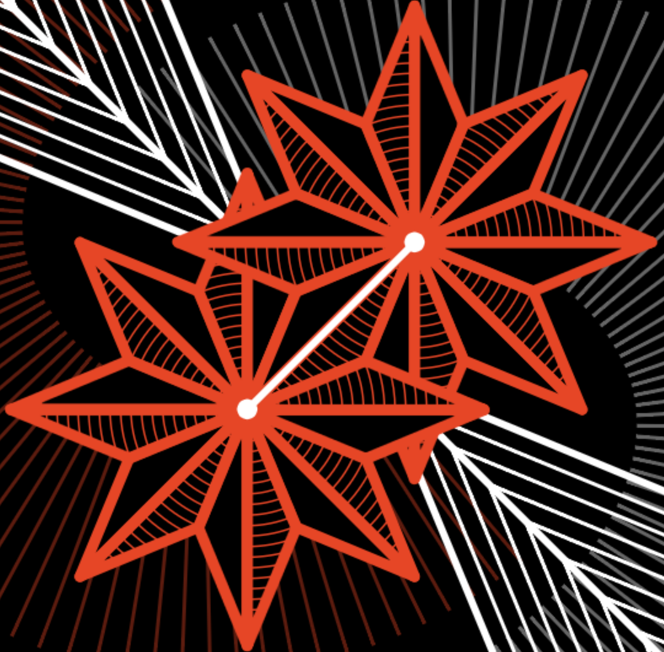
Electromagnetic follow-up of gravitational wave events



Credit: Science

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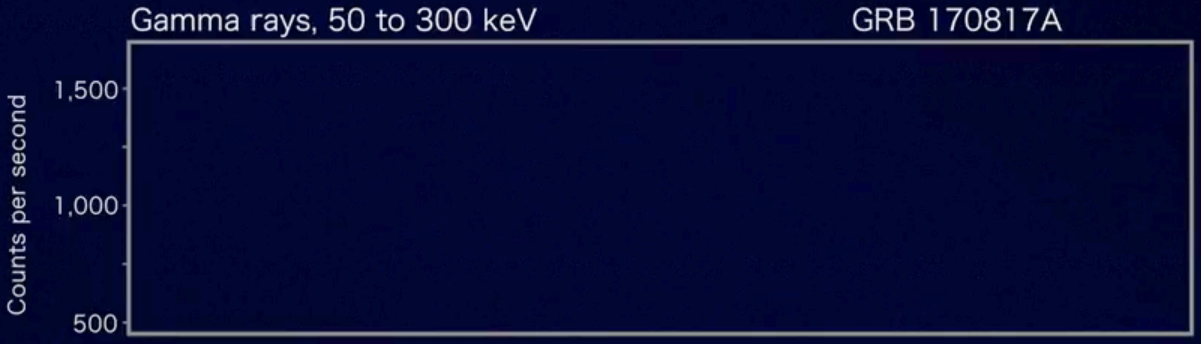
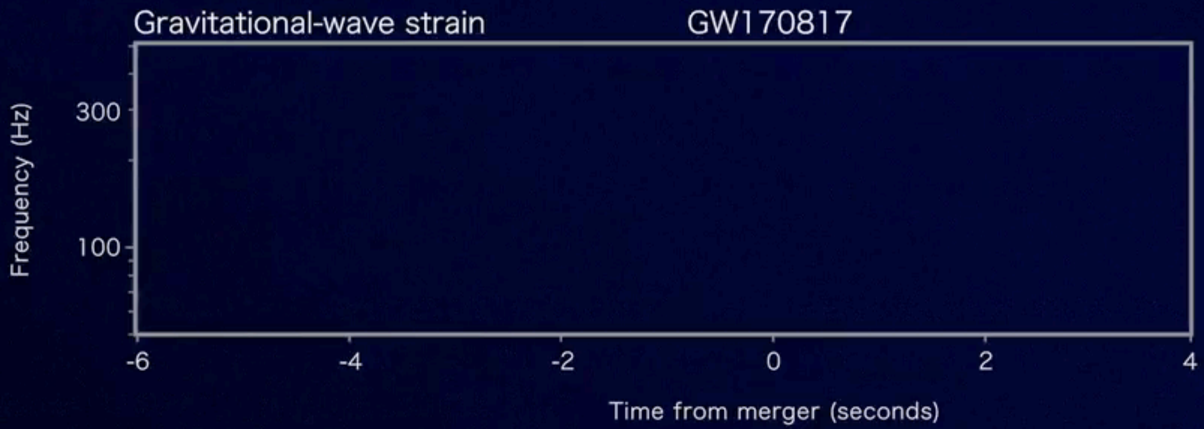
Prof. Tara Murphy
ARC Future Fellow

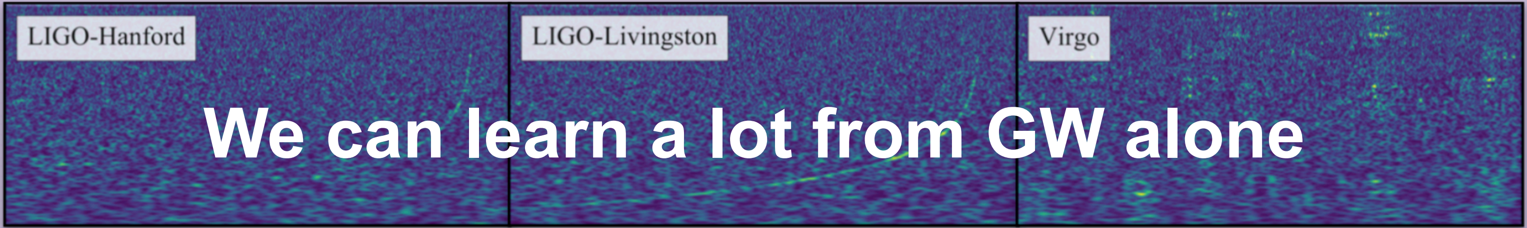
August 17th, 2017: The "chirp" of a new era

Fermi



LIGO





We can learn a lot from GW alone

observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_{\odot}$
primary NS mass	1.36 to 2.26 $M_{\odot}$
secondary NS mass	0.86 to 1.36 $M_{\odot}$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_{\odot}c^2$
radius of a 1.4 $M_{\odot}$ NS	likely $\lesssim$ 14 km

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22’53"
sky location	in Hydra constellation

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Why is electromagnetic follow-up important?

1. EM follow-up allows localization of merger events

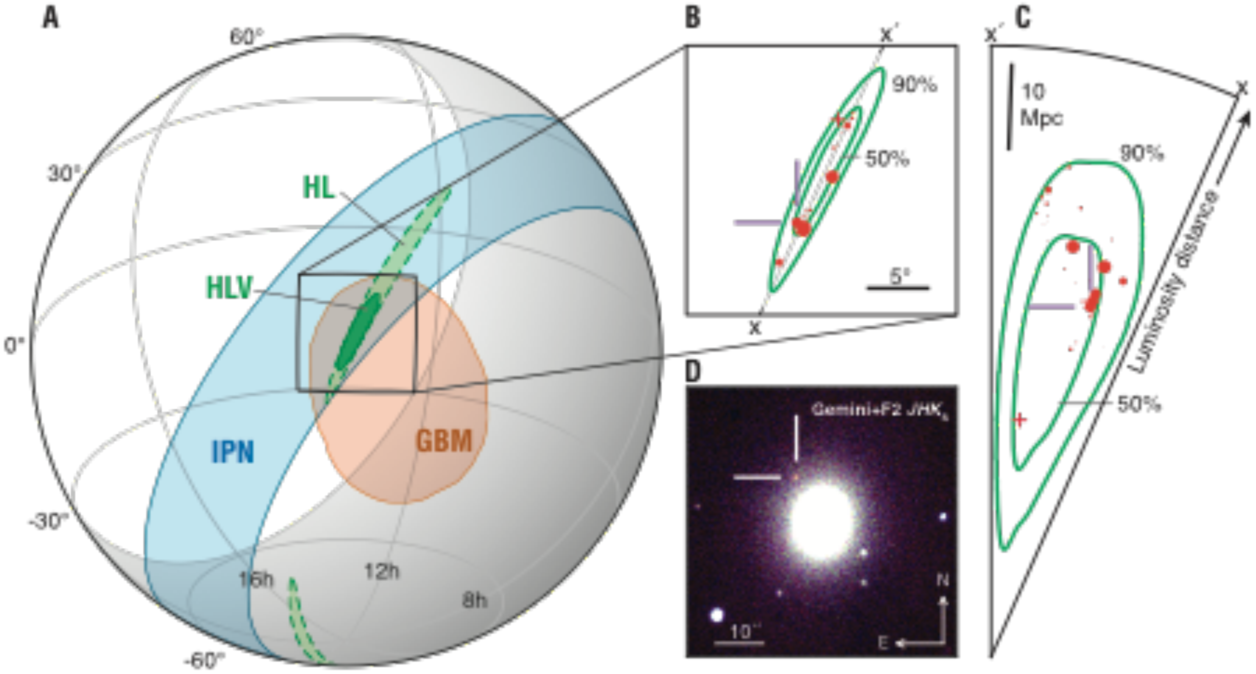
For GW170817:

~31 square degrees
(finally 28 sq. deg.)

Distance: 40 ± 8 Mpc

49 candidate galaxies in localisation volume

Census of the Local Universe: cataloguing and prioritizing galaxies for follow-up



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

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2. EM and GW allow tests of fundamental physics

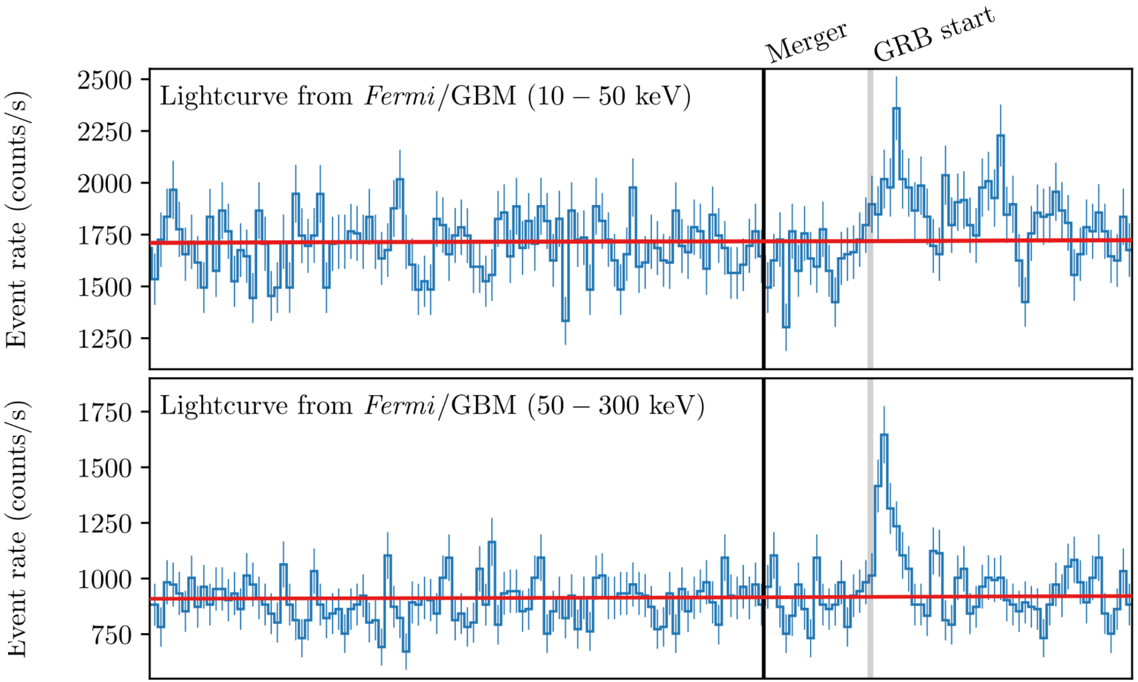
Delay of 1.74 seconds between GW and EM

Assume they are emitted at the same time → upper limit

Constraint on fractional speed difference of GW and EM of

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}.$$

Dispersion delay due to IGM is several orders of mag. less



Abbott. et al. (2017), ApJL, 848, L13

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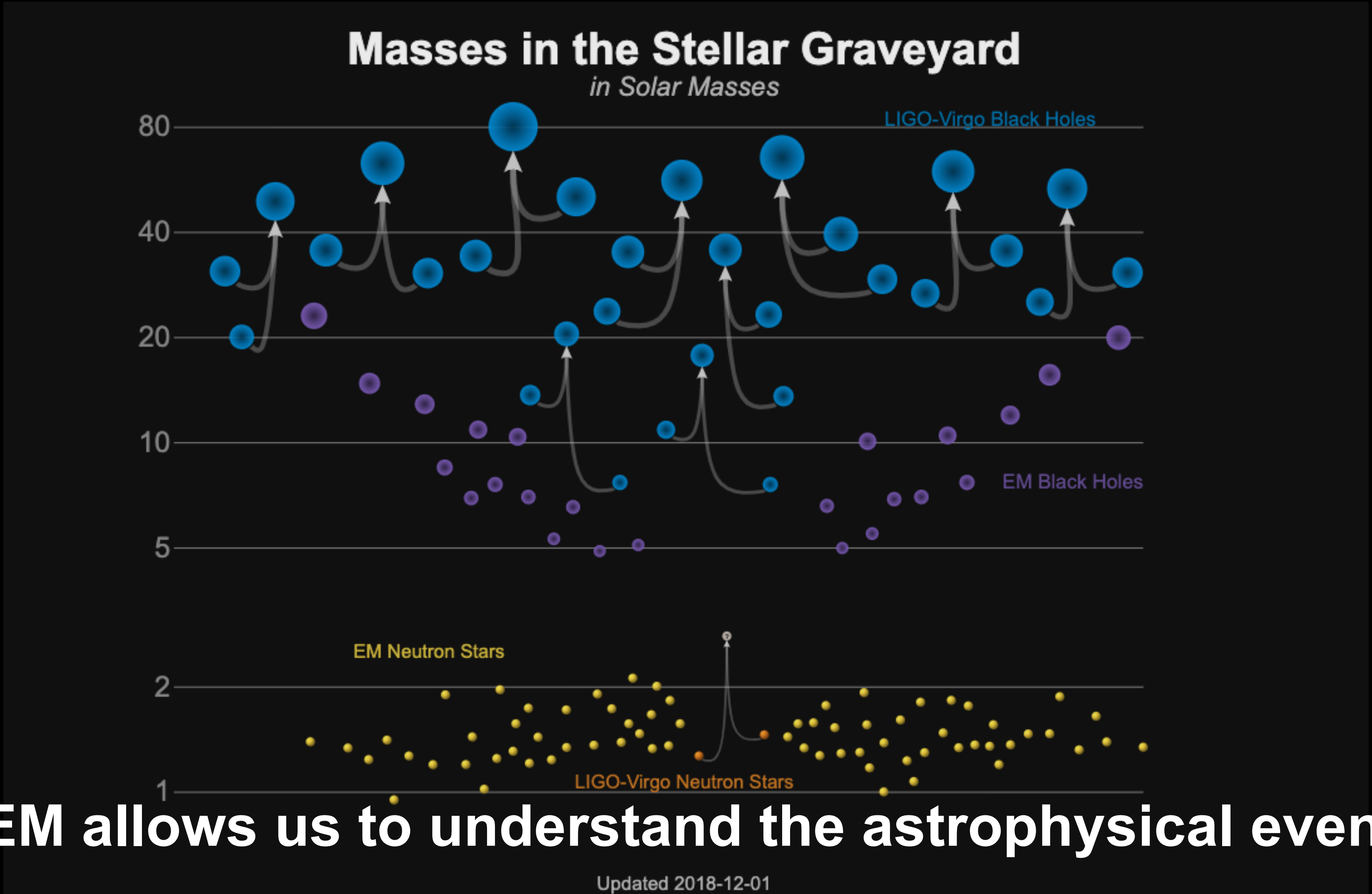


Credit: LIGO-Virgo | Frank Elavsky | Northwestern

3. EM allows us to understand the astrophysical events

GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

Distance
130 million light years

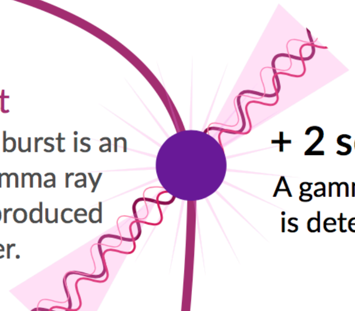
Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.



+ 2 seconds
A gamma ray burst is detected.

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GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of most of the heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

kilonova

Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

radio remnant

As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

+10 hours 52 minutes

A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

+11 hours 36 minutes

Infrared emission observed.

+15 hours

Bright ultraviolet emission detected.

+9 days

X-ray emission detected.

+16 days

Radio emission detected.

What do we learn from gamma-ray emission?

August 5th 1963: Partial Nuclear Test Ban Treaty signed

Prohibits all above-ground test detonations of nuclear weapons

"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION

NEW YORK, TUESDAY, AUGUST 6, 1963. TEN CENTS

BUILDING TRADES ACCUSED OF SNUB BY RACIAL GROUPS

Construction Men Absent From Parley Held by City Human Rights Unit

WIRTZ INVITATION CITED

But Integration Aides See 'Arrogance' and Call for Intensified Picketing

TEST BAN TREATY SIGNED IN MOSCOW; LEADERS REJOICE

Khrushchev and Ministers Join Glittering Reception After Solemn Ceremony

WARM SPIRIT PREVAILS

Thant and 70 U.S., Russian and British Officials Attend — 'First Step' Is Theme

House Group Limits Rise In Tax on Oil-Gas Industry

VILLAGERS CLASH ON COFFEEHOUSES

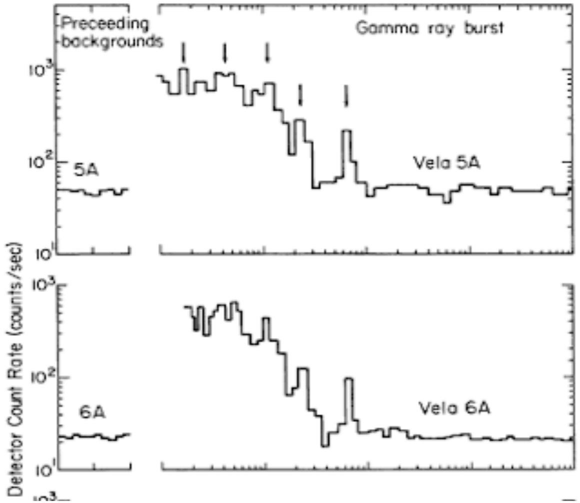
Honky-Tonk Atmosphere Is Charged — Owners Cite Entertainment Value

Landing in Haiti Reported; Exiles Claim Three Towns

BONN WILL DEFER ADHERING TO PACT

Decision Follows Meeting of McNamara and Adenauer at Chancellor's Request

JOINT RAIL TALKS RESUMING TODAY

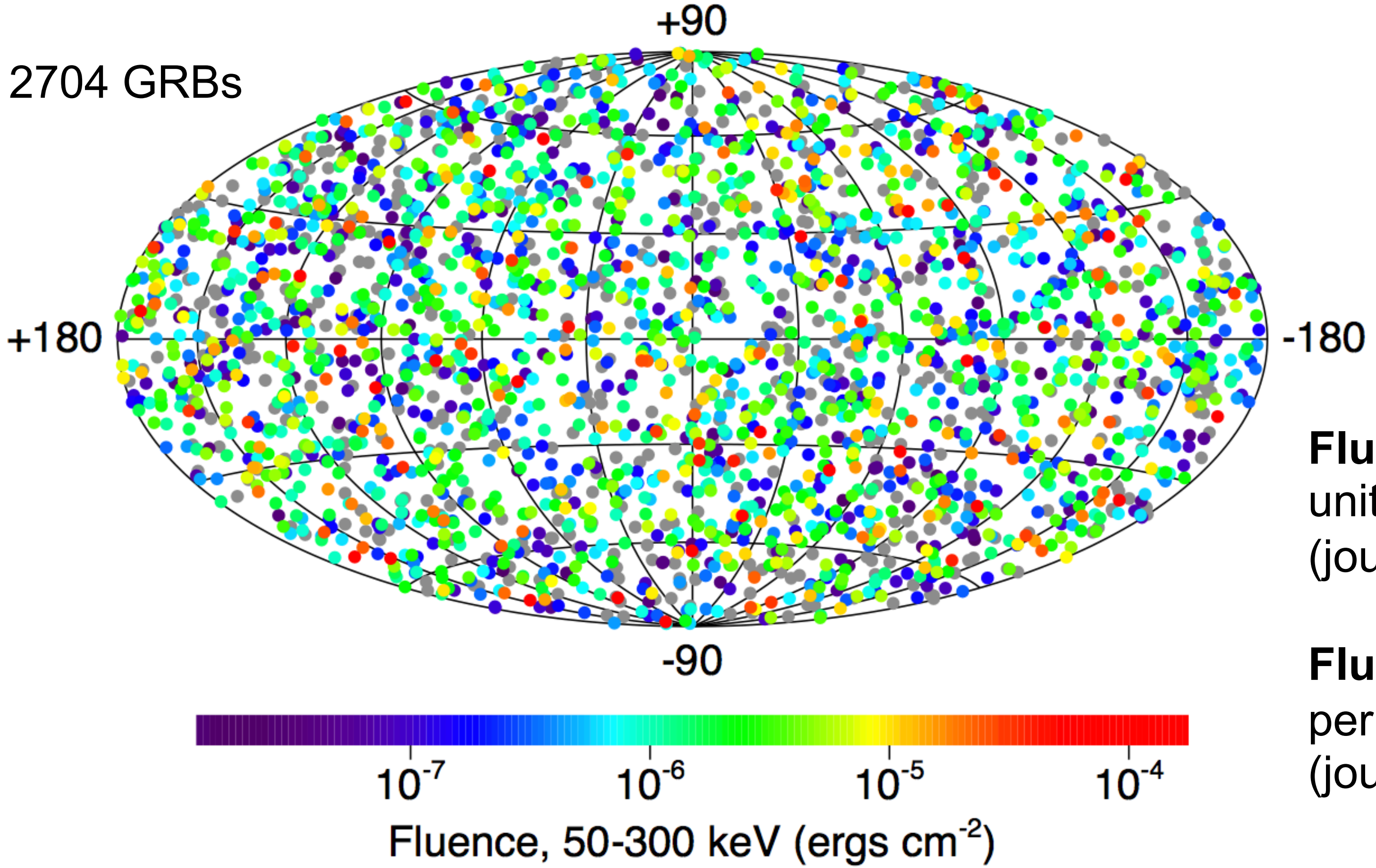


Vela was designed to detect X-rays, gamma-rays and neutrons produced in nuclear explosions.

Gamma-rays were important in case X-rays were shielded.

BATSE showed that GRBs are isotropically distributed

2704 GRBs



Flux = energy per unit area per time (joules/m^2/s)

Fluence = energy per unit area (joules/m^2)

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What causes gamma-ray emission?

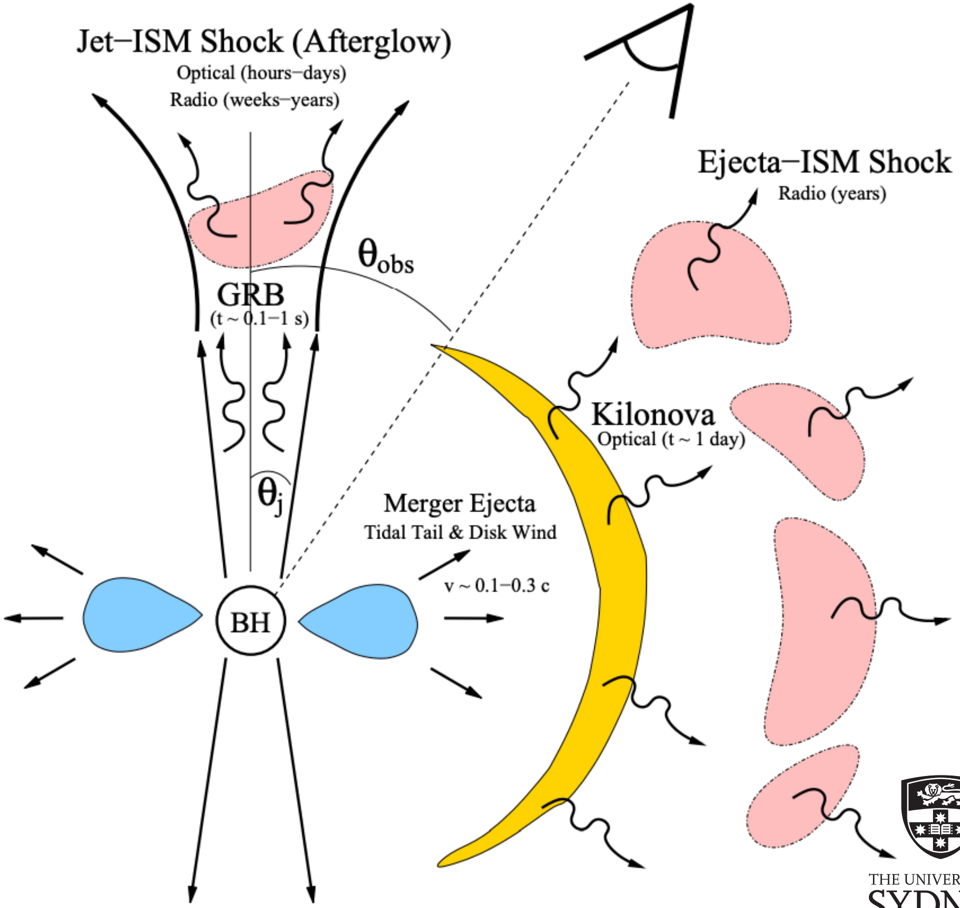
The most electromagnetically luminous objects in the Universe

Typical energy release of 10^{44} J

Ultrarelativistic energy flow converted to radiation.

Relativistic beaming means γ-ray emission restricted to $\theta obs \leq \theta j$

Relativistic beaming solves the *compactness problem*



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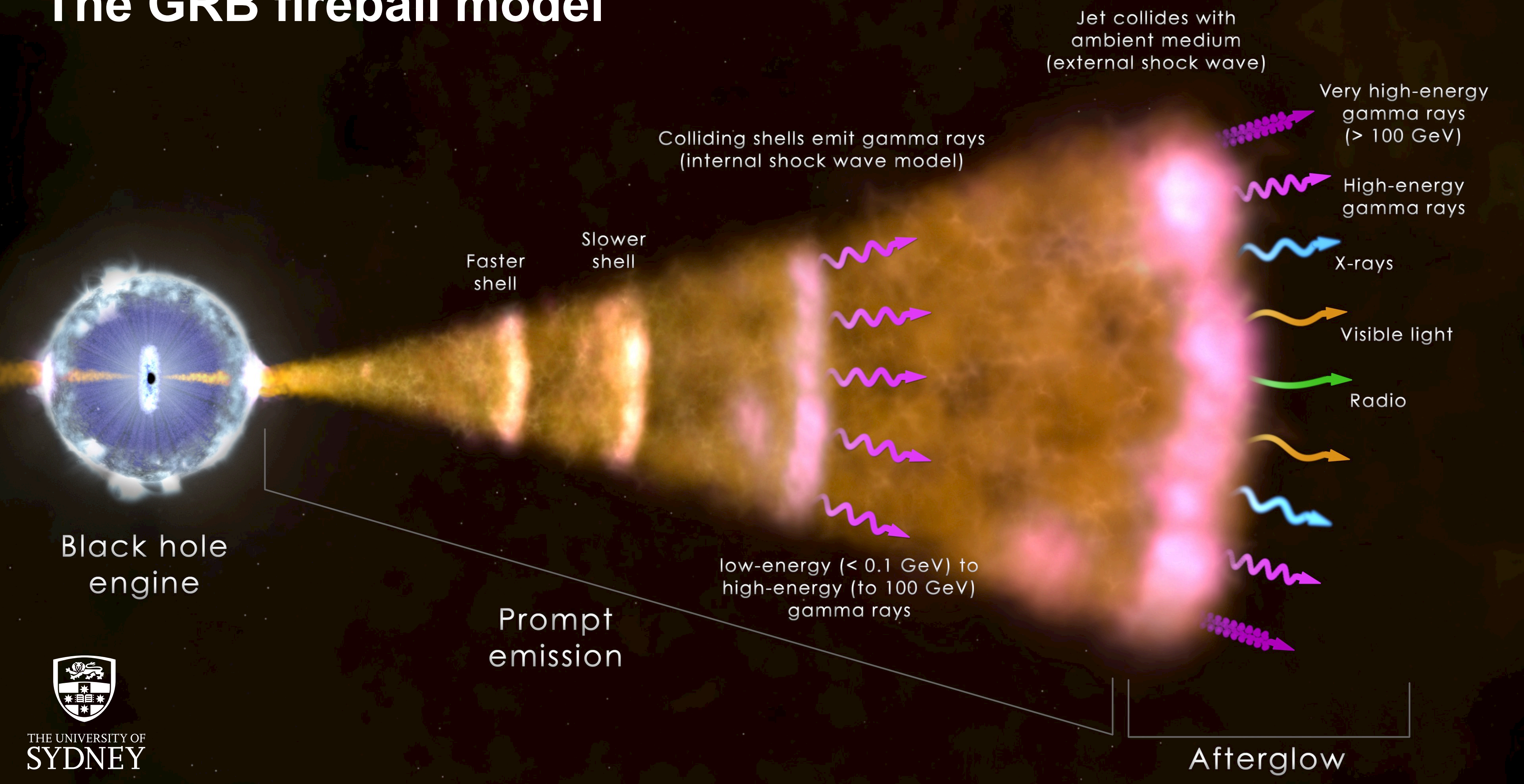
The GRB fireball model



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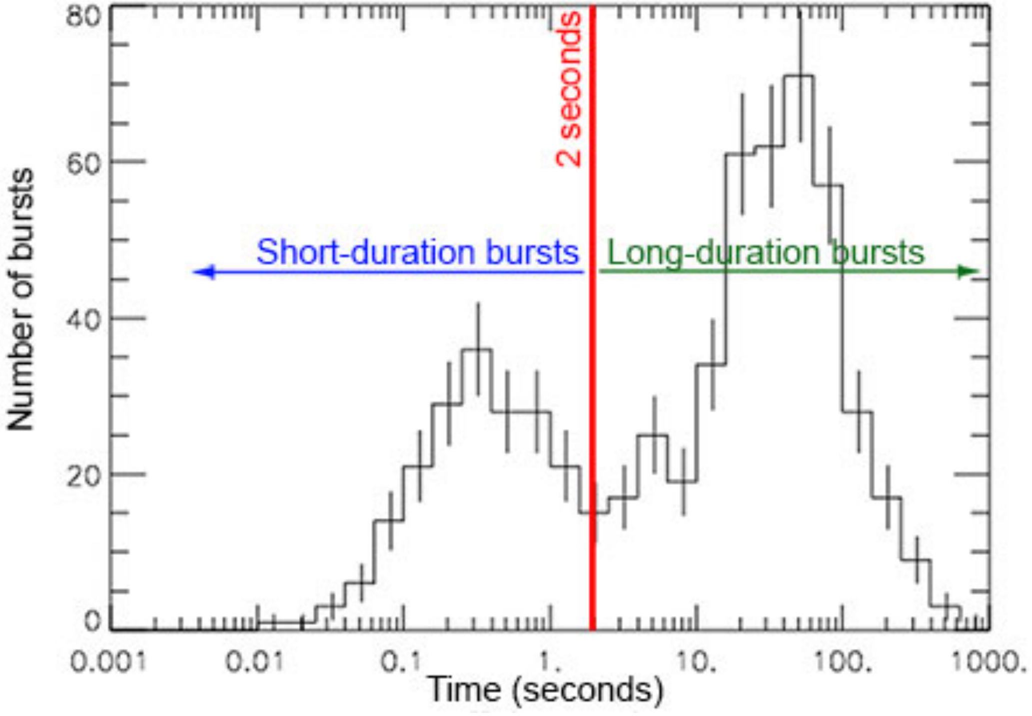
The mystery of short gamma-ray bursts

Long GRBs:
Duration: seconds – minutes
Overall tend to be brighter
Less energetic gamma-rays

→ Core collapse of massive stars

Short GRBs:
Duration: millisec – seconds
Overall tend to be dimmer
More energetic gamma-rays

→ Double neutron star merger ??



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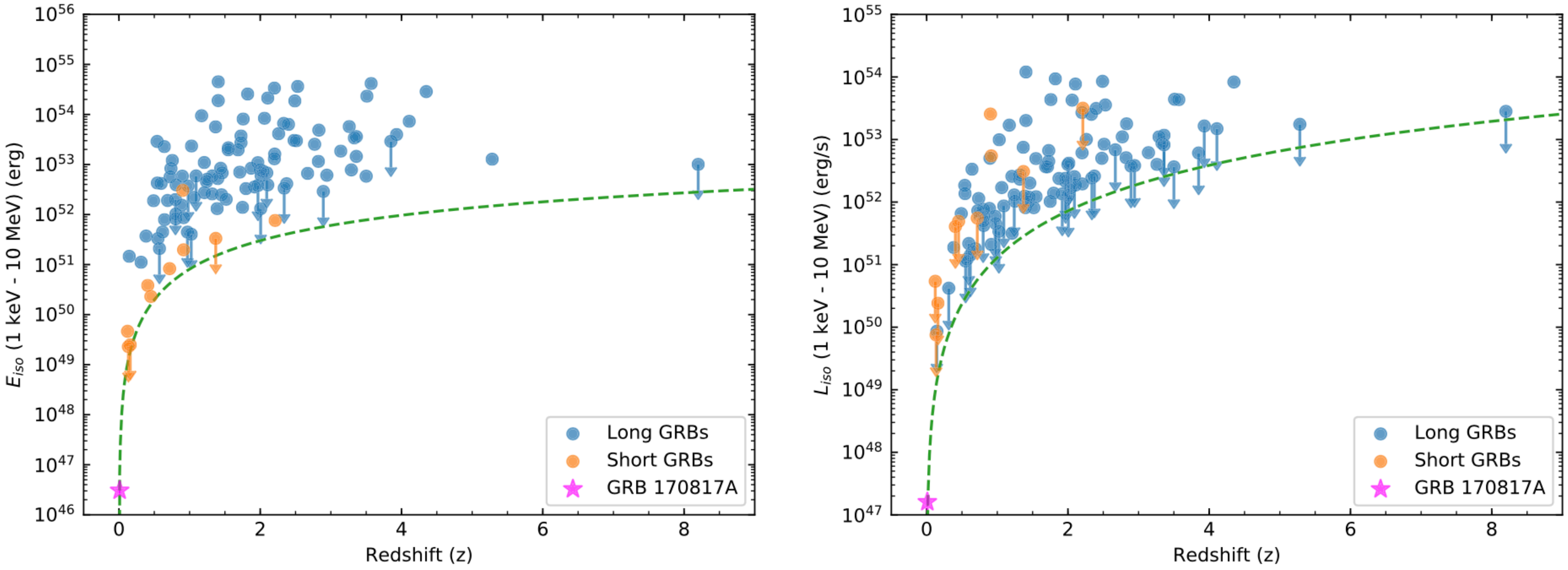
Neutron star mergers are progenitors of short GRBs



But… GW170817 is 4 orders of magnitude weaker than typical GRB

Abbott. et al. (2017), ApJL, 848, L13

What do we learn from optical emission?

Optical detection of GW170817 in NGC 4993

Merger = 2.1 kpc from centre

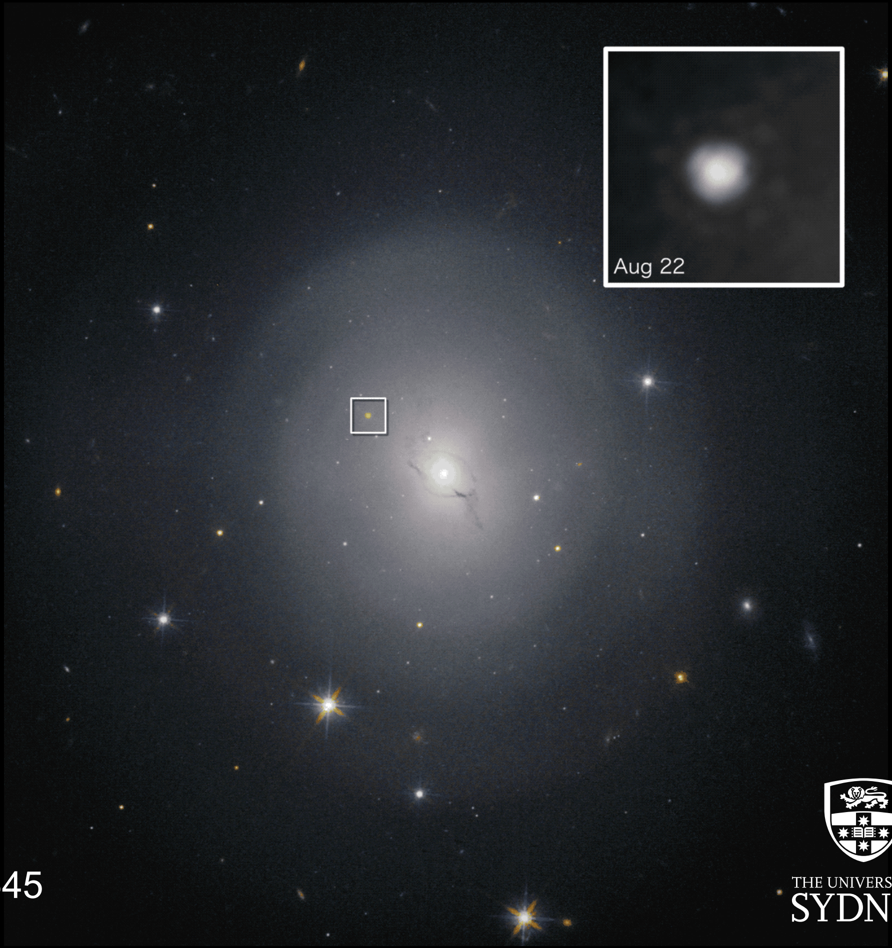
S0 galaxy; z = 0.009783 (~40 Mpc)

Old population, no globular cluster

Mean stellar age > 3 Gyr

<1% of light from stars <500 Myr

Dust lanes → past merging activity



Im et al. (2017) ApJL; Sadler et al. (2017), GCN #21645

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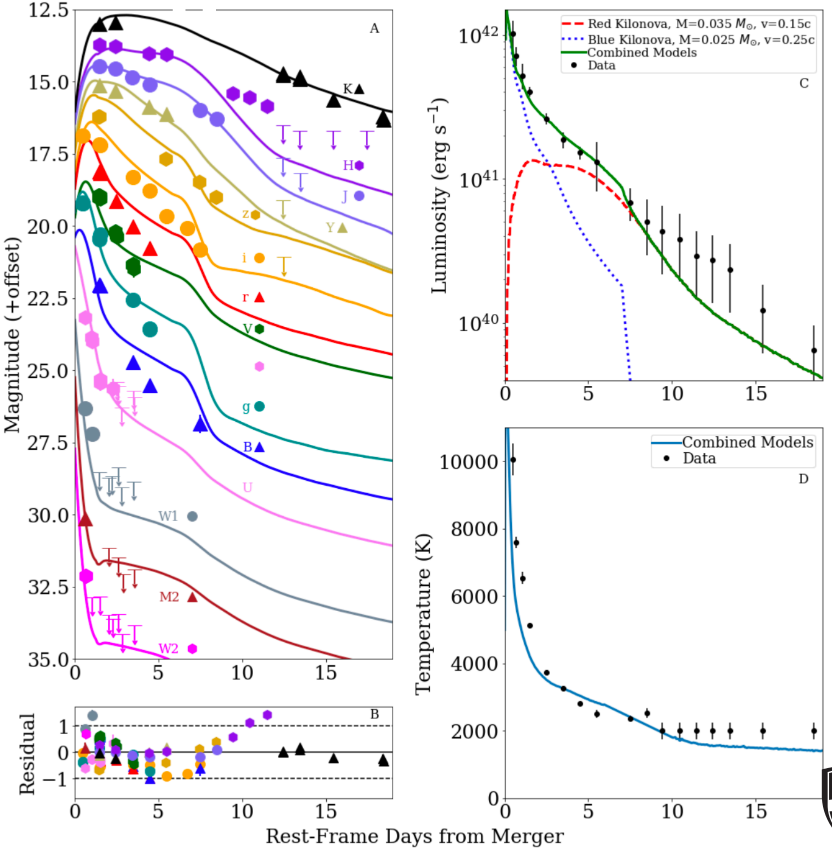
What causes UV / optical / IR emission?

A small amount of mass (10^{-4} – 10^{-2} solar masses) ejected from the explosion

Radioactive decay of unstable r-process nuclei produced in the ejecta material

Heats up ejecta which produces UV, optical and IR light

→ Observational result is ”kilonova”



Credit: Kilpatrick et al. (2017)

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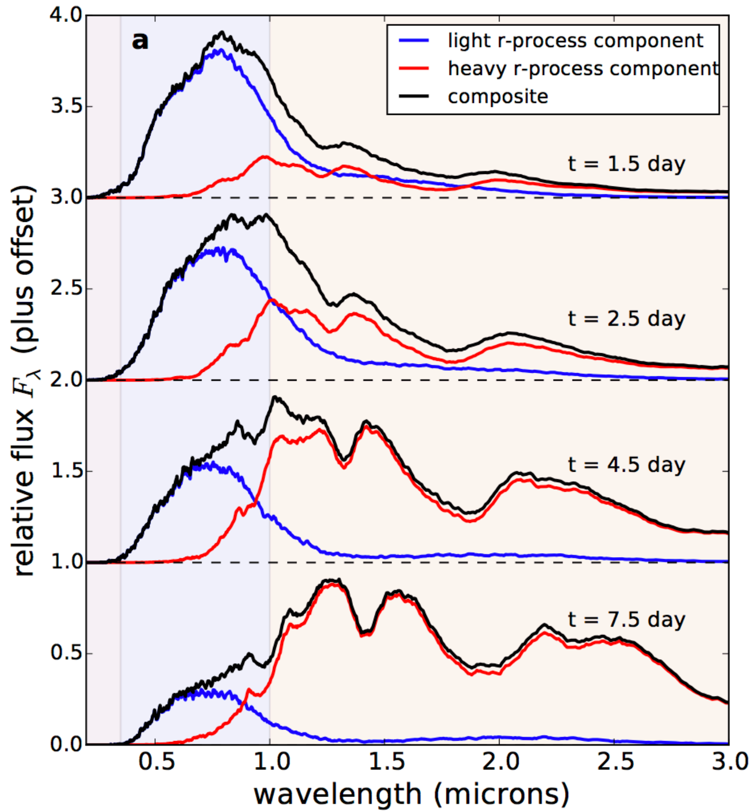
UVOIR: Direct evidence of heavy element production



Kasen et al. (2017), Nature, 551, 80

Moderate $0.6 \leq \eta \leq 0.75$ → light r-process elements ($28 \leq Z \leq 58$)

Produces optical light; fades in days

Ejecta $\approx 0.04\ M_\odot$

Neutron-rich $\eta \geq 0.75$ → heaviest r-process elements ($58 \leq Z \leq 90$)

Produces infrared; fades in weeks

Ejecta $\approx 0.025\ M_\odot$

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What do we learn from radio emission?

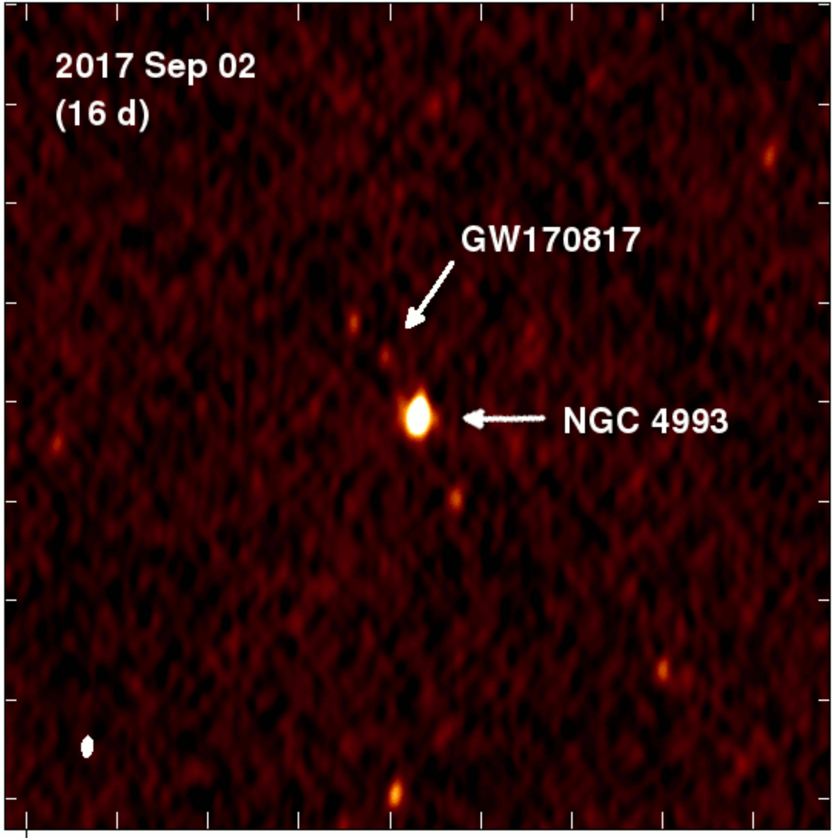
Radio follow-up of GW170817 – first detection

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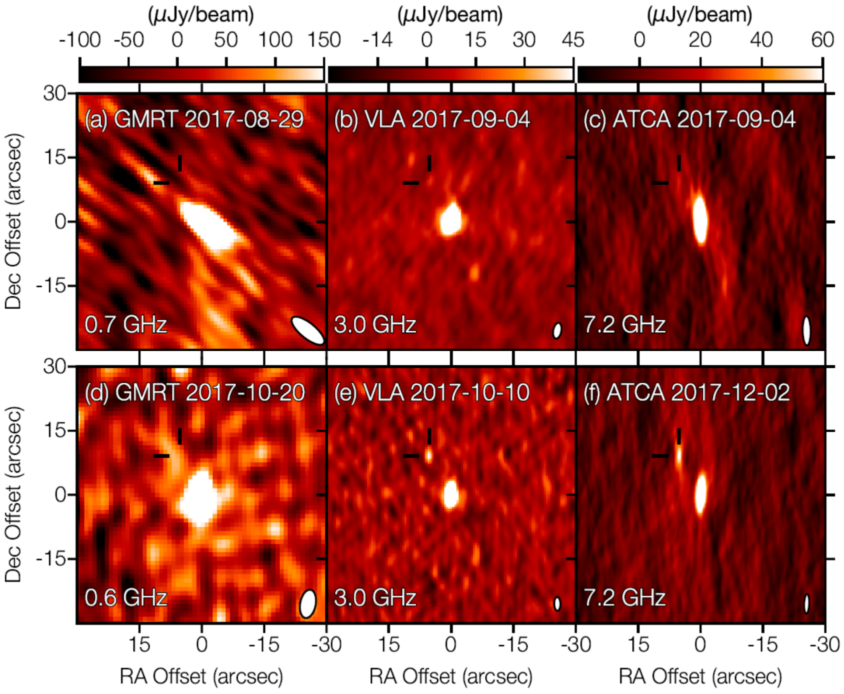
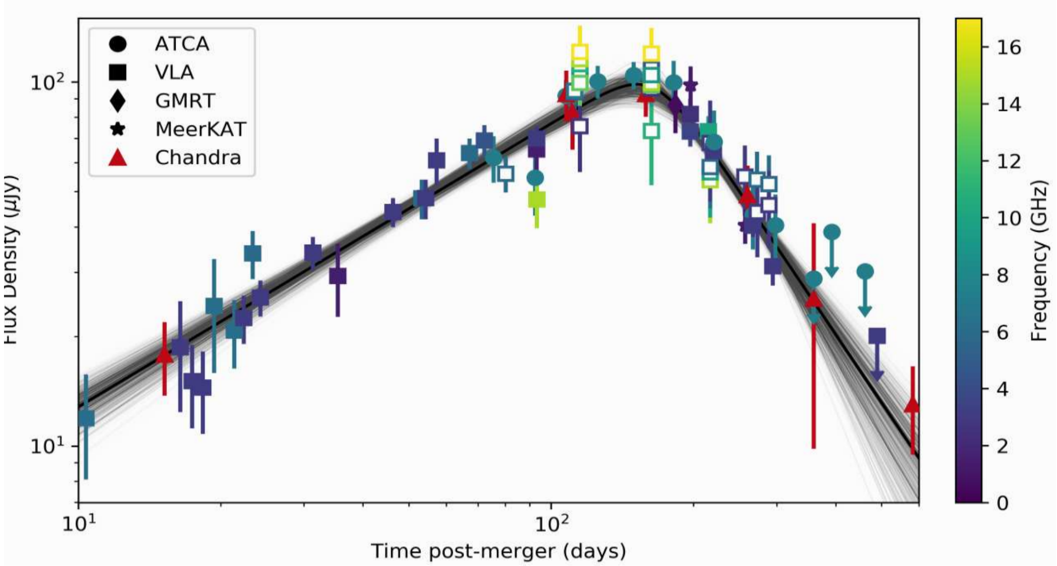
Hallinan et al. (2017), Science, 358, 1579

Image credit: David Kaplan

Ongoing radio monitoring of GW170817



Peak at 167 days post-merger



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

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

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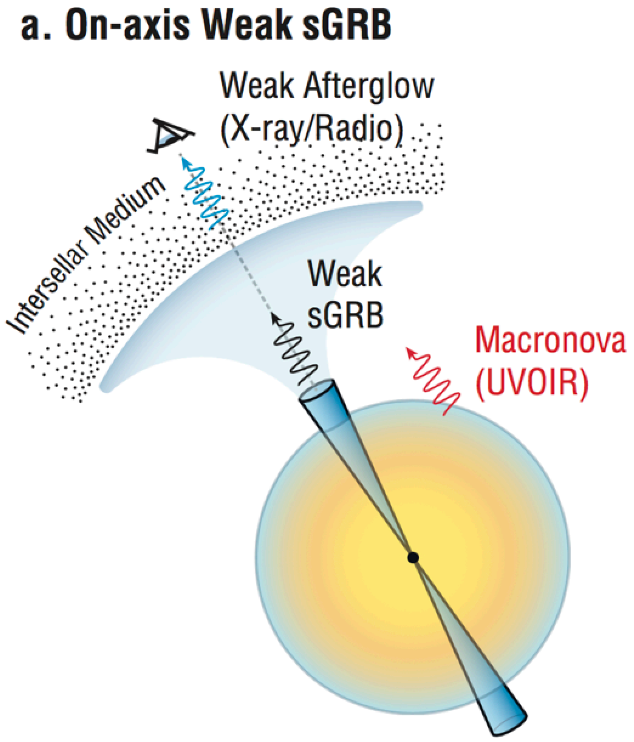
Ruled out: on-axis weak short gamma-ray burst



- 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

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

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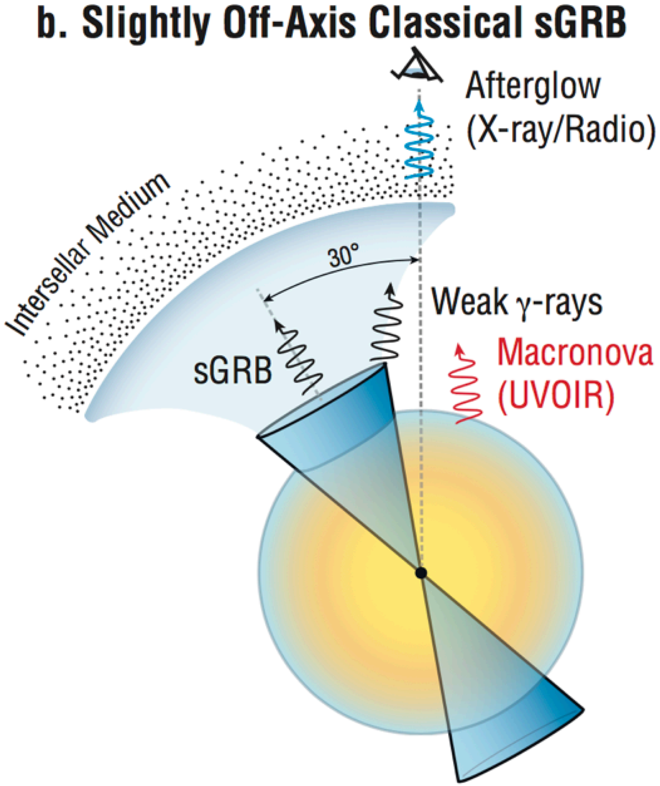
Ruled out: slightly off-axis classical short GRB



- 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 at higher energies than observed so far

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

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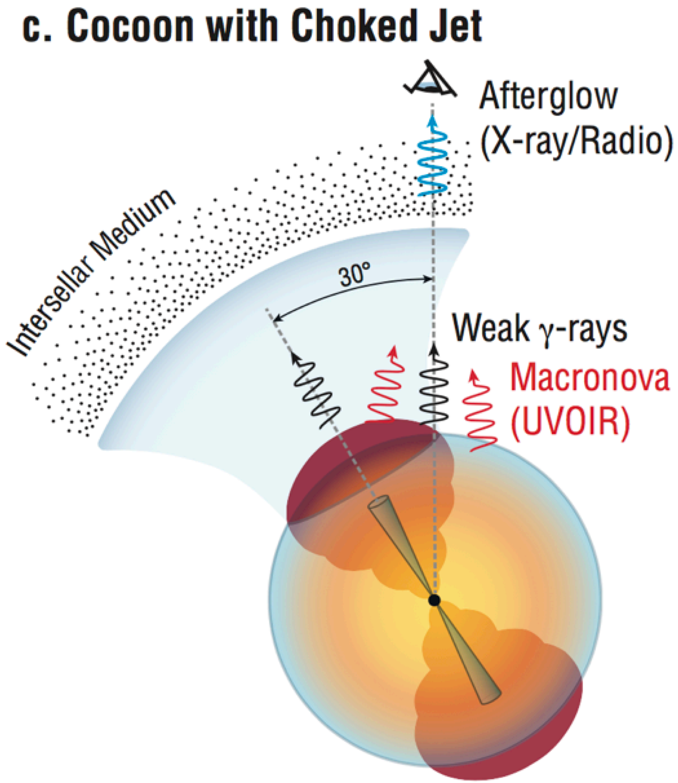
Possible: cocoon with choked jet



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

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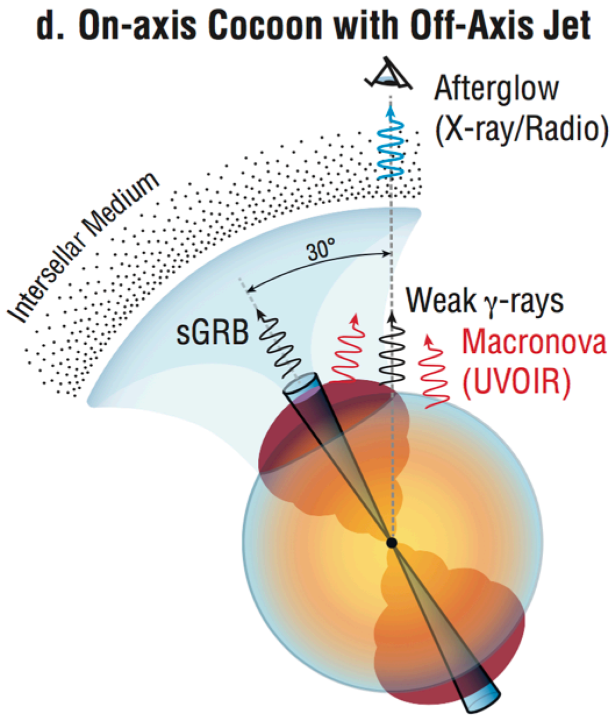
Possible: on-axis cocoon with off-axis jet



- **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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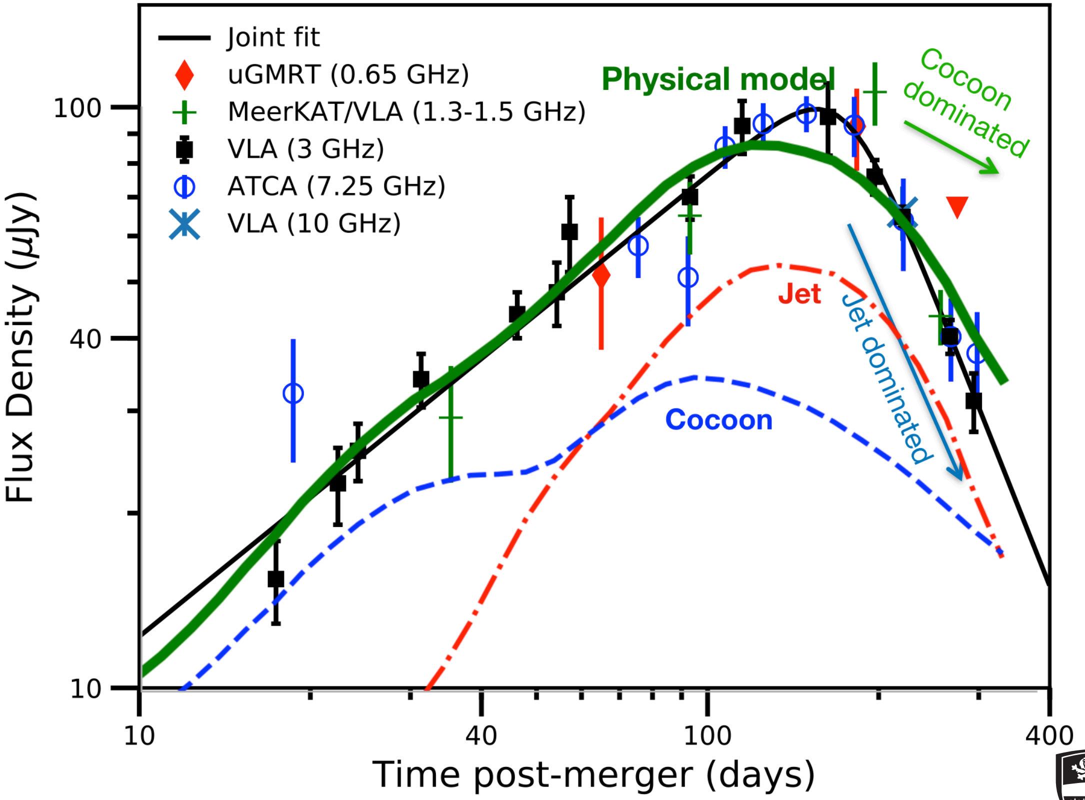
Late-time monitoring is key to physical modelling

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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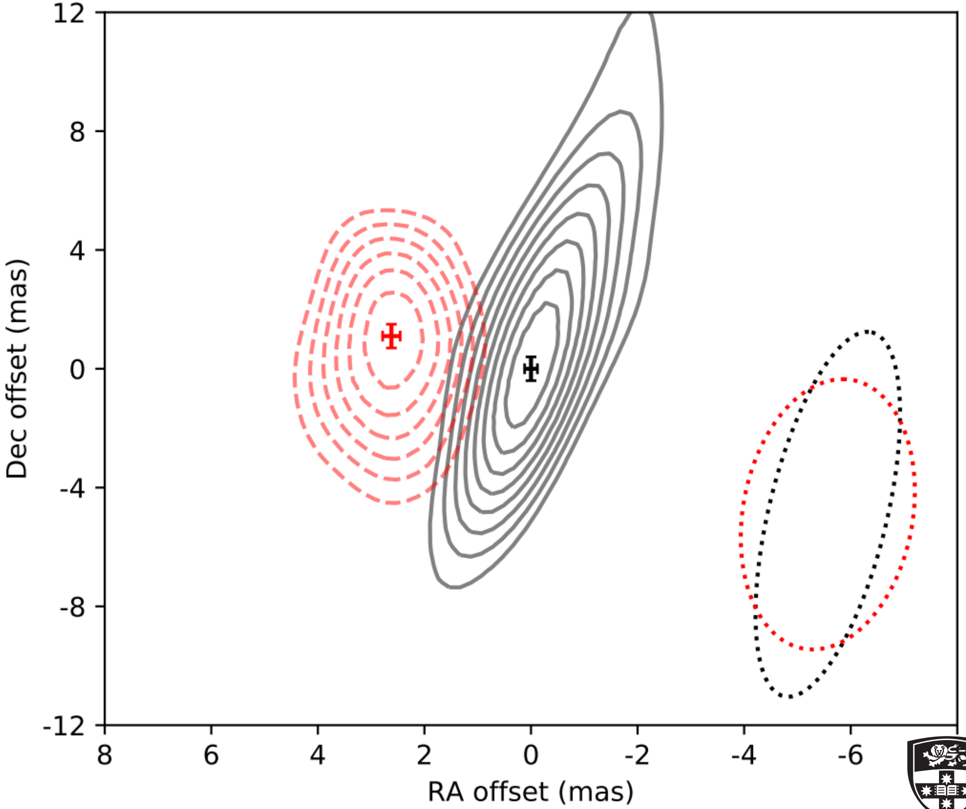
VLBI direct imaging results

- 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, Nakar, Horesh et al. (2018), Nature, 358, 1559

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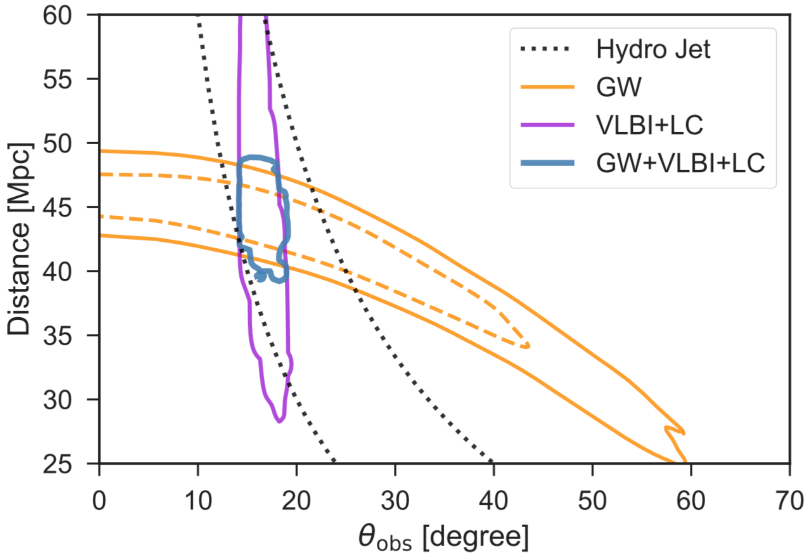
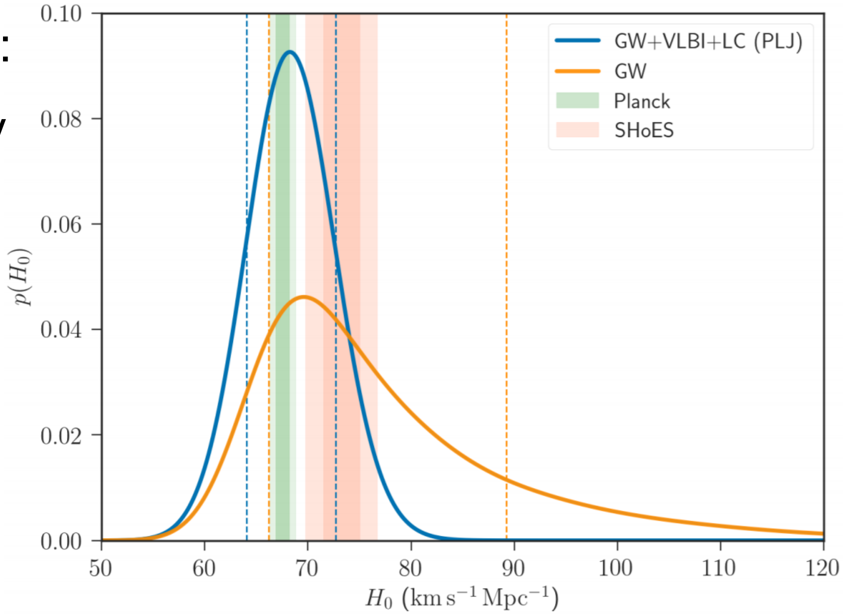
VLBI – independent estimate of Hubble Constant

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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Electromagnetic follow-up helps build a complete picture

Credit: NASA