# Do Galaxy Clusters Boil?

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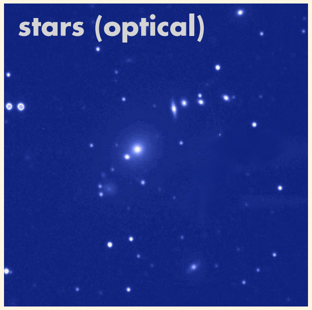
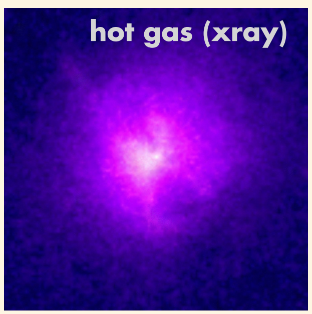
## Introduction




Galaxy clusters are the largest gravitationally bound objects in the universe. Clusters contain the most massive galaxies and the most massive black holes, and may provide useful constraints on dark energy.

Clusters are mostly dark matter by mass, but the baryons play a surprisingly important role in their evolution. Moreover, the baryons are all that we can observe. Understanding the evolution of the baryons is thus essential to improving our understanding of clusters.



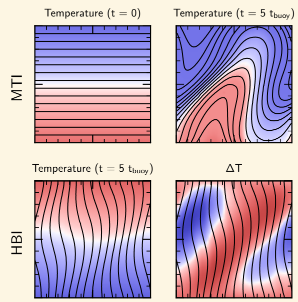

Most of the baryons in clusters (~ 80%) comprise a hot, dilute plasma known as the intracluster medium. Much about the thermal evolution of the ICM remains unclear. For example, it has only recently been discovered that the ICM is *convectively unstable at all radii*. This instability is known as the HBI (MTI) when the temperature increases (decreases) with radius.

## Method

We use the MHD code Athena, modified to implement anisotropic thermal conduction: $Q_{\rm cond} = -\kappa \hat{b}(\hat{b} \cdot \nabla T)$.

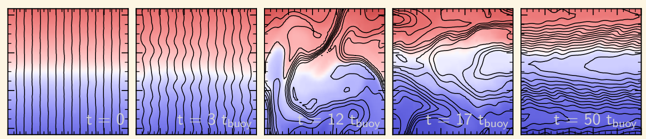
The conductivity takes this form because the electron mean free path in the ICM is much longer than its gyroradius. The electrons (which transport most of the energy) are thus confined to move along magnetic field lines.

## Physics of the HBI & MTI

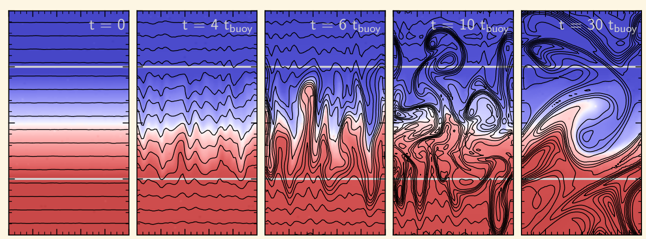



The HBI and MTI are convective instabilities driven by *anisotropic* thermal conduction in plasmas. Electrons move freely along magnetic field lines, redistribute energy and buoyantly destabilize vertically displaced fluid elements. Perturbations grow with the local dynamical time $t_{\rm HBI} \sim t_{\rm dyn} \sim \sqrt{H/g}$.

(color shows the plasma temperature and lines trace the magnetic field.)

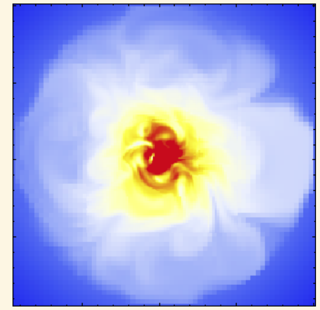



The HBI saturates quiescently by reorienting the magnetic field lines. This insulates the plasma against a conductive heat flux, and may exacerbate the cooling flow problem.

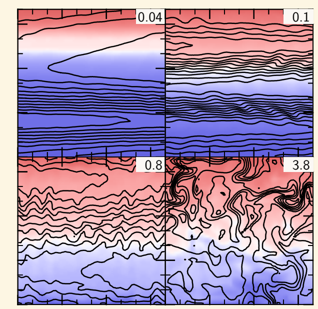



Though the linear behavior of the MTI is similar to that of the HBI, its nonlinear behavior is entirely different. The MTI does not reorient the field lines and in fact drives strong, ~ sonic turbulence.

## Implications for Clusters



The MTI may be an important source of turbulence at large radii in galaxy clusters. This influences both the strength of the magnetic field and the mixing of metals in the ICM. More importantly, MTI turbulence may introduce a *systematic, 5–10% bias* into cluster mass estimates. **Understanding this bias may be crucial for using clusters for precision cosmology.**




The HBI tends to make the magnetic field horizontal, while other sources of turbulence tend to isotropize it. These effects compete and control the mean orientation of the magnetic field $\hat{b}_z \propto (t_{\rm eddy}/t_{\rm HBI})^2$. The field angle, in turn, sets the effective thermal conductivity of the plasma, thus controlling an important source of energy to offset cooling in the ICM. **Understanding the interaction between turbulence and the HBI, particularly in a cooling plasma, is crucial for understanding the thermodynamics of the plasma at small radii in clusters.**

## Acknowledgments

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## References

***McCourt et al. (2010)***, *Sharma et al. (2009), Quataert (2008), Parrish & Quatert (2008), Parrish & Stone (2005, 2007), Balbus (2000)*