Thermal Instability and Multiphase Structure in the ICM

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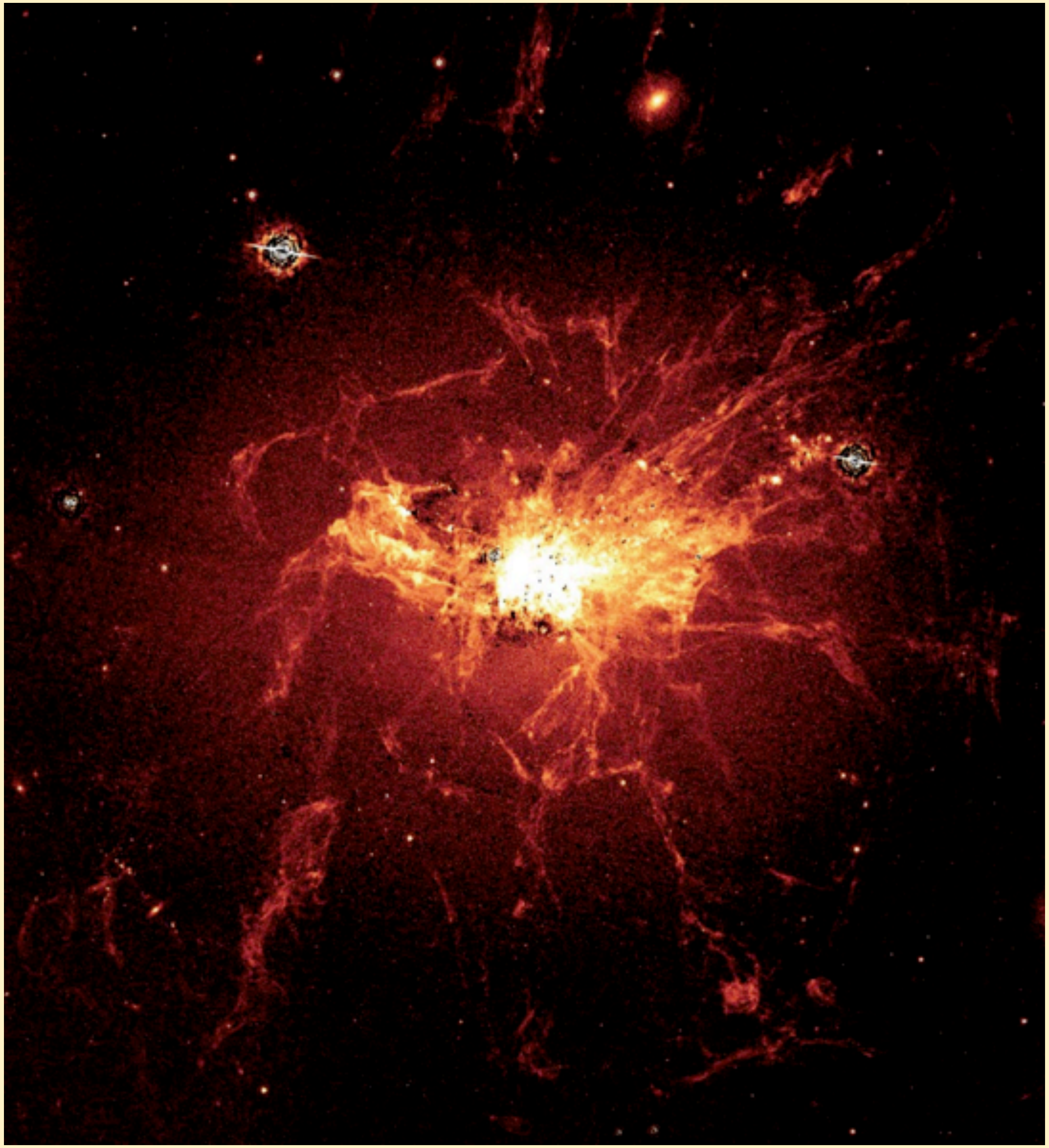
KITP Program on Galaxy Clusters
March 3, 2011

Observations: Filaments in NGC 1275



Hα emission: Fabian, et al Nature (2008)

Systematic Study of Hα with MMTF

McDonald, et al (2010), ApJ, 721, 1262

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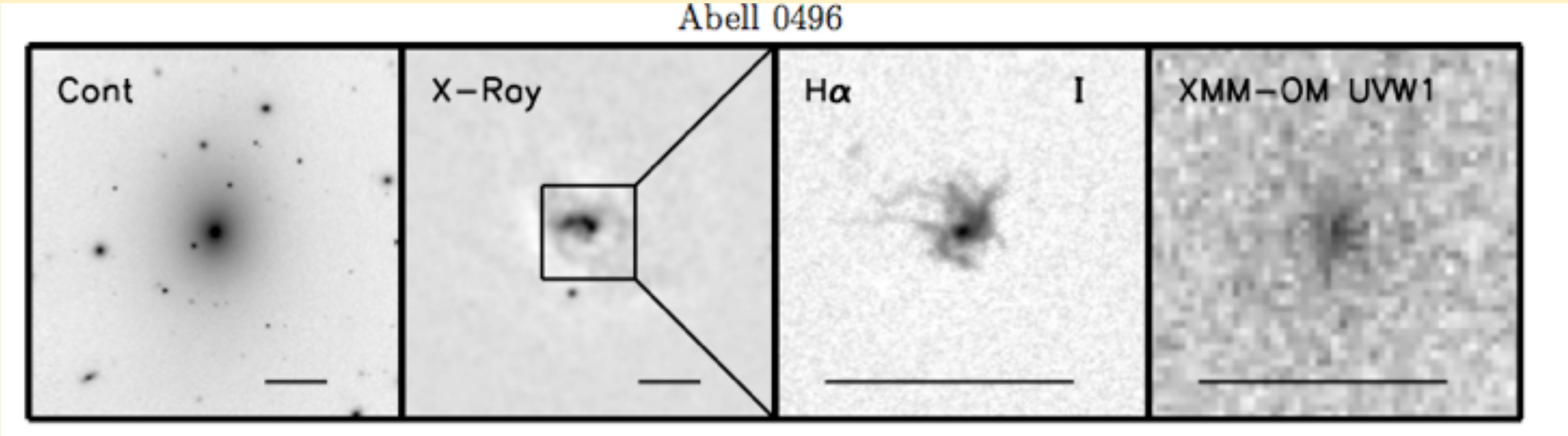

Extended Filaments

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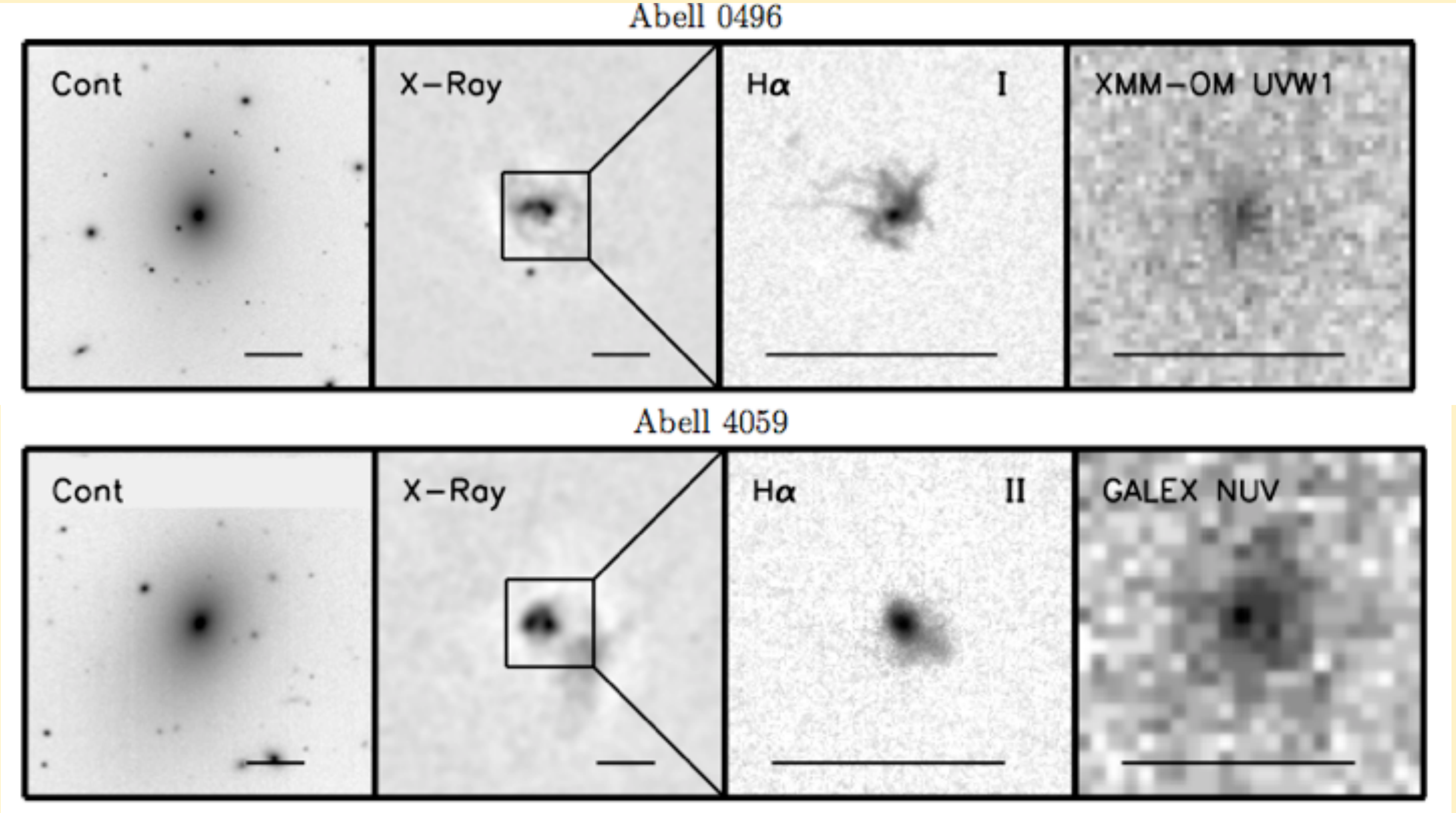

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Nuclear Emission (not filaments)

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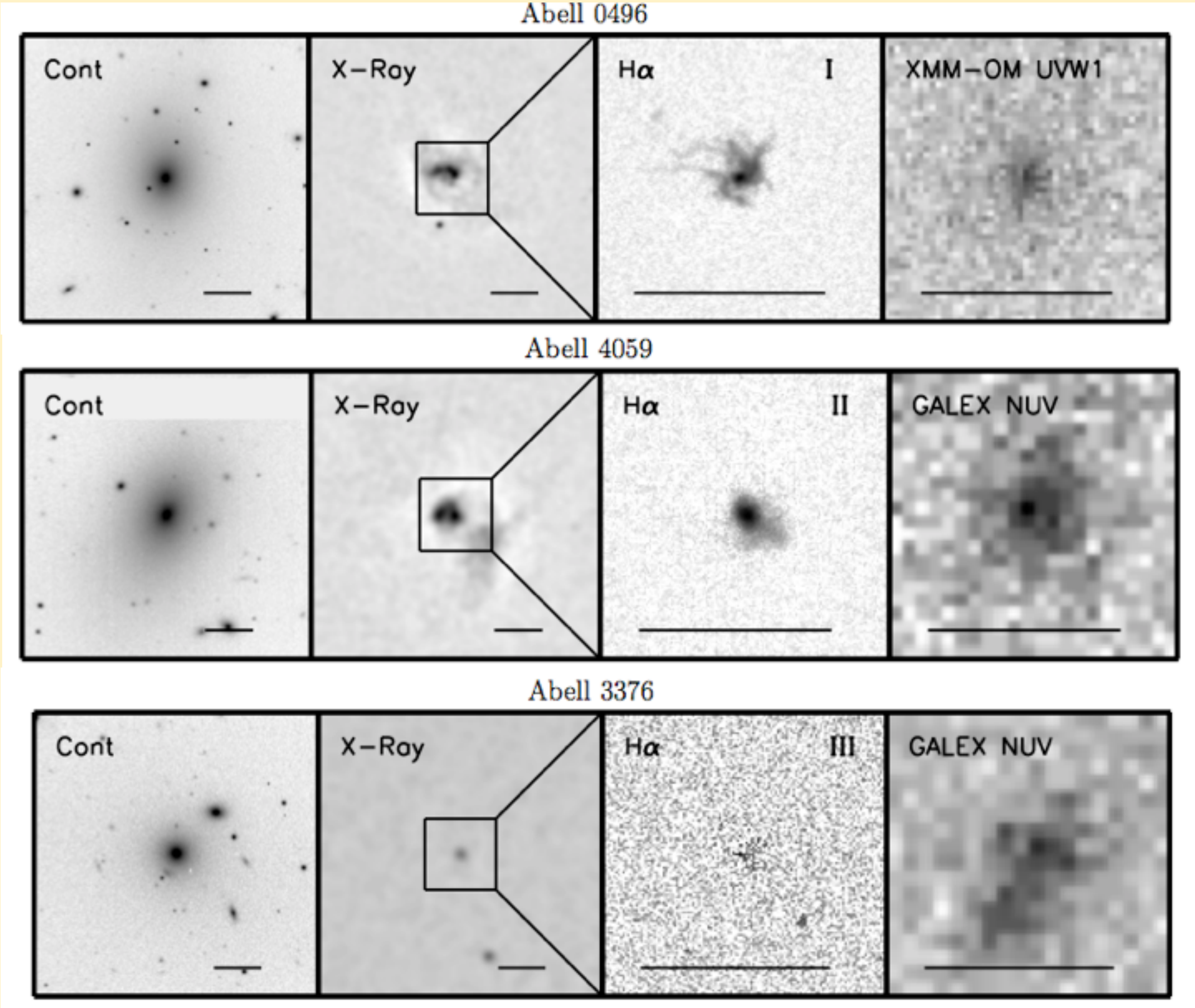

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Physics and Model

Physics: Pure hydrodynamics plus heating & cooling:

$$\rho T \frac{ds}{dt} = \mathcal{H} - \mathcal{L}$$

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Hα, CO, UV, [O II], Fe XVII, even PAH's in Herschel.

(See papers by Donahue, Edge, Fabian, Hicks, +++)

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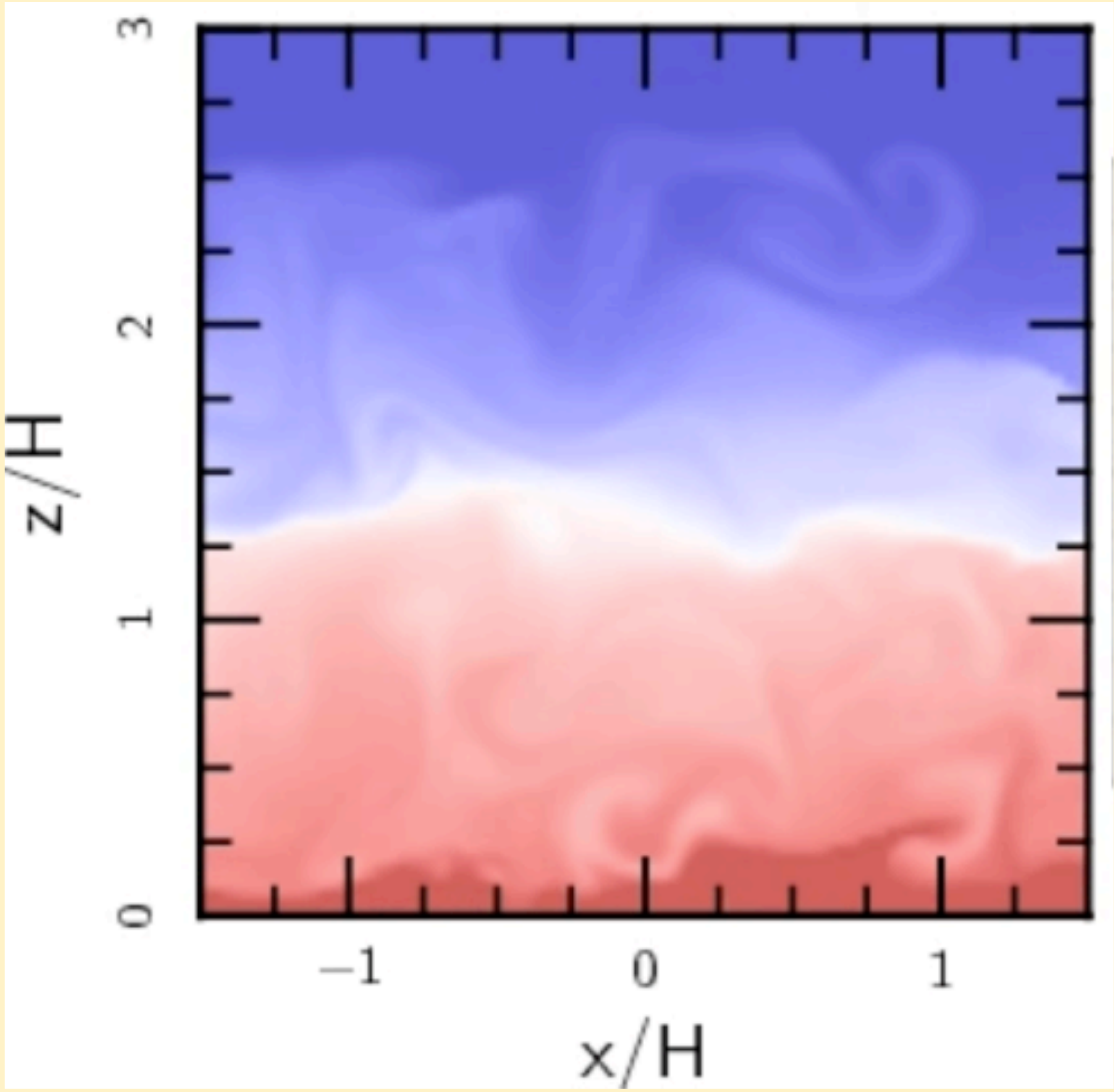

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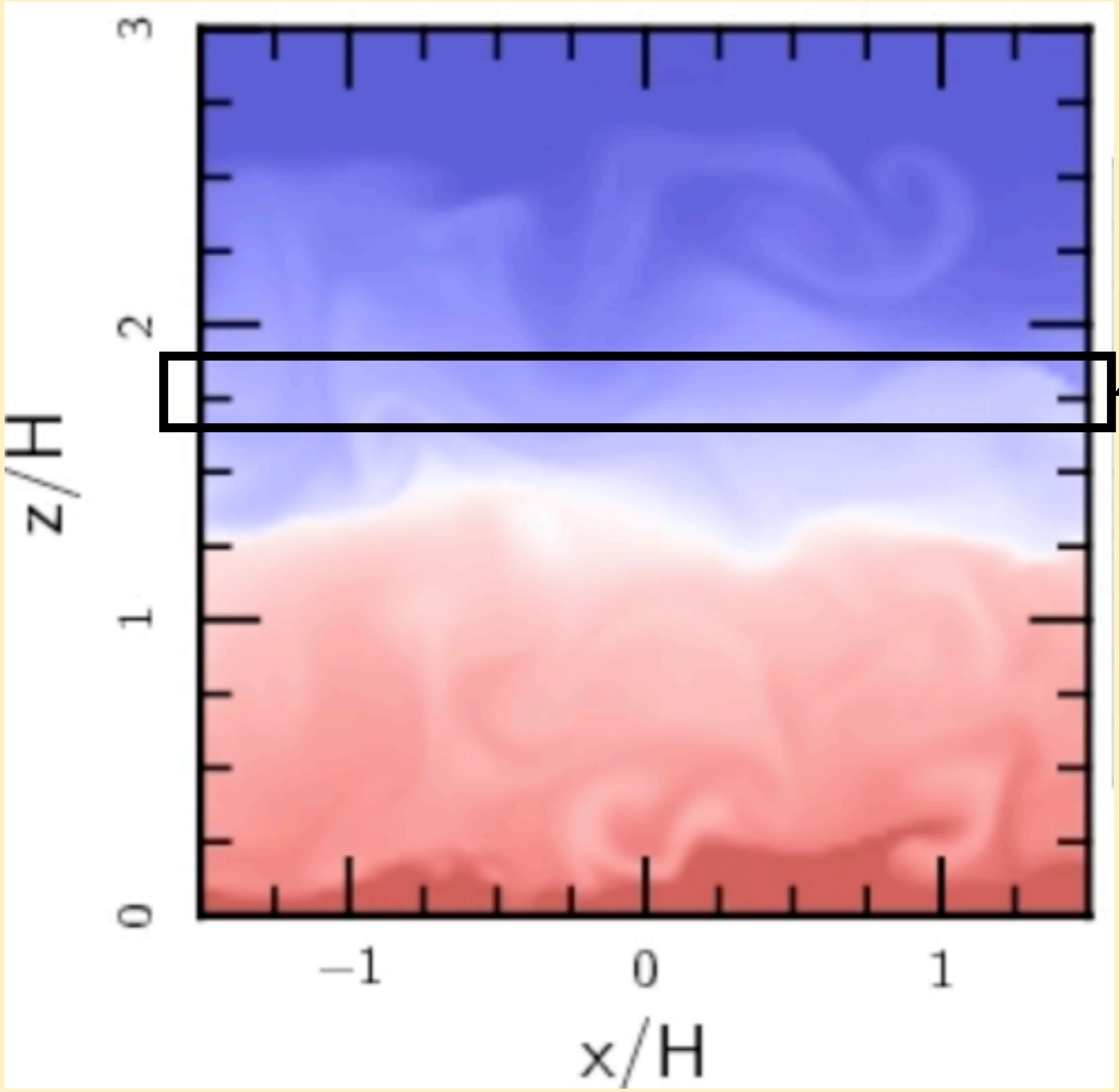

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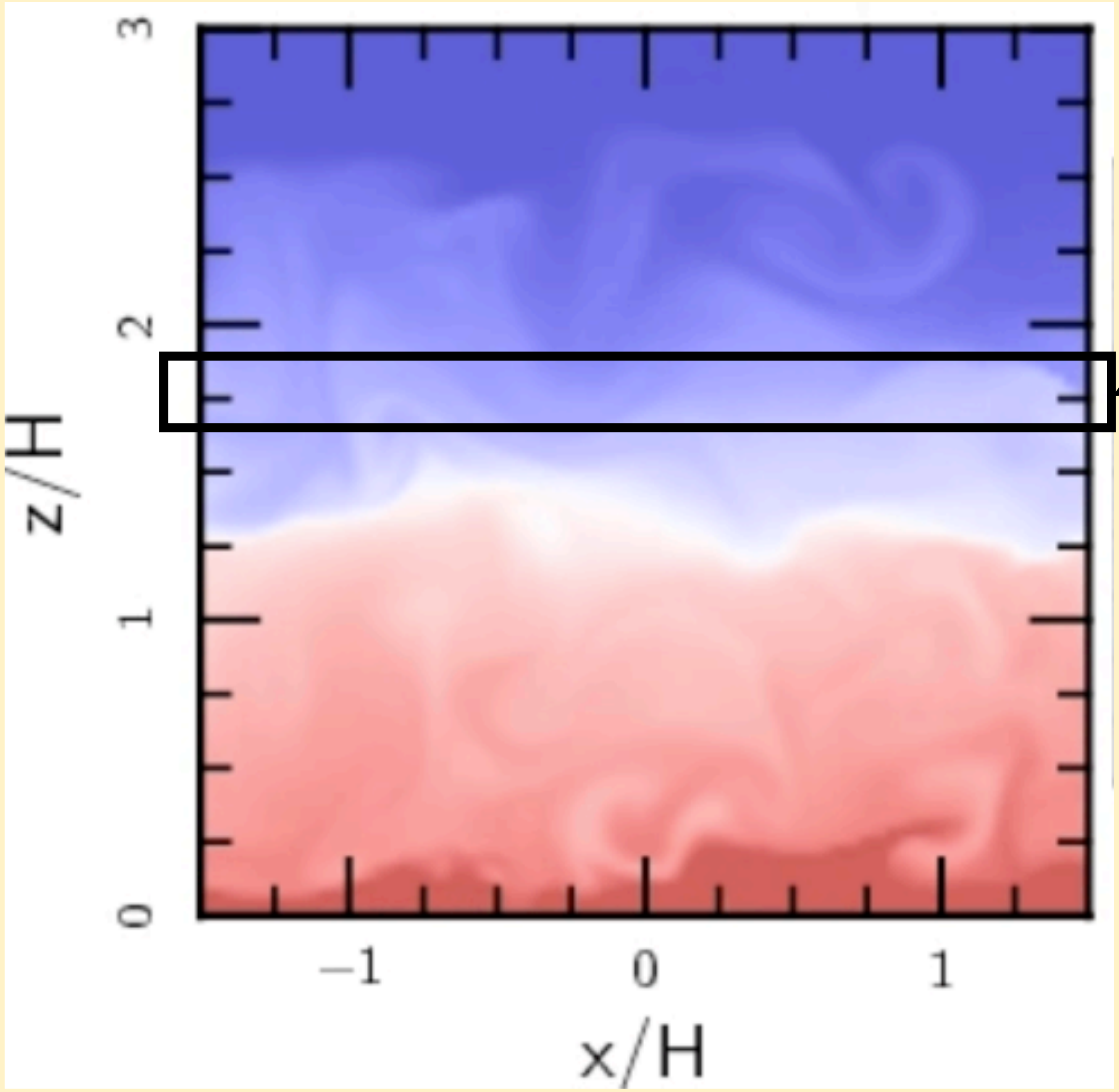

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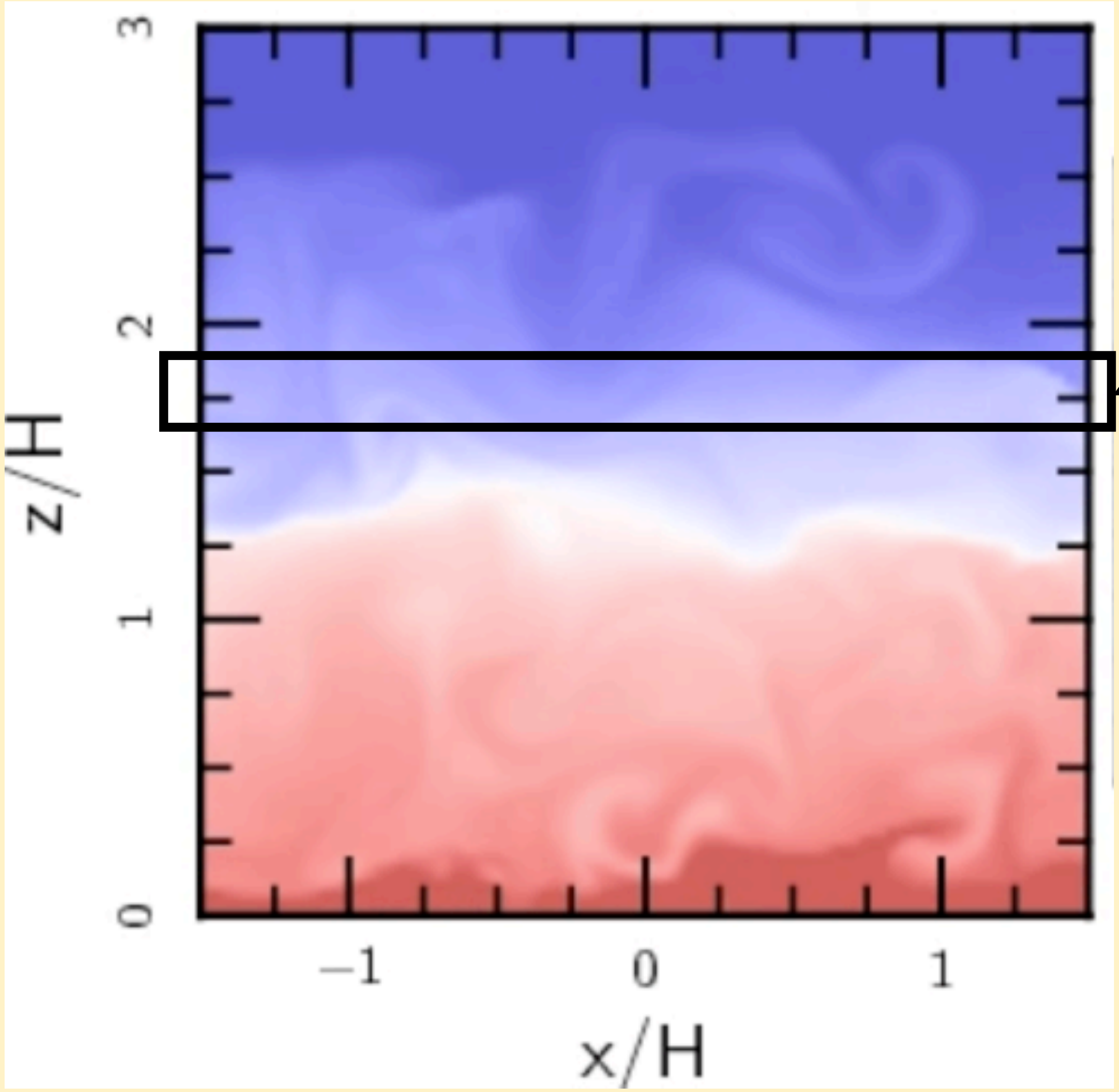

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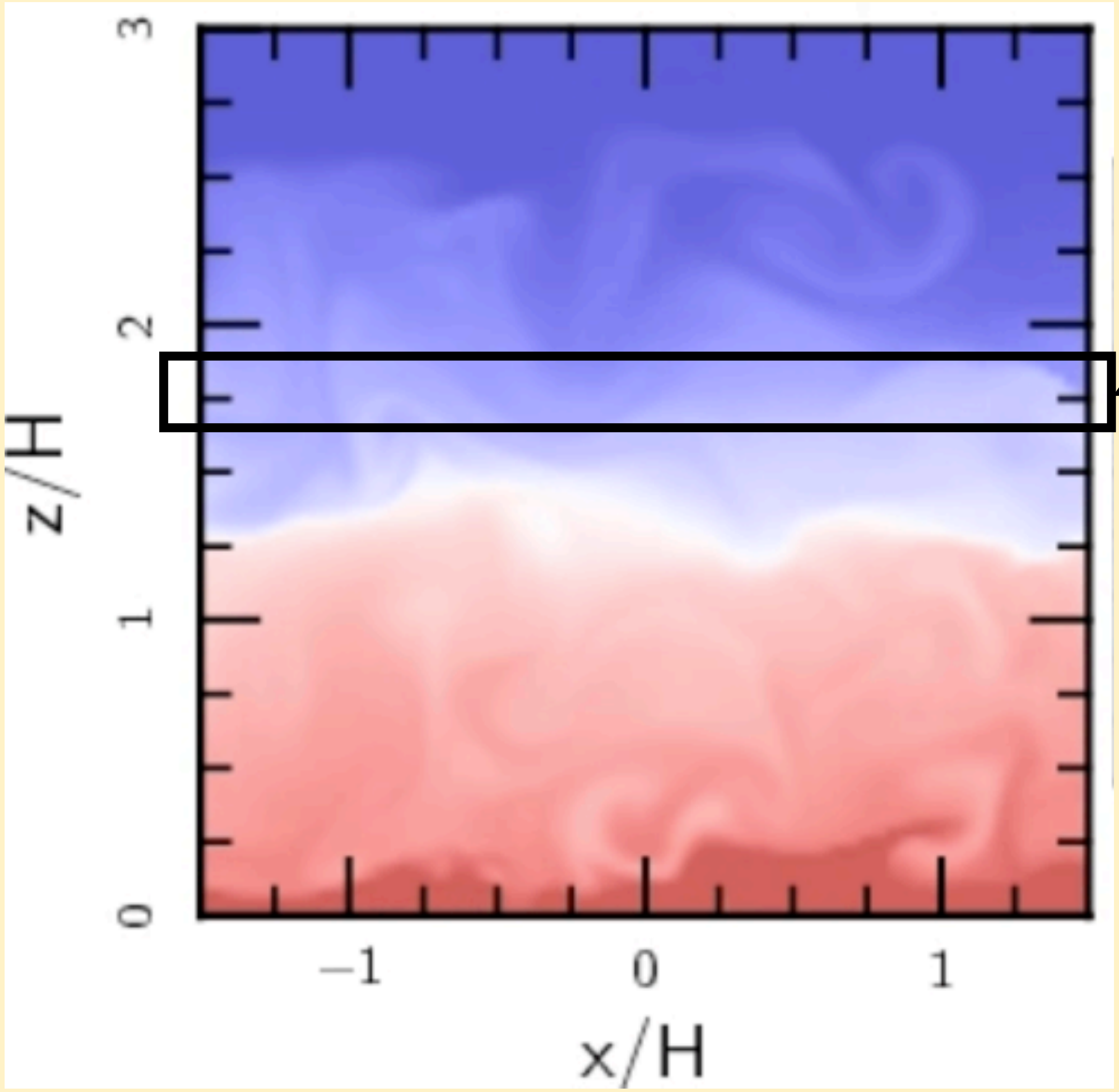

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Globally Thermally Stable

Timescales and Theory

Cooling Time: $$t_{\rm cool} = \frac{\gamma}{\gamma-1}\frac{nk_BT}{n^2\Lambda(T)} = \frac{5}{2}\frac{T^{1/2}}{n\Lambda_0}$$ (Pure Bremsstrahlung)

Free-fall Time: $$t_{\rm ff} = \left(\frac{2H}{g_0}\right)^{1/2}$$

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Multiphase Structure when: $t_{\rm cool} \ll t_{\rm ff}$

$$t_{\rm cool}/t_{\rm ff} = 1/10$$

Multiphase Structure

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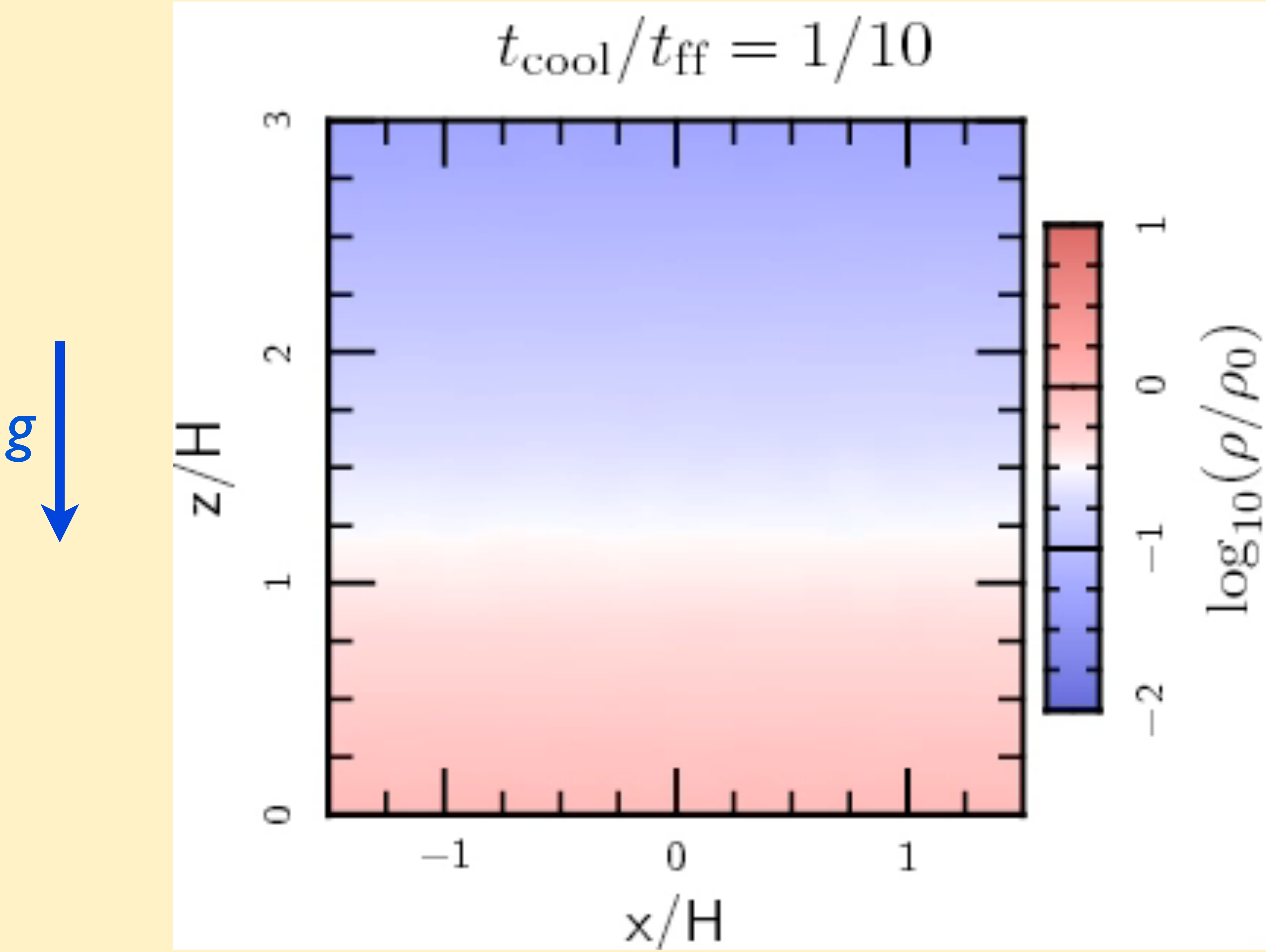

Multiphase Structure

$$t_{\rm cool}/t_{\rm ff} = 10$$

No Multiphase Structure

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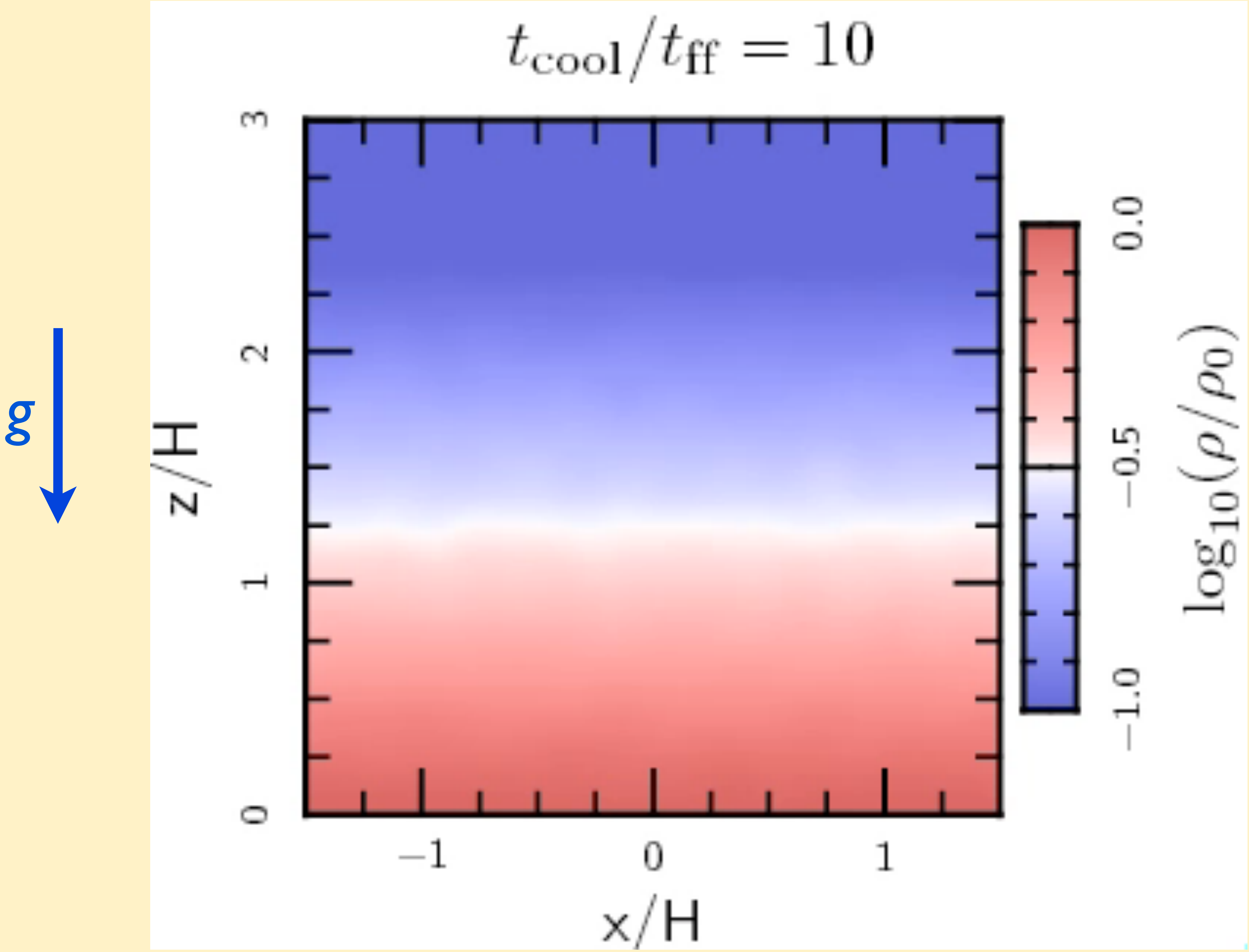
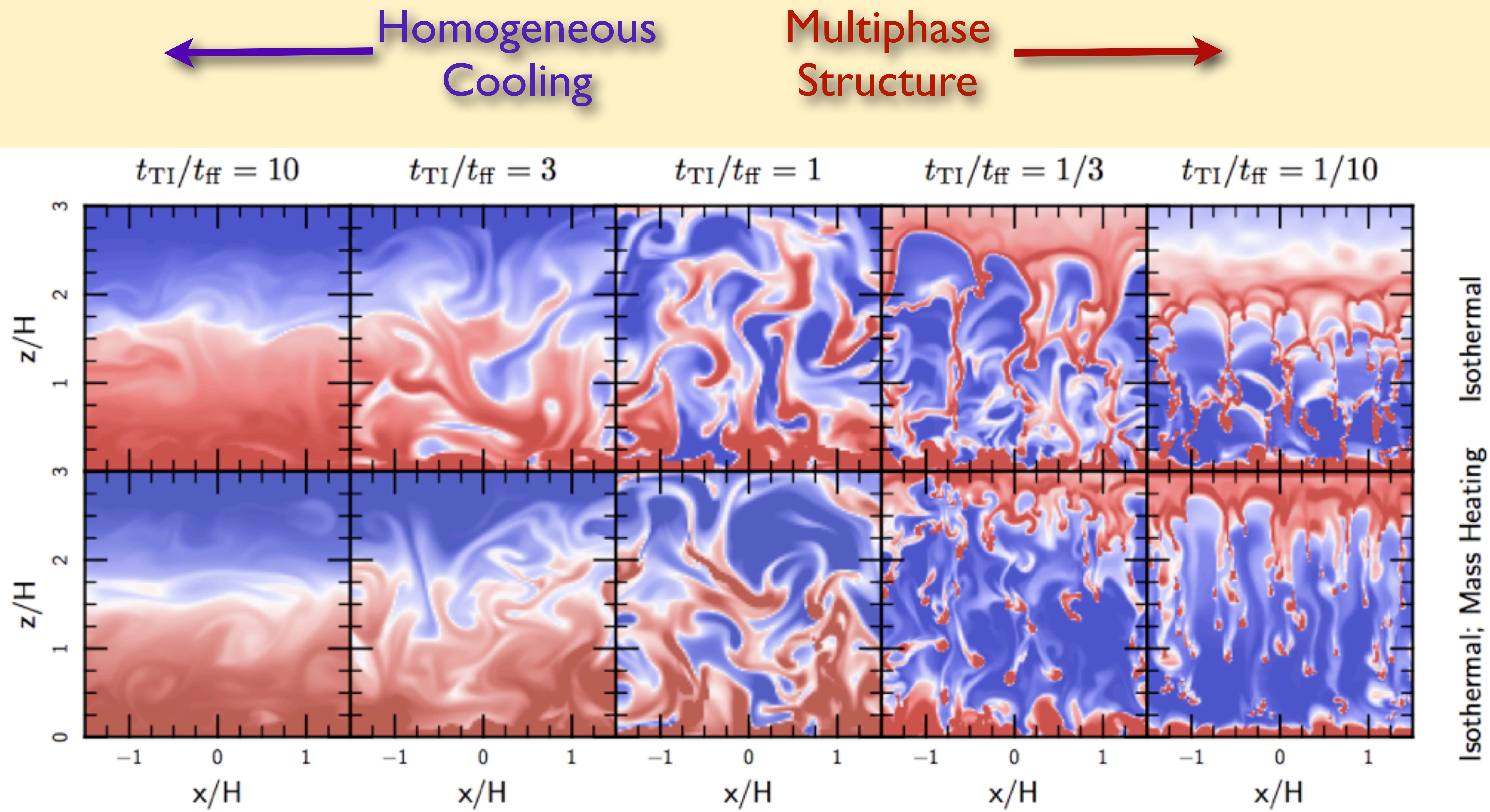


No Multiphase Structure

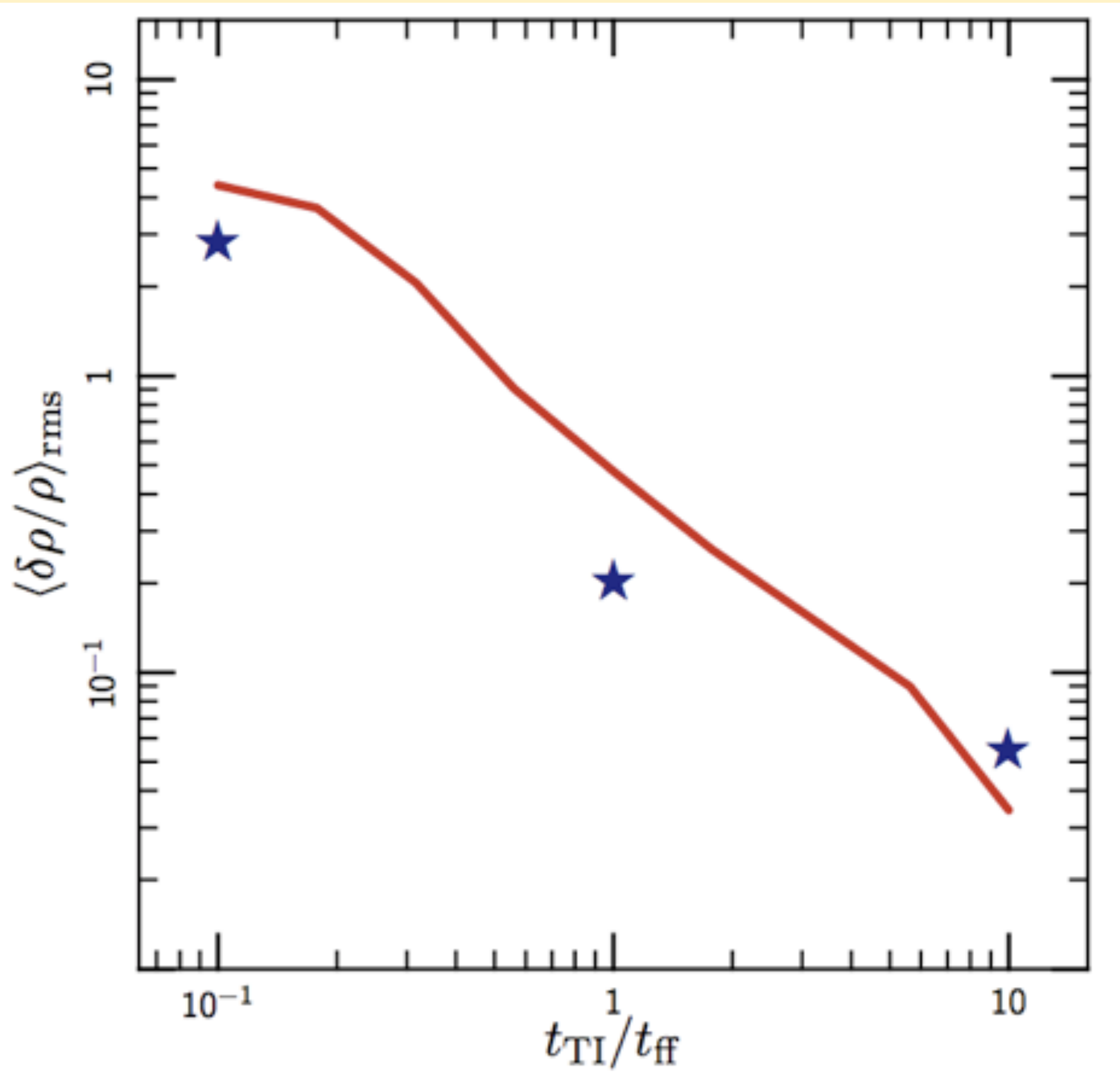
Multiphase Structure



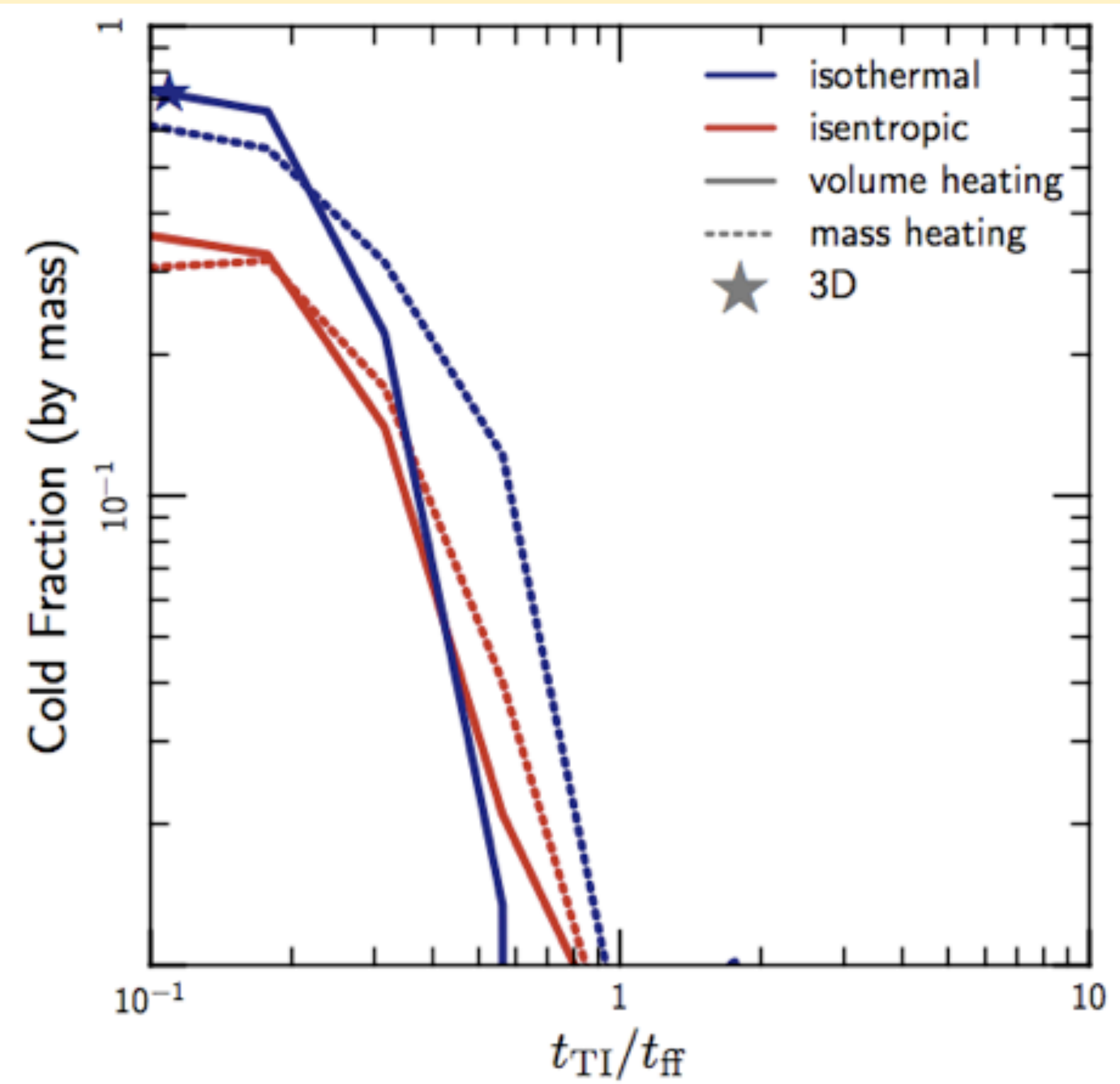
(Density snapshot for volumetric or mass-weighted heating)

Multiphase Structure Quantitatively

(Density Perturbations)



(Cold Fraction)



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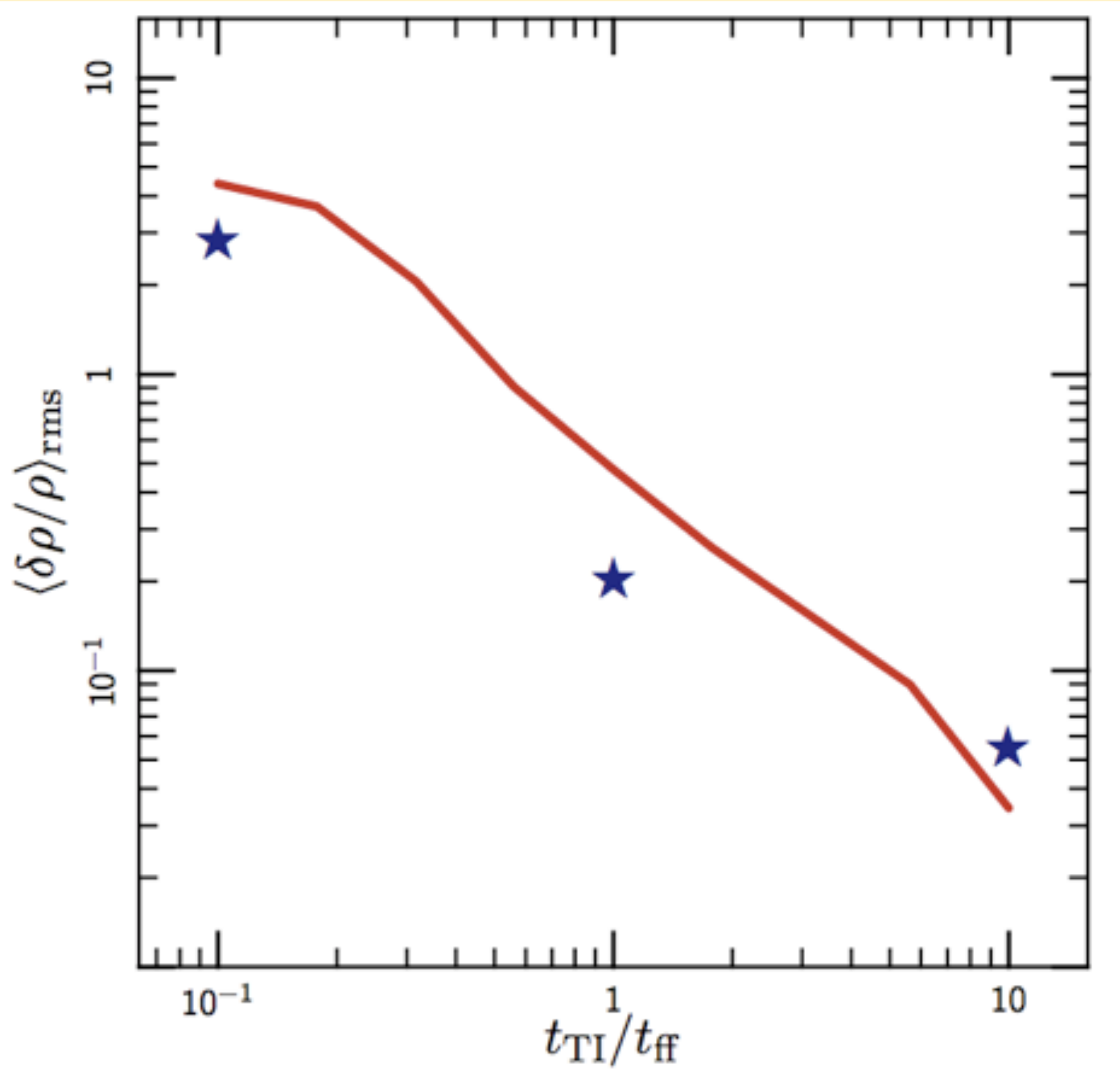

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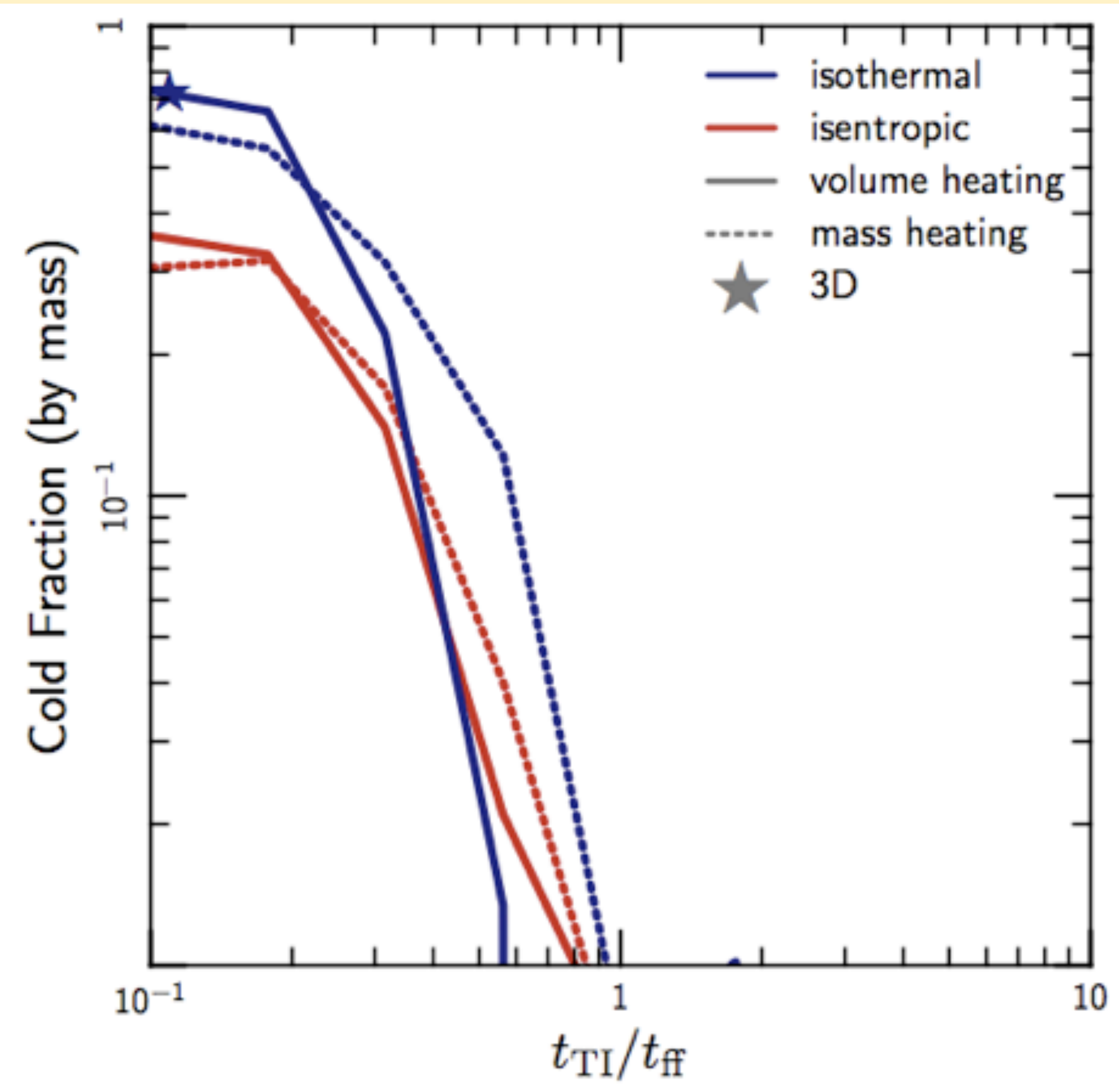

- Amplitude of $\delta\rho/\rho$ strong function of cooling versus gravity.

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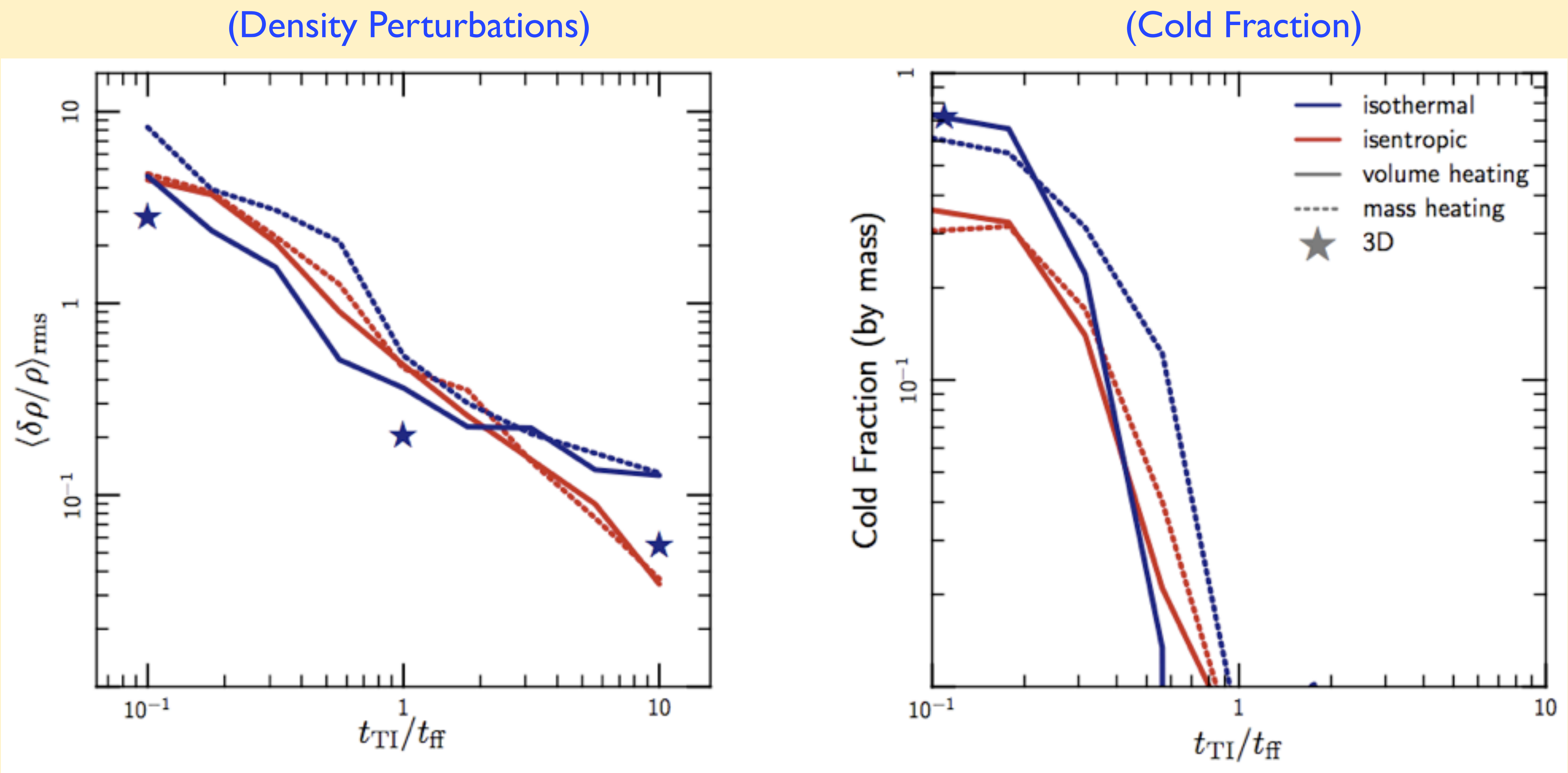

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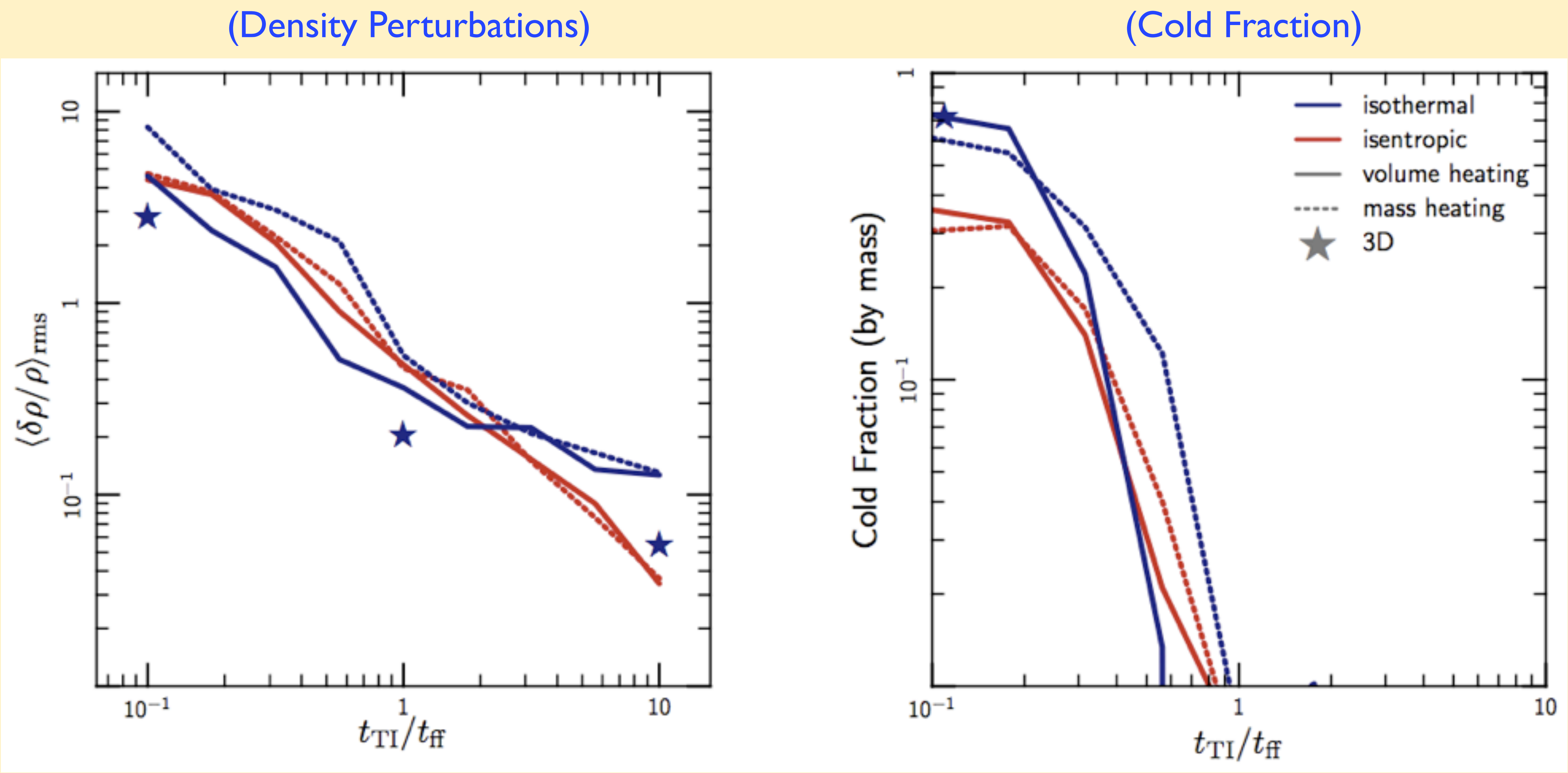

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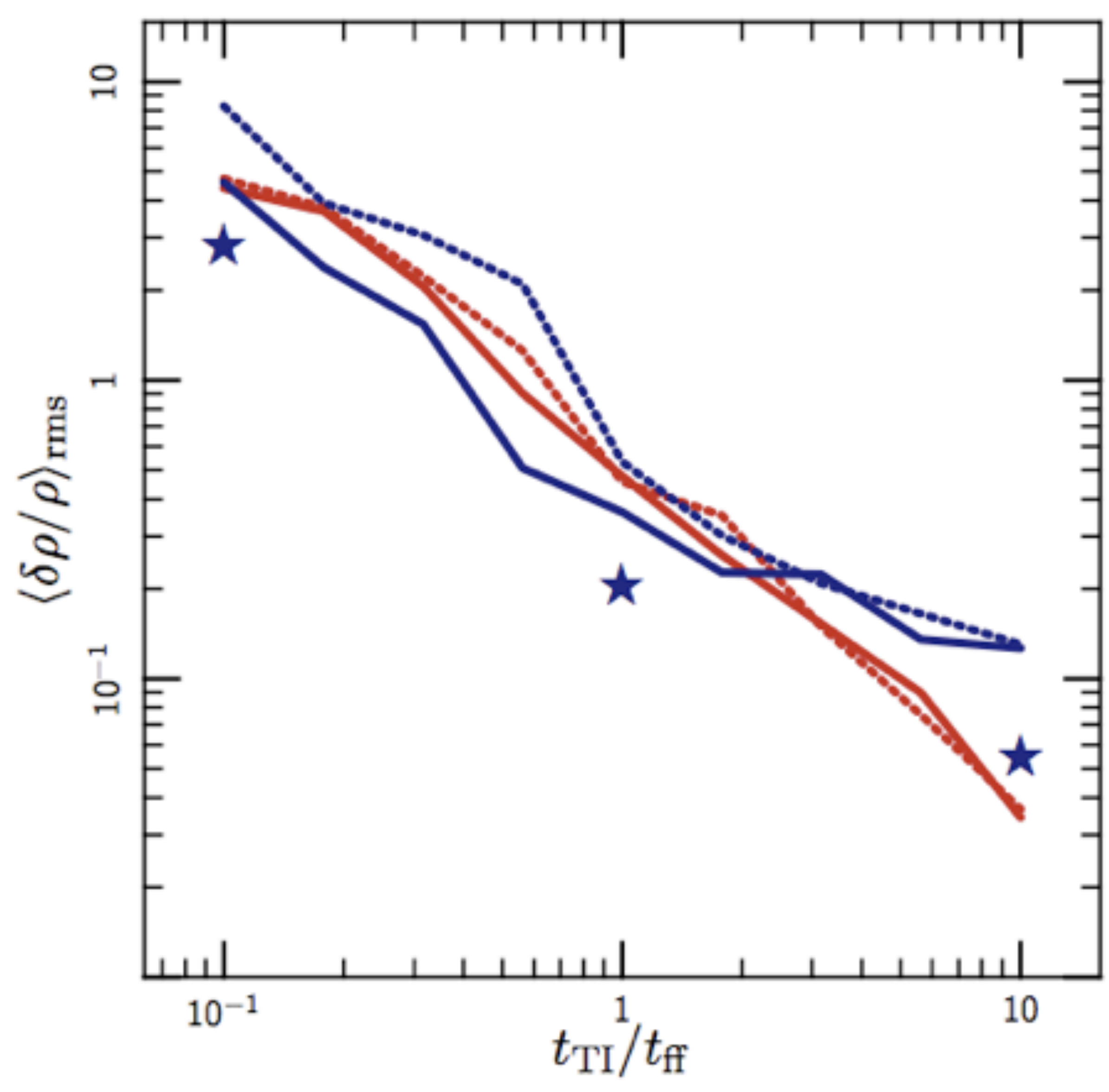

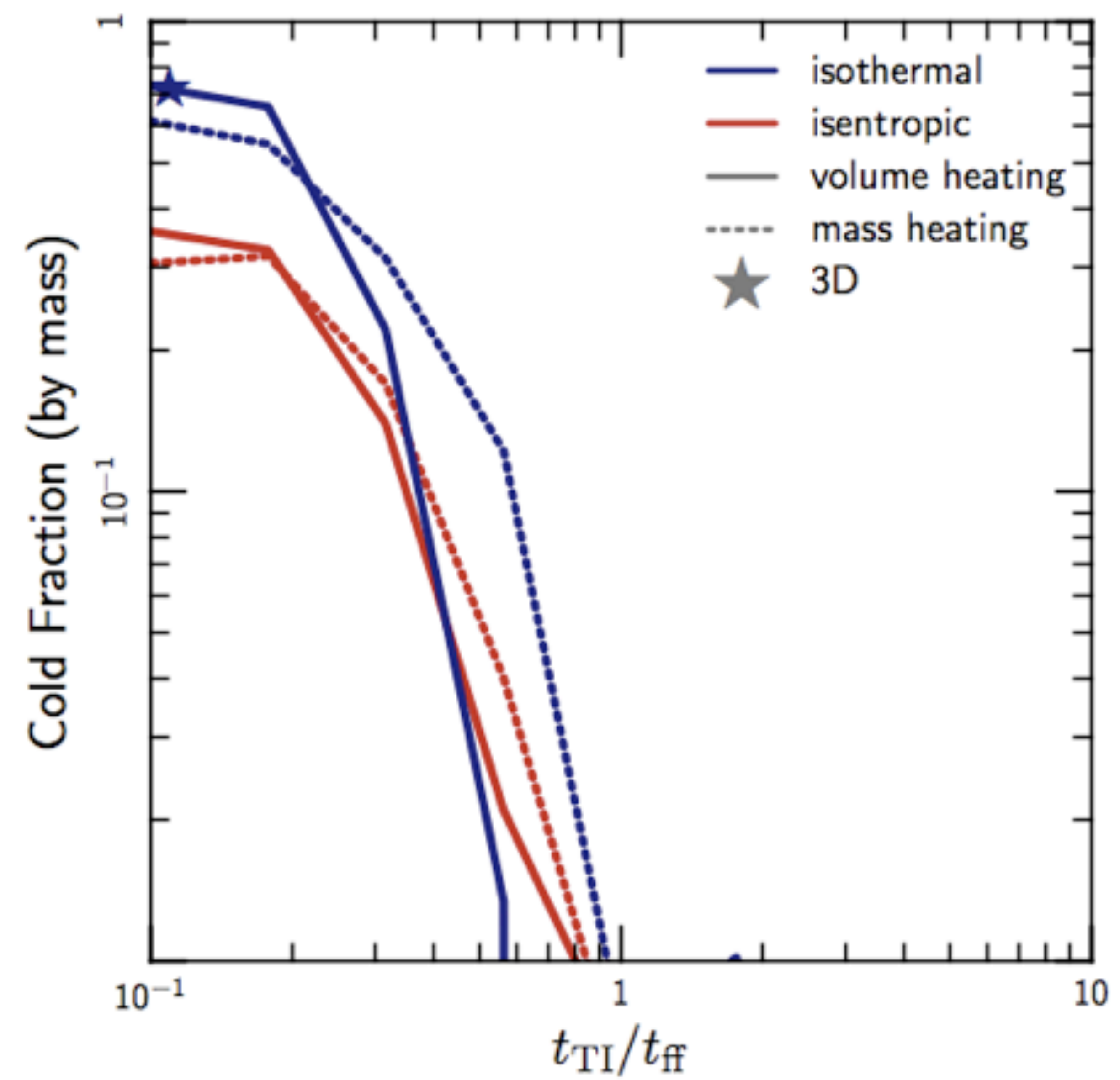

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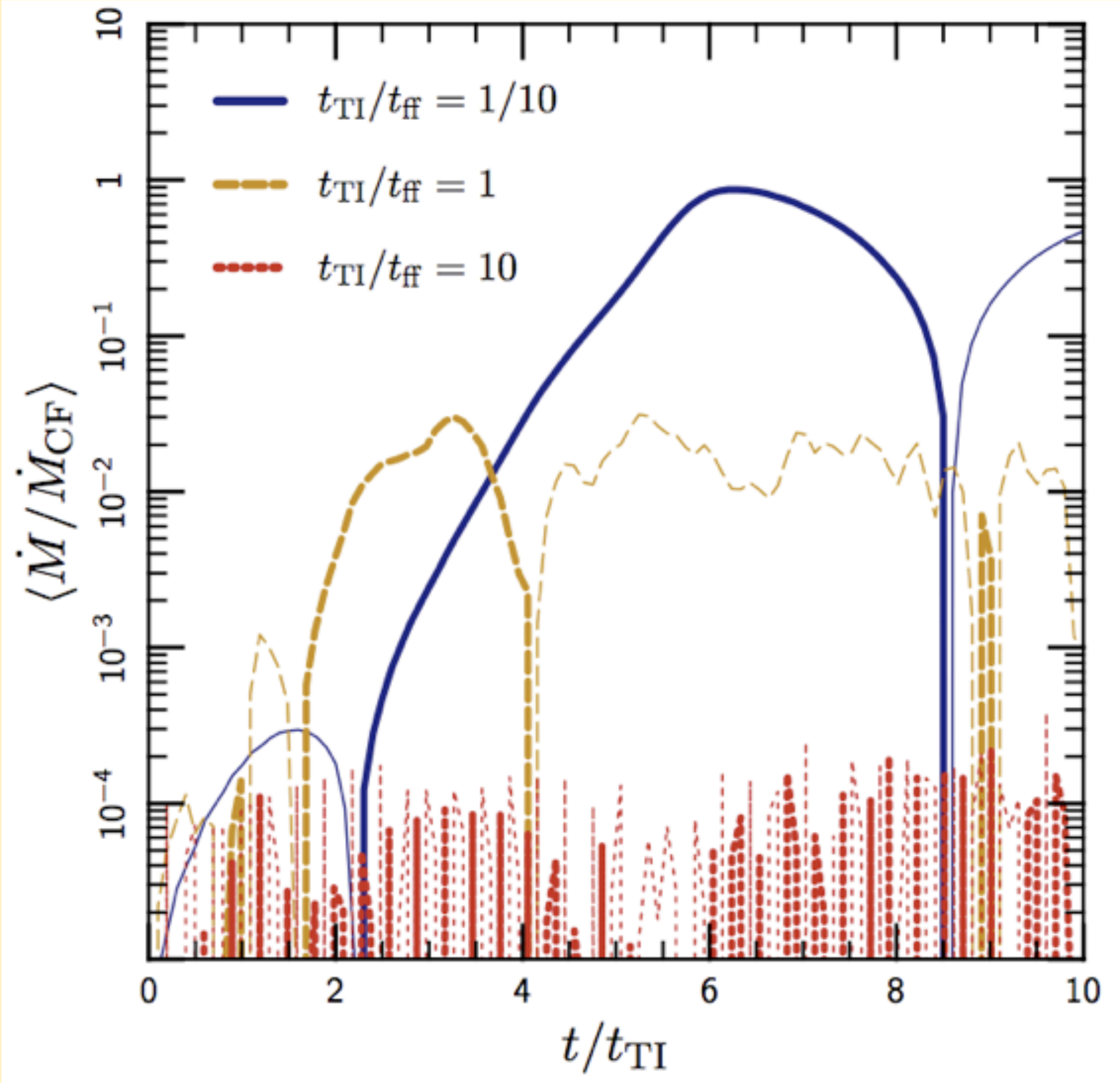
- Gas in the cold phase drops precipitously as $t_{\rm TI} \sim t_{\rm ff}$.
- Waiting longer for weak cooling, does not change results.

Suppression of Mass Accretion Rate

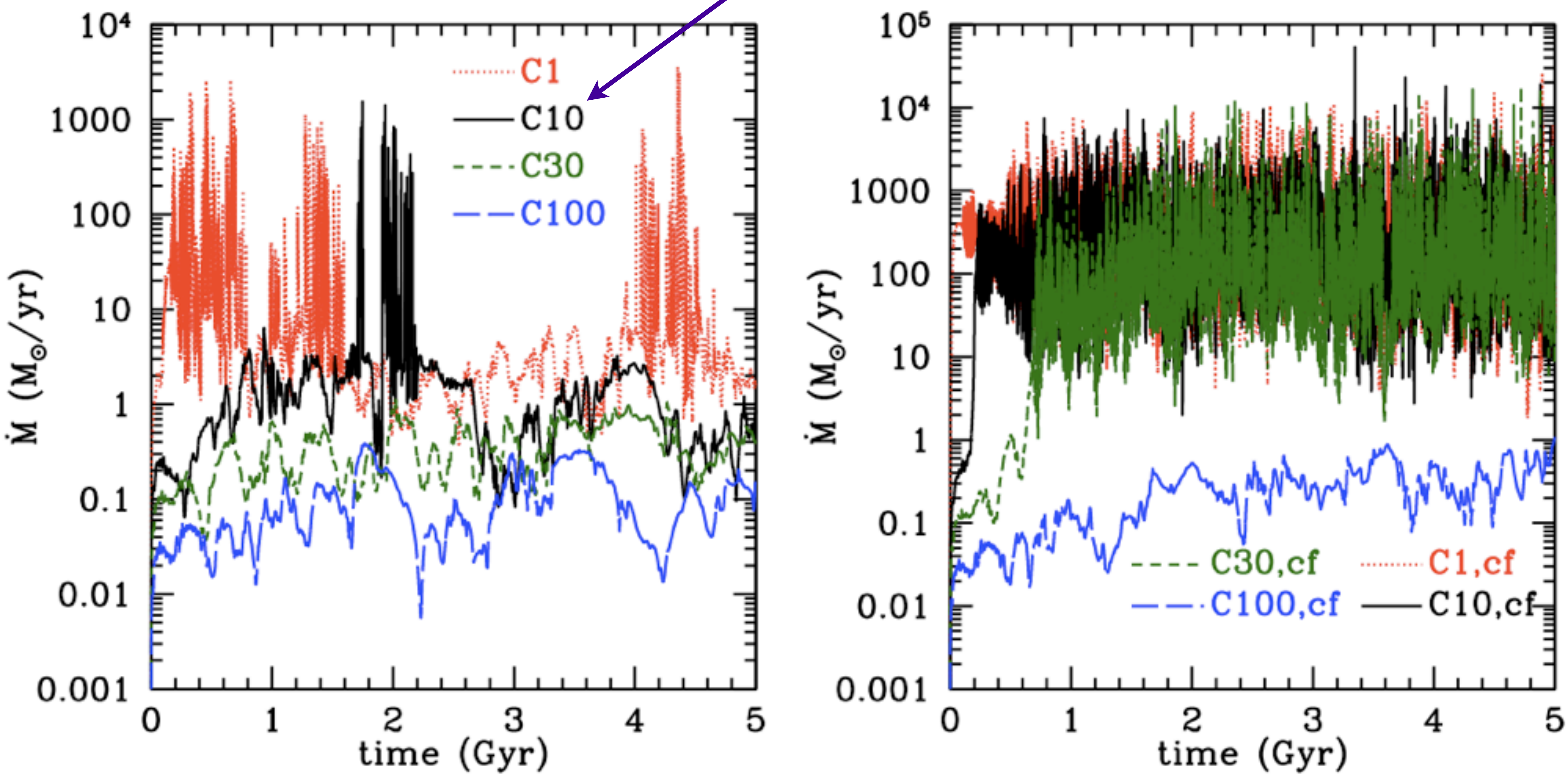


(Thick lines = outflow, Thin lines=inflow)

In real cluster models get 0.01-0.1 suppression as well.

Suppression of Mass Accretion Rate

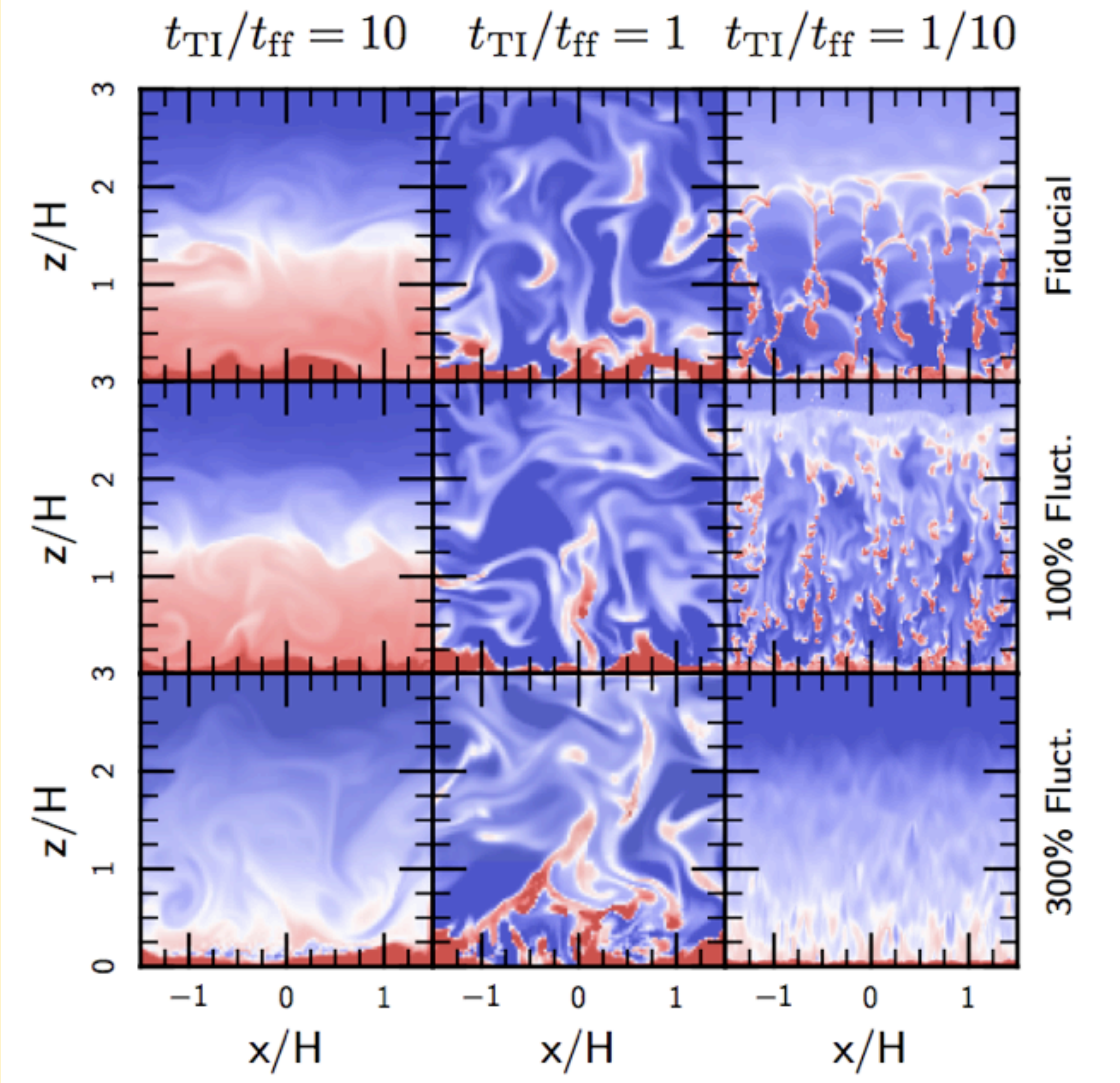
Initial Central Entropy K_0 (keV cm^{-2})



Heating = Cooling

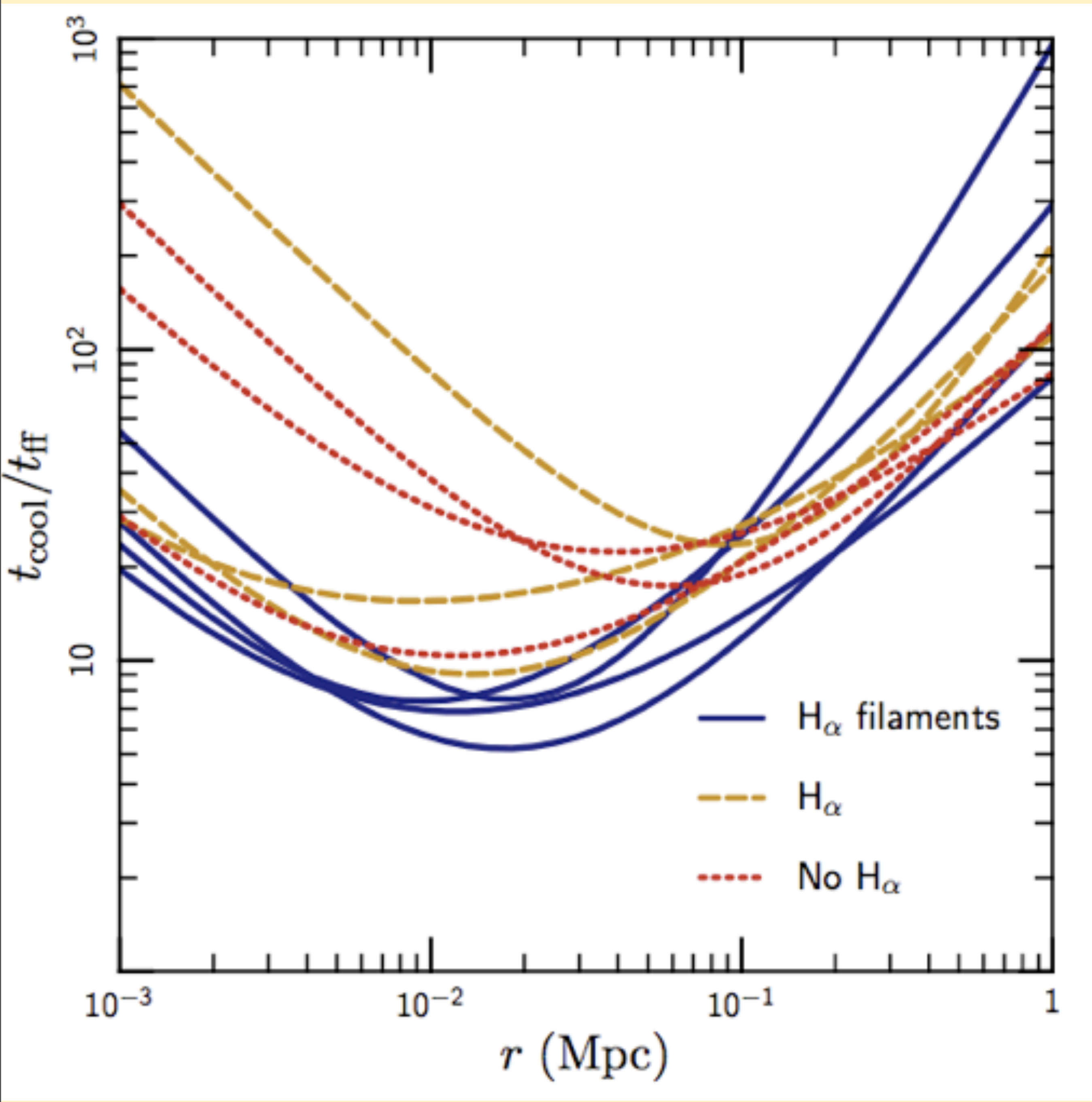
No Heating, pure C.F.

Not such a crazy *Ansatz*



$$\mathcal{H} \rightarrow \mathcal{H}(1 + \delta)$$

Tantalizing Hints in Real Data



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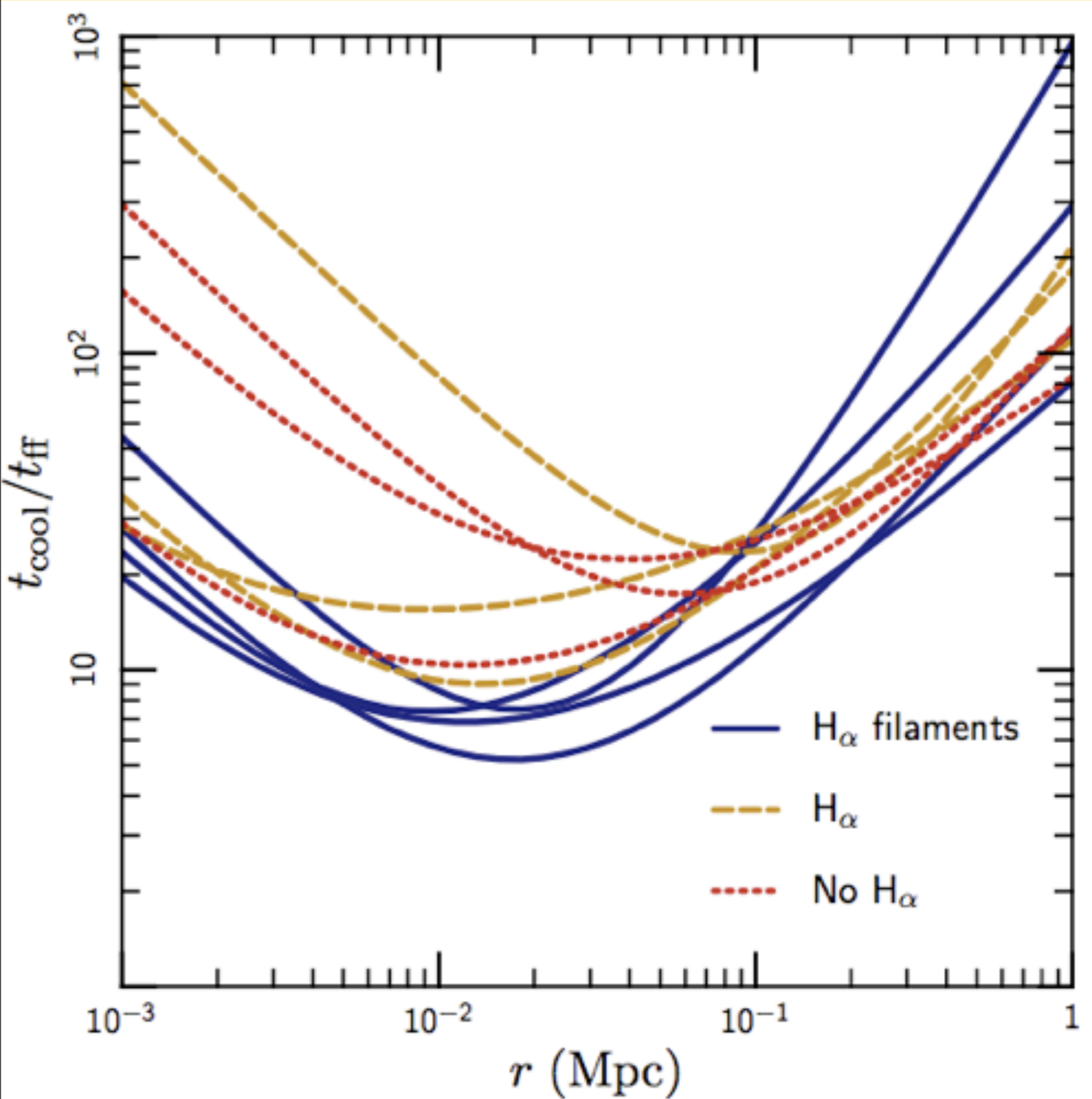

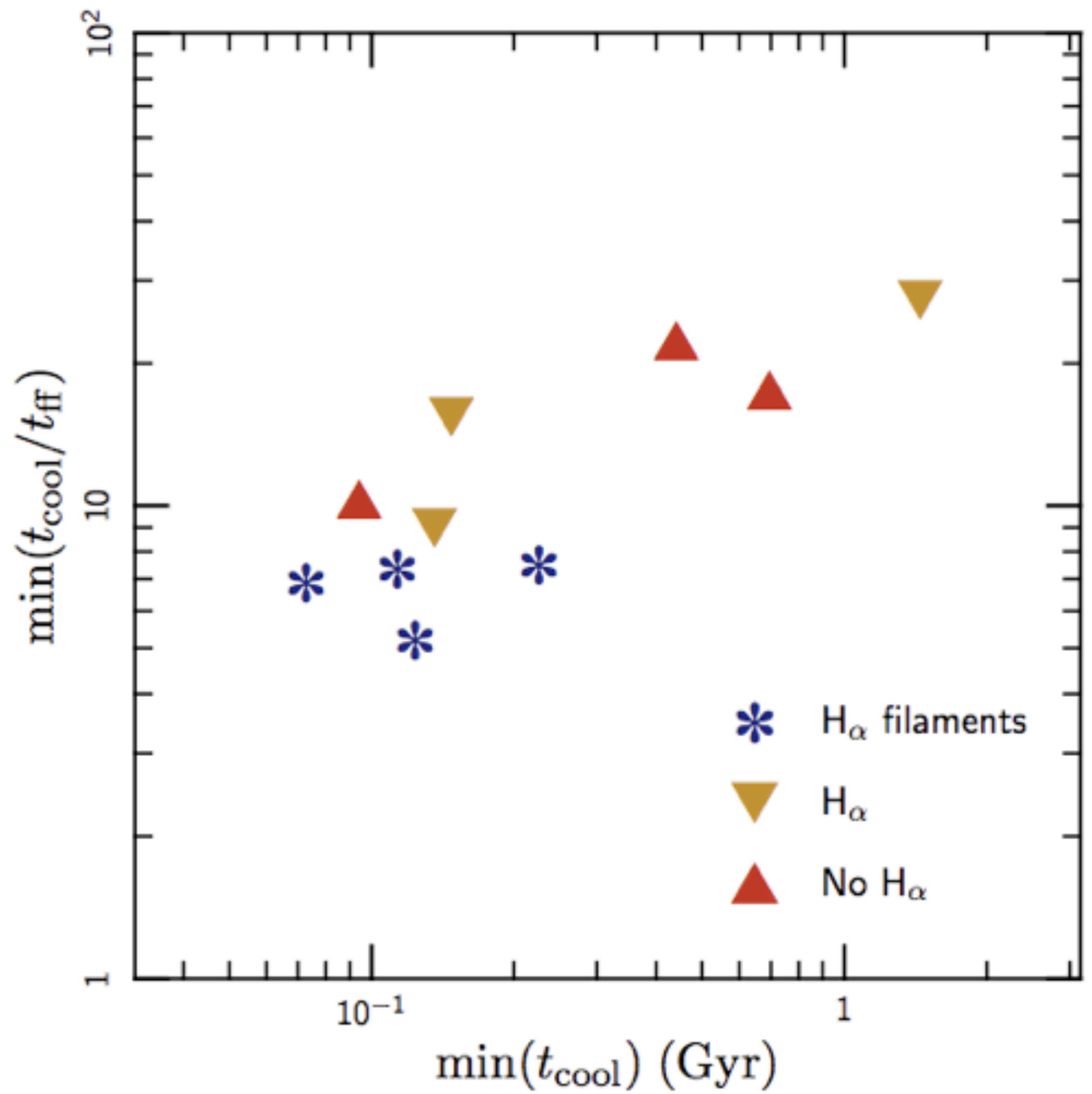

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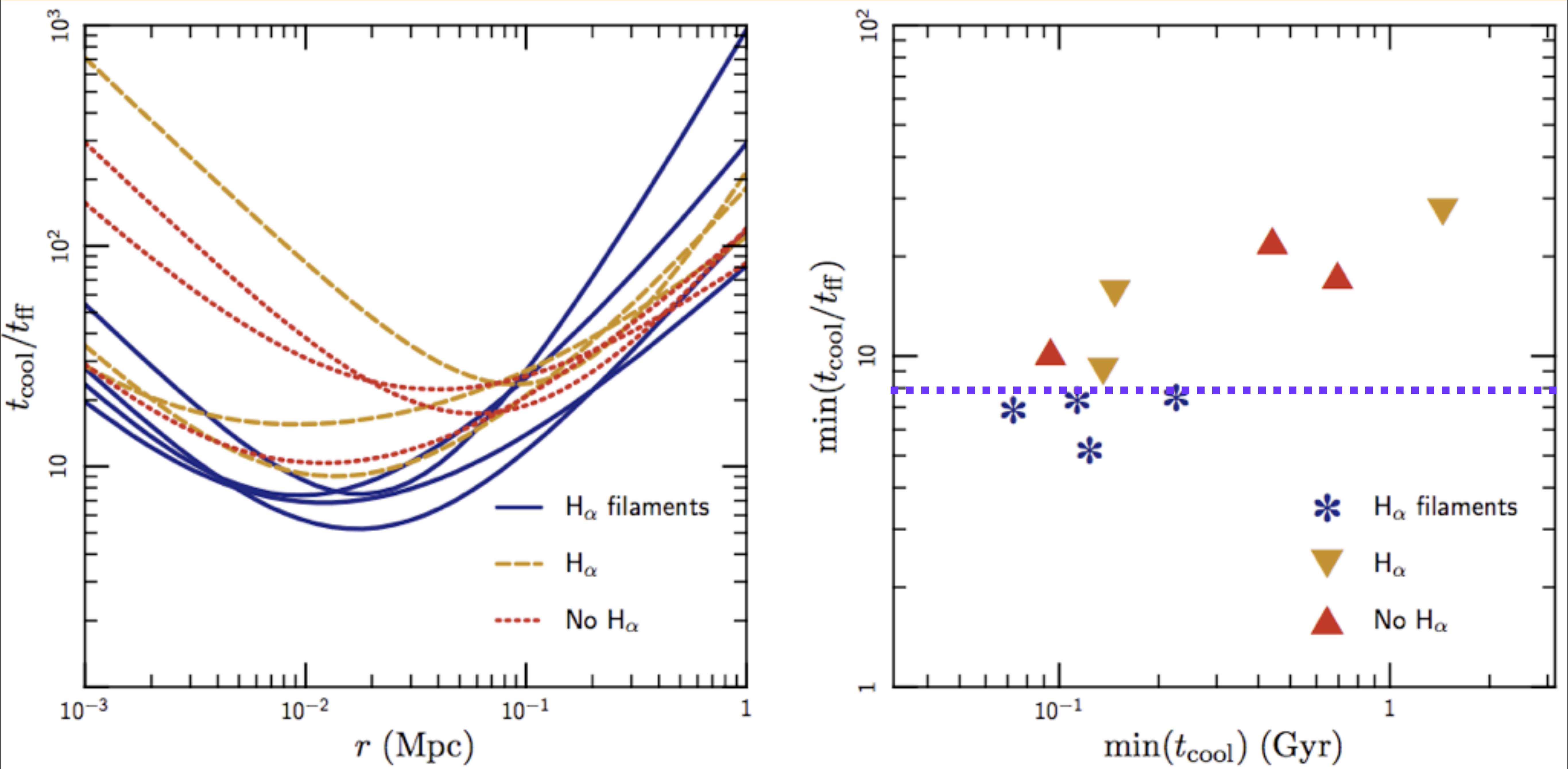

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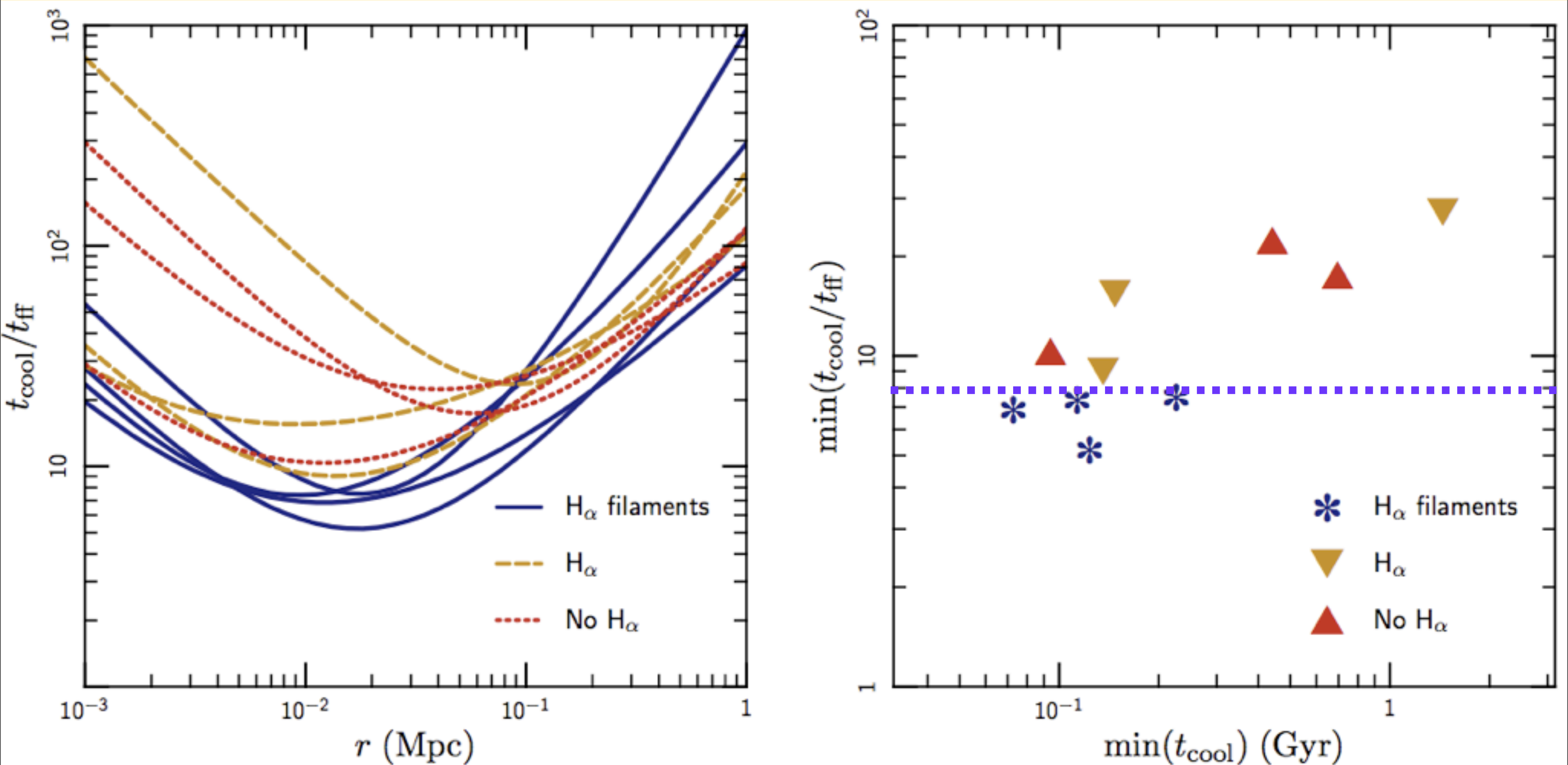

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- Suggests filaments occur below critical value of $t_{cool/}t_{crit}$~8.
- Good agreement with cluster model simulations.

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Claim: Thermal instability requires convective instability in a stratified atmosphere

$$\frac{\partial s}{\partial r} < 0$$

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Resolution: Cooling flows don't exist, so this is not appropriate.

Summary and Conclusions

- Galaxy clusters are globally thermally stable, and *sometimes* locally thermally unstable.
- If $t_{TI} < t_{ff}$, then multiphase structure is formed.
- A reasonable heating model can reduce the mass fluxes to values below the cooling flow value.
- It will be a lot of work figuring out this reasonable and robust heating model.