# Sloshing in Cluster Cores: Insights Into the Physics of the ICM

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and

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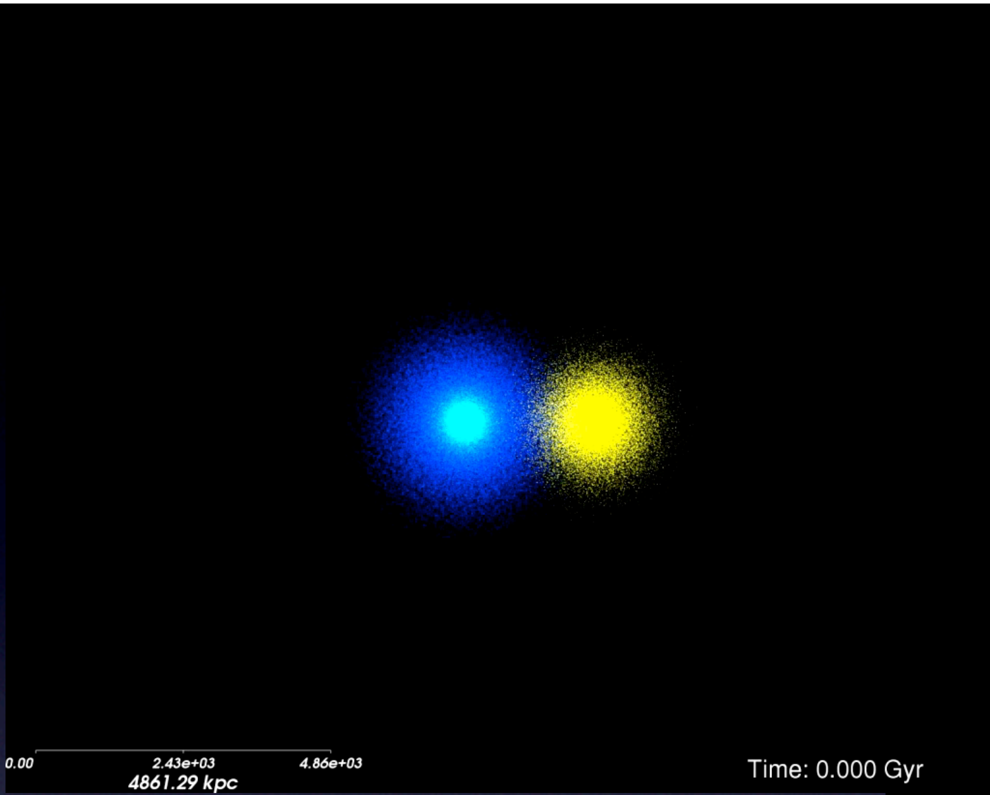
# Merging Galaxy Clusters

- "The most energetic events in the universe since the Big Bang."
- Heat gas, drive turbulence, accelerate non-thermal particles, separate gas from stars and dark matter
- *Interesting*... we can about learn the properties of the different kinds of matter and the underlying physics
- *Annoying*... drives clusters away from equilibrium, complicating mass estimates for constraining cosmology

Mass Ratio: 1:3
Impact Parameter: 0 kpc



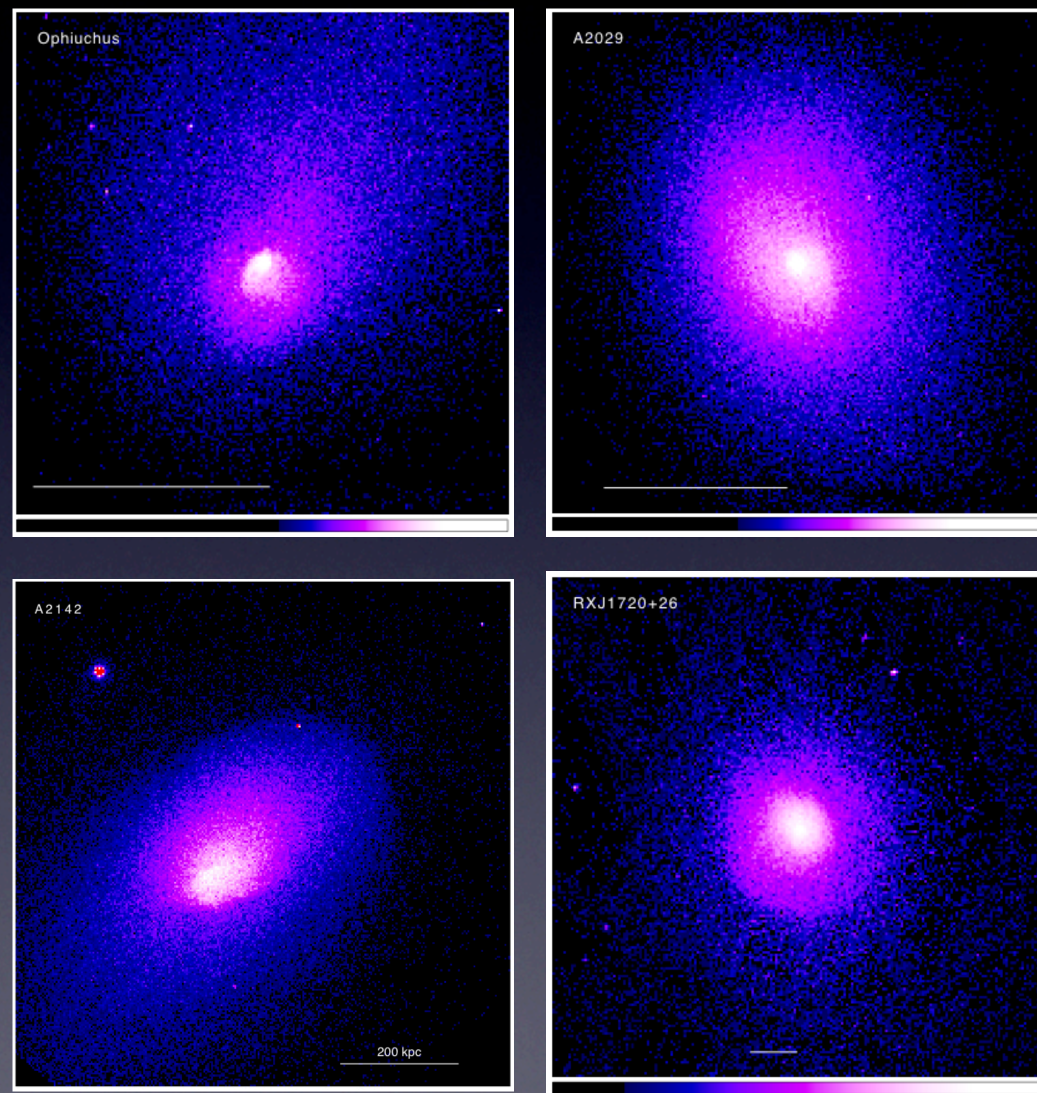

Dark Matter

Hot Gas


ZuHone 2010
arXiv:1004.3820

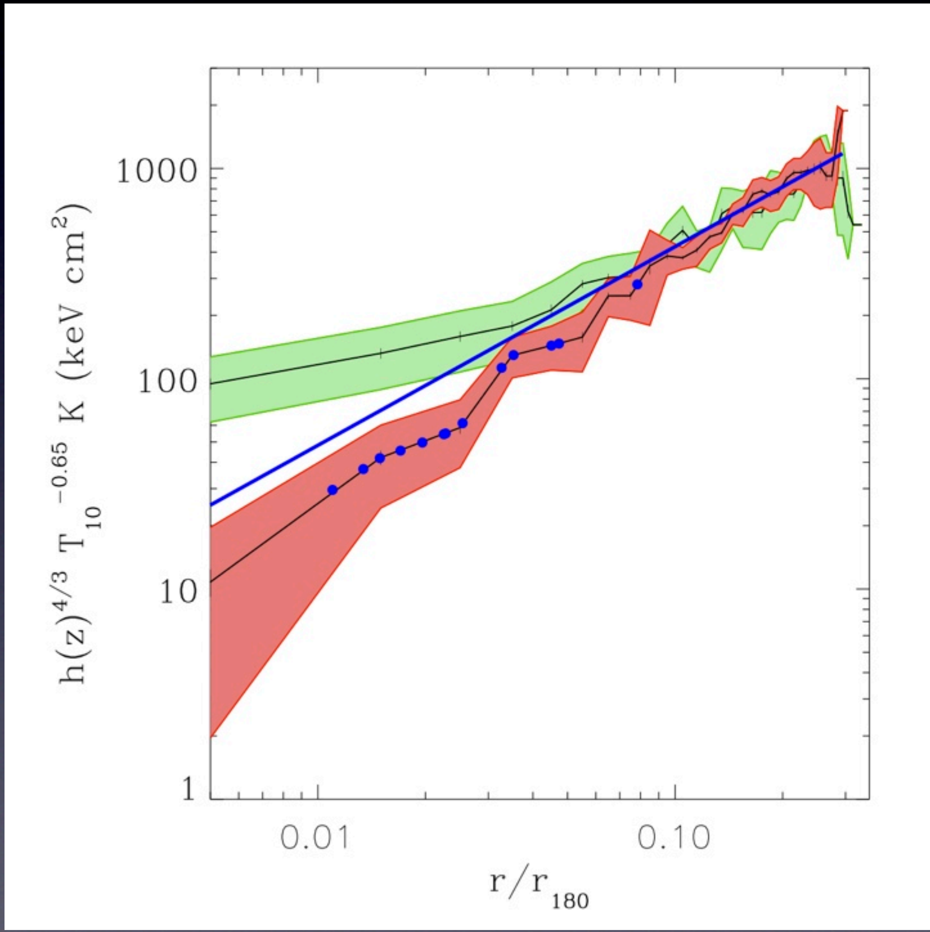
# Observations of Gas Sloshing

- The signature: cold fronts in relaxed cool-core clusters
- Spiral-shaped discontinuities in surface brightness and projected temperature
- Most easily explained by the "sloshing" of the cool core gas in the dark matter potential well
- Cold gas has been uplifted from the gravitational potential minimum and formed a contact discontinuity in pressure equilibrium with the hotter, less dense gas



# Observations of Gas Sloshing

- Sloshing cold fronts preferentially occur in clusters with steep entropy profiles in the core (Ghizzardi et al 2010)
- The entropy contrast between the core gas and the outer gas must be of a sufficient magnitude to form the cold fronts that are seen



# Why Is This Interesting?

- What are the possible applications of studying sloshing?
  - Merger characteristics (Roediger et al. 2010)
  - Constraints on diffusive processes, e.g. viscosity (ZuHone et al 2010) and conduction from the sharpness of the fronts
  - Transport of metals from cluster core (Roediger et al. 2010)
  - Generation of turbulence; producing radio mini-haloes
  - Bending Wide-Angle Tail radio sources?

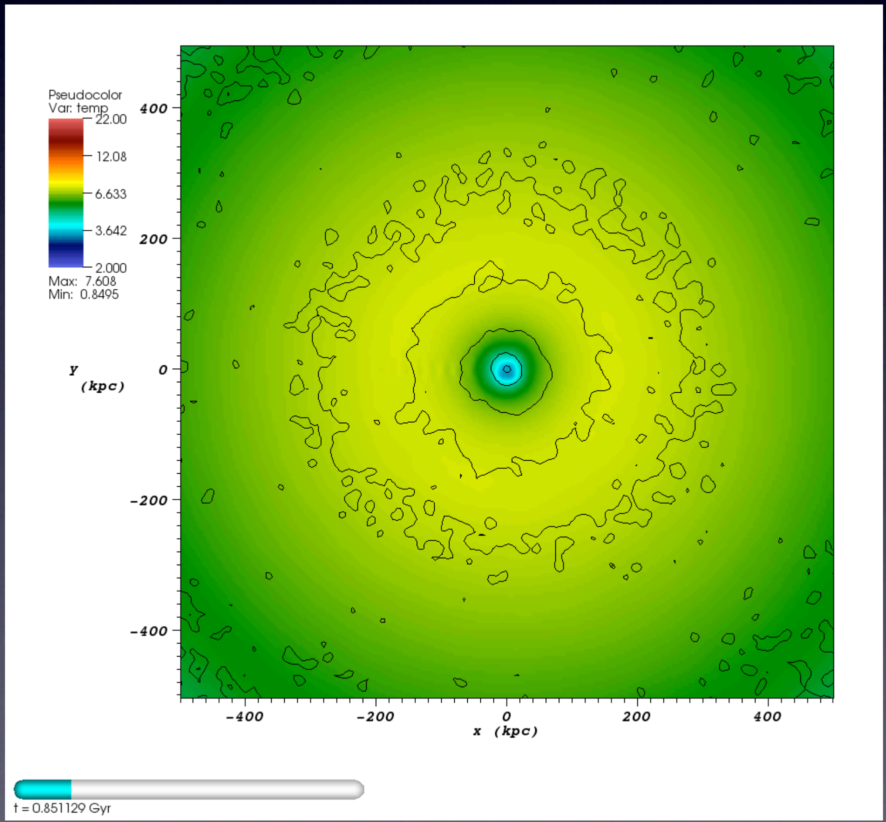
# Simulations: A Sloshing Laboratory

- Using FLASH 3.2
  - Dark Matter: N-body Particle Mesh
  - Gas: Piecewise-Parabolic Method
  - Magnetic Fields: Unsplit Staggered Mesh/Constrained-Transport
  - Gravity: Multigrid self-gravity or rigid potentials
- Physical setup (see Ascasibar & Markevitch 2006)
  - Large, cool-core cluster merging with small subcluster
  - Varying mass ratio *R* and impact parameter *b* of subcluster (some with gas, some without)
  - Simulations vary in physical details (viscosity, magnetic fields)
  - Finest Grid Resolutions Δx ~ 0.5-5 kpc

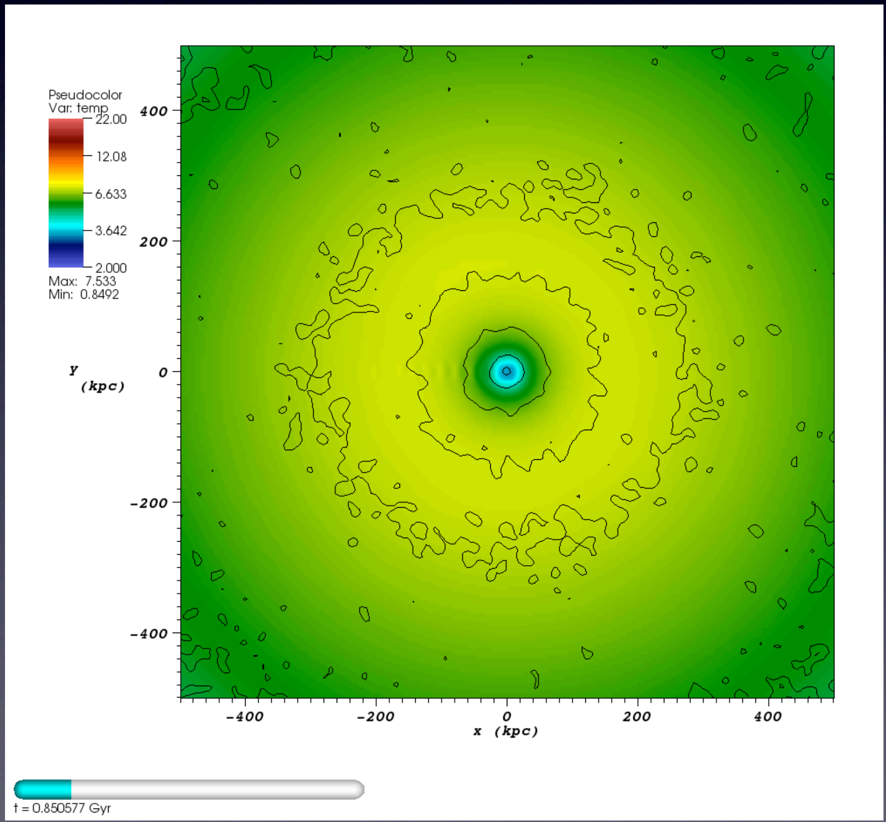
# T (keV) w/ DM contours

## $R = 5$, $b = 500$ kpc

### Inviscid



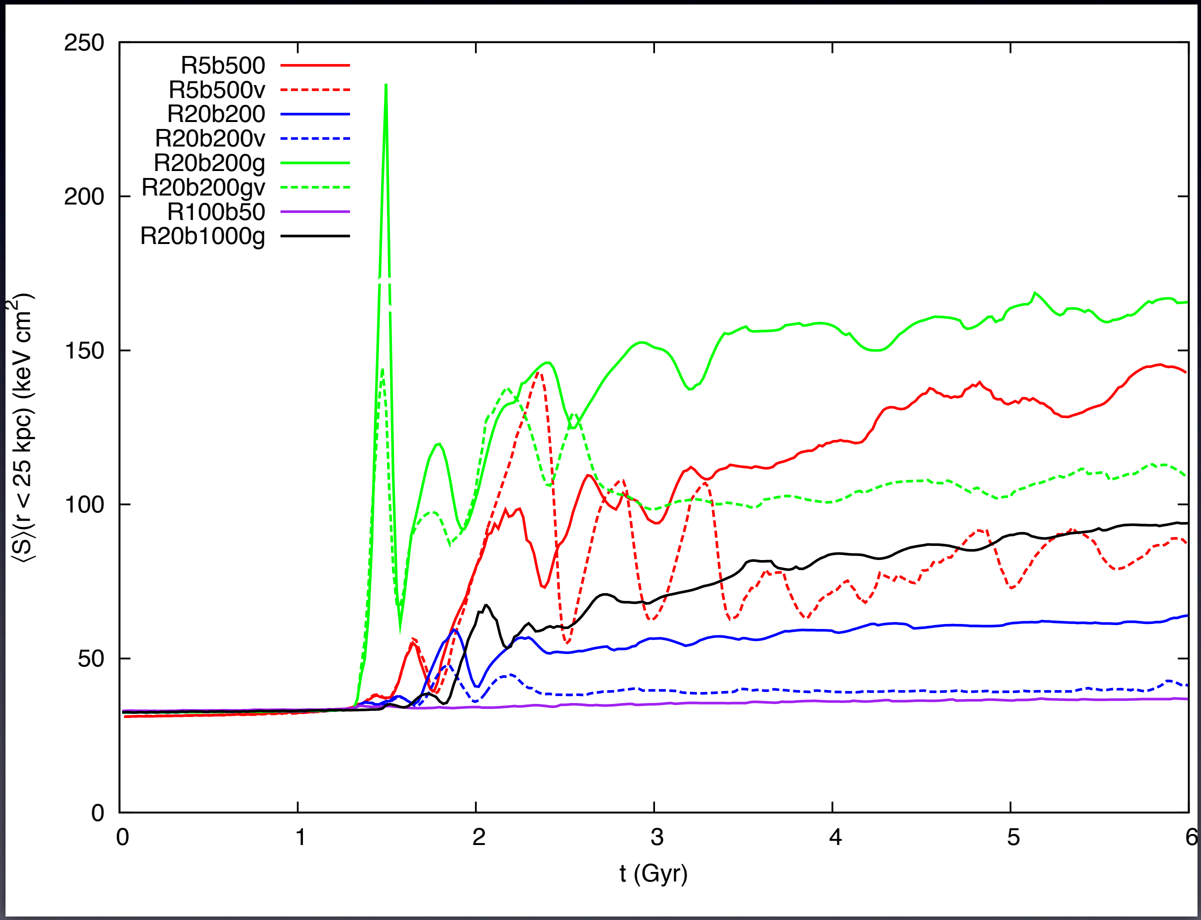

### Viscous (~Spitzer in core)



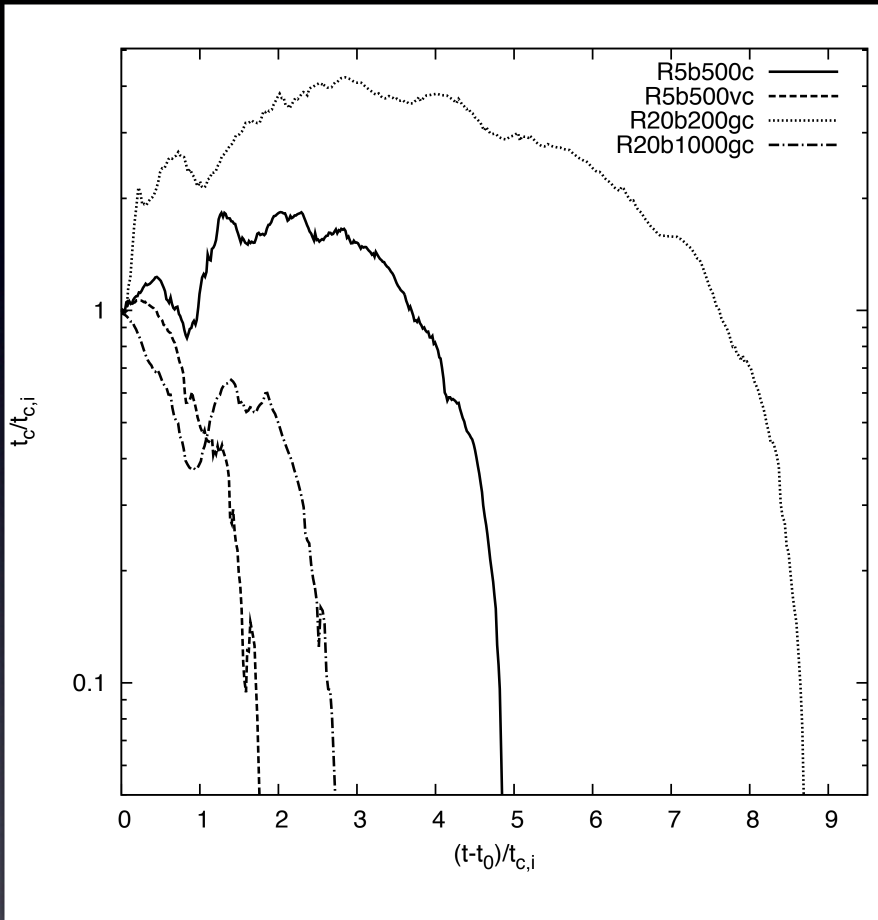
# Sloshing Heats the Core

Central entropy ($S = k_B T/n_e^{2/3}$) increases

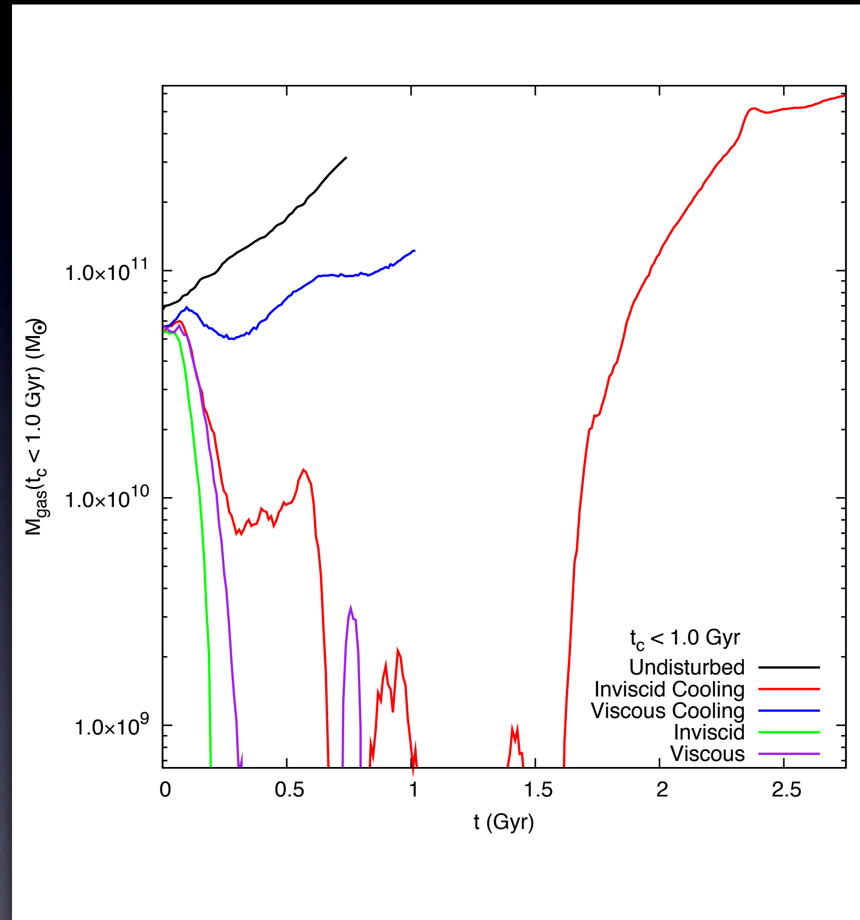
ZuHone, Markevitch, & Johnson 2009



# Heating vs. Cooling



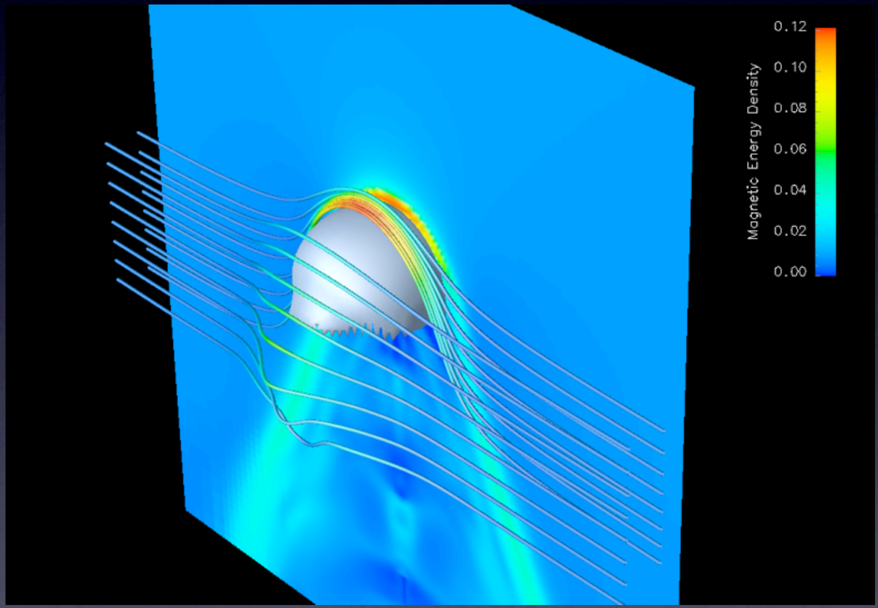

Central Cooling Time




Mass of Gas with $t_{cool} < 1$ Gyr

# Sloshing with Magnetic Fields

- Magnetic fields may alter the physics of sloshing cold fronts
- B-fields may be "draped" across the fronts, which may suppress instabilities and diffusion (Vikhlinin et al 2001, Lyutikov 2006, Asai et al. 2007, Dursi 2007)




Dursi & Pfrommer 2007

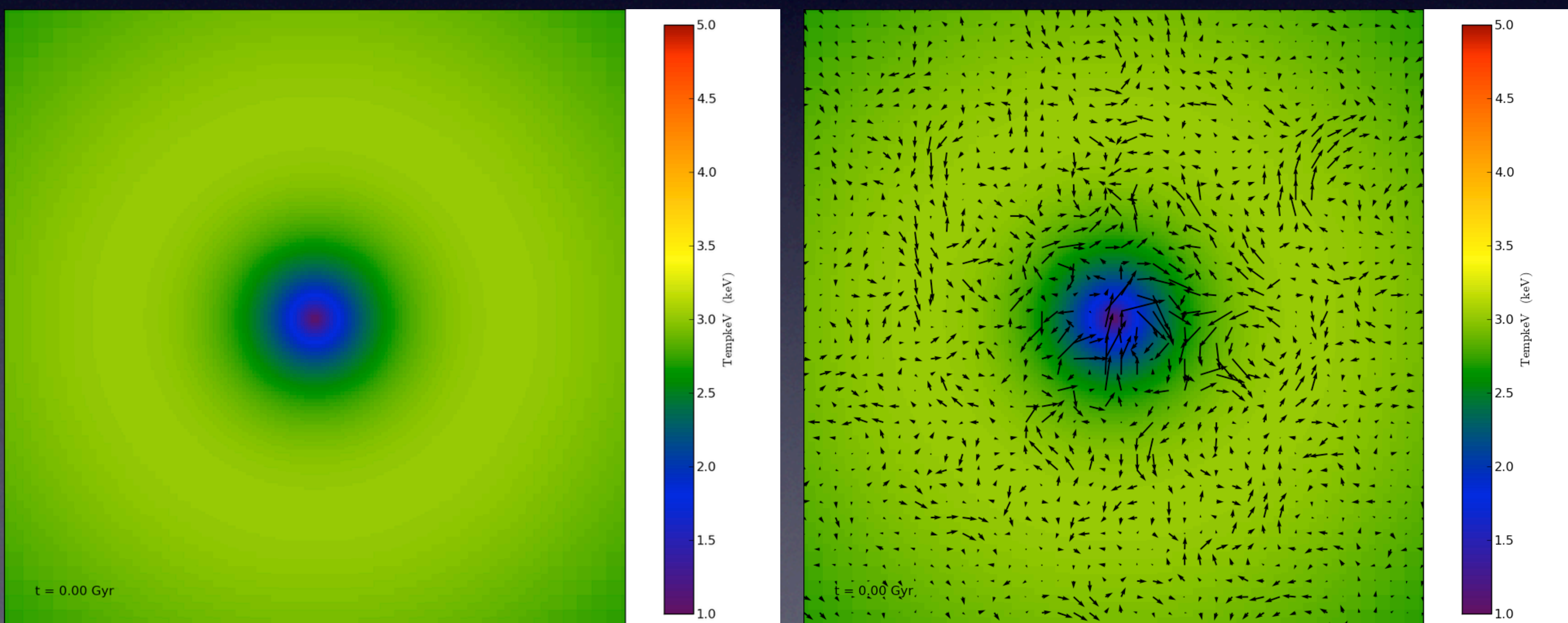
# Sloshing with Magnetic Fields

B-fields: initially tangled

$\beta_c \sim 100$; $B_c \sim 7\ \mu G$; $\Delta x = 2$ kpc

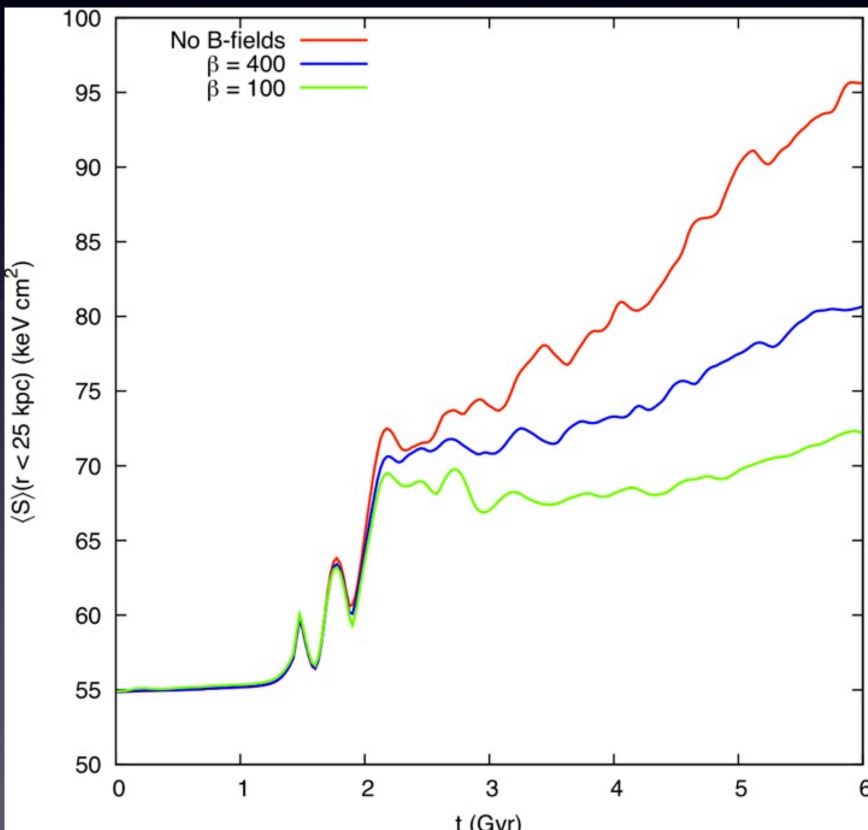
No Fields

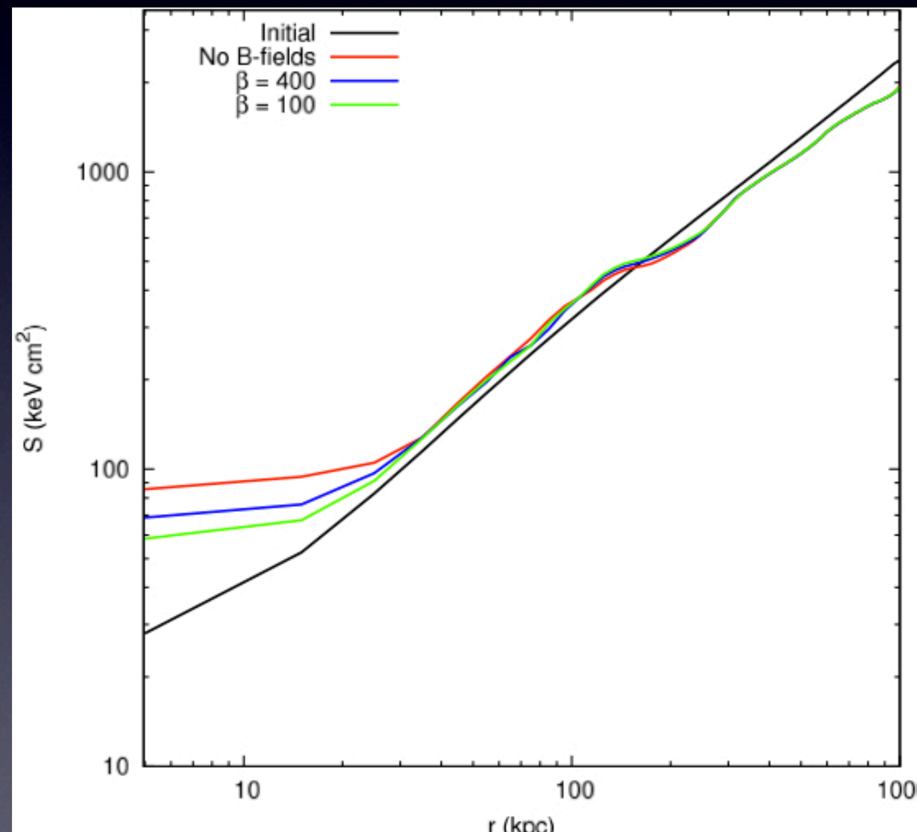
$\beta_c \sim 100$



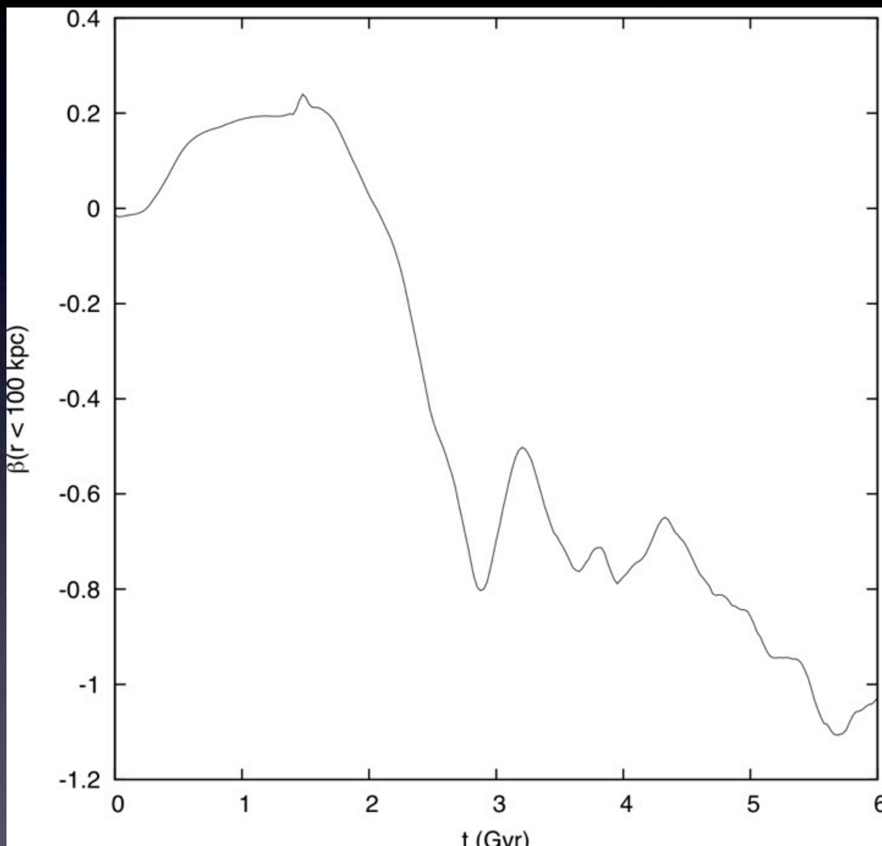

400 kpc on a side

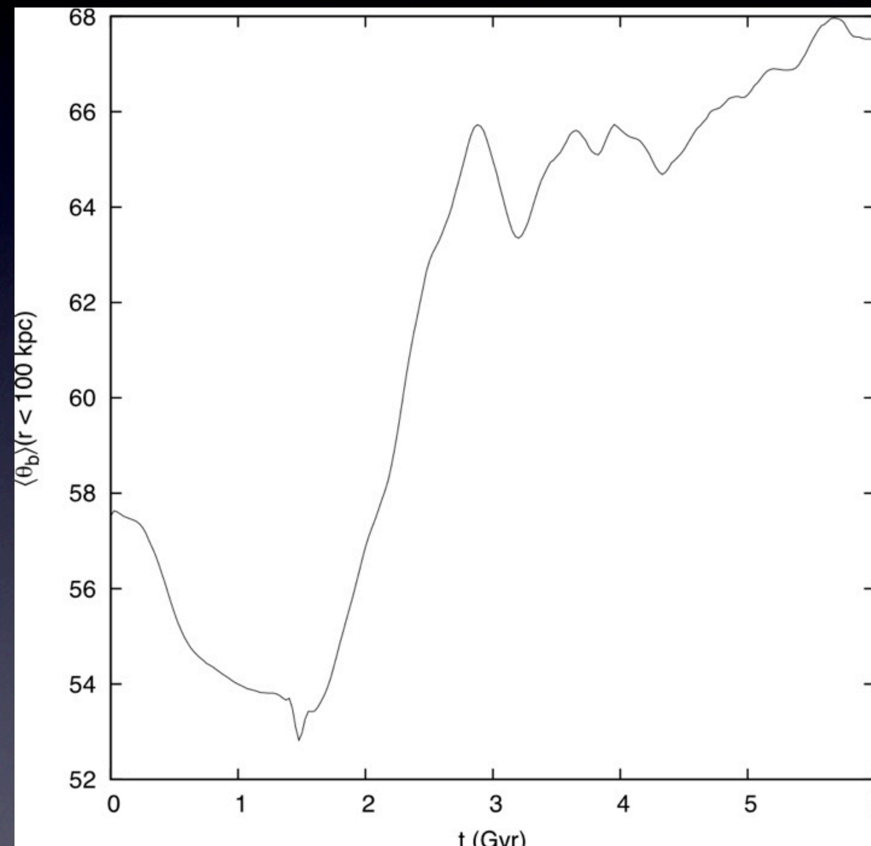
# B-fields Reduce Instabilities and Mixing



# What Happens to the Orientation of the Fields?



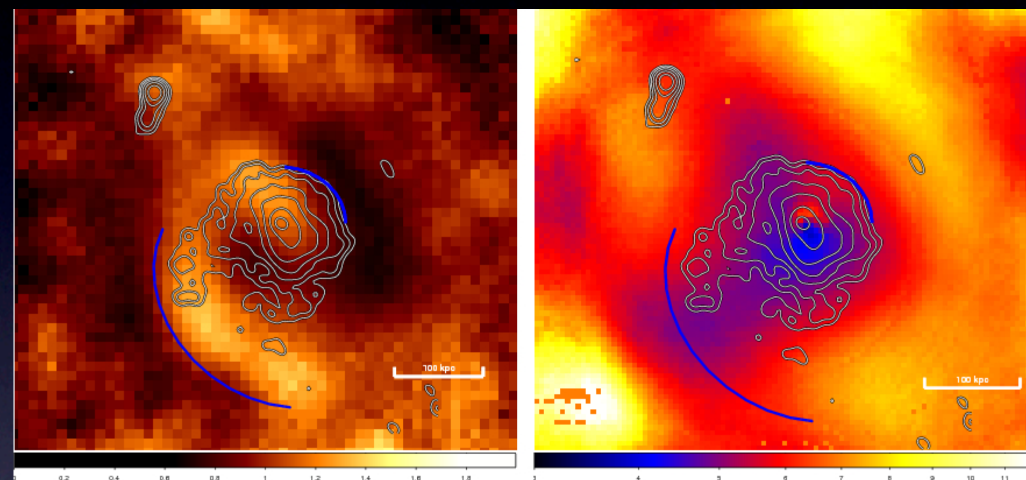




Will have to see what happens when we include anisotropic conduction....

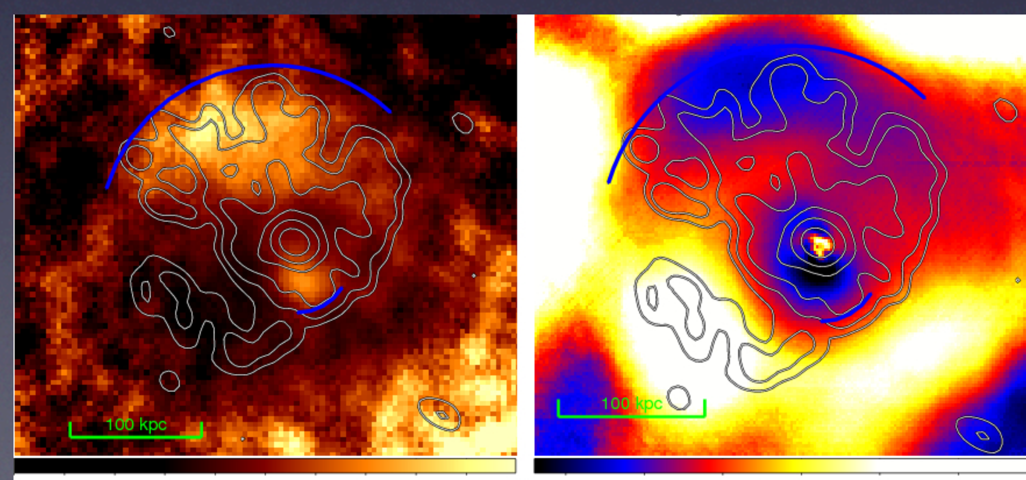
# Radio Mini-Halos

- Diffuse, regular radio emission found in cool-core clusters
  - $r_h$ ~ 100-200 kpc
  - $\alpha$ ~ 1.0-1.5
- Mazzotta & Giacintucci (2008) discovered a correlation between radio mini-halos and cold fronts in two galaxy clusters
- Suggested electrons are re-accelerated via turbulence generated by the sloshing motions

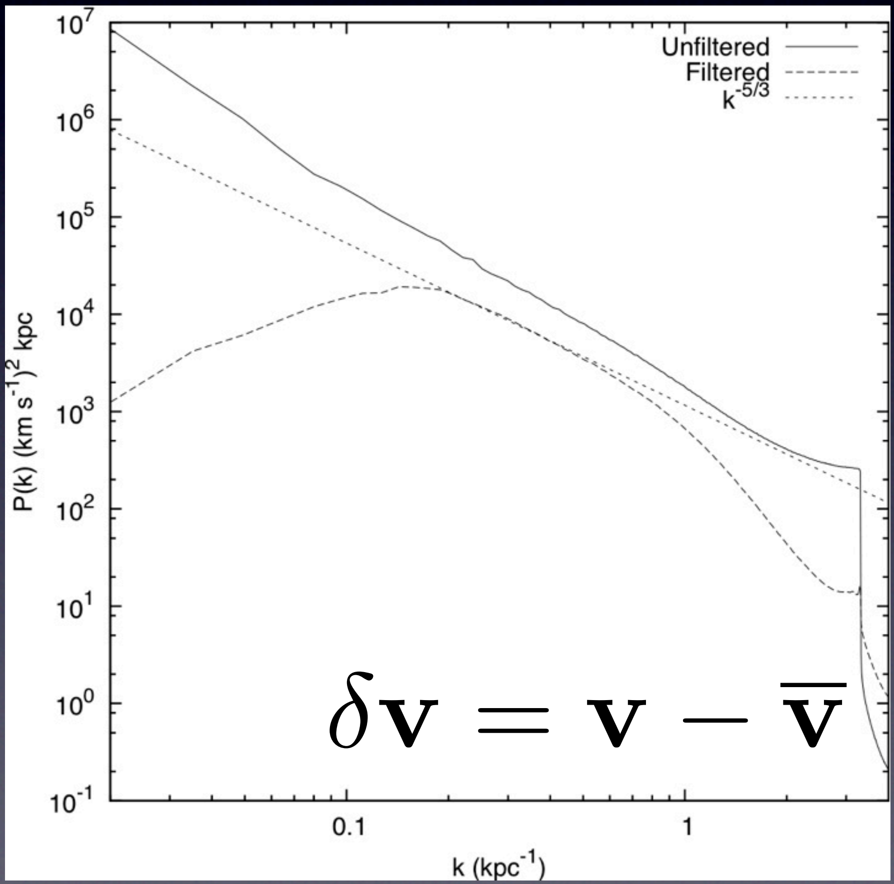
RX J1720.1+2638

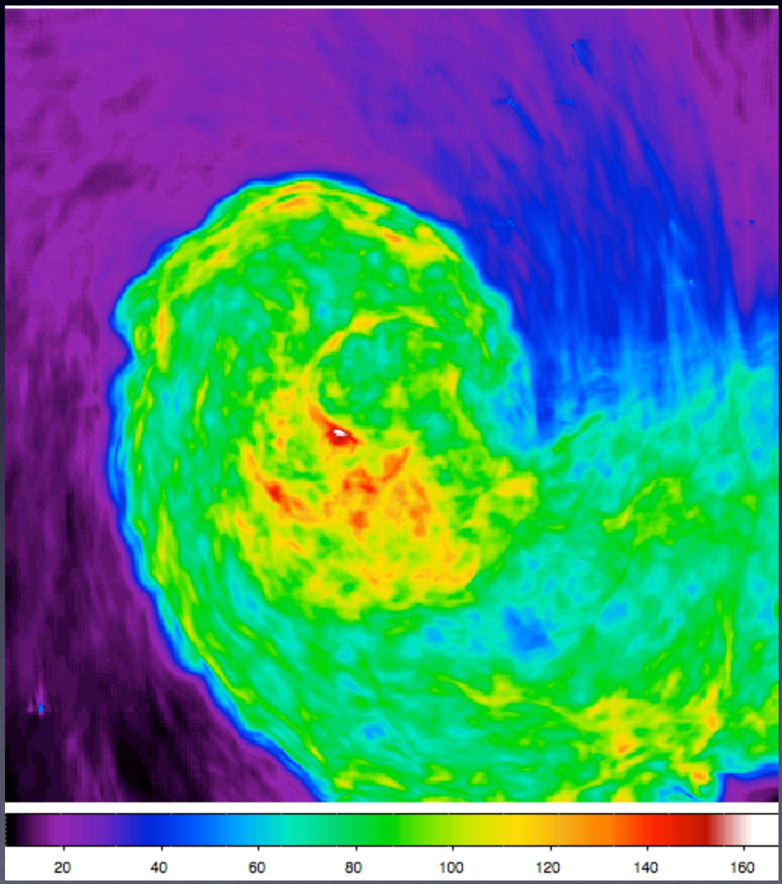


MS 1455.0+2232



# Turbulent Motions in Sloshing Cluster Cores



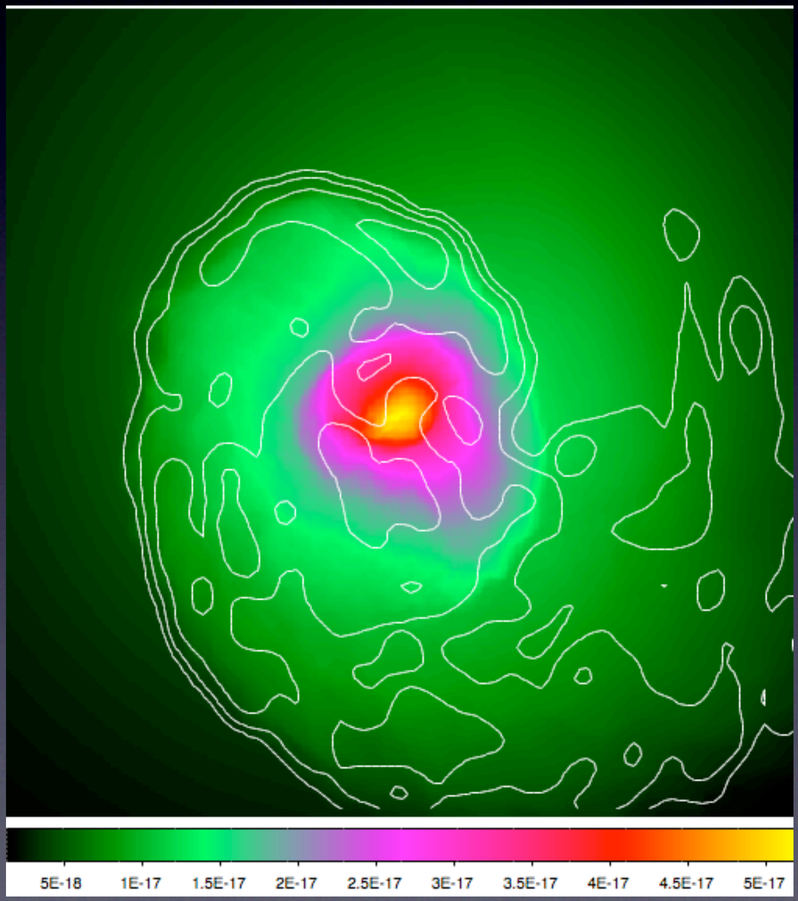




400 kpc on a side

# Reaccelerating Electrons

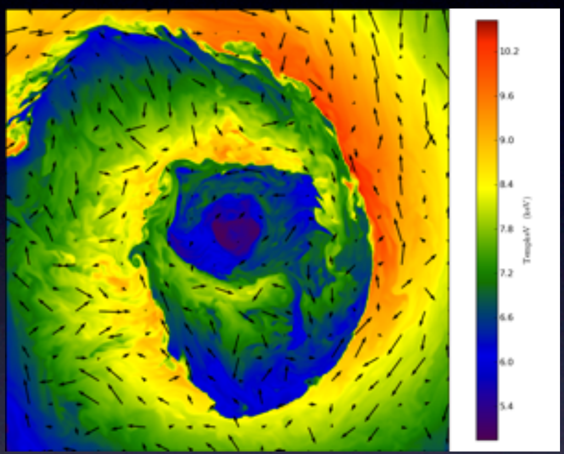
- Accelerate relativistic electrons via turbulence: transit-time damping (TTD) of magnetosonic waves (Eilek 1979, Cassano & Brunetti 2005, Brunetti & Lazarian 2007, 2010, etc.)
- Currently working on generating synchrotron spectra from simulation data
- Can make rough bolometric estimates assuming balance between turbulent gains and radiative losses of the electrons

$$\dot{\varepsilon}_{\rm syn} \propto \frac{\dot{\varepsilon}_t \times (\Gamma_{\rm rel}/\Gamma_{\rm th})}{\left[1 + \left(\frac{B_{\rm CMB}}{B}\right)^2\right]}$$

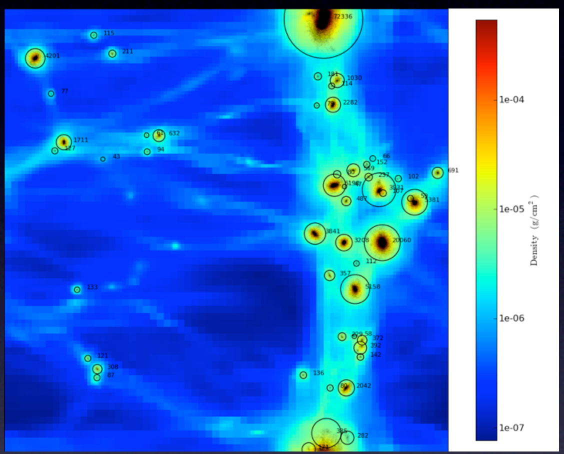



400 kpc on a side

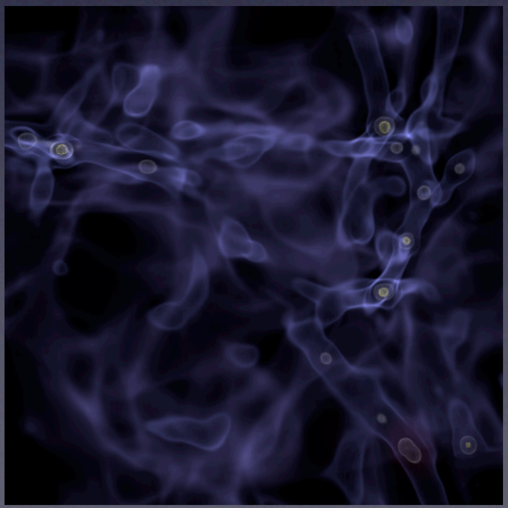
# A New Option for Analysis of FLASH Simulations: yt




http://yt.enzotools.org







# Summary

- Sloshing easily produced by interactions with subclusters
- Stability of the fronts impacted by the microphysics of the ICM, e.g. viscosity, magnetic fields
- Sloshing motions may mix in hot gas with the cold gas from the core, but this is also dependent on the microphysics
- Turbulent motions generated from sloshing may potentially serve as a reacceleration mechanism for electrons and produce radio mini-halos