Radio relics and shock fronts in galaxy clusters

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Outline

1) Radio relics: observations and theory

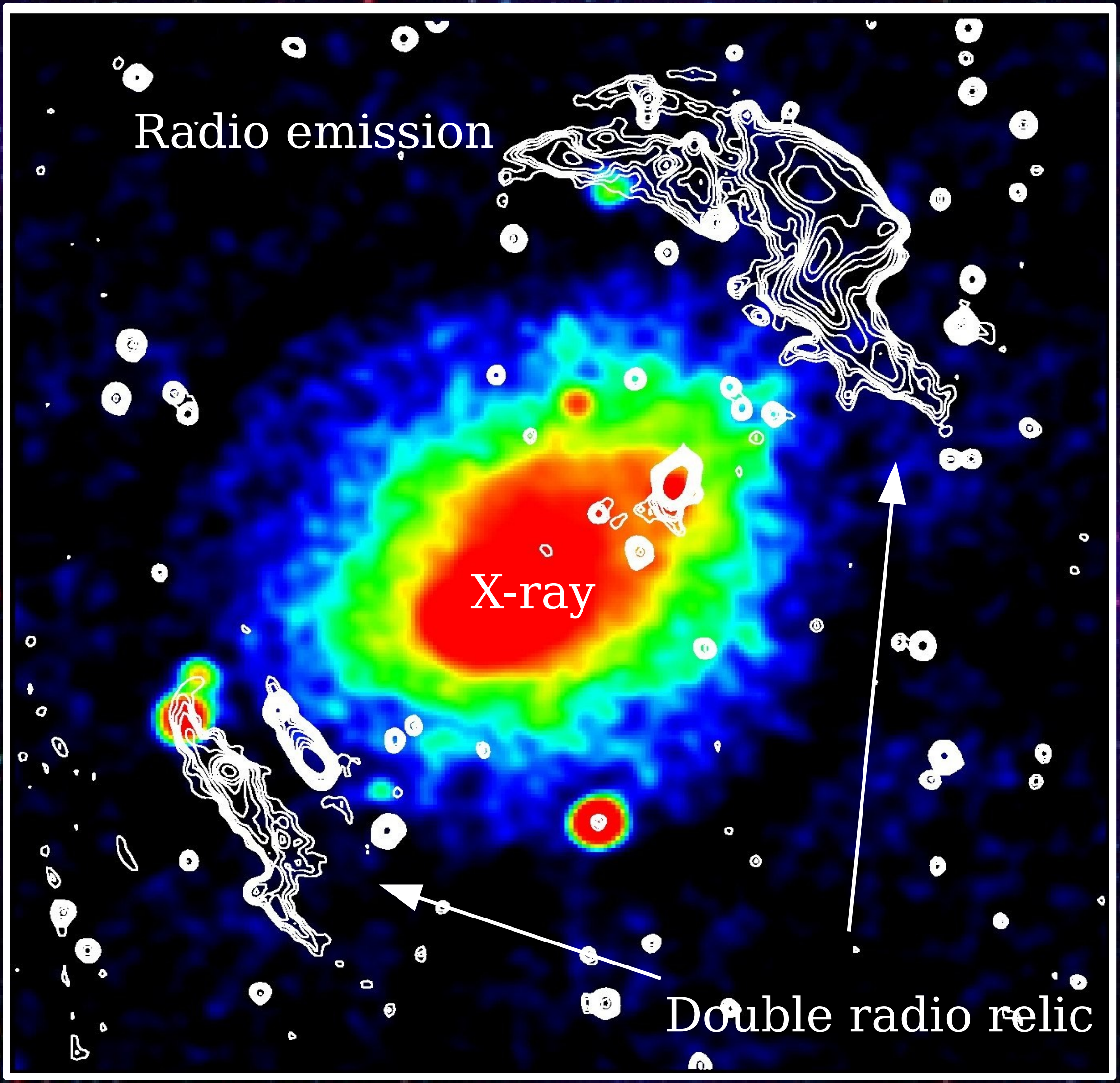
2) Simulations and radio relic model

3) Radio power scalings vs. galaxy cluster sample

4) Summary

Radio relics: observations and theory

Introduction to “radio relics”



Abell 3667
(Röttgering et al. 1997)

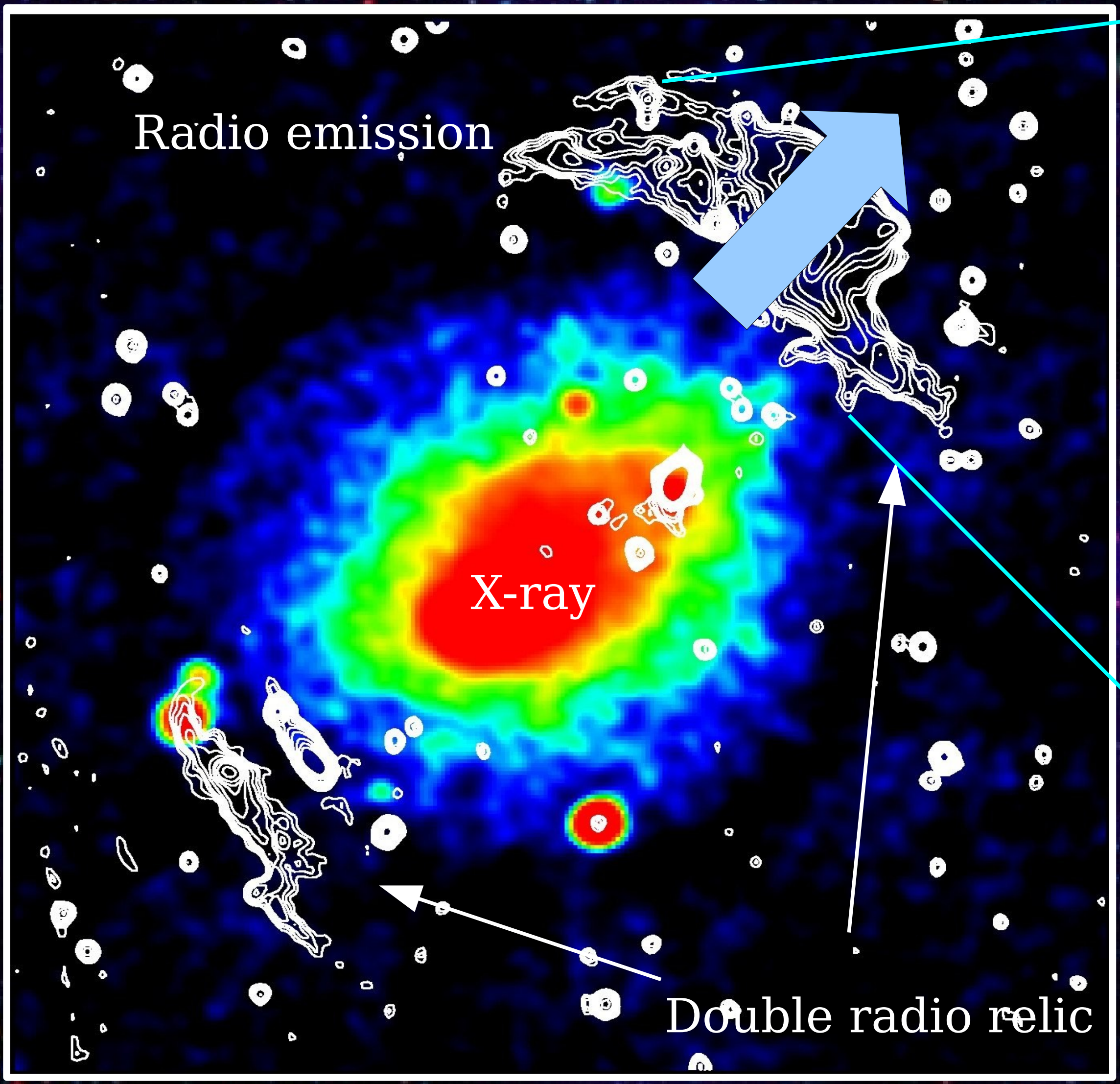
* Diffuse radio emission located in cluster periphery
* Extended sources (~Mpc)
* No optical counterpart
* Not associated with any particular radio source

Disturbed X-ray morphology:
Relics associated to perturbed galaxy clusters

↓

Merger shocks

Introduction to “radio relics”



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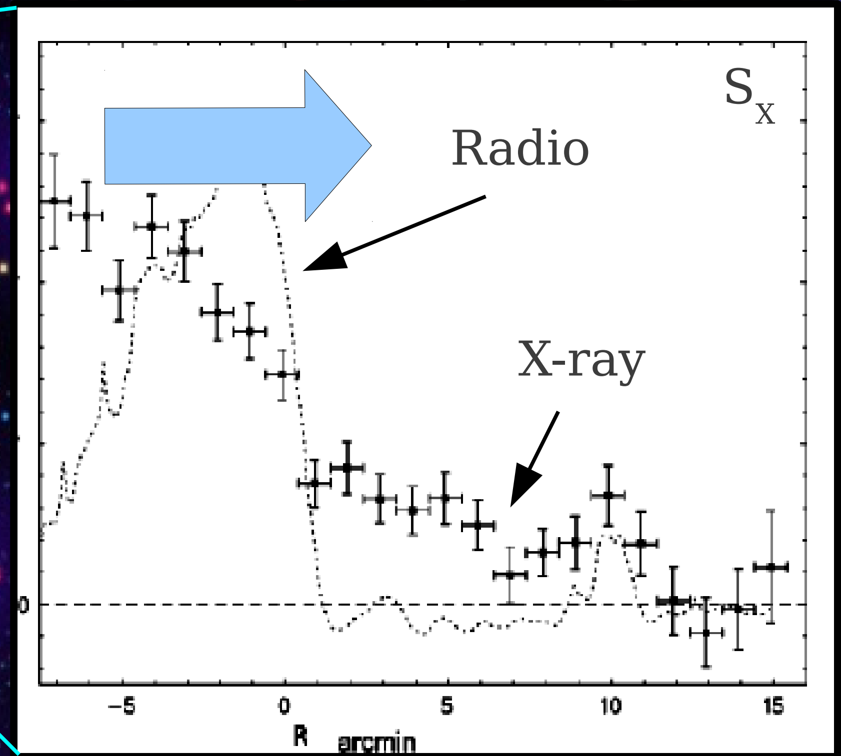
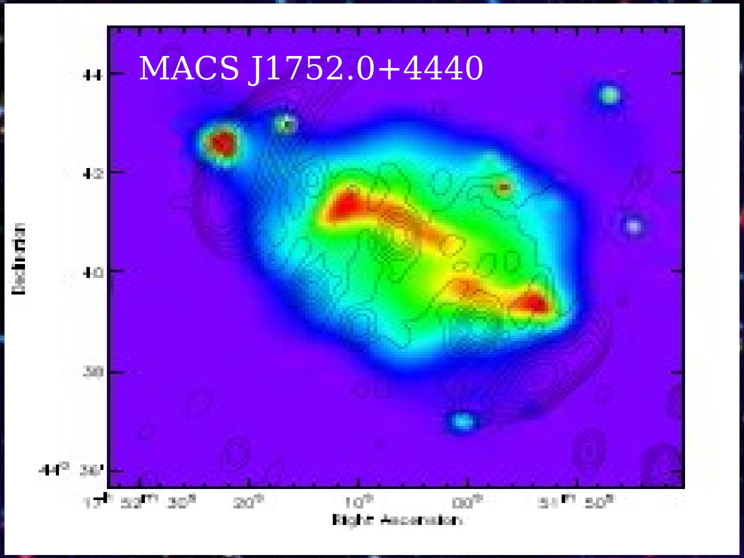


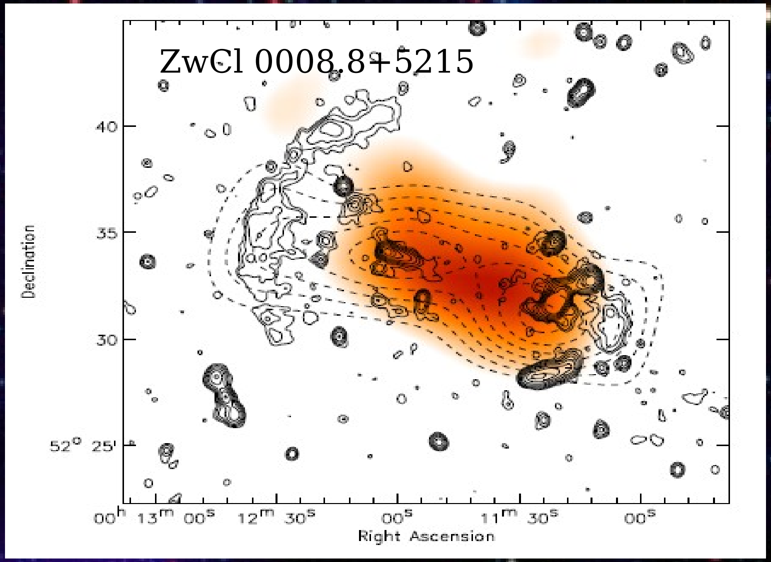
(Finoguenov et al. 2010)

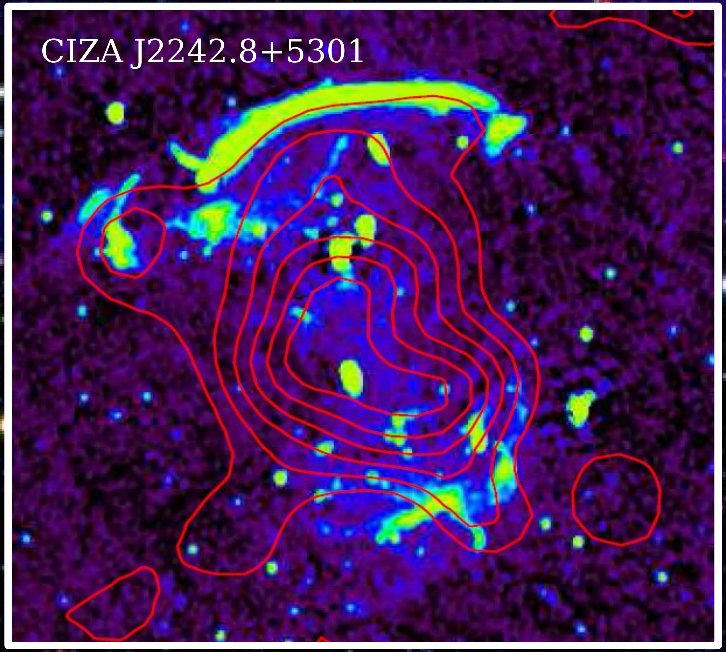
* X-ray thermal emission would imply a jump in density and temperature

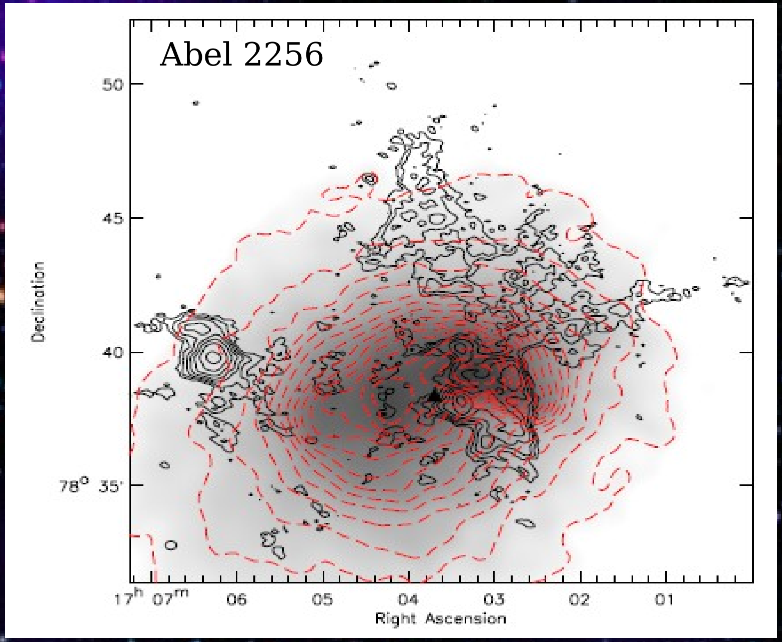
* Could be explained as a shock front of Mach number M~2

Relic observations (van Weeren et al. 2010, 2011, 2012)

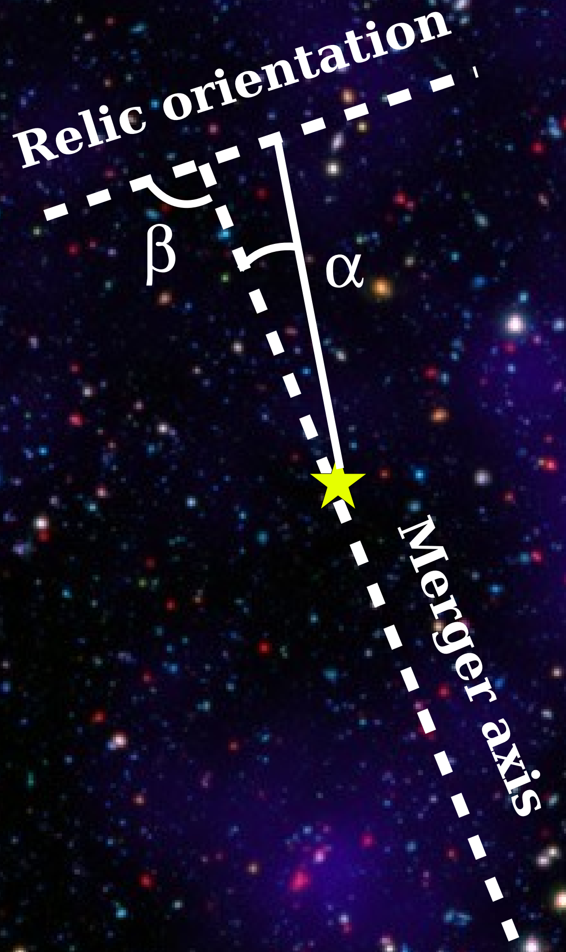








Is this scenario valid in general?



Merger axis: major axis of X-ray distribution

α: angle between merger axis and line connecting cluster and relic centers

β: angle between relic orientation and merger axis

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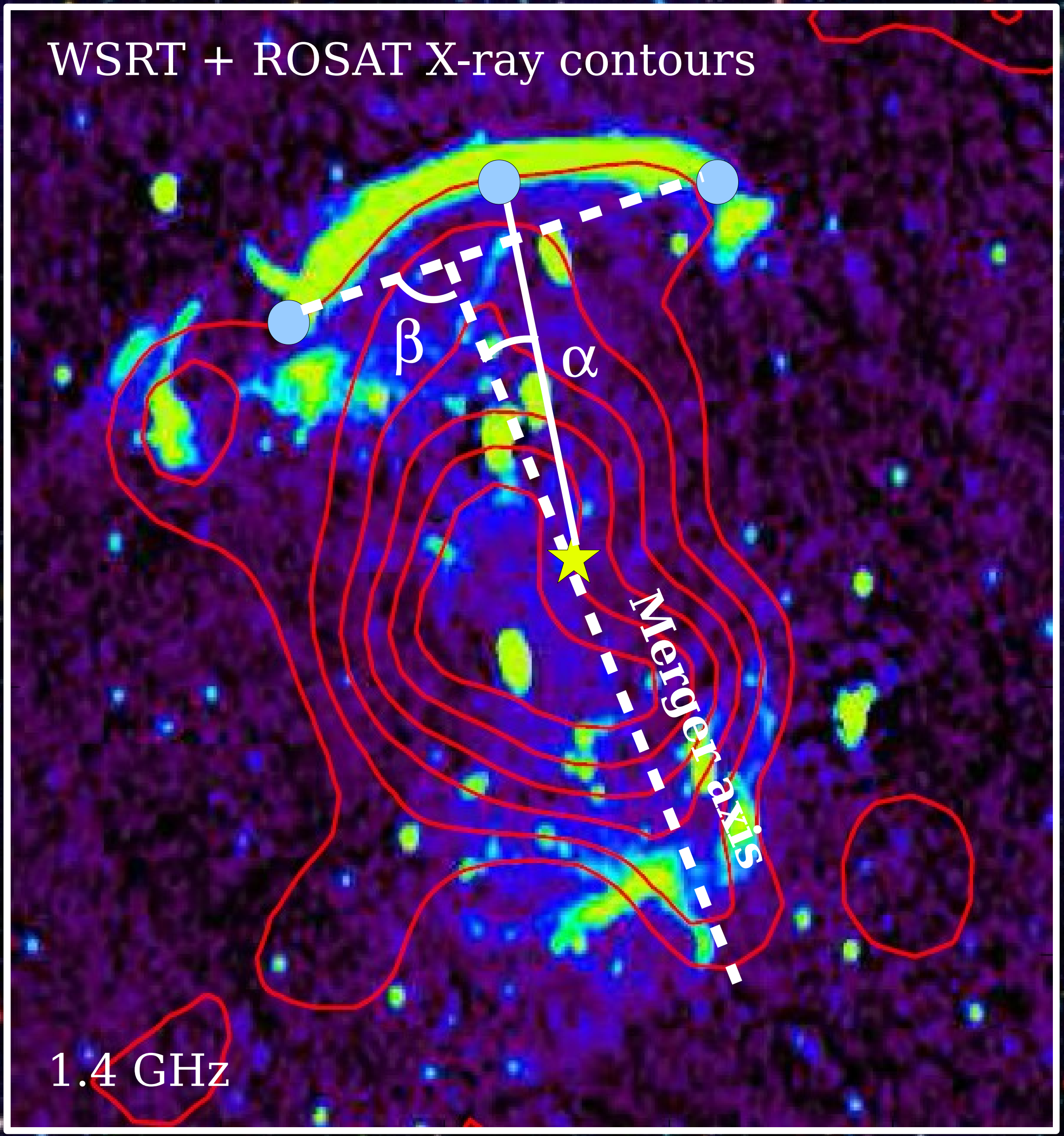

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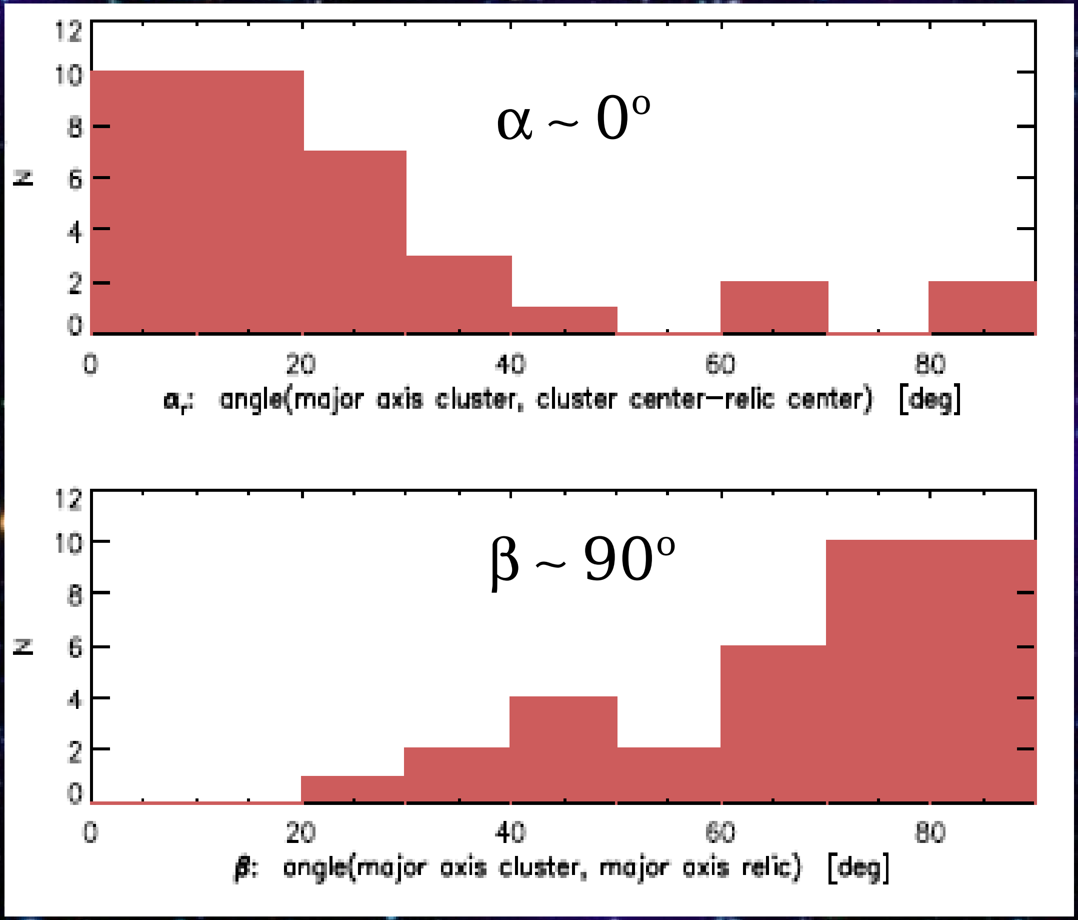


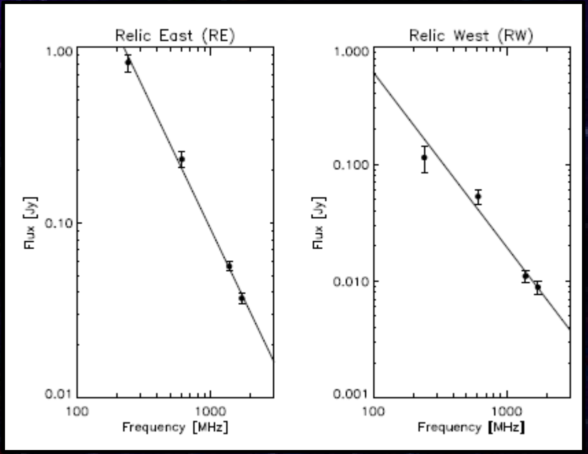
* Sample of ~35 relics

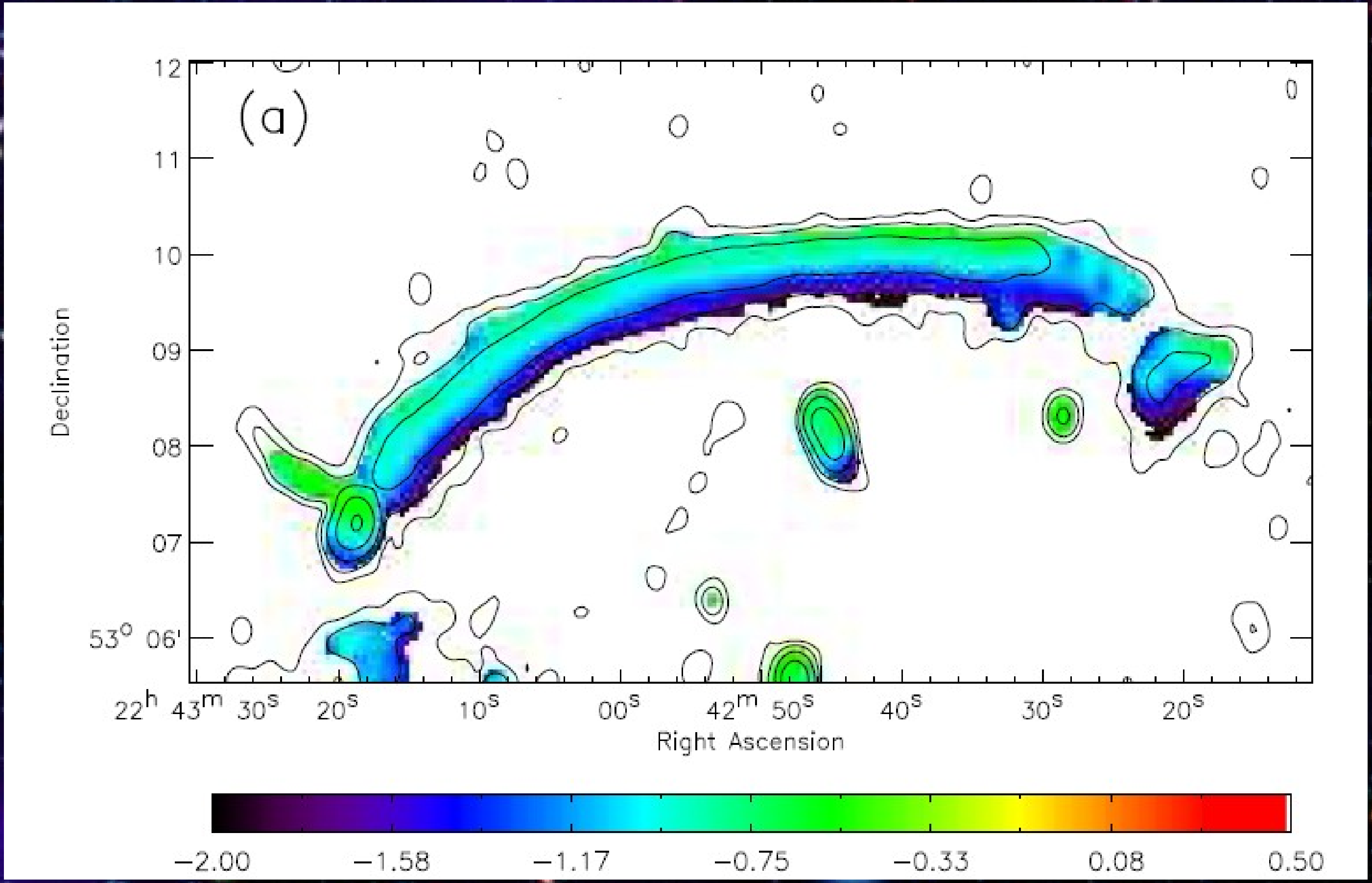
* Angles tend to cluster around $\alpha \sim 0^o$ and $\beta \sim 90^o$

* Consistent with relics tracing shock waves formed along the merger axis of clusters

(van Weeren, Brueggen, Roettgering, Hoeft, Nuza & Intema, 2011)

The radio relic emission: spectral index





* $S(\nu) \propto \nu^{-\alpha}$ (spectral index)

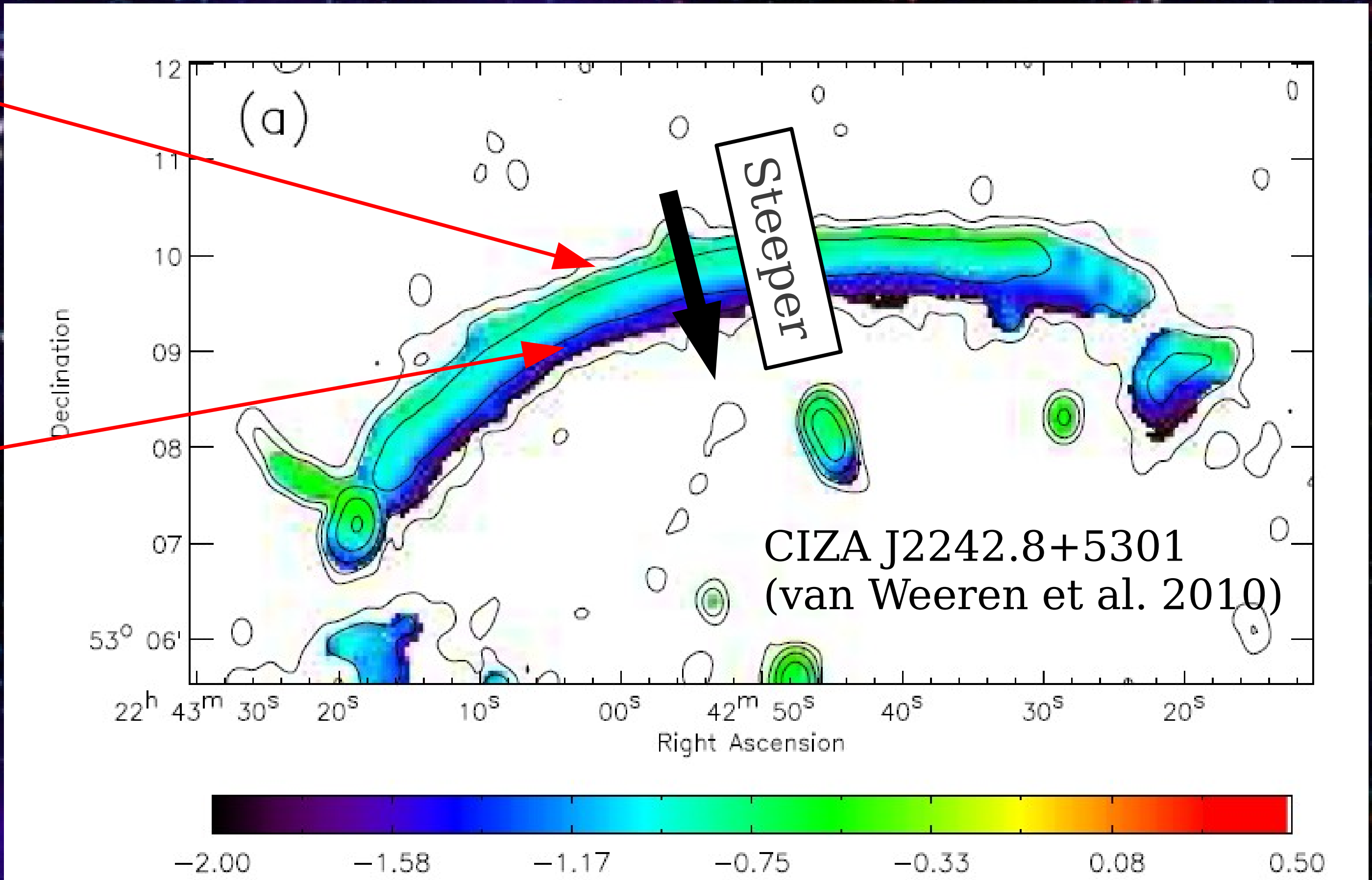
* Radio relic spectrum suggests non-thermal electron population

Spectral index gradient across the relic

The radio relic emission: spectral index

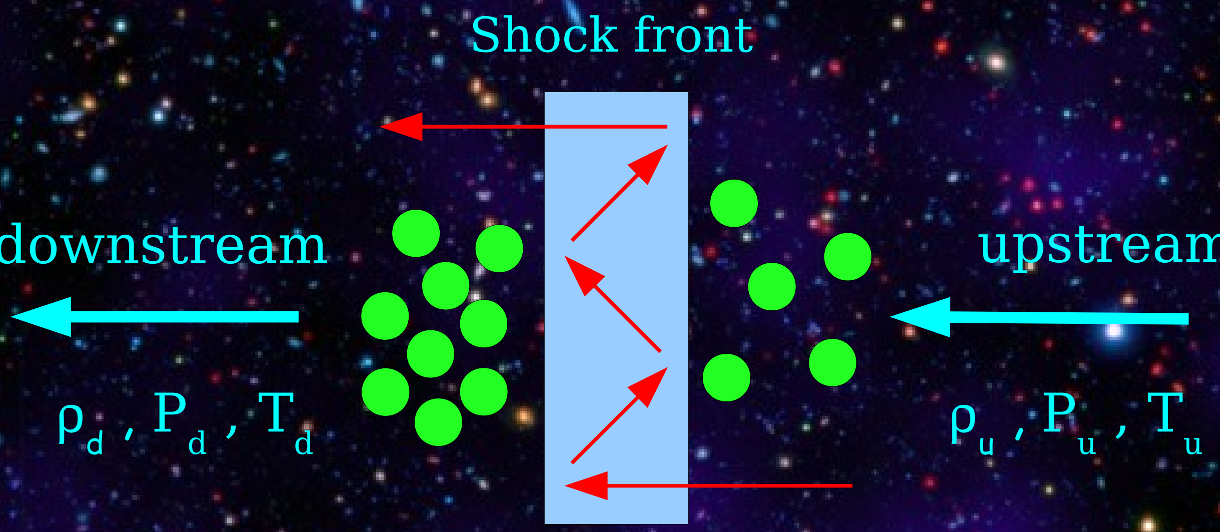
* Injection spectrum consistent with diffusive shock acceleration (DSA)

* Integrated spectrum consistent with DSA plus synchrotron and inverse Compton looses



Spectral index gradient across the relic

Diffusive shock acceleration (DSA)



DSA at shock waves

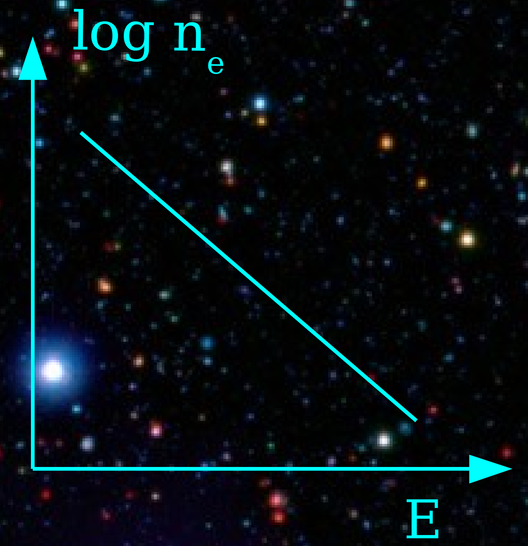
Compression ratio

$$r = \frac{\rho_d}{\rho_u}$$

* Electrons are accelerated by multiple shock crossings

* DSA predicts a supra-thermal electron distribution given by $n_e \propto E^{-s}$ (s related with spectral index)

* For Mach numbers M ~ 2 – 10 : $s = \frac{r+2}{r-1} \geq 2$

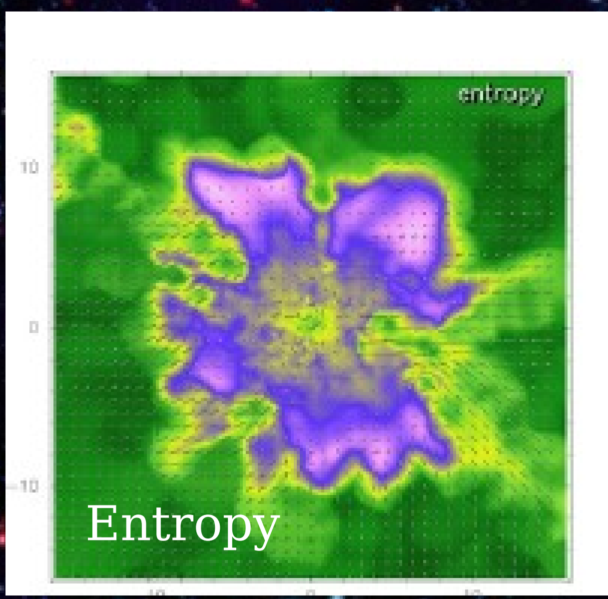


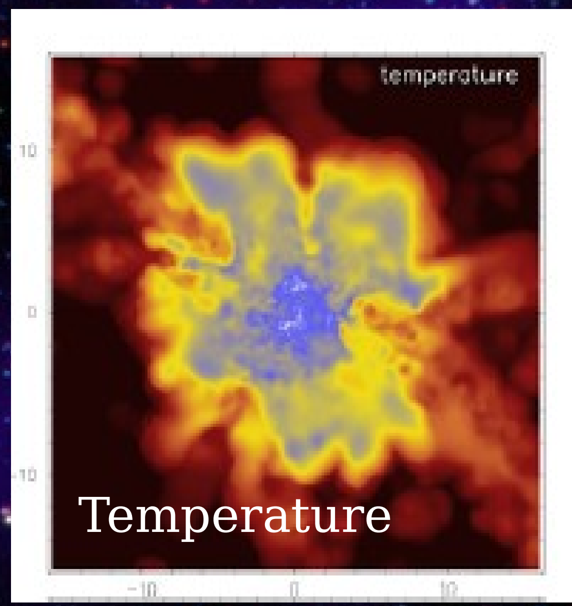
Simulations and radio relic model

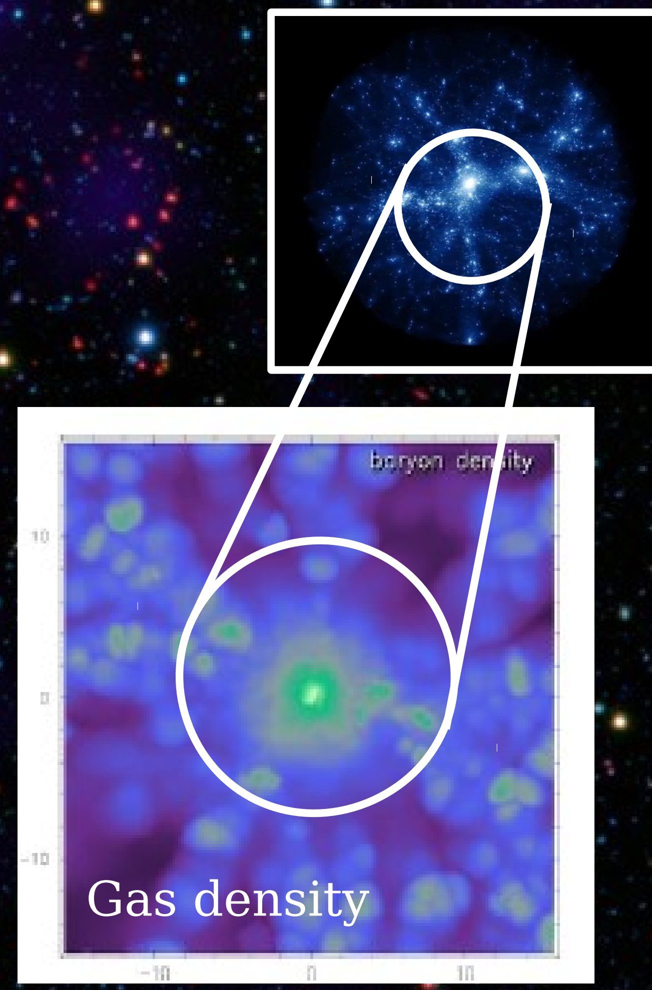
Simulate relics in a cosmological volume

<u>MareNostrum Universe:</u> (Gottloeber & Yepes 2007)

* L = 500 h^{-1} Mpc
* N = 2 x 1024^3 (dark matter + gas)
* Non-radiative GADGET-2 run
* WMAP-1 cosmology







(Hoeft et al. 2008; Nuza et al. 2012)

Finding shocks fronts

* Identify galaxy clusters in the MareNostrum Universe

* Evaluate pressure gradients (shock normal)

* Evaluate:

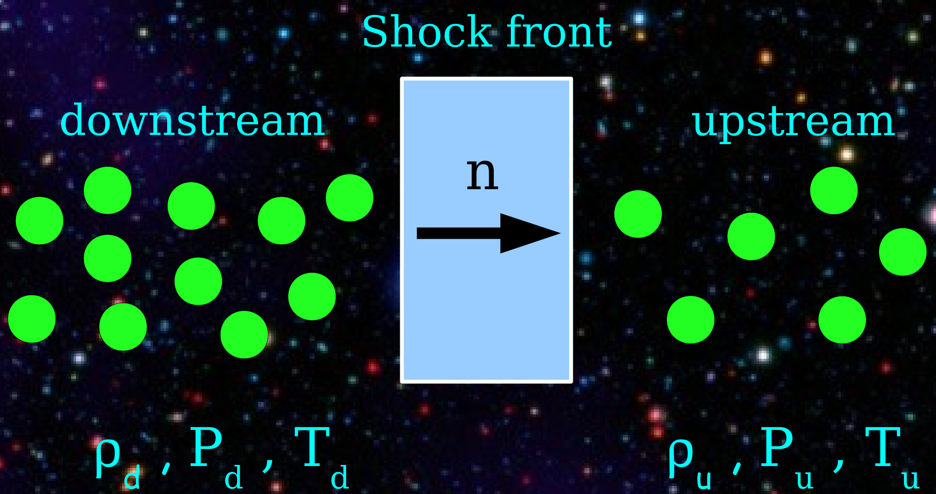
  1) Velocity jump

  2) Pressure and density jump

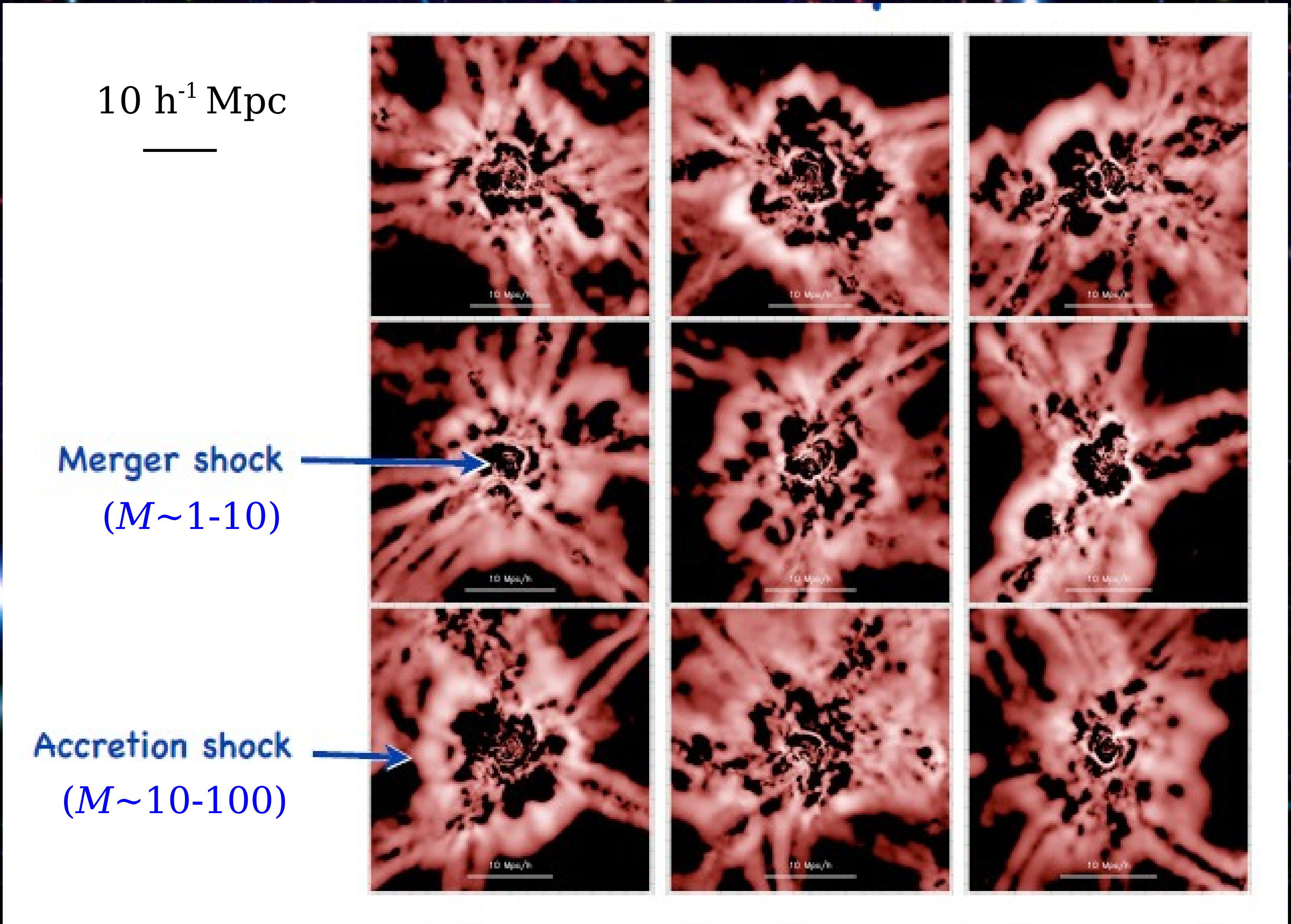
  3) Entropy jump

* Select candidate particles for shocks

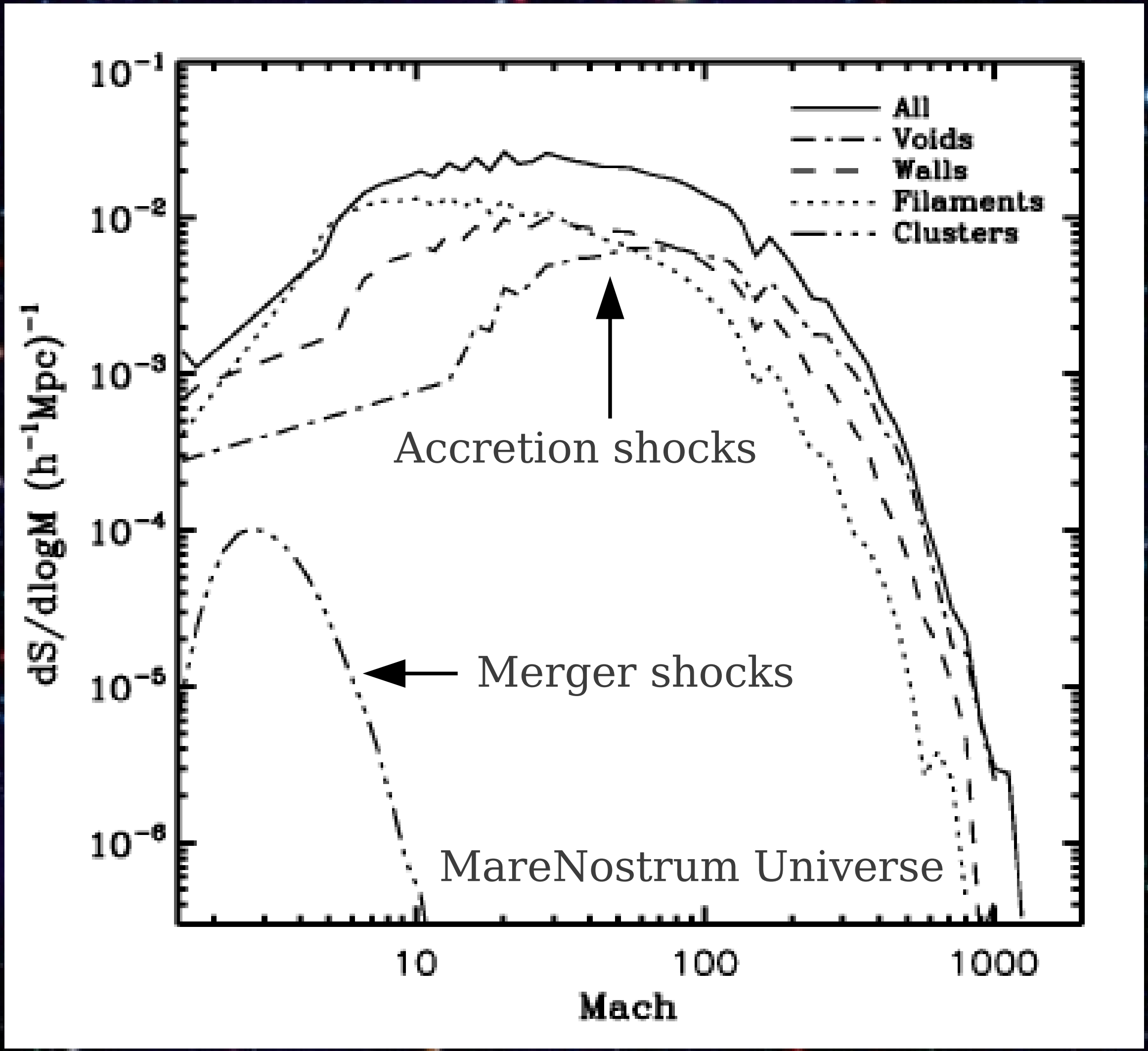
* Estimate Mach number



Shocks fronts in galaxy clusters



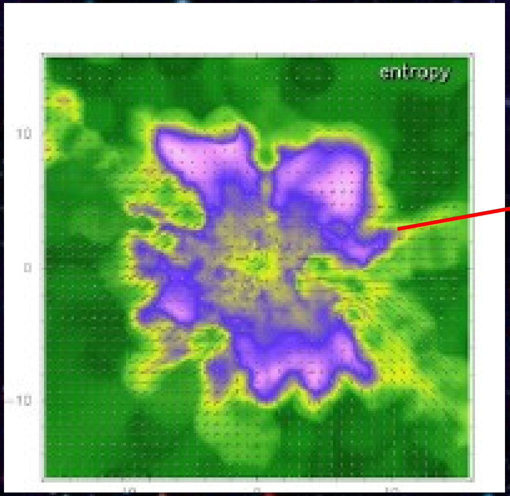
Shocks fronts: environmental distribution



(Araya-Melo et al. 2012)

The radio emission model

1) Apply shock finder to galaxy clusters



2) Radio emission (DSA + cooling) (Hoeft & Brueggen 2007)

$$\frac{dP(\nu_{\rm obs})}{d\nu} = 6.4\times10^{34}\,\frac{\rm erg}{\rm s\,Hz}\,\frac{A}{\rm Mpc^2}\,\frac{n_e}{10^{-4}\rm cm^{-3}}\,\frac{\xi_e}{0.05}\left(\frac{\nu_{\rm obs}}{1.4\,\rm GHz}\right)^{-\frac{s}{2}} \times\left(\frac{T_d}{7\,\rm keV}\right)^{\frac{3}{2}}\frac{\left(\frac{B}{\mu\rm G}\right)^{1+\frac{s}{2}}}{\left(\frac{B_{\rm CMB}}{\mu\rm G}\right)^2+\left(\frac{B}{\mu\rm G}\right)^2}\,\Psi(\mathcal{M},T)$$

ξ_e : fraction of energy injected at the shock wave that goes into the acceleration of non-thermal electrons («1%)

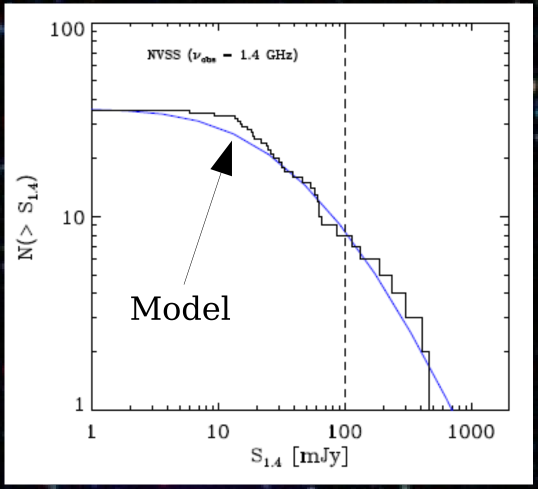
Ψ: dependence with Mach number (and temperature)

3) B-field: assume power-law scaling with electron density (Bonafede et al. 2010)

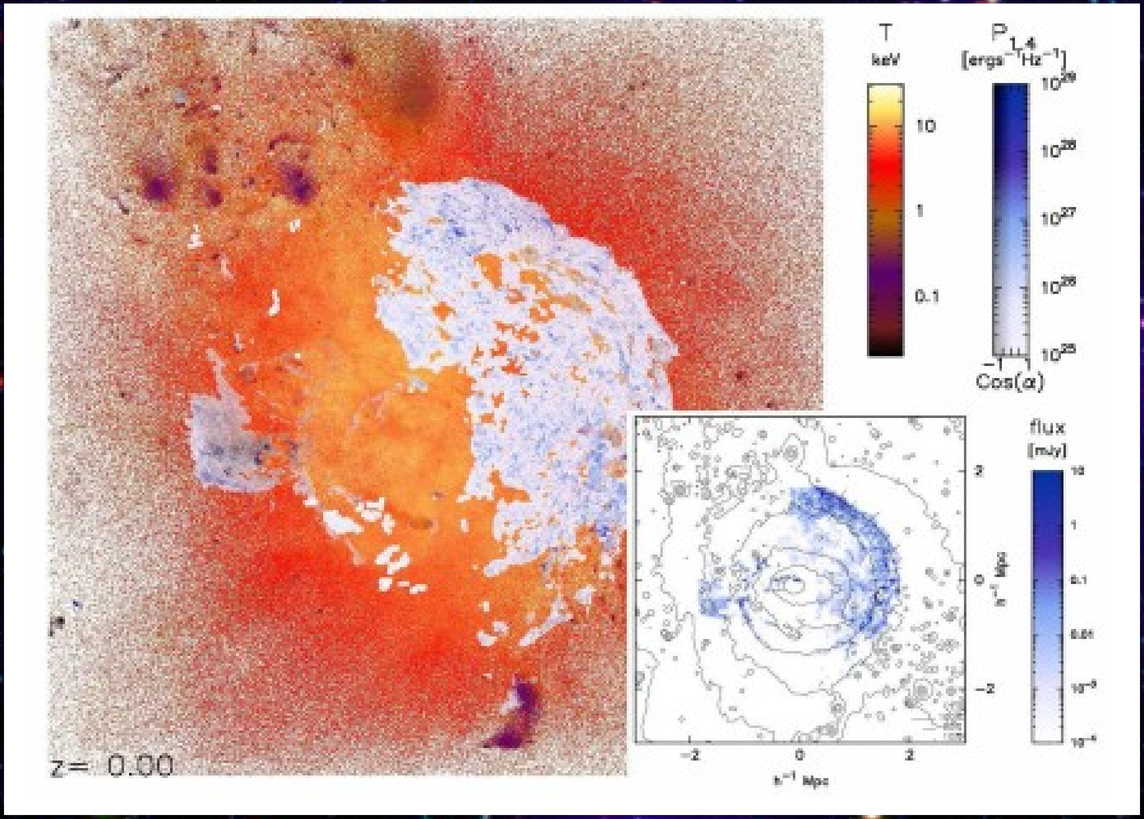
4) Derive radio power scalings from simulation:

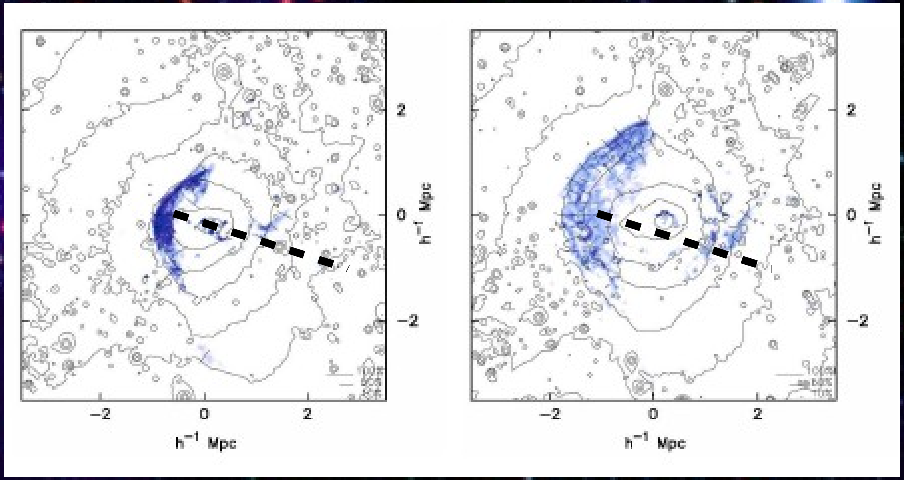
$$P_{\rm mean} \propto M^{2.5} \propto (1+z)^{3.4} \propto \nu_{\rm obs}^{-1.2}$$

5) Normalize to observed (NVSS) relic sample



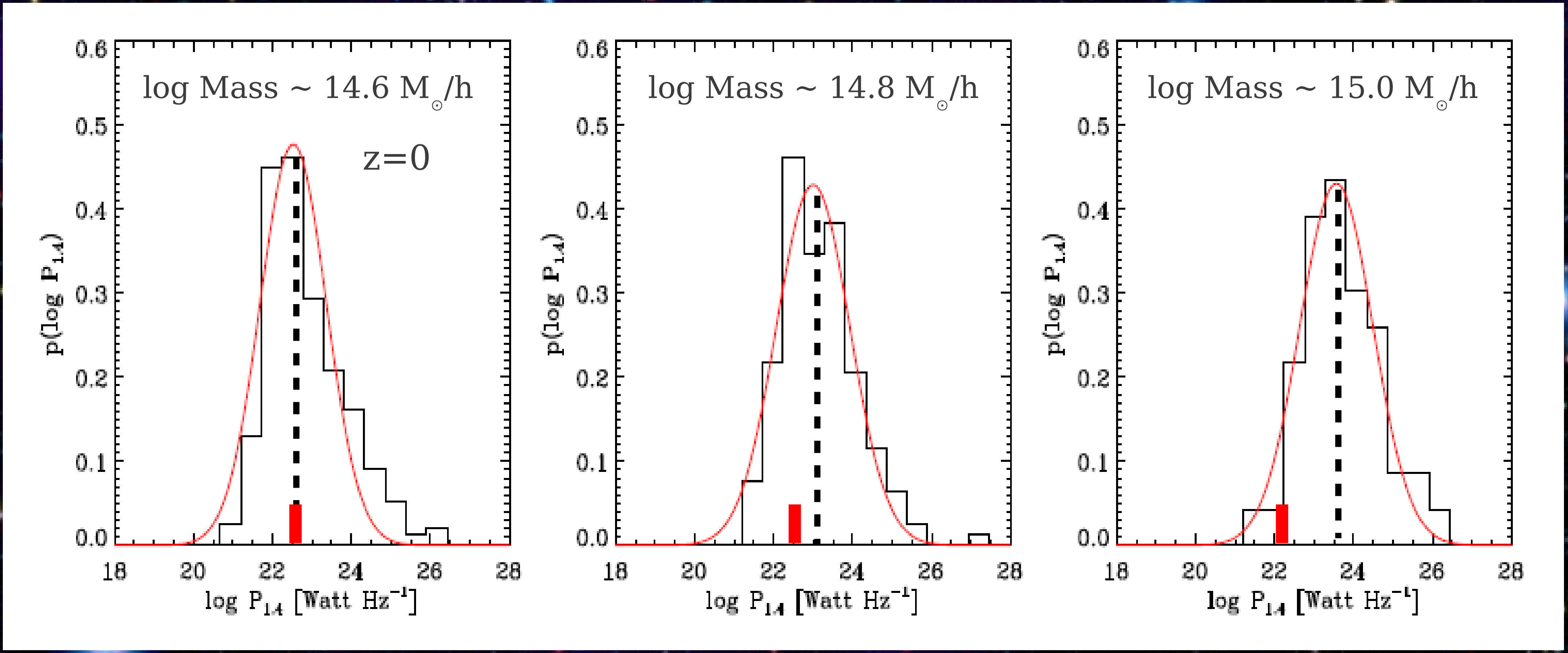
The radio emission model: output





(Hoeft, Nuza et al. 2011)

Radio relic power scalings



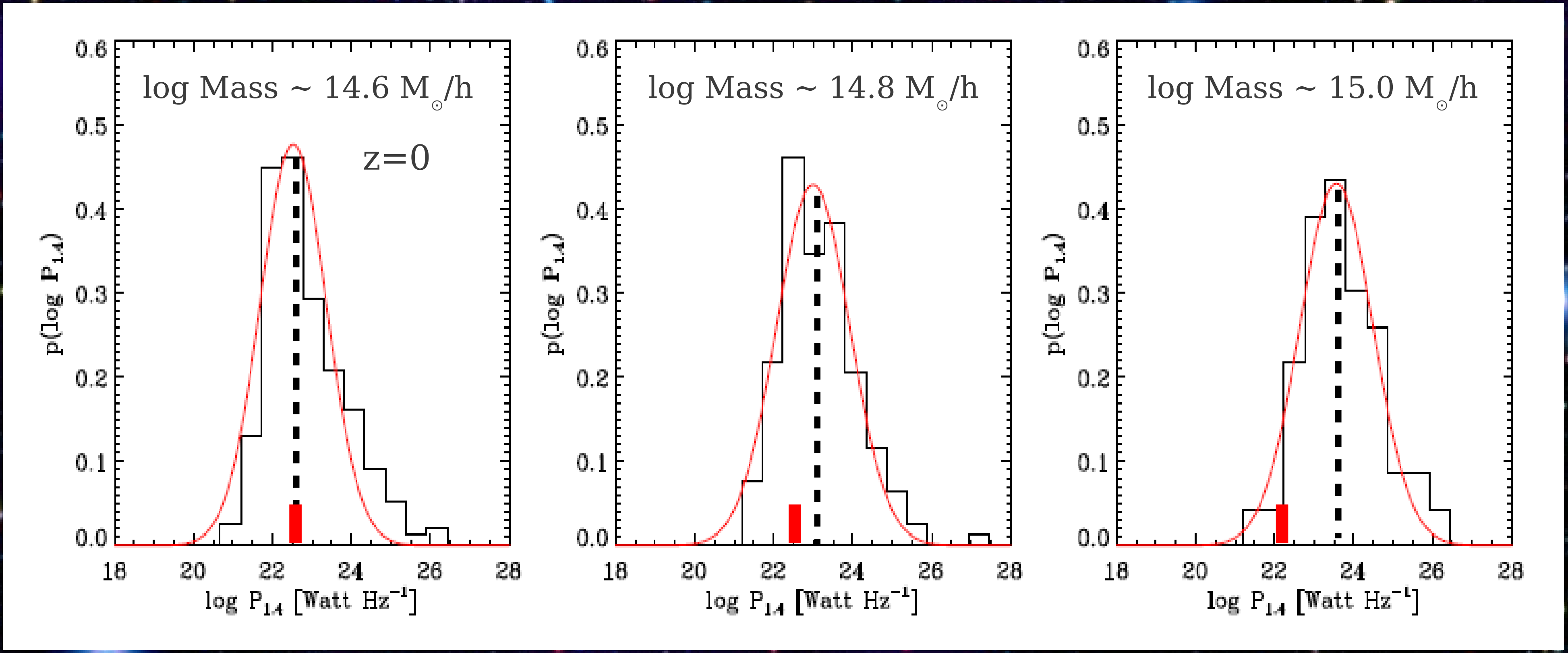
* Radio power “probability distribution”:

$$p(P_\nu, M, z) \propto \exp\left\{-\frac{(\log P_\nu - \log \bar{P}_\nu)^2}{2\sigma_P^2}\right\}$$

* Systematic trend of log <P> to higher luminosities as cluster mass increases

(Nuza et al. 2012)

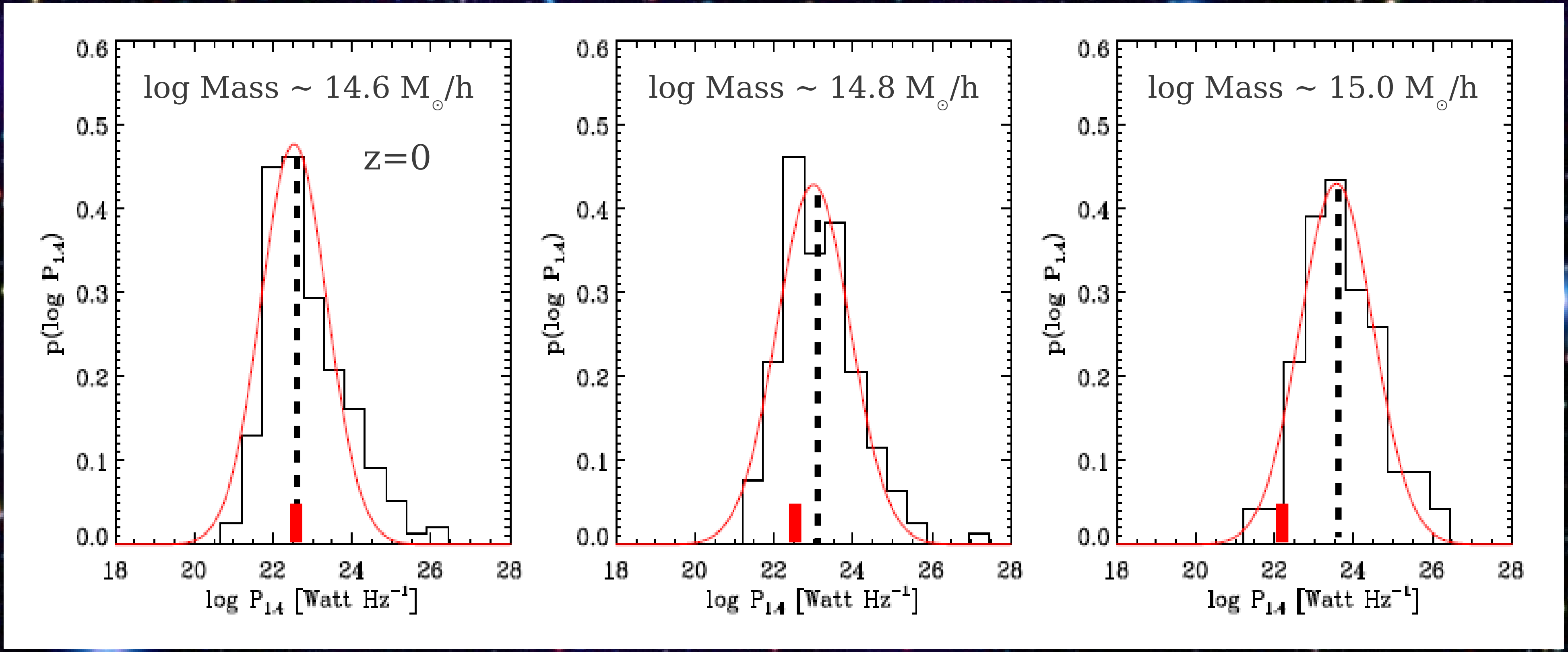
Radio relic power scalings



* We can model the mean radio power scaling:

$$\log \langle P \rangle = \log (P_0) + C_M \times \log (M)$$

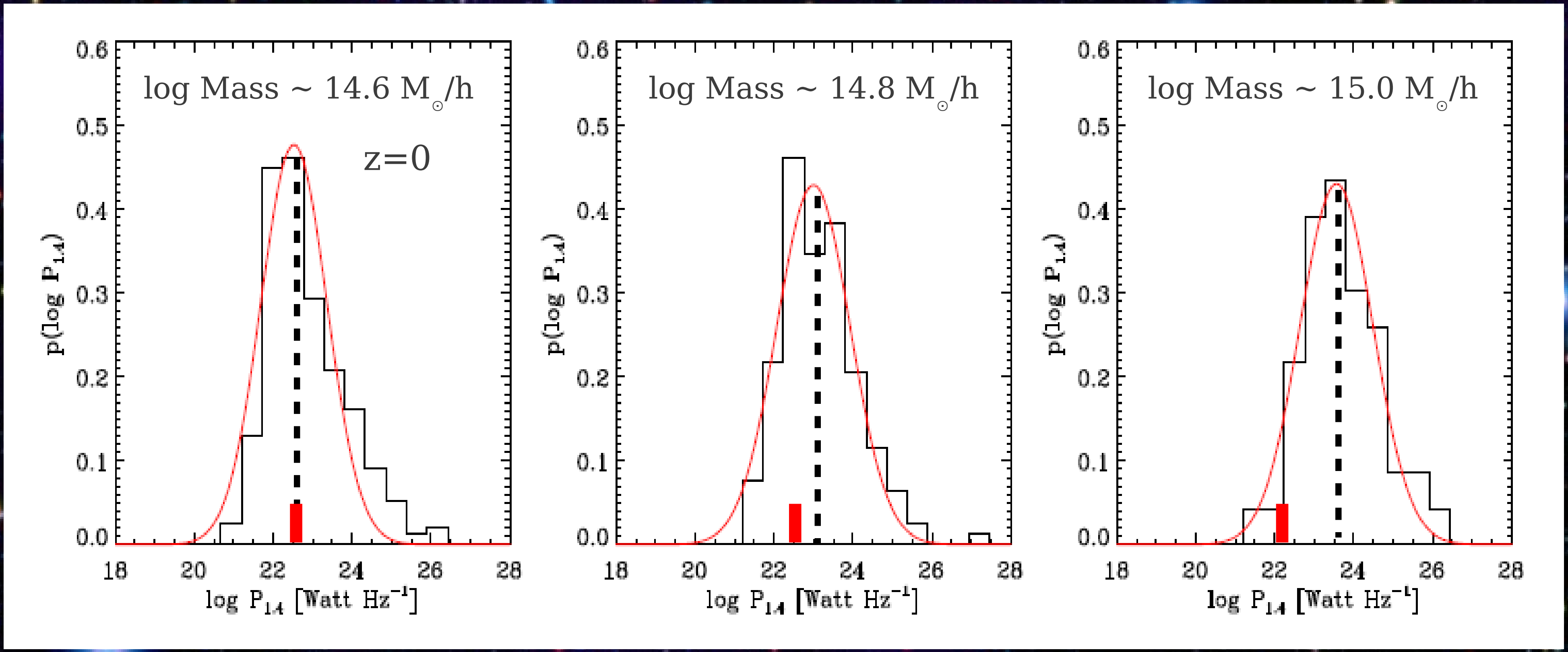
Radio relic power scalings



* We can model the mean radio power scaling:

$$\log \langle P \rangle = \log (P_0) + C_M \times \log (M) + C_z \times \log (1+z) + C_\nu \times \log (\nu_{obs})$$

Radio relic power scalings

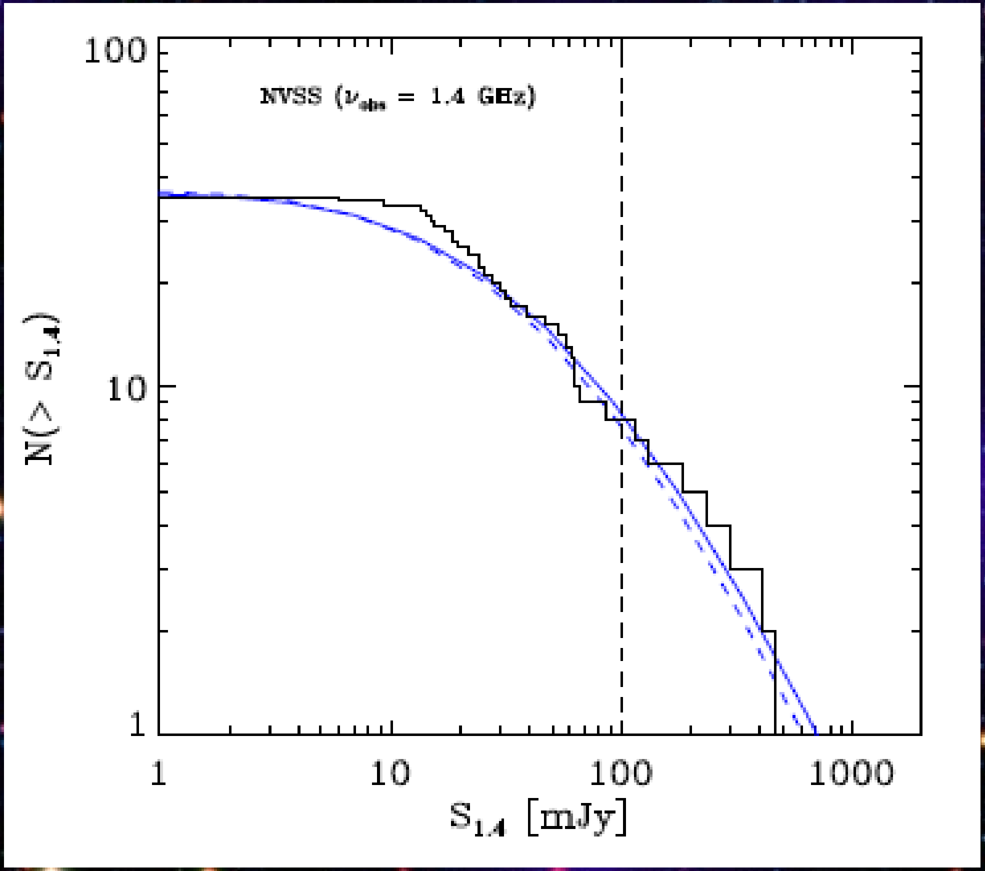


$$\log \langle P \rangle = \log (P_0) + C_M \times \log (M) + C_z \times \log (1+z) + C_\nu \times \log (\nu_{obs})$$

Normalization

Simulation

Normalization to observed counts

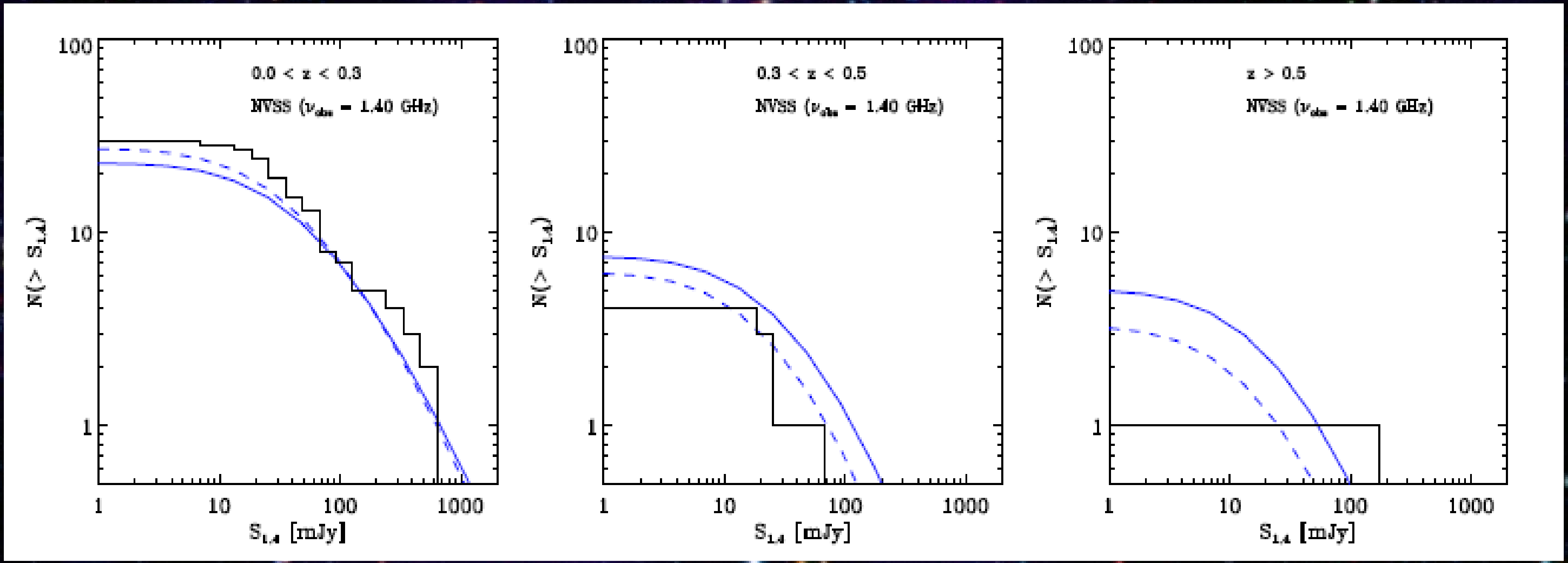


* Radio relic "probability distribution" ⊗ Mass function → Radio relic LF

* Normalize to known relic sample ("NRAO VLA Sky Survey")

* Low efficiency required (ξ_e < 0.1%)

Counts as a function of redshift

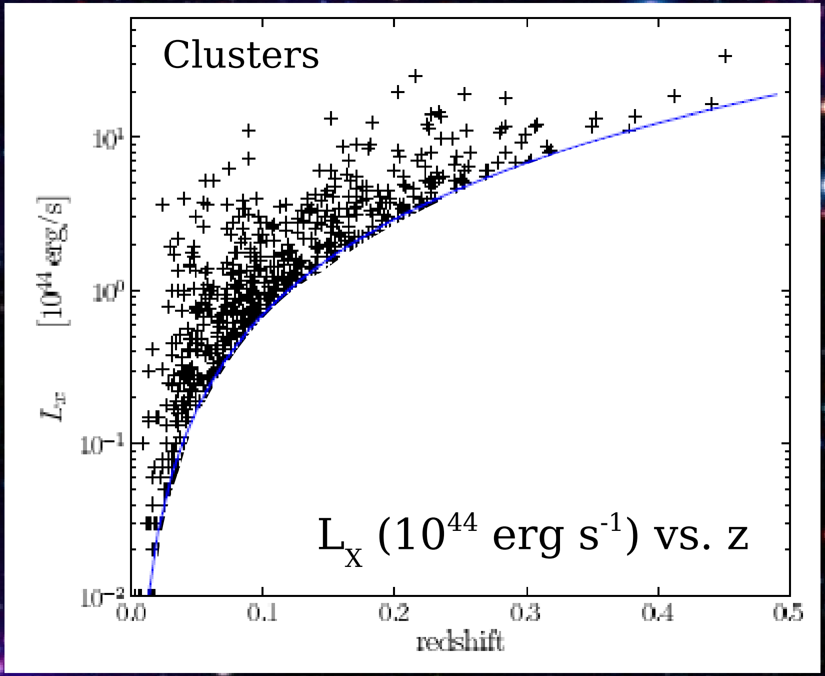


* Potential diagnostics for probing radio relic models within a cosmological context

Model scalings vs. observations: What about observed cluster X-ray luminosity and redshift distributions?

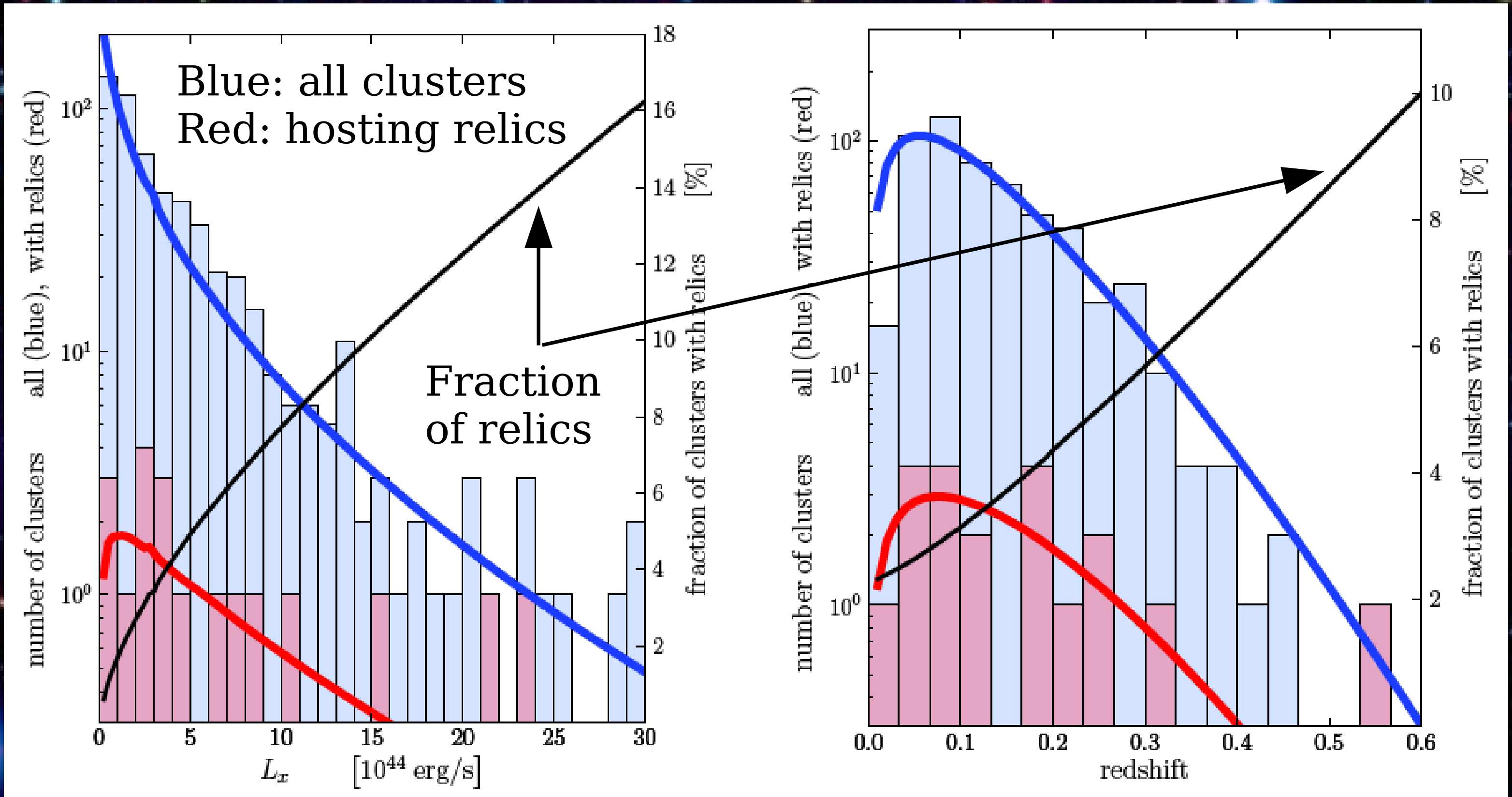
Galaxy cluster sample: NORAS/REFLEX

* NORAS+REFLEX cluster sample with F(0.1-2.4 keV) > 3.0 x 10^{-12} erg s^{-1} cm^{-2} (Boehringer et al. 2000, 2004): 540 clusters above this flux, 18 with relics
* Above the flux limit the sample is approximately complete (covered sky fraction ~ 35%)



(van Weeren, Brueggen, Roettgering, Hoeft, Nuza & Intema, 2011; Nuza et al. 2012)

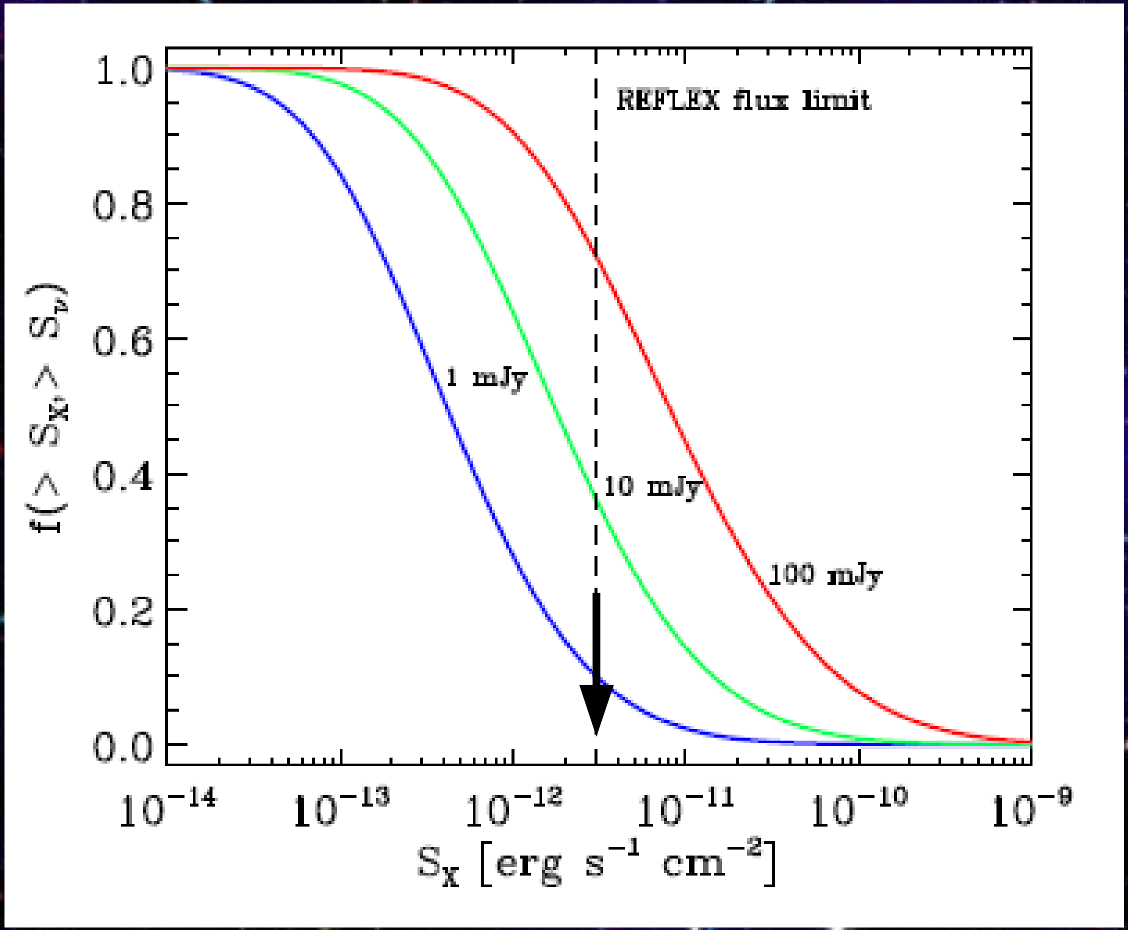
X-ray limited cluster sample: N(L_X) & N(z)



* Fraction of relics: Hint for an increase for higher X-ray luminosities and redshift
* More massive clusters host more powerful radio relics
* Related with the increase in the merger rate at higher redshifts

(van Weeren, Brueggen, Roettgering, Hoeft, Nuza & Intema, 2011; Nuza et al. 2012)

The need for deeper X-ray surveys

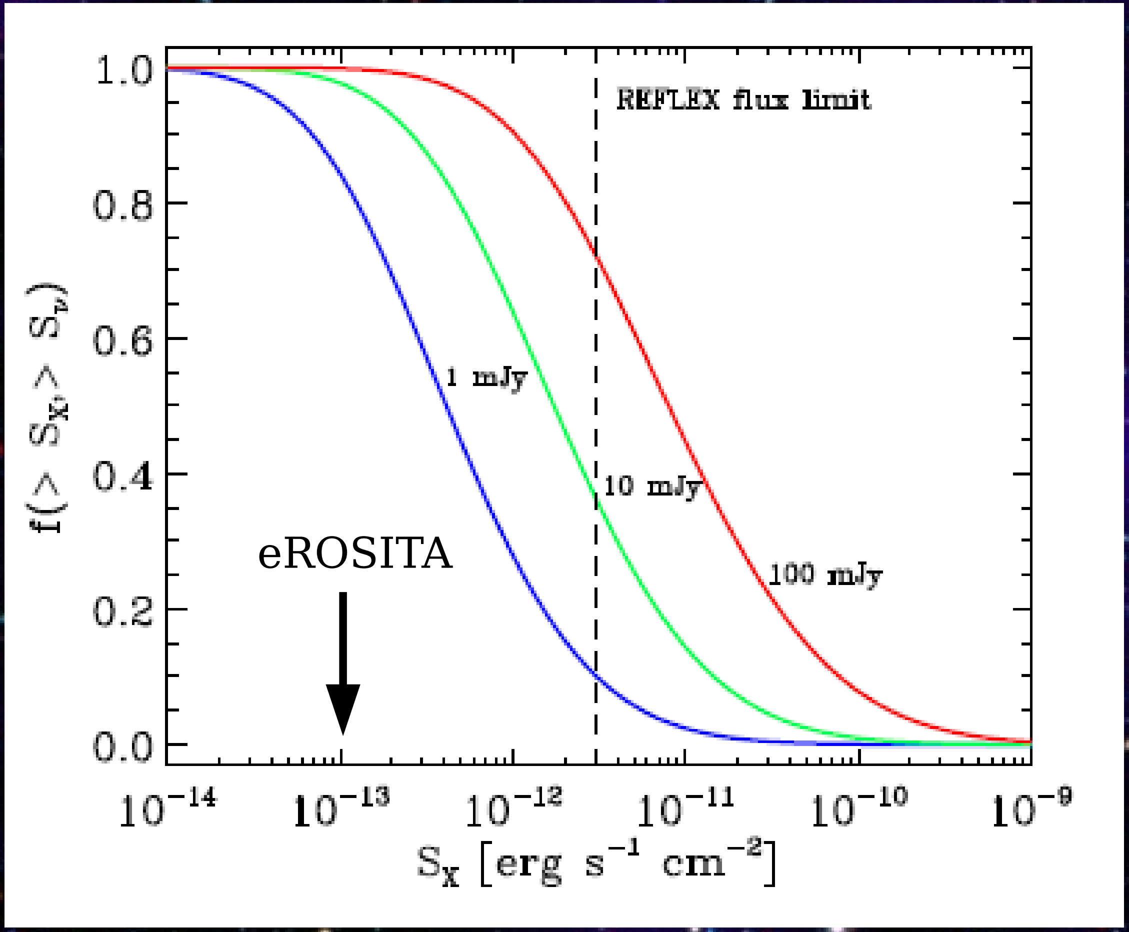


Cumulative fraction of relics above a given radio flux as a function of survey X-ray flux limit

* To identify relics cross-correlation of diffuse radio emission with galaxy clusters is crucial

(Nuza et al. 2012)

The need for deeper X-ray surveys



Cumulative fraction of relics above a given radio flux as a function of survey X-ray flux limit

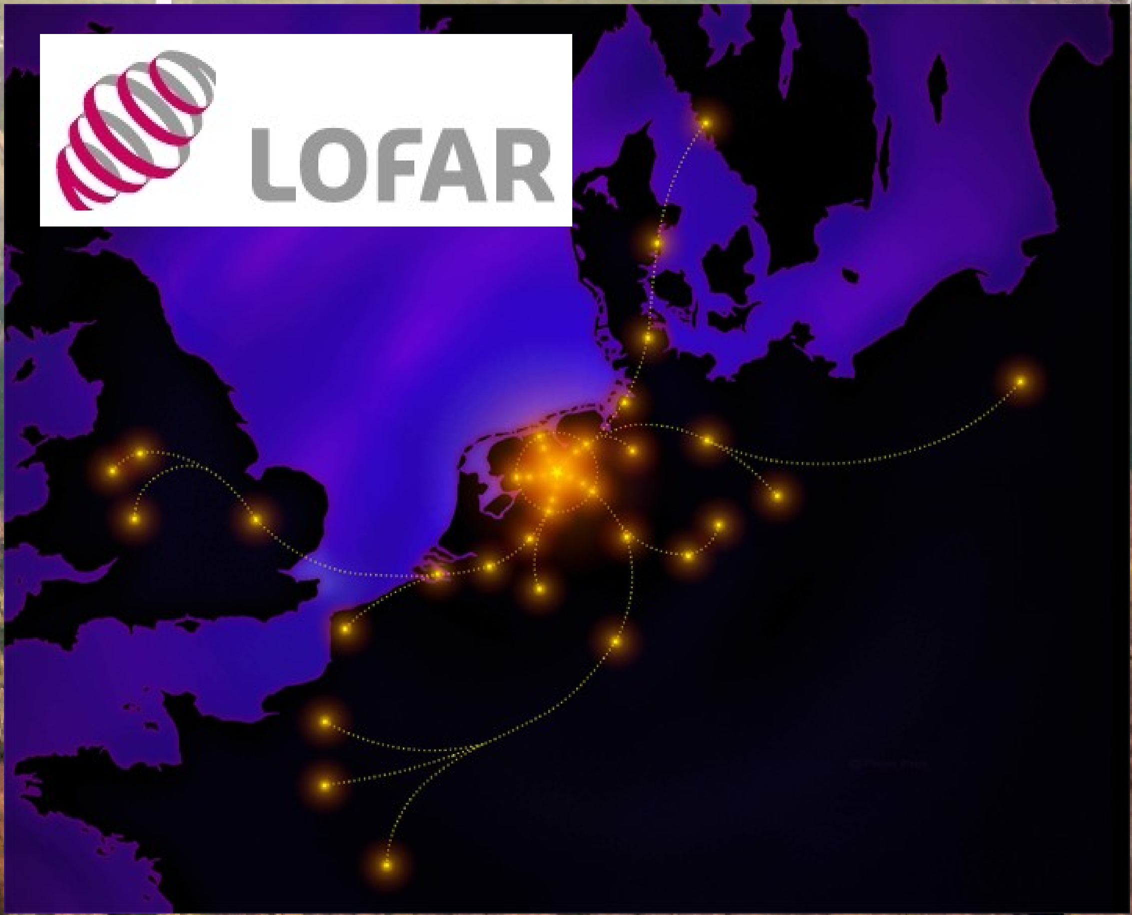
* To identify relics cross-correlation of diffuse radio emission with galaxy clusters is crucial

* Future radio surveys such as LOFAR are expected to detect hundreds of relics at ~1 mJy level

* This will require new extended X-ray cluster catalogs

(Nuza et al. 2012)

Future surveys...



Summary

* Radio relics are presumably generated in merger shocks where electrons get accelerated by DSA and cooled down due to synchrotron plus IC emission

* During cluster mergers shock waves form preferentially along the merger axis of the system

* We developed a radio relic model able to describe observational trends such as the increase in the fraction of relics for higher cluster X-ray luminosities and redshifts (larger shock fronts, higher Mach numbers and merger rates?)

* Cross-correlation with X-ray galaxy cluster surveys is crucial to identify relics. New surveys are required (e.g. LOFAR, eRosita, ...)

* Future work include:

  * Look for merger shocks in the MUSIC galaxy cluster sample
  * Improve the shock detection scheme and radio emission model
  * Include self-consistent magnetic fields
  * ...