Investigating diffuse radio emission with LOFAR: The complex merging galaxy cluster Abell 2069

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on behalf of the LOFAR surveys galaxy cluster group

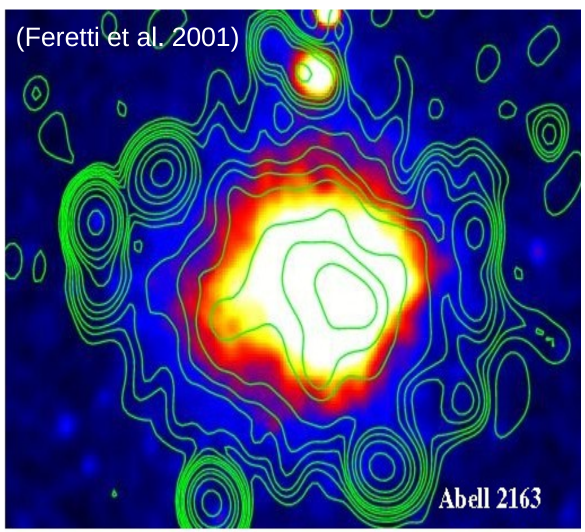
Radio halo emission in galaxy clusters

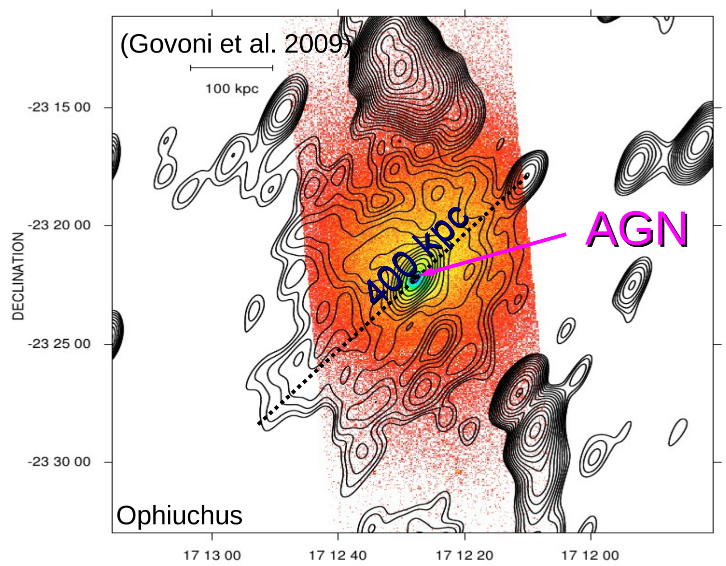
- steep spectrum: α ≲ –1 (can be bent)
- centered at the galaxy cluster
- regular, smooth shape
- unpolarized
- found in poor and rich clusters

	giant halo	mini-halo
occurrence	merging clusters	„cool-core“ clusters
size scale	≳ 1 Mpc	≲ 500 kpc
surface brightness	similar	wide range

low surface brightness

no optical counterparts





Origin of radio halos

	Primary models	Secondary models
origin of r**CRe**	**reacceleration** by merger-driven turbulence	in-situ production by **proton-proton collisions**
halo spectrum	high frequency cutoff	$\alpha \gtrapprox -1.5$
observables	connection to recent mergers	virtually visible in all clusters

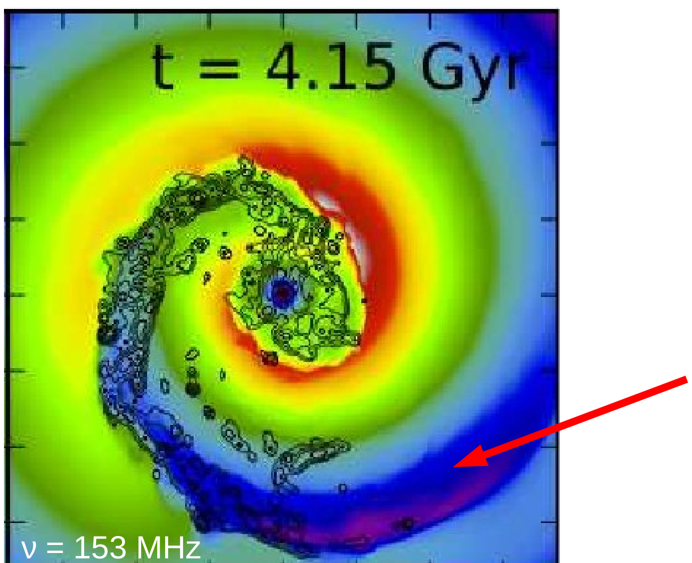
Origin of radio halos – mini-halos?

giant halos observed in merging galaxy clusters

mini-halos observed in cool-core clusters

→ cluster's cool-core **<u>not</u>** disrupted (Ascasibar and Markevitch 2006)

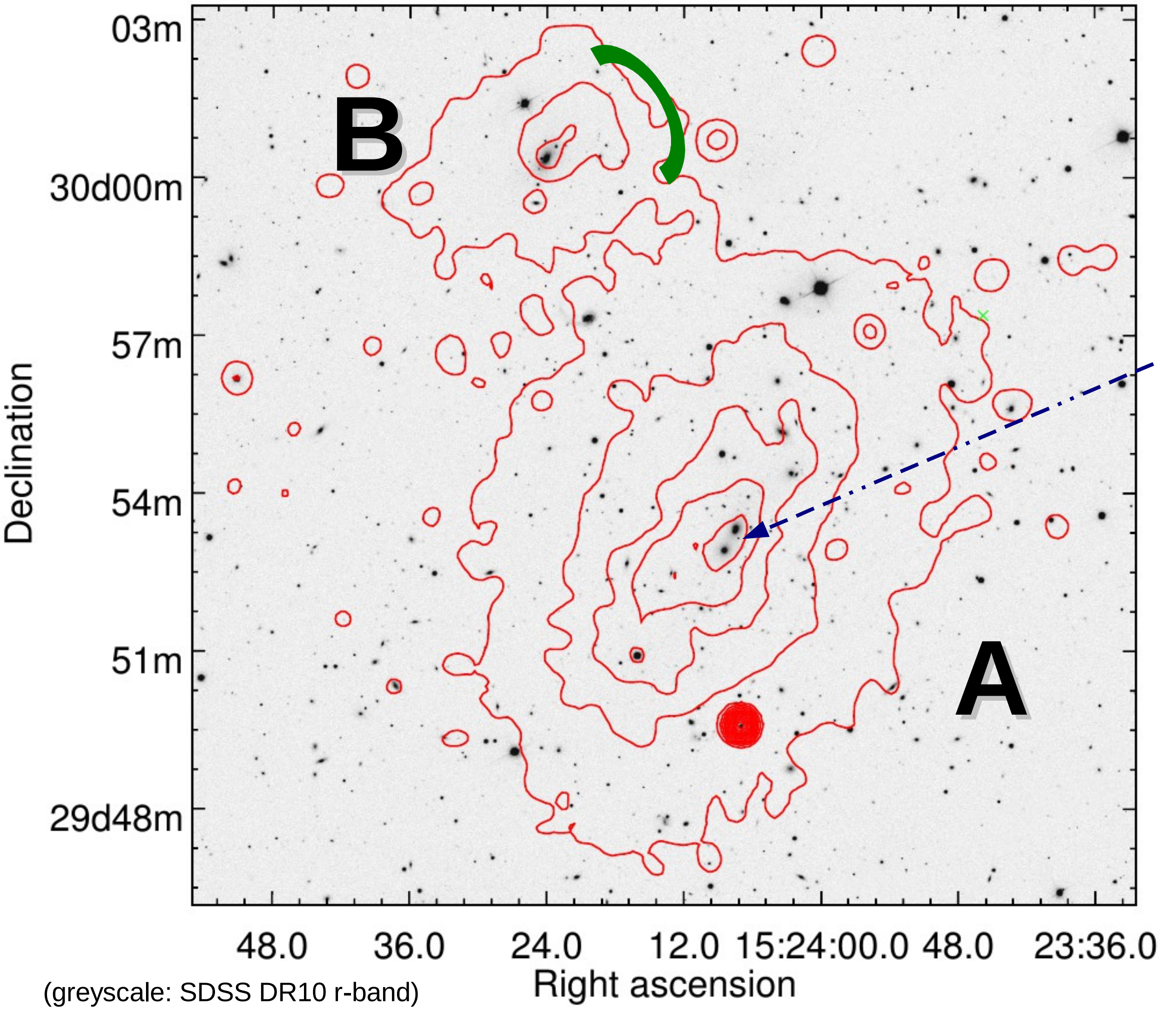
- off-axis, minor, subcluster merger (Churazov et al. 2003, Fujita et al. 2004)
- displace cool core from DM peak
- **gas-sloshing** → turbulence → **cold fronts** (ZuHone et al. 2013)
- **hadronic origin** of rCRe (Pfrommer and Enßlin 2004, ZuHone et al. 2014)



gas-sloshing can cause *cold-fronts*

Cluster details: Abell 2069

(z = 0.116)



(greyscale: SDSS DR10 r-band)
(contours: Chandra 0.5 – 7 keV)

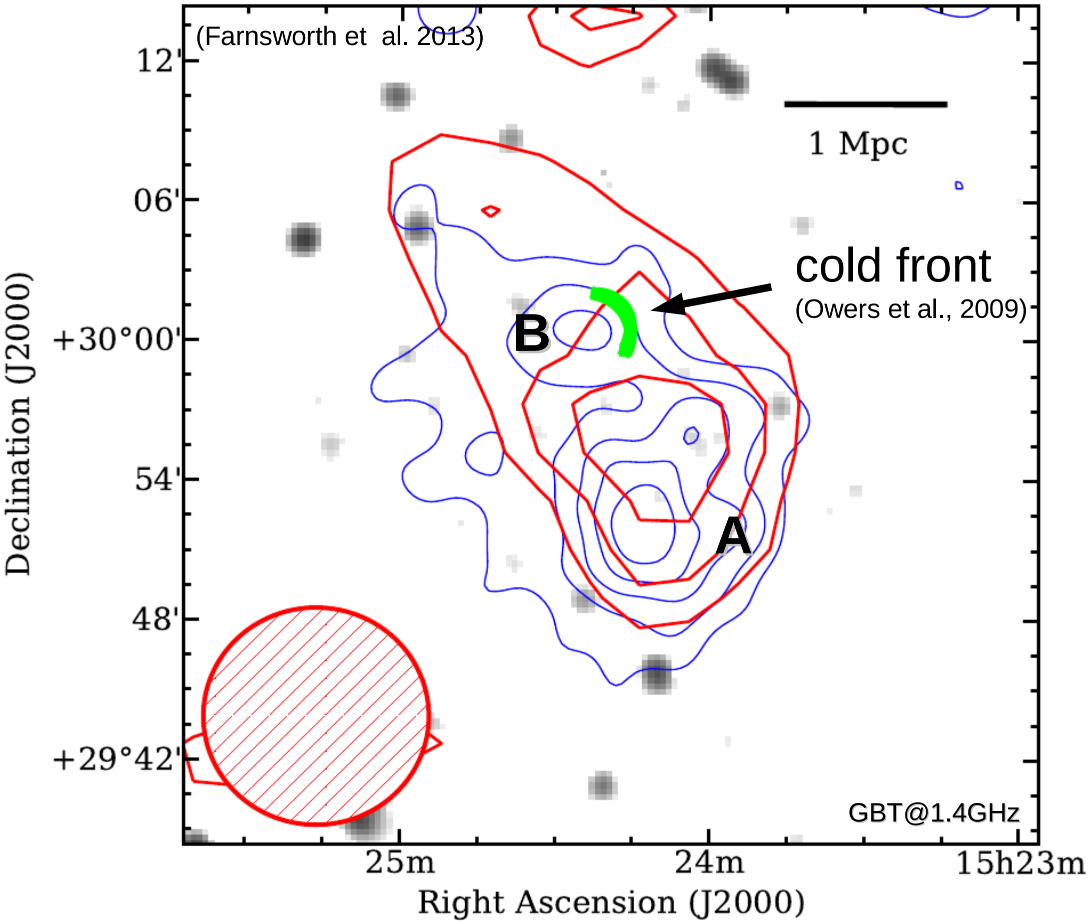
- L_X(0.1 – 2.4 keV) = 5·10^{44} erg s^{-1}
- *two distinct components*

main component **A**
- elliptically elongated
- hosts two bright elliptical galaxies
➢ **major merger**

companion **B**
- separated by ~ 1 Mpc
- peculiar velocity ~ 500 km s^{-1}
- presence of a **cold front**

(Owers et al., 2009)

Diffuse radio emission in Abell 2069



(greyscale: NVSS clipped at 1.35mJy/beam)
(red: GBT, blue: Rosat PSPC X-ray)

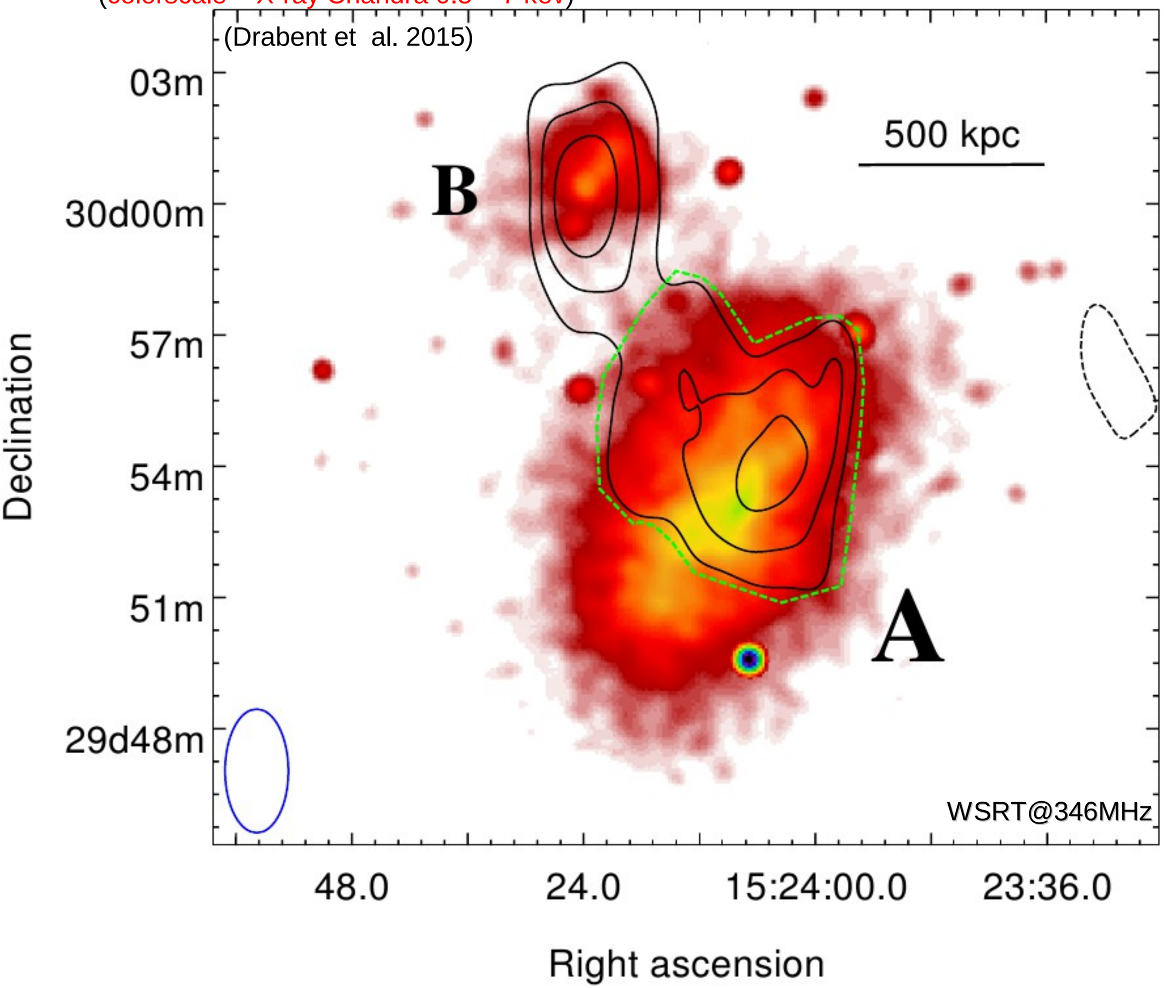
- flux density: 28.8 ± 7.2 mJy
- beam size ~ 1.1 Mpc

✗ **internal structure**

Recovery of diffuse emission in Abell 2069

WSRT: 3 × 12 h @ 346 MHz (high sensitivity for diffuse emission)
GMRT: 4.8 h @ 322 MHz (to model and subtract compact sources)

(contours: [−3.0, 3.0, 4.2 , 6.0, 8.5, 12.0] mJy/beam, beam: 182" × 91", r.m.s.: 1.0 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)



<u>main component **A**</u>

- LLS ~ 750 kpc
- roughly elongated with X-ray
- peak flux is shifted to NW
- ongoing merger
- ➢ **giant radio halo**
- ➢ **flux density: 25 ± 9 mJy**

<u>companion **B**</u>

- apparent size ~ beam width
- estimated LLS ~ 50 … 100 kpc
- ➢ **nature uncertain**
- ➢ **flux density: 15 ± 2 mJy**

Recovery of diffuse emission in Abell 2069

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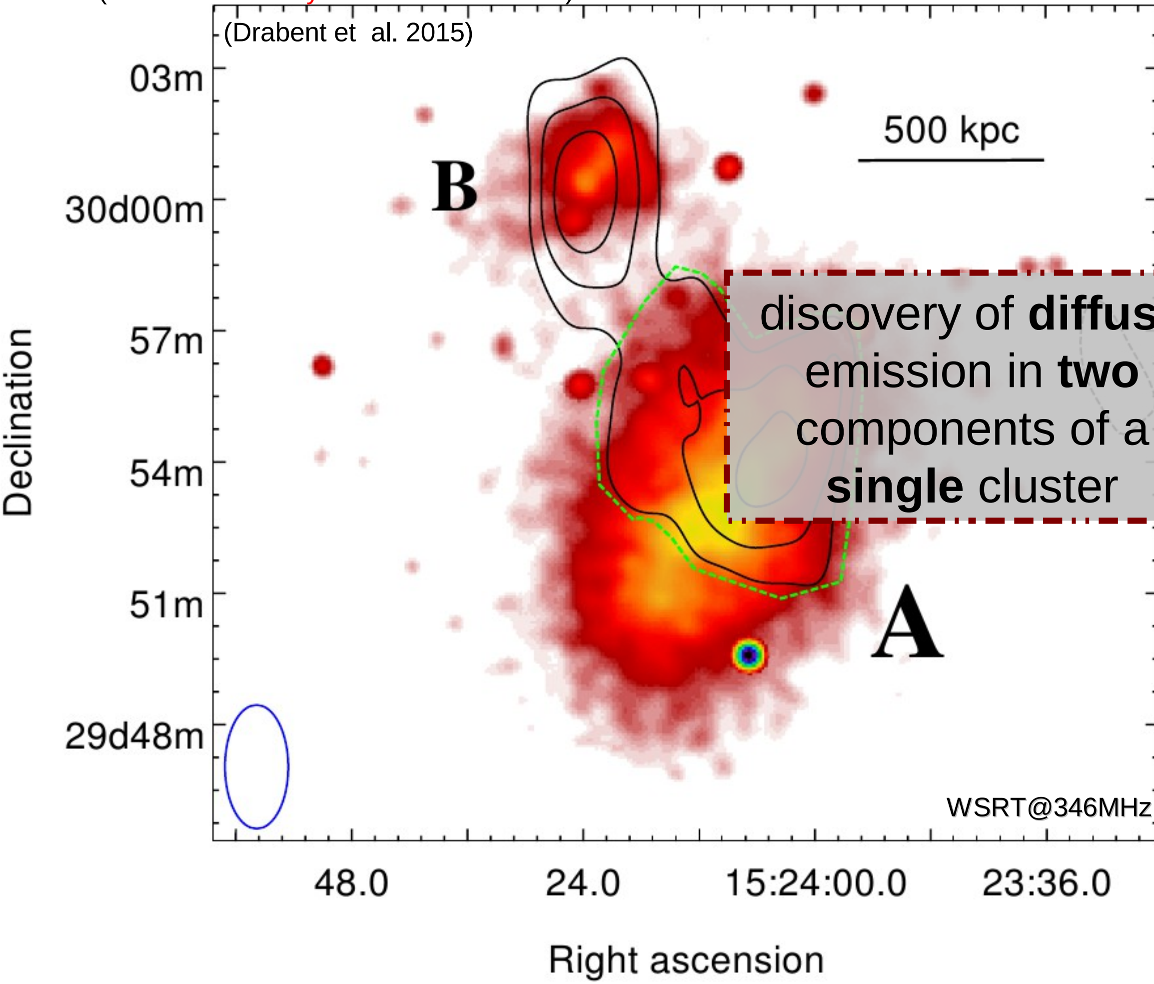

discovery of **diffuse** emission in **two** components of a **single** cluster

main component **A**
- LLS ~ 750 kpc
- roughly elongated with X-ray
- peak flux is shifted to NW
- ongoing merger
➢ **giant radio halo**
➢ **flux density: 25 ± 9 mJy**

companion **B**
- apparent size ~ beam width
- estimated LLS ~ 50 … 100 kpc
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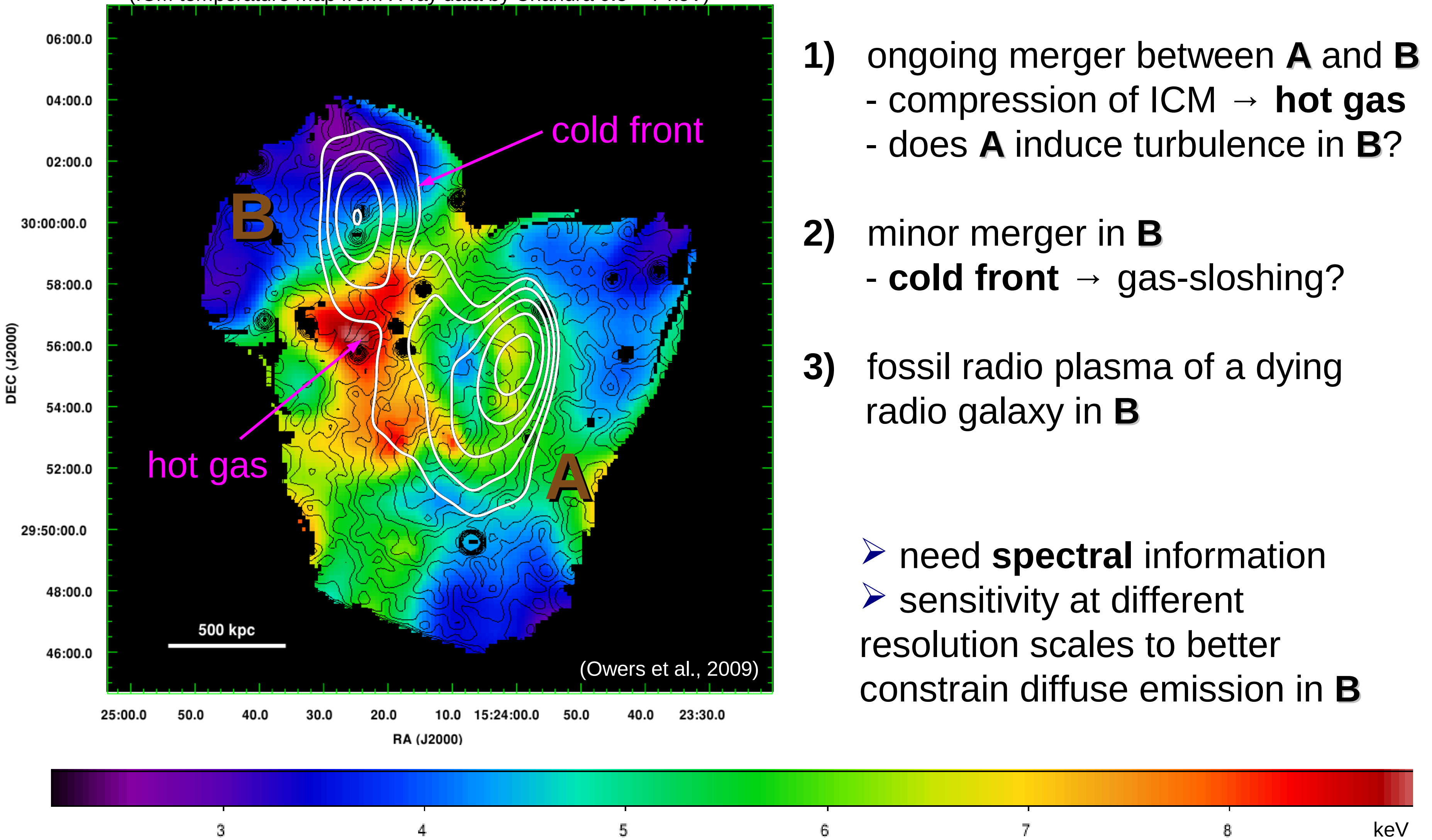
Abell 2069 possible scenarios for B

(ICM temperature map from X-ray data by Chandra 0.5 – 7 keV)



1) ongoing merger between **A** and **B**
   - compression of ICM → **hot gas**
   - does **A** induce turbulence in **B**?

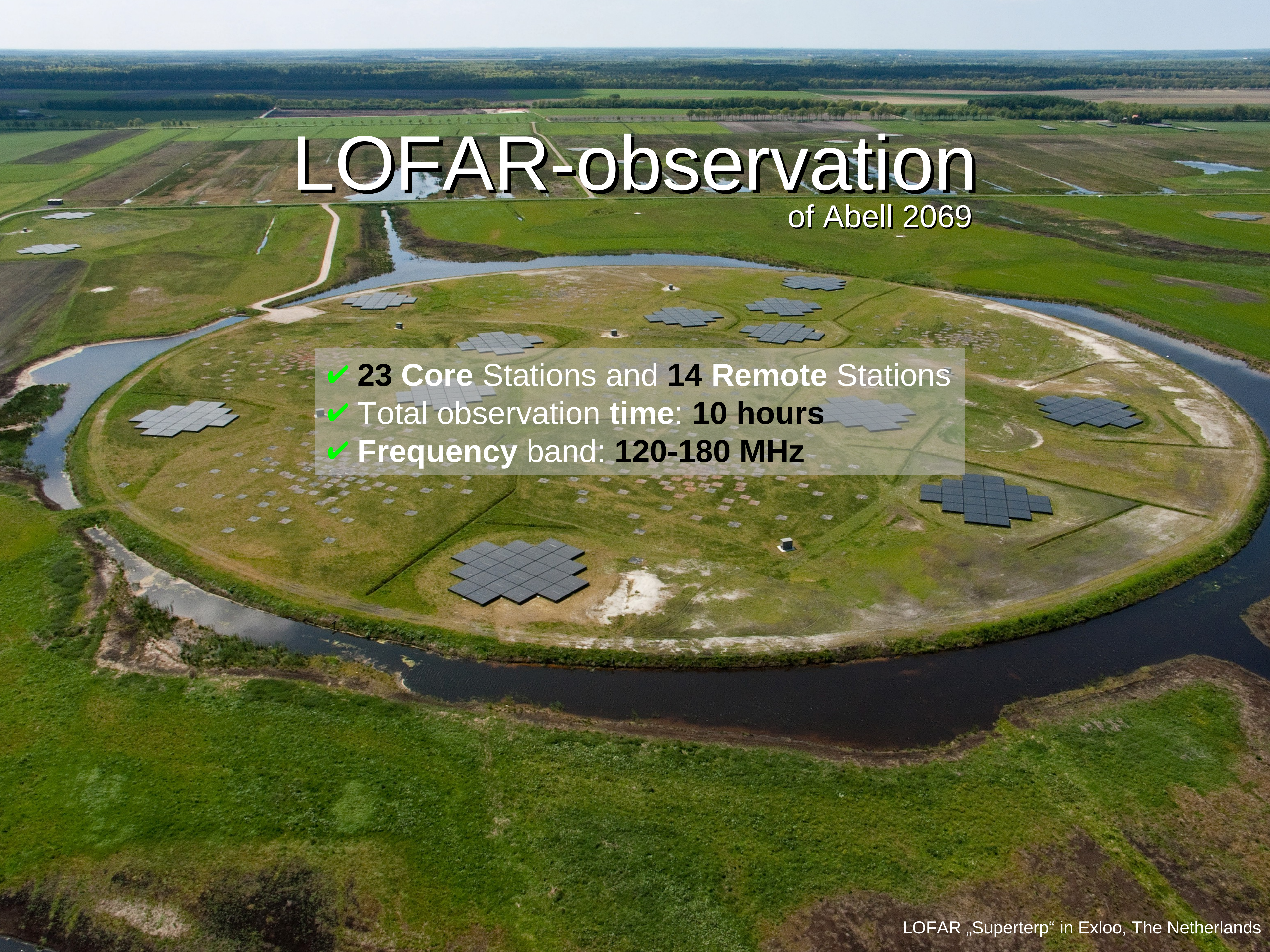
2) minor merger in **B**
   - **cold front** → gas-sloshing?

3) fossil radio plasma of a dying radio galaxy in **B**

- need **spectral** information
- sensitivity at different resolution scales to better constrain diffuse emission in **B**

LOFAR-observation

of Abell 2069

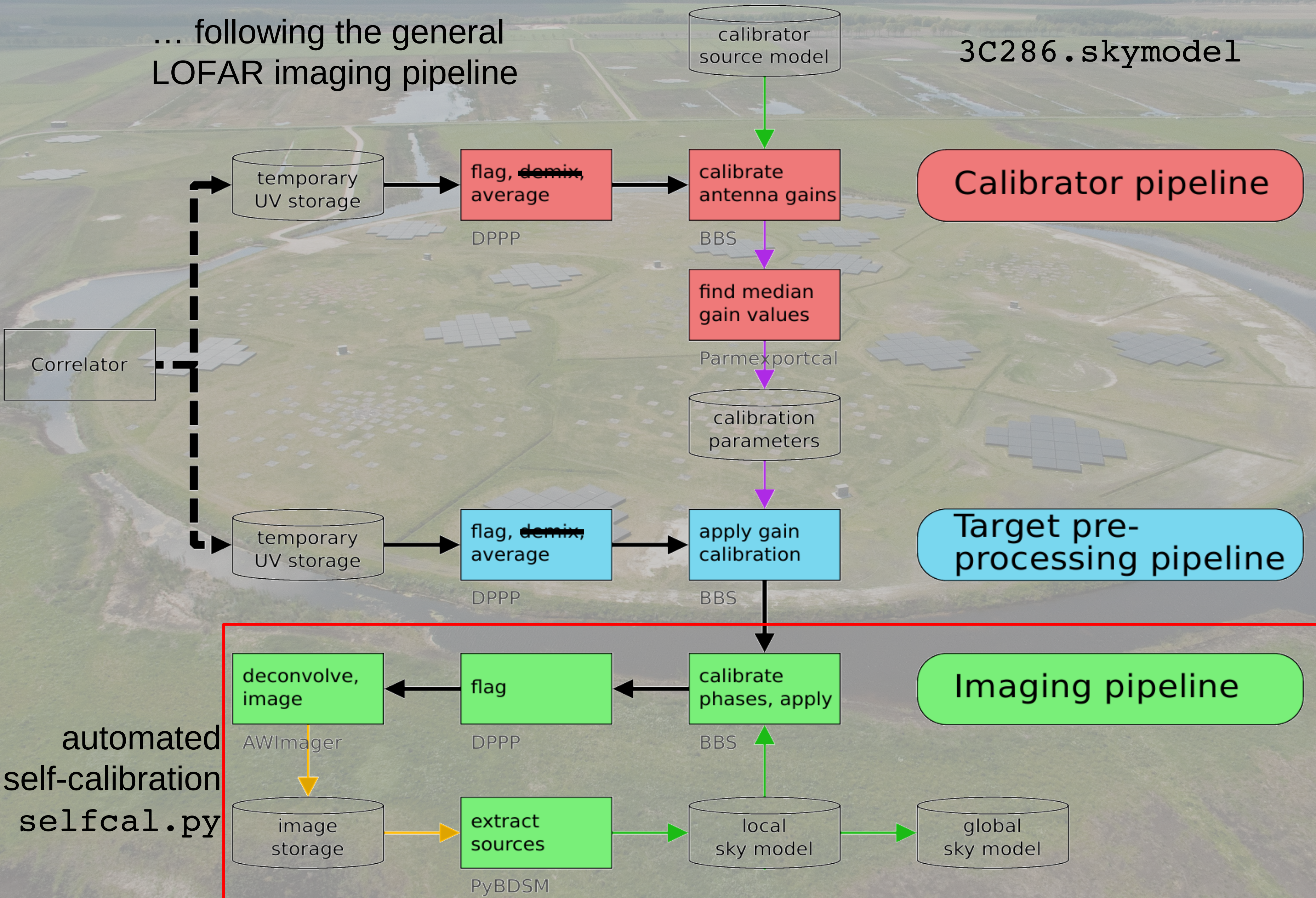


- ✔ **23 Core** Stations and **14 Remote** Stations
- ✔ Total observation **time**: **10 hours**
- ✔ **Frequency** band: **120-180 MHz**

LOFAR „Superterp“ in Exloo, The Netherlands

Calibration procedure

… following the general LOFAR imaging pipeline



automated self-calibration
`selfcal.py`

Calibration procedure

Imaging pipeline

`selfcal.py`

Skymodel
Calibrated target

✔ **target field** is flux and phase calibrated
✔ only direction-independent

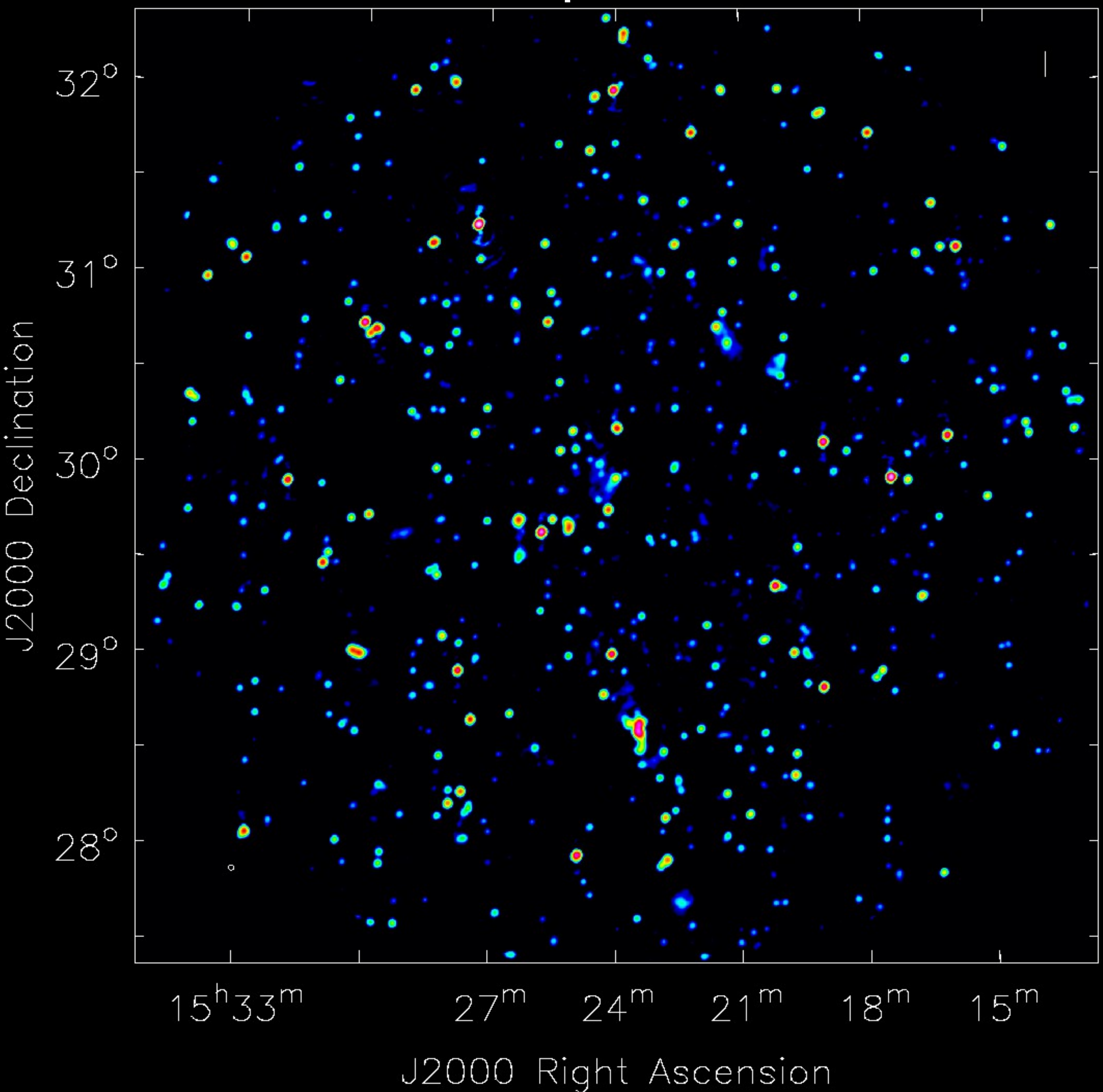
BohJones

direction-**dependent** calibration and **subtraction**

- **field sources**:
  using compact source model from highest resolution image (3" × 4")
- sources **on top of diffuse emission** (in the center)
  using lower resolution model (45" × 35")

- **final imaging** with `awimager` at desired resolution
- **stack** images (**20** subbands each)

LOFAR HBA radio map of Abell 2069 at 166 MHz



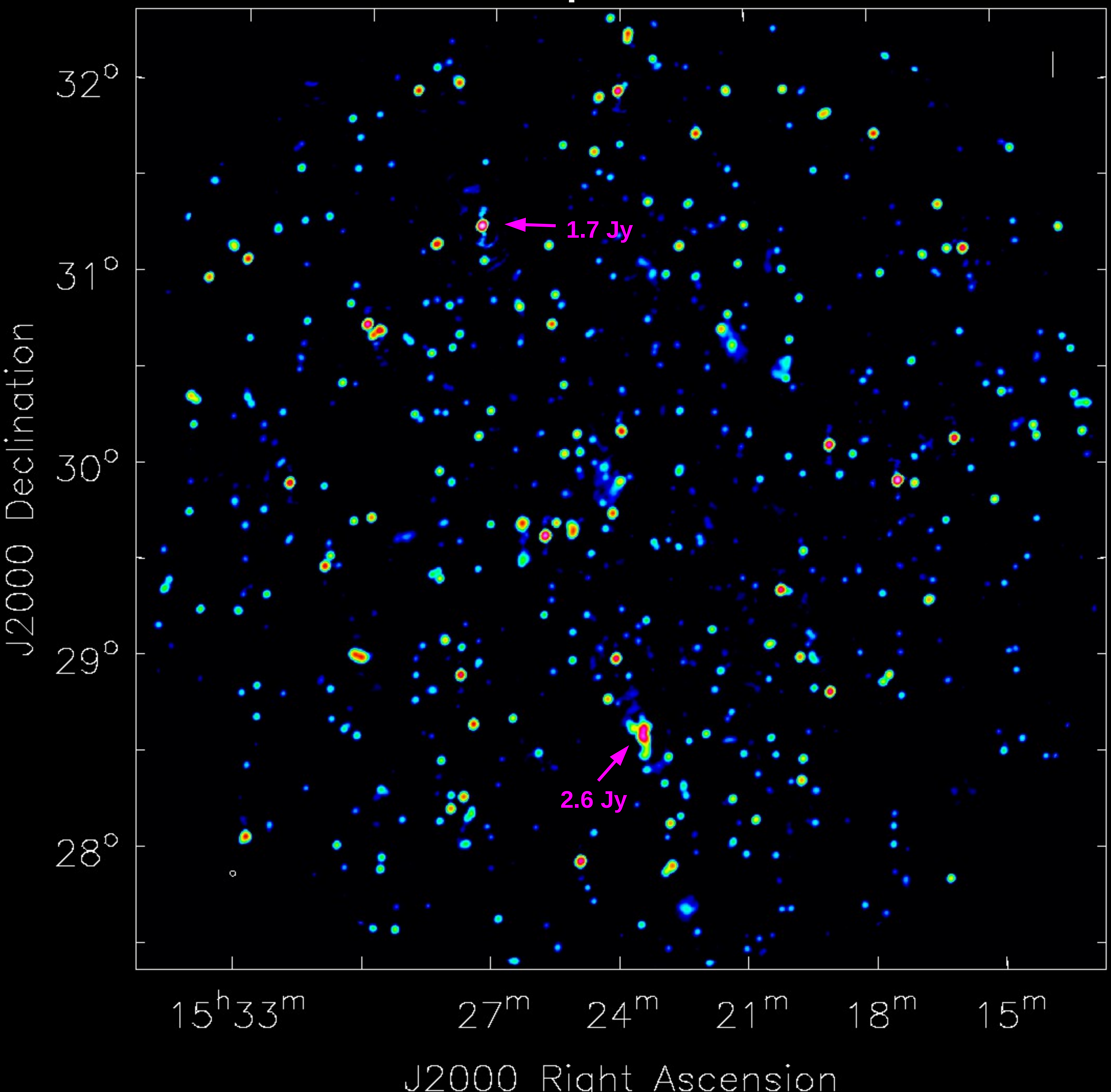
100/370 subbands used
(27%)

beam: 106" × 103"
r.m.s.: 1.5 mJy/beam

only weak ionospheric disturbances

minor A-team contribution

LOFAR HBA radio map of Abell 2069 at 166 MHz



100/370 subbands used (27%)

beam: 106" × 103"
r.m.s.: 1.5 mJy/beam

only weak ionospheric disturbances

minor A-team contribution

bright sources

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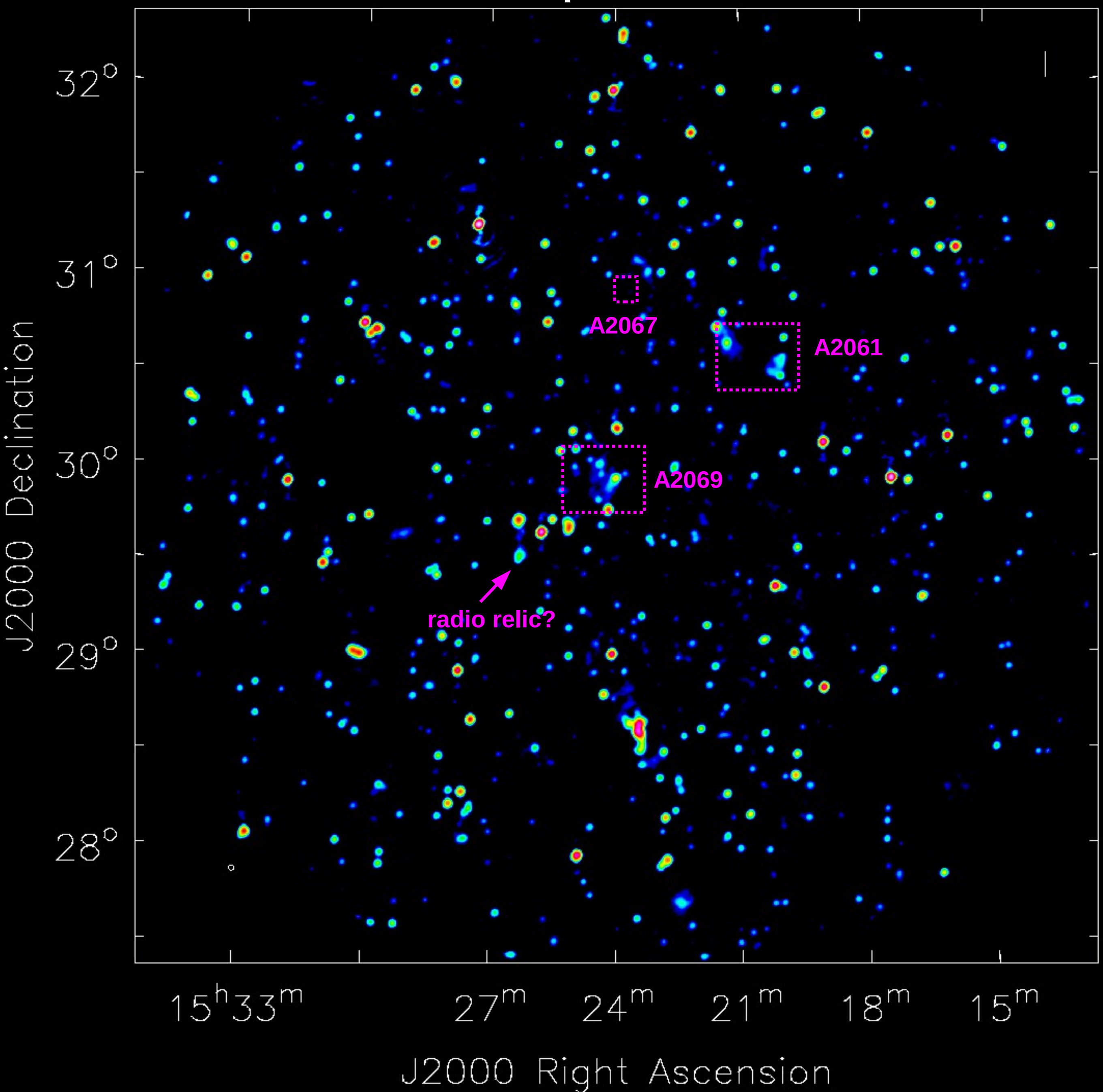


100/370 subbands used (27%)

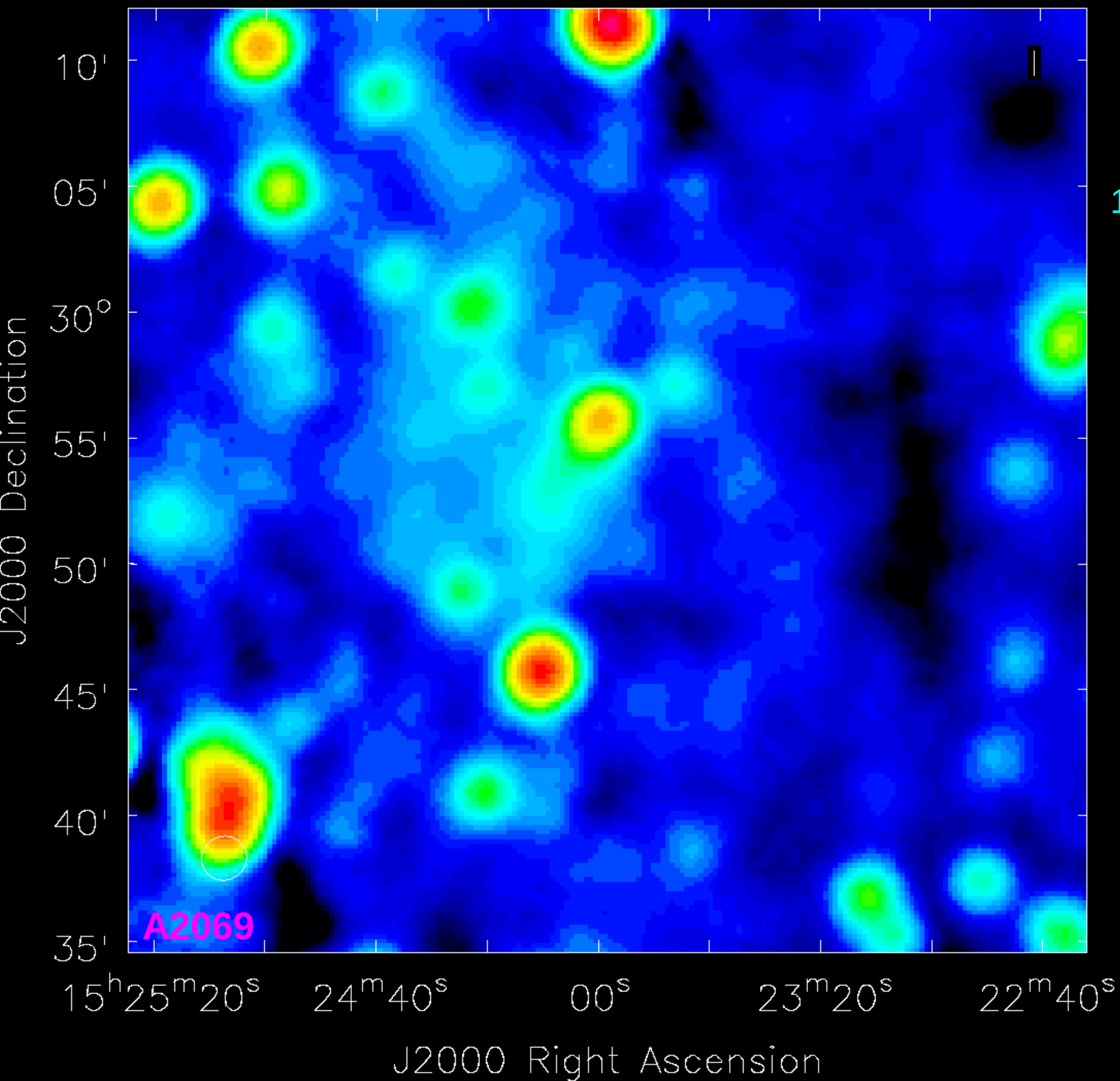
beam: 106" × 103"
r.m.s.: 1.5 mJy/beam

only weak ionospheric disturbances

minor A-team contribution

interesting fields

LOFAR HBA radio map of Abell 2069 at 166 MHz



100/370 subbands used
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beam: 106" × 103"
r.m.s.: 1.5 mJy/beam

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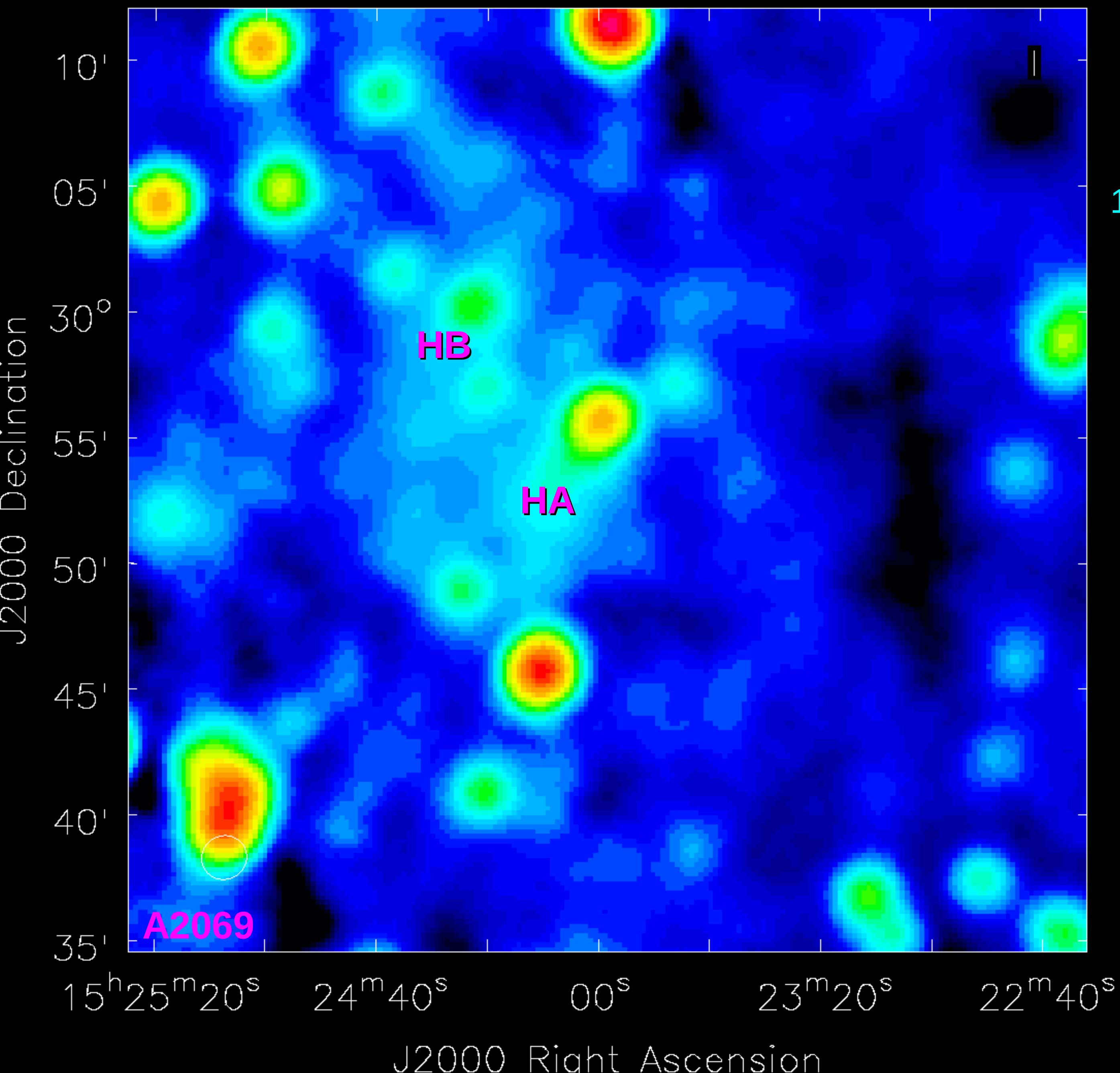
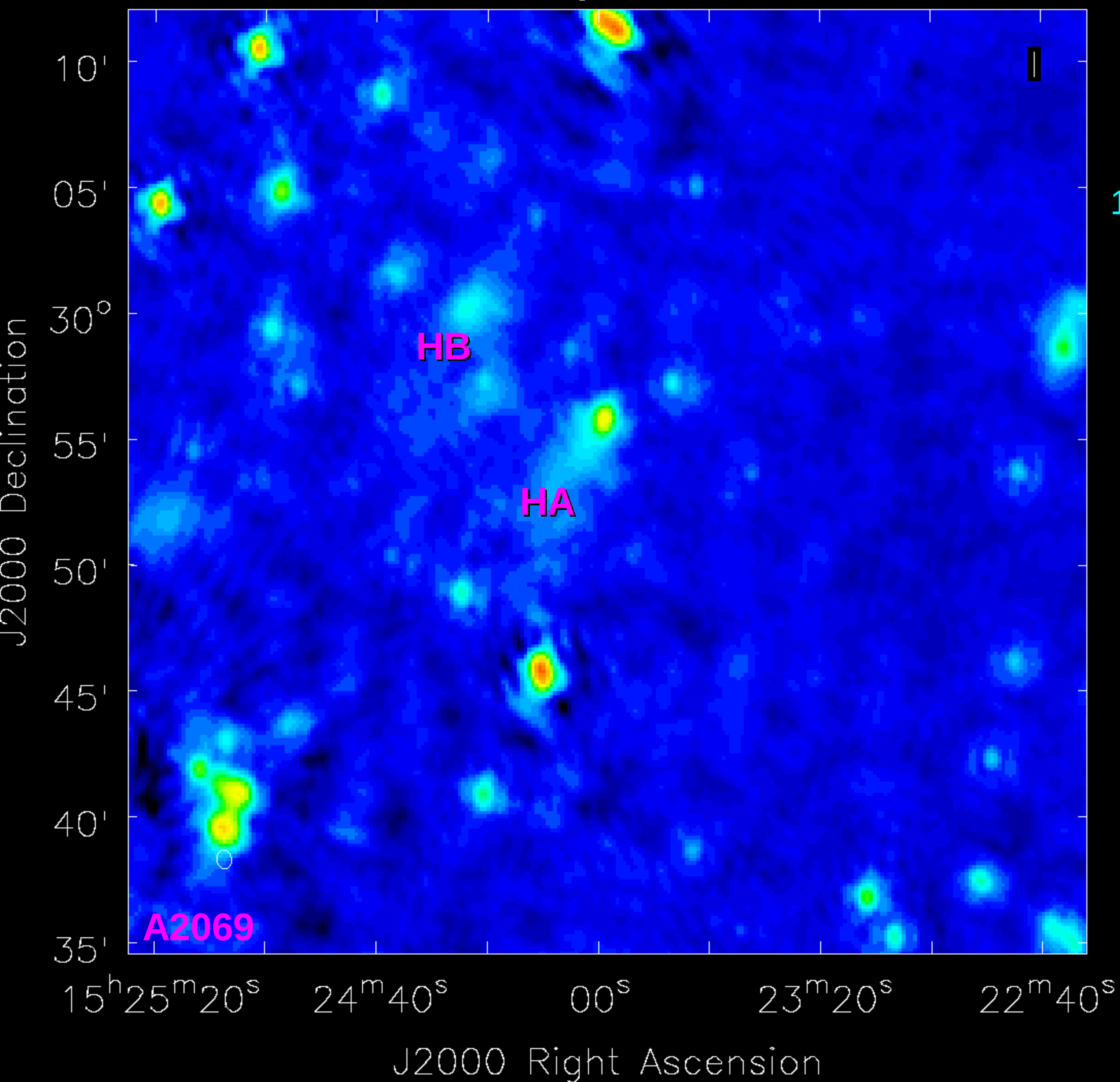


100/370 subbands used (27%)

beam: 106" × 103"
r.m.s.: 1.5 mJy/beam

diffuse components

LOFAR HBA radio map of Abell 2069 at 166 MHz

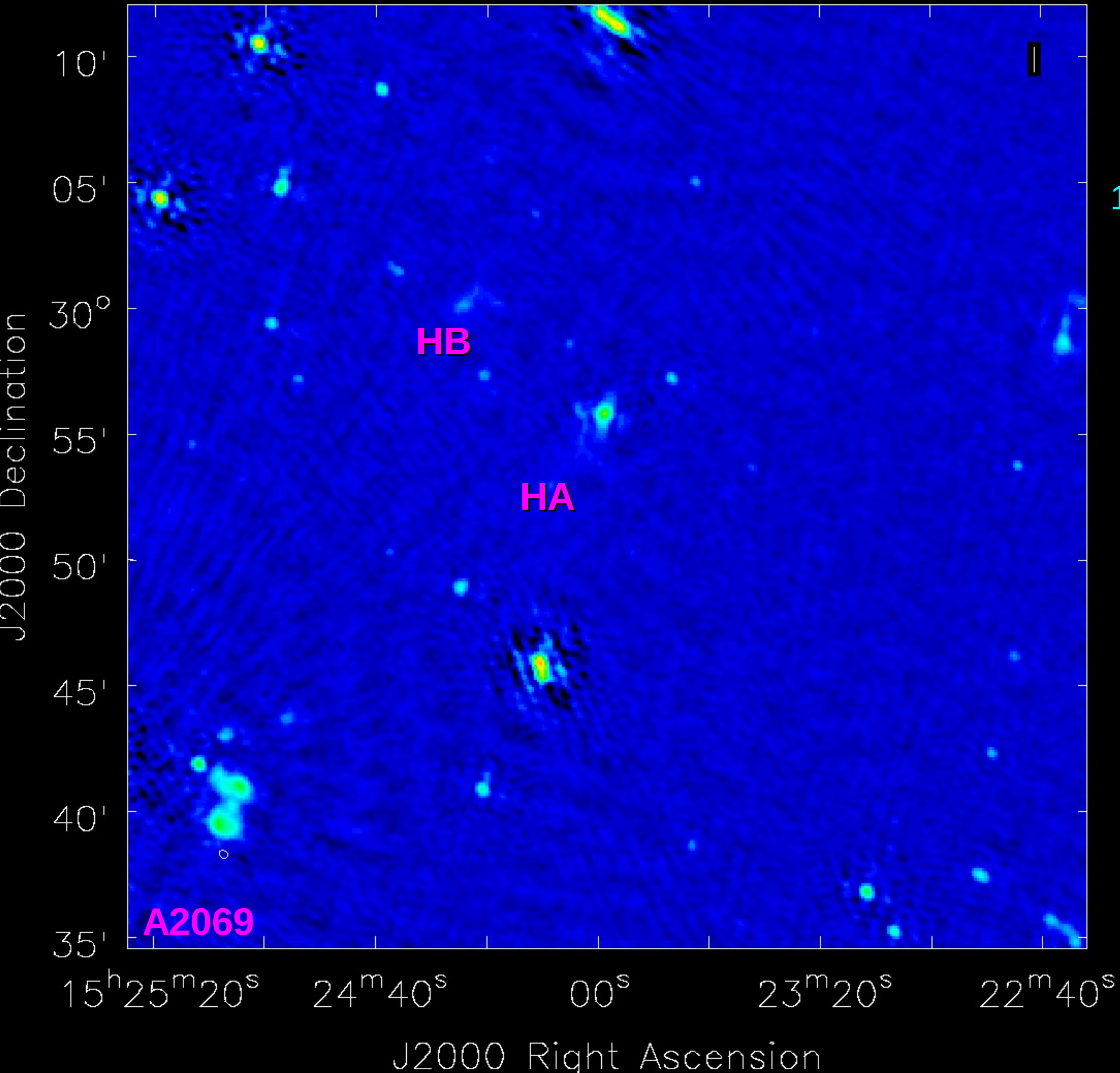


100/370 subbands used (27%)

beam: 45" × 35"
r.m.s.: 760 μJy/beam

diffuse components

LOFAR HBA radio map of Abell 2069 at 166 MHz

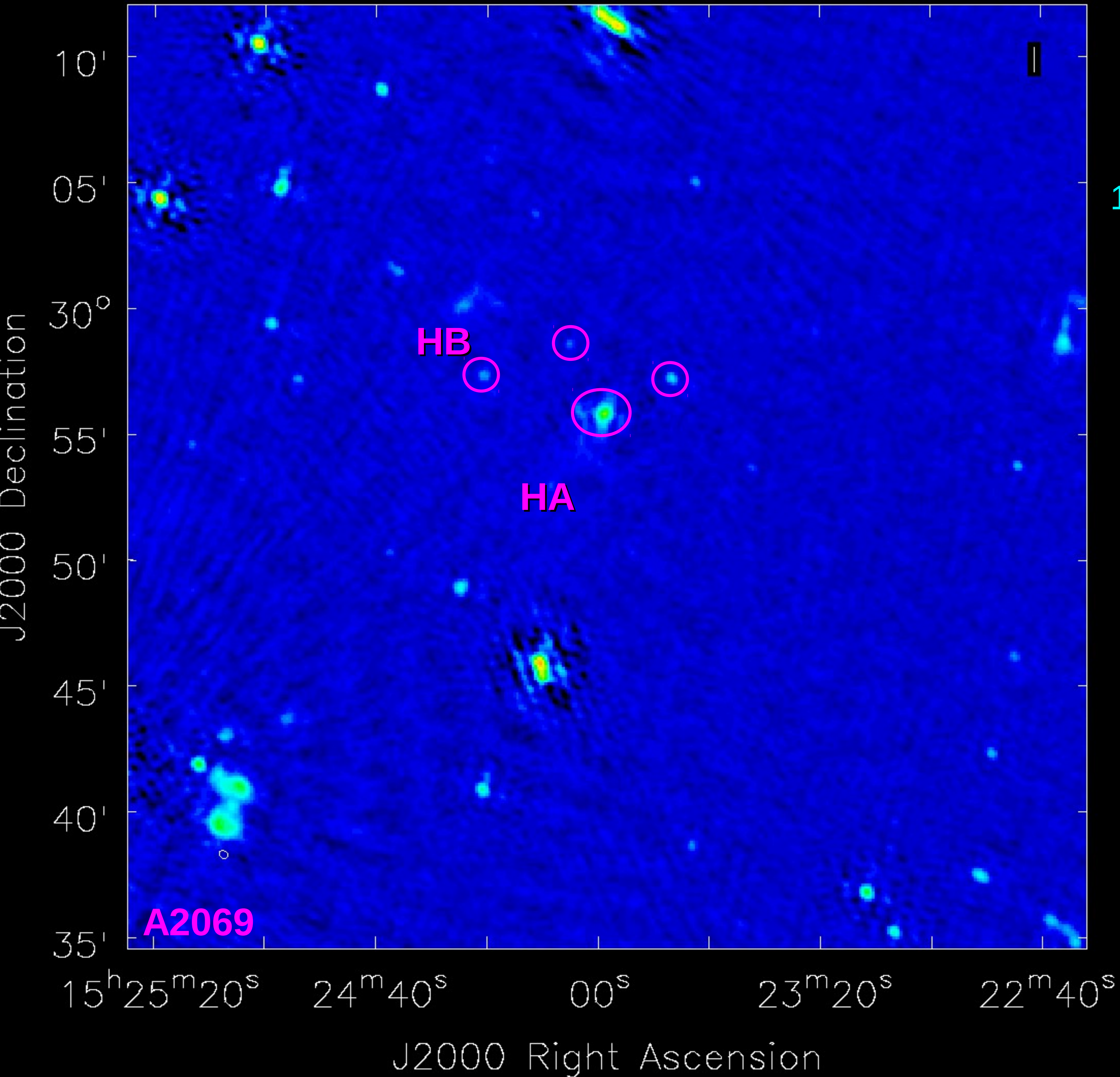


100/370 subbands used
(27%)

beam: 22" × 18"
r.m.s.: 380 μJy/beam

diffuse
components

LOFAR HBA radio map of Abell 2069 at 166 MHz



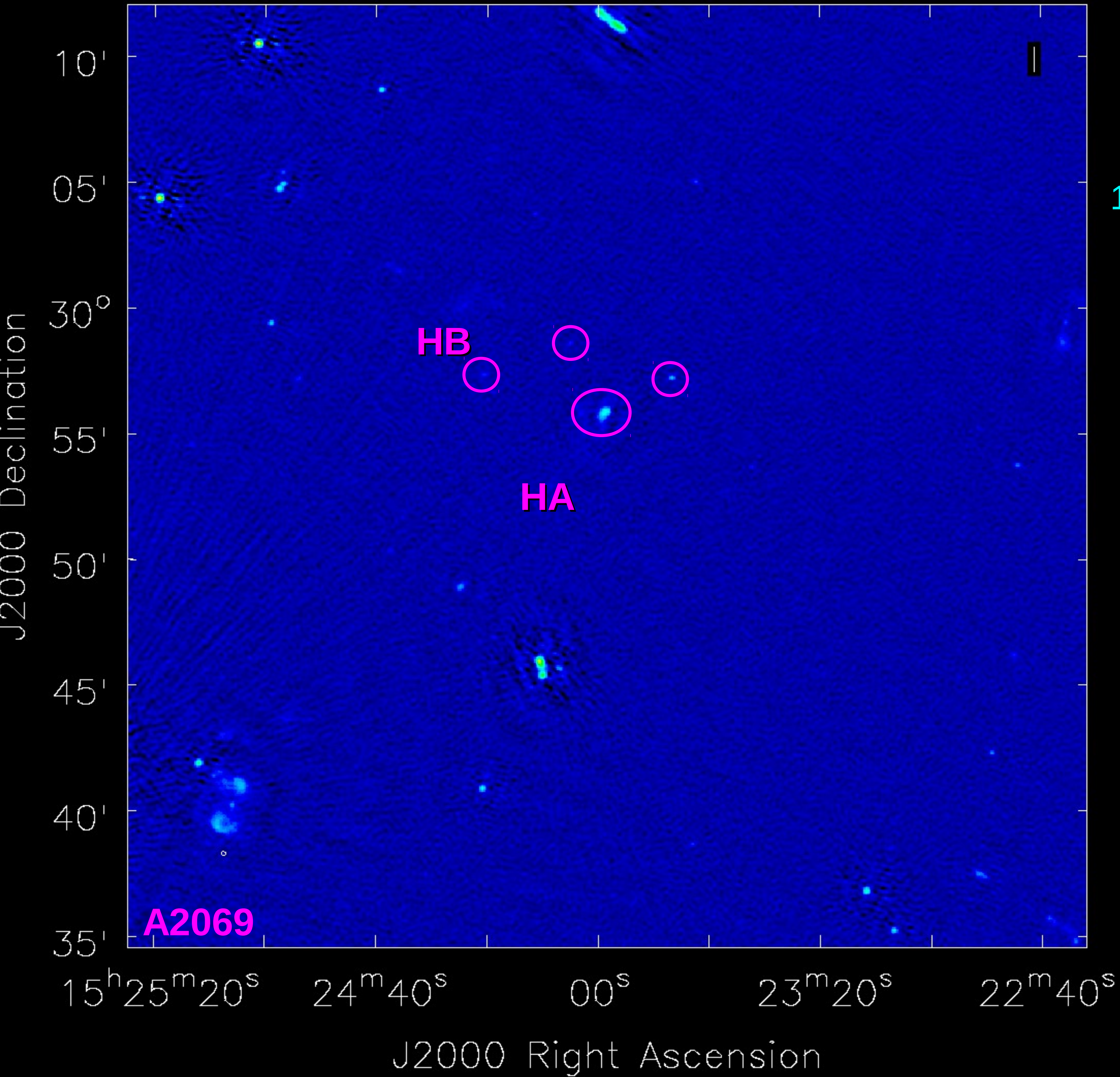
100/370 subbands used (27%)

beam: 22" × 18"
r.m.s.: 380 µJy/beam

identification of compact sources

diffuse components

LOFAR HBA radio map of Abell 2069 at 166 MHz



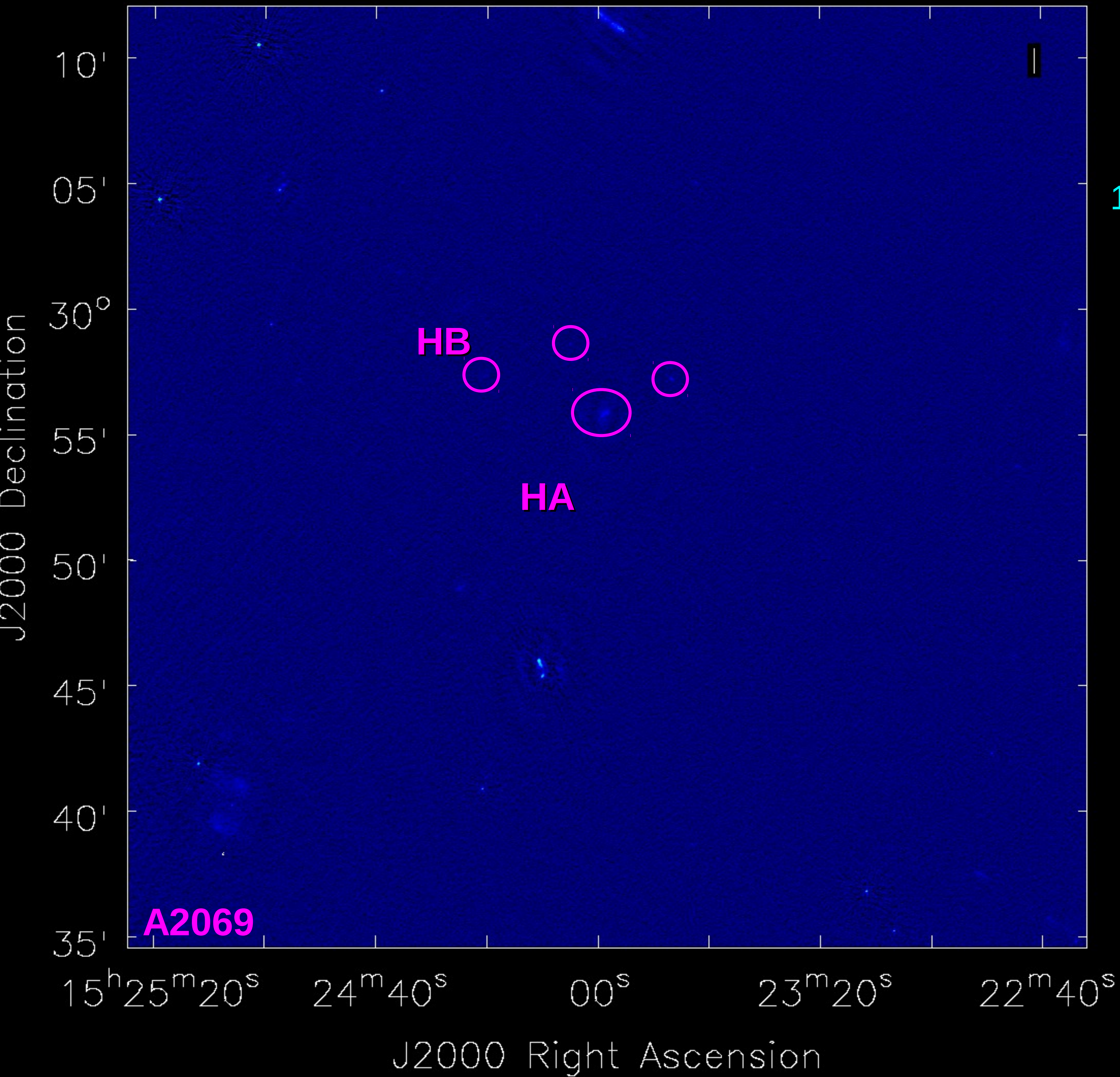
100/370 subbands used (27%)

beam: 11" × 9"
r.m.s.: 330 µJy/beam

identification of compact sources

diffuse components

LOFAR HBA radio map of Abell 2069 at 166 MHz



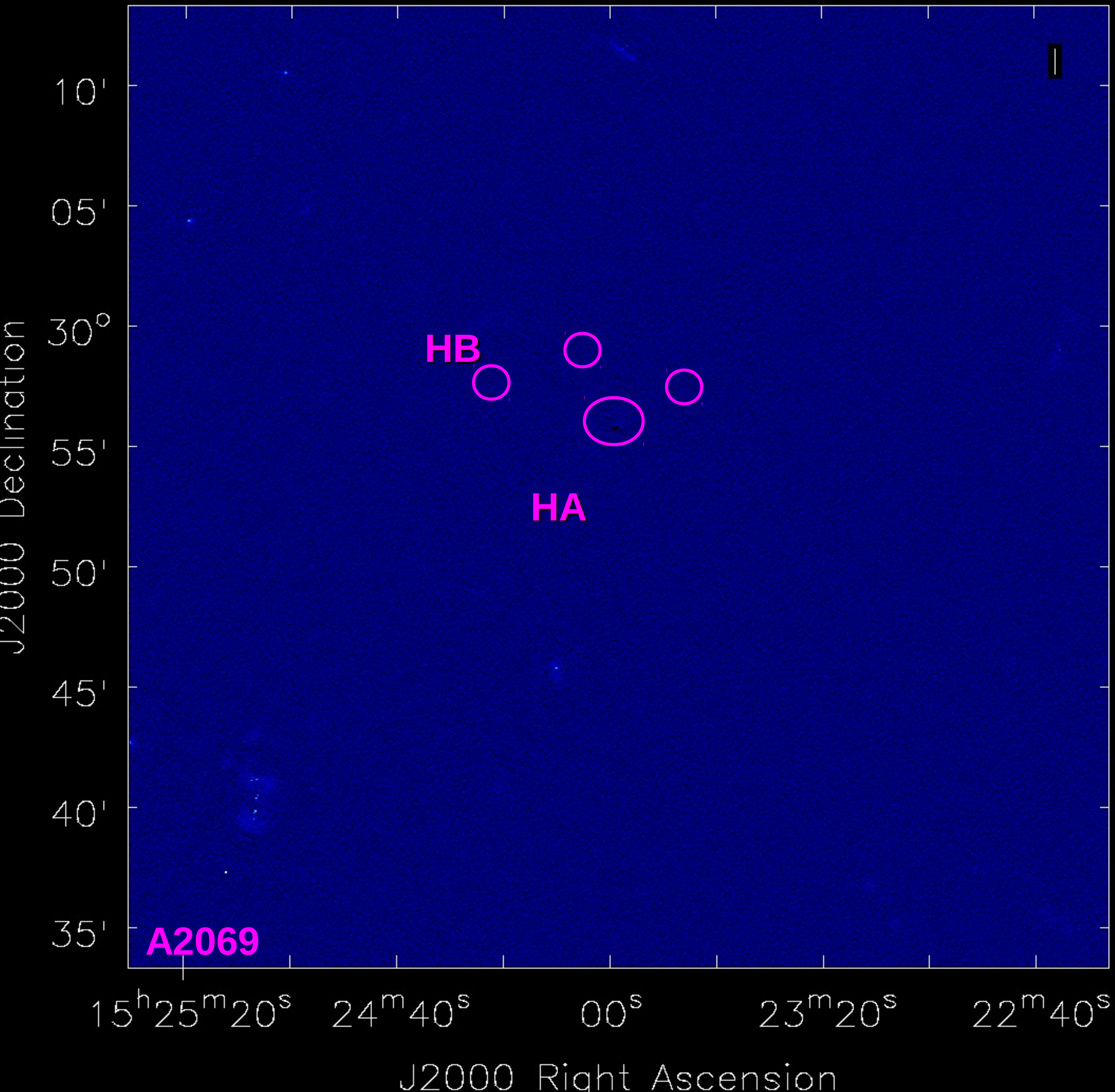
100/370 subbands used (27%)

beam: 5" × 3"
r.m.s.: 370 μJy/beam

identification of compact sources

diffuse components

LOFAR HBA radio map of Abell 2069 at 166 MHz



100/370 subbands used (27%)

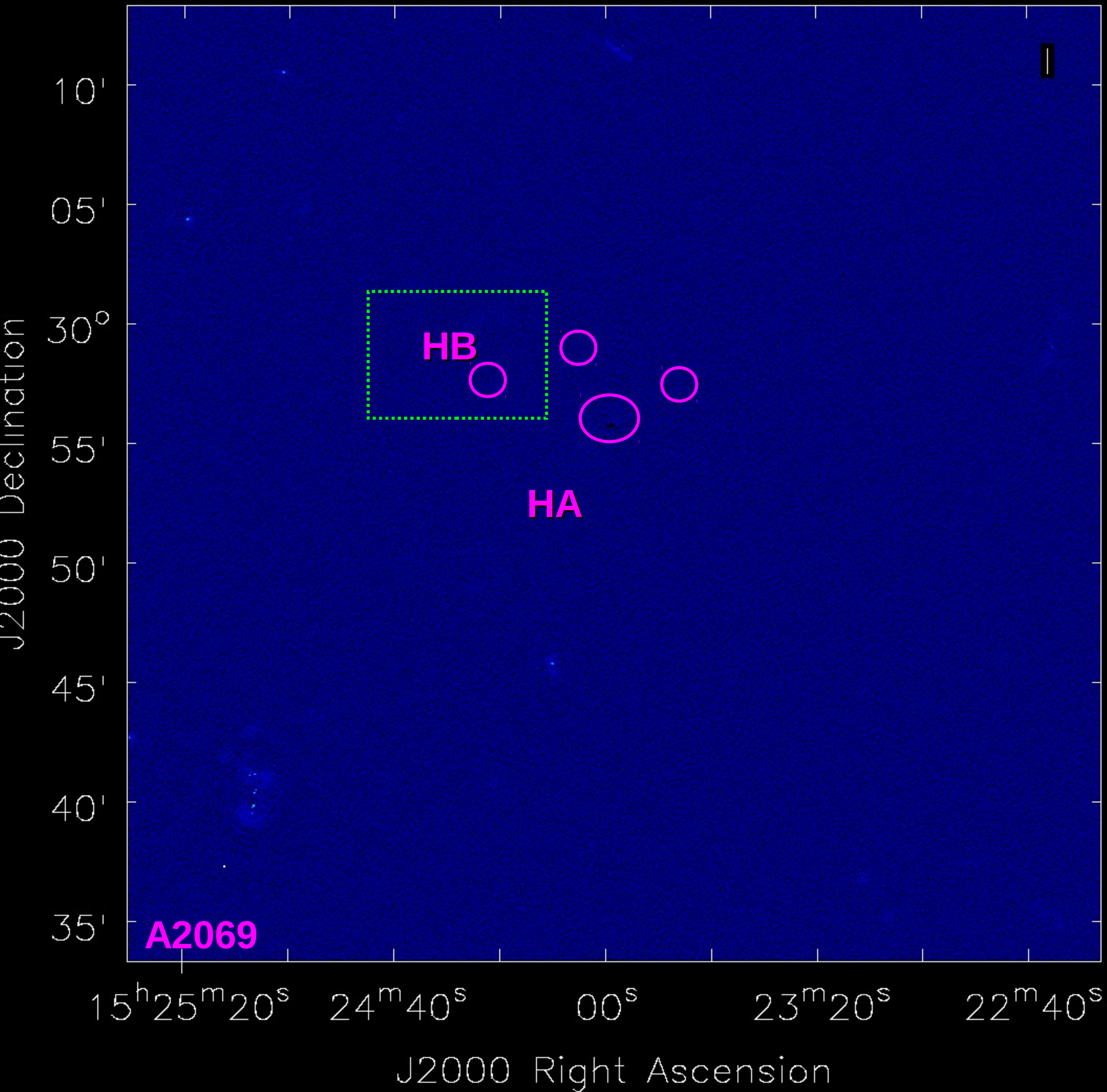
beam: 5" × 3"
r.m.s.: 370 μJy/beam

sources subtracted
beam applied

identification of compact sources

diffuse components

LOFAR HBA radio map of Abell 2069 at 166 MHz



100/370 subbands used
(27%)

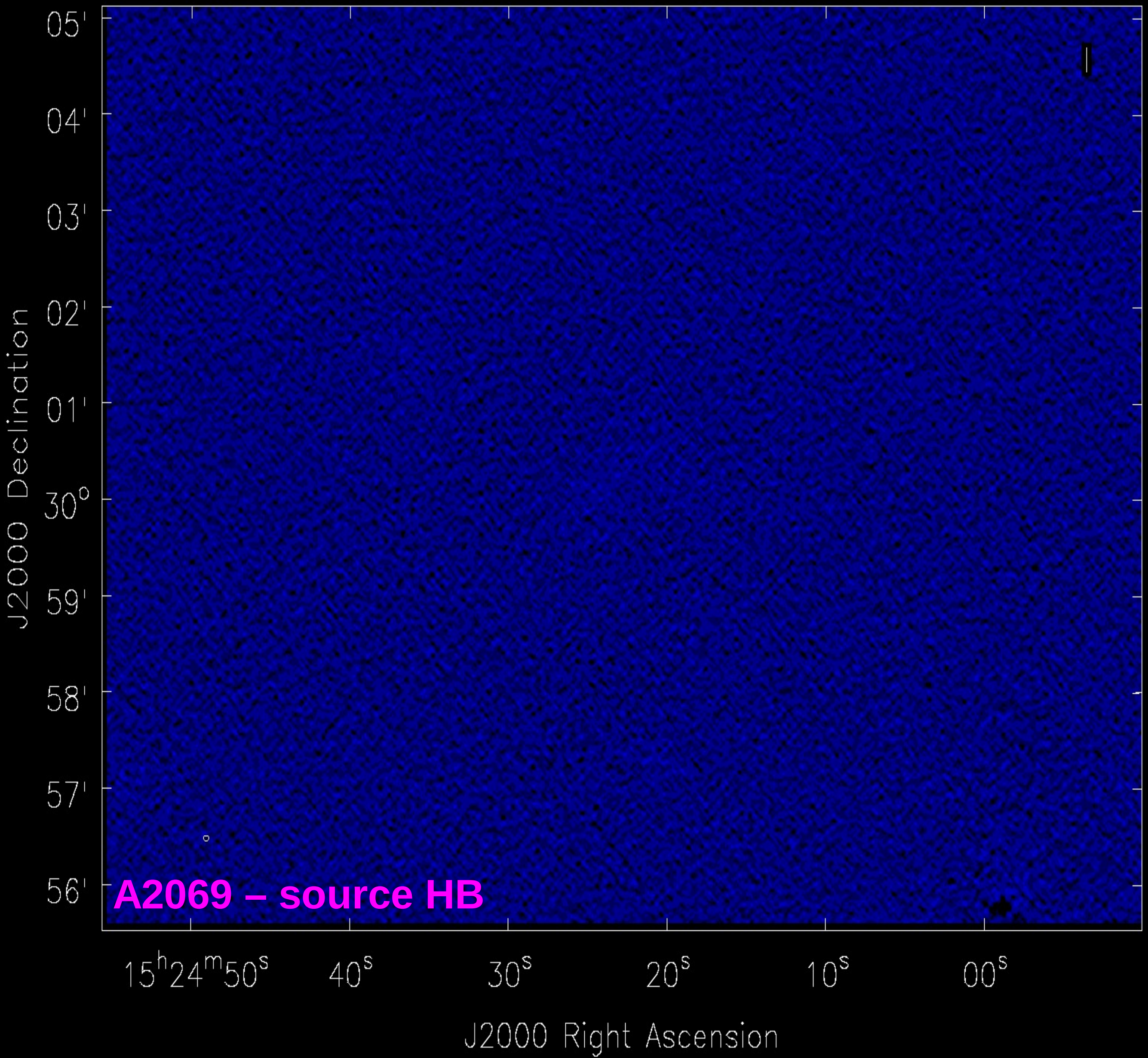
beam: 5" × 3"
r.m.s.: 370 μJy/beam

sources subtracted
beam applied

identification of
compact sources

diffuse
components

LOFAR HBA radio map of Abell 2069 at 166 MHz

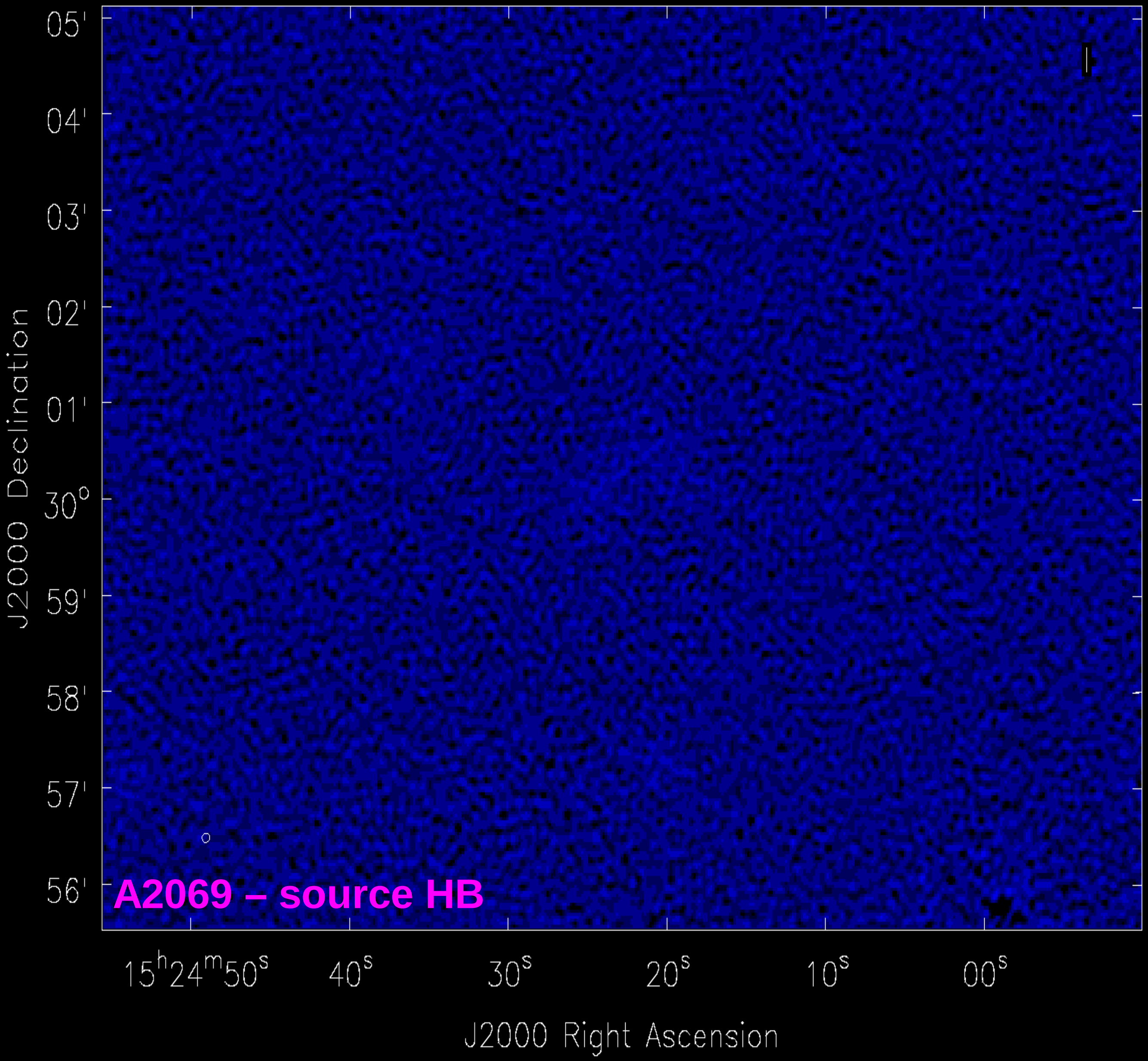


100/370 subbands used (27%)

beam: 5" × 3"
r.m.s.: 480 μJy/beam

sources subtracted
beam applied

LOFAR HBA radio map of Abell 2069 at 166 MHz

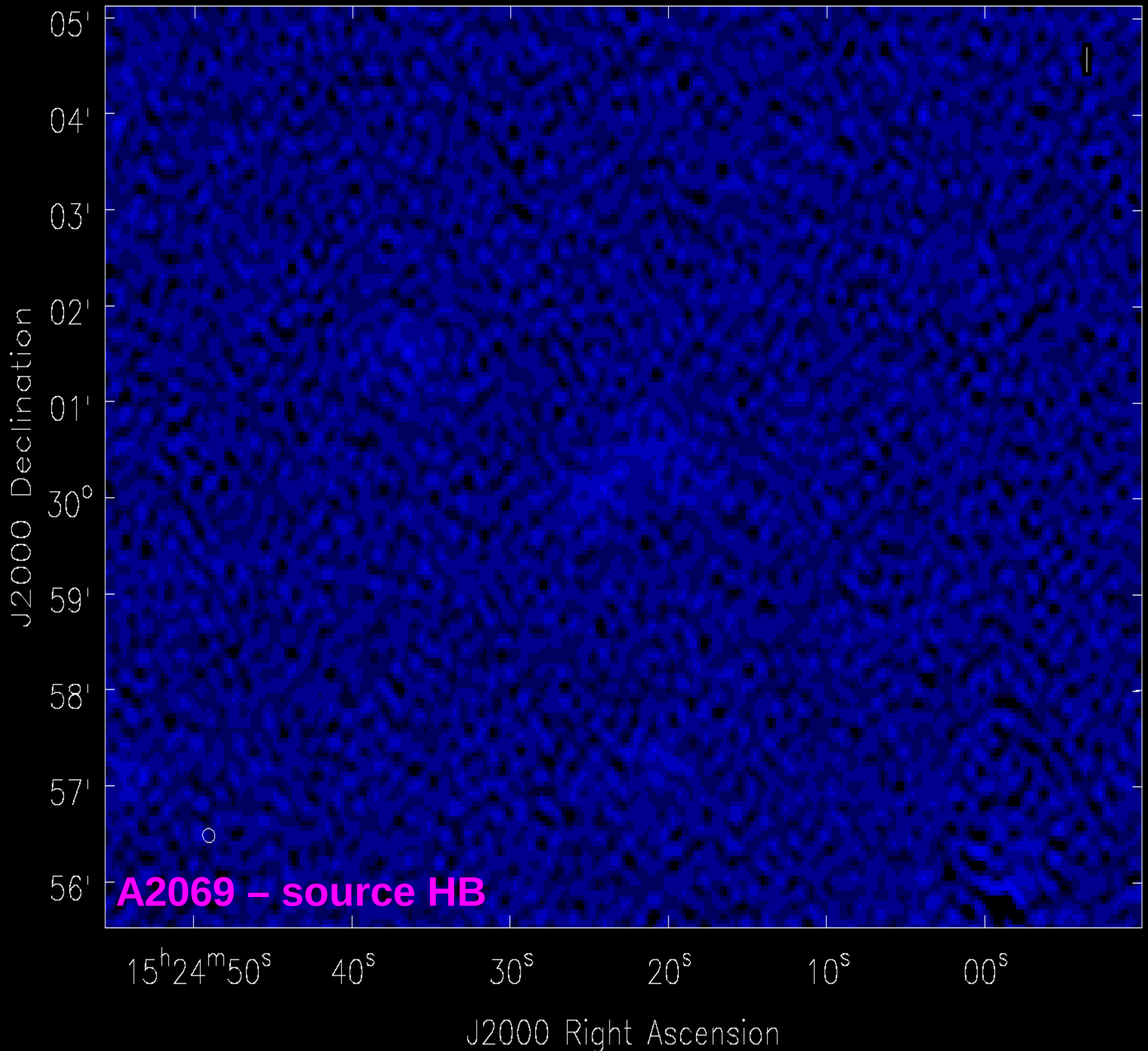


100/370 subbands used (27%)

beam: 6" × 6"
r.m.s.: 550 μJy/beam

sources subtracted
beam applied

LOFAR HBA radio map of Abell 2069 at 166 MHz

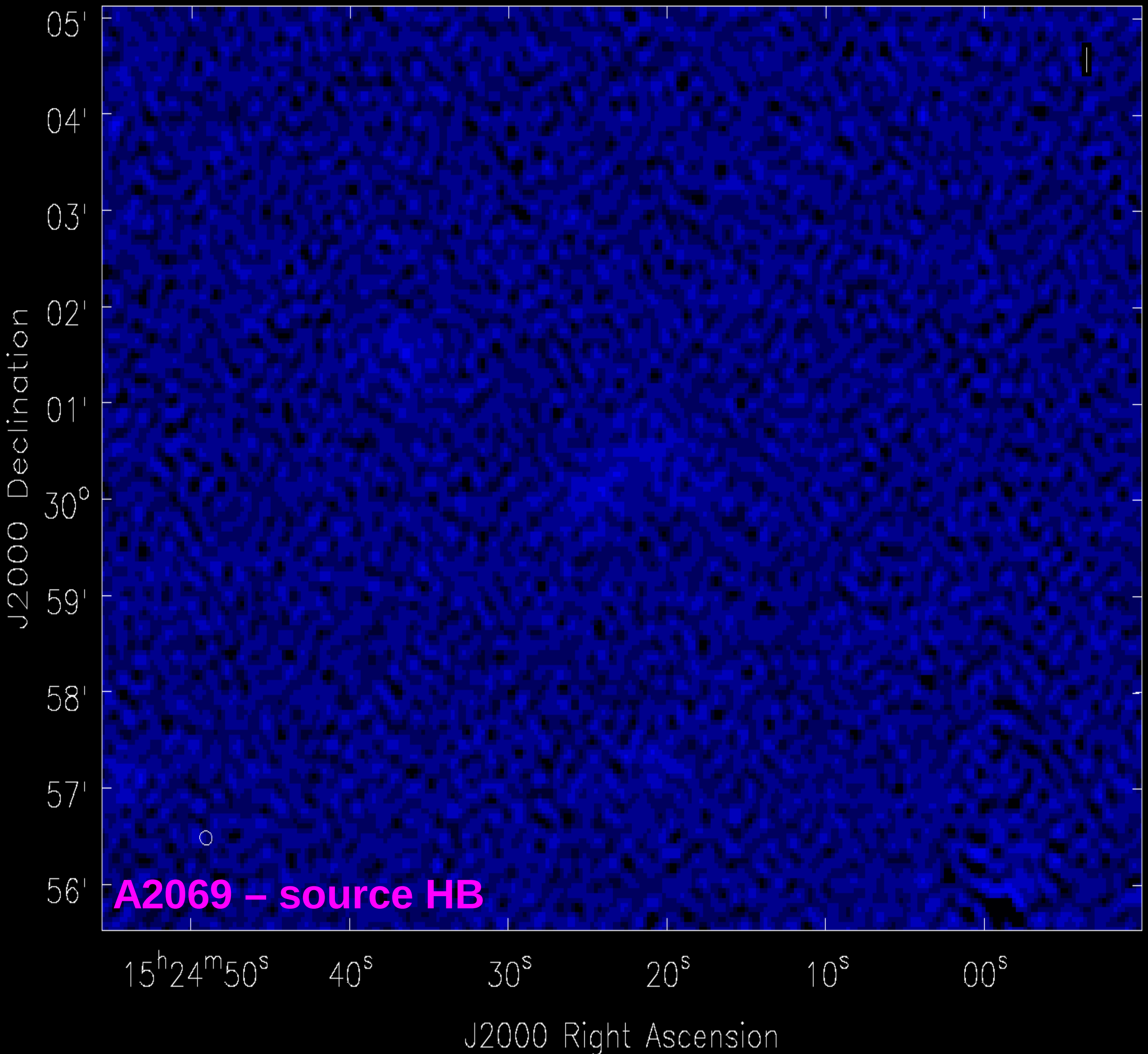


100/370 subbands used
(27%)

beam: 10" × 9"
r.m.s.: 550 μJy/beam

sources subtracted
beam applied

LOFAR HBA radio map of Abell 2069 at 166 MHz



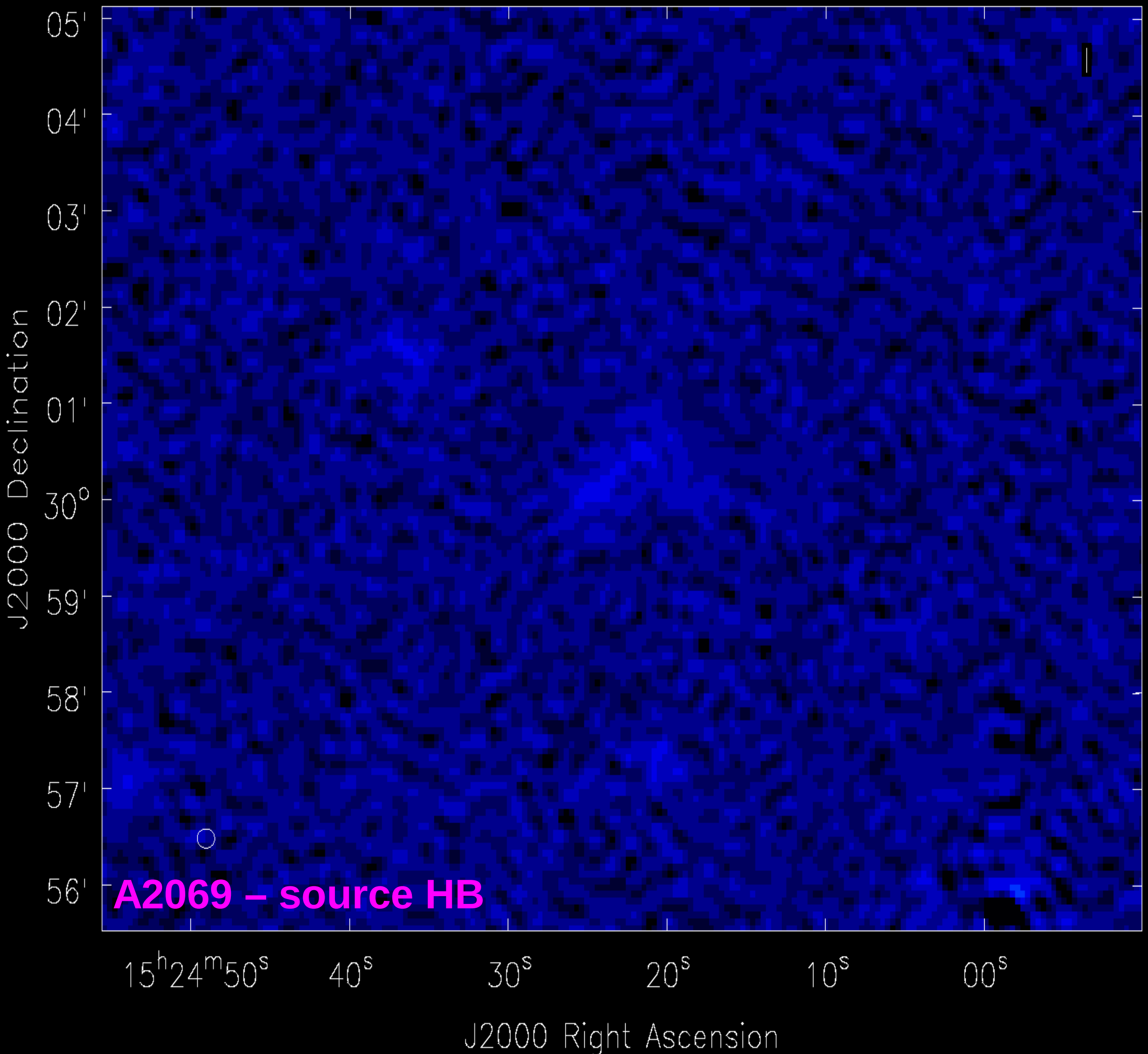
100/370 subbands used (27%)

beam: 10" × 9"
r.m.s.: 550 μJy/beam

sources subtracted
beam applied

recovered flux density: 0 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



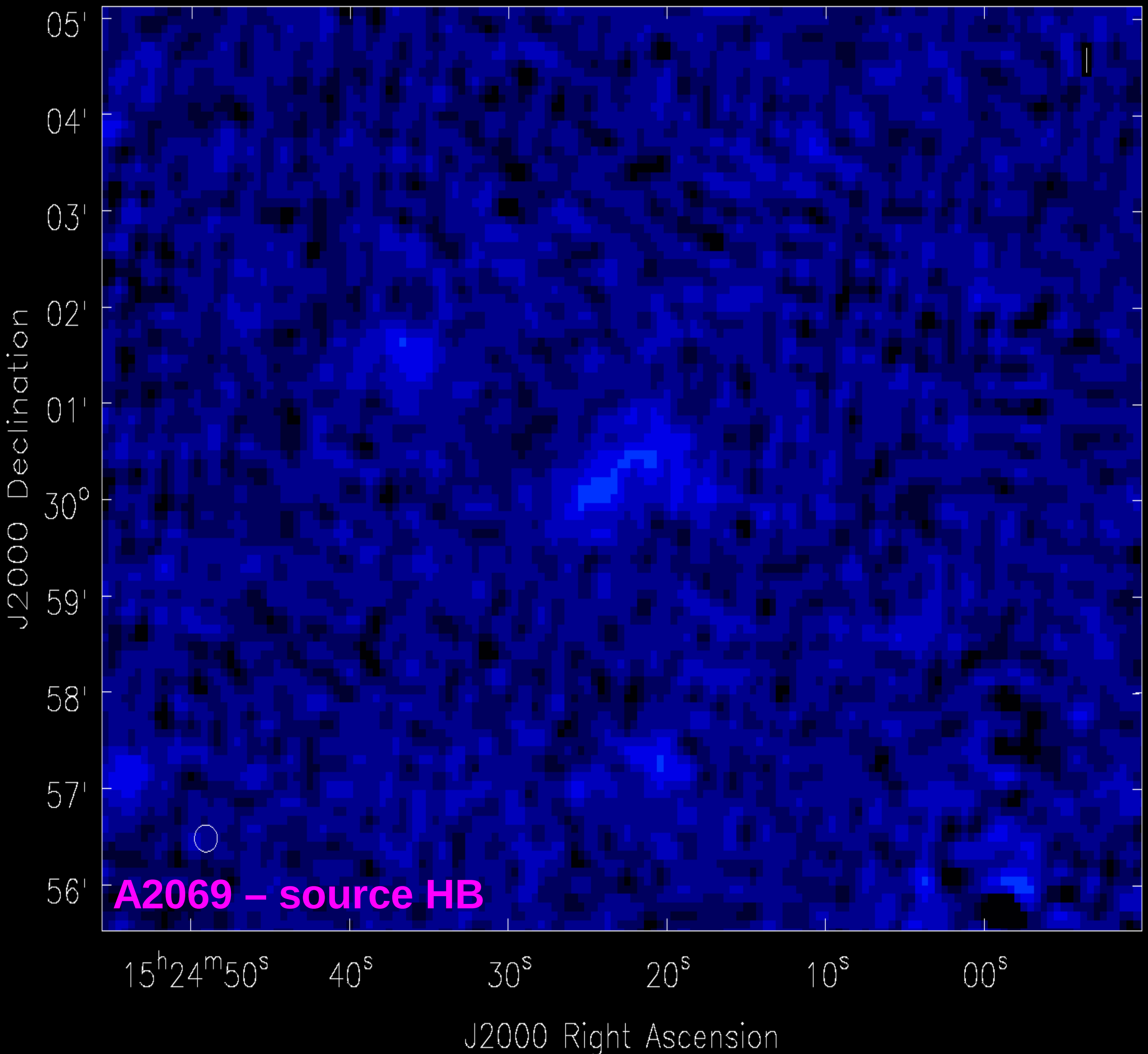
100/370 subbands used (27%)

beam: 14" × 12"
r.m.s.: 530 μJy/beam

sources subtracted
beam applied

recovered flux density: ~17 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



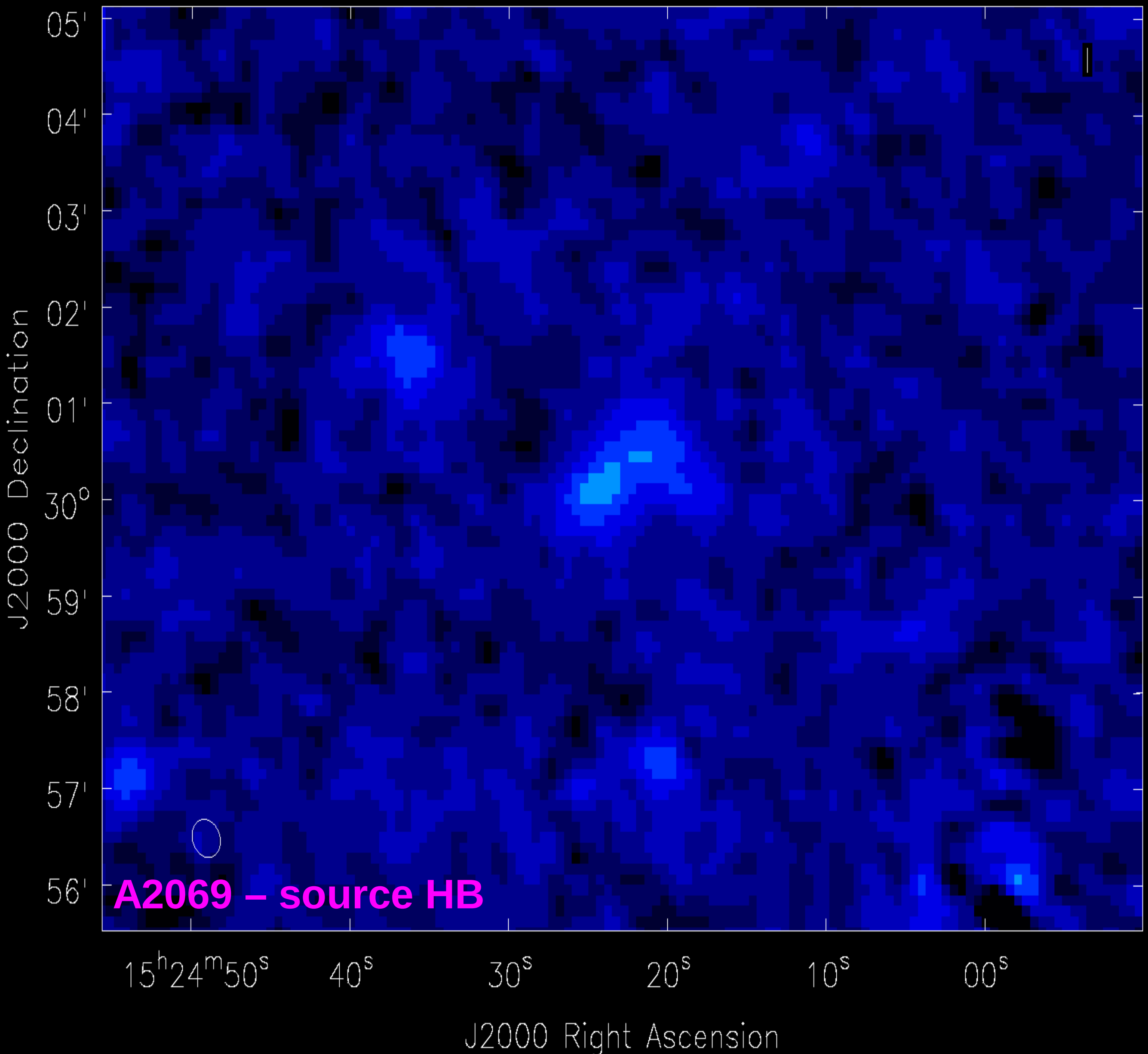
100/370 subbands used (27%)

beam: 19" × 17"
r.m.s.: 520 µJy/beam

sources subtracted
beam applied

recovered flux density: ~35 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



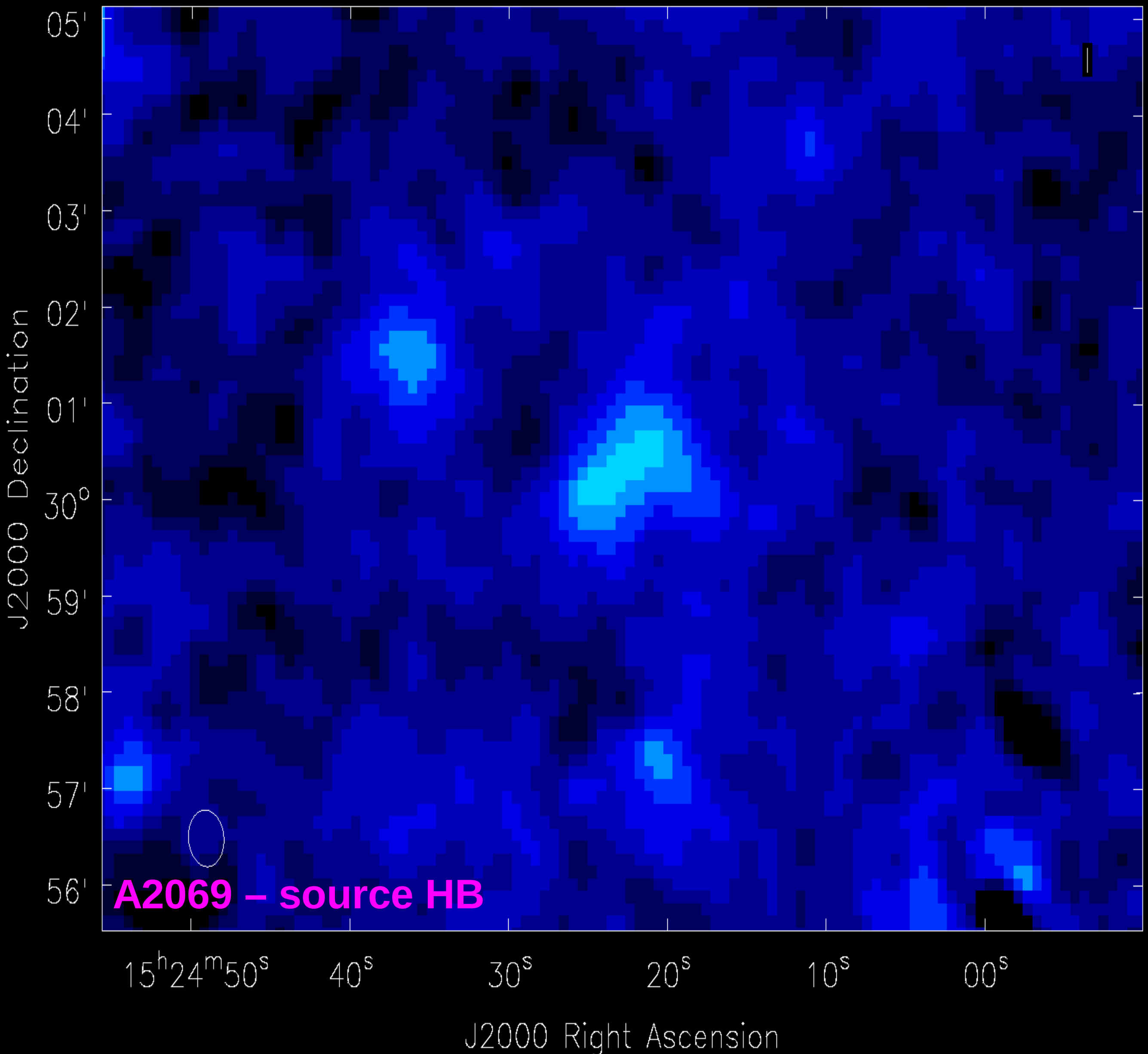
100/370 subbands used (27%)

beam: 25" × 22"
r.m.s.: 500 µJy/beam

sources subtracted
beam applied

recovered flux density: ~53 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



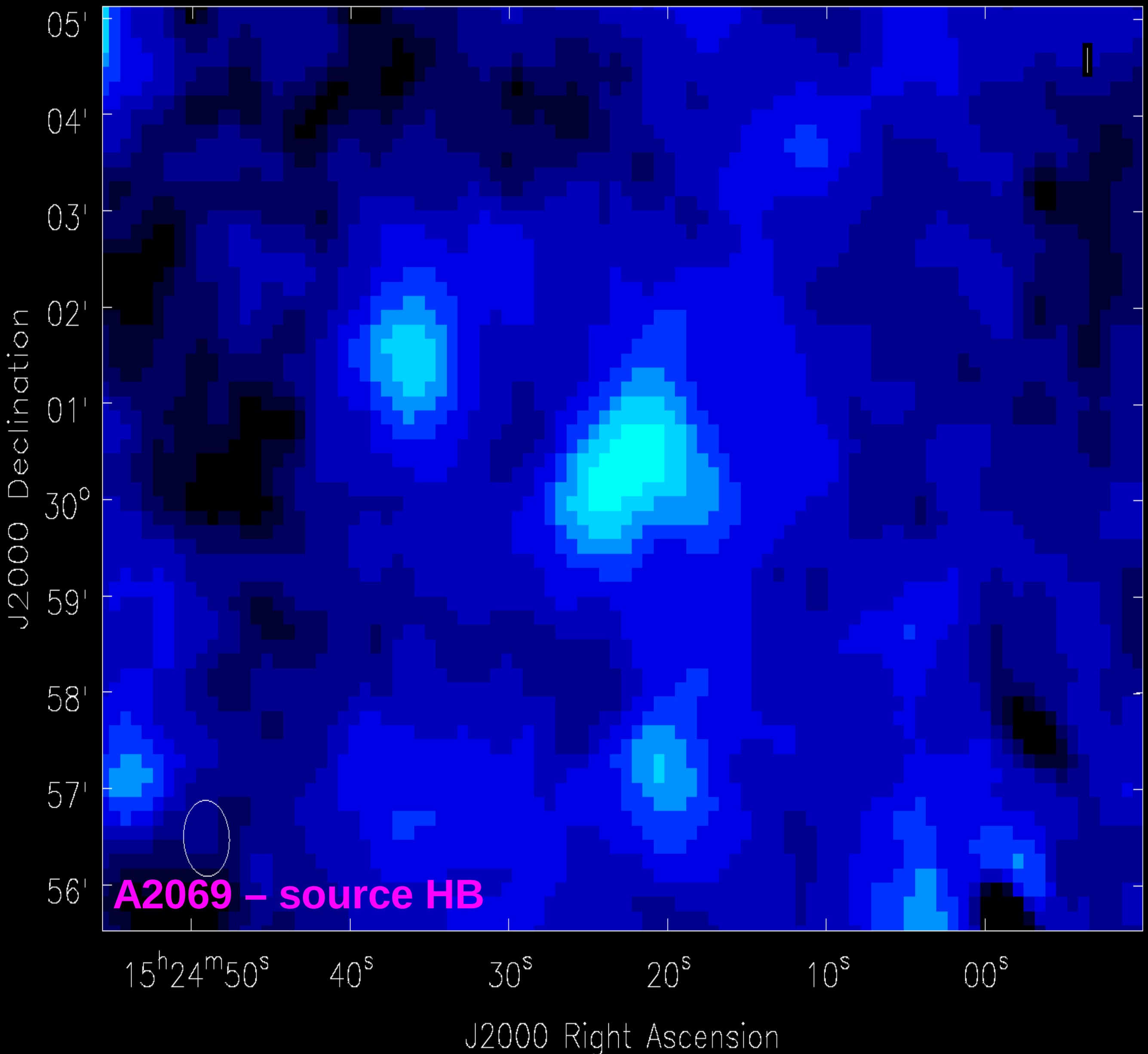
100/370 subbands used (27%)

beam: 35" × 29"
r.m.s.: 590 μJy/beam

sources subtracted
beam applied

recovered flux density: ~63 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



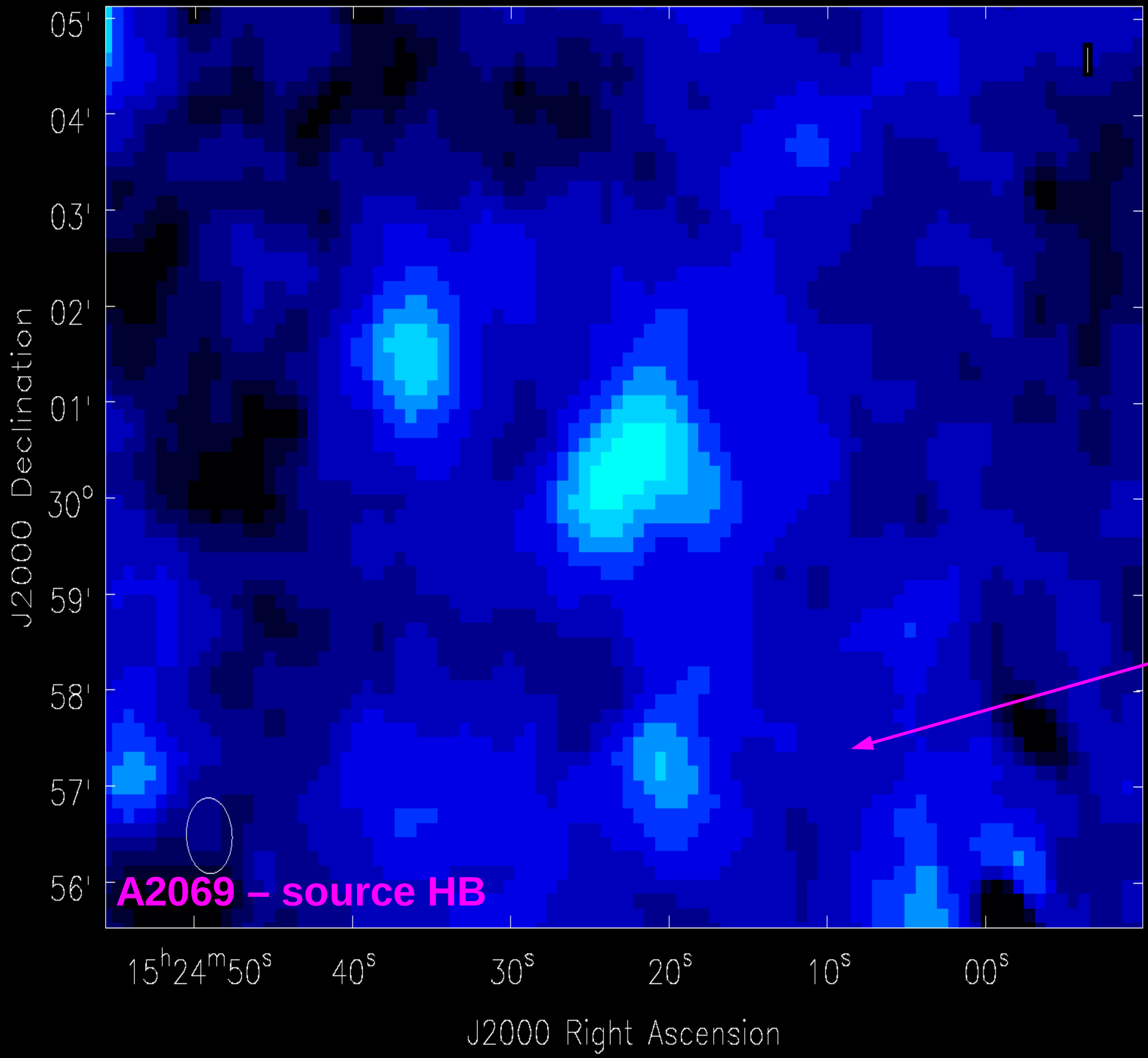
100/370 subbands used (27%)

beam: 47" × 37"
r.m.s.: 780 μJy/beam

sources subtracted
beam applied

recovered flux density: ~73 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



100/370 subbands used (27%)

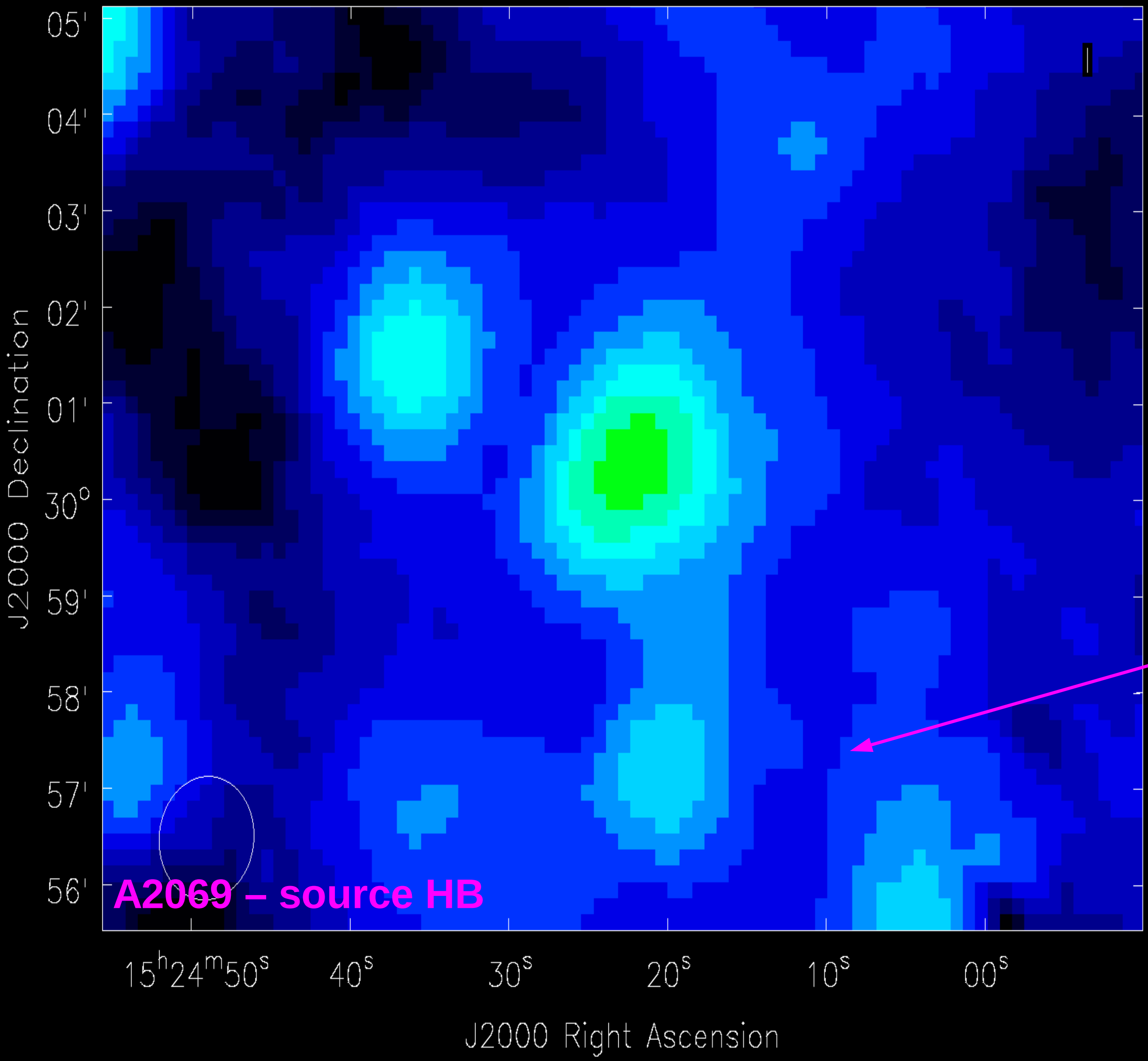
beam: 47" × 37"
r.m.s.: 780 μJy/beam

sources subtracted
beam applied

enhanced background signal

recovered flux density: ~73 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



100/370 subbands used (27%)

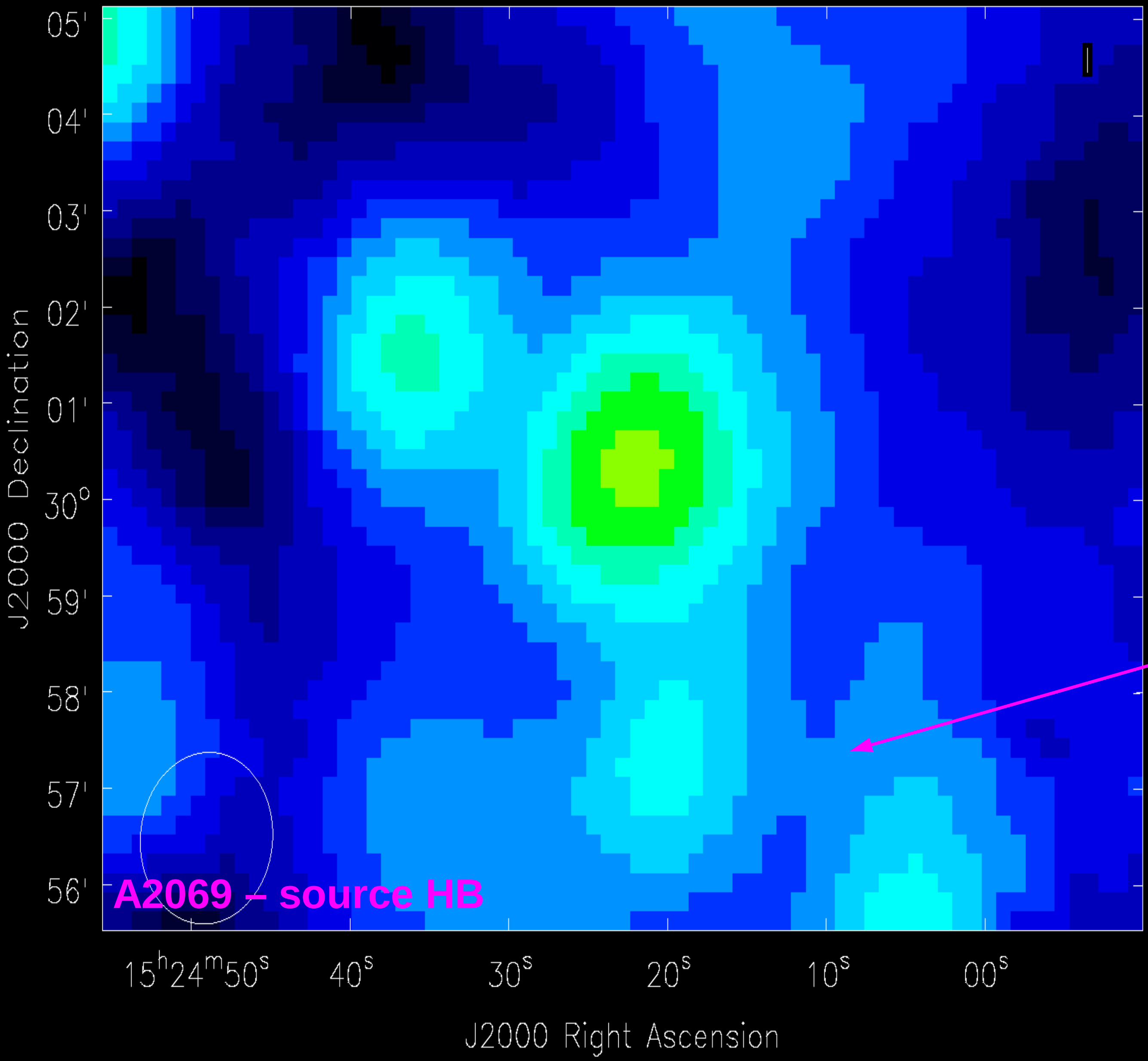
beam: 79" × 78"
r.m.s.: 1.1 mJy/beam

sources subtracted
beam applied

enhanced background signal

recovered flux density: ~74 mJy

LOFAR HBA radio map of Abell 2069 at 166 MHz



100/370 subbands used (27%)

beam: 110" × 105"
r.m.s.: 1.4 mJy/beam

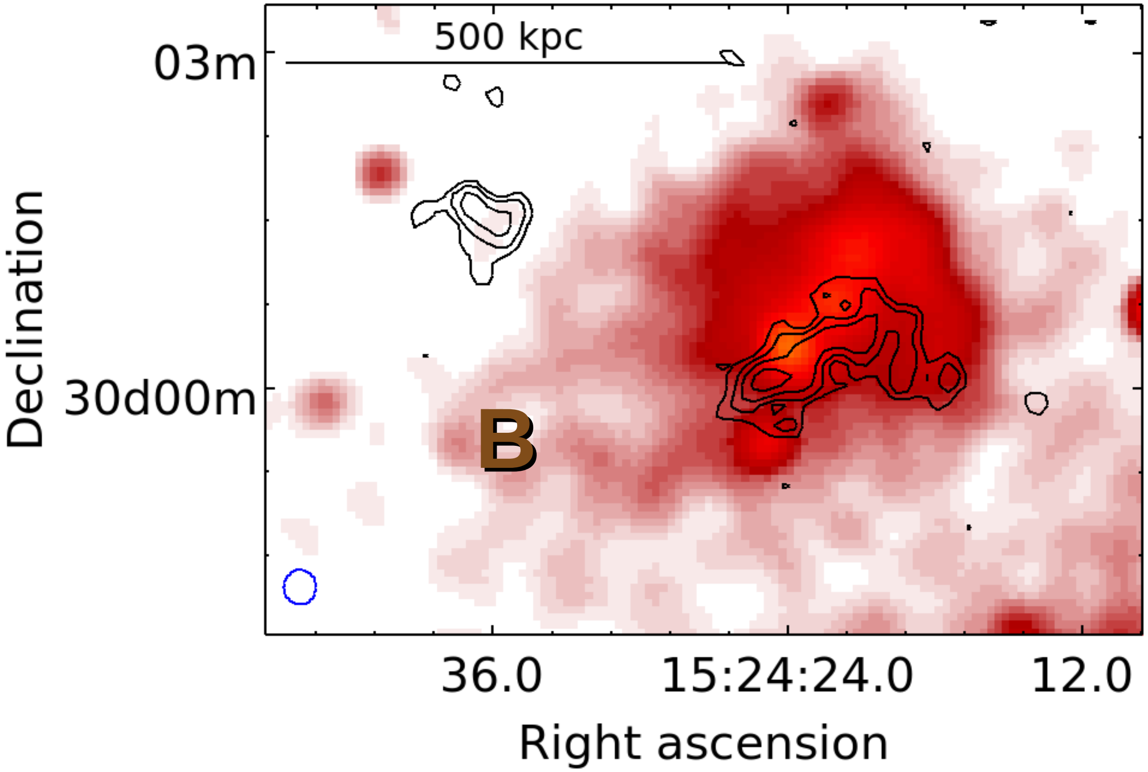
sources subtracted
beam applied

enhanced background signal

recovered flux density: ~71 mJy

beam: 19" × 17"
recovered flux density: ~35 mJy

(contours: [1.5, 2.1 , 3.0, 4.2] mJy/beam, r.m.s.: 0.5 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)



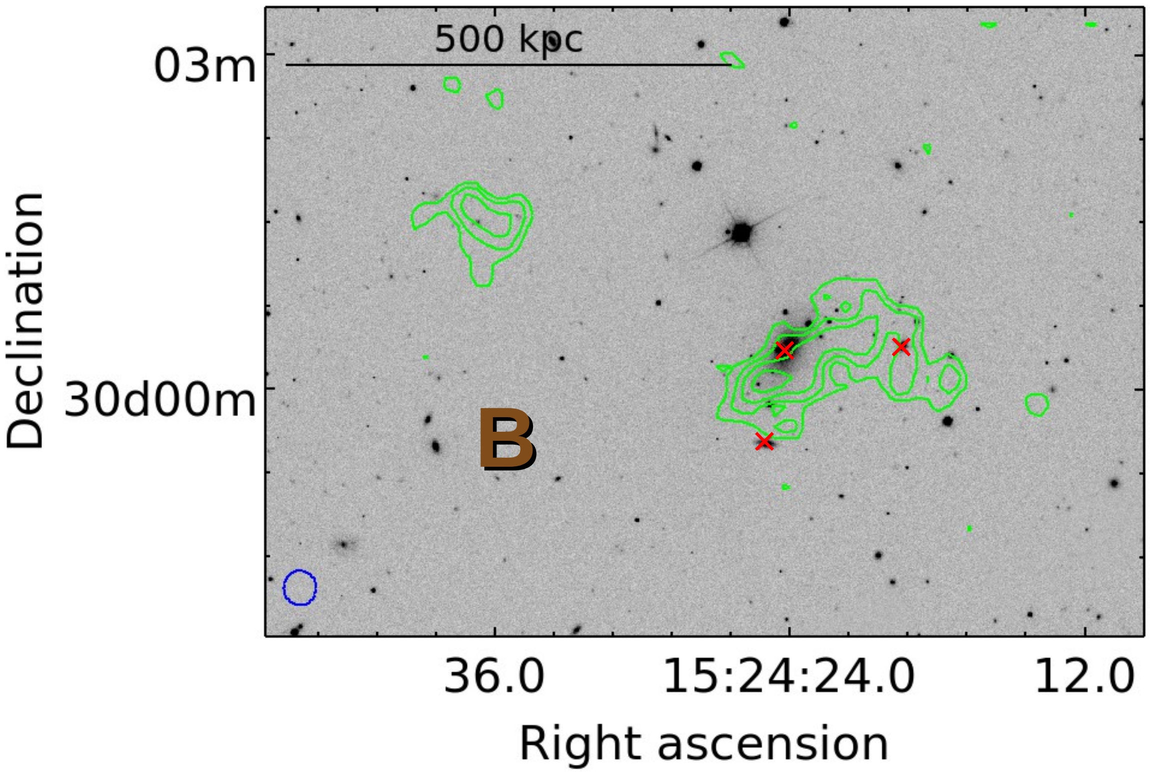
- half of the flux density is concentrated at the southern boundary but still:

3) fossil radio plasma of a dying radio galaxy

beam: 19" × 17"
recovered flux density: ~35 mJy

× cluster members

(contours: [1.5, 2.1 , 3.0, 4.2] mJy/beam, r.m.s.: 0.5 mJy/beam)
(background – SDSS DR12 r-band image)

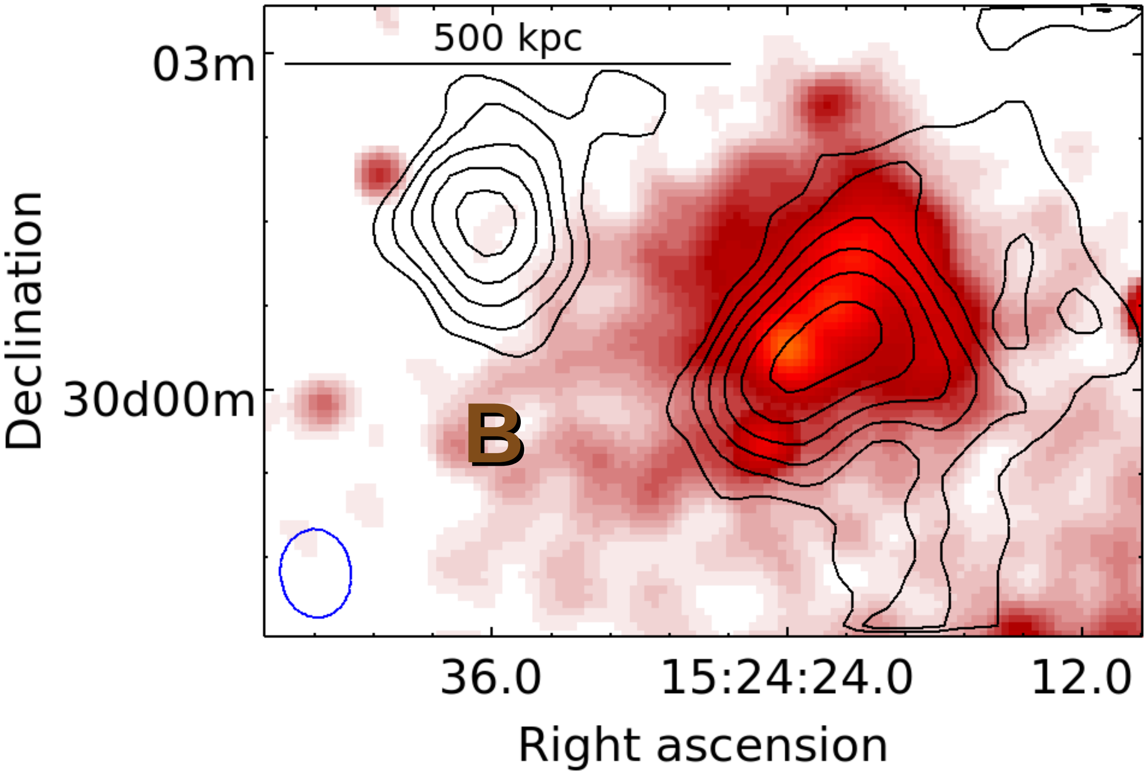


- no obvious correlation to cluster galaxies
- half of the flux density is concentrated at the southern boundary

2) fossil radio plasma distributed within cluster volume
cold front → due to **gas sloshing**?

beam: 47" × 37"
recovered flux density: ~73 mJy

(contours: [2.3, 3.3 , 4.7, 6.6, 9.4, 13.2] mJy/beam, r.m.s.: 0.8 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)

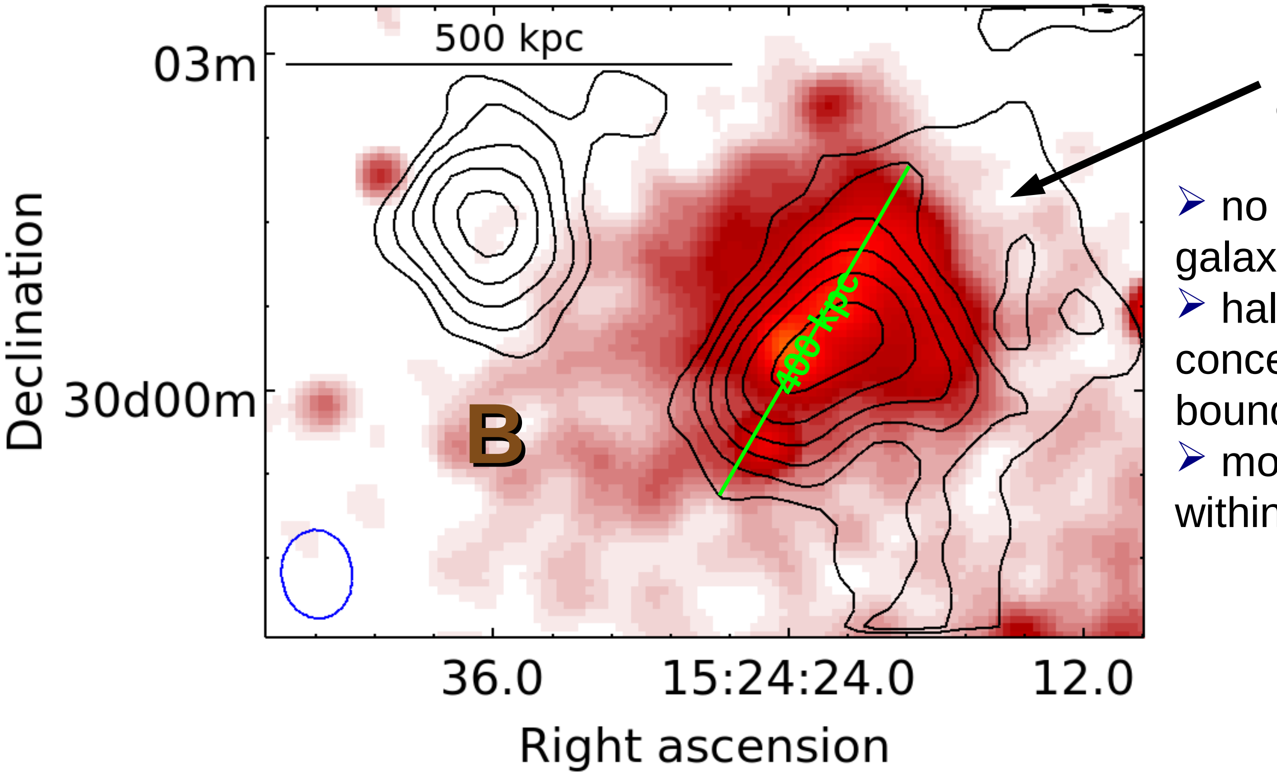


- no obvious correlation to cluster galaxies
- half of the flux density is concentrated at the southern boundary
- more extended emission confined within subcluster's boundaries

2) fossil radio plasma distributed within cluster volume
cold front → due to **gas sloshing**?

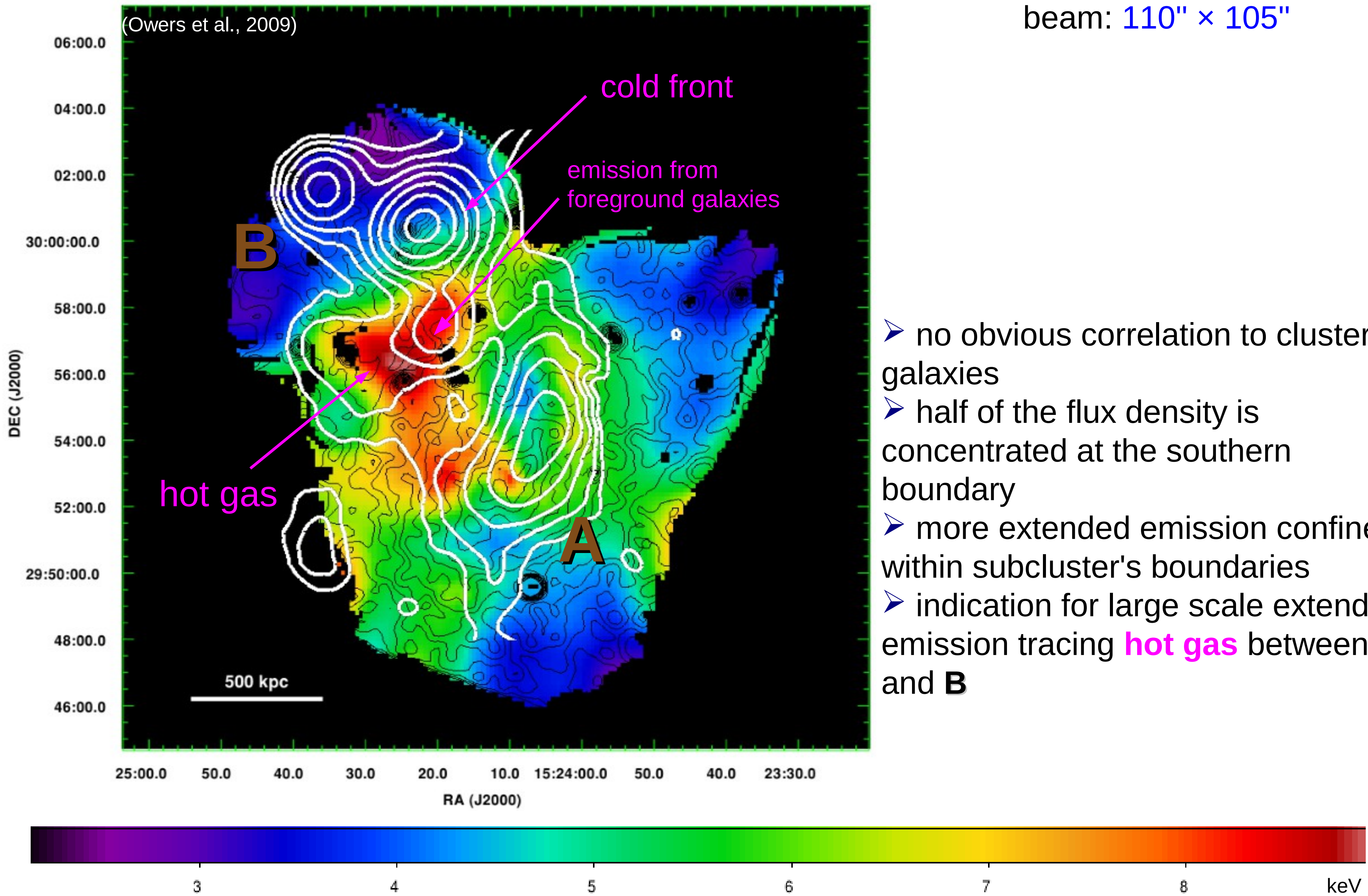
beam: 47" × 37"
recovered flux density: ~73 mJy

(contours: [2.3, 3.3 , 4.7, 6.6, 9.4, 13.2] mJy/beam, r.m.s.: 0.8 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)



- no obvious correlation to cluster galaxies
- half of the flux density is concentrated at the southern boundary
- more extended emission confined within subcluster's boundaries

(ICM temperature map from X-ray data by Chandra 0.5 – 7 keV)

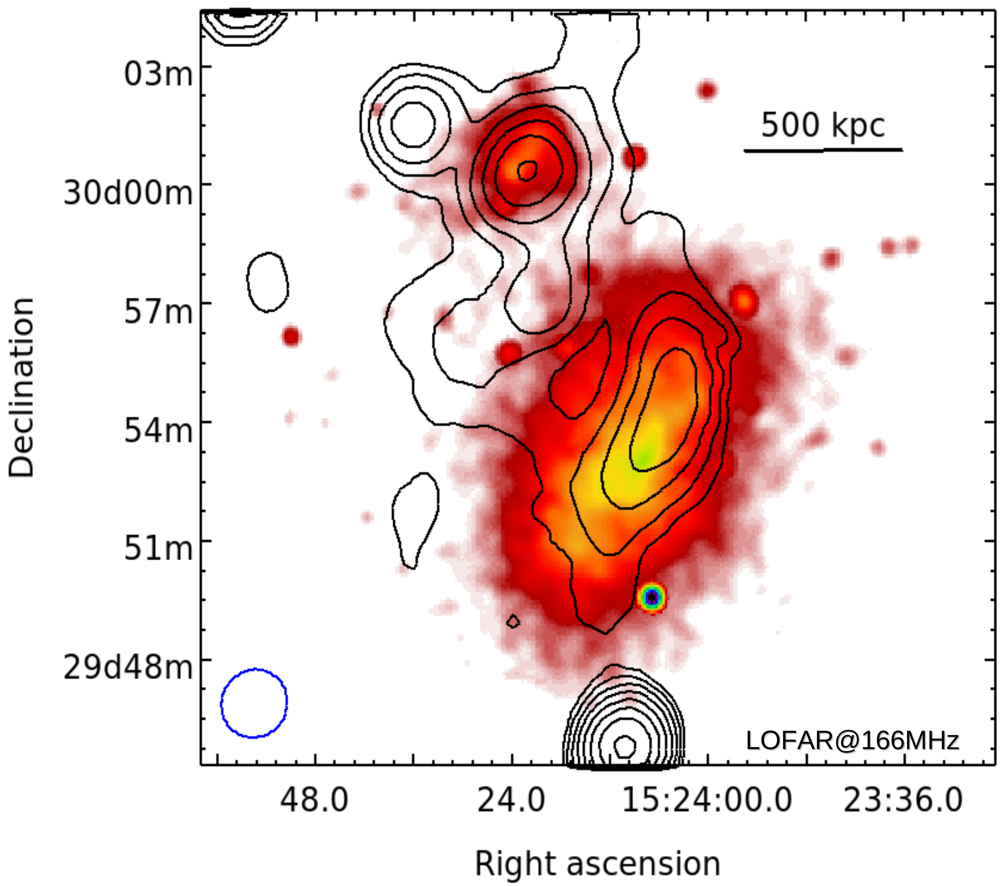


beam: 110" × 105"

- no obvious correlation to cluster galaxies
- half of the flux density is concentrated at the southern boundary
- more extended emission confined within subcluster's boundaries
- indication for large scale extended emission tracing **hot gas** between **A** and **B**

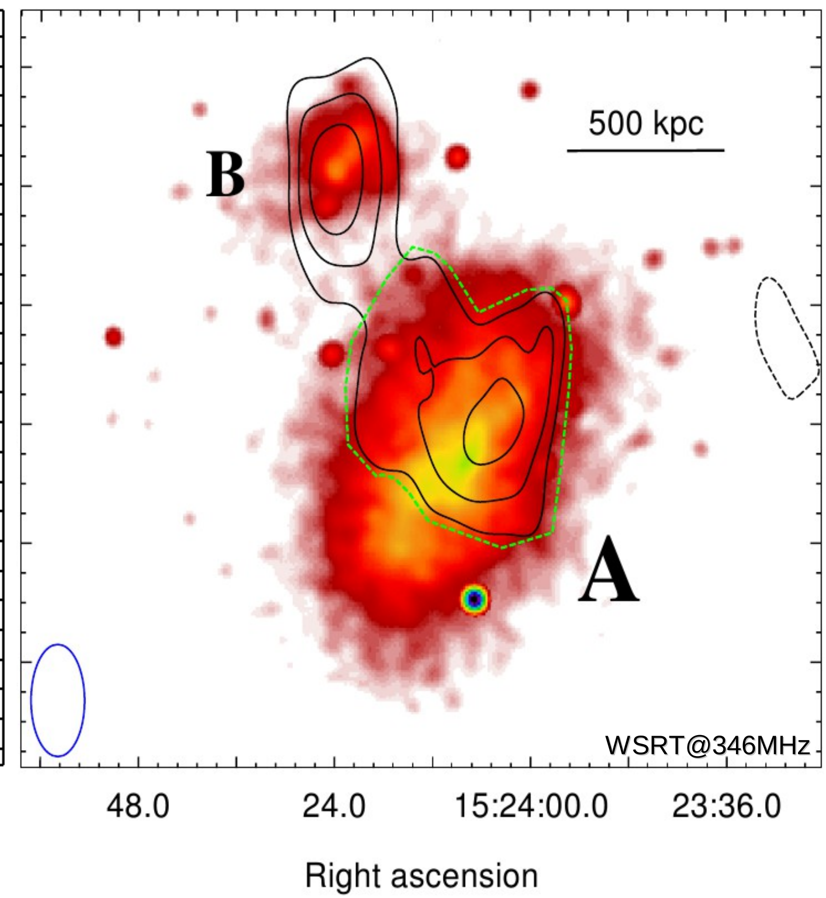
LOFAR HBA vs. WSRT – Abell 2069

(contours: $3\sigma_{r.m.s.}$ beam: 106'' × 103'', r.m.s.: 1.4 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)



flux density HA: **90 ± 14** mJy
flux density HB: **~63*** mJy
(*estimate: without extended background contribution)

(contours: $3\sigma_{r.m.s.}$ beam: 182'' × 91'', r.m.s.: 1.0 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)

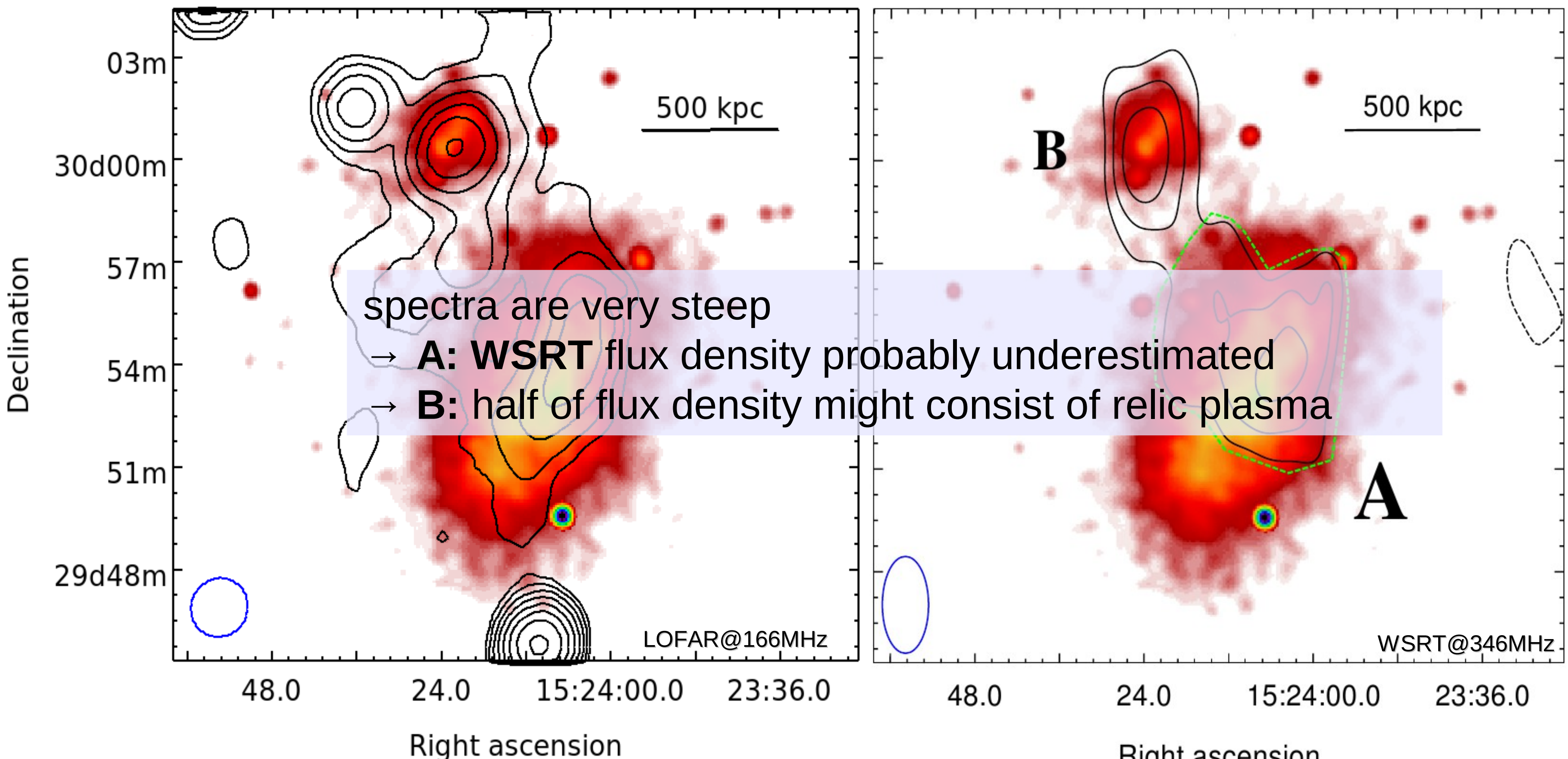


flux density HA: **25 ± 9** mJy
flux density HB: **15 ± 2** mJy

LOFAR HBA vs. WSRT – Abell 2069

(contours: $3\sigma_{r.m.s.}$ beam: 106'' × 103'', r.m.s.: 1.4 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)

(contours: $3\sigma_{r.m.s.}$ beam: 182'' × 91'', r.m.s.: 1.0 mJy/beam)
(colorscale – X-ray Chandra 0.5 – 7 kev)



spectra are very steep
→ **A: WSRT** flux density probably underestimated
→ **B:** half of flux density might consist of relic plasma

flux density HA: **90 ± 14** mJy
flux density HB: **~63*** mJy
(*estimate: without extended background contribution)

flux density HA: **25 ± 9** mJy
flux density HB: **15 ± 2** mJy

Summary: Abell 2069 with LOFAR

LOFAR HBA

- ✔ good data quality → basic pipeline already offers decent images
- ✔ highly capable of discriminating compact from extended sources

Abell 2069

- ✔ clear confirmation of radio halo in main component **A** (morphology also better coincides with X-ray than previously)
- source in companion **B** is **extended** and confined within subcluster if *halo-like* → suggests **turbulent reacceleration** caused by gas sloshing

→ still: low frequency high resolution spectral index maps are necessary to properly classify this source!

location	main component (**A**)	companion (**B**)	
flux density	90 ± 14 mJy	~63 mJy	@166 MHz
type	**radio halo**	**uncertain**	

Thank you for your attention!