AHKASH: a new Hybrid particle-in-cell code for simulations of astrophysical collisionless plasma

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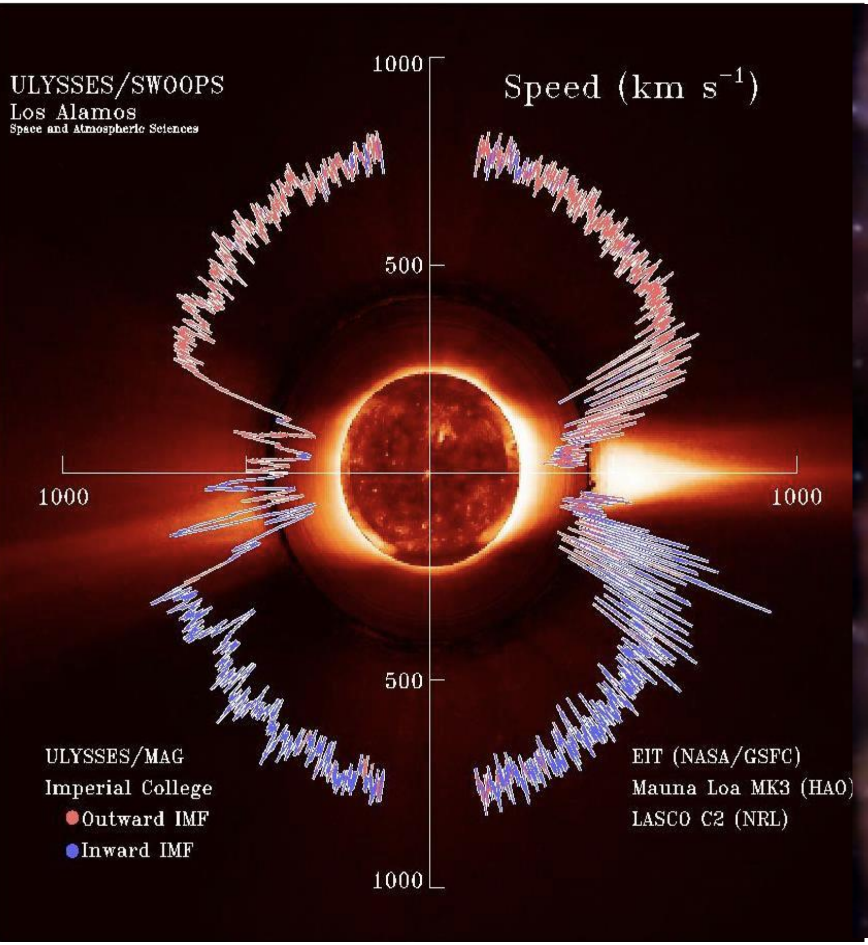
Collisionless, magnetized, turbulent astrophysical plasma

Solar wind



$\lambda_{\text{mfp}}/L \sim 1$

Galactic center

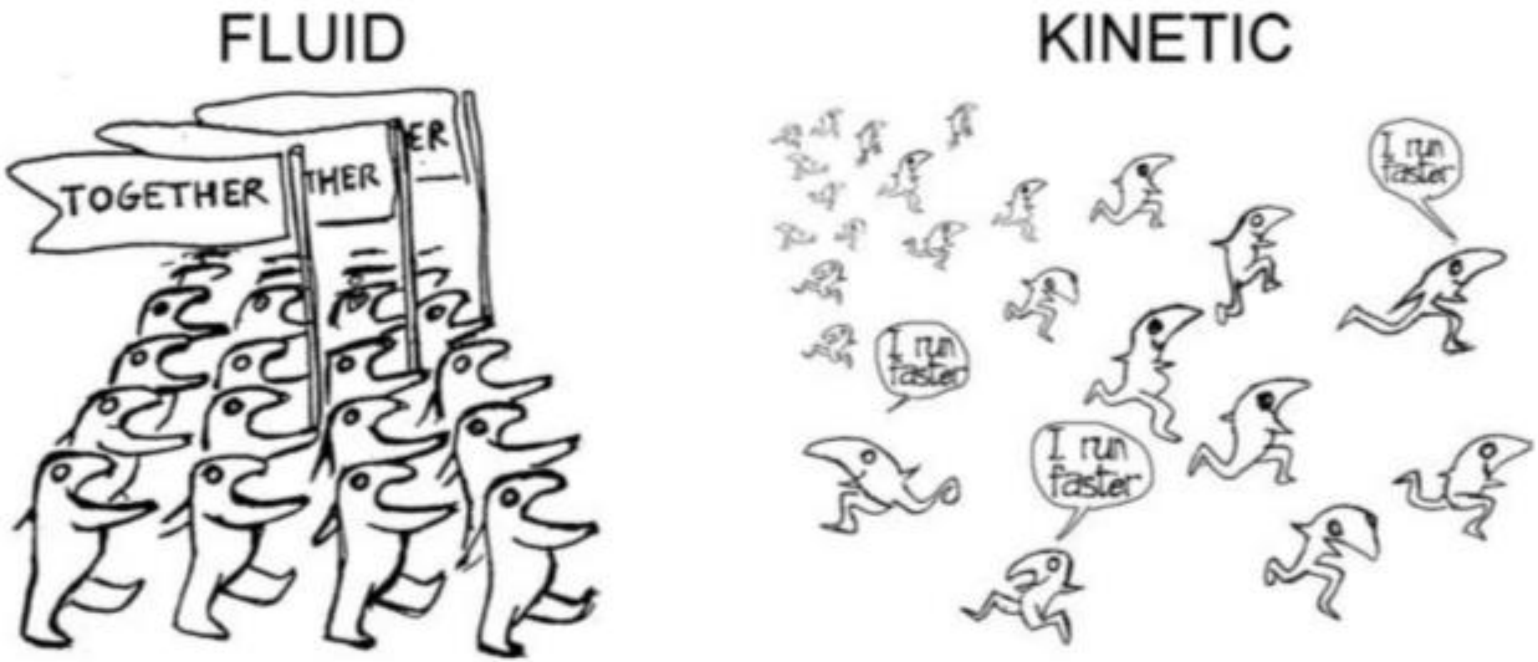
$\lambda_{\text{mfp}}/L \sim 1$

Hot gas in clusters emitting X-rays detected by Chandra (pink), optical image from Hubble and inferred dark matter distribution

$\lambda_{\text{mfp}}/L \sim 0.1$

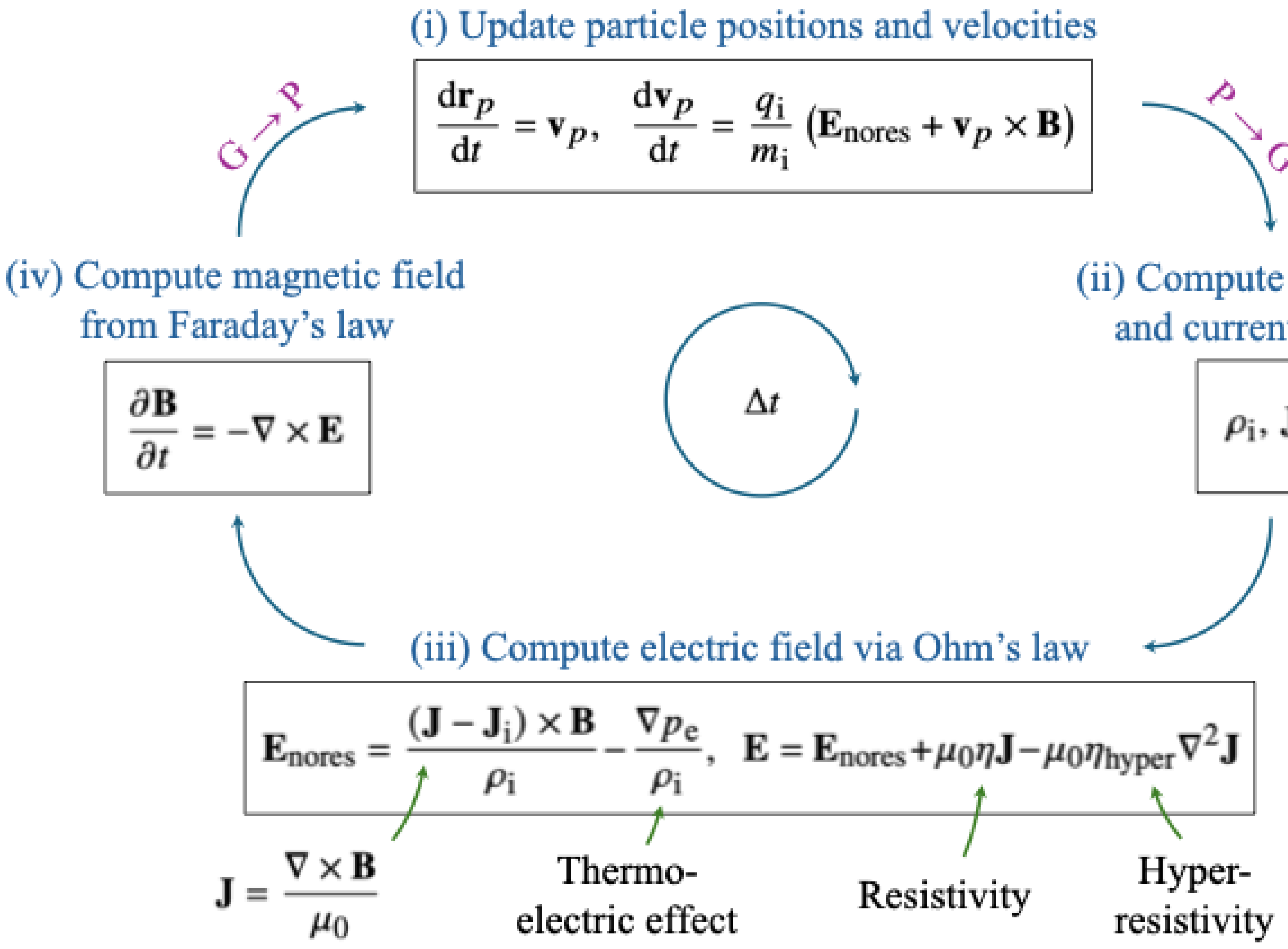
Beyond the Fluid Approach

In weakly-collisional plasma like the hot ICM, $\lambda_{\mathrm{mfp}} \sim L$
fluid approximation breaks down (MHD not applicable) → kinetic treatement of the plasma



From: Meyer-Vernet N. Basics of the solar wind. Cambridge University Press; 2007 Jan 18.

AHKASH Astrophysical Hybrid Kinetic simulations with flASH



Includes the Boris integrator, predictor-predictor corrector method, constrained transport, wave and particle time-steps, hyper-resistivity, turbulence driving and a new cooling method for ions

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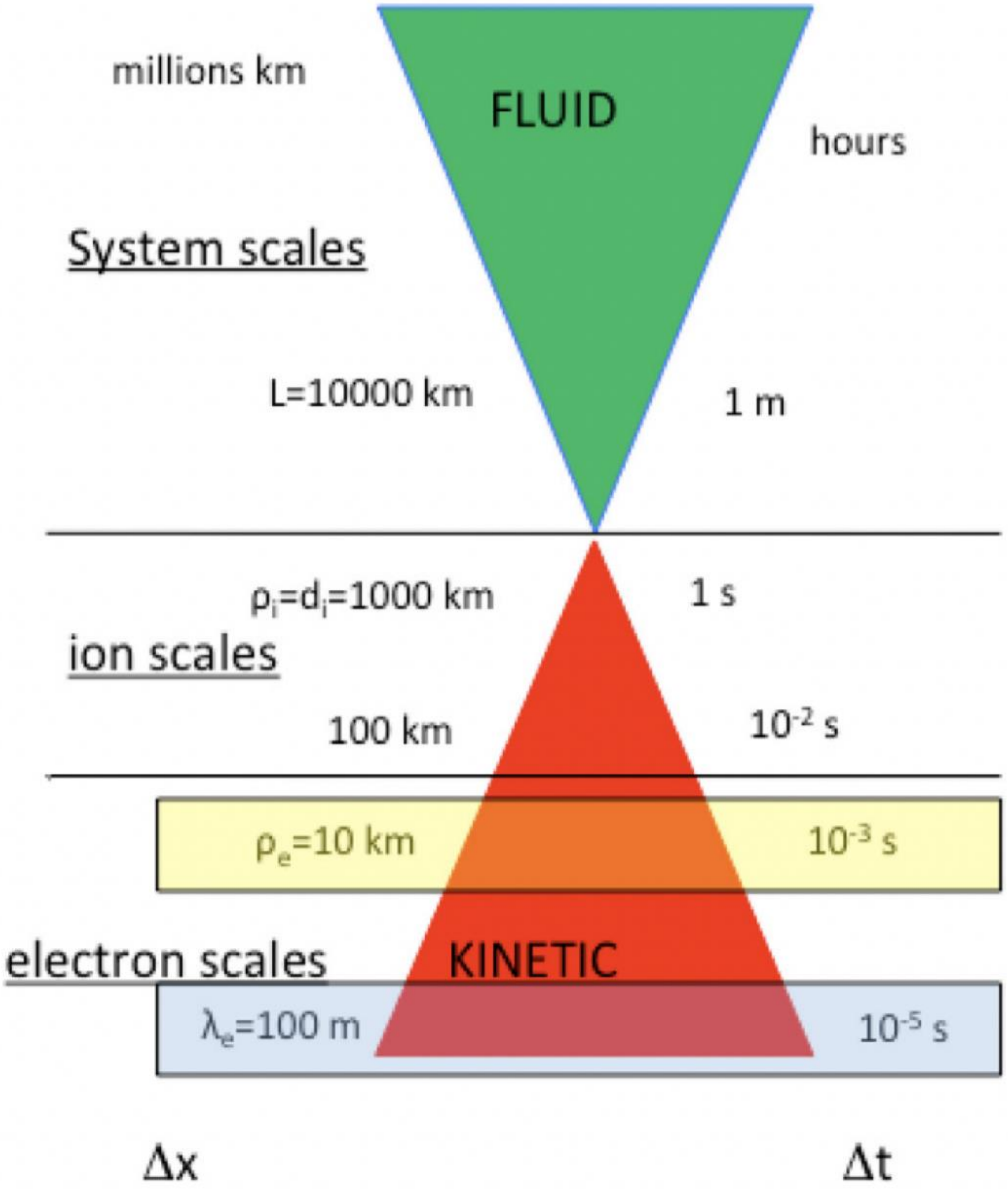
Typical length and time scales in the earth's environment

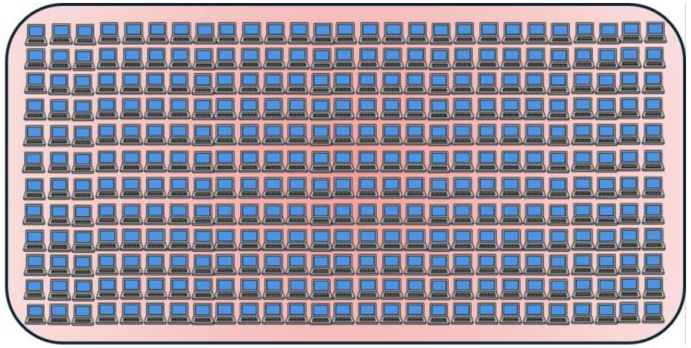
Computation cost of numerical simulations



Fluid/MHD approach

8 CPU cores, 16 GB, 12 hrs

Hybrid-kinetic / hybrid particle-in-cell

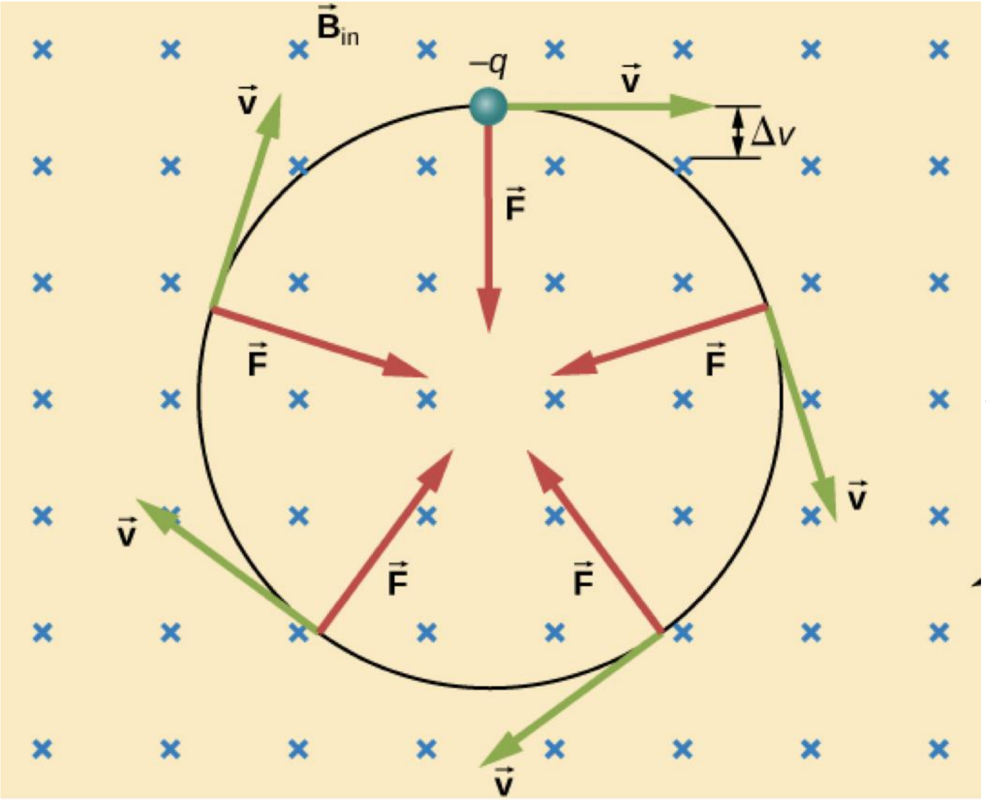


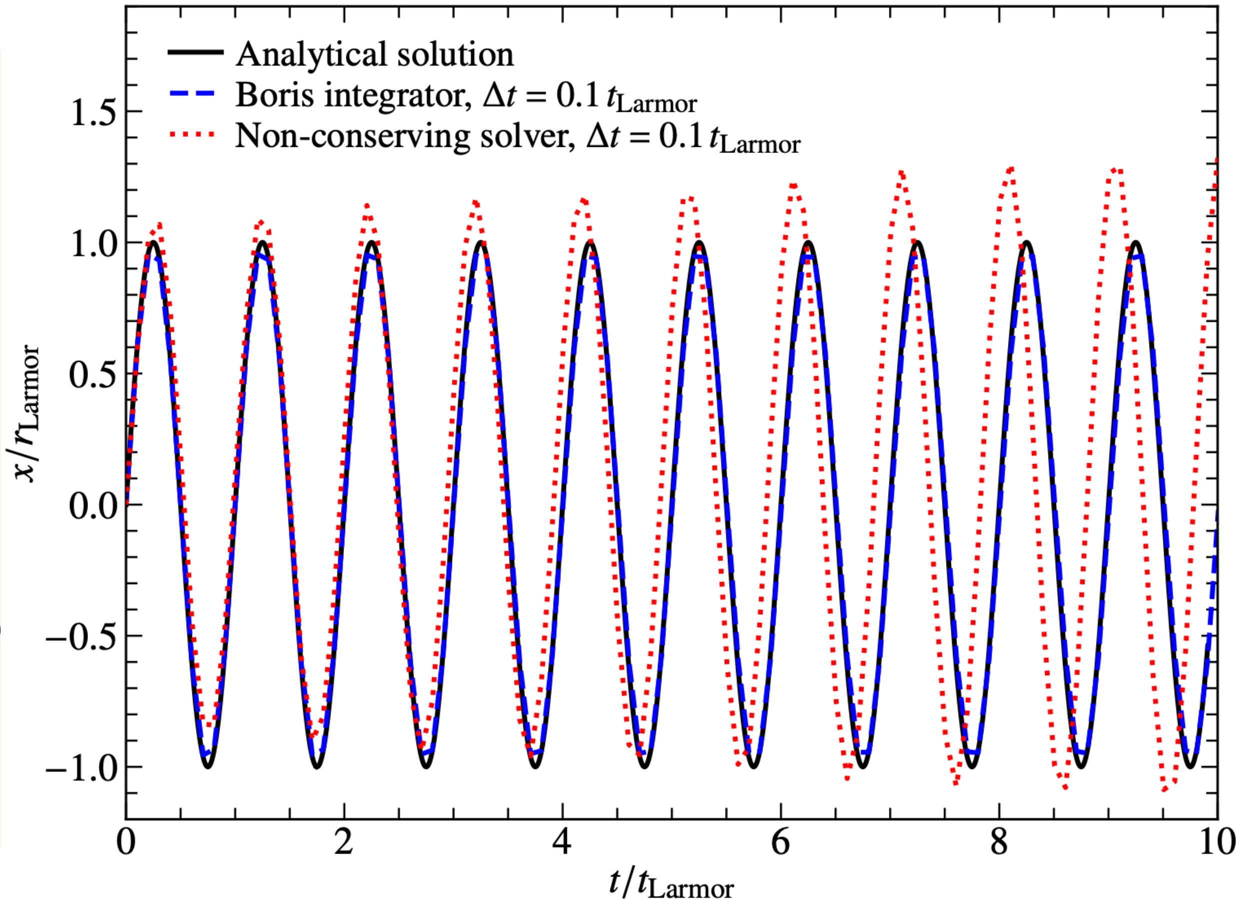
(8 CPU cores, 16 GB, 12 hrs) x 324!!

Kinetic / particle-in-cell approach

Innocenti et al. 2017

Charged particle in uniform magnetic field





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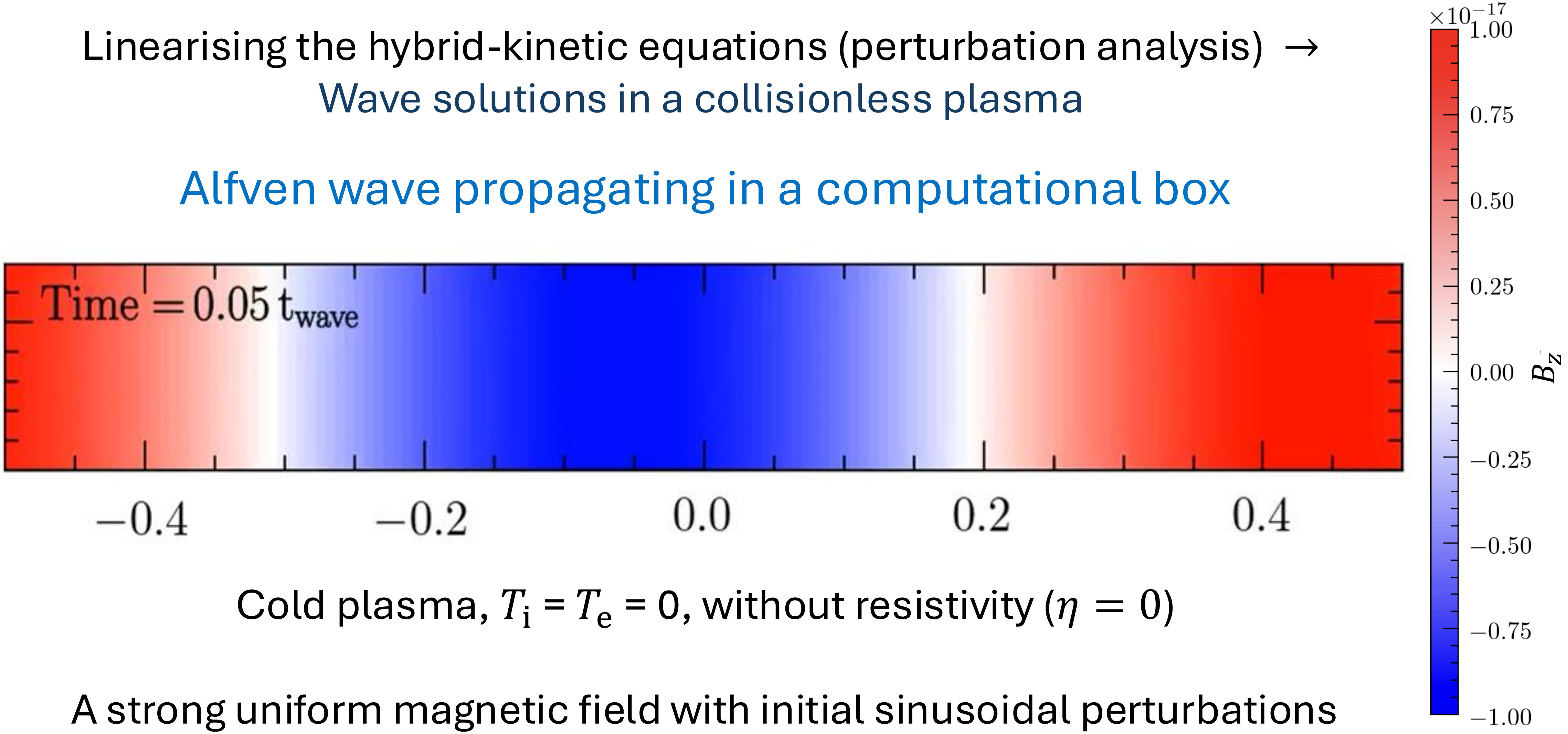
Waves in collisionless plasma

Linearising the hybrid-kinetic equations (perturbation analysis) →
Wave solutions in a collisionless plasma

Alfven wave propagating in a computational box



Cold plasma, $T_i = T_e = 0$, without resistivity ($\eta = 0$)

A strong uniform magnetic field with initial sinusoidal perturbations

Waves in collisionless plasma

○ Linear … sis) →

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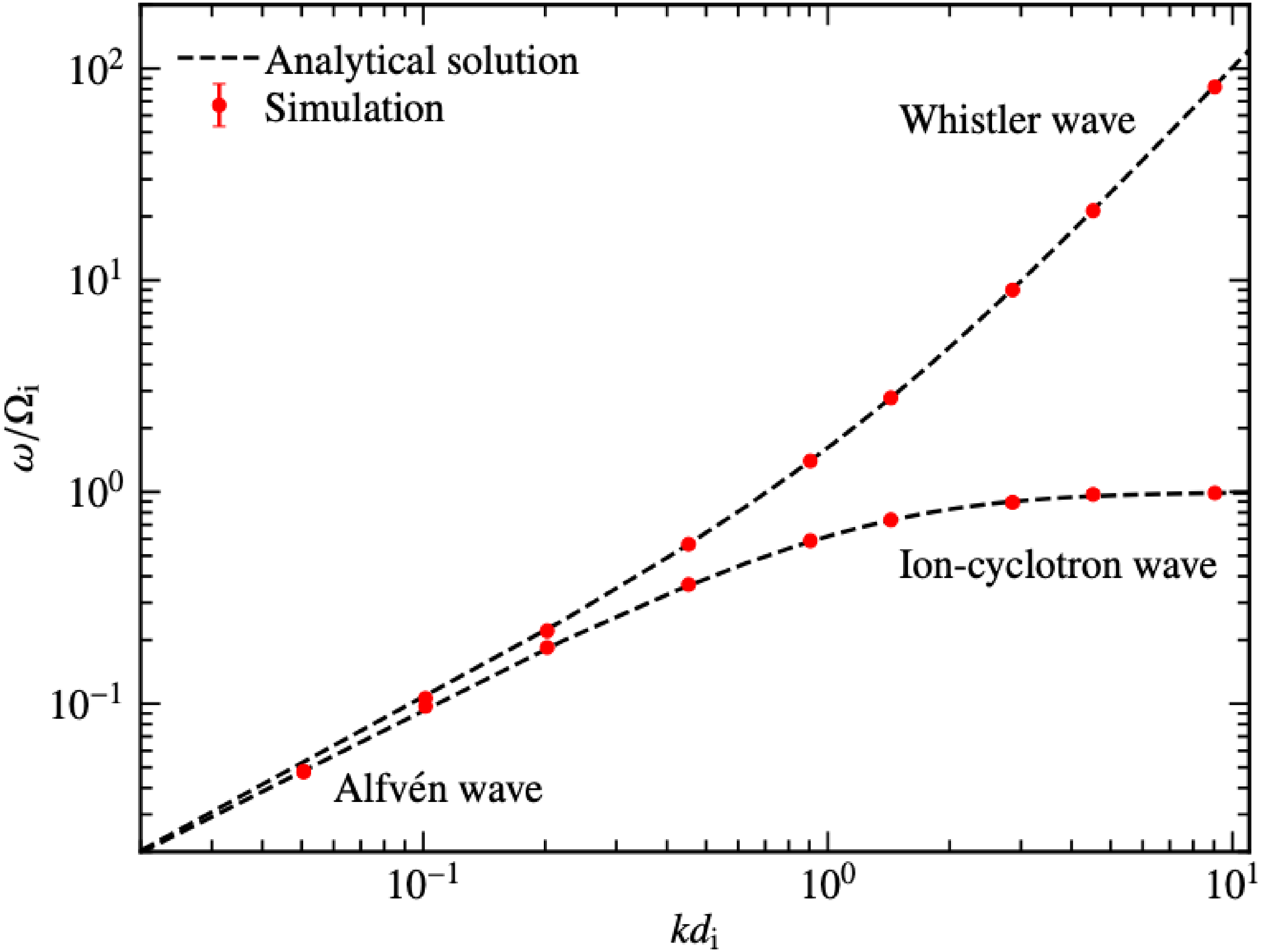

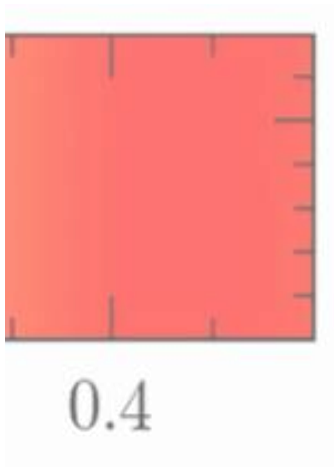

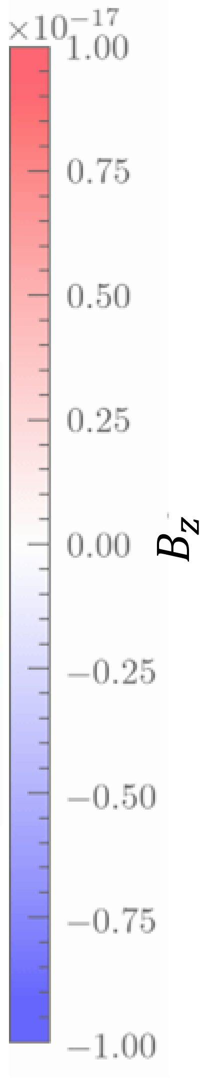

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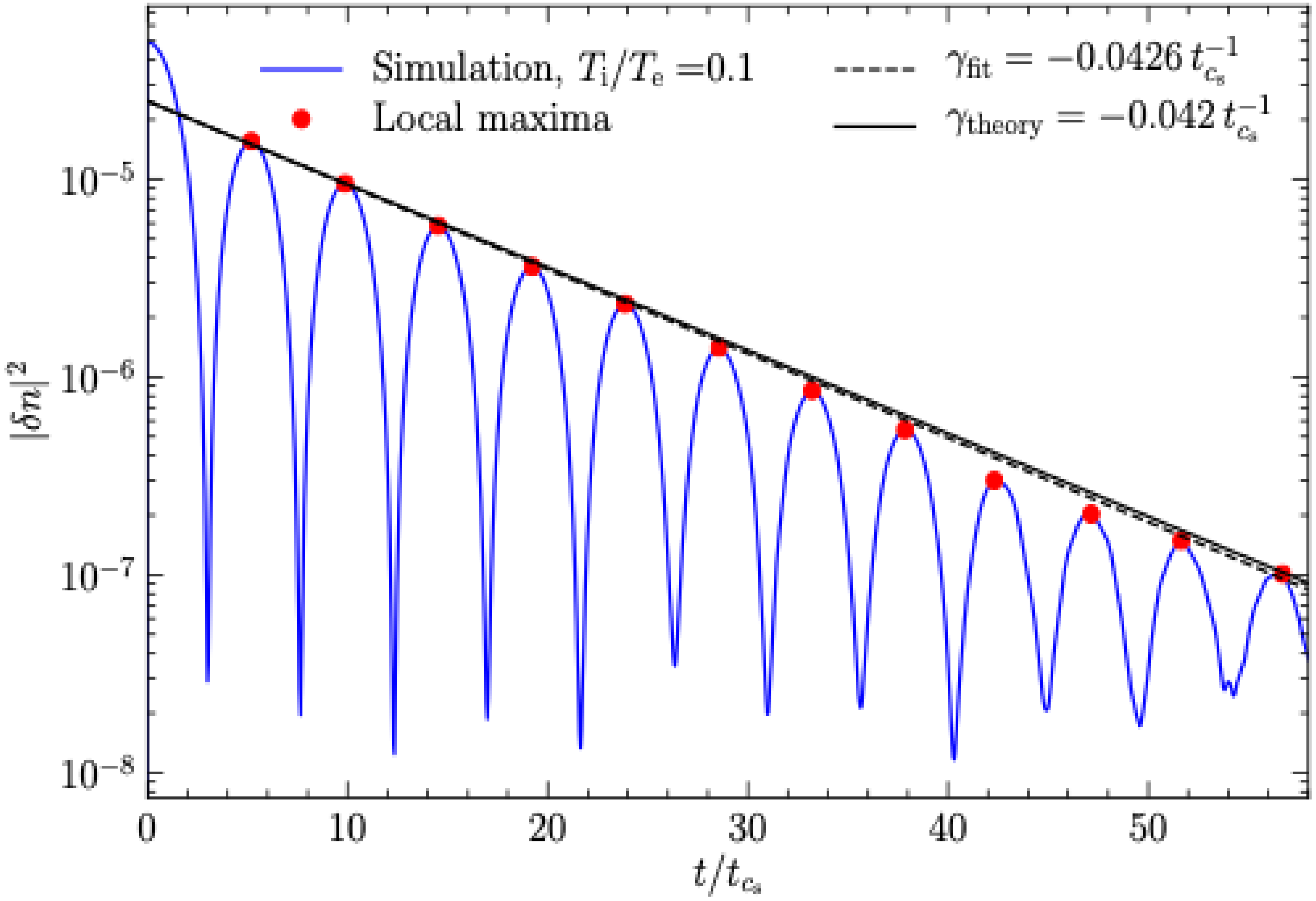
Waves particle interactions (Landau damping)

- Landau damping of ion-acoustic waves in collisionless plasma
- Dissipation of wave energy into particle thermal energy in a collisionless plasma
- Full f and δf methods *(Kunz et al 2014)*



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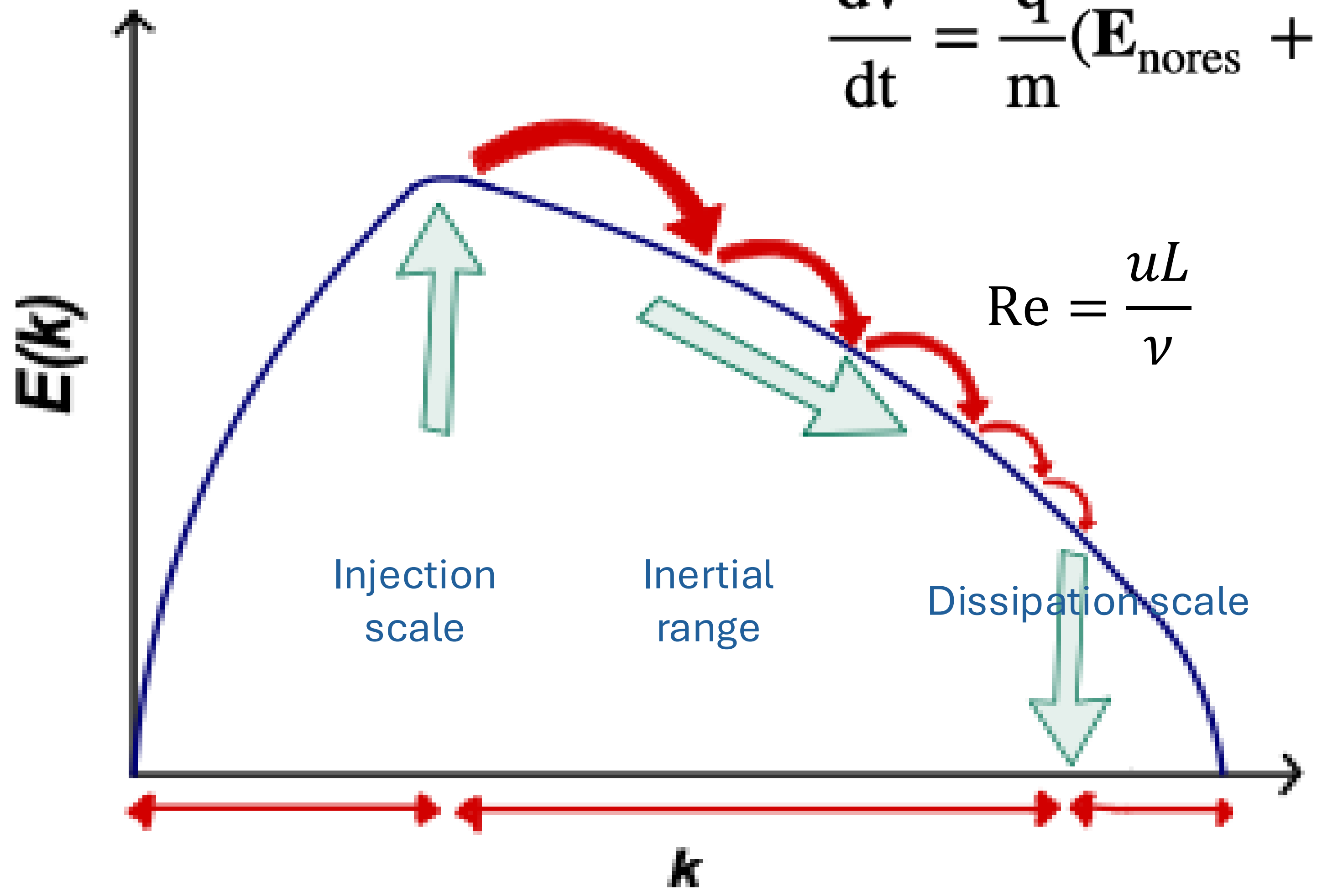
Driving turbulence in hybrid PIC simulations

turbulent driving

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}(\mathbf{E}_{nores} + \mathbf{v} \times \mathbf{B}) + \mathbf{f}$$

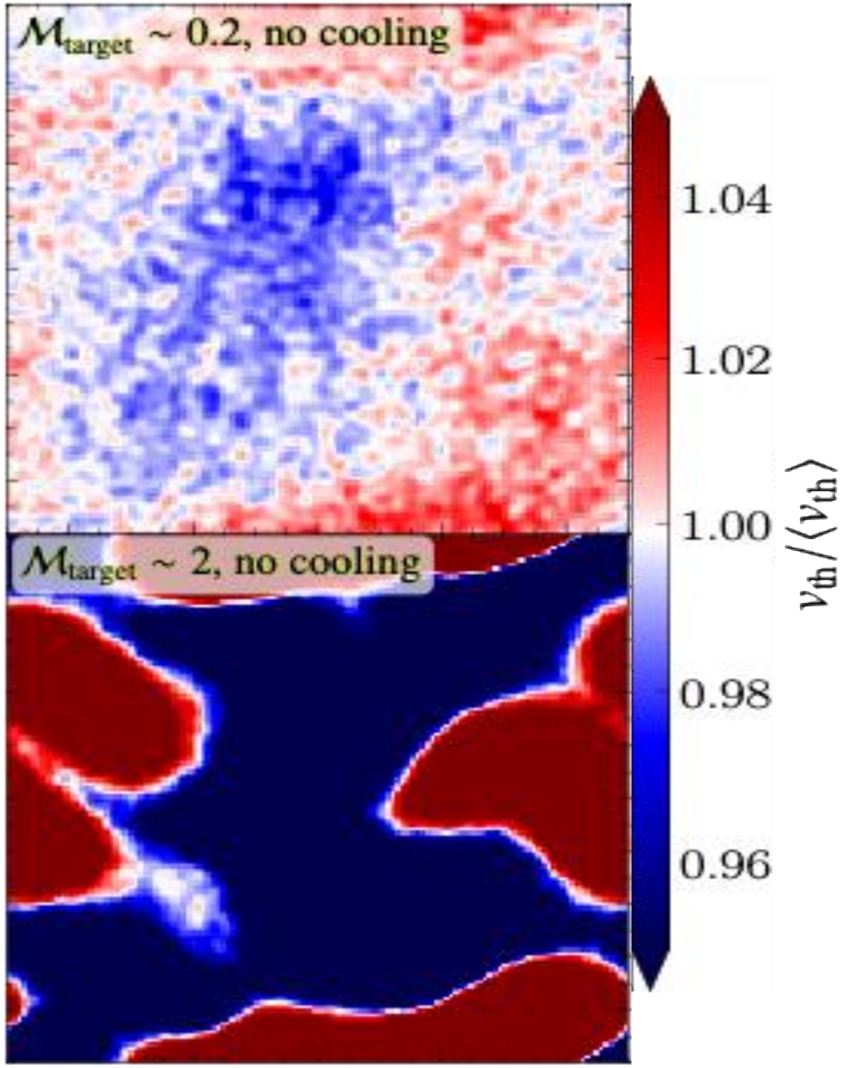


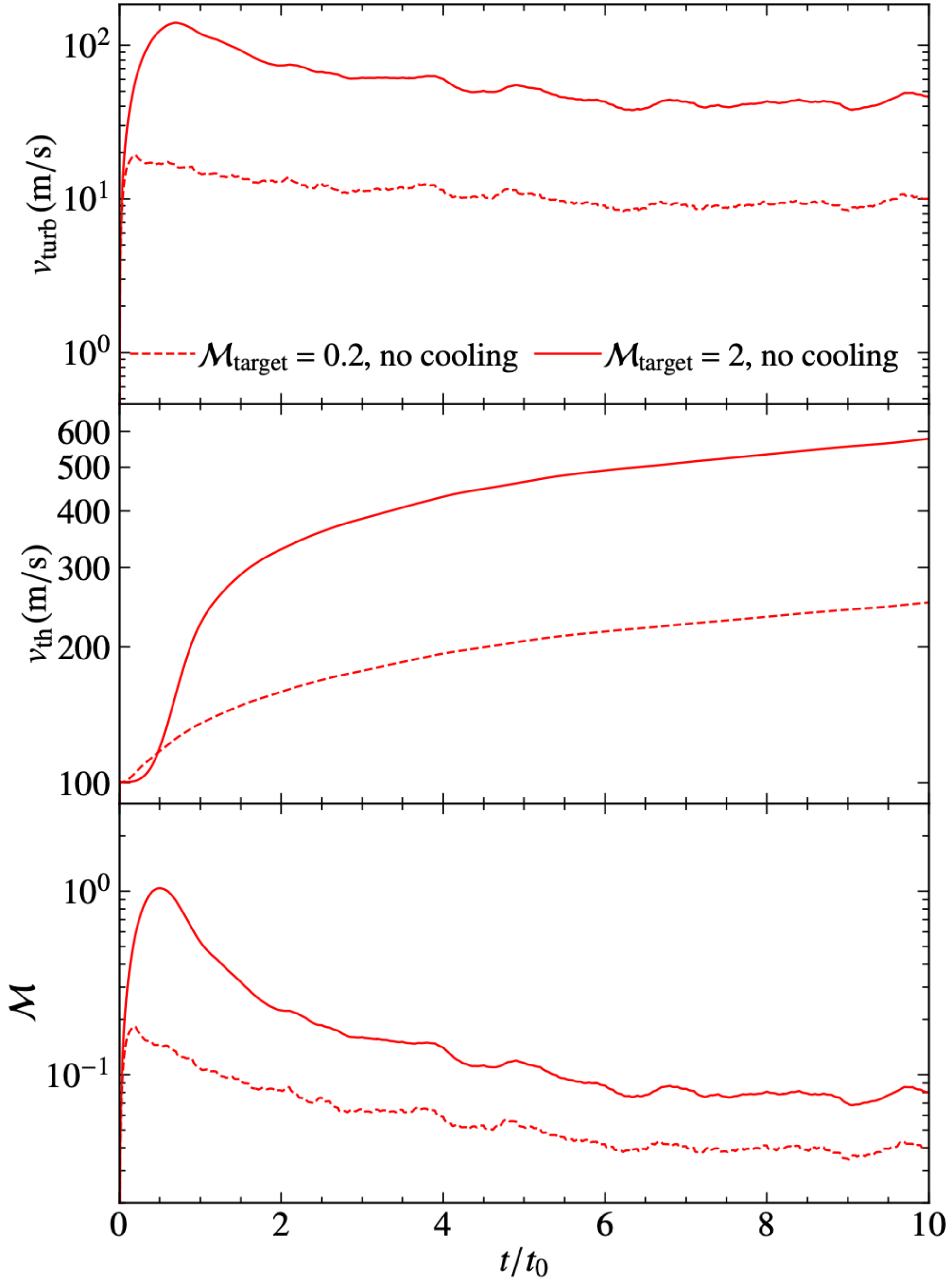
$$\mathrm{Re} = \frac{uL}{\nu}$$

Turbulent driving field is modelled using the Ornstein-Uhlenbeck process *(Federrath et al. 2010)*

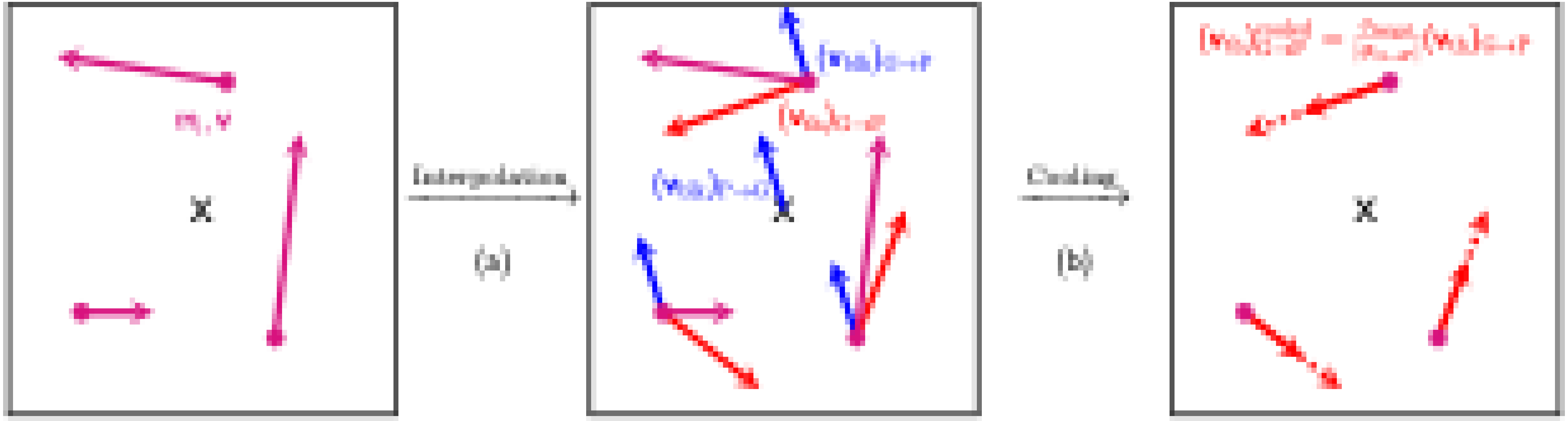
We drive the the turbulence on large scales and inject purely solenoidal driving to the particles

Turbulent driving & heating





Cooling Ions



$$\mathbf{v} \longrightarrow \mathbf{v}_{\mathrm{cooled}} = \frac{\sigma_{\mathrm{target}}}{|\boldsymbol{\sigma}_{\mathrm{G}\to\mathrm{P}}|}(\mathbf{v}_{\mathrm{th}})_{\mathrm{G}\to\mathrm{P}} + (\mathbf{v}_{\mathrm{blk}})_{\mathrm{G}\to\mathrm{P}}$$

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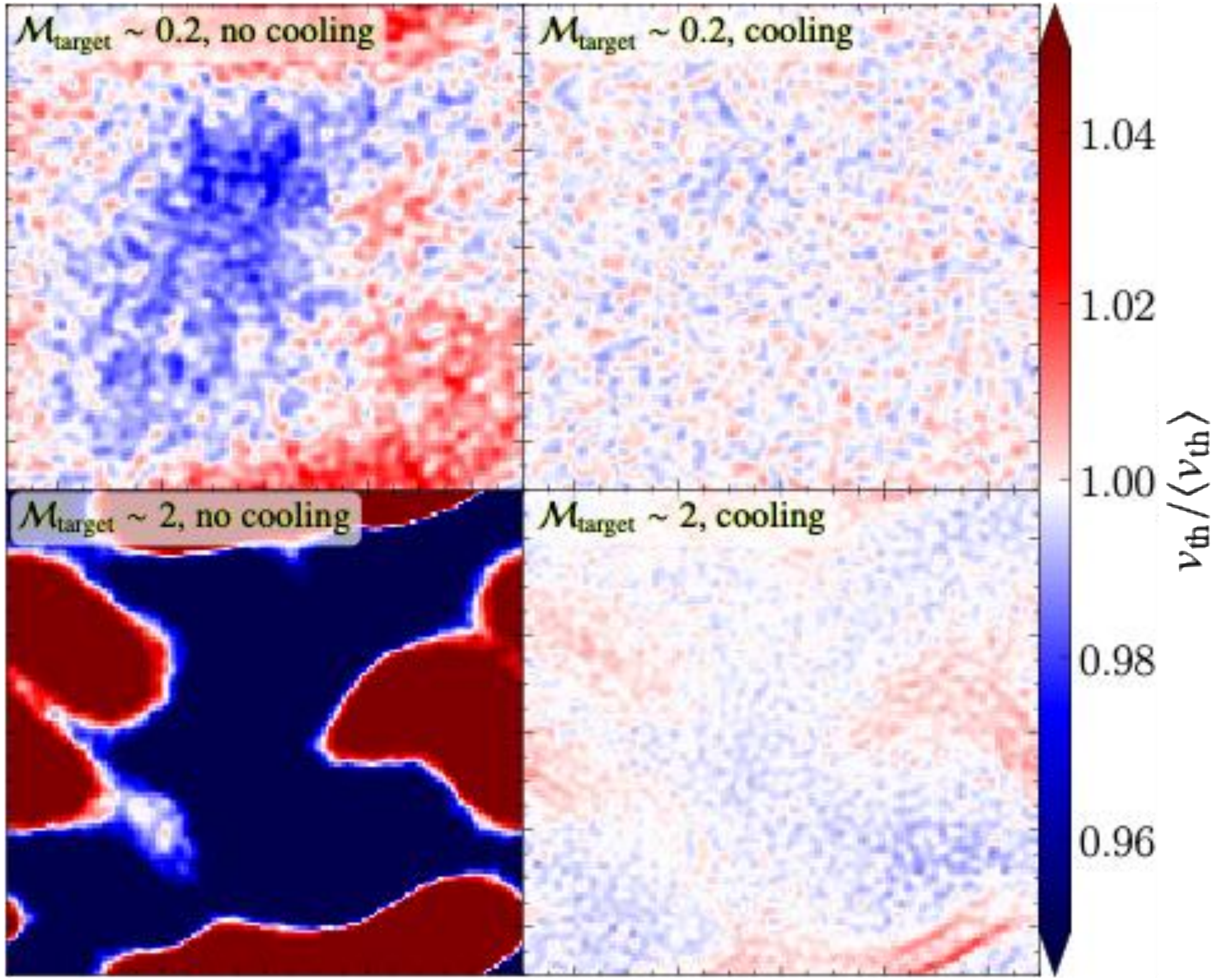
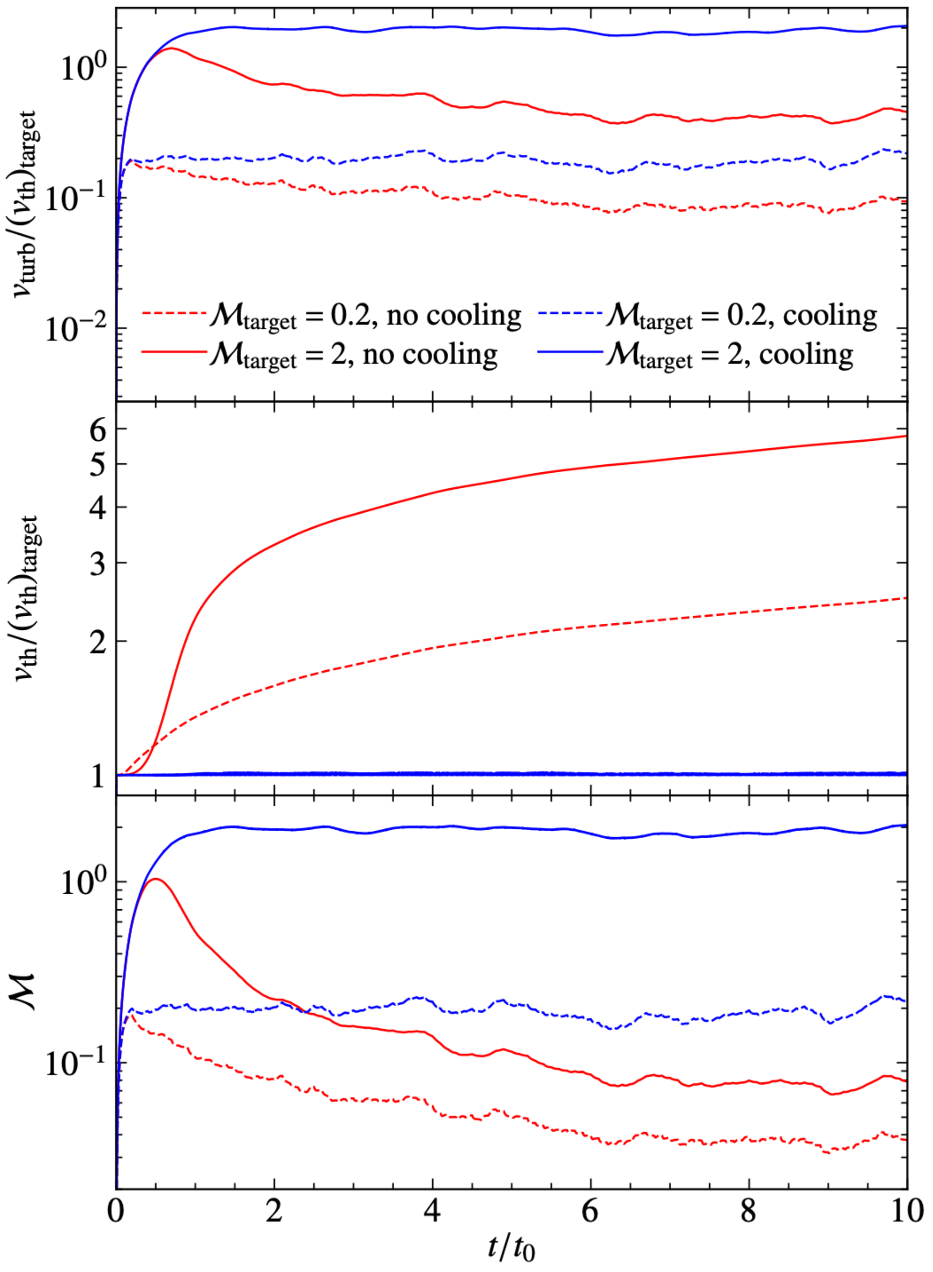
Tests with cooling





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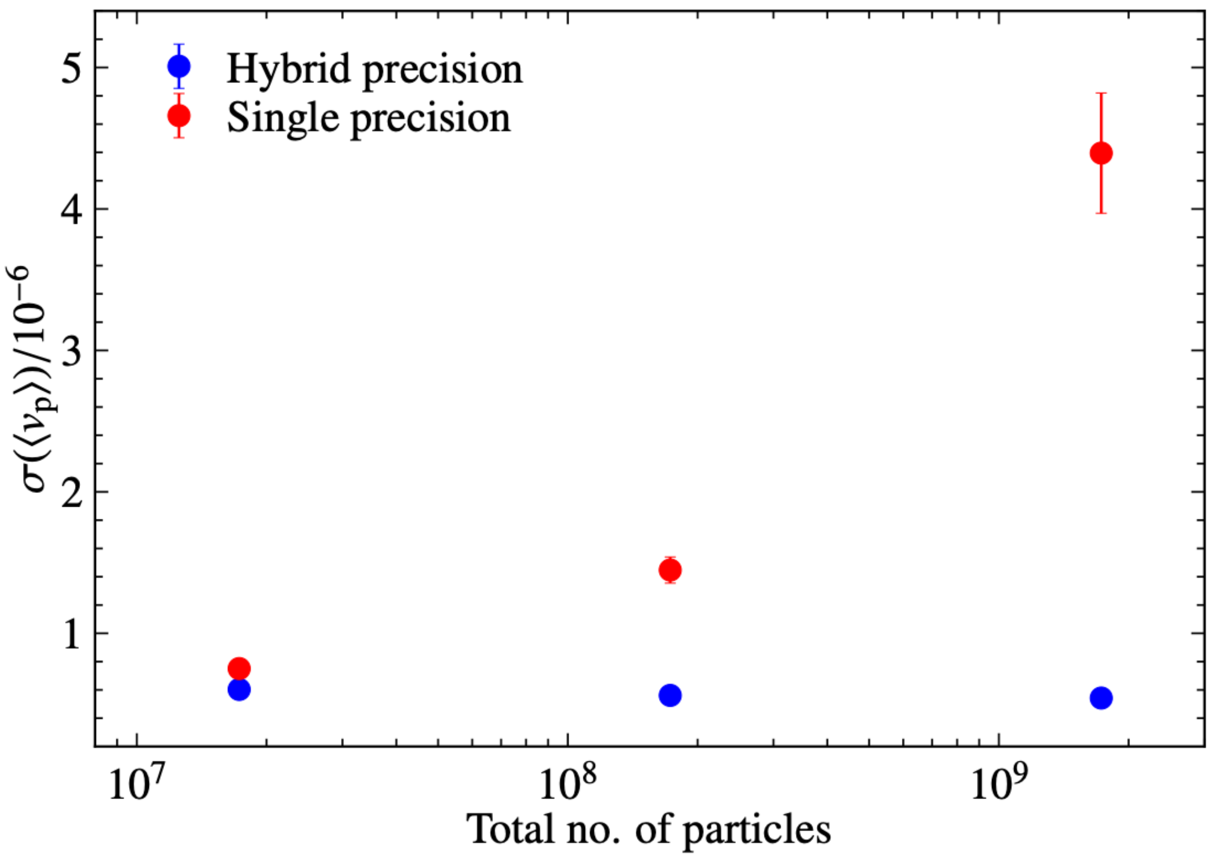
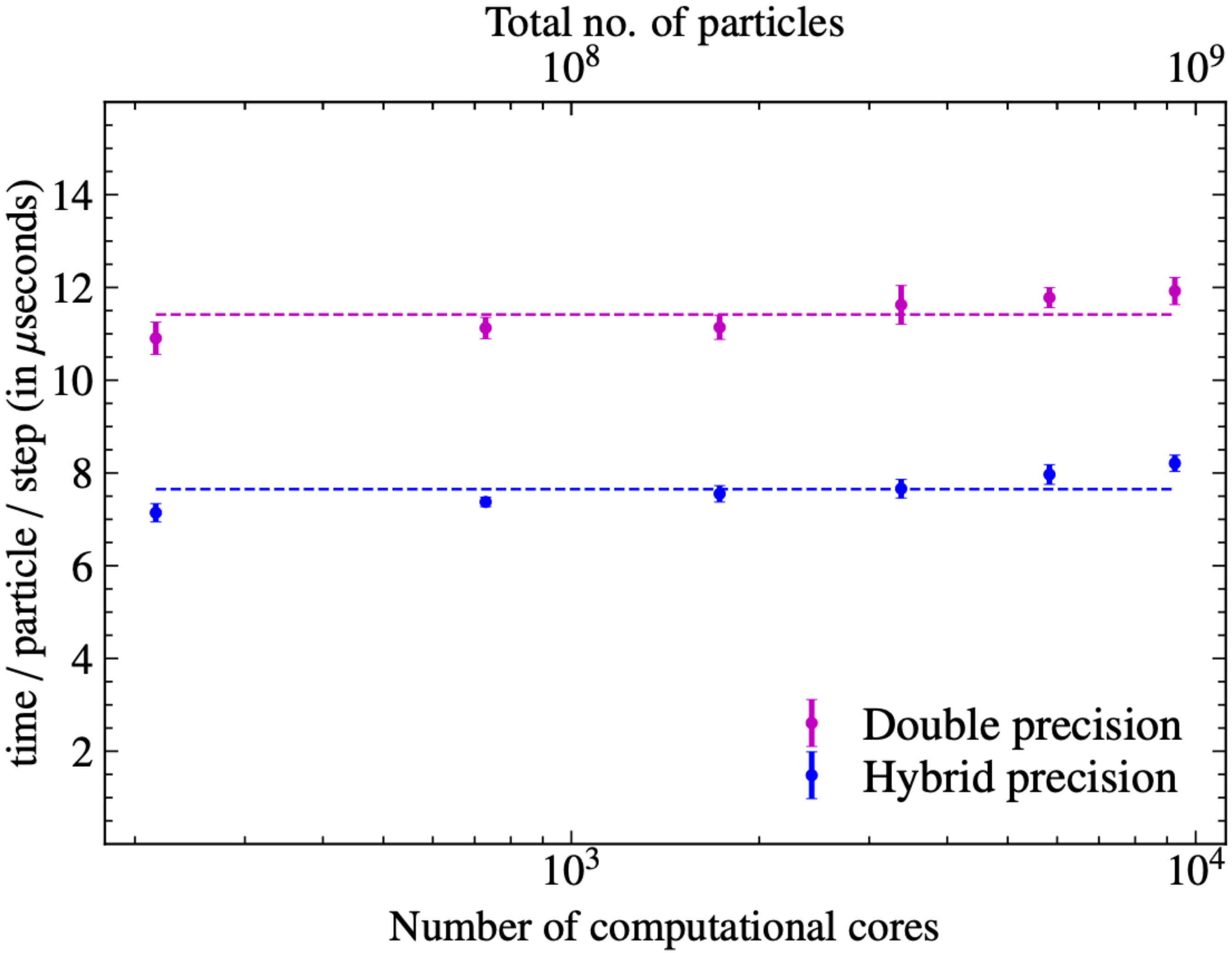
Precision tests & weak computational scaling

See Federrath et al. 2021





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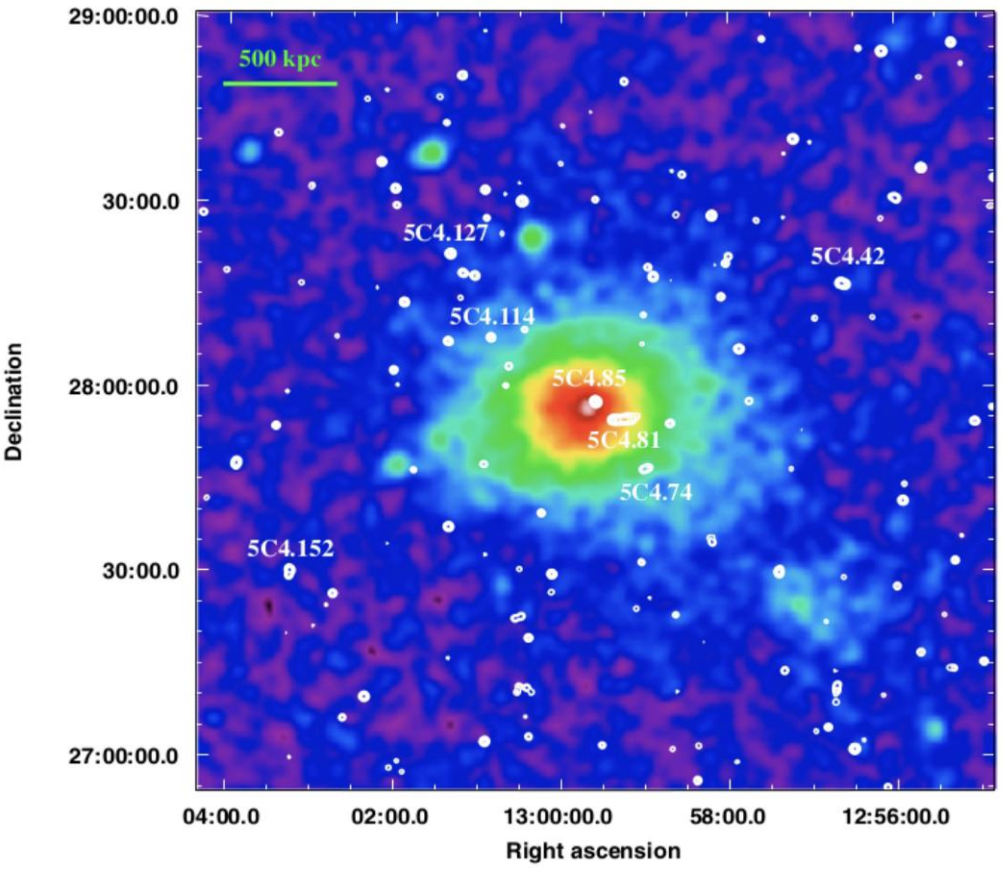
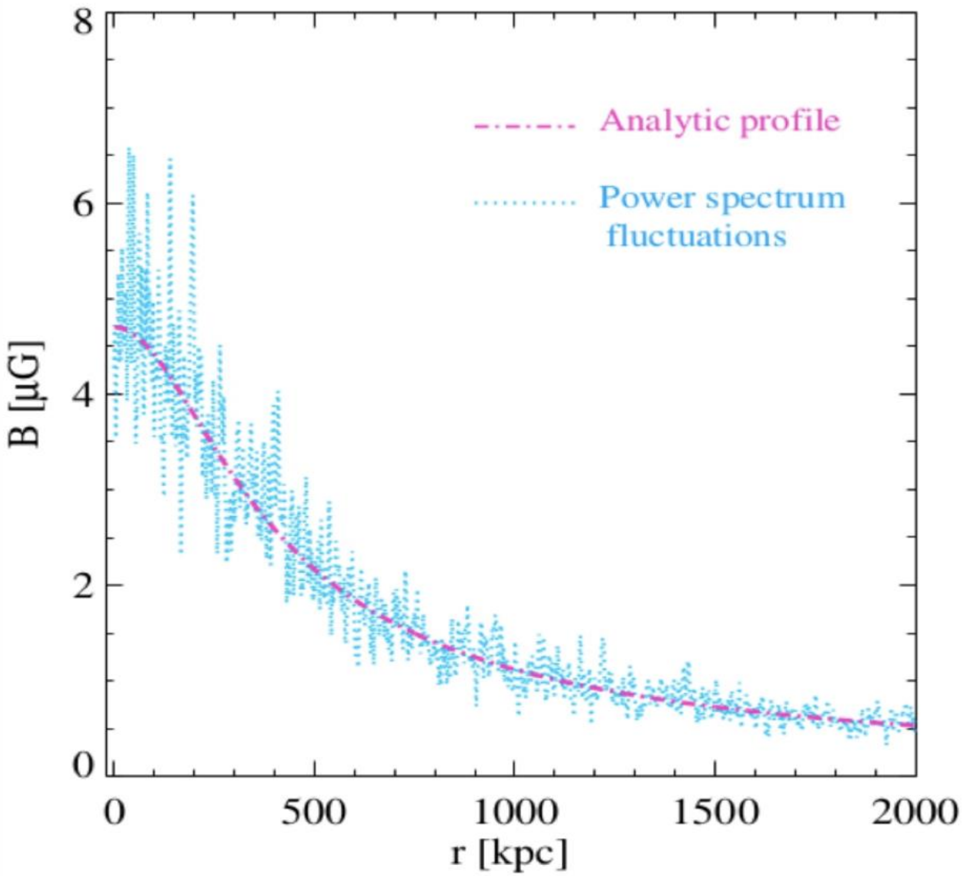
Magnetic Fields in Galaxy Clusters



Coma X-ray emission from ROSAT All Sky Survey in the energy band; Radio emission shown in contours *(Bonafede et al. 2010)*

Seed magnetic field $> 10^{-16}$ Gauss may be present in galaxy clusters but we observe $\sim\mu$Gauss fields (IGMF constraints)



Strong fields with $\sim\mu$Gauss strength observed in galaxy clusters, close to the equipartition value of magnetic field for the ICM *(Carilli & Taylor 2002, Govoni & Feretti 2004, Bonafede et al. 2010)*

Magnetic Field Amplification in MHD

Magnetic fields can be amplified by the small-scale dynamo – turbulent kinetic energy is converted to magnetic energy

Induction equation

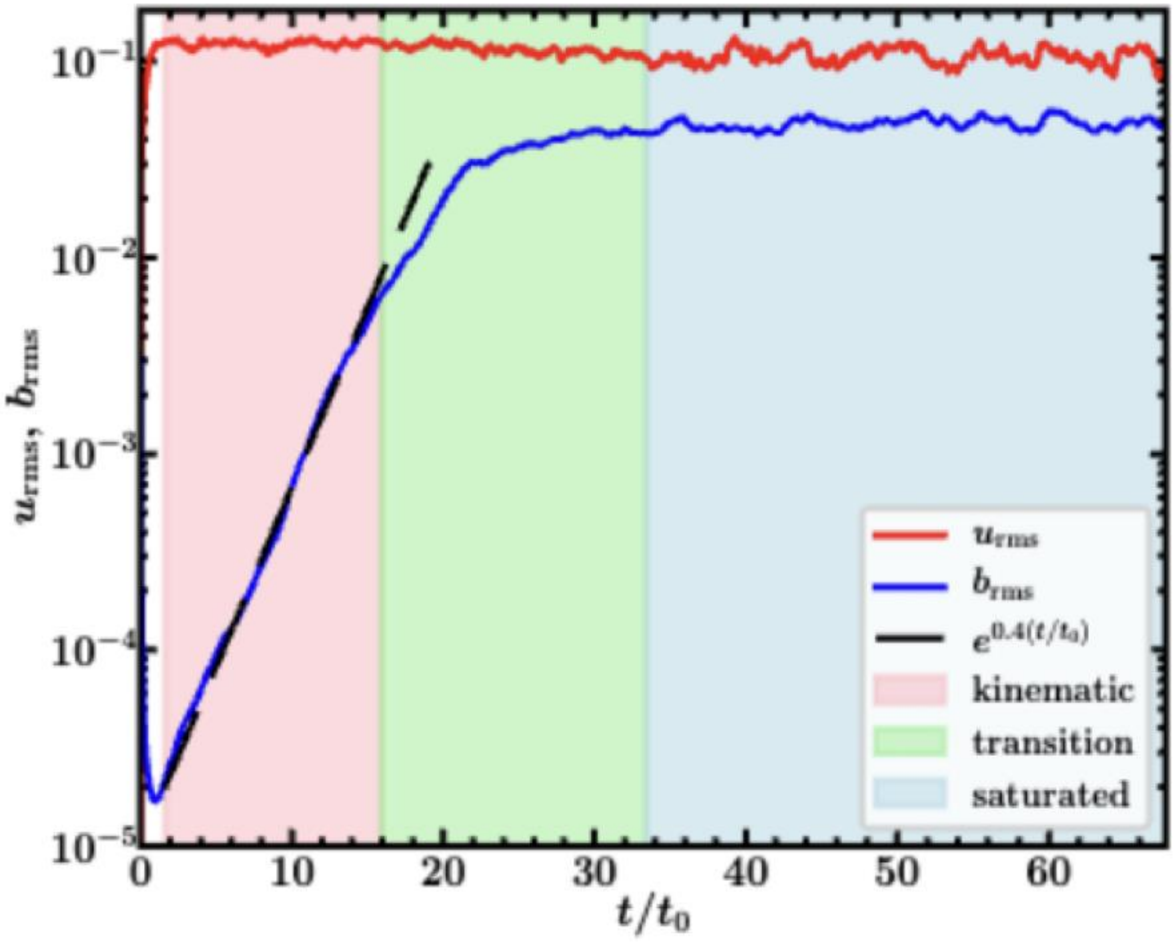
$$\frac{\partial B}{\partial t} = \nabla \times (u \times B) + \eta \nabla^2 B$$

Amplification Diffusion

$$\mathrm{Rm} = \frac{uL}{\eta} = \frac{\text{Amplification}}{\text{Diffusion}}$$

$(\mathrm{Rm} > \mathrm{Rm}_{\mathrm{crit}}) \rightarrow \text{Amplification}$

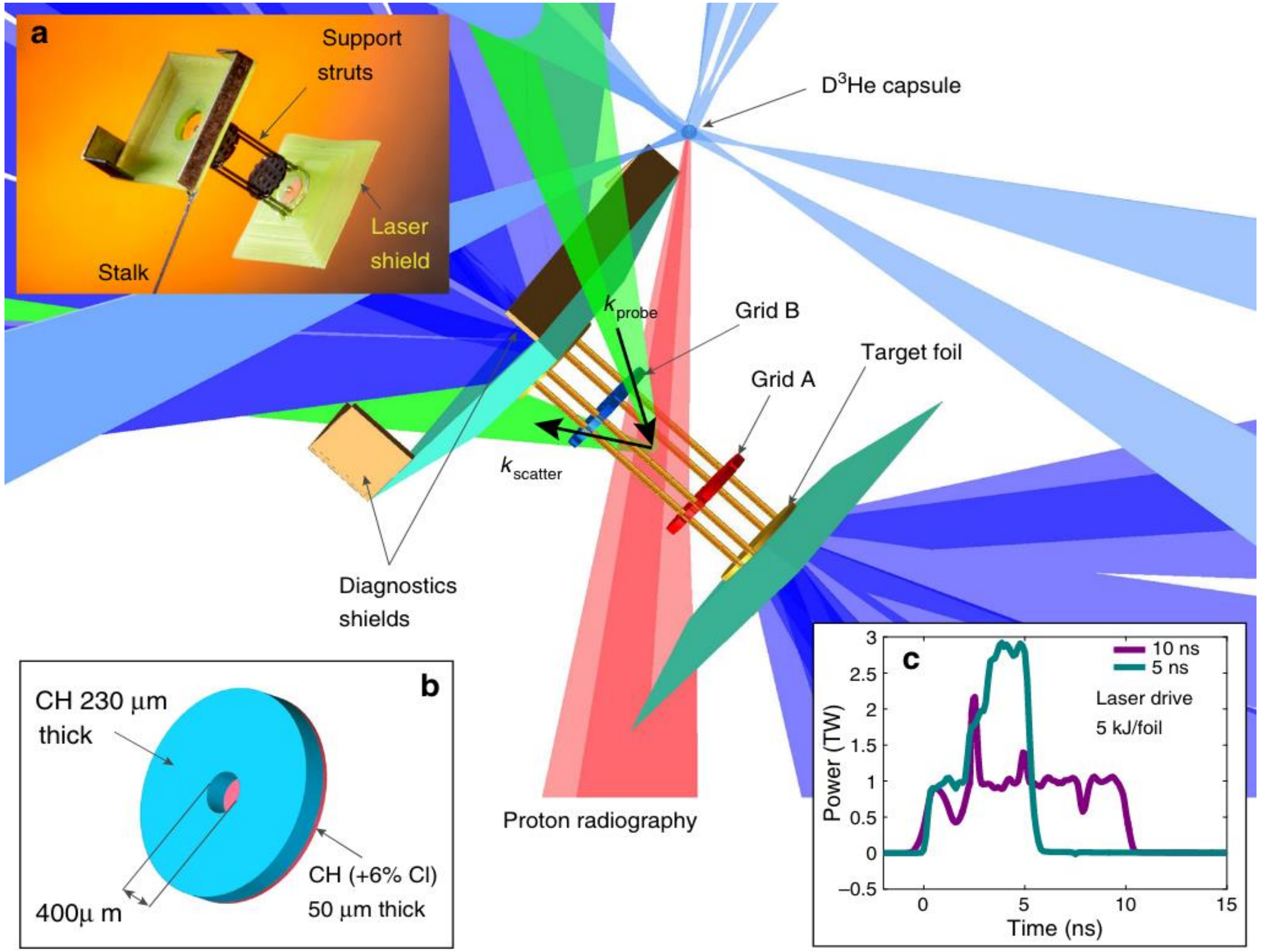
Seta and Federrath (2020)



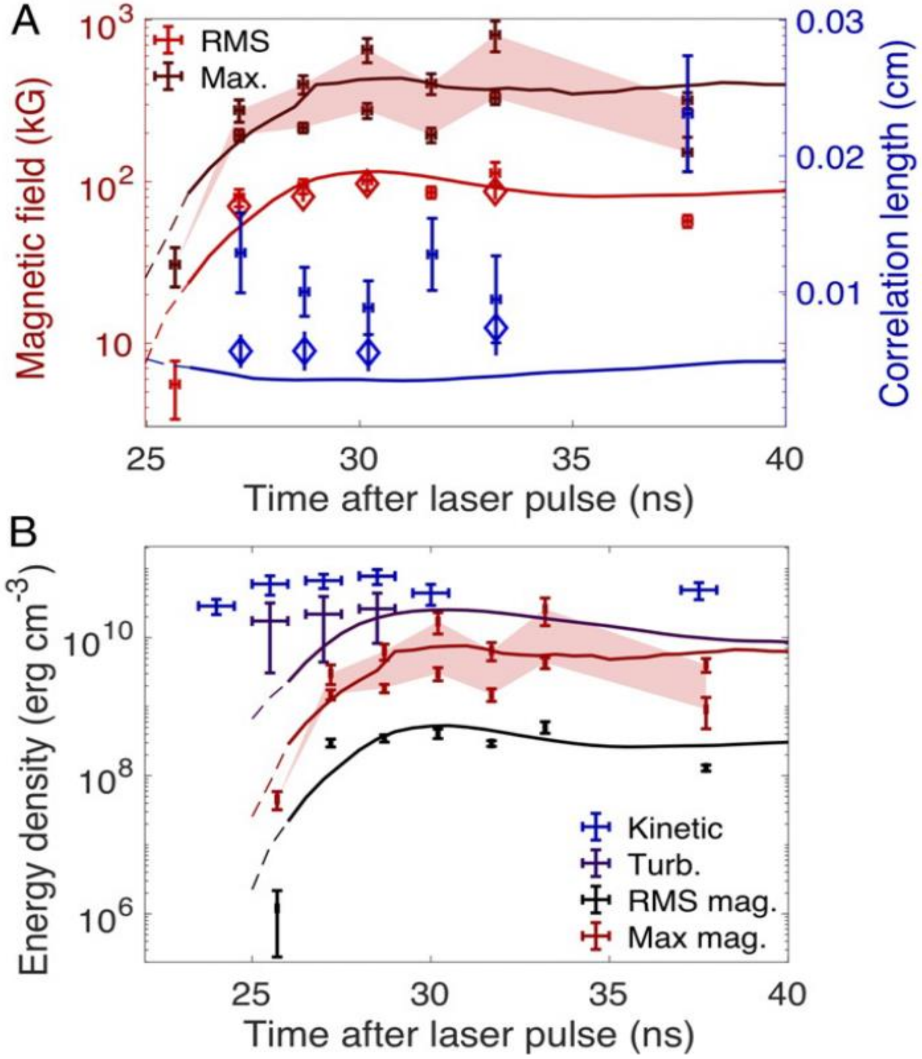
In the kinematic regime, $E_{\mathrm{m}} \propto e^{\Gamma t}$

Turbulent dynamo in laser plasma

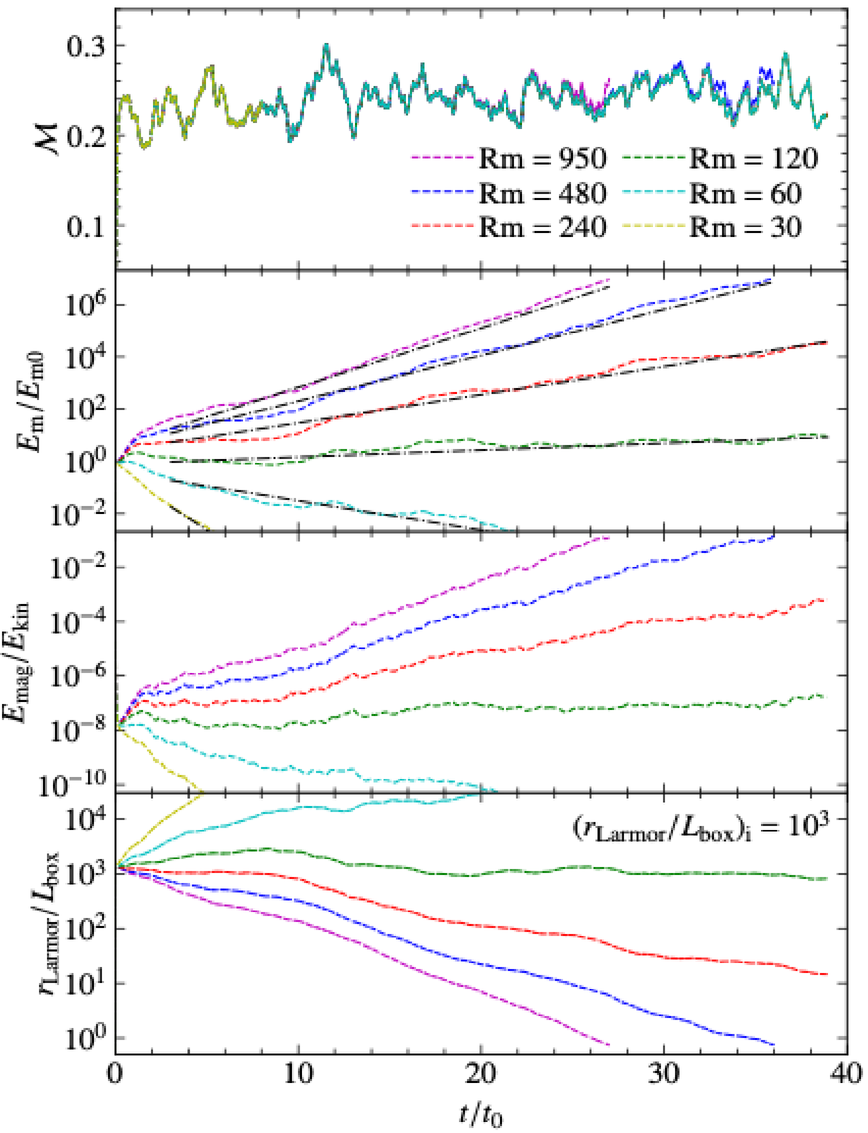
Tzeferacos+2018, Tzeferacos+2017, Chen+2020

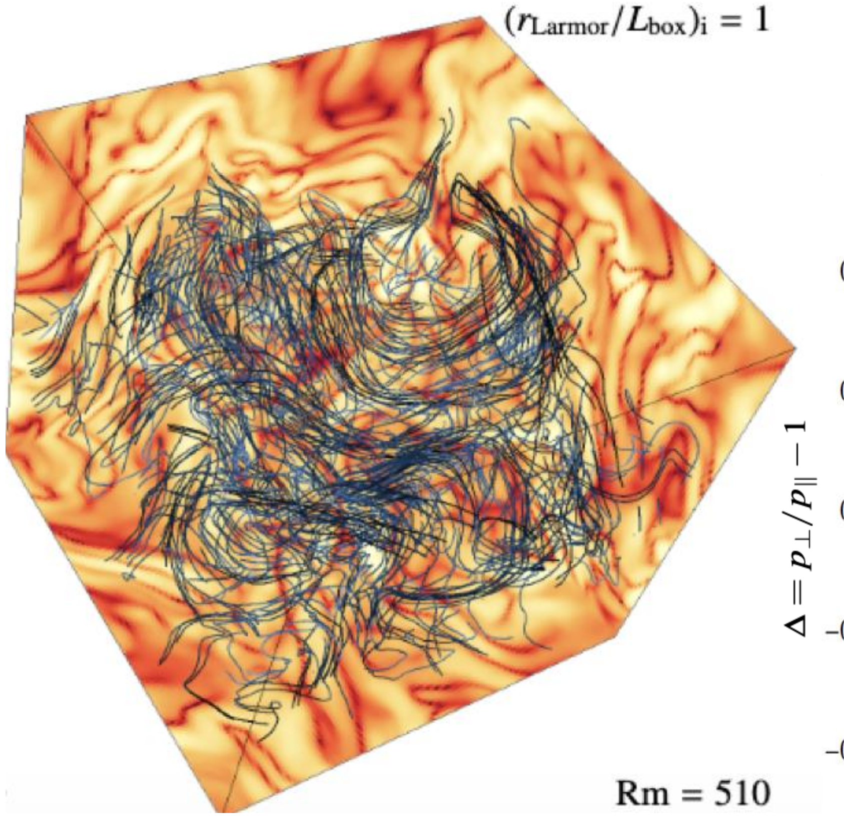


Bott+2021a, Bott+2021b



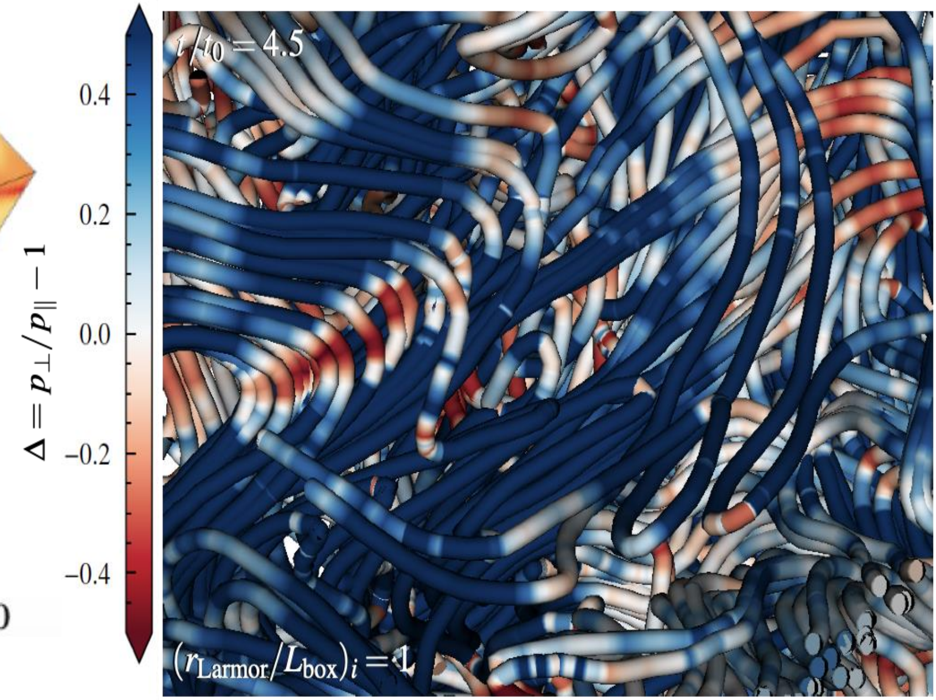
Collisionless turbulent dynamo simulations





Magnetic energy and field streamlines

Pressure anisotropy



$$\Delta = p_\perp/p_\parallel - 1$$

Also see Rincon et al 2016, St-Onge & Kunz 2018, St-Onge et al. 2020, Zhou et al. 2024

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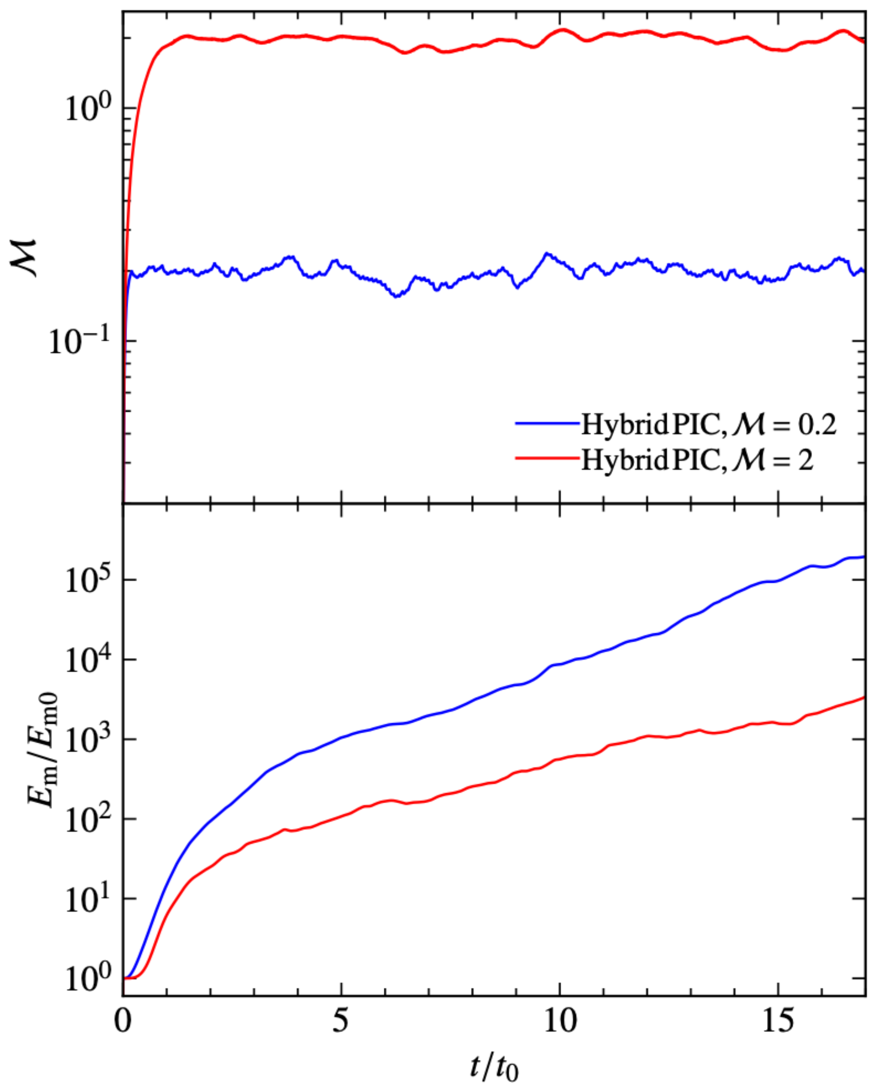
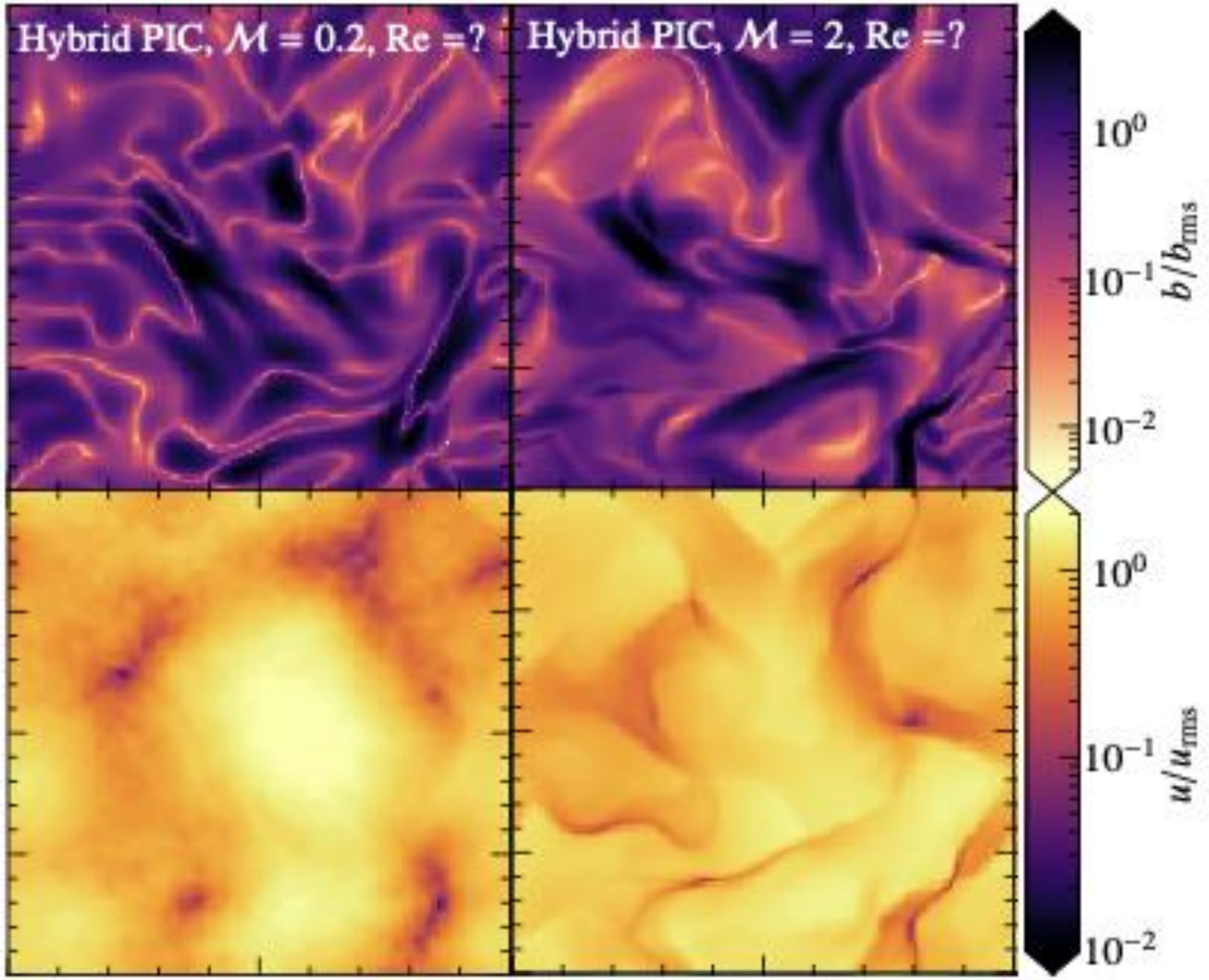
Magnetic field amplification in subsonic and supersonic plasma





Achikanath Chirakkara et al. 2024, In-prep

Conclusions & Future work

- Introducing **AHKASH : "A**strophysical **H**ybrid **K**inetic simulations with FL**ASH"**

- Boris integrator, predictor-predictor corrector method, constrained transport, wave and particle time-steps, hyper-resistivity, turbulence driving and a new cooling method for ions

- Understanding magnetic field amplification in collisionless plasma in the context of the Intracluster medium using **AHKASH**

- Features of plasma turbulence and magnetic field amplification can be different in the subsonic and supersonic regime

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