KAGRA International Workshop

GW200105

FIRST OBSERVATIONS OF BLACK HOLE & NEUTRON STAR MERGERS

GW200115

Image: Carl Knox/OzGrav/Swinburne

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On behalf of LVK collaboration

Discovery paper

Observation of gravitational waves from two neutron star–black hole coalescences

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION

(Dated: June 30, 2021)

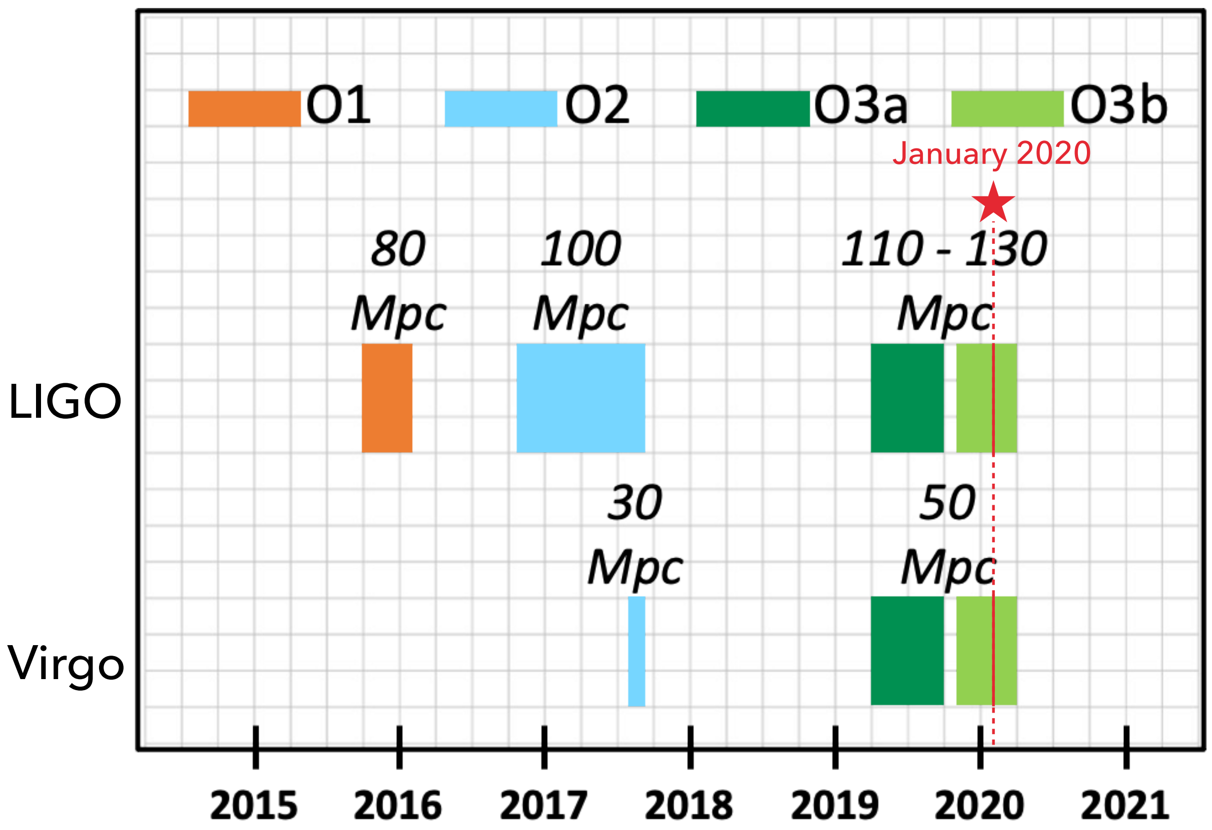
ABSTRACT

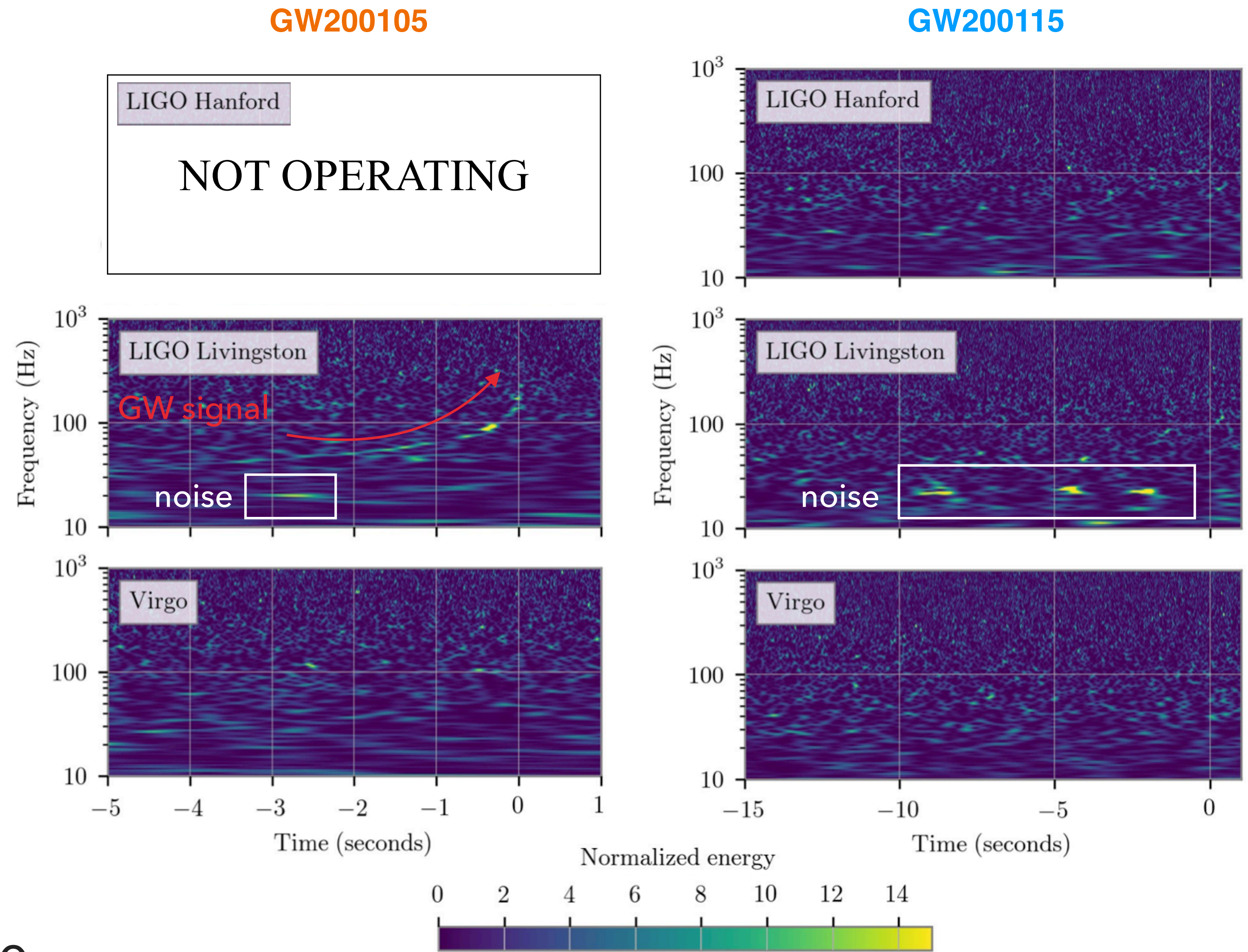
We report the observation of gravitational waves from two compact binary coalescences in LIGO's and Virgo's third observing run with properties consistent with neutron star–black hole (NSBH) binaries. The two events are named GW200105_162426 and GW200115_042309, abbreviated as GW200105 and GW200115; the first was observed by LIGO Livingston and Virgo, and the second by all three LIGO–Virgo detectors. The source of GW200105 has component masses $8.9^{+1.2}_{-1.5}\,M_\odot$ and $1.9^{+0.3}_{-0.2}\,M_\odot$, whereas the source of GW200115 has component masses $5.7^{+1.8}_{-2.1}\,M_\odot$ and $1.5^{+0.7}_{-0.3}\,M_\odot$ (all measurements quoted at the 90% credible level). The probability that the secondary's mass is below the maximal mass of a neutron star is 89%–96% and 87%–98%, respectively, for GW200105 and GW200115, with the ranges arising from different astrophysical assumptions. The source luminosity distances are 280^{+110}_{-110} Mpc and 300^{+150}_{-100} Mpc, respectively. The magnitude of the primary spin of GW200105 is less than 0.23 at the 90% credible level, and its orientation is unconstrained. For GW200115, the primary spin has a negative spin projection onto the orbital angular momentum at 88% probability. We are unable to constrain the spin or tidal deformation of the secondary component for either event. We infer an NSBH merger rate density of 45^{+75}_{-33} Gpc^{-3} yr^{-1} when assuming that GW200105 and GW200115 are representative of the NSBH population, or 130^{+112}_{-69} Gpc^{-3} yr^{-1} under the assumption of a broader distribution of component masses.

R. Abbott *et al* 2021 *ApJL* **915** L5

arXiv : 2106.15163

Three detector network

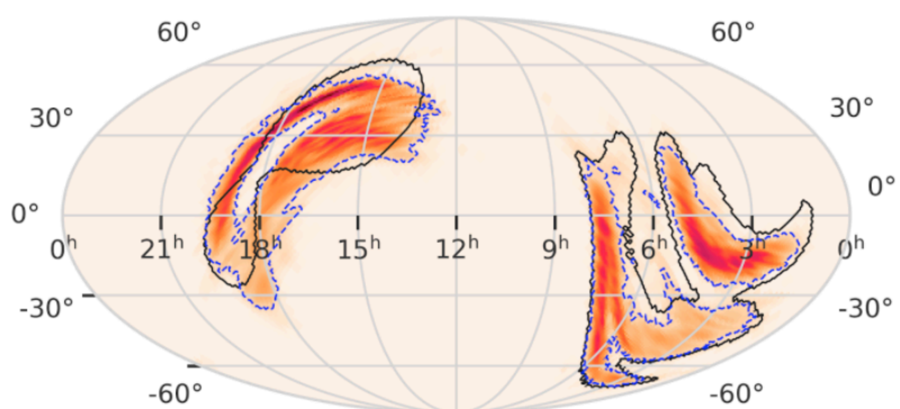
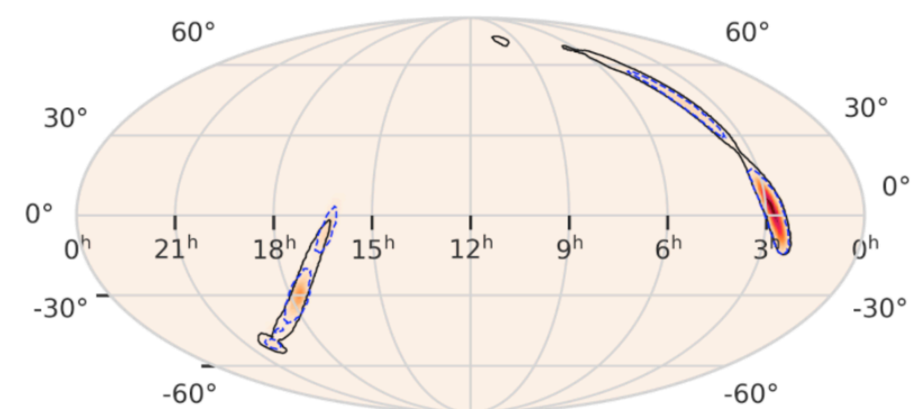




- Two significant events in January 2020
  sensitivity : Hanford (~120Mpc), Livingston (~130Mpc), Virgo (~45Mpc)

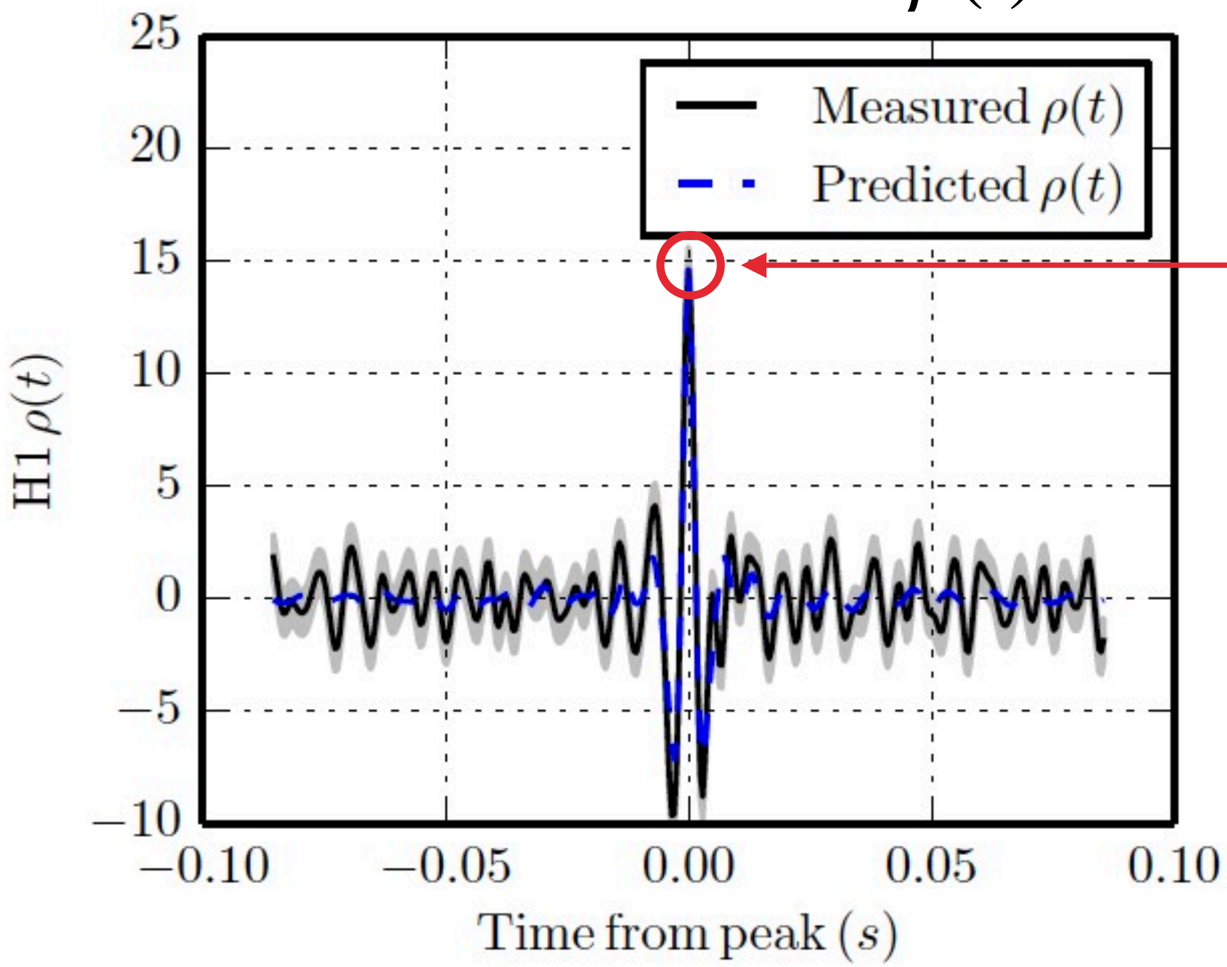
- Data quality
  GW200105 : noise 3sec before the event in L1 ➔ de-glitched (BayesWave)
  GW200115 : overlapping noise at ~20Hz in L1 ➔ excluded from the analysis

Detection summary

NSBH Event	GW200105	GW200115
SNR (H1, L1, V1)	N/A, 13.6, 2.7 (Livingston only)	6.9, 8.6, 2.9 (HL coincidence)
False Alarm Rate (FAR)	low latency : 1 / (15 days) offline : 1 / (3 yr)	low latency : 1 / (1513 yr) offline : 1/(182 yr) ~ < 1/ (10^5 yr)
GCN Notice Latency	More than **1 day**, *GstLAL* only	After **6 mins**, multiple pipelines
Sky Localization	7700 deg^2 (*low latency*) 	900 deg^2 (*low latency*) 
Distance	~ 283 Mpc (*low latency*)	~ 340 Mpc (*low latency*)
# Follow-up GCNs	21 (**No EM/Neutrino Counterpart**)	31 (**No EM/Neutrino Counterpart**)

How to detect signals?

Simulated
SNR timeseries $\rho(t)$



Messick et.al 2017

- Signal-to-Noise Ratio ρ

$$\rho = 4\mathrm{Re}\int \frac{\underbrace{\tilde{h}^*(f)}_{\text{template}}\underbrace{\tilde{d}(f)}_{\text{data}}}{S_n(f)}\mathrm{d}f$$

<u>Loudness of a signal</u>

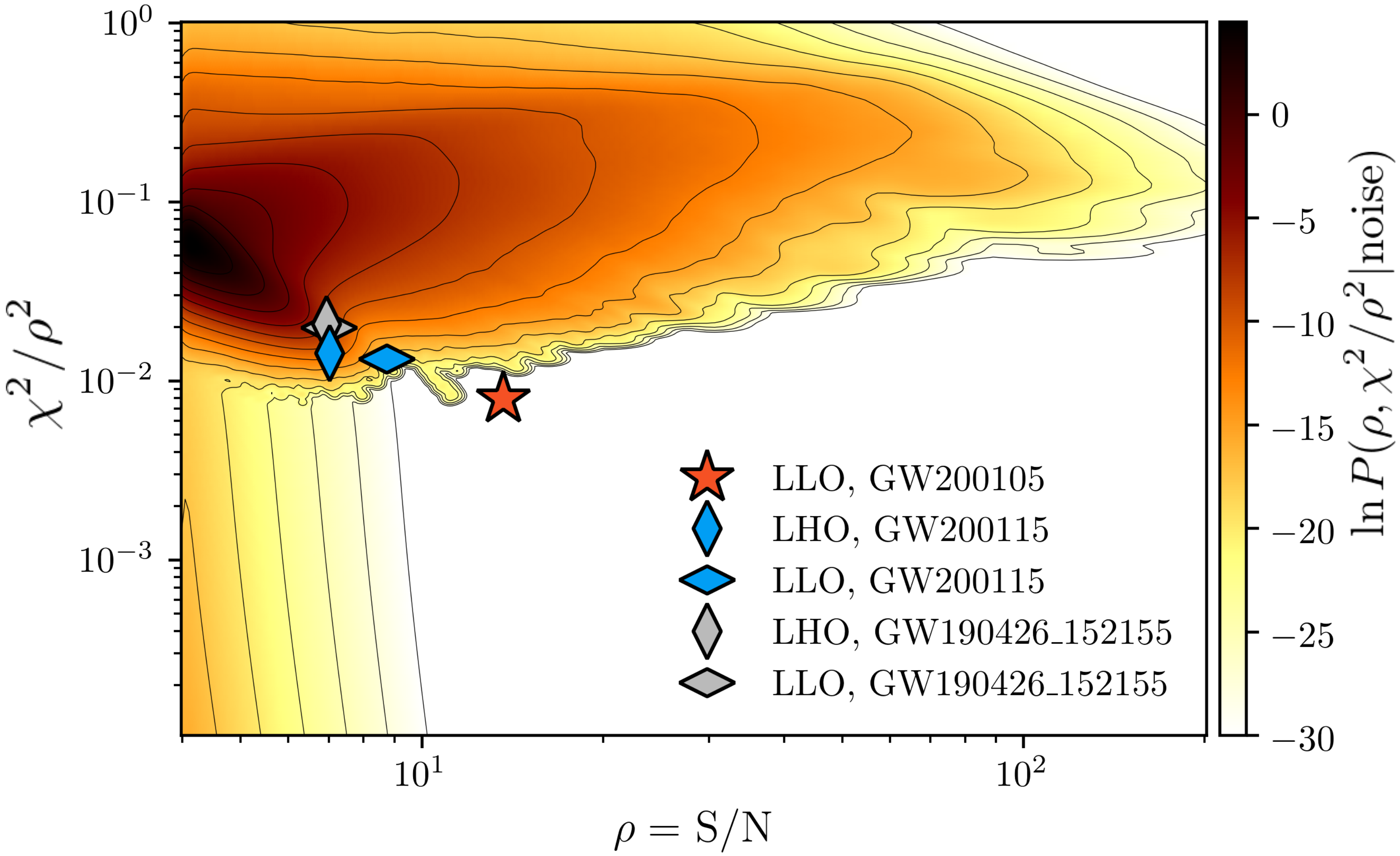
- Chi squared χ^2

$$\chi^2 \propto \int \Big|\underbrace{\rho(t)}_{\text{observed}} - \underbrace{\bar{\rho}(t)}_{\text{predicted}}\Big|^2 \mathrm{d}t$$

<u>Signal consistency test</u>

GW200105 : single-detector event

NSBH triggers compared against O3 noise background



- Coincident detection elevates the significance for GW200115.
- GW200105 stands out of the background and is most significant by single detector alone.

Parameter Estimation

- Bayes' theorem

posterior Likelihood prior

$$p(\theta|d) = \frac{p(d|\theta) \cdot p(\theta)}{p(d)}$$

$\theta = \{m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, D, ...\}$

- Likelihood

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\langle d(f) - h(f;\theta) | d(f) - h(f;\theta)\rangle\right]$$

$d(f)$: data; $h(f;\theta)$: waveform model

- Waveform models based on GR

NSBH waveform
 Phenom NSBH/EOBNR NSBH
(tides on the secondary)

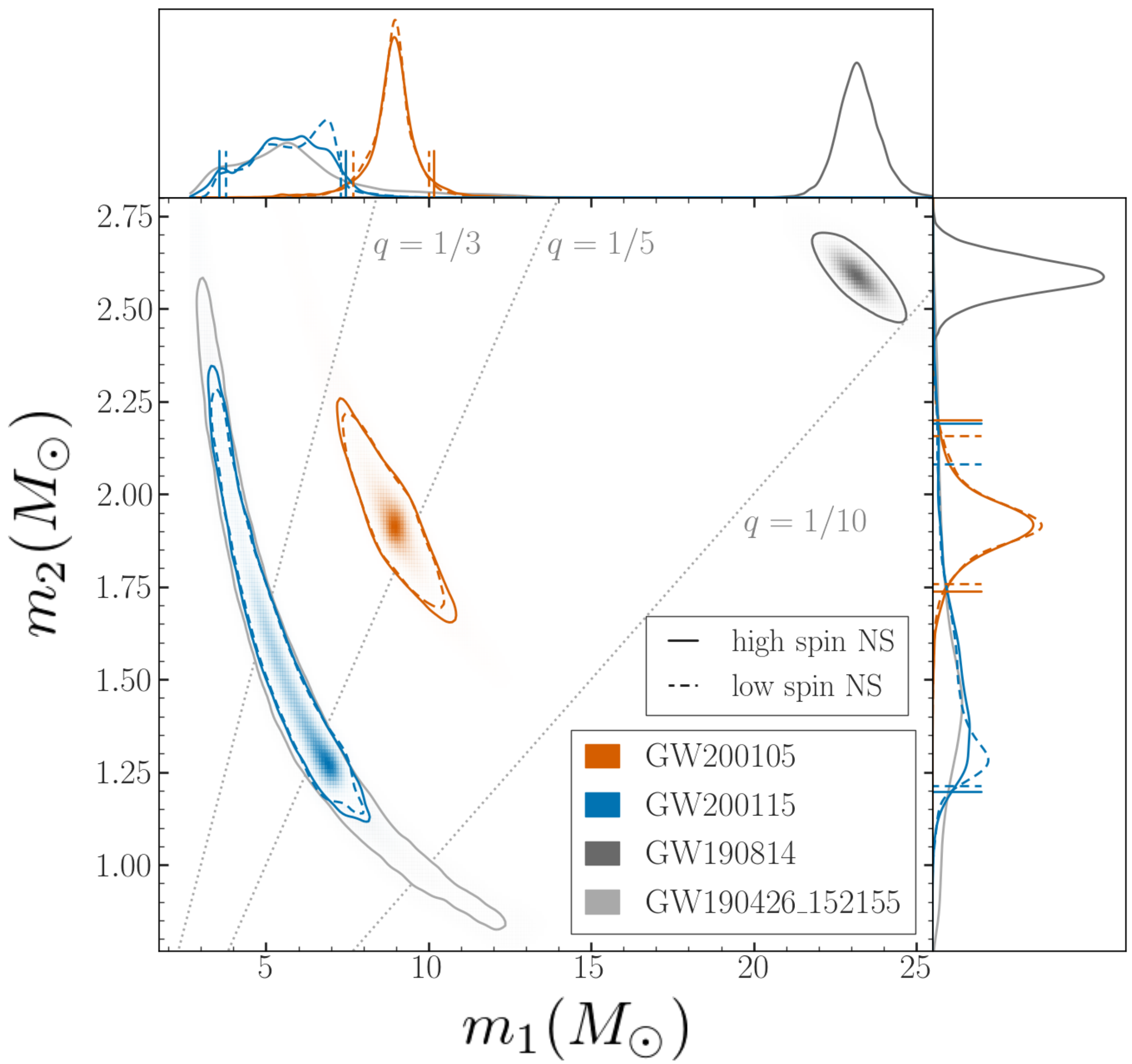
BBH waveform
 Phenom PHM/EOBNR PHM
(PHM=Precession+Higher Order Modes)

- Two priors on the secondary spin

High spin ($\chi_2 < 0.99$)

Low spin ($\chi_2 < 0.05$)

Masses



	m_1	m_2
GW190814	$23.2^{+1.1}_{-1.0}\,M_\odot$	$2.59^{+0.08}_{-0.09}\,M_\odot$
GW200105	$8.9^{+1.2}_{-1.5}M_\odot$	$1.9^{+0.3}_{-0.2}M_\odot$
GW200115	$5.7^{+1.8}_{-2.1}M_\odot$	$1.5^{+0.7}_{-0.3}M_\odot$

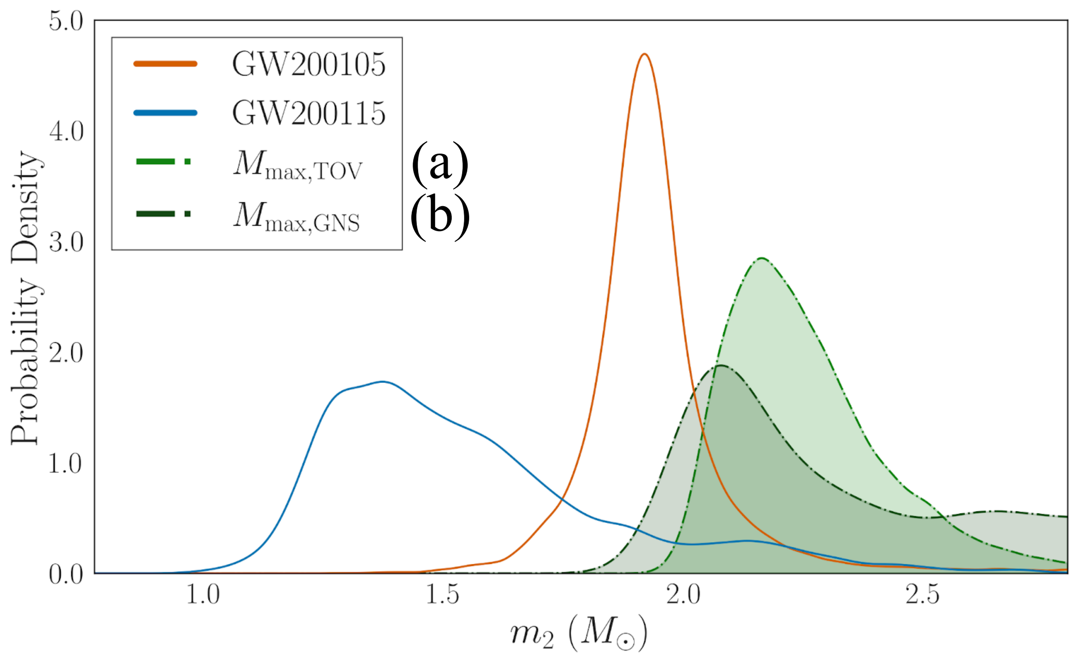
Plausible NSs

- Are GW200105 and GW200115 lensed??

  No, given the inconsistent redshifted chirp masses.

Is the secondary really NS?

- Comparison with the maximum NS mass



	spin prior	choice of $M_{\max}$	$p(m_2 < M_{\max})$ GW200105	$p(m_2 < M_{\max})$ GW200115
(a)	$\|\chi_2\| < 0.05$	$M_{\mathrm{max,TOV}}$	96%	98%
(a')	$\|\chi_2\| < 0.99$	$M_{\max}(\chi_2)$	94%	95%
(b)	$\|\chi_2\| < 0.99$	$M_{\mathrm{max,GNS}}$	93%	96%

- (a) : Equation of state inferred from radio/X-ray/GW observations.

(Landry, Essick & Chatziioannou 2020)

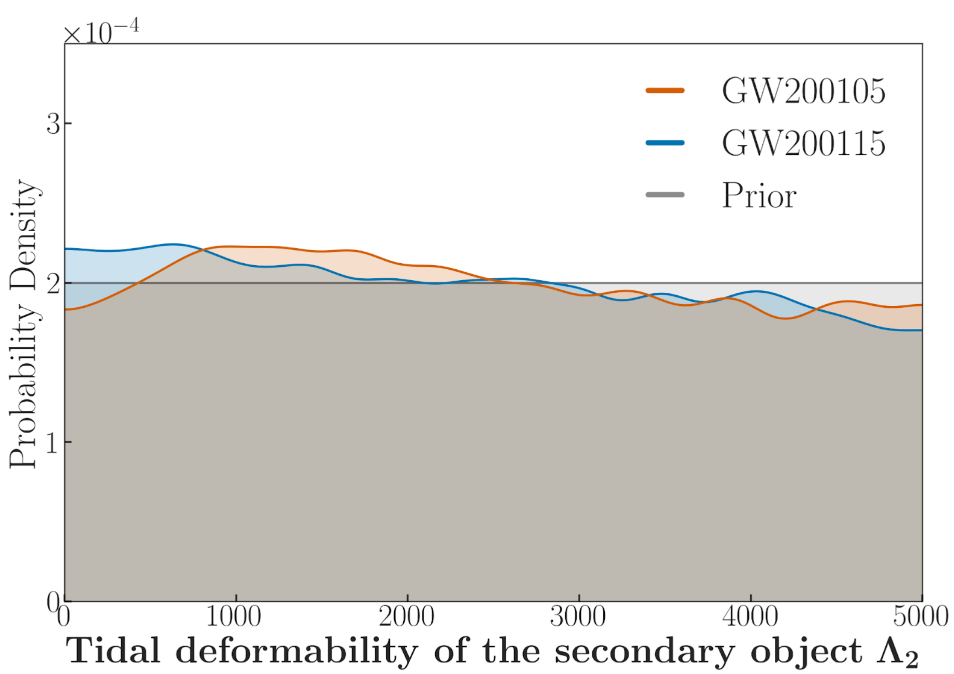
(b) : Fit to Galactic BNS systems

(Farr & Chatziioannou 2020)

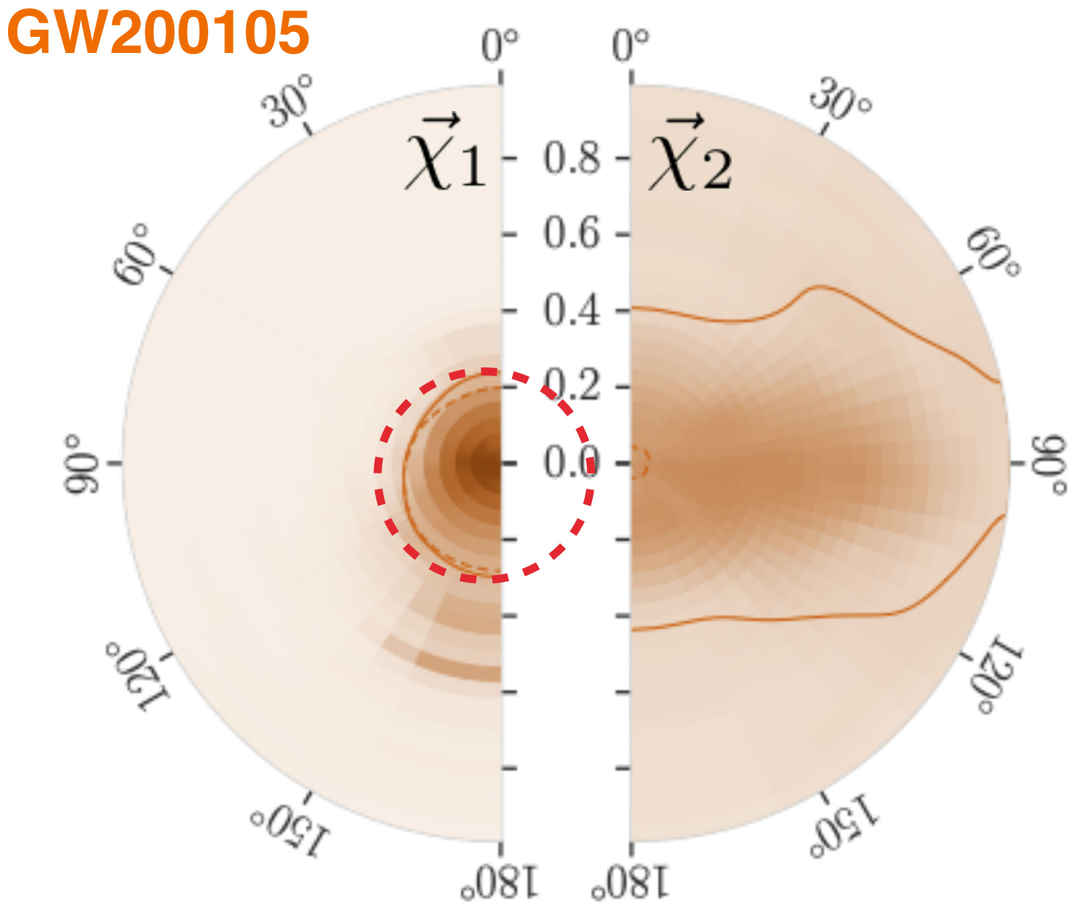
- Given no information from tides or EM signals, the NS identification is purely based on the mass.

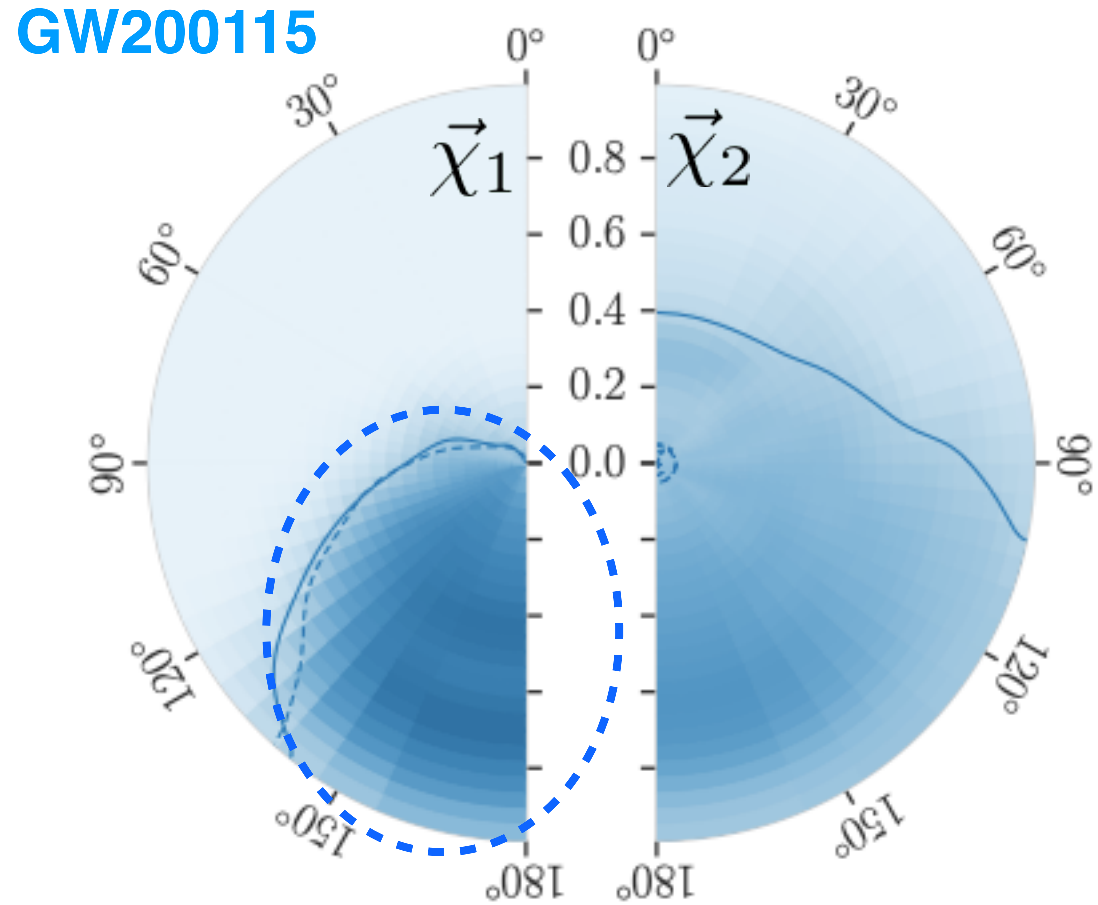
- Still, primordial BHs cannot be ruled out.

- Tidal effect



Spins

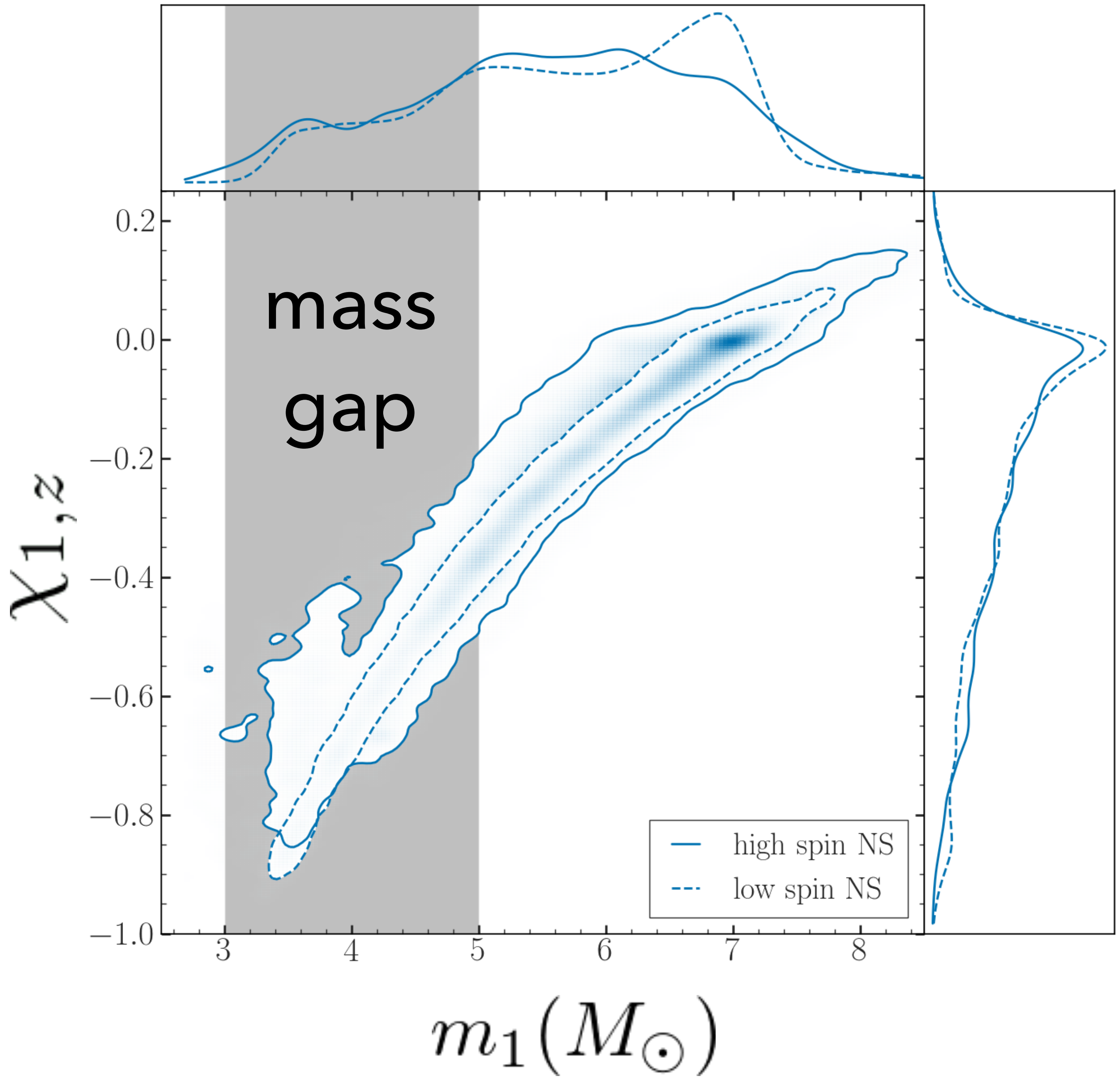




	GW200105	GW200115
$\vec{\chi}_1$	$\lvert\vec{\chi}_1\rvert < 0.23$ (90% confidence)	$\chi_{1,z} = -0.19^{+0.24}_{-0.50}$ $P(\chi_{1,z} < 0) = 88\%$
$\vec{\chi}_2$	unconstrained	unconstrained

Mass-spin Correlation in GW200115

GW200115

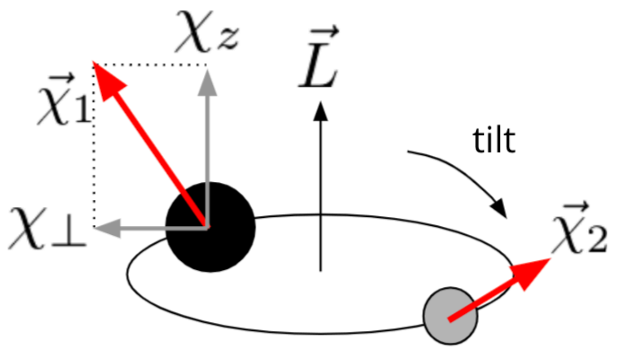


- m_1 is correlated with $\chi_{1,z}$.

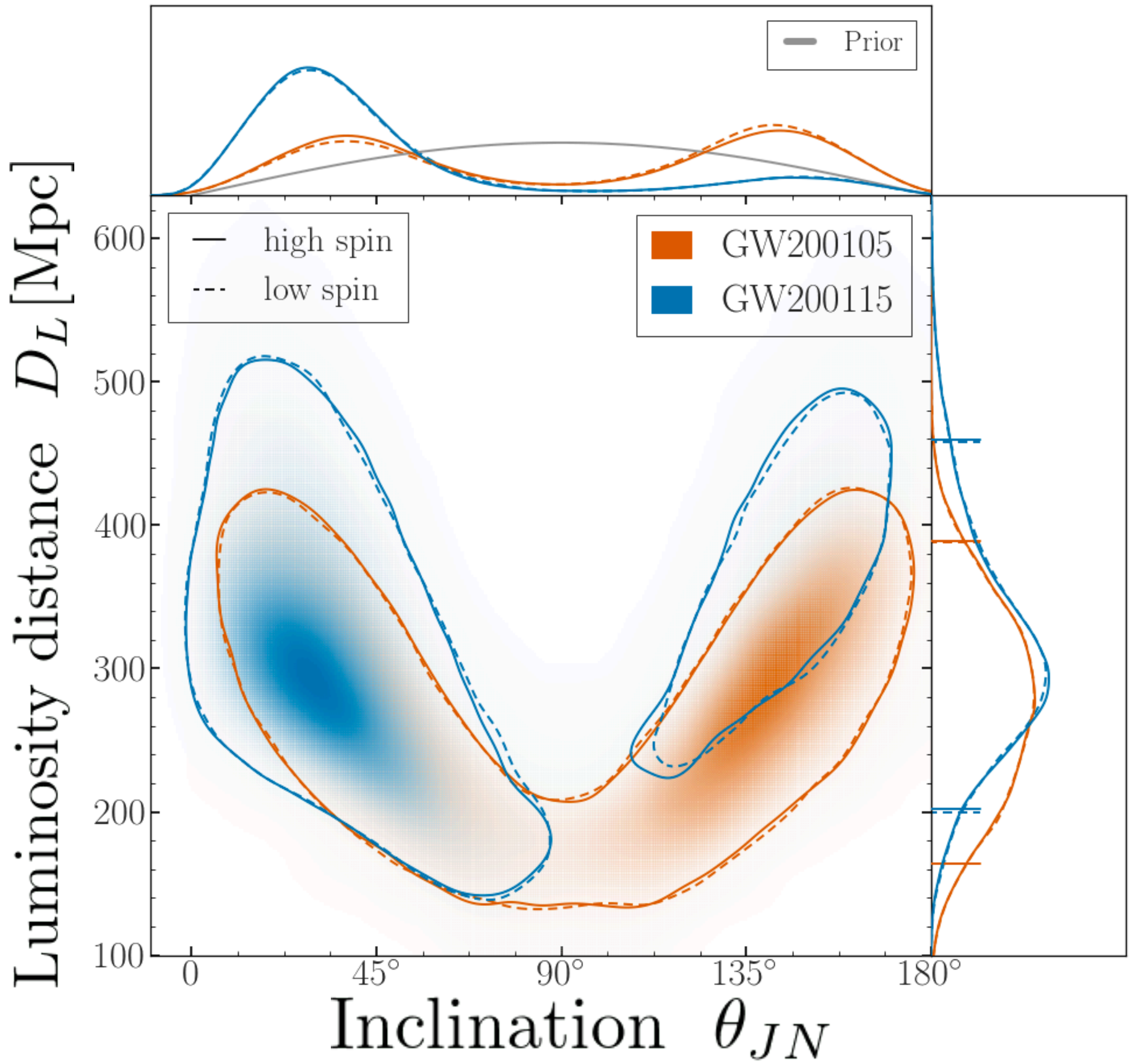
  Caused by the mass-spin degeneracy in the phase evolution

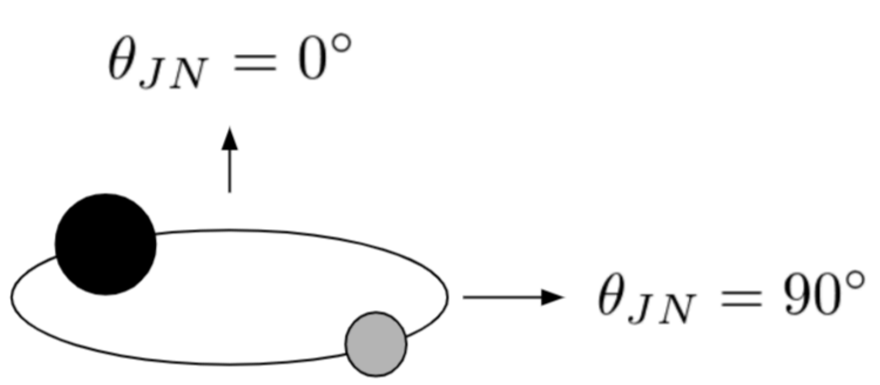
- $P(3M_\odot \leq m_1 \leq 5M_\odot) = 30\%$

  If the BH is in the mass gap, its spin is likely to be anti-aligned with $\vec{L}$.



Distance – Inclination





- Distance D_L

GW200105	280^{+110}_{-110} Mpc
GW200115	300^{+150}_{-100} Mpc
GW170817	40 Mpc

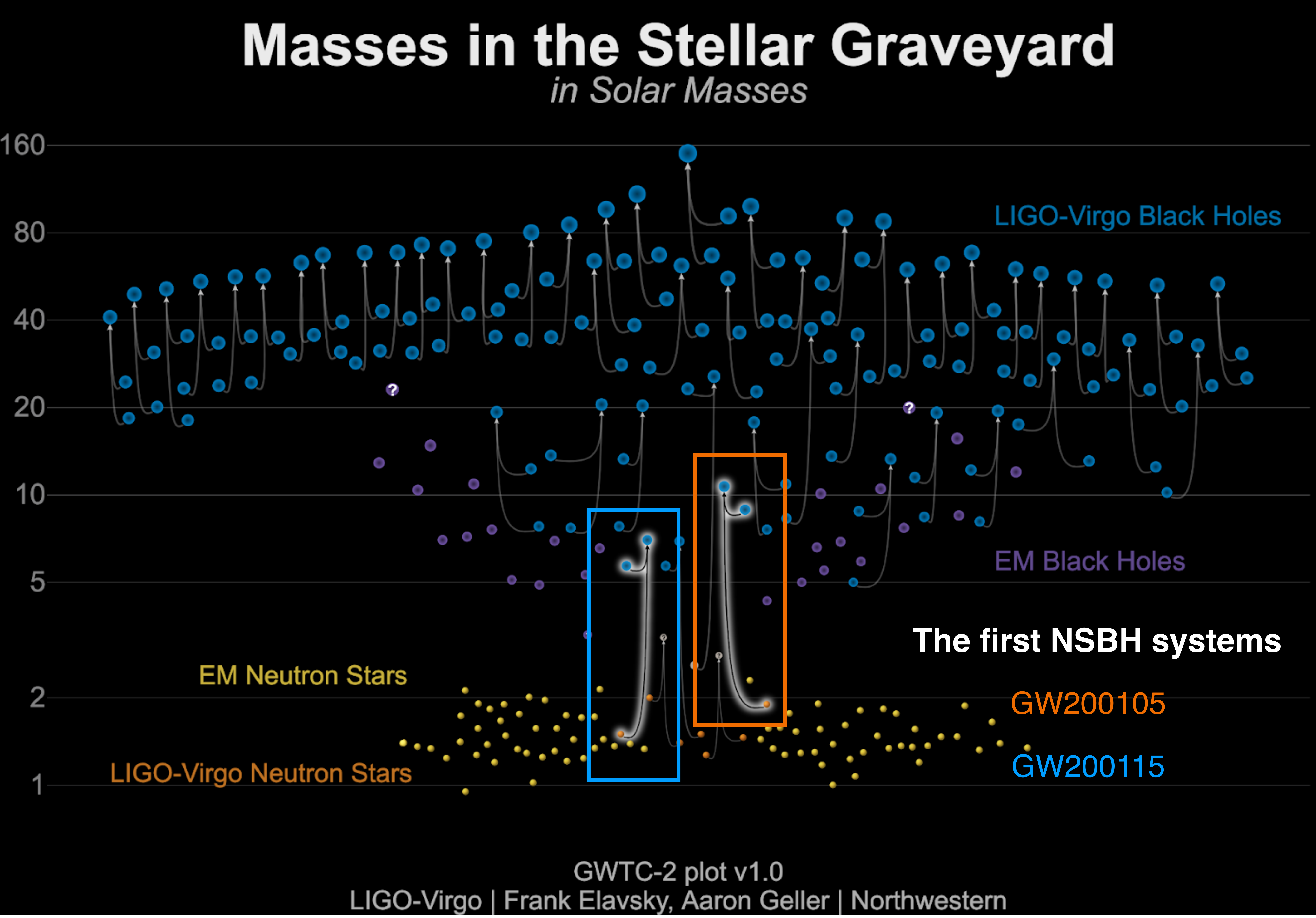
Too distant to detect EM signals

- Inclination θ_{JN}

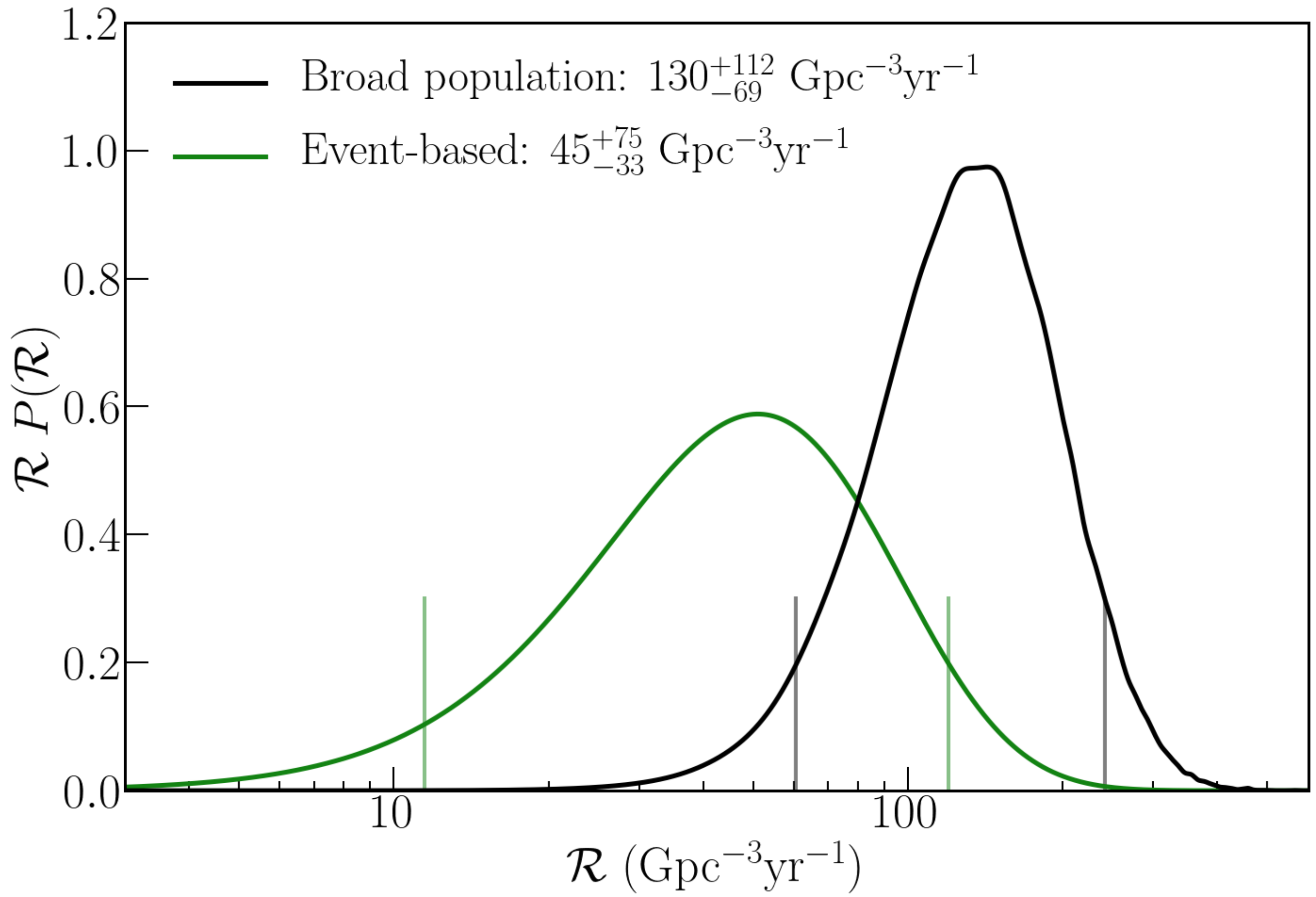
Both events disfavor $\theta_{JN} \sim 90°$.

Higher order modes tend to be less significant.

Masses in the Stellar Graveyard



Merger rate



- Merger rate estimate

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

- Broad population

count all the triggers in NSBH

regime $\begin{cases} m_1 \in [2.5 - 40]M_\odot \\ m_2 \in [1 - 3]M_\odot \end{cases}$

➡ sub-threshold event contribute to rate estimates.

- Event-based

assume 1 count in each GW200105/GW200115-like population

➡ rate estimates based on the detection alone.

Formation scenarios

- **Isolated binary evolution**
  stellar progenitors co-evolve as a binary through common envelope
  rate : $0.1 - 800\ \mathrm{Gpc^{-3}yr^{-1}}$

- **Young star cluster**
  dynamical interaction in close encounter + isolated formation
  rate : $0.1 - 100\ \mathrm{Gpc^{-3}yr^{-1}}$

- **AGN disks**
  asymmetric-mass merger driven by gas torques and migration traps
  rate : $\lesssim 300\ \mathrm{Gpc^{-3}yr^{-1}}$

Given the large uncertainty, any of these channels can individually account for the observed events.

Summary

- *First-ever* detection of likely NS-BH GW inspirals in January 2020

  GW200105 : $9\ M_\odot + 1.9\ M_\odot$ (single detector)

  GW200115 : $6\ M_\odot + 1.5\ M_\odot$ (coincident detection)

- The secondary masses *suggest* NS-BH systems.

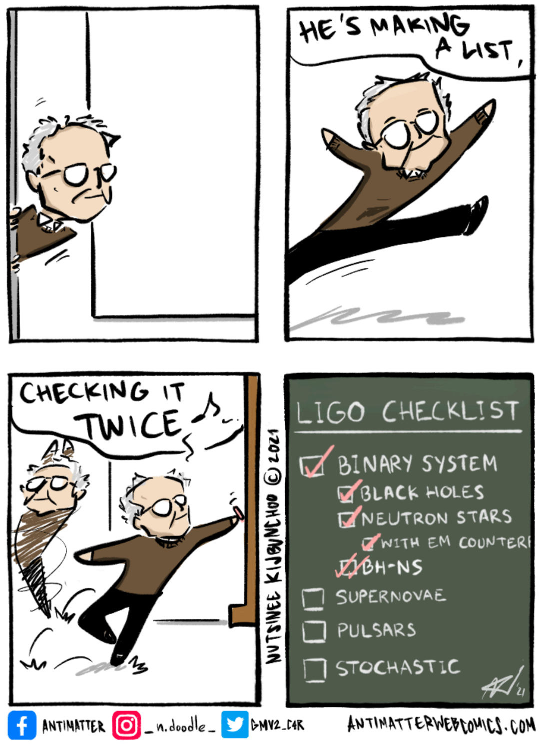
  consistent with maximum NS masses

  despite no detection of EM signals or tides

- Merger rate is estimated to be $\sim 100\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

  consistent with plausible formation scenarios

  multiple channels may contribute to astrophysical merger rate.



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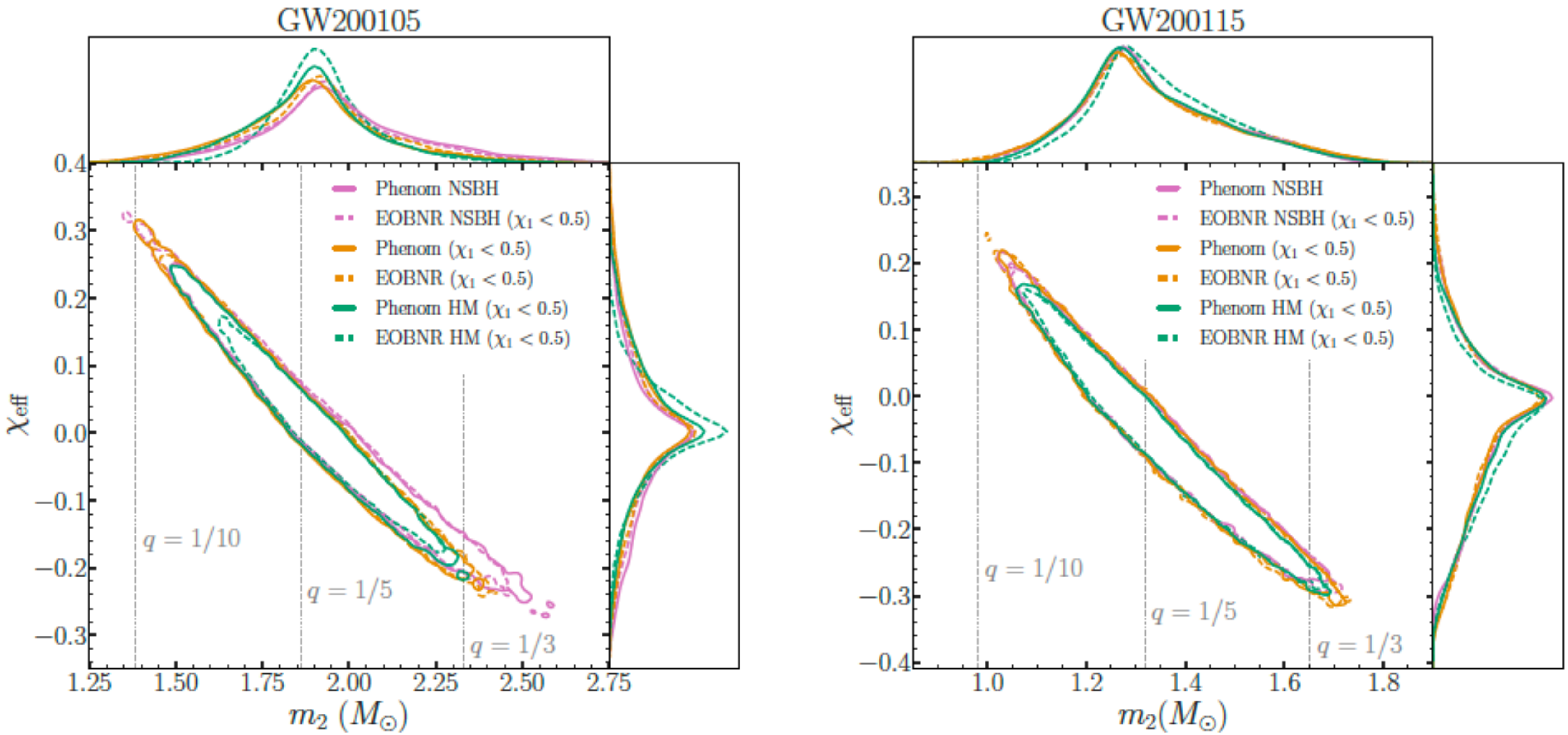
LOOK FORWARD TO MORE O3B RESULTS !

BACKUP

waveform systematics

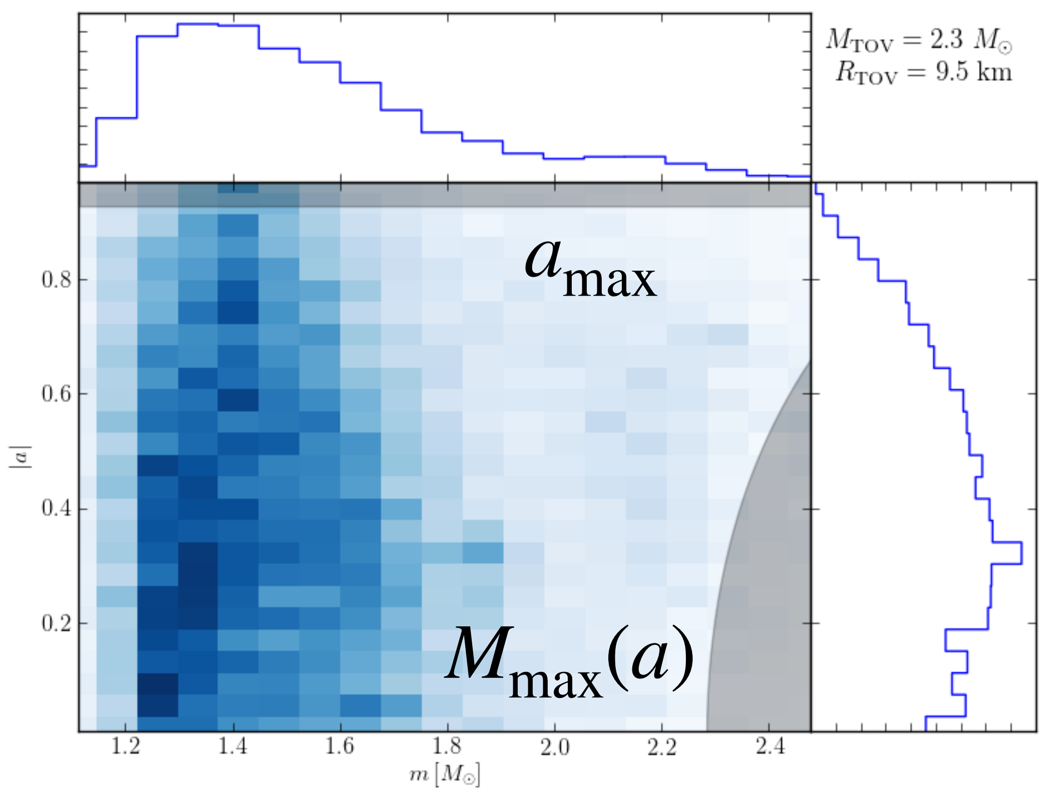


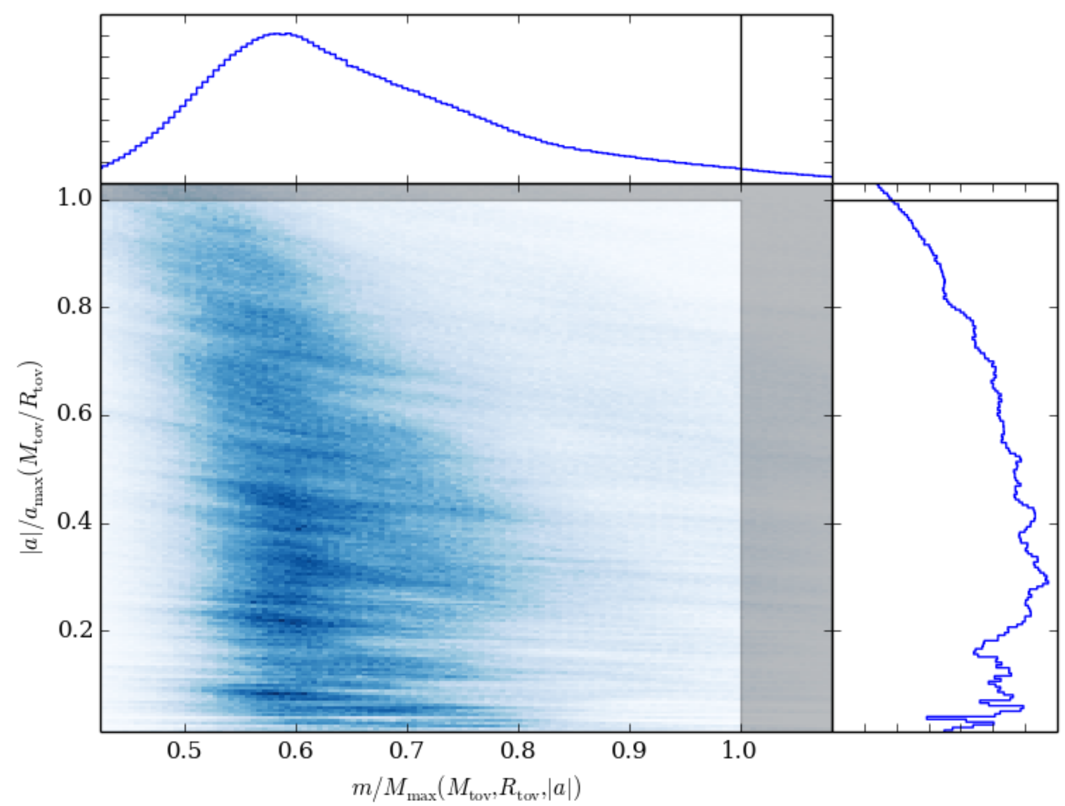
$M_{max}(\chi_2)$

- $a > 0$ extension of TOV model using the universal relation count the posterior samples where $m < M_{max} \cap |a| < a_{max}$.

GW200115

flat component mass prior





$|a| \to |a|/a_{max}$

$m \to m/M_{max}$

$P(m < M_{max} \cap |a| < a_{max}) = 95.0\ \%$

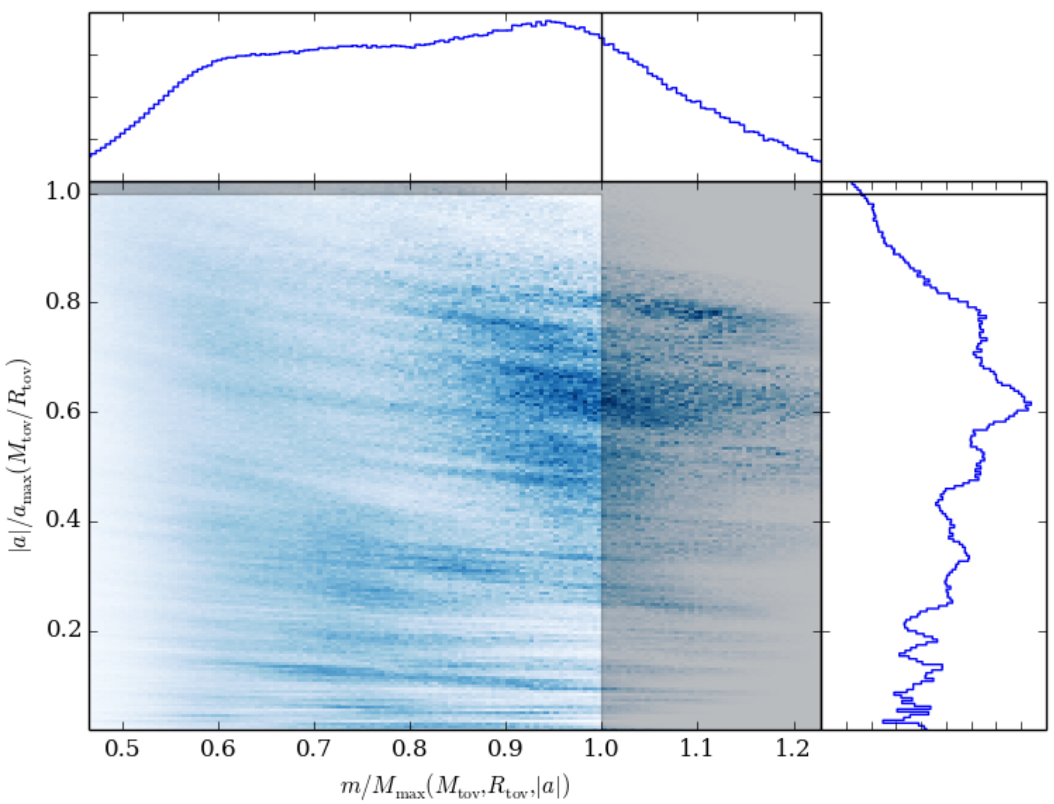
credit : R. Essick, P. Landry

$M_{max}(\chi_2)$

- Different mass priors yield slightly different values

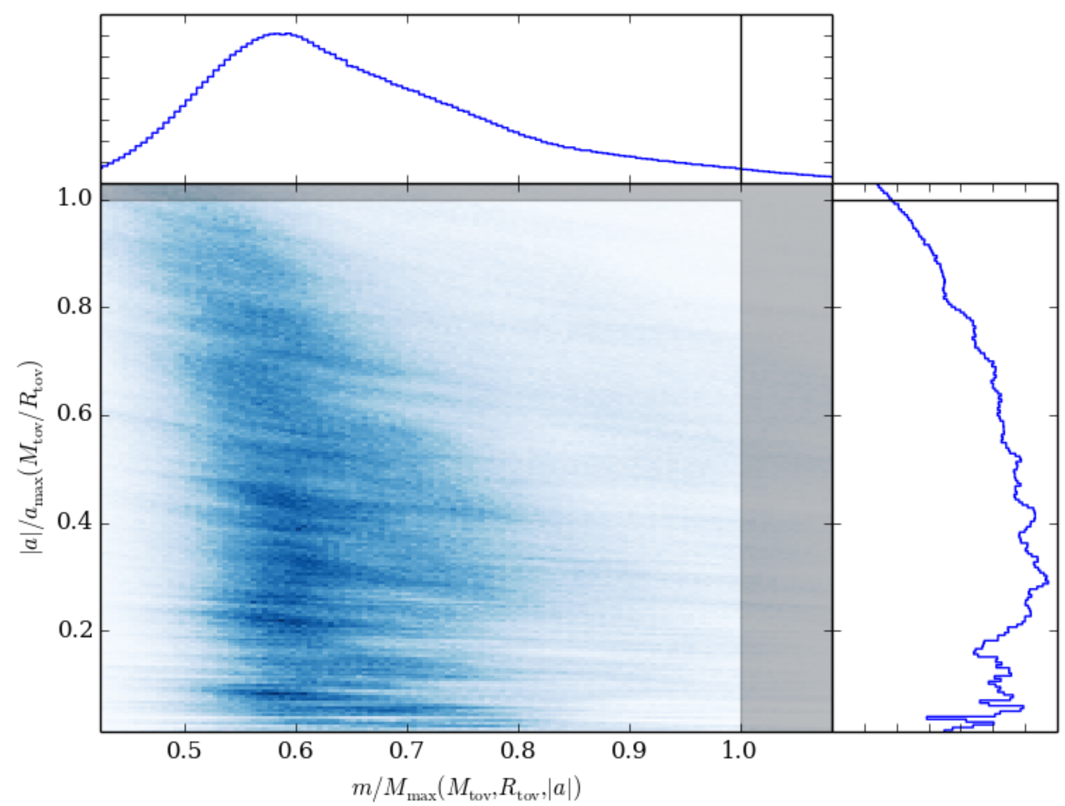
GW200115

broken power-law mass prior



$$P(m < M_{max} \cap |a| < a_{max}) = 89.0\,\%$$

flat component mass prior



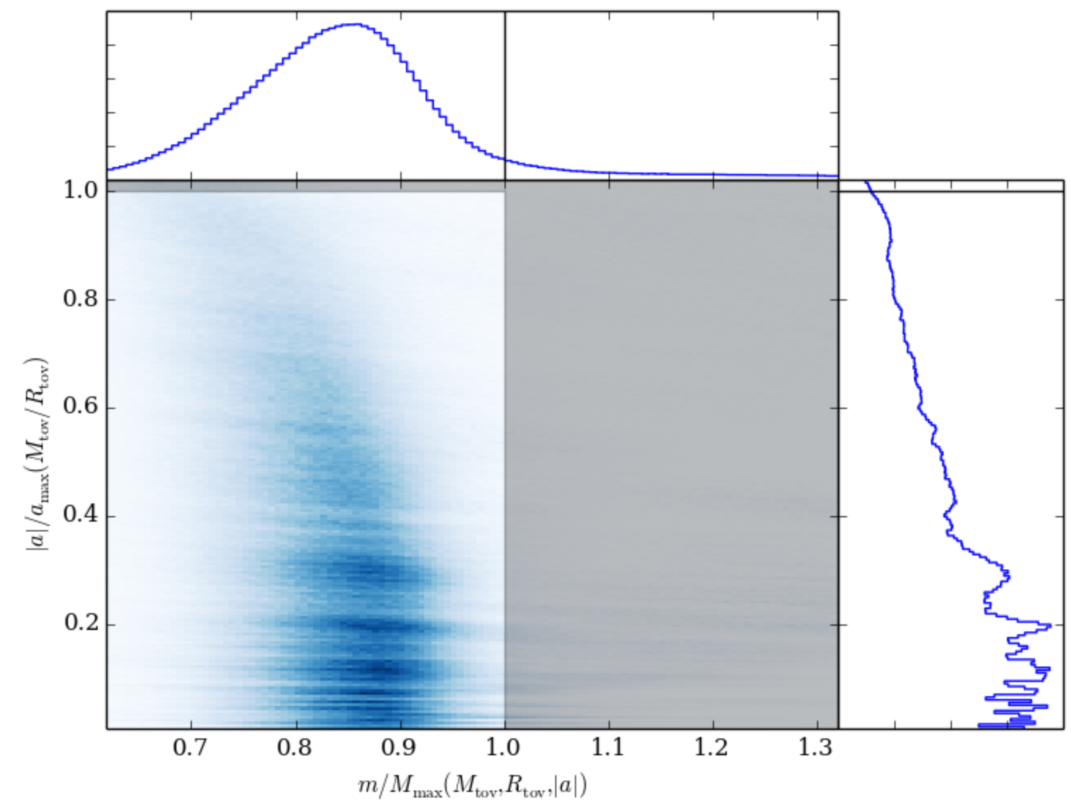
$$P(m < M_{max} \cap |a| < a_{max}) = 95.0\,\%$$

credit : R. Essick, P. Landry

$M_{\max}(\chi_2)$

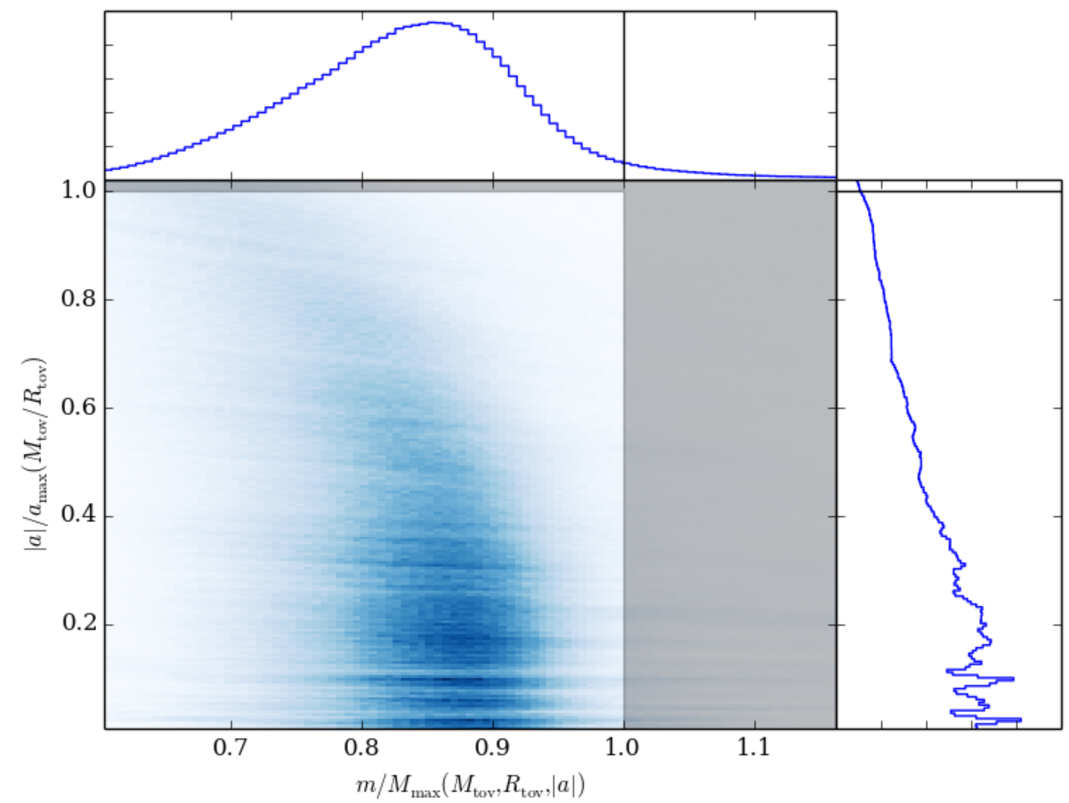
GW200105

broken power-law mass prior



$P(m < M_{\max} \cap |a| < a_{\max}) = 91.0\,\%$

flat component mass prior



$P(m < M_{\max} \cap |a| < a_{\max}) = 94.5\,\%$

credit : R. Essick, P. Landry

Miscellaneous Properties

- Remnant objects

  Mass

$$M_{\mathrm{f}} = \begin{cases} 10.4^{+2.7}_{-2.0}\ M_\odot & (\mathrm{GW200105}) \\ 7.8^{+1.4}_{-1.6}\ M_\odot & (\mathrm{GW200115}) \end{cases}$$

  Spin

$$\chi_{\mathrm{f}} = \begin{cases} 0.43^{+0.04}_{-0.03} & (\mathrm{GW200105}) \\ 0.38^{+0.04}_{-0.02} & (\mathrm{GW200115}) \end{cases}$$

- Test of general relativity

  Less tight constraints on non-GR parameters due to low SNR.

- Higher order multipoles

  SNR for the $(\ell, m) = (3, 3)$ mode

$$\rho_{33}^{\perp} = \begin{cases} 1.70^{+0.94}_{-1.11} & (\mathrm{GW200105}) \\ 0.86^{+0.90}_{-0.65} & (\mathrm{GW200115}) \end{cases}$$

$$(\mathrm{cf.}\ \ \rho_{33}^{\perp} = 6.6 \quad \mathrm{for\ GW190814})$$

  ⇨ Inconclusive evidence

- Precession effect

  $P(\mathrm{precesion\ vs\ non\text{-}precession})$

$$= \begin{cases} 0.58 : 1 & (\mathrm{GW200105}) \\ 0.76 : 1 & (\mathrm{GW200115}) \end{cases}$$

Tidal disruption and electromagnetic counterpart

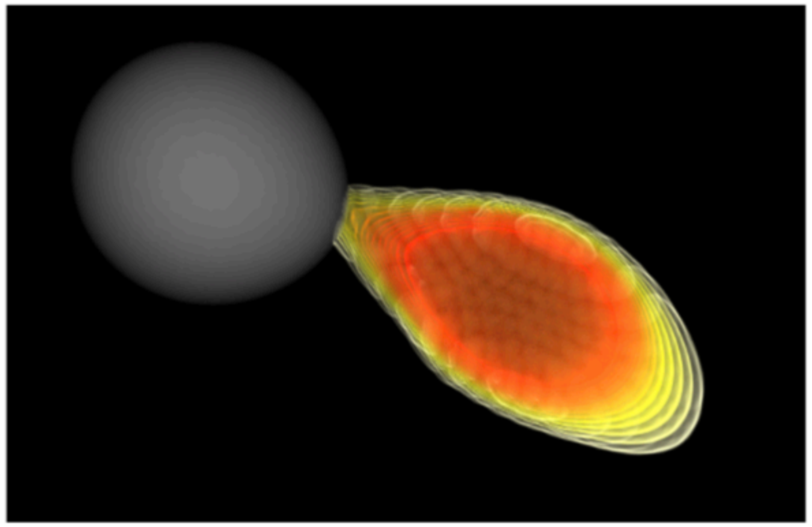
Tidal disruption is **preferred** for

+ **comparable mass ratio**
  GW200105: ~1.9Msun and ~9Msun ✖
  GW200115: ~1.5Msun and ~6Msun ✖

+ black hole with **aligned spin**
  GW200105: $|\vec{\chi}_1| < 0.23$ ✖
  GW200115: $\chi_{1,z} = -0.19^{+0.24}_{-0.50}$ ✖

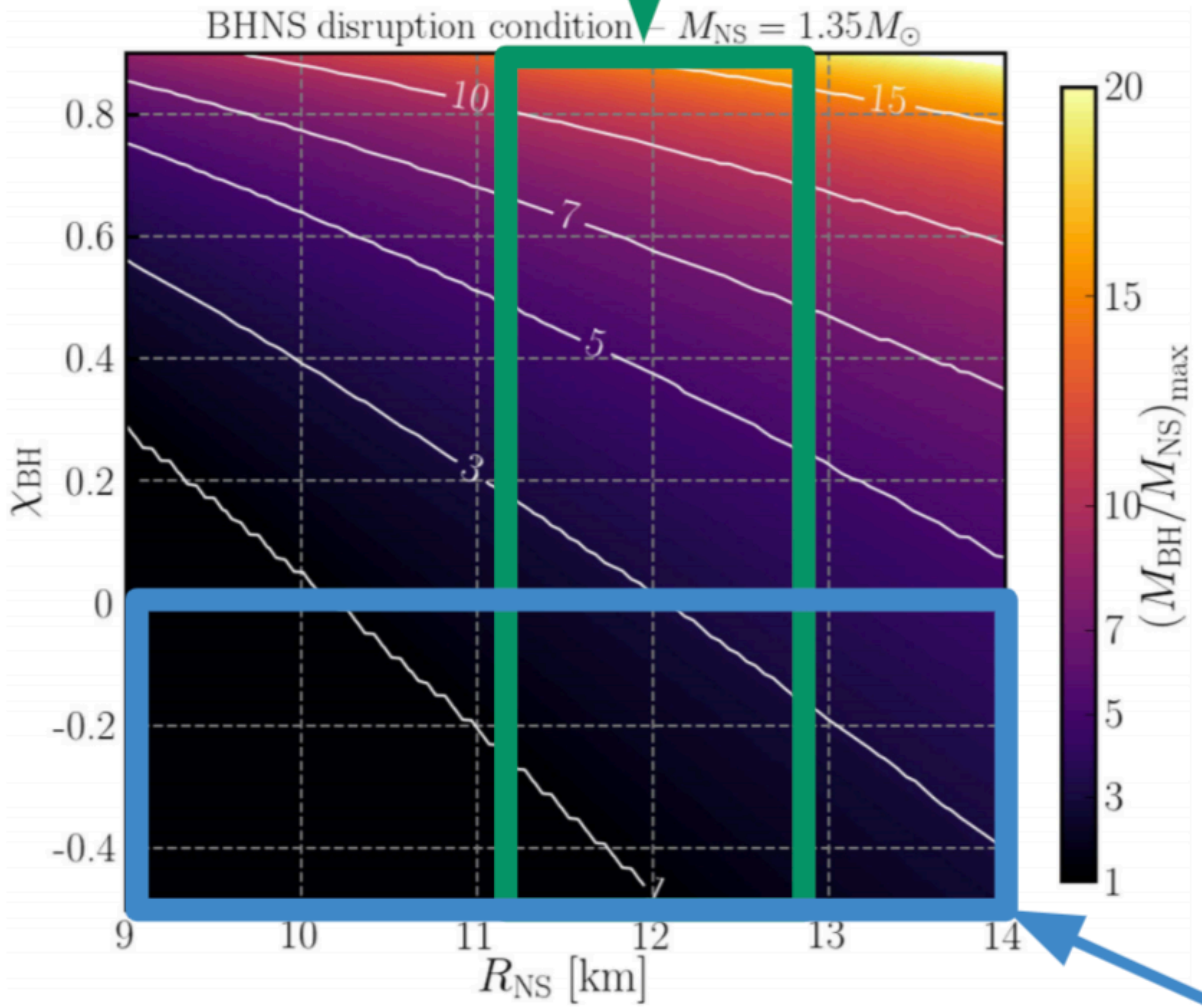
+ **small** neutron star **compactness**
  GW170817 disfavored stiff equations of state and GW200115 and GW200105 are no low-mass neutron stars ✖

Electromagnetic signals disfavored if neutron star is 'swallowed' by the black holes



Tidal disruption and electromagnetic counterpart

Typical neutron star radii



Credit: F.Foucart, Front. Astron. Space Sci., 7, 46 (2020)

GW200105 and **GW200115** source properties make a tidal disruption and a detectable electromagnetic signal unlikely.

small spin or anti-aligned spinning black hole