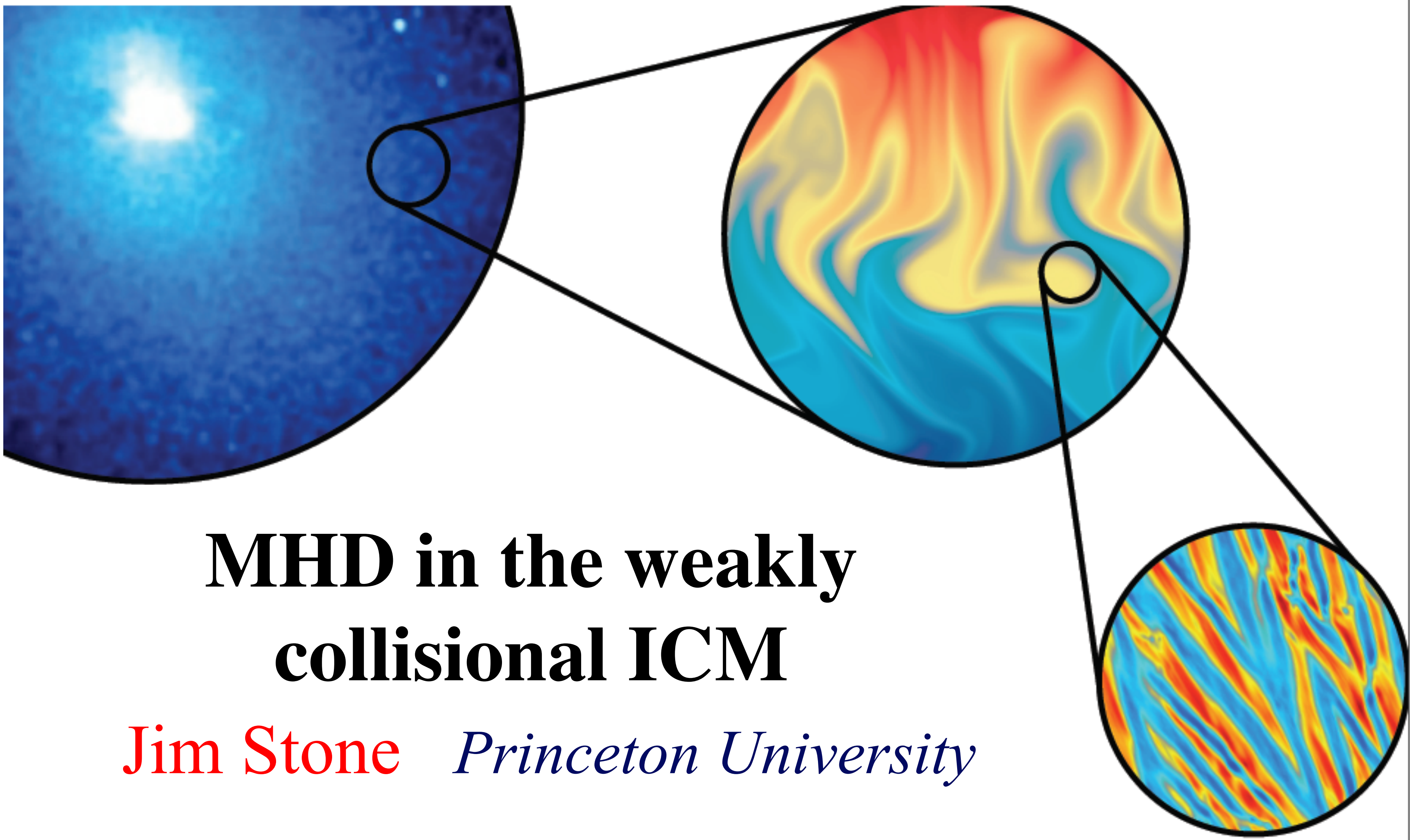


MHD in the weakly collisional ICM

Jim Stone *Princeton University*

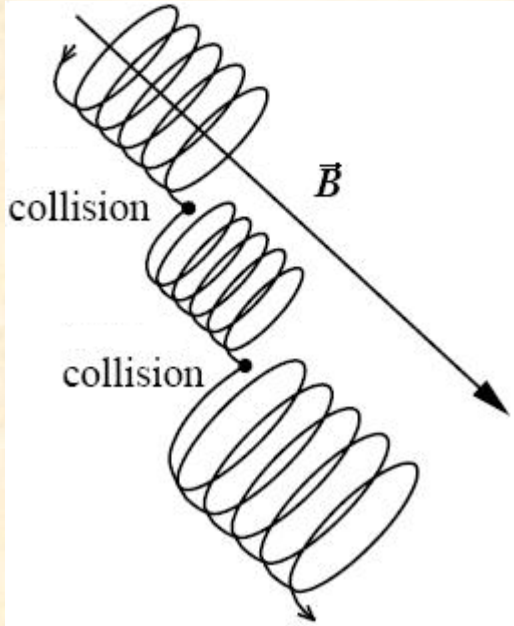
Work with: Matt Kunz, Stephanie Tonnesen, John ZuHone
Also: V. Biffi, M. Markevitch, A. Schekochihin

Image courtesy of Matt Kunz

Key properties of kinetic MHD.

Anisotropic transport coefficients when particle mean free path is much larger than gyro-radius.

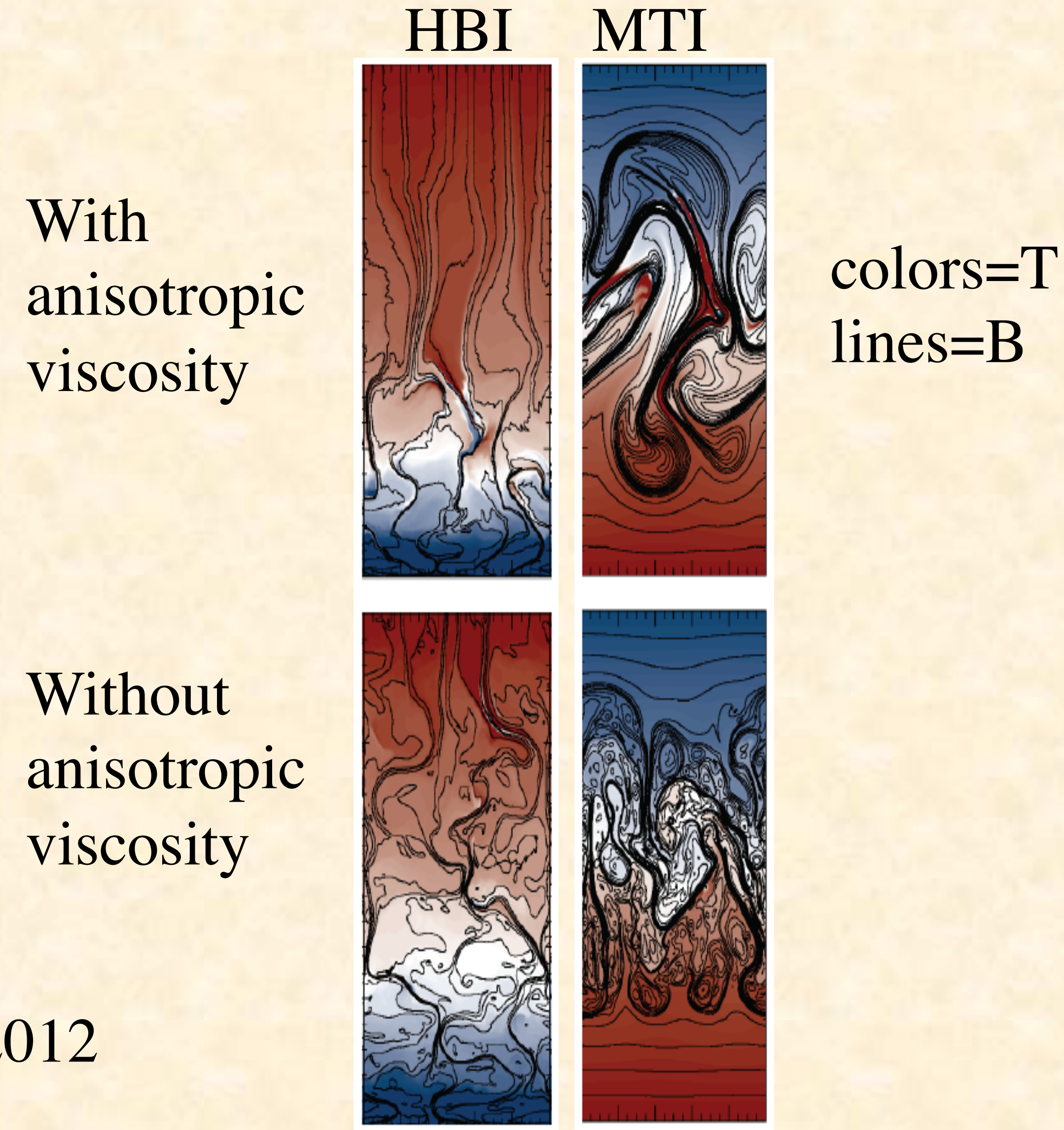
Both anisotropic conduction and viscosity can be important.



Microscopic instabilities (such as firehose and mirror) occur when pressure is anisotropic.

May tangle magnetic field on very small scales, produce particle scattering

New physics with anisotropic transport: MTI and HBI and kinetic MRI.



Kunz+ 2012; Parrish+ 2012

Important questions

- Are these instabilities important in the cosmological context?
  - McCourt et al. (2013)
  - e.g., see Ian Parrish's talk

- Can the effects of anisotropic transport be observed?
  - Effect on structures observed in cluster sloshing
  - MHD effects in ram pressure stripping

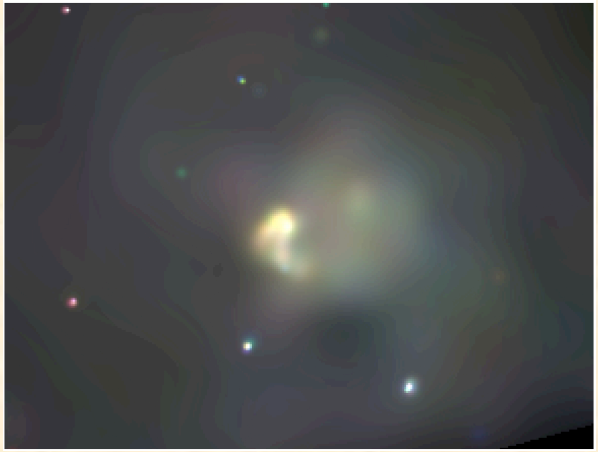
- What are the consequences of microscopic instabilities (firehose/mirror) on ICM dynamics?
  - *Ab initio* studies of saturation of firehose/mirror instabilities

Focus of this talk

1. Kinetic MHD simulations of sloshing in merging clusters.

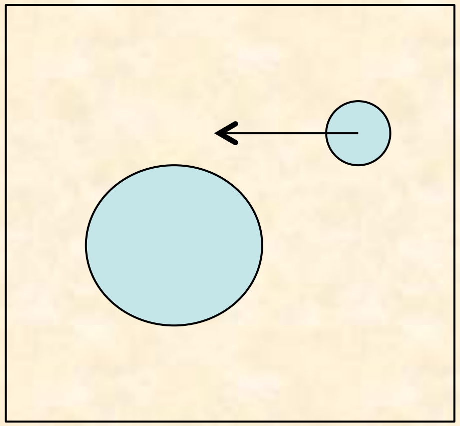
ZuHone+ 2014

Goal: investigate whether anisotropic transport affects structures (e.g. cold fronts) observed in merging clusters



Abell 1644

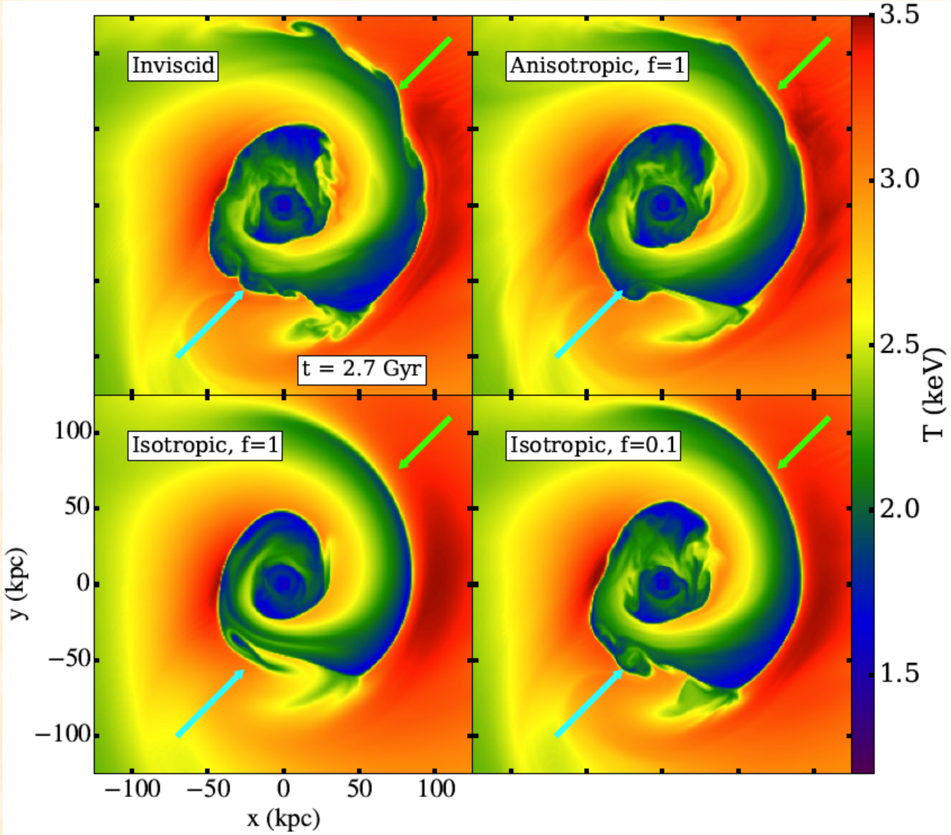
Method: Study idealized problem of two merging gravitationally bound spheres using MHD + Braginskii viscosity + anistropic conduction using Athena.



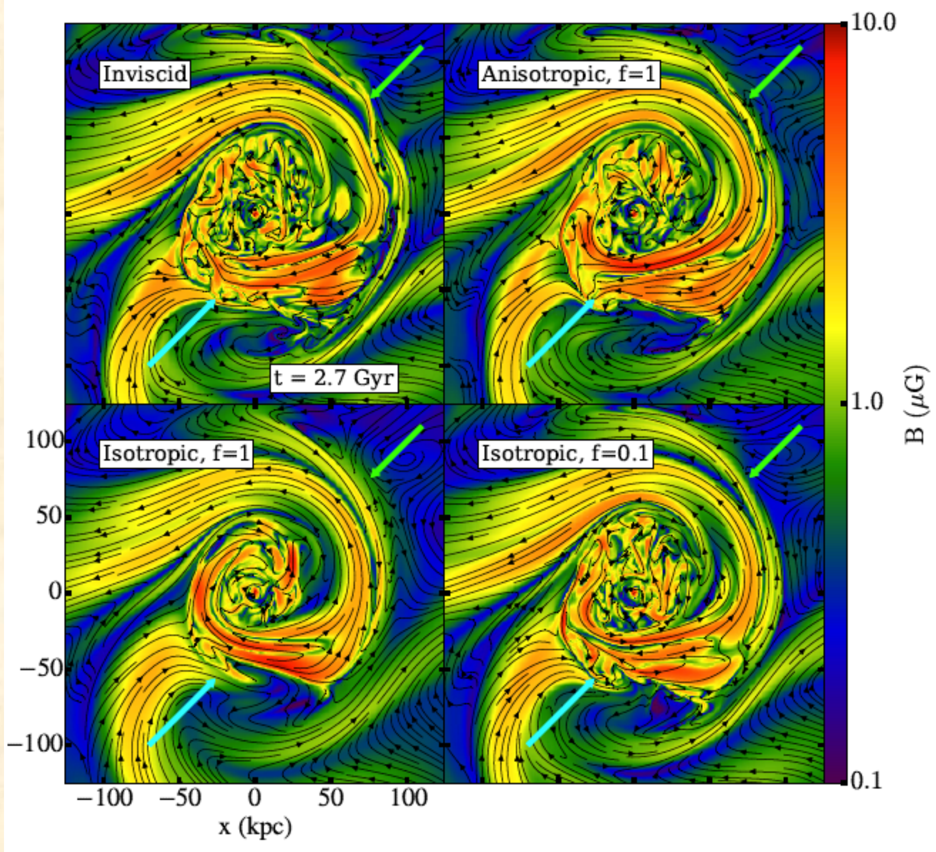
$M_{primary} = 10^{14} M_{sun}$
mass ratio = 0.1
Impact parameter = 100 kpc
4 levels of refinement, 256^3 per level, $\delta x = 1$ kpc
Tangled field, $\beta_0 = 1000$

Comparing physics using slices at 2.7Gyr

Temperature

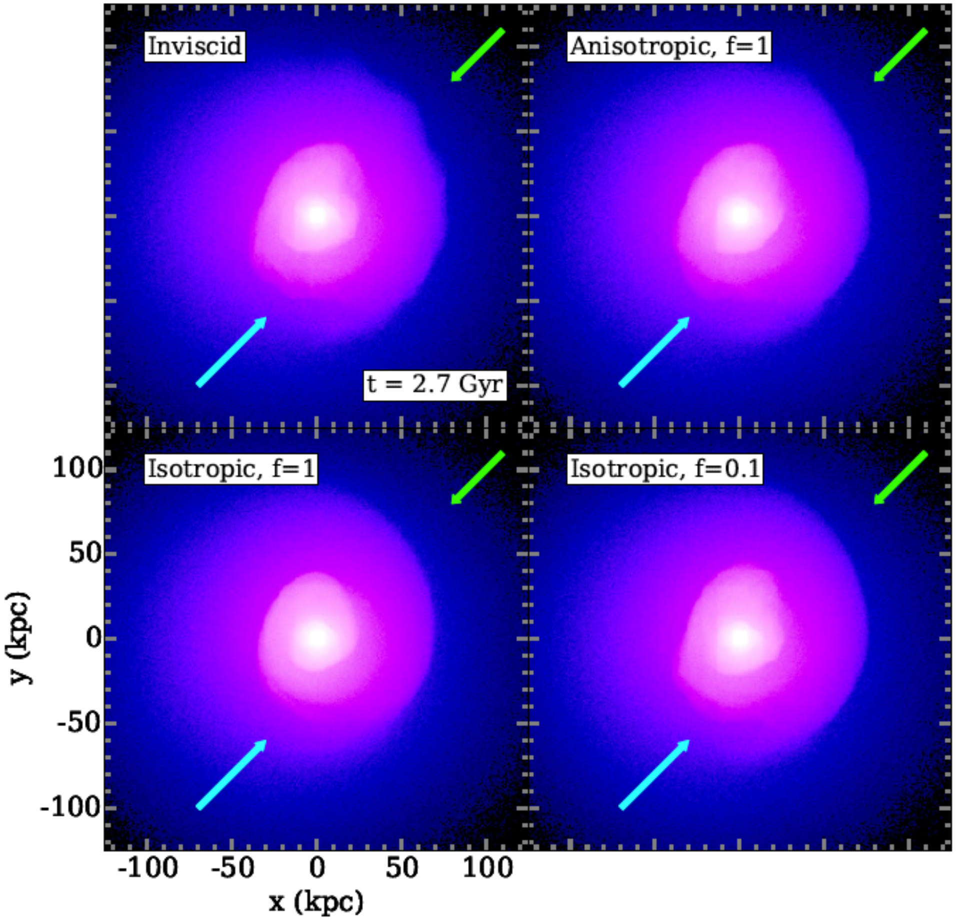


Magnetic field strength
(direction in-plane)

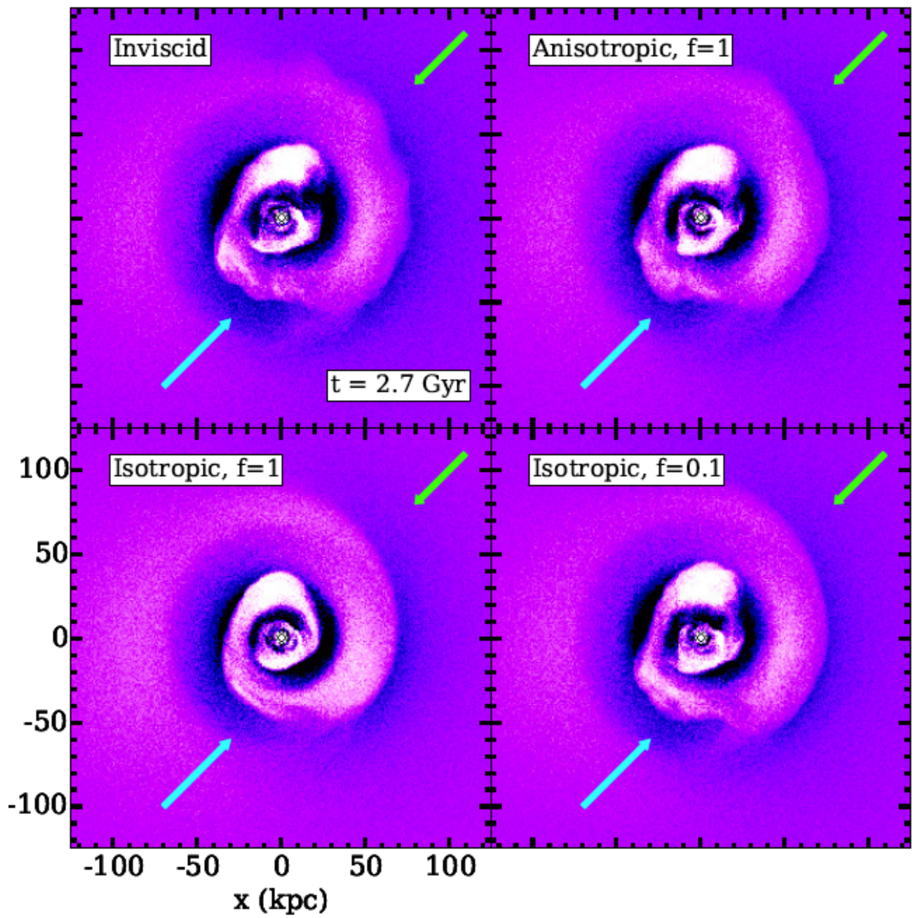


Isotropic transport strongly suppresses KH instability.

Comparing physics using emission at 2.7Gyr

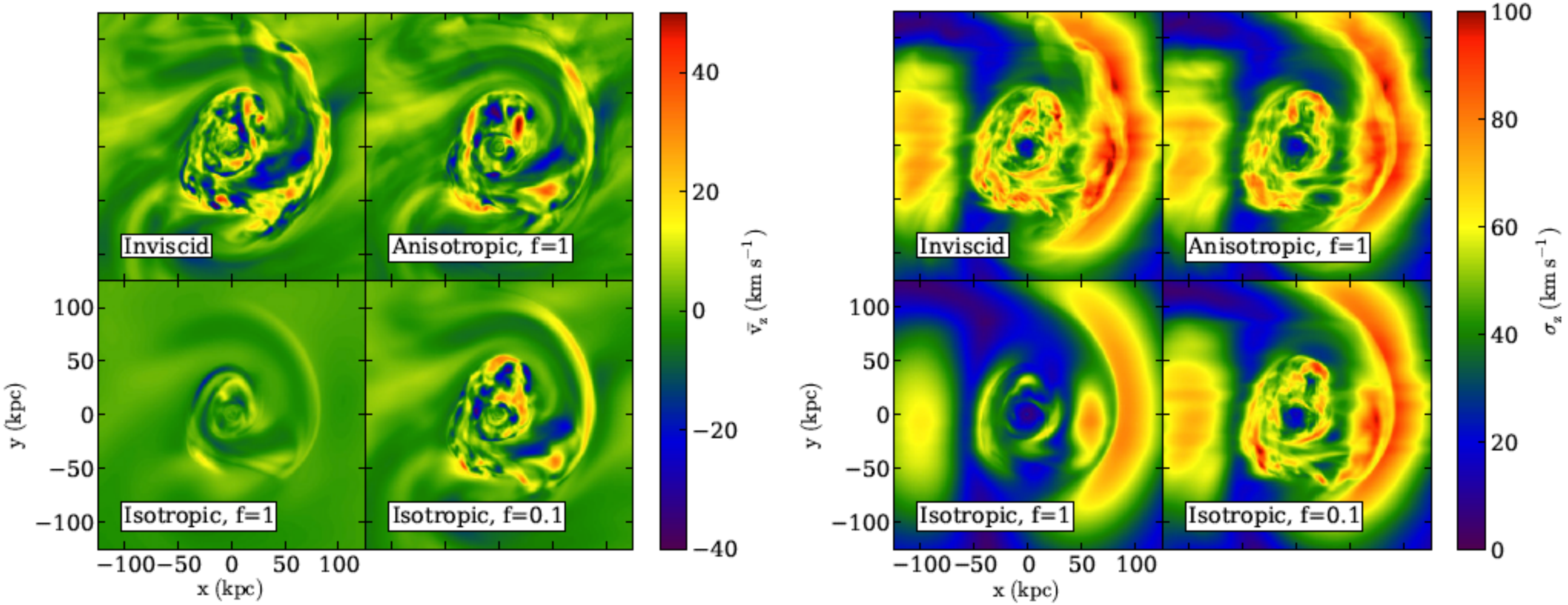


Synthetic X-ray emission, 300 ks exposure



Synthetic X-ray emission after subtracting spherically symmetric model

Comparing physics using kinematics at 2.7Gyr



Line-of-sight velocity

Velocity dispersion

Turbulence only weakly suppressed by anisotropic viscosity.

Summary of sloshing simulations

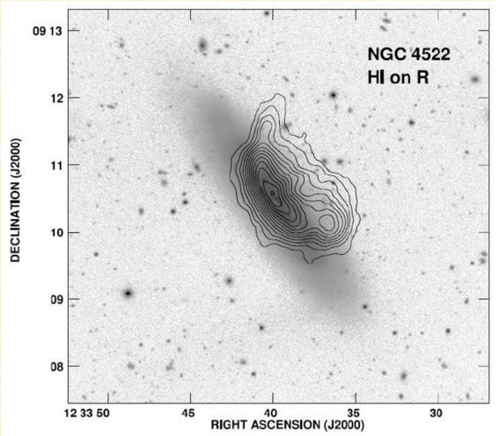
- Either anisotropic (Braginskii) or reduced Spitzer transport best matches observed structures.

- But distinguishing between these two possibilities is difficult.

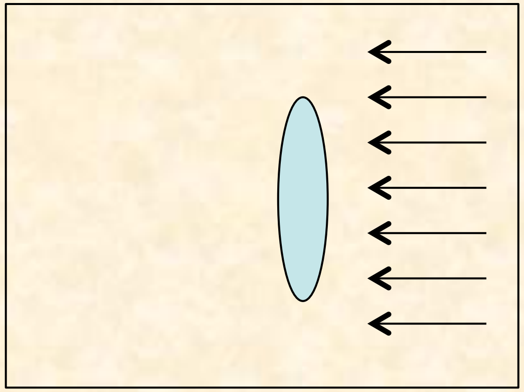
2. MHD simulations of ram pressure stripping

Tonnesen & Stone (2014)

Goal: can we find unique signatures of MHD in HI tails in galaxies undergoing ram pressure stripping by the ICM?



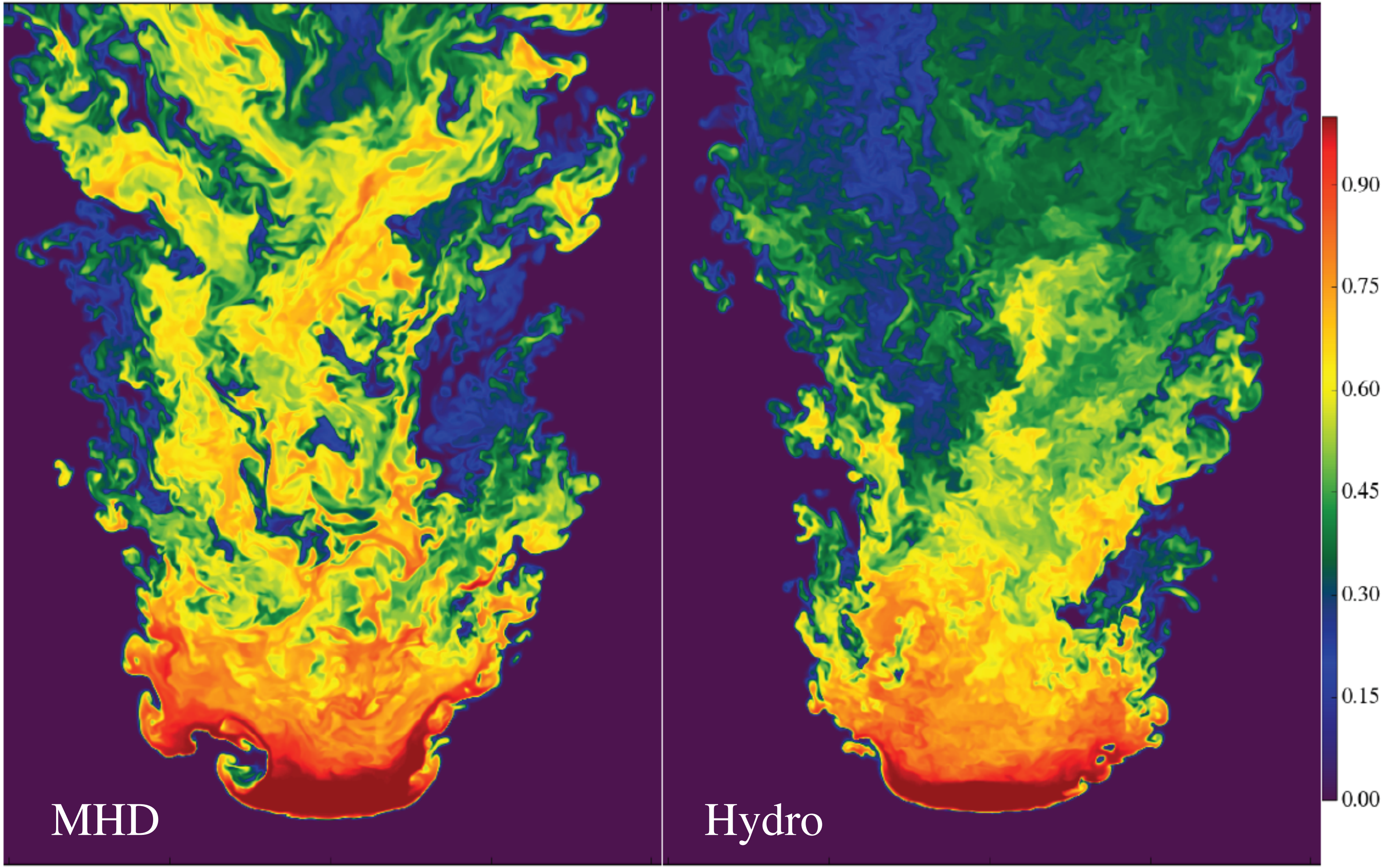
Method: compare tails produced by hydro versus MHD simulations of ram pressure stripping using Athena (no kinetic effects yet)



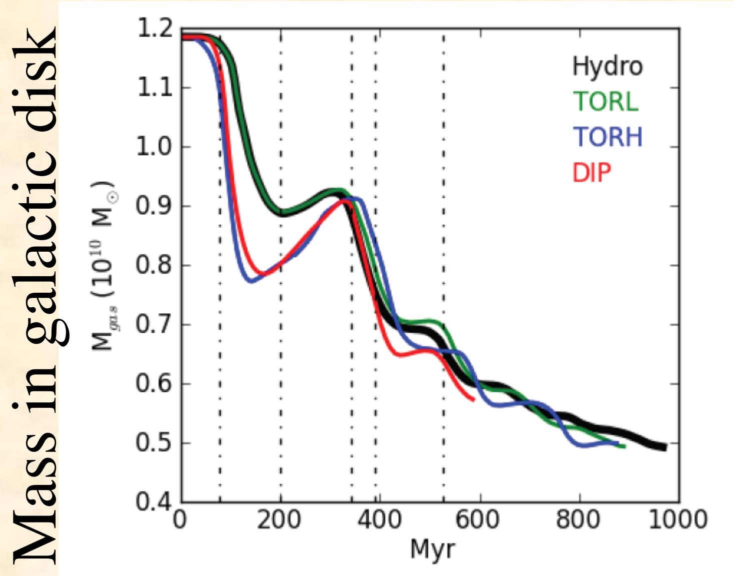
Fixed stellar and dark matter potential
Uniform toroidal or dipolar magnetic field
Uniform unmagnetized ICM wind
160 kpc box, resolution 0.16 kpc (~1000^3 cells)

See also Ruszkowski+ 2012; Pfrommer & Dursi 2010

MHD versus hydro at 750Myr

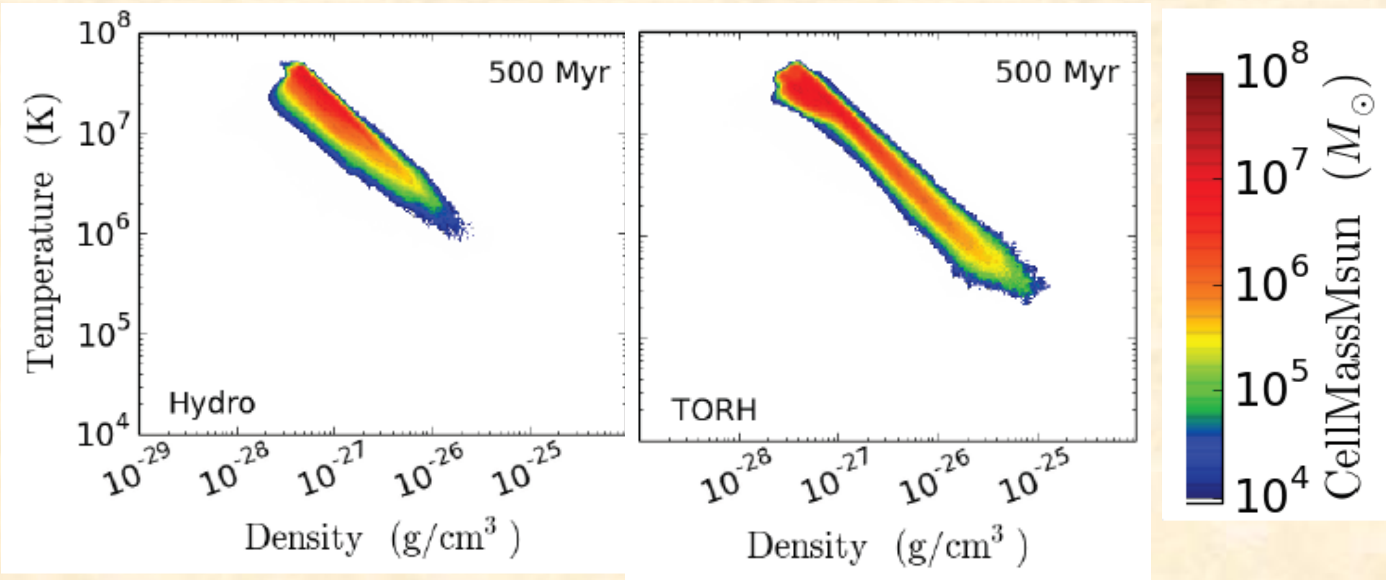


Passive contaminant showing gas originating in galaxy.

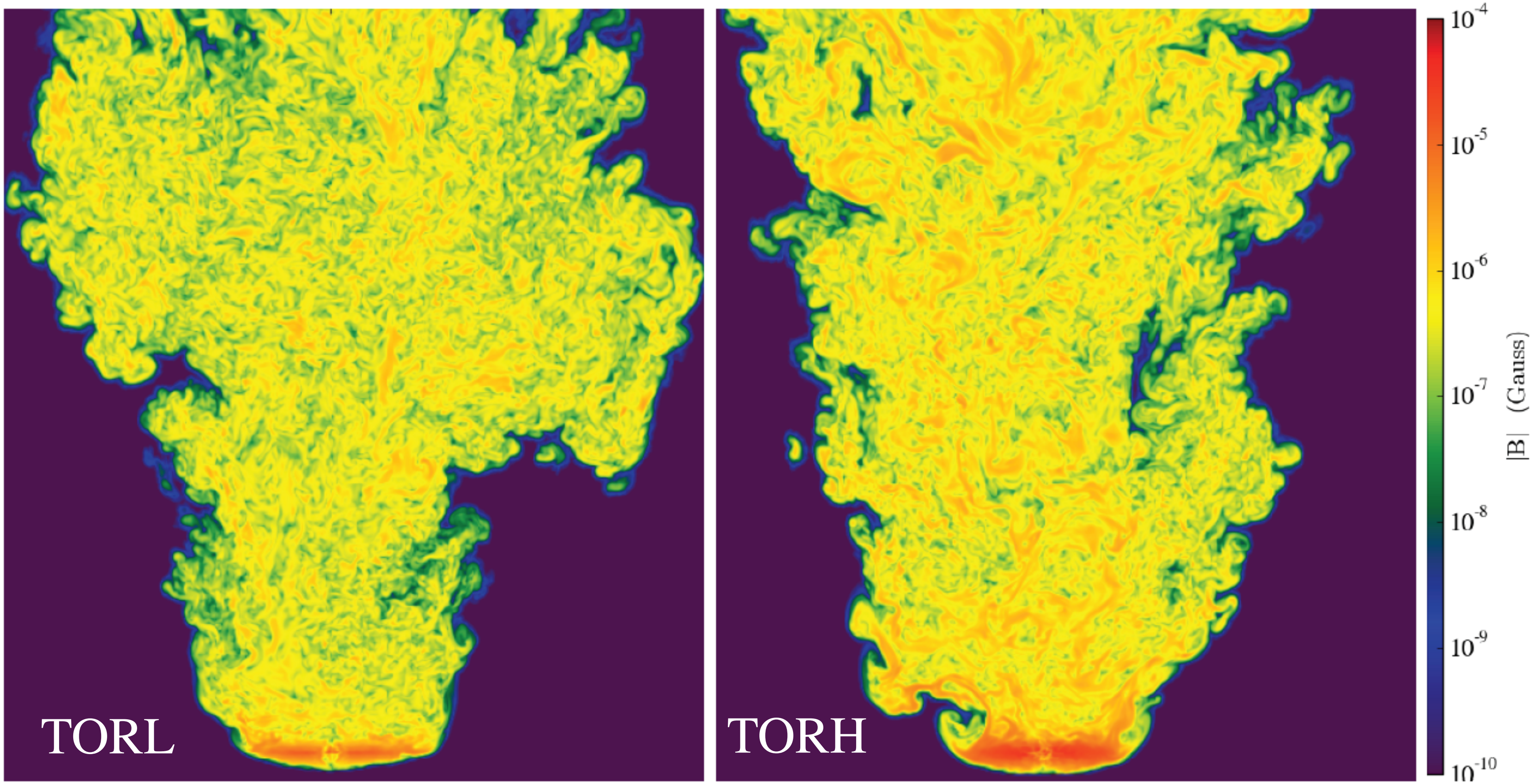


Mass stripping rate is little changed in MHD compared to hydro.

But detailed structure of gas in tail is changed, based on comparing mass at given density and temperature.



Significant magnetic field in tail



Magnetic energy grows to 10^{56} ergs, average field 0.3-0.6 μG

Stripping may contribute to magnetization of ICM

Summary of MHD ram-pressure stripping results.

- Little difference in total amount of mass stripped from galaxy between MHD and hydro

- Magnetic fields lead to less mixing in the tail

- Stripping leads to μG fields throughout the tail, and may contribute to magnetization of the ICM

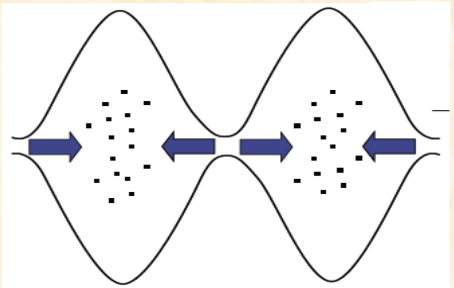
Future simulations will include anisotropic transport to investigate whether measurable differences occur in properties of tail compared to ideal MHD.

3. Saturation of firehose and mirror instabilities

Goal: Perform *ab initio* simulations of firehose and mirror instabilities to investigate saturation mechanism, and whether they tangle field on small scales and thereby suppress transport.

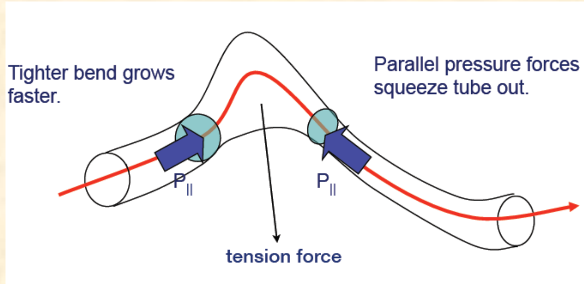
mirror

$$p_\perp - p_\parallel \geq \frac{B^2}{8\pi}$$

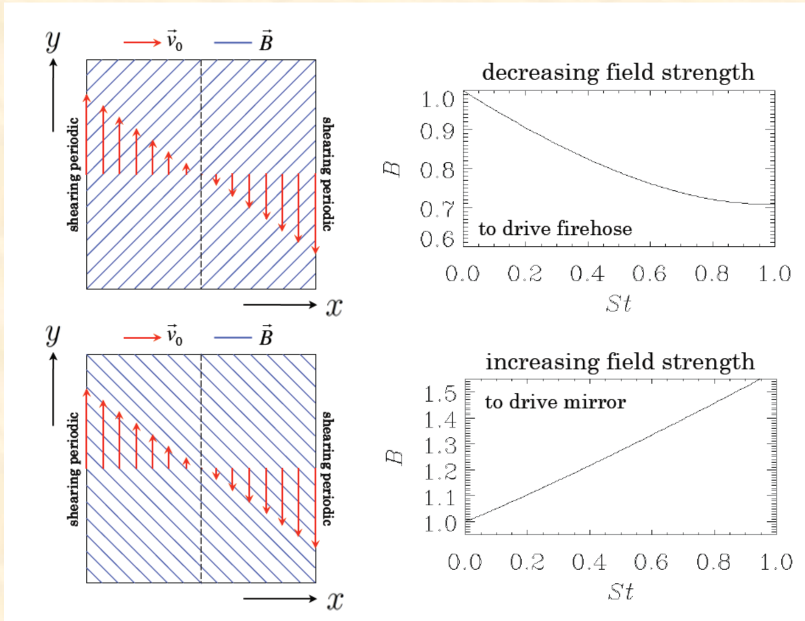


firehose

$$p_\parallel - p_\perp \geq \frac{B^2}{4\pi}$$



Method: 2D hybrid PIC simulations in the shearing box approximation



Method: hybrid particle-in-cell (PIC)

kinetic ions: $$\left(\frac{\partial}{\partial t} - Sx\frac{\partial}{\partial y}\right) f_{\rm i} + \boldsymbol{v}\boldsymbol{\cdot}\boldsymbol{\nabla} f_{\rm i} + \left[\frac{Ze}{m_{\rm i}}\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right) + Sv_x\hat{\boldsymbol{y}}\right]\boldsymbol{\cdot}\frac{\partial f_{\rm i}}{\partial \boldsymbol{v}} = 0$$

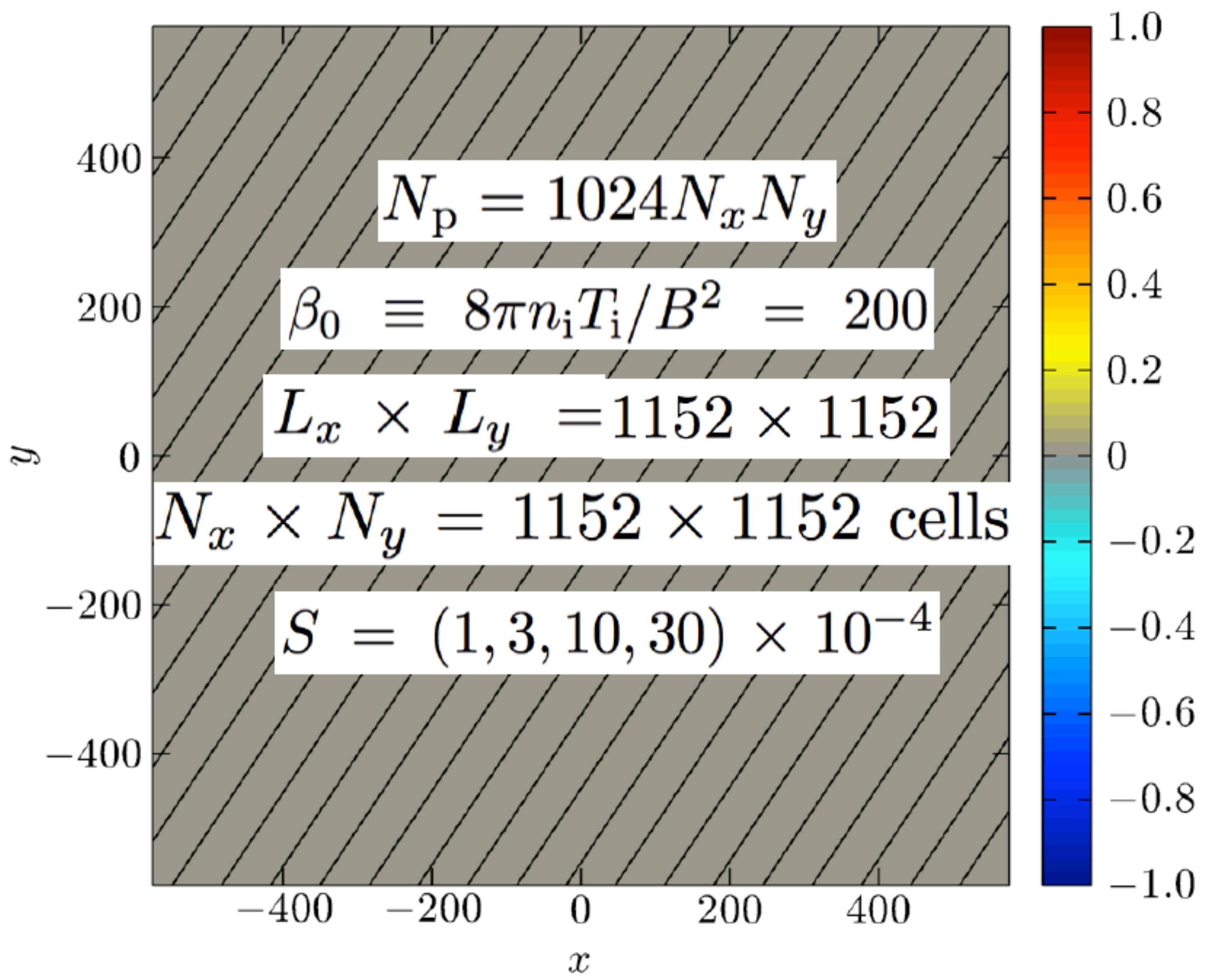
Faraday: $$\left(\frac{\partial}{\partial t} - Sx\frac{\partial}{\partial y}\right)\boldsymbol{B} = -c\boldsymbol{\nabla}\times\boldsymbol{E} - SB_x\hat{\boldsymbol{y}}$$

massless fluid electrons: $$\boldsymbol{E} = -\frac{\boldsymbol{u}_{\rm i}\times\boldsymbol{B}}{c} + \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi Zen_{\rm i}} - \frac{T_{\rm e}\boldsymbol{\nabla}n_{\rm i}}{en_{\rm i}}$$

Integrate using **Pegasus** (Kunz et al, JCP 2014), built within Athena

- Symplectic, 2^{nd}-order integrator for ions
- CT for magnetic field
- δf or full-f methods
- Shearing box with orbital advection
- Efficient: 1 μs per particle-push, 90% efficiency on 4000 cores.

Evolution of firehose instability



$$N_{\mathrm{p}} = 1024 N_x N_y$$

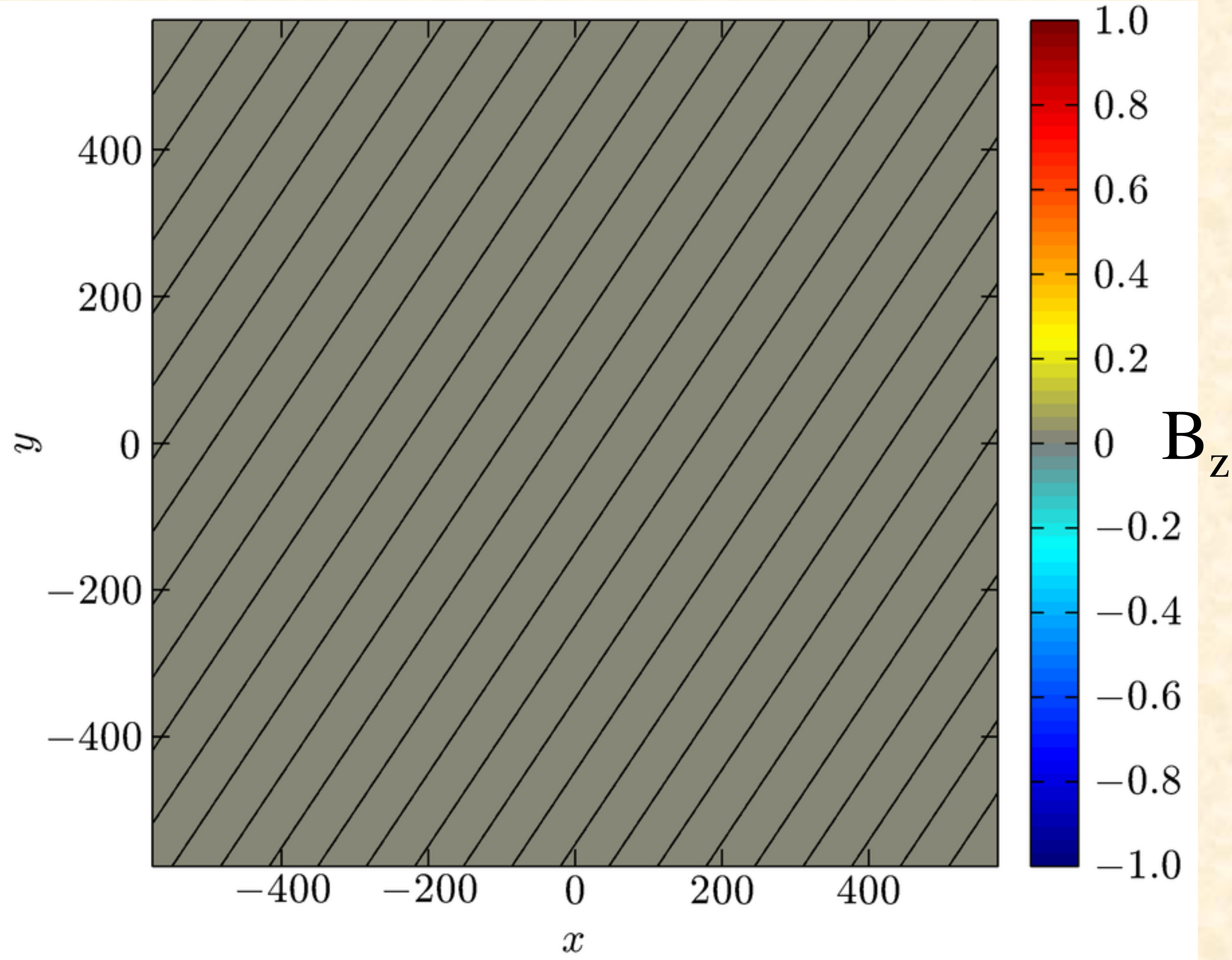
$$\beta_0 \equiv 8\pi n_{\mathrm{i}} T_{\mathrm{i}} / B^2 = 200$$

$$L_x \times L_y = 1152 \times 1152$$

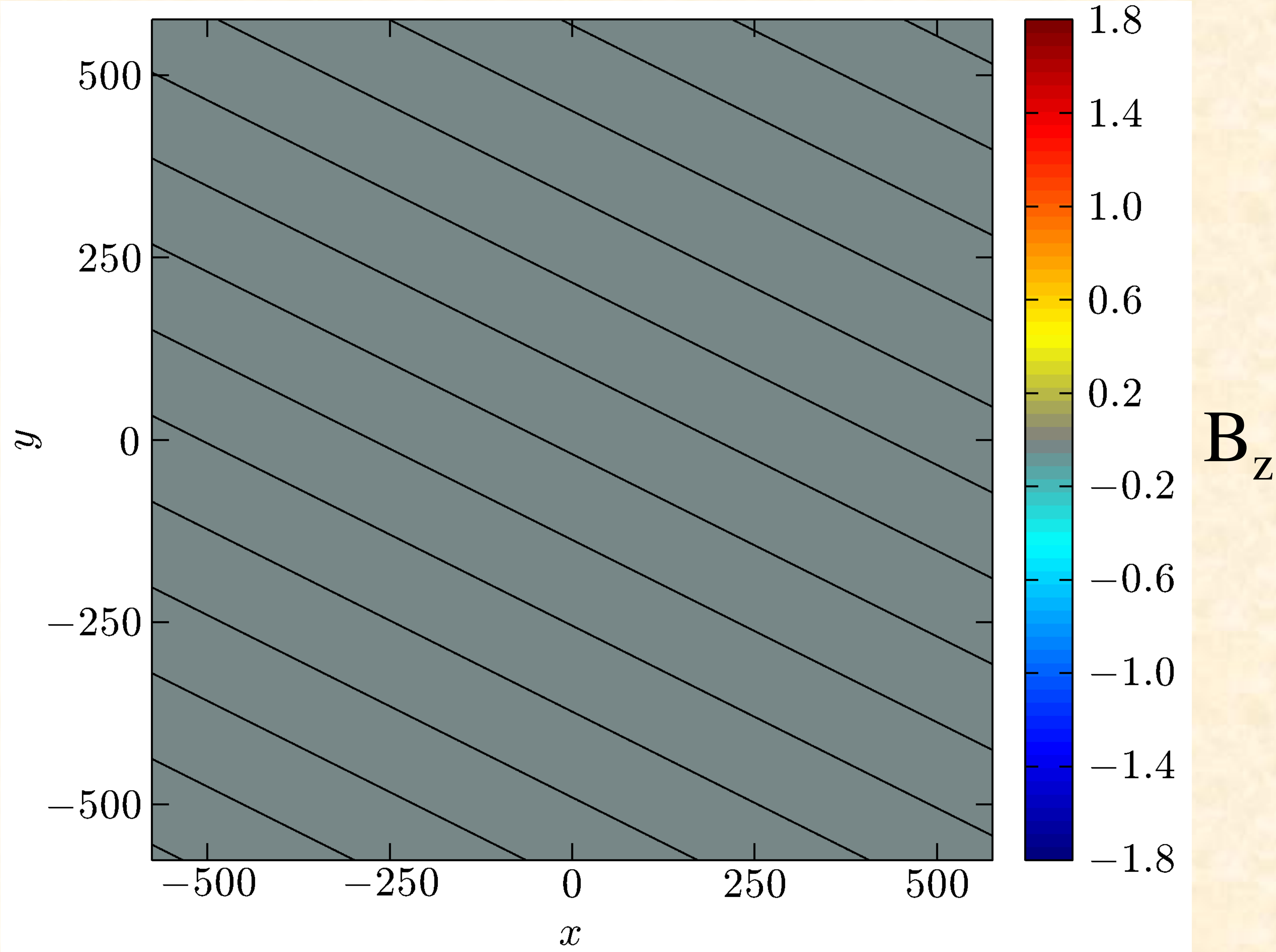
$$N_x \times N_y = 1152 \times 1152 \text{ cells}$$

$$S = (1, 3, 10, 30) \times 10^{-4}$$

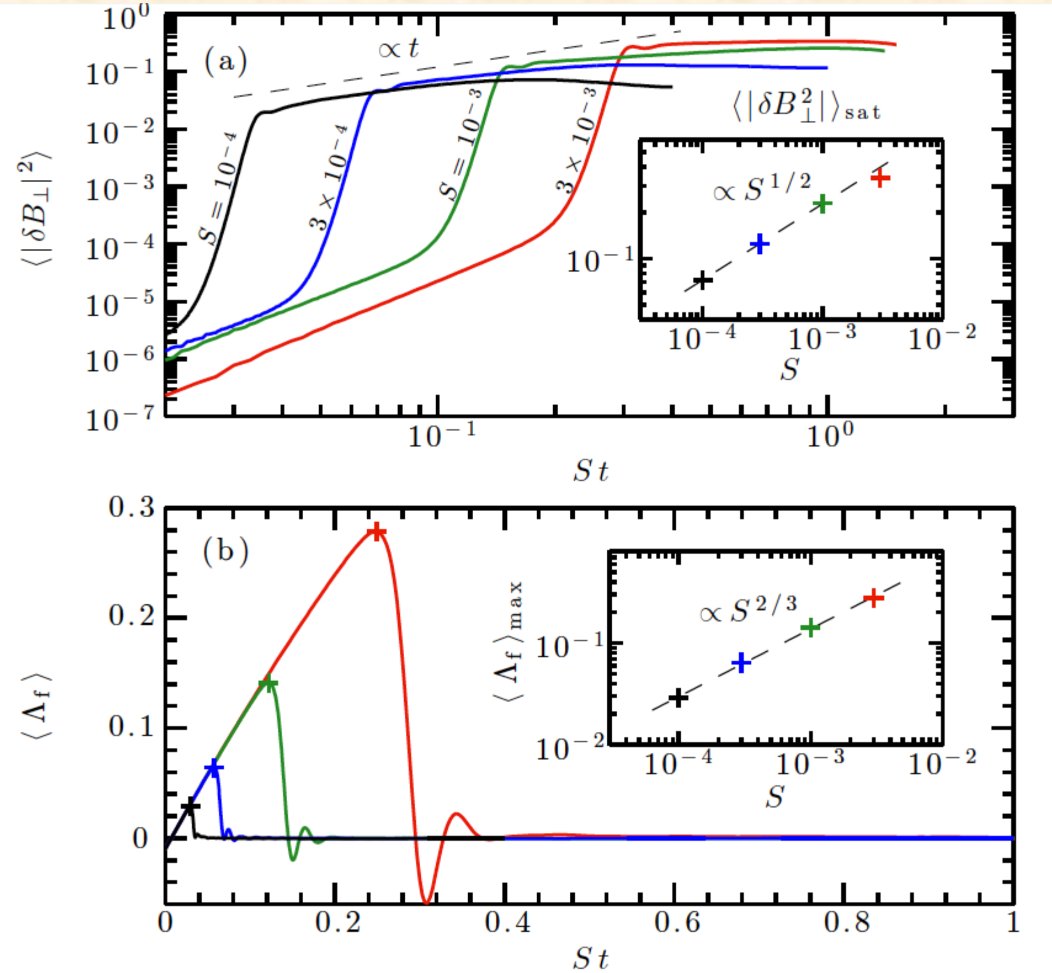
Evolution of firehose instability



Evolution of mirror instability



Firehose: three stages of evolution.



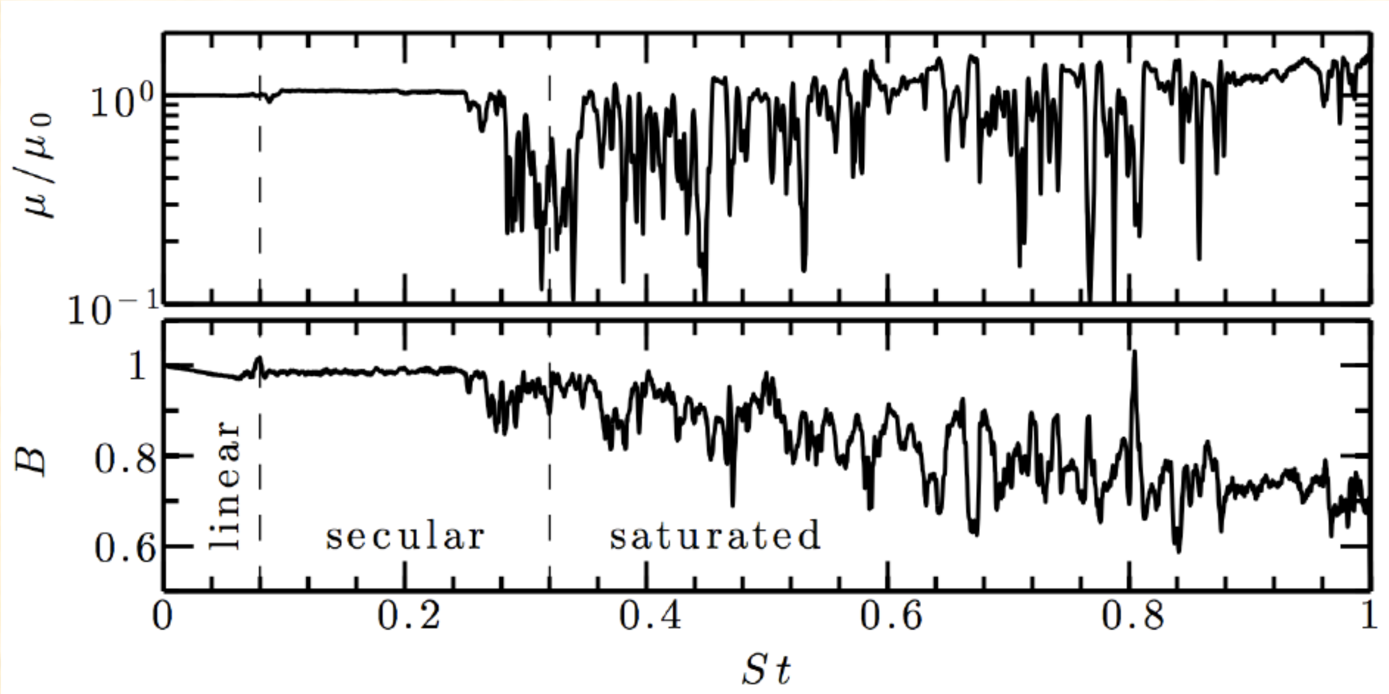
$$\Lambda_f \equiv 1 - p_\perp/p_\parallel - 2/\beta_\parallel$$

Exponential growth of oblique modes, with stability parameter increasing

Secular growth, with stability parameter pinned at marginal (Schekochihin et al 2005; Rosin et al 2011)

Saturation as firehose turbulence, with stability parameter pinned at marginal

At saturation, scattering breaks μ conservation



Pressure anisotropy in saturated state of firehose turbulence is regulated by scattering – suggests subgrid model

Similar analysis shows saturation of mirror regulated by particle trapping in regions where dlnB/dt ~ 0 – subgrid model more difficult

Final Summary

The Effect of Anisotropic Viscosity on Cold Fronts in Galaxy Clusters
ZuHone, Kunz, Markevitch, Stone, & Biffi, ApJ, (submitted)

- Reduced viscosity and conduction are required to match data
- It is difficult to distinguish between Braginskii versus reduced Spitzer transport

Galactic Magnetic Fields and ram Pressure Stripping.
Tonnesen & Stone, ApJ, (submitted)

- Magnetic fields produce less mixing in tails
- Stripping may contribute to magnetization of ICM

Firehose and Mirror Instabilities in a Collisionless Shearing Plasma
Kunz, Schekochihin, & Stone, PRL (2014)

- Saturation of firehose by particle scattering
- Saturation of mirror by particle trapping