Identifying Electromagnetic Counterparts to NS-NS Mergers

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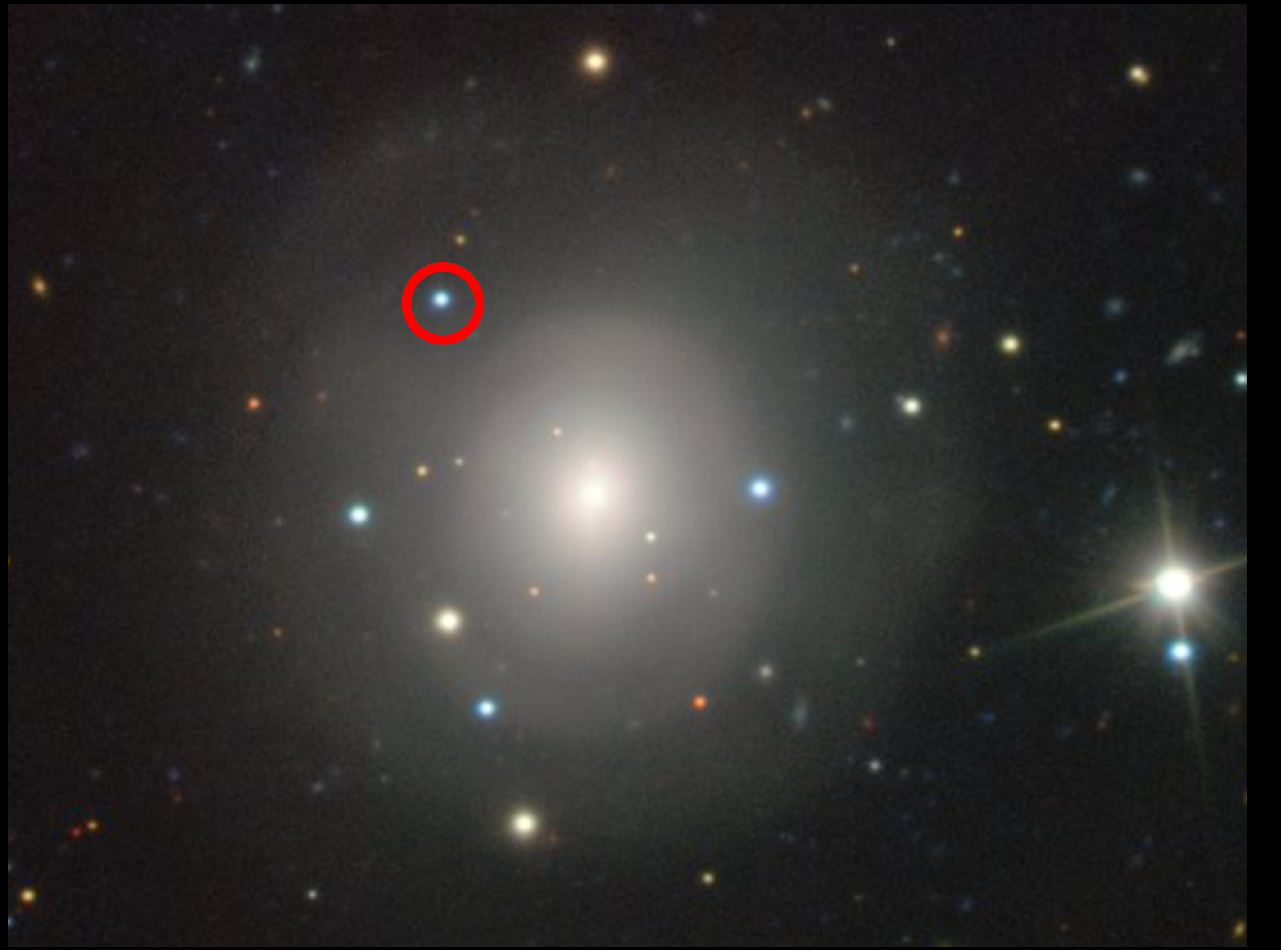
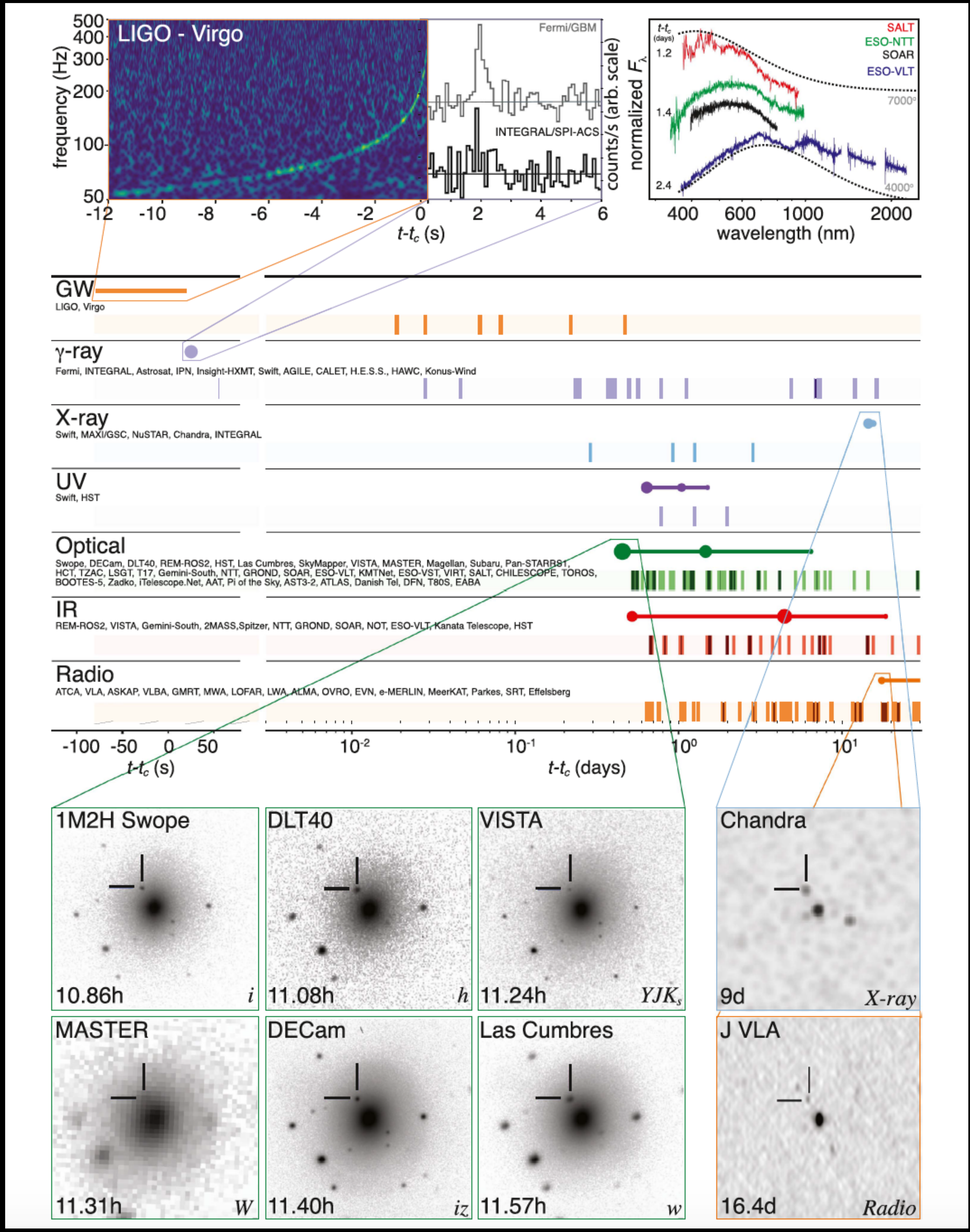


Credit: European Southern Observatory
Very Large Telescope

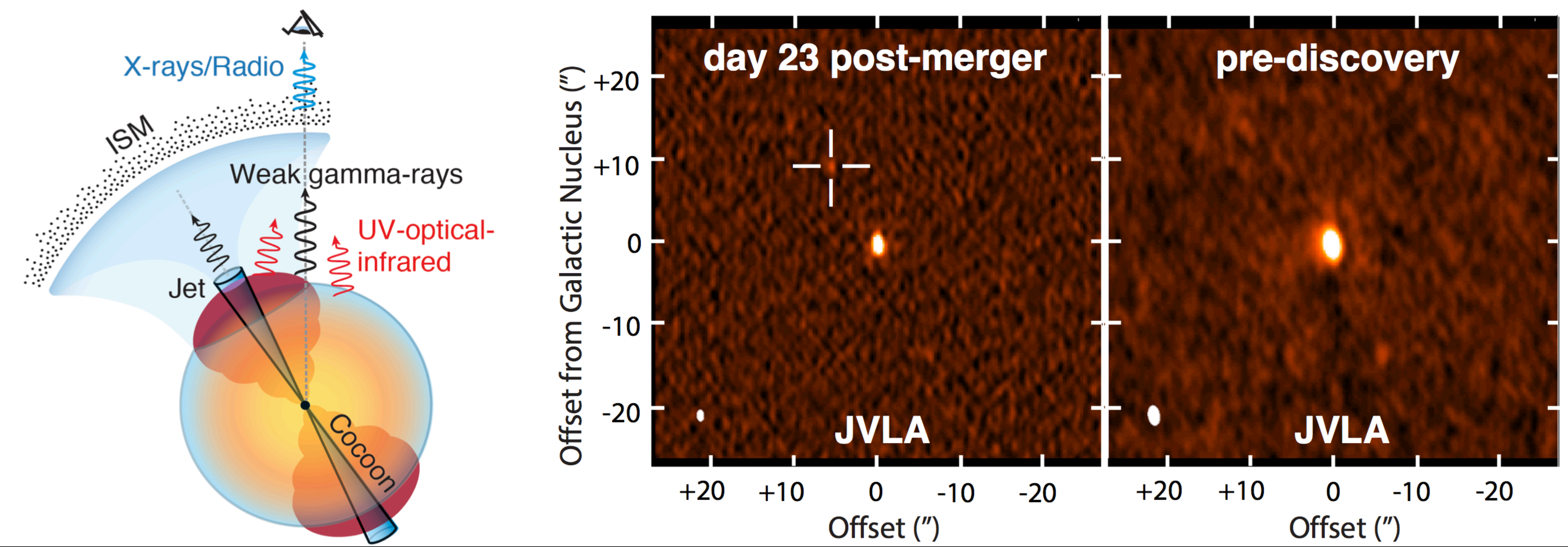


First detection of a binary neutron start mergers in gravitational waves.

First detection of the same event in both gravitational and electromagnetic waves.

Abbott et al., ApJL, 848:L12, 2017

... all the way to radio!



Hallinan, Corsi, et al. 2017, Science,
0.1126/science.aap9855

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Motivation

- NS-NS mergers will be routine - be prepared!
- The optical/IR counterpart of GW170817 was very distinct from other optical transient in the (relatively small) LIGO/Virgo error region.
  - It might not be the case for other events…
- GW170817 was very close (~40 Mpc), making any follow up easier than other, further away events.

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Motivation

- Use radio because:
  - Ubiquitous - independent of the geometry.
  - Tracks different components than UV/opt/IR.
  - Long lived, no Sun constraints.
- We have an approved JVLA large program for 280 hours (JAGWAR team).
- Determine best follow-up strategy with lowest number of observations.
  - We cannot observe future events as much as we did for GW170817.

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Questions we want to address

- Can we optimize the radio follow-up strategy to detect neutron star mergers and correctly and uniquely identify their physical parameters?
- Is radio the only (or best) channel through which we can probe the emission from fast ejecta in binary neutron-star mergers?
- How will a next generation Very Large Array (ngVLA) and Square Kilometer Array (SKA) improve the current picture?

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Method - Simulated Sources

- We simulated off-axis short GRBs @40 Mpc.
  (van Eerten et al., ApJ, 79:44, 2012)
- We have also simulated sources using the best fit of GW170817 light curve.
  (Lazzati et al., PRL 120, 241103, 2018)

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Method - Simulated Sources

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- We have also simulated sources using the best fit of GW170817 light curve.
  (Lazzati et al., PRL 120, 241103, 2018)
- We assume that radio observations follow up a specific, and well localized (~arcsec) optical transient.
  - It may or may not be the optical counterpart to the GW trigger!
  - We included this possibility in our analysis by including contaminant sources.

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Method - Simulated Sources

Circumstellar density

10^{-2}, 10^{-3}, 10^{-4} cm^{-3}.

Off-axis angle

20, 30, 45 degrees.

We created 9 families of sources with these parameters, simulating 90000 sources per family.

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Method - Simulated Sources

Circumstellar density

10^{-2}, 10^{-3}, 10^{-4} cm^{-3}.

Off-axis angle

20, 30, 45 degrees.

We created 9 families of sources with these parameters, simulating 90000 sources per family.

We included errors in the models by varying the microphysical parameters:

- ε_E = 0.1, 0.05, 0.01
- ε_B = 0.01, 0.005, 0.001

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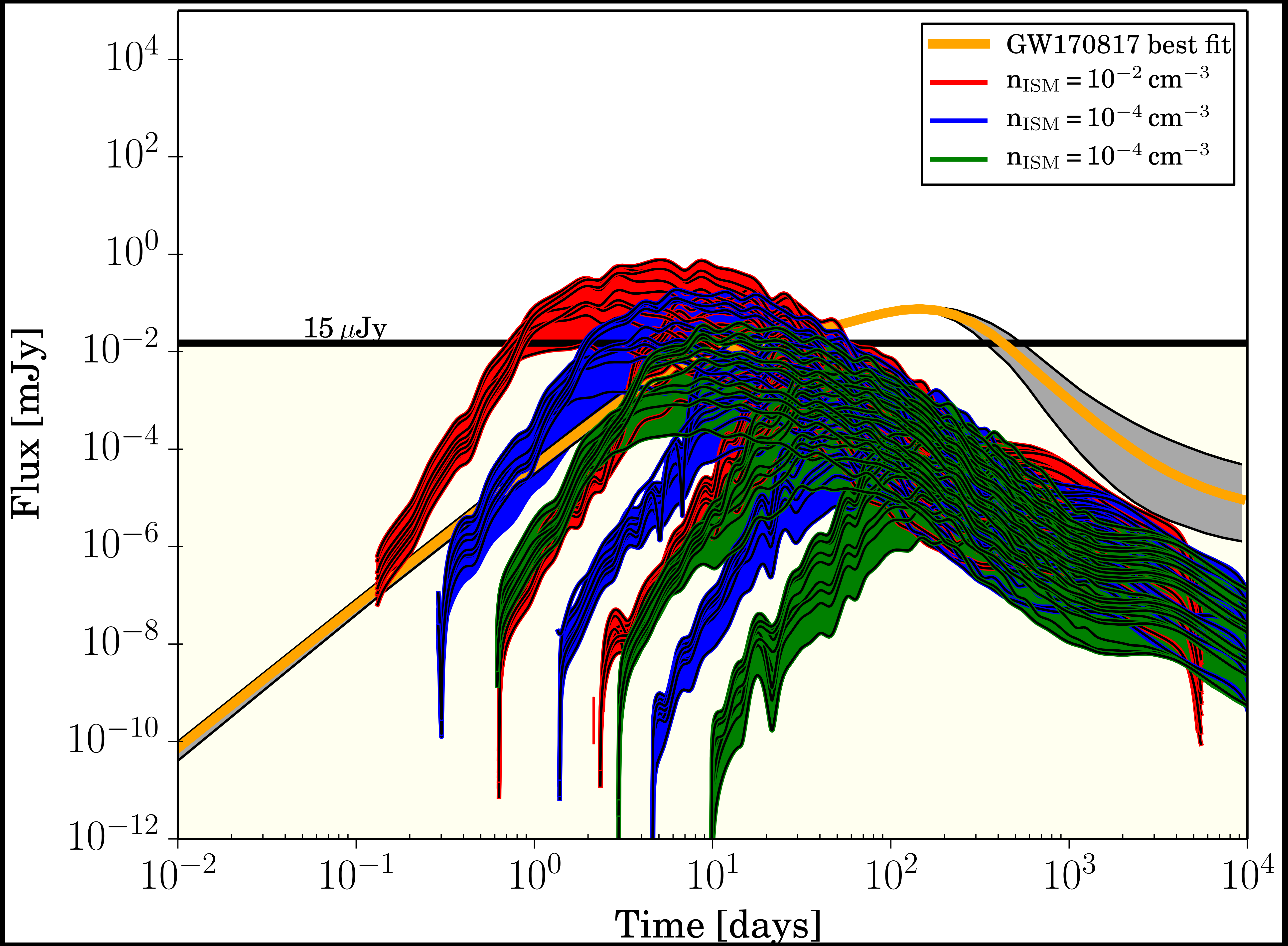
Simulated LC

E = 10^{50} erg

Jet half-opening angle = 12 deg



Adapted from Carbone & Corsi, APJ, 867, 135, 2018

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Method - Radio Observations

- We simulated radio observations performed by the JVLA at 5 GHz, with 4 GHz of bandwidth.
- Each observation has total time of 2h and reaches a 3σ sensitivity of 15 μJy.
- The maximum number of observations per event is set by expected event rate and typical VLA-1 year time allocation.
- Light curve association to physical model done by comparing measured flux to expected flux.

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Results

- The parameter we maximized is the probability to discover a source and correctly/uniquely identify its physical parameters (i.e. circumstellar density and viewing angle).
- The optimal observational setup and efficiency depend on the available observing time.
- Eight 2h observations are required to uniquely identify ~60% of all possible sources we simulated.
- Only 4 families of sources are actually identifiable!

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Conclusions

- We can correctly and uniquely identify the physical parameters of radio counterparts to NS-NS mergers for several combinations of these parameters.

- Future is bright & exiting!
  - LIGO/Virgo O3 cycle will start next week!
  - More events to be discovered (~5 per year).
  - ngVLA will push the horizon much further (for GW170817: 55 Mpc, now, to 176 Mpc, with ngVLA).

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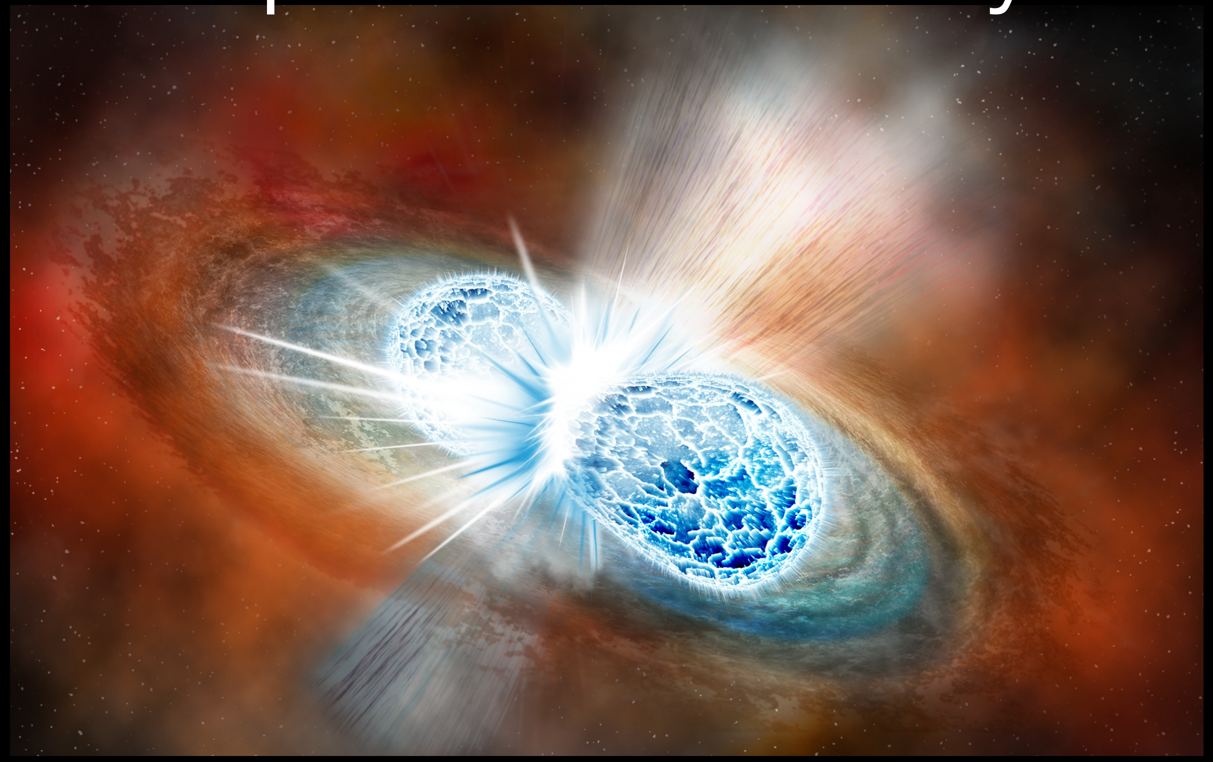
Delay between merger & radio observation

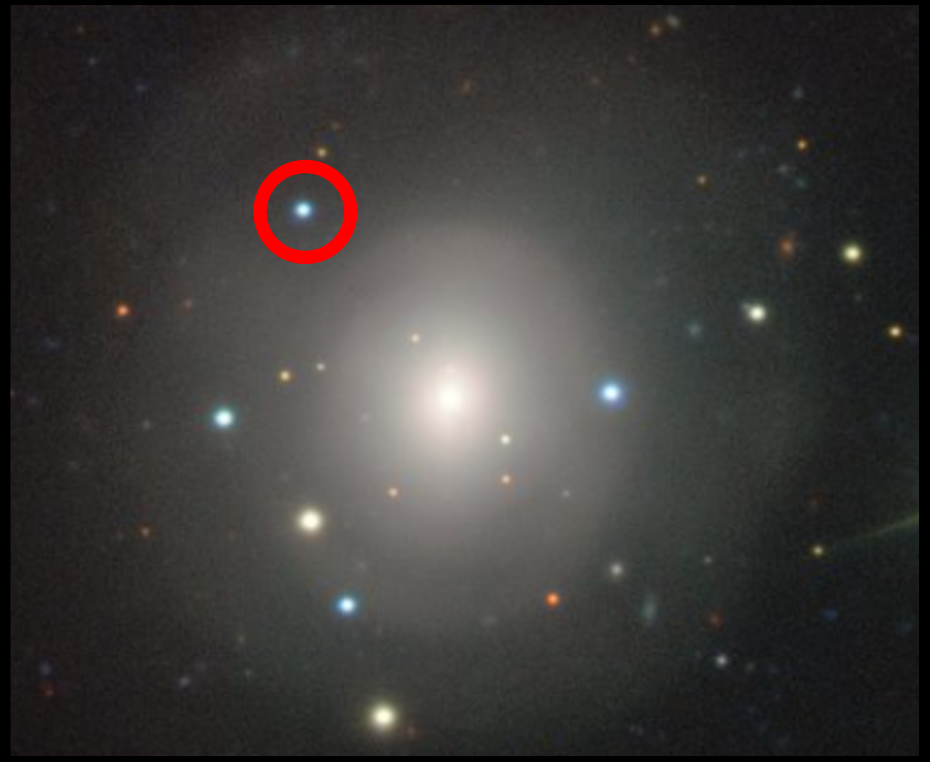
Optical discovery



1 - 3 days

$\longrightarrow$

$t_{0,\ opt}$



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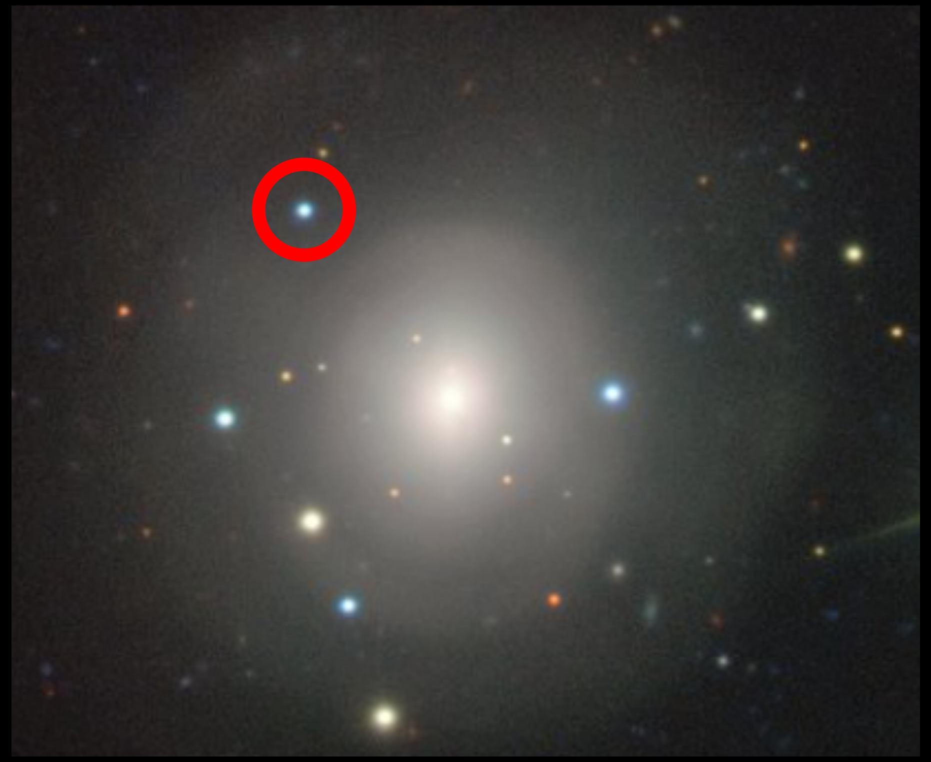

a) 1 hour - 2 days

b) 3 - 5 days

c) 7 - 15 days

$\longrightarrow$

ΔT_0

Telescope availability

=

$$t_{0,\ radio} = t_{0,\ opt} + \Delta T_0$$

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X-rays & Optical

- We produced X-ray and optical light curves of our targets (the emission coming from the jet), at 1 keV and at 658 nm (R band).
- We calculated their average fluxes at 1h, 1d, 2d and 6d.

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X-rays & Optical

- We produced X-ray and optical light curves of our targets (the emission coming from the jet), at 1 keV and at 658 nm (R band).
- We calculated their average fluxes at 1h, 1d, 2d and 6d.

- None of the optical light curves are brighter than magnitude 24, and are therefore undetectable.
- Only one of our targets is detectable up to 6 days after the merger by Chandra (3σ sensitivity ~3×10^{-15} erg cm^{-2} s^{-1}, unabsorbed flux).
- Radio is critical to probing the dynamics of the relativistic jets.

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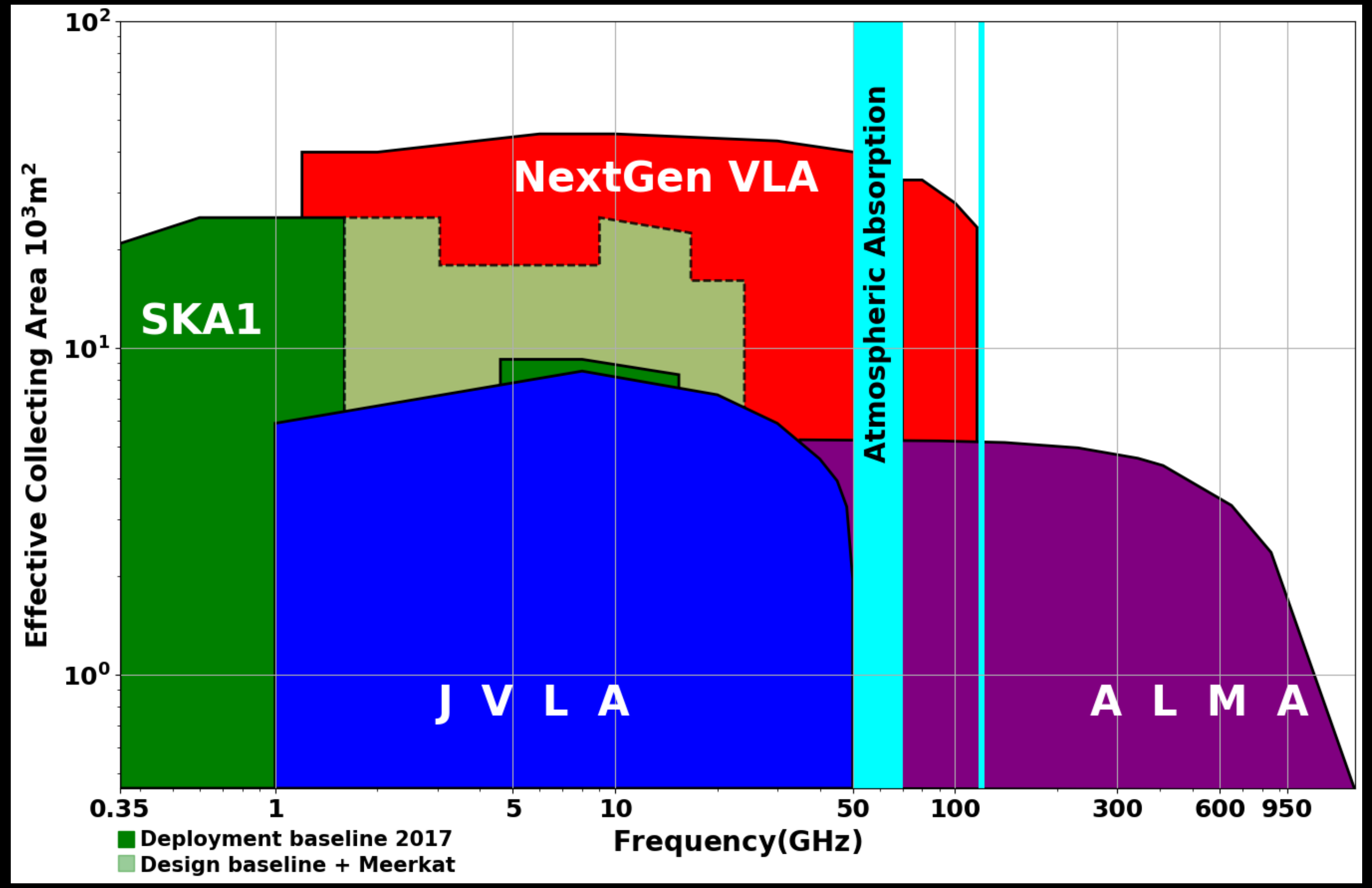
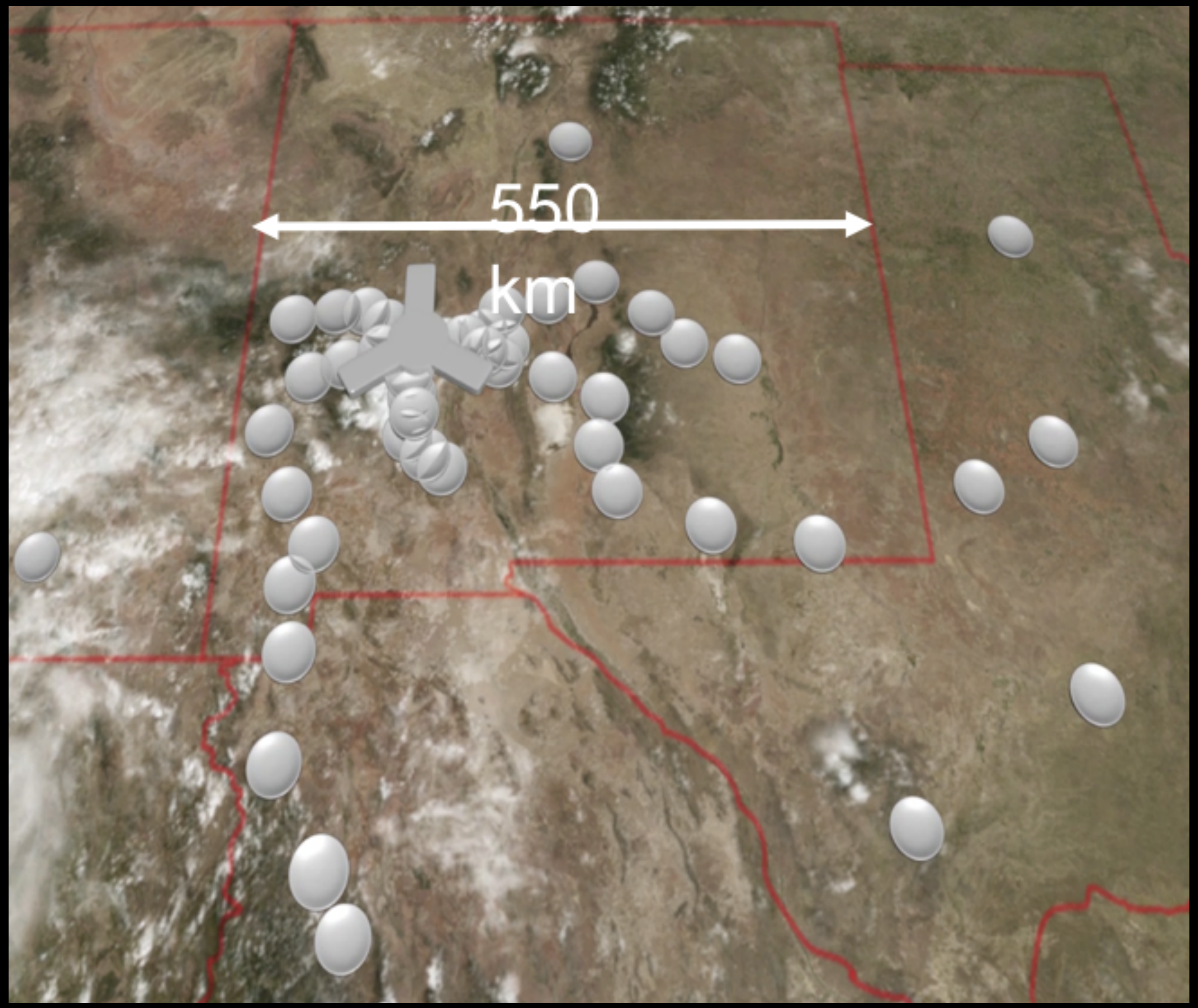
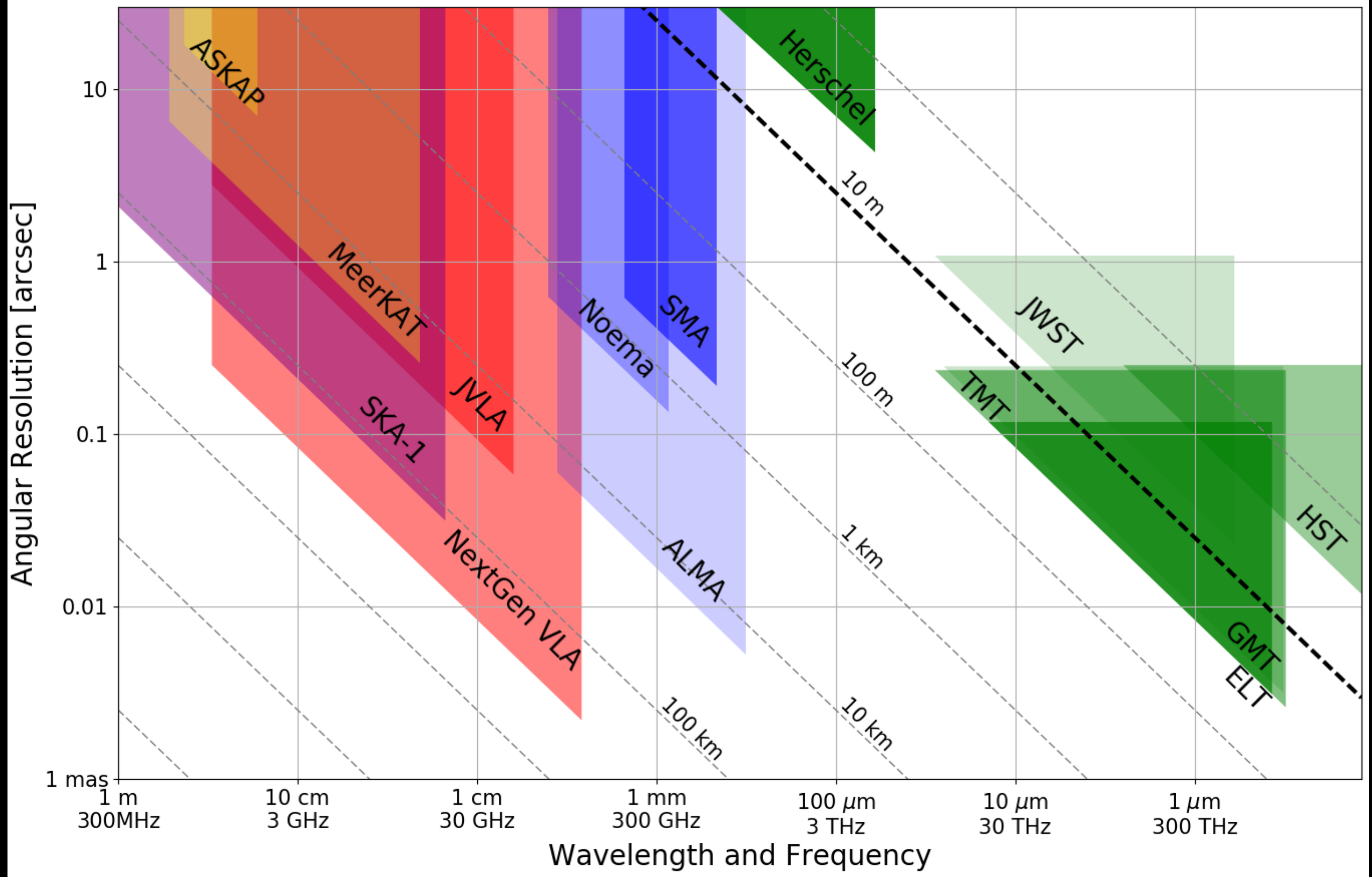
Next Generation Very Large Array (ngVLA)

- 10x the collecting area JVLA & ALMA
- Frequency range 1 - 115 GHz
- 10x longer baselines (300 km) for mas-resolution
- Dense antenna core on km-scales
- Early Science 2028 - fully operational 2034



ngvla.nrao.edu





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Targets horizons

- With ngVLA the distance to which we can detect these sources will be comparable to the one of aLIGO (~150-200 Mpc).

Class	JVLA Distance Horizon (Mpc)	ngVLA Distance Horizon (Mpc)
Target 0	288	910
Target 1	147	465
Target 2	64	203
Target 3	136	429
Target 4	56	176
Target 5	21	67
Target 6	44	138
Target 7	17	53
Target 8	6	19

Adapted from Carbone & Corsi, APJ, 867, 135, 2018

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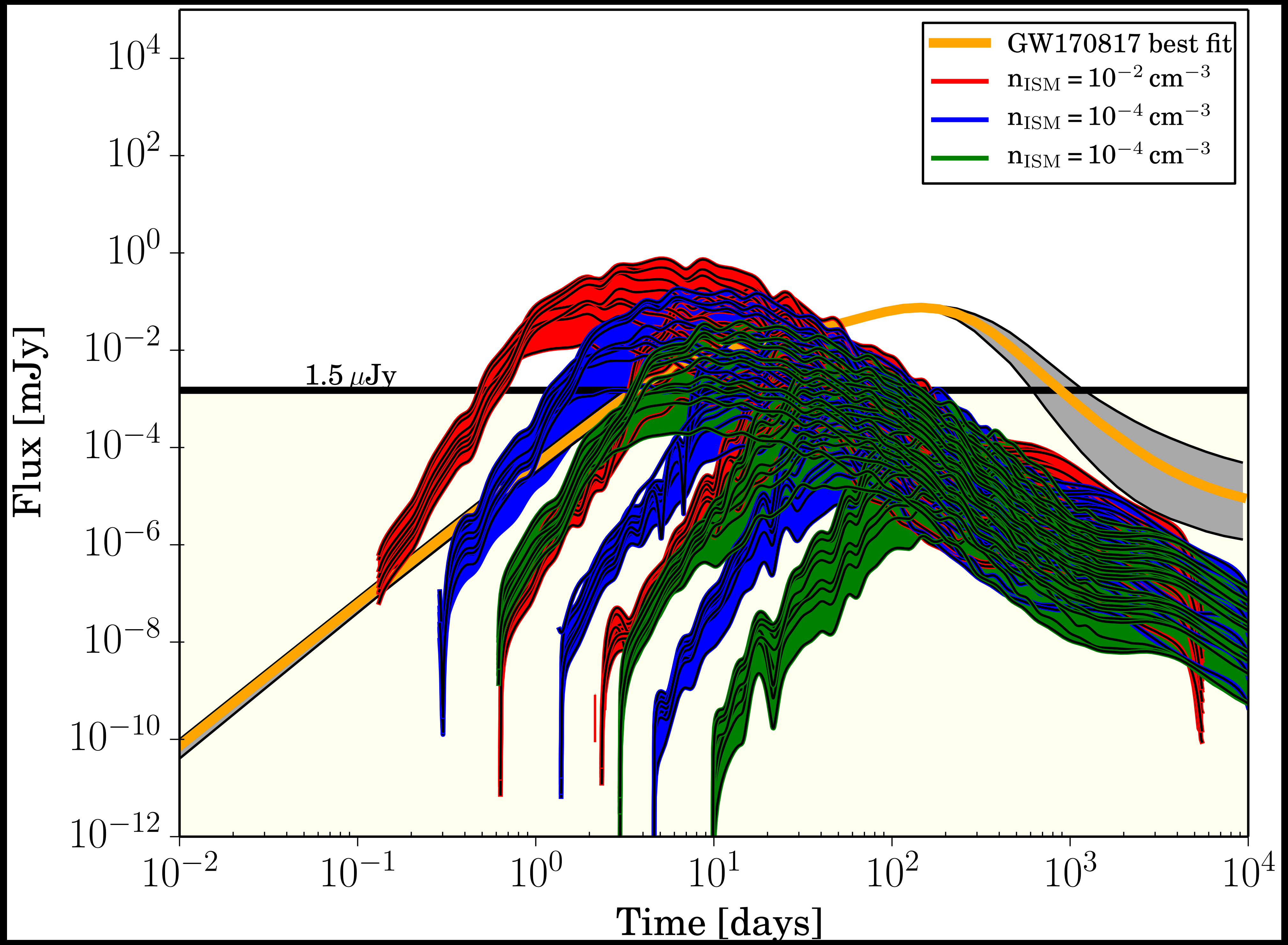
ngVLA

ngVLA pushes the horizon much further!

- We can explore sources 10x dimmer.
  - We can detect sources with different combinations of viewing angle and circumstellar density, at the current horizon distance.
  - We can detect sources ~3x further away, i.e. 30x more frequent



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Results - part II

- We repeated the same exercise, for sources 3x further away (120 Mpc).
- Eight 2h observations are required to uniquely identify ~60% of all possible sources we simulated.
- We obtain the same efficiency a the current generation VLA, for sources ~30 more numerous.

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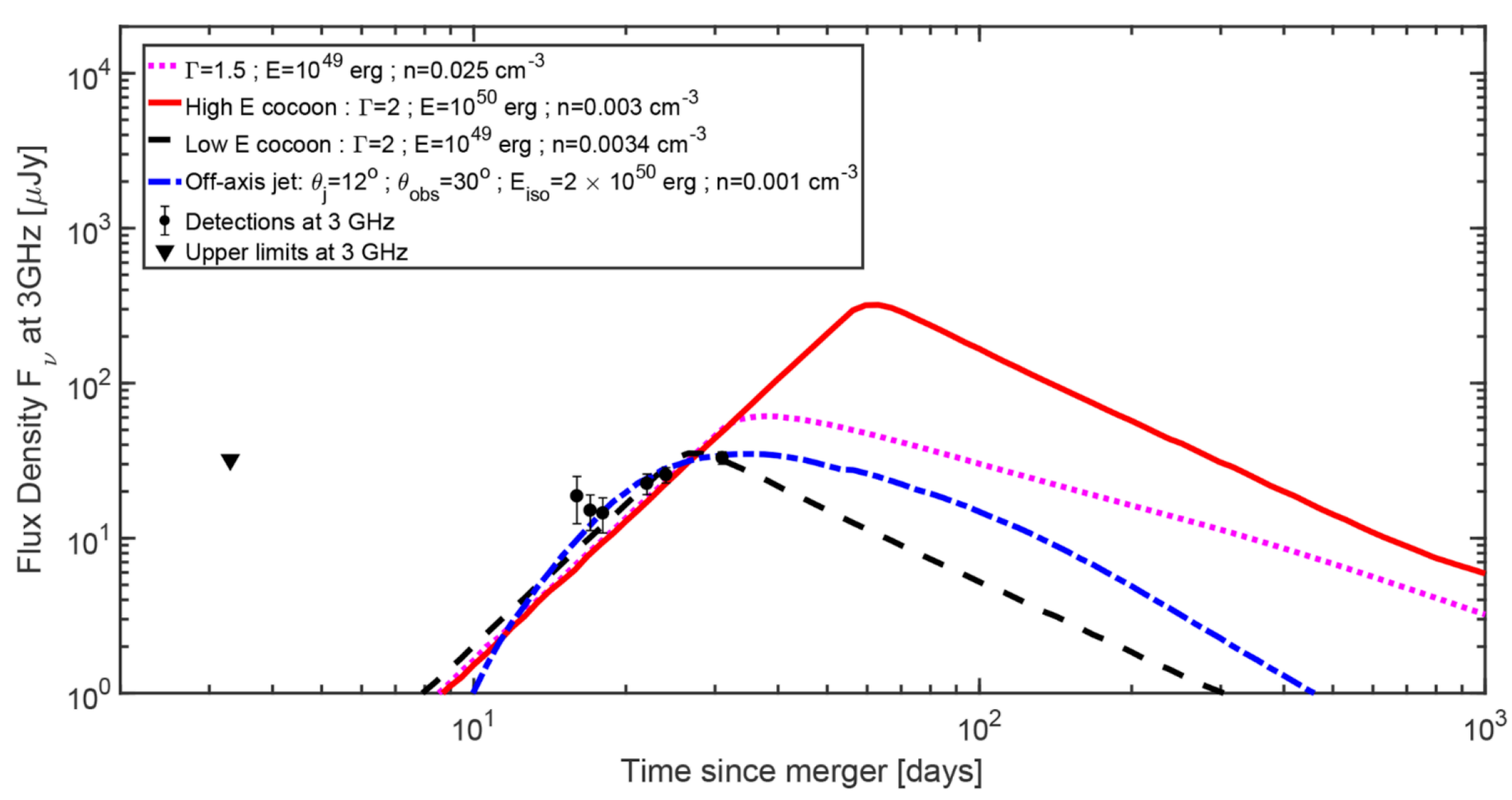
The unfolding radio story…



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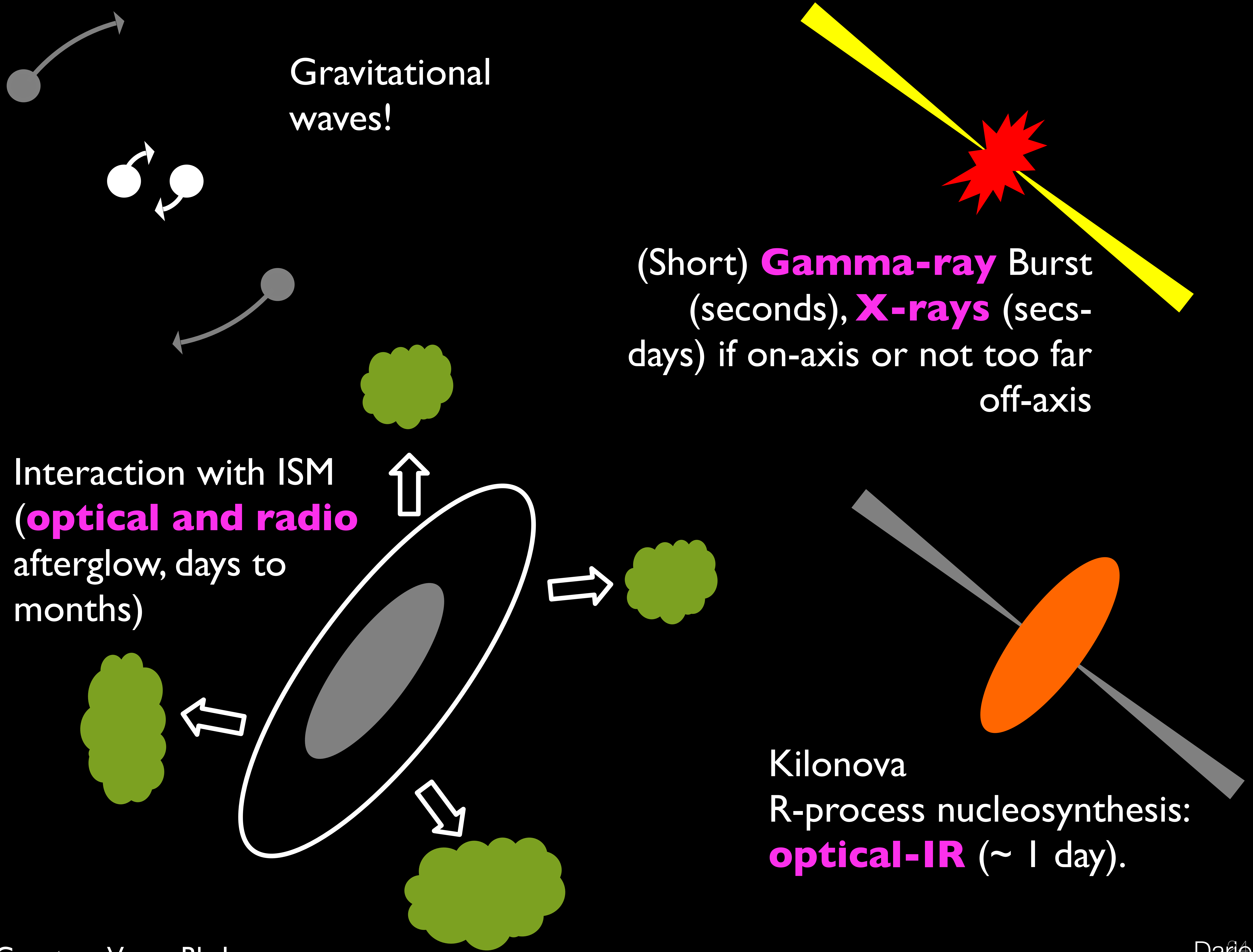

Courtesy: Varun Bhalerao

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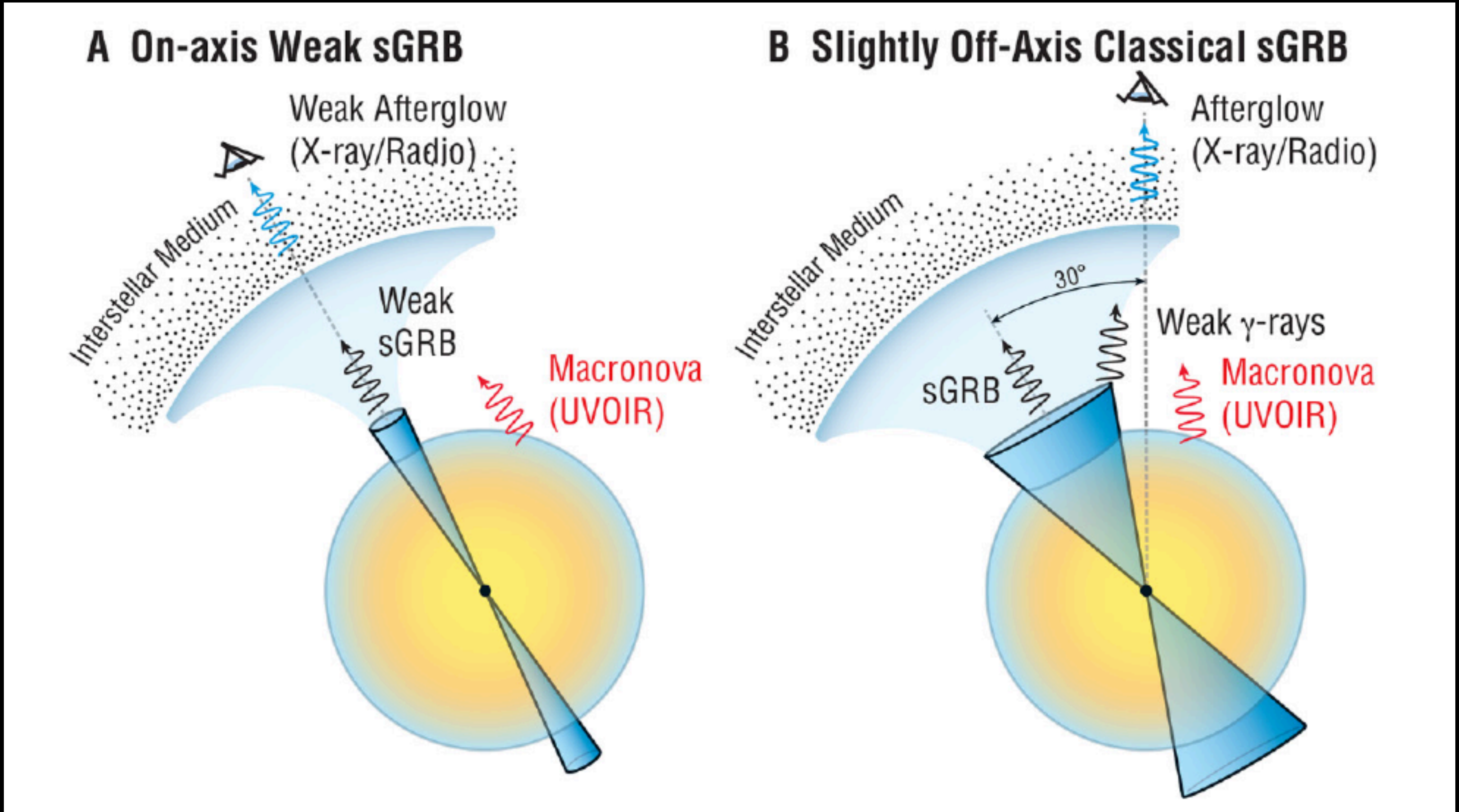
Why so dim?



M. M. Kasliwal et al., Science 10.1126/science.aap9455 (2017)

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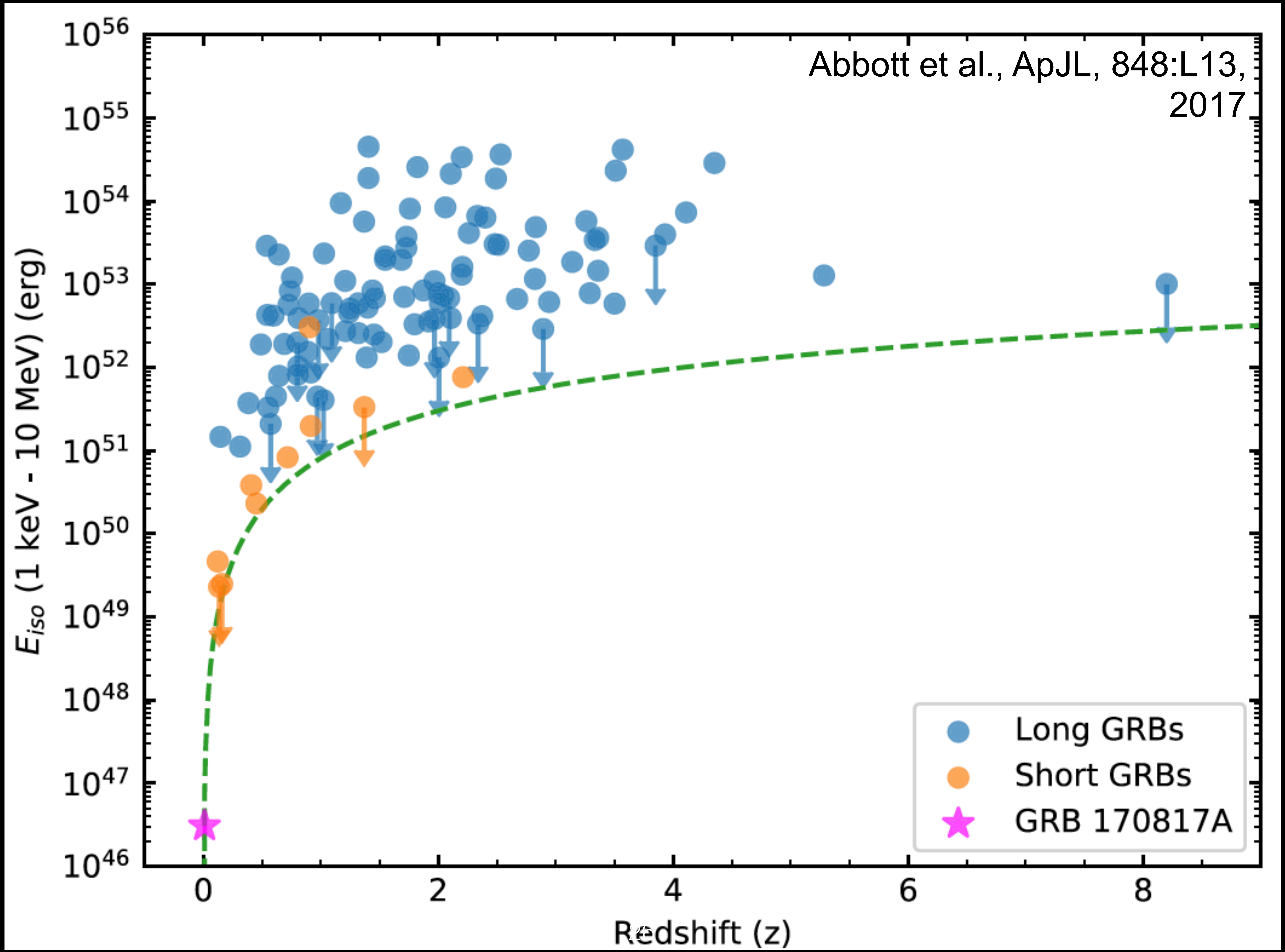
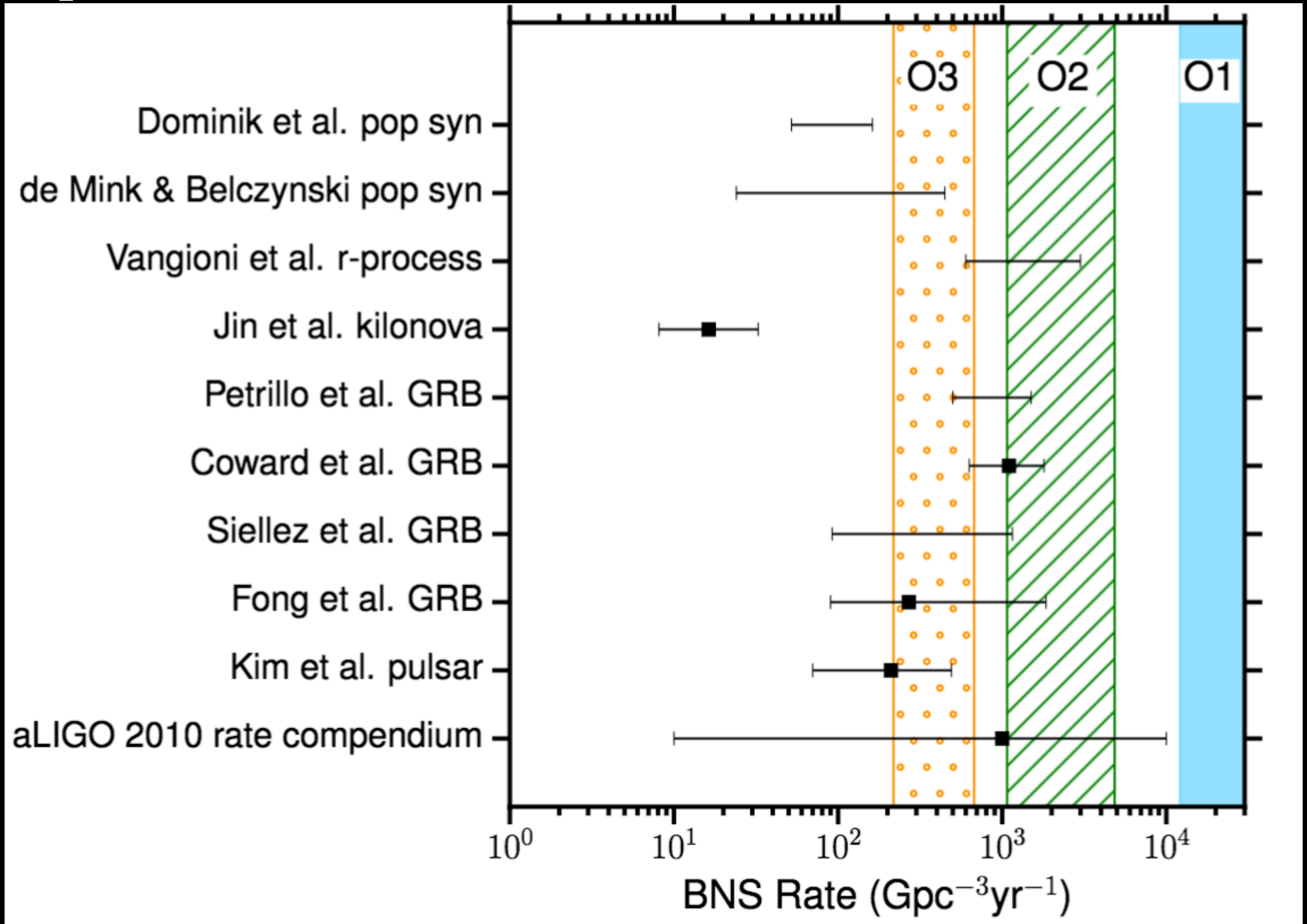
GRB170817: A dim outlier!



Pre-GW170817 expectations: NS-NS rates



Abbott et al. 2016, ApJ, 832, L21

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