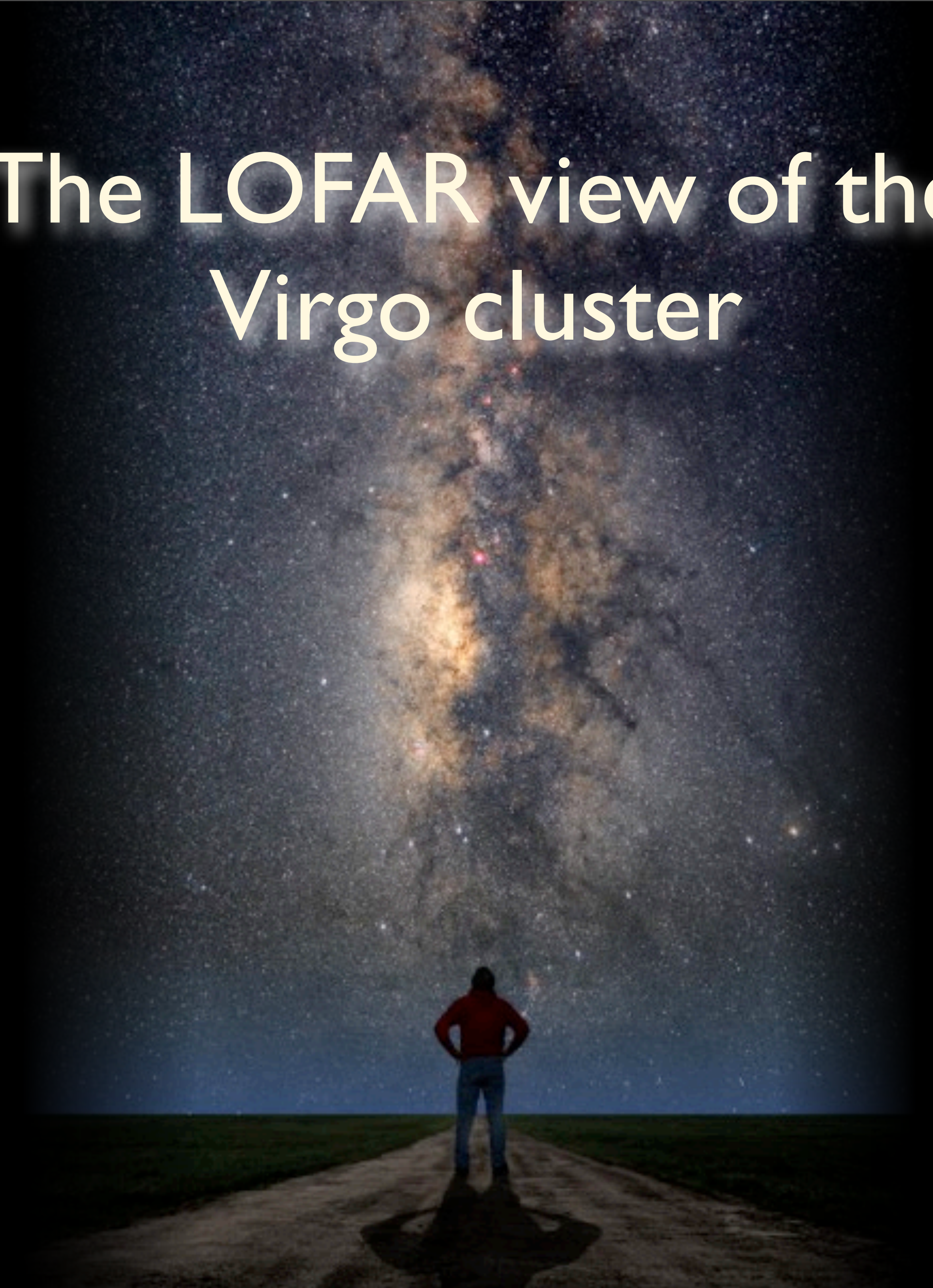

The LOFAR view of the Virgo cluster

Francesco de Gasperin

E. Orru', M. Murgia, A. Merloni, H. Falcke

R. Beck, R. Beswick1 L. Bırzan, A. Bonafede, M. Brueggen, G. Brunetti, K. Chyzy, J. Conway, J.H. Croston, T. Enßlin, C. Ferrari, G. Heald, S. Heidenreich, N. Jackson, G. Macario, J.P. McKean, G. Miley, R. Morganti, A. R. Offringa, R. Pizzo, D. Rafferty, H. Rottgering, A. Shulevski, M. Steinmetz, C. Tasse, S. van der Tol, W. van Driel, R. J. van Weeren, J. E. van Zwieten

Max-Planck-Institut für Astrophysik

ASTRON

12/07/2012

Outline

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LOFAR observations

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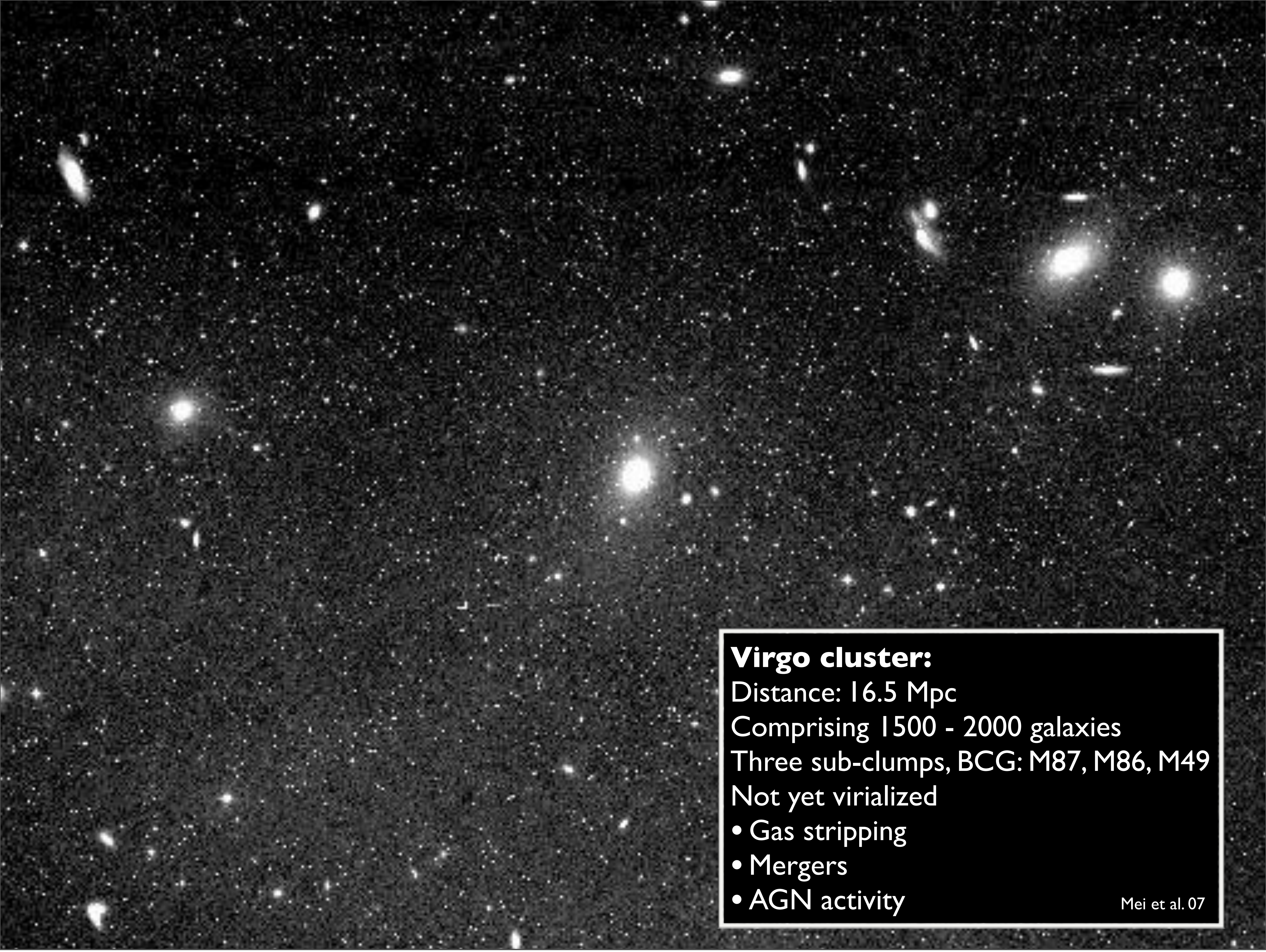
Mei et al. 07



Virgo cluster:

Distance: 16.5 Mpc

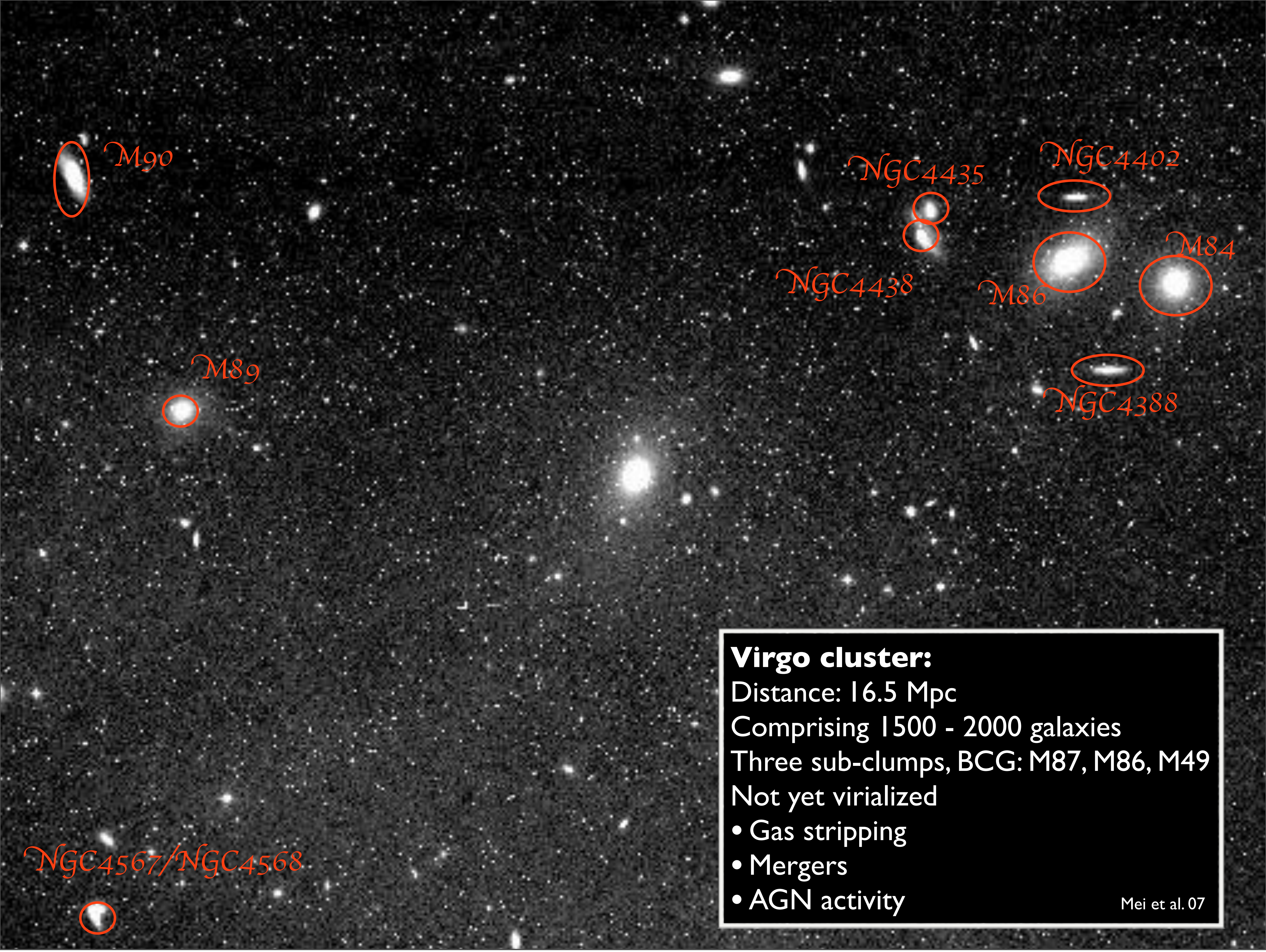
Comprising 1500 - 2000 galaxies

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

Not yet virialized

- Gas stripping
- Mergers
- AGN activity

Mei et al. 07



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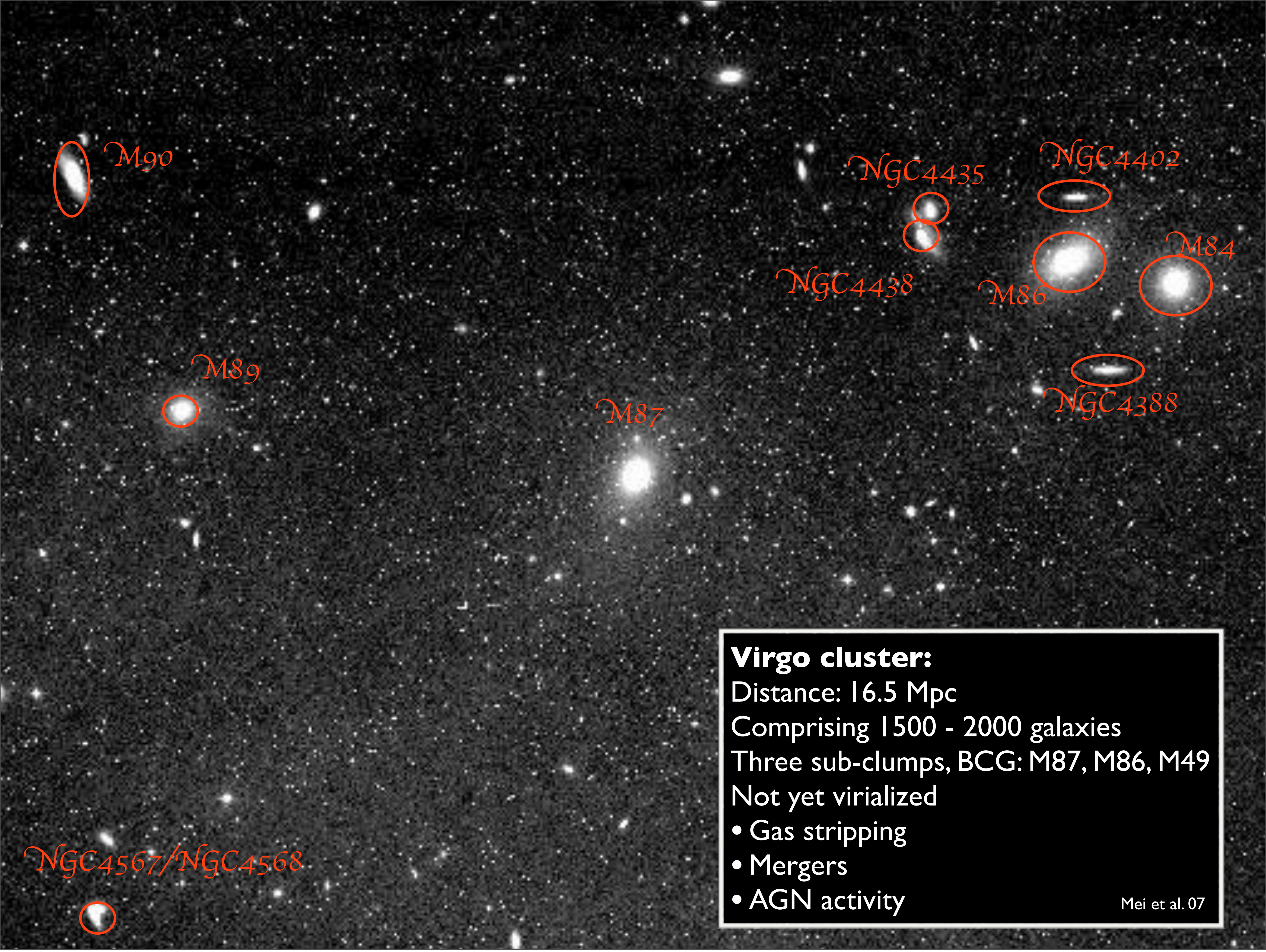

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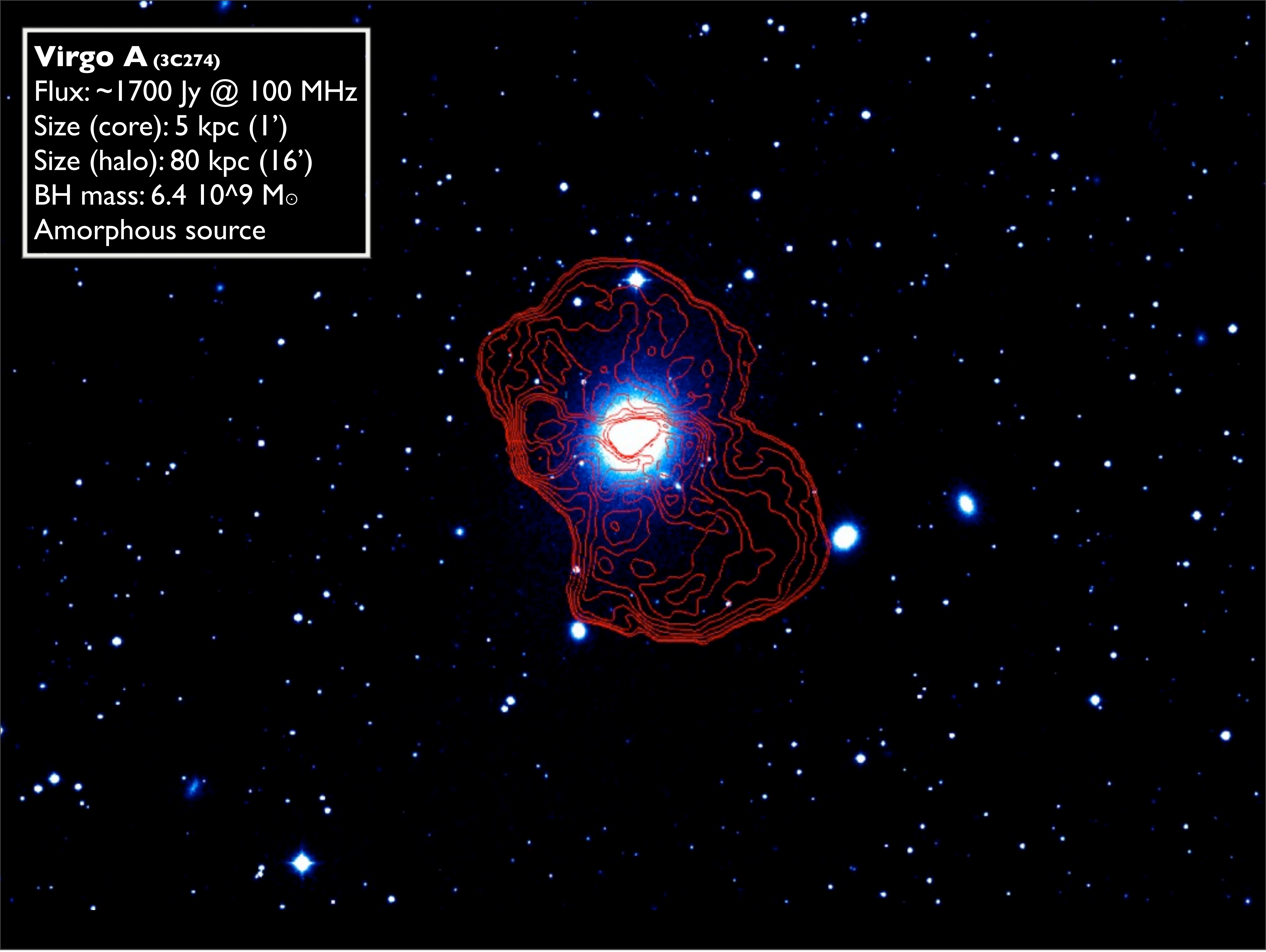
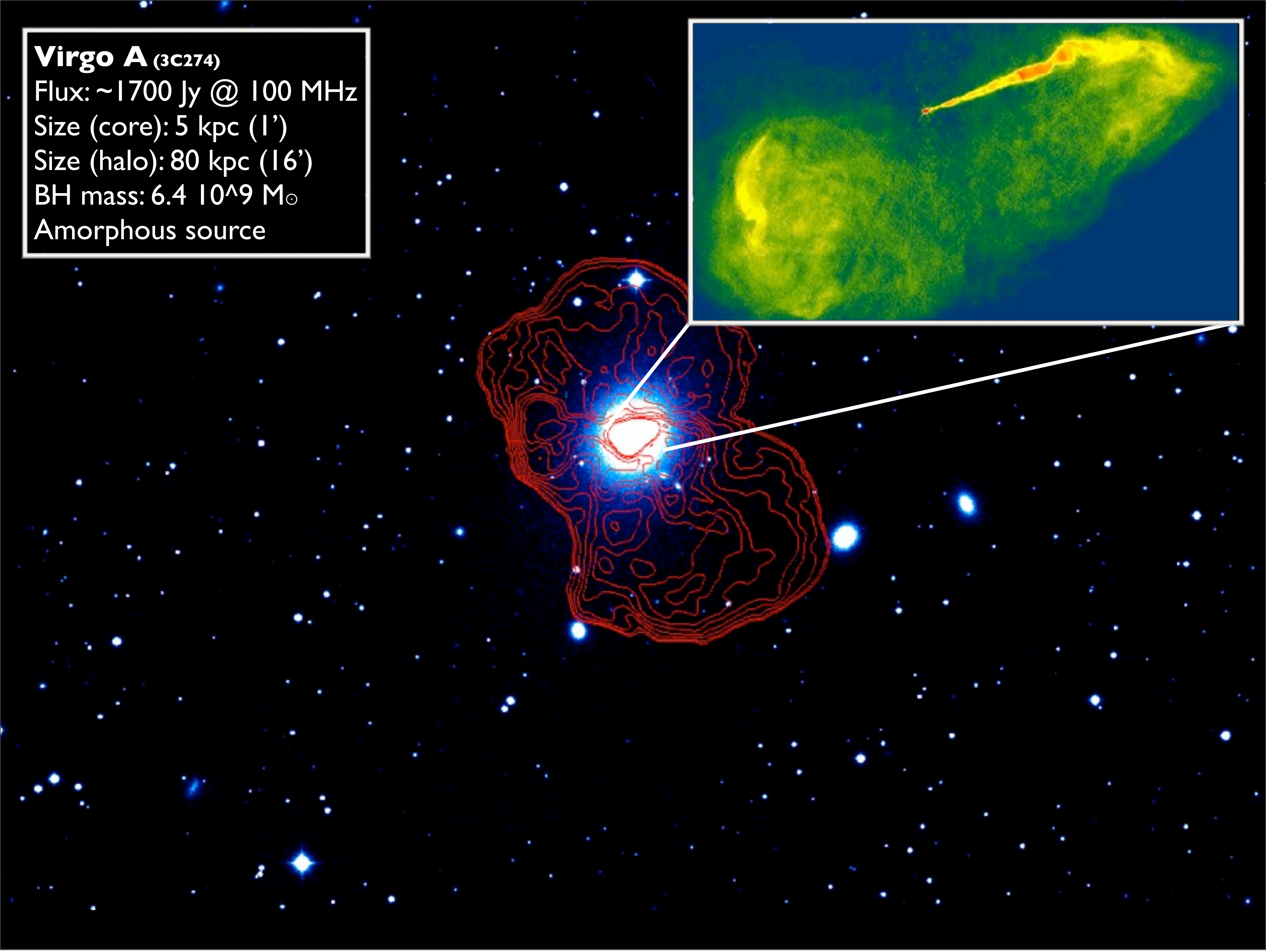

Virgo A (3C274)
Flux: ~1700 Jy @ 100 MHz
Size (core): 5 kpc (1’)
Size (halo): 80 kpc (16’)
BH mass: 6.4 10^9 M☉
Amorphous source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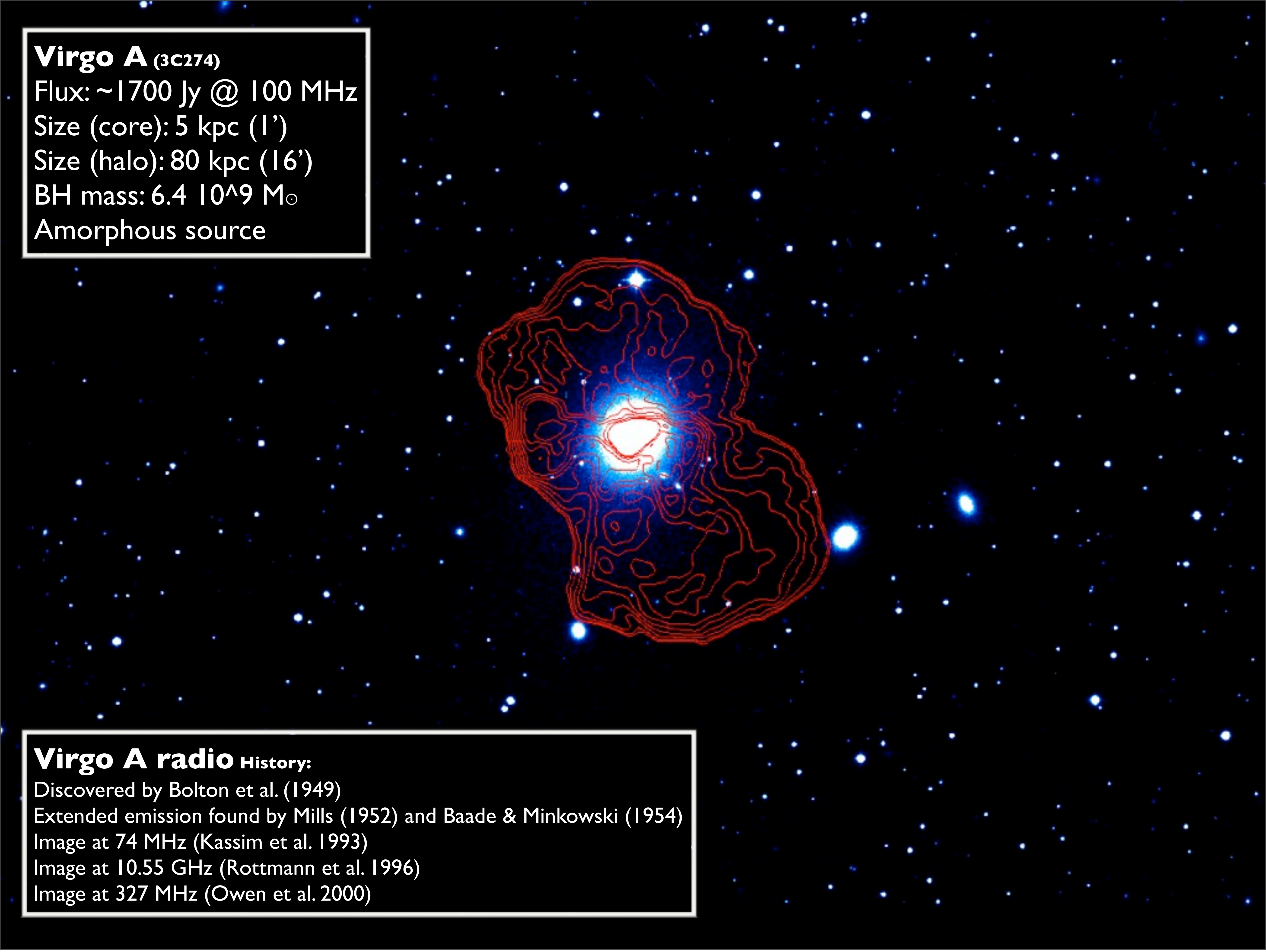
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Virgo A radio History:
Discovered by Bolton et al. (1949)
Extended emission found by Mills (1952) and Baade & Minkowski (1954)
Image at 74 MHz (Kassim et al. 1993)
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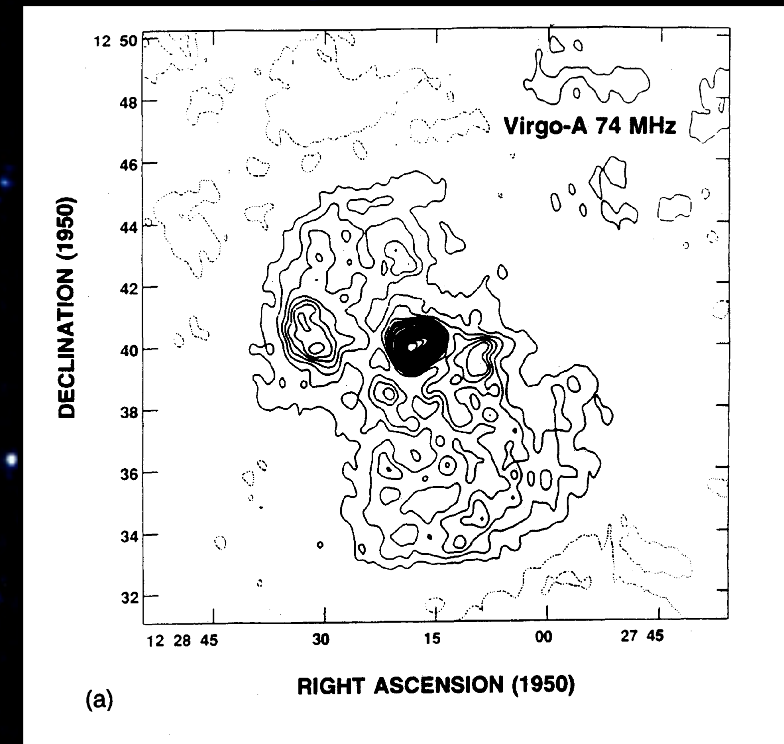
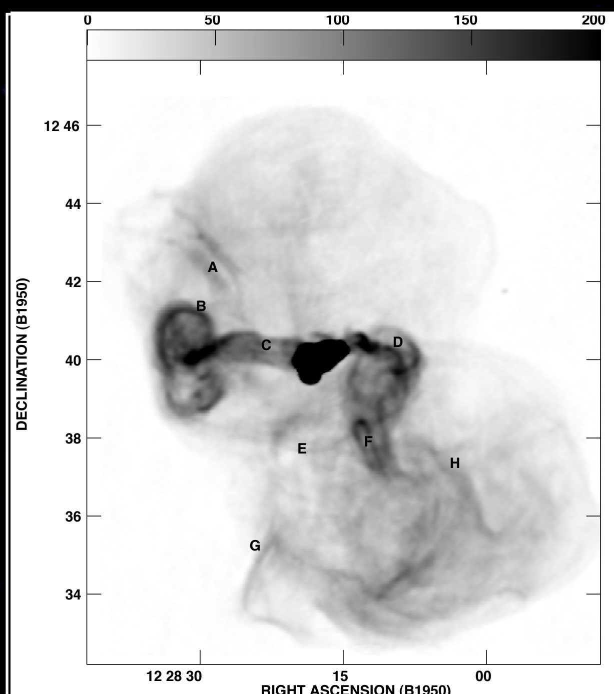
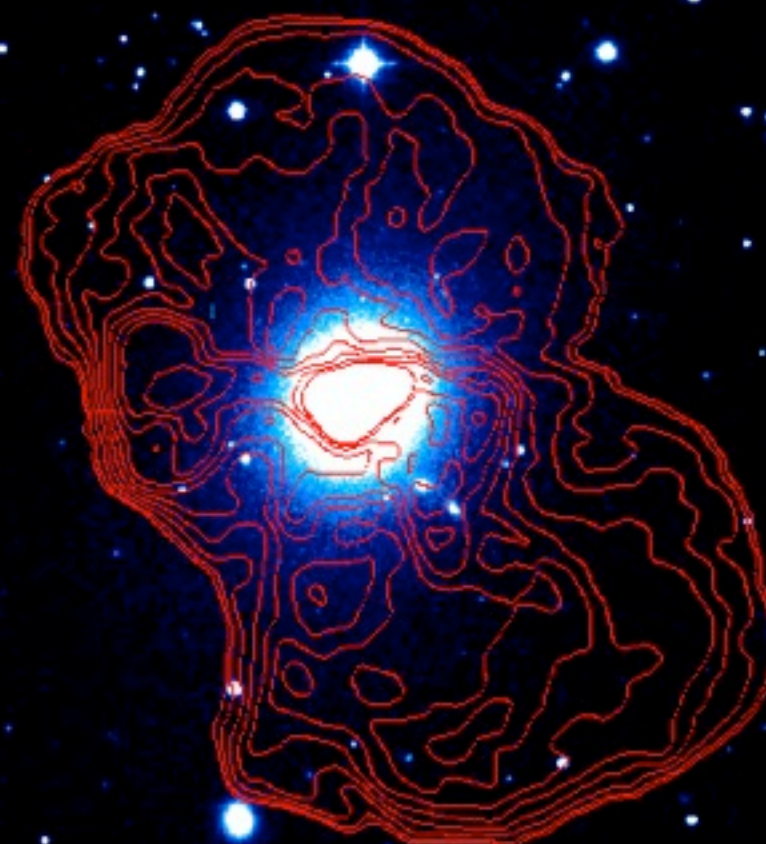
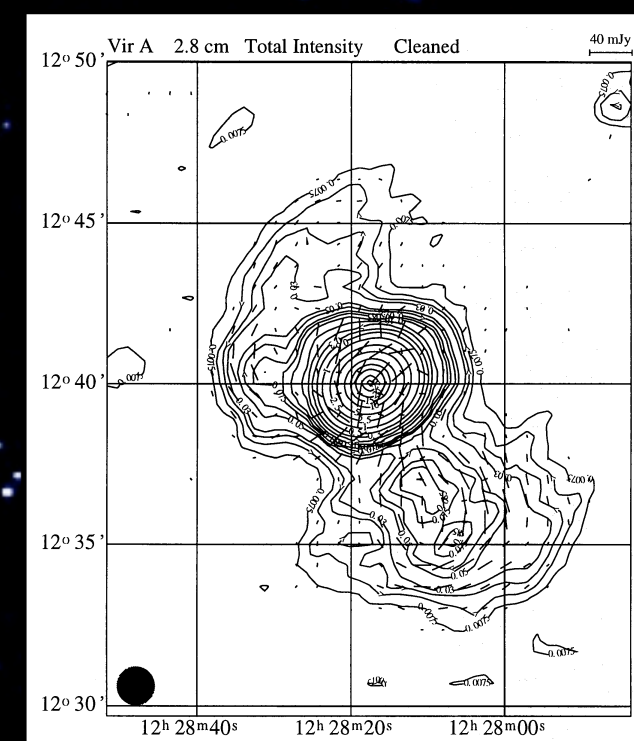


74 MHz



327 MHz





10.55 GHz

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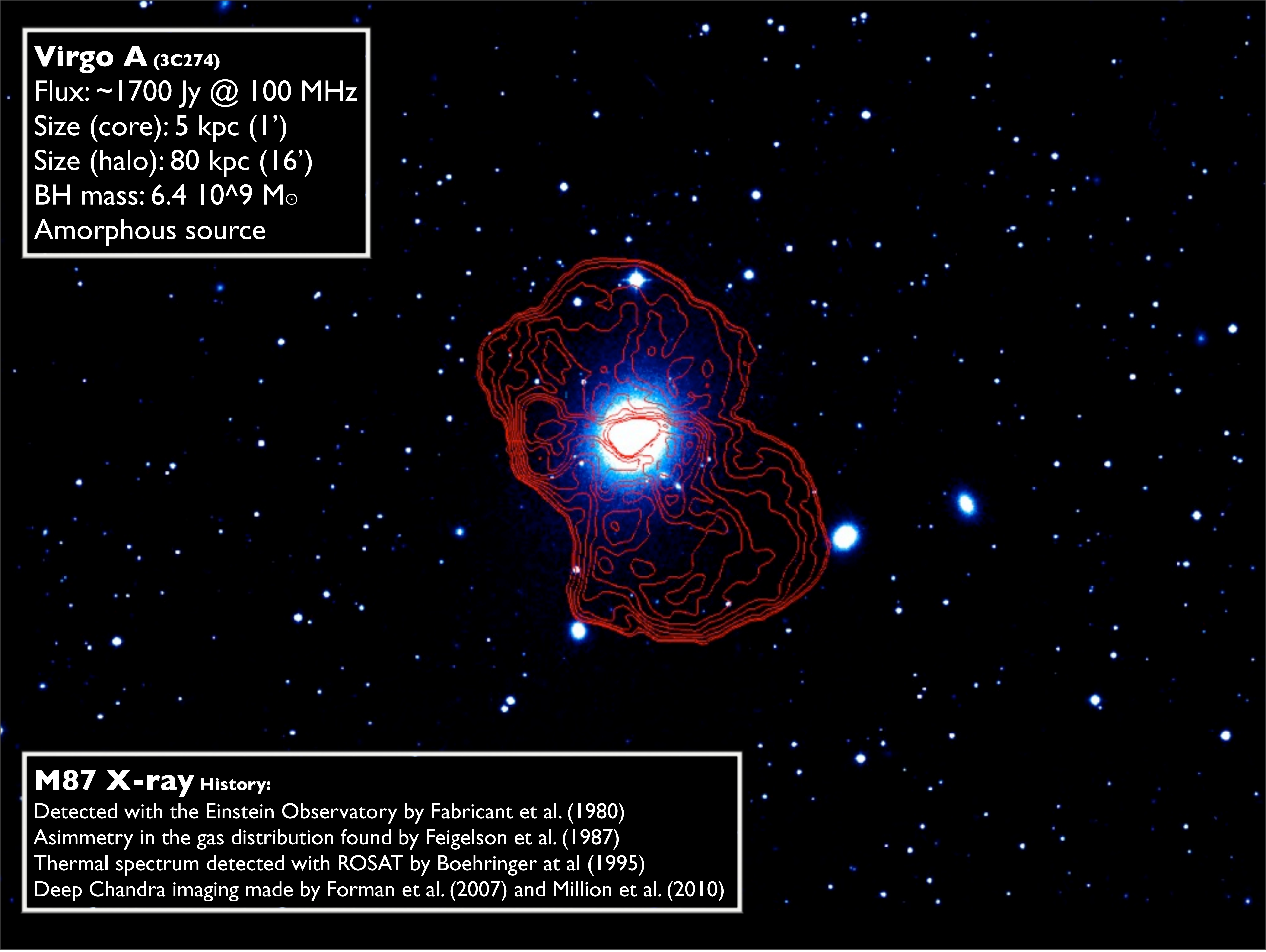

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Detected with the Einstein Observatory by Fabricant et al. (1980)
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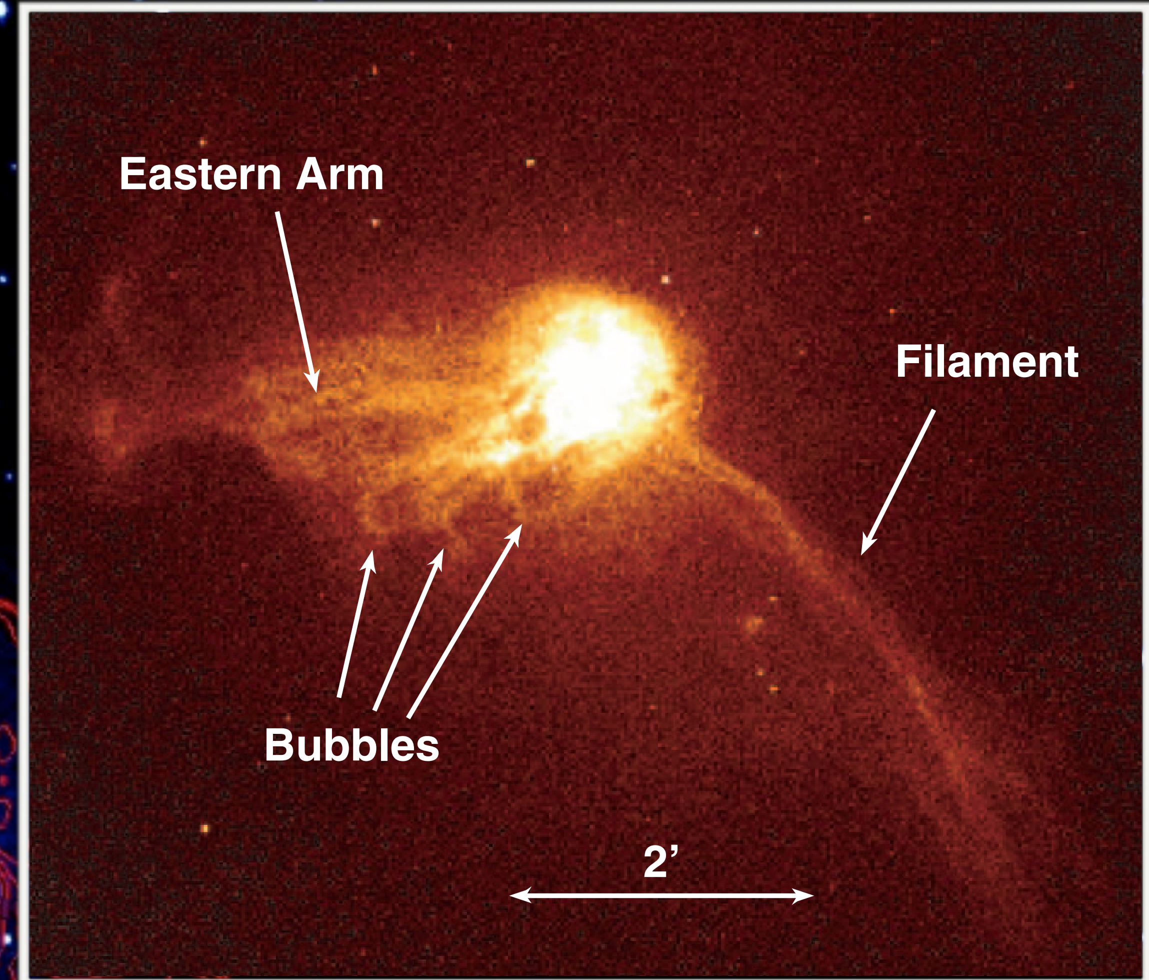

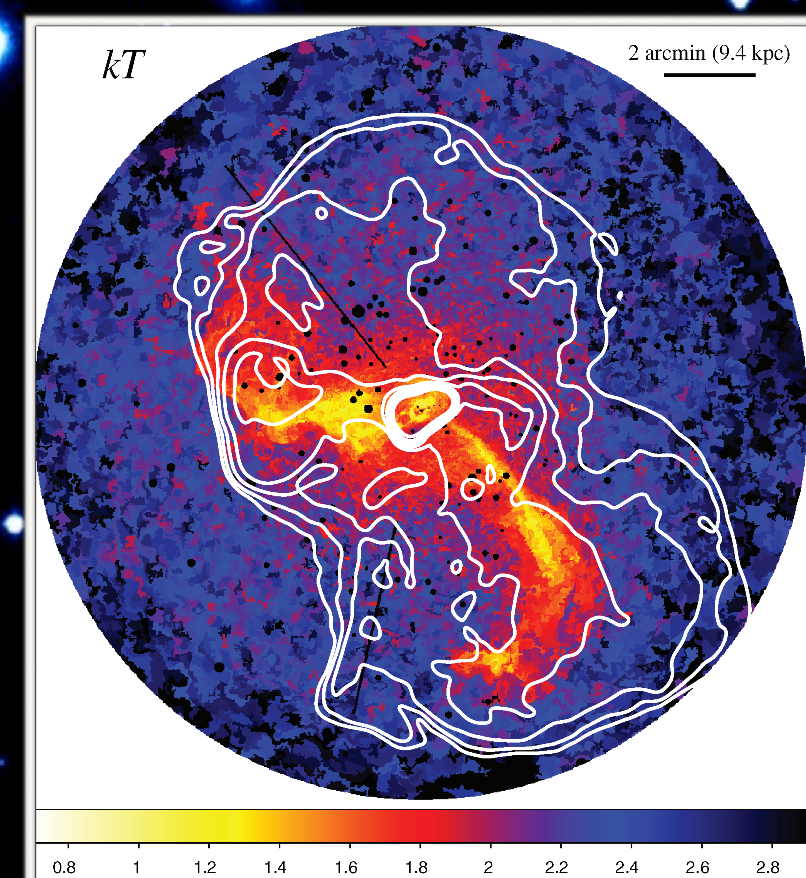

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Outline

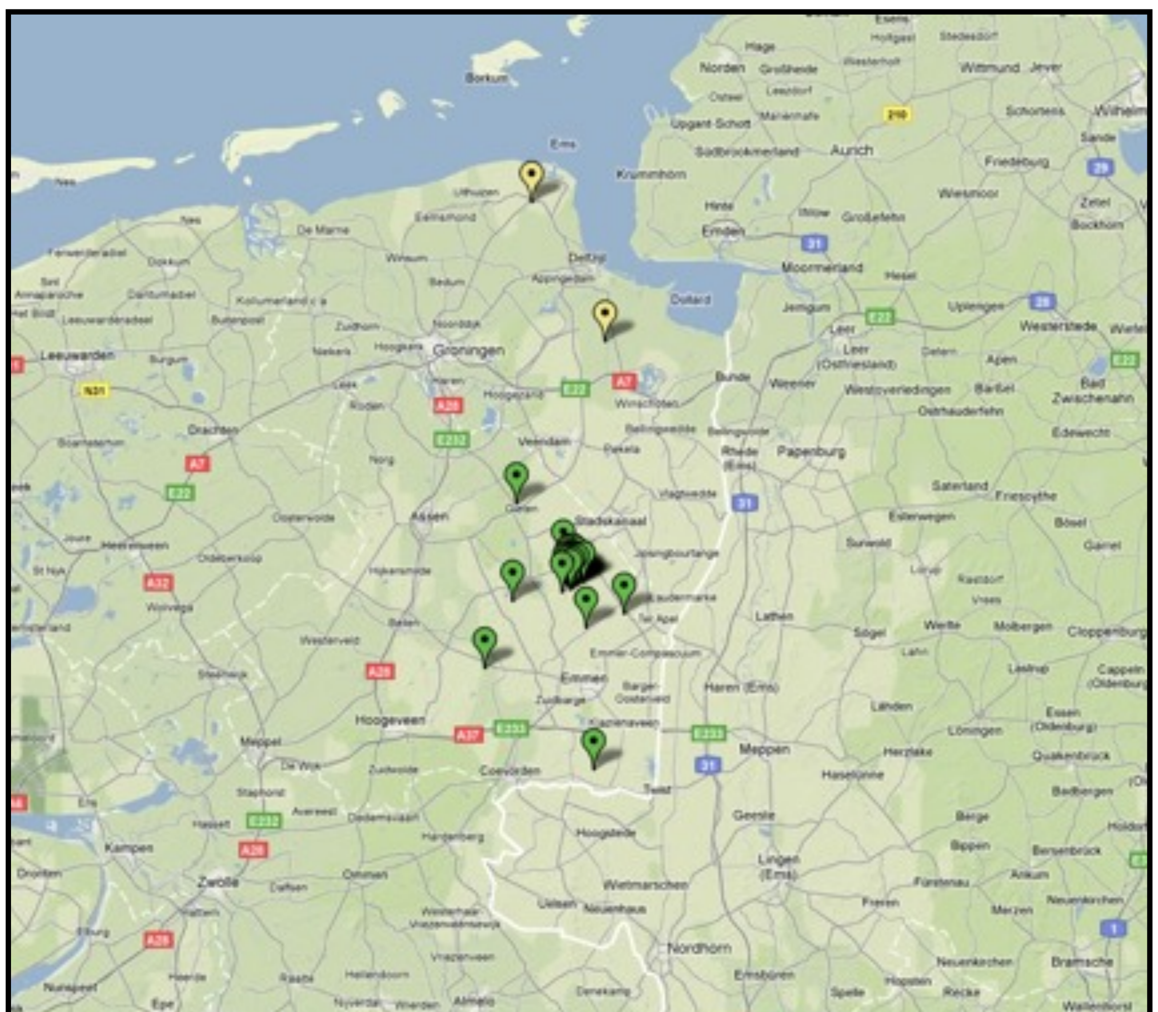
- Nice Historical introduction
- LOFAR observations
- Pretty Images
- Spectral Analysis + a bit of science
- The Virgo field
- RM synthesis

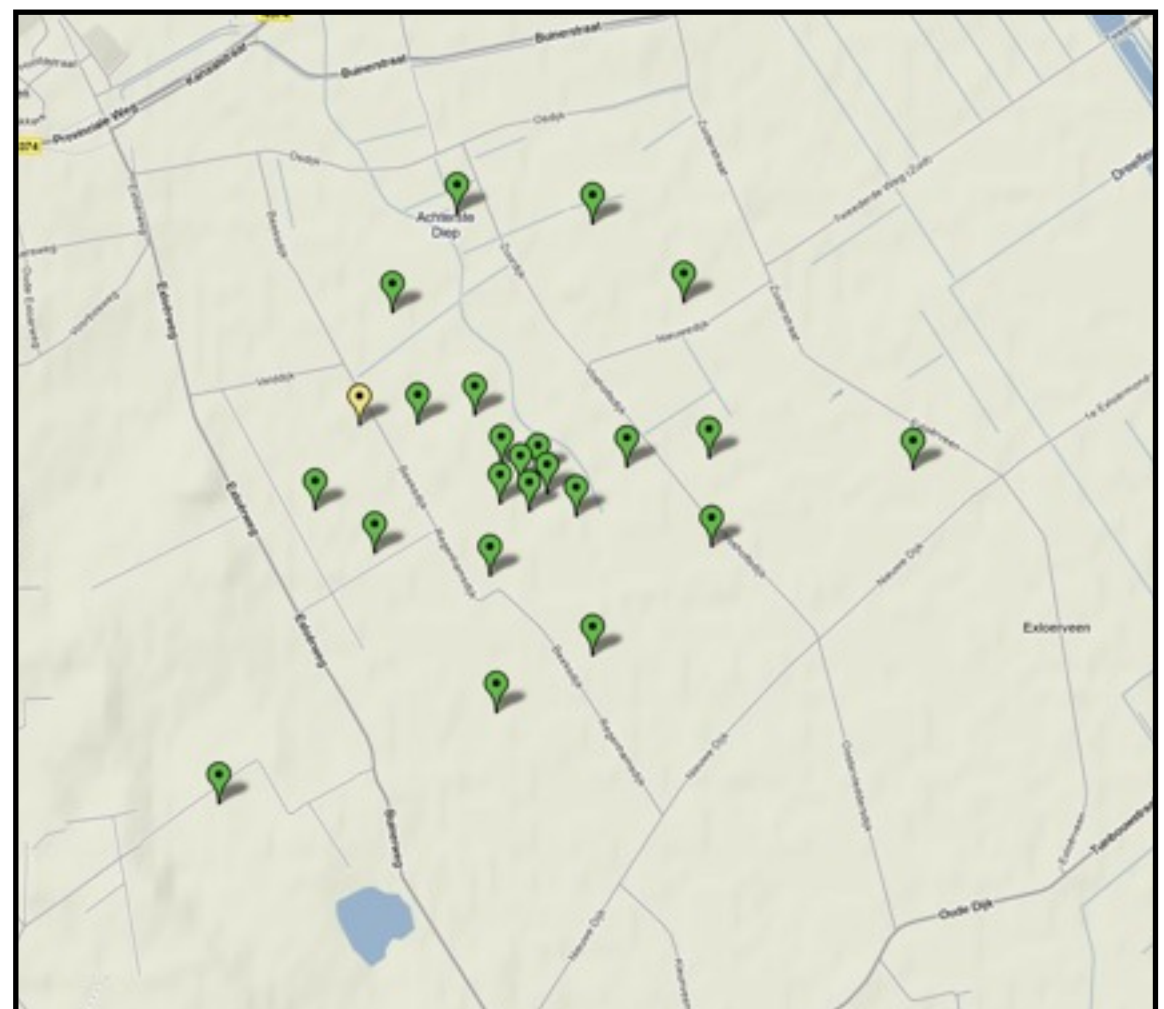
The Observations

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

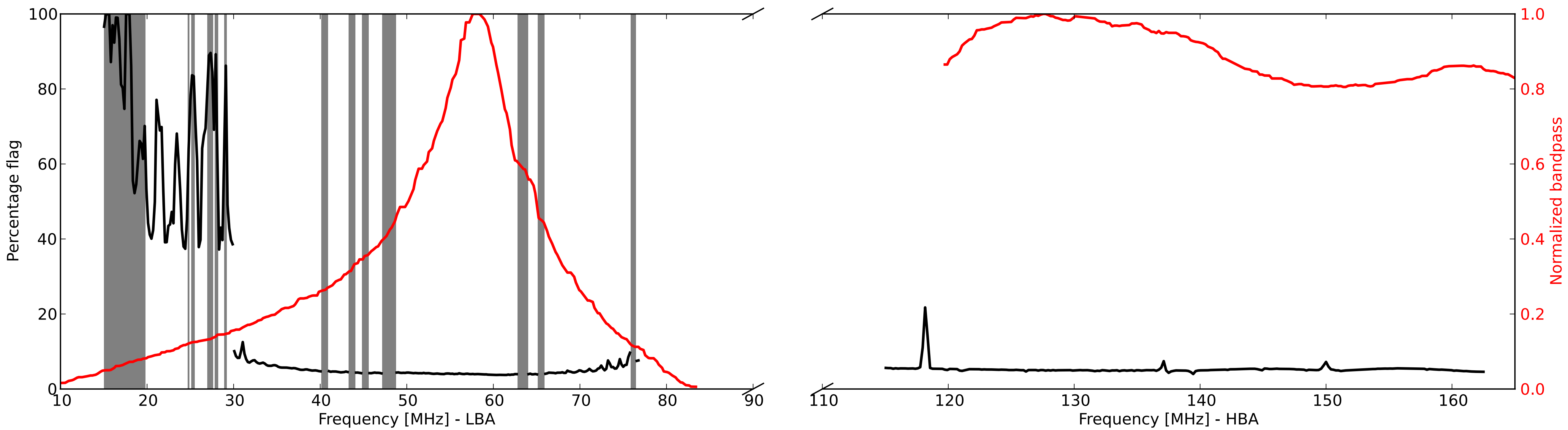
HBA:
115 - 162 MHz
2/3 Apr 2011
28810 s (~8 h)
45 ant (dual)



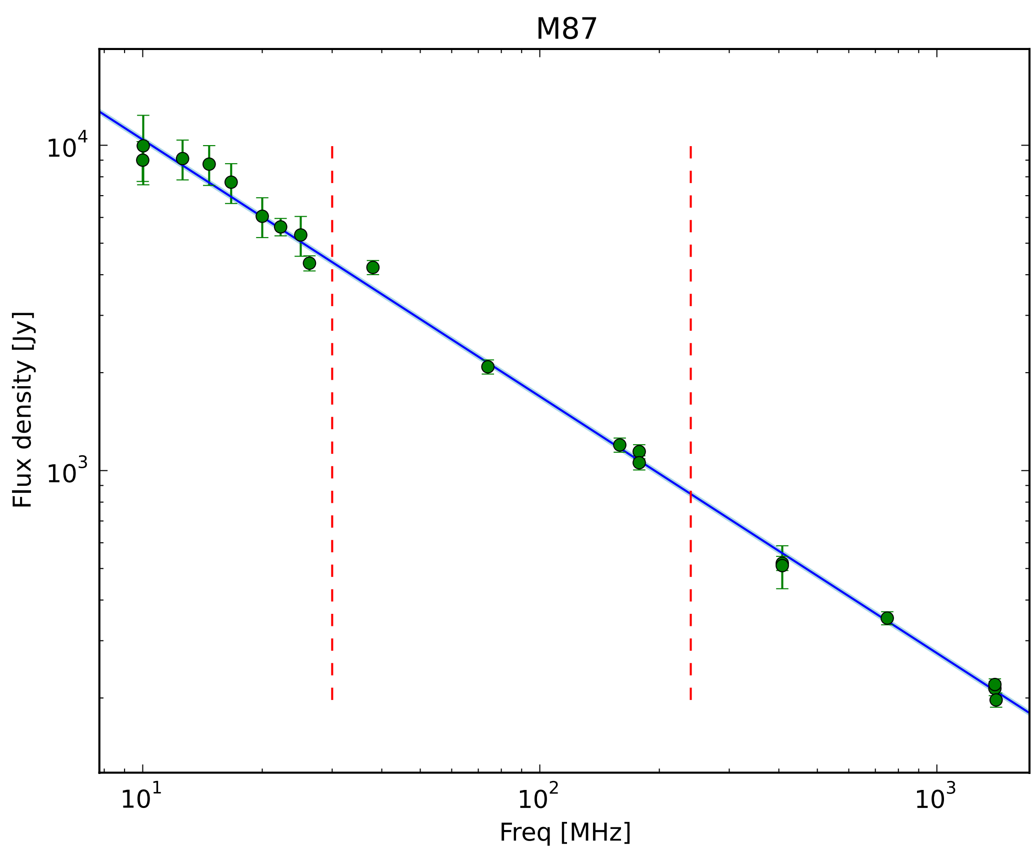


Images from: http://www.astron.nl/~heald/lofarStatusMap.html

The Observations



Black: % flagged data (!= RFI)
Red: normalised bandpass



No flux calibrator
Data from literature (10 - 1400 MHz)
Integrated flux → slope: -0.79
Total flux rescaled to its expected value

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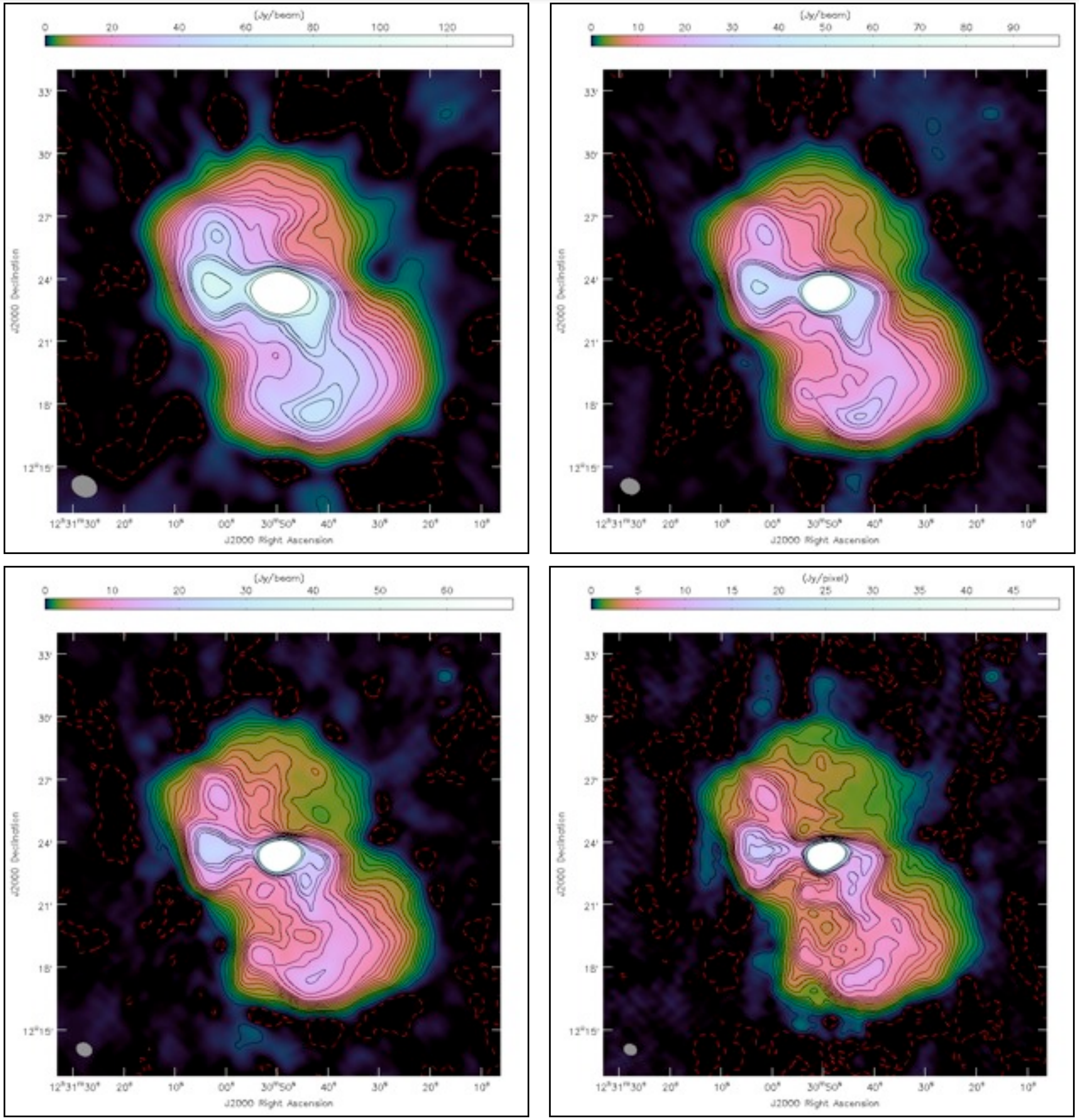


36 MHz

48 MHz

59 MHz

71 MHz

LBA maps:

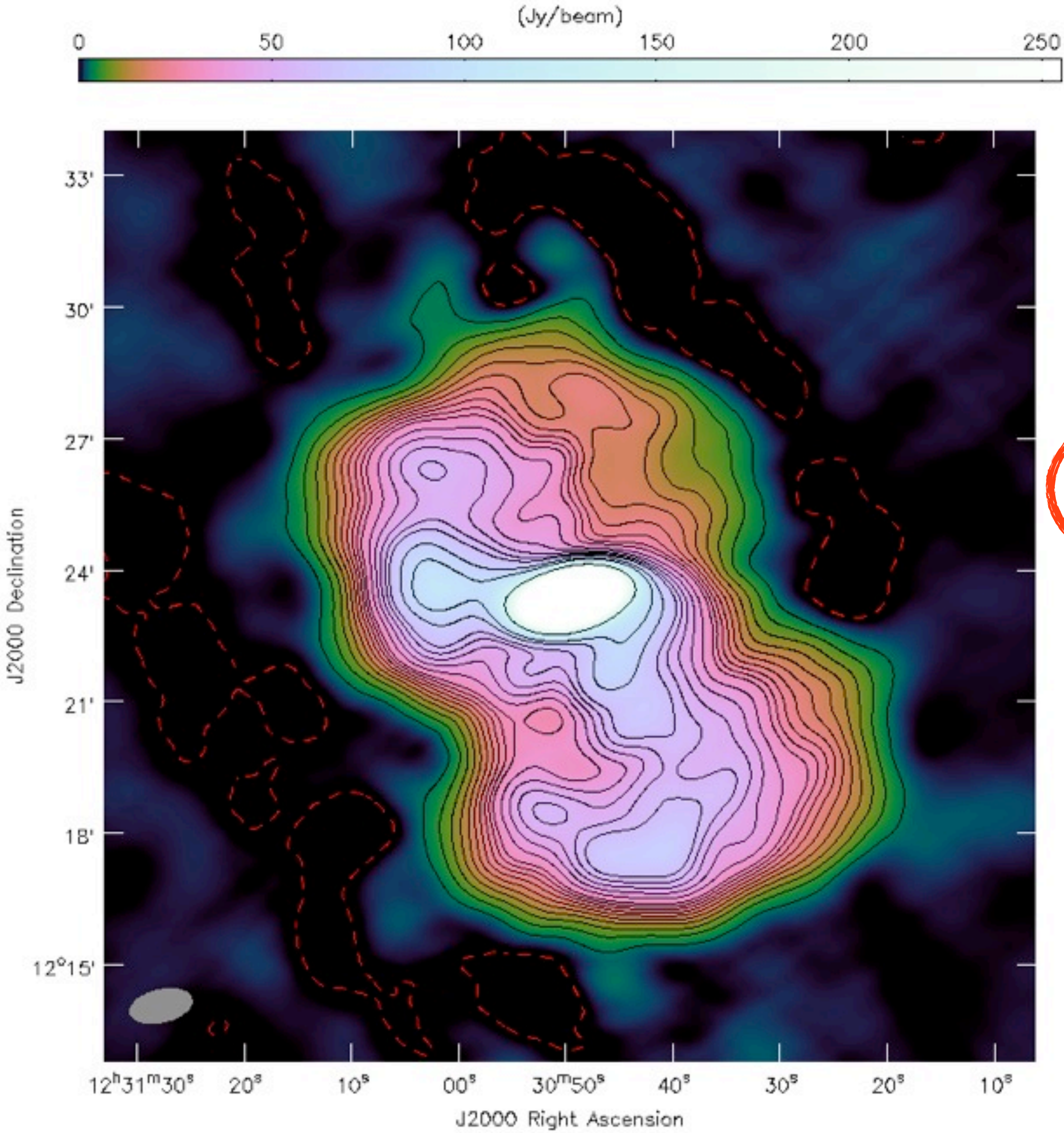
Freq: 36 MHz
Beam: 73" x 58"
RMS: 0.2 Jy/beam

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

M87



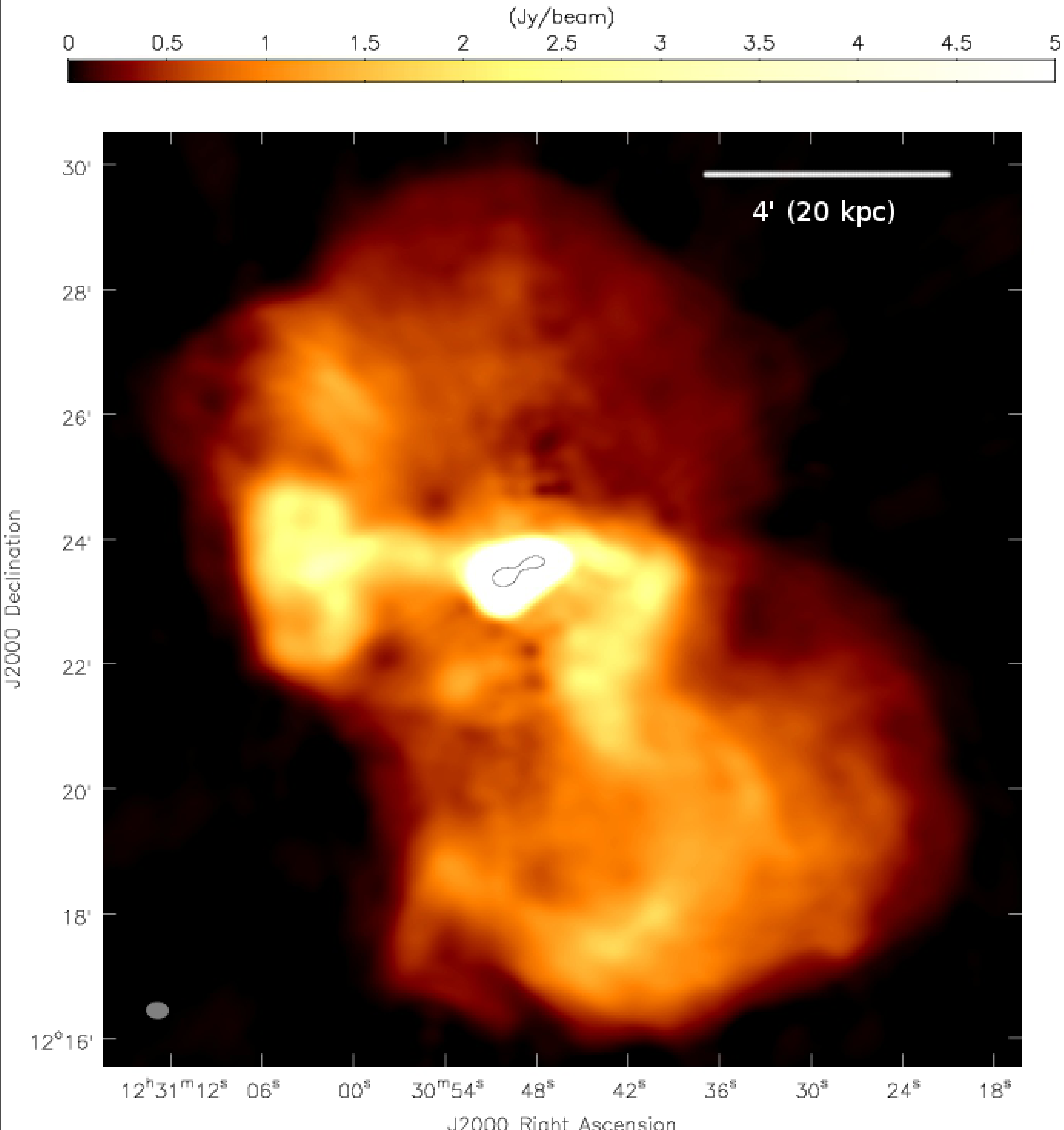
LBA map:

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"?

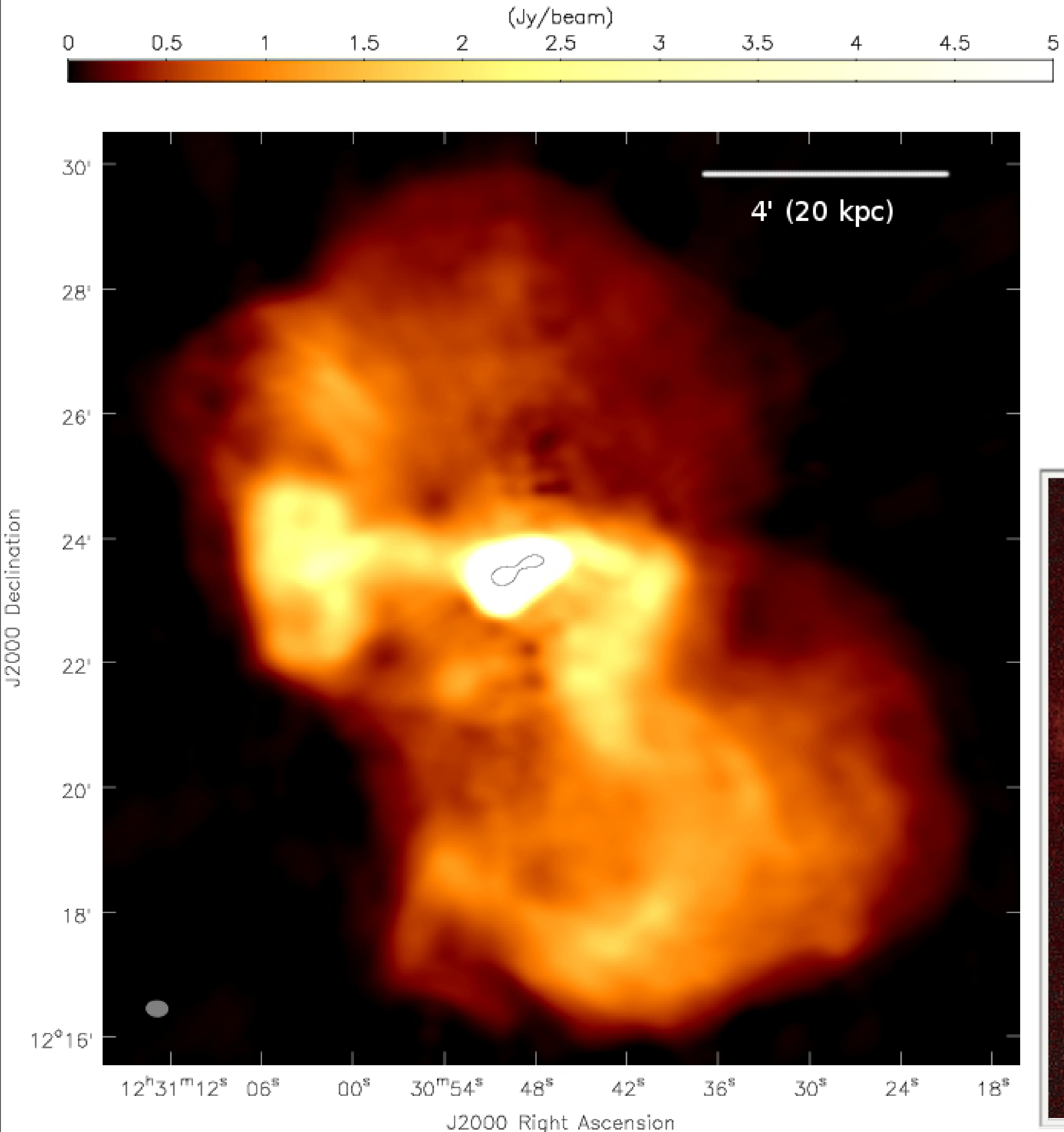


HBA map:

RMS: 20 mJy/beam
Beam: 21" x 15"
Dyn Range > 5000
Frequency: 140 MHz

NOTES:

- Imaging of the core with standard Clean algorithm
- Imaging of the extended emission with MS-clean



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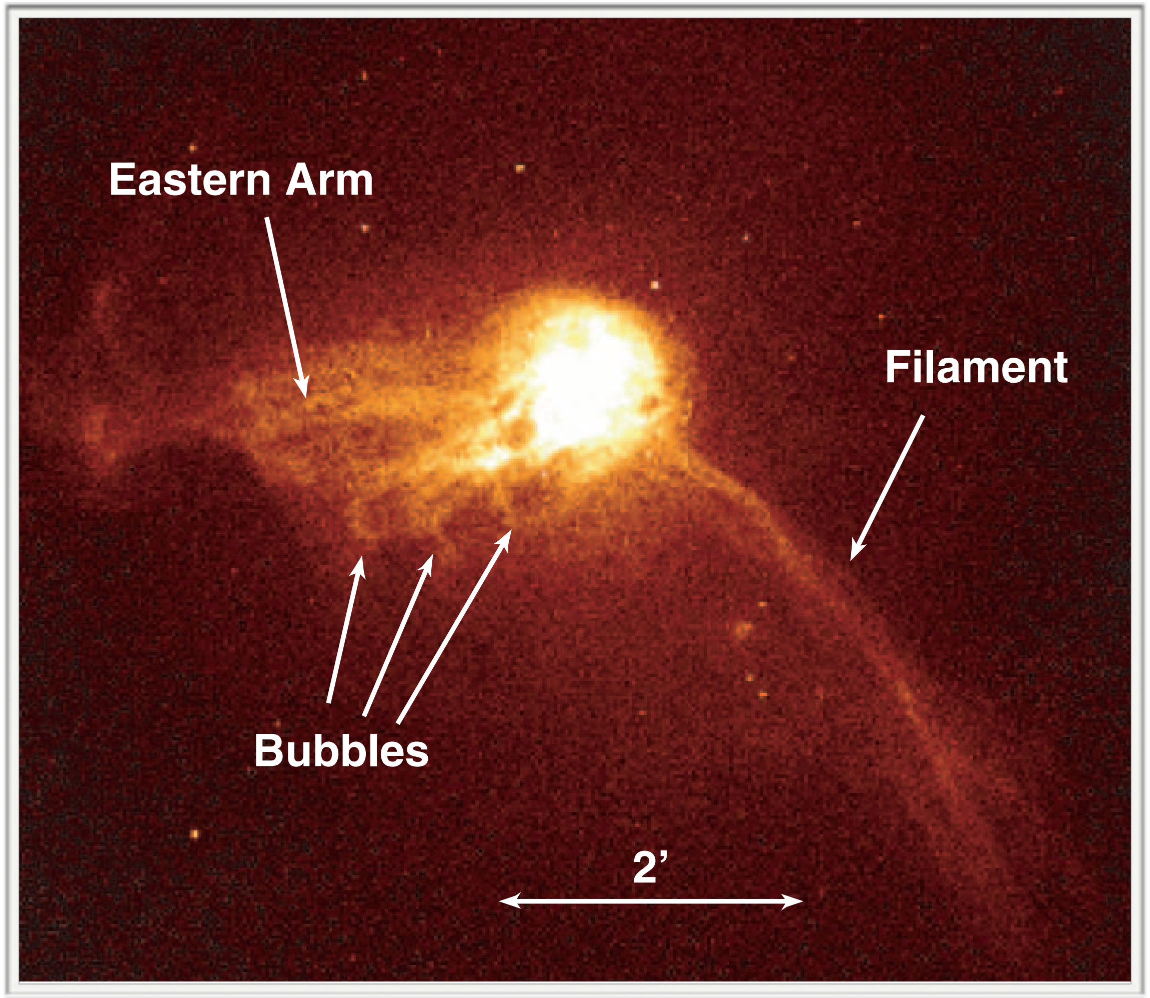
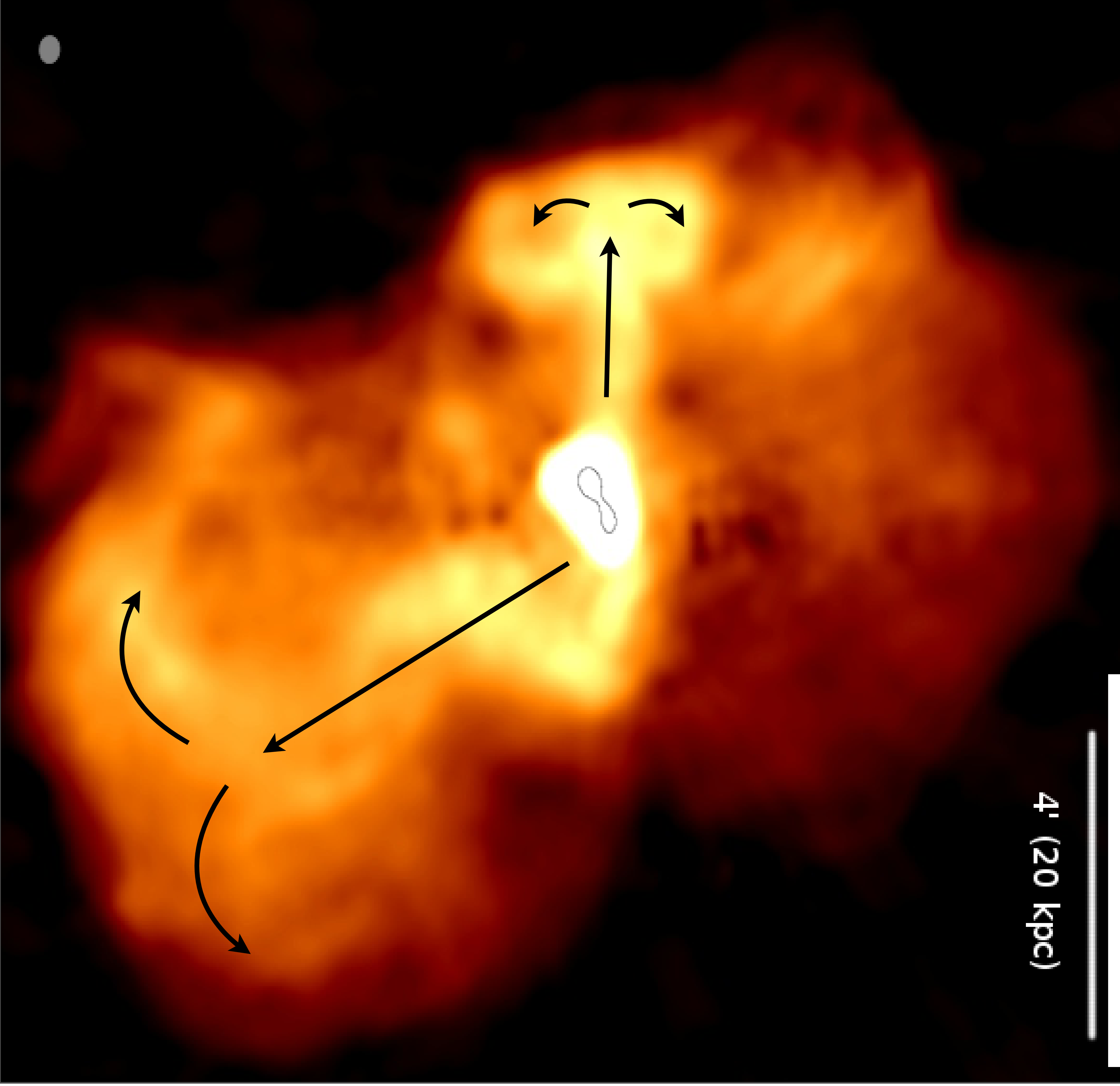
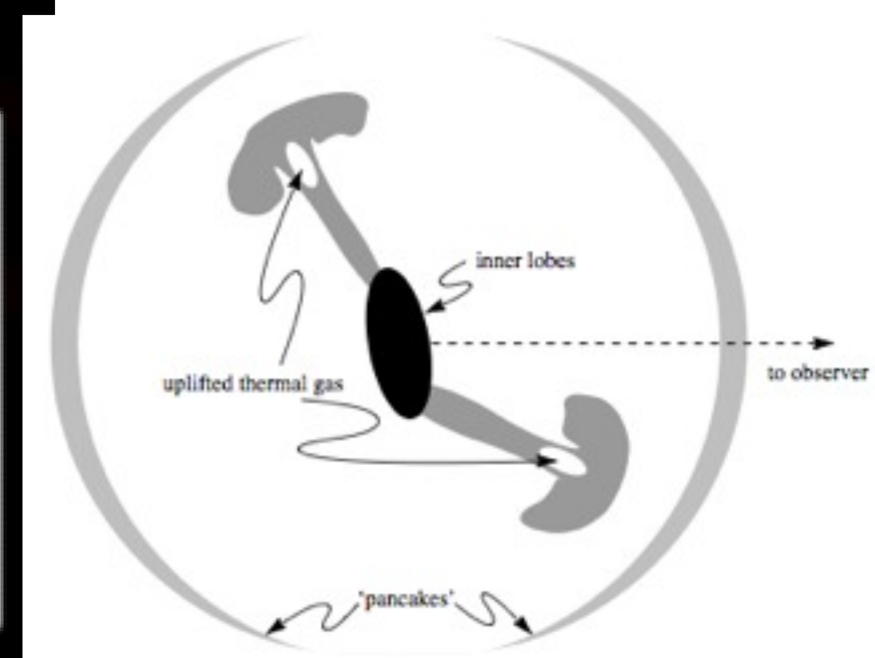


M87



Churazov et al. 2001



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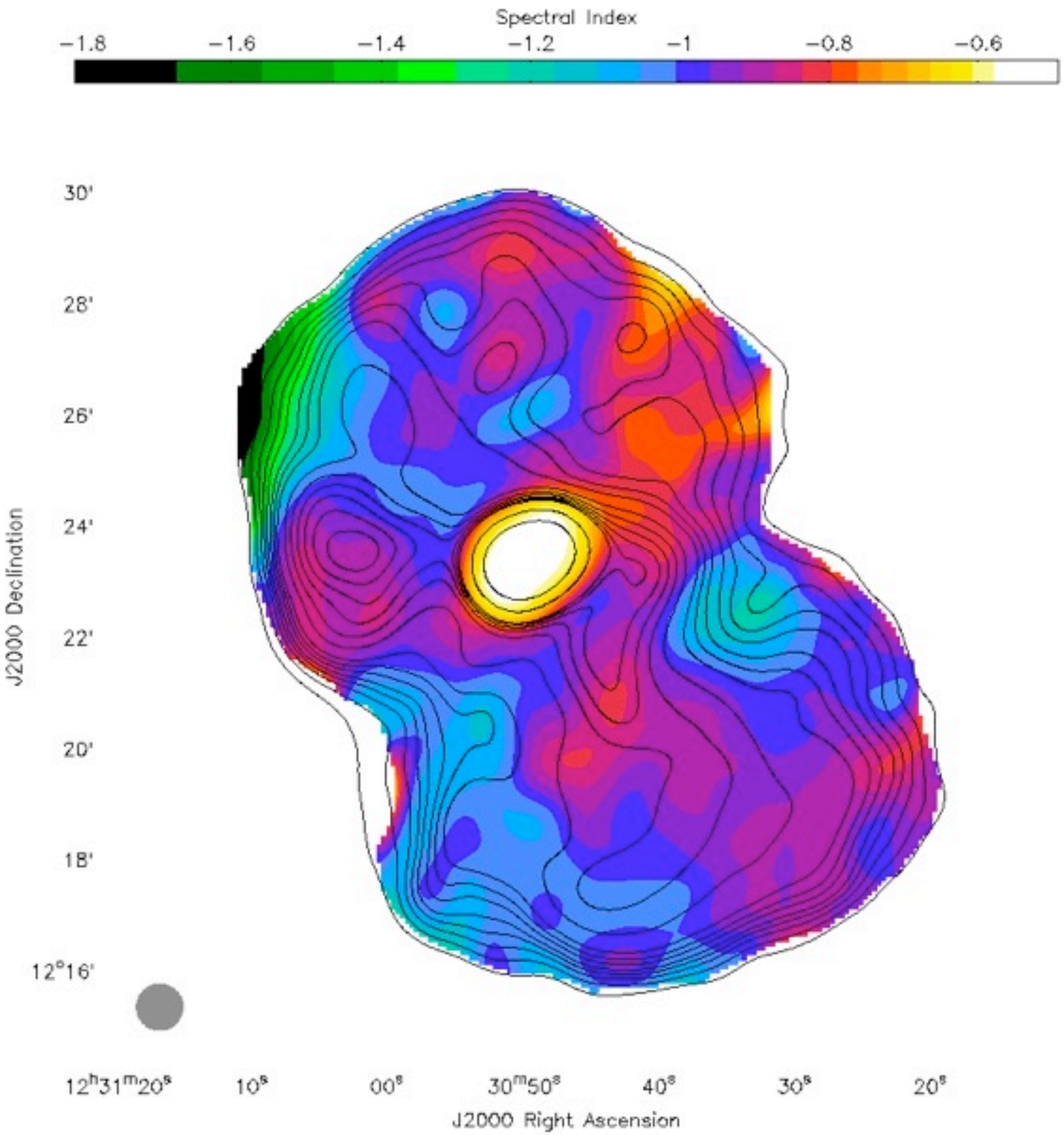
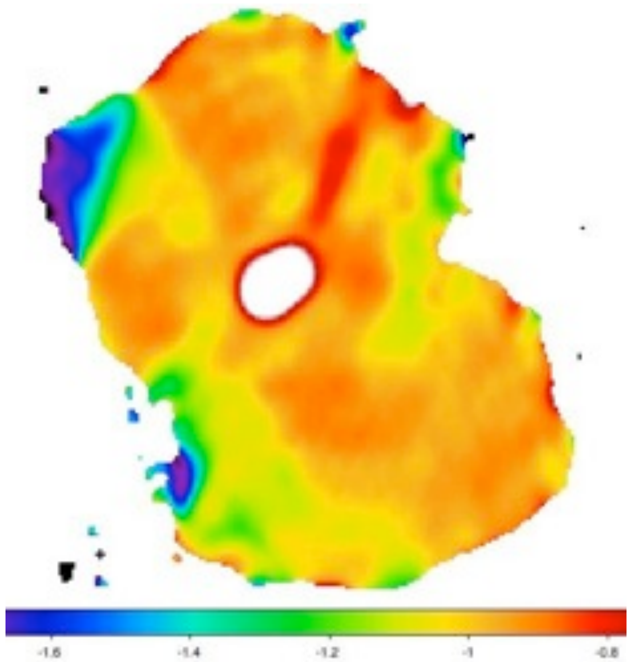
M87 – spectral index

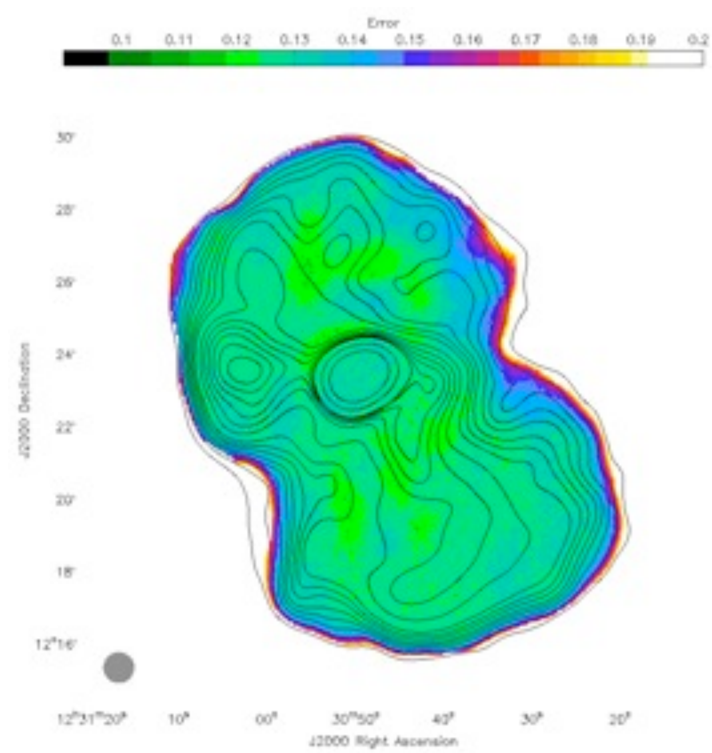
Spectral index map



VLA spectral index map (74-333 MHz)

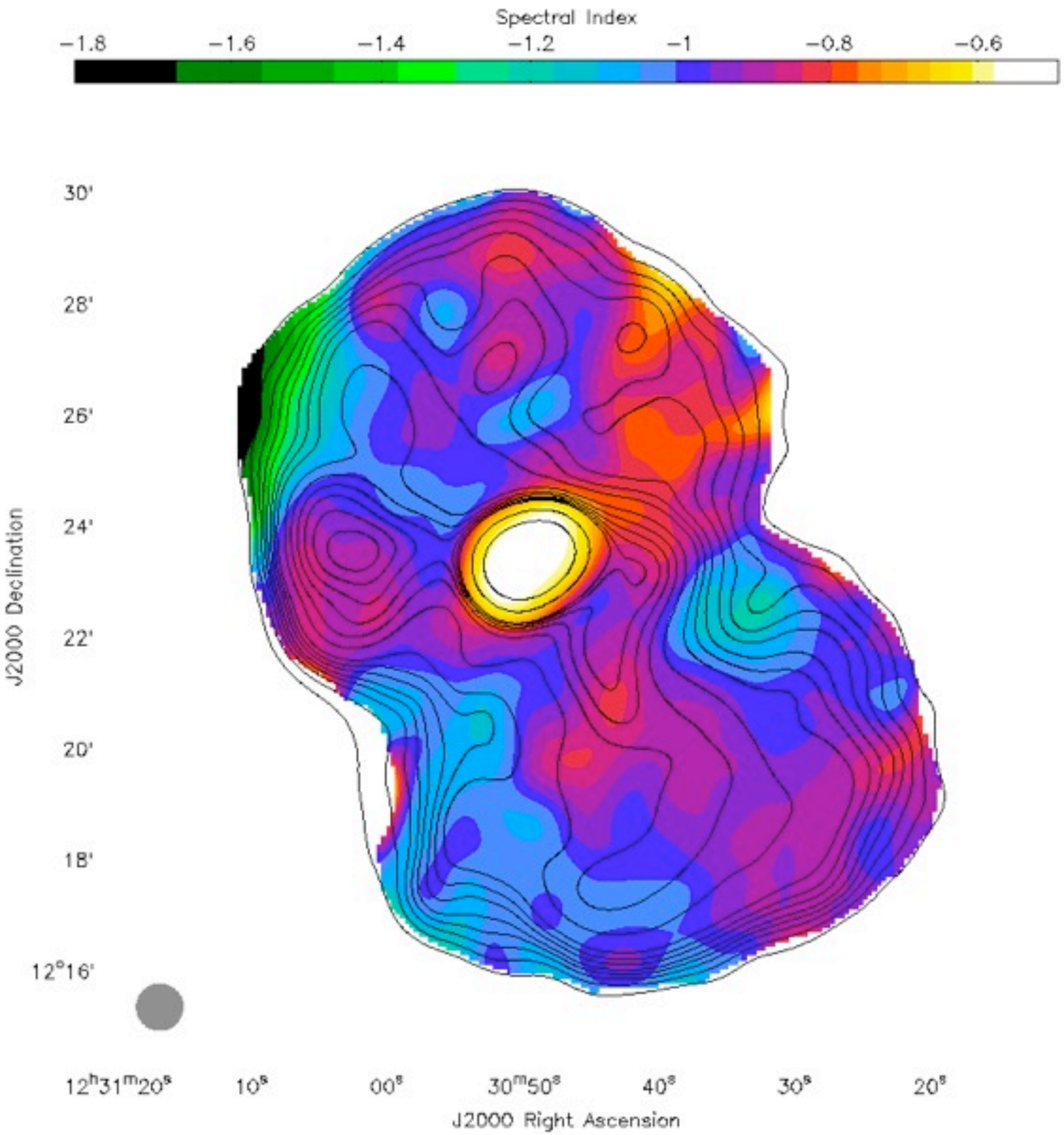


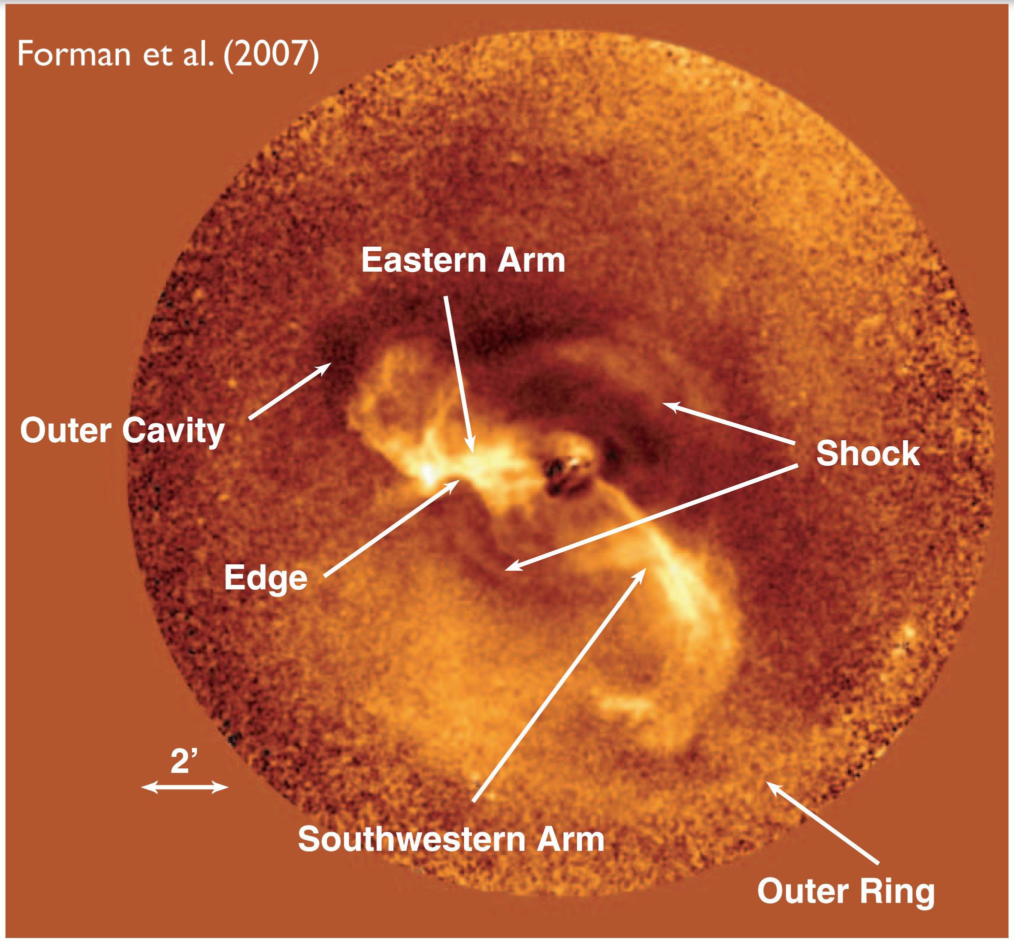
Error (1σ) map



M87 – spectral index

Spectral index map





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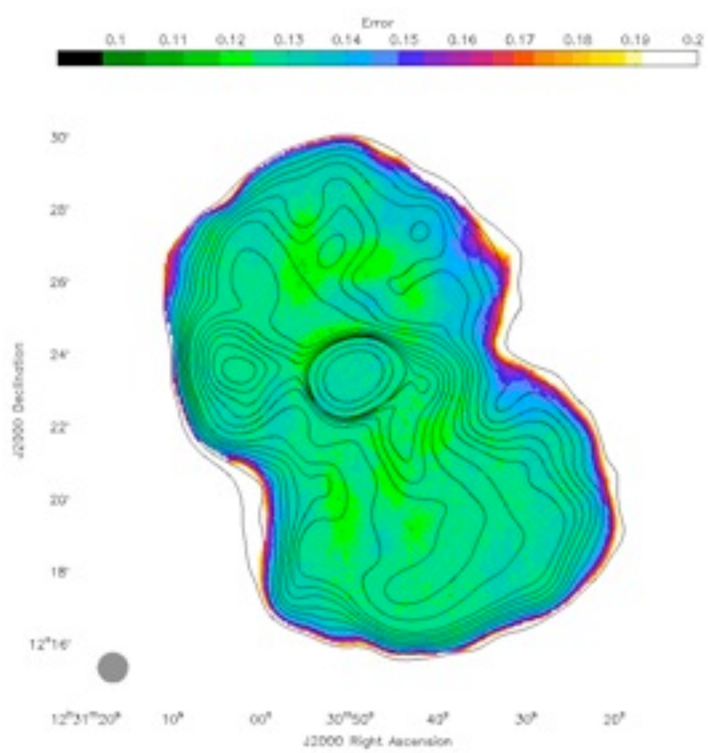
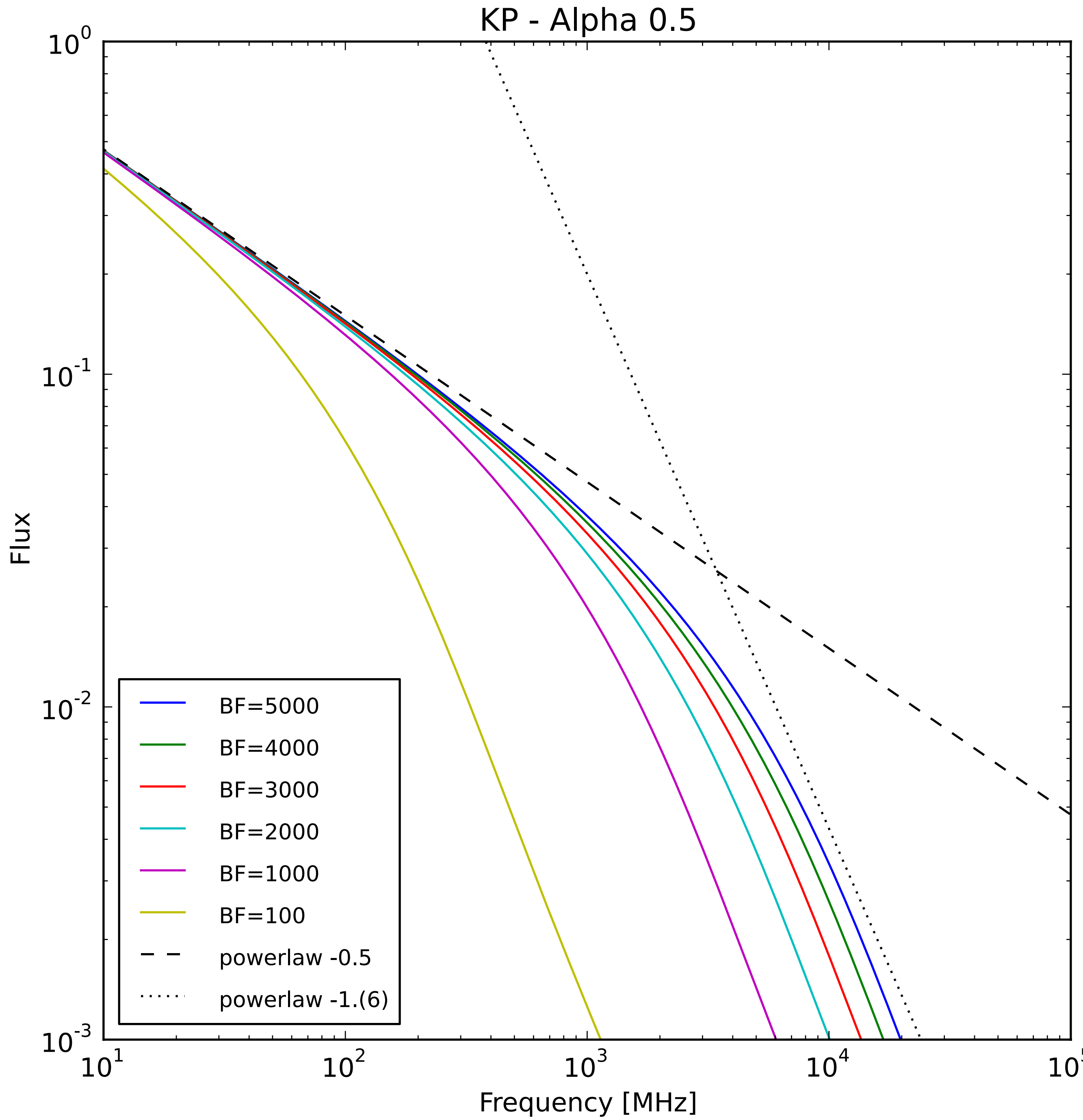
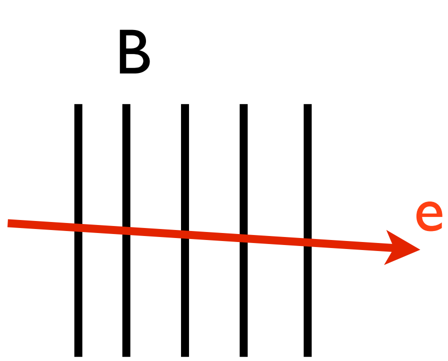


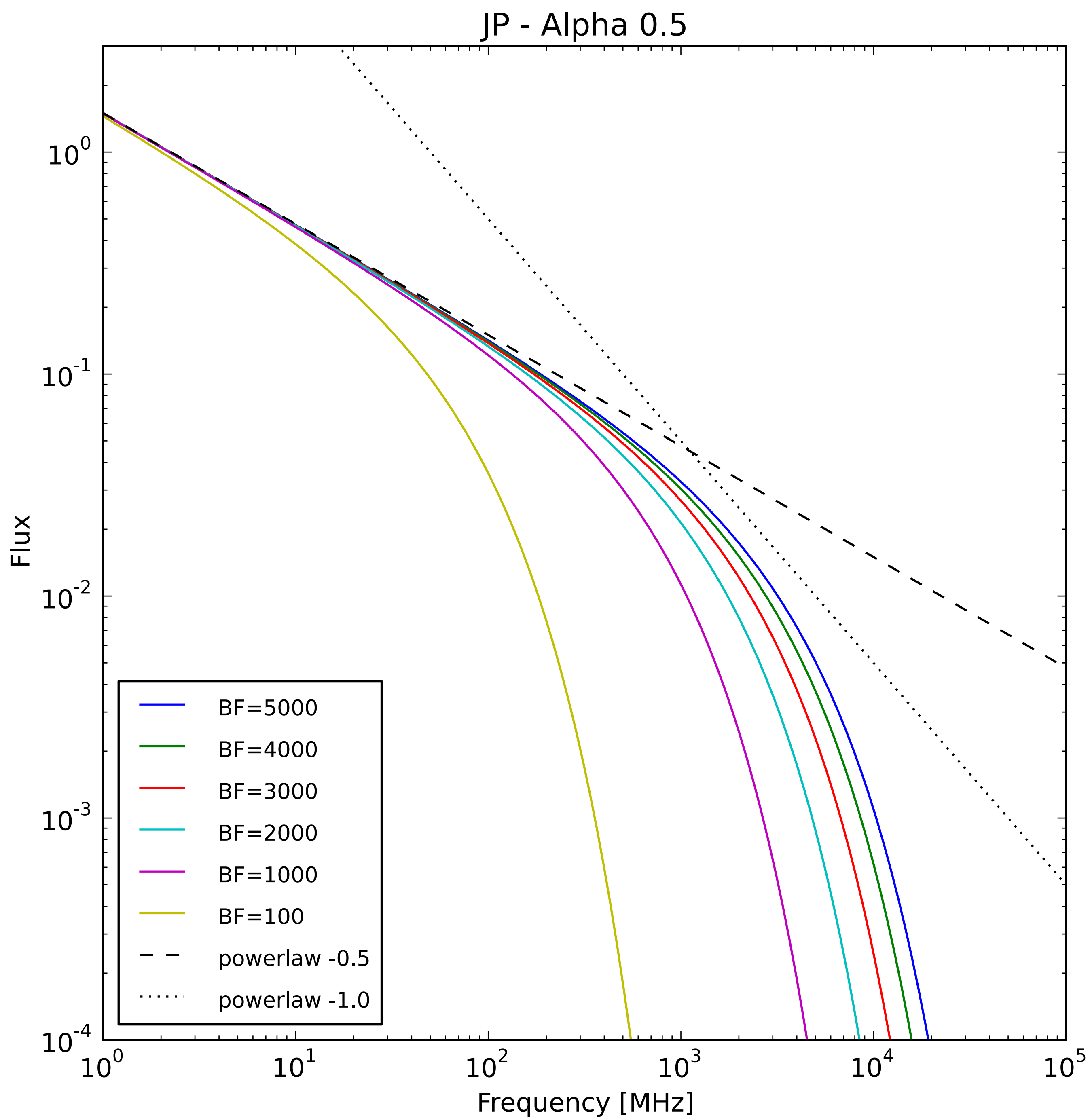
KP Model

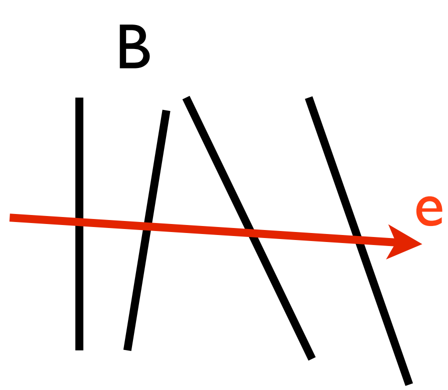


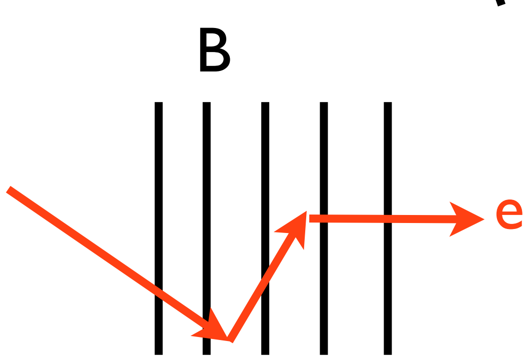


$$\nu_b \propto \frac{1}{t^2 B^3}$$

JP Model







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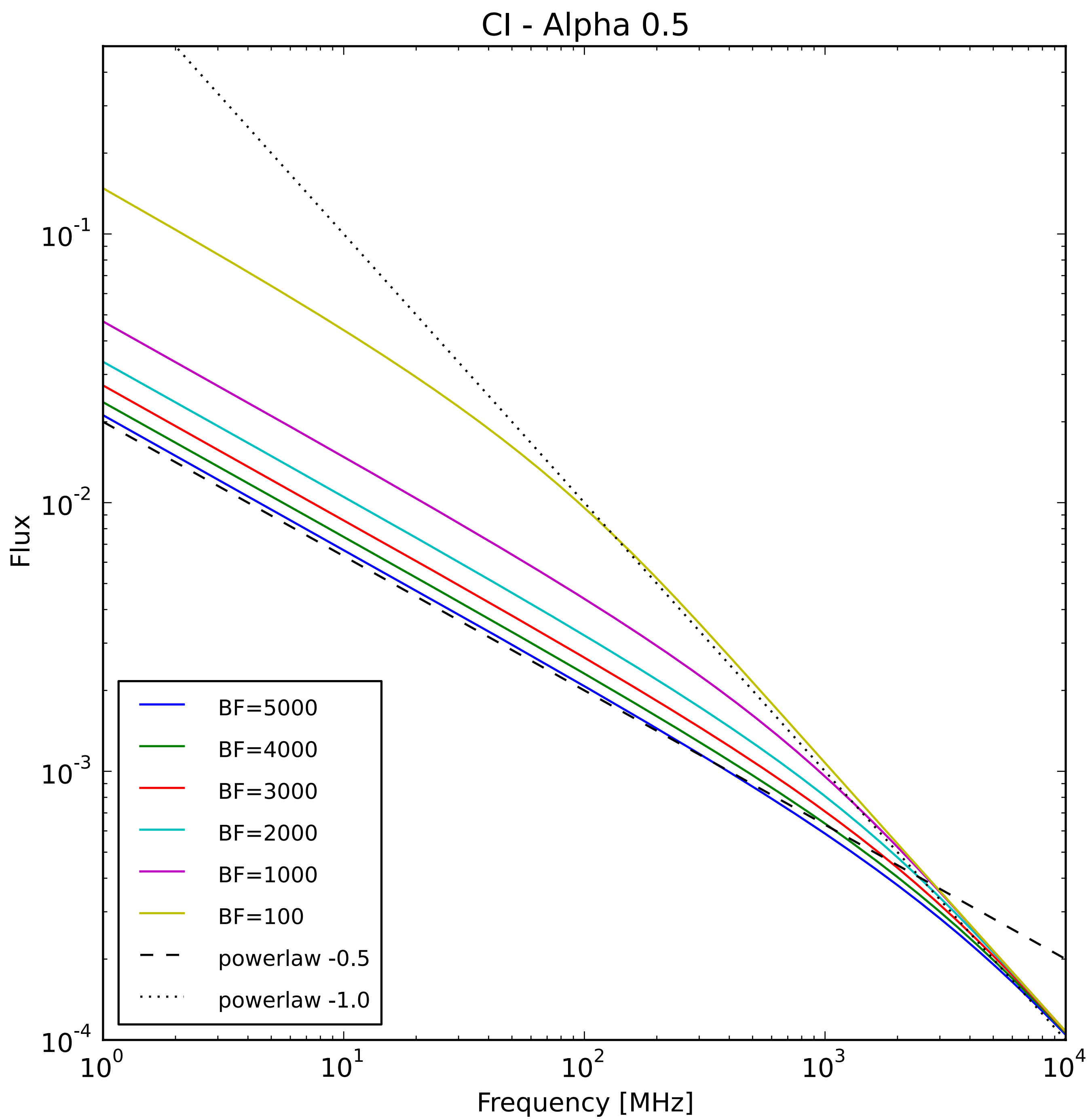
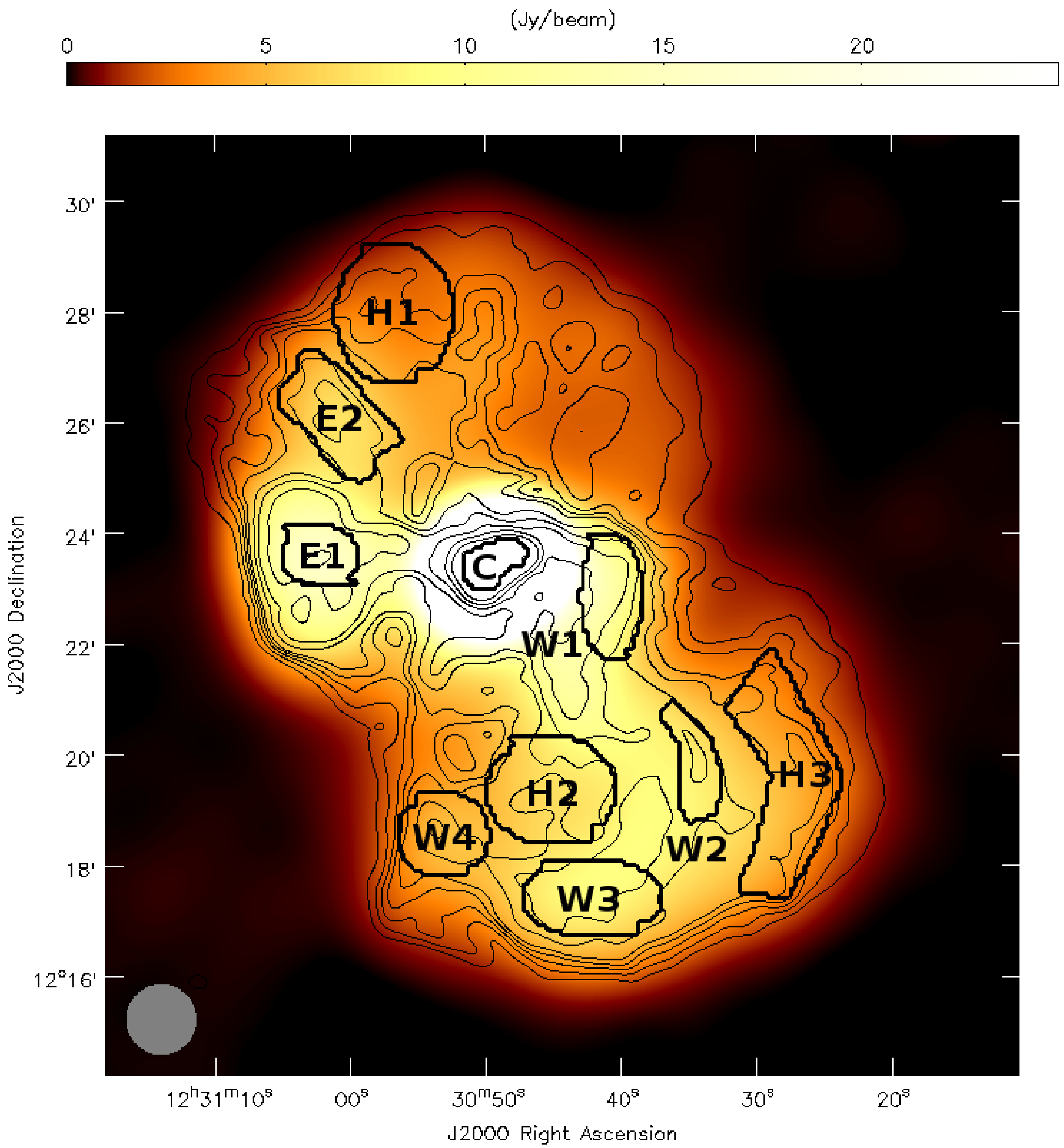
CI Model



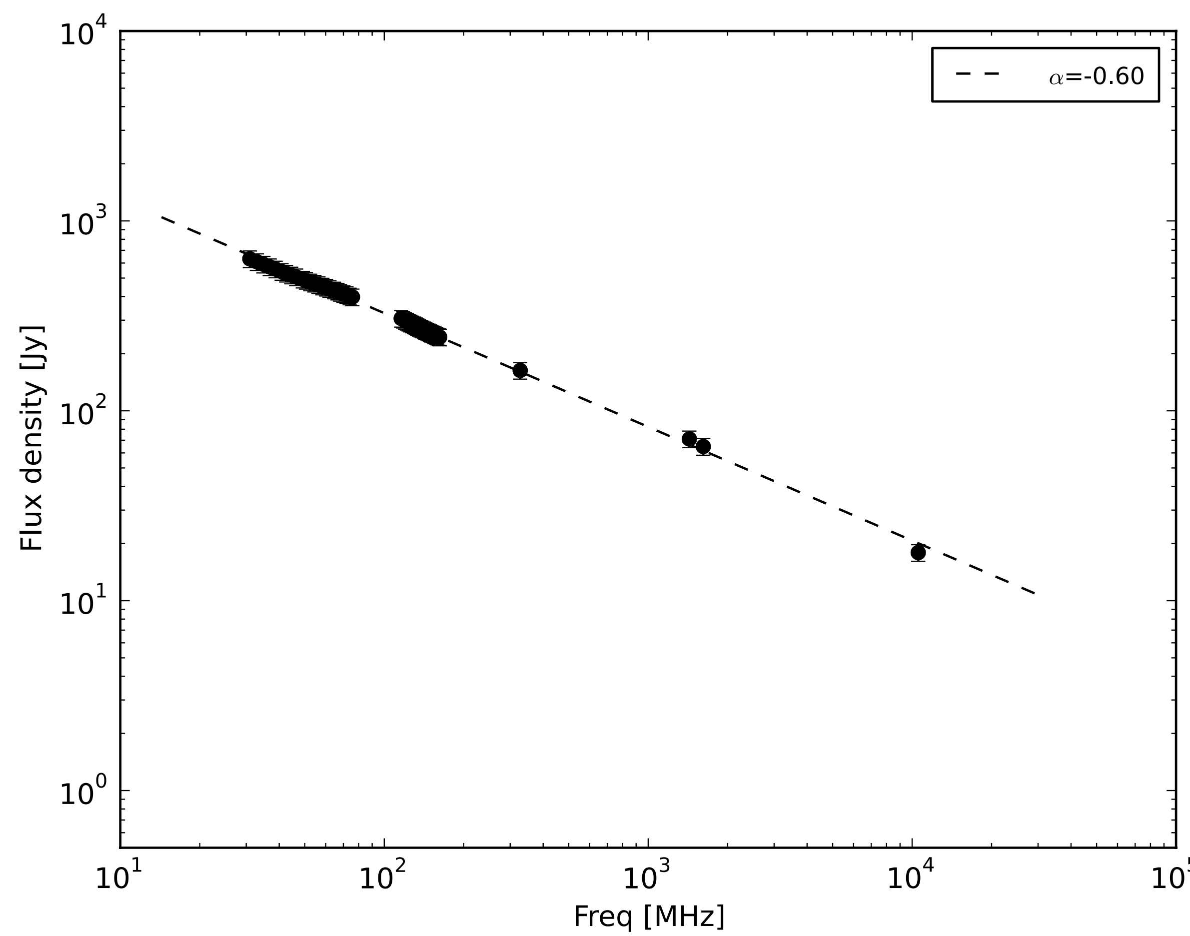
$$\nu_b \propto \frac{1}{t^2 B^3}$$

M87 – Core



Spectral index analysis:

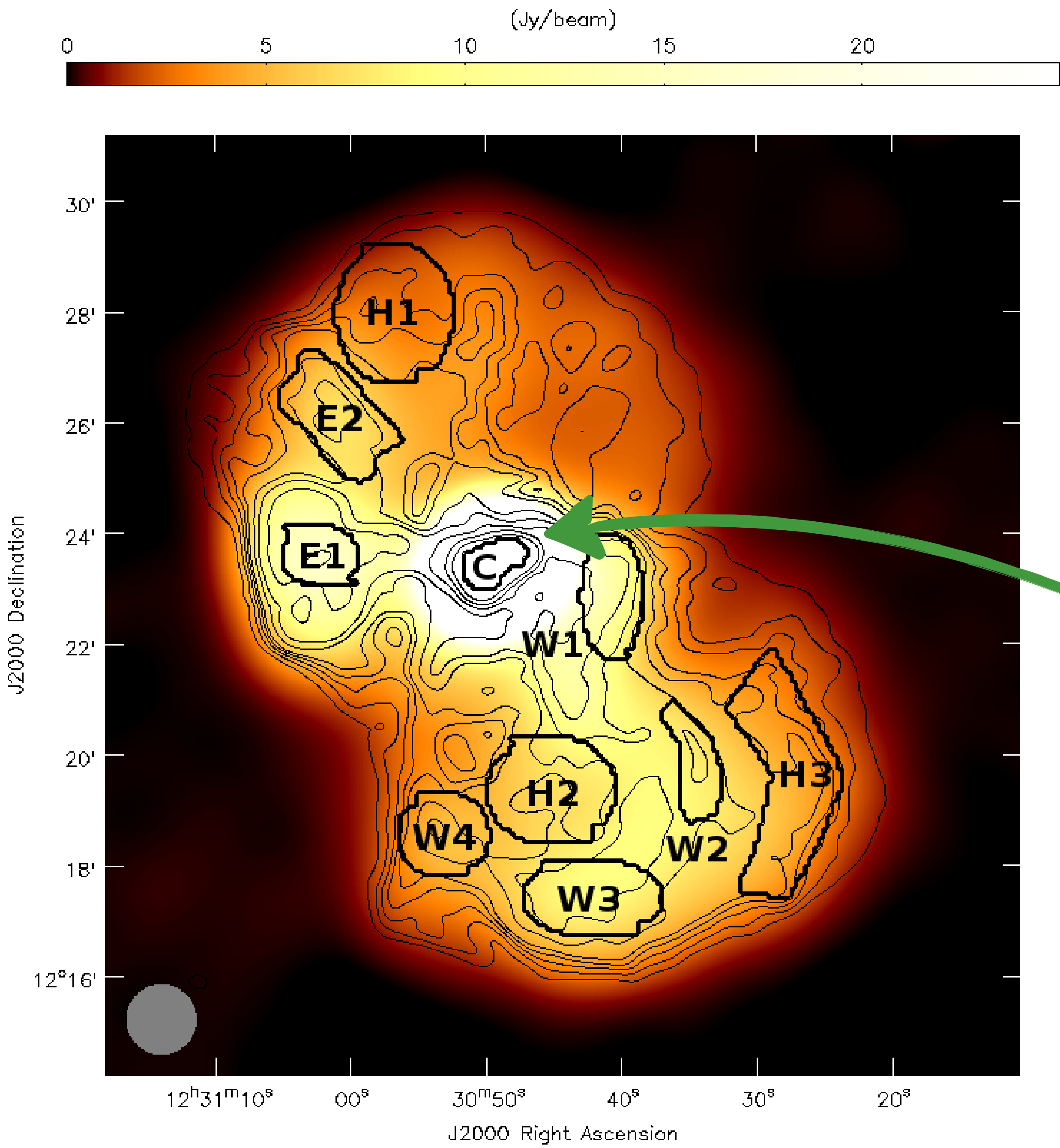
- LOFAR-LBA @ 30-77 MHz
- LOFAR HBA @ 115-162 MHz
- VLA @ 327 MHz
- VLA @ 1.4-1.6 MHz
- Effelsberg @ 10.55 GHz



Possible issues:

- Absolute flux scale
- UV-cov of different interferometers
- Curvature dominated by a single frequency
- Averaging of different parts of the source

M87 – Core



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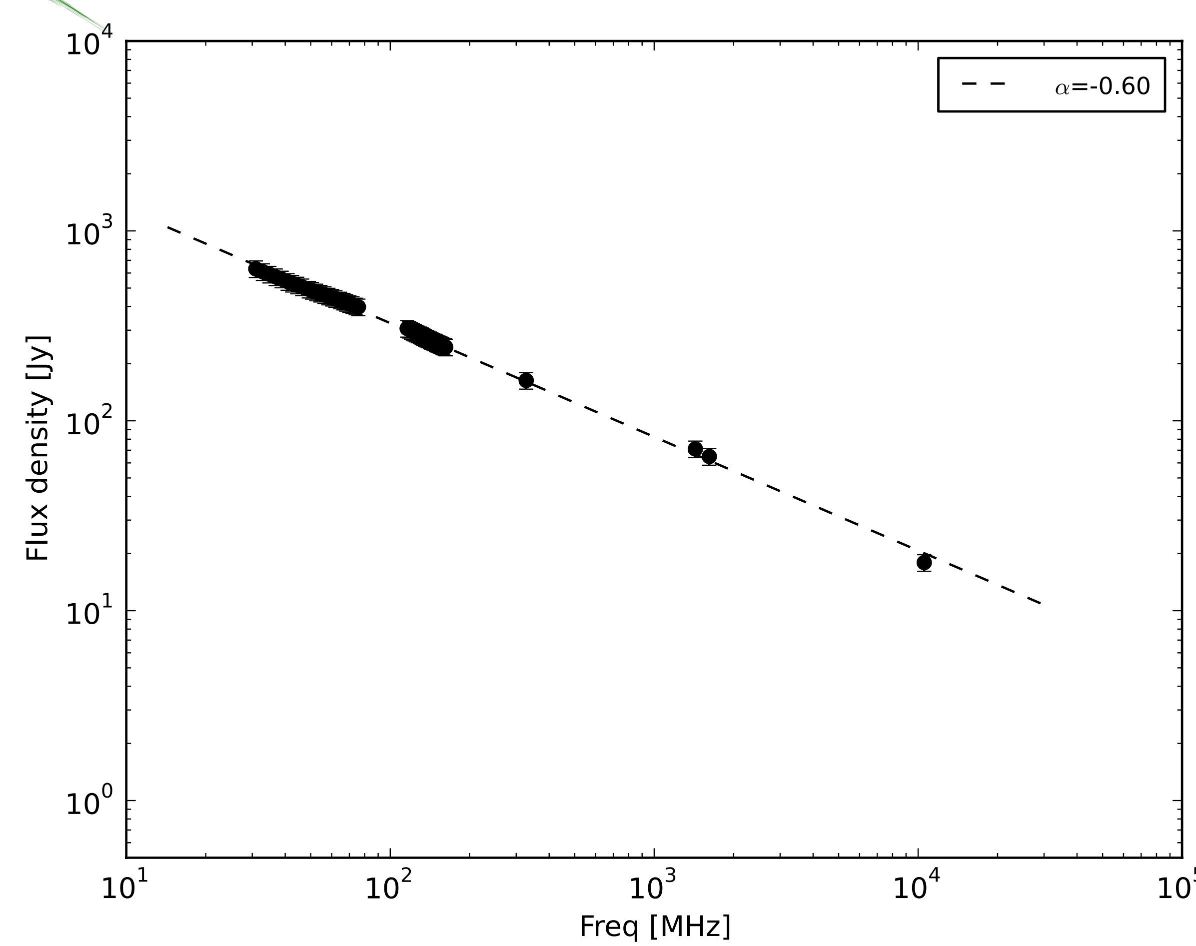

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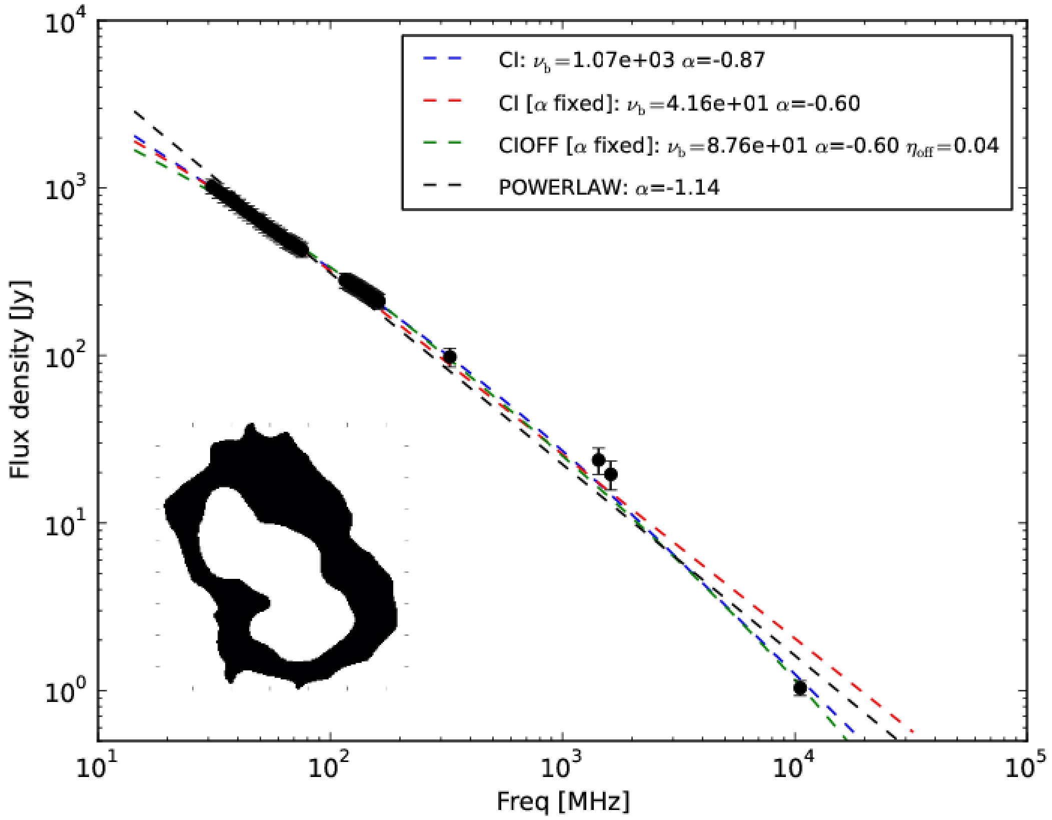
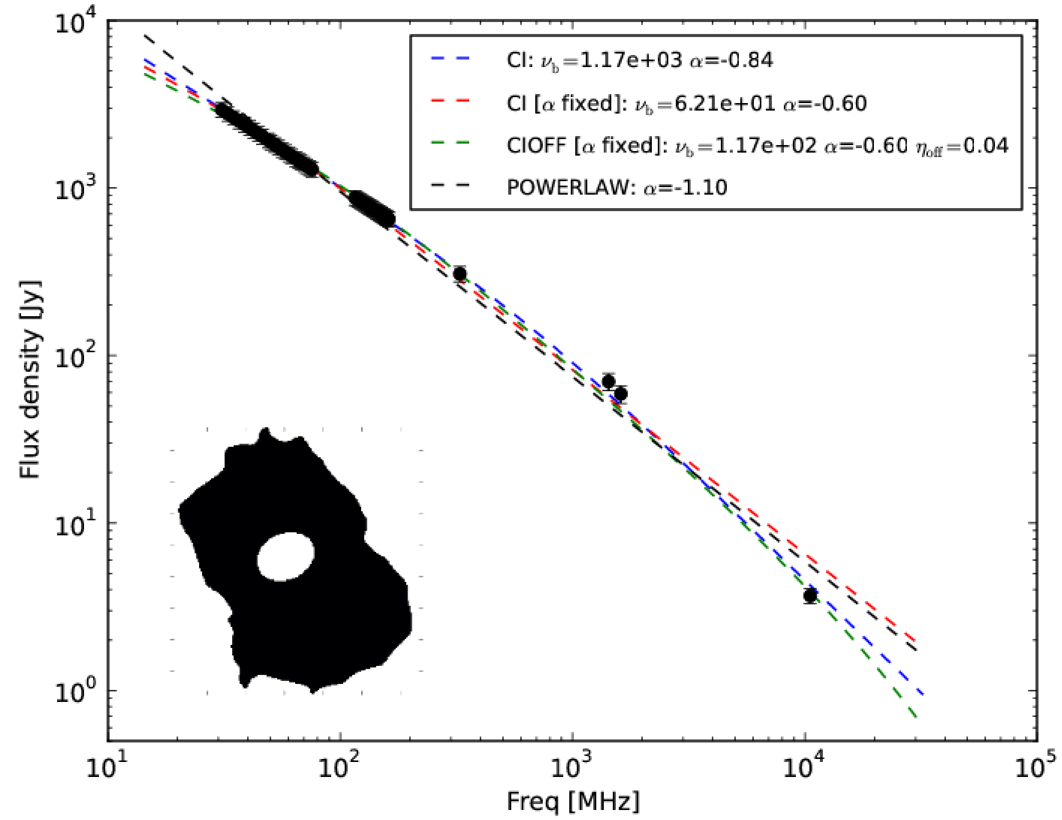
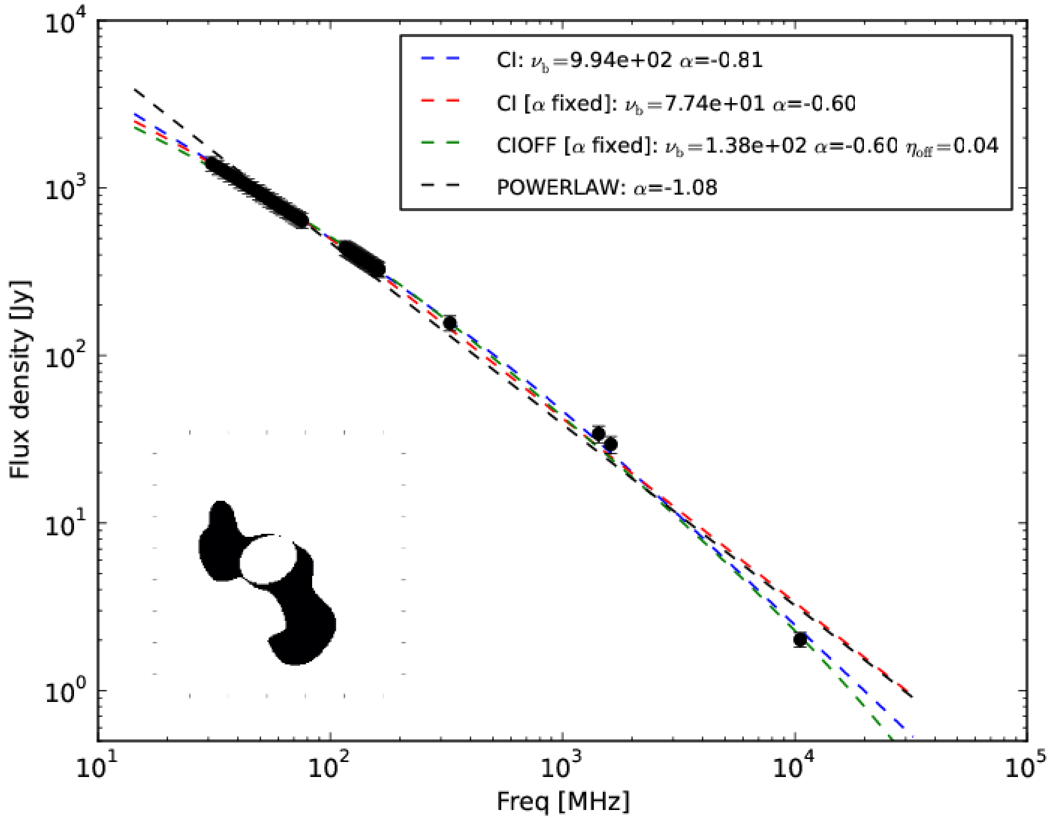
M87 – Macro regions



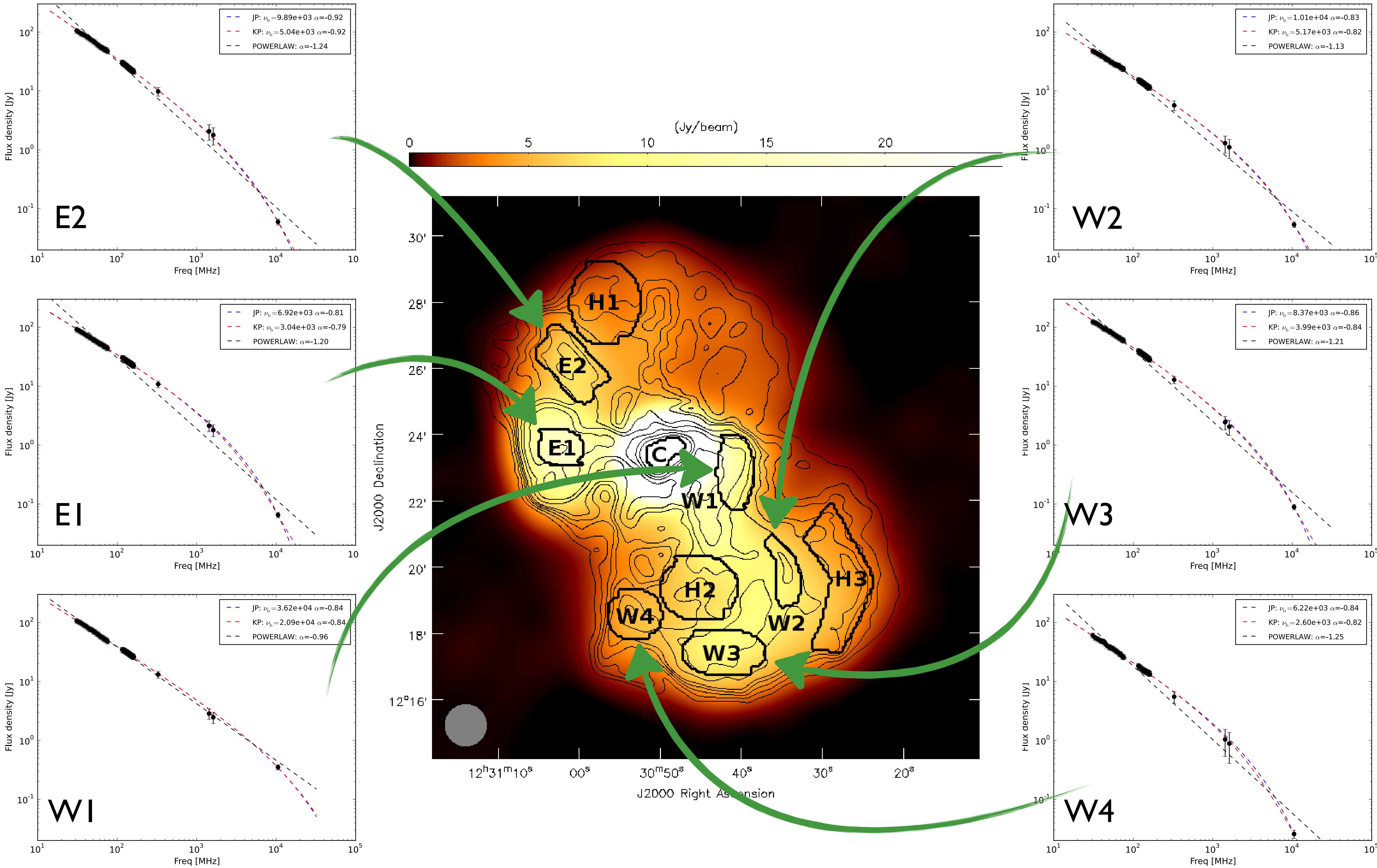




- CI (fixed α=-0.6) fails to fit the data

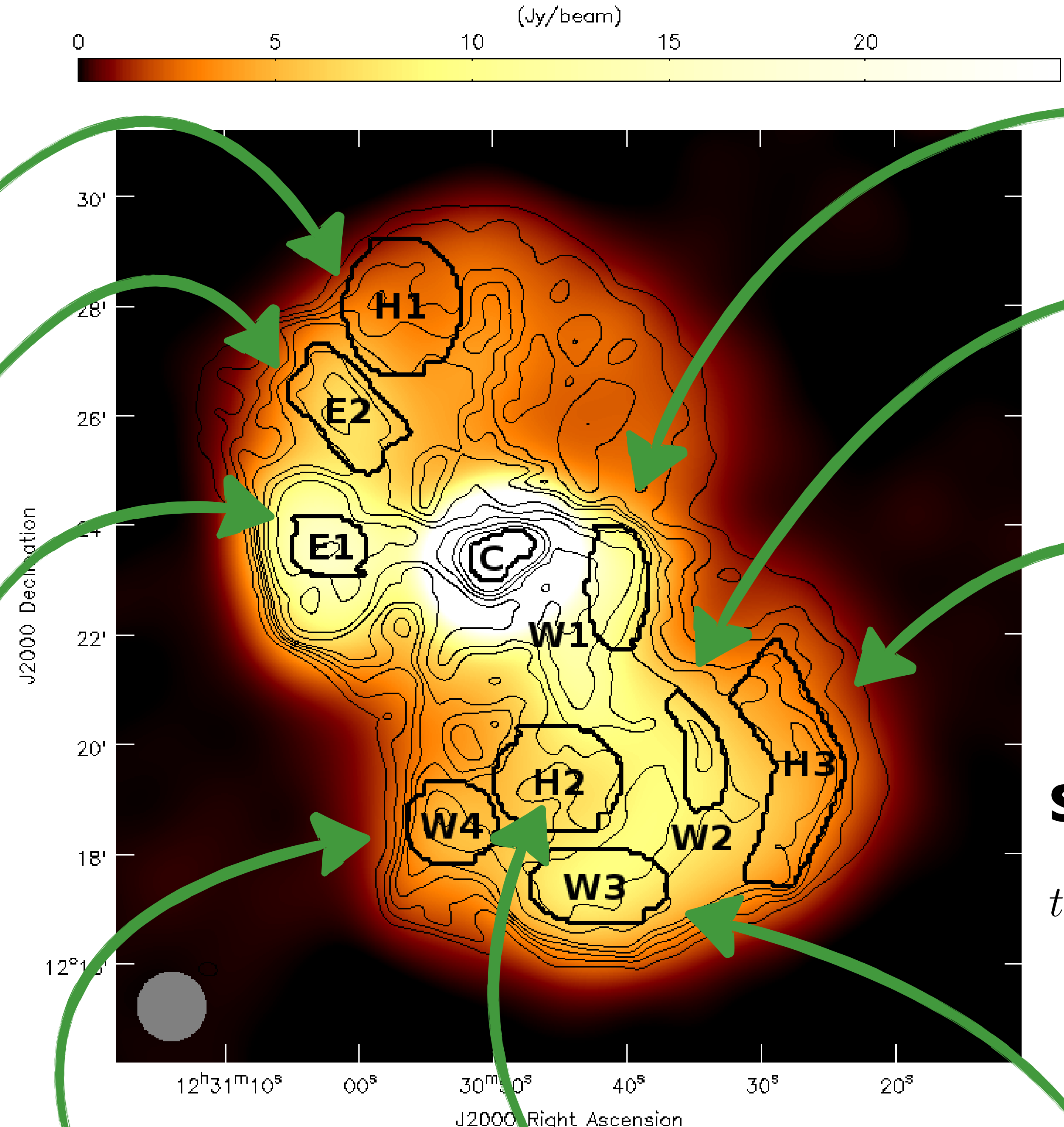
- CI (free α) fits the data
  - α~-0.85
  - break frequency of ~1.3 GHz
  - halo age ~ 40 Myr (B=10 uG)

M87 – Regions



E2
JP: ν_b=9.89e+03 α=-0.92
KP: ν_b=5.04e+03 α=-0.92
POWERLAW: α=-1.24
E1
JP: ν_b=6.92e+03 α=-0.81
KP: ν_b=3.04e+03 α=-0.79
POWERLAW: α=-1.20
W1
JP: ν_b=3.62e+04 α=-0.84
KP: ν_b=2.09e+04 α=-0.84
POWERLAW: α=-0.96
W2
JP: ν_b=1.01e+04 α=-0.83
KP: ν_b=5.17e+03 α=-0.82
POWERLAW: α=-1.13
W3
JP: ν_b=8.37e+03 α=-0.86
KP: ν_b=3.99e+03 α=-0.84
POWERLAW: α=-1.21
W4
JP: ν_b=6.22e+03 α=-0.84
KP: ν_b=2.60e+03 α=-0.82
POWERLAW: α=-1.25
Flux density [Jy]
Freq [MHz]
(Jy/beam)
0
5
10
15
20
H1
E2
E1
C
W1
H2
W2
W3
W4
H3
J2000 Declination
J2000 Right Ascension

M87 – Regions



B = 10.5 uG
P = 3e-12 dyn/cm^2
t = 14.8 Myr

B = 13.2 uG
P = 4.8e-12 dyn/cm^2
t = 10.1 Myr

B = 15.6 uG
P = 6.7e-12 dyn/cm^2
t = 9.0 Myr

B = 14.3 uG
P = 5.6e-12 dyn/cm^2
t = 7.1 Myr

B = 13 uG
P = 4.7e-12 dyn/cm^2
t = 10.6 Myr

B = 11.1 uG
P = 3.4e-12 dyn/cm^2
t = 13.1 Myr

Synchrotron ageing:

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

1/4 dynamical time (no momentum)

Pressure:
equipartition needs k>1000, thermal component, filling factor?

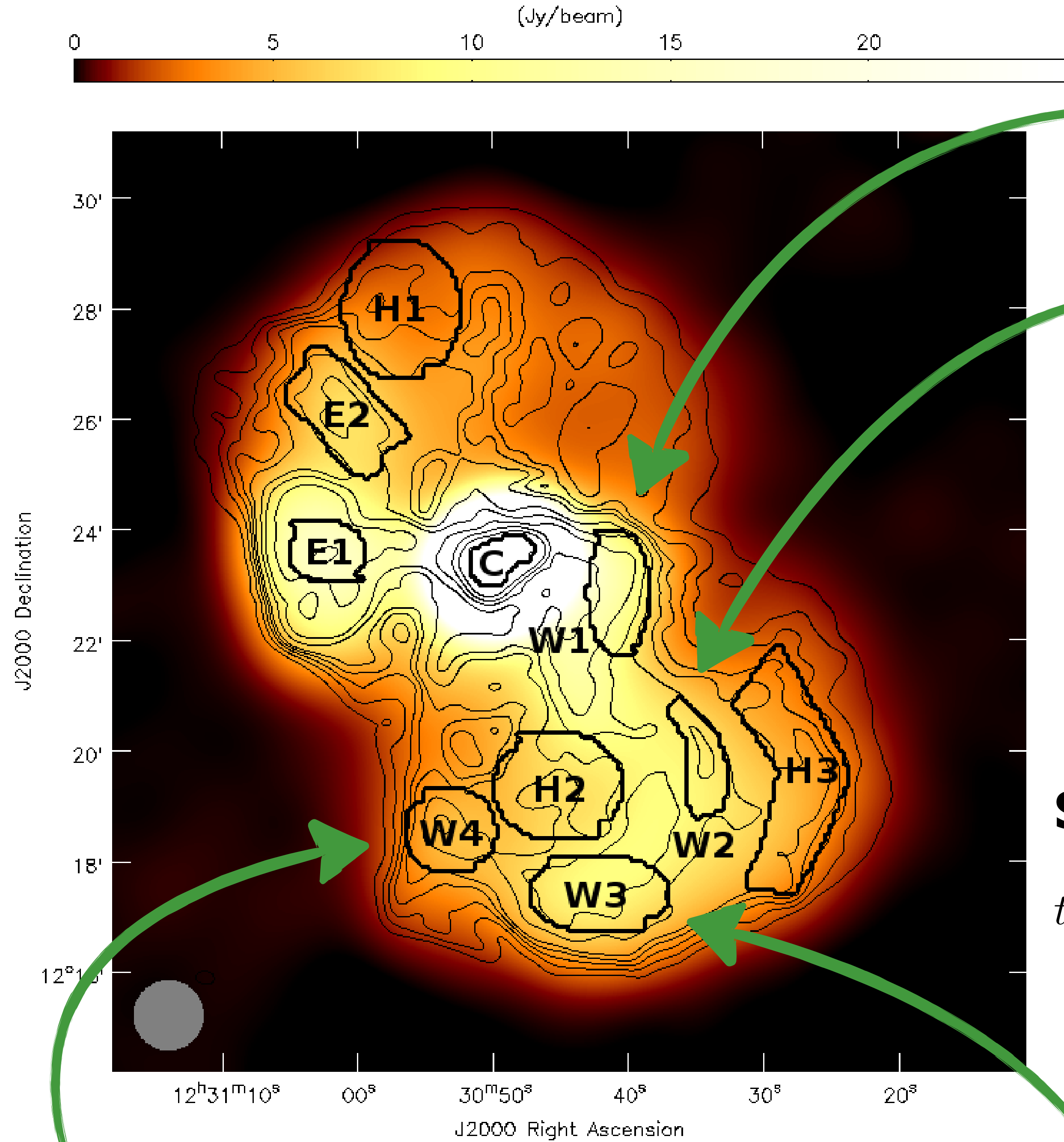
Equipartition:
- k = 1
- γ min = 100
- D = 20 kpc
- Filling factor = 1

B = 12.4 uG
P = 4.2e-12 dyn/cm^2
t = 12.0 Myr

B = 13.1 uG
P = 4.7e-12 dyn/cm^2
t = 9.4 Myr

B = 13.7 uG
P = 5.2e-12 dyn/cm^2
t = 9.5 Myr

M87 – Regions



B = 14.3 uG
P = 5.6e-12 dyn/cm^2
t = 7.1 Myr

B = 13 uG
P = 4.7e-12 dyn/cm^2
t = 10.6 Myr

Synchrotron ageing:

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

1/4 dynamical time (no momentum)

Pressure:
equipartition needs k>1000, thermal component, filling factor?

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

B = 12.4 uG
P = 4.2e-12 dyn/cm^2
t = 12.0 Myr

B = 13.7 uG
P = 5.2e-12 dyn/cm^2
t = 9.5 Myr

M87 – Models

Possible explanations for the low-freq steepening:

- Adiabatic expansion of plasmas at different ages (CIE model) → halo age ~ 40 Myr
- Plasma in a range of many different magnetic field strengths
- Spectrum intrinsically bended $\gamma \propto (\nu/B)^{(1/2)}$
- The halo is a relic of a past activity (different injection slope)

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

Discrepancy with dynamic time (~50 Myr):

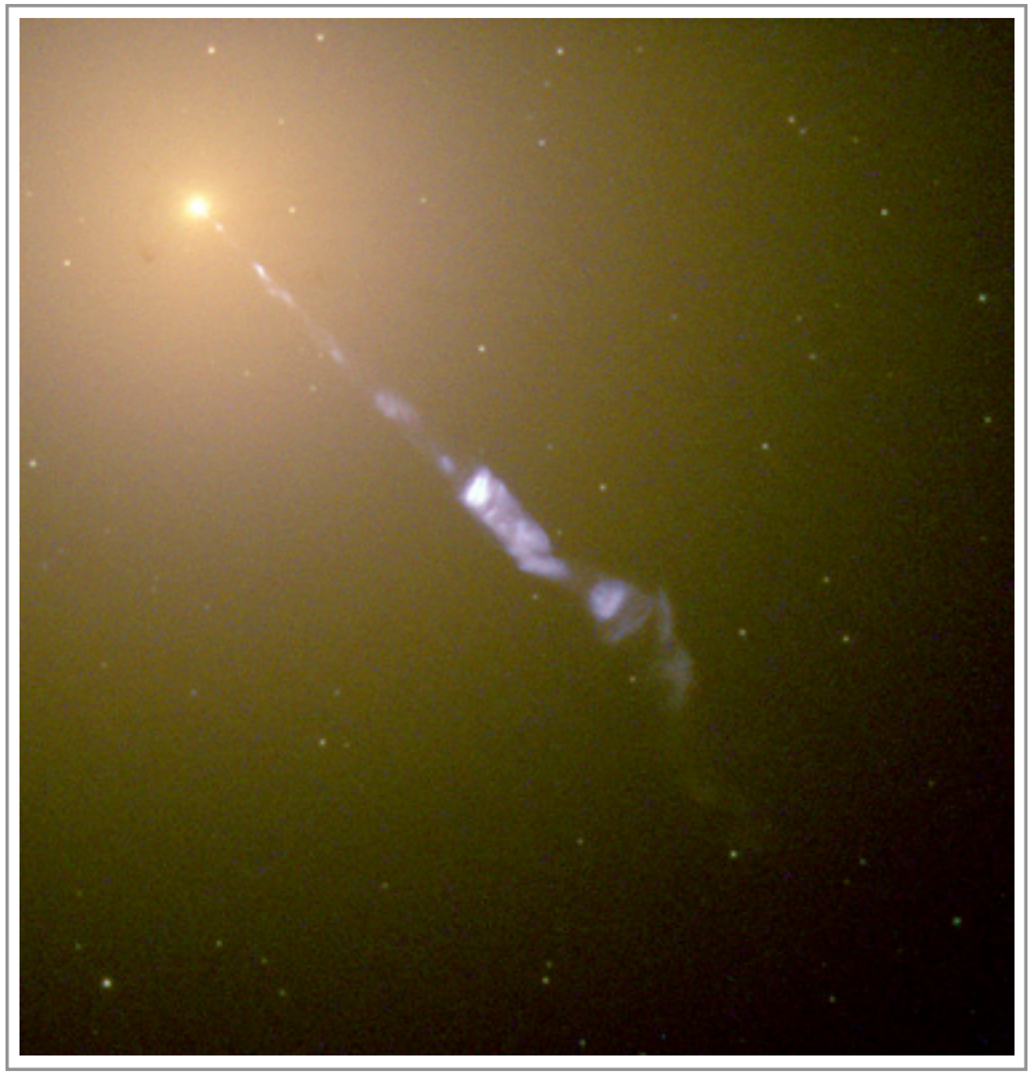
- Mix of weak and strong magnetic fields (filamentary structure)
- In situ re-acceleration
- Plasma flow along pre-existing channels

- Bubbles plasma has initial momentum: ~20 kpc in 15 Myr

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

M87 – Jet Power

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



Assuming:

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

Jet power: 6-10 e 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

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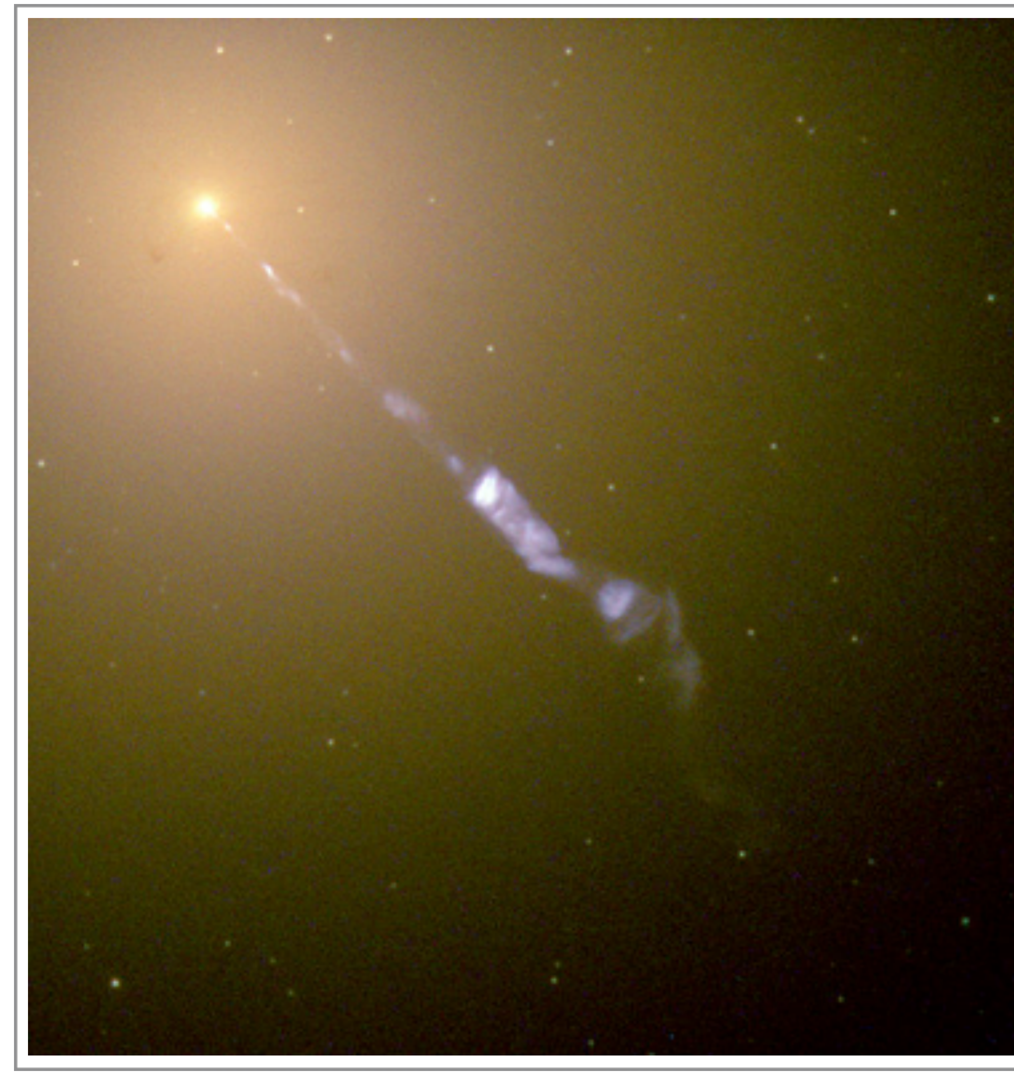

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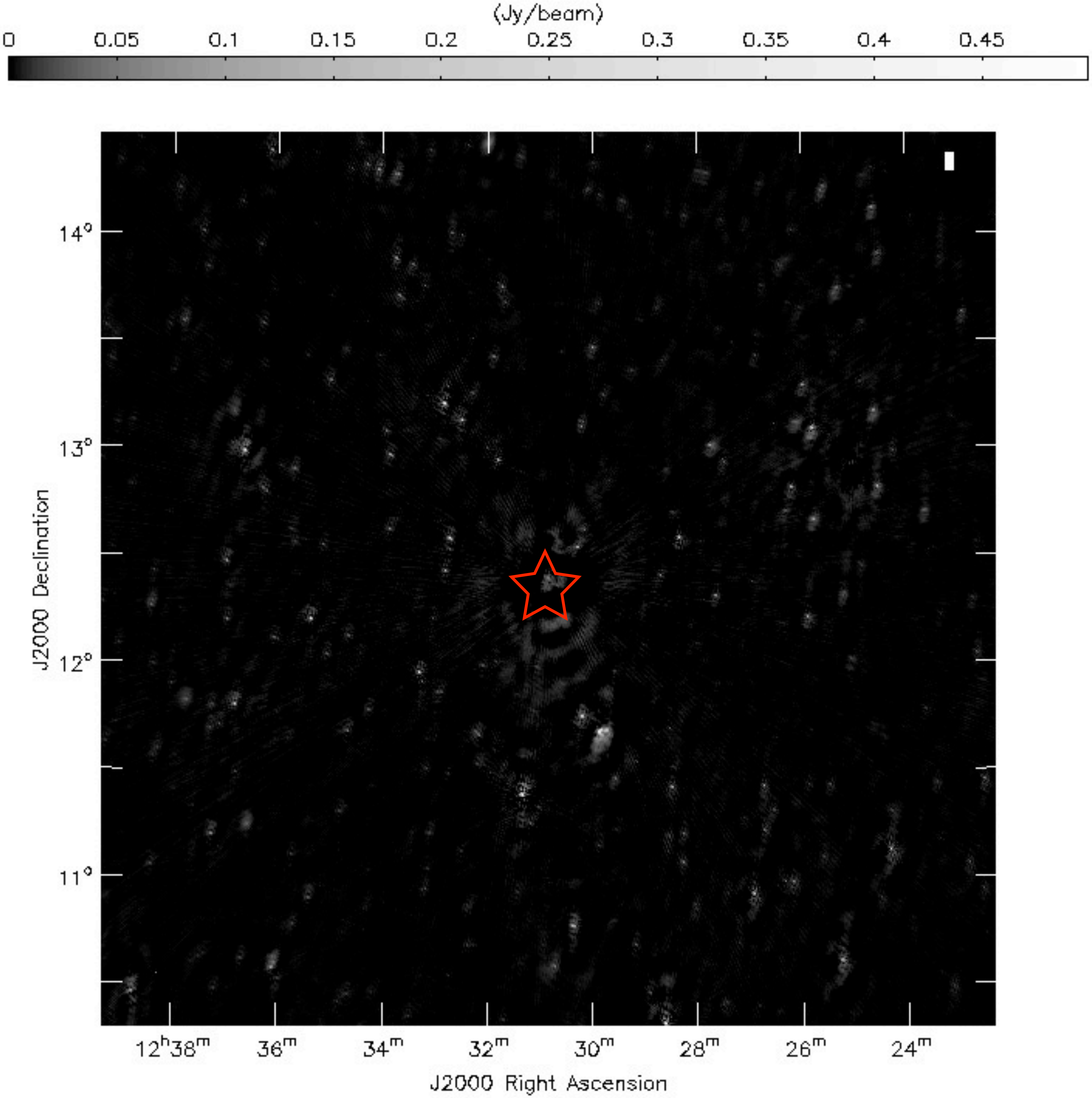
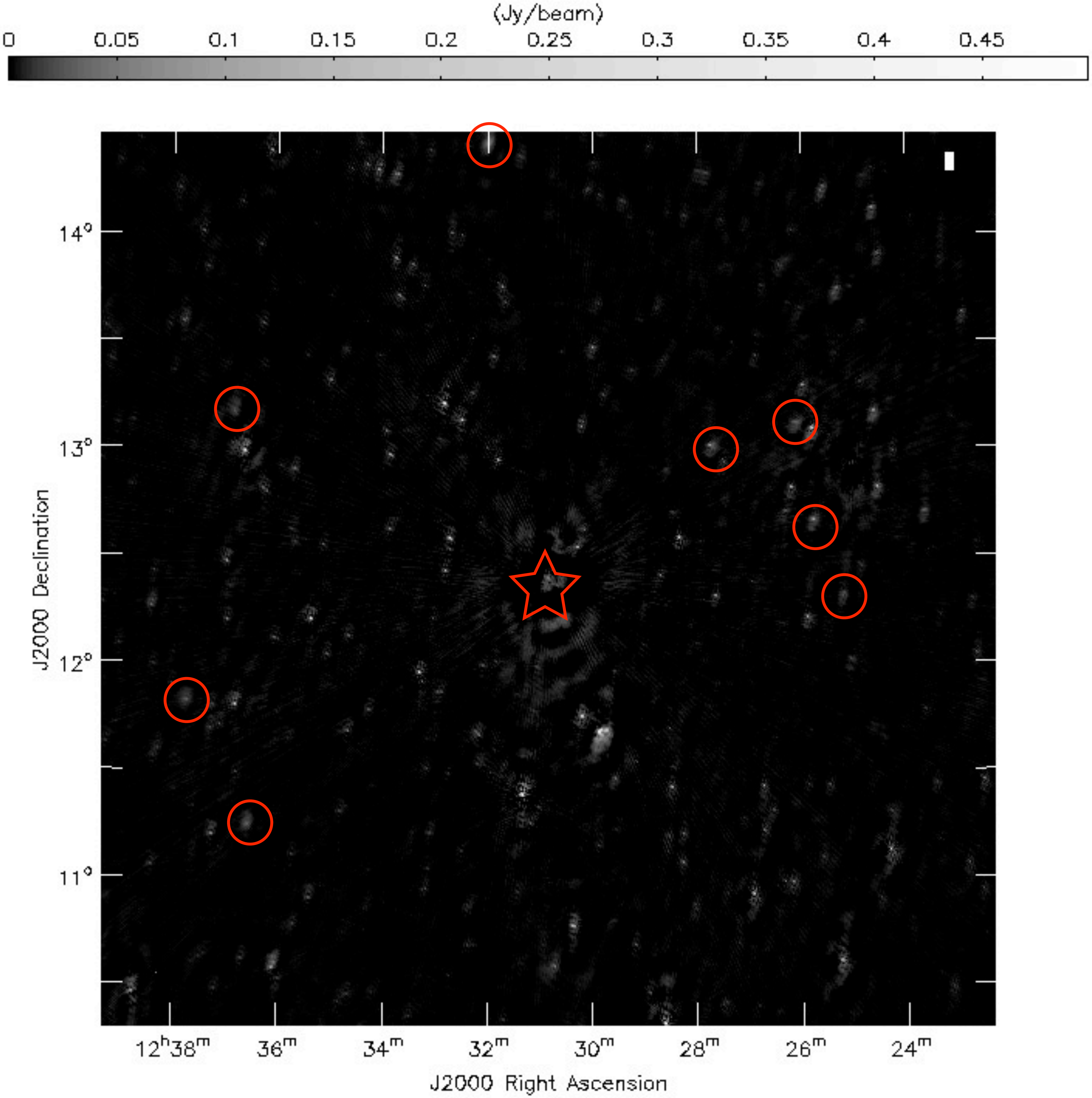


(Jy/beam)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
14°
13°
12°
11°
J2000 Declination
12h38m
36m
34m
32m
30m
28m
26m
24m
J2000 Right Ascension



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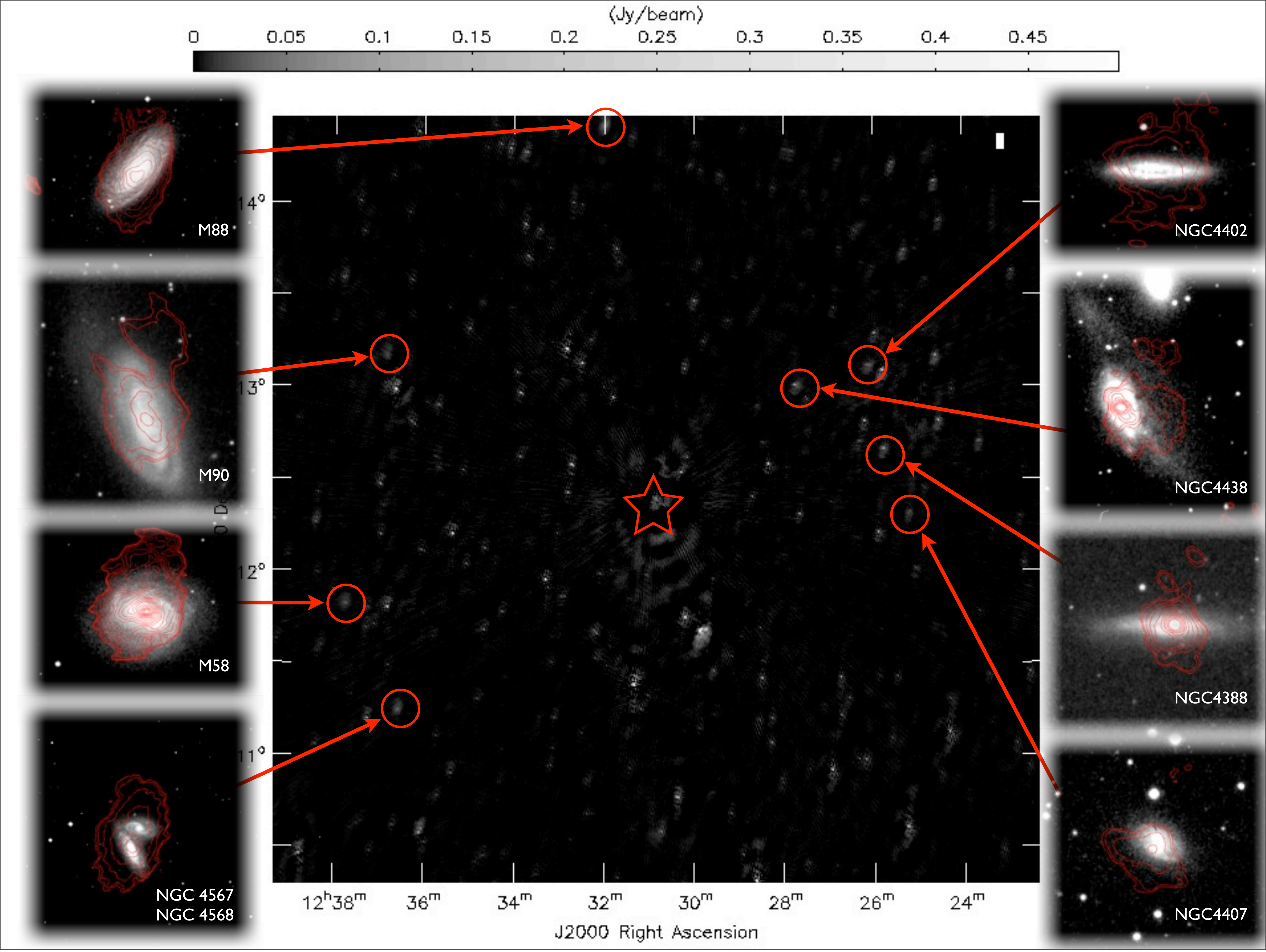
(Jy/beam)
0
0.05
0.1
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0.2
0.25
0.3
0.35
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0.45
M88
M90
M58
NGC 4567
NGC 4568
NGC4402
NGC4438
NGC4388
NGC4407
14°
13°
12°
11°
12h38m
36m
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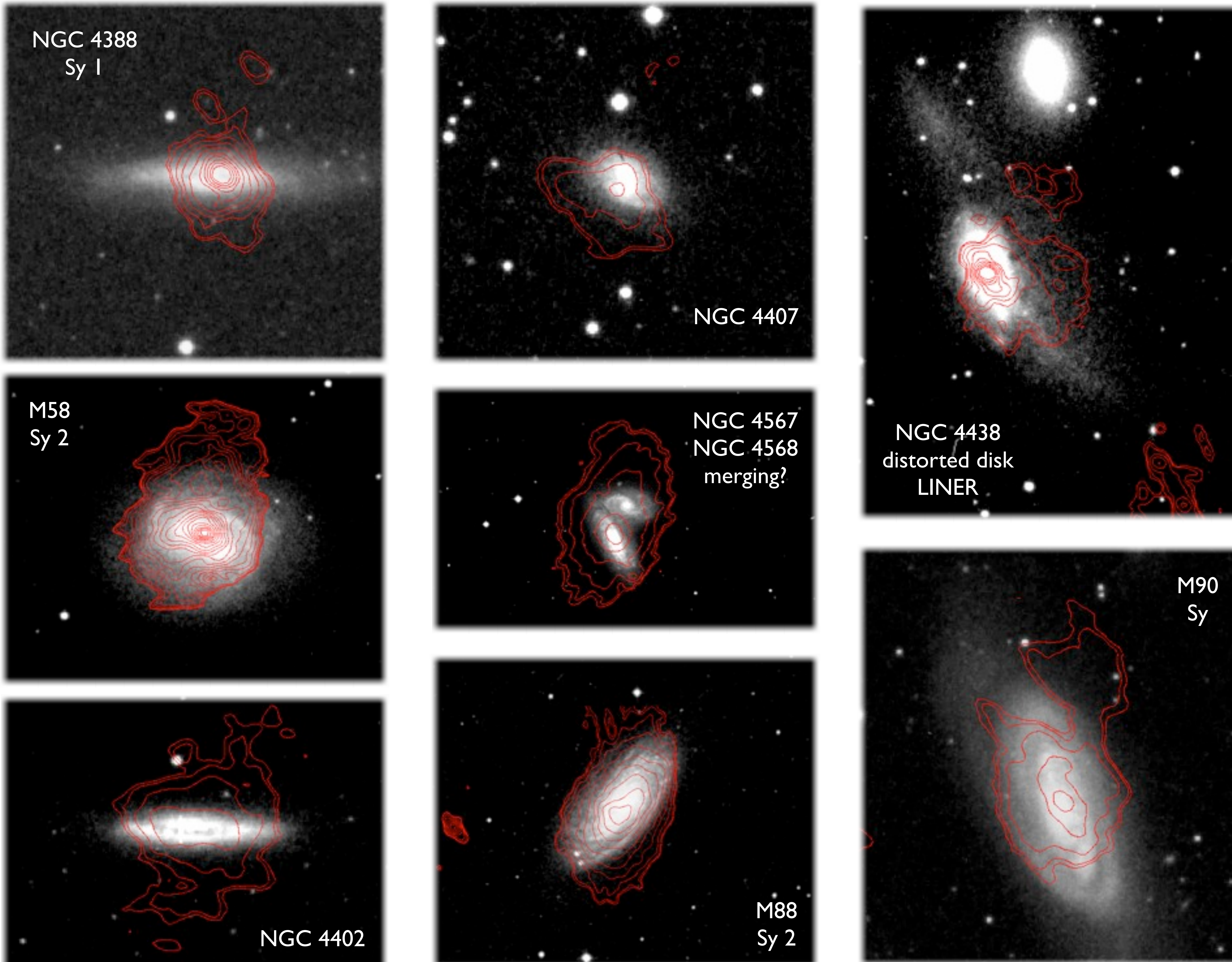
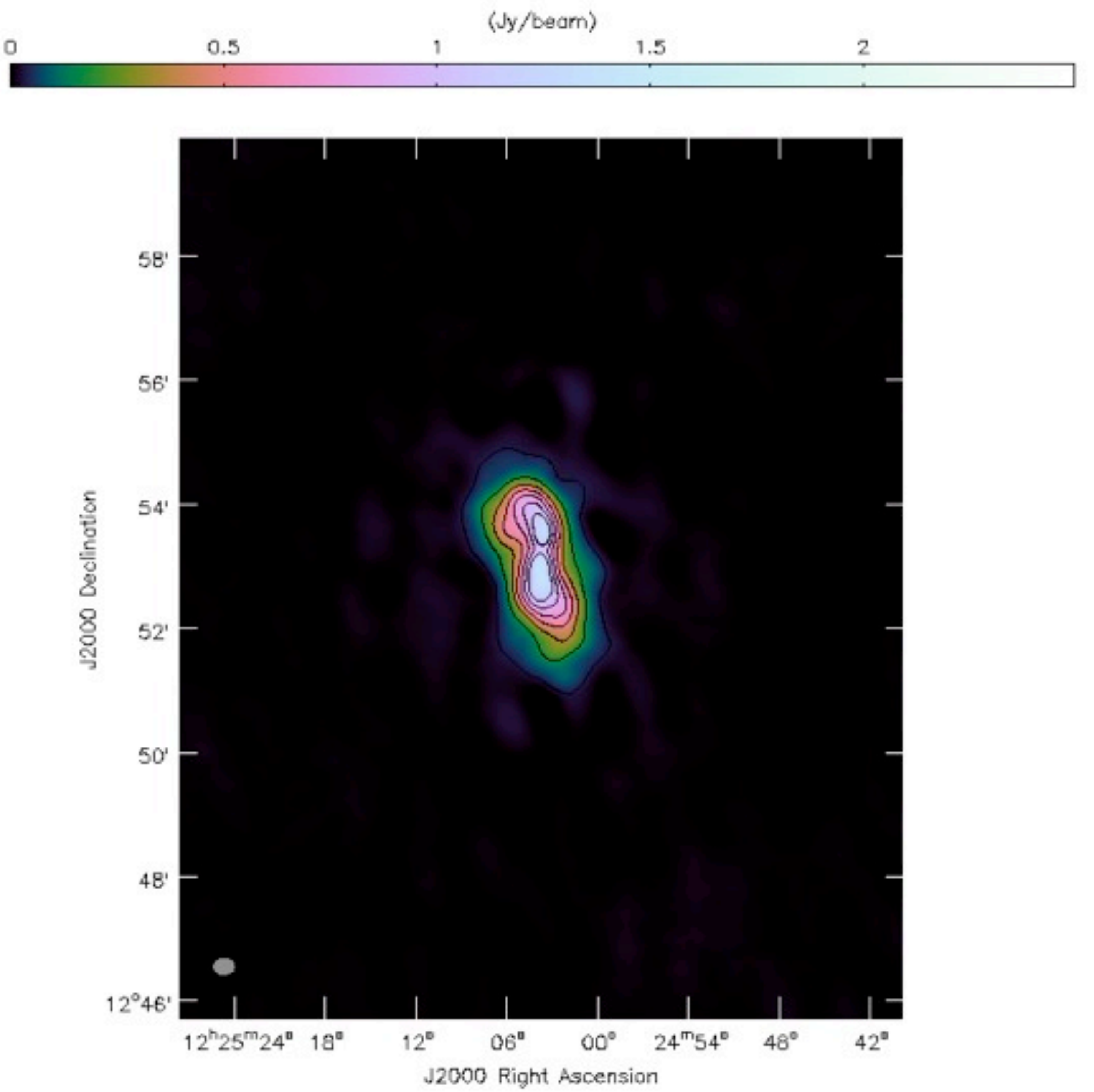
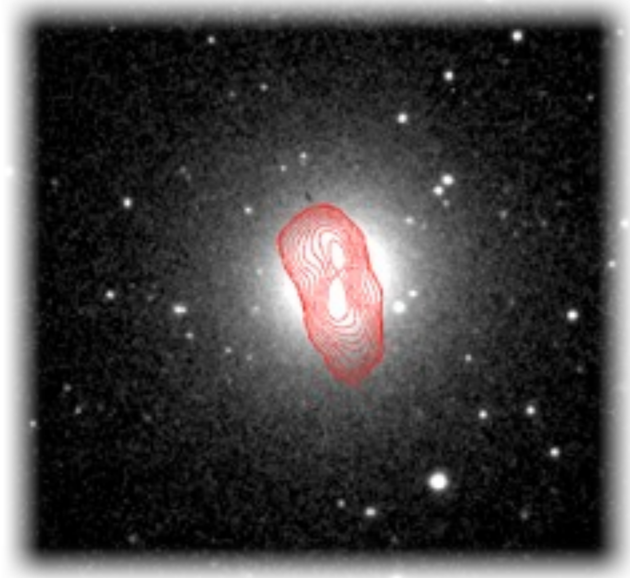
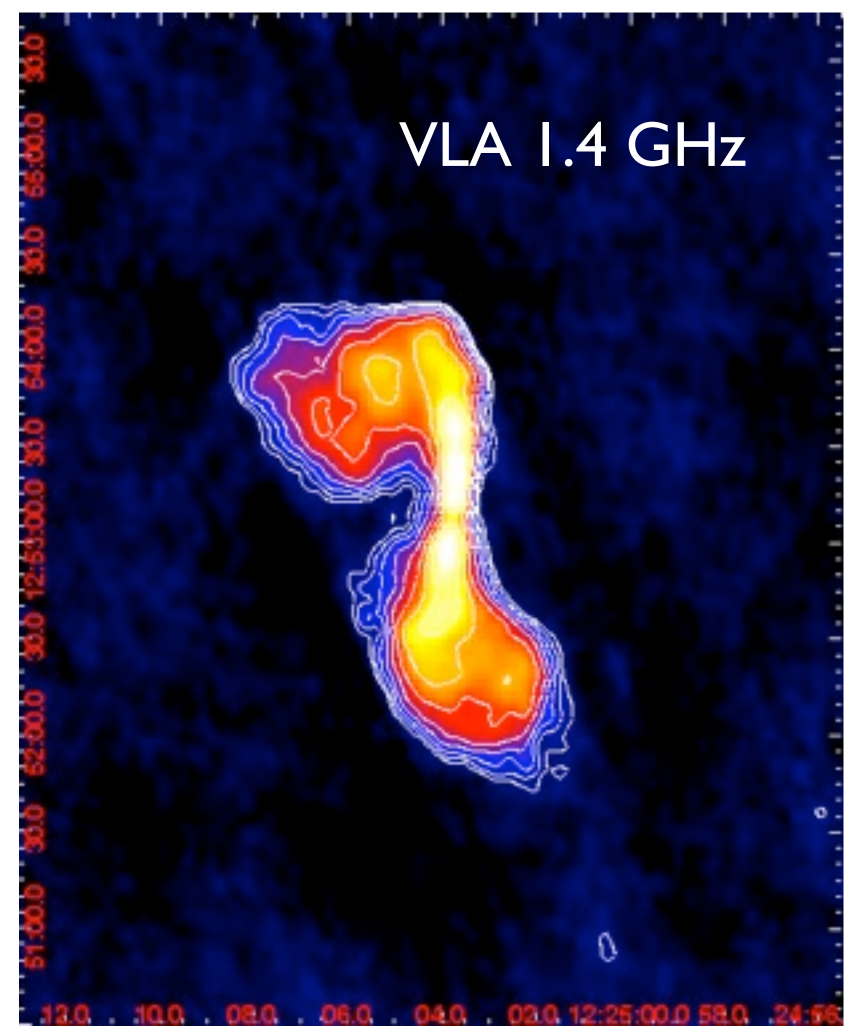

NGC 4388
Sy 1
NGC 4407
NGC 4438
distorted disk
LINER
M58
Sy 2
NGC 4567
NGC 4568
merging?
M90
Sy
NGC 4402
M88
Sy 2

M84







HBA map:

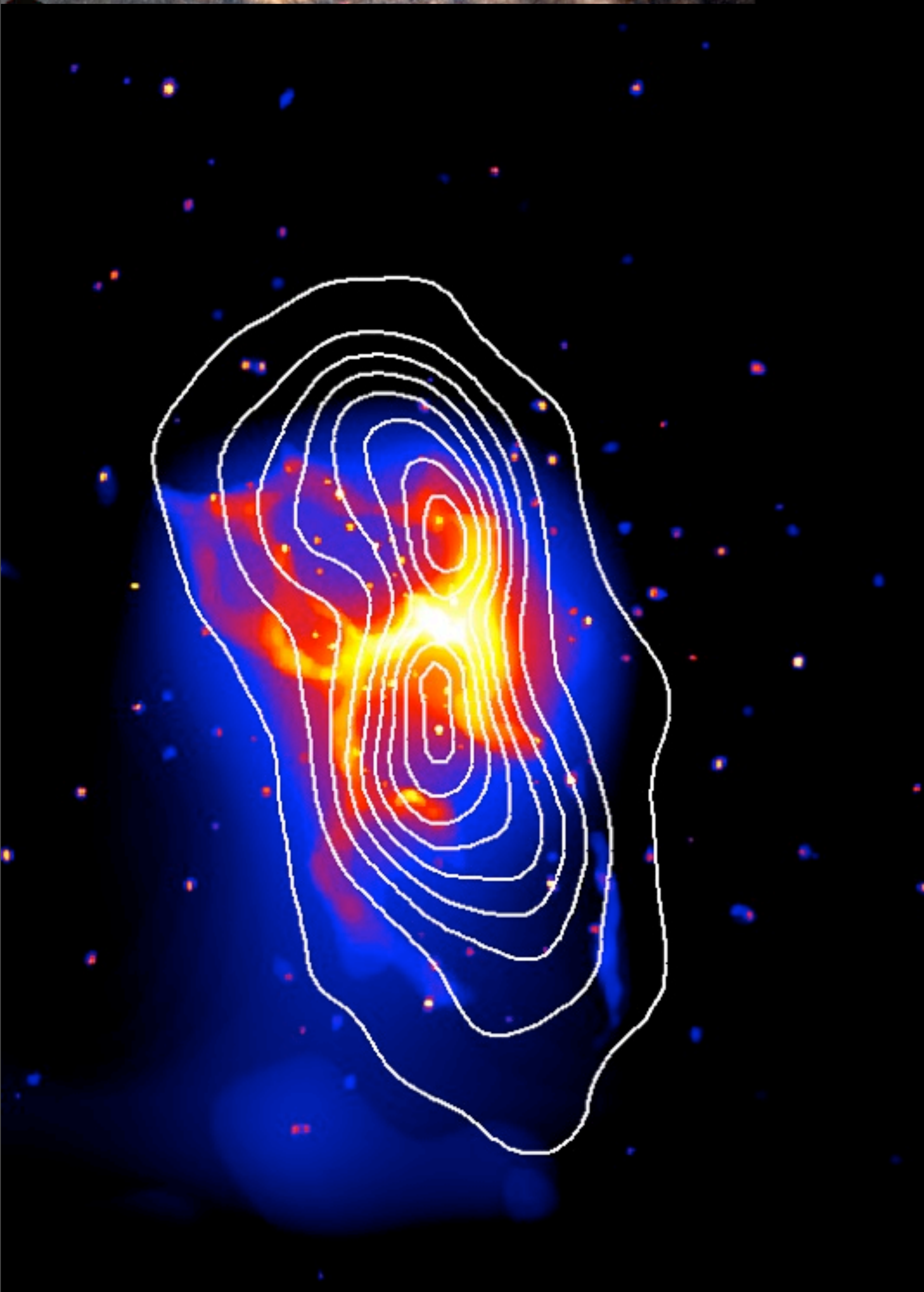
RMS: 1.5 e -3 Jy/beam
Beam: 23" x 14"
Dyn Range: ~ 600

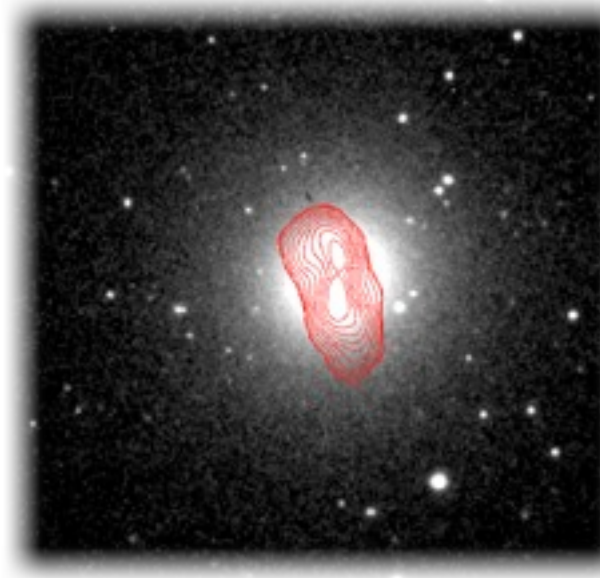
NOTE:

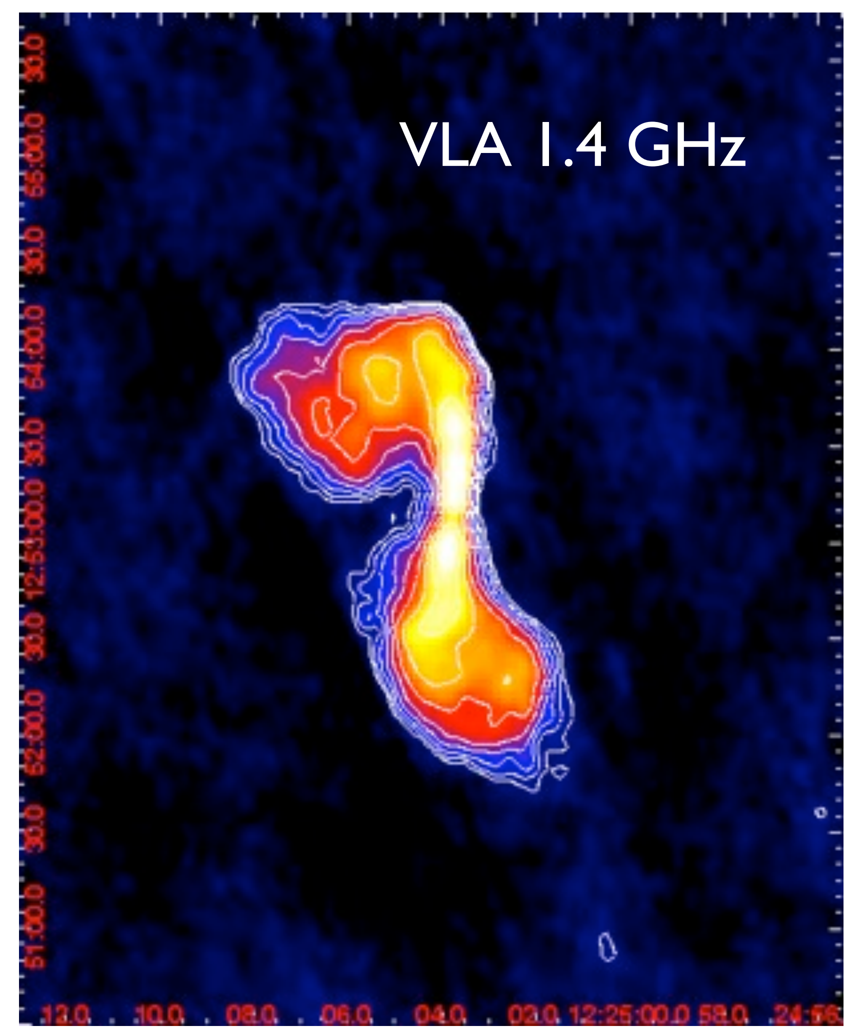
- Virgo A calibrated and uv-subtracted
- Other strong sources uv-subtracted
- Data self-recalibrated in the direction of M84
- Beam correction **not** included!

VLA image: Laing et al. 2011

M84







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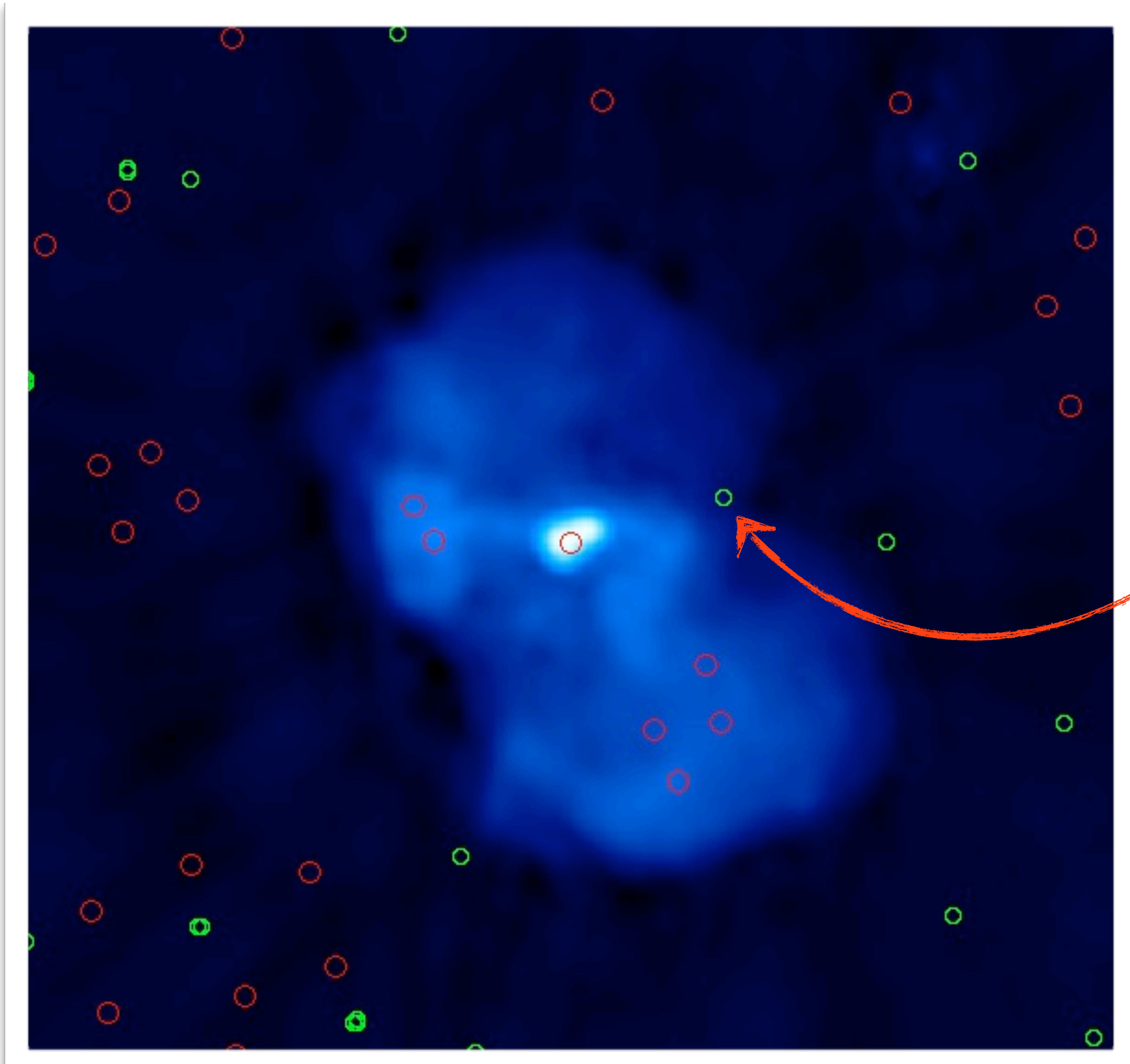
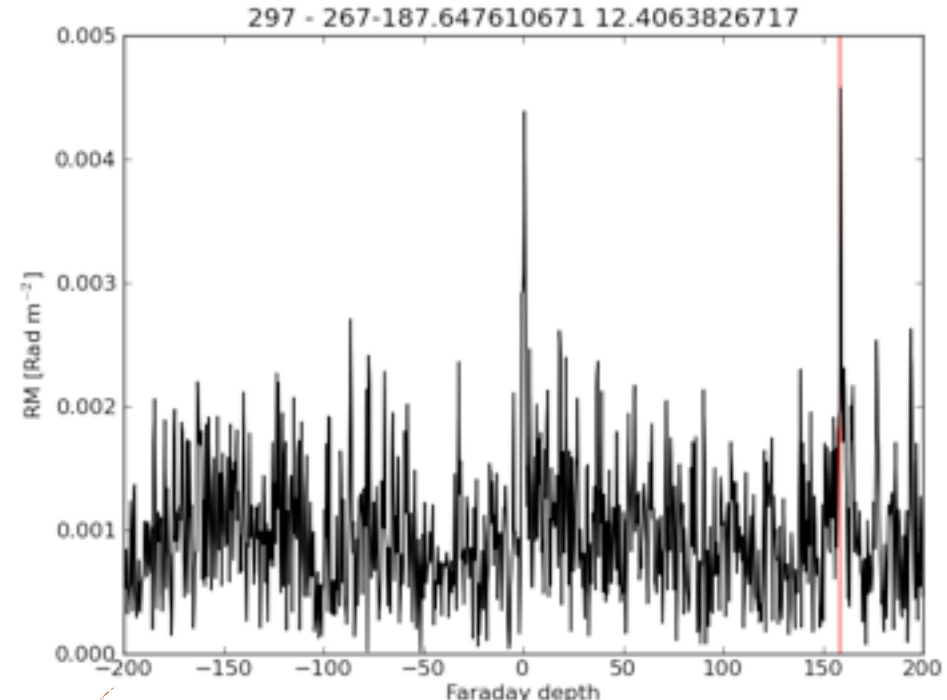


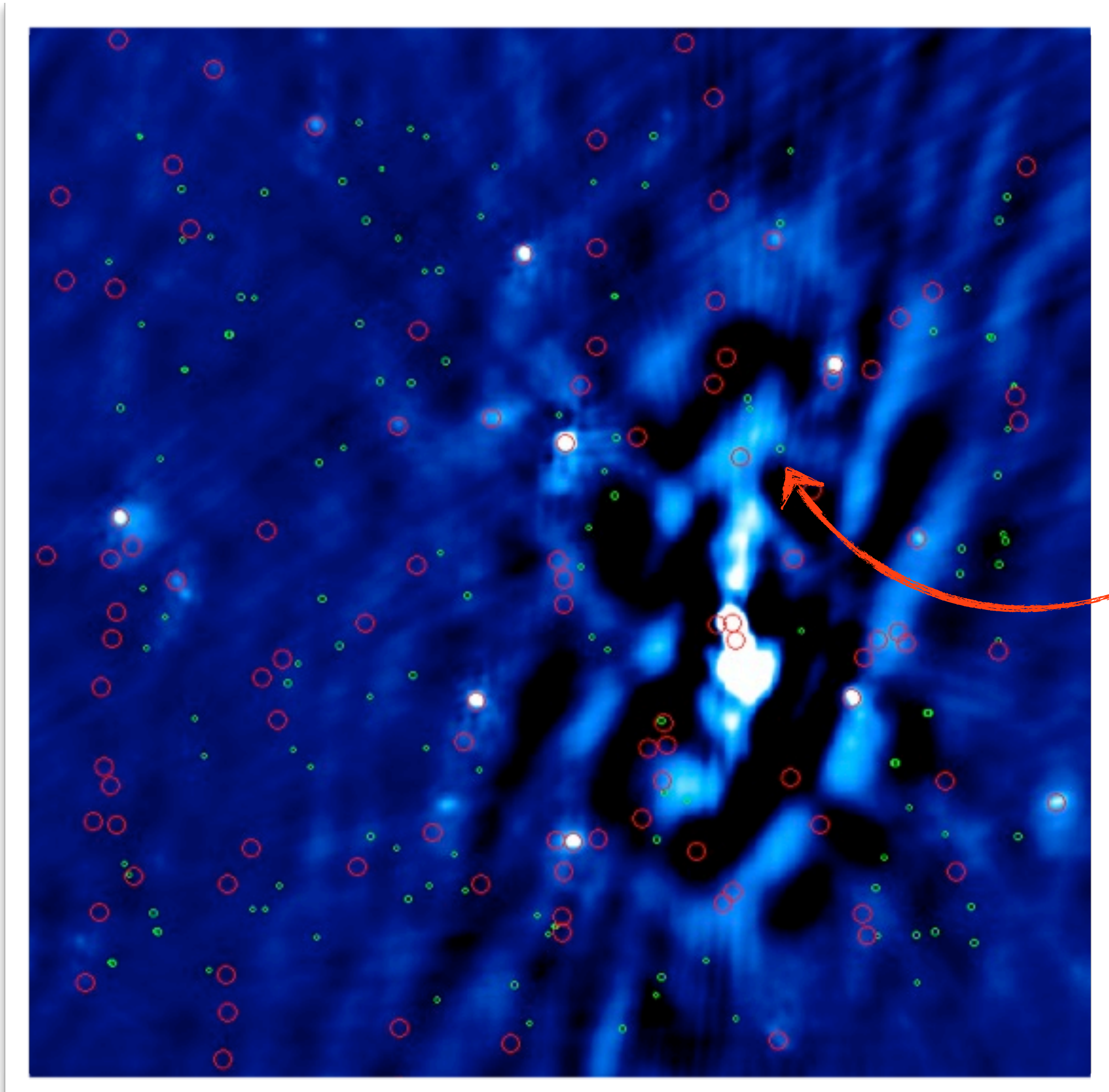


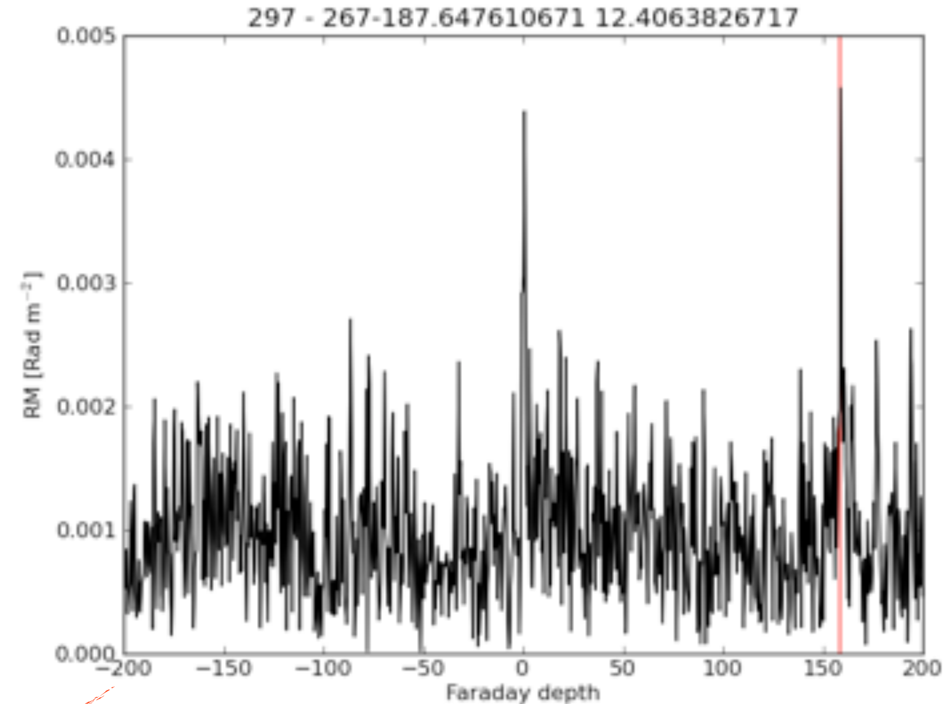
RM source extractor
on 8 σ peaks
outside FD ±10

in progress...

in collaboration with Mike Bell

RM synthesis





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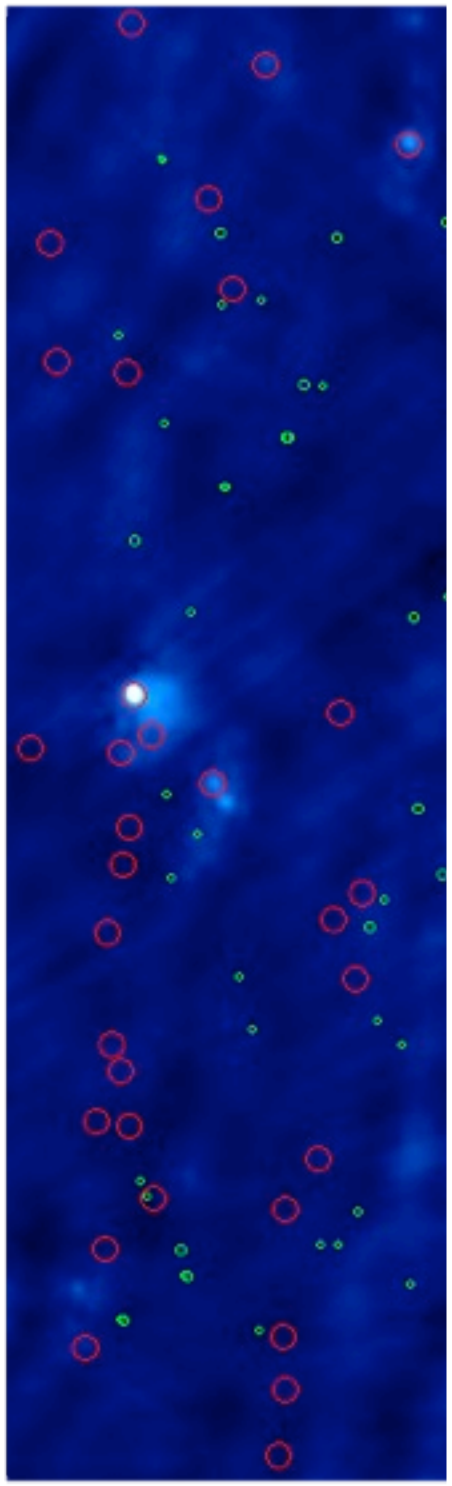

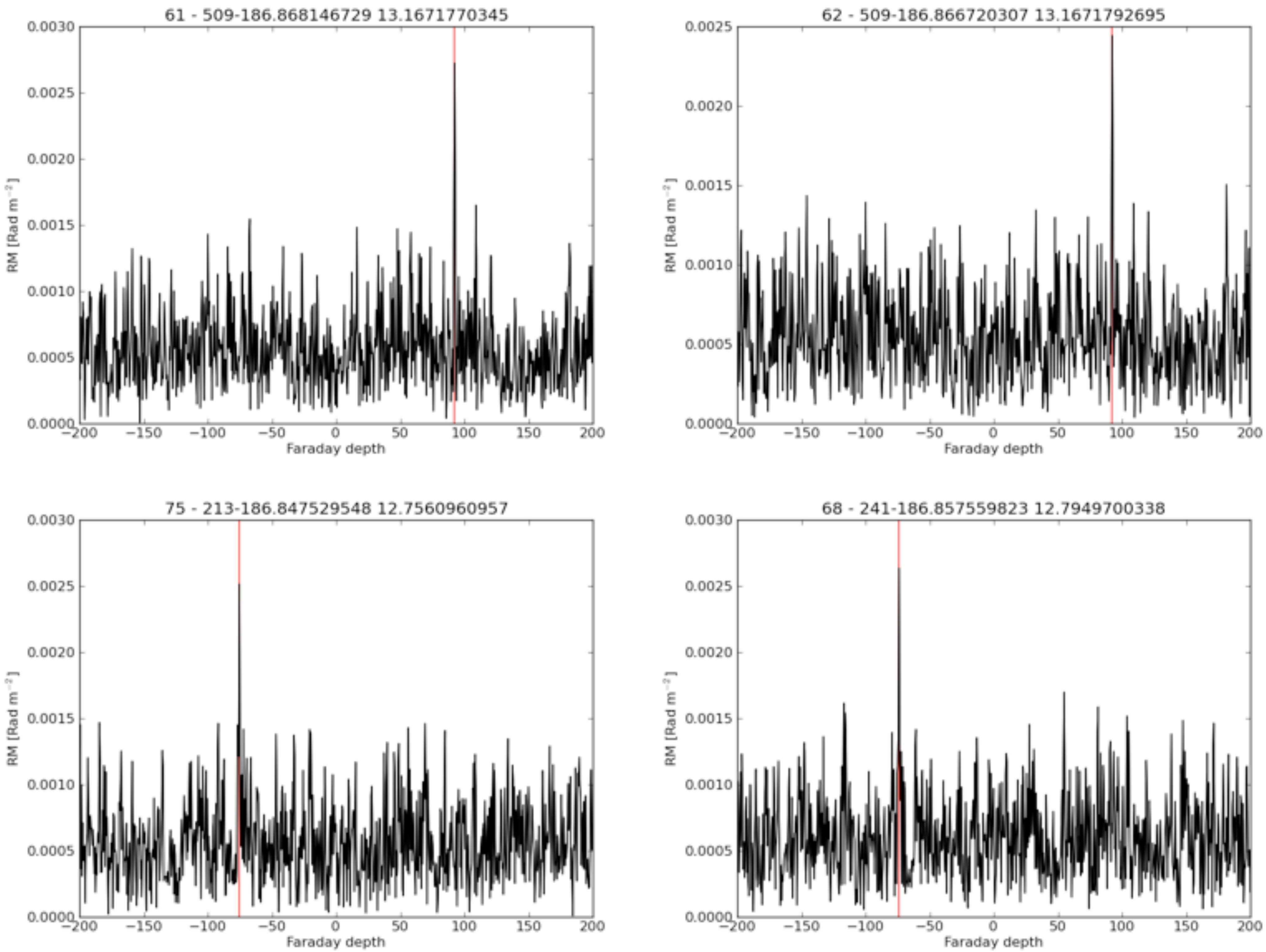

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Conclusions:

- 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 $\simeq 13\ \mu G$ found in the flow regions, and of $\simeq 10\ \mu G$ in the halo regions
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