Title: Radiation from fast magnetic dissipation around compact objects

Speakers: Andrei Beloborodov

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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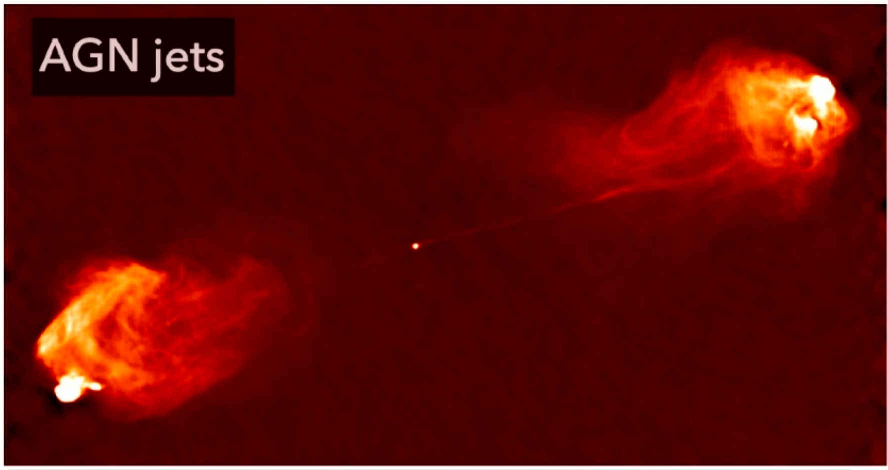
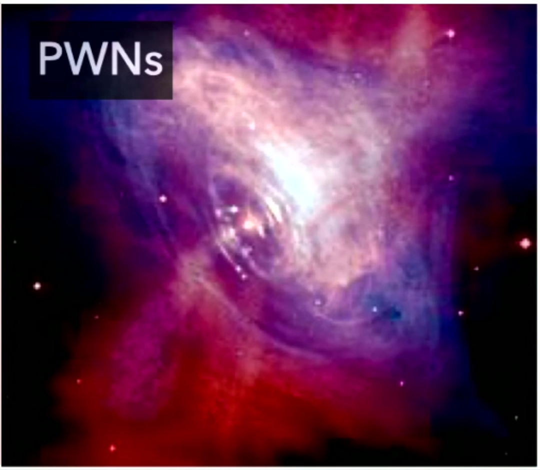
Abstract:

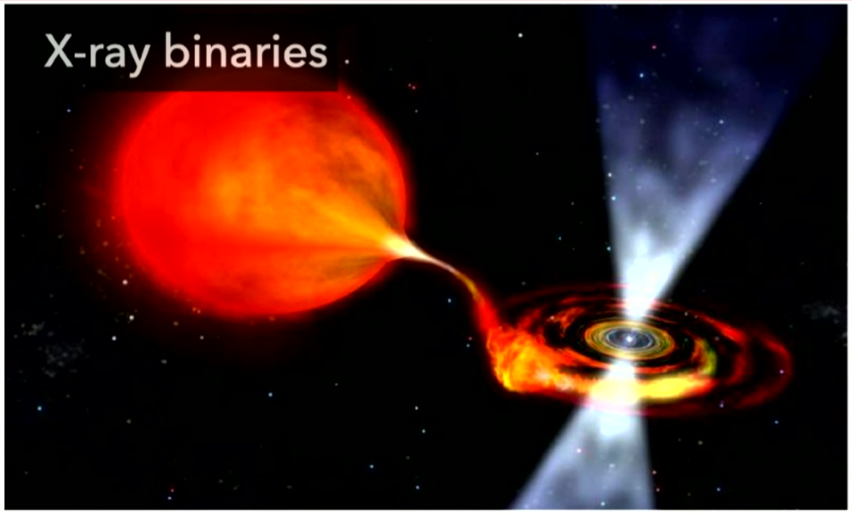
Fast magnetic dissipation powers the bursting activity of isolated neutron stars, merging neutron stars, and flares from black holes. Four mechanisms of fast dissipation can operate in the magnetospheres of compact objects: Alfvenic turbulent cascade, magnetic reconnection, collision of Alfvén waves, and monsters shocks. Radiation produced by these dissipation modes is controlled by the compactness parameter. The main radiative output is usually in X-rays; in some cases, radio bursts are produced.

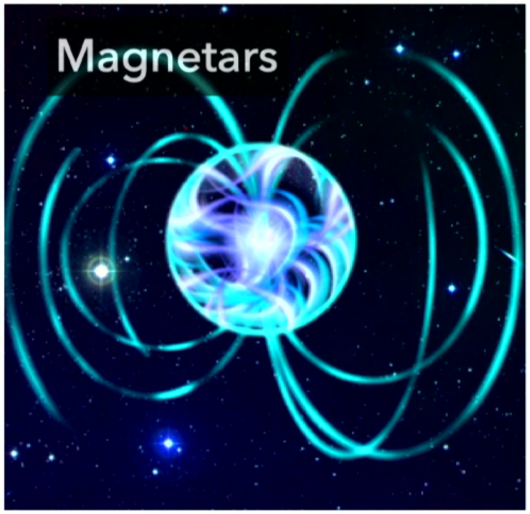
Radiation from fast magnetic dissipation around compact objects

Andrei Beloborodov









magnetically dominated corona/jet/magnetosphere $\sigma = B^2/4\pi\rho c^2 \gtrsim 1$

Plasma magnetization

$$\boxed{\sigma \equiv \frac{B^2}{4\pi n m_e c^2} = \frac{\omega_B^2}{\omega_p^2} \gg 1}$$

$$\omega_B = \frac{eB}{m_e c}$$

$$\omega_p = \left(\frac{4\pi e^2 n}{m_e}\right)^{1/2}$$

magnetic energy per particle $\gg m_e c^2$ (e+- plasma)

Alfven waves propagate with speed of light: $\frac{v_{\mathrm{A}}}{c} = \sqrt{\frac{\sigma}{1+\sigma}}$

characteristic timescale ~ light-crossing time

Mechanisms for fast magnetic dissipation

1. Turbulence cascade
2. Reconnection (tearing)

~10 light crossing times
(dissipation on small scales)

RMHD

3. Collision of relativistic Alfven waves
4. Monster shocks

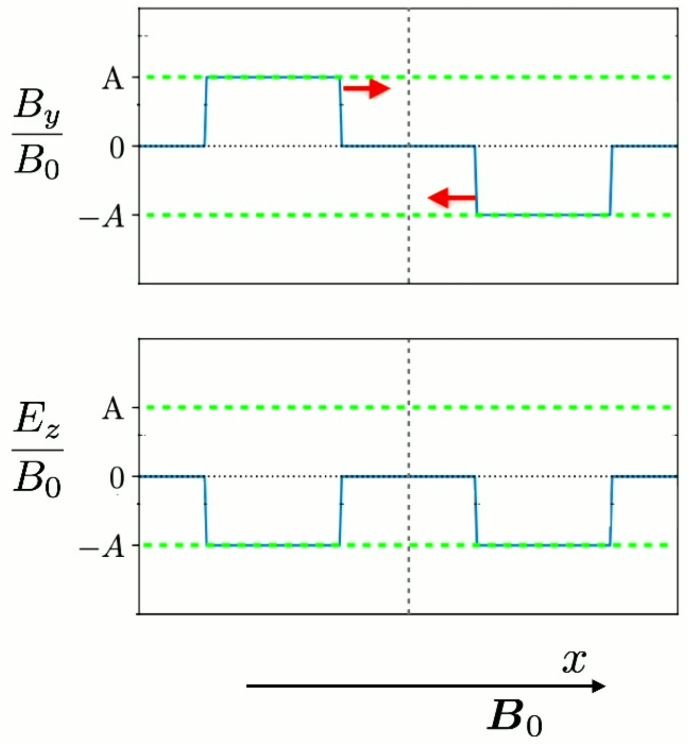
~1 light crossing time
$(E^2 - B^2 \to 0)$

slower “resistive” dissipation: electric discharge (charge starvation)
radiative drag resisting electric current

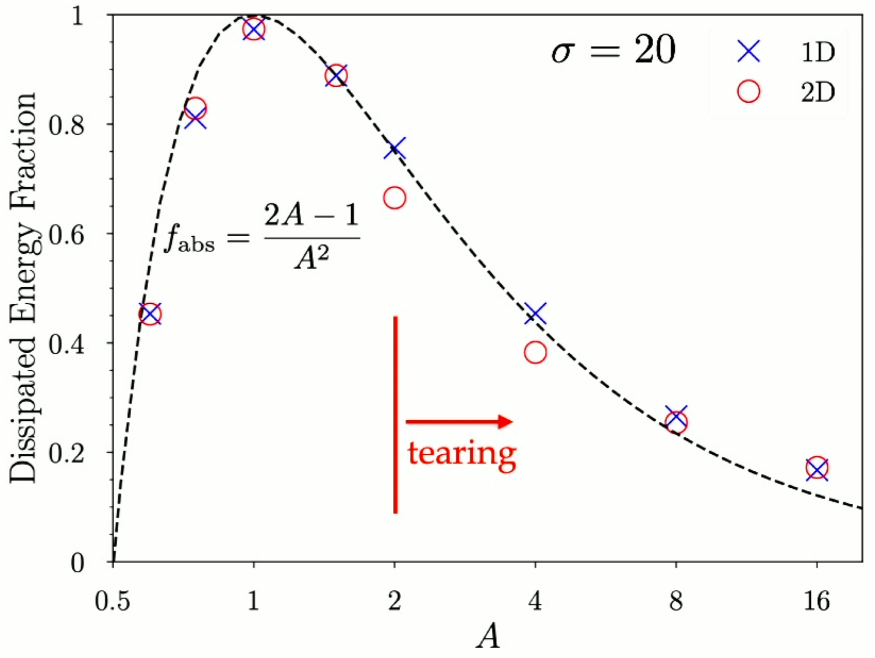
— talks by Jens Mahlmann, Sasha Philippov

Collision of two strong Alfven waves

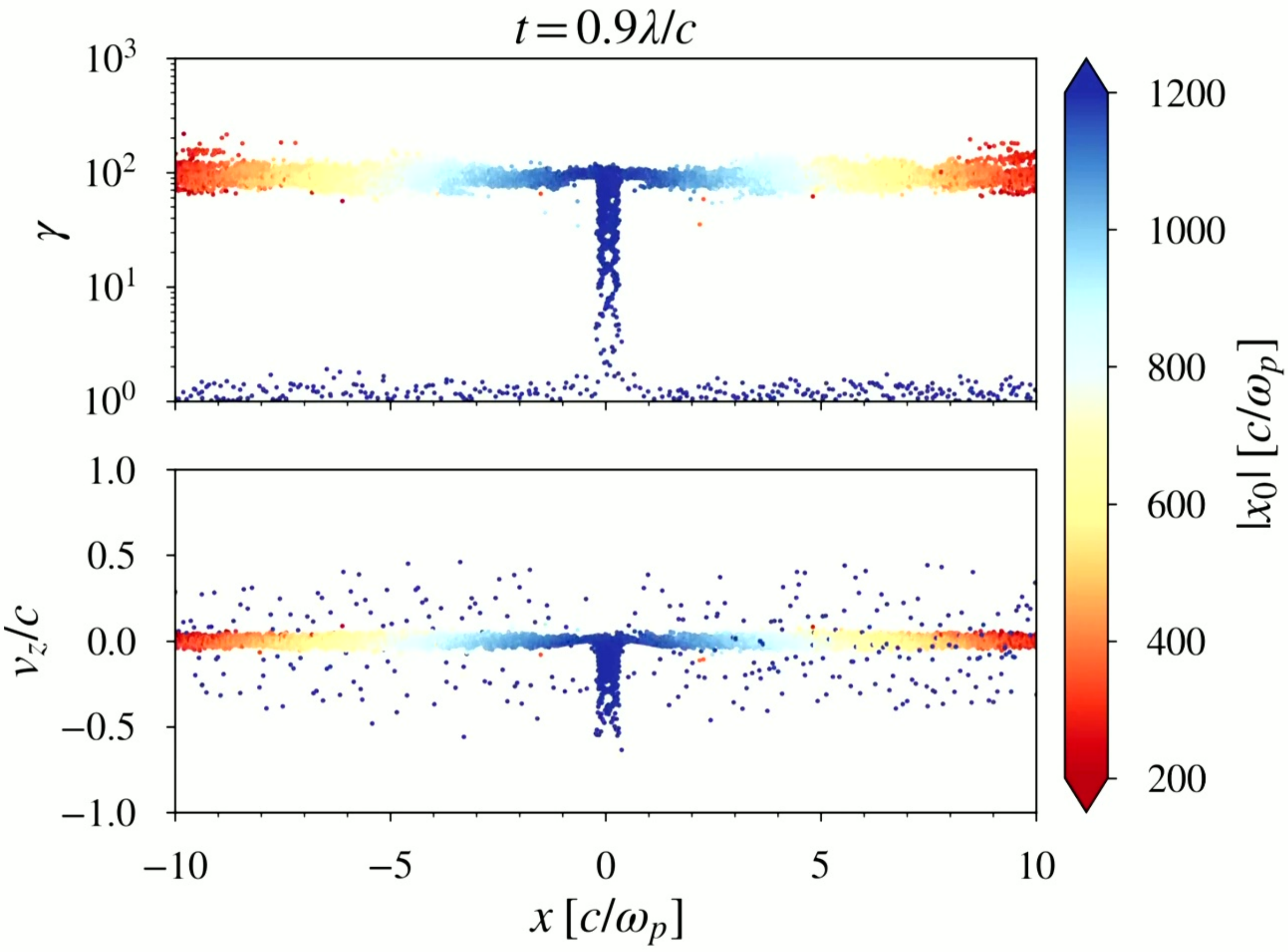
$$\boldsymbol{B} = (B_0, B_y, 0)$$
$$\boldsymbol{E} = (0\,,\,0\,,\,E_z)$$

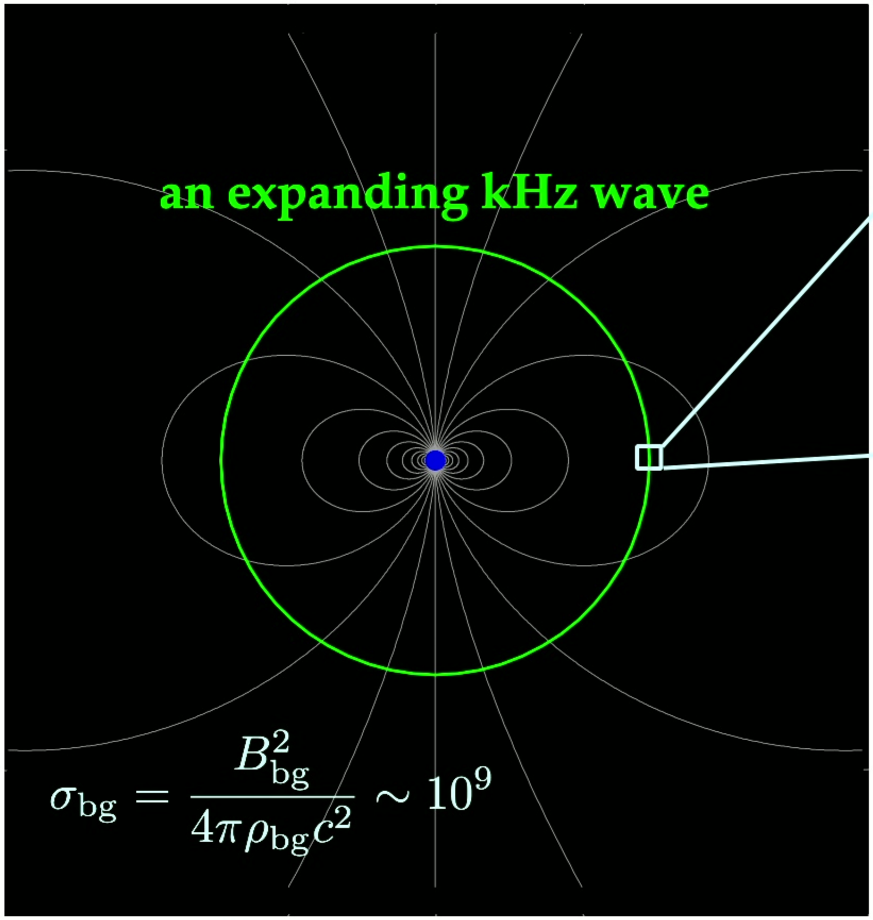


PIC simulations



Li, AB, Sironi 2021


$t = 0.9\lambda/c$
10^3
10^2
10^1
10^0
γ
1.0
0.5
0.0
−0.5
−1.0
v_z/c
−10
−5
0
5
10
$x\ [c/\omega_p]$
1200
1000
800
600
400
200
$|x_0|\ [c/\omega_p]$



$$\sigma_{\rm bg} = \frac{B_{\rm bg}^2}{4\pi\rho_{\rm bg}c^2} \sim 10^9$$

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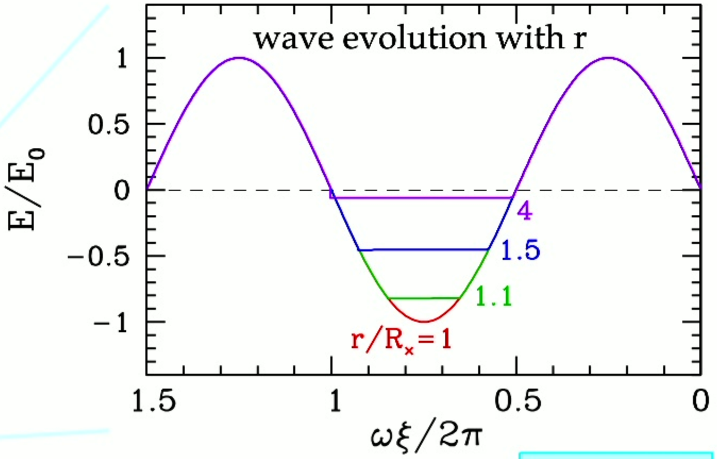
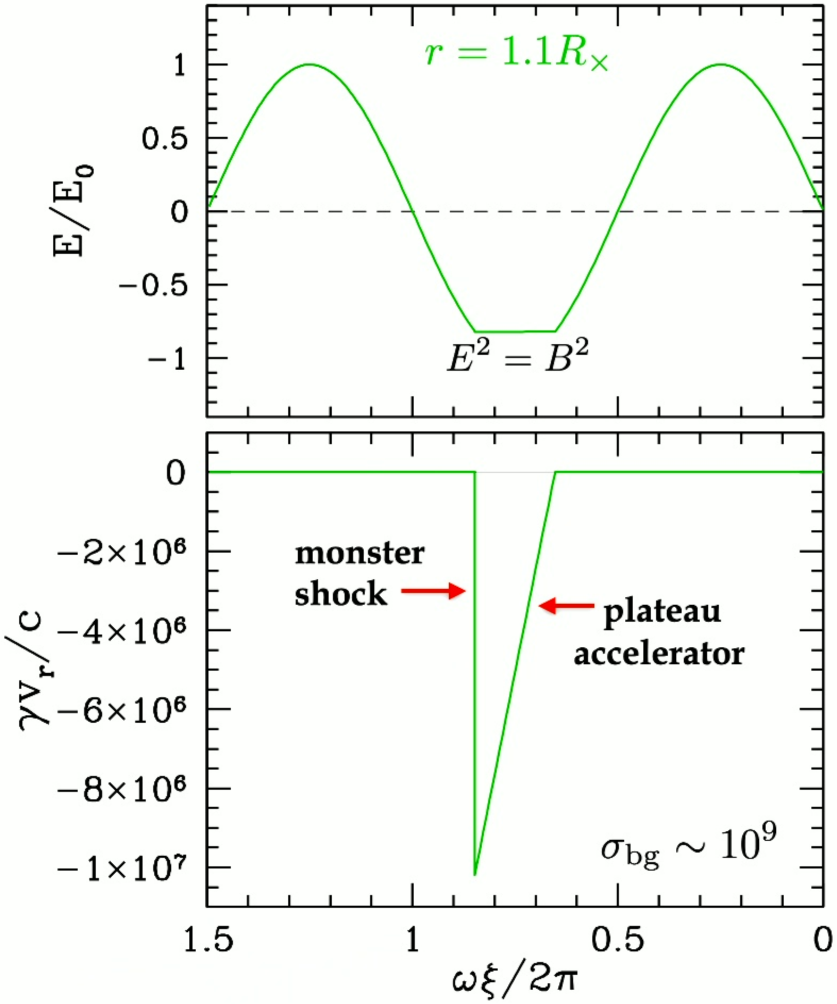


$$\boxed{\xi \equiv t - \frac{r}{c}}$$

initial profile: $E(\xi) = E_0 \sin(\omega\xi)$

plateau: $|E| = |B| = \dfrac{B_{\rm bg}}{2} \propto r^{-3}$

AB 2023



plateau: a linear accelerator

plateau width $W_{\rm p} \sim \dfrac{c}{\omega}$

$$\boxed{\gamma = \frac{W_{\rm p}}{r}\,\sigma_{\rm bg}} \sim 10^7\,!$$

1. Turbulence cascade
2. Reconnection (tearing)
3. Collision of relativistic Alfven waves
4. Monster shocks

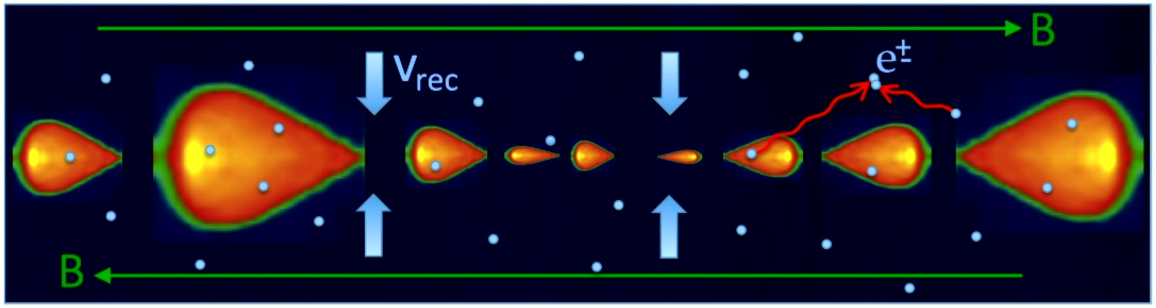
work on particles in a magnetized plasma can be done by “ideal” or “non-ideal” E

$$\boldsymbol{E}' = \gamma \left(\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c} \right)$$

non-ideal E: unscreened E′ on small scales ("injection" at X-points in reconnection, Landau damping in turbulence cascade; Larmor-mediated shock)

ideal E (E′=0): diffusive acceleration of nonthermal particles
bulk acceleration (reversible): "snapping" in reconnection
upstream acceleration in monster shocks
in a radiation field: friction — irreversible damping

Radiative magnetic reconnection

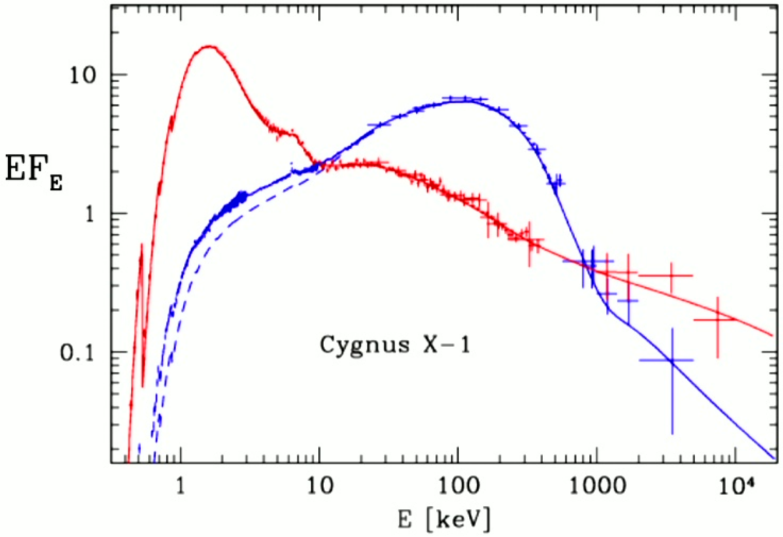


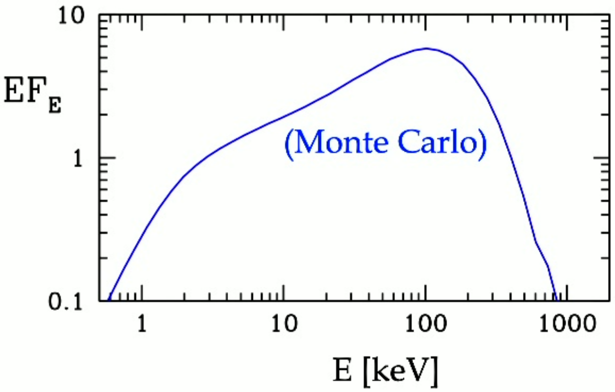
- Compton cooling keeps most of the plasma cold
- B stresses pull plasma through radiation drag

dissipation:

photon upscattering by moving cold plasmoids

(photon viscosity)

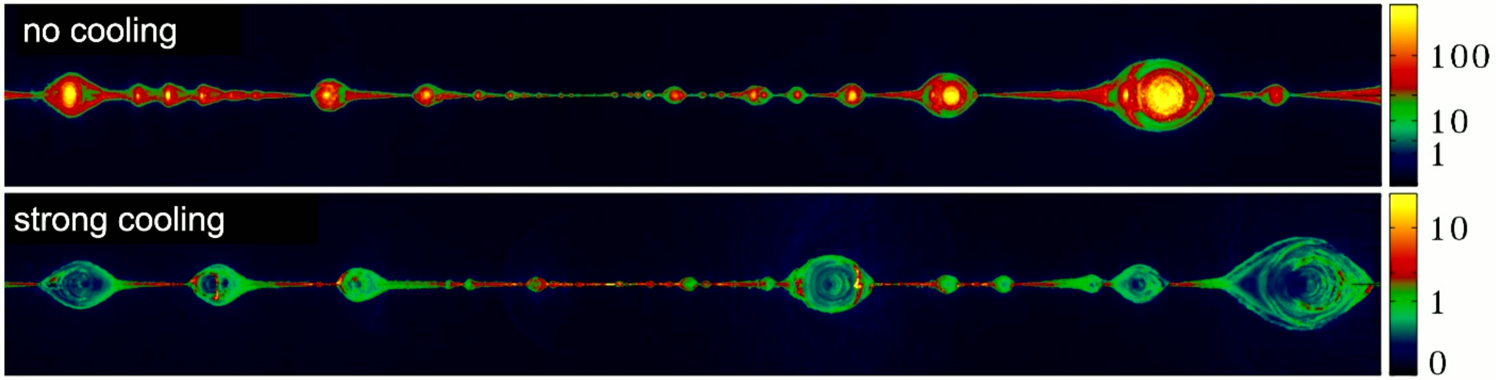




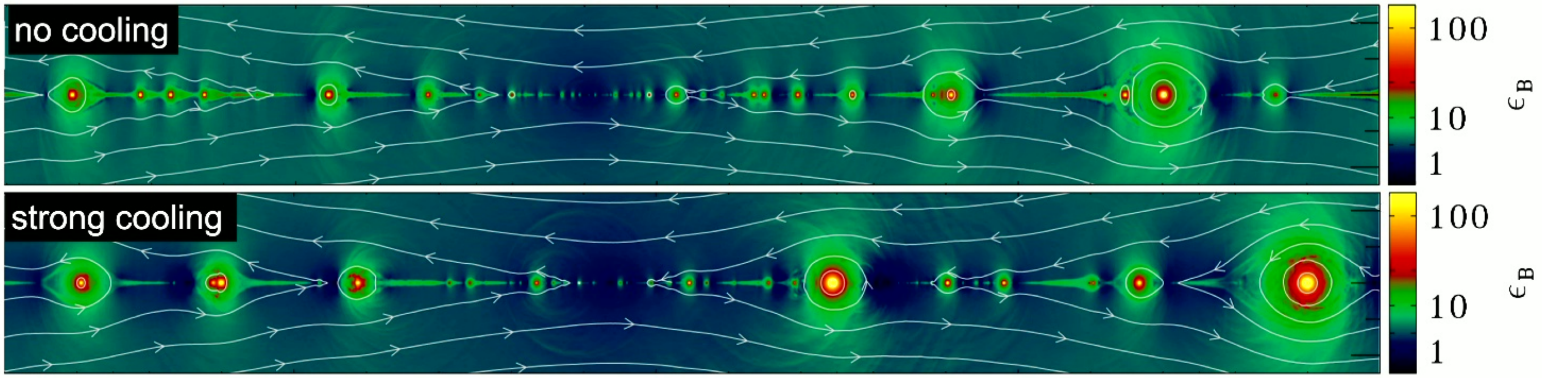
AB 2017

Kinetic simulations

heat



magnetic energy

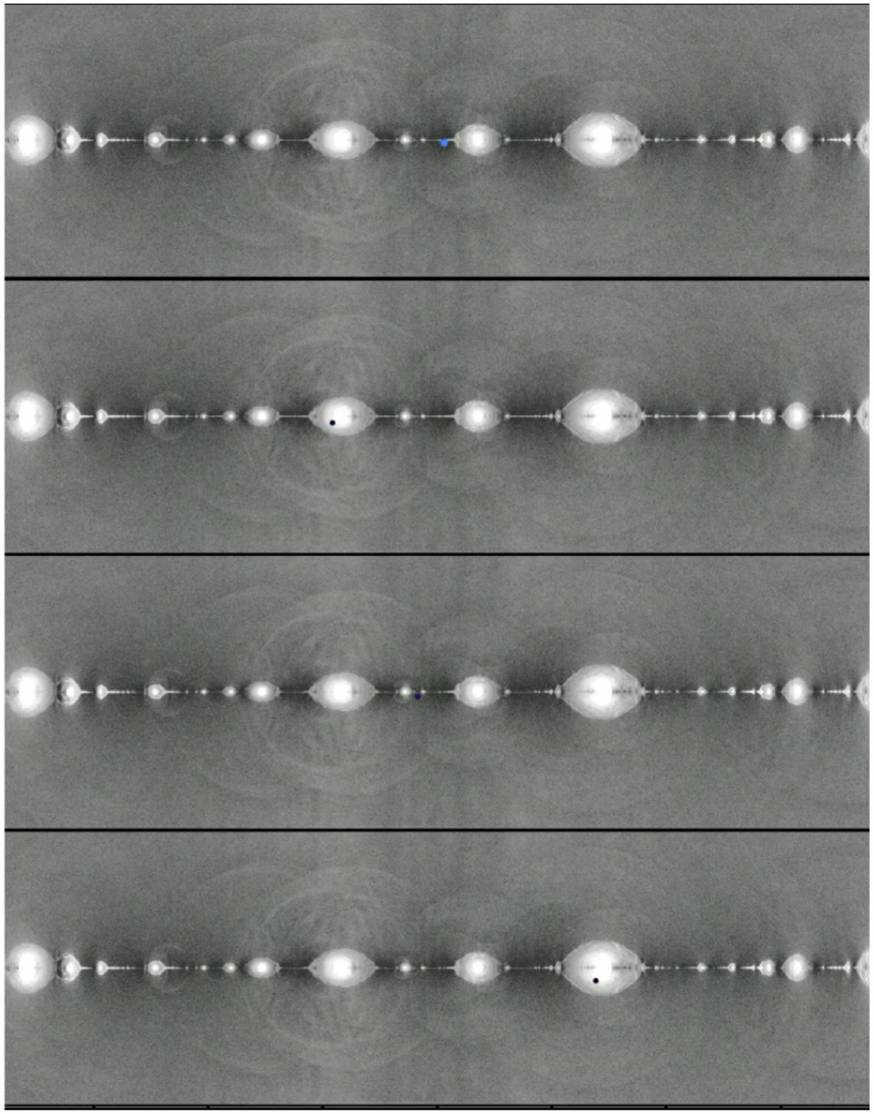


Sironi & AB 2020

PIC+ radiative transfer (Comptonization) in real time

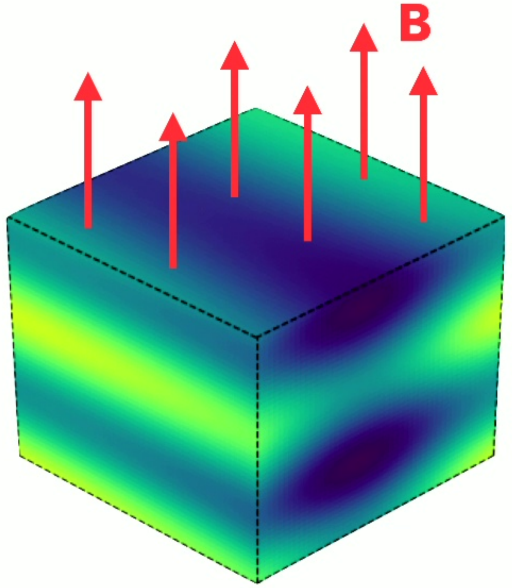
$e^{\pm}$

$\sigma = 10$



Hakobyan et al.
in preparation

Magnetically dominated turbulence



Kinetic simulations

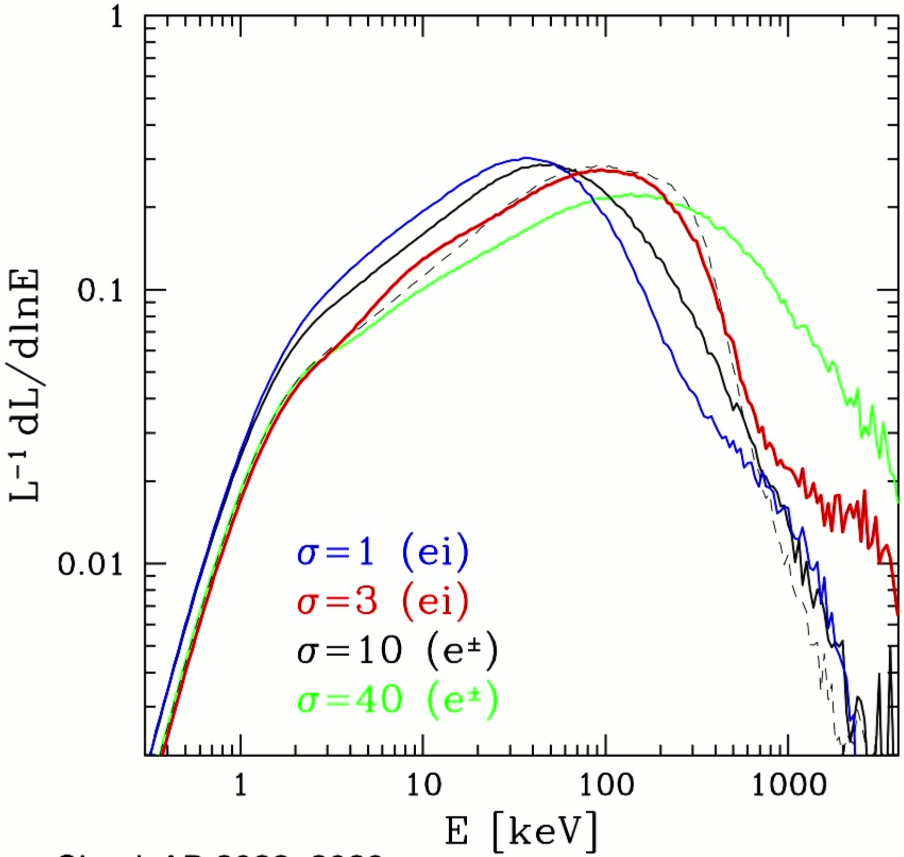
Zhdankin et al. 2018, 2019
Comisso & Sironi 2018, 2019
Nattila & AB 2021, 2022
Groselj et al. 2023

Excitation $\delta B/B \sim 1$ on a large scale l_0

→ turbulence cascades to scales $l \ll l_0$ where it dissipates

dissipation heats the plasma and accelerates particles

post-processing radiative transfer



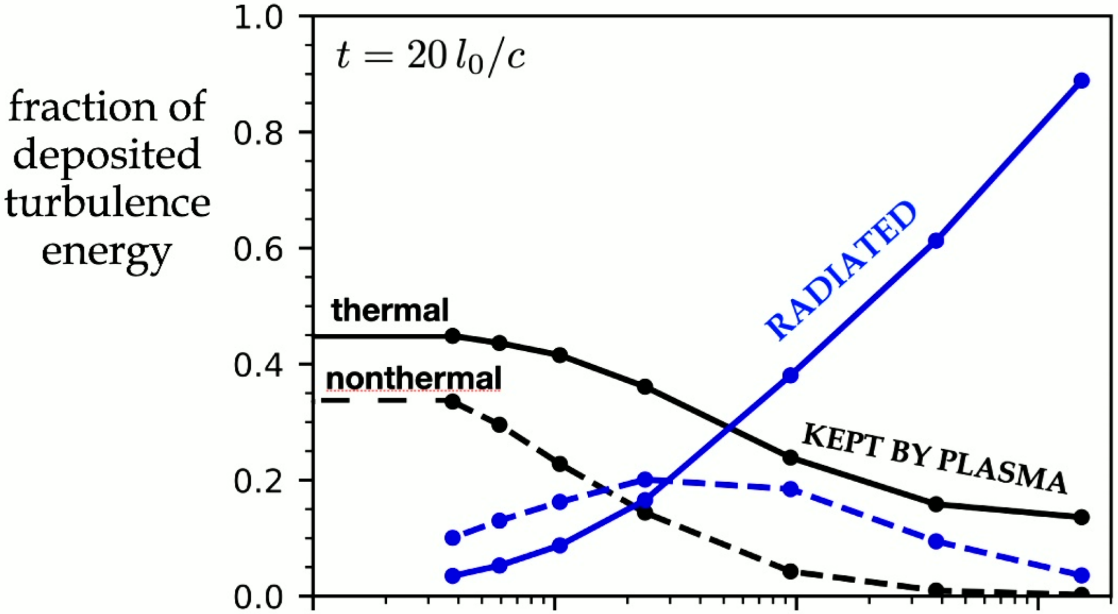
Sridhar, Sironi, AB 2022, 2023

- 2T plasma
- Coulomb coupling is marginal

Moderate sigma (a few) is consistent with observed hard-state spectrum

— see Navin Sridhar's talk

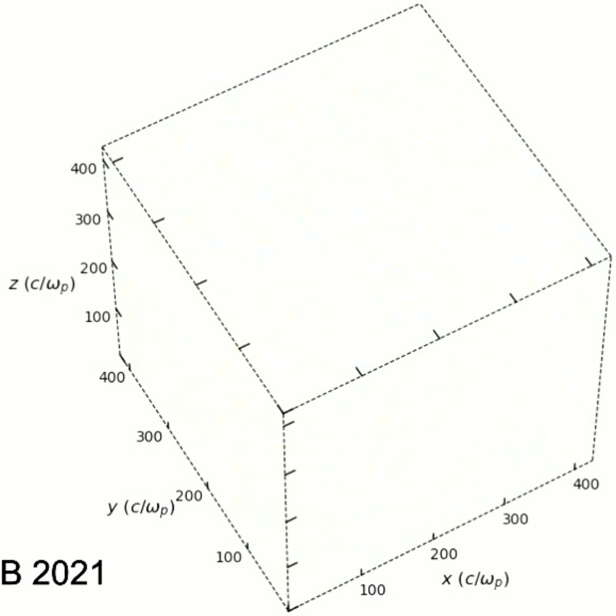
Energy partition in radiative turbulence



cooling parameter $\mathcal{A}$

$$\left(\dot{\gamma}_{\rm cool} = -\mathcal{A}\,\frac{c}{l_0}\,\gamma^2\right)$$

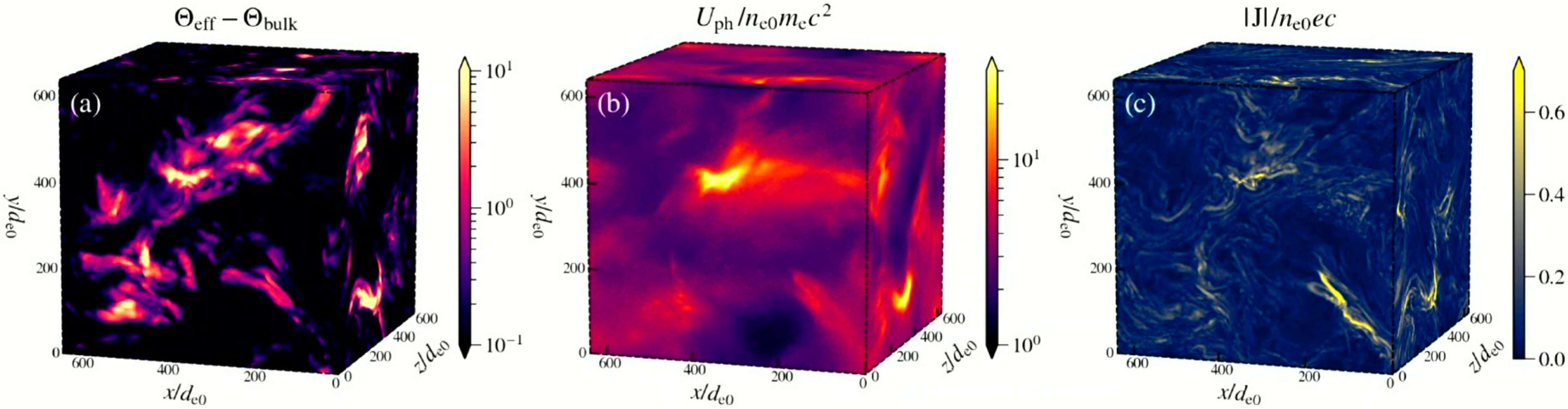
- losses suppress diffusive particle acceleration
- plasma stays cool
- energy is radiated by bulk motions



Nattila & AB 2021

Turbulent plasma (PIC) + radiative transfer in real time

Groselj et al. 2023



box size / plasma skin depth = 640

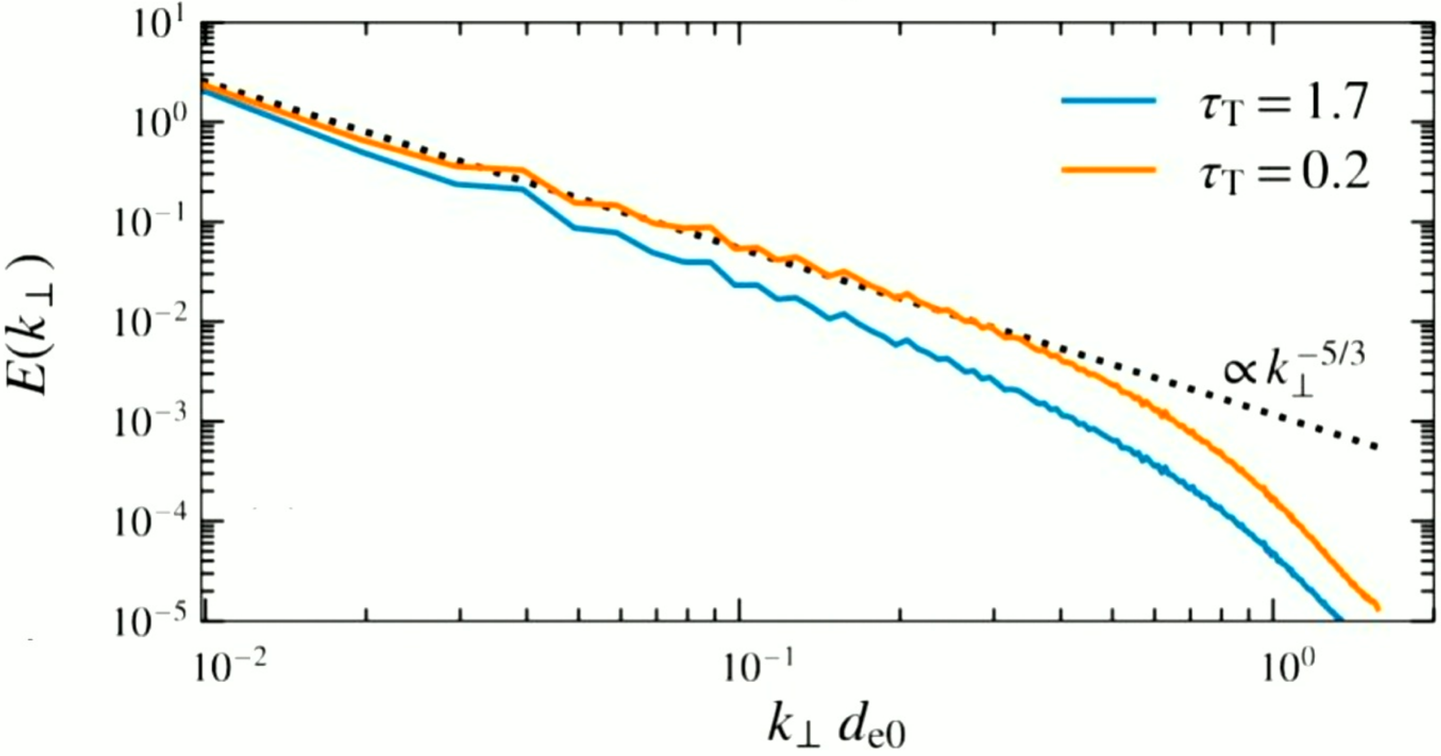
grid: 1280 x 1280 x 1280

- simplest composition: e+- plasma
- injection of soft (blackbody) photons

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

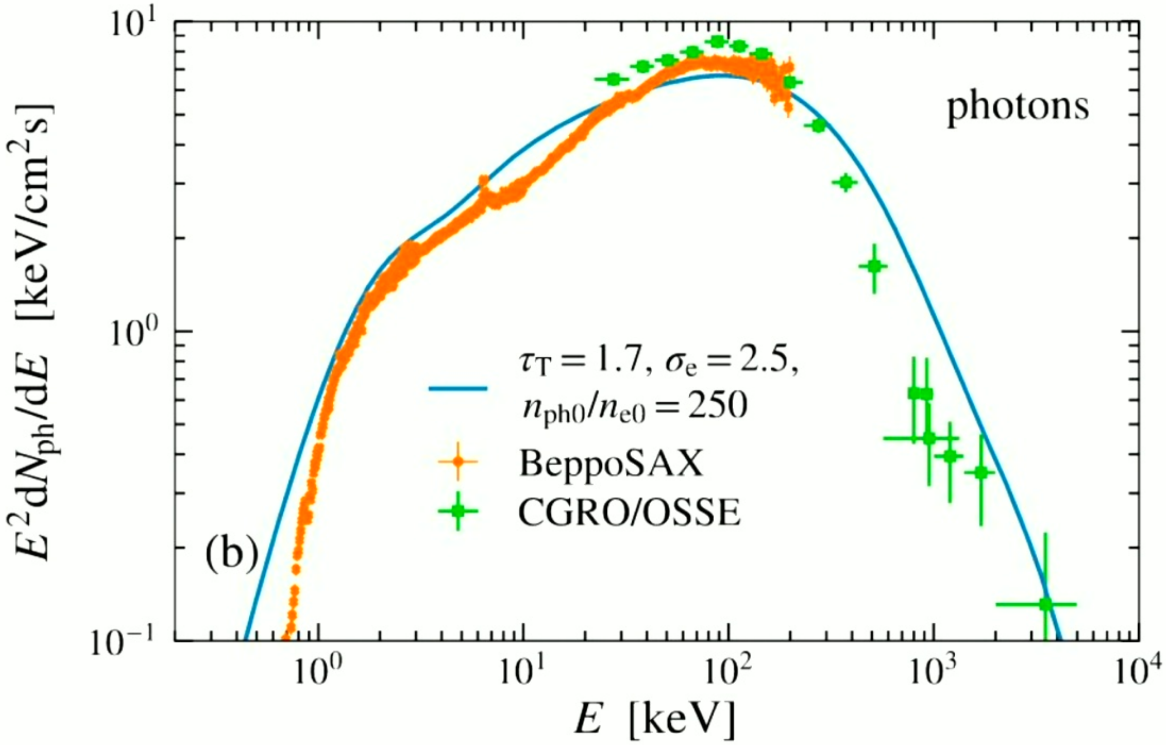
magnetization parameter: $\sigma = 2.5$

Turbulence spectrum



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

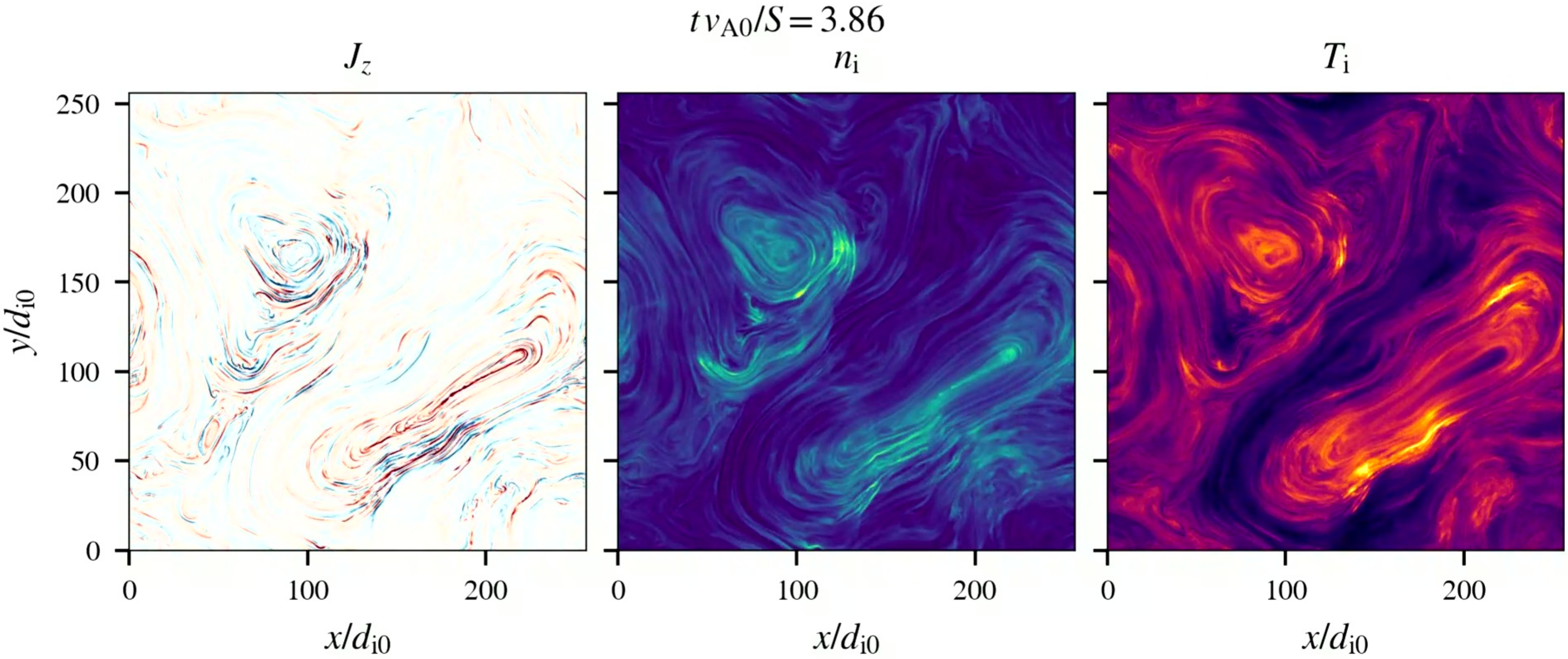
Escaping radiation spectrum: comparison with Cyg X-1

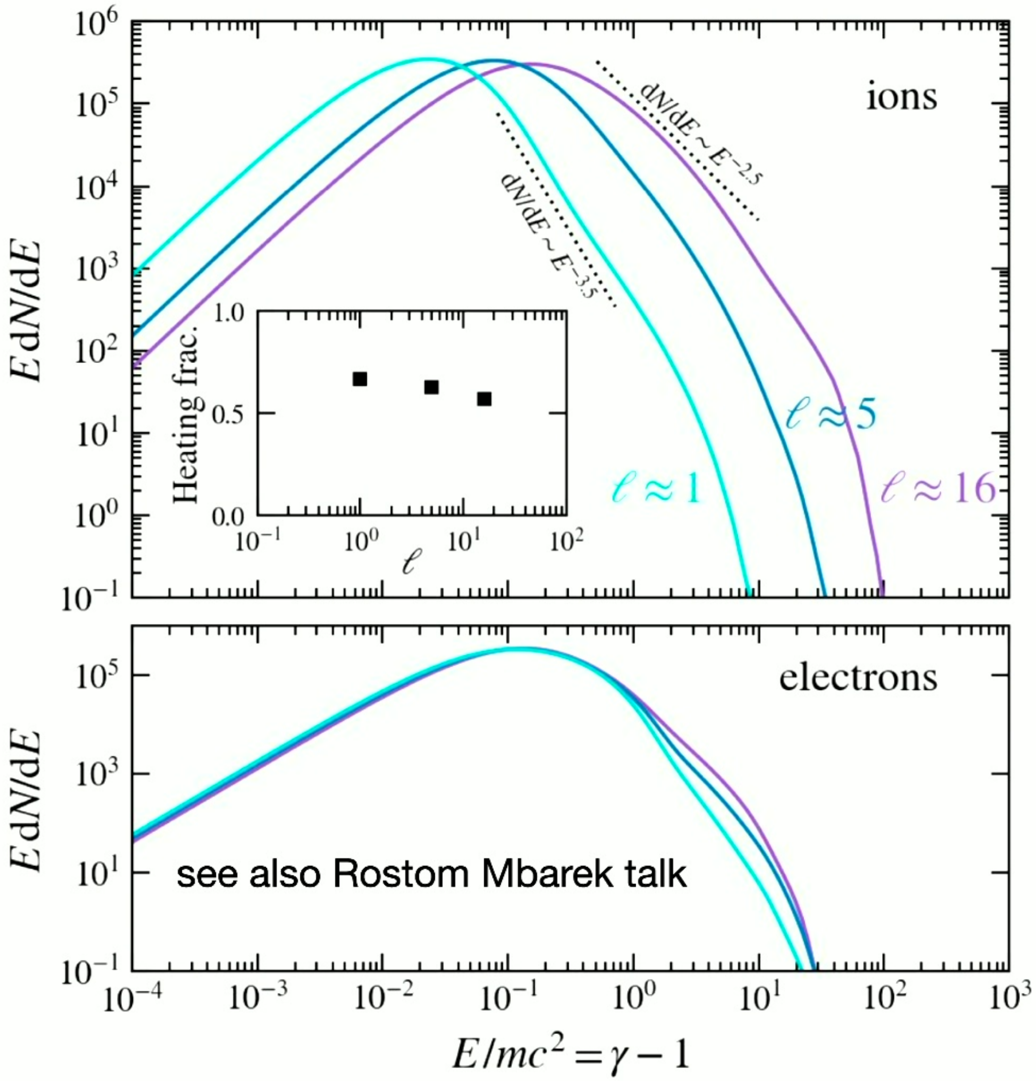


anisotropic luminosity: $L_\perp \approx 3L_\parallel$

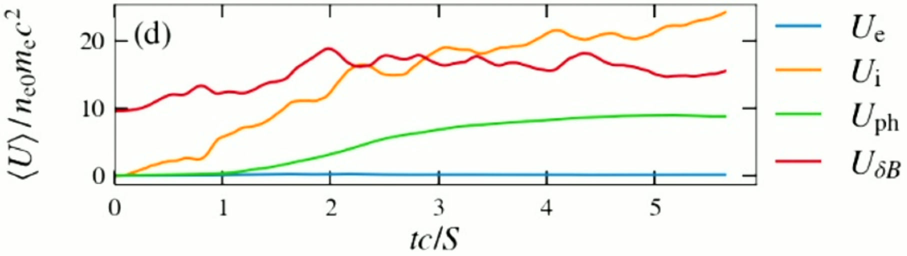
i-e plasma turbulence with radiation

Groselj et al. in preparation



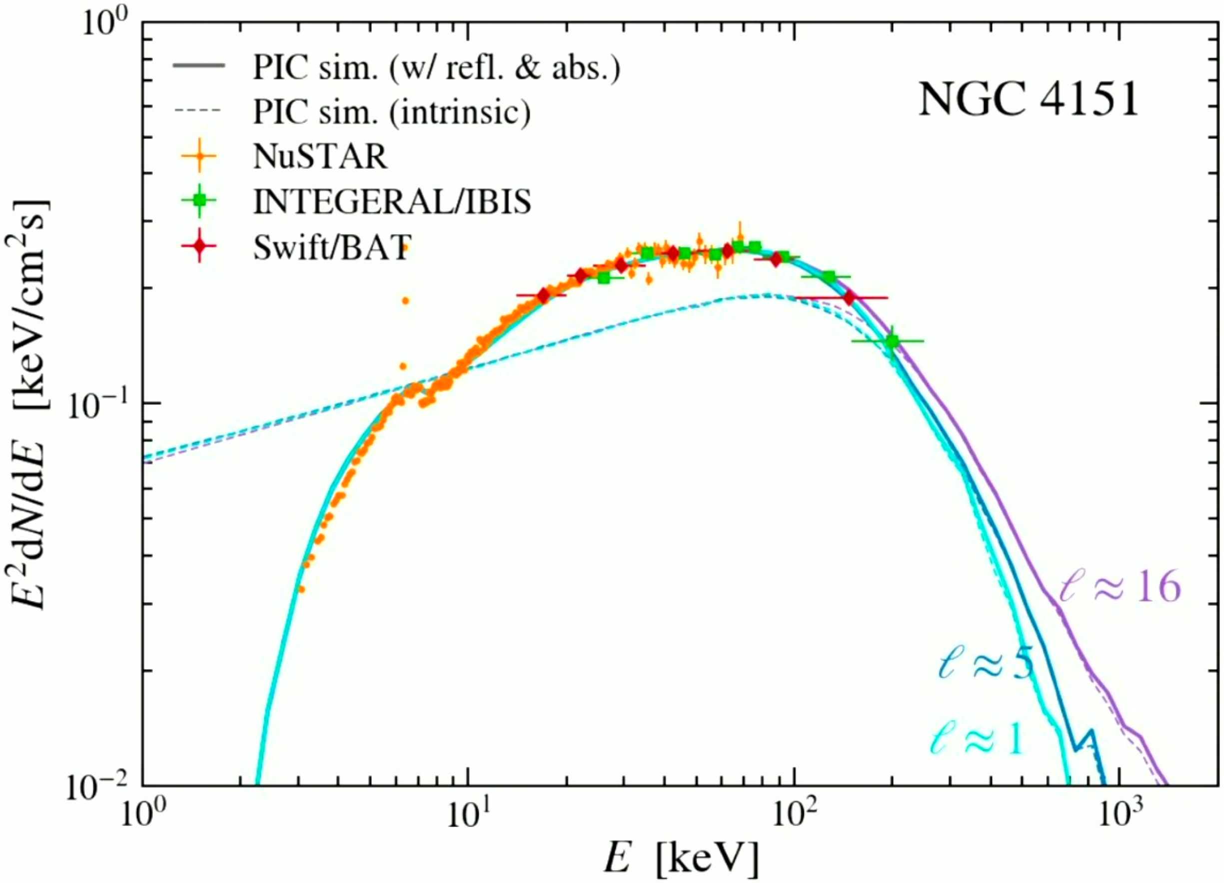


see also Rostom Mbarek talk

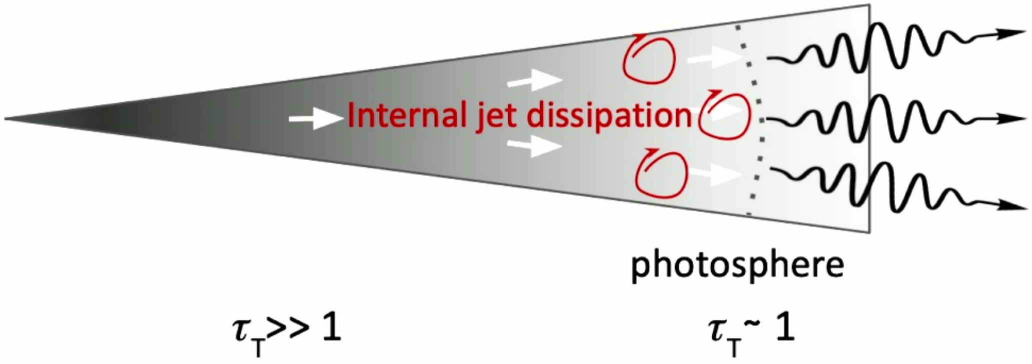


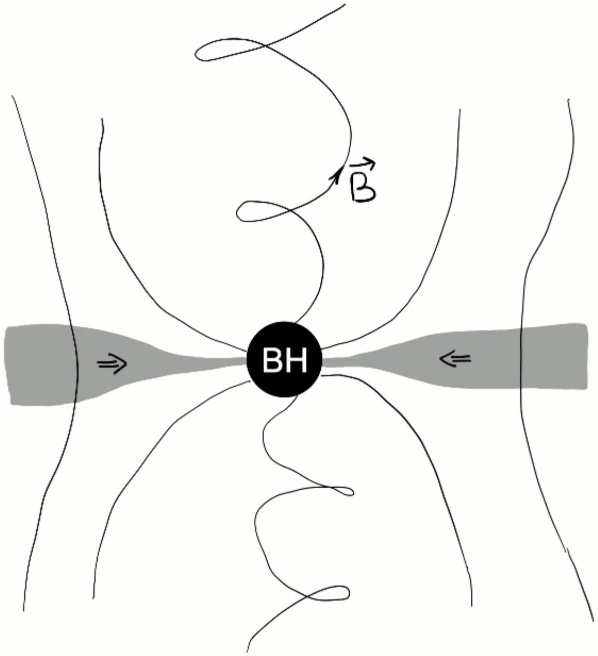
Significant fraction of turbulence power goes to ions, i.e. the ion “heating” fraction is $\gtrsim 50\%$

see also Rostom Mbarek talk


PIC sim. (w/ refl. & abs.)
PIC sim. (intrinsic)
NuSTAR
INTEGERAL/IBIS
Swift/BAT
NGC 4151
$\ell \approx 16$
$\ell \approx 5$
$\ell \approx 1$
$E^2 \mathrm{d}N/\mathrm{d}E$ [keV/cm^{2}s]
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3
E [keV]

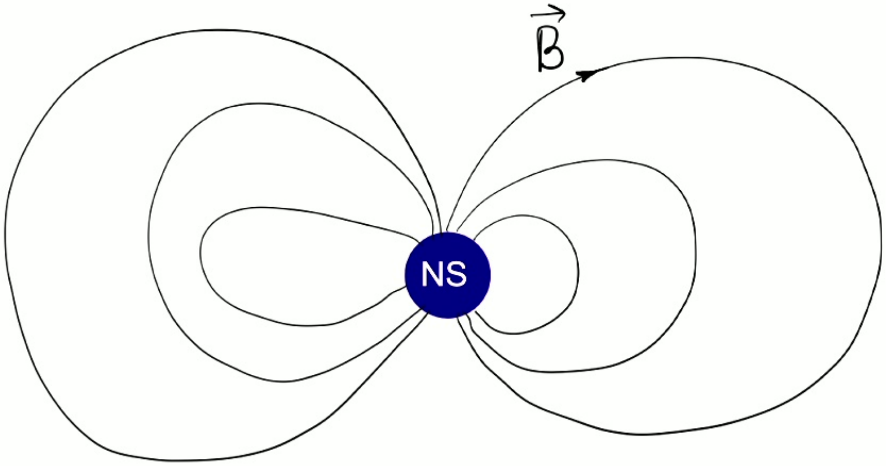
GRBs





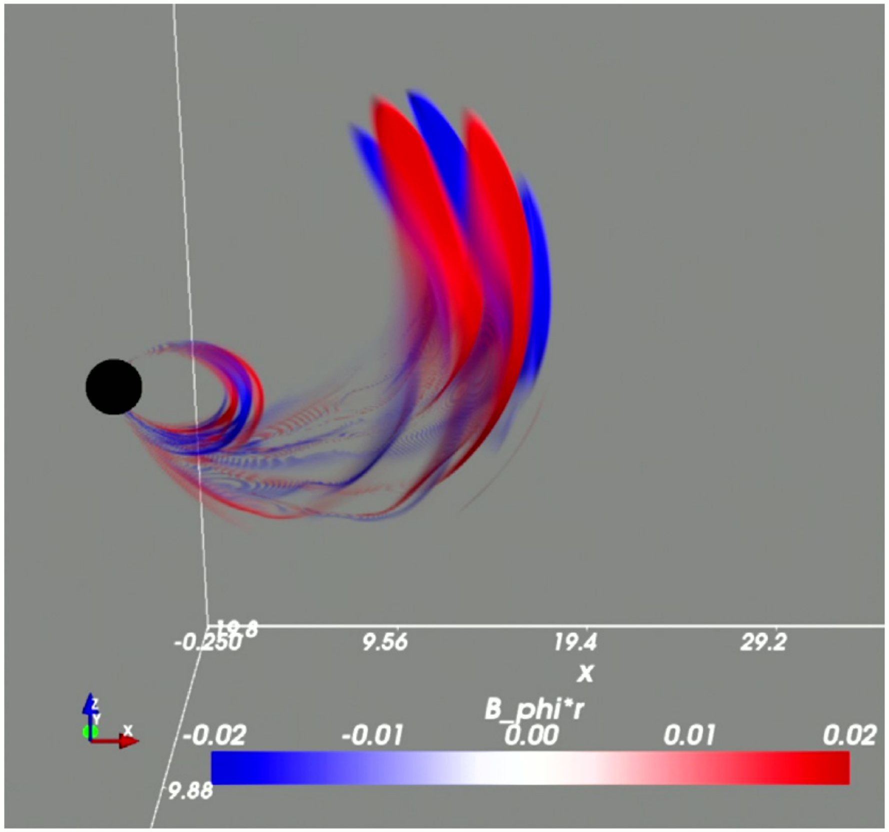
Black holes have externally imposed magnetic fields (brought by accretion)

– lower magnetization, variable, with persistent fast dissipation



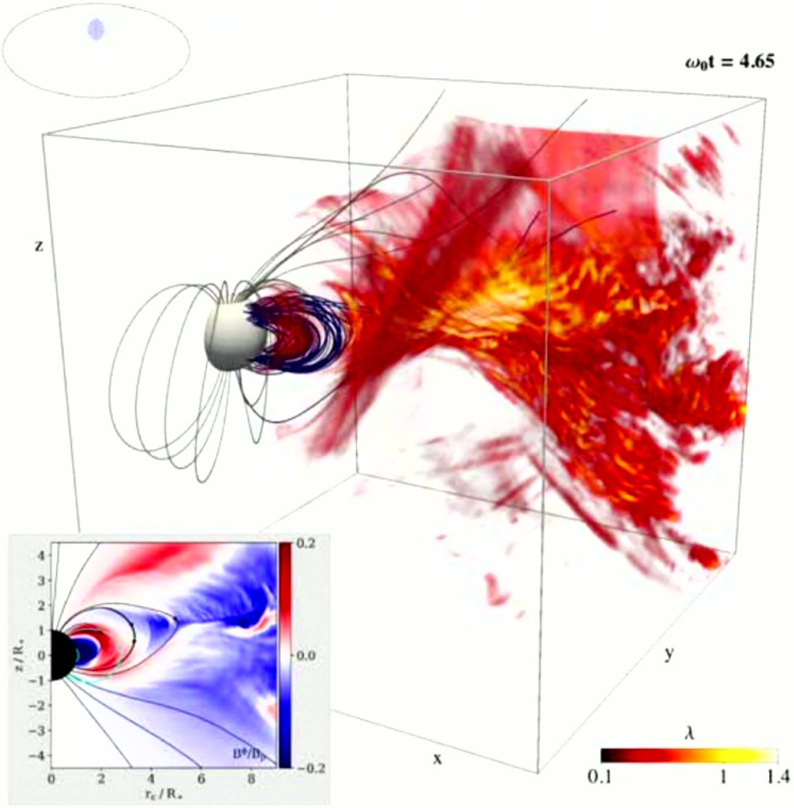
Neutron stars have lold long-lived ulstrastrong magnetic fields

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



Yuan et al. 2022

starquake



Mahlmann et al. 2023

magnetospheric instability

for first MHD simulations see Koushik Chatterjee's talk

"Compactness":

energy density

size of the system

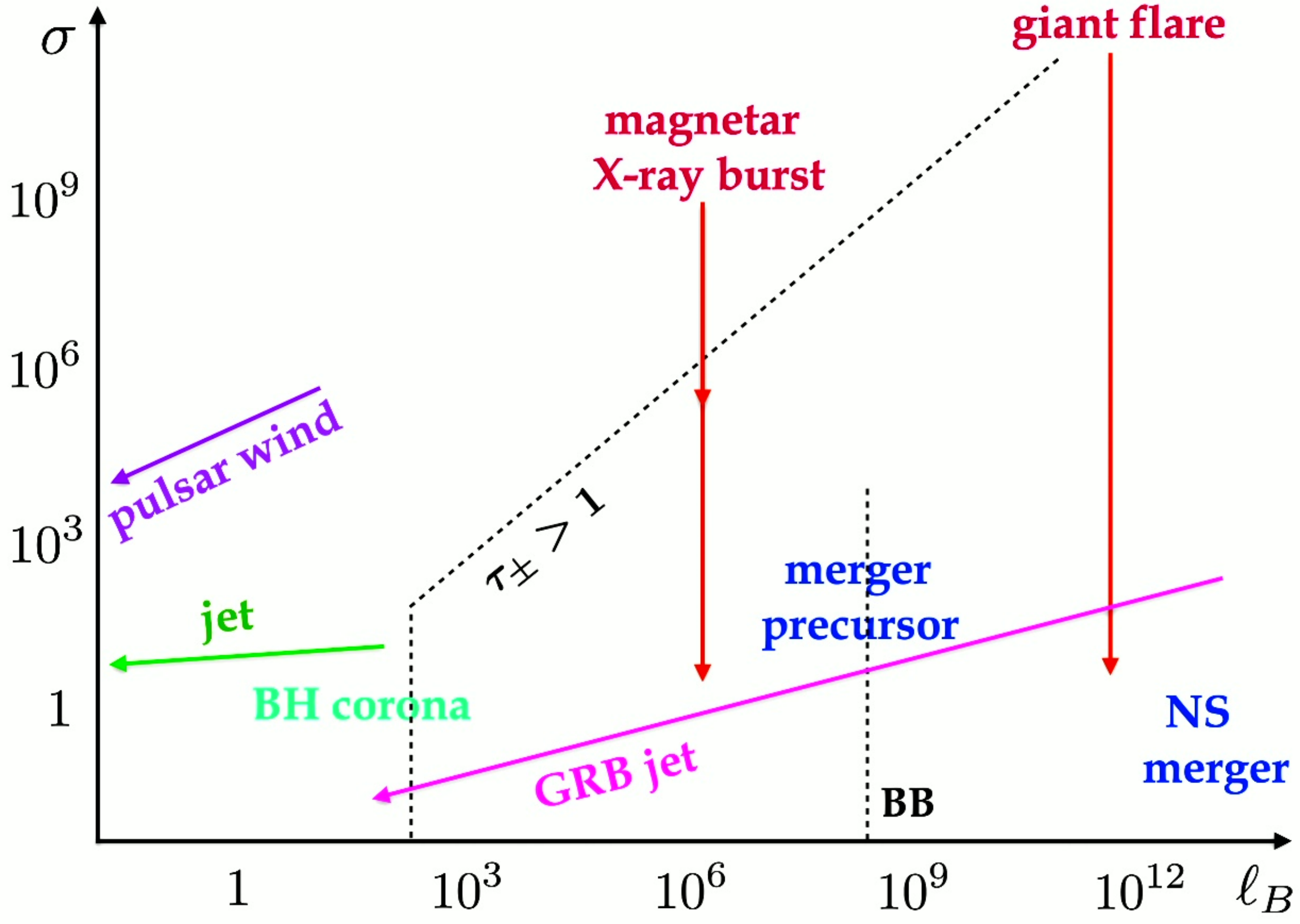
$$\boxed{\ell \equiv \frac{U}{m_e c^2}\,\sigma_{\rm T}\, s} \qquad \frac{t_{\rm IC}}{s/c} = \frac{3}{4\gamma_e\,\ell_{\rm rad}}$$

- photons with energies $> m_e c^2$ convert to e+-: $\gamma + \gamma \rightarrow e^+ + e^-$

- at high ℓ the plasma reaches annihilation balance with optical depth:

$$\boxed{\tau_\pm \sim (Y\ell)^{1/2}} \qquad Y = \frac{\dot{n}_\pm m_e c^2}{\dot{U}}$$ ("pair yield")

- heat capacity is dominated by photons



$$\sigma_{\rm e} = \frac{2U_B}{n_\pm m_e c^2}$$

$$\sigma_{\rm pl} = \frac{2U_B}{n_\pm m_e c^2 + n_{\rm i} m_{\rm i} c^2}$$

$$\sigma_{\rm rad} = \frac{2U_B}{U_{\rm rad} + n_\pm m_e c^2 + n_{\rm i} m_{\rm i} c^2}$$

$$\tau_\pm \sim \frac{\ell_B}{\sigma_{\rm e}} \frac{s/c}{t_{\rm diss}}$$

effects of spectral tails:

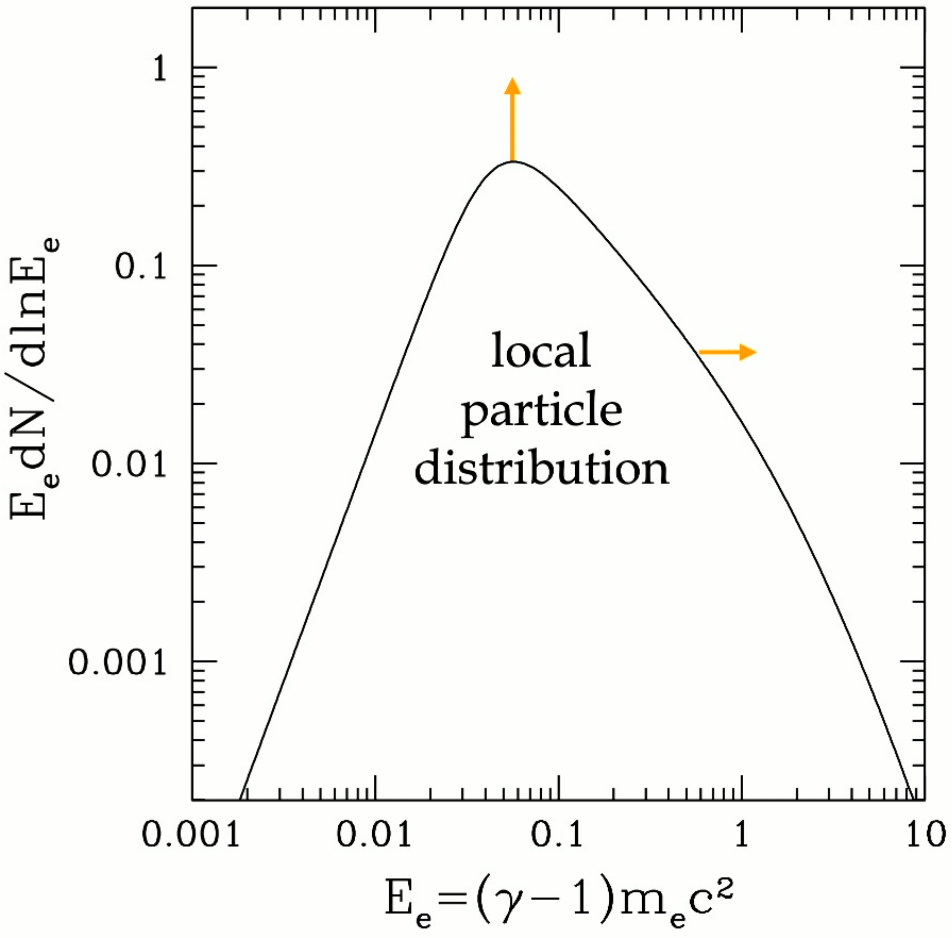
electrons:

– e+- pair production

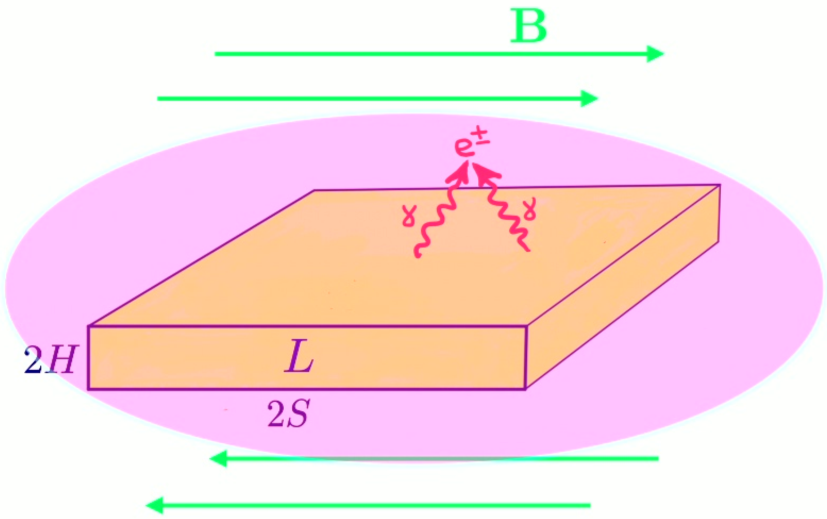
– photon production

ions:

neutrino production



e+- creation

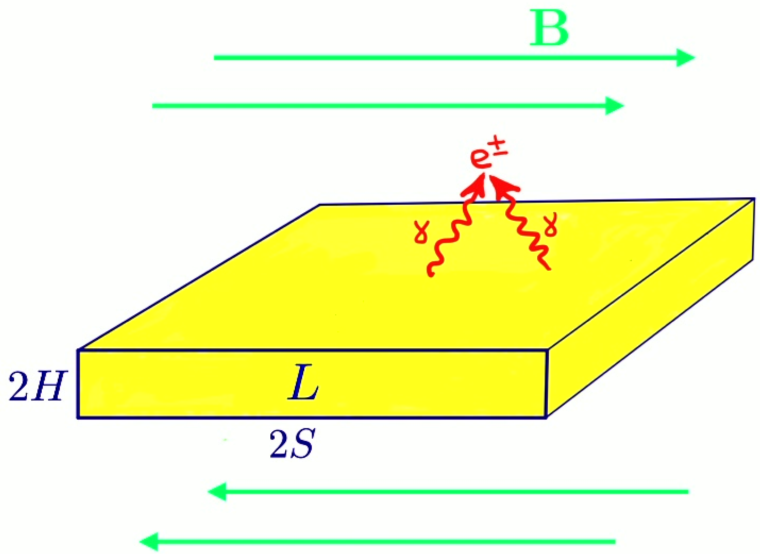


- energy balance
- e+- balance
- photon balance

self-regulated
energy per particle $T_{\rm eff}$
and density $n_{\pm}$

$$\ell_B \equiv \frac{U_B}{m_e c^2}\,\sigma_{\rm T} S \approx 3\times10^5\; B_9^2\, S_7$$

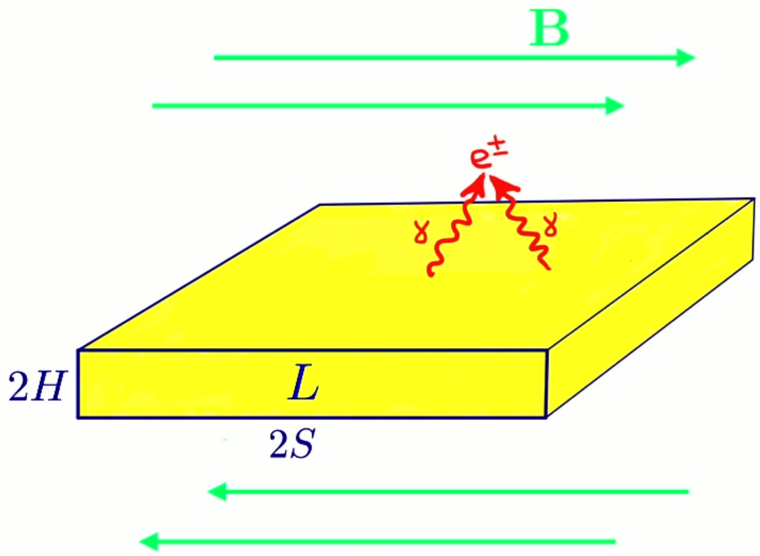
Magnetar bursts:
optically thick e+- plasma



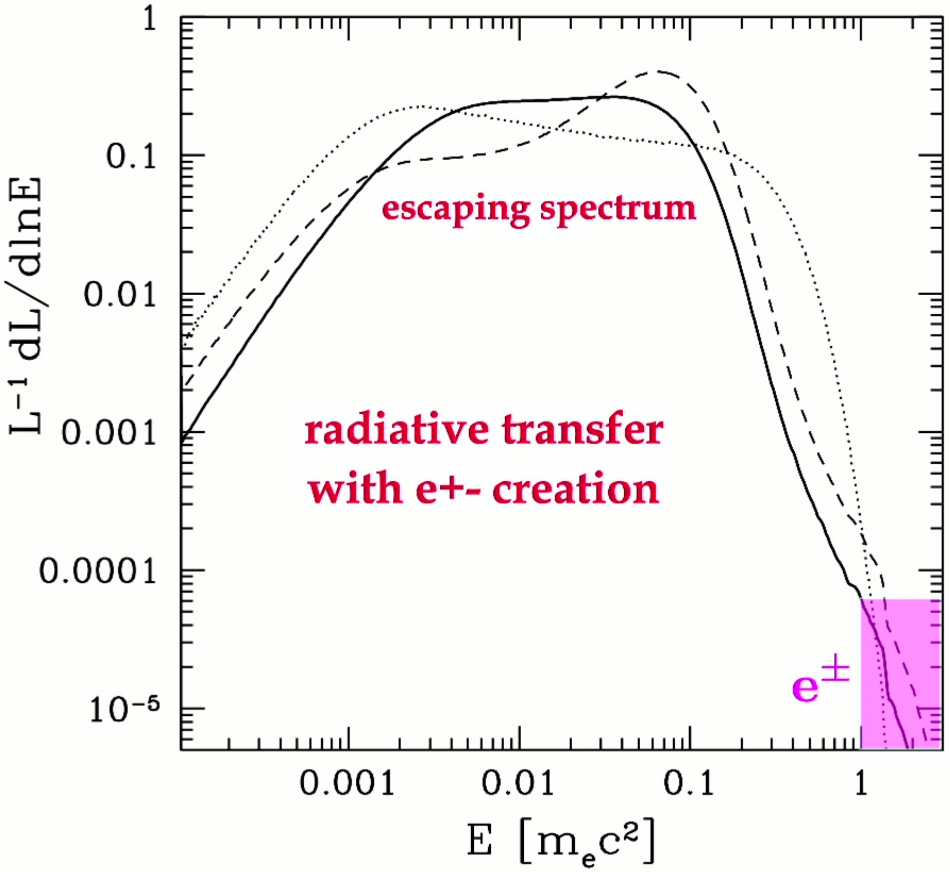
$$\ell_B \equiv \frac{U_B}{m_e c^2}\,\sigma_{\rm T} S \approx 3\times 10^5\; B_9^2\, S_7$$

AB 2021

Magnetar bursts:
optically thick e+- plasma



$$\ell_B \equiv \frac{U_B}{m_e c^2}\,\sigma_{\rm T} S \approx 3\times10^5\; B_9^2\, S_7$$

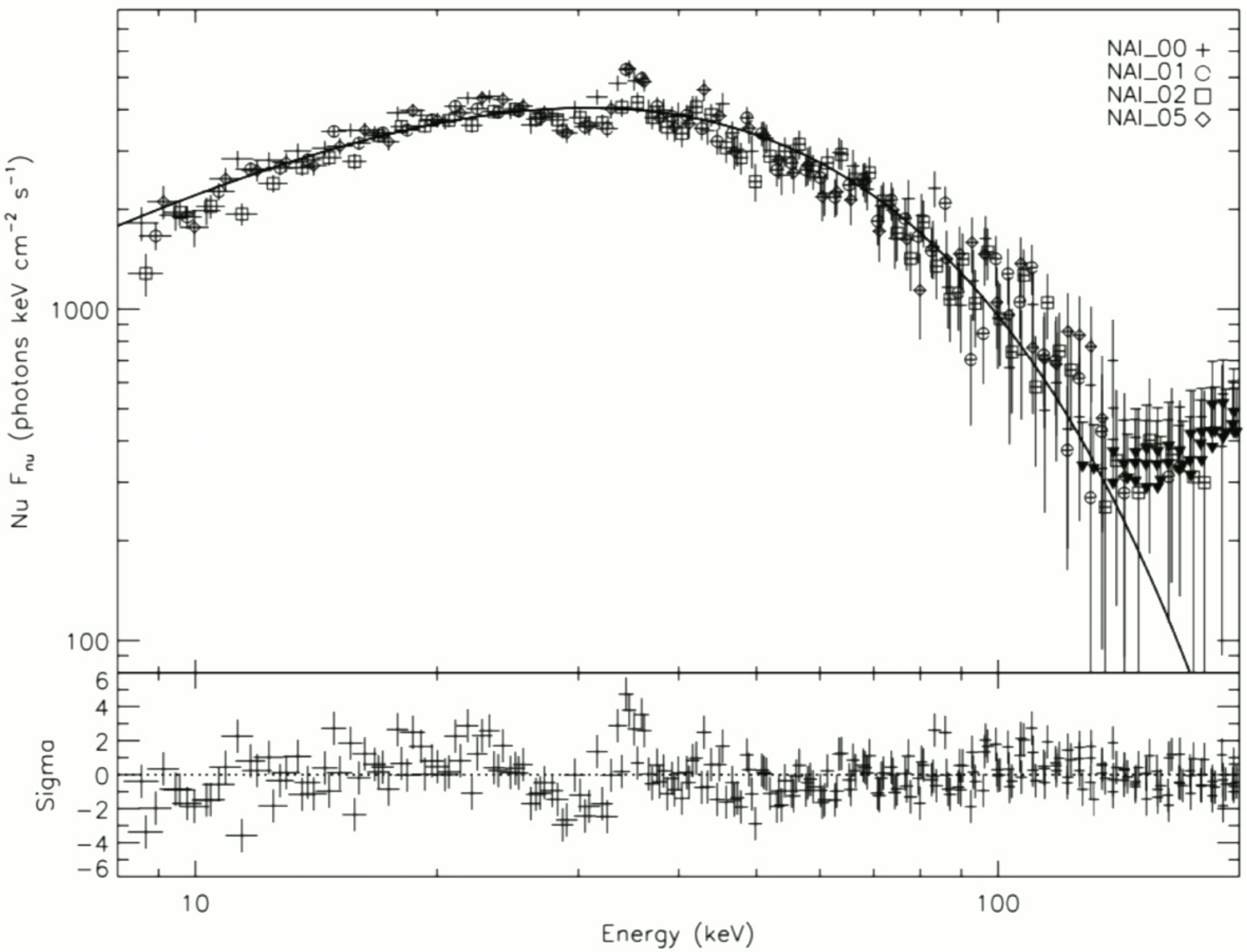


$$\boxed{\frac{n_\pm}{n_\gamma} \sim 10^{-5}}$$

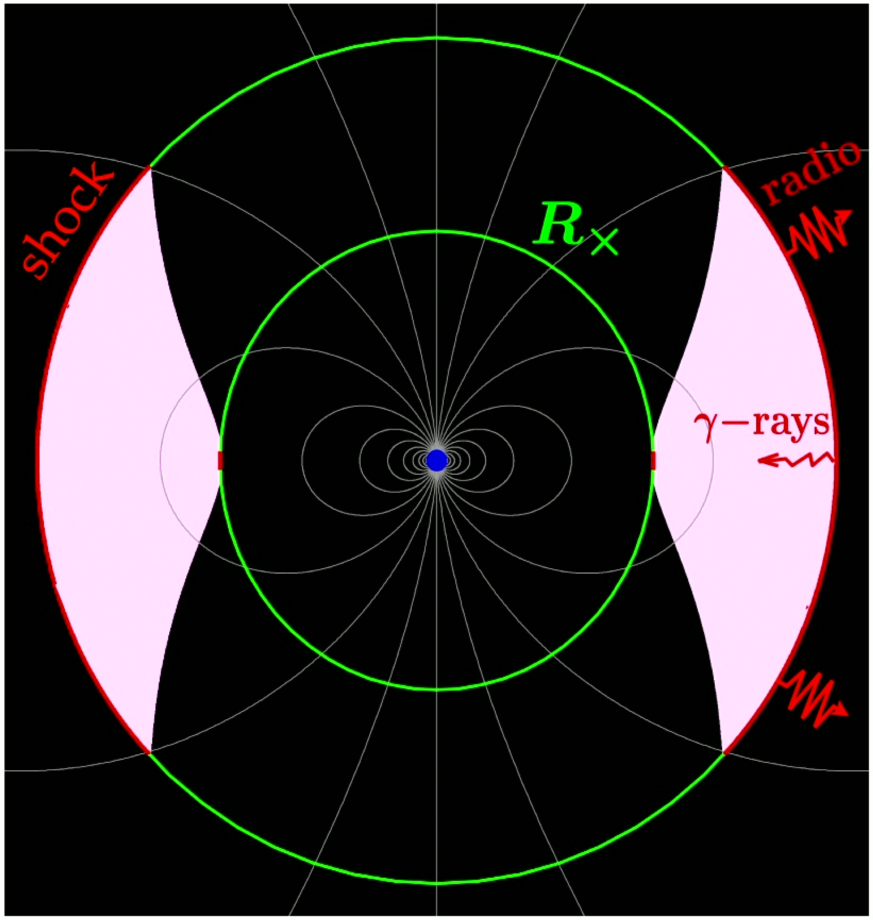
$$\boxed{\frac{kT}{m_e c^2} \sim 0.1}$$

AB 2021

Burst example: SGR J1550−5418



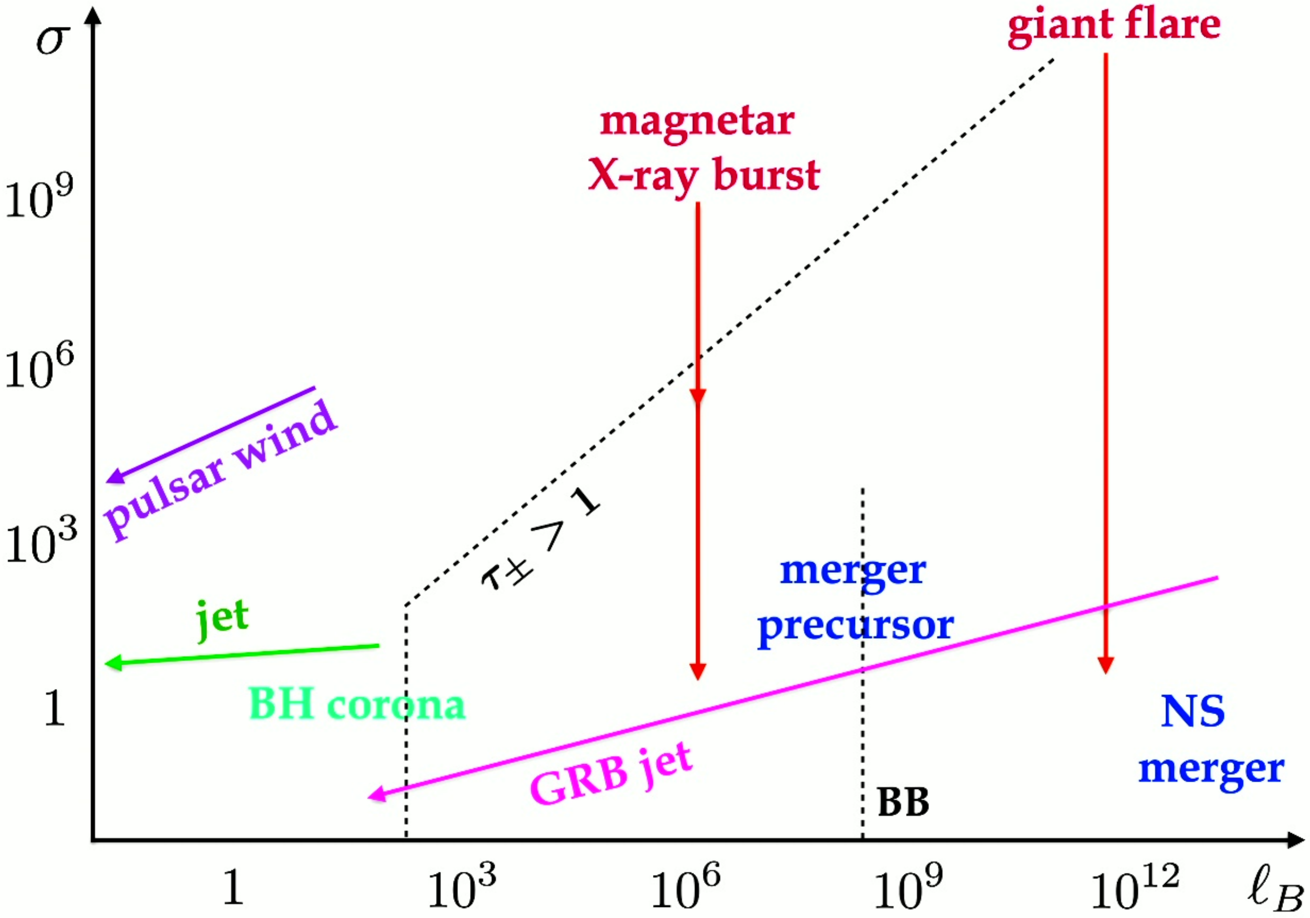
van der Horst et al. 2012



generic outcome of perturbing a neutron star magnetosphere:
radiative shocks

1. gamma-rays behind the shock
   convert to e+- pairs
   energy is reprocessed to X-rays

2. radio waves ahead of the shock
   (riding the explosion and escaping)



$$\sigma_e = \frac{2U_B}{n_\pm m_e c^2}$$

$$\sigma_{pl} = \frac{2U_B}{n_\pm m_e c^2 + n_i m_i c^2}$$

$$\sigma_{rad} = \frac{2U_B}{U_{rad} + n_\pm m_e c^2 + n_i m_i c^2}$$

$$\tau_\pm \sim \frac{\ell_B}{\sigma_e} \frac{s/c}{t_{diss}}$$