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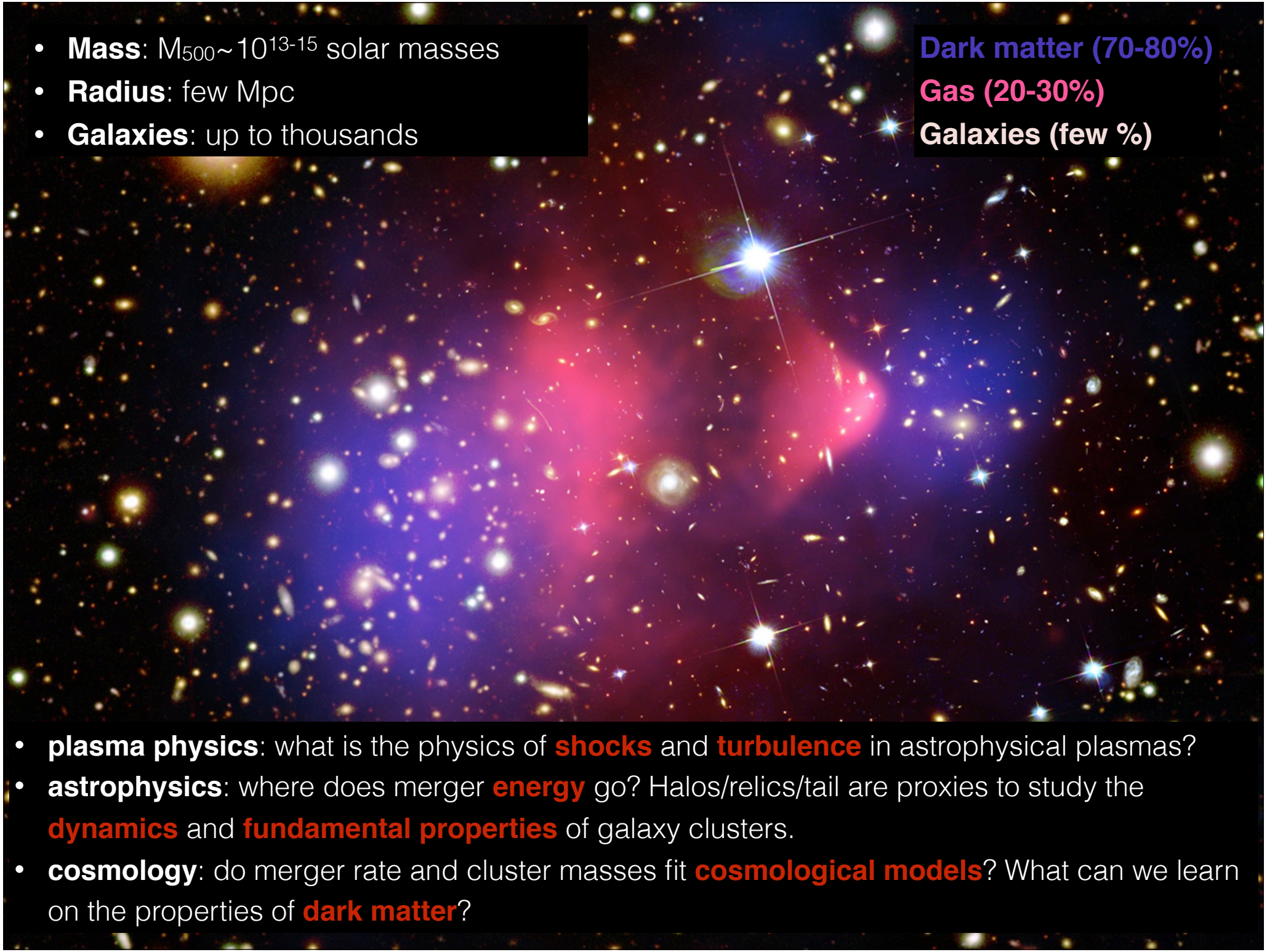
Leiden University
online version: bit.do/lowfreq
LOFAR ASTRON
Galaxy clusters at the lowest frequencies
Albuquerque - 3/12/2015


• **Mass**: M_{500}~$10^{13\text{-}15}$ solar masses
• **Radius**: few Mpc
• **Galaxies**: up to thousands
Dark matter (70-80%)
Gas (20-30%)
Galaxies (few %)
• **plasma physics**: what is the physics of **shocks** and **turbulence** in astrophysical plasmas?
• **astrophysics**: where does merger **energy** go? Halos/relics/tail are proxies to study the **dynamics** and **fundamental properties** of galaxy clusters.
• **cosmology**: do merger rate and cluster masses fit **cosmological models**? What can we learn on the properties of **dark matter**?

Taxonomy of cluster-sources at low-frequency

Mergers

- **Radio halo**: central, unpolarized, Mpc-size
  - **turbulence** (re)acceleration
- **Radio relic**: periferal, polarized, Mpc-size
  - **shock** (re)acceleration
- **Radio phoenix**: central, ~100 kpc-size
  - **compression** of old AGN lobes

This talk

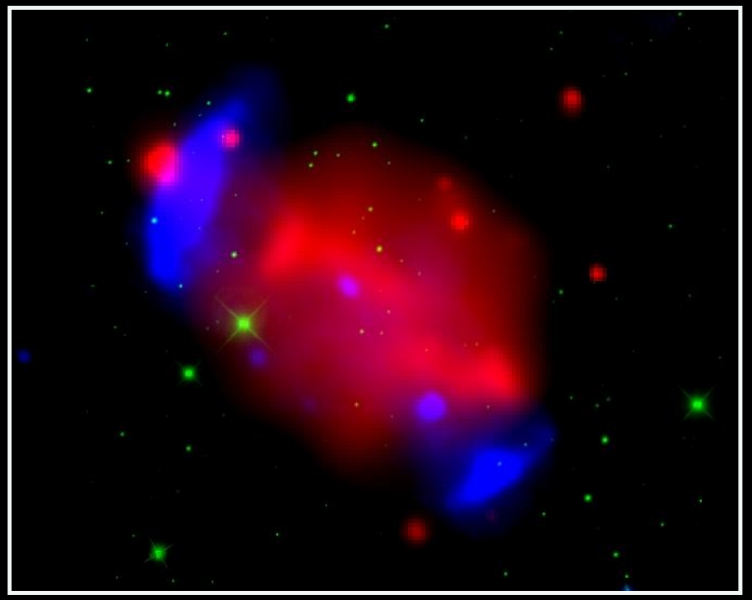
Relics: Mpc-long shock waves

MACSJ1752.0+4440

X-ray: XMM-Newton (Ebeling et al. 2013)

Optical: SDSS

Radio (325 Mhz): GMRT (Bonafede et al. 2012)



Double relics
(only 15 cases)

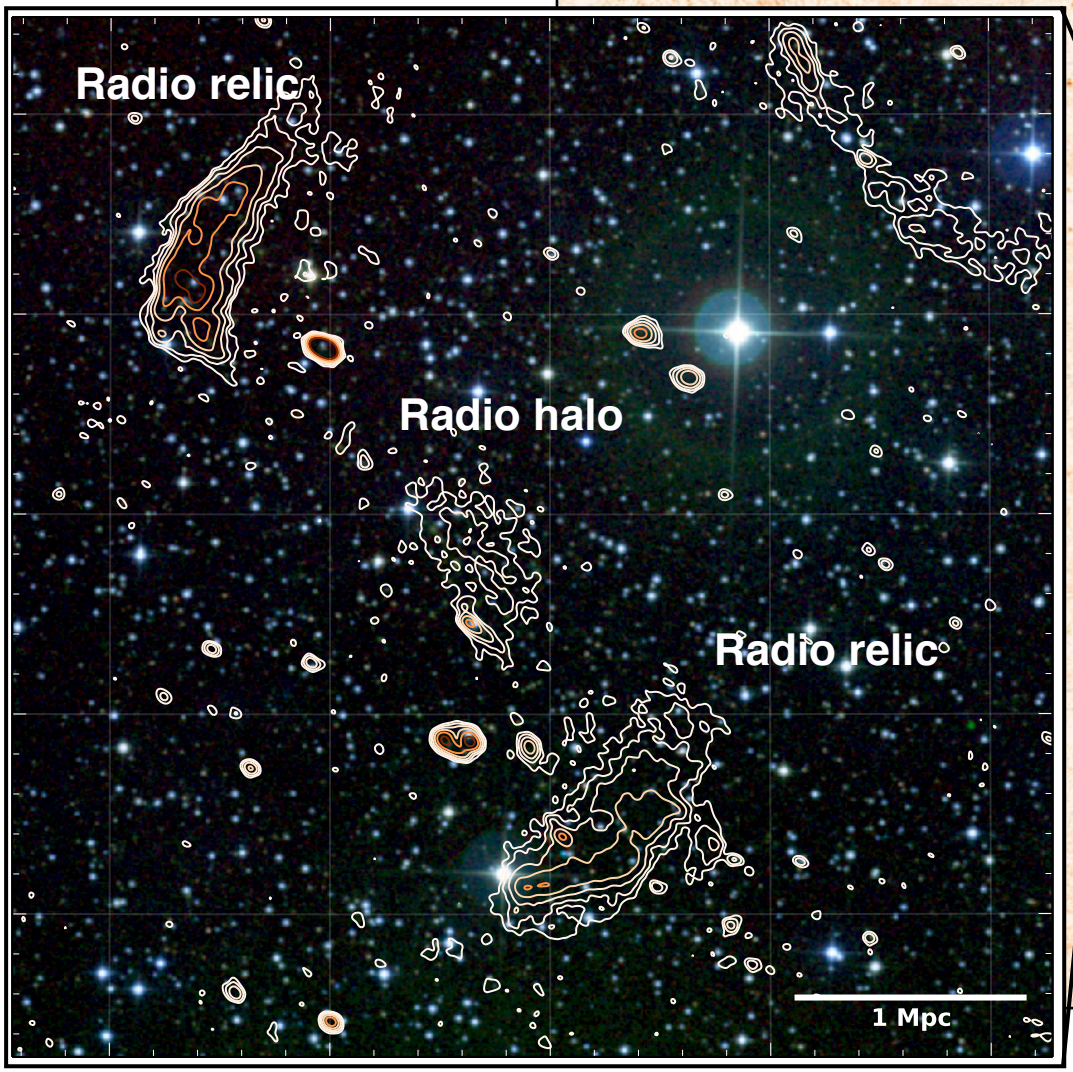
- Extended radio sources
- Cluster peripheral regions
- Low radio brightness
- Steep Spectrum $\alpha < -1$
- Polarized 20-30%

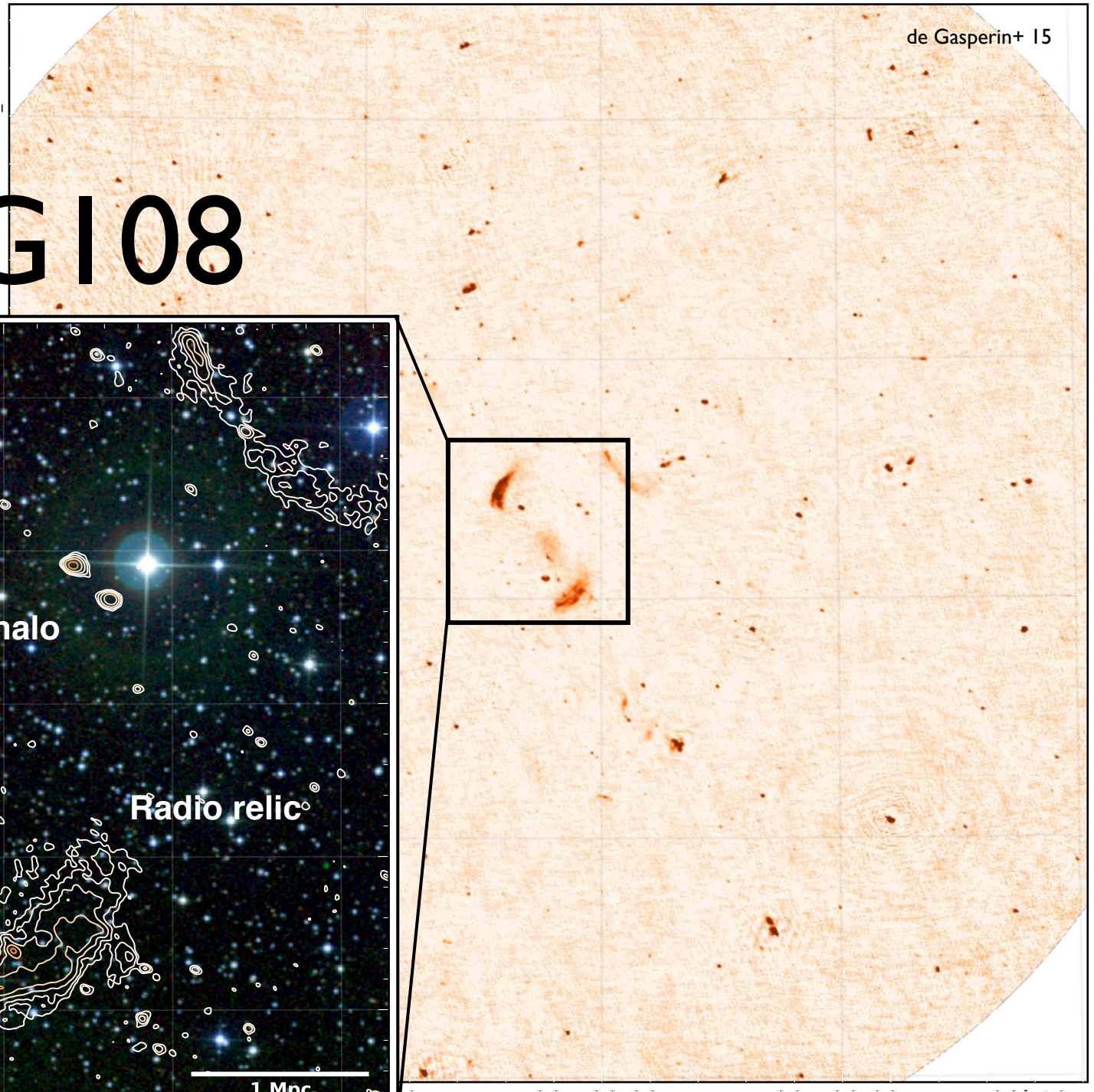
Credits: vanWeeren

$z = 0.334$

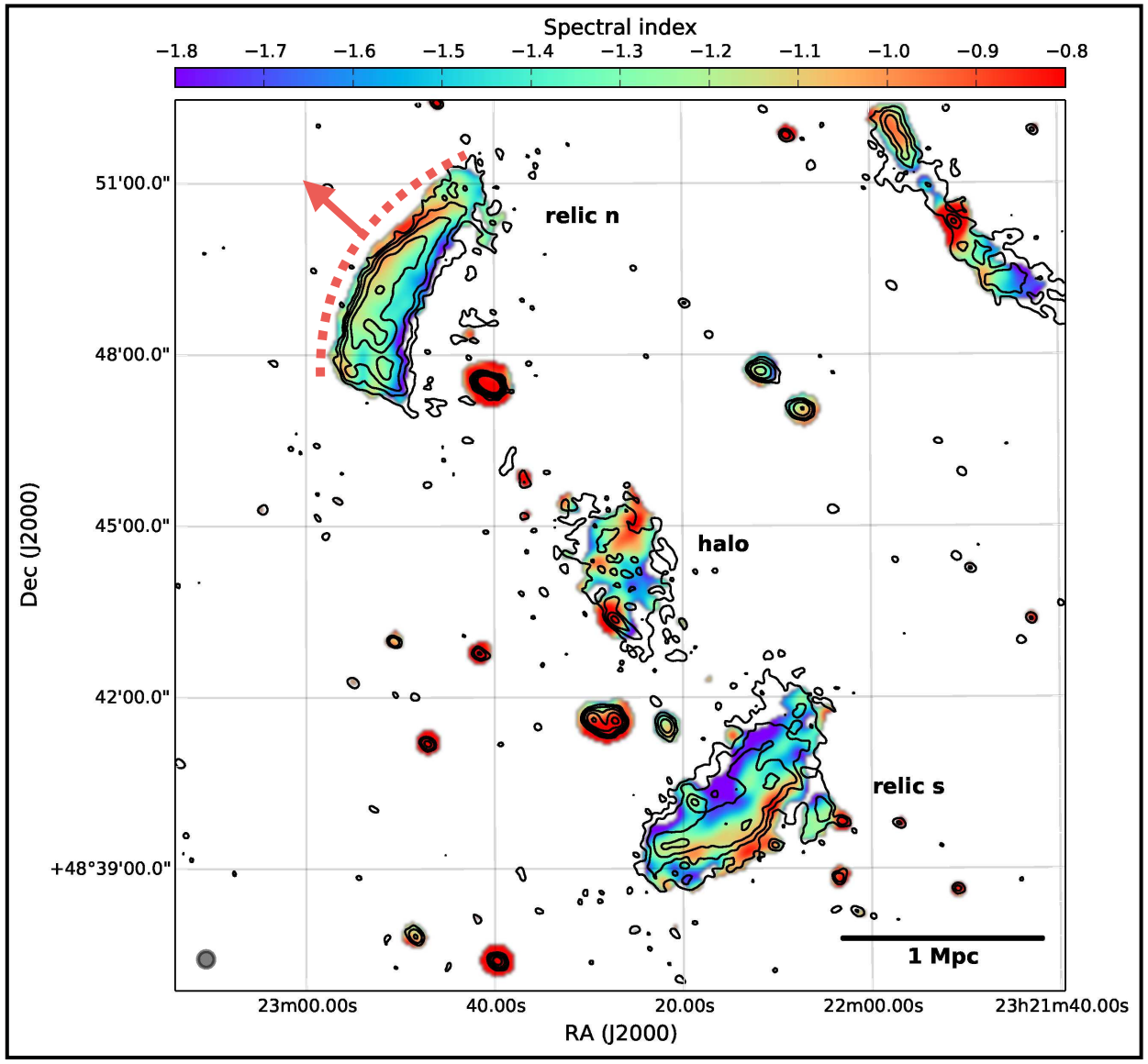
$M_{500} = 7.7 \times 10^{14} M_{\odot}$

PSZ1G108



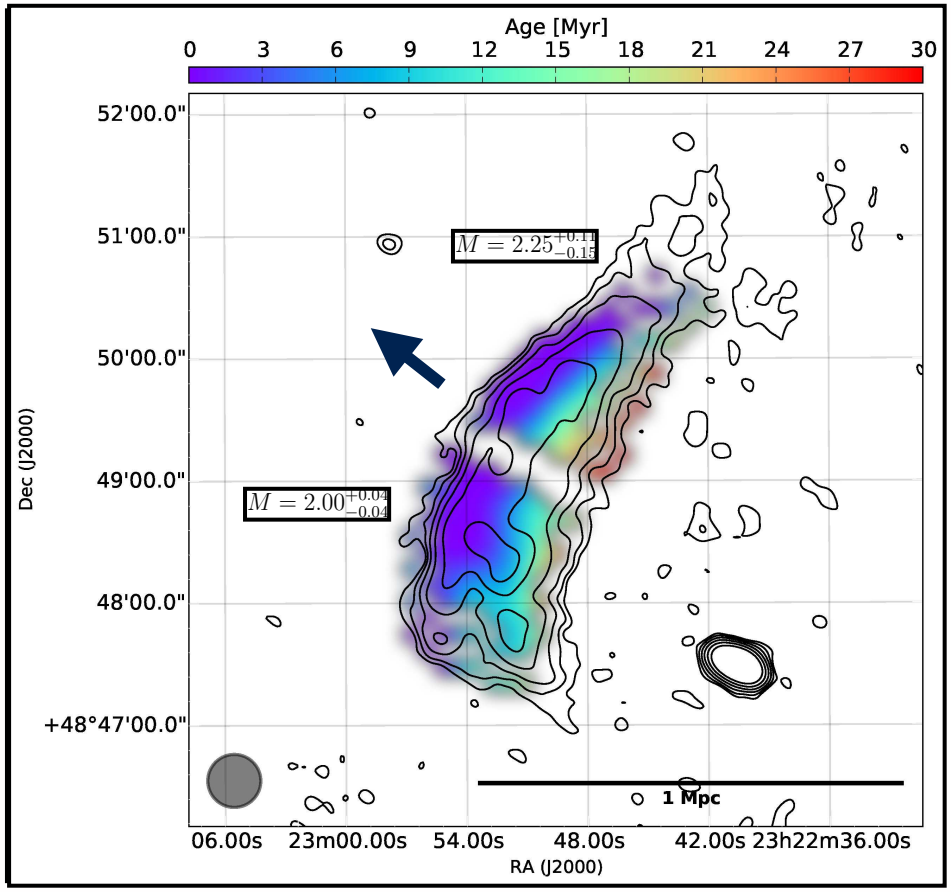


PSZ1G108: spectral index

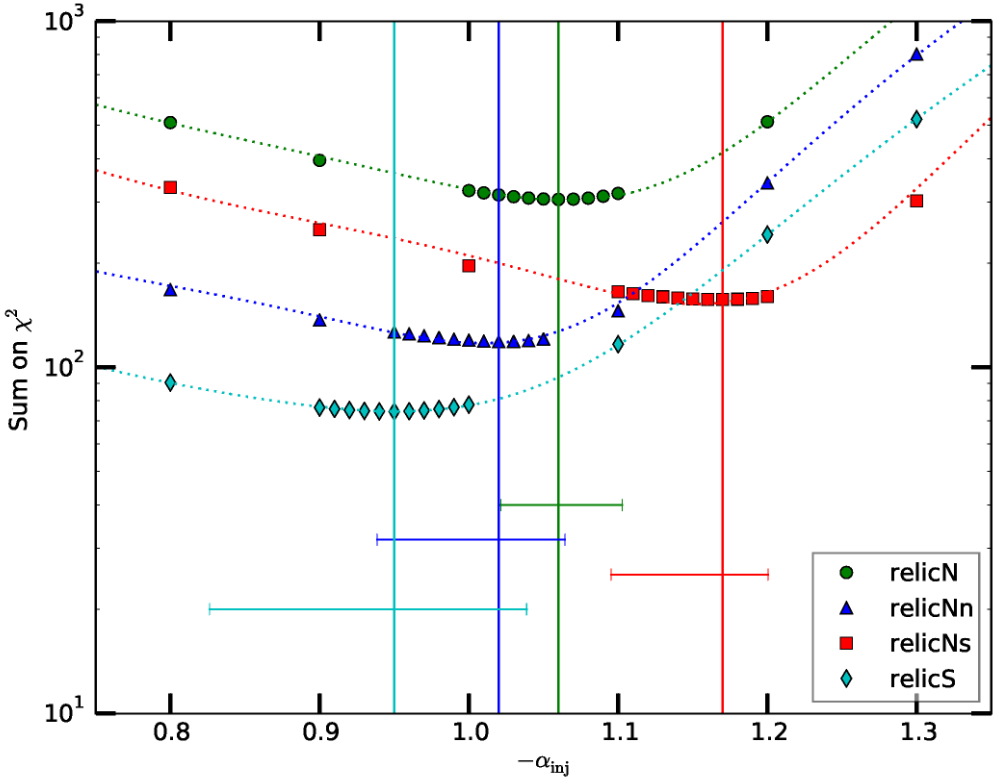


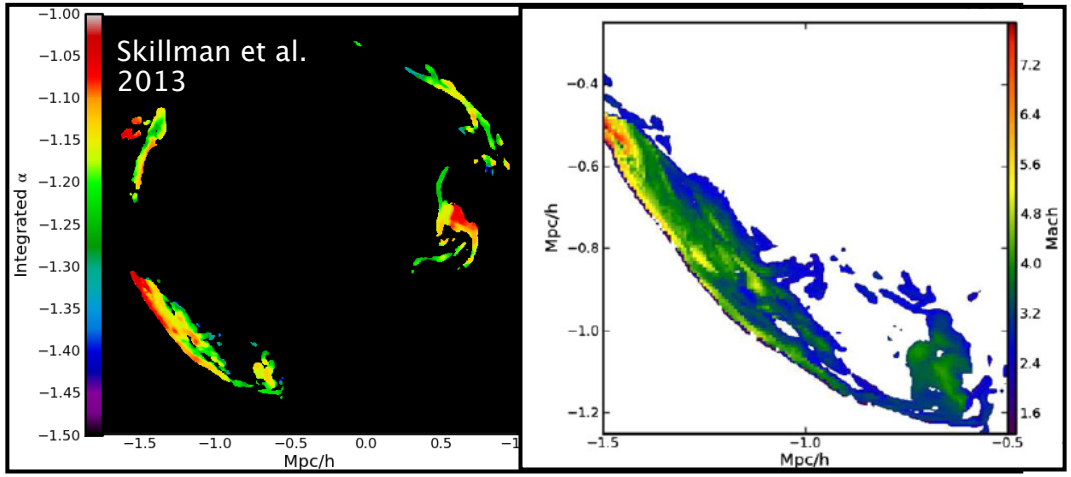
$$M = \sqrt{\frac{2\alpha_{\rm inj} + 3}{2\alpha_{\rm inj} - 1}}$$

330-1400 GHz

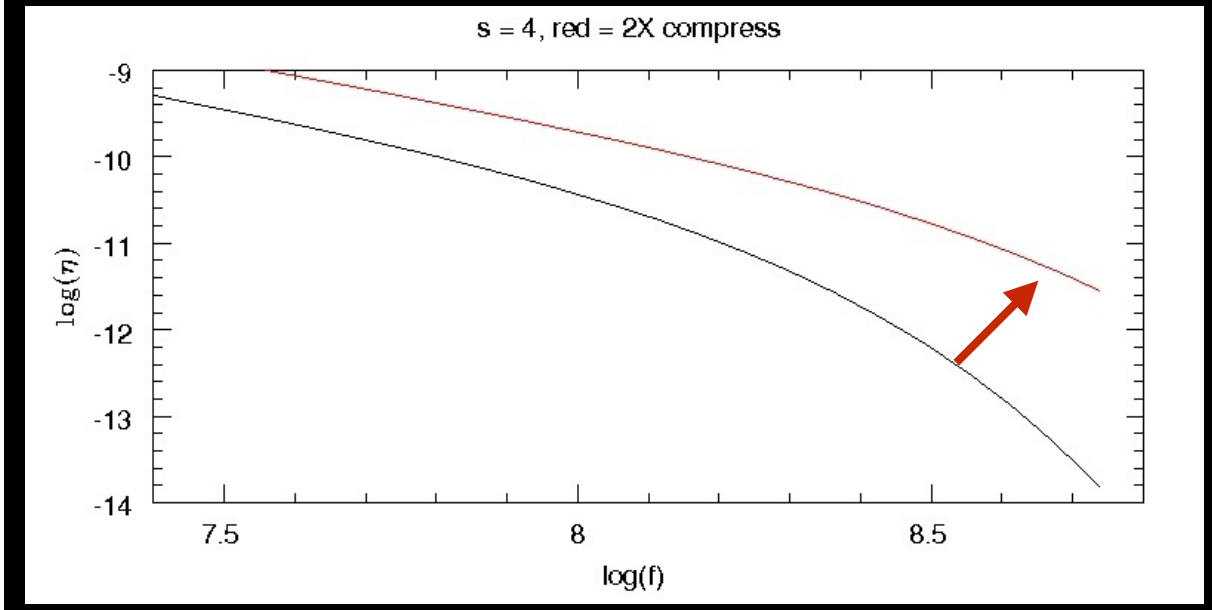


$\alpha_{\rm inj} = 1.04^{+0.4}_{-0.4} \rightarrow M = 2.17^{+0.6}_{-0.7}$

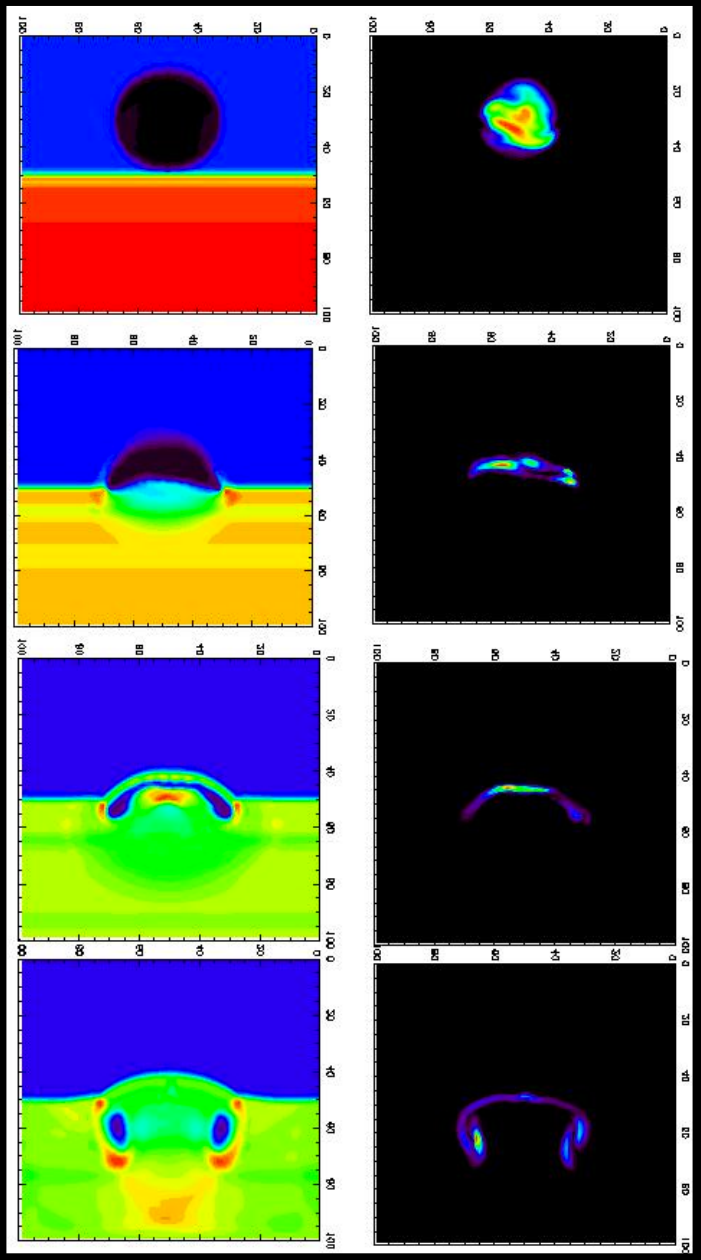




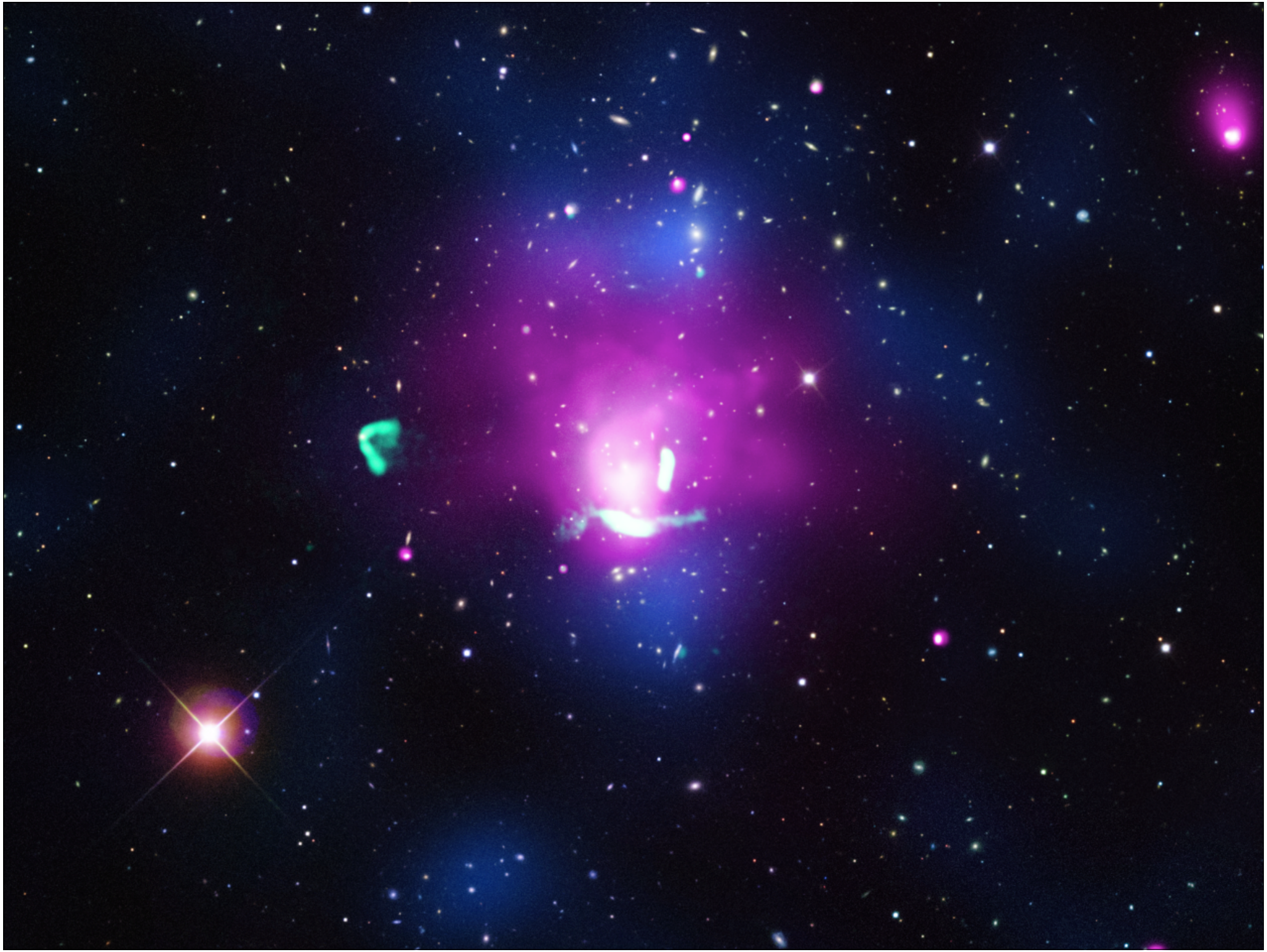
Phoenixes: reviving old plasma



Credits: Tom Jones

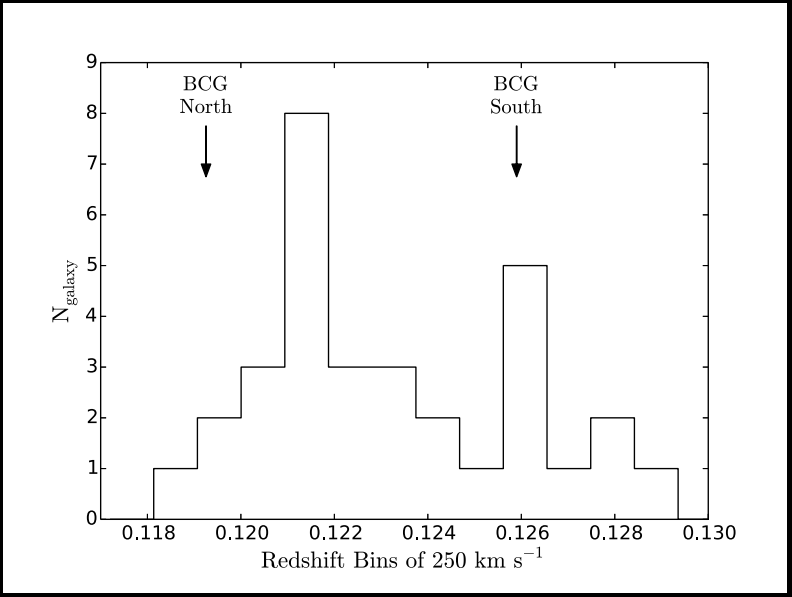


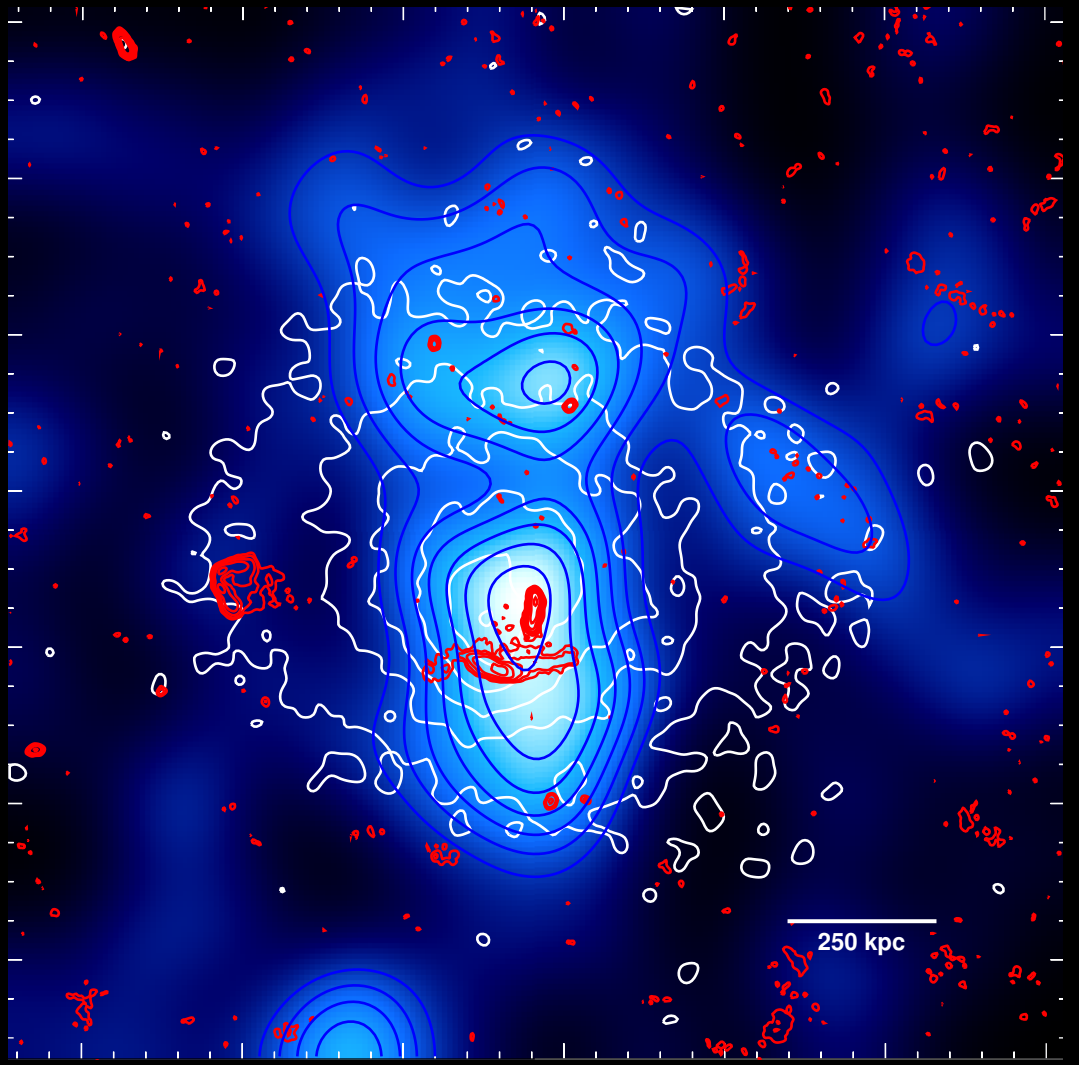
Ensslin & Gopal-Krishna 2001



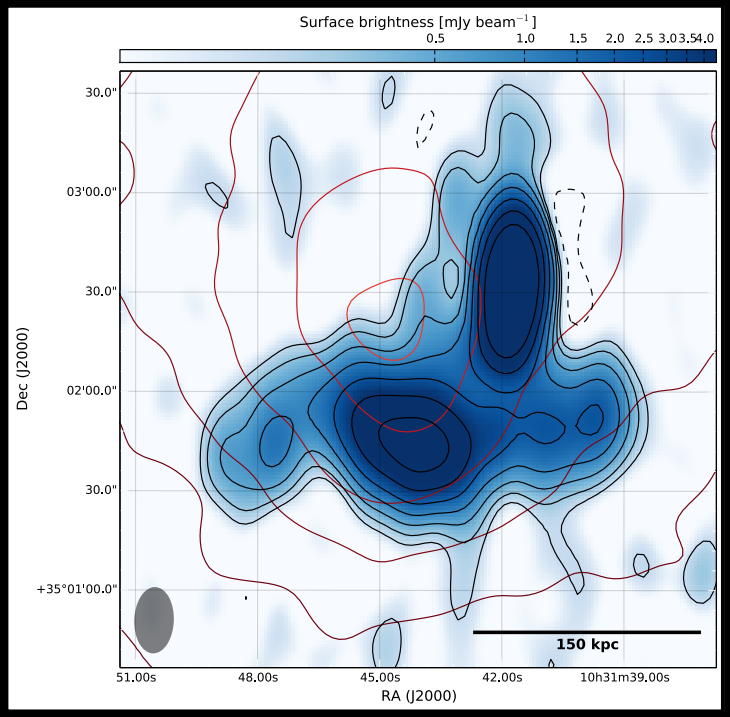
PSZ1G189: a merger

Two optical peaks, merger ~along LoS





PSZ1G189

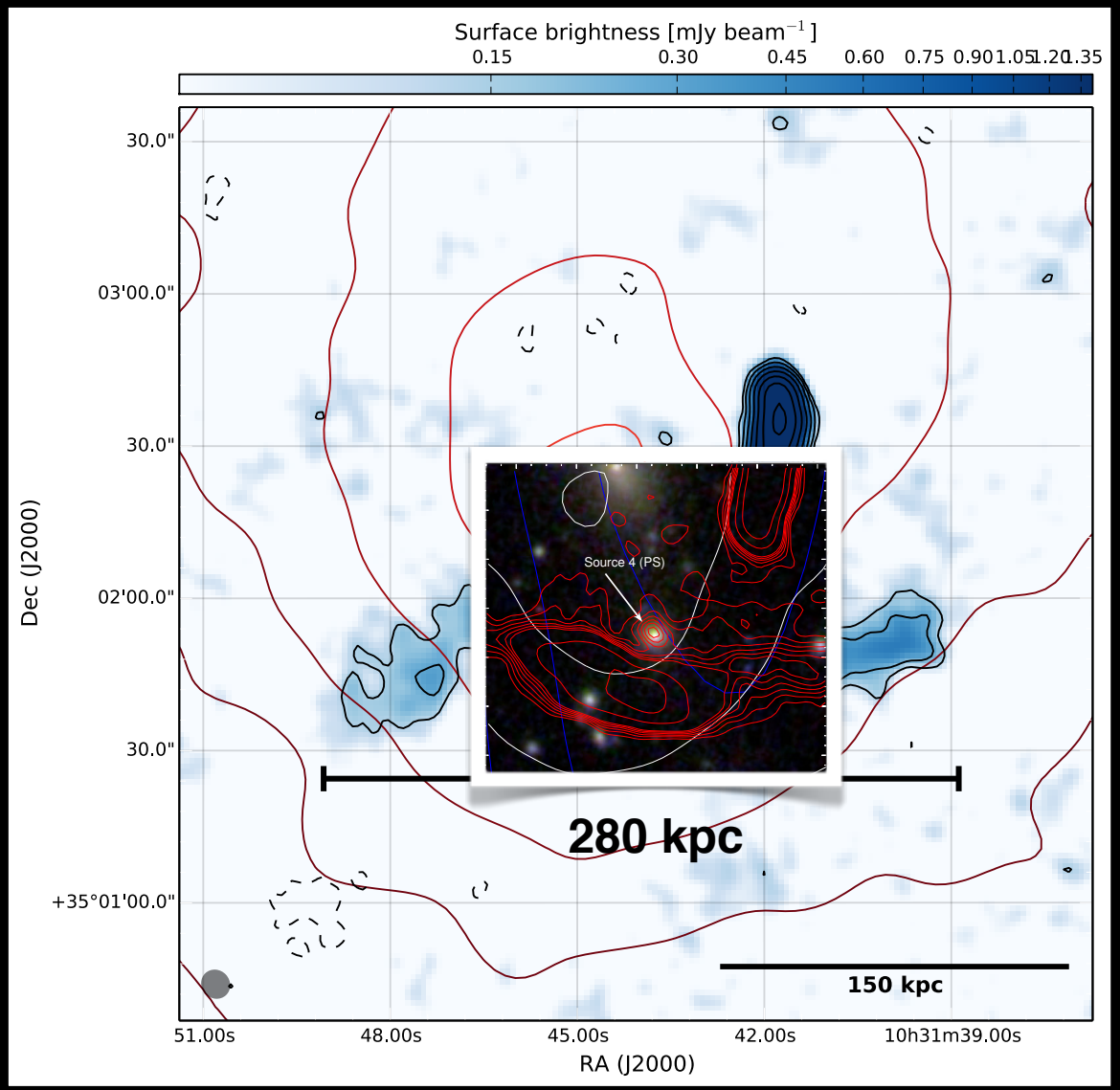


WSRT 1.4 GHz

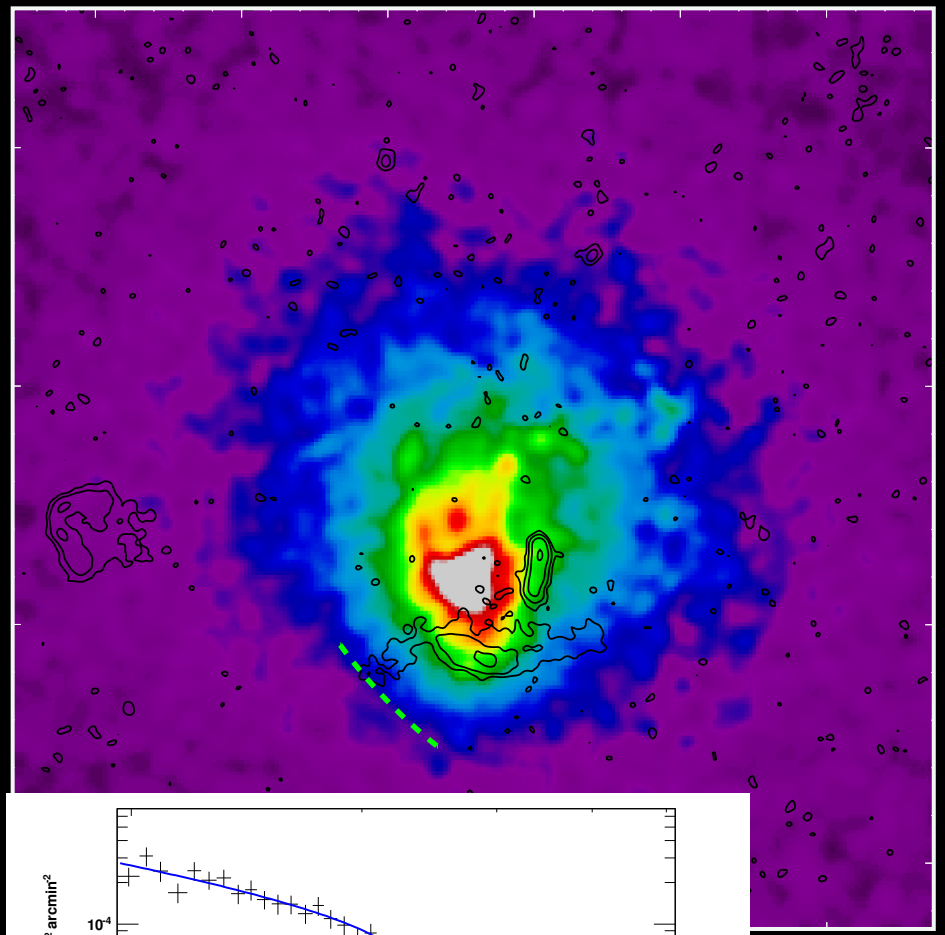
$$z = 0.12$$
$$M = 3.4 \times 10^{14} M_{\odot}$$

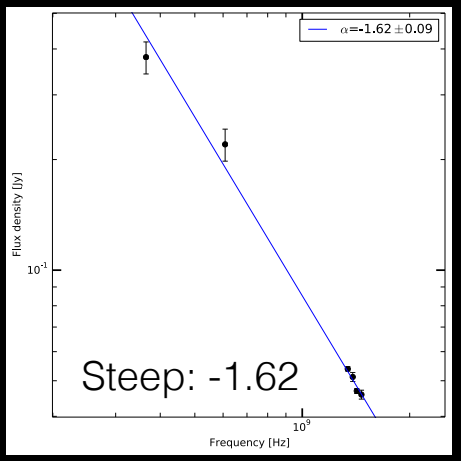
de Gasperin+ 15

VLA (B) 1.4 GHz

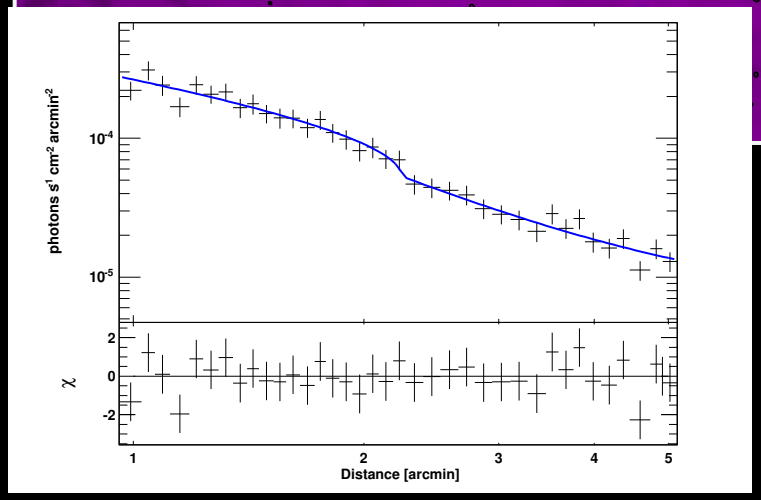


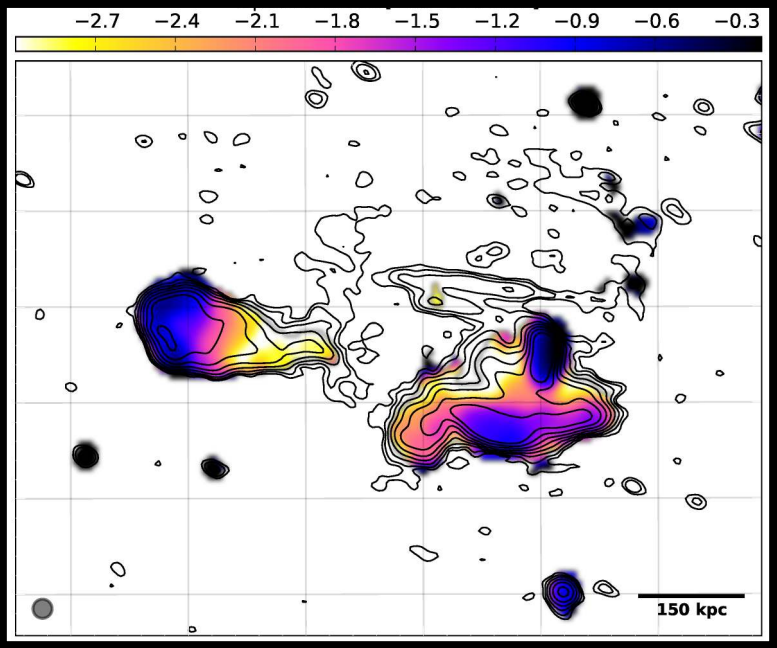
PSZ1G189: a relic?



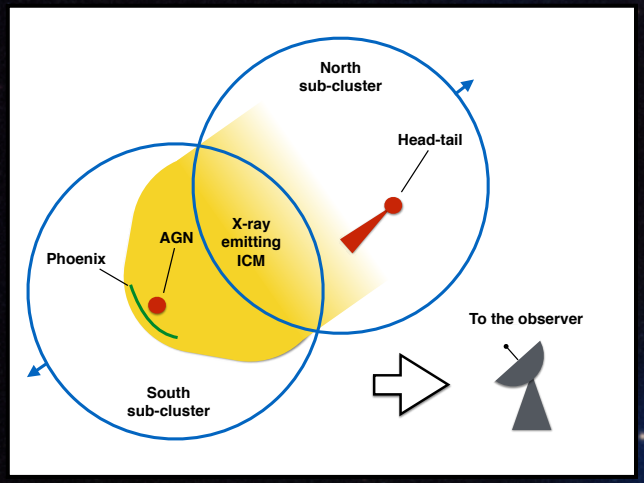


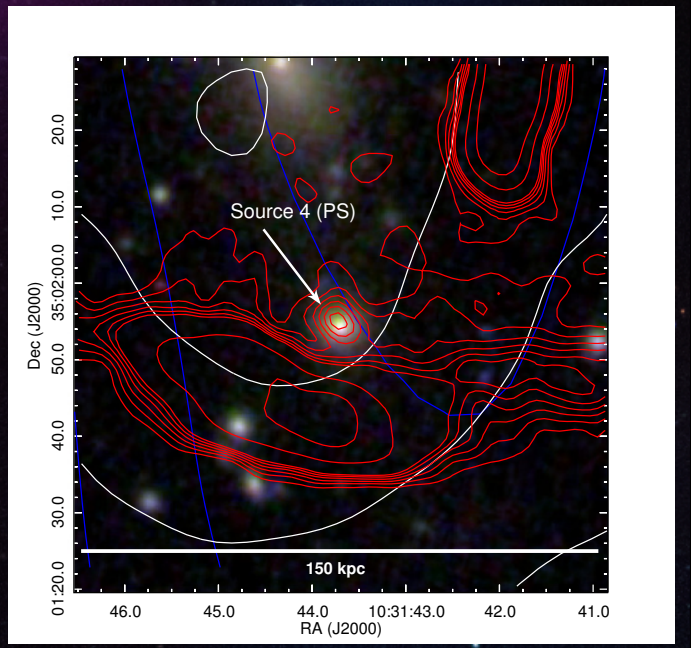
1. **No polarization**
2. **Very small**
3. **Very central**
4. **Very steep**
5. **No shock** (well, not in the right place)
6. **Spectral index not relic-like**



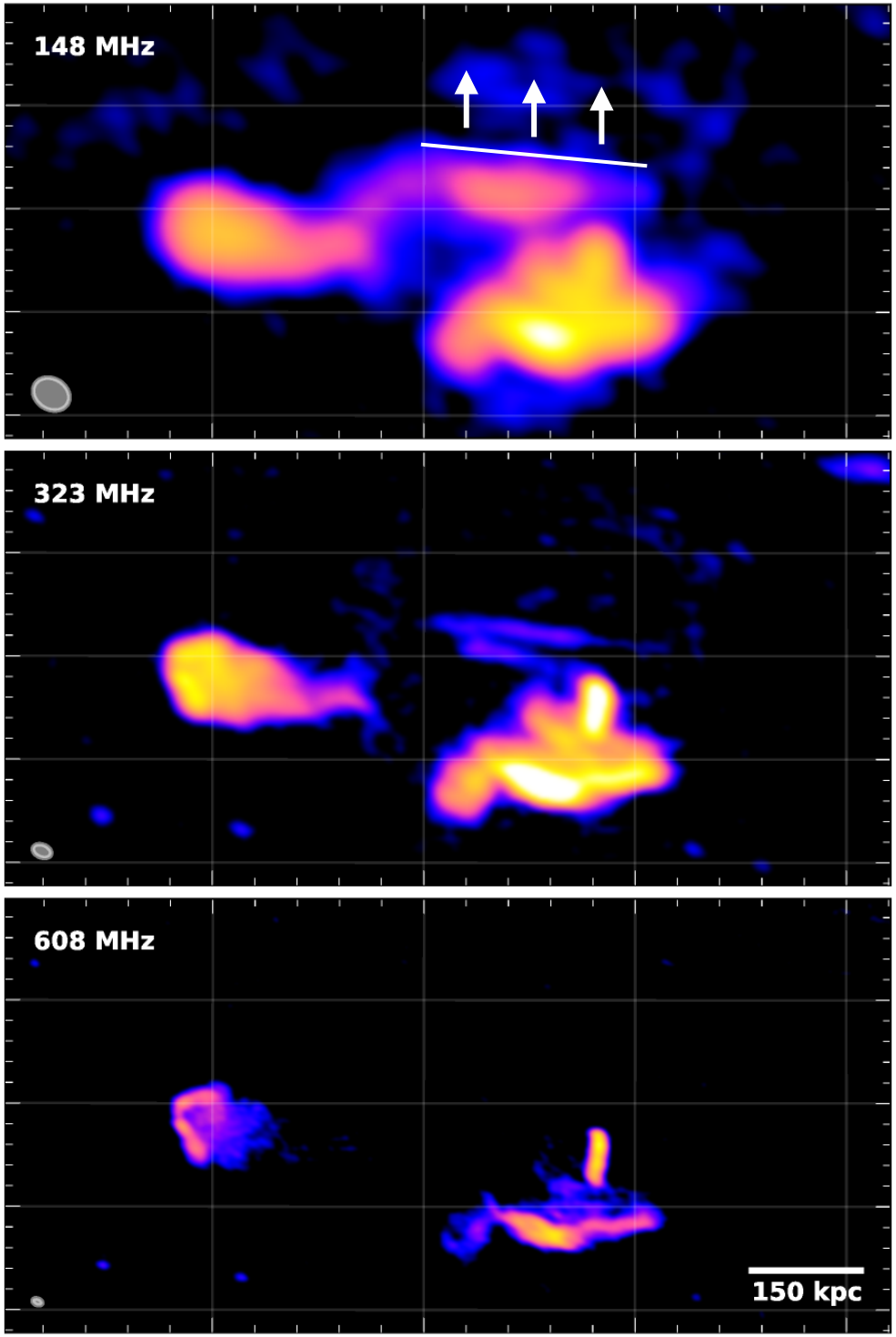


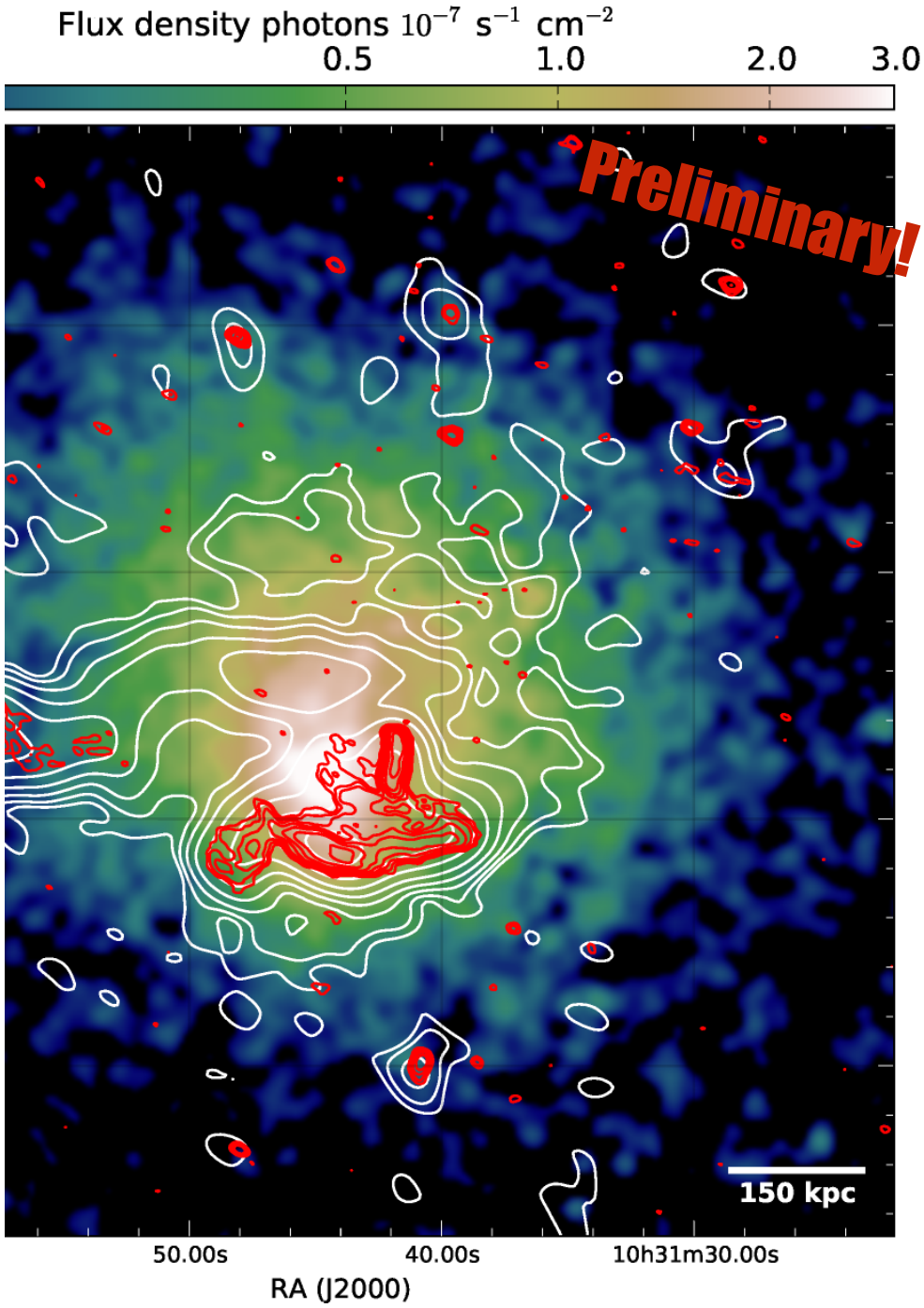
Birth of a radio phoenix: displaced (compressed?) by cluster weather



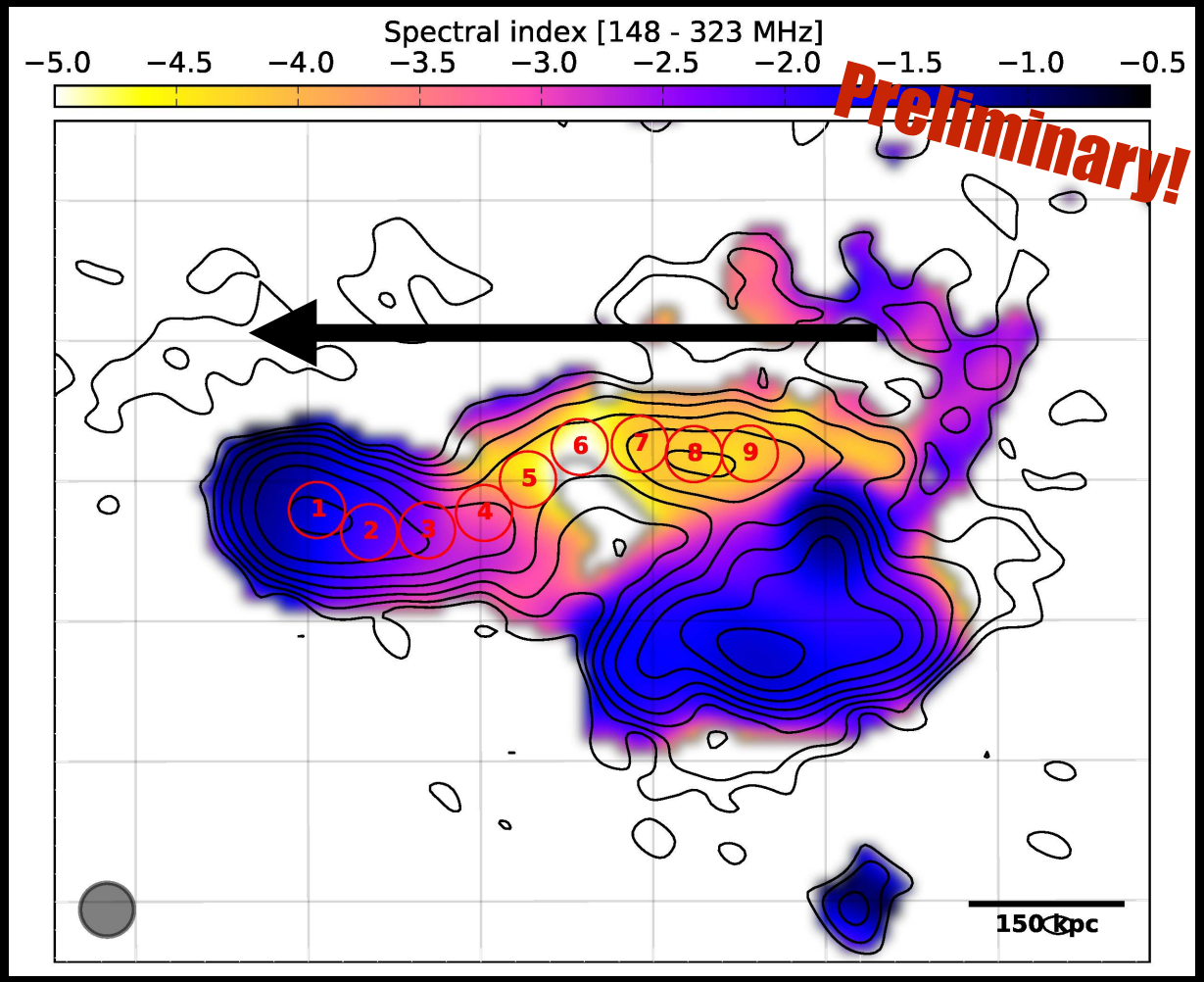


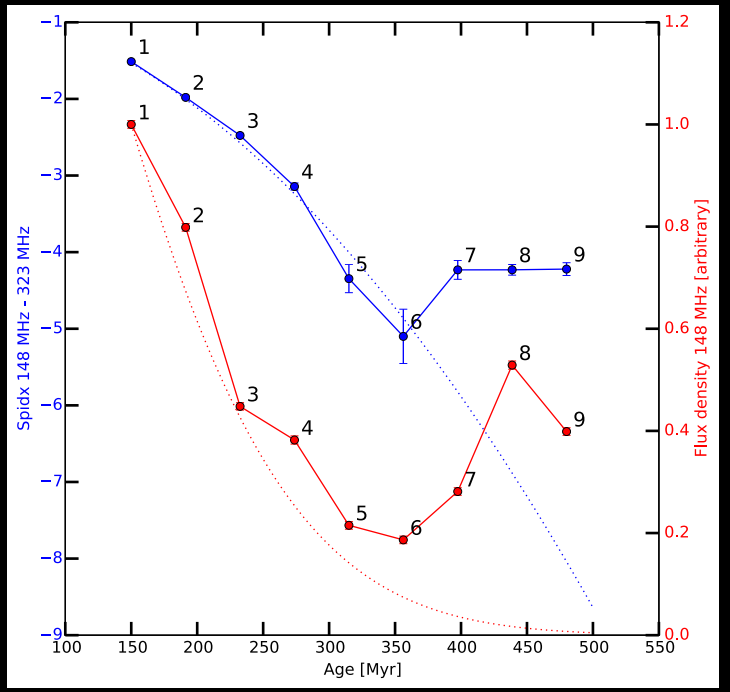
Chandra press release


148 MHz
323 MHz
608 MHz
150 kpc


Flux density photons 10^{-7} s^{-1} cm^{-2}
0.5
1.0
2.0
3.0
Preliminary!
150 kpc
50.00s
40.00s
10h31m30.00s
RA (J2000)

Spectral evolution





Adiabatic compression shifts the curved spectrum and boosts the flux.

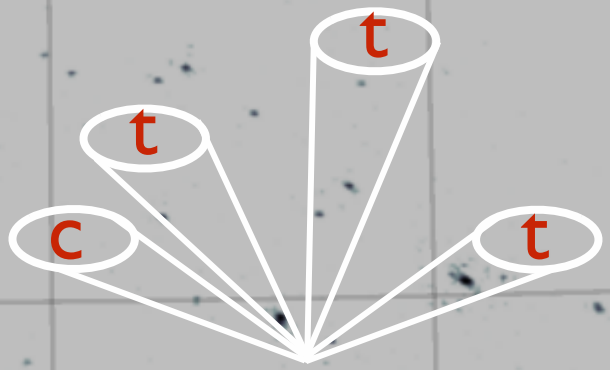
The tail is ~500 Myr old

The LOFAR LBA Survey

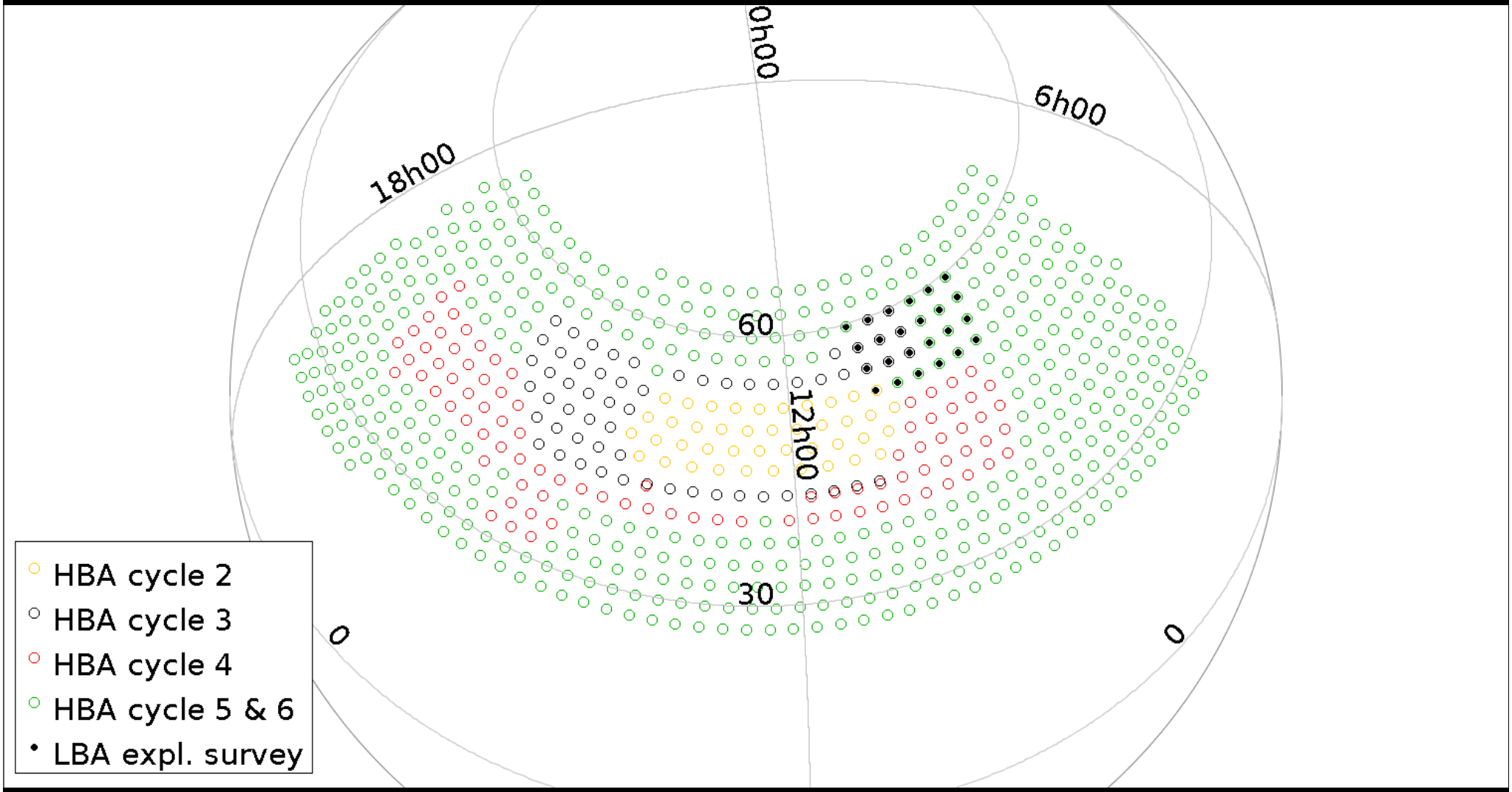
Beams: 4 (1 calibrator + 3 targets)
Mode: LBA_OUTER (4 deg FWHM) - SPARSE?
Obs time: 8 hrs per pointing - total pointings: 3170

Frequency coverage: 42 - 66 MHz
Resolution: 15" to 30"
Noise level: 5-10 mJy (DIE) - 1 mJy (expected DDE)

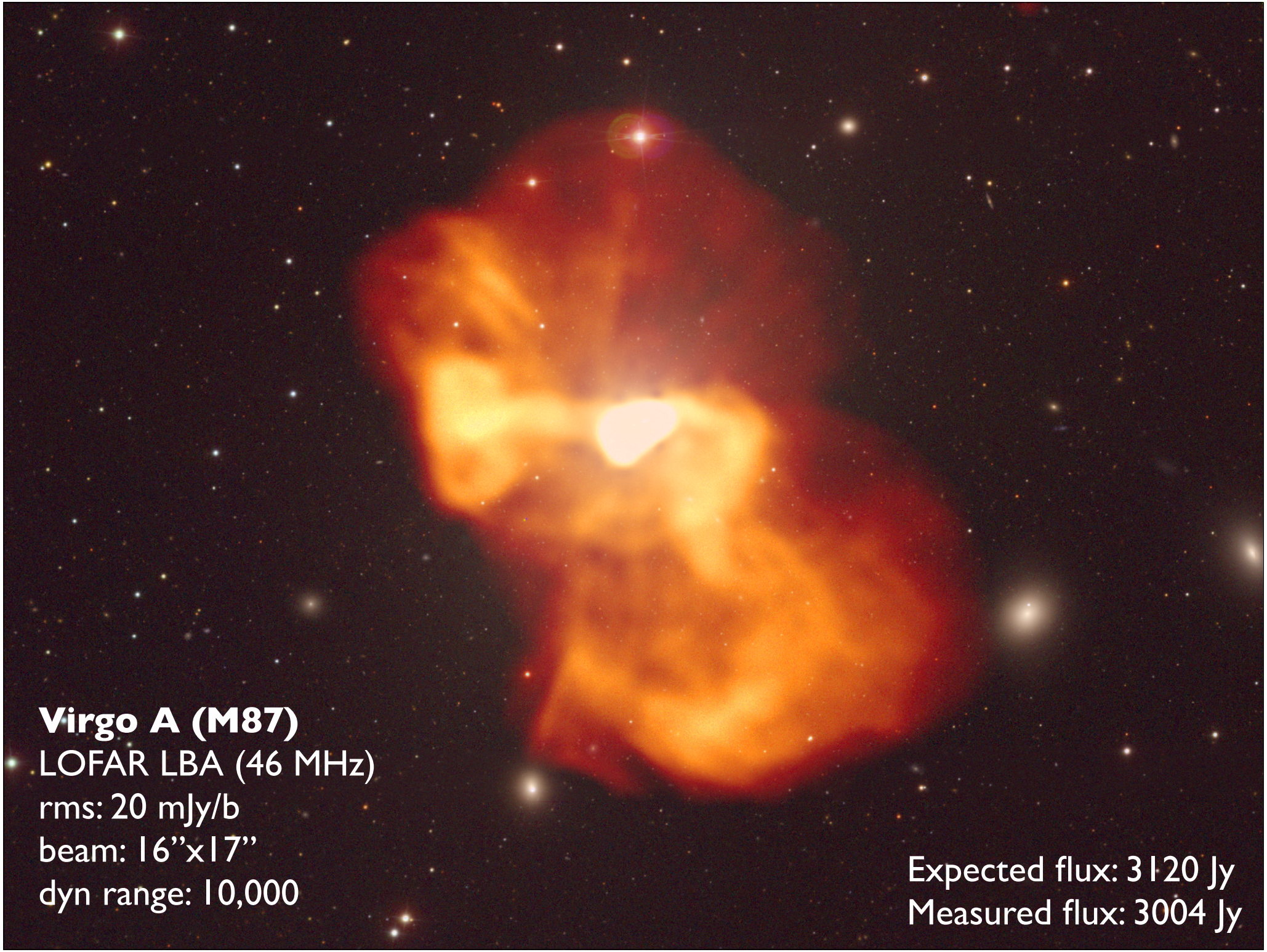
LoLSS - Vs - VLSS
10 - 20 times better noise
2 - 3 times better resolution

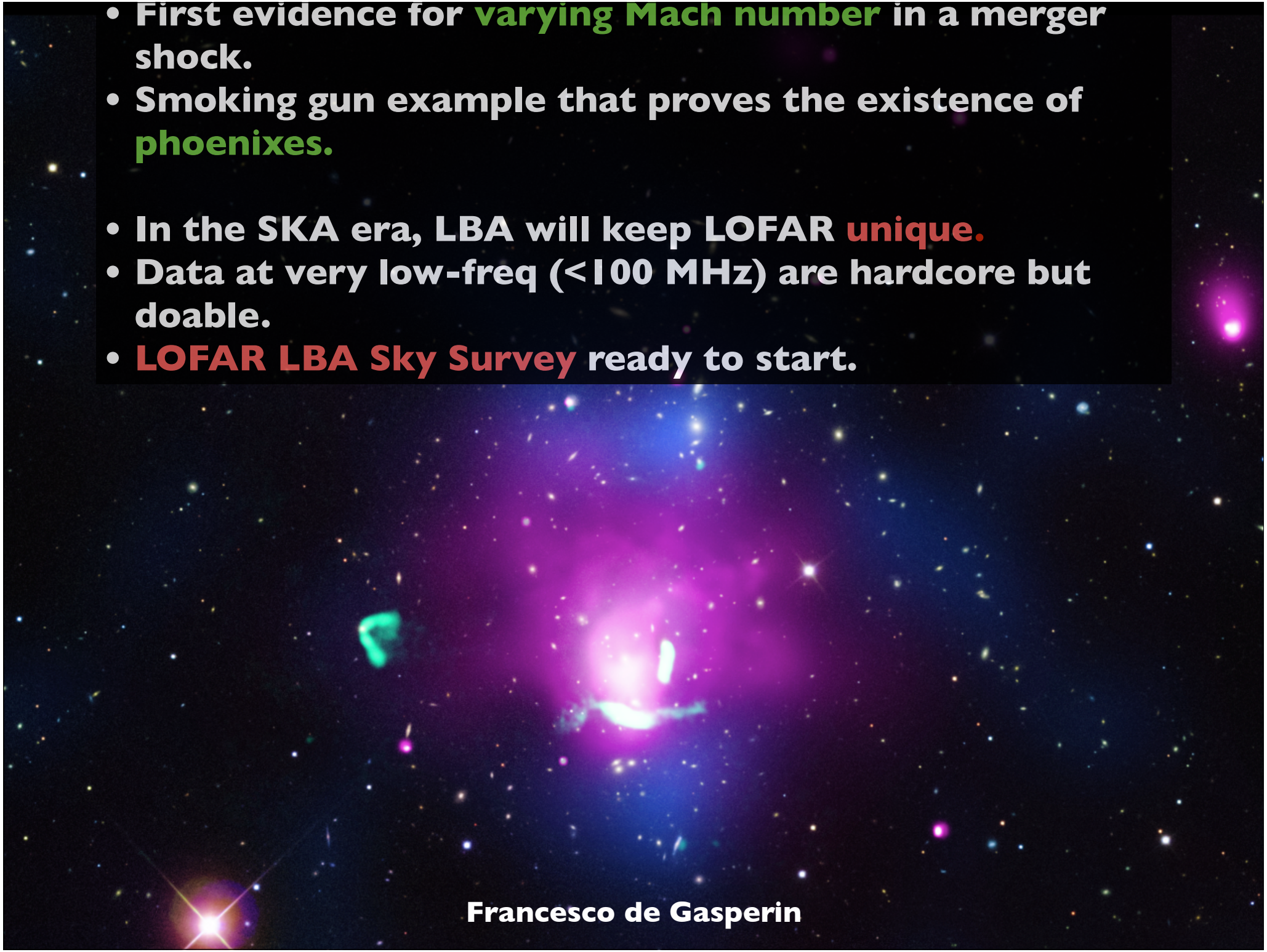


The LOFAR LBA Survey

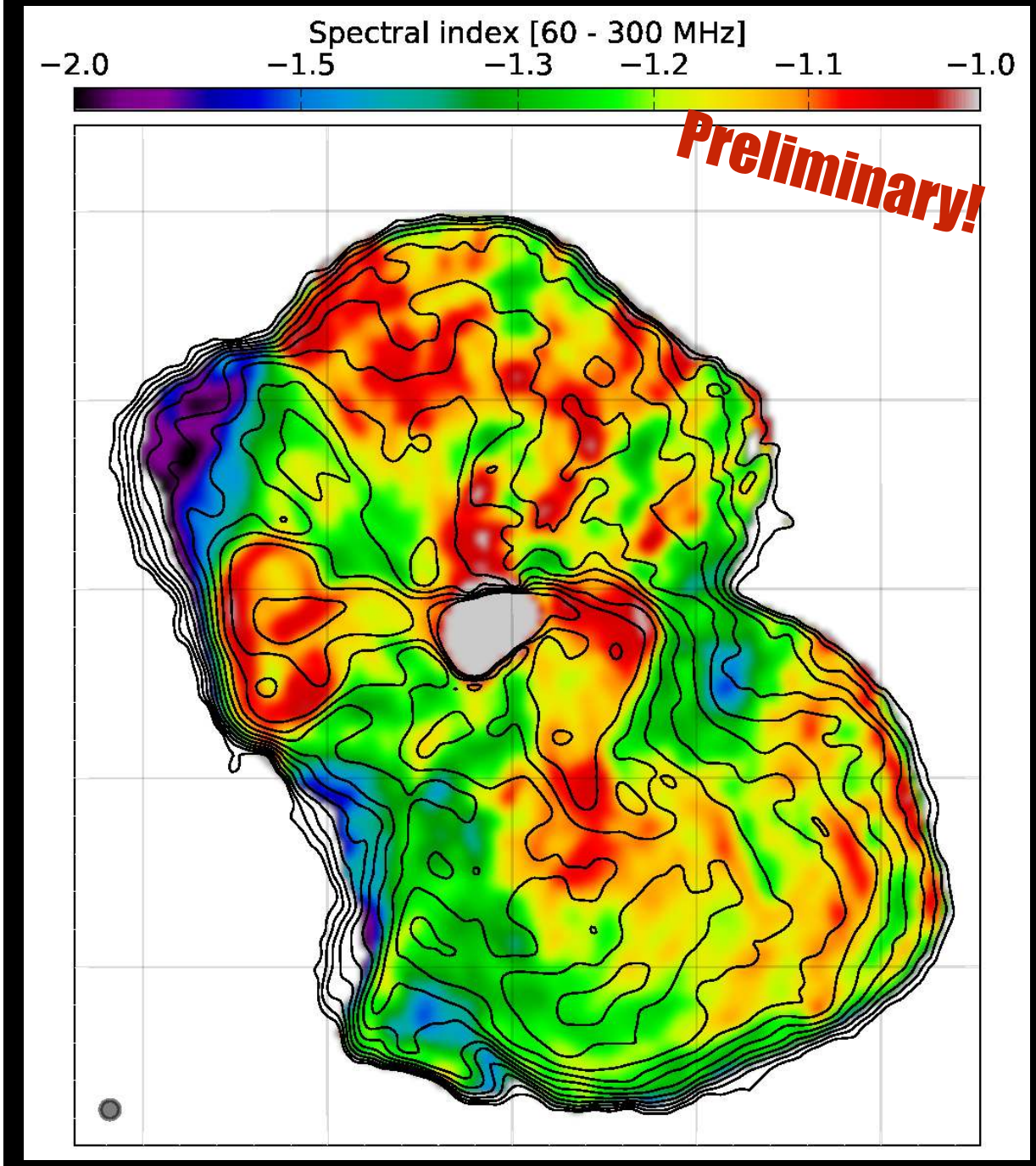


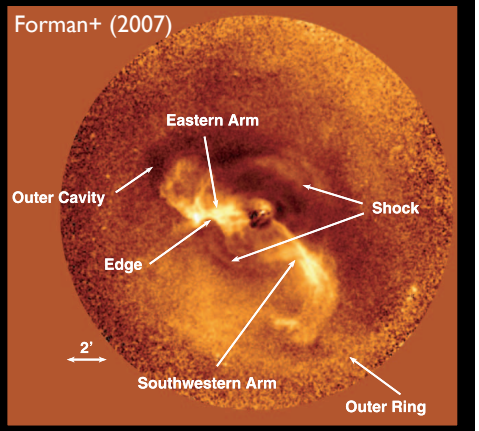
The LBA Exploratory Survey: 24 pointings (160 sqdeg)


Virgo A (M87)
LOFAR LBA (46 MHz)
rms: 20 mJy/b
beam: 16”x17”
dyn range: 10,000
Expected flux: 3120 Jy
Measured flux: 3004 Jy

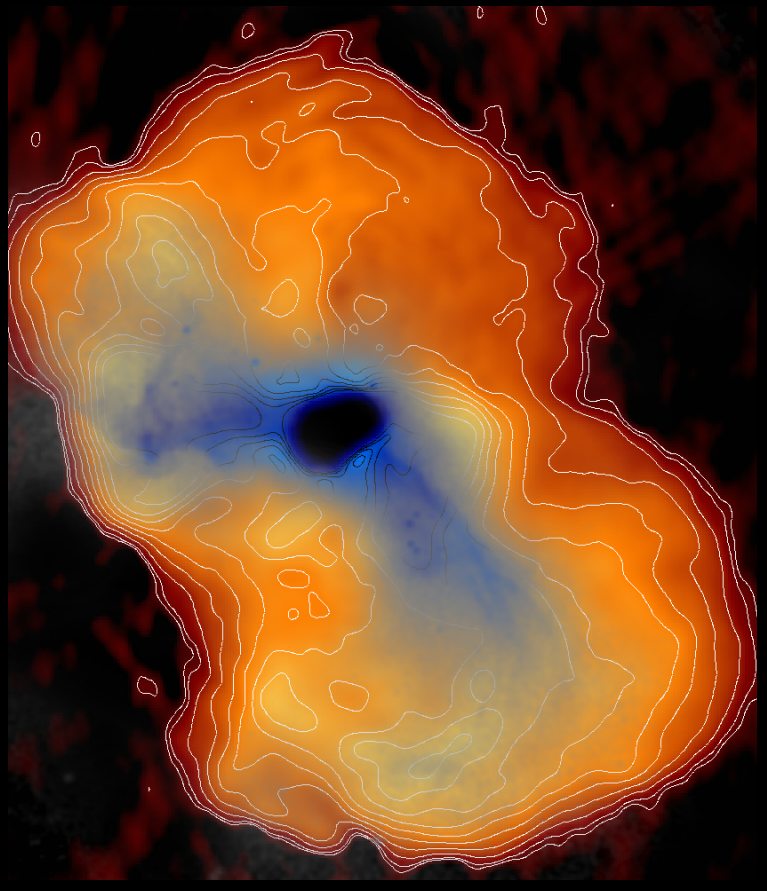

• First evidence for varying Mach number in a merger shock.
• Smoking gun example that proves the existence of phoenixes.
• In the SKA era, LBA will keep LOFAR unique.
• Data at very low-freq (<100 MHz) are hardcore but doable.
• LOFAR LBA Sky Survey ready to start.
Francesco de Gasperin

60-300 MHz spectral index map





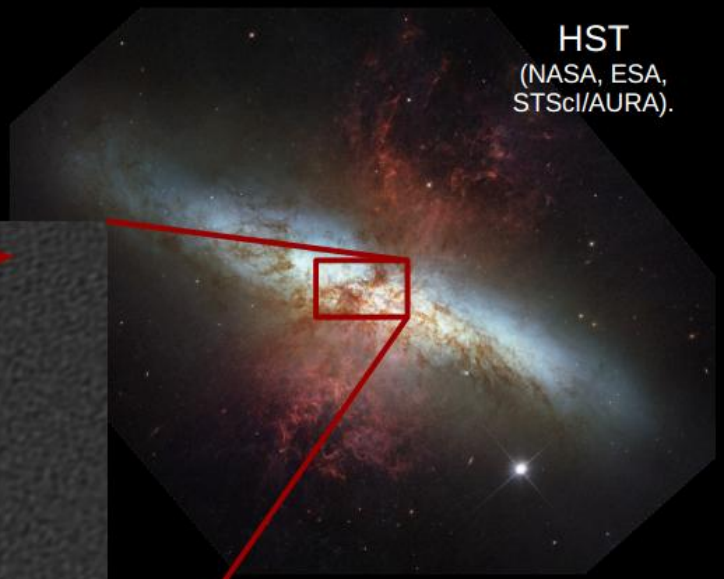
Curved injection+higher B?
Reacceleration?

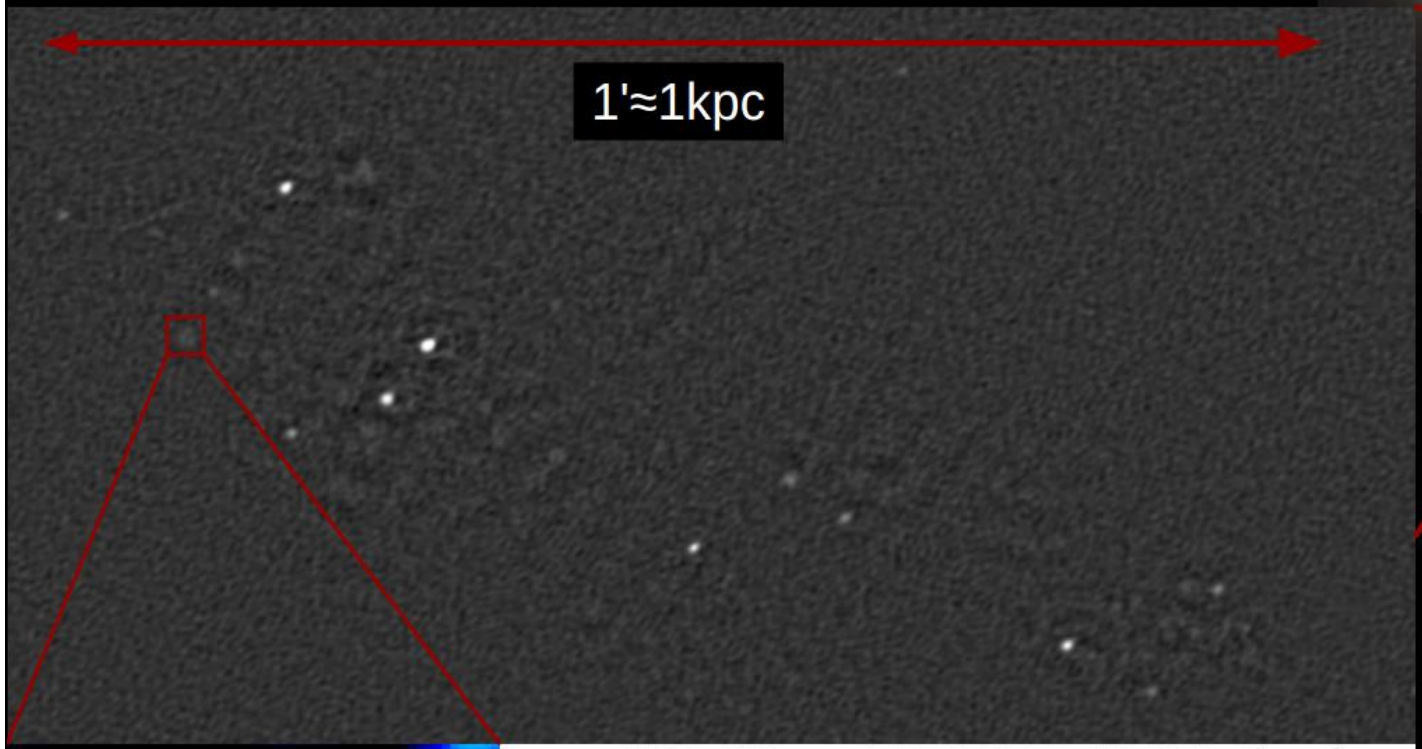


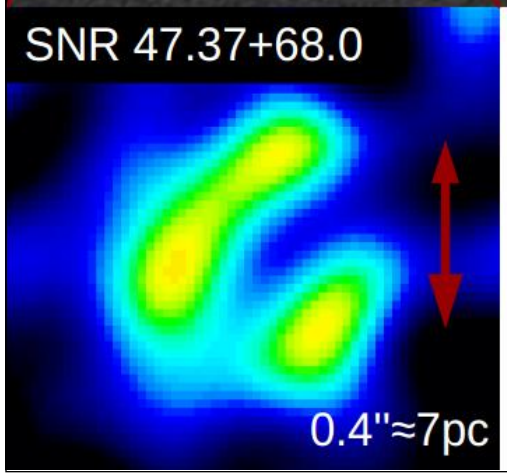
International baseline imaging: M82 at 150 MHz

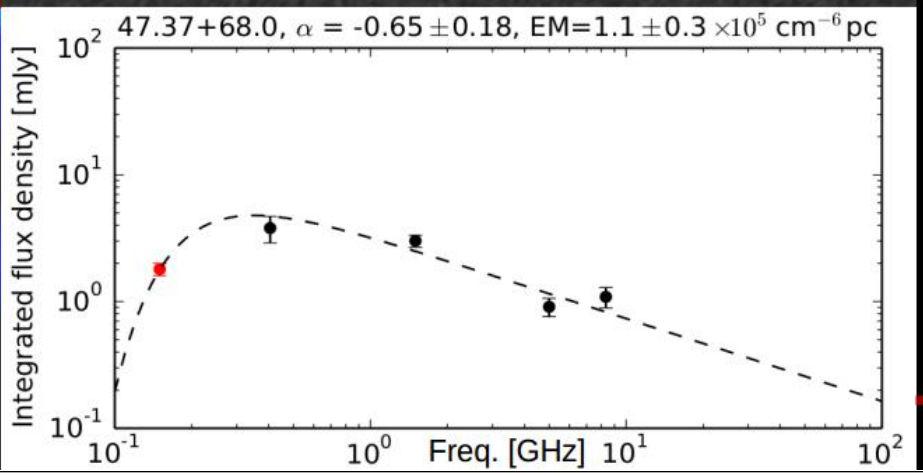
Star forming galaxy, 3.6 Mpc.

Resolution 0.3", image noise σ=0.15 mJy/beam.







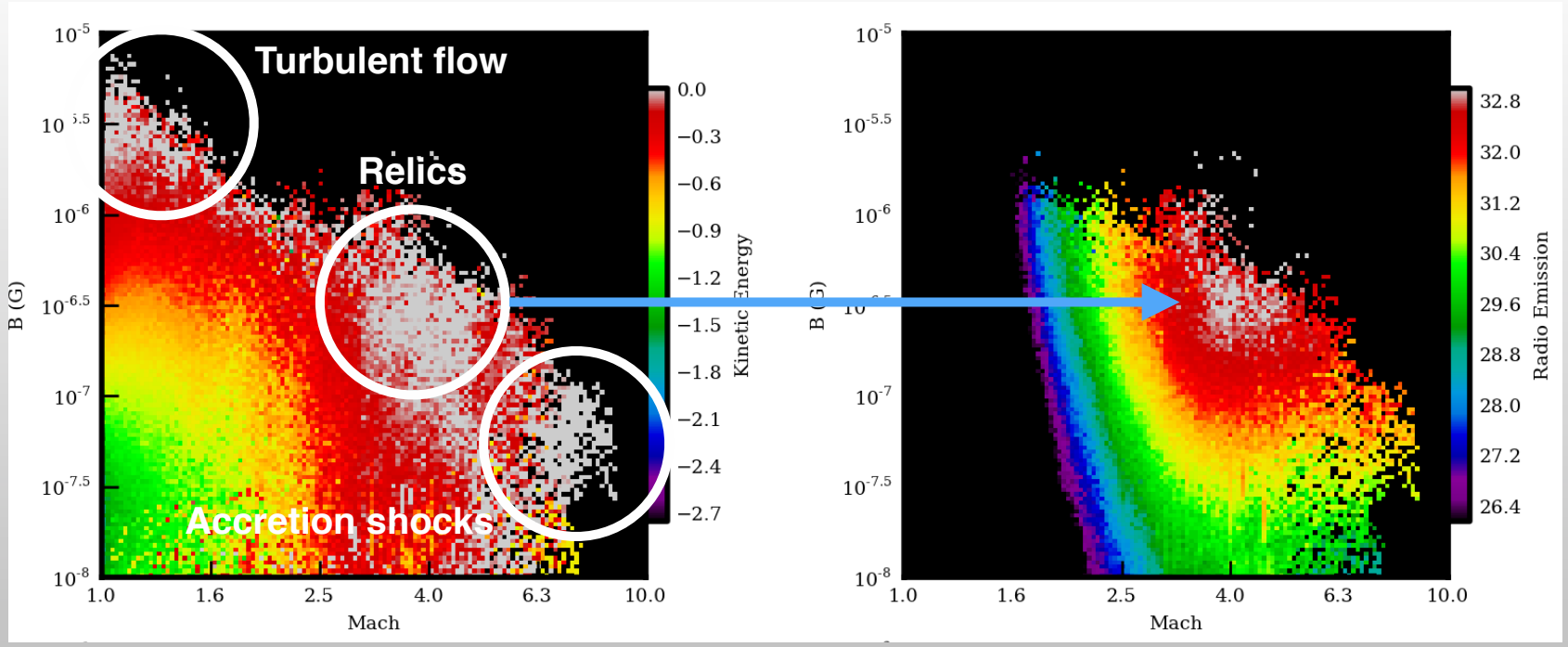


Some results

- Detect 16 objects (7 new)
- Resolve SNR shells
- Probe ISM structure through low-freq turnovers in SNR spectra.

Varenius et al. (2015), A&A.

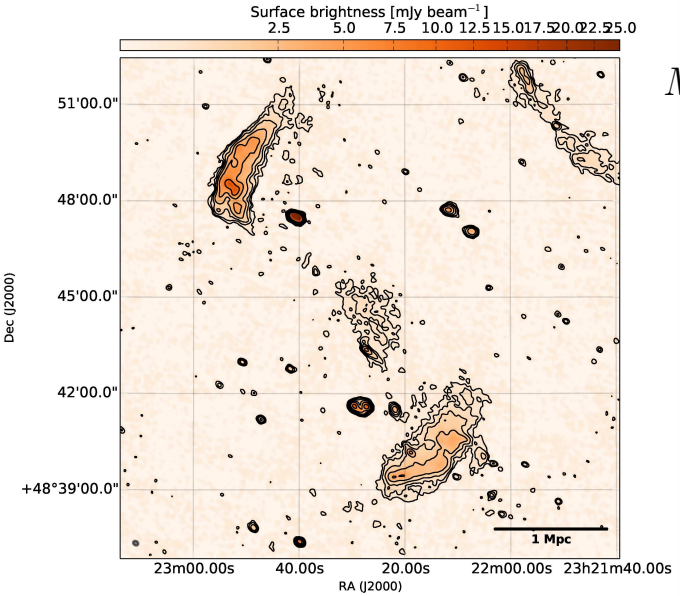
Relics: theory to observations



Skillman et al.

Radio Relics are powered by **Shock waves** which form in the Intra-cluster Medium during **mergers** (low Mach numbers ≈ 2-4, average magnetic field ≈ 1 uG)

The most luminous relics



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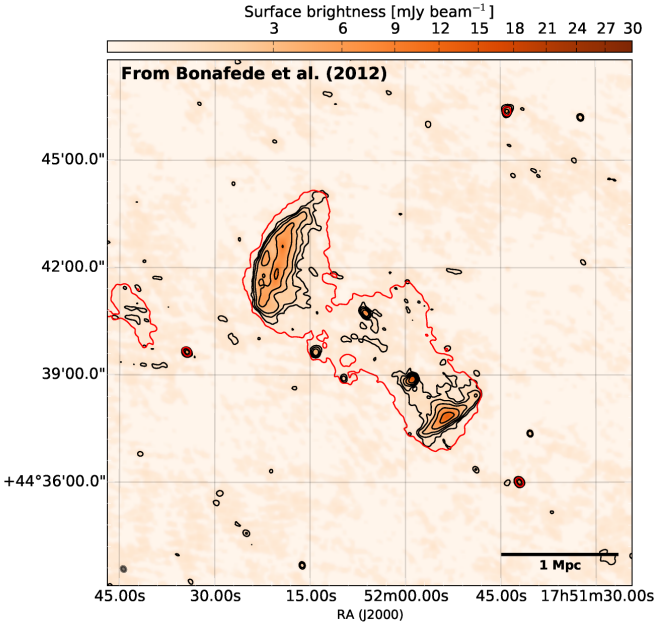

MACSJ1752.0+4440

$z = 0.366$

$M_{500} = 7.0 \times 10^{14} M_{\odot}$