

# *Multi-Messenger Astronomy*

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# The golden era of multi-messenger astronomy

- Multi-messenger astronomy has a long history
- 1960s: Solar neutrinos
- 1987: Supernova 1987A
- 2015: First GW detection (GW150914)
- 2017: First GW event with EM counterparts (GW170817)
- 2017: A high-energy neutrino detected from a blazar (an active black hole in a galactic centre)
- 2021: A high-energy neutrino detected from a tidal disruption event (a star disrupted by a supermassive BH)

# GRAVITATIONAL WAVE SPECTRUM

Observatories & experiments

Ground-based experiment



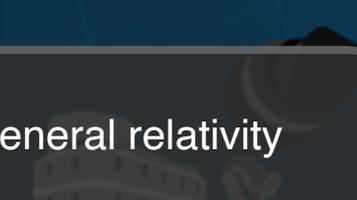
Space-based observatory



Pulsar timing array



Cosmic microwave background polarisation



Timescales

milliseconds

seconds

hours

years

billions of years

Frequency (Hz)

100

1

$10^{-2}$

$10^{-4}$

- Gravitational waves are predictions from general relativity
  - Ripples in space-time
- Any time-varying non-axisymmetric mass distribution can produce gravitational waves
  - Compact binary coalescence (CBCs), Supernova explosion, Pulsars ... etc.
- Current ground-based detectors observe gravitational waves at  $\sim 10$  - a few 1000 Hz

Cosmic sources



Supernova



Pulsar



Compact object falling onto a supermassive black hole



Merging neutron stars in other galaxies



Merging stellar-mass black holes in other galaxies



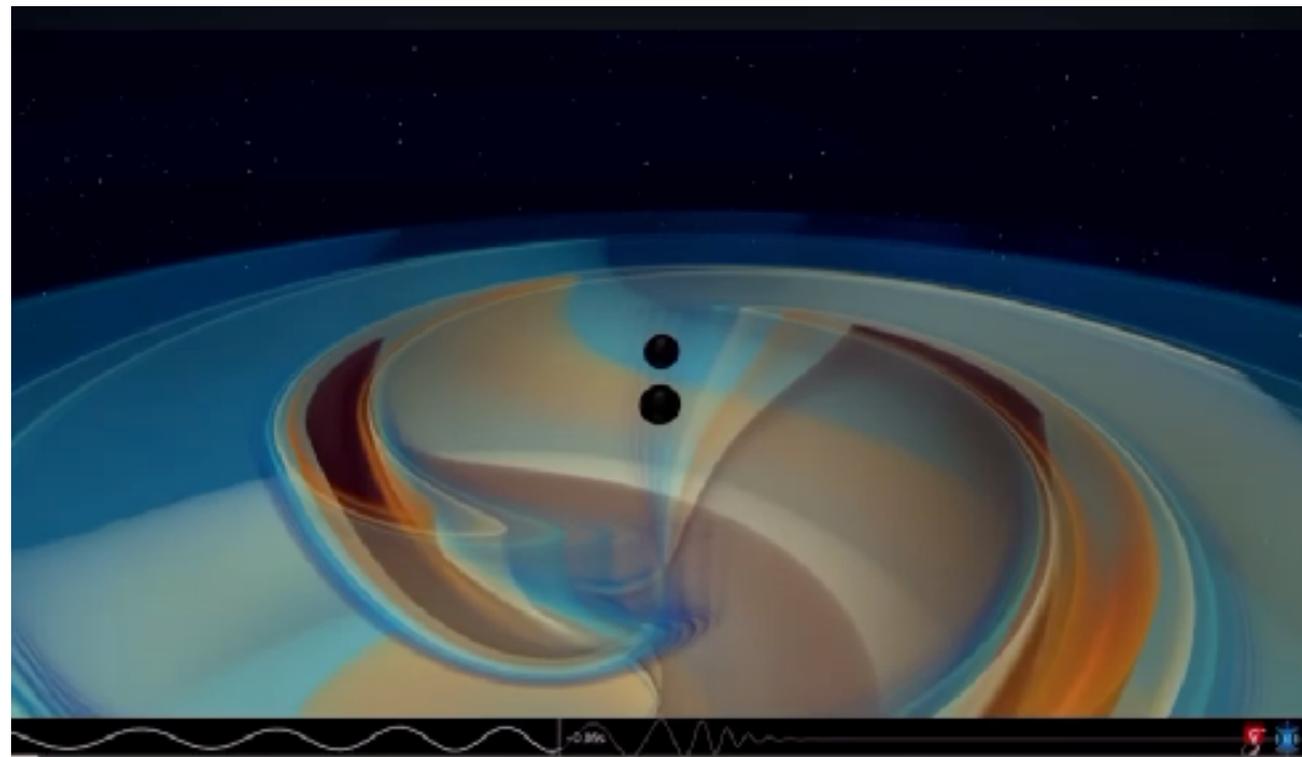
Merging white dwarfs in our Galaxy

Merging supermassive black holes



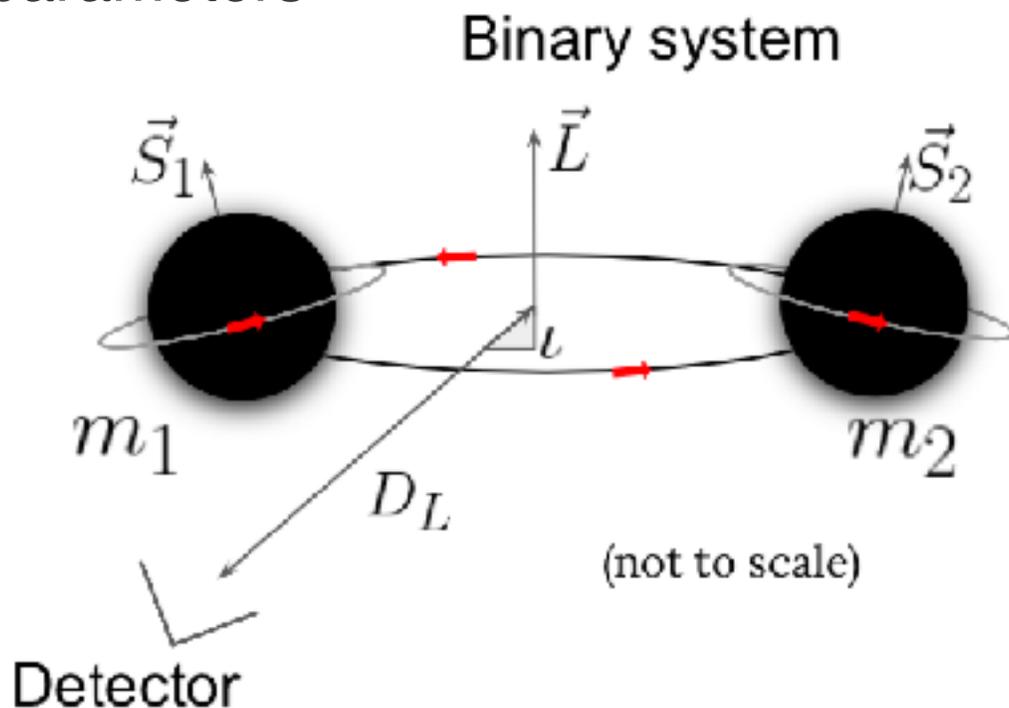
# Compact Binary Coalescence

- A pair of compact objects (white dwarfs, neutron stars, black holes)
  - So far we detect **binary neutron star (BNS)**, **binary black hole (BBH)** and **neutron star-black hole (NSBH)** mergers
- As objects orbit, they lose energy to GWs
  - The orbit shrinks and speeds up, releasing more energy to GWs
  - Frequency and amplitude increase monotonically
  - Creates a runaway process leading to inspiral and merger



# Modelling Compact Binary Mergers

The signal from a binary system made up of black holes is described by 15 parameters



*More parameters required if matter or new physics is included*

## Intrinsic parameters

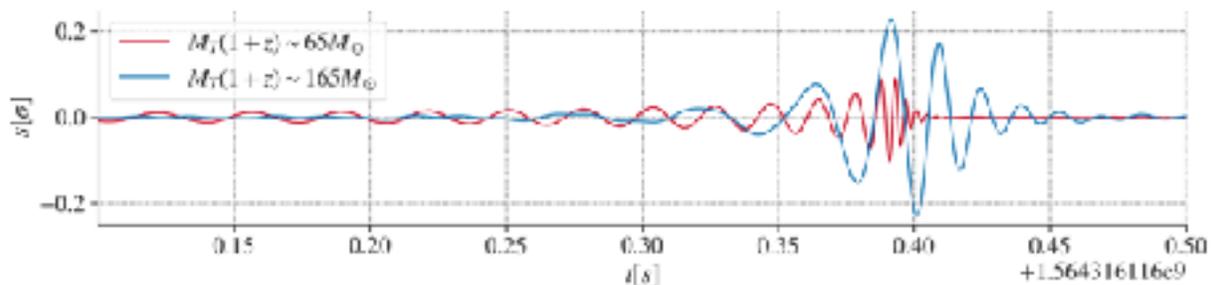
- Two component masses:  $m_1, m_2$
- Six spin Components:  $\chi_1, \chi_2$

## Extrinsic parameters

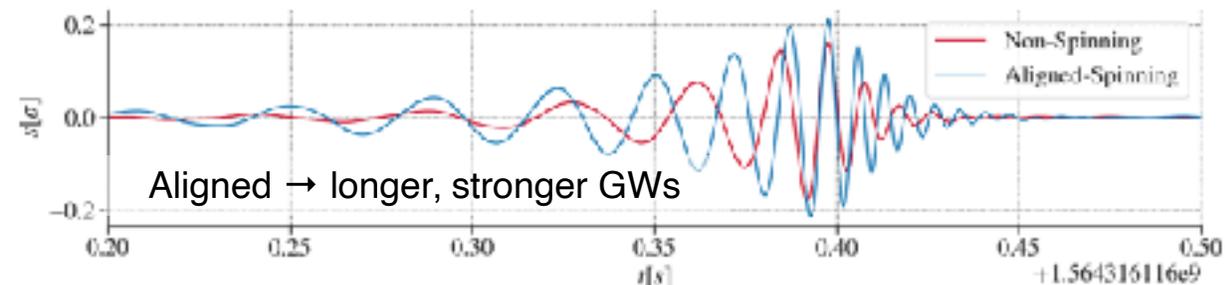
- Sky Location:  $(\alpha, \delta)$
- Luminosity distance:  $D_L$  (or equivalently the redshift  $z$ )
- Binary orientation parameters:  $(i, \varphi)$
- Polarisation angle:  $\psi$
- Merger time:  $t_c$

# Phenomenology of black hole binaries

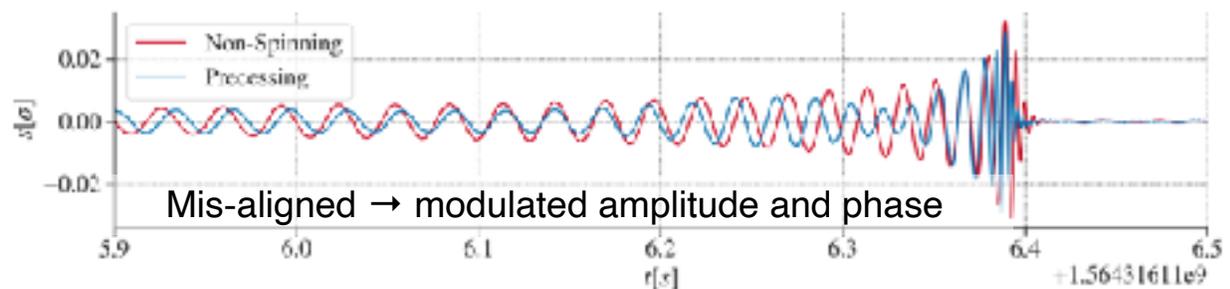
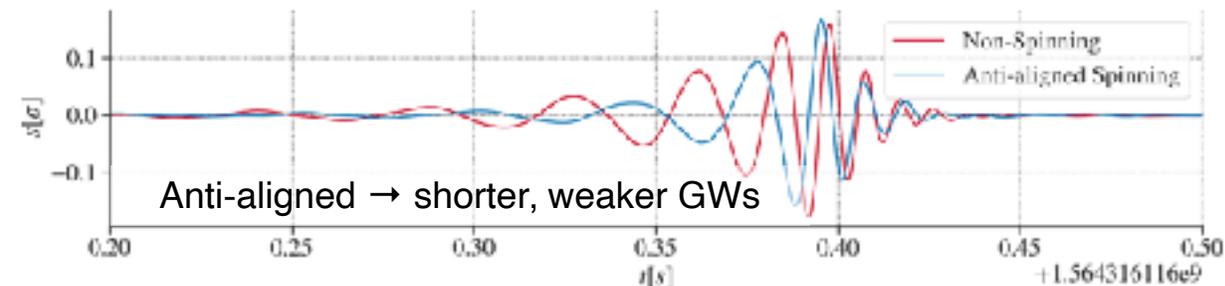
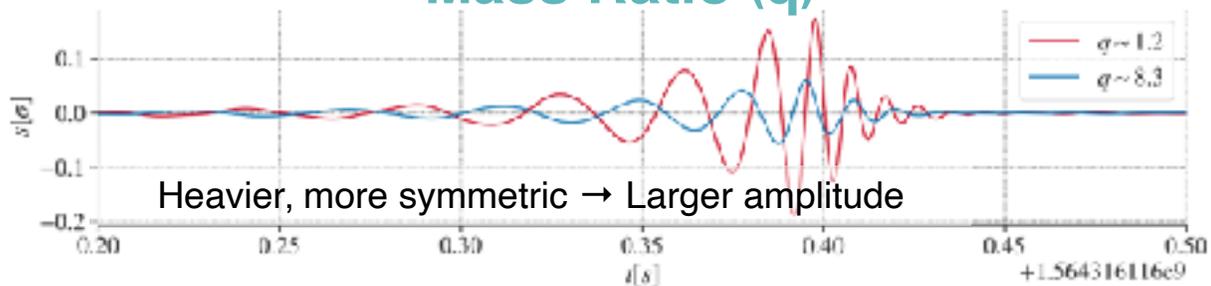
## Mass



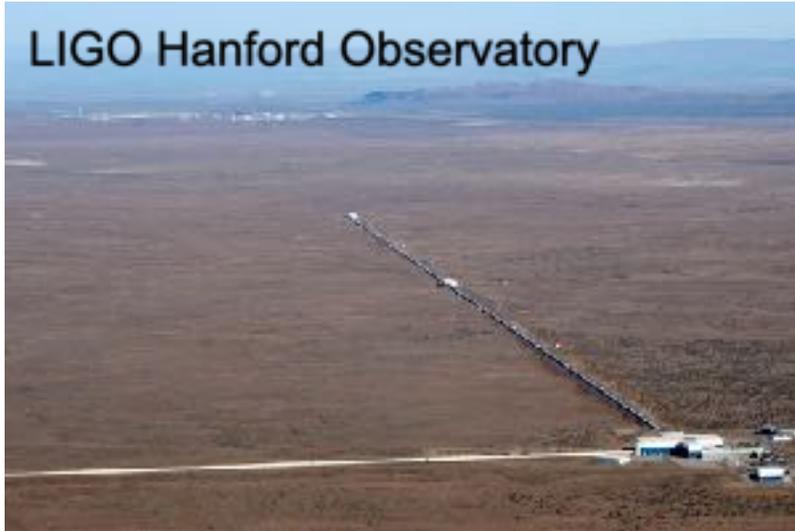
## Spins



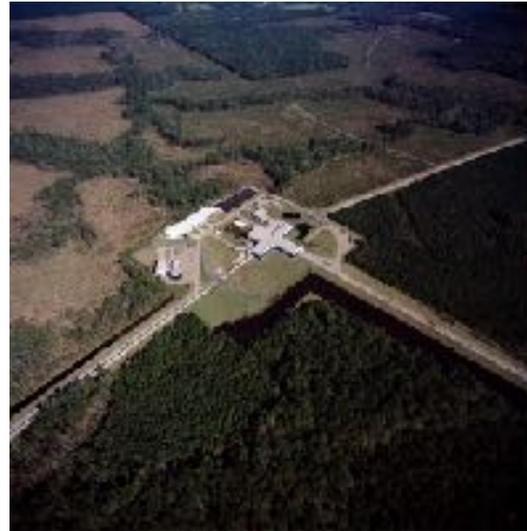
## Mass Ratio (q)



LIGO Hanford Observatory



LIGO Livingston Observatory



Virgo

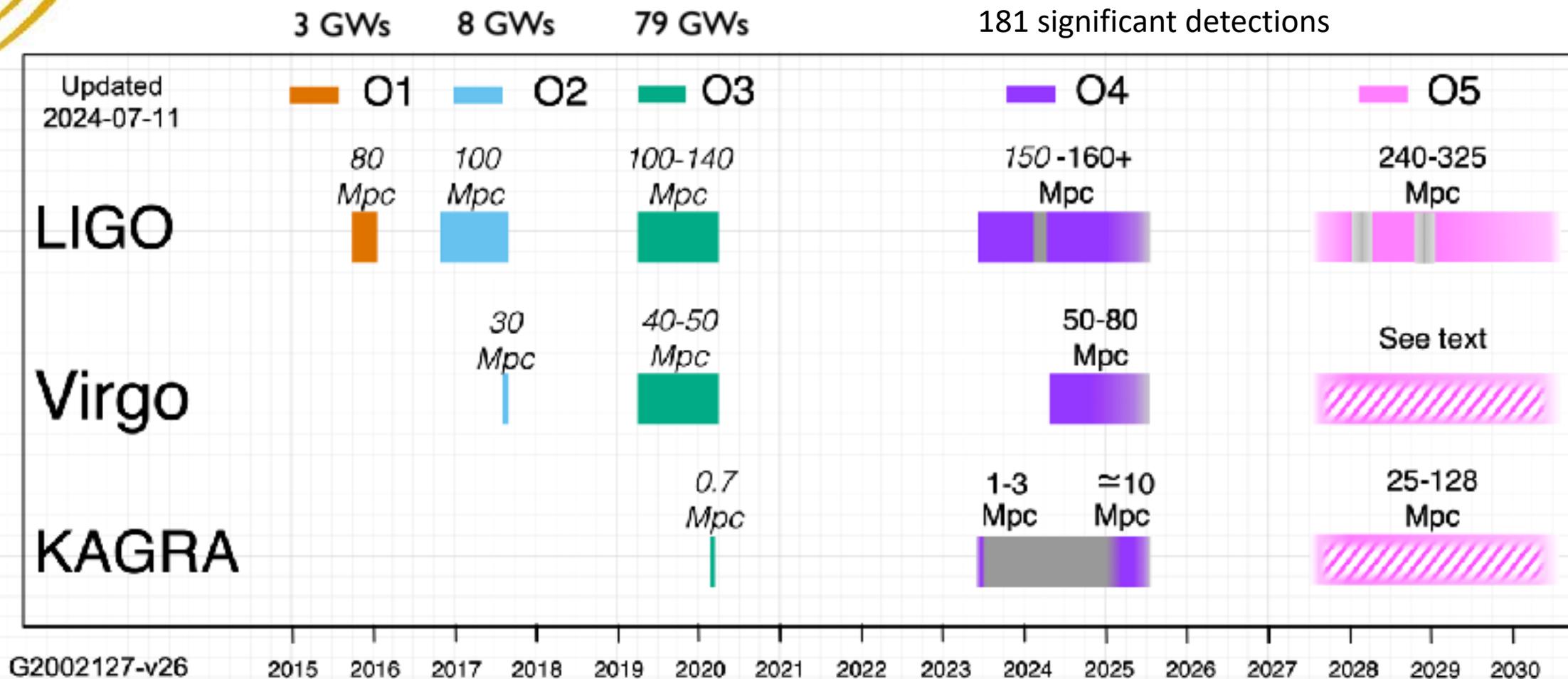


大型低温重力波望遠鏡  
KAGRA



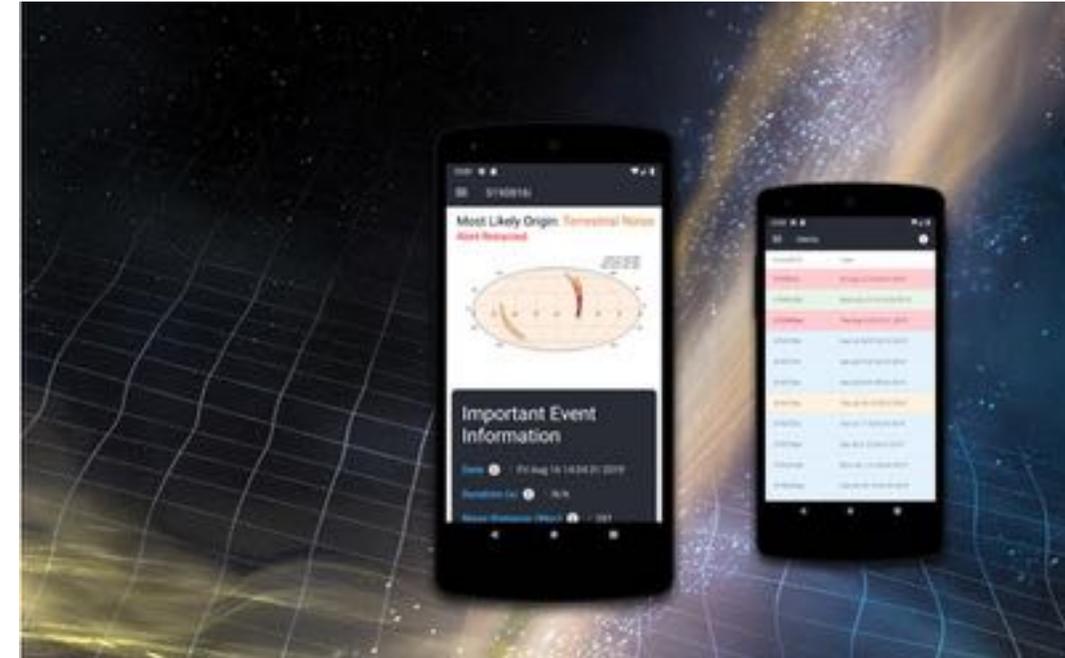
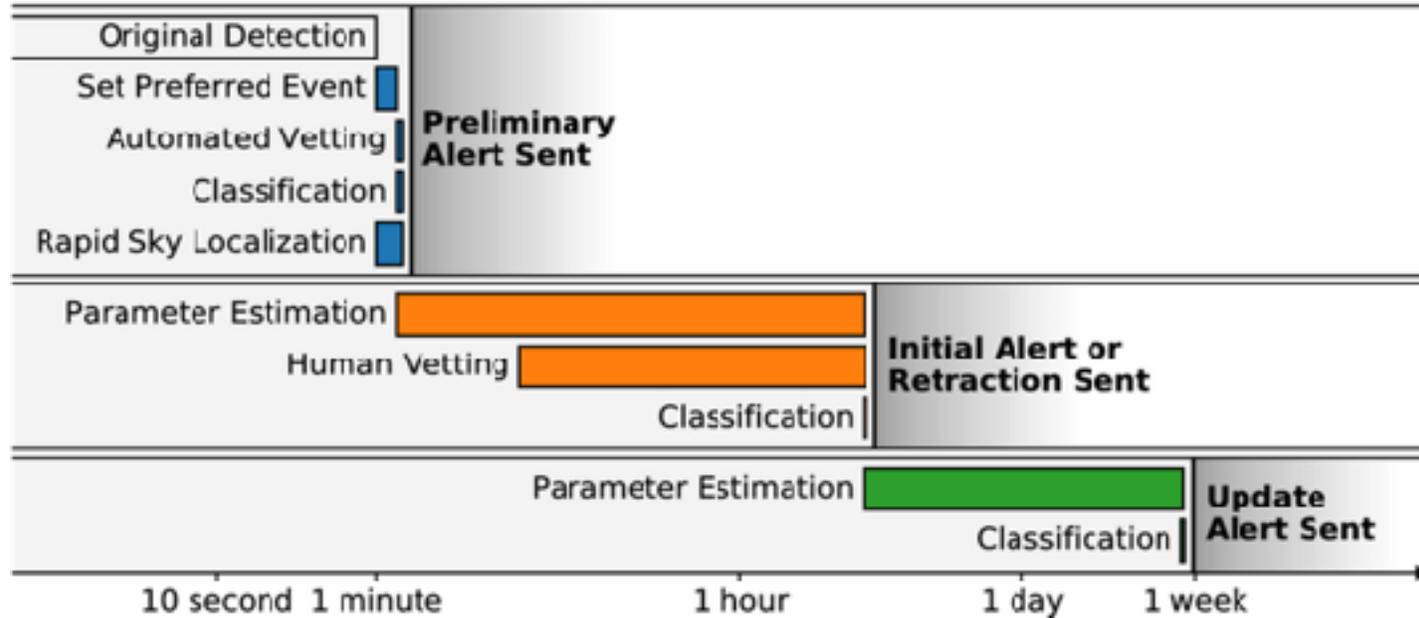


As of Jan 14  
181 significant detections



# Public Alerts

Time since gravitational-wave signal





**Gravitational Wave Events**  
LIGO/Virgo alerts from GCN  
Designed for iPhone. Not verified for macOS.

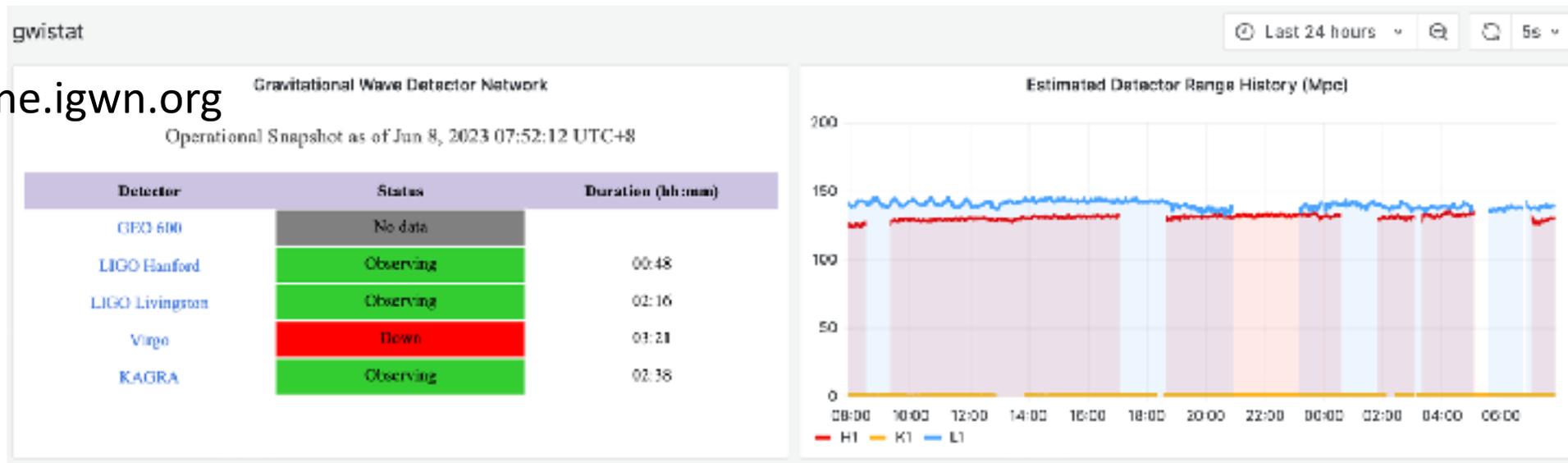




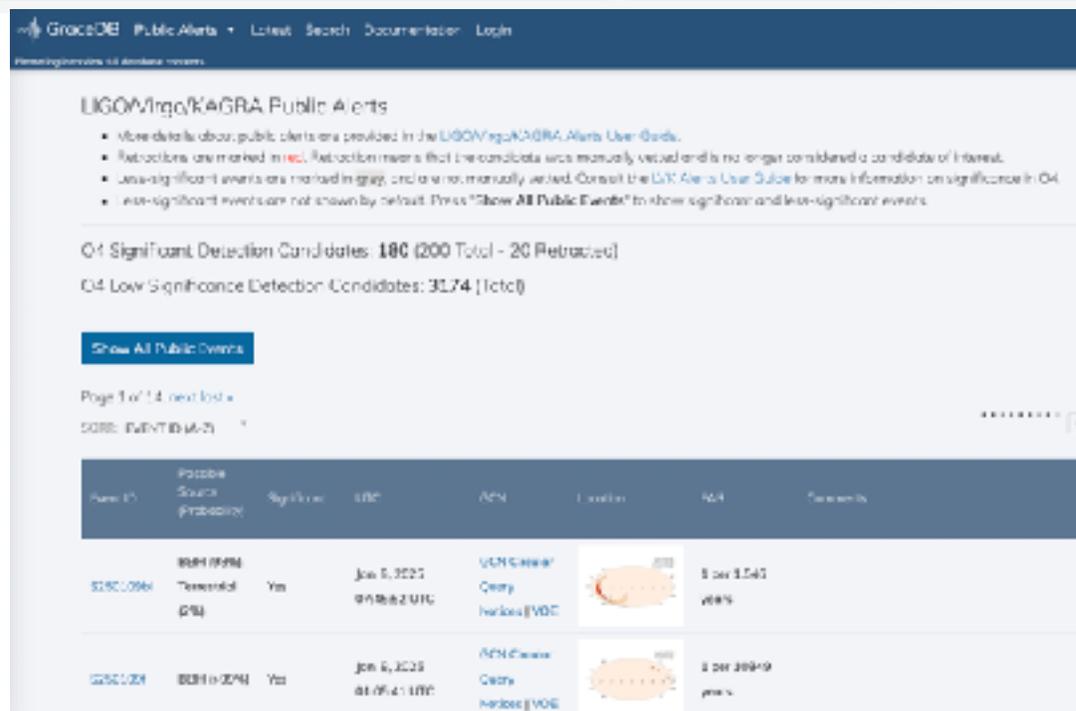
**Chirp - gravitational wave app**  
signal alerts and updates  
Designed for iPad. Not verified for macOS.



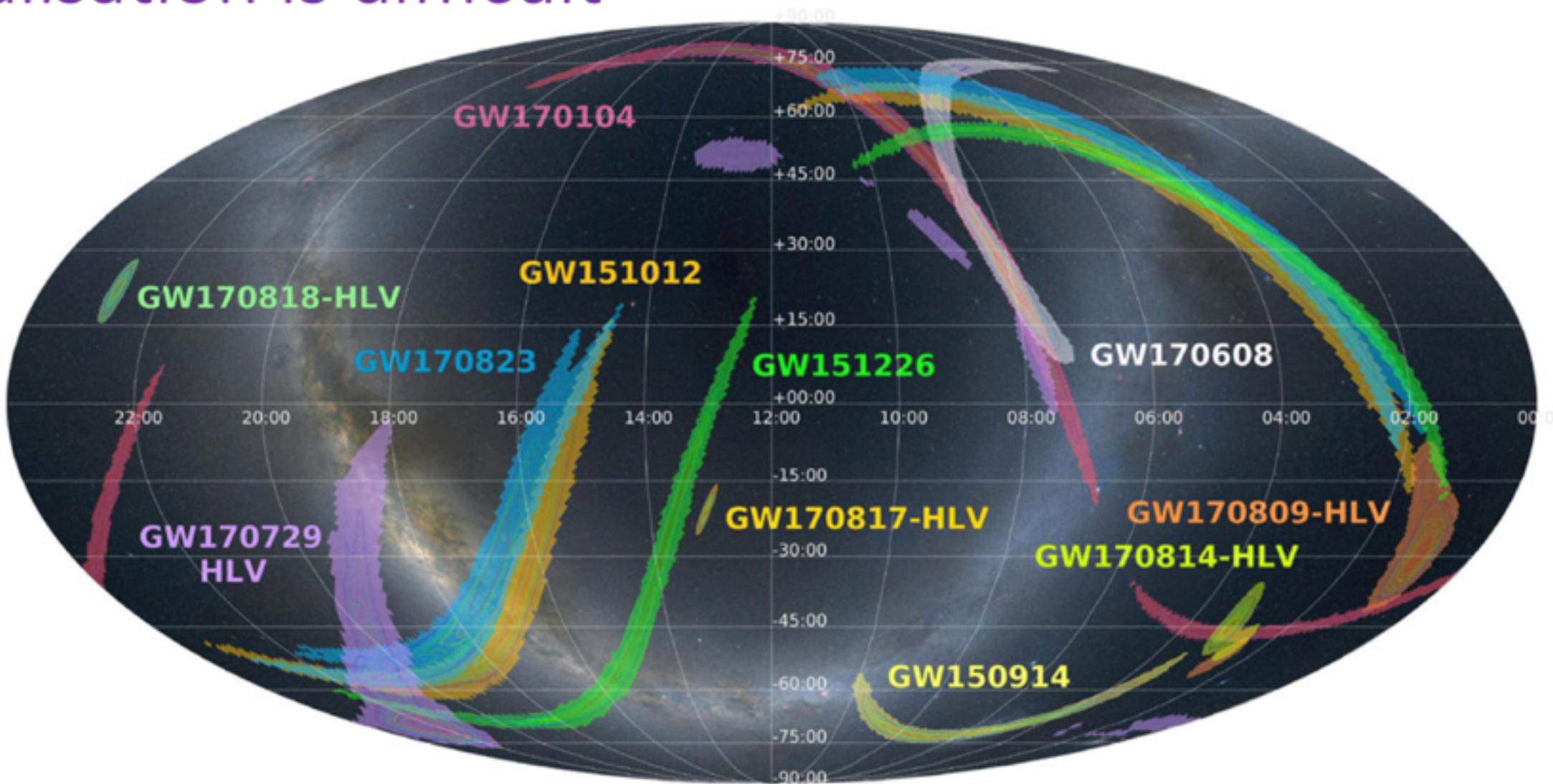
<https://online.igwn.org>



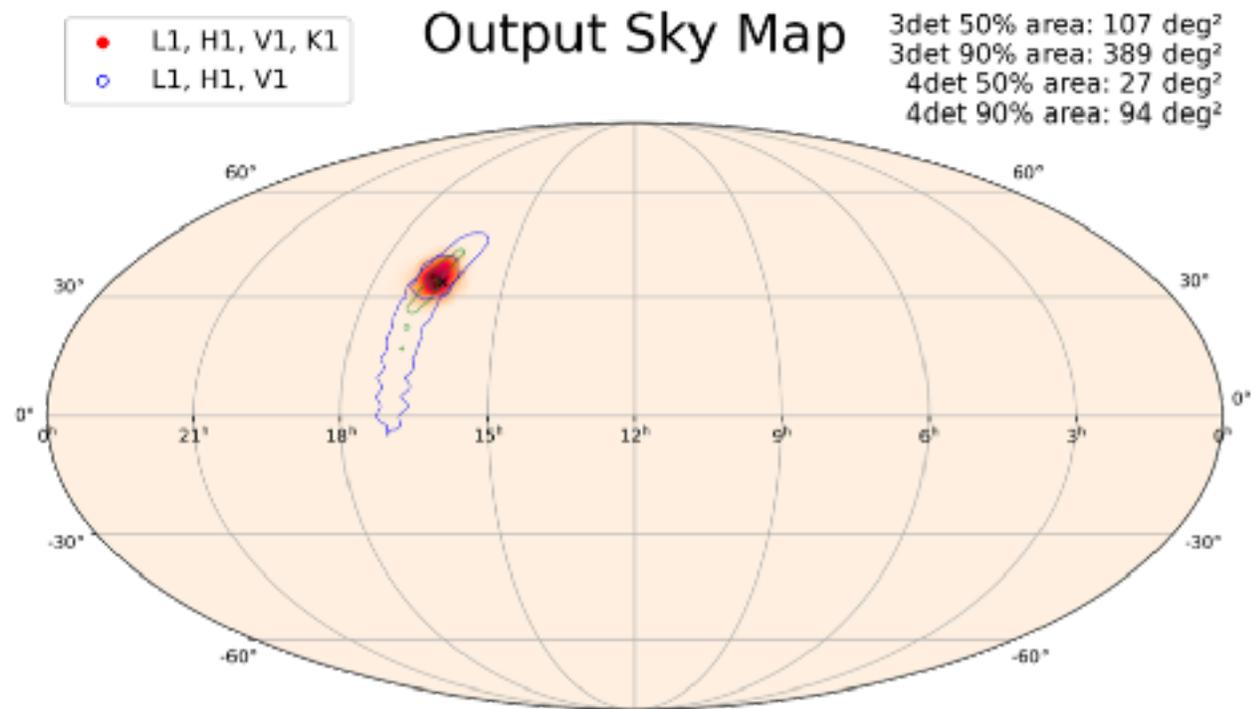
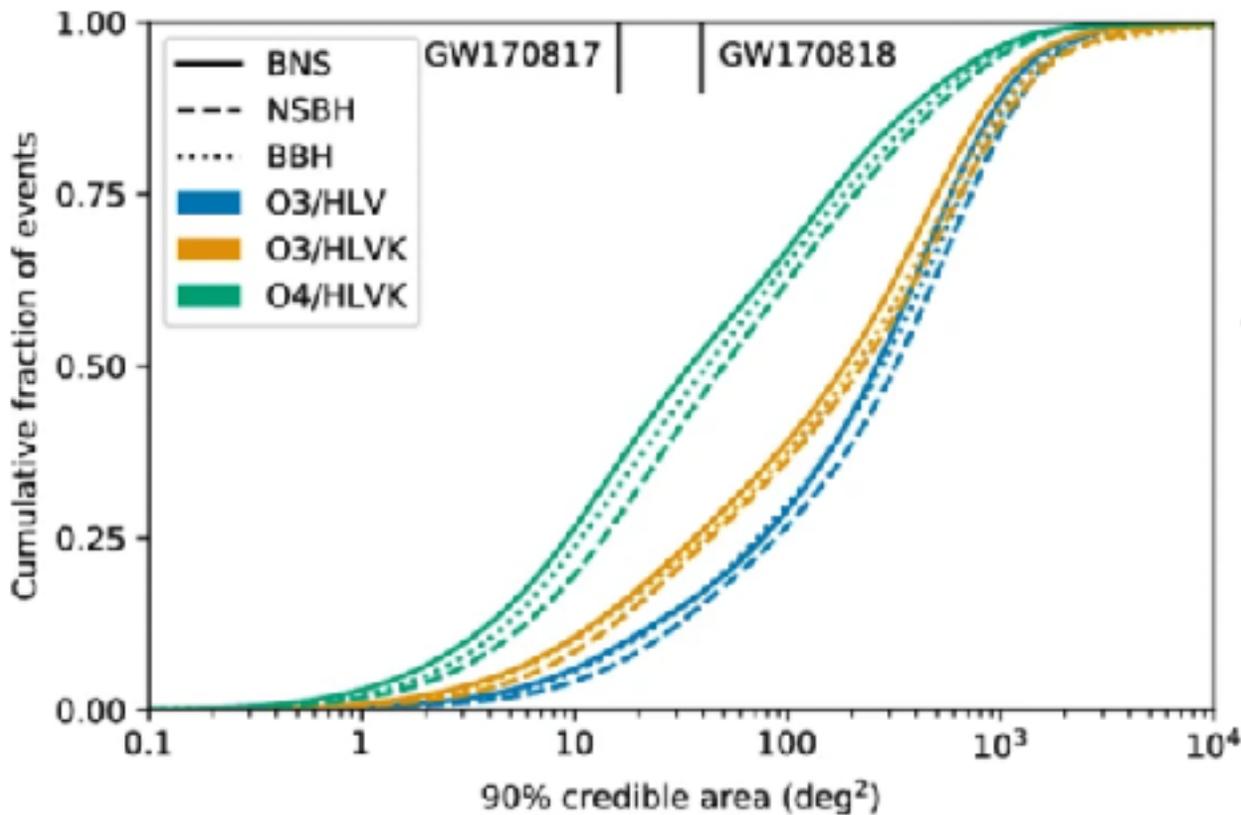
<https://gracedb.ligo.org/>



# Localisation is difficult

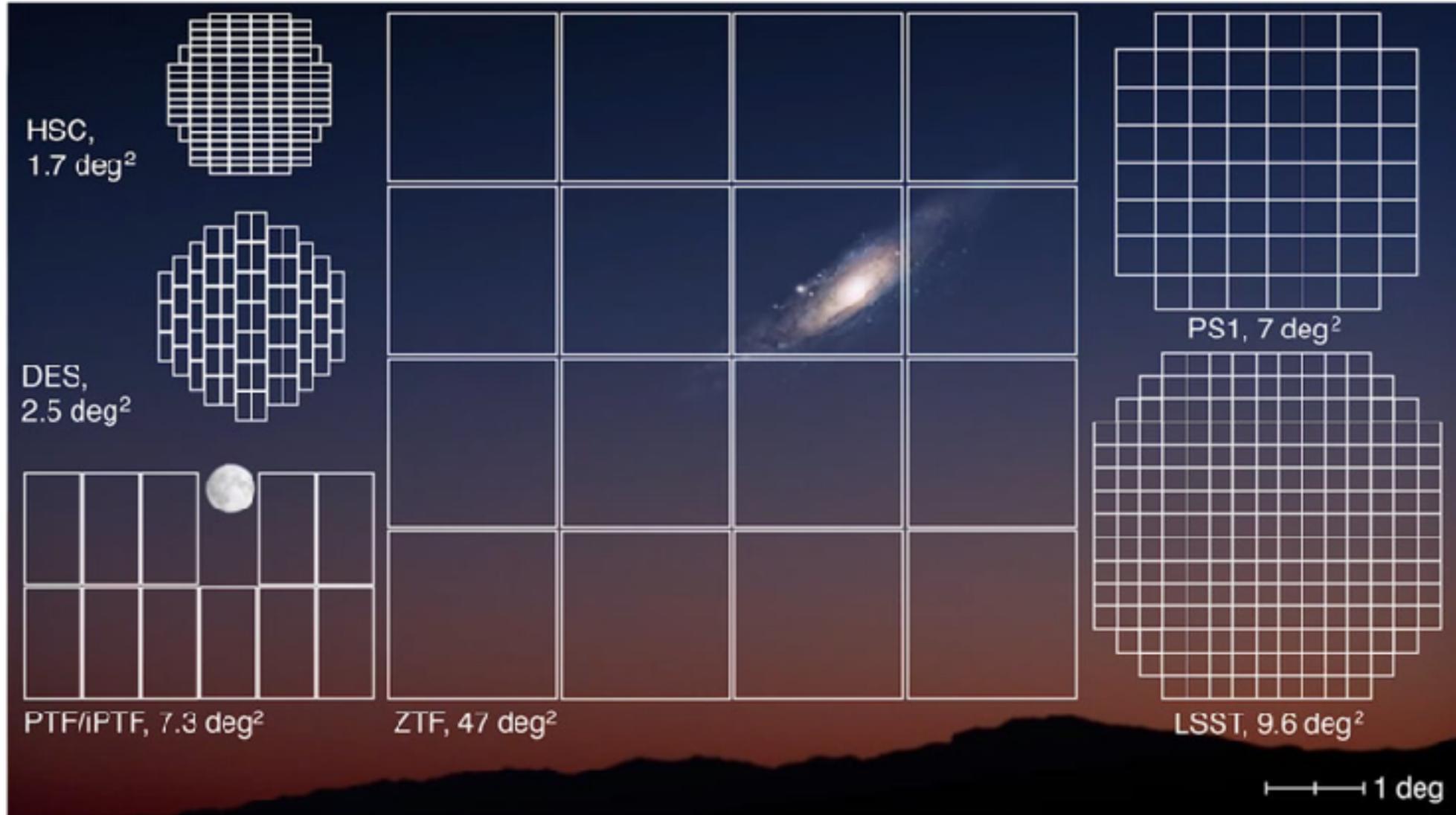


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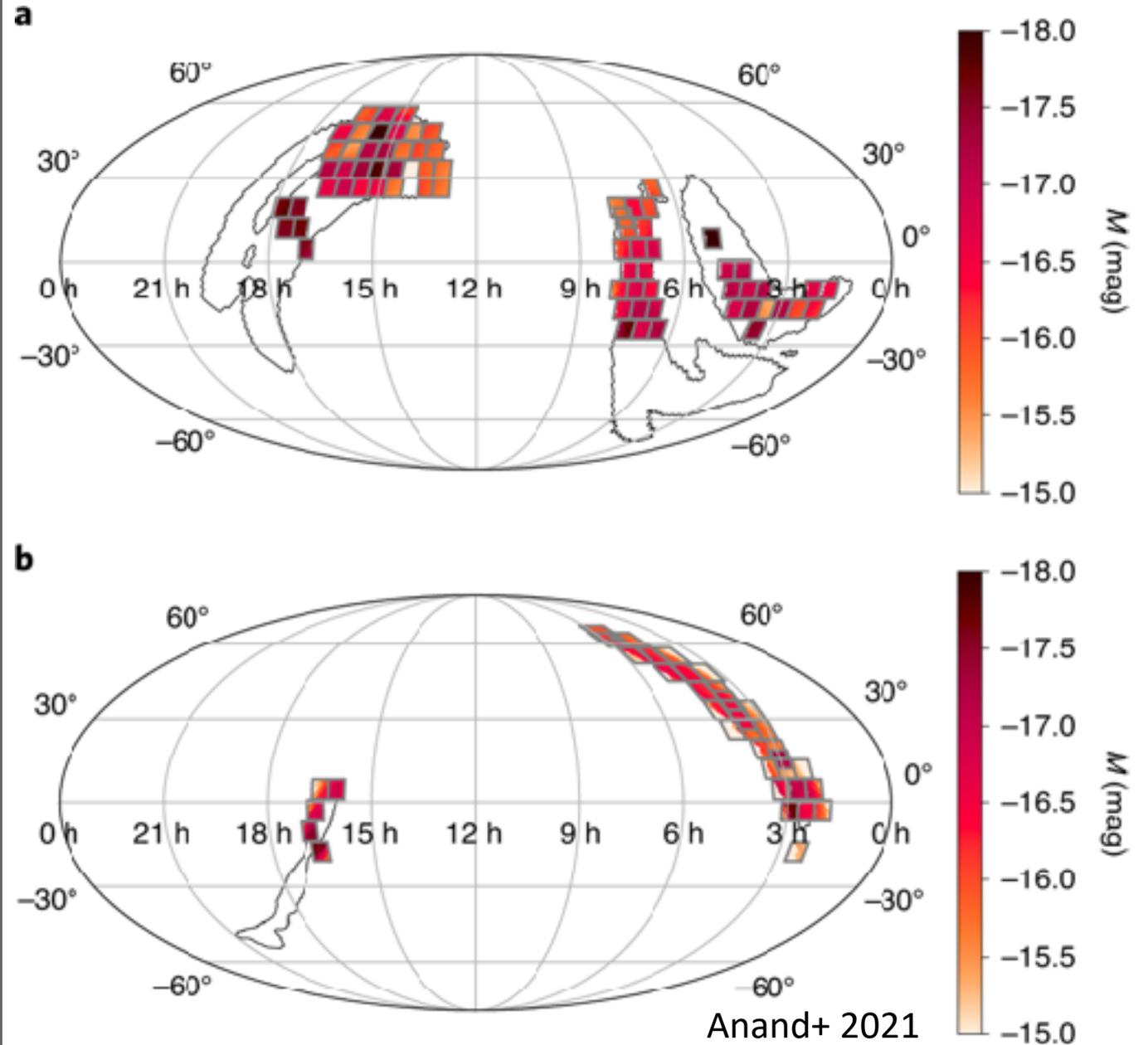


Chang+ in prep.

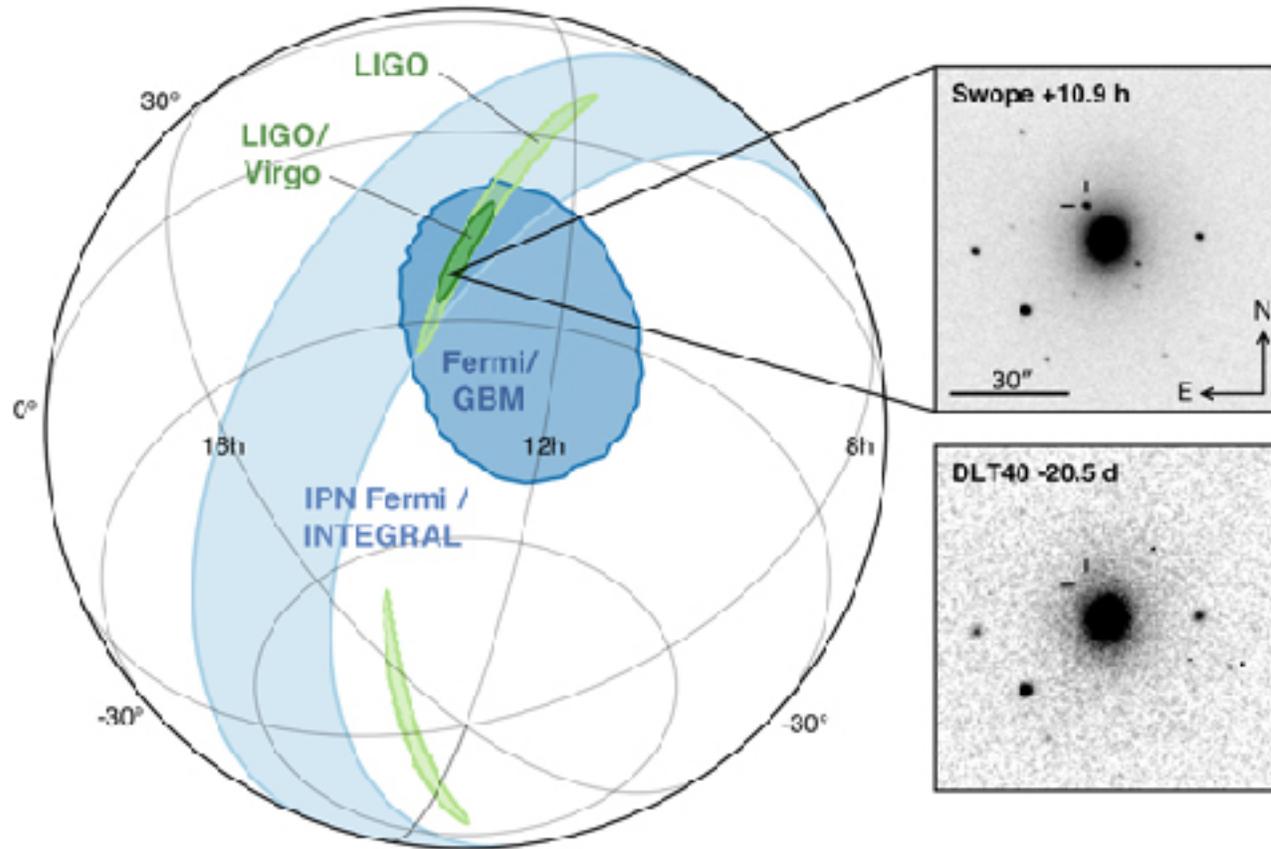
# Field-of-view of optical survey telescopes



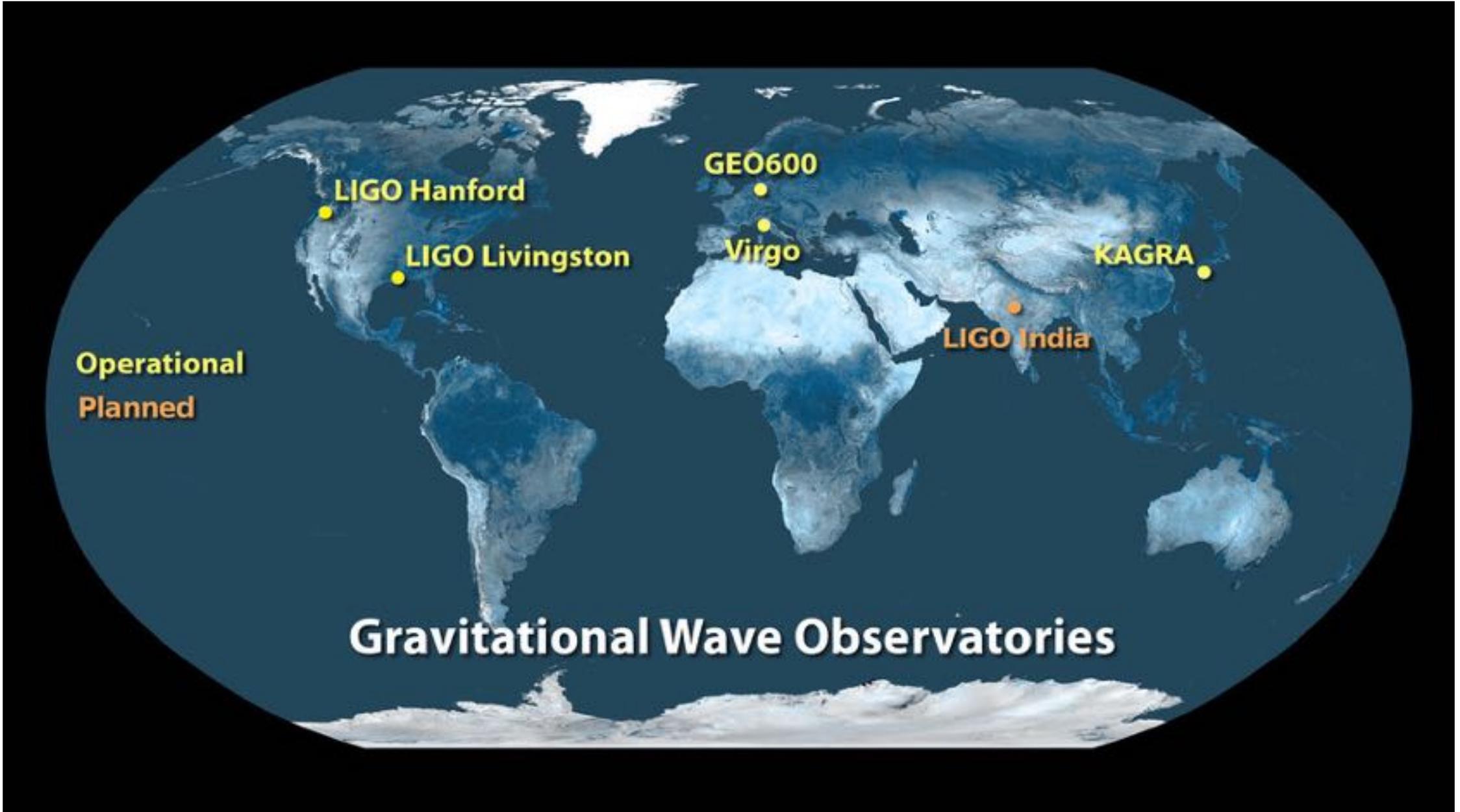
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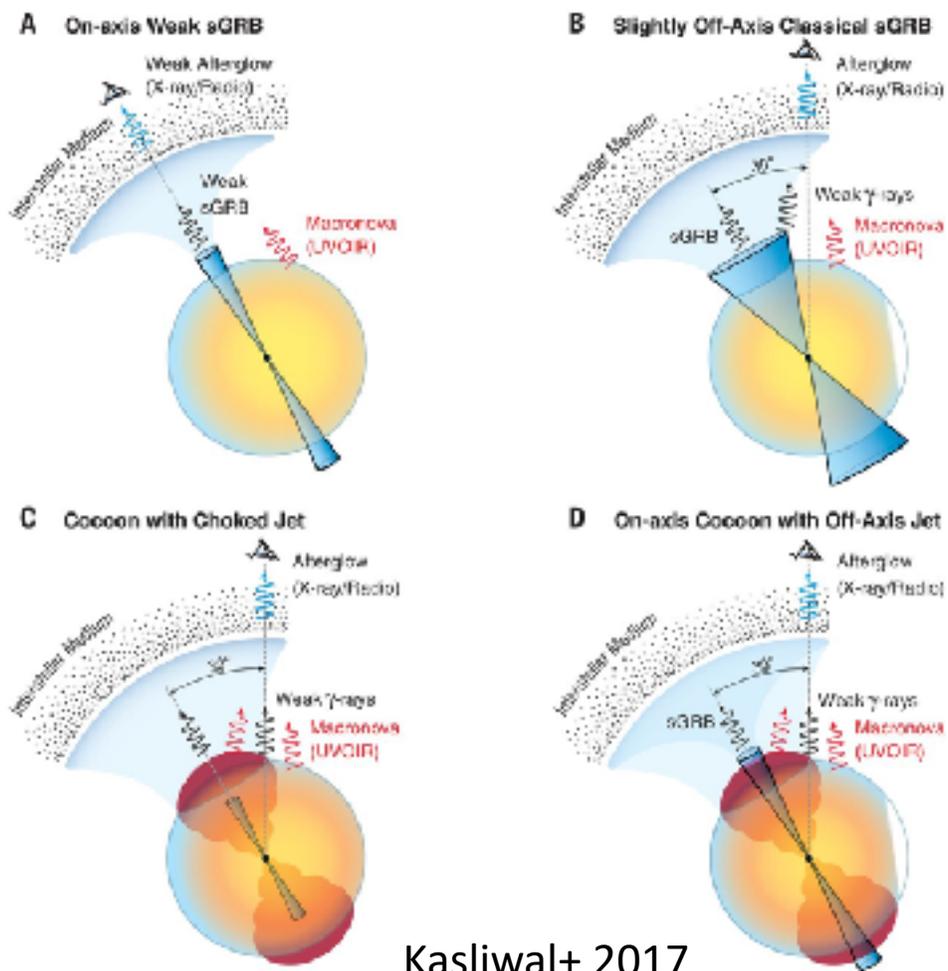
# Multi-messenger is difficult for GW events



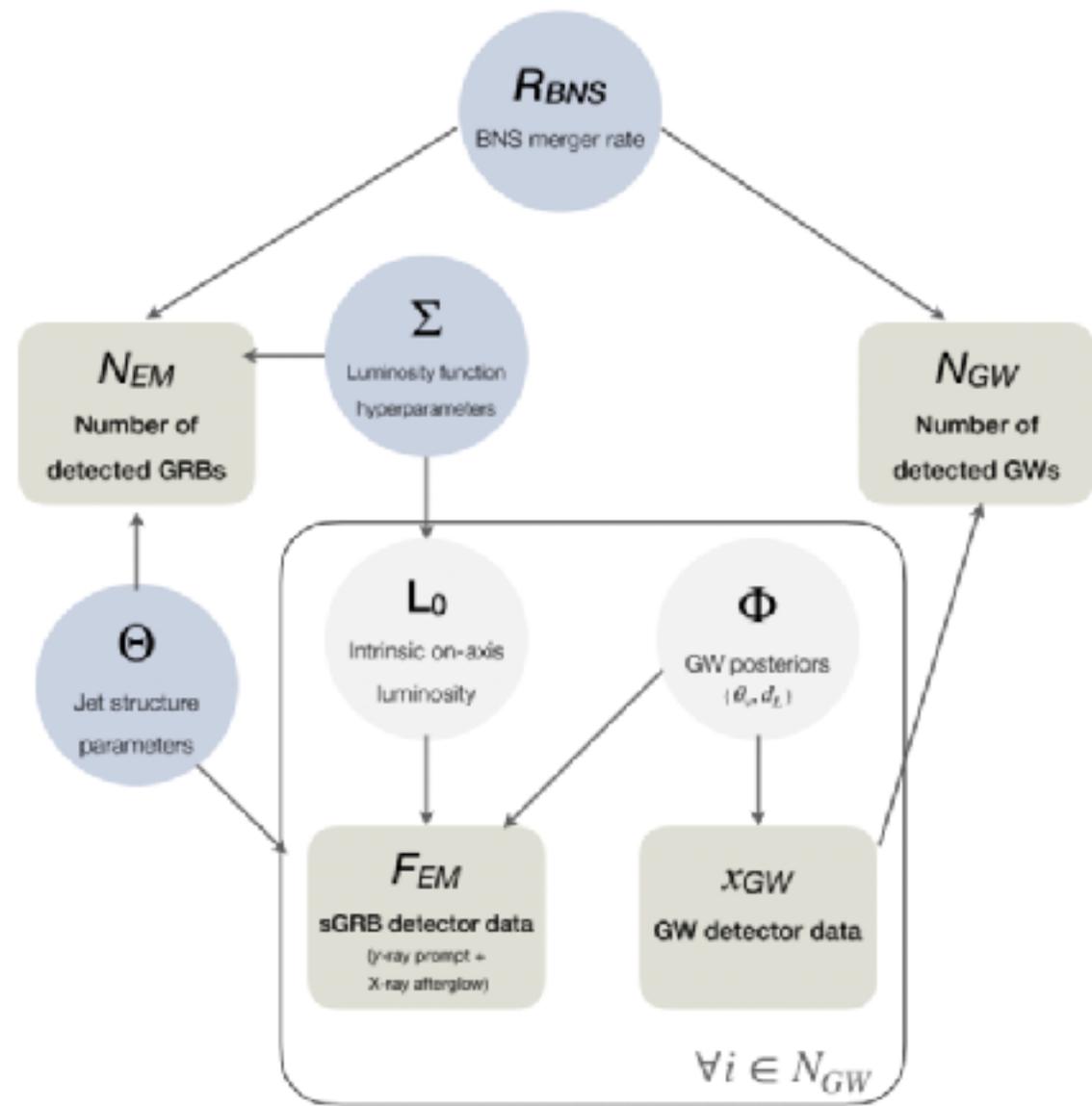
- With LIGO's Hanford and Livingston only
- Localisation:  $O(100)$  deg<sup>2</sup>
- GW170817: 190 deg<sup>2</sup> (LIGO only)  
31 deg<sup>2</sup> (LIGO+Virgo)
- Three or more detectors are required for triangulation
- Four detectors can localise a unique position by just using time delay



# Everything is connected

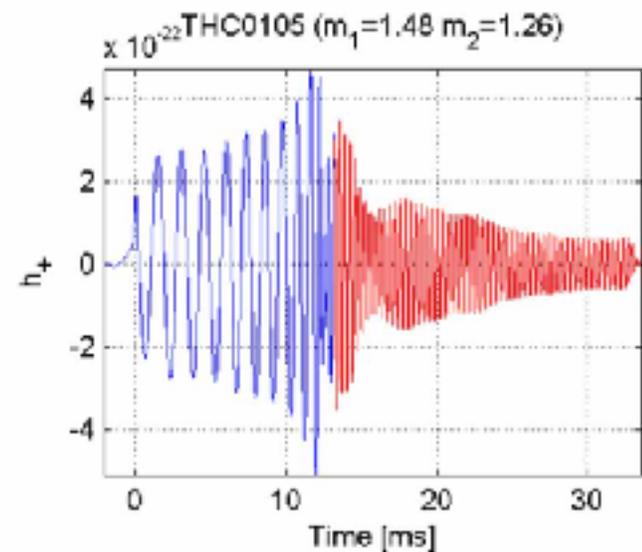
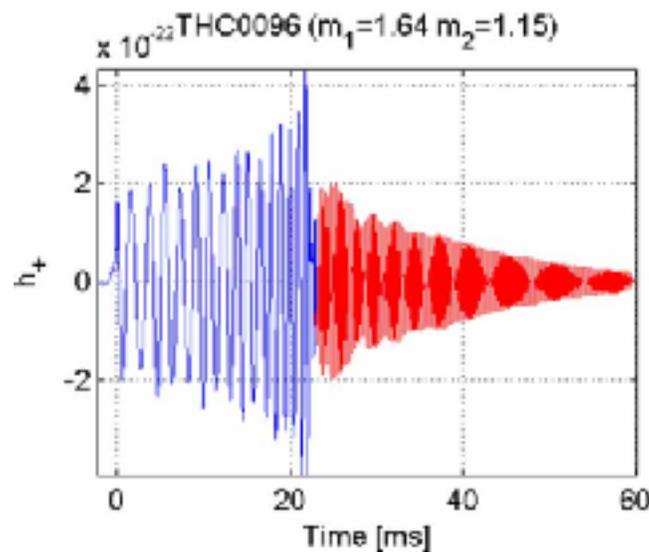
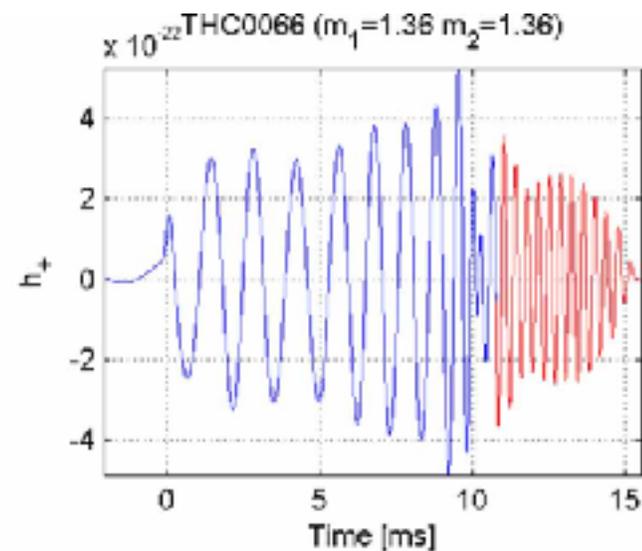
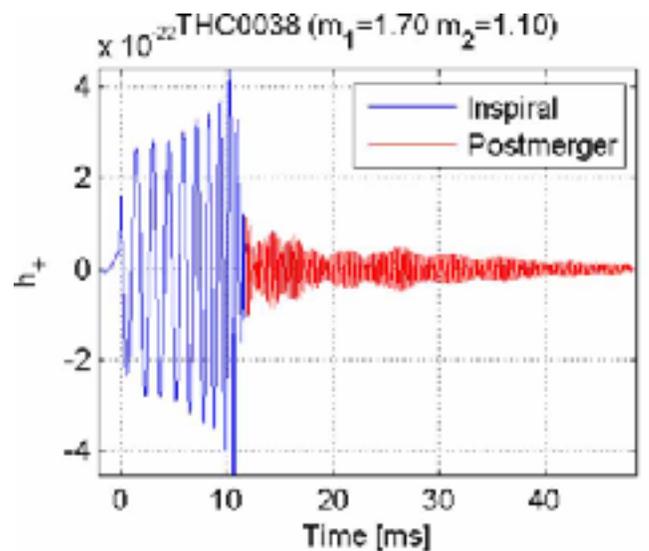


Kasliwal+ 2017

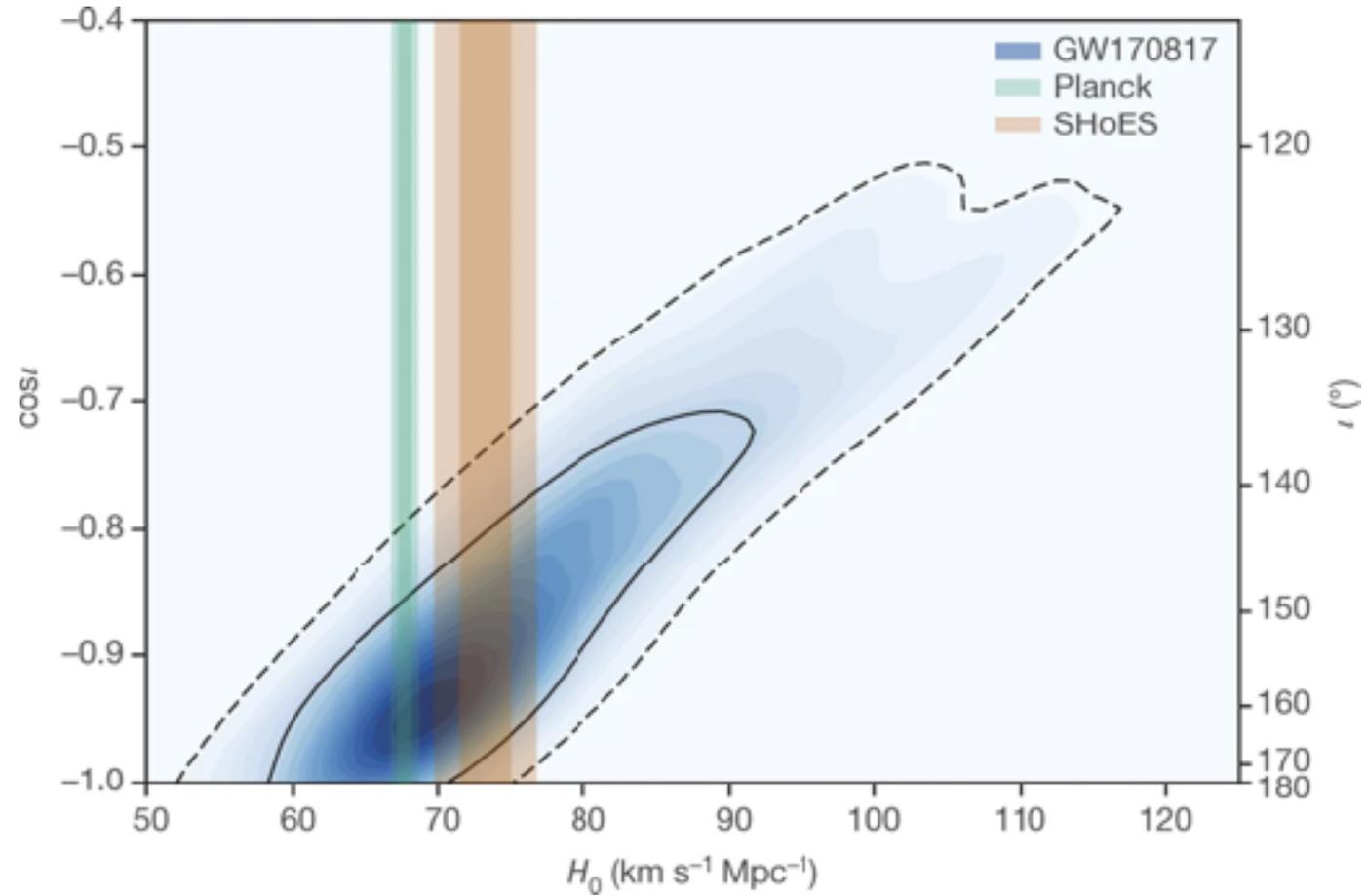


Lin+ in prep.

# Postmerger GWs from BNSs



# GW as a cosmological probe

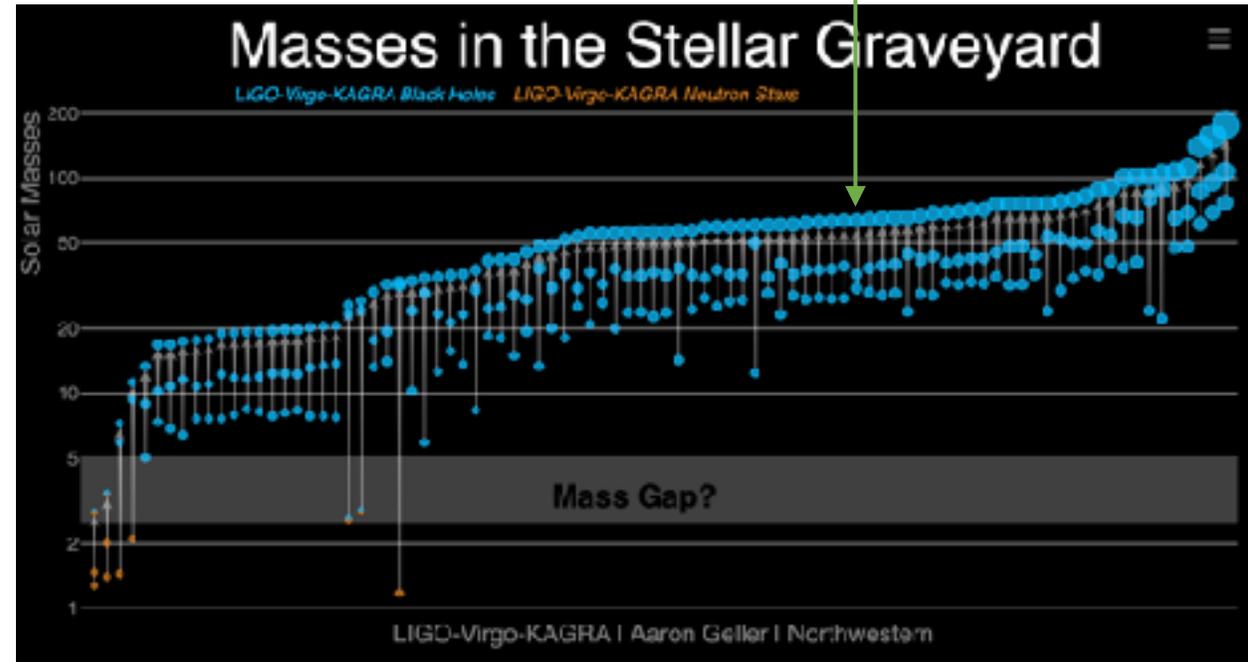
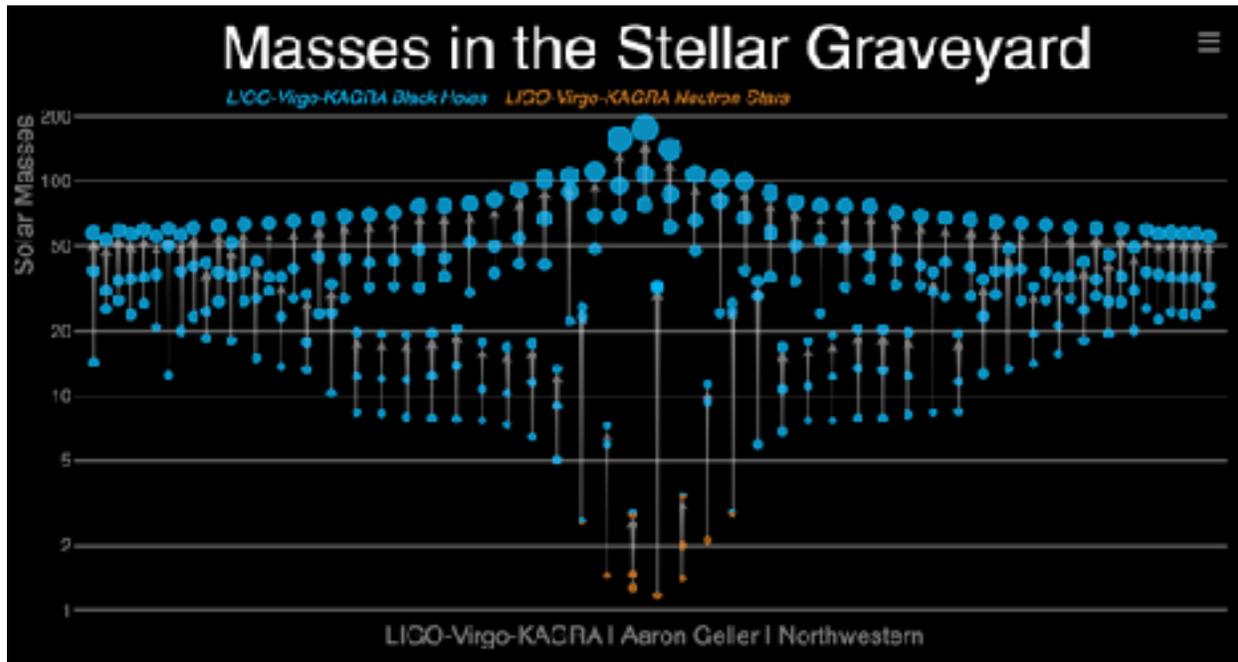


LV Collaboration et al. 2017

# Discovery of Intermediate-mass Black Holes

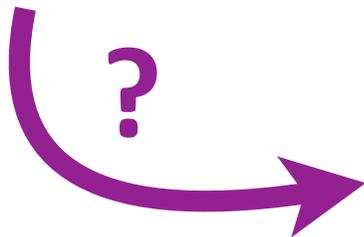
- Three (in O1-O3) in total
- The most massive one (in O1-O3) is  $142 M_{\odot}$ 
  - GW190521 ( $85+66 M_{\odot}$ )

The first GW event

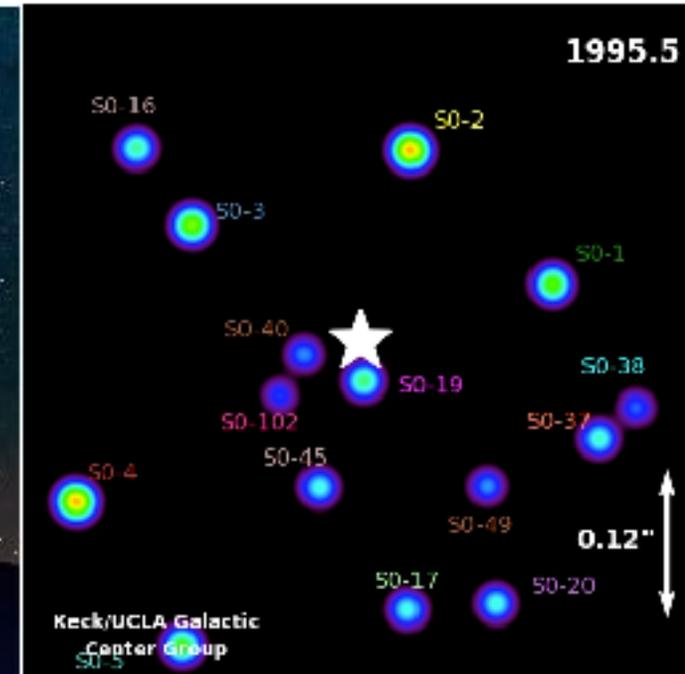


# Key messages from GW and EHT

- Black hole is real!
- Multiple black holes can merge together
- How do supermassive BHs form in the early universe?
  - Intermediate-mass BHs can help



Supermassive BHs ( $\sim 10^6-9 M_{\text{sun}}$ )



# Intermediate-mass BHs (IMBHs)

- One of the exciting discoveries from GW observations is the detection of IMBHs. They can grow becoming more massive BHs (e.g. Matsushita+ 2000).
- One simple method to look for IMBHs before GW observations is using X-ray observations.
  - Ultraluminous X-ray sources (ULXs)
  - Searching for off-nuclear X-ray sources with luminosity above the Eddington limit of a stellar-mass BH (say,  $> 10^{40}$  erg/s).
- EM observations can only probe the relatively nearby universe while GW can look into the high-z universe.
- Comparing the two populations will allow us to investigate their correlation.

# What do we expect in O4 (20 months)?

- Expect  $O(300)$  binary black holes
- Expect  $O(10)$  events containing neutron stars (Colombo+ 2022)
  - Hopefully  $\sim 1$  MMA event
  - Virgo and KAGRA will be crucial (even with low S/N KAGRA data)
- Early warning pipelines have been implemented
- Constraints on the maximum mass of black hole and neutron star
- Better constraints on rates, populations, formation channels, and cosmological parameters
- GW from exotic binaries such as FRB and magnetar?
- Continuous GW from neutron stars?
- If we are really lucky, GW from a nearby core collapse supernova

# The golden era of multi-messenger astronomy

- LIGO-Virgo-KAGRA
- IceCube, KM3Net
- X-ray/gamma-ray: Einstein Probe, Swift, Chandra, XMM-Newton, IXPE, CTA, LHAASO, HAWC, and many smaller missions
- Radio: ALMA, VLA, FAST, SKA
- Optical/IR survey: Rubin Observatory, Euclid, Roman
- Countless numbers of small (1m class) optical telescopes