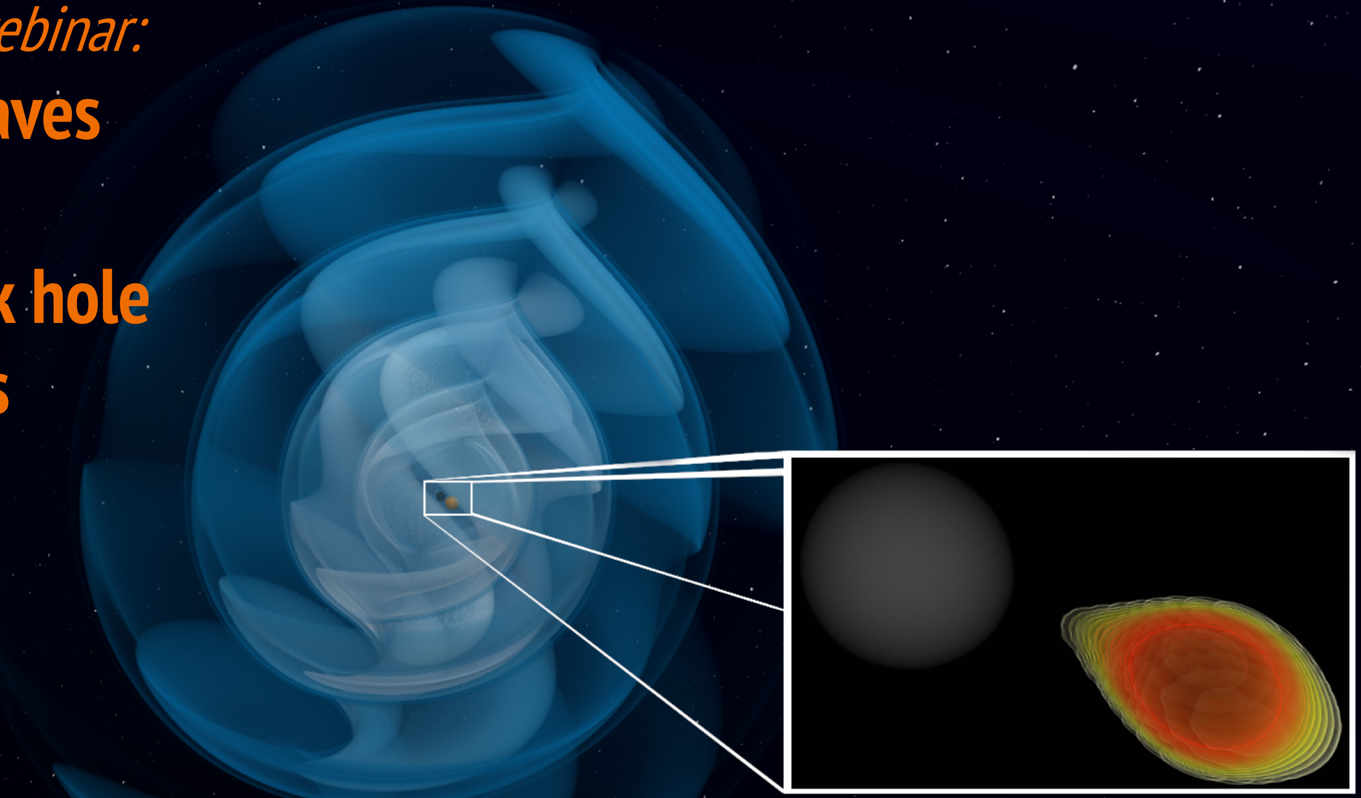
LIGO-Virgo-KAGRA webinar:

Gravitational waves from neutron star-black hole coalescences

July 1, 2021



ApJL 915 L5 (2021)

arXiv:2106.15163

Data releases:
GW200105_162426, GW200115_042309

These slides:
https://dcc.ligo.org/G2101412

LSC LIGO Scientific Collaboration VIRGO KAGRA

Visualisation: T. Dietrich, N Fischer, S. Ossokine; AEI, UP

Speakers & their topics

Speaker	Topic
Astrid Lamberts Observatoire Cote d'Azur, Nice	What are neutron stars, black holes & gravitational waves?
Guillermo Valdes Texas A&M University	How do gravitational wave detectors work?
Bhooshan Gadre Albert-Einstein Institute, Potsdam	How did we detect these signals?
Leo Tsukada Penn State University	What are the properties of the binaries?
Soichiro Morisaki Univ. Wisconsin, Milwaukee	What do we know about the smaller objects?
Chase Kimball Northwestern University	What does this teach us about astrophysics?
Harald Pfeiffer Albert-Einstein Institute, Potsdam	Moderator

Q+A Panelists

- Tim Dietrich — University of Potsdam
- Reed Essick — Perimeter Institute
- Maya Fishbach — Northwestern University
- Otto Hanuksela — Utrecht University
- Anarya Ray — Univ. Wisconsin, Milwaukee

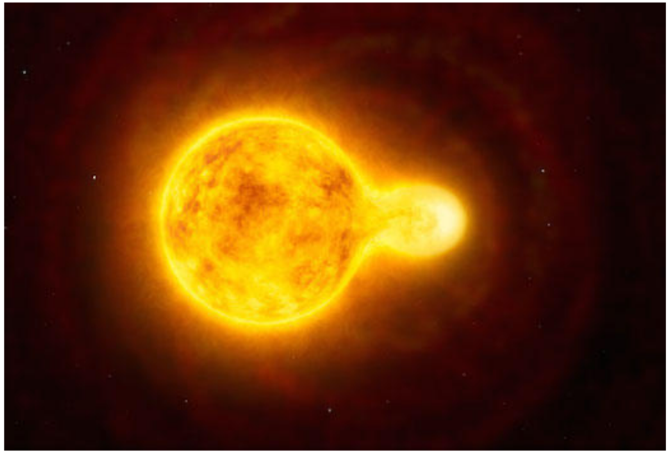
Please type questions into Q+A at any time.

Black holes and neutron stars: compact objects

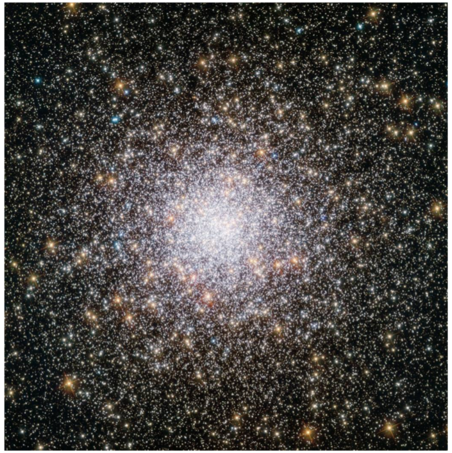
Compact objects: unique way to study massive stars (1 out of 10 000 stars)

- Stars with ~8 to ~20 $M_\odot$ → neutron stars
- Stars above ~20 $M_\odot$ → black holes

Most massive stars form in pairs, triples or dense groups => many interactions



Interacting binary HR5171 Credit ESO

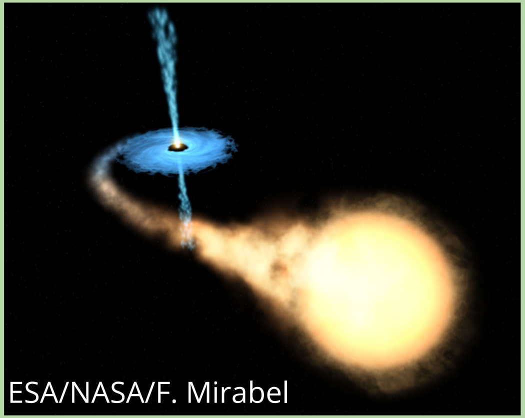


Cluster NGC 362 Credit: ESA/Hubble& NASA

Compact objects = often dark objects

With electromagnetic observations

X-ray binary



ESA/NASA/F. Mirabel

Pulsar binary

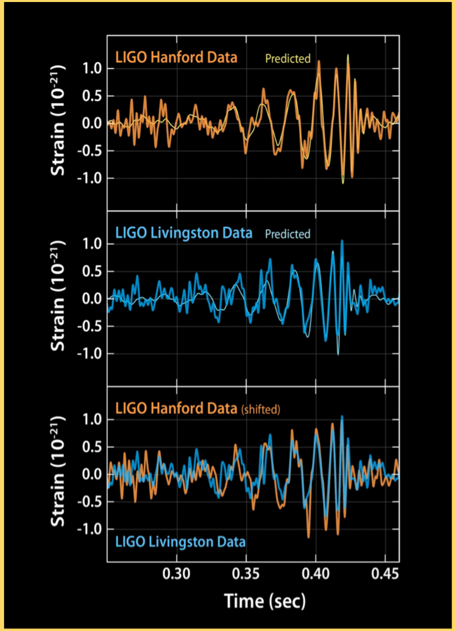
Arecibo Observatory/U. Of Central Florida

Black hole binary

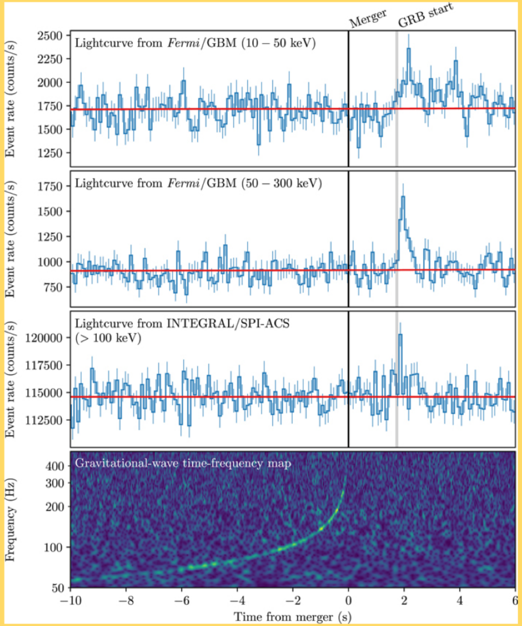
Compact objects = mostly dark objects

Gravitational Waves

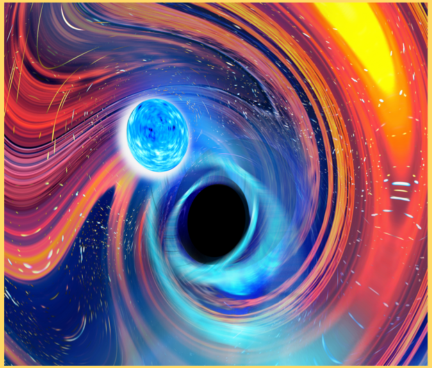
GW150914: BBH



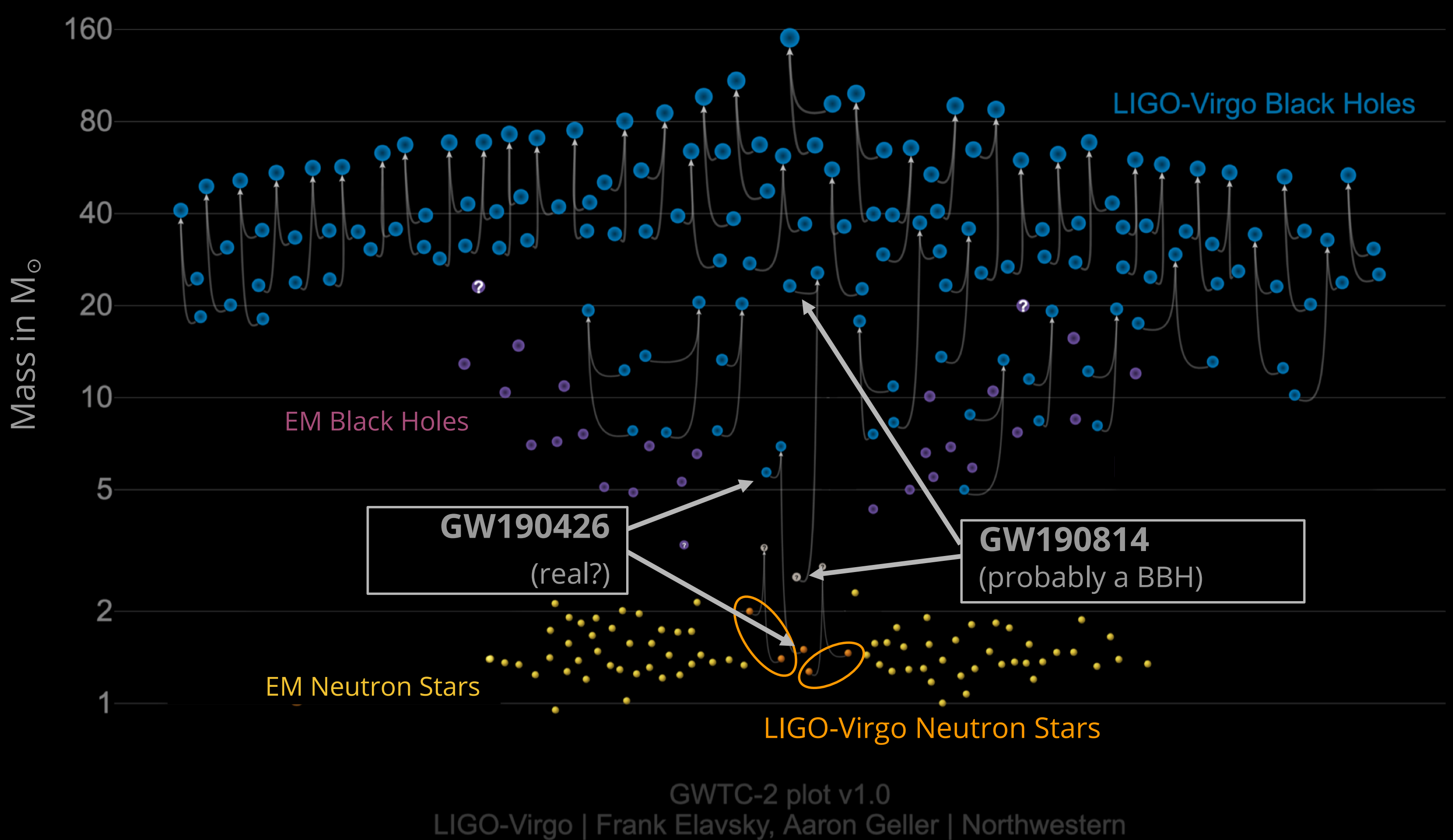
GW170817: BNS



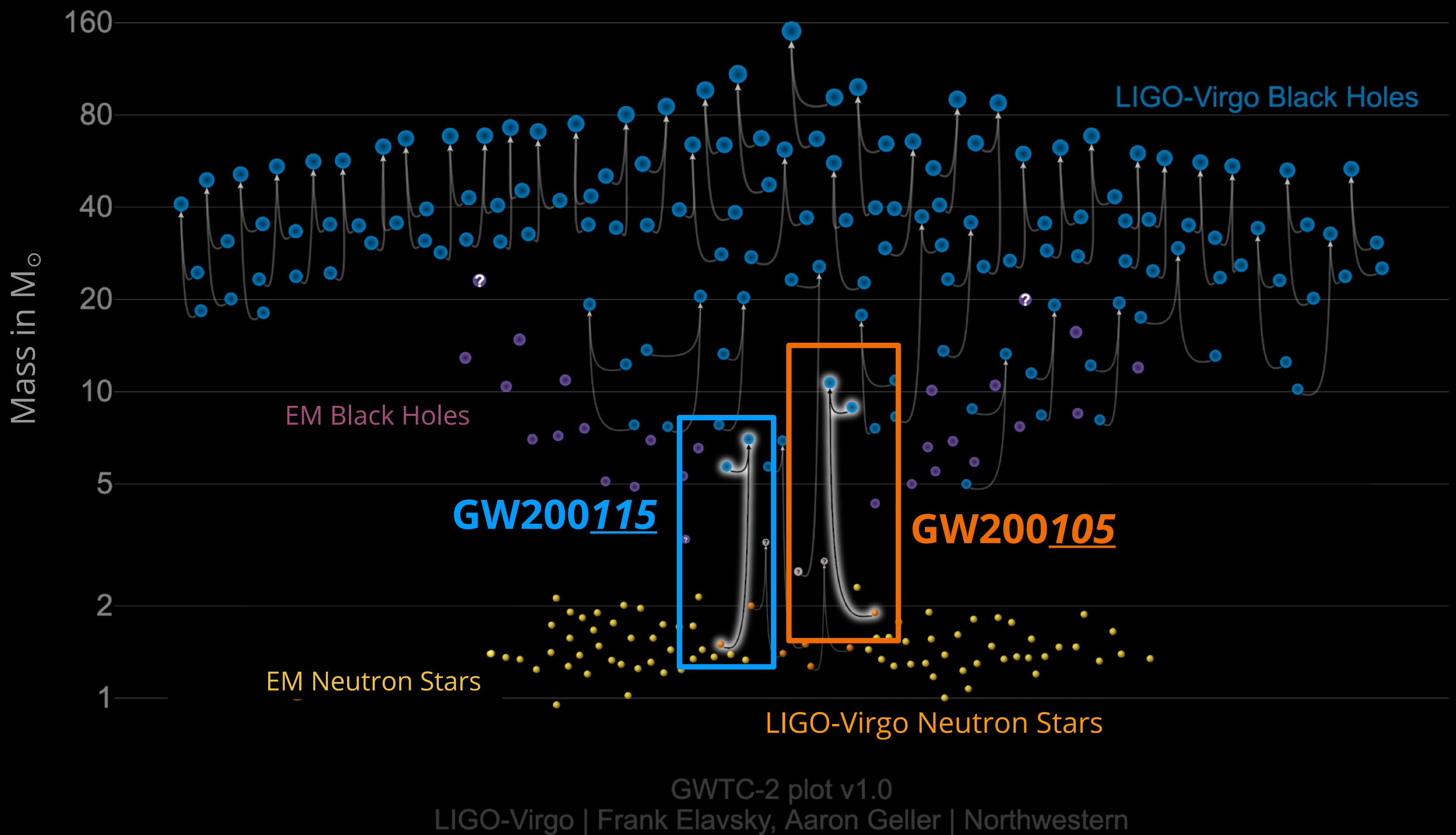
2020: NSBH



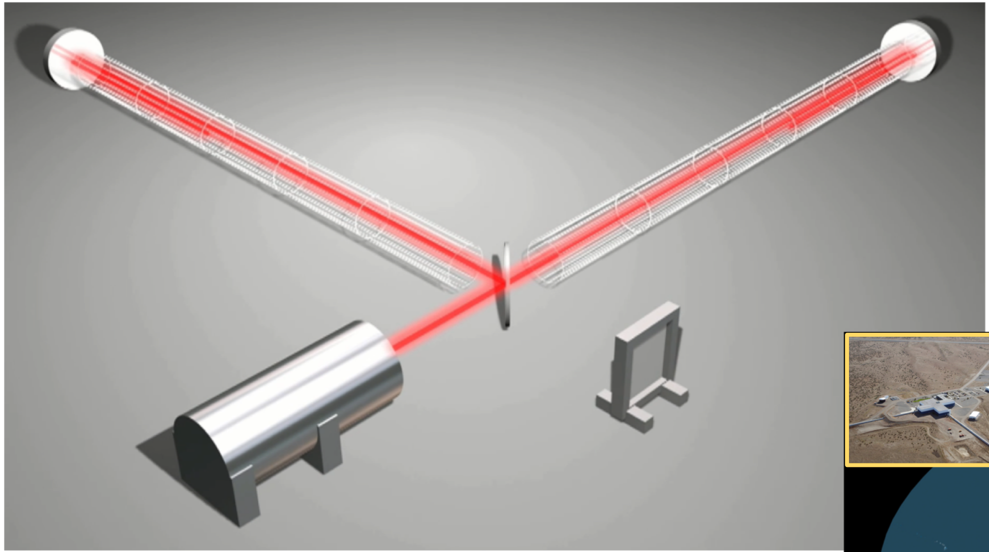
The 2nd Gravitational Wave Transient Catalog (GWTC2)



Today's new observations

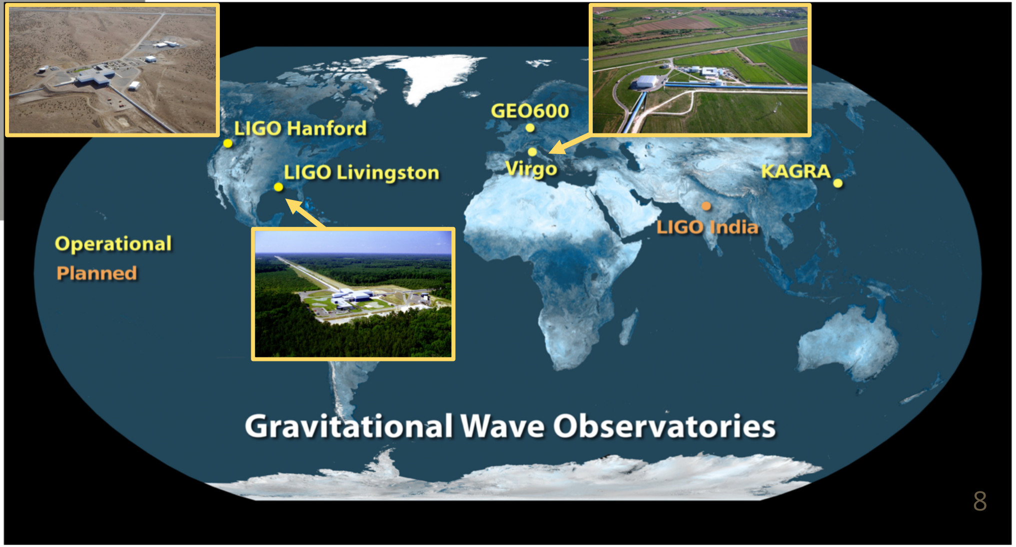


How do we detect gravitational waves?



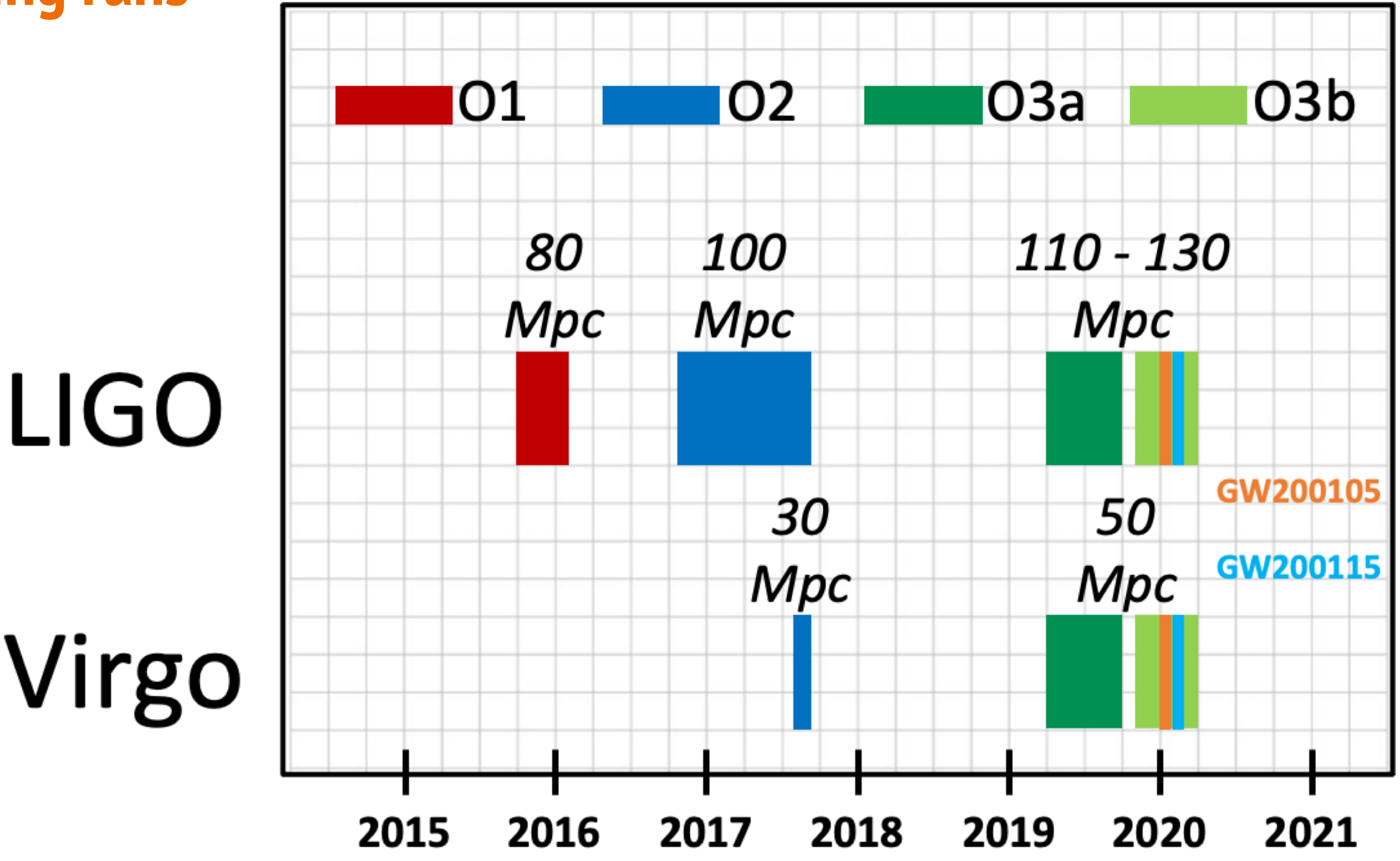
Laser interferometer inside each detector.

- Gravitational-wave detectors are extremely sensitive instruments.
- LIGO and Virgo are detectors with 4 km and 3km long arms, respectively.

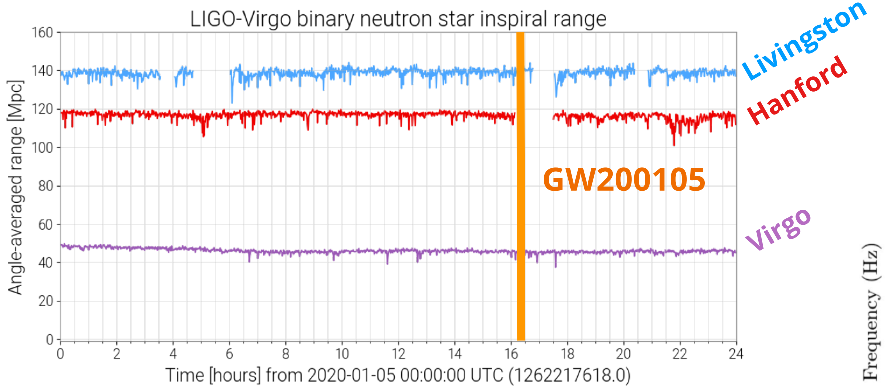


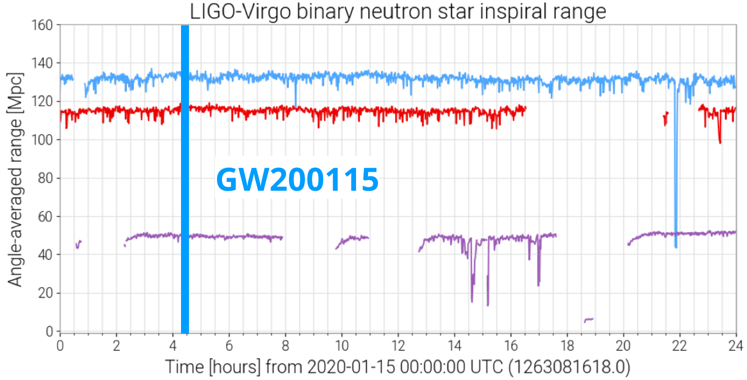
Gravitational-wave observatories across the globe.

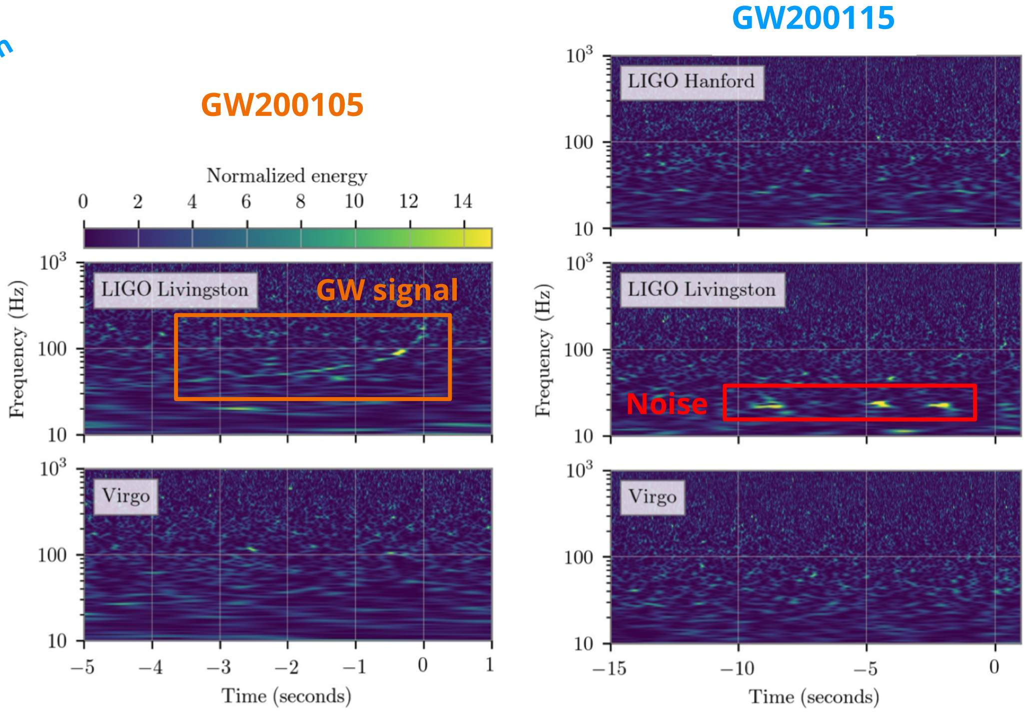
Observing runs



Detectors status at the time of GW200105 and GW200115

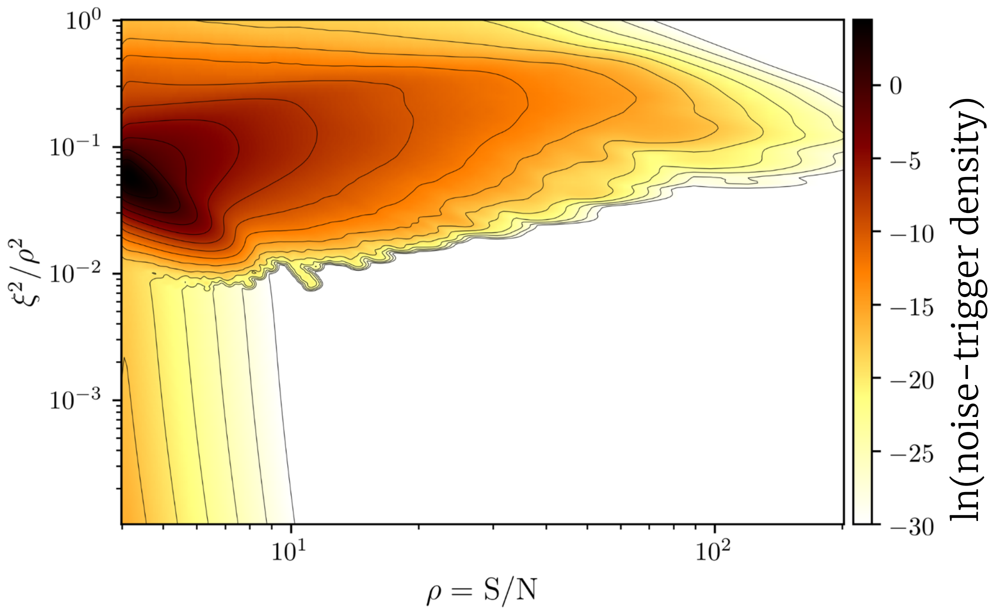






Time–frequency maps of data containing GW200105 (left) and GW200115 (right).
Times relative to the signals' merger times, Jan 05, 2020 at 16:24:26 UTC and Jan 15, 2020 at 04:23:10 UTC.

Detector Noise and Background



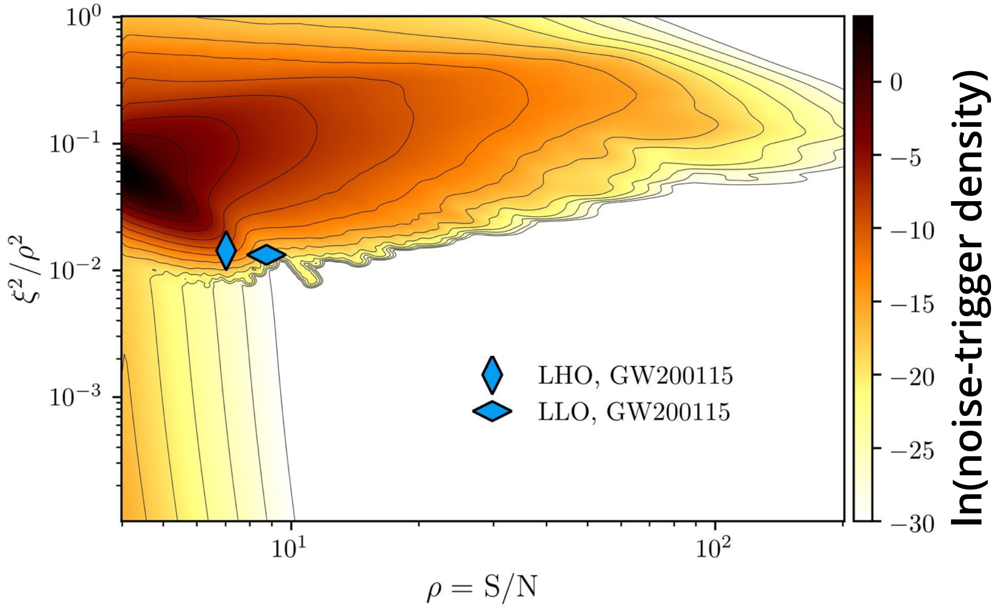
Joint SNR–ξ^2 noise probability density function
(Hanford+Livingston+Virgo, M_{chirp}< 4 $M_{\odot}$ for O3 data)

- **S/N (ρ) is not enough** in CBC search
  - ***Non-stationary***, ***non-Gaussian***
  - Signal **consistency** autocorrelation **ξ^2**

- **Large SNR + Low ξ^2 / SNR^2**
  - Farther from the background
  - More likely **Astrophysical**

➔ Multi-detector **coincidence** → confident detection

GW200115: Coincident Multi-Detector Observation

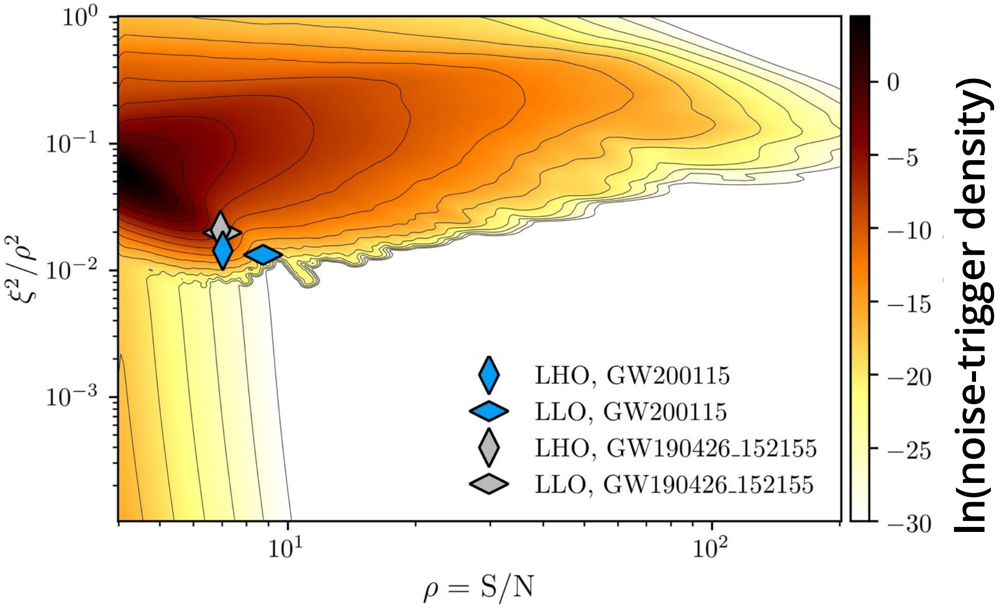


Hanford and Livingston triggers for **GW200115**

- **GW200115**: A **coincident** event
- H1 or L1: Do not stand out individually
- Significance (**F**alse **A**larm **R**ate):

  From **1/ (182 yr)** to less than **1 / (10^5 yr)**
- **GCN Notice** to astronomers after **6 mins**

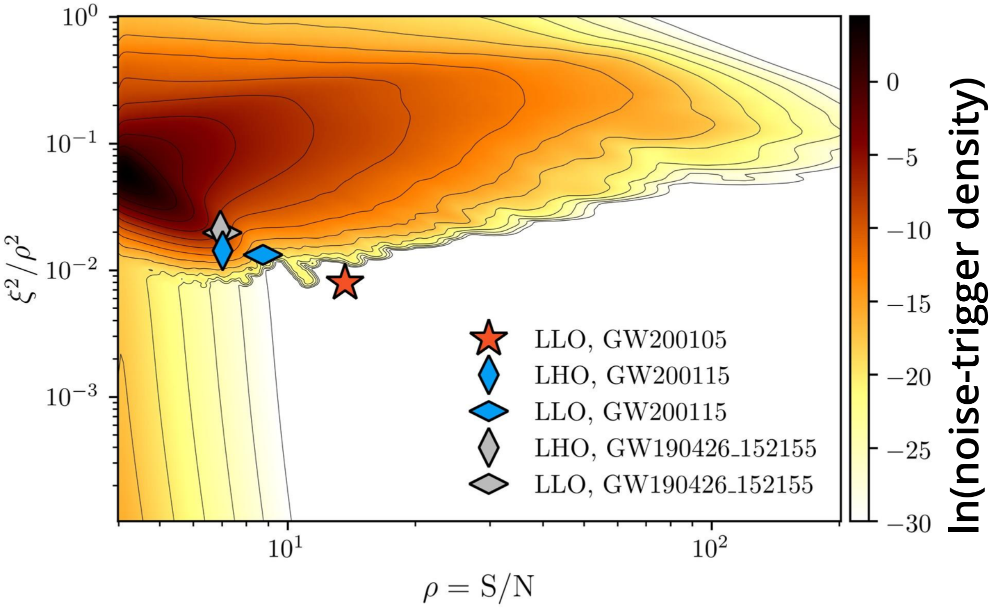
When even Coincidence is not Enough!



Hanford and Livingston triggers for **GW190426_152155**

- **GW190426_152155**, A **marginal coincidence**!
- Buried in noise distribution
  - **SNRs < 7**, Larger ξ^2 / SNR^2
  - Coincident **FAR ~ 1 / (1.4 yr)**
  - Astrophysical or noise??
- **Very low SNR + coincidence → Not helpful**

GW200105: L1 only Single-Detector Observation

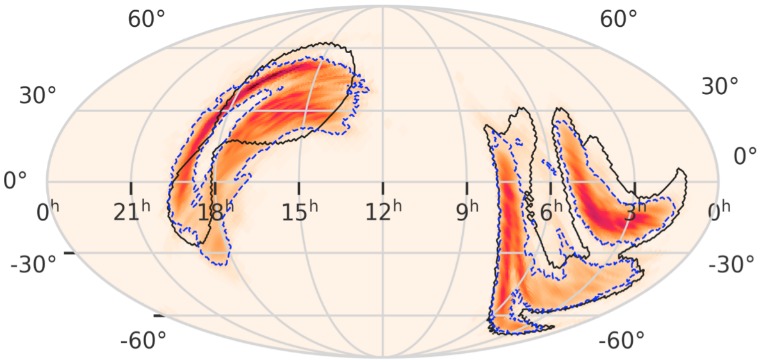


Livingston only trigger for **GW200105**

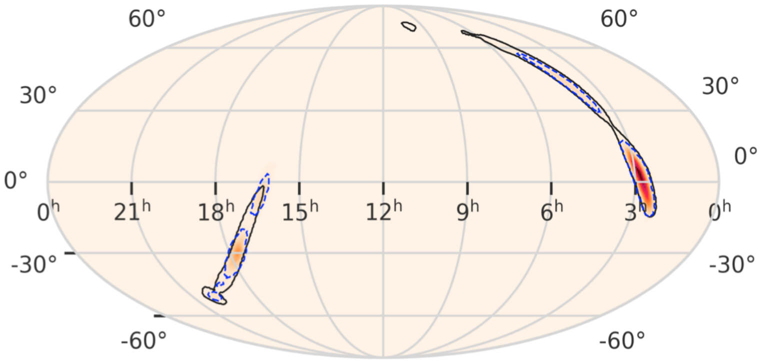
- Observed by **L1** and **V1** /w SNR
  - Livingston: **13.6**
  - Virgo: 2.7 (very weak)
- **GW200105** in **L1 (★): distinctly** separate
- Significance as **FAR**
  - Inverse of observation time
  - **Extrapolation** assuming noise properties → **1 / (3 yrs)**
- **GCN Notice** to astronomer after **1 day**!
  - Further checks for authenticity

Sky maps and Multi-Messenger Astronomy

GW200105



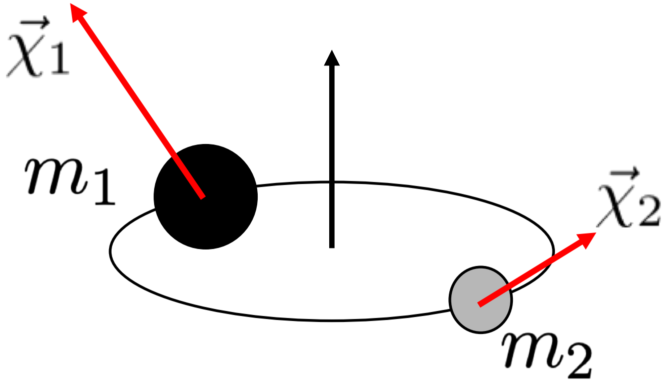
GW200115



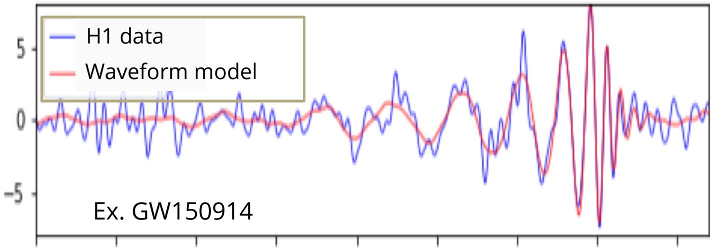
Detectors	Livingston + Virgo	Hanford + Livingston + Virgo
Sky Localization: Low-Latency	7700 deg^2 (*BAYESTAR*)	900 deg^2 (*BAYESTAR*)
Sky Localization: Improved	**7100** deg^2 (*RIFT and parallel-Bilby)*	**600** deg^2 (*RIFT and parallel-Bilby)*
Luminosity Distance	**170 - 390** Mpc	**200-450** Mpc
# Follow-up GCNs	31 (No EM/Neutrino Counterpart)	21 (No EM/Neutrino Counterpart)

How do we infer masses, spins and other properties?

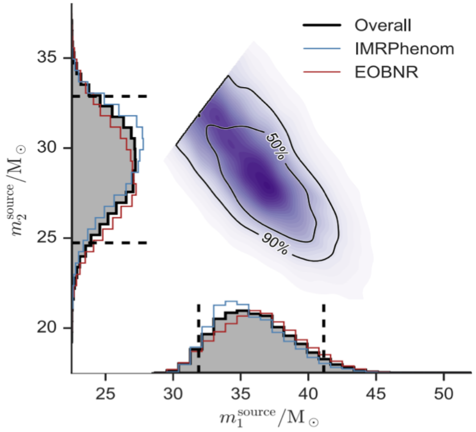
1) Binaries' properties



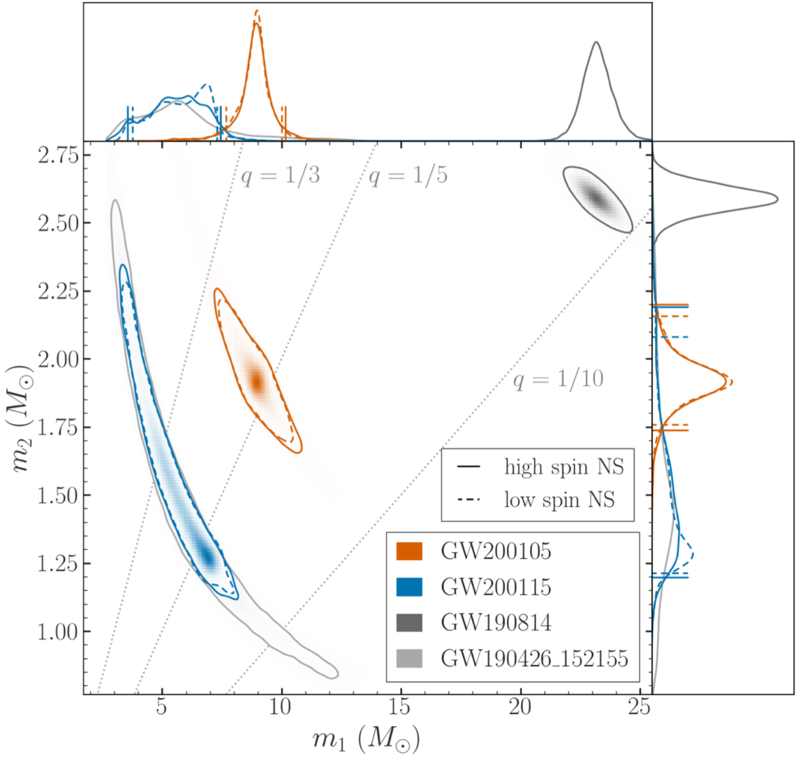
2) Comparison with data



3) Find regions of good agreement



Masses of binary components



	m_1	m_2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

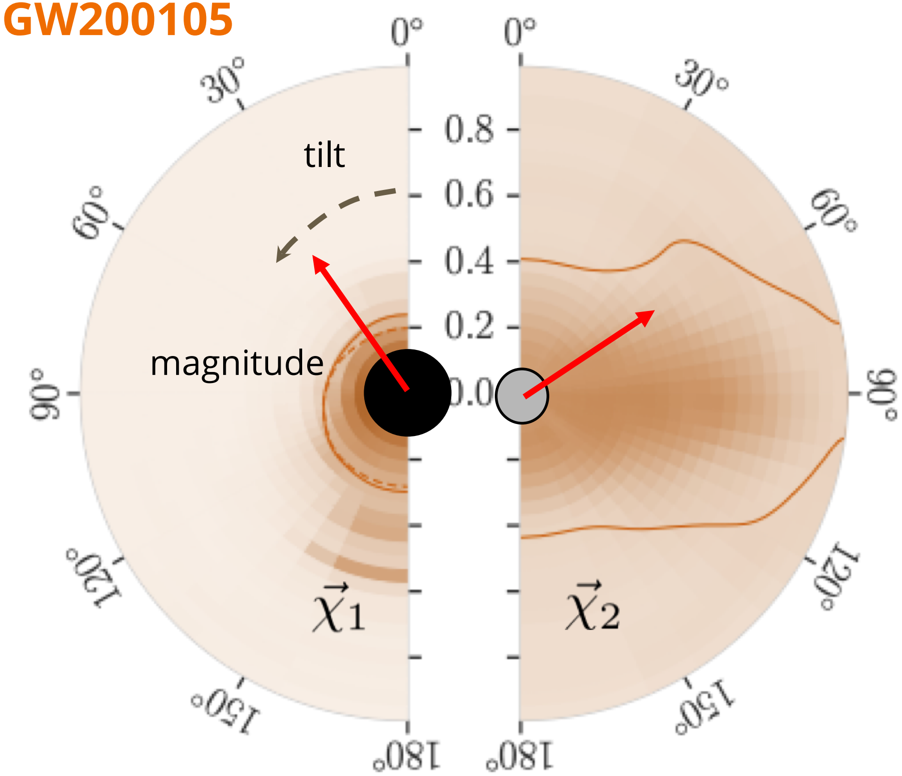
Plausible neutron star

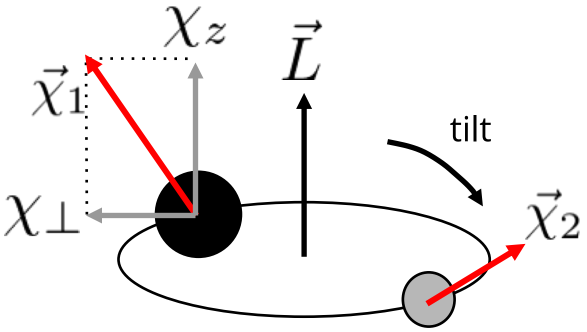
- Modest support for GW200115's primary being in lower mass gap

$$P(3M_\odot \leq m_1 \leq 5M_\odot) = 30\%$$

Component spins

GW200105





$$\vec{\chi} = c\vec{S}/(Gm^2)$$

$$(0 \leq |\vec{\chi}| \leq 1)$$

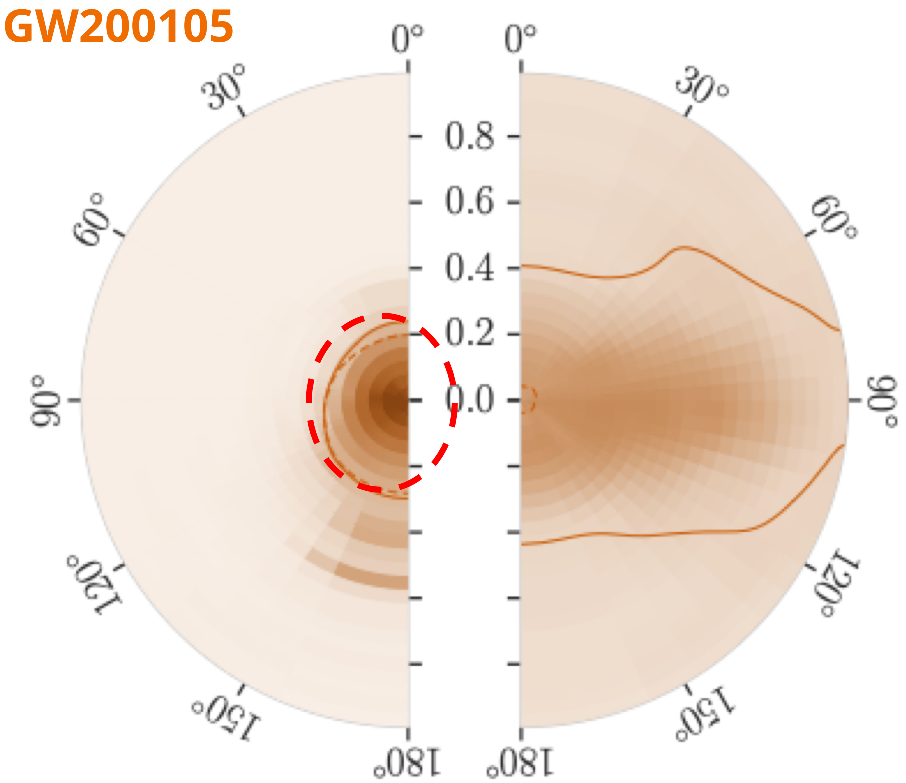
χ_z ⇨ affect phase evolution

$\chi_\perp$ ⇨ cause precession effect

⇩

Binaries' formation channel and environment

GW200105: small primary spin magnitude



- Primary spin

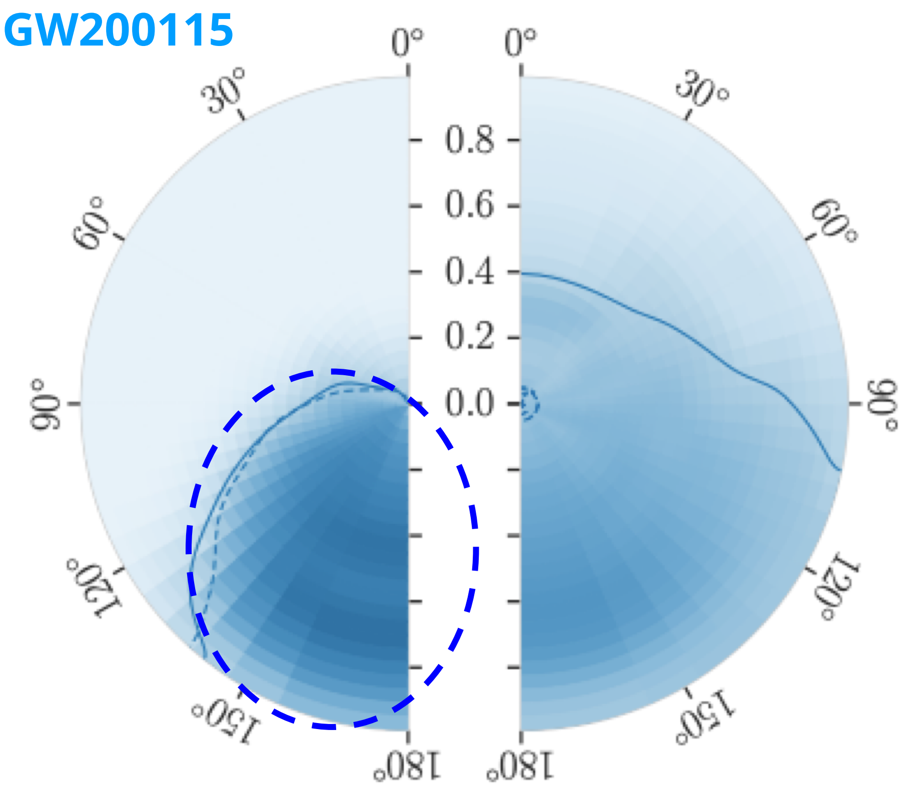
  $|\vec{\chi}_1| < 0.23$ (90% confidence)

  ⇩

  Strong support for small
  Spin magnitude

- Secondary spin
  Broadly unconstrained

GW200115: primary spin likely anti-aligned



- Primary spin

  $$\chi_{1,z} = -0.19^{+0.24}_{-0.50}$$

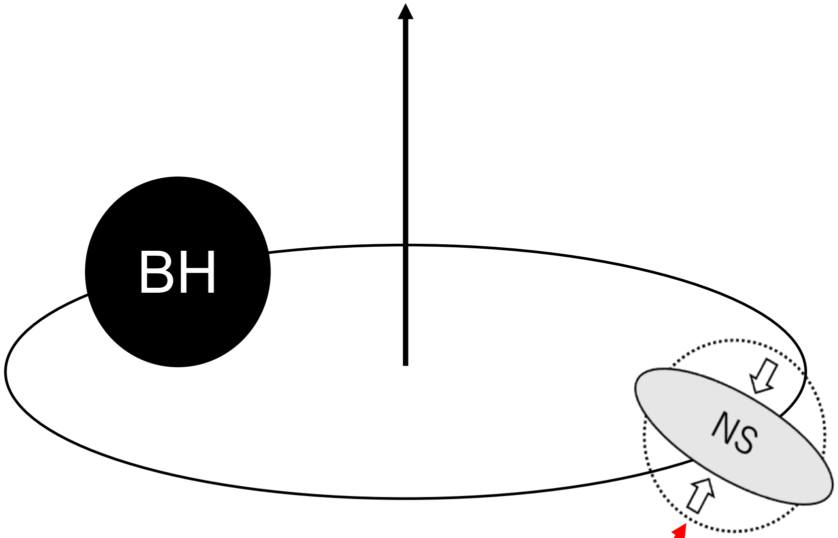
  $$P(\chi_{1,z} < 0) = 88\%$$

  Likely anti-aligned with $\vec{L}$.

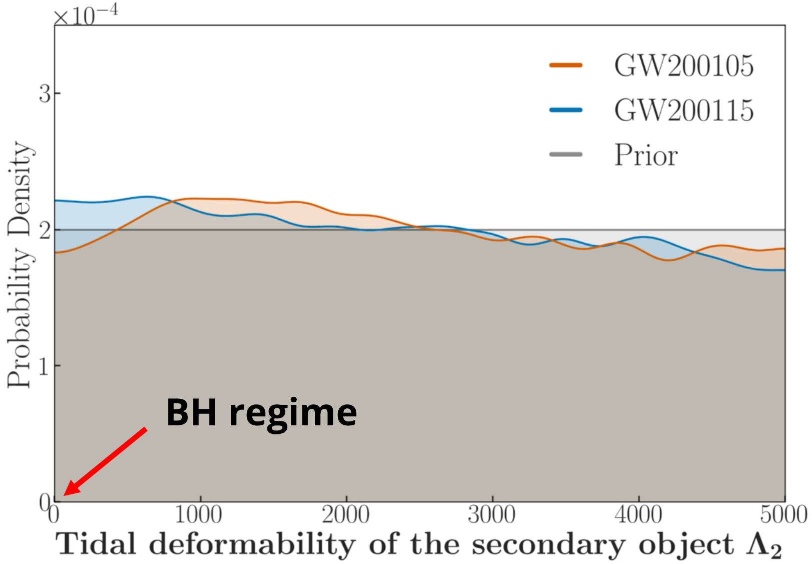
- Secondary spin

  Broadly unconstrained

Matter effects of the secondary objects



Tidal deformation dissipates energy and changes inspiral rate of binary.



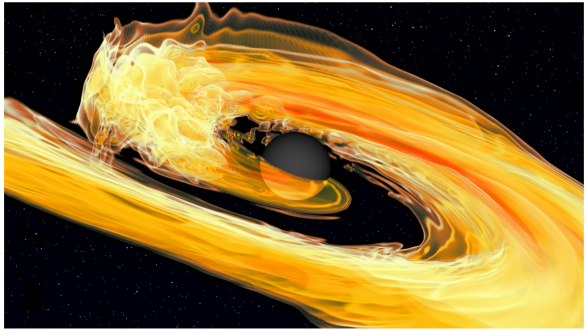
No information on the matter effects of the secondary

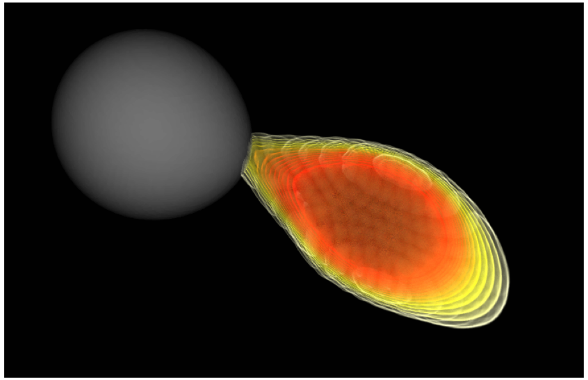
Electromagnetic observations

No significant detections of electromagnetic counterparts for both events.

This is consistent with

- **No** tidal disruption expected due to highly asymmetric masses (and negative spins for GW200115)
- The large distances (~7 times more distant than GW170817) and large uncertainties of their sky localization





Comparison with the maximum NS mass

The maximum mass depends on the uncertain nuclear equation of state.

- **$M_{max,TOV}$** Equation of state inferred from radio, GW, and X-ray observations
  (Landry, Essick & Chatziioannou 2020)
- **$M_{max,GNS}$** Fit to Galactic NS population
  (Farr & Chatziioannou 2020)
- **M_{max}(spin)** Allows for potentially large NS spins (not shown)

$p(m_2 < M_{max}) \sim 95\%$, but do not exclude light BHs (e.g. primordial BH).

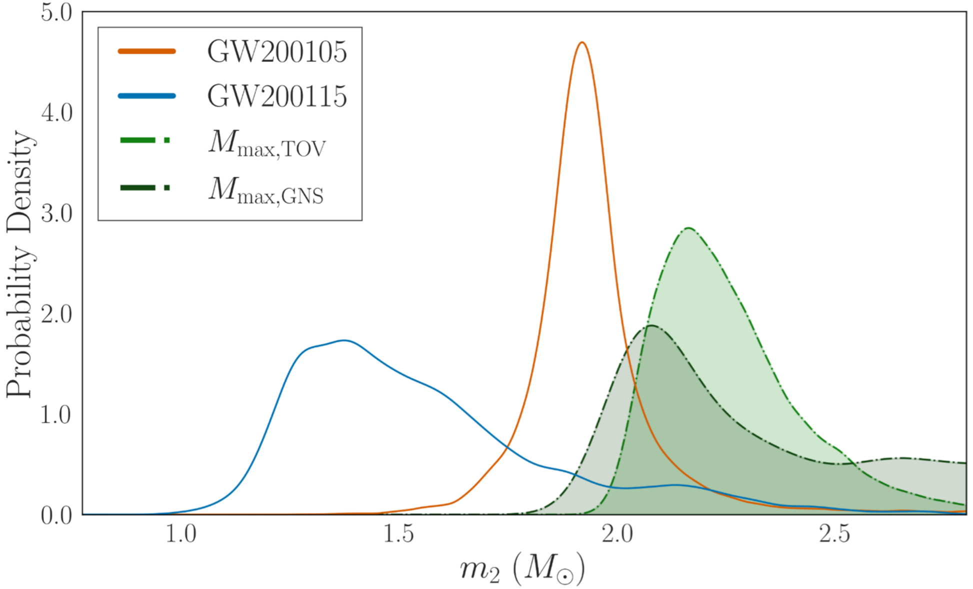
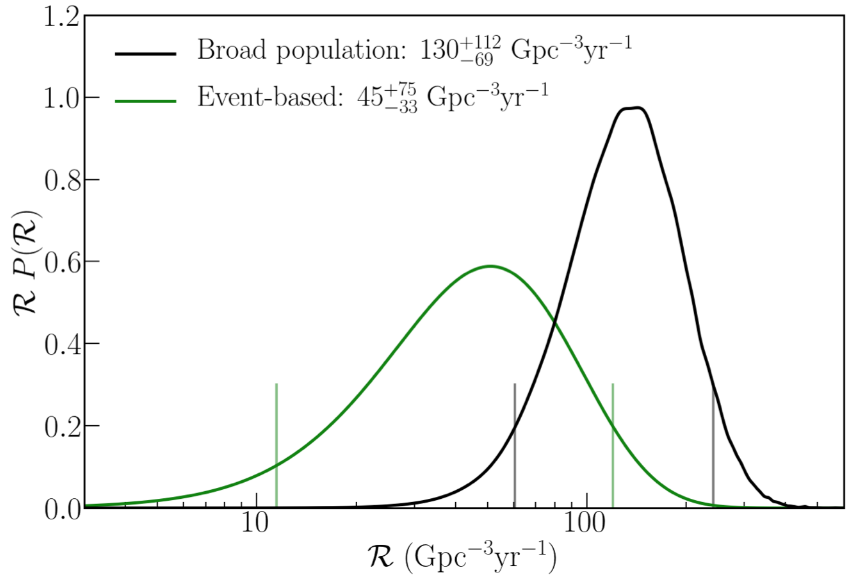


Figure: estimated masses of secondary objects in comparison with the maximum NS mass

NSBH Merger Rate



Event-based rate

- Assumes 1 count each from event-like populations
- **12-120 Gpc^{-3} yr^{-1}**

Broad population rate

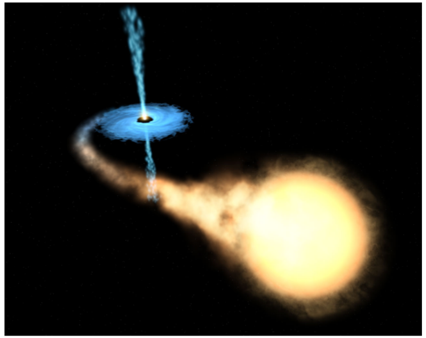
- Includes all foreground triggers in a fixed NSBH-like mass range
- **61-242 Gpc^{-3} yr^{-1}**

All merger rates now empirically measured:

NSBH	BNS	BBH
12-242 Gpc^{-3} yr^{-1}	80-810 Gpc^{-3} yr^{-1}	15-38 Gpc^{-3} yr^{-1}

LVC populations analysis (2020)

Formation Channels



Credit: European Space Agency, NASA, and Felix Mirabel

Isolated binary evolution

- Merger rate **~0.1-800 $Gpc^{-3}yr^{-1}$**
- Large uncertainties due to treatment of **supernova kicks**, **common envelope** treatment

NGC 4755 Credit: ESO

Young star clusters

- Merger rate **~0.1-100 $Gpc^{-3}yr^{-1}$**
- Most NSBHs ejected before undergoing dynamical exchanges, merge in the field
- Encompasses contribution from **isolated binary evolution**

Formation Channels

Credit: ESA / NASA / Hubble / Rosario et al.

AGN disks

- Merger rate **≲300 Gpc^{-3} yr^{-1}**
- Depends on contribution of AGNs to overall merger rate

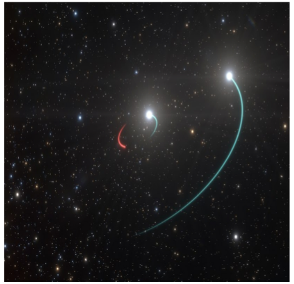
Credit: ESA / NASA / Hubble

Globular clusters

- Merger rate **~0.01 Gpc^{-3} yr^{-1}**

Hierarchical triples

- Merger rate **~0.001-0.01 Gpc^{-3} yr^{-1}**
- Enhanced if no supernova kicks



Credit: ESO / L. Calçada

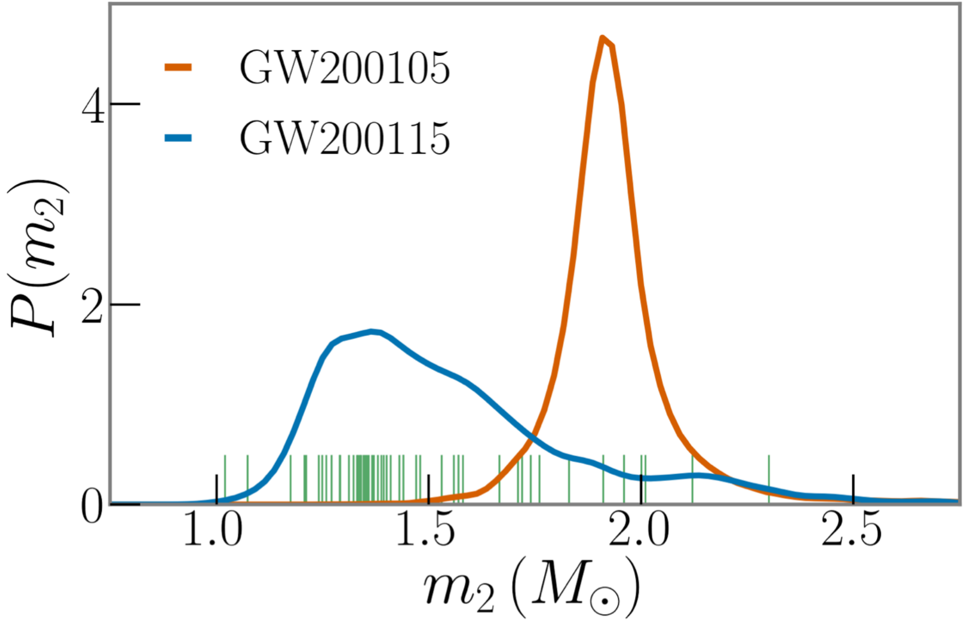
Masses

Neutron Star Masses

- Consistent with Galactic NS population from EM observations

Black hole masses

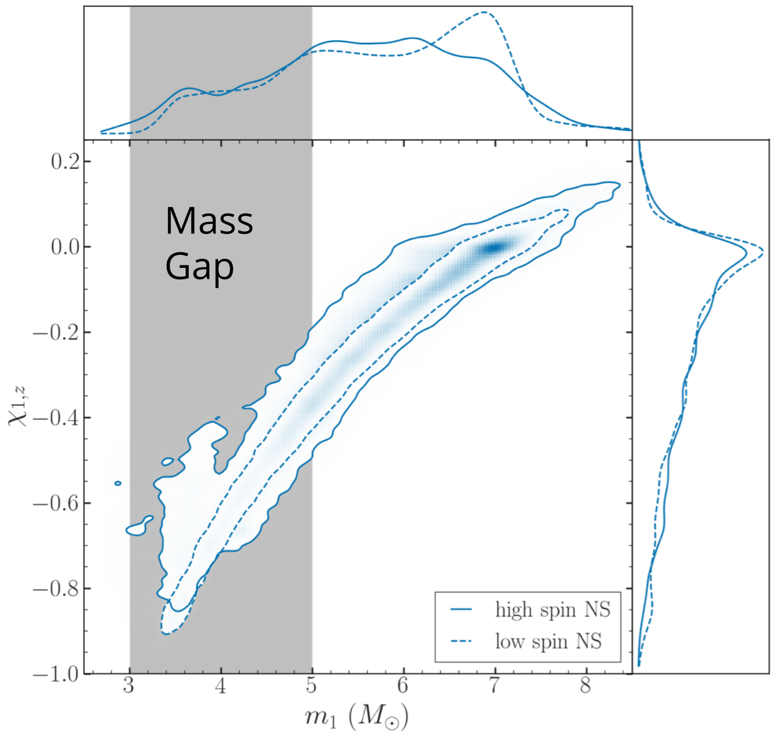
- GW200115 BH may be in the lower mass gap
  - P(mass gap) ≈ 30%
  - Correlated with negatively-aligned primary spin



Galactic NS masses from Alsing et al. 2020, MRAS 478, 1

Spins

GW200115



Magnitudes

- BHs consistent with zero spin
- GW200115: can't rule out high BH spin
  - Consistent with high BH spins from NSBH progenitors

Alignment

- GW200115 BH: possibly negatively-aligned
  - Correlated with low primary mass
  - P($\chi_{1,z}$<0) ≈ 88%

Summary

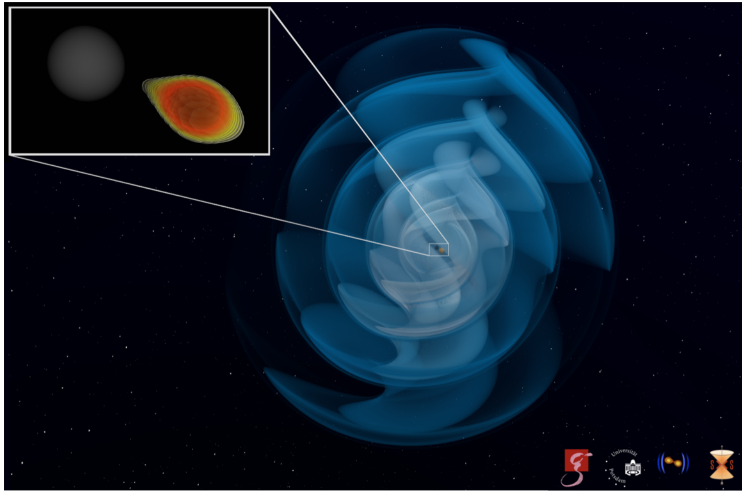
Observation of GW inspirals consistent with **neutron star--black hole binaries:**

GW200105 **~ 1.9 and 9 $M_\odot$** (two detectors)
GW200115 **~ 1.5 and 6 $M_\odot$** (three detectors)

No definite proof of nature of secondary, but **suggestive**

- Secondary masses smaller than maximum NS mass
- Masses consistent with known galactic NS and formation scenarios

NS-BH merger rate of **~100 Gpc^{-3} yr^{-1}** consistent with several formation scenarios.



More results from O3b are in preparation.
The LIGO, Virgo and Kagra detectors resume operations in mid 2022 at increased sensitivity.
Stay tuned for more exciting observations!