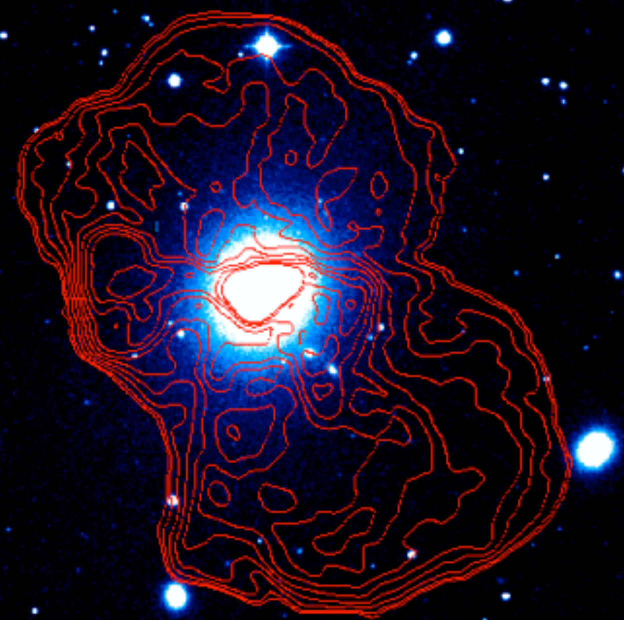
AGN feedback in clusters of galaxies: M87 under the LOFAR microscope



Andrea Merloni (MPE)

Francesco De Gasperin (MPA, EXC)

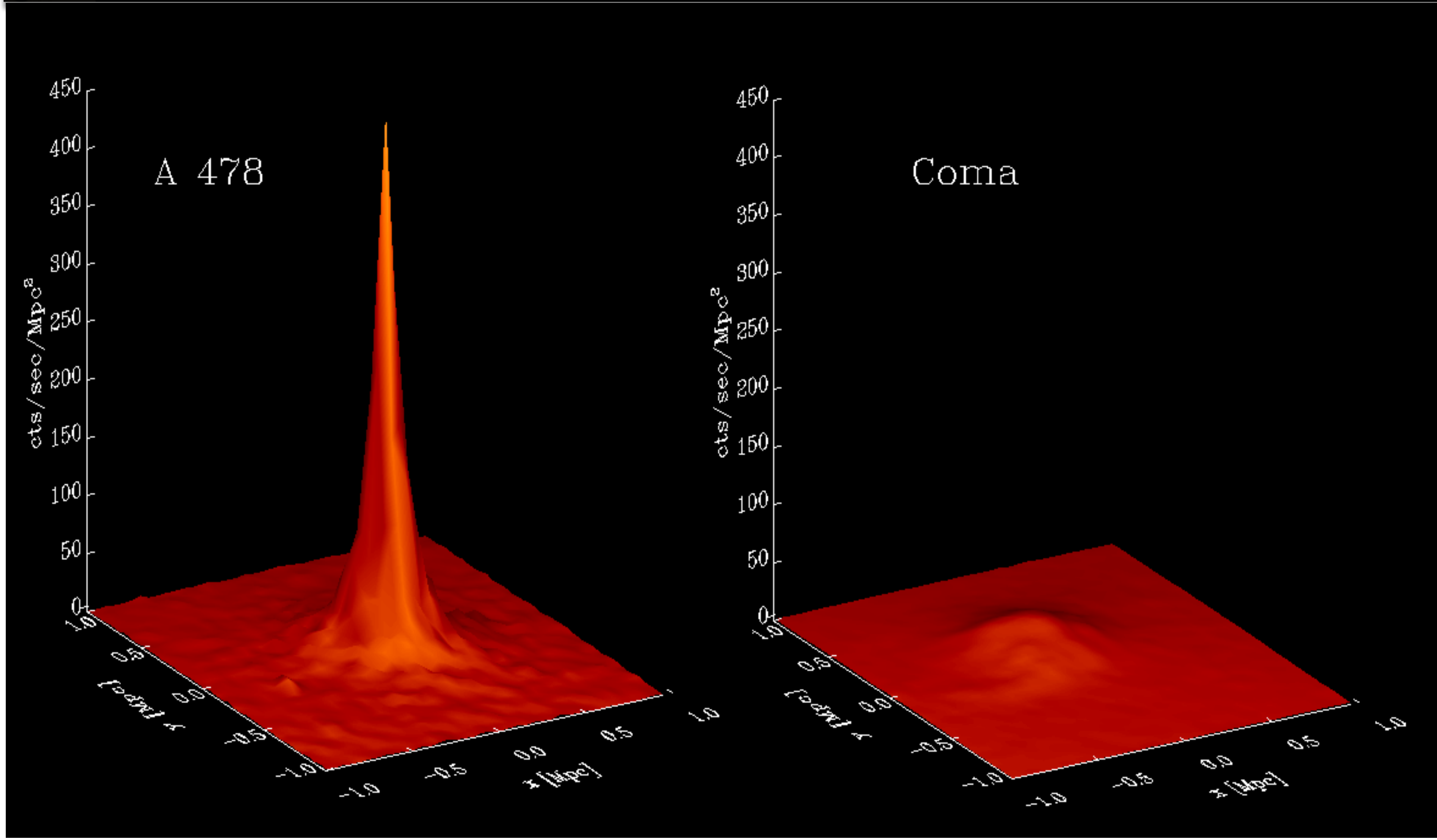
Black Hole Universe, Bamberg, 6/2012,

Excellence Cluster Universe

Outline

- The role of LLAGN jet in galaxy evolution: one solution to two problems?
- The physics of LLAGN: Jet dominance
- The case of M87
- LOFAR observations: age and energetics (De Gasperin et al. 2012)

X-ray surface brightness of galaxy clusters

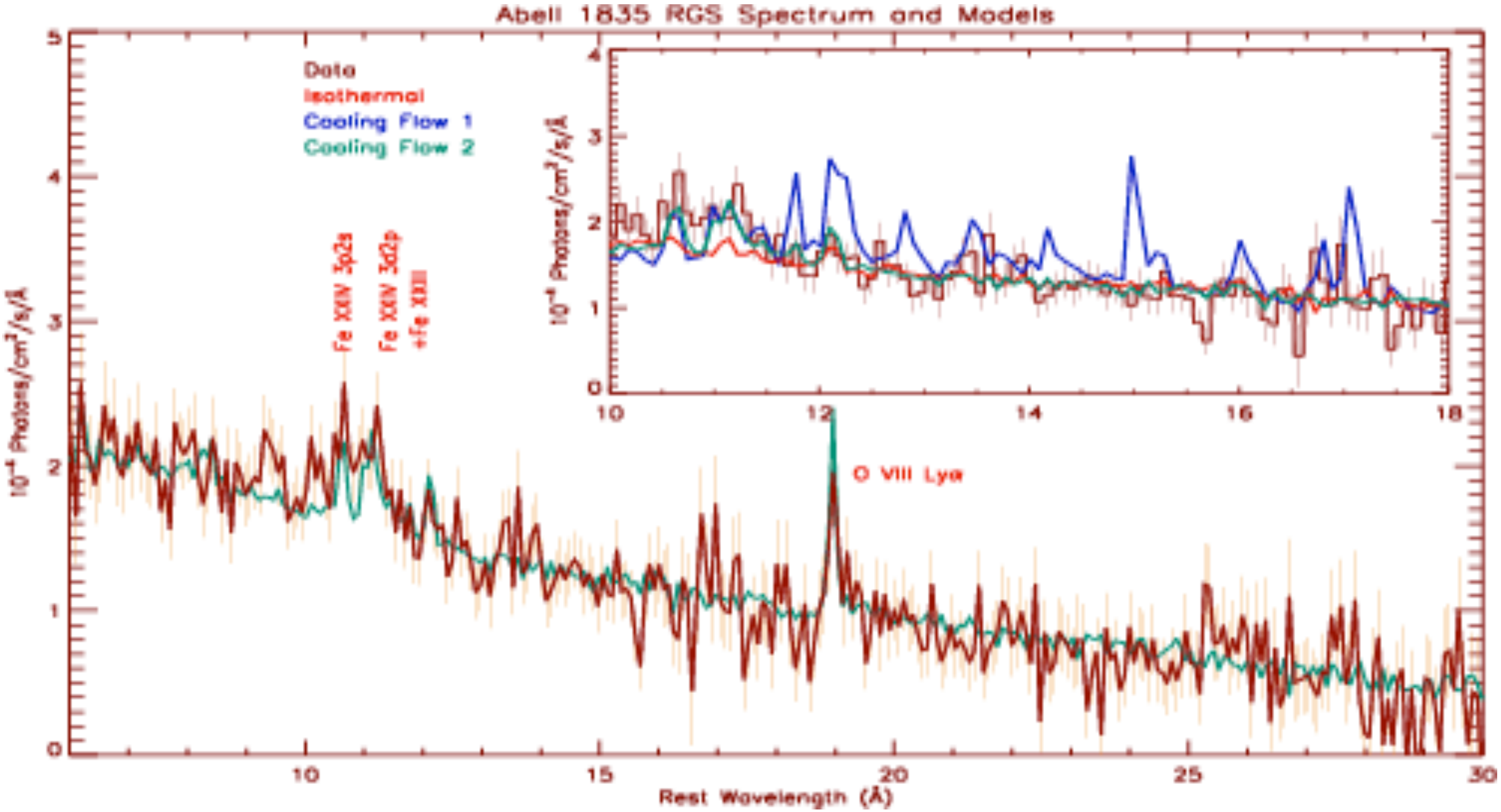


"Cool core cluster" "Non-Cool core cluster"

Image courtesy of A. Fabian

The cooling flow problem

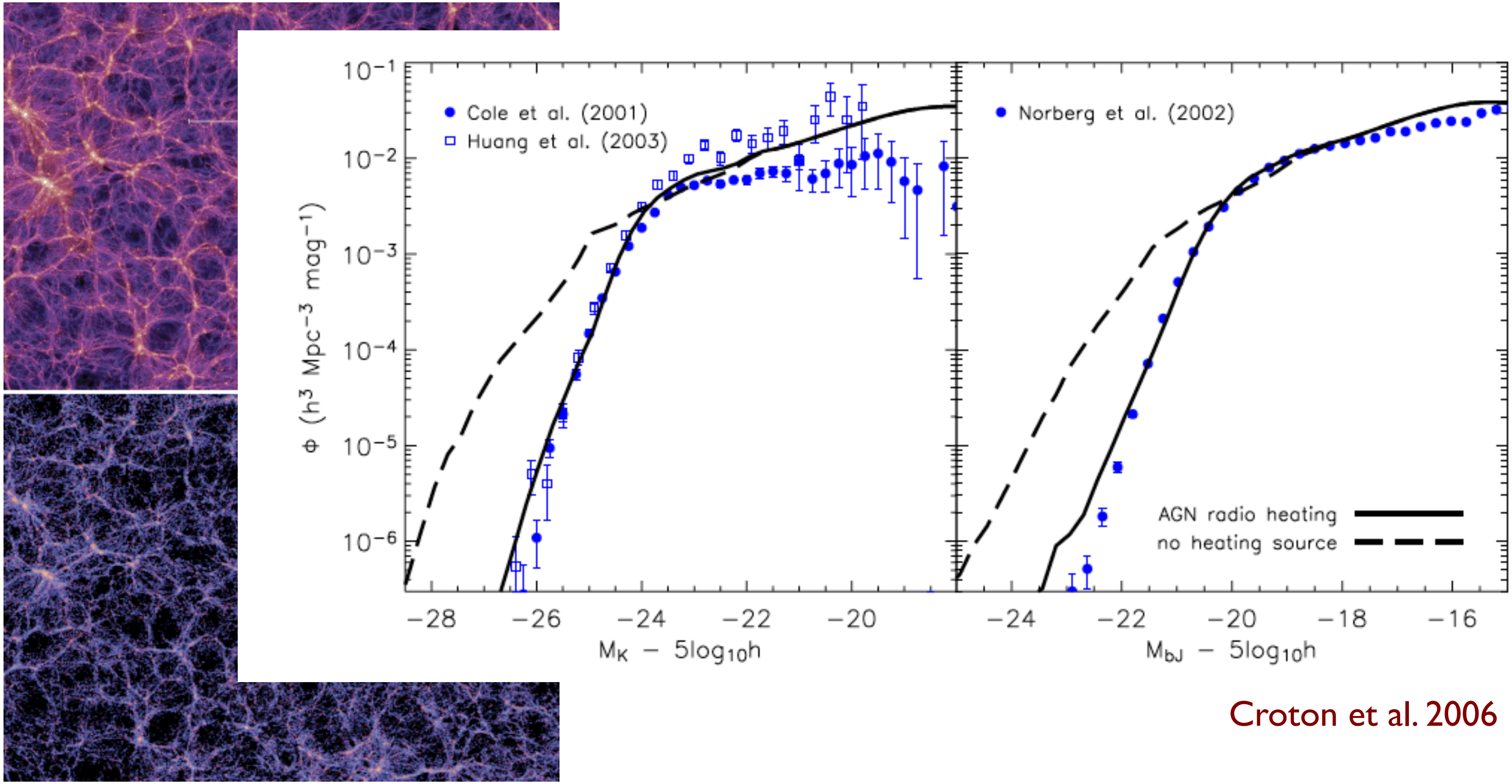
Problem #1: Cooling gas is not observed!



High-res. X-ray spectrum of a cooling core cluster (Peterson et al. 2001)

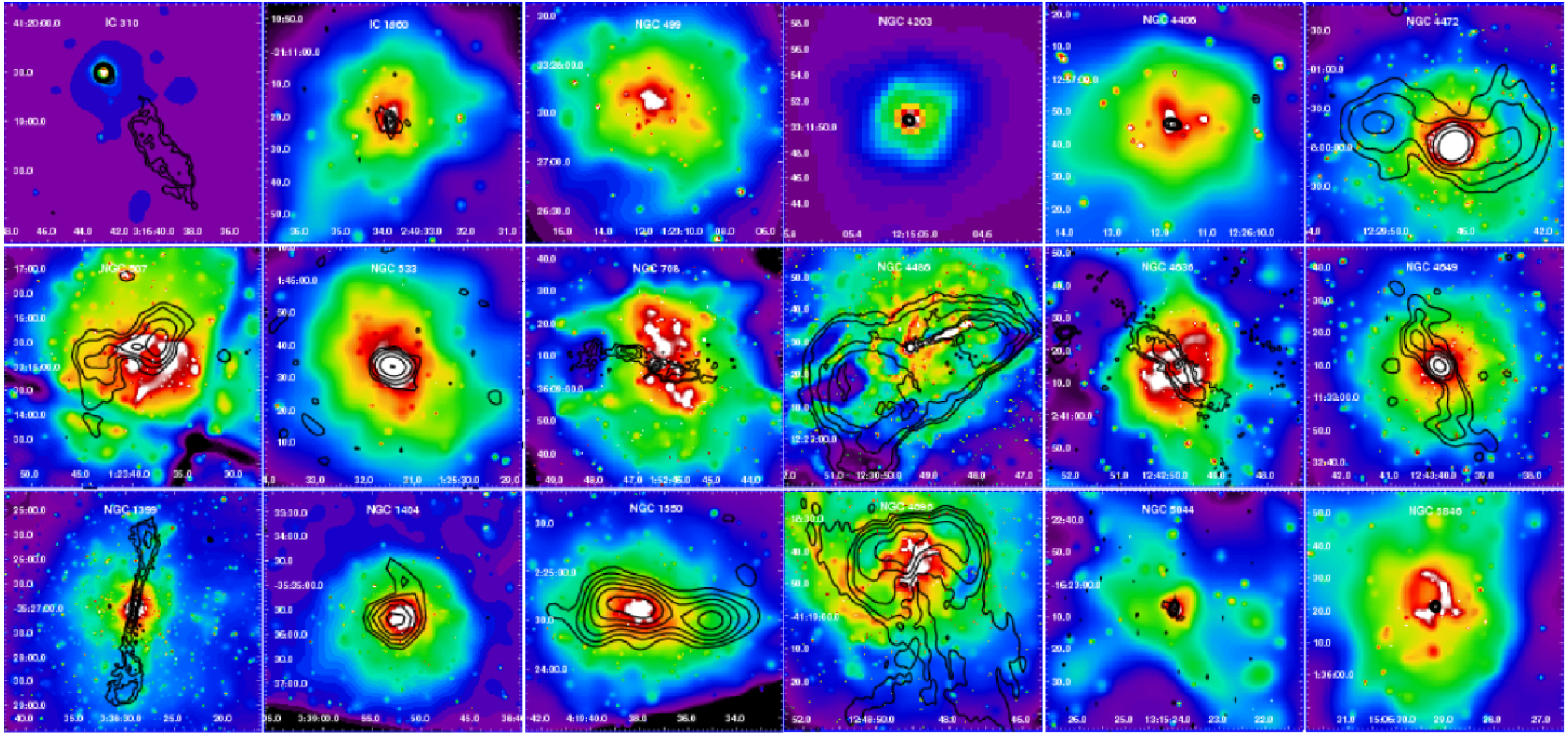
AGN feedback in clusters and groups

Problem #2: Galaxy mass function:
Needs a mechanism to prevent large masses of gas cooling into massive galaxies at late times



Croton et al. 2006

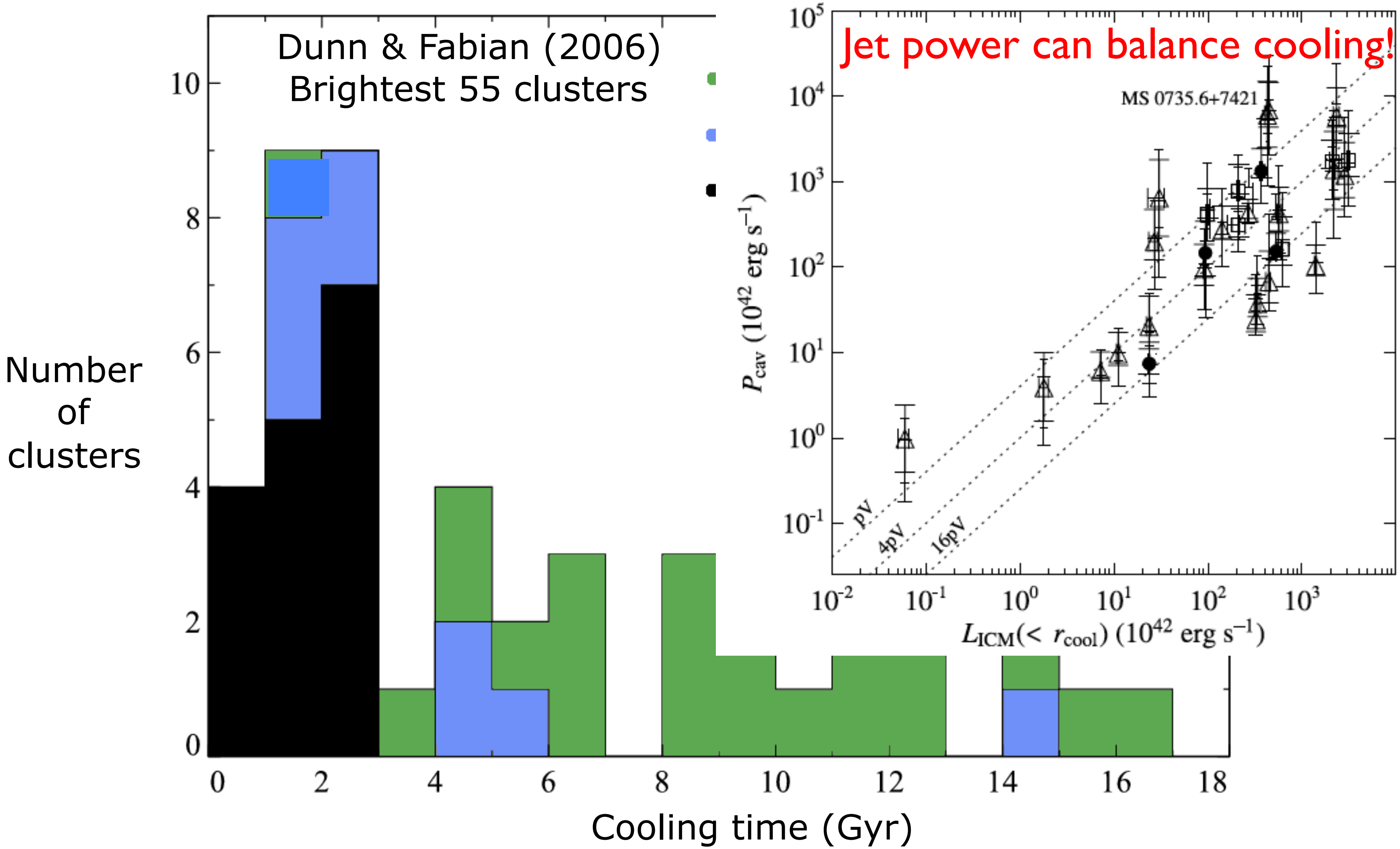
LL radio AGN in clusters/groups cores



A complete, X-ray selected sample of nearby, massive elliptical galaxies

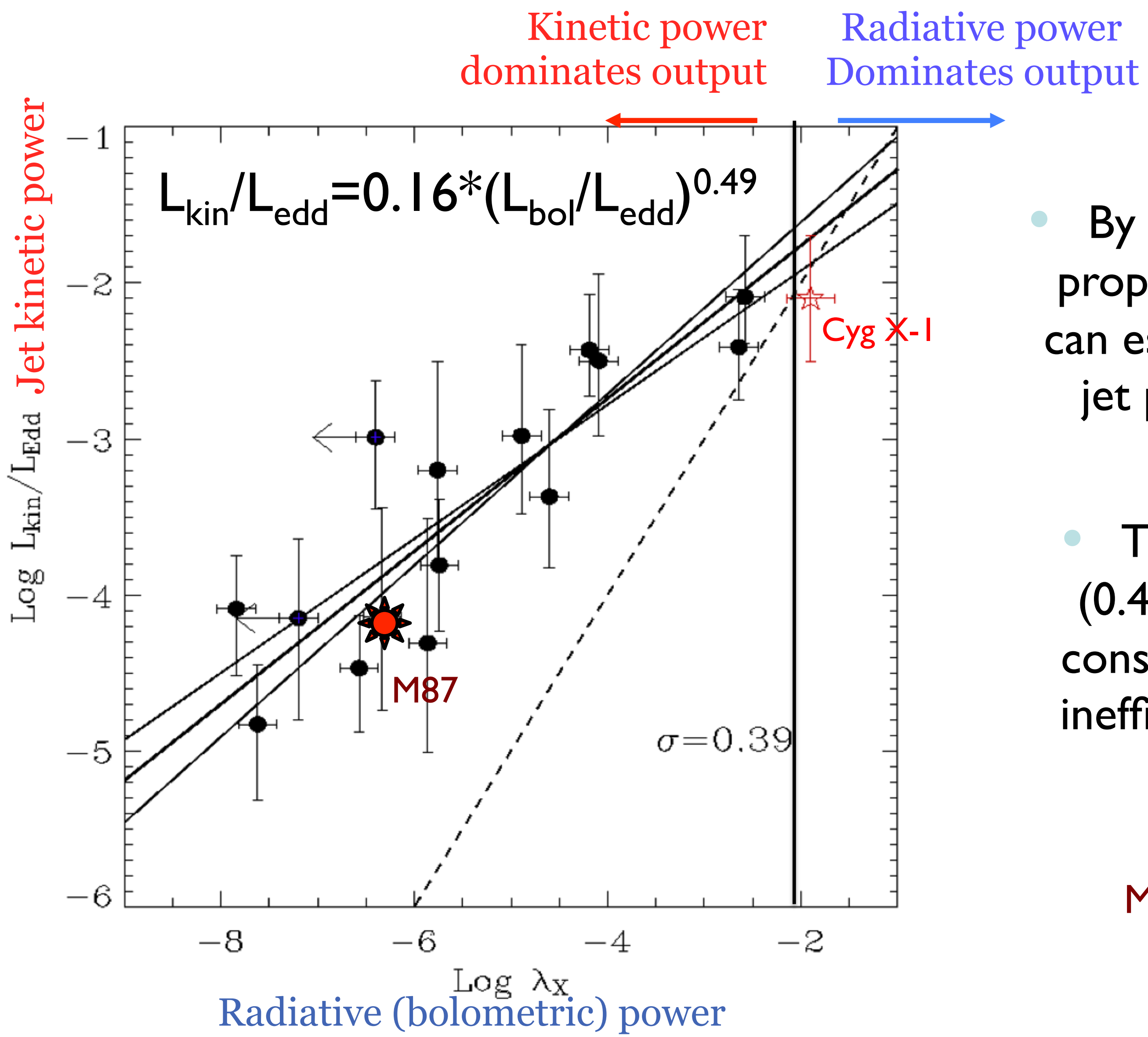
Dunn et al. 2010

Duty cycle is ~100%



See also Birzan+04, Rafferty+06+08, Dunn+F07

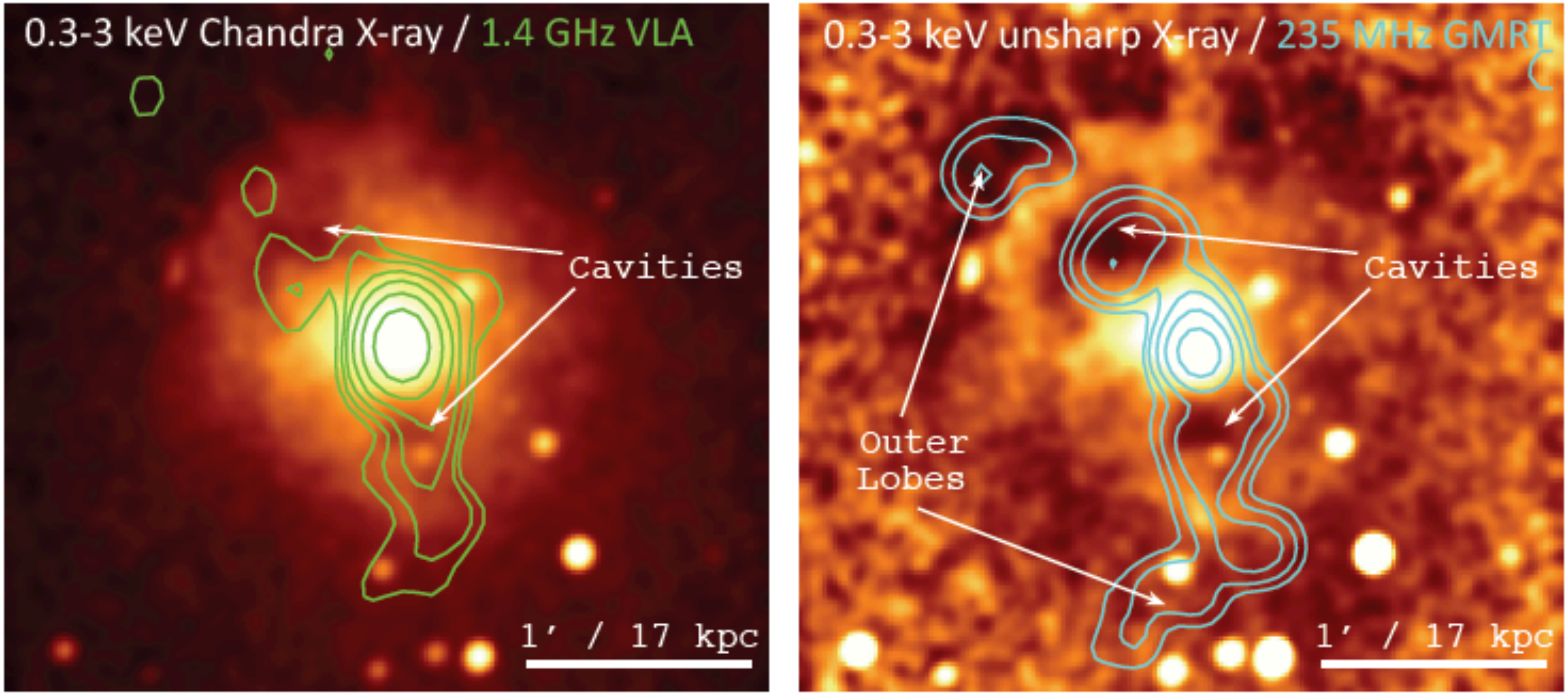
Low-mdot (radio) AGN are "jet dominated"



- By studying the nuclear properties of the AGN we can establish a link between jet power and accretion power
- The observed slope (0.49±0.045) is perfectly consistent with radiatively inefficient "jet dominated" models

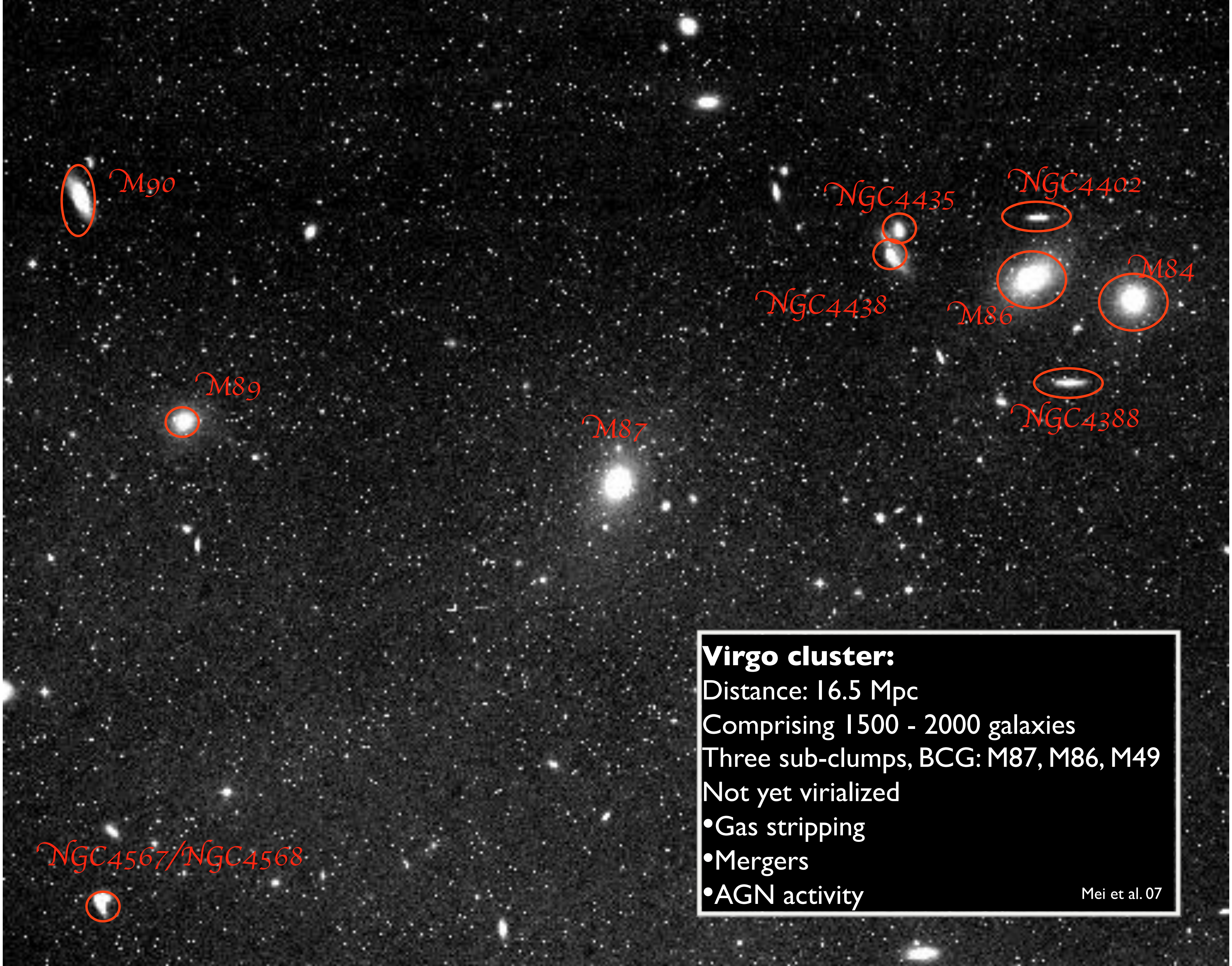
Merloni & Heinz 2007

Low–frequency radio observations are key!



Radio AGN in the group HCG62. Low-‐frequency radio
Sensitive to older electron population, reveals previously
unknown outer lobes

Gitti et al. 2010



Virgo cluster:

Distance: 16.5 Mpc

Comprising 1500 - 2000 galaxies

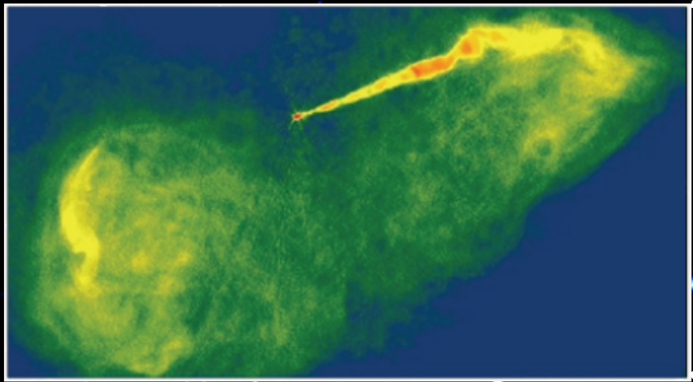
Three sub-clumps, BCG: M87, M86, M49

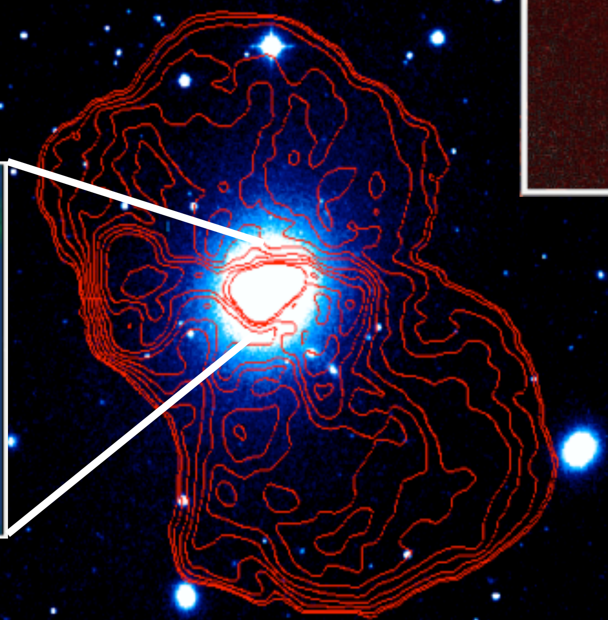
Not yet virialized

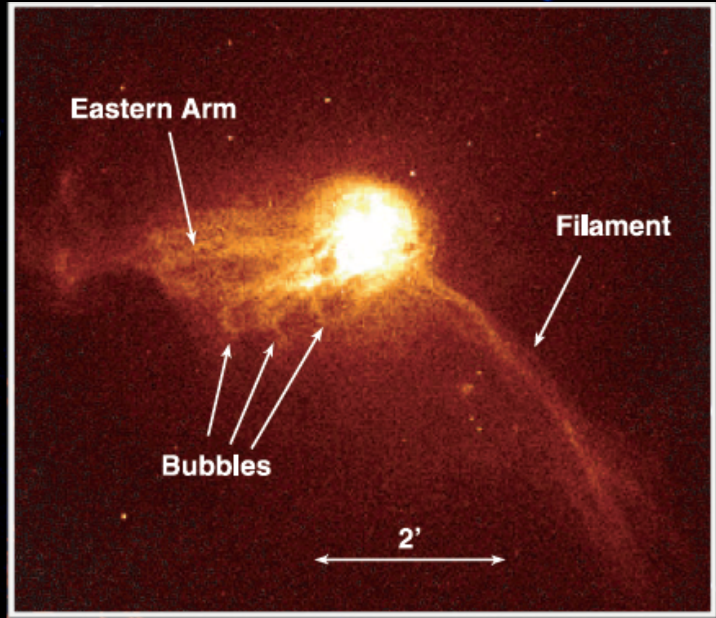
- Gas stripping
- Mergers
- AGN activity

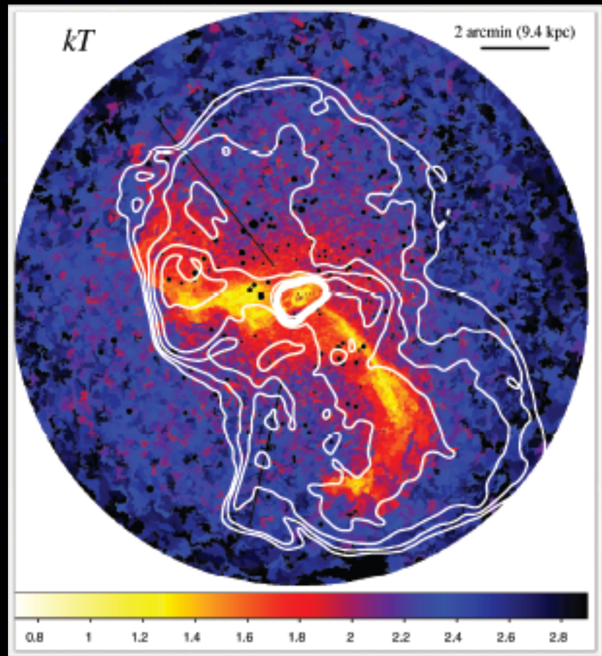
Mei et al. 07

Virgo A (3C274)
Flux: ~1700 Jy @ 100 MHz
Size (core): 5 kpc (1')
Size (halo): 80 kpc (16')
BH mass: 6.4 10^9 M⊙
Amorphous source









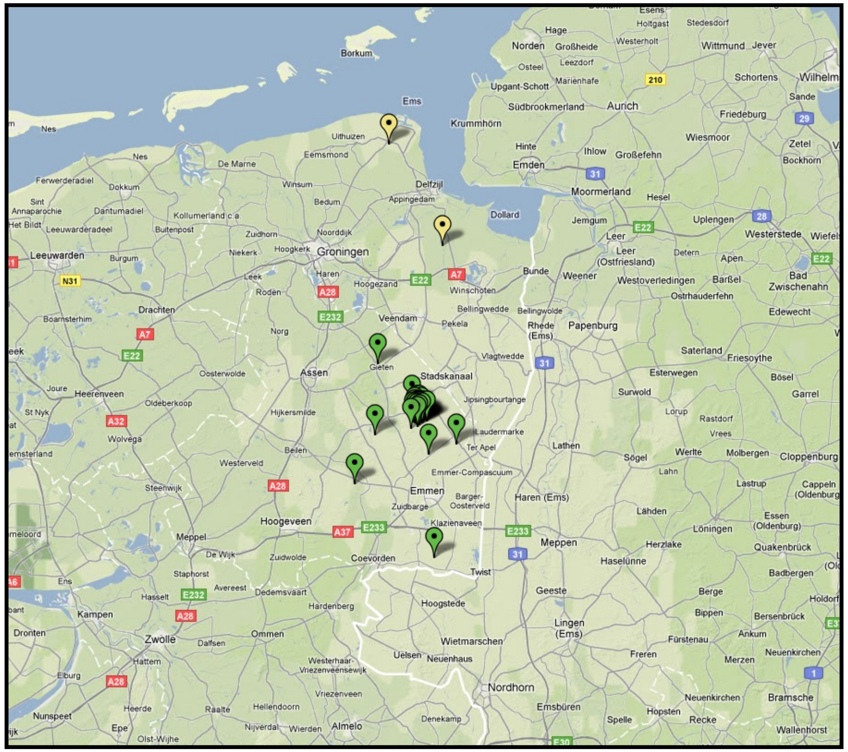
M87 X-ray History:
Detected with the Einstein Observatory by Fabricant et al. (1980)
Asimmetry in the gas distribution found by Feigelson et al. (1987)
Thermal spectrum detected with ROSAT by Boehringer at al (1995)
Deep Chandra imaging made by Forman et al. (2007) and Million et al. (2010)

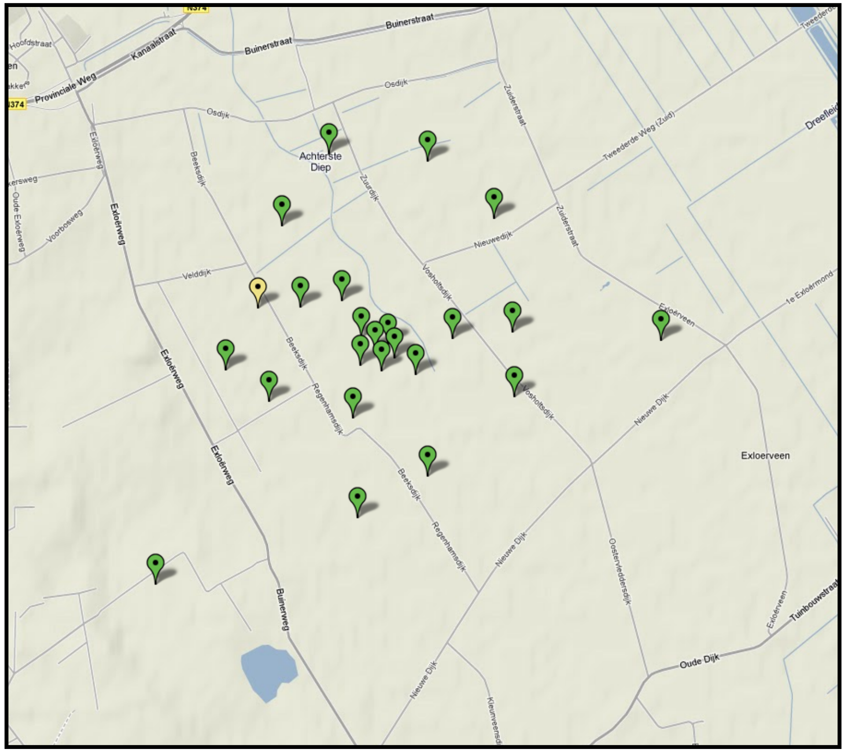
The Observations

LBA (low):
15 - 30 MHz
16 Jul 2011
28805 s (~8 h)
25 ant

LBA (high):
30 - 77 MHz
14/15 Apr 2011
28810 s (~8 h)
24 ant

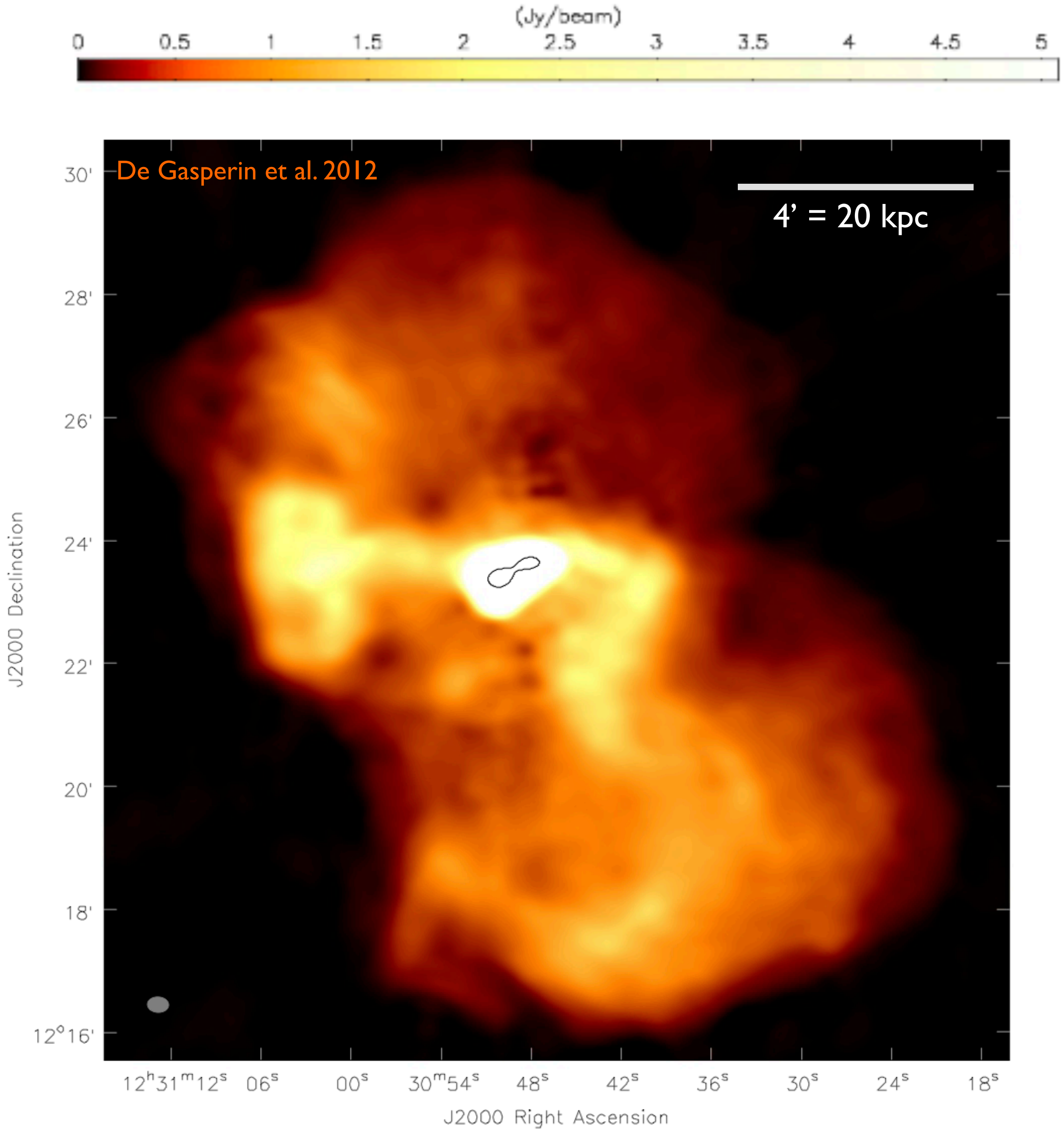
HBA:
115 - 162 MHz
2/3 Apr 2011
28810 s (~8 h)
45 ant (dual)





Images from: http://www.astron.nl/~heald/lofarStatusMap.html

M87



HBA map:

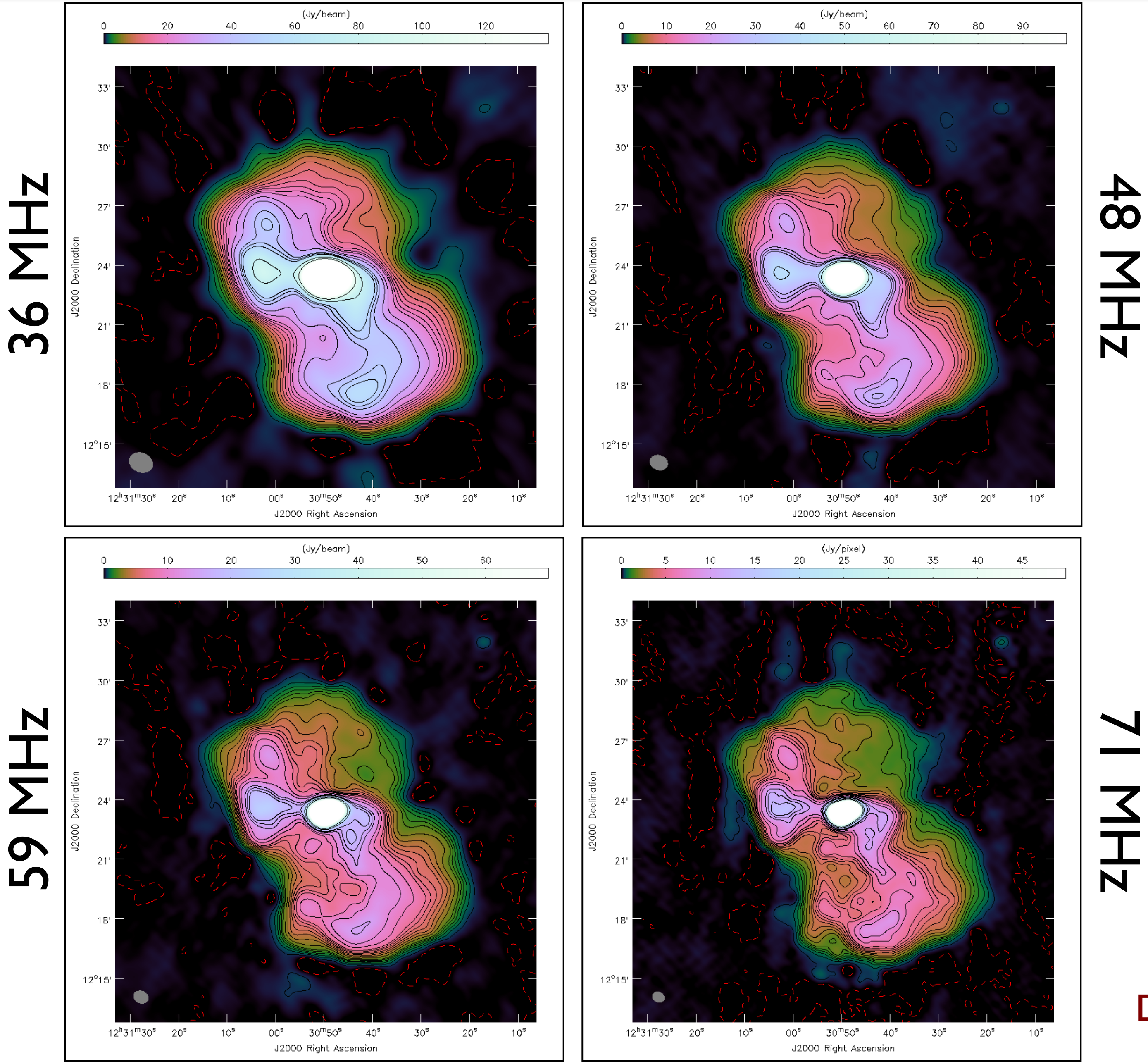
RMS: 6 mJy/beam
Beam: 19” x 14”
Dyn Range > 13000
Frequency: 140 MHz

NOTES:

•Other strong sources uv-subtracted
•Imaging of the core with standard Clean algorithm
•Imaging of the extended emission with Maximum Entropy (flat prior)

De Gasperin et al. 2012

M87



LBA maps:

Freq: 36 MHz
Beam: 73" x 58"
RMS: 0.2 Jy/beam

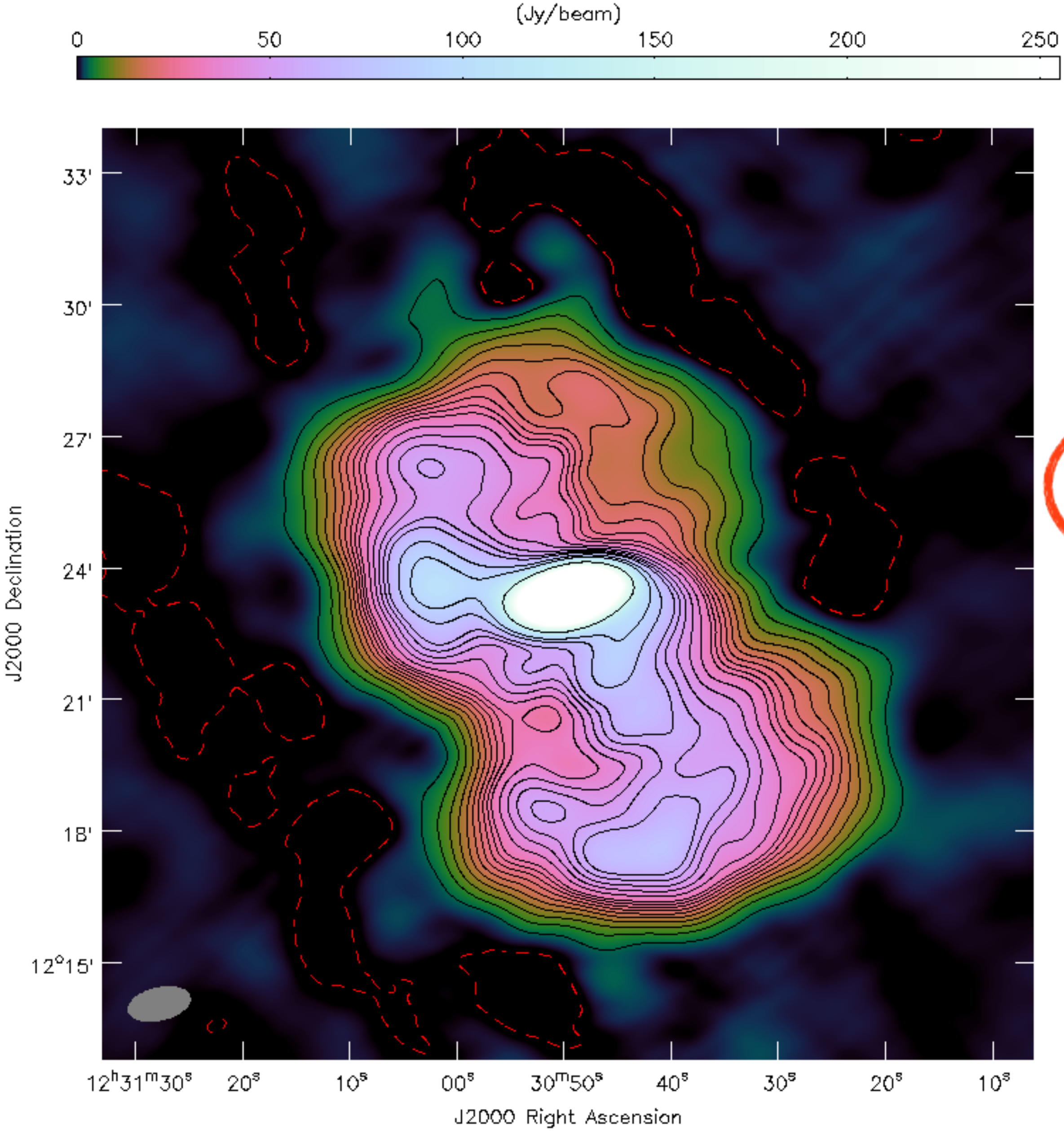
Freq: 48 MHz
Beam: 55" x 43"
RMS: 0.09 Jy/beam

Freq: 59 MHz
Beam: 55" x 36"
RMS: 0.08 Jy/beam

Freq: 71 MHz
Beam: 37" x 30"
RMS: 0.05 Jy/beam

De Gasperin et al. 2012

M87



LBA map:

RMS: 0.6 Jy/beam

Beam: 85” x 44”

Freq: 25 MHz

Lowest frequency image of Virgo A extended structure

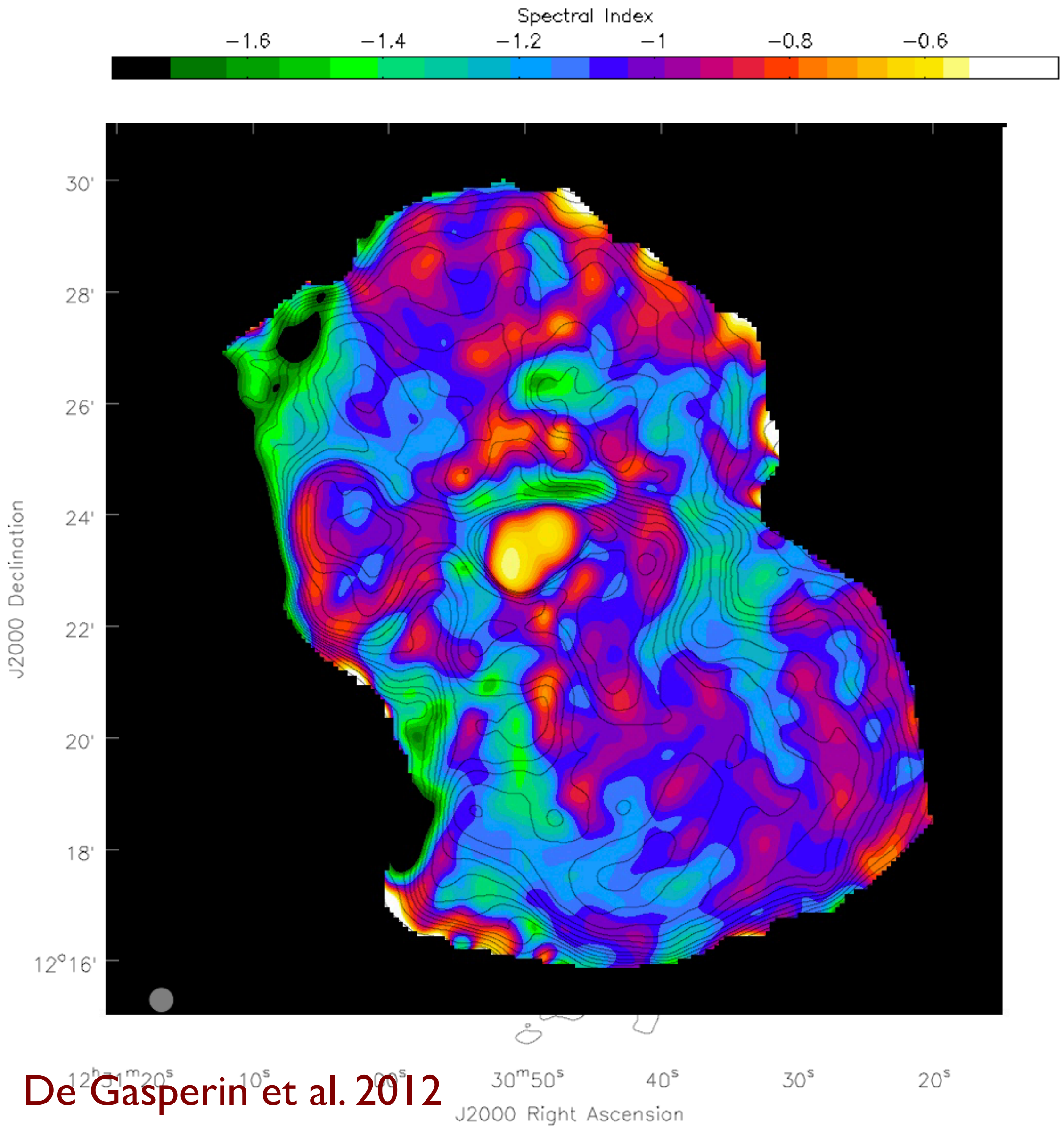
No new extended features

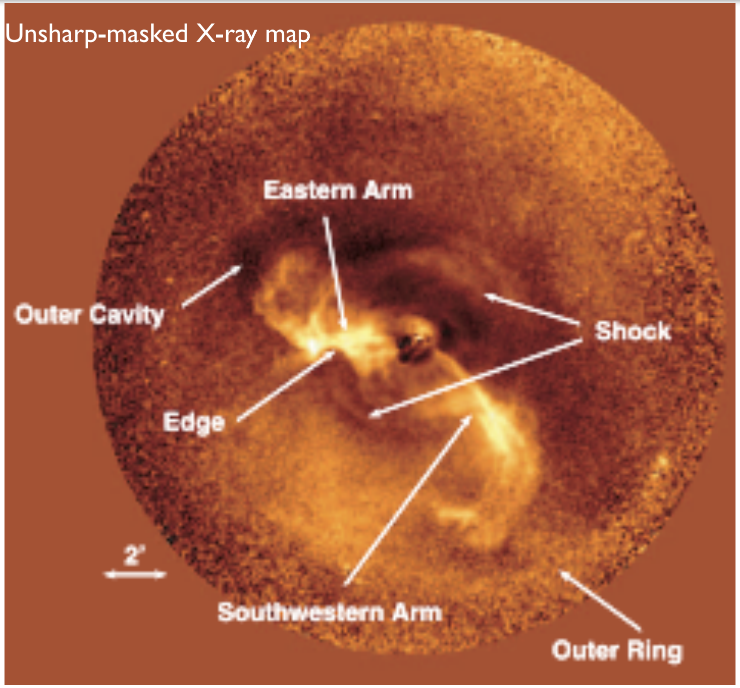
Are lobes “alive”?

De Gasperin et al. 2012

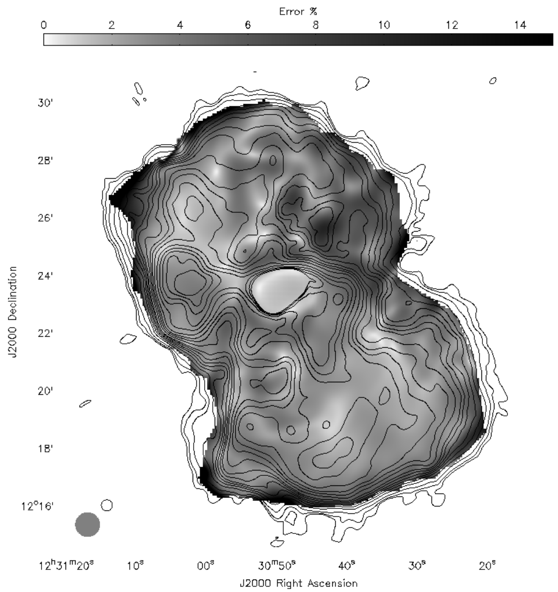
M87 – spectral index

LOFAR Spectral index map



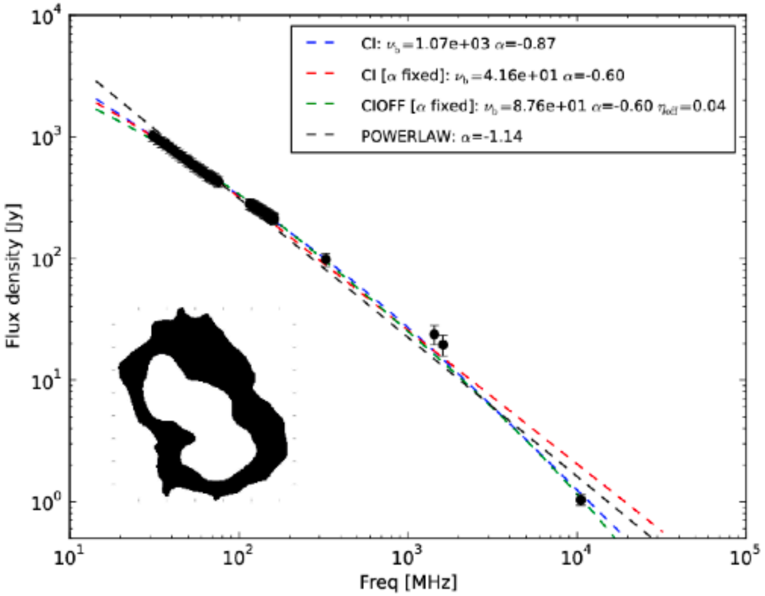


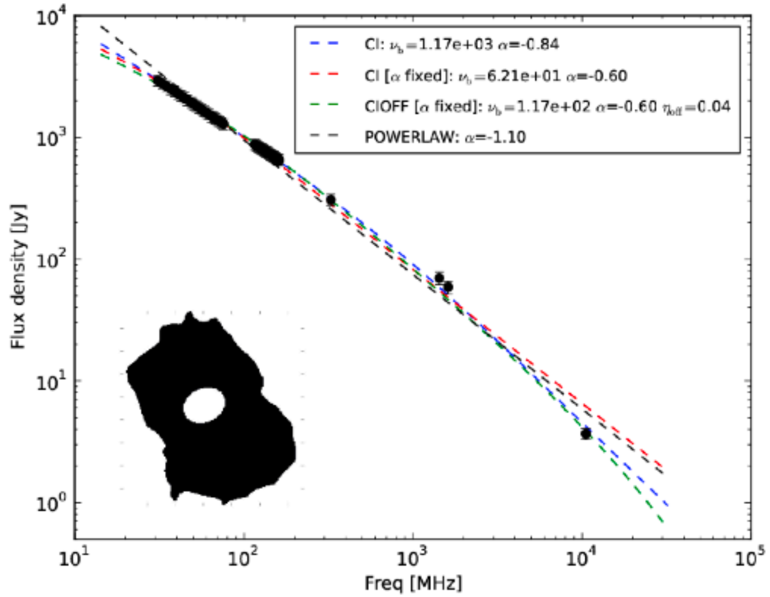
Error (%) map

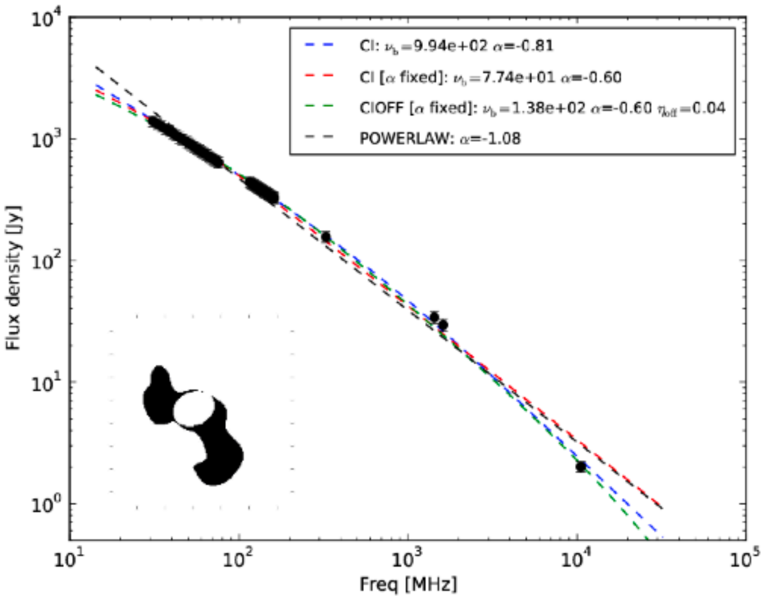


De Gasperin et al. 2012

M87 – Macro regions







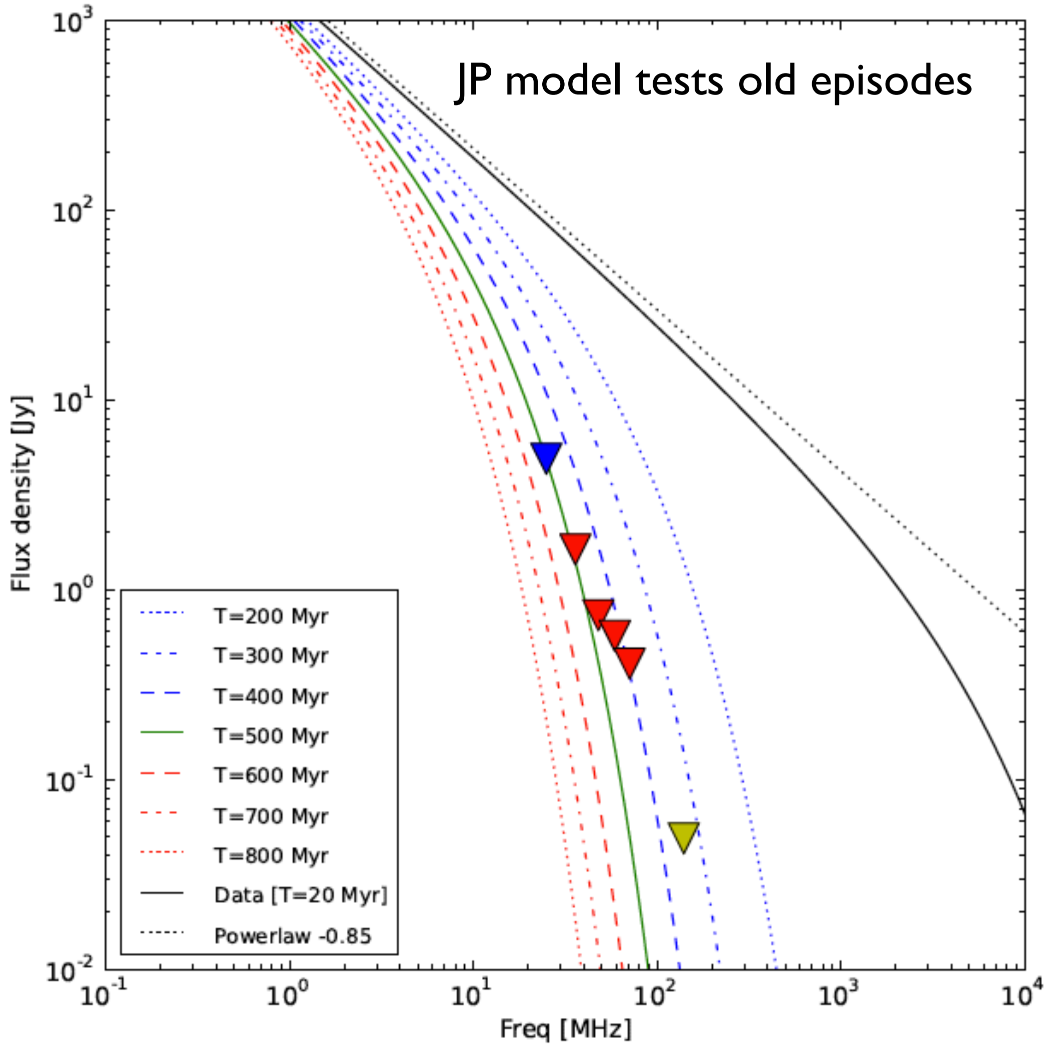
- CI (fixed α=-0.6) fails to fit the data

- CI (free α) fits the data

- α~-0.85
- break frequency of ~1.2 GHz
- halo age ~ 40 Myr (B=10 uG)

De Gasperin et al. 2012

Synchrotron electron ageing



We don't see any old (<500 Myrs) electron population:

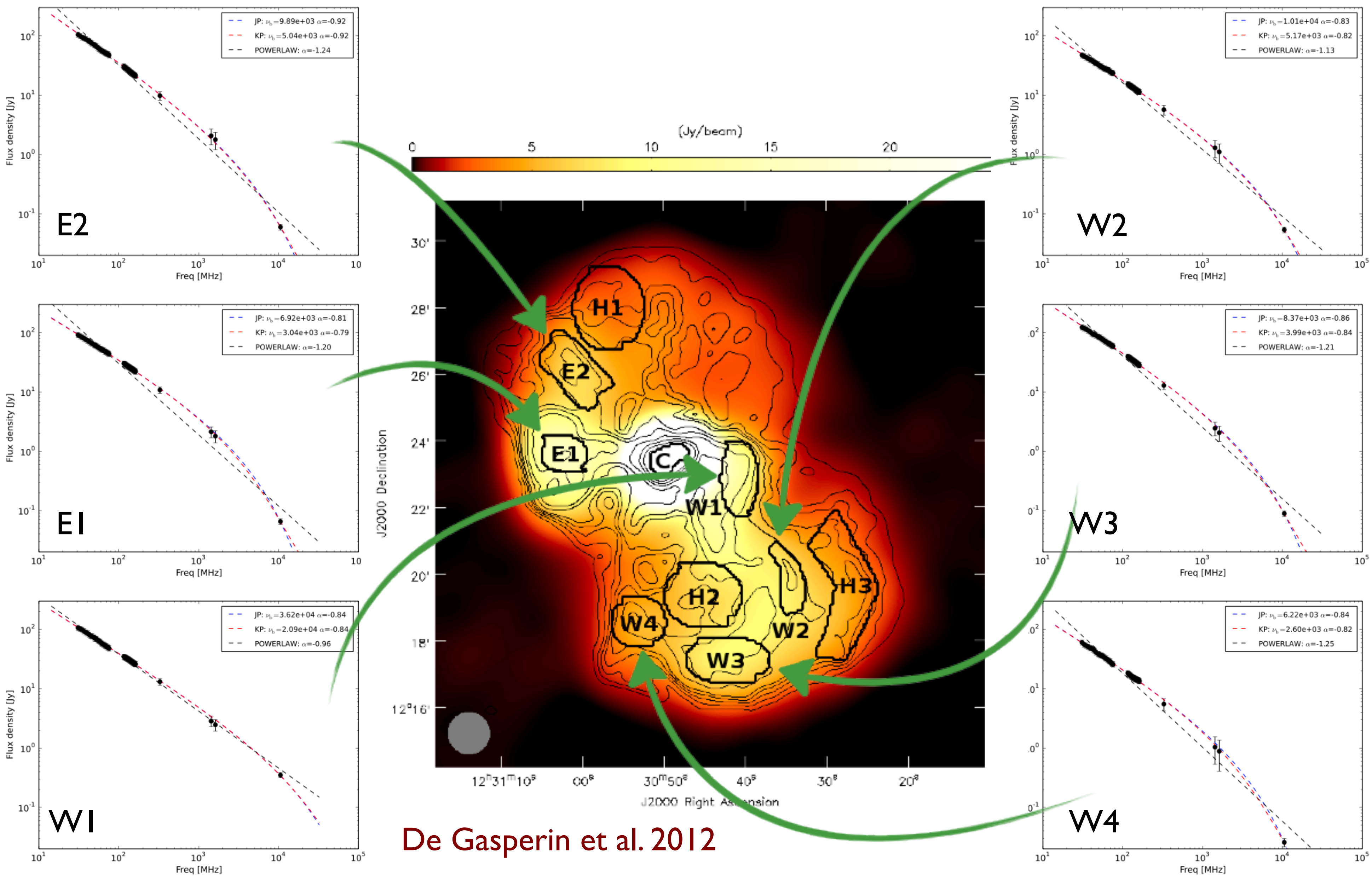
-Either the source has been active for ~40 Myrs only, or

- The halo keeps being confined in the same volume (Morsony et al. 2010)

$$\nu_b \propto \frac{1}{t^2 B^3}$$

De Gasperin et al. 2012

M87 – Regions



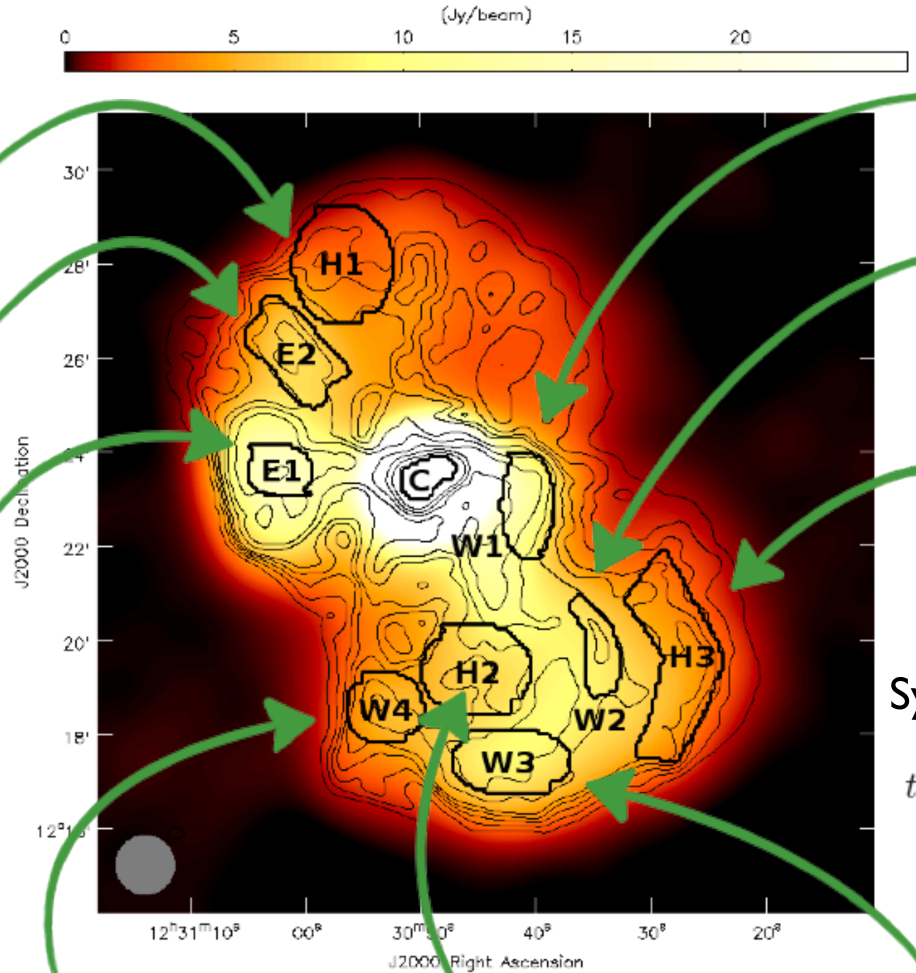
De Gasperin et al. 2012

M87 – Regions

B = 10.5 uG
P = 3e-12 dyn/cm^2
t = 15.7 Myr

B = 13.2 uG
P = 4.8e-12 dyn/cm^2
t = 10 Myr

B = 15.6 uG
P = 6.7e-12 dyn/cm^2
t = 9.4 Myr



B = 14.3 uG
P = 5.6e-12 dyn/cm^2
t = 4.7 Myr

B = 13 uG
P = 4.7e-12 dyn/cm^2
t = 10 Myr

B = 11.1 uG
P = 3.4e-12 dyn/cm^2
t = 13.5 Myr

Synchrotron ageing:

$$t_s = 1590 \frac{B^{0.5}}{(B^2 + B_{IC}^2)\left[(1+z)\,\nu_b\right]^{0.5}}$$

Pressure:
equipartition needs k>1000, thermal component?

Equipartition:
- k = 1
- γ min = 100
- D = 20 kpc

B = 12.4 uG
P = 4.2e-12 dyn/cm^2
t = 13.7 Myr

B = 13.1 uG
P = 4.7e-12 dyn/cm^2
t = 9.6 Myr

B = 13.7 uG
P = 5.2e-12 dyn/cm^2
t = 10.3 Myr

De Gasperin et al. 2012

M87 – Issues and Models

Possible explanations for low-frequency steepening (from core~-0.6 to halo~-0.85)

- **Adiabatic expansion** of plasmas at different ages → halo age ~ 30 Myr
- Plasma in a range of many different magnetic field strengths
- Spectrum intrinsically bended $\gamma \propto (\nu/B)$^(1/2)

Murgia et al. (1999), Blundell et al. (1999)

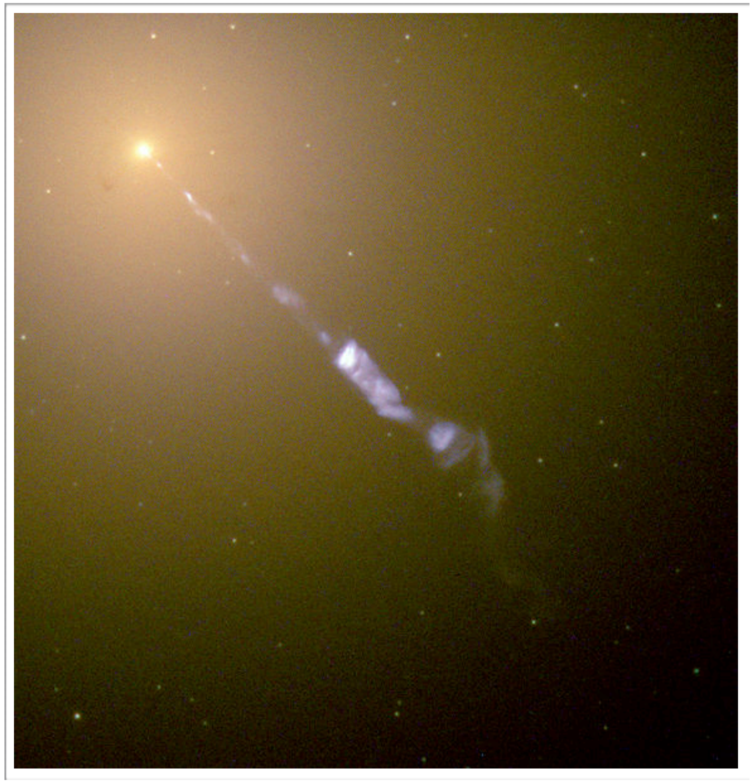
Discrepancy with dynamic time (~50 Myr from simulations):

- Mix of weak and strong magnetic fields (filamentary structure)
- In situ re-acceleration
- Plasma flow along pre-existing channels
- Bubbles plasma has initial momentum: ~20 kpc in 15 Myr

Churazov et al. (2001), Blundell & Rowlings (2000), Owen et al. (2000), Brueggen et al. (2002)

M87 – Jet Power

$$\frac{\mathrm{d}U_{\mathrm{int}}}{\mathrm{d}t} = P_{\mathrm{J}} - p\frac{\mathrm{d}V}{\mathrm{d}t} - \cancel{L_{\mathrm{rad}}}$$



Assuming:
- R = 35 kpc
- Jet power time independent
- p approximated with the surrounding medium
- Halo age: 40 Myr

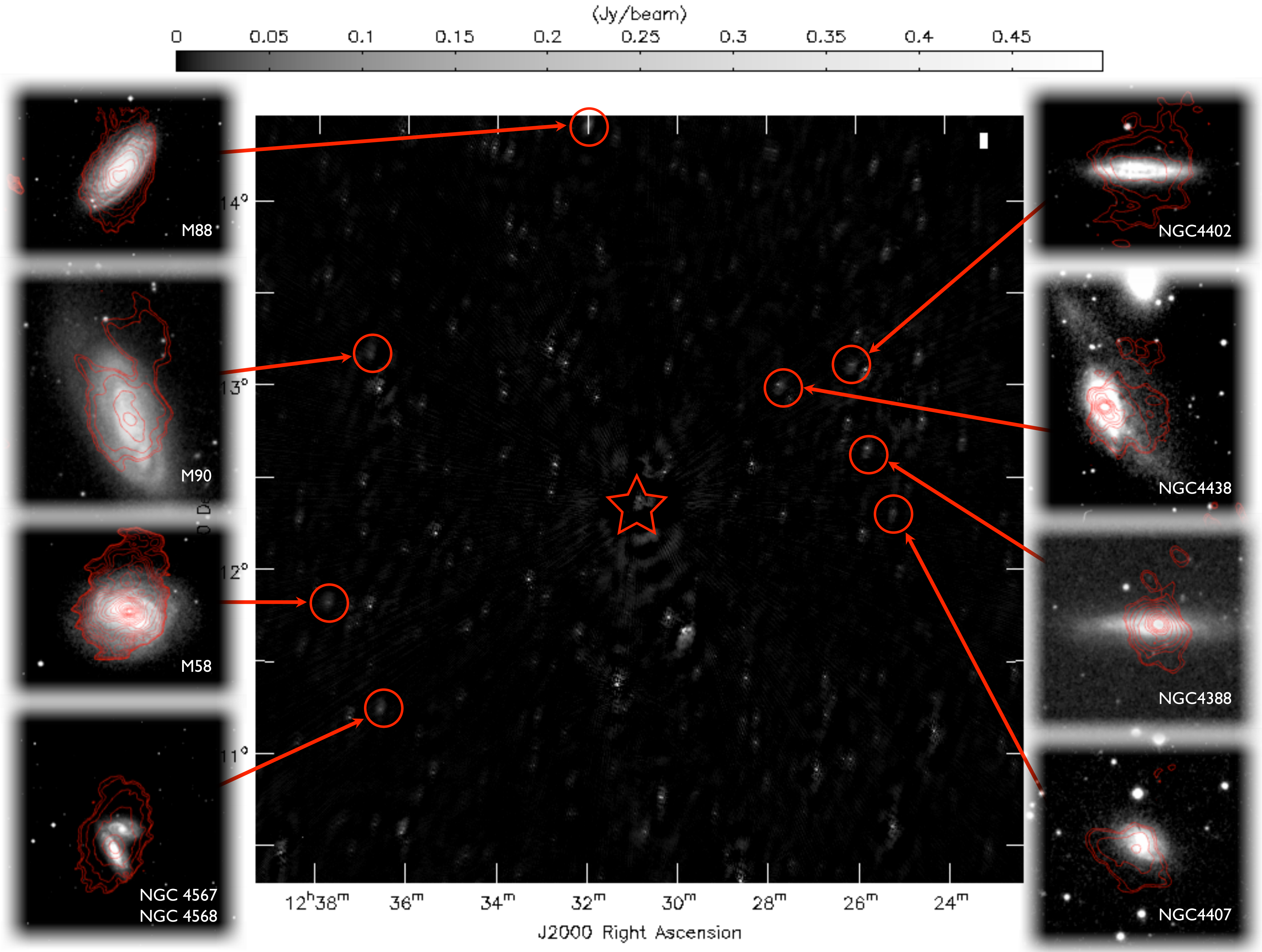
Jet power: 6 -10 x 10^{44} erg/s

(from 10 to 100 times the X-ray luminosity of the cooling flow)

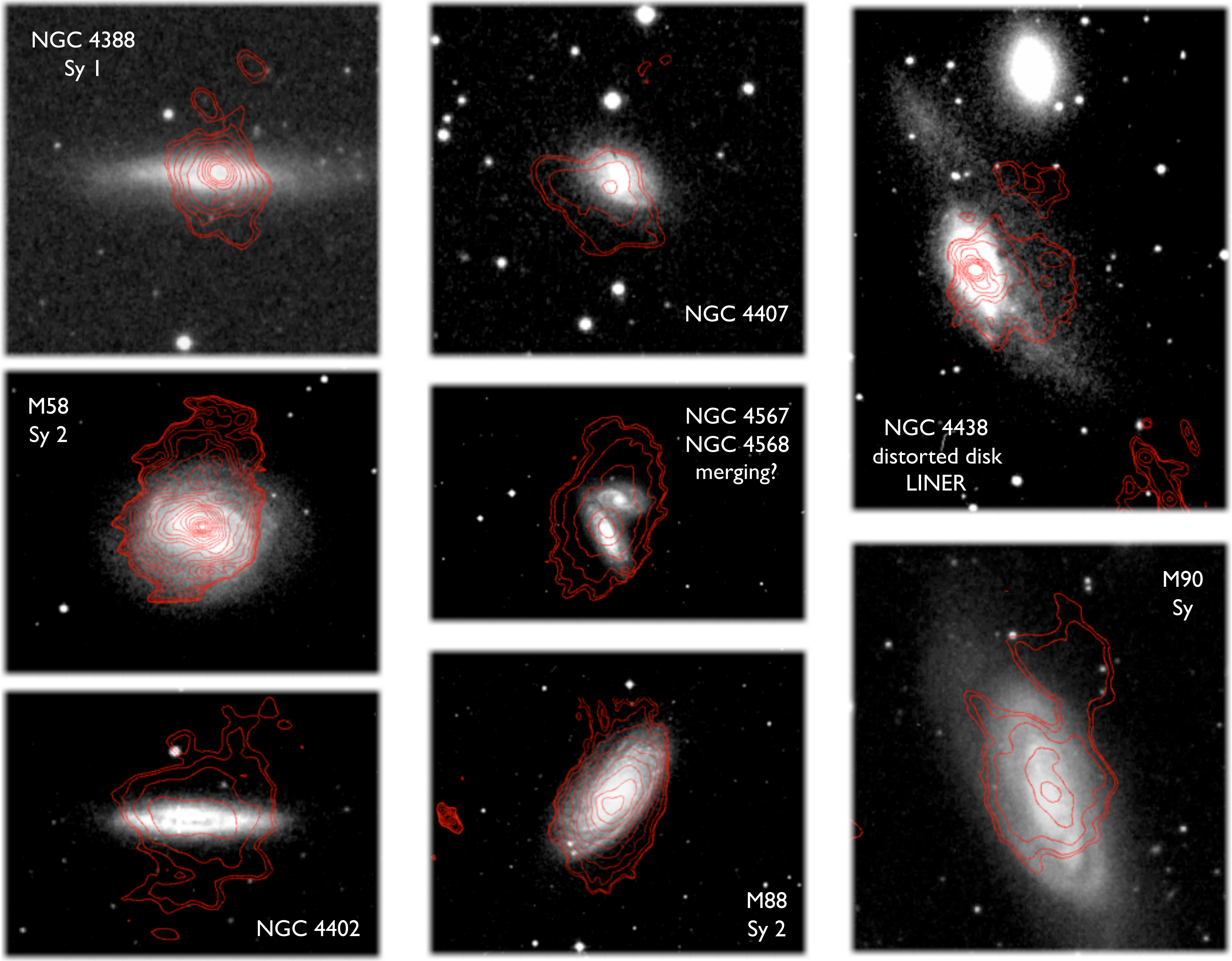
Eilek & Shore (1989), Owen et al. (2000), Matushita et al. 2002

M87 – Conclusions

- Virgo A extended halo is an active and living source
- Down to 25 MHz no previously unseen steep-spectrum features were detected
- Steepening in the low-frequency end of the spectra can be connected to adiabatic expansion of the plasma bubble
- Magnetic field strength $\simeq$13 μG found in the flow regions, and of $\simeq$10 μG in the halo regions
- Pressure generated by the plasma and the magnetic fields less than what required to sustain the halo. Probably, thermal gas plays a role in sustaining the halo.
- Synchrotron ageing analysis provided a global halo age of $\simeq$40 Myr
- Estimate jet power $P_{jet} \simeq$ 6-10 x10^{44} erg/s. 10 to 100 times higher than the X-ray luminosity due to cooling flow



(Jy/beam)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
14°
13°
12°
11°
12h38m
36m
34m
32m
30m
28m
26m
24m
J2000 Right Ascension
M88
M90
M58
NGC 4567
NGC 4568
NGC4402
NGC4438
NGC4388
NGC4407


NGC 4388
Sy I
NGC 4407
NGC 4438
distorted disk
LINER
M58
Sy 2
NGC 4567
NGC 4568
merging?
M90
Sy
NGC 4402
M88
Sy 2

Conclusions – II

- LOFAR is ready for science!