Diffuse Radio Emission from Galaxy Clusters

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St. John's College
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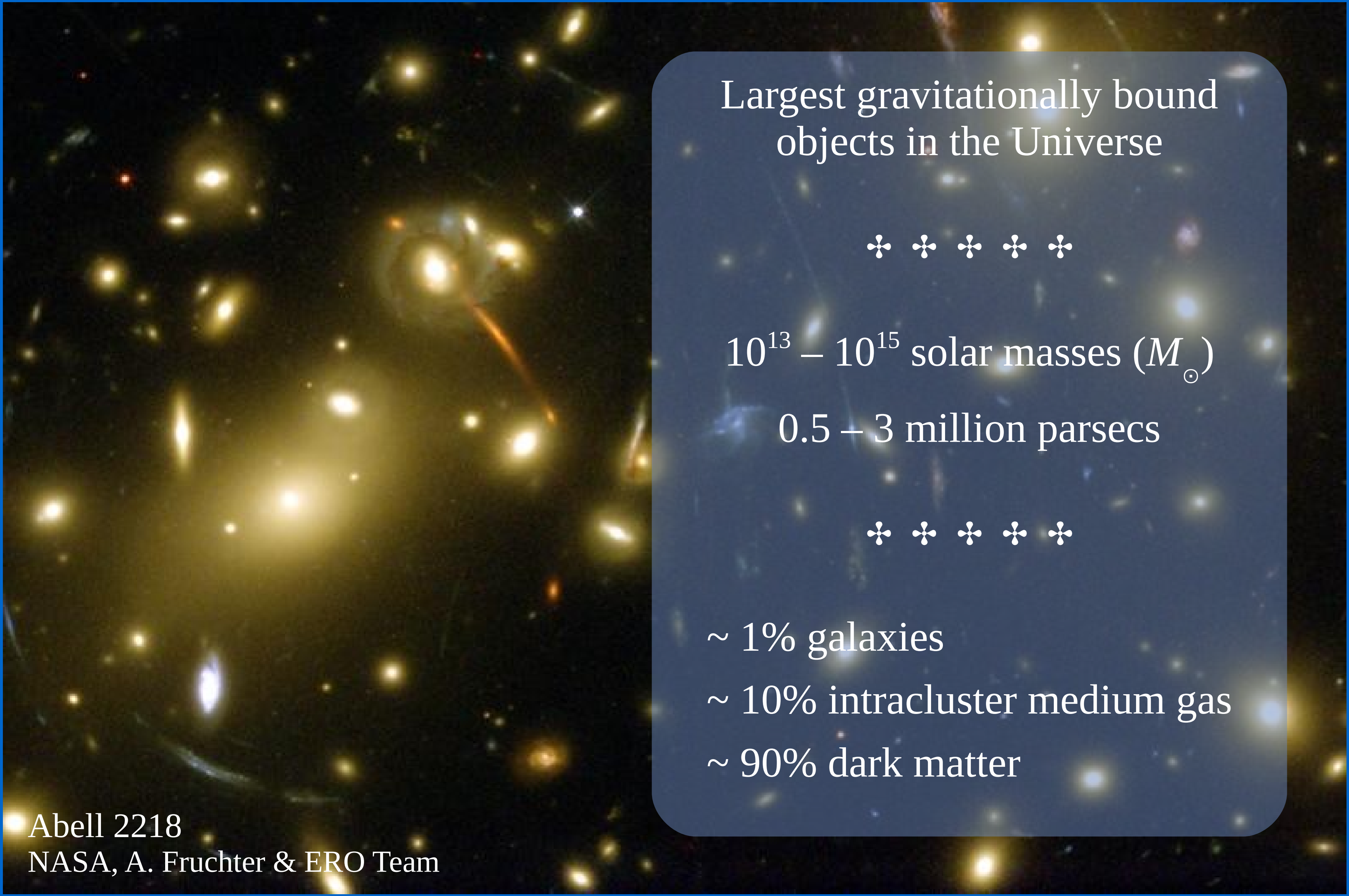
Clusters of galaxies



Largest gravitationally bound objects in the Universe

✣ ✣ ✣ ✣ ✣

$10^{13} – 10^{15}$ solar masses ($M_{\odot}$)

0.5 – 3 million parsecs

✣ ✣ ✣ ✣ ✣

~ 1% galaxies

~ 10% intracluster medium gas

~ 90% dark matter

Abell 2218
NASA, A. Fruchter & ERO Team

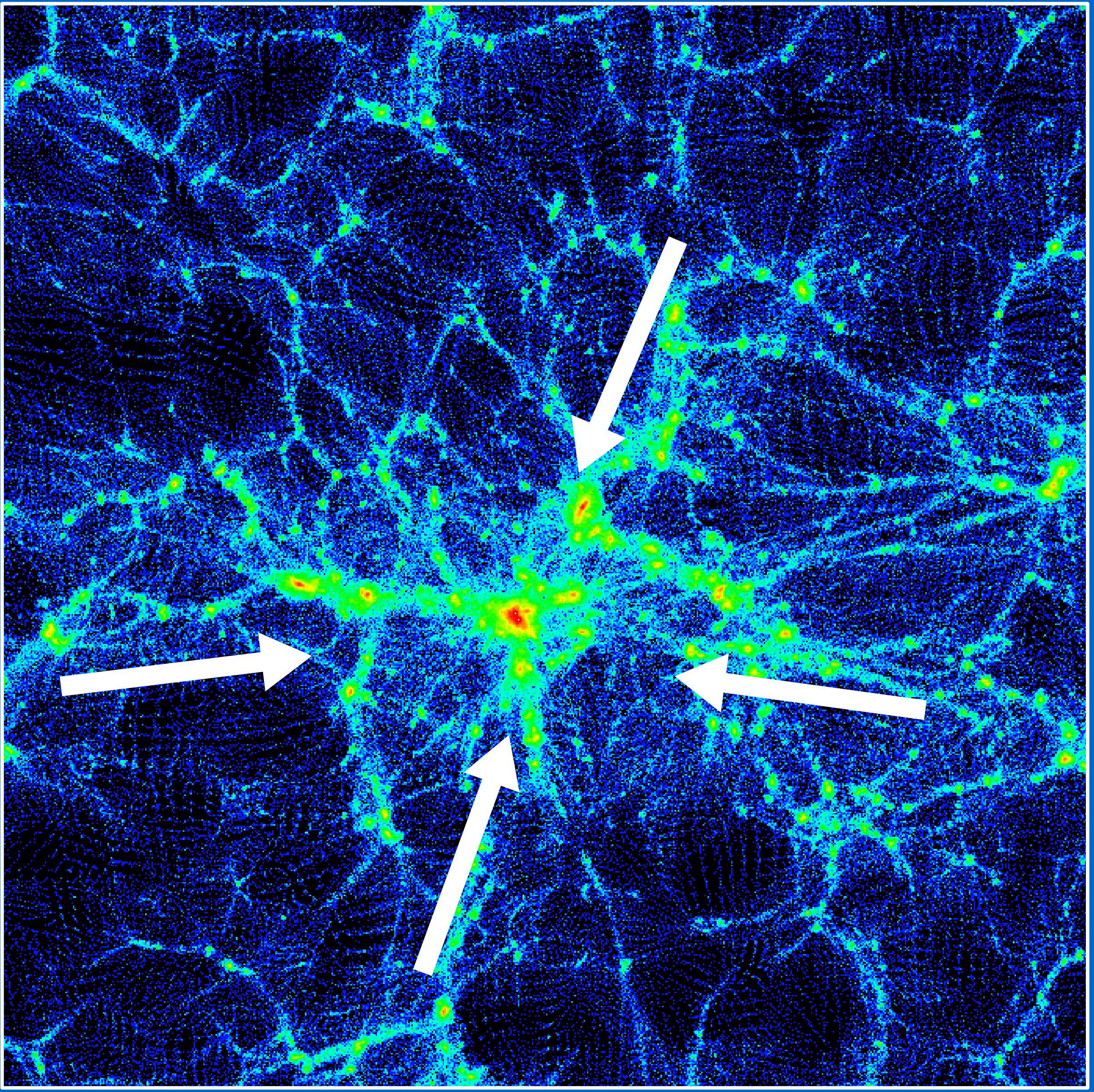
Clusters in cosmological context

Clusters form through merging and accretion of smaller objects

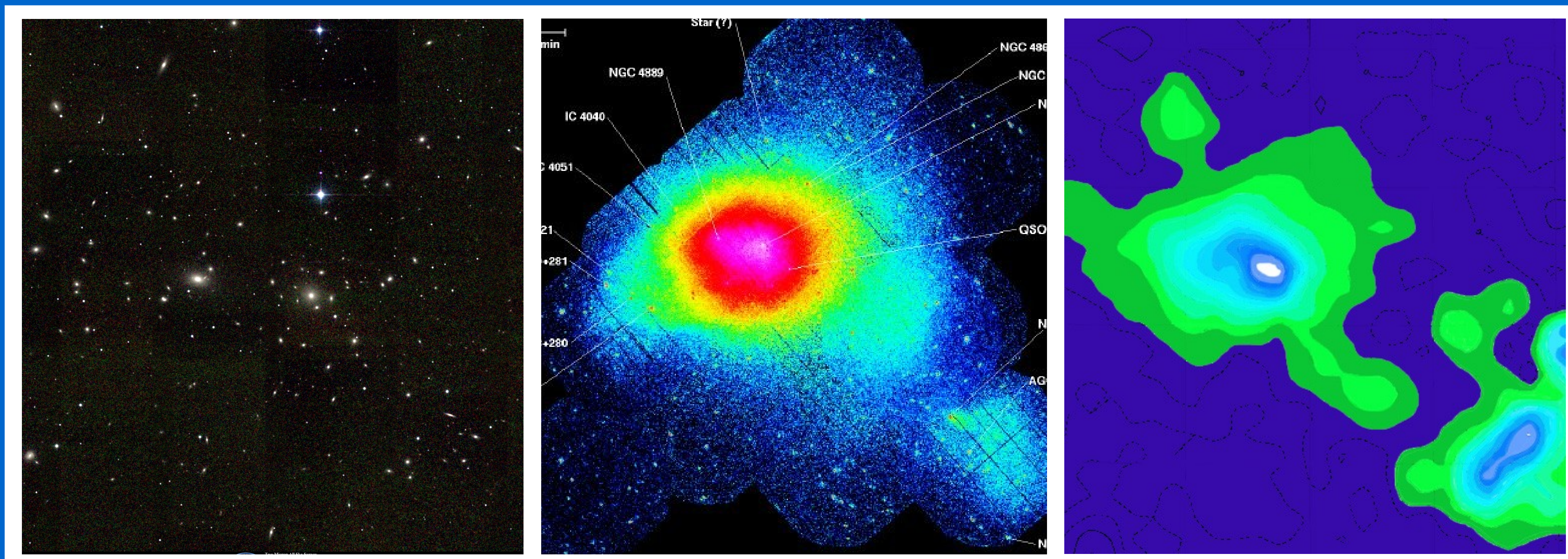
Filament-void network:

matter collects in filaments, then flows toward intersections

Rich clusters lie at the intersections



Observing clusters



Optical/Infrared

Galaxies
Intracluster stars

Dark matter via
gravitational lensing

X-Ray

Thermal hot gas

Radio

Nonthermal particles

Thermal hot gas via
Sunyaev-Zel'dovich effect
(microwave)

Mpc-scale diffuse radio emission

Radio halos

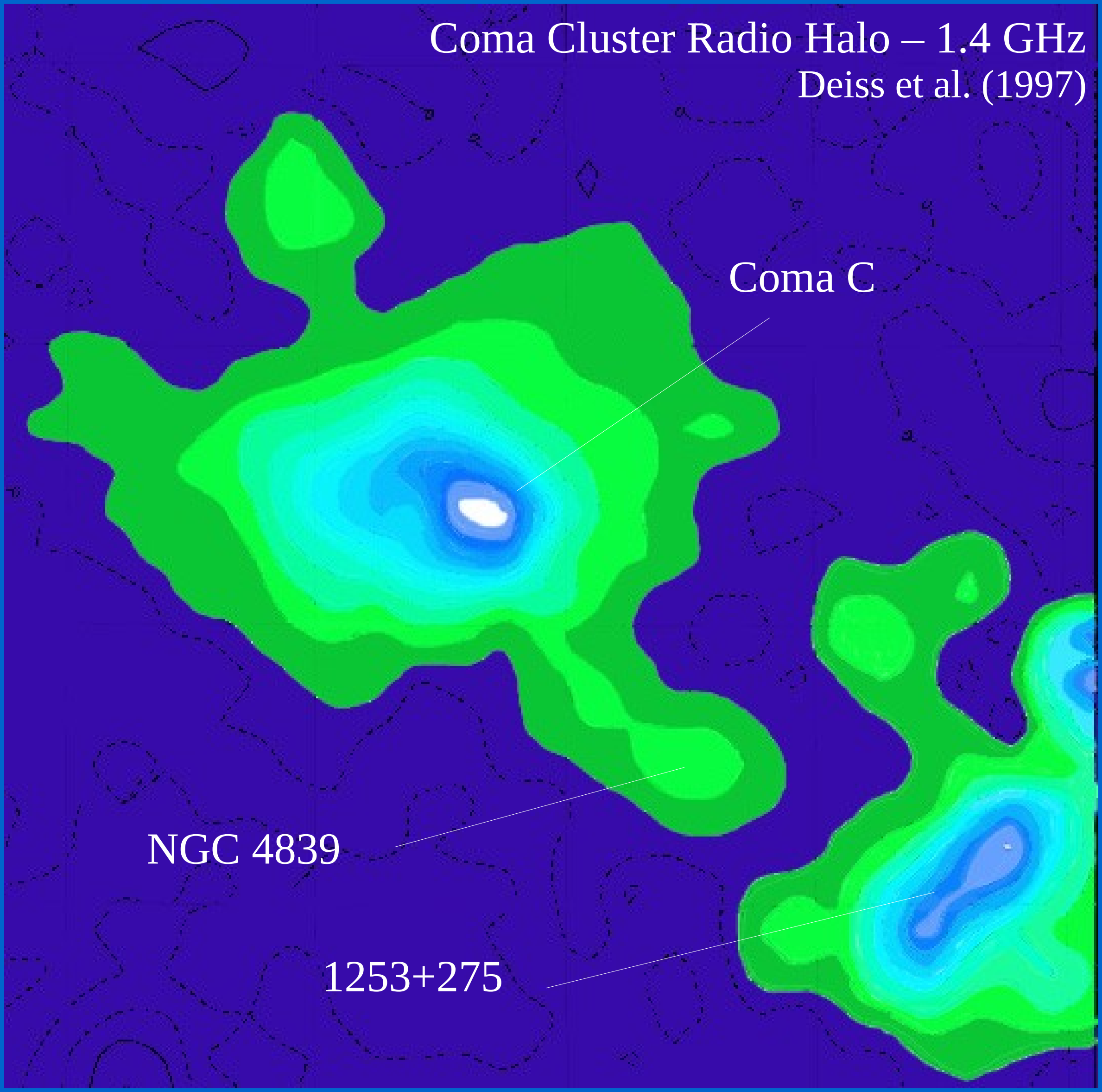
- Round
- Unpolarized
- Covers most of cluster

Radio relics

- Elongated
- Polarized
- Outskirts only

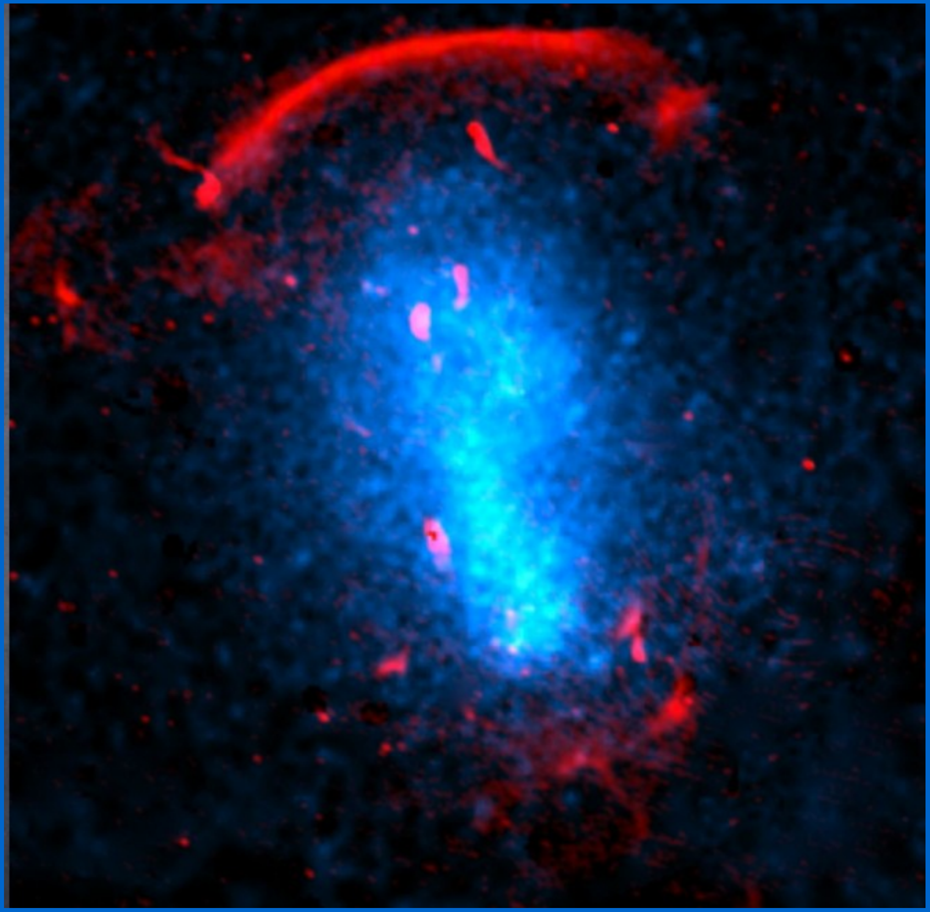
Radio minihalos

- Round
- Polarized
- Centers of cool-core clusters



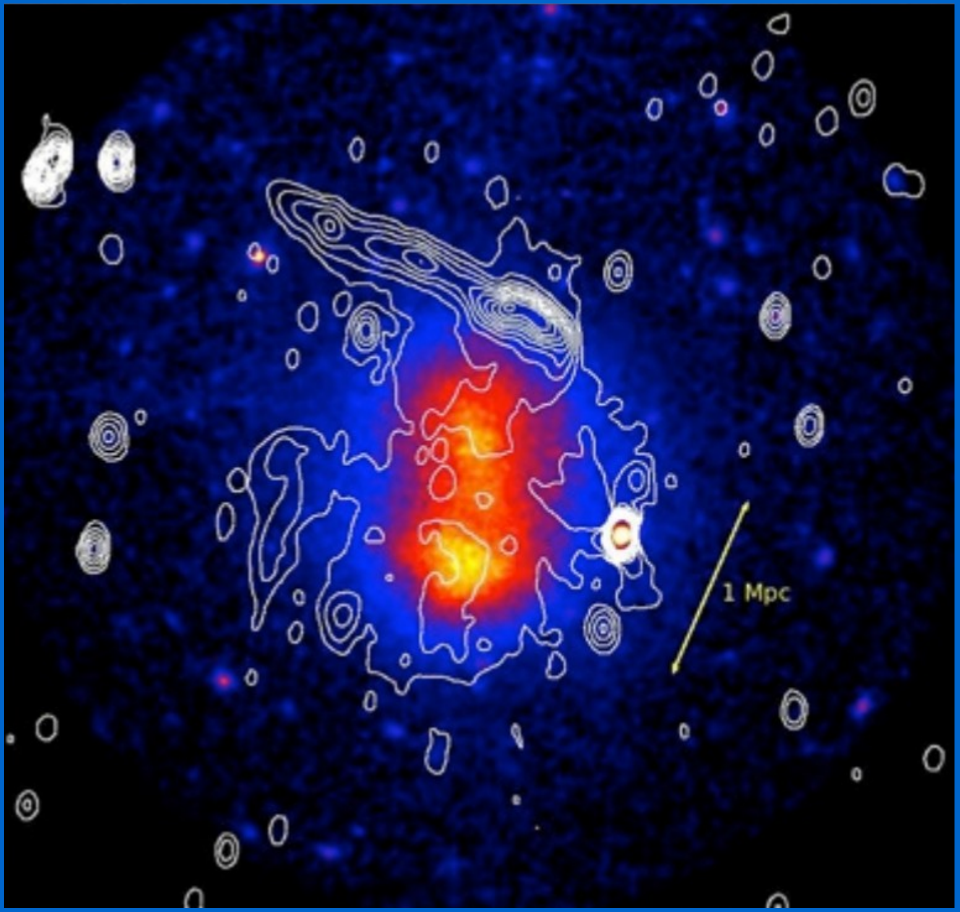
Relics – examples

CIZAJ2242.8+5301 (“Sausage”)



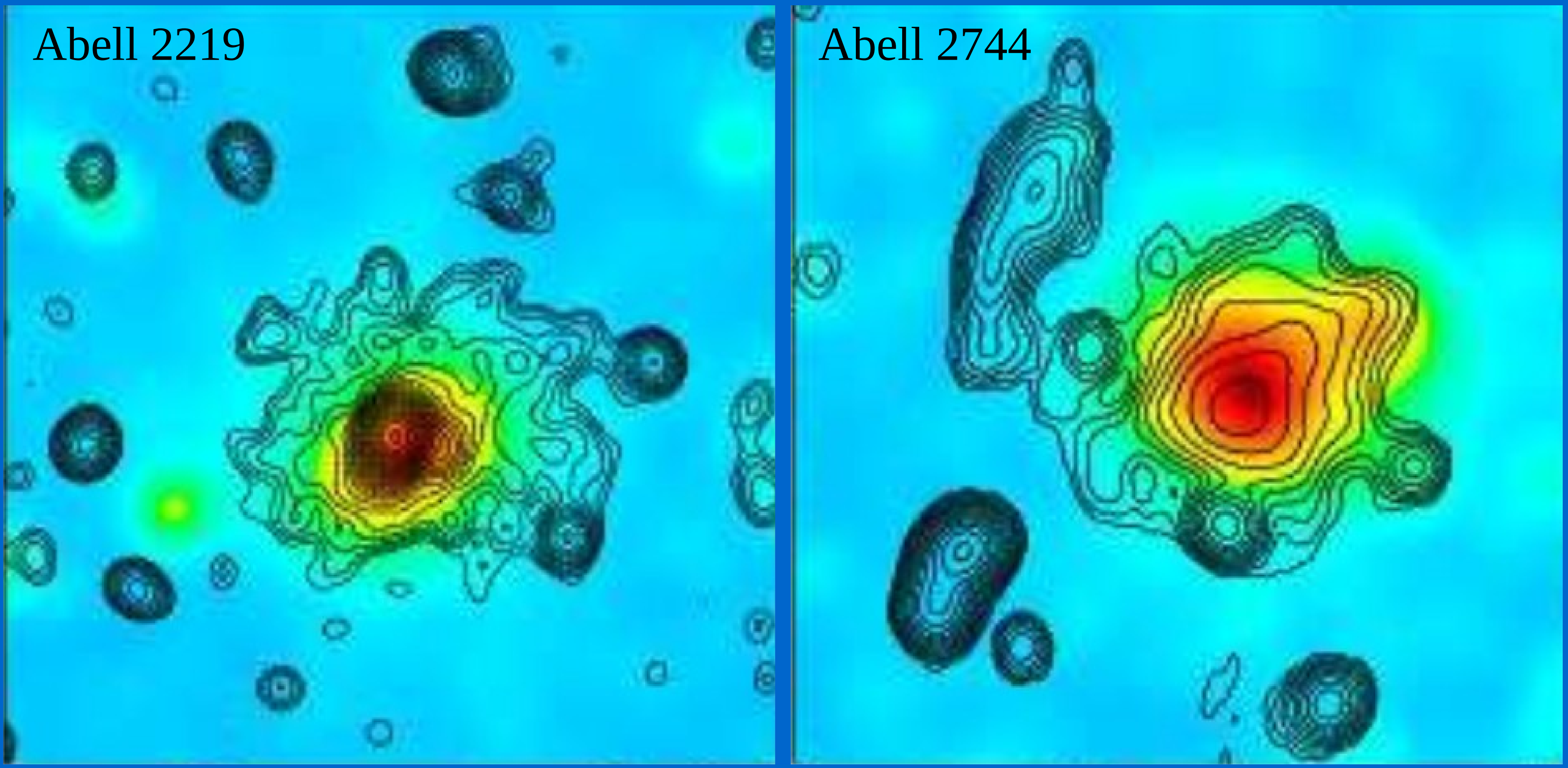
XMM X-ray (blue) + 610 MHz GMRT (red)
(Ogrean et al. 2012)

1RXS 0603.3+4214 (“Toothbrush”)



XMM X-ray image (Ogrean et al. 2013)
1.4 GHz radio contours (van Weeren et al.)

Halos – examples



Feretti et al. (2012)

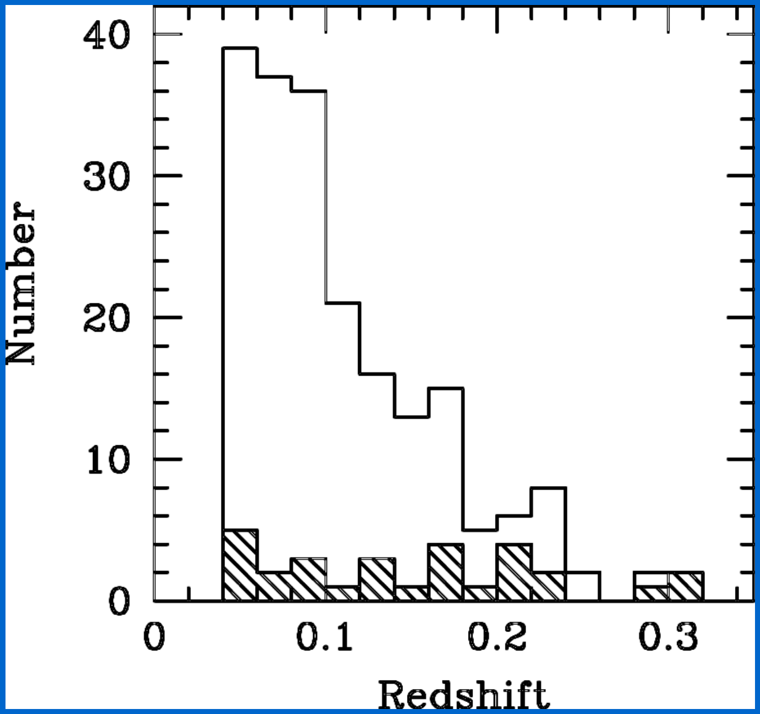
Detections of radio halos

Earliest

- Coma C source detected by Large et al. (1959), identified as diffuse by Willson (1970)
- By 1982 only ~ 4 – 5 radio halos known (Hanisch 1982)
  - Coma, A2255, A2256, A2319; Perseus (minihalo)

Recent searches

- NVSS – 13 out of 205 XBACS clusters (Giovannini et al. 1999)
- WENSS – 18 of 1001 ACO clusters (Kempner & Sarazin 2001)
- GMRT – 10 of 50 REFLEX+eBCS clusters (Venturi et al. 2007, 2008)
- Extended GMRT survey: additional 12 clusters w/ no new halo detections (Kale et al. 2013)



~42 clusters with halos known to date

Common features of radio halos

Radio power

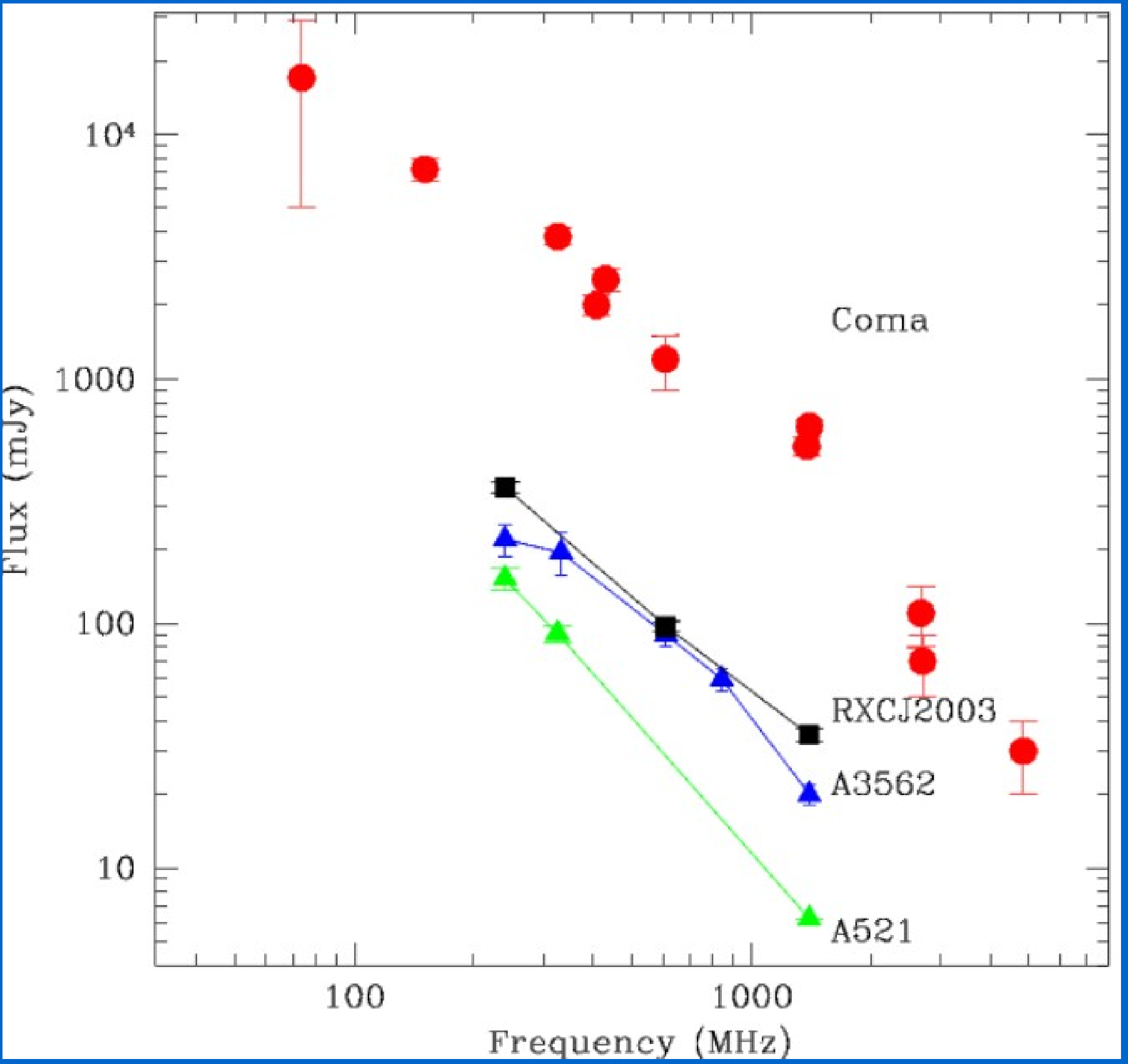
- $P_{1.4\,GHz} \sim 10^{23\text{-}26}$ W Hz^{-1}

Spectrum

- $P_\nu \propto \nu^{-\alpha}$, $\alpha = 1.2 - 2$
- "Normal" and "ultra steep spectrum"

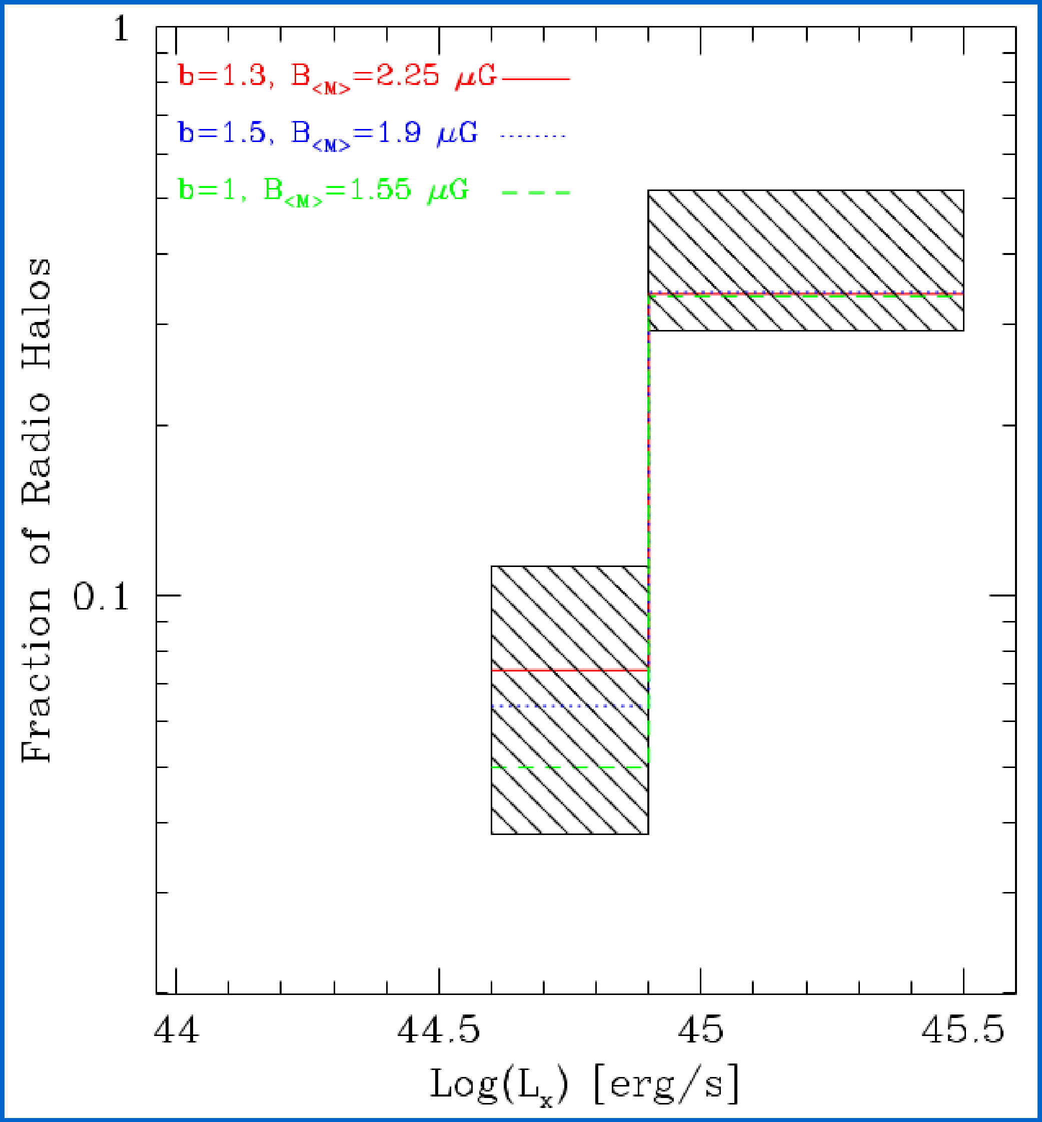
Morphology

- All show distorted X-ray morphology
- No "cool-core" clusters host full-size radio halos



Venturi (2011)

Bimodality



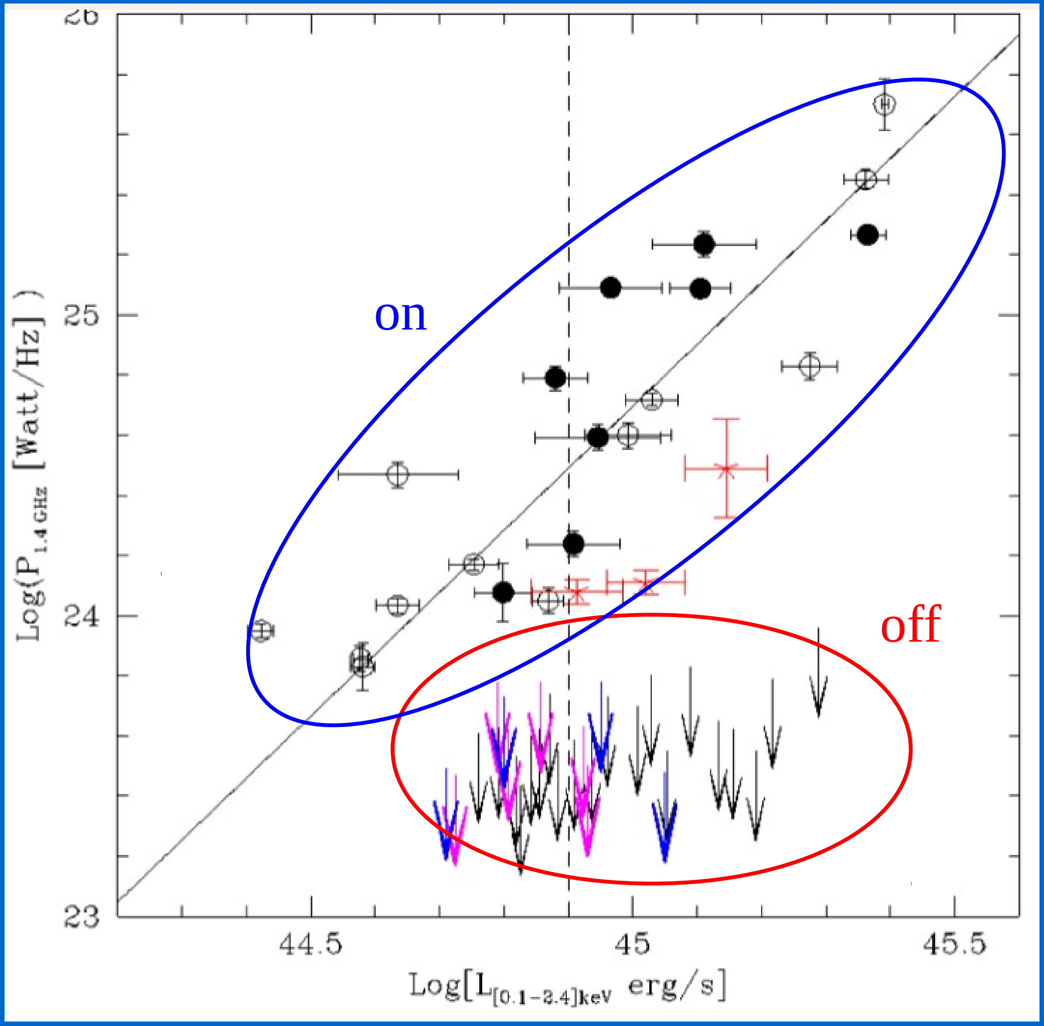
Cassano et al. (2008)

Likelihood of hosting a halo

- ~ 5% of all clusters
- ~ 35% of clusters with $L_X > 10^{45}$ erg s^{-1} ($M \sim 10^{15}\ M_\odot$)

Inference: separate "on" and "off" states

X-ray luminosity/radio power correlation



Kale et al. (2013)

For clusters hosting radio halos, 1.4 GHz radio power correlates with (Liang et al. 2000; Feretti 2000)

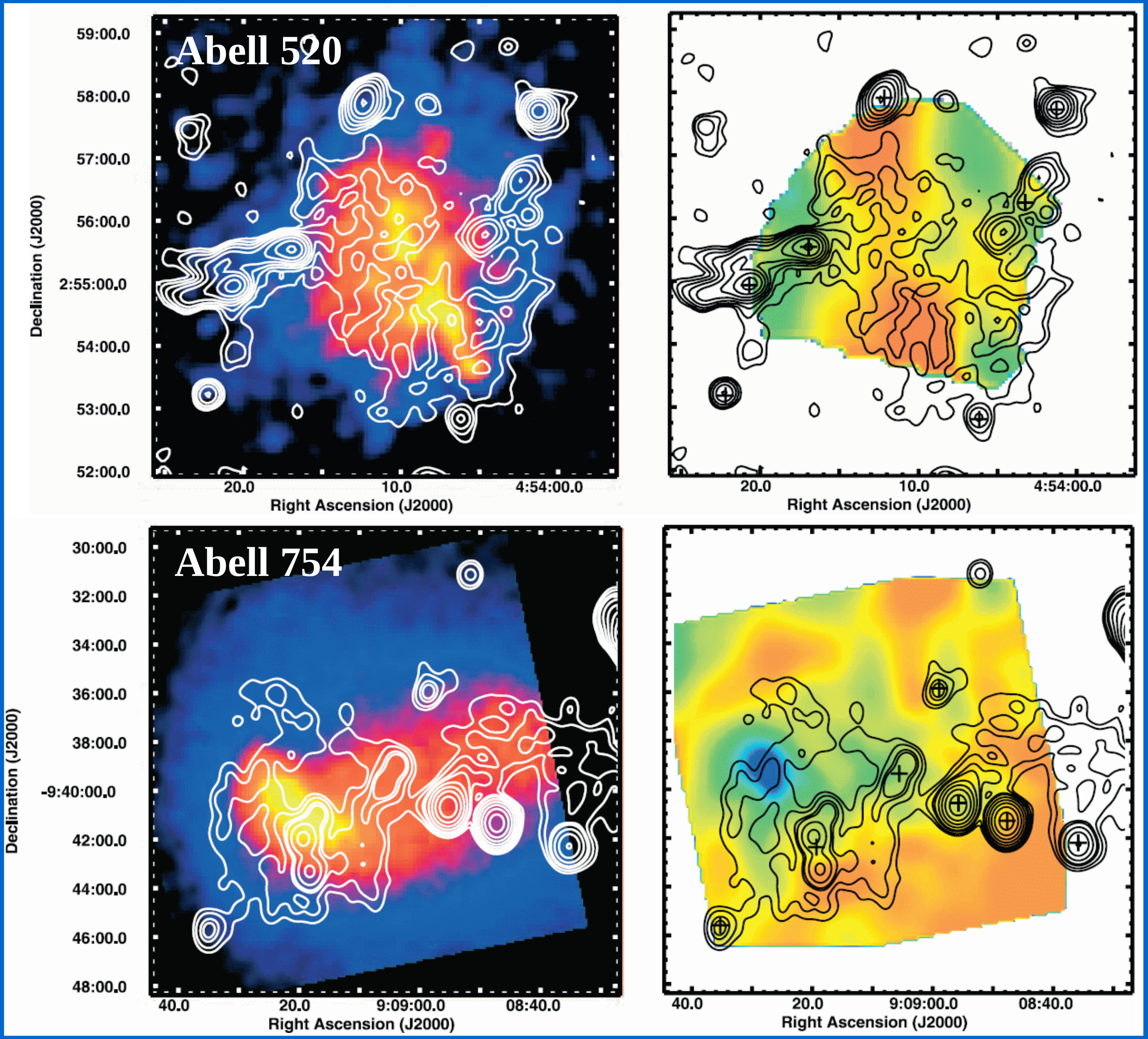
- X-ray luminosity
- X-ray temperature
- Isophotal size

Spatial correlations with X-rays

Some halos show spatial correlations with X-ray surface brightness and temperature ...

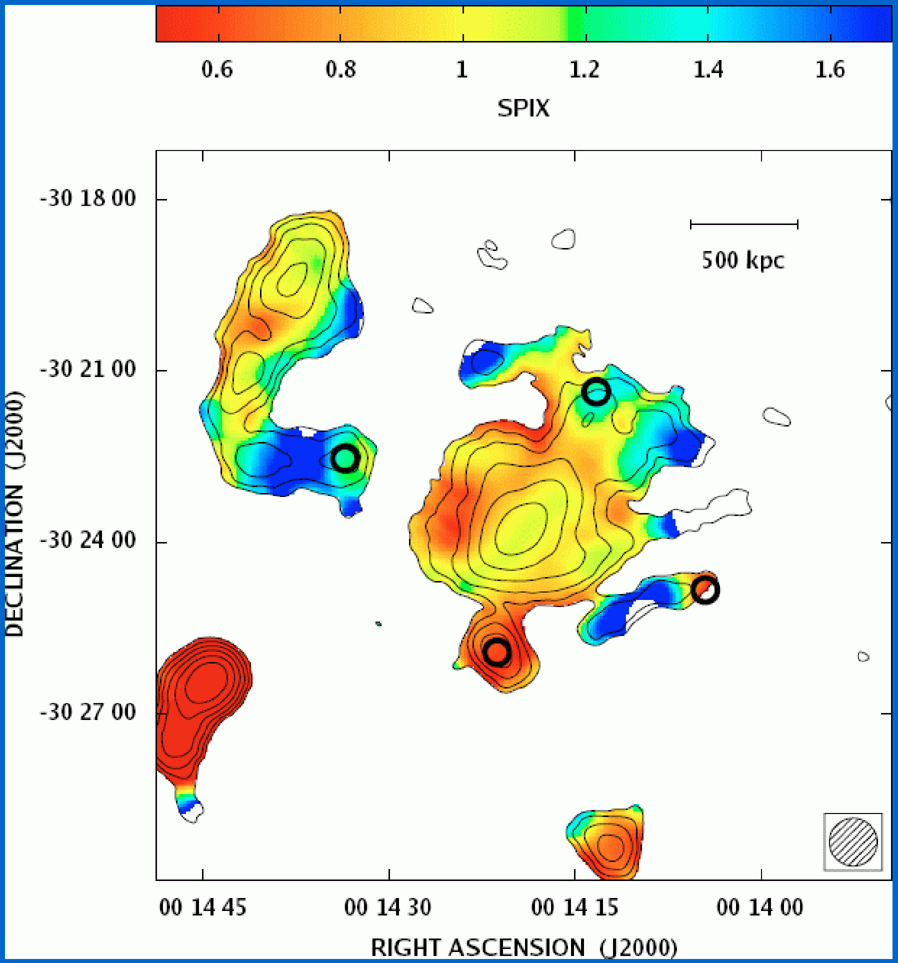
... but not all!

Govoni et al. (2004)

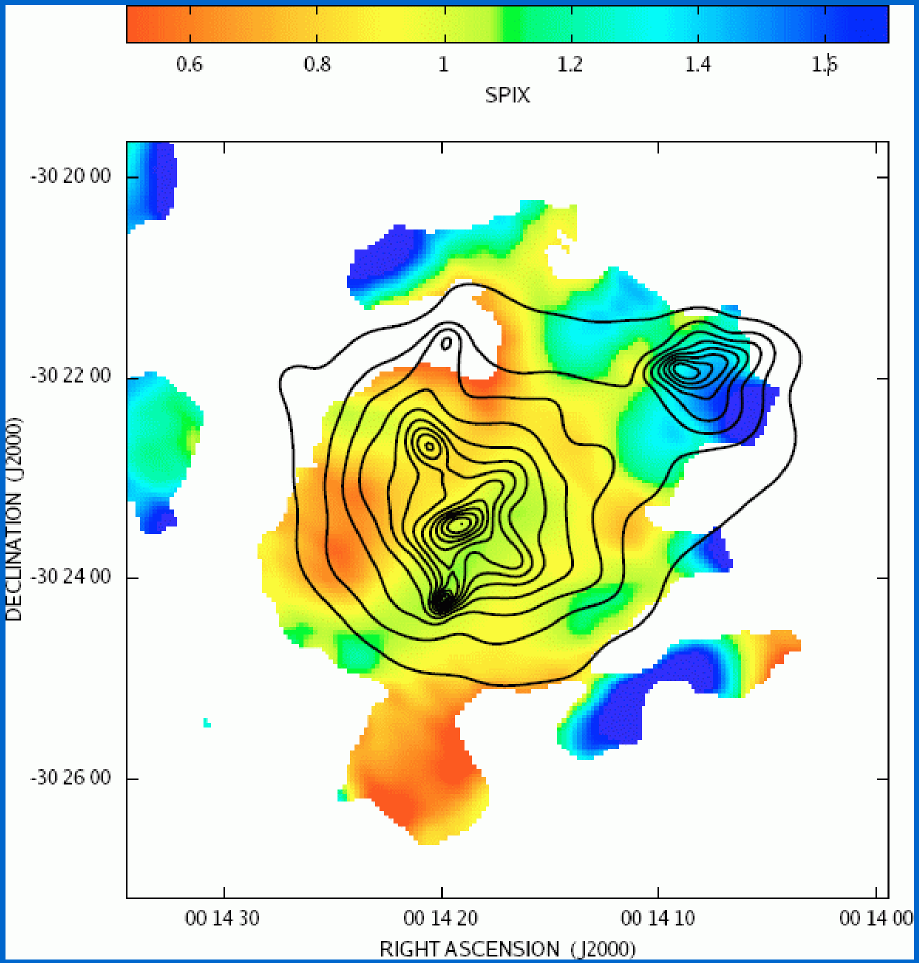


Radio spectral index and X-ray emission

Abell 2744 (Orru et al. 2007)



VLA (325 MHz – 1.4 GHz)



Chandra X-ray

Radio spectral index and X-ray temperature

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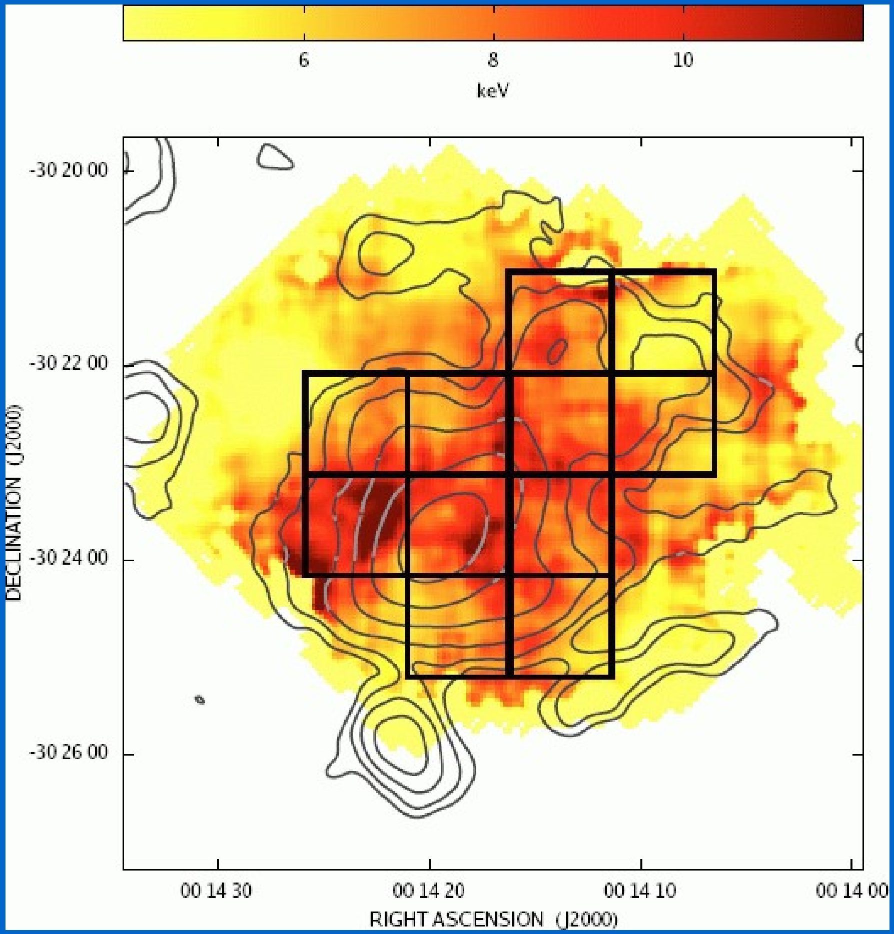
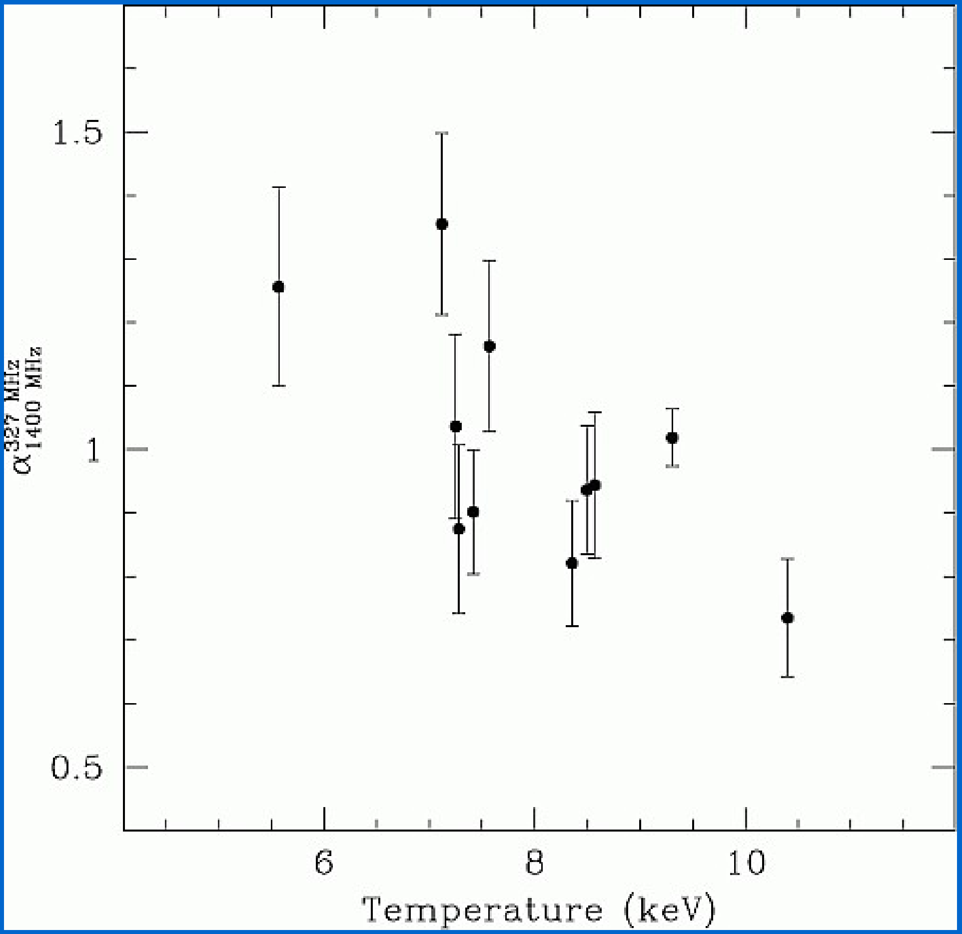




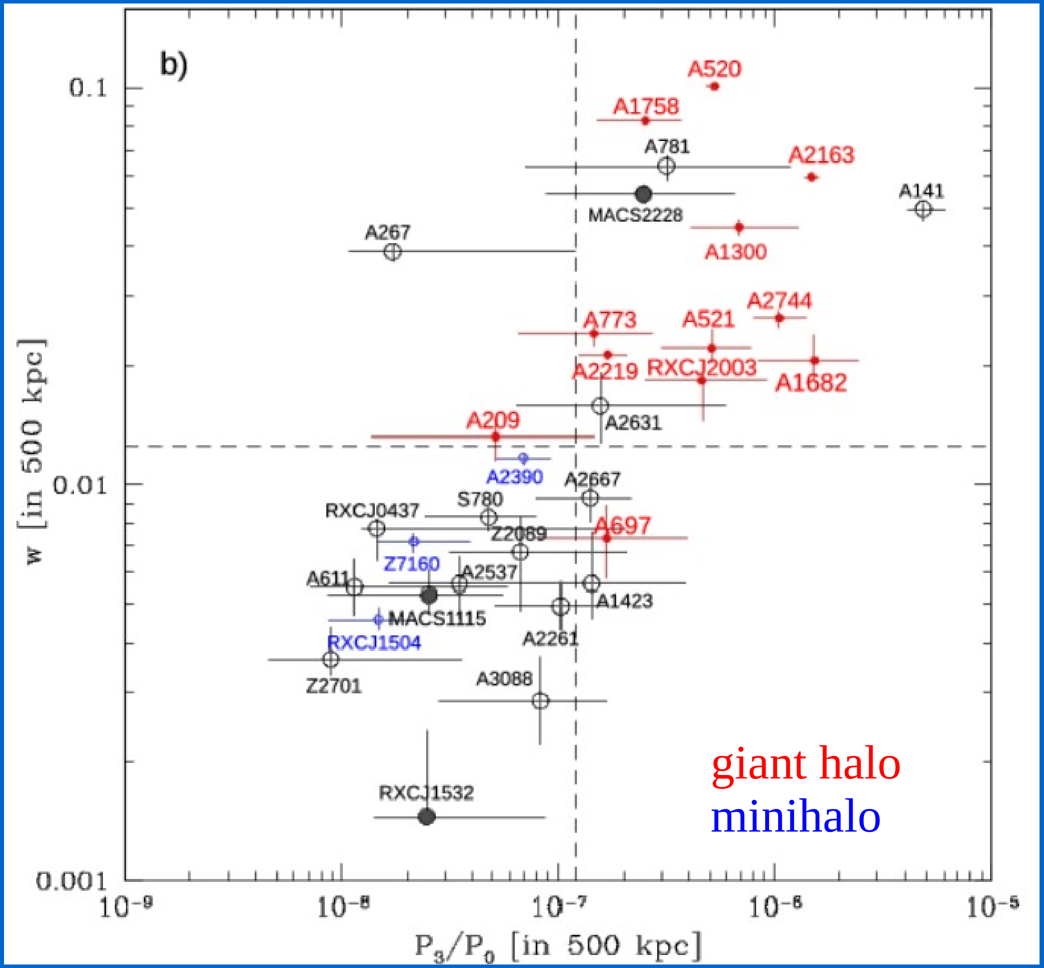
Why do clusters have radio halos?

Mergers clearly matter

- All radio halos are in morphologically distorted clusters
- Radio power increases with amount of distortion
- Clusters are brighter and hotter in X-rays during mergers, and brighter in radio

Mass also matters

- Only the most massive clusters host halos, and only 1/3 of them



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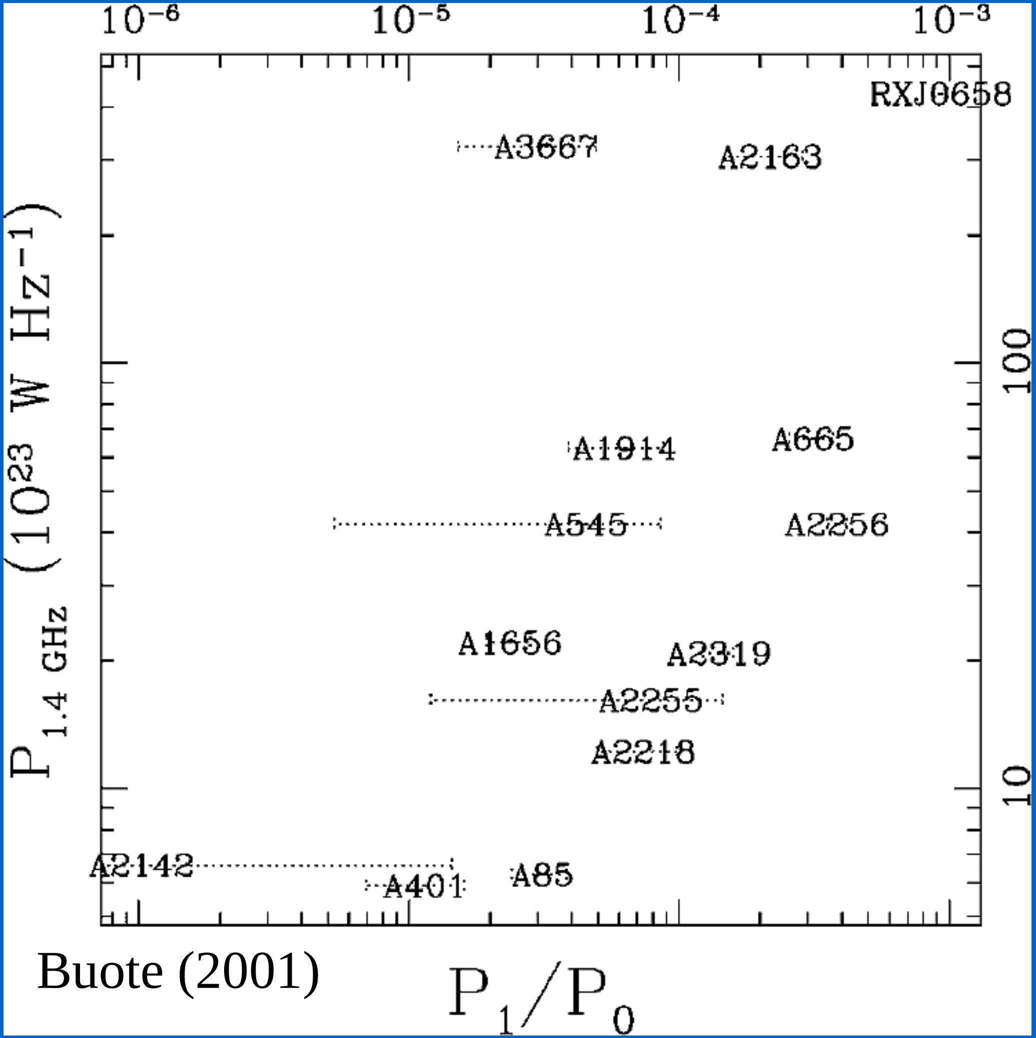


Buote (2001)

Production of relativistic electrons

Primary electrons (Jaffe 1977)

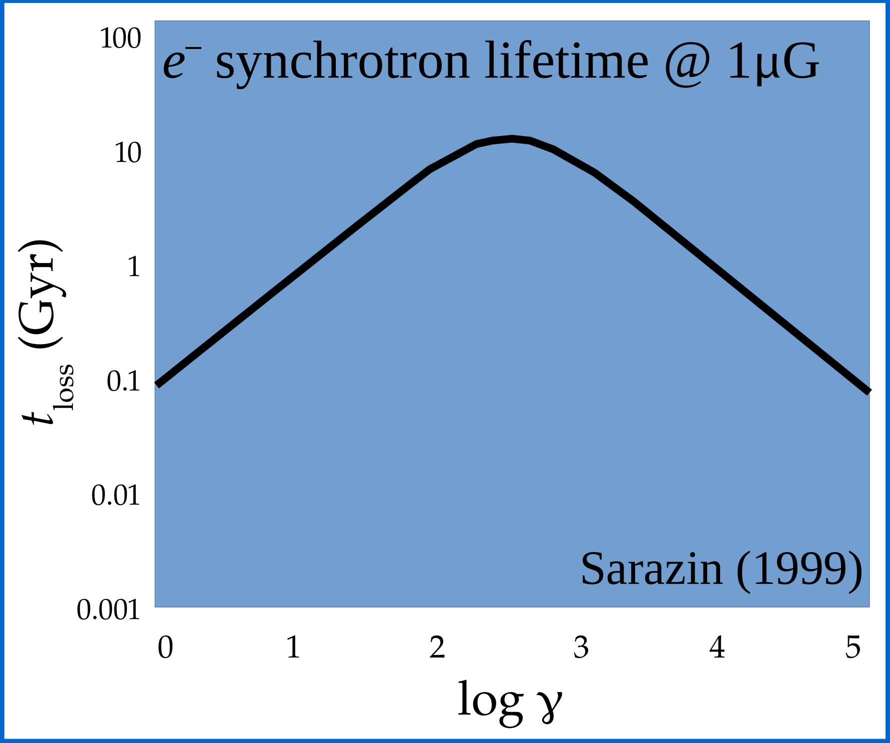
- From intracluster medium or radio galaxies
- Require reacceleration to explain diffuse halos of size ~ 1 Mpc

Hadronic secondaries (Dennison 1980)

- From interactions of cosmic-ray protons with thermal protons:

$$p + p \rightarrow p + p + \begin{cases} \pi^{\pm} \rightarrow e^{\pm} + \nu \\ \pi^{0} \rightarrow \gamma \end{cases}$$

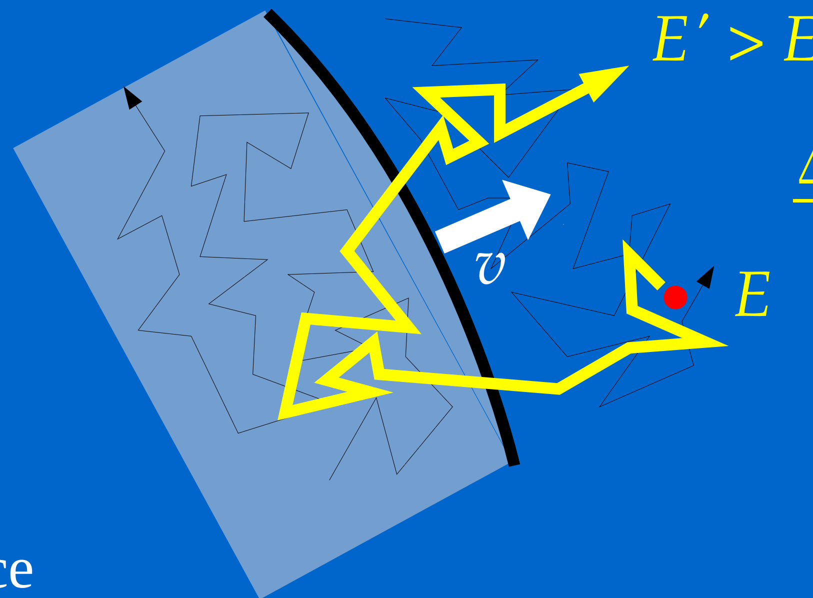
- Do not require reacceleration; relativistic protons last (practically) forever
- Problem: γ-rays not seen by *Fermi* (Jeltema & Profumo 2011)



(Re-)acceleration mechanisms

First-order Fermi acceleration

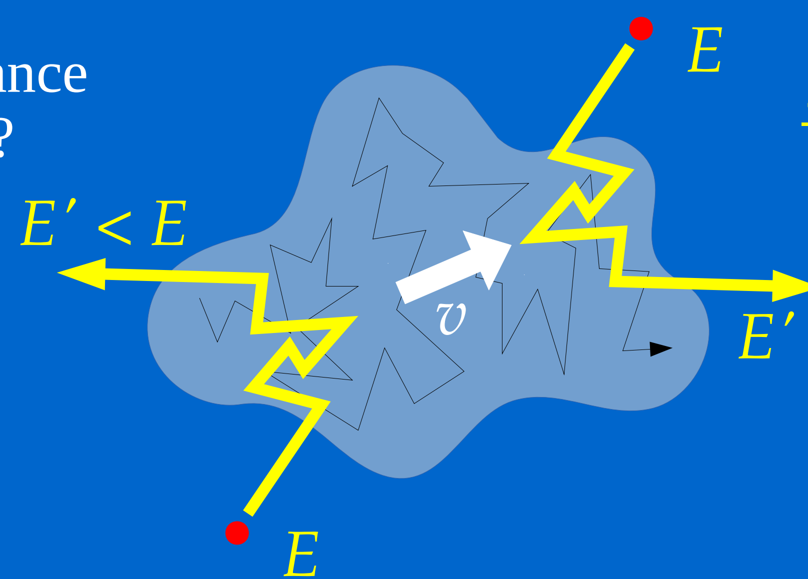
- Origin: merger shocks
- Problem: should trace shocks
- Problem: Mach #s too low



$$\frac{\Delta E}{E} \sim \frac{v}{c}$$

Second-order Fermi acceleration

- Origin: merger-induced turbulence
- Needs efficient cascade to resonance scale – fast magnetosonic waves?



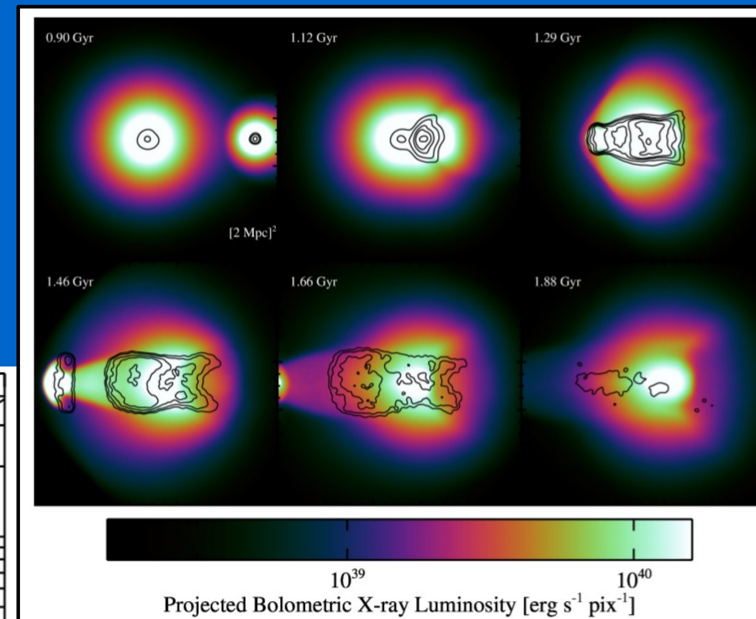
$$\frac{\Delta E}{E} \sim \left(\frac{v}{c}\right)^2$$

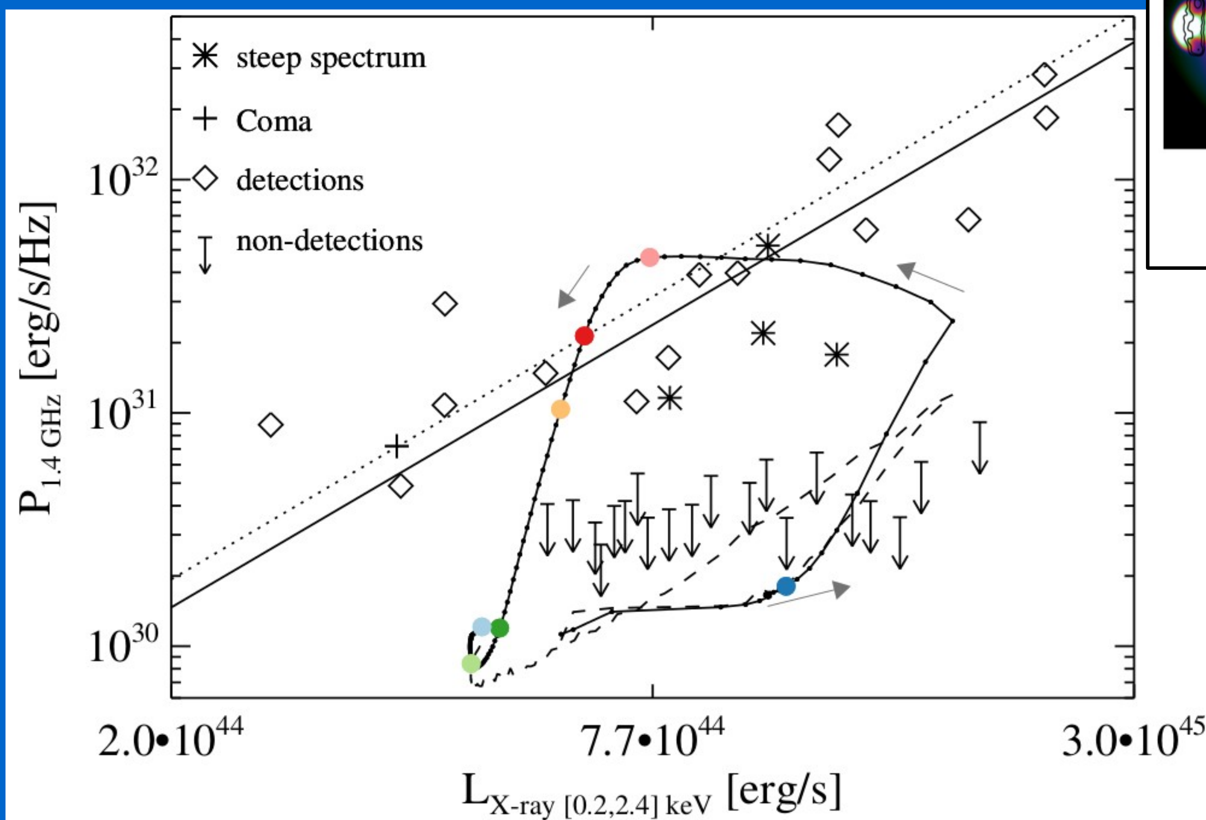
Maybe both operate

- Halos: turbulence
- Relics: shocks

Mergers can turn on halos

Donnert et al. (2013) – MHD simulation of head-on merger shows transition from “off” to “on” state and back





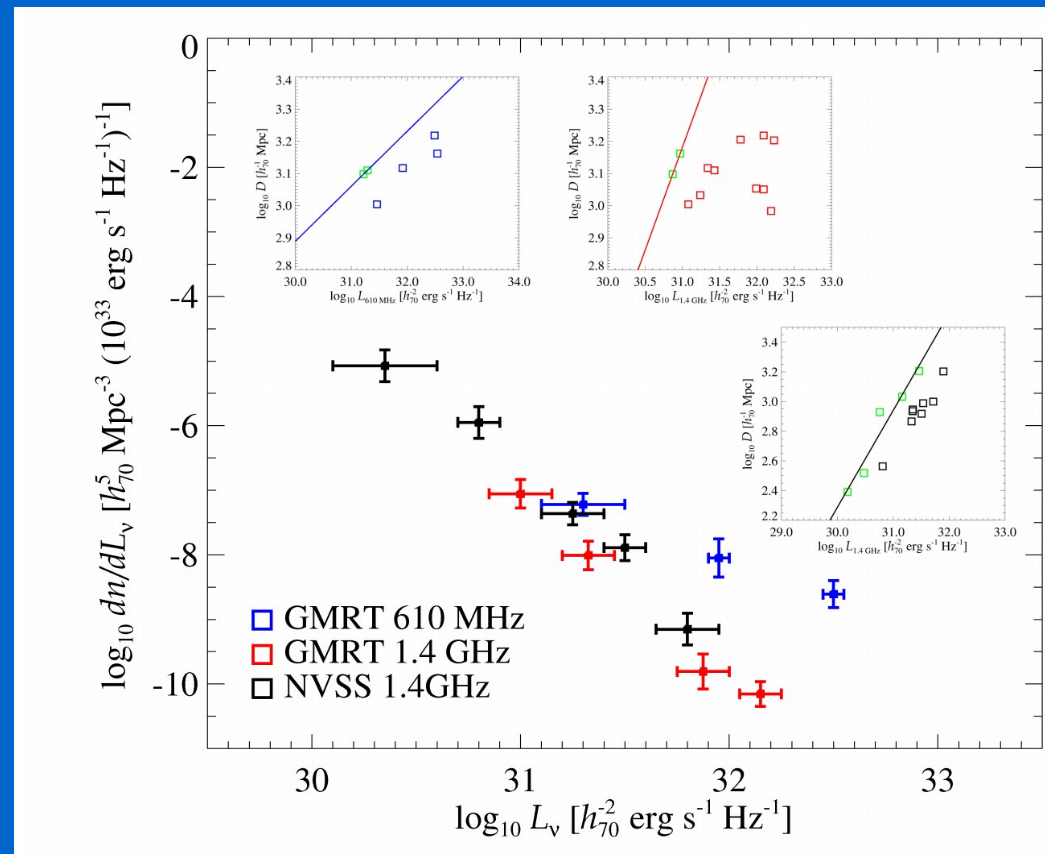
Intermission

What can we learn from radio halo statistics?

- Magnetic field scaling with cluster mass
- Cluster merger rate as a function of redshift
- Relative contributions of hadronic and turbulent sources
- Cosmological parameters?

Observations

- Power-law radio halo luminosity function (RHLF) sensitive to sample completeness
- “On” and “off” states
- Spectral index ~ 1.2 – 1.3 at 1.4 GHz, possibly steeper at lower frequencies



Zandanel et al. (2013)

Theoretical expectations for the RHLF

- Purely from observed scalings

  Enßlin & Röttgering (2002)

  Press-Schechter mass function ×

  L_X-M × $P_{1.4}$-L_X × 0.3

- Turbulent reacceleration

  Cassano et al. (2006, 2012)

  PS × $B(M)$ scaling × acceleration efficiency ⁎ spectral cutoff

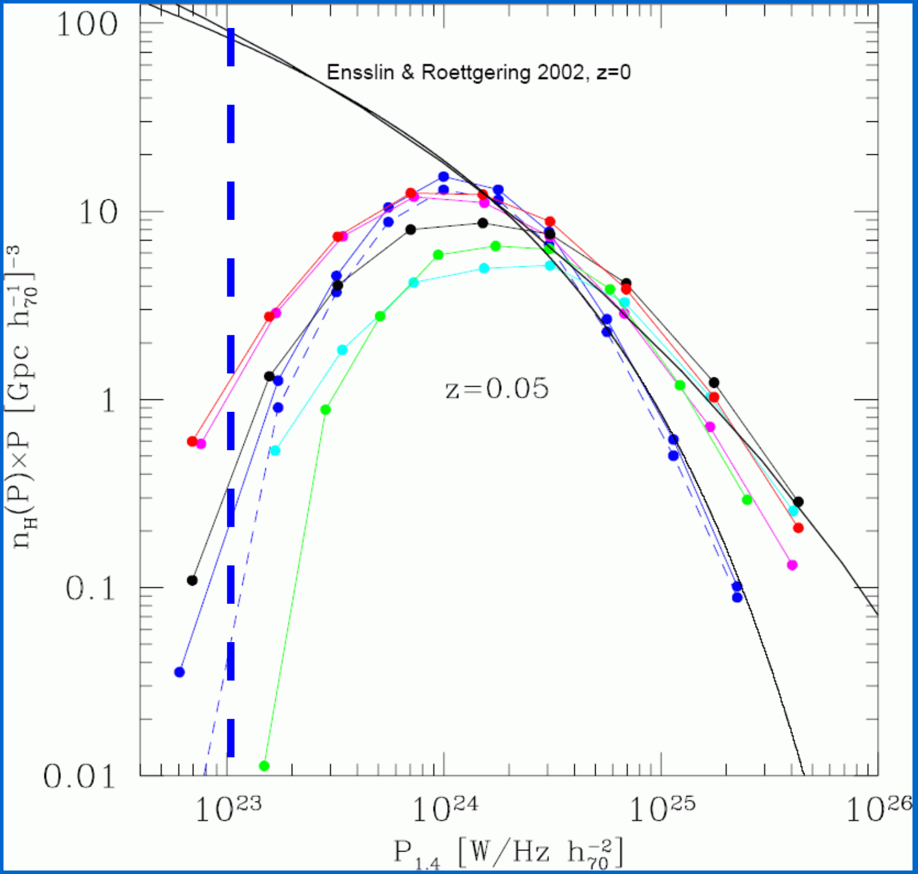
  Merger tree + Fokker-Planck model of turbulence decay

- Hadronic secondaries

  Zandanel et al. (2013)

  (N-body halos + gas model) ×

  $B(M)$ scaling × (turbulent advection, streaming)



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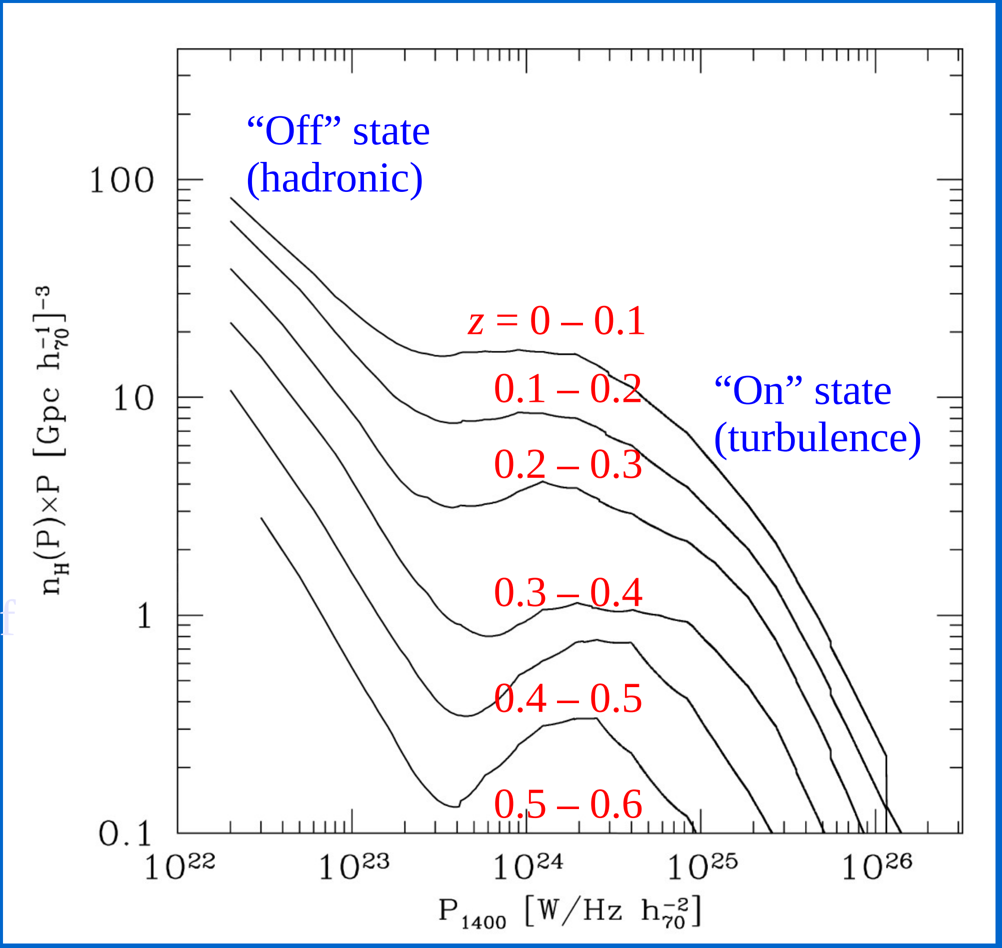

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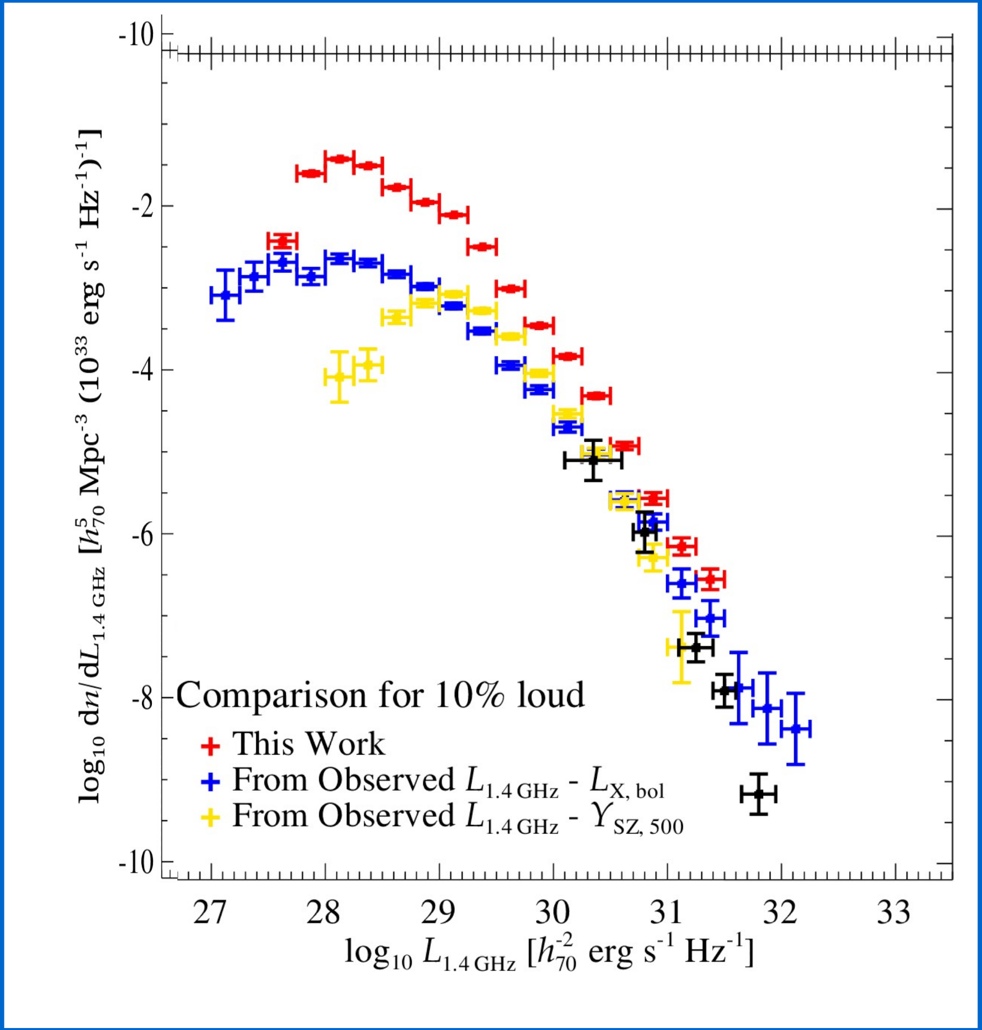


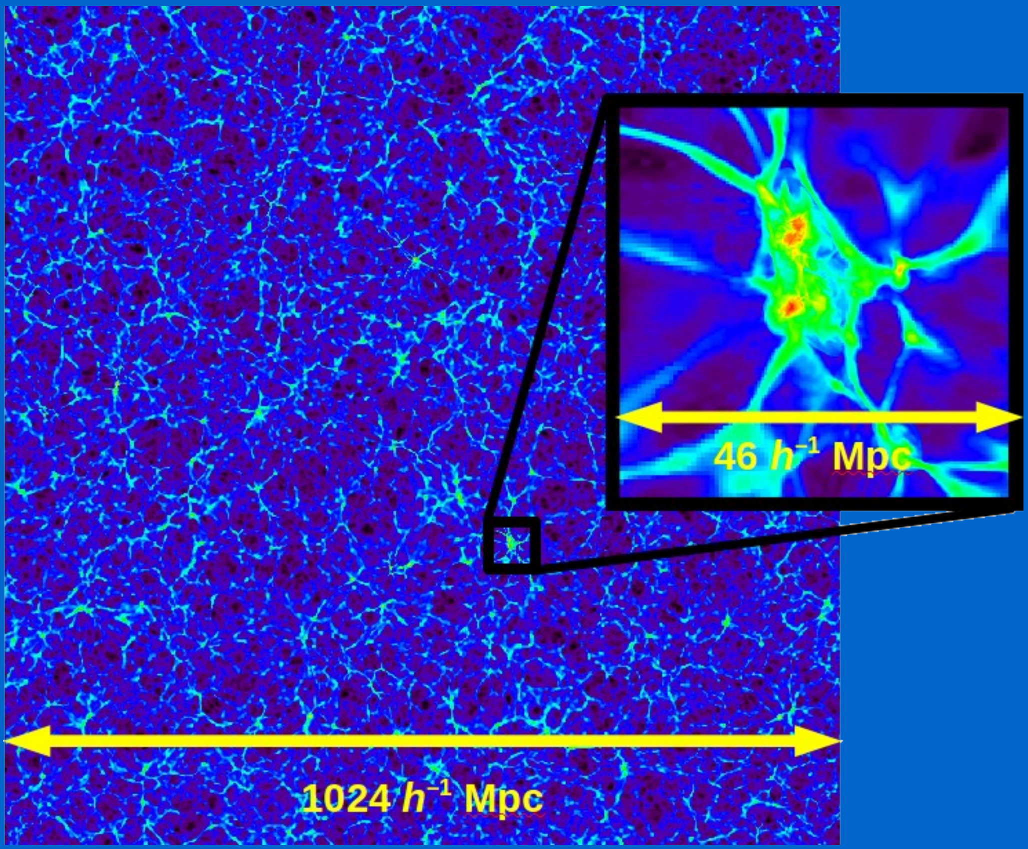
Zandanel et al. (2013)

FLASH 3.3 simulation (Sutter & Ricker 2012)

- ΛCDM

  $\Omega_m = 0.262$, $\Omega_b = 0.0437$

  $h = 0.719$, $\sigma_8 = 0.74$
- DM + preheated hydro
- Volume 1024 h^{-1} Mpc
- Particles $6.7\times10^{10}\ h^{-1}\ M_\odot$
- AMR within 100 regions to $\Delta x = 32\ h^{-1}$ kpc
- Jaguar (ORNL), 16K cores, 450K hours



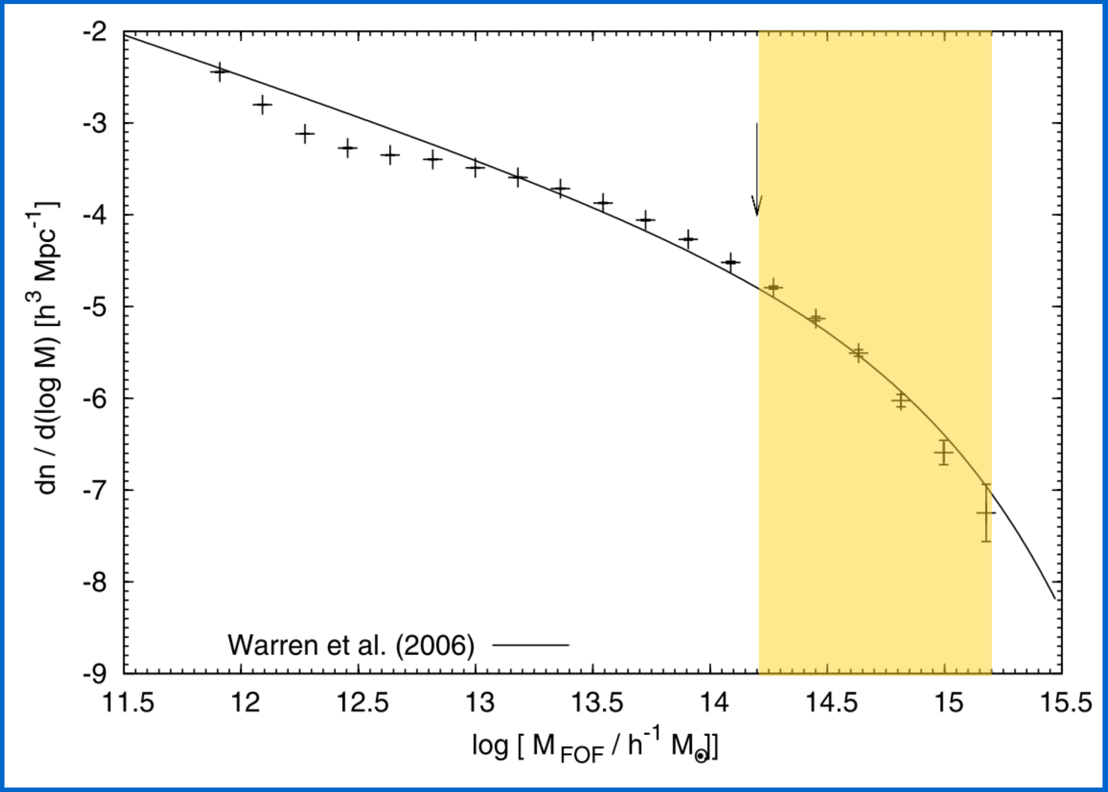
Cluster samples

- High-resolution (131)

  clusters found in the 100 refined regions

- Low-resolution (3900)

  clusters outside refined regions; assign radio power using mean scalings from high-resolution sample



Modeling radio halo emission

- Allow for dependence of radio power on mass M_{vir} and turbulent pressure Γ_{vir}

$$P_{1.4\ \mathrm{GHz}} = C_S B_S(M_{\mathrm{vir}}) M_{\mathrm{vir}}^a \Gamma_{\mathrm{vir}}^c$$

$$\Gamma_{\mathrm{vir}} \equiv \sum_{\mathrm{cells}} \rho \Delta x^3 \mid \mathbf{v} - \bar{\mathbf{v}}_{300\ \mathrm{kpc}} \mid^2$$

- Magnetic field dependence on mass

$$B_S(M_{\mathrm{vir}}) = \frac{B(M_{\mathrm{vir}})^2}{(B(M_{\mathrm{vir}})^2 + B_{\mathrm{CMB}}^2)^2} \; , \quad B(M_{\mathrm{vir}}) \equiv \langle B \rangle (M_{\mathrm{vir}} / \langle M \rangle)^b$$

- Calibration using observed X-ray/radio correlation and X-ray luminosity/mass correlation for most massive cluster

- Two states assuming fixed radio halo probability of 5%

Parameter constraints

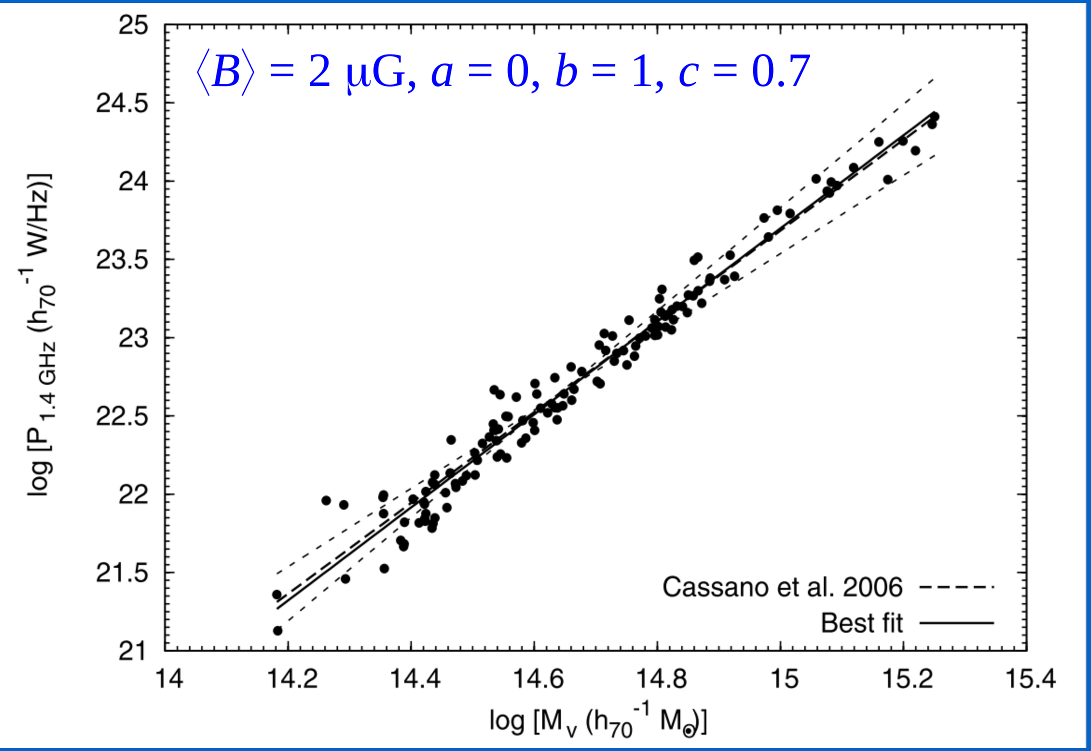
- $\langle B \rangle$ limits

  Upper: 6.0 μG from Faraday rotation measurements

  Lower: 0.2 μG from limits on hard X-rays

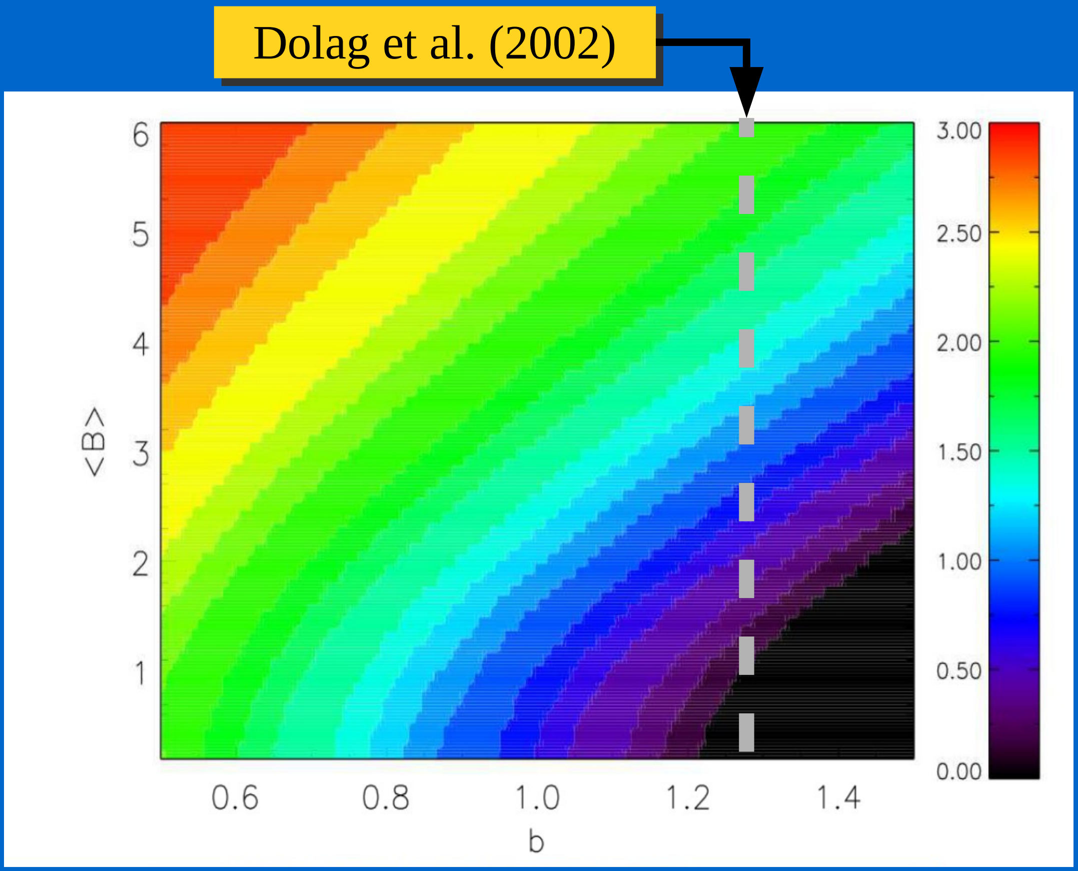
- Limits on scaling exponents

  Compare fit to our $P_{1.4}$-M relation to observed one



Parameter constraints from observed *P*-*M* relation

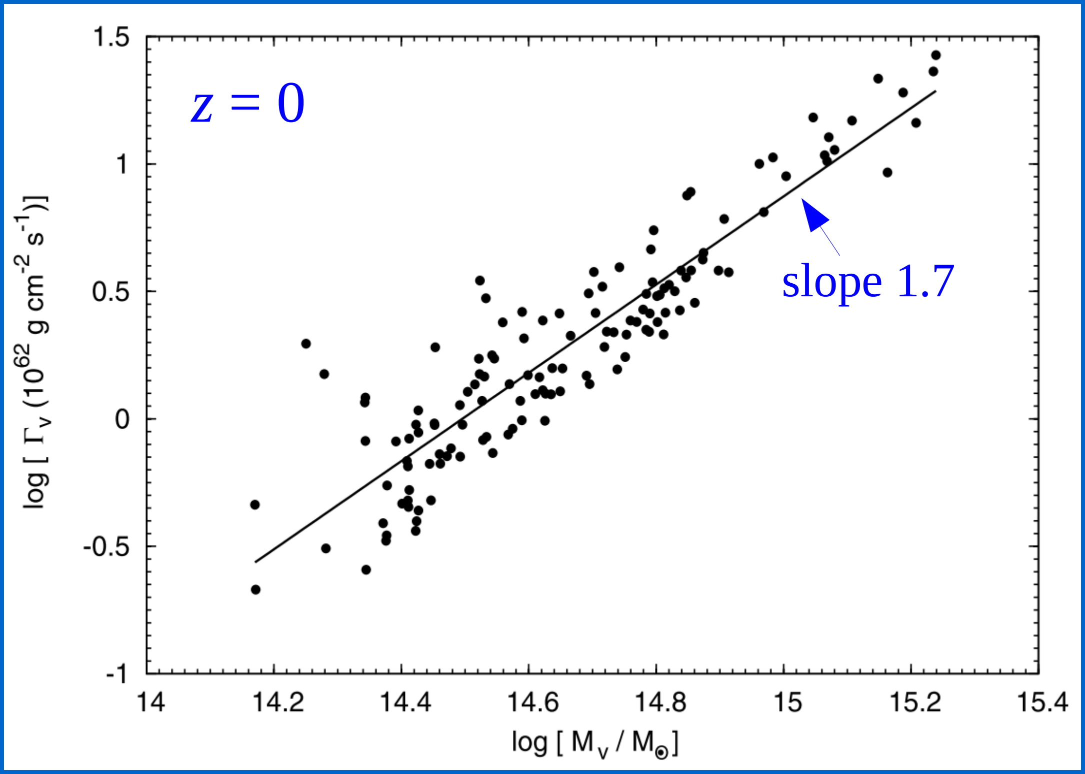
- Large $\langle B \rangle$ requires steep emissivity dependence on M_{vir} and Γ_{vir}
- Steep $B(M_{vir})$ essentially requires emissivity depend only on mass, or else high $\langle B \rangle$



Max allowed $a+c$

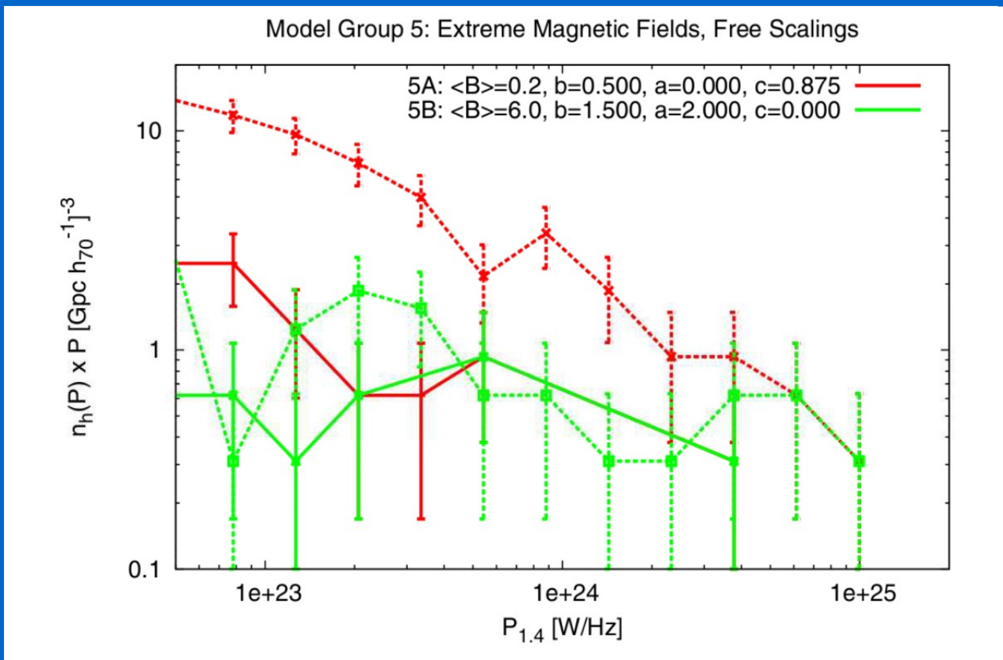
Scaling of turbulent energy with mass

- Scaling of mean turbulence-mass relation comparable to Vazza et al. (2006) result
- Large scatter due to mergers

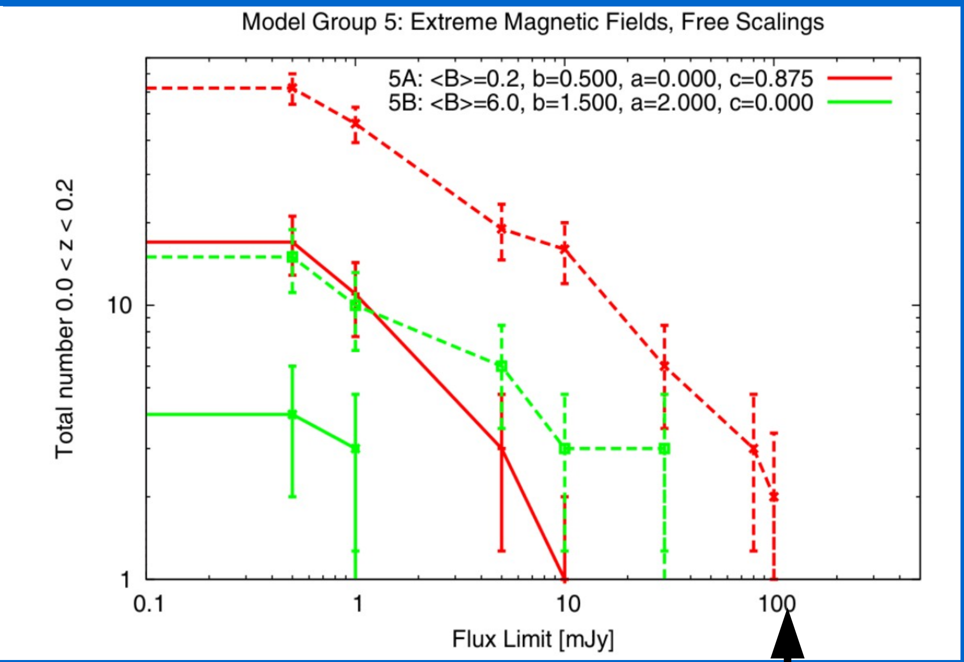


Radio halo luminosity function at $z = 0$

Differential



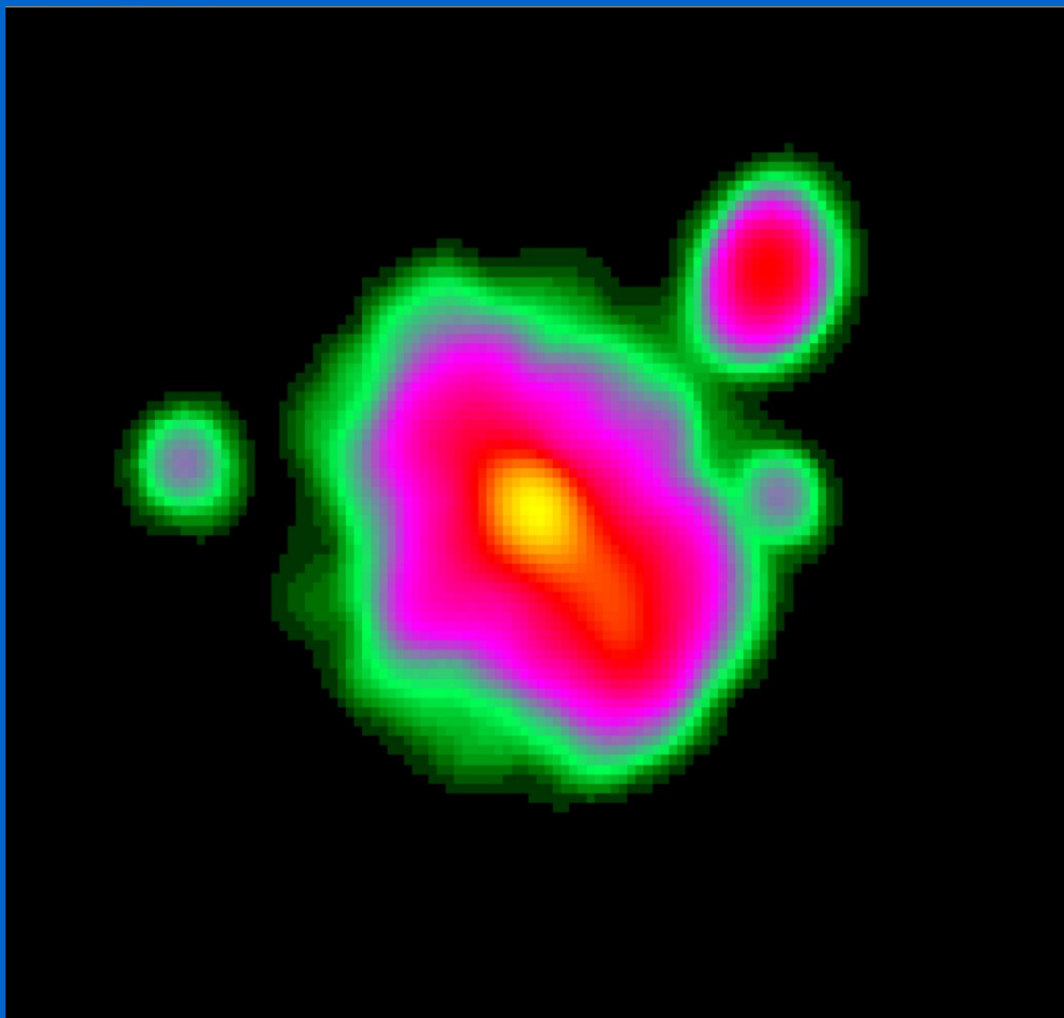
Cumulative



Missing ~ 12 high-luminosity clusters because of limited volume

Solid: 1.4 GHz
Dashed: 150 MHz
(assuming spectral slope -1.2)

Sky maps



- Light cones with replicated box using simulated observations of individual clusters
- Pixel size 2'
- 200 MHz
- FITS

http://sipapu.astro.illinois.edu/foswiki/bin/view/Main/RadioHaloMaps

Conclusions

- Parameters allowed by observed *P*-*M* relation

  Large $\langle B \rangle$ requires steep emissivity dependence on M_{vir} and Γ_{vir}

  Steep $B(M_{vir})$ requires weak turbulence dependence or large $\langle B \rangle$

- Wide range of RHLFs allowed at present

  Need better constraints on *P*-*M* relation

  Shape of RHLF at low luminosities and frequencies is an important discriminator between models

  Need better understanding of survey completeness

- Next steps for our simulations

  Larger/more boxes – RHs are rare!

  MHD, physical cosmic ray injection and transport