Re-solving the jet/cocoon riddle of the first gravitational wave with an electromagnetic counterpart

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Based on
Ghirlanda, Salafia, Paragi, Giroletti, et al.
2019, Science 363, 6430

Outline

- Instrumentation: GW detectors & VLBI arrays
- GRB 170817A & GW 170817: discovery & MWL observations
- Radio observations: light curves and high angular resolution data

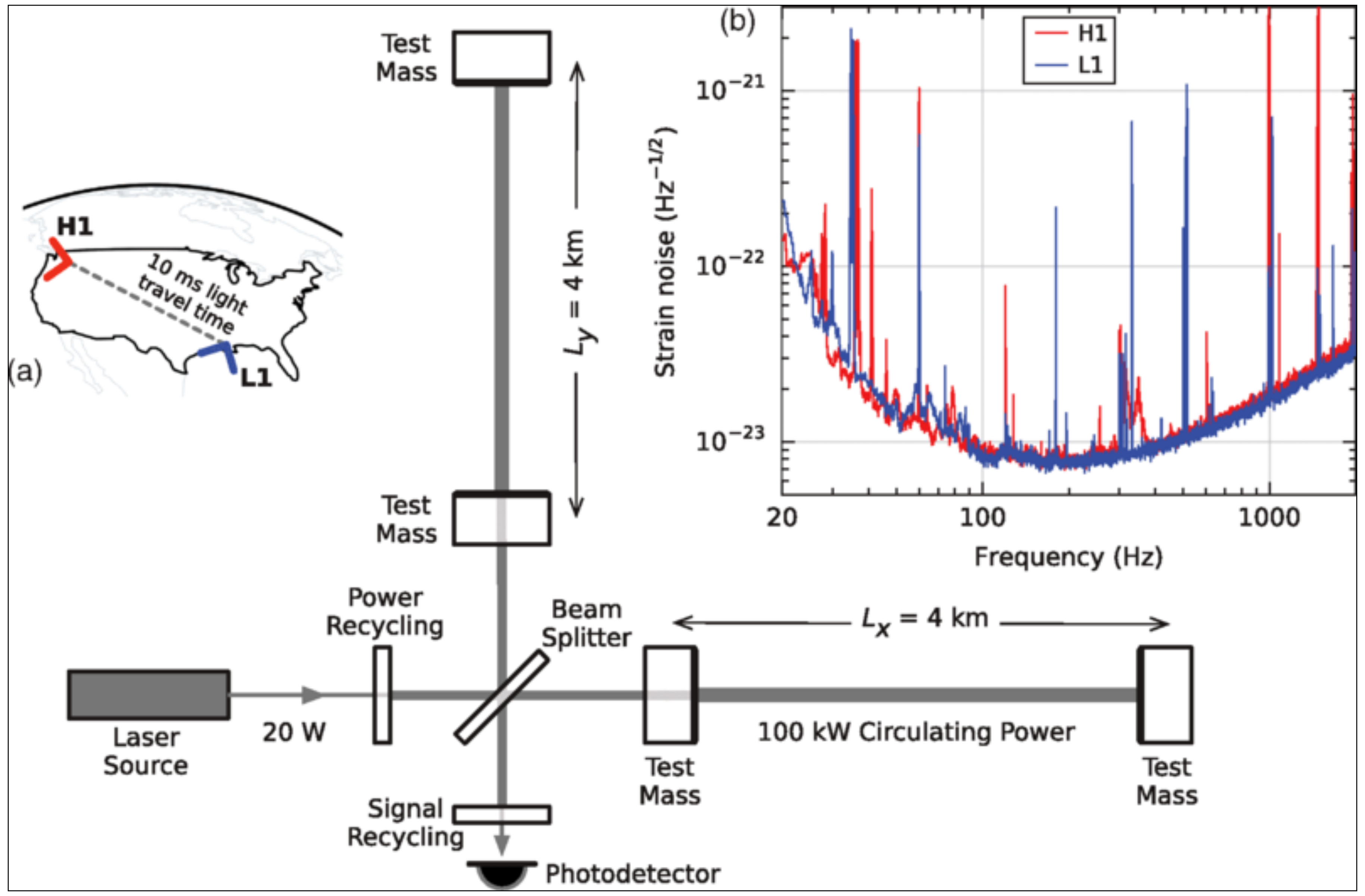
Gravitational wave detectors

- Advanced LIGO (Laser Interferometer Gravitational Observatory), two interferometers in the US (Hanford, WA, and Livingstone, LA)

- Advanced Virgo, in Italy (near Pisa), closer horizon, improves localisation and significance

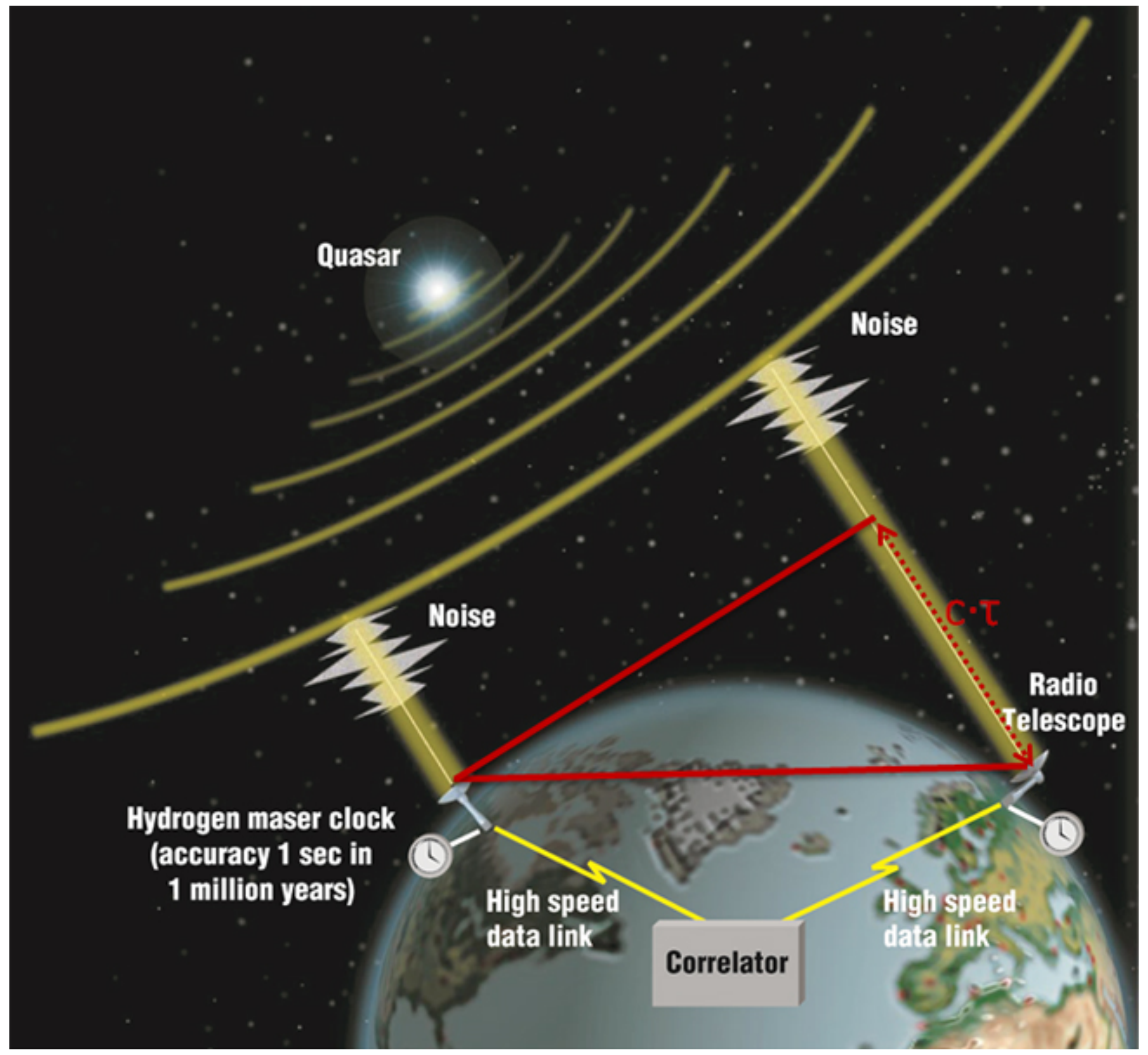
- 10 Hz - 10 kHz (compact objects)

- 10’s-100’s Mpc horizon (depending on mass of the final object)



Very Long Baseline Interferometry

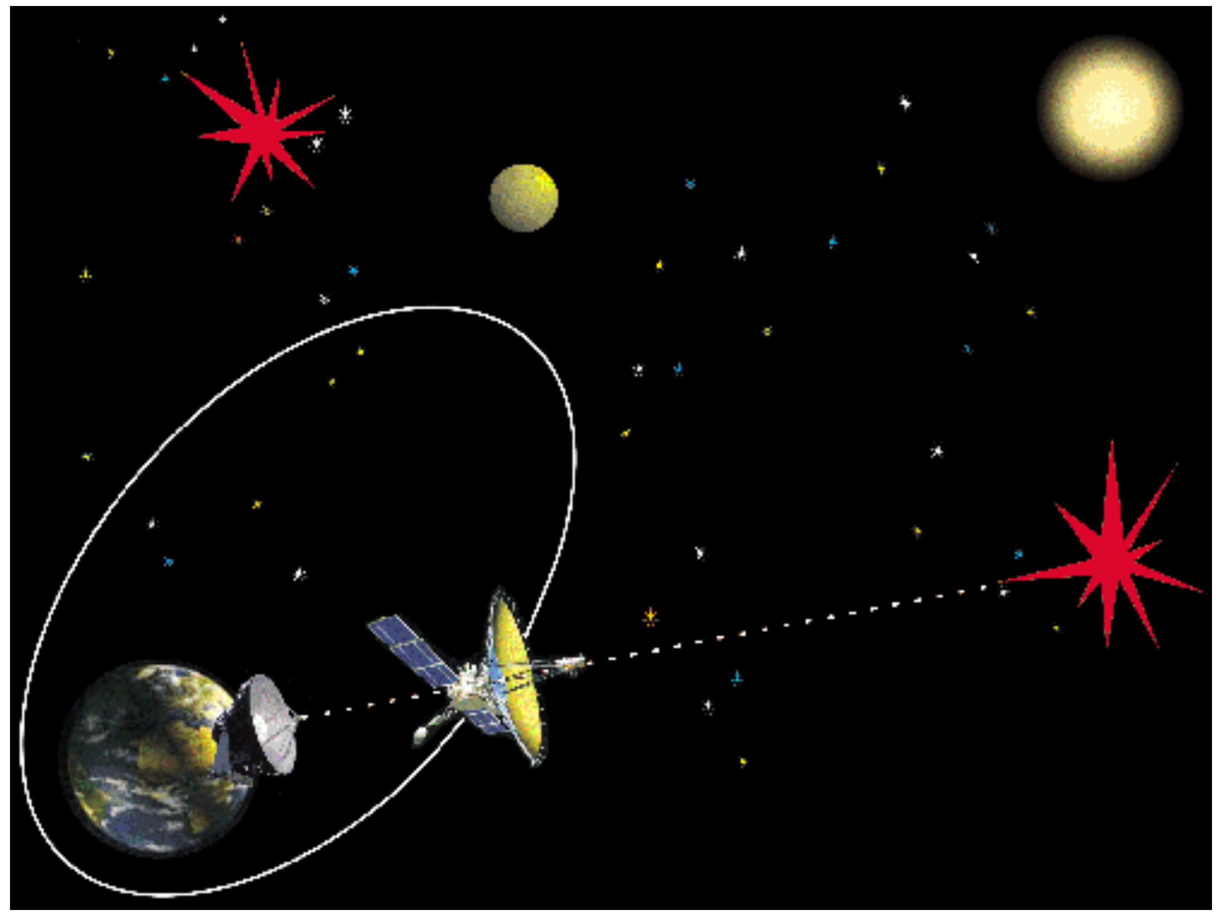
- VLBA: Very Long Baseline Array, 10 US stations, 24/7 operations *(also HSA, High Sensitivity Array, with addition of GBT, VLA)*



- EVN: European VLBI Network, up to ~20 stations in Europe and beyond, operated in “sessions” between other activities

- Global-VLBI: VLBA+EVN, for enhanced angular resolution and sensitivity

- Other regional networks: Australia (LBA), Japan (VERA), Korea (KVN), combinations thereof, and now **Italy**; in future: African VLBI Network in coordination with SKA1_MID



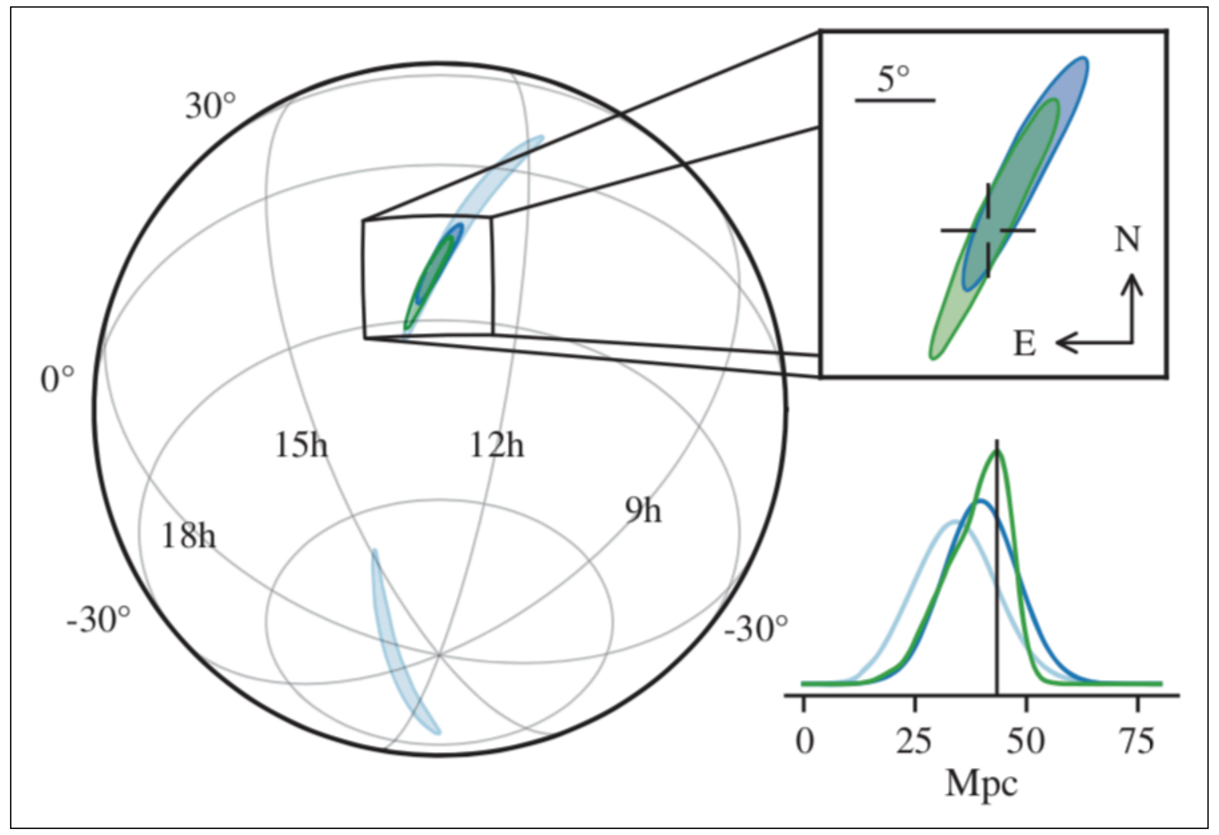
- Also Space-VLBI (Radioastron) for ultra-high angular resolution (down to few microarcseconds)

The era of multi-messenger astrophysics

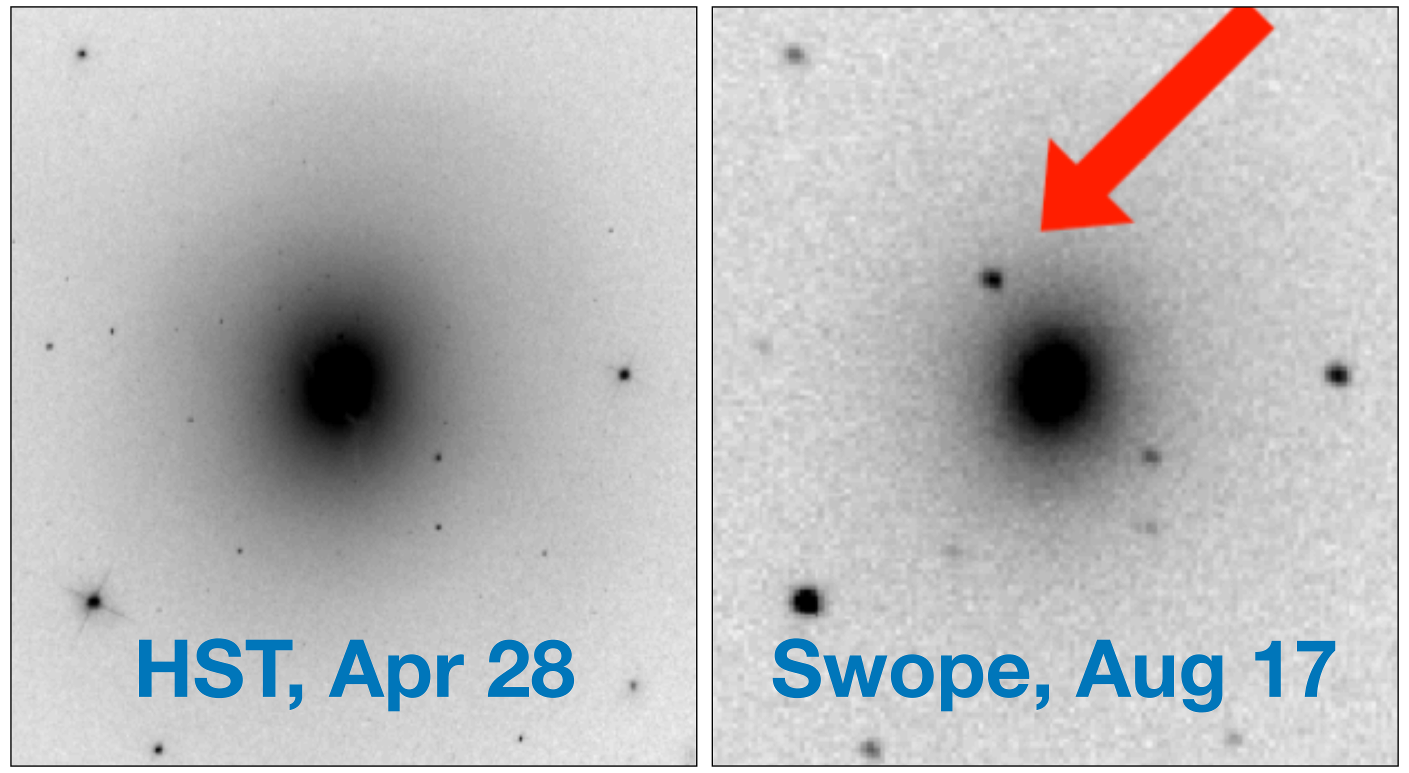
- GW 150914: first detection of GW from LIGO interferometer
- GW 170814: first detection of GW from LIGO+Virgo interferometer
- 2017 August 17: *Fermi* and Integral reveal GRB 170817A, a weak short GRB, just 1.7s after GW 170817 (6th GW detection, 2nd with LIGO+Virgo, 1st from binary NS)
- *[2017 Sep: IC 170922 neutrino, later associated with blazar TXS 0506+056]*

GW 170817/GRB 170817A/SSS 17a

- Initial localisation within 28 deg^2 area at d=40±8 Mpc (Abbott+17)
- optical emission detected 11 hr later (Coulter+17), pinpointing merger to S0-type galaxy NGC 4993, 10.6” (2 kpc) from its nucleus
- X-rays (off-axis) afterglow detected with *Chandra* at t=9 days, $L_{X,\,iso}$~10^{39} erg s^{-1} (Troja+17)
- Radio emission first detected at t=16 days with VLA and ATCA (Hallinan+17)



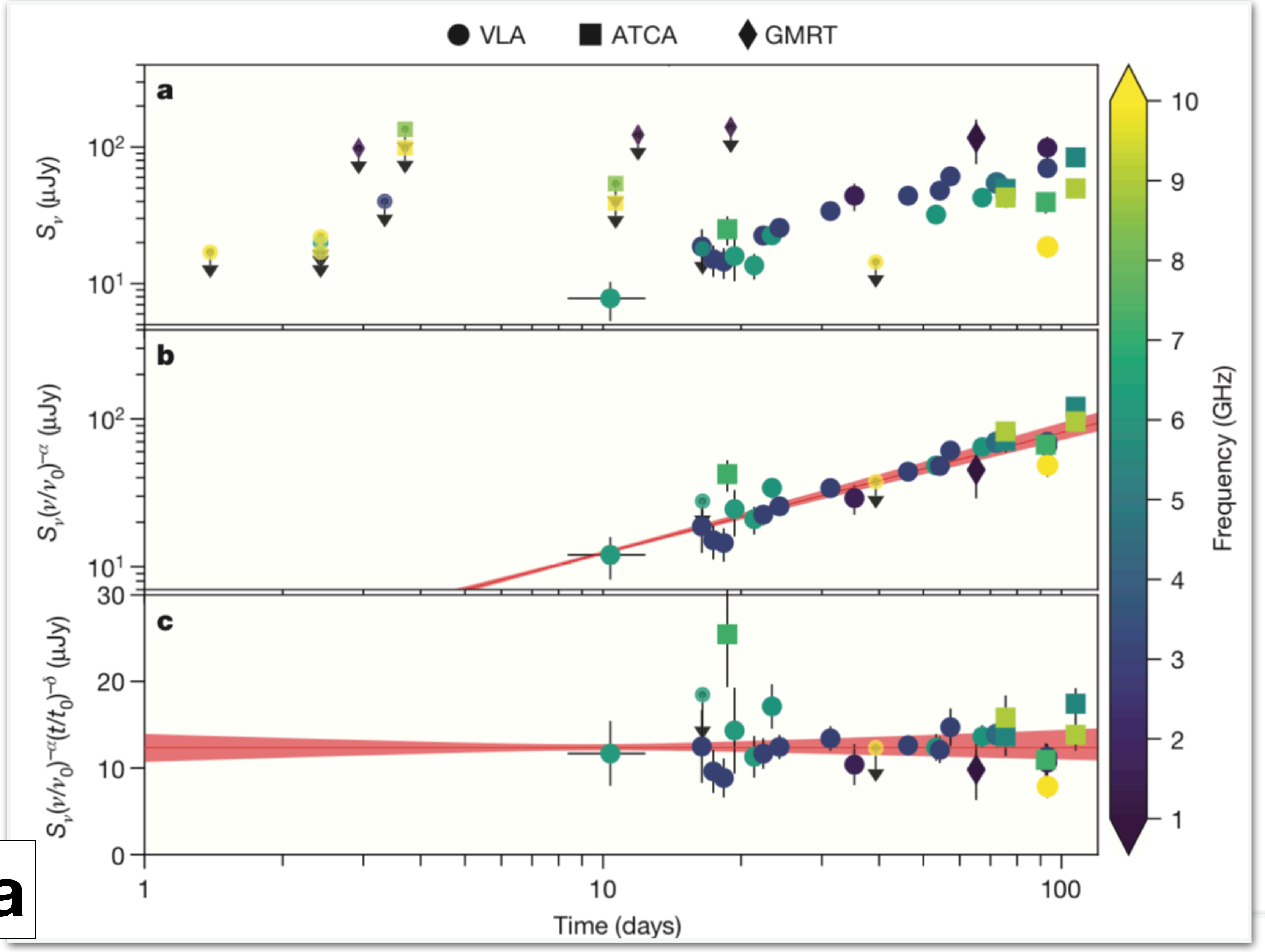
(Abbott+17)



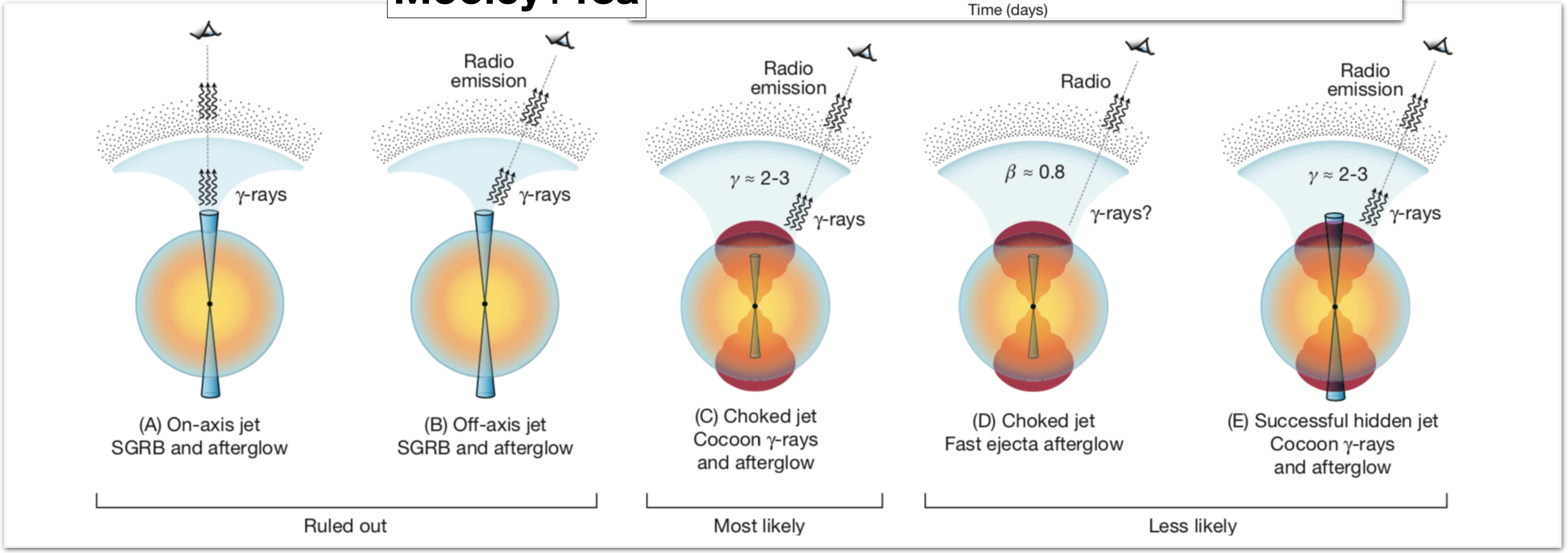
(Coulter+17)

Early radio observations

- Late, slow ($S \sim t^{0.8}$) rise of radio emission at GHz frequency
- Optically thin power-law spectrum: $S \sim \nu^{-0.6}$
- Off-axis structured jet, or cocoon?
- How to tell apart? High angular resolution structure/size, motions
- Can VLBI do it??? (remind 030329, and also 151027A, Nappo+17)



Mooley+18a



Global-VLBI observations

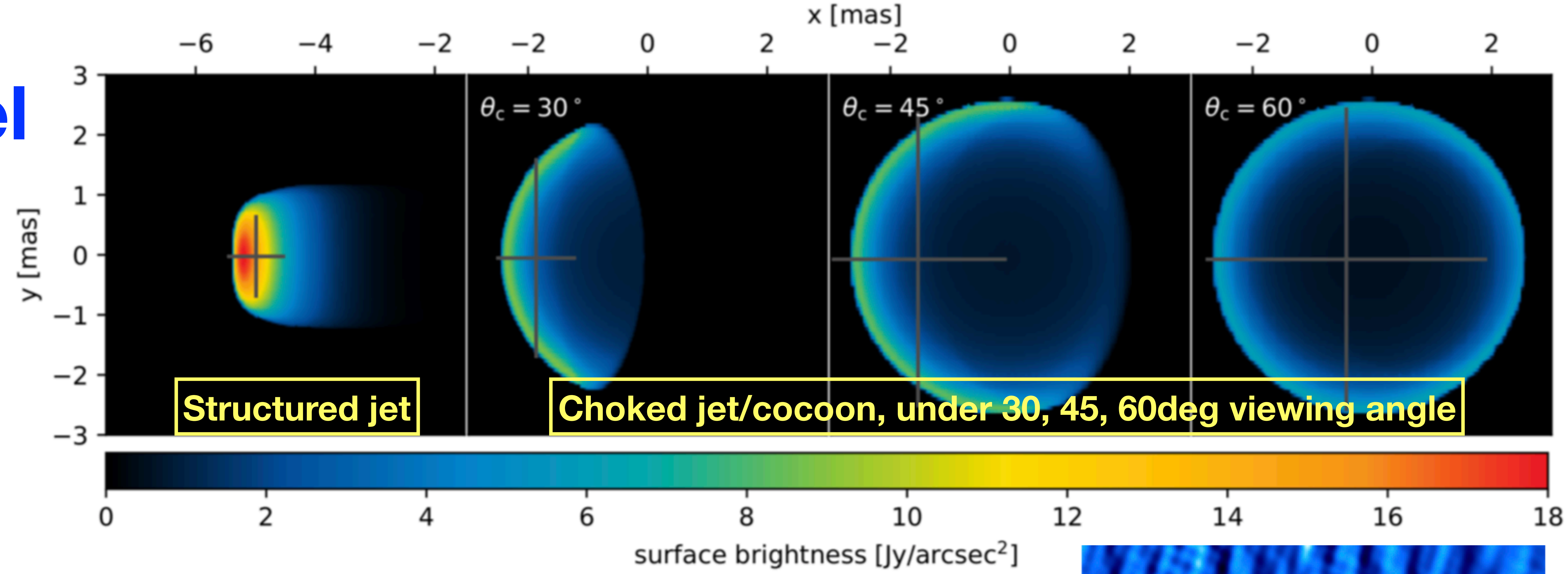
- 2018 March 12 (t=207 d)
- 32 radio telescopes over 5 continents, including southern hemisphere
- Longest baseline of 11787 km (SA-US); sensitive elements such as ATCA (5 x 22m), Tianma (65m), Effelsberg (100m), Green Bank (110m)
- **8 μJy beam^{-1}** rms
- **3.5 x 1.5 mas** resolution, in PA ~0°

Dec -23° target!

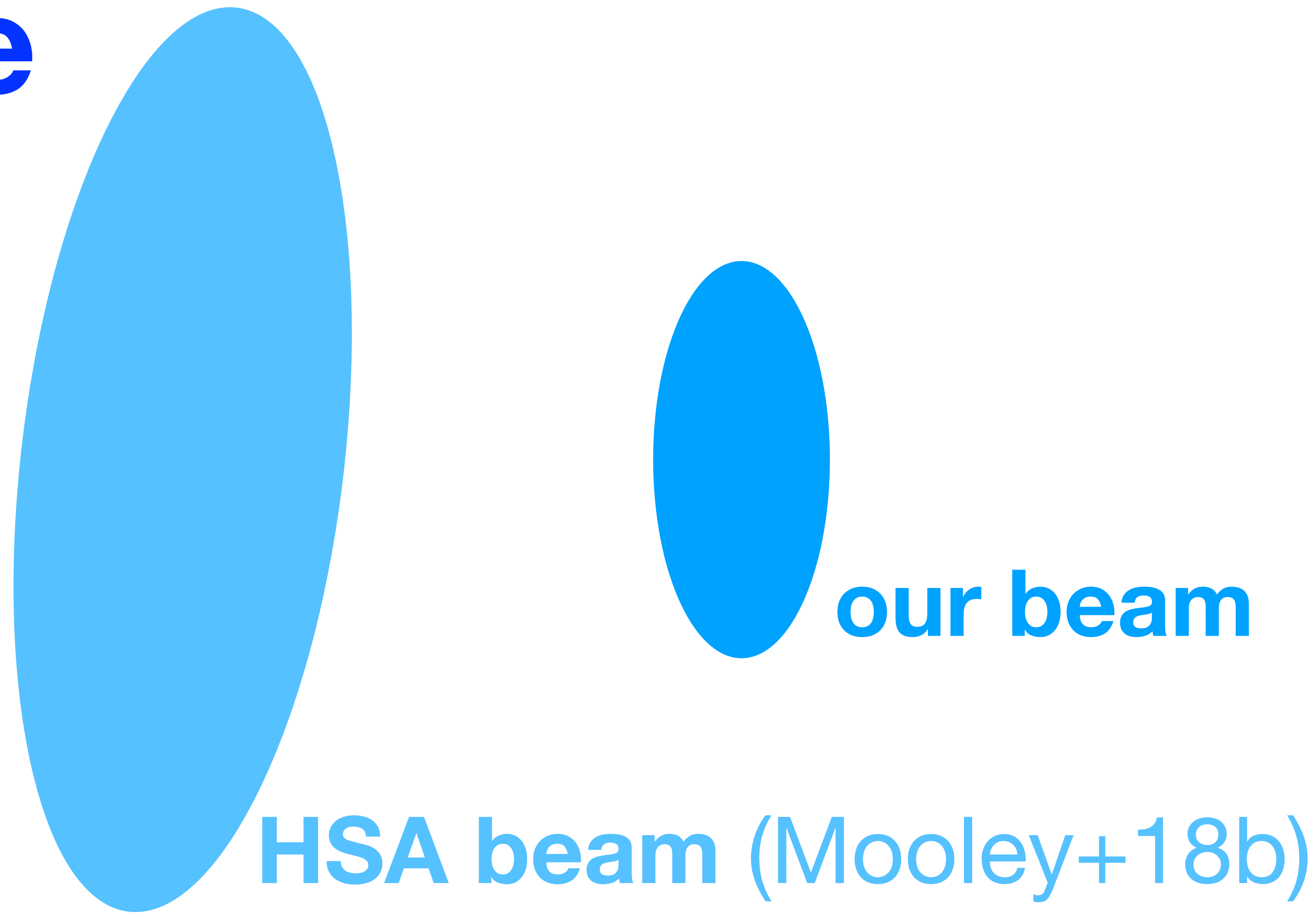
PI Ghirlanda code GG084

Model images… and real data

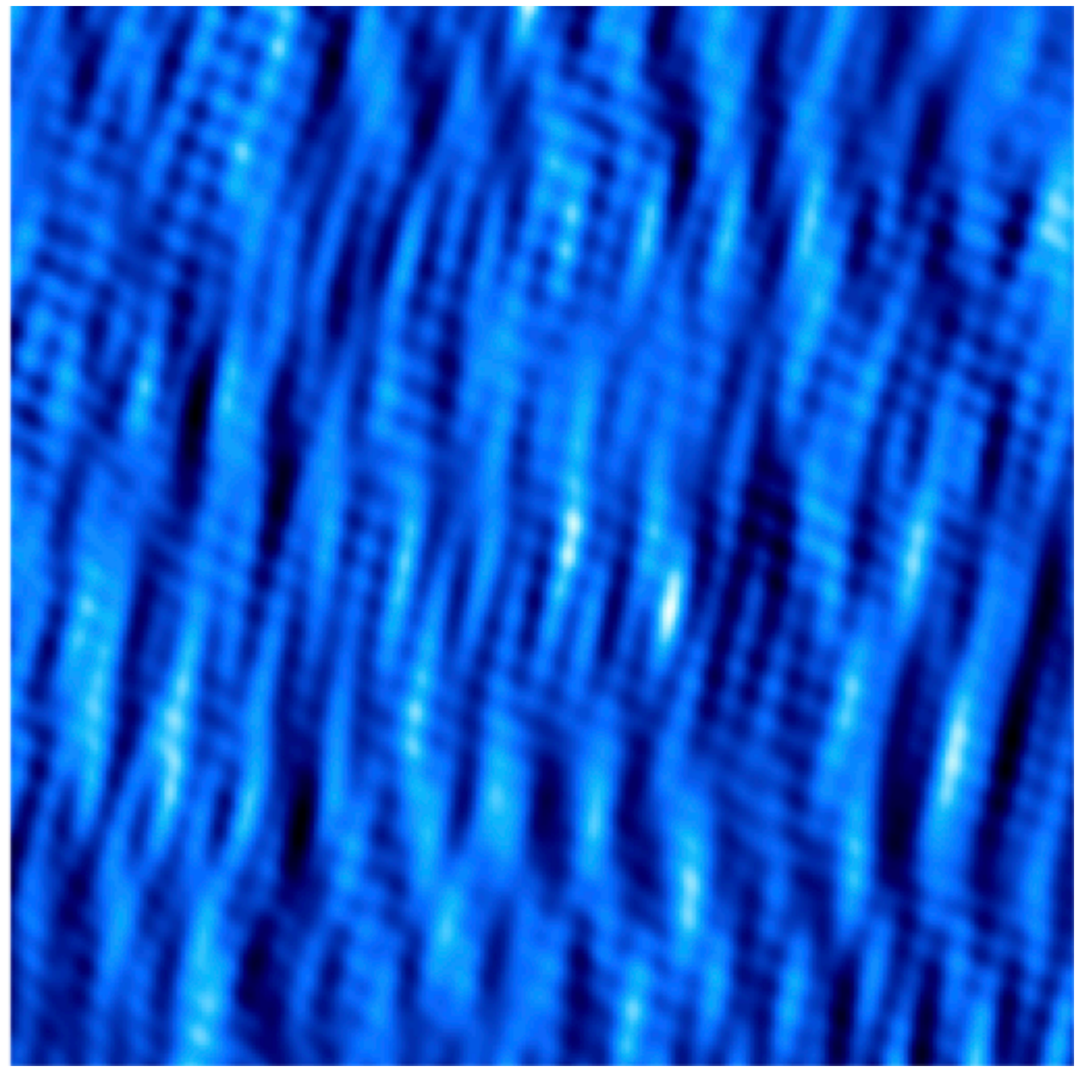
1. Develop model



2. Convolve with beam



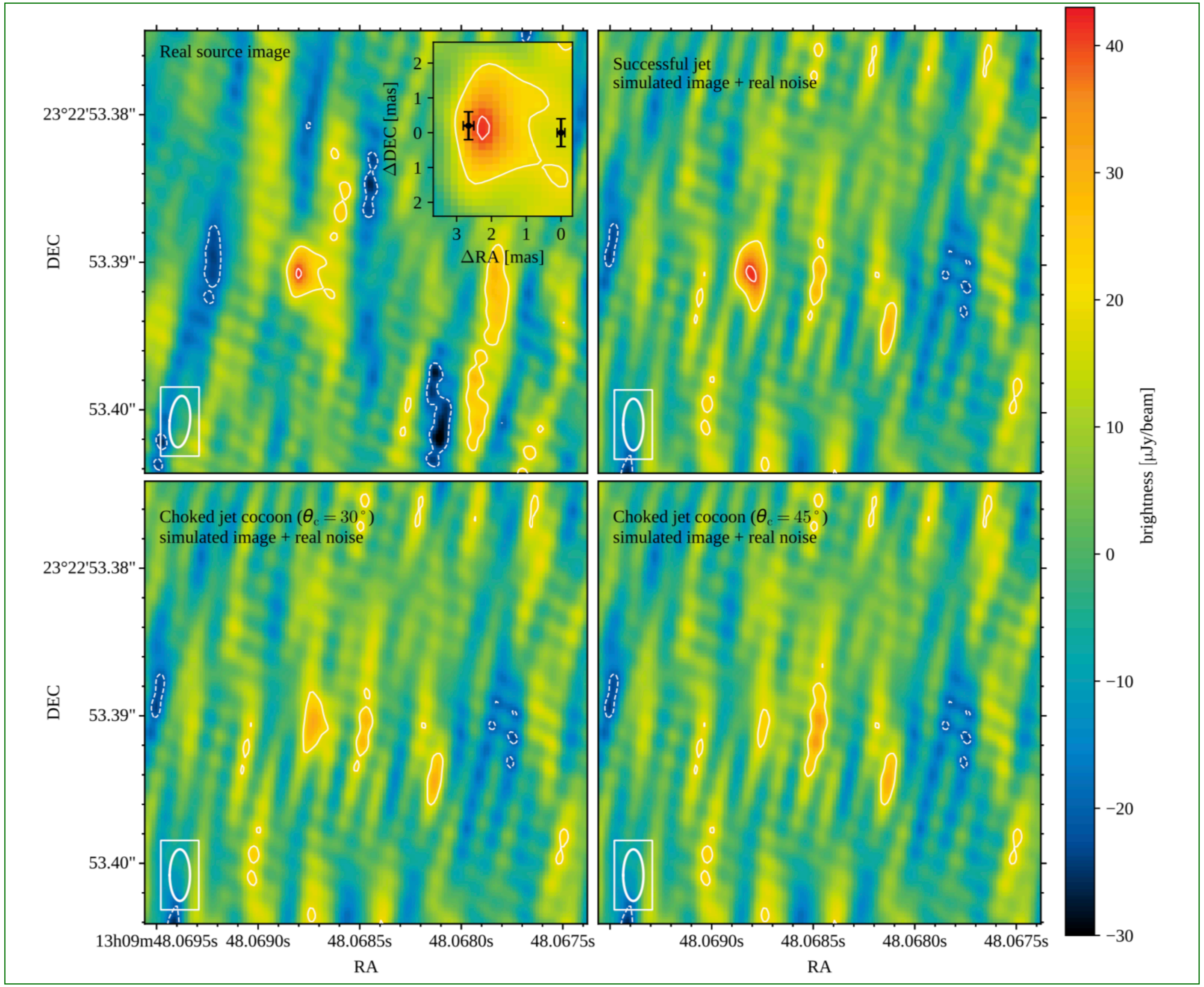
3. Add noise



Results

Real image

Simulated image, successful jet + real noise

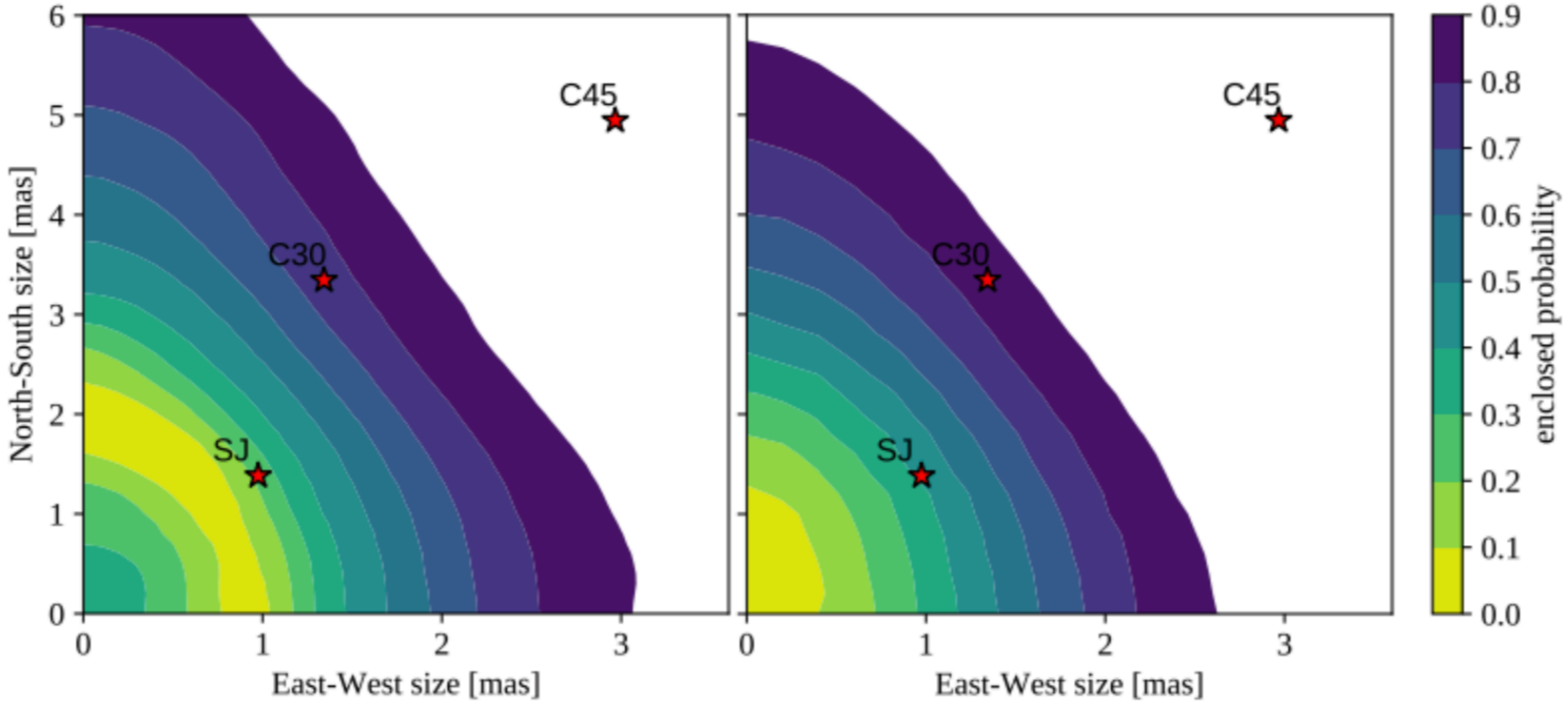


Simulated image, choked jet (θ=30°) + real noise

Simulated image, choked jet (θ=45°) + real noise

Test #1: size

- Image peak is 42±8 μJy beam^{-1} (>5.2σ), consistent with near time VLA flux density (47±9 μJy) and quasi-simultaneous e-Merlin upper limit (60 μJy beam^{-1}, 3σ)



- There should not be any missing extended emission

- Source size <2.5 mas at 90% c.l.

- Inconsistent with choked jet cocoons

- OK with narrow (θ_c=3.4±1°) and energetic ($E_{iso,\ core}$= $2.5_{+7.5/-2.0}\times10^{52}$ erg) core seen under a viewing angle θ_v~15°

Test #2: motion

- HSA images show displacement of radio feature by $\Delta r=(2.7\pm0.3)$ mas between t=75 and t=230 days (Mooley+18b)

- Our global-VLBI data fall nicely between the two positions (t=207d)

t (days)	RA (s)
75	48.068638±8
207	48.068800±20
230	48.068831±11

- $\beta_{app} = 4.1 \pm 0.5$

- $\theta_c \ll \theta_v \sim 14.5°$ and $\Gamma \sim 4$

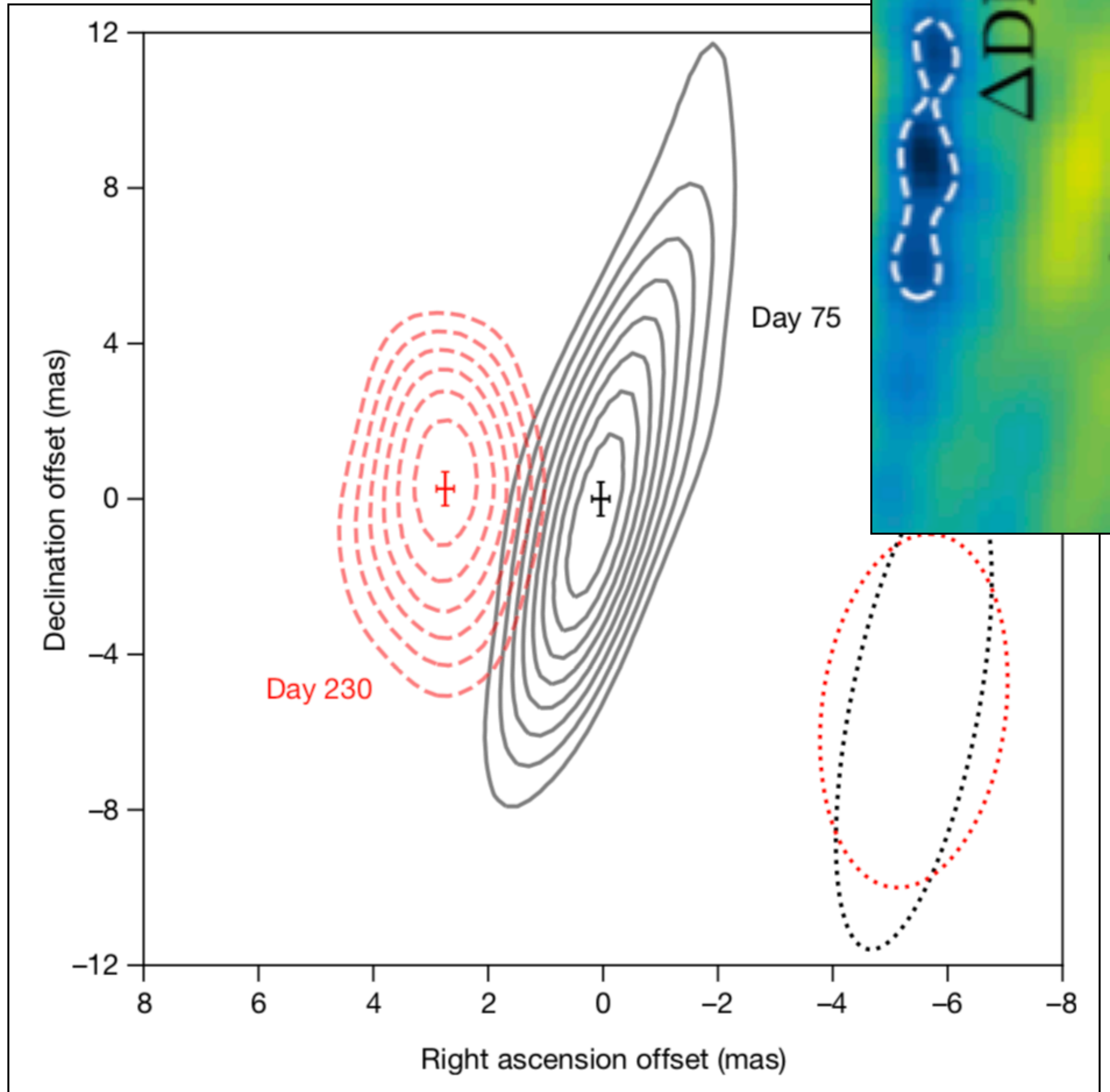
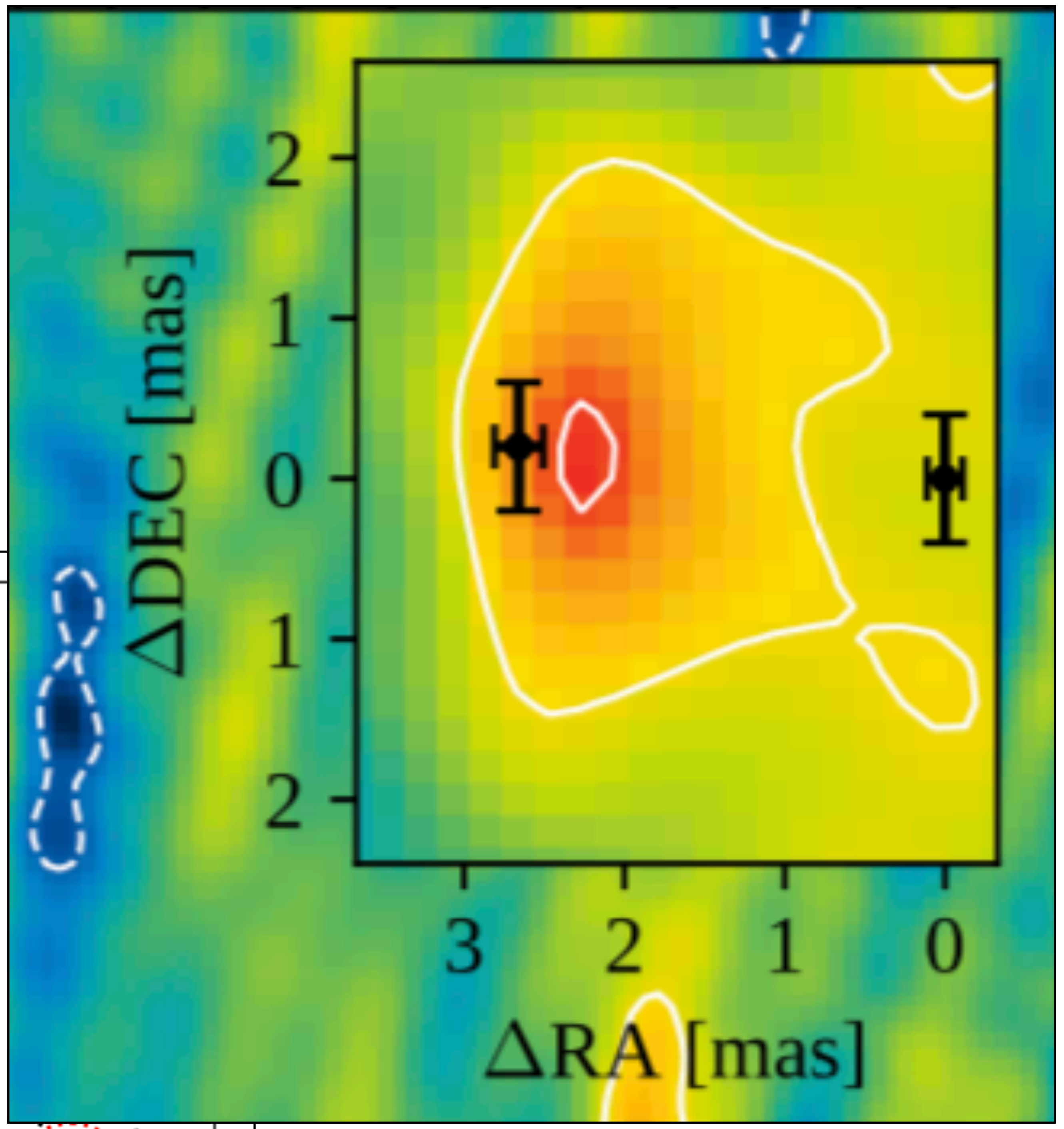
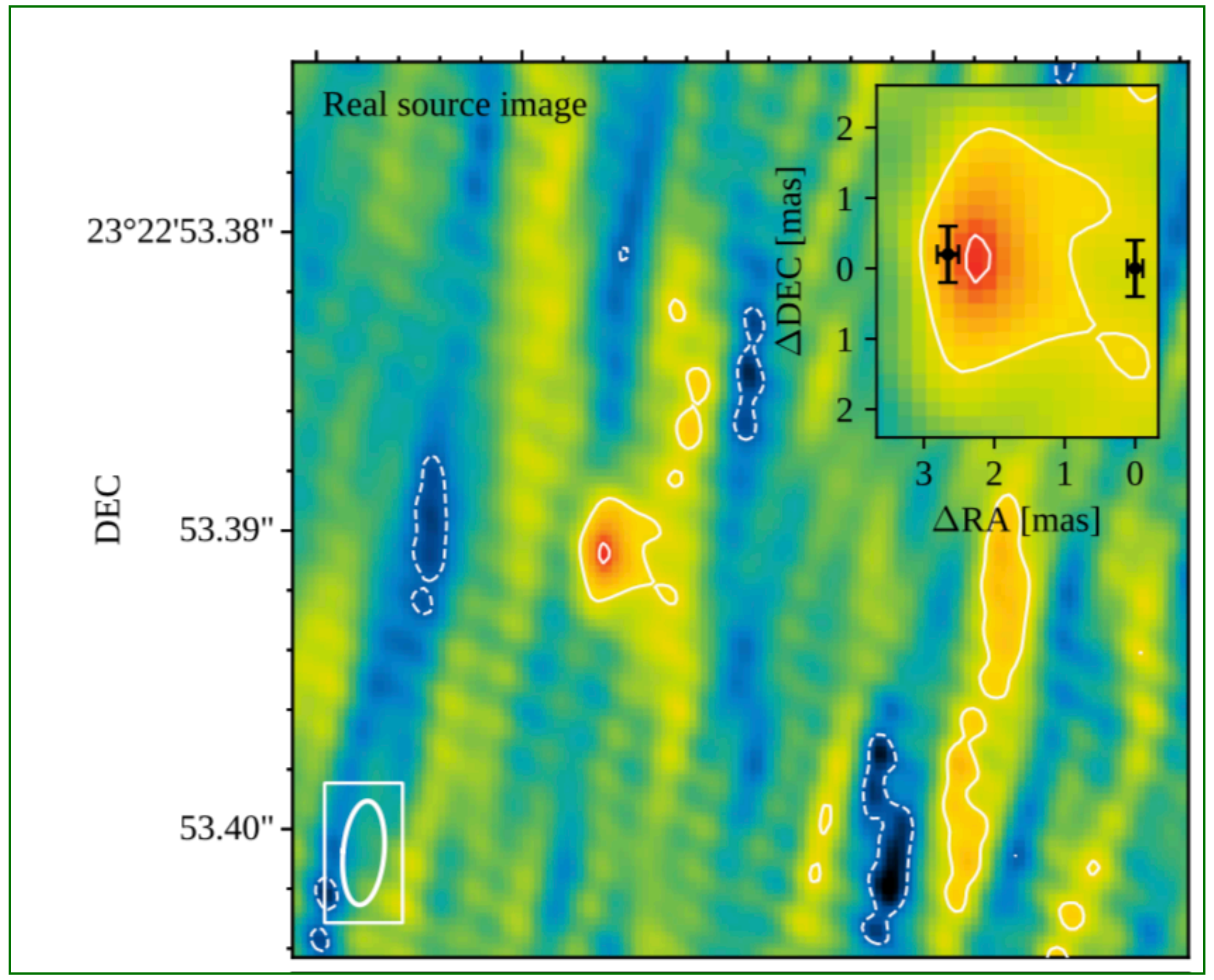


Fig. 1 | Proper motion of the radio counterpart of GW170817. The



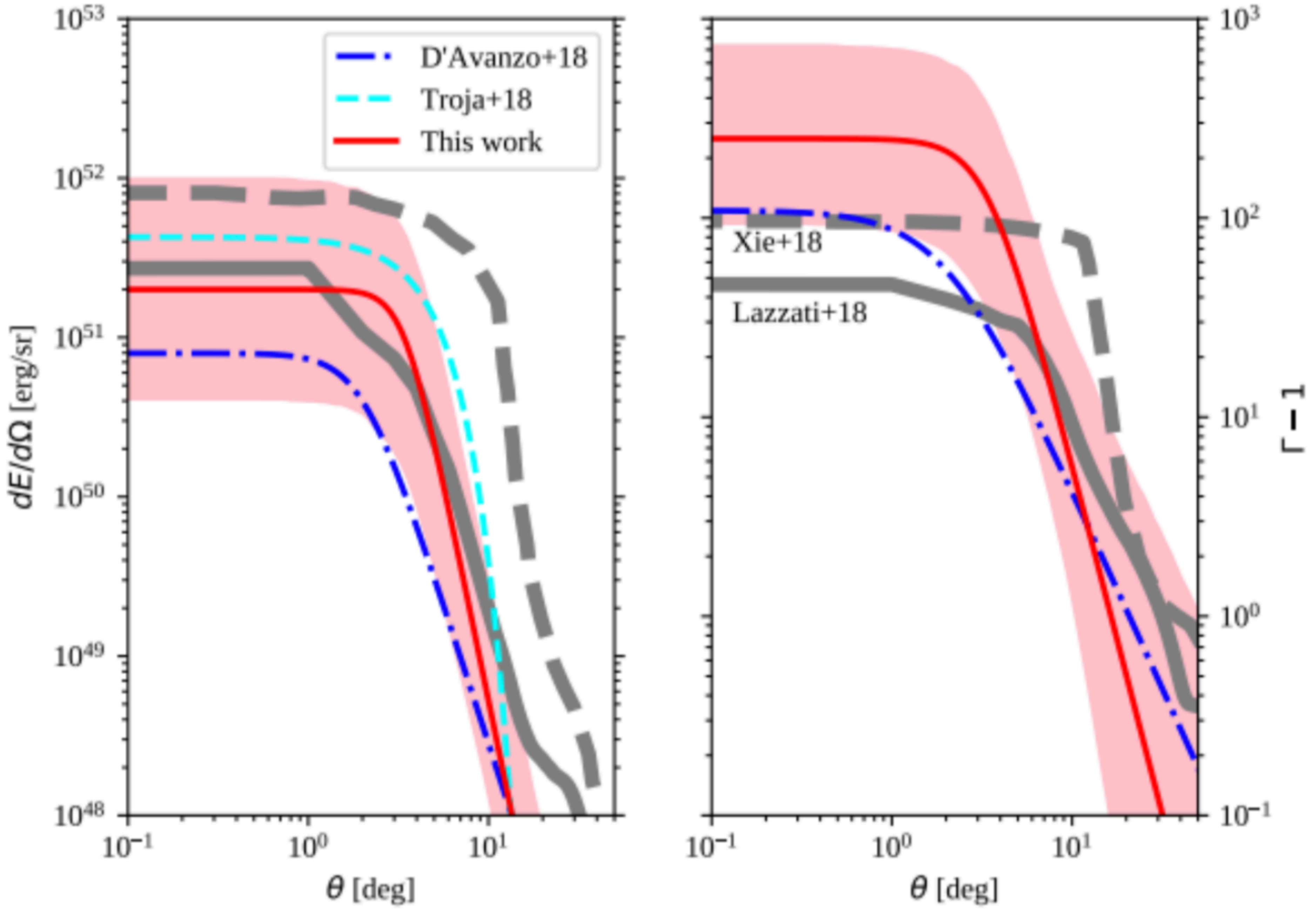
Summary

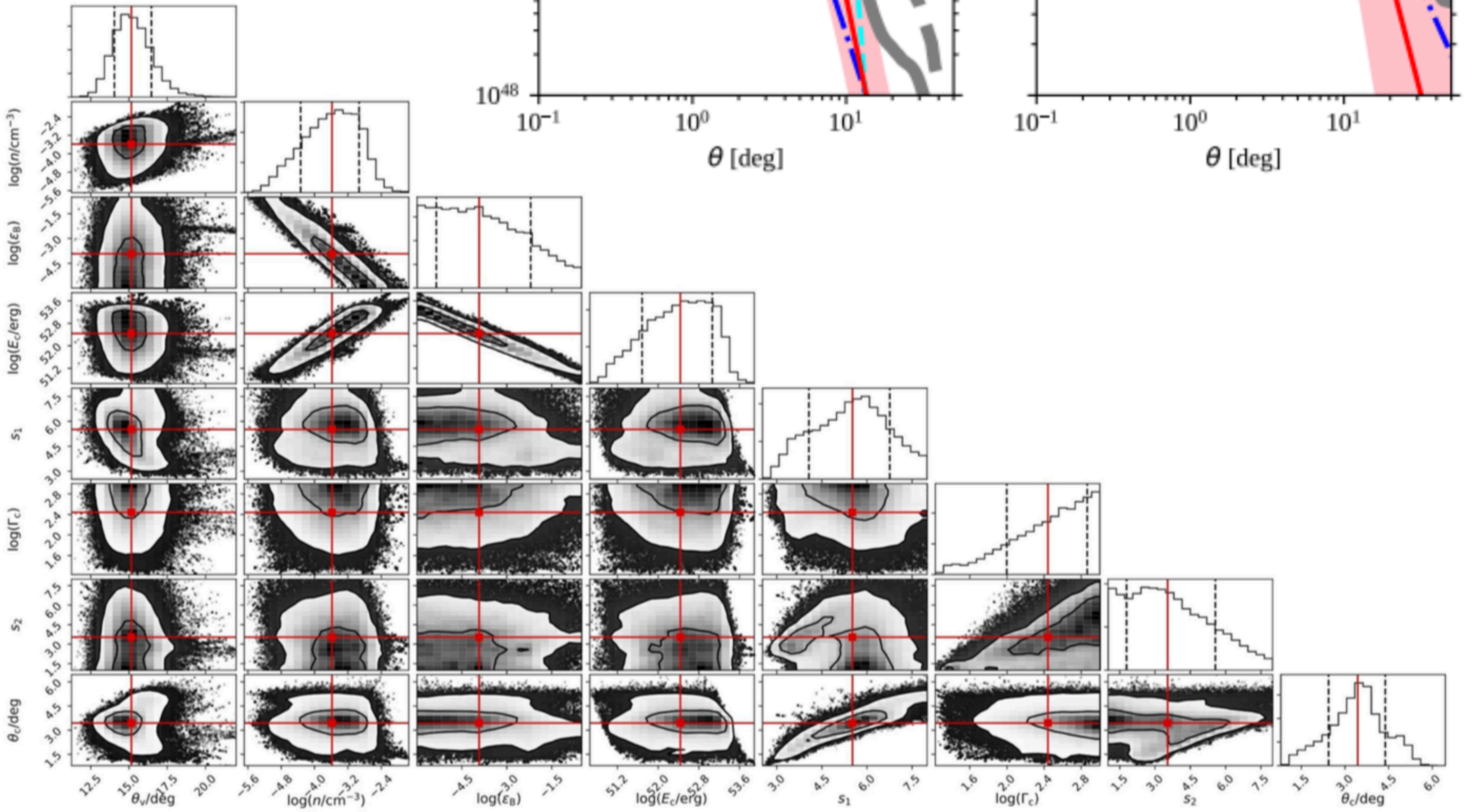
1. NS-NS merger did launch a successful structured jet
2. VLBI is a fundamental tool for GRB studies…
3. …and for compact objects science in general



Waiting for a multi-messenger event in O3!!!

Backup material





Parameter	best fit value	one sigma range
Flat prior on θ_v		
$\log(E_c/\mathrm{erg})$	52.4	(51.7, 53.0)
s_1	5.5	(4.1, 6.8)
$\log(\Gamma_c)$	2.4	(2.0, 2.9)
s_2	3.5	(1.8, 5.6)
θ_c/deg	3.4	(2.4, 4.4)
$\log(\epsilon_B)$	−3.9	(−5.4, −2.2)
$\log(n/\mathrm{cm}^{-3})$	−3.6	(−4.3, −2.9)
θ_v/deg	15	(14, 16.5)

MWL light curves

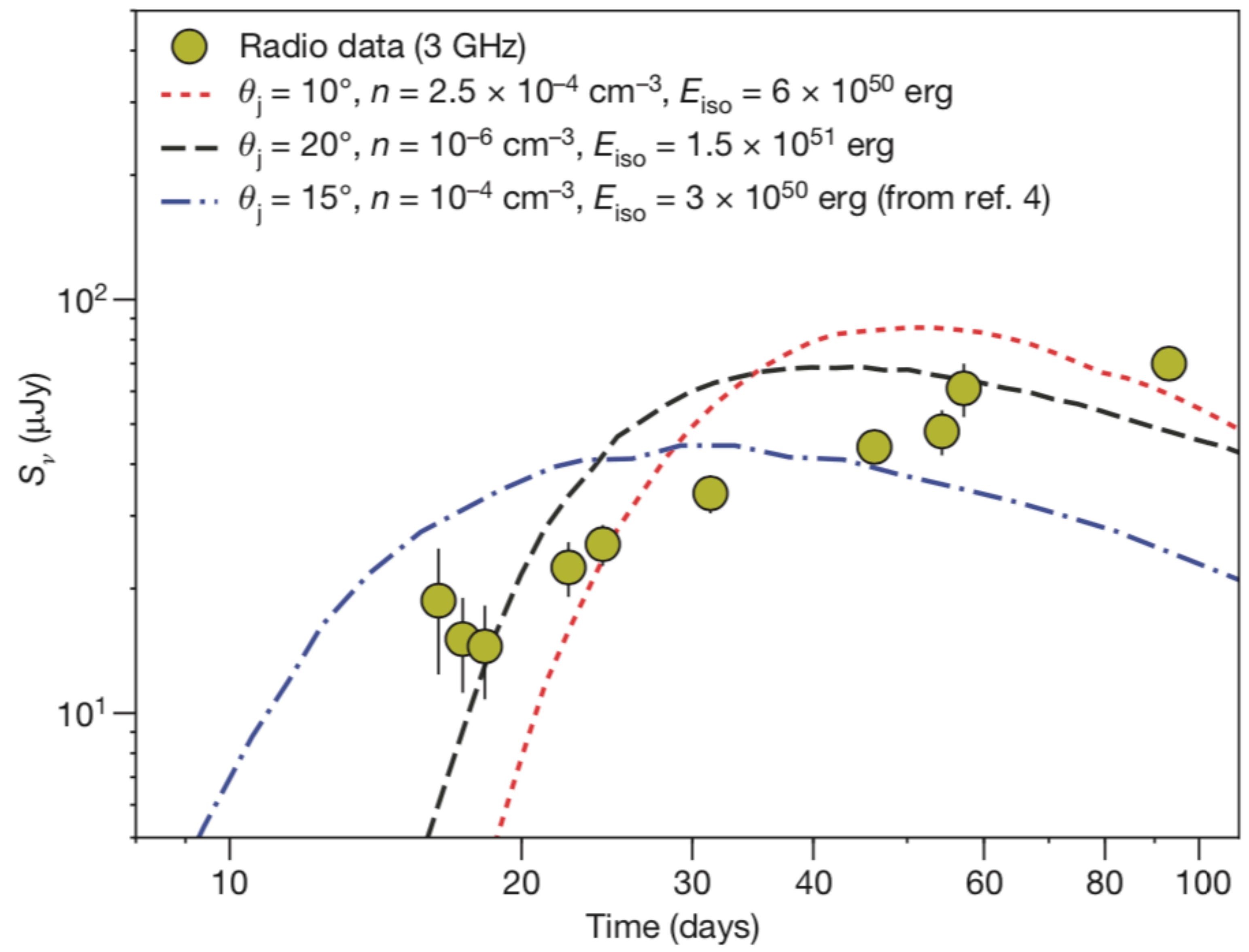


Figure 3 | Off-axis jet models. Synthetic light curves with a range of

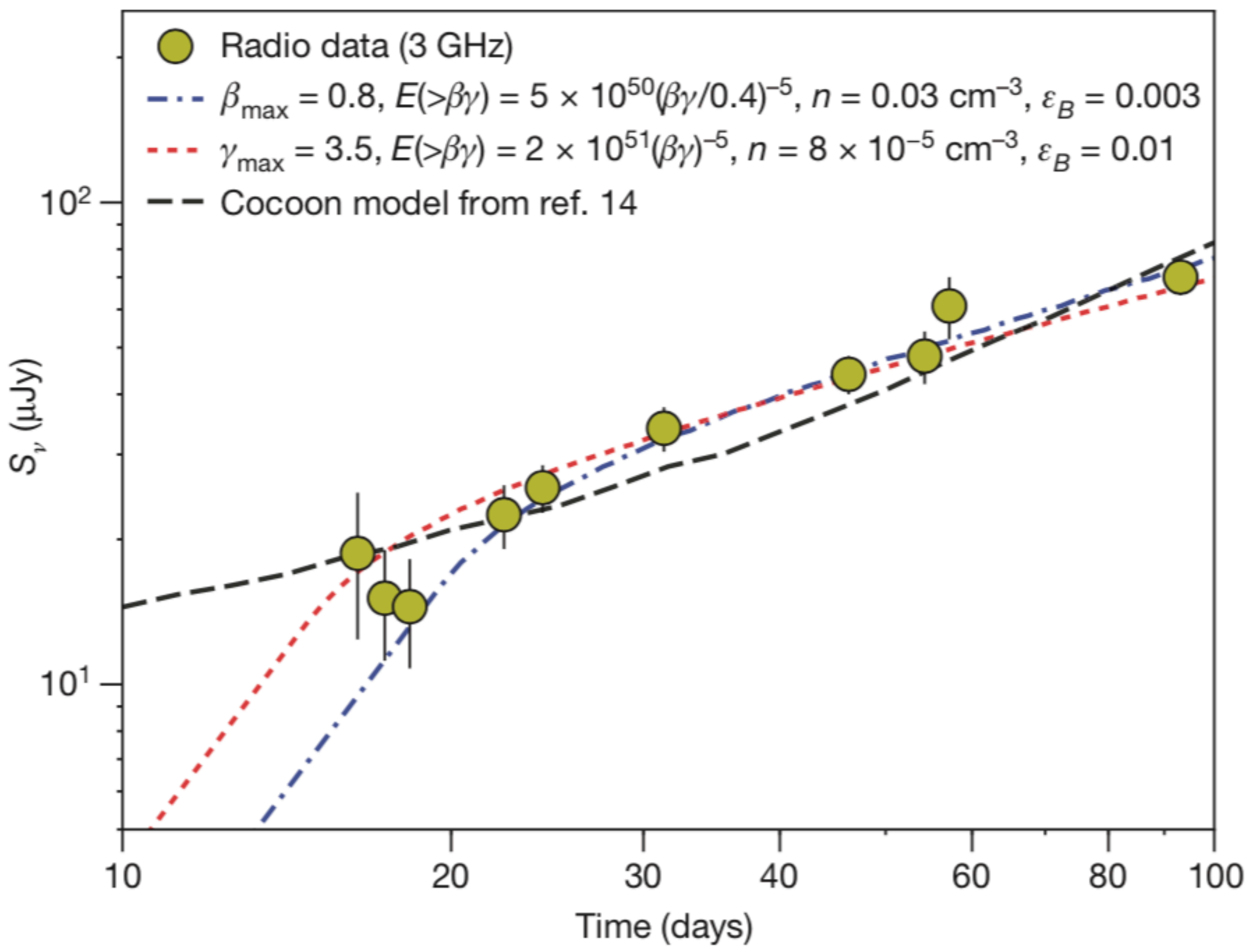
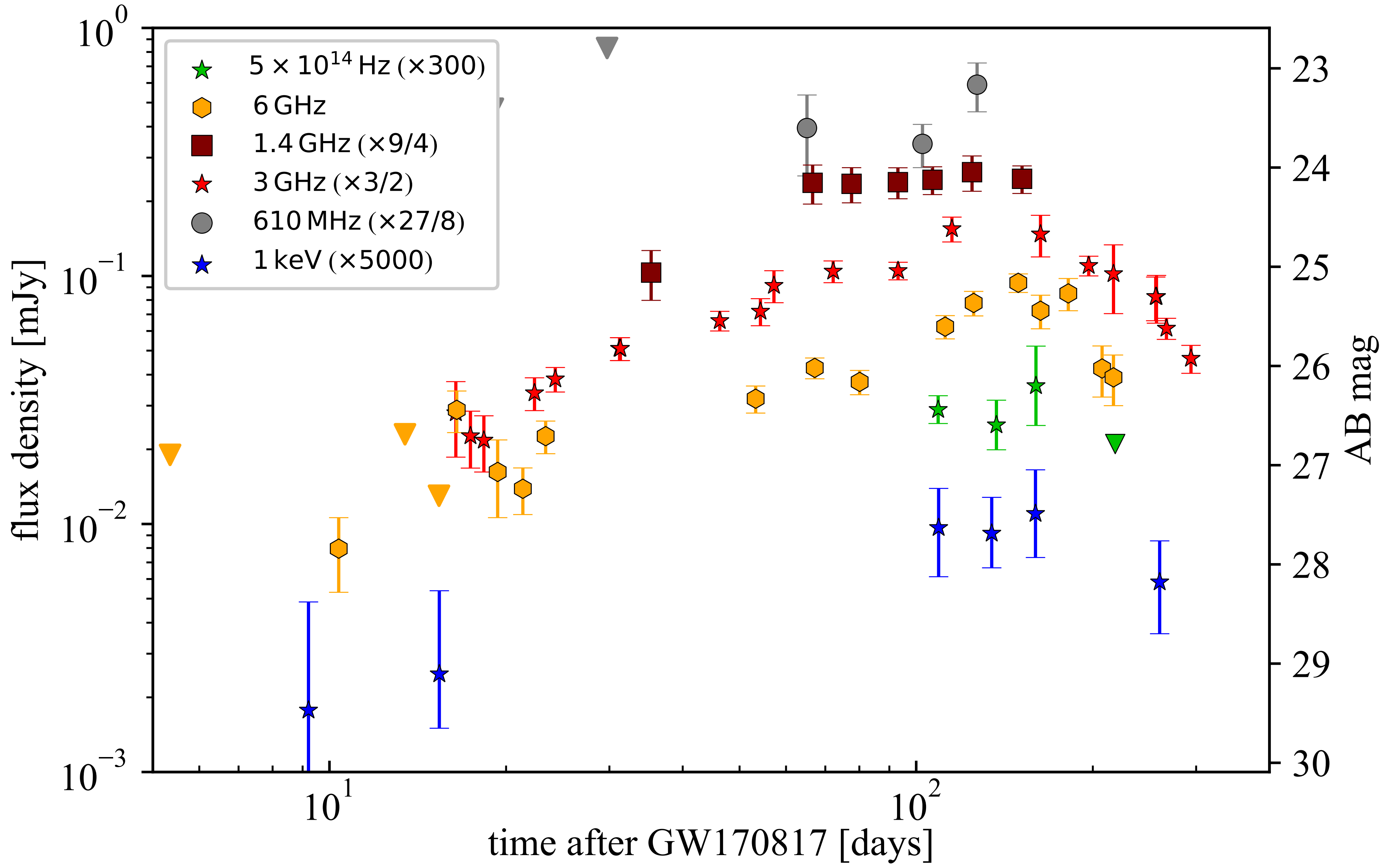


Figure 4 | Quasi-spherical ejecta models. Radio light curves arising from



Radio @3 GHz, 0-100 days, from Mooley+18a

MWL, 0-300 days, from Ghirlanda+18

151027A, another GRB studied with VLBI

A&A 598, A23 (2017)
DOI: 10.1051/0004-6361/201628801

Astronomy & Astrophysics

The 999th *Swift* gamma-ray burst: Some like it thermal

A multiwavelength study of GRB 151027A

F. Nappo[1,2], A. Pescalli[1,2], G. Oganesyan[3], G. Ghirlanda[2], M. Giroletti[4], A. Melandri[2], S. Cam
O. S. Salafia[5,2], P. D'Avanzo[2], M. G. Bernardini[6], S. Covino[2], E. Carretti[7], A. Celotti[3], V. D'
E. Palazzi[11], S. Poppi[7], I. Prandoni[4], S. Righini[4], A. Rossi[11], R. Salvaterra[12], G. Tagliafe
T. Venturi[4], and S. D. Vergani[13]

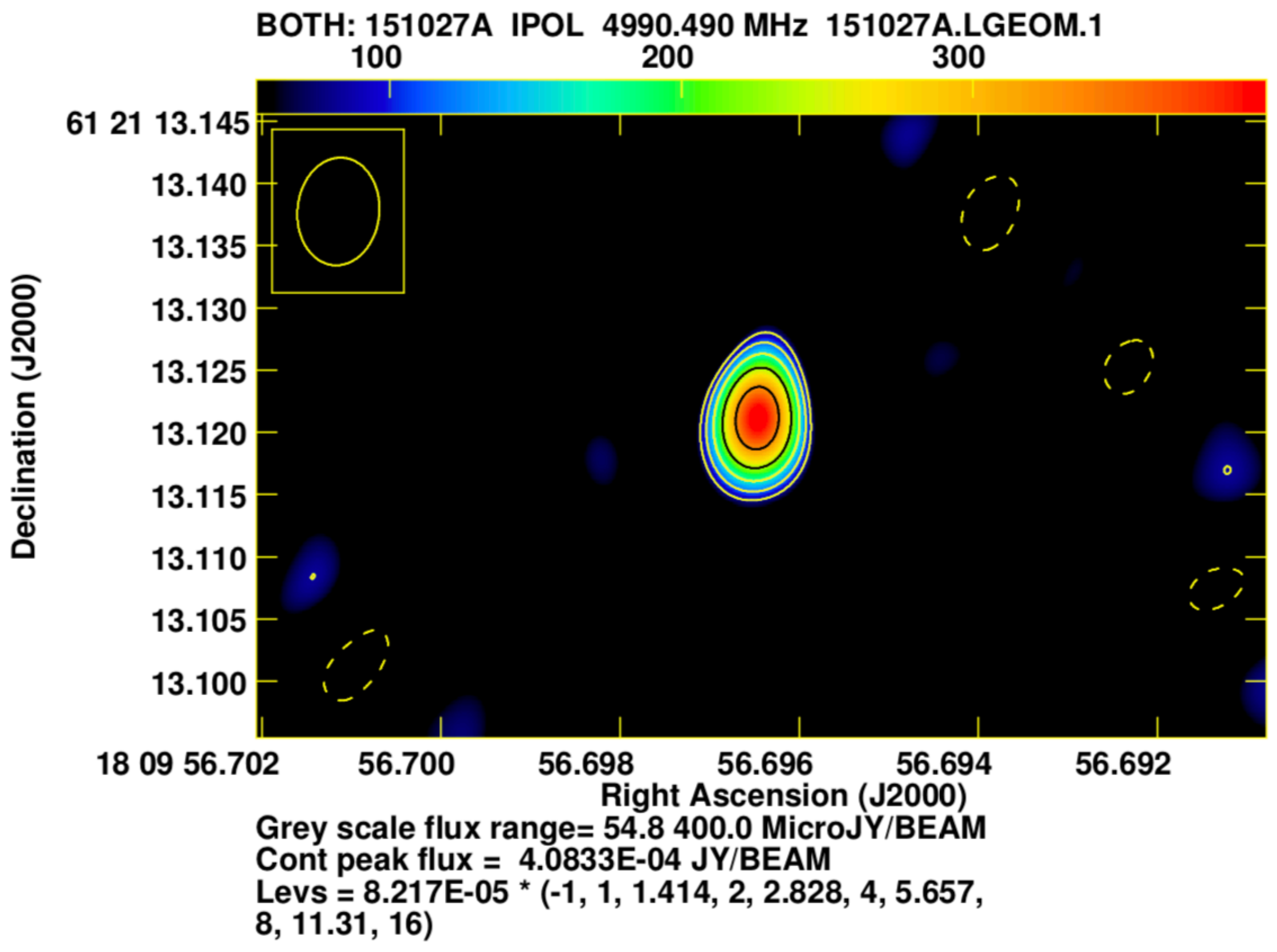


Fig. 3. 5 GHz VLBI image of GRB 151027A taken with the EVN on 2015 November 18.