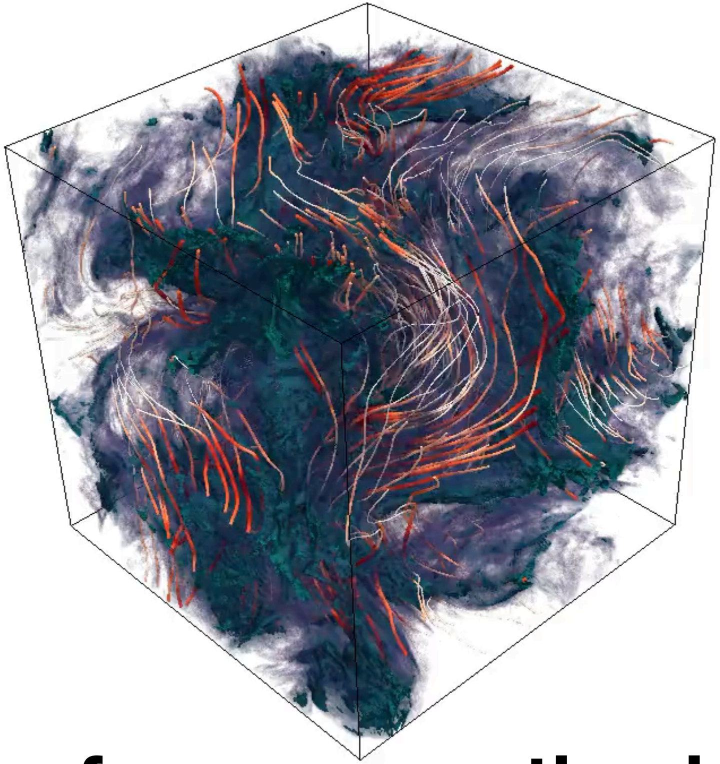


Radiation from magnetized plasmas

Joonas Nättilä

Relativistic magnetically-dominated plasmas

$$\sigma \equiv \frac{U_B}{U_\pm} = \frac{B^2}{4\pi n_\pm m_e c^2} \gtrsim 1$$

Magnetically dominated

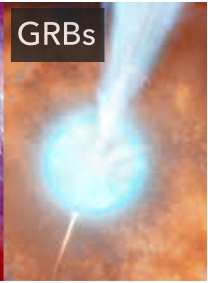
$$v_\mathrm{A} \equiv c\sqrt{\frac{\sigma}{\sigma+1}} \rightarrow c$$

Relativistic Alfven motions

$\sigma \sim 0.1$

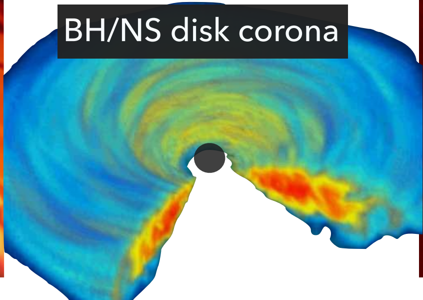
$\sigma \sim 1$

$\sigma \sim 1$

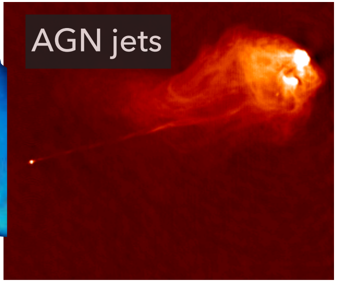


$\sigma \gtrsim 1$

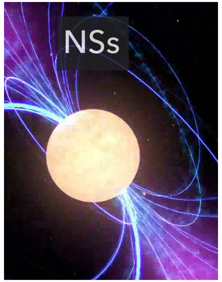
$\sigma \sim 10$



$\sigma \gtrsim 100$



$\sigma \gtrsim 10^4$



Radiative plasma physics

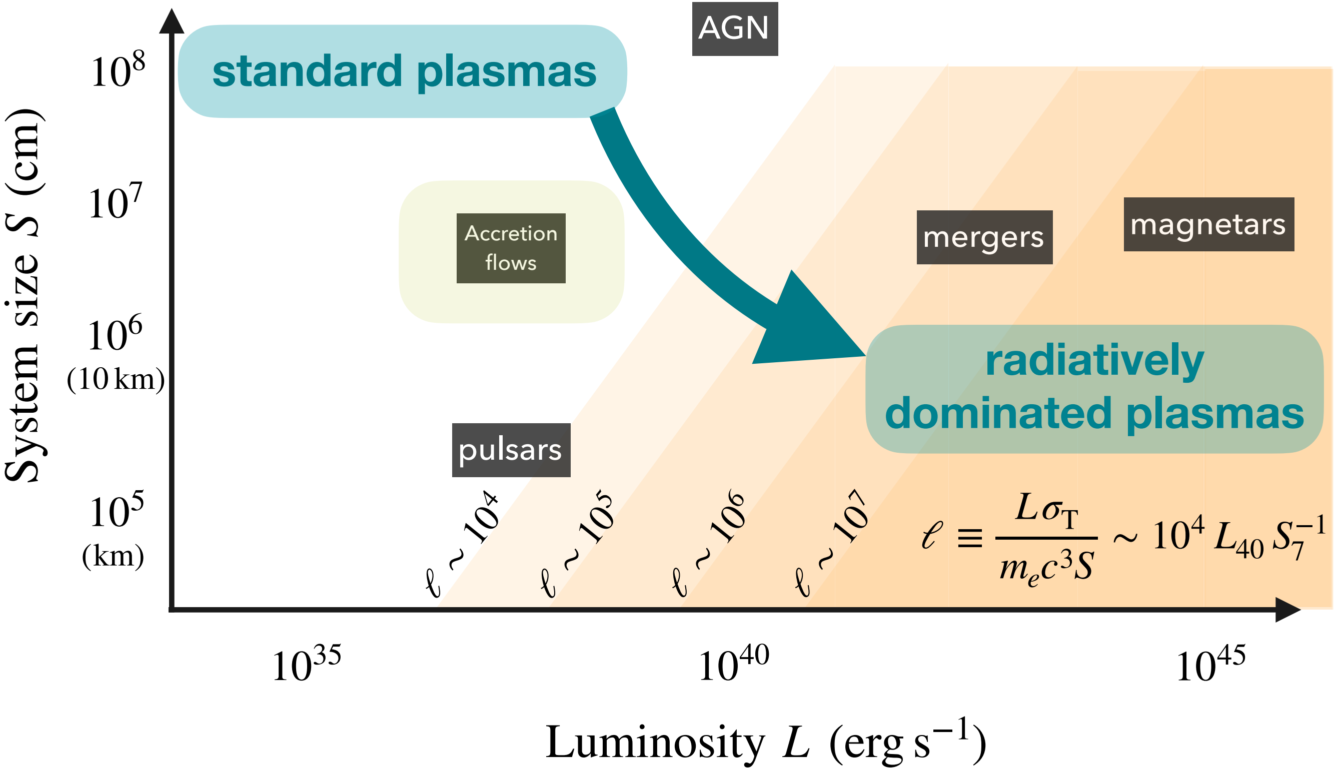
System size via optical depth

$$\tau = \sigma_{\mathrm{T}} n_{\pm} H$$

Compactness (or dimensionless luminosity)

$$\ell \equiv \frac{L\sigma_{\mathrm{T}}}{m_e c^3 H} \sim 10^4\, L_{40}\, H_7^{-1}$$

Radiative plasma physics



standard plasmas

AGN

Accretion flows

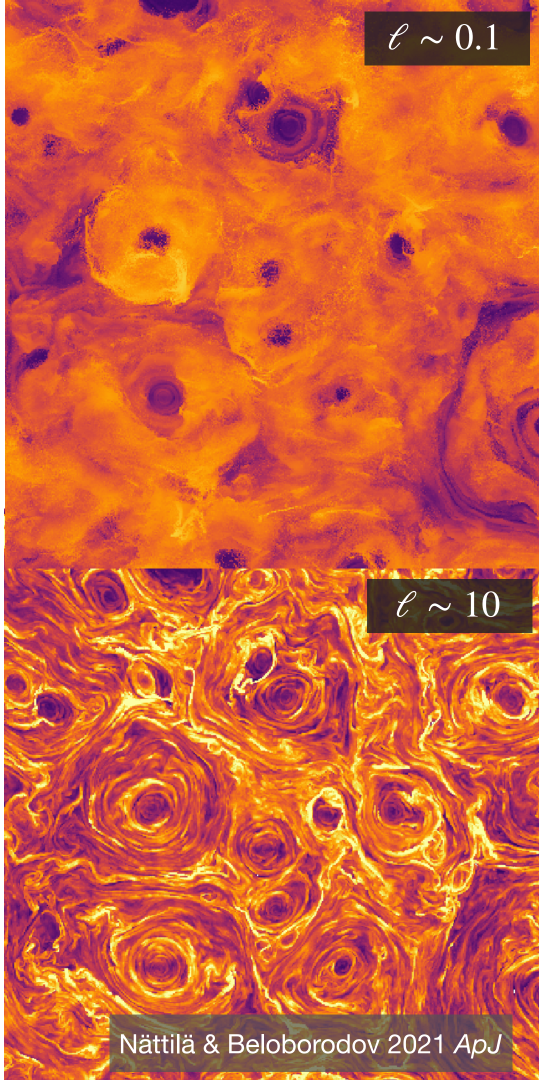
pulsars

mergers

magnetars

radiatively dominated plasmas

$$\ell \equiv \frac{L \sigma_{\mathrm{T}}}{m_e c^3 S} \sim 10^4 \, L_{40} \, S_7^{-1}$$



Nättilä & Beloborodov 2021 *ApJ*

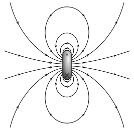
First-principles simulations of radiative plasmas

Particle-in-cell method

Electromagnetic field propagation

$$\nabla\times\boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{J} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}.$$

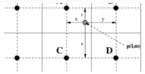
$$\nabla\times\boldsymbol{E} = -\frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t},$$



Field interpolation

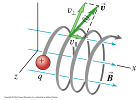
$$\mathbf{E}_p = \mathbf{E}(\mathbf{x}_p) = \int d\mathbf{x}\, \mathbf{E}(\mathbf{x}) S(\mathbf{x}-\mathbf{x}_p)$$

$$\mathbf{B}_p = \mathbf{B}(\mathbf{x}_p) = \int d\mathbf{x}\, \mathbf{B}(\mathbf{x}) S(\mathbf{x}-\mathbf{x}_p)$$



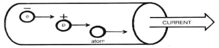
Particle propagation

$$m\frac{d\mathbf{u}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) + F_{\rm rad}$$



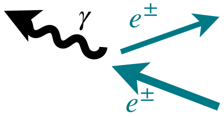
Current deposition

$$\boldsymbol{J}_s \equiv q_s\int f_s \boldsymbol{v}\; d\boldsymbol{u} = q_s \int f_s \frac{\boldsymbol{u}}{\gamma}\; d\boldsymbol{u}.$$

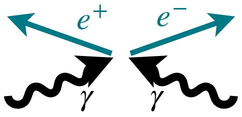


Monte-Carlo radiation/QED reactions (in situ)

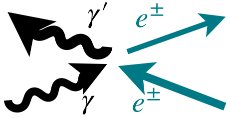
Synchrotron + SSA



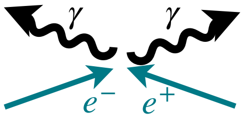
Photon annihilation



Compton scattering



Pair annihilation



Adaptive Monte-Carlo scheme with automatic energy-dependent particle-weight splitting & merging

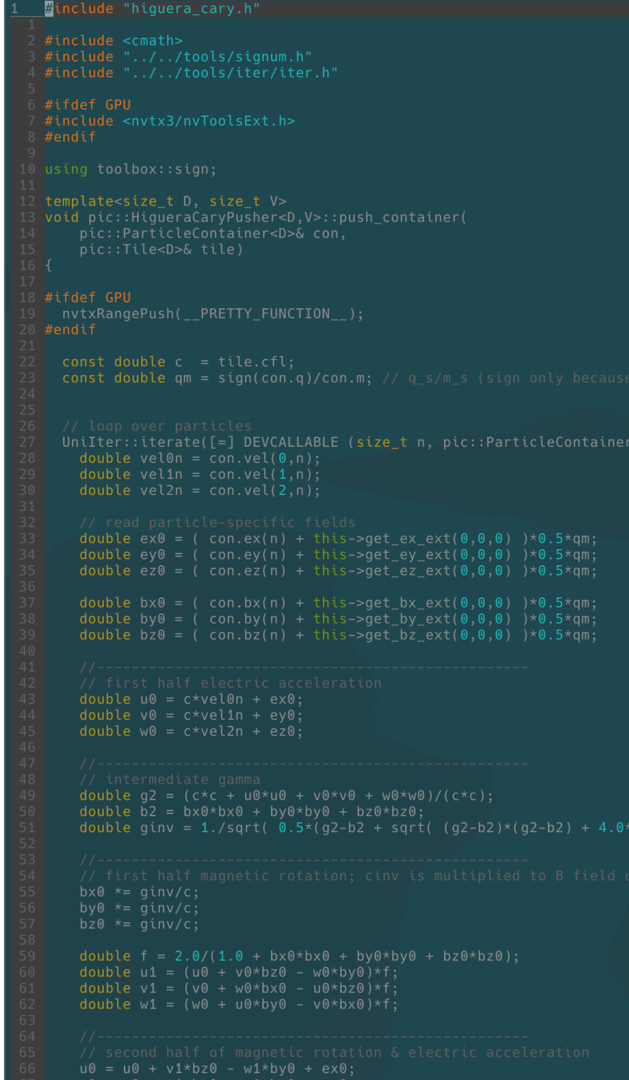
runko

open-source simulation toolkit

Nättilä 2022 *A&A;* https://github.com/natj/runko

Technological features:

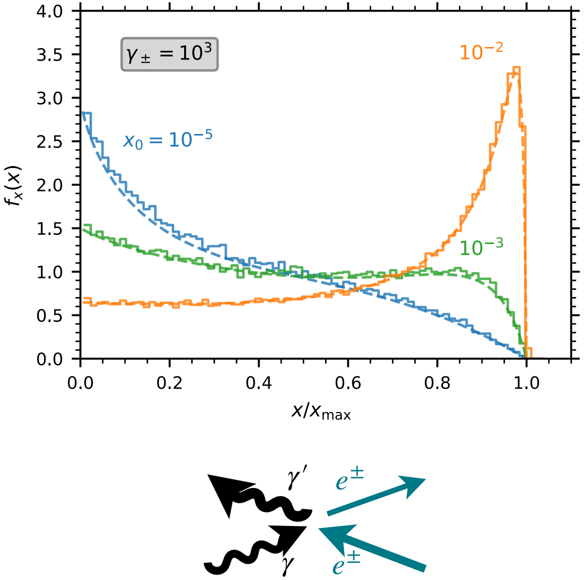
- **CPU/GPU** portable 3D particle-in-cell code
- **Modern** C++17/Python3 high-performance code
- **Full 3-level parallelization** (w/ SIMD/openMP/MPI)
- **Open source** (incl. problem setups, analysis scripts, etc.)



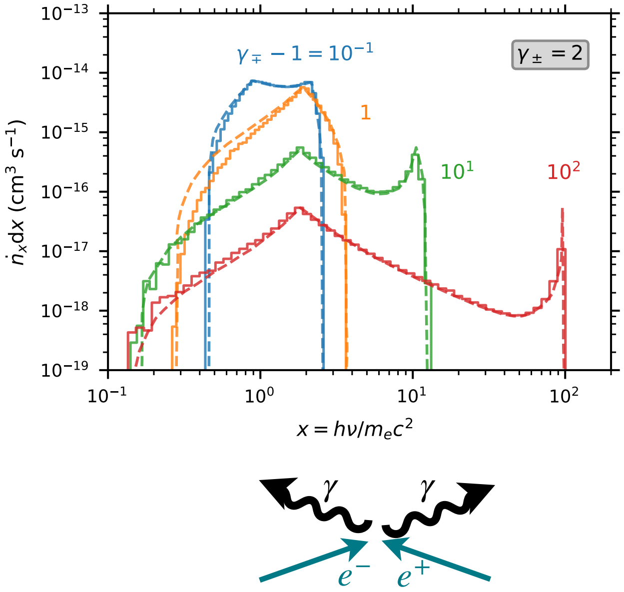
```
#include "higuera_cary.h"

#include <cmath>
#include "../../tools/signum.h"
#include "../../tools/iter/iter.h"

#ifdef GPU
#include <nvtx3/nvToolsExt.h>
#endif

using toolbox::sign;

template<size_t D, size_t V>
void pic::HigueraCaryPusher<D,V>::push_container(
    pic::ParticleContainer<D>& con,
    pic::Tile<D>& tile)
{

#ifdef GPU
  nvtxRangePush(__PRETTY_FUNCTION__);
#endif

  const double c  = tile.cfl;
  const double qm = sign(con.q)/con.m; // q_s/m_s (sign only because


  // loop over particles
  UniIter::iterate([=] DEVCALLABLE (size_t n, pic::ParticleContainer
    double vel0n = con.vel(0,n);
    double vel1n = con.vel(1,n);
    double vel2n = con.vel(2,n);

    // read particle-specific fields
    double ex0 = ( con.ex(n) + this->get_ex_ext(0,0,0) )*0.5*qm;
    double ey0 = ( con.ey(n) + this->get_ey_ext(0,0,0) )*0.5*qm;
    double ez0 = ( con.ez(n) + this->get_ez_ext(0,0,0) )*0.5*qm;

    double bx0 = ( con.bx(n) + this->get_bx_ext(0,0,0) )*0.5*qm;
    double by0 = ( con.by(n) + this->get_by_ext(0,0,0) )*0.5*qm;
    double bz0 = ( con.bz(n) + this->get_bz_ext(0,0,0) )*0.5*qm;

    //--------------------------------------------------
    // first half electric acceleration
    double u0 = c*vel0n + ex0;
    double v0 = c*vel1n + ey0;
    double w0 = c*vel2n + ez0;

    //--------------------------------------------------
    // intermediate gamma
    double g2 = (c*c + u0*u0 + v0*v0 + w0*w0)/(c*c);
    double b2 = bx0*bx0 + by0*by0 + bz0*bz0;
    double ginv = 1./sqrt( 0.5*(g2-b2 + sqrt( (g2-b2)*(g2-b2) + 4.0*

    //--------------------------------------------------
    // first half magnetic rotation; cinv is multiplied to B field c
    bx0 *= ginv/c;
    by0 *= ginv/c;
    bz0 *= ginv/c;

    double f = 2.0/(1.0 + bx0*bx0 + by0*by0 + bz0*bz0);
    double u1 = (u0 + v0*bz0 - w0*by0)*f;
    double v1 = (v0 + w0*bx0 - u0*bz0)*f;
    double w1 = (w0 + u0*by0 - v0*bx0)*f;

    //--------------------------------------------------
    // second half of magnetic rotation & electric acceleration
    u0 = u0 + v1*bz0 - w1*by0 + ex0;
```

Robust QED processes with adaptive Monte Carlo

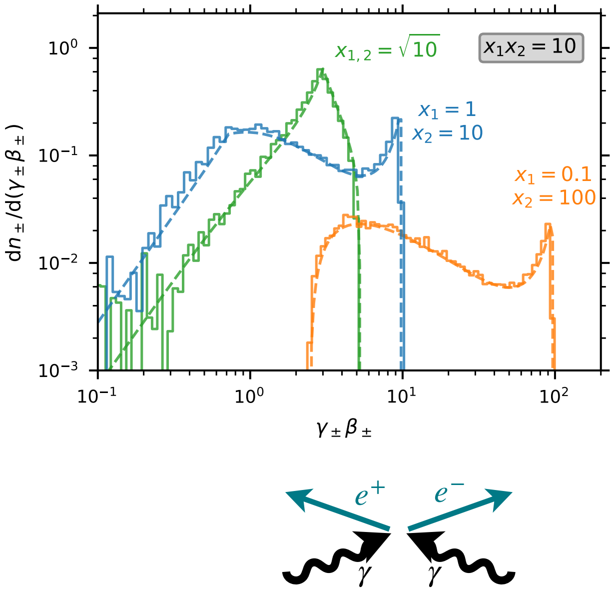
Compton scattering



Pair annihilation

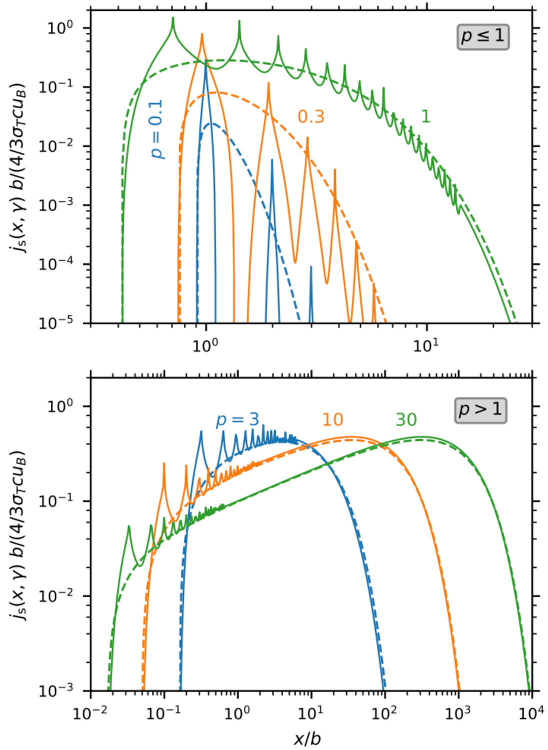


Photon annihilation

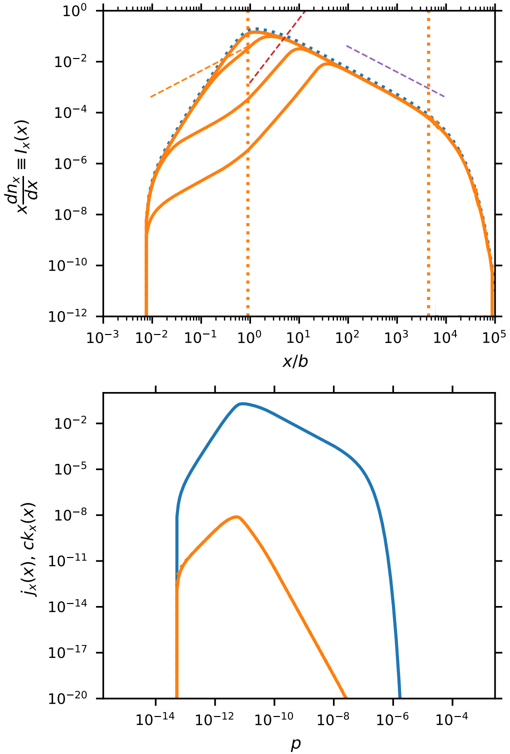


Robust cyclo-synchrotron with hybrid Fokker-MC

Cyclo-synchrotron emissivity



cyclo-synchrotron self-absorption



Coupled kinetic equations

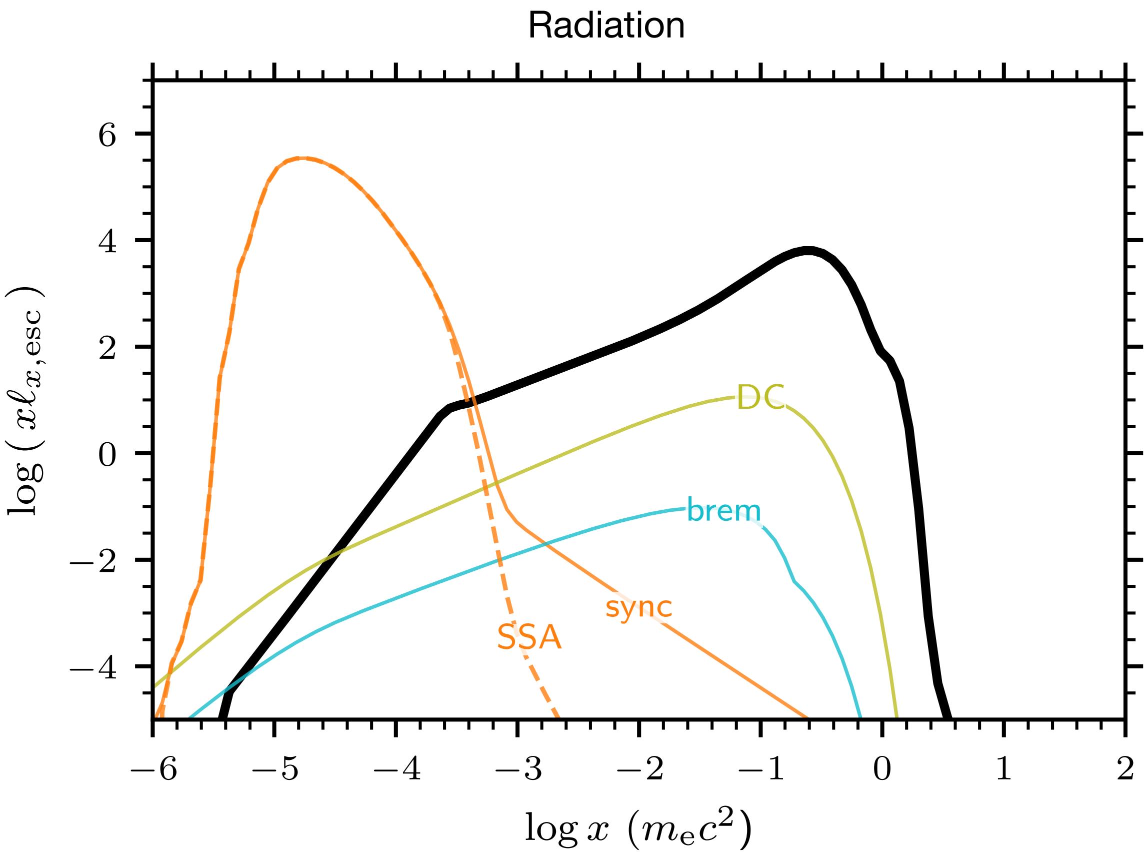
$$\frac{\partial n_x(x)}{\partial t} = \sum_i \dot{n}_{x,i} - \frac{n_x}{t_{x,esc}(x)} + \frac{Q_x(x)}{x}$$

$$\frac{\partial n_\pm(p)}{\partial t} = \sum_i \dot{n}_{\pm,i} - \frac{n_\pm}{t_{\pm,esc}(p)} + \frac{Q_\pm(p)}{p}$$

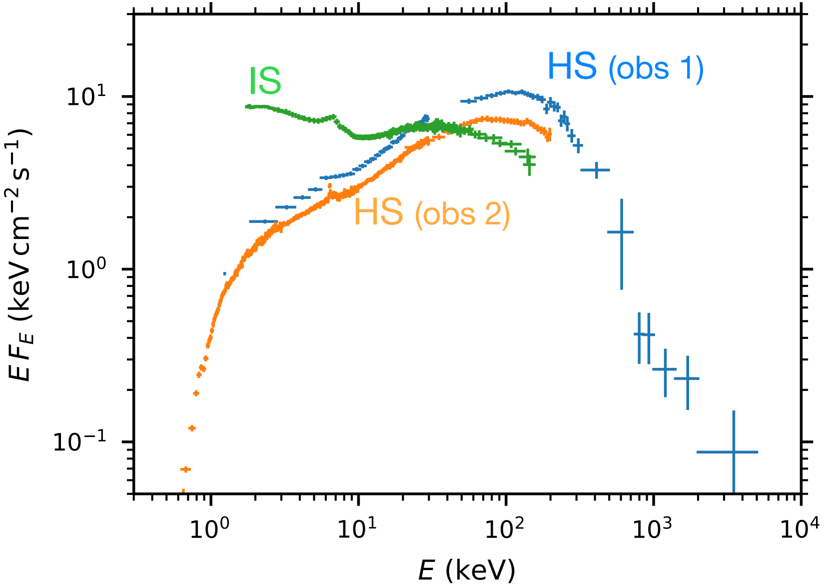
Monte Carlo sampling

Sample X_t from a distribution $f(\mathbf{x}, t)$ experiencing a (stochastic) process W_t

Photon supply in magnetized plasmas



Hard-state spectra from Cyg X-1



Hard state (obs 1) Ginga-OSSE1991 Jun 6 (Gierlinski+ 1997) + CGRO/COMPTEL (McConnel+ 2002)

Hard state (obs 2) BeppoSAX May 3–4 1998 (Di Salvo+ 2001)

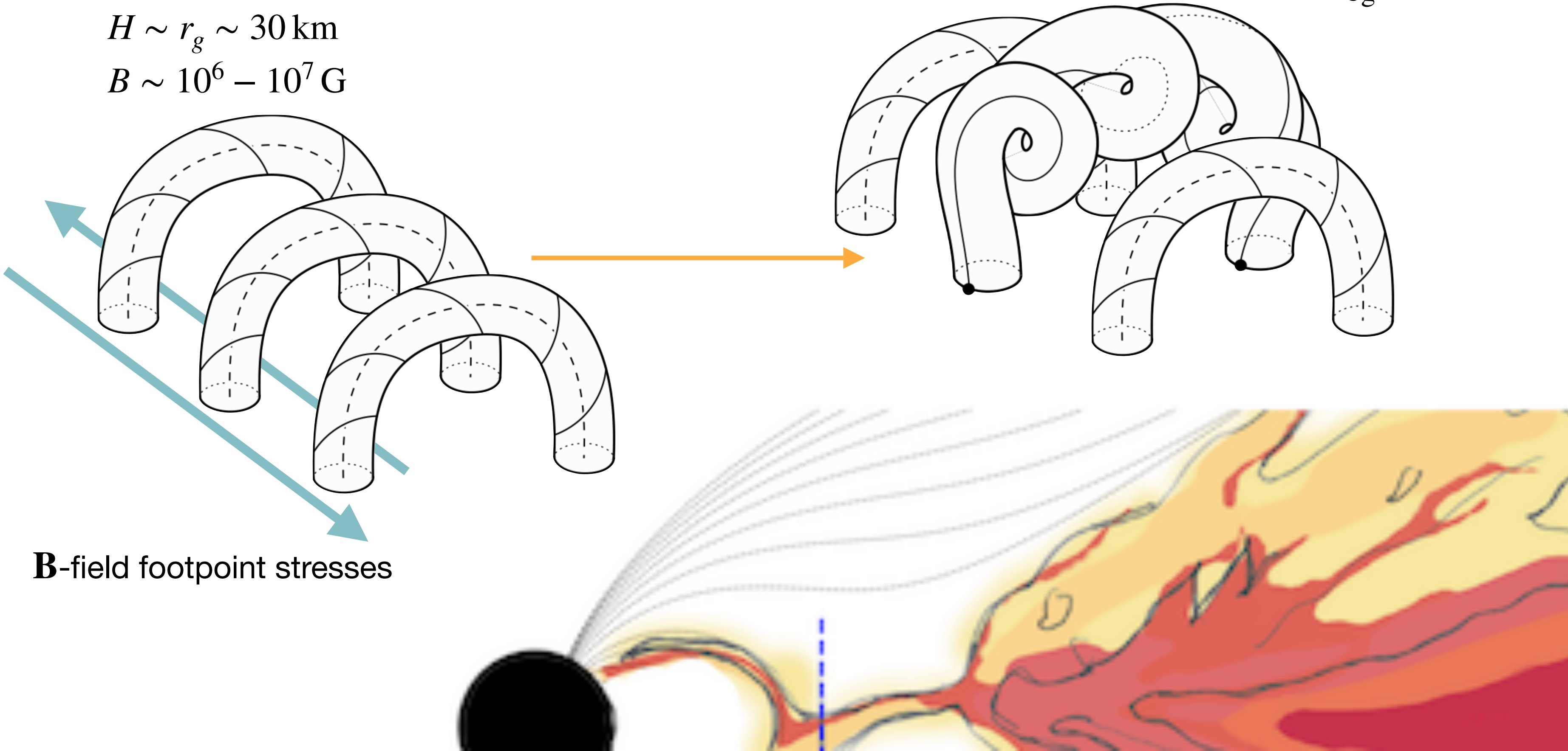
Intermediate state RXTE May 23 1996 (Gierlinski+1999)

Flaring in magnetized XRB accretion flows

$\delta B \sim B_{\rm bg}$

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

$B \sim 10^6 - 10^7\,\mathrm{G}$

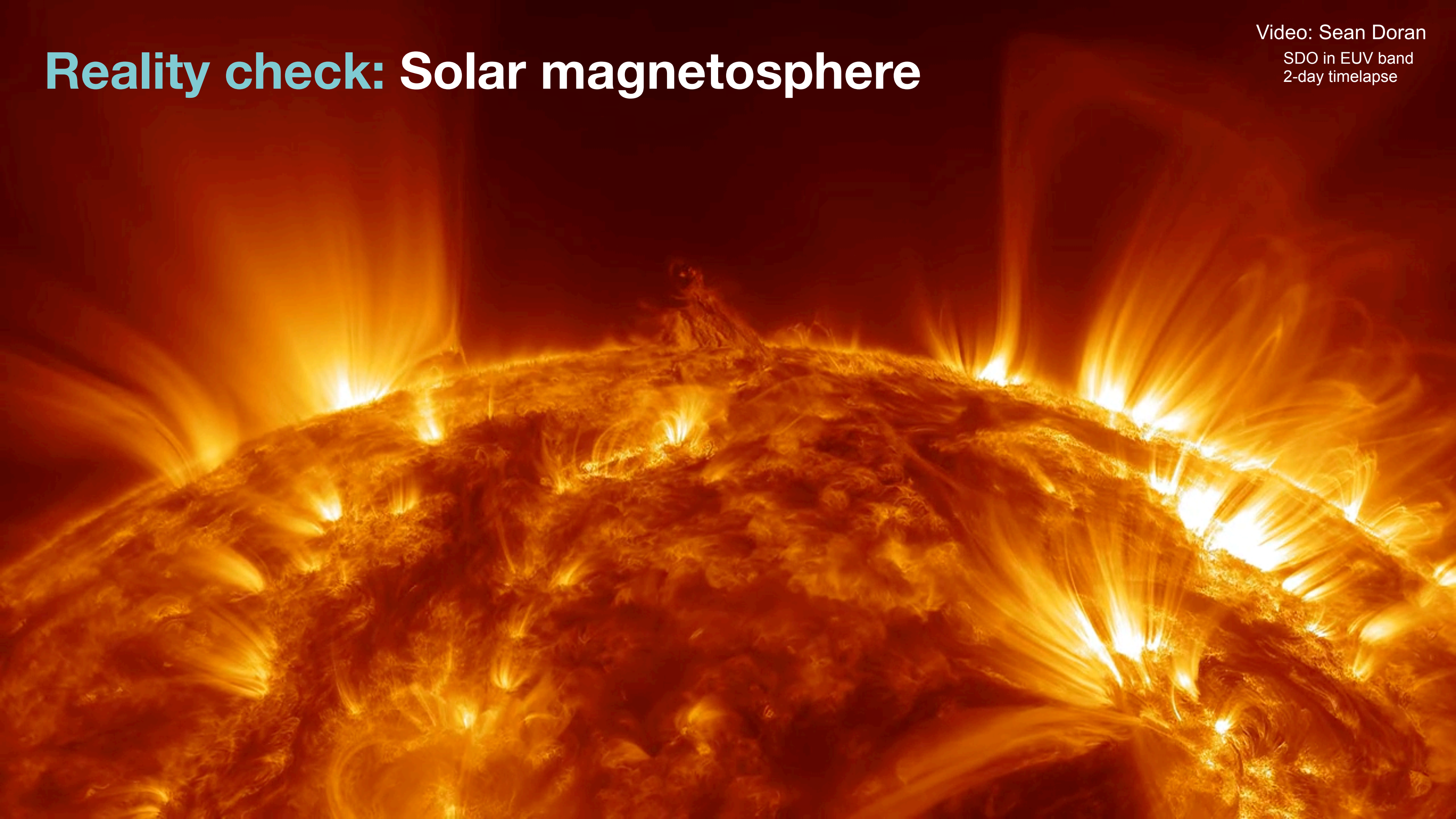


B-field footpoint stresses

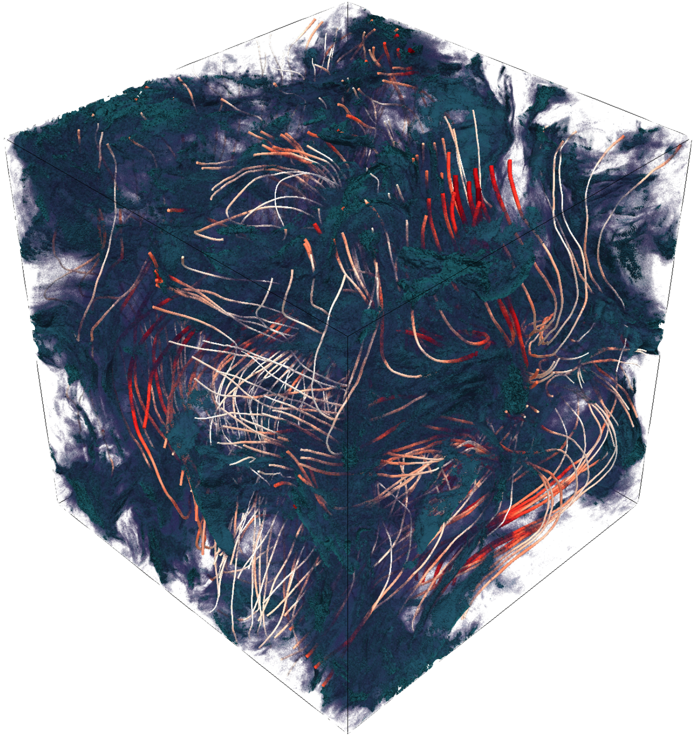
Reality check: Solar magnetosphere

Video: Sean Doran

SDO in EUV band
2-day timelapse



X-ray output from a magnetic flare



Small magnetized turbulent region characterized with

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

$$t_g \sim \frac{H}{c} \sim 100\,\mathrm{ms}$$

$$B \sim 10^7\,\mathrm{G}$$

locally injected power from magnetic perturbations

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

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

compactness

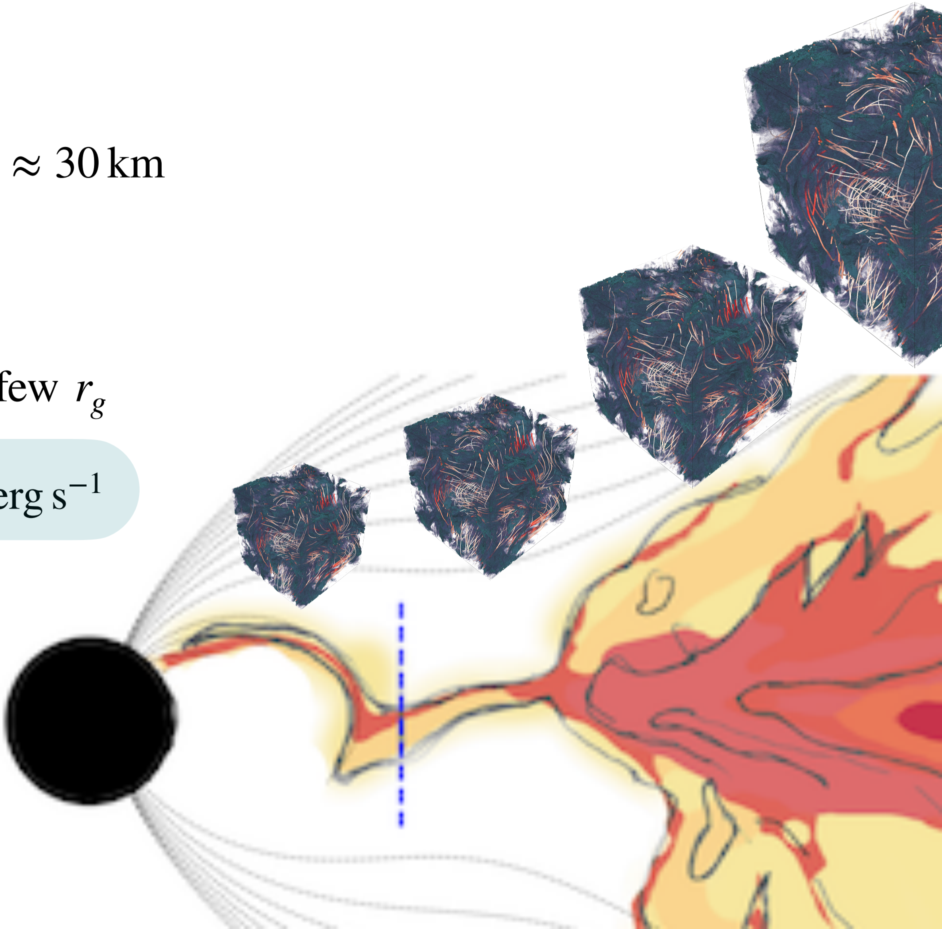
Multiple flares in corona

locally injected power per flare region of size $H \sim r_g \approx 30\,\mathrm{km}$

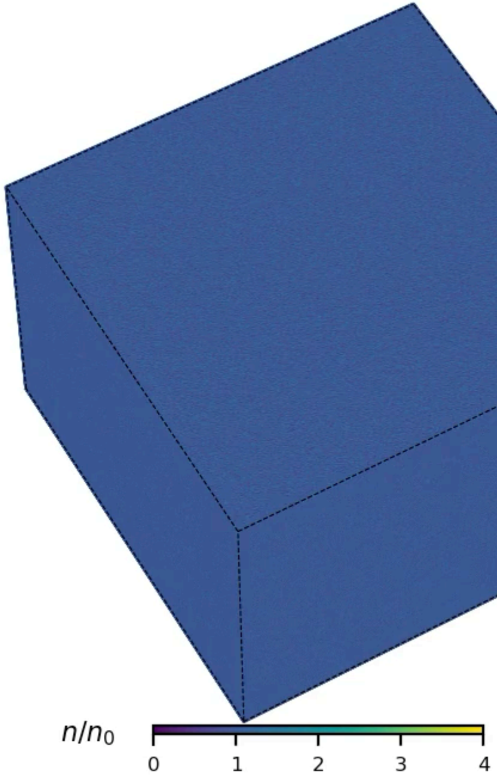
$$L_{\mathrm{flare}} \approx \dot{U}_B H^3 \approx \frac{U_B}{H/c} H^3 \sim 10^{36}\,\mathrm{erg\,s^{-1}}$$

total luminosity from corona with a size $H_{\mathrm{corona}} \sim \mathrm{a\ few}\ r_g$

$$L = \sum L_{\mathrm{flare}} \sim L_{\mathrm{flare}} \frac{H_{\mathrm{corona}}^3}{H^3} \sim 10 L_{\mathrm{flare}} \sim \boxed{10^{37}\,\mathrm{erg\,s^{-1}}}$$



First-principles simulations of photon-plasmas

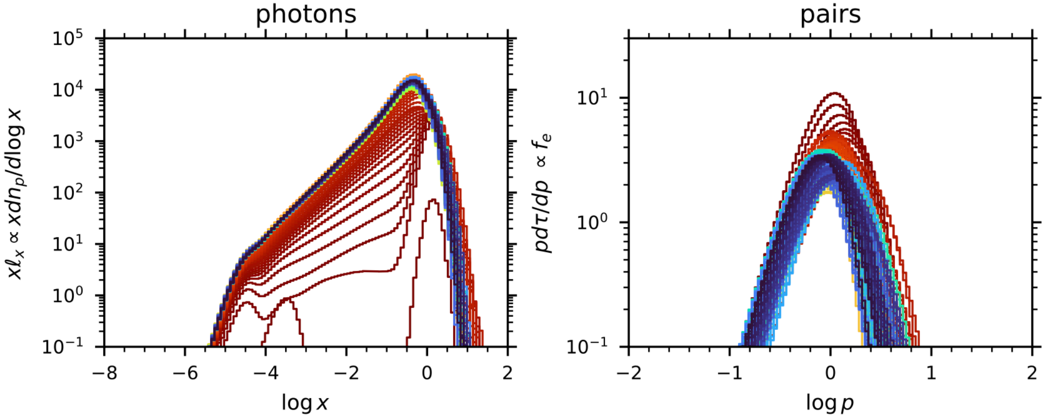


electron-positron-photon plasma

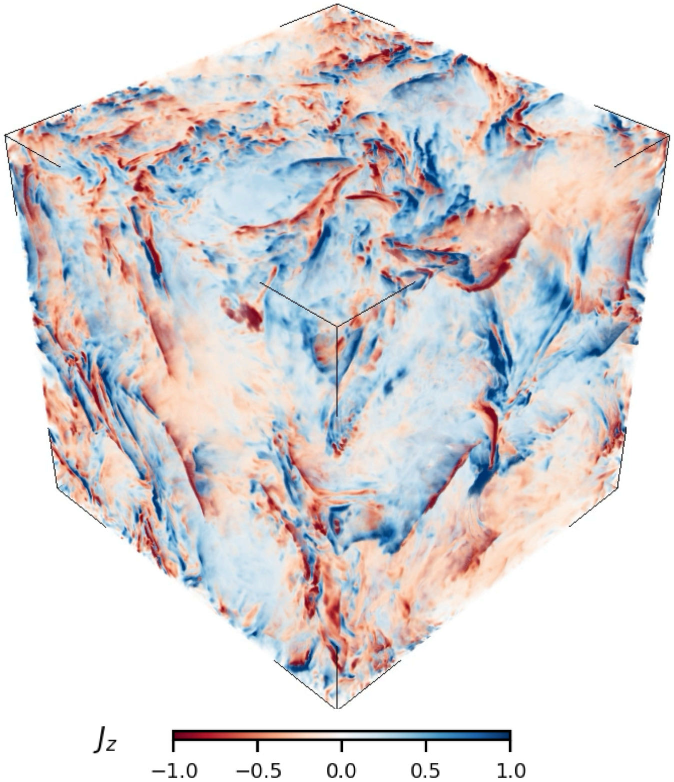
in a box 1024^3 with $\Delta x = 1\, c/\omega_p$

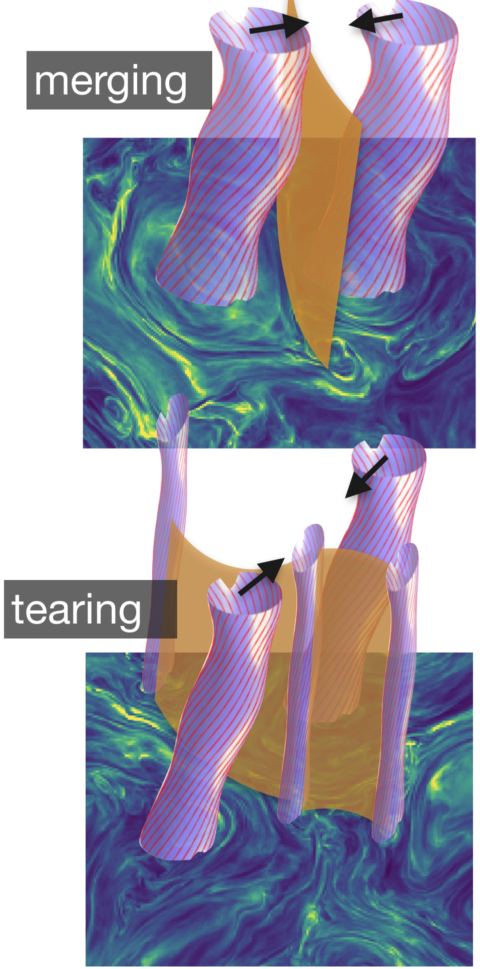
turbulence is driven on large-scales by Langevin antenna:

- background field $\mathbf{B}_{\rm bg}$ perturbed with $\langle \delta B \rangle \sim B_{\rm bg}$
- antenna power $\ell_{\rm ant} \approx 20$

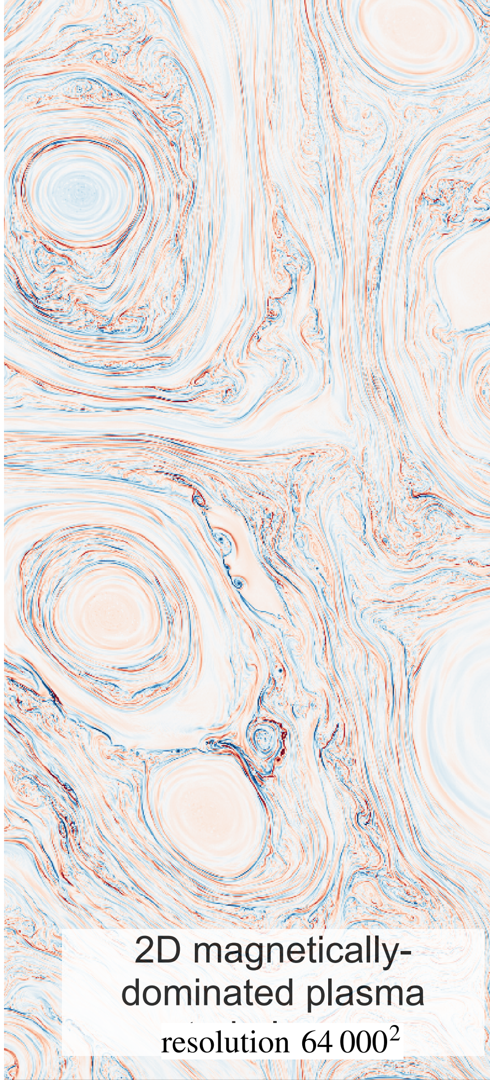


Intermittent current sheets





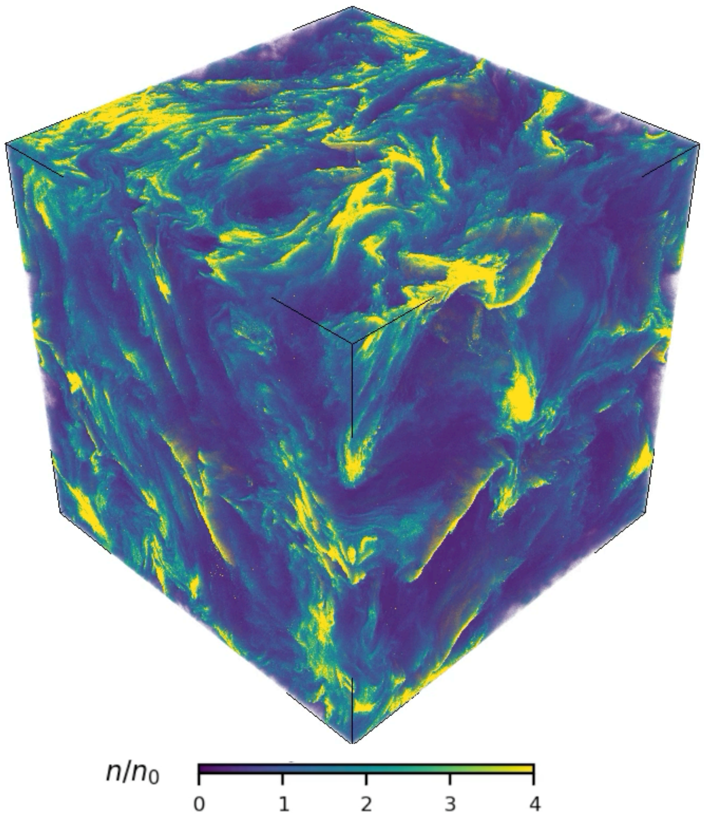
Comisso & Sironi
Zhdankin et al



2D magnetically-dominated plasma

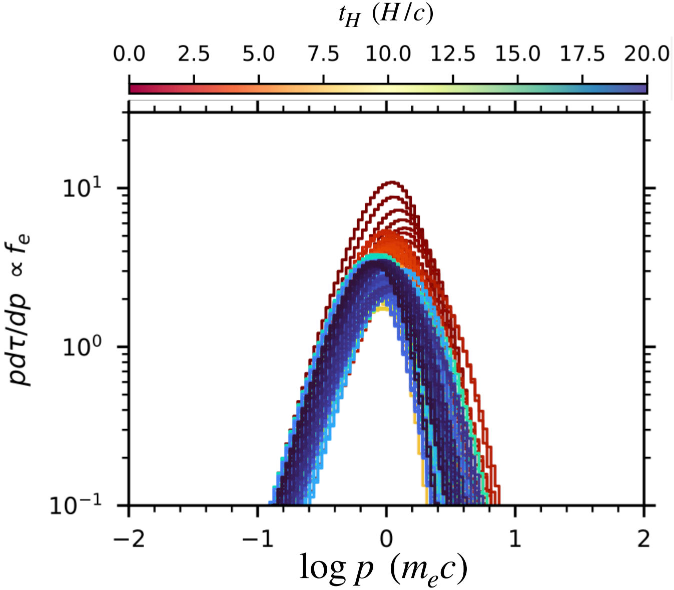
resolution $64\,000^2$

Self-consistent plasma magnetization via pair-creation

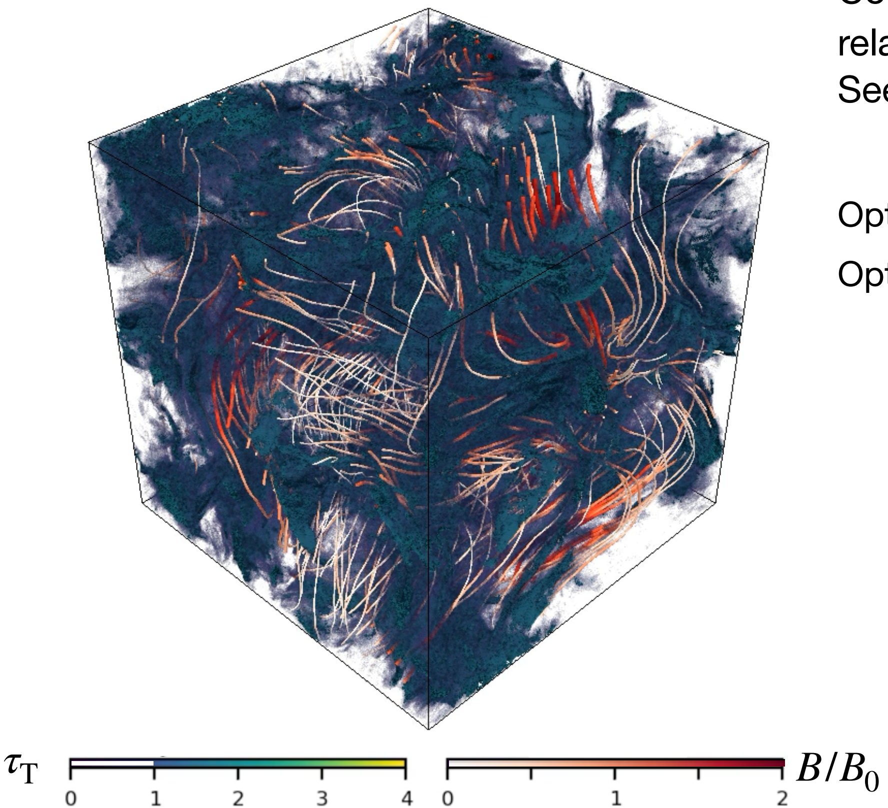


$e^{\pm}$ density is self-consistently set at $\sigma \sim 3$ for $\ell \sim 20$

Efficient cooling increases density contrast
($t_{\rm cool} \sim 0.1\, t_{\rm eddy}$)



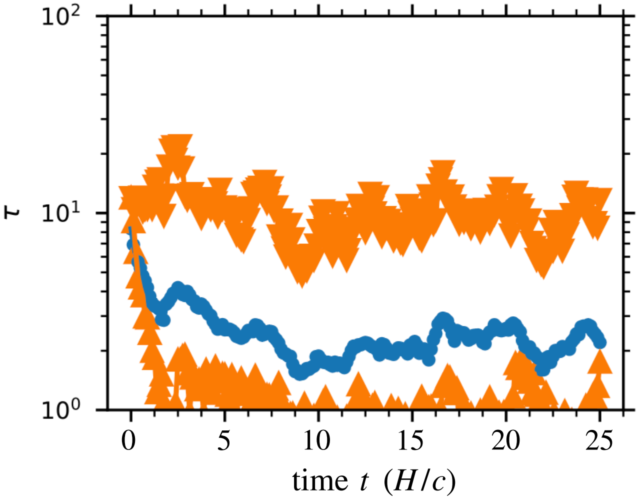
Turbulent bulk Comptonization



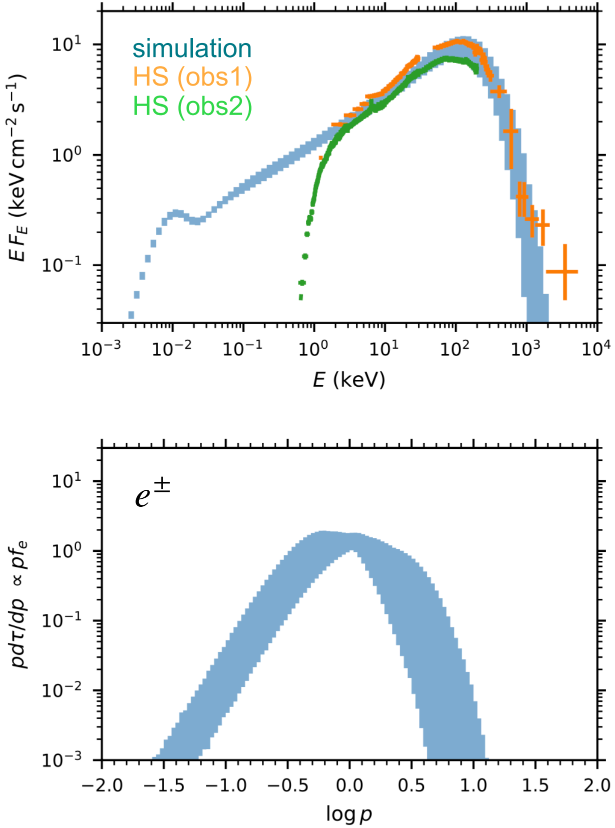
Comptonization occurs in "plasma pockets" with sub-relativistic Alfvenic bulk motions $\Gamma_{\mathrm{bulk}} \sim 1 - 3$.
See also Groselj et al. 2023

Optically thin regions $\tau \ll 1$ have $\delta B / B \sim 1$ (weak guide field)

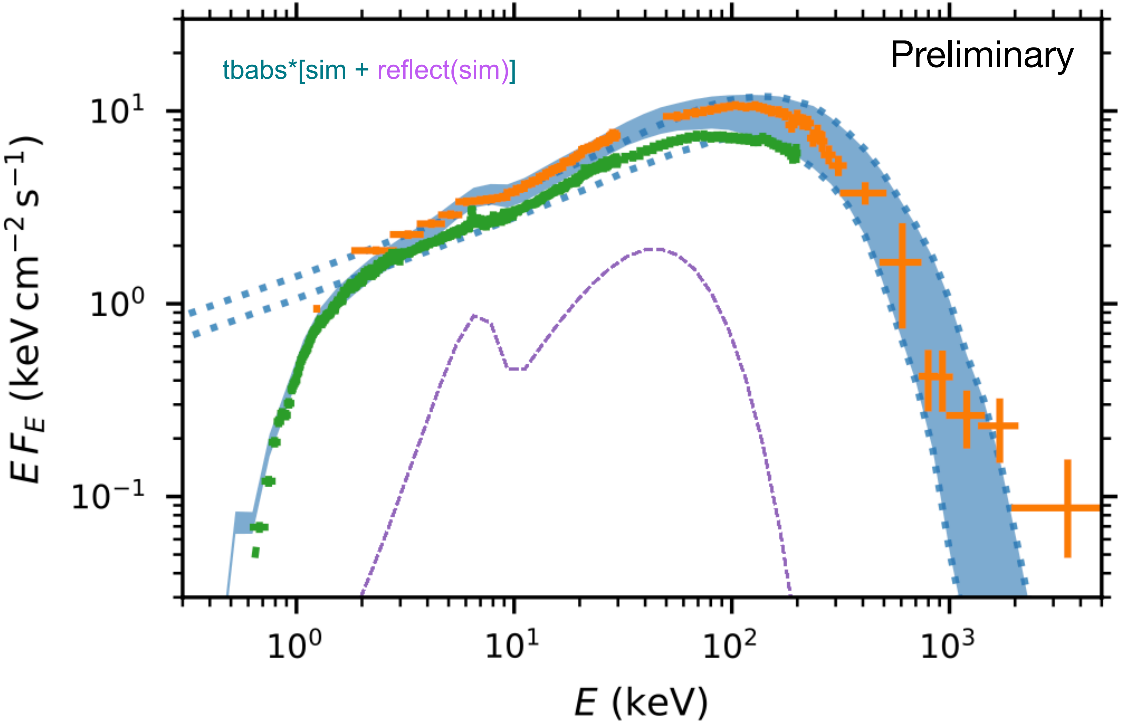
Optically thick regions $\tau \sim 10$ have $\delta B / B \ll 1$ (strong guide field)



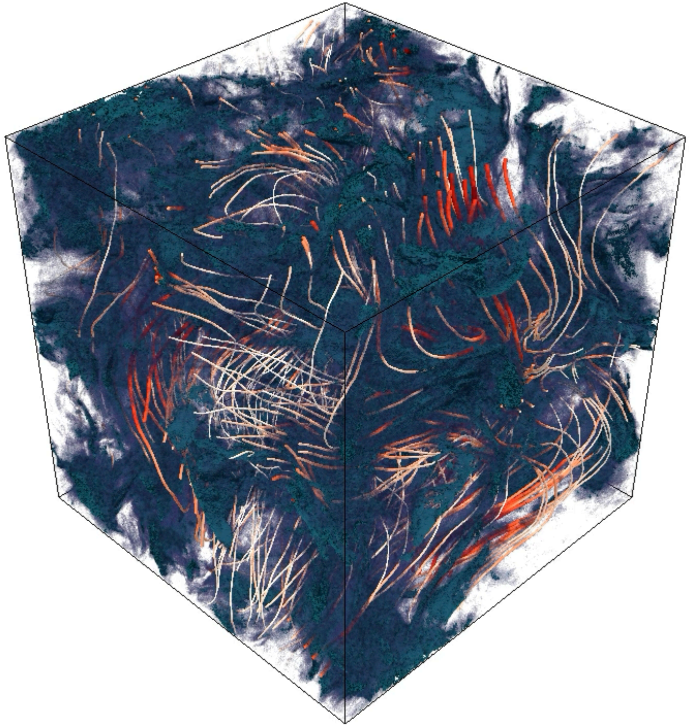
Escaping radiation for Cyg X-1 hard state



First-principle simulations vs observations



Conclusions



First-principles radiative plasma simulations are here!

in-situ Comptonization generates realistic spectra

in-situ pair-production sets plasma magnetization σ

Simulations can reproduce XRB Cyg X-1 hard state