Simulations of Gas Sloshing in Galaxy Cluster Cores: Application to Radio Mini-Halos

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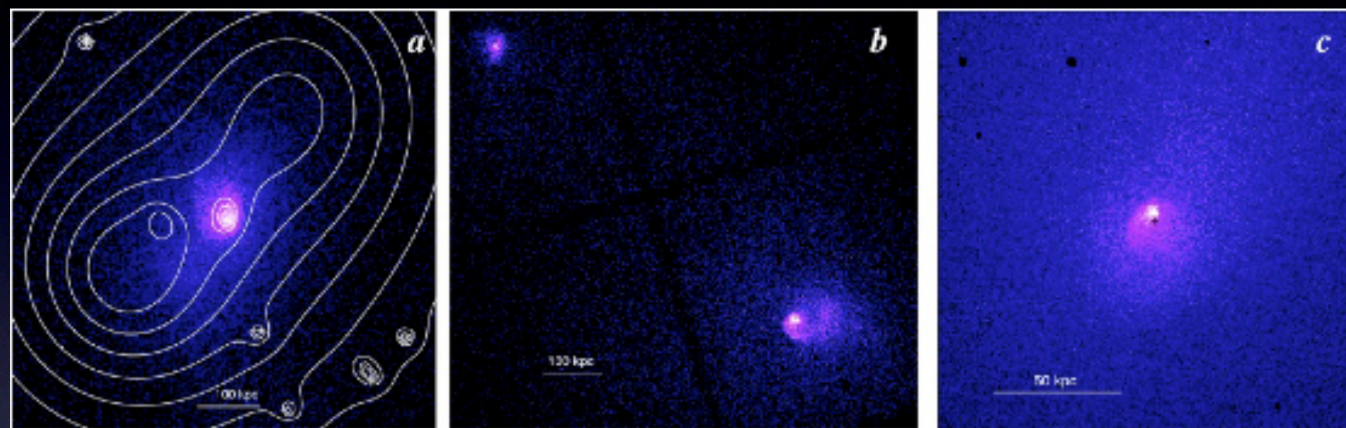
Observations of Gas Sloshing

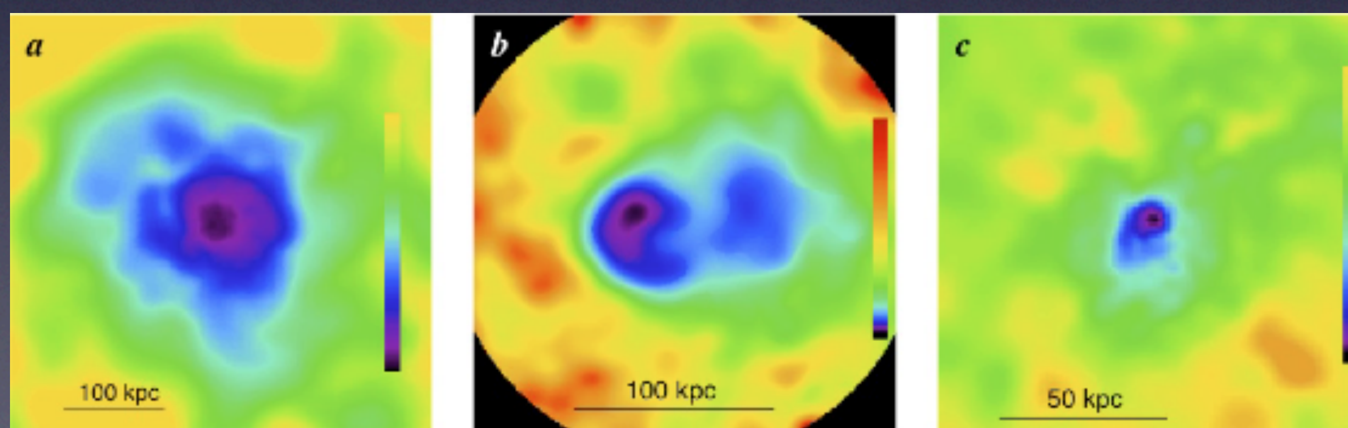
RXJ 1347-1145 Abell 1644 Ophiuchus

Surface Brightness
S_X



Abell 2204 Abell 1644 Ophiuchus

Projected Entropy
$S = k_B T / n_e^{2/3}$



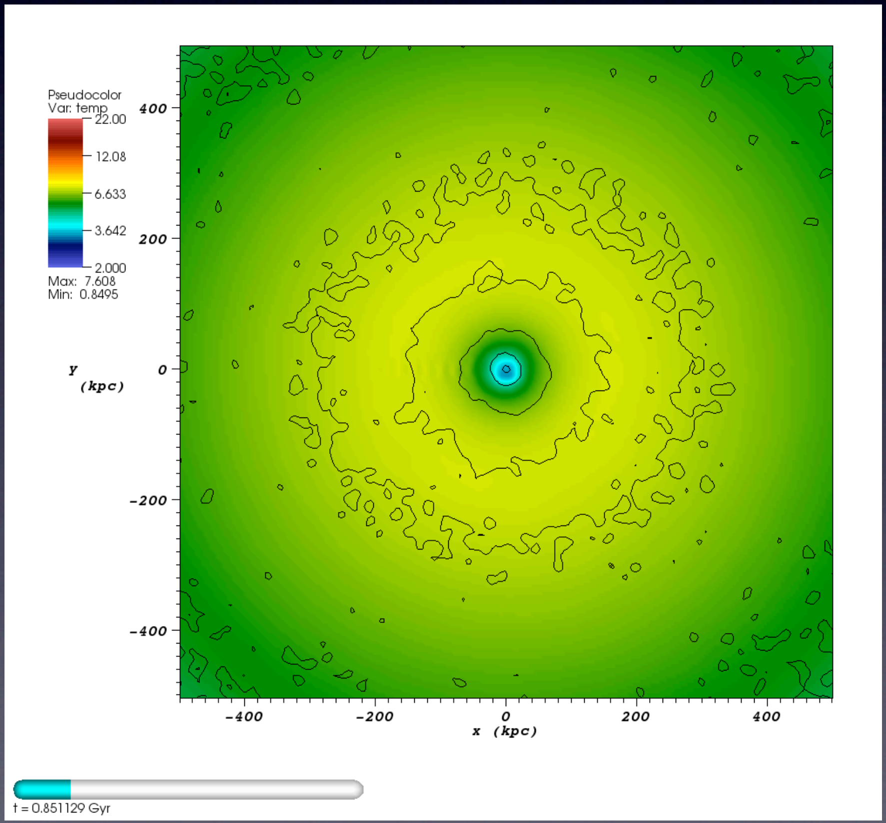
Simulations: A Sloshing Laboratory

- 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 (same as Ascasibar & Markevitch 2006)
  - Large, cool-core cluster (A2029, M ~ 10^{15} $M_{\odot}$) 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 ~ 1-5 kpc

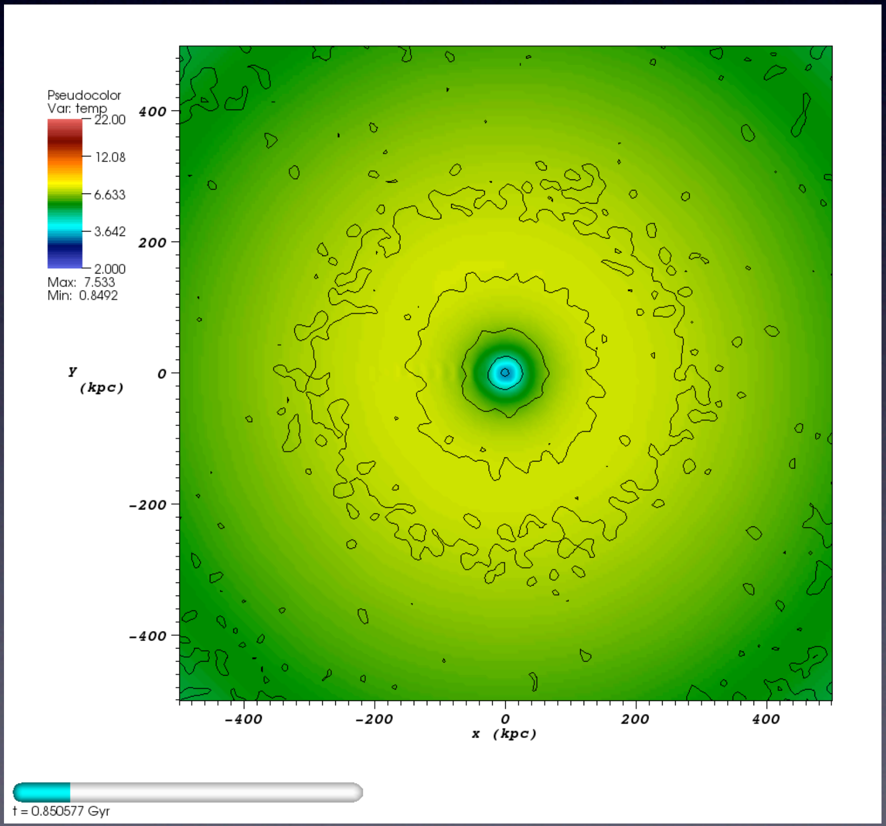
T (keV) w/ DM contours

R = 5, b = 500 kpc

Inviscid



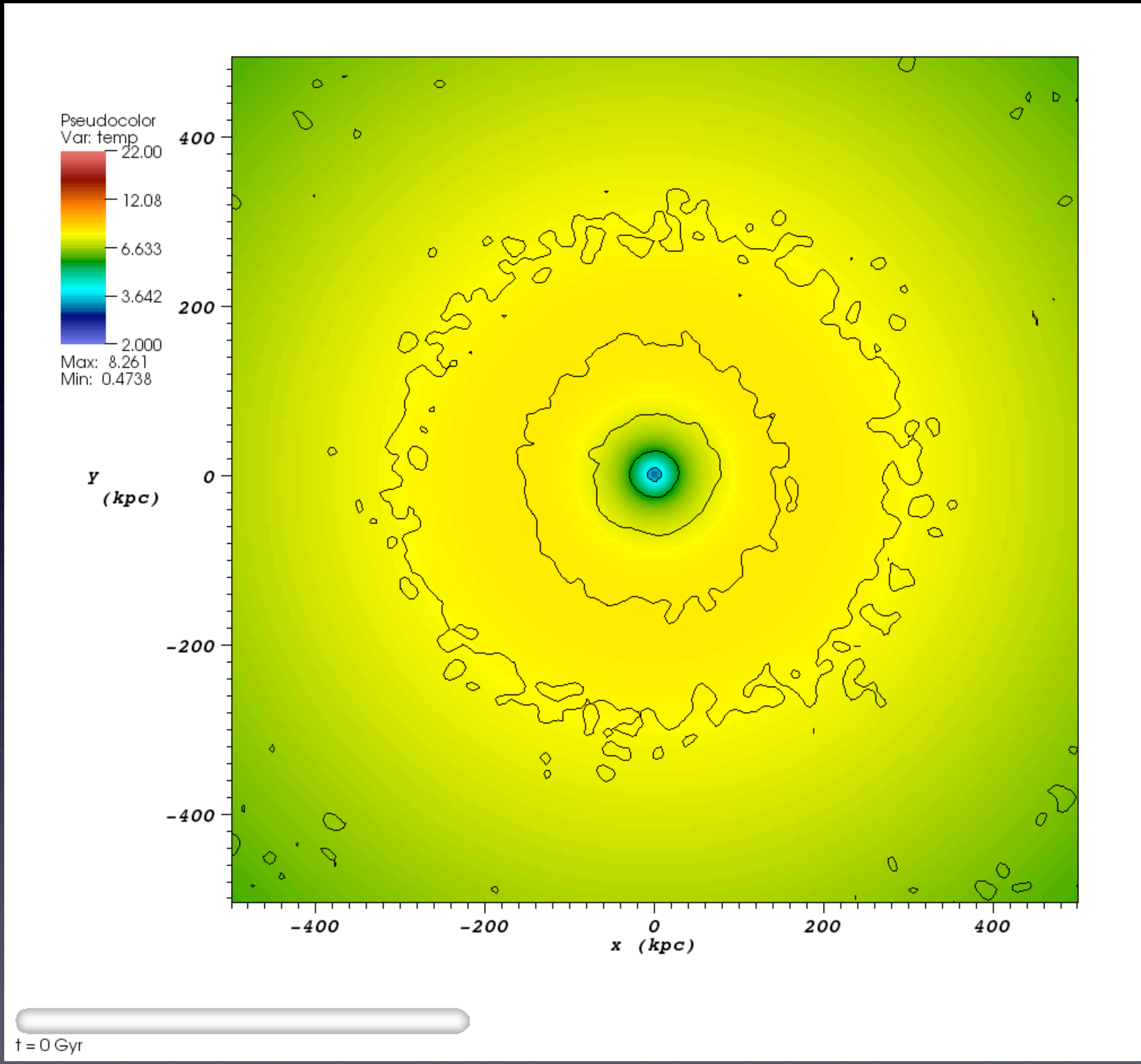
Viscous (~Spitzer in core)



R = 20,

b = 1000 kpc,

gas-filled subcluster

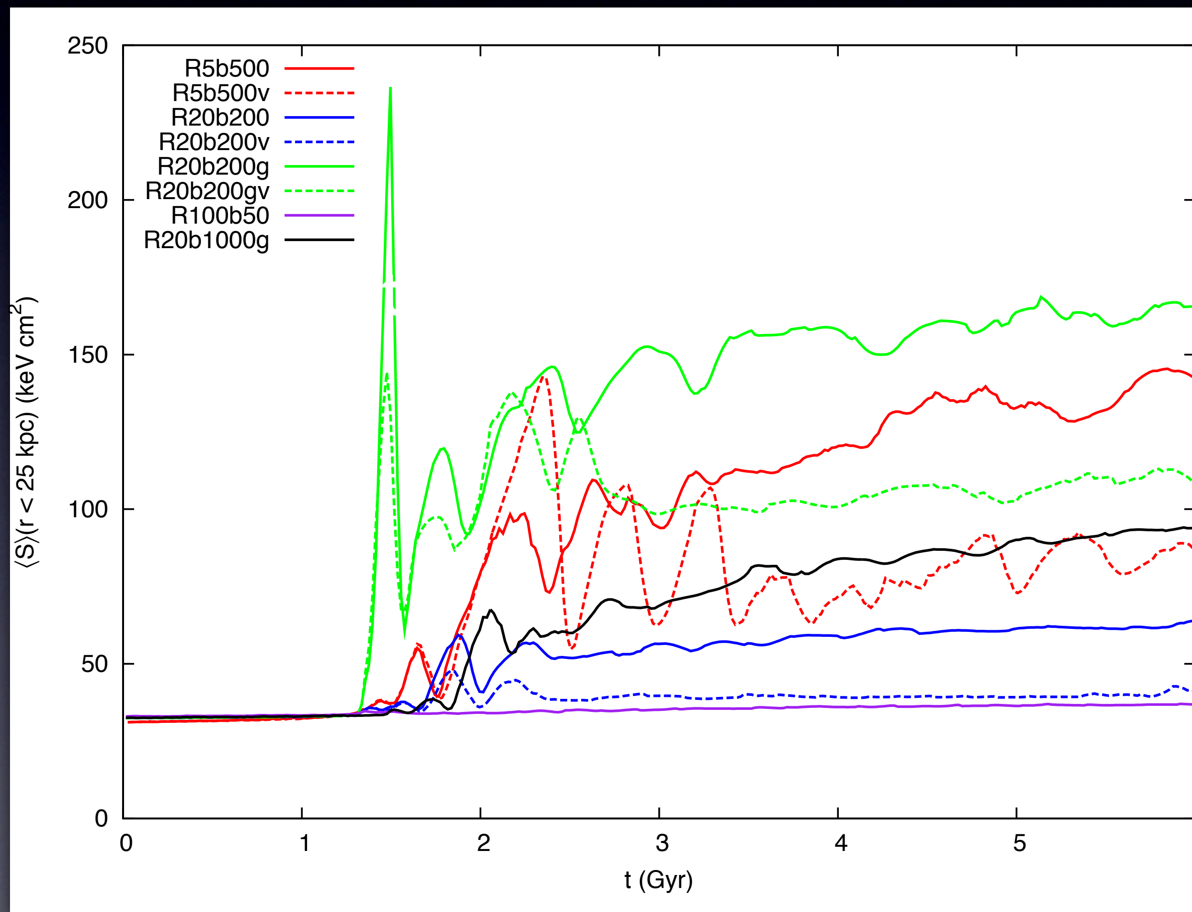


Sloshing Heats the Core

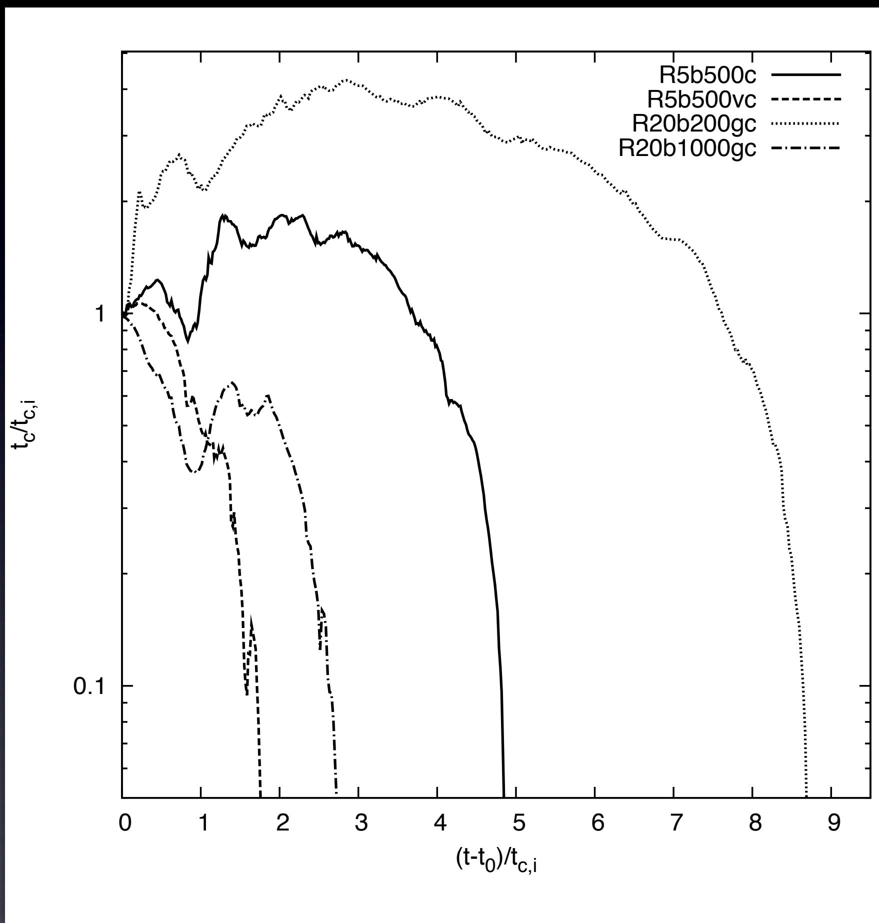
Central entropy ($S = k_B T / n_e^{2/3}$) increases

ZuHone, Markevitch, & Johnson 2009

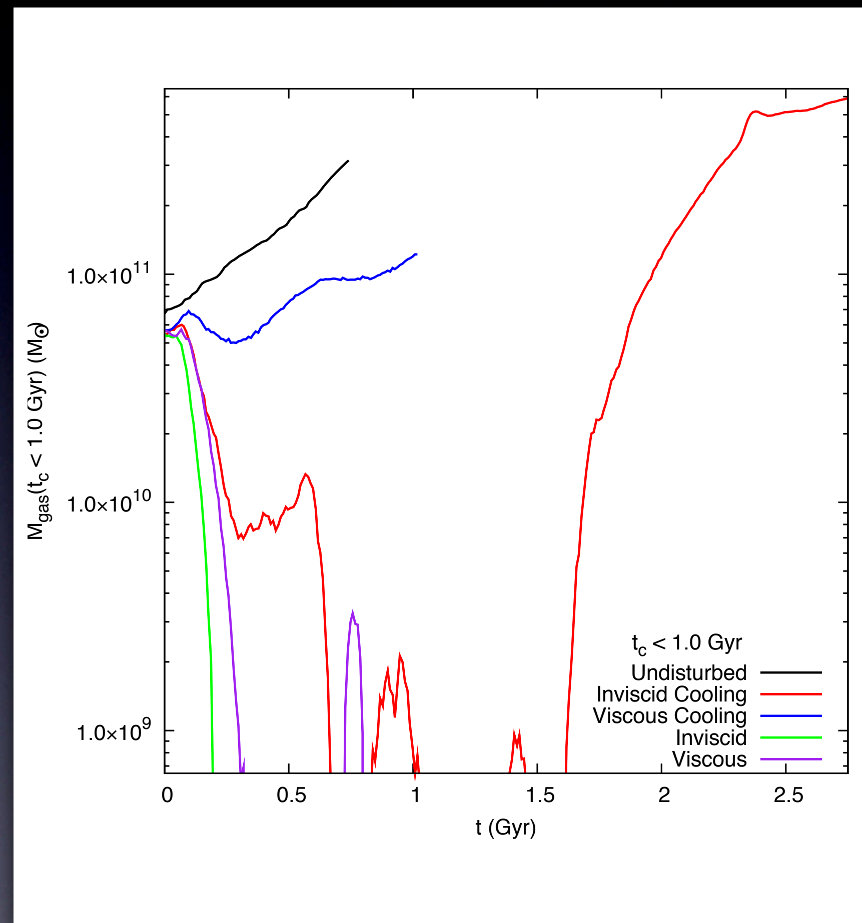
arXiv: 0912.0237



Heating vs. Cooling



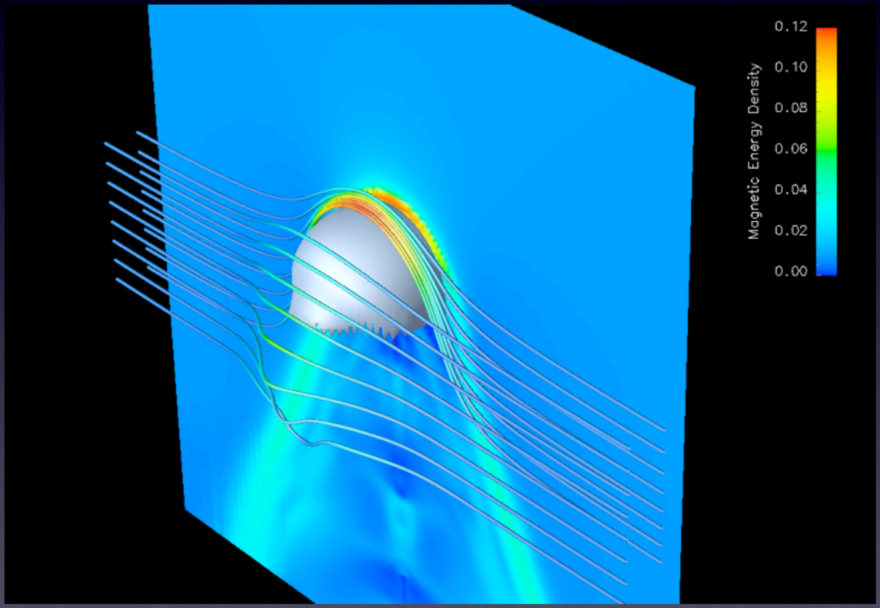
Central Cooling Time



Mass of Gas with t_{cool} < 1 Gyr

Sloshing w/ Magnetic Fields

- Magnetic fields may play a role similar to viscosity
- The sloshing cold fronts may cause the B-fields to be "draped" across the fronts, which may suppress instabilities (Vikhlinin et al 2001, Lyutikov 2006, Asai et al. 2007, Dursi 2007)



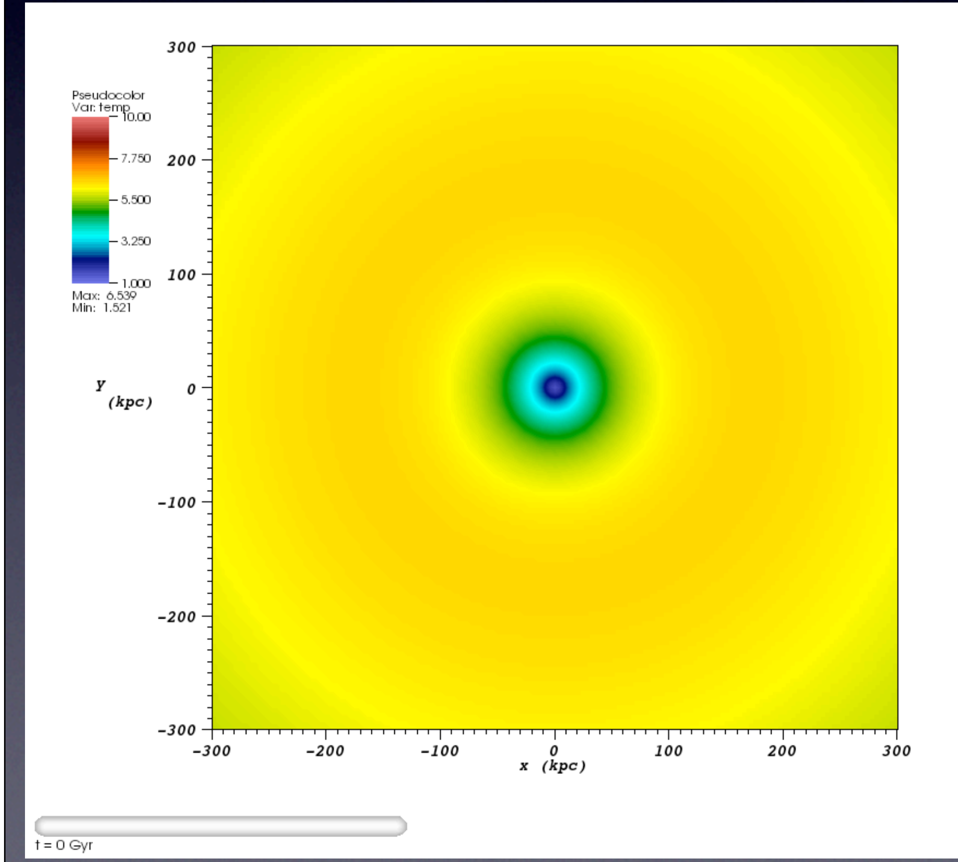
Dursi & Pfrommer 2007

Sloshing w/ Magnetic Fields

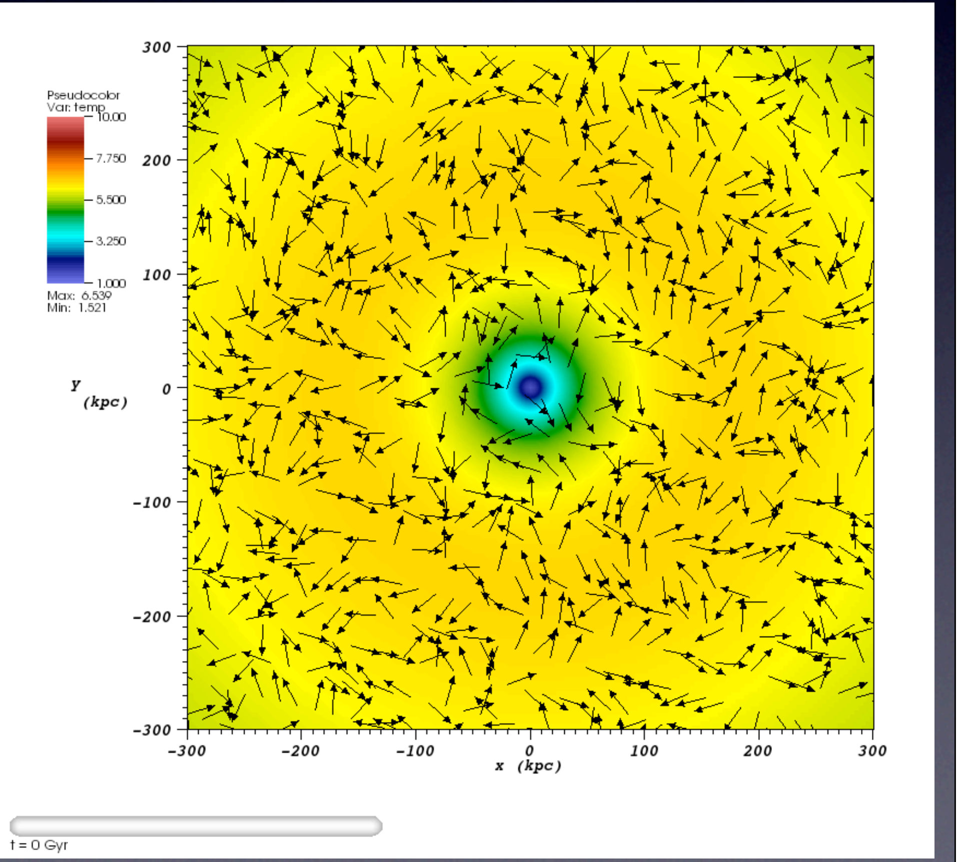
B-fields: initially tangled

$\beta_c \sim \{450, 100\}$; $B_c \sim \{7, 16\}$ μG; $B(r) \propto \rho(r)^{2/3}$; Δx = 4 kpc

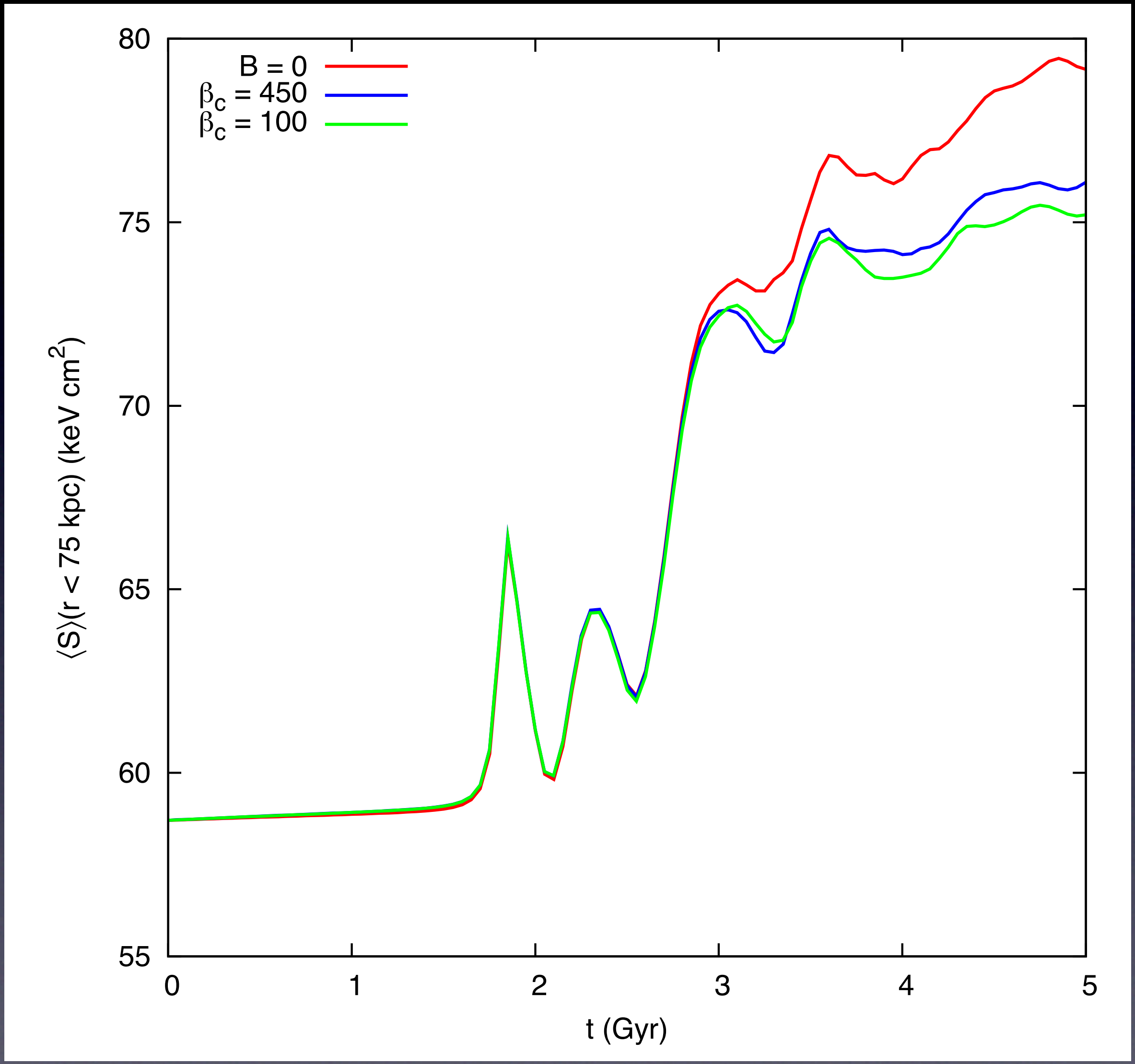
No Fields



$\beta_c \sim 100$



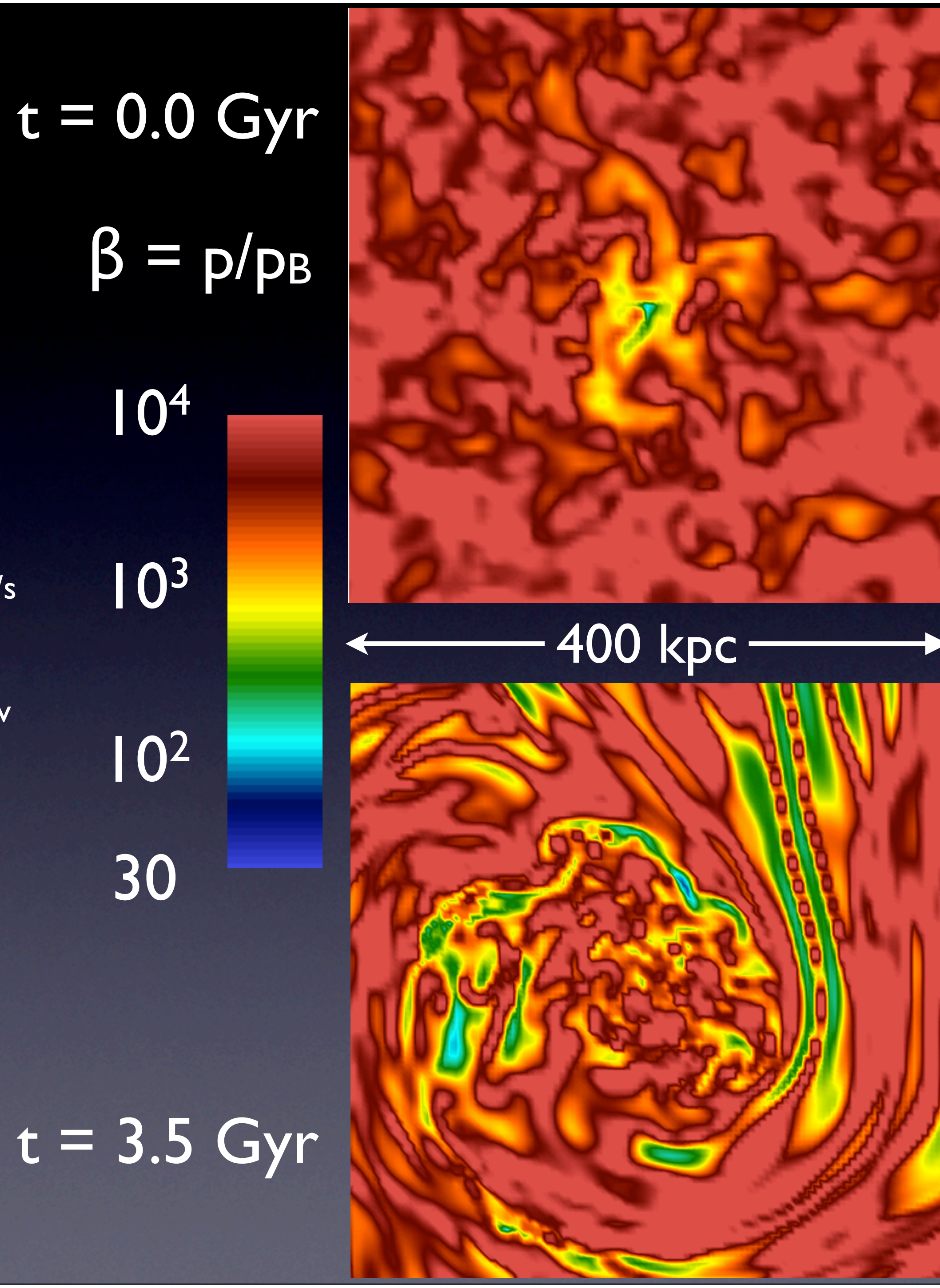
Less Mixing, Less Heating



- What happened?
    - B-fields amplified, but not enough
    - $\cancel{v_A^2 \geq 2(2\Delta v)^2}$ (Dursi 2007)
    - $v_A \sim 100$ - 200 km/s, $\Delta v \sim 400$-500 km/s
    - Even subsonic motions can push $\beta \sim 1$ in a thin layer across the front (Lyutikov 2006)

$$\frac{\Delta r}{L} \sim \frac{1}{\mathcal{M}_A^2} \lesssim 1 \text{ kpc}$$

    - Need to go to higher resolution



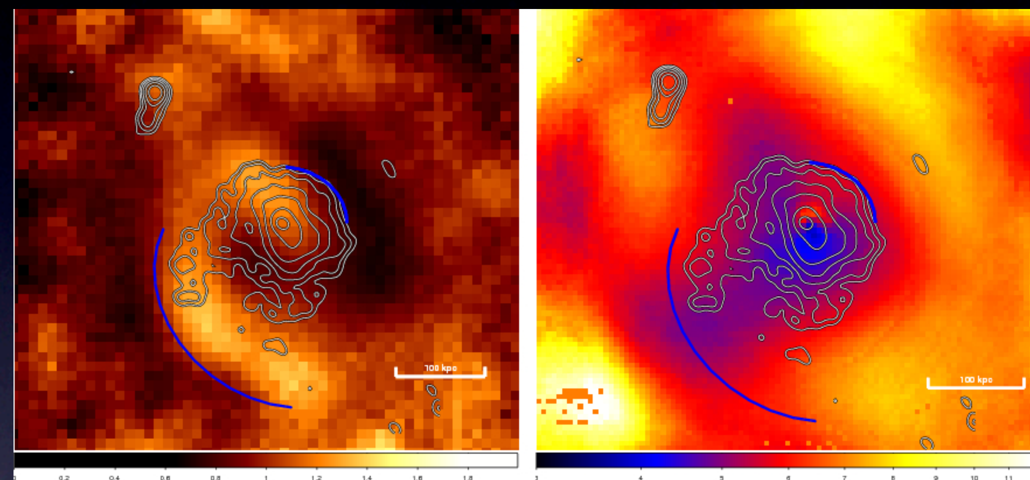
Radio Mini-Halos (MHs)

- Diffuse radio emission found in cool-core clusters
- Extends roughly over the cooling region (r_c ~ 100-200 kpc)
- Characterized by regular morphology, low surface brightness, and high spectral indices (α ~ 1.0-1.5)

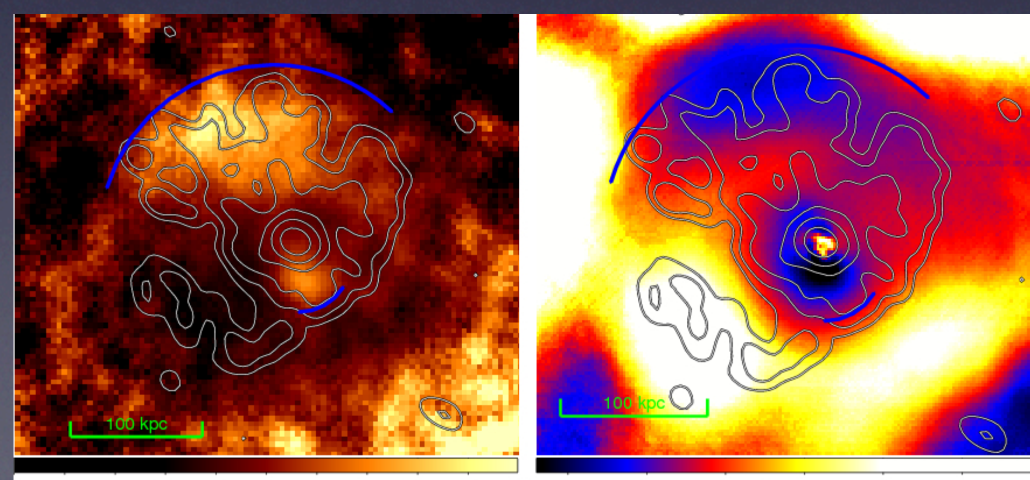
Coincidence?

- Mazzotta & Giacintucci (2008) noted a correlation between radio mini-halos and cold fronts in two galaxy clusters
- Diffusive timescale for relativistic electrons much longer than radiative lifetime
- Suggested electrons are re-accelerated via turbulence generated by the sloshing motions

RX J1720.1+2638



MS 1455.0+2232



Accelerating CR Electrons

- Accelerate relativistic electrons via turbulence: transit-time damping of magnetosonic waves (Eilek 1979, Cassano & Brunetti 2005, Brunetti & Lazarian 2007, etc.)
- Rough condition for acceleration: need $t_{acc} \sim t_{loss}$ (synchrotron + IC losses)
- Would like to be able to accelerate electrons with $\gamma \sim 2000$-9000 ($t_{loss} \sim 0.2$-0.5 Gyr)

Accelerating CR Electrons

- To estimate t_{acc}:
  - Compute the diffusion coefficient (Eliek 1979, Cassano & Brunetti 2005)

$$D_{pp}(p,t) \simeq 4.45\pi^2 \frac{v_M^2}{c} \frac{p^2}{B^2} \int_{k_{\max}}^{k_{\min}} k\mathcal{W}_k^B(t)dk$$

  - Integrate over spectrum of magnetosonic waves

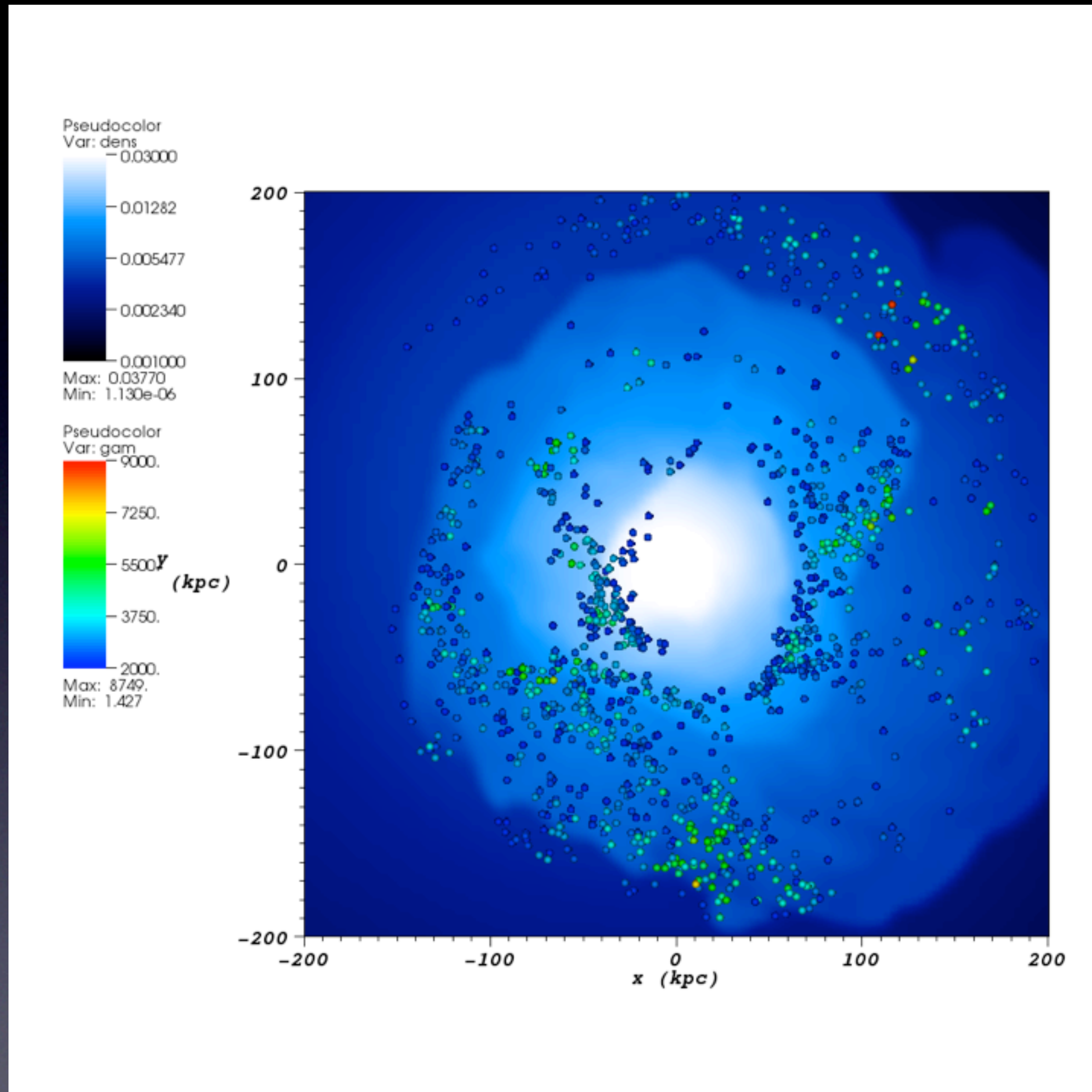
$$\tau_{\rm acc}^{-1} = \chi \simeq 4\frac{D_{pp}}{p^2}$$

  - Need density, temperature, magnetic field of gas

Accelerating CR Electrons

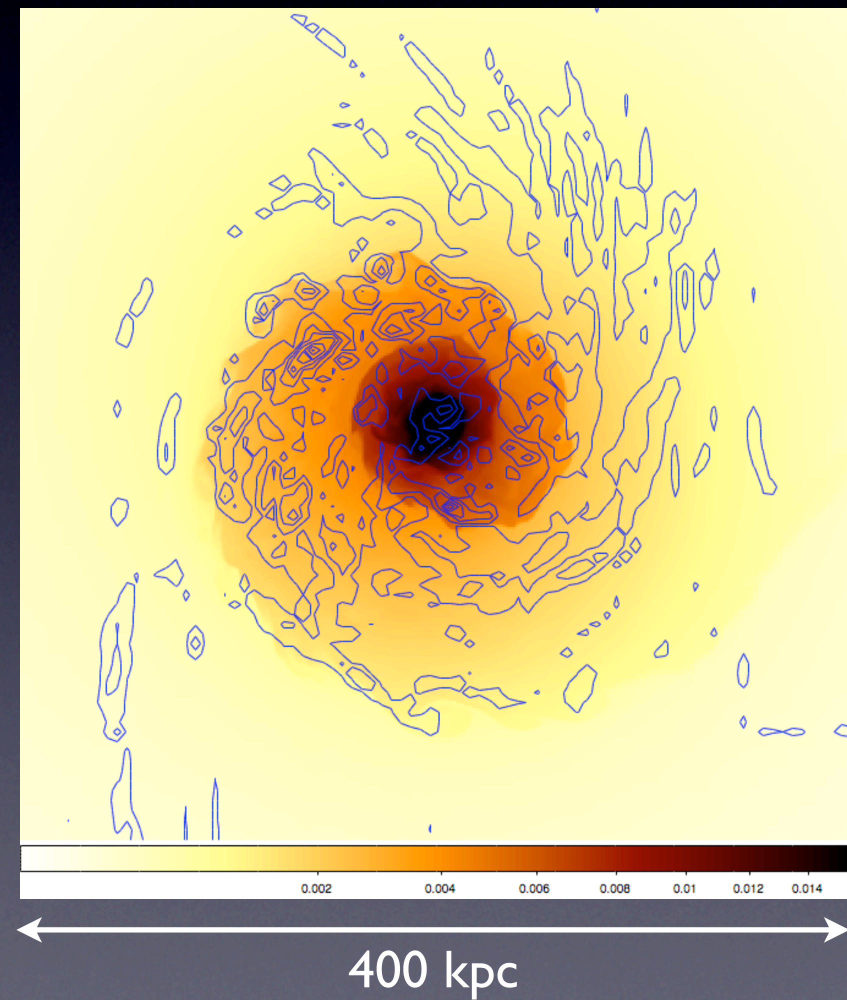
- From the simulations, this can be a bit tricky:
  - Ideally, one would determine spectrum of fluctuations from simulation
  - For now, assume a spectrum $W_k^B \approx W_k \beta^{-1}$ and normalize W_k by the kinetic energy not associated with bulk motions
  - We determine this by taking the velocity of a tracer particle and subtracting the mean velocity of the cells in a spherical region around it (e.g., Dolag et al. 2005, Vazza et al. 2006)

- Tracer particles with γ_{crit} = 2000-9000 (t_{loss} ~ 0.2-0.5 Gyr)
- Acceleration of fast electrons associated with regions inside cold fronts
- r_{mean} = 50 kpc
- ***Preliminary***: probably contaminated by shear flows at fronts



Amplifying Magnetic Fields

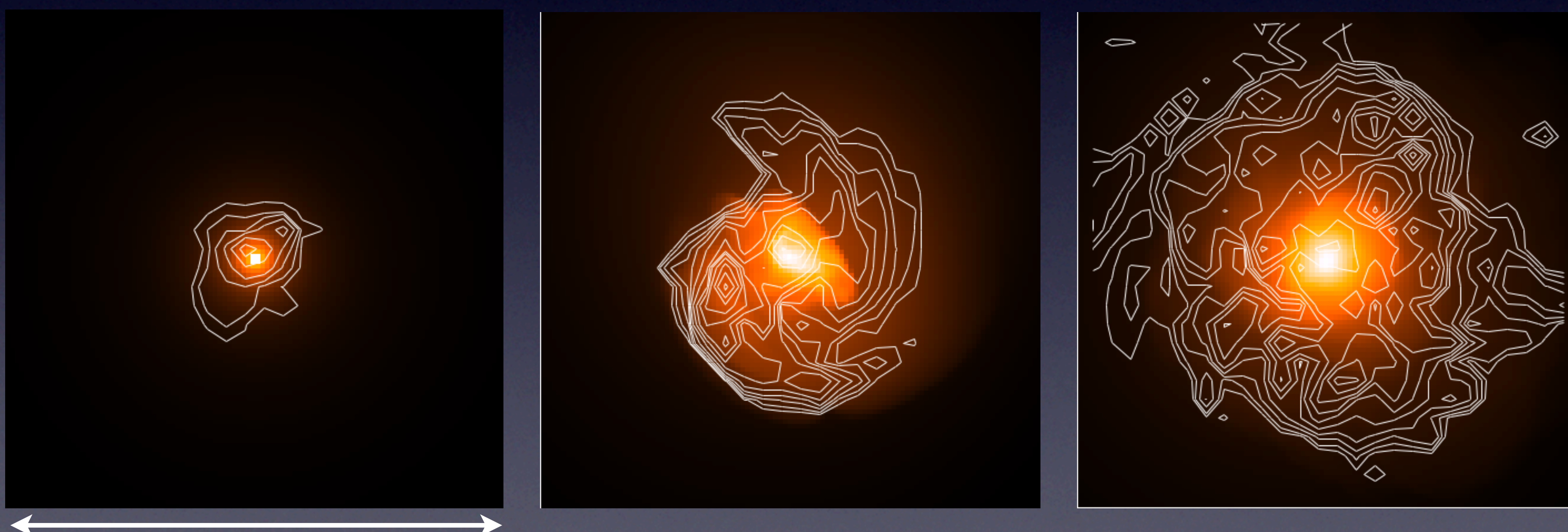
Sloshing strengthens B-fields parallel to cold fronts and within the fronts due to shear amplification (Keshet et al. 2009)



Amplifying Magnetic Fields

X-ray Emission (pseudocolor)
MEKAL Model
0.5-7.0 keV band

Radio Emission (2x contours)
assuming equipartition
ν_0 = 1.5 GHz, α = 1.5

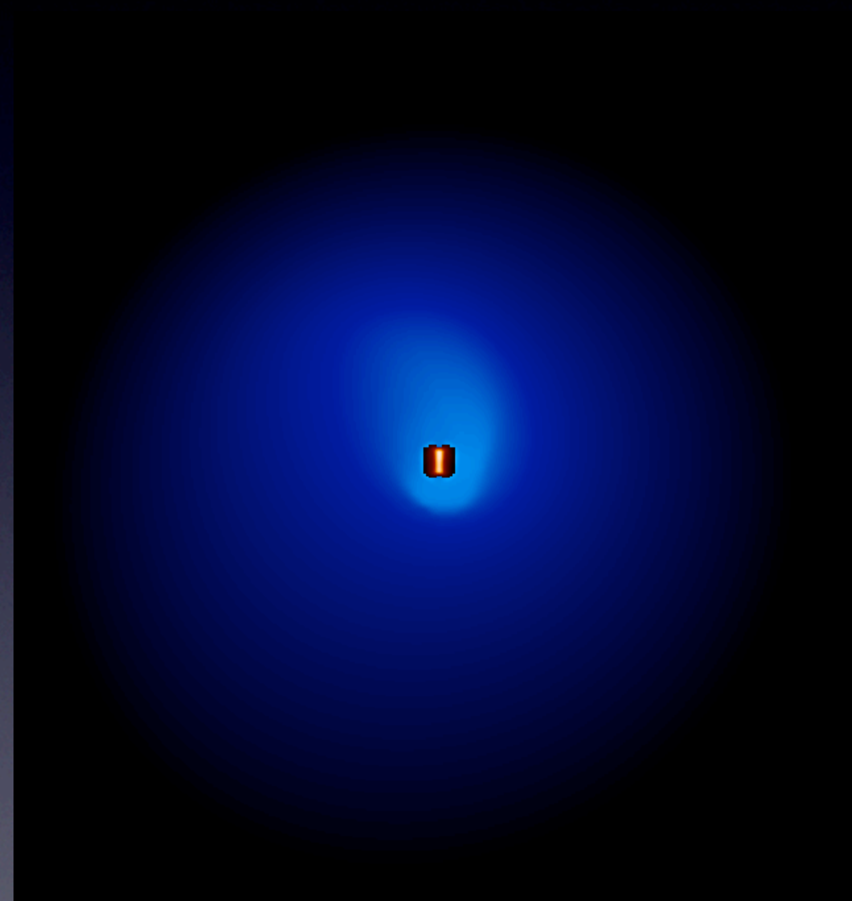


400 kpc

t = 0 Gyr | t = 3 Gyr | t = 5.5 Gyr

Summary

- Sloshing in Simulated Clusters
  - Easily produced by subcluster mergers
  - Appearance of cold fronts influenced by ICM microphysics, e.g. viscosity, B-fields
  - B-field amplification at fronts: resolution effects may be at play
- Sloshing and Radio Mini-Halos
  - The resulting turbulence *may* be able to reaccelerate CR electrons, but need more accurate characterization of turbulent motions (and higher resolution)
  - B-field amplification from sloshing can result in the formation of mini-halos, provided a population of electrons



Coming up... Sloshing and WATs