

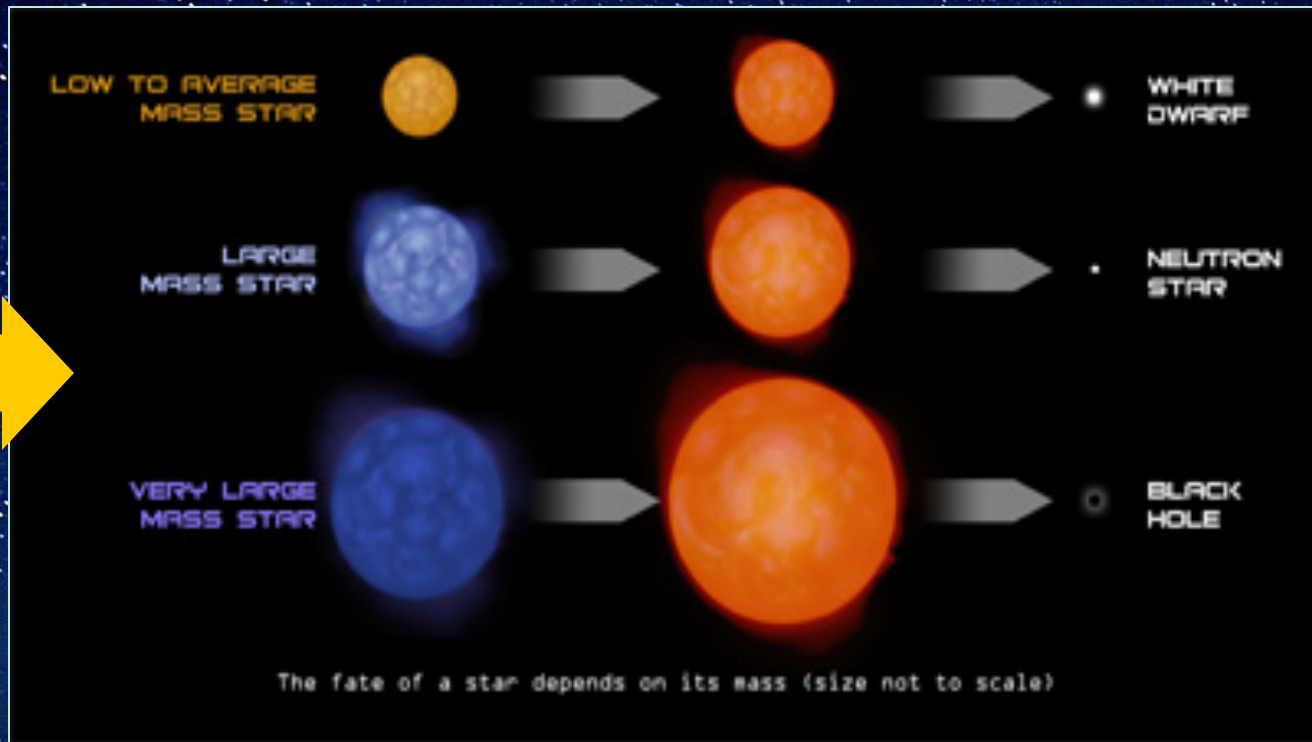
Binary neutron stars



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Stellar Evolution and Compact Objects: the simplest and the actual picture



? How?

In the last century, after > 40 years of neutron star studies, the idea of a single mass scale was firmly rooted in the community

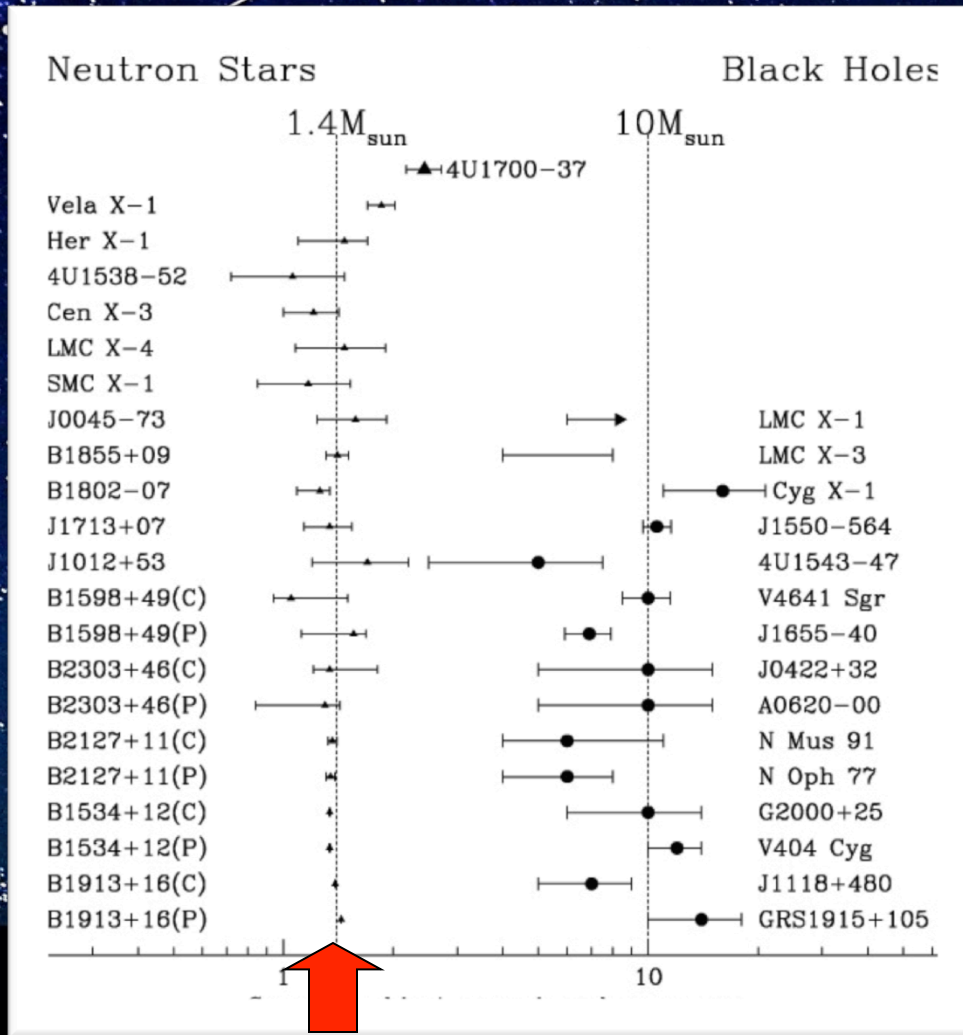
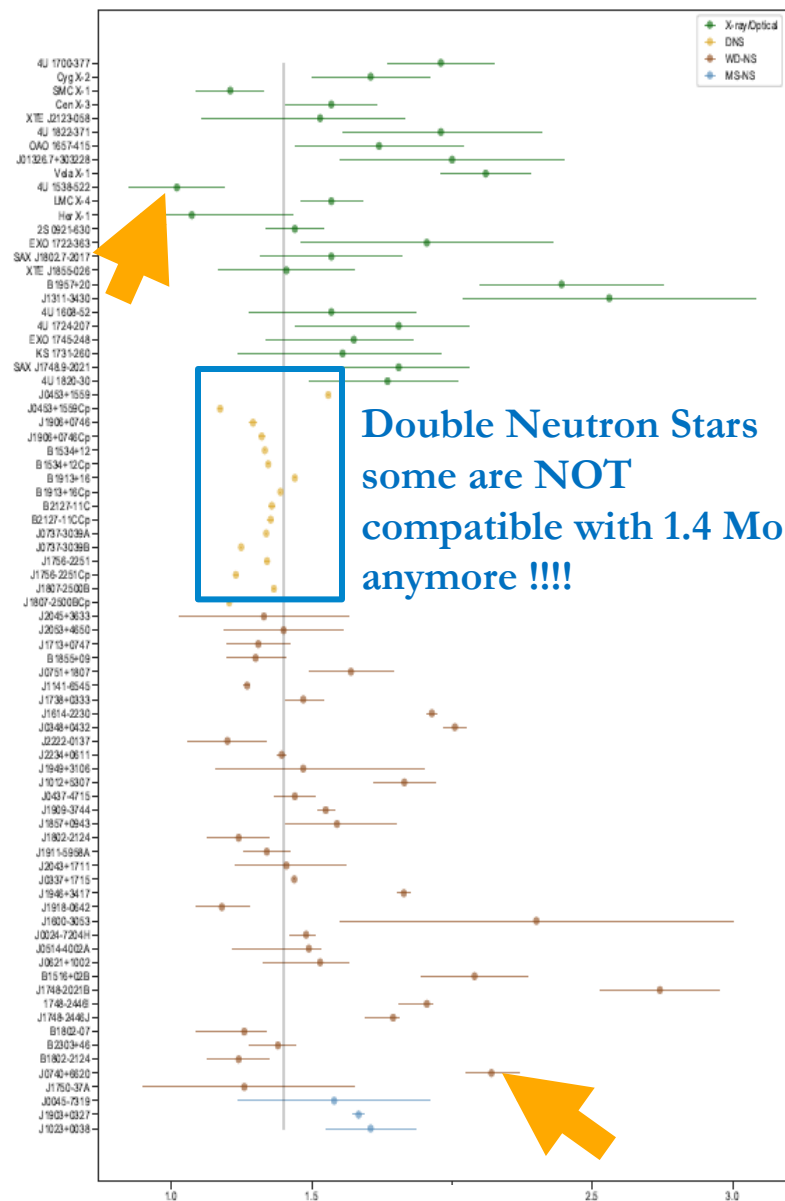


Figure from
Clark et al.
A&A 392, 909 (2002)

Consistent with 1.4 M_⊙



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However, in the last 20 years or so, firm evidence points towards a *much wider* range of masses

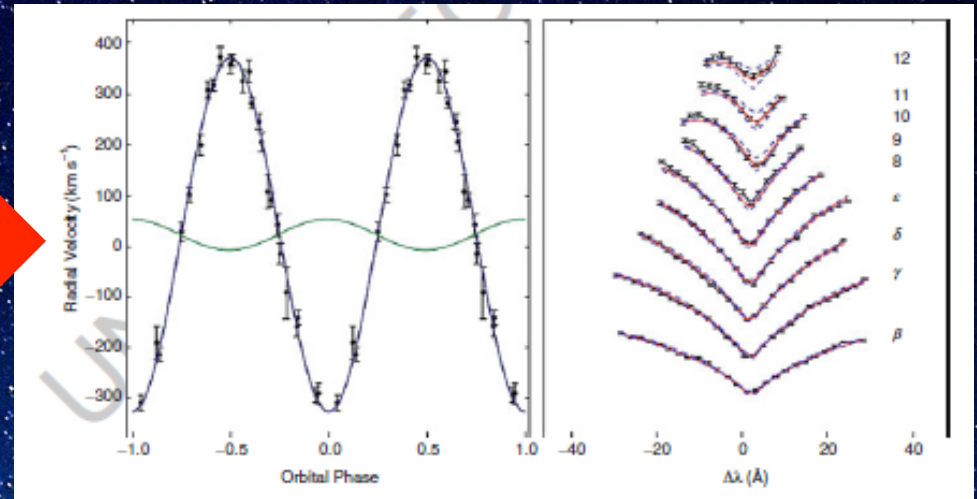
Updated sample by L.S. Rocha

Which are the lessons for us?
Where do these objects form?
Do they gain mass (binaries?) How much?

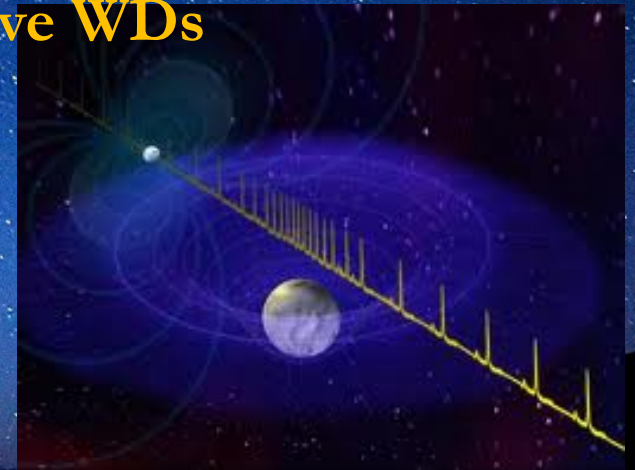
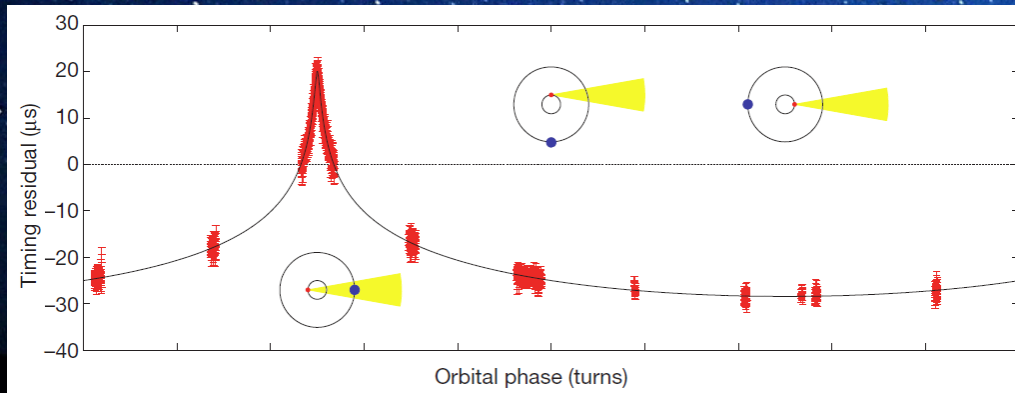
Which are the lowest and highest values? What does it mean for the constitution of dense matter?

Methods include modeling of the light curve + spectral features
→ extract individual masses

Radial velocities (left) and
Balmer lines (right) in
the PSR J0348+0432
(Antoniadis et al. 2013)



...and the celebrated detection of Shapiro delay of the pulses: needs
suitable line of sight, tight orbits and massive WDs



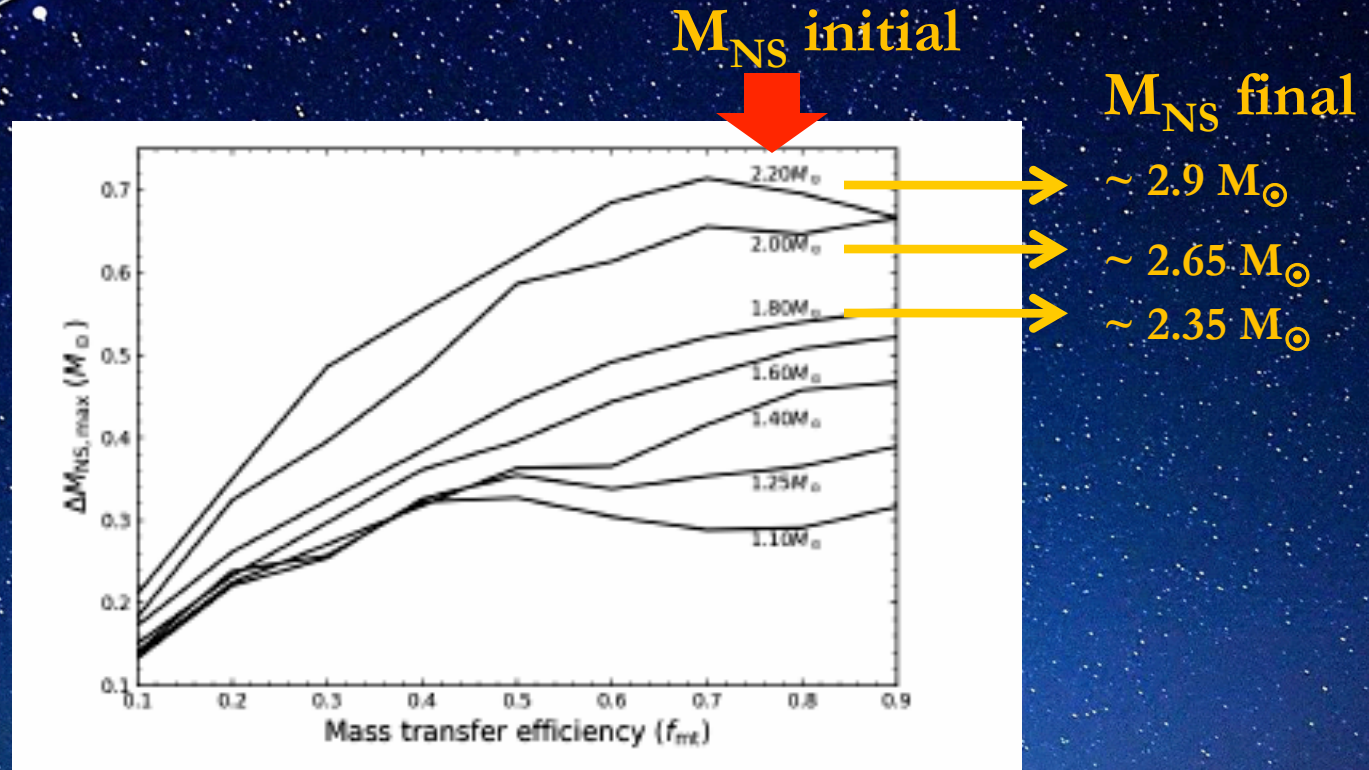
Demorest et al. (2010): $1.93 \pm 0.016 M_{\odot}$

Cromartie et al. (2020): $2.14 \pm 0.1 - 0.09 M_{\odot}$

A few more candidates being studied...

Is accretion efficient enough to grow NS masses?

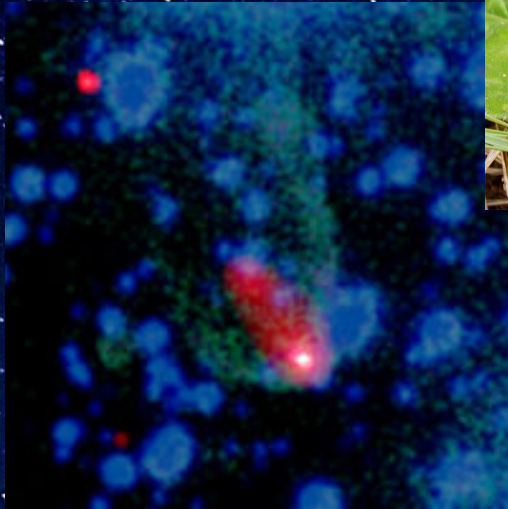
Recycled pulsar calculations leading to NS-WD systems



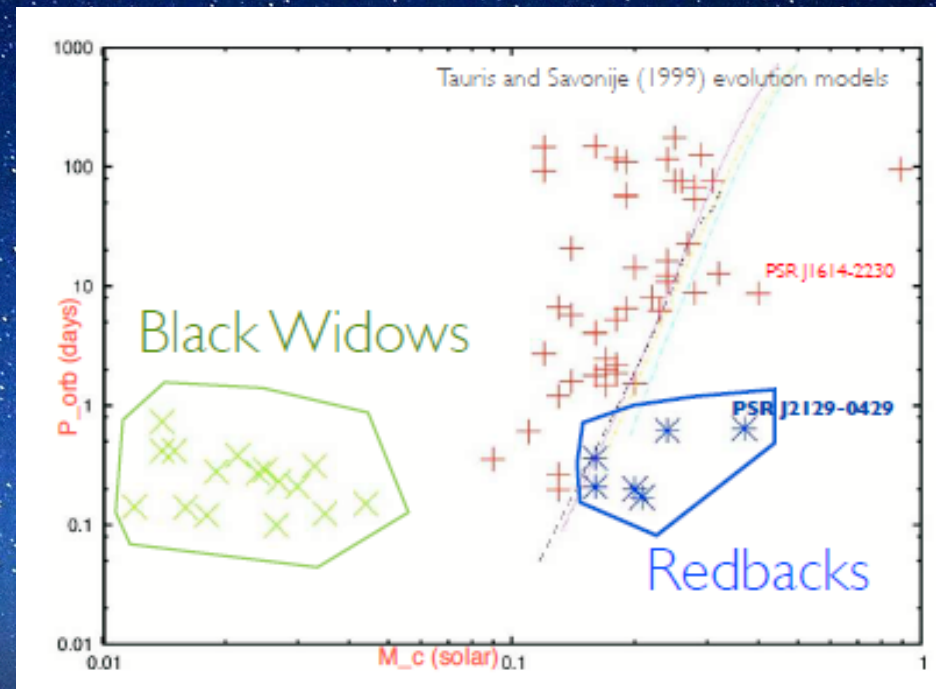
Li et al. (2021)

Accretion over $\sim$ Gyr can produce the highest possible masses
("Spiders" in which backillumination is important not included here)

A class of NS systems which may be crucial for the high-mass bin and the M_{max} as an additional parameter issue: the “spider” systems

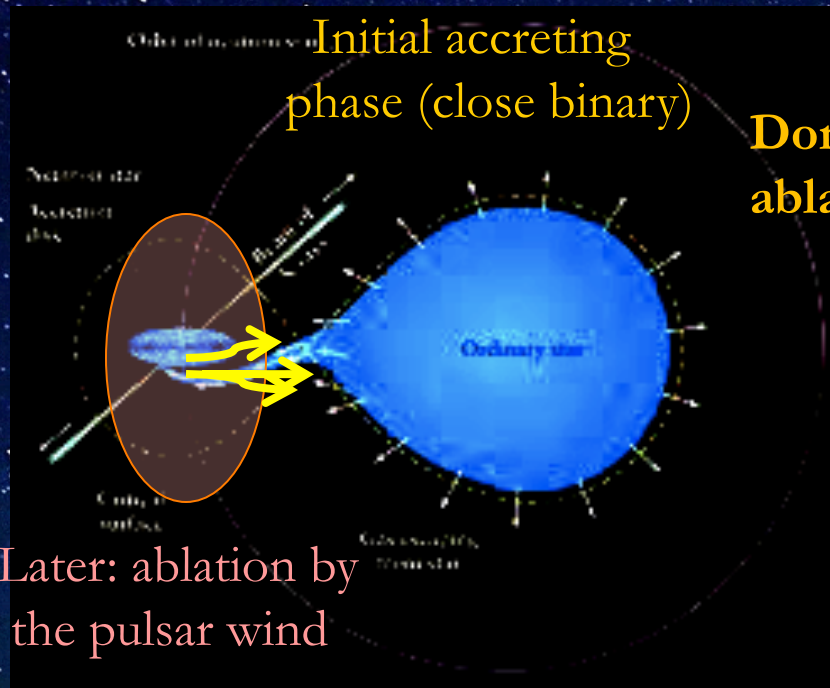


PSR 1507+20 original
“black widow”: the previously
accelerated pulsar is now ablating
its companion



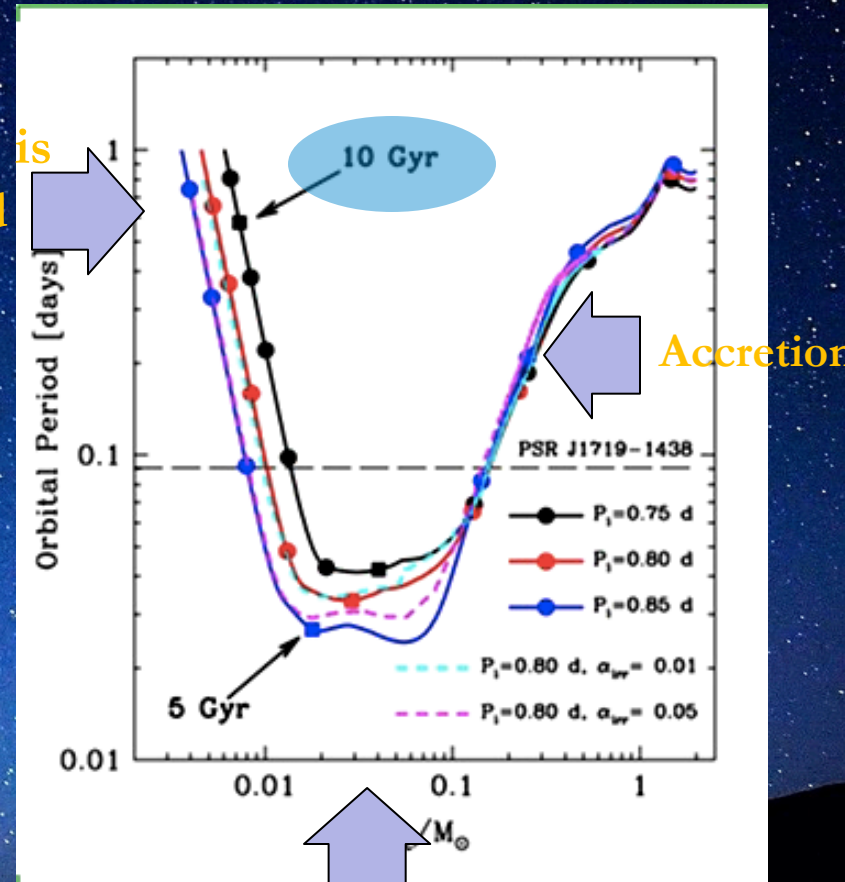
Two important ingredients for their evolution: back illumination and ablation by the pulsar wind

(Benvenuto, De Vito & Horvath ApJL 753, L33, 2012)



Donor is ablated

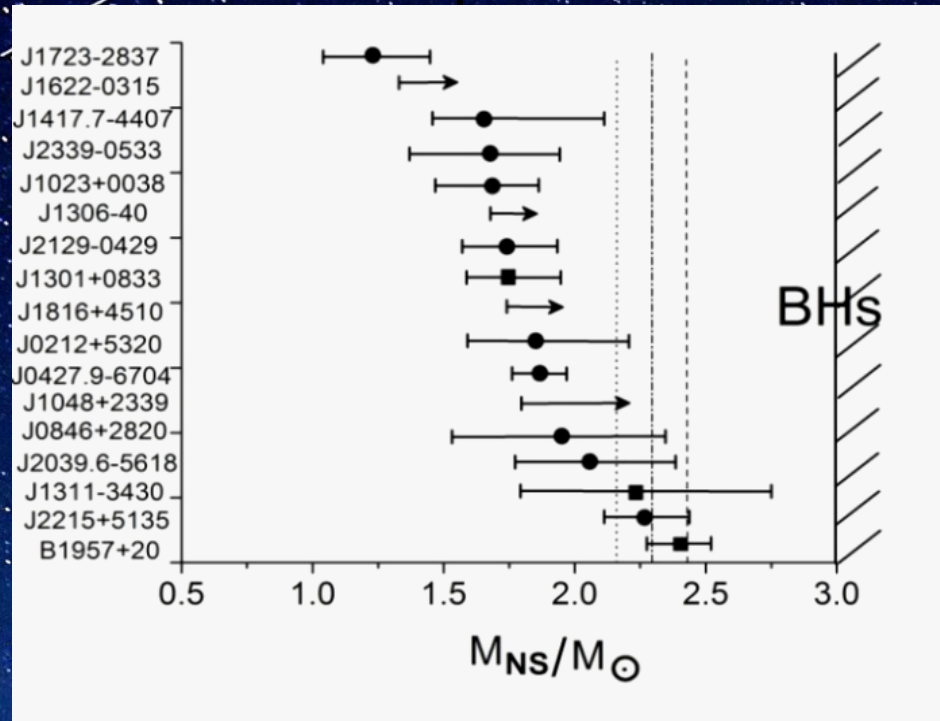
Later: ablation by the pulsar wind



Donor becomes degenerate

The history of accretion phase alone lasts $\sim$ Gyr, therefore the mass transfer onto the pulsar has to be substantial (theory)

17 known observed Redback/Black Widow systems



Error bars are still substantial, but these systems should in some cases produce the heaviest neutron stars in Nature, and possibly the lightest Black Holes immediately above the maximum mass value with $\sim 3 M_{\odot}$ (Horvath et al. *Science China* 2020)

Frequentist analysis of the binary distribution

A mixture of Gaussians has been widely employed (Valentim, Horvath & Rangel 2011, Ozel et al. 2012, Alsing et al. 2018...) to model the full distribution. Starting from a basic hypothesis tests (Kolmogorov-Smirnov and Anderson-Darling) We compare the empirical distribution with the mix-of-Gaussians model to see which one is better

The old “one-mass-fits-all” $1.4 M_{\odot}$ may be called *unimodal*; two mass-scales *bimodal* and three a *trimodal*.

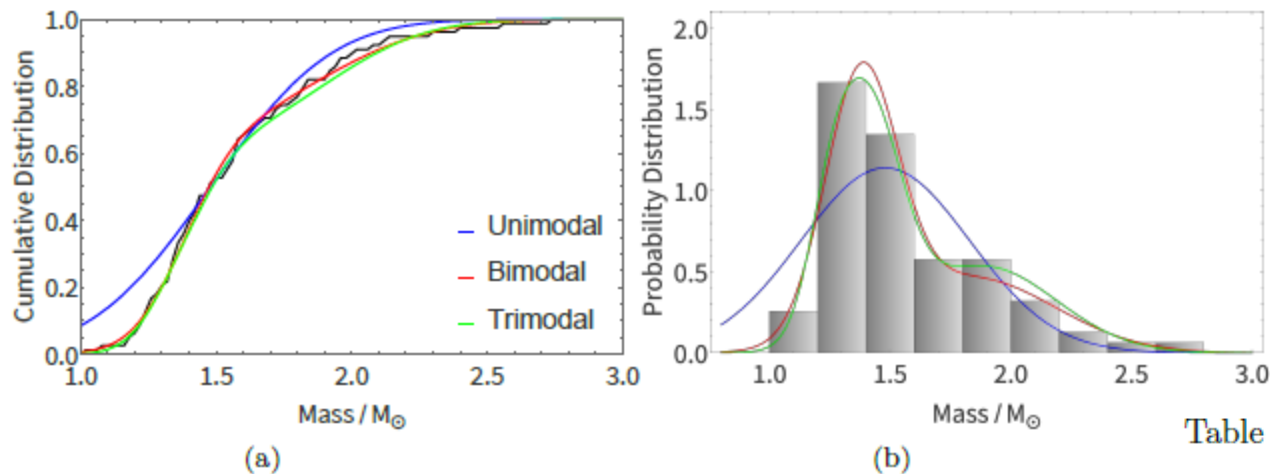


Table 1.1: Hypothesis test for three models

Model	K-S	A-D	Conclusion
Unimodal	0.025	0.032	Reject
Bimodal	0.971	0.990	Do not reject
Trimodal	0.974	0.953	Do not reject

The “blend” at $1.25 M_{\odot}$ is likely but does not stand out clearly as it should

Bayesian analysis

Likelihood
(given the data)

Prior distribution

$$P(\theta|D) = \frac{\mathcal{L}(D|\theta)P(\theta)}{P(D)}$$

$$\mathcal{L}(m_p|\theta) = \sum_i^n r_i \mathcal{N}(m_p|\mu_i, \sigma_i),$$

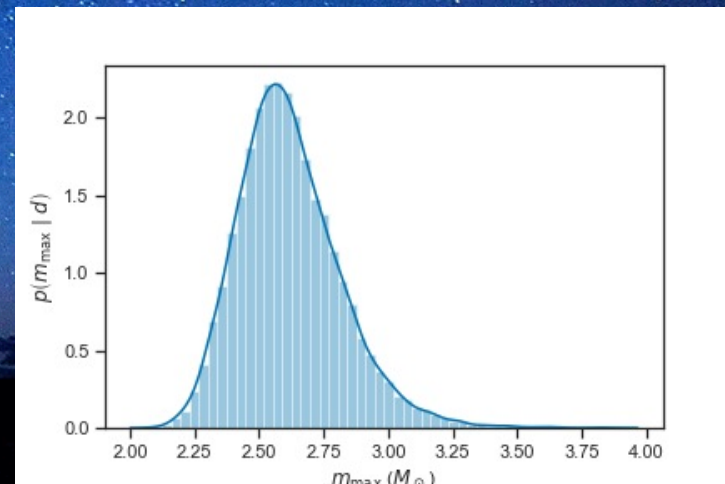
Mixture of Gaussians with weights r_i

Location of the peak

$$\mathcal{N}(m_p|\mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left[\frac{-(m_p - \mu)^2}{2\sigma^2} \right].$$

Width of the peak

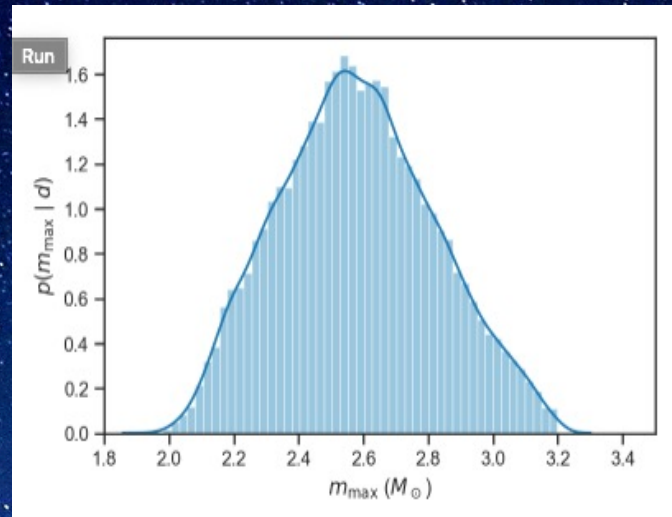
If assumed to be the 3σ value of the μ_2 peak, the $M_{\max}$ is quite robust and looks like this



The MCC algorithm finds the optimal values, which happen to be compatible with the ones found within the frequentist ones $\mu_1 \sim 1.36 M_{\odot}$; $\mu_2 \sim 1.79 M_{\odot}$

One step ahead: introducing $M_{\max}$ as an additional parameter

A Gaussian truncated beyond $M=M_{\max}$



$M=M_{\max}$ is determined to be $\sim 2.5 M_{\odot}$, although its probability distribution depends somewhat on the *prior*. Whatever its value, $M_{\max}$ is a physical cutoff, although its inference has a width

Empirically the observed distribution allows a large value of $M_{\max}$, if these are confirmed for individual objects, theory must accommodate them (even if close to the Rhoades-Ruffini limit)

In brief, Bayesian analysis (Valentim, Rangel & Horvath, *MNRAS* 414 1427, 2011) points out that one mass scale is strongly disfavored, two masses are present : ~ 1.36 and $\sim 1.79 M_{\odot}$

Other works finding the same pattern (somewhat different values):

Zhang et al. *A&A* 527, A83, 2011

Özel et al., *ApJ* 757, 55, 2012

Kiziltan, Kottas & Thorsett, 2013

Alsing, Silva & Berti, *MNRAS* 2018

Shao et al., *PRD* 2020

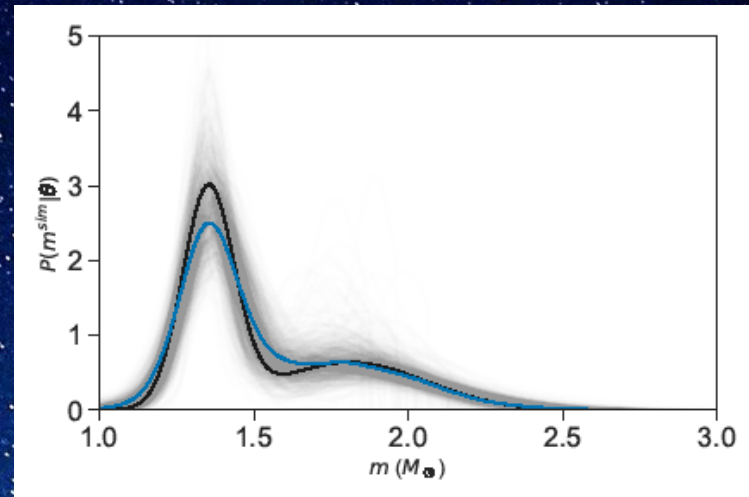
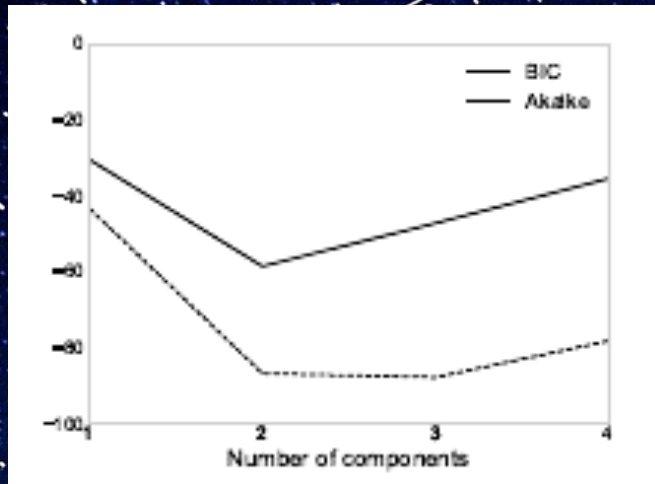
Is this related to the size of the Fe core? (“jump” @ $19 M_{\odot}$)

Are some of them born as such, massive ?

Probably not, but there is a problem here...

simulations of SN explosions in binaries are too crude to produce “heavy enough” NSs under any circumstances (see later)...

Two, maybe three peaks ? And a cutoff



We have obtained M_{max} from a Bayesian marginalization of the binary system mass distribution, $M_{\text{max}} = 2.59 M_\odot$

However, many works have deduced M_{max} from the remnant of the GW170817 event

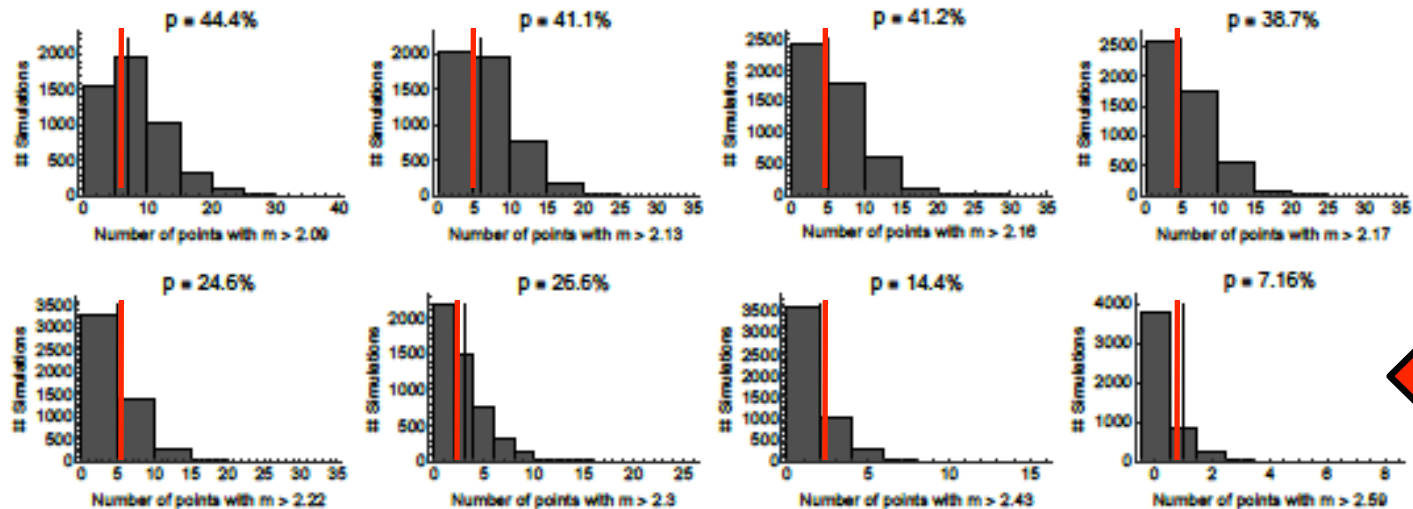
...and this is what they obtain

Table 1.3: Inferred value of M_{TOV} from the behavior of GW170817 according to a) Shao *et al.* (2020); b) Ai *et al.* (2020); c) Shibata *et al.* (2019); d) Ruiz *et al.* (2018) ; e) Rezzolla *et al.* (2018a); f) Margalit and Metzger (2017) ; g) Alsing *et al.* (2018)

Value [$M_{\odot}$]	Type of the resulting object/assumption
$2.13 \pm_{0.07}^{0.08}$ (a)	SMNS
$2.09 \pm_{0.09}^{0.11}$ (b)	SMNS
$2.43 \pm_{0.08}^{0.10}$ (b)	SMNS
$2.43 \pm_{0.08}^{0.10}$ (b)	SNS
2.3 (c)	Conserv. + simulation
2.16 – 2.28 (d)	Minimal assumption
$2.16 \pm_{0.15}^{0.17}$ (e)	–
2.17 (f)	–
2.6 (g)	(3σ)

Therefore, we can compare these two ways of obtaining M_{max} generating 5000 synthetic samples and counting the outliers for each value of M_{max} above

Conclusion: M_{max} can not be lower than $\sim 2.3 M_{\odot}$, the higher $\sim 2.5 M_{\odot}$ is the most likely



Another way of quantifying the disagreement: since M_{max} is a physical (not probabilistic) cutoff, all points beyond must be large fluctuations or outliers. The Local Outlier Factor probes the outlier character of detections for a given % of tolerance

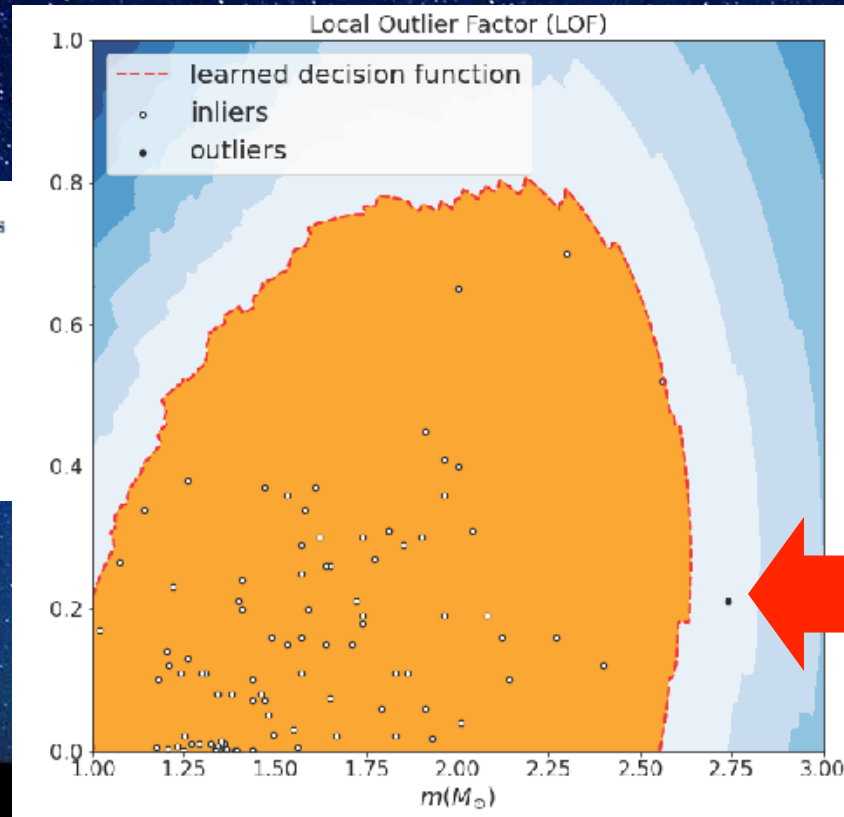


TABLE III: The NS with six highest LOF scores

Mass ($M_{\odot}$)	sd	outlier	LOF
2.74	0.21	yes	2.234
2.56	0.52	no	1.996
2.90	0.70	no	1.832
2.40	0.12	no	1.676
2.27	0.16	no	1.395
2.14	0.10	no	1.128

For $M_{\text{max}} = 2.59 M_{\odot}$
only $2.74 \pm 0.21 M_{\odot}$
is flagged as an outlier

but if M_{max} is lower,
more measurements
will be outliers,
Aggravating the mismatch

O-Mg-Ne cores of electron capture SN are degenerate and of “fixed” mass $\sim 1.37 M_{\odot}$ $\rightarrow$ after emission of the binding energy

$$\frac{M_B - M_G}{M_G} = 0.6 \frac{\beta}{1 - 0.5\beta} \quad \text{with} \quad \beta = GM_G/c^2 R_0 \quad \text{Lattimer \& Prakash (2001)}$$

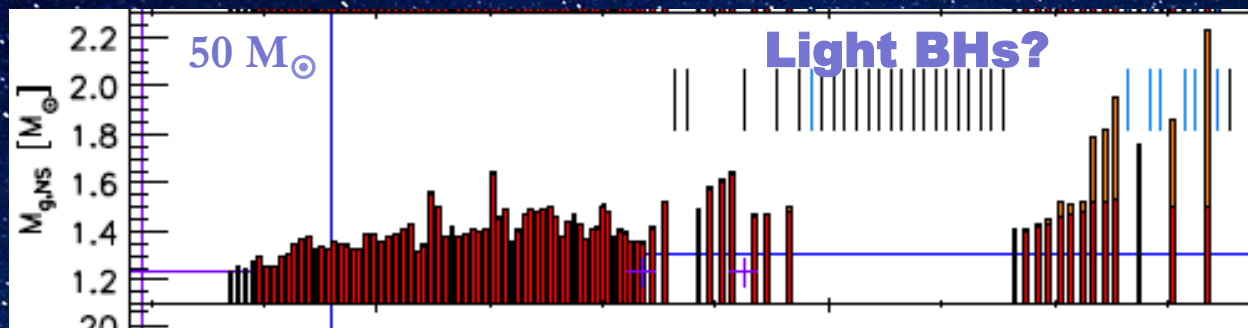
the formed NS would have essentially a fixed mass of $\sim 1.25 M_{\odot}$
However, we did not find strong evidence for this group which must be there

The lightest NS ever observed is PSR J1453+1559 companion with $1.174 \pm 0.004 M_{\odot}$

therefore, small iron cores from progenitors having $M > 9 M_{\odot}$ must be produced to obtain NSs lighter than electron-capture SN

Origin of masses: binary star evolution and explosions

Common evolution prescription : removal of the hydrogen envelope
Pre-SN structure not really known



Ertl et al. (2020)

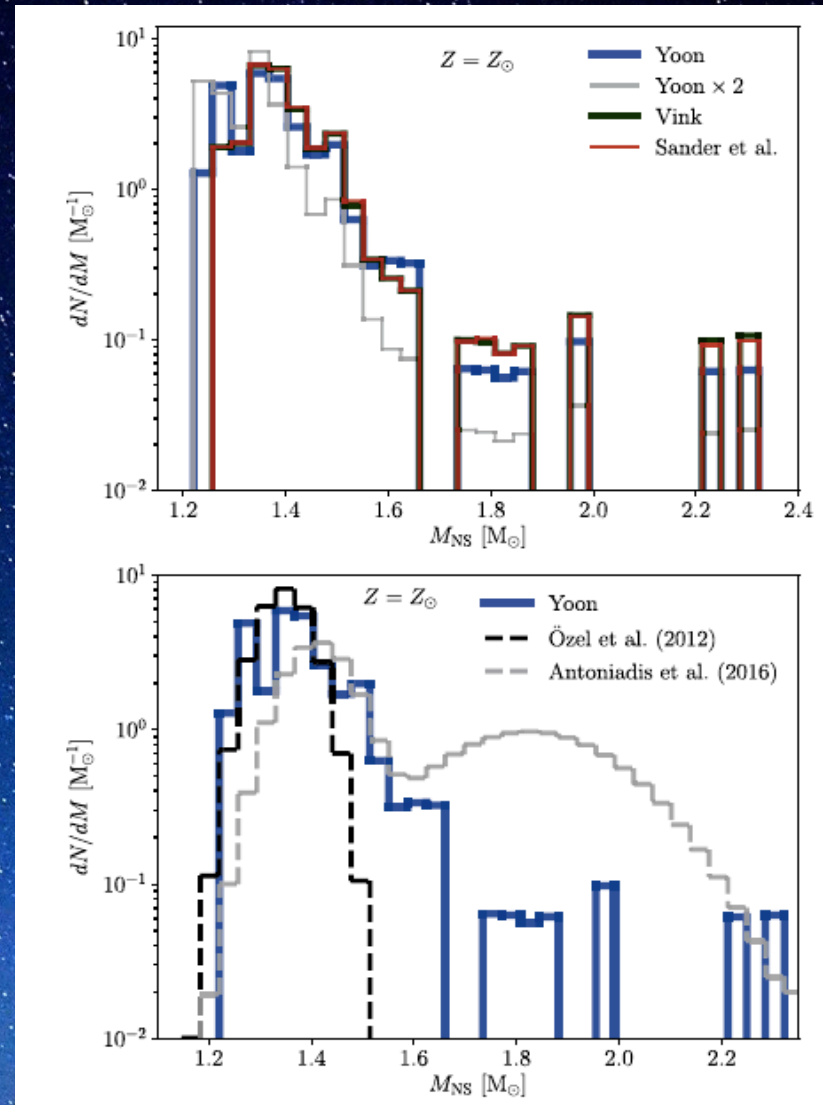
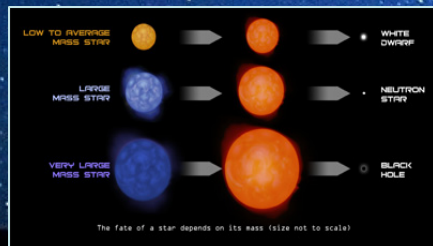
Substantial fallback now produces heavy NS, but for very heavy progenitors only

This could allow a “born massive” NS such as PSR J1640+2224
(Deng, Gao, Li & Shao 2020)

Recent work (Woosley, Sukhbold & Janka, 2020) shows the birth function of NS in binaries produces masses beyond 2 Mo at birth with little effect of the mass-loss winds

Again, NSs do not appear in a monotonic way, intermittency of BH, NS formation appears

(compare to what is said in books...
There is no “threshold” for BH formation



But yet, extremely heavy NSs in the galactic sample require accretion

Masses of NS from GW: the unseen fellows

In general the chirp mass $\mathcal{M} = M [q/(1+q)^2]^{3/5}$ and the total mass M can be measured, but not the individual masses

Based on known DNS almost all works dealing with GW170817 assumed $q=1$

However, recent works have provided accurate masses for two very asymmetric systems

PSR J0453+1559 (Martinez et al. 2015)

PSR J1913+1102 (Ferdman et al. 2020)

The second will merge within a Hubble time, and they may be up to $\sim 30\%$ of the total

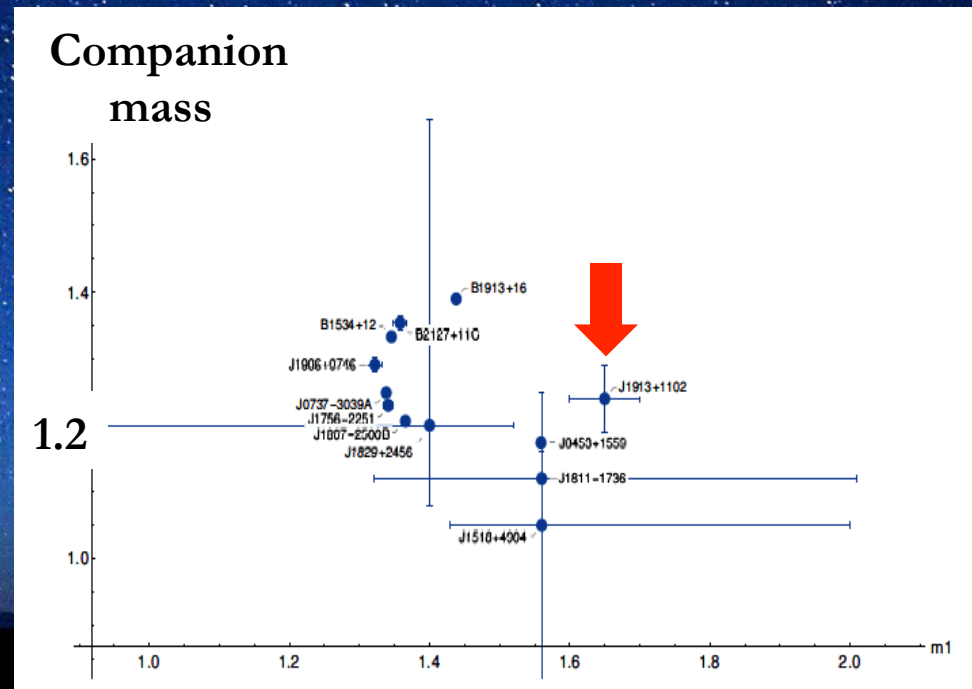


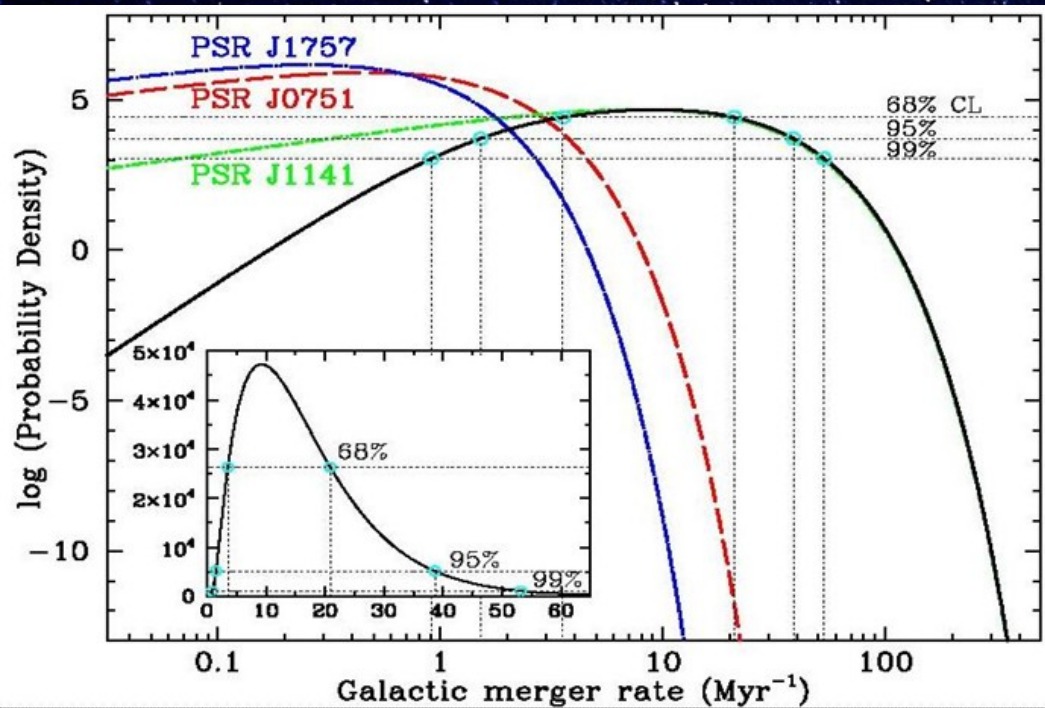
Figure by A. Bernardo

Well-measured binaries with one NS: different formation channels



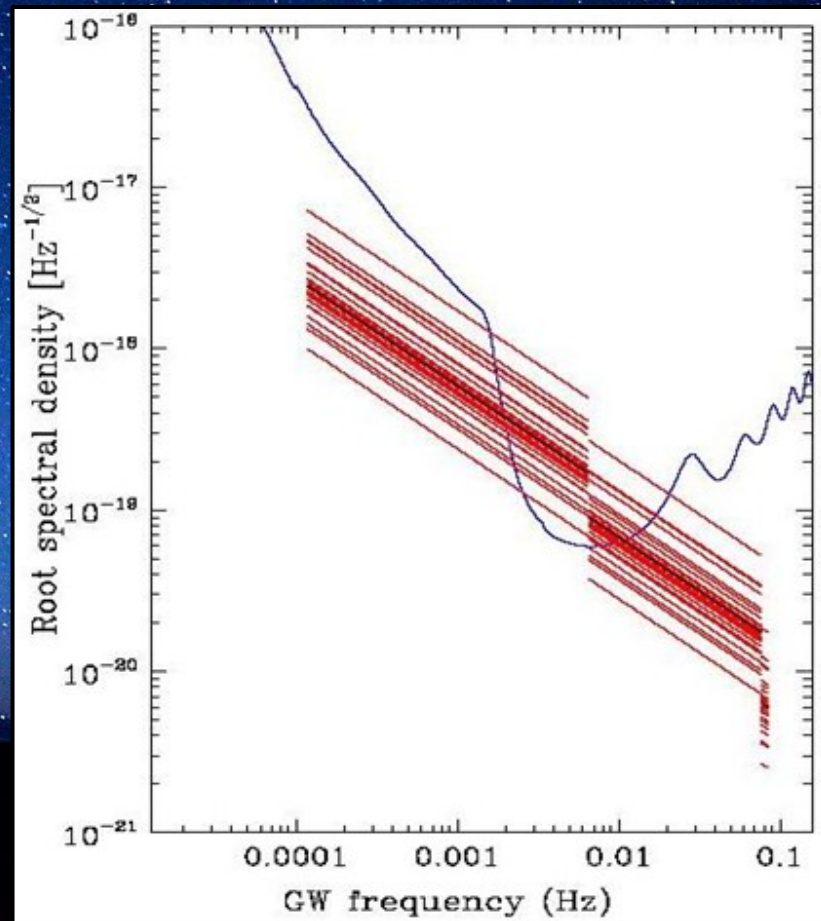
Almost certainly **He** WDs
(correlated)

Mass of the secondary ($M_\odot$)

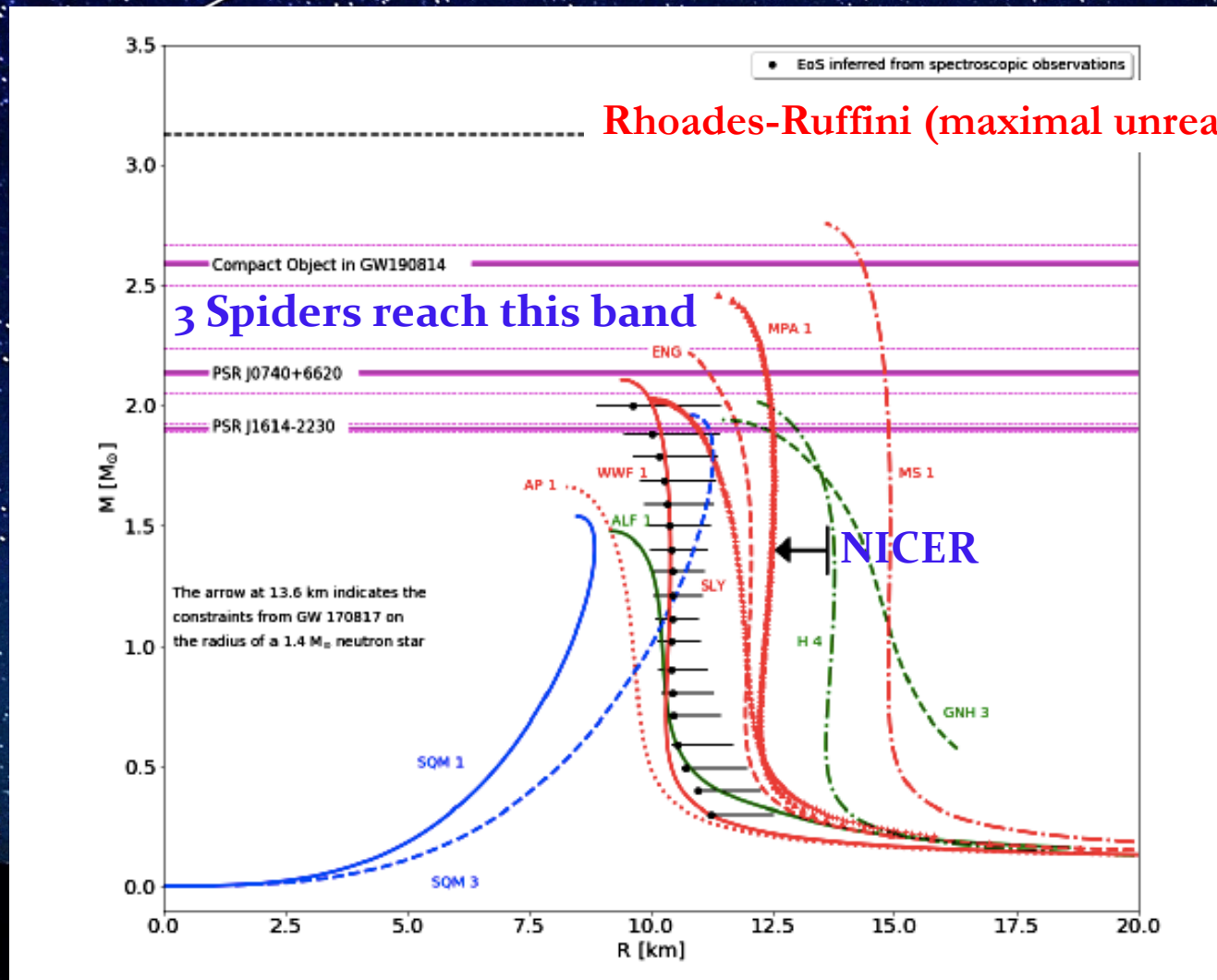


Most likely NS-WD galactic merging rate $\sim 1\text{-}20 \text{ Myr}^{-1}$

NS-WD systems would contribute to foreground “noise” to planned space LISA interferometer



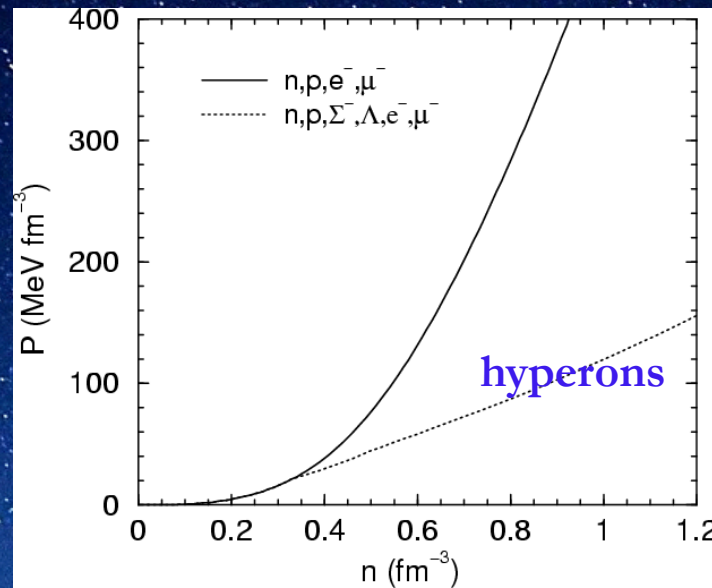
Where do we stand? Is the “gap” between NSs and BHs being filled?



Some “light” BHs have been recently reported

What do high masses mean: the “hyperon puzzle” again

- Hyperons soften the equation of state, do they?



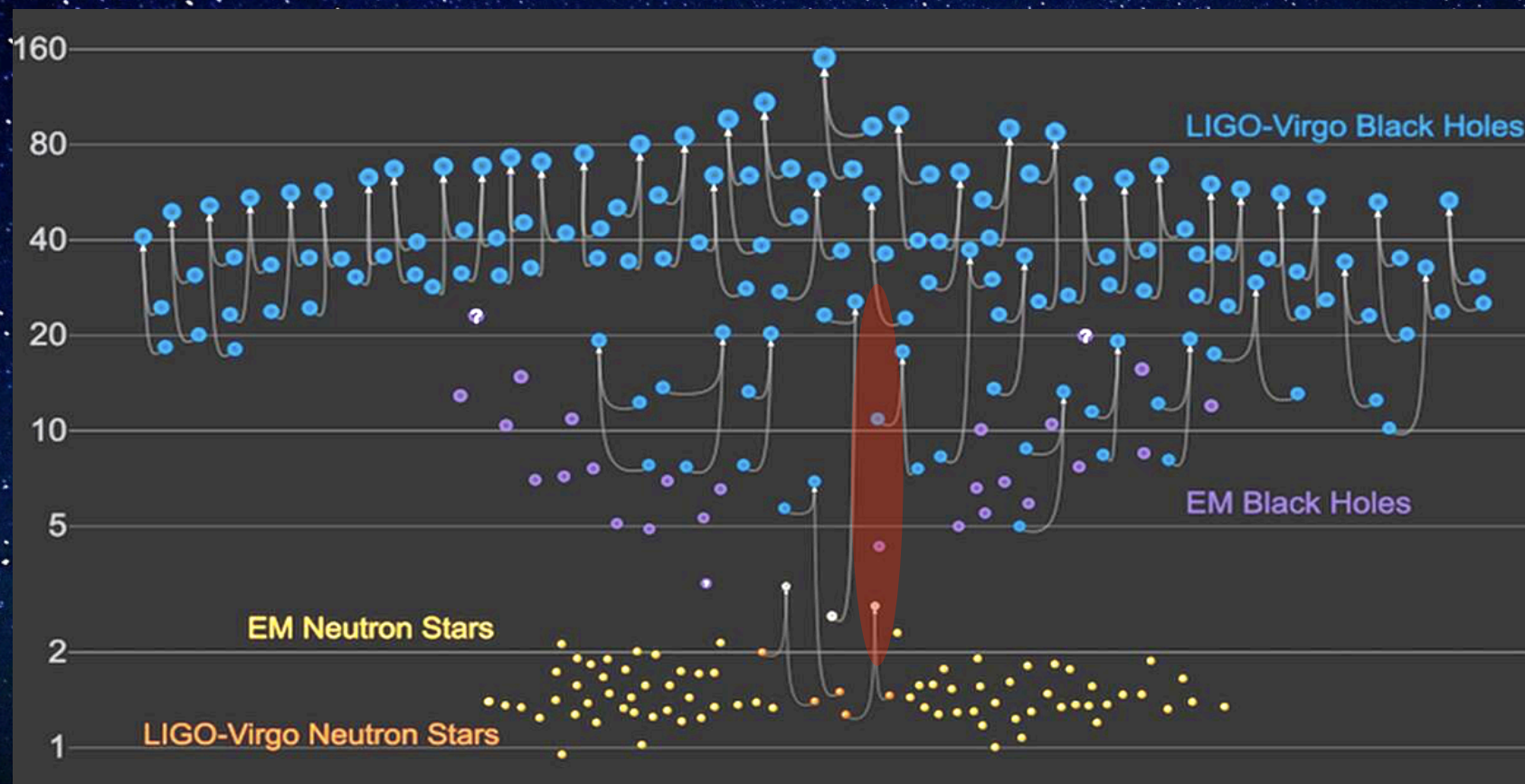
(but unexpected repulsion may make the “hyperon puzzle” go away)

- Alternatively, can NS *avoid* the presence of hyperons?

Yes, under some conditions

(the return of “pure neutrons”, or “hyperonless hyperon stars”)

Population properties of compact objects from the second LIGO-Virgo Gravitational-Wave Transient Catalog



The lower mass object in GW190814 ($\sim 2.5 M_{\odot}$) is an outlier of the BH distribution

Conclusions

- Never talk or write of a “canonical” mass again.
 - * There is no such a thing. The mass distribution is wide
- Double Neutron Stars are **not** symmetrical in mass, although the standard formation channel may be incomplete, and it is
 - * not clear how
- The “mass gap” may be being filled, or at least NS with $> 2.2 M_{\odot}$ must be considered, as indicated by observations (*spiders* first)
- * The plot thickens for the description of dense matter, particularly if the $M_{\max}$ is effectively as high as $2.5\text{--}2.6 M_{\odot}$.
A few well-measured higher individual masses may confirm the statistical inference.
- There may be something wrong with the simplest analysis of the GW remnant to deduce $M_{\max}$

Thank you ! Questions?

Uhhhh

