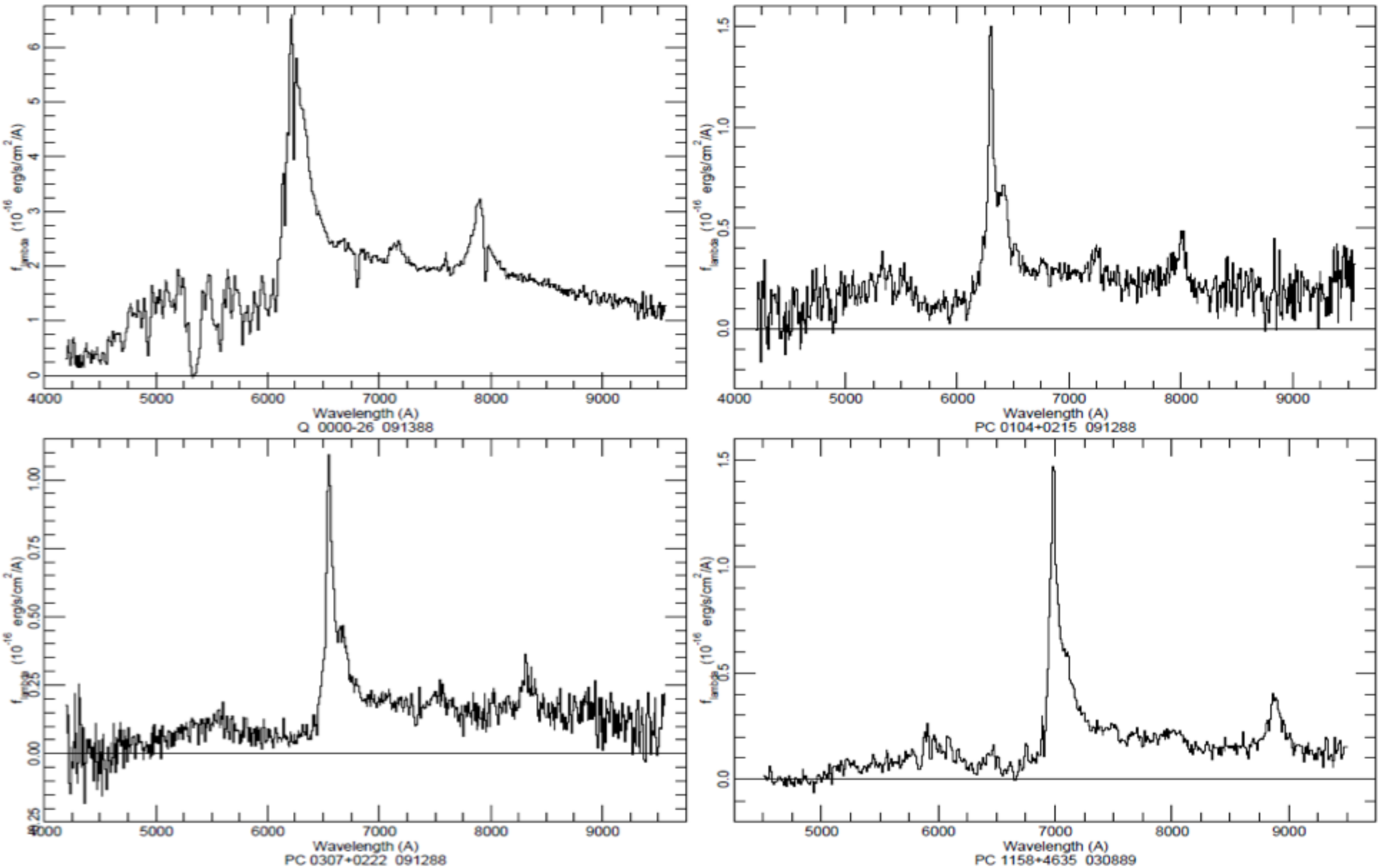
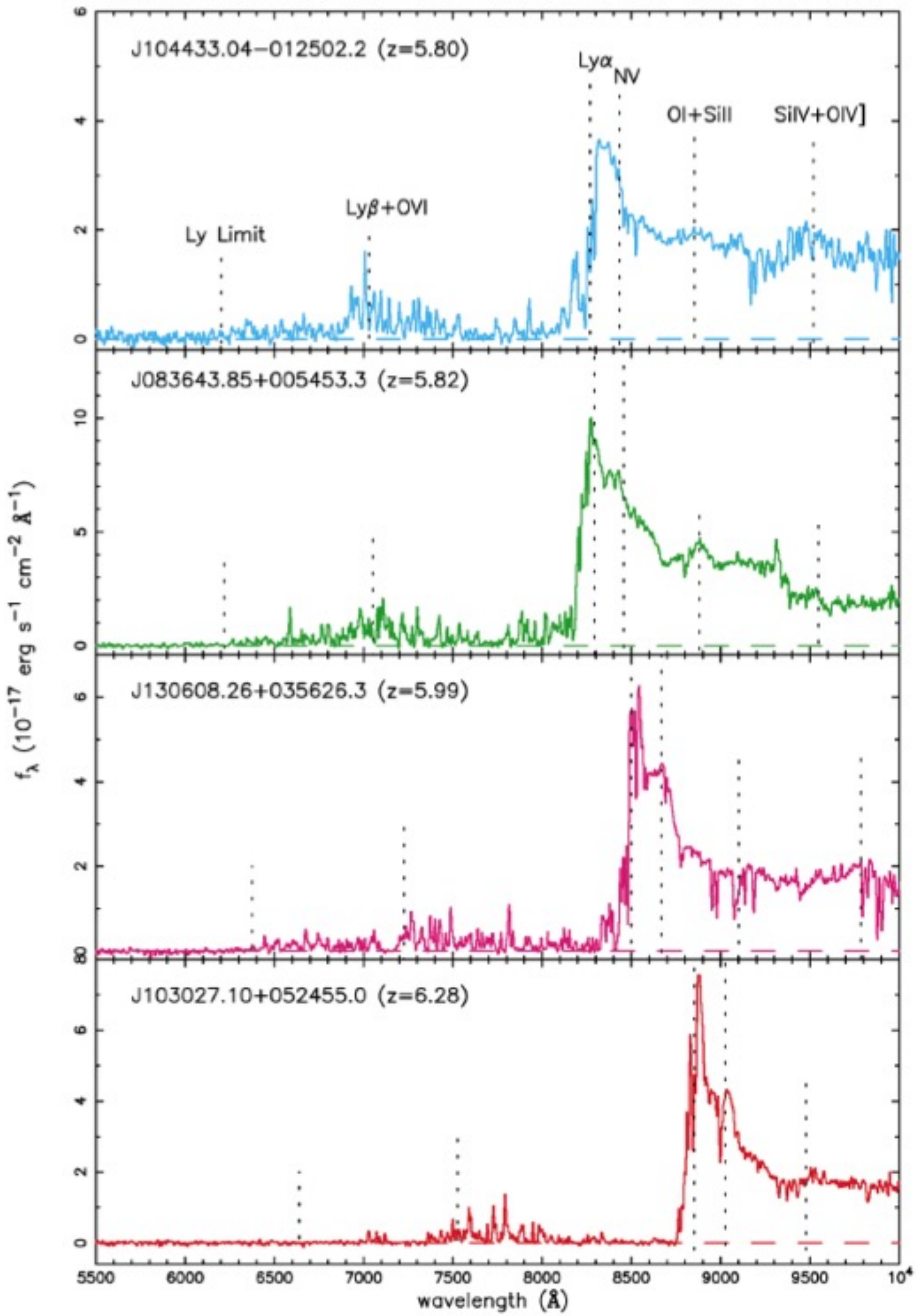
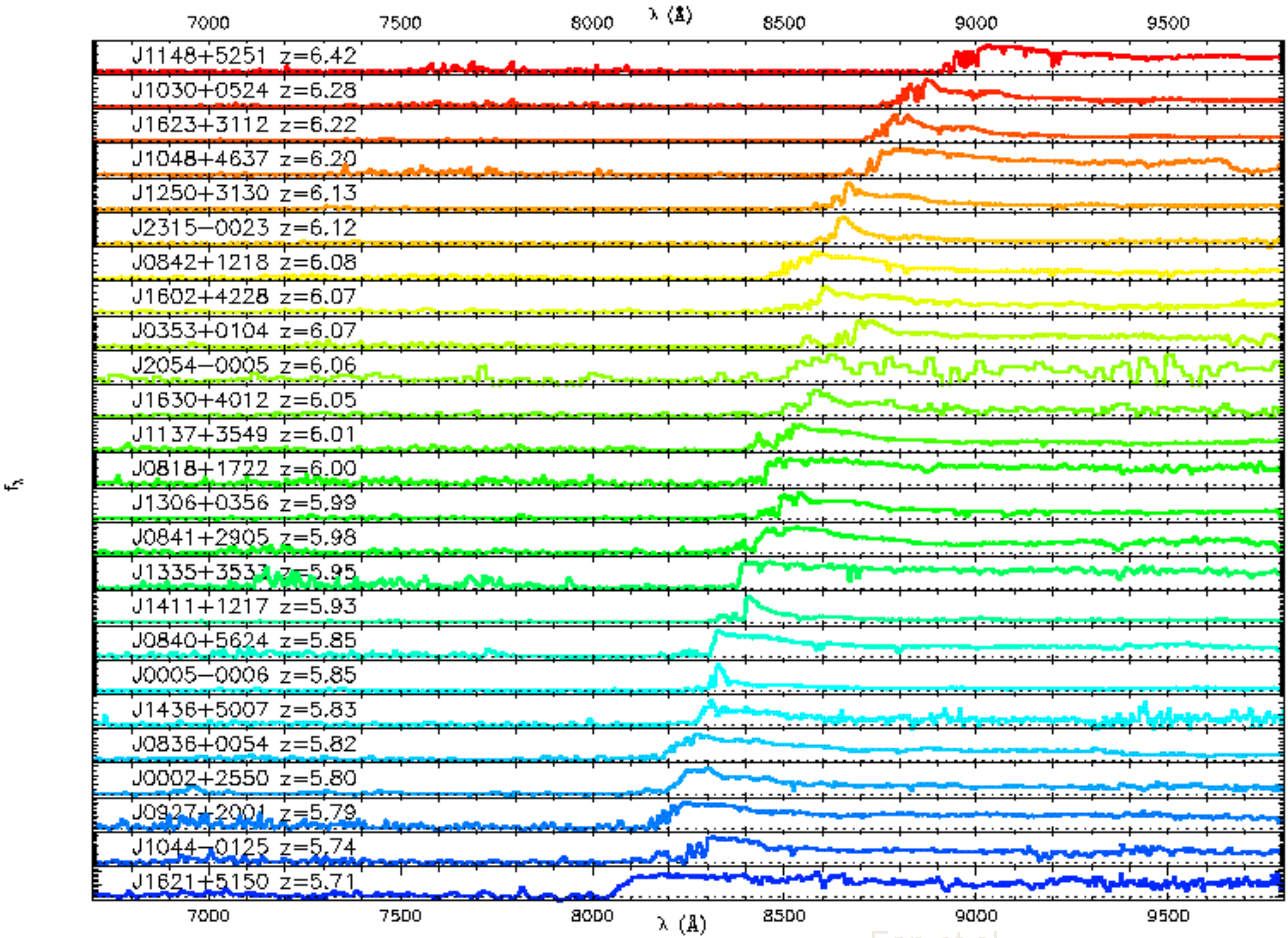
Indications of rapid increase of H I Opacity at z ~ 4





Detection of Gunn-Peterson Troughs in z ~ 6 Quasars in 2001

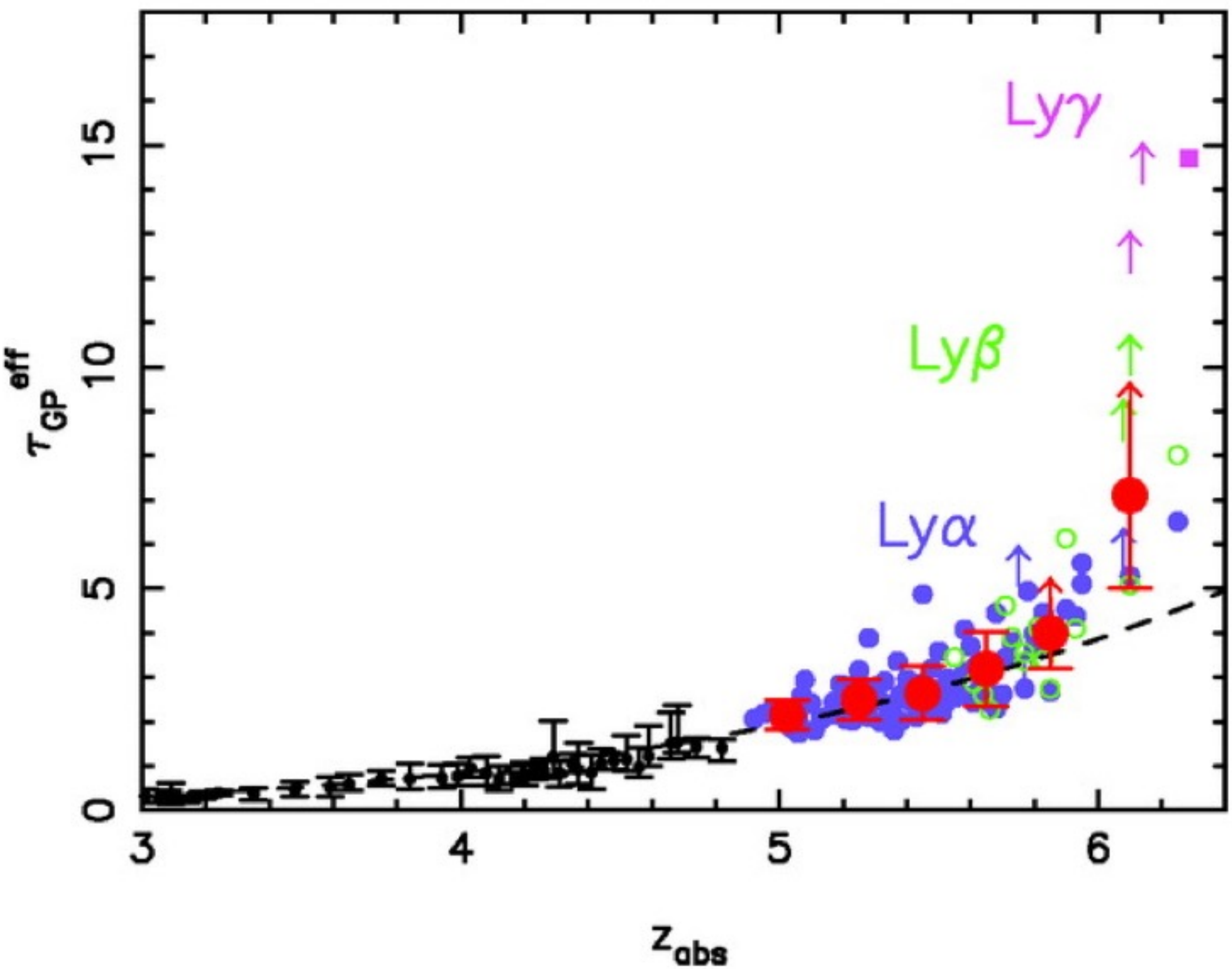
Becker et al (2001)



λ (Å)
7000
7500
8000
8500
9000
9500
J1148+5251 z=6.42
J1030+0524 z=6.28
J1623+3112 z=6.22
J1048+4637 z=6.20
J1250+3130 z=6.13
J2315−0023 z=6.12
J0842+1218 z=6.08
J1602+4228 z=6.07
J0353+0104 z=6.07
J2054−0005 z=6.06
J1630+4012 z=6.05
J1137+3549 z=6.01
J0818+1722 z=6.00
J1306+0356 z=5.99
J0841+2905 z=5.98
J1335+3533 z=5.95
J1411+1217 z=5.93
J0840+5624 z=5.85
J0005−0006 z=5.85
J1436+5007 z=5.83
J0836+0054 z=5.82
J0002+2550 z=5.80
J0927+2001 z=5.79
J1044−0125 z=5.74
J1621+5150 z=5.71
f_λ

Fan et al.

Rapid increase in H I Opacity at z ~ 6

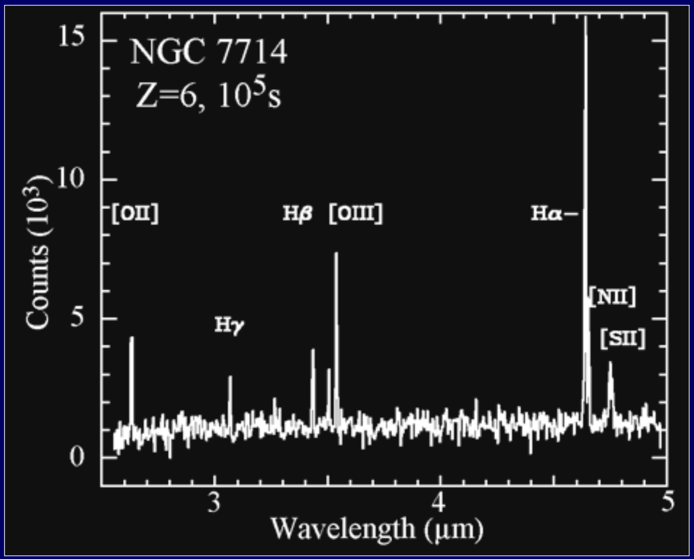


Fan et al (2006)

JWST: The assembly of galaxies

- Where and when did the Hubble Sequence form?
- How did the heavy elements form?
- Can we test hierarchical formation and global scaling relations?
- What about ULIRGs and AGN?

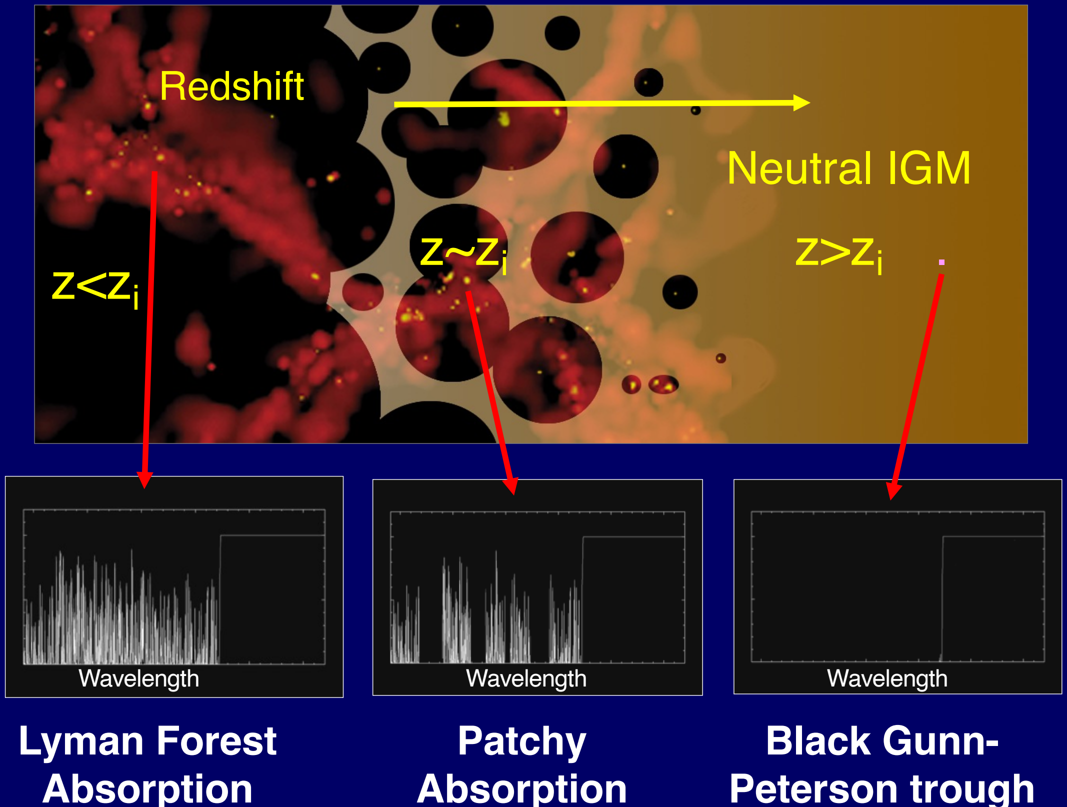
Galaxies in GOODS Field

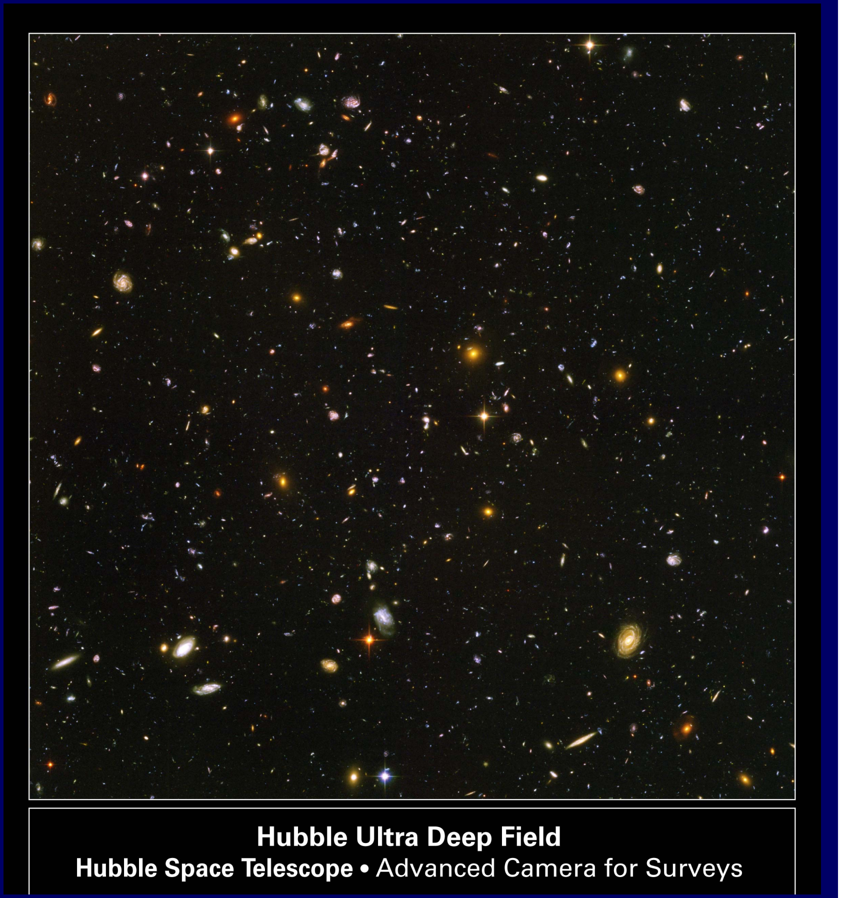


- Wide-area imaging survey
- R=1000 spectra of 1000s of galaxies at 1 < z < 6
- Targeted observations of ULIRGs and AGN

End of the dark ages: first light and reionization

- What are the first galaxies?
- When did reionization occur?
  - Once or twice?
- What sources caused reionization?





- Ultra-Deep NIR survey (1.4 nJy), spectroscopic & Mid-IR confirmation.
- QSO spectra: Ly-α forest
- Galaxy spectra: Balmer lines (2×10^{-19} ergs/cm^2/sec)

Announcements

- Homework #9 due Thursday

Presentation Schedule (RH114)

Dec 3 11:00-12:15

- ○ Dean Montroy (ASU)
- ○ Giovanna Cartagena (MIT)
- ○ Franco Uribe Lavalle (Stanford)
- ❖ Olwyn Hagerty (UCLA)
- ❖ Alex Robinson (Caltech)
- ❖ Mason Winner (UA)
- • Charles Dana (NAU)

Powerpoint talk
Length = 7 min + 2 min Q&A

Send slides to me the day before and I will put them on a presentation laptop (mac).

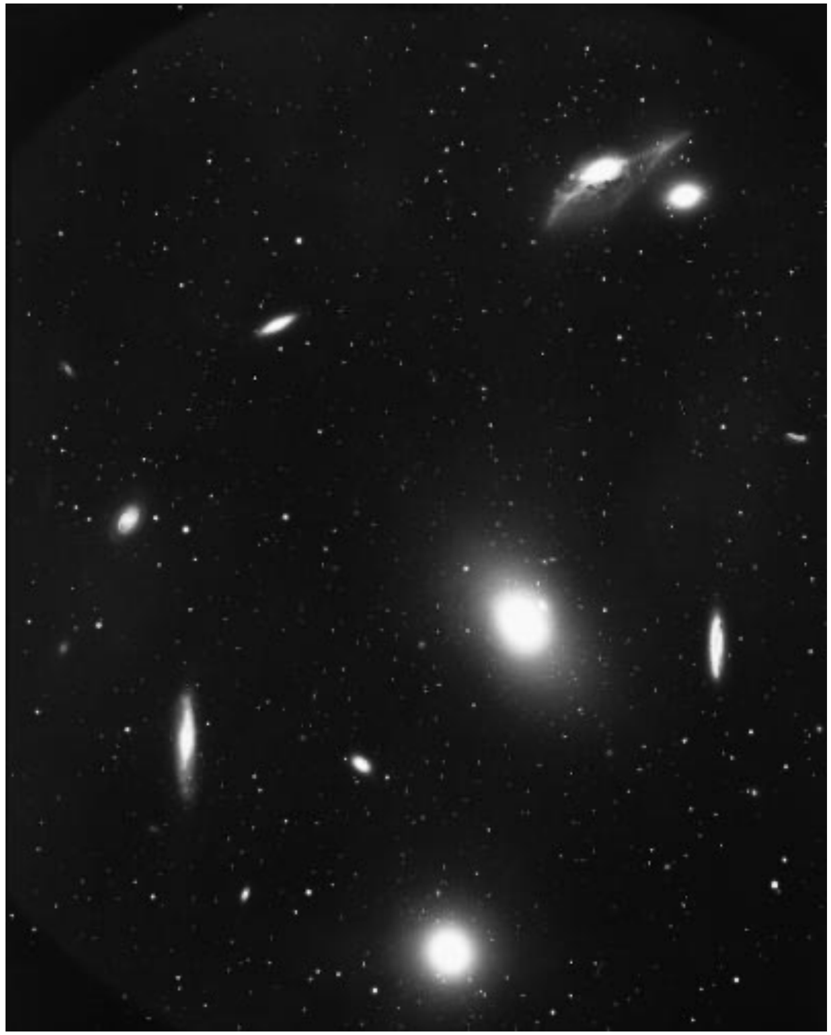
Dec 5 11:00-12:15

- • Govind Sarraf (UNM)
- • Elizabeth Shields (NMSU)
- ❑ Madeline Ayling (UA)
- ❑ Sara Pezzaili (Harvard)
- ❑ Aniketh Sarkar (JHU)
- ▪ Emma Barney (UC Boulder)
- ▪ Louis Jencka (UC Boulder)

Dec 10 12:30-2:30

- ▪ Jacky Privette (Berkeley)
- ➢ Viktoria Aivaliotis (Caltech)
- ➢ Stephanie Paiva-Flynn (ASU)
- ➢ Juaquin Sanchez (UCLA)
- ✓ Santiago Armijo (Berkeley)
- ✓ Arnel Oczon (TTU)

Galaxy Clusters



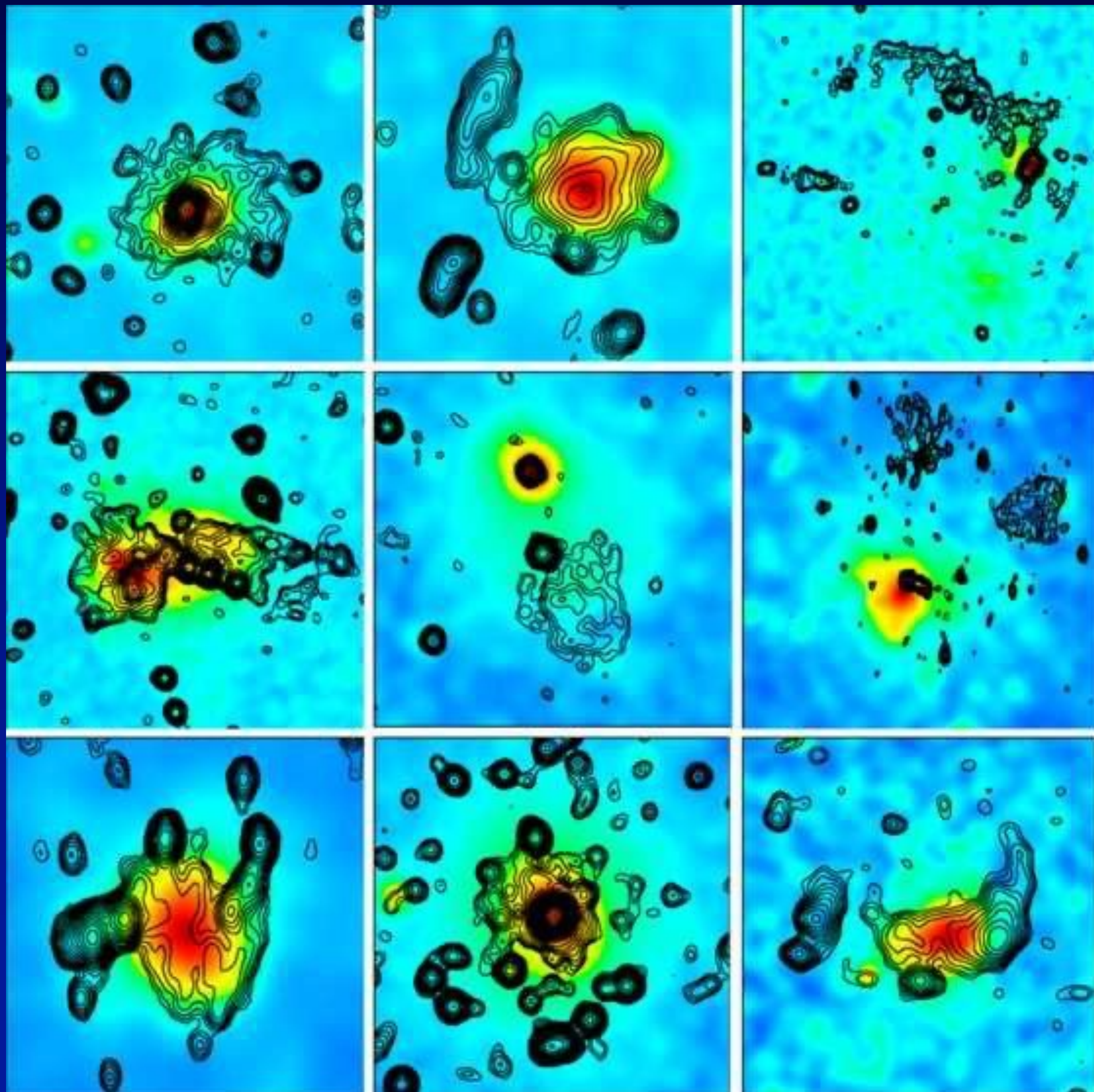
There is more mass between galaxies in clusters than within them

Abell 2029: galaxies (blue), hot intracluster gas (red)

X-ray satellites (e.g. ROSAT, Chandra) have revealed massive amounts of hot (10^7-10^8 K) gas in between galaxies in clusters ("intracluster gas"). A few times more mass than in stars

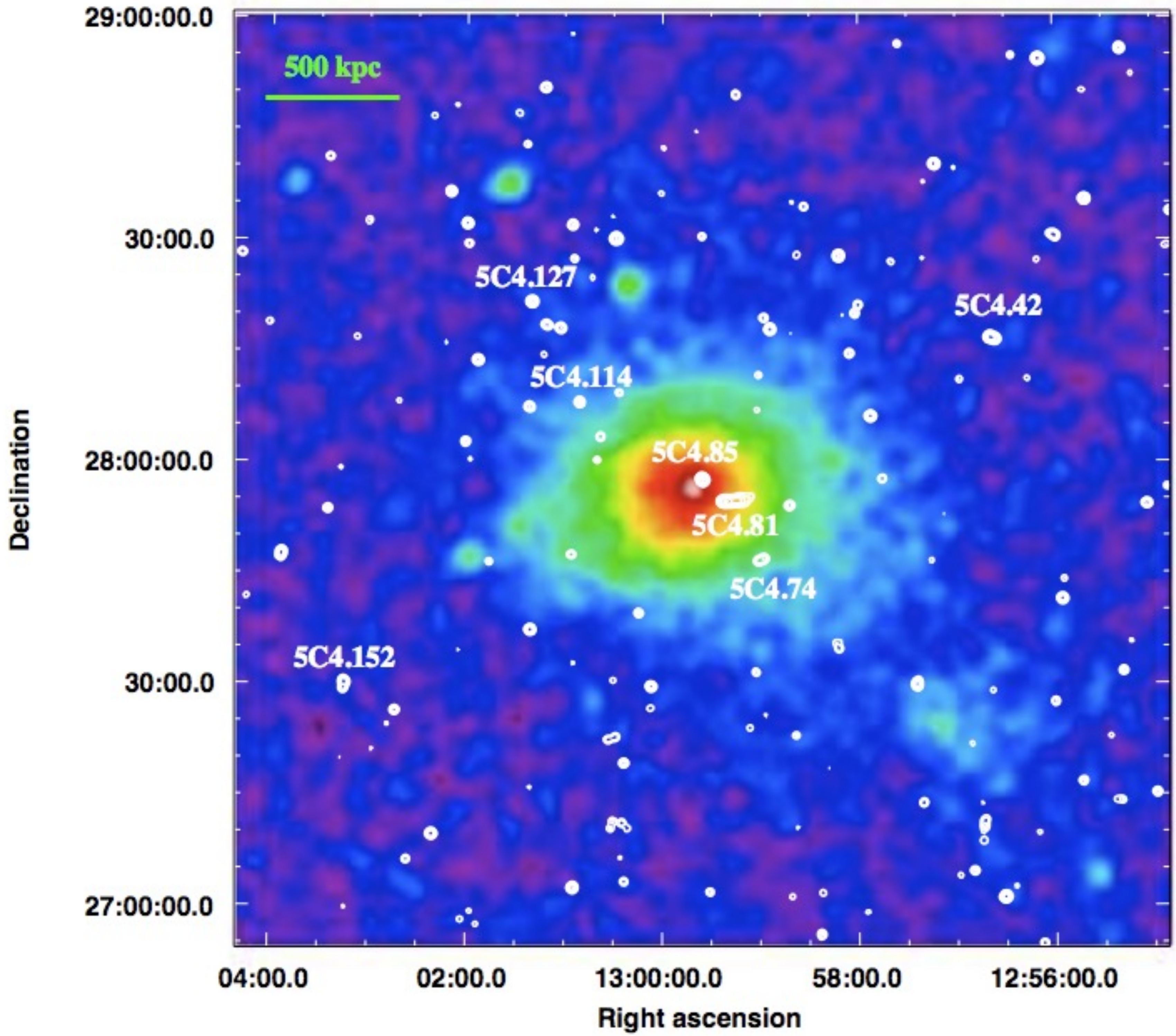
Halos and Relics

Feretti et al. 2012



Coma

X-ray
+
radio

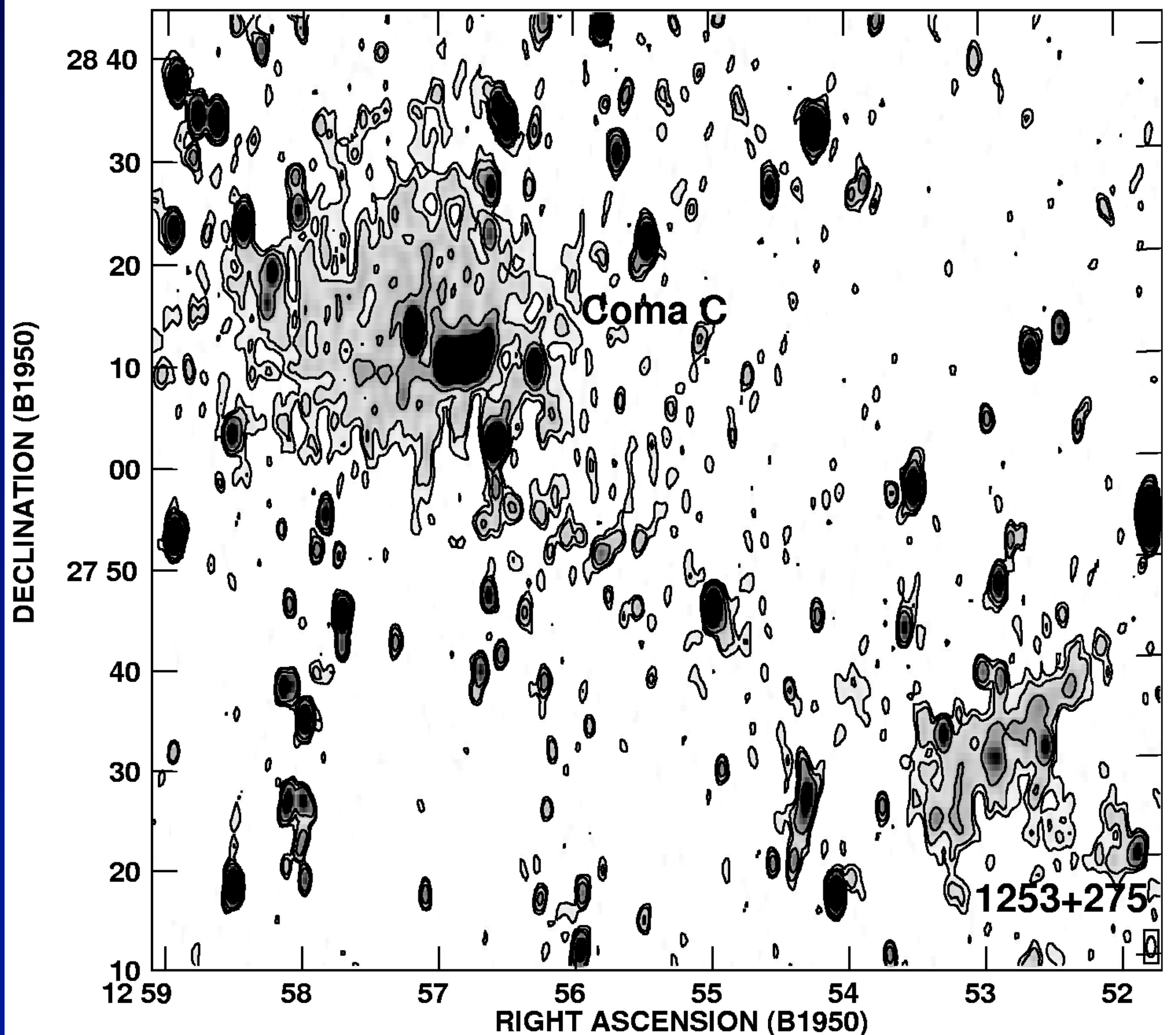


Cluster Halo in Coma

Feretti & Giovannini 1998

WSRT at 90cm

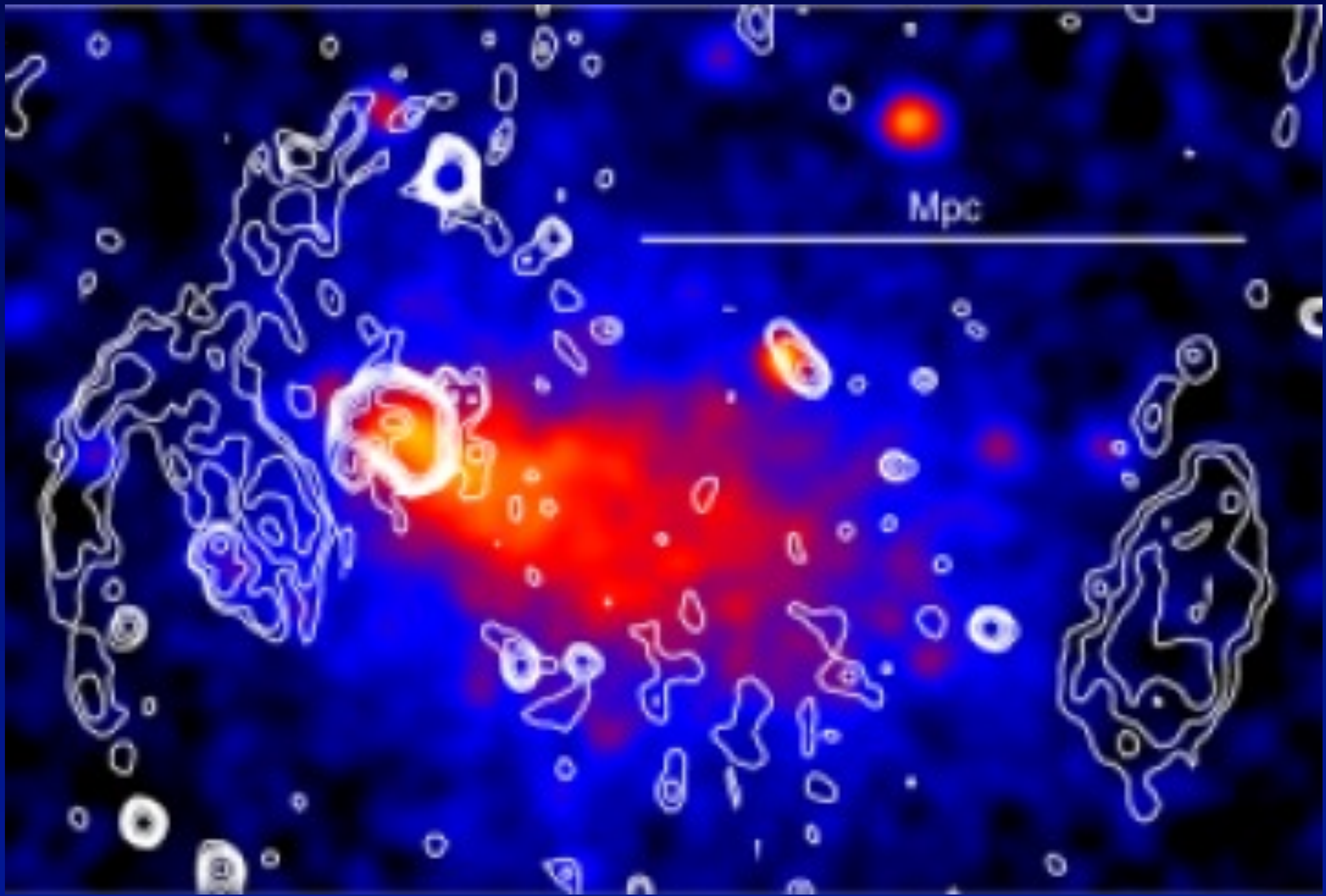
B ~ 1 μG



Double Relic in A3376

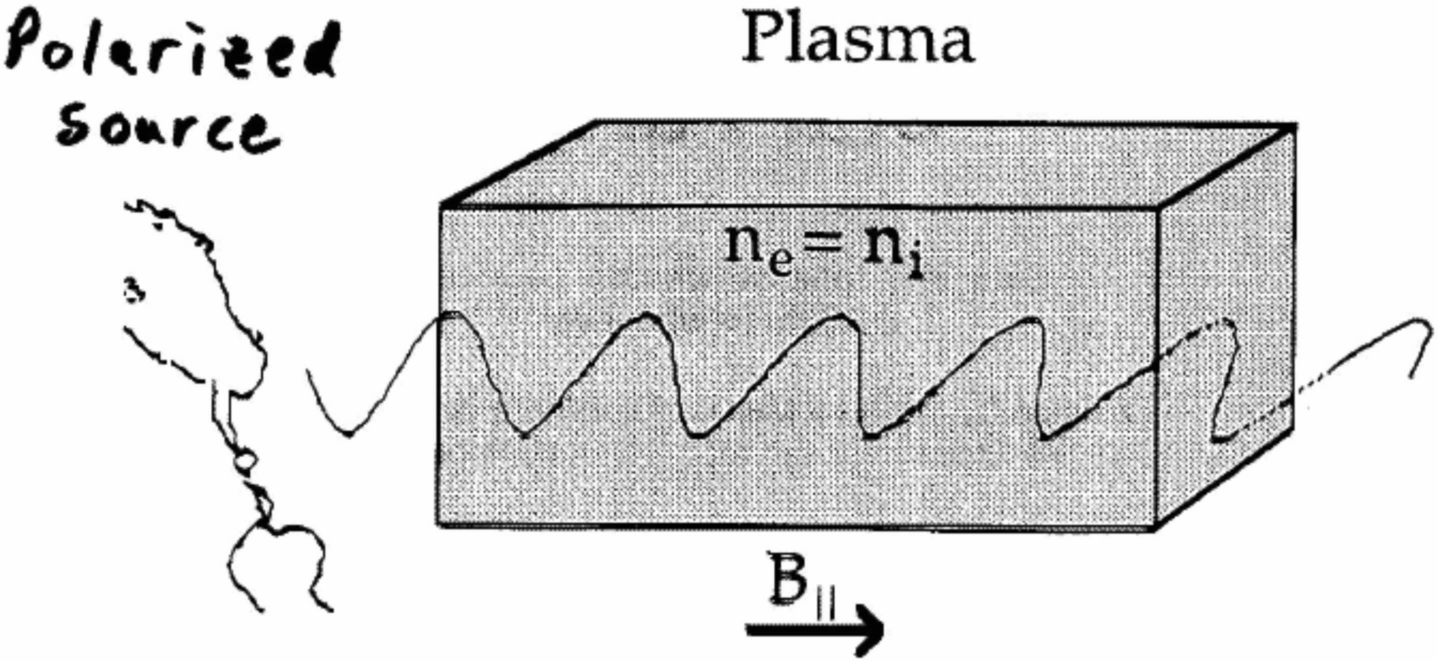
Kale et al. 2018

GMRT



The Largest Magnets

Faraday Rotation



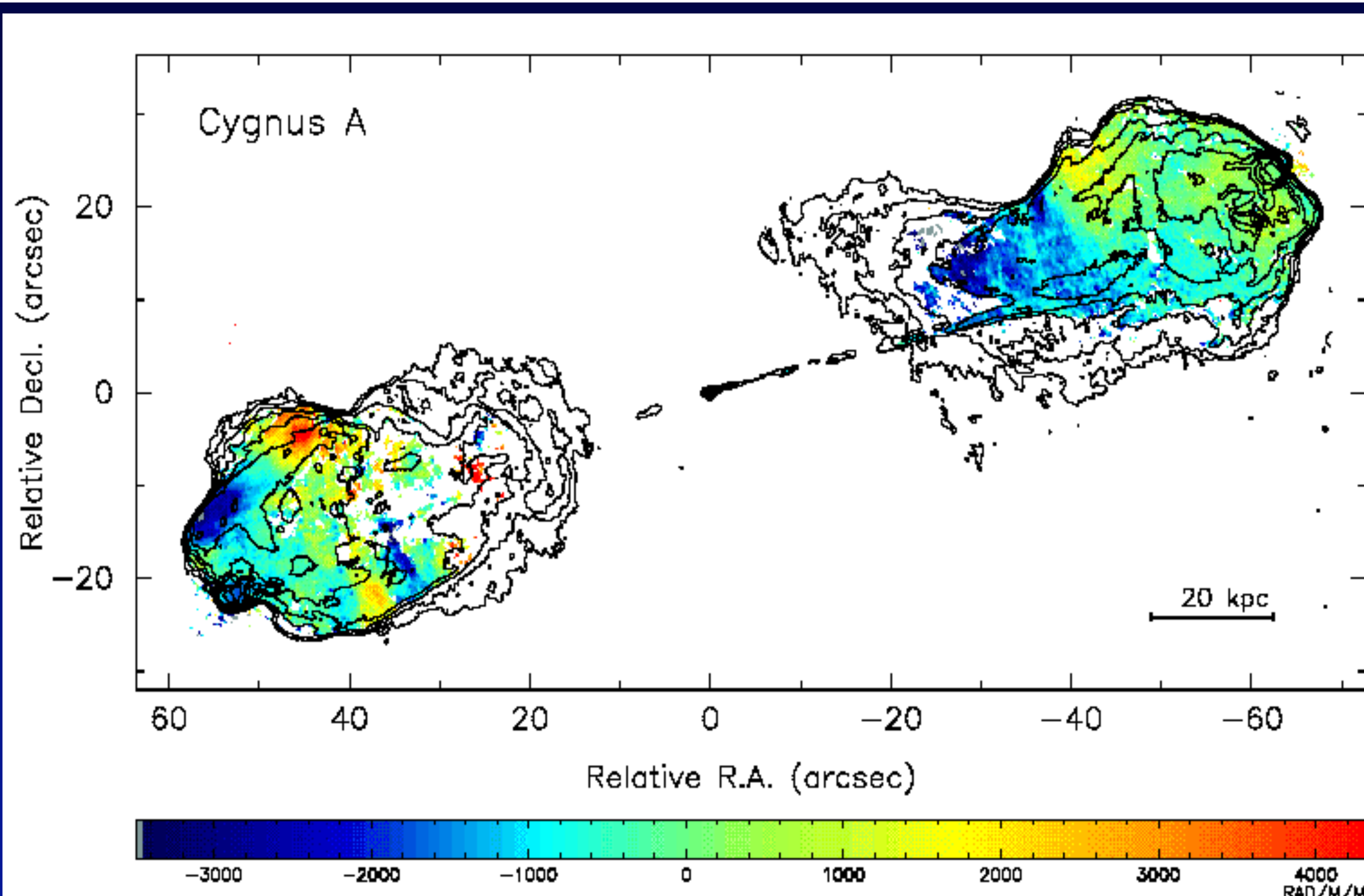
$$\Psi = \Psi_0 + RM\,\lambda^2$$

kpc

mGauss

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

cm^{-3}



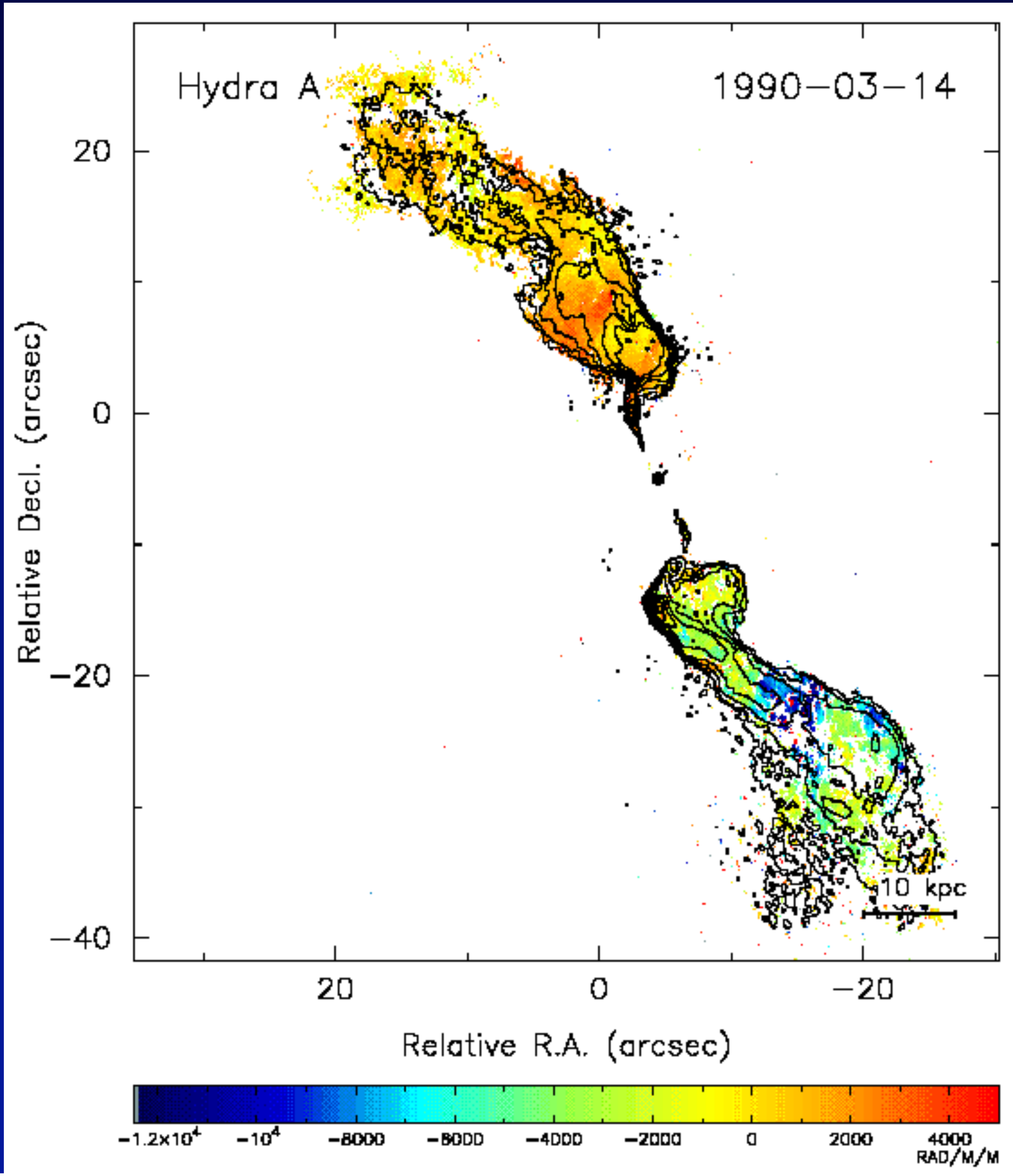
Carilli & Taylor 2002 (ARA&A)

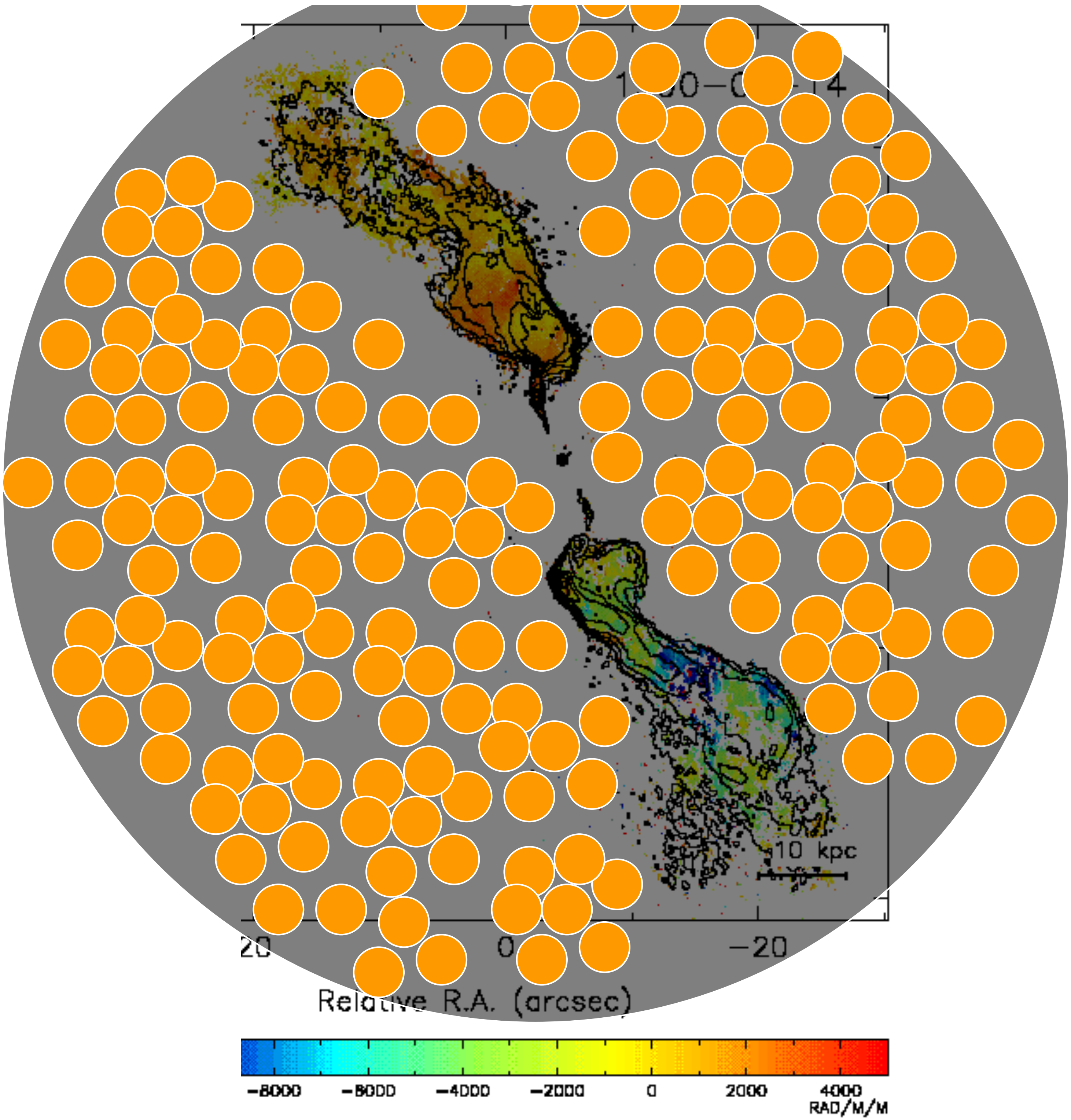
B ~ 10 μG

Hydra A

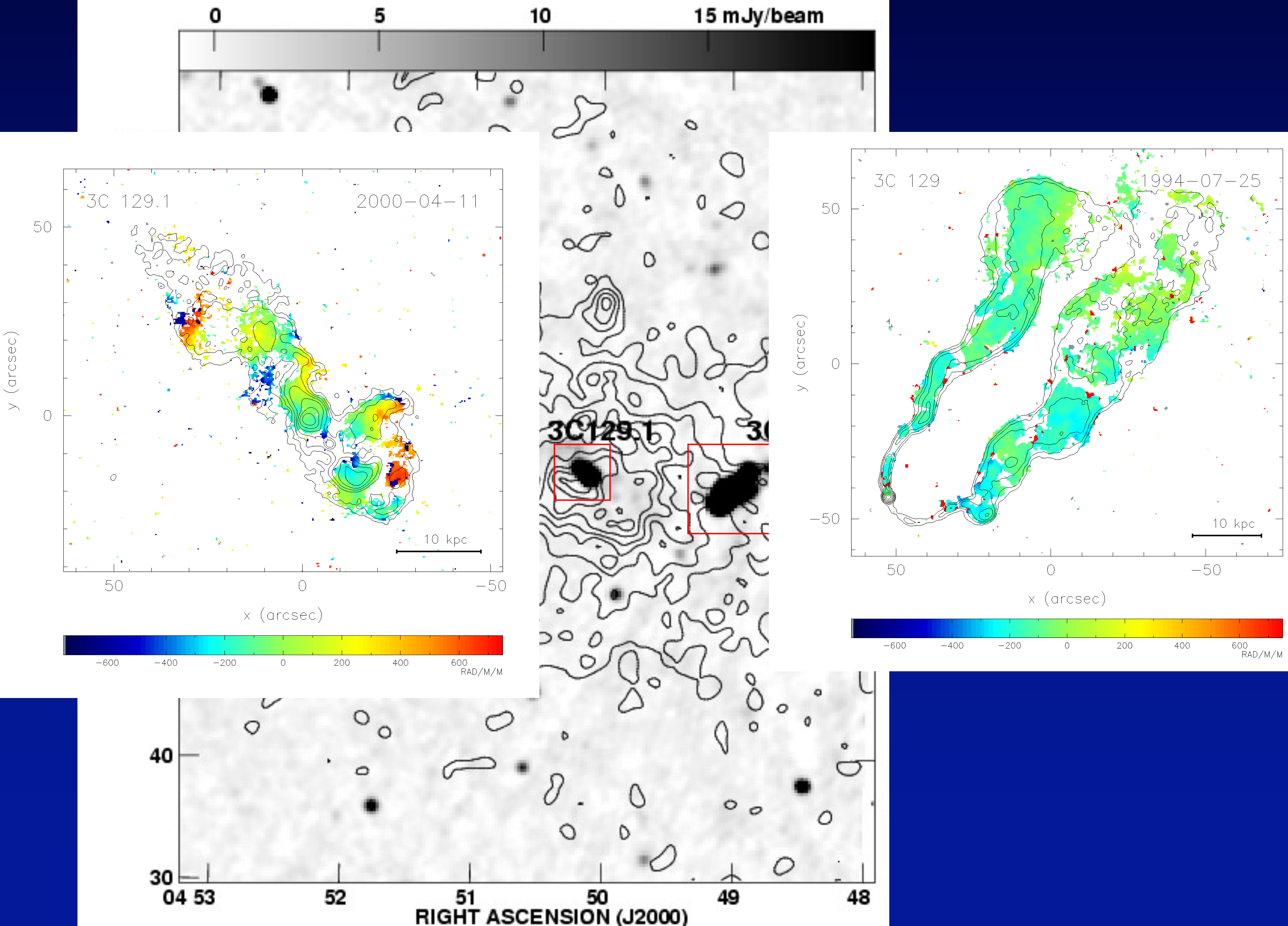
Faraday Rotation Measures

B ~ 30 μG



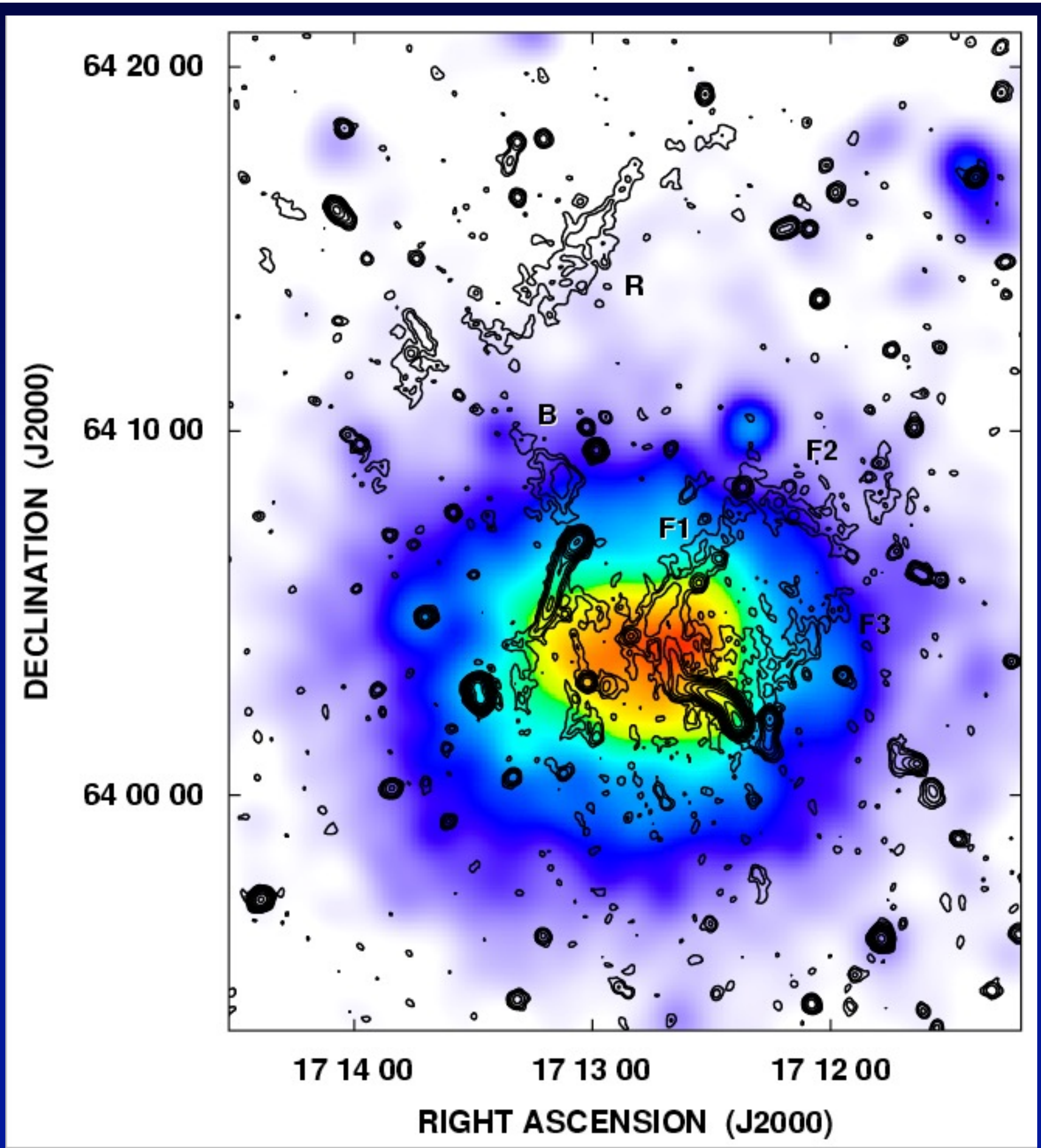


10 kpc
20
0
−20
Relative R.A. (arcsec)
−8000
−6000
−4000
−2000
0
2000
4000
RAD/M/M


0
5
10
15 mJy/beam
3C129.1
3C
40
30
04 53
52
51
50
49
48
RIGHT ASCENSION (J2000)
3C 129.1
2000−04−11
y (arcsec)
x (arcsec)
10 kpc
−600
−400
−200
0
200
400
600
RAD/M/M
3C 129
1994−07−25
y (arcsec)
x (arcsec)
10 kpc
−600
−400
−200
0
200
400
600
RAD/M/M

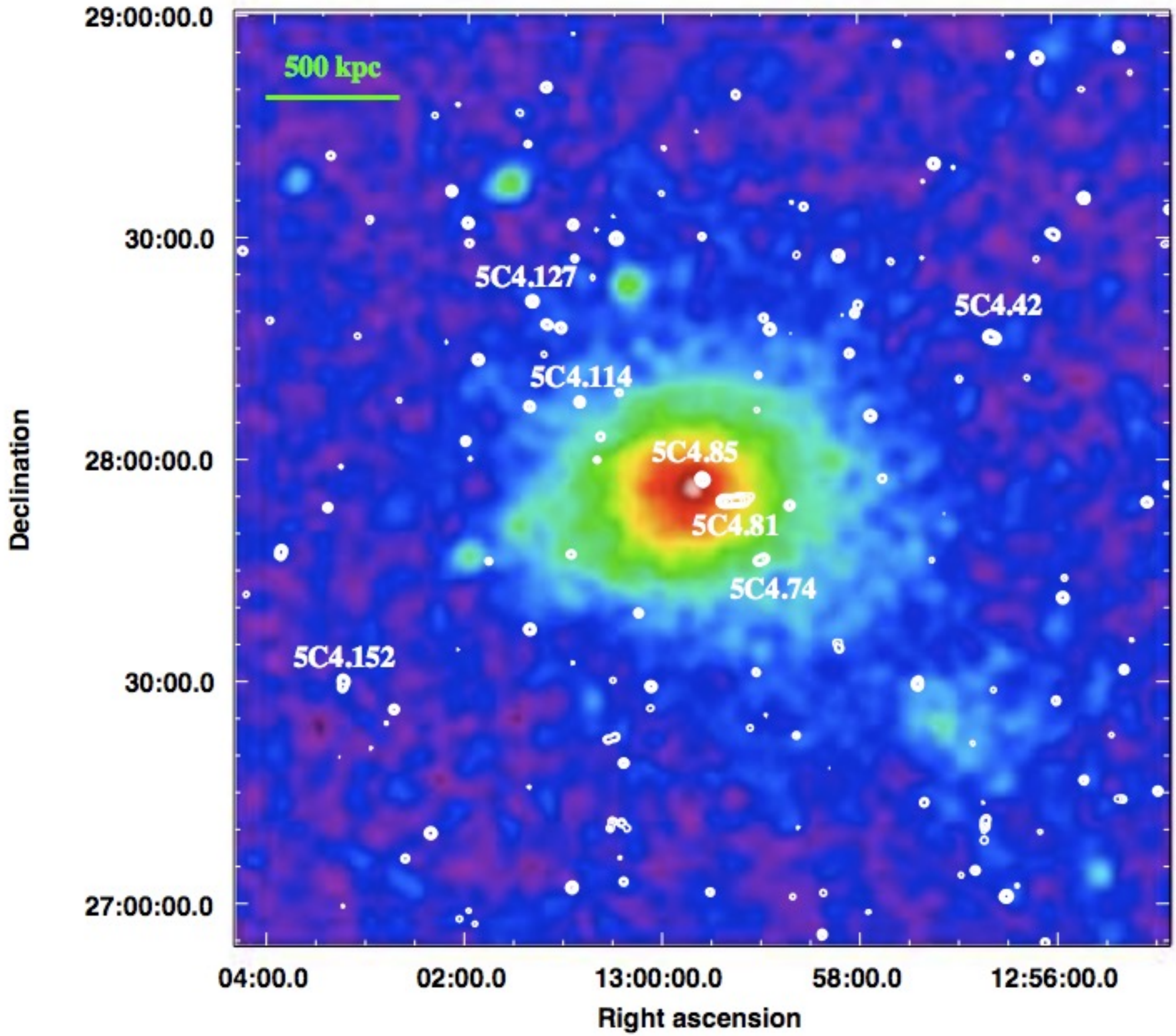
X-ray and Radio View of A2255

Govoni et al. 2005

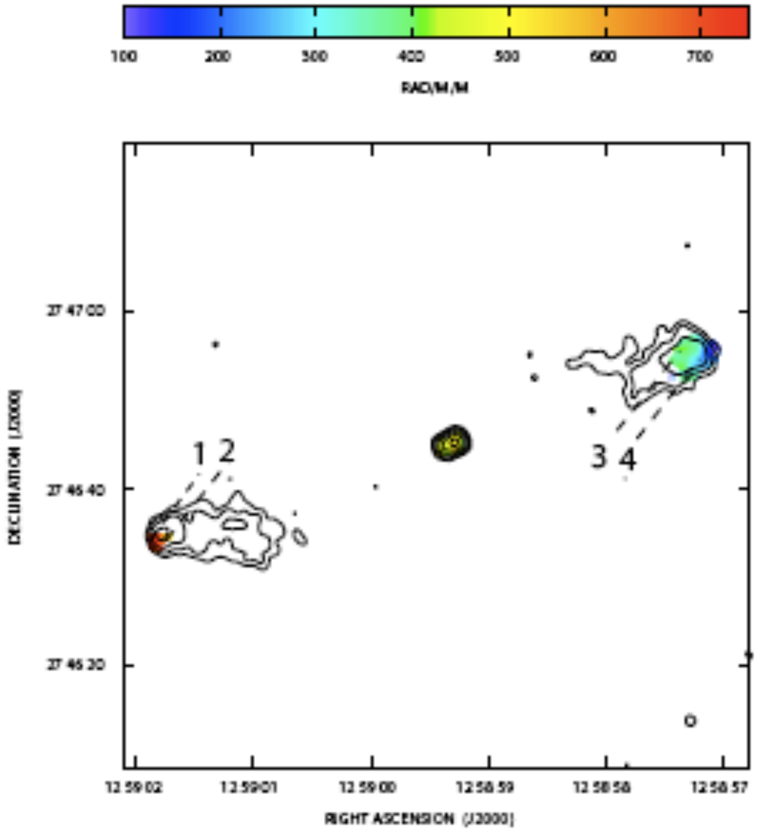


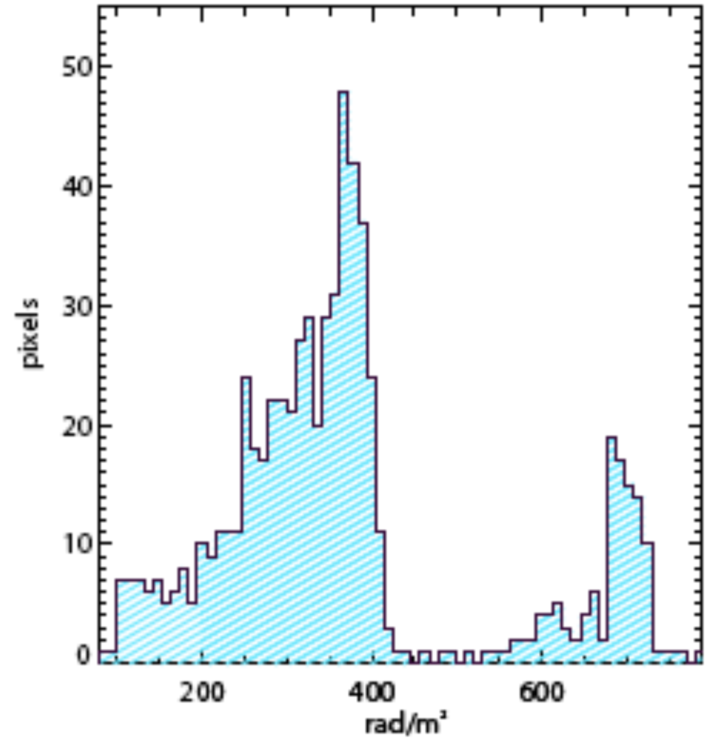
Coma

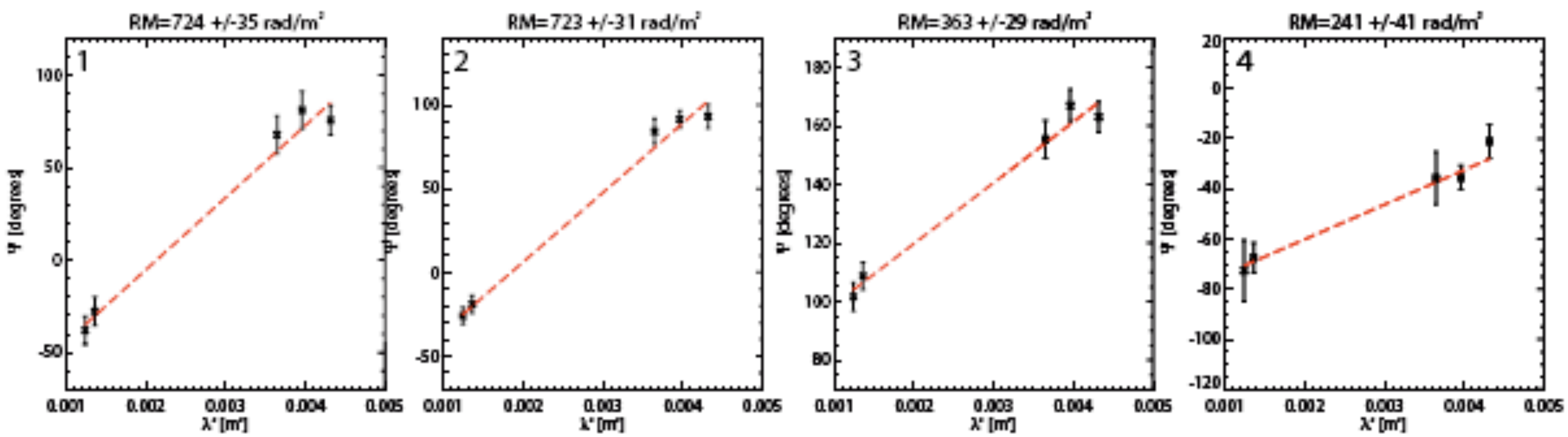
X-ray
+
radio



5C4.74 in Coma







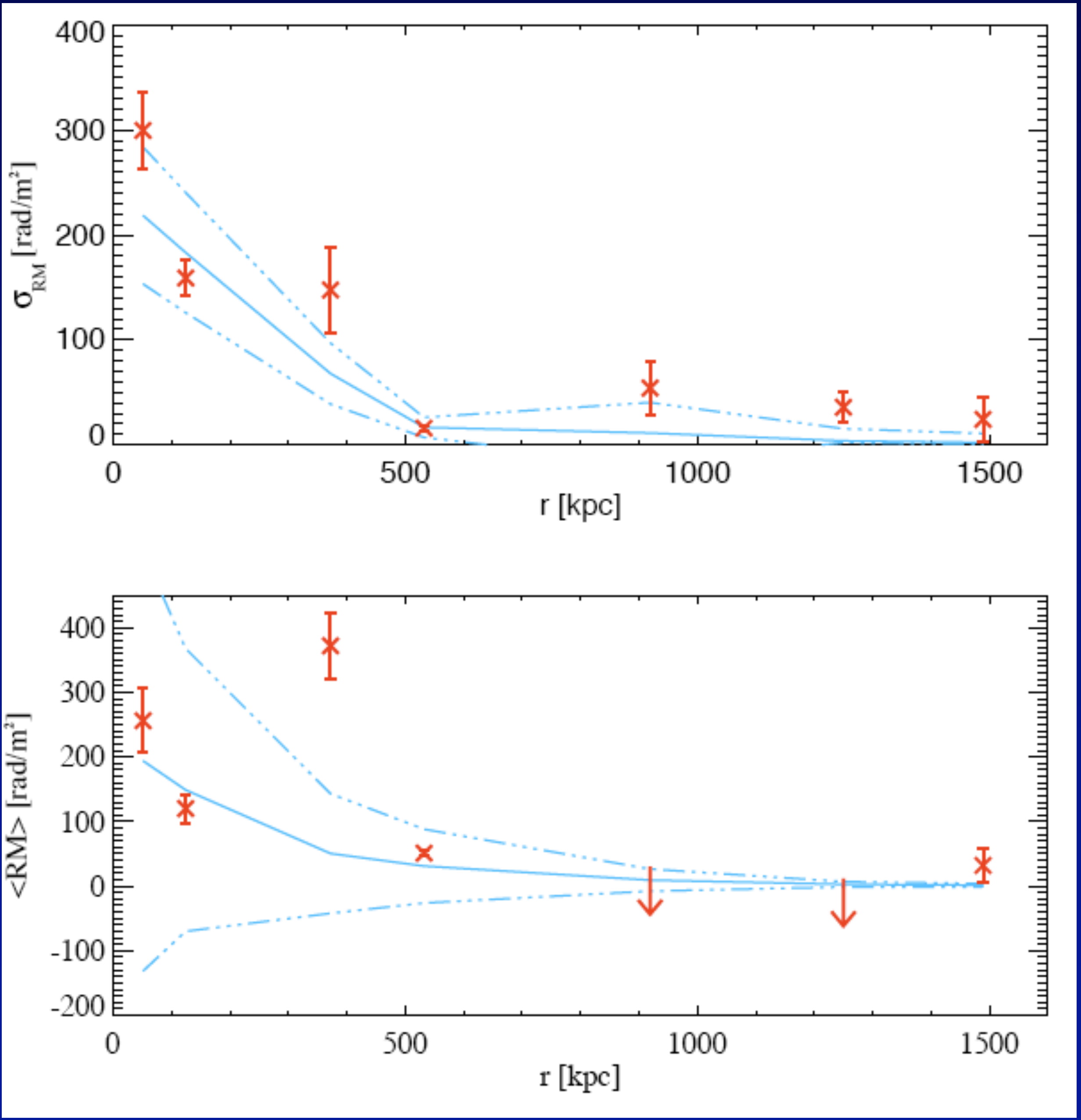
Results

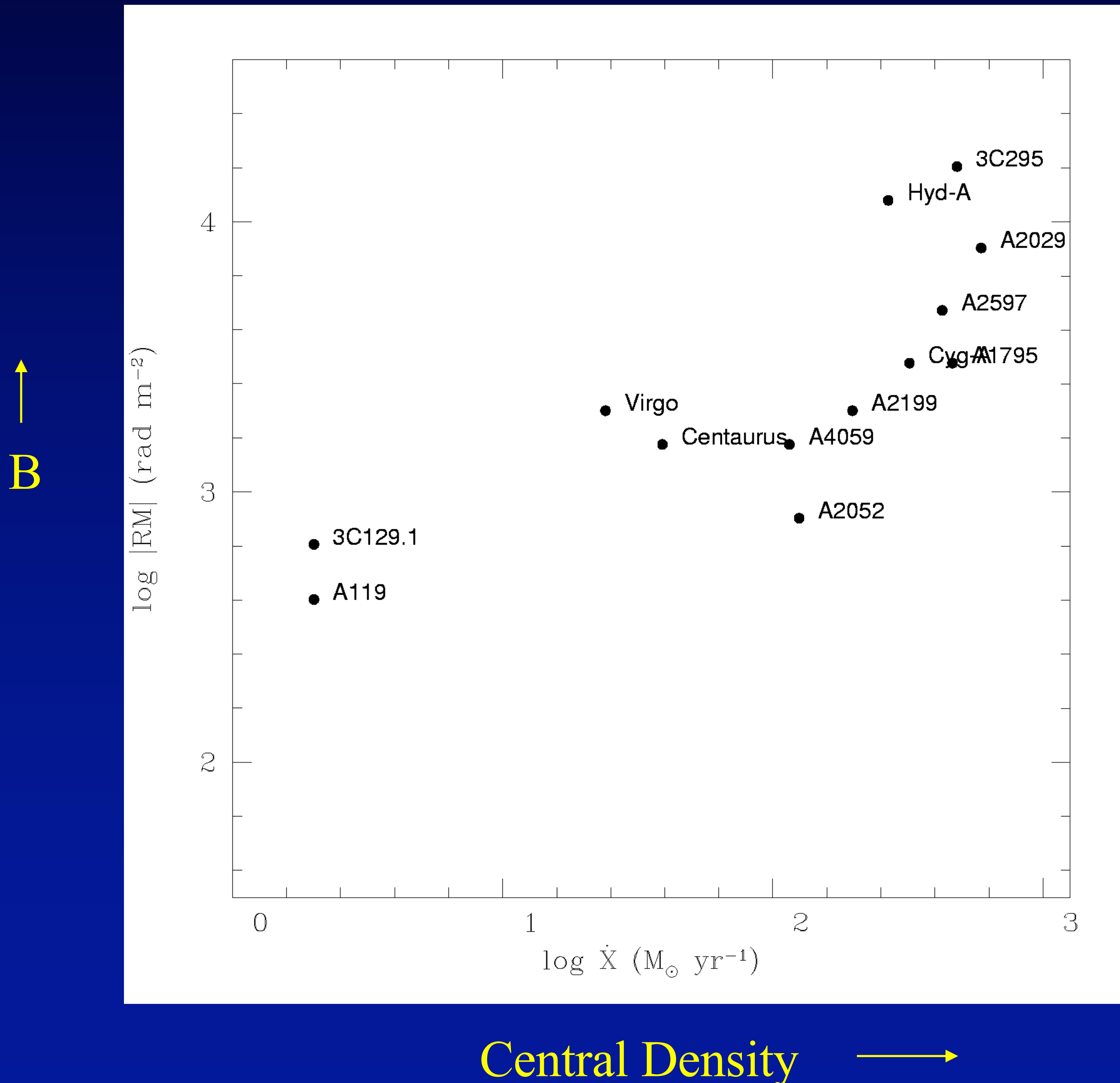
$B_0 = 4.6$ +/- $0.7\ \mu G$

scale lengths between 2 and 30 kpc

average $B \sim 2\ \mu G$

Bonafede et al. 2009



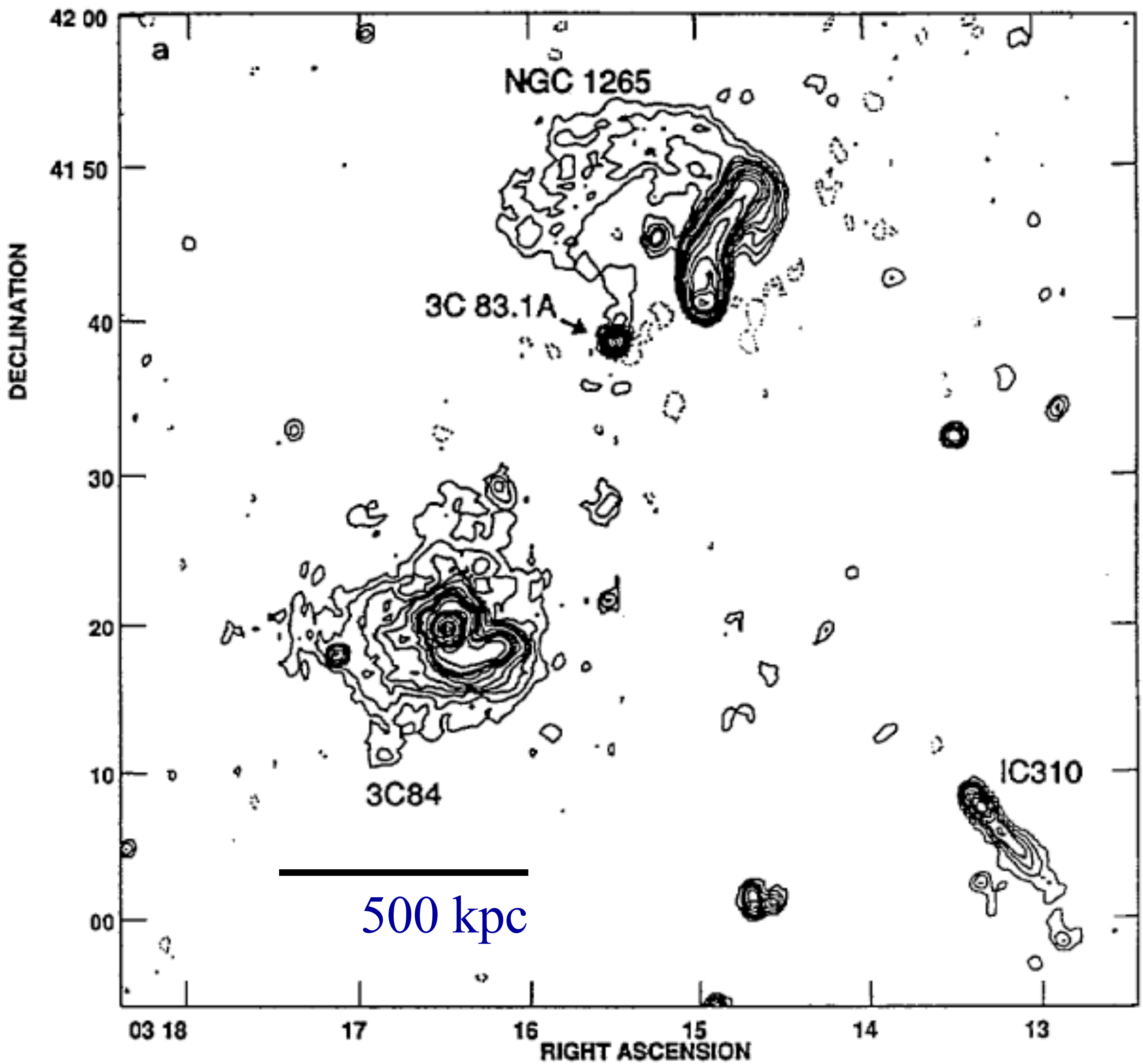

3C295
Hyd-A
A2029
A2597
Cyg-A
A1795
Virgo
A2199
Centaurus
A4059
A2052
3C129.1
A119
log |RM| (rad m^{-2})
log $\dot{X}$ ($M_\odot$ yr^{-1})
B
Central Density

Perseus Cluster

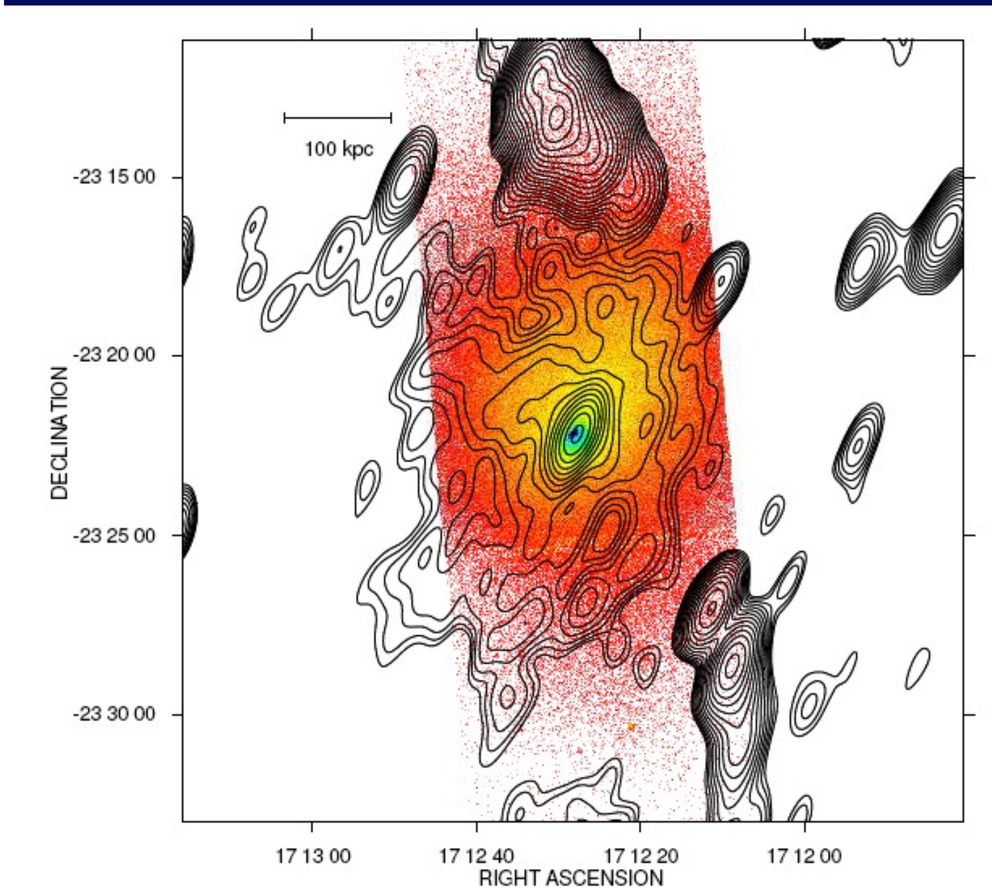
Mini-Halo in Perseus

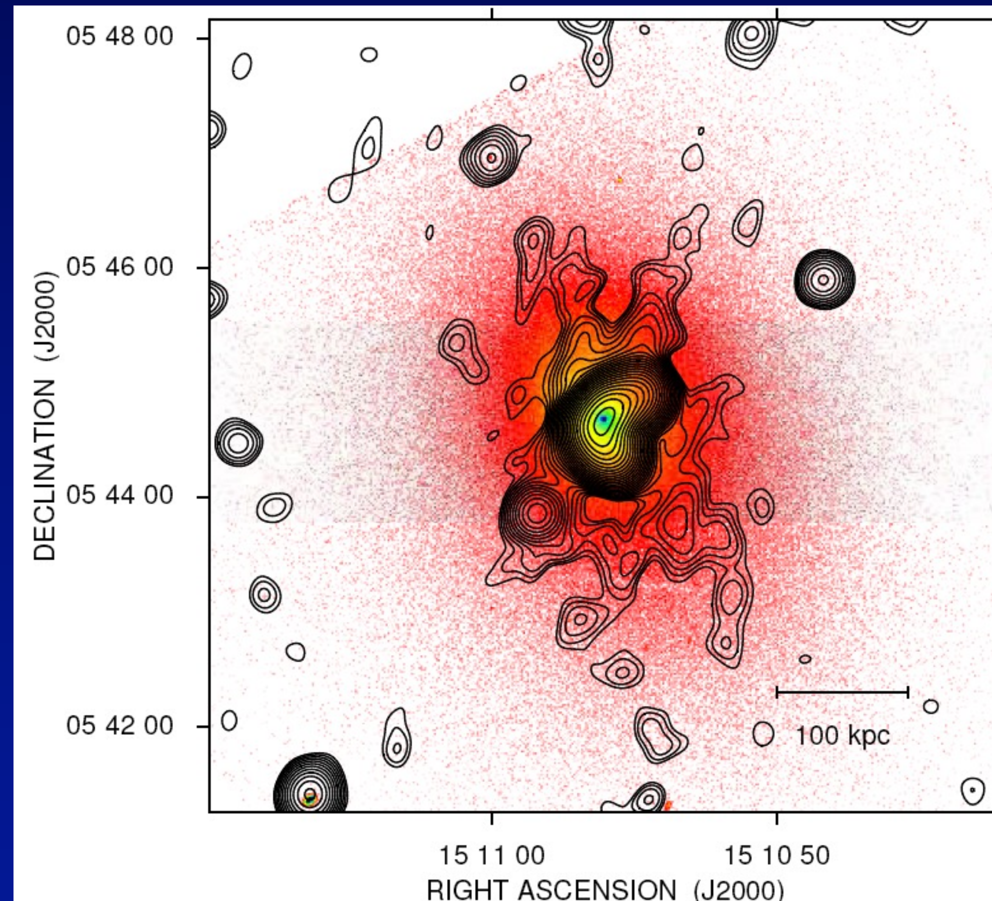
VLA
330 MHz

Burns
et al.
1992



More mini halos…



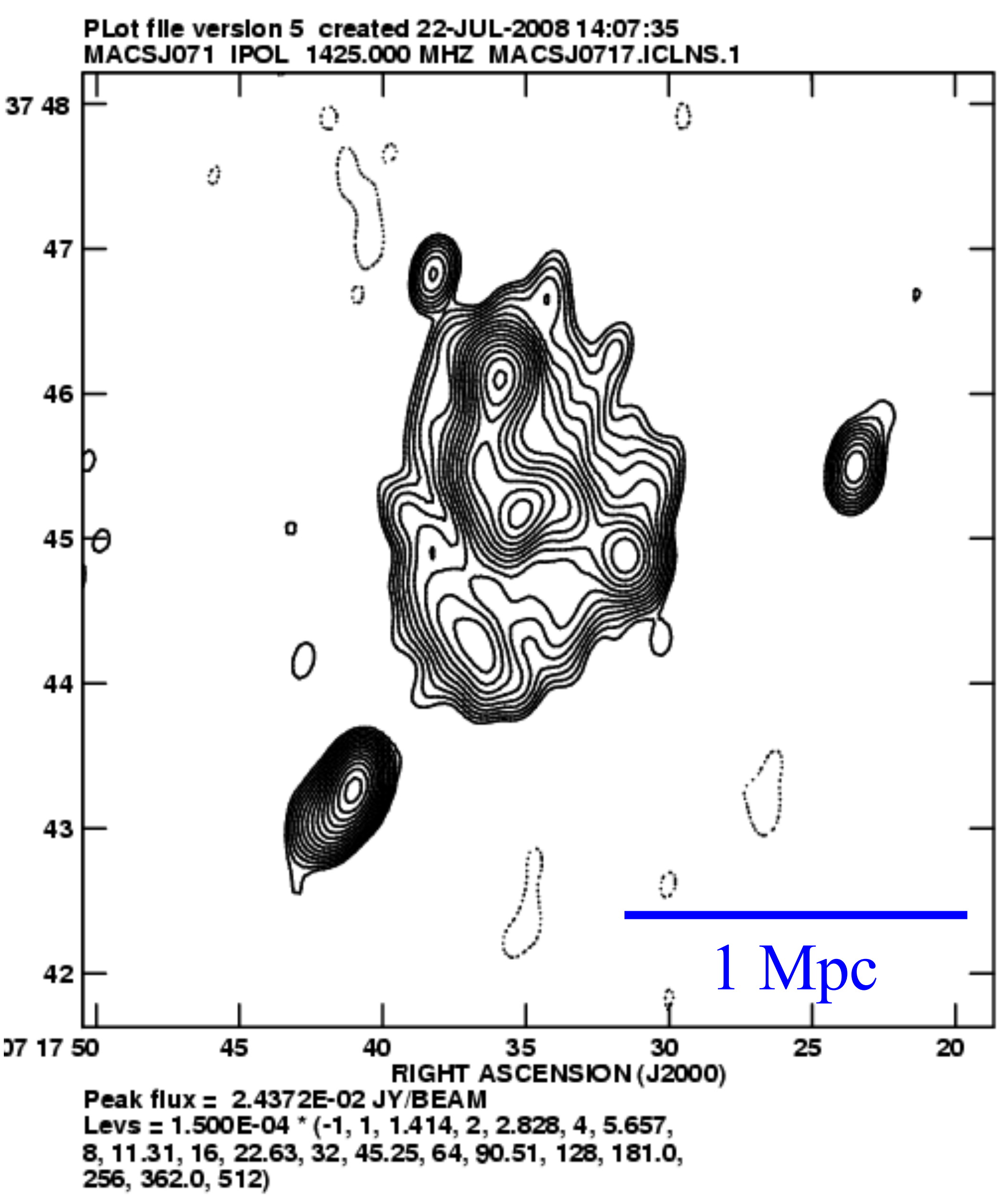


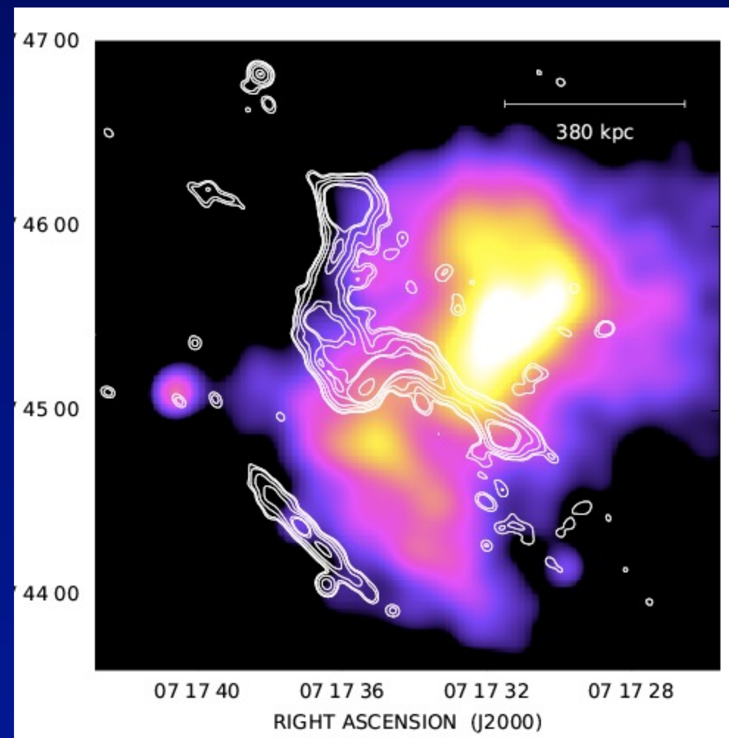
Ophiuchus and A2029 at 1.4 GHz

Govoni et al. 2009

MACS clusters at high z

MACSJ0717 at z=0.546

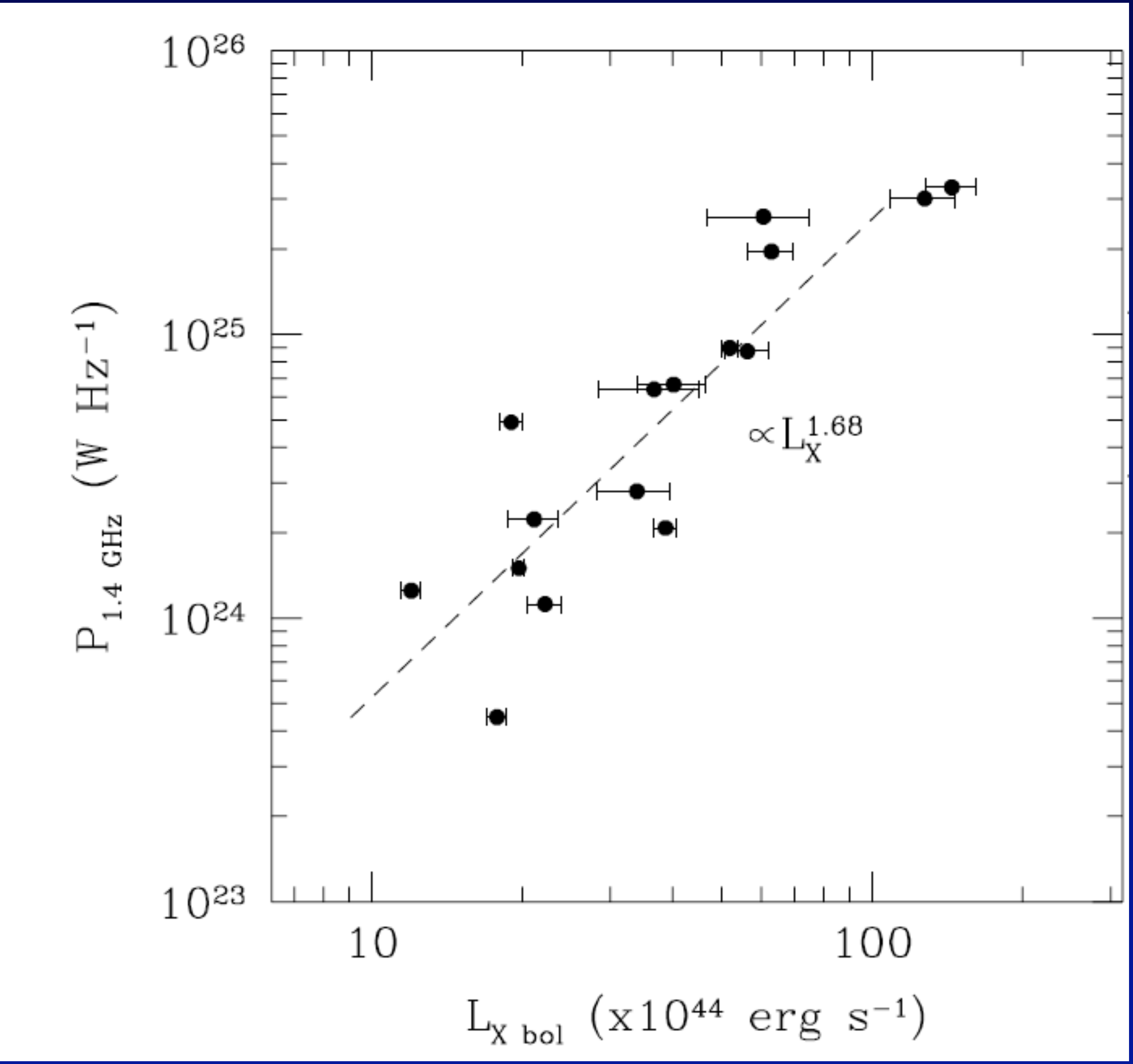




5 GHz + X-ray

1.4 GHz

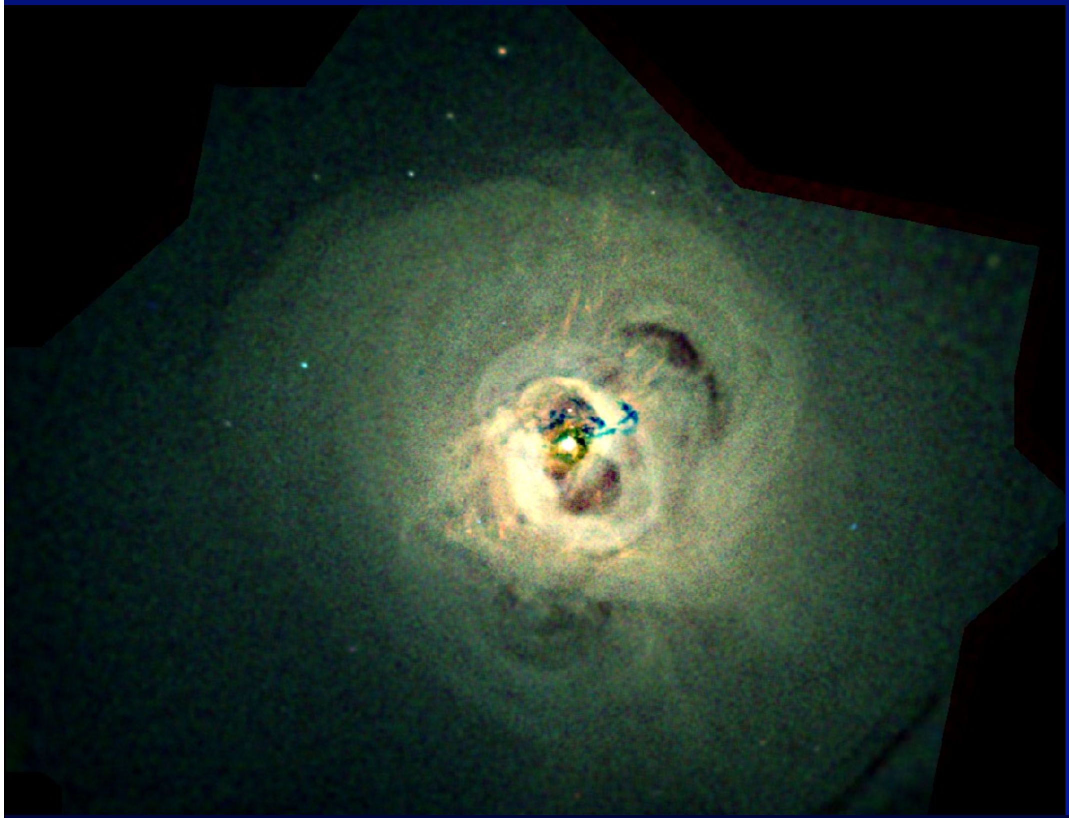
Radio Halo vs X-ray Luminosity

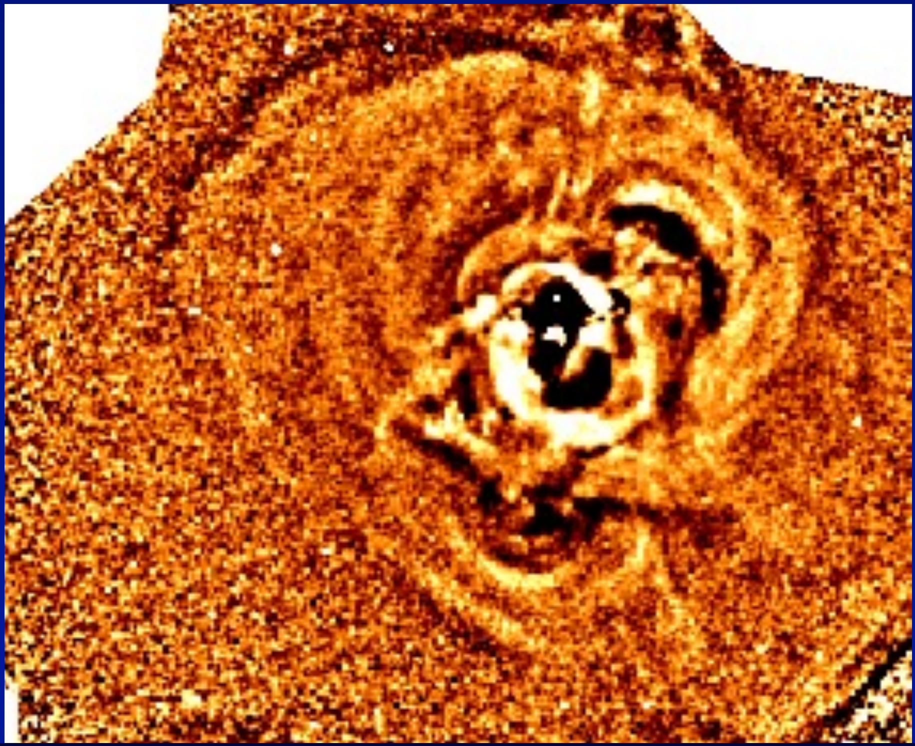


AGN Feedback

AGNs feedback energy to the cluster gas, prevent further cooling

Fabian, Forman: studies of nearby clusters ⇒ In Perseus and in M87
directed energy from jets is being redistributed
more isotropically via bubbles blown, compression waves, … .



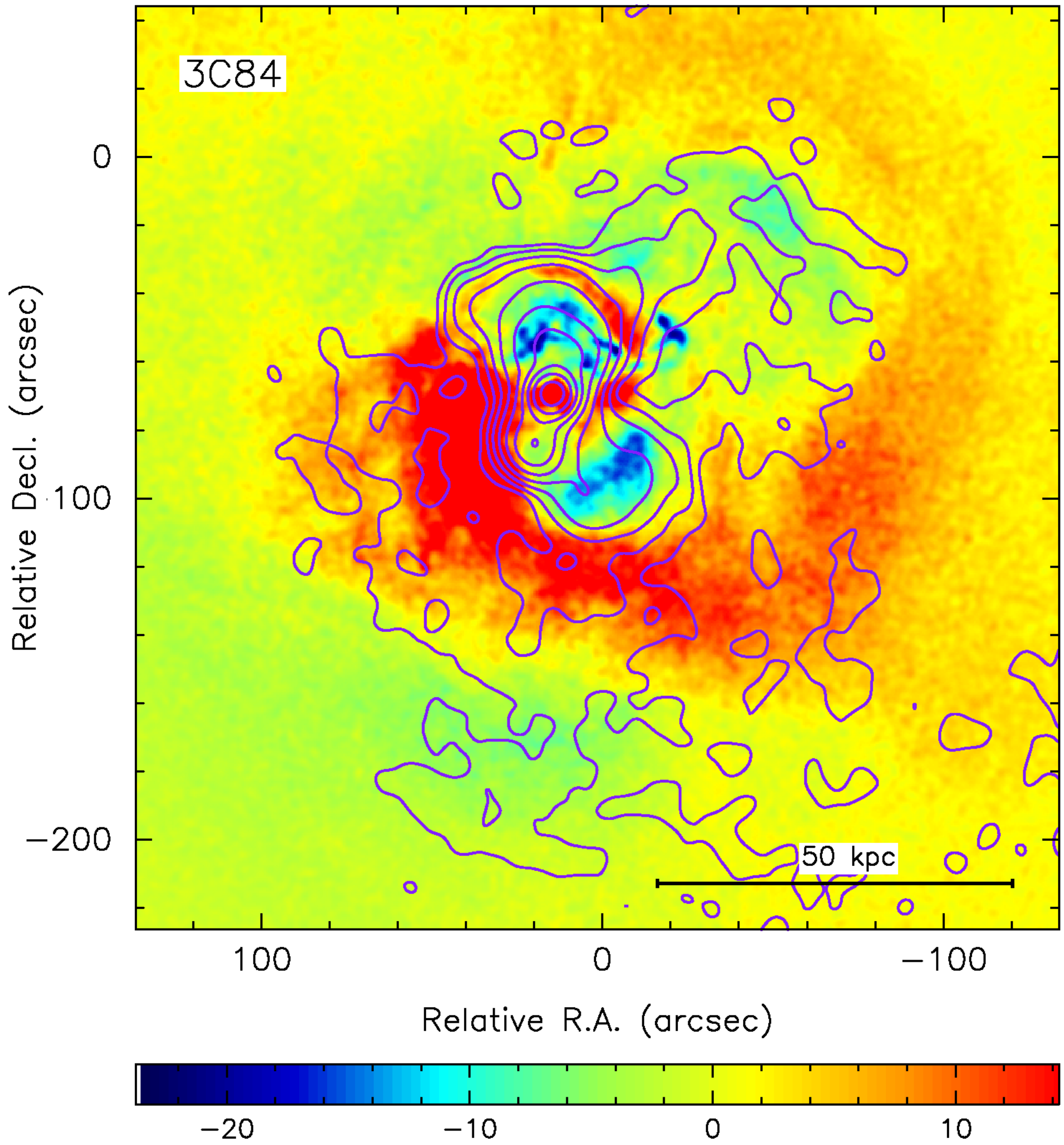


Chandra 900 ks image of Perseus cluster, unsharp-masked at right (Fabian et al. 2006)

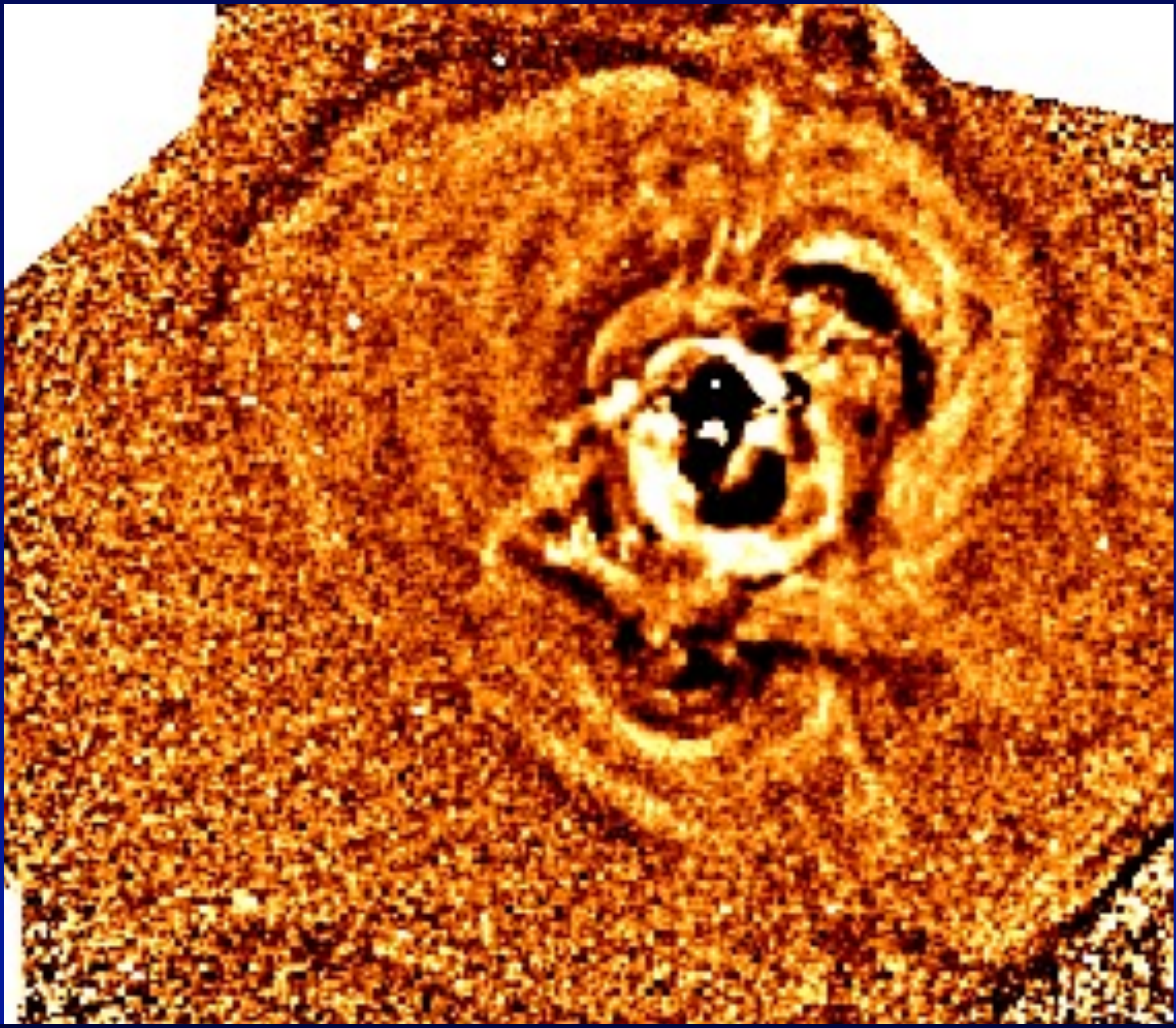
Cluster Dominant Galaxy (cD)

Fabian et al. 2003

Chandra + VLA



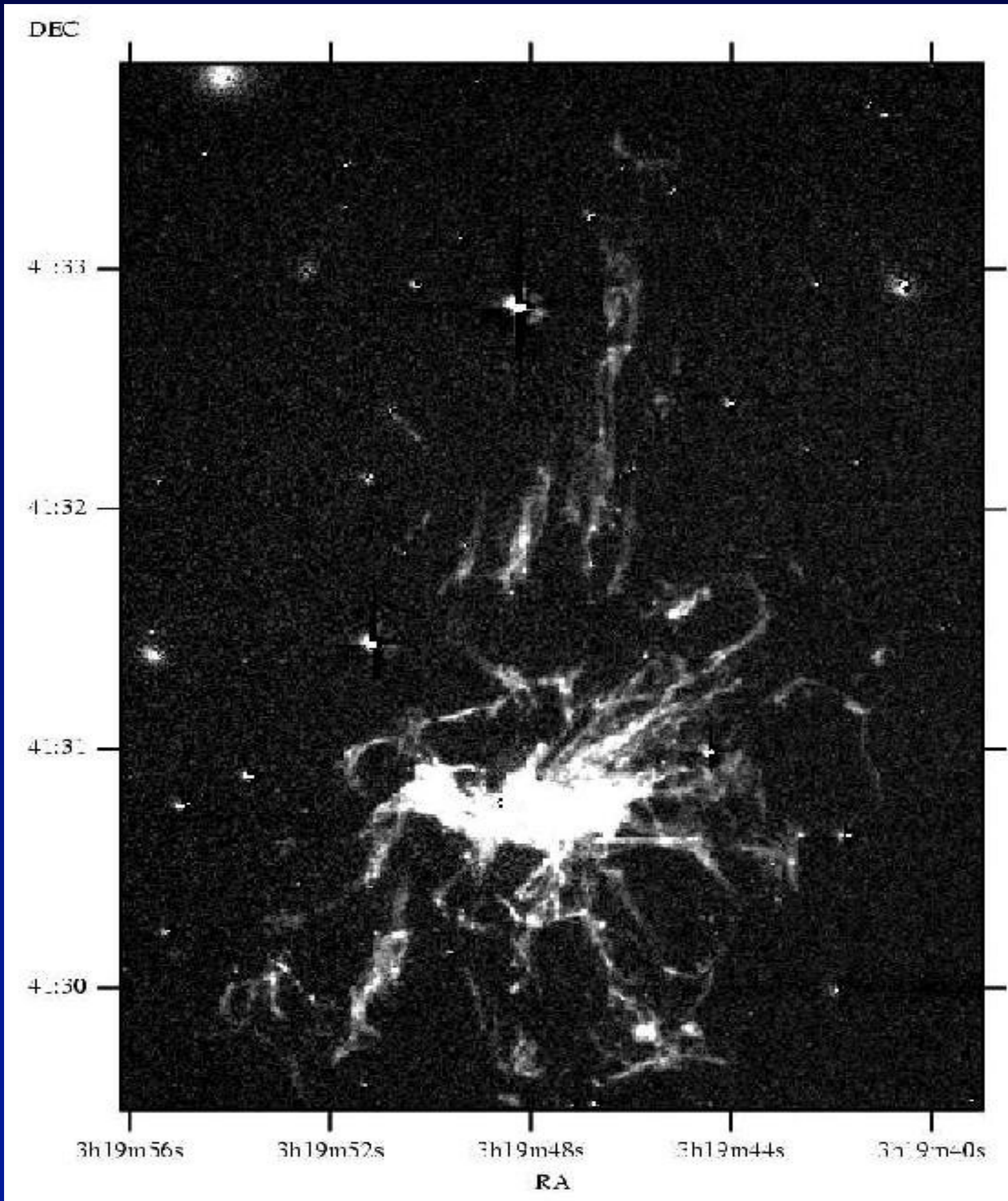
AGN Feedback



Chandra 900 ks image of Perseus cluster, unsharp-masked at right (Fabian et al. 2006)

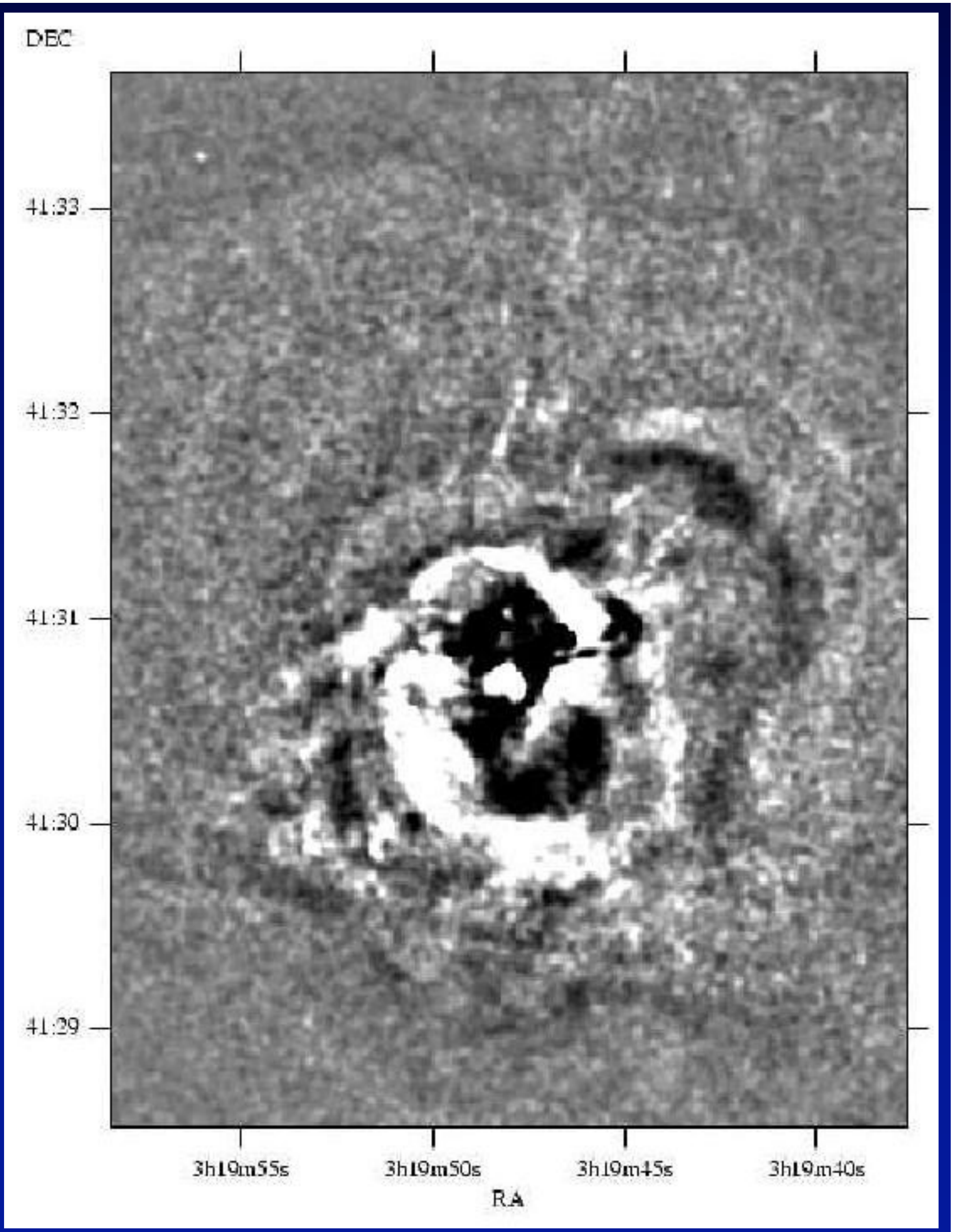
H alpha filaments in Perseus

Conselice et al. 2001
Fabian et al. 2003



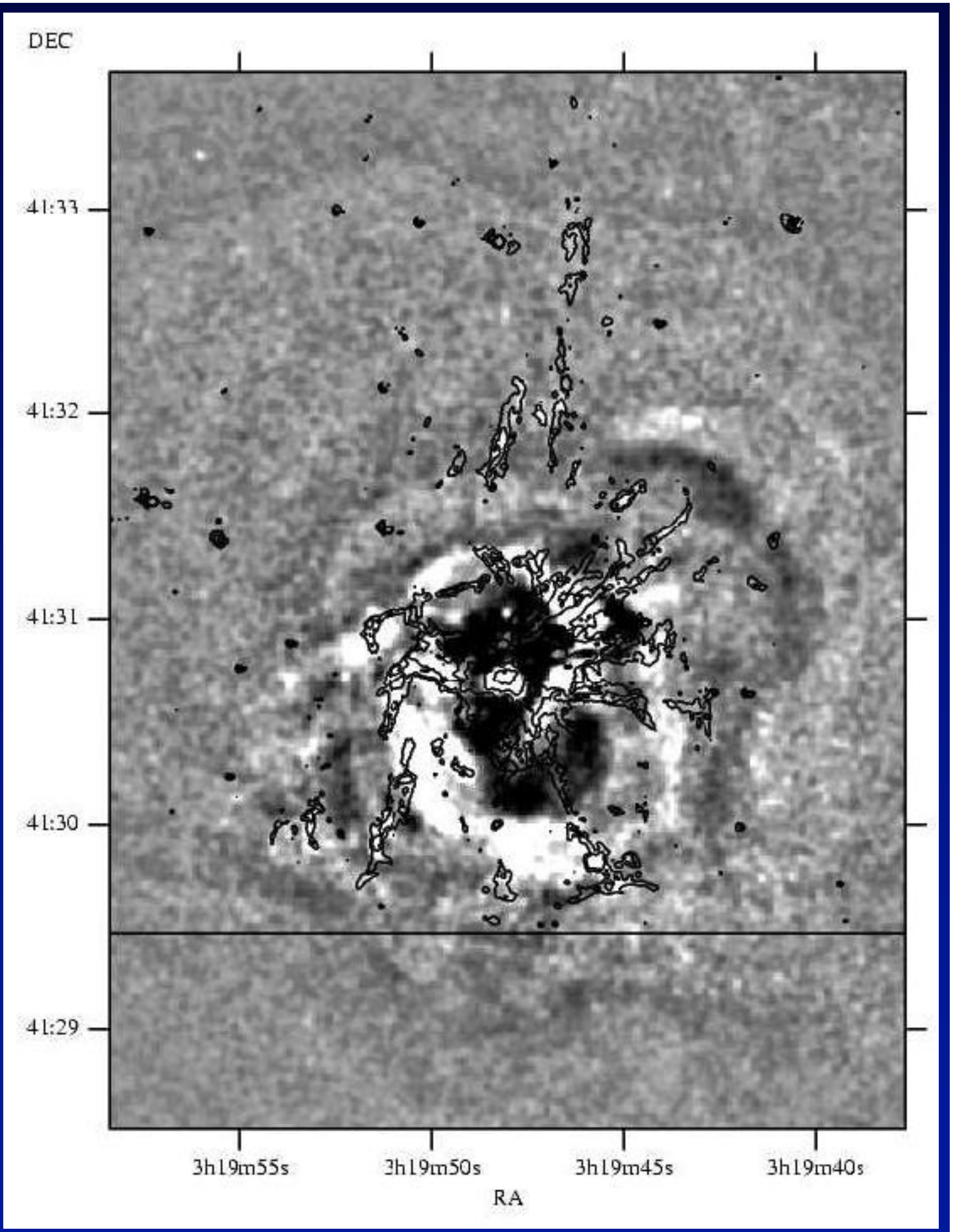
H alpha filaments in Perseus

Chandra X-ray obs (unsharp-masked)

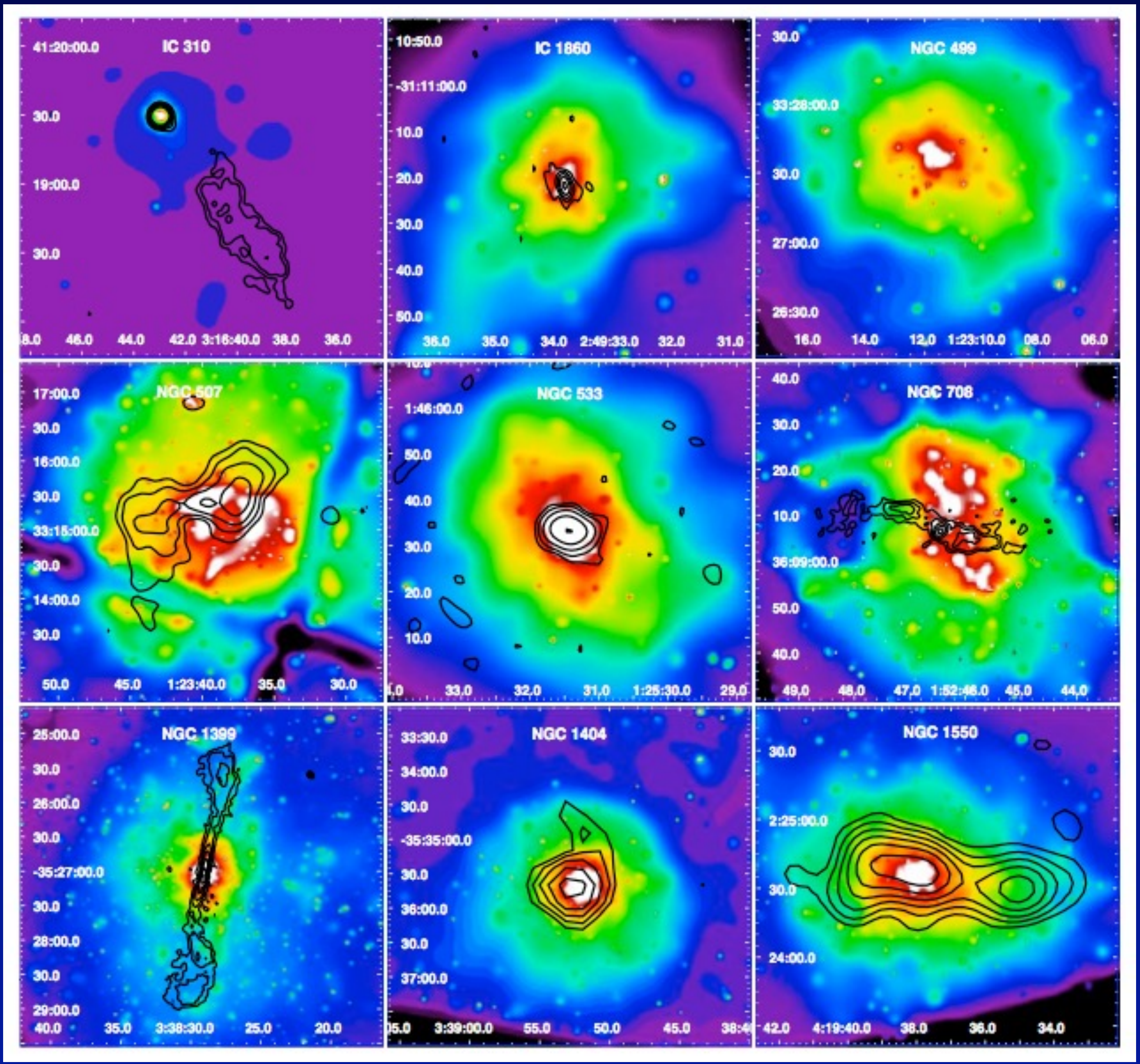


H alpha filaments in Perseus

X-ray
+
Halpha



X-ray and radio images of nearby Ellipticals - Dunn et al. 2009



17/18 radio detections

10/18 extended lobes

9/18 show X-ray radio correlations

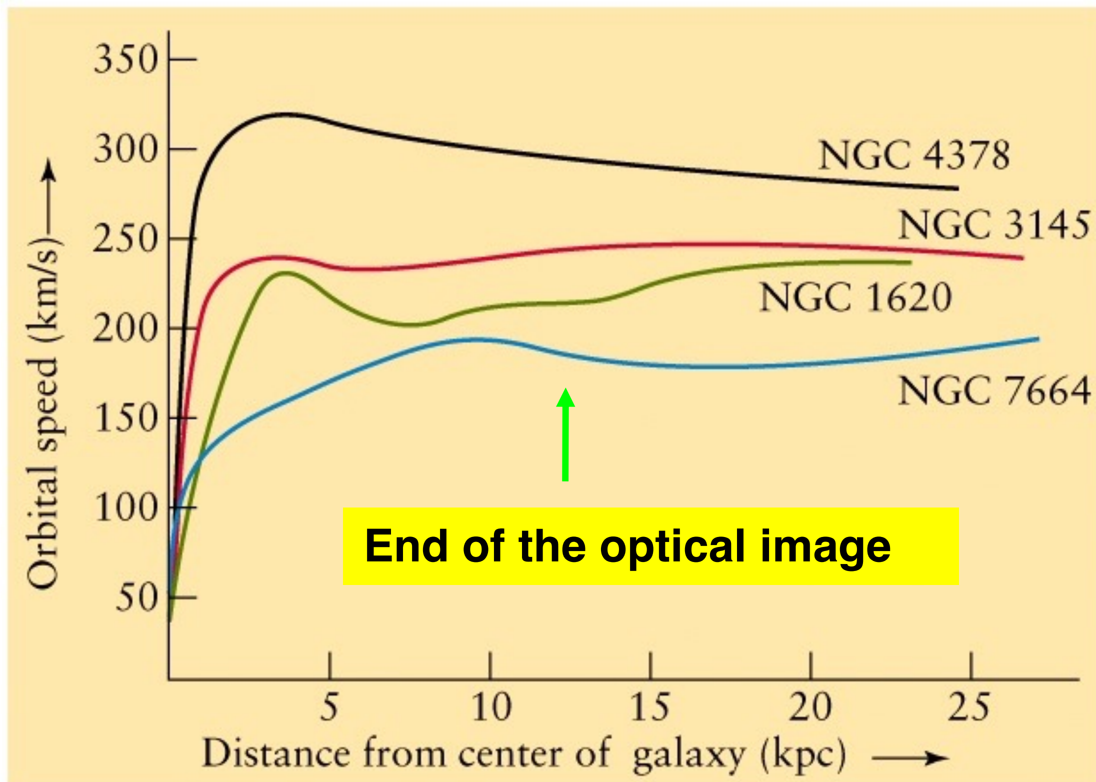
Mass in clusters

- The mass of a cluster can be estimated using the virial theorem:

$$M \approx \frac{RV^2}{G}$$

- The mass of the individual galaxies can be estimated using their rotation curves:

- Note that not only are the rotation curves flat, but they extend far farther (in radio) than the optical image.



Dark matter on large scales

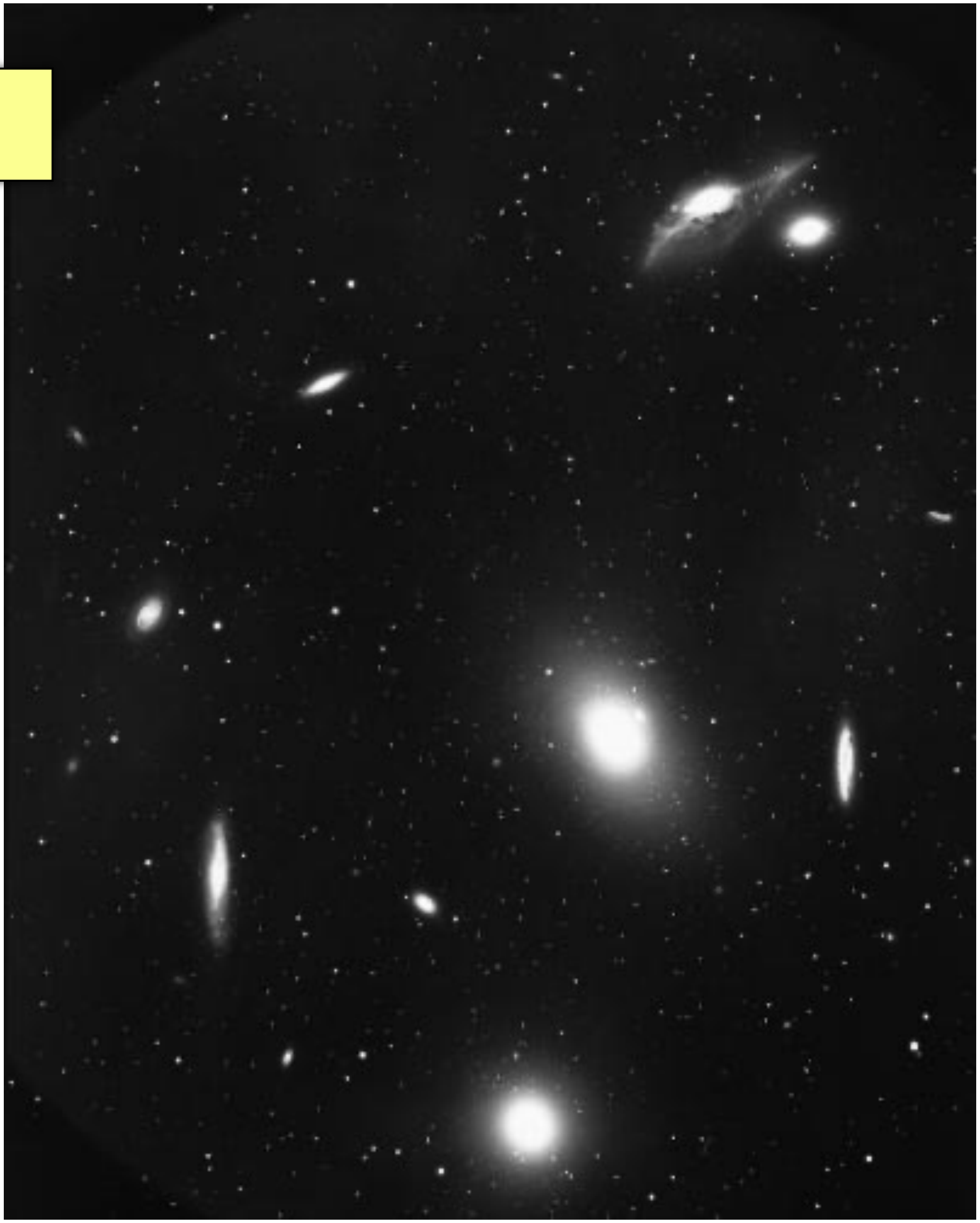
- Dark matter problem gets worse as you look at larger scales.

- As we move from single galaxies to clusters, the influence of the dark matter increases with the size of the system.

- This implies that the dark matter is more diffusely spread than the stars, dust, and gas that we see.

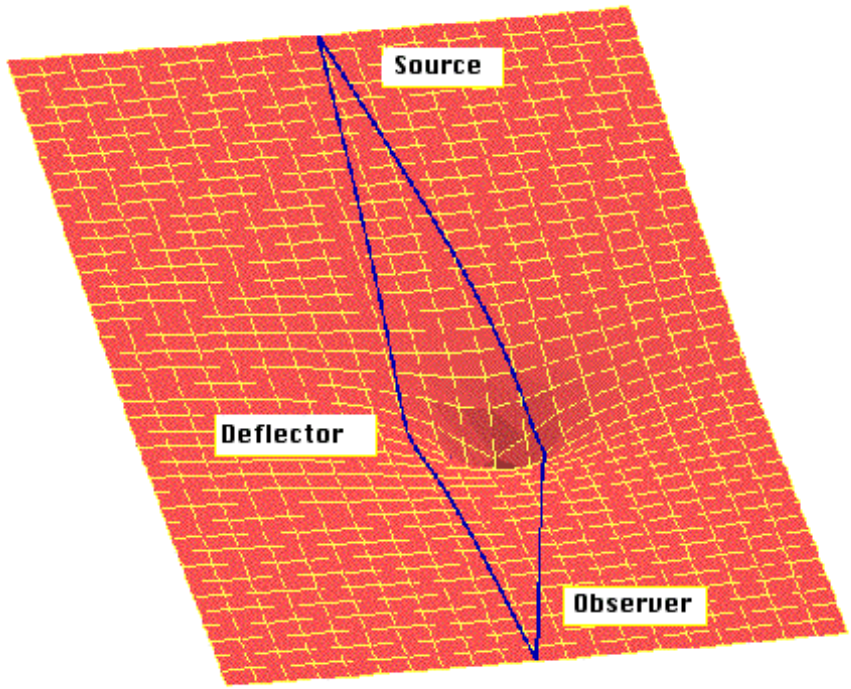
We cannot see the dark matter, but we can probe its distribution using *gravitational lensing.*

The center of the Virgo cluster

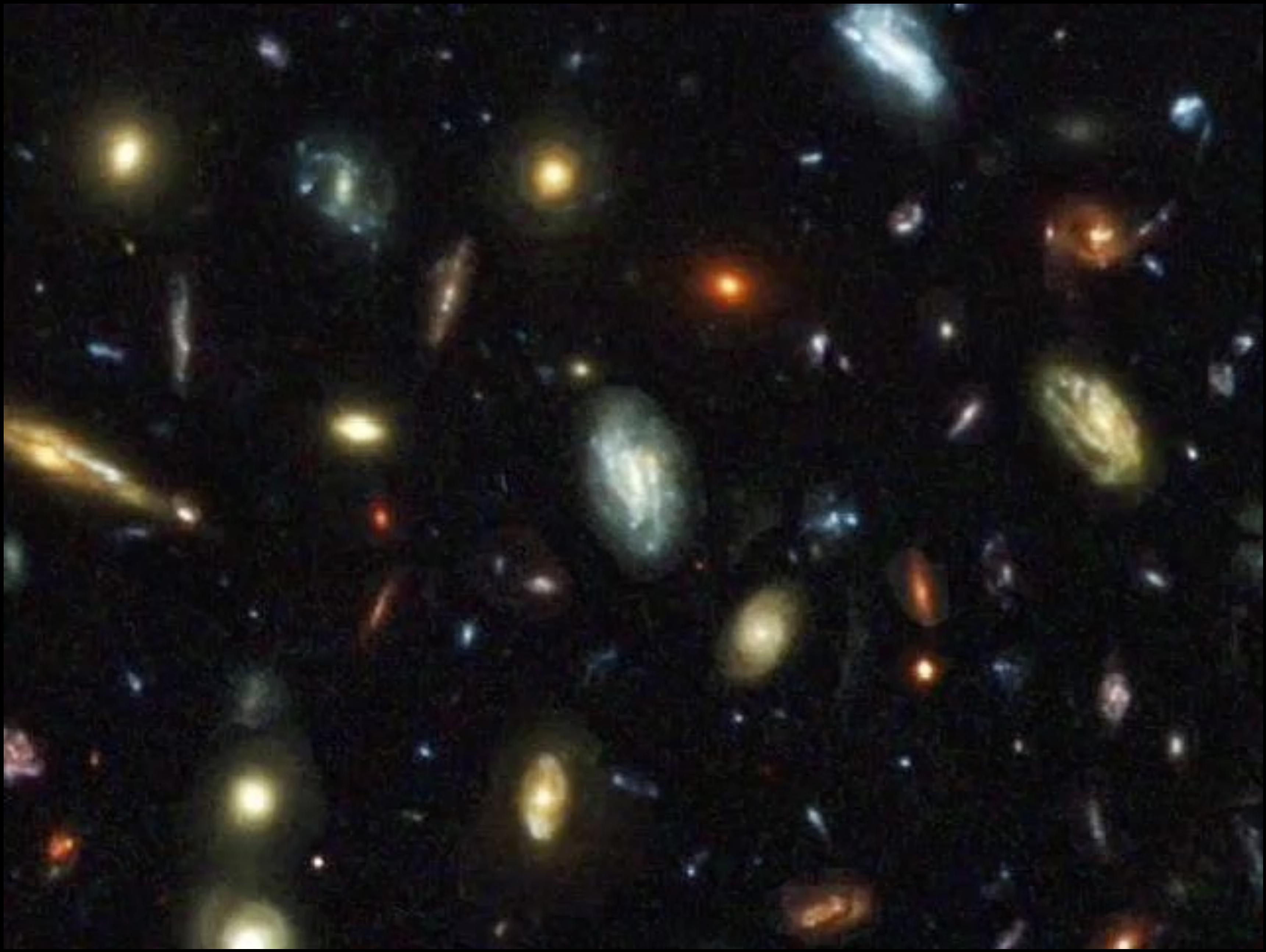


Gravitational lensing

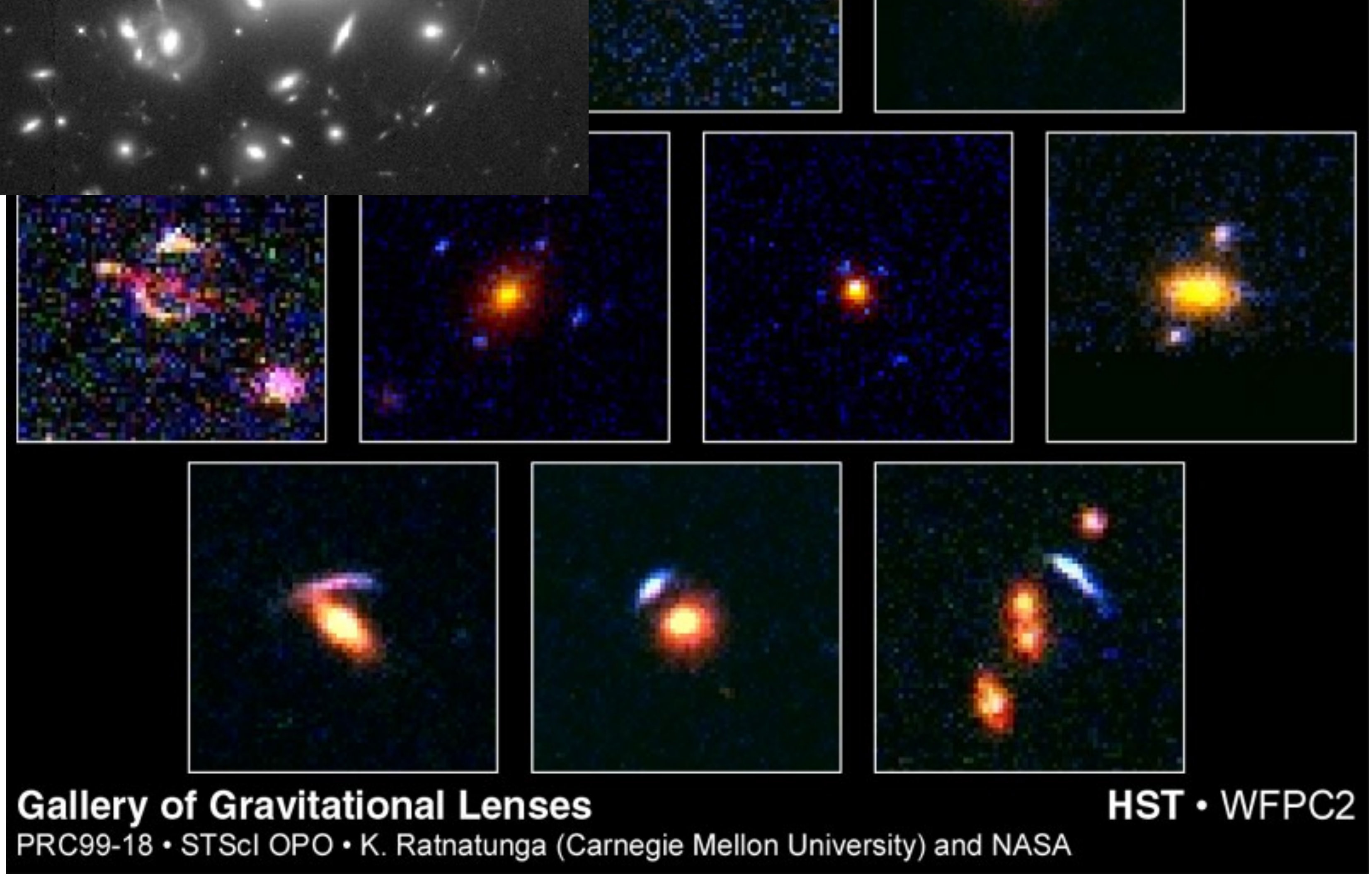
- The presence of matter distorts the path of the light.
- The distribution of matter determines how this distortion occurs.
- If we can measure the distortion, we can estimate the distribution of the matter!

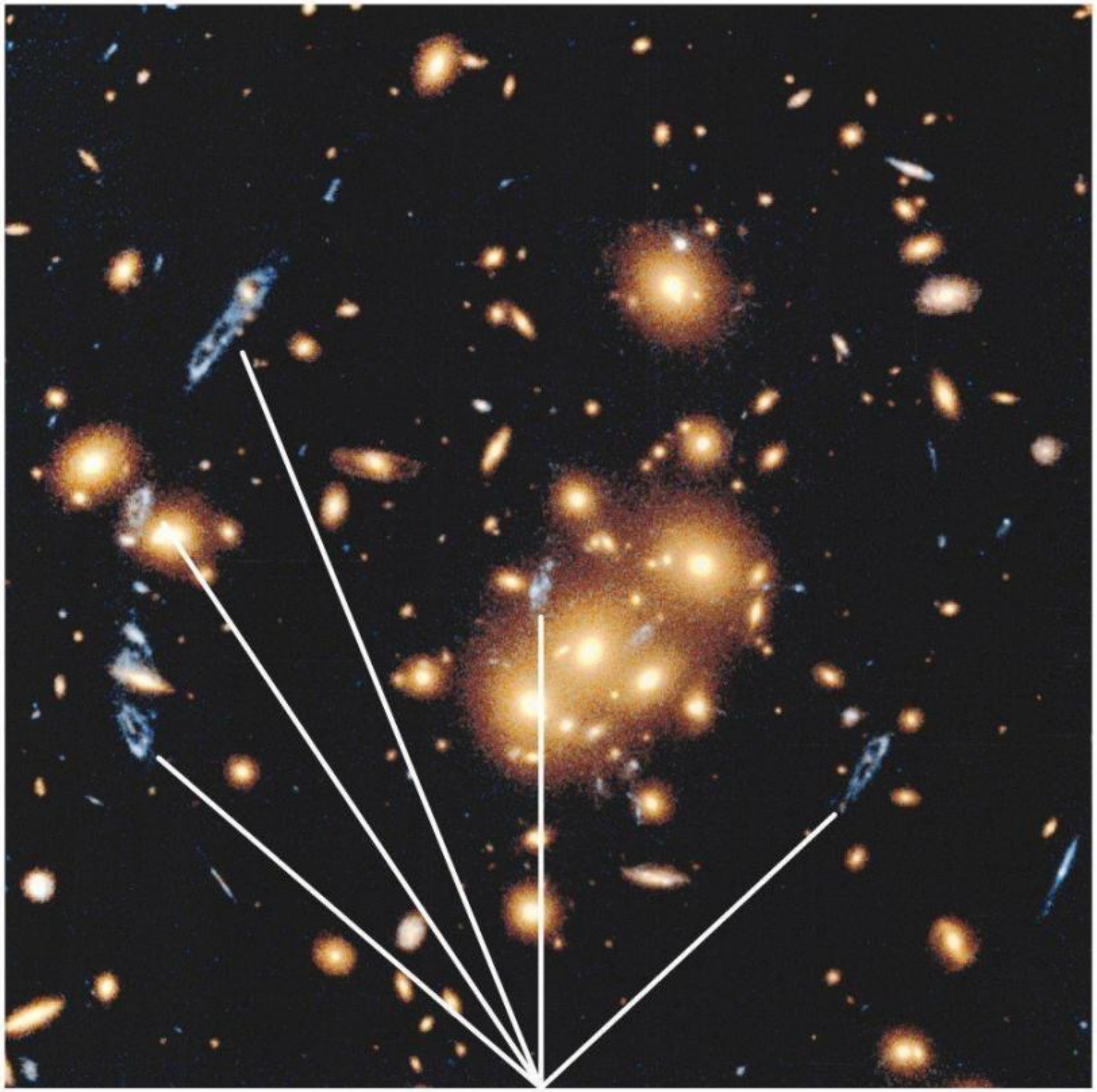


Simulation



HST examples of lensed systems





All of these blue arcs are images of the same distant galaxy.

Dark matter distribution in cluster revealed by gravitational lensing of a background (blue) galaxy

Bullet cluster: proving dark matter (?)

Two colliding group of galaxies, red shows distribution of hot gas, blue is distribution of dark matter as measured by gravitational lensing.

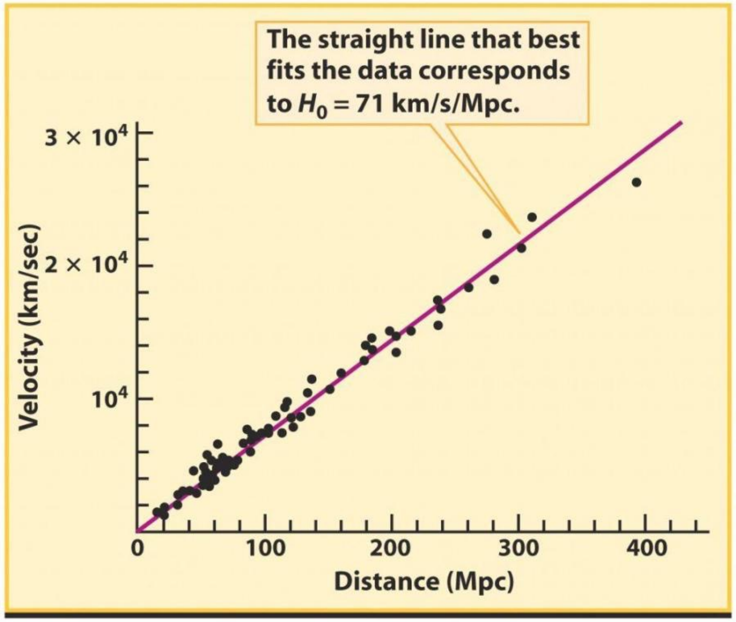
Markevitch et al. 2006

Superclusters: clusters of clusters

- Sizes up to 50 Mpc, 10^{15} - 10^{16} $M_{\odot}$.
- 90-95% empty space (voids).
- Often long and filamentary in shape.
- Superclusters are the largest coherent structures seen in the Universe.

Local mass concentrations

- Expansion of the Universe: called the *Hubble flow*.

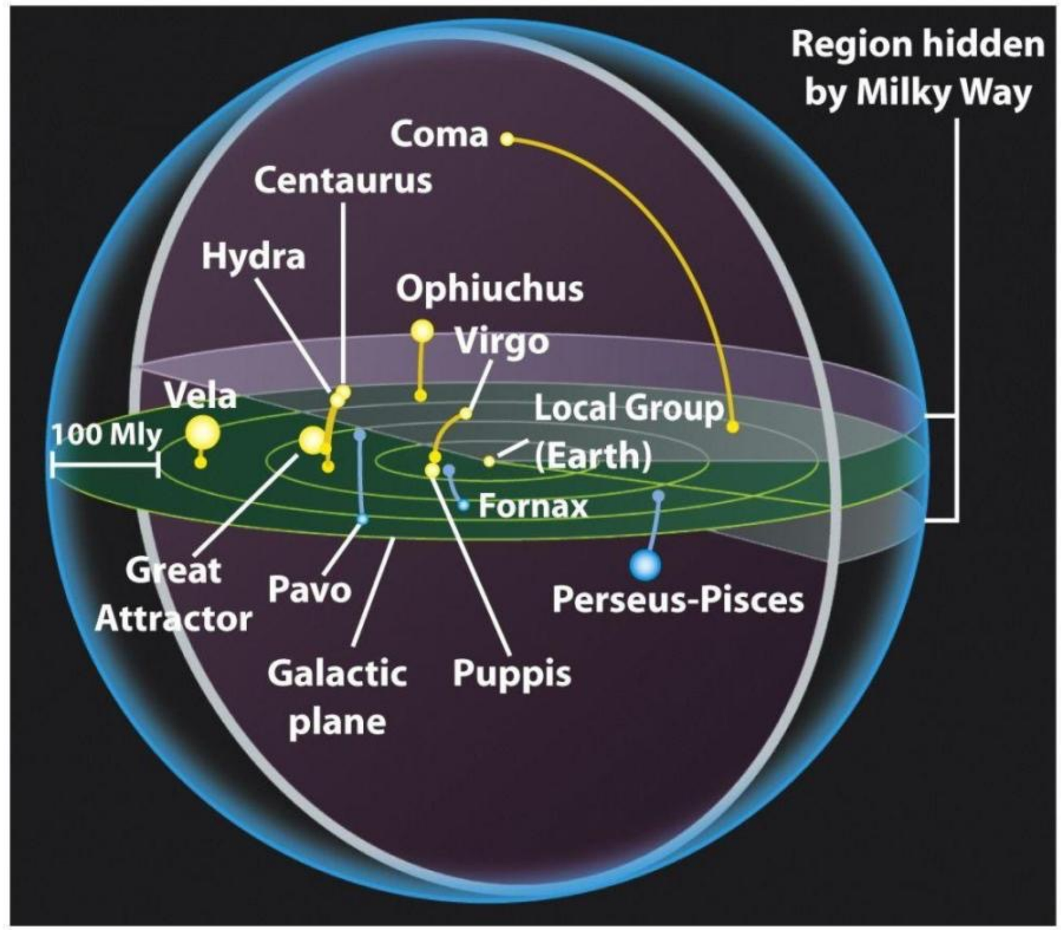


- Deviating velocities of galaxies are called *peculiar velocities.*

- Measuring the peculiar velocities of clusters and superclusters => positions of local mass concentrations

The Great Attractor

- For most components in the Local Supercluster, there is large scale streaming flow superposed on the Hubble flow.
- $10^{16}\ M_{\odot}$ at 65 Mpc? Again, 10 times too little matter…

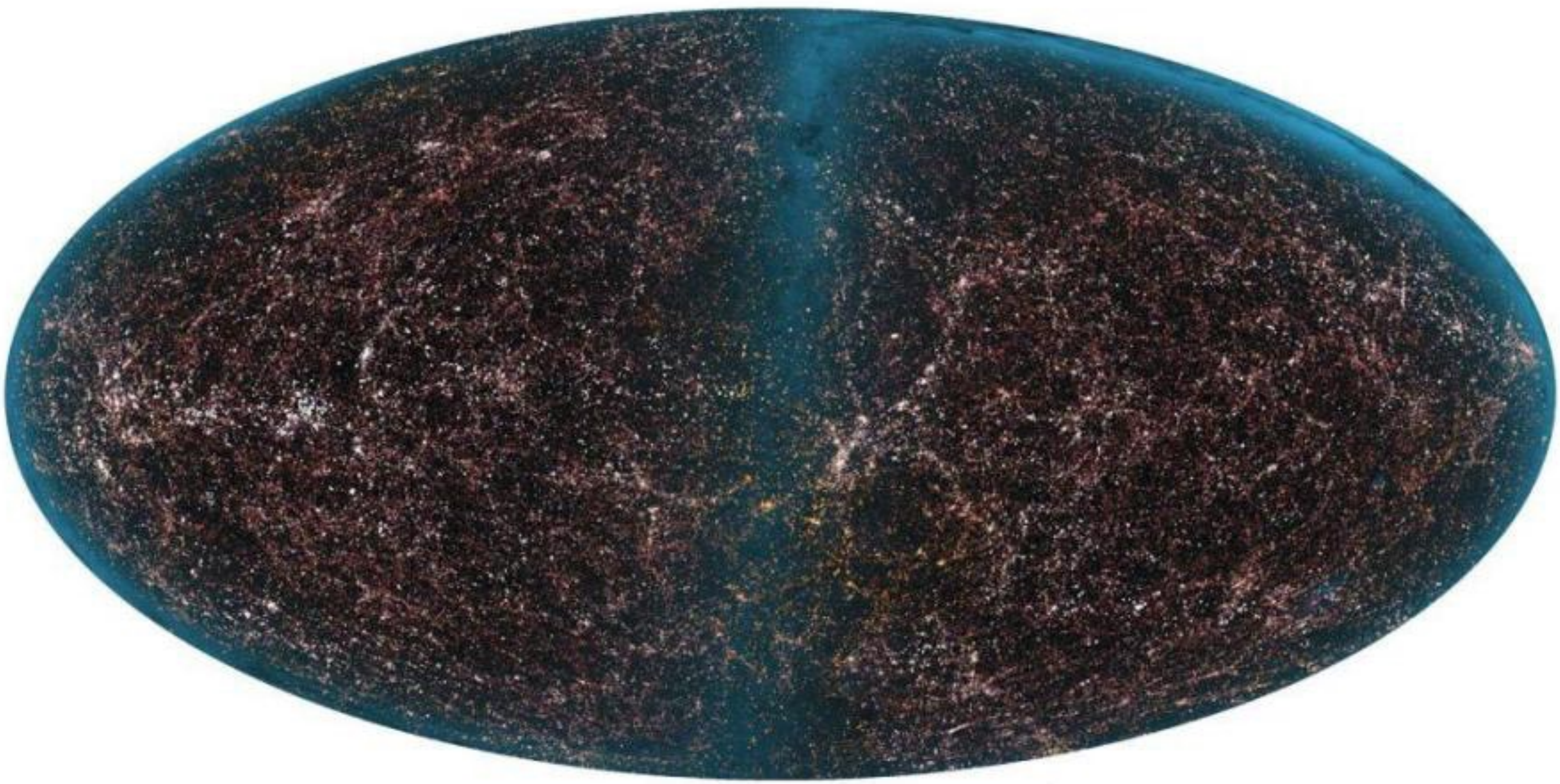


Local Supercluster

- Roughly centered on the Virgo Cluster.
- Size: ~20 Mpc, mass: ~10^{15} $M_{\odot}$ (only 5% of volume occupied by galaxies).
- The Local Group is on the outskirts of the Local Supercluster, and falling into the Virgo Cluster at about 250 km/s.

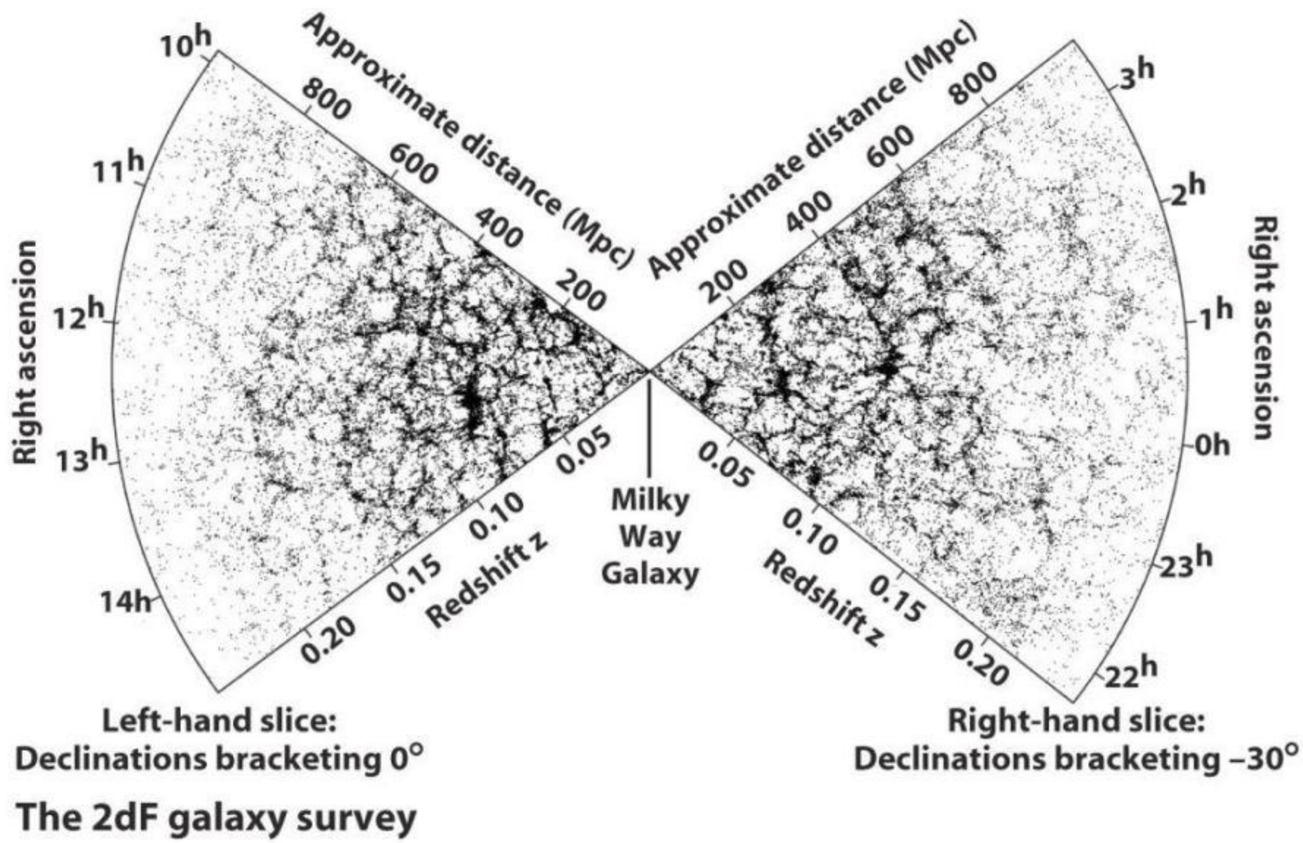
Large scale structure

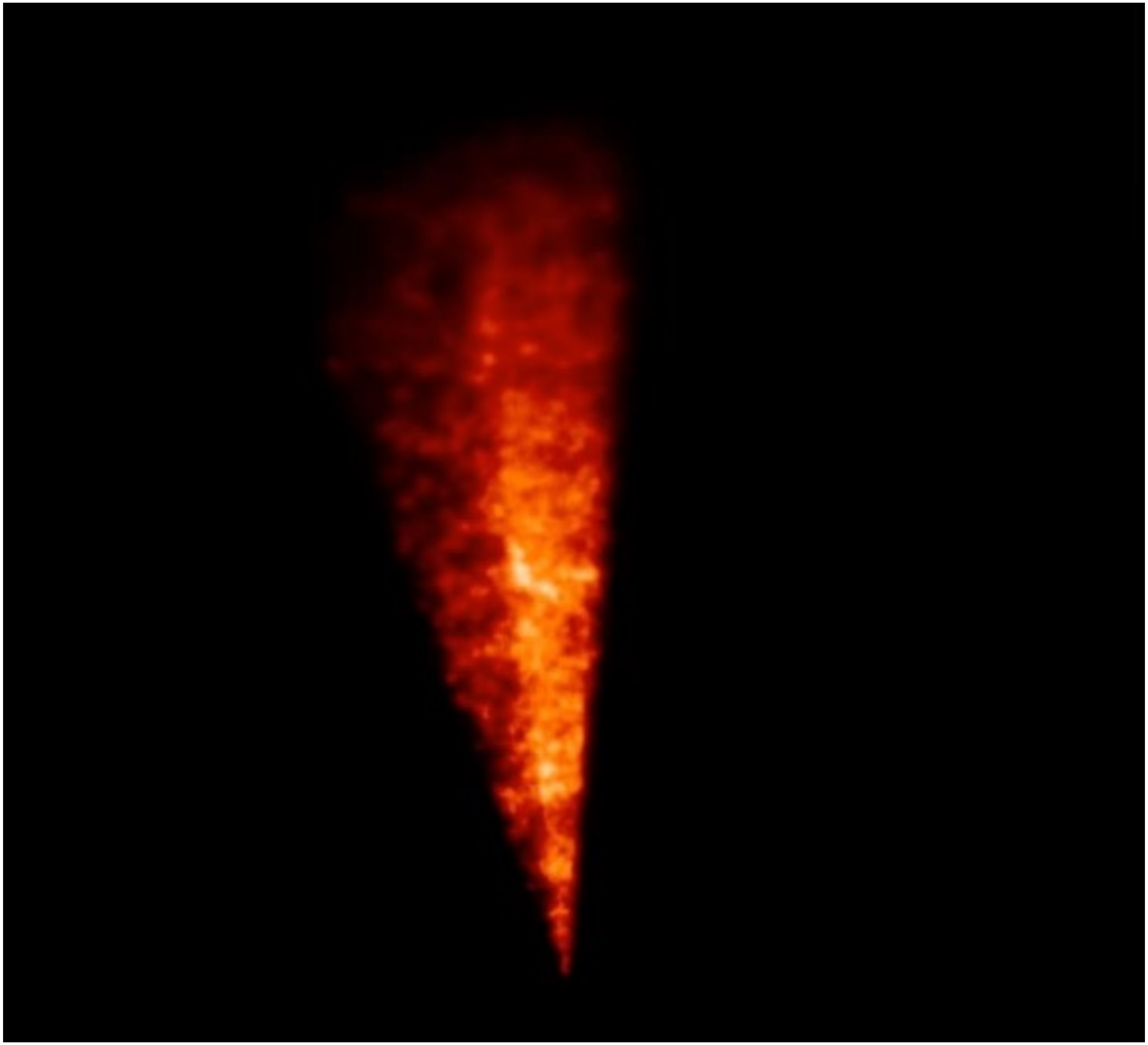
- Large scale structure of the Universe (2MASS): 1.6×10^6 galaxies



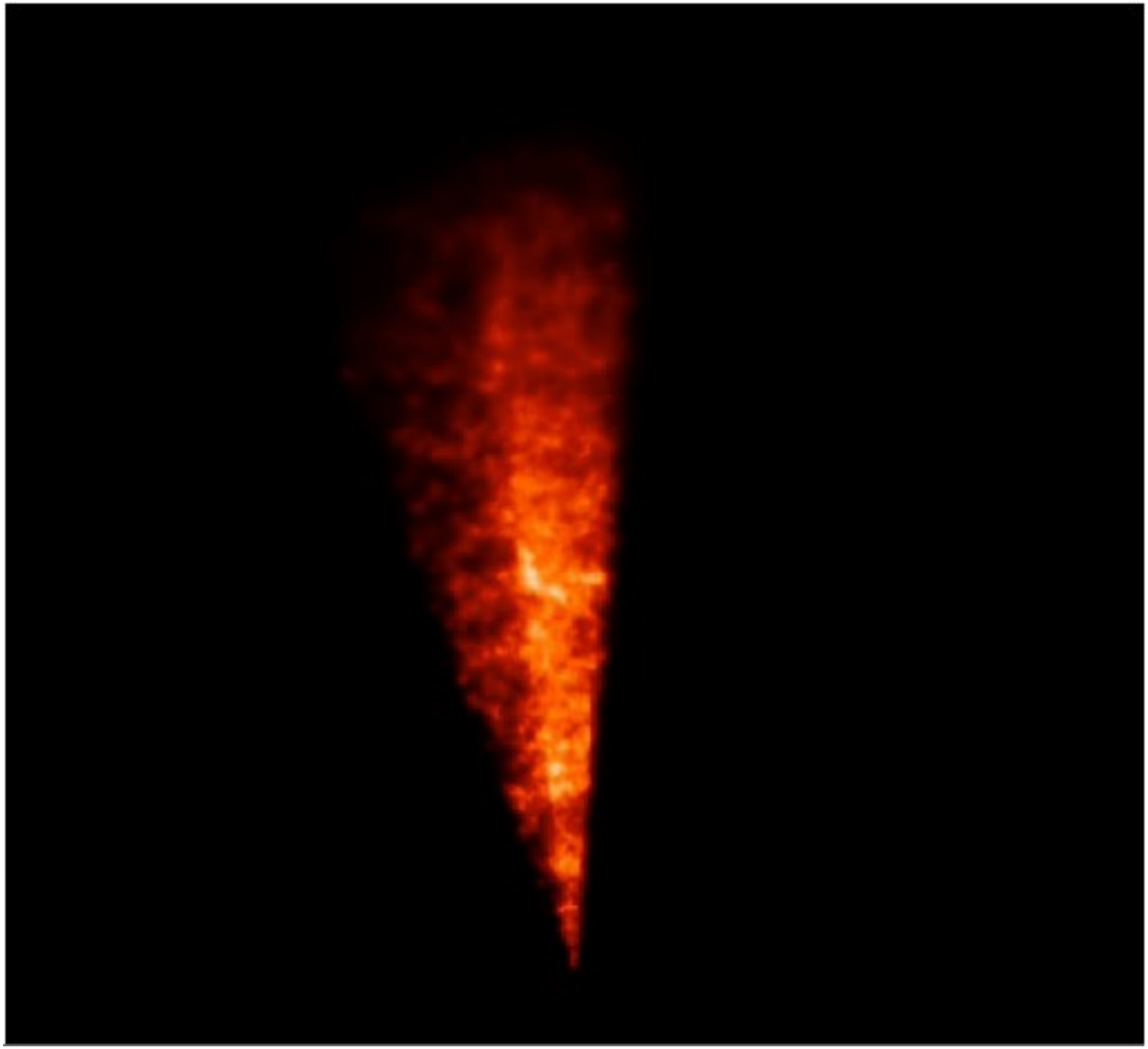
Slices through large scale structure

- We see "sheets" of galaxies, and voids in the distribution.
- Filaments: huge chains of superclusters (occupy ~10% of the Universe).
- Voids: empty bubbles, 25-50 Mpc in diameter. 5-10 times fewer galaxies than in superclusters.





Rotate the slice



Large Scale Structure: Implications

- Information on how galaxies formed:
  - Large structures formed by gravity
  - Concentrations of matter where galaxies form

- Still unanswered:
  - Why do galaxies form in particular places?
  - How empty are the voids?
  - Did galaxies or clusters form first?