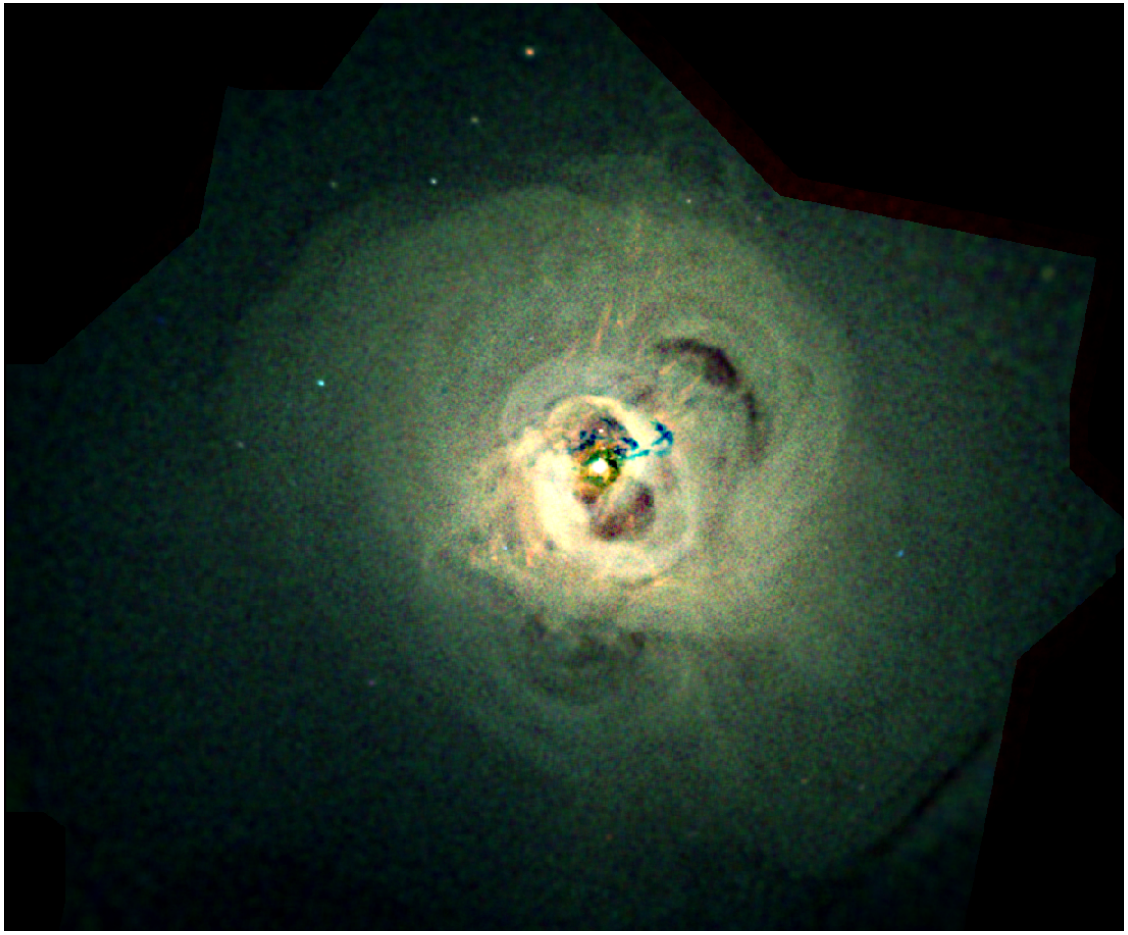
Astronomy 422



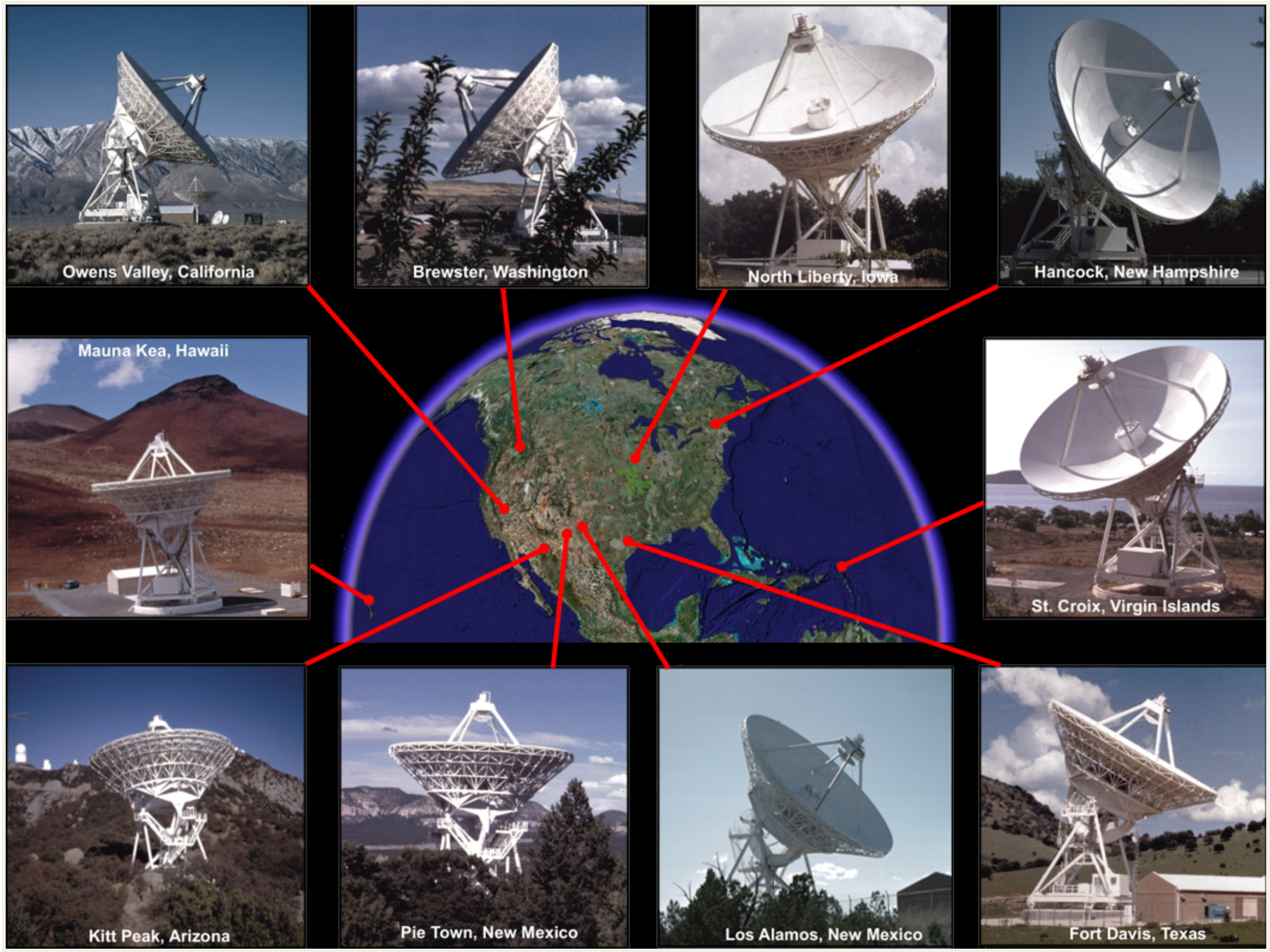
Lecture 18: Clusters and AGN Feedback

Key concepts:

AGN energetics

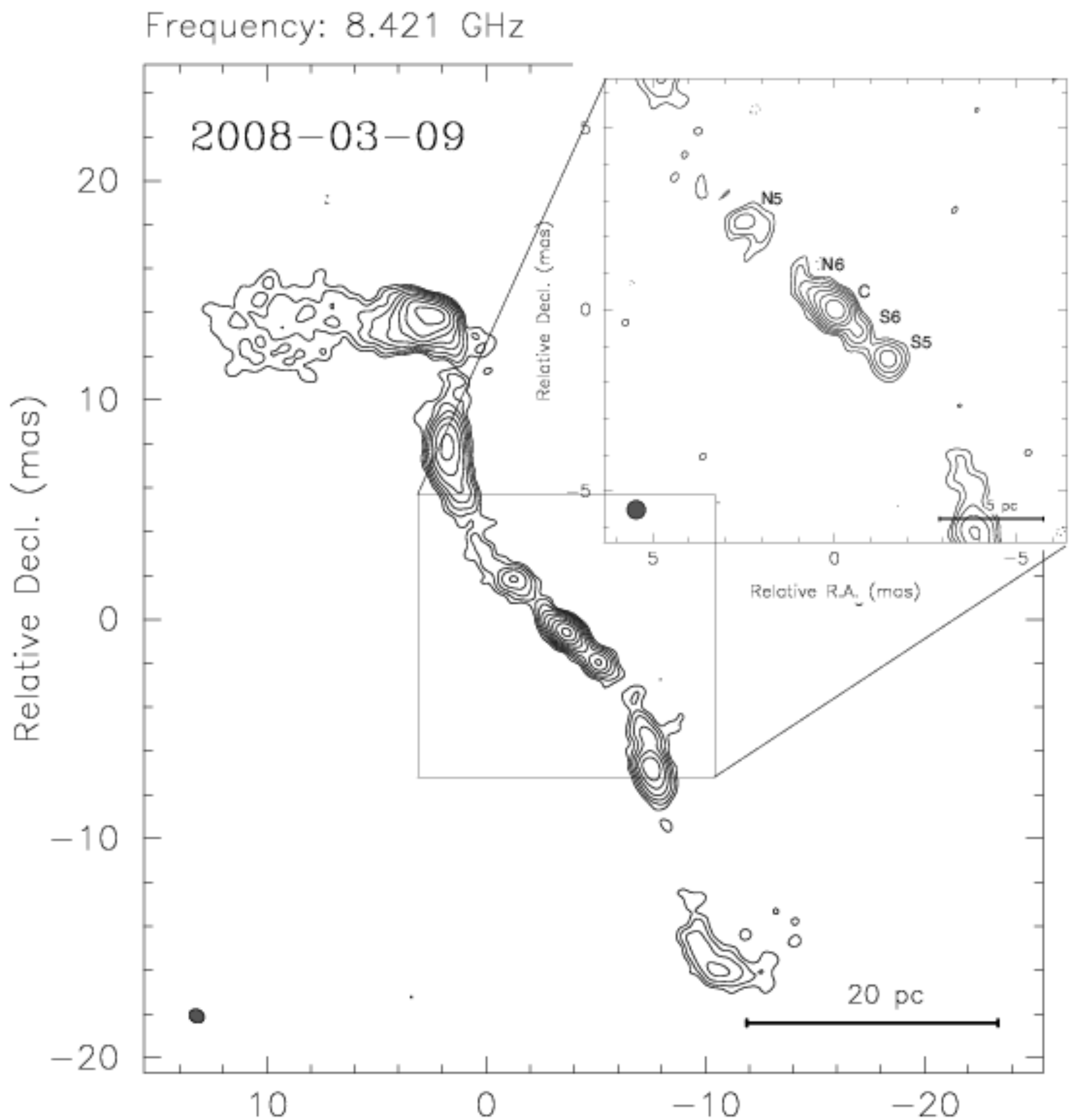
AGN Feedback in clusters

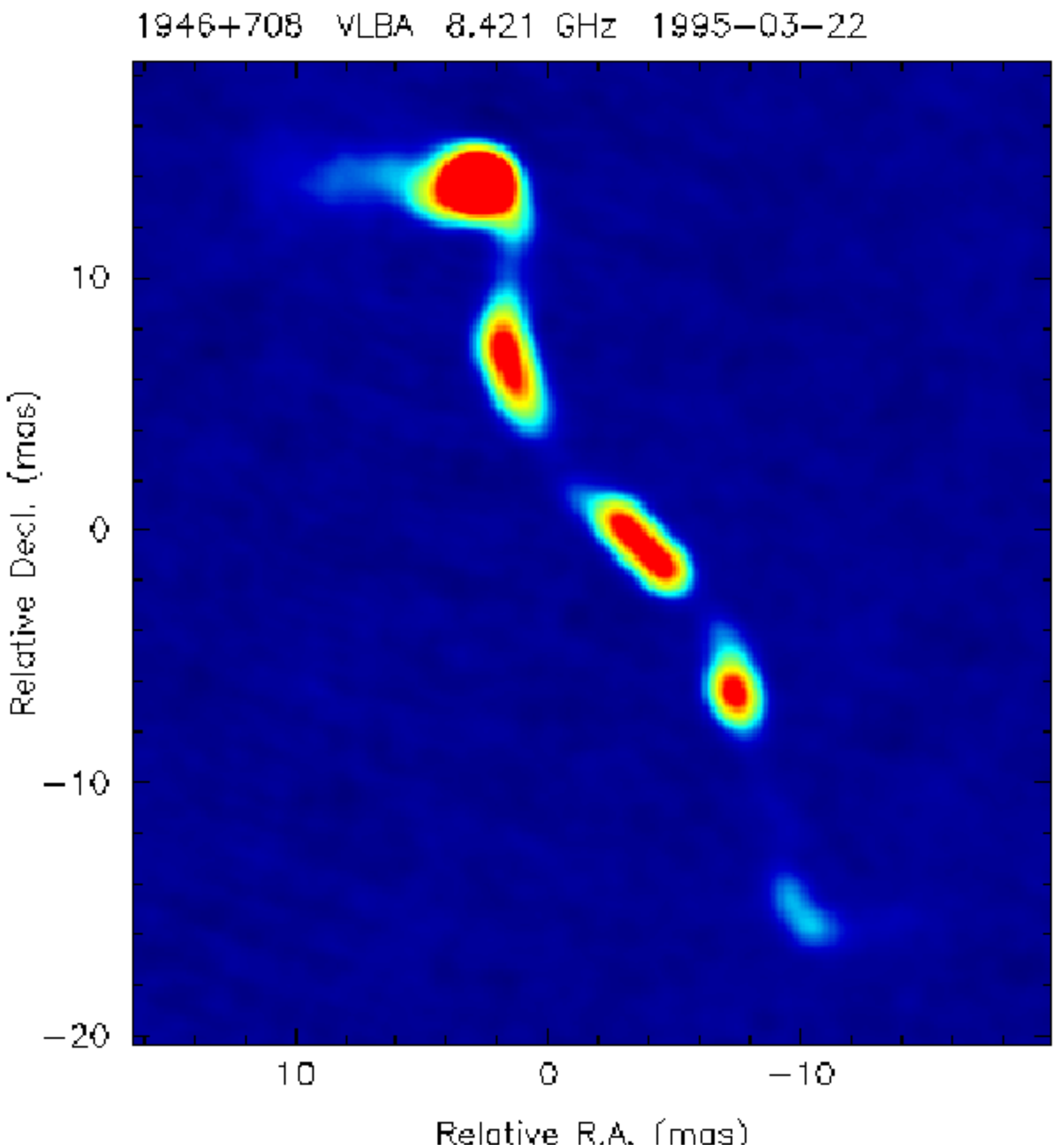
Faraday Rotation



The Very Long Baseline Array (VLBA).

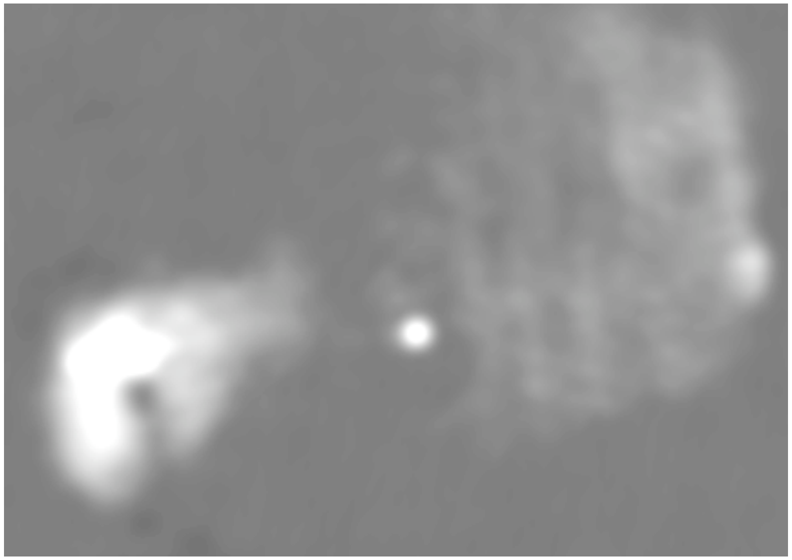
VLBA operates from 330 MHz to 90 GHz


Frequency: 8.421 GHz
2008−03−09
Relative Decl. (mas)
20
10
0
−10
−20
10
0
−10
−20
20 pc
N5
N6
C
S6
S5
Relative Decl. (mas)
Relative R.A. (mas)
5 pc


1946+708 VLBA 8.421 GHz 1995-03-22
Relative Decl. (mas)
10
0
−10
−20
10
0
−10
Relative R.A. (mas)

Evolution

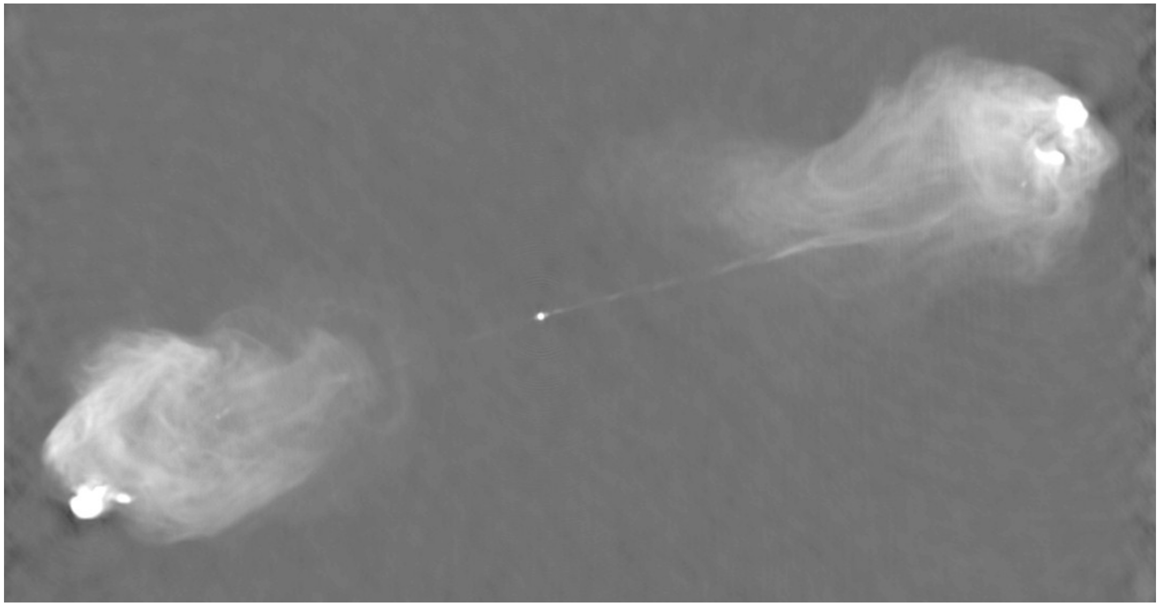
4C31.04



100 pc

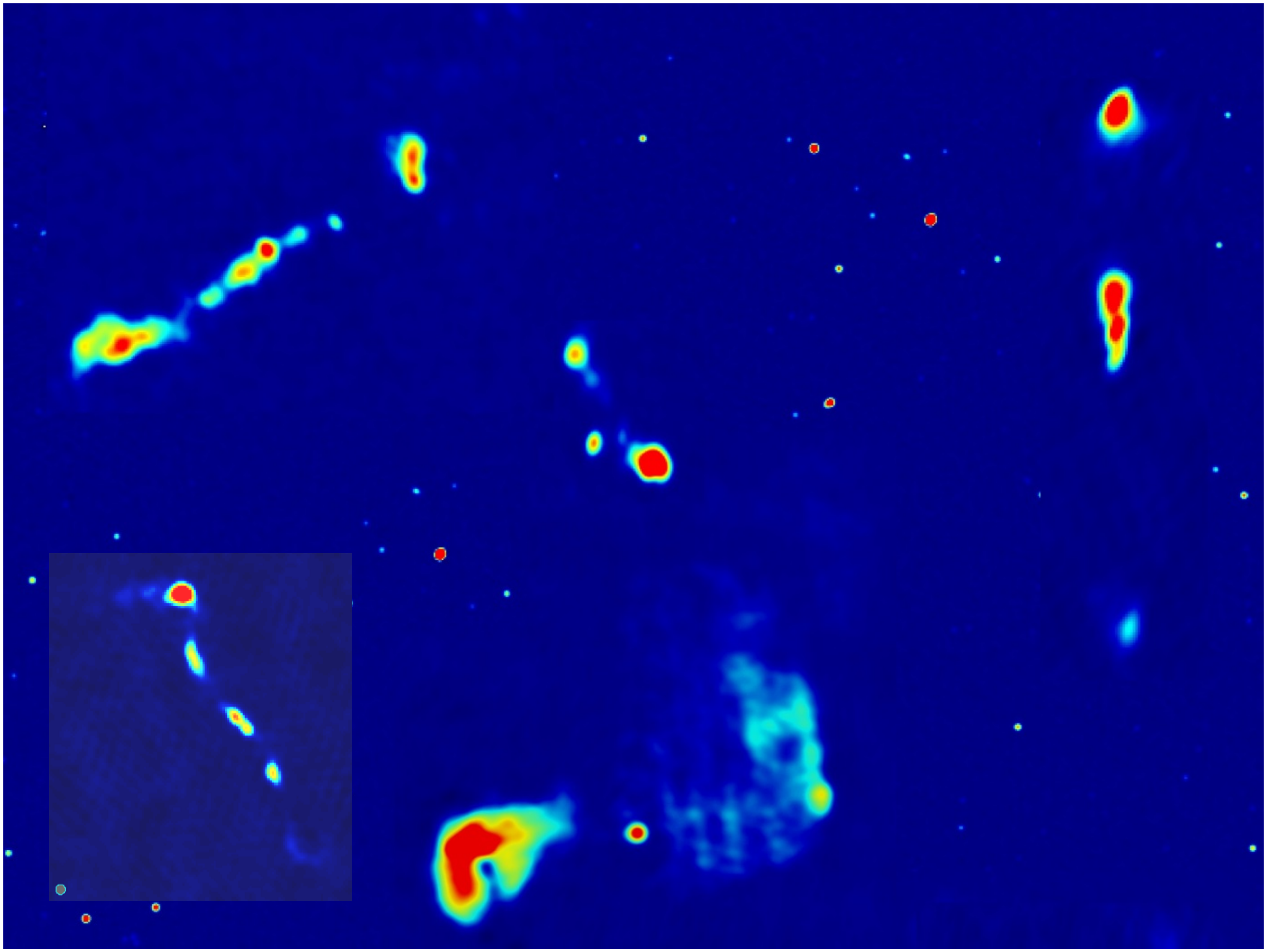
?

Cygnus A



100 kpc

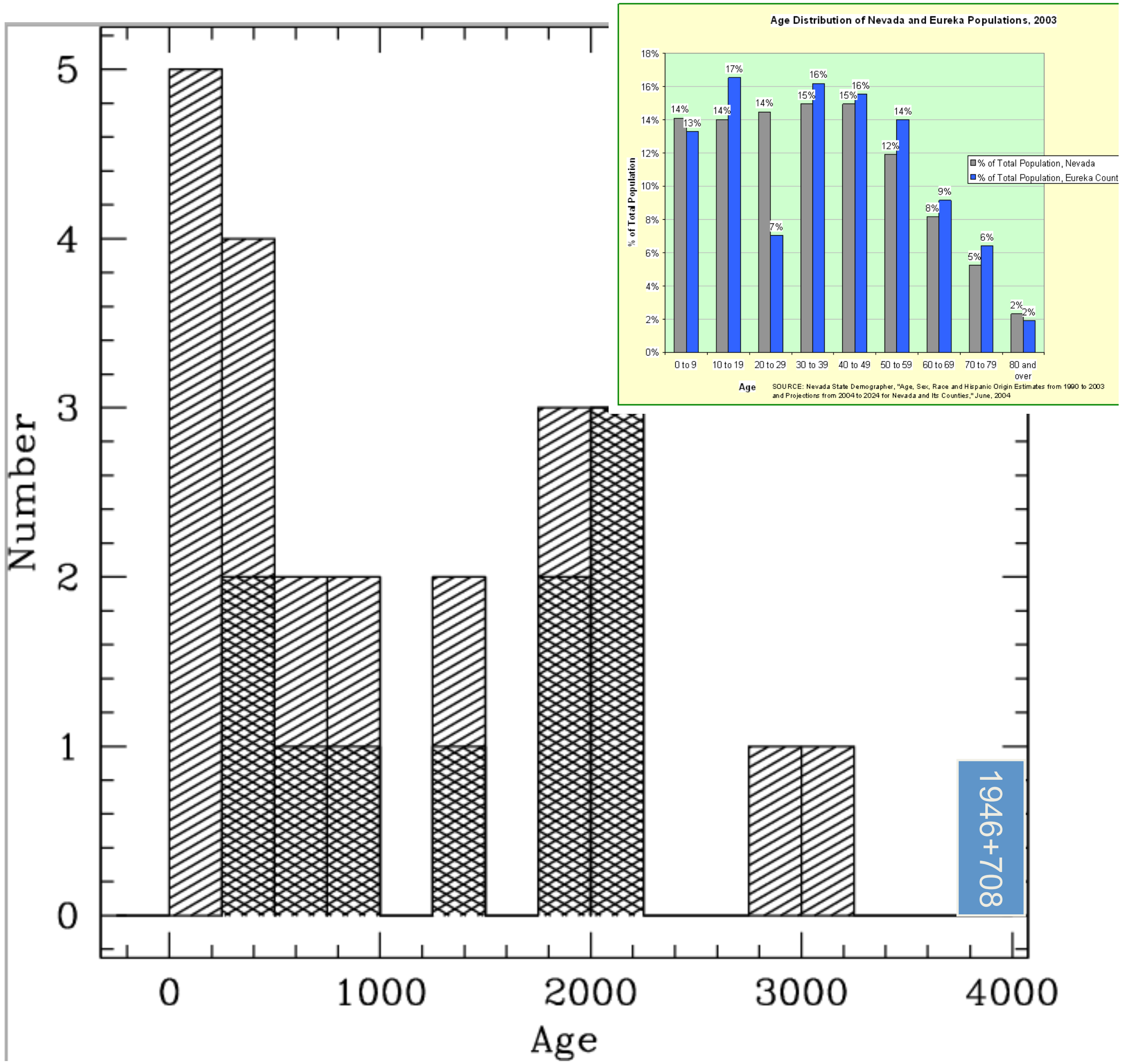
Compact Symmetric Objects (CSOs)



CSO Ages

Gugliucci et al. 2005

9/23 sources have
ages < 500 years



AGN engines - SMBHs?

Theoretical arguments:

- Radiation pressure (lower limit on M)
- Radiation efficiency of BH accrection

Observational arguments:

- High central stellar velocity dispersions found
- Megamaser disks (e.g., NGC4258)
- Radial velocities from ionized gas
- Broad iron Ka lines
- Reverberation mapping
- Sgr A*

Radiation pressure and black hole mass limits

If the AGN and AGN gas should be stable in the long term, the gravitational force should exceed or equal the radiation pressure from the AGN:

$F_{grav} > F_{rad}$

Radiation force on electron:

$$F_{rad} = \sigma_e \frac{L}{4\pi r^2 c}$$

Gravitational force on e-p pair (neutral medium):

$$F_{grav} = -\frac{GM(m_p + m_e)}{r^2}$$

This brings us to the Eddington limit:

$$L \leq \frac{4\pi G c m_p}{\sigma_e} M \simeq 6/31 \times 10^4 M \;\; \mathrm{ergs\,s^{-1}} \simeq 1.26 \times 10^{38} \left(\frac{M}{M_\odot} \right) \;\; \mathrm{ergs\,s^{-1}}$$

The Eddington limit can be used to establish a minimum for the mass of the black hole:

$$M_E = 8 \times 10^5 \;\; L_{44} M_\odot$$

For typical Seyfert galaxies: $L \simeq 10^{44}\,\mathrm{erg\,s^{-1}} \;\Rightarrow\; M_{Sy} \simeq 8 \times 10^5 M_\odot$

QSOs: $L \simeq 10^{46}\,\mathrm{erg\,s^{-1}} \;\Rightarrow\; M_{QSO} \simeq 8 \times 10^7 M_\odot$

- The Eddington luminosity is the maximum luminosity emitted by a body of mass M, that is powered by spherical accretion.

- Thus, the AGN luminosity sets a limit on its mass, independent of size and distance (both radiation pressure and gravity decrease as $1/r^2$).

- This does NOT imply a SMBH, but combined with upper limits on the volume (for example from variability), it can delimit the alternatives (for example clusters of compacts objects).

Example:

- How much mass needs to be accreted to power a typical quasar at the Eddington Luminosity?

Accretion efficiency for non-rotating black holes

In accretion onto the SMBH, some of the rest mass energy is converted into radiated energy:

$$L = \eta \frac{dM}{dt} c^2$$

Through slow accretion via an accretion disk, material falls onto the black hole via quasi-circular orbits.

Potential energy of matter is turned into radiation via collisions with other gas particles.

$$\eta = 0.06 - 0.42$$

for non- to maximally rotating black holes. So how much matter falls in?

Radiation from a thin accretion disk

Consider gas flowing inward through a thin disk. We can estimate the radial distribution of the temperature:

The potential energy per unit mass at a radius R is:

$$E = -\frac{GM}{R} \;\Rightarrow\; \frac{dE}{dR} = \frac{GM}{R^2}$$

Assume that mass dM flows inward a distance dR. The change in potential energy is:

$$\Delta E = \frac{GM}{R^2} dM dR$$

Half of this energy goes into increased kinetic energy of the gas. If the other half is radiated, the luminosity will be:

$$L = \frac{\Delta E}{\Delta t} = \frac{GM\dot{M}}{2R^2} dR$$

Divide by the radiating area to get luminosity per unit area.

$$F = \frac{L}{A} = \frac{GM\dot{M}}{2R^2(2 \times 2\pi R \times dR)} dR = \frac{GM\dot{M}}{8\pi R^3}$$

Equate to the rate of energy loss via blackbody radiation (Stefan-Boltzmann):

$$\frac{GM\dot{M}}{8\pi R^3} = \sigma T^4$$

This gives the radial temperature distribution as:

$$T = \left(\frac{GM\dot{M}}{8\pi\sigma R^3} \right)^{1/4}$$

Correct dependence on mass, accretion rate and radius but off by a constant factor.
Must also account for:

a) Radial energy flux through the disk (transport of angular momentum means transport of energy).

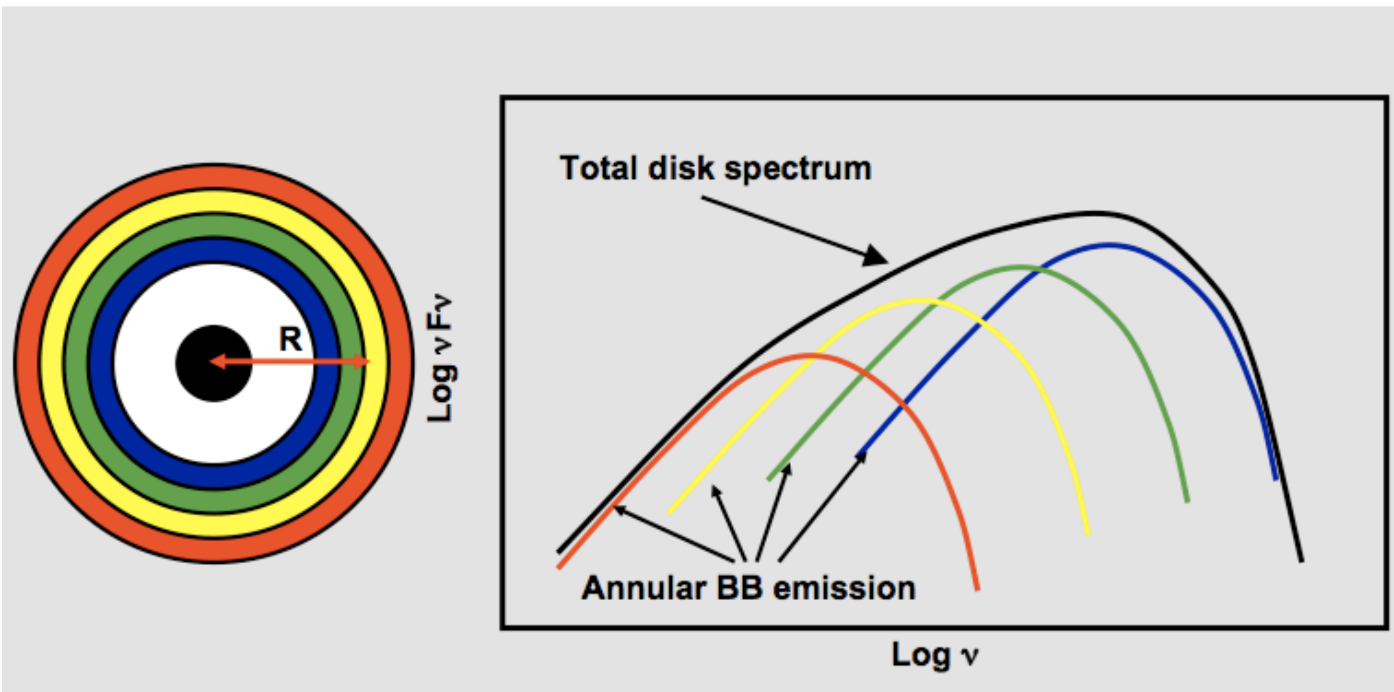
b) Boundary conditions at inner edge of disk

If this is done, we find that for a SMBH:

$$T(R) \simeq 6.3 \times 10^5 \left(\frac{\dot{M}}{\dot{M}_E}\right)^{1/4} \left(\frac{M}{10^8 M_\odot}\right)^{-1/4} \left(\frac{R}{R_s}\right)^{-3/4} \text{ K}$$

Using the Wien's Law, we'll find that this corresponds to strong emission at ~10^{16} Hz <=> 50nm.

Thus, expect disk emission in AGN accreting at close to the Eddington limit to be strong in the UV - origin of the broad peak, the Big Blue Bump.



Quasar absorption lines

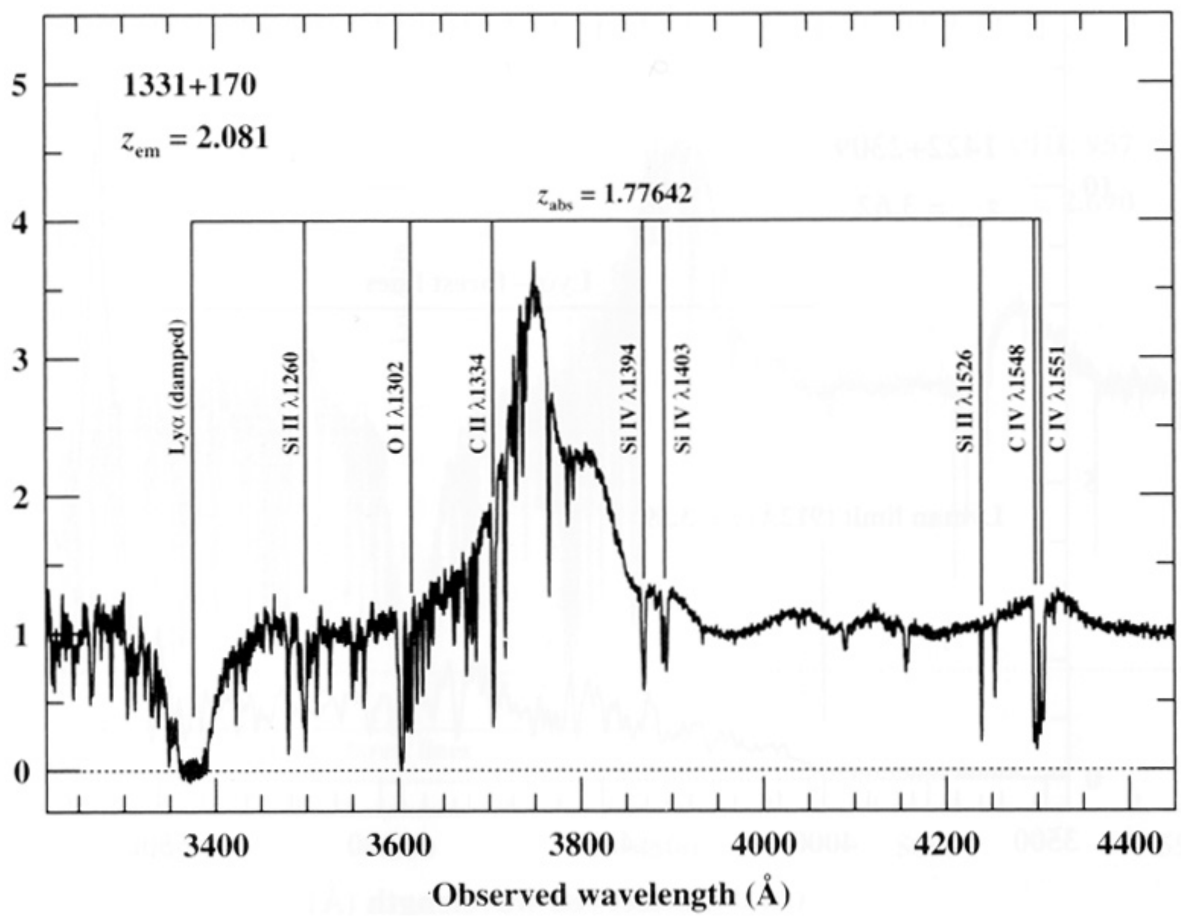
- The light emitted from high z quasars must traverse huge distances before it reaches us
  - High probability that some light will suffer extinction by the IGM and intervening galaxies.

- Depending on z, a quasar might have > 100 individual absorption lines in its spectrum!
  - Almost all system contain Lyman α 1216 Å, and CIV 1550 Å absorption features.

- Different classes of systems exist, Damped Lyman α, Lyman α forest and the broad absorption line systems.

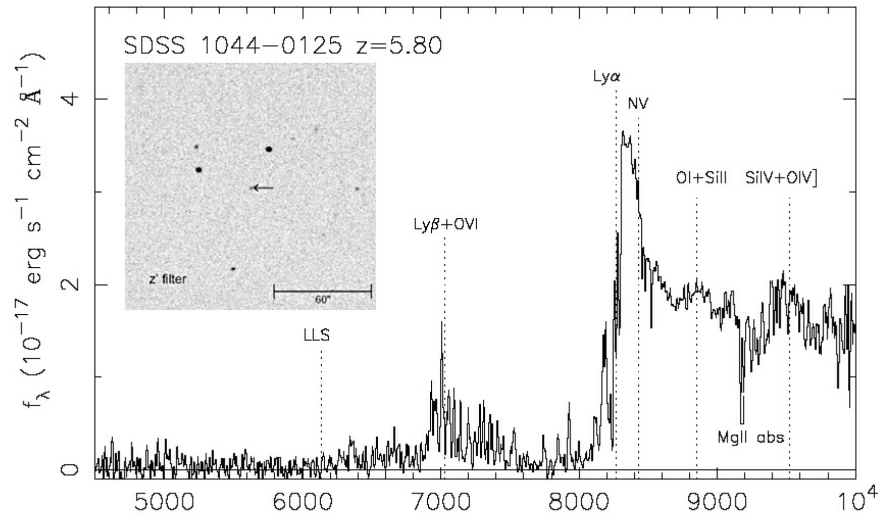
Damped Lyman α Systems

Absorption lines with strong and broad ('damped') Lyman α absorption in addition to other lines due to ionized and neutral metals. Assumed to be due to passage through galactic disks.



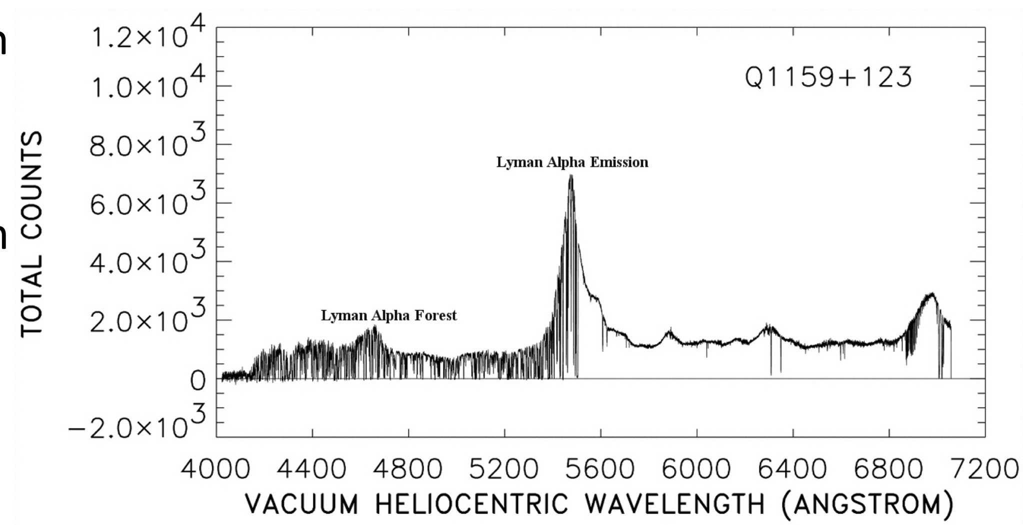
The Lyman α forest

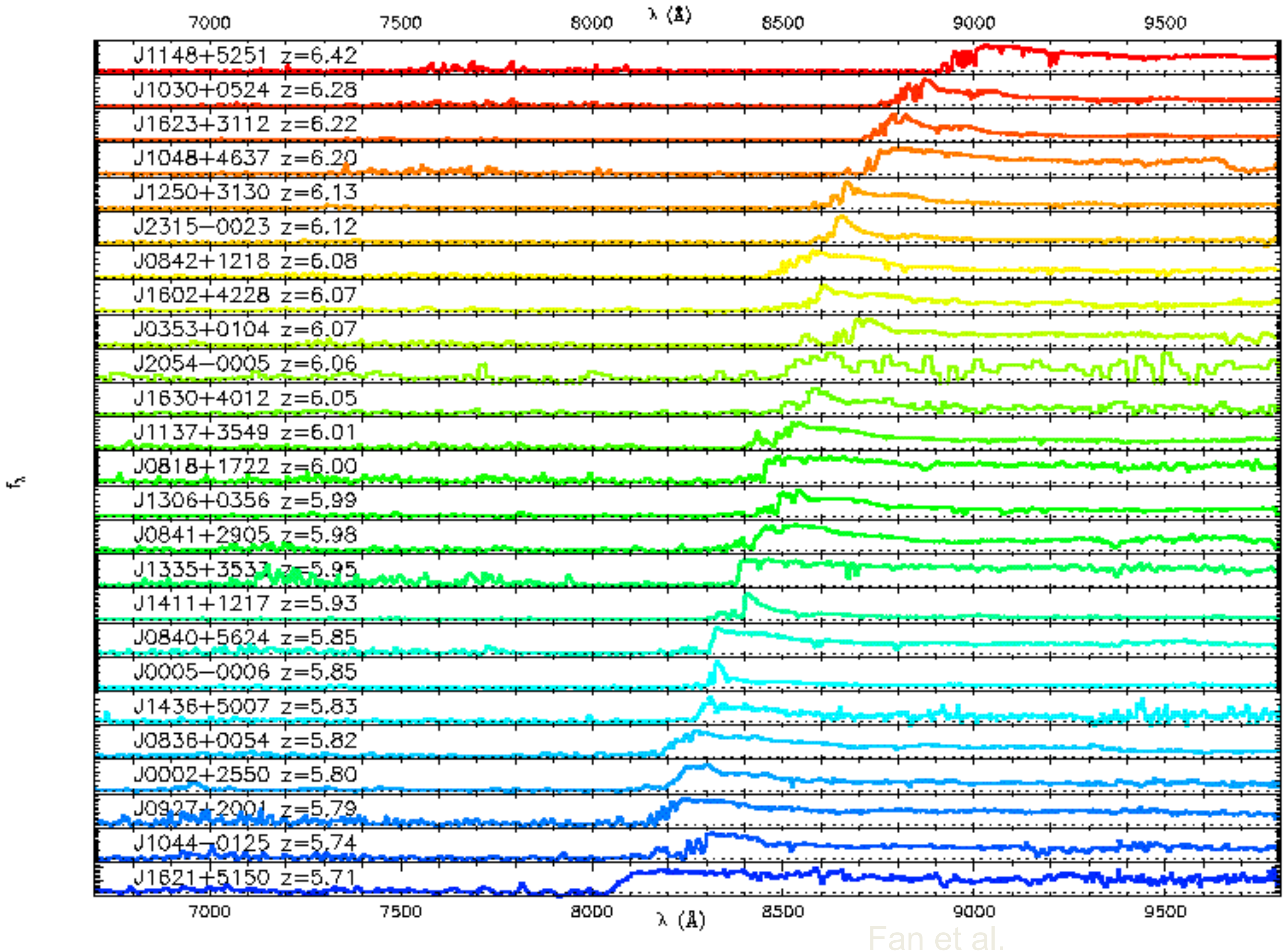
At wavelengths shortward of Lymanα, the number of absorption lines per unit wavelength increases rapidly, and the spectrum is covered by absorption features. These lines are referred to as *the Lyman α forest.*



They are probably due to dense HI clouds in the IGM at various z along the LOS.

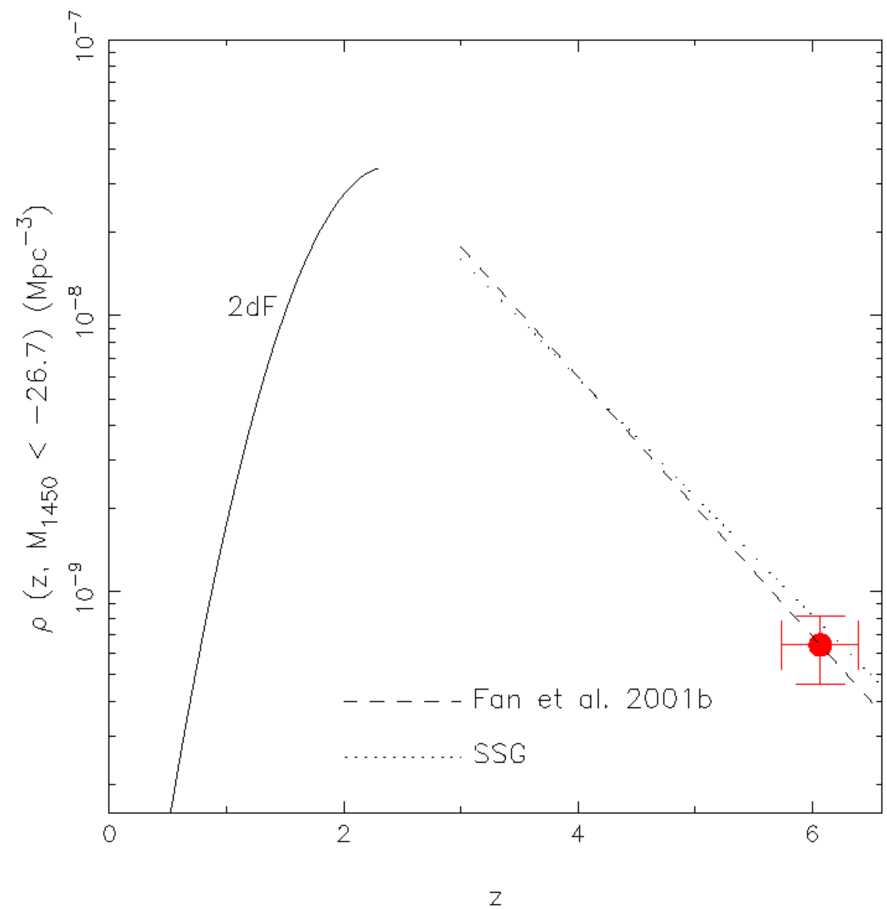
In some high z quasar spectra all continuum shortward of the ionization edge (912A) is completely absorbed - *the Lyman Limit.*




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
λ (Å)
Fan et al.

Quasar Density at z~6

- From SDSS i-dropout survey
  - Density declines by a factor of ~40 from between z~2.5 and z~6
- Cosmological implication
  - M_{BH}~10^{9-10} M_{sun}
  - M_{halo} ~ 10^{12-13} M_{sun}
  - rare, 5-6 sigma peaks at z~6 (density of 1 per $Gpc^{3)}$
  - Universe is 10^9 yr old
- **Formation of supermassive BHs?**

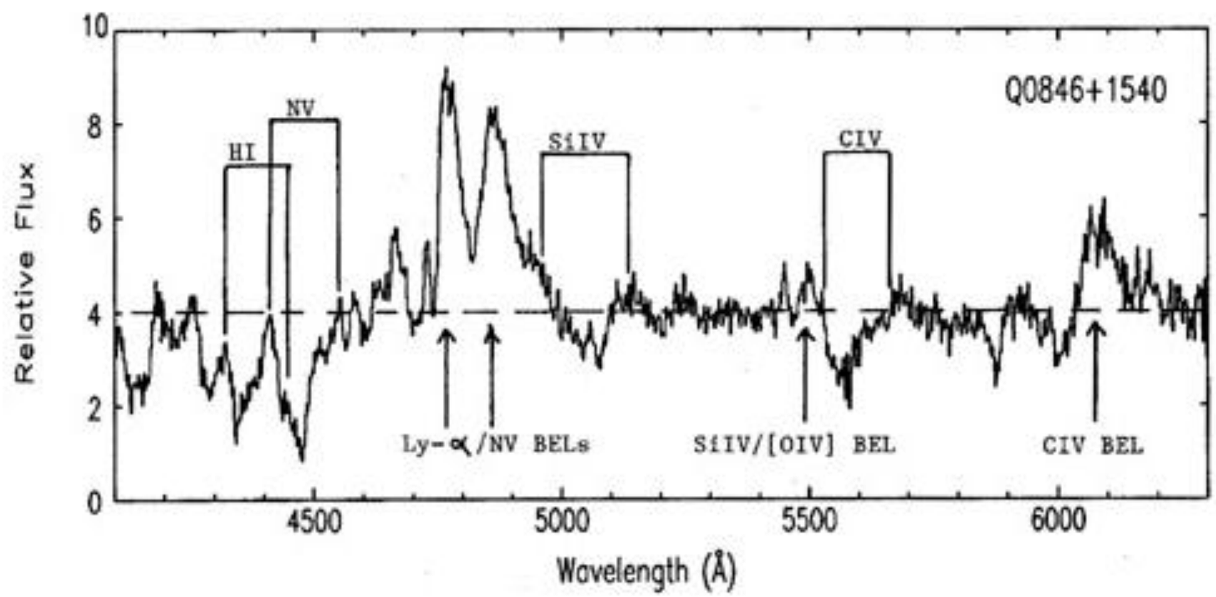


Fan et al. 2004

Broad absorption line quasars (BALs)

Very broad absorption lines are seen in some quasar spectra, blueward of the corresponding emission lines. These are presumed intrinsic to the quasars, arising from absorbing clouds flowing out from the quasar nucleus.

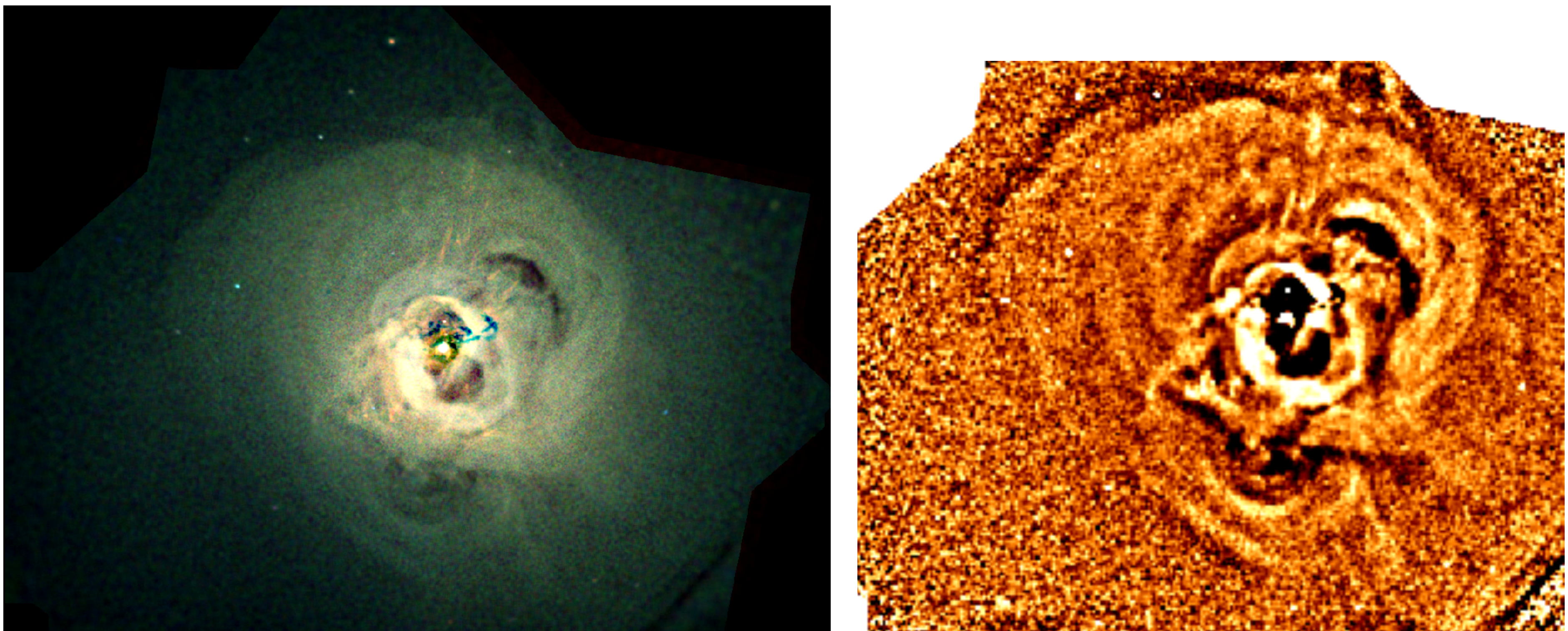
BALs are blueshifted as much as 10,000 km/s, and given the amount of radiative flux removed and highly ionized species observed therein the acceleration mechanism is radiative force from central AGN.



AGN Feedback

AGNs feedback energy to the cluster gas, heats it up

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

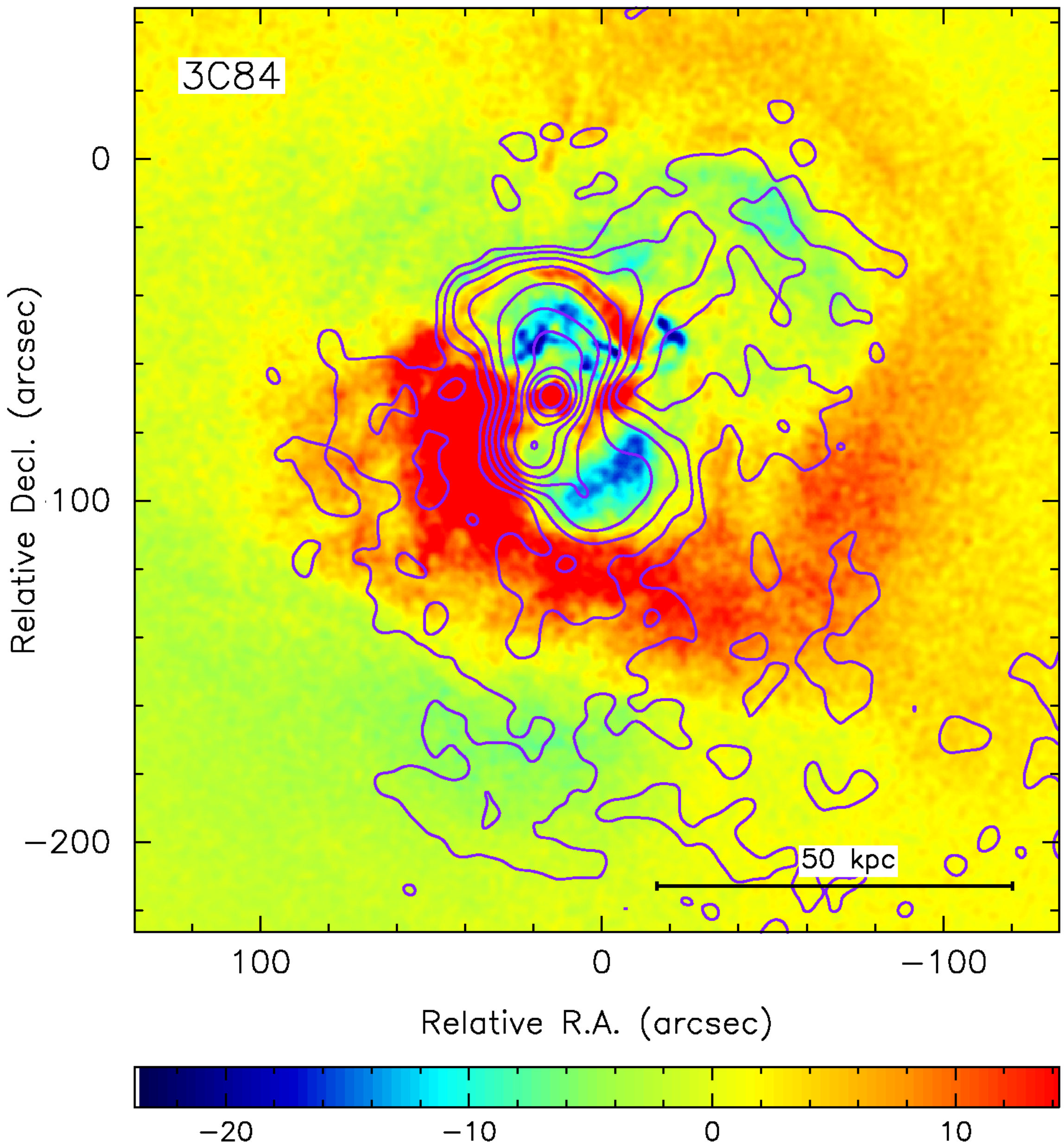


Chandra 900 ks image of Perseus cluster, unsharp-masked at right (Fabian et al. 2006)

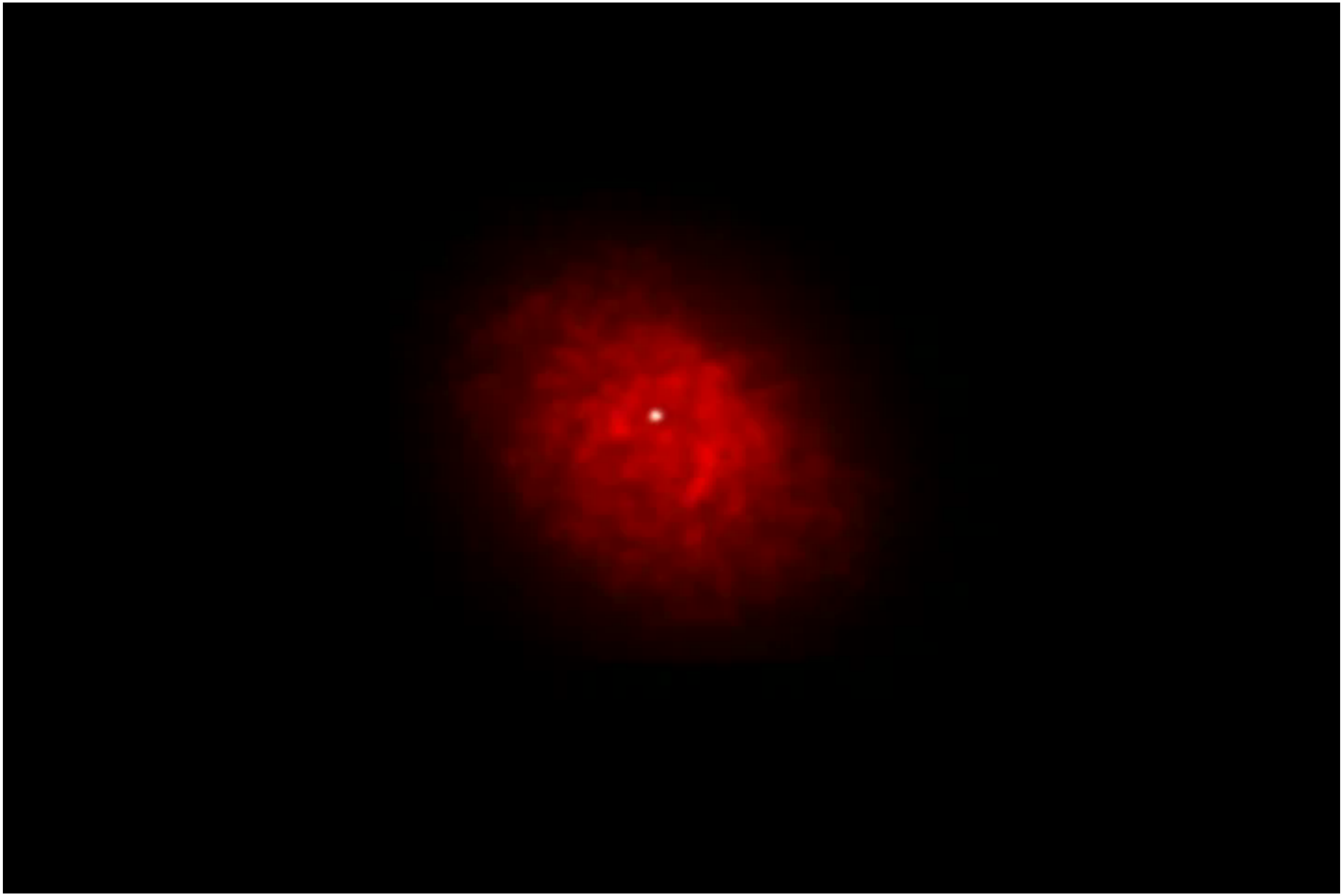
Cluster Dominant Galaxy (cD)

Fabian et al. 2003

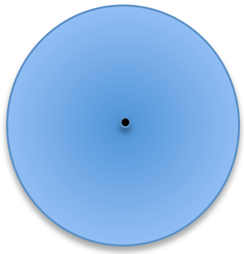
Chandra + VLA



NASA animation of sound waves produced by 3C84



Bondi Accretion



Spherical accretion of a hot gas onto a black hole

$R_b = R_{BH} \, (c/c_s)^2$

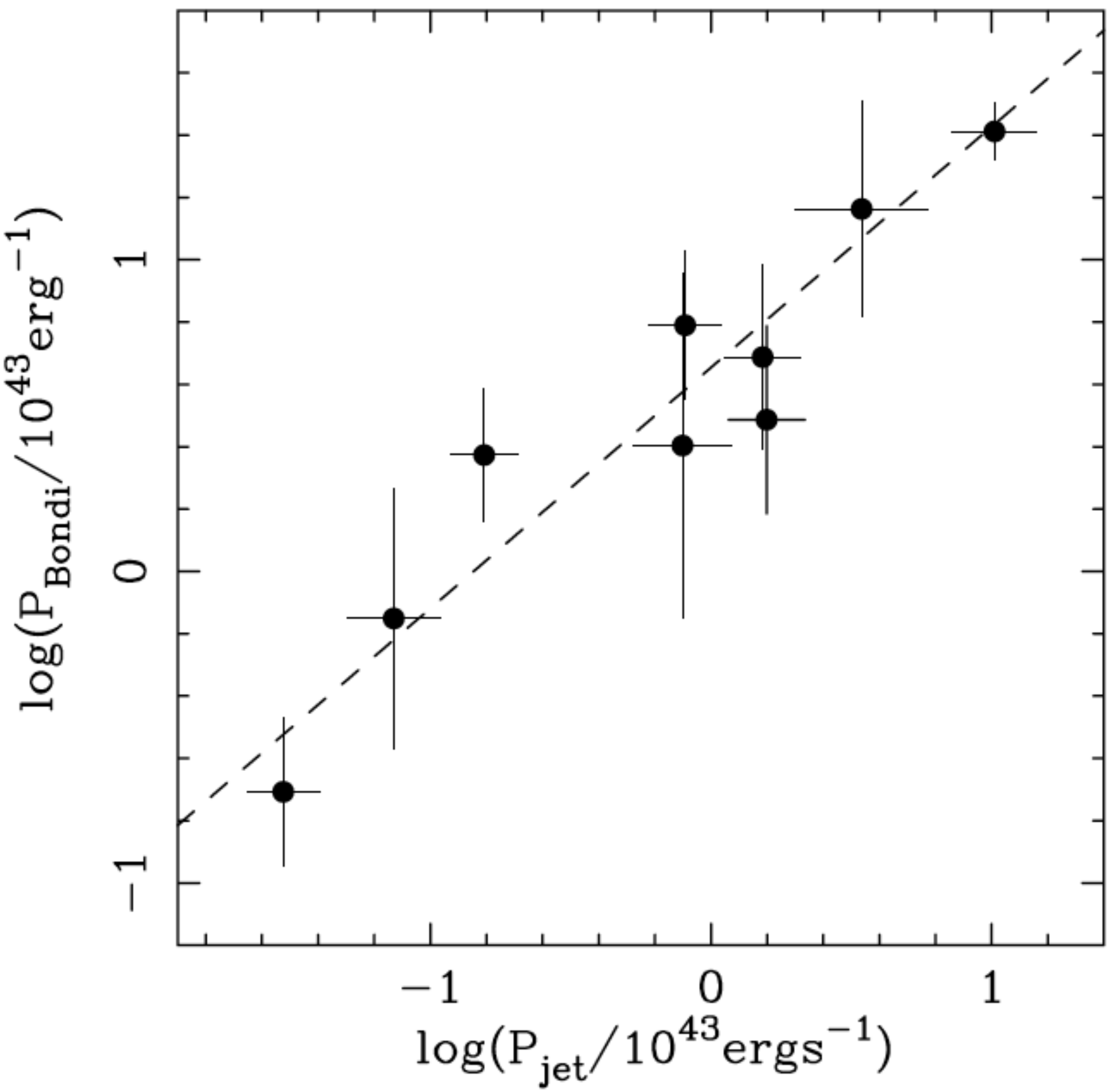
c_s = sound speed ~ $10^4 T^{1/2}$ cm/s
R_{BH} = Schwarzschild radius ~ $2GM/c^2$

$\dot{M} = 4\pi R_b^2 \rho c_s$

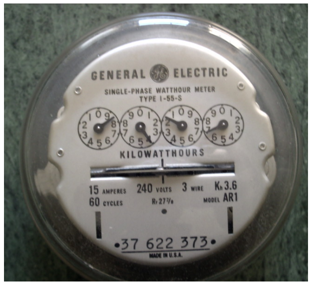
ρ is the mass density of the hot gas

$= 0.013\ M_{sun}/yr$ for PKS 1246-410 in the Centaurus cluster

$L_b = 0.1\ \dot{M}\ c^2$
$= 8 \times 10^{43}$ erg/s >> $L_{X\text{-rays}} = 4 \times 10^{39}$ erg/s



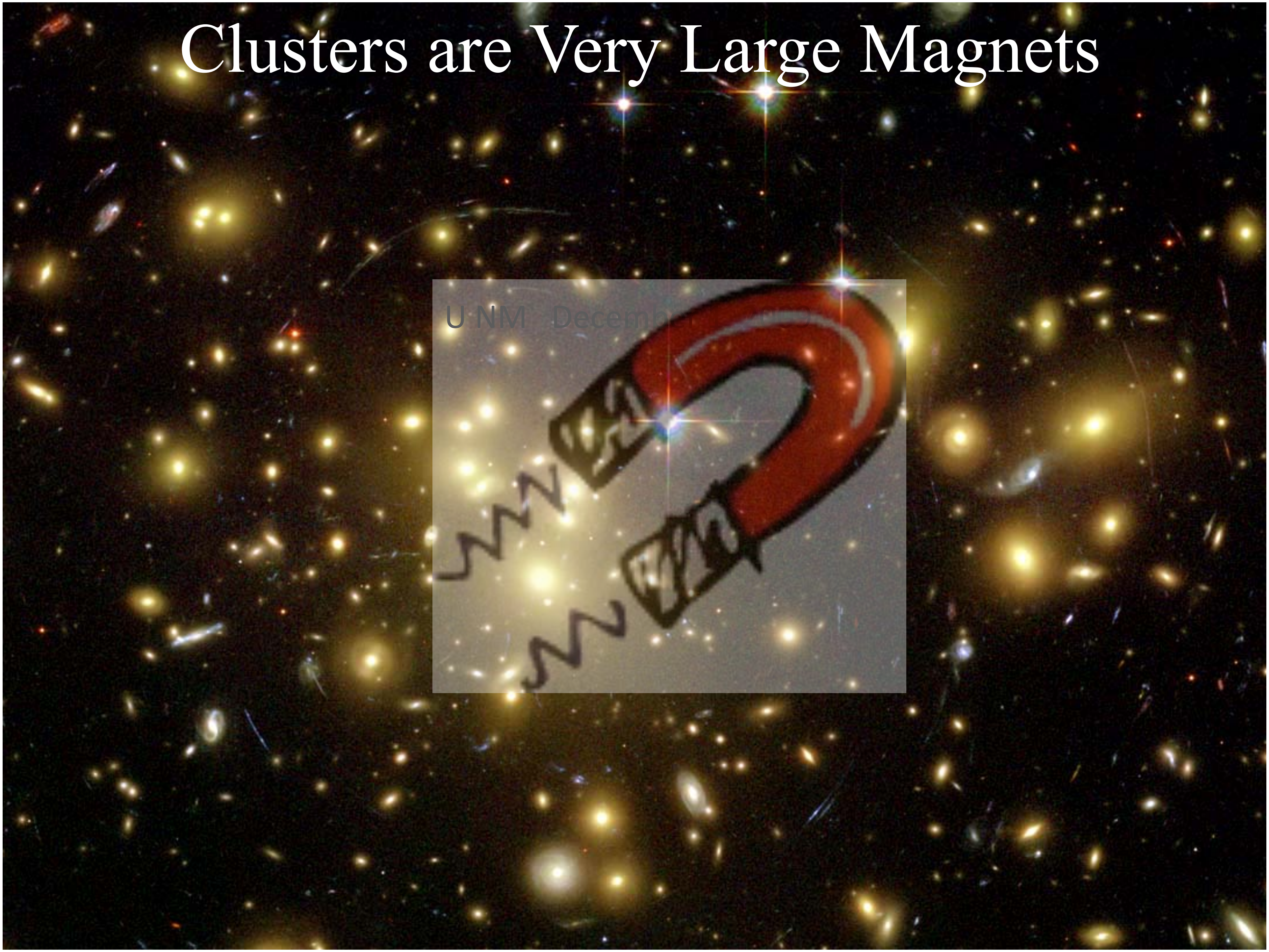
Allen et al.
2006



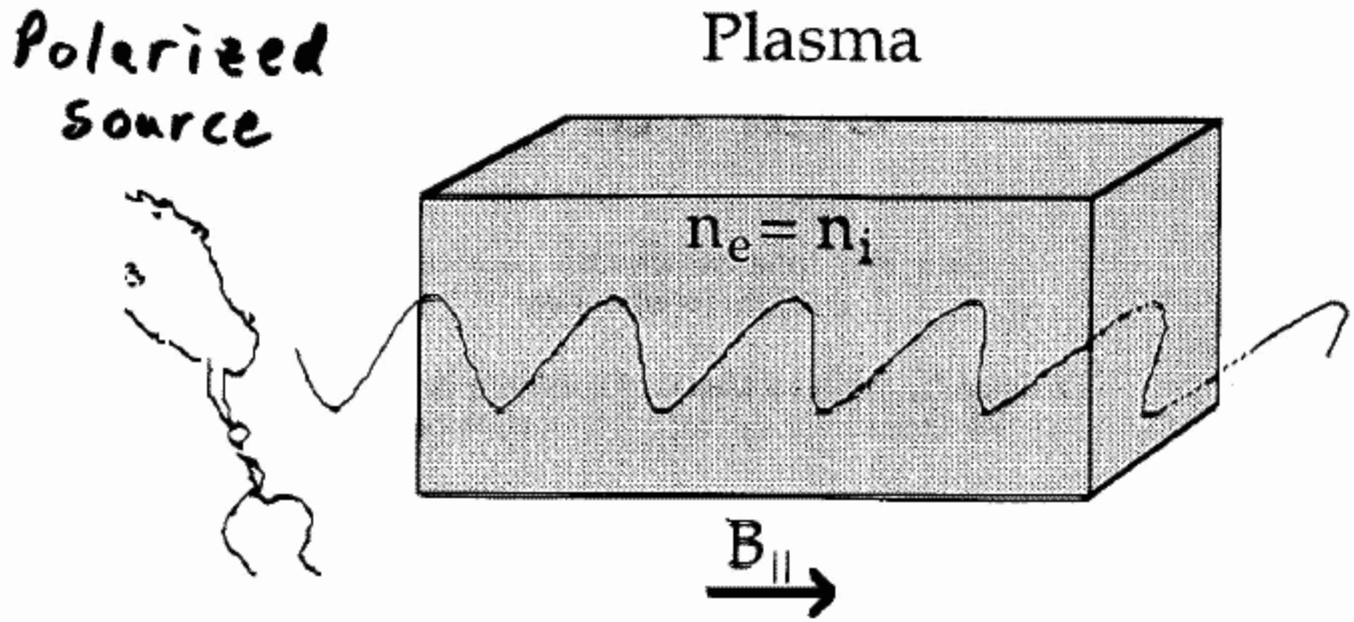
Implications

- Bondi formalism provides a reasonable description despite the presence of magnetic fields and possibly angular momentum
- Accretion flows must be stable over the bubble inflation times of a few million years
- Black holes are converting a few percent of their rest mass into jet energy
- Feedback from the central black holes may be important for shaping the bright end of the galaxy luminosity function (limiting accretion)

Clusters are Very Large Magnets



Faraday Rotation

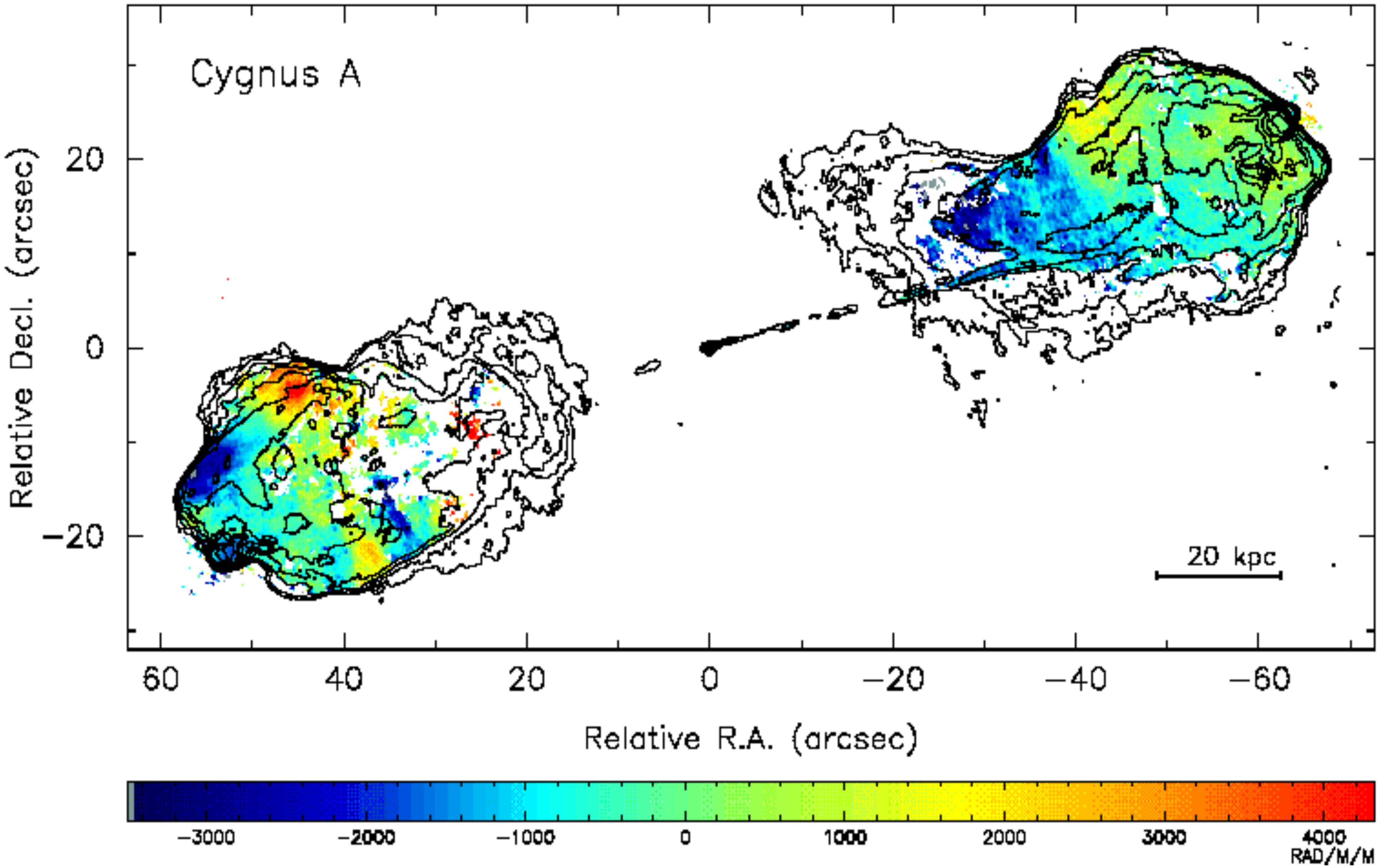


$$\Psi = \Psi_o + RM\,\lambda^2$$

kpc   μGauss

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

cm^{-3}

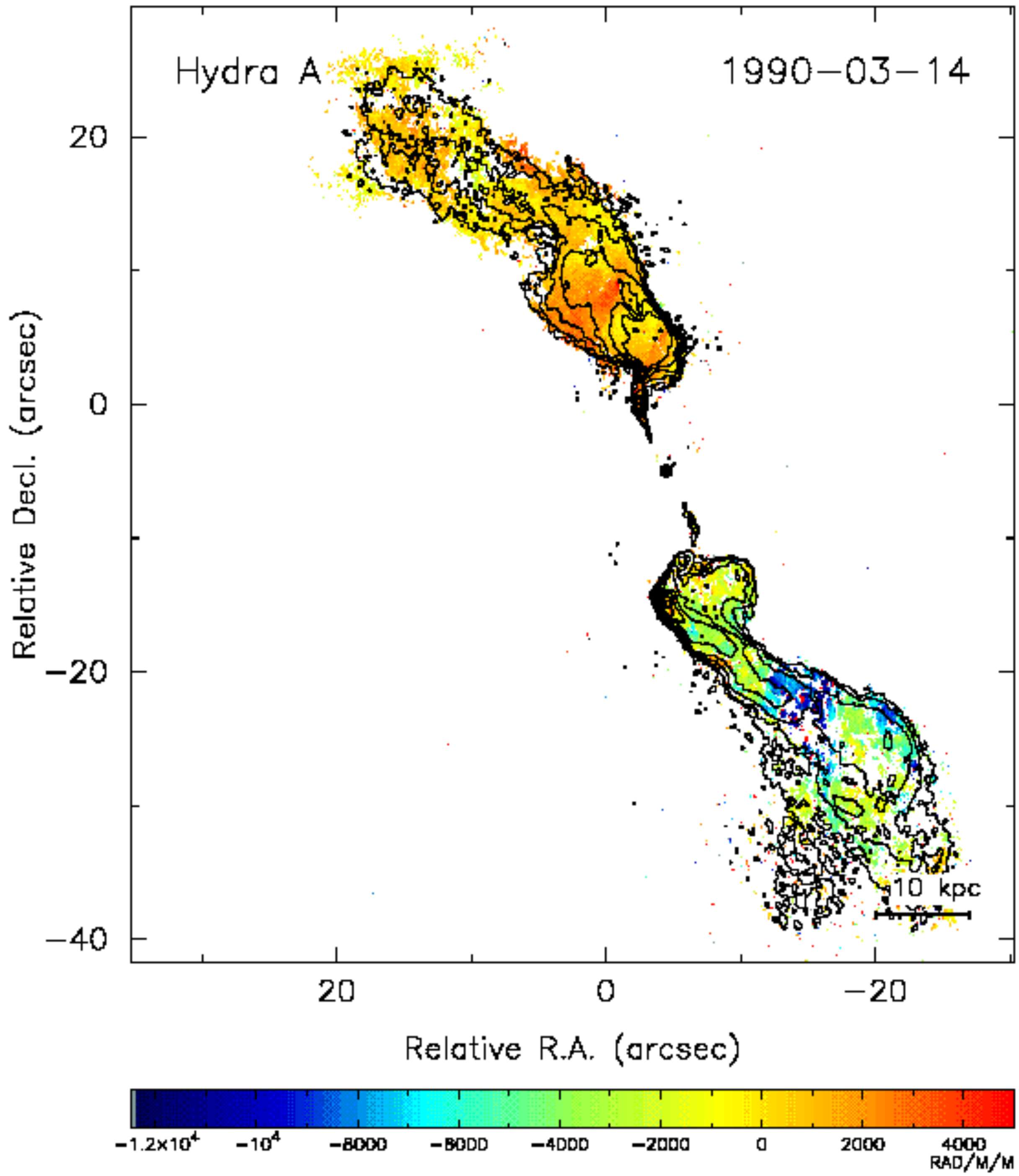


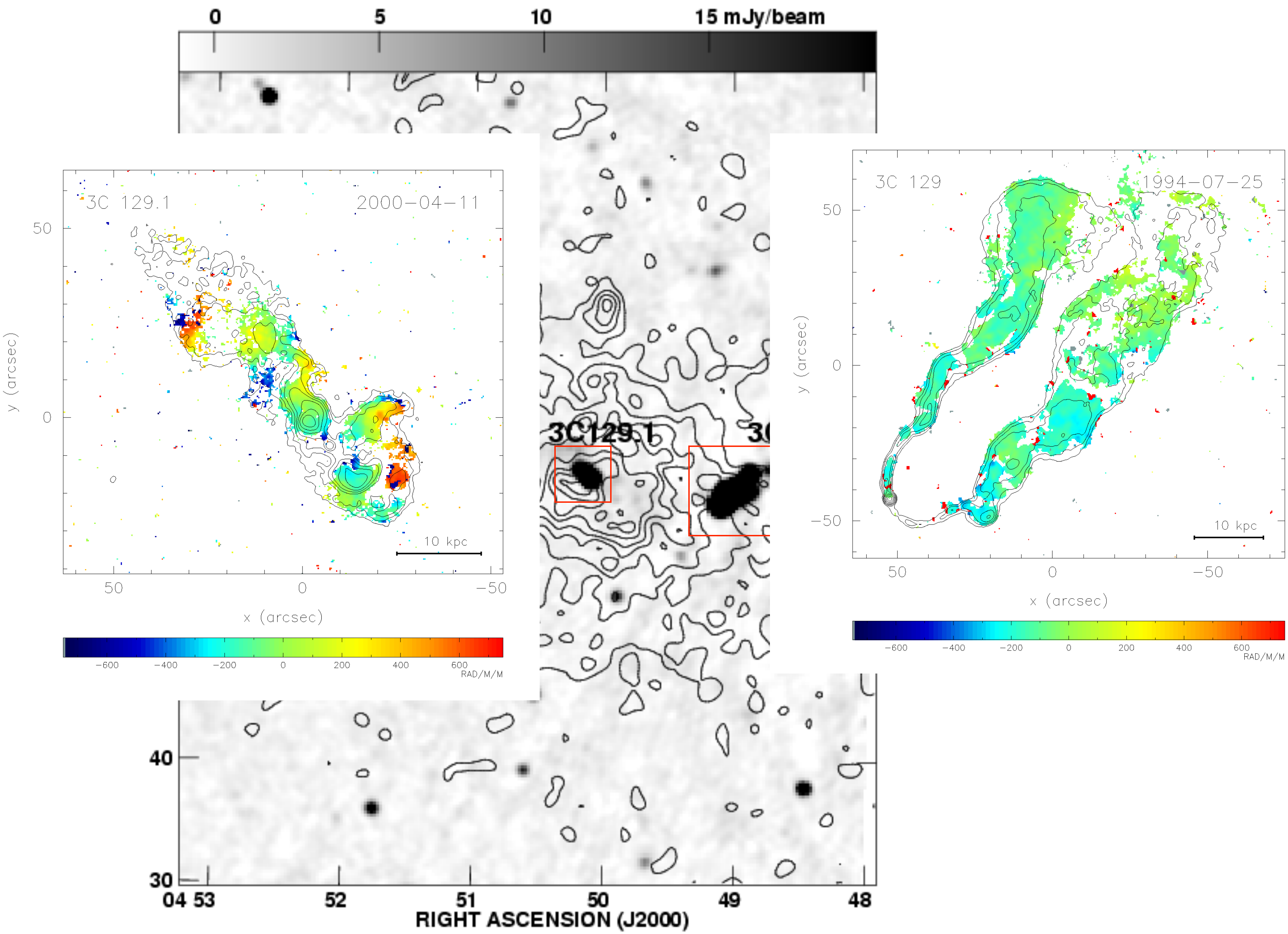
Carilli & Taylor 2002 (ARA&A)

Hydra A

Faraday
Rotation
Measures

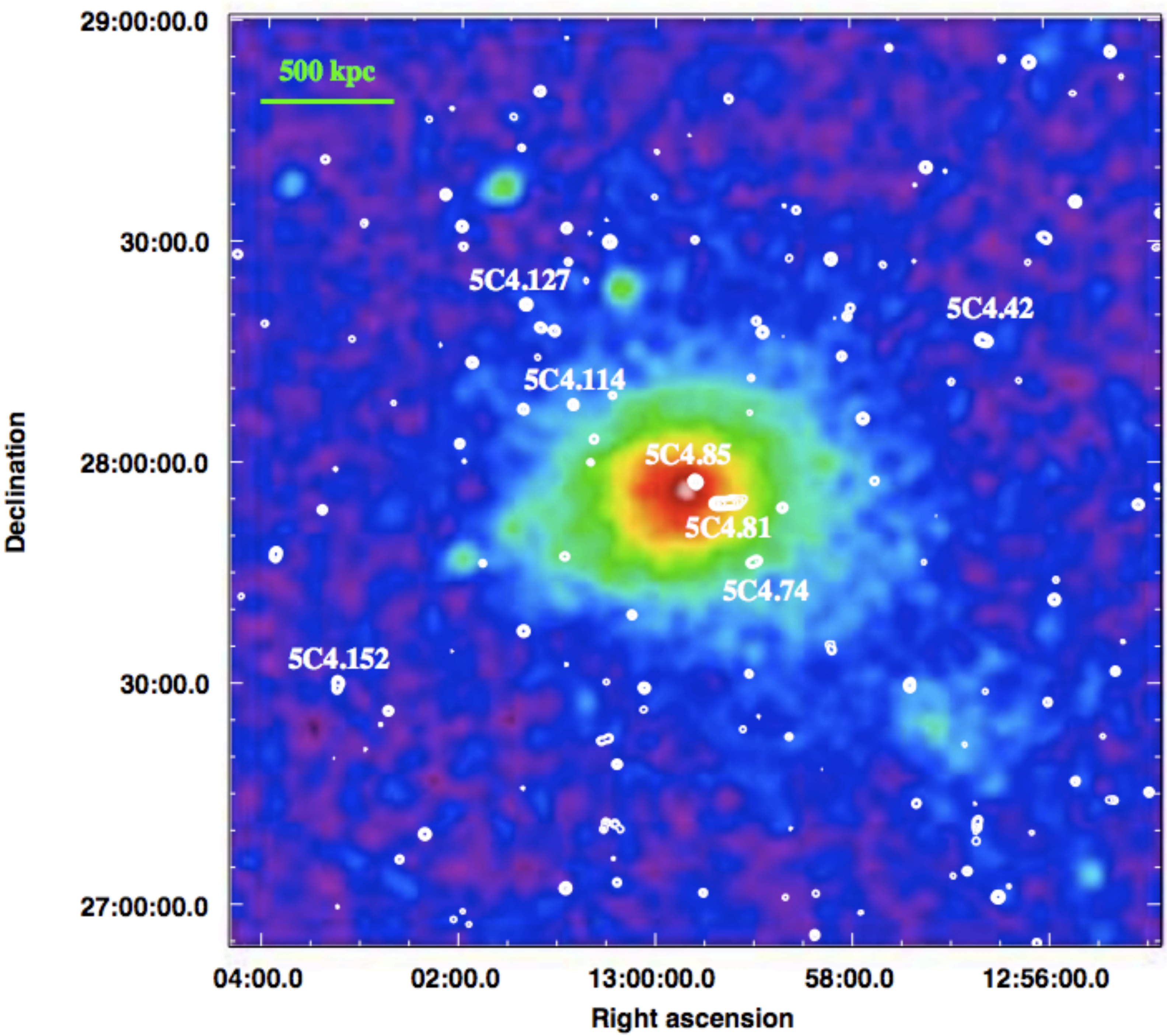
B ~ 30 μG



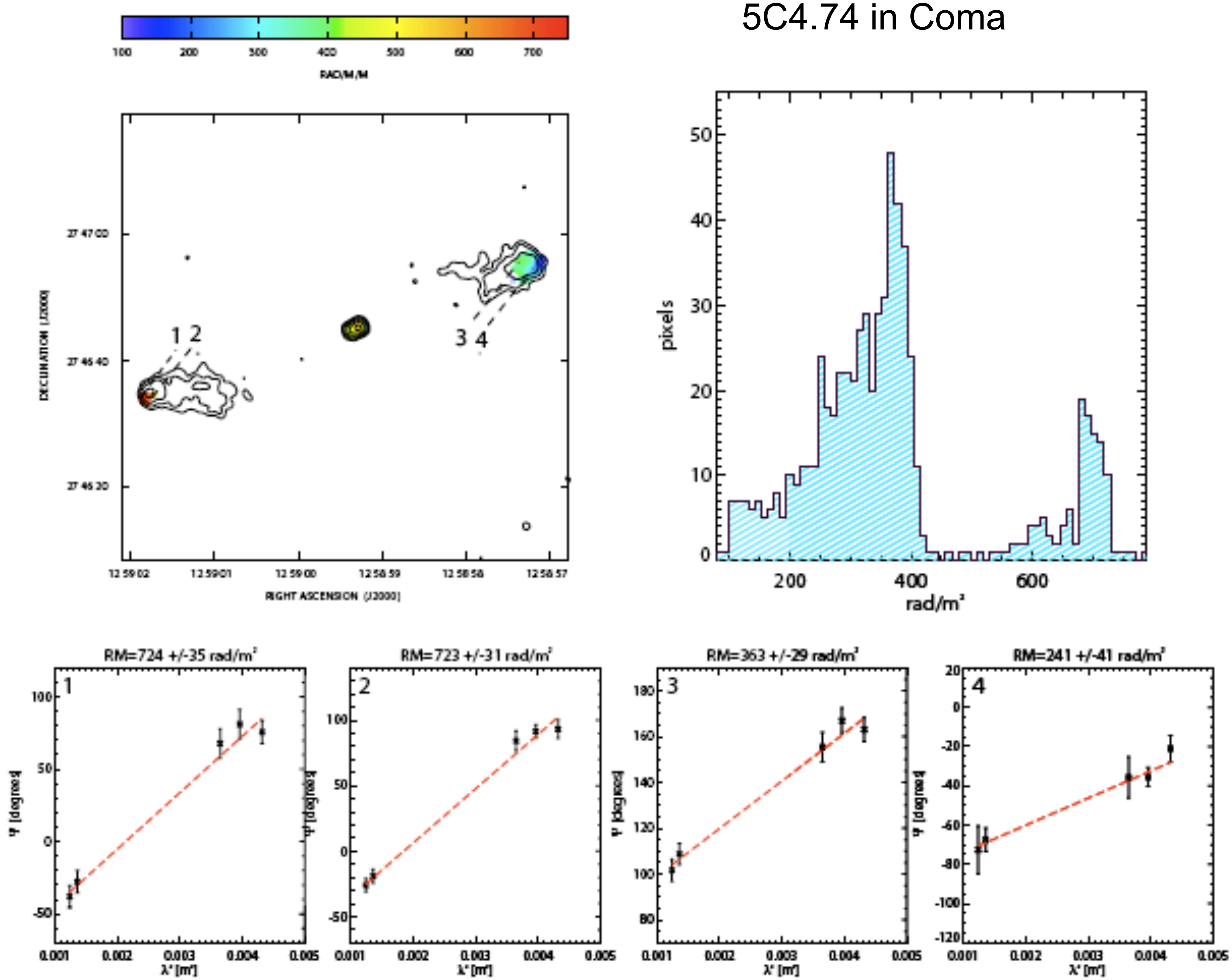

0
5
10
15 mJy/beam
3C129.1
40
30
04 53
52
51
50
49
48
RIGHT ASCENSION (J2000)
3C 129.1
2000−04−11
50
0
y (arcsec)
−50
x (arcsec)
10 kpc
−600
−400
−200
200
400
600
RAD/M/M
3C 129
1994−07−25

Coma

X-ray
+
radio



5C4.74 in Coma

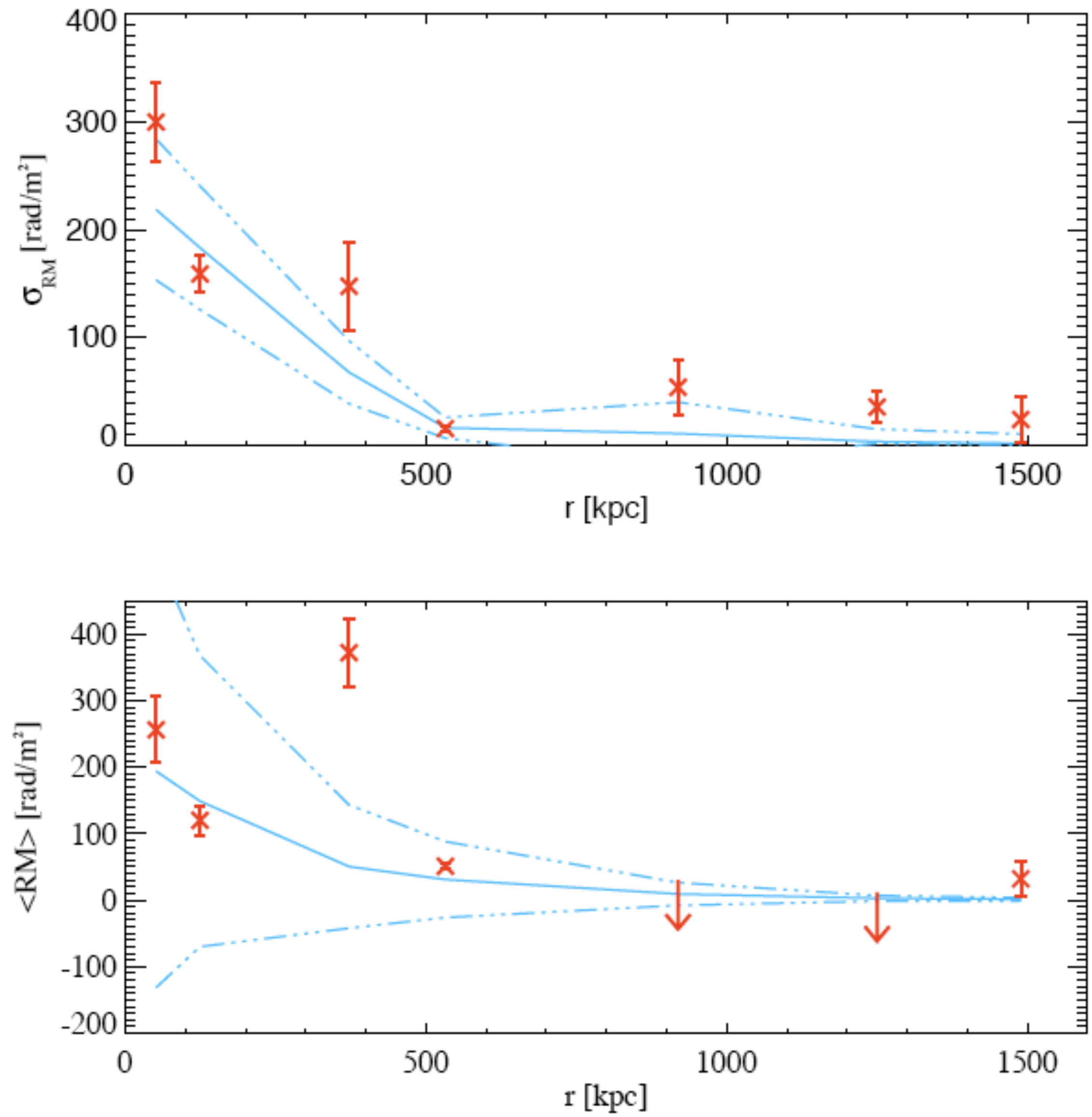


Results

B_0 = 4.6 +/- 0.7 μG

scale lengths between 2 and 30 kpc

average B ~ 2 μG



Bonafede et al. 2009

Next time:

CHAPTER 29.1

Newtonian cosmology