The Role of the MTI and HBI in the Intracluster Medium

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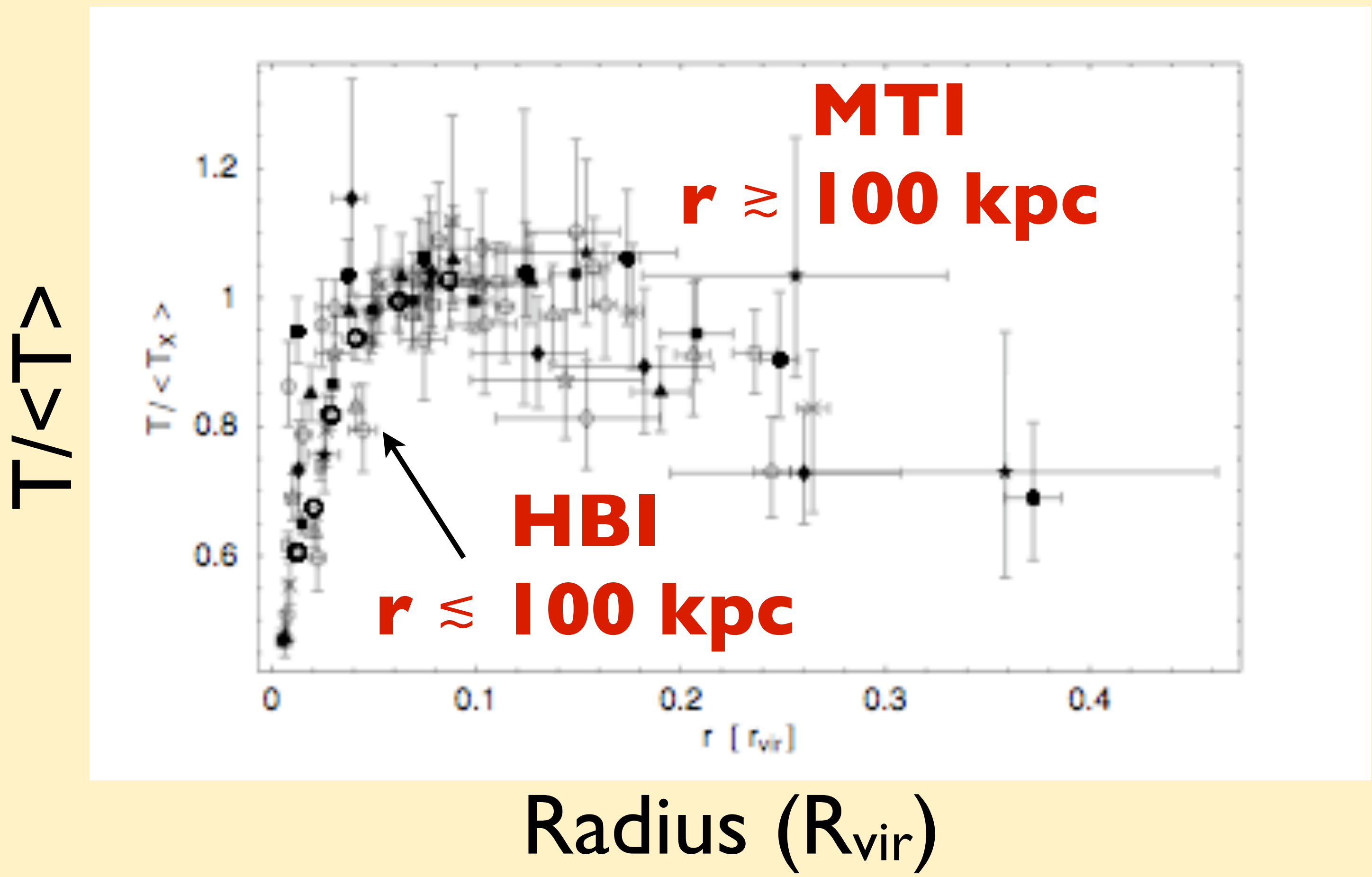
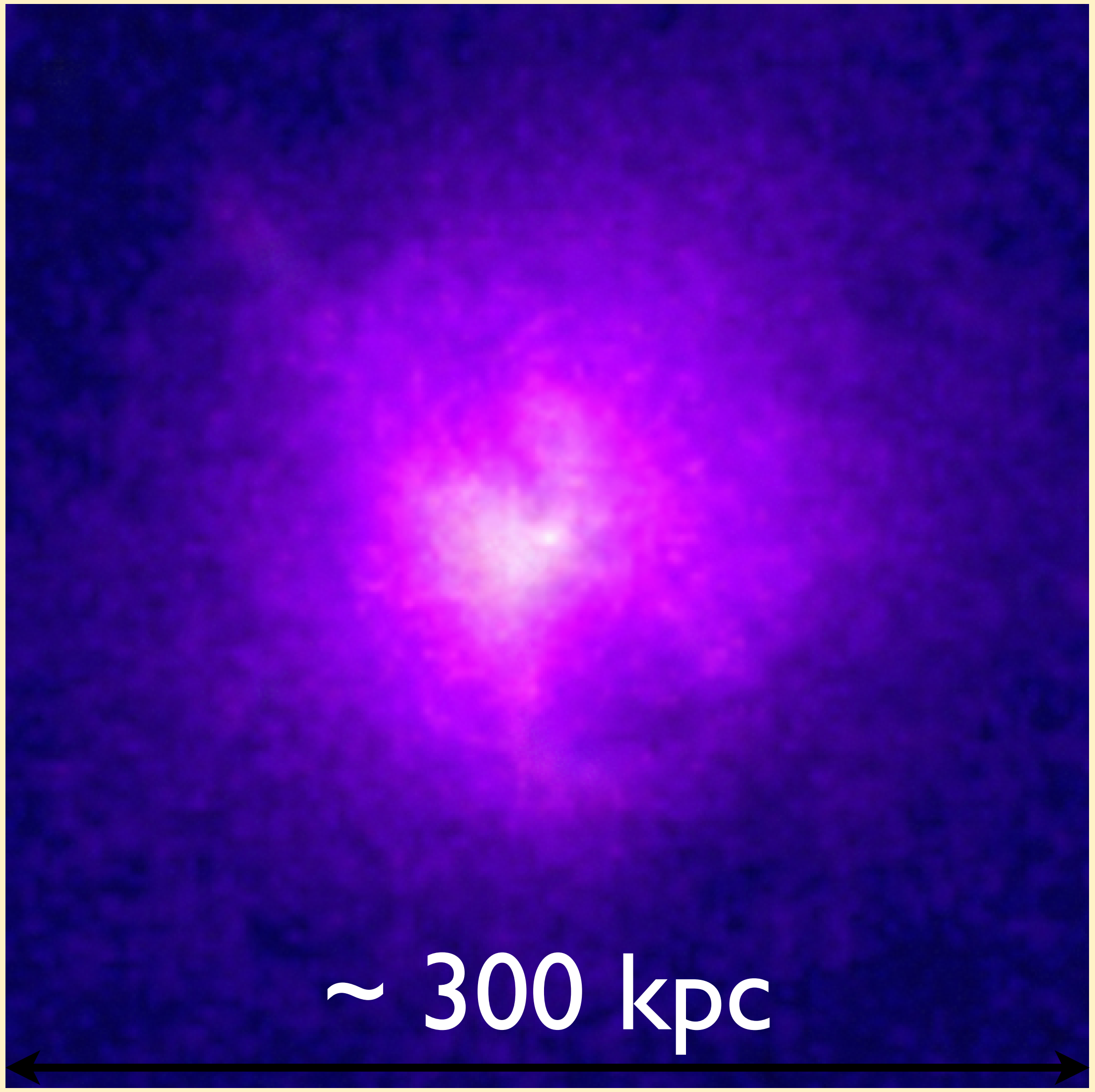
Monsters, Inc.
KITP
March 15, 2011

The MTI & HBI in Clusters

average cluster temperature profile

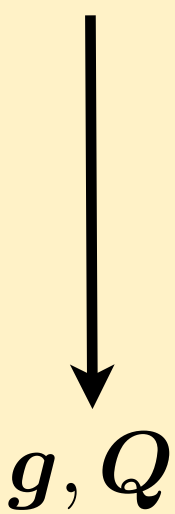


Piffaretti et al. 2005



The Entire Cluster is Convectively Unstable!

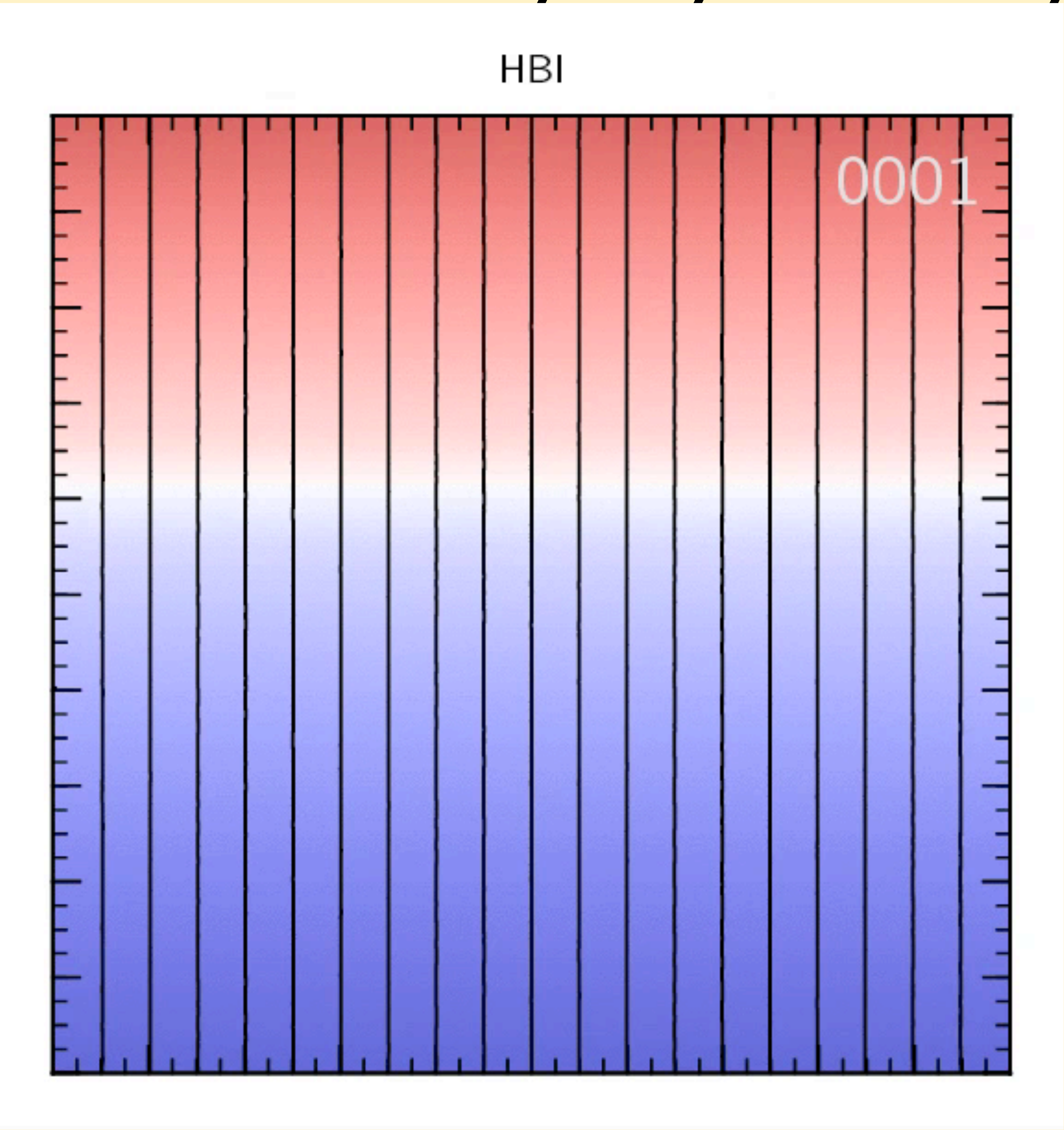
Heat-Flux Driven Buoyancy Instability (HBI)



Quataert (2008)
Parrish & Quataert (2008)

Heat-Flux Driven Buoyancy Instability (HBI)

$\boldsymbol{g}, \boldsymbol{Q}$



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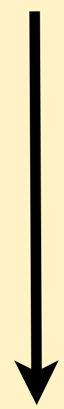

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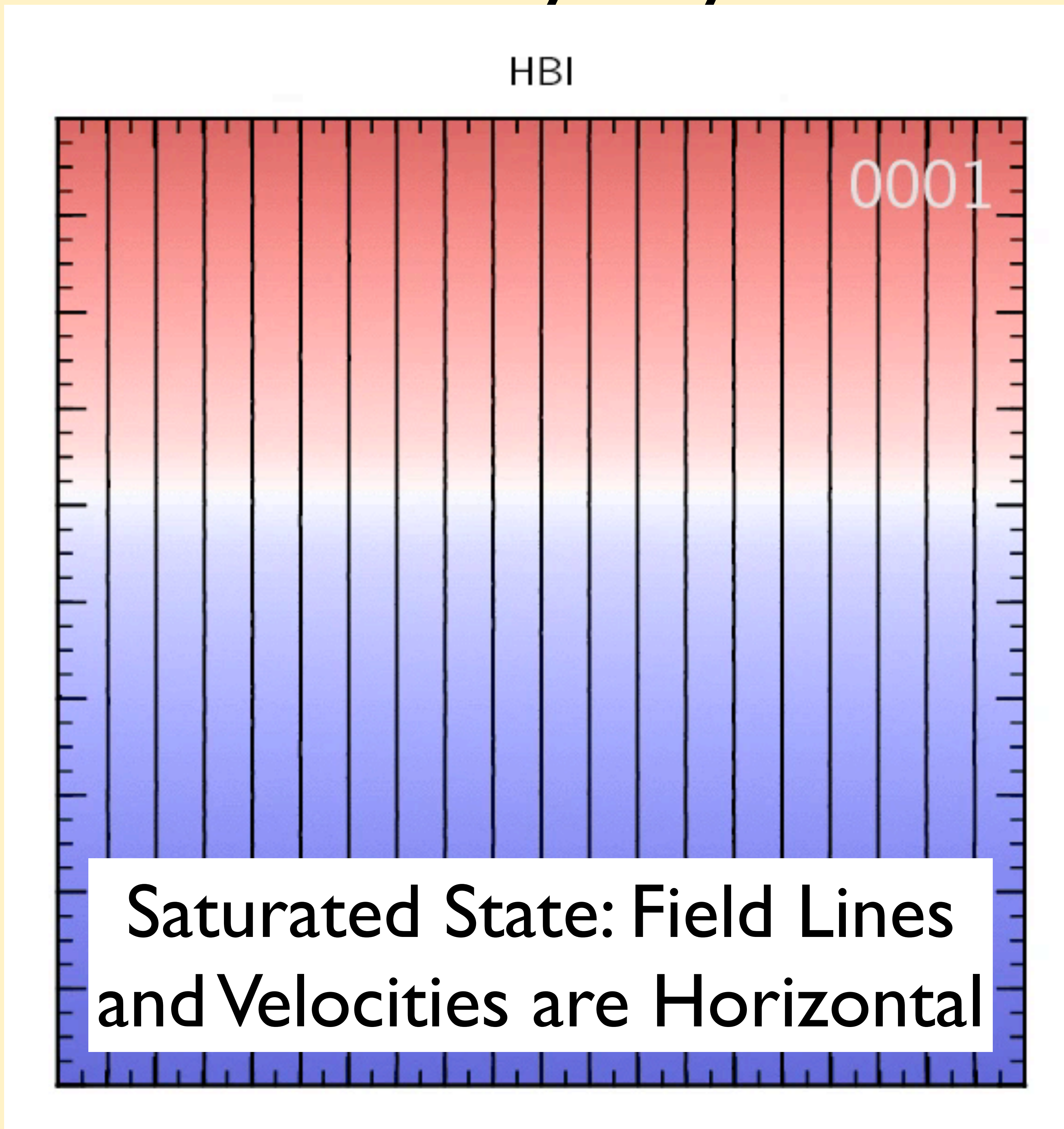
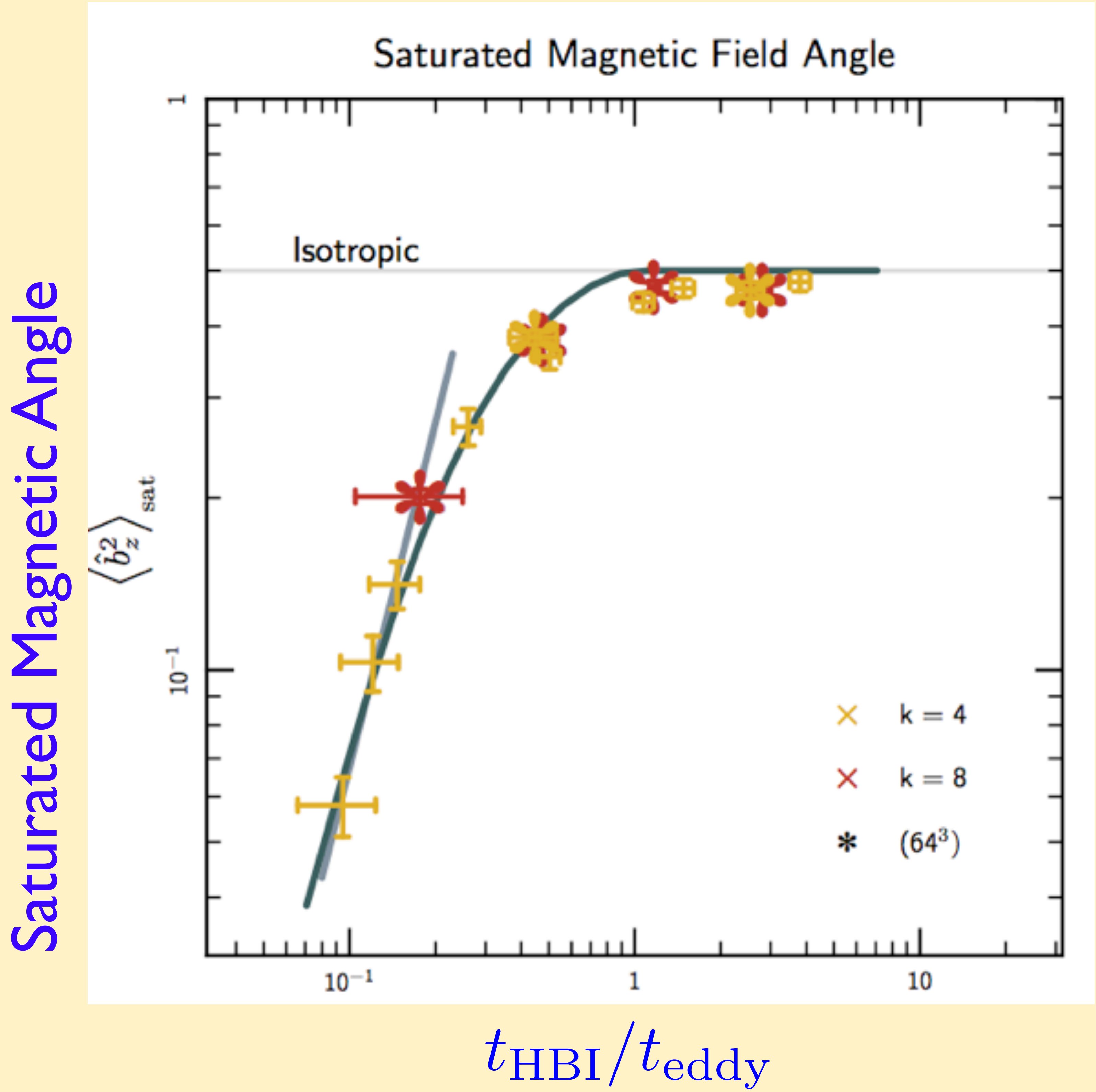


Saturated State: Field Lines and Velocities are Horizontal

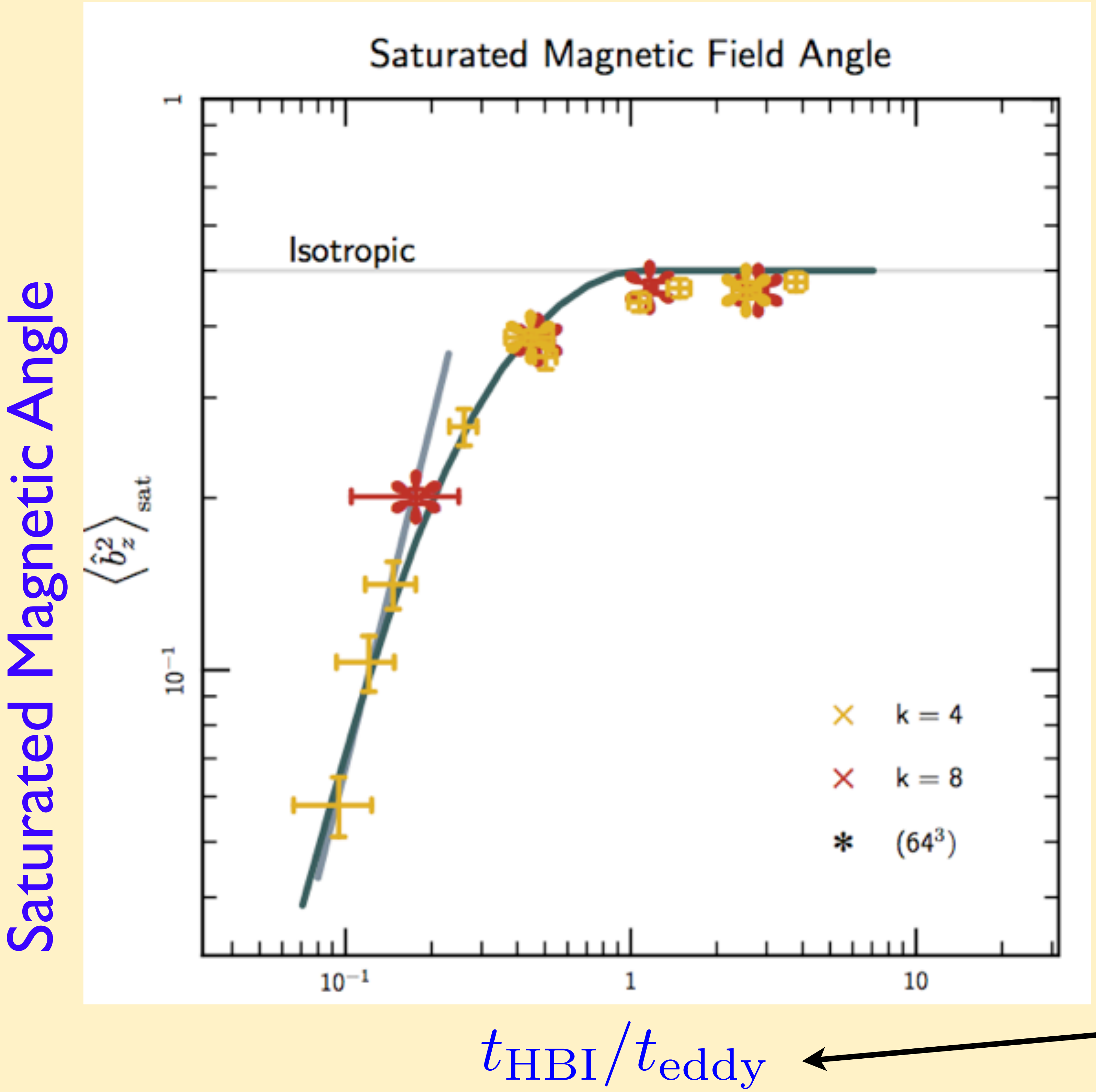
Quataert (2008)
Parrish & Quataert (2008)

The HBI and Turbulence



McCourt, Parrish, Sharma, & Quataert (2011)

The HBI and Turbulence



Richardson Number (Ri)

$$\mathrm{Ri} = \mathrm{Fr}^{-1/2}$$

McCourt, Parrish, Sharma, & Quataert (2011)

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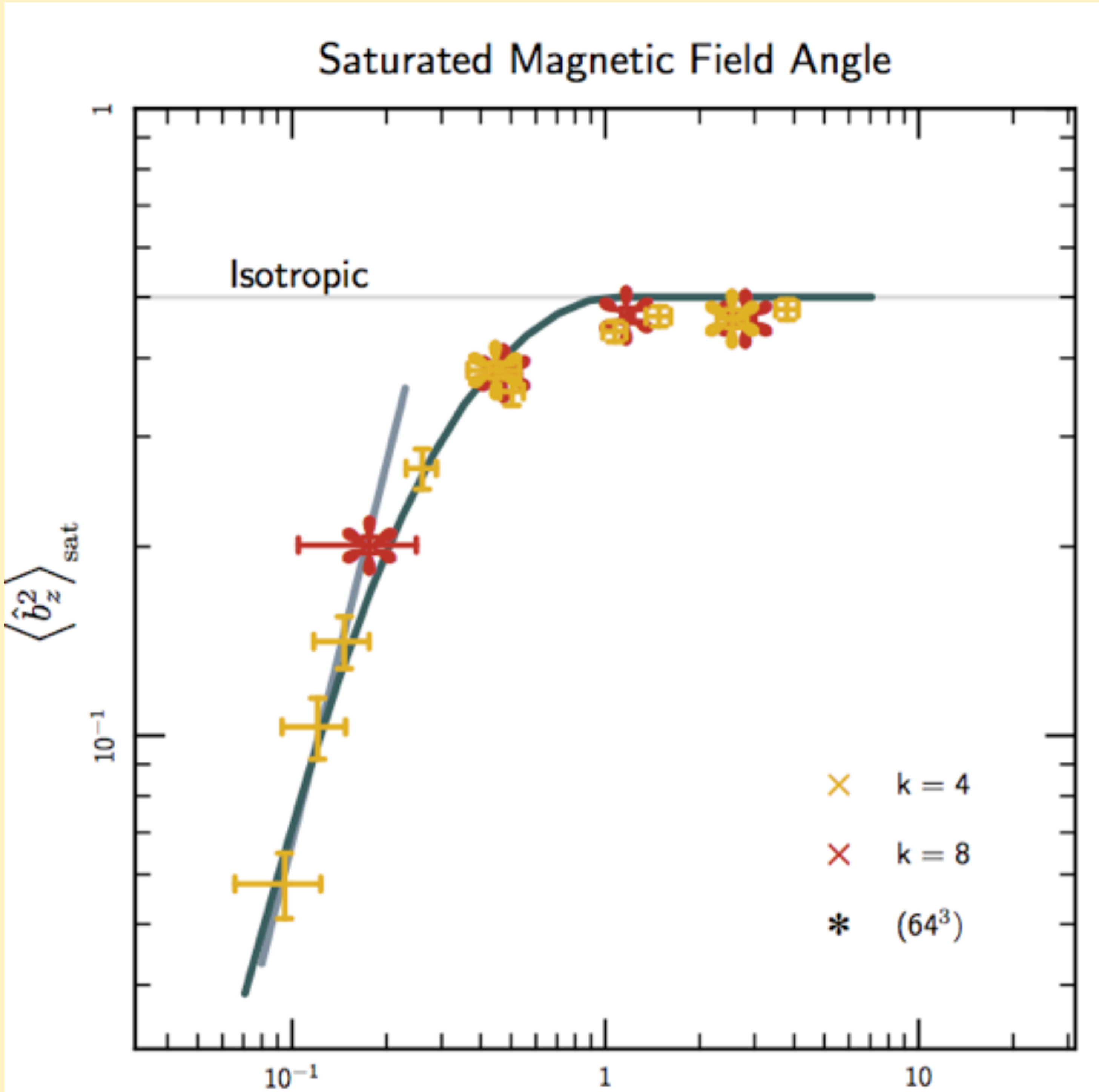

Saturated Magnetic Angle

$t_{\rm HBI}/t_{\rm eddy}$

McCourt, Parrish, Sharma, & Quataert (2011)

Two Limits:

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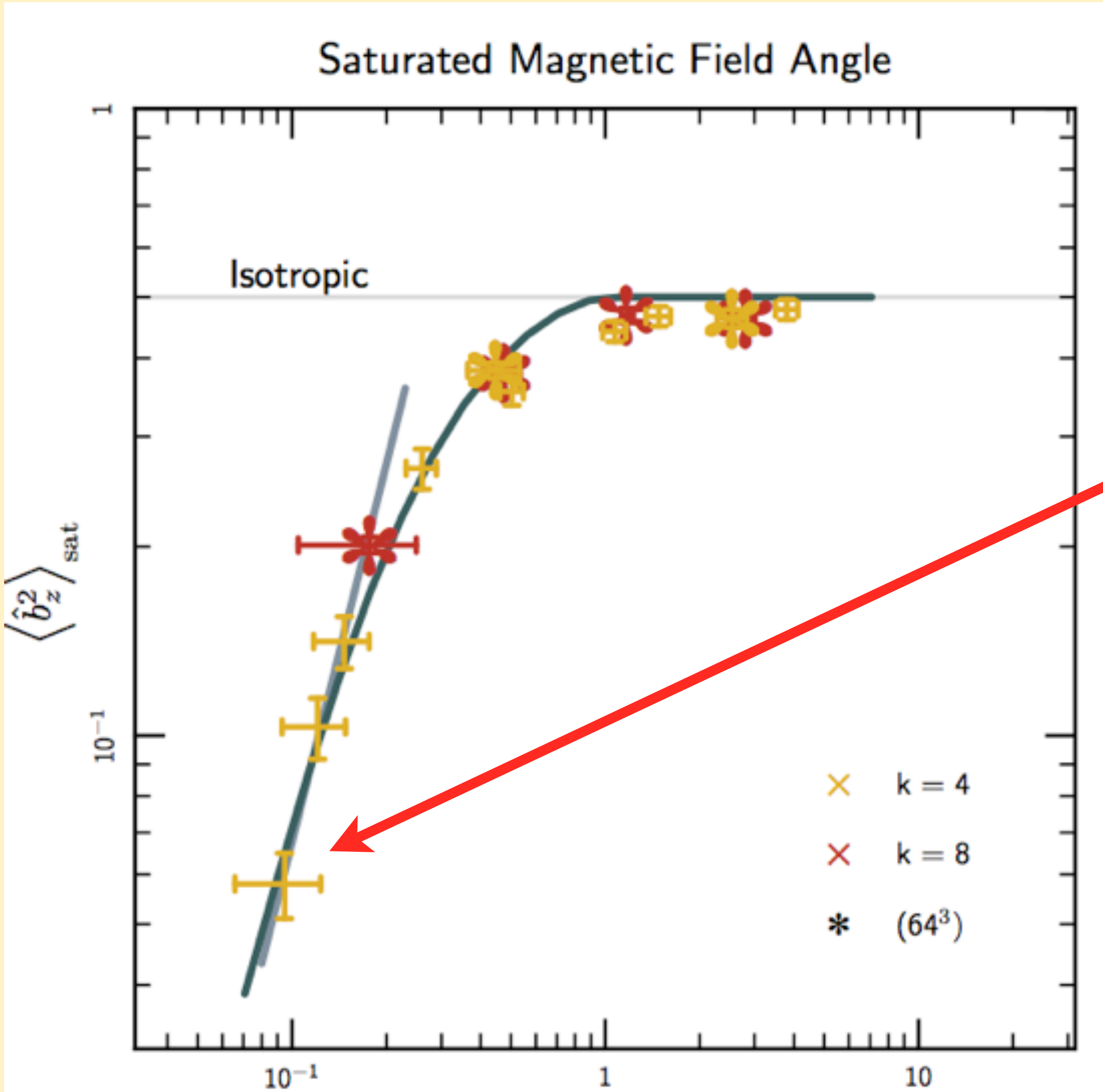
The HBI and Turbulence



Saturated Magnetic Angle

$t_{\rm HBI}/t_{\rm eddy}$

Two Limits:

1) HBI efficient:

$t_{\rm HBI} < t_{\rm eddy}$

$f_{\rm Sp} \to 0$

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McCourt, Parrish, Sharma, & Quataert (2011)

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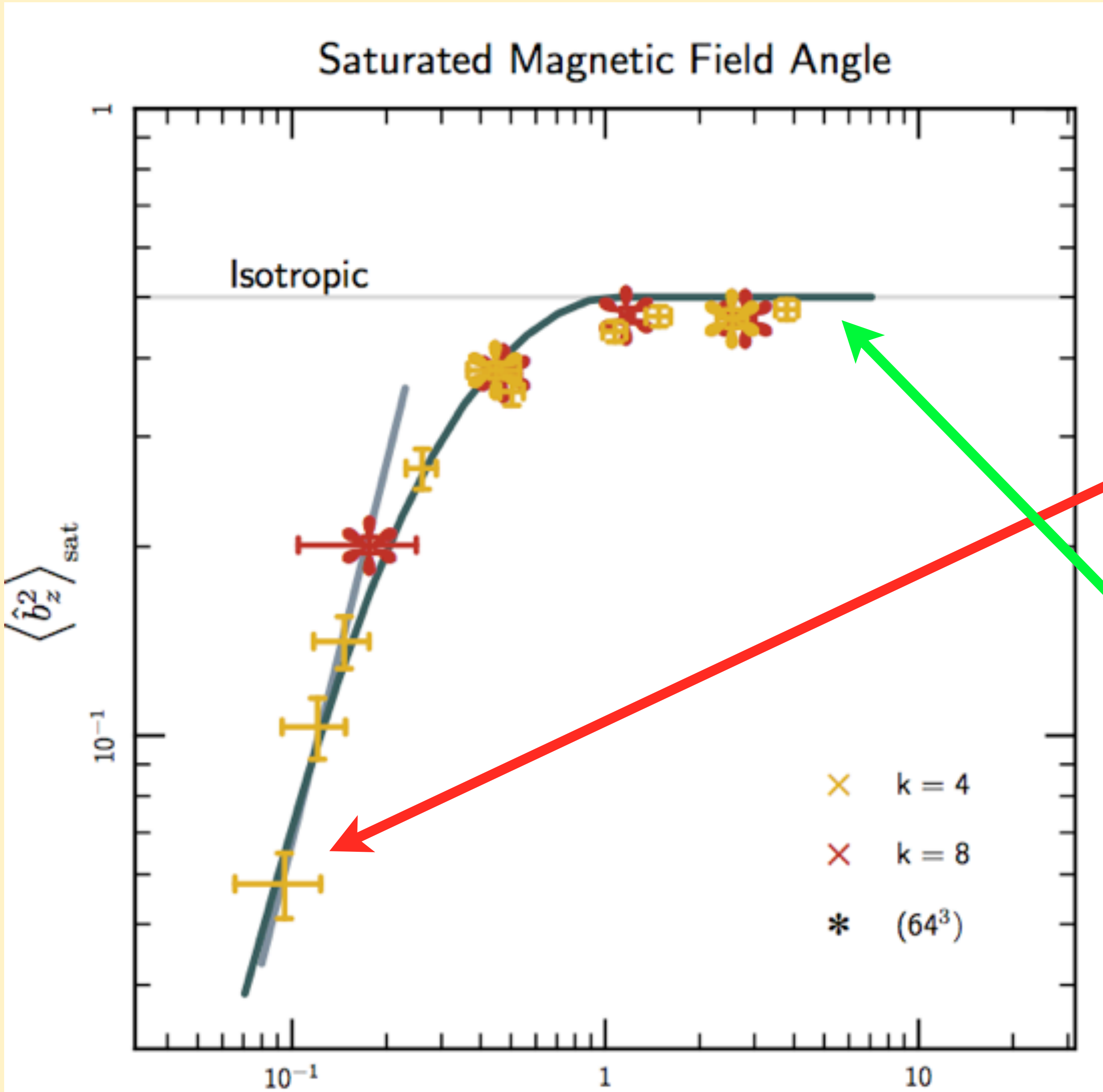

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McCourt, Parrish, Sharma, & Quataert (2011)

Two Limits:

1) HBI efficient:

$$t_{\rm HBI} < t_{\rm eddy}$$

$$f_{\rm Sp} \rightarrow 0$$

2) Turbulence wins:

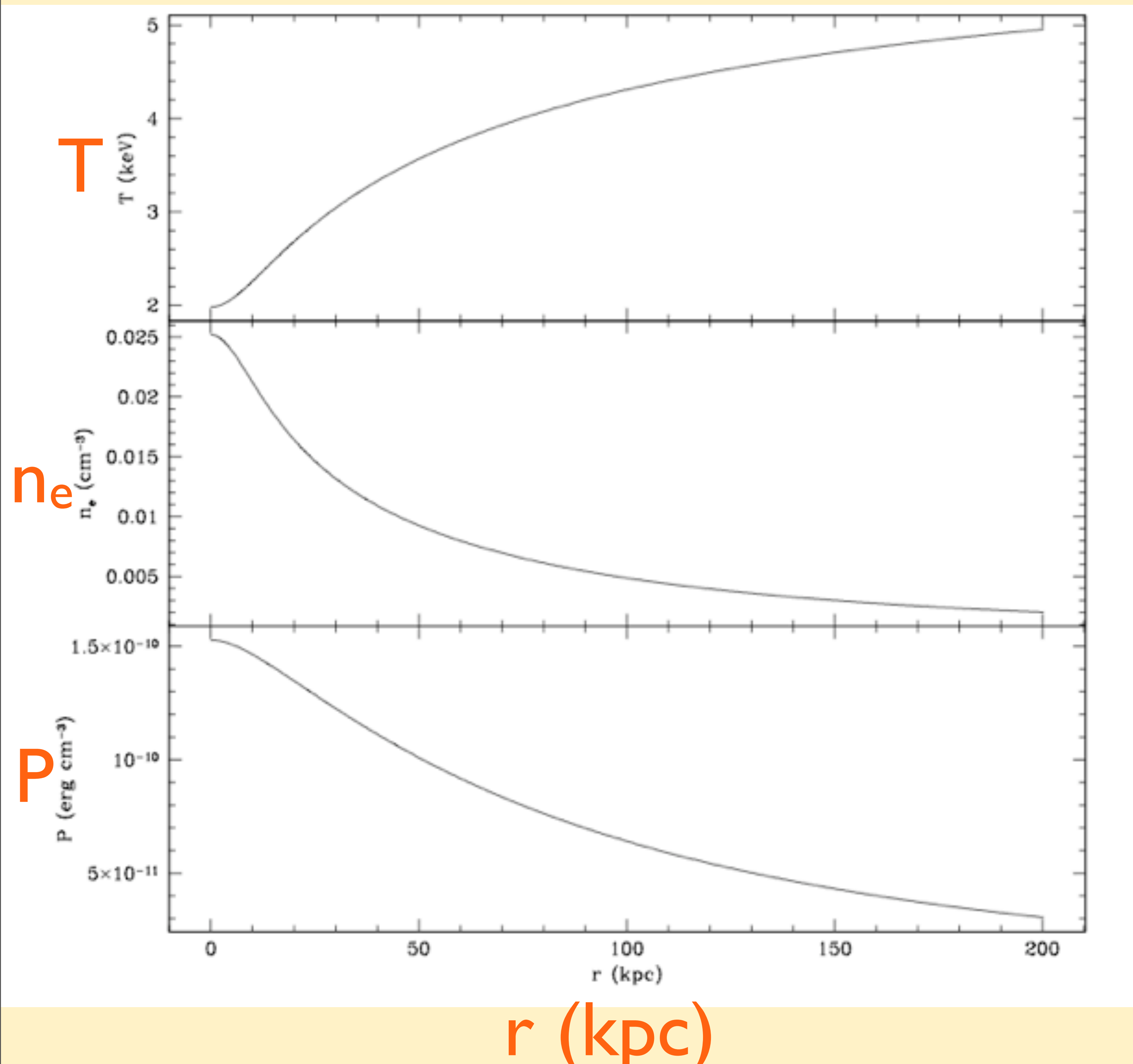
$$t_{\rm HBI} > t_{\rm eddy}$$

$$f_{\rm Sp} \rightarrow \frac{1}{3}$$

Richardson Number (Ri)

$$\mathrm{Ri} = \mathrm{Fr}^{-1/2}$$

HBI in Clusters: Abell 2199



Cluster Parameters:

- Mass 3.8 x 10^{14} M_{sun}
- r_s ~ 390 kpc (Johnstone, et al 2002)
- Hydrostatic Equilibrium
- Thermal Equilibrium
- Tangled Magnetic Fields

(Parrish, Quataert, & Sharma 2009)
(Bogdanovic, et al 2009)

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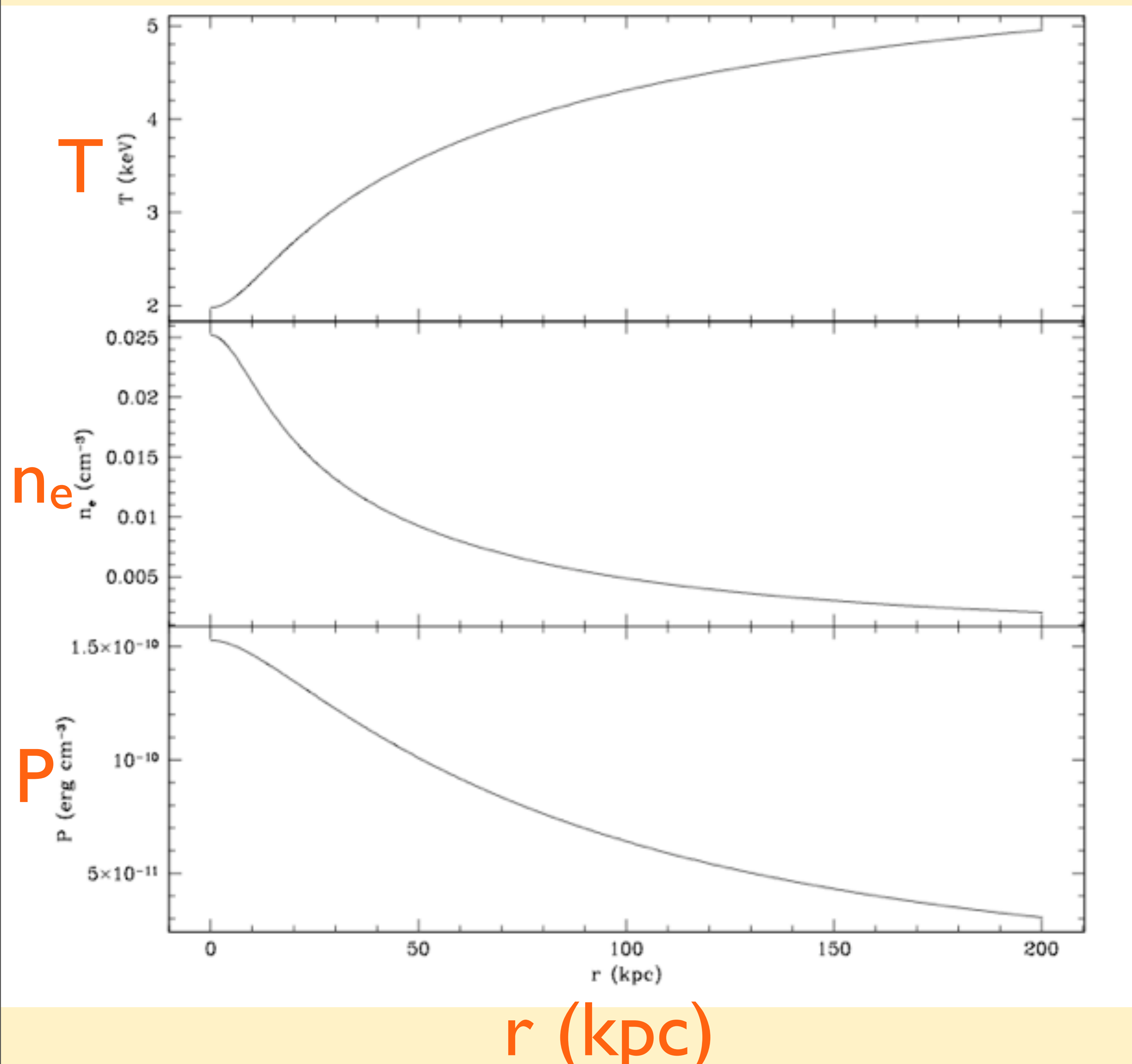

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HBI Growth Time: 120 Myr

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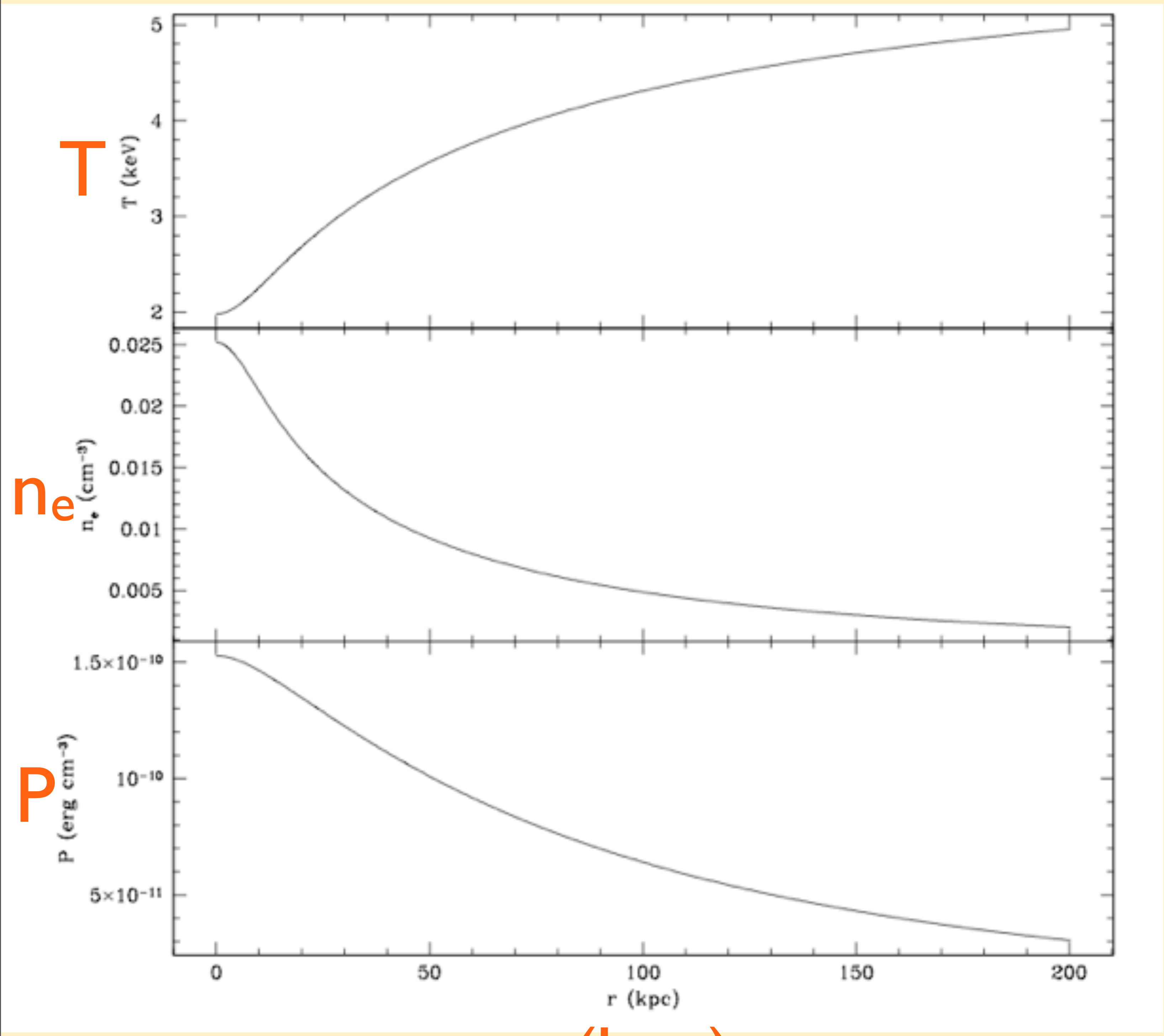

r (kpc)

(Parrish, Quataert, & Sharma 2009)
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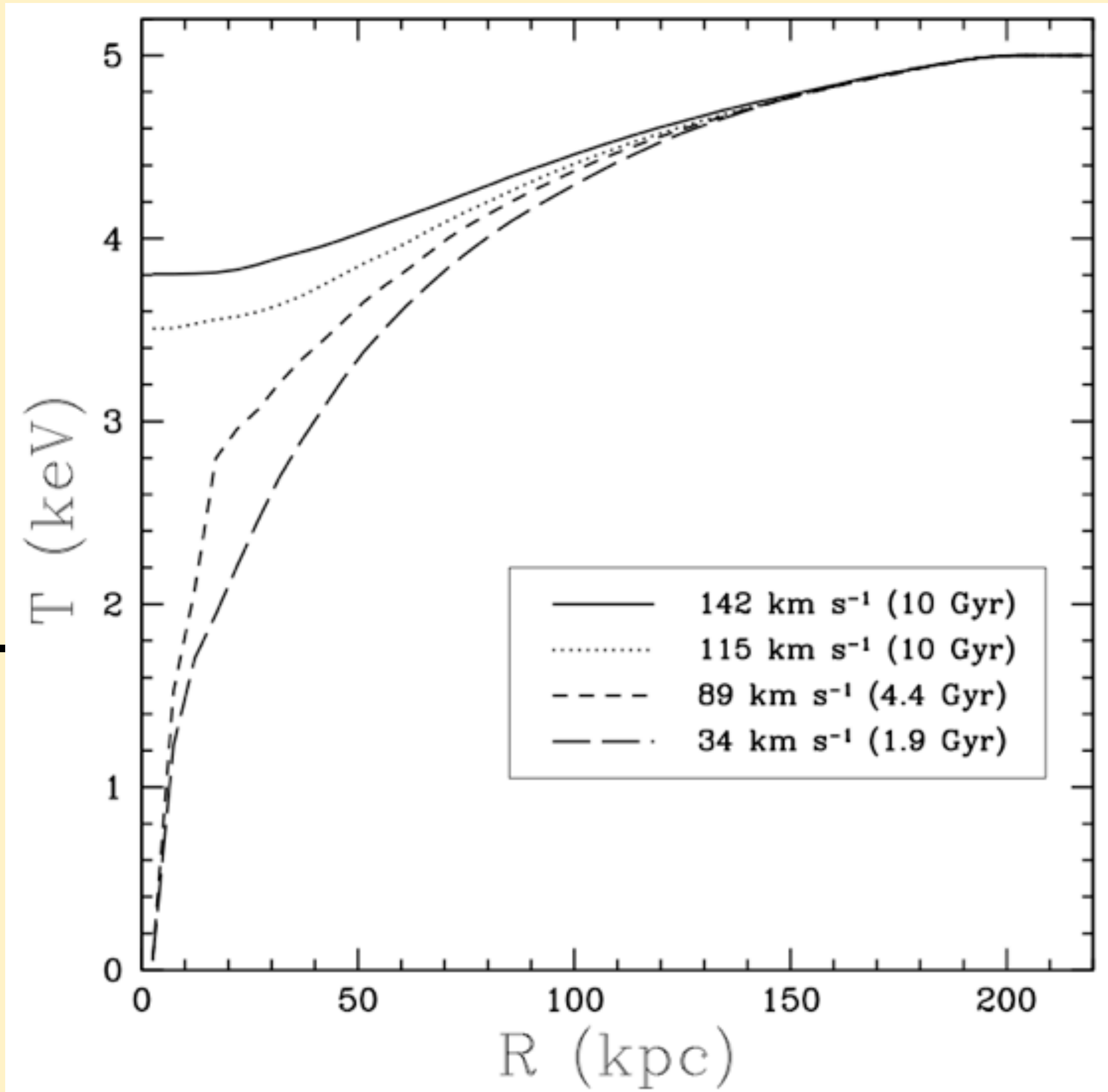
HBI Growth Time: 120 Myr

Drive turbulence: (v_{rms}, L_{outer})

Turbulence and Bimodality

Final Temperature Profiles



Exact Same
Initial Conditions
Turbulence of *L = 40* kpc.

Parrish, Quataert, & Sharma (2010)
See also Ruszkowsi & Oh (2010, 2011)

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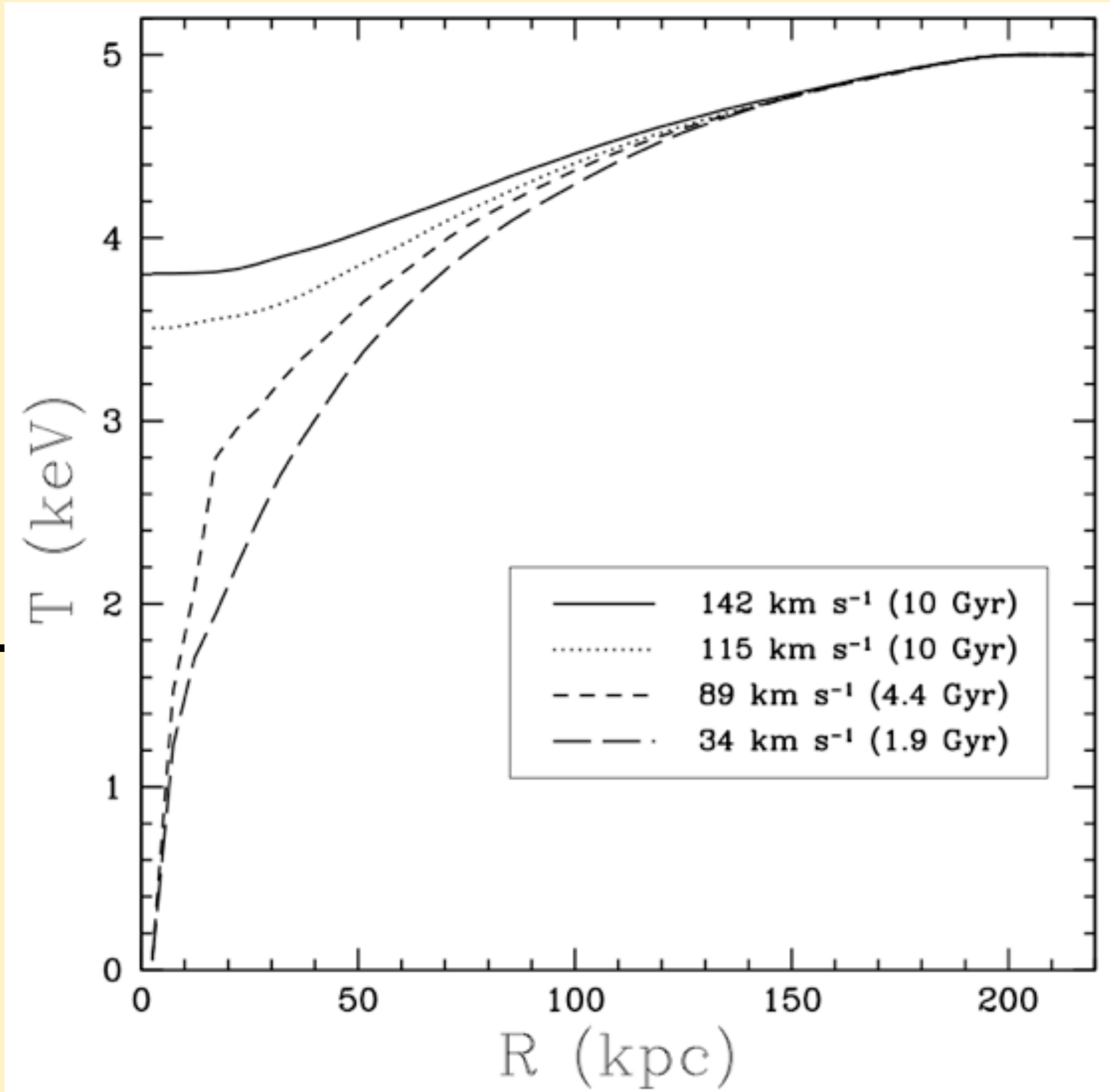

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$t_{\rm HBI} \approx 100\,{\rm Myr}$

$t_{\rm cool} \approx 400\,{\rm Myr}$

$t_{\rm eddy} \approx 100 - 450\,{\rm Myr}$

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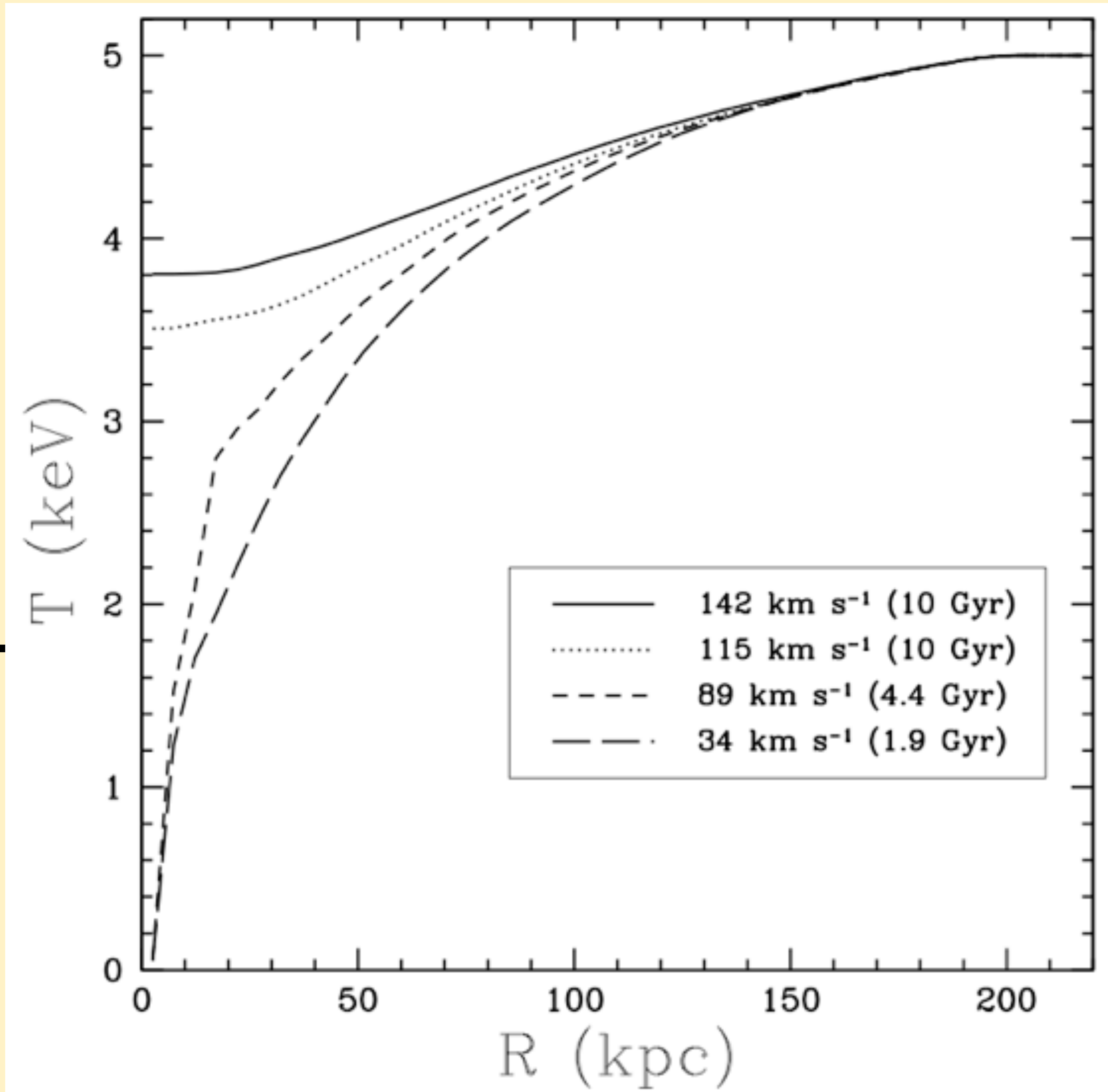

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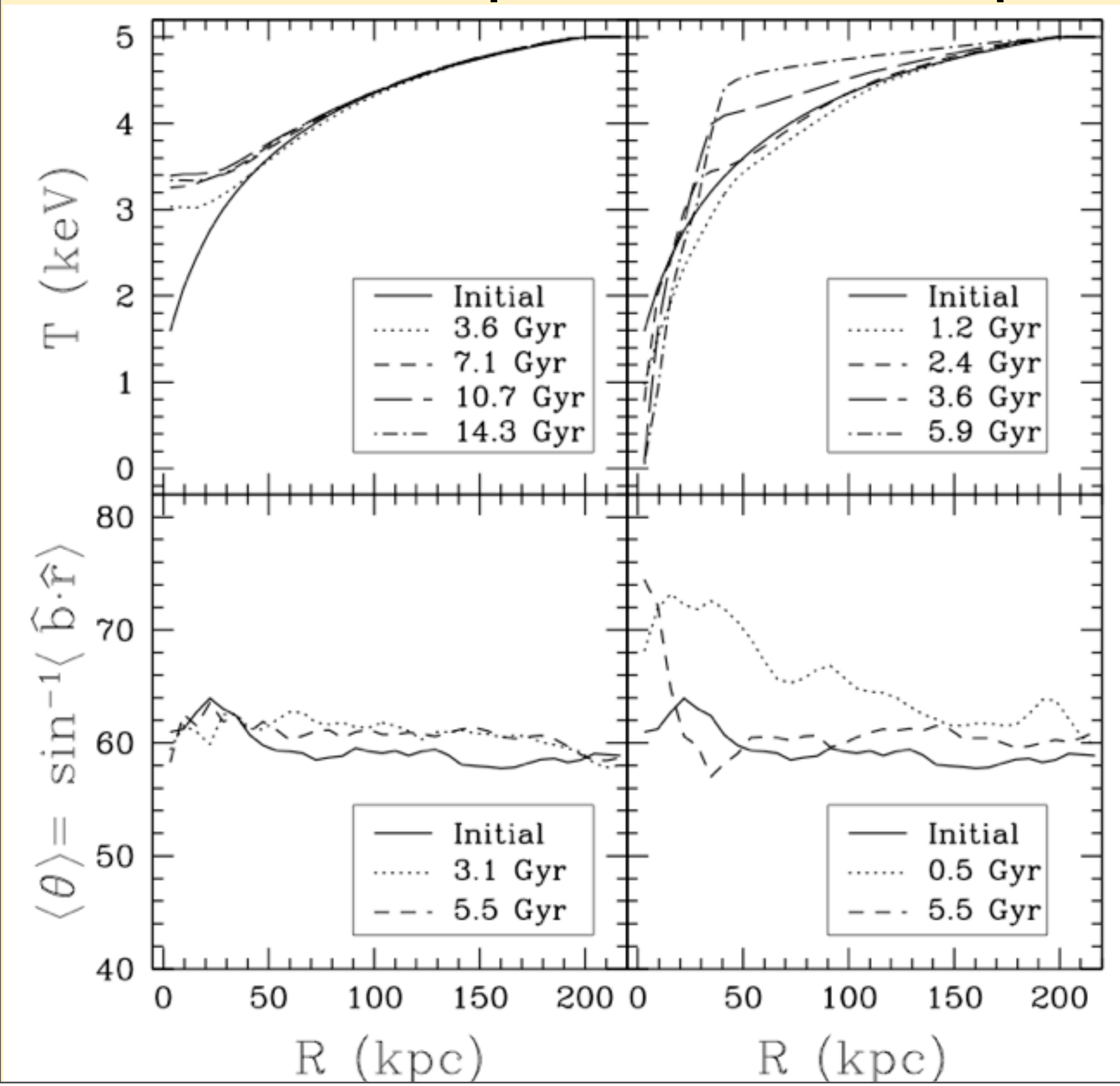
Clear Bimodality:
~25 km/s velocity difference
- Stable ~isothermal profile
- Cooling Catastrophe

Turbulence and Bimodality

L = 40 kpc   L = 100 kpc



Same δv ~ 115 km/s

$$t_{\rm eddy} \sim L/\delta v$$

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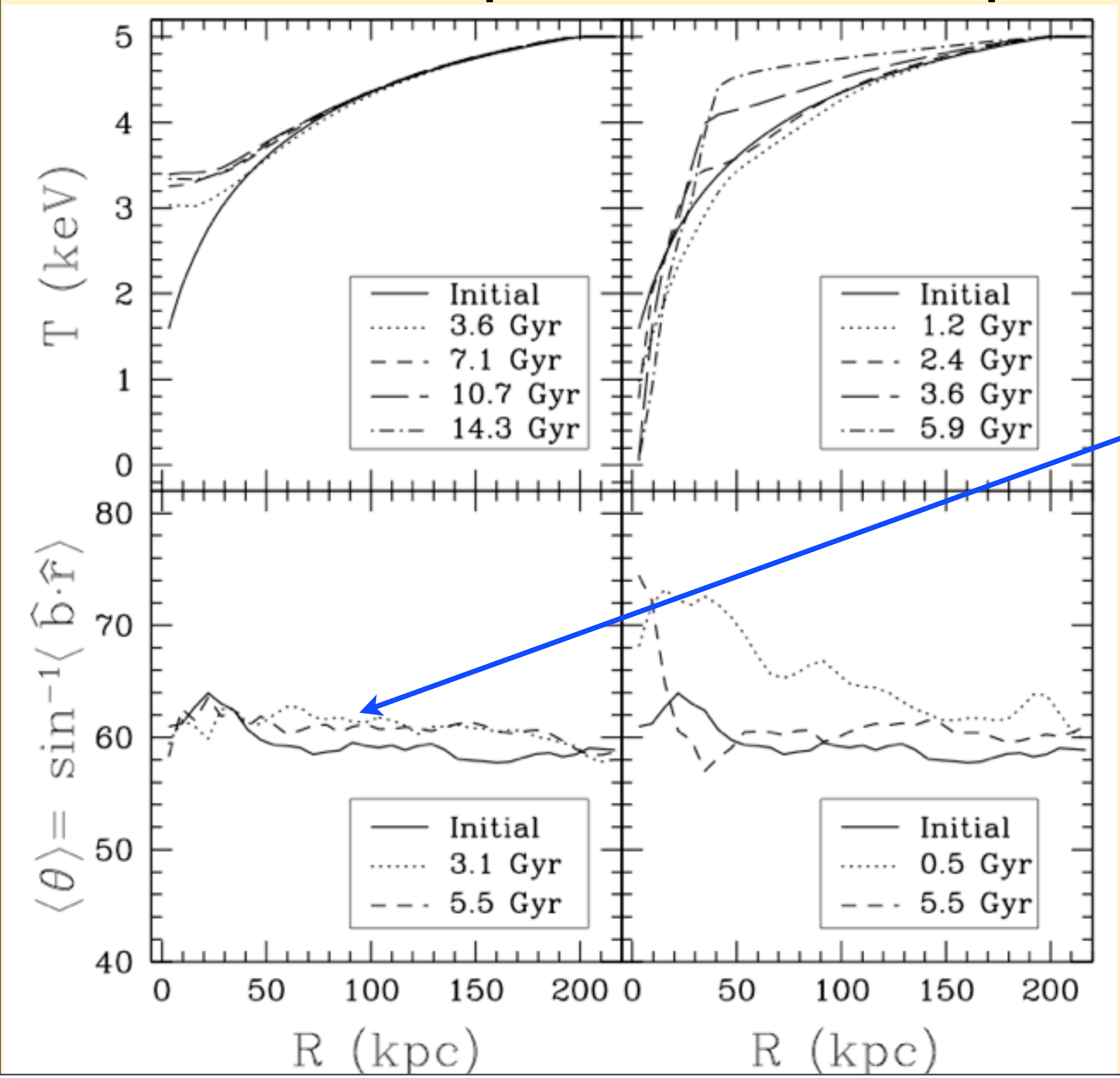

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Turbulence keeps conduction at f_{sp}~1/3.

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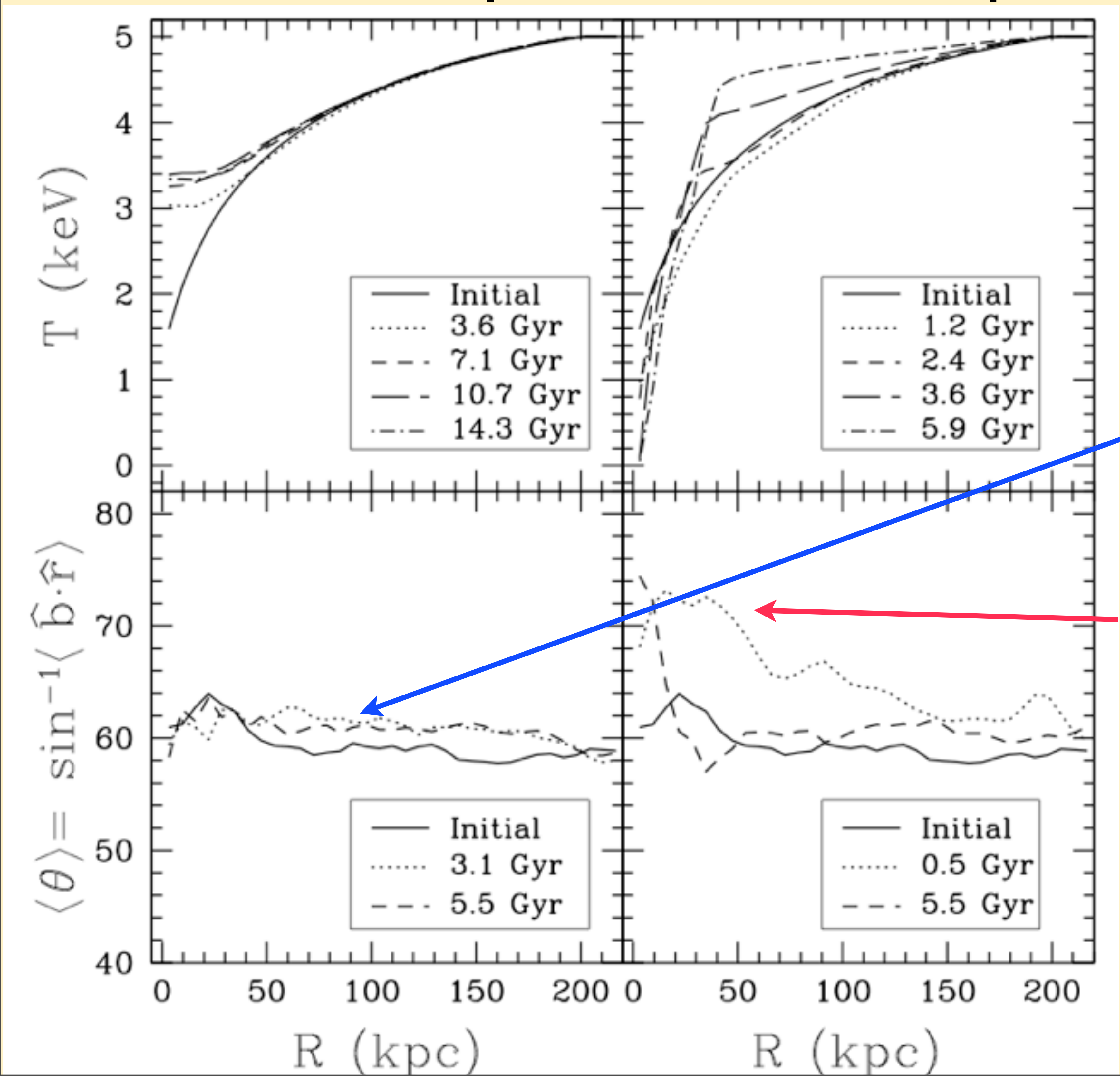

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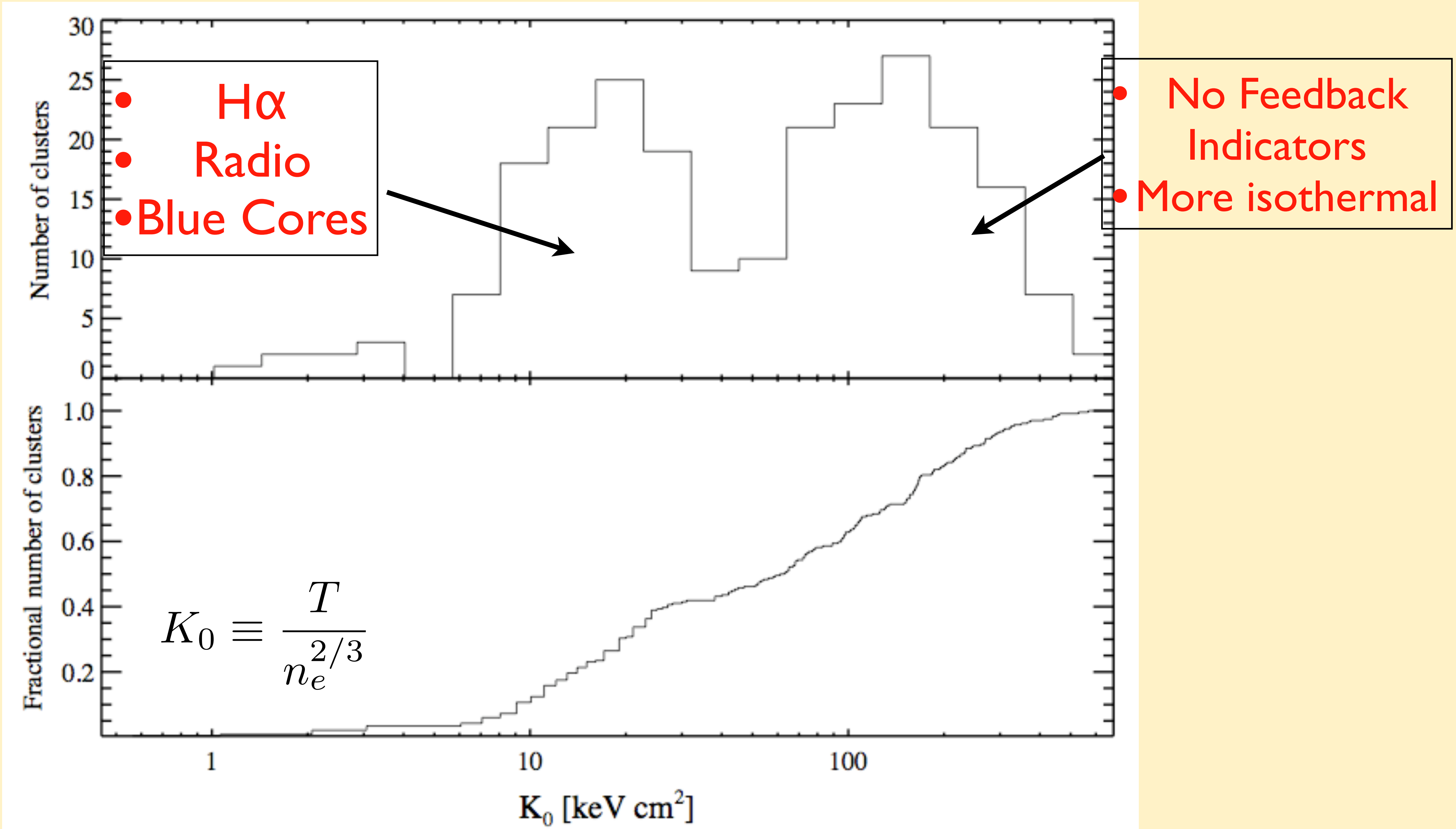
HBI shuts off conduction

Turbulence and Entropy

Cavagnolo, Voit, Donahue, et al (2009)



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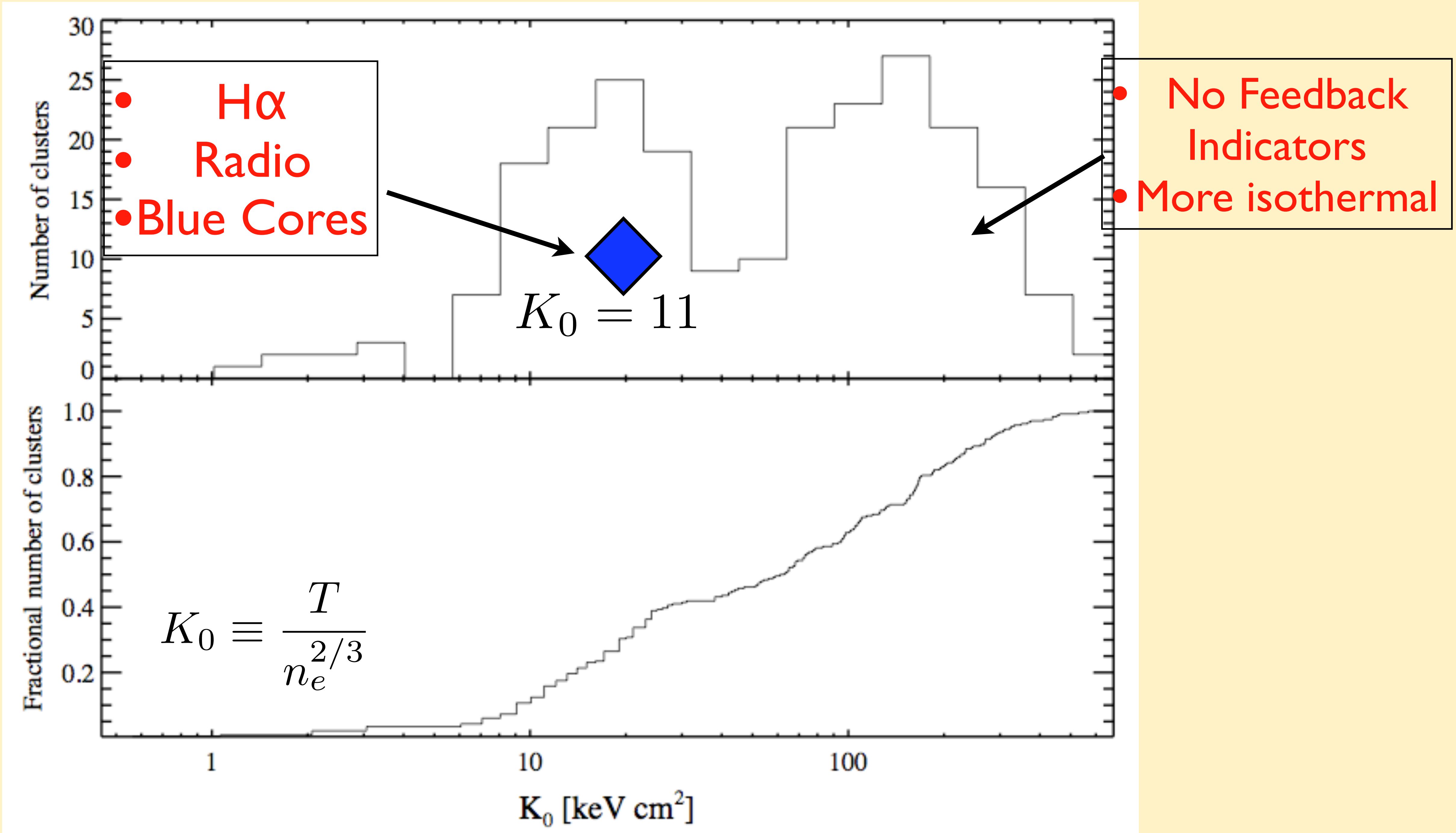

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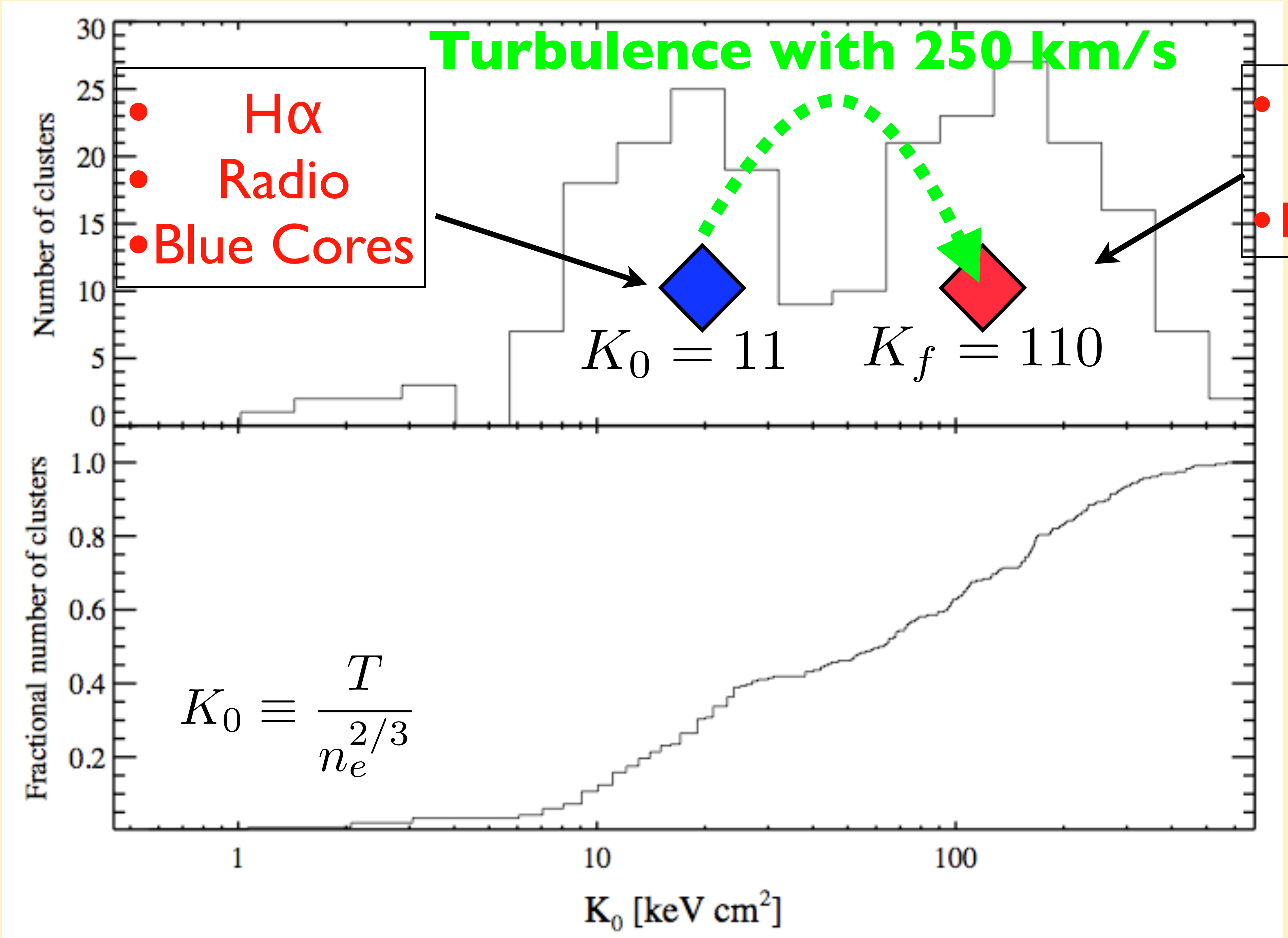

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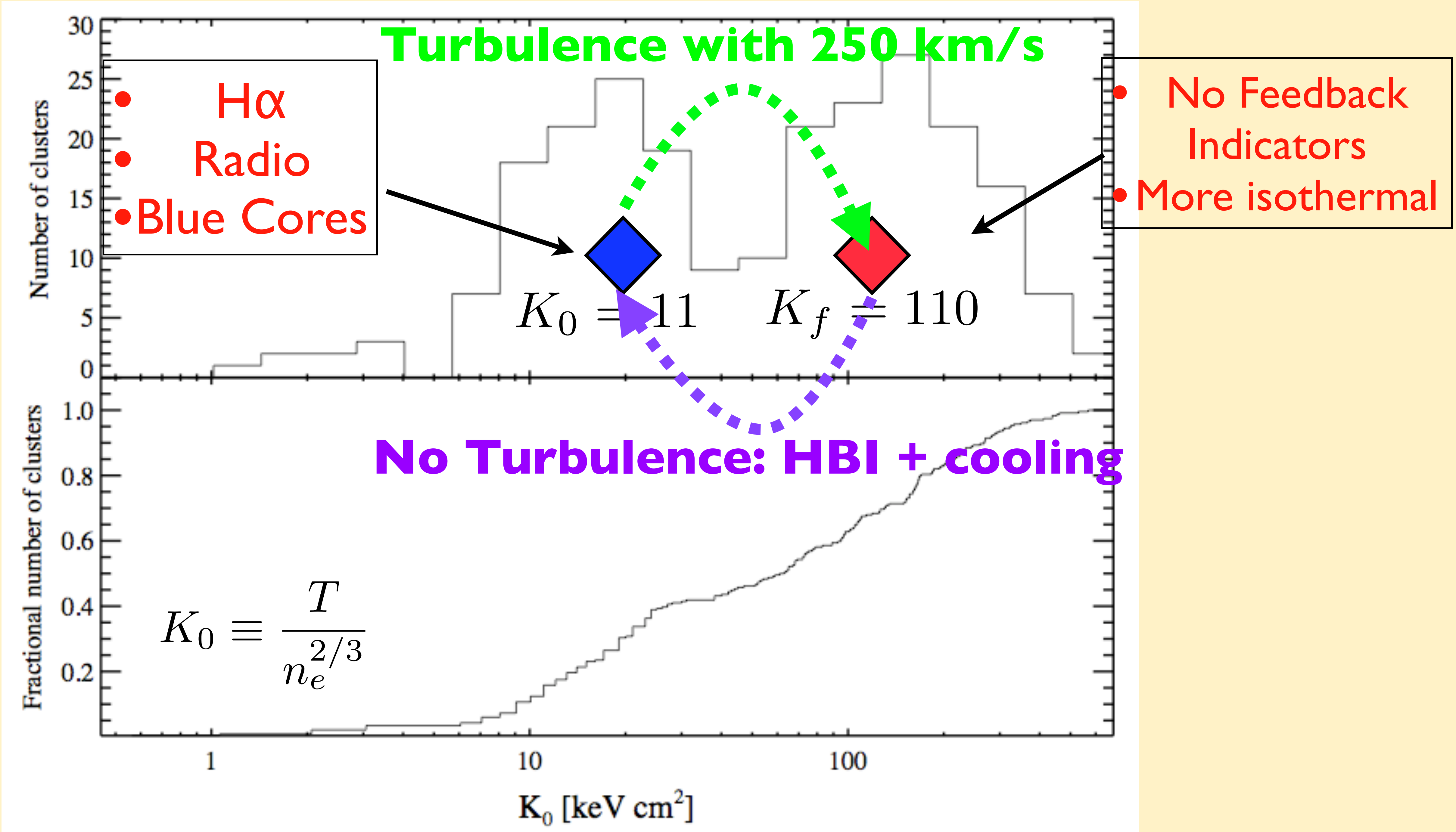

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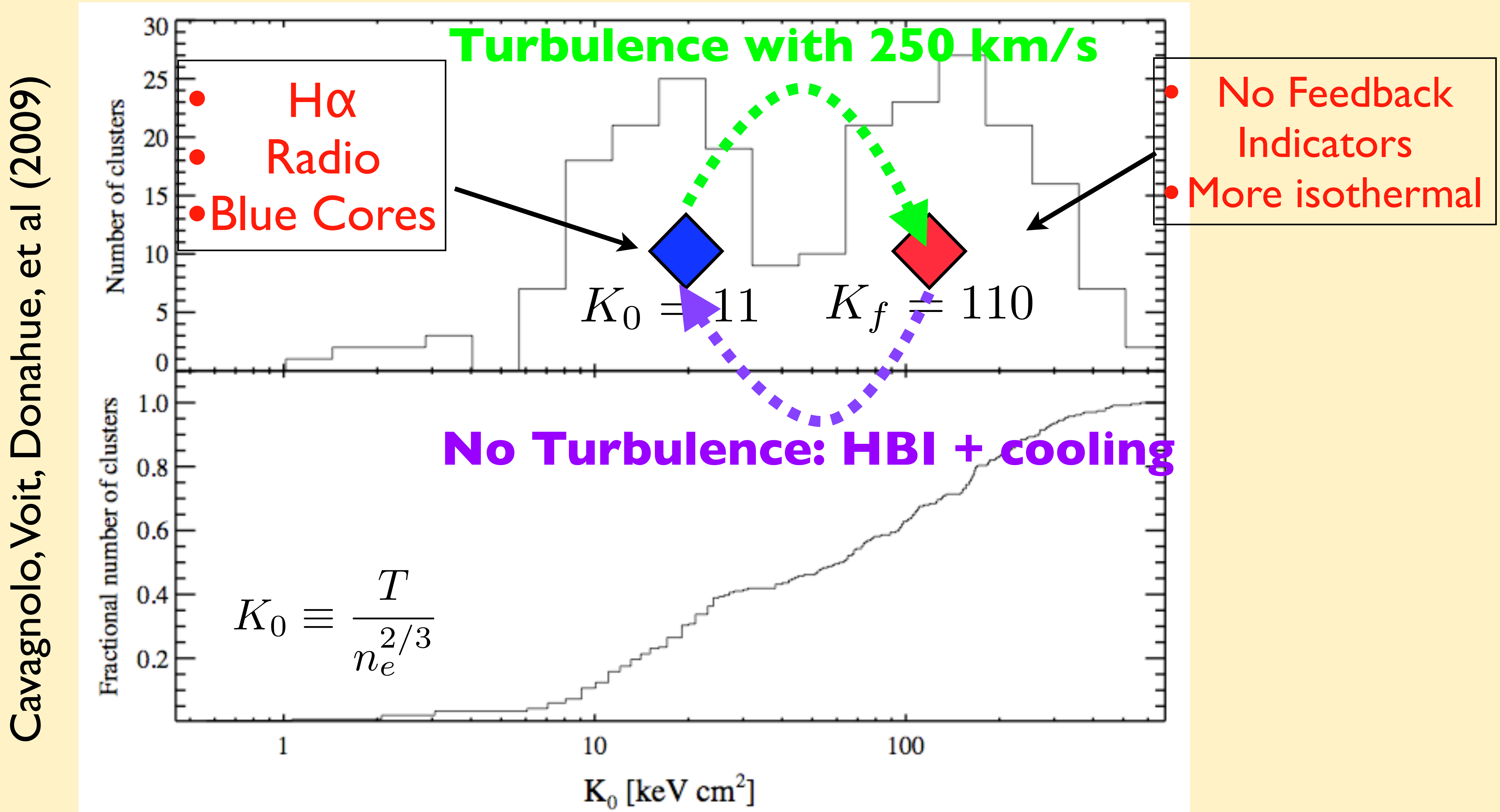

• Conduction is a natural way to *volumetrically* raise entropy

• Turbulence (energetically weak) can be a catalyst for changing the cool core/non-cool core state.

Turbulence and Entropy

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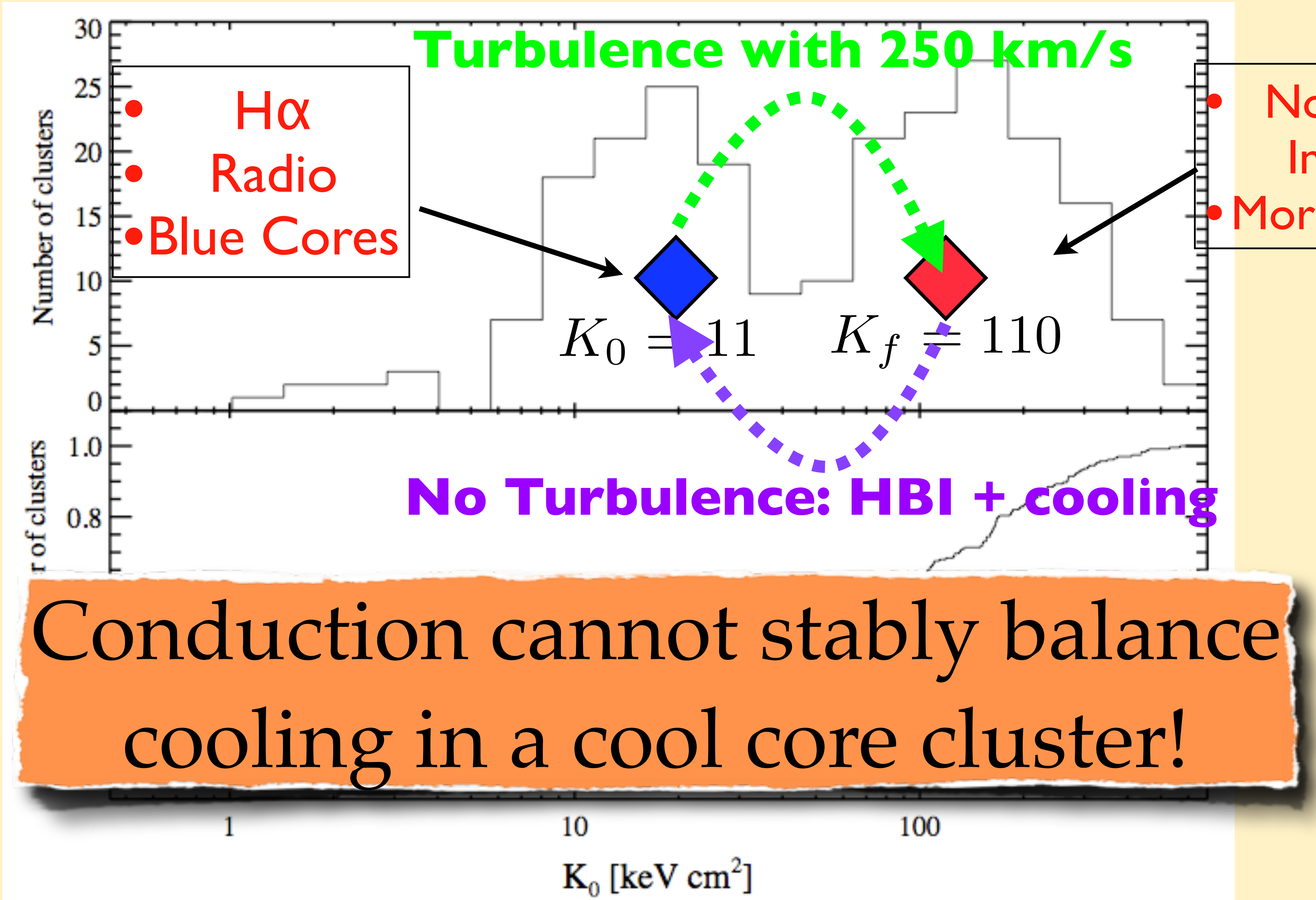

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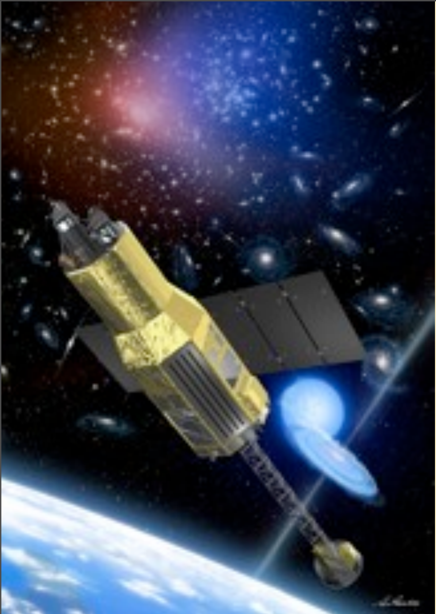
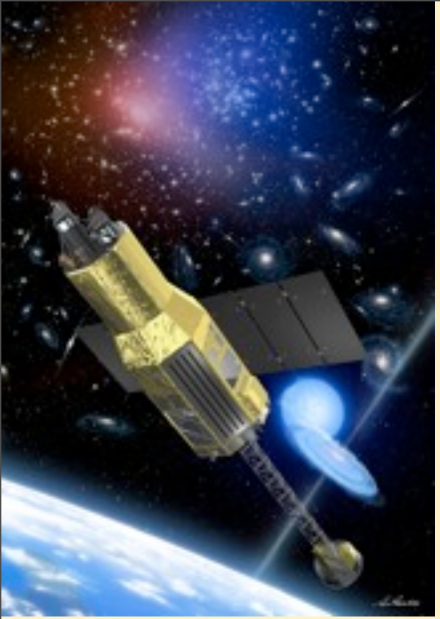
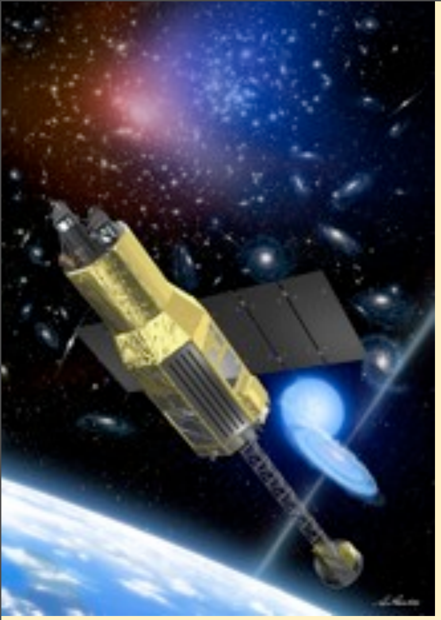


Putting my chips on the table: Predictions for Astro-H



Putting my chips on the table: Predictions for Astro-H

For a typical cool-core cluster like A2199:
No turbulence with v_{rms} > 150 km/s (L_{outer} > 40 kpc).



Putting my chips on the table: Predictions for Astro-H

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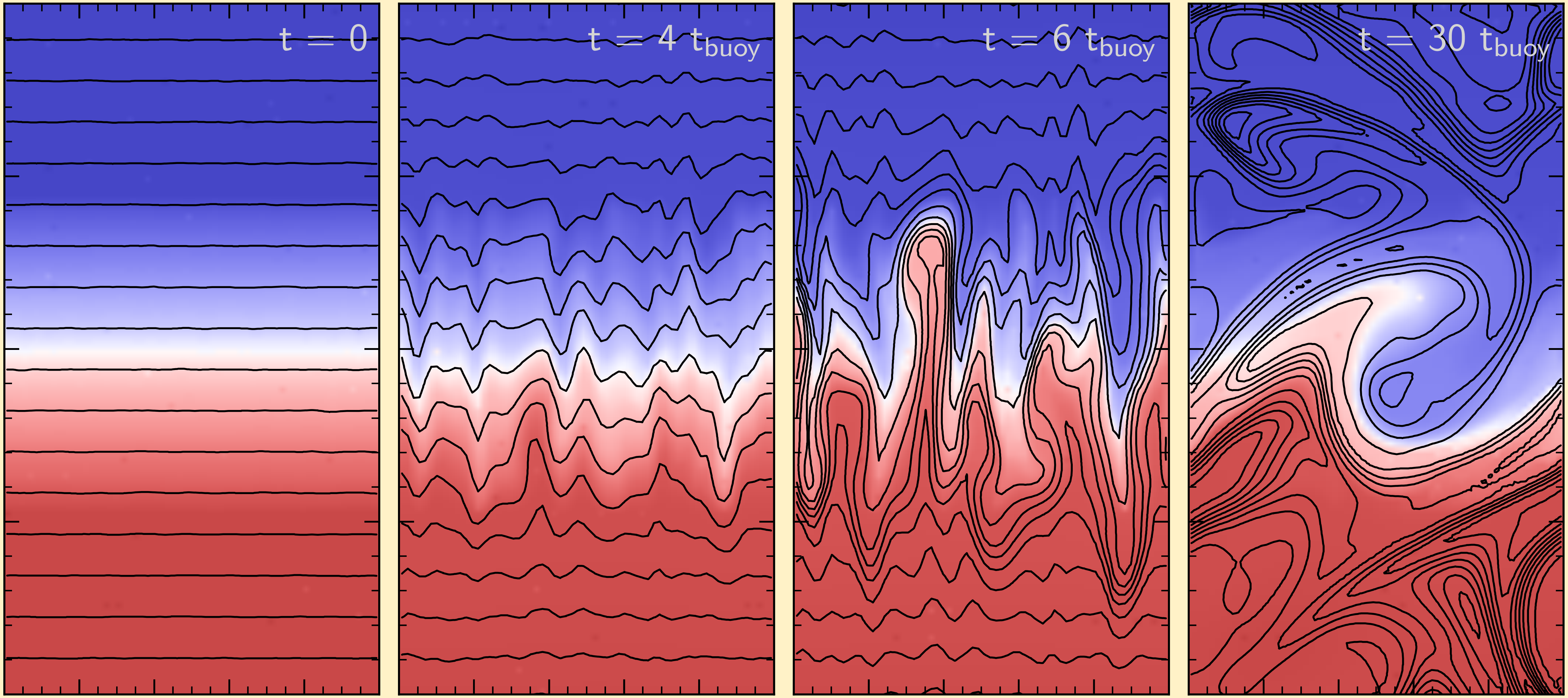
Consistent with current evidence:

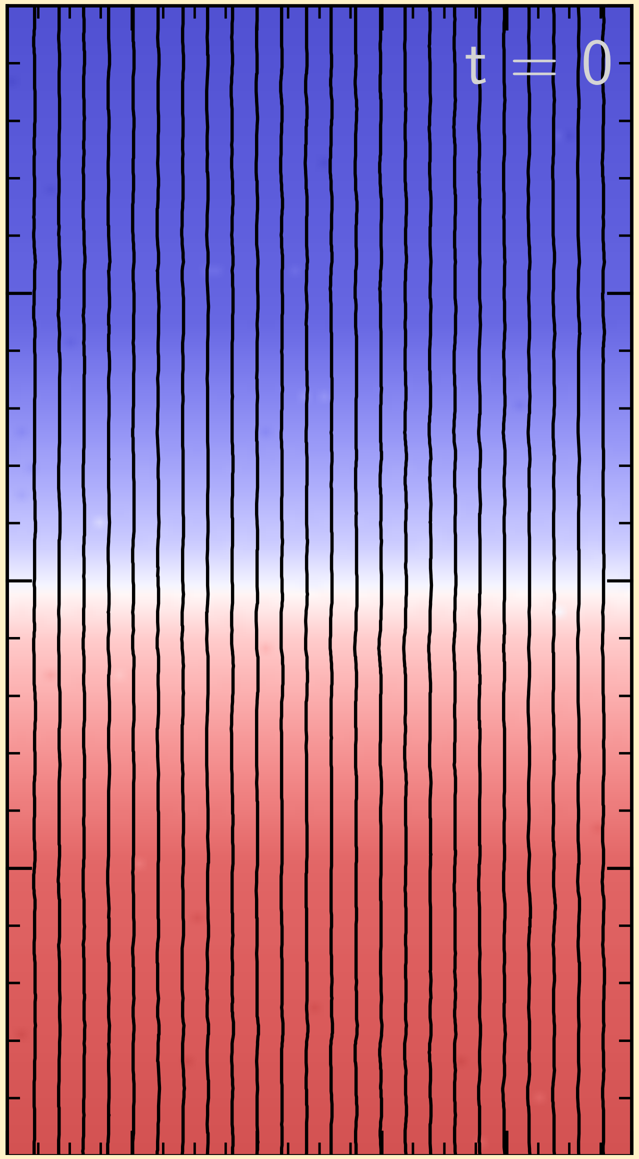
- Straight filaments: NGC 1275 (Fabian+ 08), M 87 (Werner+ 11)
- Direct RGS measurements of A1895 (Sanders+ 10, 11)
- Fe XVII line ratios in ellipticals (Werner+ 10)
- Smooth surface brightness profiles in many cool cores.

The MTI Saturates Differently



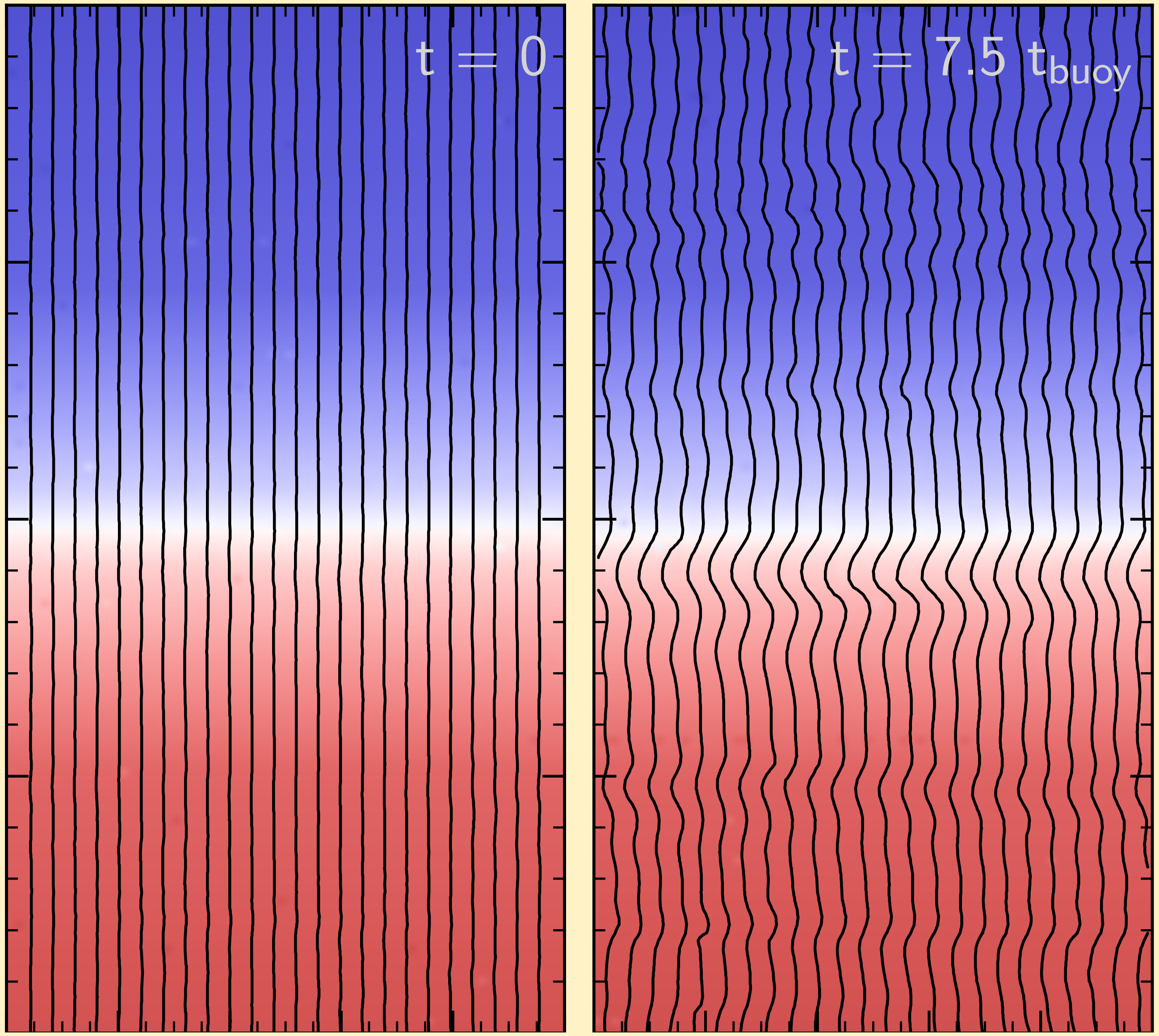
MTI does not saturate quiescently like the HBI

The MTI Saturates Differently



Vertical Fields:
Stable state of MTI?

The MTI Saturates Differently



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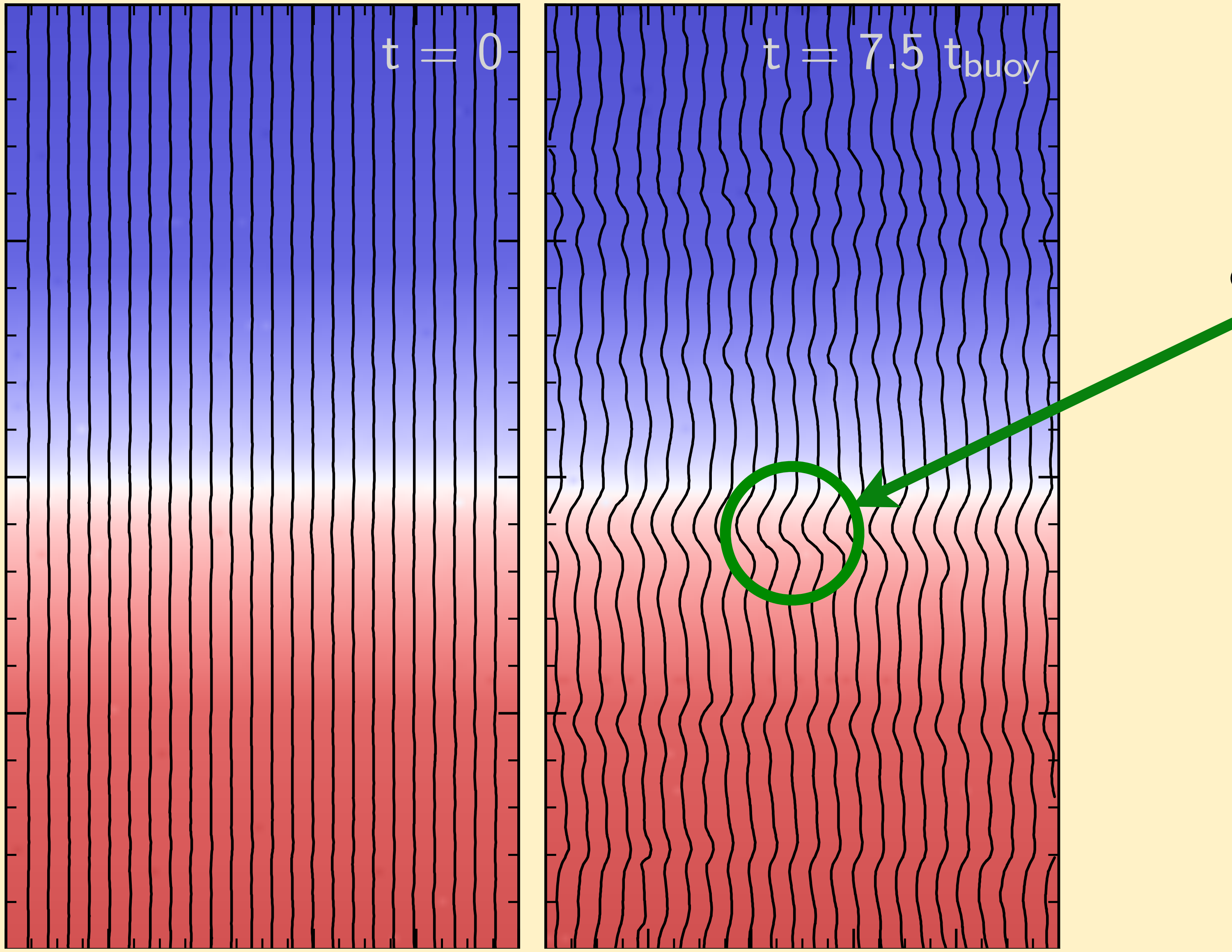

- Horizontal displacements not damped.

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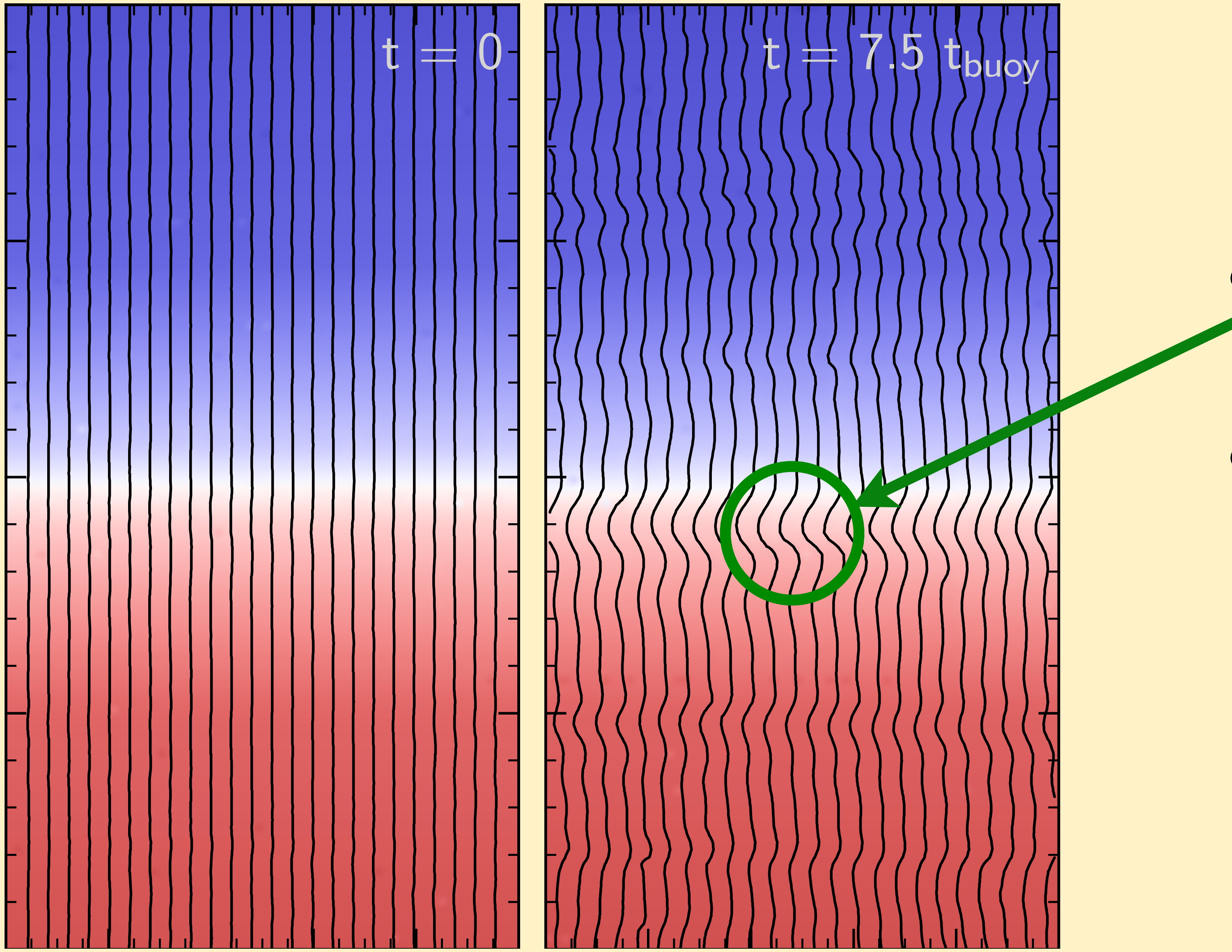

- Horizontal displacements not damped.
- Nonlinearly unstable.

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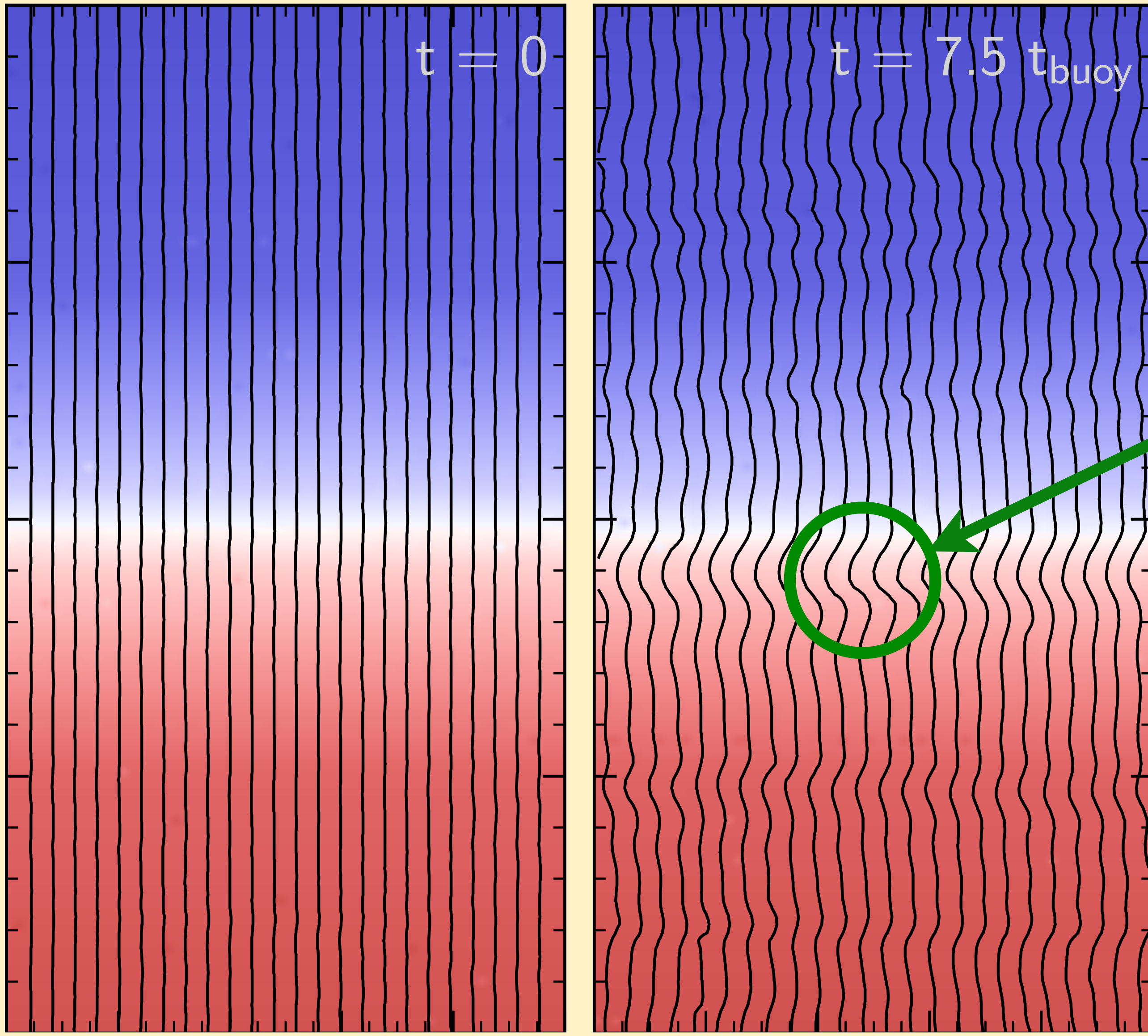
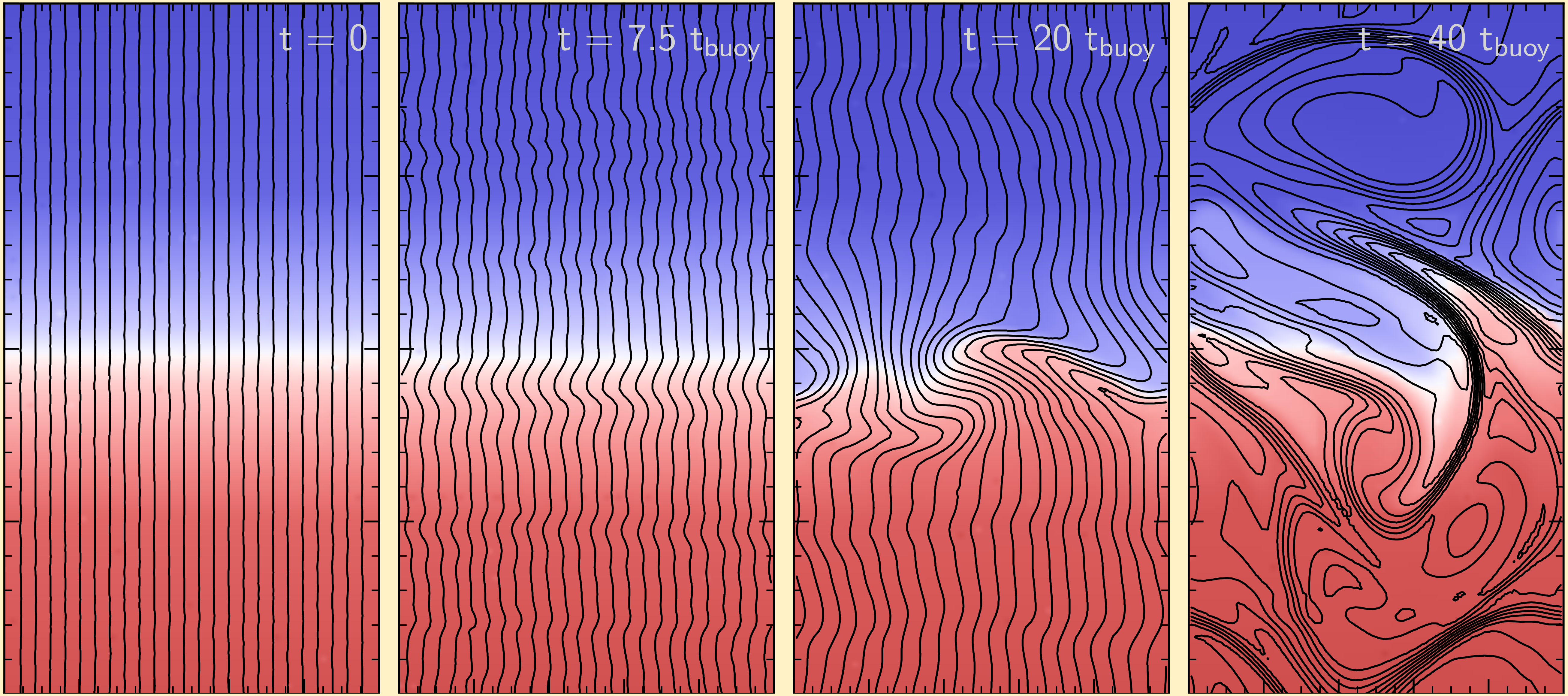


- Horizontal displacements not damped.
- Nonlinearly unstable.
- Closes dynamo loop.

The MTI Saturates Differently



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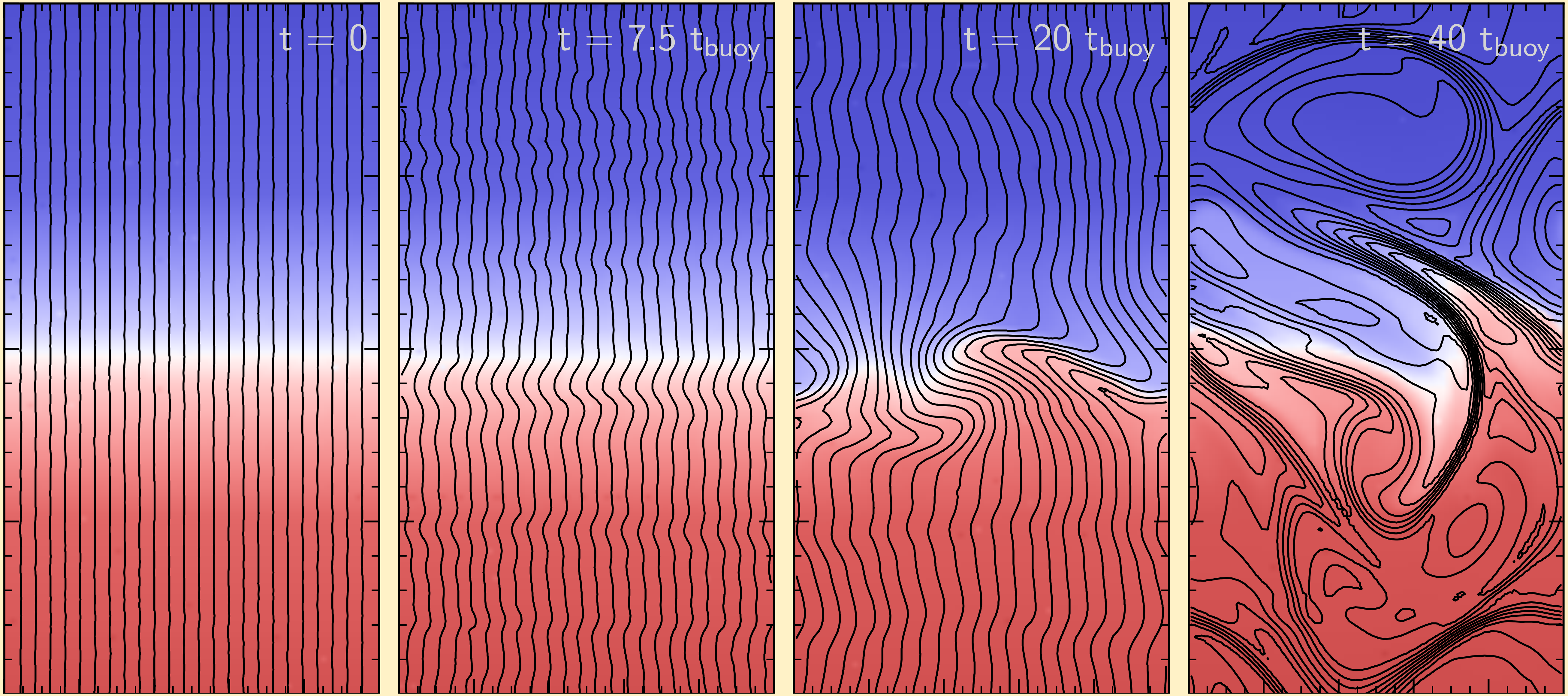

- Does not saturate with vertical (radial) fields.
  (Small radial bias over isotropic.)

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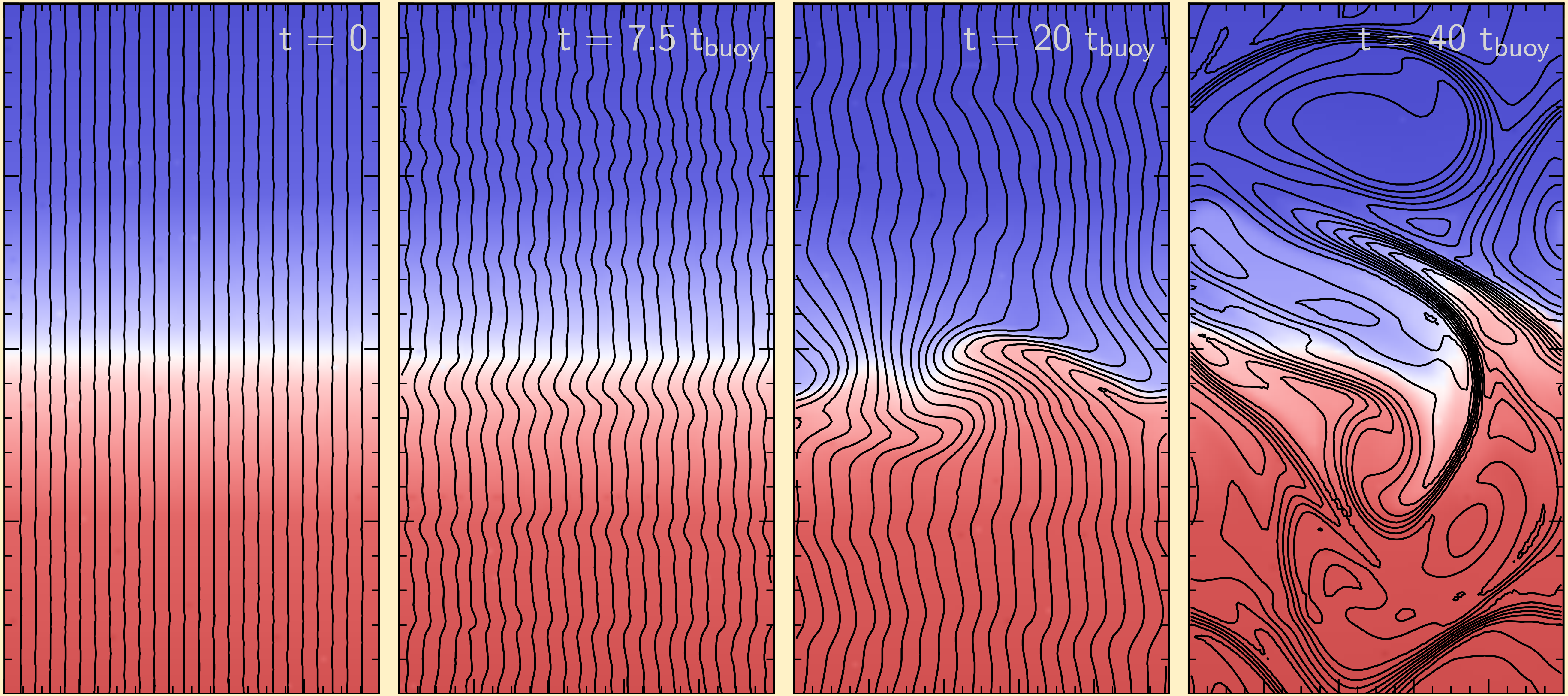

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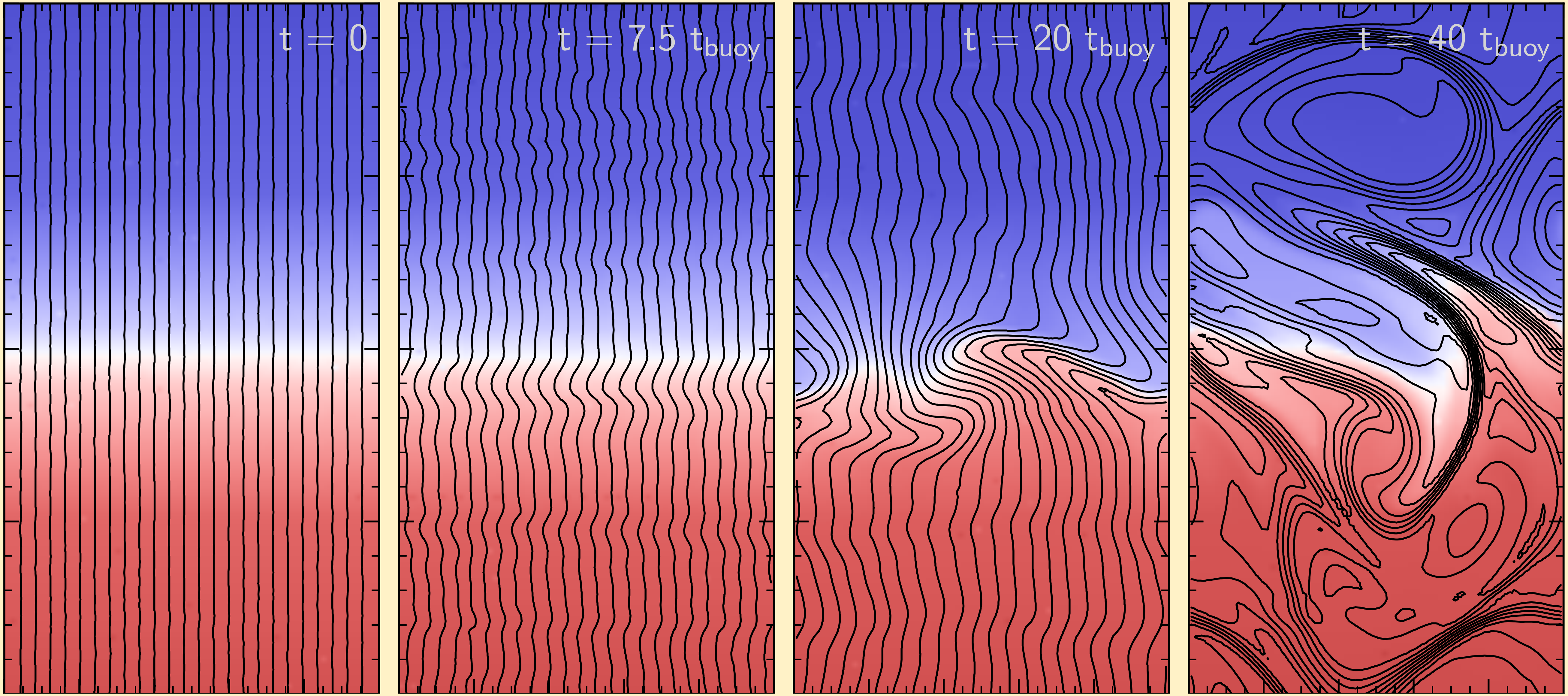

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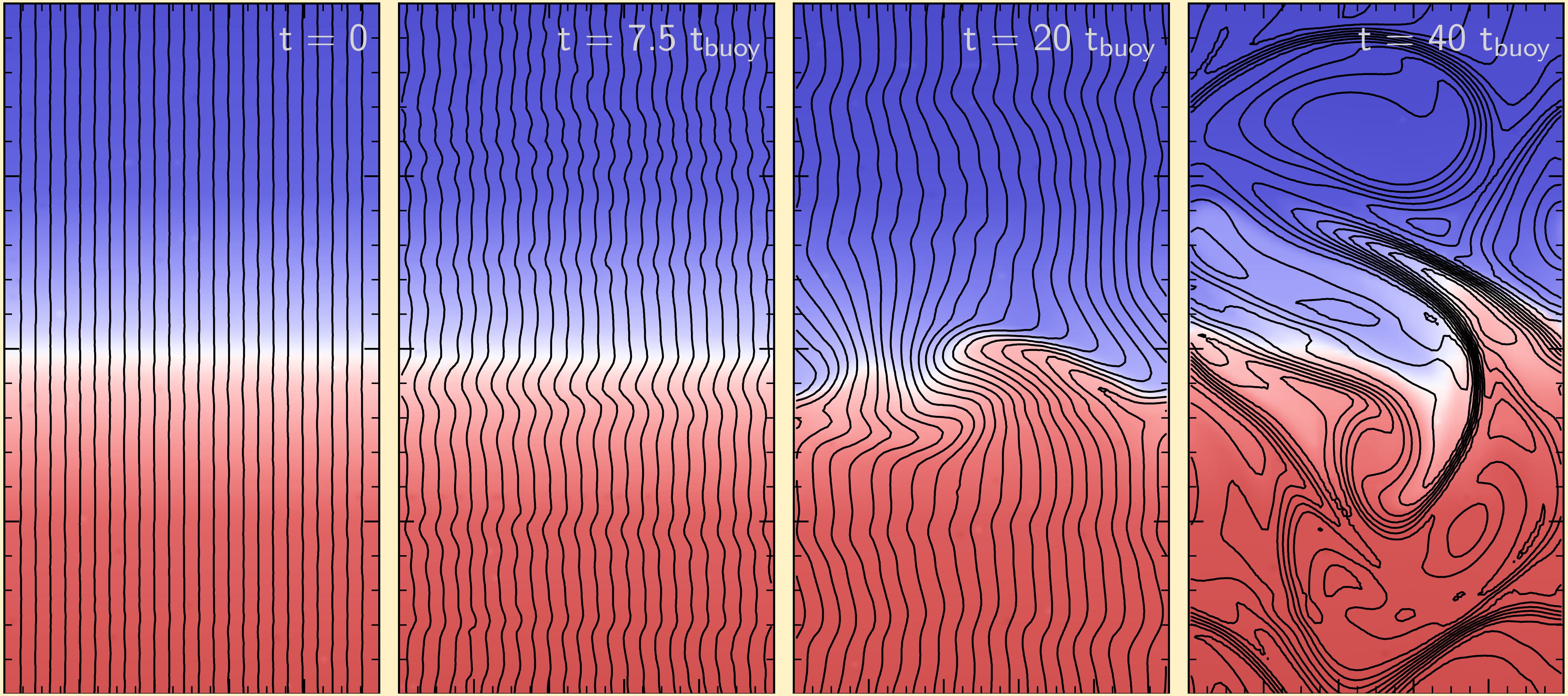

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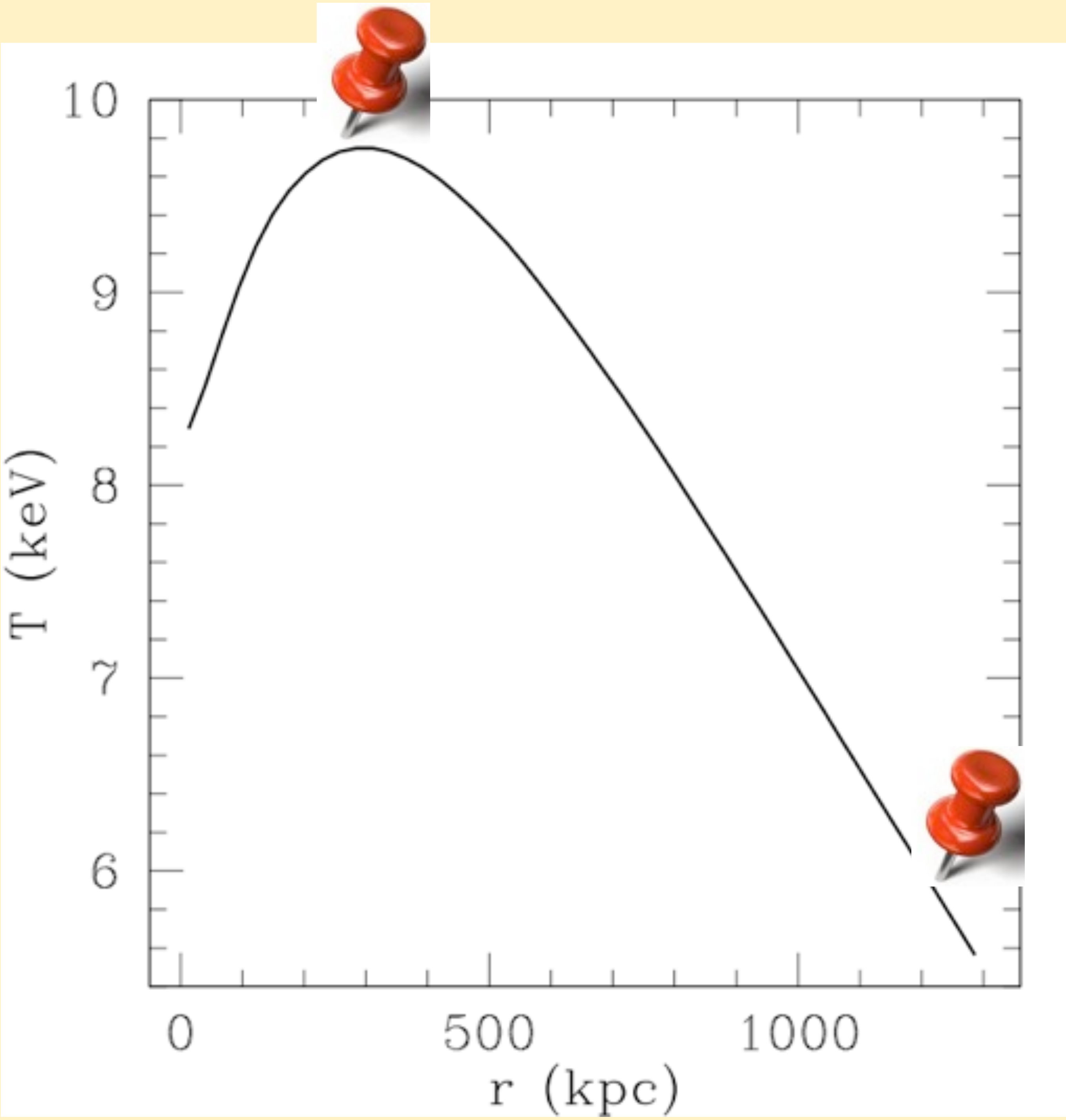
- Generates vigorous turbulence (up to supersonic).
- Generates a magnetic dynamo almost to equipartition.
- Turbulence does ***not*** suppress the MTI.

MTI in Clusters: A1576



- Non-Cosmological: Fix T at core and outskirts
- NFW: $M = 1.5 \times 10^{15}\ \mathrm{M}_\odot$

$$R_S = 600\ \mathrm{kpc}$$

- Tangled magnetic fields.
- No cooling.

For cosmological: Ruszkowski+ 2011 (yesterday's talk)

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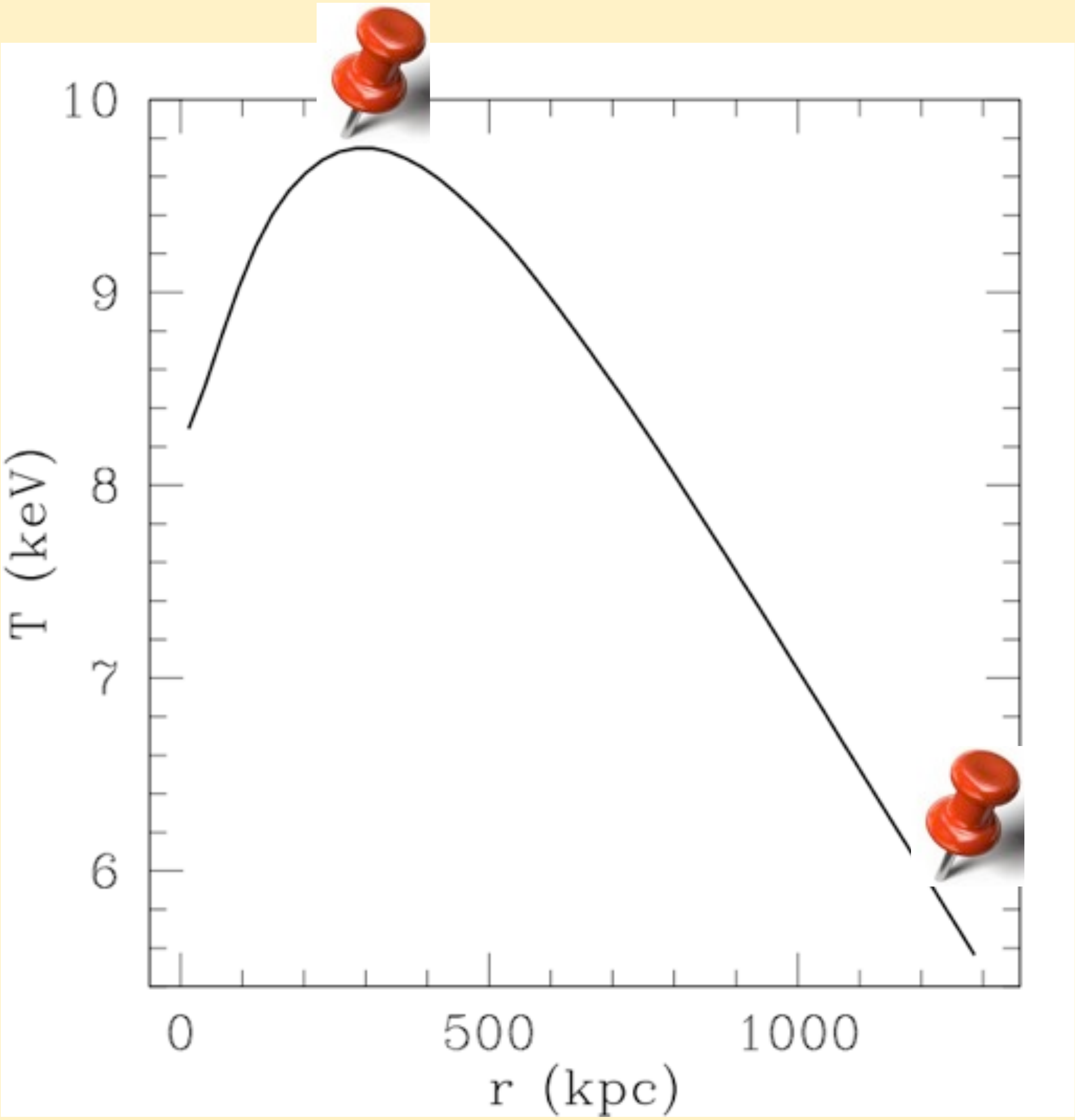

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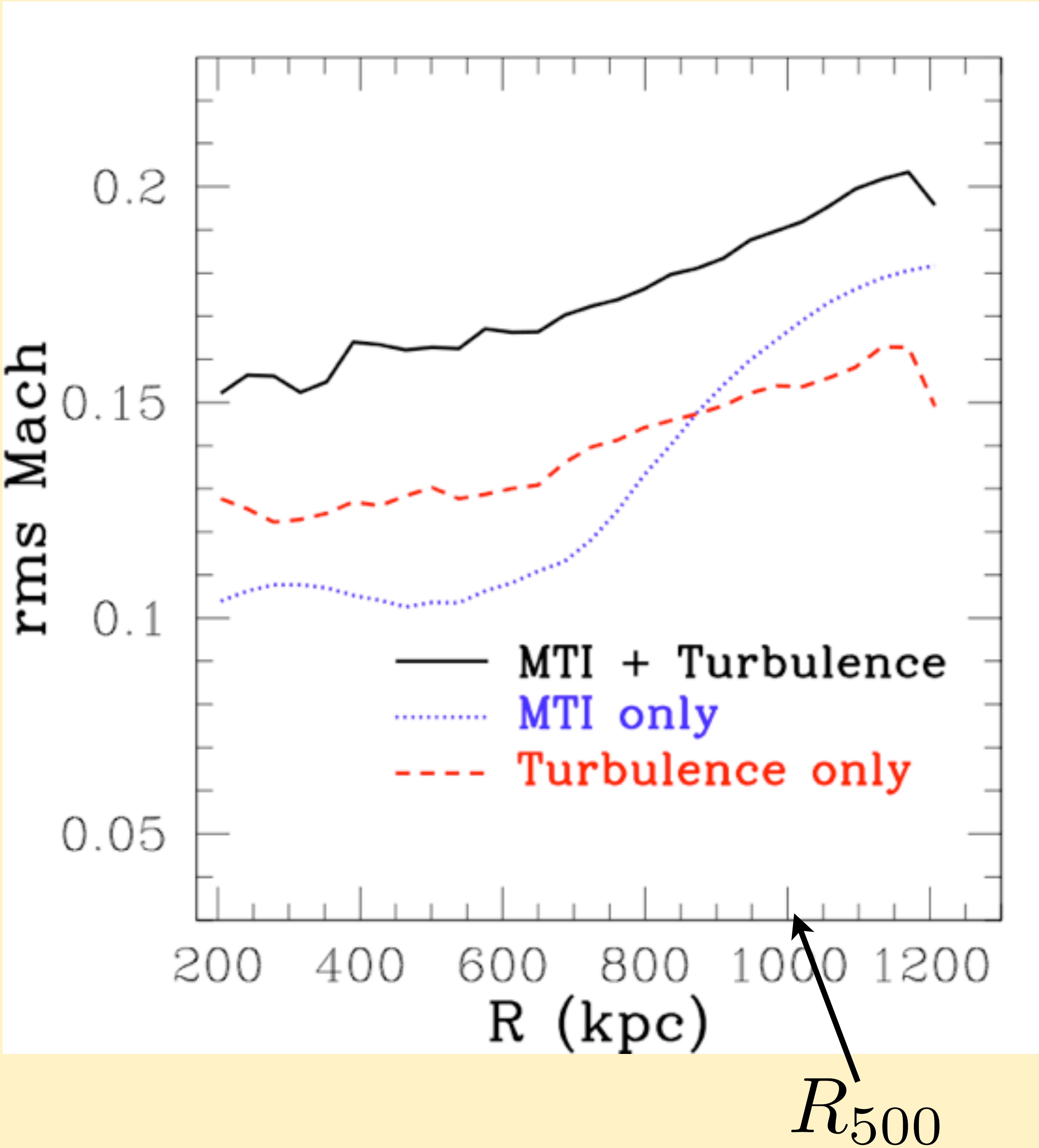
MTI Growth Time: 600 Myr

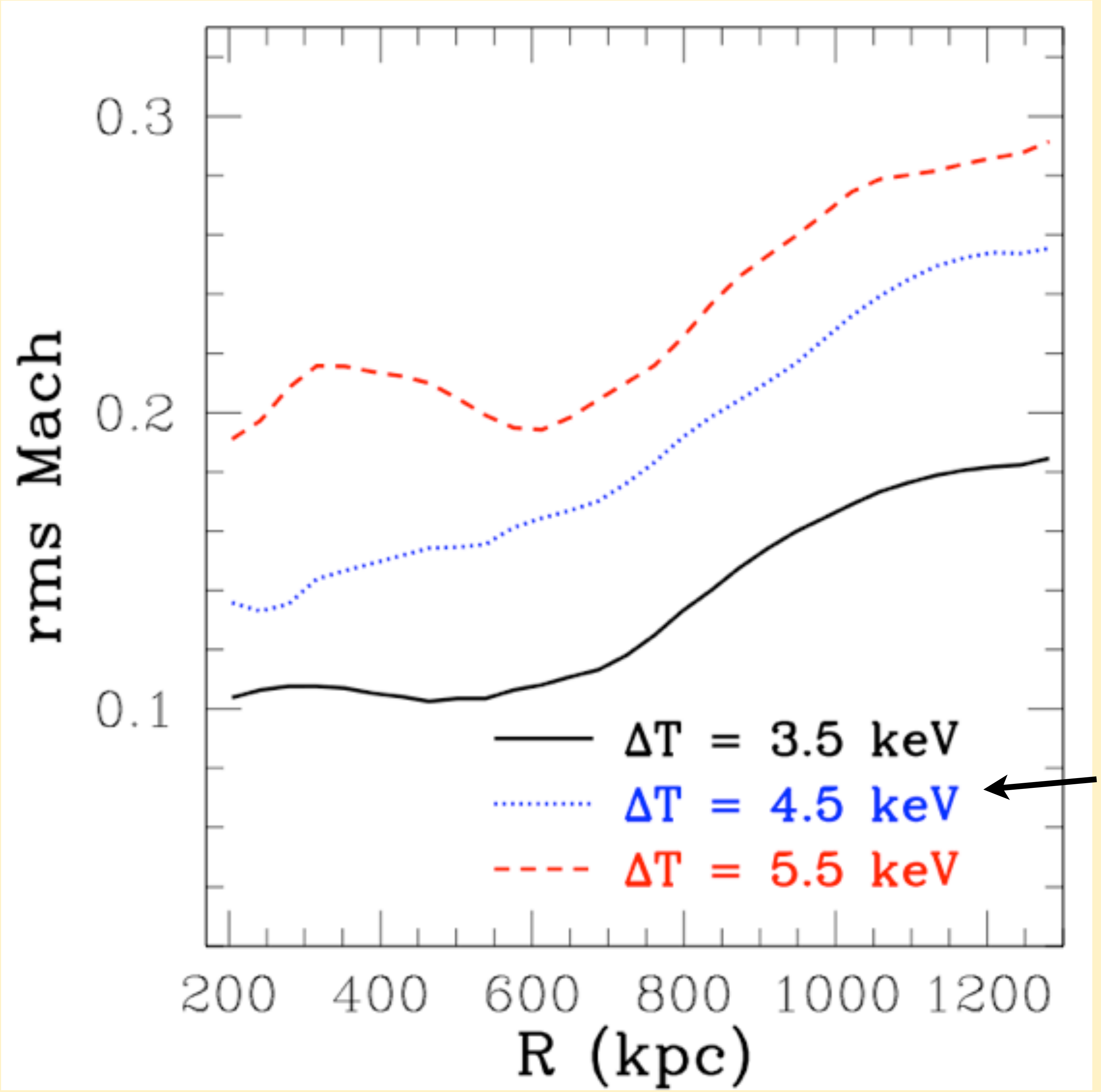
For cosmological: Ruszkowski+ 2011 (yesterday's talk)

Saturated MTI Velocities



- MTI can provide pressure support in outskirts.
- Max. Mach is supersonic.
- Driven turbulence (L ~ 200 kpc), adds to MTI turbulence.
- Kinetic energy saturated by ~2 Gyr.

Saturated Velocity Scaling and Bias



Temperature Drop over ~1 Mpc (max T to r_{500})

- Velocities scale with temperature gradient.
- Turbulent pressure support can lead to SZ bias.

Conclusions

<u>Cluster Cores:</u>

- HBI alone quiescently saturates with azimuthal fields.
- Turbulence + HBI can lead to a naturally strong bimodality between cool core and non cool core clusters.
- Conduction *cannot* stably balance cooling in cool cores → AGN.
- Prediction: Cool cores will have weak turbulence.

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Cluster Outskirts:

- MTI does *not* saturate quiescently or radially.
- MTI can generate non-thermal pressure support that adds to existing turbulence from formation.
- The turbulence scales with ΔT, which introduces a bias for mass determinations, especially for the SZ.
- A modest magnetic dynamo is driven.