Are Galaxy Clusters Precise Cosmology Probes?

Cool Cores, Merger Shocks, Cosmic Rays & Radio Relics

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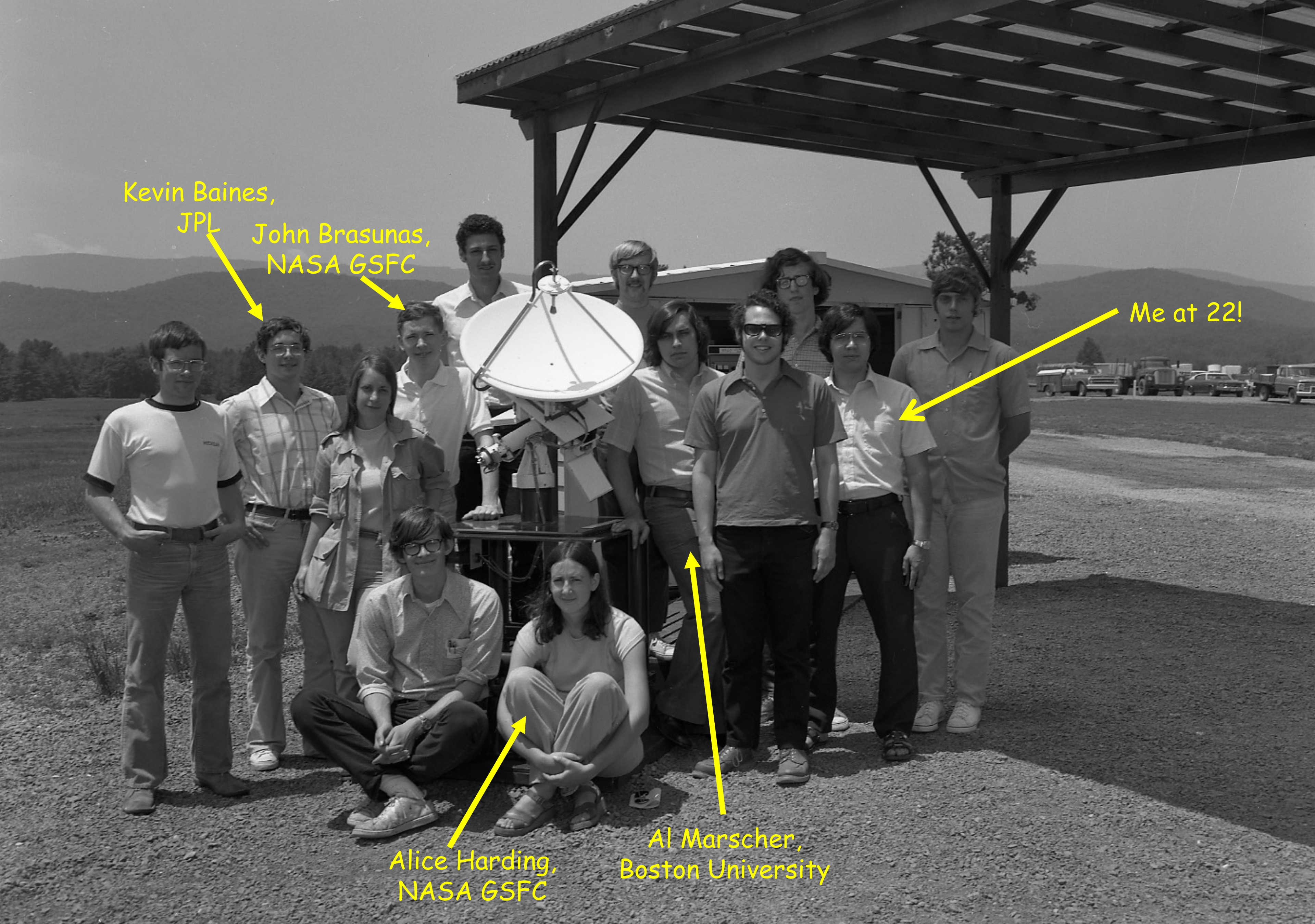
Brian O'Shea, Michigan State U.
Michael Norman, University of California, San Diego

National Radio Astronomy Observatory
September 17, 2008

NRAO Summer Student Class of 1975



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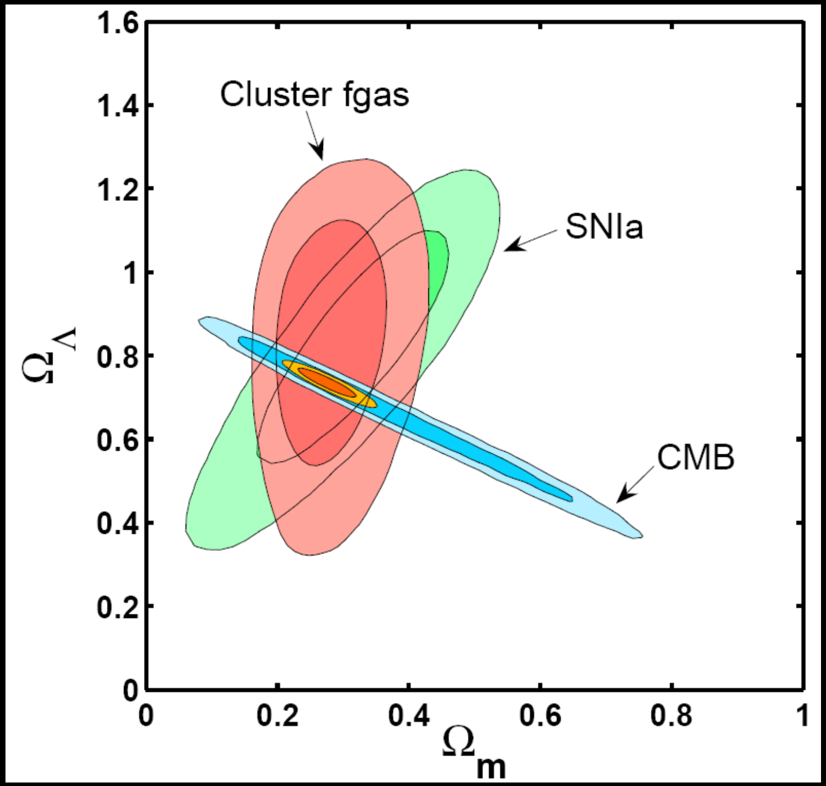
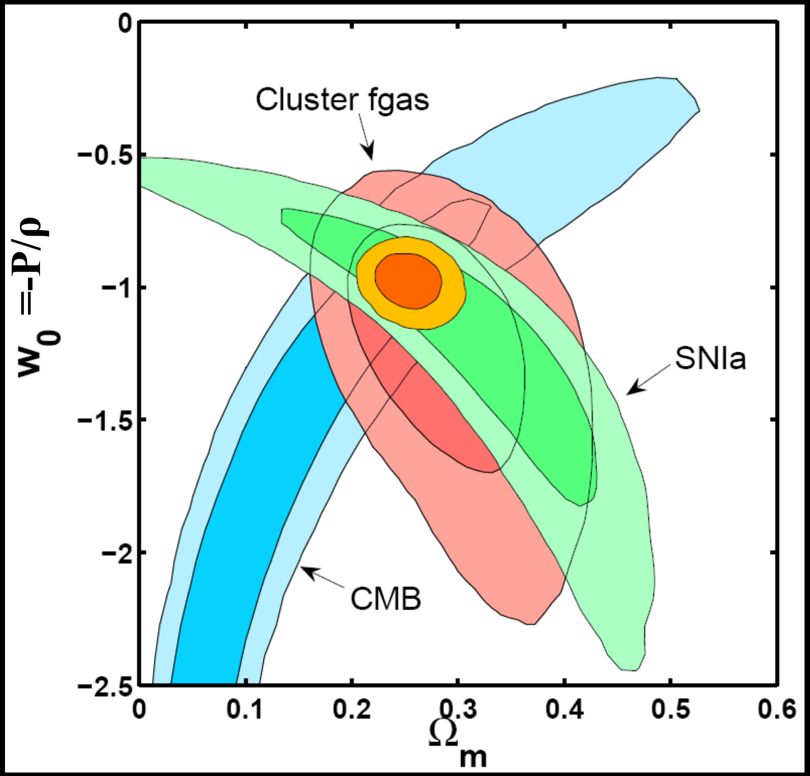
September 12, 2008

Are Clusters Accurate Probes of Cosmological Parameters?

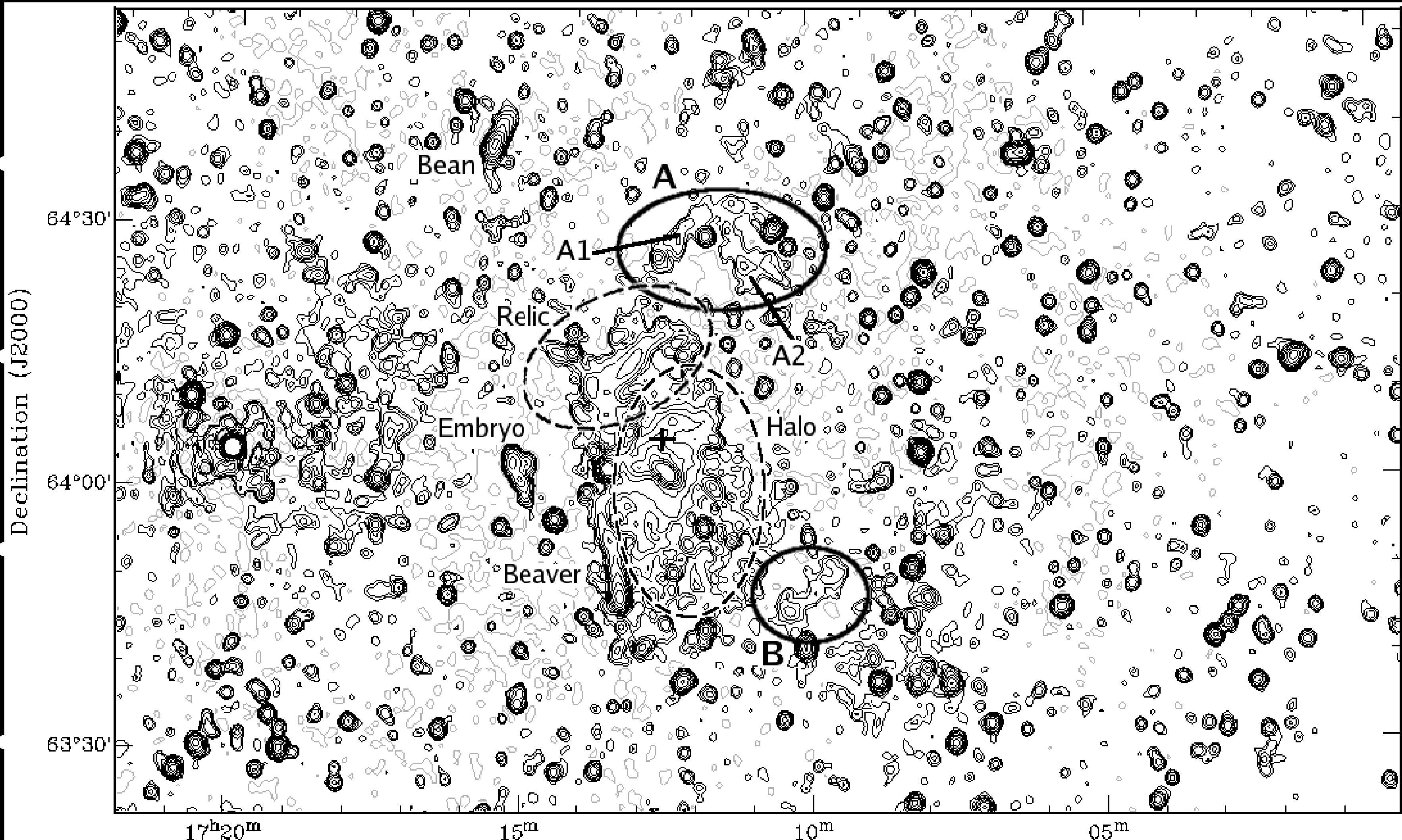




- Baryon fraction (f_{gas}) in X-ray clusters is potentially powerful tool as shown above (Allen et al. 2008, MNRAS, 383, 879).
- Angular diameter distance (depends on Dark Energy model) $d_A \sim f_{gas}^2$ (assume f_{gas} is constant and ICM is in hydrostatic equilibrium).
- Above used only cool core clusters.

What the Dark Energy Task Force said about Galaxy Clusters:

Galaxy clusters have "the statistical potential to exceed the baryon acoustic oscillations and supernovae techniques but at present have the largest **systematic errors**. Its eventual accuracy is currently very difficult to predict and its ultimate utility as a dark energy technique can only be determined through the development of techniques that control systematics due to non-linear astrophysical processes."



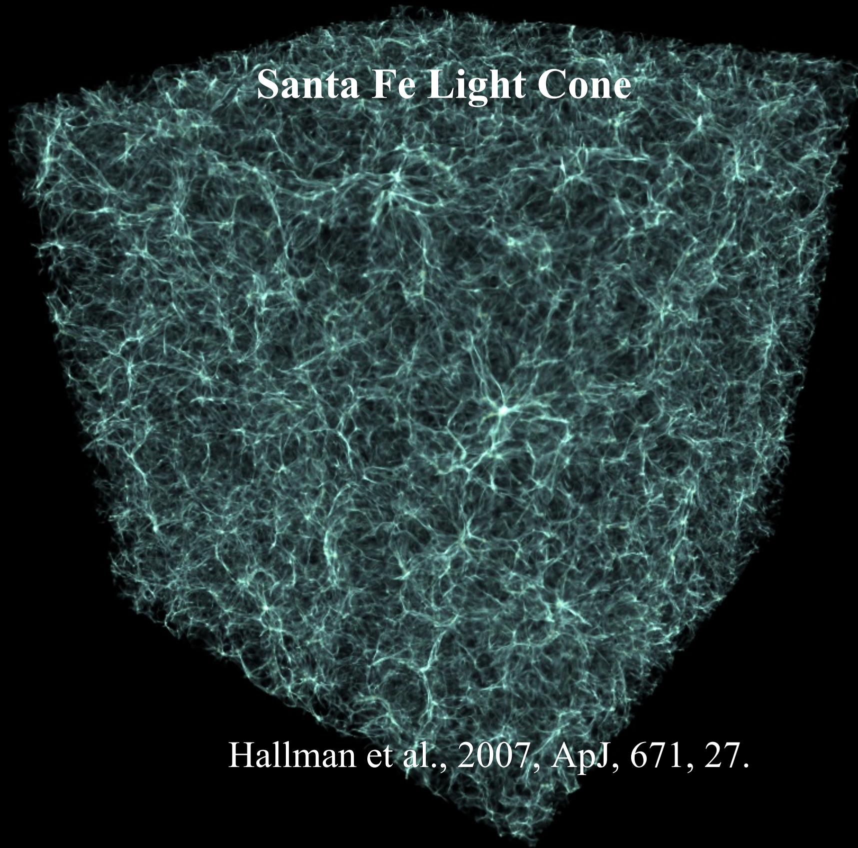
Pizzo et al. 2008, A&A, 481, L91

Abell 2255

=> Use numerical simulations to model and correct for these biases and errors.

Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution

Enzo (e.g., O'Shea et al. 2004, http://lca.ucsd.edu/portal/software/enzo)

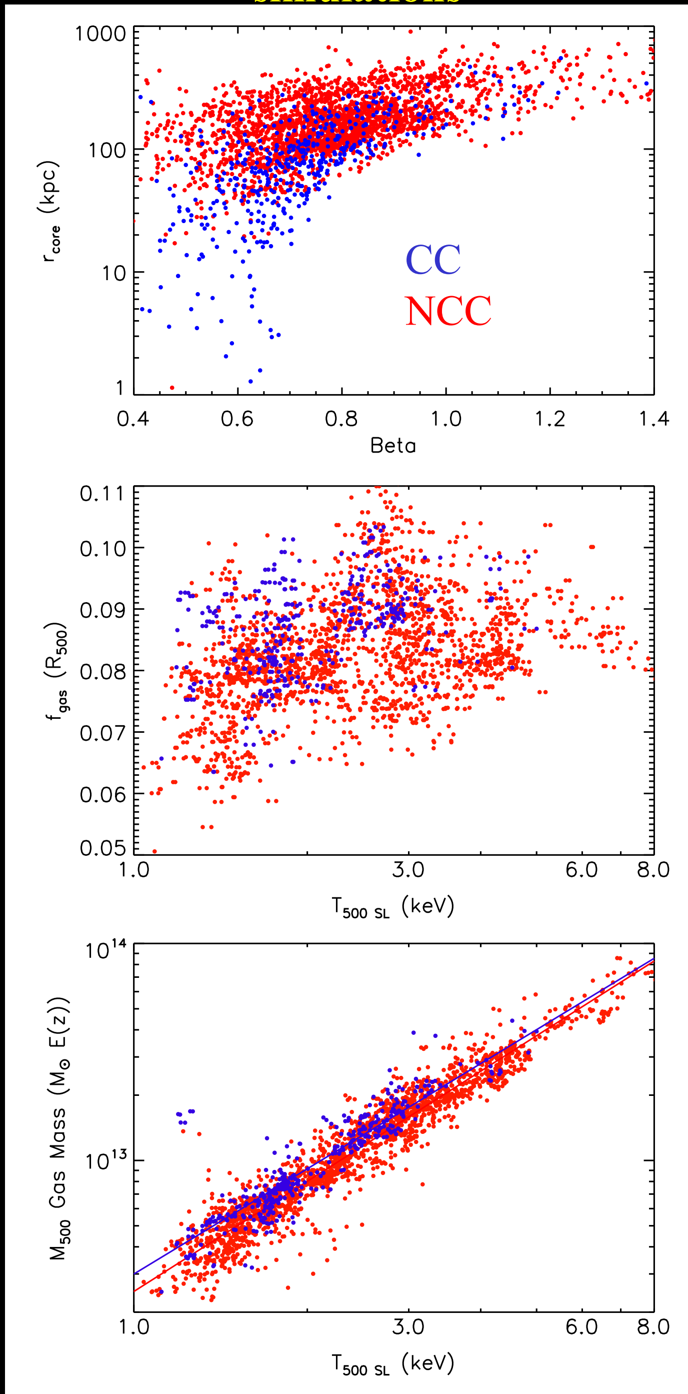


Hallman et al., 2007, ApJ, 671, 27.

- ΛCDM with $\Omega_m = 0.3$, $\Omega_b = 0.04$, $\Omega_\Lambda = 0.7$, $h = 0.7$, and $\sigma_8 = 0.9$.
- AMR achieves 8-16 h^{-1} kpc resolution in dense regions.
- $(256\text{-}512\ h^{-1}\ \mathrm{Mpc})^3$, 7 levels of refinement => 1500 clusters with $>10^{14}\ M_\odot$ for $z < 1$
- Dark matter mass resolution is $10^{10}\ h^{-1}\ M_\odot$.
- Baryon physics includes radiative cooling, star formation, & feedback.
  => *Approximate balance of heating and cooling.*
- *First simulation to produce both cool and non-cool cores in same volume.*

Movies

simulations

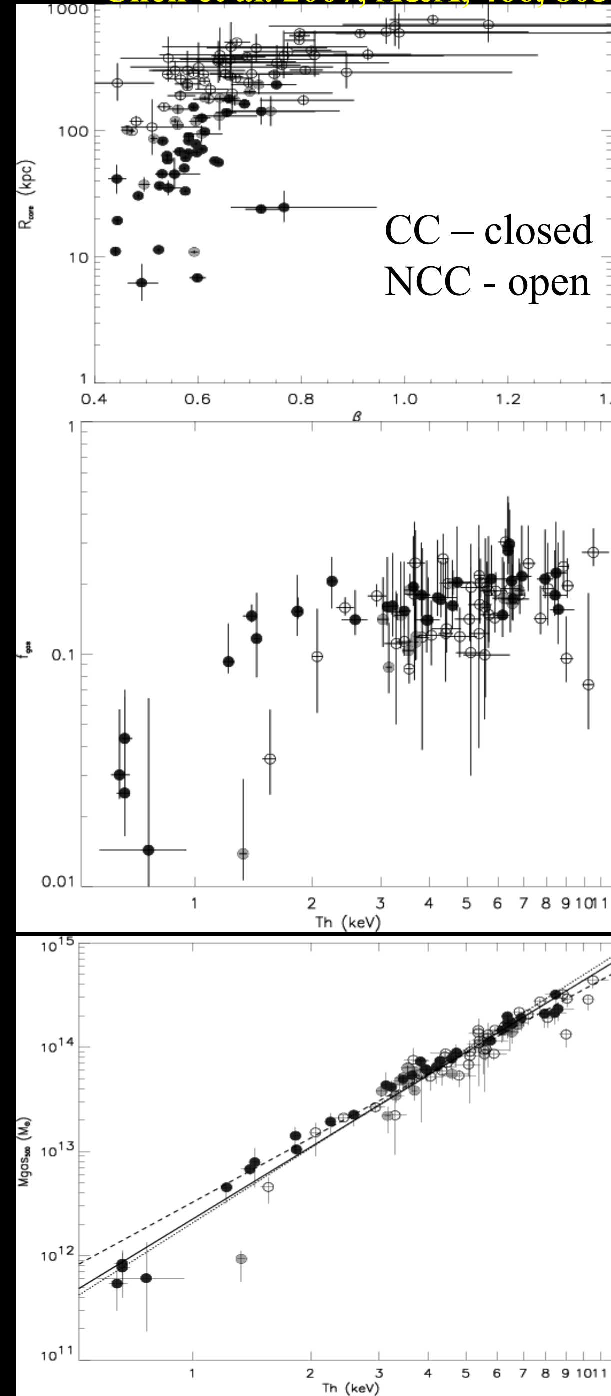


r_{core}
vs.
beta

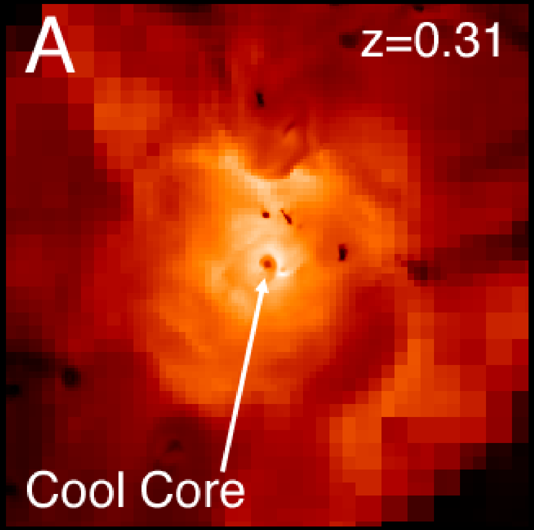
gas fraction
vs.
temperature

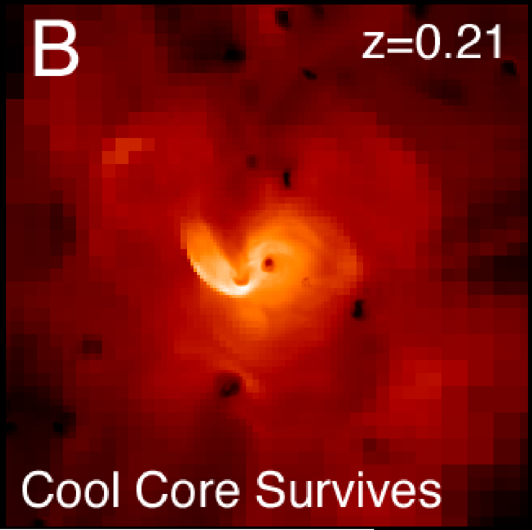
gas mass
vs.
temperature

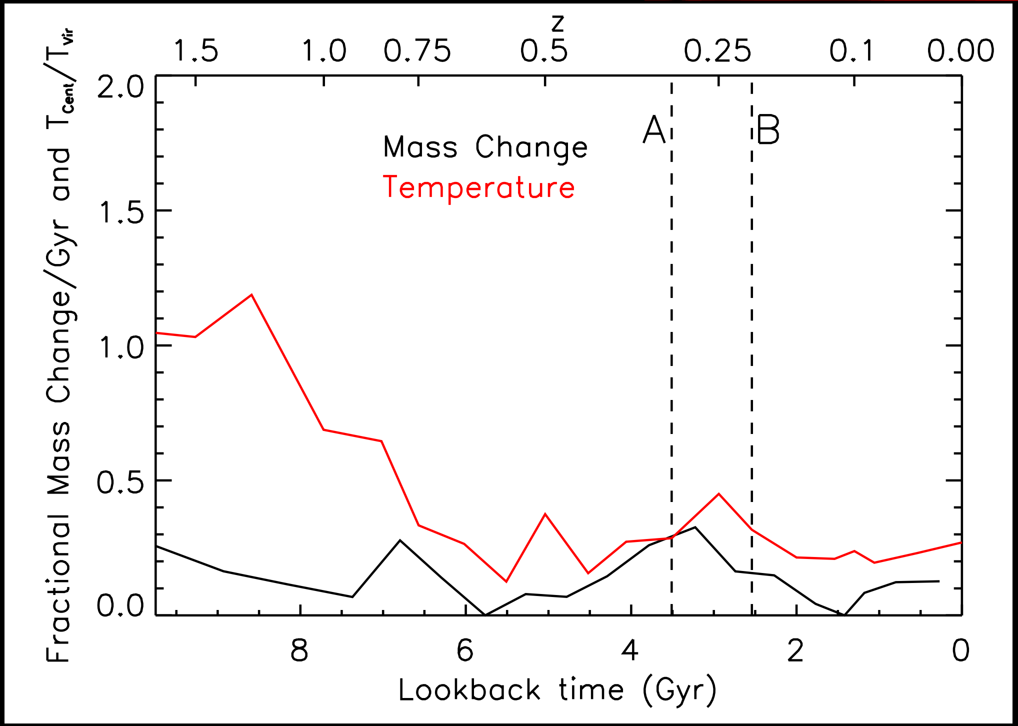
Chen et al. 2007, A&A, 466, 805



Evolution of a Cool Core Cluster



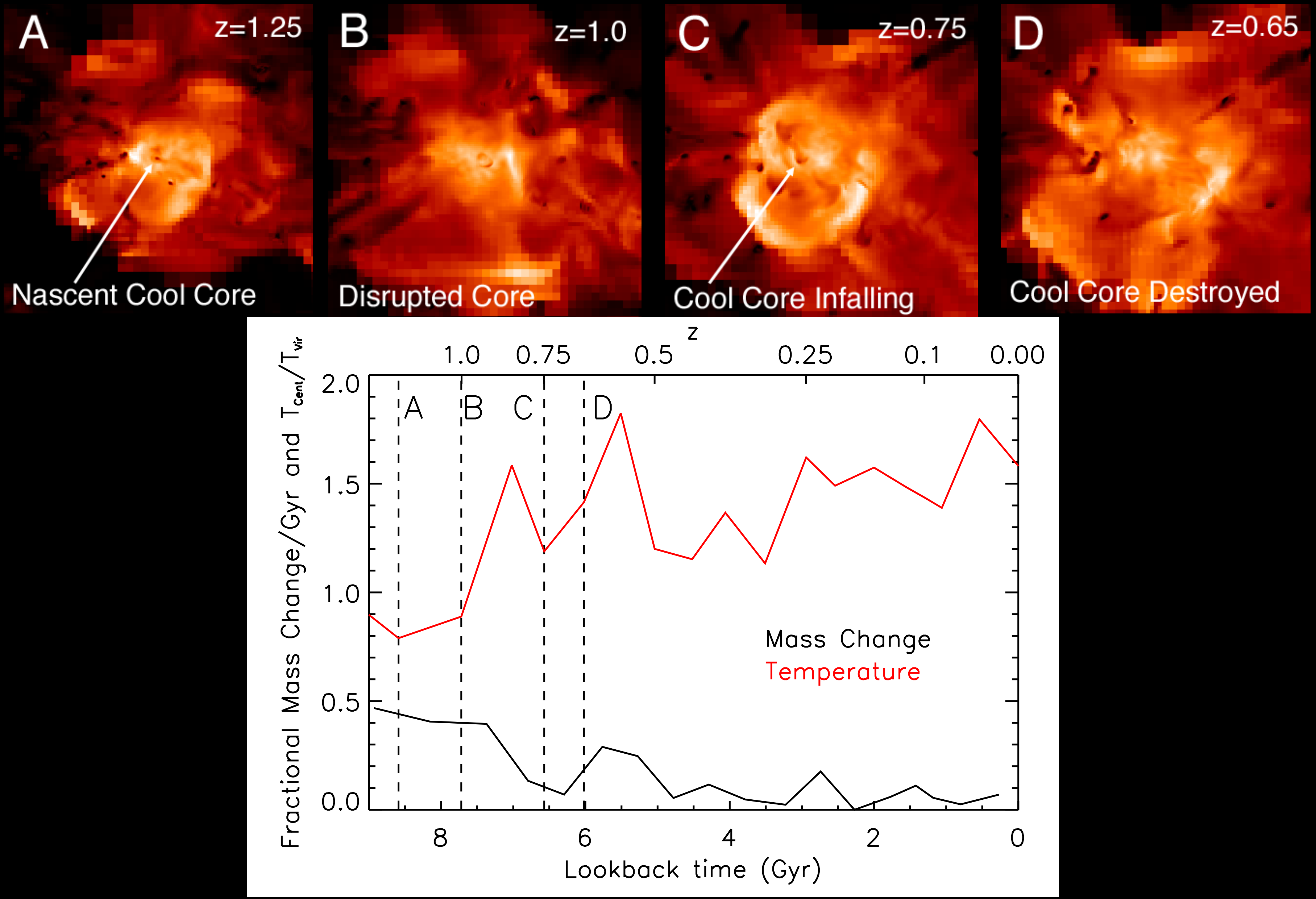




Burns *et al*. 2008, ApJ, 677, 1125.

Cool core clusters avoid major mergers with high fractional mass changes early in their histories.

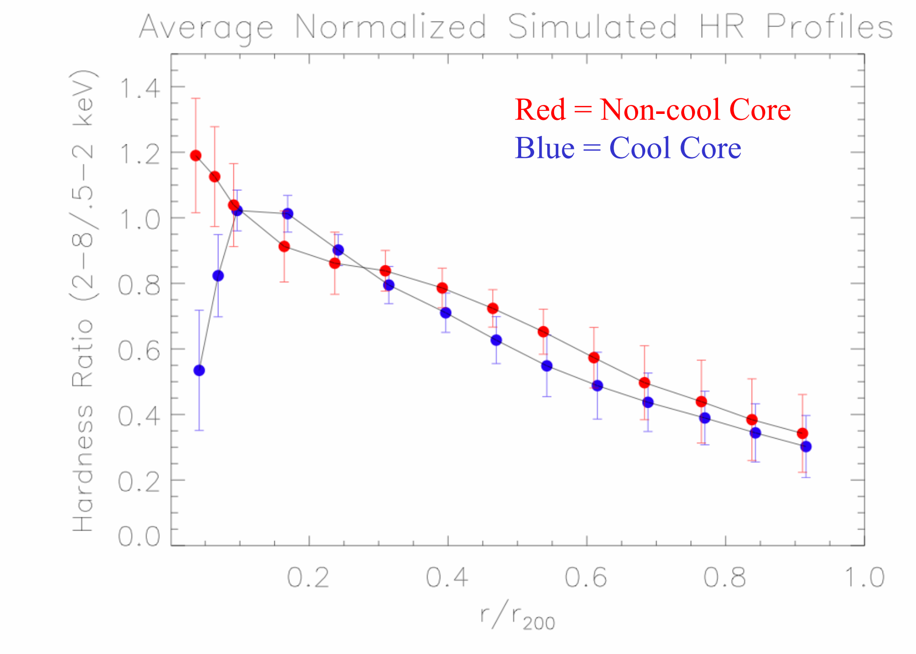
Evolution of a Non-cool Core Cluster

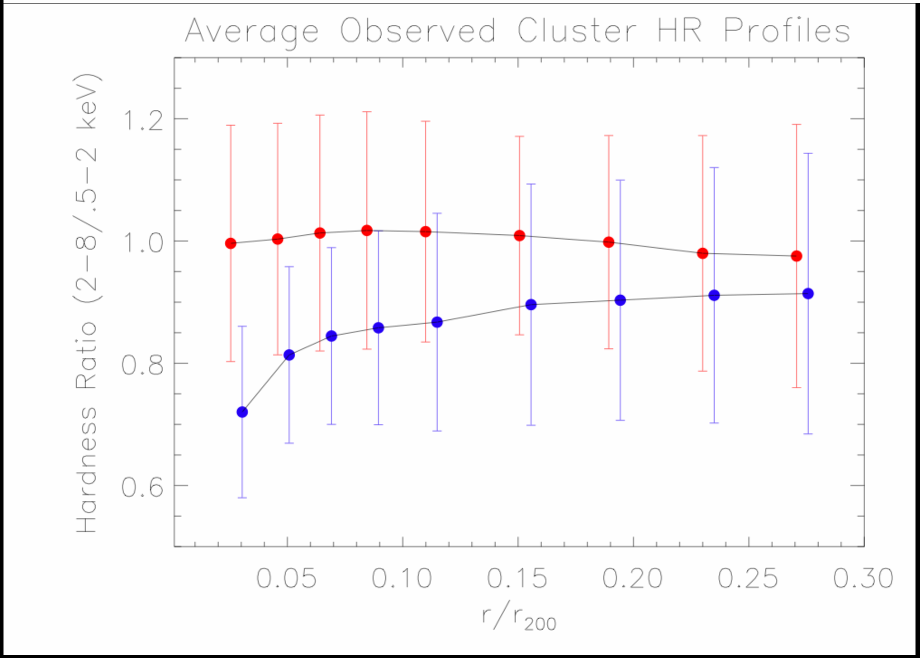


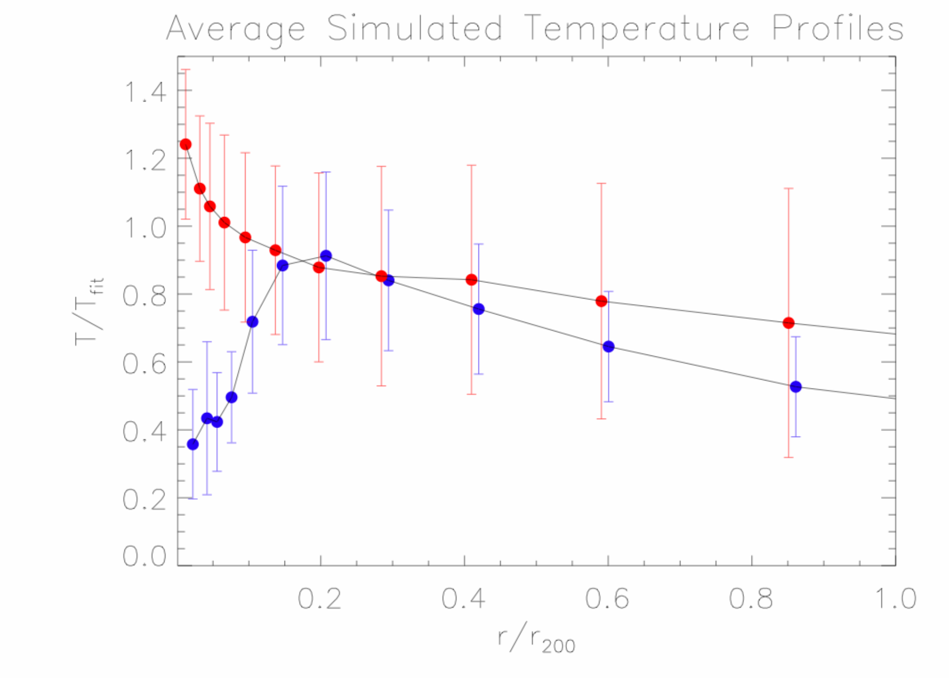
NCC clusters suffer major mergers early in their evolution, destroying embryonic cool cores.

Comparison of Temperature & Hardness Ratio Profiles

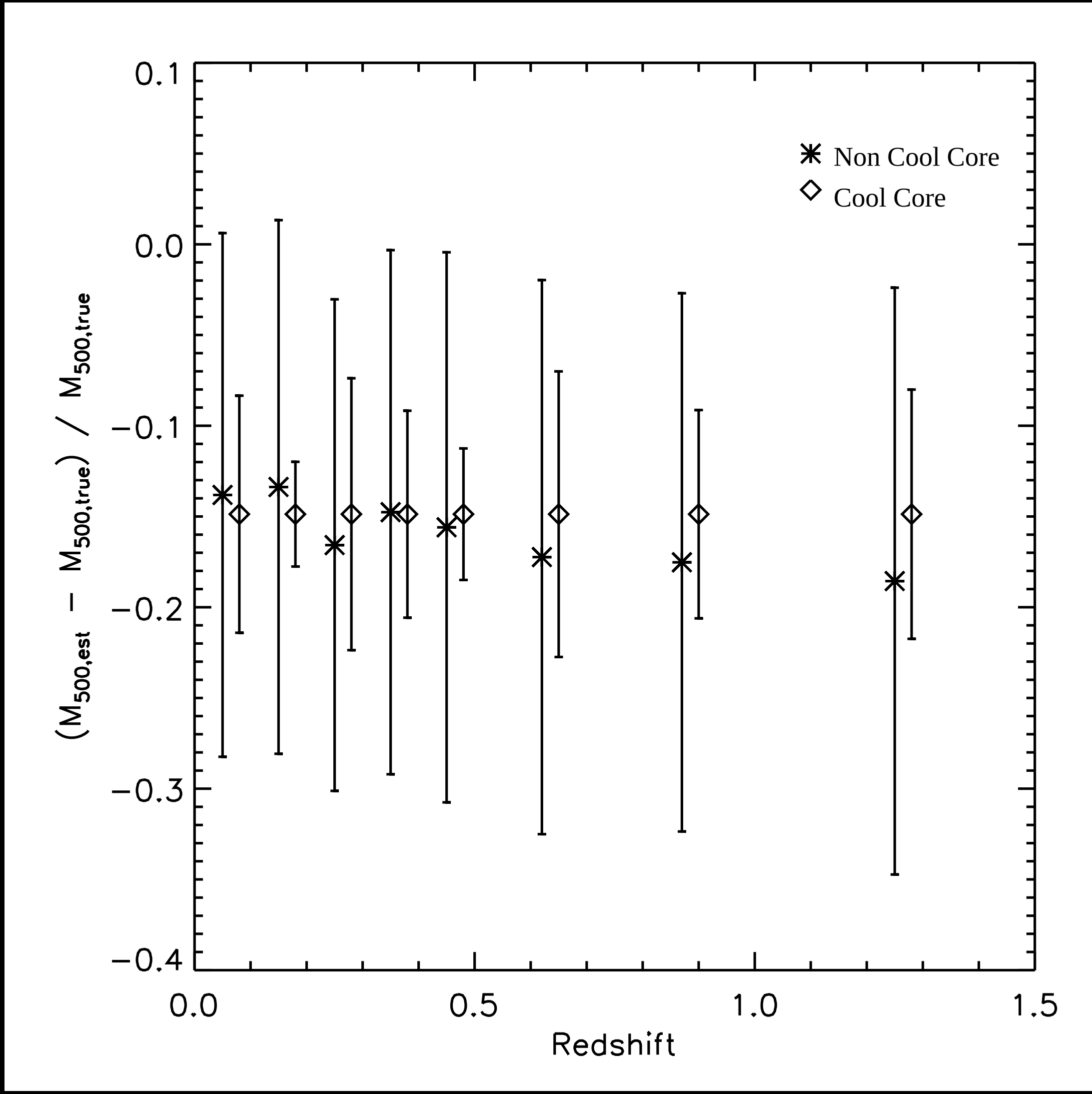
- Simulated temperature profiles for CC & NCC clusters have notable differences beyond the cores.
- Normalized Hardness Ratio profiles reflect this difference between CC & NCC clusters in both simulations and observed (Chandra) samples.





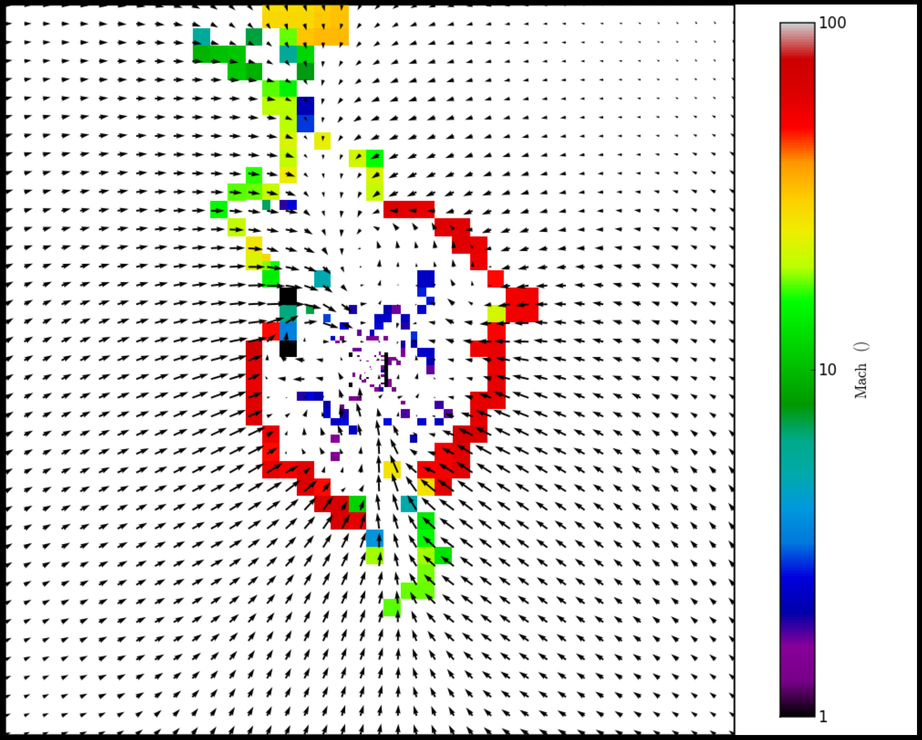


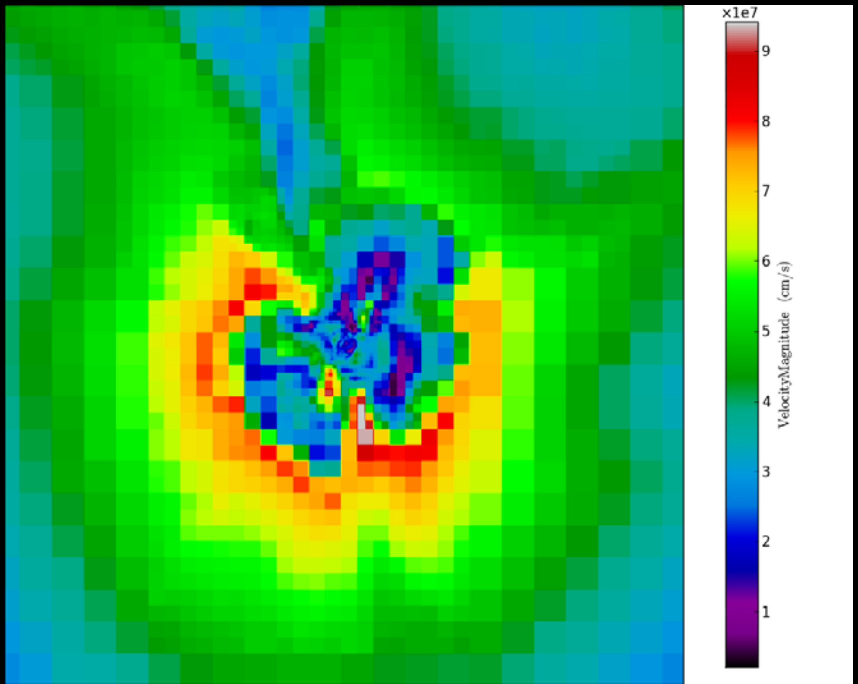
Are CC clusters in Hydrostatic Equilibrium?



- Burns *et al.* 2008.
- Jeltema, Hallman, Burns & Motl, 2008, ApJ, 681, 167.
- Our results are consistent with X-ray to Lensing mass ratios from Mahdavi *et al.* 2008, MNRAS, 384, 1567.

CC clusters are biased low by ~15%, just like NCC clusters. Kinetic energy of bulk gas motions contributes ~10% of total energy.





Large Scale Structure Shocks: Generating Cosmic Rays

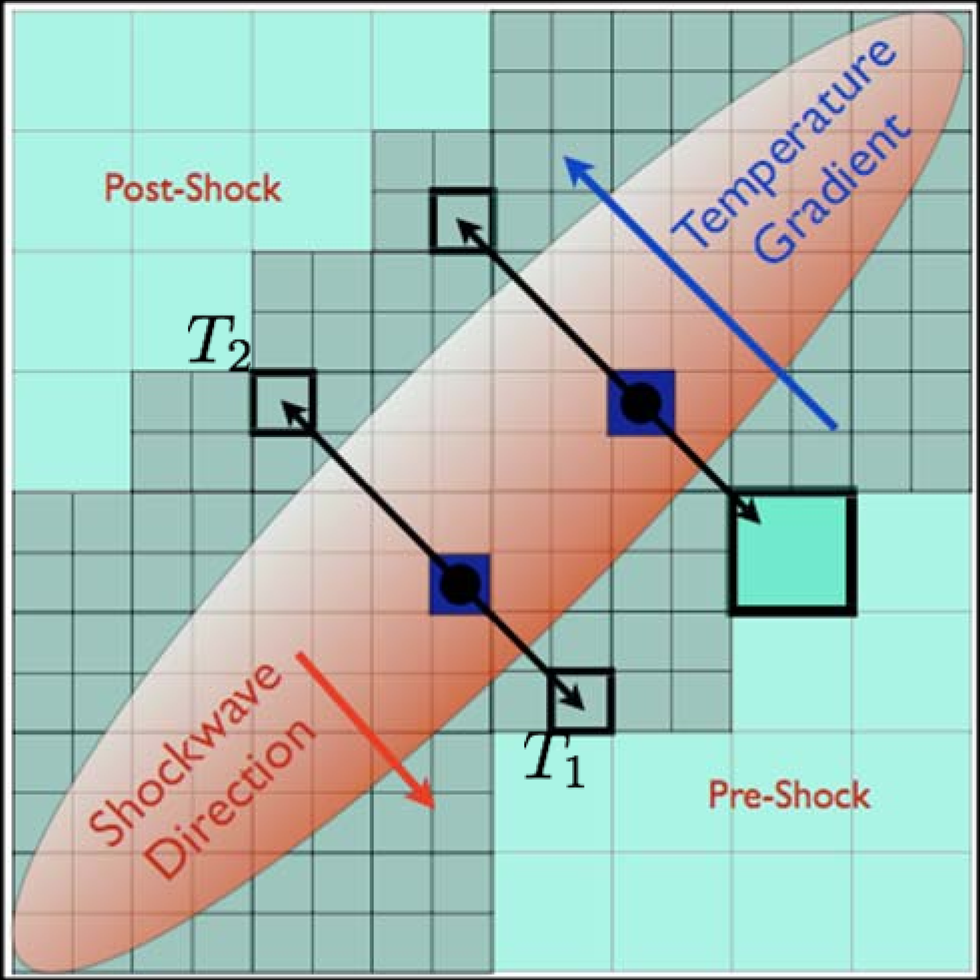
- Thermalization
- Dynamic Effects of Cosmic Rays
- Mass Estimates of Clusters
  - ➢ Can we trust hydrostatic equilibrium?
  - ➢ Effects on the Dark Energy Eq. of State
- Origin of high-energy Cosmic Rays

Shock-Finding in AMR

Skillman et al. 2008, ApJ, in press.

- Previous studies used coordinate-split analysis
- We allow for any orientation of the shock
- Rankine-Hugoniot Jump Conditions

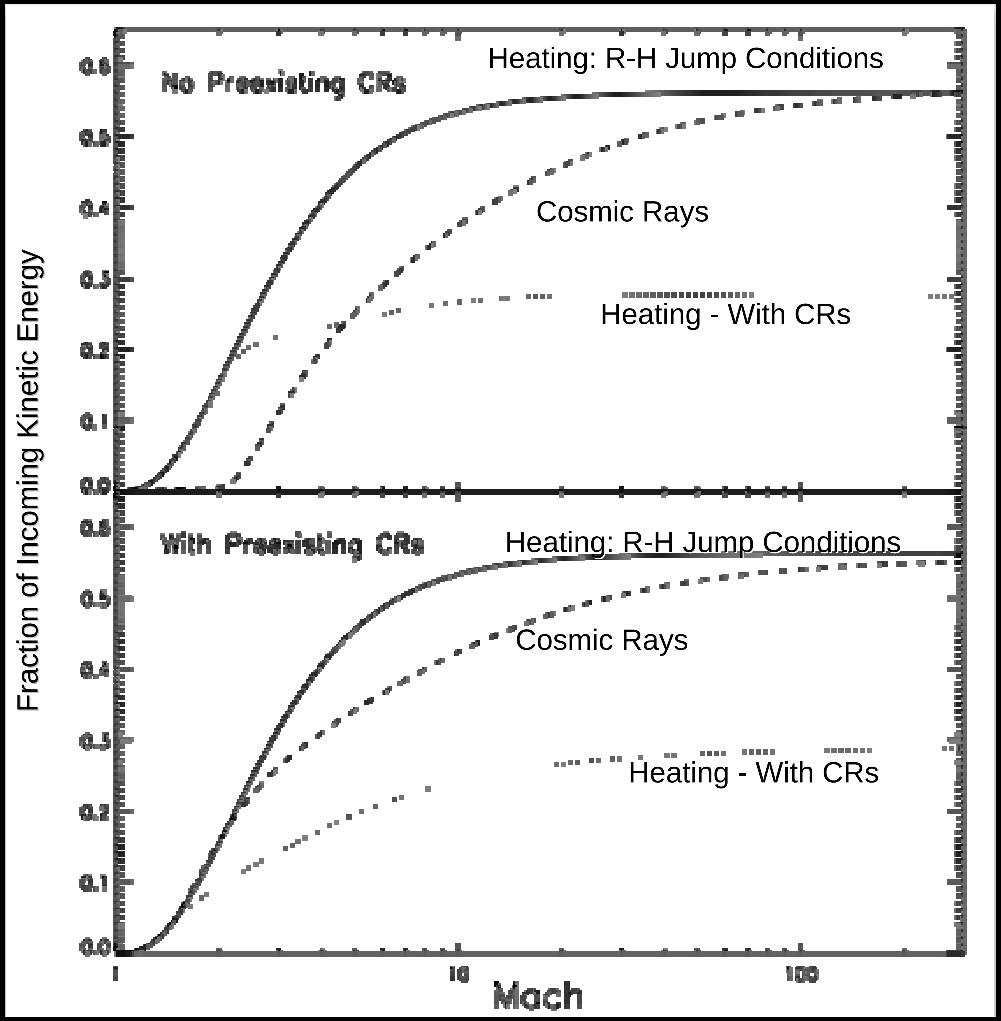
$$\nabla \cdot \vec{v} < 0$$
$$\nabla T \cdot \nabla S > 0$$
$$T_2 > T_1$$
$$\rho_2 > \rho_1,$$



$$\frac{T_2}{T_1} = \frac{(5\mathcal{M}^2 - 1)(\mathcal{M}^2 + 3)}{16\mathcal{M}^2},$$

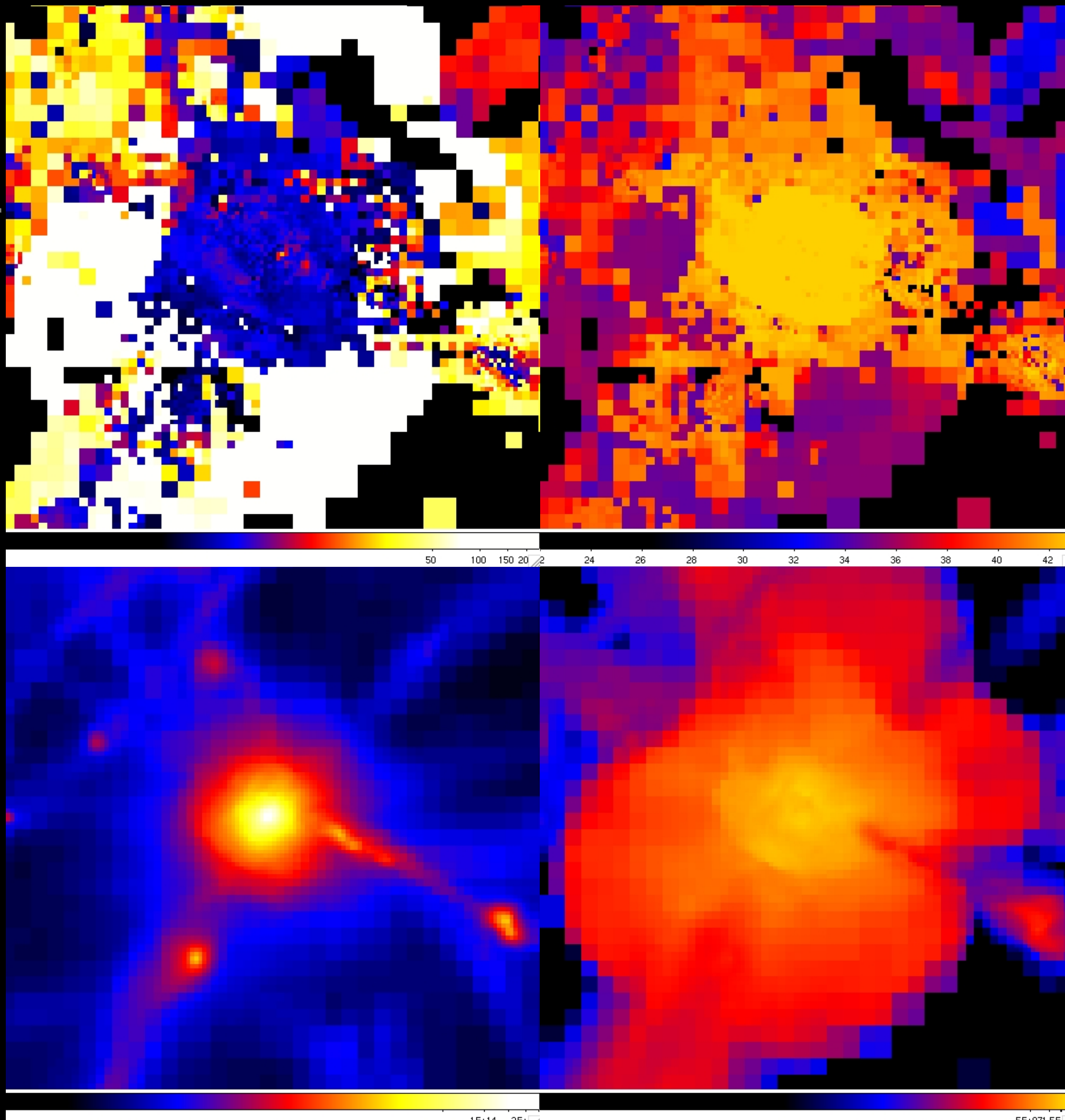
Numerical Results of Diffusive Shock Acceleration Simulations

- Kang & Jones (2002, 2007) – First-order Fermi acceleration at shock fronts.
- Two Models:
  - With and Without pre-existing CRs (30% Pressure)



Mach Number

Cosmic Ray Generation Rate

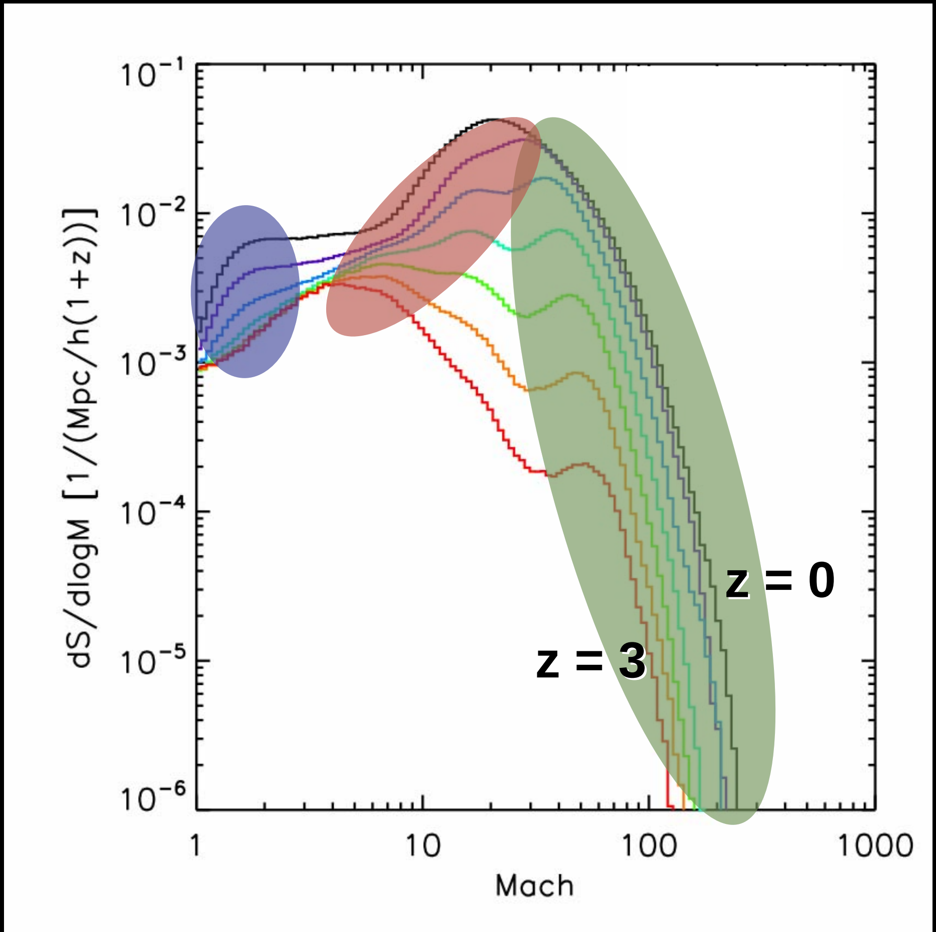


Density

Temperature

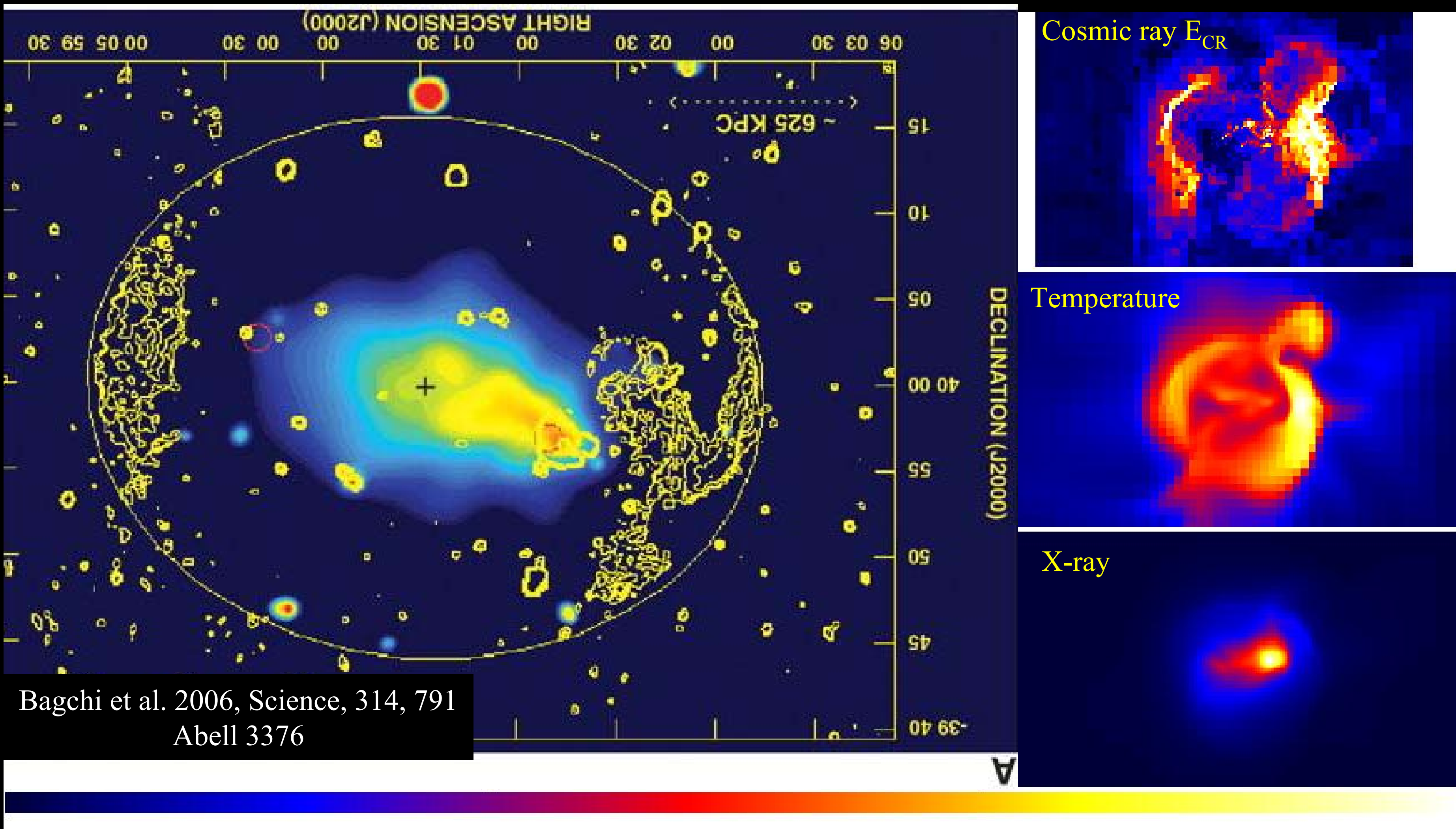
Mach Number Evolution

- Accretion shocks onto clusters.
- Accretion shocks onto filaments.
- Turbulent Flow/ merger shocks.



Simulated Radio Relics

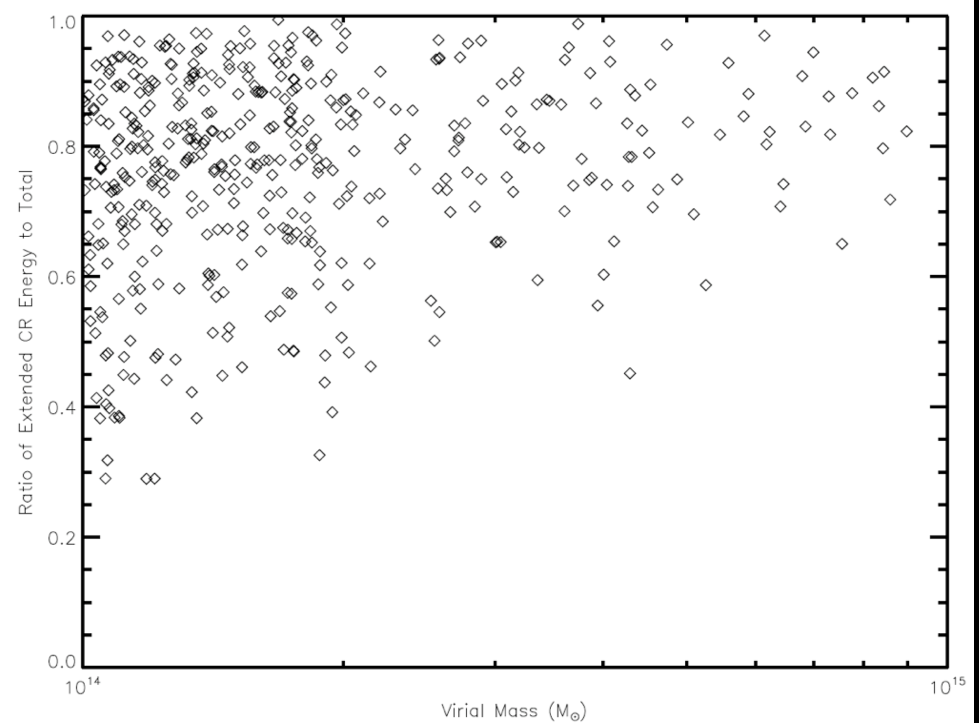
- Sort for images where extended CR Rate(outside 200 h^{-1} kpc) is high ($E_{CR,\ extended}/E_{CR,\ total} \sim 0.9\text{-}1.0$)

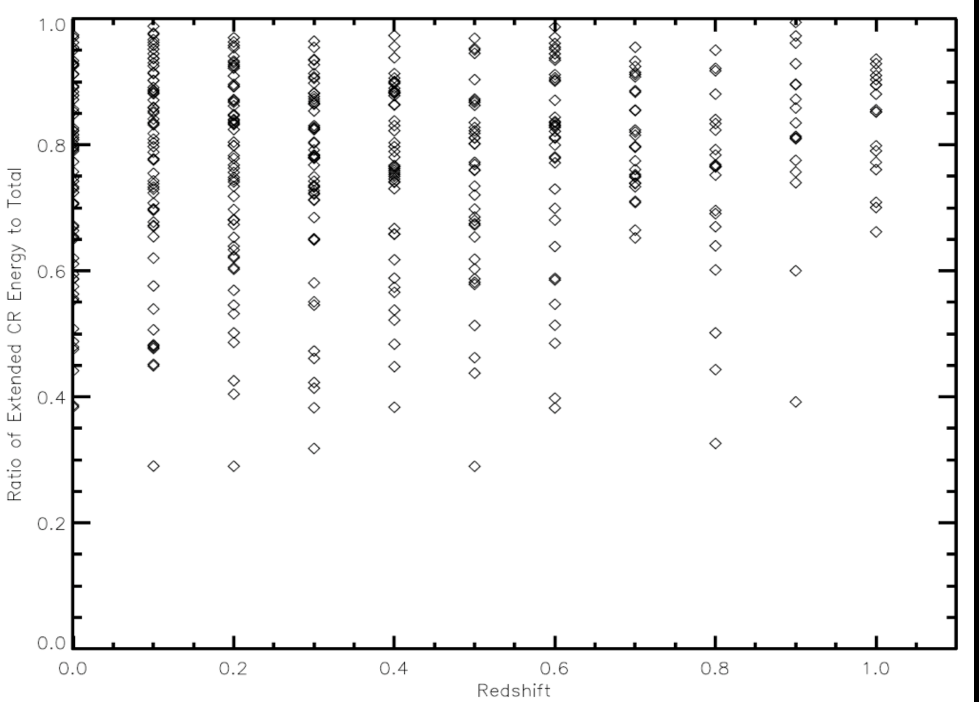


Bagchi et al. 2006, Science, 314, 791
Abell 3376

Distribution as F(M, z)

- About 15-20% have obvious merger shocks outside 200 kpc radius





Conclusions

- Galaxy clusters have potential to be the most precise tools for cosmological parameter estimation but are limited by our understanding of the astrophysics.
- Cool core (CC) clusters are assumed to be dynamically relaxed and, thus, best choice as dark energy probes. But, CC clusters are biased 15% low in mass assuming hydrostatic equilibrium.
- Shock-generated cosmic rays and B-field amplification are underappreciated nonthermal pressure components in the ICM that must be understood to realize full potential of clusters as precision probes.
- Shock morphologies look similar to radio relics. 15-20% of clusters expected to have relics.
- *Future directions:* MHD (with H. Li, LANL); model radio relics (including luminosity function) & gamma-ray emission.

LUNAR: Lunar University Node for Astrophysics Research

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