# Radio Relics in Galaxy Clusters: *Insights from Cosmological Simulations for Future Observations*


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Giant Ringlike Radio Structures Around Galaxy Cluster Abell 3376
Joydeep Bagchi, *et al.*
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# Giant Ringlike Radio Structures Around Galaxy Cluster Abell 3376

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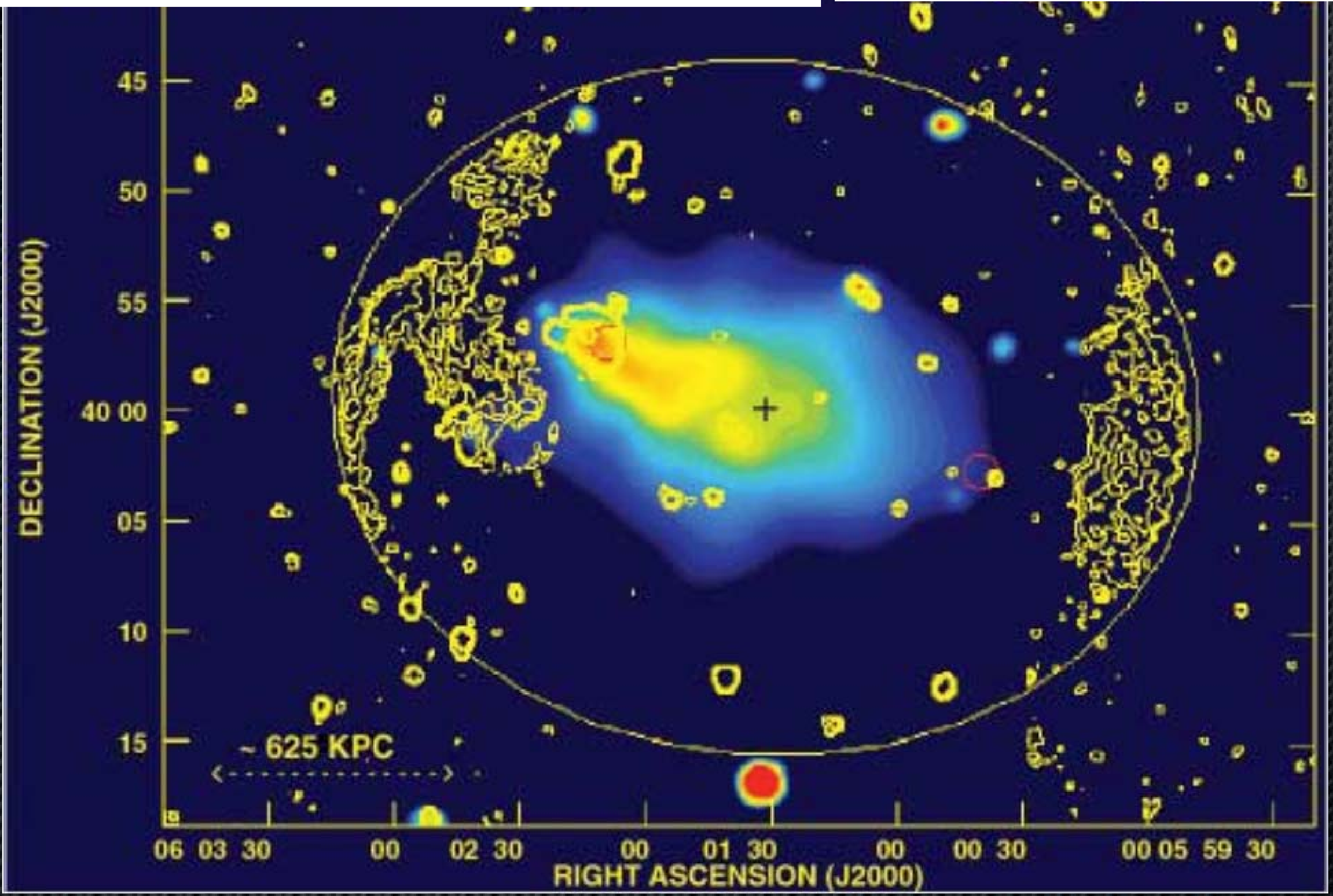


**Fig. 1.** (**A**) A composite map of radio and x-ray emissions from the galaxy cluster Abell 3376. The radio emission is represented by yellow contours (0.12, 0.24, 0.48, and 1 mJy per beam; beam width: 20 arc sec full width at half maximum Gaussian) obtained from the VLA 1.4-GHz observations (*12*). The yellow ellipse shows an elliptical fit to the peripheral radio structures, and the "+" marks the center of the ellipse. The central color image depicts the thermal bremsstrahlung x-ray emission detected by the Position Sensitive Proportional Counter instrument onboard the Roentgen Satellite (≈12-ks exposure, within 0.14- to 2.0-keV band). The red circles mark the position of the two brightest cluster galaxies—the brightest elliptical galaxy on the lower right and the second brightest elliptical galaxy associated with the bent-jet radio source MRC 0600-399 near the x-ray peak. (**B**) Composite images obtained from superposing the radio and optical images. The VLA 1.4-GHz radio maps (in red) for the eastern (left) and the western (right) radio structures are shown overlayed on the red band Digitized Sky Survey image (in blue).

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

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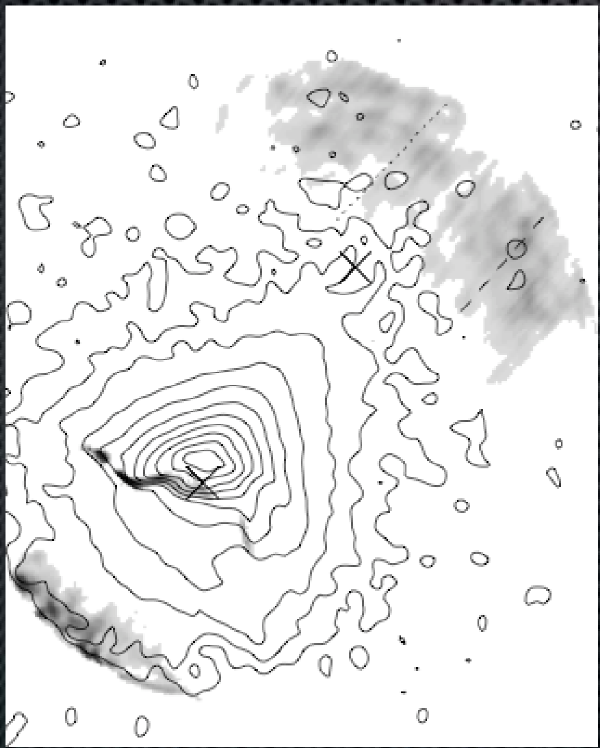
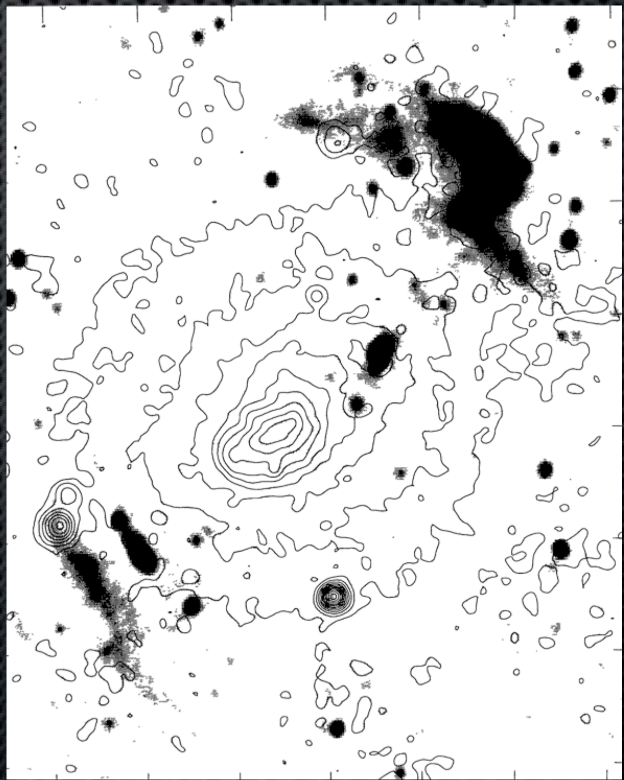
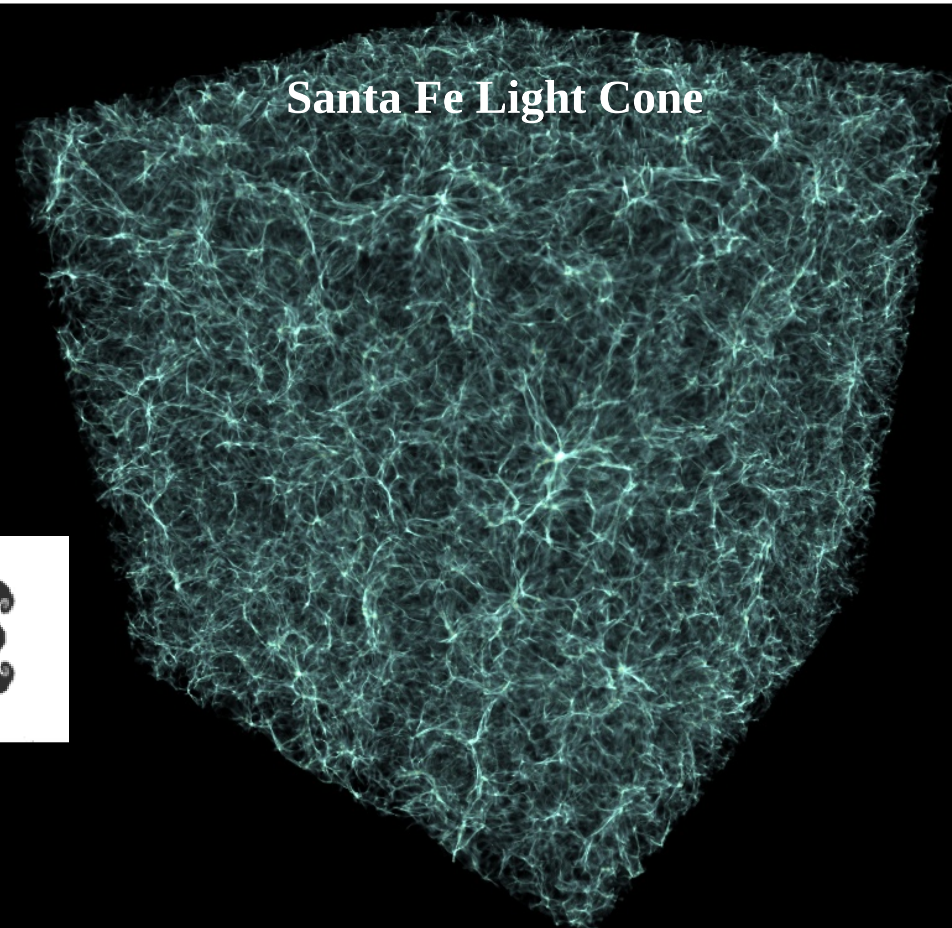




# Adaptive Mesh Refinement (AMR) Simulations of Cluster Formation and Evolution

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




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

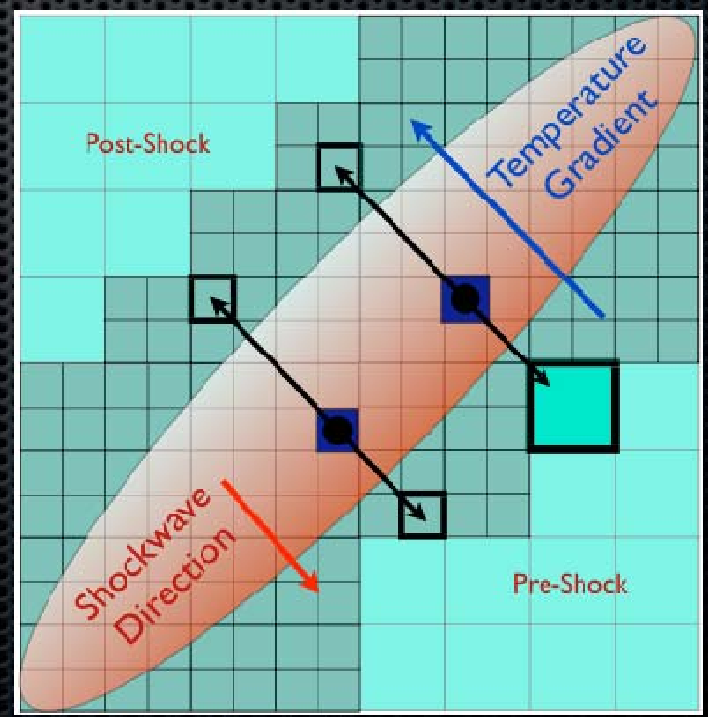
- $\Lambda$CDM with $\Omega_m = 0.27$, $\Omega_b = 0.04$, $\Omega_\Lambda = 0.73$, $h = 0.7$, and $\sigma_8 = 0.82$.
- AMR achieves 24.4 $h^{-1}$ kpc resolution in dense regions with $256^3$ root grid cells.
- $(200\ h^{-1}\ \mathrm{Mpc})^3$, 5 levels of refinement.
- Dark matter mass resolution is $6.2\mathrm{x}10^{10}\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

# Shock Finding & Characterizing

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

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

- 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.

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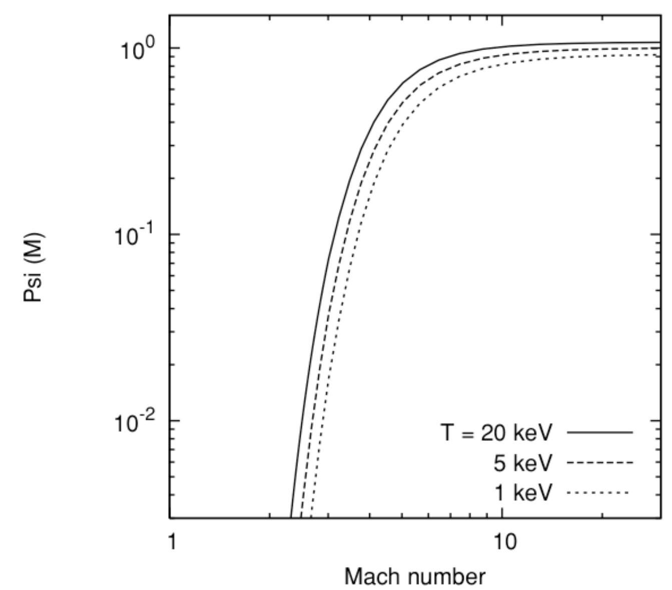
$$n_E(E) \equiv \frac{\mathrm{d}n_\mathrm{e}}{\mathrm{d}E} = \begin{cases} n_\mathrm{e}\, C_\mathrm{spec}\, \frac{1}{m_\mathrm{e} c^2}\, \tilde{e}^{-s} \left(1 - \frac{\tilde{e}}{\tilde{e}_\mathrm{max}}\right)^{s-2} & : \quad \tilde{e} < \tilde{e}_\mathrm{max} \\ 0 & : \quad \text{elsewhere} \end{cases},$$

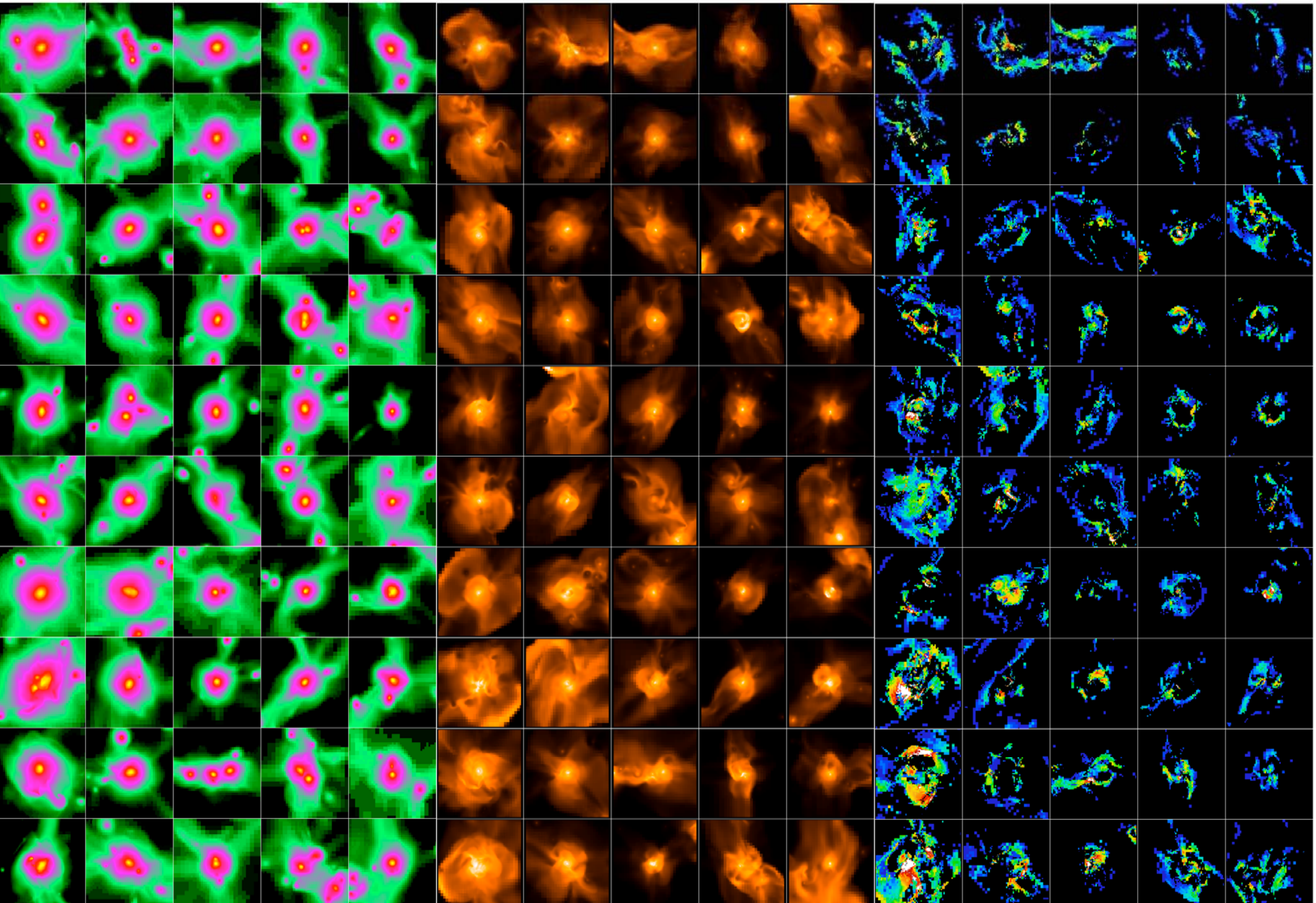
$$\frac{\mathrm{d}P(\nu_\mathrm{obs})}{\mathrm{d}\nu} = A\, n_\mathrm{e}\, C^{p}_\mathrm{spec}\, C_\mathrm{sync} \left(\frac{B}{\mu\mathrm{G}}\right)^{s/2} \left(\frac{1.4\,\mathrm{GHz}}{\nu_\mathrm{obs}}\right)^{s/2} \frac{\sqrt{u_\mathrm{d}}}{C_\mathrm{cool}} \frac{1}{C_\Psi}\, \Psi(\mathcal{M})$$

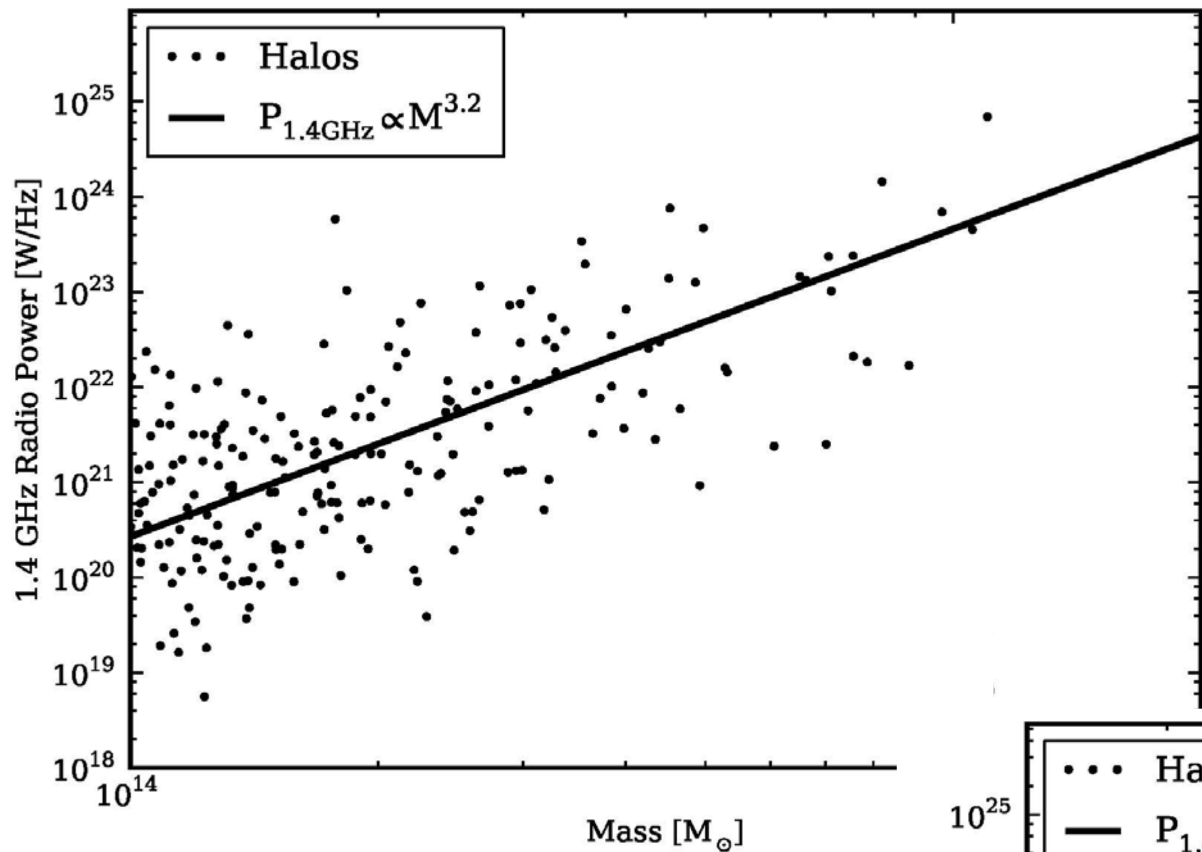
$$= 6.4 \times 10^{34}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}\, \frac{A}{\mathrm{Mpc}^2}\, \frac{n_\mathrm{e}}{10^{-4}\,\mathrm{cm}^{-3}}\, \frac{\xi_\mathrm{e}}{0.05} \left(\frac{\nu_\mathrm{obs}}{1.4\,\mathrm{GHz}}\right)^{-s/}$$

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



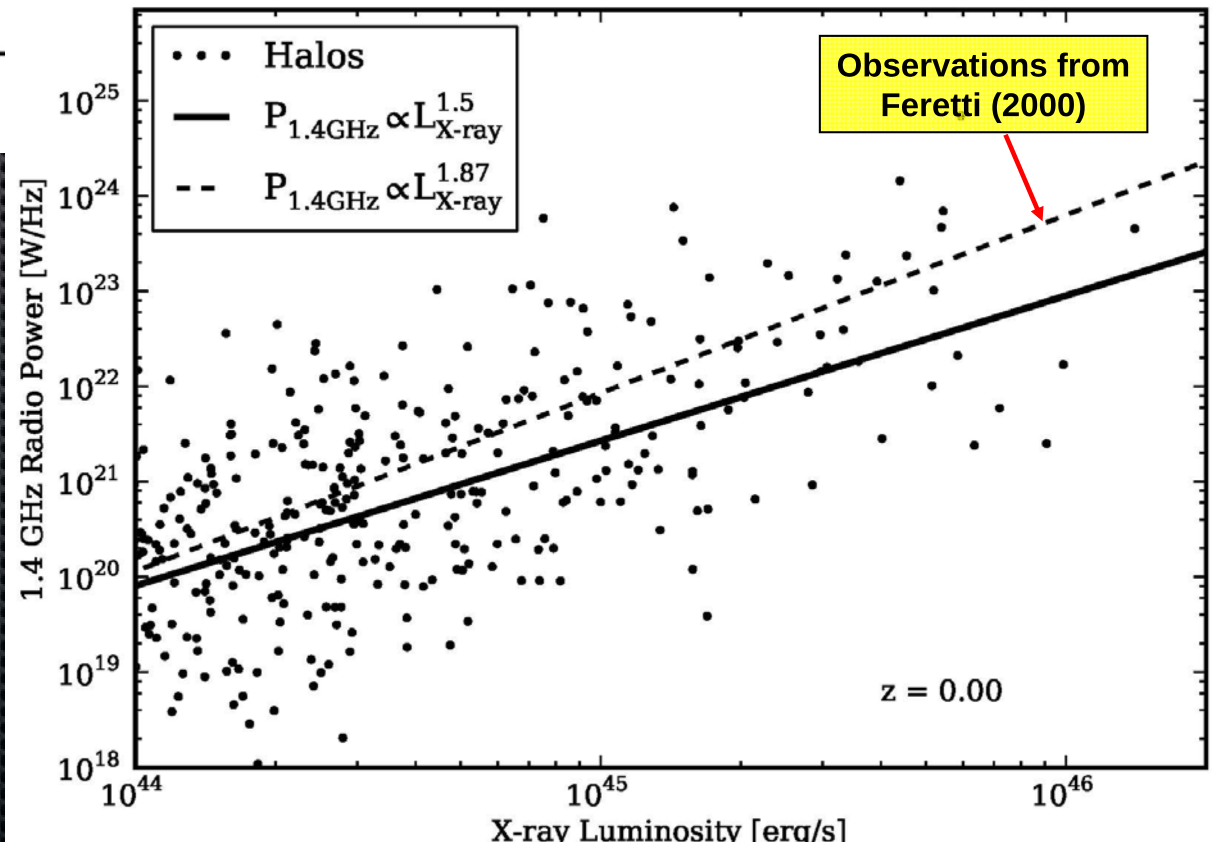

Ψ as a function of the Mach number. Also the downstream temperature has a small impact.



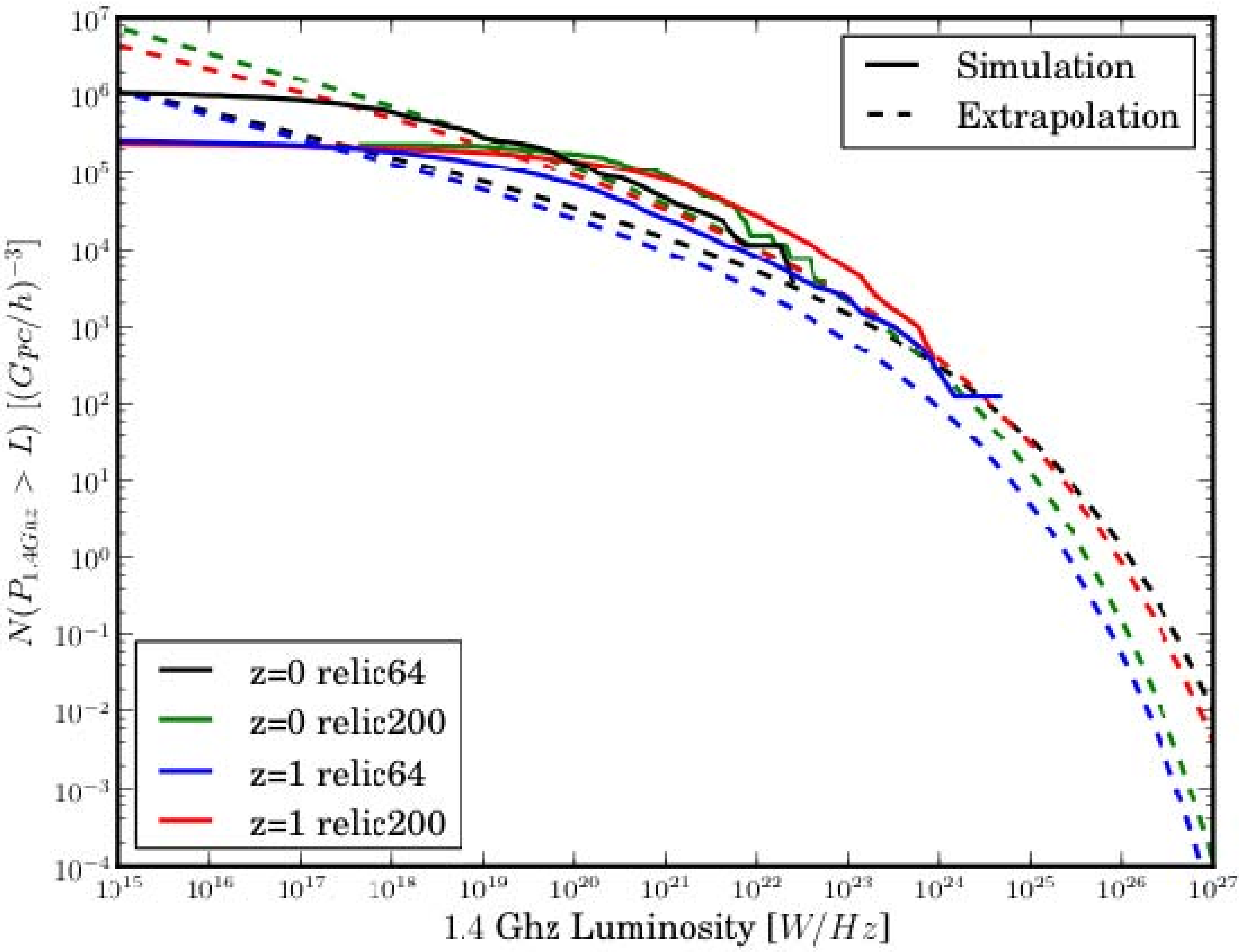



# Scaling Relations

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



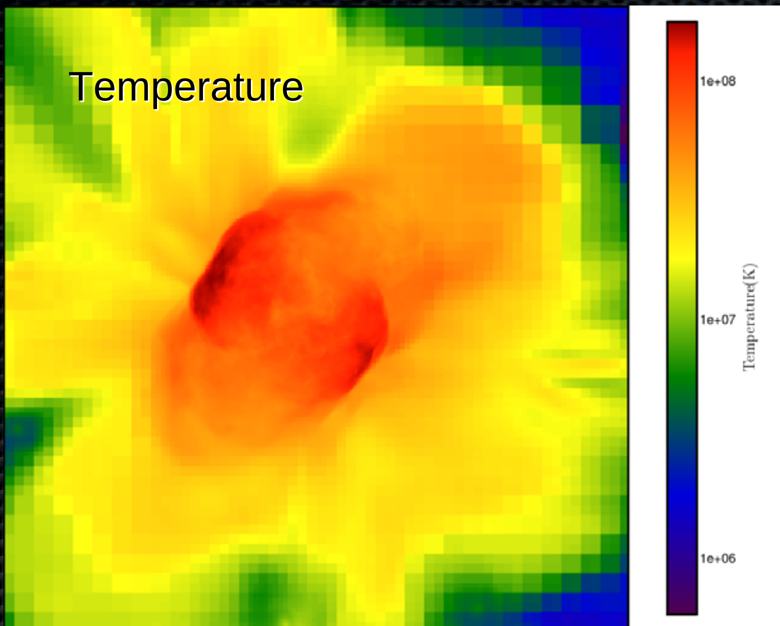
# Relic Cluster Radio Luminosity Function

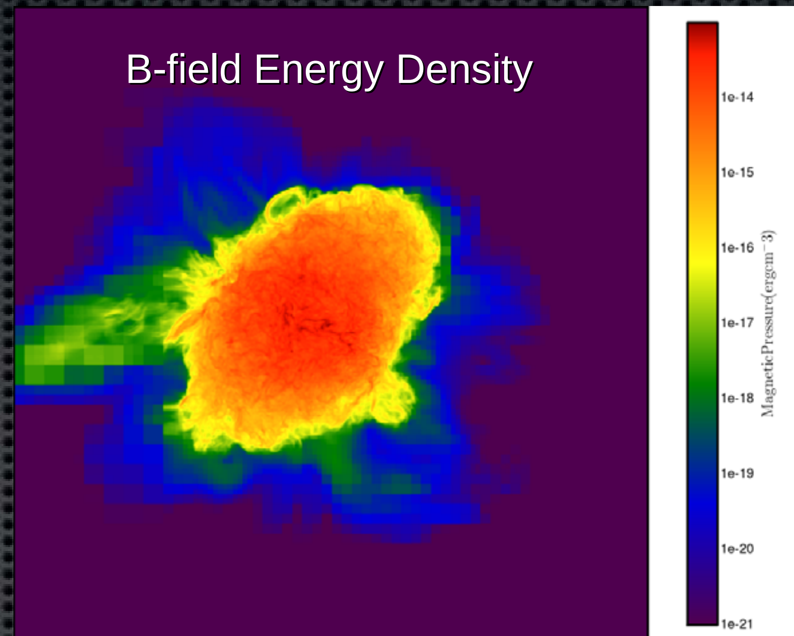


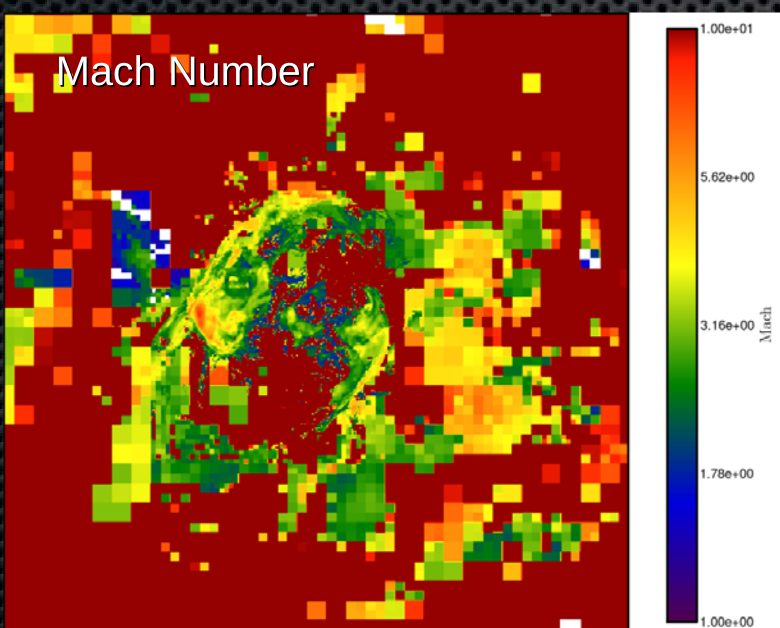

**=> We expect to find 140-400 radio relic clusters with $P_{1.4GHz} > 10^{25}$ W/Hz in surveys of 100 $deg^2$**

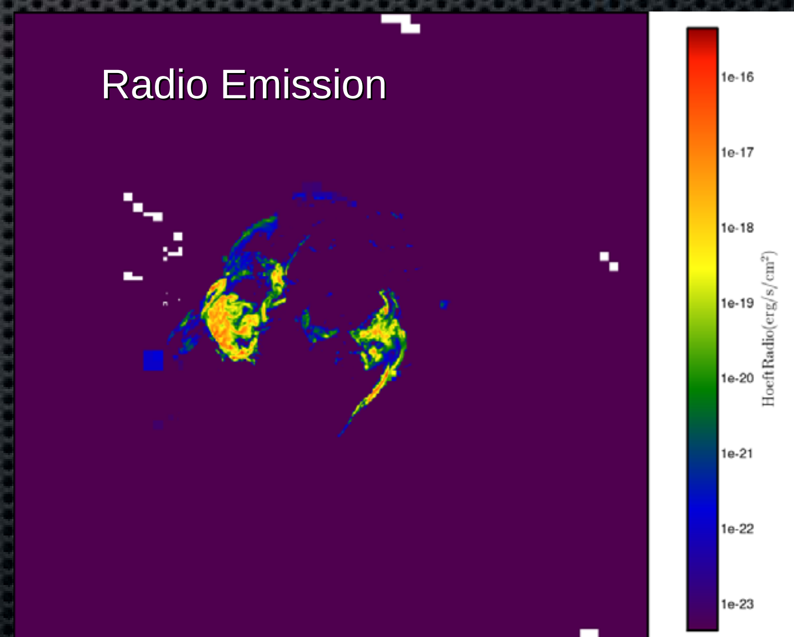
# On the Horizon: MHD

## with H. Xu & H. Li, LANL



# Summary & Conclusions

- We produced radio relics within a sample galaxy clusters from cosmological simulations with properties that resemble observed clusters.
- Radio/X-ray scaling relations agree with present observations.
- We predict factors of 10-100 increase in the numbers of steep-spectrum radio relics in clusters with $P_{1.4GHz} > 10^{25}$ W/Hz from large area surveys using new radio arrays (EVLA, LOFAR).