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Radio Astrometry of Energetic Transients: NS merger afterglows and Fast Radio Bursts

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Swinburne University of Technology · Australian National University · Monash University · The University of Adelaide · The University of Melbourne · The University of Western Australia · AAO · CSIRO

Outline

- The NS merger 'zoo'
- High angular resolution radio (VLBI) applications
- Key results from VLBI astrometry of GW170817
  - Relativistic outflow physics
  - Tuning the standard siren
- Prospects for the future
- Fast Radio Bursts – an observational perspective
- Applications of astrometry to FRBs
- How might FRBs and NS mergers be connected?

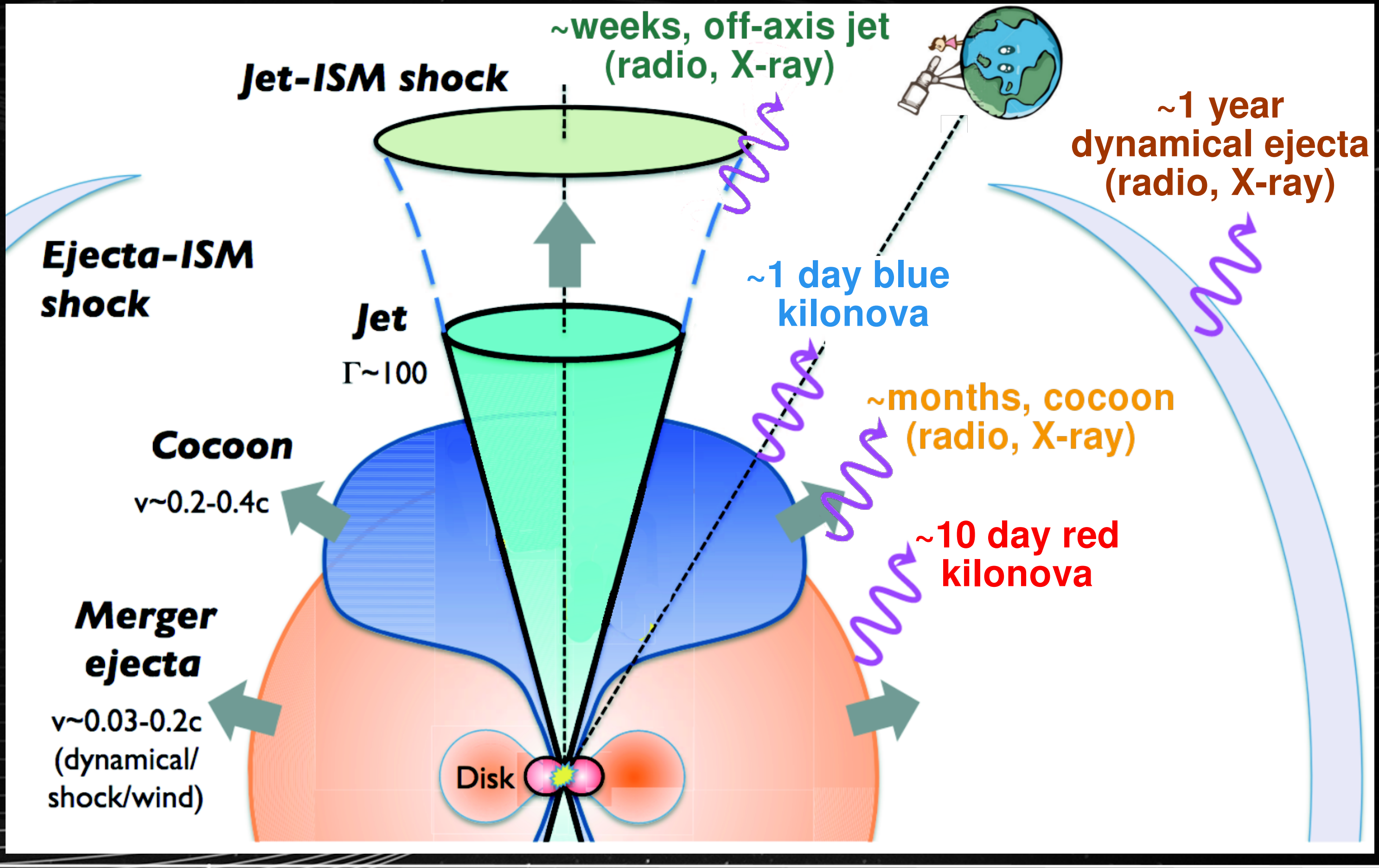
GW170817 VLBI Observation / modeling team
Swinburne: Deller
Caltech: Mooley, Hallinan
Tel Aviv: Nakar, Gottlieb
NRAO: Frail
Chalmers: Bourke

ASKAP FRB team
Swinburne: Deller, Shannon, Day
Farah, Flynn, Oslowski, Kumar
CSIRO: Bannister, Bhandari,
Ekers, Phillips, Mahoney
Curtin: Macquart,, James, Scott
UCSC: Prochaska
Macquarie: Ryder, Marnoch
Sydney: Qiu
PUCV: Tejos
Washington: McQuinn

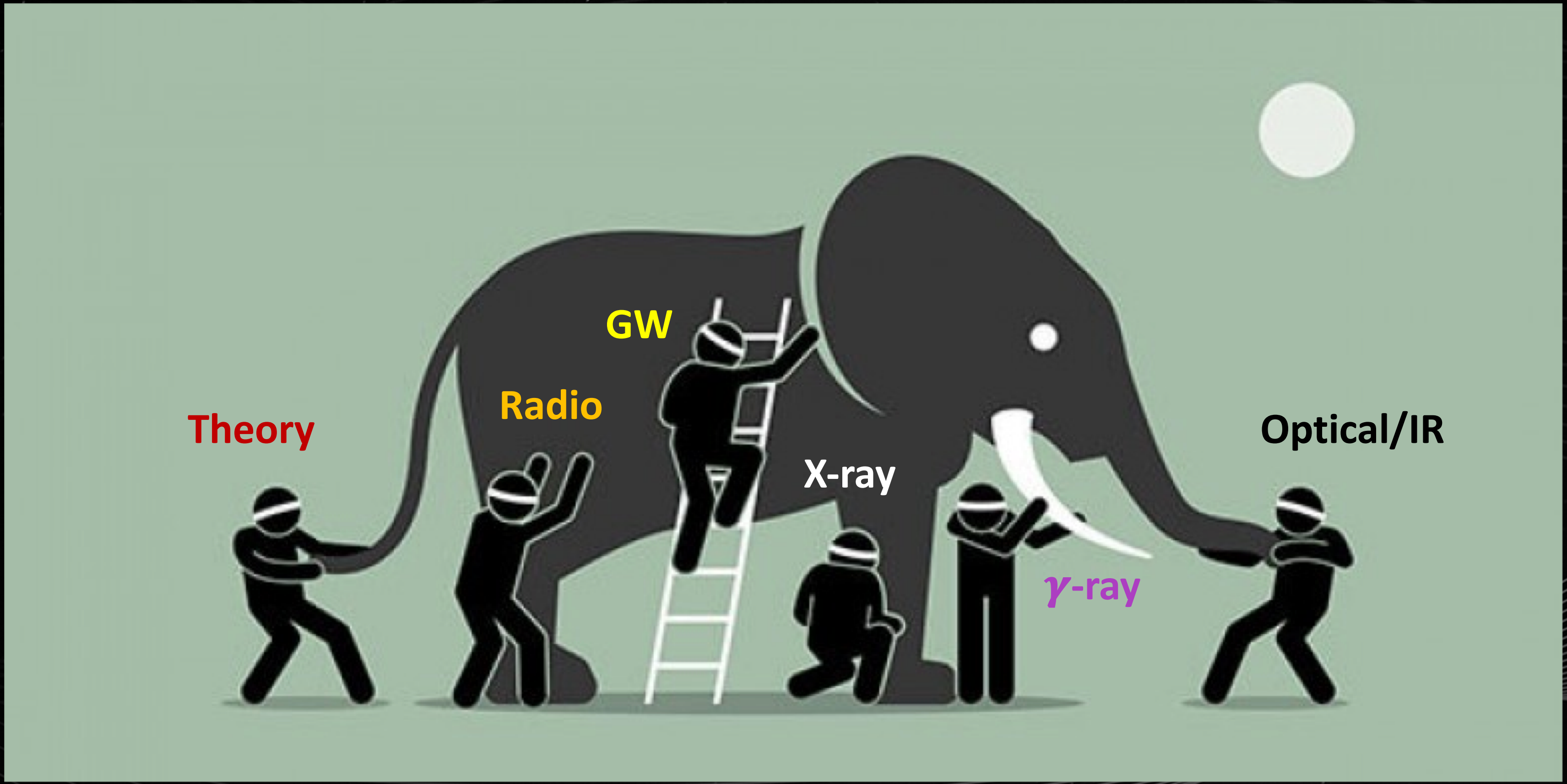
The NS merger zoo: what comes out

- Optical/UV/IR (probes primarily ejecta)
- Radio/X-ray (shocks)
- γ-ray (launching of relativistic ejecta)
- GW (binary properties)

Image: K. Mooley, (adapted from Ioka & Nakamura, 2018)



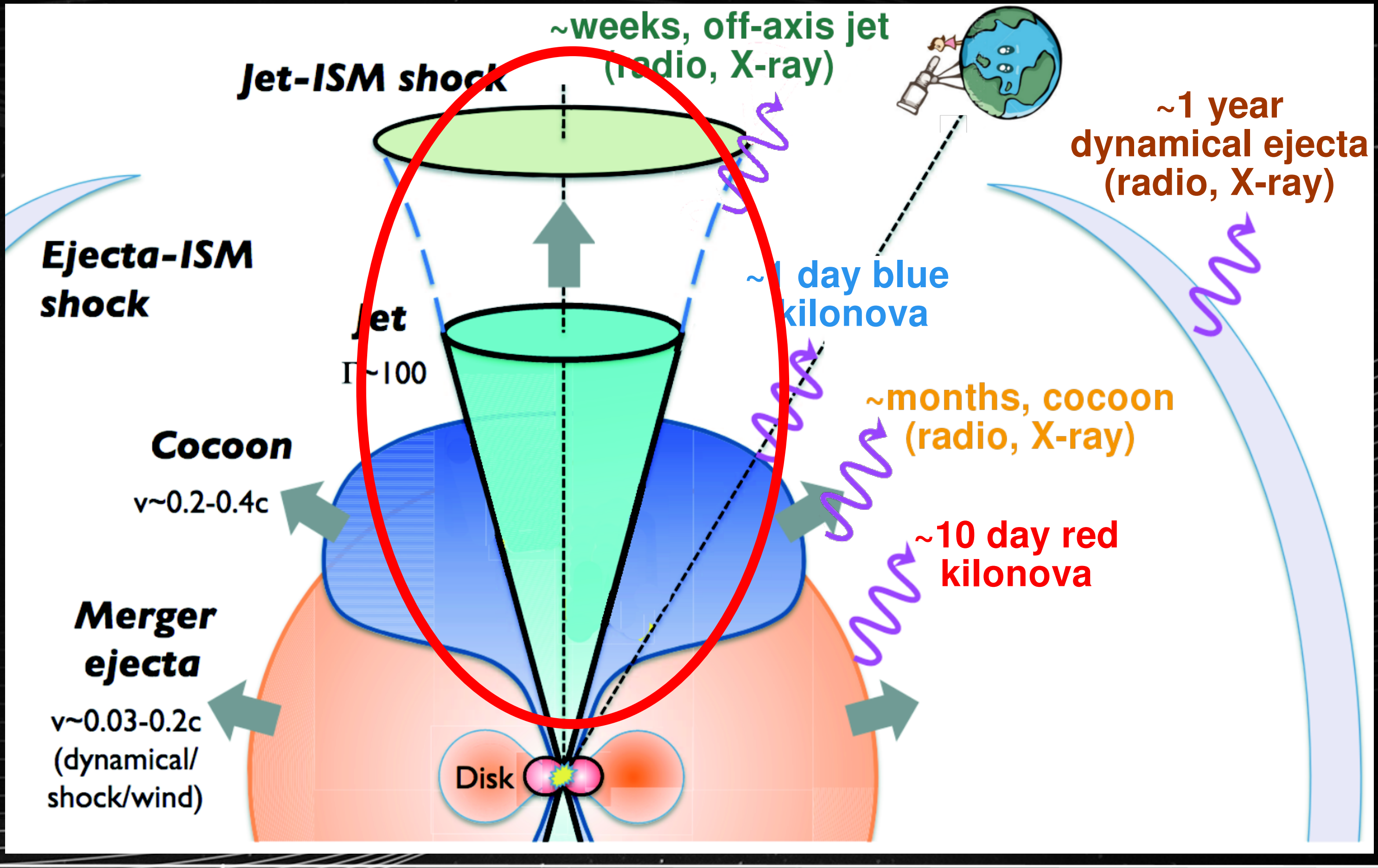
Picking apart the wreckage of a merger



The NS merger zoo: what goes in

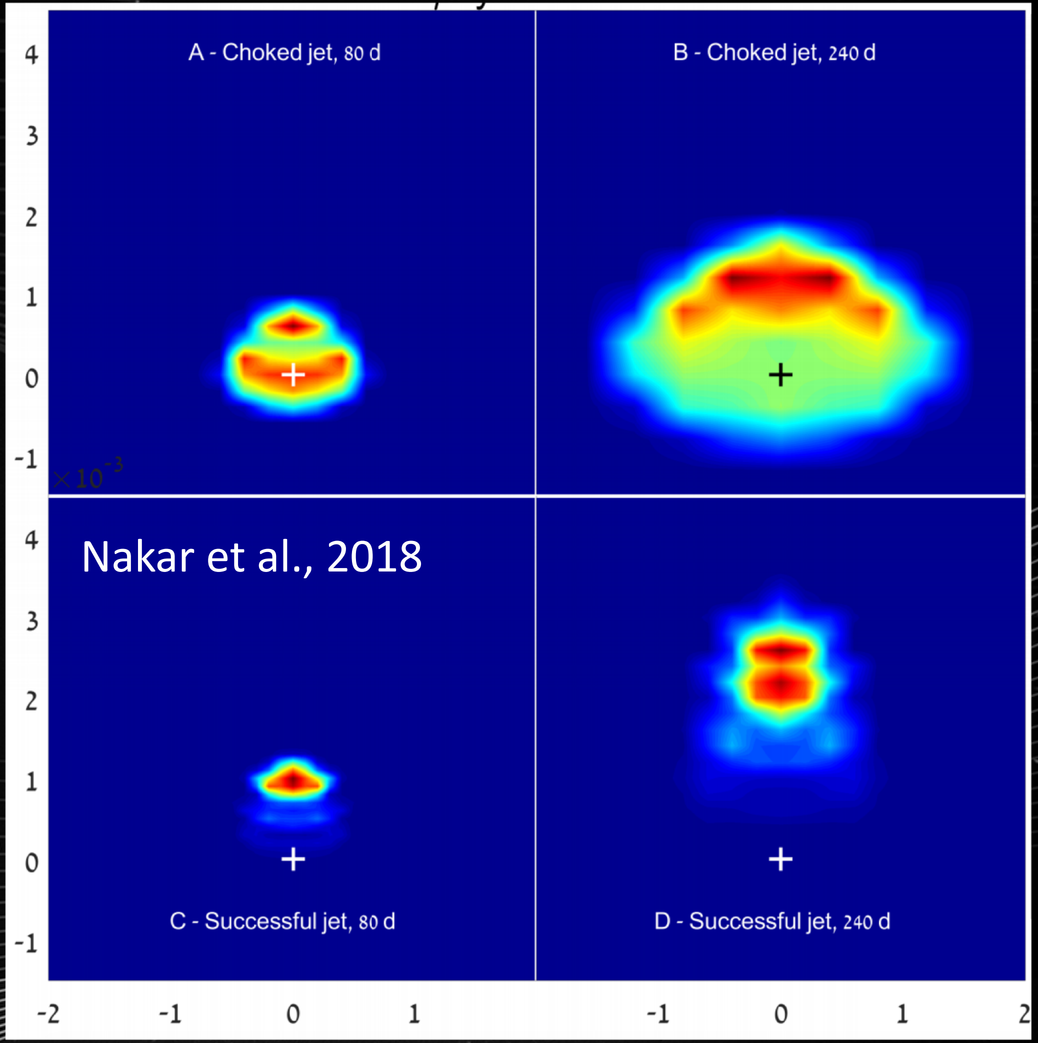
- What: The mass, spin, and radius of the merging stars (stellar evolution)
- Where: The surrounding ISM density
- Geometrical viewing angle

Image: K. Mooley, (adapted from Ioka & Nakamura, 2018)



Merger outflows at the highest angular resolution

- **Outflows flow out.** Emission gets more diffuse, and position centroid shifts, with time. Morphology depends on bulk motion + Doppler boosting + light travel time effects



A brief diversion: apparent superluminal motion

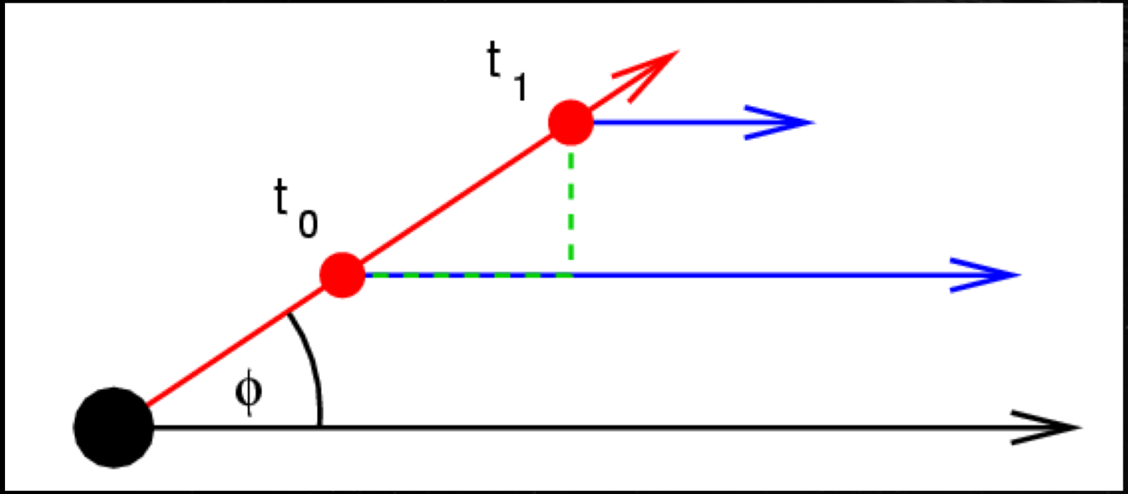


Image: http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/intro2_0809/intro_ba0233.html

Difference in time of emission $\Delta t_e = t_1 - t_0$

For material moving at velocity *v*:

- Observer sees signal separated by $\Delta t_e - \Delta t_e \cos(\Phi)\, v/c$
- Offset in the plane of the sky: $v\, \Delta t_e \sin(\Phi)$
- Apparent velocity: $v \sin(\Phi) / (1 - \cos(\Phi)\, v/c)$
- When *v* approaches *c* and Φ is small, apparent velocity exceeds *c*

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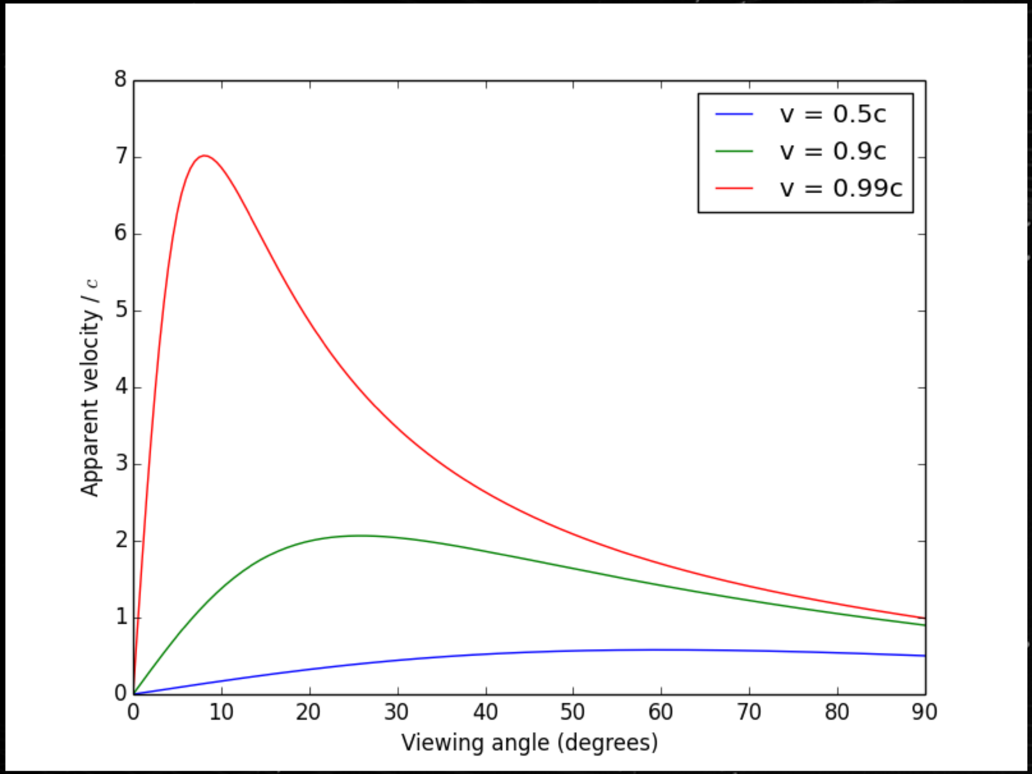

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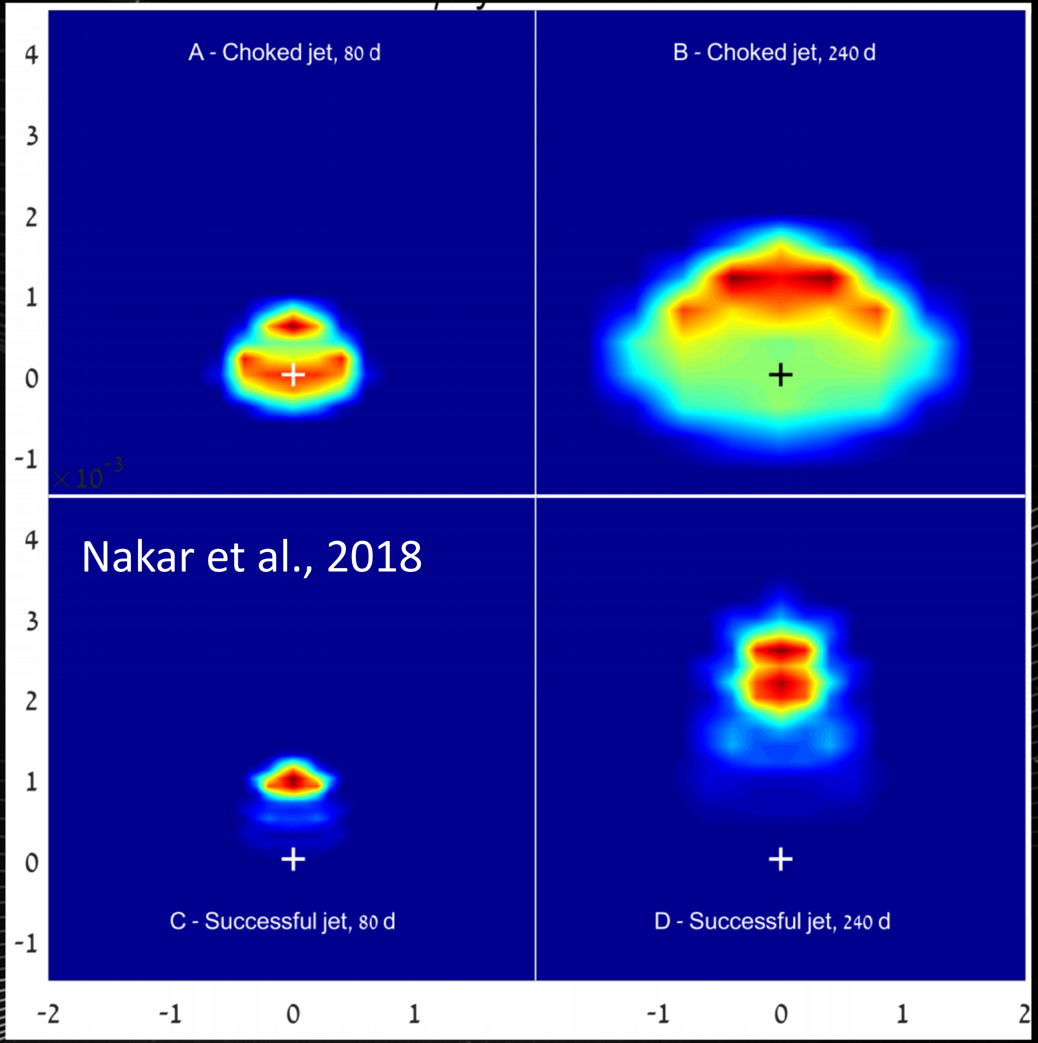
Oversimplified: assumes single component, constant speed, etc

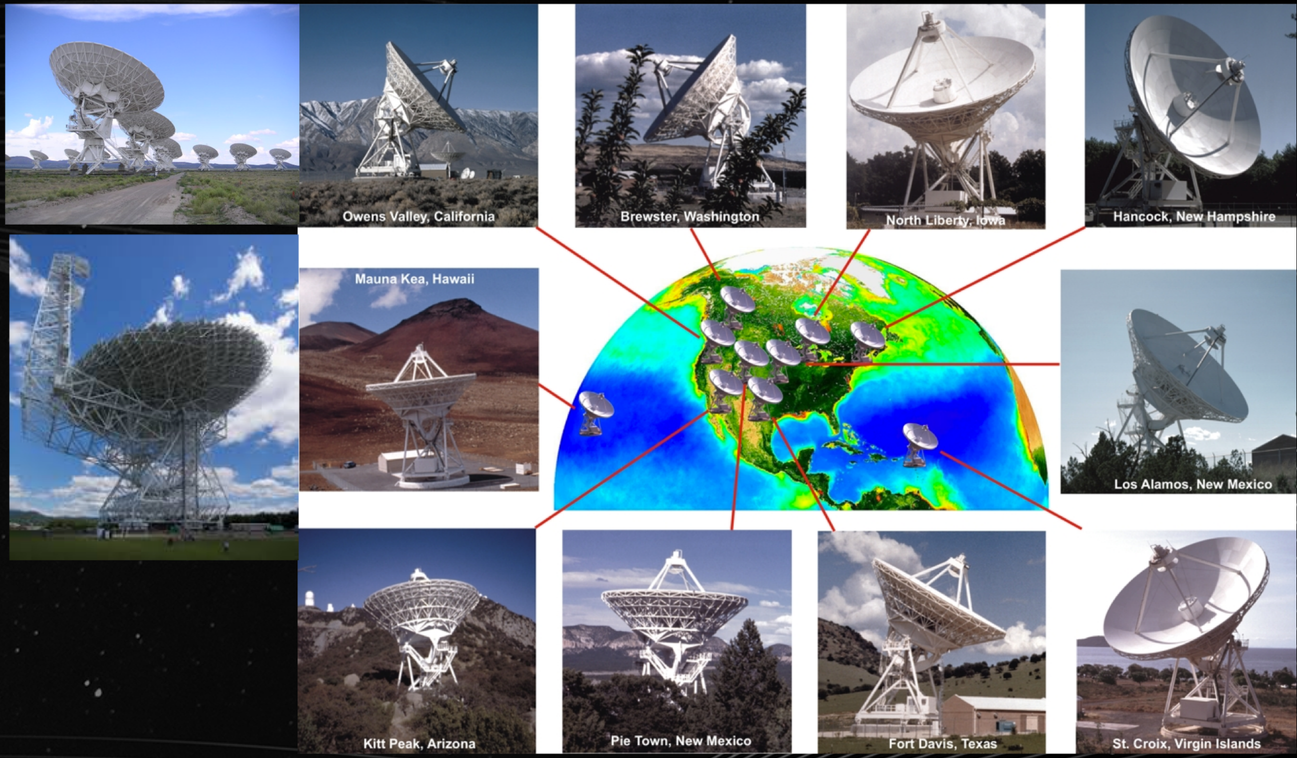
Merger outflows at the highest angular resolution

- **Outflows flow out.** Emission gets more diffuse, and position centroid shifts, with time. Morphology depends on bulk motion + Doppler boosting + light travel time effects
- But scale is tiny: displacement of ~pc at distances ~10^8 pc -> 10^{-8} radian ⇒ milliarcseconds
- Radio wavelengths ~10^1 cm ⇒ resolution of ~10^{-8} radian requires baseline lengths 10^9 cm $\simeq 1\ R_{earth}$



Very Long Baseline Interferometry

- Highest angular resolution direct imaging in astronomy
- 8,000 km baseline @ 5 GHz -> 10 nanoradian -> 2 mas
- 1pc resolution at 100 Mpc
- **Astrometry** is simply recovering position from these observations. Can generally centroid to much better than 1/10th of a resolution element (much easier to characterise location than size, especially at low S/N).



The High Sensitivity Array

GW170817: the prototypical NS merger

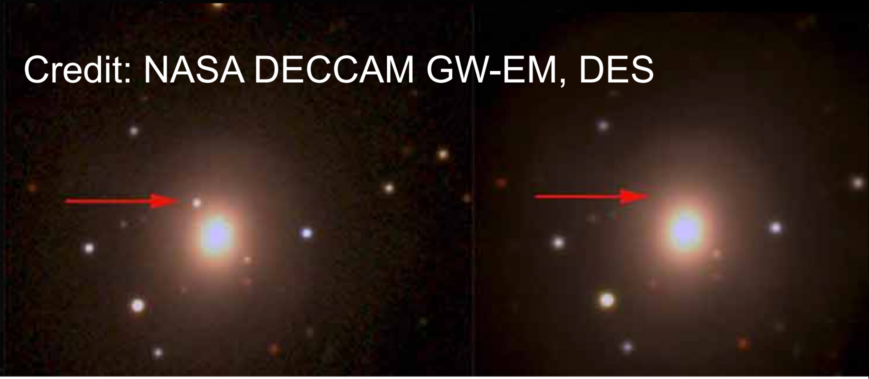
Gravitational wave data provides information about the merging stars and the geometry (limited)

	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8} Mpc	40^{+8} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$

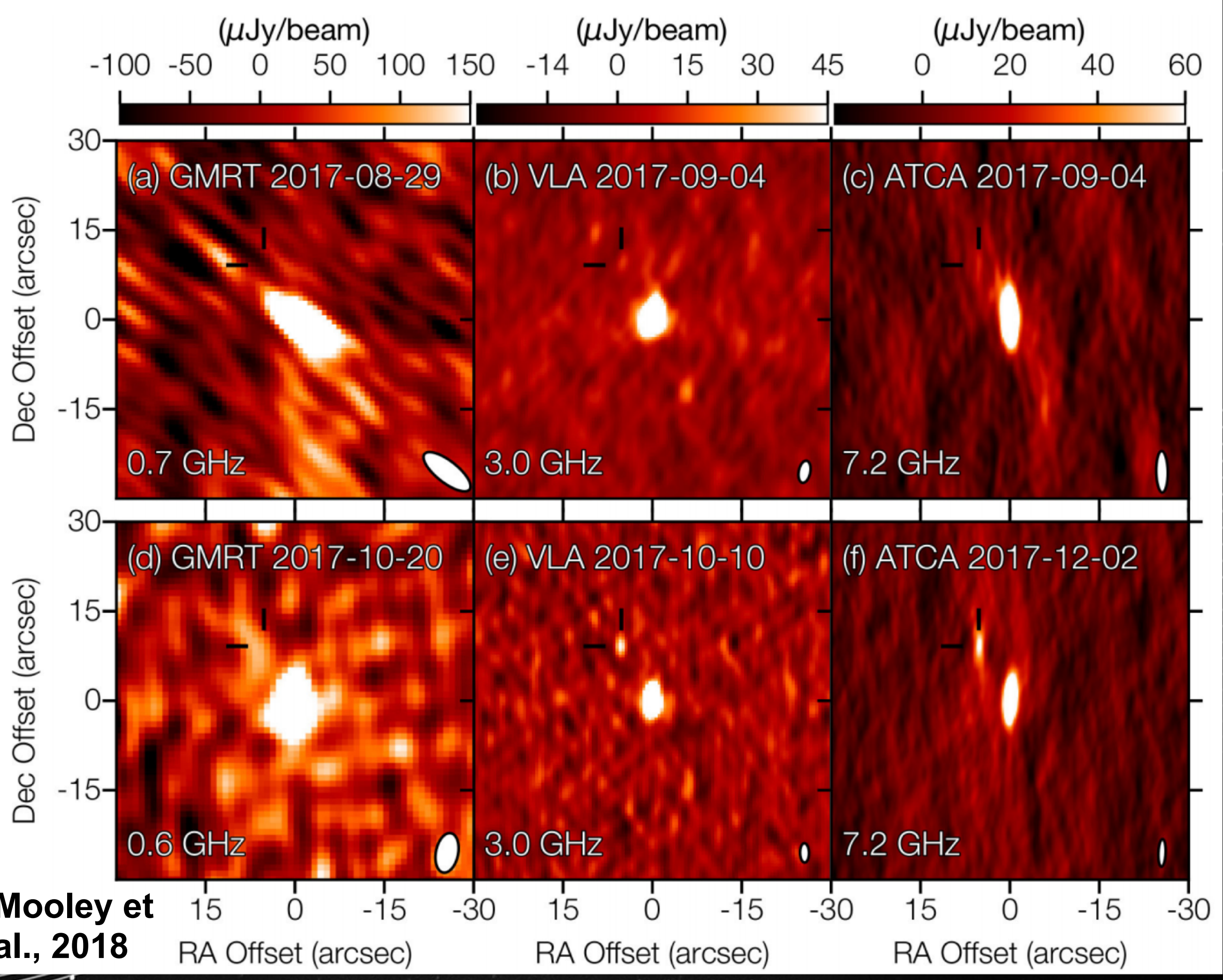
Abbott et al., 2017, PRL, 119, 161101

GW170817: the prototypical NS merger

Credit: NASA DECCAM GW-EM, DES



- Optical ‘kilonova’ association within 11h
- Optical/NIR studies in first weeks provide detailed view of dynamical ejecta, nucleosynthesis
- After glow detected in the X-ray 9 days post-merger, in the radio 16d post-merger



Mooley et al., 2018

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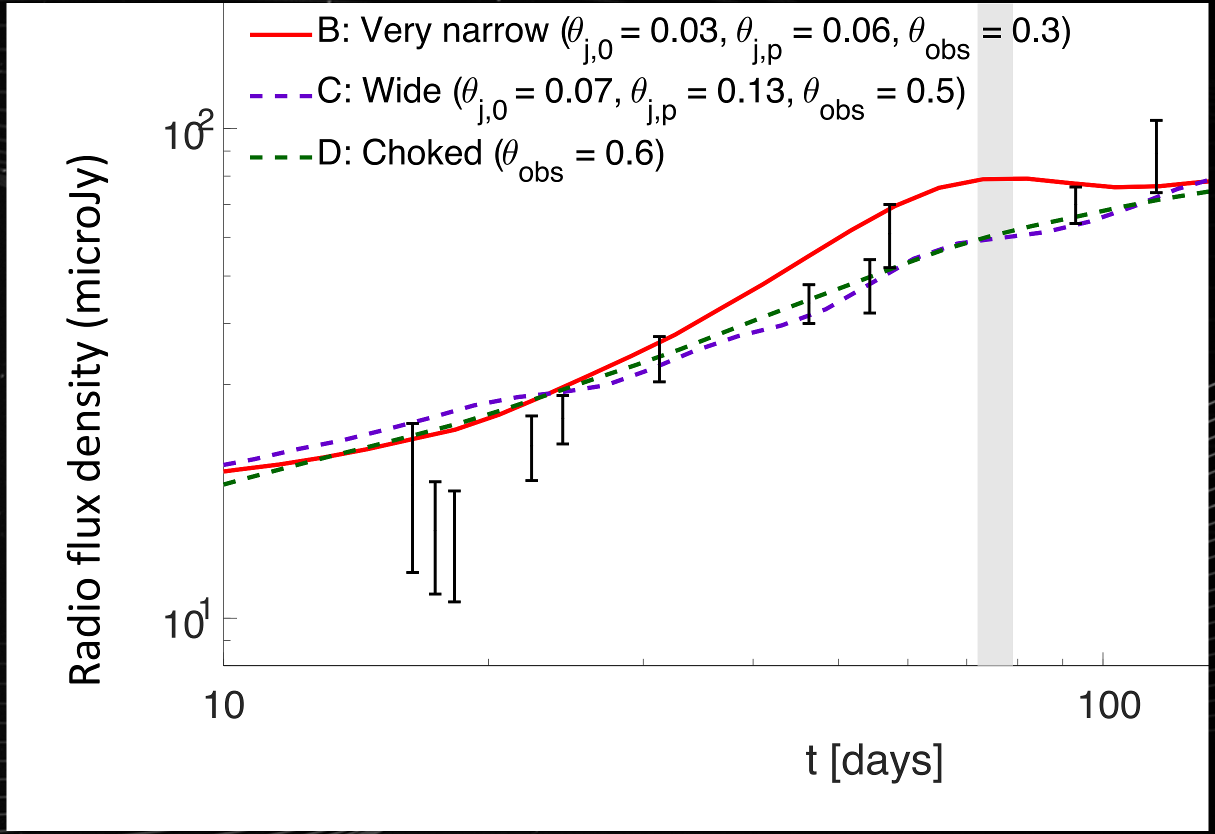
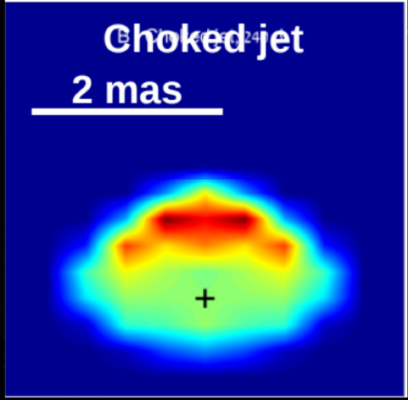
- Optical/NIR studies in first weeks provide detailed view of dynamical ejecta, nucleosynthesis
- After glow detected in the X-ray 9 days post-merger, in the radio 16d post-merger
- Rising light curve out to 100+ days contributed to ‘concordance’ picture (e.g. Kasliwal+2017) invoking mildly relativistic cocoon, but could not rule in/out successful jet: time-dependent morphology would be definitive

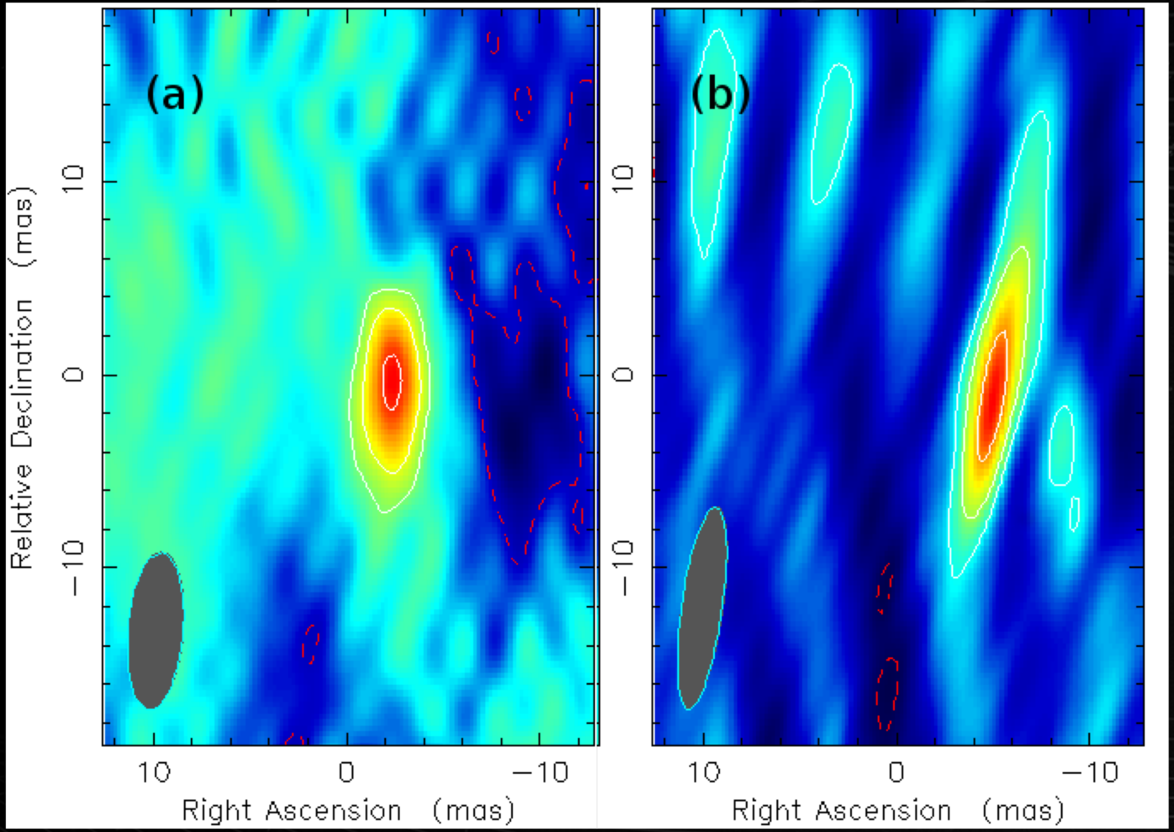
Mooley et al (2018)



Simulations from
Nakar et al., 2018

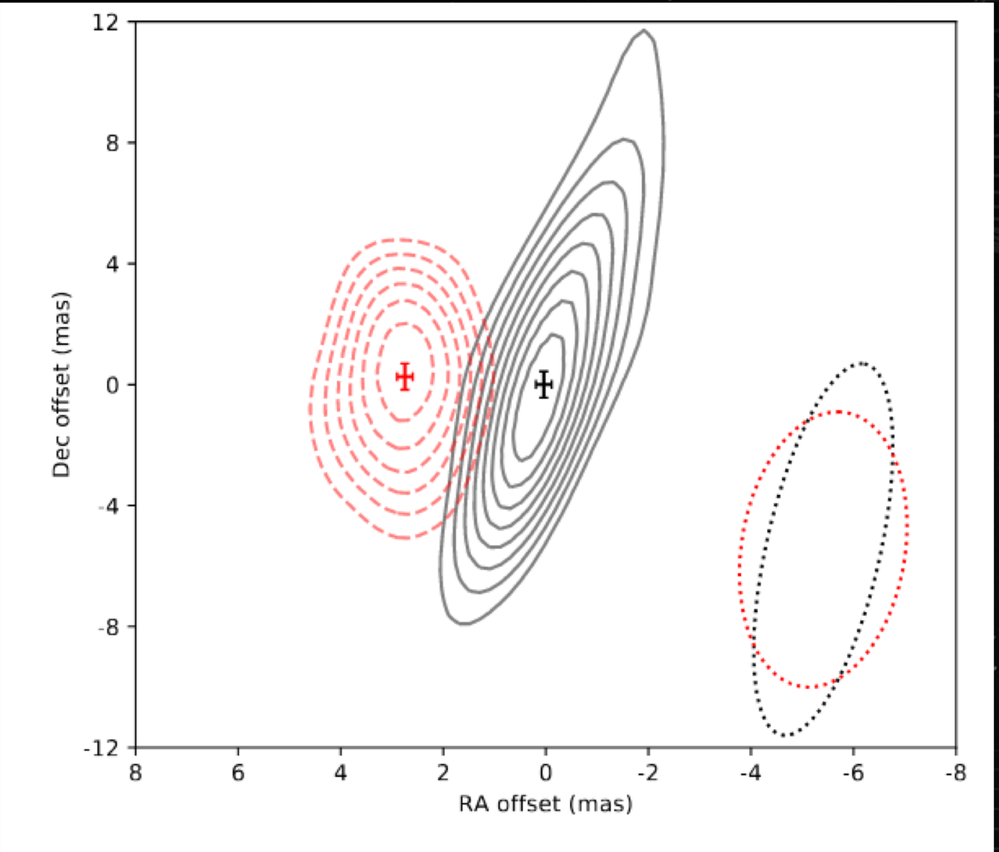


GW170817 afterglow: the VLBI observations



- High Sensitivity Array (VLBA + VLA + GBT) observations at early times at 2.3 and 1.6 GHz yielded non-detections (observing issues)
- Then observations at 4.5 GHz detected a compact source with 12σ significance (58 μJy) at day 75 (right)
- and then again with 9σ significance (48 μJy) at day 230 (left)

GW170817 afterglow: the VLBI observations



- Positional offset is 2.7 +/- 0.2 **+/- 0.2** milliarcseconds (statistical, **systematic**)
- Fortunate that proper motion was largely in R.A. (narrower PSF)
- Used NGC4993 AGN as check source to confirm no large systematic errors: AGN position is constant to well within our systematic uncertainty estimate

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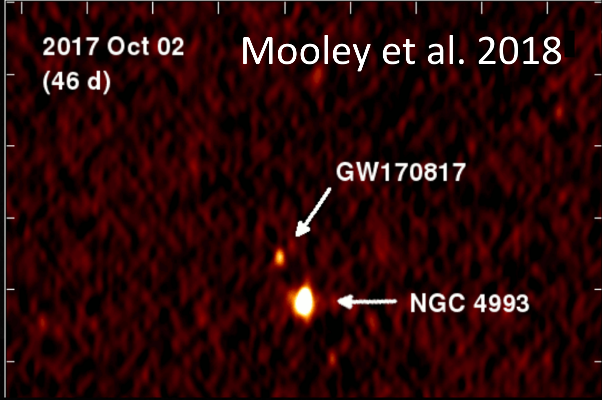

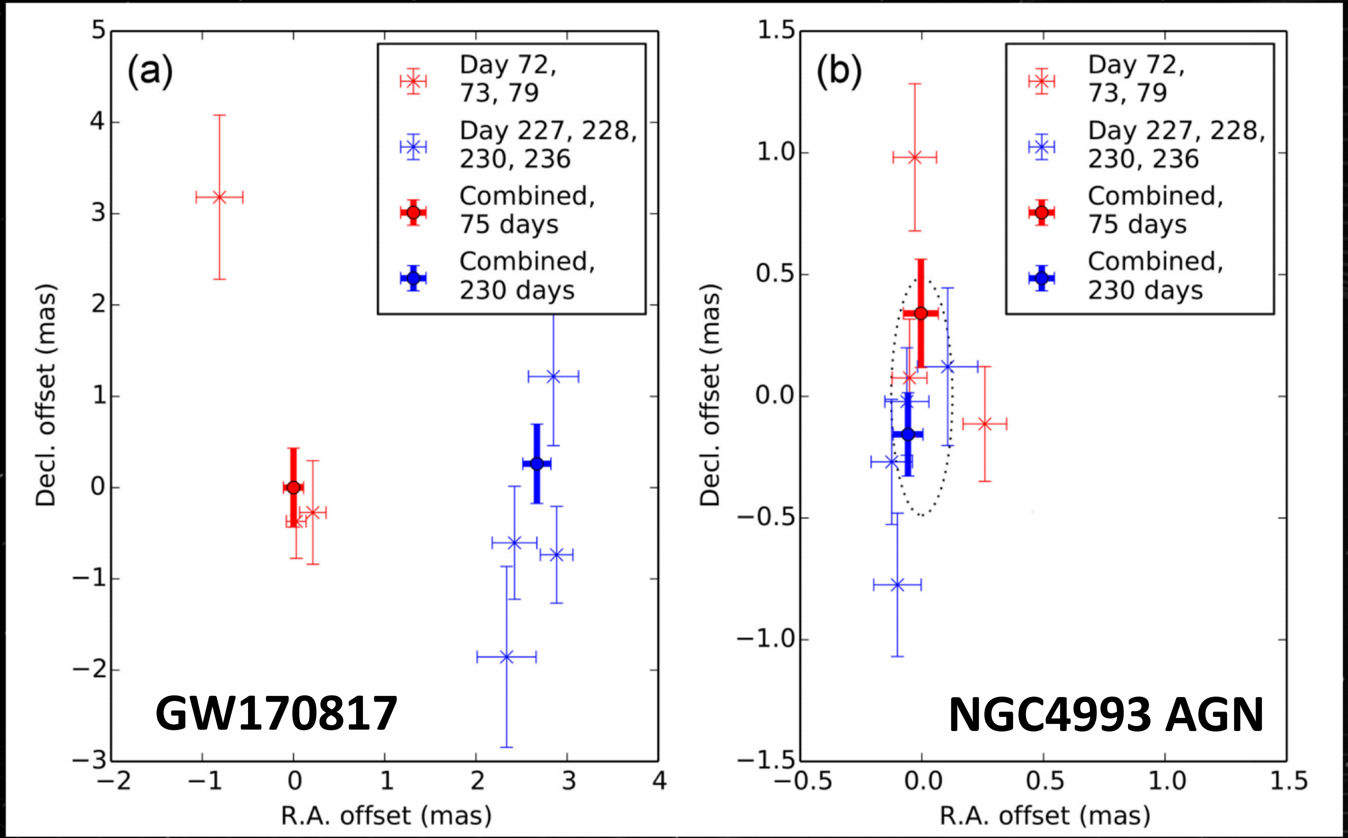

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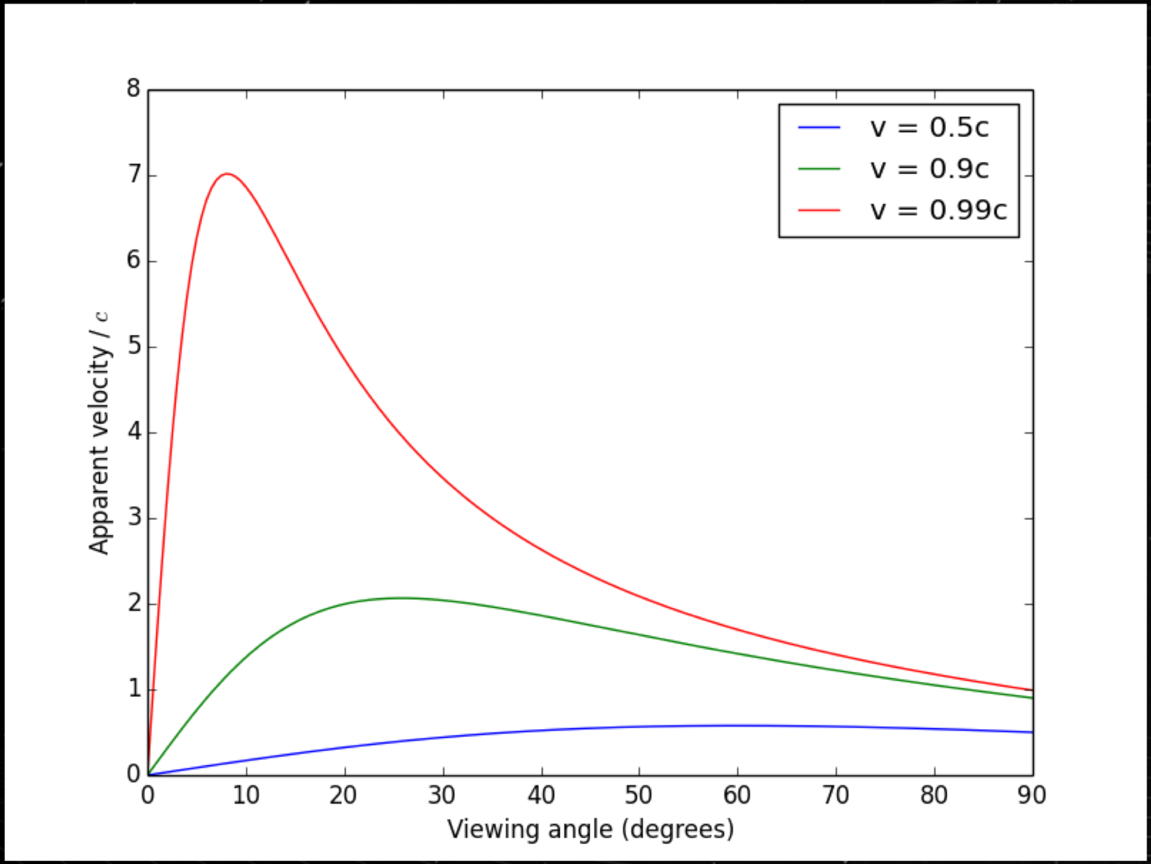
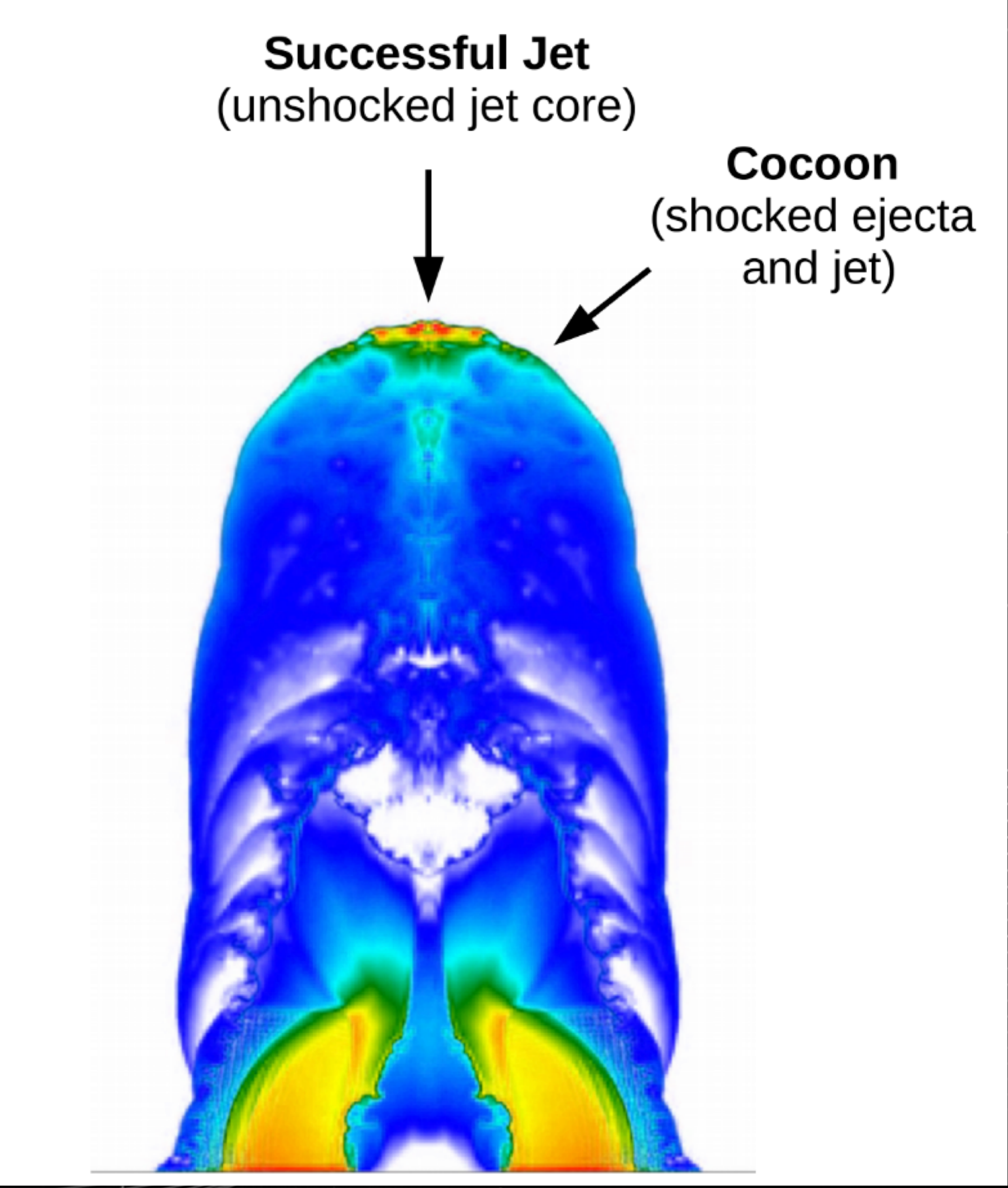


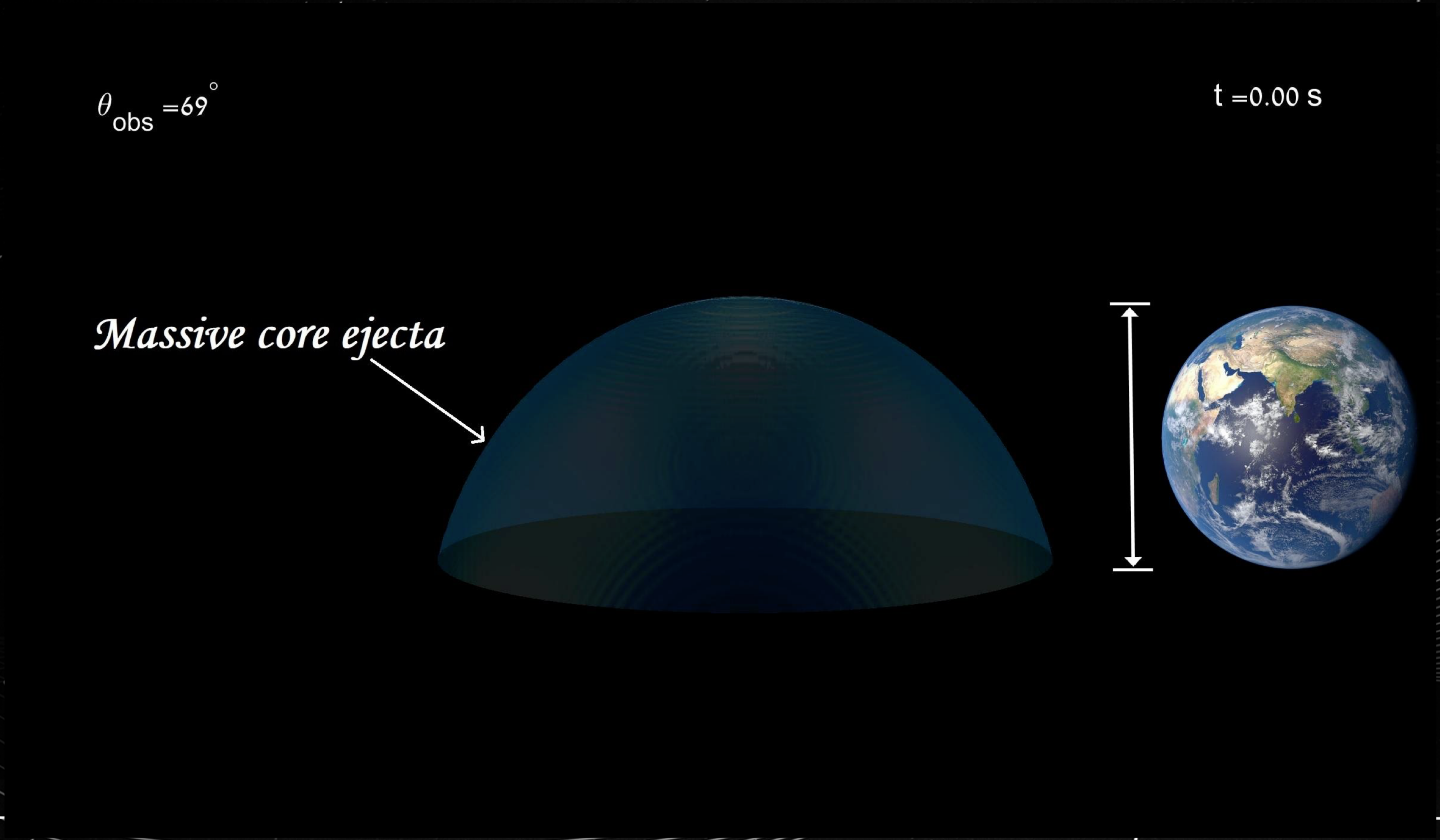
- At NGC4993 (41 Mpc): 6.4 mas/yr ⇒ $\boldsymbol{\beta}_{app}$ = 4.1 ± 0.5 *c*
- Rough and ready estimate: light curve peak around this time implies Lorentz factor $\boldsymbol{\gamma}$ ~= $\boldsymbol{\beta}_{app}$ ~= 1/sin $\boldsymbol{\theta}$, so 15-20 degrees
- But extracting reliable best-fit viewing angle and uncertainty demands full MHD modelling + radiative transfer

GW170817 afterglow: modelling

- Numerical simulations performed in PLUTO
  - Phase 1 (3D): propagation of the jet in cold core and fast ejecta tail, and breakout.
  - Phase 2 (2D): propagation of jet to homologous phase
  - Phase 3 (2D): interaction with ISM (afterglow)
- Each phase set up by the output of the previous phase
- Full details in Nakar et al. (2018)



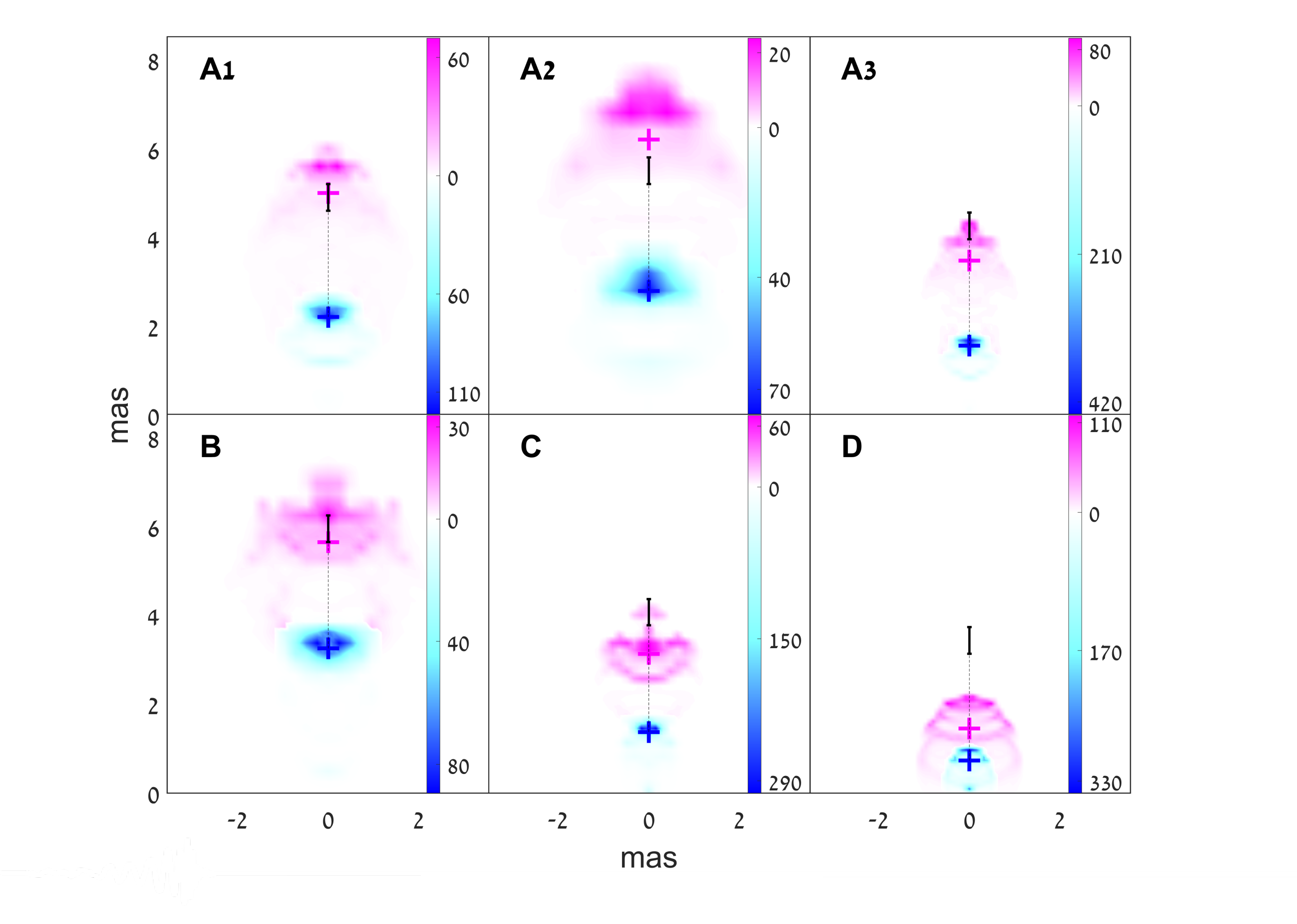
GW170817 afterglow: modelling

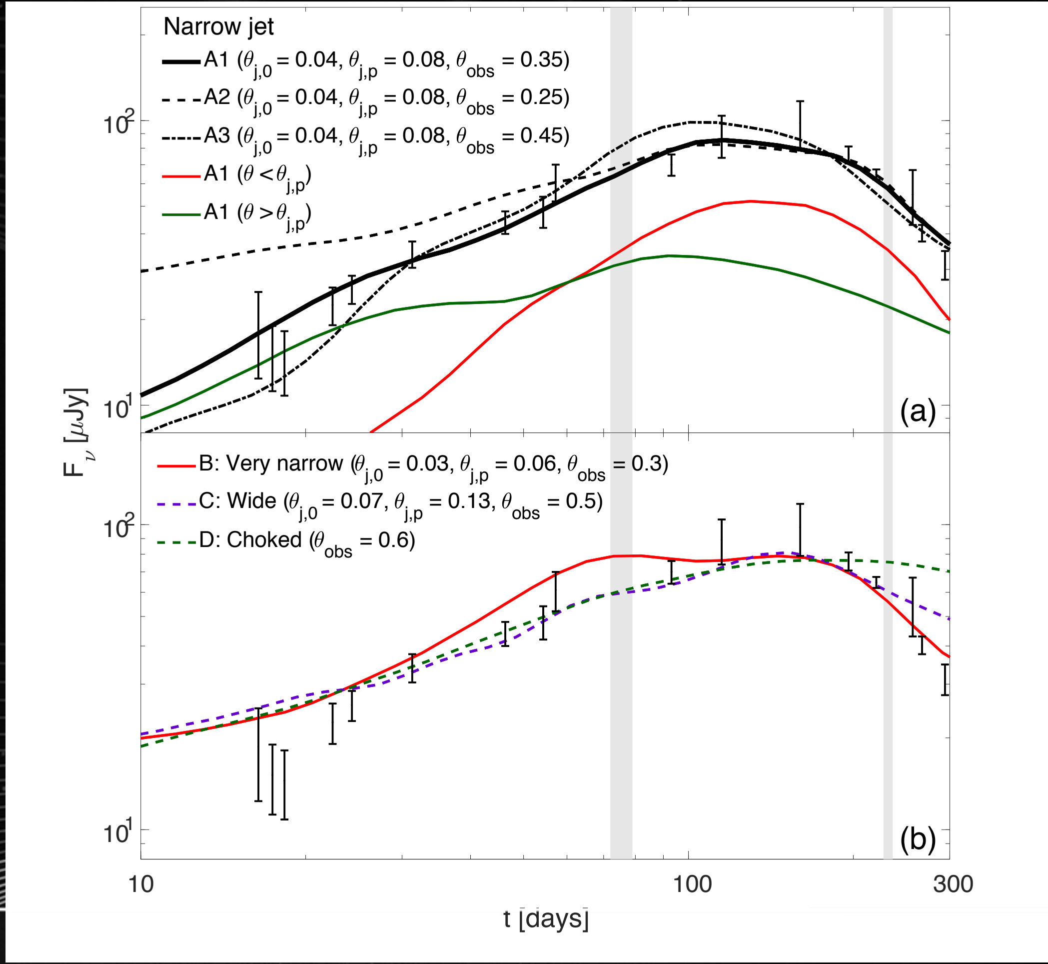


Movie credit: Ore Gottlieb

GW170817 afterglow: modelling

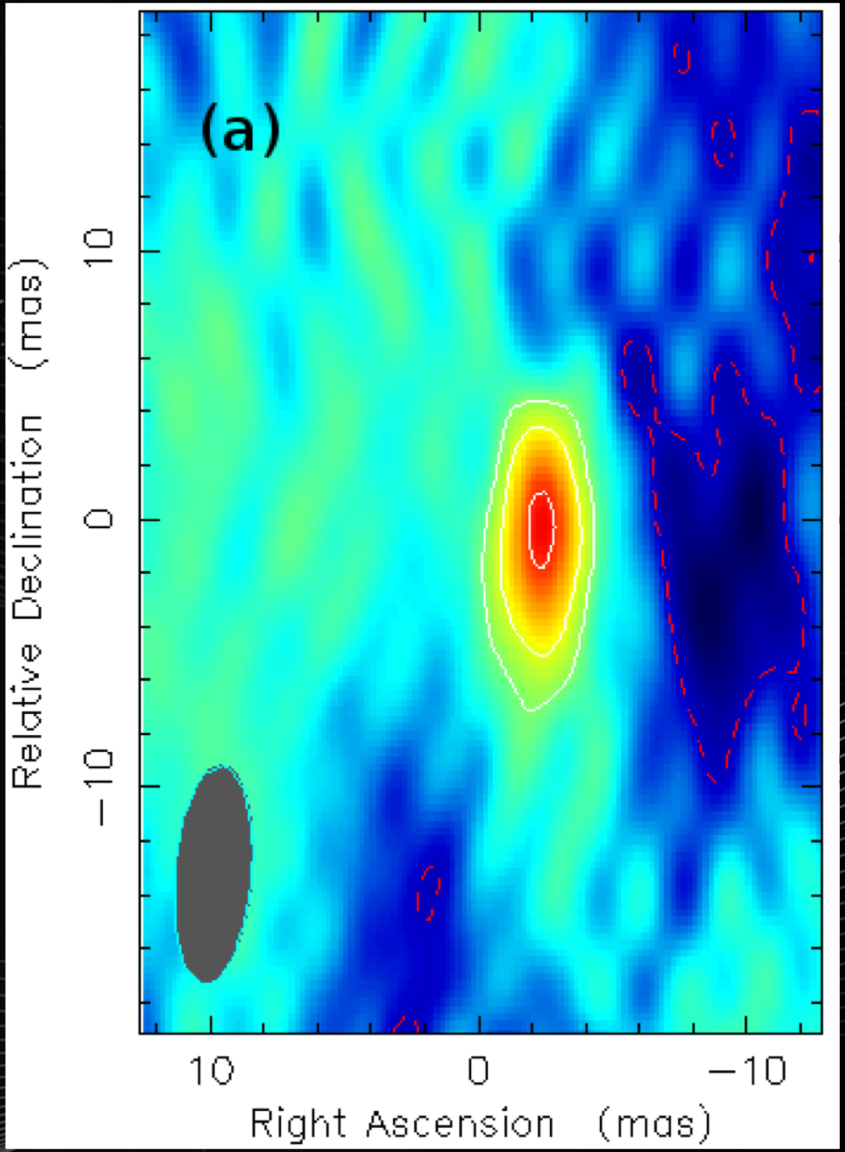
Models predict both the offset between VLBI epochs, and the radio light curve





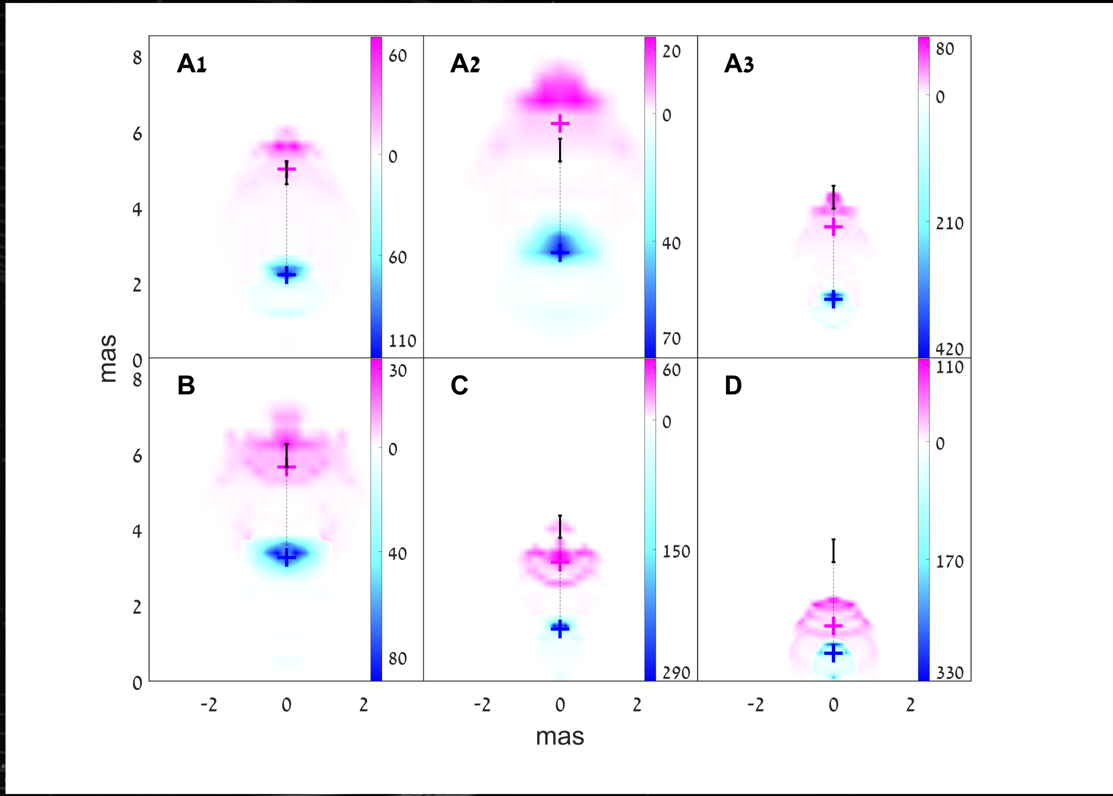
GW170817 afterglow: the results

- Hydro sim converted to synthetic radio observation and then clean-component model, constrained fit to VLBI data using *difmap* (free translation and rotation only, limited systematic offset allowed between epochs)
- χ^2 compared to that from a single gaussian fit, and to single gaussian fit offset by $1\boldsymbol{\sigma}$ and $2\boldsymbol{\sigma}$ in R.A. and Decl.
- Cross-check against positions obtained by fitting single gaussian to each epoch



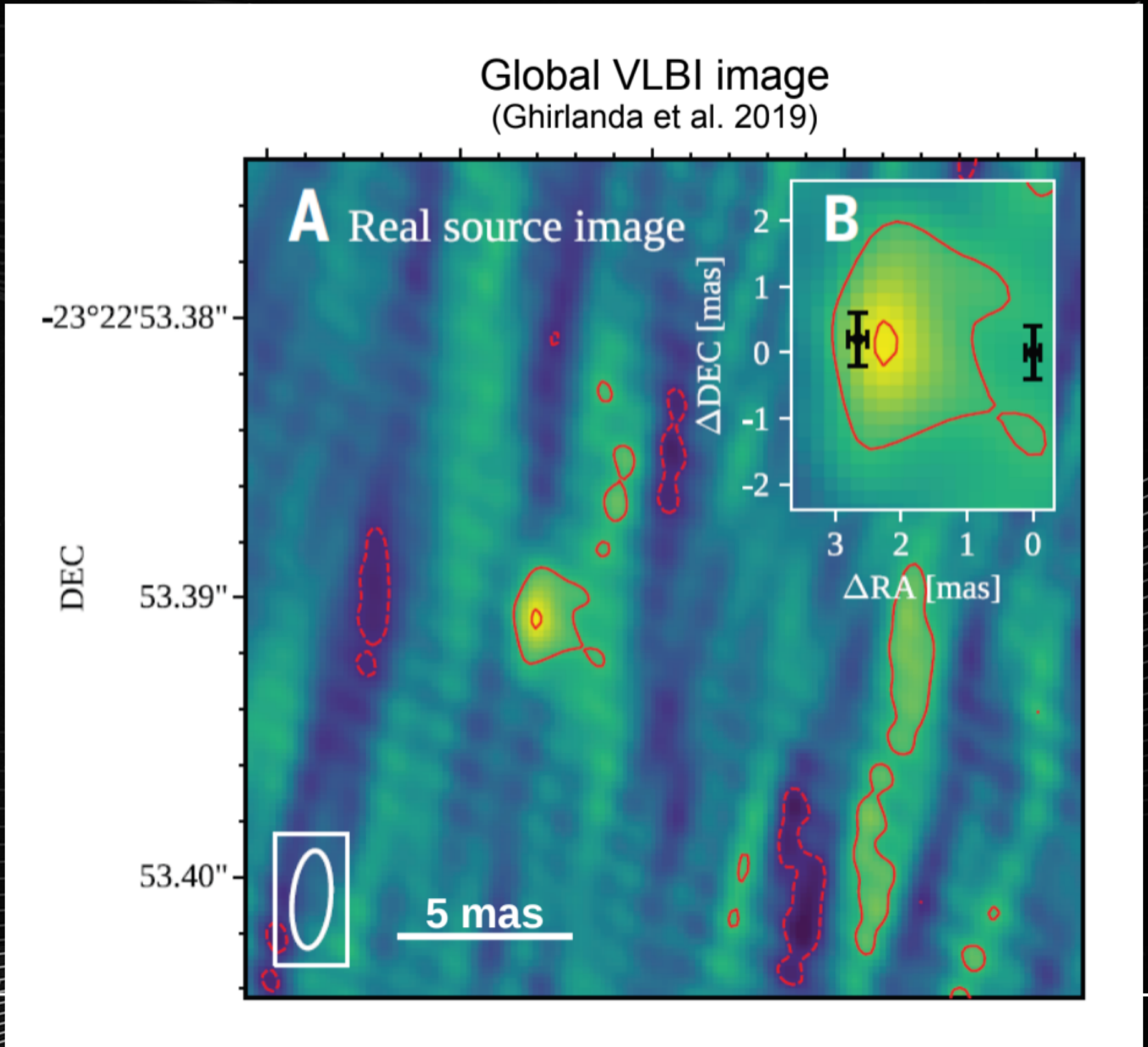
GW170817 afterglow: the results

- Best fit: narrow jet (opening angle 4∘ at the time of observations) observed from a viewing angle of 20° (reduced χ^2 comparable to single gaussian fit at each epoch)
- Viewing angles <15° produce too much positional shift (**and** predict source too large at day 230, **and** give a poor light curve fit), >25° positional shift is too small (**and** light curve fit gets worse).
- Tricky to estimate uncertainty: we consider 20^{+8}_{-6}° to be conservative



Added confirmation: global VLBI results

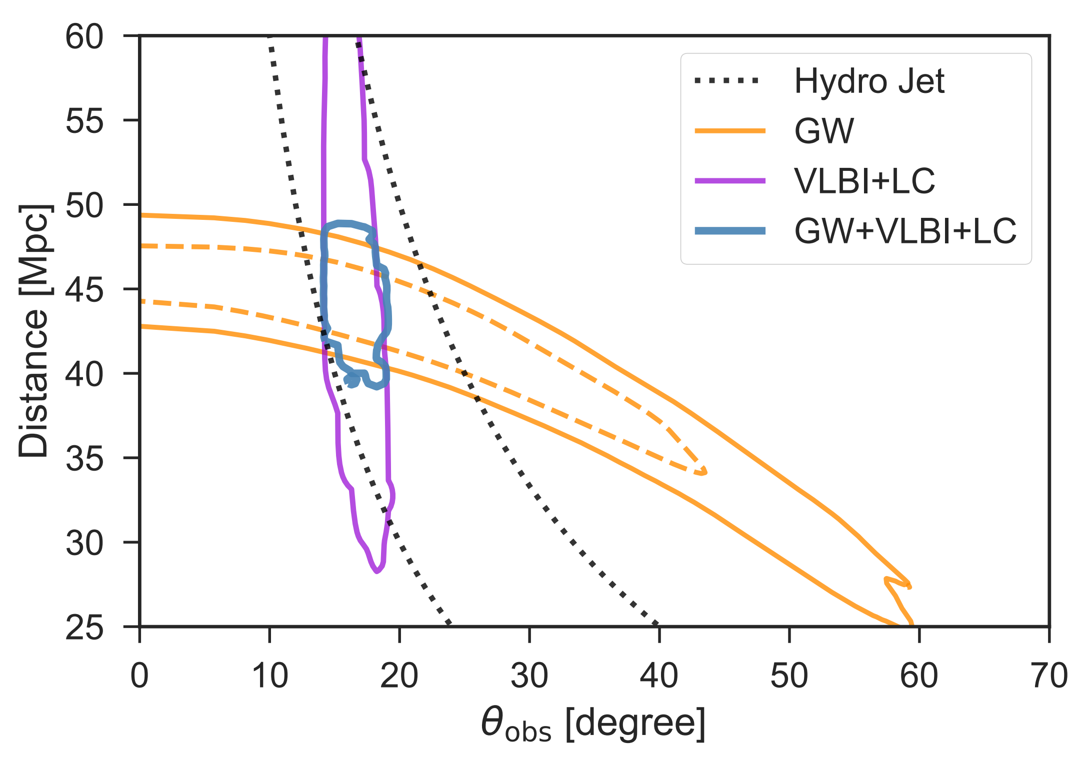
- Size constraint slightly stronger than HSA and likewise strongly disfavours choked jet
- Position (at day 207) is fully consistent with expectations based on the best-fitting jet + cocoon model



GW170817 afterglow: implications #1 (sGRBs)

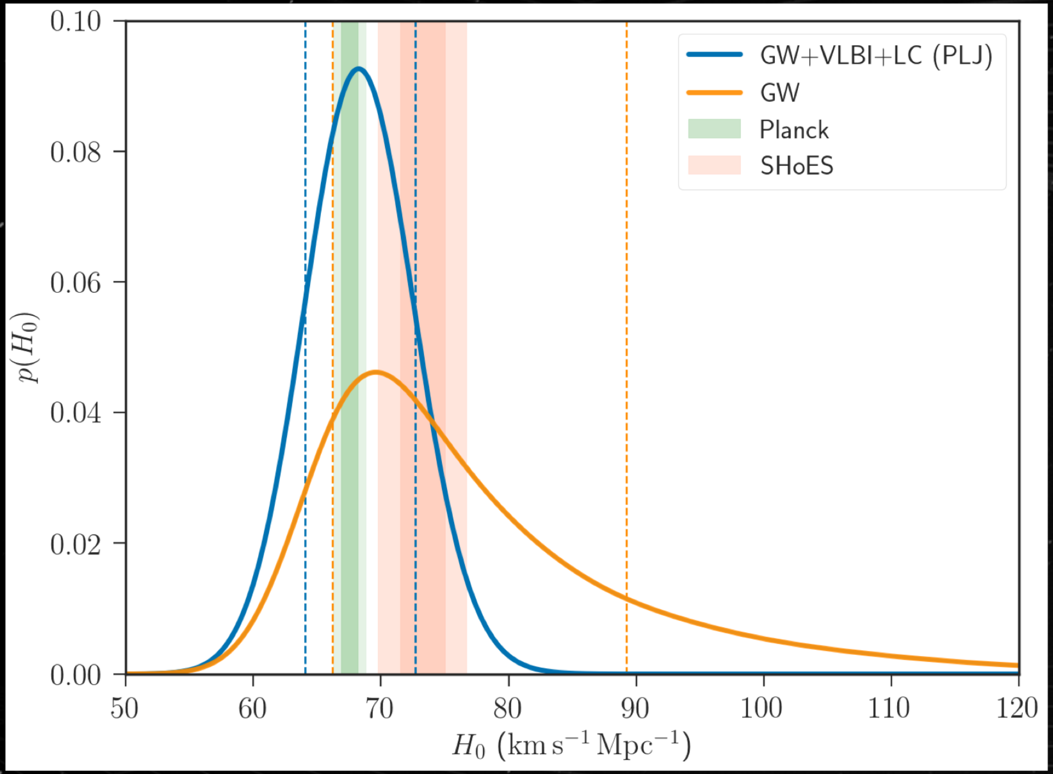
- GW170817 has a successful jet: NS-NS mergers produce sGRBs!
- To the on-axis observer, this would have been bright: the hydro sims for the acceptable models predict peak gamma-ray luminosity L_{ISO} ~ 10^{52} erg/s
- Only ~1% of sGRBs seen from Earth are this bright
  - Did we get super lucky? Or…
- GW170817's jet was very narrow: ~4 degrees. Are tightly beamed events brighter?
  - Say every 10^{52} erg/s sGRB has a 4 degree jet: only 1 in 1000 events will be viewed on-axis
  - Would require 3-30% of the NS-NS merger rate to produce this kind of narrow, bright sGRB, and this kind of event is much more common than previously thought (since we'd rarely see them)
  - Anticorrelation between L_{ISO} and jet opening angle would make total jet energy fairly constant

GW170817 afterglow: implications #2 (H_0)



- VLBI + light curve modeling constrains observing angle very well, which is highly complementary to the GW modeling (which constrains distance)
- Hotokezaka+2019 use semi-analytic jet models to perform MCMC calculations

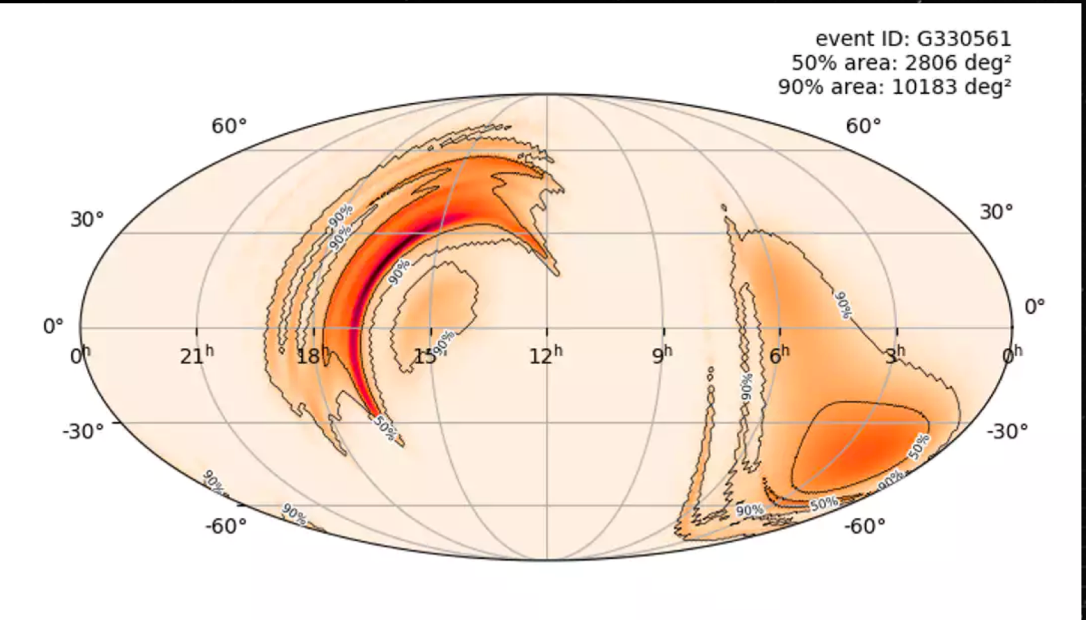
GW170817 afterglow: implications #2 (H_0)



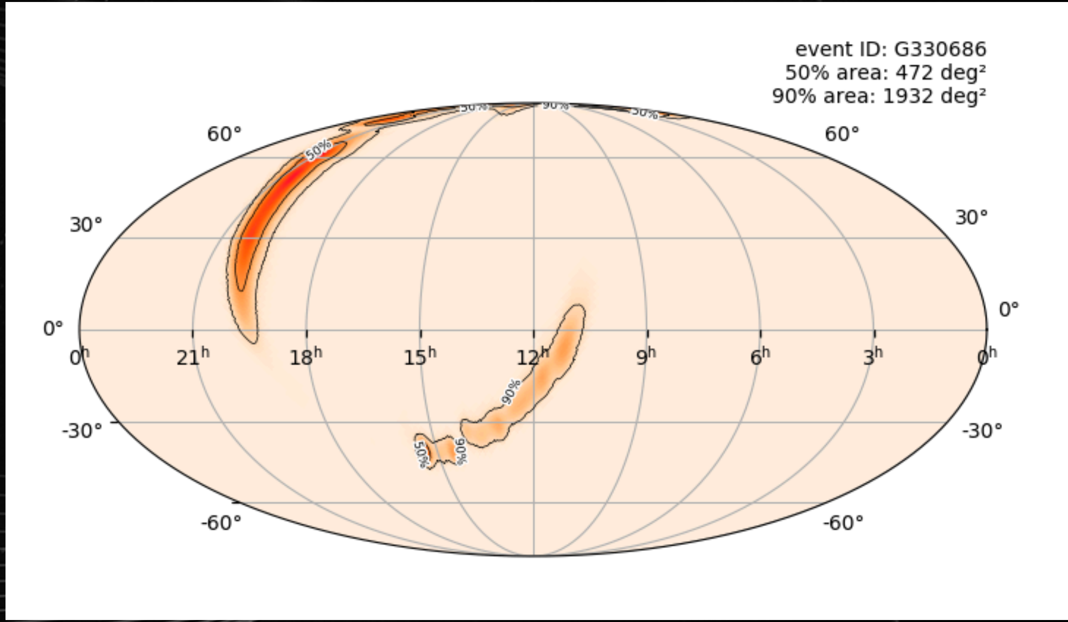
- VLBI + light curve modeling constrains observing angle very well, which is highly complementary to the GW modeling (which constrains distance)
- Hotokezaka+2019 use semi-analytic jet models to perform MCMC calculations
- Adding VLBI data shrinks confidence interval for H_0 from $70^{+12}_{-8} \Rightarrow 70.3 \pm 5.3$ km/s/Mpc

A look to the future: NS-merger VLBI

- We expected O(5-10) times more NS mergers detected in O3.



Left: S190425z
Right: S190426c
LIGO



A look to the future: NS-merger VLBI

- We expected O(5-10) times more NS mergers detected in O3.
  - 6 NS-NS and 4 NS-BH candidates in the first half of O3 (not all ironclad, but rate estimate is encouraging!), but no EM counterpart found for any yet – so no chance to trigger VLBI observations.
  - 104 hours of HSA priority A time awarded to follow up 2 merger events
  - Was GW170817 typical? Or will many NS mergers go off in denser environments and be brighter?
  - How many will be bright enough and nearby enough to have VLBI "model differentiation" power? VLBI is not a magic wand: if model differences fall within VLBI uncertainties, then no added value

A look to the future: NS-merger VLBI

- With larger sample:
  - Are the intrinsic jet properties mediated by the nature of the merging objects?
  - Are the observed jet properties mediated by the debris from the merging objects? Do any jets get choked?
  - H_0 will continue to be a focus: to obtain ~2% uncertainty on H_0, one would only need ~15 GW170817-like events with VLBI data, vs 50+ events with GW data alone
  - But modelling will become crucial: ”uncertainty in uncertainty” won’t be negligible

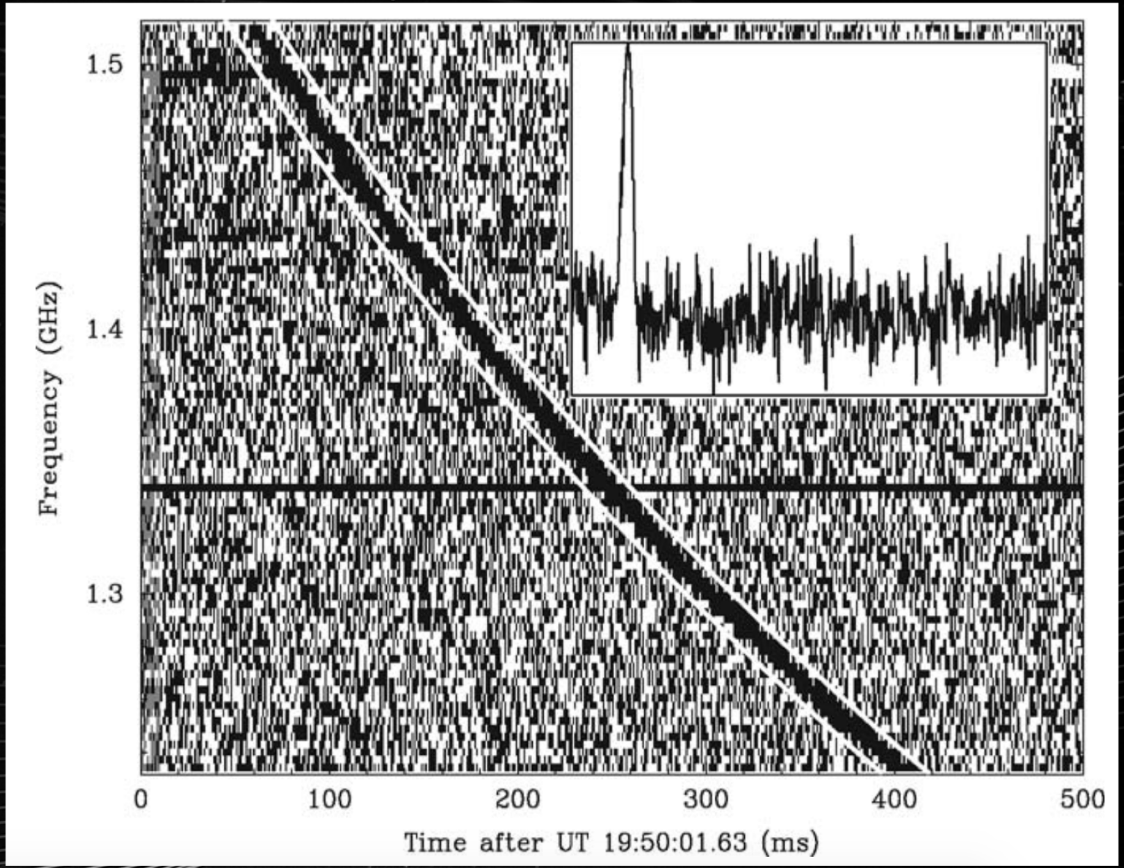
Changing gears: Astrometry elsewhere

- What are the applications of radio astrometry to other classes of explosive radio transients?

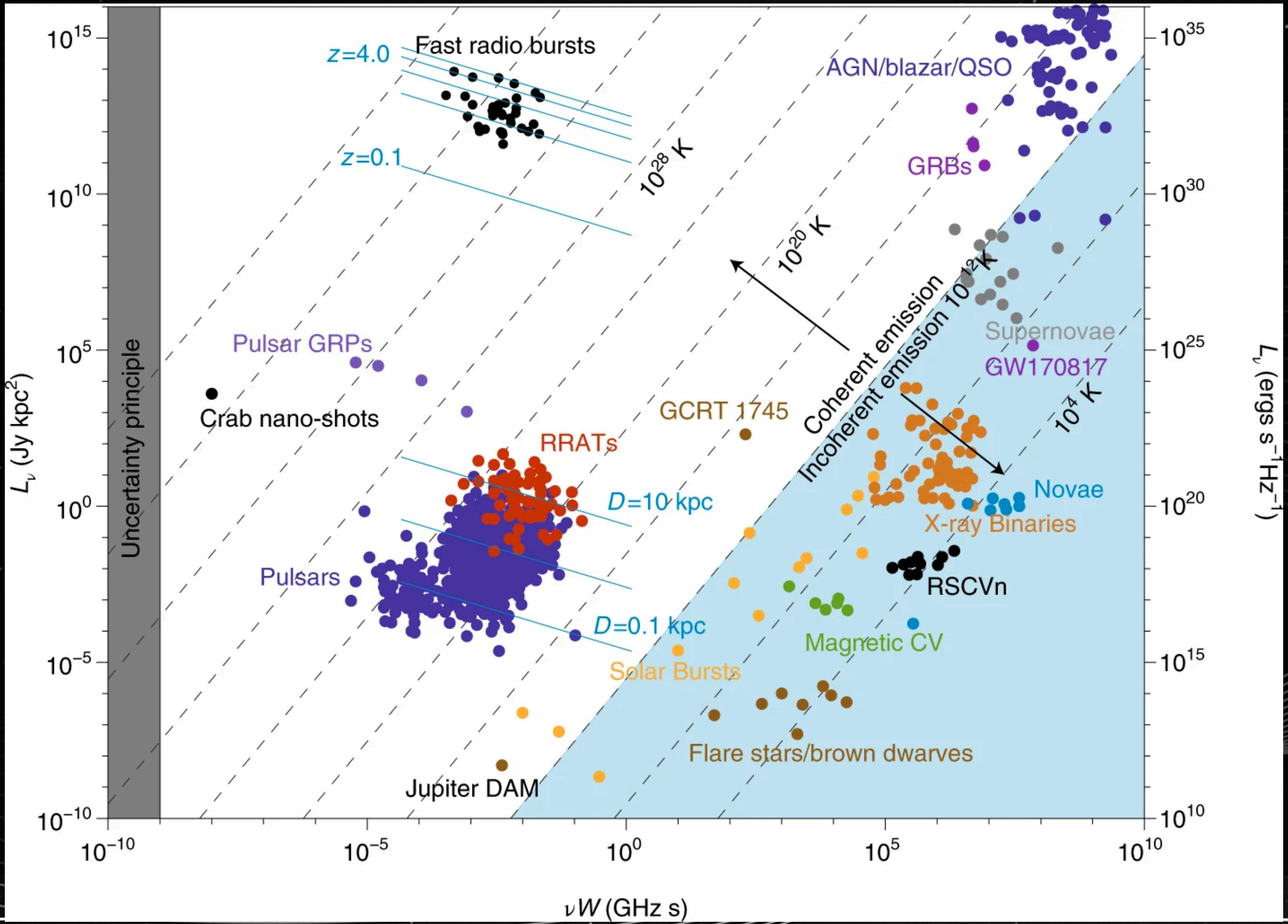
Fast Radio Bursts

- Short (~1 ms) duration transients seen at ~0.5 – 5 GHz
- Ionised IGM / ISM causes frequency-dependent (dispersive) delay
  - Dispersion Measure (DM) encodes total electron column to high precision
- FRB DMs > Milky Way line-of-sight DM
  - FRBs are extragalactic
- Often highly linearly polarised
  - Rotation Measure can be used to study line-of-sight B fields
- Some seen to repeat, most only seen once

Lorimer et al., 2007



Fast Radio Bursts



Pietka, Fender, & Keane, 2015.

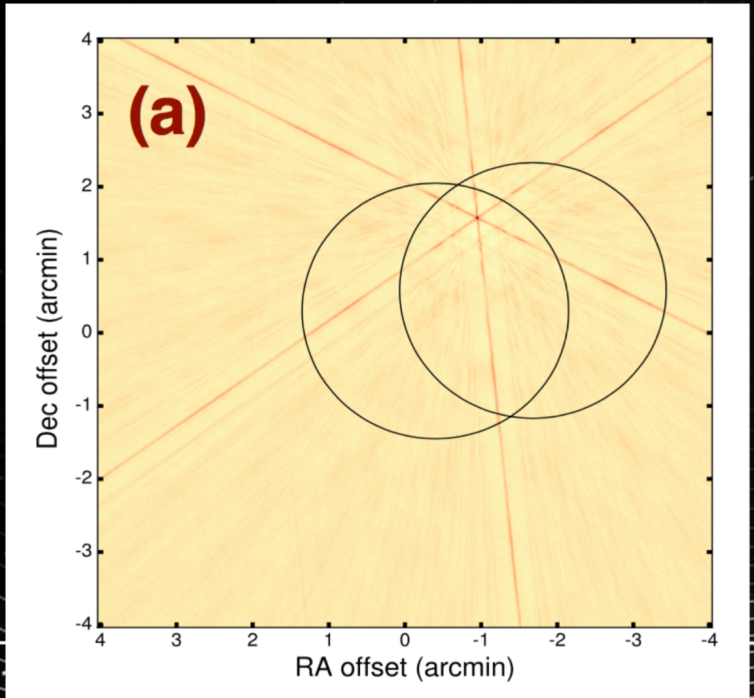
Fast Radio Burst applications

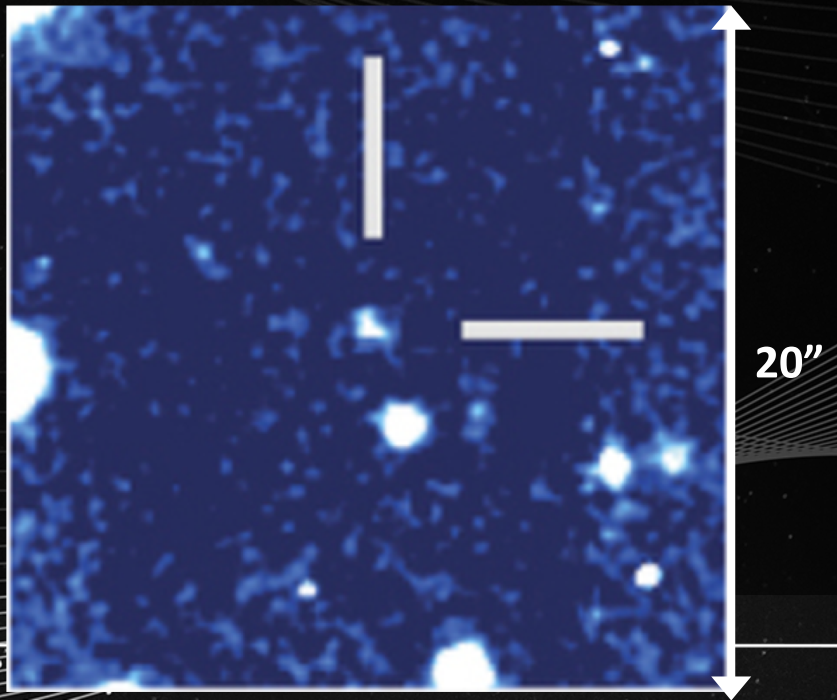
- Understanding the extreme physics that must operate in the progenitors
  - B. Zhang talk later today
- Ignoring the progenitor entirely: FRBs have DM (electron column) + RM (B field) + are visible to large distances = ideal probe of the IGM, CGM, Milky Way ISM, & host ISM
  - All at once! Wait, that's not so great.
  - Need a population to disentangle various contributions
  - Requires one very important piece of additional information for every FRB: **accurate sky position and redshift**

Fast Radio Burst astrometry

- As simple as making a 1-ms duration image… Just need the right 1ms of data!
- First FRB was localised in 2017: repeating FRB 121102
  - Known location and DM = computational complexity vastly reduced

Radio localization with the VLA (Chatterjee+17)





Gemini r’ band optical image of host galaxy (Chatterjee+17)

Inferences from the FRB 121102 host galaxy

- Low mass, low metallicity dwarf galaxy with high specific star formation rate
- Suspiciously similar to the typical hosts of superluminous supernovae!
- A faint, compact, and modestly time-variable radio continuum source was found co-located with the FRB position
    - Properties explainable with a nebula powered by a magnetar
- To account for all this plus time-dependent rotation measure and frequency-dependent temporal structure, Margalit & Metzger (2018) propose a concordance picture with flaring magnetar embedded in magnetised pulsar wind nebula
- **But is FRB121102 typical?**

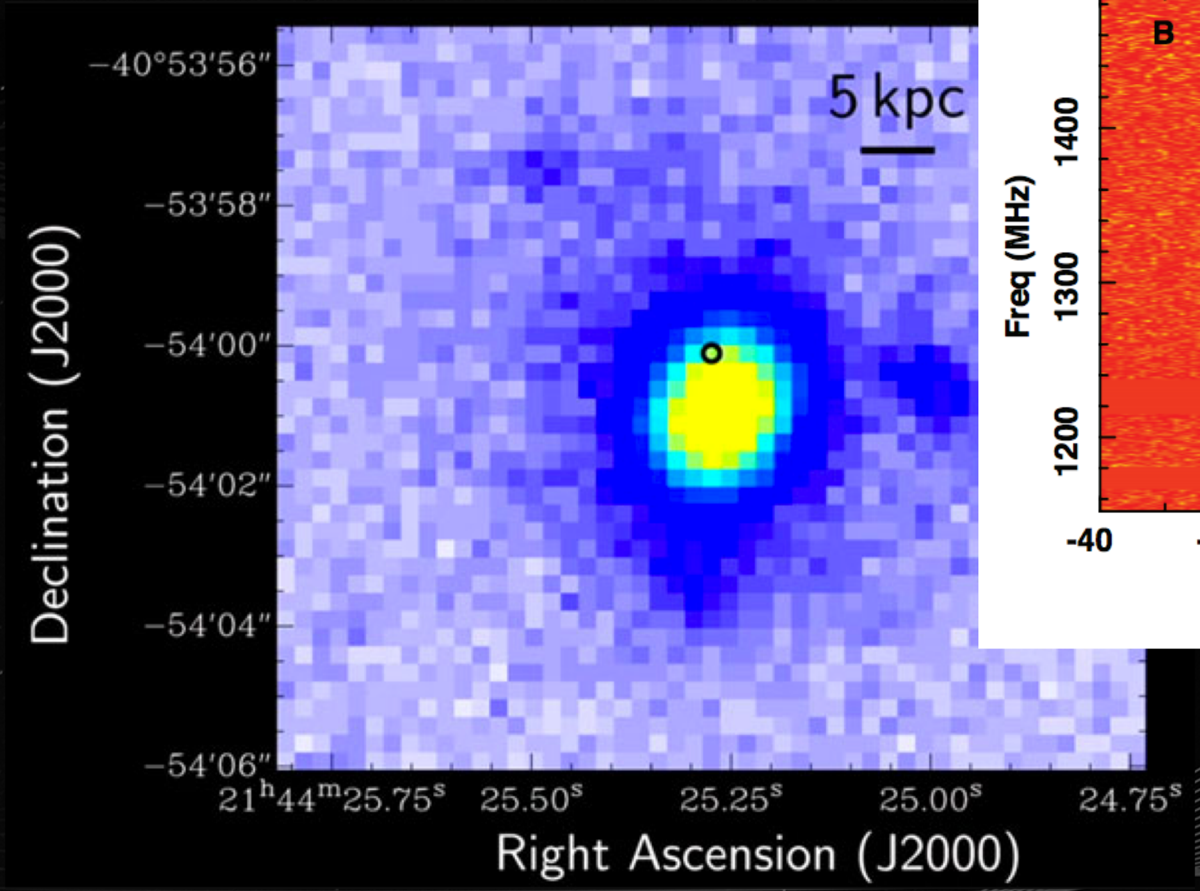
A new generation of “blind” FRB localising machines

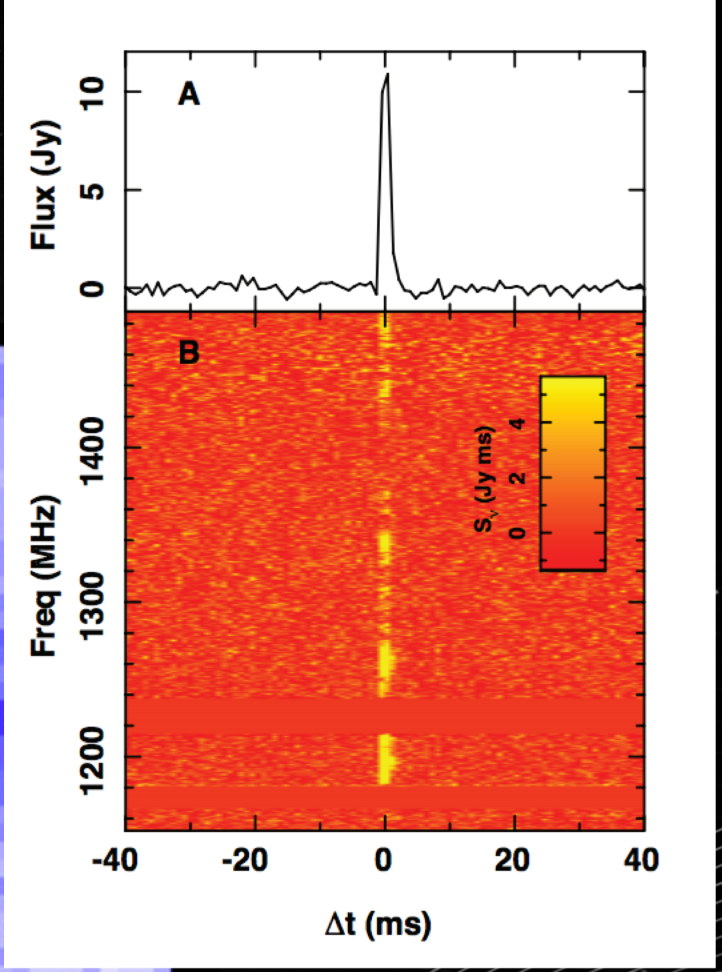
- ASKAP: 36 12m dishes in Western Australia
- DSA-10: 10 4.5m dishes in California
- MeerKAT: 64 dishes in South Africa
- UTMOST-2D: 2x 1600m cylindrical reflectors near Canberra, Australia
- realFAST: commensal system on the VLA in New Mexico

The ASKAP radio telescope: image credit CSIRO

Newly localised FRBs: FRB180924

- ASKAP's first localised FRB: z = 0.3214
- Lenticular host galaxy differs markedly from FRB121102: 500x more massive, more metal rich, much lower specific SFR
- In the galactic outskirts!

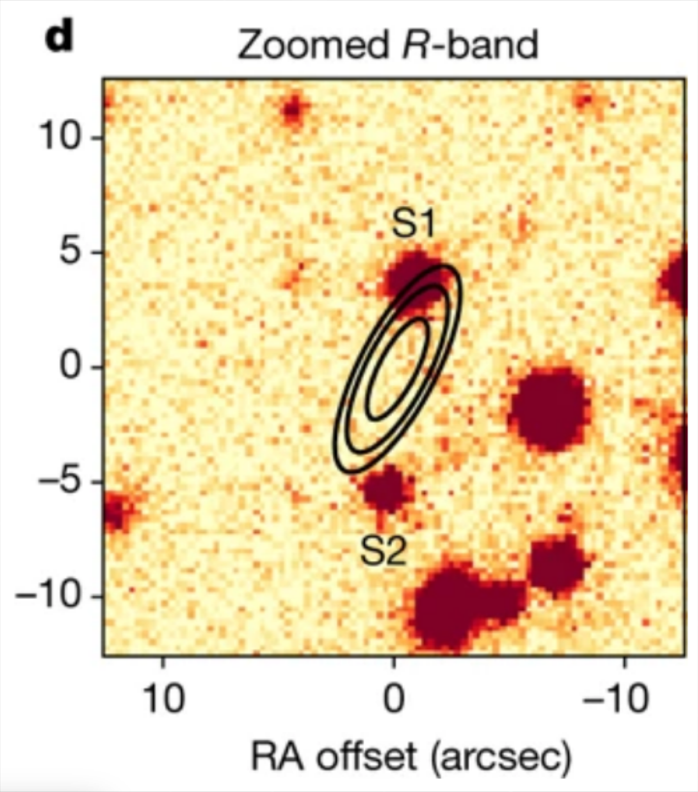


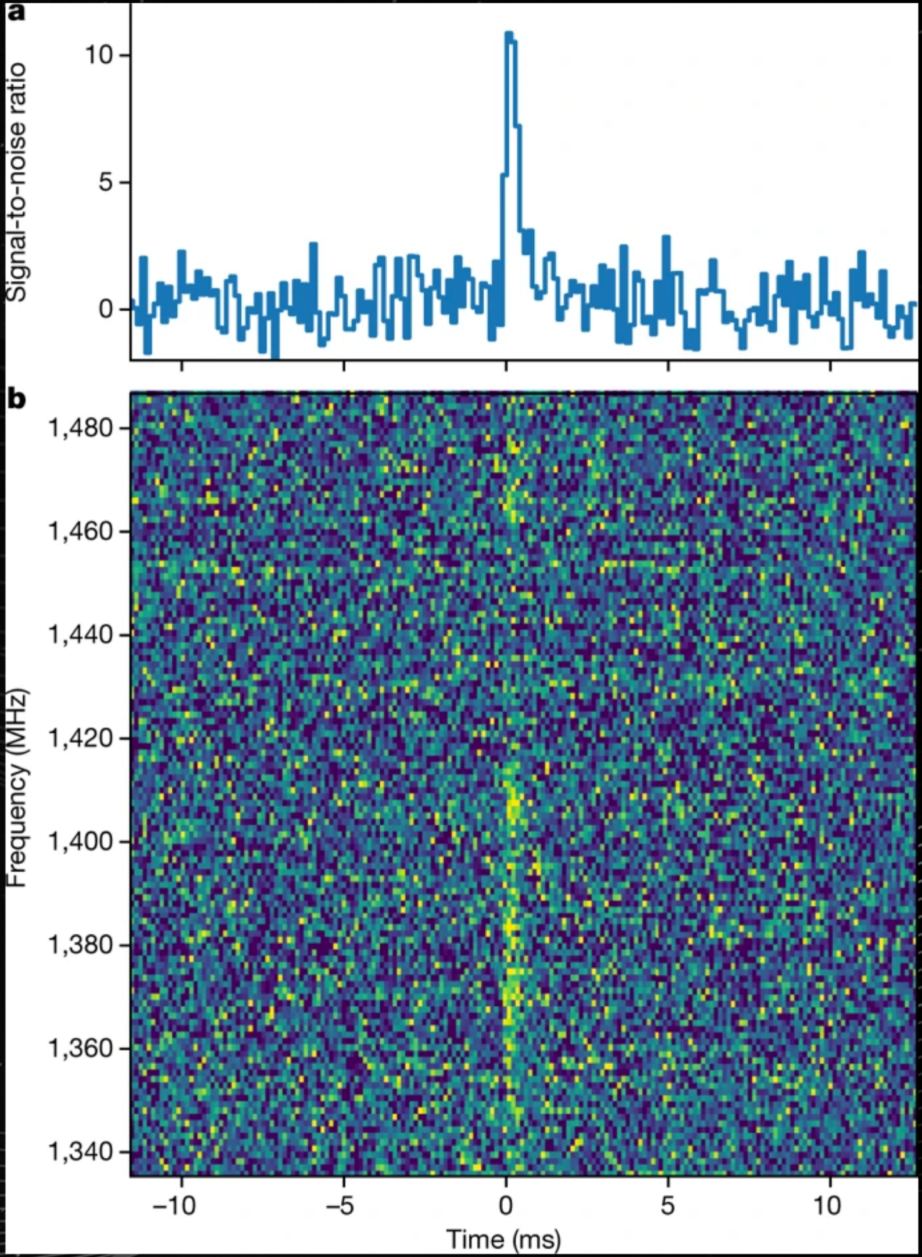


Bannister, Deller et al., Science, 2019

Newly localised FRBs: FRB190523

- DSA-10's first FRB: z = 0.66
- Few times more massive again than FRB180924 host, with even lower SFR
- Location likewise inferred in outskirts!
- DM was used as a prior to aid the association

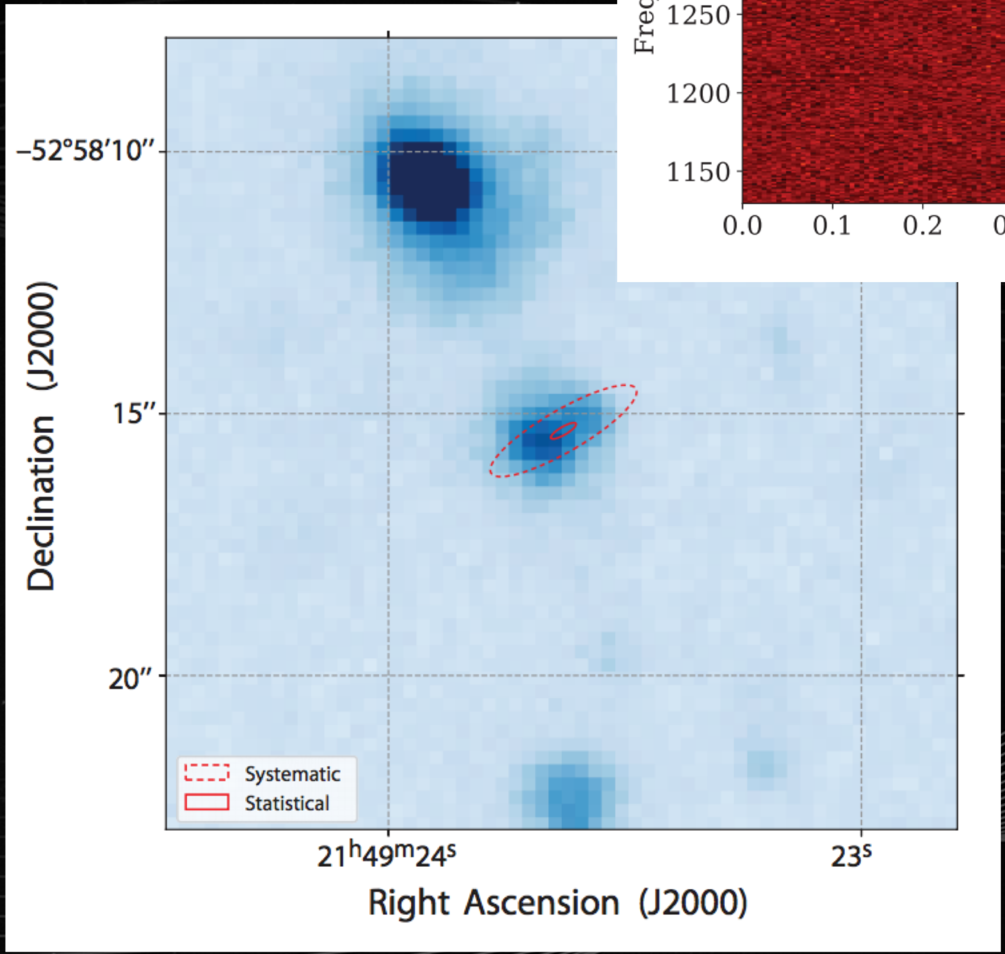


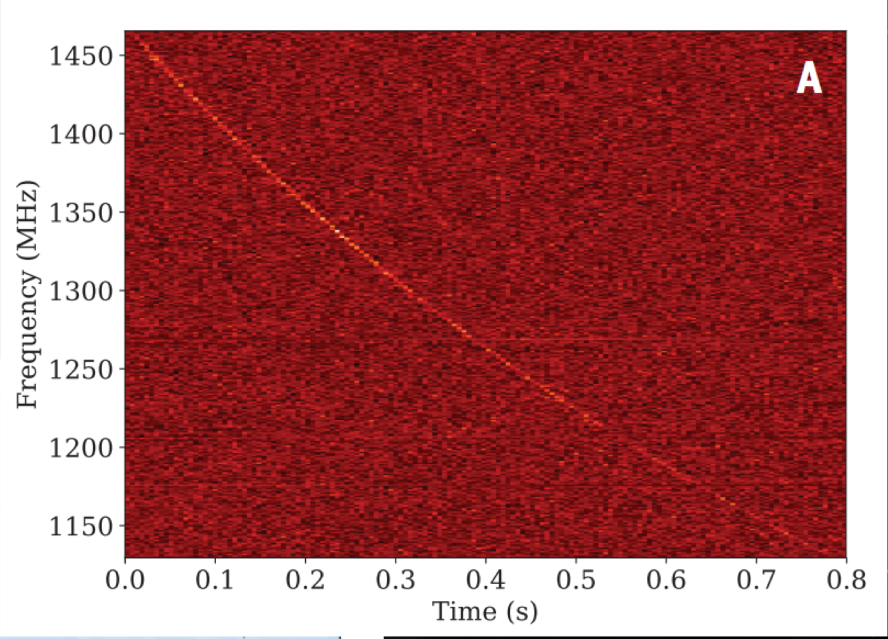


Ravi et al., Nature, 2019

Newly localised FRBs: FRB181112

- ASKAP's second localised FRB: z = 0.4755
- Another run-of-the-mill galaxy: mass $10^{9.4}$ M_{solar}, SFR 0.6 M_{solar}/year
- But burst passes through a foreground halo at z = 0.3674!
- No significant temporal scattering: diffuse halo gas





Prochaska et al., Science, 2019,
Cho et al., in prep

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