

The case for very massive neutron stars



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Until the 2000's every book or paper stated that neutron stars had a characteristic mass of $1.4 M_{\odot}$, termed "canonical" and believed to be related to the Chandrasekhar limit of the imploding iron core

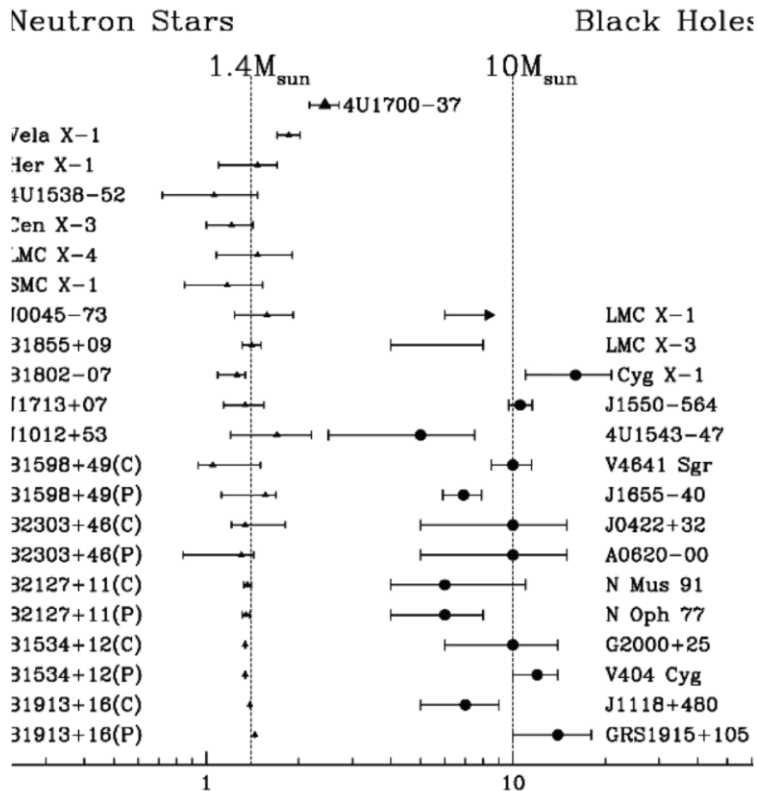


Figure from
Clark et al. A&A 392, 909 (2002)

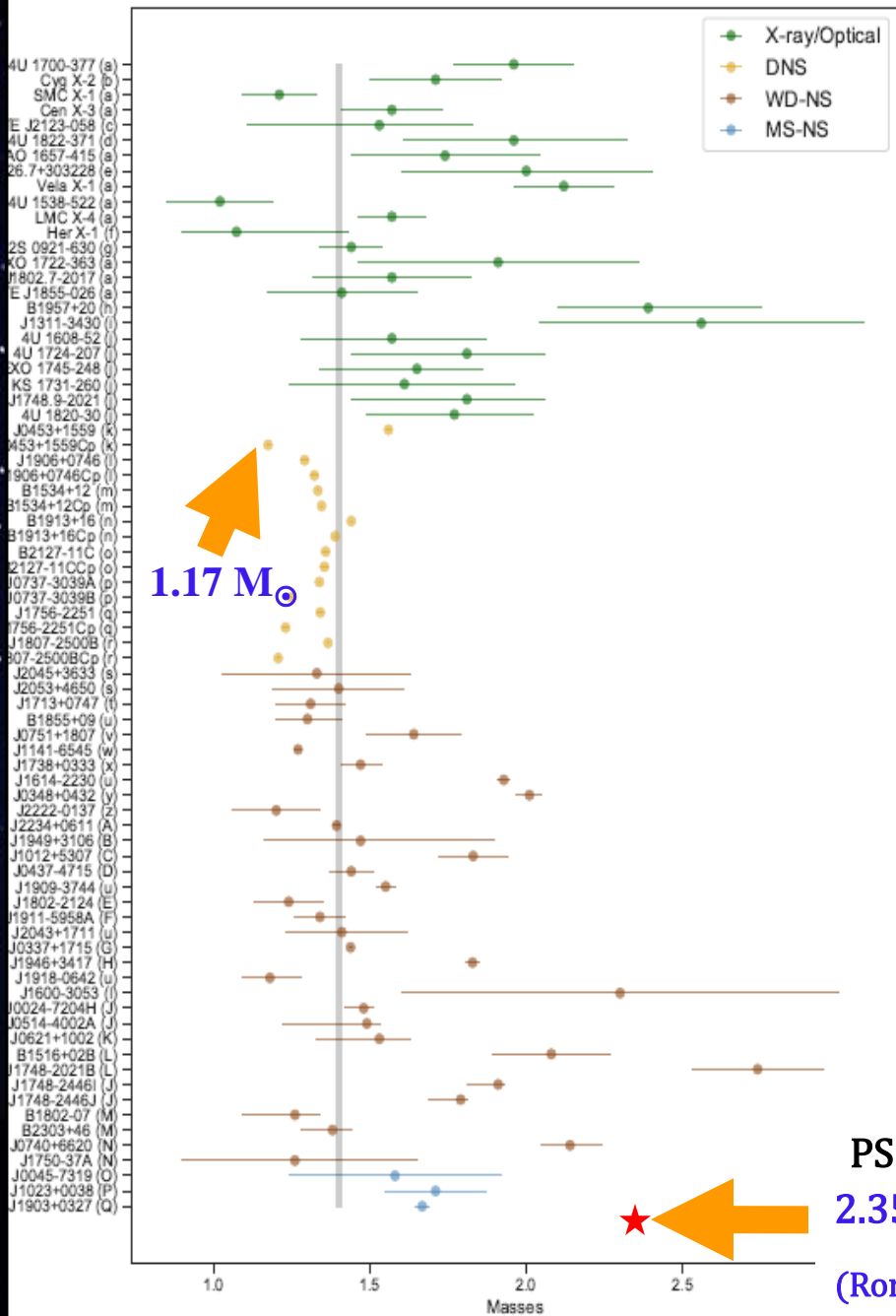
Observational Constraints on the Maximum Neutron Star Mass

Show affiliations

Bethe, H. A. ; Brown, G. E.

We review estimates of the mass of the compact core in SN 1987A and conclude that the most accurate determination can be obtained from the known value of approximately 0.075 solar mass of Ni production in the explosion. With binding energy correction, this gives an upper limit of gravitational mass of approximately 1.56 solar mass, slightly larger than Brown & Bethe's previous estimate of approximately 1.5 solar mass. Observation by Observing System

...and the M_{max} hypothesized to be near the "canonical" (Bethe & Brown, 1995)



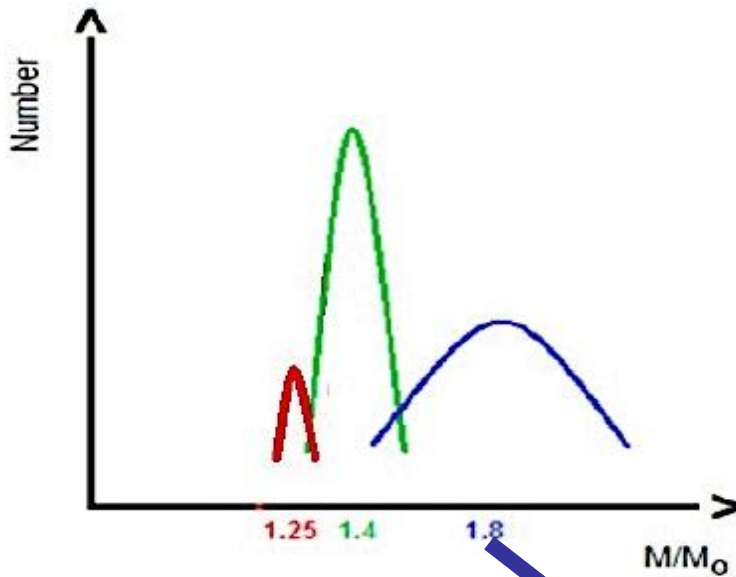
However, things change !

NS mass range today
is much wider
than it used to be

Compilation of 105
measurements by L.S. Rocha

(see also Valentim & Horvath, in
Handbook of Supernovae 2017
astro-ph/1607.06981)

The analysis of the observed NS distribution is a Gaussian bimodal, or a more complex multipeak expression



(Valentim, Rangel & Horvath 2011
C.M. Zhang et al. 2011
Özel et al. 2012
Kiziltan et al. 2013)

Bayesian analysis gives the position of the peaks, the amplitudes and the widths within a Gaussian parametrization (R. Valentim)

$$P(m) = \frac{0.14}{\sqrt{2\pi} \sigma_0} e^{-\frac{(m-1.25 M_\odot)^2}{2\sigma_0^2}} + \frac{0.5}{\sqrt{2\pi} \sigma_1} e^{-\frac{(m-1.4 M_\odot)^2}{2\sigma_1^2}} + \frac{0.36}{\sqrt{2\pi} \sigma_2} e^{-\frac{(m-1.8 M_\odot)^2}{2\sigma_2^2}}$$

Mainly from electron capture SN (Schwab, Podsiadwolski & Rappaport 2010)

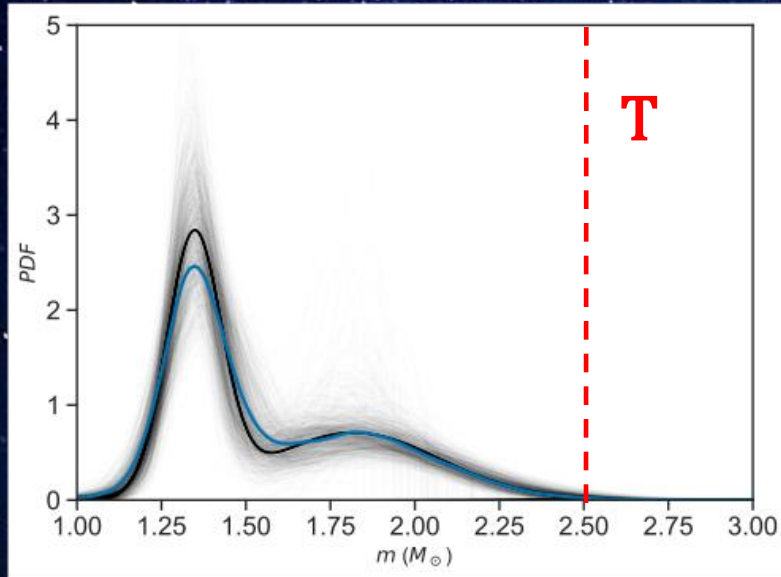
$$\sigma_0 = 0.07 M_\odot$$

$$\sigma_1 = 0.08 M_\odot$$

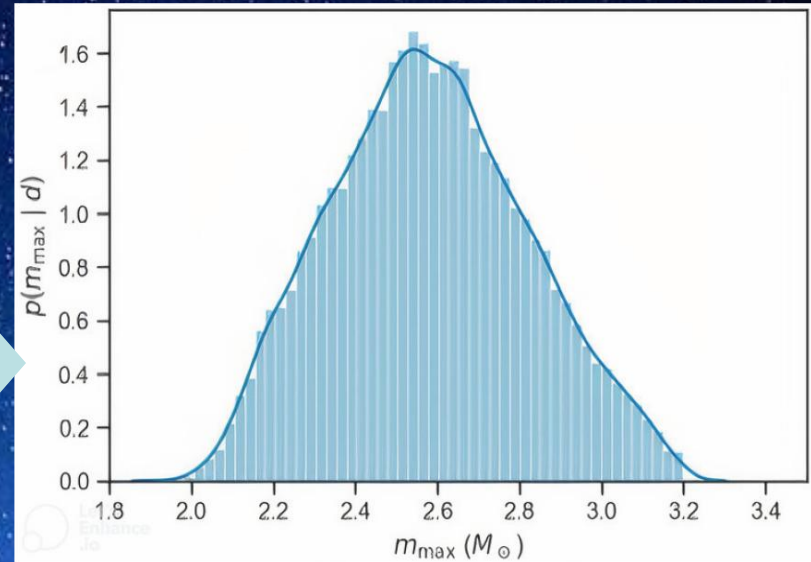
$$\sigma_2 = 0.28 M_\odot$$

A maximum mass inferred from the same existing sample

The available sample yields a 3σ $M_{\max} \sim 2.5 M_{\odot}$



Posterior curves of the 105 NS sample with a truncation parameter



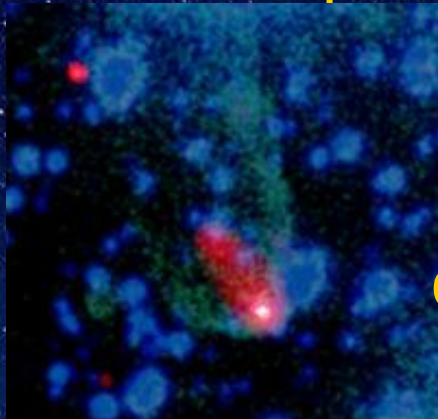
Marginalized distribution of the truncation parameter T

The same value emerges if a truncation parameter T is determined, its more likely value is almost the same

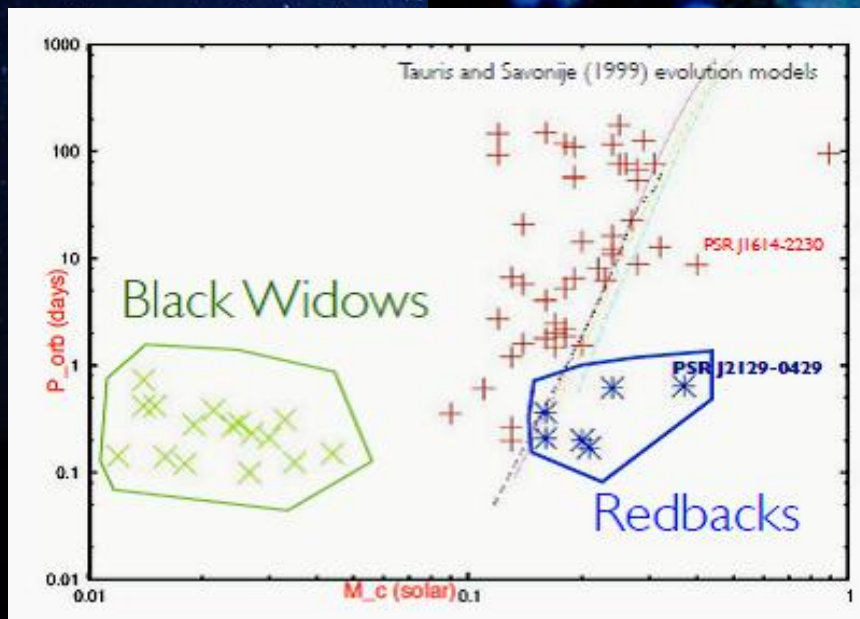
2.59 M_{\odot}

Which are the heaviest NS?: Spiders in the garden

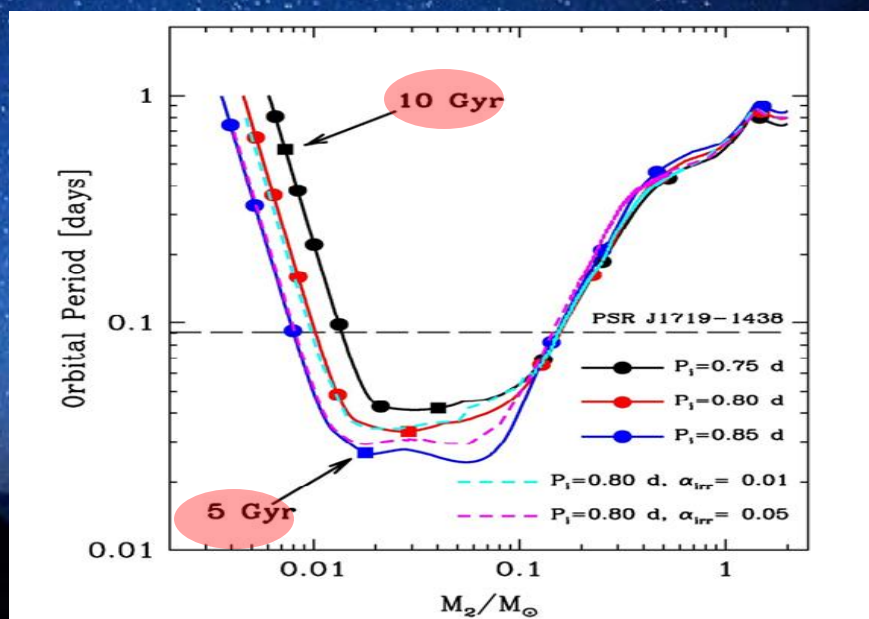
1988: Fruchter, Stinebring & Taylor (Nature 333, 237, 1988) found an eclipsing pulsar with a very low mass companion being ablated by the wind



Composite Image from *Chandra* (2012)
PSR 1957+20 system



M. Roberts, arXiv:1210.6903



Benvenuto, De Vito & Horvath 2012

Spiders have a ~few *Gyr* age,
long accretion history

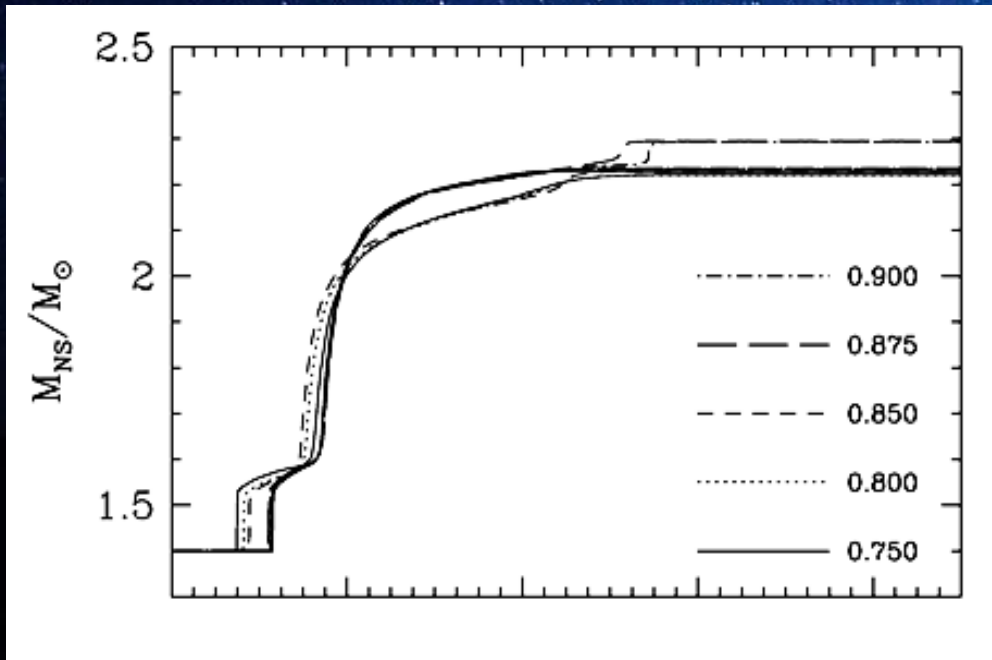
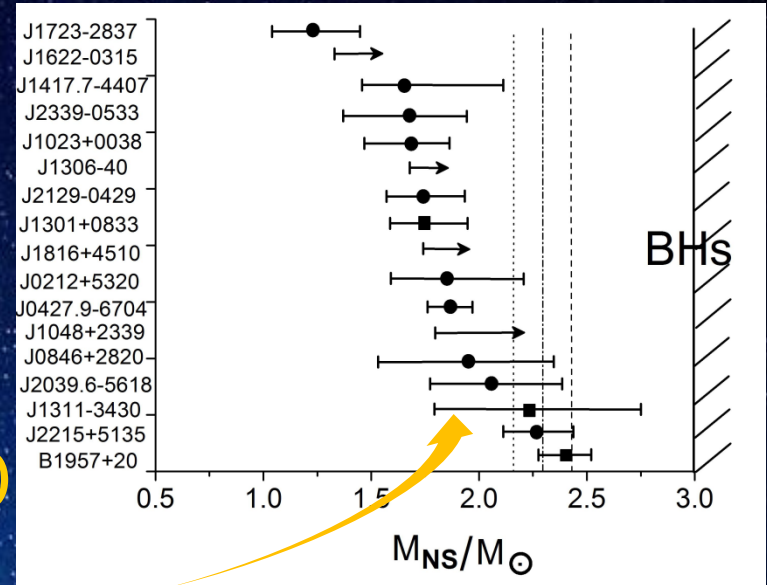


High NS masses expected



$$M_{\text{psr}} = 2.35 \pm 0.17 M_{\odot}$$

Romani et al. (ApJLett 760, L36, 2022)
reported for PSR J1311-3430




Redback mass evolution
calculations for several
values of the initial period,
and fixed accretion efficiency
of 0.5 yield
(Benvenuto & Horvath 2013)

Another recent individual case of a very high mass

PSR J0952-0607: Tightening a Record-high Neutron Star Mass

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Romani, Roger W.  ; Beleznay, Maya  ; Filippenko, Alexei V.  ; ...

We report on new orbit-minimum photometry and revised radial-velocity fitting that provide an improved measurement of the mass of the neutron star (NS) in pulsar PSR J0952-0607 at $M_{NS} = 2.35 \pm 0.11 M_{\odot}$. With an unusually low magnetic field, this NS has evidently experienced unusual evolution, likely connected with its high

Romani et al.
ApJ 996, id.101
(2026)

And there is yet another candidate to the highest mass on the market (not yet confirmed, unpublished)

Long-Term Timing of Pulsars in NGC 6440: An Updated Mass Limit of Millisecond Pulsar J1748-2021B 1144 views

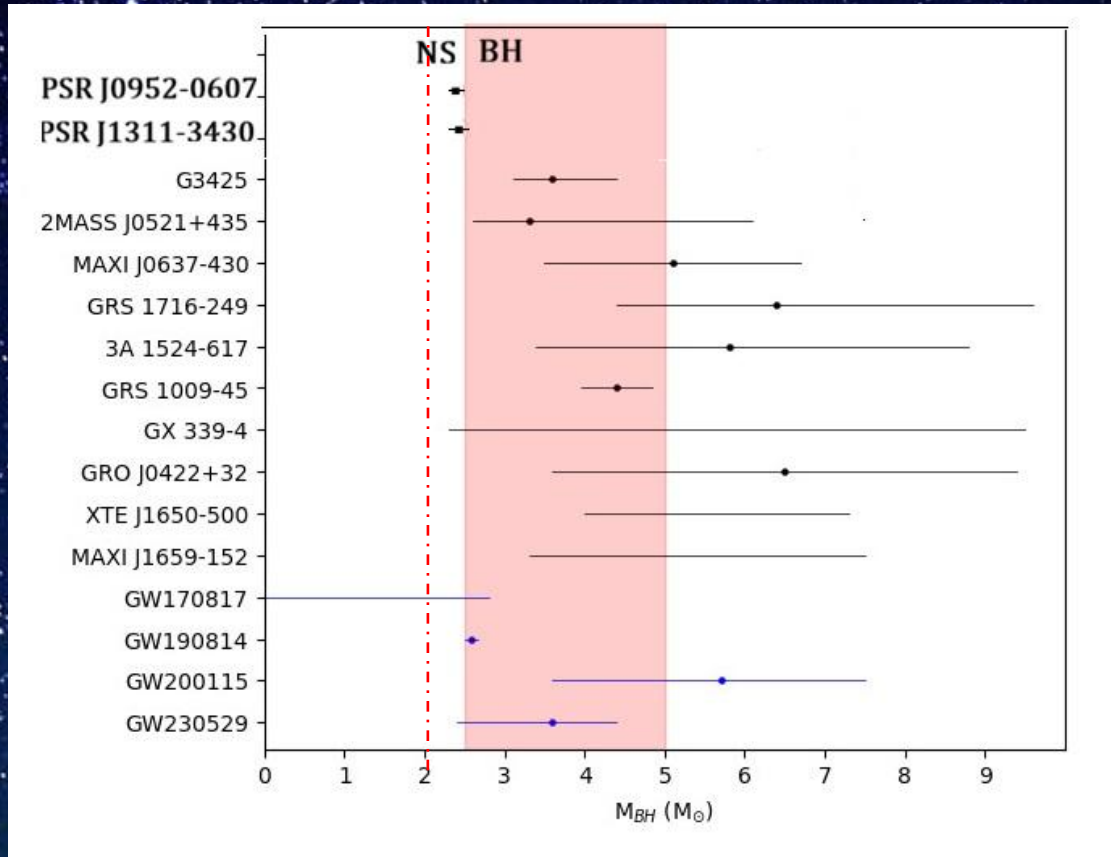
Author
Clifford, Nick, Astronomy, University of Virginia  0000-0002-5694-4110

Advisors
Ransom, Scott, Department of Astronomy, University of Virginia

Abstract
After 11 years of continued observations with the Green Bank Telescope (GBT), we present updated timing solutions of 6 previously published pulsars in NGC 6440. We obtain improvements in timing parameters that allow us to better describe the dynamics of the cluster, such as measure the proper motion of the pulsars and estimate the cluster's motion ($\mu_{\alpha} = -1.04(20)$ mas yr⁻¹, $\mu_{\delta} = -3.0(2.5)$ mas yr⁻¹). Using additional observing bandwidth, we measure the flux densities and spectral indices of each pulsar and investigate the effects of refractive scintillation on the variance of each pulsar's flux density as a function of observing frequency. For the eccentric binary millisecond pulsar (MSP) NGC 6440B, we report on a much more precise rate of periastron advance, $\dot{\omega} = 0.003684(21)$ yr⁻¹, which if purely relativistic, would indicate a total system mass of 2.675 ± 0.022 and a median pulsar mass of $2.548 + 0.047 - 0.078 M_{\odot}$ assuming random inclinations. We also measure the rate of periastron advance for NGC 6440F ($\dot{\omega} = 0.0673(28)$ yr⁻¹) despite its incredibly low flux density ($S_{1.5} = 0.019$ Jy).



A final word on the lower Mass Gap



The Mass Gap may be a depleted region, but by no means empty (de Sá et al., ApJ 941, 130 (2022)). We see it as a statistical anomaly

However, it is now more difficult than before to separate NSs and BHs

The case of 4U 1820-30

Known for ~ 50 yr. It's an ultra-short period LMXB ($P_{\text{orb}} = 693$ s)

The companion is a $0.07 M_{\odot}$ WD.

The projected semiaxis has not been reliably measured, hence there is no mass estimation using just Kepler's laws

We shall show other methods and results obtained for the NS mass

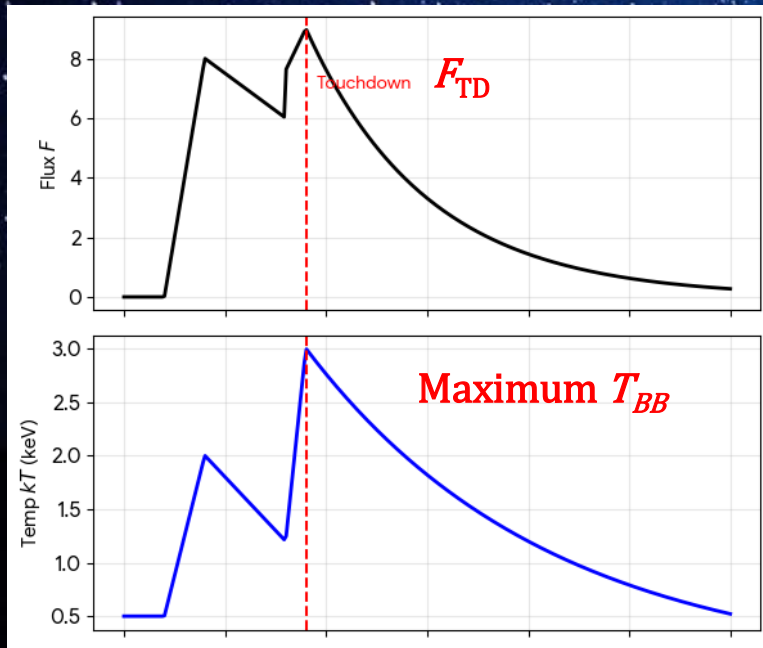
ROSAT PSPC
4U 1820-30 Pointing
0.5-1.6 keV
40 arcmin off-axis



The “touchdown flux” method

During an X-ray burst the photosphere expands (PRE), and then shrinks to return to the surface (**assumption**). This is the *touchdown point* and the flux reaches a maximum F_{TD} related to the Eddington limit.

During the cooling tail the emitting area A can be estimated, assuming a black body spectrum \rightarrow radius and mass



$$F_{TD, \infty} = \frac{GMc}{\kappa D^2} \left(1 - \frac{2GM}{Rc^2}\right)^{1/2},$$

opacity (atmosphere)
Distance to the source

$$A \equiv \frac{F_{\infty}}{\sigma T_{bb, \infty}^4} = f_c^{-4} \frac{R^2}{D^2} \left(1 - \frac{2GM}{Rc^2}\right)^{-1},$$

Color correction

Using this method, Guver et al. (2010) measured for the mass of 4U 1820-30

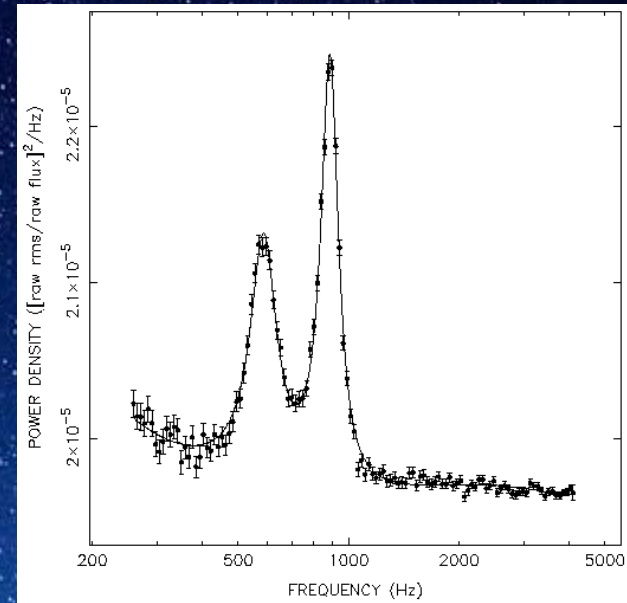
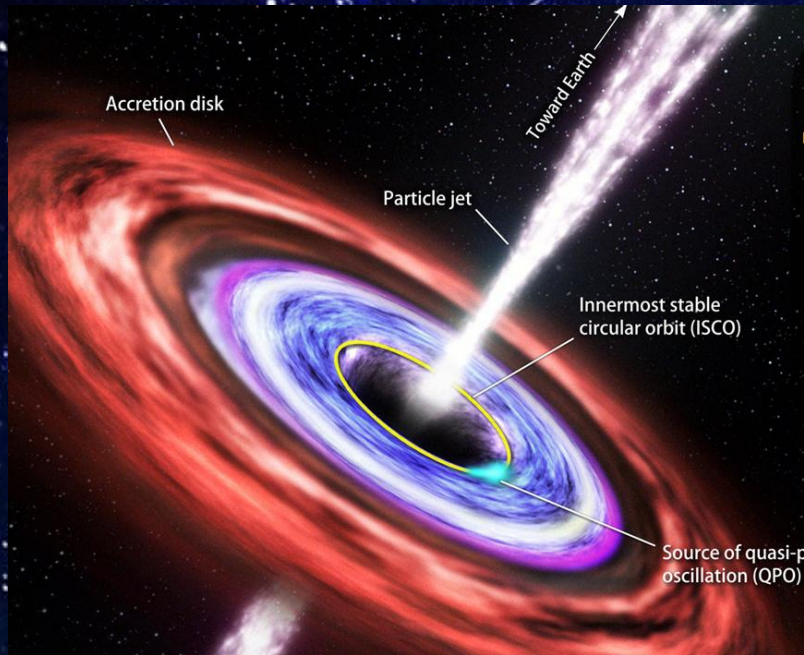
$$M = 1.58 \pm 0.06 M_{\odot}$$

Later corrected (Özel et al. 2016) to

$$M = 1.77^{+0.25}_{-0.28} M_{\odot}$$

One important question is whether the touchdown happens when $r_{ph} = R$, questioned by Steiner et al. (2010). In fact Kim et al (2021) studied the problem and concluded that $r_{ph} > R$. This may be one of the problems to be resolved to pin down the mass

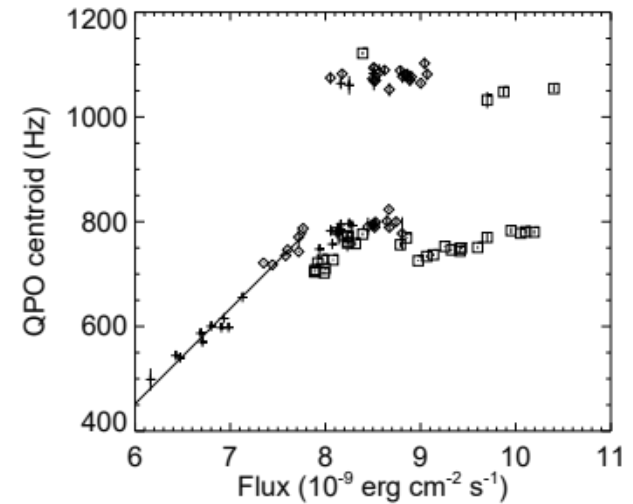
The QPO ISCO method



Pairs of Quasi Periodic Oscillations have been detected in many sources. Independently of the exact mechanism that produces the pair, the **highest** frequency one is often associated with the Innermost Stable Circular Orbit (ISCO)

In the case of 4U 1820-30, the QPOs **saturate**, interpreted as evidence that The ISCO has been reached (Kaaret et al, 1999)

The highest frequency QPO at 1065 Hz gives a direct estimate of the mass of the non-rotation compact object



$$M_{NS} = 2.2 \left(\frac{1000 \text{ Hz}}{\nu_{QPO}} \right) M_{\odot}$$

However, 4U 1820-30 **rotates at 716 Hz** (Jaisawal et al. 2024), therefore the full Kerr metric must be used (Hartle & Thorne 1968, Abramowicz et al. 2003)

$$\nu_{K,ISCO} = \frac{c^3}{2\pi 6^{3/2} GM} \times \left[1 + \frac{11}{6\sqrt{6}} j + \frac{1}{864} \left(-160583 + 397710 \ln \frac{3}{2} \right) j^2 + \frac{5}{32} \left(1193 - 2946 \ln \frac{3}{2} \right) q \right]$$

(hold on...this will be important soon...)

Latest news from 4U 1820-30

Iaria et al. (2026) reported an absorption line @ 3.8 keV seen with NICER and identified as highly ionized Fe., yielding

$$1+z = 1.72$$

$$\frac{R}{M} = \frac{2}{1 - (1+z)^{-2}}$$

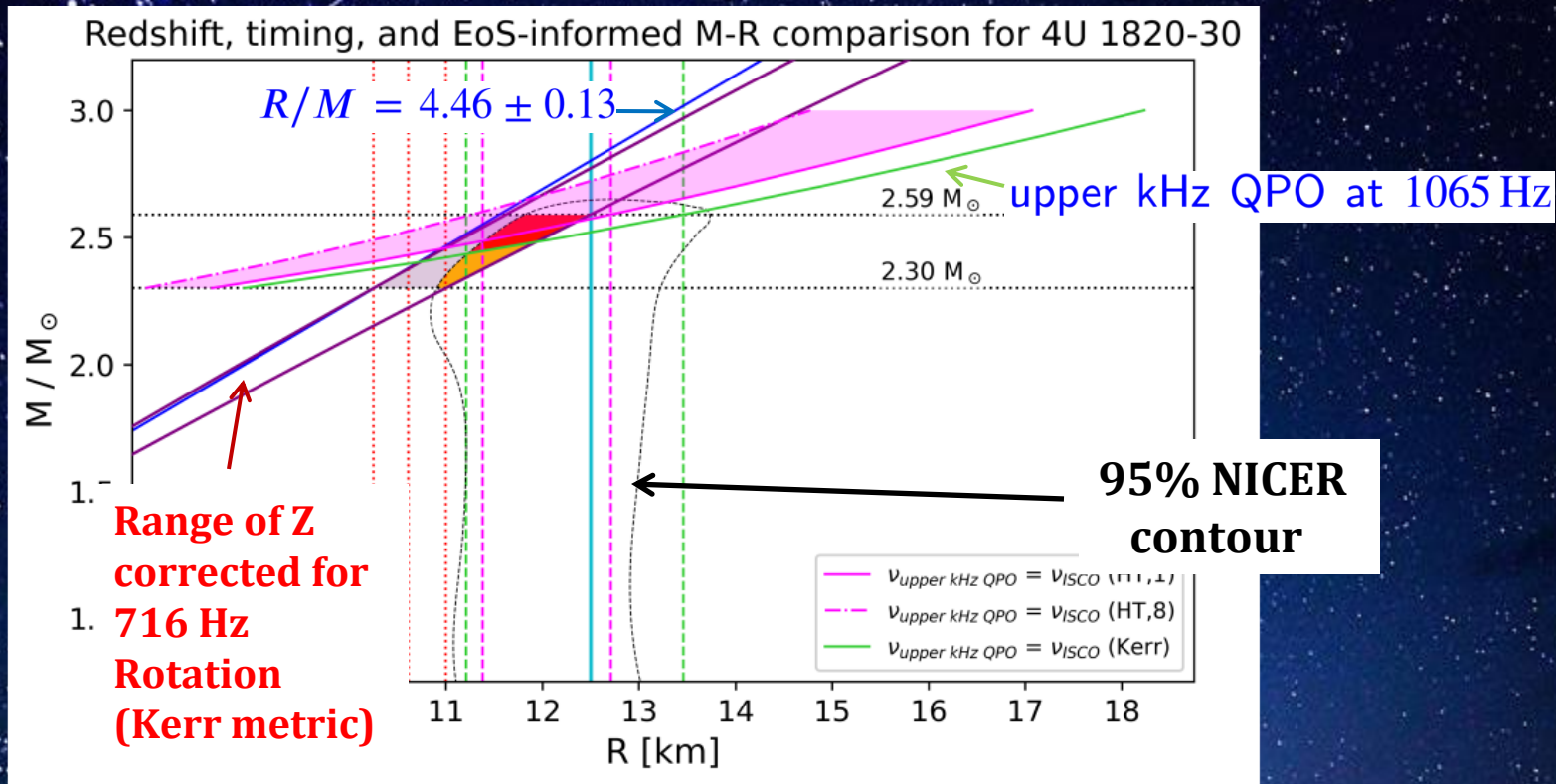


$$R/M = 4.46 \pm 0.13 \text{ km}/M_{\odot}$$

The compactness

Taking into account the 716 Hz rotation, this results in a constraint in the M-R plane in the form of a “wedge”

We compare all three (touchdown, ISCO and *Fe* line) with the 95% confidence contour derived from NICER in the same plane (Brandes & Weise 2025)



The ISCO and *Fe* line are consistent with each other only for a very high value of the mass (Roger Romani smiles...we too) inside the red sector.

The touchdown value is inconsistent with both.

Conclusions

- The “accepted” maximum mass went from $\sim 1.5 M_{\odot}$ to $\sim 2 M_{\odot}$, then to $\sim 2.2 M_{\odot}$ but it is surely larger than this ($2.5 M_{\odot}$?)
- If you have to bet your money on a high-mass search, spiders have the best odds (recycled millisecond pulsars too)
- There is no mass gap, several objects are inside the $2-5 M_{\odot}$, although the issue of M_{\max} blurs the separation NS-BHs
- Methods other than Kepler’s law (touchdown, QPO ISCO, redshift) must be revised to achieve crossed reliability

Are we wrong about M_{\max} ???



Supervised by Rodin (1907)