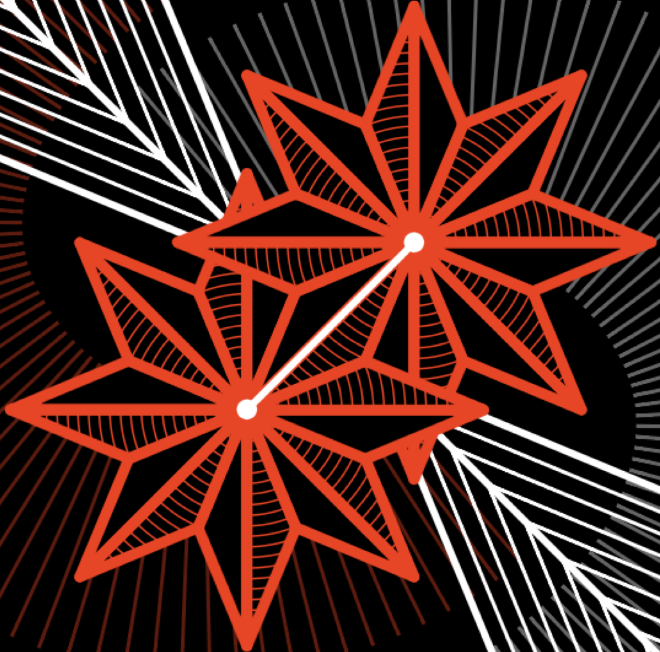
Radio follow-up of gravitational wave events in LIGO O3



Credit: Science

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A/Prof Tara Murphy (Sydney)
A/Prof David Kaplan (UWM)

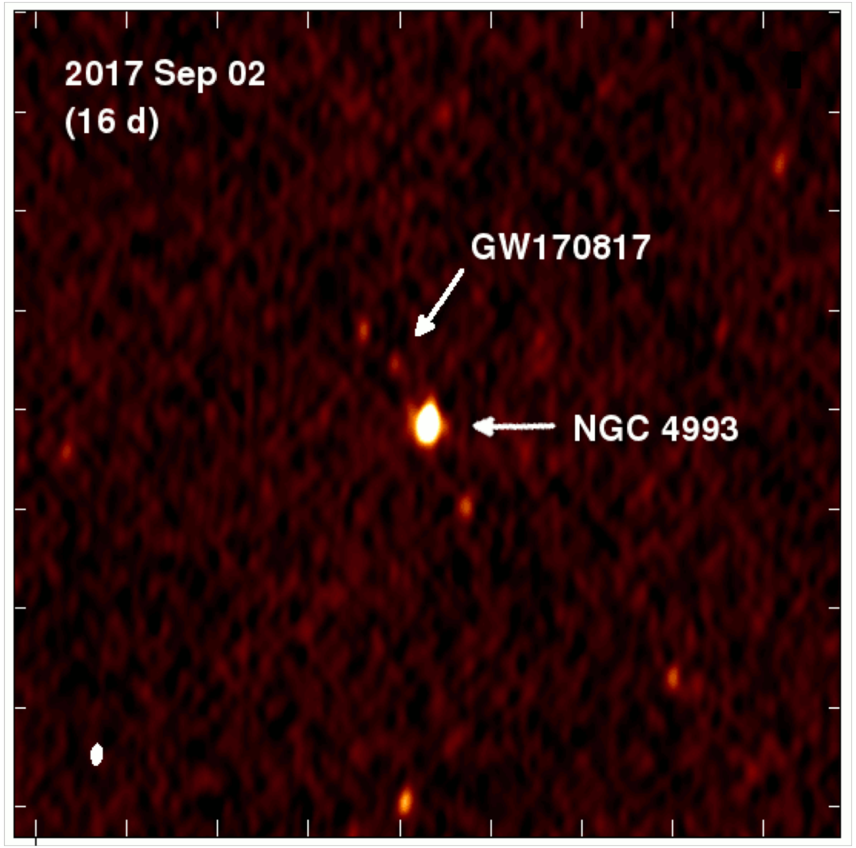
Radio follow-up of GW170817 – first detection

- Started searching at t = 10 hours
- (ATCA first radio telescope observing)
- Initially targeted list of galaxies
- Then daily observations of NGC 4993 (distance 41 Mpc)

Radio detection at t = 16 days

VLA detections:
Sept 3rd 3 GHz = ~19 μJy, 6 GHz = ~28 μJy

ATCA detection: Sept 5th 7.25 GHz = ~25 μJy



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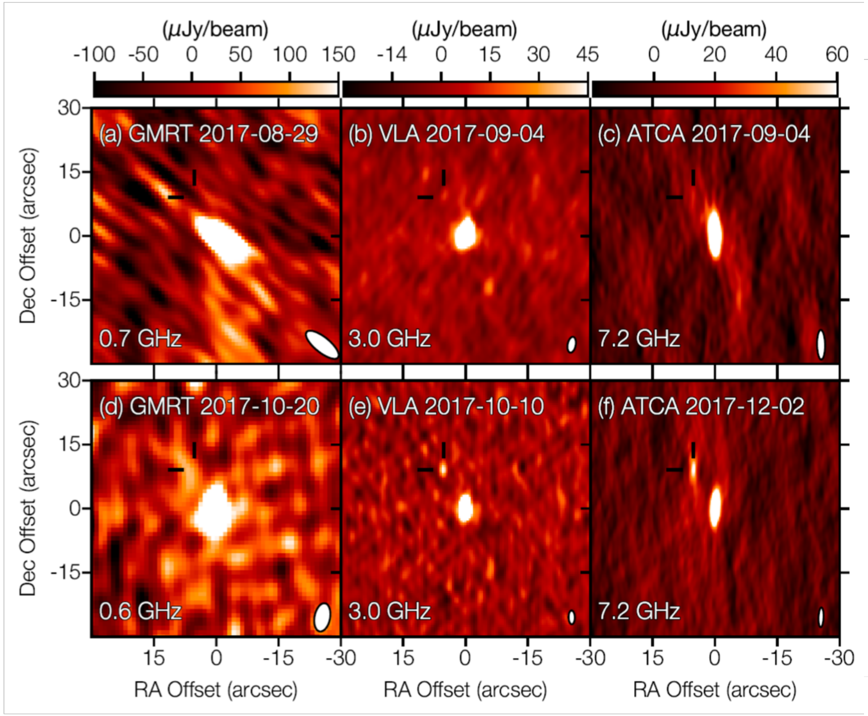
Hallinan et al. (2017), Science, 358, 1579

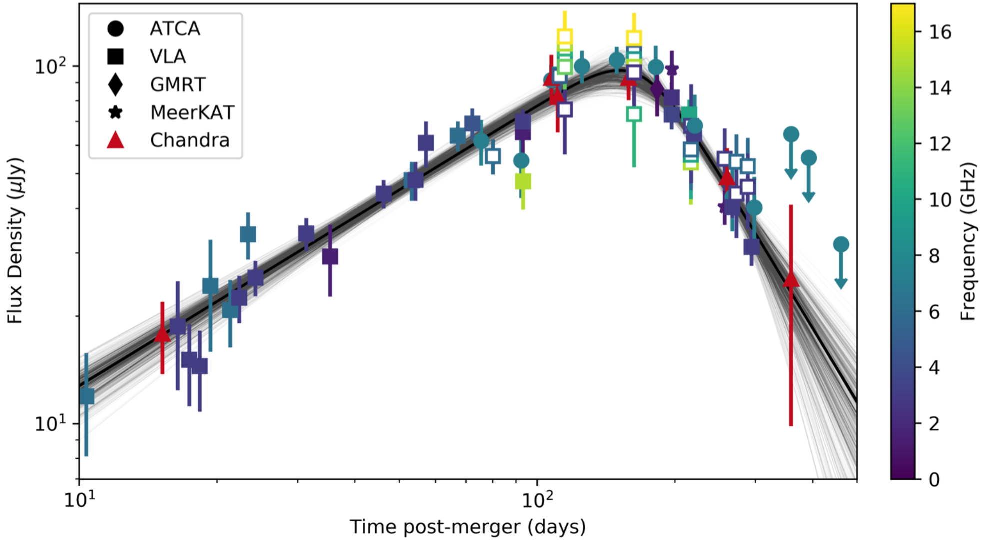
Image credit: David Kaplan

Ongoing radio monitoring of GW170817



Mooley et al. (2017), Nature, 554, 207

Peak at 167 days post-merger



Updated from Dobie et al. (2018), ApJL, 858, 15

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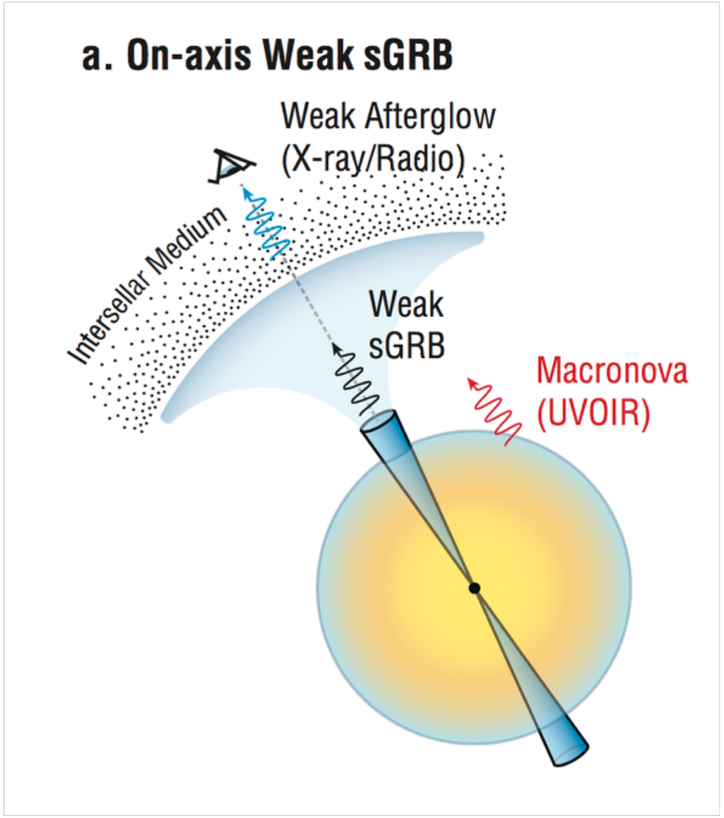
Ruled out: on-axis weak short gamma-ray burst



Kasliwal et al. (2017) Science, 358, 1559

- Classic sGRB is a jet in line-of-sight
- Narrow (<10 deg); ultra-relativistic
- Gamma-ray luminosity 4 orders of magnitude lower than typical sGRBs
- Weak sGRB needs low ejecta mass (< 3 x 10^{-6} Msun)
- Wider jet => even less material
- Contradicted by UVOIR (0.05 Msun), late X-ray, radio

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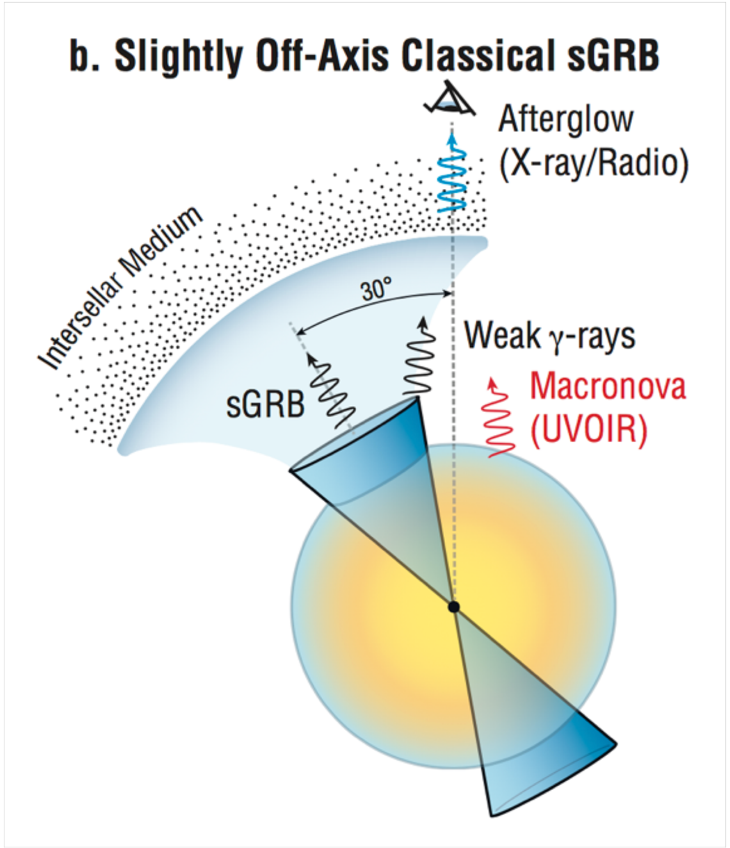
Ruled out: slightly off-axis classical short GRB



Kasliwal et al. (2017) Science, 358, 1559

- sGRB observed off-axis (~ 8 deg)
- Expect bright afterglow at all wavelengths when external shock decelerates
- Velocity $\Gamma \sim 10$ one day later.
- Radio and X-ray early non-detections constrain to low density ($<10^{-6}$ cm^{-3}).
- Hypothetical on-axis observer would see photons harder than observed so far

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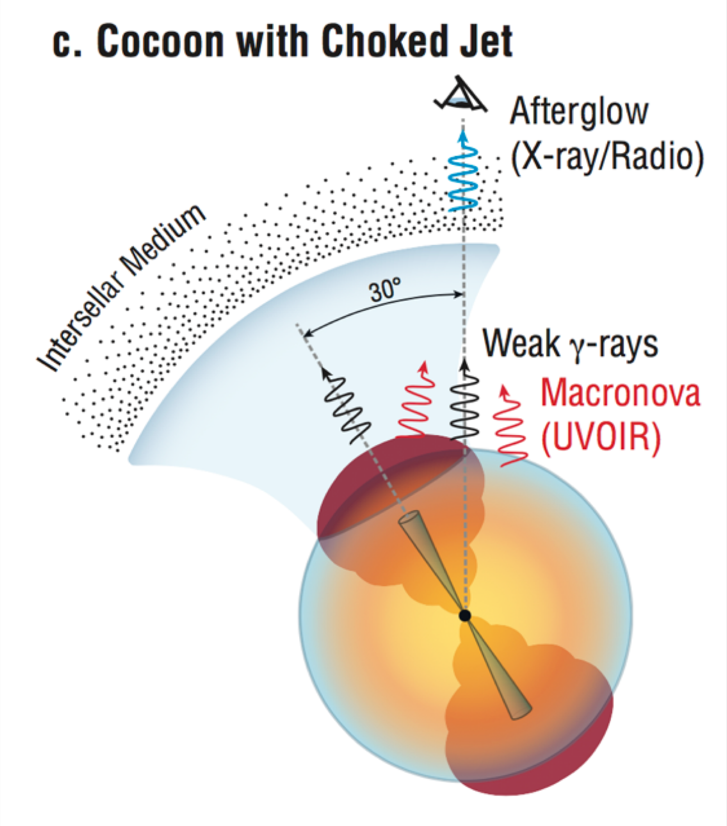
Possible: cocoon with choked jet

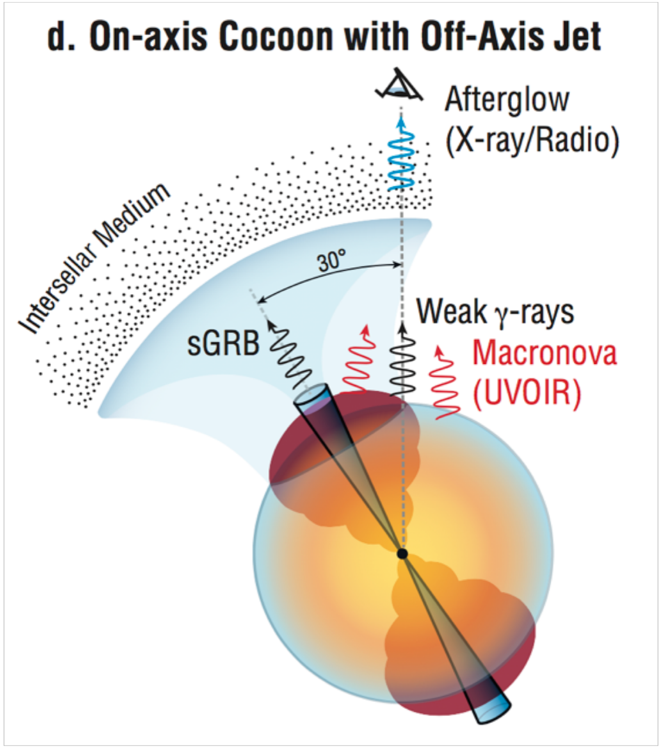


Kasliwal et al. (2017) Science, 358, 1559

- ~0.02 $M_{\odot}$ of ejecta into circumburst medium
- Velocities of ~0.2c
- Short delay (maybe collapse of hyper-massive neutron star into black hole)
- Ultra-relativistic jet launched
- Material enveloping jet forms pressurized cocoon

- **Scenario 1**: Wide-angle jet (≈30 deg) => jet is choked
- Radio emission from forward shock

Possible: on-axis cocoon with off-axis jet



- **Scenario 2**: Narrow-angle jet (≈10 deg) => jet escapes ejecta
- Radio emission from afterglow

How can we distinguish between these two scenarios?

Kasliwal et al. (2017) Science, 358, 1559

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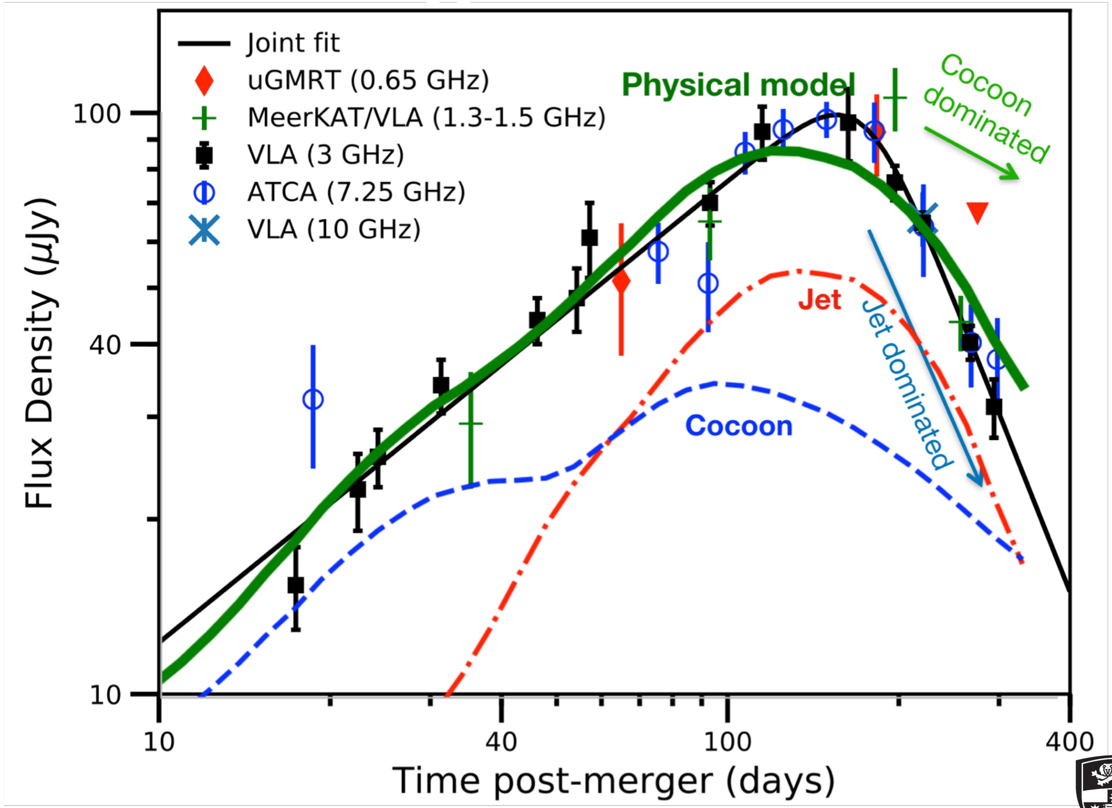
Late-time monitoring is key to physical modelling

Semi-analytic and numerical model fits give:

- Jet opening angle
- Density of ISM
- Isotopic-equiv. energy

More broad questions:

- What fraction of NS-NS mergers have relativistic jets?
- Relationship between mergers and sGRBs



Credit: David Kaplan, adapted from Mooley et al. (2018), ApJL, 868, 111

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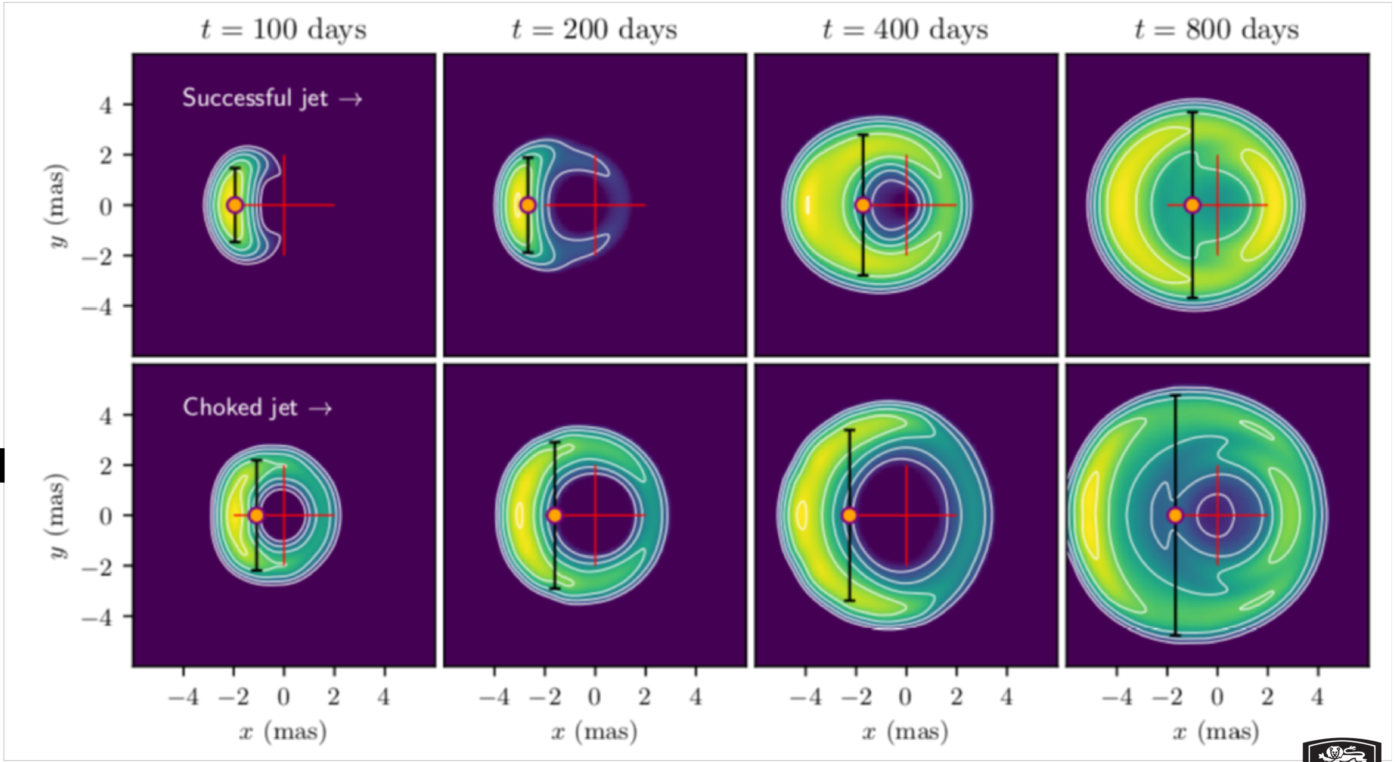
Can we break this degeneracy with VLBI?

Jet dominated

Proper motion but limited expansion

Cocoon dominated

Expansion but no proper motion



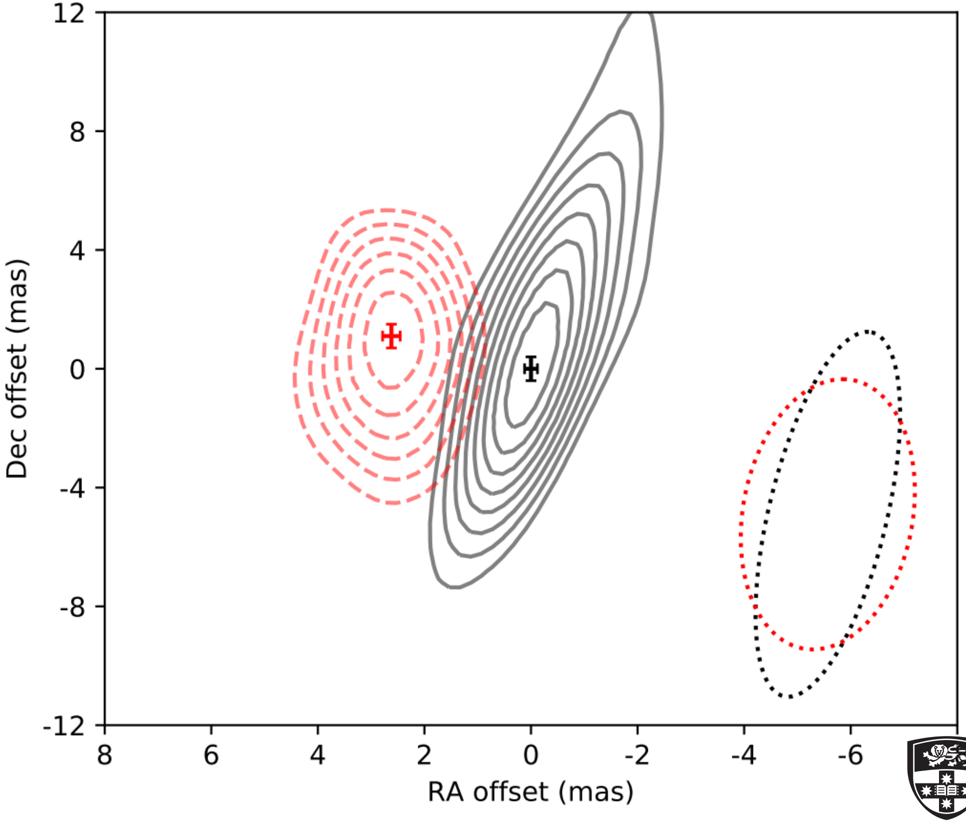
Zrake et al. ApJL, 865, L2 (2018)

VLBI direct imaging results

- 3-12σ contours of the radio counterpart to GW170817
- Black - 75 days post-merger
- Red - 230 days post-merger.
- Unresolved:

  <1 mas (0.2 pc) ⊥

  <10 mas (2pc) ∥
- Superluminal motion: ~4.1c
- Rules out isotropic ejecta: **emission likely jet-dominated**
- Viewing angle: ~20 deg



Mooley, Deller et al. (2018), Nature, 358, 1559

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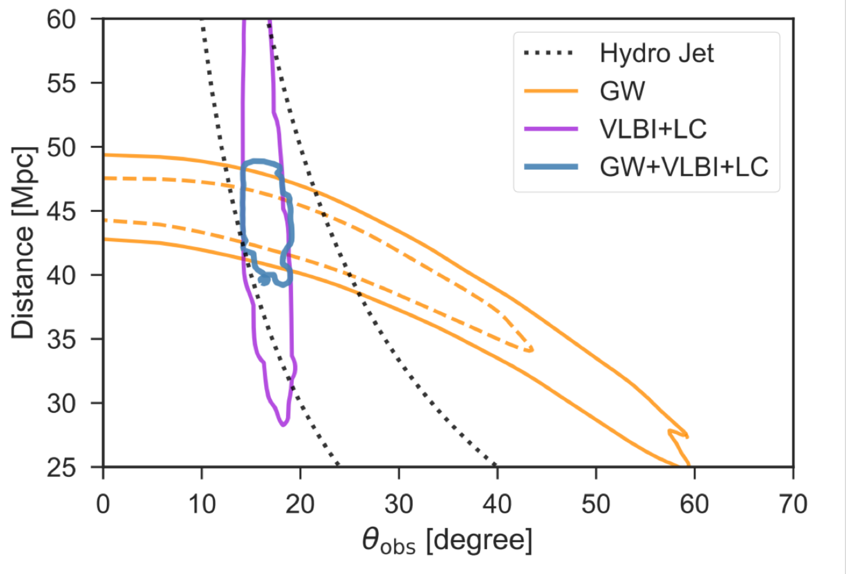
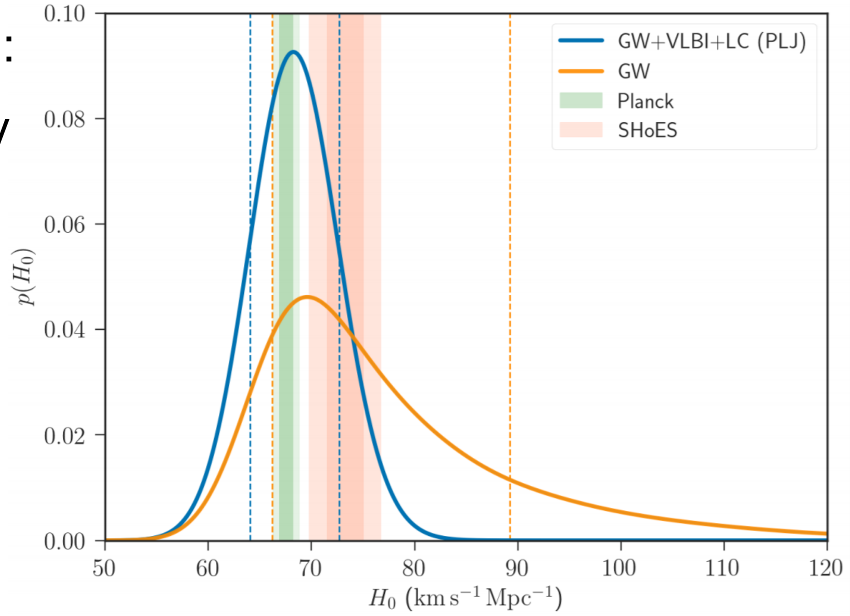
VLBI – independent estimate of Hubble Constant

Abbott et al. (2017): H_0 using **standard siren**:

- Compare distance from GW strain directly to redshift of host galaxy
- Uncertainty due to peculiar velocity and distance/inclination degeneracy

Hotokezaka et al. (2018), arXiv:1806.10596





Decrease uncertainty by factor of 2-3 by constraining inclination and distance with radio observations

More sources improves this further

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Plans for radio observations in LIGO O3

Team based at University of Sydney:
CIs: Tara Murphy, David Kaplan (UWM), Martin Bell (UTS),
Staff: Adam Stewart, Emil Lenc (CSIRO), Keith Bannister (CSIRO), *new postdoc*
Students: Dougal Dobie, Andrew Zic, Harry Qiu, Joshua Pritchard, *2 new PhD students*
Collabs: Adam Deller (OzGrav AI), Douglas Bock, Phil Edwards (OzGrav partners)

Members of the **NSF GROWTH collaboration** led by Caltech
"Global Relay of Observatories Watching Transients Happen"
PI: Mansi Kasliwal; thirteen US & international partners

Members of the **JAGWAR radio collaboration**
"Jansky VLA mapping of Gravitational Wave bursts as Afterglows in Radio"
Dale Frail, Kunal Mooley, Greg Hallinan, Kenta Hotokezaka, …

We lead the **VAST collaboration** on ASKAP
"ASKAP survey for Variables and Slow Transients"

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Plans for radio observations in LIGO O3

1) Australia Telescope Compact Array (ATCA) observing program

- 750 hours allocated over 5 semesters
- **Strategy 1:** galaxy targeting using CLU (Cook et al. 2017)
- **Strategy 2:** targeting candidate counterparts detected in other bands
- **Strategy 3:** long term monitoring of counterparts

2) Australian Square Kilometre Array Pathfinder (ASKAP) observing program

- 100 hours – pilot survey for radio transients
- 100 hours – GW time for follow-up when localization is poor **(TBC)**

3) Murchison Widefield Array (MWA) observing program

- Automatic triggering with latency 10s to ~1 minute
- May also search for long time scale afterglow – weak at low freq.

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1. Source localization

First LIGO events localized to 520 – 1600 deg^2
First LIGO/Virgo event localized to 60 deg^2
GW170817 localized to 28 deg^2

ASKAP field of view is 30 deg^2

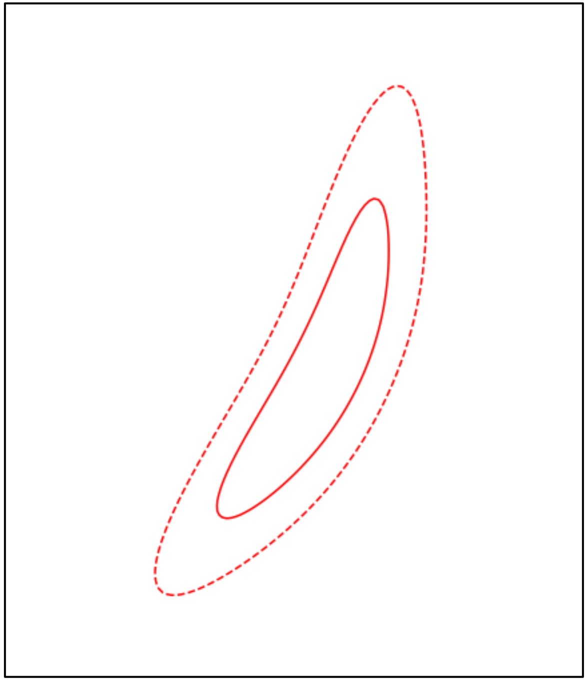
Median for O3 is expected to be 150 deg^2

ASKAP will be ideal when:

- There is no identified EM counterpart;
- GW localization is poor;
- Source is in Southern sky (<$+30^o$ Dec);

Investigating optimal tiling strategies for ASKAP

Animation of shifted ranked tiling algorithm



Dobie et al. (2019), PASA, (*submitted*)

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2. Radio monitoring of NS-NS and NS-BH mergers

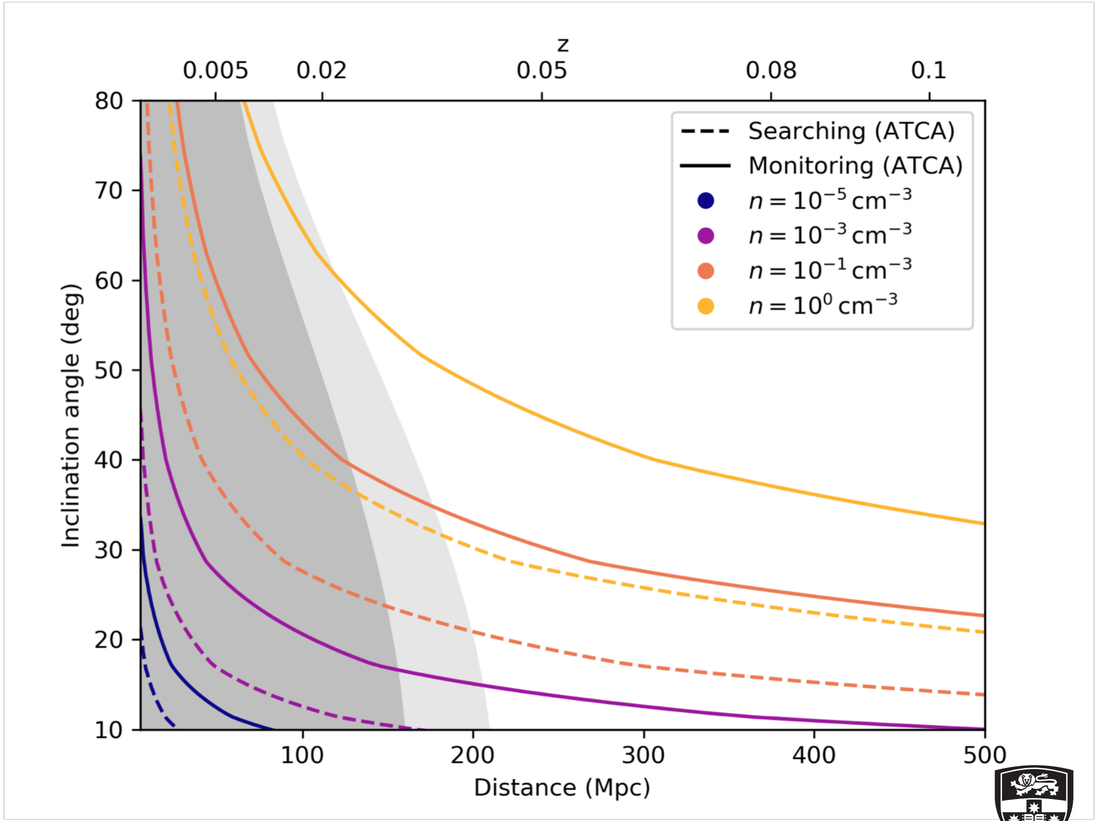
Sensitive observations with narrow field-of-view telescopes (VLA, ATCA)

ATCA: 750 hours over 2 years

Detectability depends on:

- inclination angle
- distance to host
- density interstellar medium

NS-NS: maybe ~1 per month
NS-BH: maybe ~2-3 over O3



Dobie et al. (2019), *in prep*

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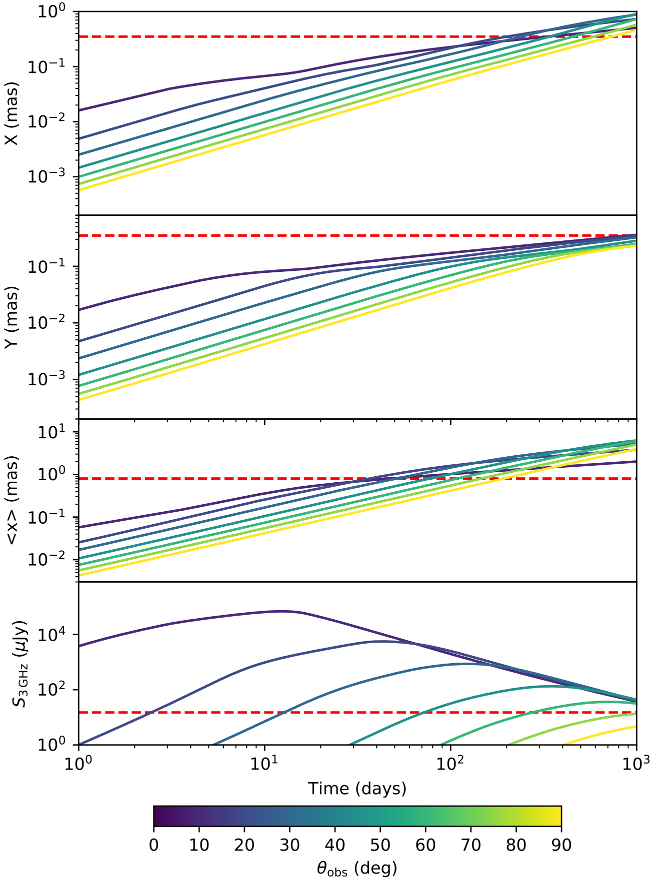
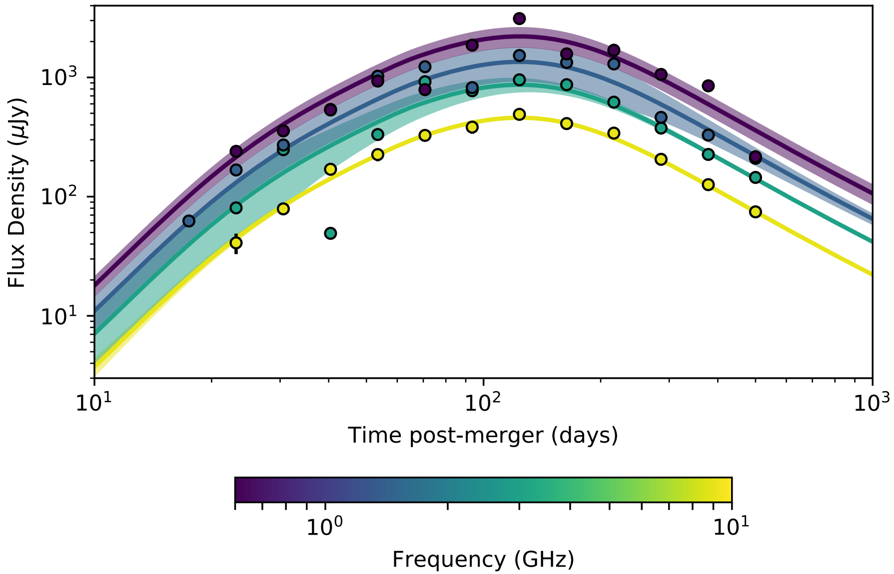
3. VLBI – expansion and superluminal motion



Aim to detect expansion and superluminal motion through:

a) VLBI observations
b) Interstellar scintillation



Dobie, Kaplan, Hotokezaka et al. (2019), *in prep*

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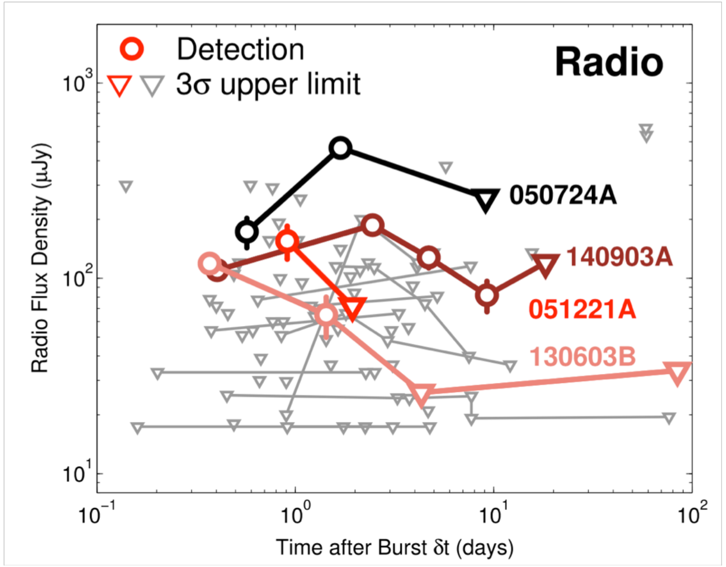
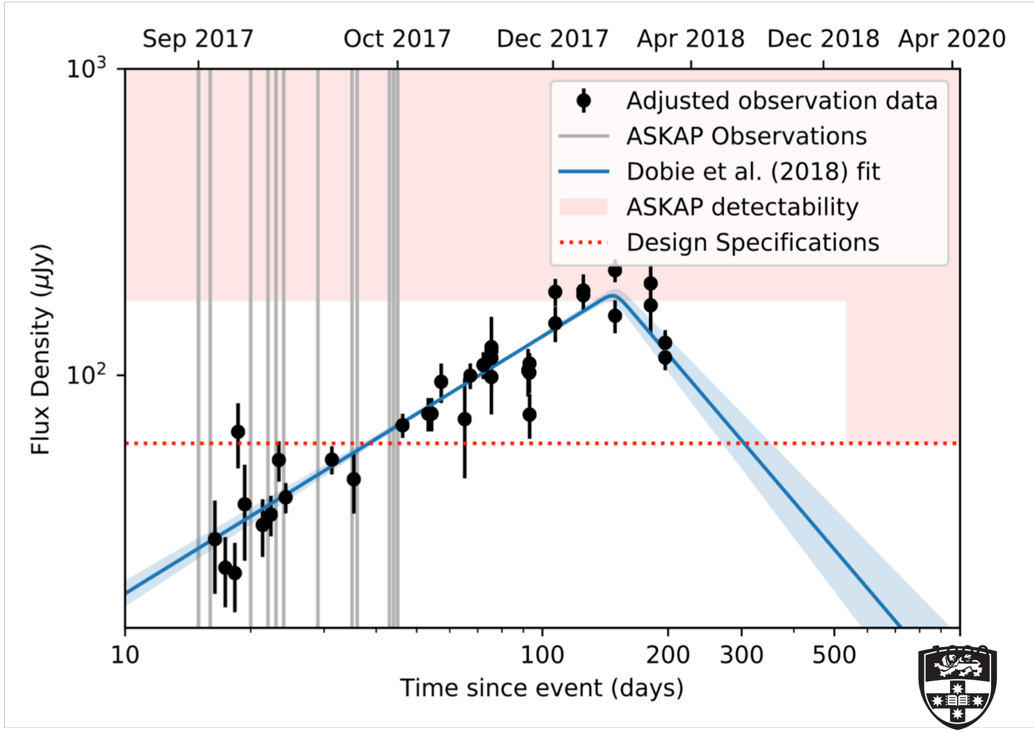
4. Unbiased surveys for orphan afterglows

Example 100 hour ASKAP pilot survey for GRB/GW orphan afterglows:

- 4 epochs (months apart)
- 5 min observations
- 5 sigma rms = 1.4 mJy
- area = 8390 square degrees



Fong et al. (2015), ApJ, 815, 201



Dobie et al. (2019), PASA, (*submitted*)

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Radio follow-up in OzGrav

Radio observations will allow us to:

- Measure physical properties of the explosion (energy, mass/velocity);
- Investigate the nature of the circum-merger medium;
- Determine what fraction of NS-NS mergers produce short GRBs;
- Find neutron star mergers (SGRB orphan afterglows) with no GW trigger
- Search for counterparts if localization is poor;

Also:

- Can observe day and night (and in poor weather)
- Low false positive rate (low sky density of radio transients)
- Australian facilities add to time and frequency coverage
- Australian facilities allow us to cover the Southern sky

We're looking forward to working with OzGrav in O3 and beyond ☺