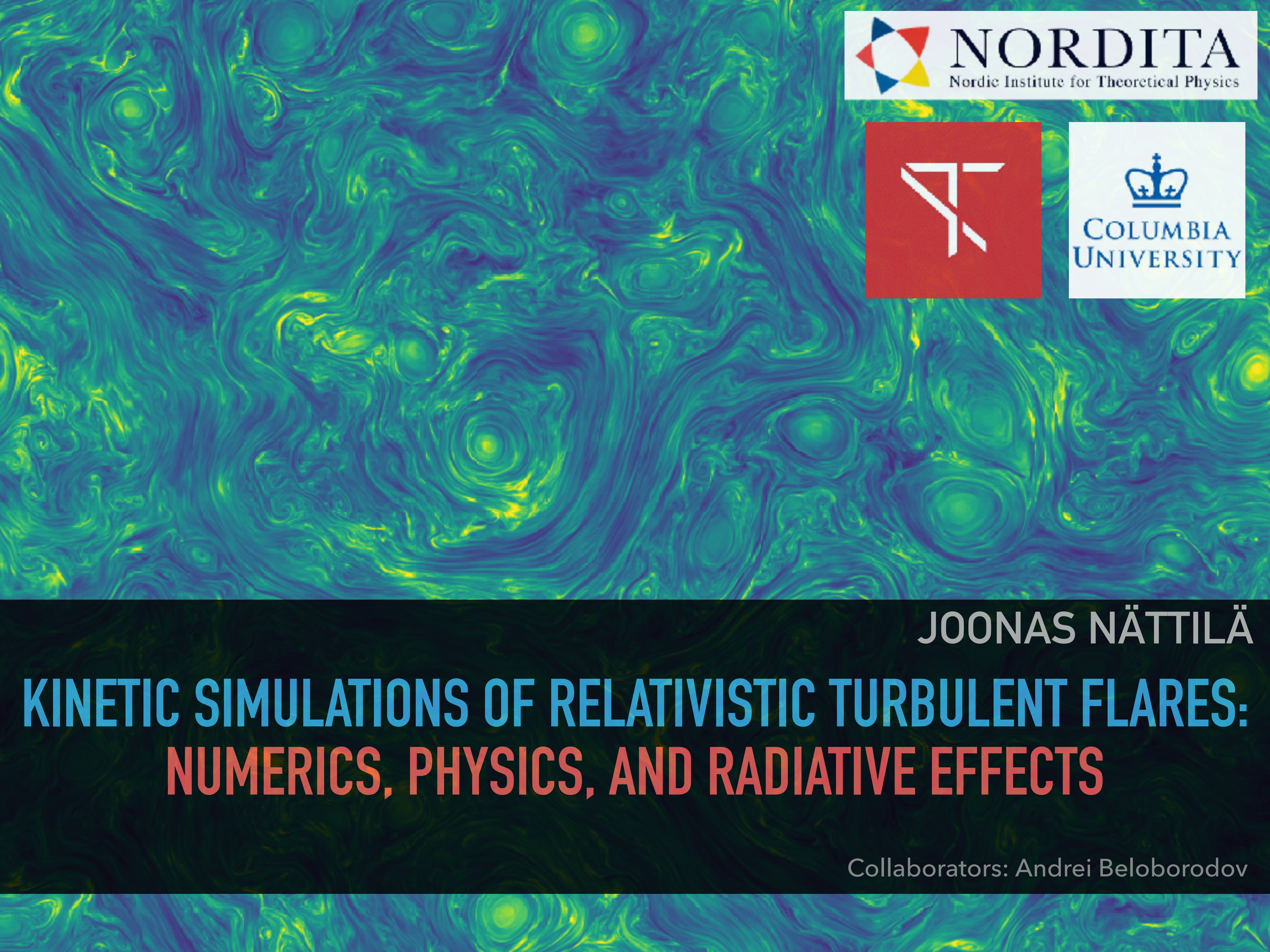


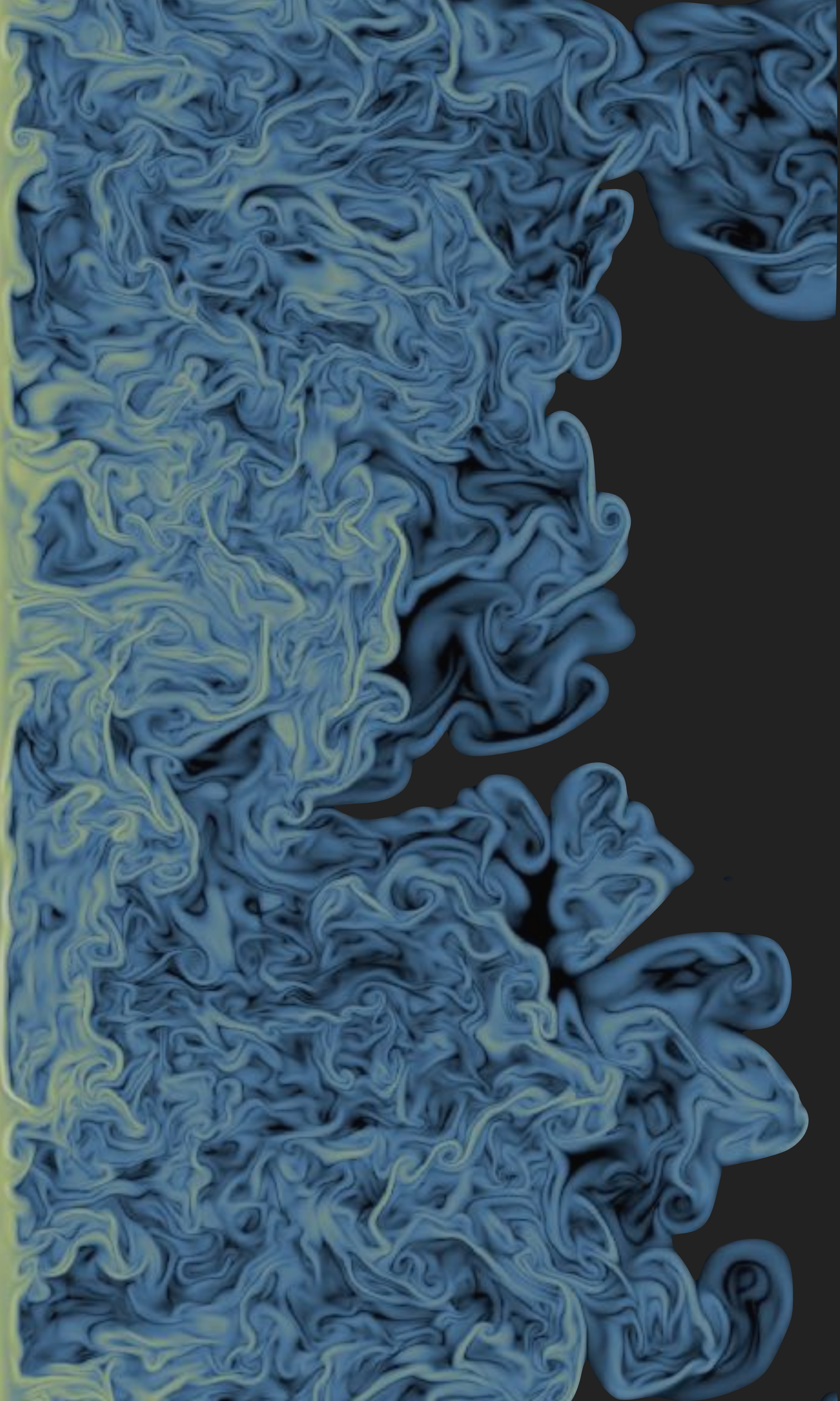
NORDITA
Nordic Institute for Theoretical Physics

Columbia University

JOONAS NÄTTILÄ

KINETIC SIMULATIONS OF RELATIVISTIC TURBULENT FLARES: NUMERICS, PHYSICS, AND RADIATIVE EFFECTS

Collaborators: Andrei Beloborodov

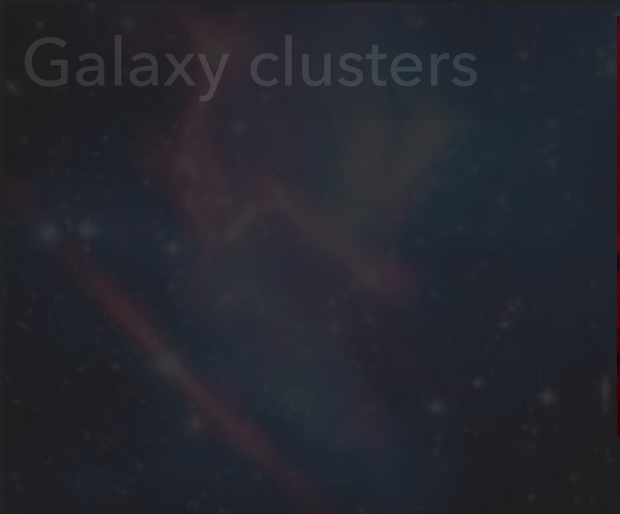


INTRODUCTION TO

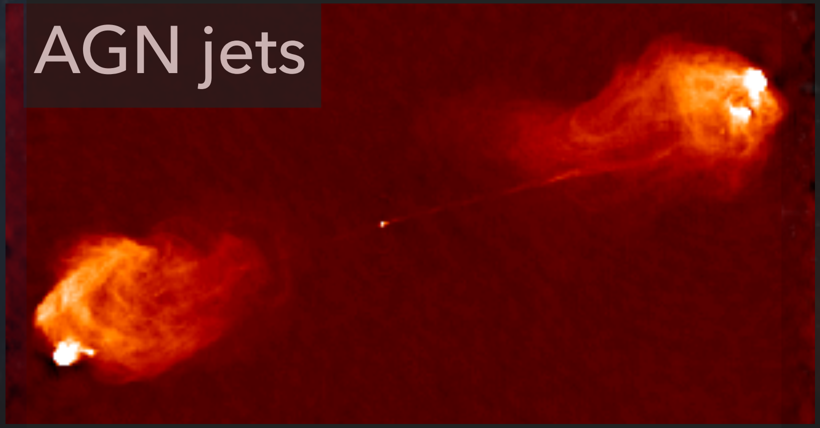
ASTROTURBULENCE

PLASMA TURBULENCE IN ASTROPHYSICS

PLASMA TURBULENCE IN ASTROPHYSICS



Galaxy clusters

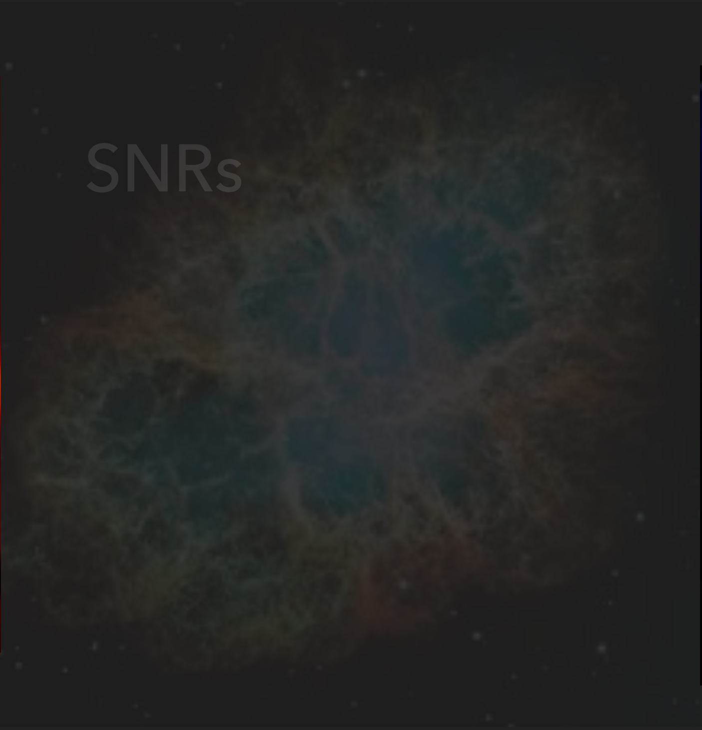


AGN jets

Giant radio lobes

ISM

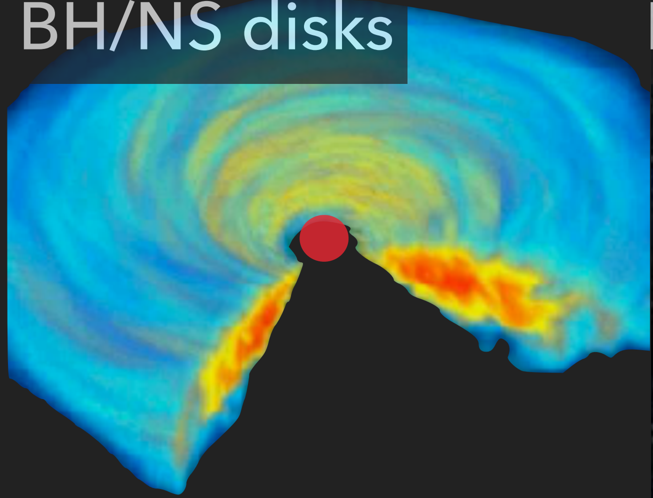
BH magnetospheres



SNRs

PWNs

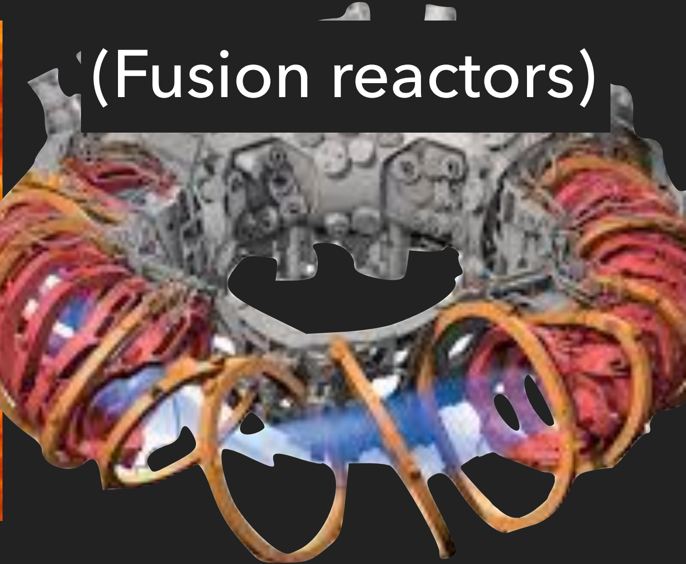
GRBs



BH/NS disks

NS-NS mergers

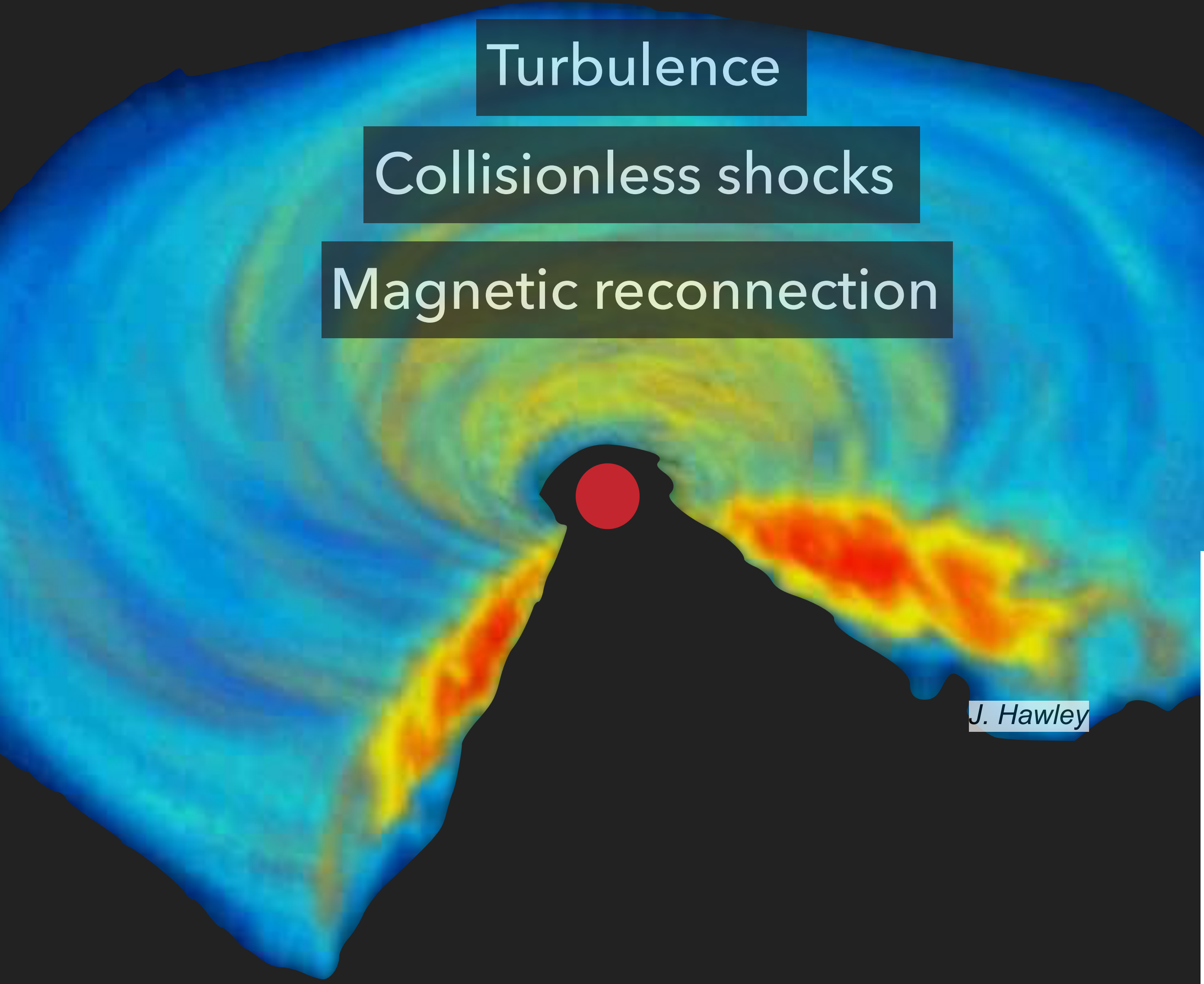
Solar flares/wind



(Fusion reactors)

Observed radiation

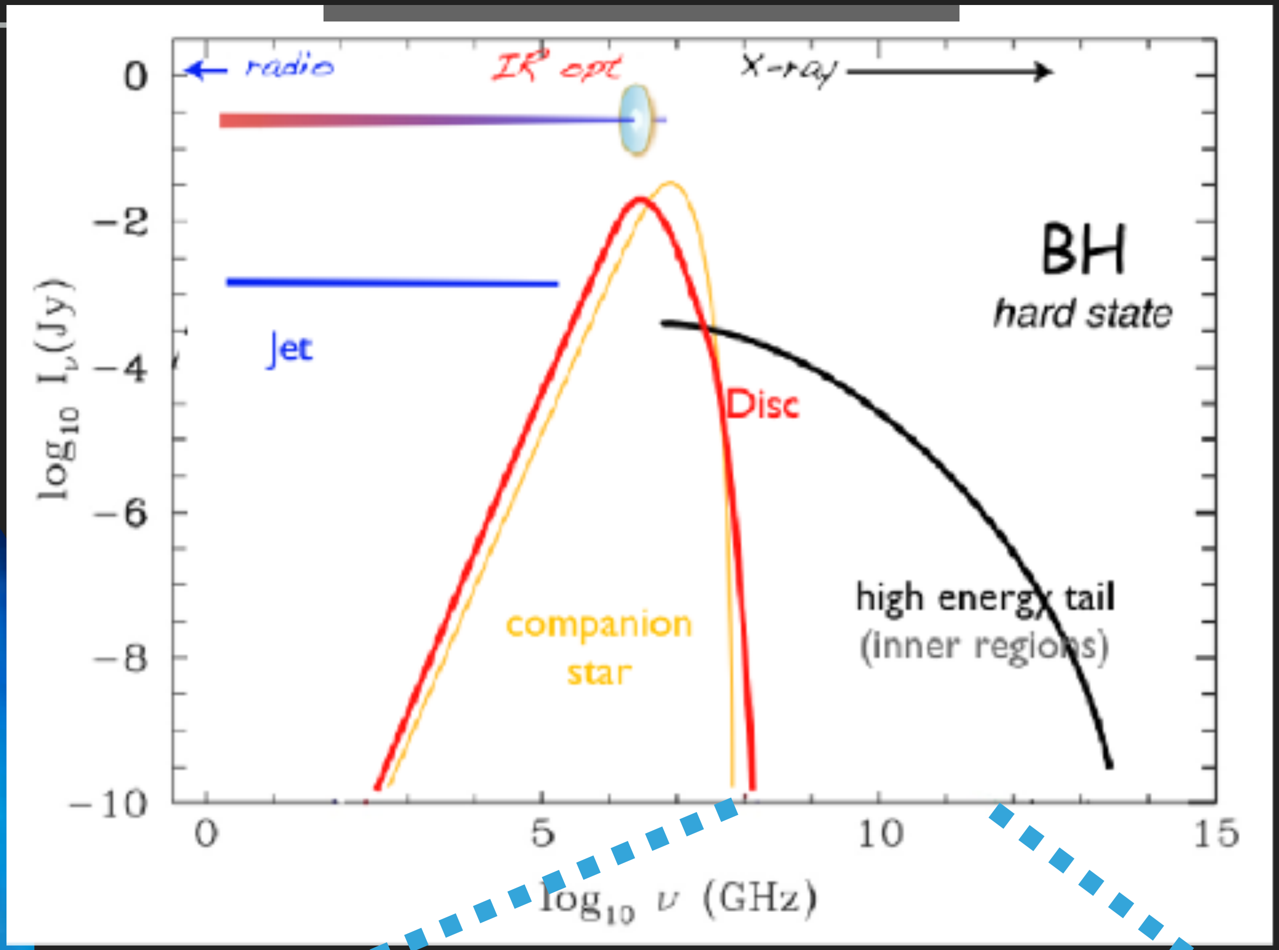
- Energization of disk corona

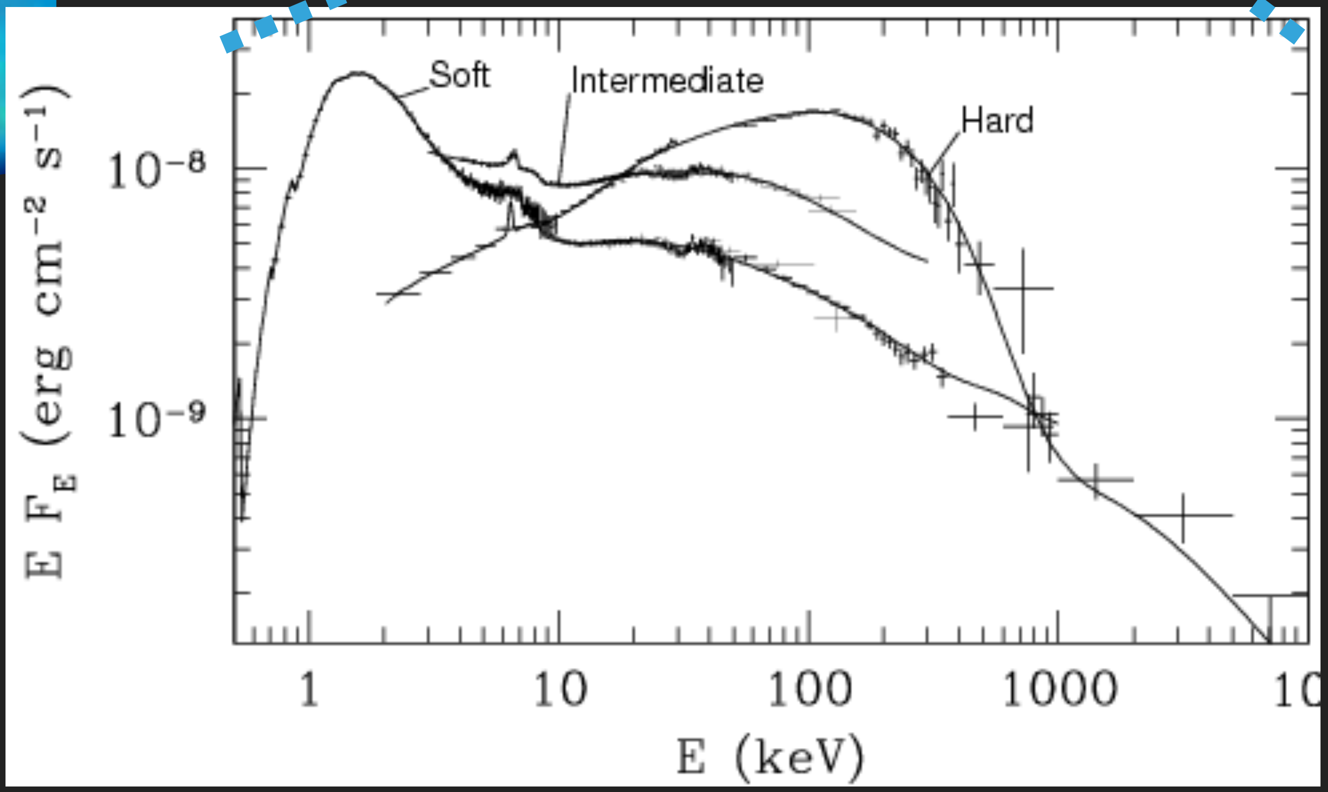


Turbulence

Collisionless shocks

Magnetic reconnection





NUMERICAL TOOLS

```
#pragma once

#include <omp.h>

#include "amr_momentum_solver.h"
#include "amr_spatial_solver.h"


namespace vlasov{


void stepLocation( vlasov::Grid& grid )
{

#pragma omp parallel
  {
#pragma omp single
    {

      for(auto cid : grid.getCellIds() ){
#pragma omp task
        {
          vlasov::AmrSpatialLagrangianSolver<Realf> ssol;
          vlasov::VlasovCell& cell
            = dynamic_cast<vlasov::VlasovCell&>(grid.getCell( cid ));
          ssol.solve(cell, grid);
        }// end of omp task
      }


    }// end of omp single
  }// end of omp parallel

}



void stepVelocity( vlasov::Grid& grid )
{

#pragma omp parallel
  {
#pragma omp single
    {

      for(auto cid : grid.getCellIds() ){
#pragma omp task
        {
          vlasov::AmrMomentumLagrangianSolver<Realf> vsol;
          vlasov::VlasovCell& cell
            = dynamic_cast<vlasov::VlasovCell&>(grid.getCell( cid ));
          vsol.solve(cell);
        }// end of omp task
      }


    }// end of omp single
  }// end of omp parallel

}


/// Update Yee lattice bounderies
/*
void updateBoundaries()
{

  for(auto cid : getCellIds() ){
    vlasov::VlasovCell& cell = dynamic_cast<vlasov::VlasovCell& >(getCe
ll( cid ));
    cell.updateBoundaries( *this );
  }
```

runko

github.com/natj/runko

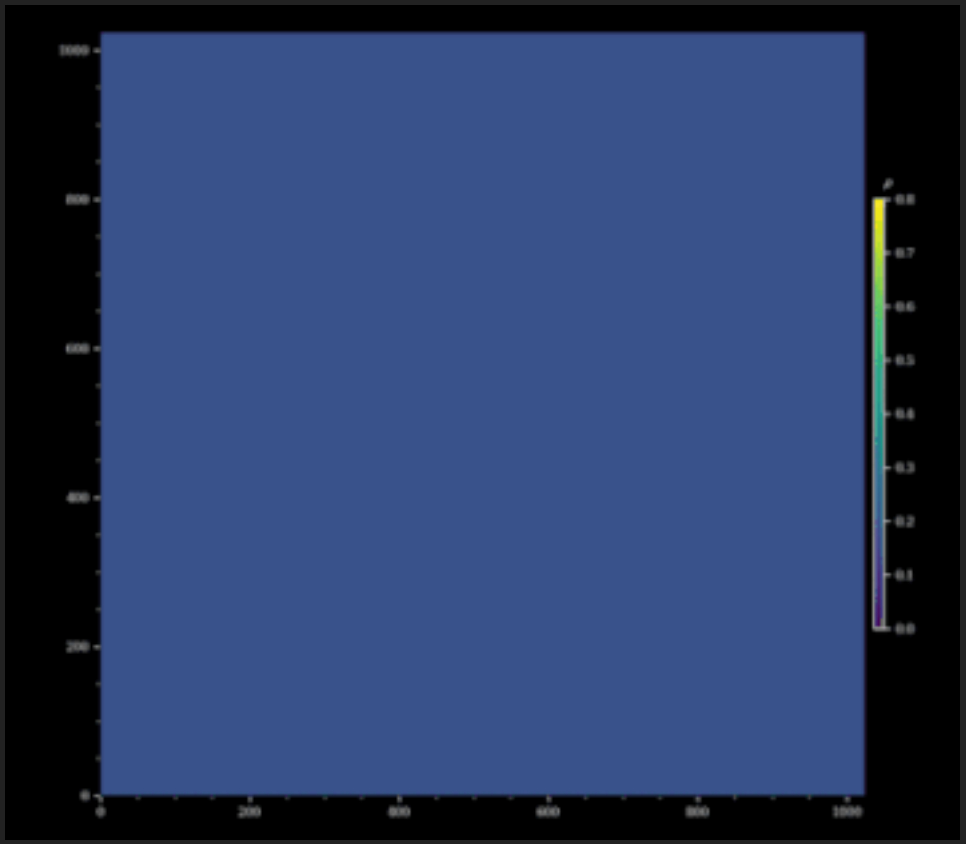
Nättilä 2019

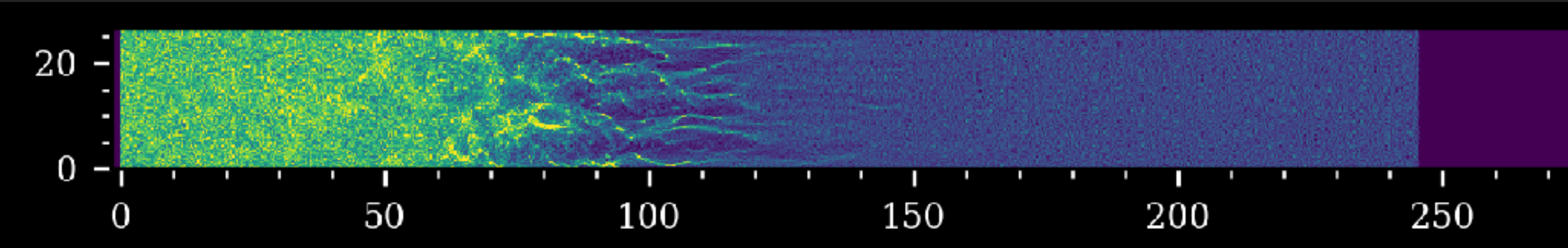
Modern C++14/Python3 framework for plasma simulations

- C++ for computing kernels
- Python3 for `driving` the simulations

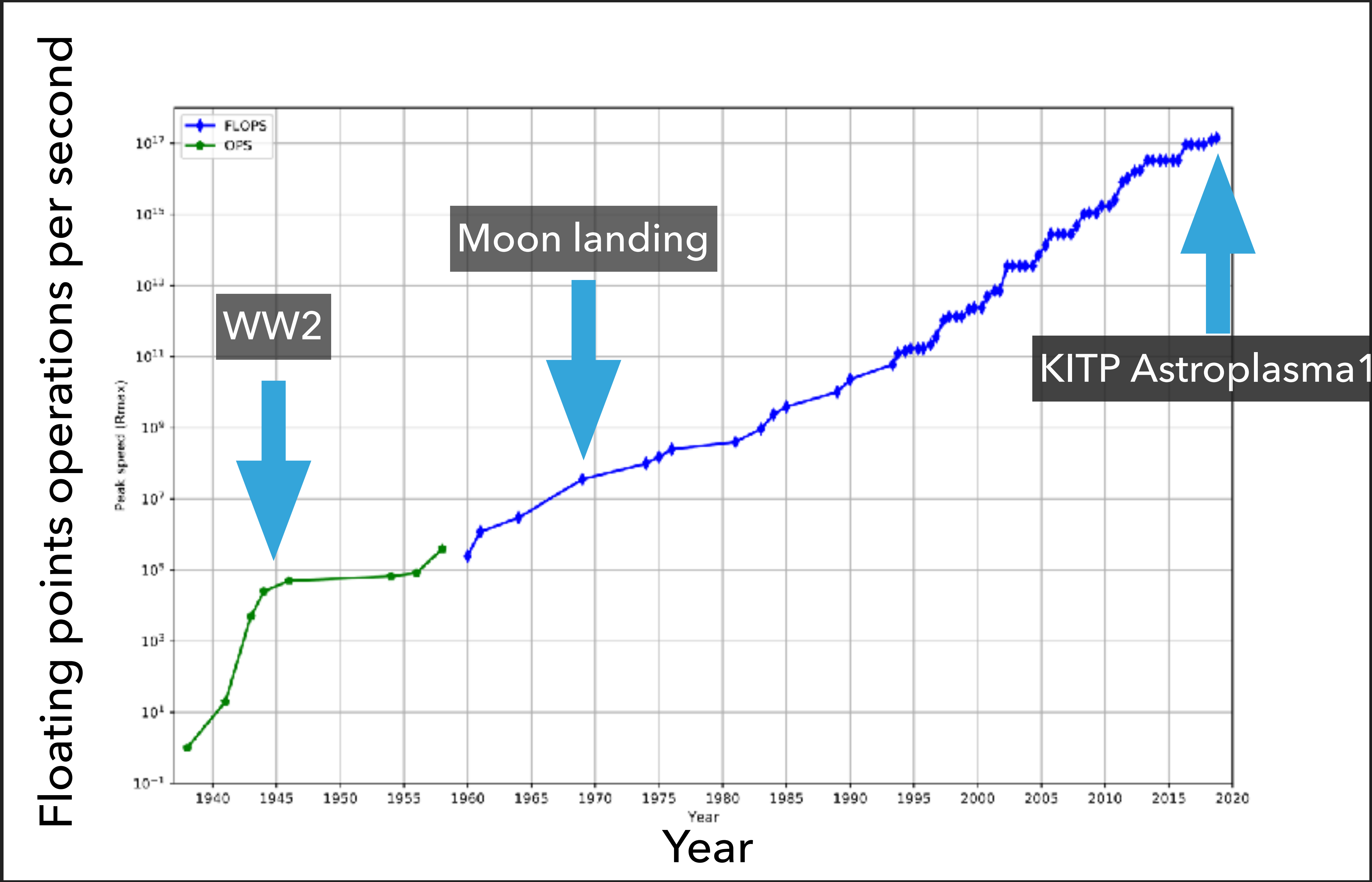
Kinetic plasma simulations:

- turbulence
- collisionless shocks
- beam instabilities
- arXiv: 1906.06306





ENTERING THE EXASCALE ERA

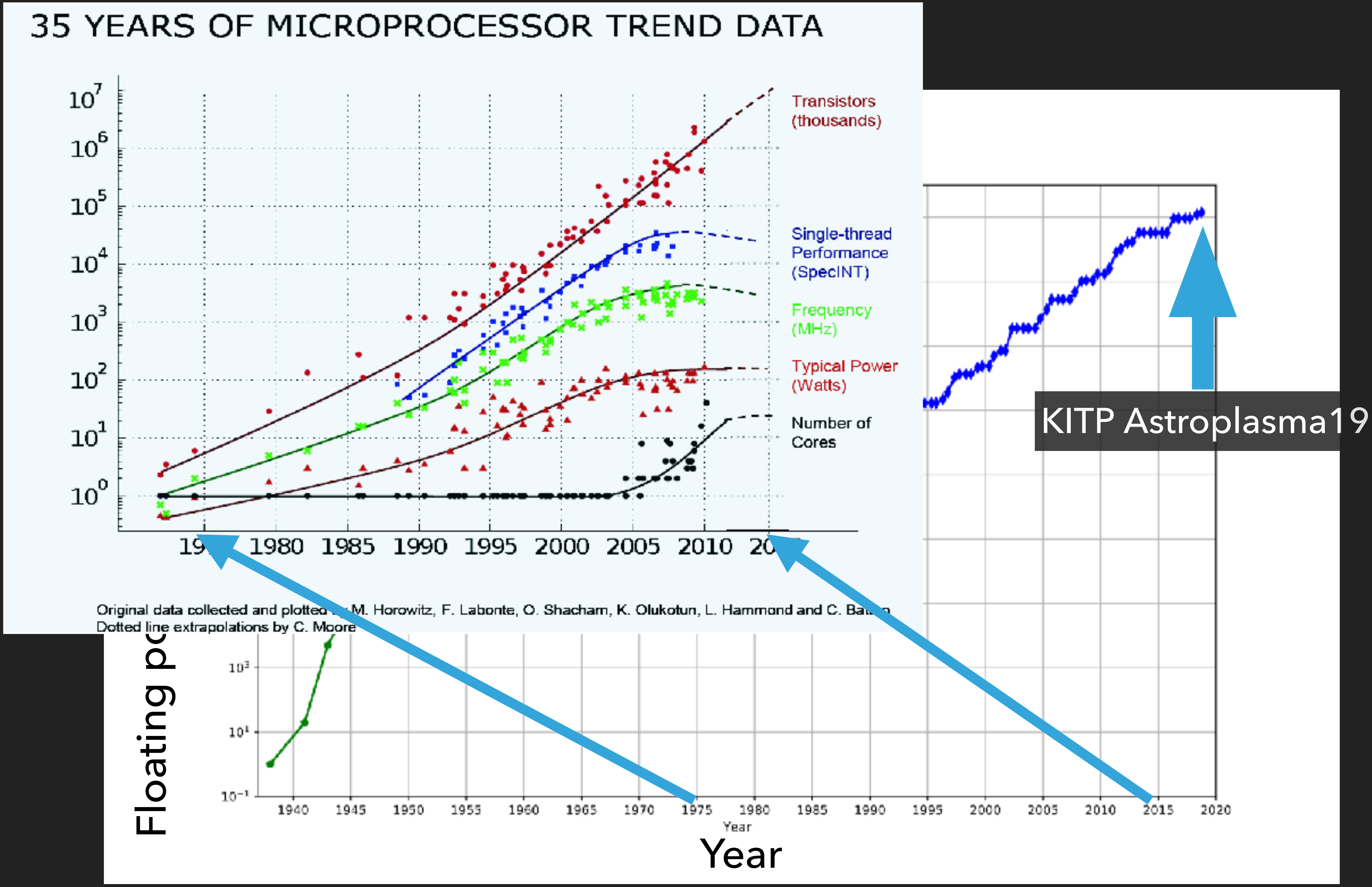


WW2

Moon landing

KITP Astroplasma19

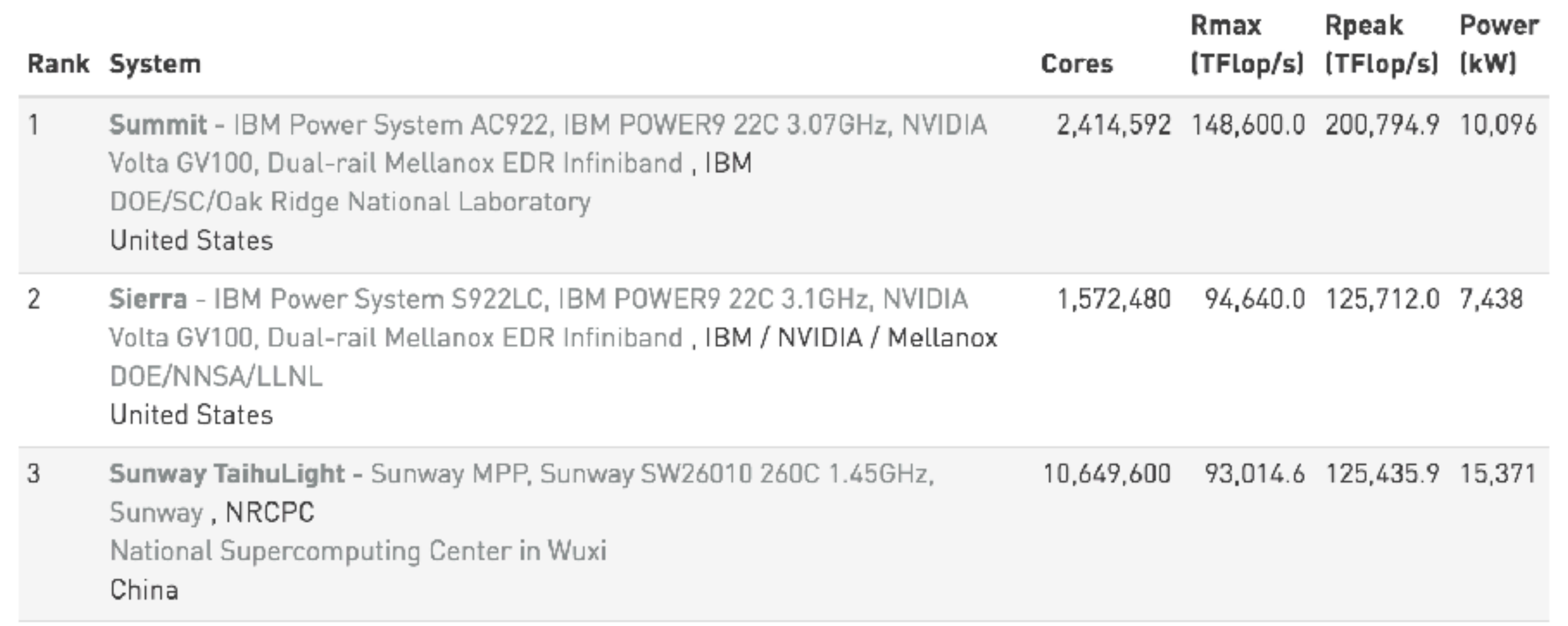
TOOLS



Original data collected and plotted M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Ba
Dotted line extrapolations by C. Moore

ENTERING THE EXASCALE ERA

- Exascale = 100 million (GPU) cores
  - We need to rethink parallelization

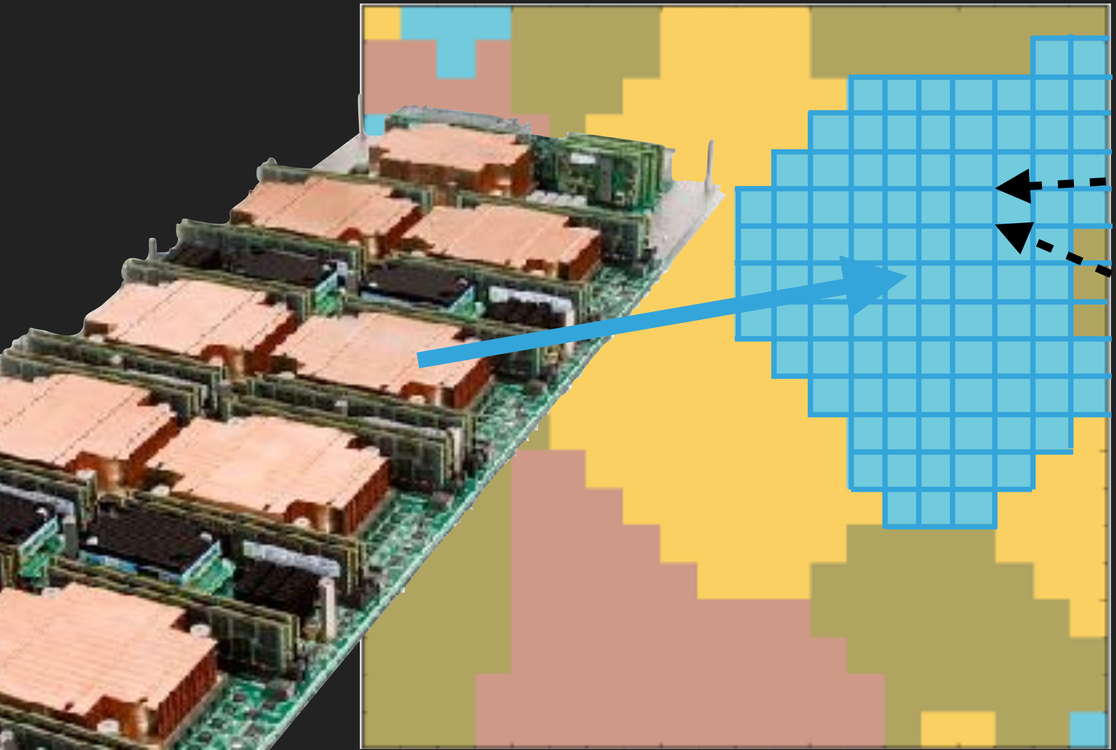


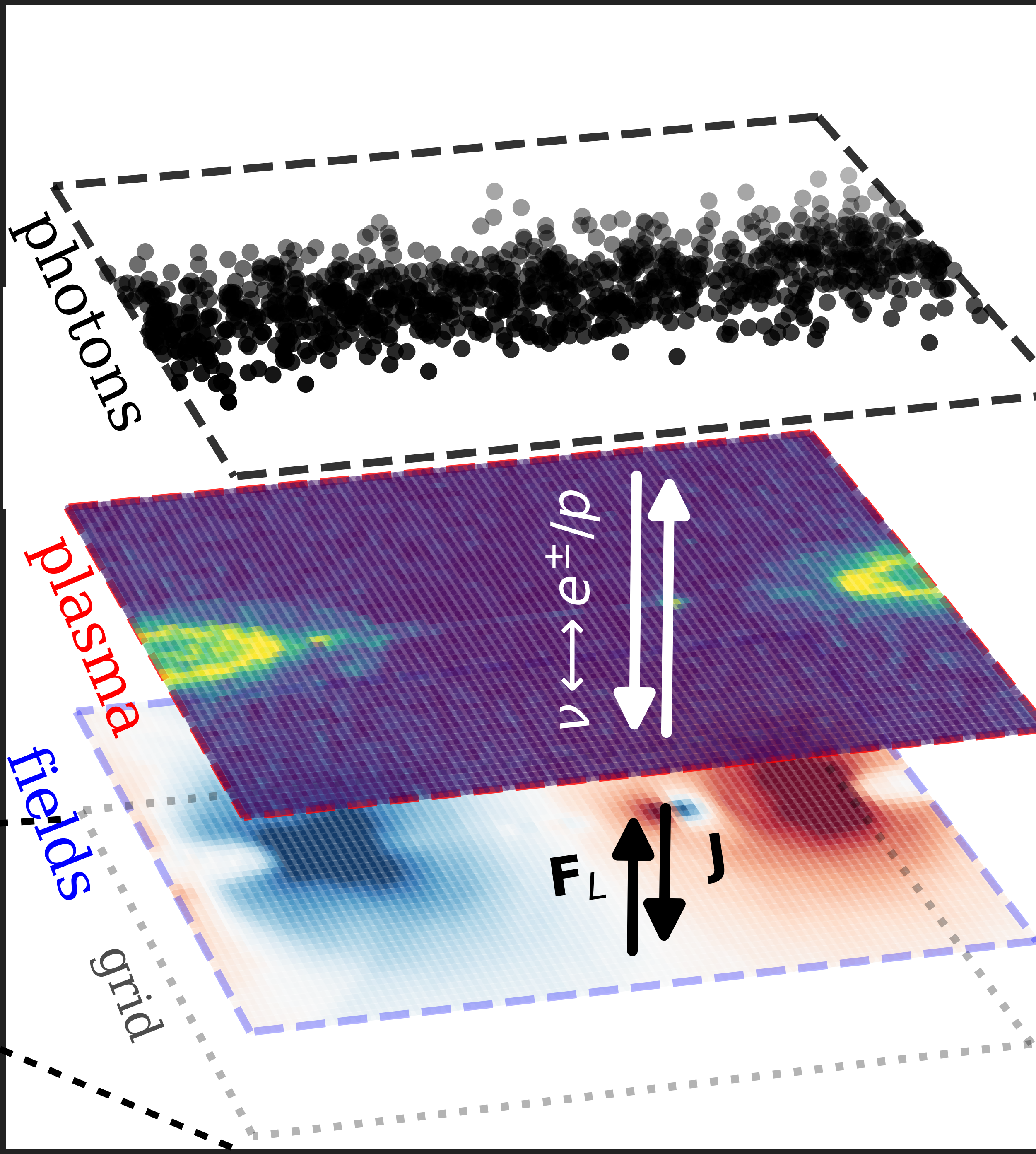
Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**Summit** - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband , IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148,600.0	200,794.9	10,096
2	**Sierra** - IBM Power System S922LC, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband , IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94,640.0	125,712.0	7,438
3	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway , NRCPC National Supercomputing Center in Wuxi China	10,649,600	93,014.6	125,435.9	15,371

https://www.top500.org/lists/2019/06/

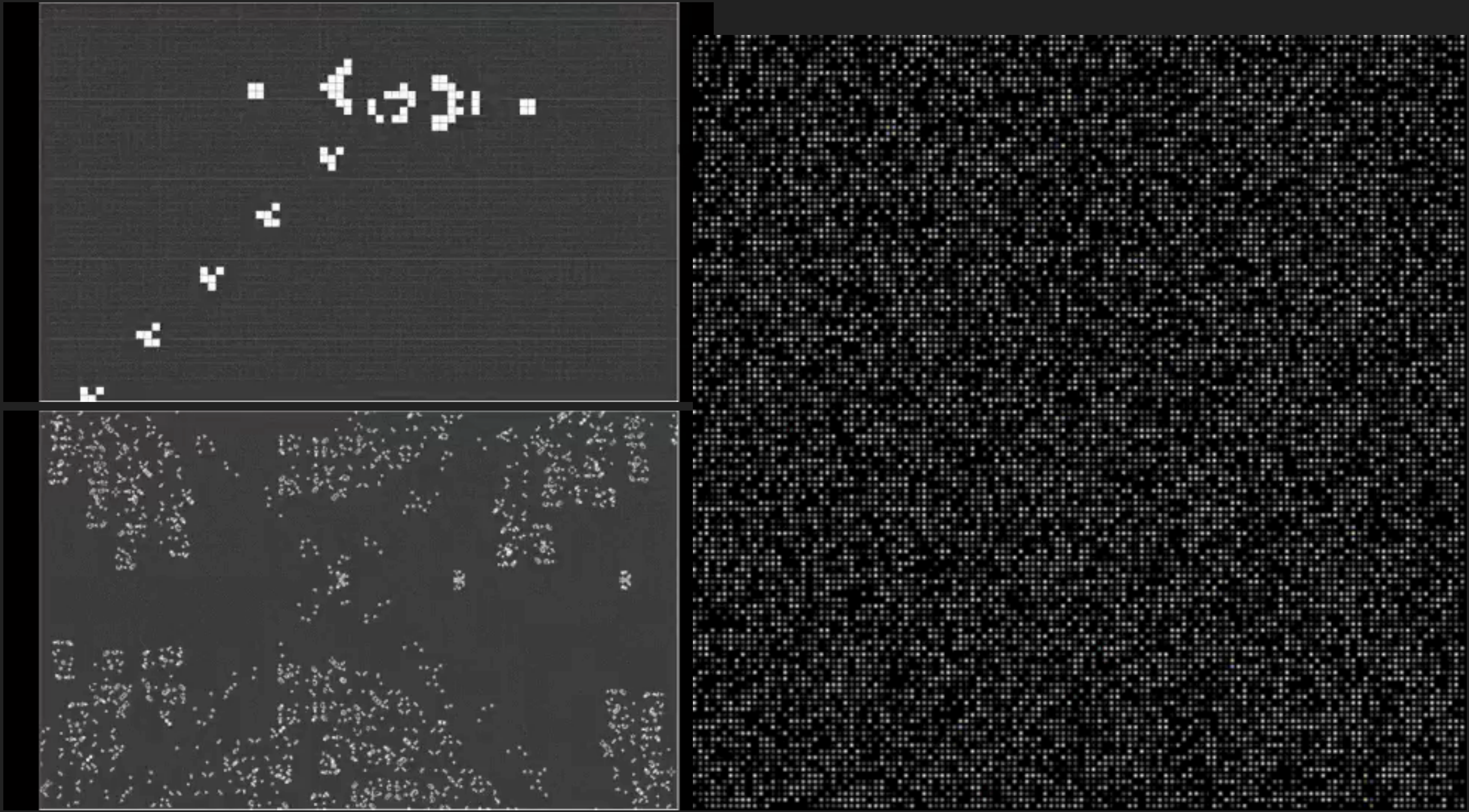
RUNKO: SIMULATION FRAMEWORK

- Computational grid with *tiles*
  - MPI communications
- Electromagnetic module
  - FDTD solver
- Particles/Vlasov module
  - Pusher, Depositer, Interpolator





Conway's Game of Life (2D CA)

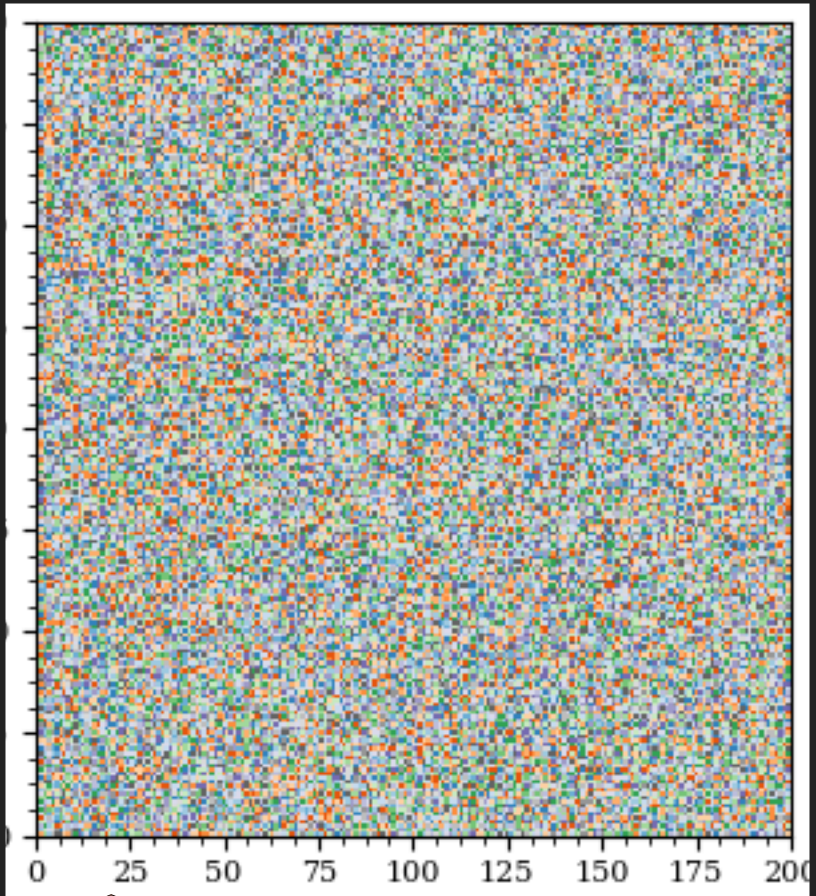


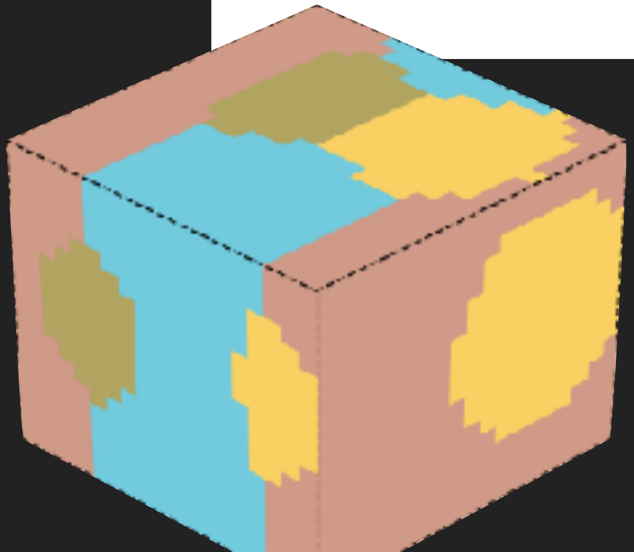
Images: https://thatscienceguy.tumblr.com/post/96312770512/john-conway-first-theorized-that-it-would-be

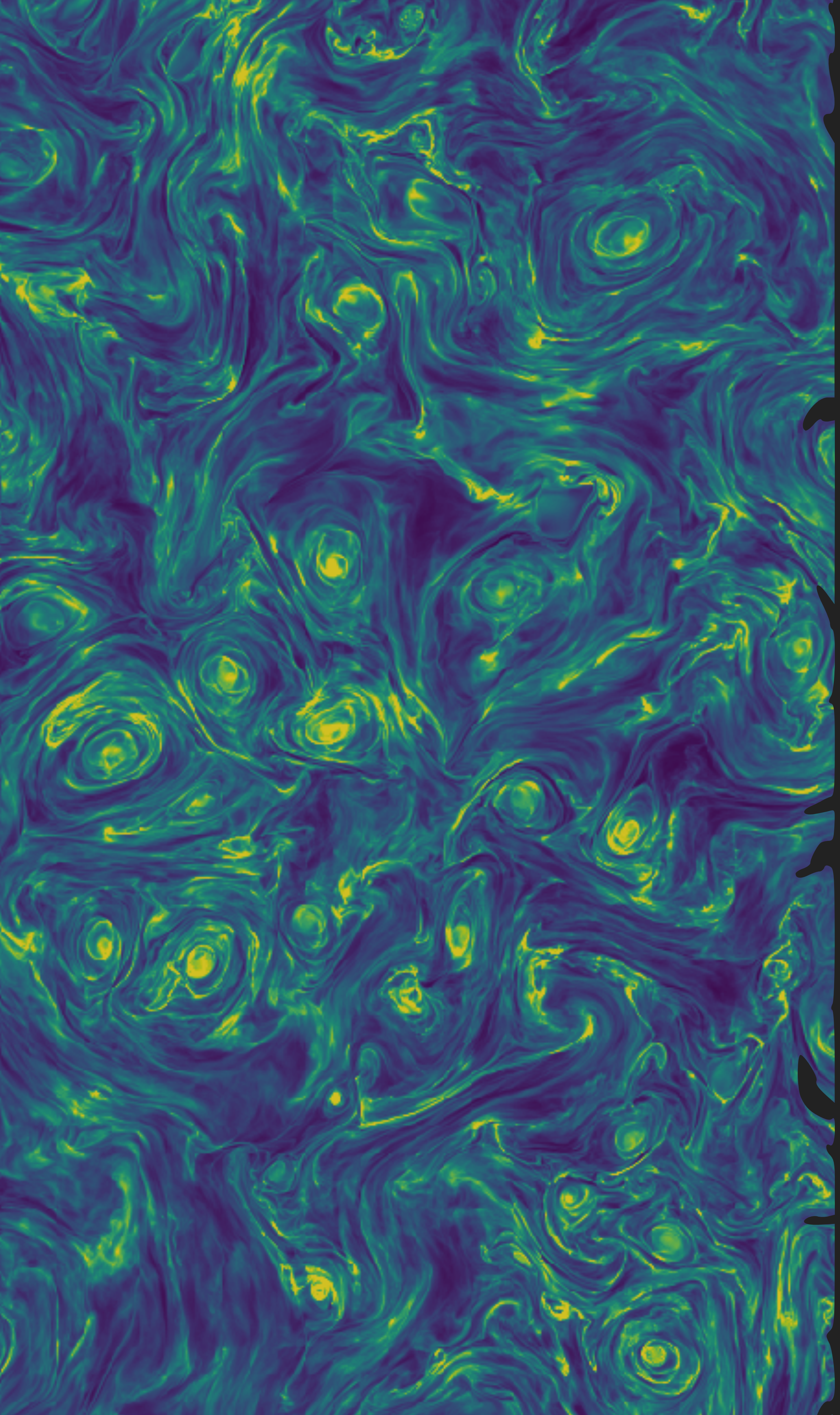
CORGI GRID INFRASTRUCTURE

- *C++ Object oRiented Grid Infrastructure*

- Dynamic adaptive load balancer
- Based on novel cellular automata (aka game of life) theory
  - Discrete geometric flows of hypersurfaces in Riemannian manifold
  - Surface tension flow given an arbitrary N-dimensional metric







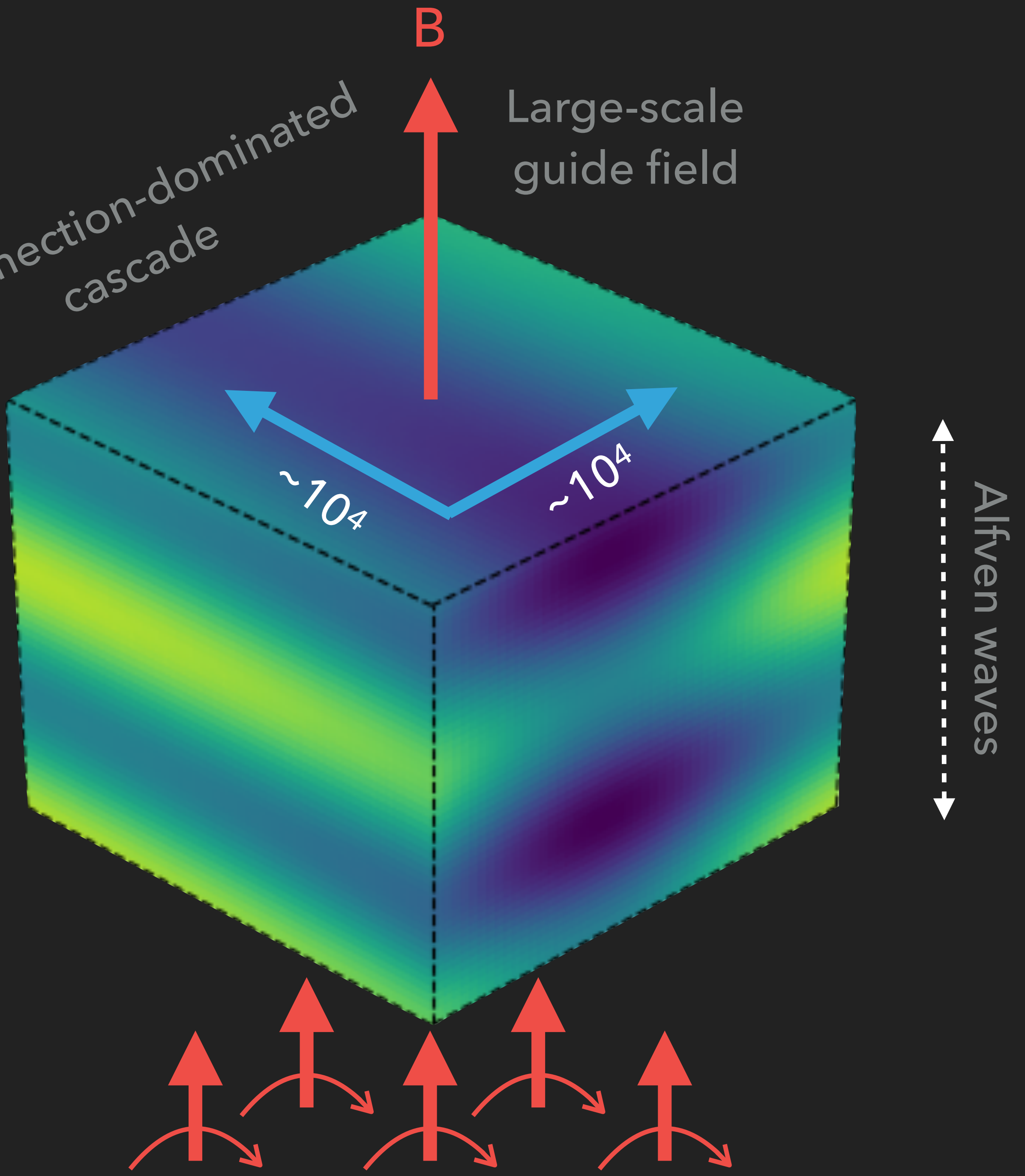
RELATIVISTIC KINETIC TURBULENCE

TURBULENT FLARES IN CORONA

NASA/JPL-Caltech

NASA's Goddard Space Flight Center/

2D3V DECAYING TURBULENCE SETUP

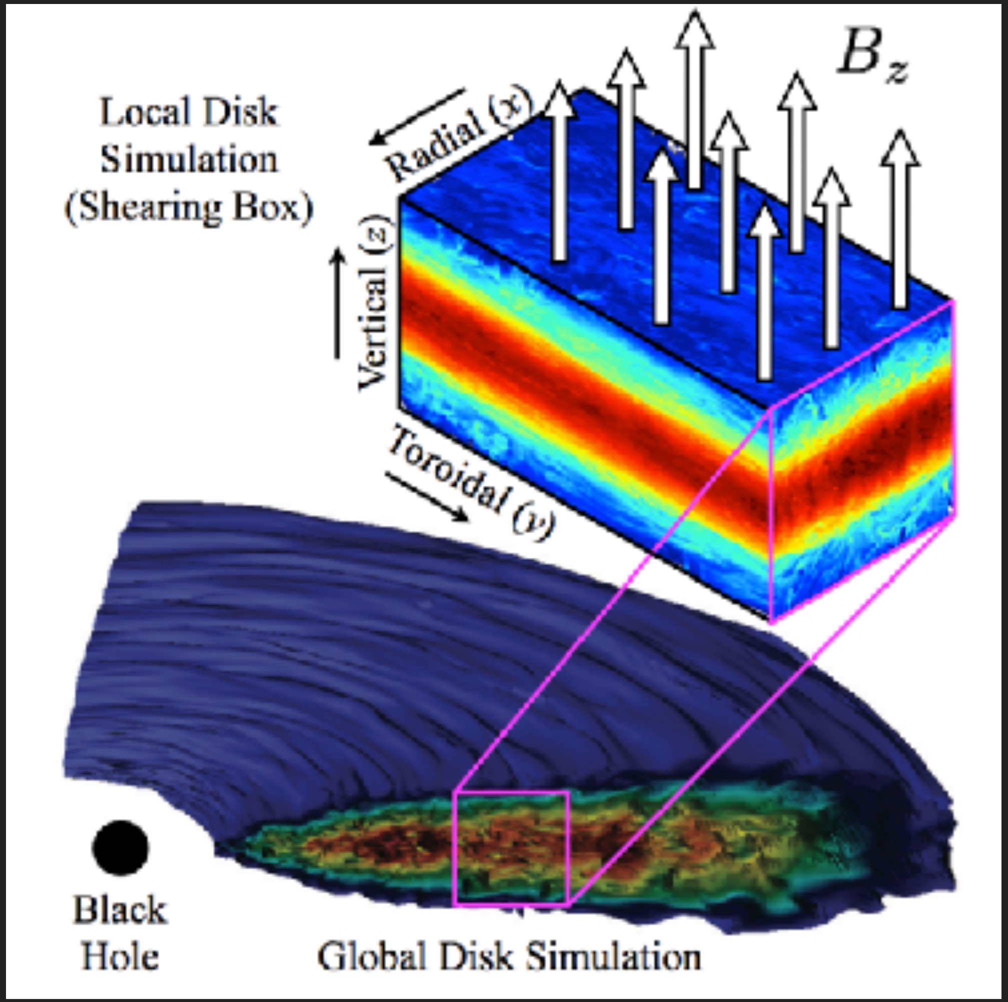


Large-scale guide field

Reconnection-dominated cascade

Alfven waves

Initial perturbations

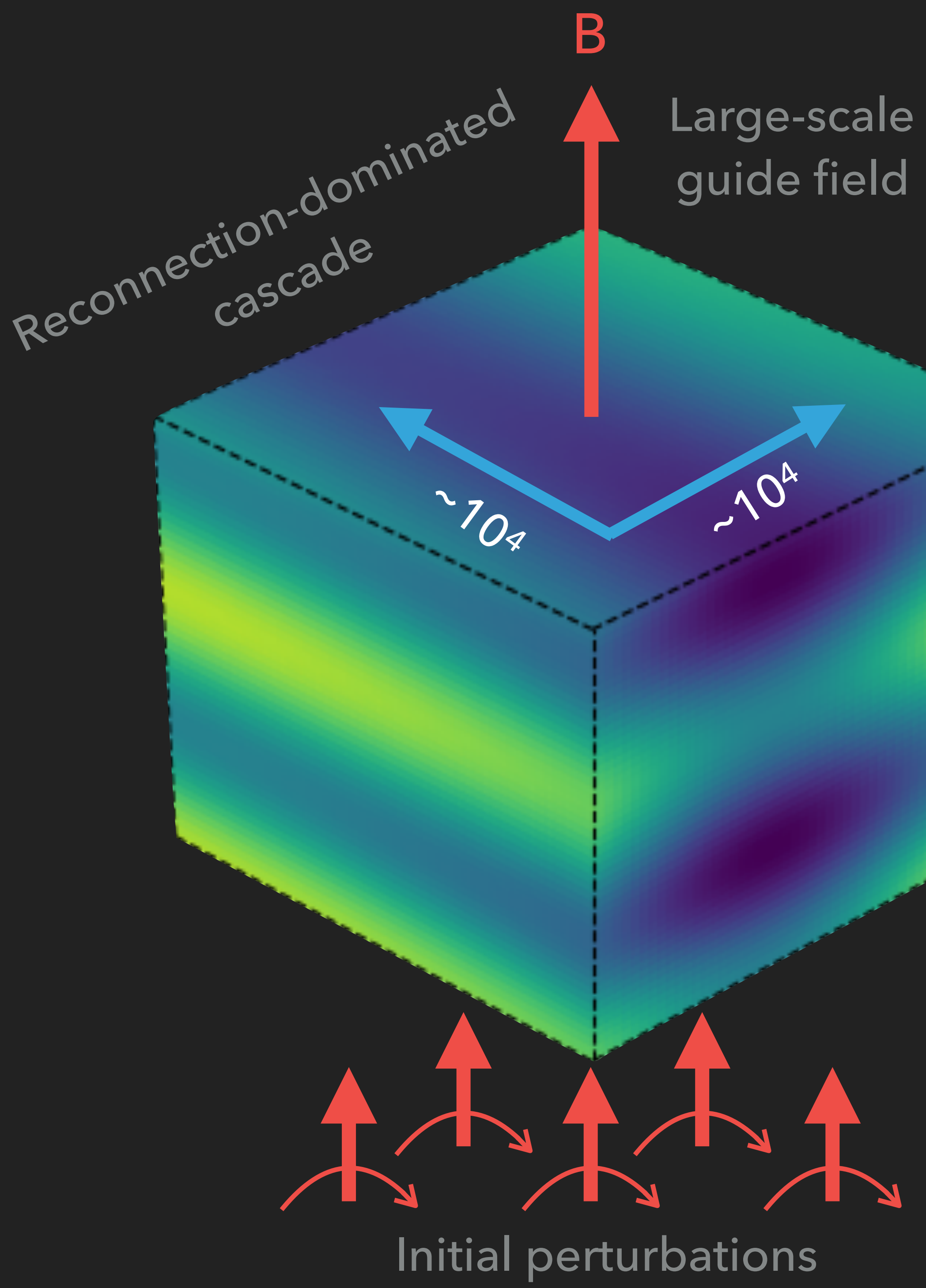


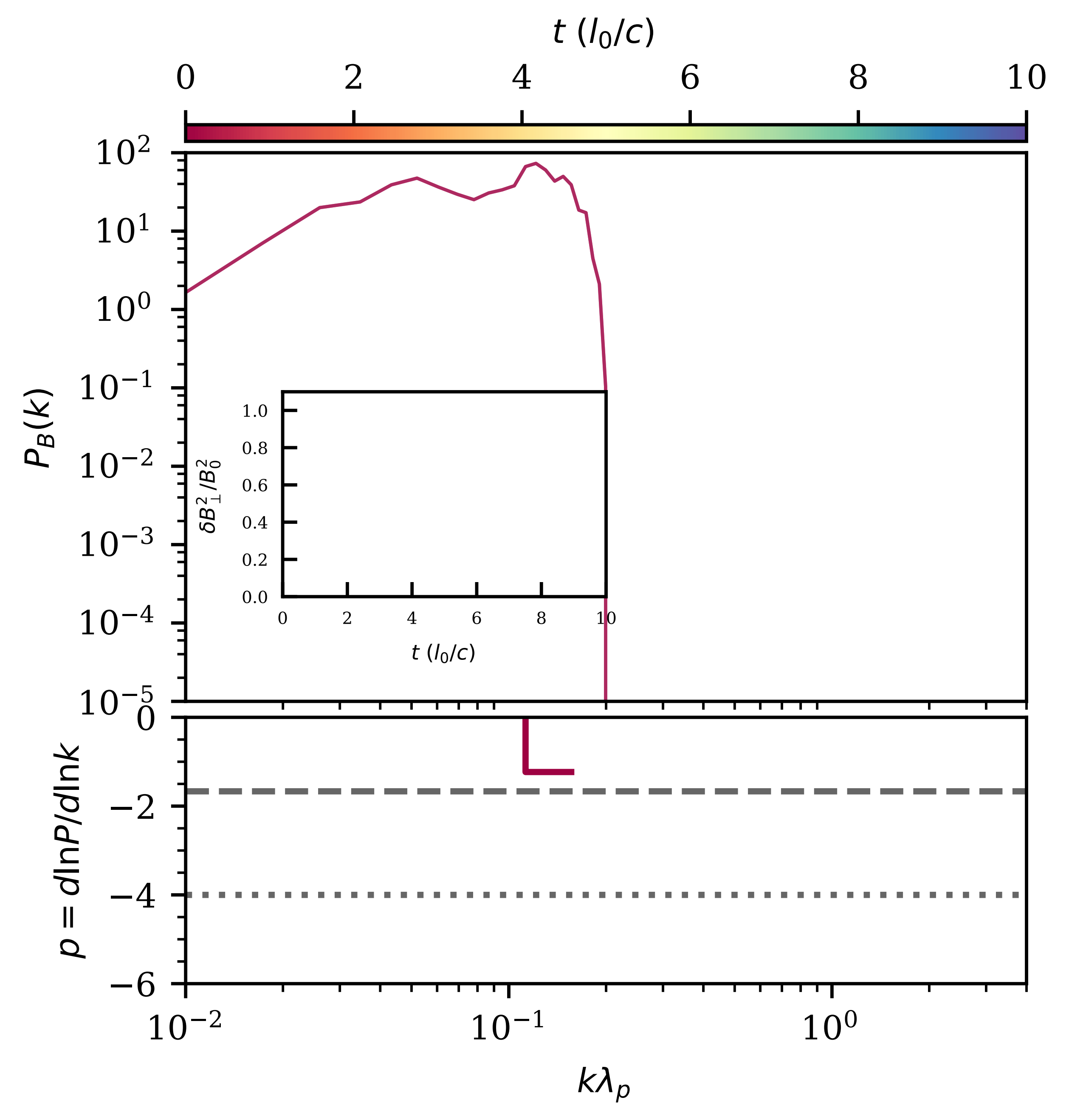
NASA/M. Druckmüller

See also:
Zhdankin et al.
Comisso & Sironi

Large number of particles ($\sim 10^{10}$) is needed to represent a fluid

2D3V DECAYING TURBULENCE SETUP





Large number of particles (~10^{10}) is needed to represent a fluid

CHARACTERISING THE PLASMA

- Warm pair plasma

$$\theta_0 = \frac{kT_0}{m_e c^2} = 0.3$$

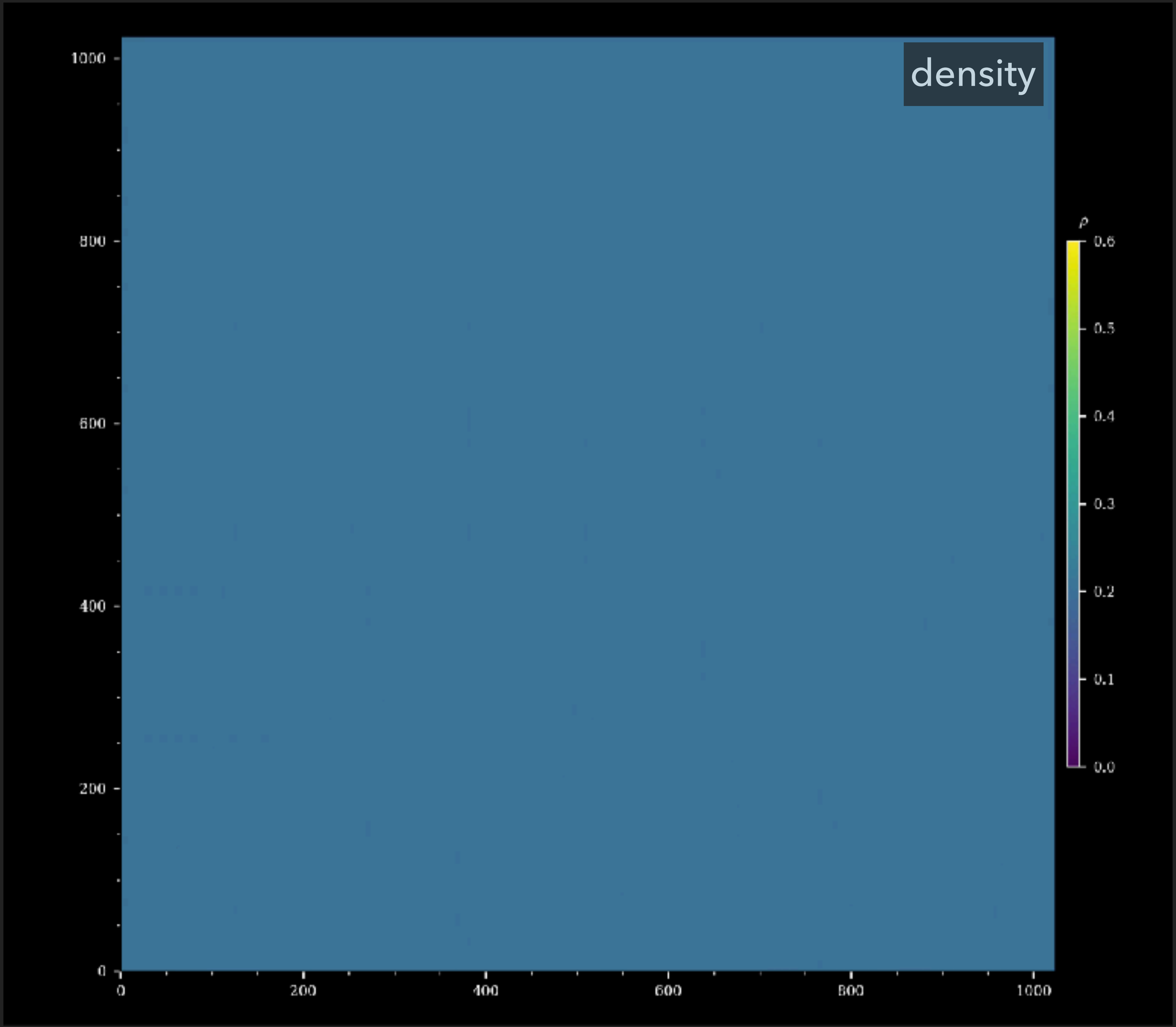
- Strongly magnetized
  - low-beta plasma

$$\sigma = \frac{B_0^2}{4\pi\rho_0(1+3\theta_0)c^2} = \{1, 5, 10, 40\}$$

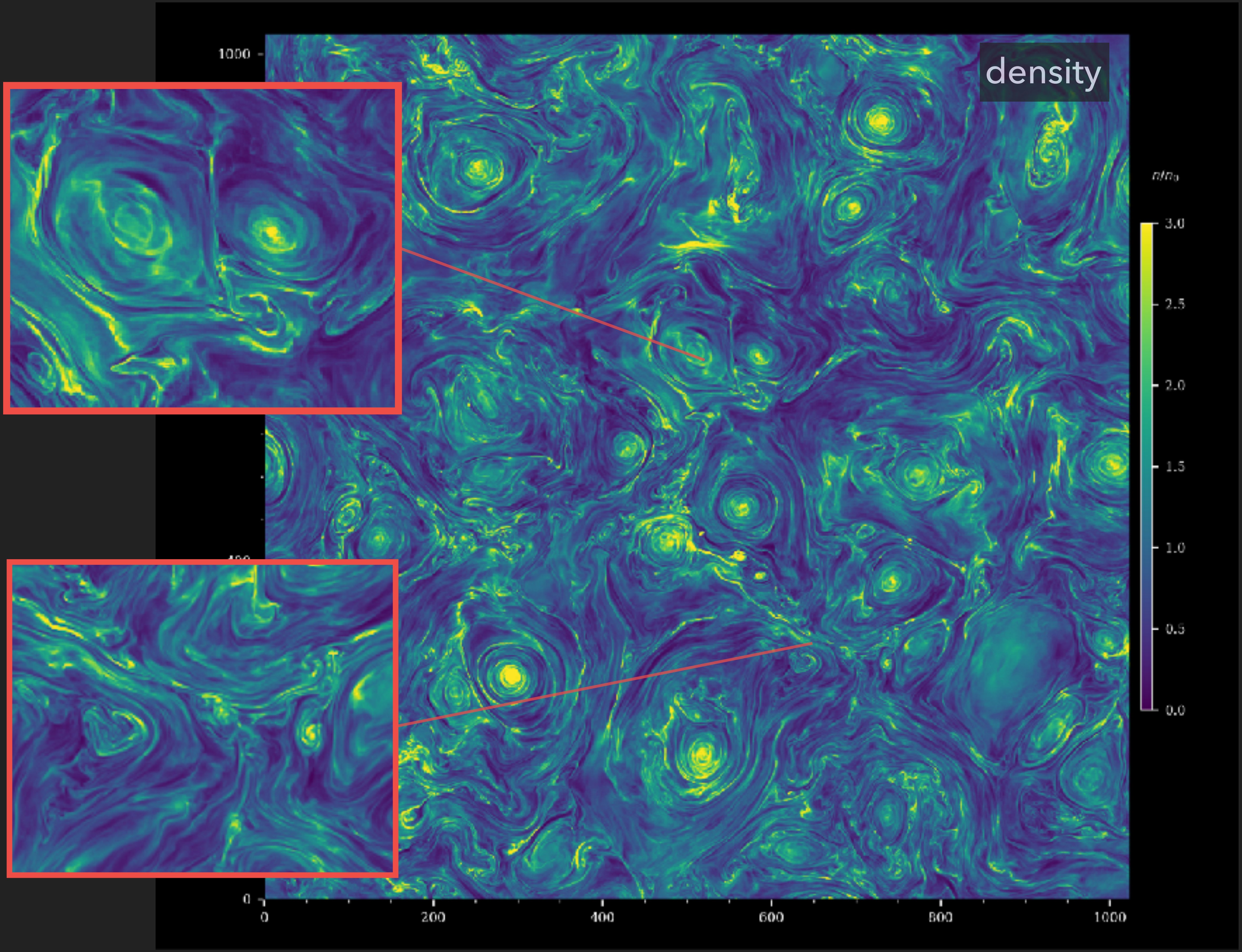
- Strong transverse perturbations
  - relativistic bulk motions

$$V_A = c\sqrt{\frac{\sigma}{1+\sigma}} \approx c.$$

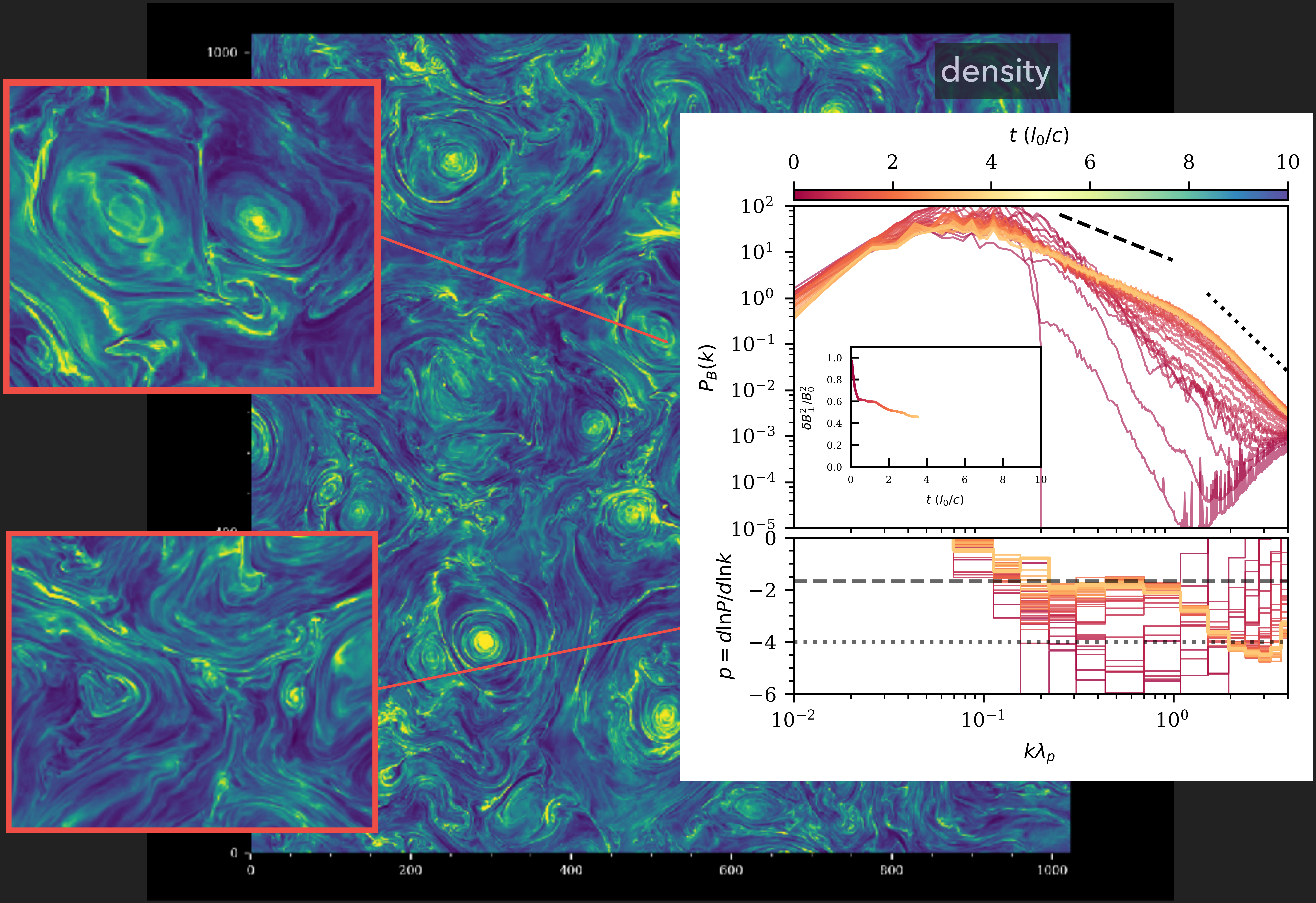
RESULTS


density
ρ
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1000
800
600
400
200
0
0
200
400
600
800
1000

RESULTS

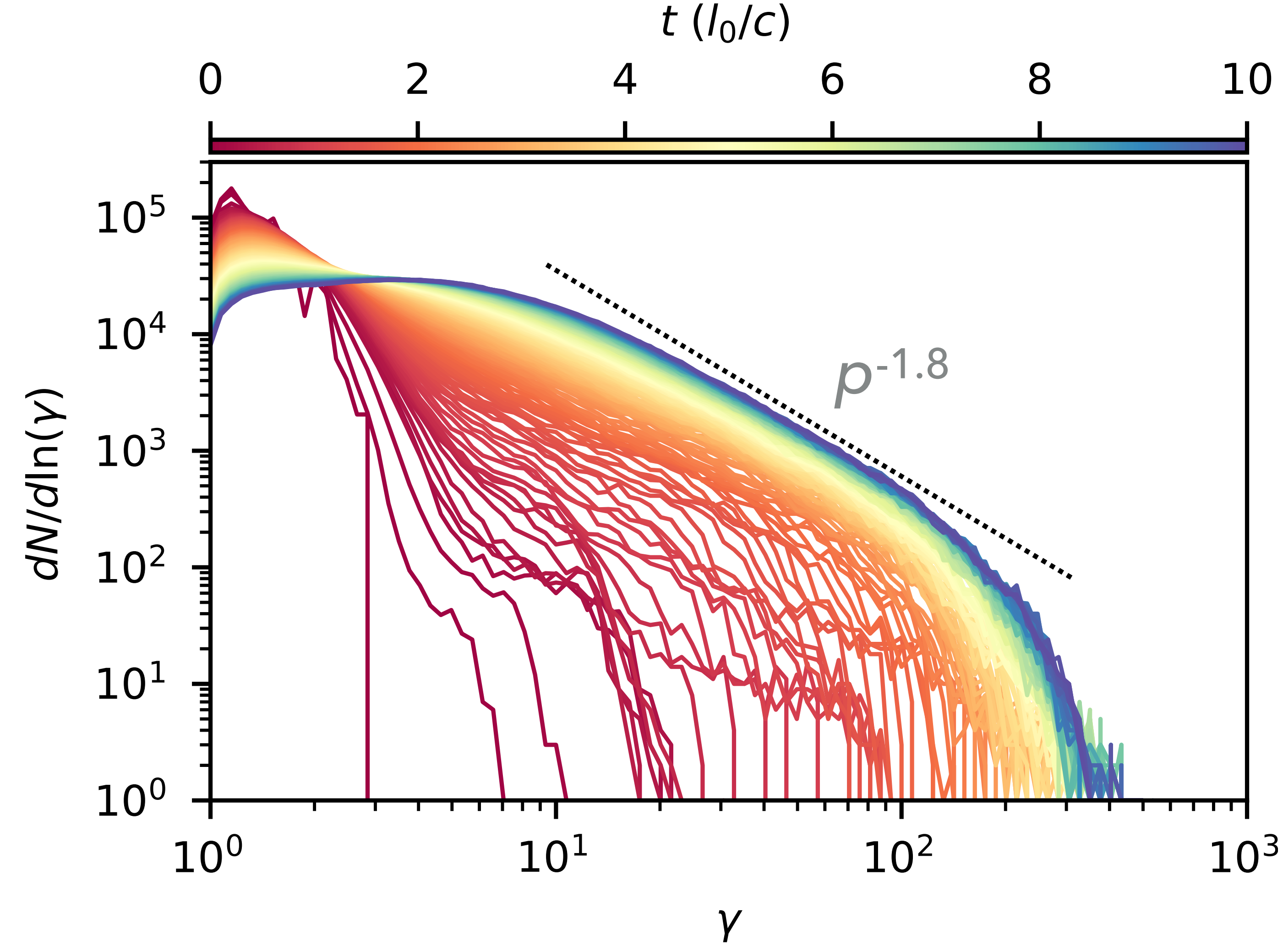


RESULTS

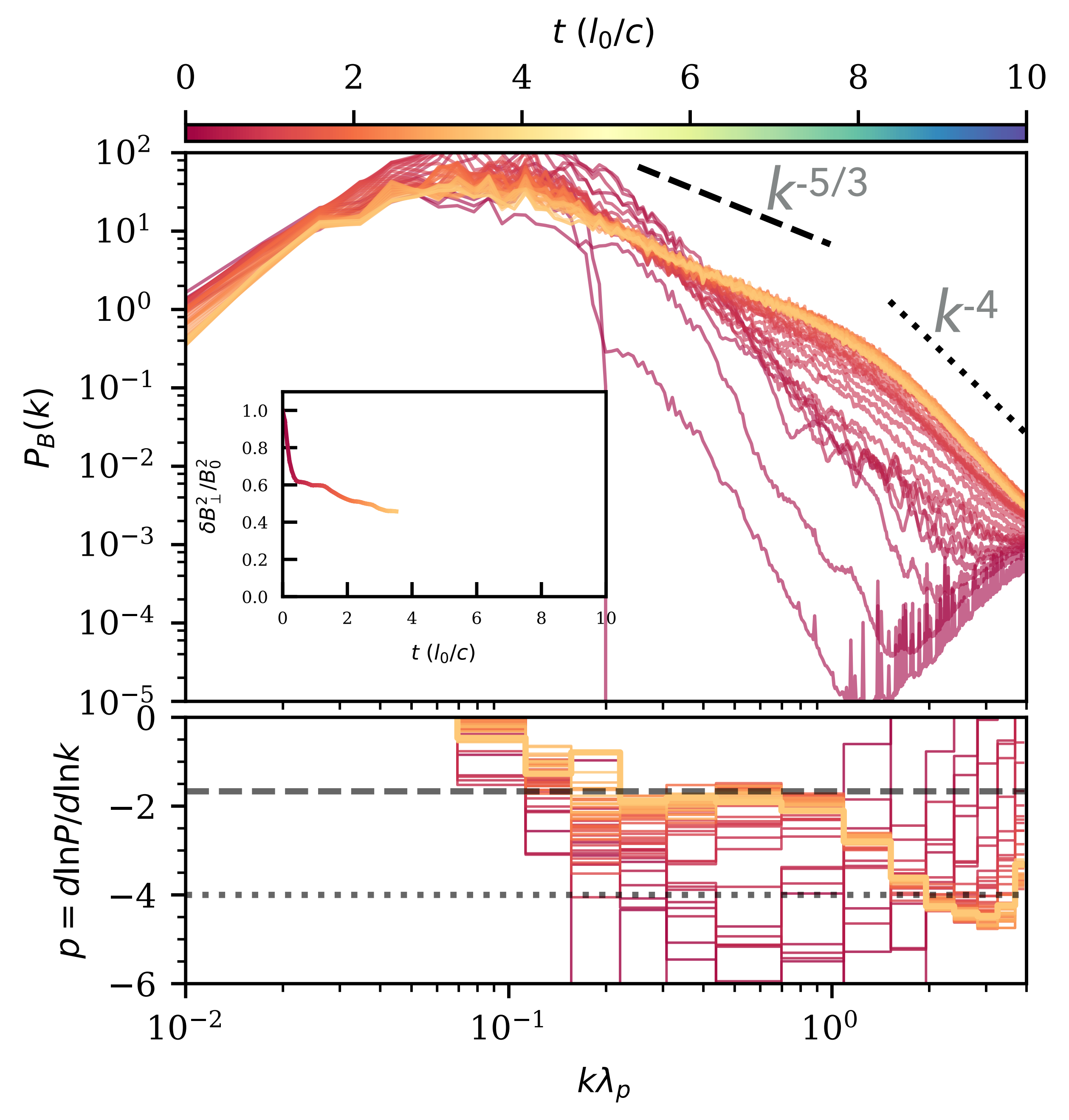

density
0
200
400
600
800
1000
$t\ (l_0/c)$
0
2
4
6
8
10
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$P_B(k)$
$\delta B_\perp^2/B_0^2$
1.0
0.8
0.6
0.4
0.2
0.0
$t\ (l_0/c)$
$p = d\ln P/d\ln k$
0
−2
−4
−6
10^{-2}
10^{-1}
10^{0}
$k\lambda_p$

RESULTS

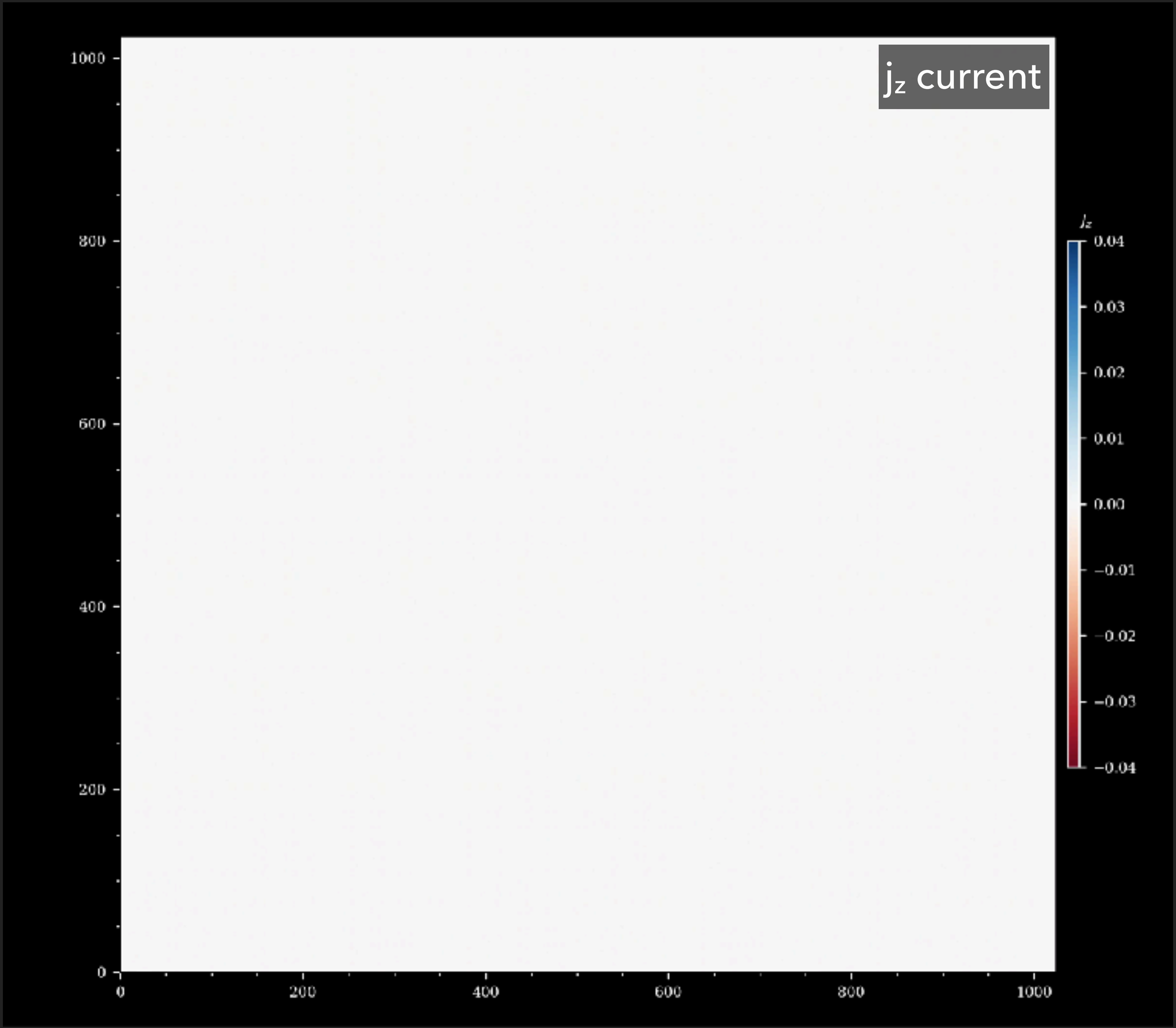
Particle spectra



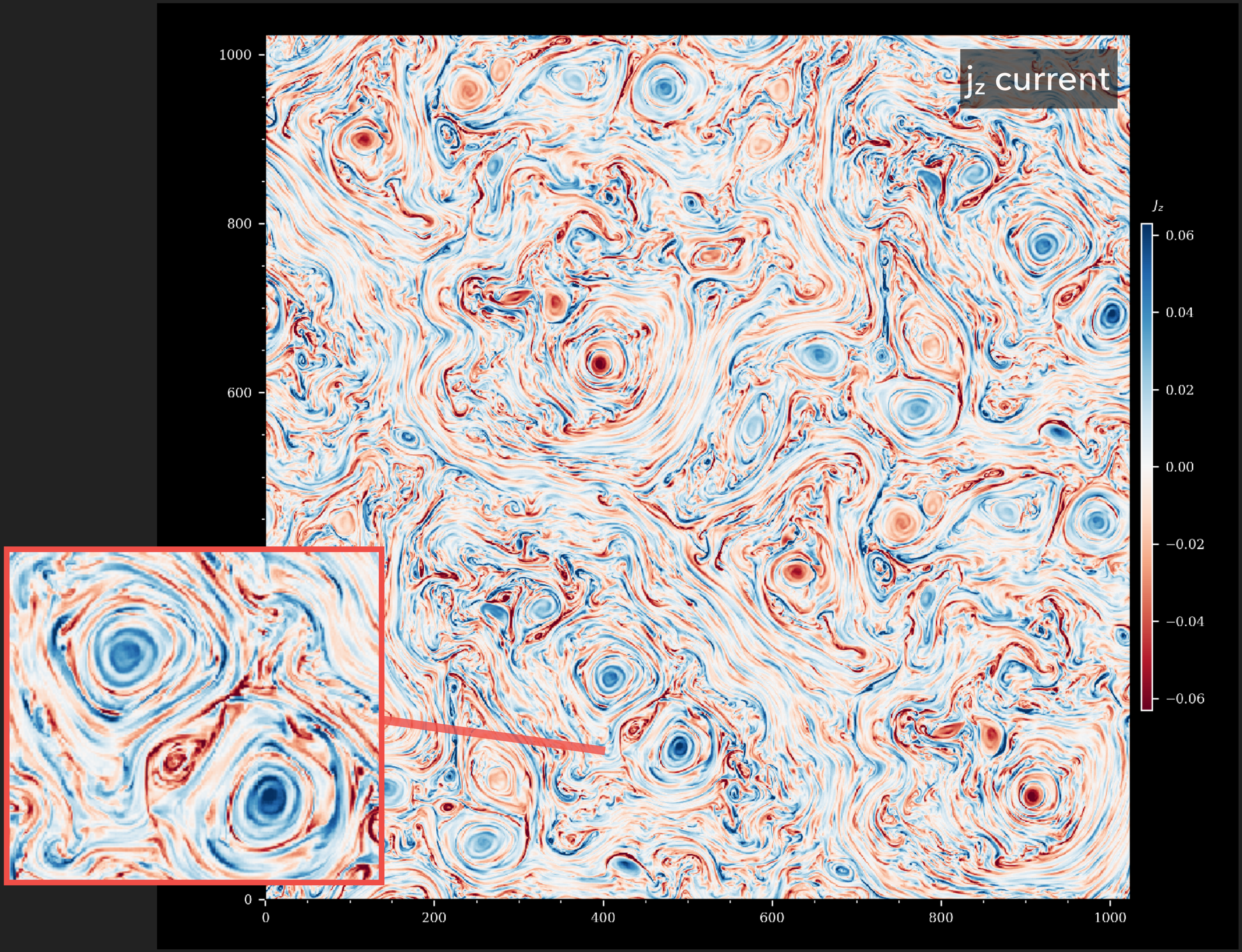
B-field power spectra



RESULTS

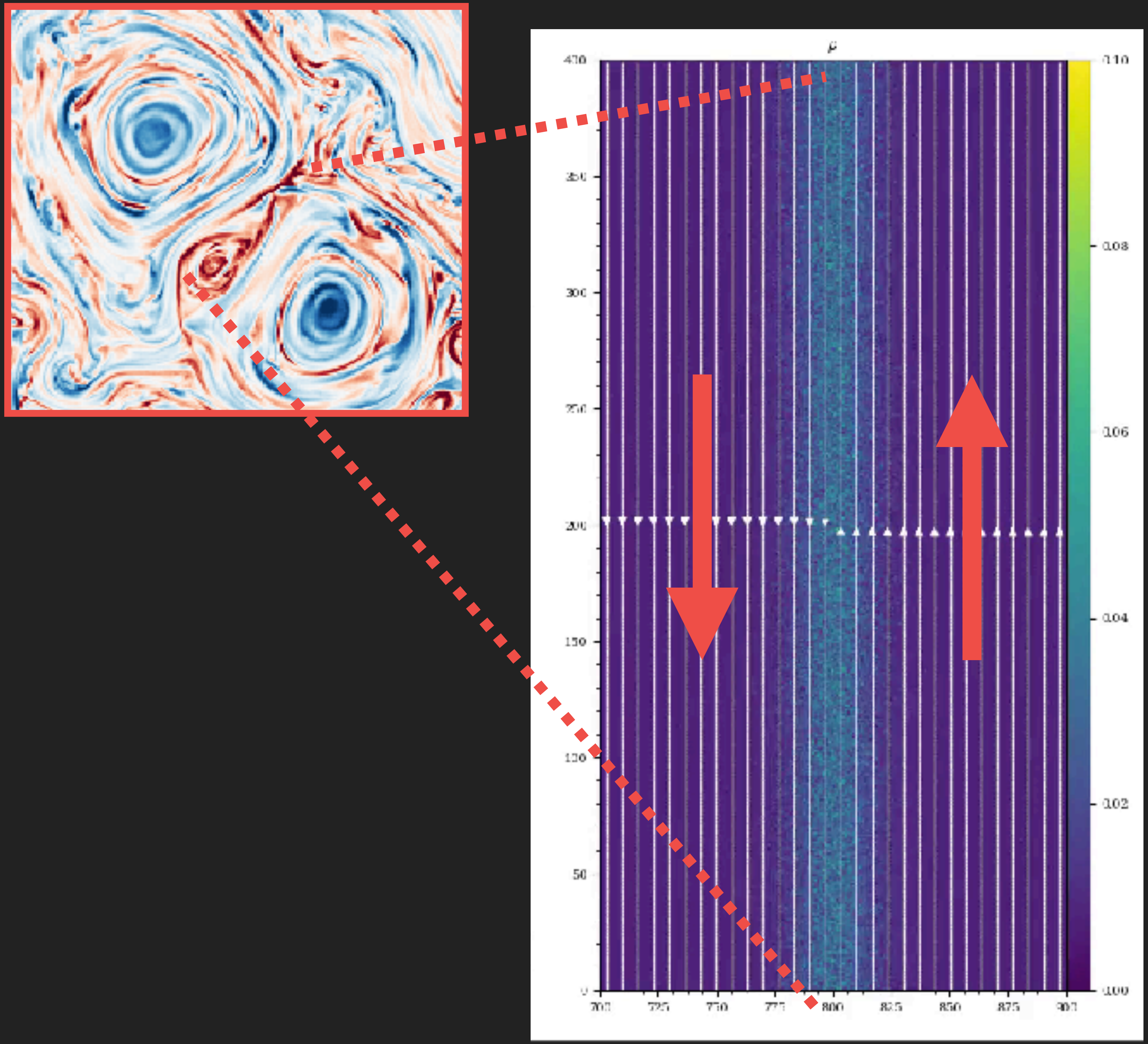

jz current
1000
800
600
400
200
0
0
200
400
600
800
1000
j_z
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04

RESULTS



j_z current
J_z
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
1000
800
600
0
0
200
400
600
800
1000

NON-THERMAL PARTICLE ACCELERATION



Magnetic reconnection

- pre-accelerates particles to $\gamma \sim \sigma$

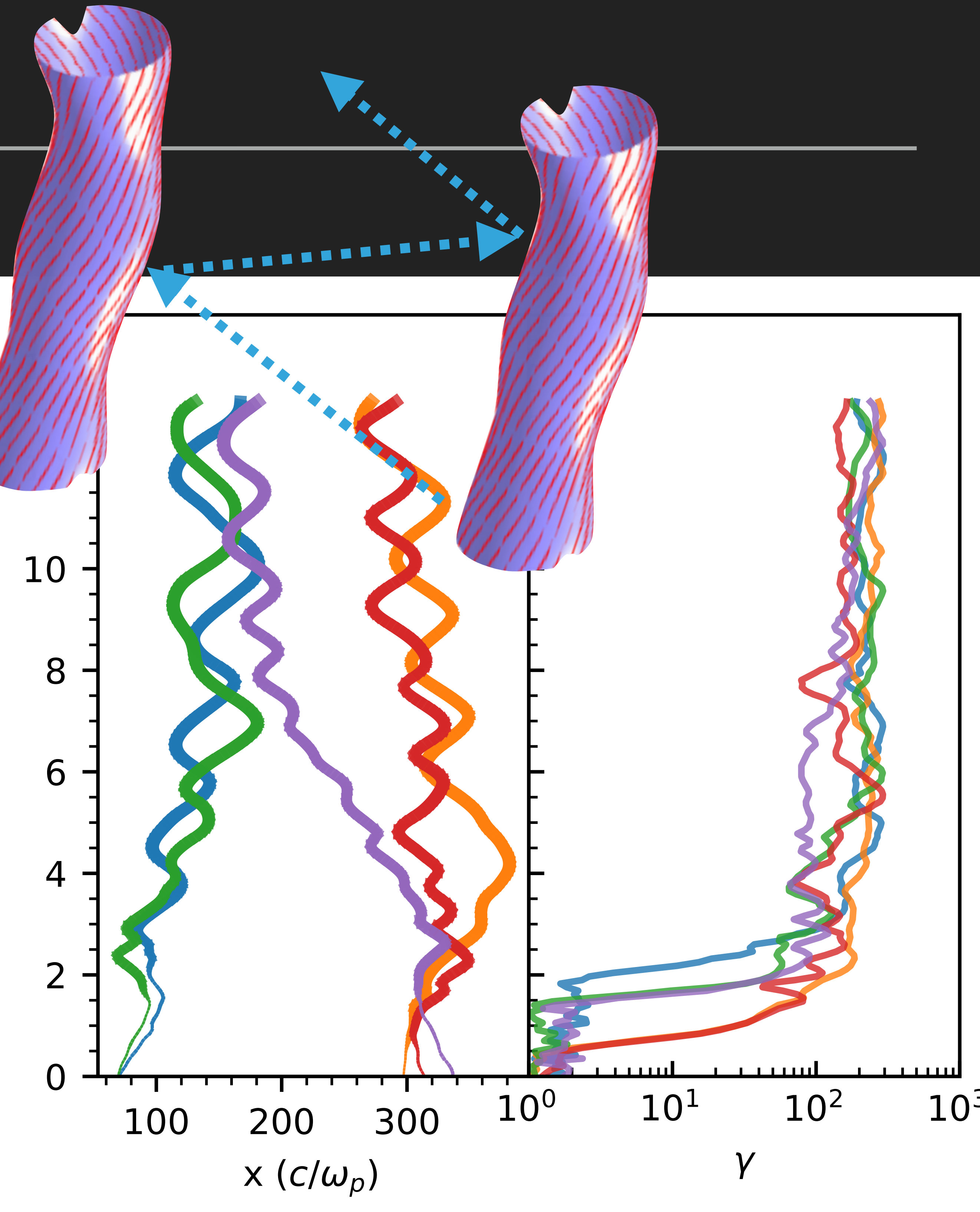
See Comisso & Sironi 2018, 2019

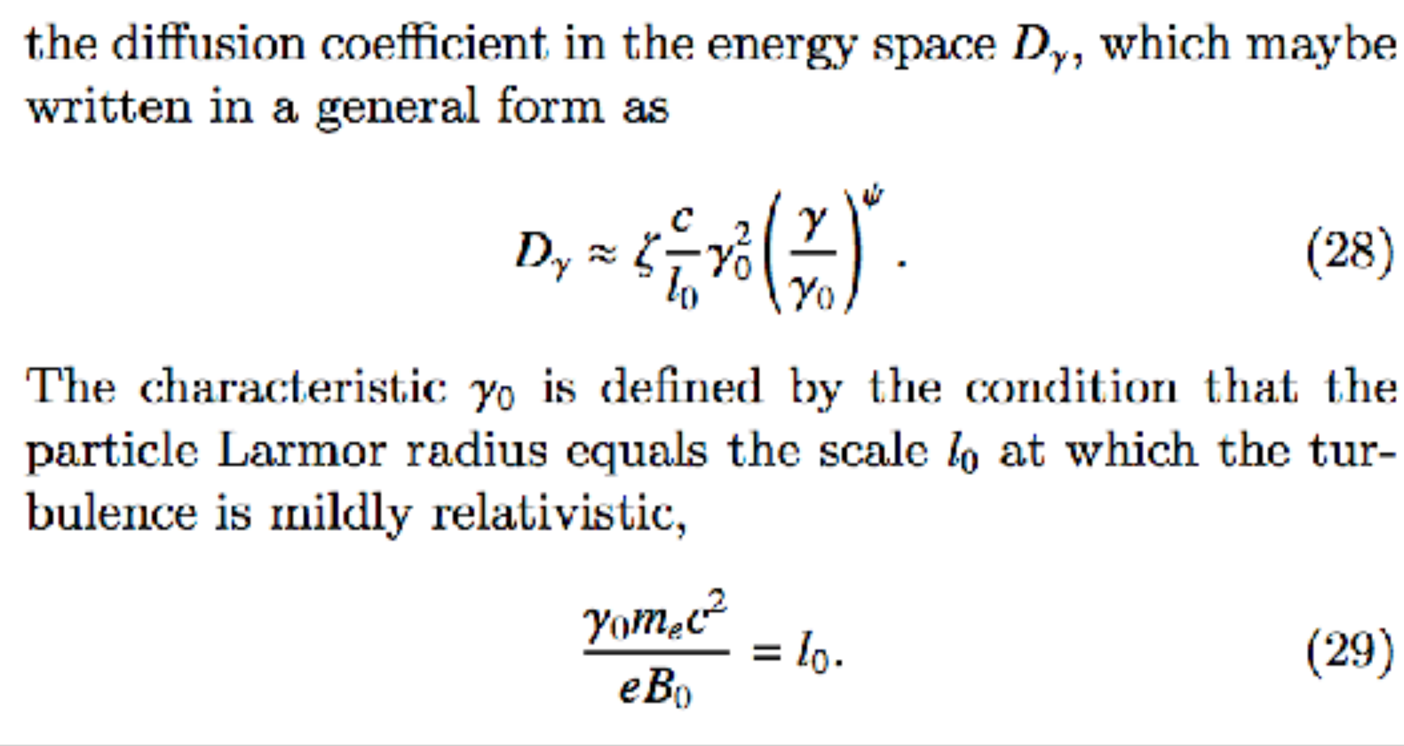
NON-THERMAL PARTICLE ACCELERATION

1) Reconnection injection

2) Diffusive particle acceleration

- accelerates particles to a power-law
- Fermi-II -like process





the diffusion coefficient in the energy space D_γ, which maybe written in a general form as

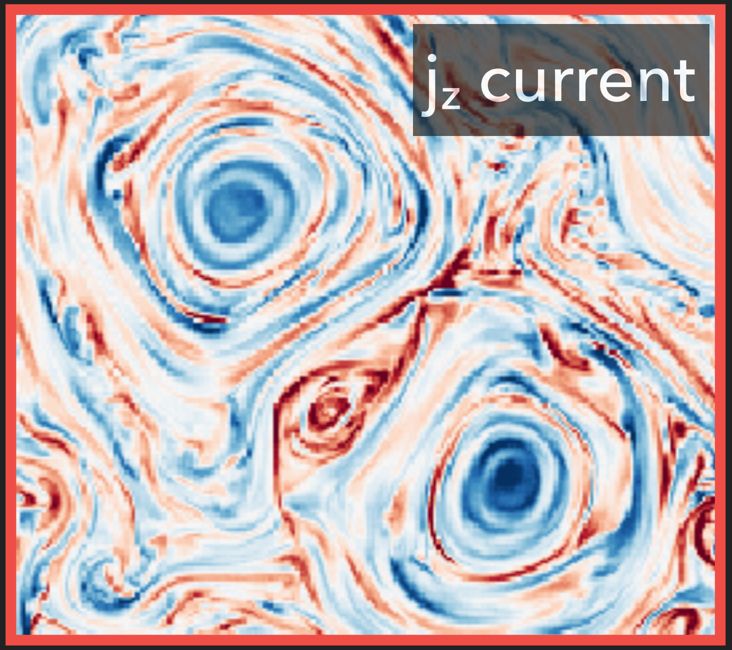
$$D_\gamma \approx \zeta \frac{c}{l_0} \gamma_0^2 \left(\frac{\gamma}{\gamma_0} \right)^{\psi}. \tag{28}$$

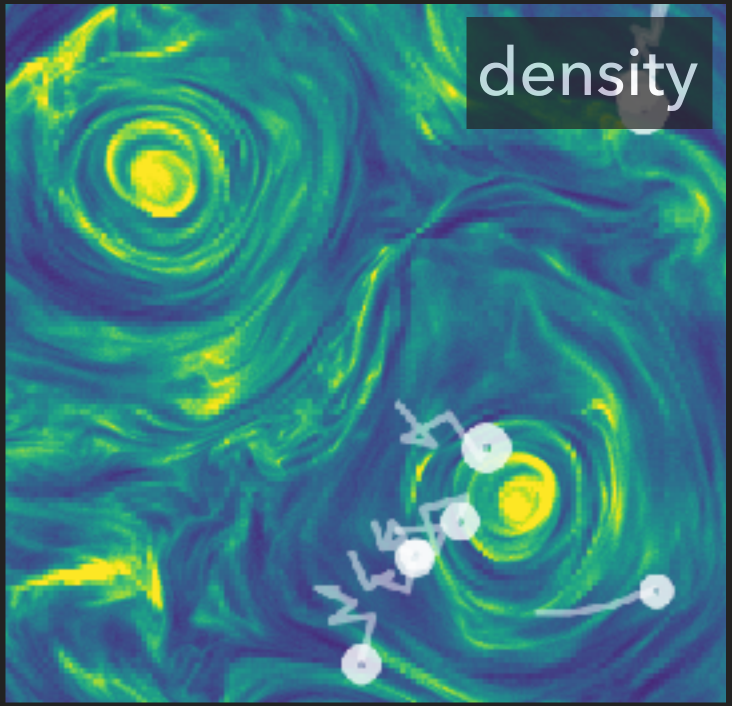
The characteristic γ_0 is defined by the condition that the particle Larmor radius equals the scale l_0 at which the turbulence is mildly relativistic,

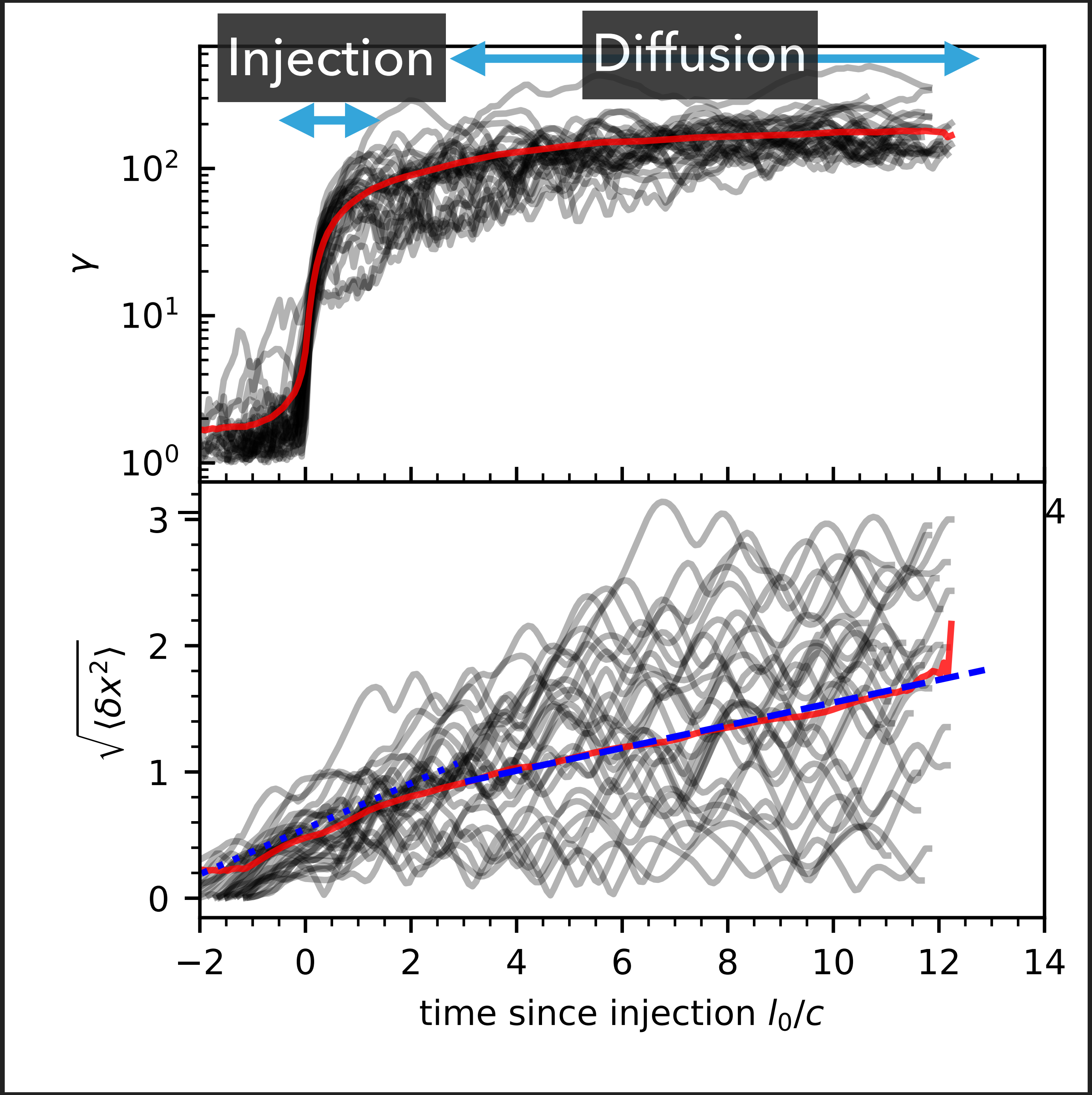
$$\frac{\gamma_0 m_e c^2}{e B_0} = l_0. \tag{29}$$

See Comisso & Sironi 2018, 2019

PARTICLE ACCELERATION = DISSIPATION

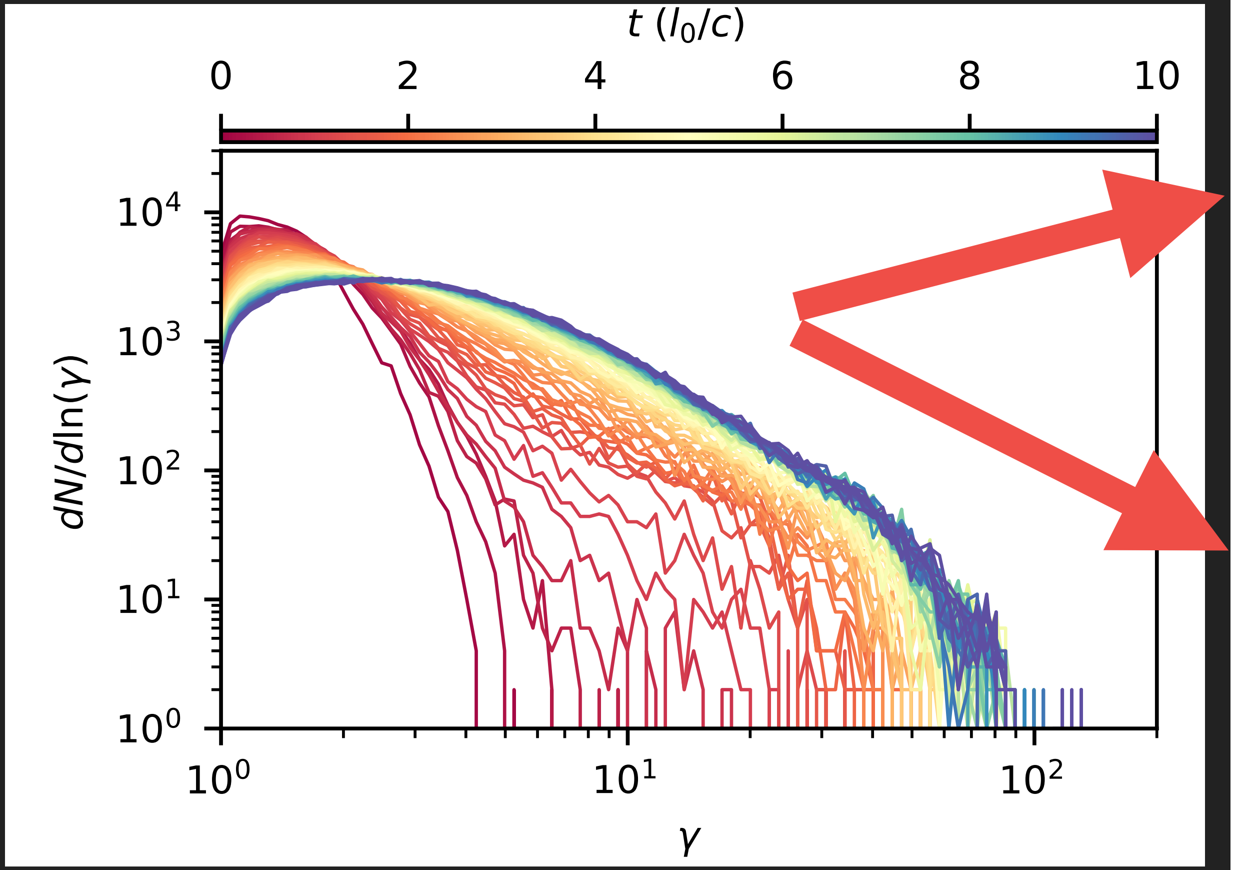


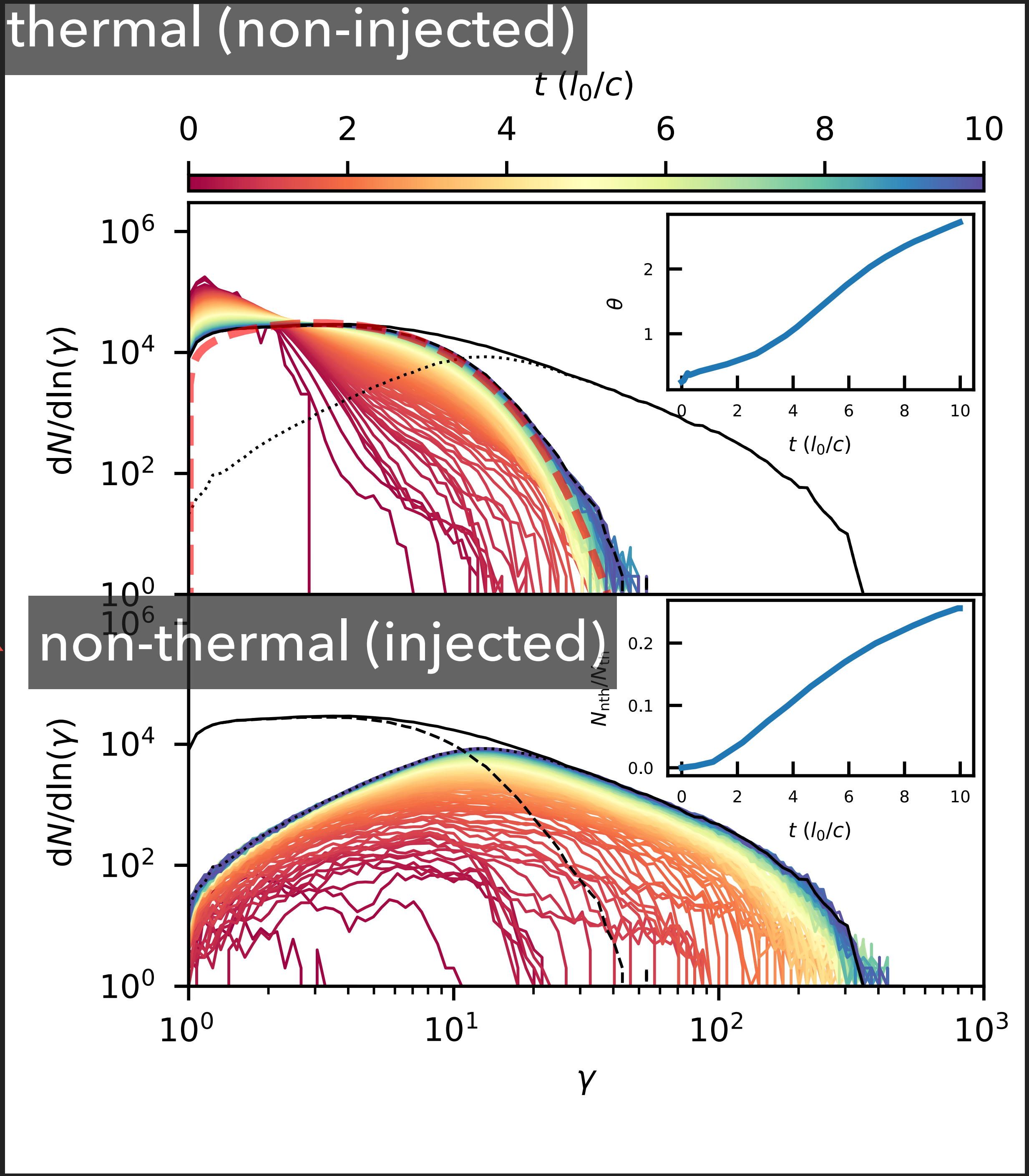




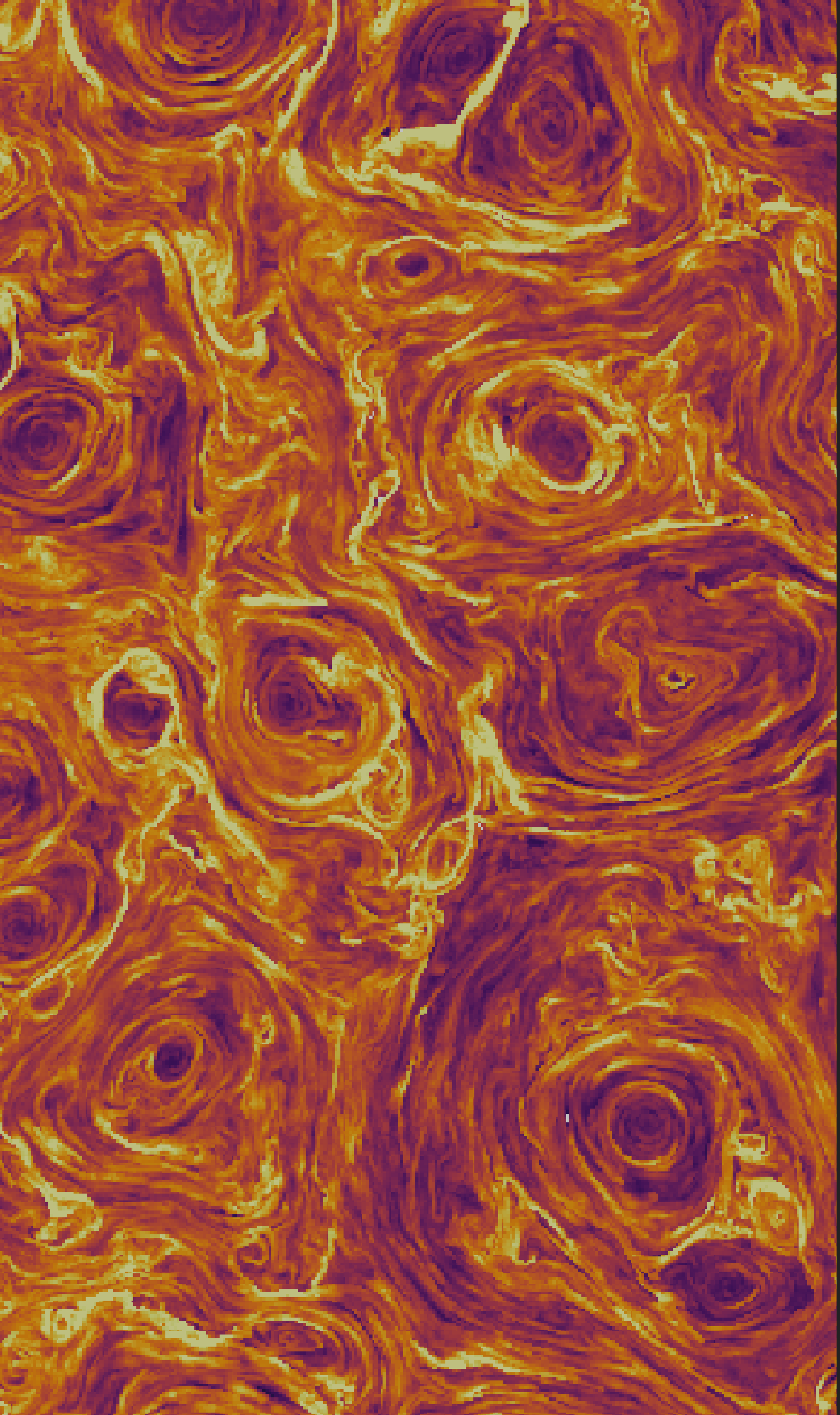
See Comisso & Sironi 2018, 2019

PARTICLE ACCELERATION = DISSIPATION



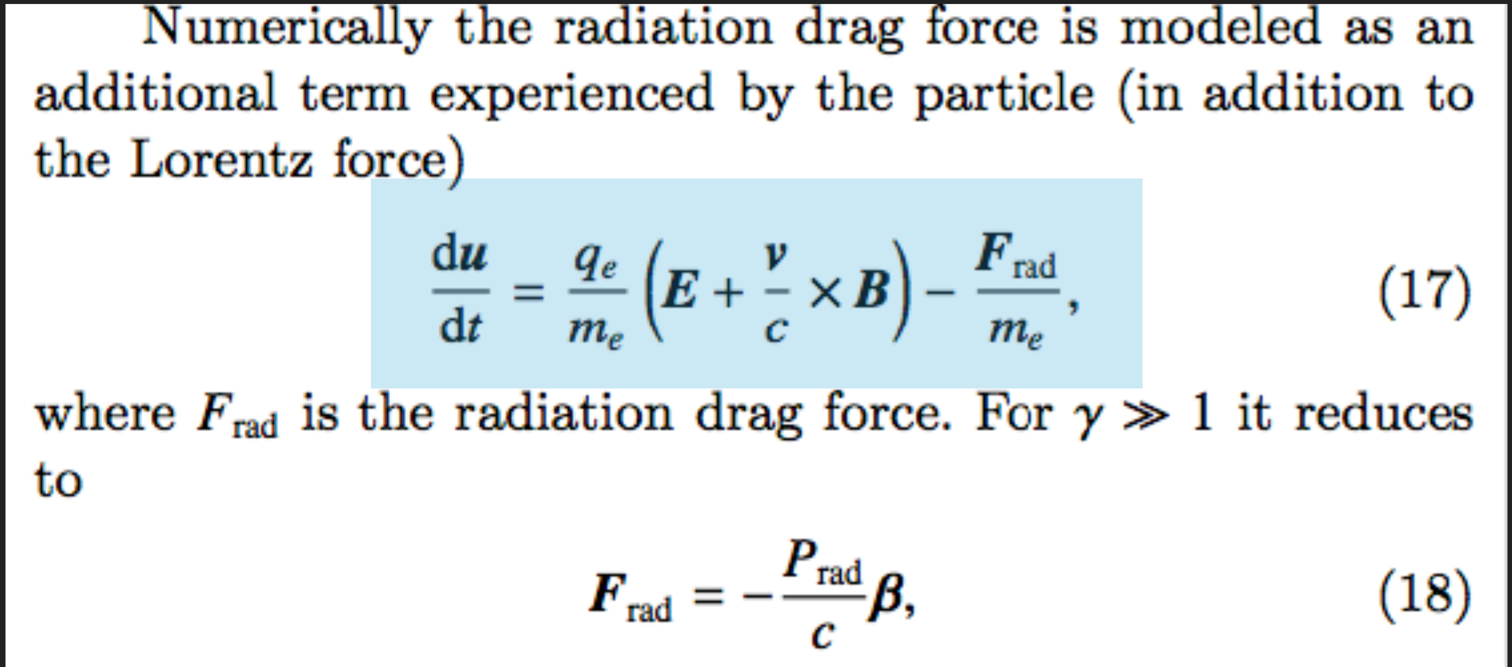

thermal (non-injected)

non-thermal (injected)



TURBULENT FLARES WITH RADIATIVE LOSSES

RADIATIVE DRAG

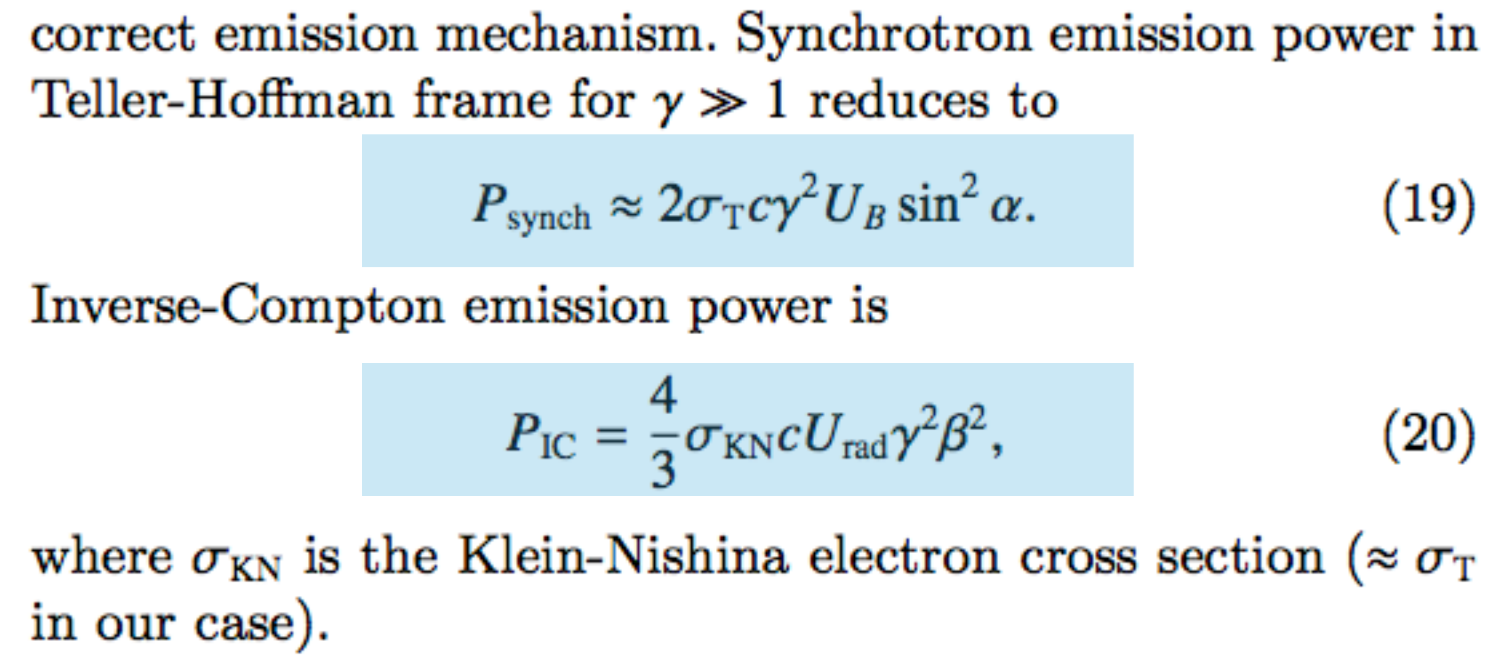


Numerically the radiation drag force is modeled as an additional term experienced by the particle (in addition to the Lorentz force)

$$\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = \frac{q_e}{m_e}\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right) - \frac{\boldsymbol{F}_{\mathrm{rad}}}{m_e}, \tag{17}$$

where $\boldsymbol{F}_{\mathrm{rad}}$ is the radiation drag force. For $\gamma \gg 1$ it reduces to

$$\boldsymbol{F}_{\mathrm{rad}} = -\frac{P_{\mathrm{rad}}}{c}\boldsymbol{\beta}, \tag{18}$$



correct emission mechanism. Synchrotron emission power in Teller-Hoffman frame for $\gamma \gg 1$ reduces to

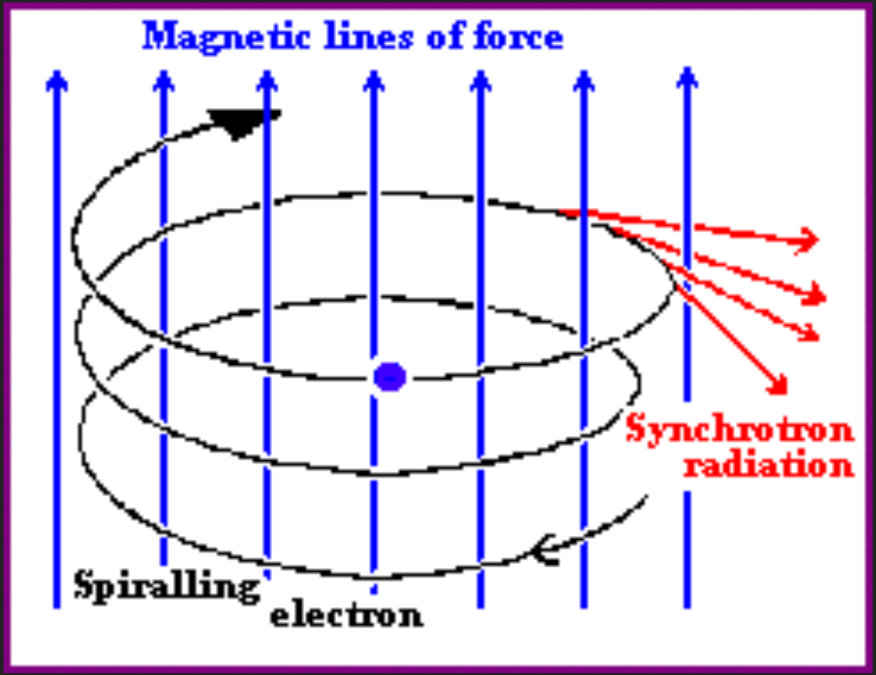
$$P_{\mathrm{synch}} \approx 2\sigma_{\mathrm{T}} c \gamma^2 U_B \sin^2\alpha. \tag{19}$$

Inverse-Compton emission power is

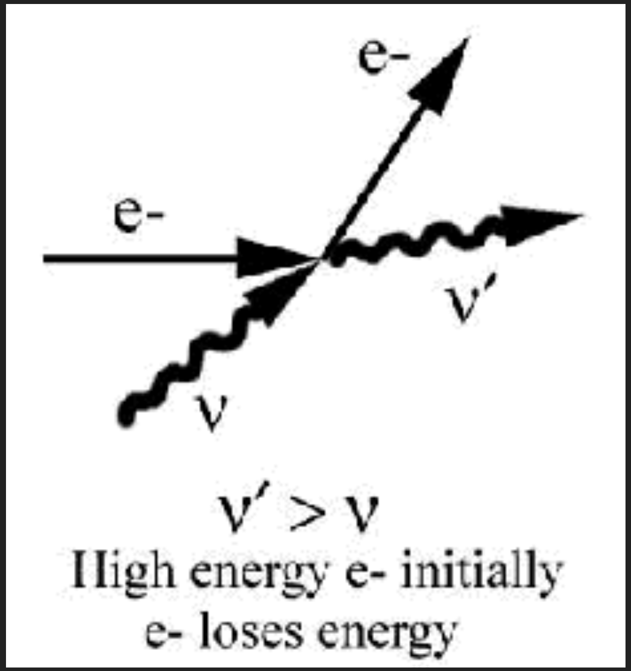
$$P_{\mathrm{IC}} = \frac{4}{3}\sigma_{\mathrm{KN}} c U_{\mathrm{rad}} \gamma^2 \beta^2, \tag{20}$$

where σ_{KN} is the Klein-Nishina electron cross section ($\approx \sigma_{\mathrm{T}}$ in our case).

Synchrotron radiation



Inverse Compton scattering

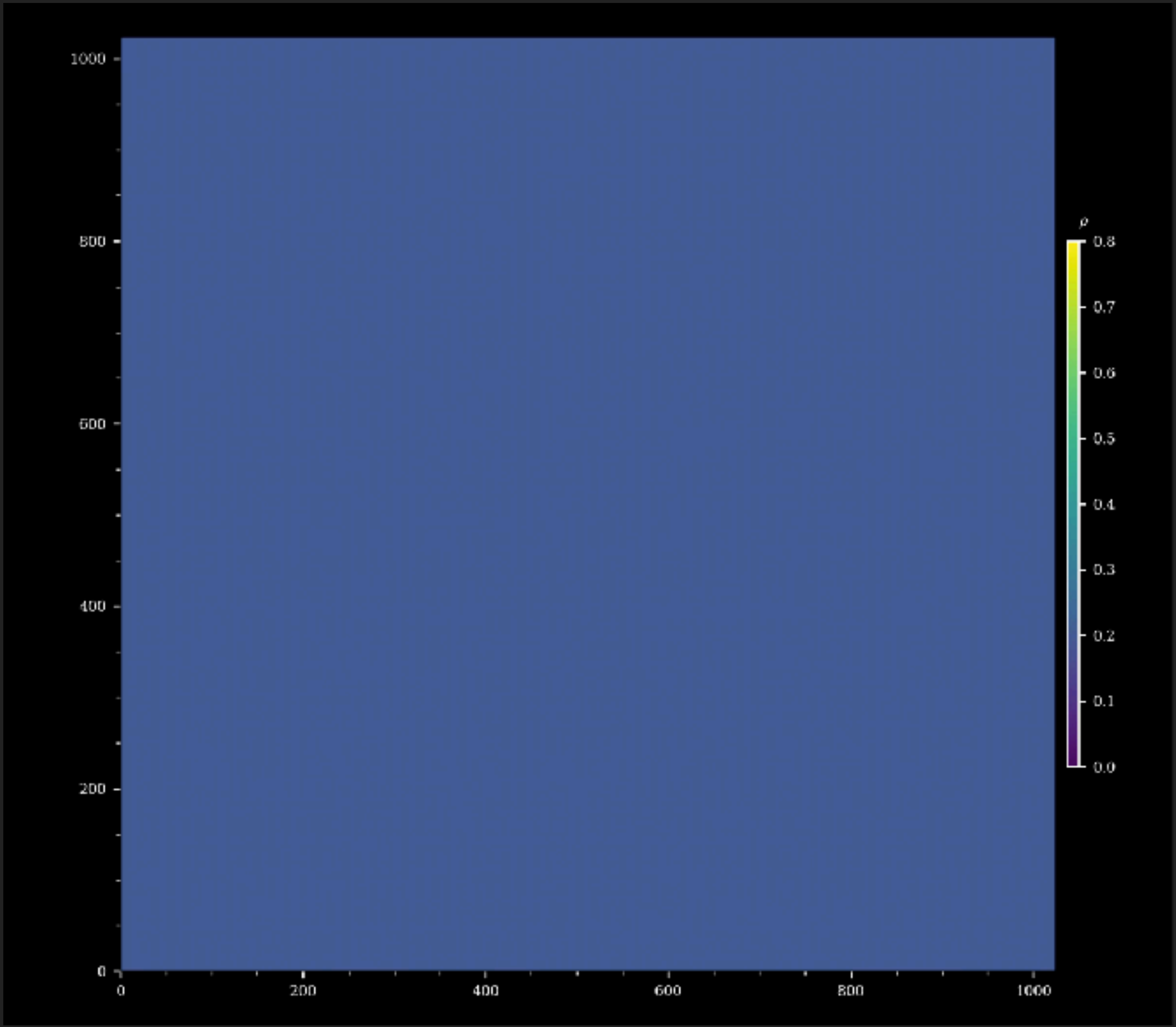


$\nu' > \nu$

High energy e- initially

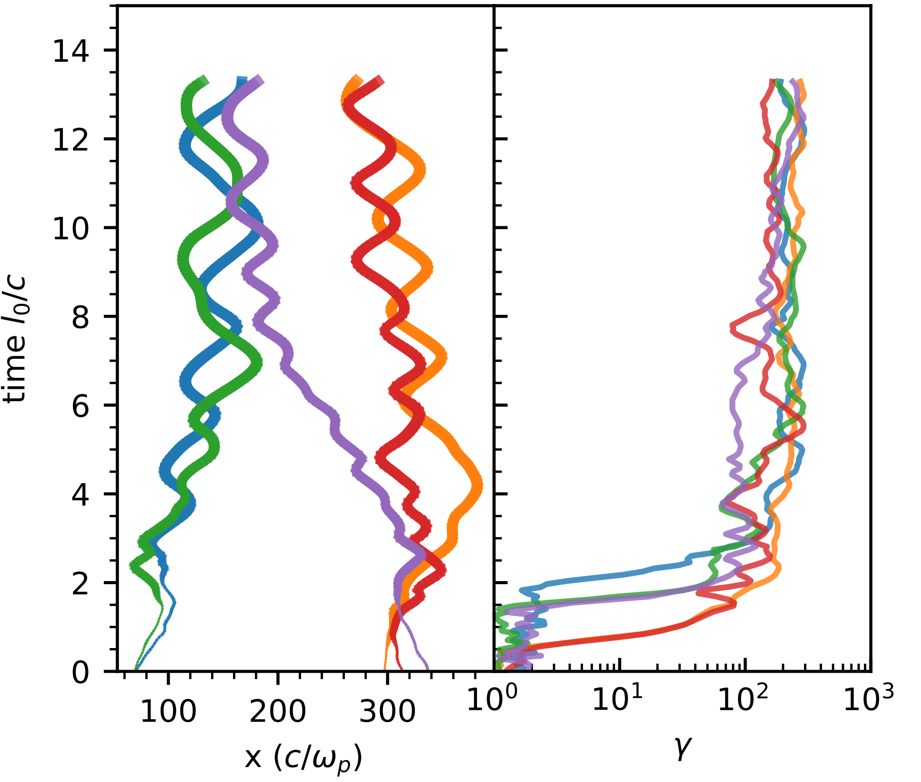
e- loses energy

STRONGLY COOLING REGIME

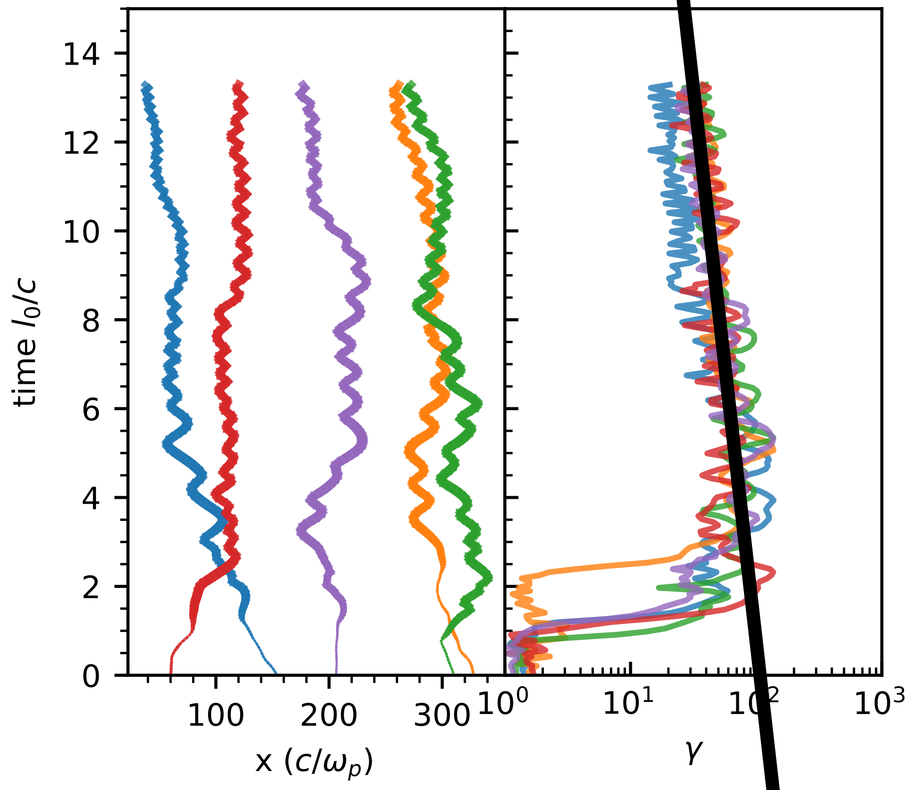


RADIATIVE TURBULENCE

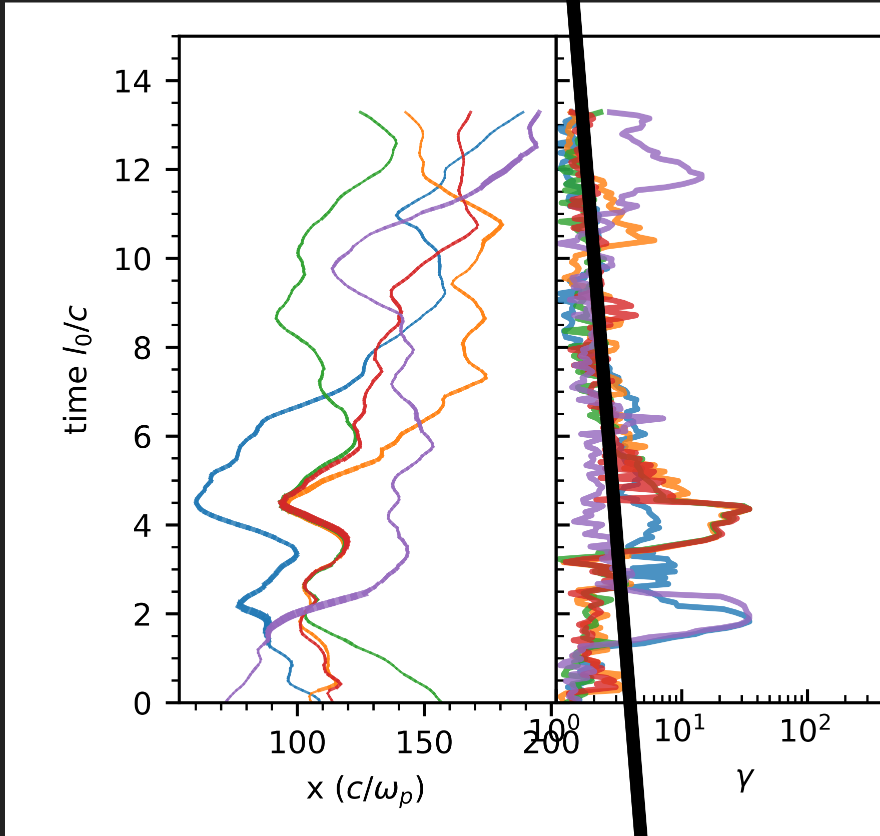
No radiation



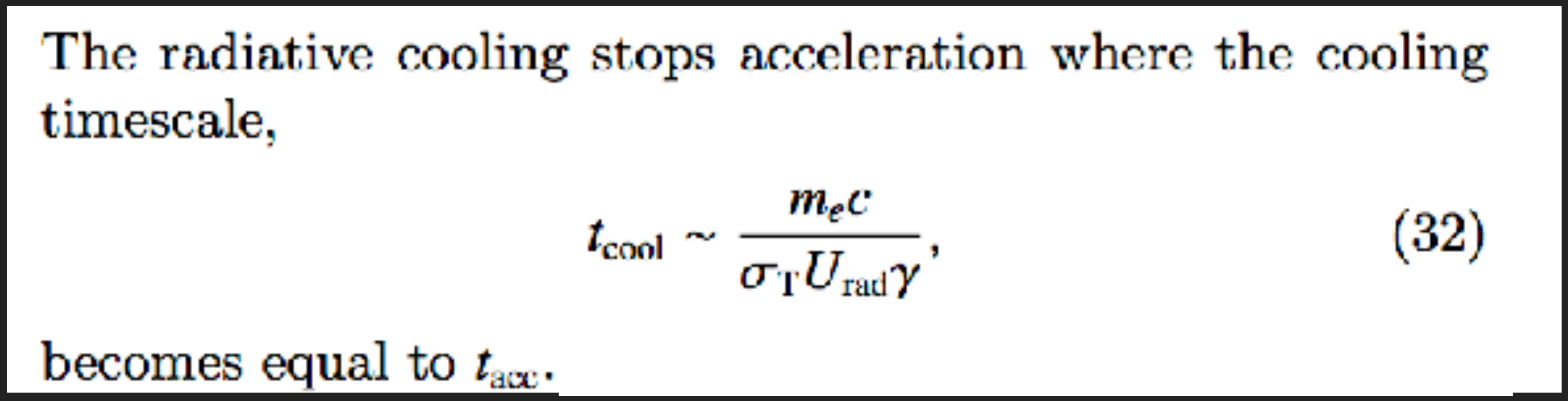
Weakly cooling regime



Strongly cooling regime



Radiation “ceiling”



The radiative cooling stops acceleration where the cooling timescale,

$$t_{\rm cool} \sim \frac{m_e c}{\sigma_{\rm T} U_{\rm rad} \gamma}, \qquad (32)$$

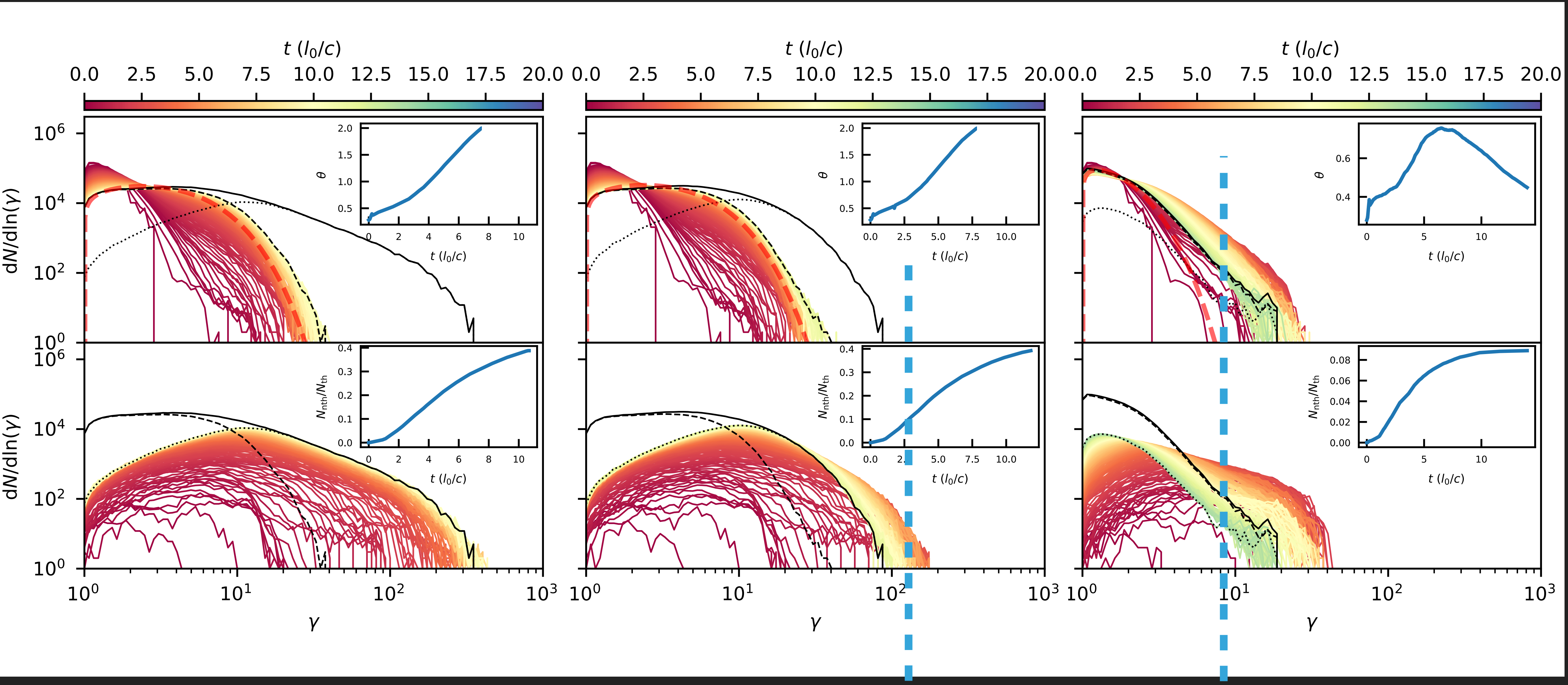
becomes equal to $t_{\rm acc}$.

RADIATIVE TURBULENCE

No radiation

Weakly cooling regime

Strongly cooling regime



Radiation “ceiling”

Cooling non-thermal component

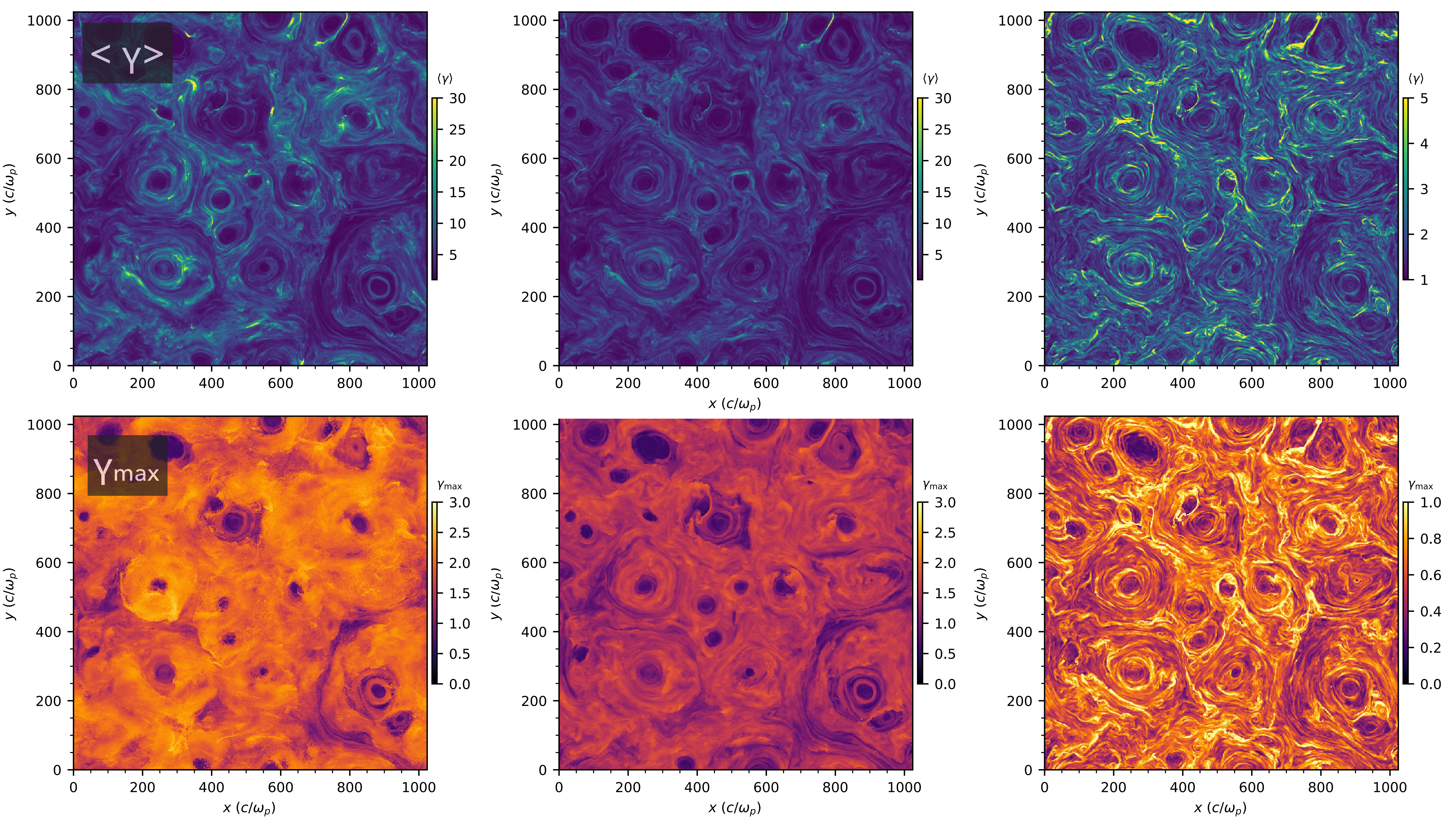
Bulk-motion dragged & volumetric dissipation

RADIATIVE TURBULENCE: FLICKERING SHEETS

No radiation

Weakly cooling regime

Strongly cooling regime

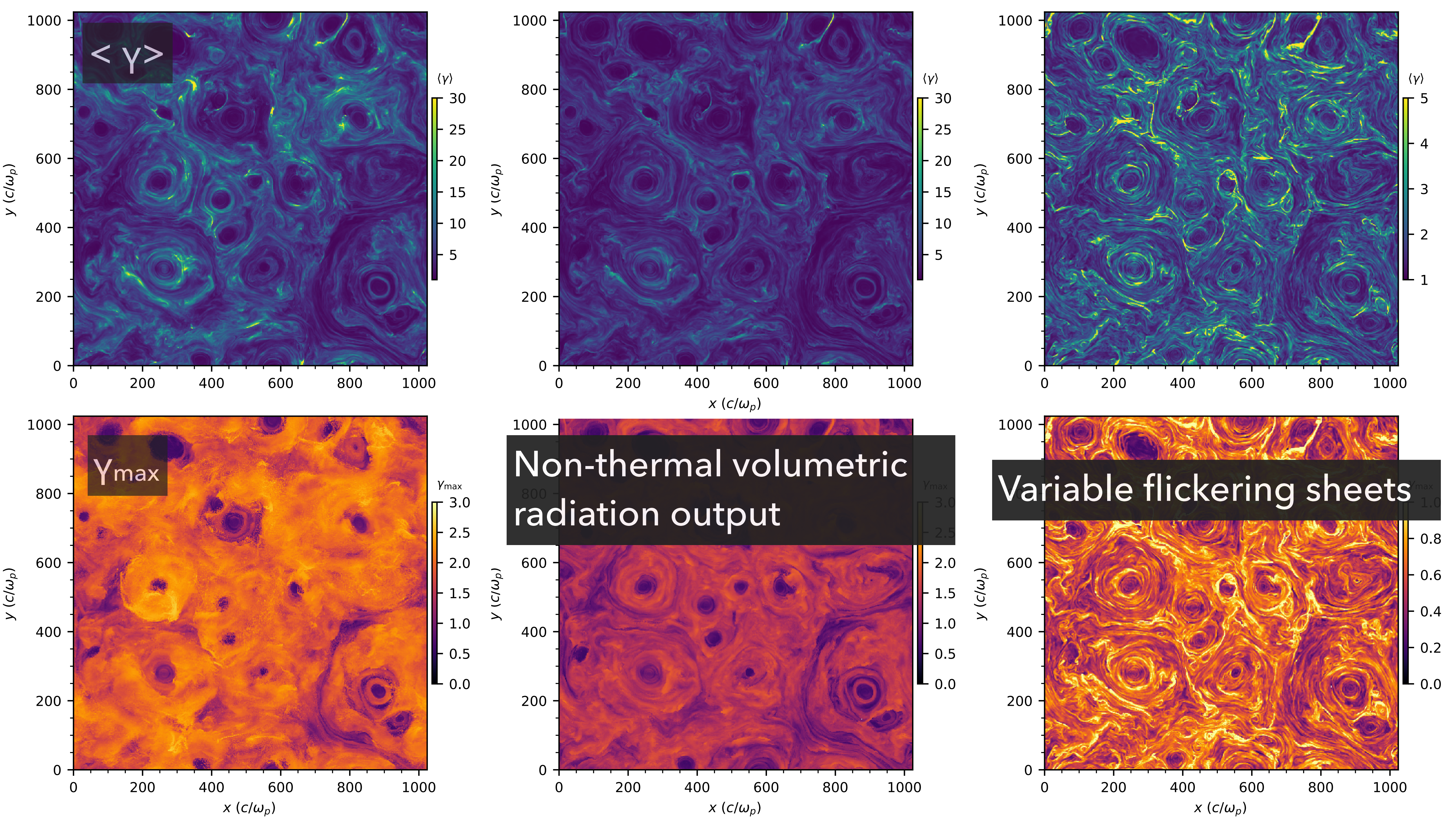


RADIATIVE TURBULENCE: FLICKERING SHEETS

No radiation

Weakly cooling regime

Strongly cooling regime



Non-thermal volumetric radiation output

Variable flickering sheets

TURBULENCE IN COLLISIONLESS PLASMA

- Kinetic turbulent shows similar properties as MHD turbulence
  - with an addition of a new regime: kinetic scales (k^{-4})
- Shows a novel dissipation mechanism: non-thermal particle acceleration
  - Particles are accelerated inside reconnecting current sheets
  - Larmor radius increases and they decouple from “bulk” plasma
  - leads to Diffusive Particle Acceleration (Fermi-II)

- Radiation bath adds an additional energy sink
  - weakly cooling regime (only non-thermal population affected)
  - intermediate transitional regime (current sheets start to dissipate)
  - strongly cooling regime (bulk motions also affected)