# The Physics of Gas Sloshing in Galaxy Clusters

John ZuHone (NASA/GSFC, CfA)

with
M. Markevitch (NASA/GSFC, CfA),
D. Lee (Chicago), G. Brunetti (INAF),
M. Ruszkowski (Michigan),
R. Johnson (Dartmouth, CfA)

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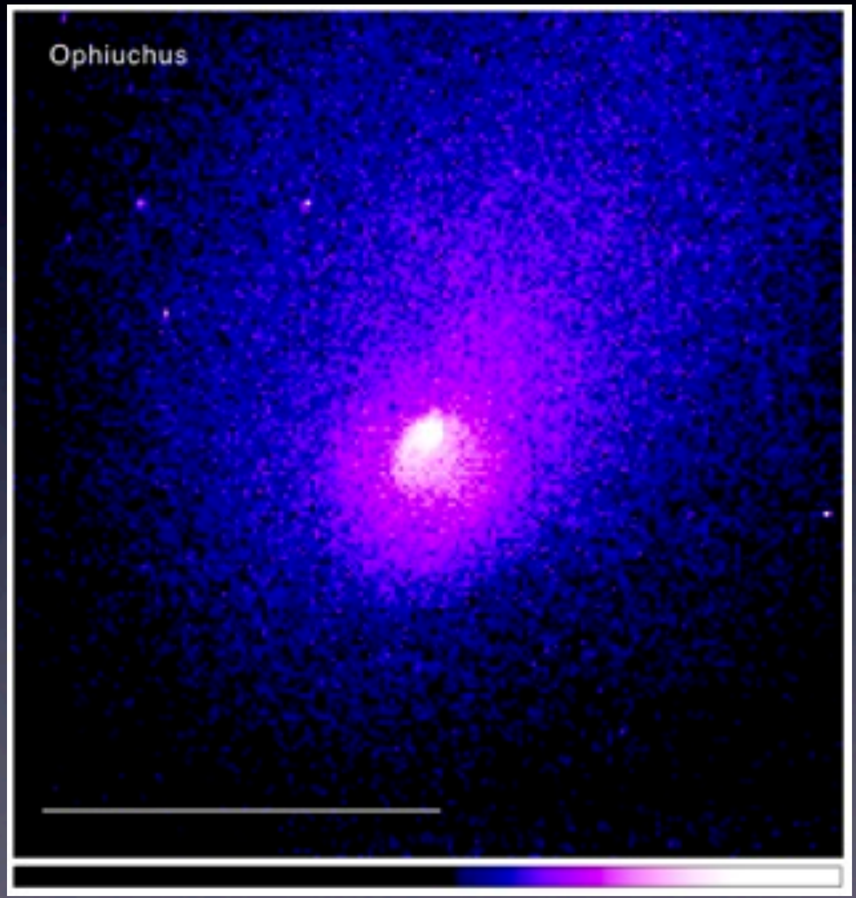
# Some Important Questions...

- What causes sloshing?
- Why are the fronts so smooth?
- What other effects may sloshing have on the cluster core?



# Simulations: A Sloshing Laboratory

- Using FLASH 3
  - Gas: Piecewise-Parabolic Method
  - Dark Matter: N-body Particle Mesh (~$10^6$-$10^7$ particles)
  - Magnetic Fields: Unsplit Staggered Mesh/Constrained-Transport
  - Gravity: Multigrid self-gravity or "rigid body" models for the dark matter-dominated potential
- 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)
  - Finest Grid Resolutions $\Delta x$ ~ 1-5 kpc

# What Causes Sloshing?

T (keV) w/ DM contours

- Interactions with small subclusters (Ascascibar & Markevitch 2006)
- A passing subcluster accelerates both the gas and dark matter components of the cluster core, but the gas component is decelerated by ram pressure, resulting in a separation between the two
- As the ram pressure weakens, the cold core gas falls back into the DM core, but overshoots it and begins to "slosh"

Mass Ratio $R$ = 5, Impact Parameter $b$ = 500 kpc

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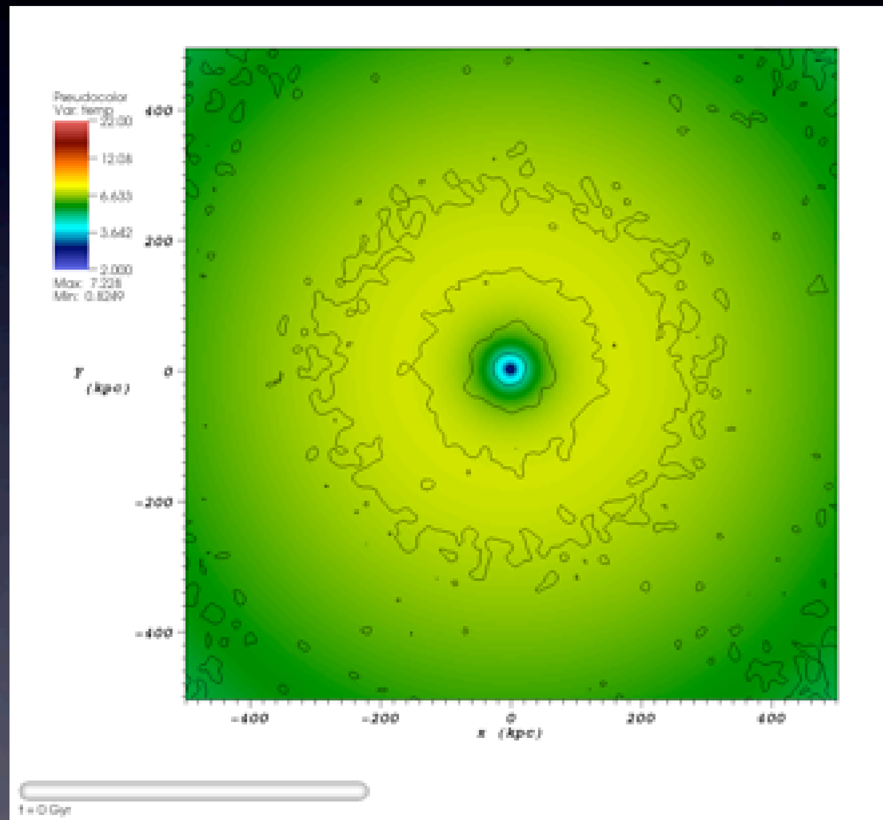


Mass Ratio *R* = 5, Impact Parameter *b* = 500 kpc

Interaction with a gas-filled subcluster

R = 20

b = 1000 kpc

Interaction with a gas-filled subcluster

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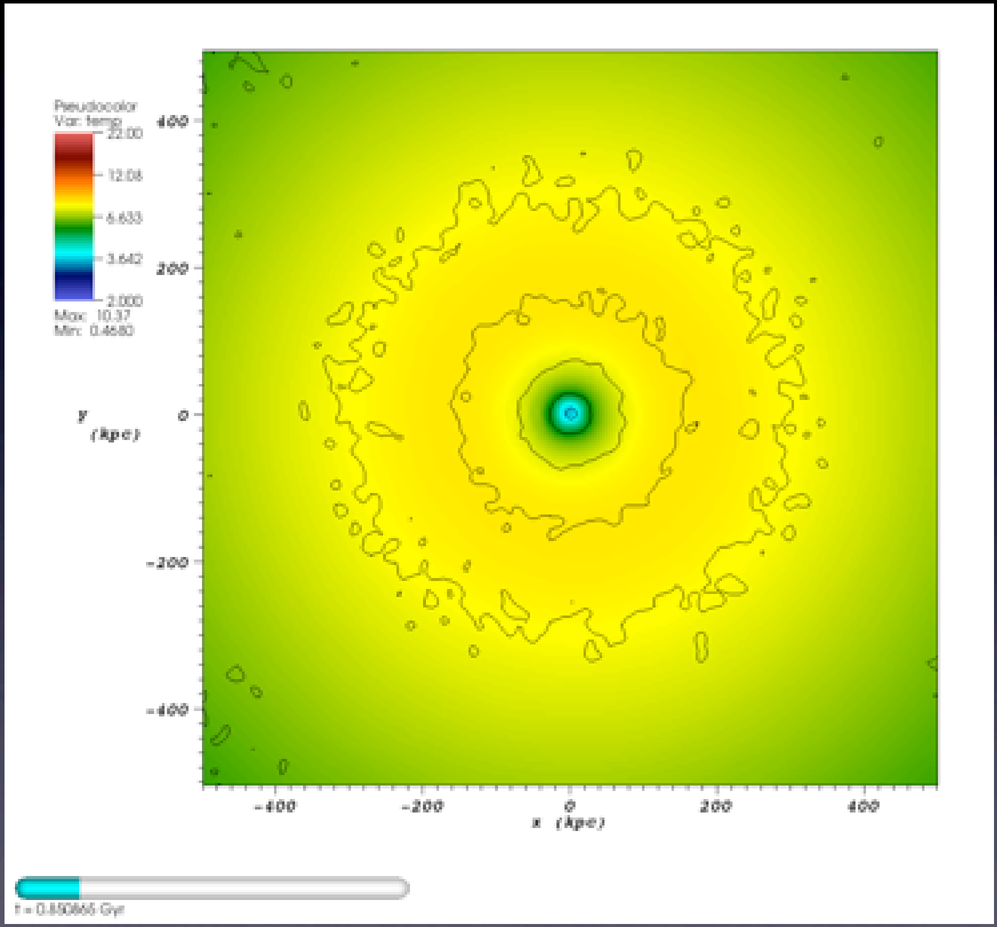


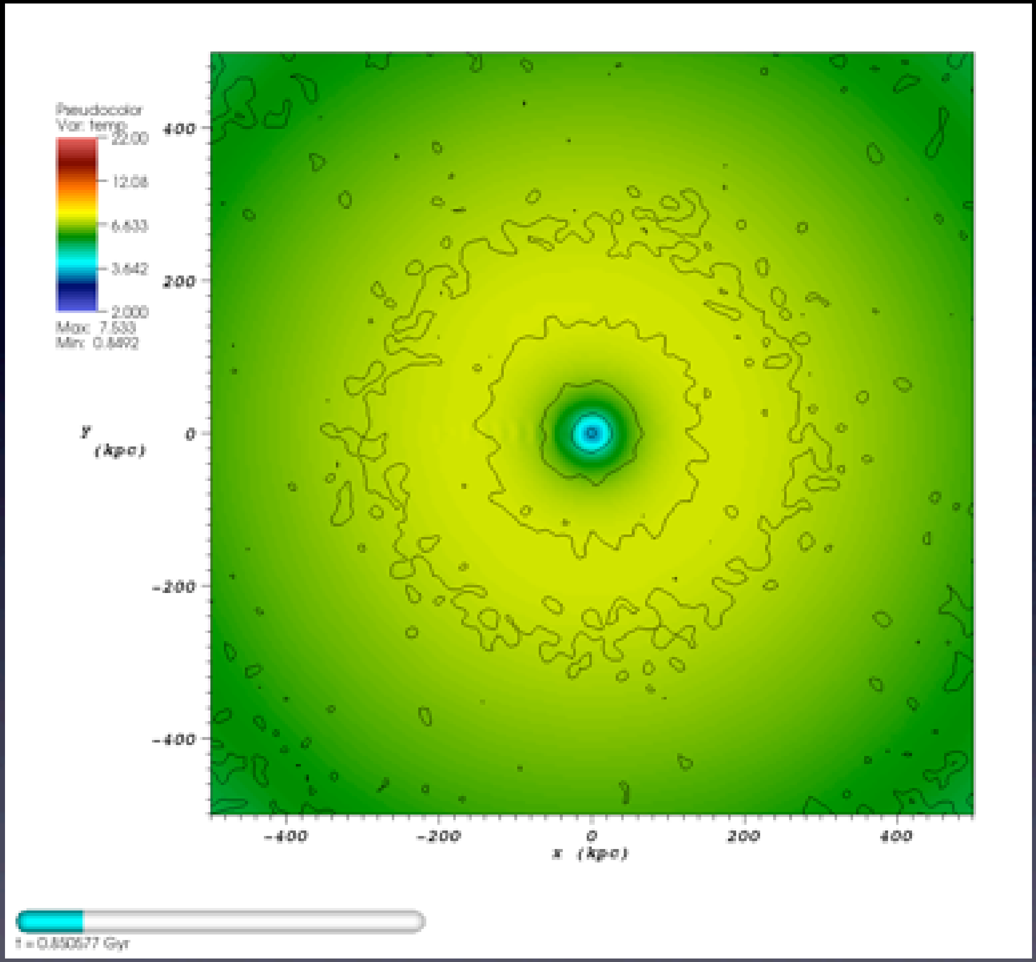
# Why Are the Observed Fronts Stable?

- Large velocity shears exist across the cold front; the fronts should be susceptible to the effects of the Kelvin-Helmholtz instability
- Thermal conduction, if present, should smooth out the temperature gradient
- What could stabilize the front surfaces?
  - Viscosity?
  - Magnetic fields?
- Sloshing cold fronts could tell us something about the physics of the ICM

T (keV) w/ DM contours

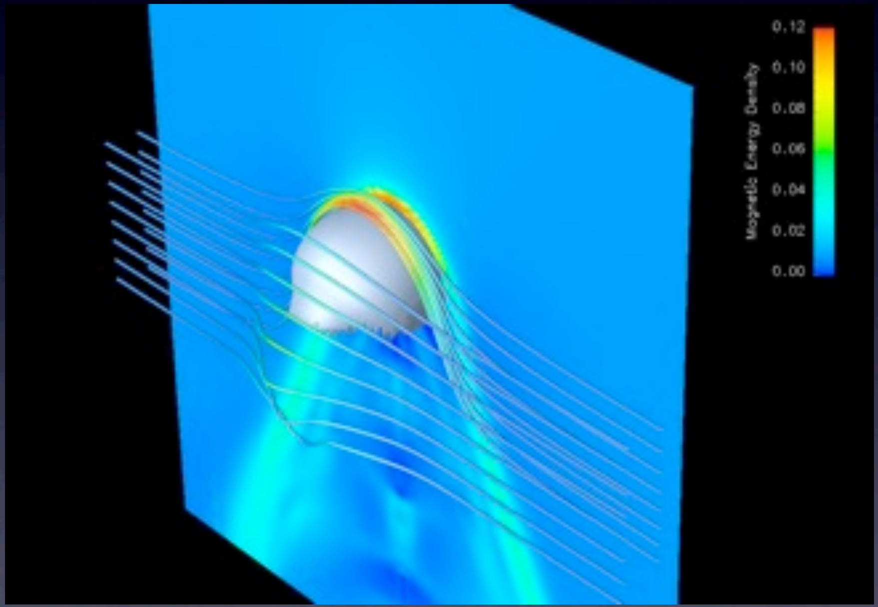
$R$ = 5, $b$ = 500 kpc

Isotropic Spitzer Viscosity



# Sloshing with Magnetic Fields

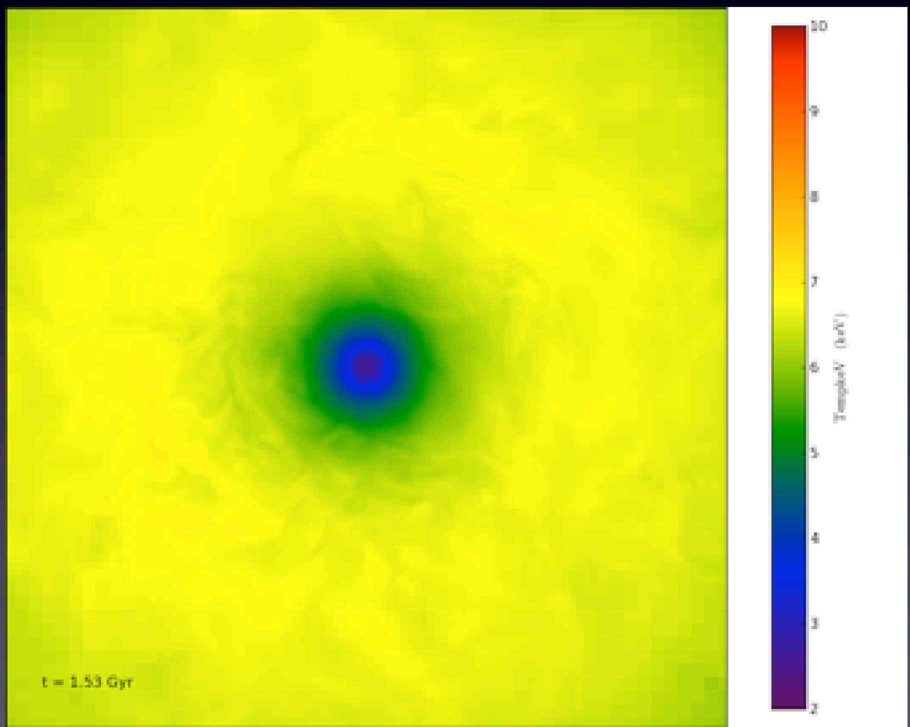
- Magnetic fields may alter the physics of sloshing cold fronts
- B-fields may be “draped” across the fronts, which may suppress instabilities and diffusion (Vikhlinin et al 2001, Lyutikov 2006, Asai et al. 2007, Dursi 2007)



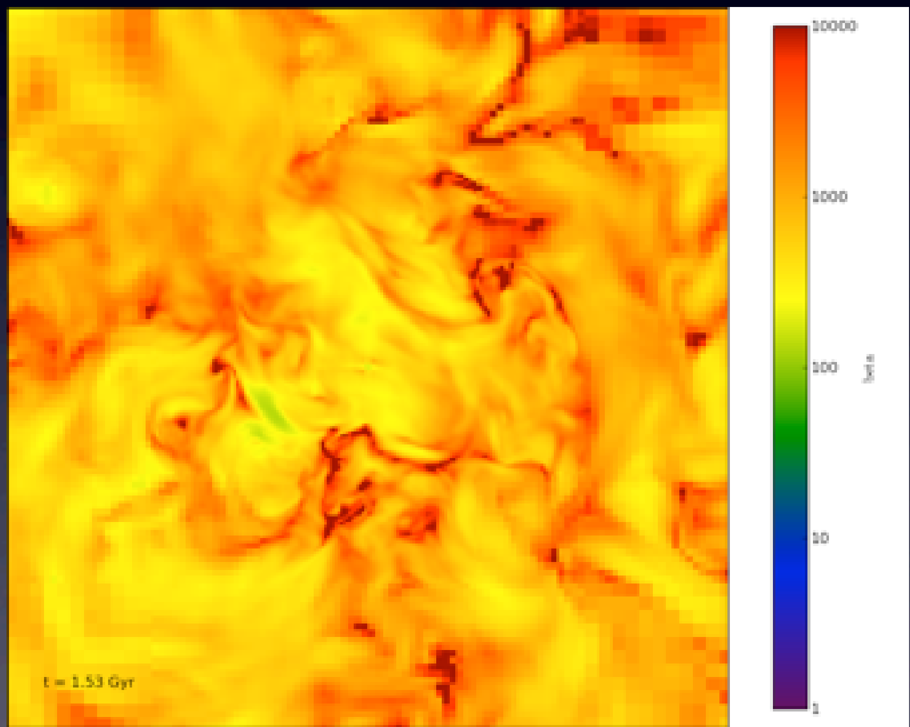

Dursi & Pfrommer 2007

# Sloshing with Magnetic Fields

T (keV)




$\beta = p/p_B$

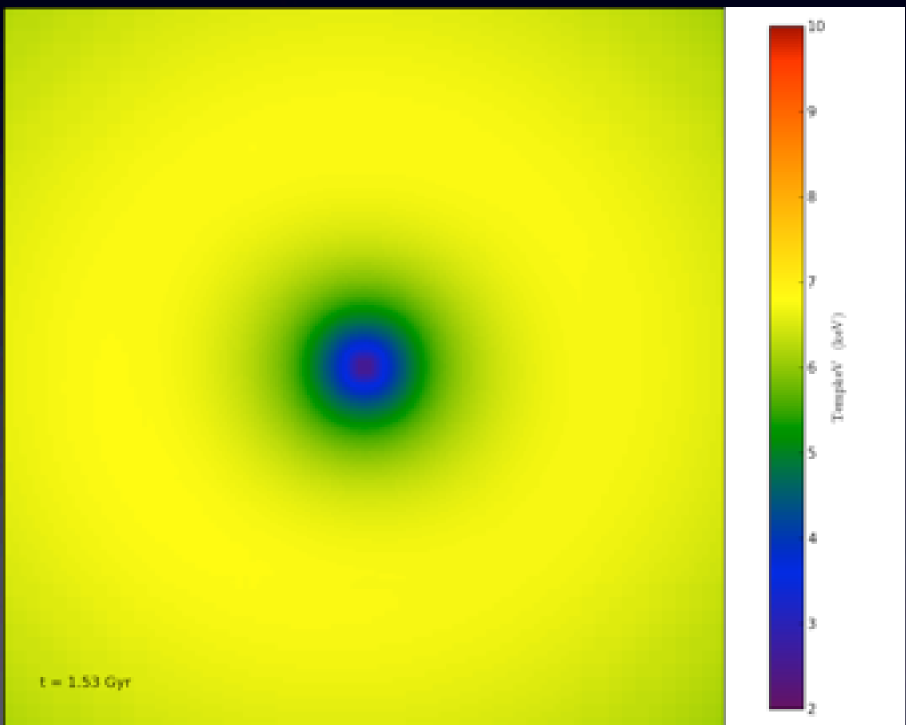



400 kpc

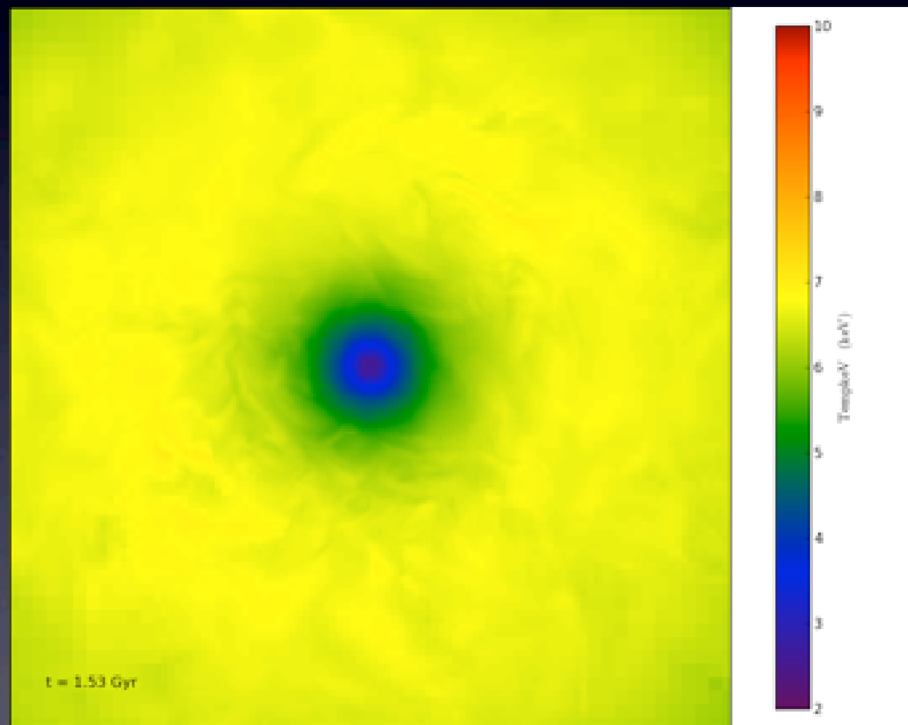
# Sloshing with Magnetic Fields

T (keV)

No Fields




$\beta_{ini} \sim 400$



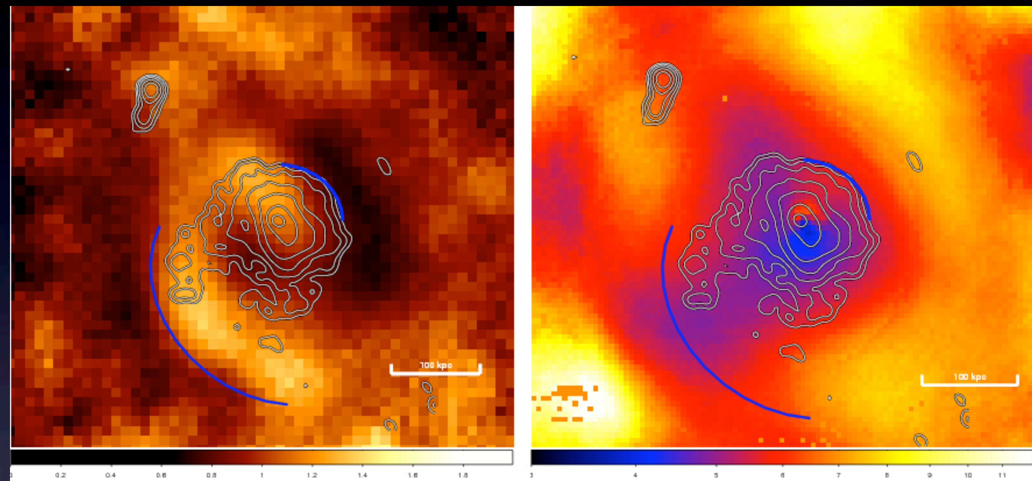

400 kpc

ZuHone, Markevitch, and Lee 2011
(submitted to ApJ)

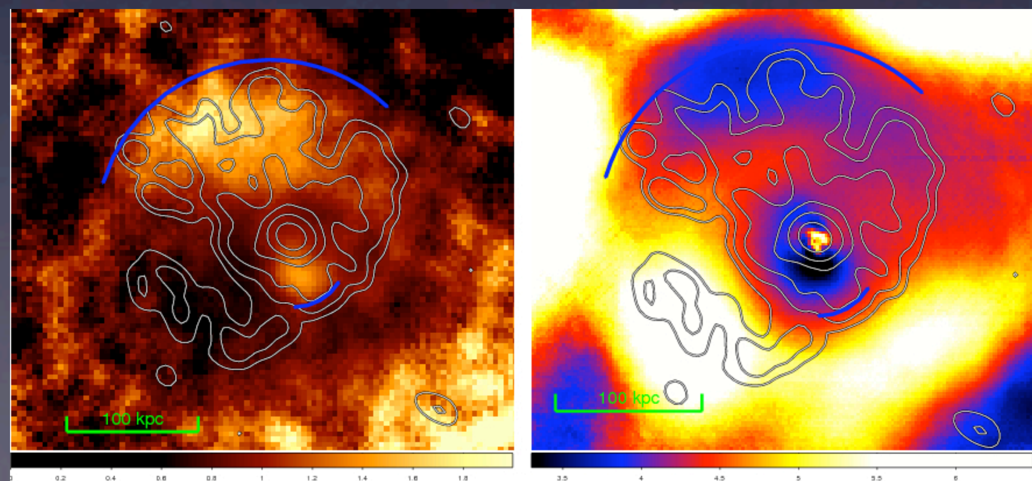
# Radio Mini-Halos

- Diffuse, regular radio emission found in cool-core clusters
  - $r_h \sim$ 100-200 kpc
  - $\alpha \sim$ 1.0-1.5
- Mazzotta & Giacintucci (2008) discovered a correlation between radio mini-halos and cold fronts in two galaxy clusters

RX J1720.1+2638

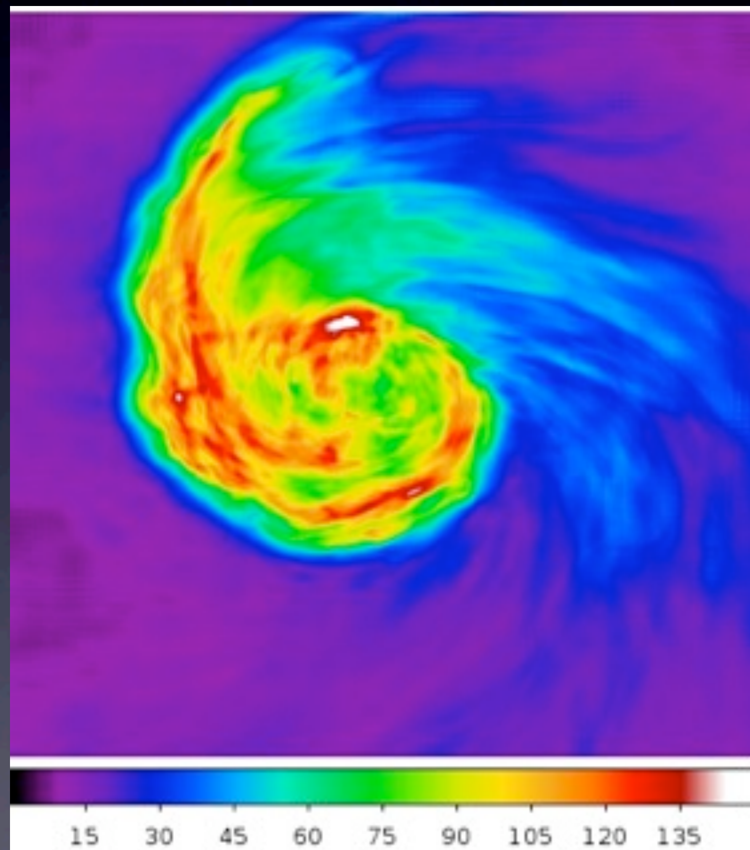


MS 1455.0+2232



# Turbulent Motions in Sloshing Cluster Cores

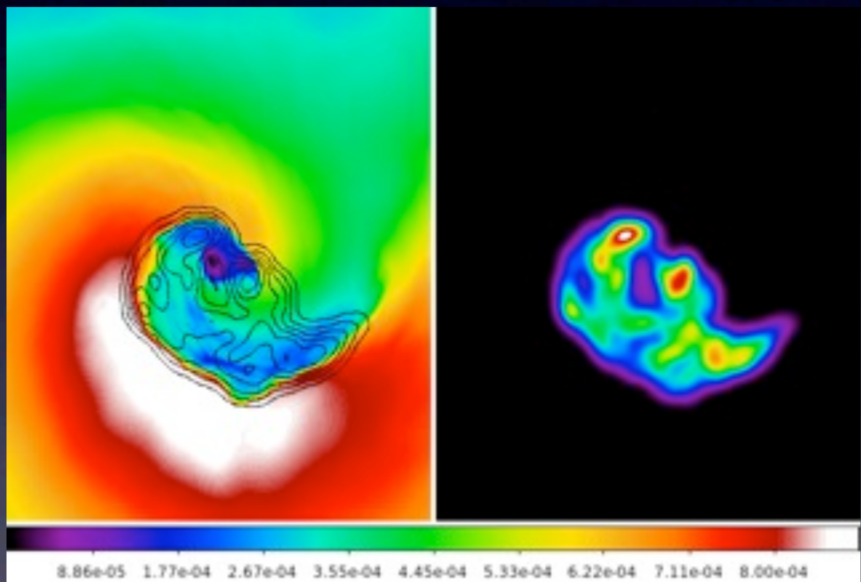
Assume the relativistic electrons are reaccelerated via transit time damping (TTD) of MHD turbulence (Eilek 1979, Cassano & Brunetti 2005, Brunetti & Lazarian 2007, 2010, etc.)

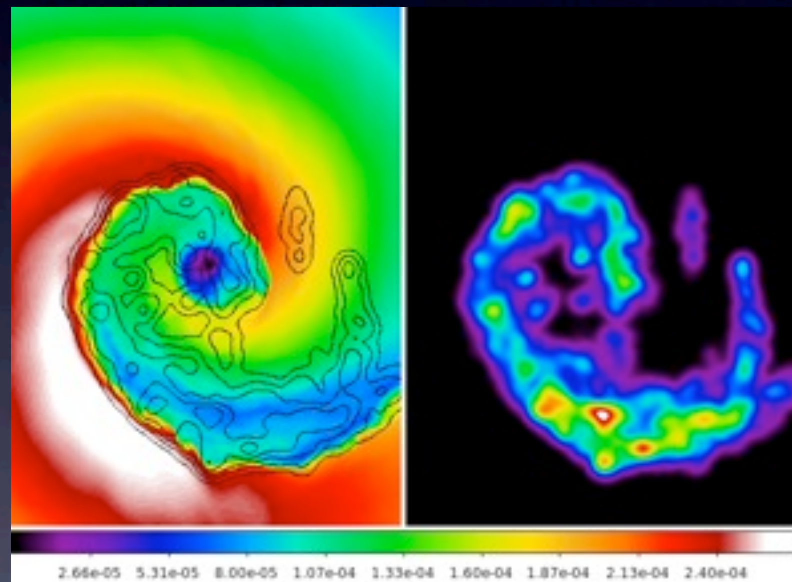



Projected $v_{turb}$ (km/s)

# Comparing Synchrotron With X-Ray

300 MHz contours, z-projection



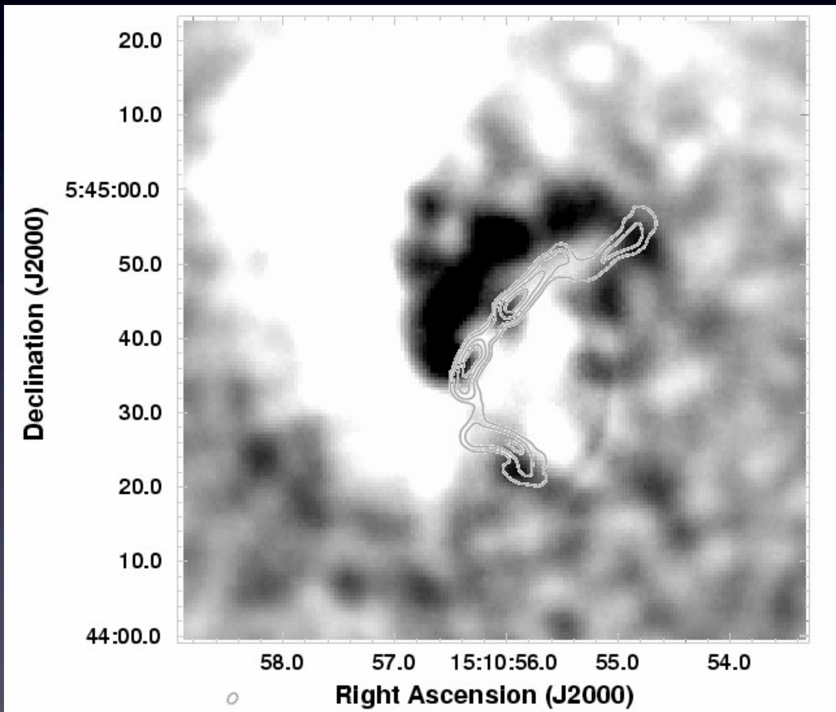




400 Myr later

800 Myr later

ZuHone et al. 2011 (arXiv:1101.4627)

# Wide-Angle Tails




A2029: Clarke, Blanton, and Sarazin 2004

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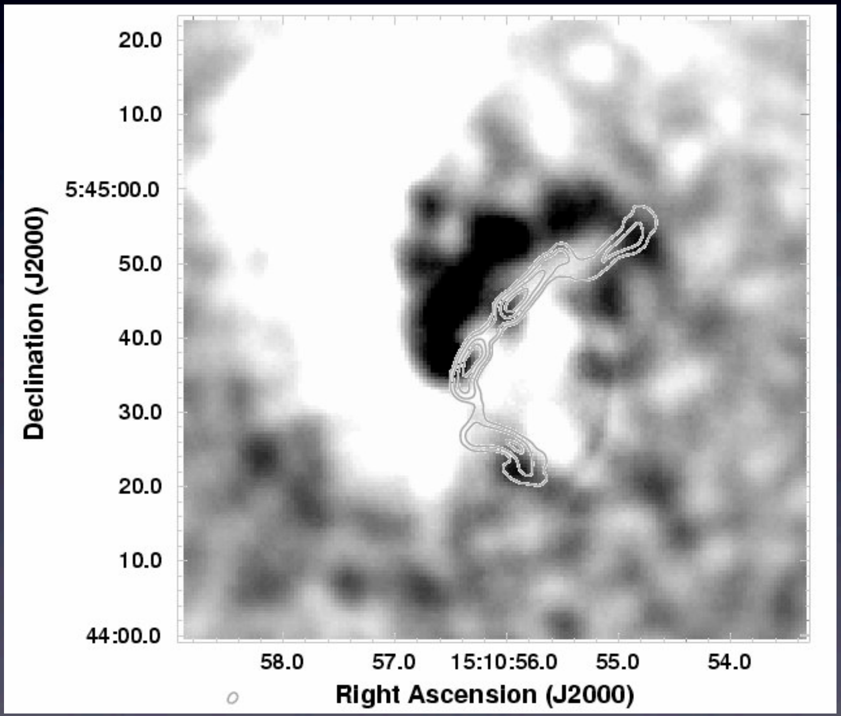


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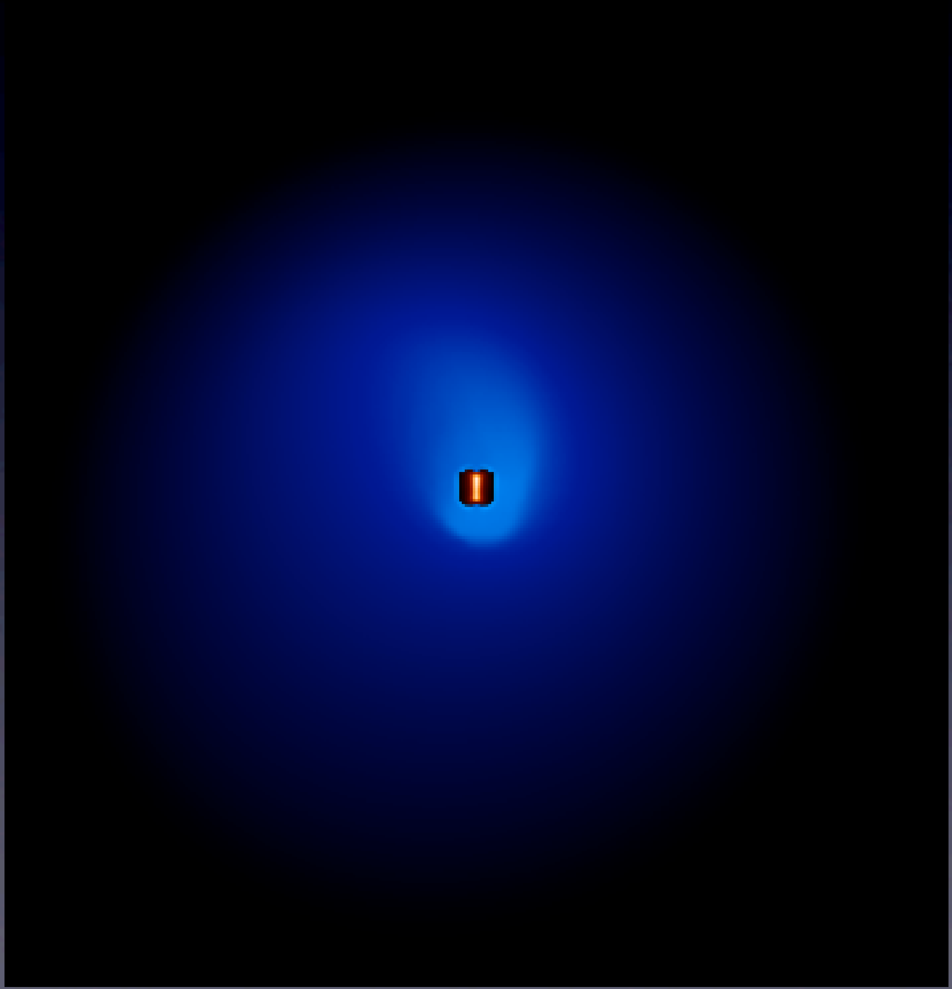
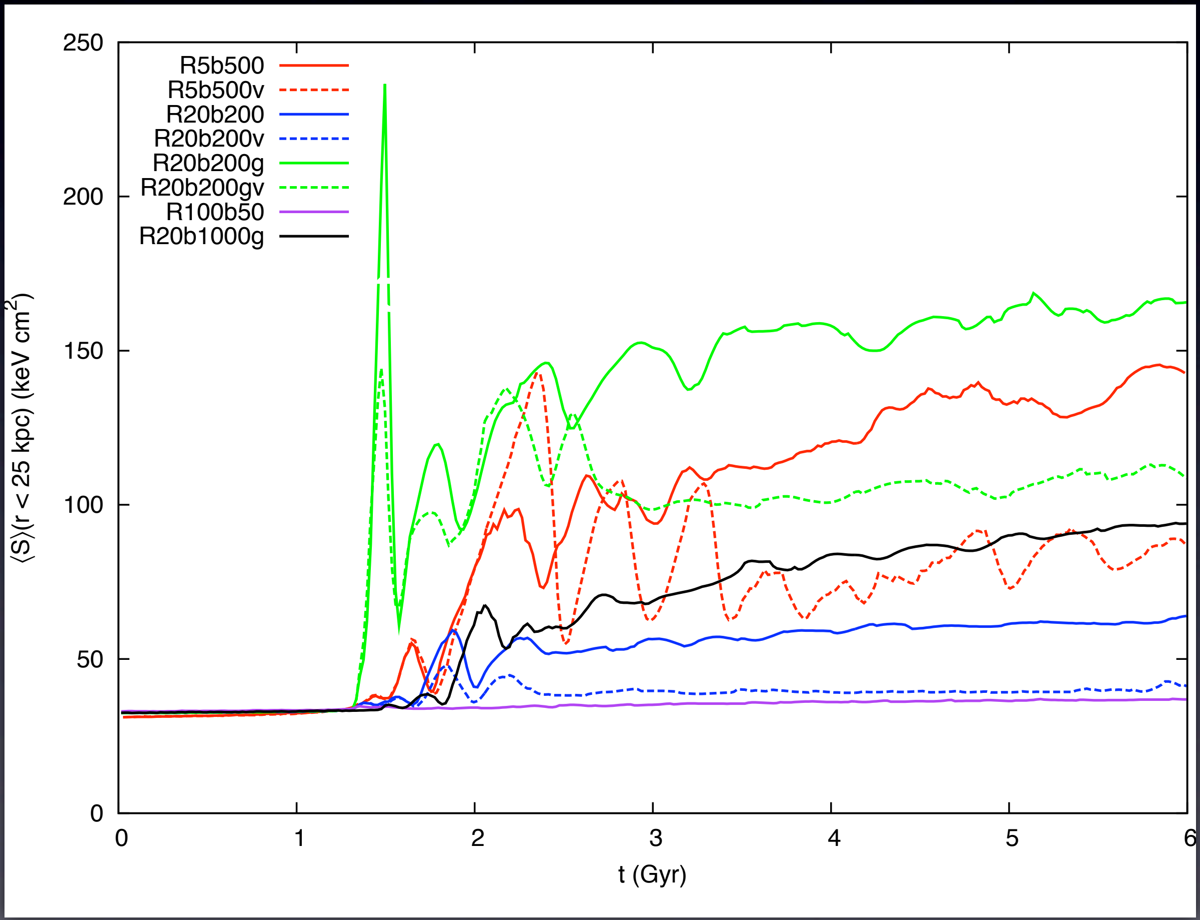


# Sloshing Heats the Core

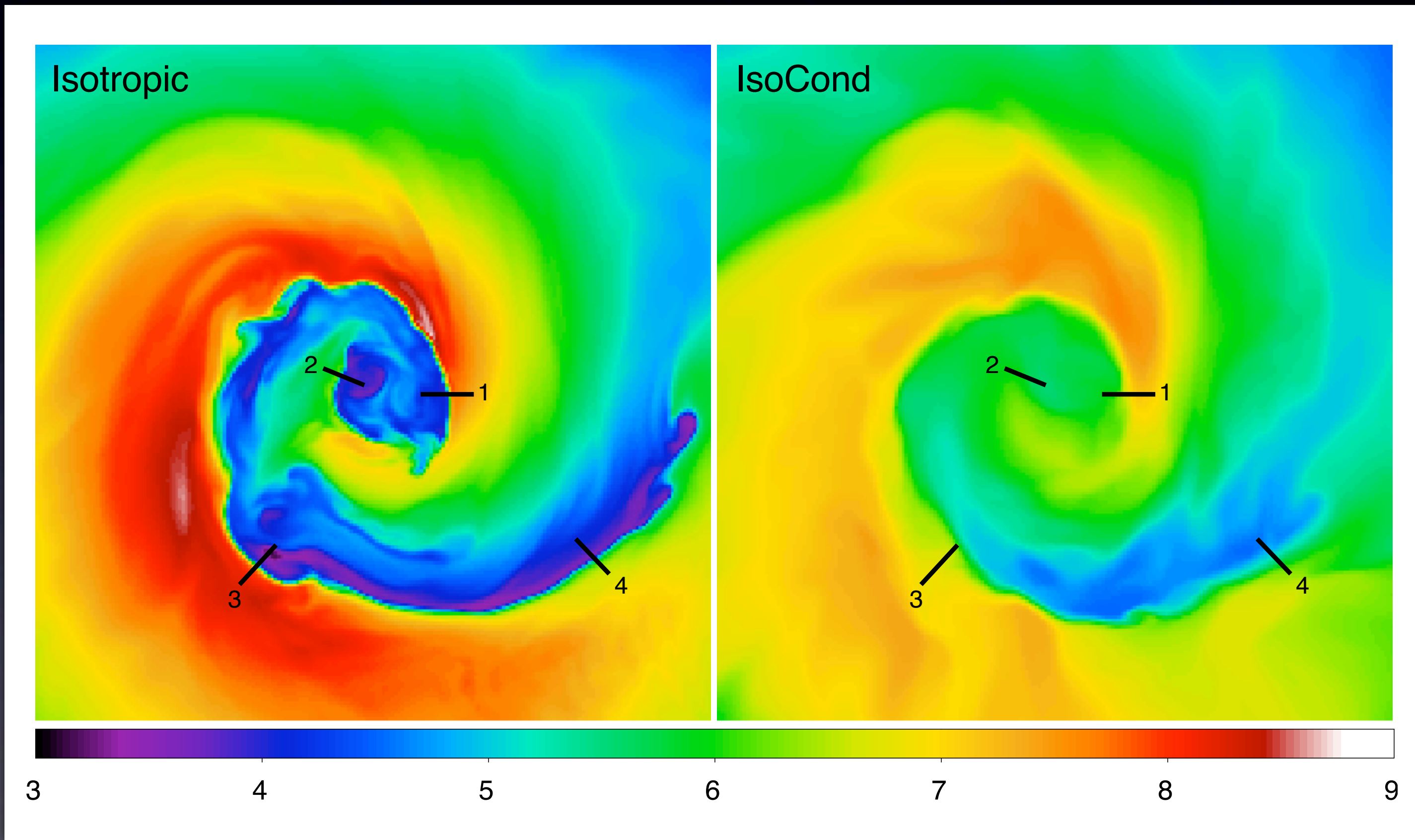
Central entropy ($S = k_B T / n_e^{2/3}$) increases




ZuHone, Markevitch, & Johnson 2010

# Anisotropic Conduction

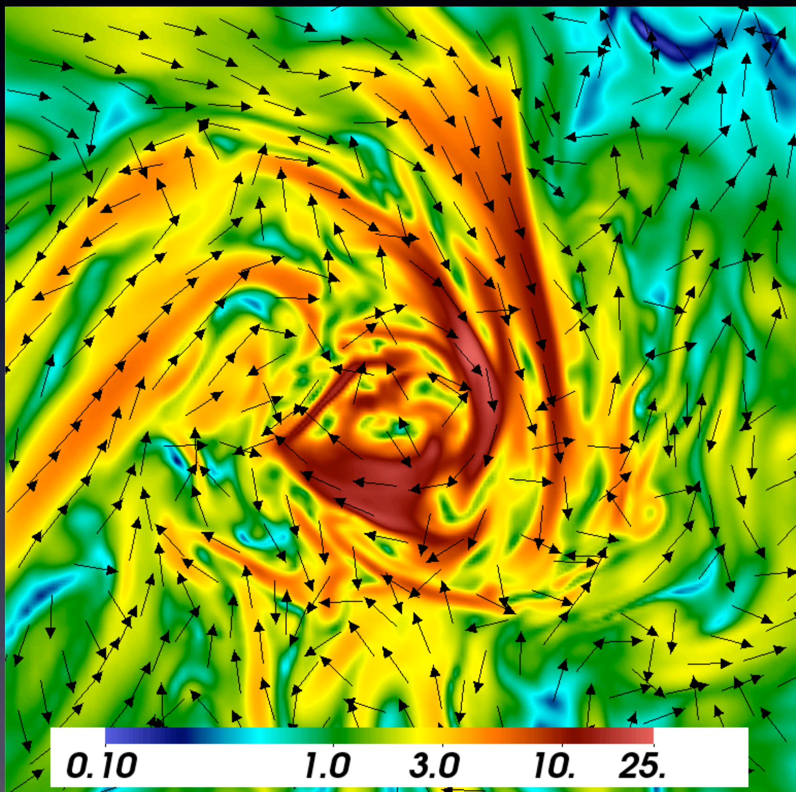
T (keV)



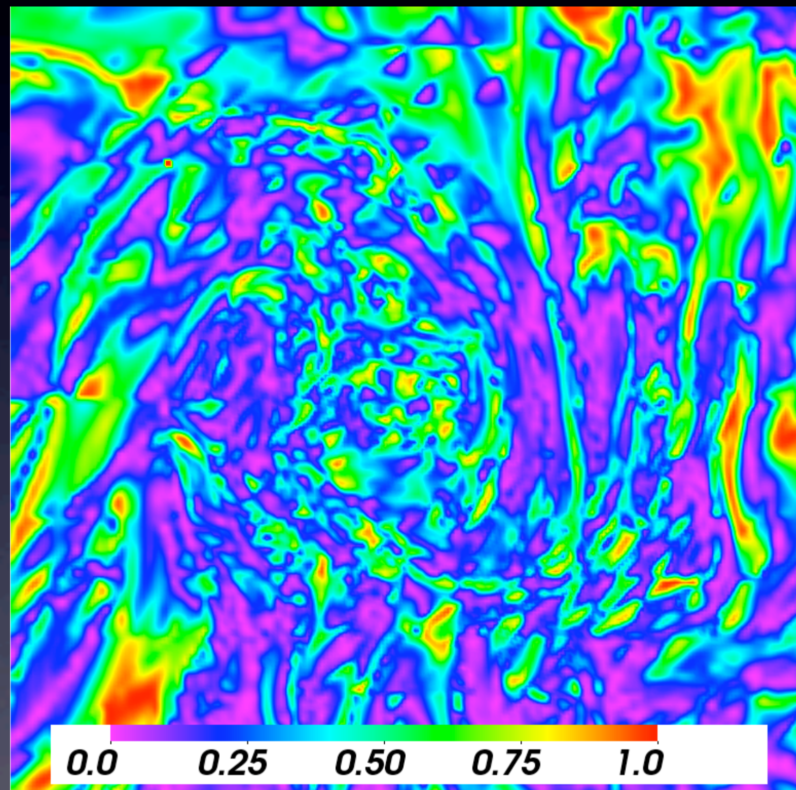

No Conduction

Spitzer Conduction

# Anisotropic Conduction




B (μG)




$|\hat{b} \cdot \nabla T| / |\nabla T|$

# Summary and Conclusions

- Simulations establish that sloshing occurs naturally in relaxed galaxy clusters, initiated by encounters with small subclusters
- Viscosity and/or magnetic fields in galaxy clusters can act to stabilize sloshing cold fronts against instabilities
- Magnetic fields are amplified by sloshing motions along cold fronts, sometimes to over an order of magnitude over their initial field energy
- Sloshing may be responsible for other effects, including radio mini-halos, wide-angle tails, and the heating of the cluster core