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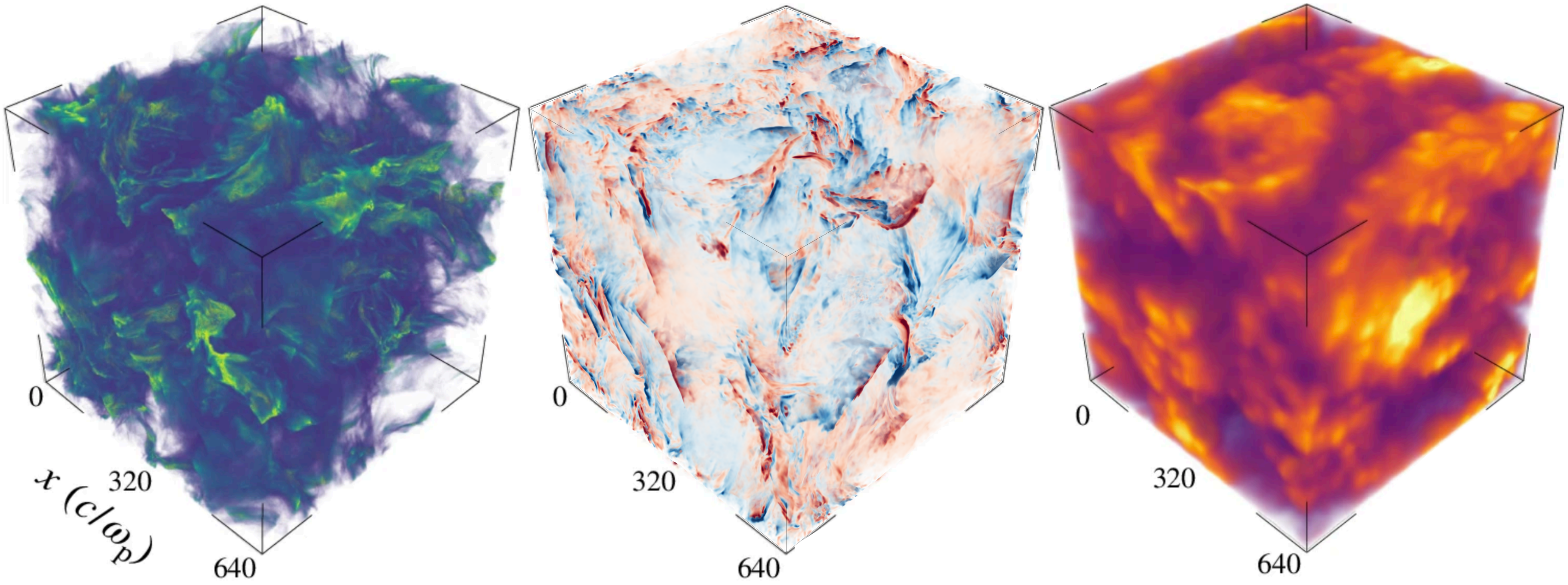
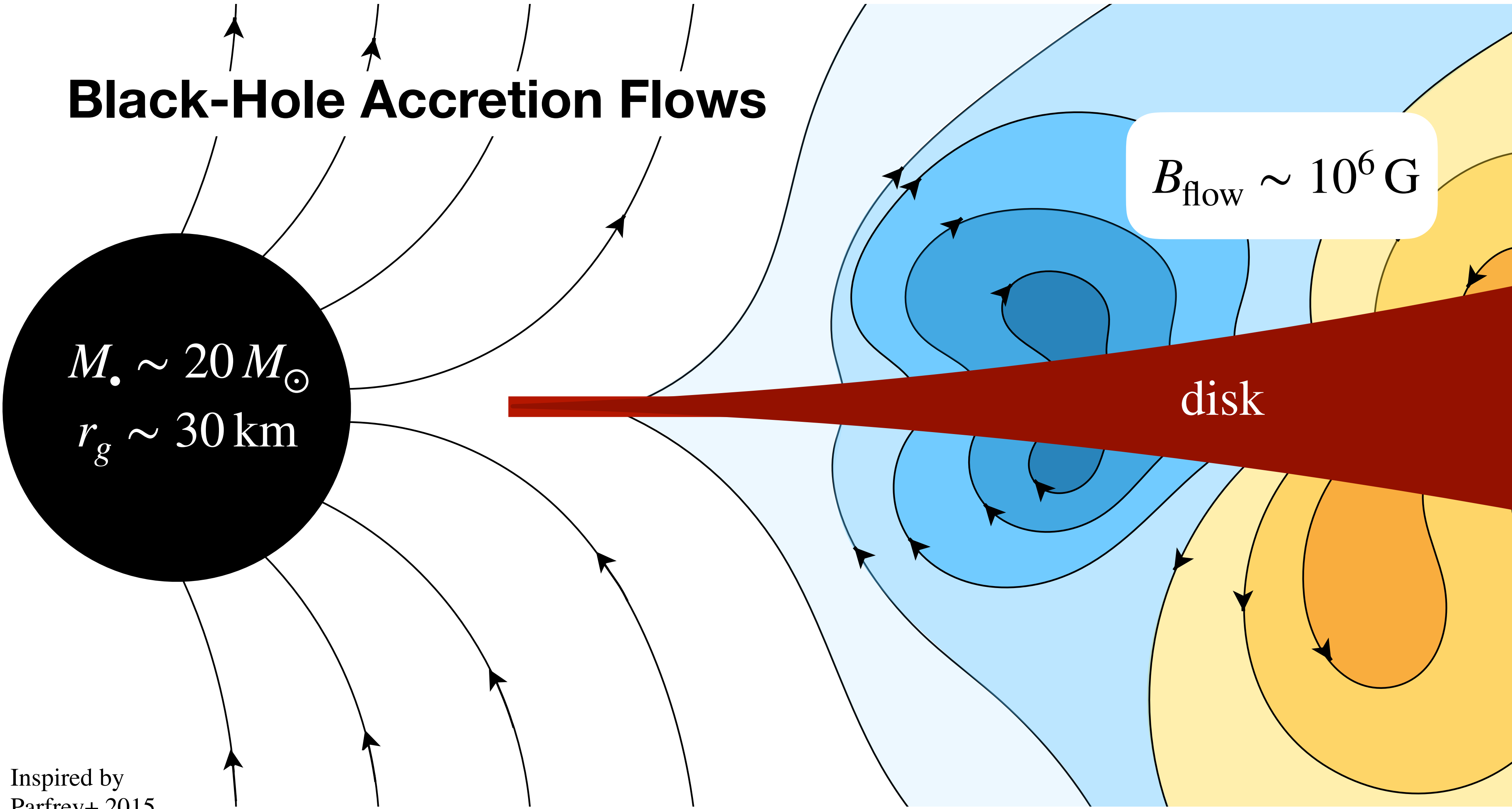


Radiative plasma simulations of turbulent accretion flows

Joonas Nättilä (University of Helsinki, Finland)

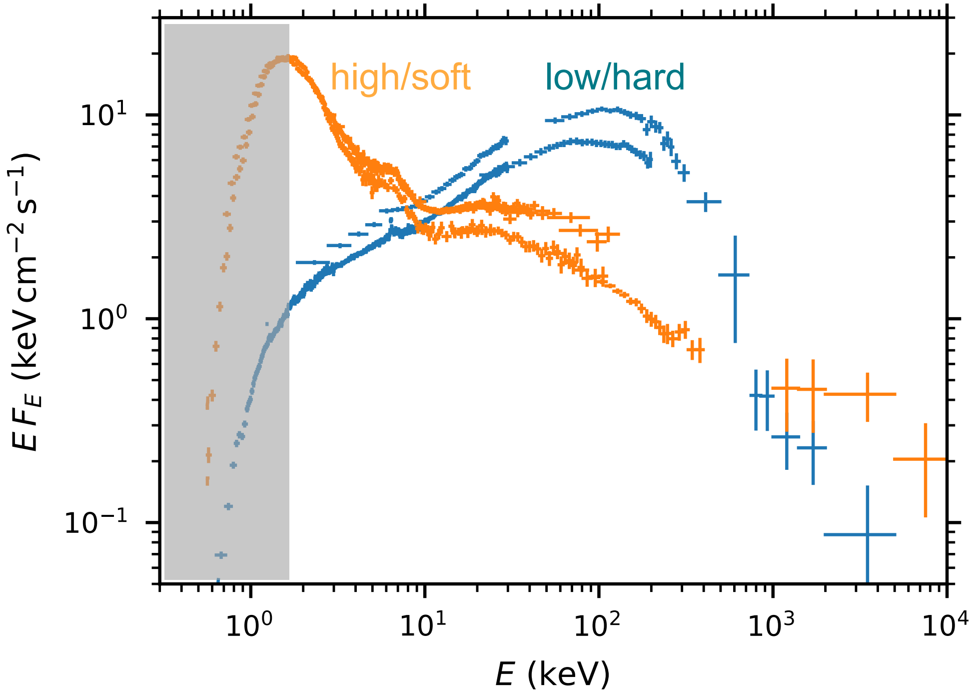
Black-Hole Accretion Flows



Inspired by
Parfrey+ 2015

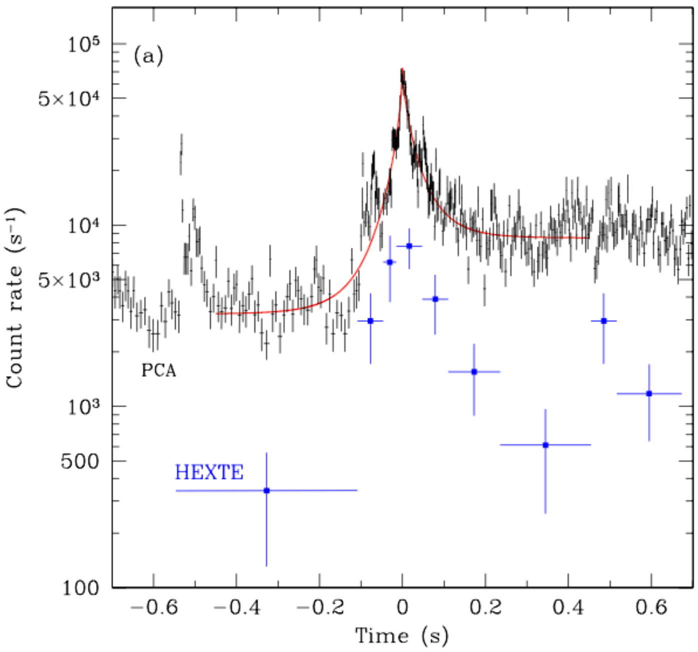
Reality check: Observations of Cyg X-1

Spectral state changes between hard and soft states



Adapted from Zdziarski et al 2002

Millisecond flares



Gierlinski & Zdziarski 2003

Patch of magnetized turbulent corona

$H \sim r_g \sim 30\,\mathrm{km}$

$t_g \sim \frac{H}{c} \sim 0.1\,\mathrm{ms}$

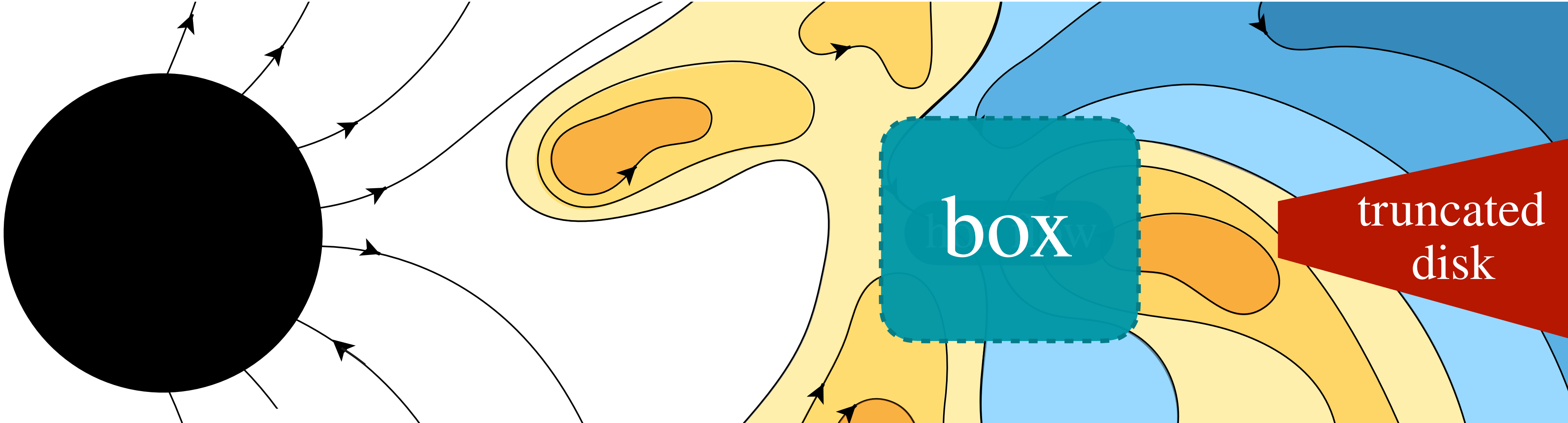
$B \sim 10^6\,\mathrm{G}$

Injected power:

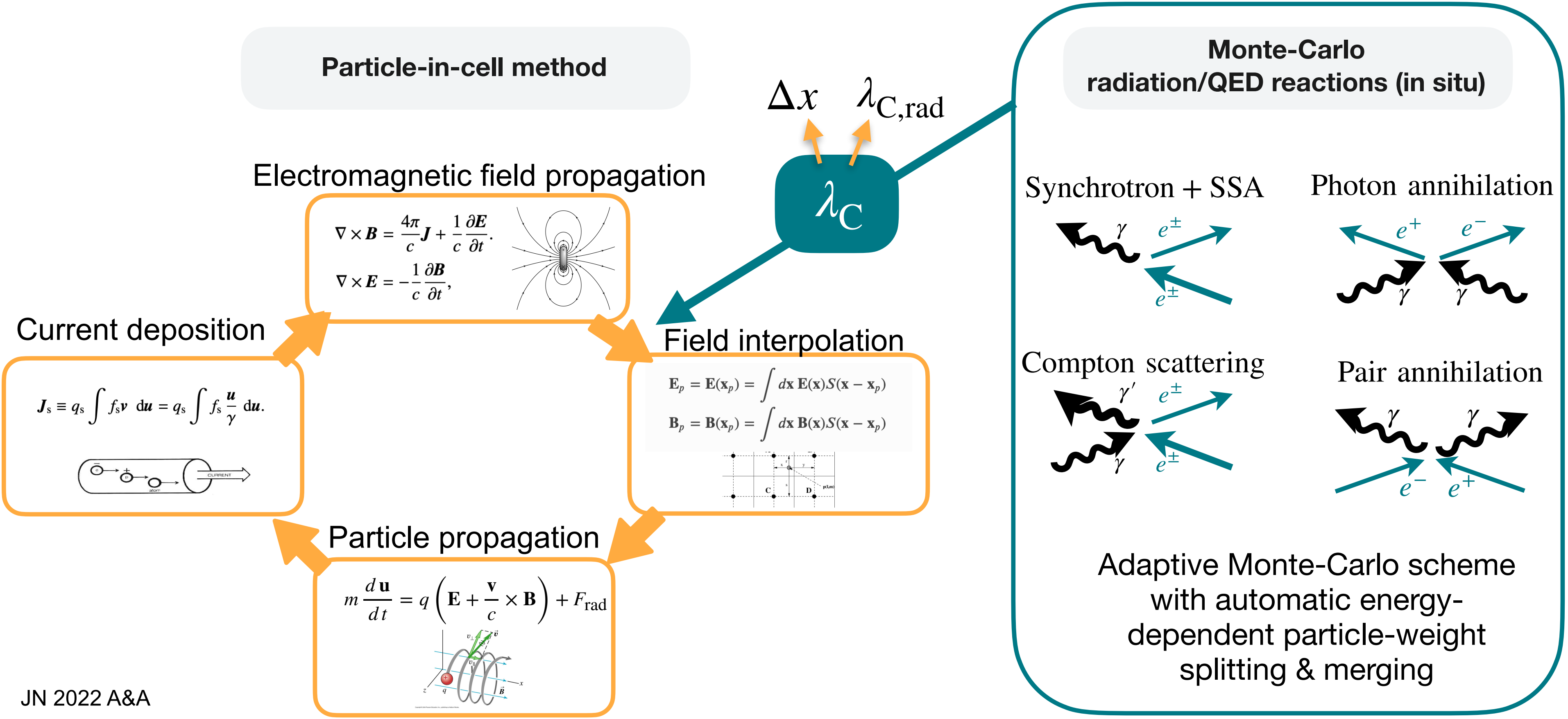
$$L_{\mathrm{flare}} \approx \dot{U}_B H^3 \approx \frac{U_B}{t_g} H^3 \sim 10^{36}\,\mathrm{erg\,s^{-1}}$$

Compactness parameter

$$\ell \equiv \frac{L_{\mathrm{flare}}}{m_e c^2} \frac{\sigma_T}{Hc} \sim 10$$



First-principles simulations of radiative plasmas



JN 2022 A&A

Simplified radiative simulations: $3D3V \rightarrow 0D1V$

Solve radiative & QED processes in 0D for a prescribed energy injection (see JN 2024, Supp. Mat.)

QED processes — Energy injection — Escape

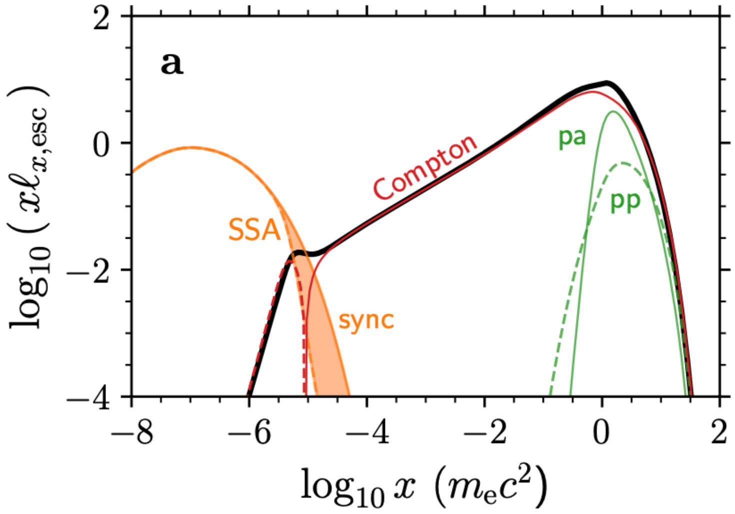
radiation
$$\frac{\partial n_x(x)}{\partial t} = \dot{n}_{x,\mathrm{syn}}(x) + \dot{n}_{x,\mathrm{cs}}(x) + \dot{n}_{x,\mathrm{pp}}(x) + \dot{n}_{x,\mathrm{pa}}(x) + \dot{n}_{x,\mathrm{br}}(x) + \dot{n}_{x,\mathrm{dc}}(x) + Q_x(x) - \frac{n_x(x)}{t_{x,\mathrm{esc}}(x)}$$

pairs
$$\frac{\partial n_\pm(p)}{\partial t} = \dot{n}_{\pm,\mathrm{syn}}(p) + \dot{n}_{\pm,\mathrm{cs}}(p) + \dot{n}_{\pm,\mathrm{pa}}(p) + \dot{n}_{\pm,\mathrm{pp}}(p) + \dot{n}_{\pm,\mathrm{br}}(p) + \dot{n}_{\pm,\mathrm{dc}}(p) + \dot{n}_{\pm,\mathrm{coul}}(p) + \dot{n}_{\pm,\mathrm{heat}}(p) + Q_\pm(p) - \frac{n_\pm(p)}{t_{\pm,\mathrm{esc}}(p)}$$

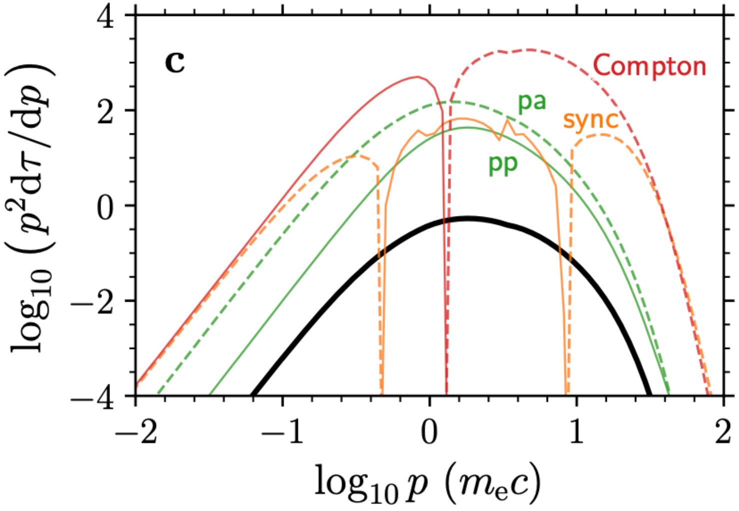
See also, e.g.:
Stern+ 1995
Coppi+ 1999
Vurm+ 2009

Photon-plasma in the hard state

Radiation spectra

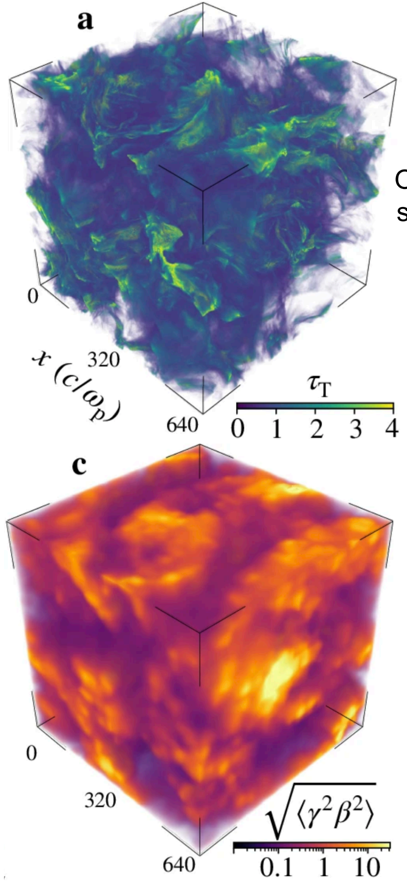


Plasma distribution



See also, e.g.:
Poutanen & Vurm 2009

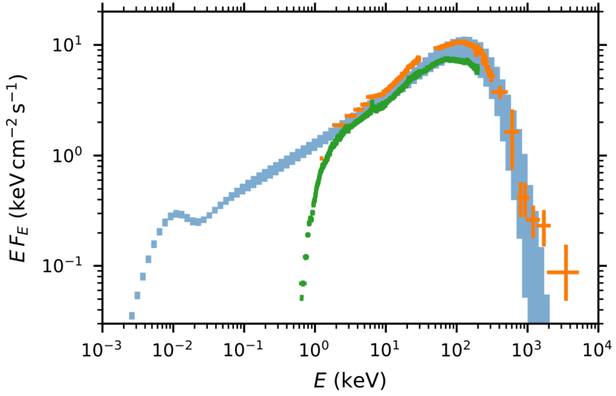
PIC simulations: Hard-state simulations

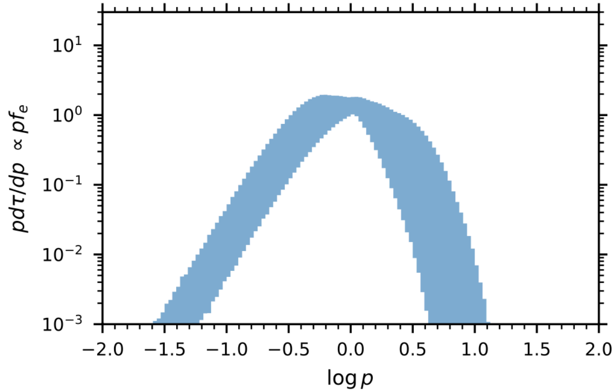


Optical depth $\tau_T \approx 1.5$ self-consistently set by pair creation

Comptonization set by turbulent bulk motions

Escaping photon flux

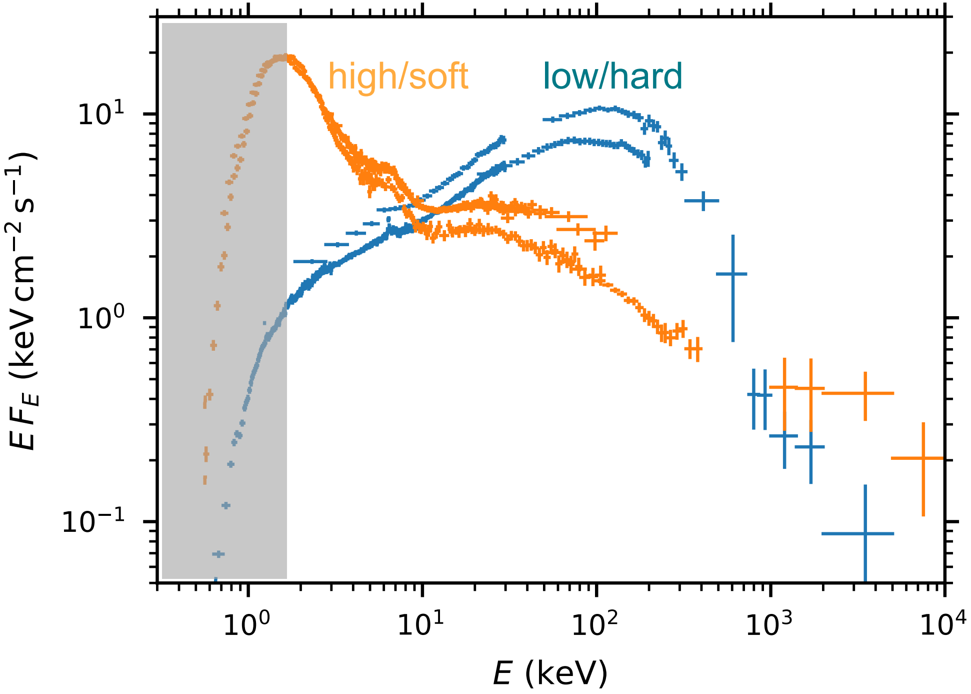




See also:
Beloborodov 17
Sridhar+ 21
Groselj+23

Reality check: Observations of Cyg X-1

Spectral state changes between hard and soft states



Adapted from Zdziarski et al 2002

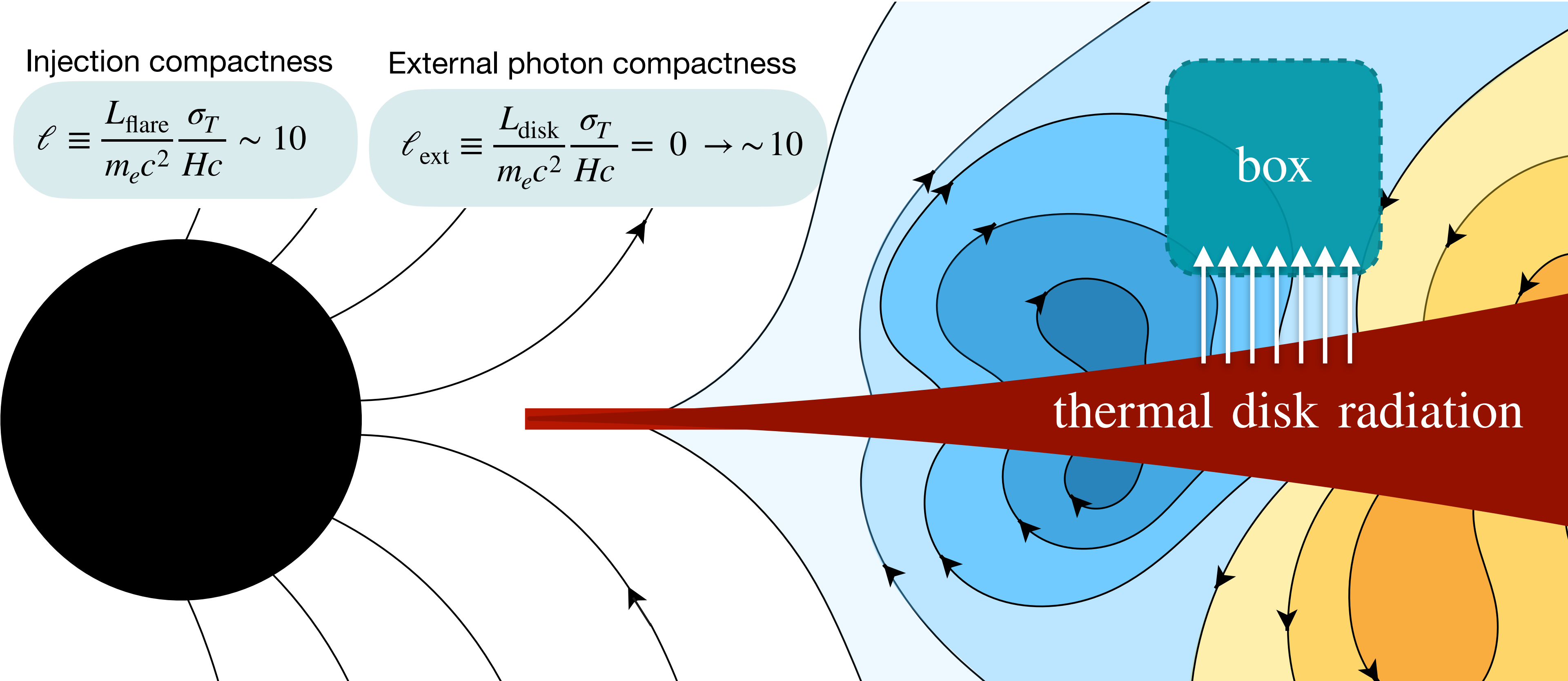
External (soft x-ray) disk photons

Injection compactness

$$\ell \equiv \frac{L_{\rm flare}}{m_e c^2} \frac{\sigma_T}{Hc} \sim 10$$

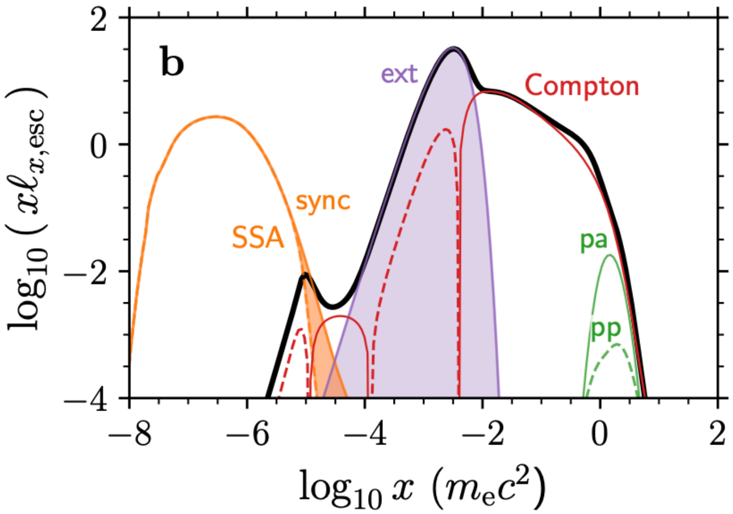
External photon compactness

$$\ell_{\rm ext} \equiv \frac{L_{\rm disk}}{m_e c^2} \frac{\sigma_T}{Hc} = 0 \rightarrow \sim 10$$

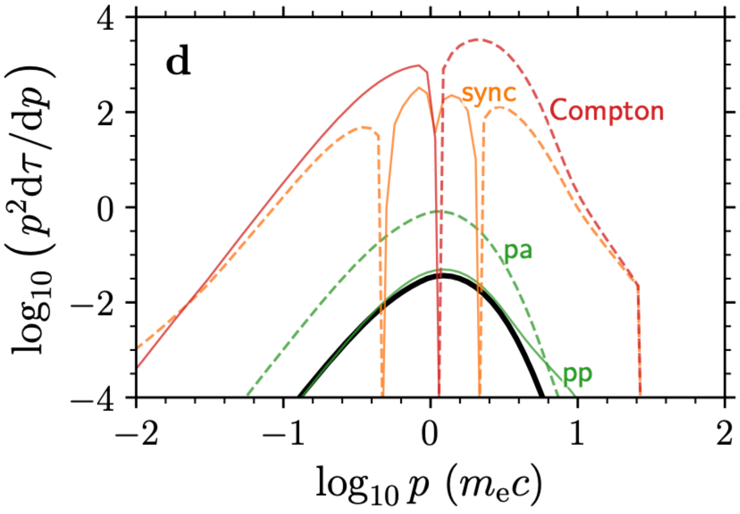


Photon-plasma in an external photon bath

Radiation spectrum

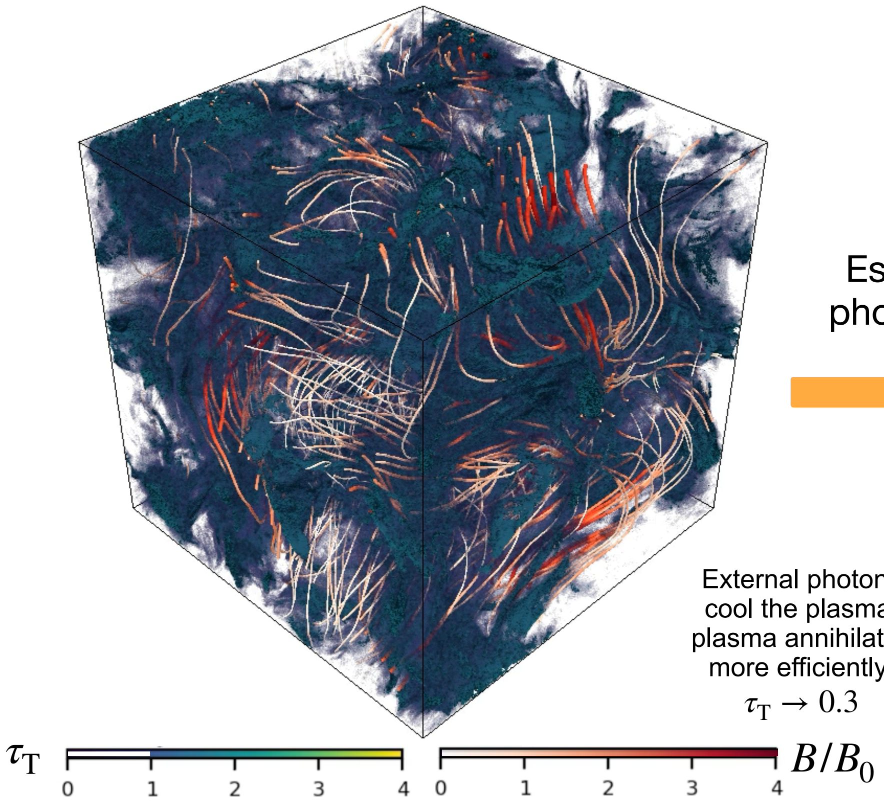


Plasma distribution

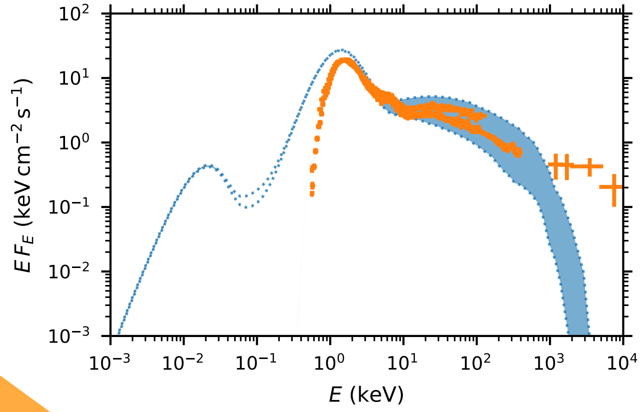


See also, e.g.:
Poutanen & Vurm 2009

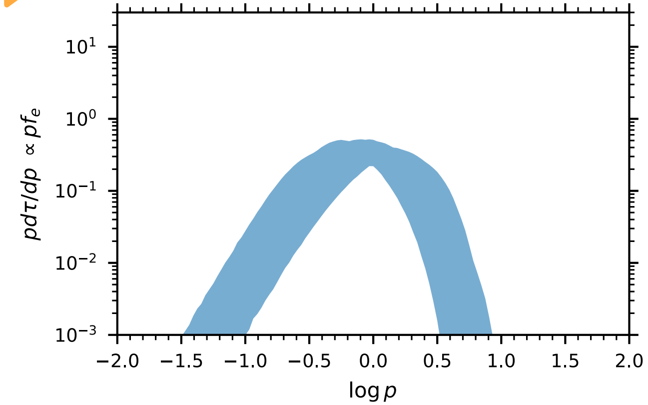
PIC simulations: **Soft-state simulations**



Escaping photon flux



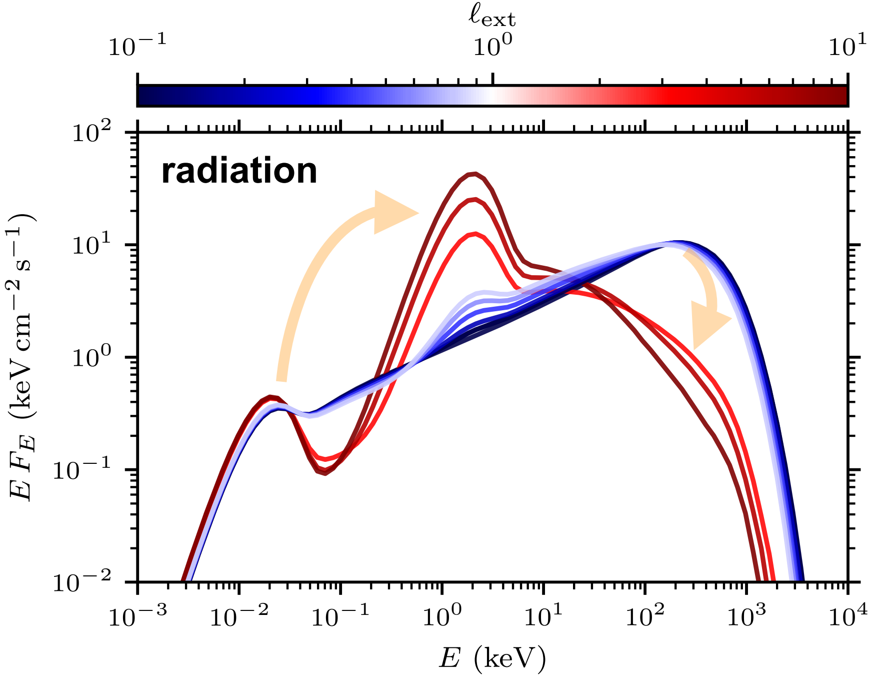
External photons cool the plasma; plasma annihilates more efficiently; $\tau_T \to 0.3$



PIC simulations: Two equilibrium states of turbulent plasma

no external radiation

dominant radiative background



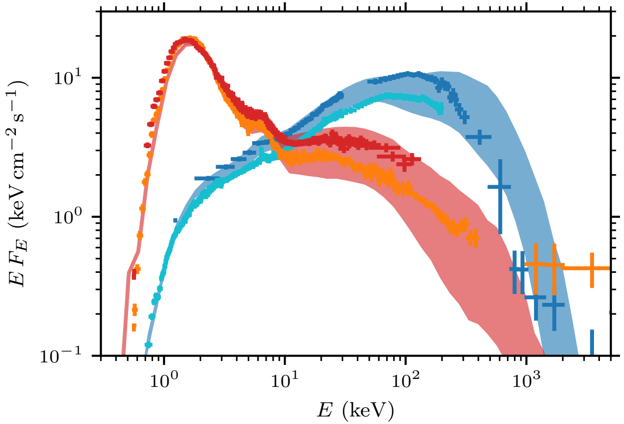
Nättilä 2024; Nature Communications

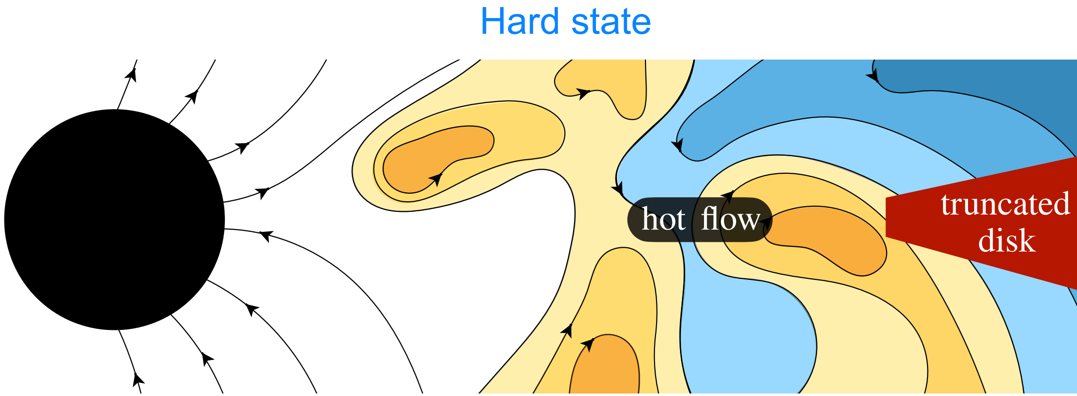
Conclusions → Predictions

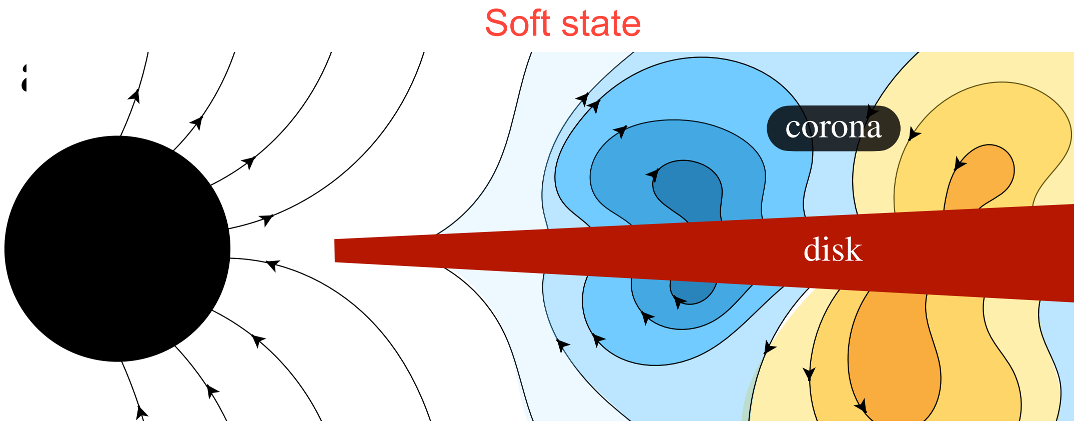
1. Corona is turbulent → millisecond flares

2. No external radiation in hard state
 → disk is truncated
 → suppression of low-frequency variability

3. External irradiation in soft state
 → full disk
 → high-frequency variability

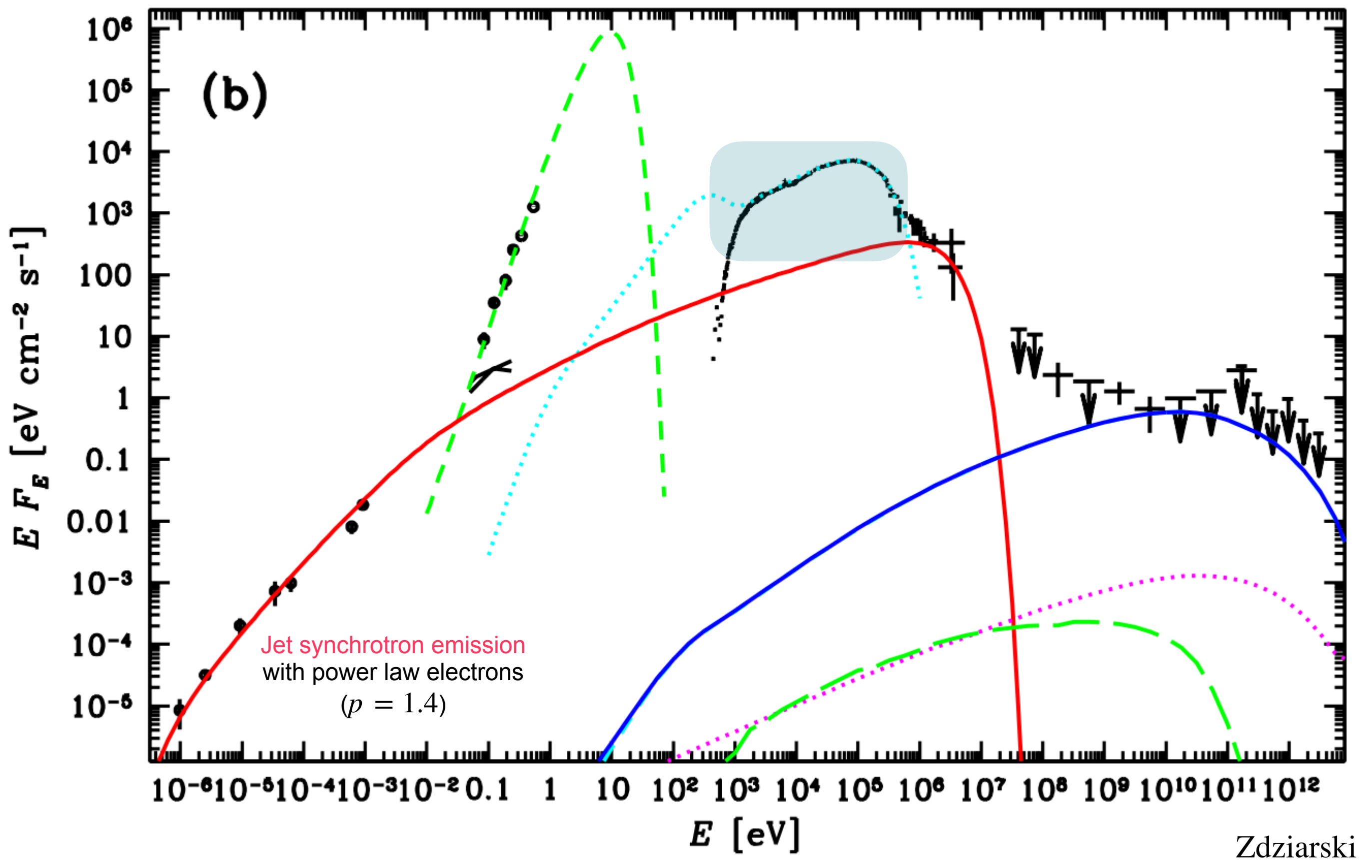






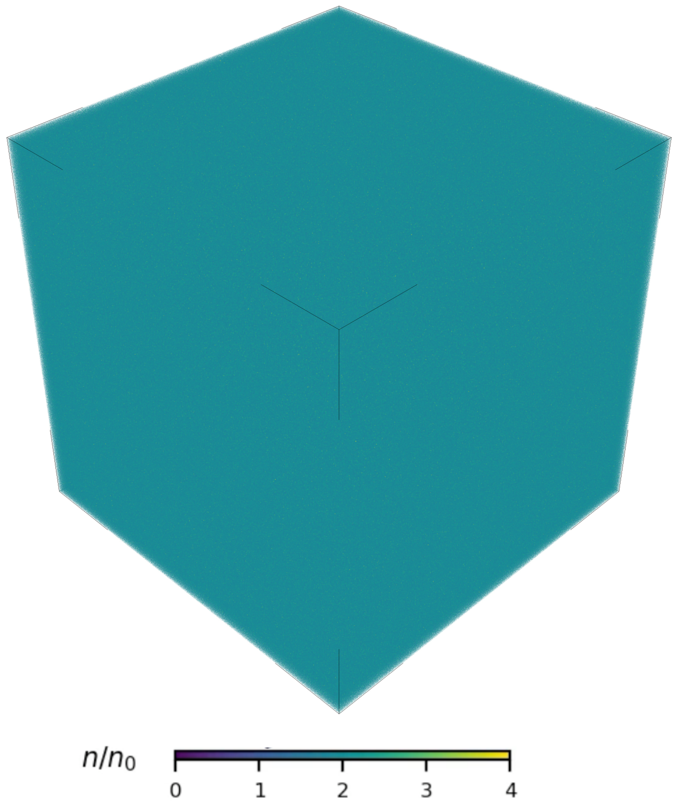
EXTRAs:

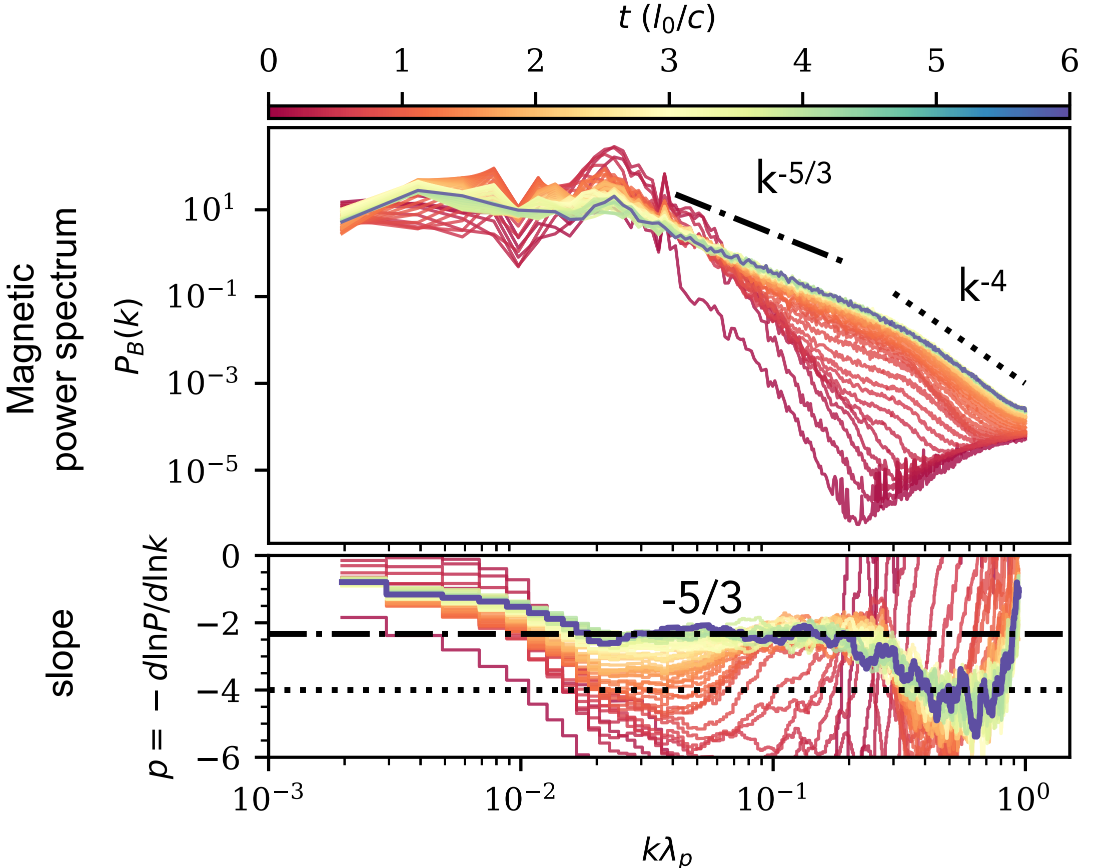
Multi-wavelength observations of Cyg X-1



Zdziarski et al 2014

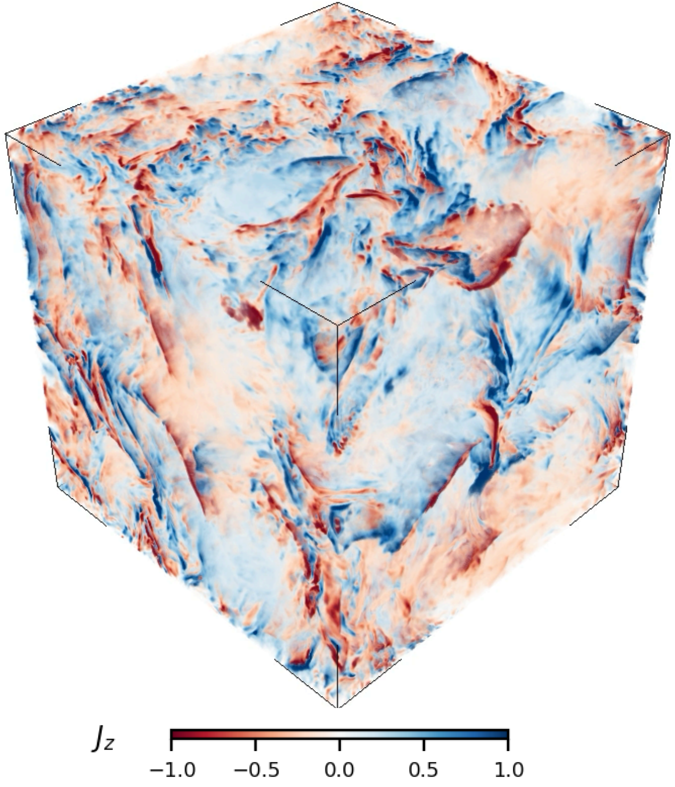
Plasma turbulence in the corona



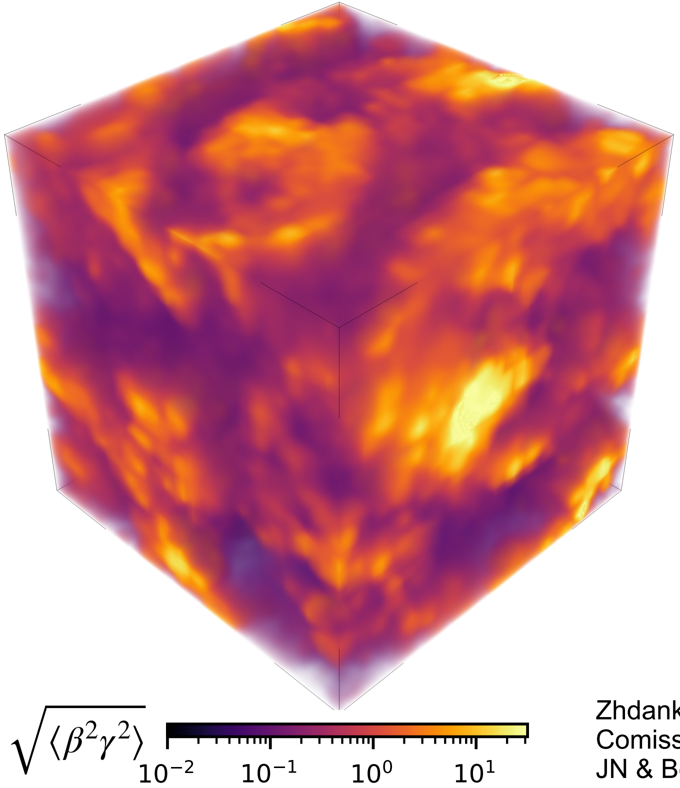


Intermittency controls plasma energization

B-field dynamics creates current sheets

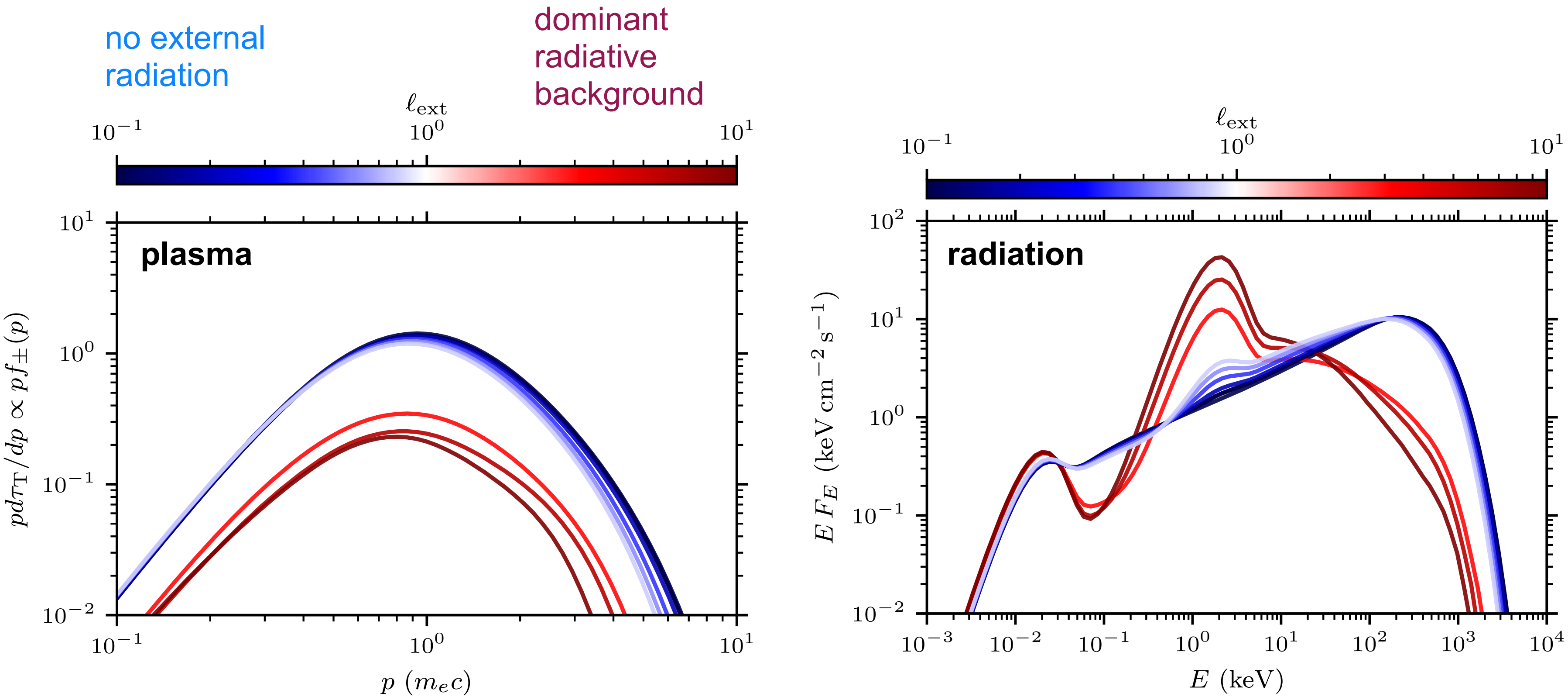


Regions of enhanced energy dissipation



Zhdankin et al.
Comisso & Sironi
JN & Beloborodov

Two quasi-equilibrium states of radiative plasma



Effect of external photon flux

Injection of $\sim 1\mathrm{keV}$ x-ray photons from the disk

When $\ell_{\mathrm{ext}} > \ell_{\mathrm{crit}} \approx 1$ pairs cool from $\theta_{\pm} \approx 1 \rightarrow 0.2$

Cool pair population has enhanced pair annihilation that sustains lower optical depth $\langle \tau_{\mathrm{T}} \rangle \approx 1 \rightarrow 0.3$