Searching for Shocks on Radio, SZE, and X-ray Temperature Images

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Monsters, Inc.:Astrophysics and Cosmology with Galaxy Clusters
15 March 2011

CENTER FOR ASTROPHYSICS AND SPACE ASTRONOMY

LUNAR

THE ASTROPHYSICAL JOURNAL, 518:603–612, 1999 June 20

A CLUSTER MERGER AND THE ORIGIN OF THE EXTENDED RADIO EMISSION IN ABELL 3667

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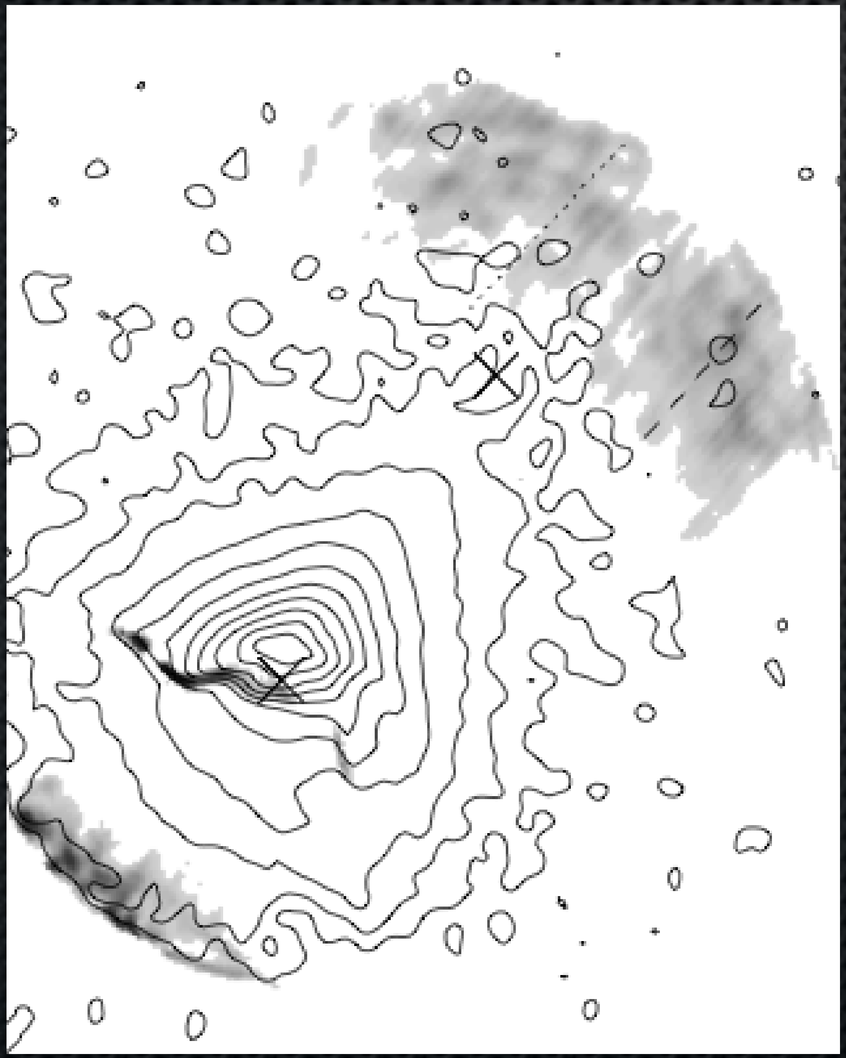
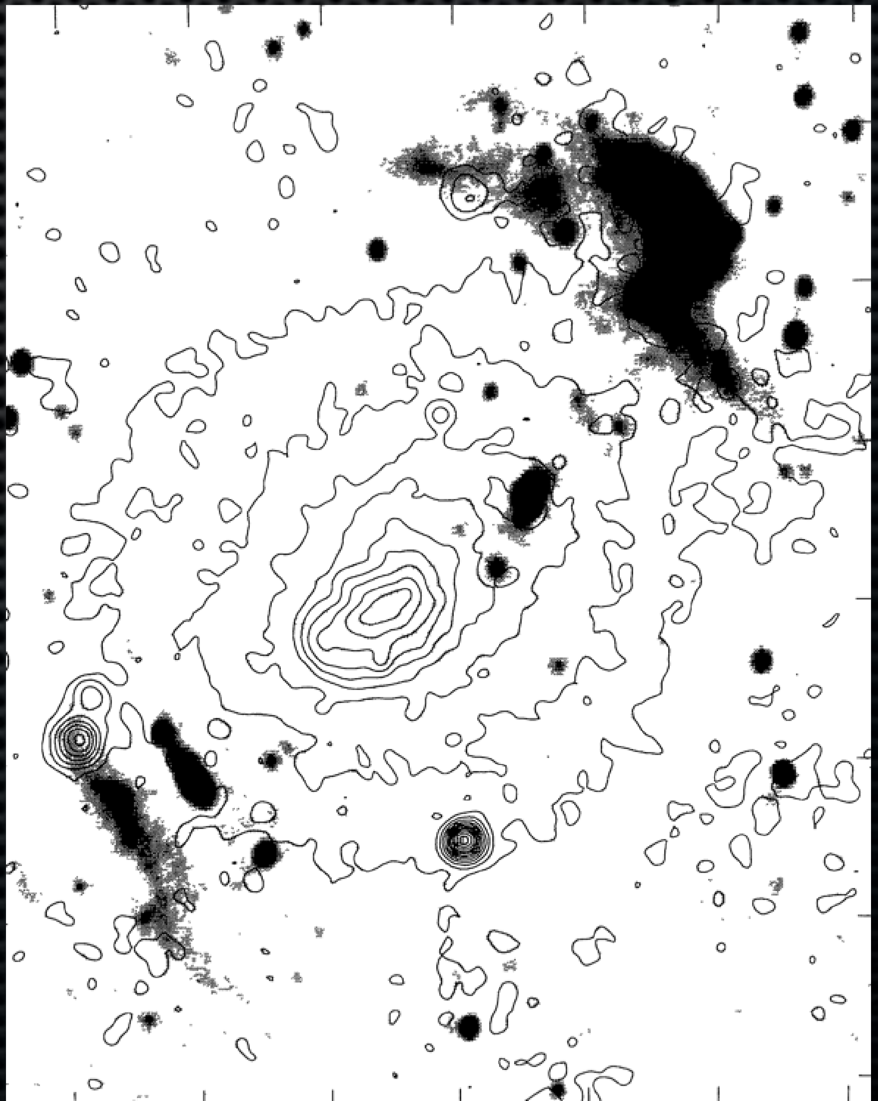
Received 1998 December 3; accepted 1999 January 26

ZEUS-MHD simulations

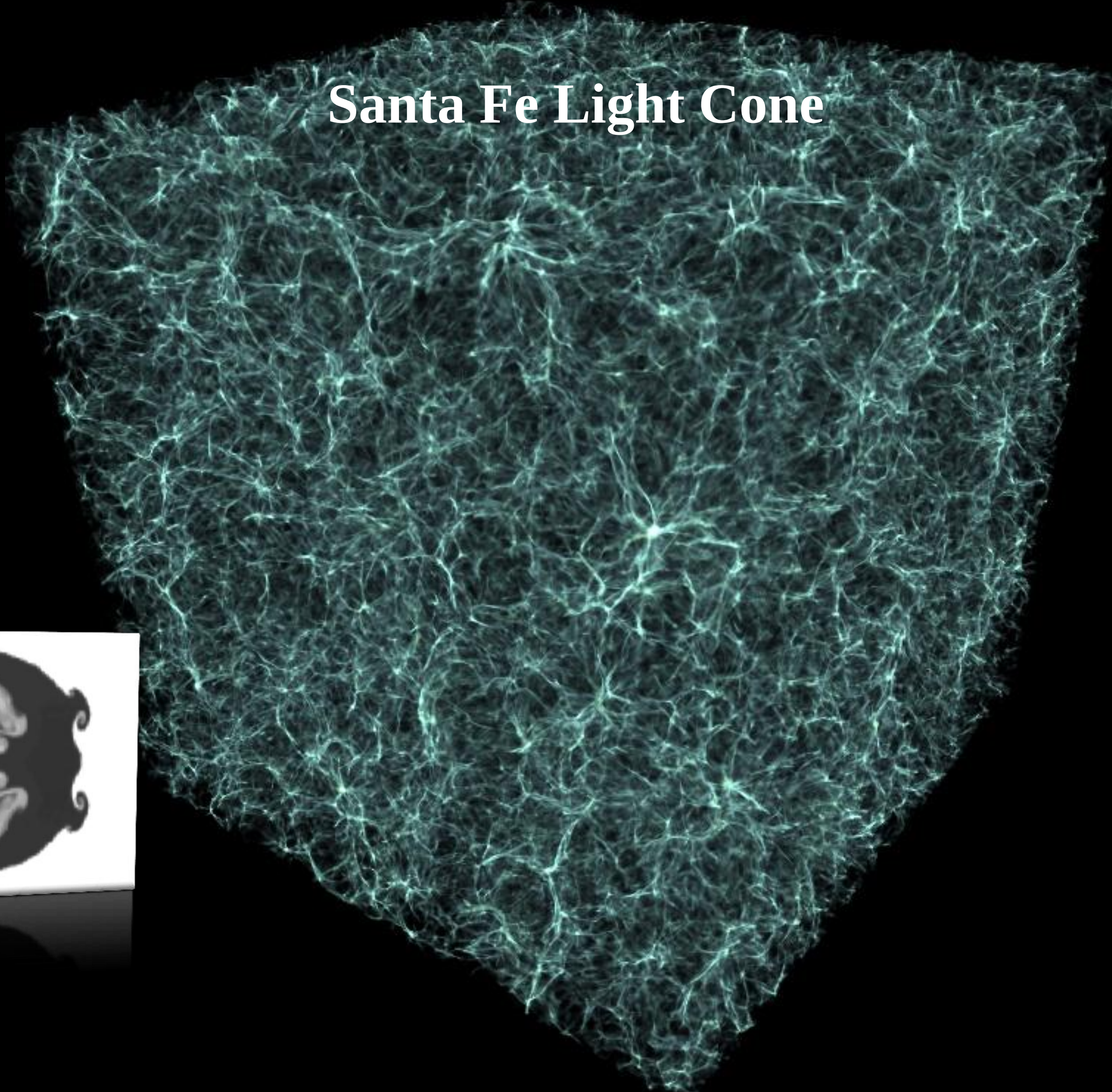




X-ray/radio observations

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

Enzo (e.g., O'Shea et al. 2005, http://enzo.googlecode.com)



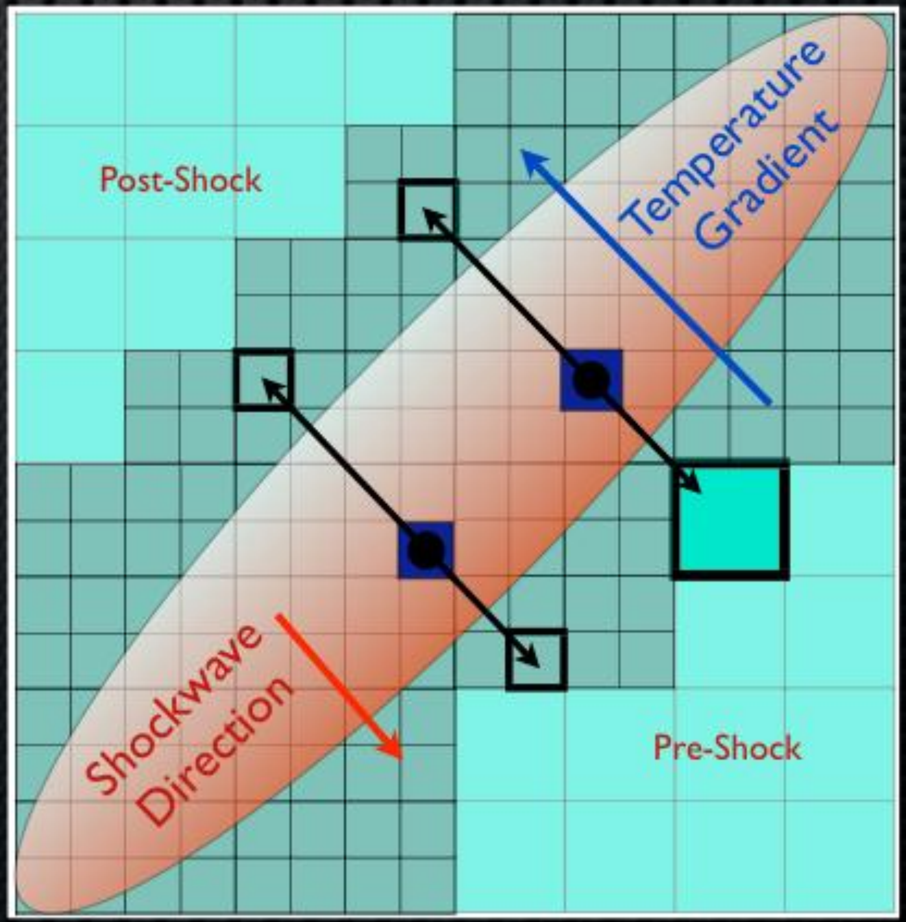
Hallman et al., 2007, ApJ, 671, 27.

- ΛCDM with $\Omega_m = 0.27$, $\Omega_b = 0.04$, $\Omega_\Lambda = 0.73$, $h = 0.7$, and $\sigma_8 = 0.82$.
- AMR achieves 24.4 h^{-1} kpc resolution in dense regions.
- (200 h^{-1} Mpc)^3, 256^3 root grid cells, 5 levels of refinement.
- Dark matter mass resolution is $6.2 \times 10^{10}\ h^{-1}\ M_\odot$.
- Adiabatic gas physics.

Shock Finding & Characterization

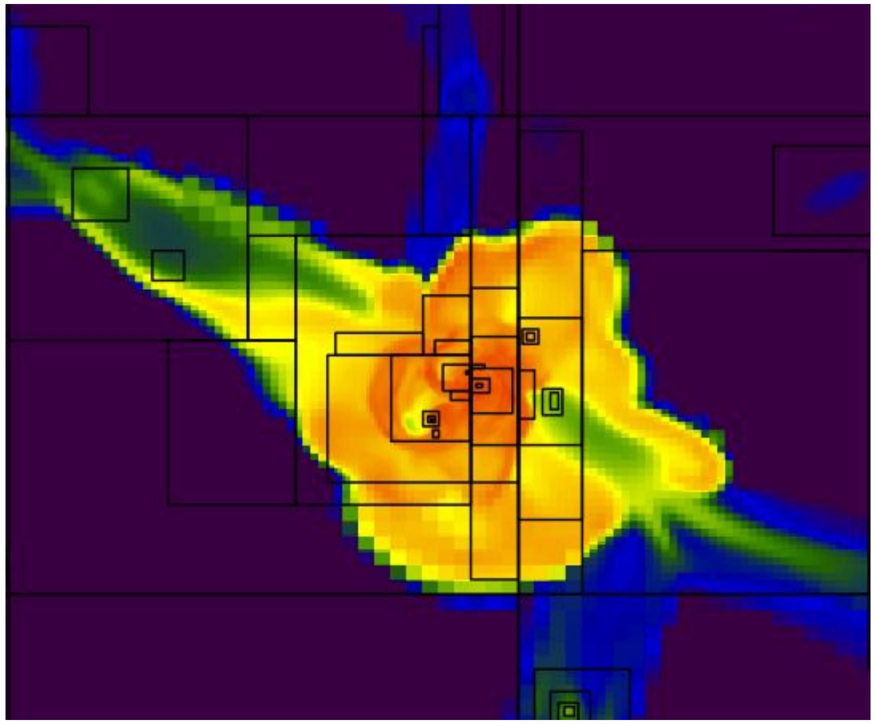
$$\nabla \cdot \vec{v} < 0$$
$$\nabla T \cdot \nabla S > 0$$
$$T_2 > T_1$$
$$\rho_2 > \rho_1,$$
$$\frac{T_2}{T_1} = \frac{(5\mathcal{M}^2 - 1)(\mathcal{M}^2 + 3)}{16\mathcal{M}^2},$$

- Converging Gas
- Entropy increases across shockwave
- Rankine-Hugoniot Jump Conditions
- We allow for any orientation of the shock

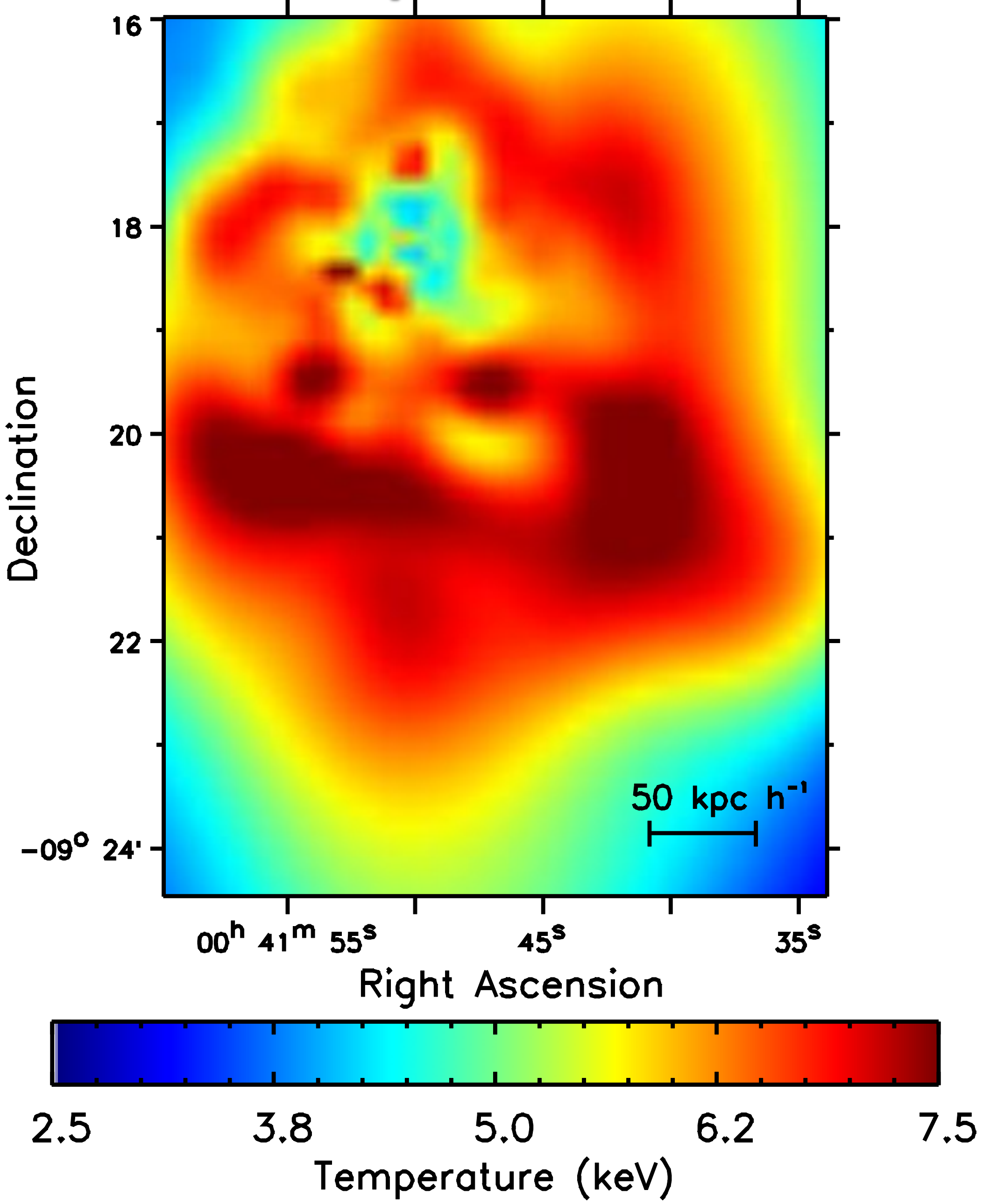


Skillman et al. 2008, ApJ, 689, 1063.

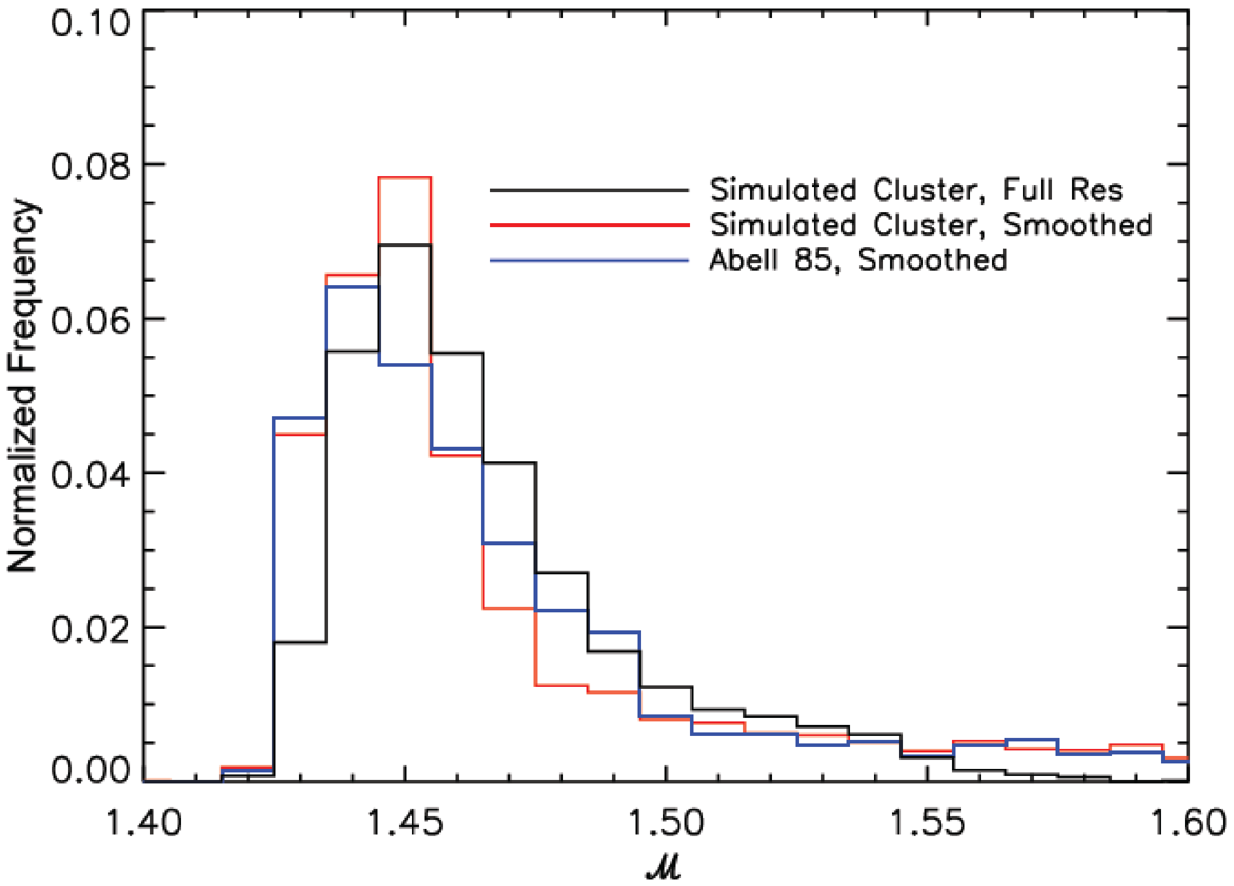
Shocks in AMR Simulations & in Adaptively Binned Observed X-ray Temperature Maps



Simulated Temperature Map with AMR grid



Adaptively-binned temperature map of A85 constructed from joint fit of XMM & Chandra spectra



Comparison of calculated Mach number distributions from simulated cluster & from above temperature map of A85.

Synchrotron Emission

Mon. Not. R. Astron. Soc. **375,** 77–91 (2007) doi:10.1111/j.1365-2966.2006.11111.x

Radio signature of cosmological structure formation shocks

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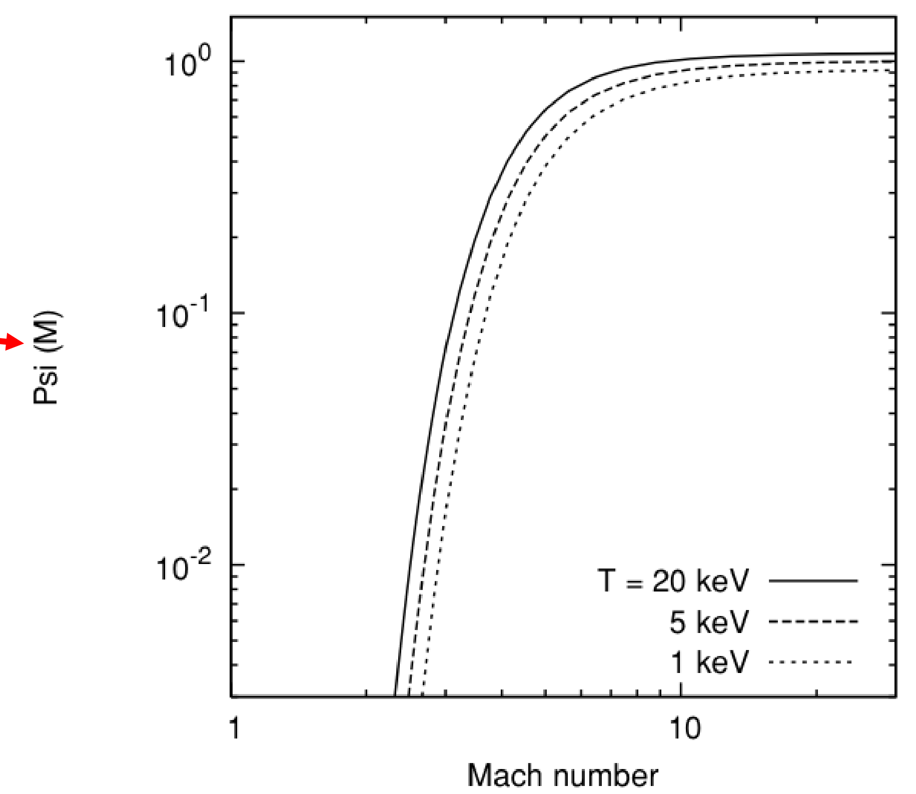
$$n_E(E) \equiv \frac{\mathrm{d}n_\mathrm{e}}{\mathrm{d}E} = \begin{cases} n_\mathrm{e}\, C_\mathrm{spec}\, \frac{1}{m_\mathrm{e} c^2}\, \tilde{e}^{-s} \left(1 - \frac{\tilde{e}}{\tilde{e}_\mathrm{max}}\right)^{s-2} & : \quad \tilde{e} < \tilde{e}_\mathrm{max} \\ 0 & : \quad \text{elsewhere} \end{cases},$$

$$\frac{\mathrm{d}P(\nu_\mathrm{obs})}{\mathrm{d}\nu} = A\, n_\mathrm{e}\, C^p_\mathrm{spec}\, C_\mathrm{sync} \left(\frac{B}{\mu\mathrm{G}}\right)^{s/2} \left(\frac{1.4\,\mathrm{GHz}}{\nu_\mathrm{obs}}\right)^{s/2} \frac{\sqrt{u_\mathrm{d}}}{C_\mathrm{cool}} \frac{1}{C_\Psi}\, \Psi(\mathcal{M})$$

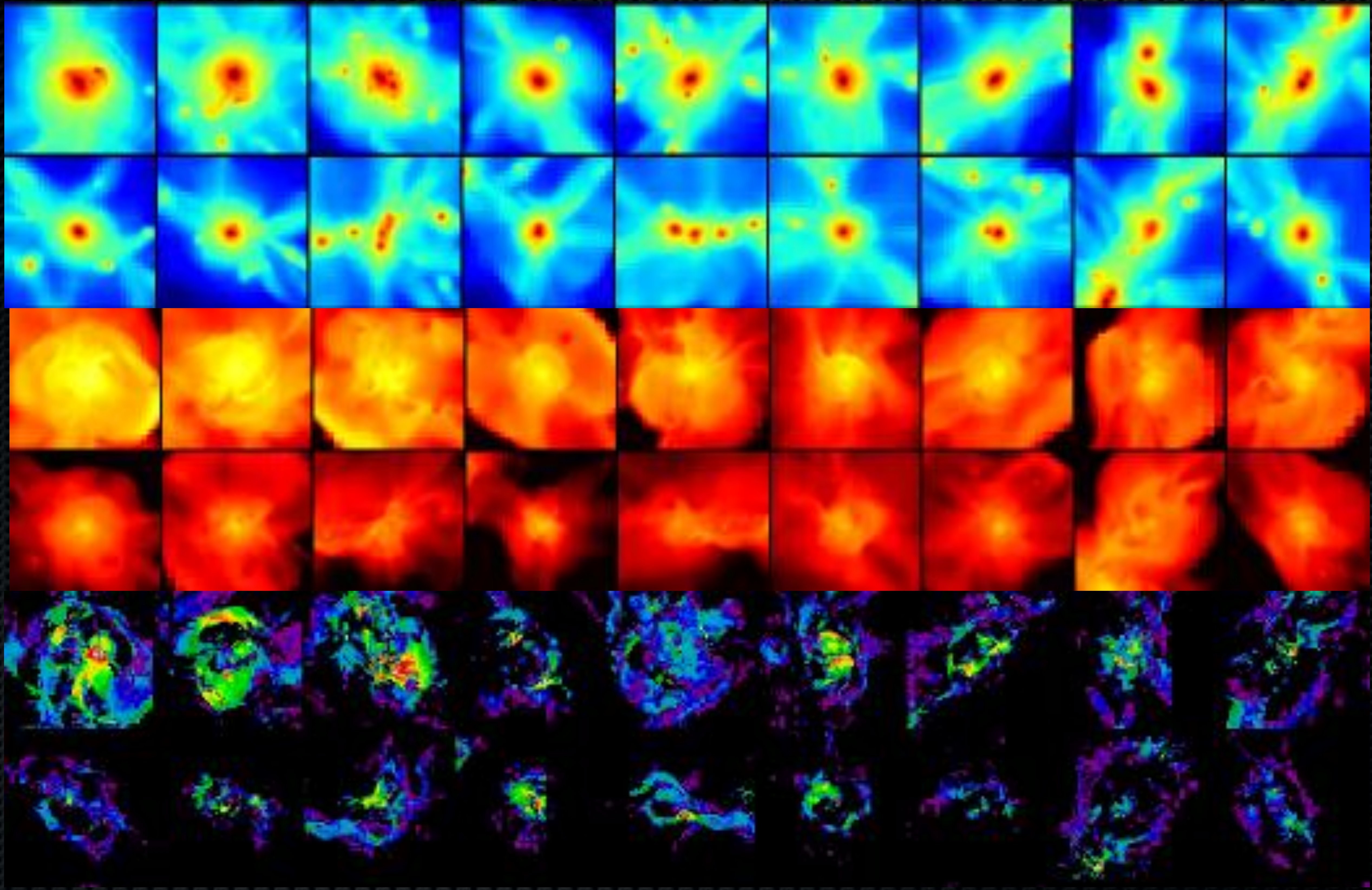
$$= 6.4 \times 10^{34}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}\, \frac{A}{\mathrm{Mpc}^2} \frac{n_\mathrm{e}}{10^{-4}\,\mathrm{cm}^{-3}} \frac{\xi_\mathrm{e}}{0.05} \left(\frac{\nu_\mathrm{obs}}{1.4\,\mathrm{GHz}}\right)^{-s/2}$$

$$\times \left(\frac{T_\mathrm{d}}{7\,\mathrm{keV}}\right)^{3/2} \frac{(B/\mu\mathrm{G})^{1+(s/2)}}{(B_\mathrm{CMB}/\mu\mathrm{G})^2 + (B/\mu\mathrm{G})^2}\, \Psi(\mathcal{M}).$$



Ψ as a function of the Mach number. Also the downstream temperature has a small impact.

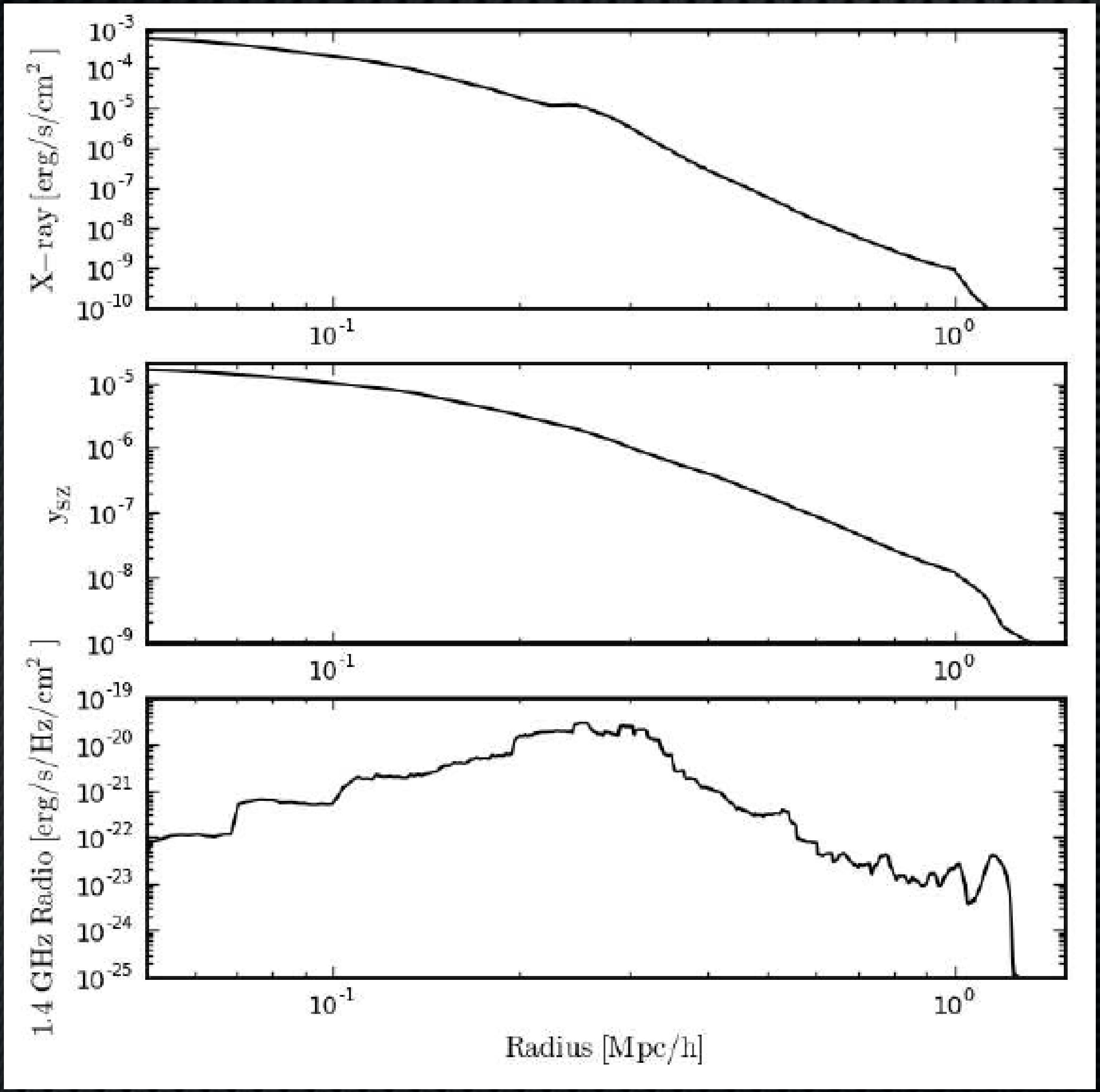
Density (top), Temperature (middle), Radio (bottom)



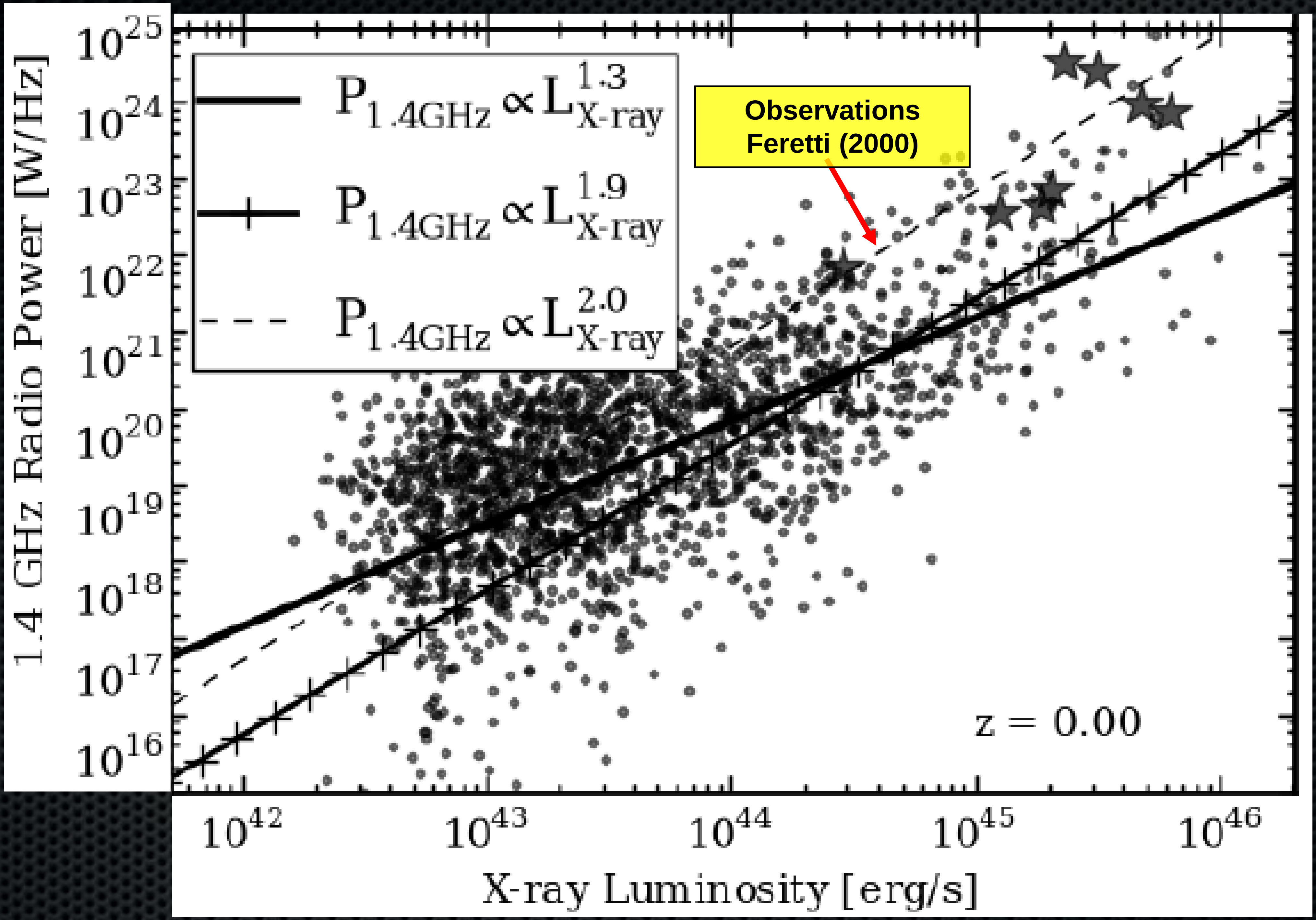
Density/X-ray is centered-filled, whereas Radio is edge-brightened, thus illuminating the merger shocks

Skillman et al. 2011, submitted to ApJ (astro/ph, arXiv:1006.3559)

Line-of-Sight Radio Relics do NOT have surface brightness profiles that align with X-ray or SZE

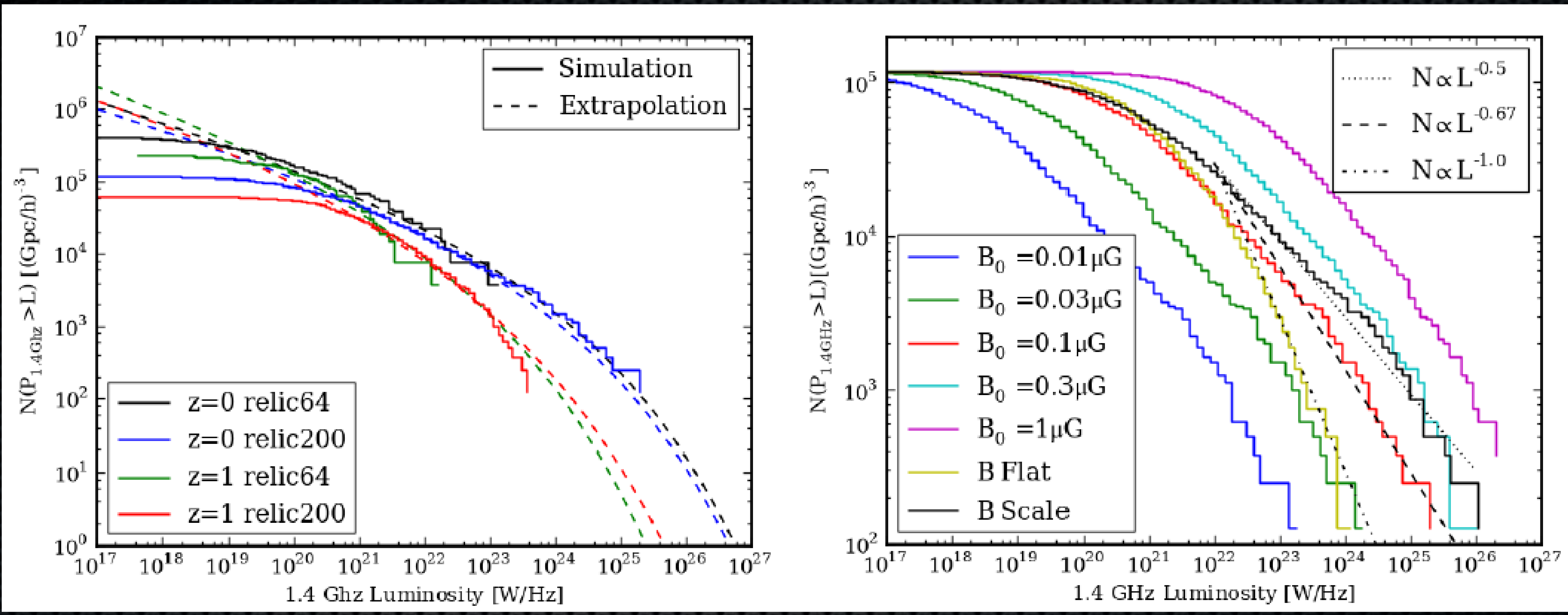


X-ray/Radio Scaling Relation



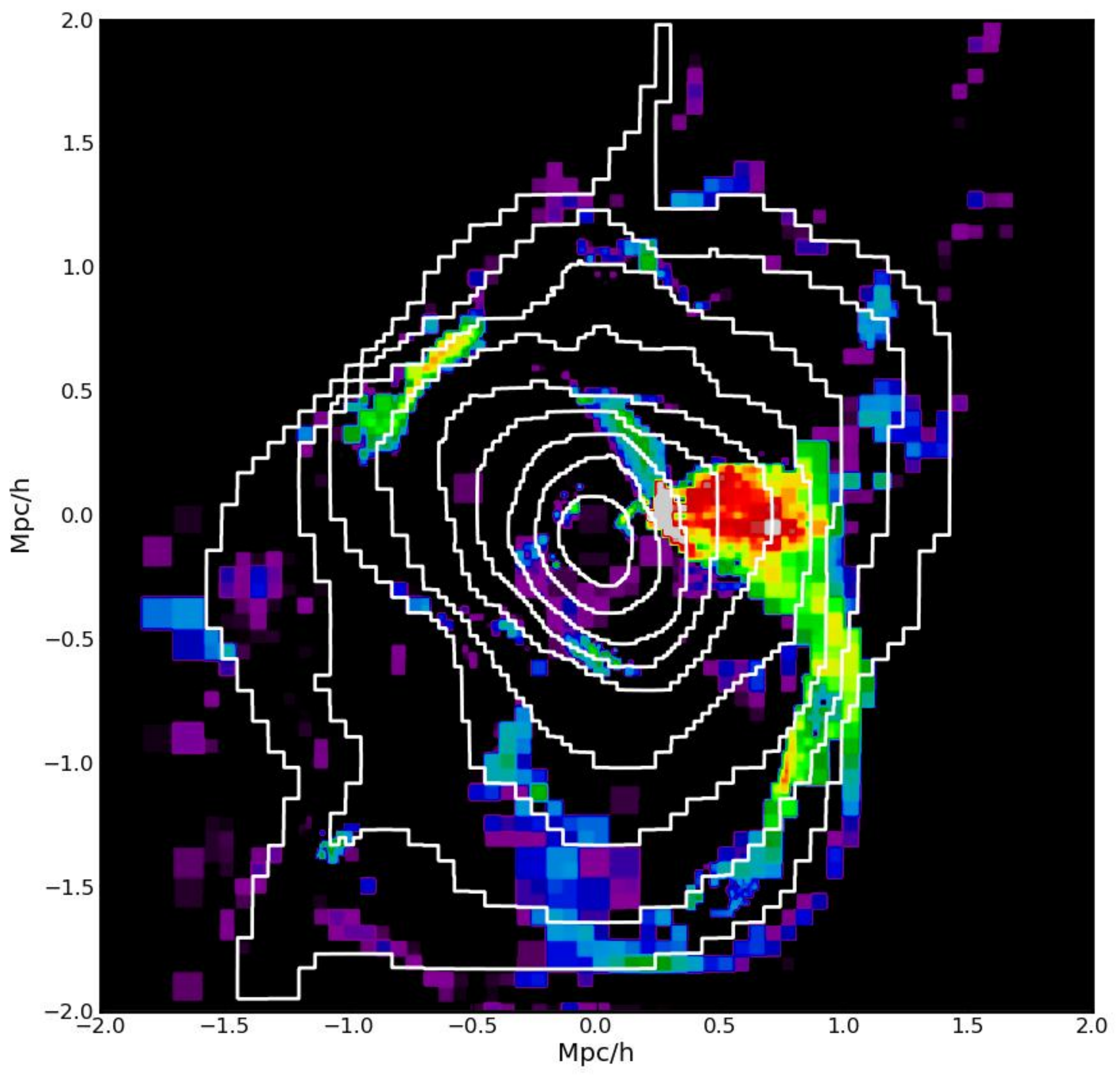
=>Large scatter produced by variety of evolutionary/merger states of the clusters.

1.4 GHz Radio Luminosity Function for Clusters

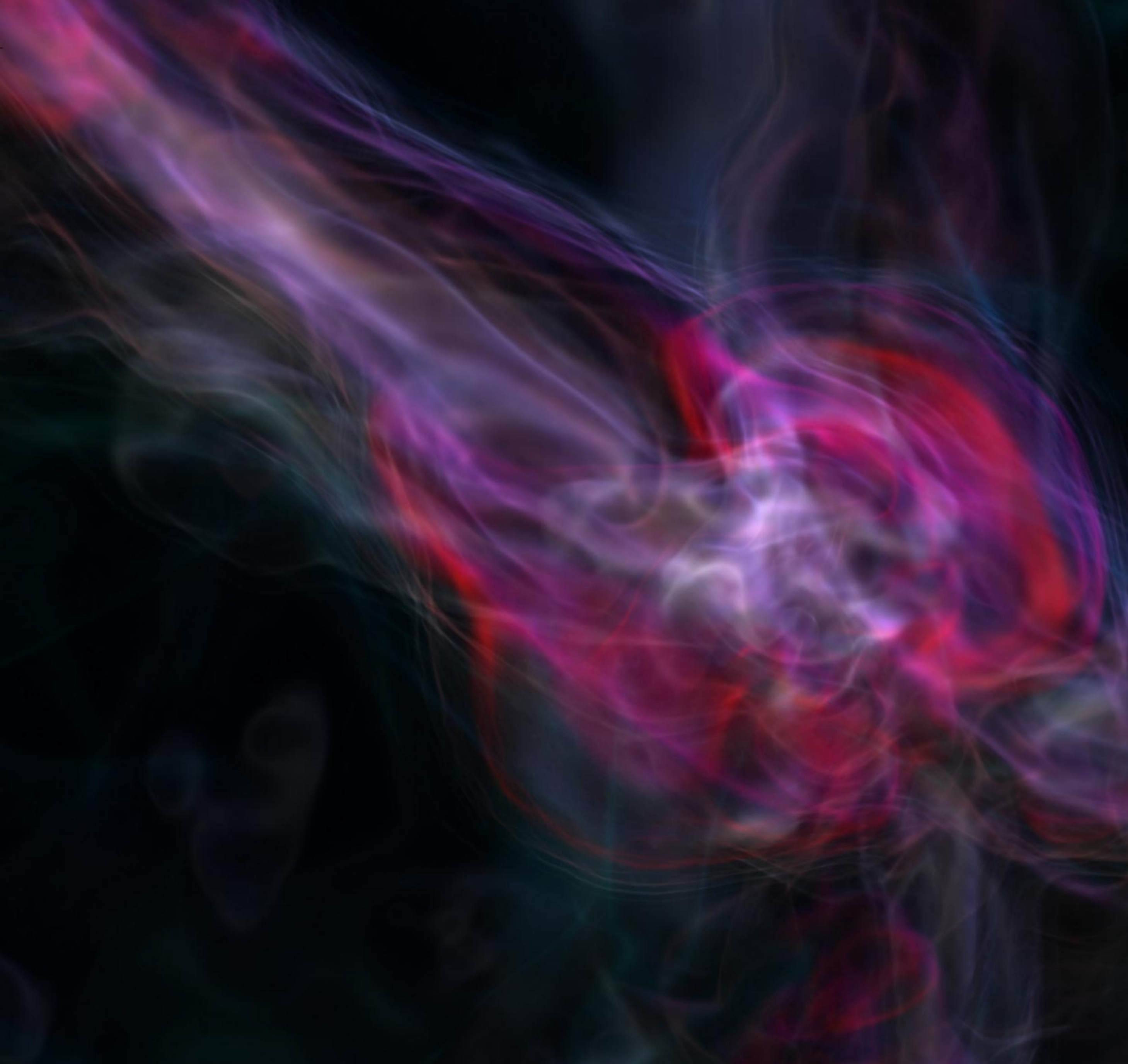


⇒We expect to find 180-1000 radio relic clusters with $P_{1.4GHz} > 10^{25}$ W/Hz for an all-sky survey out to z<0.5.

SZE Gradients Correlate with Radio Emission & Locations of Shocks



Summary & Conclusions



Isodensity contours of temperature in a cluster + filament

- We produced radio relics within a sample of galaxy clusters from cosmological simulations with properties that resemble those observed in clusters.
- Radio/X-ray scaling relation agrees with present observations.
- We predict 180-1000 radio relics in clusters with $P_{1.4GHz} > 10^{25}$ W/Hz from all-sky surveys for $z<0.5$. Candidates for new radio arrays (EVLA, LOFAR).
- See poster by O’Shea et al. for more details!