VLBI observations of transient events in a multi-messenger context

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Black Hole Astrophysics with VLBI: Multi-Wavelength and Multi-Messenger Era
2021 January 19, ICRR Tokyo Univ. (on-line)

Outline

- Astrophysical transients & VLBI: a good match
- Selected highlights:
  1. GW & short GRBs
  2. VHE & long GRBs
  3. FRBs
  4. novae and other galactic binaries
  - *neutrinos covered in other talks*

Astrophysical transients and VLBI

- why are they connected? short-time variability implicates small linear size, calling for extreme angular resolution
- why are they blooming? the wide-field revolution + the start of multi-messenger era + technological VLBI improvements
- the unique role of VLBI:

1. localisation
2. resolved imaging and evolution

Highlight #1: GW and NS mergers

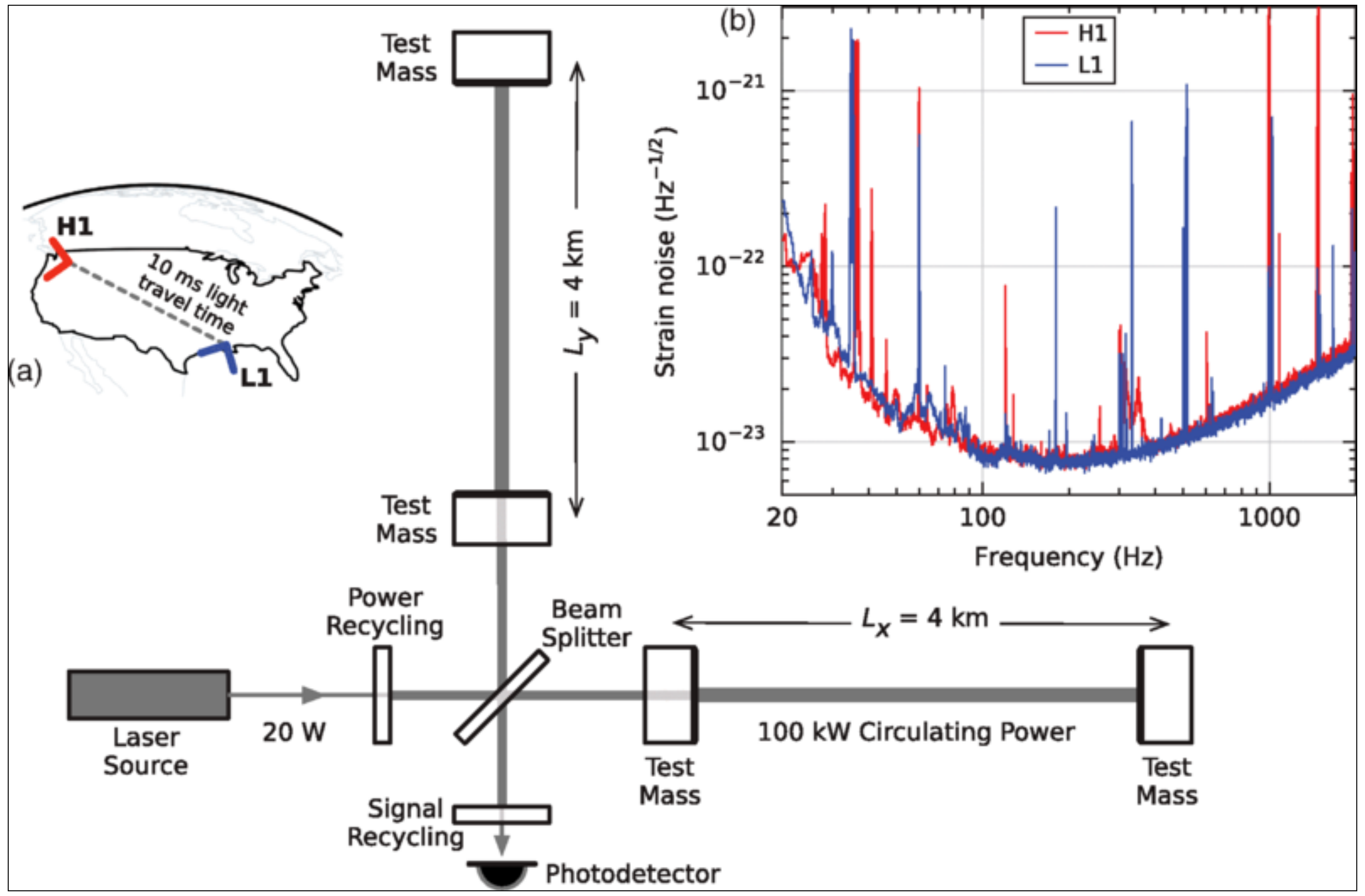
- Advanced LIGO+Advanced Virgo interferometers, sensitive to waves in 10 Hz-10 kHz frequency range (compact objects)

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

- BH-BH mergers (BBH): potentially quite massive (>10 M_{sun}) progenitors, distant horizon, no EM counterpart expected

- NS-NS mergers (BNS): much lighter progenitors, nearby, thought to give rise to short GRBs (if geometry's right)

- NS-BH mergers: intermediate case in terms of mass and distance, unclear whether an EM counterpart is allowed



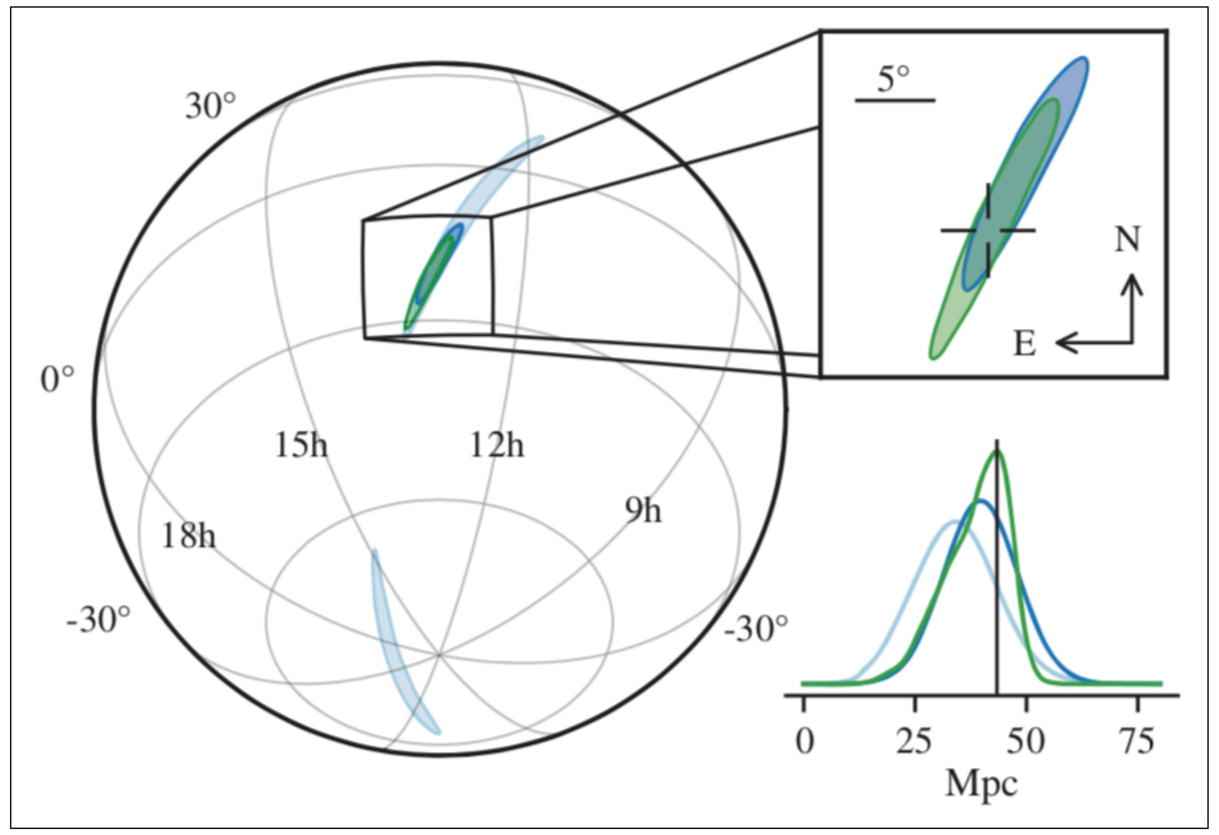
GW 170817/GRB 170817A/SSS 17a

- Initial GW and *Fermi*-GBM localisation within 28 deg² area at *d*=40±8 Mpc (Abbott+17)

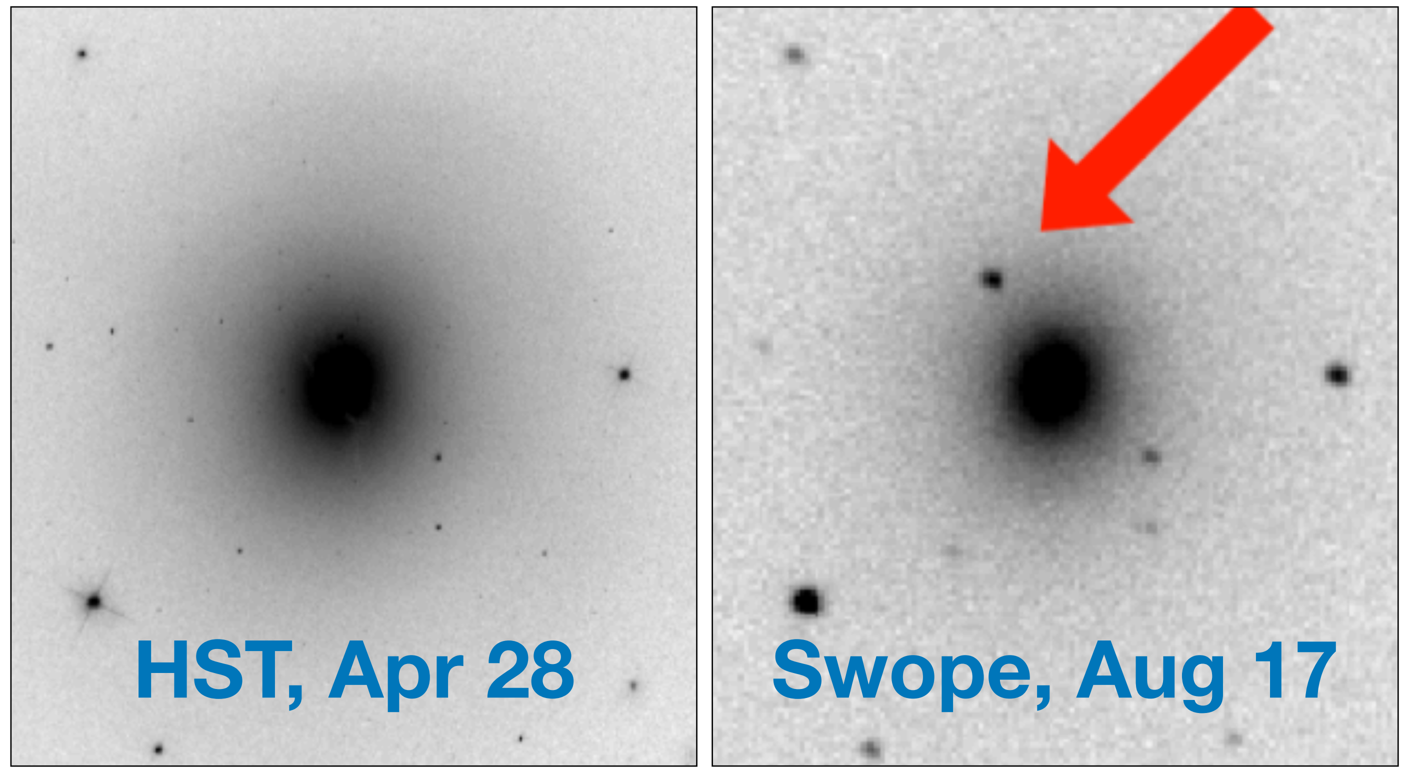
- optical emission detected 11 hr later (Coulter+17), pinpointing merger to S0-type galaxy NGC 4993, 10.6” (2 kpc) from its nucleus

- 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)



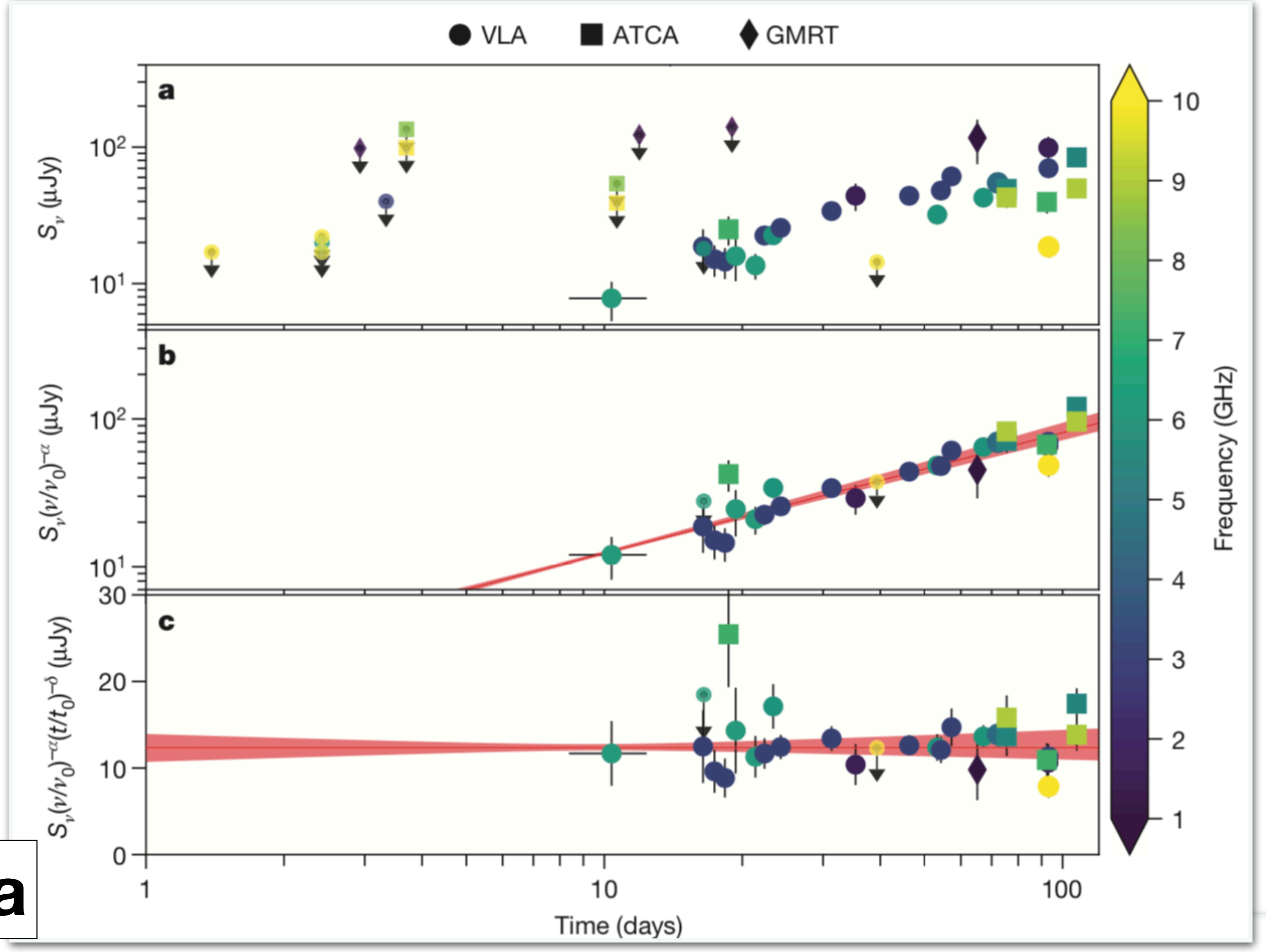
(Abbott+17)



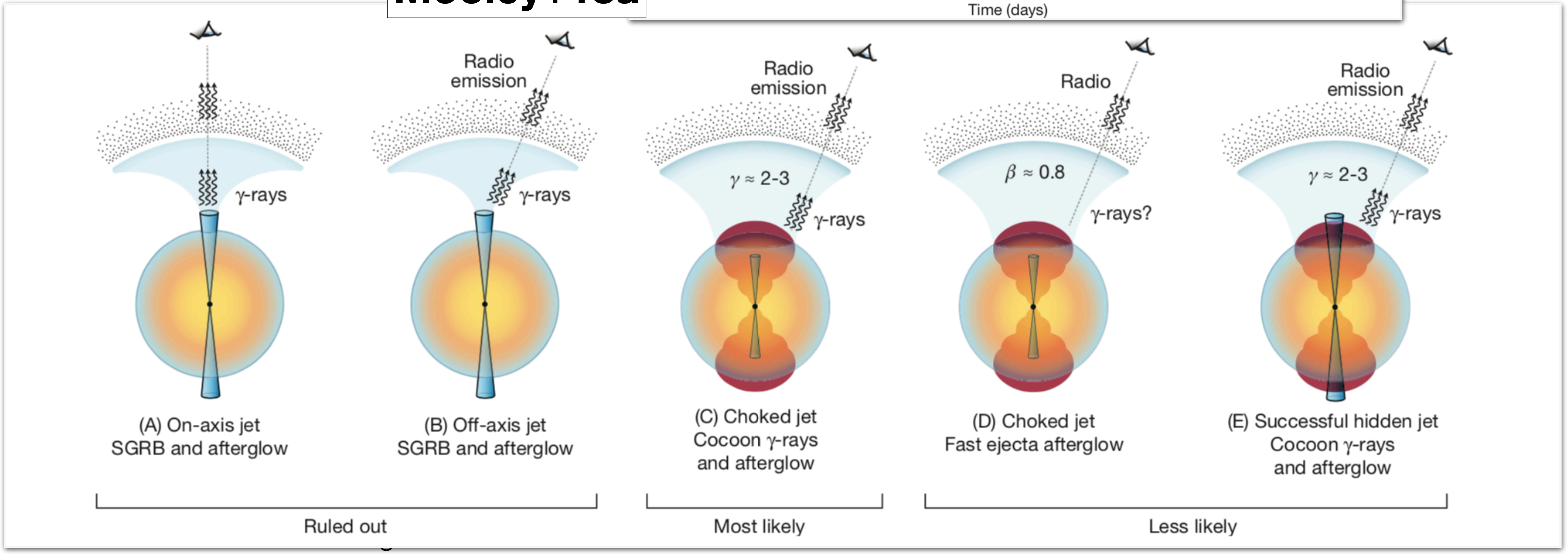
(Coulter+17)

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)



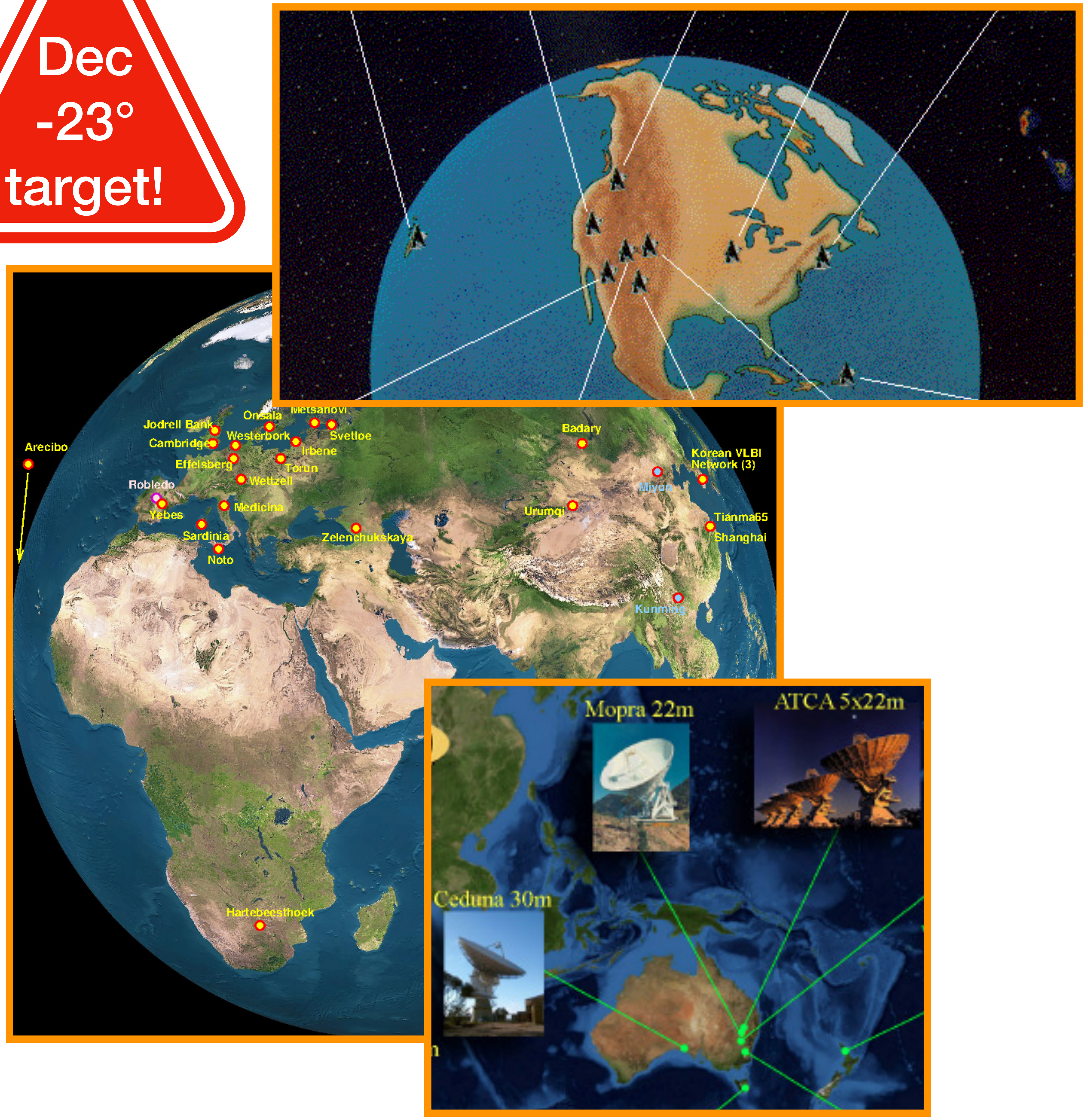
Mooley+18a



Global-VLBI observations

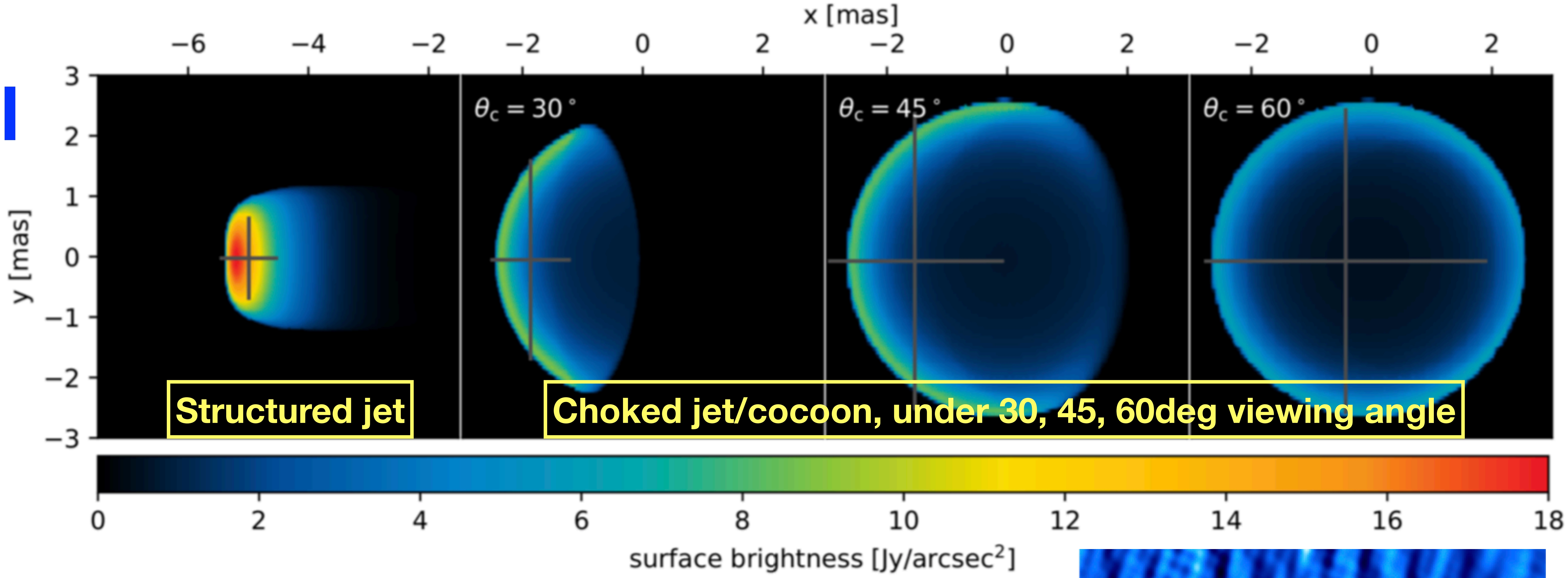
- 2018 March 12 (t=207 d)
- 32 radio telescopes over 5 continents, including southern hemisphere
- Longest baseline of 11787 km (SA-US); sensitive elements such as ATCA (5 x 22m), Tianma (65m), Effelsberg (100m), Green Bank (110m)
- **8 μJy beam^{-1}** rms
- **3.5 x 1.5 mas** resolution, in PA ~0°

Dec -23° target!

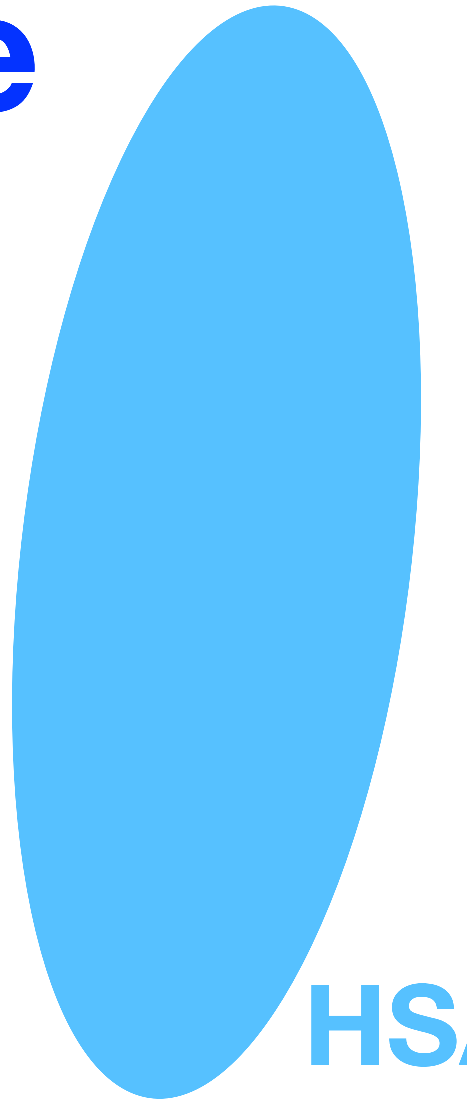


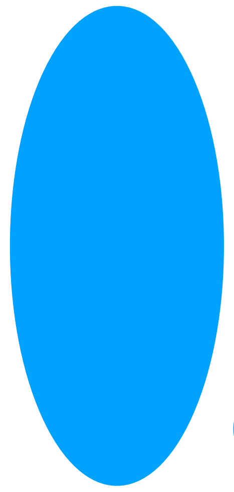
Model images… and real data

1. Develop model



2. Convolve with beam

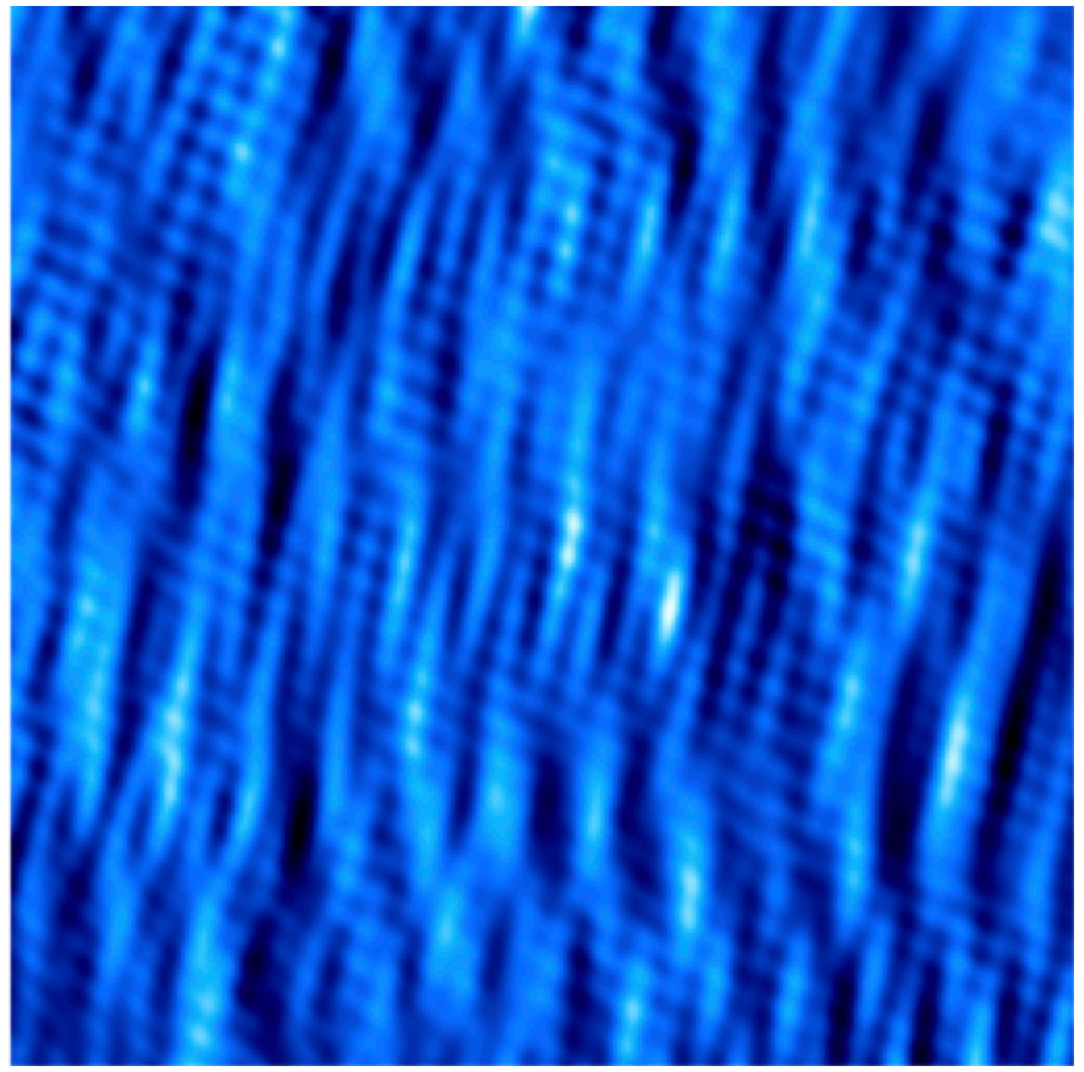




our beam

HSA beam (Mooley+18b)

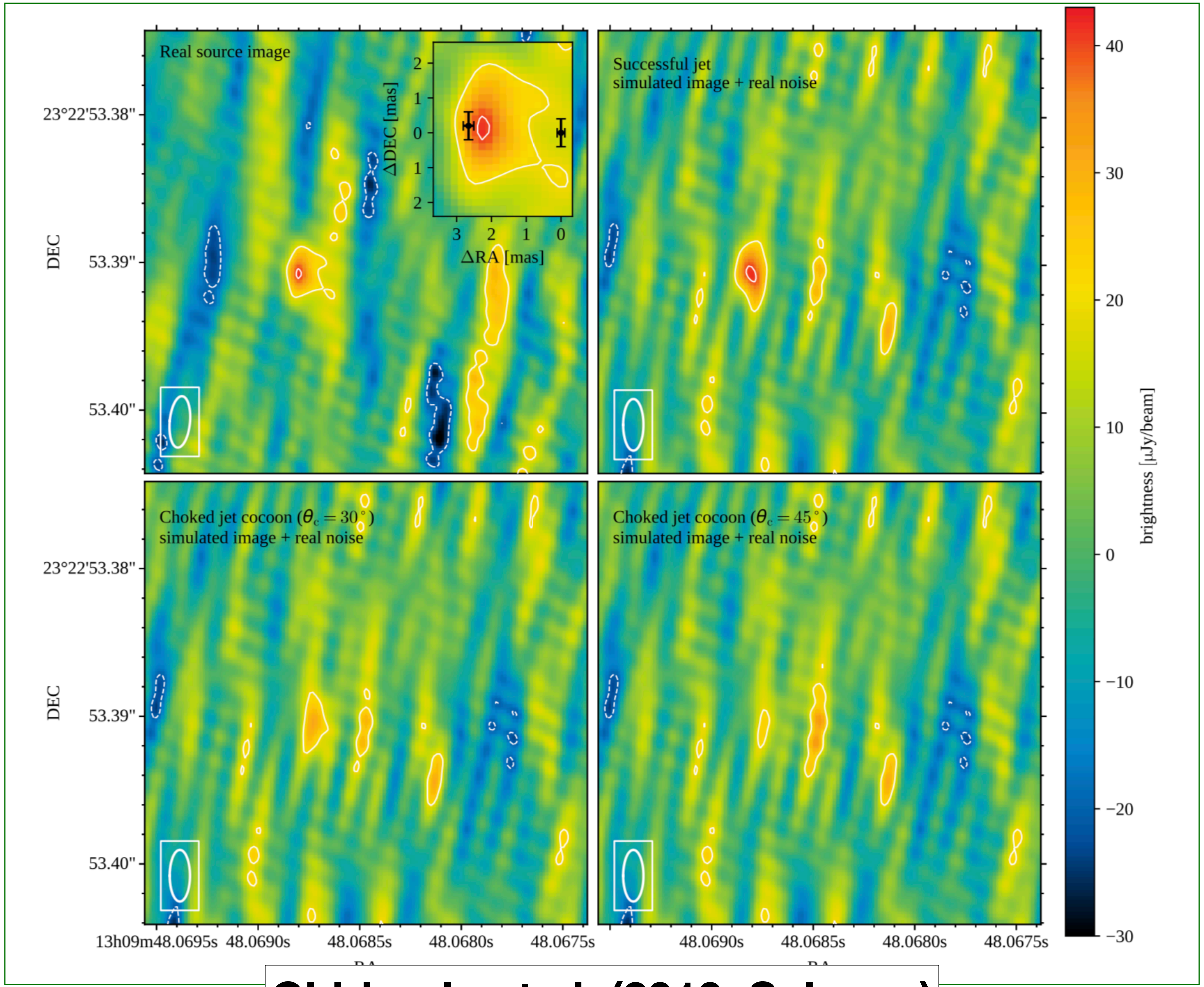
3. Add noise



Results

Real image

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



Simulated image, successful jet + real noise

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

Ghirlanda et al. (2019, Science)

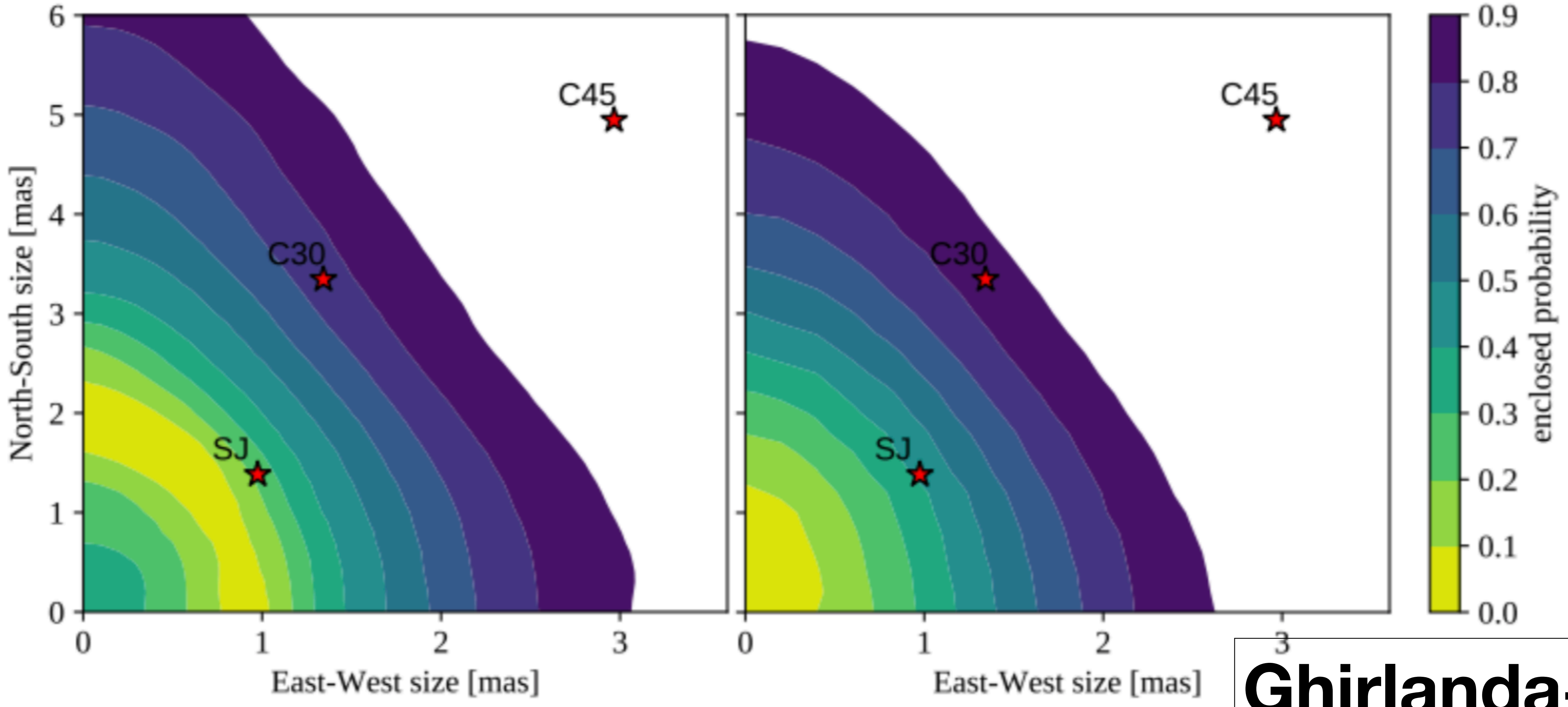
Test #1: size

- 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



Ghirlanda+19

- 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 $\Delta r = (2.7 \pm 0.3)$ 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 $\Gamma \sim 4$

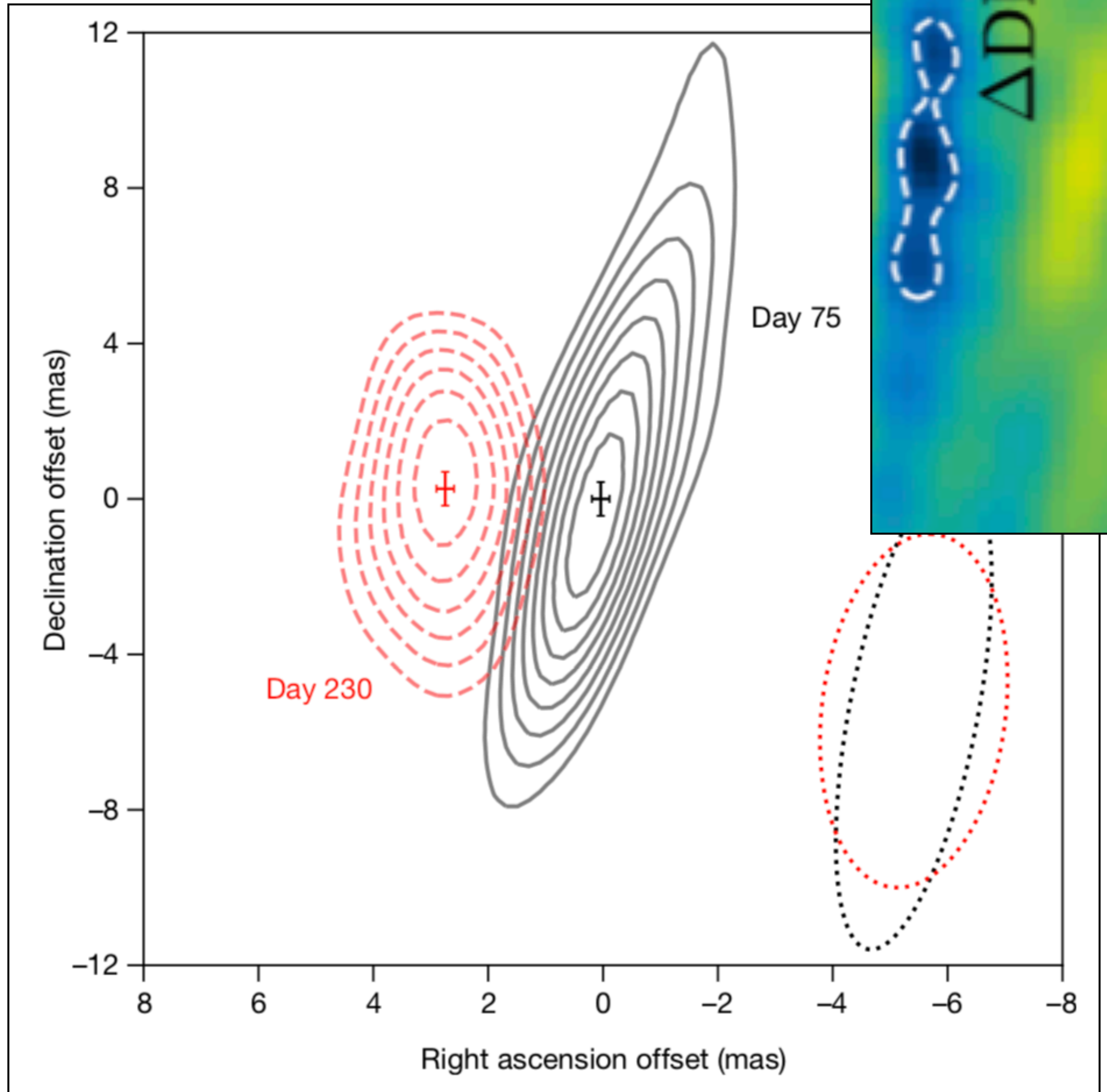
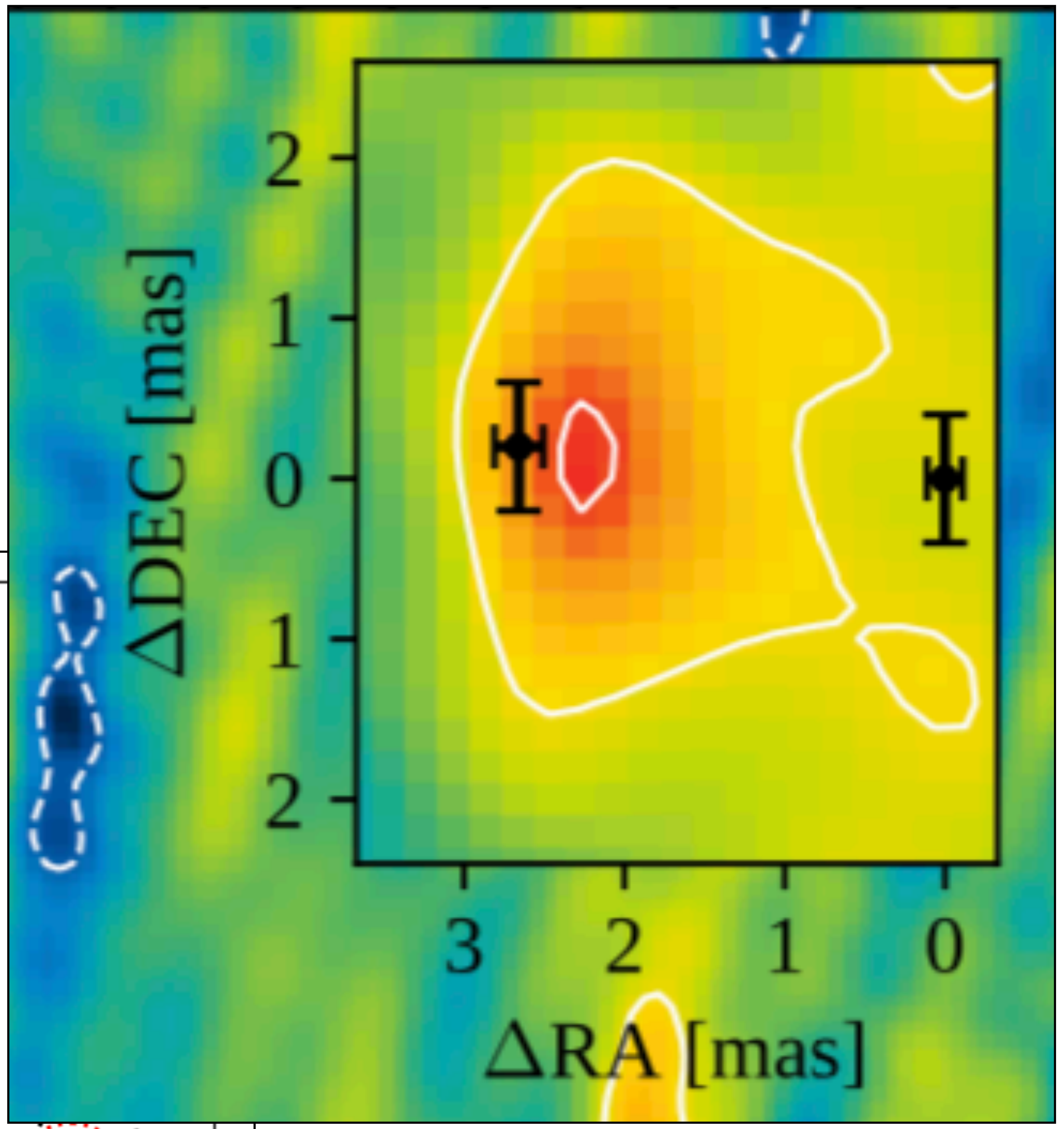


Fig. 1 | Proper motion of the radio counterpart of GW170817. The



Ghirlanda+19

Mooley+18

GW 170817 - conclusions

- NS-NS merger was able to produce a relativistic jet, with narrow opening angle, a transverse velocity structure, slightly misaligned to our line of sight
- Based on this result, at least 10% of BNS should be able to do the same
- **SENSITIVITY** and **EW+NS HIGH ANGULAR RESOLUTION** offered by Global VLBI both key to this result

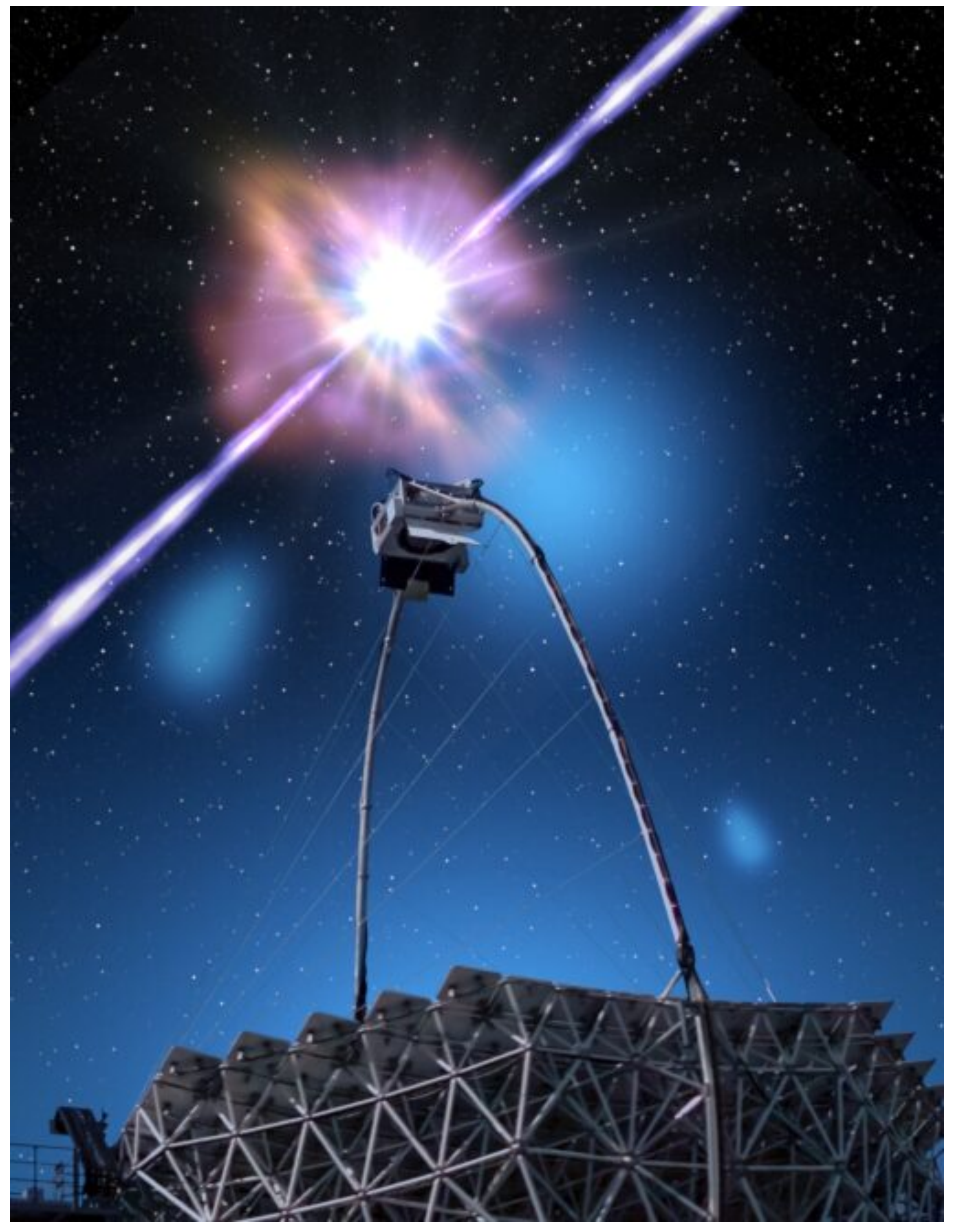
Highlight #2: long GRBs

- Long GRBs are the result of core-collapse SNe, which explode up to cosmological distances

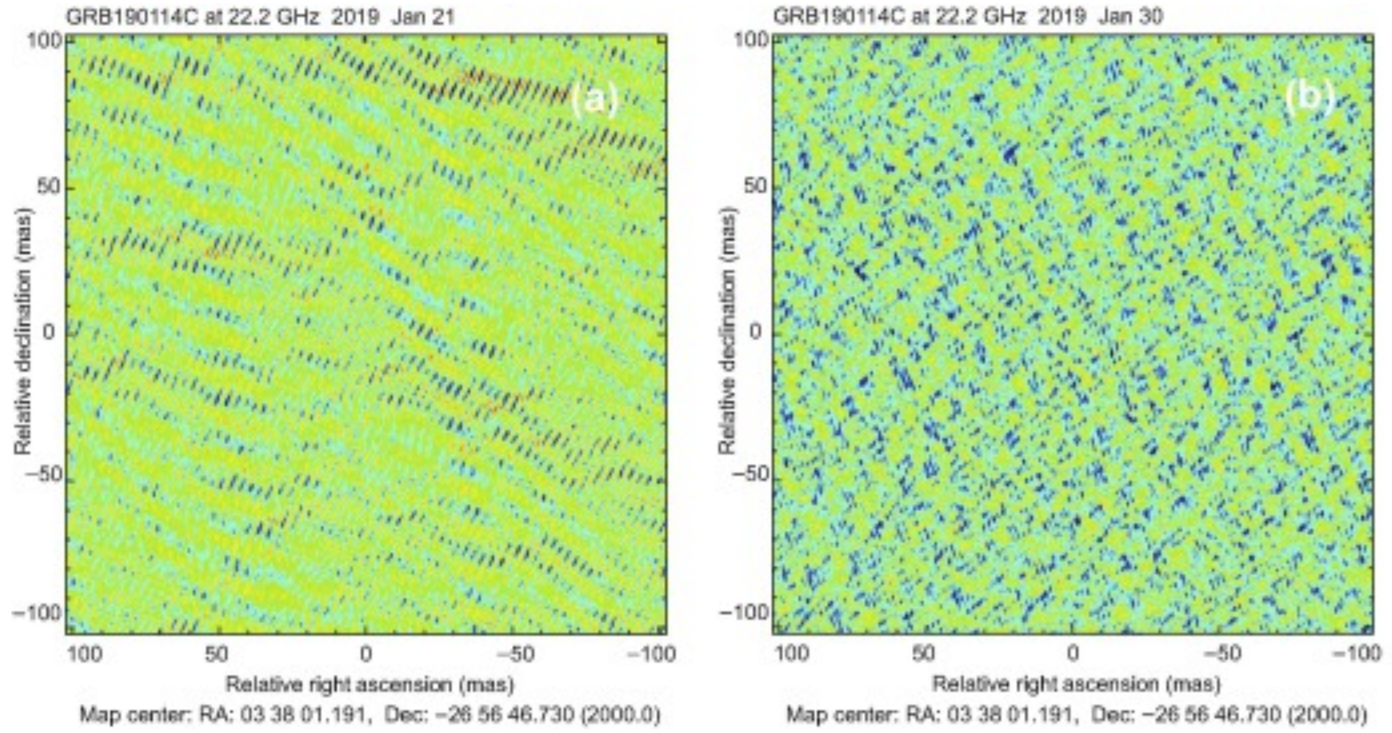
- Due to intrinsic electron energy distribution, rapid losses, and absorption from EBL, detection at VHE remained elusive for decades

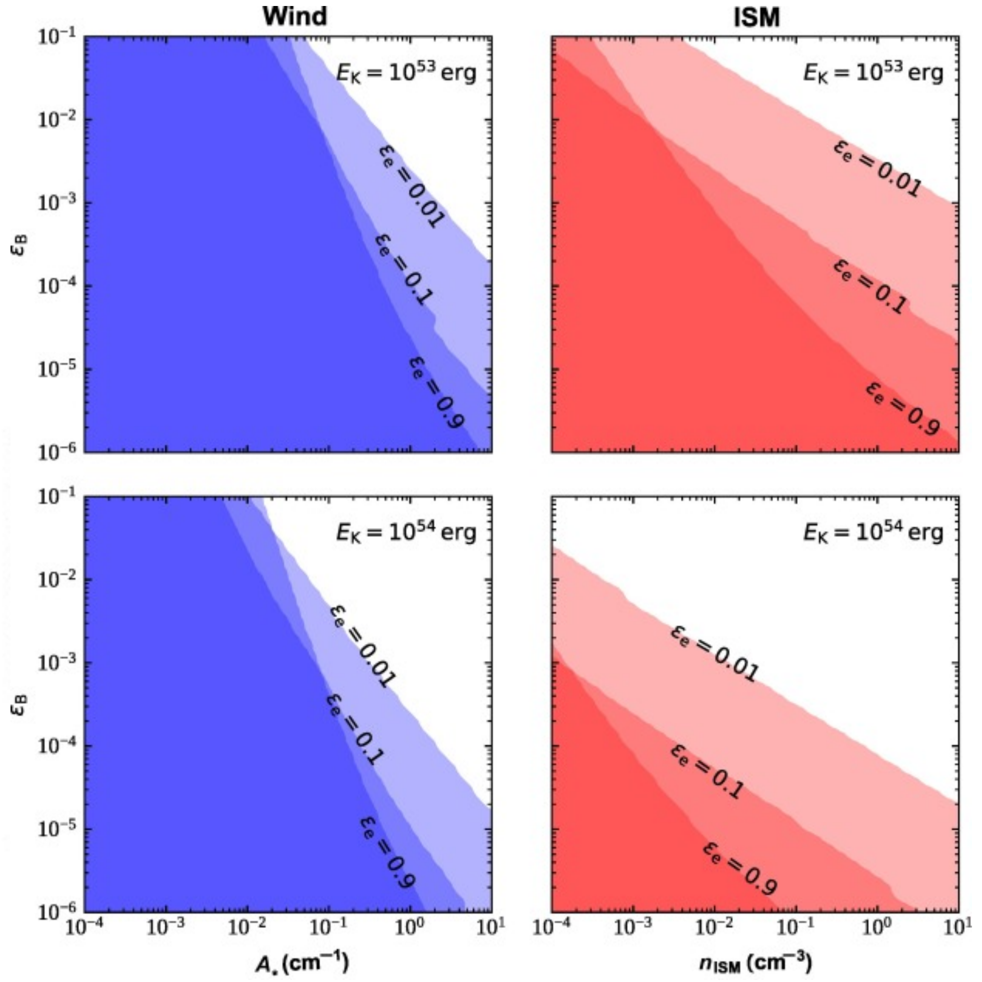
- A first report occurred for 190114C from MAGIC, and a few more have been announced since

MAGIC collaboration (2019, Nature 575)



EAVN 22 GHz ToO observations An et al. (2020)





GRB 190829A

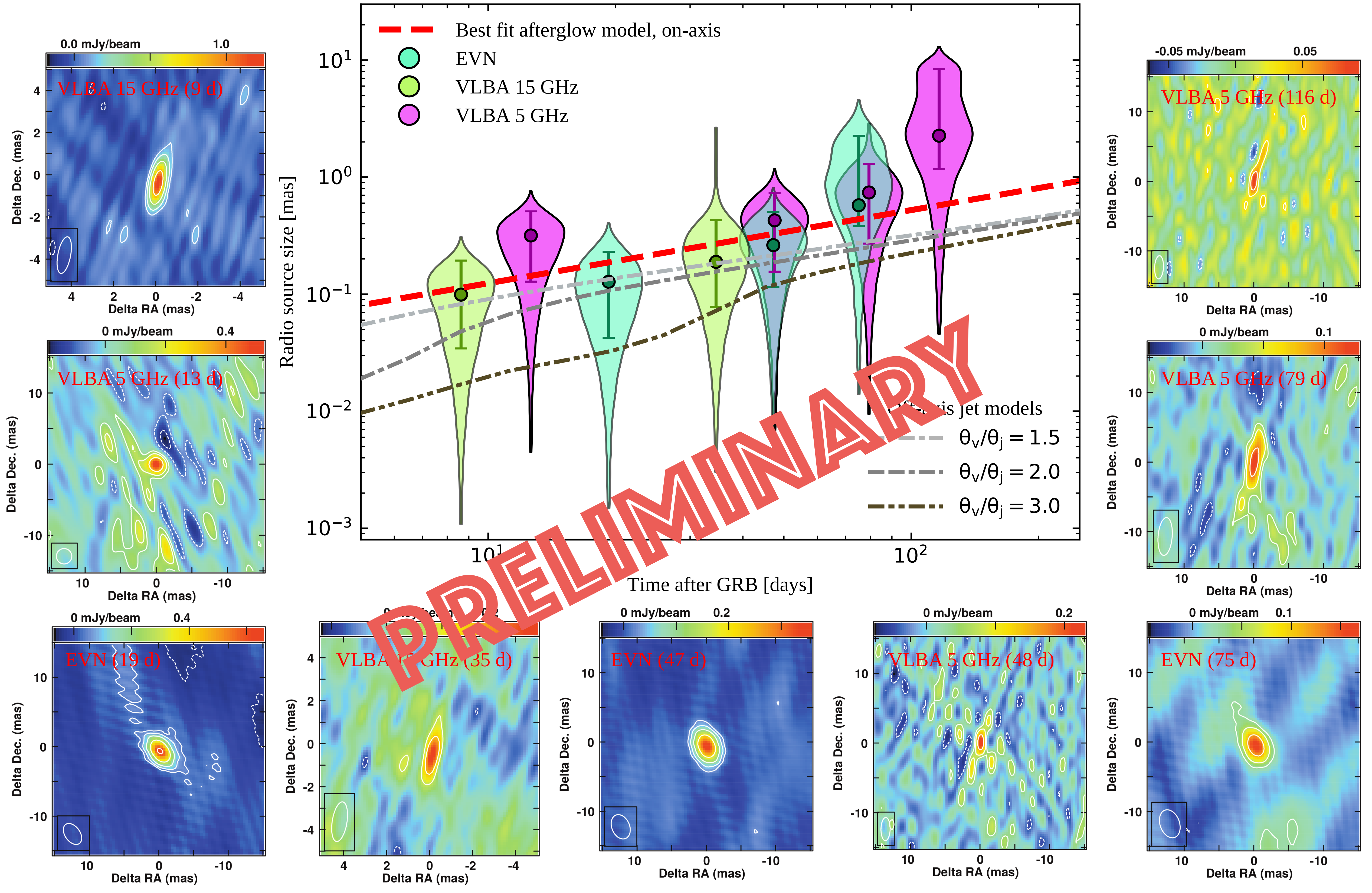
- Reported by Fermi-GBM and Swift-BAT, its afterglow was detected at VHE by HESS ~4hr later (GCN 25566)
- Host galaxy is at z = 0.0785 (d_L=368 Mpc, 1 mas~1.5 pc)
- Low angular resolution AMI-LA and MeerKAT observations hinted at presence of forward+reverse shock (Rhodes et al. 2020)
- We followed it up with VLBI: EVN @5 GHz, VLBA at 5, 15 GHz, for a total of 9 epochs between 9 and 116 days since discovery

- Source size increases by 0.74(+1.41/–0.48) mas in 66 days, or 0.57(+1.08/–0.37) pc in 61.7 r.f. days

- This implies an apparently superluminal expansion with average β_{app}= 11(+21/-7)

- These numbers point to **a relativistic shock** expanding into a **low-density ambient medium**, caused by a powerful explosion

- VLBI result in excellent agreement with independent estimates from MWL light curve modelling



Salafia, Ravasio, Yang, An, Orienti et al. (Nature, submitted)

Highlight #3: fast radio bursts

- **FAST** -> millisecond duration
- **RADIO** -> typically discovered somewhere between 800 MHz and 10 GHz (initially mostly at 1.4 GHz)
- **BURSTS** -> very bright, ~a few Jy x msec
- Moreover: very large dispersion measure (ie received through a denser medium than that of our Galaxy)

Thus:

- Very large brightness temperature: non-thermal, likely coherent emission
- Strong magnetic fields likely involved
- Short duration (down to sec structures): very compact (km scale) progenitors

Open questions

- What are the progenitors? Is there more than one type? To what extent are repeaters and non-repeaters distinct?
- What are the source counts, luminosity distribution, cosmological density and evolution?
- Wide fields of view are necessary to discover FRBs, but wide field of views typically means poor spatial accuracy
- Localisation is necessary for determination of host galaxy, and hence intrinsic power
- Chances increase when an FRB “repeats”: the error region can be targeted with higher resolution observations, e.g. VLBI

Hunting for FRBs

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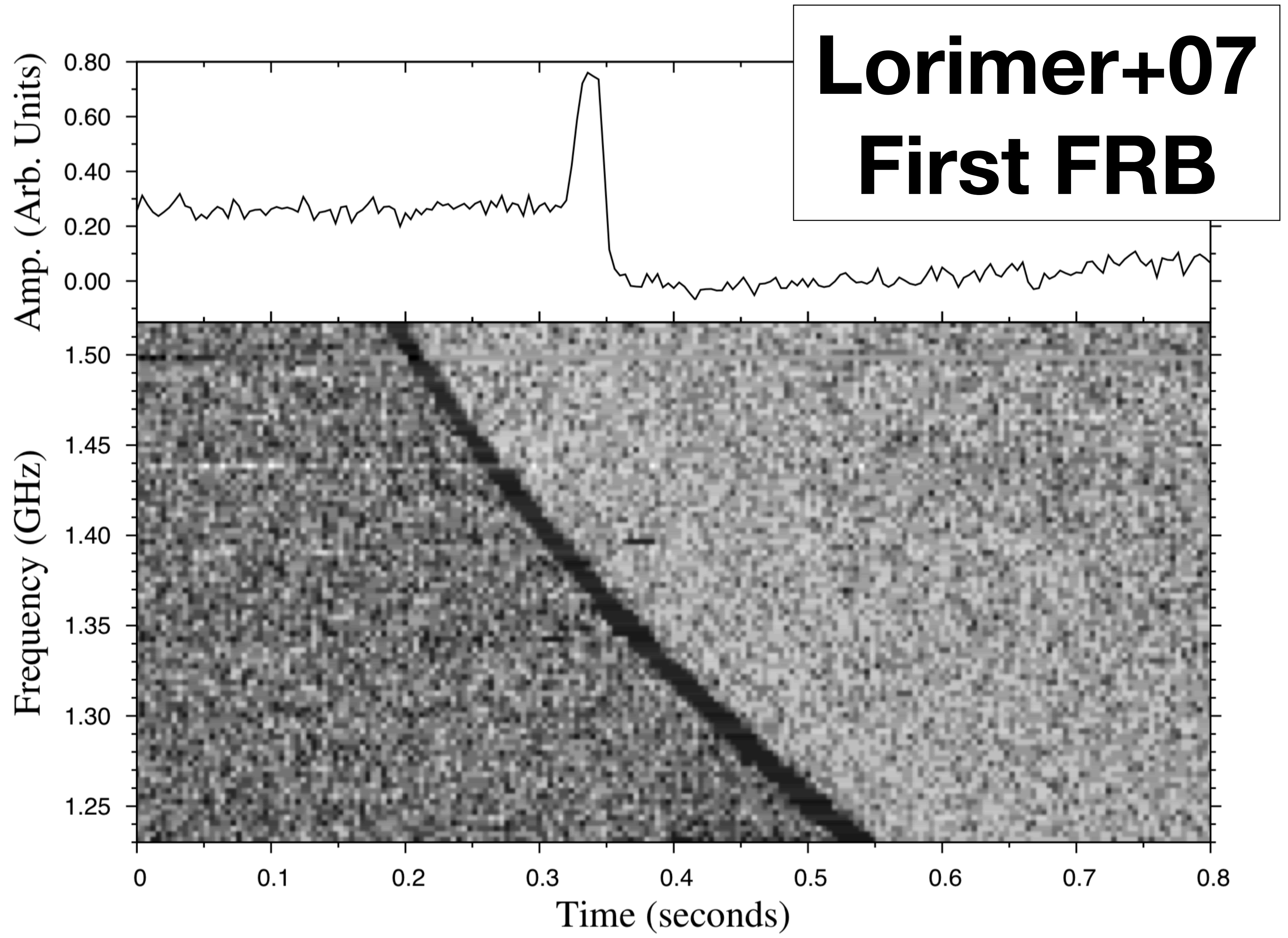
- Localisation is necessary for determination of host galaxy, and hence intrinsic power

- Chances increase when an FRB “repeats”: the error region can be targeted with higher resolution observations, e.g. VLBI

- Do repeating and non-repeating FRBs belong to the same class?

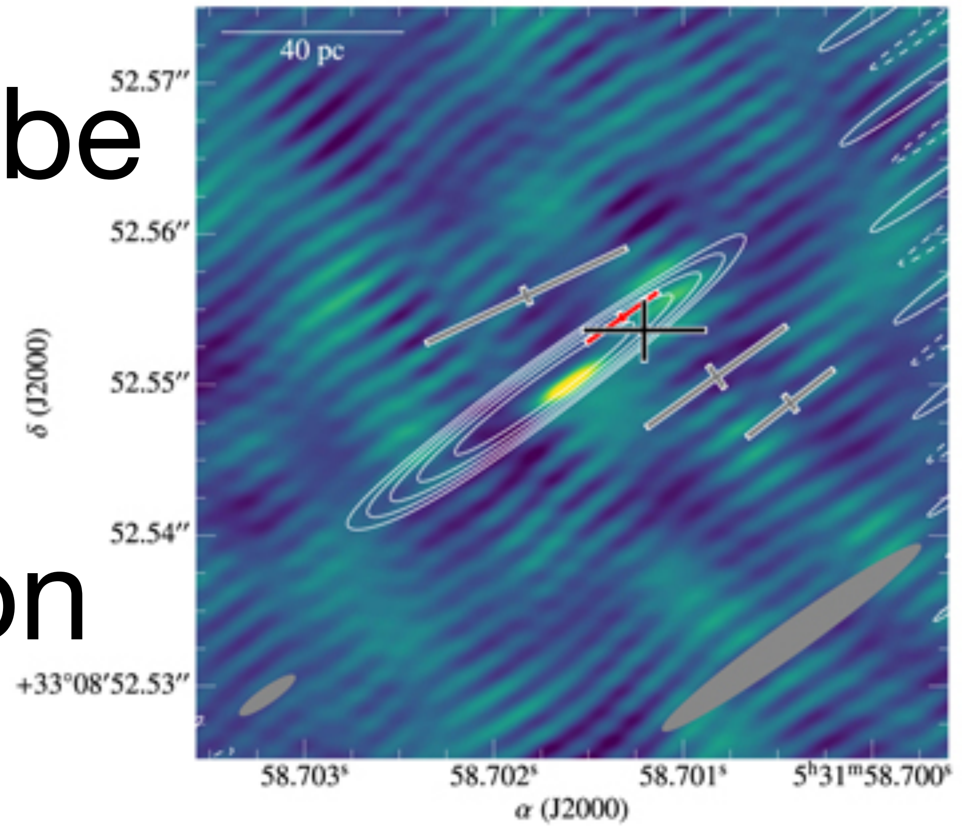


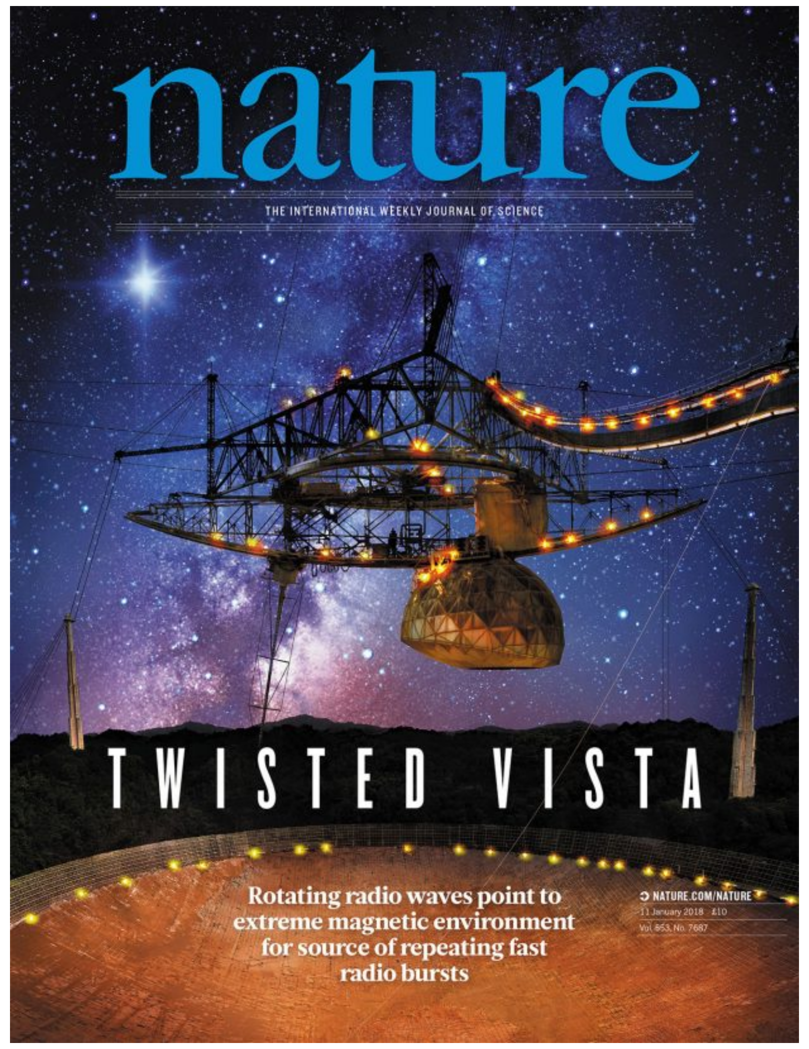
FRB VLBI localisations

- FRB 121102 (Arecibo) was the first FRB not discovered at Parkes and the first one found to be repeating: catastrophic event origin ruled out!

- JVLA and EVN observations revealed association with inner region of z=0.193 dwarf galaxy (Chatterjee+17, Marcote+17)

- FRB 180916 (CHIME) was localised using the same technique - but to a different environment! a star-forming region in a nearby (z=0.0337) massive spiral galaxy (Marcote+20)



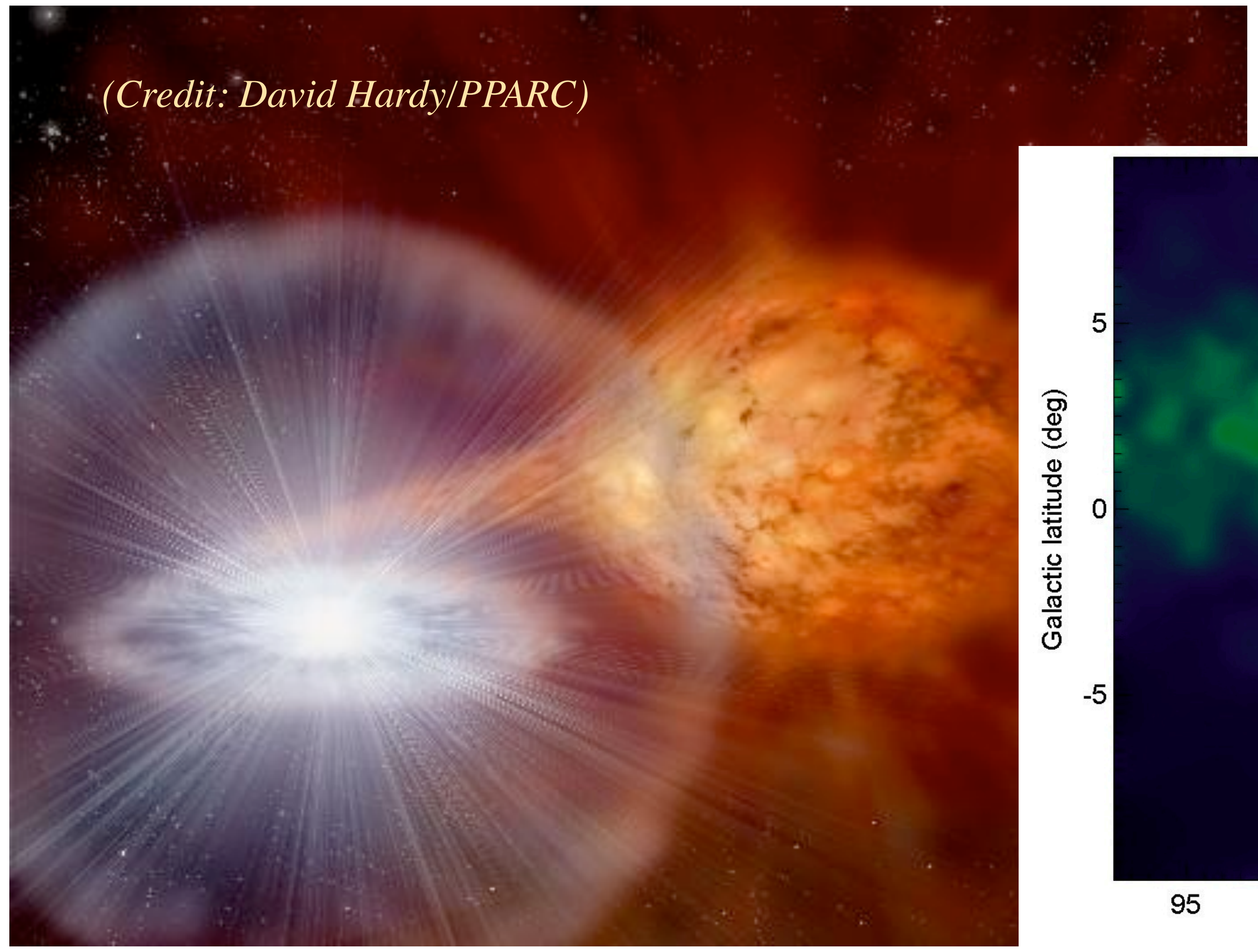


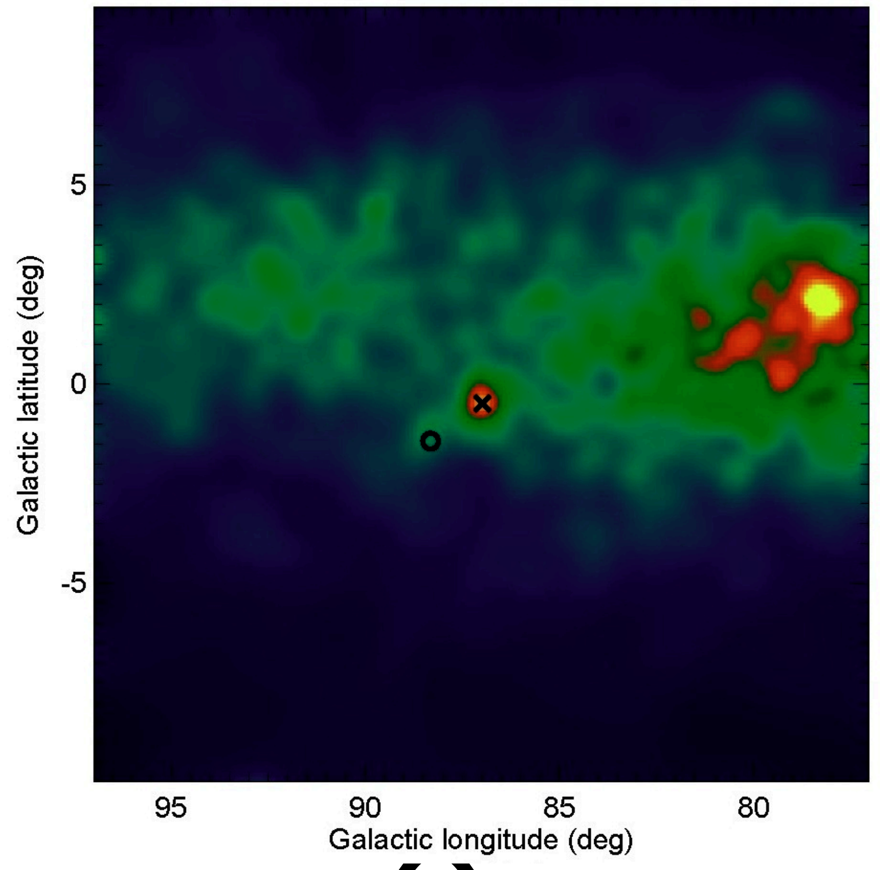
FRB & magnetars

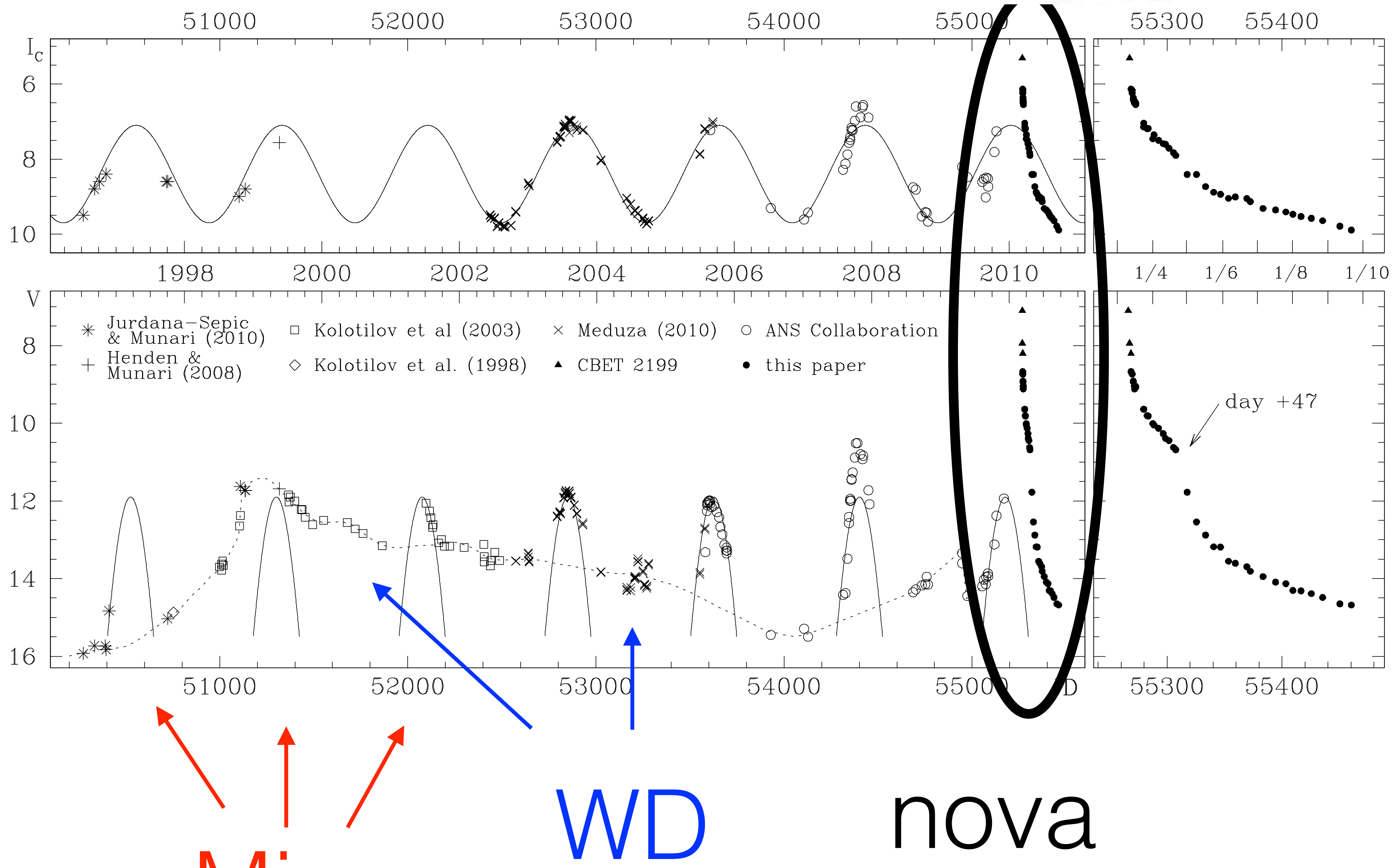
- SGR 1935+2154 is a Galactic magnetar: a neutron star with exceptionally strong (10^{14} – 10^{16} G) magnetic field
- In April 2020 it produced a bright MWL and radio outburst (CHIME/FRB Coll.; Bochenek et al; Mereghetti et al. 2020)
- The characteristics of the radio signal are consistent with a low-luminosity FRB!
- Continued monitoring with VLBI dishes revealed four more bursts (Kirsten et al. 2020)
- … and search for FRB MWL emission becomes even more intriguing!

Highlight #4: novae

- Novae are thermonuclear outbursts in binary systems containing an accreting white dwarf (WD)
- Accreted material accumulates until pressure at base of accreted shell produces thermonuclear ignition; result is ejection of shell, expanding into surroundings
- Symbiotic novae: the WD companion is a pulsating red giant (RG); the nova ejecta expand in its dense wind
- V407 Cyg (d~2.7kpc) was detected in γ-rays by Fermi-LAT in March 2010: **first high energy detection of any nova/WD**:
    - pion decay from collisions of accelerated protons or inverse Compton by accelerated electrons?







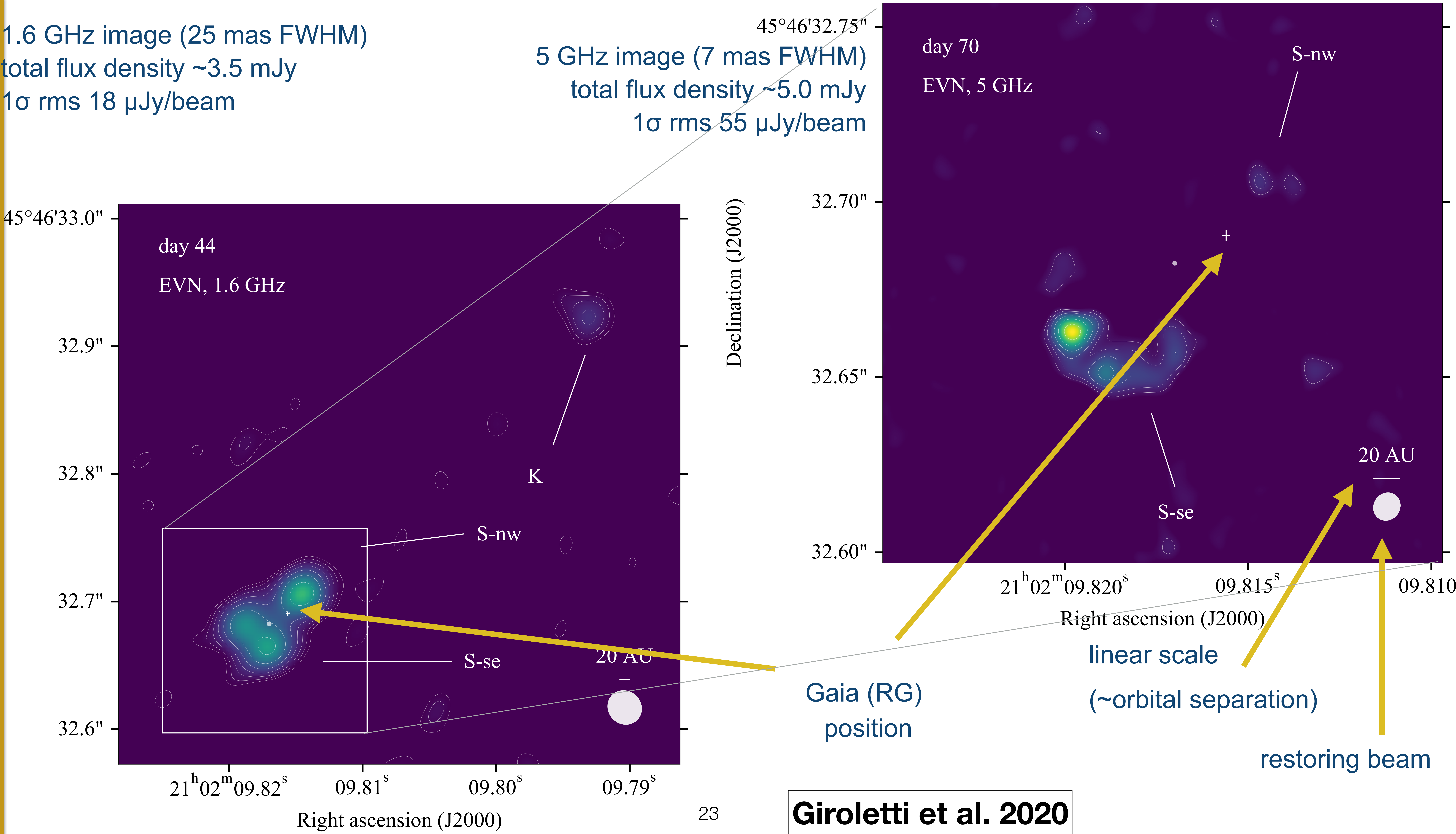
I-, V-band l.c. (Munari+11)

VLBI and (symbiotic) novae

- VLBI detection requires significant flux density in very compact region: high brightness temperature (eg blazar jets, maser spots)
- Previous case of symbiotic nova: RS Oph in 2006 (O'Brien et al, Nature, 2006); no gamma-ray satellite
- What about V407 Cyg? 16 EVN/VLBA runs, from day 20 to day 203, at 1.6 and/or 5 GHz
- detections in 10/16 epochs, showing strong structural evolution

1.6 GHz image (25 mas FWHM)
total flux density ~3.5 mJy
1σ rms 18 μJy/beam

5 GHz image (7 mas FWHM)
total flux density ~5.0 mJy
1σ rms 55 μJy/beam



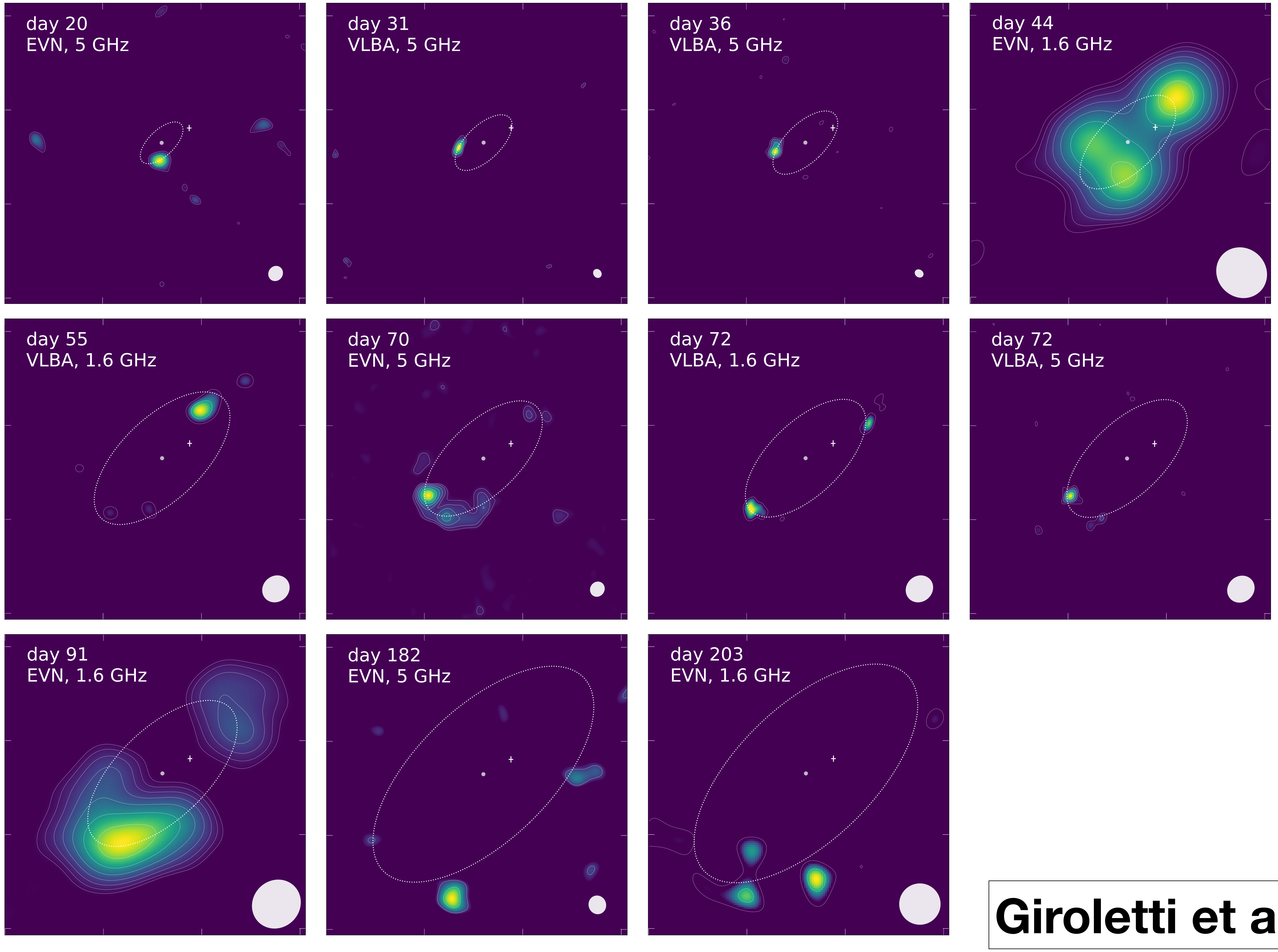
Gaia (RG) position

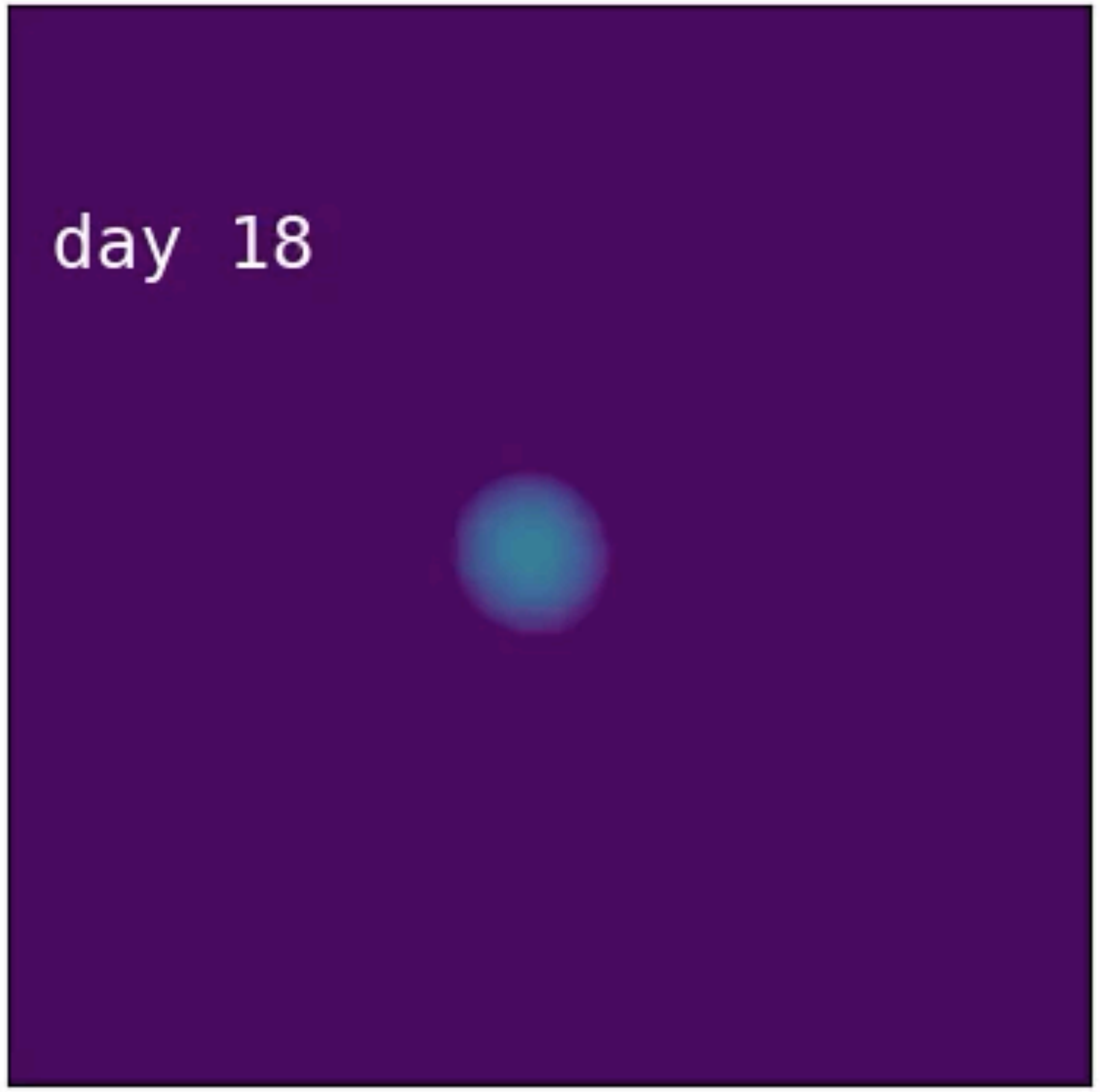
linear scale (~orbital separation)

restoring beam

Giroletti et al. 2020

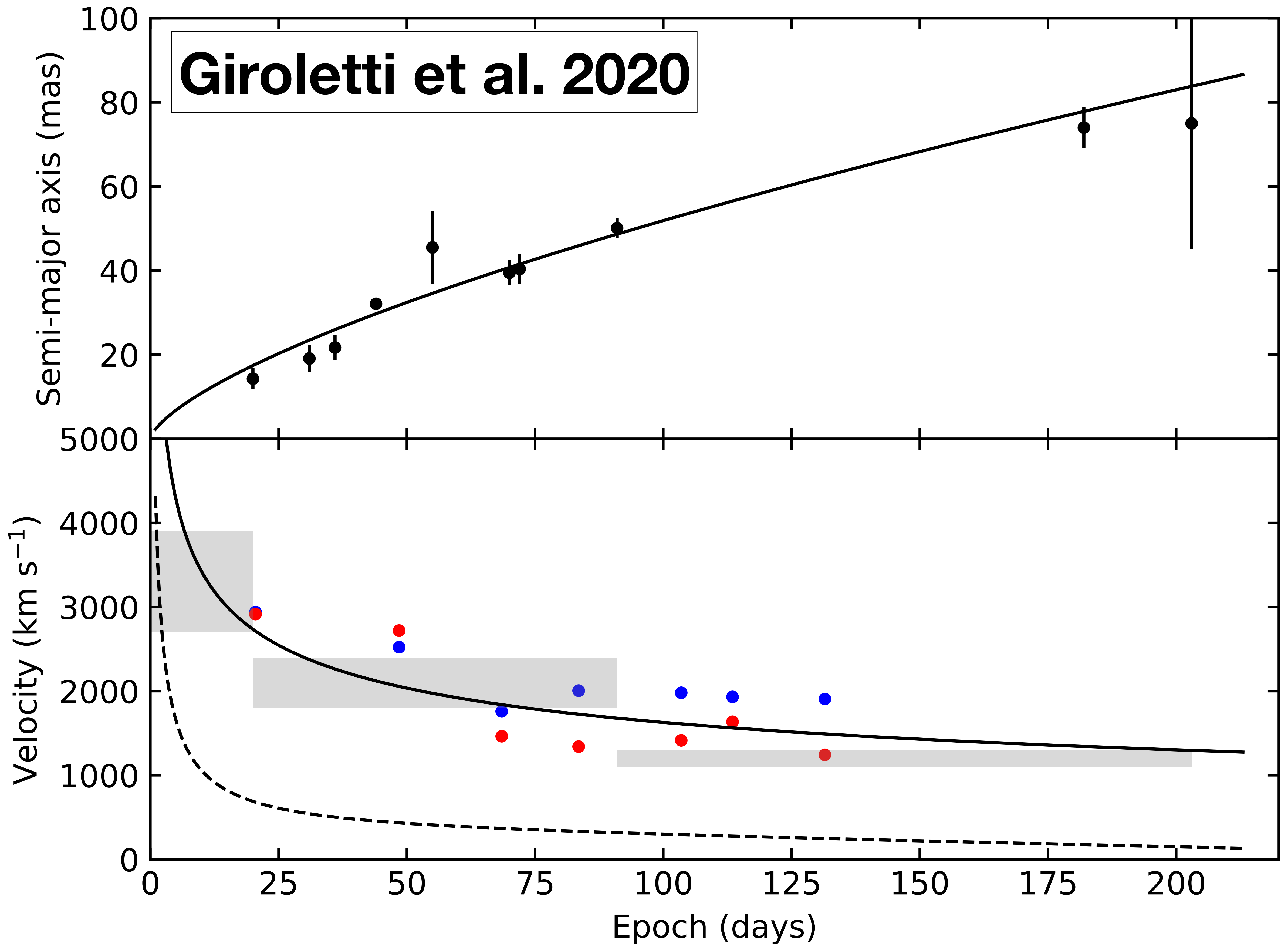
Results - all images & movie



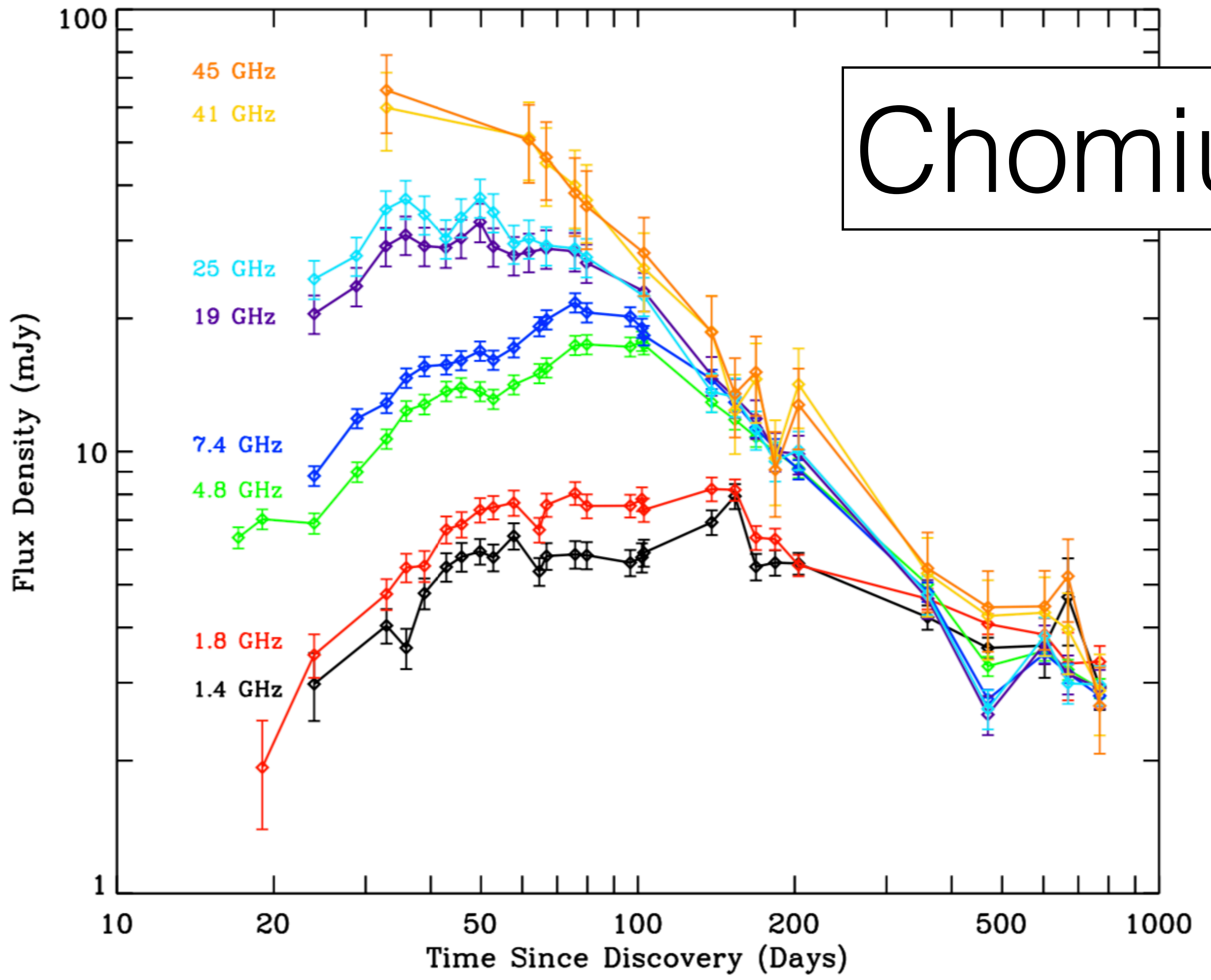


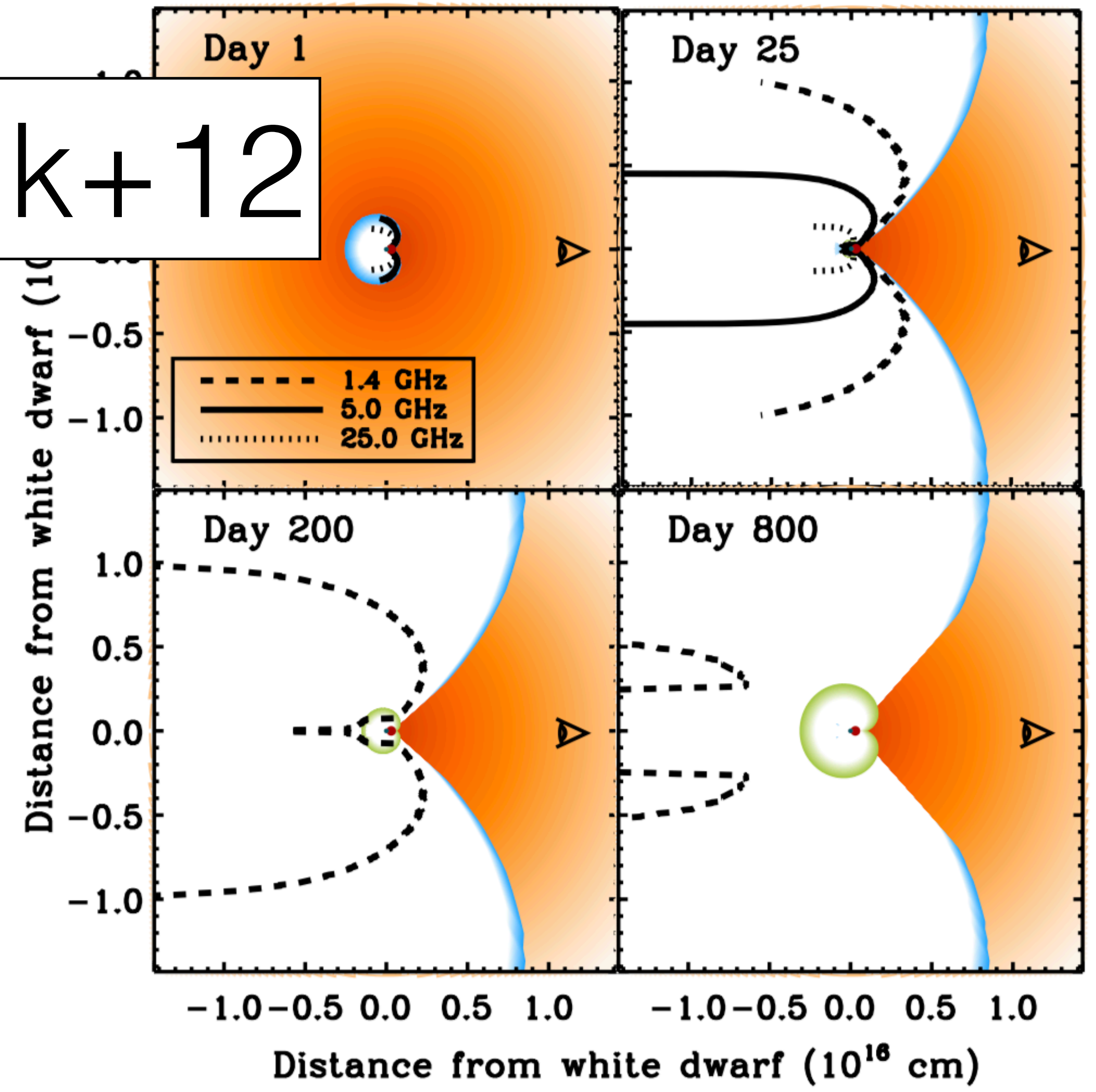
Giroletti et al. 2020

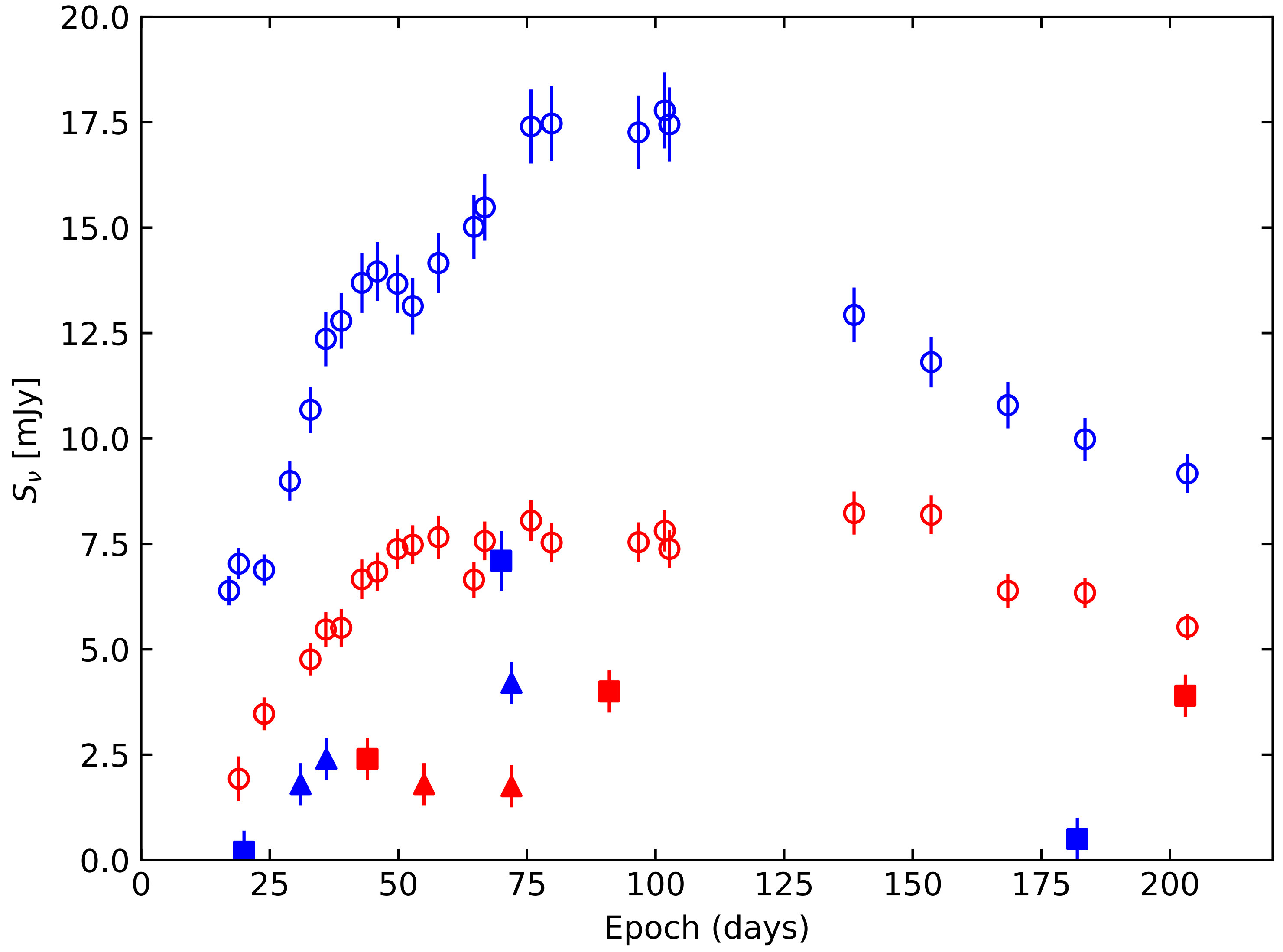
Expansion velocity



- Total extension of components grows as a function of time from (39±7) AU to (200±13) AU (day 20-182)
- Features advance mainly along p.a. -45°, but with significant transversal motion component
- $r \sim t^p$, $p=0.68\pm0.04$; $v \sim t^{p-1}$, $p-1=-0.32\pm0.04$
- Initial velocity ~3300 km/s or larger, then slows down to 2100±300 km/s (20d<t<90d), 1200±100 km/s (t>90d)
- Good agreement with maximum velocity from optical lines (Shore et al. 2011), excess w.r.t line width (Munari et al. 2010)







empty=VLA

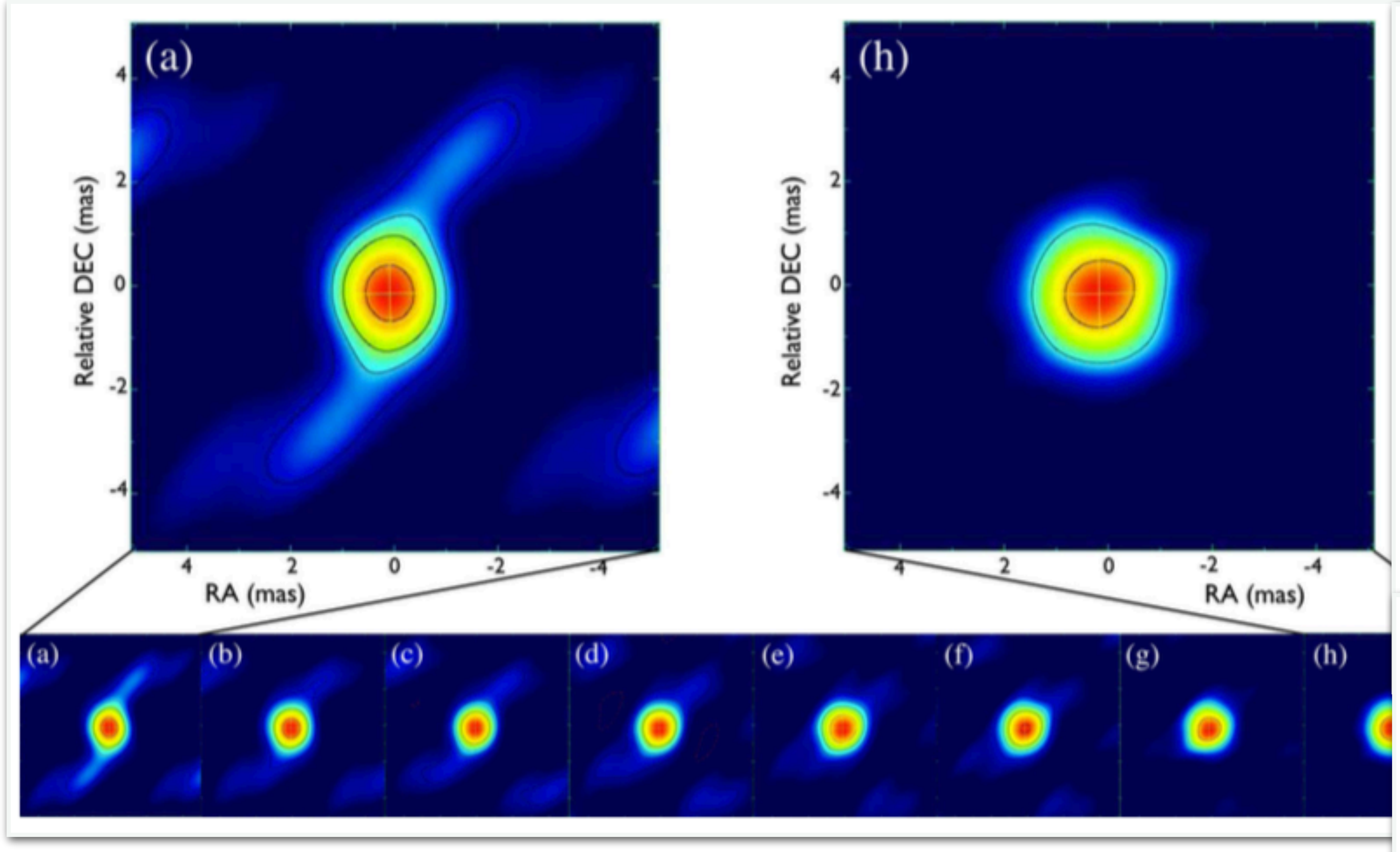
filled=VLBI

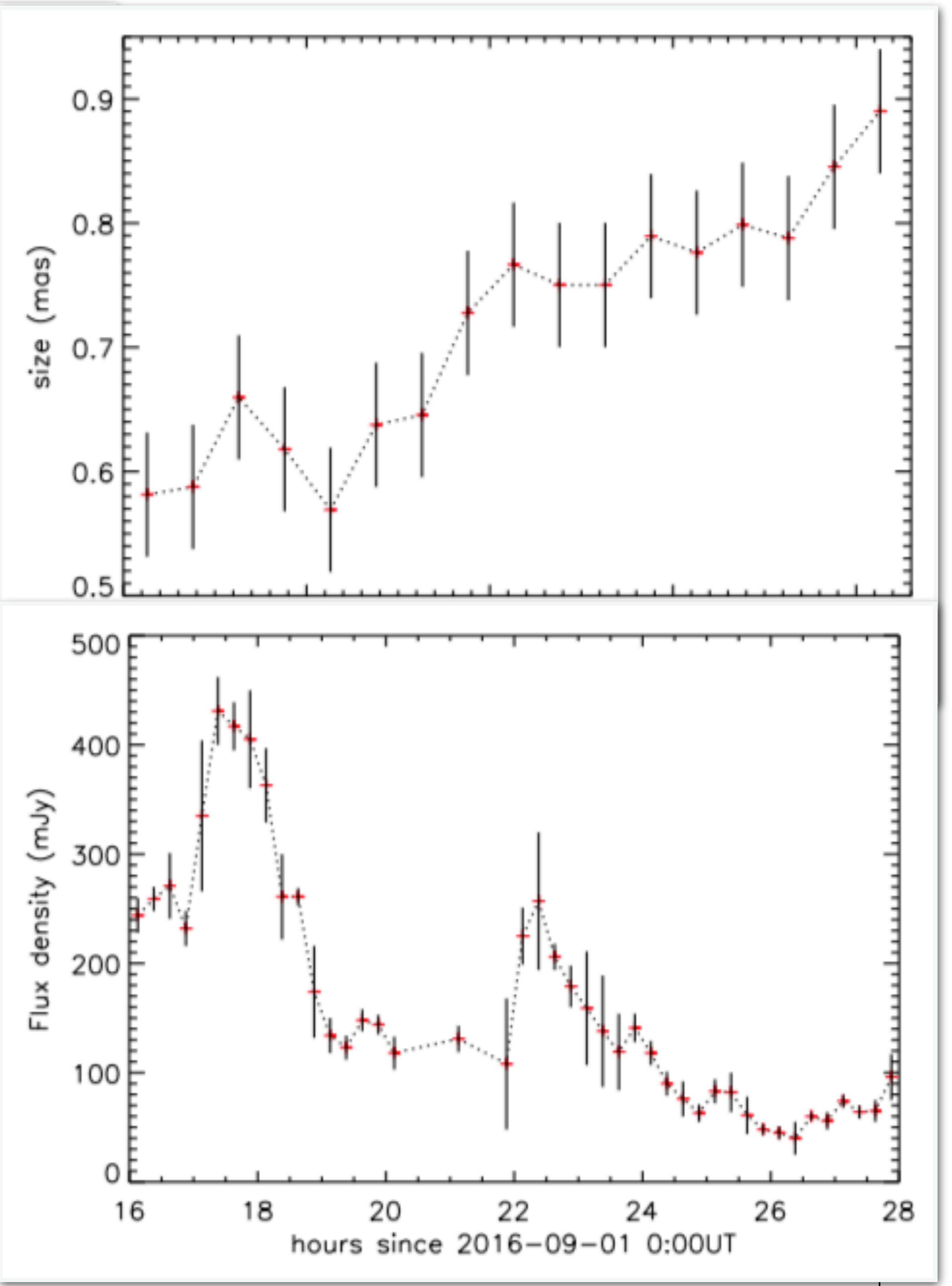
red=1.6 GHz

blue=5 GHz

- VLA light curve dominated by thermal emission from ionised Mira wind
- VLBI data resolve out wind emission:
  - too bright for thermal ejecta
  - most likely synchrotron from shocked ejecta
  - ok with gamma rays, unusual spectral index
- Brightness temperature (size & flux density) confirms shock acceleration
- Emission is present also on larger scales, connected to previous episode of activity

One slide on X-ray binaries…

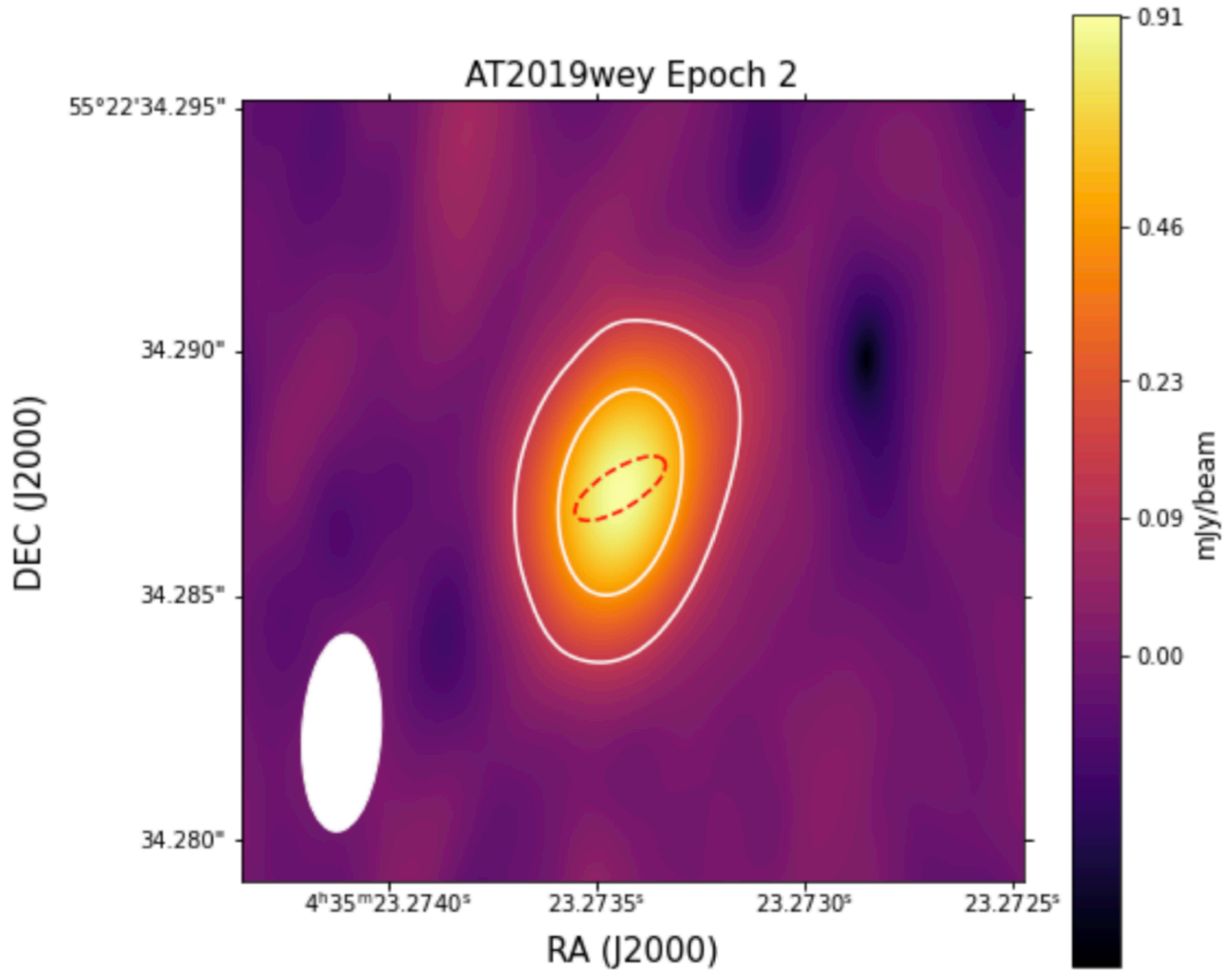




$$\frac{\Delta\theta}{\Delta t} = \frac{0.3 \text{ mas}}{4 \text{ hr}} \sim 0.08c$$

Case 1: Cyg X-3, a famous and very active source!

Egron et al. (2016): VLBI observations show hour-timescale expansion and flux density variability!



Case 2: AT2019wey, a newly discovered transient (by SRG, ATLAS)

Yadlapalli et al. (2021); Cao et al. (in preparation): VLBI observations can shed light on jet/accretion coupling for this and many more events to come!

Take home messages

- Other events omitted for various reasons - but VLBI scope for astrophysical transient is huge and growing
  - Targets: binary mergers and their surroundings, compact objects in various stages, short and long GRBs, FRBs, novae, SNe, XRBs, TDEs, AGNs, etc.
  - Key elements: structural evolution, accurate localisation
- From Galactic to cosmological sources, huge range of masses and powers, implications on physics of targets, their environment and intervening medium
- Very significant synergy with MWL & MM facilities: neutrinos, GWs, VHE, …