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Pulsar Masses

The Remnant Mass Distribution in Neutron Stars

Literature Report
in Galactic Astronomy
eingereicht von

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Contents

1 Pulsars and Neutron Stars

The first mention of the "Possible existence of a Neutron" was made by Chadwick in 1932. Shortly afterwards Landau anticipated a dense-compact star composed of neutrons. Then in 1934 Baade and Zwickey first mentioned the term "neutron star", possible evolutionary paths producing a neutron star and put constraints on the mass and radius [2]. The mass is one of the most important parameters of a neutron star. With the birth mass it is possible to infer information about the stellar evolution, core collapse and super nova mechanisms by testing previous studies about the stellar and binary evolution. The maximum mass outlines the low-mass limit for stellar black holes. Furthermore if the matter composition of a neutron star is well constrained by the equation of state it becomes possible to test nuclear physics of superdense matter. Additionally with the gravitational strength of the star it is possible to test Einstein's general relativity in the strong gravity regime [4, 6].
Even before Baade and Zwickey Chandrasekhar in 1931 and Landau in 1932 calculated theoretical upper mass limits for white dwarfs at $0.91 M_{\odot}$ and $1.5 M_{\odot}$. Following this work and using formalism's by Tolman, Oppenheimer and Volkoff predicted an upper mass limit for neutron stars between $0.7 M_{\odot}$ and $3.4 M_{\odot}$. Since then many mass ranges have been heavily discussed in the literature. In 1994 Finn's attempt constrained the mass range to $1.3 M_{\odot}$ and $1.6 M_{\odot}$. A few years later in 1999 Thorsett and Chakrabarty found the very narrow mass distribution of $1.38^{-0.06}_{+0.10} M_{\odot}$ for the observed pulsars back then [2, 6]. But recent observations of pulsars show significant deviations from the canonical value of $1.4 M_{\odot}$ (Fig. 1) [2]. Therefore it has become important to find out how exactly the remnant mass of a neutron star is distributed, where the limits towards the white dwarfs and black holes are to predetermine the outcome of future super novae, study the nature of compact remnants and infer the number of neutron stars in the galaxy [6].

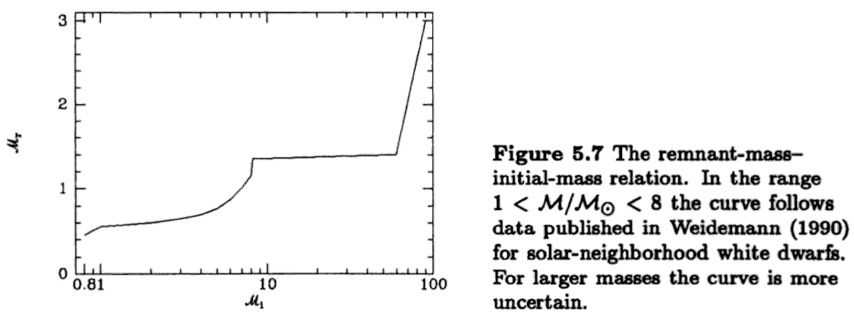

Figure 1: Binney, Merrifield - Galactic Astronomy - **Now Outdated** [1]

1.1 Phenomenology

Pulsars are rapidly spinning, highly magnetized neutron stars. They follow the "lighthouse" model meaning the spin axis is not aligned with the symmetry axis of the magnetic field and can only be observed when it's symmetry axis is directed at the earth. The rotational period is normally around a few seconds but can also decrease down to milliseconds. A pulsar's spin is gradually slowing down and therefore increases it's period due to the radiation gradually carrying away the rotational kinetic energy [3].

The neutron star itself is one of the possible remnant objects of a main sequence star normally evolving through a super nova explosion. The ZAMS mass is believed to be around $8 - 60 M_\odot$ [2, 3, 4]. The radius of a measured neutron star is in the range of $9.9 - 11.2km$ which makes the stars probably the most dense objects to be found in our universe [5]. This results in unusual high strengths of the magnetic field at the surface ($> 10^{10} T$, for the earth $\approx 50 \mu T$). The gravitational field at the surface is about 10^{11} times stronger than on earth which should make it possible to act as a gravitational lens [3].

Unlike the spin period of a pulsar and its decay the mass of the neutron star itself can only be measured in a binary system. This poses a major problem because about 90% of the ~ 2500 known pulsars are isolated stars (far more than the typical 50%) and therefore no mass measurement is possible [3, 5].

1.2 Measurements

The precise measurement of the mass is only possible due to the orbital motion in a binary system. There are two different methods in two different observational regimes with different underlying models [4, 6]. The first more common and precise method uses timing measurements in the radio regime. The pulsar's orbit can be described in classical gravity with the five Kelperian parameters. The mass function only needs the binary period P_b, the semi major axis a and the inclination angle i between the orbital angular momentum and the line of sight [2, 5, 6].

$$f_{mass} = \frac{(M_{cmp}\, sin\, i)^3}{(M_{psr} + M_{cmp})^2} = (\frac{2\pi}{P_b})^2 \frac{(a\, sin\, i)^3}{G} \tag{1}$$

If the effects of general relativity are measurable these five parameters are not enough as is the case here due to orbital periods of just a few hours. Then the gravitational influence can be measured with the post-Keplerian parameters: $\dot{\omega}$ advance of periastron, $\dot{P}_b$ orbital period decay, γ time dilation-gravitational redshift, r range of Shapiro delay and s shape of Shapiro delay [2, 4, 5, 6].

$$\dot{\omega} = 3 * (\frac{P_b}{2\pi})^{-5/3} (T_\odot M_{tot})^{2/3} (1 - e^2)^{-1} \tag{2}$$

$$\dot{P}_b = \frac{-192\pi}{5} * (\frac{P_b}{2\pi})^{-5/3}(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4)(1-e^2)^{-7/2}T_\odot^{5/3}M_{psr}M_{cmp}M_{tot}^{-1/3} \quad (3)$$

$$\gamma = e * (\frac{P_b}{2\pi})^{1/3}T_\odot^{2/3}M_{tot}^{-4/3}M_{cmp}(M_{psr} + 2m_{cmp}) \quad (4)$$

$$r = T_\odot M_{cmp} \quad (5)$$

$$s = a * (\frac{P_b}{2\pi})^{-2/3}T_\odot^{-1/3}M_{tot}^{2/3}M_{cmp}^{-1} \quad (6)$$

With eccentricity e, longitude and time of periastrom passage ω, $T_\odot$ from classical Keplerian. This can become difficult for millisecond pulsar systems because they tend to have a very circular orbit or so low eccentricity that no relativistic effects can be measured to resolve the masses [4, 5]. If two of these post-Keperian parameters are measured the individual masses of the pulsar M_{psr} and companion M_{cmp} can be derived. Even more measured parameters present a method to test the consistency of the strong field gravitational theories [2, 4, 5, 6].

The other significant but not equally precise method only works in a X-ray binary system. In these systems we have a pulsar emitting in the X-ray regime due to the mass accretion and an optical companion star. By measuring the cyclical doppler shifts of the pulse period and the doppler shifts in the spectral features of the optical companion it is possible to determine the orbital period P_b and the radial velocity v_{rad}. These parameters provide us with the systems mass function and in combination with the inclination angle we can infer the masses of both stars. This method has an typical error of about 10% [4, 5, 6].

Mixing both methods in an analysis about the mass distribution could lead to an additional systematic errors besides the normal statistical one and should be handled carefully [2]. Because of the very small sample size choosing the right statistical approach to determine the distribution becomes also very important. A simple Gaussian may yield a good first insight as done by Zhang et al., but the flaws have to be considered [4]. A better method is the Bayesian approach which reviews the overall likelihood for the distributions posterior parameters provided by a Monte Carlo Markov Chain [2, 6].

1.3 Types and Population

The type of neutron star is closely linked to the initial mass of the system and each follows specific evolutionary paths (Fig. 2) [3].

But as mentioned before it is very unlikely to find a neutron star in a binary system. This is due to the balanced distribution between binaries and isolated stars during the main sequence stage and after a super nova explosion there is a high probability that the system is disrupted by the violent nature of the super nova [3].

The general evolutionary path for a neutron star in a binary system starts with its own evolved giant star undergoing a super nova explosion. If the binary system

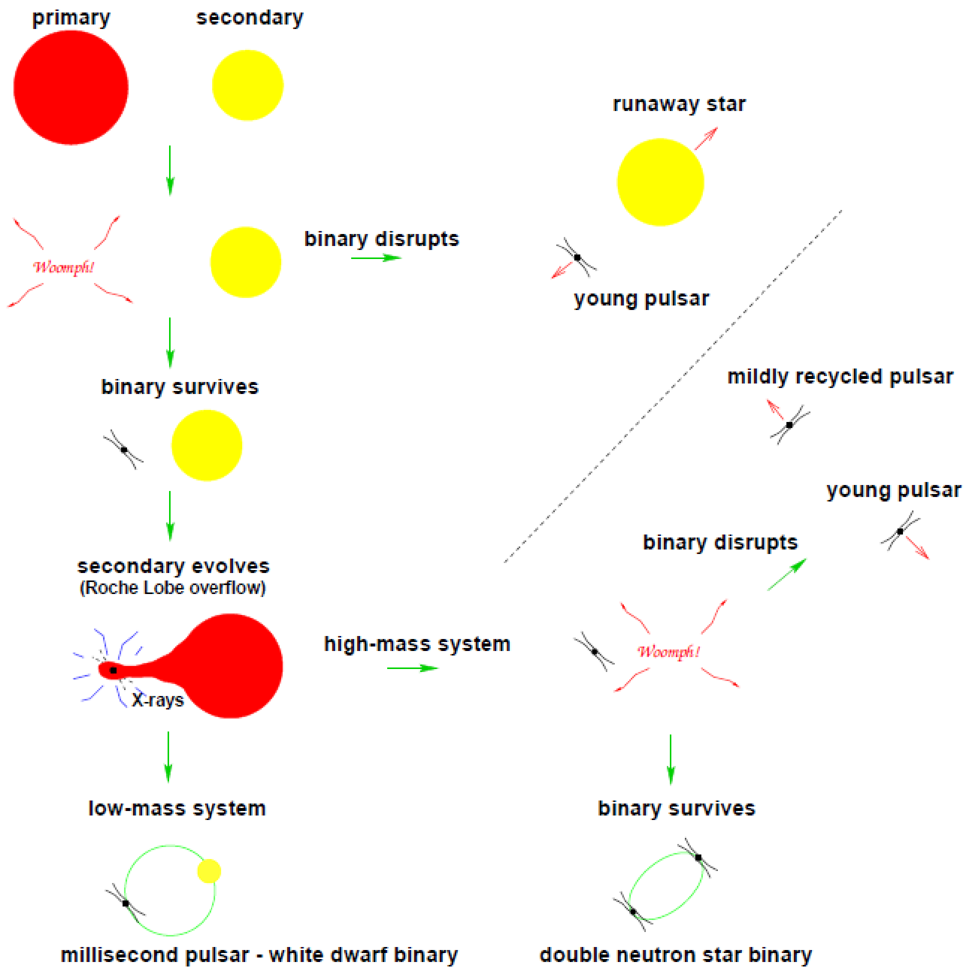

Figure 2: Lorimer - Evolutionary scenarios involving binaries

survives the violent conditions of this disruption and is not forcefully kicked out of the system the neutron star can start to accrete matter from its companion star. This happens when the companion star evolves and can not get a hold on all the matter inside its Roche Lobe. The matter will start to fall of the star onto anything that gravitationally attracts them in an so called Roche Lobe overflow or is just blown onto it by winds [3].

During this based on the lifetime of a star short phase the neutron stars get the simple name of "accreting neutron star" (aNS) or "slow pulsar" and when observed they are near their birth masses [6]. Due to the extended mass accretion from his companion through winds, a disk or a common envelope the system turns itself into an observable X-ray binary. Further evolution then depends on the mass of the system and therefore induces a bias to the distribution because we are observing the last stages of a stars evolution we are biased to observe the heavy systems as they have shorter lifetimes [3].

In a high mass system the companion star can also evolve through a super nova explosion and if the binary system can survive this second disruption it will be called a "double neutron star" system (DNS). Because of the two disruptions of the

binary these have high eccentricities and make up for only about 5% of the binary systems [5]. Due to only a short accretion phase both stars will be close to the birth mass of neutron stars with the older one having a little more recycled mass [6].
In a low mass binary system the neutron star becomes a "recycled neutron star" (rNS) [3, 5, 6]. After the accretion phase the companion star turns into a white dwarf making the binary a so called "white dwarf-neutron star" system (WDNS) [2]. Depending on the accreted mass and by that the transferred angular momentum the neutron stars period can reach the millisecond regime making it one of the "millisecond pulsars" (MSP). These millisecond pulsars not only have a very fast rotation but also a very stable one [3]. The Period-Period decay diagrams suggest that about 30% [2] of the millisecond pulsars are produced through non-standard evolutionary channels. One possible channel are "accretion induced collapses" (AIC) where white dwarfs accrete mass until they reach the Chandrasekhar mass limit and then go trough a core collapse turning them into neutron stars [2, 4]. Theoretically it would also be possible to reach the angular momentum right from the super nova.

1.4 Theoretical Mass Values

As talked about above since the first mention of neutron stars multiple mass constraints have been calculated and proposed.
One of particular interest is the birth mass [2, 6]. The previous canonical mass of $1.4M_\odot$ is an approximation for the critical mass beyond which the remnant core of a white dwarf will lose gravitational stability and collapse into a neutron star. The critical mass is more precisely defined through the Chandrasekhar mass $M_{ch} = 5.83Y_e^2 = 1.457M_\odot$ with the electron fraction $Y_e = n_p/(n_p + n_e) = 0.5$. This value has to be corrected to a smaller value because of a more reasonable smaller electron fraction, general relativistic implications, surface boundary pressure and a reduction of pressure from the Coulomb interactions at high pressure. But the electrons of the progenitor material are not completely relativistic leading to an increase of required mass to reach the gravitational potential that collapses a star. Also finite entropy corrections and rotational effects lead to a higher stable mass. These processes are not well understood and the different evolutionary paths lead to uncertainties of about 20% [2]. As this is the baryonic mass we also have to apply a quadratic correction to obtain the actual measured effective gravitational masses, therefore $M_{birth} \sim 1.08 - 1.57M_\odot$ according to Kiziltan et al. [2] and $M_{birth} \sim 1.06 - 1.22M_\odot$ to Özel et al. [6].
The actual mass then depends on the amount of fallback of stellar matter right after the super nova explosion and the length of the time of stable accretion. Meaning DNS and slow pulsars should both be around their birth mass due to only short or still ongoing accretion phases [6].

With typical accretion rates of $\dot{M} \sim 10^{-3}\dot{M}_{Edd}$ and estimations on the amount of angular momentum needed to spin up the neutron star to millisecond periods the accretion mass is proposed to be $\Delta M_{acc} \approx 0.1 - 0.2M_{\odot}$ [2].
The maximum mass of a neutron star highly depends on its composition and is directly linked to equation of state (EOS). The composition is hard to study leading to wide range of very different theoretical EOS. But upper limits can be found by numerically integrating the Oppenheimer-Volkoff equations which lead Rhoades & Ruffini to an extreme upper bound reasoned by general relativity and causal limitations at $M_{max} \sim 3.2M_{\odot}$ in 1974. More modern EOSs give a new range of $M_{max} \approx 1.5 - 2.2M_{\odot}$ by Thorsson (1994) and Kalogera & Baym (1996) [2].

2 Mass Distribution

2.1 General approach

The general approach used by each group is important to evaluate the obtained results and understand the flaws.
The first paper in question was published in 2011. Zhang et al. started with a statistical mass analysis of all neutron stars in binaries. The simple Gaussian distribution fitted onto the data of every neutron star yielded $M = 1.4 \pm 0.19M_{\odot}$ which coincides with the canonical mass value (Fig. 15). But they acknowledged the drawback of using neutron stars in different types of evolutionary stages. Therefore their investigation concentrated on the pulsar recycling hypothesis and divided their sample depending on the spin period of the pulsar [4].
In 2012, Özel et al. followed up on the work of Schwab et al. (2010) who used a bimodal distribution. This yielded for double neutron stars two very narrow mass peaks with errors of $0.008M_{\odot}$ and $0.025M_{\odot}$. Özel raised the question if double neutron stars are a representative sample for the birth mass of neutron stars. Therefore they modeled distributions for different subgroups of neutron stars based on the spin and companion nature with a Bayesian approach to find the most likely posterior parameter values for the distributions. Hence they also included measurements not only of the pulsar timing method but also based on the X-ray and optical combination method (Fig. 24) [6].
One year later Kiziltan et al. wanted to derive useful quantities like the birth mass, accreted mass and a maximum mass after discussing the theory behind them. They thought a single homogeneous population would be over-simplistic because of the increasing number of mass measurements that evidently differ from the canonical value especially from pulsars observed in globular clusters(Fig. 31). So they divided the neutron stars into a group of double neutron stars and white dwarf neutron star binaries and modeled their distribution in a similar fashion to Özel et al. with a

Bayesian approach [2].
At last Özel and Freire took another look at the latest mass measurements in DNS and WD-NS systems while discussing possible EOS. With these updates they repeated their earlier investigations. These latest used masses with low uncertainties from pulsar timing were in a range of $1.17 - 2.01 M_\odot$. In the case of unresolved masses and more inaccurate measurements from the X-ray regime these range can be exceeded quite far(Fig. 38).
It has to be noted that by the time Özel and Freire did their latest work only 66 of ≈ 250 binary neutron star masses were known and dividing them up into different subsets further reduces the accuracy of the applied statistics and biases can be introduced [5].
The actual data used by each group is added in the appendix together with various graphics showing their own research result. The included graphs are selfmade for better comparison and to highlight certain values unless stated otherwise.

2.2 Mass results

2.2.1 Double Neutron Stars

Zhang et al. averaged the mass of all neutron stars in DNS systems with a simple Gaussian at $M_{DNS} = 1.32 \pm 0.14 M_\odot$ (Fig. 15; Tab 14). Additionally he looked separately at the higher mass recycled ($M_{rcy} = 1.38 \pm 0.12 M_\odot$) and lower mass non-recycled ($M_{nrcy} = 1.25 \pm 0.13 M_\odot$) neutron stars and derived a mass ratio close to unity ($q = 0.91$) with two outliers which conincidentally are also the only systems with orbital periods around 10 days while the others are just a few hours to a day short (Fig. 17). Statistically there can not be drawn any conclusion from this [4].
Özel et al. (2012) on the other hand modeled the distribution and came nearly to the same result with an even smaller dispersion $M_{DNS} = 1.33 \pm 0.05 M_\odot$(Fig. 24; Tab. 18, 20). They divided the neutron stars by their pulsar timing with the faster one being the "pulsar" ($M_{psr} = 1.35 \pm 0.05 M_\odot$) and the slower as the "companion" ($M_{cmp} = 1.32 \pm 0.05 M_\odot$). Therefore their mass ratio is even closer to unity. In a final step they compared the predicted cumulative distribution for neutron star pairs independently drawn from a single Gaussian and a double Gaussian (done by Schwab et al., 2010) with the observed systems. The single Gaussian described the overall distribution better because the double Gaussian favored mass ratios closer to unity (Fig. 3 [6].
With a likewise modeling approach Kiziltan et al. determined the mass of a neutron star in a DNS system. Their result was very similar with $M_{DNS} = 1.35 \pm 0.13 M_\odot$(Fig. 32, 33; Tab. 29). For their research they did not divide the stars into two further subgroups [2].
At last Özel and Freire (2016) updated their general mass result with a slightly bigger

diviation $M_{DNS} = 1.33 \pm 0.09 M_\odot$ (Fig. 37; Tab. 34) because of new measurements of DNS systems with significant lower mass ratios of $q = 0.75$.

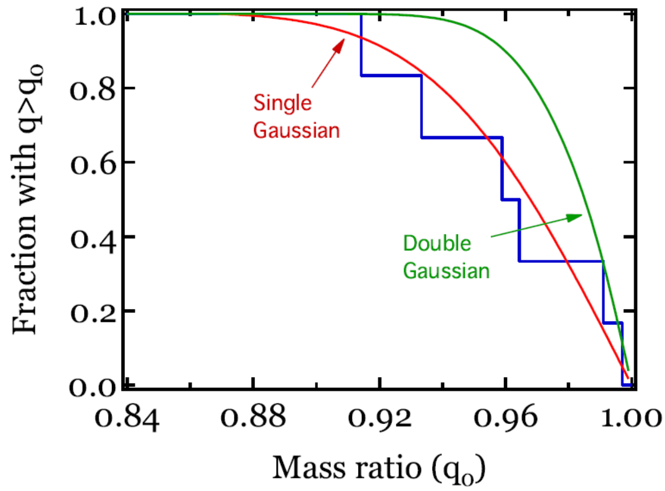

FIG. 8.— The histogram shows the cumulative mass ratio distribution for the six double neutron stars with precise mass measurements. The red line shows the predicted cumulative distribution for neutron star pairs drawn independently from a single Gaussian distribution with a central value and a dispersion equal to the most likely parameters shown in Figure 7. The green line shows the predicted cumulative distribution for neutron star pairs drawn independently from the double Gaussian distribution suggested by Schwab et al. (2010). The observed distribution of mass ratios is in agreement with a mass distribution represented by a single Gaussian. Note that, for consistency, we show in this figure the mass ratio histogram generated from the data used by Schwab et al. (2010).

Figure 3: Özel et al. - Cumulative DNS mass ratio distribution

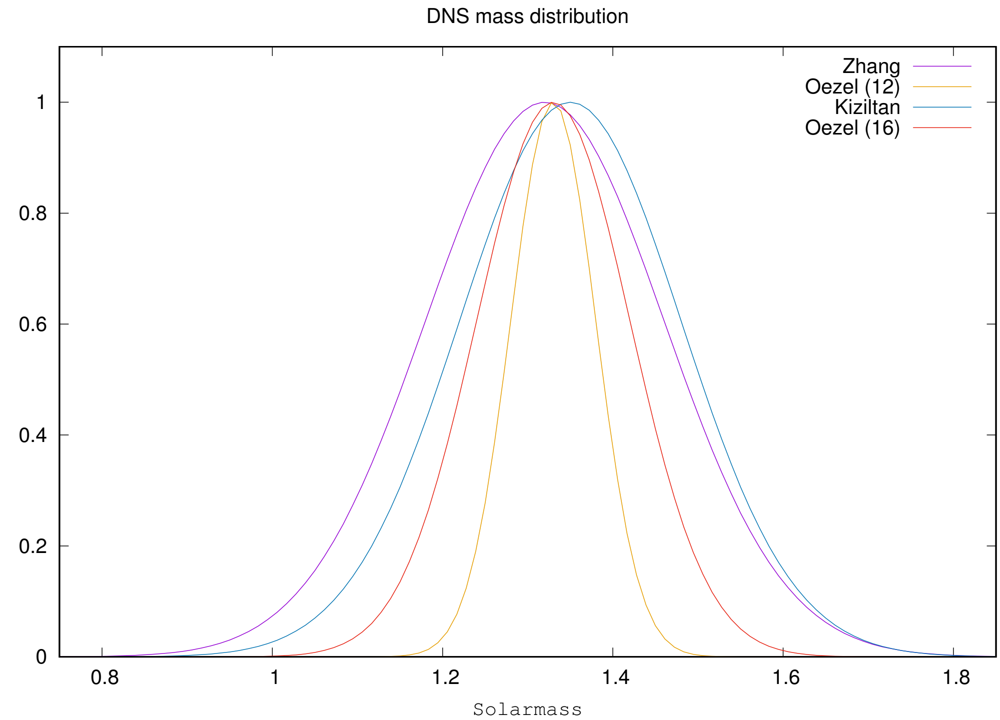

Figure 4: DNS distribution

2.2.2 Accreting NS / Slow Pulsar

Zhang et al. and Kiziltan et al. did not look at this population thus the only result was given by Özel et al. from high mass binaries and slow pulsars as these stars are believed to be close to their birth mass like the stars in DNS systems. This is due

to only short amount of time spend in the X-ray binary phase but therefore they can be wider distributed because of the different amount of accreted mass.
For the first approach the most likely modeling value was surprisingly shifted a bit to even lower masses and had a significantly higher dispersion ($M_{aNS} = 1.28 \pm 0.24 M_{\odot}$) (Fig. 25; Tab. 23). They tried to improve this result by combining it with the numerical results of Rawls et al. about eclipsing X-ray pulsar binaries (2011) and got the similar $M_{aNS} = 1.24 \pm 0.20 M_{\odot}$ as a result [6].
In 2016 Özel and Freire found a new and as initially expected higher result with $M_{aNS} = 1.49 \pm 0.19 M_{\odot}$(Fig. 37; Tab. 34, 35) which was better able to describe the ongoing accretion.

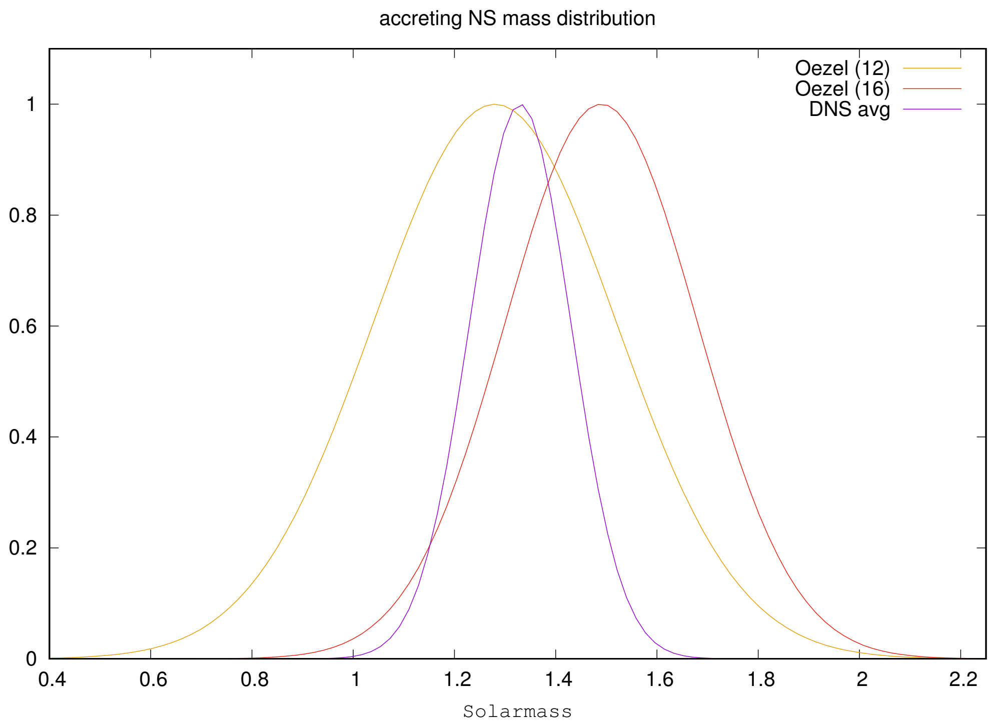

Figure 5: accreting NS/slow Pulsar distribution

2.2.3 White Dwarf - Neutron Star System (Recycled)

As Zhang et al. divided the pulsars by spin period they had no explicit look at recycled neutron stars in a WDNS system but the MSP can be included here as they are normally recycled. This sample can be biased because only the oldest binaries evolved far enough to reach this stage.
In this group Özel et al. included alongside the Millisecond Pulsars also the low mass X-ray binaries which are still undergoing long time accretion. Their most likely value was yielded at $M_{rNS} = 1.48 \pm 0.20 M_{\odot}$(Fig. 26, 28; Tab. 19, 21, 22). Because of the inclusion of the larger uncertainties of spectroscopic measurements from the X-ray binaries they did the same modeling also without these stars but found a very

similar value $M_{rNS} = 1.46 \pm 0.21 M_\odot$ due to the statistically insignificance of them [6].
A year later Kiziltan et al. used the similar likelihood modeling which resulted in a slightly increased mass of $M_{rNS} = 1.50 \pm 0.25 M_\odot$ (Fig. 32, 33; Tab. 30) [2] and when Özel and Freire revisited these stars they got an even higher distribution at $M_{rNS} = 1.54 \pm 0.23 M_\odot$ (Fig. 37; Tab. 35, 36) [5].

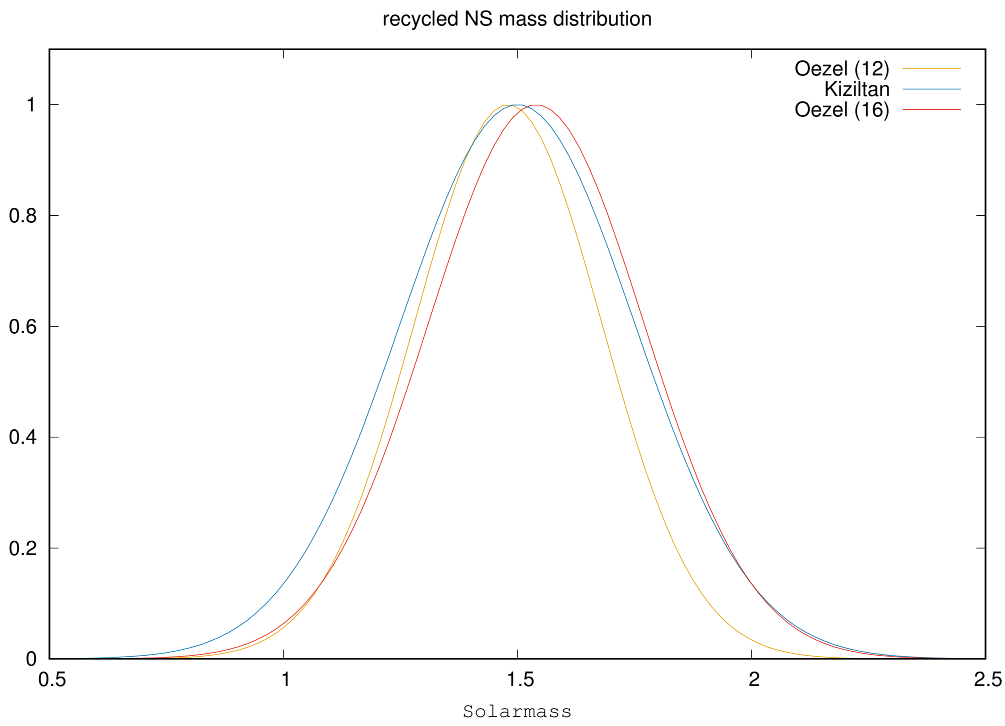

Figure 6: recycled NS distribution

2.2.4 Millisecond Pulsar

Zhang et al. counted every pulsar with a spin period lower than 20ms as a MSP. Their mass was averaged at $M_{MSP} = 1.57 \pm 0.35 M_\odot$ and was significantly higher than the mass of all the slower spinning neutron stars($M_{NS} = 1.37 \pm 0.23 M_\odot$) (Fig. 16; Tab. 12, 13, 14). This proved the association of the spin-up with the necessary amount of mass needed to reach those periods. 4 of the MSP had masses less than the Chandrasekhar mass limit of $1.44 M_\odot$. They argued that these are possible candidates for "Accretion Induced Collapses" from white dwarfs but also acknowledge the possibility of a really low birth mass [4].
The other groups did not investigate the MSP population any further but Özel and Freire mention in their last paper the work of Antoniadis et al. (2016) on which they contributed. There they found the possibility of a millisecond pulsar distribution with two peaks in the population. Those peaks appeared at $M_{MSP} = 1.388 \pm 0.058 M_\odot$ and $M_{MSP} = 1.814 \pm 0.152 M_\odot$ (Tab. 36). Those can be described

by the AIC neutron stars scenario for the first and the recycled neutron stars for the second.

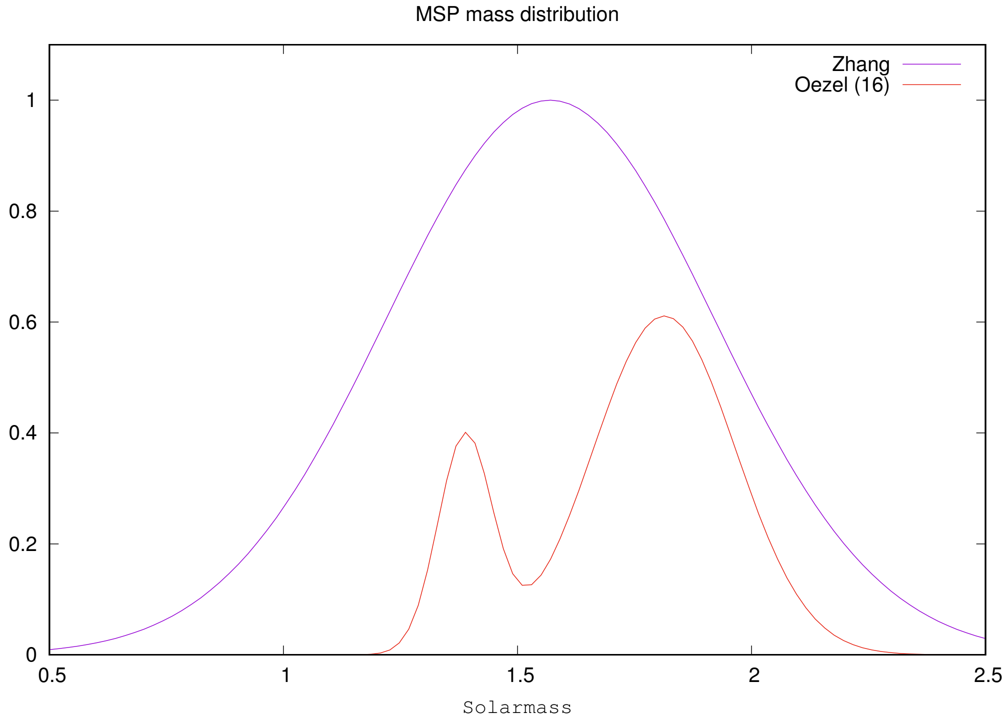

Figure 7: MSP distribution

2.3 Deduced Masses

2.3.1 Birth Mass

Zhang et al. based their birth mass on a accretion mass - spin period relation:

$$M = M_{birth} + M_{ca}(P/ms)^{-2/3} \tag{7}$$

with the spin period P and a characteristic accretion mass M_{ca} when a pulsar is spun-up to one ms. This resulted in a birth mass of $M_{birth} = 1.40 \pm 0.07 M_{\odot}$ but with a very low confidence level (Fig. 16) [4].
Kiziltan et al. had the opinion that the samplesize was to sparse and wanted a more diverse sample to do more rigorous testing to review this topic [2].
On the other hand Özel et al. (2012) avoided to mention one value and always referenced the masses of the neutron stars in DNS systems ($M_{DNS} = 1.33 \pm 0.05 M_{\odot}$) and accreting NS/slow pulsars ($M_{aNS} = 1.28 \pm 0.24 M_{\odot}$) as these pulsars have a low spin period which is indicative for mild or no recycling [6].
The updated values published with Freire (2016) were $M_{DNS} = 1.33 \pm 0.09 M_{\odot}$ for the DNS system and $M_{aNS} = 1.49 \pm 0.19 M_{\odot}$for the accreting NS [5].

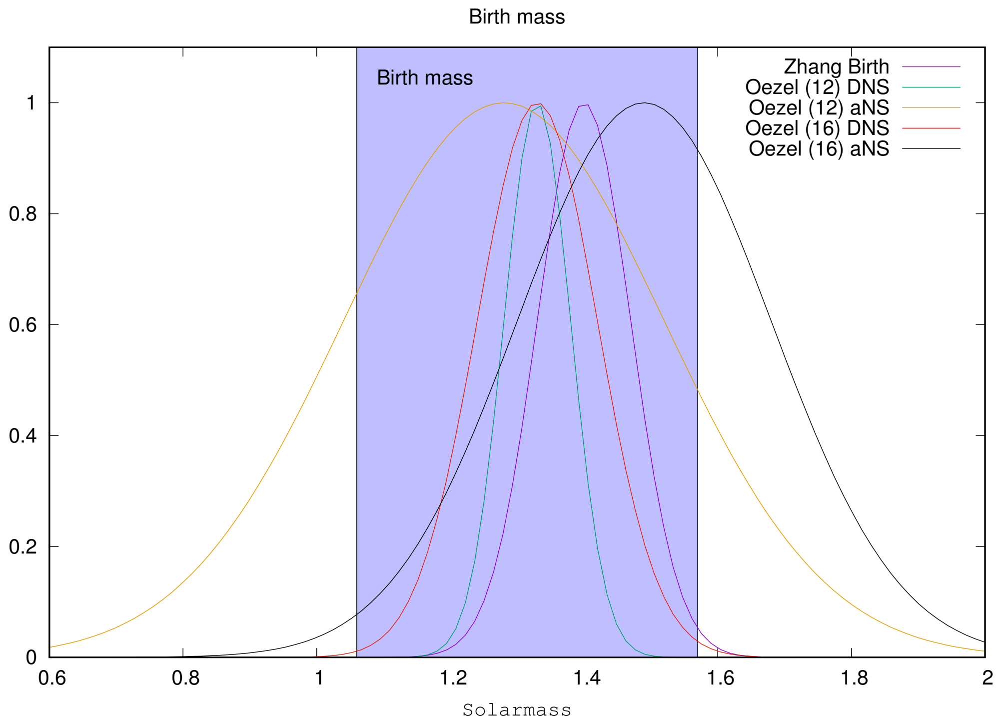

Figure 8: Birth mass distribution with theoretical mass range highlighted

2.3.2 Accretion Mass

With (7) Zhang et al. had a general solution for the accretion mass - spin period relation. The value for the characteristic accretion mass turned out to be $M_{ca} = 0.43 \pm 0.23 M_\odot$. For the accretion mass needed to create a MSP they looked at the mass difference of the two spin period regimes which yielded $\sim 0.2 M_\odot$ (Fig. 16)[4]. Özel et al. agreed with this value and the sufficiency to create MSPs with this amount of accreted mass. Additionally they proposed another formula to calculate the mass required to spin-up the pulsar:

$$\Delta M = 0.034 (\frac{\nu_s}{300Hz})^{4/3} (\frac{M}{1.48 M_\odot})^{-2/3} (\frac{I}{10^{45} gcm^2}) M_\odot \tag{8}$$

with spin frequency ν_s and moment of inertia I. Unfortunately they did not specify the M used for the calculations, how the reference values were determined or how meaningful the results with the proposed formula turned out to be [6].

2.3.3 Maximum Mass

Kiziltan et al. wanted to find out if the distribution is showing any kind of truncation at higher masses indicating a transition to low mass black holes. As they found no such cut off they thought the high mass end must be driven by evolutionary constraints and not by general relativity or a universal EOS. This result could of cause be statistically biased and there is an actual cut off mass value but their data

is just not sufficient enough to show it. But they were certain that a mass of $2M_{\odot}$ is a minimum secure limit for the maximum mass for neutron stars. Therefore every EOS with a lower limit can be ruled out (Fig. 31) [2].
Özel and Freire found the highest measured mass with a good precision at $2.01 \pm 0.04 M_{\odot}$(Fig. 38). They still see the possibility for even higher neutron stars which would irradiate their low mass companion and therefore be called Black Widows. But their were no convincing results found until that point [5].

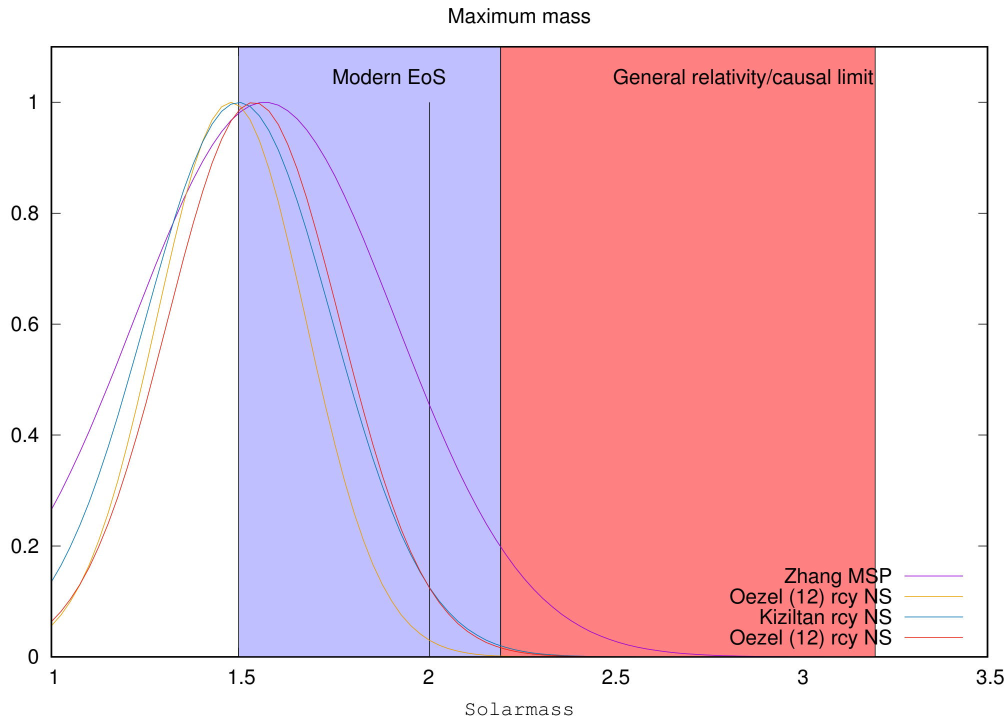

Figure 9: Max mass distribution - Black Vertical line is max known mass from Özel and Freire - highlighted are the theoretical mass limits from modern EOS and by general relativity and causal reasons

2.4 Further Results

Zhang et al. compared the wide mass distribution of the slow rotating pulsars ($M_{NS} = 1.37 \pm 0.23 M_{\odot}$) with the narrow average DNS mass ($M_{DNS} = 1.32 \pm 0.14 M_{\odot}$) (Fig. 17; Tab. 14). So they thought this means that the mass formation or evolutionary history of DNS should differ from other binary systems. Additionally they put a constraint on the formation rate of AIC by investigating the ratio of neutron stars with masses lower than the Chandrasekhar mass limit (4/22). This lead to no more than 20% leaving 10% of the non standard evolutionary MSPs unaccounted for [4].
Özel et al. came to the same conclusion about the DNS distribution. They suggest electron capture supernova in ONeMg white dwarfs but the mean mass would be

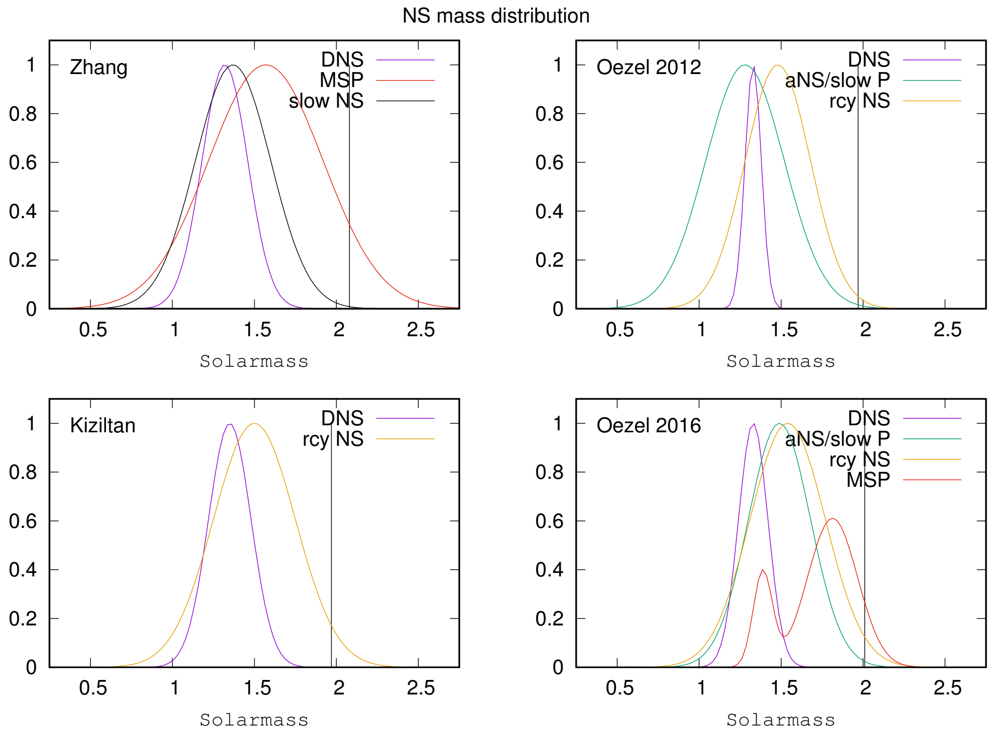

Figure 10: All mass distributions with the max mass as black vertical line

highly inconsistent with the distribution of DNS. For the core collapse supernova scenario they expect a wider distribution due to the stochastic nature of supernova fallback. Comparing it with the distributions of accreting neutron stars and slow pulsars lead to their conclusions that the DNS distribution is special and somehow related to a specific evolutionary history that leads to their formation. In the end they expected a significantly higher mean mass value for the recycled neutron stars closer to $2M_{\odot}$. This meant for them that the model for the low mass X-ray binary evolution should need some revision [6].

Besides that ~ 66 neutron stars are not enough for clear cut investigation of the mass distribution and therefore where the birth and maximum mass are located Kiziltan et al. had one other problem. This was about the evolution of NS-WD systems. The peaks between DNS and NS-WD systems are consistent with accretion masses of $0.15M_{\odot}$ but the typical accretion phase during the low-mass X-ray binary phase can not form neutron stars with $2M_{\odot}$. Therefore those would require an even longer stable accretion phase or unusually high accretion rates [2].

For Özel and Freire the DNS distribution still stands out as not representable for neutron stars as a whole. Therefore it should be linked to another evolutionary scenario that has a high constraint on the mass although recent discoveries indicate a possibly wider distribution [5].

3 Conclusion

Right now we are at the beginning of getting statistically significant mass constraints for pulsars. Kiziltan et al. were right when they said that ~ 66 are not enough to draw definite conclusions but now we are able to think about the value of the theories leading to the different binary systems and get a first indicator for the specific mass distributions and limits.
The first important note to make is about the DNS systems. Every group found the narrowness of the distribution peculiar and tried to find an approach to explain it. But the question still remains and further investigation into it is necessary to find the right answers but with every new system measured it can become more unlikely that it is just a random statistic phenomenon. Also still open is the question if there indeed is a relation between the mass ratio and the orbital period as proposed by Zhang et al. even though this also might seem very unlikely.
The accreting neutron star/slow pulsar population is underrepresented in the analysis. Özel et al. found two very different and concerning the theory opposite results. For a final test of the underlying mass relation to DNS and recycled neutron stars further measurements would be necessary but unlikely to find due to the relatively short time spend in the X-ray binary phase.
Then we need to look into how the the really heavy neutron stars are created. Does the low mass X-ray binary model need some revision because we actually have even longer stable accretion times or is the accretion rate higher than previously thought. Might there even be the possibility for significantly higher birth masses leading to the neutron stars with masses around $2M_{\odot}$.
But there are also some good results. Özel and Freire mentioned the paper of Antoniadis which found the double peak population for MSPs. Addiationally Zhang et al. put a formation rate constraint onto the AICs and were able to confirm that $0.2M_{\odot}$ are sufficient to create MSP.
We are now able to further constrain the maximum mass at round about $2M_{\odot}$. Combining those results with radii measurements provides a new set of restrictions on the EOS and shapes the knowledge about the nuclear physics at superdense matter. As of now it seems that the upper limit is driven by some evolutionary constraint but statistically it can not be ruled out there is a truncation after which the neutron stars evolve into still undetected low mass black holes.
Therefore Özel and Freire provide us with some hope as they expect an increase in measured neutron star masses in the upcoming years.

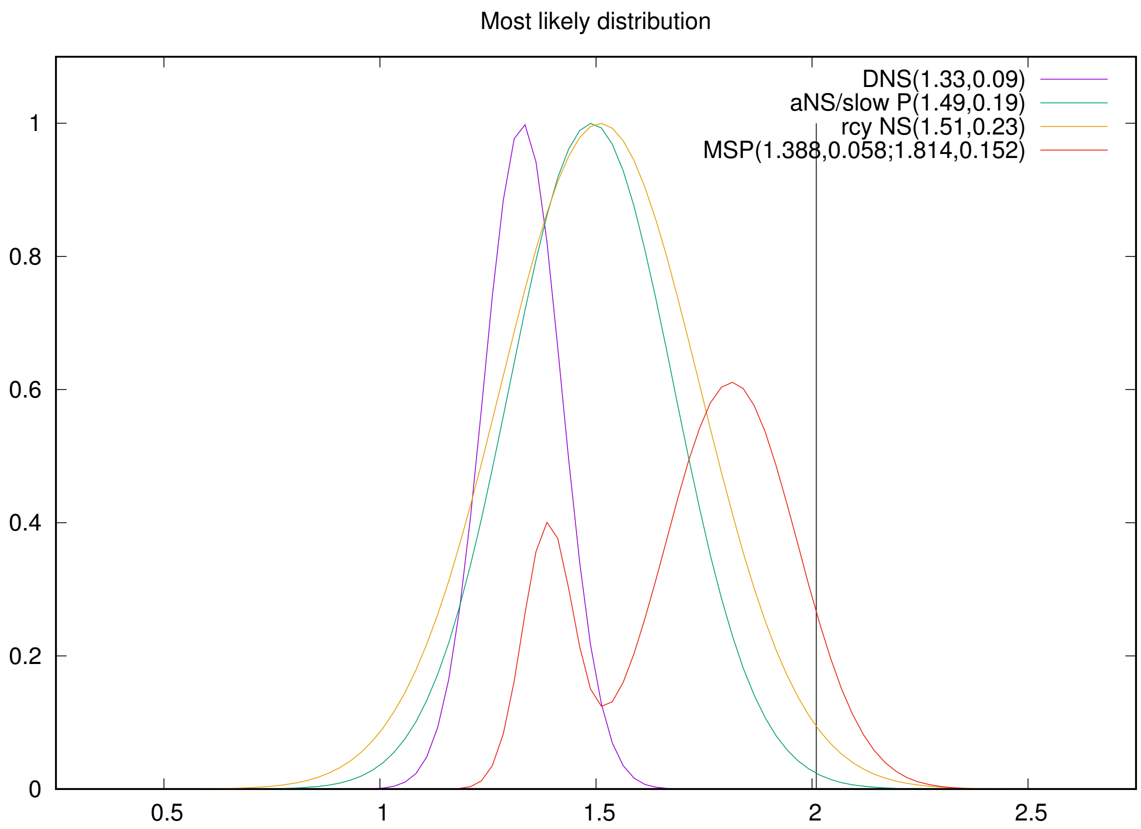

Figure 11: Most likely mass distribution

4 References

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5 Appendix

Table 3. Parameters of Galactic cluster pulsars

System	M($M_\odot$)	M_c($M_\odot$)	P_{orb}(d)	P_{spin}(ms)	eccentricity	*type*	*Refs*
J0024-7204I(B0021-72I)	1.44	0.15	0.23	3.49	6.3×10^{-5}	GC	G1
J0024-7204H(B0021-72H)	$1.41^{+0.04}_{-0.08}$	$0.18^{+0.086}_{-0.016}$	2.380	3.21	0.071	GC	G1
J1518+0204B(B1516+02B)	2.08±0.19	> 0.13	6.860	7.95	0.14	GC	G2
J1911-5958A	$1.40^{+0.16}_{-0.10}$	0.18	0.837	3.48	$< 10^{-5}$	GC	G2
J1802-2124	1.21±0.1	> 0.81	0.699	12.65	3.2×10^{-6}	GC	G3
J1824-2452C	< 1.367	> 0.26	8.078	4.158	0.847	GC	G4
J0514-4002A	< 1.52	> 0.96	18.79	4.99	0.888	GC	G5
J1748-2021B	2.74 ± 0.2	> 0.11	20.55	16.76	0.57	GC	G6
J1748-2021I(Ter 5 I)	1.3 ± 0.02	0.24	1.328	9.57	0.428	GC	G7
J1748-2021J(Ter 5 J)	$1.88^{+0.02}_{-0.08}$	0.38	1.102	80.34	0.35	GC	G7

GC—Globular cluster pulsars. G1—Manchester et al. 1991; Freire et al. 2003; Lorimer et al. 2008. G2—Wolszczanet al. 1989; Bassa et al. 2006; Cocozza et al. 2006; Freire et al. 2007; Lorimer et al. 2008; Freire et al. 2008b. G3—Lorimer et al. 2008; Lorimer et al. 2008; Faulkner et al. 2004; Ferdman et al. 2010 (1.24±0.11$M_\odot$). G4—Ransom and Freire, 2009. G5—Freire & Ransom 2007. G6—Freire & Ransom, 2008; Freire et al. 2008a; Freire 2009. G7—Ransom et al. 2005.

Figure 12: Zhang et al. - 2011

Table 1. Parameters of neutron stars in X-ray binaries

System	M($M_\odot$)	M_c($M_\odot$)	P_{orb}(d)	P_{spin}(ms)	eccentricity	*type*	*Refs*
4U 1538-52	$1.06^{+0.41}_{-0.34}$	$16.4^{+5.2}_{-4.0}$	3.73	5.28×10^5	0.08	HMXB	X1
SMC X-1	1.05±0.09	15.5±1.5	3.89	708	$< 4 \times 10^{-5}$	HMXB	X2
Cen X-3	1.24±0.24	19.7±4.3	2.09	4814	$< 8 \times 10^{-4}$	HMXB	X3
LMC X-4	1.31±0.14	15.6±1.8	1.41	1.35×10^4	< 0.01	HMXB	X2
Vela X-1	1.88±0.13	23.1±0.2	8.96	2.83×10^5	0.09	HMXB	X4
	1.86±0.16	23.8±0.2	8.96	2.83×10^5	0.09	HMXB	X4
$4U1700-37^*$	2.44±0.27	58±11	3.41	No	0.2	HMXB	X5
Her X-1	1.5±0.3	2.3±0.3	1.70	1240	$< 3 \times 10^{-4}$	XB	X6
4U1820-30	$1.29^{+0.19}_{-0.07}$	≤ 0.106	0.08	6.9×10^5	No	XB	X7
2A 1822-371	0.97±0.24	0.33±0.05	0.23	590	< 0.03	LMXB	X8
XTE J2123-058	$1.46^{+0.30}_{-0.39}$	$0.53^{+0.28}_{-0.39}$	0.25	3.9	No	LMXB	X9
Cyg X-2	1.78 ±0.23	0.60±0.13	9.84	No	0.0	LMXB	X10
	1.5 ±0.3	0.63 ±0.16	9.84	No	0.0	LMXB	X10
V395 CAR/2S 0921C630	1.44 ± 0.10	0.35 ± 0.03	9.02	No	No	LMXB	X11
Sax J 1808.4-3658	<1.4	<0.06	0.08	2.49	< 0.0005	LMXB	X12
HETE J1900.1-2455	<2.4	< 0.085	0.06	2.65	< 0.005	LMXB	X13

* The compact object may be a black hole (Lattimer & Prakash 2007). LMXB—Low-mass X-ray binary, HMXB—High-mass X-ray binary. X1—van Kerkwijk et al. 1995 (M, M_c, P_{orb}, eccentricity); Robba et al. 2001 (P_s). X2—van Kerkwijk et al. 1995 (P_{orb}, eccentricity); van der Meer et al. 2005 (M, M_c); van der Meer et al. 2007 (P_s). X3—van Kerkwijk et al. 1995; Ash et al. 1999 (P_{orb}, eccentricity); van der Meer et al. 2005 (M, M_c); van der Meer et al. 2007 (P_s). X4—Quaintrell et al. 2003 (M=2.27,1.88$M_\odot$, M_c, P_{orb}, eccentricity, P_s); Barziv et al. 2001 (M=1.86$M_\odot$). X5—Clark et al. 2002 (M, M_c); Hammerschlag-Hensberge et al. 2003 (P_{orb}, eccentricity). X6—Cheng et al. 1995 (P_{orb}, eccentricity); Reynolds et al. 1997 (M, M_c); Martin et al. 2001 (P_s); van der Meer et al. (2007) (P_s). X7—Wang et al. 2010 (M, M_c, eccentricity, P_s); Shaposhnikov et al. 2004 (M, P_{orb}); Dib et al. 2004 (P_{orb}). X8—Jonker & van der Klis 2001 (P_{orb}, eccentricity, P_s); Jonker et al. 2003 (M, M_c). X9—Tomsick et al. 1999 (P_s); Tomsick et al. 2002 (M, M_c, P_{orb}, eccentricity). X10—Cowley, Crampton & Hutchings 1979 (P_s); Orosz & Kuulkers 1999 (M, M_c, P_{orb}, eccentricity); Elebert, Callanan & Torres, et al. **2009a**. X11—Steeghs & Jonker 1996; 2007 (1.44$M_\odot$); Shahbaz, & Watson 2007 (1.370.13 $M_\odot$). X12 — Elebert et al. **2009b**; Chakrabarty & Morgan 1998; Jain, Dutta & Paul (P_{orb}). X13— Elebert et al. 2008; Kaaret, Morgan & Vanderspek et al. 2006 (P_{orb}).

Figure 13: Zhang et al. - 2011

Table 2. Parameters of radio binary pulsars

System	M($M_\odot$)	M_c($M_\odot$)	P_{orb}(d)	P_{spin}(ms)	eccentricity	type	Refs
J1518+4904	$1.56^{+0.20}_{-1.20}$	$1.05^{+1.21}_{-0.14}$	8.63	40.9	0.249	DNS	R1
J1811-1736	$1.5^{+0.12}_{-0.4}$	$1.06^{+0.45}_{-0.1}$	18.8	104.2	0.828	DNS	R2
J1829+2456	$1.15^{+0.1}_{-0.25}$	$1.35^{+0.46}_{-0.15}$	1.176	41.0	0.139	DNS	R3
B1534+12	1.33±0.0020	1.35±0.0020	0.421	37.9	0.274	DNS	R4
B1913+16	1.44±0.0006	1.39±0.0006	0.323	59.0	0.617	DNS	R5
B2127+11C	1.35±0.080	1.36±0.080	0.335	30.5	0.681	DNS	R6
J0737-3039A(B)	1.34±0.010	1.25±0.010	0.102	22.7 (2773)	0.088	DNS	R7
J1756-2251	$1.40^{+0.04}_{-0.06}$	$1.18^{+0.06}_{-0.04}$	0.320	28.5	0.181	DNS	R8
J1906+0746@	1.25	1.37	0.166	144	0.085	DNS	R9
J0437-4715	1.58±0.18	0.24±0.017	5.74	5.76	1.9×10^{-5}	NSWD	R10
J0621+1002	$1.70^{+0.59}_{-0.63}(^{+0.32}_{-0.29})$	$0.97^{+0.43}_{-0.24}(^{+0.27}_{-0.15})$	8.32	28.9	0.003	NSWD	R11
J0751+1807	1.26 ± 0.14	0.19±0.03	0.263	3.48	3×10^{-6}	NSWD	R12
	$2.1^{+0.4}_{-0.5}$(corrected)	0.19±0.03	0.263	3.48	3×10^{-6}	NSWD	R12
J1012+5307	1.7±1.0	0.16 ± 0.02	0.605	5.26	$< 10^{-6}$	NSWD	R13
	1.64 ± 0.22	0.16 ± 0.02	0.605	5.26	$< 10^{-6}$	NSWD	R13
J1045-4509	< 1.48	0.13	4.08	7.47	$< 10^{-5}$	NSWD	R14
J1141-6545	1.27±0.01	1.02±0.01	0.198	394	0.172	NSWD	R15
	1.3 ± 0.02	0.986 ± 0.02	0.198	394	0.172	NSWD	R15
J1713+0747	$1.53^{+0.08}_{-0.06}(1.6 \pm 0.24)$	0.33 ± 0.04	67.83	4.75	7.5×10^{-5}	NSWD	R16
B1802-07	$1.26^{+0.15}_{-0.67}$	$0.36^{+0.67}_{-0.15}$	2.62	23.1	0.212	NSWD	R17
J1804-2718	< 1.73	0.2	11.1	9.34	4×10^{-5}	NSWD	R18
B1855+09	$1.58^{+0.10}_{-0.13}$	$0.27^{+0.010}_{-0.014}$	12.33	5.36	2.2×10^{-5}	NSWD	R19
J1909-3744	1.44±0.024	0.20±0.0022	1.53	2.95	10^{-7}	NSWD	R20
J2019+2425	< 1.51	$0.32 - 0.35$	76.5	3.93	1.1×10^{-4}	NSWD	R21
B2303+46	1.34±0.10	1.3±0.10	12.34	1066	0.658	NSWD	R22
J0437-4715	1.76±0.20	0.25±0.018	5.74	5.76	1.918×10^{-5}	NSWD	R23
J1023+0038	1.0-3.0	0.14-0.42	0.198	1.69	$\leq 2 \times 10^{-5}$	NSWD	R24
J1738+0333	1.6 ± 0.2	0.2	0.354	5.85	1.1×10^{-6}	NSWD	R26
J0045-7319	1.58±0.34	8.8±1.8	51.17	926	0.808	NSMS	R27
J1740-5340	1.53±0.19	> 0.18	1.35	3.65	$< 10^{-4}$	NSMS	R28
J1903+0327	1.67 ± 0.01	1.05	95.17	2.15	0.437	NSMS	R29
J1753-2240	~ 1.25	~ 1.25	13.64	95.1	0.304	uncertain	U

DNS—double neutron star; NSWD—pulsar-white dwarf binary; NSMS—neutron star/main-sequence binary; @ The recycled NS should be the companion because of the strong magnetic field of PSR J1906+0746 $\sim 10^{12}$ G. R1—Nice et al. 1995 (P_{orb},P_s, eccentricity); TC99 (M,M_c); Janssen et al. 2008 ($m_p < 1.17$ and $m_c > 1.55M_\odot$). R2—Lyne et al. 2001 (P_{orb},P_s, eccentricity); Lorimer et al. 2008 (M,M_c); Breton, 2009 (M,M_c). R3—Champion et al. 2004 (P_{orb},P_s, eccentricity); Lorimer et al. 2008 (M,M_c); Breton et al. 2009 (M,M_c). R4—Wolszczan 1991 (P_{orb},P_s, eccentricity); Stairs et al. 2002 (M,M_c). R5—Hulse & Taylor 1975 (P_{orb},P_s, eccentricity); Weisberg & Taylor 2003 (M,M_c). R6—Anderson et al. 1990 (P_{orb},P_s, eccentricity); Jacoby, Cameron & Jenet et al. 2006; TC99 (M,M_c). R7—Burgay et al. 2003 (P_{orb}, P_s, eccentricity); Lyne et al. 2004 (M,M_c). R8—Manchester et al. 2001 (P_{orb}, P_s, eccentricity); Faulkner et al. 2005 (M,M_c). R9—Lorimer & Stairs 2006 (P_{orb}, P_s, eccentricity); Kasian et al. 2007; Lorimer et al. 2008 (M,M_c); Breton et al. 2009 (M,M_c). R10—Johnston et al. 1993 (P_{orb}, P_s, eccentricity); van Straten et al. 2001 (M,M_c). R11—Camilo et al. 1996 (P_{orb}, P_s, eccentricity); Splaver et al. 2002 (M,M_c). R12—Lundgren et al. 1995 (P_{orb}, P_s, eccentricity); Nice et al. 2004 (M,M_c); Nice et al. 2005, Nice et al. 2008 (M,M_c). R13—Nicastro et al. 1995 (P_{orb}, P_s, eccentricity); van Kerkwijk et al. 1996, 2005; Callanan et al. 1998; TC99 (M,M_c). R14—Bailes et al. 1994 (P_{orb}, P_s, eccentricity); TC99 (M,M_c). R15—Kaspi et al. 2000 (P_{orb}, P_s, eccentricity); Burgay et al. 2003 (M,M_c); Bailes et al. 2003; Bhat & Bailes, 2008 (M,M_c). R16—Foster et al. 1993 (P_{orb}, P_s, eccentricity); Splaver et al. 2005 (M,M_c). R17—DAmico et al. 1993 (P_{orb}, P_s, eccentricity); TC99 (M,M_c); Lorimer et al. 2008 (M,M_c); Breton et al. 2009 (M,M_c); Freire 2000. R18—Lorimer et al. 1996 (P_{orb}, P_s, eccentricity); TC99 (M,M_c); Breton et al. 2009 (M,M_c). R19—Segelstein et al. 1986 (P_{orb}, P_s, eccentricity); Nice, Splaver & Stairs 2003 (M,M_c). R20—Jacoby et al. 2003 (P_{orb}, P_s, eccentricity); Jacoby et al. 2005 (M,M_c). R21—Nice et al. 1993 (P_{orb}, P_s, eccentricity); Nice et al. 2001 (M,M_c). R22—Dewey et al. 1985 (P_{orb}, P_s, eccentricity); Kerkwijk & Kulkarni 1999 (M,M_c). R23—Johnston et al. 1993 (P_{orb}, P_s, eccentricity); van Beveren et al. 2008 (M,M_c). R24—Archibald et al. 2009 (P_{orb},P_s,eccentricity,M,M_c). R26—Jacoby, PhD thesis, (2004); Freire PhD thesis, 2000. R27—Bell & Bessell et al. 1995 (M,M_c); Kaspi, Bailes & Manchester et al. 1996 (P_{orb}, P_s, eccentricity). R28—Kaluzny et al. 2003 (P_{orb},M); D"Amico et al. 2001 (P_s,eccentricity,M_c). R29—TC99 (P_{orb}, P_s, eccentricity, M_c). R29—Champion et al. 2008 (P_{orb}, P_s, eccentricity, M, M_c); Freire et al. 2009. U—uncertain companion type, Keith et al. 2009ab (P_{orb}, P_s, eccentricity, M, M_c).

Figure 14: Zhang et al. - 2011

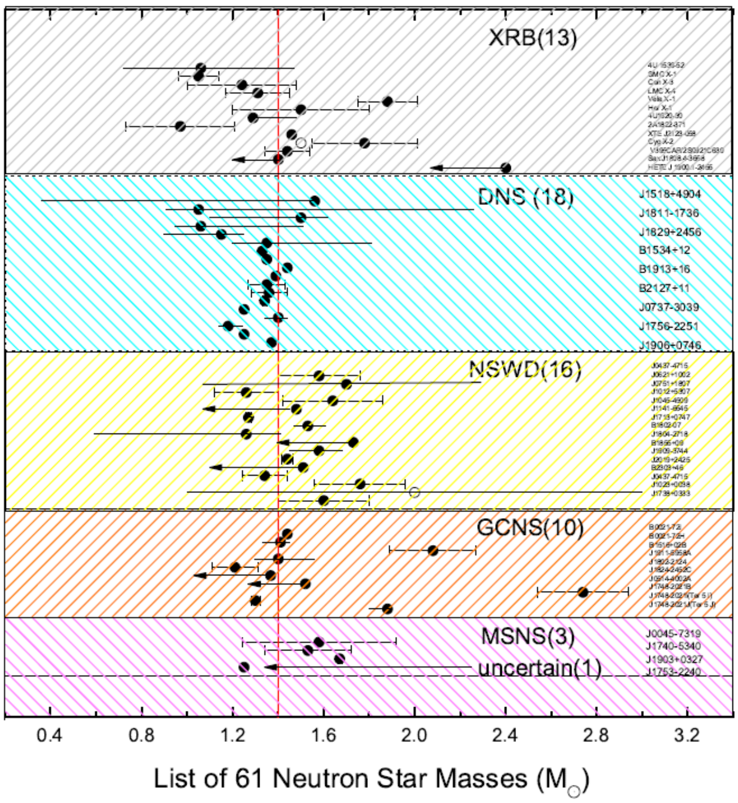

Fig. 1. List of 61 measured NS masses in the different types of NS binary systems. Their details and references can be seen in Table 1-3. Vertical line M=1.4 $M_\odot$ delineates the mass mean value inferred from Gaussian fitting.

Figure 15: Zhang et al. - 2011

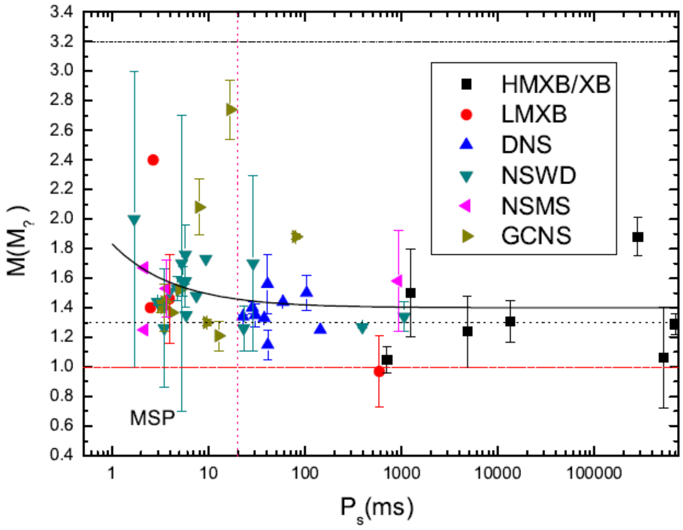

Fig. 3. Diagram of mass versus spin period for 39 NSs. The horizontal line M=1 M$_\odot$(3.2 M$_\odot$) stands for the measured minimum mass (theoretical maximum mass, see Rhoades & Ruffini 1974). The vertical line at 20 ms separates the samples into two groups, MSP ($<$ 20 ms) and less recycled NS ($>$ 20 ms). It is found that the mass averages of two groups are, respectively, 1.57 ± 0.35 M$_\odot$ and 1.37 ± 0.23 M$_\odot$. The solid curve stands for the relation between accretion mass and spin period of recycled pulsar as described in Eq.(1) and (2), $M = 1.40 + 0.43(\frac{P_s}{\rm ms})^{-2/3}$ (M$_\odot$) .

Figure 16: Zhang et al. - 2011

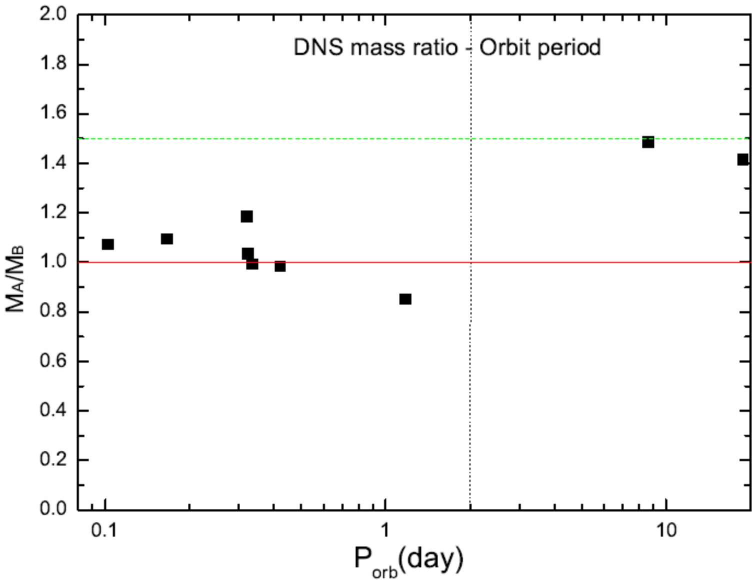

Fig. 4. Mass ratio versus orbital period diagram for 9 pairs of DNSs, where the vertical axis M_A/M_B represents the mass ratio of the recycled NS to non-recycled one.

Figure 17: Zhang et al. - 2011

TABLE 1
PRECISE MASSES OF DOUBLE NEUTRON STAR SYSTEMS[a]

Name	Mass ($M_\odot$)	Error ($M_\odot$)	Refs[b]
J0737-3039	1.3381	0.0007	1
pulsar B	1.2489	0.0007	1
B1534+12	1.3332	0.0010	2
companion	1.3452	0.0010	2
J1756-2251	1.312	0.017	3
companion	1.258	0.018	3
J1906+0746	1.323	0.011	4, 5
companion	1.290	0.011	4, 5
B1913+16	1.4398	0.002	6
companion	1.3886	0.002	6
B2127+11C	1.358	0.010	7
companion	1.354	0.010	7

[a] Defined as systems with ≥ 2 PK parameters measured.
[b] References: 1. Kramer et al. 2006; 2. Stairs et al. 2002; 3. Ferdman 2008; 4. Lorimer et al. 2006; 5. Kasian 2012; 6. Weisberg et al. 2010; 7. Jacoby et al. 2006

Figure 18: Özel et al. - 2012

TABLE 2
PRECISE MASSES OF NEUTRON STARS WITH WHITE DWARF COMPANIONS[a]

Name	Mass ($M_\odot$)	Error ($M_\odot$)	Refs[b]
J0437-4715	1.76	0.2	1
J0751+1807	1.26	0.14	2, 3
J1141-6545	1.27	0.01	4
J1614-2230	1.97	0.04	5
J1713+0747	1.30	0.2	6
J1802-2124	1.24	0.11	7
B1855+09	1.57	0.11	8, 9
J1903+0327	1.667	0.021	10
J1909-3744	1.438	0.024	11

[a] Defined as systems with ≥ 2 PK parameters measured.
[b] References: 1. Verbiest et al. 2008; 2. Nice et al. 2005; 3. Nice et al. 2008; 4. Bhat et al. 2008; 5. Demorest et al. 2010; 6. Splaver et al. 2005; 7. Ferdman et al. 2010; 8. Nice et al. 2003; 9. Kaspi et al. 1994; 10. Freire et al. 2011; 11. Jacoby et al. 2005

Figure 19: Özel et al. - 2012

TABLE 3
Dynamical Data for Double Neutron Stars with 1 PK parameter

Name	$f(M)$ ($M_\odot$)	$\dot{\omega}$ (deg yr^{-1})	M_{tot} ($M_\odot$)	Refs[a]
PSR J1518+4904	0.115988	0.0113725(9)	2.7183(7)	1
PSR J1811-1736	0.128121(5)	0.0090(2)	2.57(10)	2
PSR J1829+2456	0.29413(1)	0.2929(16)	2.59(2)	3

[a] References: 1. Janssen et al. 2008; 2. Corongiu et al. 2007; 3. Champion et al. 2005

Figure 20: Özel et al. - 2012

TABLE 4
Data for NS-WD binaries with 1 PK parameter

Name	$f(M)$ ($M_\odot$)	$\dot{\omega}$ (deg yr^{-1})	M_{tot} ($M_\odot$)	Refs[a]
J0024-7204H	0.001927	0.066(2)	1.61(4)	1
J0514-4002A	0.14549547	0.01289(4)	2.453(14)	2
J0621+1002	0.027026849	0.0102(2)	2.32(8)	3
B1516+02B	0.000646723	0.0142(7)	2.29(17)	4
J1748-2021B	0.0002266235	0.00391(18)	2.92(20)	5
J1748-2446I	0.003658		2.17(2)	4, 6
J1748-2446J	0.013066		2.20(4)	4, 6
J1750-37A	0.0518649	0.00548(30)	1.97(15)	5
B1802-07	0.00945034	0.0578(16)	1.62(7)	7
J1824-2452C	0.006553		1.616(7)	4
B2303+46	0.246332	0.01019(13)	2.64(5)	7

[a] References: 1. Freire et al. 2003; 2. Freire et al. 2007; 3. Kasian 2012; 4. Freire et al. 2008a; 5. Freire et al. 2008b; 6. Ransom et al. 2005; 7. Thorsett & Chakrabarty 1999

Figure 21: Özel et al. - 2012

TABLE 5
Data for NS-WD Binaries with Optical Observations

Name	$f(M)$ ($M_\odot$)	$M_{\rm WD}$ ($M_\odot$)	q	Refs[a]
J1012+5307	0.00058709(2)	0.156±0.02	10.7±0.5	1,2
B1911-5958A	0.002687603(13)	0.18±0.02	7.36±0.25	3,4

[a] References: 1. Callanan et al. 1998; 2. Nicastro et al. 1995; 3. Bassa et al. 2006; 4. D'Amico et al. 2002

Figure 22: Özel et al. - 2012

TABLE 6
Orbital Solutions for Eclipsing X-ray Pulsars

Name	Rawls et al. (2011)[a] Mass $M_\odot$	i deg	β	This Work Mass $M_\odot$	i deg	β
Vela X−1	1.770±0.083	78.8±1.2	1	1.70±0.13	86.3±2.6	0.99±0.01
4U 1538−52	0.996±0.101	76.8±6.7	0.88	1.18±0.25	76.9±8.0	0.87±0.07
SMC X−1	1.037±0.085	68.5±5.2	0.95	0.93±0.12	77.2±8.0	0.87±0.07
LMC X−4	1.285±0.051	67.0±1.9	0.95	1.11±0.12	77.9±7.5	0.87±0.07
Cen X−3	1.486±0.082	66.7±2.4	1	1.26±0.15	78.6±7.0	0.91±0.05
Her X−1	1.073±0.358	$>$ 85.9	1	1.08±0.36	84.1±4.1	0.94±0.04

[a] These values are taken from Table 4 of Rawls et al. (2011).

Figure 23: Özel et al. - 2012

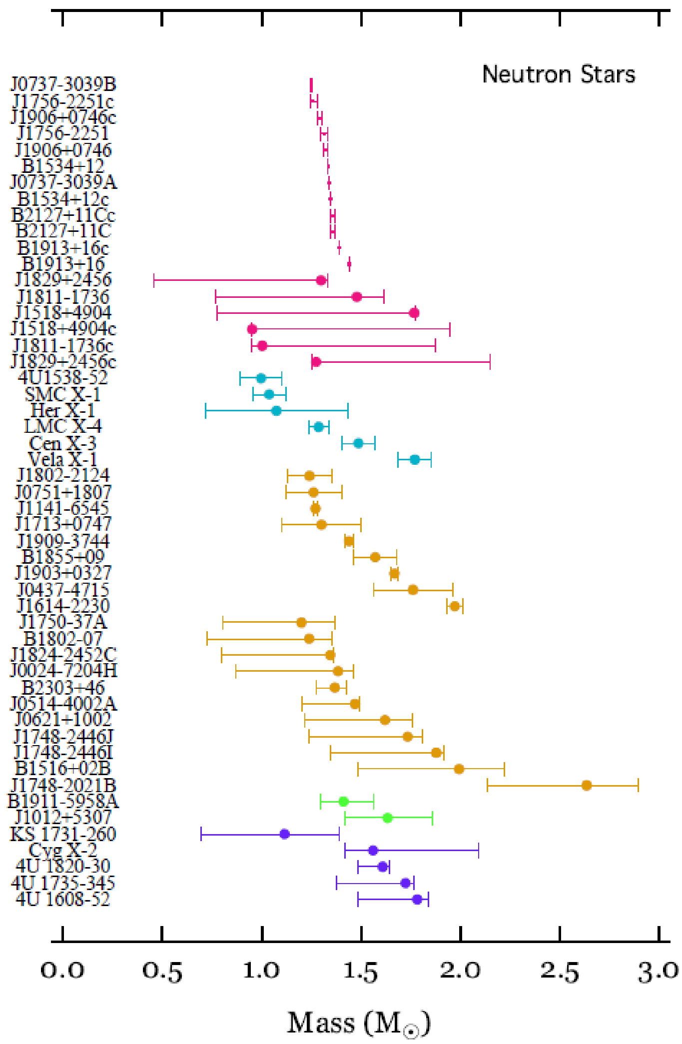

FIG. 13.— The masses of neutron stars measured in double neutron stars (magenta; categories Ia and IIa), in eclipsing binaries with primarily high mass companions (cyan; category IV; these are the numerical values from Rawls et al. 2011 given in column 2 of Table 6), with white dwarf companions (gold; categories Ib and IIb), with optical observations of the white dwarf companions (green; category III), and in accreting bursters (purple; category V).

Figure 24: Özel et al. - 2012

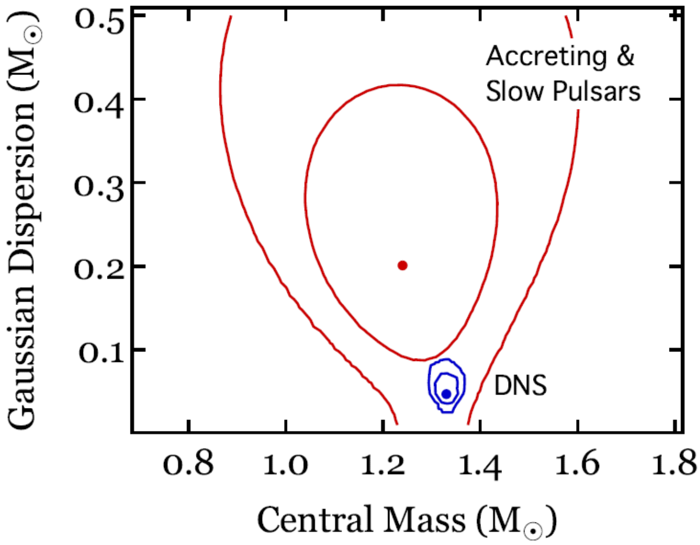

FIG. 10.— The confidence contours over the parameters of a Gaussian distribution for the accreting and slow pulsars using the analytic mass measurements discussed in the text. The confidence contours for the double neutron stars are also shown for comparison.

Figure 25: Özel et al. - 2012

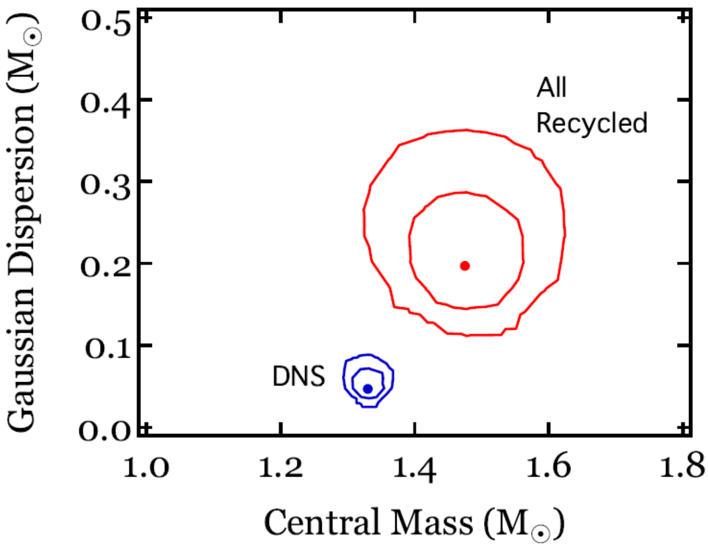

FIG. 11.— The confidence contours over the parameters of a Gaussian distribution for the recycled neutron stars. The confidence contours for the double neutron stars are also shown for comparison. As expected, the recycled neutron stars have on average larger masses than those in double neutron stars.

Figure 26: Özel et al. - 2012

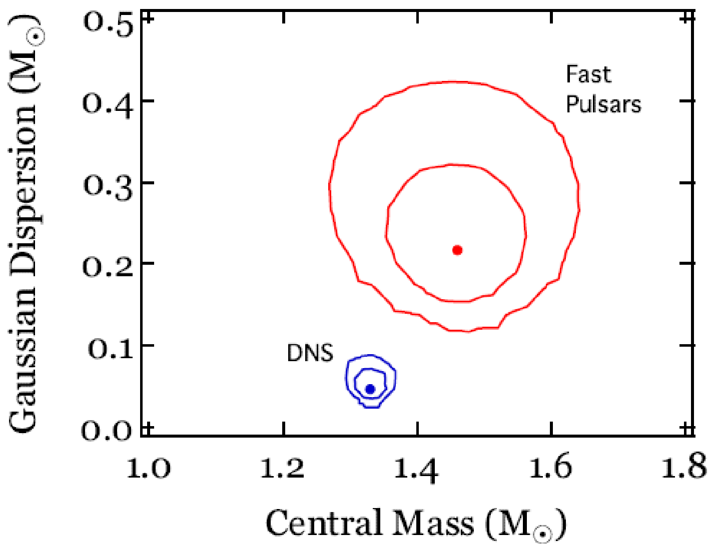

FIG. 12.— The confidence contours over the parameters of a Gaussian distribution for a subgroup of the recycled neutron stars that includes only pulsars in orbit around white dwarfs. Considering only these sources with dynamical mass measurements does not alter the results shown in Figure 11.

Figure 27: Özel et al. - 2012

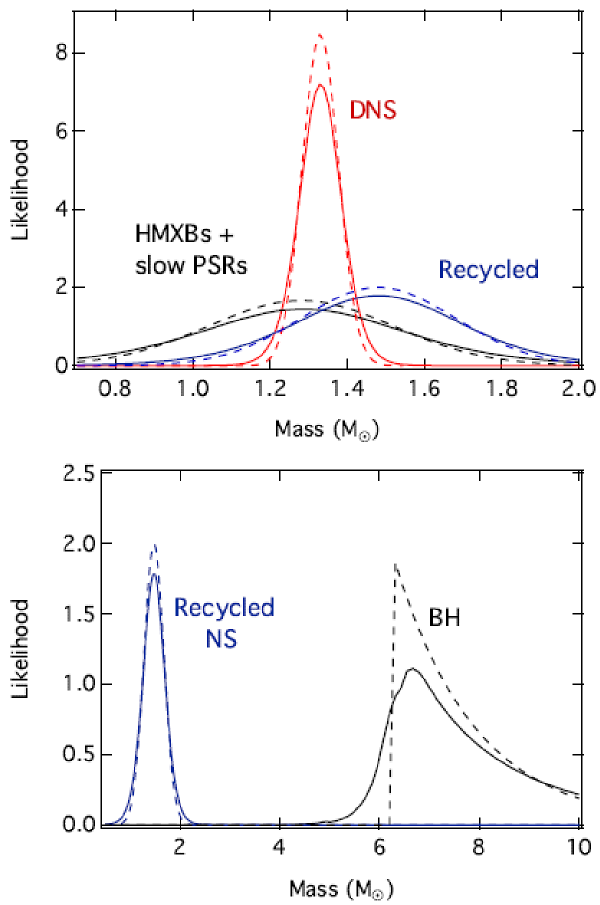

FIG. 15.— The inferred mass distributions for the different populations of neutron stars (top) and black holes (bottom) discussed in the text. The dashed lines correspond to the most likely values of the parameters. For the different neutron star populations these are: $M_0 = 1.33 M_\odot$ and $\sigma = 0.05 M_\odot$ for the double neutron stars, $M_0 = 1.28 M_\odot$ and $\sigma = 0.24 M_\odot$ for the other neutron stars near their birth masses, and $M_0 = 1.48 M_\odot$ and $\sigma = 0.20 M_\odot$ for the recycled neutron stars. For the case of black holes, we used the exponential distribution with a low mass cut-off at $M_c = 6.32 M_\odot$ and a scale of $M_{\rm scale} = 1.61 M_\odot$ obtained in Özel et al. (2010a). The solid lines represent the weighted mass distributions for each population, for which appropriate fitting formulae are given in the Appendix. The distributions for the case of black holes have been scaled up by a factor of three for clarity.

Figure 28: Özel et al. - 2012

Table 1
Double neutron star systems

Pulsar	Mass [$M_\odot$]	68% central limits	Refs.[a]
	Double neutron star binaries		
J0737−3039			[1]
pulsar A	1.3381	±0.0007	
pulsar B	1.2489	±0.0007	
total	2.58708	±0.00016	
J1518+4904			[2]
pulsar	1.56	$+0.13/-0.44$	
companion	1.05	$+0.45/-0.11$	
total	2.61	±0.070	
B1534+12			[3]
pulsar	1.3332	±0.0010	
companion	1.3452	±0.0010	
total	2.678428	±0.000018	
J1756−2251			[4]
pulsar	1.40	$+0.02/-0.03$	
companion	1.18	$+0.03/-0.02$	
total	2.574	±0.003	
J1811−1736			[5, 6]
pulsar	1.56	$+0.24/-0.45$	
companion	1.12	$+0.47/-0.13$	
total	2.57	±0.10	
J1829+2456			[7]
pulsar	1.20	$+0.12/-0.46$	
companion	1.40	$+0.46/-0.12$	
total	2.59	±0.02	
J1906+0746			[8, 9]
pulsar	1.248	±0.018	
companion	1.365	±0.018	
total	2.61	±0.02	
B1913+16			[10, 11]
pulsar	1.4398	±0.002	
companion	1.3886	±0.002	
total	2.82843	±0.0002	
B2127+11C			[12]
pulsar	1.358	±0.010	
companion	1.354	±0.010	
total	2.71279	±0.00013	

[a] References: 1: Kramer et al. (2006), 2: Thorsett & Chakrabarty (1999), 3: Stairs et al. (2002), 4: Faulkner et al. (2005), 5: Stairs (2006), 6: Corongiu et al. (2007), 7: Champion et al. (2005), 8: Kasian (2008), 9: Lorimer et al. (2006), 10: Weisberg et al. (2010), 11: Taylor (1992), 12: Jacoby et al. (2006)

Figure 29: Kiziltan et al. - 2013

Table 2
Neutron star - white dwarf binary systems

Pulsar	Mass $[M_\odot]$	68% central limits	Refs.[a]
Neutron star - white dwarf binaries			
J0437−4715	1.76	± 0.20	[1]
J0621+1002	1.70	$+0.10/-0.17$	[2]
J0751+1807	1.26	± 0.14	[2]
J1012+5307	1.64	± 0.22	[3]
J1141−6545	1.27	± 0.01	[4]
J1614−2230	1.97	± 0.04	[5]
J1713+0747	1.53	$+0.08/-0.06$	[6]
J1802−2124	1.24	± 0.11	[7]
B1855+09	1.57	$+0.12/-0.11$	[8]
J1909−3744	1.438	± 0.024	[9]
B2303+46	1.38	$+0.06/-0.10$	[10]
Neutron stars in globular clusters			
J0024−7204H	1.48	$+0.03/-0.06$	[*]
J0514−4002A	1.49	$+0.04/-0.27$	[*]
B1516+02B	2.10	± 0.19	[*]
J1748−2446I	1.91	$+0.02/-0.10$	[*]
J1748−2446J	1.79	$+0.02/-0.10$	[*]
B1802−07	1.26	$+0.08/-0.17$	[10]
B1911−5958A	1.40	$+0.16/-0.10$	[11]

[a] References: *: This work; Freire (personal communication), 1: Verbiest et al. (2008), 2: Nice et al. (2008), 3: Callanan et al. (1998), 4: Bhat et al. (2008), 5: Demorest et al. (2010) 6: Splaver et al. (2005), 7: Ferdman et al. (2010), 8: Nice et al. (2003), 9: Jacoby et al. (2005), 10: Thorsett & Chakrabarty (1999), 11: Bassa et al. (2006)

Figure 30: Kiziltan et al. - 2013

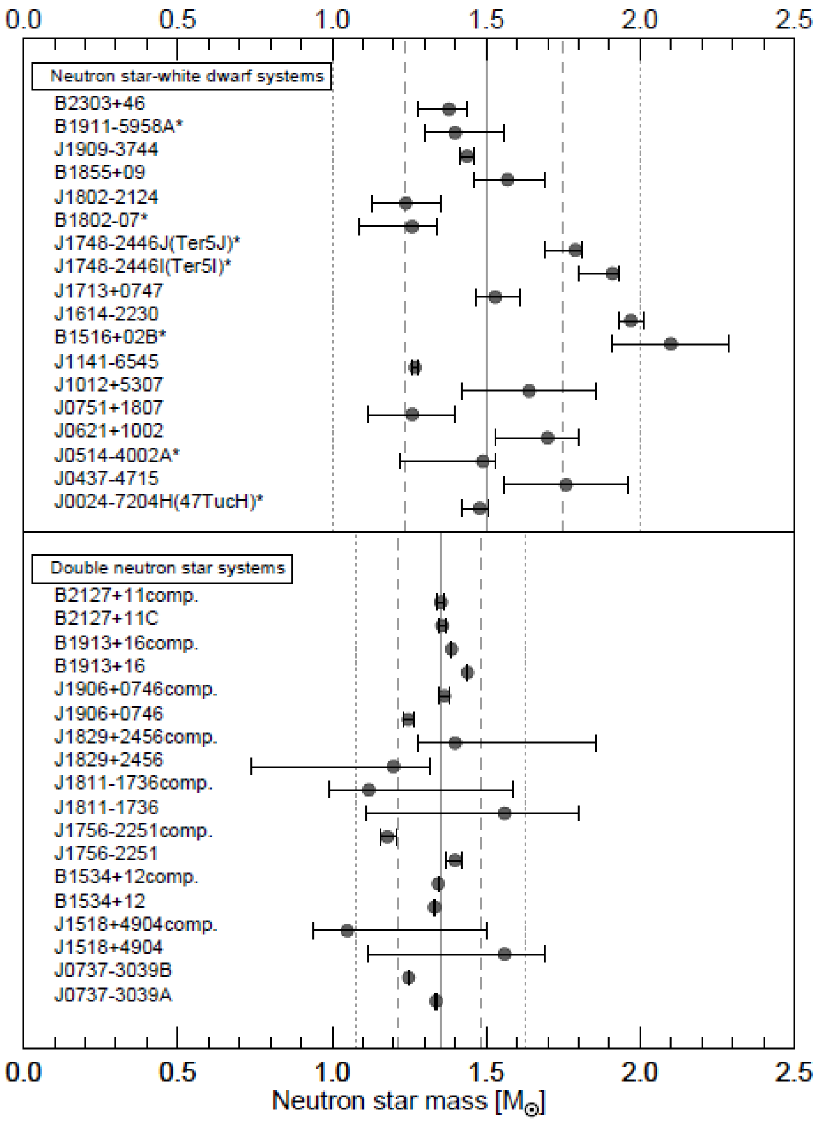

Figure 1. Measured masses of radio pulsars. All error bars indicate the central 68% confidence limits. Vertical solid lines are the peak values of the underlying mass distribution for DNS ($m = 1.35$ M$_\odot$) and NS-WD ($m = 1.50$ M$_\odot$) systems. The dashed and dotted vertical lines show the central 68% and 95% predictive probability intervals of the underlying mass distribution shown in Figure 2. "$\star$" points to pulsars found in globular clusters.

Figure 31: Kiziltan et al. - 2013

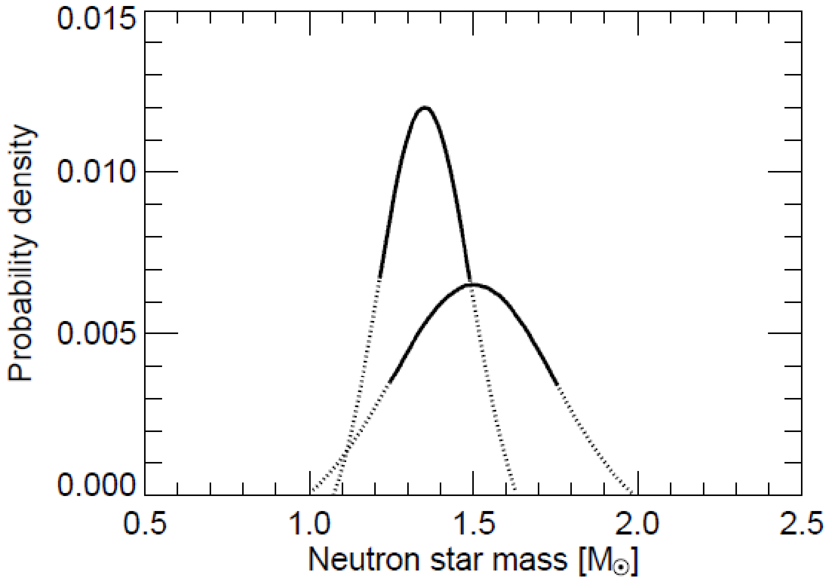

Figure 2. Posterior predictive density estimates for the neutron star mass distribution. DNS and NS-WD systems have respective peaks at 1.35 $M_\odot$ and 1.50 $M_\odot$. Probability densities are normalized to show the 95% posterior probability range. The solid parts of the curves show the central 68% probability range which correspond to 1.35 ± 0.13 $M_\odot$ and 1.50 ± 0.25 $M_\odot$ for the DNS and NS-WD system, respectively.

Figure 32: Kiziltan et al. - 2013

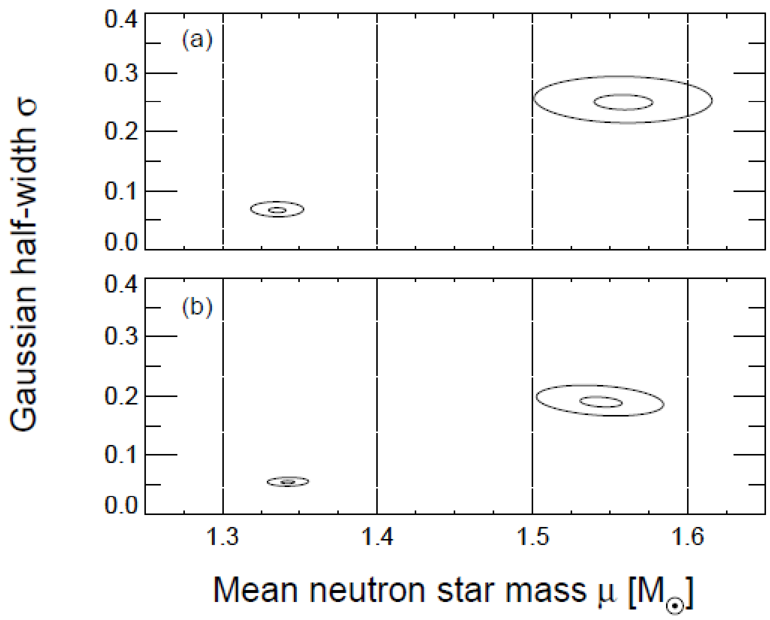

Figure 3. Likelihood surfaces (a) and posterior densities (b) of model parameters μ and σ for the NS mass distribution. In each panel, the tight contours on the left and wider contours on the right correspond to the data from DNS and NS-WD systems, respectively.

Figure 33: Kiziltan et al. - 2013

Table 1 Masses of Double Neutron Star Systems and Non-recycled Pulsars

System	M_T ($M_\odot$)	M_{PSR} ($M_\odot$)	M_c ($M_\odot$)	Mass const.	Ref.
		Systems with well-measured component masses			
J0453+1559	2.734(4)	1.559(5)	1.174(4)	$\dot{\omega}, h_3$	1,2
J0737−3039	2.58708(16)	1.3381(7)	1.2489(7) y	$\dot{\omega}, q$	3
B1534+12	2.678463(8)	1.3330(4)	1.3455(4)	$\dot{\omega}, \gamma$	4
J1756−2251	2.56999(6)	1.341(7)	1.230(7)	$\dot{\omega}, \gamma$	5
J1906+0746	2.6134(3)	1.291(11) y	1.322(11) ?	$\dot{\omega}, \gamma$	6
B1913+16	2.828378(7)	1.4398(2)	1.3886(2)	$\dot{\omega}, \gamma$	7
B2127+11C g	2.71279(13)	1.358(10)	1.354(10)	$\dot{\omega}, \gamma$	8
		Systems with total binary mass measurement only			
J1518+4904	2.7183(7)	<1.768	>0.950	$\dot{\omega}$	9
J1811−1736	2.57(10)	<1.64	>0.93	$\dot{\omega}$	10
J1829+2456	2.59(2)	< 1.34	>1.26	$\dot{\omega}$	11
J1930−1852	2.59(4)	< 1.32	>1.30	$\dot{\omega}$	12
		Non-recycled pulsars with massive WD companions			
J1141−6545	2.2892(3)	1.27(1) y	1.01(1)	$\dot{\omega}, \gamma$	14,15
B2303+46	2.64(5)	1.24-1.44 y	1.4-1.2	$\dot{\omega}, M_{WD}$	15,16

Notes: The systems indicated with a "g" are located in globular clusters. A question mark indicates that the NS nature of the companion is not firmly established. The mass measurements for neutron stars detected as normal (non-recycled) radio pulsars are indicated with the letter "y". References are to the latest mass measurements: 1. Deneva et al. (2013) 2. Martinez et al. (2015) 3. Kramer et al. (2006) 4. Fonseca, Stairs & Thorsett (2014) 5. Ferdman et al. (2014) 6. van Leeuwen et al. (2015) 7. Weisberg, Nice & Taylor (2010) 8. Jacoby et al. (2006) 9. Janssen et al. (2008) 10. Corongiu et al. (2007) 11. Champion et al. (2005) 12. Swiggum et al. (2015) 13. Bhat, Bailes & Verbiest (2008) 14. Antoniadis et al. (2011) 15. Thorsett & Chakrabarty (1999) 16. van Kerkwijk & Kulkarni (1999)

Figure 34: Özel and Freire - 2016

Table 3 Masses of Neutron Stars in High-Mass and Low-Mass X-ray Binaries

System	M_{NS} ($M_\odot$)	Error ($M_\odot$)	References
	Neutron Stars in High-Mass X-ray Binaries		
LMC X−4	1.57	0.11	1
Cen X−3	1.57	0.16	1
4U 1538−522	1.02	0.17	1
SMC X−1	1.21	0.12	1
SAX J1802.7−2017	1.57	0.25	1
XTE J1855−026	1.41	0.24	1
Vela X−1	2.12	0.16	1
EXO 1722−363	1.91	0.45	1
OAO 1657−415	1.74	0.30	1
Her X−1	1.07	0.36	1
	Neutron Stars in Low-Mass X-ray Binaries		
4U 1608−52	1.57	$^{+0.30}_{-0.29}$	2
4U 1724−207	1.81	$^{+0.25}_{-0.37}$	2
KS 1731−260	1.61	$^{+0.35}_{-0.37}$	2
EXO 1745−248	1.65	$^{+0.21}_{-0.31}$	2
SAX J1748.9−2021	1.81	$^{+0.25}_{-0.37}$	2
4U 1820−30	1.77	$^{+0.25}_{-0.28}$	2
Cyg X−2	1.90	$^{+0.22}_{-0.35}$	3

Notes. 1. See Falanga et al. (2015), Özel et al. (2012), Rawls et al. (2011), and references therein. We exclude 4U 1700−377, for which there is no evidence that it is a neutron star. 2. See Özel et al. (2015) for the latest constraints. 3. Orosz & Kuulkers (1999).

Figure 35: Özel and Freire - 2016

Table 2 Masses of Millisecond Pulsars

System	M_T ($M_\odot$)	M_{PSR} ($M_\odot$)	M_c ($M_\odot$)	Mass const.	Ref.
		MSPs with WD companions and low-eccentricity orbits			
J0348+0432		2.01(4)	0.172(3)	q, M_{WD}	Antoniadis et al. (2013)
J0437−4715		1.44(7)	0.224(7)	r, s	Reardon et al. (2016)
J0621+1002	2.32(8)	$1.53^{+0.10}_{-0.20}$	$0.76^{+0.28}_{-0.07}$	$\dot{\omega}, s$	Kasian (2012)
J0751+1807		1.72(7)	0.13(2)	$s, \dot{P}_b$	Desvignes et al. (2016)
J1012+5307		1.83(11)	0.16(2)	q, M_{WD}	Antoniadis et al. (2016)
J1614−2230		1.928(17)	0.500(6)	r, s	Fonseca et al. (2016)
J1713+0747		1.31(11)	0.286(12)	r, s	Zhu et al. (2015)
J1738+0333		$1.47^{+0.07}_{-0.06}$	$0.181^{+0.007}_{-0.005}$	q, M_{WD}	Antoniadis et al. (2012)
J1802−2124		1.24(11)	0.78(4)	r, s	Ferdman et al. (2010)
J1807−2500B	2.57190(73)	1.3655(21)	1.2064(20)(?)	$\dot{\omega}, h_3$	Lynch et al. (2012)
B1855+09		1.58^{+10}_{-13}	$0.267^{+0.010}_{-0.014}$	r, s	Splaver (2004)
J1909−3744		1.47(3)	0.2067(19)	r, s	Reardon et al. (2016)
J2222−0137		1.20(14)	1.05(6)	r, s	Kaplan et al. (2014a)
		MSPs with eccentric orbits and triples			
J0337+1715		1.4378(13)	0.19751(15) 0.4101(3)	i, q	Ransom et al. (2014); Kaplan et al. (2014b)
J1903+0327	2.697(29)	1.667(21)	1.029(8)	$\dot{\omega}, h_3$	Freire et al. (2011)
J1946+3417	2.097(28)	1.832(28)	0.2659(30)	$\dot{\omega}, h_3$	Barr et al. (2016)
J2234+0611	1.668(6)	1.393(13)	0.276(9)	$\dot{\omega}, h_3$	Stovall & et al. (2015)
		MSPs in globular clusters			
J0024−7204H	1.61(4)	< 1.52	> 0.164	$\dot{\omega}$	Freire et al. (2003)
J0514−4002A	2.453(14)	< 1.50	> 0.96	$\dot{\omega}$	Freire, Ransom & Gupta (2007)
B1516+02B	2.29(17)	< 2.52	> 0.13	$\dot{\omega}$	Freire et al. (2008a)
J1748−2021B	2.92(20)	< 3.24	> 0.11	$\dot{\omega}$	Freire et al. (2008b)
J1748−2446I	2.17(2)	< 1.96	> 0.24	$\dot{\omega}$	Ransom et al. (2005)
J1748−2446J	2.20(4)	< 1.96	> 0.38	$\dot{\omega}$	Ransom et al. (2005)
J1750−37A	1.97(15)	< 1.65	> 0.53	$\dot{\omega}$	Freire et al. (2008b)
B1802−07	1.62(7)	< 1.7	> 0.23	$\dot{\omega}$	Thorsett & Chakrabarty (1999)
J1824−2452C	1.616(7)	< 1.35	> 0.26	$\dot{\omega}$	Bégin (2006)
J1910-5958A		1.3(2)	0.180(18)	q, M_{WD}	Bassa et al. (2006); Cocozza et al. (2006)

Notes: J1807−2500B is located in the globular cluster NGC6544. A question mark indicates that the nature of the companion is uncertain. The total mass is indicated only when it is known more precisely than the masses of the components. References are to the latest mass measurements.

Figure 36: Özel and Freire - 2016

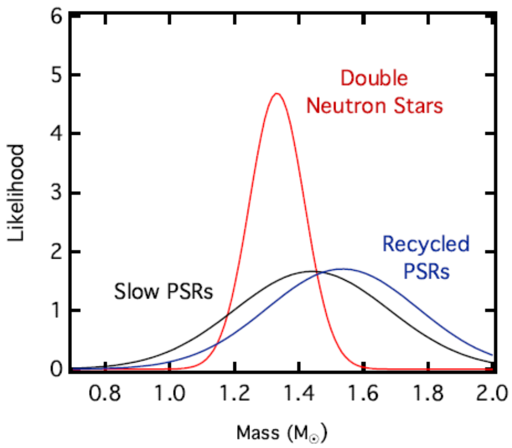

Figure 3

The inferred mass distributions for the different populations of neutron stars.

Figure 37: Özel and Freire - 2016

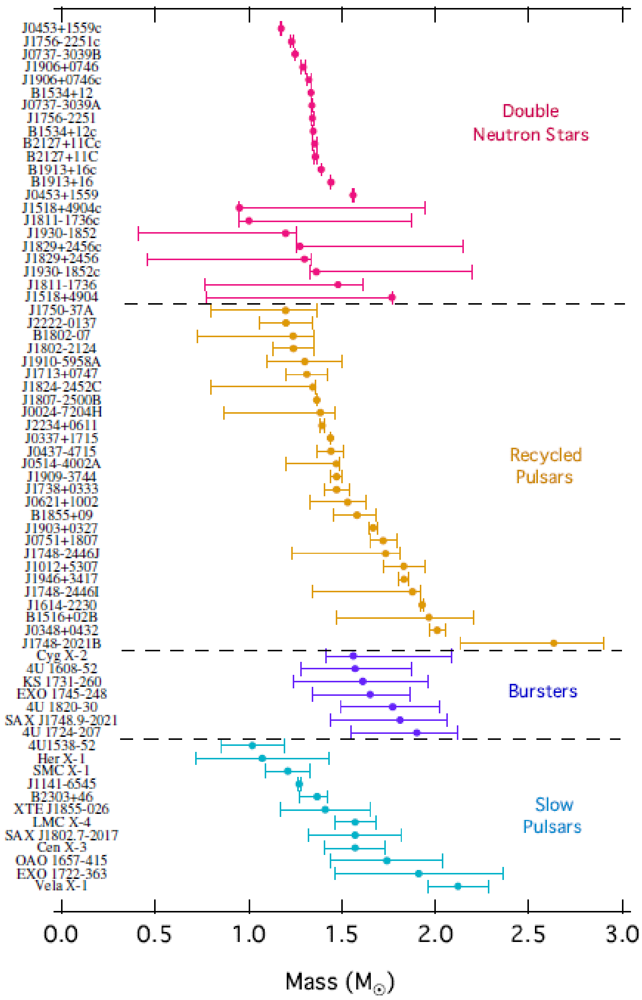

Figure 2

The most recent measurement of neutron star masses. Double neutron stars (magenta), recycled pulsars (gold), bursters (purple), and slow pulsars (cyan) are included.

Figure 38: Özel and Freire - 2016