NEUTRON STAR MASS LIMITS

Recent Insights

Lívia S. Rocha

DDF24 - 10 to 15 of May, 2024

ABOUT ME

- Currently: PostDoc at IFUSP, Brazil.
  - CTAO Consortium: High energy emissions of Spider Systems.

- August 2023: PhD at IAG-USP, Brazil
  - Mass distribution and formation scenarios of neutron stars
  - Part of GARDEL group


Jorge Horvath


Lívia Rocha


Lucas de Sá


Antônio Bernardo


Pedro Moraes


Riis Rhavia

MAXIMUM MASS OF NS

- Under general relativity, the hydrostatic equilibrium is given by the TOV equation:

$$\frac{dP(r)}{dr} = -\frac{Gm(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{c^2\rho(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{c^2 m(r)}\right)\left(1-\frac{2Gm(r)}{c^2 r}\right)^{-1}$$

$$m(r) = 4\pi\int_0^r r'^2\rho(r')dr'$$

- Foresess the existence of an upper limit of mass for stable configuration
- Highly dependent on the Equation of State (EoS)

THE OLD PICTURE

- NS's formed from core-collapse supernova of Fe cores

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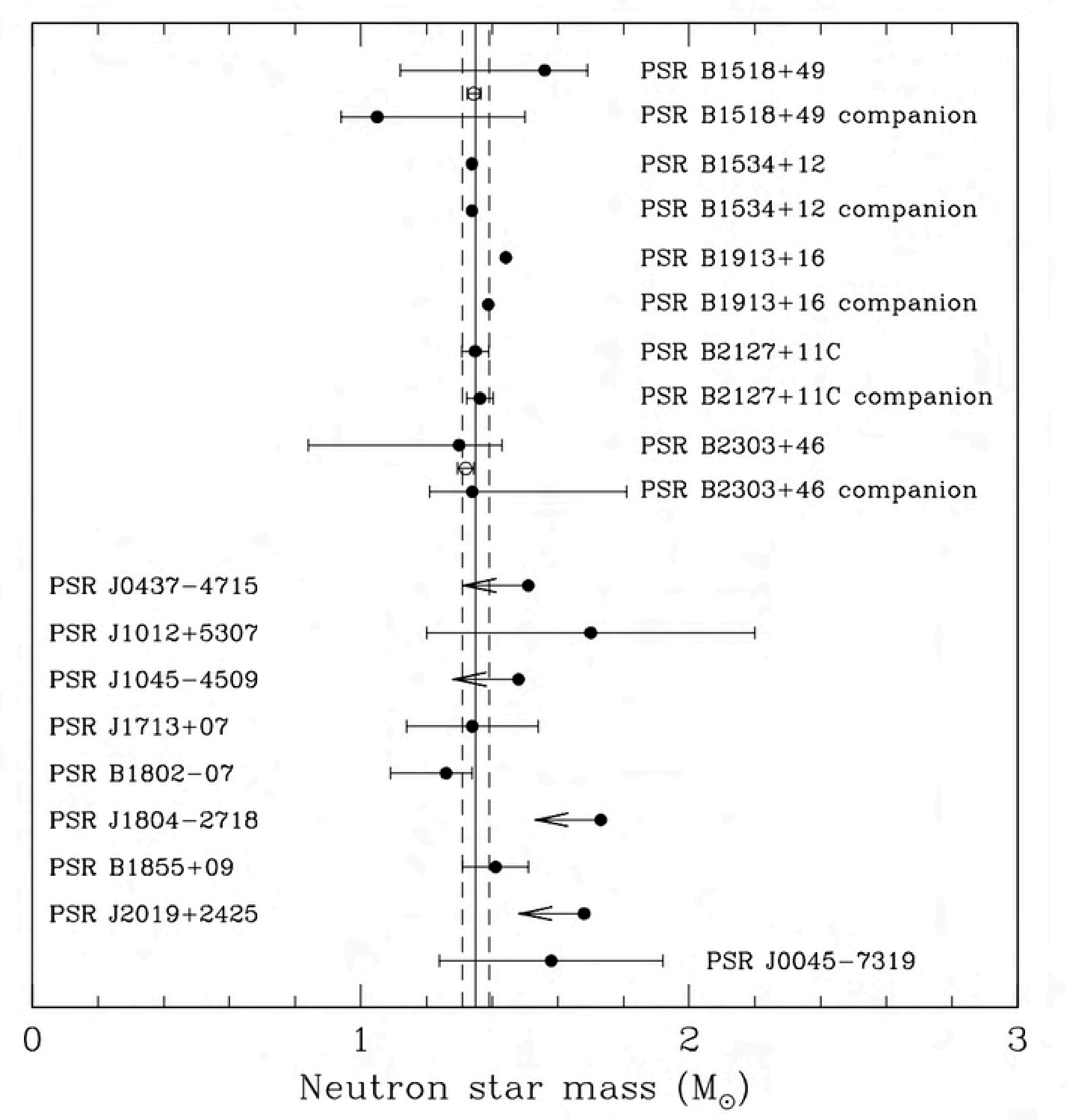
THORSETT AND CHAKRABARTY (1999)



Observations match with theory!

$$m = 1.35 \pm 0.04\ M_\odot$$

THE OLD PICTURE

- NS's formed from core-collapse supernova of Fe cores

Core subject to electron degeneracy press

↓

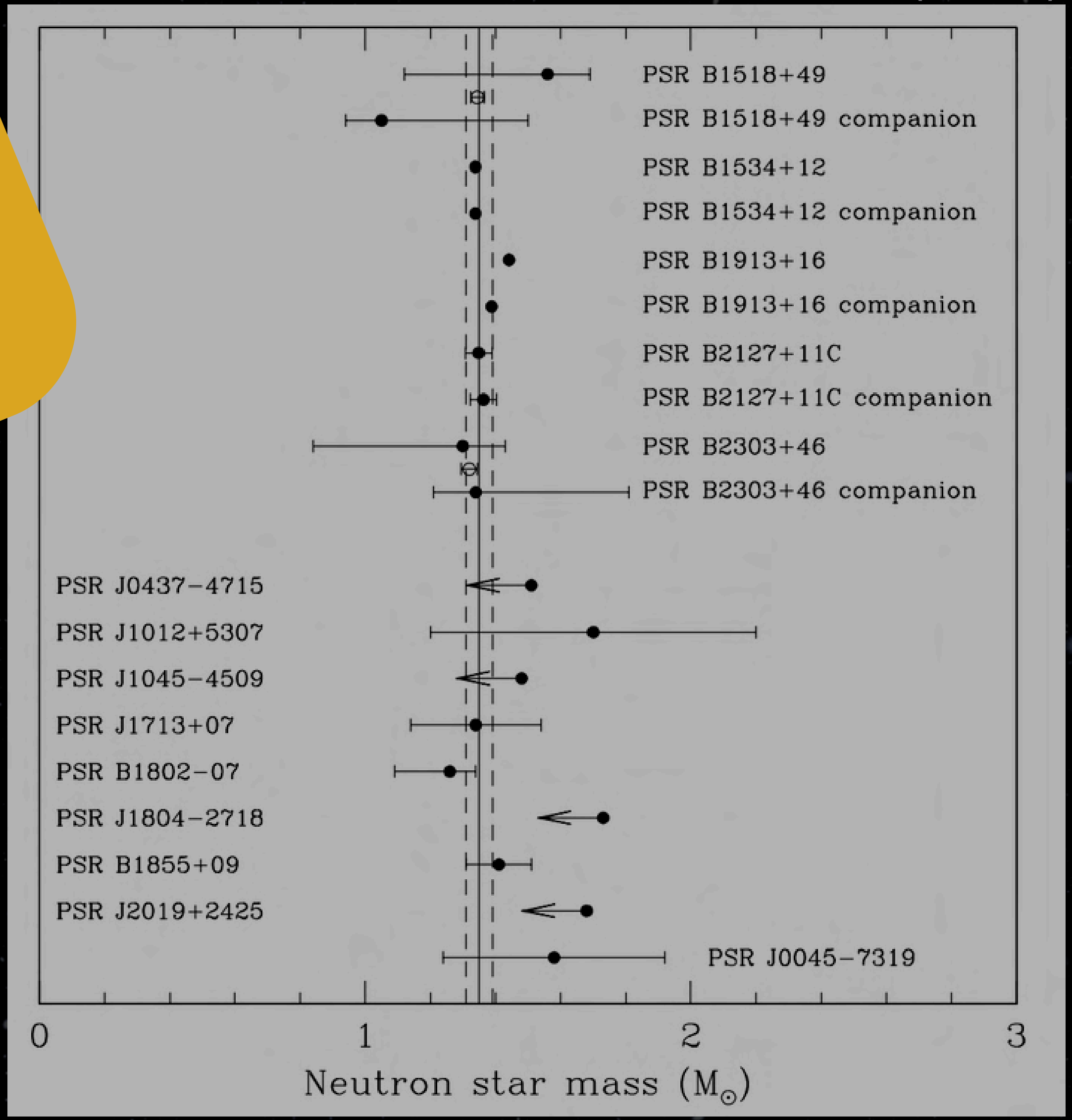
Core w/ almost invarian

↓

NS's with m ~ 1.4

Problem solved!
...Really?

THORSETT AND CHAKRABARTY (1999)

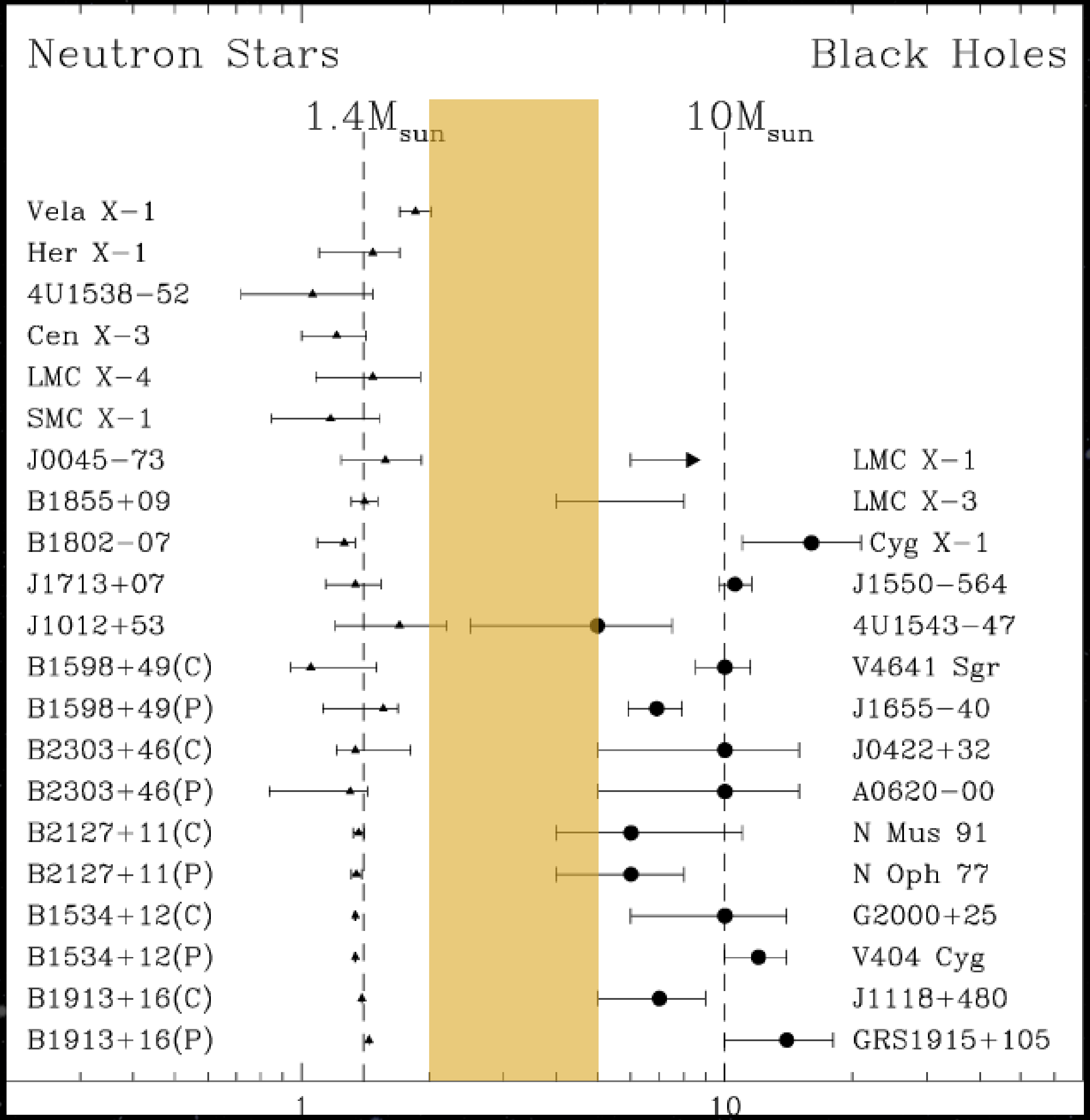


Observations match with theory!

$$m = 1.35 \pm 0.04\ M_\odot$$

THE LOWER MASS GAP

- NSs below 2 $M_\odot$ + BH candidates in LMXBs + supernova mechanisms:
  - Lack of compact objects between 2 - 5 $M_\odot$



A FEW YEARS LATER…

LETTER

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

- EoS must be stiffer than we thought

CURRENT SCENARIO

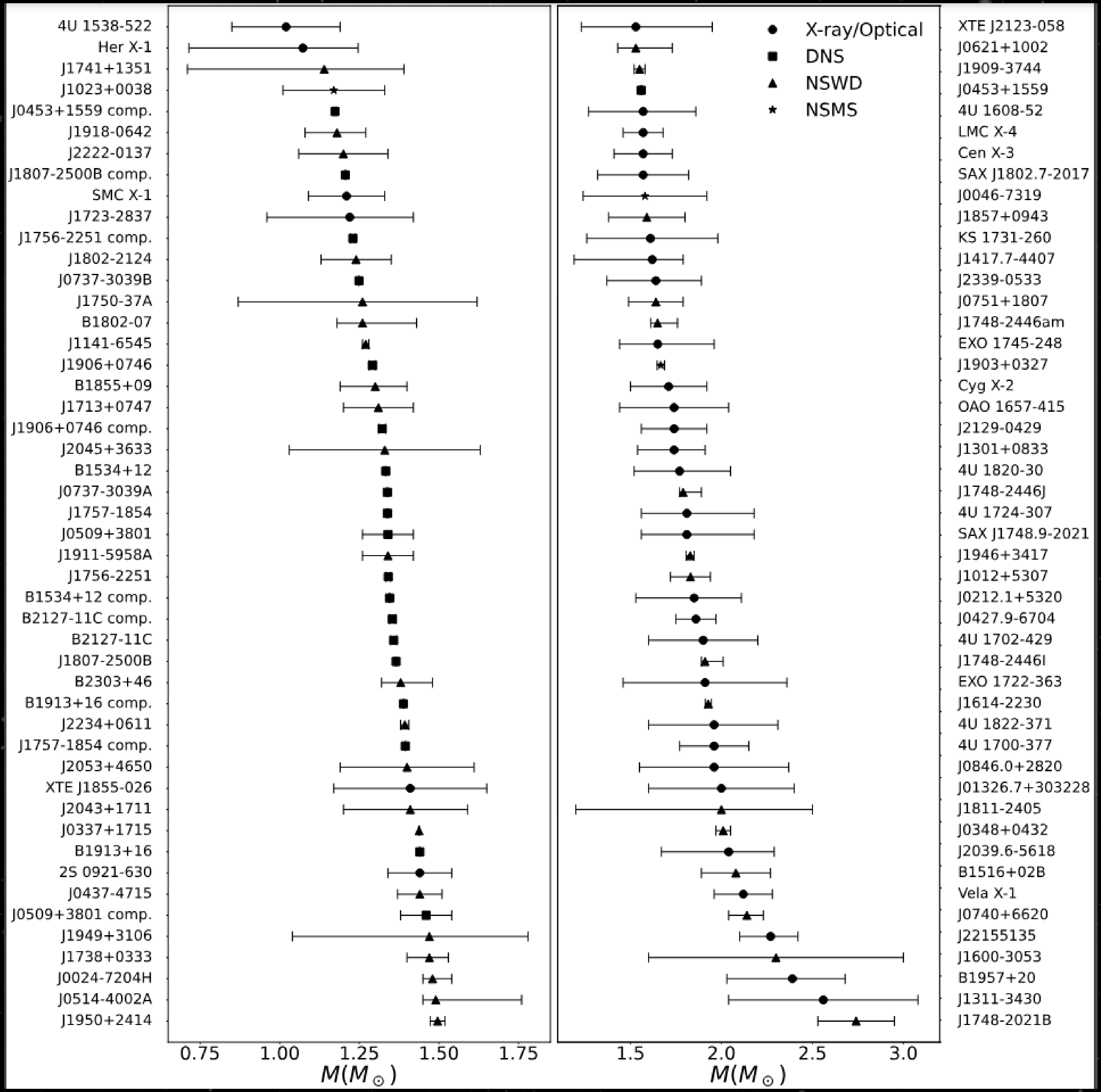
In short...

- Bimodal gaussian distribution
  - Another formation mechanisms/accretion history ?
    - Electron capture supernovae
    - SNe leading to initial masses up to 1.9 $M_{\odot}$ (Burrows and Vartanyan, 2021)

- Maximum mass:

  Shao et al. (2020); Fan et al. (2024);

$$M_{max} \sim 2.26\ M_{\odot}$$



DE SÁ ET AL. (2022)

THE BNS MERGER

GW170817:

- New channel to probe NS physics
- Electromagnetic counterpart

Atempt to calculate TOV mass

- Margalit and Metzger (2017):

$$M_{max} \lesssim 2.17\ M_\odot\ (90\%)$$

- Ruiz et al. (2018)

$$M_{max} \lesssim 2.3\ M_\odot$$

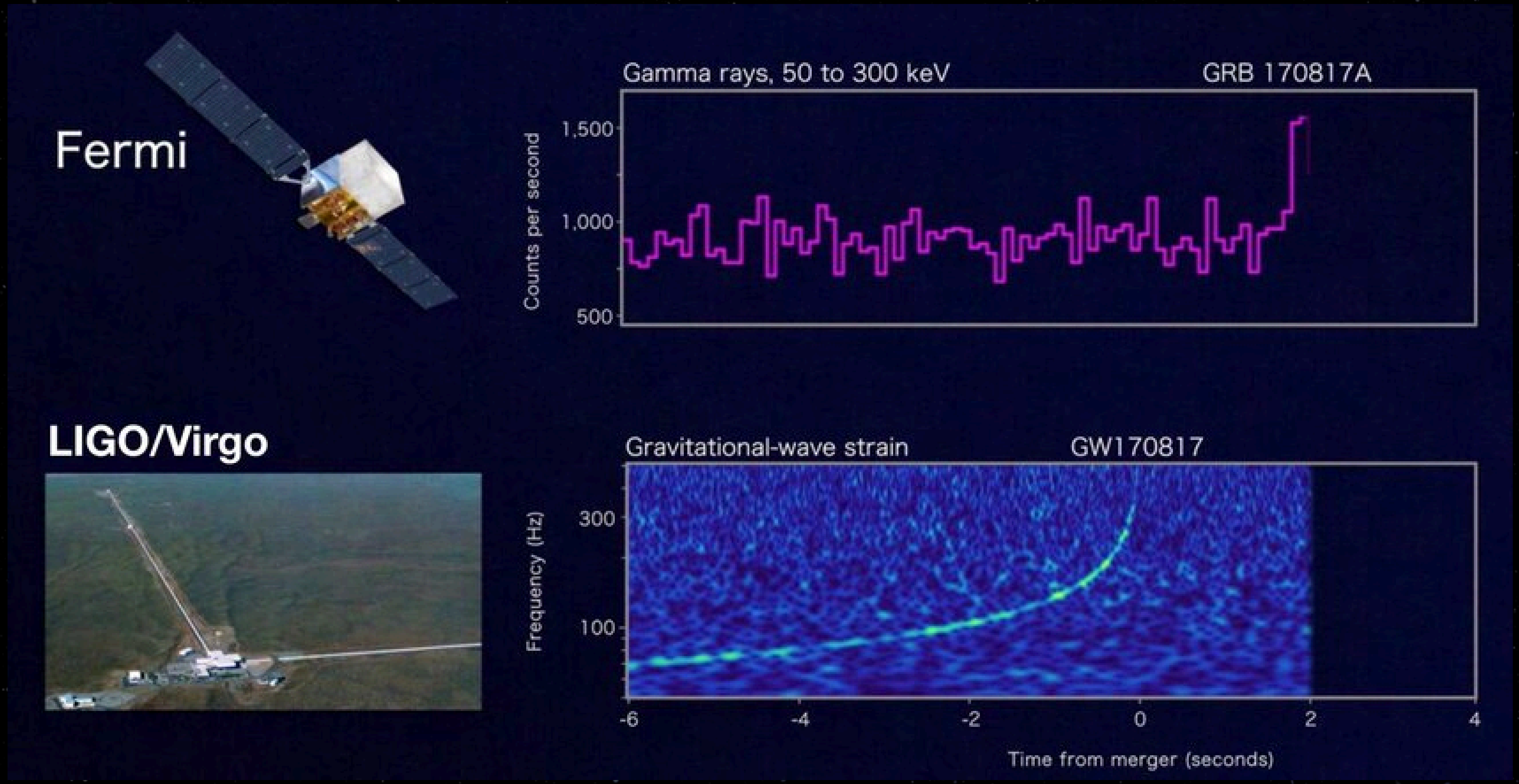
- Shibata et al. (2019):

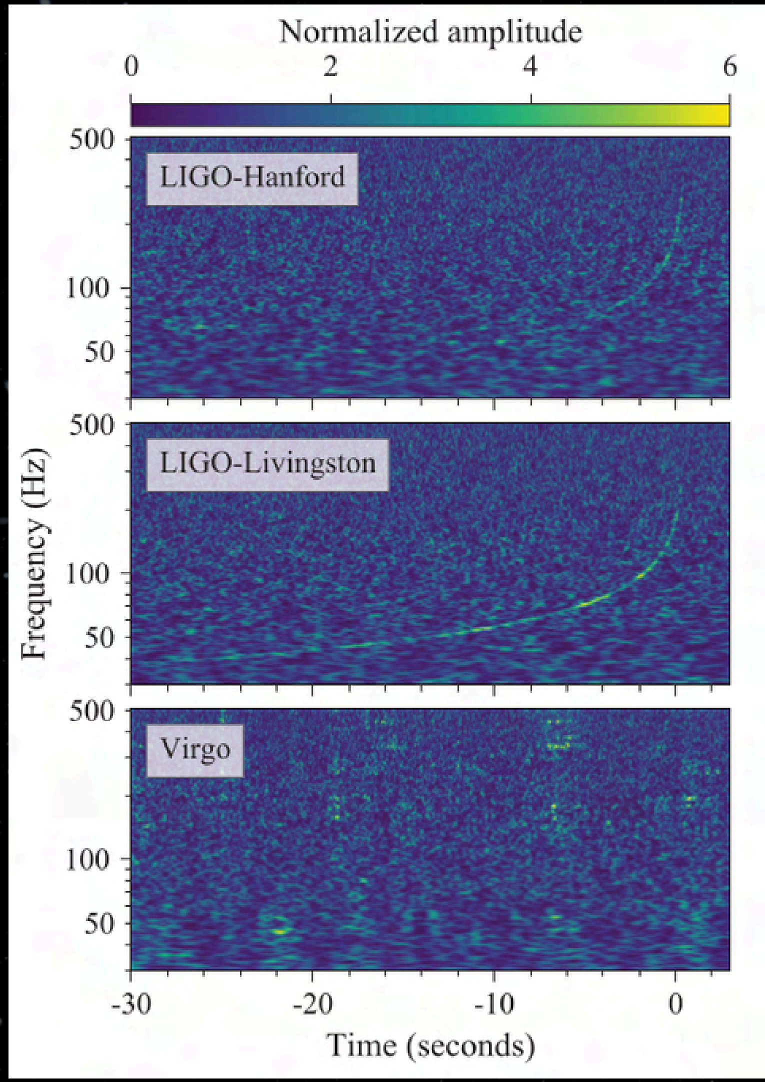
$$M_{max} \sim 2.16 - 2.28\ M_\odot$$

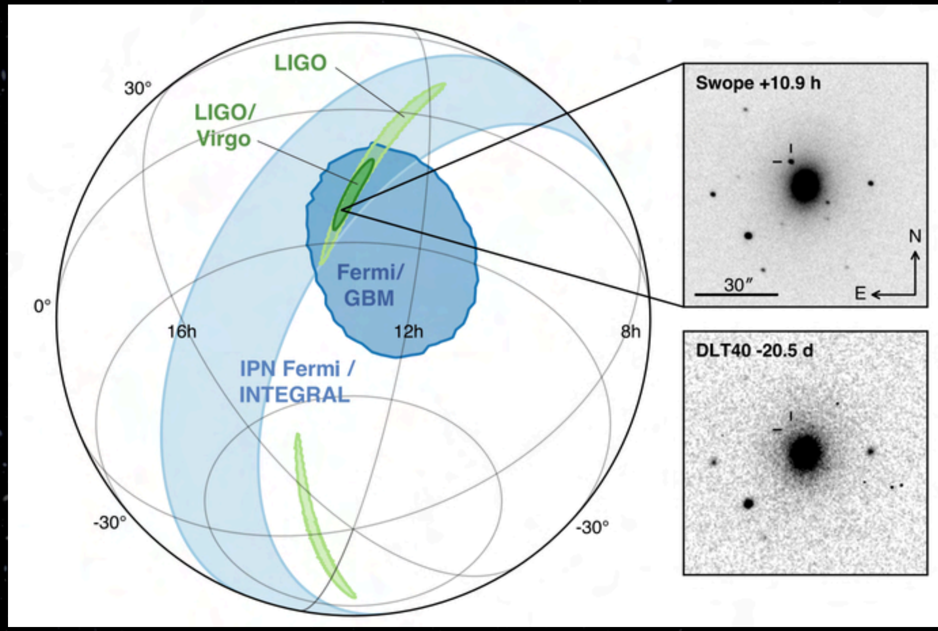
- Ai et al. (2020)

$$2.09 \lesssim M_{max} < 2.43\ M_\odot$$

Match maximum mass from galactic pulsars!

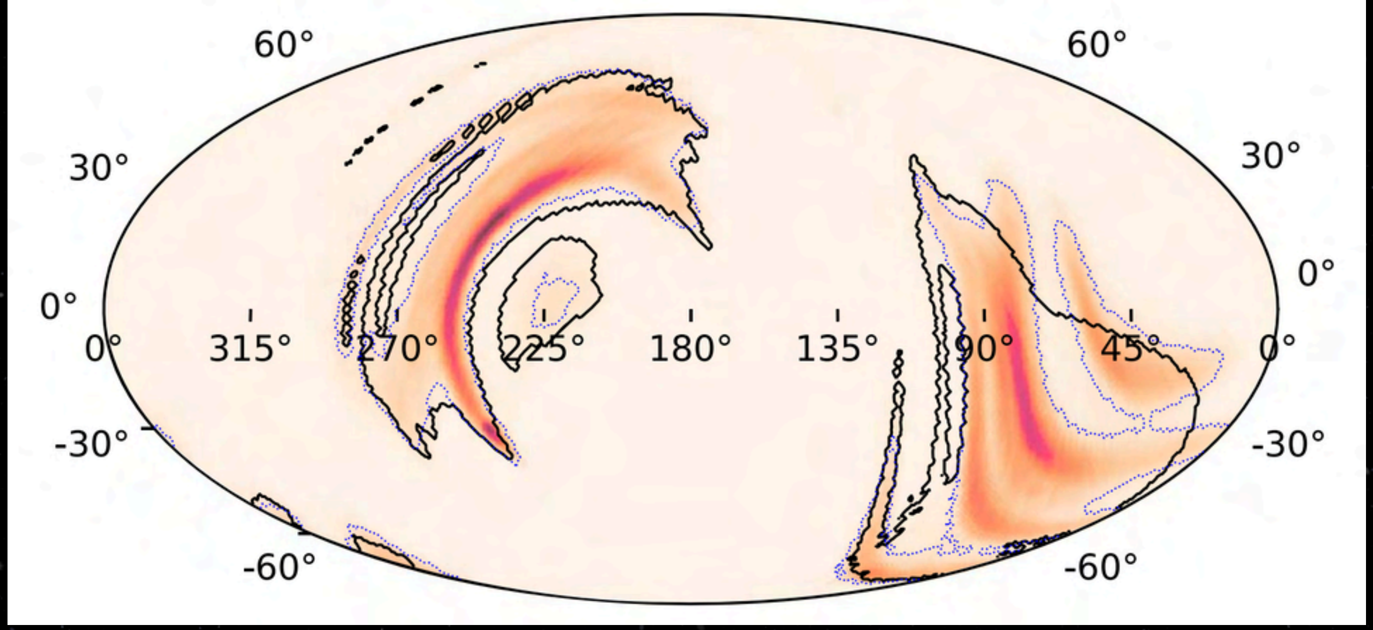




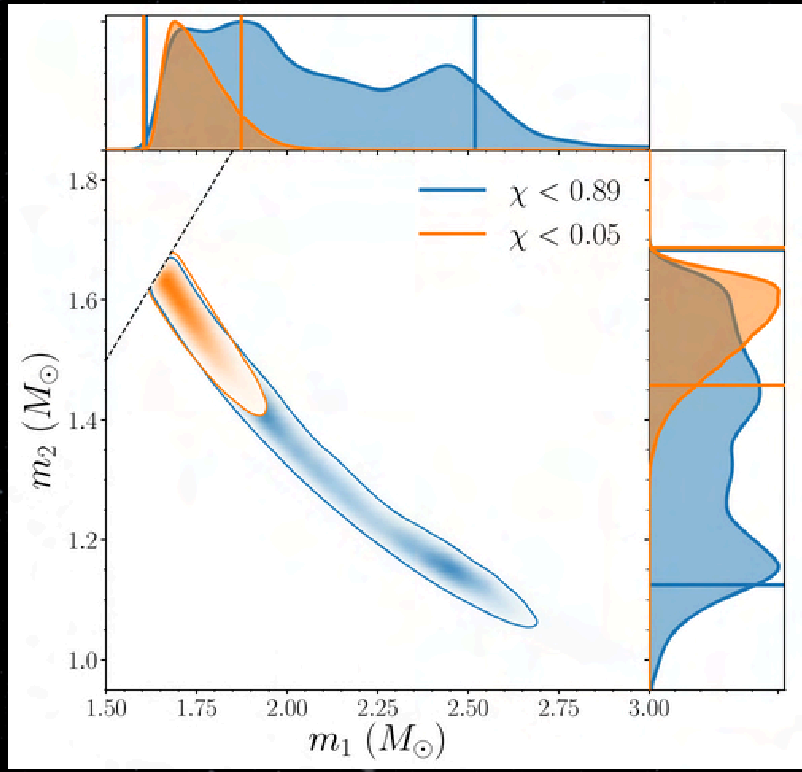


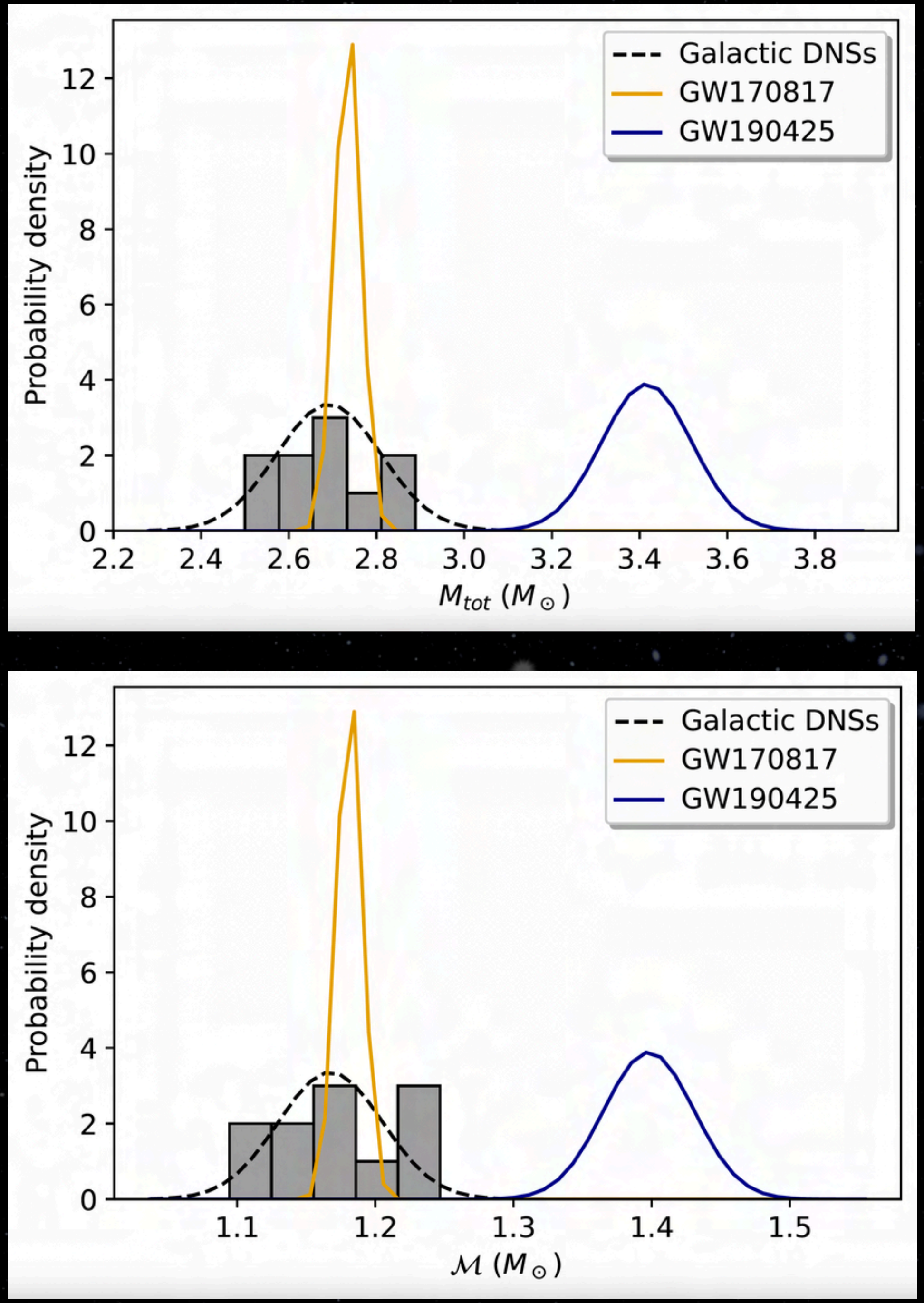
ABBOTT ET AL. (2018)

GW190425



ABBOTT ET AL. (2020)





ROCHA ET AL. (IN PREP)

Low-spin prior:

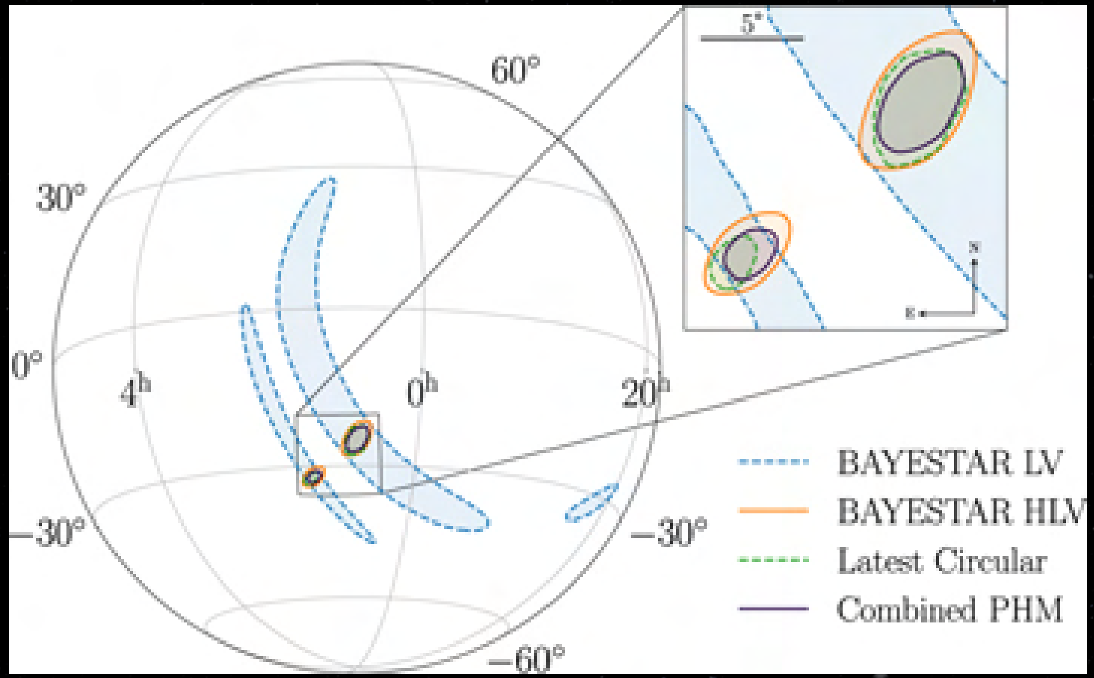
$$\begin{cases} 1.60 \leq m_1(M_\odot) \leq 1.87 \\ 1.46 \leq m_2(M_\odot) \leq 1.69 \end{cases}$$

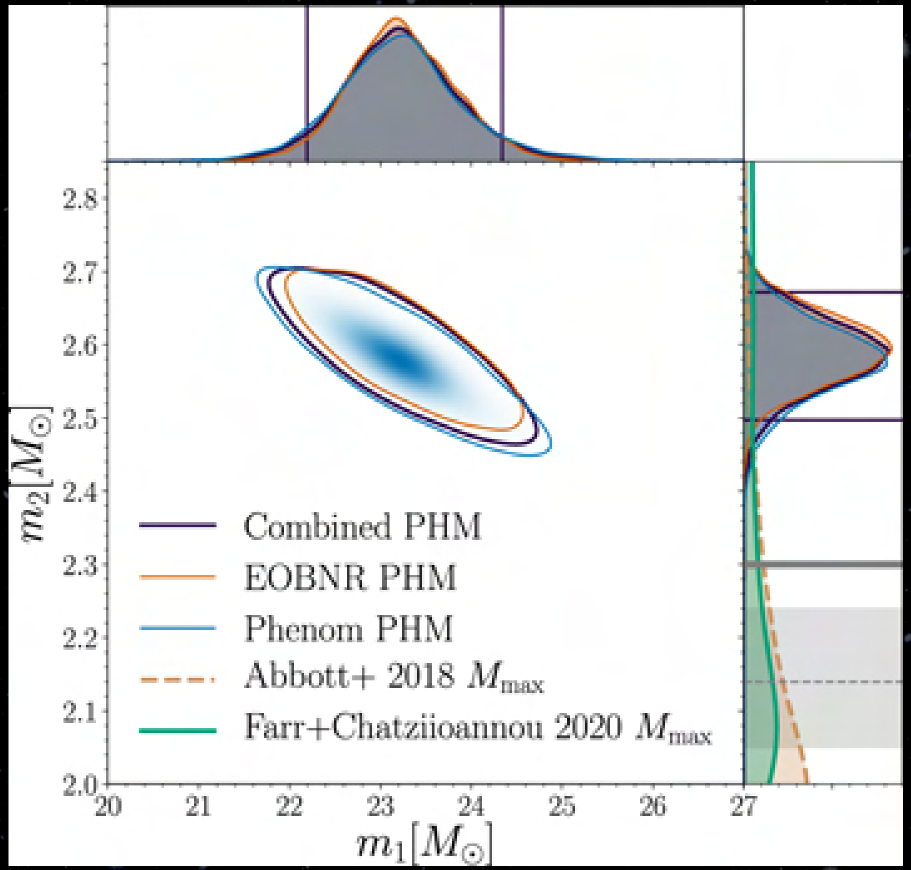
$$\begin{cases} M_{TOT} = 3.3 \pm 0.1 \ M_\odot \\ \mathcal{M} = 1.44 \pm 0.02 \ M_\odot \end{cases}$$

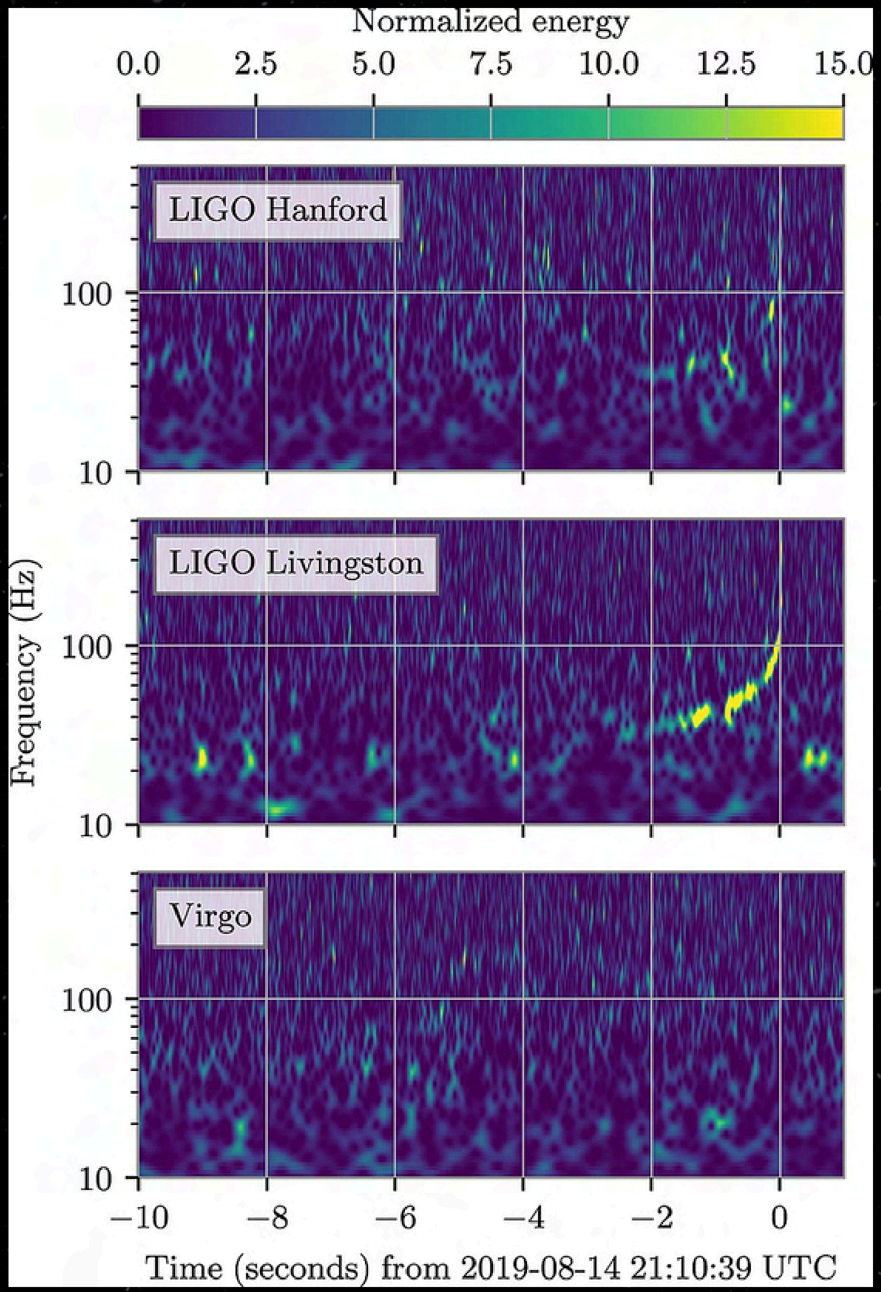
$> 5\sigma$ away from DNS sample

A TENSION FROM GW DETECTIONS

GW190814







ABBOTT ET AL. (2020)

$$\begin{cases} m_1 = 23.2^{+1.1}_{-1.0}\ M_\odot \\ m_2 = 2.59^{+0.08}_{-0.09}\ M_\odot \end{cases}$$

Constraints on M_{TOV}:

- GW170817:

$$M_{TOV} \leq 2.3\ M_\odot$$

- GW190814 and GW200210:

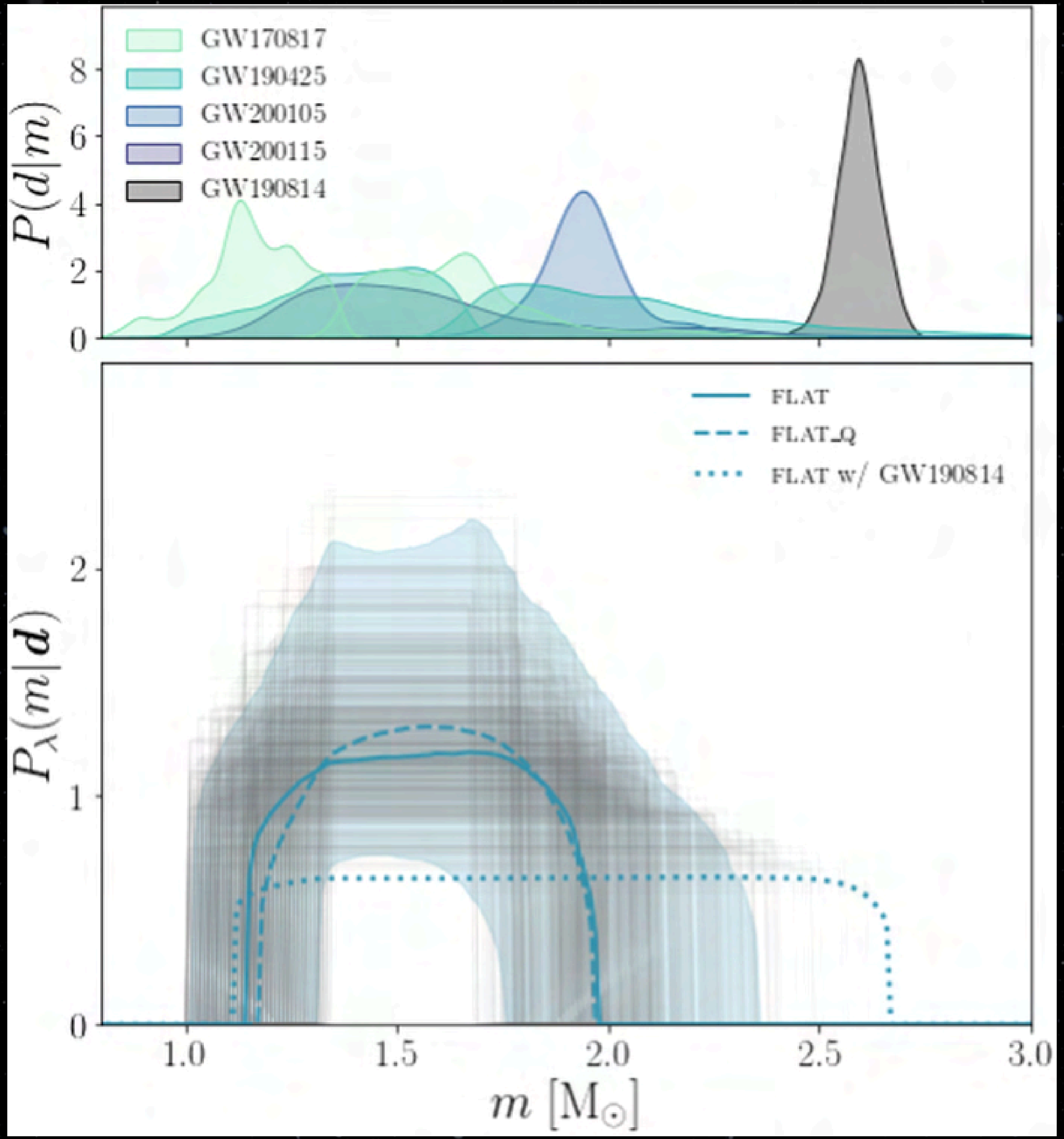
$$M_{TOV} \geq 2.5\ M_\odot$$

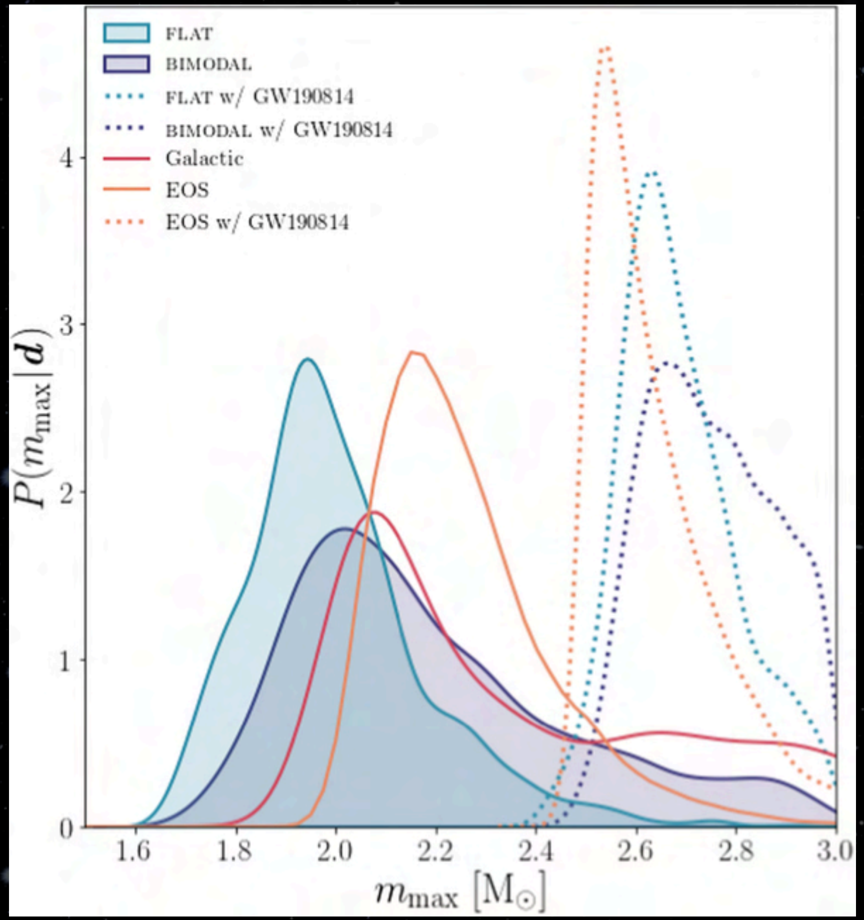
(IF companion is a NS!)

The Astrophysical Journal Letters, 921:L25 (7pp), 2021 November 10 https://doi.org/10.3847/2041-8213/ac2f3e

The Mass Distribution of Neutron Stars in Gravitational-wave Binaries

Philippe Landry and Jocelyn S. Read
Nicholas & Lee Begovich Center for Gravitational-Wave Physics & Astronomy, California State University, Fullerton, 800 N State College Boulevard, Fullerton, CA 92831, USA
Received 2021 July 16; revised 2021 October 12; accepted 2021 October 13; published 2021 November 3





- Their conclusion:
  - Extragalactic sample of NSs should be different from the galactic one
- Maybe too early to take such conclusion.

LATEST DISCOVERIES IN OUR GALAXY

PSR J1653-0158

Black widow pulsar

$$m_p = 2.15 \pm 0.16\ M_\odot$$

KANDEL AND ROMANI. (2022)

PSR J0952-0607

Black widow pulsar

$$m_p = 2.35 \pm 0.17\ M_\odot$$

$$M_{max} > 2.19\ M_\odot$$

ROMANI ET AL. (2022)

PSR J0514-4002E

Pulsar with a compact companion (BH or NS)

$$m_c = 2.35^{+0.20}_{-0.18}\ M_\odot$$

$$2.09 \leq m_c \leq 2.71\ (95\% C.I.)$$

$$M_{TOT} = 3.8870 \pm 0.0045\ M_\odot$$

ROMANI ET AL. (2022)

THE GALACTIC SAMPLING

- Differentiate measurements based on measured post-Keplerian parameters

$$P(d|m_p) \propto \mathcal{N}(m, \sigma)$$

$$P(d|m_p) \propto \int\int P(\hat{m}_T, \hat{f}|m_p, m_T, i)P(m_T)P(i)didm_T \longrightarrow \int exp\left(-\frac{(m_T-\mu_T)^2}{2\sigma_T^2}\right)\frac{m_T^{4/3}}{3(m_T-m_p)^2 f^{1/3}\sqrt{1-\frac{f^{2/3}m_T^{4/3}}{(m_T-m_p)^2}}}dm_T$$

$$P(d|m_p) \propto \int\int P(\hat{q}, \hat{f}|m_p, q, i)didq \longrightarrow \int exp\left(-\frac{(q-\mu_q)^2}{2\sigma_q^2}\right)\frac{(1+q)^{4/3}}{3f^{1/3}m_p^{2/3}q^2\sqrt{1-\left(\frac{f}{m_p}\right)^{2/3}\frac{(1+q)^{4/3}}{q^2}}}dq$$

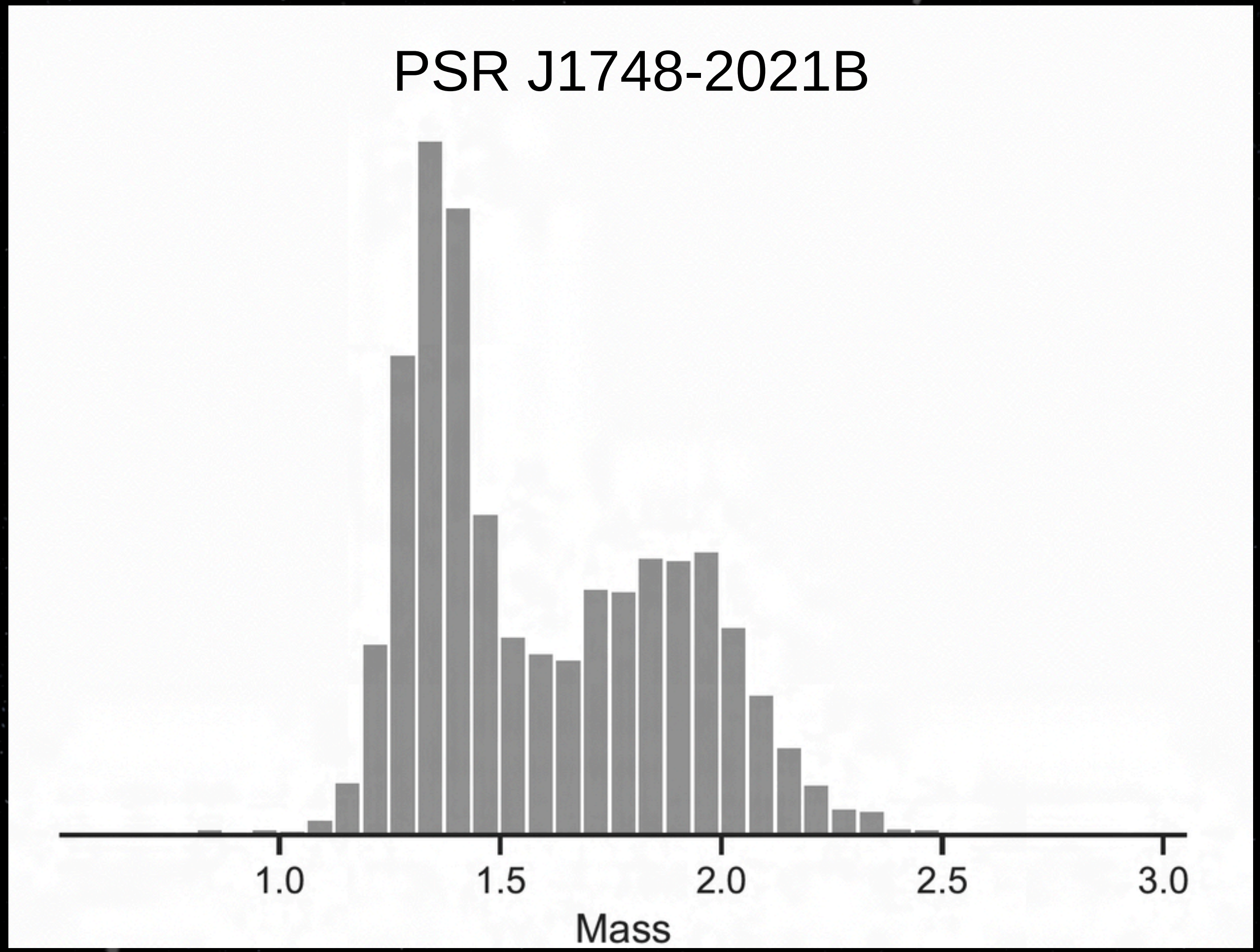
Assumes a uniform distribution over cos i, which means that i can go from 0 to 90°.

Orbital inclination is the main source of uncertainty for mass measurements.

$$m_p \propto \frac{1}{sin^3 i}$$

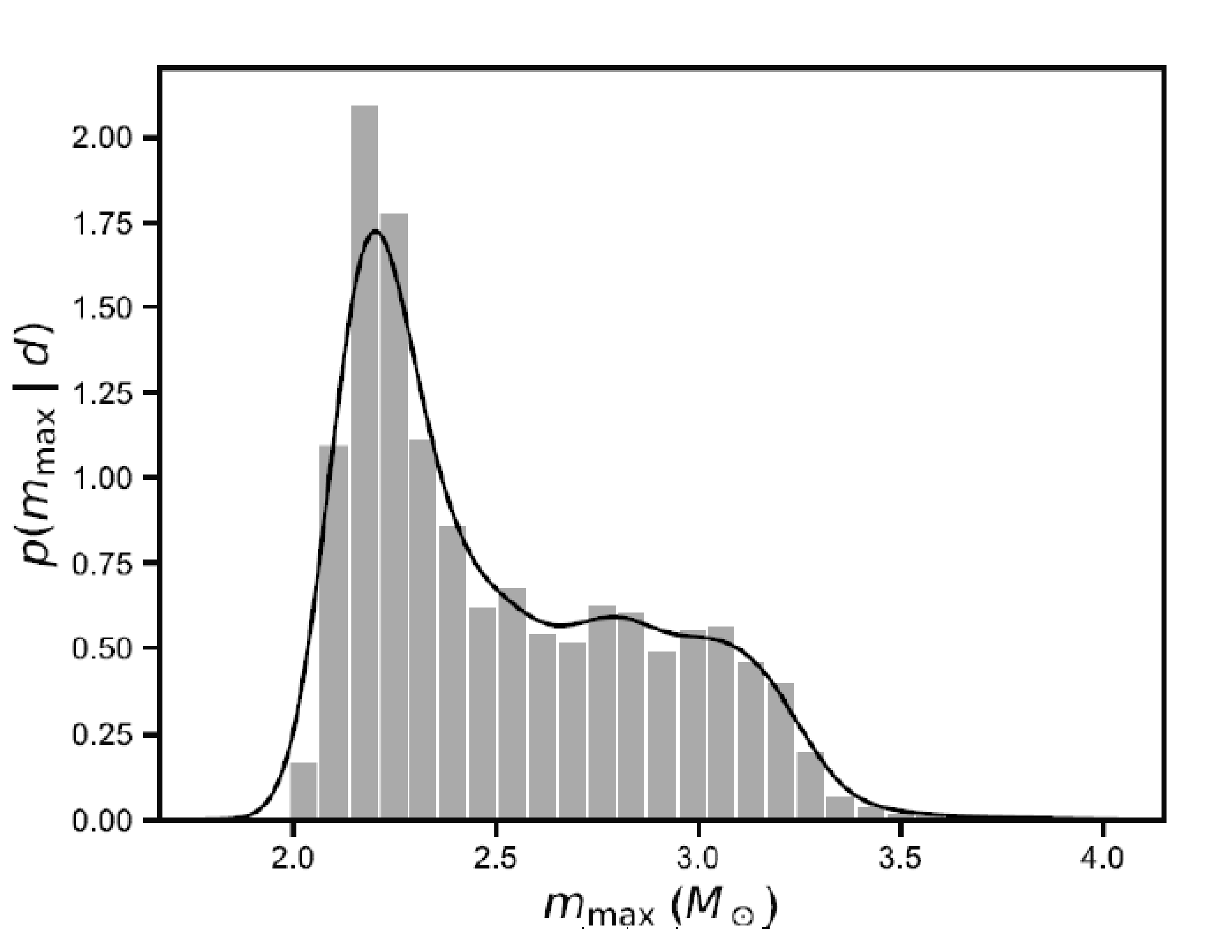
PSR J1748-2021B:

- Freire et al. (2008)
  - m = $2.74 \pm 0.21 \ M_{\odot}$
  - Probability of m < $2M_{\odot}$ is 1%
  - Probability of being between 1.2 < m($M_{\odot}$) < 1.44 is 0.10%

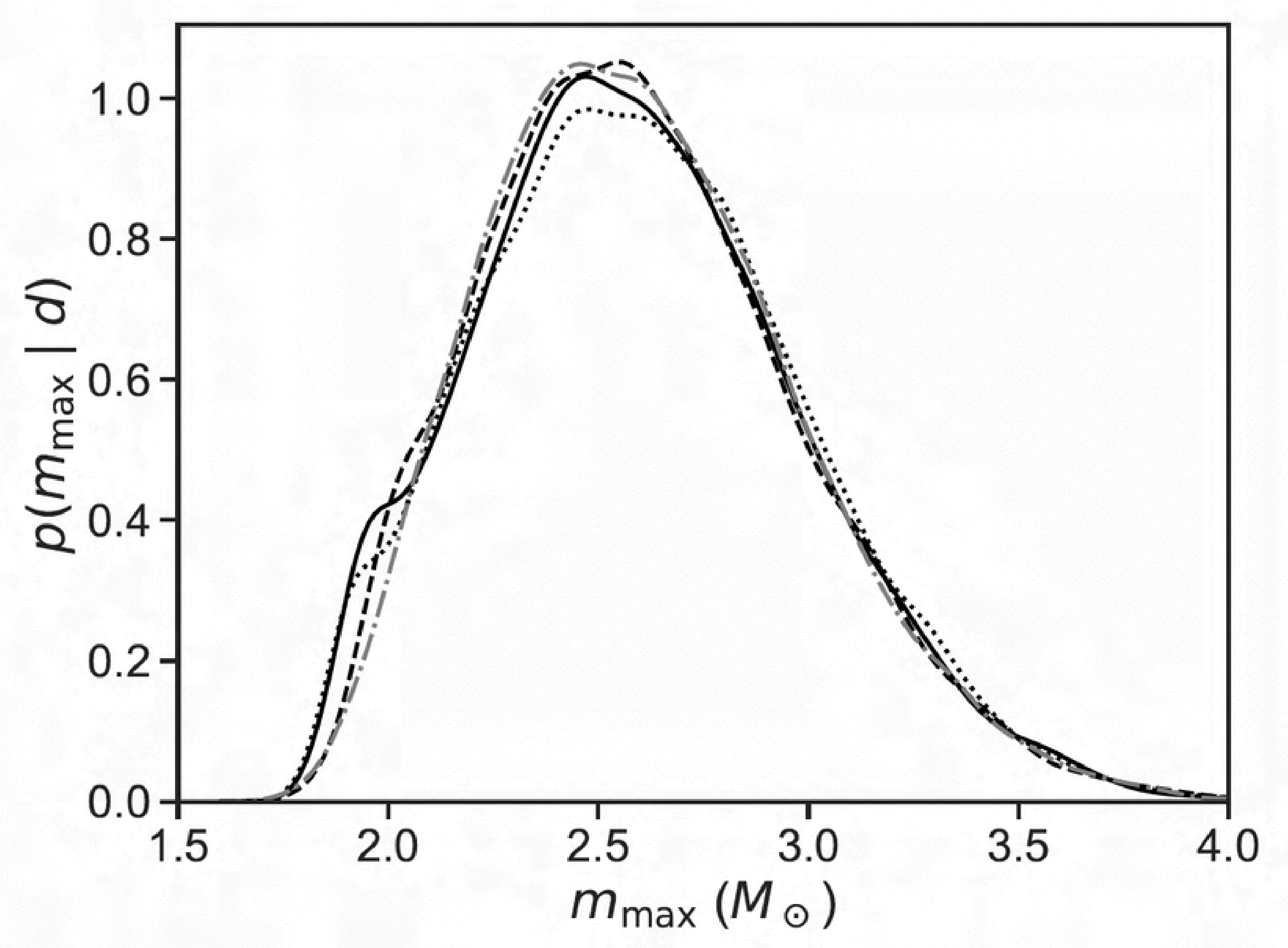


- What do we obtain treating all masses equaly, compared with the standard treatment?

Sampling with uniform distribution over cos i

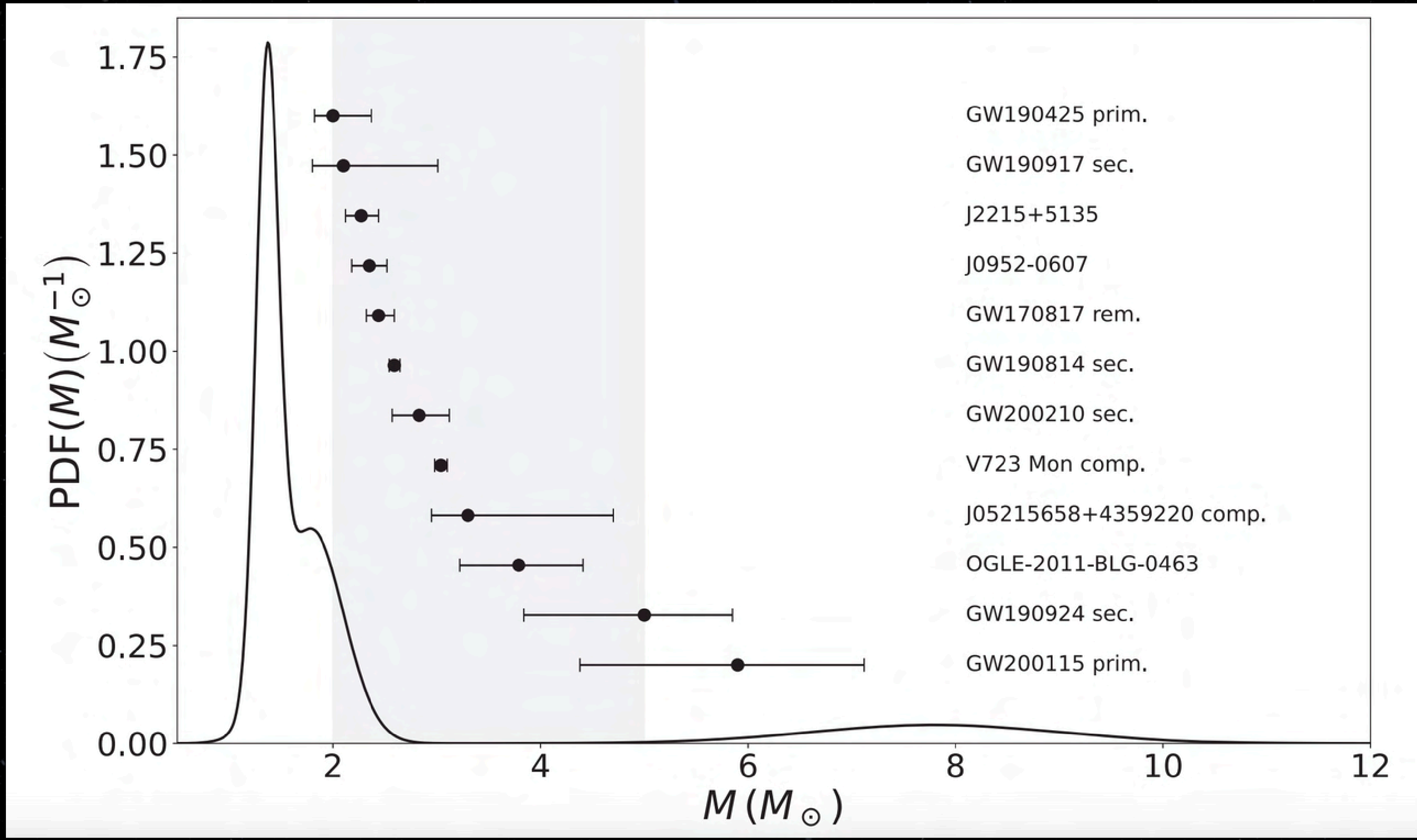


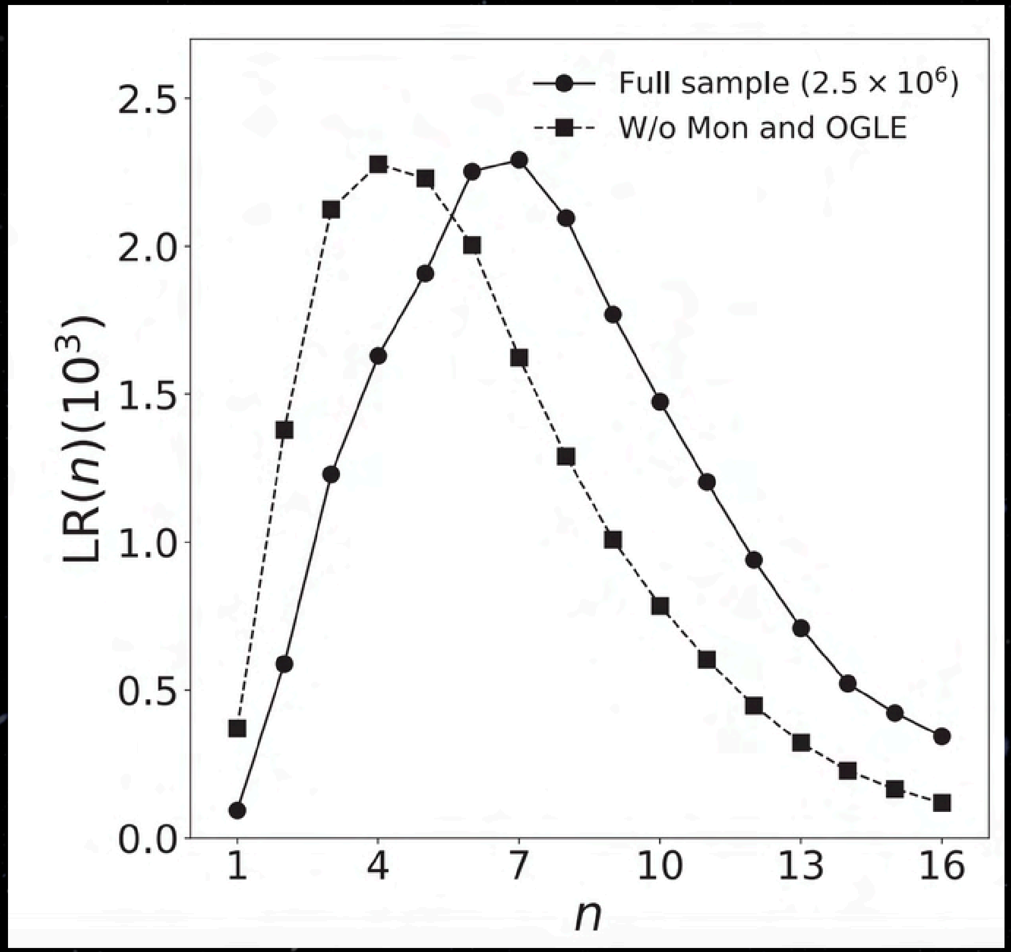
All systems with normal likelihoods



- We need to be more careful with this assumption.
- Ideal case: include constraints of orbital inclination in the analysis (to be done)

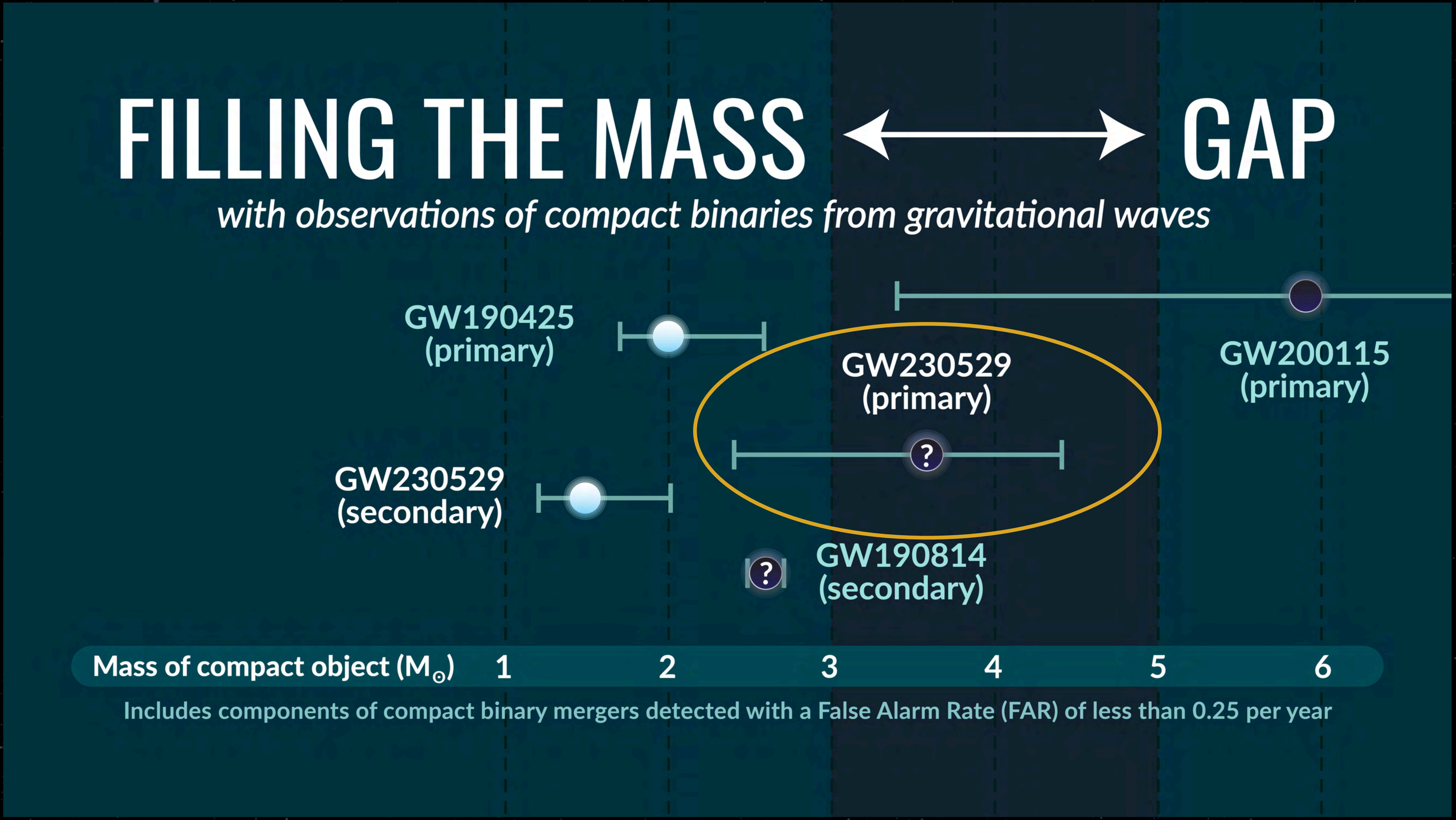
EVIDENCE AGAINST A MASS GAP





DE SÁ ET AL. (2022)

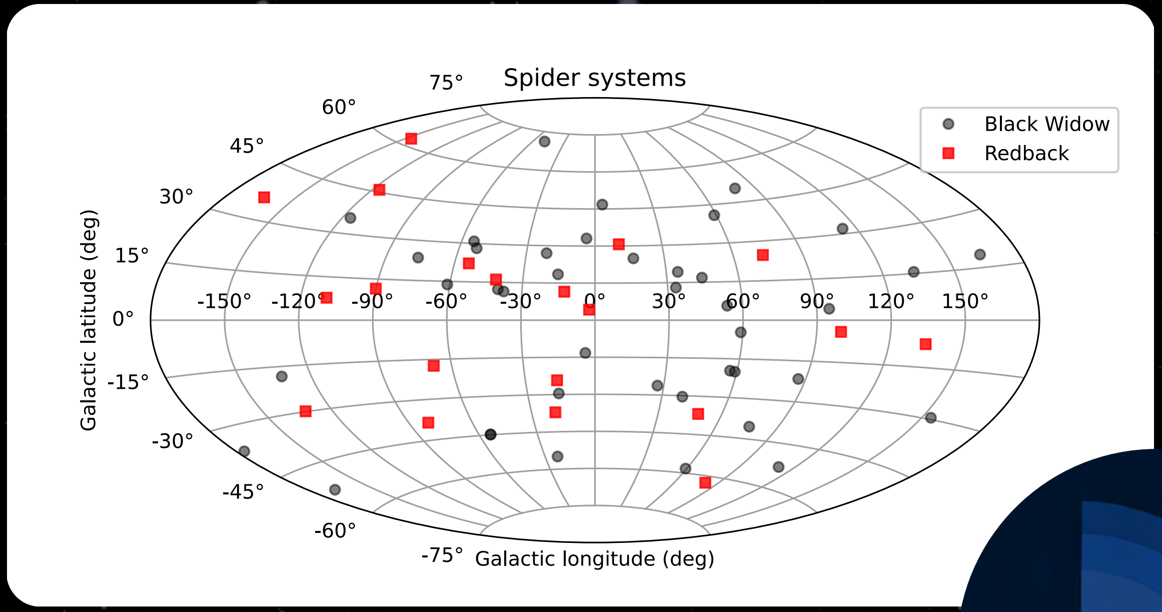
- There is no absolute gap!

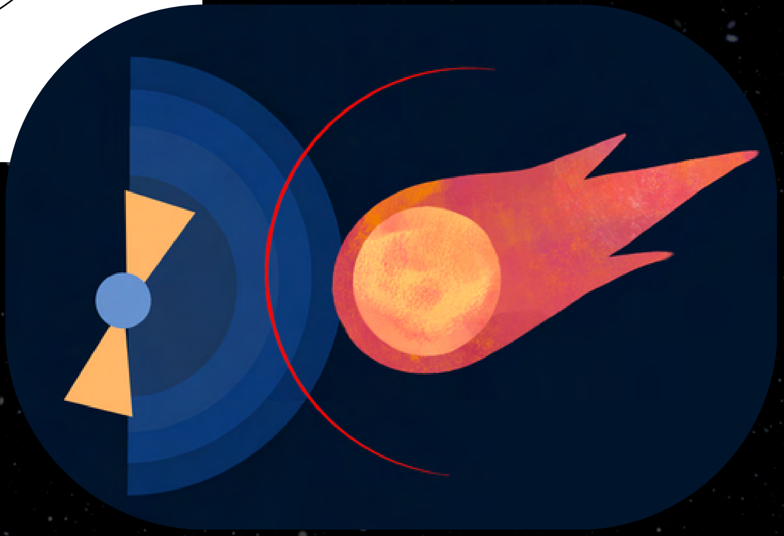


LLVK COLLABORATION

SPIDER PULSAR BINARIES

- Millsecond pulsars (< 15 ms)
- Low-mass companion
  - Redbacks: 0.1 - 0.5 $M_\odot$
  - Black widows: << 0.1 $M_\odot$
- Short-orbits (< 1 day)
- Circular orbits (?)
- Radio (and gamma) eclipses
- Old systems
- Long accretion phase





Clark et al. (2022): searched for gamma-ray eclipses in spider systems:

- Found in only 5
- PSR B1957+20:

$$m_p = 2.4 \pm 0.1\ M_\odot \longrightarrow m_p = 1.81 \pm 0.07\ M_\odot$$

STRANGE STARS

- CFL state (Lugones and Horvath, 2002)

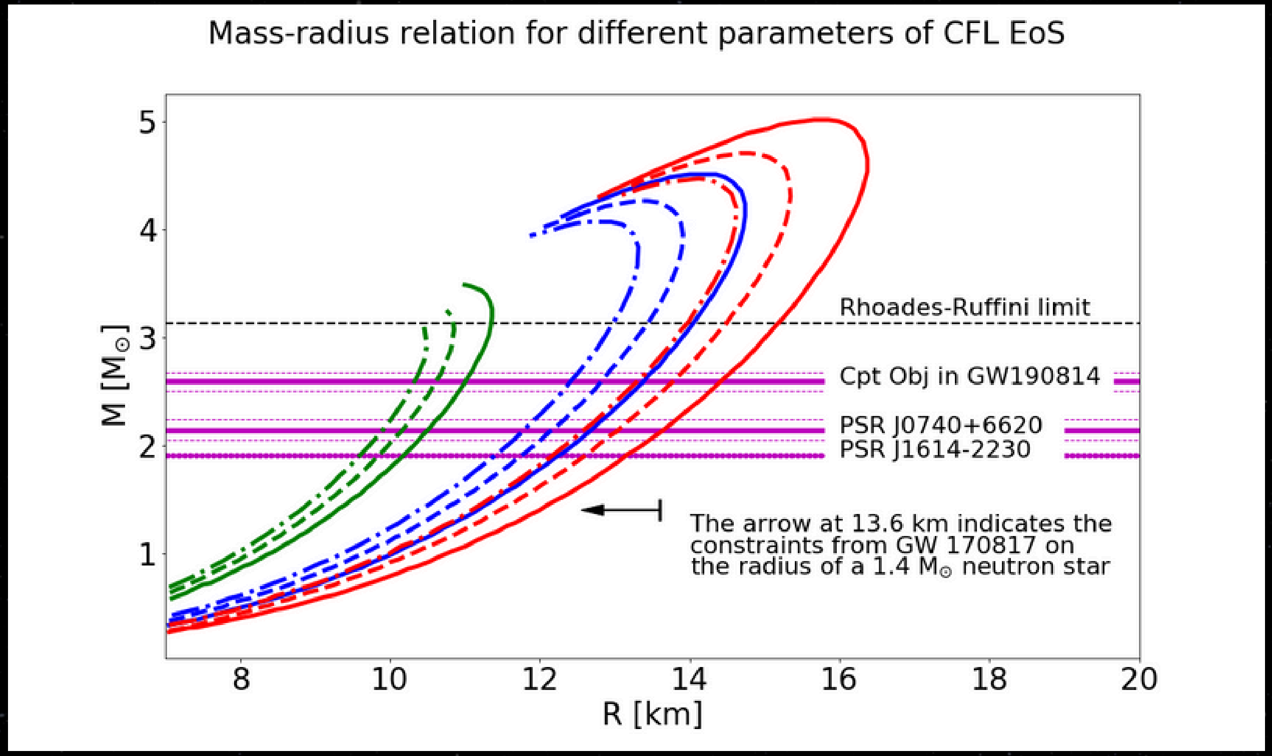
$$P(r) = \frac{1}{3}\rho + \frac{2\eta}{\pi}\rho^{1/2} - \left(\frac{2\eta^2}{\pi^2} + \frac{4B}{3}\right)$$

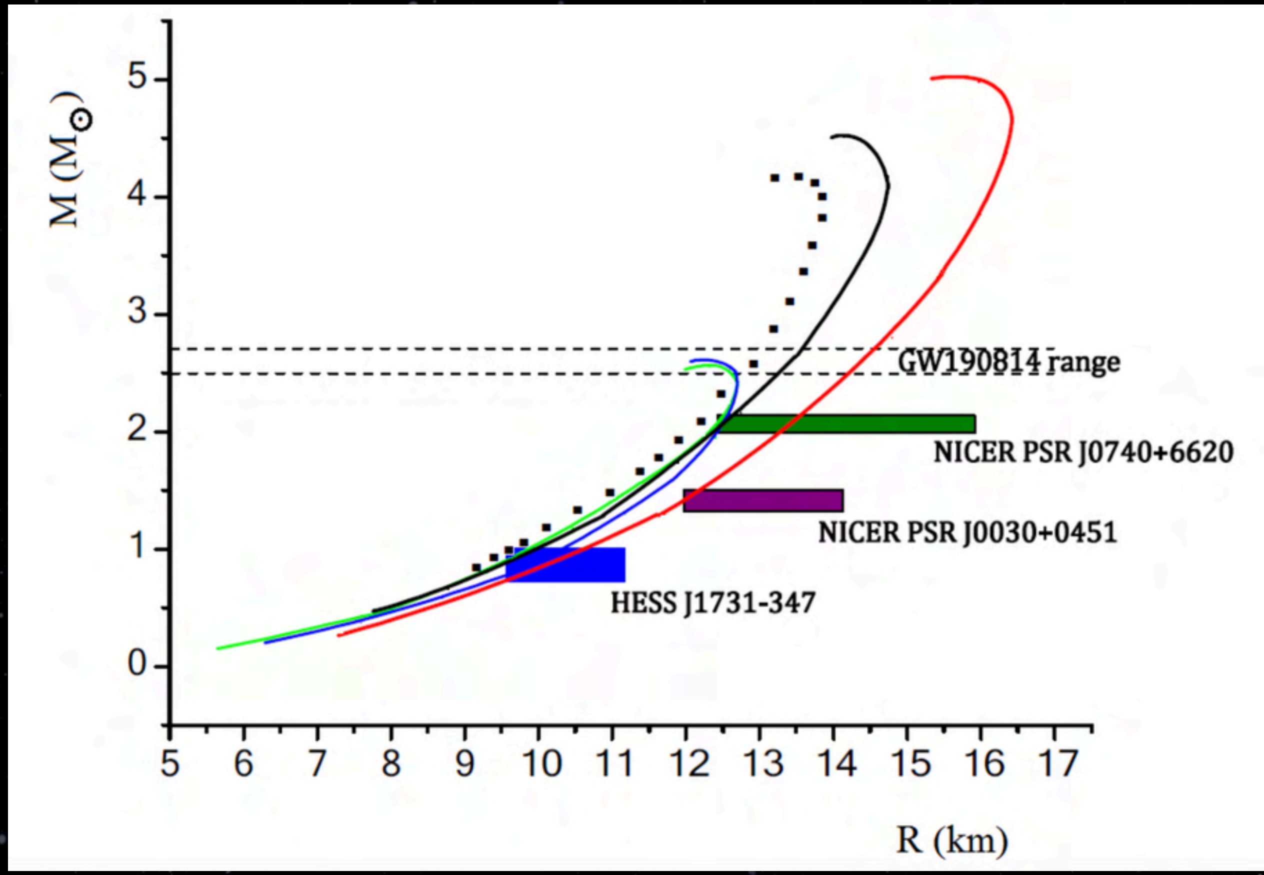
$$\eta = -\frac{m_s^2}{6} + \frac{2\Delta^2}{3}$$

- CENTRAL COMPACT OBJECT HESS J1731-347

$$m = 0.77^{+0.20}_{-0.17} M_\odot$$

$$R = 10.4^{+0.86}_{-0.78}\ km$$





HORVATH ET AL. (2023)

SUMMARY

- Galactic DNS sample follows a bimodal gaussian.
- The analysis of galactic sample should include constraints on orbital inclination.
- An absolute mass gap is ruled out.
- We cannot ignore the possibility of at least some of the mass gap objects being NSs
  - Maximum mass of NSs > 2.5
- Strange star models are doing a good job to explain the MGO

THANK YOU
FOR YOUR ATTENTION!