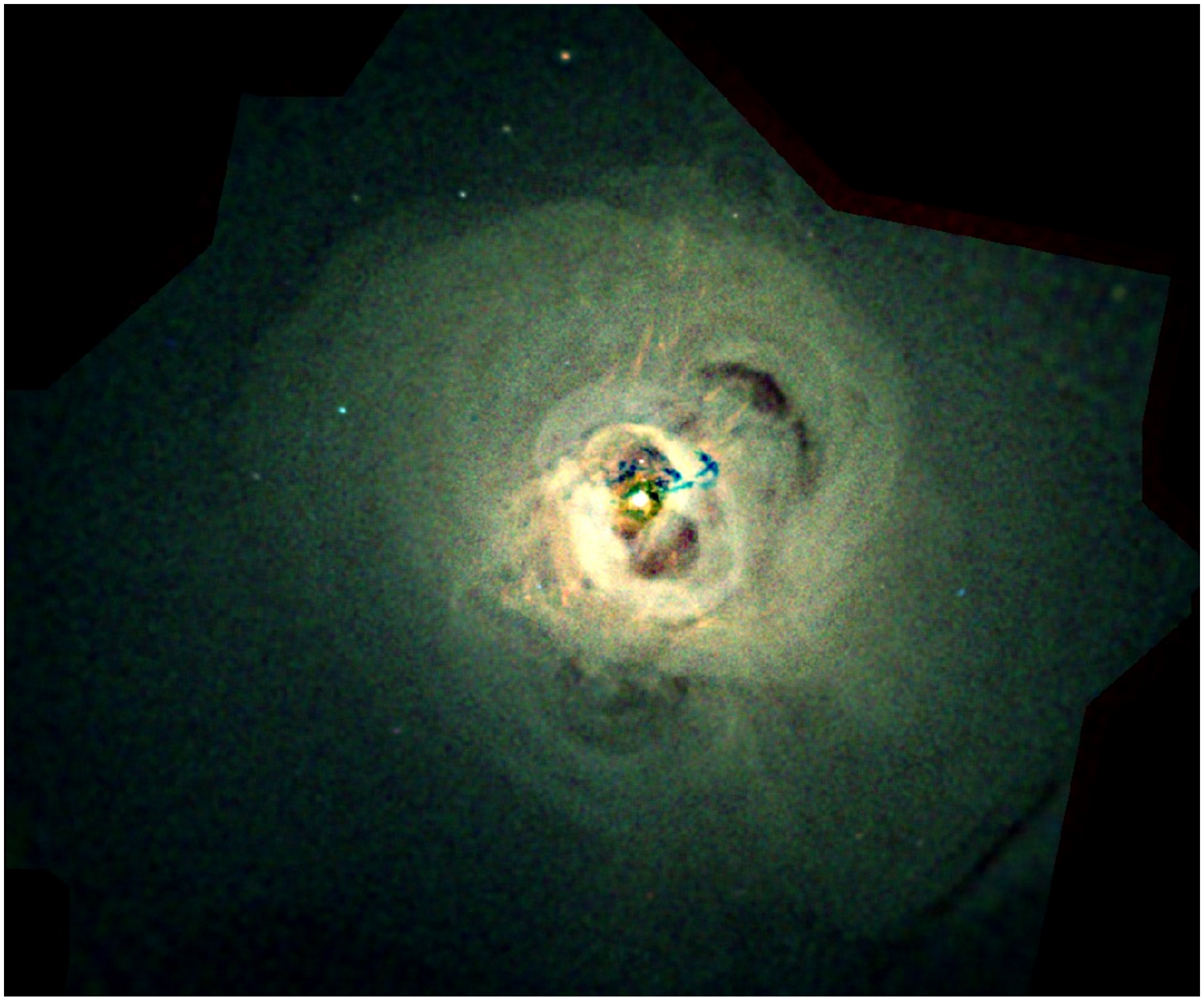
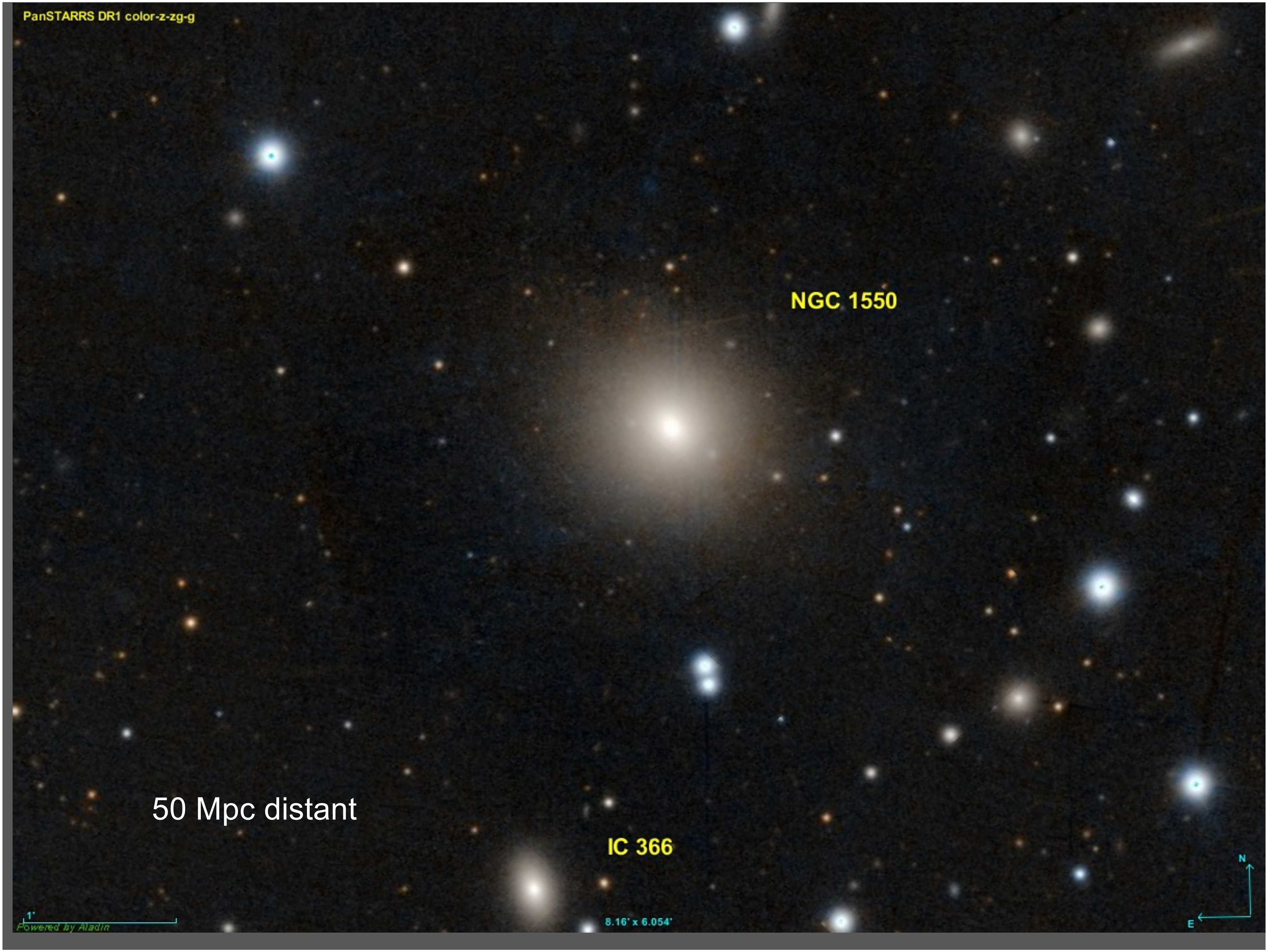
Astronomy 537

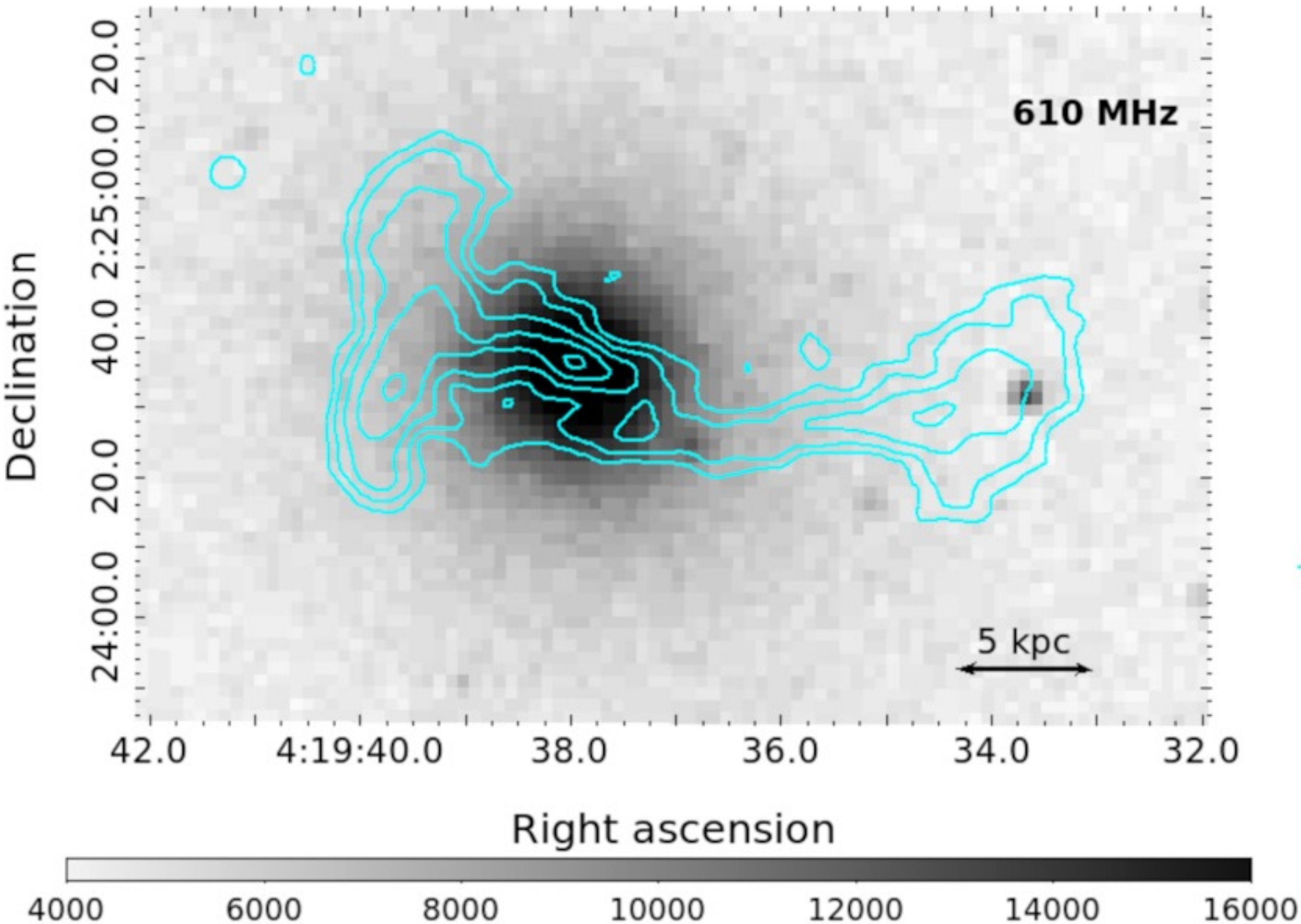


Lecture 14: Groups and Clusters

Fig. 7.1. Stephan's Quintet (compact group Hickson 92) is ~85 Mpc distant and 80 kpc across, or 3.2′ on the sky. North is at the top and east is to the left. NGC 7319, the barred spiral, has an active nucleus: it is a Seyfert 2. The large spiral in the lower center, NGC 7320, is not a group member; it is in the foreground with a much smaller redshift – D. J. Pisano, WIYN telescope.


PanSTARRS DR1 color-z-zg-g
NGC 1550
50 Mpc distant
IC 366
1'
Powered by Aladin
8.16' x 6.054'
N
E

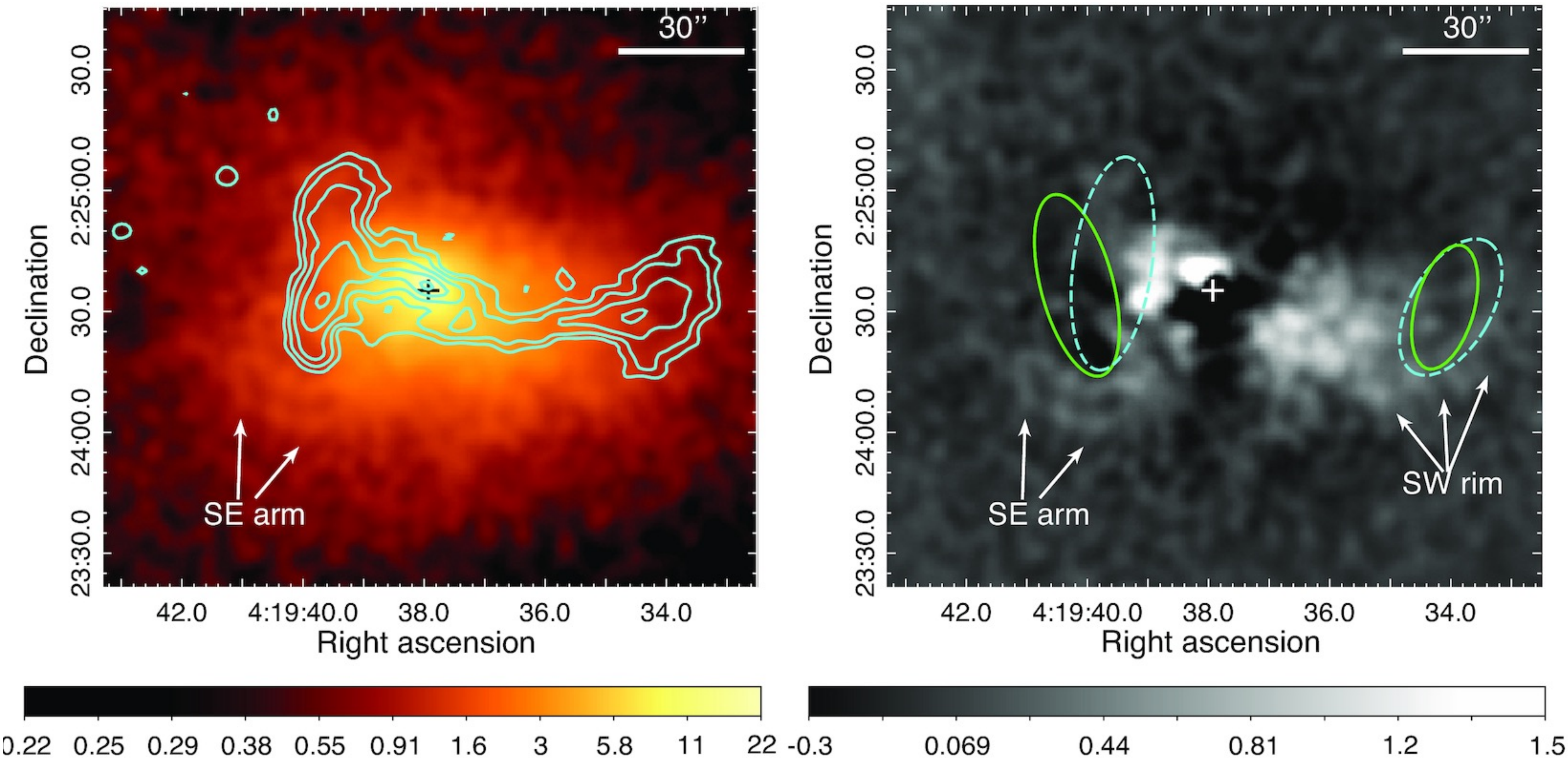
Optical + GMRT radio



Kolokythas et al. 2020

Chandra X-ray + GMRT radio

unsharp-masked Chandra



Kolokythas et al. 2020

Consider NGC1550 group of galaxies

Velocity dispersion is ~ 310 km/s
Application of the virial theorem yields:

$$\frac{3\mathcal{M}\sigma_r^2}{2} = \mathcal{KE} = -\frac{\mathcal{PE}}{2} = \frac{3\pi}{64}\frac{G\mathcal{M}^2}{a_P}, \quad \text{so } \mathcal{M} \approx 2 \times 10^{13}\mathcal{M}_\odot.$$

We can also estimate the X-rays from free-free emission:

$$L_X = n^2\Lambda(T_X), \quad \text{where } \Lambda \approx 3 \times 10^{-27} T_X^{1/2} \text{erg s}^{-1}.$$

Hydrostatic equilibrium tells us how much gravity is needed to keep the hot gas from blowing away:

$$\frac{dp}{dr} = -\rho(r)\frac{G\mathcal{M}(<r)}{r^2}.$$

Worksheet: Use hydrostatic equilibrium and the ideal gas law derive the mass of the NGC 1550 cluster assuming T = 1.6 x 10^7 K, and $\rho(r) \propto r^{-1.1}$ out to 200 kpc

Ways to measure Cluster mass?

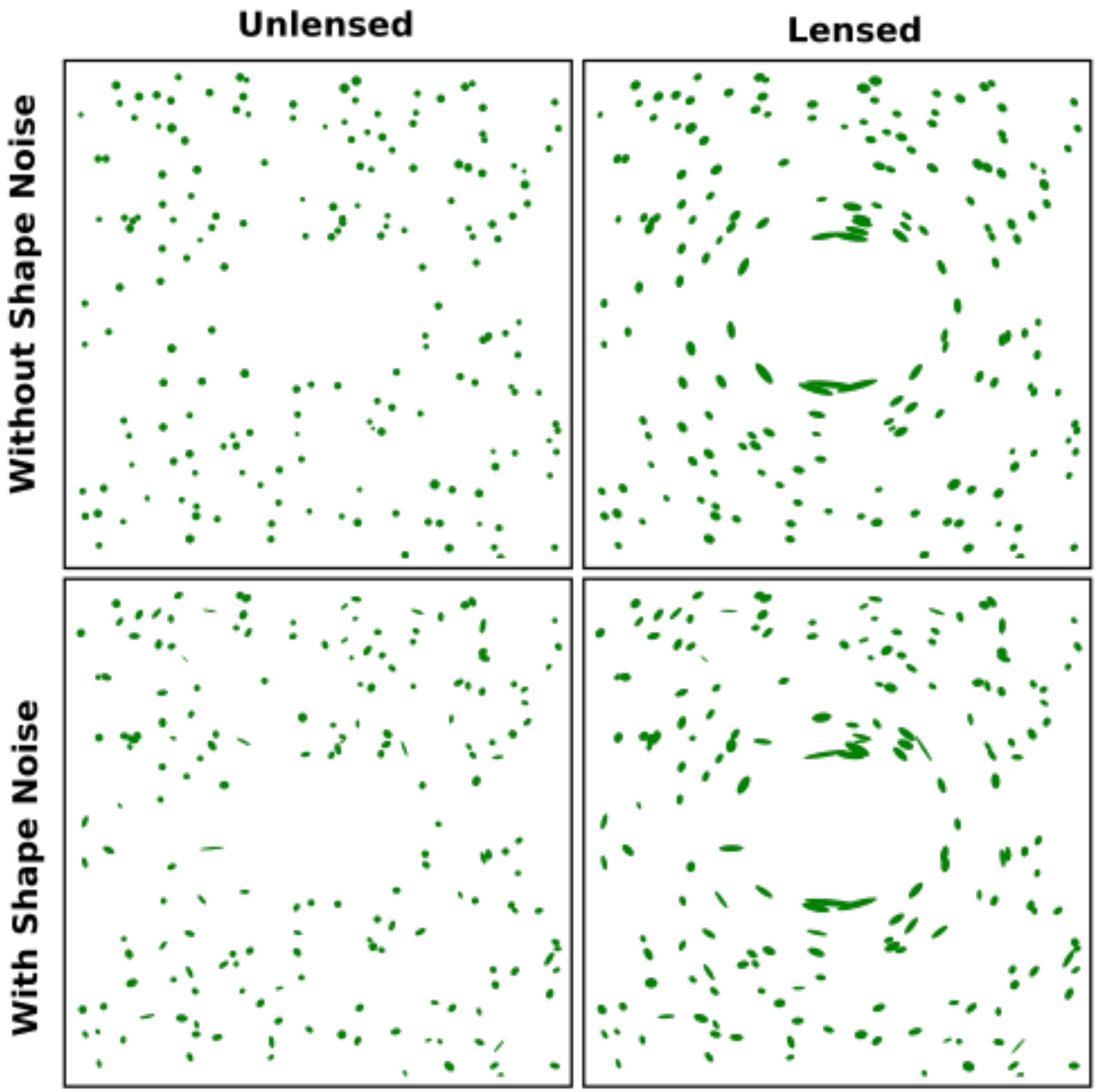
- X-ray luminosity of the hot gas [see previous slides]

- Gravitational lensing (strong and weak)
- S-Z effect
- Faraday rotation

Strong lensing. The gravity of a foreground cluster of galaxies distorts the images of background galaxies into arcs

Saturn-mass
black hole

Weak Lensing



Strong and Weak Lensing of the bullet cluster

Blue = mass from lensing; Red = X-rays from hot gas

Journal Class

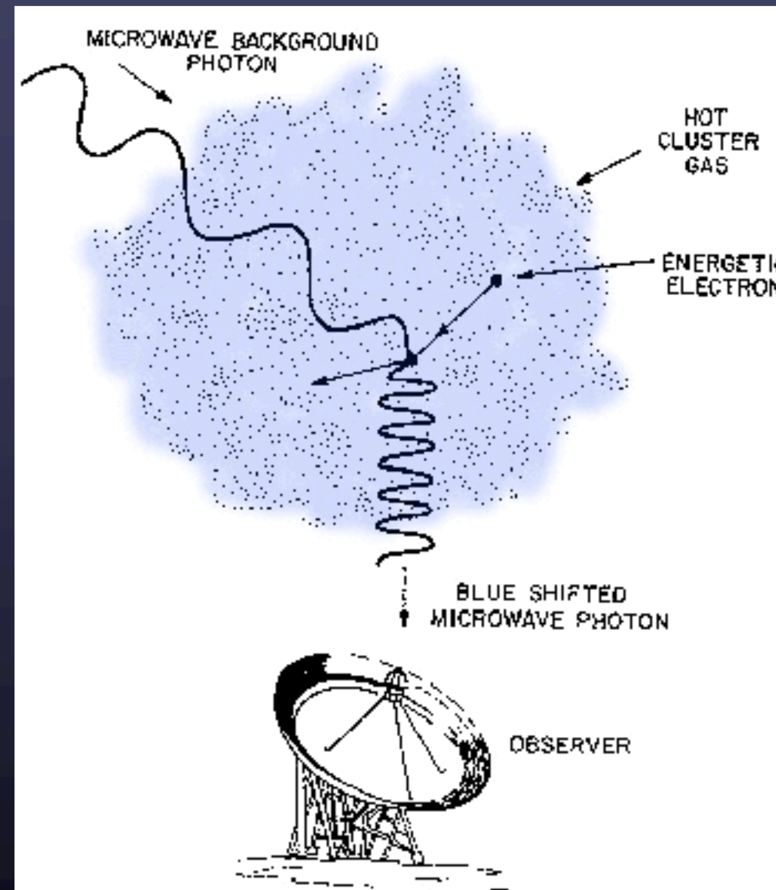
- **The Bullet cluster at its best: weighing stars, gas, and dark matter**
- Paraficz et al. 2016

Discussion leader: **Izabela Pavel**

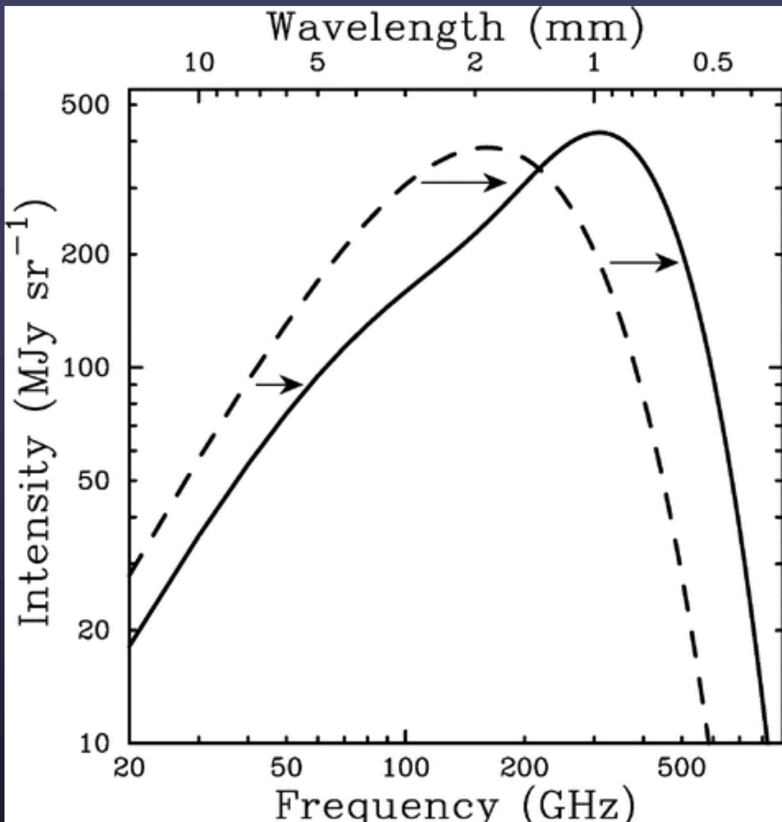
Note: To encourage discussion everybody must pose at least one question during the group discussion

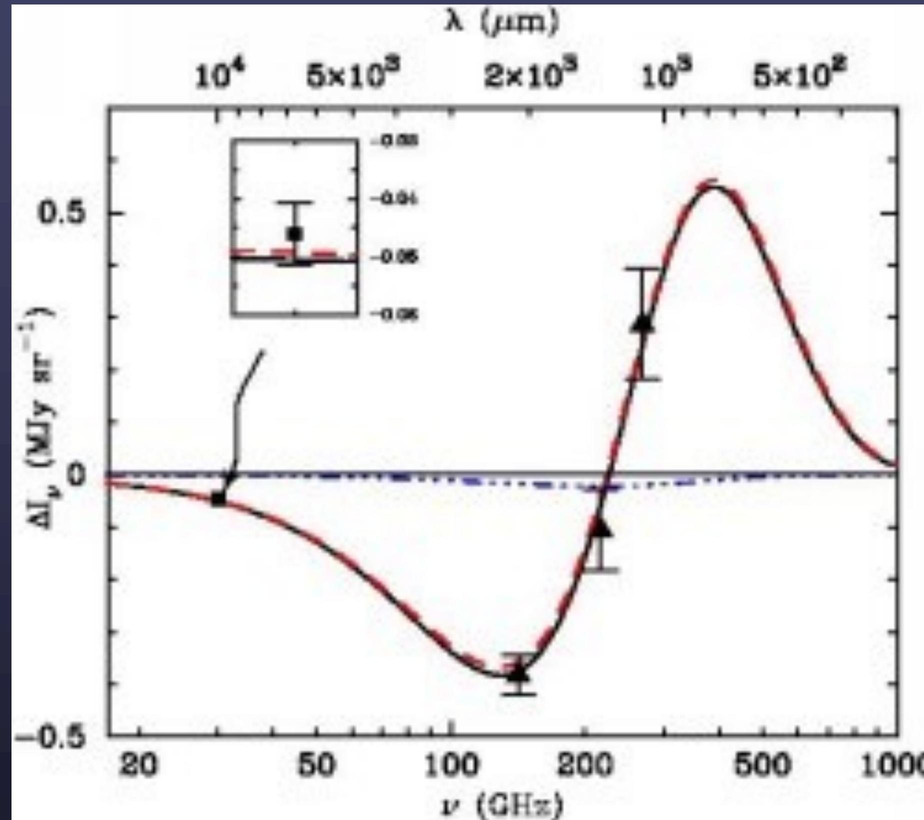
Sunyaev-Zeldovich effect

- The Sunyaev-Zeldovich effect
  - Photons of the CMB are scattered to higher frequencies by hot electrons in galaxy clusters, causing a negative brightness **decrement**.
  - Decrement is proportional to integral of electron pressure through the cluster, or electron density if cluster is isothermal.
  - Electron density and temperature can be estimated from X-ray observations, so the linear scale of the cluster is determined.
  - This can be used to measure the cluster distance and combined with z to get H_0.



Sunyaev-Zeldovich effect





SZ images

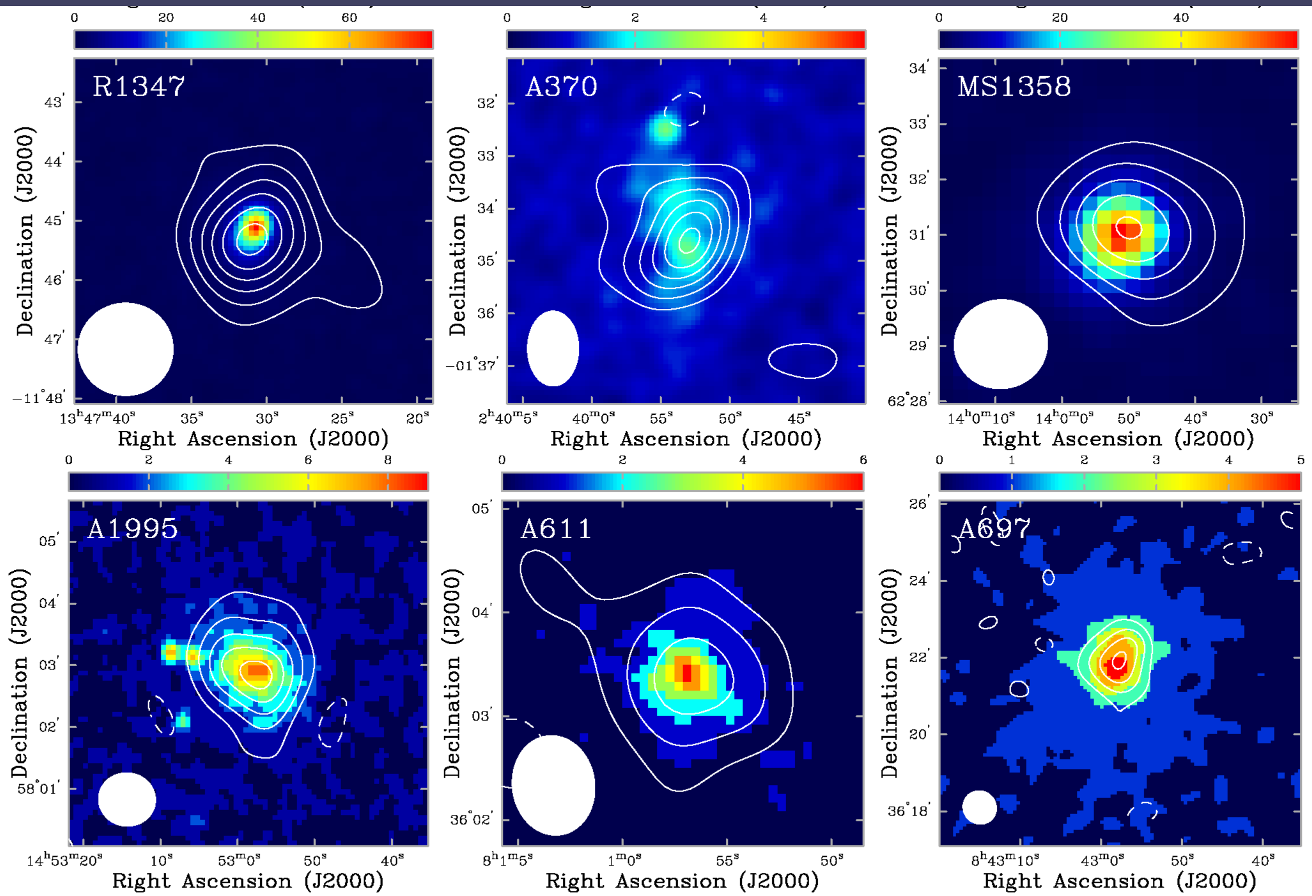


FIG. 2.—SZE (contours) and X-ray (color scale) images of each cluster in our sample. Negative contours are shown as solid lines. The contours are multiples of 2 σ and the FWHM of the synthesized beams are shown in the bottom left corner. The X-ray color scale images are raw counts images smoothed with Gaussians with $\sigma = 15''$ for PSPC data and $\sigma = 5''$ for HRI data. There is a color scale mapping for the counts above each image. The 30 GHz image statistics are summarized in Table 4.

Reese et al. astro-ph/0205350

Thermal SZ effect

The Astrophysical Journal, 647:25–54, 2006 August 10

DETERMINATION OF THE COSMIC DISTANCE SCALE FROM SUNYAEV-ZEL'DOVICH EFFECT AND *CHANDRA* X-RAY MEASUREMENTS OF HIGH-REDSHIFT GALAXY CLUSTERS

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Erik D. Reese,[5] and Kyle S. Dawson[6]
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ABSTRACT

We determine the distance to 38 clusters of galaxies in the redshift range $0.14 \le z \le 0.89$ using X-ray data from *Chandra* and Sunyaev-Zeldovich effect (SZE) data from the Owens Valley Radio Observatory and the Berkeley-Illinois-Maryland Association interferometric arrays. The cluster plasma and dark matter distributions are analyzed using a hydrostatic equilibrium model that accounts for radial variations in density, temperature, and abundance, and the statistical and systematic errors of this method are quantified. The analysis is performed via a Markov chain Monte Carlo technique that provides simultaneous estimation of all model parameters. We measure a Hubble constant of $H_0 = 76.9^{+3.9}_{-3.4}{}^{+10.0}_{-8.0}$ km s^{-1} Mpc^{-1} (statistical followed by systematic uncertainty at 68% confidence) for an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology. We also analyze the data using an isothermal β-model that does not invoke the hydrostatic equilibrium assumption and find $H_0 = 73.7^{+4.6}_{-3.8}{}^{+9.5}_{-7.6}$ km s^{-1} Mpc^{-1}; to avoid effects from cool cores in clusters, we repeated this analysis excluding the central 100 kpc from the X-ray data and find $H_0 = 77.6^{+4.8}_{-4.3}{}^{+10.1}_{-8.2}$ km s^{-1} Mpc^{-1} (statistical followed by systematic uncertainty at 68% confidence). The consistency between the models illustrates the relative insensitivity of SZE/X-ray determinations of H_0 to the details of the cluster model. Our determination of the Hubble parameter in the distant universe agrees with the recent measurement from the *Hubble Space Telescope* Key Project that probes the nearby universe.

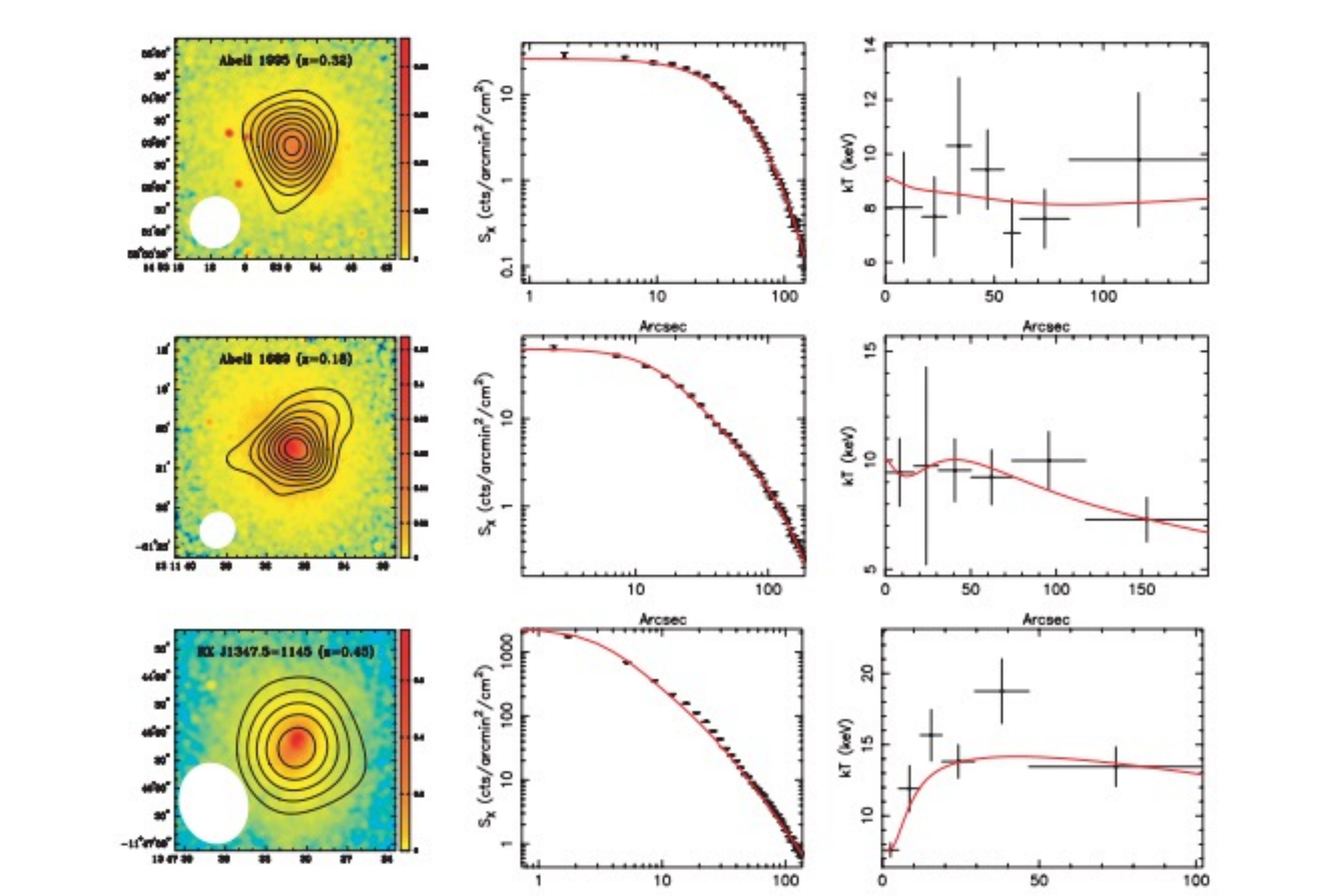
Subject headings: cosmic microwave background — distance scale — X-rays: galaxies: clusters

Online material: color figures, machine-readable table

$$H_0 = 76.9^{+3.9}_{-3.4}{}^{+10.0}_{-8.0}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

The University of New Mexico

SZ profiles


Abell 1995 (z=0.32)
Abell 1689 (z=0.18)
RX J1347.5-1145 (z=0.45)
Arcsec
kT (keV)

SZ Results

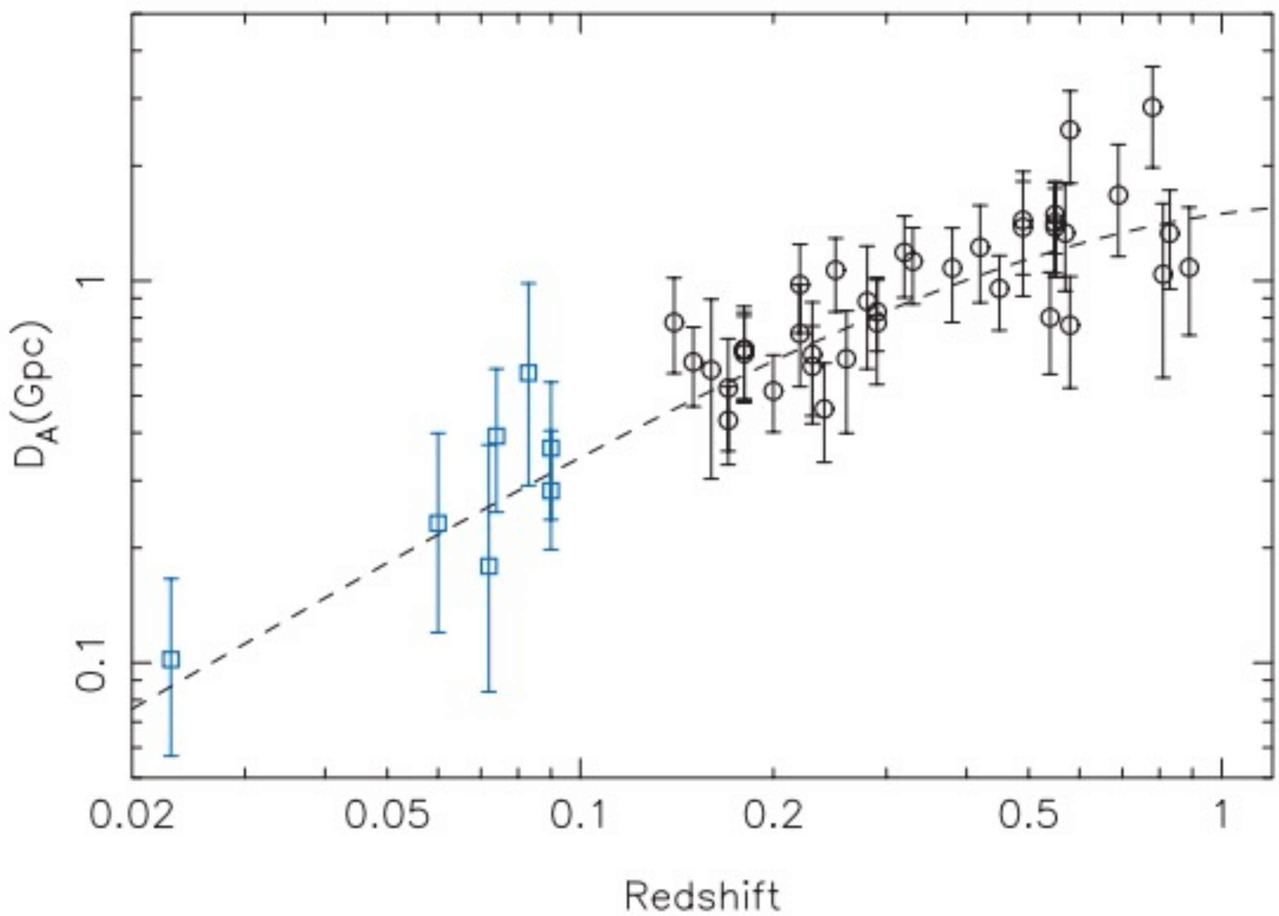


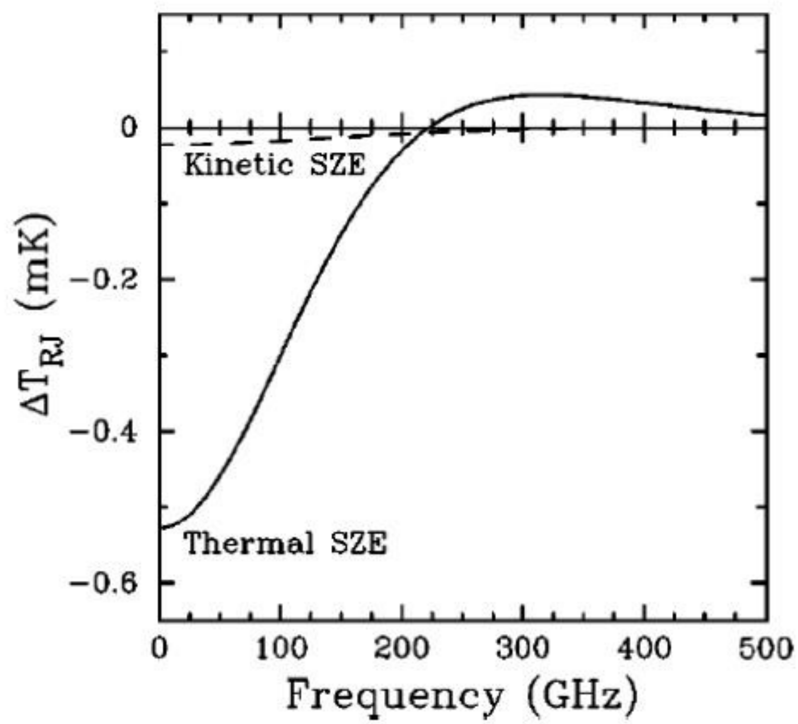
FIG. 3.—Angular diameter distances of the 38 clusters (*circles*). The error bars are the total statistical uncertainties, obtained by combining the X-ray and SZE data modeling uncertainties (Table 2) and the additional sources of random error described in § 3.3 and Table 3. The systematic errors of Table 3 are not shown. The dashed line is the angular diameter curve using the best-fit Hubble constant $H_0 = 76.9$ km s^{-1} Mpc^{-1} and $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$. The squares are from the low-redshift sample of Mason et al. (2001), and they are not included in the fit.

kSZ Effect

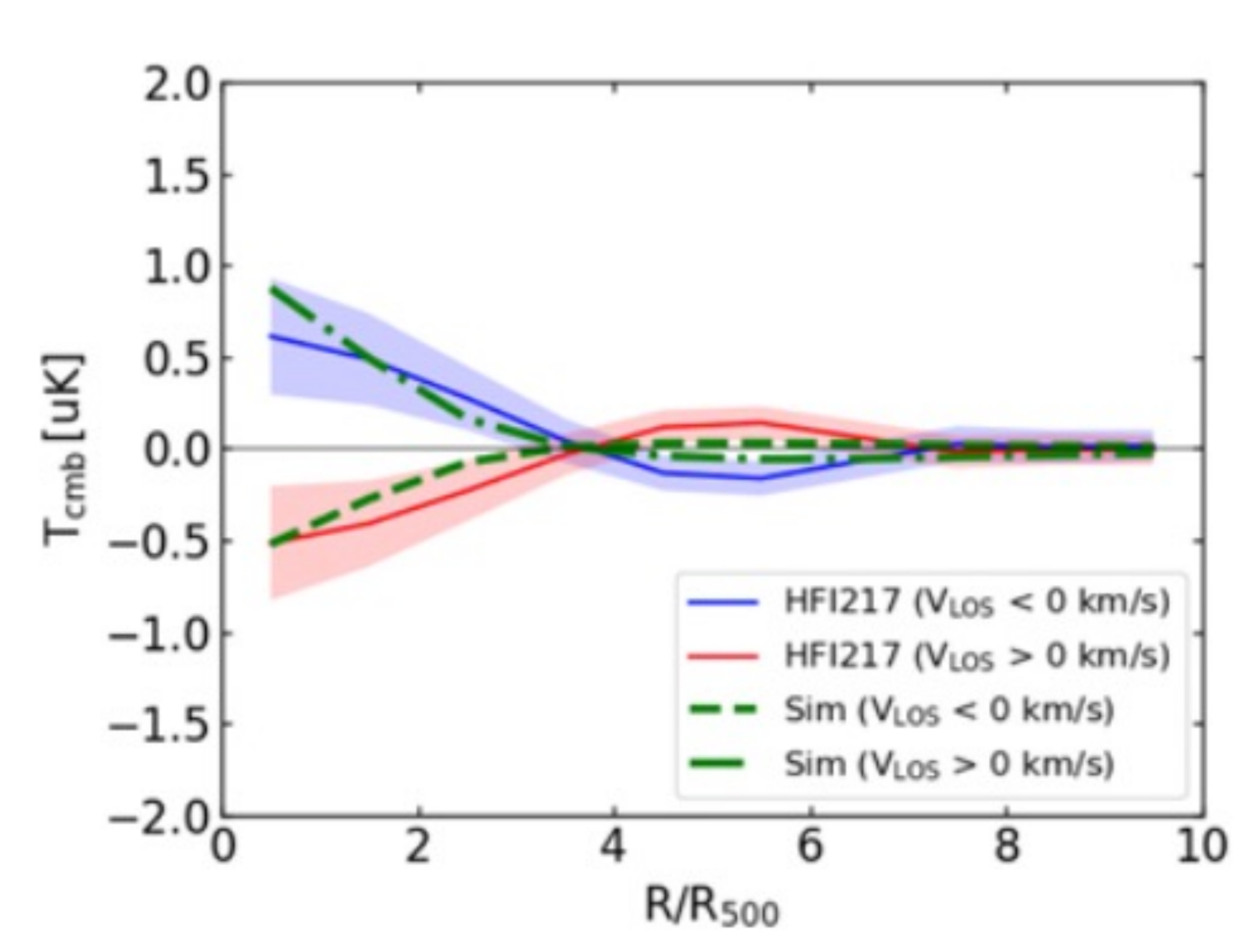
The Doppler effect of line of sight cluster velocity -> observed shift of the CMB spectrum.

In the nonrelativistic limit, the spectral signature of the kinetic SZE is a pure thermal distortion of magnitude of the CMB signal:

$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c} \right)$$



Kinetic SZ Results



Tanimura et al. 2021

Effects of the Environment on Galaxy Type

- Spirals are generally found in galaxy groups
- Ellipticals are more prevalent in rich clusters
- cD galaxies are only found at the center of rich clusters

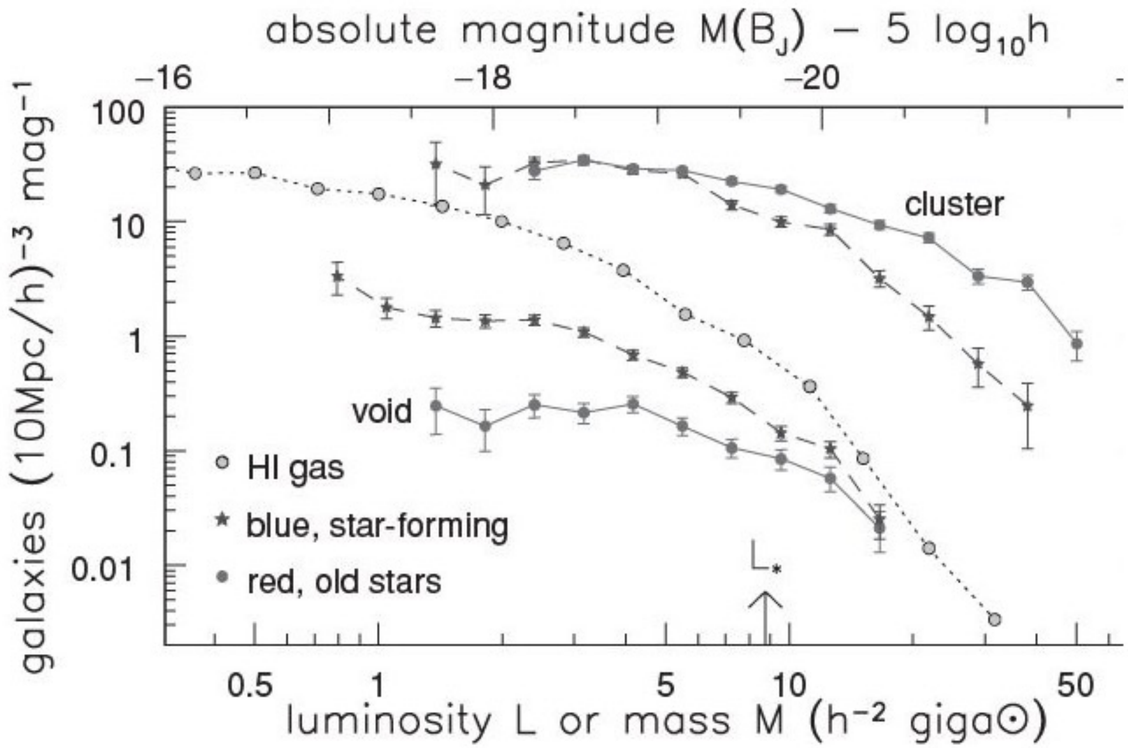


Fig. 7.11. Luminosity functions of blue star-forming galaxies (stars) and red galaxies (filled dots). Bright red galaxies predominate in clusters, but dim blue galaxies are more frequent in the low-density field or void regions. Clouds of neutral hydrogen, found in low-density regions, resemble blue galaxies in that small systems are far more common than big ones – D. Croton, 2dF survey; M. Zwaan, HIPASS.

Hot Gas in Clusters

- There is lots of gas, in the richest clusters up to 10 times more than in stars

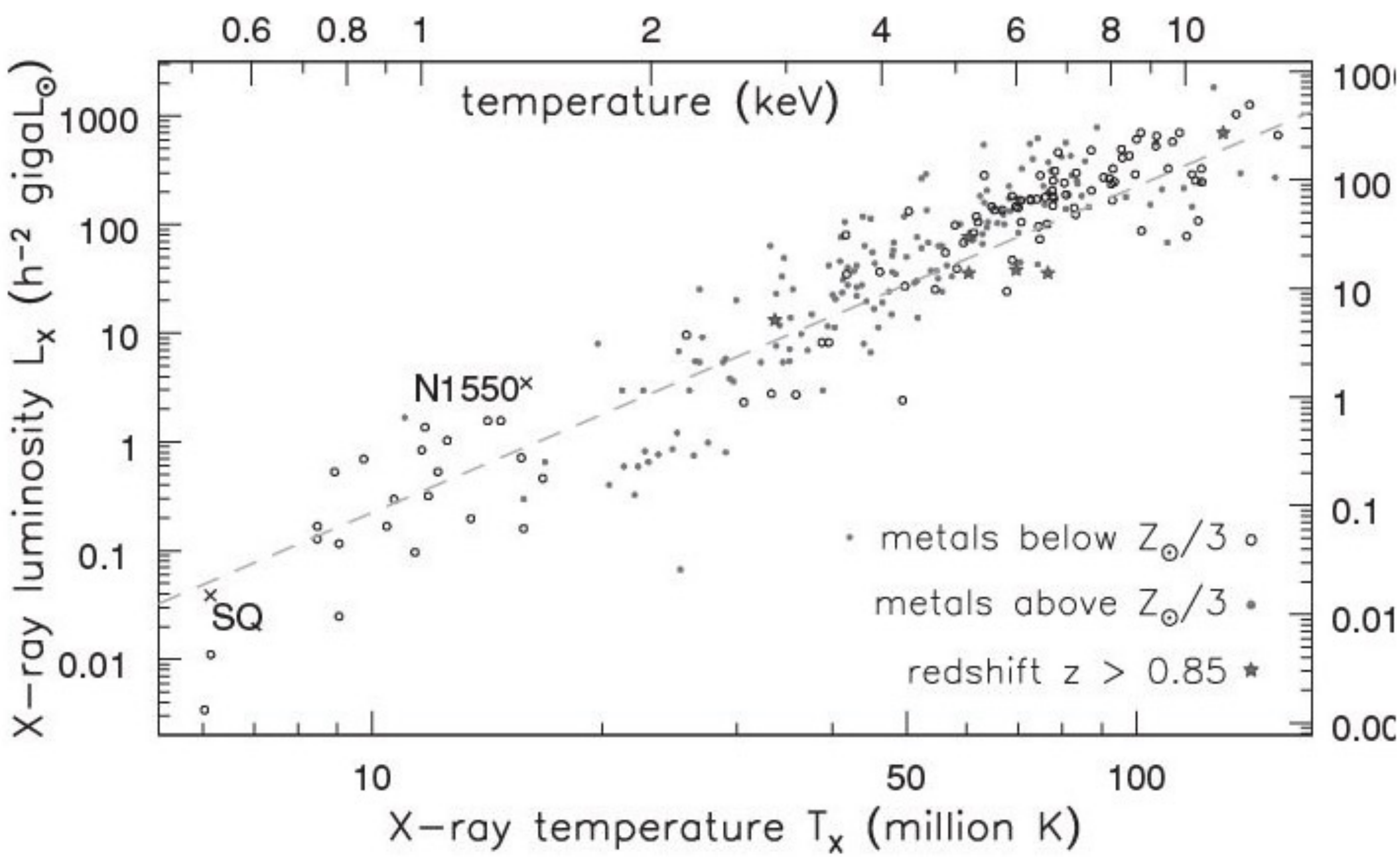


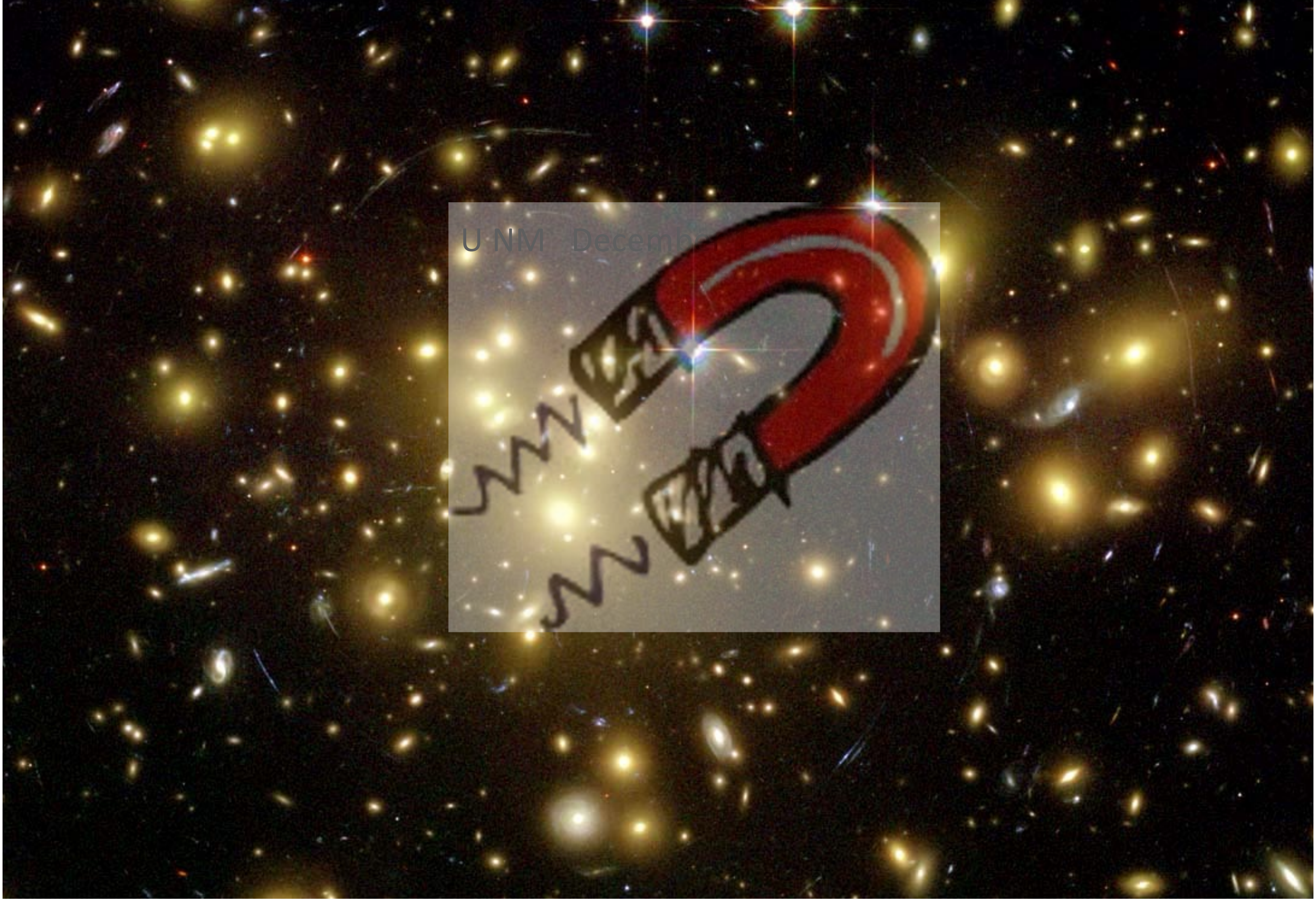
Fig. 7.12. The X-ray luminosity L_X of a galaxy cluster or group, in units of the Sun's bolometric luminosity, increases with the gas temperature T_X: the dashed line shows $L_X \propto T_X^3$. Stephan's Quintet and the NGC 1550 group follow the same trend. This relation has changed little since redshift $z \approx 1$. In most clusters with $T_X > 3 \times 10^7$ K, the gas has roughly one-third of the solar content of iron – D. Horner.

Hot Gas in Clusters

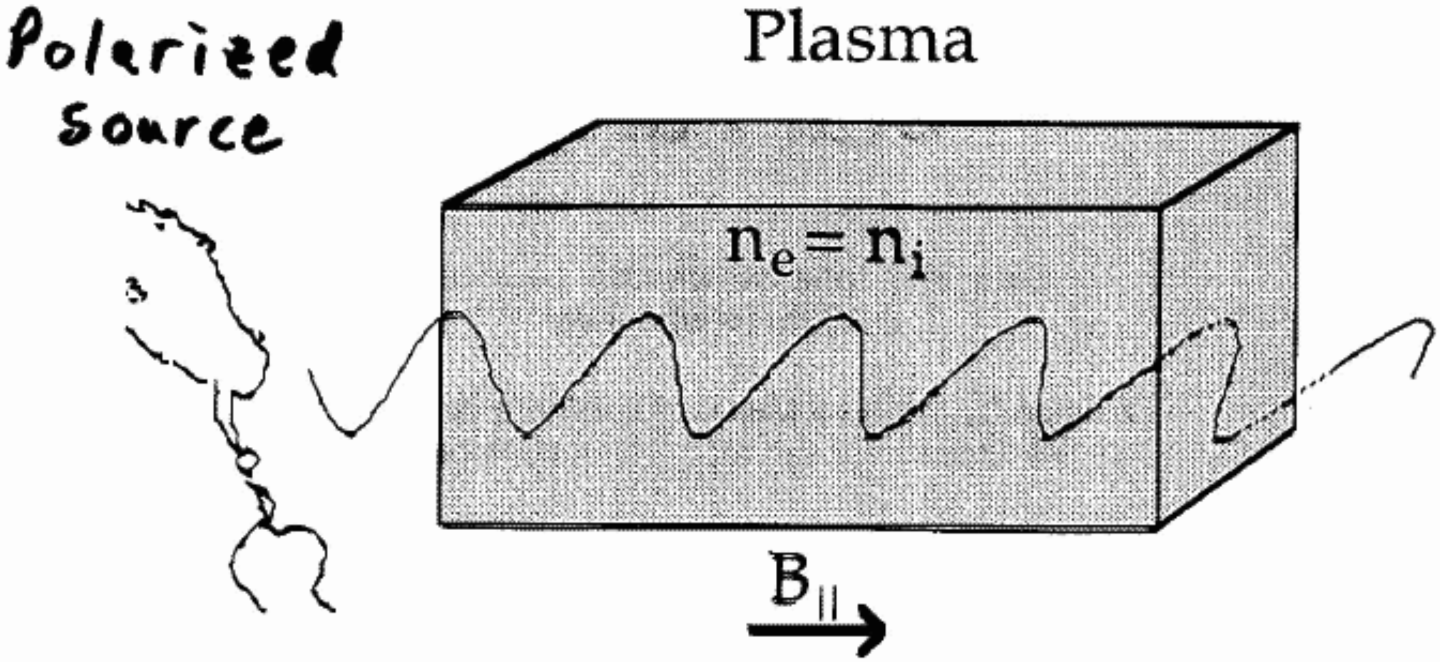
- The gas is densest near the center of the cluster, and drops off
With radius as you might expect
Since X-ray emission goes as n^2 the gas at the center should cool,
Generate optical line emission, and form molecular gas and stars
There is some evidence for cooler gas, but not enough

$$t_{\rm cool} = \frac{3nk_{\rm B}T}{3\times 10^{-27}n^2\sqrt{T}}\ {\rm s} \approx 14\left(\frac{10^{-3}\ {\rm cm}^{-3}}{n}\right)\left(\frac{10^{7}\ {\rm K}}{T}\right)^{1/2}\ {\rm Gyr}.$$

Clusters are Very Large Magnets



Faraday Rotation

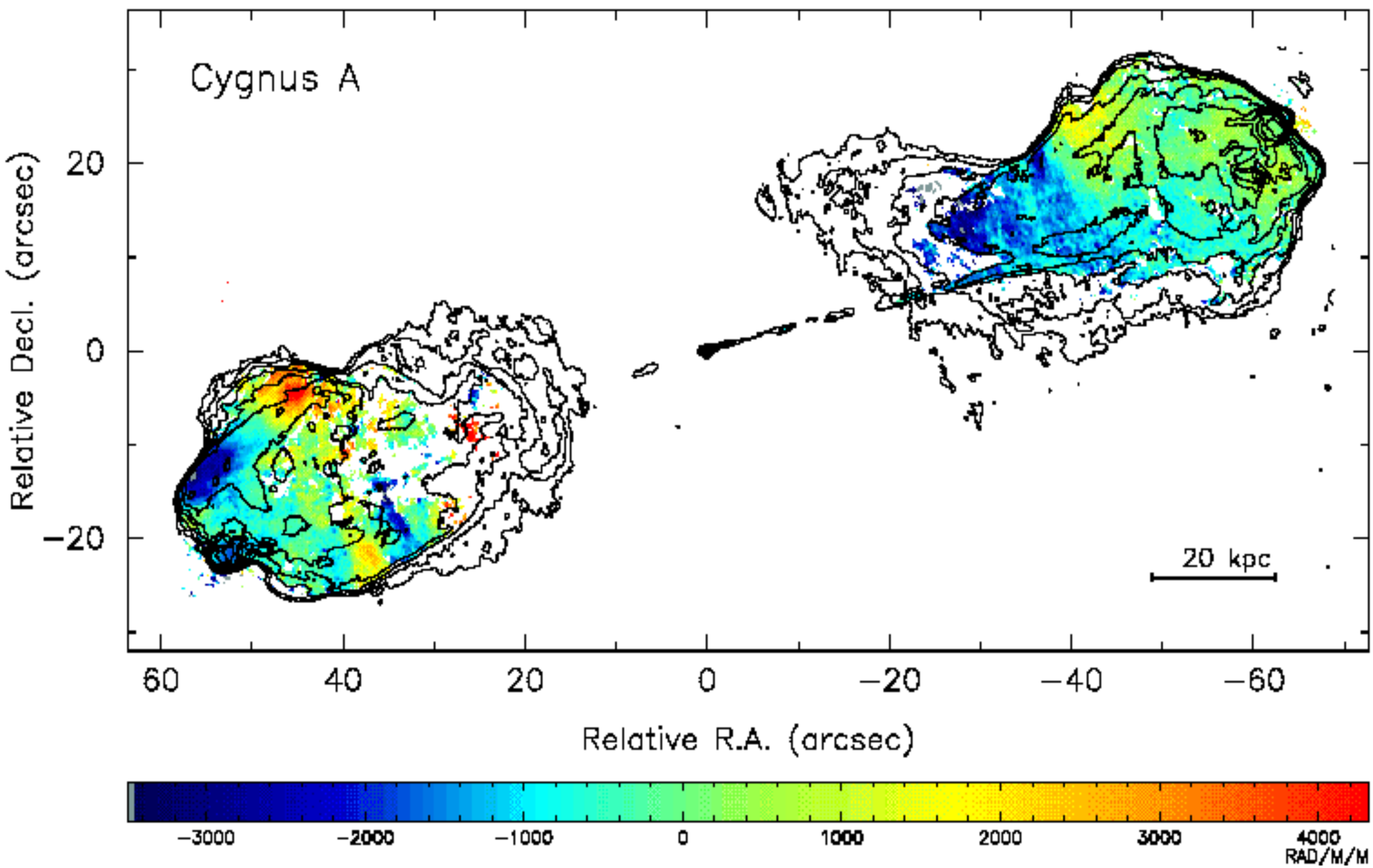


$$\Psi = \Psi_o + \mathrm{RM}\,\lambda^2$$

kpc
μGauss

$$\mathrm{RM} = 812 \int_0^L n_e B_{||}\, dl \ \text{radians/m}^2$$

cm^{-3}

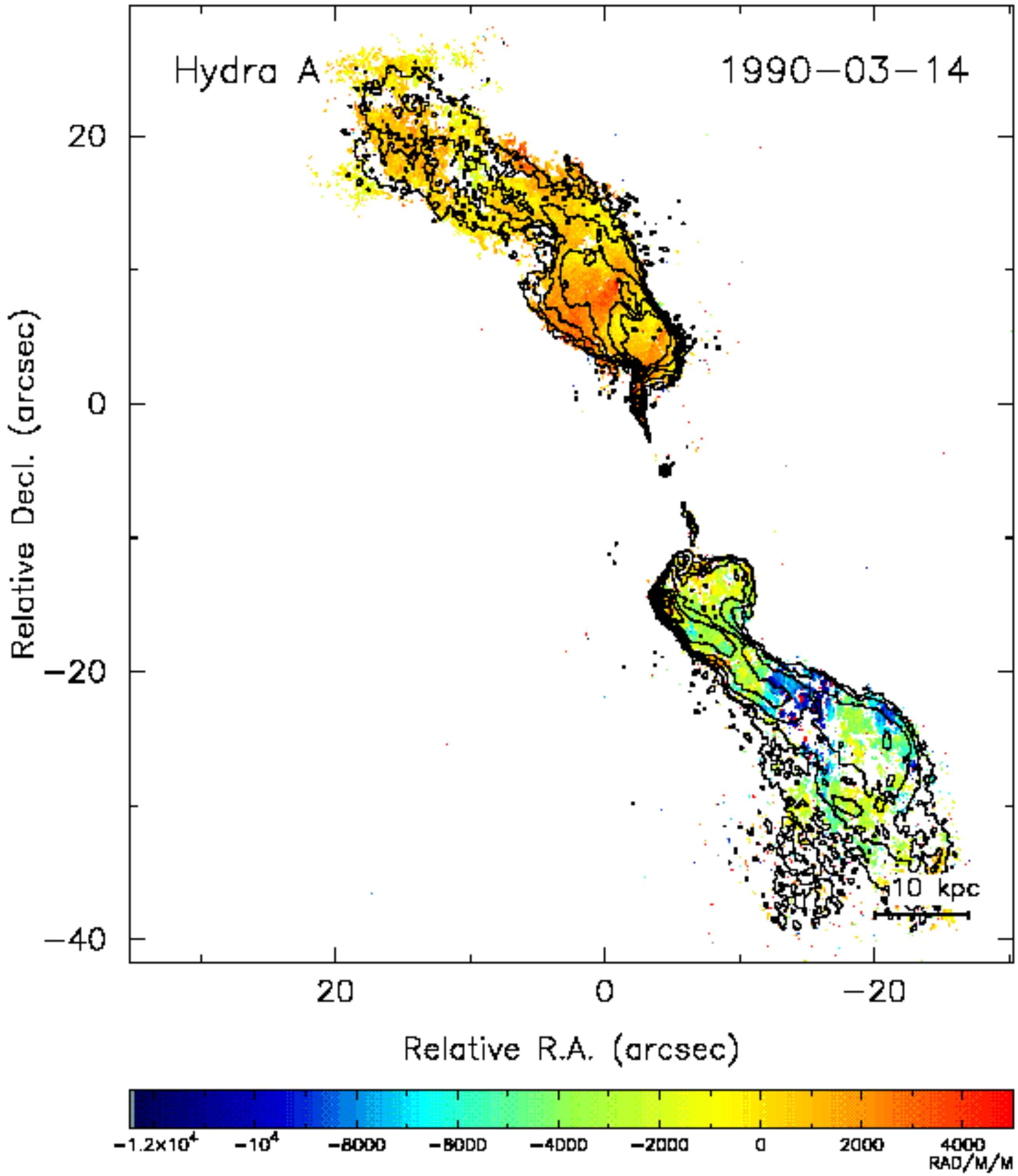


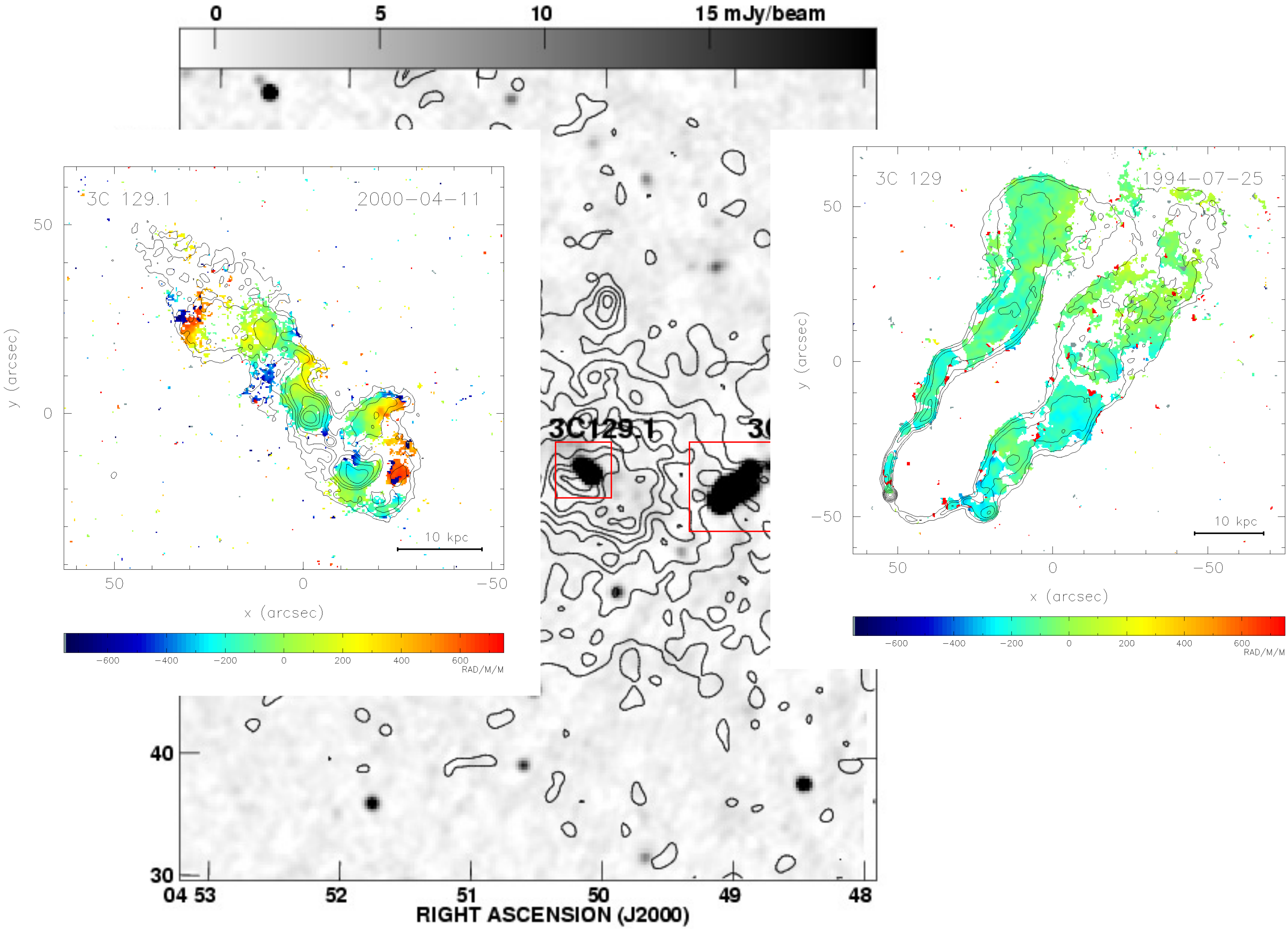
Carilli & Taylor 2002 (ARA&A)

Hydra A

Faraday Rotation Measures

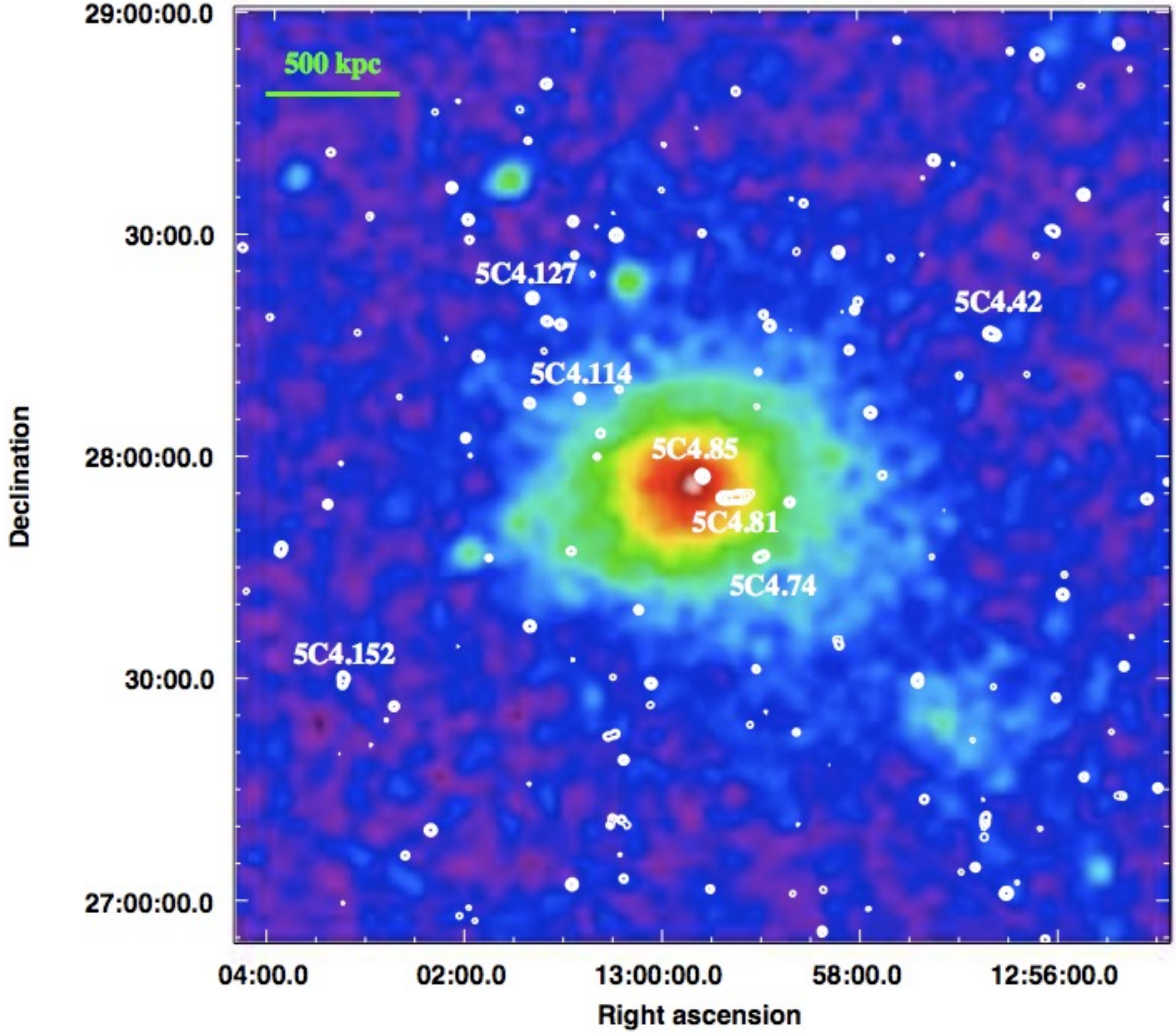
B ~ 30 μG



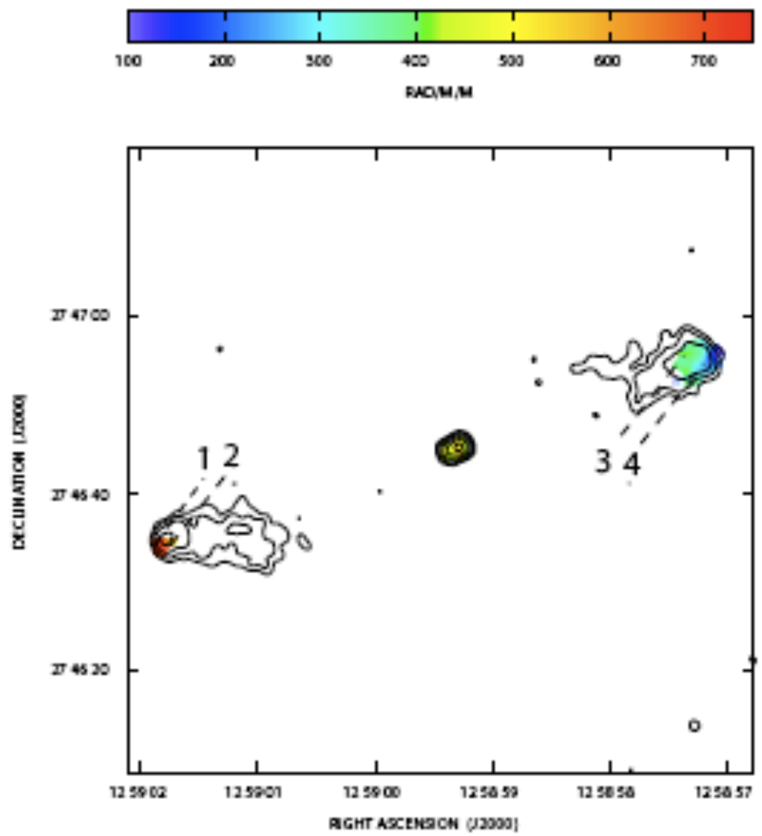

0
5
10
15 mJy/beam
3C129.1
3C 129.1
2000−04−11
y (arcsec)
x (arcsec)
10 kpc
RAD/M/M
3C 129
1994−07−25
40
30
04 53
52
51
50
49
48
RIGHT ASCENSION (J2000)

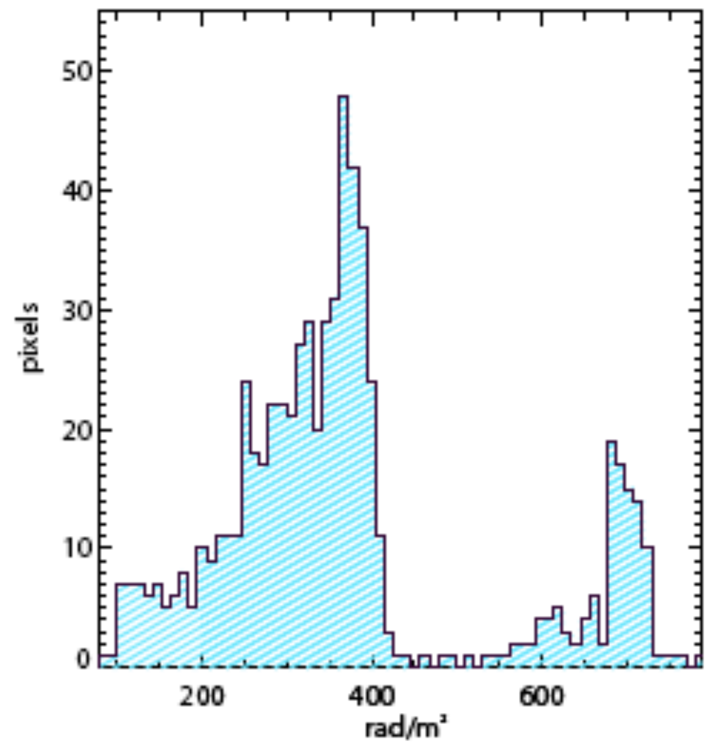
Coma

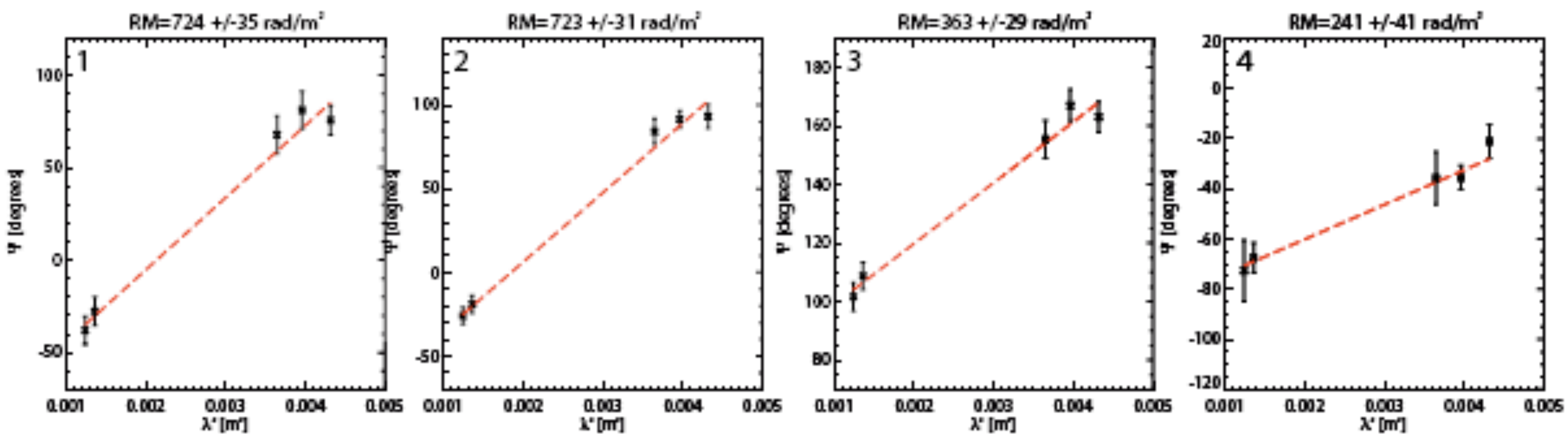
X-ray
+
radio



5C4.74 in Coma





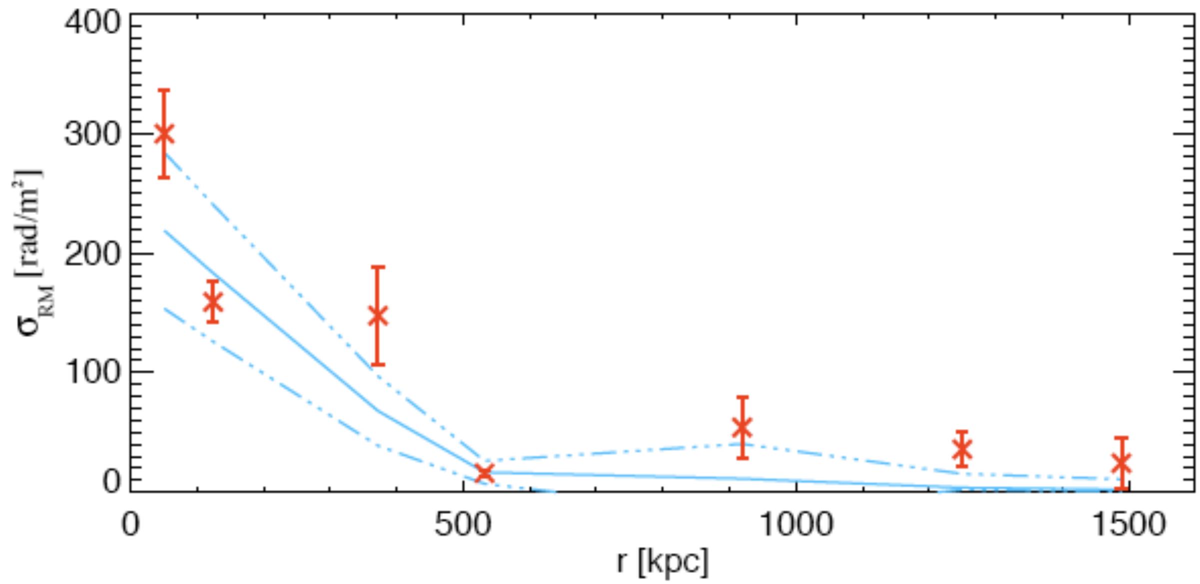


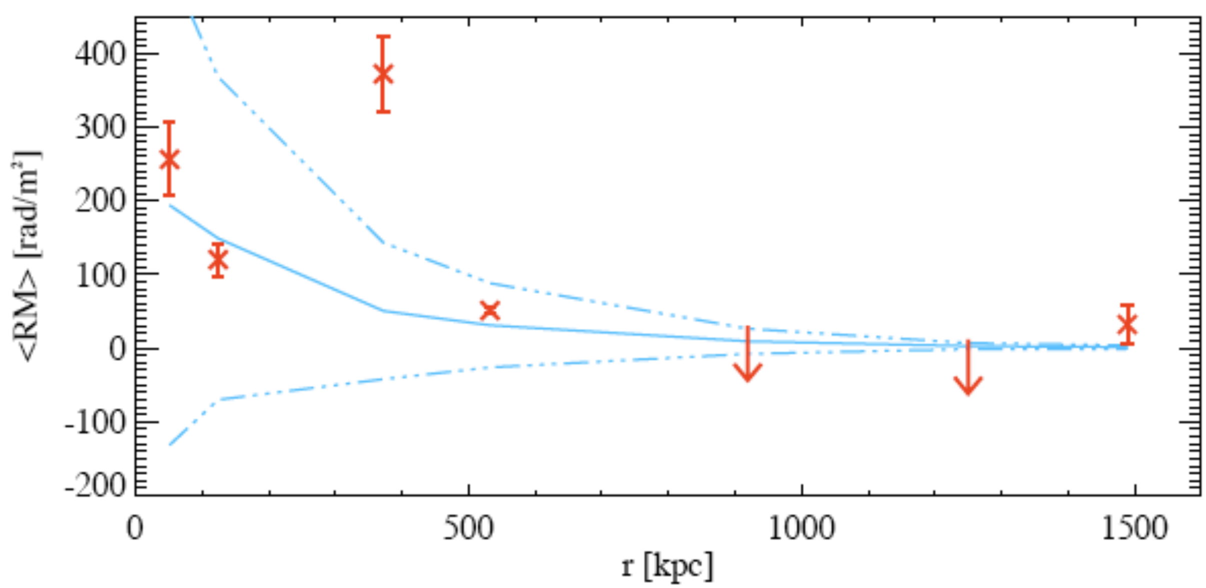
Results

B_0 = 4.6 +/- 0.7 μG

scale lengths between 2 and 30 kpc

average B ~ 2 μG





Bonafede et al. 2009