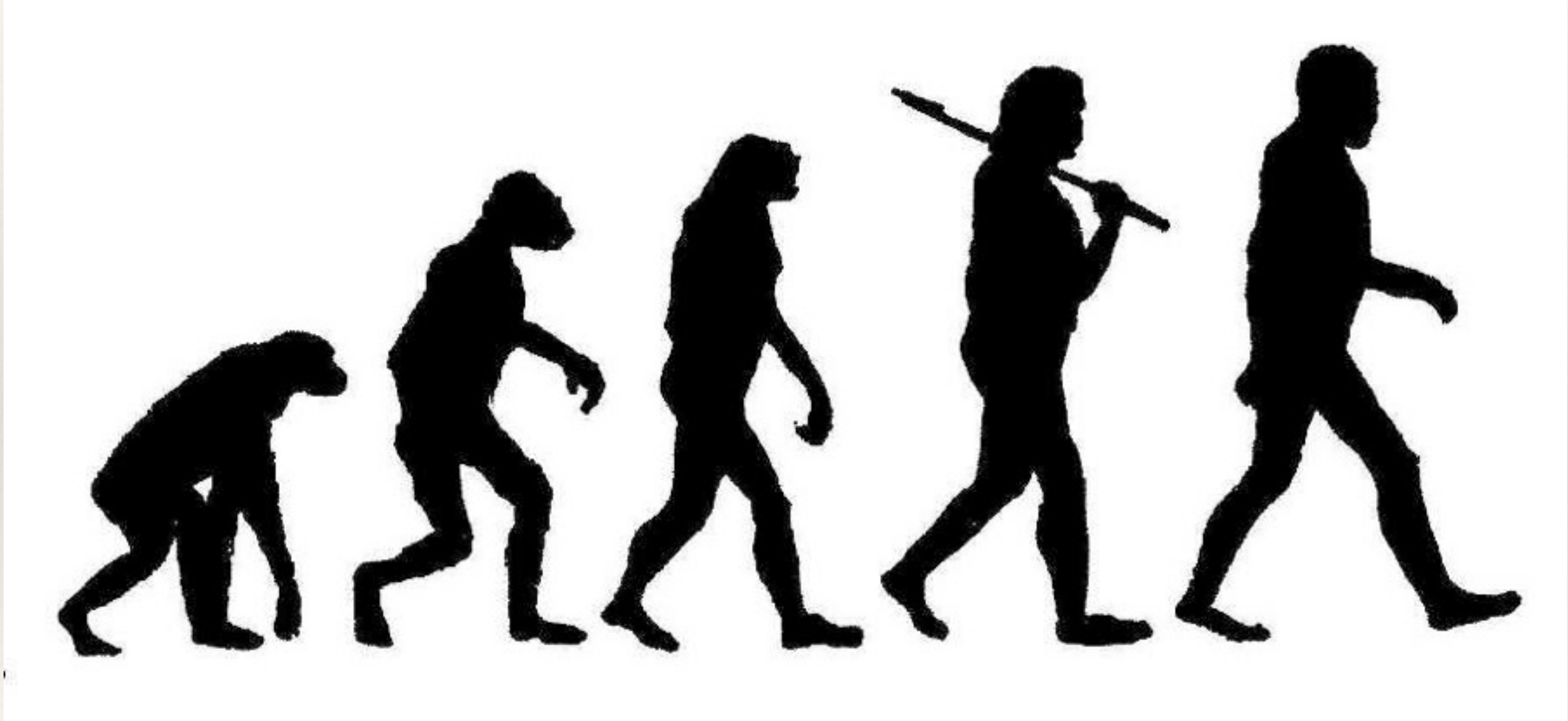
# Why study the CGM?

I: It's easier than galaxies…



| IGM | CGM | Galaxies |
|---|---|---|
| Essentially no subgrid physics | Harder: B-fields, cosmic rays, multi-phase … | Hard! |

# Why study the CGM?

II: it tells us what the galaxy is up to …


Inflow

Outflow

Understanding cycle of warm, T ~ 10^4 K gas is particularly critical

Fuel for star formation

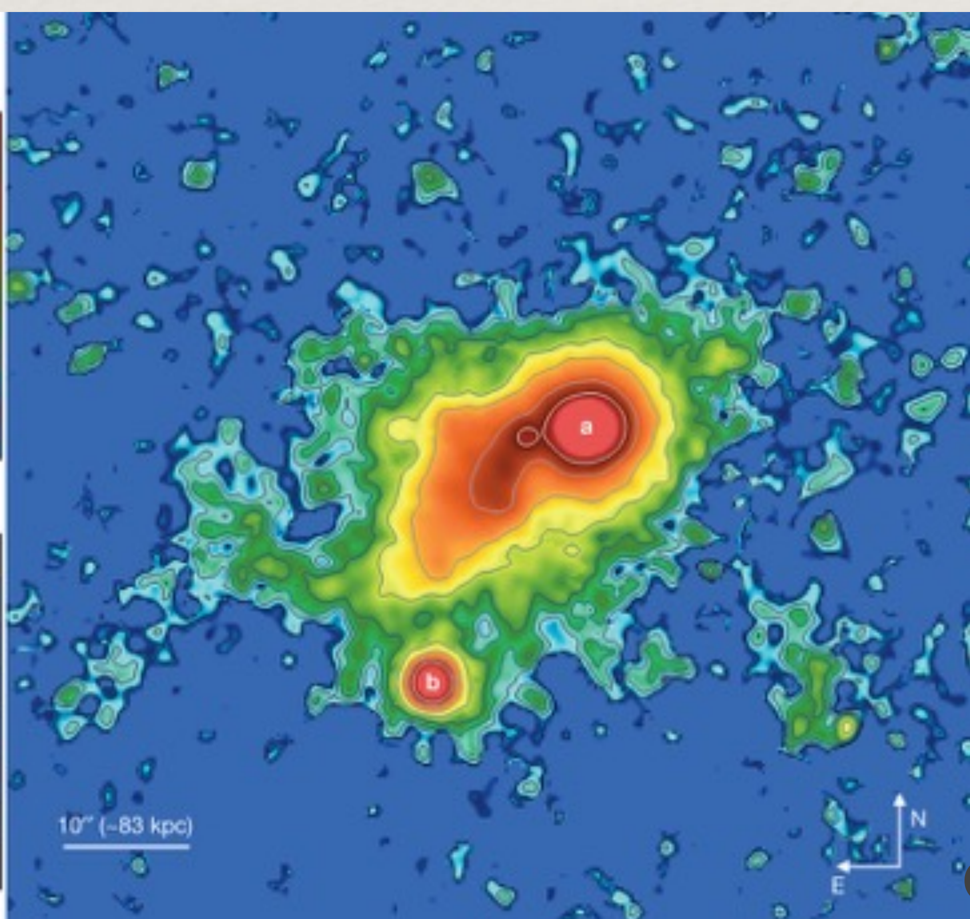
Tracer of galactic winds

III. Now lots of data (esp COS) to compare against

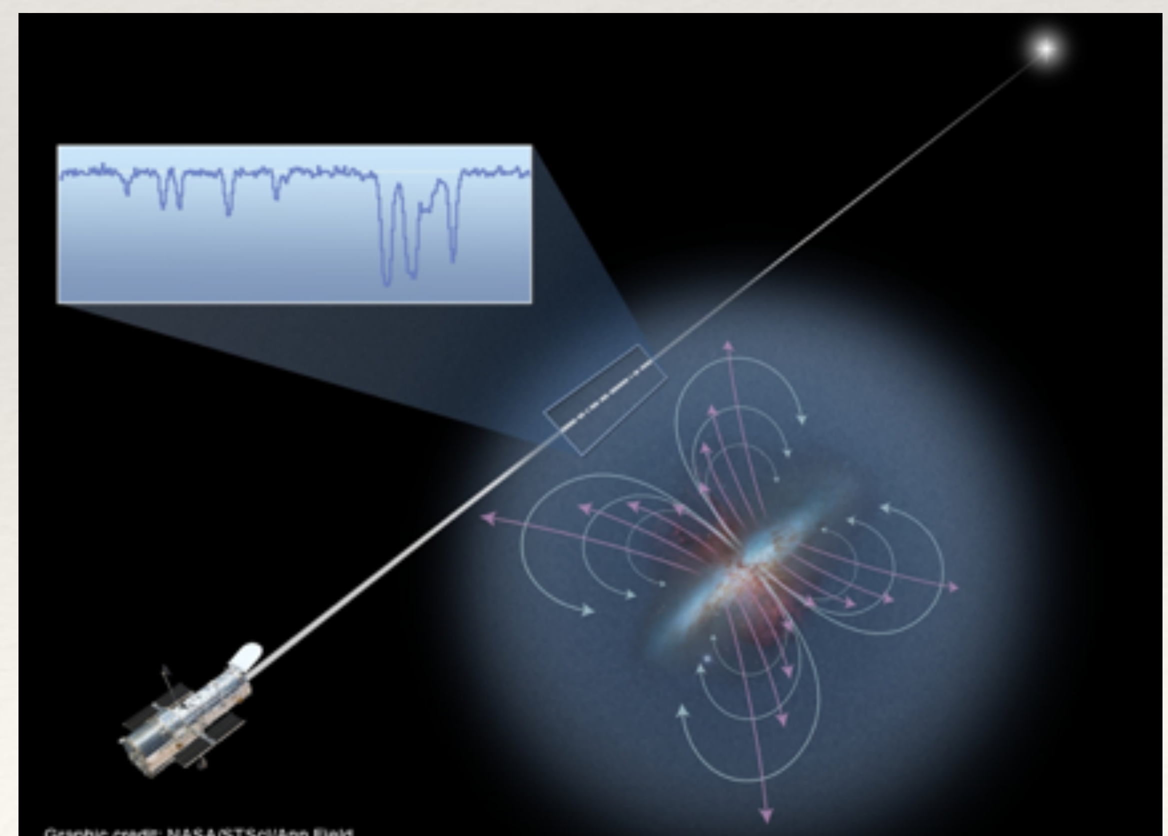
# Key question: life cycle of warm gas

Hard to see hot gas via X-ray or SZ — at best, have to stack

See cold gas via quasar spectroscopy + Ly-alpha fluorescence— best probe of CGM




Cantalupo et al 2014



# Today's menu


Make it How does warm gas form?
Via thermal instability?
How do B-fields change thermal instability?

Shake it How do hydrodynamic instabilities sculpt the gas?

Is there a characteristic lengthscale?

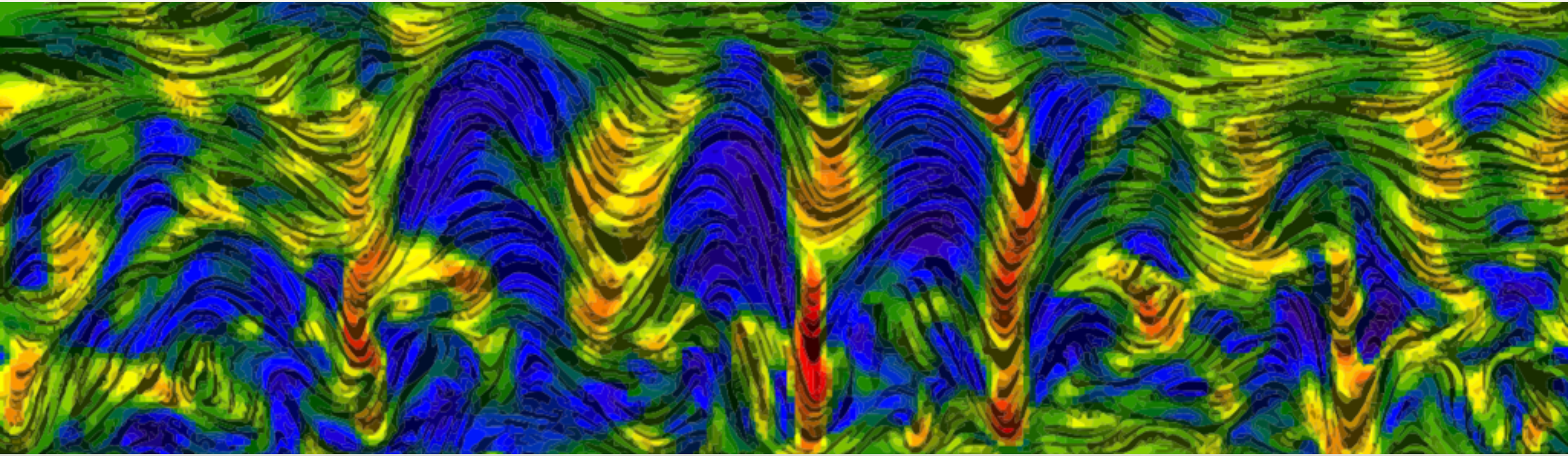
Can resonant radiative line transfer probe this?

~~Bake it~~ ~~What pushes and heats the gas?~~

~~What is the effect of non-thermal processes like cosmic rays?~~

Approach: few ingredient meals, not gourmet

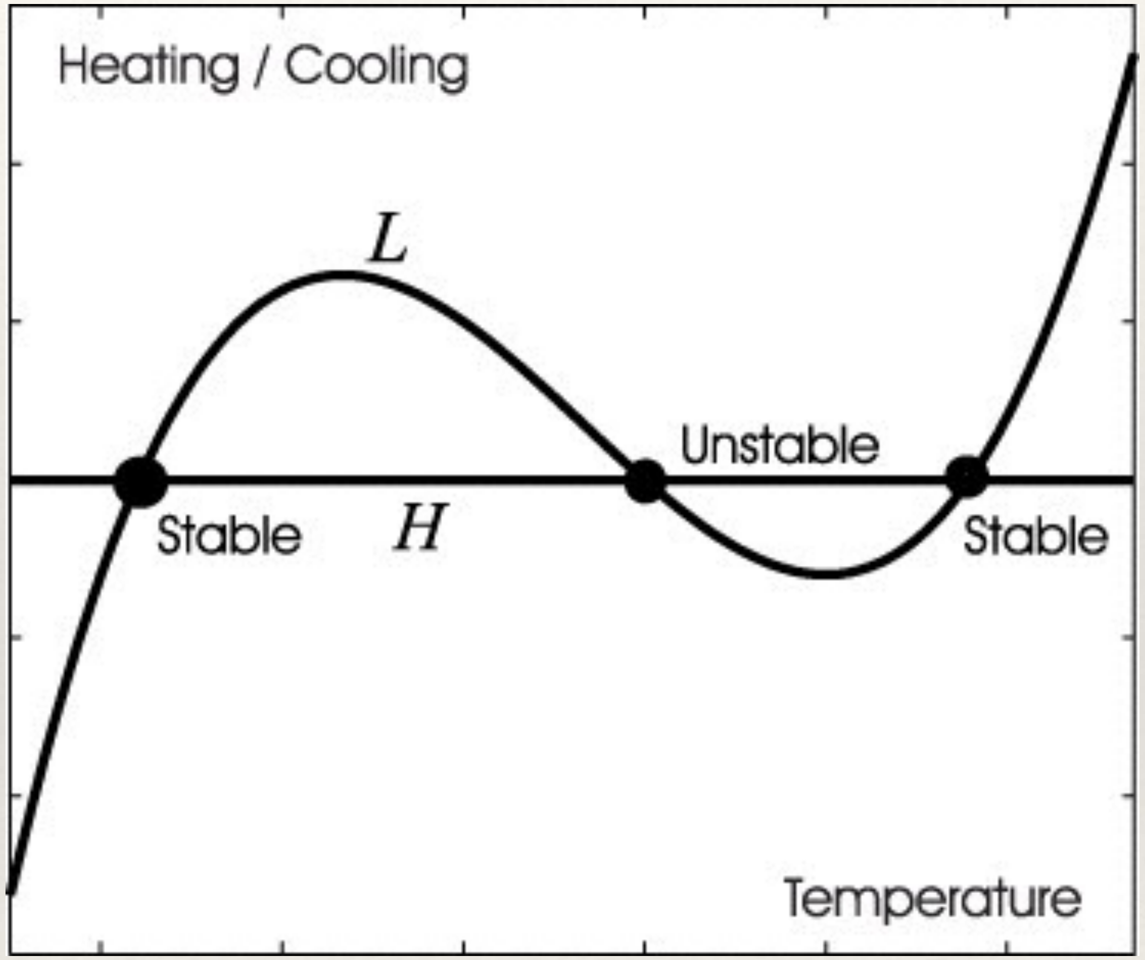
# Make it: Thermal Instability with B-fields



Ji, Oh, McCourt, 2017, in prep

# Where does the warm gas come from?

Exported from the galaxy?




Made in-house?

Focus on thermal instability

# Thermal instability in stratified medium

Long thought that

Thermally unstable $\Longleftrightarrow$ Unstable to convection

THEORY OF LOCAL THERMAL INSTABILITY IN SPHERICAL SYSTEMS

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ABSTRACT

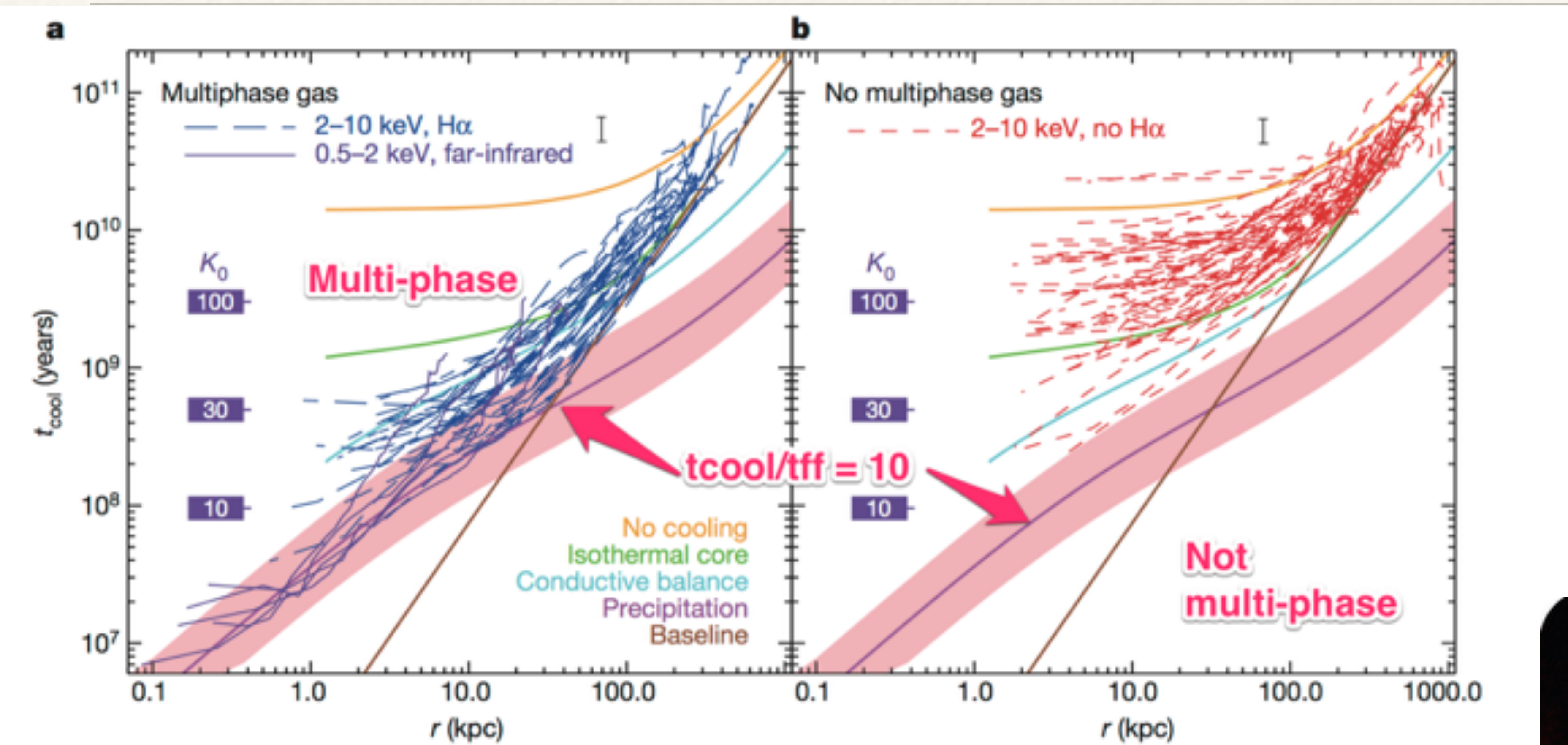
We have reexamined the nature of local thermal instability in static and dynamical media described by an equilibrium cooling function. Several new results have been found. In a medium characterized by both thermal and hydrostatic equilibrium, if the cooling function is not an explicit function of position and does not display isentropic thermal instability (i.e., sound waves are thermally stable), then isobaric thermal instability by the Field criterion is present if and only if convective instability is present by the Schwarzschild criterion. In this case, thermal overstability cannot occur. An explicit spatial dependence in … h to alter this conclusion would also ensure that either classical convective i … a- bility must be present. Convective instability by the Schwarzschild crit… n

mention that 'read the fine print'! — heating explicit function of position with AGN heating

also mention factor of 10 for spherical

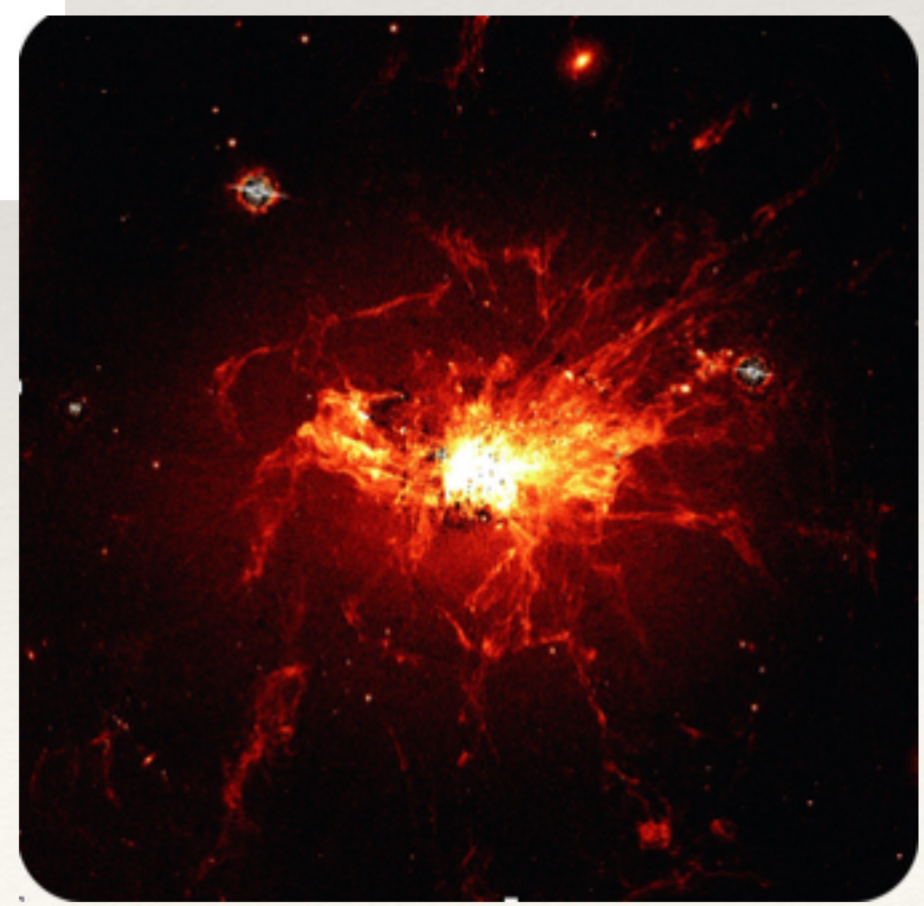
McCourt et al 2012: $\frac{t_{\rm cool}}{t_{\rm ff}} < 1 \Rightarrow$ thermal instability

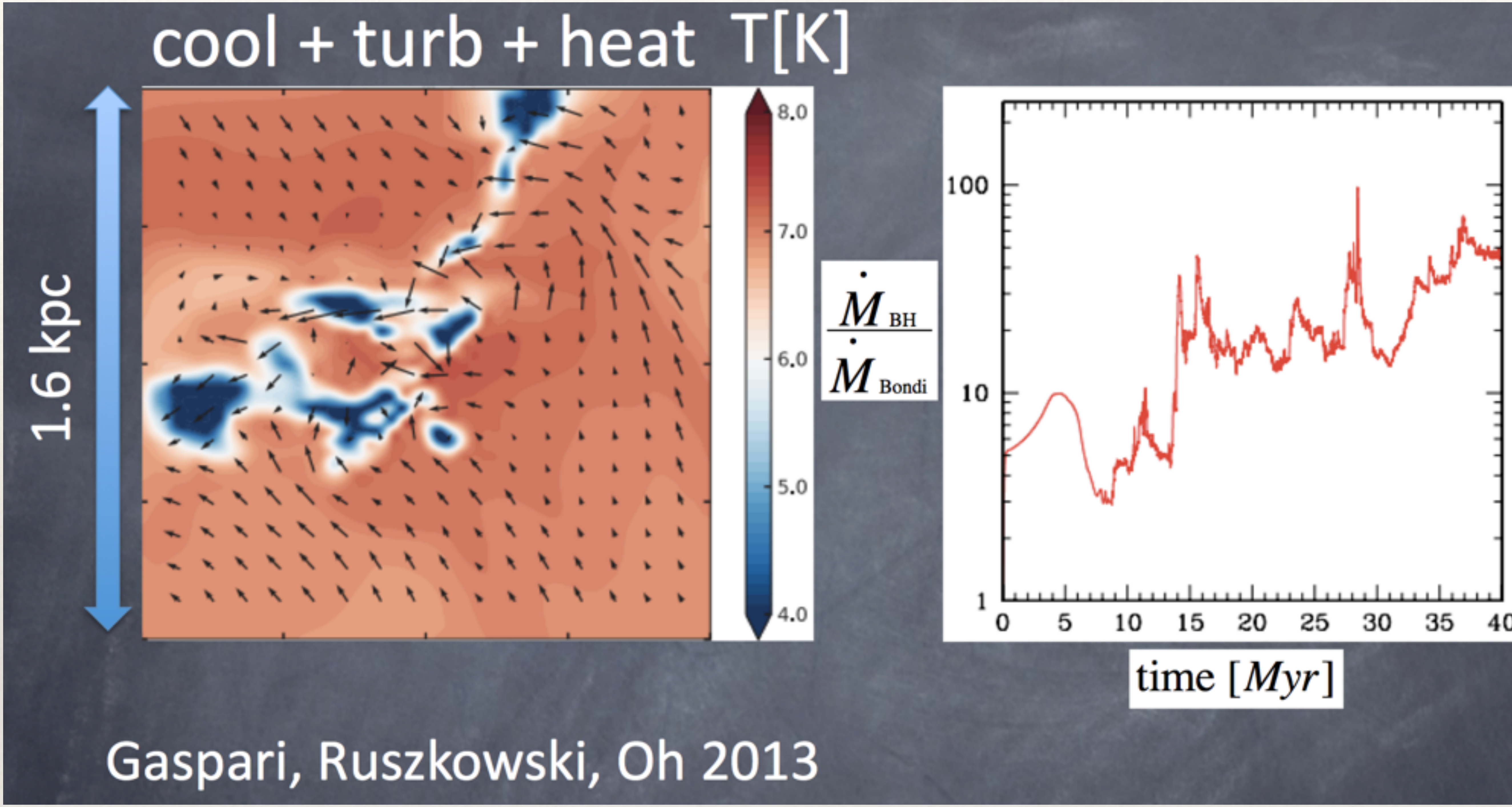
# Important in many environments!




Voit et al 2015

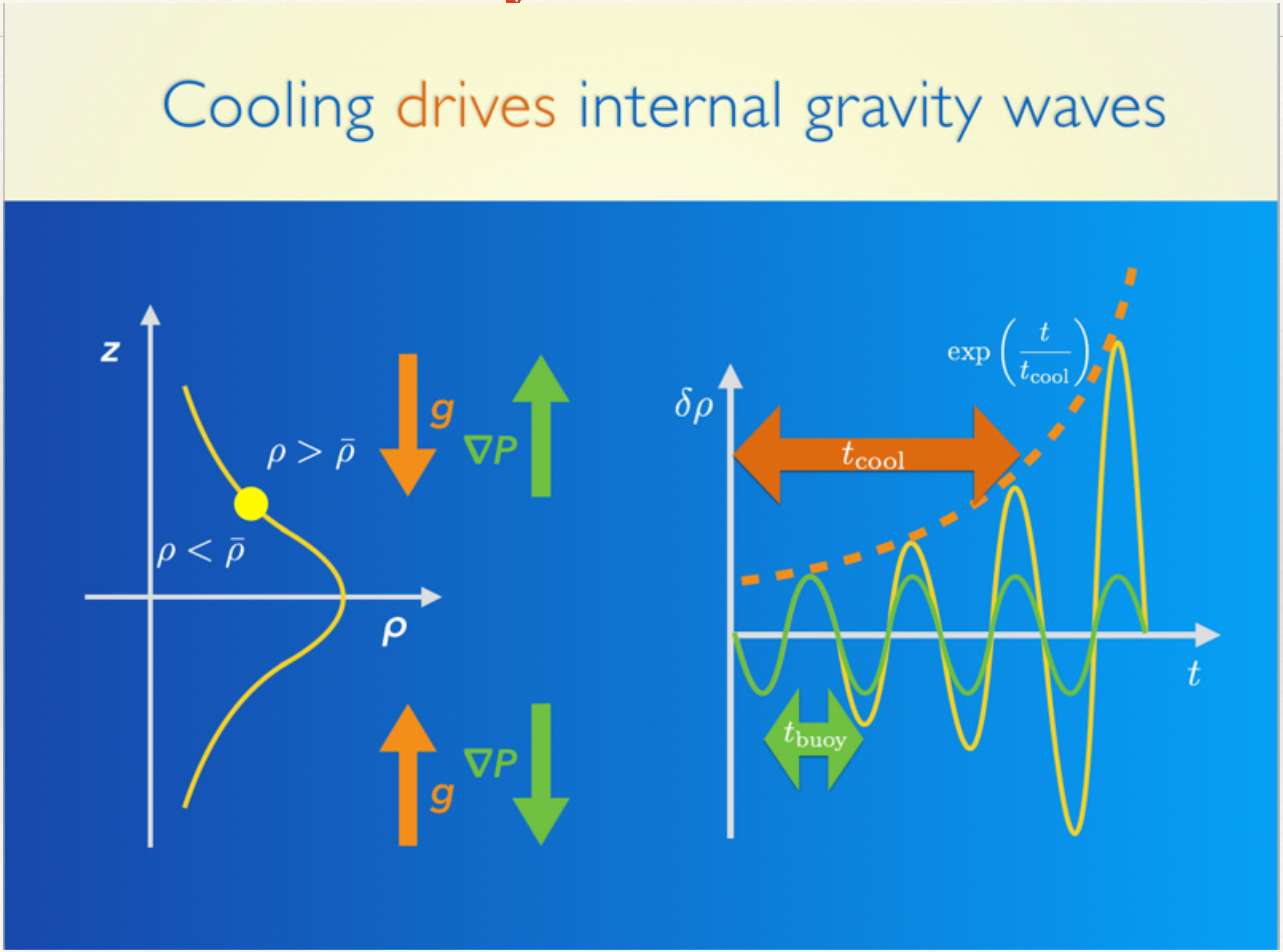
Cluster filaments

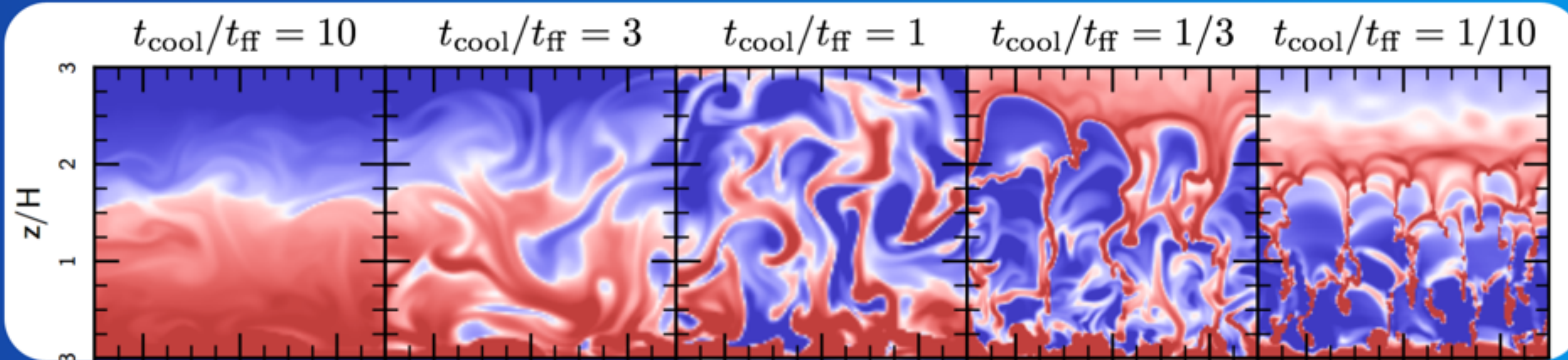




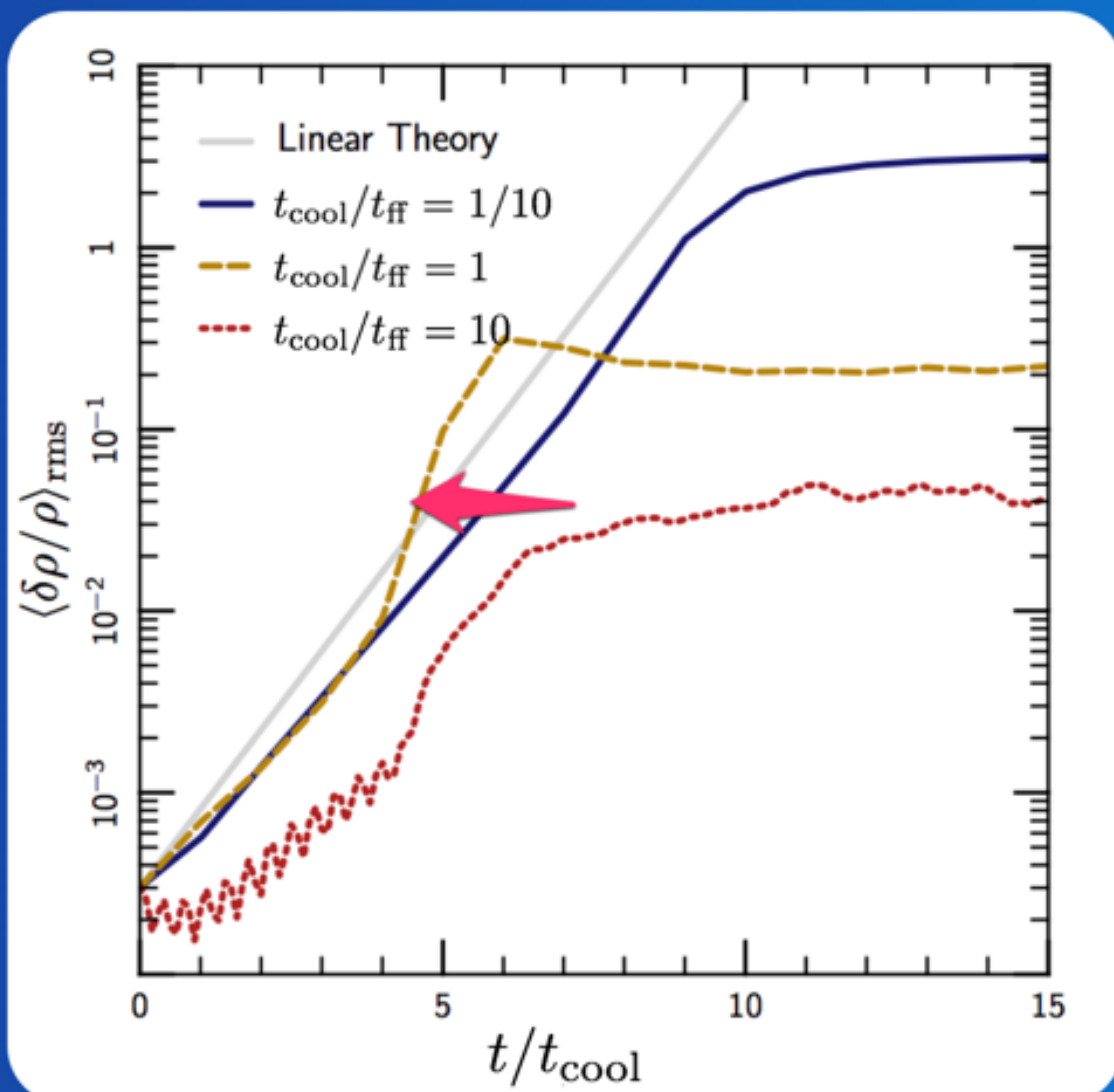

Chaotic cold accretion of gas onto black holes

# Why this ratio?






McCourt +, 2012




… which saturate due to non-linear dissipation

$$t_{drive} \sim t_{damp}$$

$$t_{cool} \qquad t_{buoy} \sim t_{ff}$$

Can show

$$\frac{\delta\rho}{\rho} \propto \left(\frac{t_{\rm cool}}{t_{\rm ff}}\right)^{-1}$$

# What about B-fields?

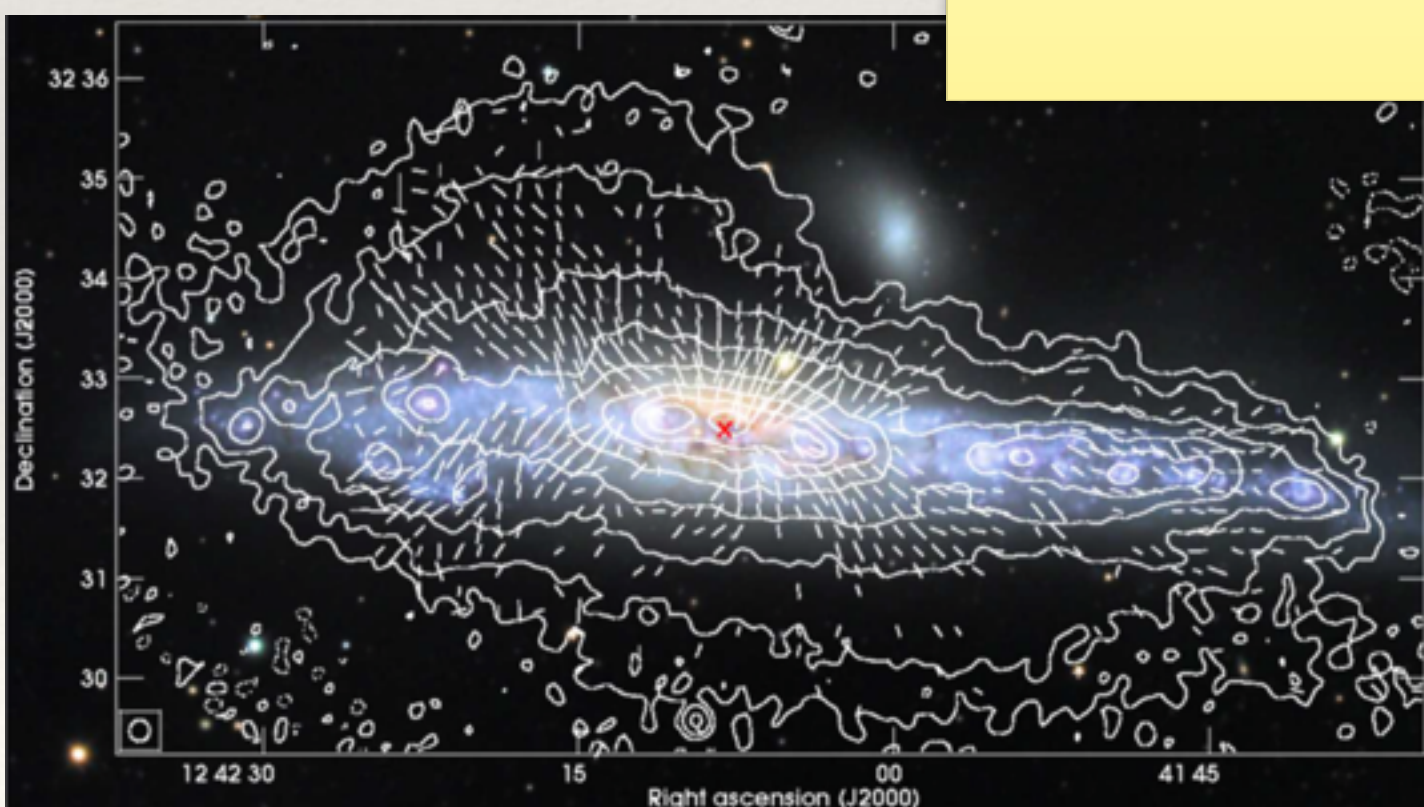
Define $\beta \equiv \dfrac{P_{\rm gas}}{P_{\rm B}}$

$\beta \sim 10 - 100$ for galaxy clusters

$\beta \sim 0.1 - 10$ for ga… …e ~$\mu$G fields — Faraday…

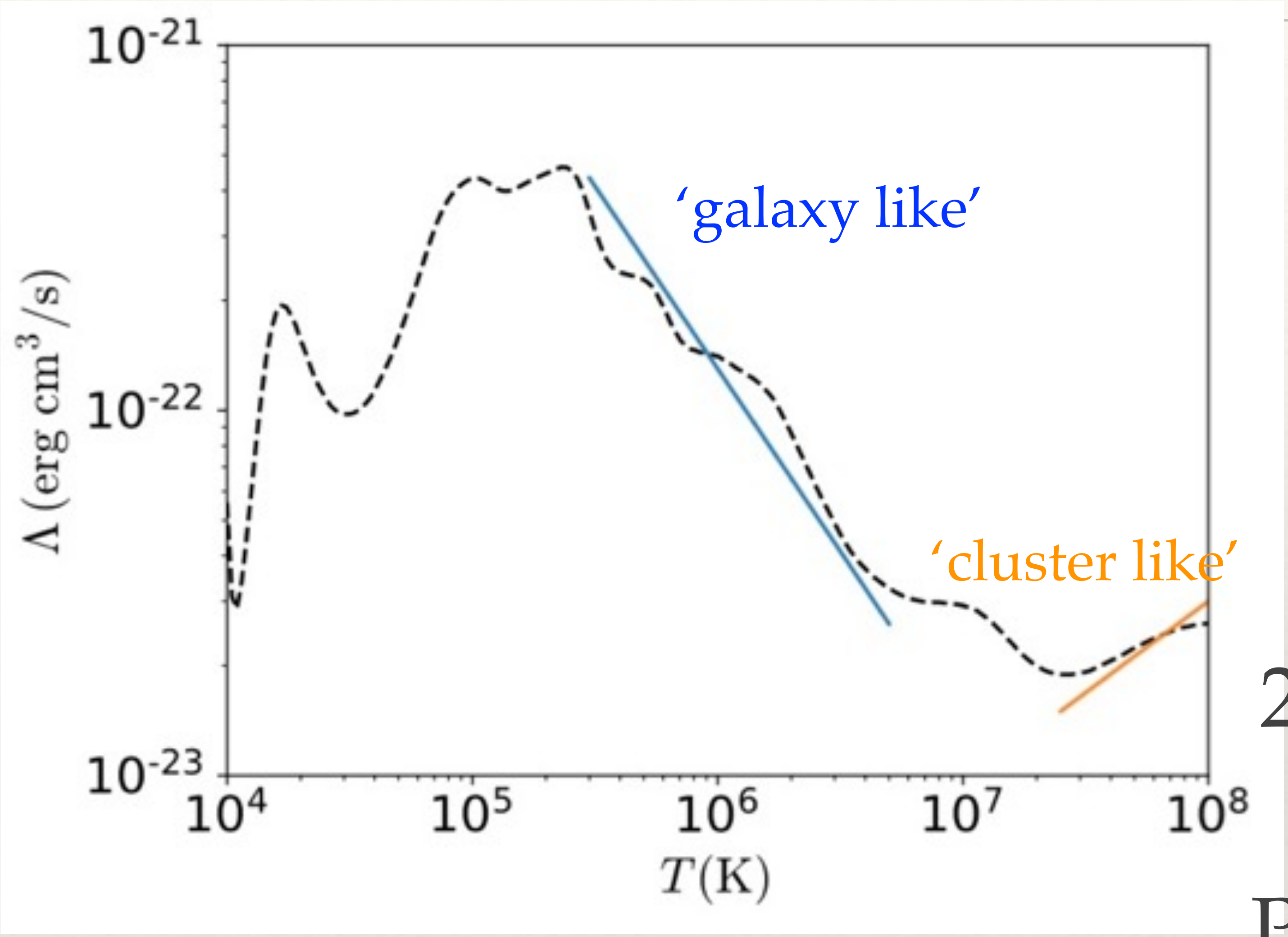
…otation or synchrotron)

Pict is radio intensity map for NGC 4631 with apparent B-field orientation. Faraday-corrected polarization data. Edge on disk with ~ 10 muG field strength in both disk and halo




Mora & Krause 2013

# Simulate this!




256^3 FLASH 3D MHD sims

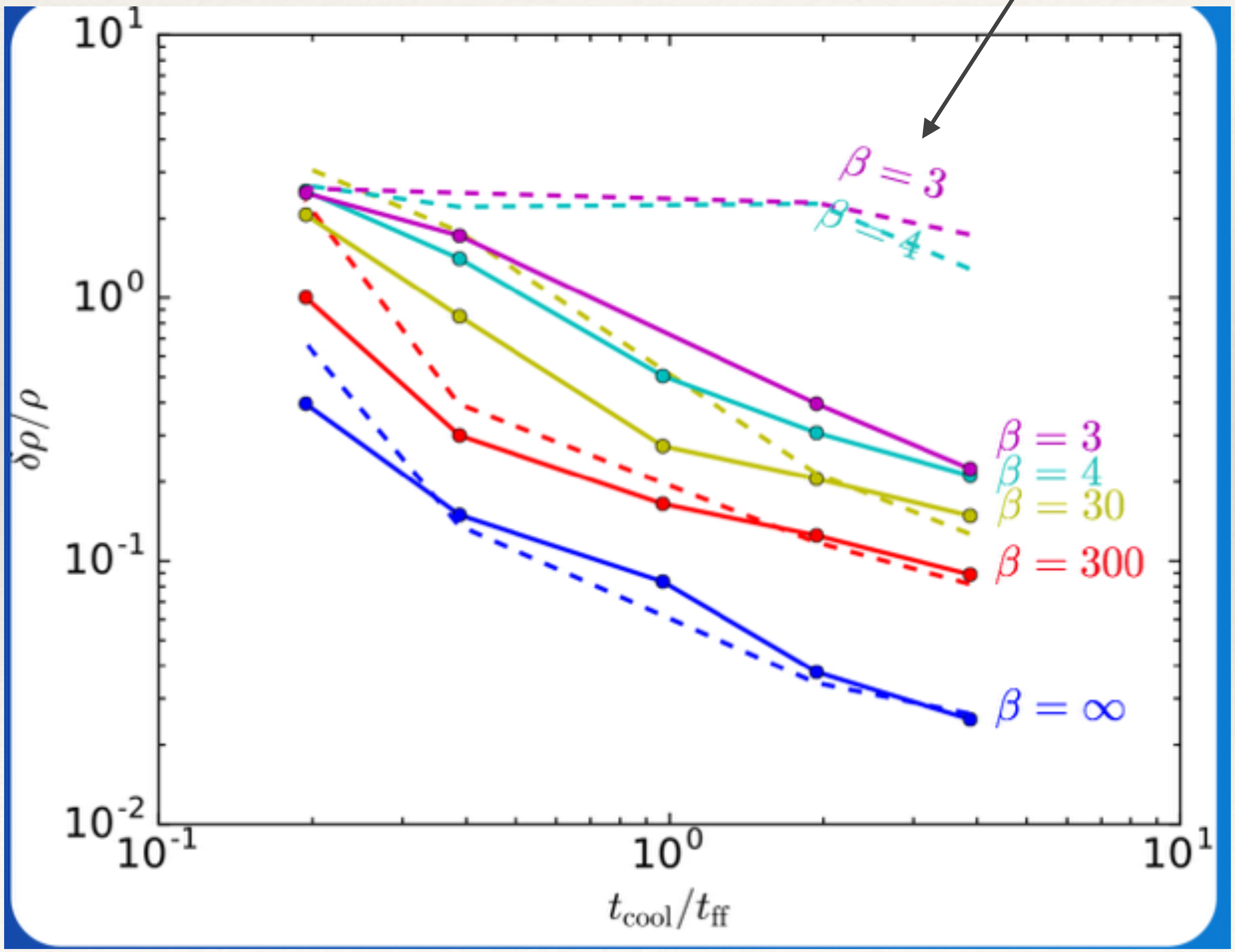
Planar, stratified, set up to be in global thermal equilibrium

Look for local thermal instability

# B-fields have a big effect!

**independent of** $t_{\rm cool}/t_{\rm ff}$ !

$\frac{\delta\rho}{\rho}$ changes



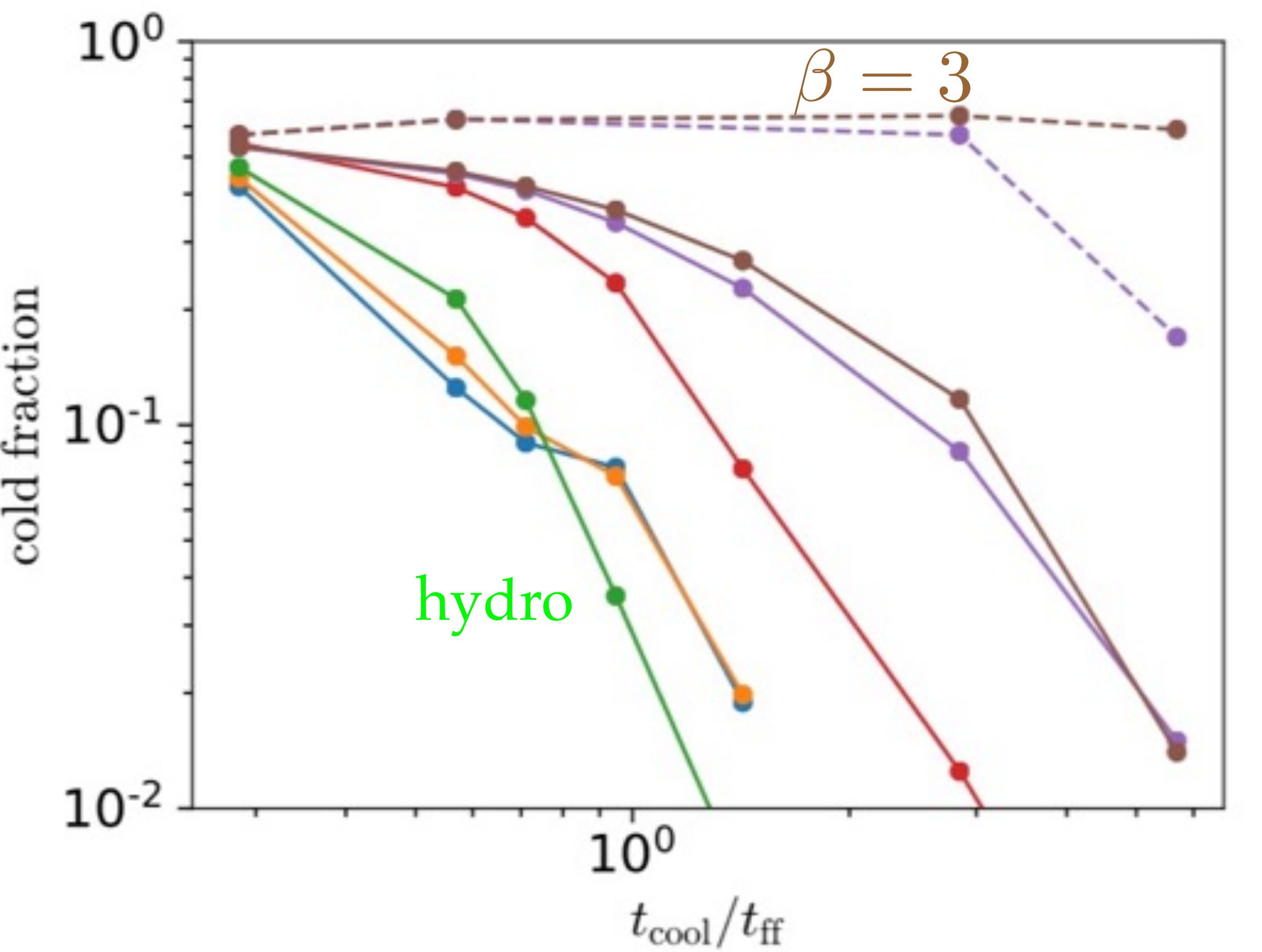

solid— cluster cooling curve

dashed — galaxy cooling curve

Why do such weak fields matter?

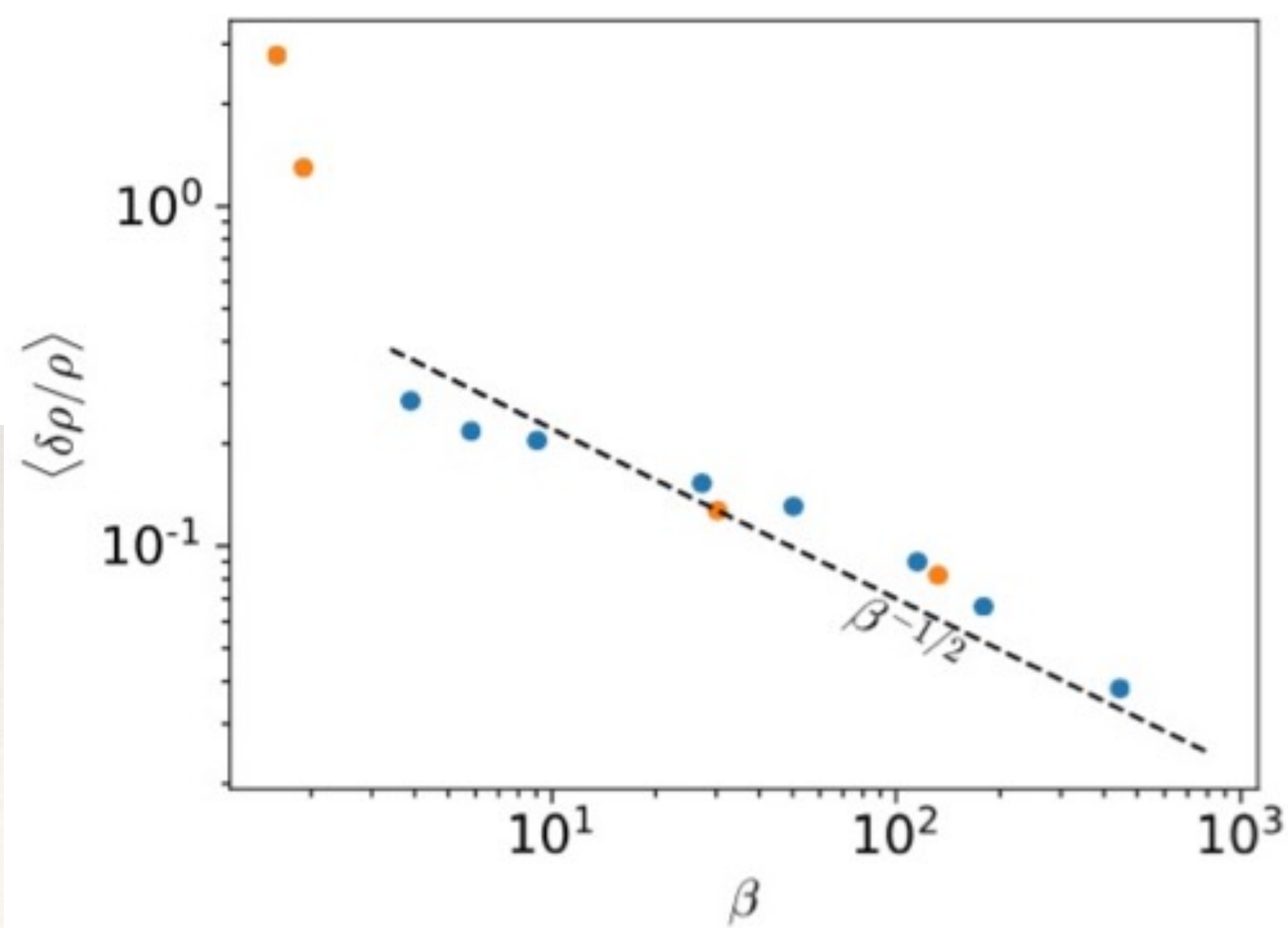
$$\beta \equiv \frac{P_{\rm thermal}}{P_{\rm B}}$$

# B-fields have a big effect!




B-fields change threshold $\frac{t_{cool}}{t_{ff}}$ for a multiphase medium

Can be independent of $\frac{t_{cool}}{t_{ff}}$

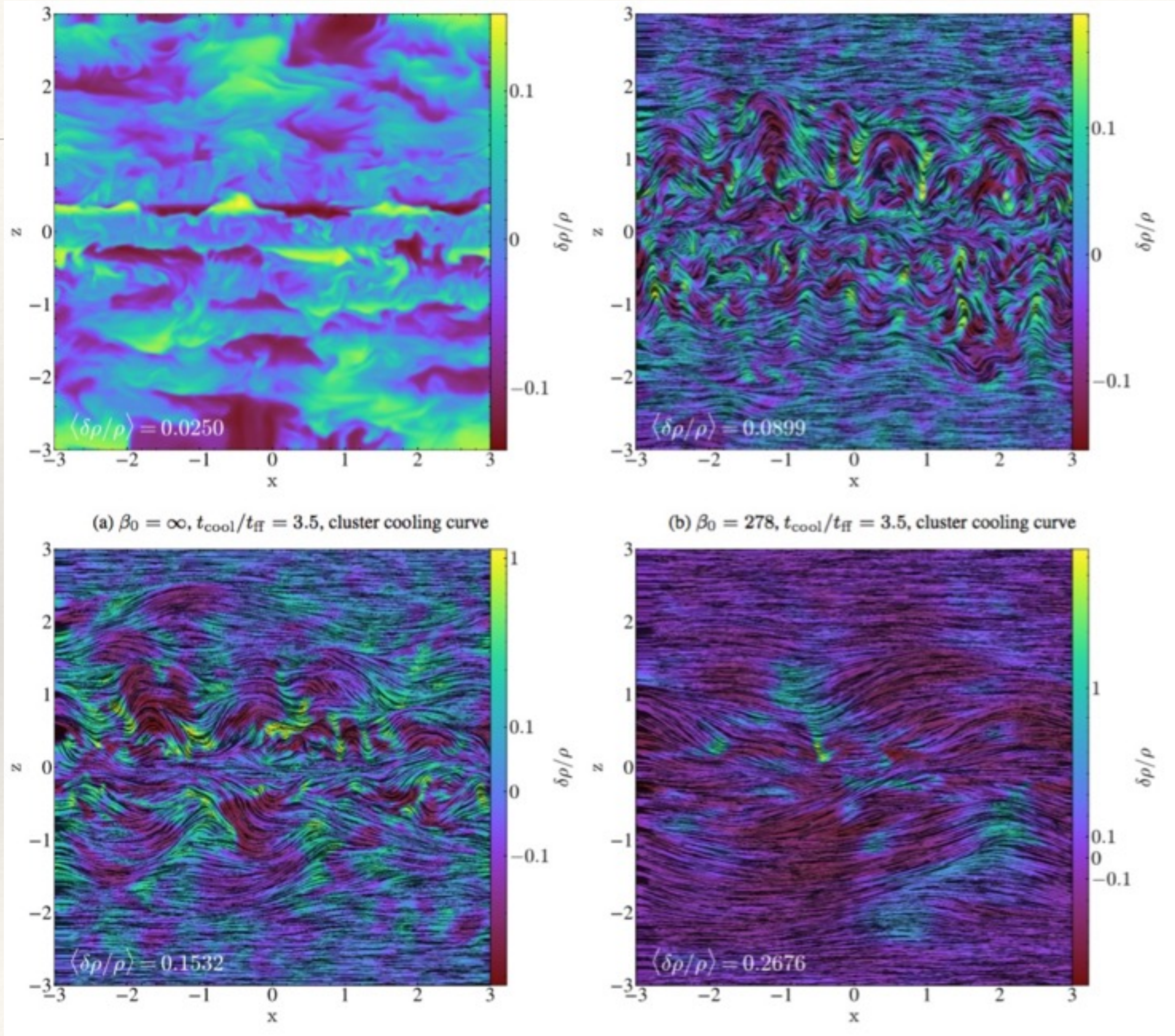



Follows scaling $\frac{\delta\rho}{\rho} \propto \beta^{-1/2}$

# B-fields have a big effect!

Hydro

$\beta = 300$

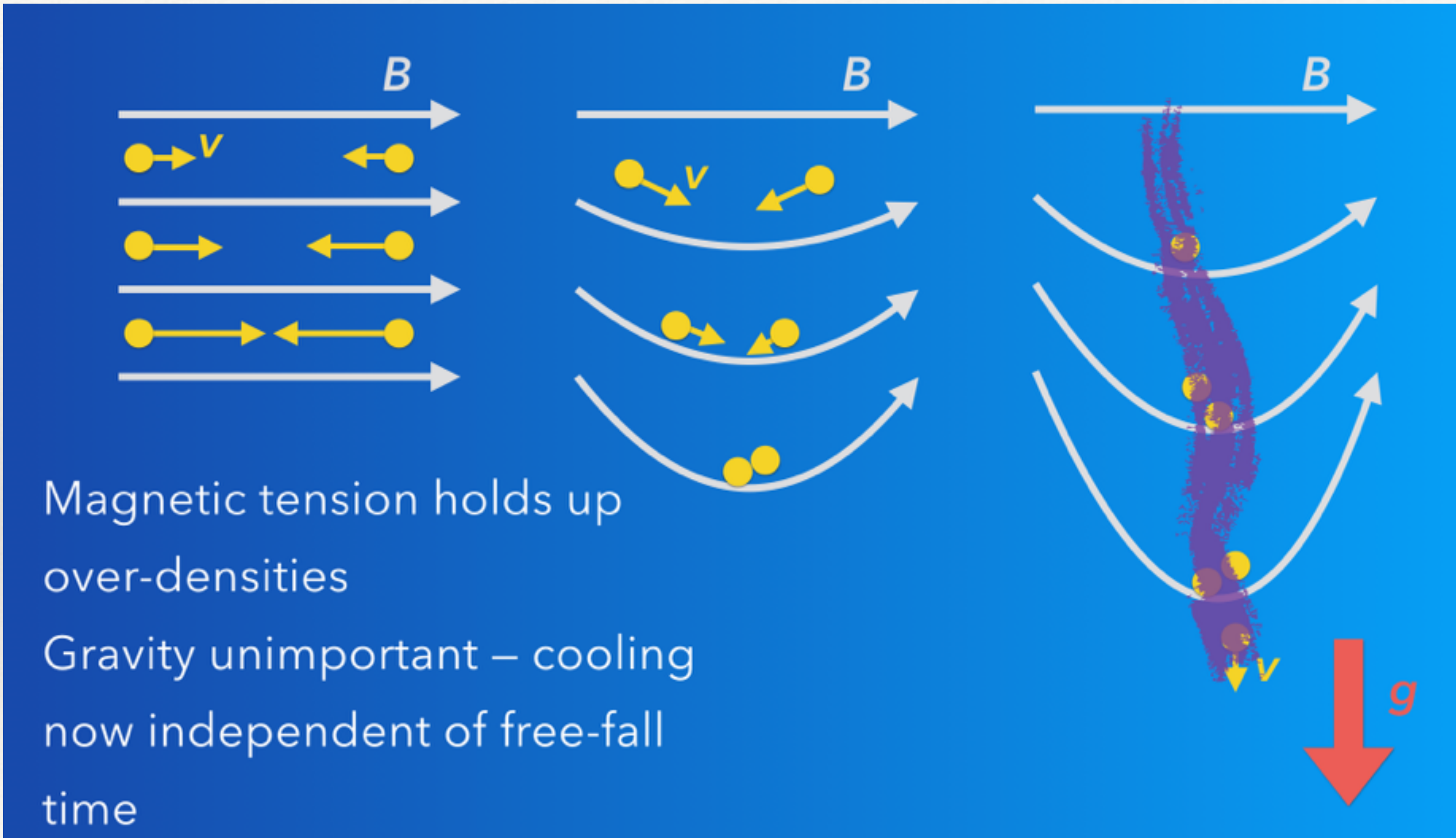



$\beta = 30$

$\beta = 3$

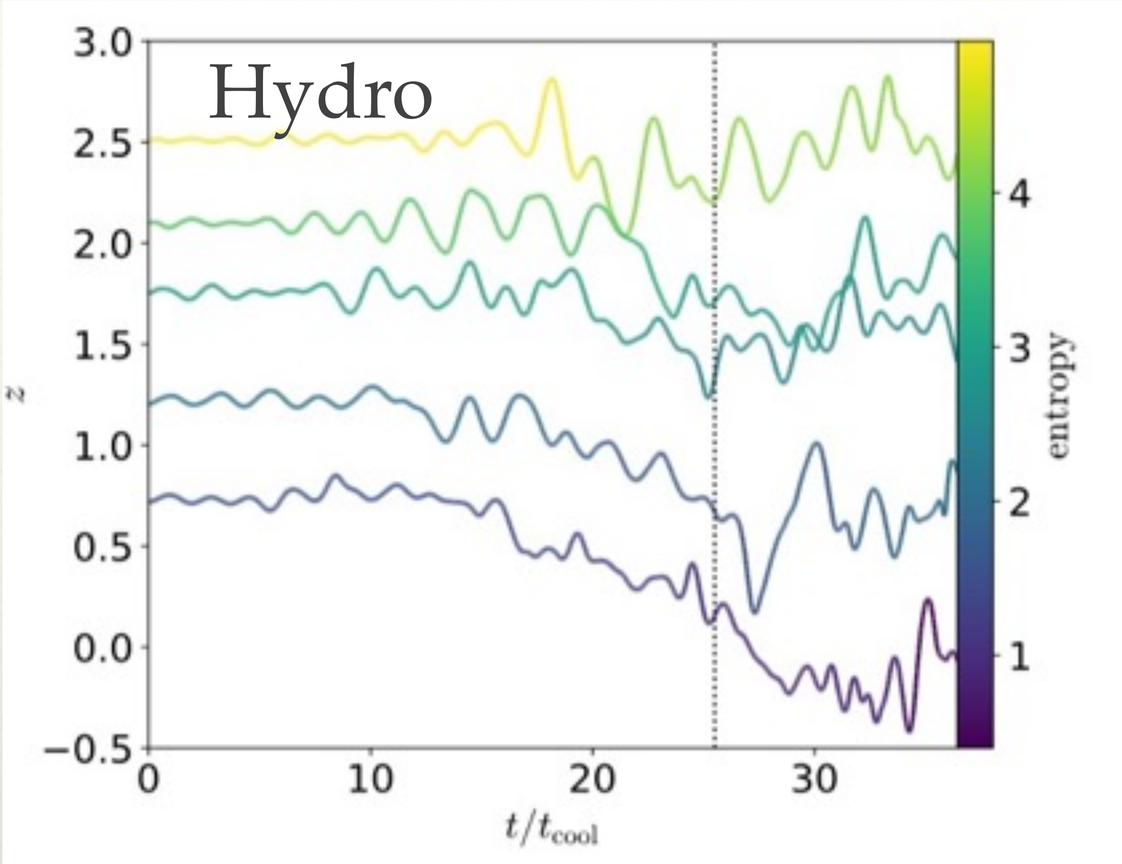
# What's going on?

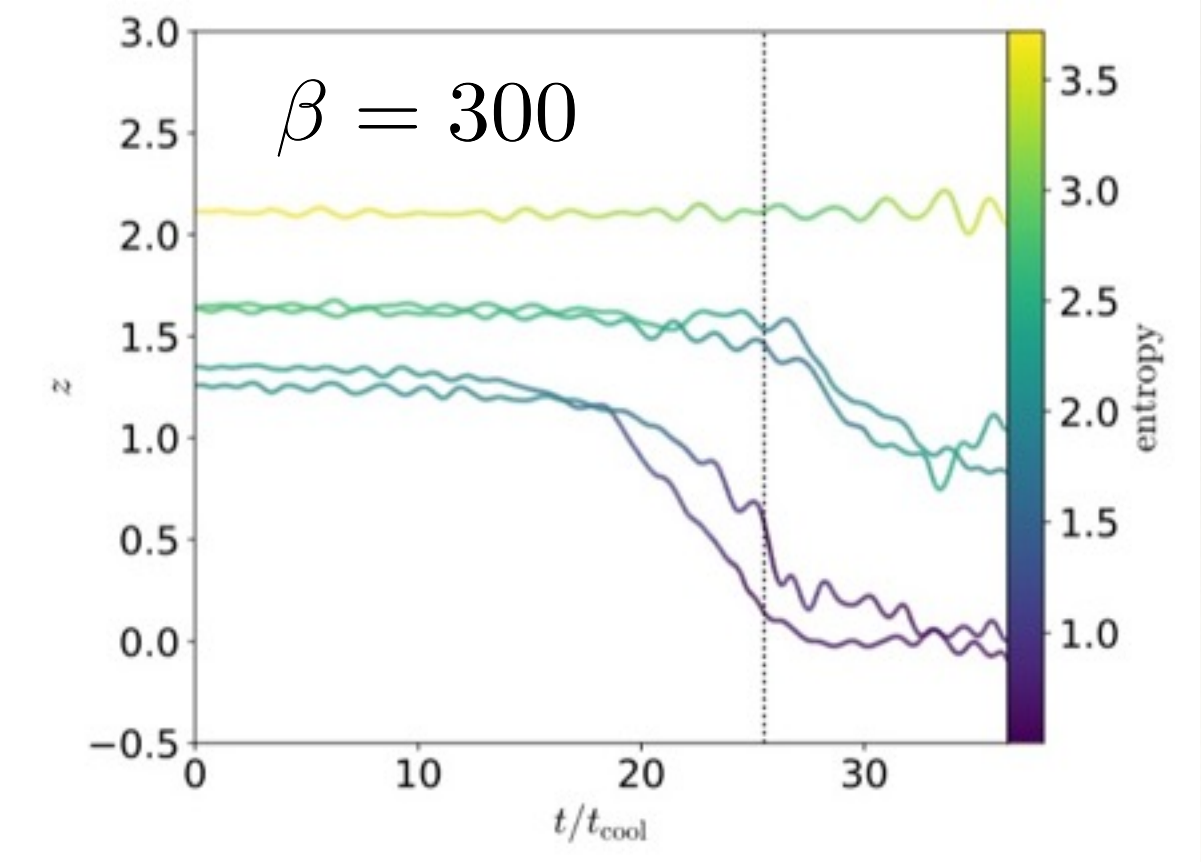
Consider horizontal fields

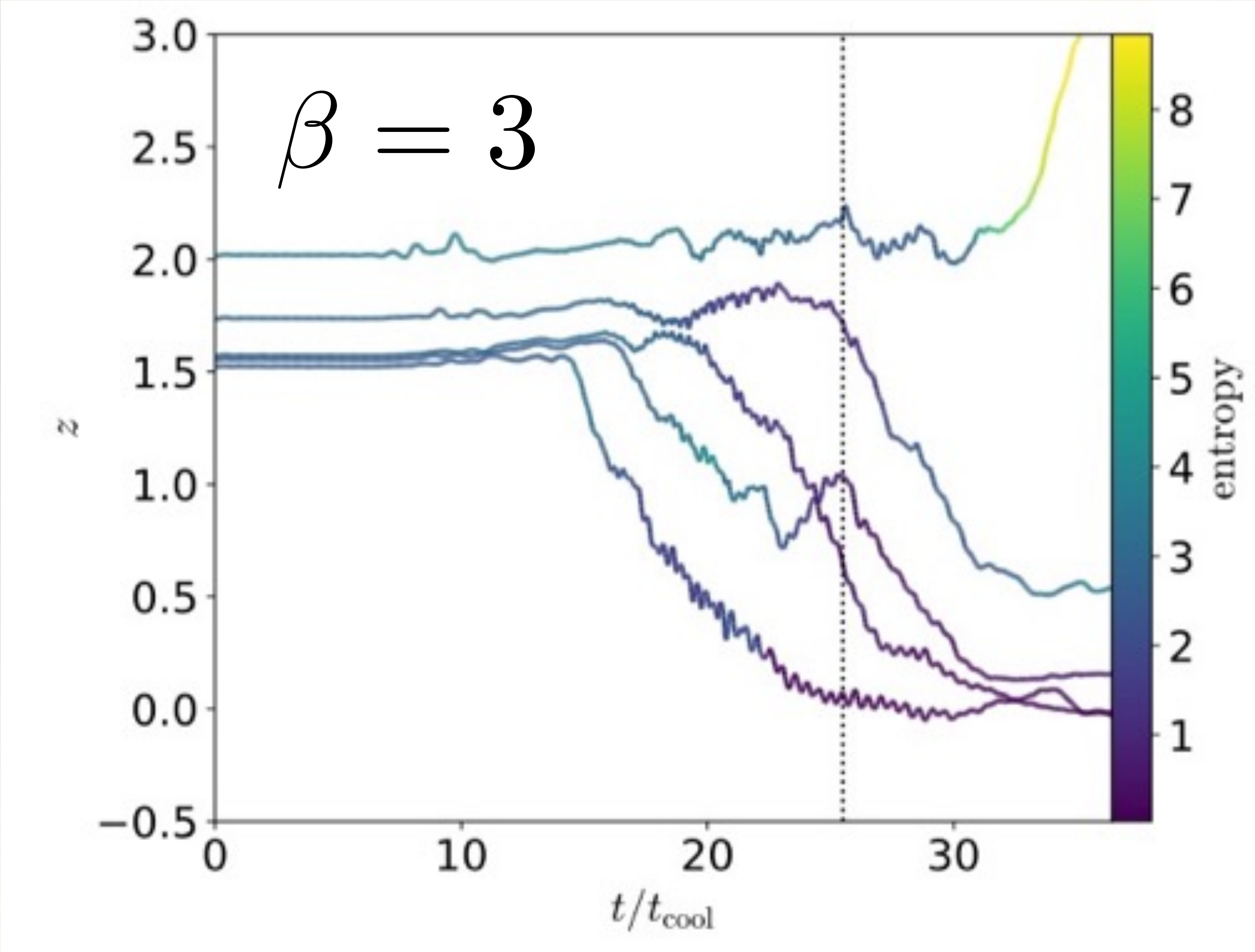



Singles out a lengthscale $\sim v_A t_{\mathrm{cool}}$
Small scales don't move and are destabilized

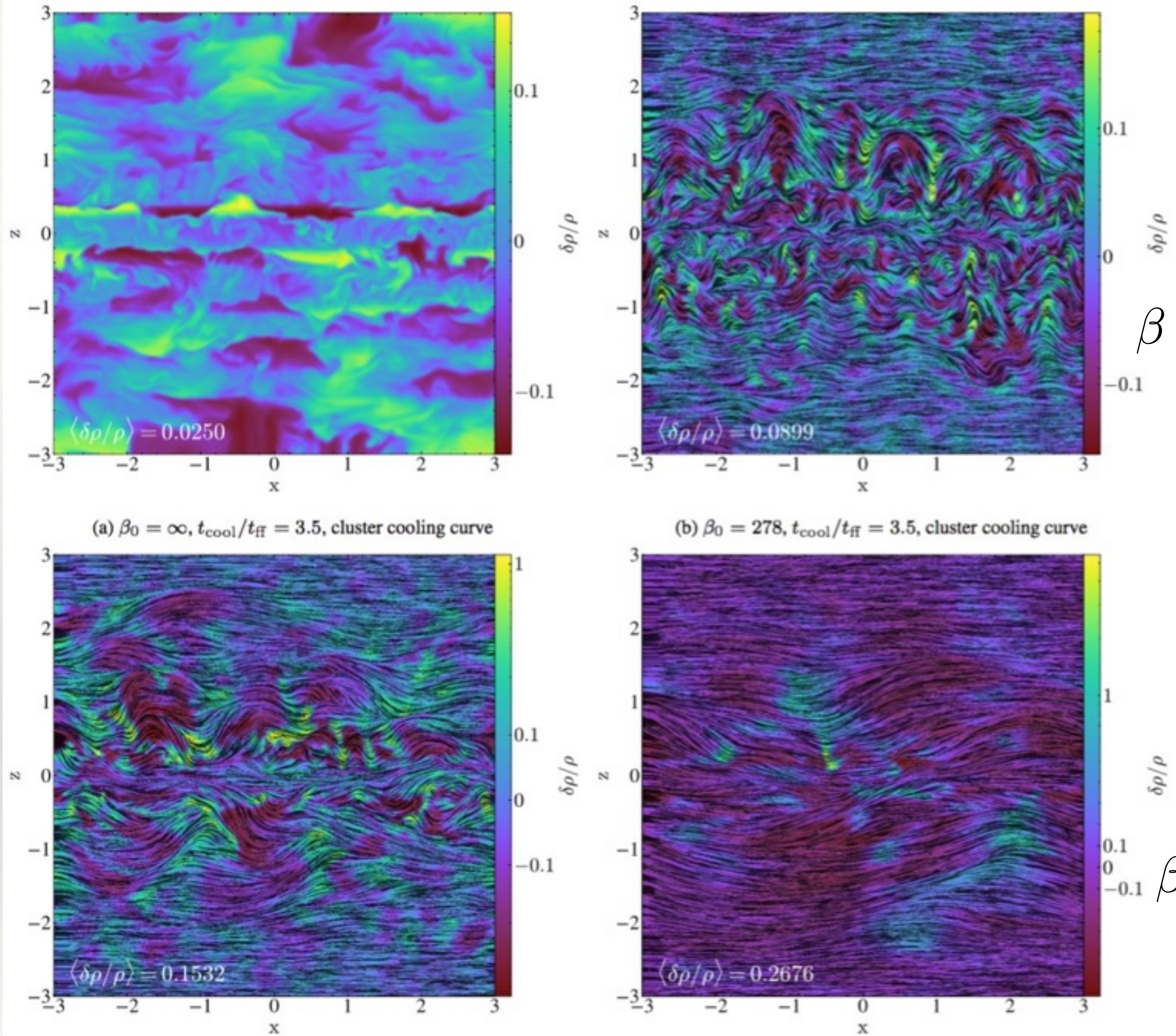
# Consistent with particle plots



Hydro




(a) $\beta_0 = \infty$, $t_{\rm cool}/t_{\rm ff} = 3.5$, cluster cooling curve

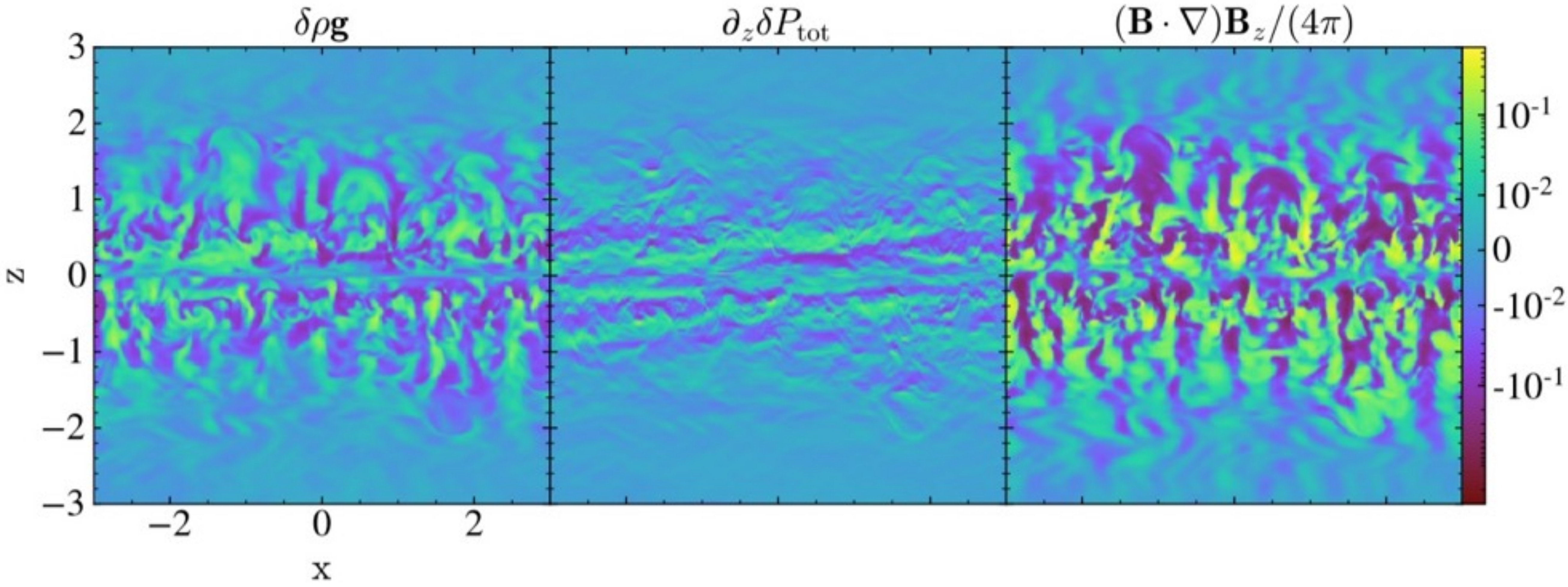
(b) $\beta_0 = 278$, $t_{\rm cool}/t_{\rm ff} = 3.5$, cluster cooling curve

$\beta = 300$

$\beta = 30$

$\beta = 3$

Lengthscales

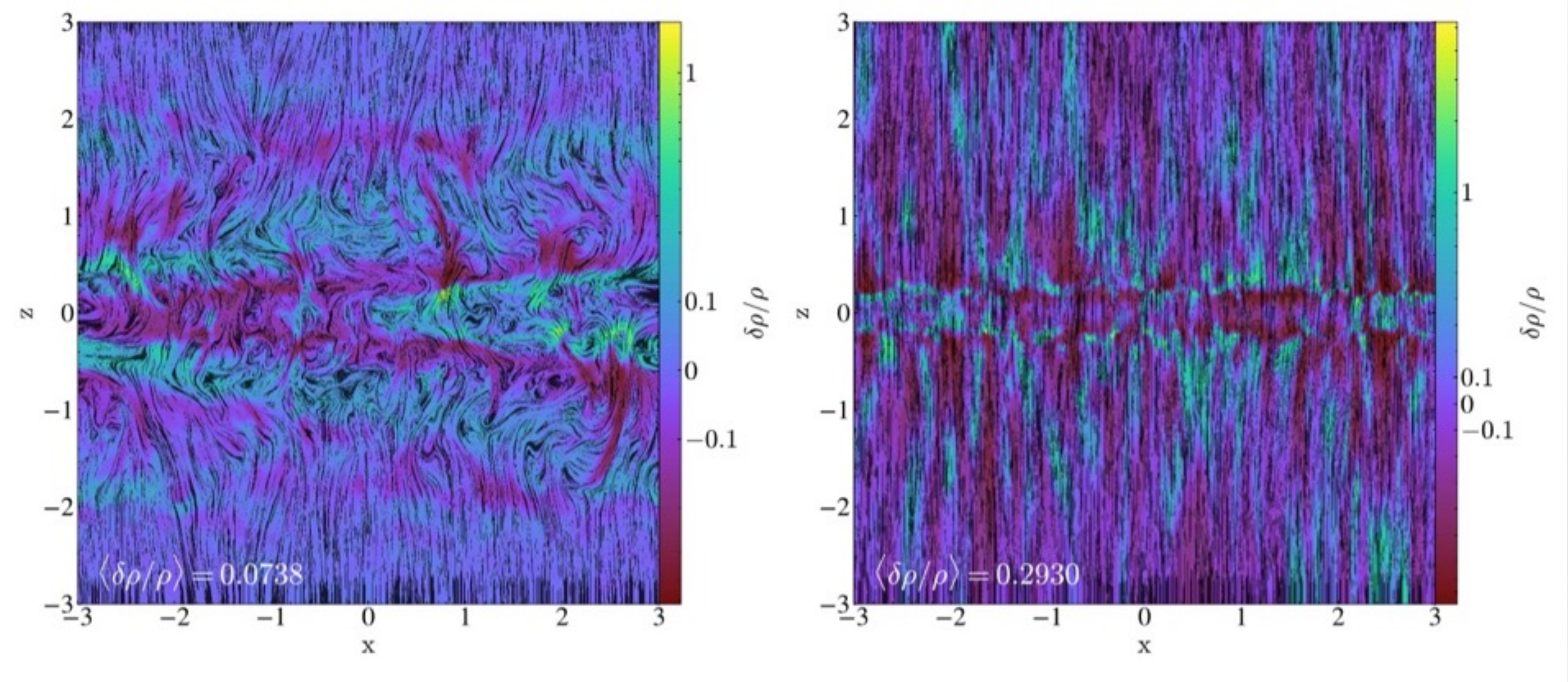



Perturbed forces

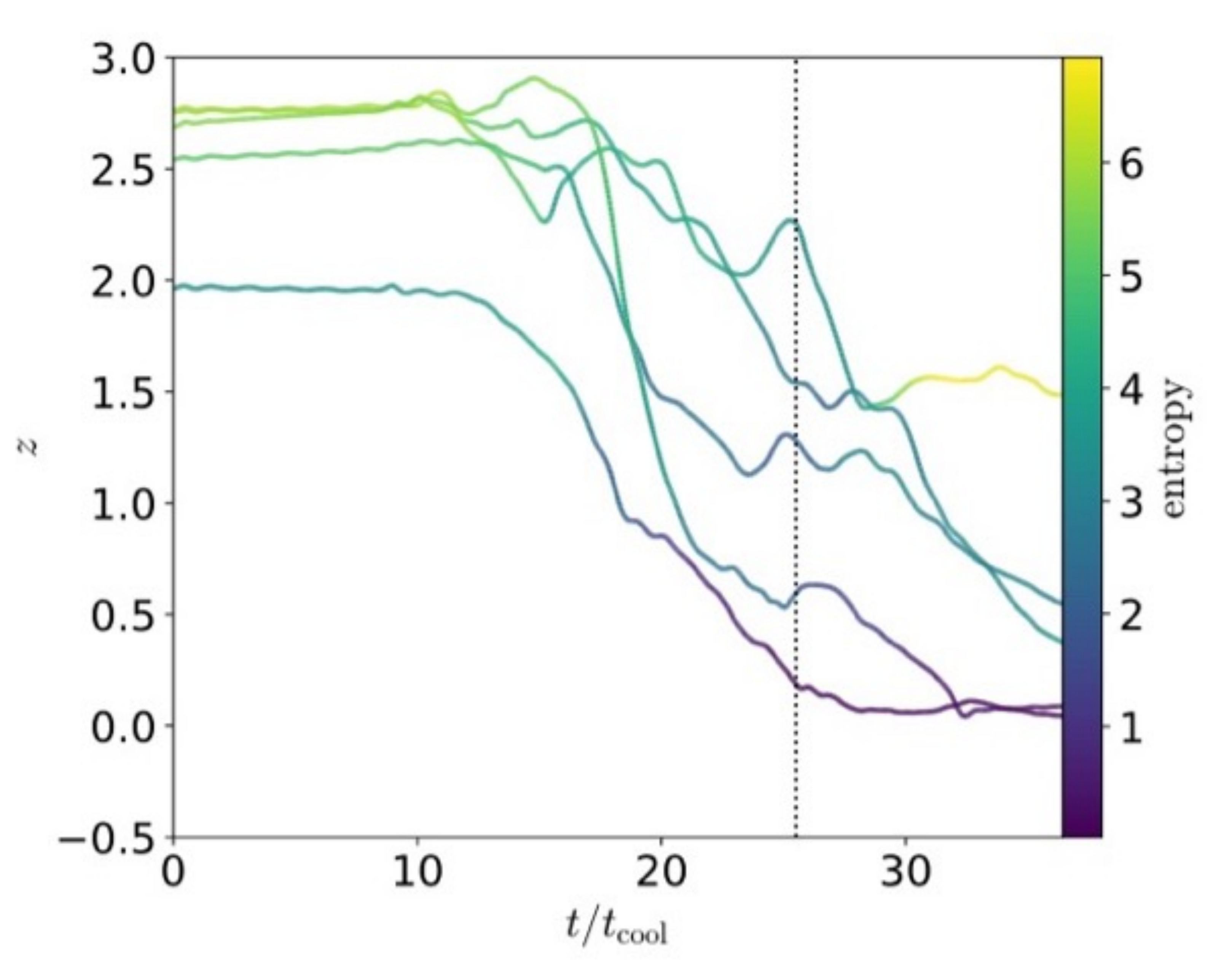
Note: B-fields get amplified

# But what about vertical fields??

$\beta = 300$ $\beta = 3$

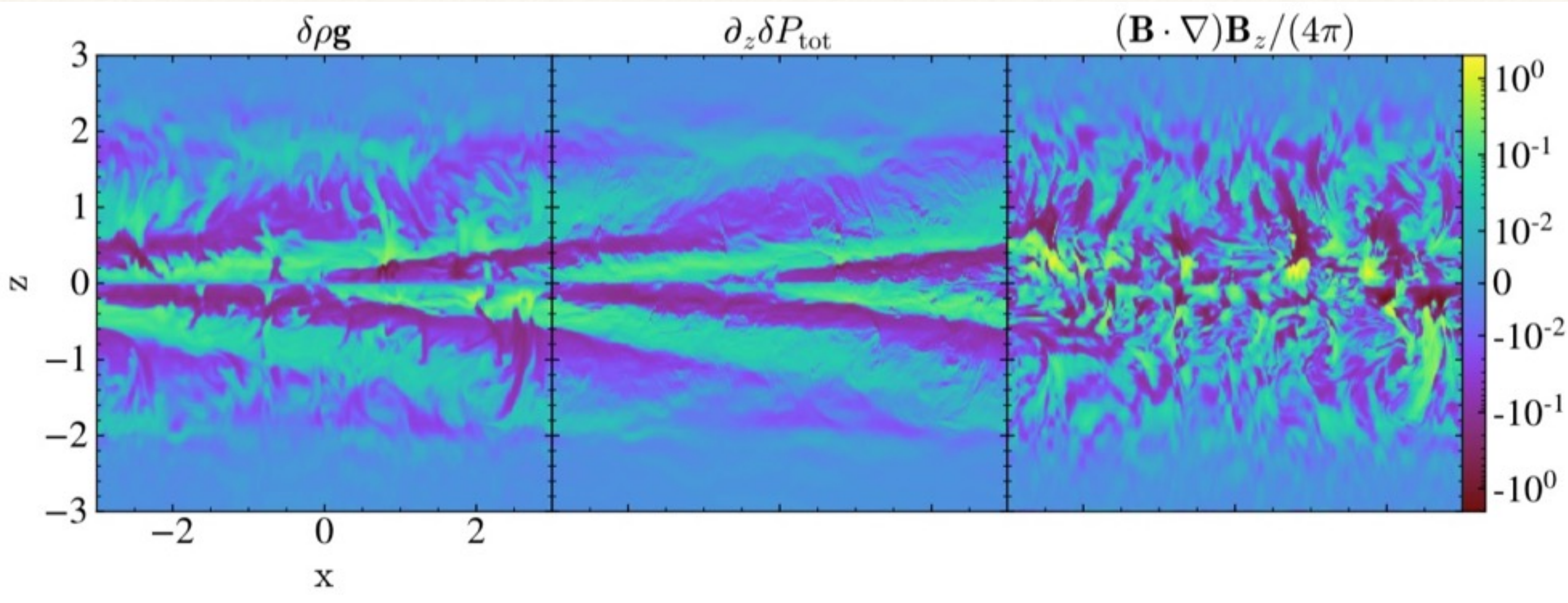



Same density fluctuations with completely different morphology

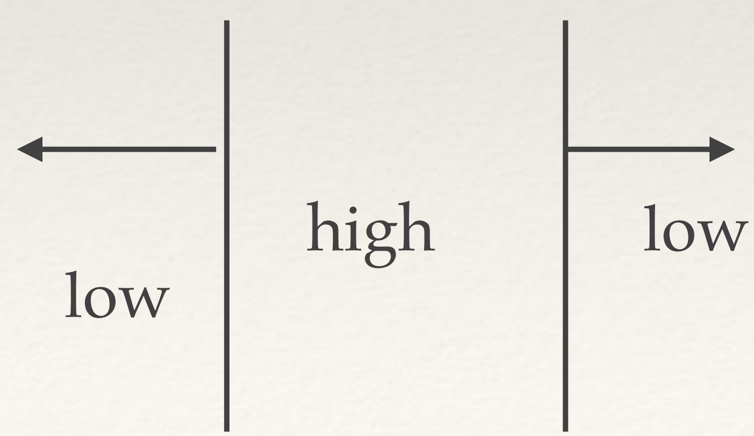



$\beta = 3$

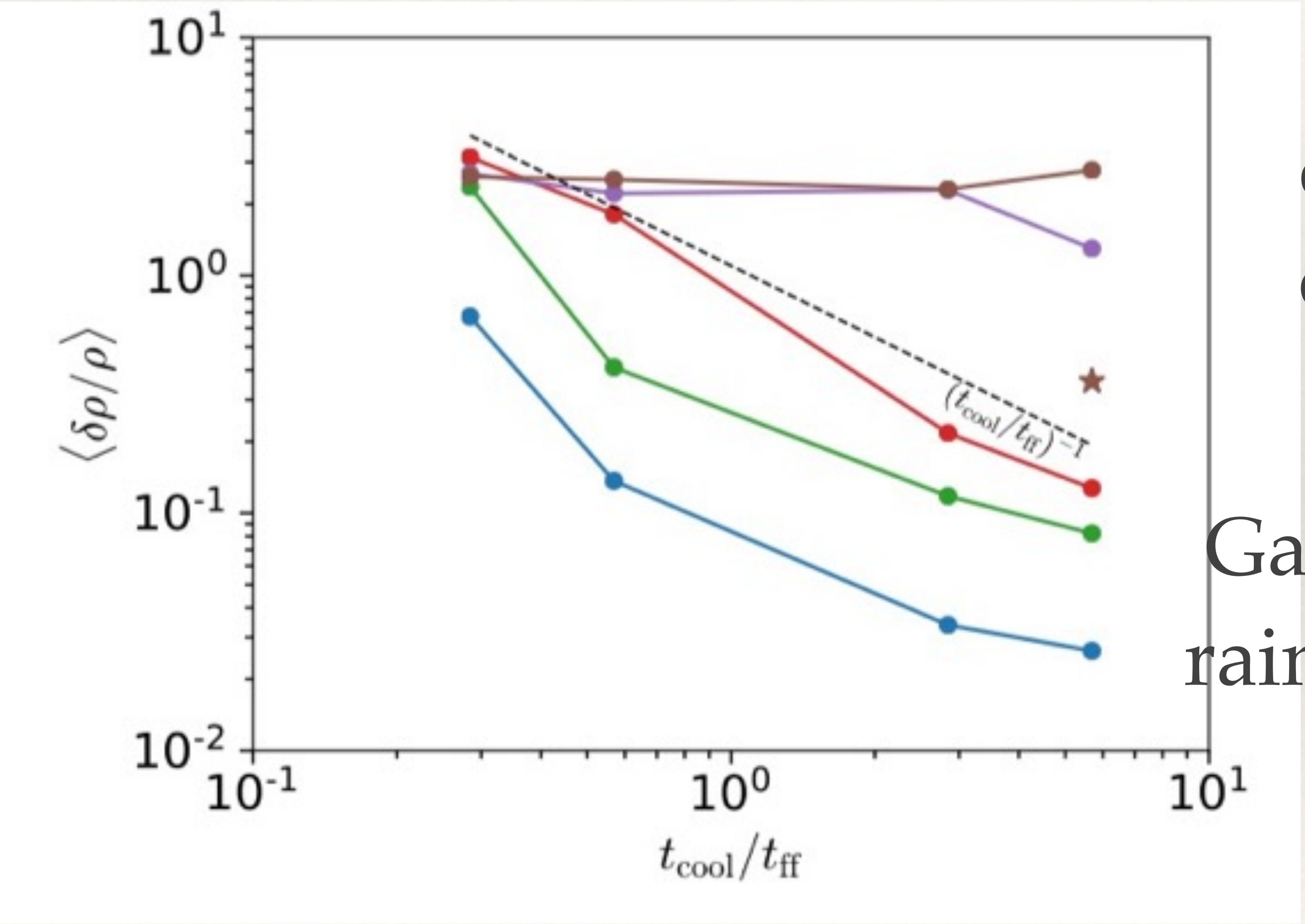
Particles also don't move!




Supported by pressure gradients…which develop because of confining magnetic tension



# THE BOTTOM LINE




In magnetized galaxy halos, can become independent of $\dfrac{t_{\rm cool}}{t_{\rm ff}}$

Gas can condense anyway and rain down on galaxy!

Not a good idea to ignore B-fields