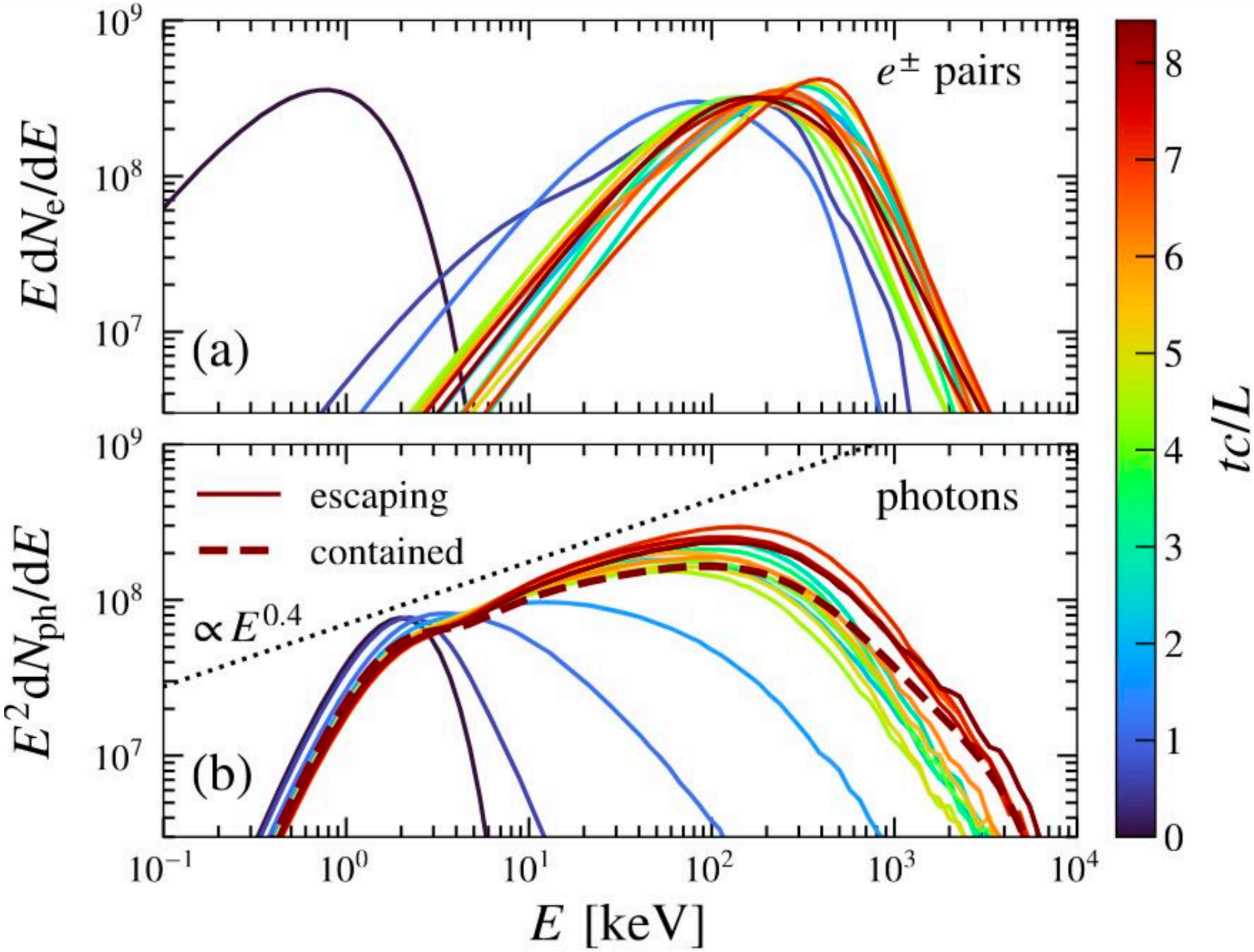
– simplest composition: e+- plasma

– injection of soft (blackbody) photons

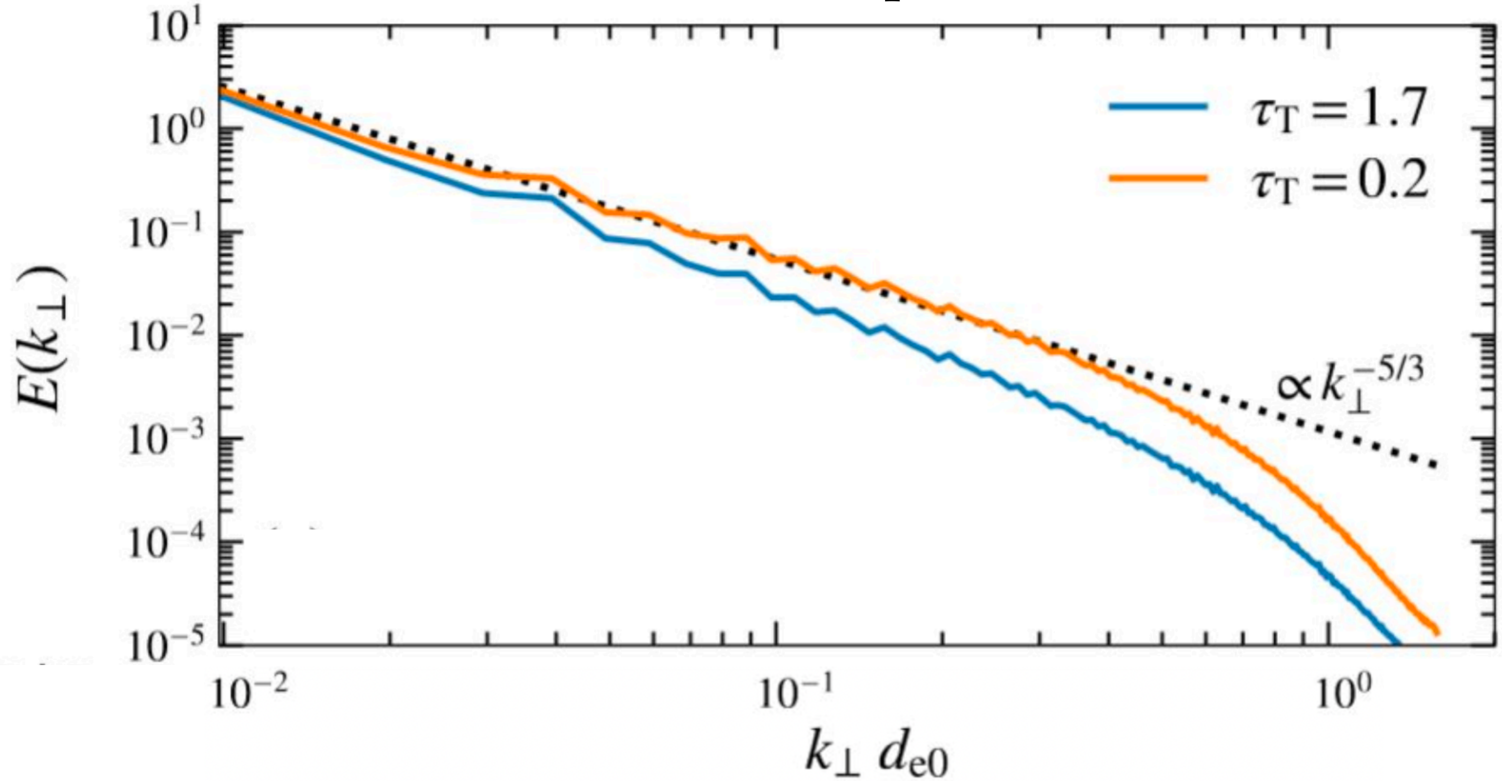
optical depth: $\tau_{\rm T} = \sigma_{\rm T} n \, l_{\rm esc} = 1.7$

magnetization parameter: $\sigma = 2.5$

Evolution to steady state after turbulence activation

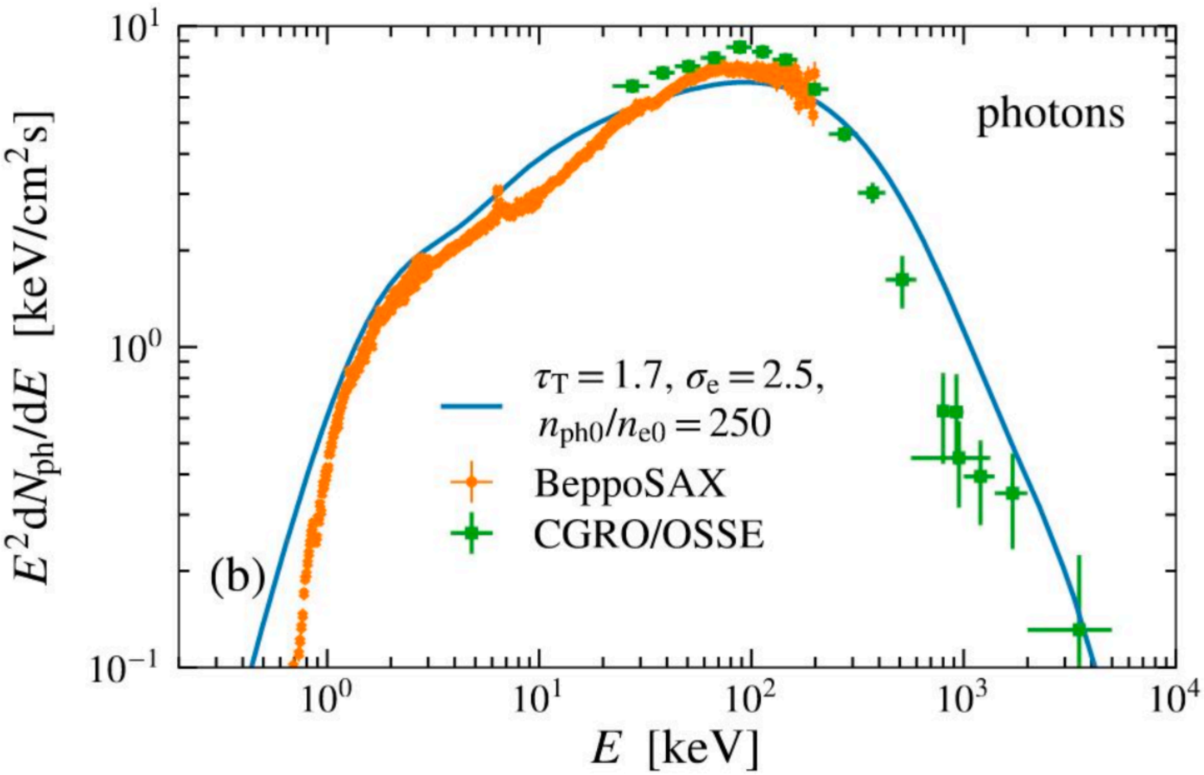


Turbulence spectrum

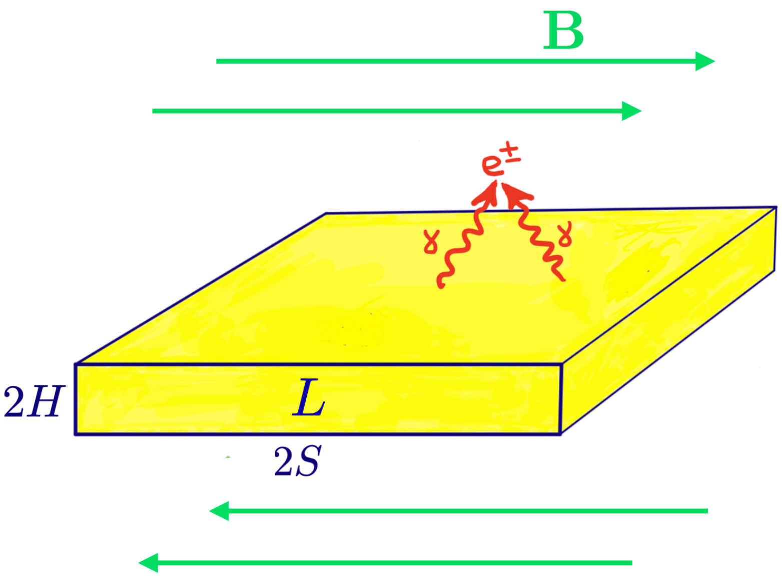


~ 80% of turbulence energy is radiated by "turbulent Comptonization"
— scattering by turbulent fluid motions

Escaping radiation spectrum: comparison with Cyg X-1



Magnetar bursts:
optically thick e+- plasma



$$\ell_B \equiv \frac{U_B}{m_e c^2}\,\sigma_{\rm T} S \approx 3 \times 10^5 \; B_9^2 \, S_7$$

AB 2021

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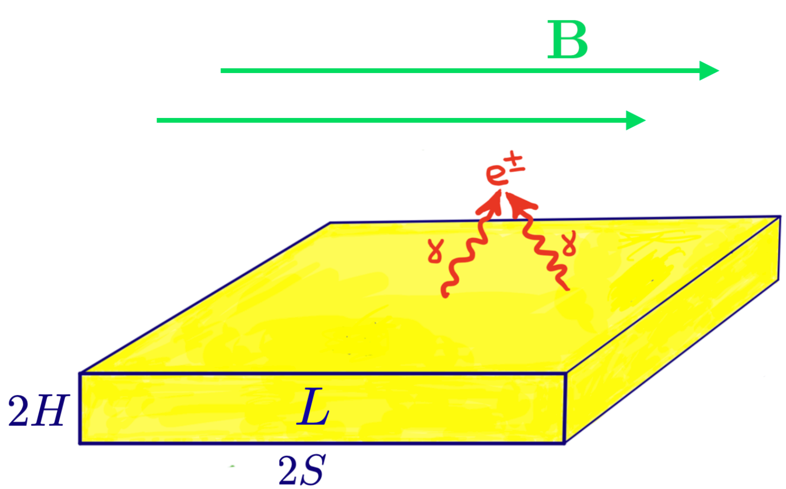
optically thick e+- plasma



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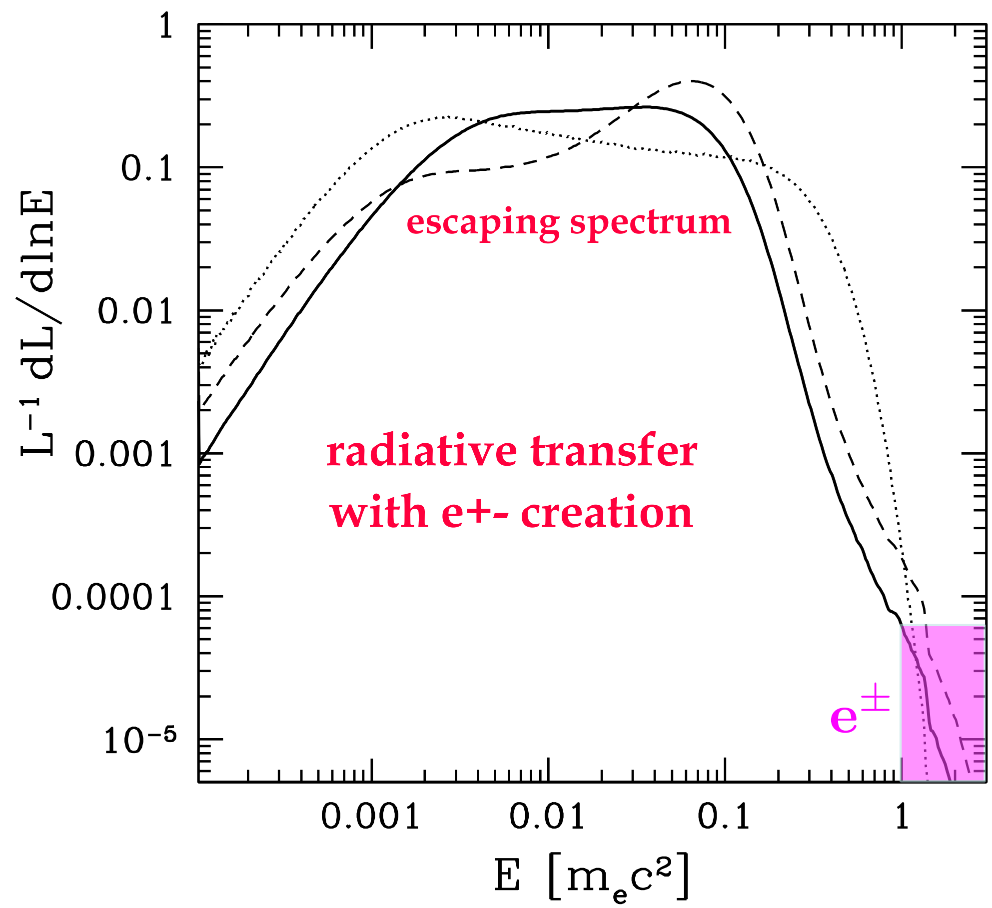

$$\frac{n_\pm}{n_\gamma} \sim 10^{-5}$$

$$\frac{kT}{m_e c^2} \sim 0.1$$

AB 2021

Summary

- 4 mechanisms for fast dissipation:

  magnetic reconnection, turbulent cascade, collision of strong Alfven waves, shocks

  ~10 light crossing times ~1 light crossing time

- In bright compact sources radiation keeps plasma cool and exerts drag on plasma bulk motions. Magnetic energy is dissipated via photon viscosity.

  Radiation gains main energy from stochastic fluid motions (driven by magnetic stresses) rather than from individual particles

- The first kinetic plasma simulation of magnetic dissipation with real-time Comptonization of ambient soft radiation has been performed.

  The found Comptonized spectrum is consistent with the hard state of black holes

- Magnetar bursts: e+- pairs with $\tau_{\rm T} \gg 1$, producing hard X-rays