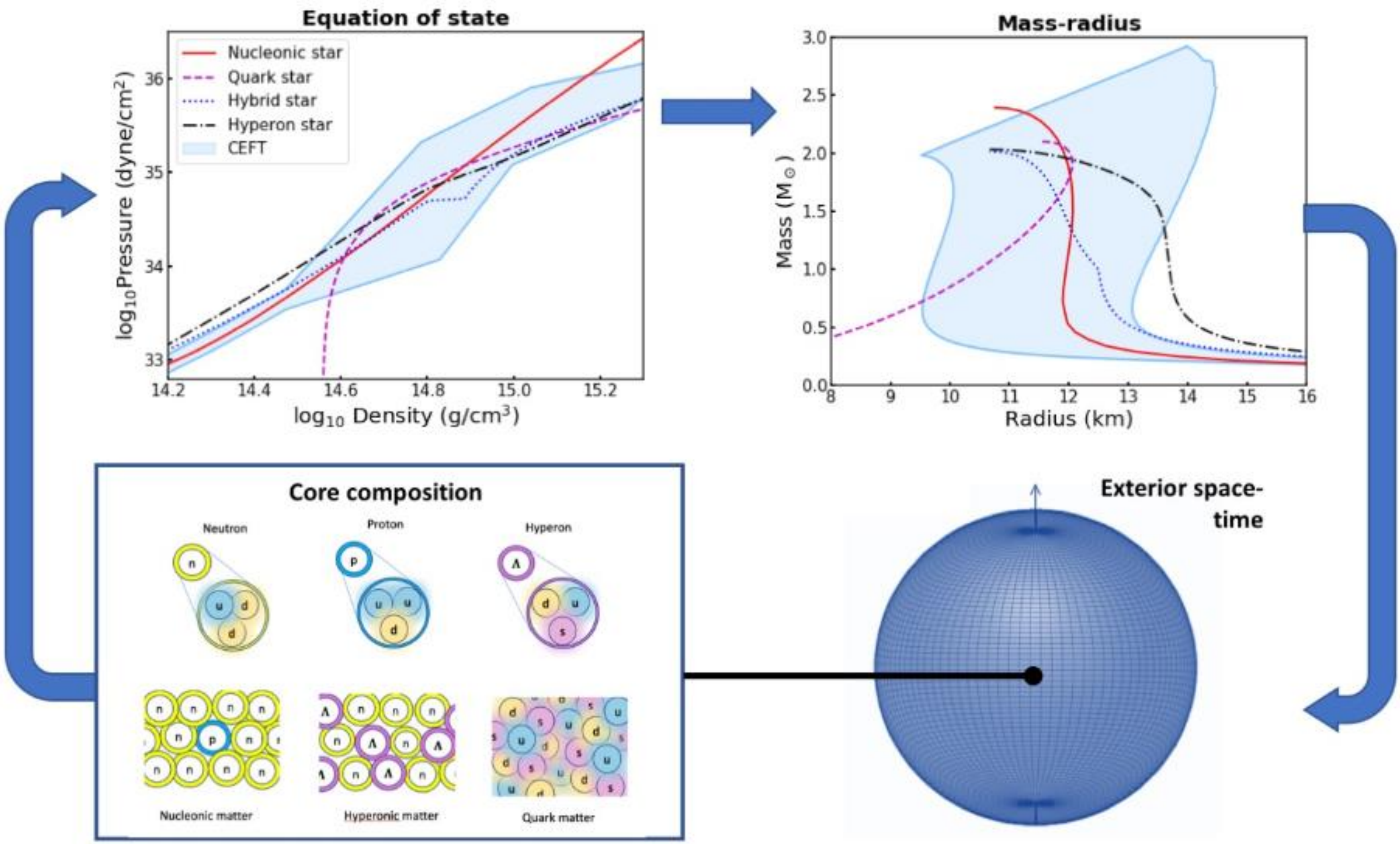
Neutron Star masses and radii

Why important?



1903.04648, a short review on M-R measurements related to EoS

NS Masses

- Stellar masses are directly measured in binary systems
- Accurate NS mass determination for PSRs in relativistic systems by measuring PK corrections
- Gravitational redshift may provide M/R in NSs by detecting a *known* spectral line,

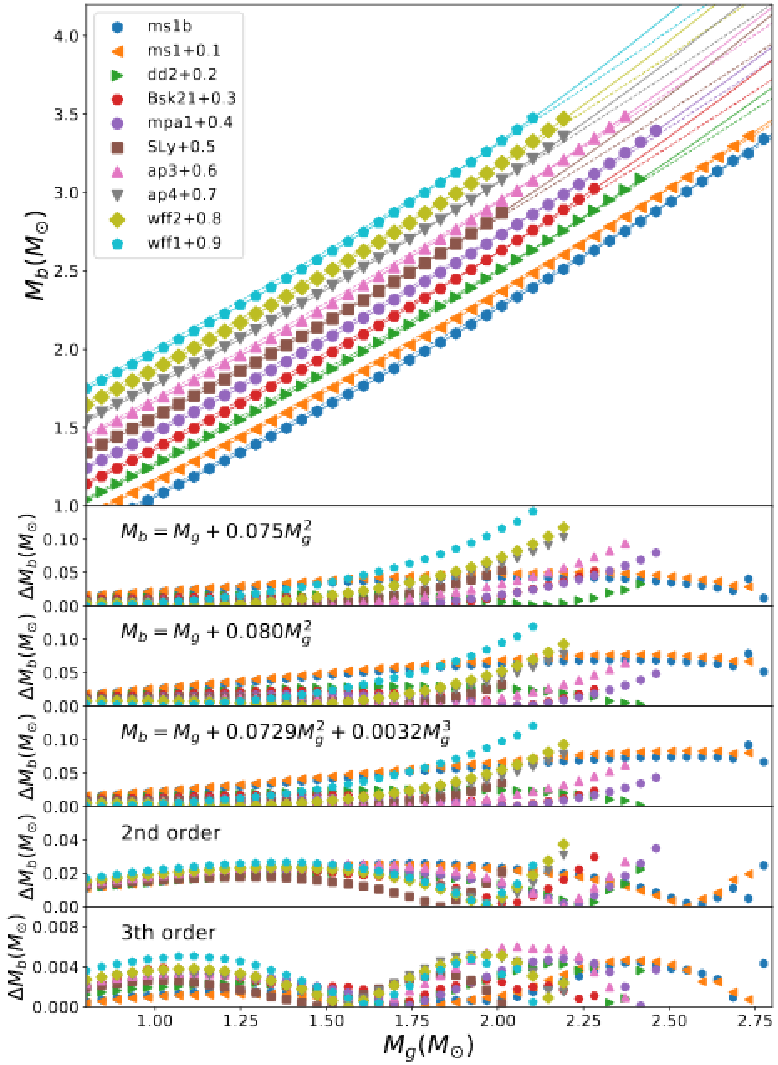
$E_\infty = E(1-2GM/Rc^2)^{1/2}$

Baryonic vs. gravitational

$$M_b = M_g + A_1 \times M_g^2 + A_2 \times M_g^3$$

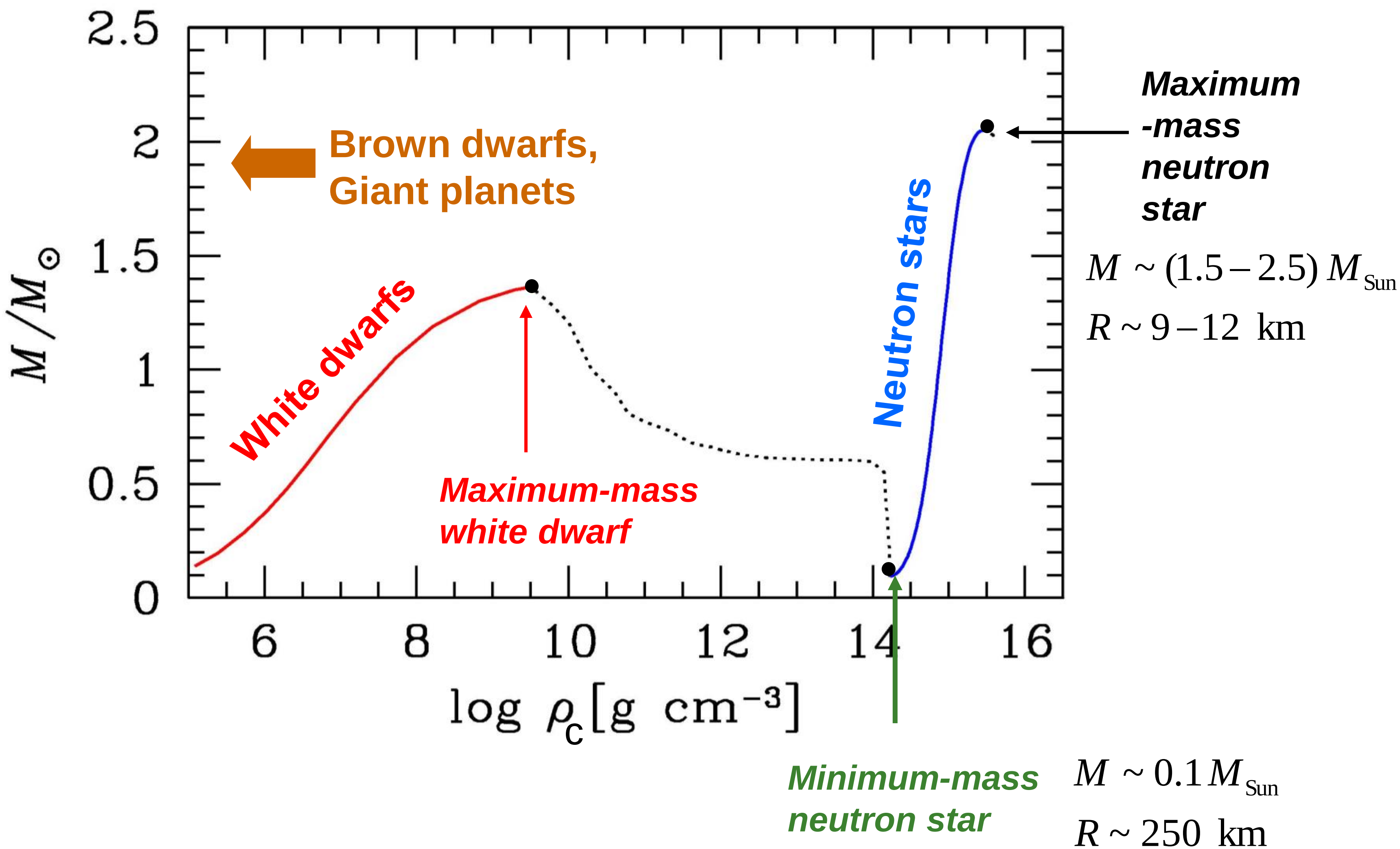
$$A_1\ 0.0729 \quad A_2\ 0.0032$$

$$M_b = M_g + R_{1.4}^{-1} \times M_g^2$$ here $R_{1.4}$ in km



1905.03784

Neutron stars and white dwarfs



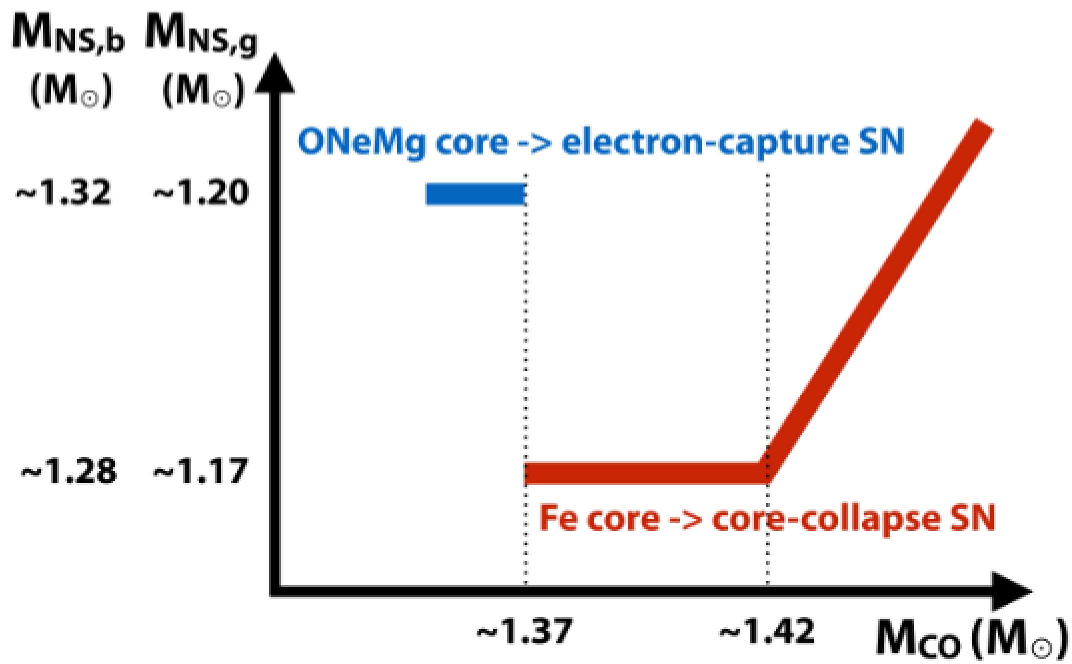
Remember about the difference between baryonic and gravitational masses in the case of neutron stars!

Minimal mass

In reality, the minimal mass is determined by properties of protoNSs.
Being hot, lepton rich they have much higher limit: about 0.7 solar mass.

Stellar evolution does not produce NSs with baryonic mass less than about 1.1-1.2 solar.

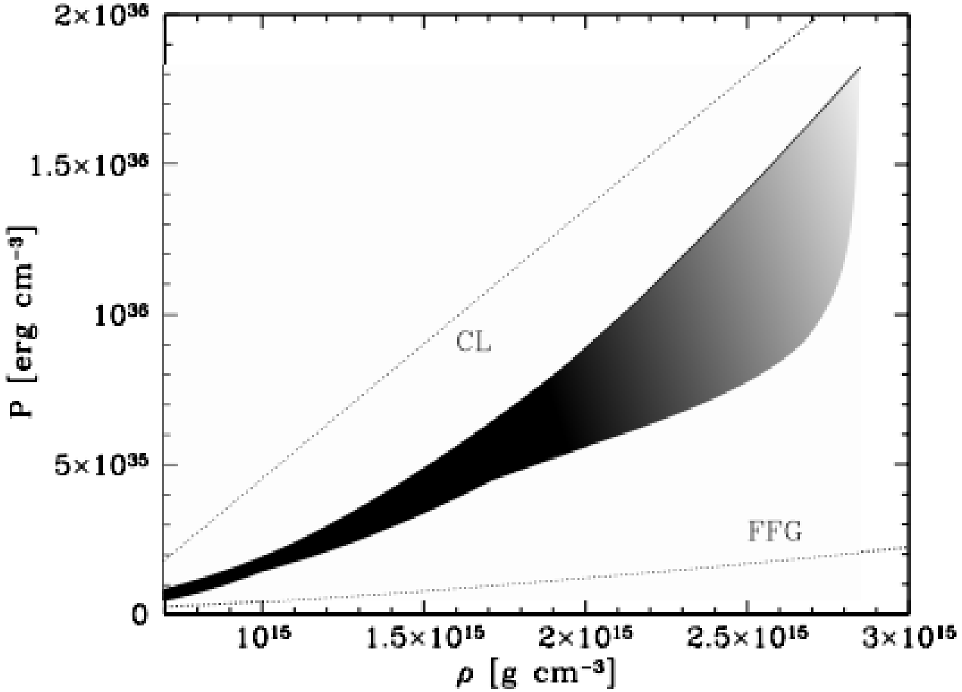
Fragmentation of a core due to rapid rotation potentially can lead to smaller masses, but not as small as the limit for cold NSs.

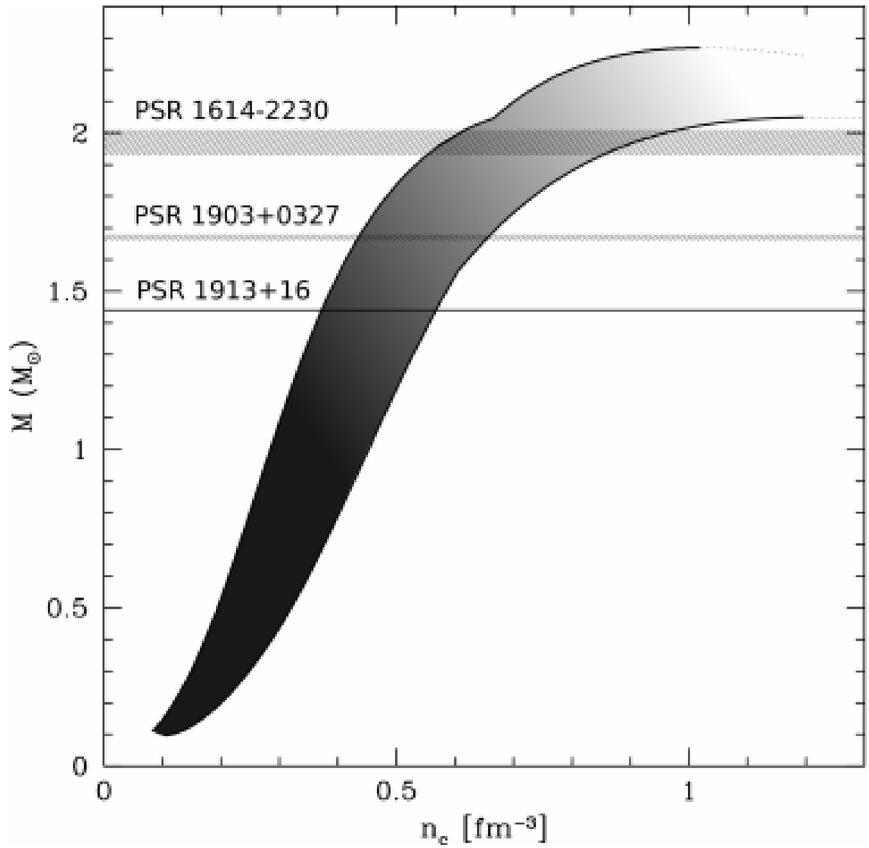


1808.02328

Maximum mass

Detailed discussion about the maximum mass is given in 1307.3995



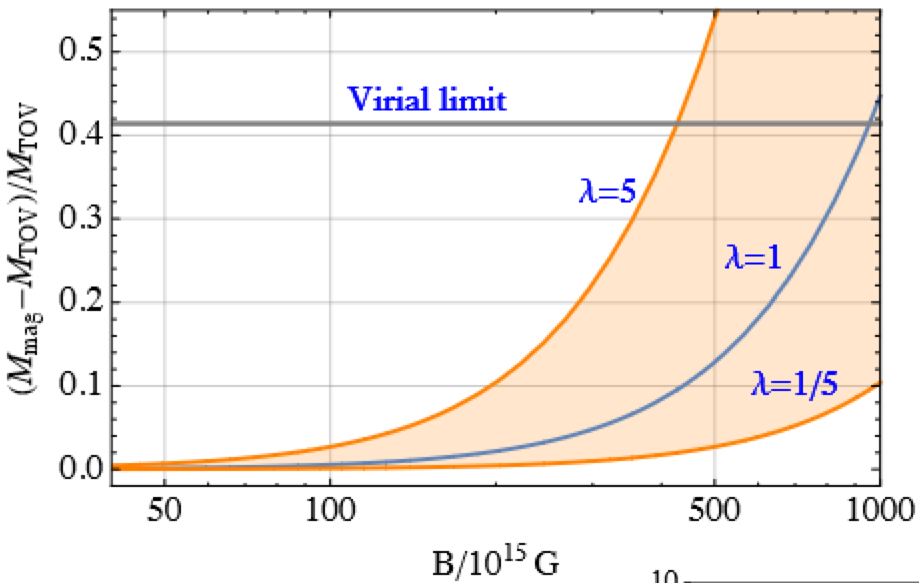


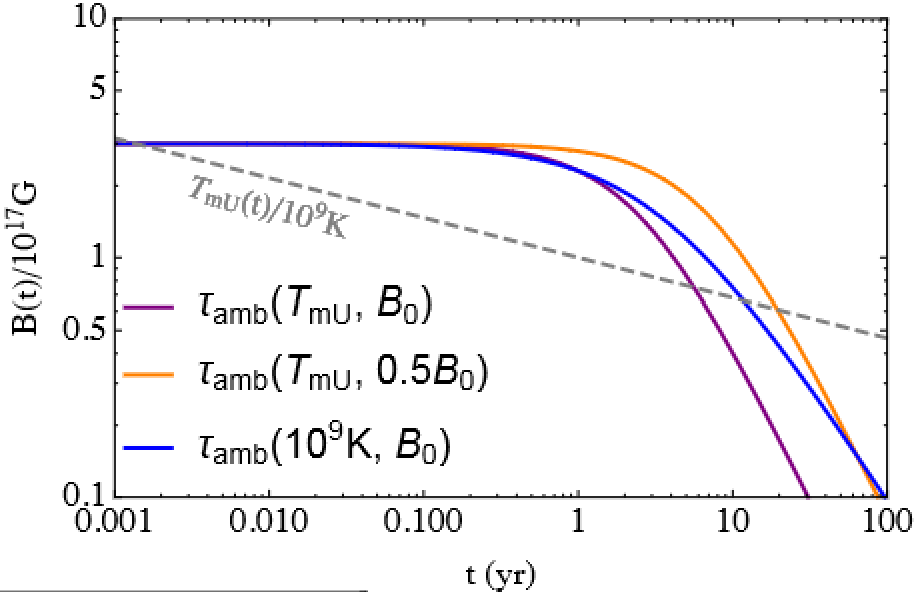
Correlations between macroscopic parameters for M-Mmax are discussed in 2005.03549

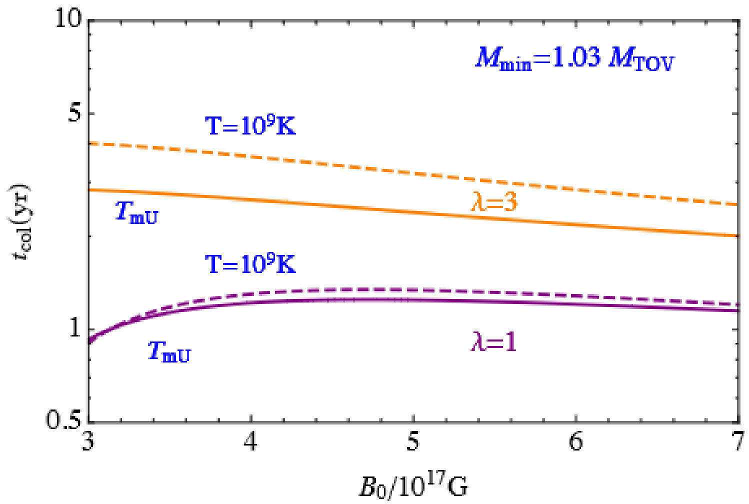
Supramassive magnetic NSs

$$\frac{M_{\rm mag}}{M_{\rm TOV}} = \left(1 + \frac{5\lambda}{18}\frac{B^2R^4}{GM_{\rm TOV}^2}\right)^{1/2}$$

$$B(t) = B_0\left(1 + \frac{t}{\tau_{\rm amb}}\right)^{-1}$$

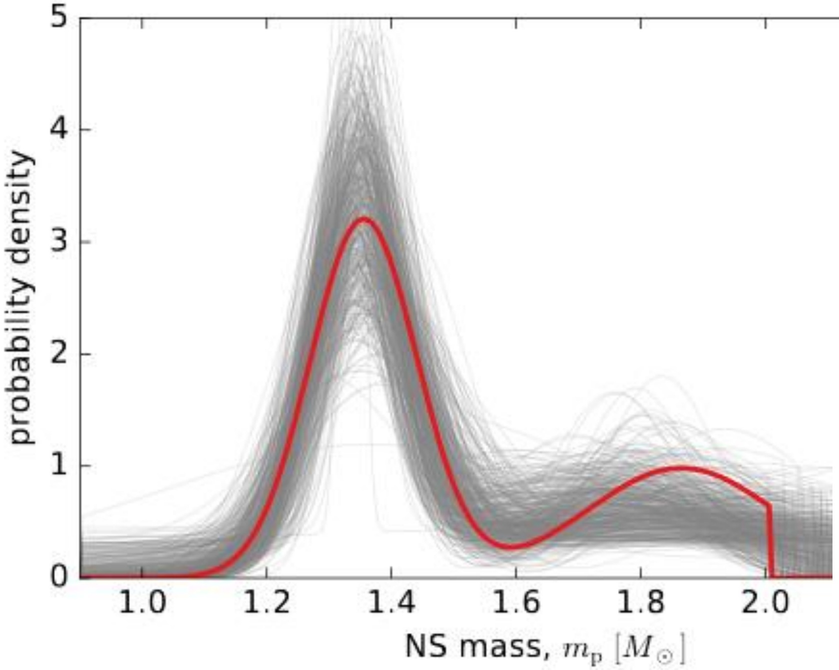




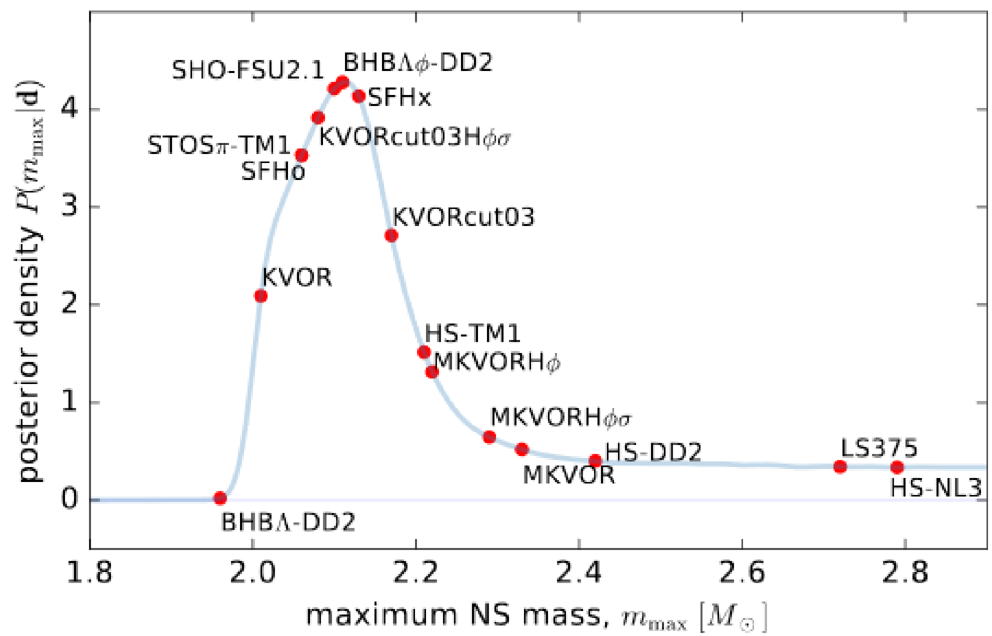


2109.08276

Maximum mass and cut-off

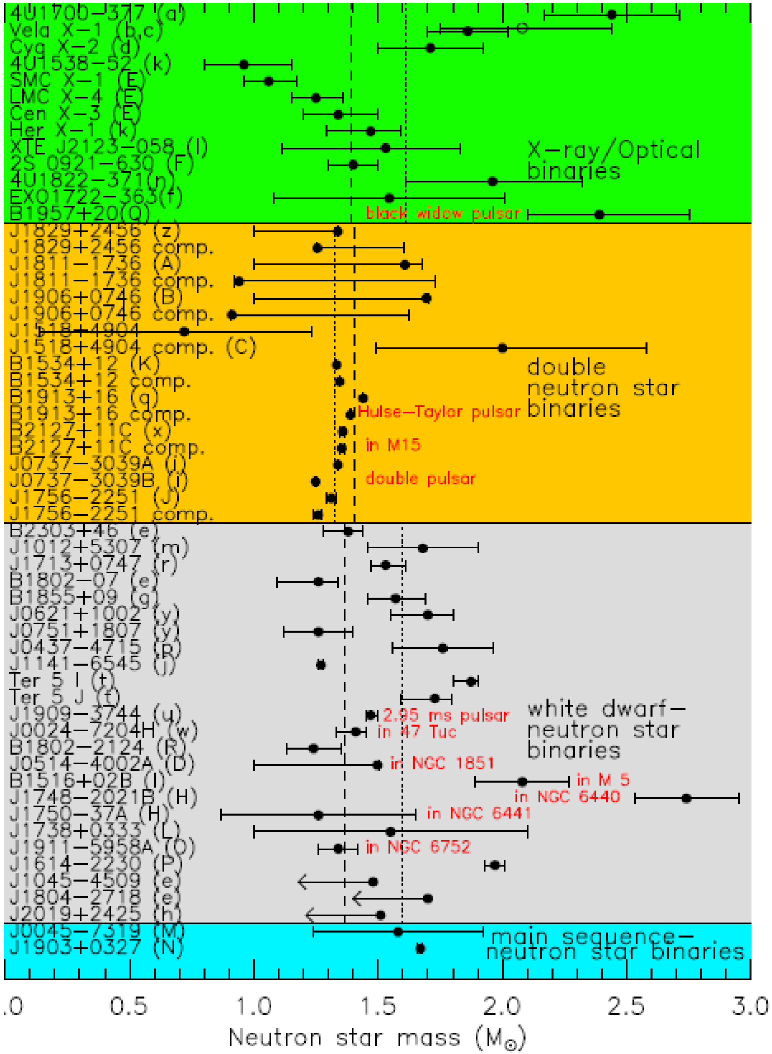


Two gaussians and a hard cut at Mmax



1709.07889

Neutron star masses

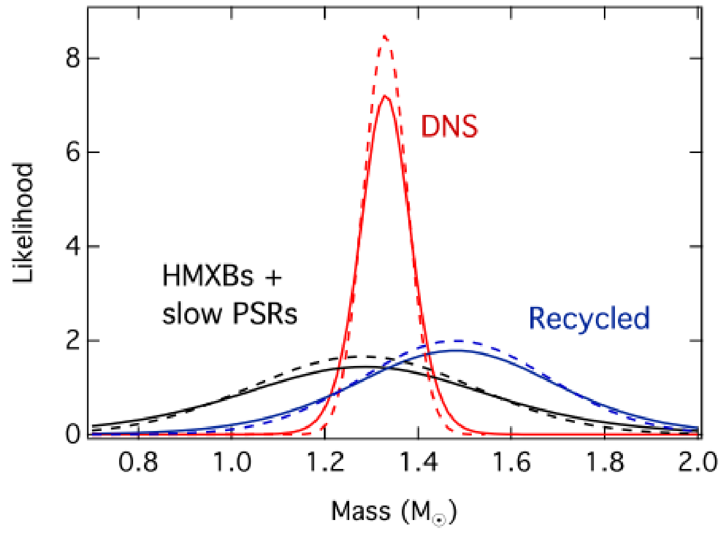


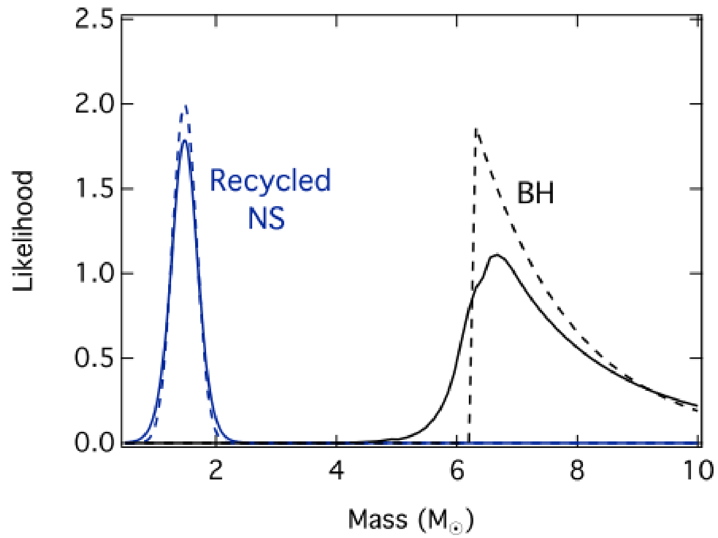
Object	Mass ($M_\odot$)	Reference	Object	Mass ($M_\odot$)	Reference
X-Ray/Optical Binaries (mean = 1.609 $M_\odot$, weighted mean = 1.393 $M_\odot$)					
4U1700-377	$2.44^{+0.27}_{-0.27}$	a (10)	Vela X-1	$1.86^{+0.16}_{-0.16}$	b, c (11, 12)
Cyg X-2	$1.71^{+0.21}_{-0.21}$	d (13)	4U1538-52	$0.96^{+0.19}_{-0.16}$	k (14)
SMC X-1	$1.06^{+0.11}_{-0.10}$	E (15)	LMC X-4	$1.25^{+0.11}_{-0.10}$	E (15)
Cen X-3	$1.34^{+0.16}_{-0.14}$	E (15)	Her X-1	$1.47^{+0.12}_{-0.18}$	k (14)
XTE J2123-058	$1.53^{+0.30}_{-0.42}$	l (16, 17)	2S 0921-630	$1.4^{+0.1}_{-0.1}$	F (18)
4U 1822-371	$1.96^{+0.36}_{-0.35}$	n (19)	EXO 1722-363	$1.545^{+0.465}_{-0.465}$	f (47)
B1957+20	$2.39^{+0.36}_{-0.29}$	Q (49)			
Neutron Star – Neutron Star Binaries (mean = 1.325 $M_\odot$, weighted mean = 1.403 $M_\odot$)					
J1829+2456	$1.338^{+0.002}_{-0.338}$	z (20)	J1829+2456 (c)	$1.256^{+0.346}_{-0.003}$	z (20)
J1811-1736	$1.608^{+0.066}_{-0.608}$	A (21)	J1811-1736 (c)	$0.941^{+0.787}_{-0.021}$	A (21)
J1906+07	$1.694^{+0.012}_{-0.694}$	B (22)	J1906+07 (c)	$0.912^{+0.710}_{-0.004}$	B (22)
J1518+4904	$0.72^{+0.51}_{-0.58}$	C (23)	J1518+4904 (c)	$2.00^{+0.58}_{-0.51}$	C (23)
1534+12	$1.3332^{+0.0010}_{-0.0010}$	K (24)	1534+12 (c)	$1.3452^{+0.0010}_{-0.0010}$	K (24)
1913+16	$1.4398^{+0.0002}_{-0.0002}$	q (25)	1913+16 (c)	$1.3886^{+0.0002}_{-0.0002}$	q (25)
2127+11C	$1.358^{+0.010}_{-0.010}$	x (26)	2127+11C (c)	$1.354^{+0.010}_{-0.010}$	x (26)
J0737-3039A	$1.3381^{+0.0007}_{-0.0007}$	i (27)	J0737-3039B	$1.2489^{+0.0007}_{-0.0007}$	i (27)
J1756-2251	$1.312^{+0.017}_{-0.017}$	J (28)	J1756-2251 (c)	$1.258^{+0.017}_{-0.017}$	J (28)
Neutron Star – White Dwarf Binaries (mean = 1.599 $M_\odot$, weighted mean = 1.362 $M_\odot$)					
B2303+46	$1.38^{+0.06}_{-0.10}$	e (29)	J1012+5307	$1.68^{+0.22}_{-0.22}$	m (30)
J1713+0747	$1.53^{+0.08}_{-0.04}$	r (31, 51)	B1802-07	$1.26^{+0.08}_{-0.17}$	e (29)
B1855+09	$1.57^{+0.12}_{-0.11}$	g (32, 51)	J0621+1002	$1.70^{+0.10}_{-0.17}$	y (33)
J0751+1807	$1.26^{+0.14}_{-0.14}$	y (33)	J0437-4715	$1.76^{+0.20}_{-0.20}$	p (34)
J1141-6545	$1.27^{+0.01}_{-0.01}$	j (35)	Ter 5 I	$1.874^{+0.32}_{-0.068}$	t (36)
Ter 5 J	$1.728^{+0.066}_{-0.136}$	t (36)	J1909-3744	$1.47^{+0.03}_{-0.02}$	u (37)
J0024-7204H	$1.41^{+0.04}_{-0.08}$	w (38)	B1802-2124	$1.24^{+0.11}_{-0.11}$	R (50)
J0514-4002A	$1.497^{+0.008}_{-0.497}$	D (39)	B1516+02B	$2.08^{+0.19}_{-0.19}$	I (40)
J1748-2021B	$2.74^{+0.21}_{-0.21}$	H (41)	J1750-37A	$1.26^{+0.39}_{-0.39}$	H (41)
J1738+0333	$1.55^{+0.55}_{-0.55}$	L (42)	J1911-5958A	$1.34^{+0.08}_{-0.08}$	O (43)
J1614-2230	$1.97^{+0.04}_{-0.04}$	P (48)	J1045-4509	< 1.48	e (29)
J1804-2718	< 1.70	e (29)	J2019+2425	< 1.51	h (44)
Neutron Star – Main Sequence Binaries					
J0045-7319	$1.58^{+0.34}_{-0.34}$	M (45)	J1903+0327	$1.67^{+0.01}_{-0.01}$	N (46)

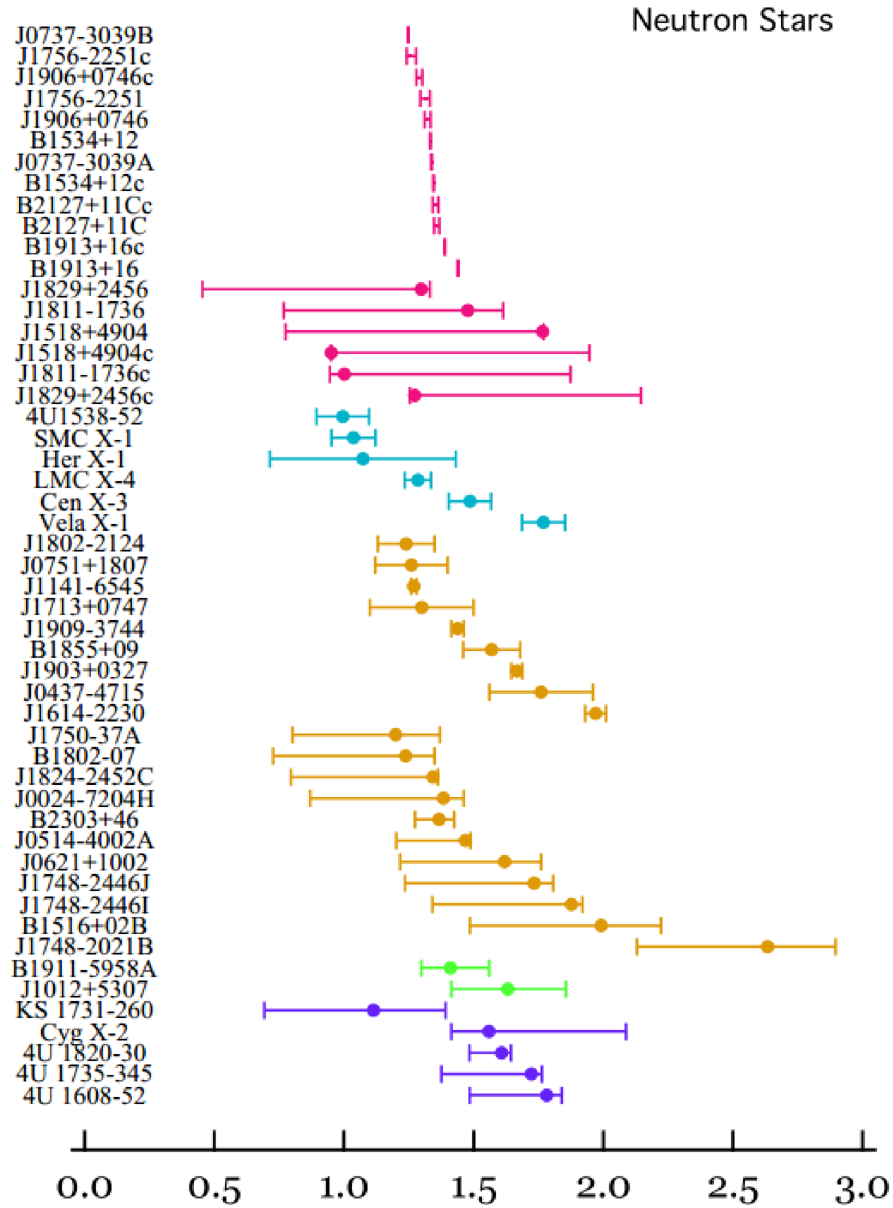
Follow updates at https://stellarcollapse.org/nsmasses

arXiv: 1012.3208

Update - 2012

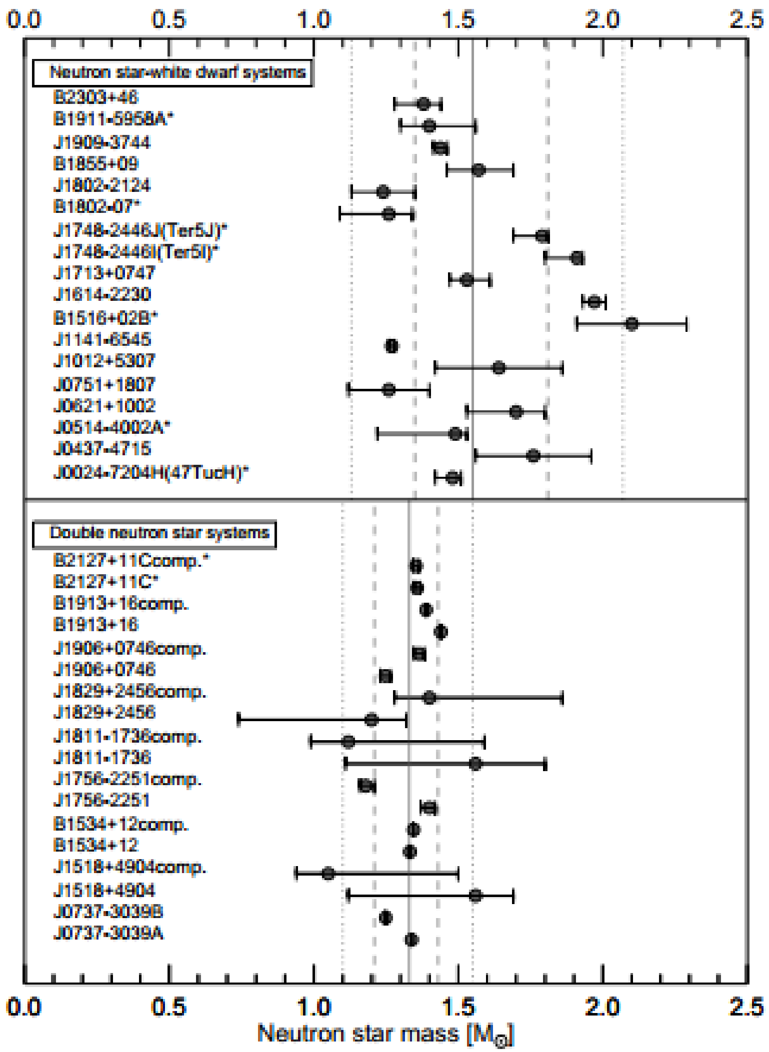


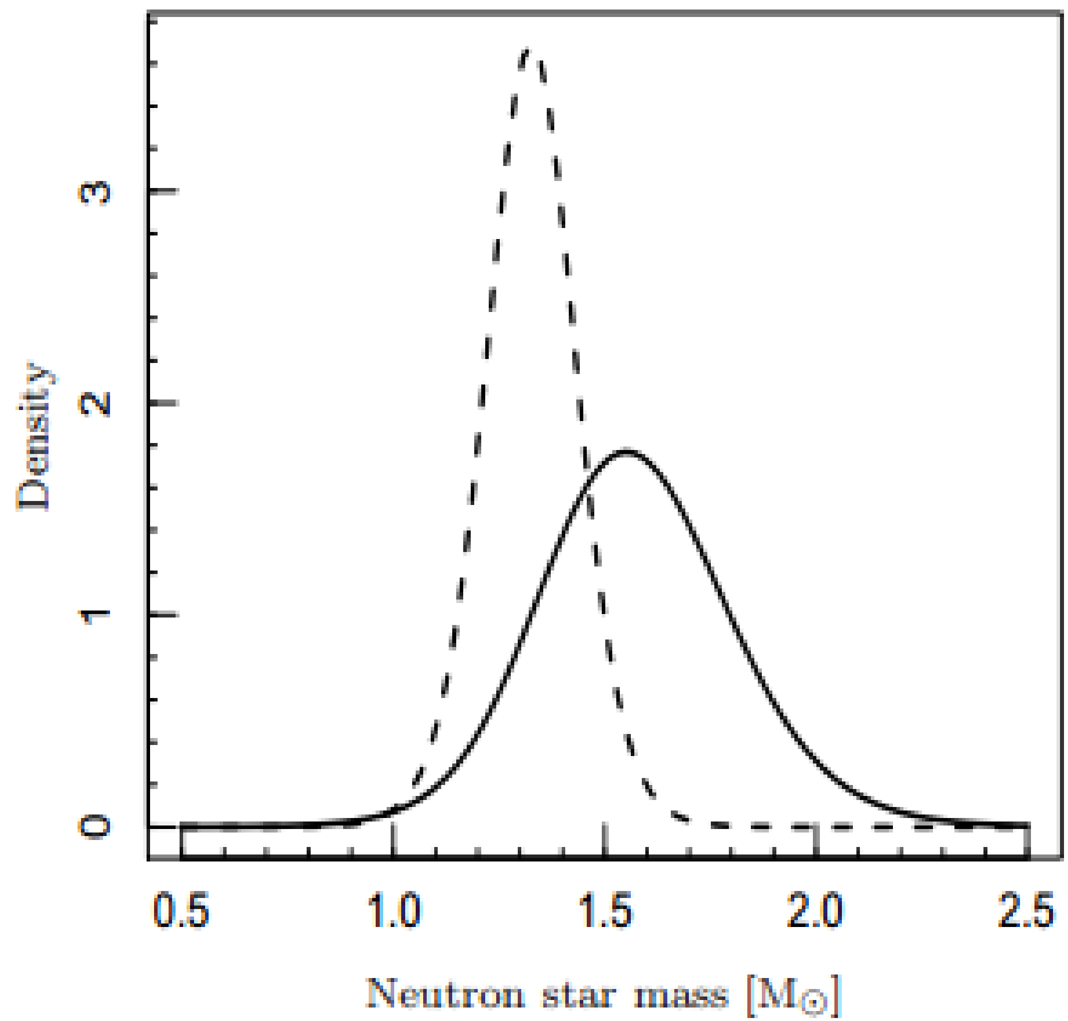




1201.1006

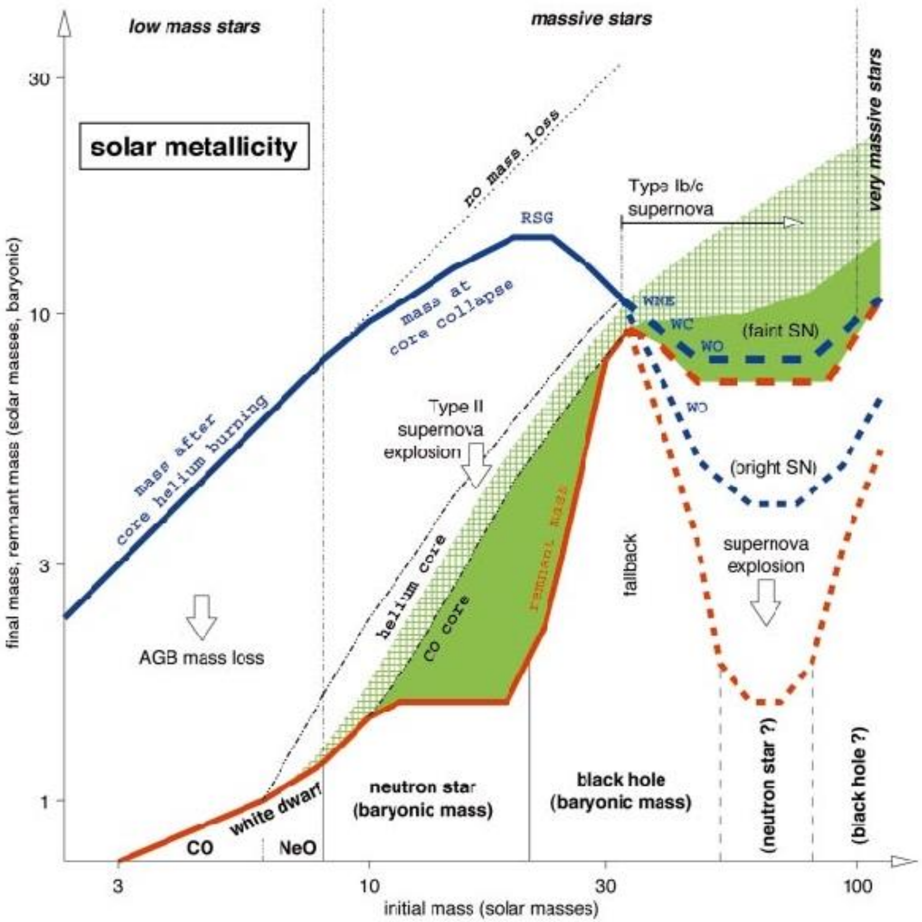
Update - 2013





1309.6635

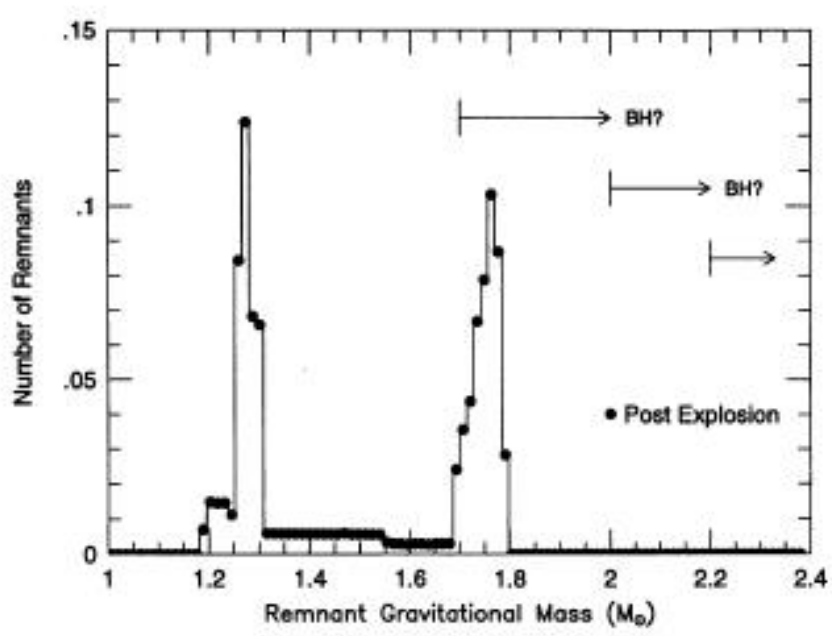
Compact objects and progenitors. Solar metallicity.



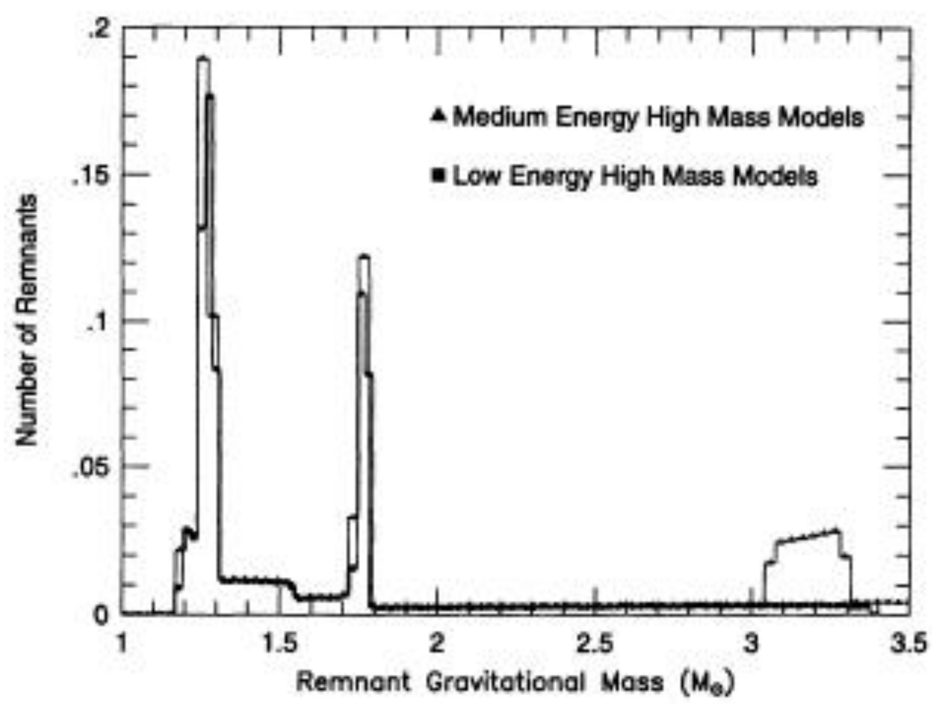
There can be a range of progenitor masses in which NSs are formed, however, for smaller and larger progenitors masses BHs appear.

Woosley et al. 2002

Mass spectrum of compact objects

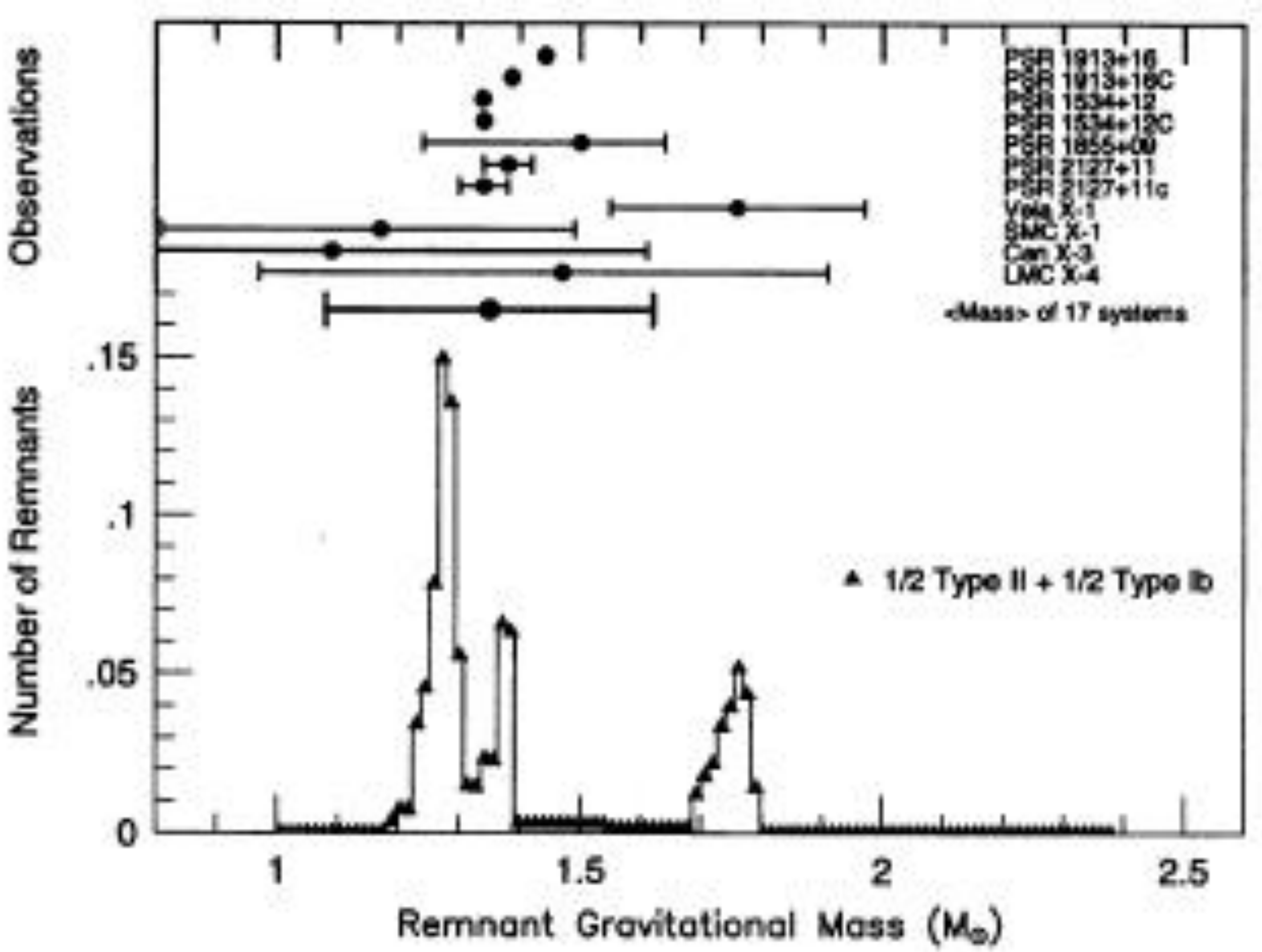


Results of calculations
(depend on the assumed model
of explosion)



Timmes et al. 1996, astro-ph/9510136

Mass spectrum of compact objects

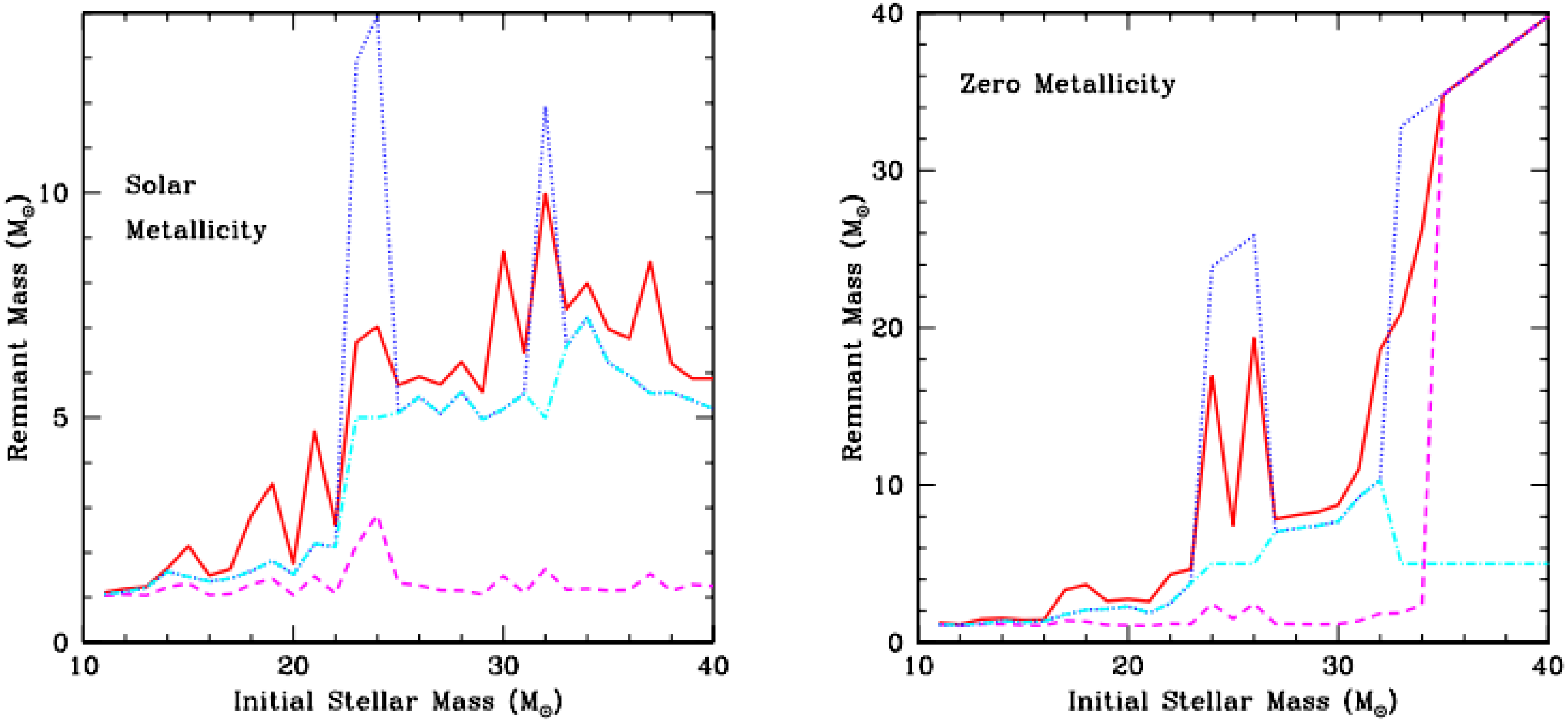


Comparison of one of the model with observations.

However, selection effects can be important as observed NSs a all in binaries.

Timmes et al. 1996, astro-ph/9510136

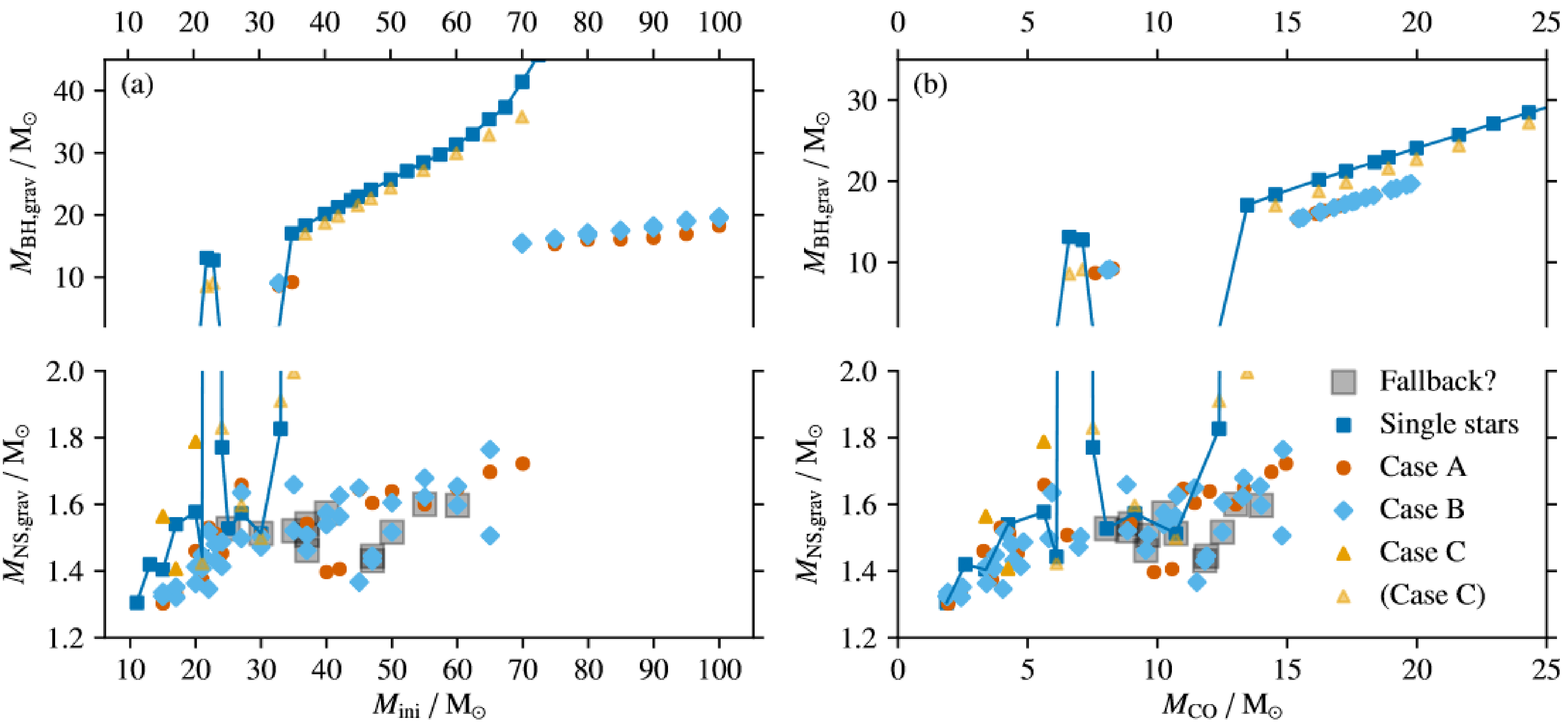
Newer calculations of the mass spectrum



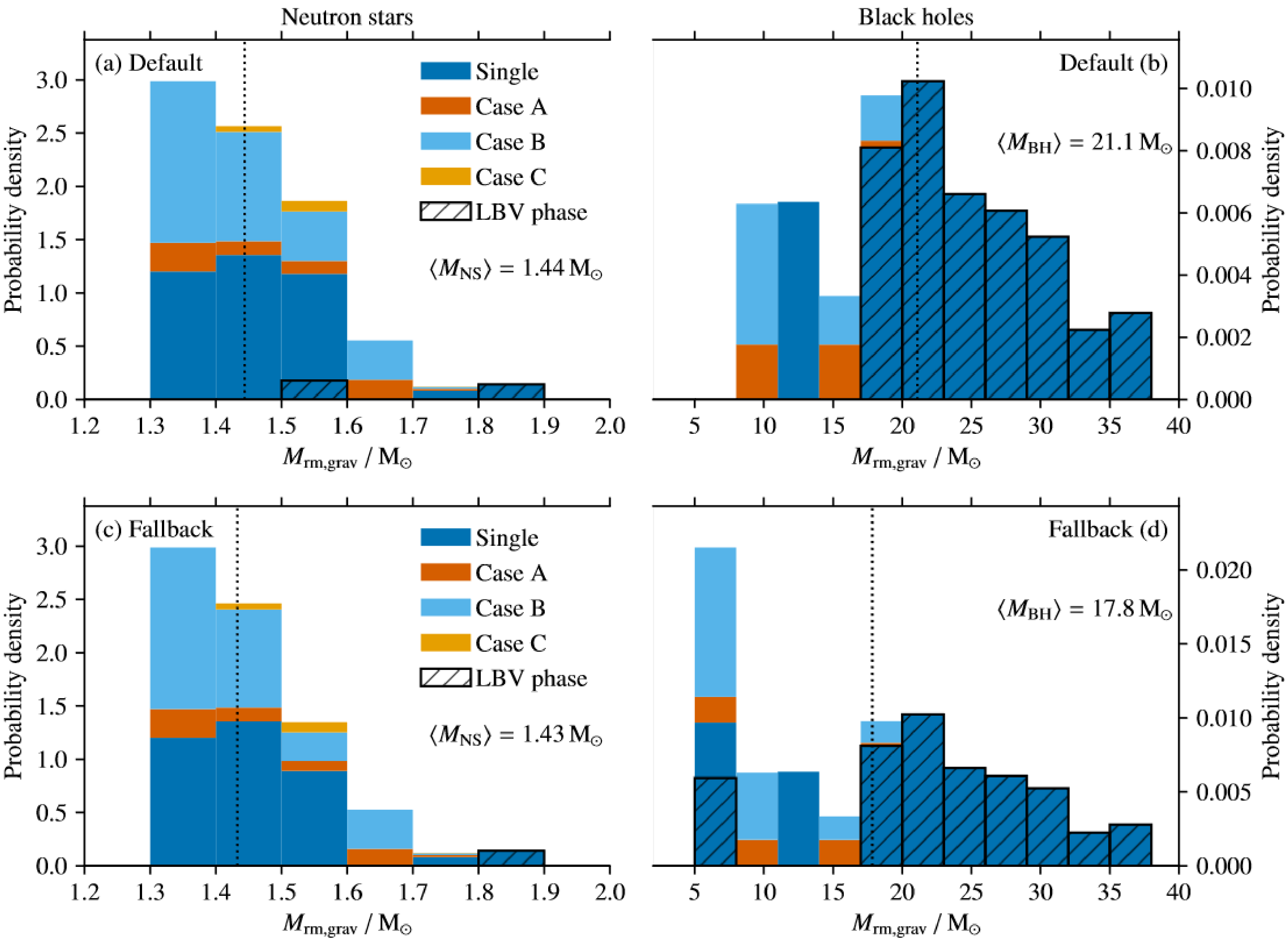
Different curves are plotted for different models of explosion:
dashed – with a magnetar

1110.1726

Role of binaries



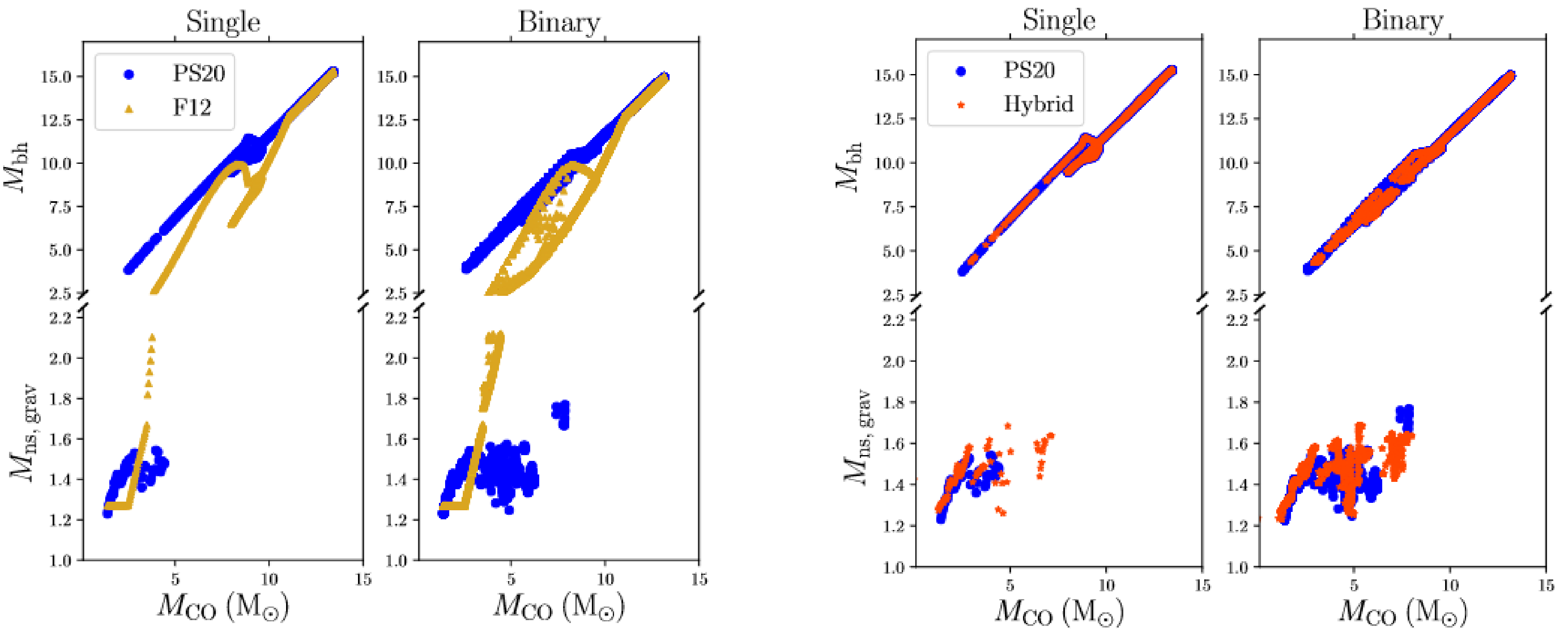
2008.08599



Neutron stars
Black holes
(a) Default
Single
Case A
Case B
Case C
LBV phase
⟨M_{NS}⟩ = 1.44 $M_\odot$
Default (b)
⟨M_{BH}⟩ = 21.1 $M_\odot$
(c) Fallback
⟨M_{NS}⟩ = 1.43 $M_\odot$
Fallback (d)
⟨M_{BH}⟩ = 17.8 $M_\odot$
Probability density
$M_{rm,grav}$ / $M_\odot$

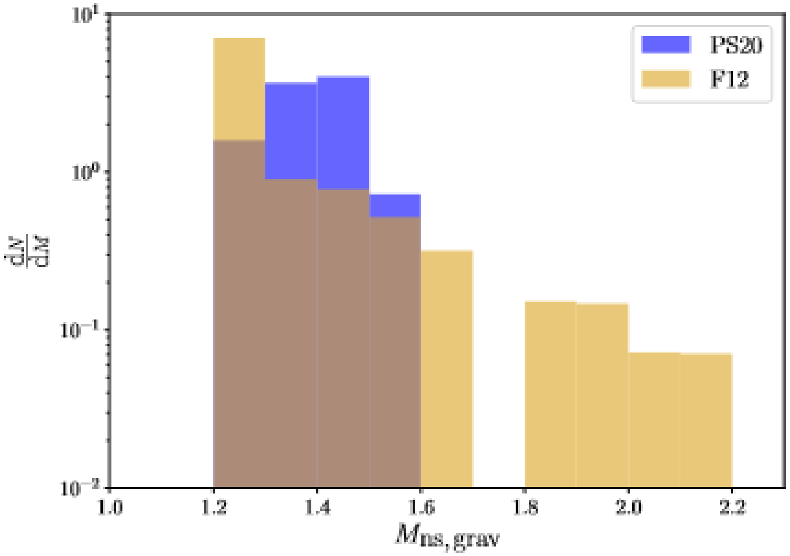
2008.08599

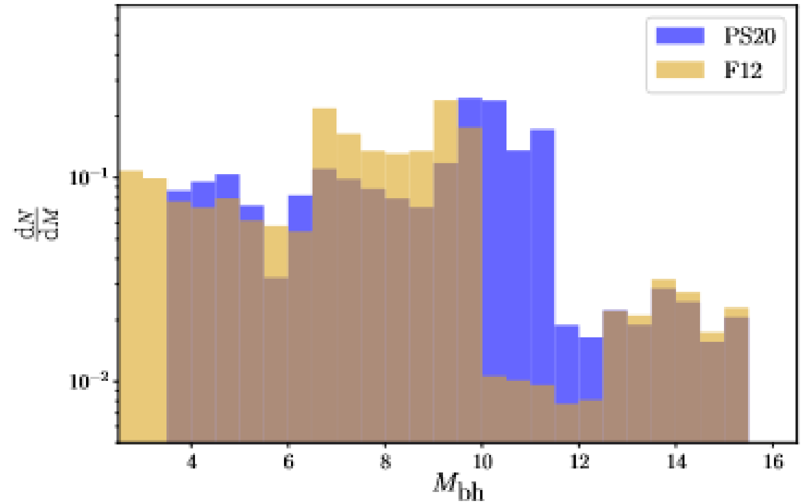
Comparison of different prescriptions

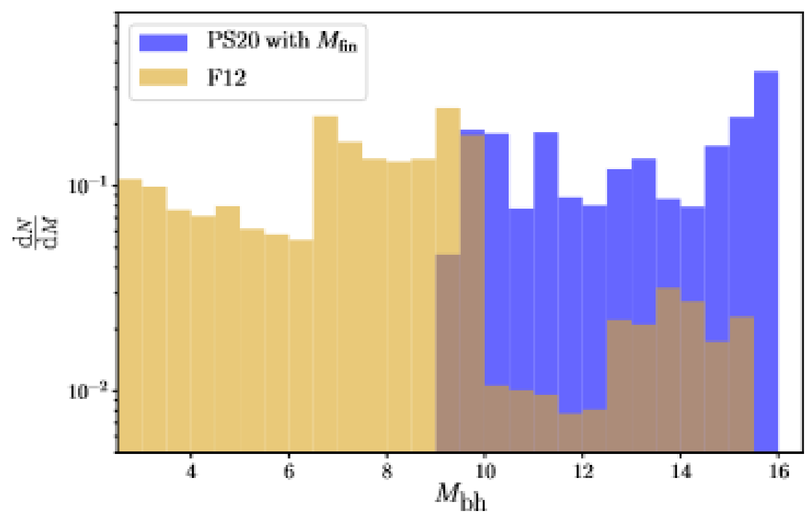


2106.05978

Comparison of different prescriptions. Single stars

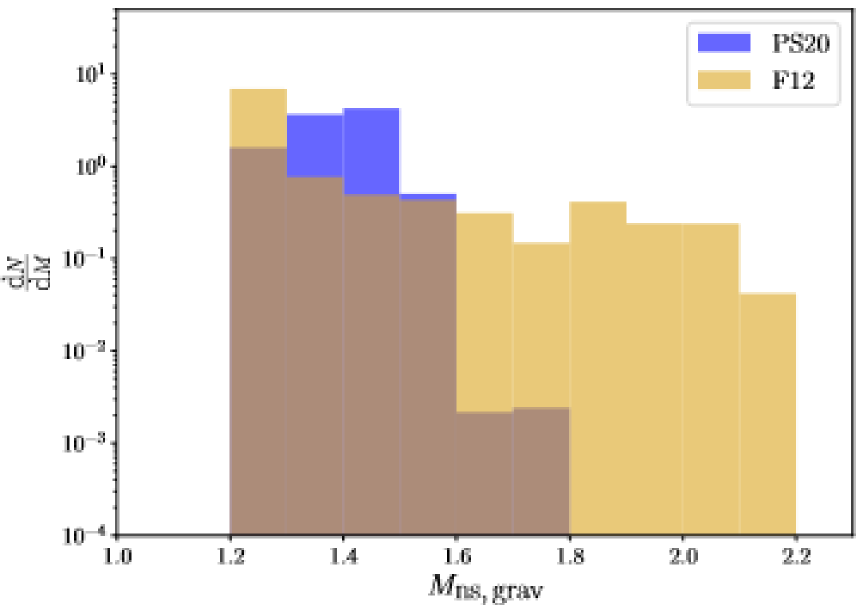


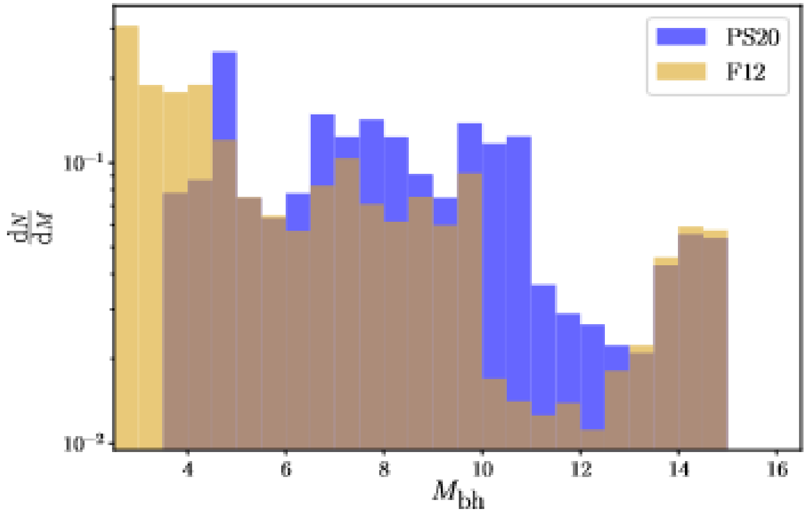


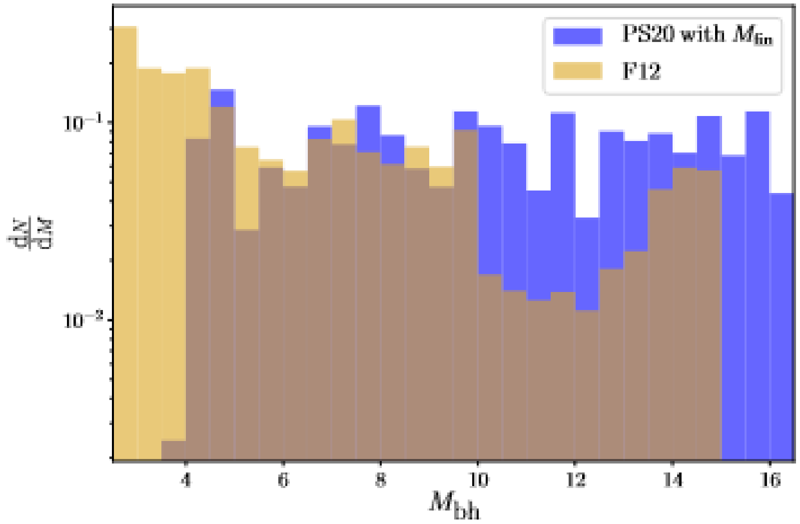


2106.05978

Comparison of different prescriptions. Binary stars.





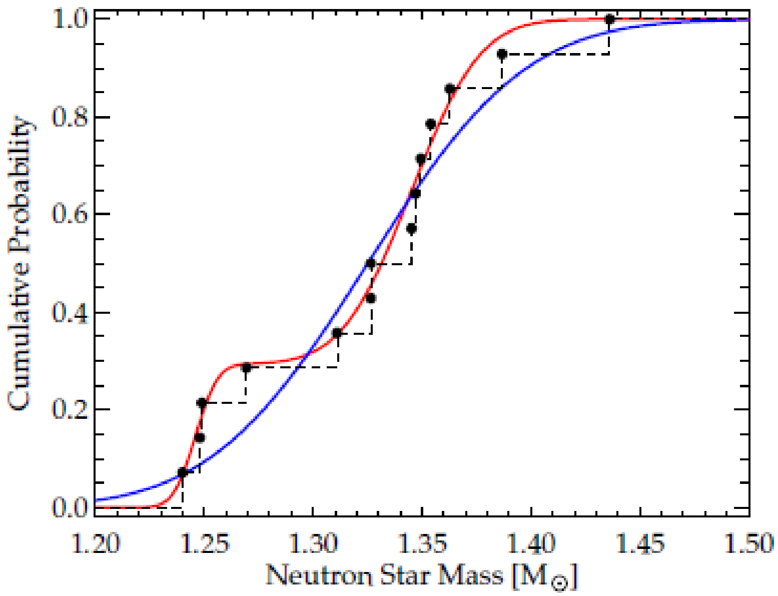


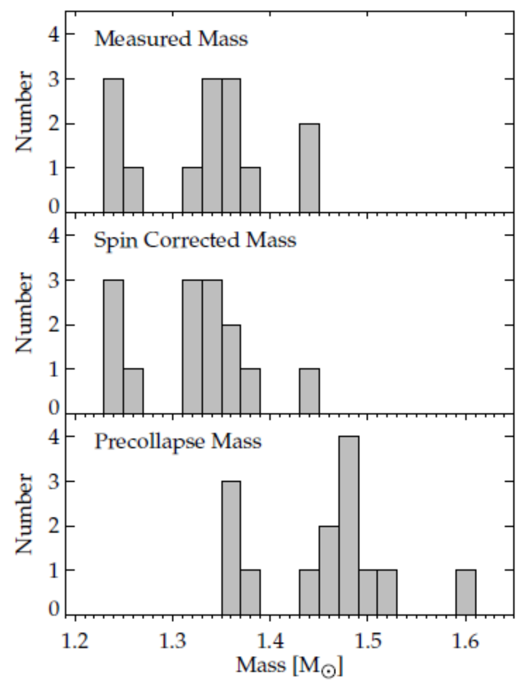
2106.05978

Bi-modal mass spectrum?

Pulsar Name	Mass of Recycled Neutron Star ($M_\odot$)	Mass of Young Neutron Star ($M_\odot$)	P_{orb} (hours)	Eccentricity	Pulse Period (ms)	Reference
J0737-3039A/B	1.3381 ± 0.0007	1.2489 ± 0.0007	2.4	0.088	23	Kramer et al. (2006)
B1534+12	1.3332 ± 0.0010	1.3452 ± 0.0010	10.1	0.273	38	Stairs et al. (2002)
J1756-2251	1.32 ± 0.02	1.24 ± 0.02	7.67	0.18	28	Stairs (2008)
J1906+0746	1.365 ± 0.018	1.248 ± 0.018	3.98	0.085	144†	Kasian (2008)
B1913+16	1.4414 ± 0.0002	1.3867 ± 0.0002	7.92	0.617	59	Weisberg & Taylor (2005)
B2127+11C	1.358 ± 0.010	1.354 ± 0.010	8.05	0.681	30	Jacoby et al. (2006)
J1909-3744	1.438 ± 0.024	white dwarf	36.7	$\lesssim 10^{-6}$	2.9	Jacoby et al. (2005)
J1141-6545	white dwarf	1.27 ± 0.01	4.74	0.172	393†	Bhat et al. (2008)

The low-mass peak the authors relate to e⁻-capture SN.

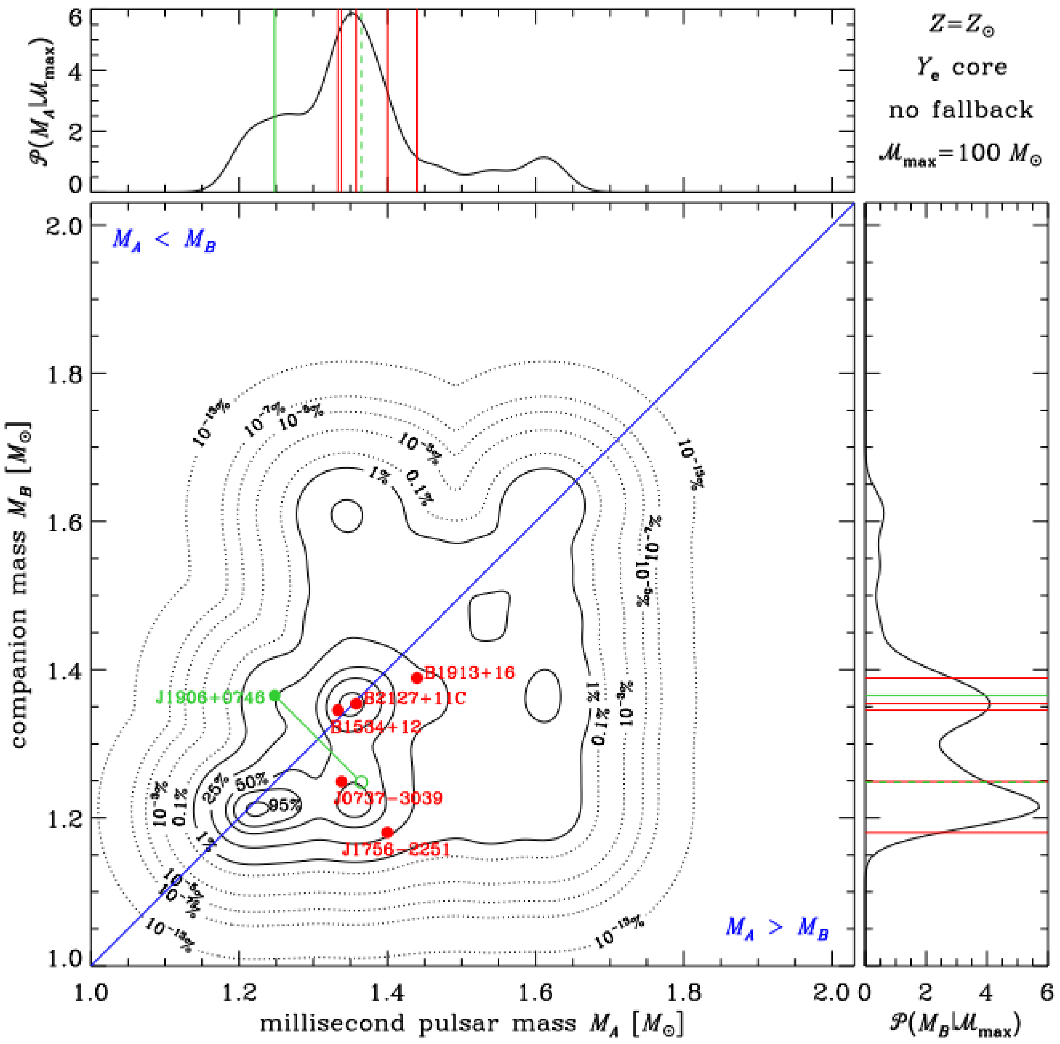




Based on 14 observed systems

1006.4584

Comparison of observations with theory

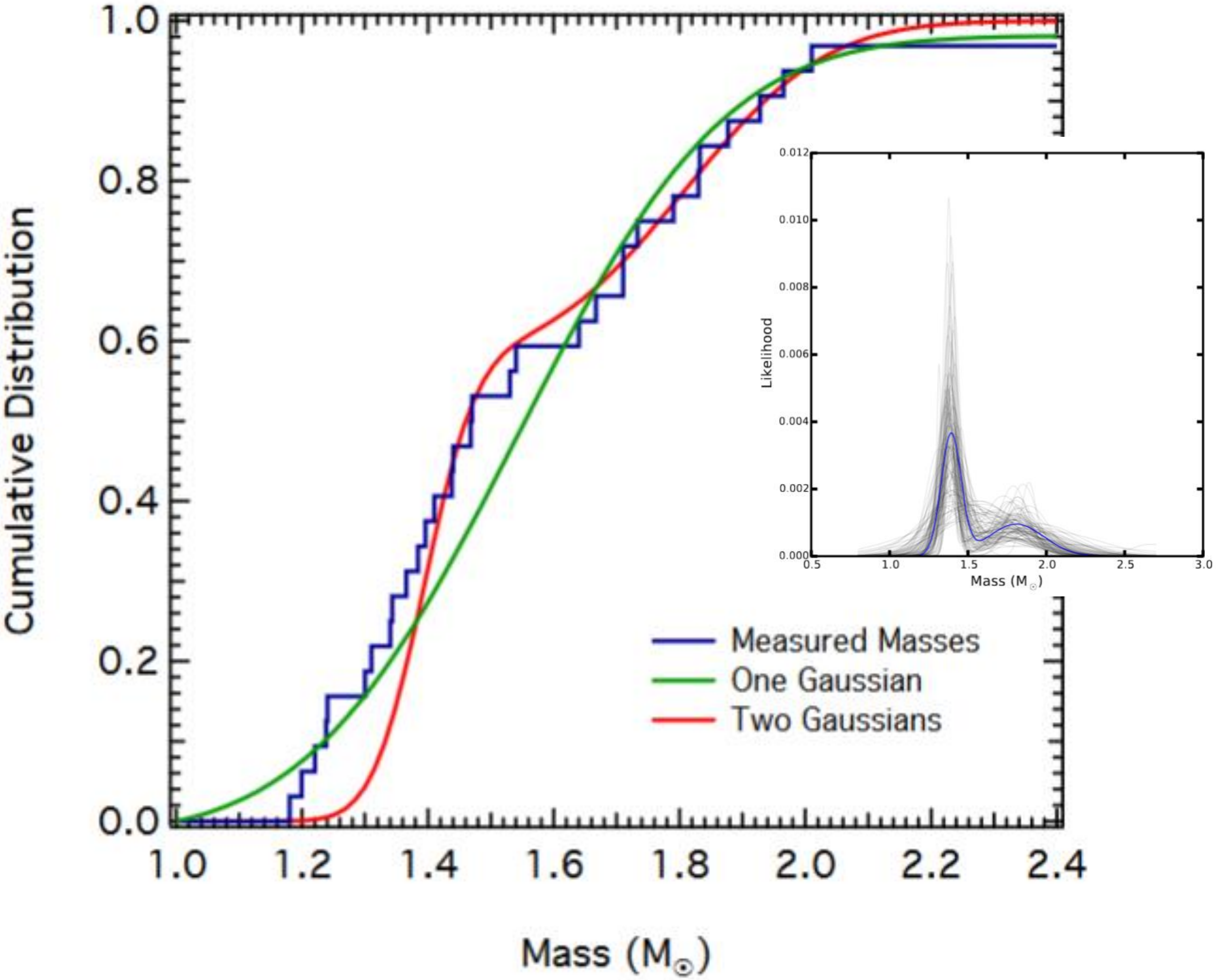


1204.5478

Bimodality in mPSR mass distribution

#	PSR Name	Mass [$M_\odot$]
1	J0337+1715	1.4378(13)
2	J0348+0432	2.01(4)
3	J0437−4715	1.44(7)
4	J0751+1807	1.64(15)
5	J1012+0507	1.83(11)
6	J1023+0038	1.71(16)
7	J1614−2230	1.928(17)
8	J1713+0747	1.31(11)
9	J1738+0333	1.47(7)
10	J1802−2124	1.24(11)
11	J1807−2500B	1.3655(21)
12	B1855+09	1.30(11)
13	J1903+0327	1.667(7)
14	J1909−3744	1.540(27)
15	J1910−5959A	1.34(8)
16	J1918−0642	1.18(11)
17	J1946+3417	1.832(13)
18	J2234+0611	1.396(11)

+ 14 PSR with less precisely determined masses



The bimodality reflects birth properties?

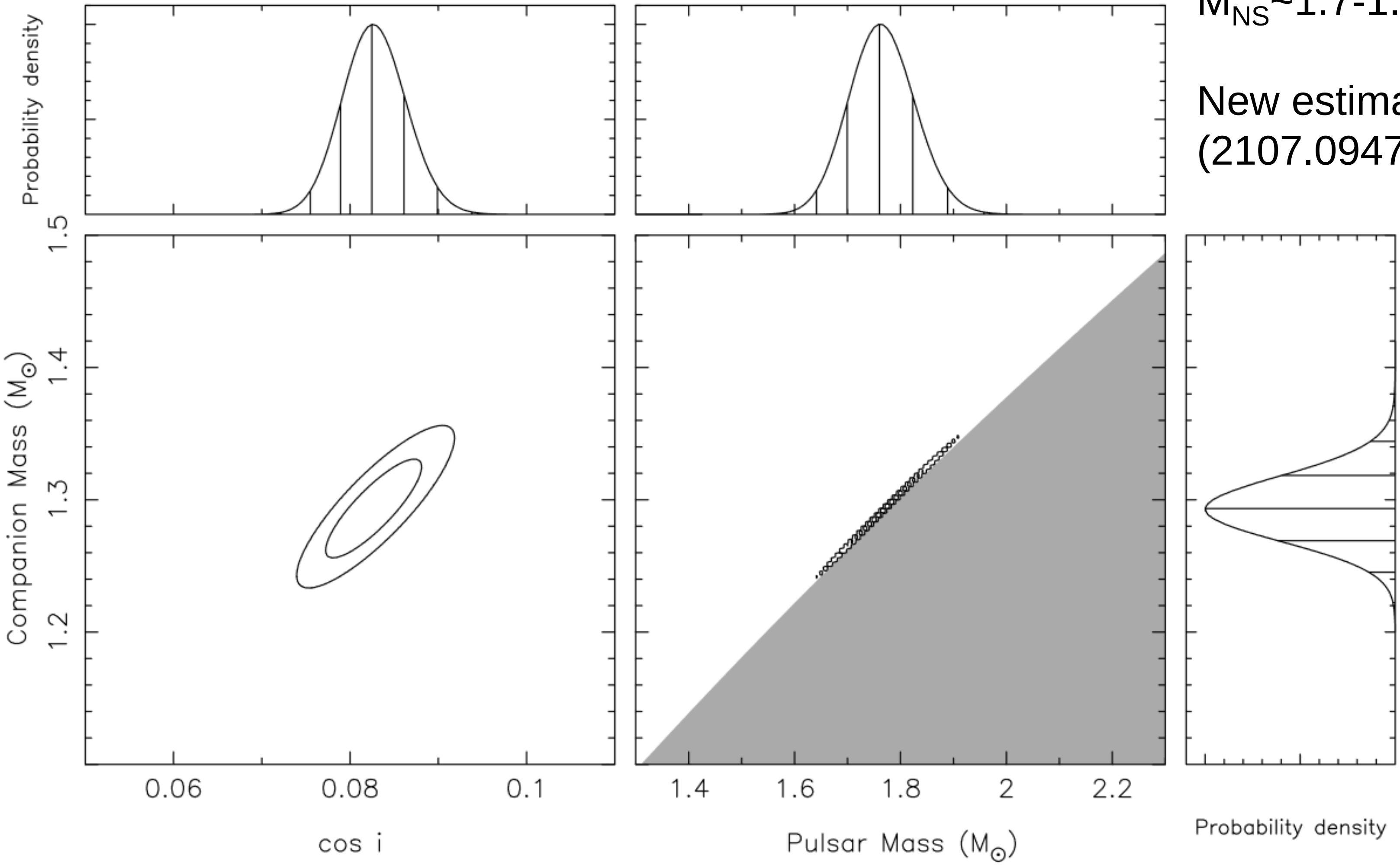
1605.01665

Massive born NS

PSR J2222−0137
WD companion
P=32.8 msec
M_{NS}~1.7-1.8 Msun

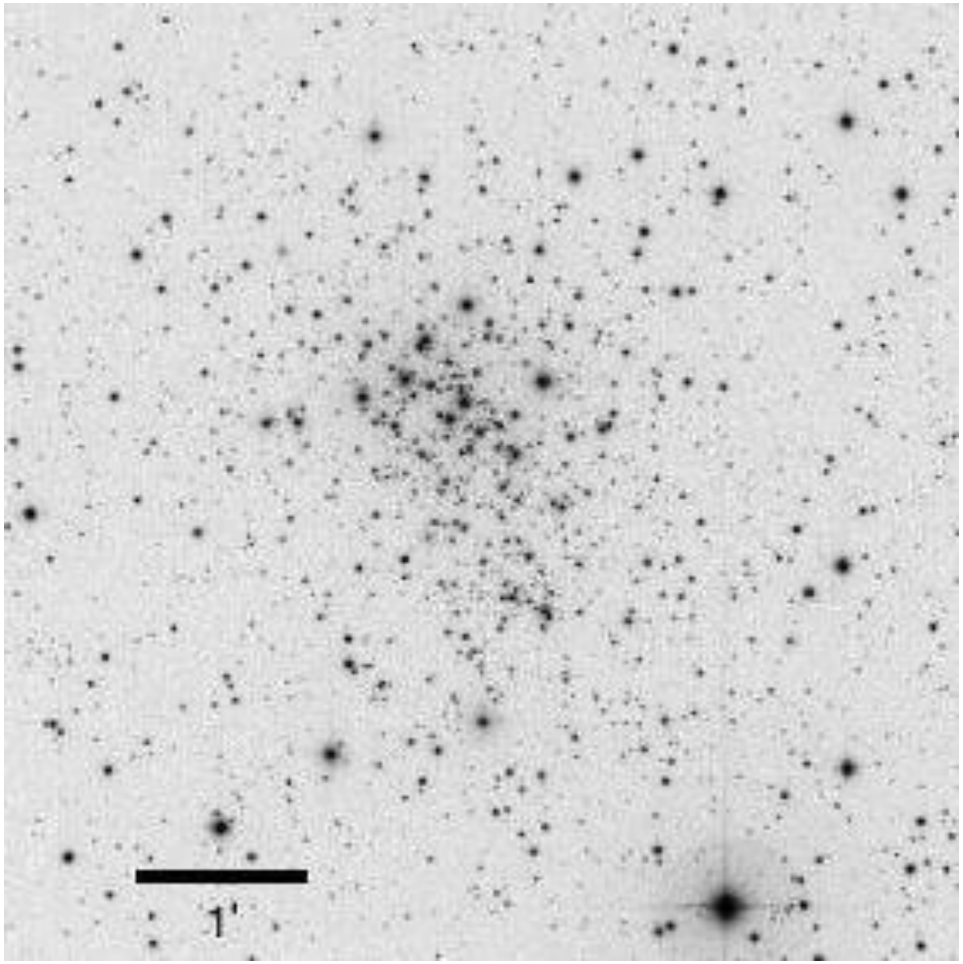
New estimate: 1.81-1.85
(2107.09474)

WD born first!!!!



1706.08060, see also 2002.12583 about PSR J1640+2224

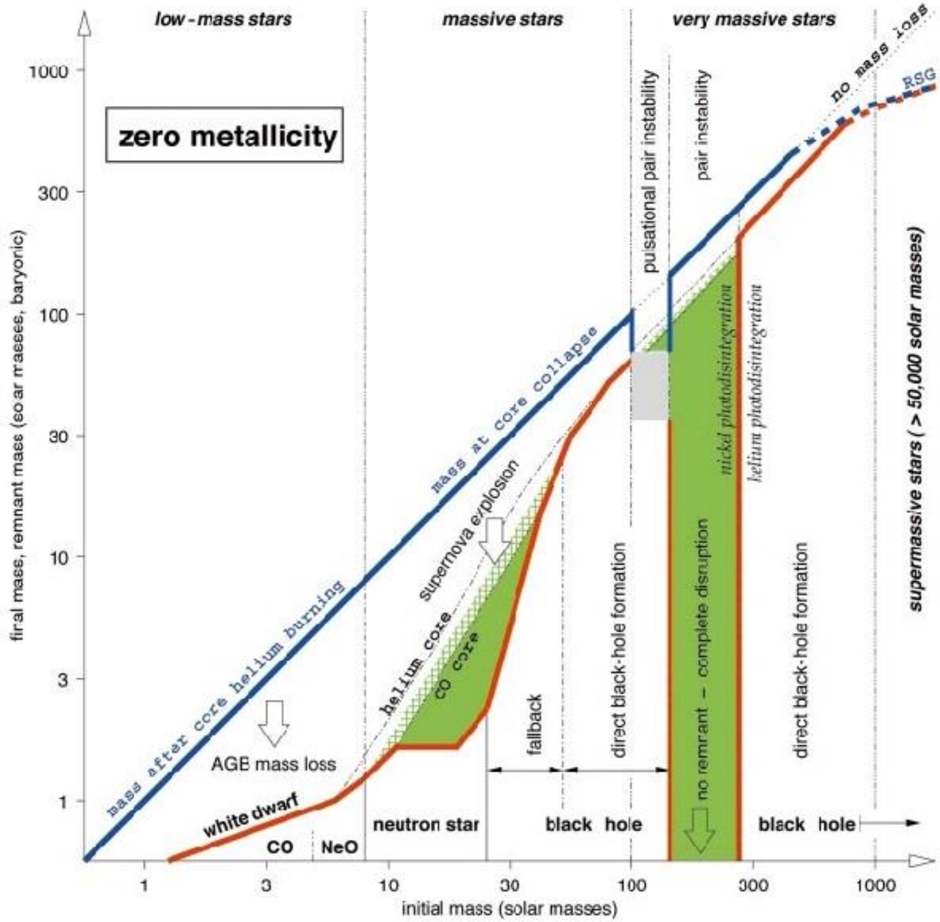
A NS from a massive progenitor



Anomalous X-ray pulsar
in the association
Westerlund1 most probably has
a very massive progenitor, >40 $M_{\odot}$.

astro-ph/0611589

The case of zero metallicity

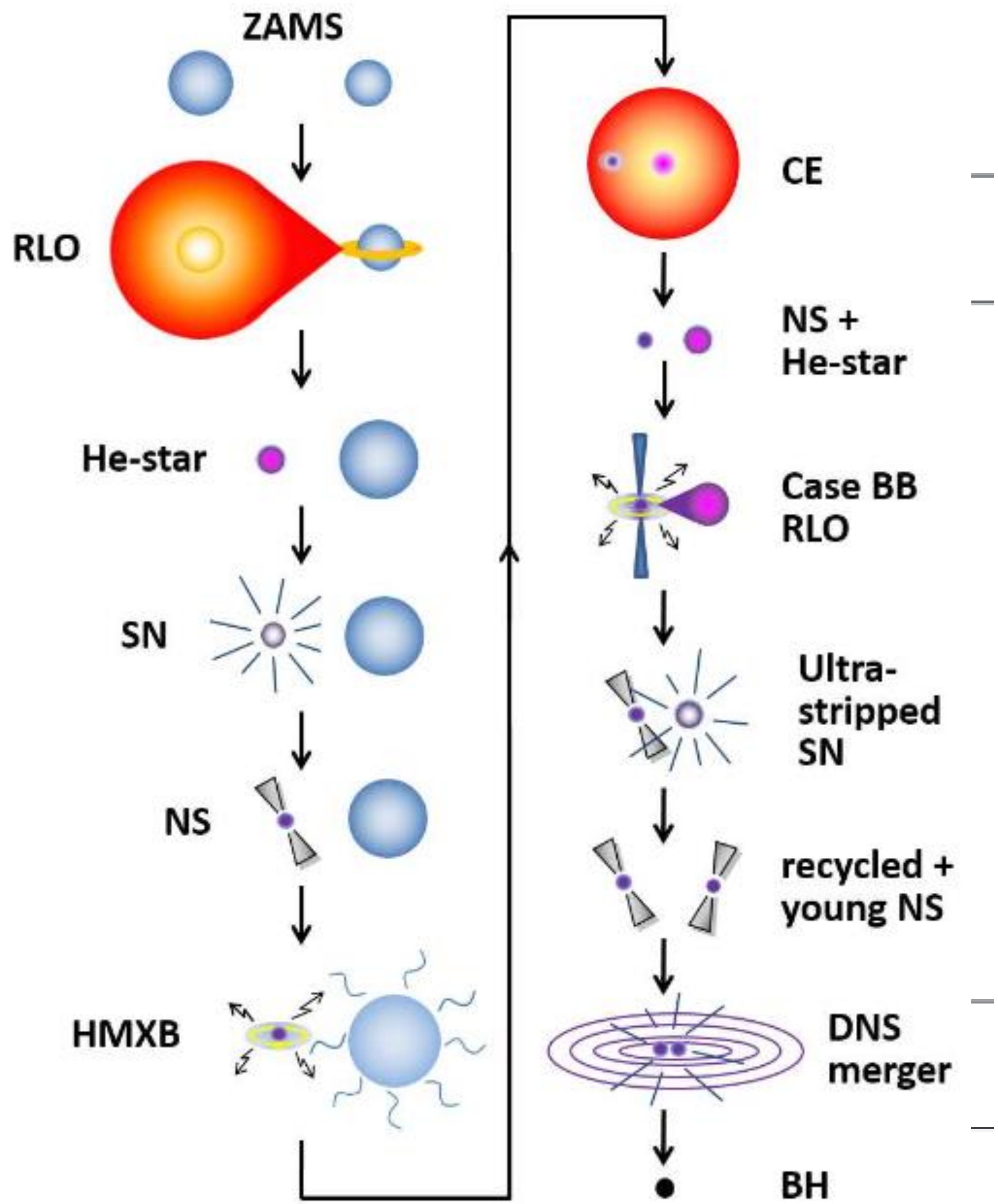


No intermediate mass range for NS formation.

Woosley et al. 2002

DNS

Radio Pulsar	Type	P (ms)
J0453+1559[a]	recycled	45.8
J0737−3039A[b]	recycled	22.7
J0737−3039B[b]	young	2773.5
J1518+4904[c]	recycled	40.9
B1534+12[d]	recycled	37.9
J1753−2240[e]	recycled	95.1
J1755−2550[f]*	young	315.2
J1756−2251[g]	recycled	28.5
J1811−1736[h]	recycled	104.2
J1829+2456[i]	recycled	41.0
J1906+0746[j]*	young	144.1
J1913+1102[k]	recycled	27.3
B1913+16[l]	recycled	59.0
J1930−1852[m]	recycled	185.5
J1807−2500B[n]*	GC	4.2
B2127+11C[p]	GC	30.5



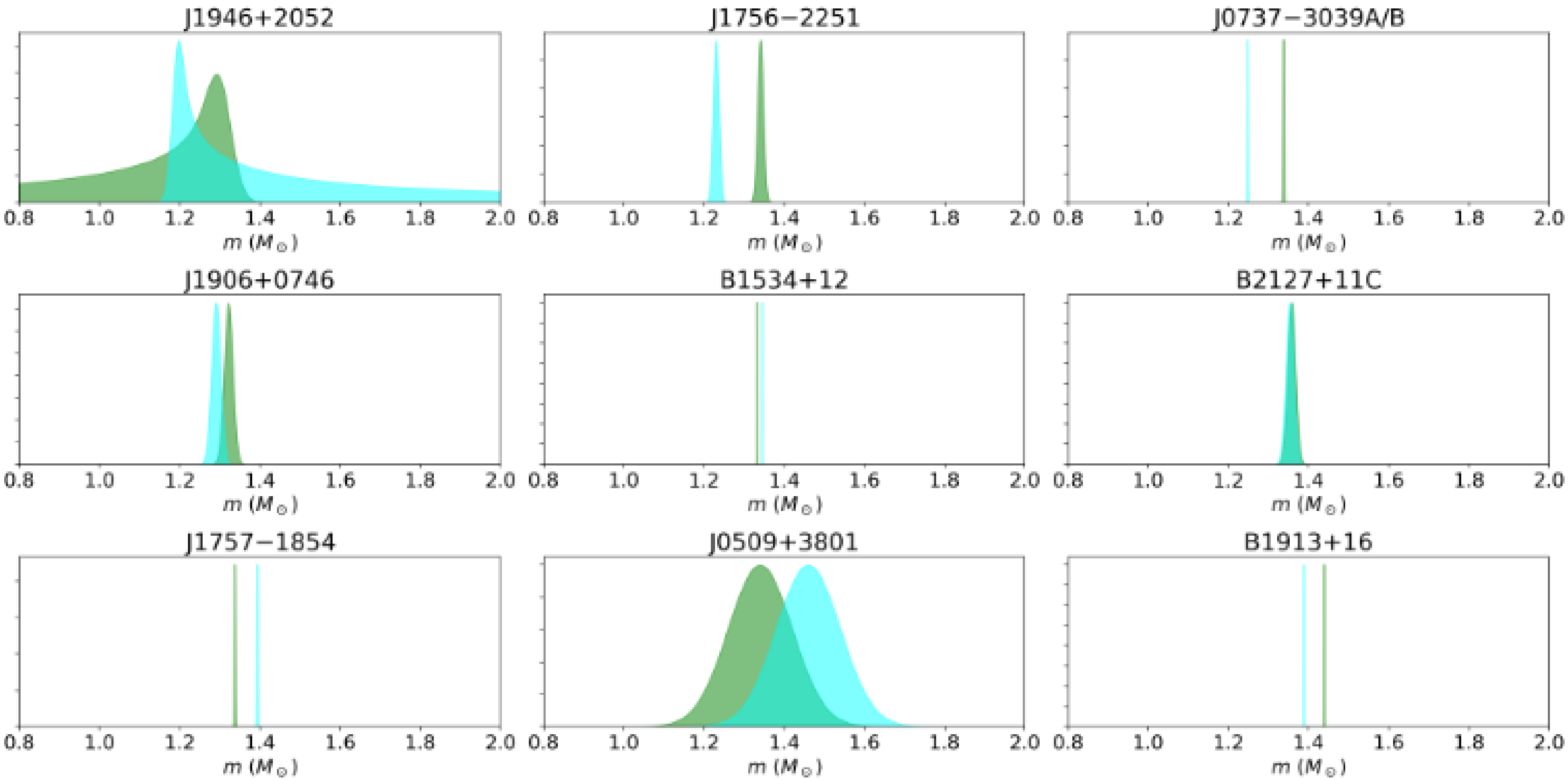
1706.09438

DNS parameters

Pulsar Name	M_T ($M_\odot$)	m_r ($M_\odot$)	m_s ($M_\odot$)	$\mathcal{M}_c$ ($M_\odot$)	q	P_b (day)	T_c (Gyr)
Systems will merge within a Hubble time							
J1946+2052	2.50(4)	< 1.35	> 1.17	(1.05, 1.11)	(0.68, 1)	0.078	0.046
J1756−2251	2.56999(6)	1.341(7)	1.230(7)	1.1178(3)	0.92(1)	0.320	1.656
J0737−3039A/B	2.58708(16)	1.3381(7)	1.2489(7)	1.1253(1)	0.933(1)	0.102	0.086
J1906+0746	2.6134(3)	1.322(11)	1.291(11)	1.1372(2)	(0.956, 1)	0.166	0.308
B1534+12	2.678463(4)	1.3330(2)	1.3455(2)	1.165870(2)	0.9907(3)	0.421	2.734
B2127+11C	2.71279(13)	1.358(10)	1.354(10)	1.18043(8)	(0.975, 1)	0.335	0.217
J1757−1854	2.73295(9)	1.3384(9)	1.3946(9)	1.18930(4)	0.960(1)	0.184	0.076
J0509+3801	2.805(3)	1.34(8)	1.46(8)	1.215(5)	(0.793, 1)	0.380	0.574
B1913+16	2.828378(7)	1.4398(2)	1.3886(2)	1.230891(5)	0.9644(3)	0.323	0.301
J1913+1102	2.886(1)	1.65(5)	1.24(5)	1.242(8)	0.75(5)	0.206	0.473
Systems will not merge within a Hubble time							
J1807−2500B	2.57190(73)	1.3655(21)	1.2064(21)	1.1169(3)	0.883(3)	9.957	1044
J1518+4904	2.7183(7)	1.41(8)	1.31(8)	1.181(5)	(0.794, 1)	8.634	8832
J0453+1559	2.733(4)	1.559(5)	1.174(4)	1.175(2)	0.753(5)	4.072	1453
J1411+2551	2.538(22)	< 1.64	> 0.92	(1.05, 1.11)	(0.57, 0.95)	2.616	466
J1811−1736	2.57(10)	< 1.75	> 0.91	(1.02, 1.17)	(0.58, 0.95)	18.78	1794
J1829+2456	2.59(2)	< 1.36	> 1.25	(1.08, 1.14)	(0.65, 1)	1.176	55
J1930−1852	2.59(4)	< 1.32	> 1.30	(1.07, 1.15)	(0.58, 0.96)	45.06	$\sim 10^5$

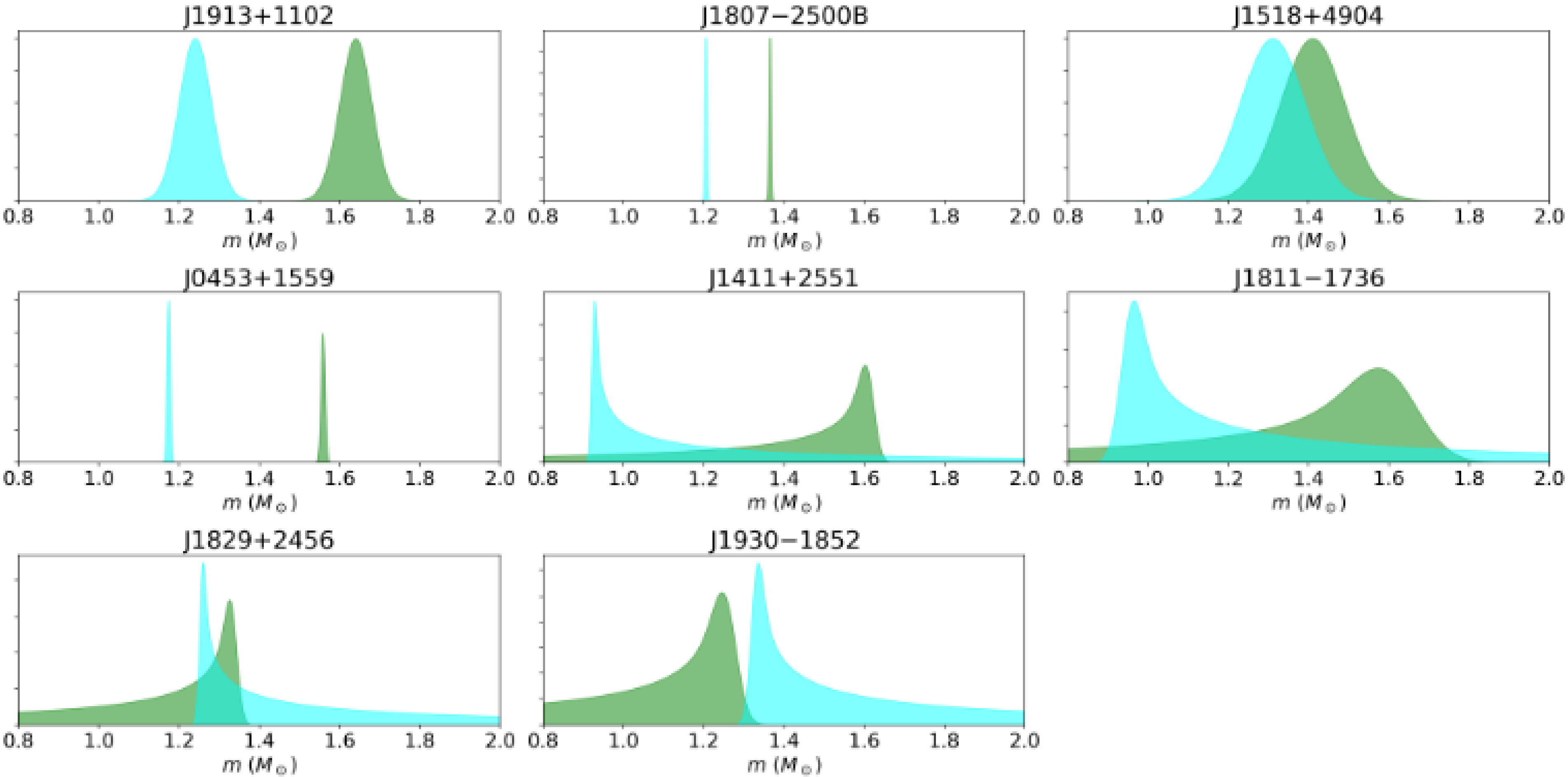
1902.03300

Individual masses of DNS



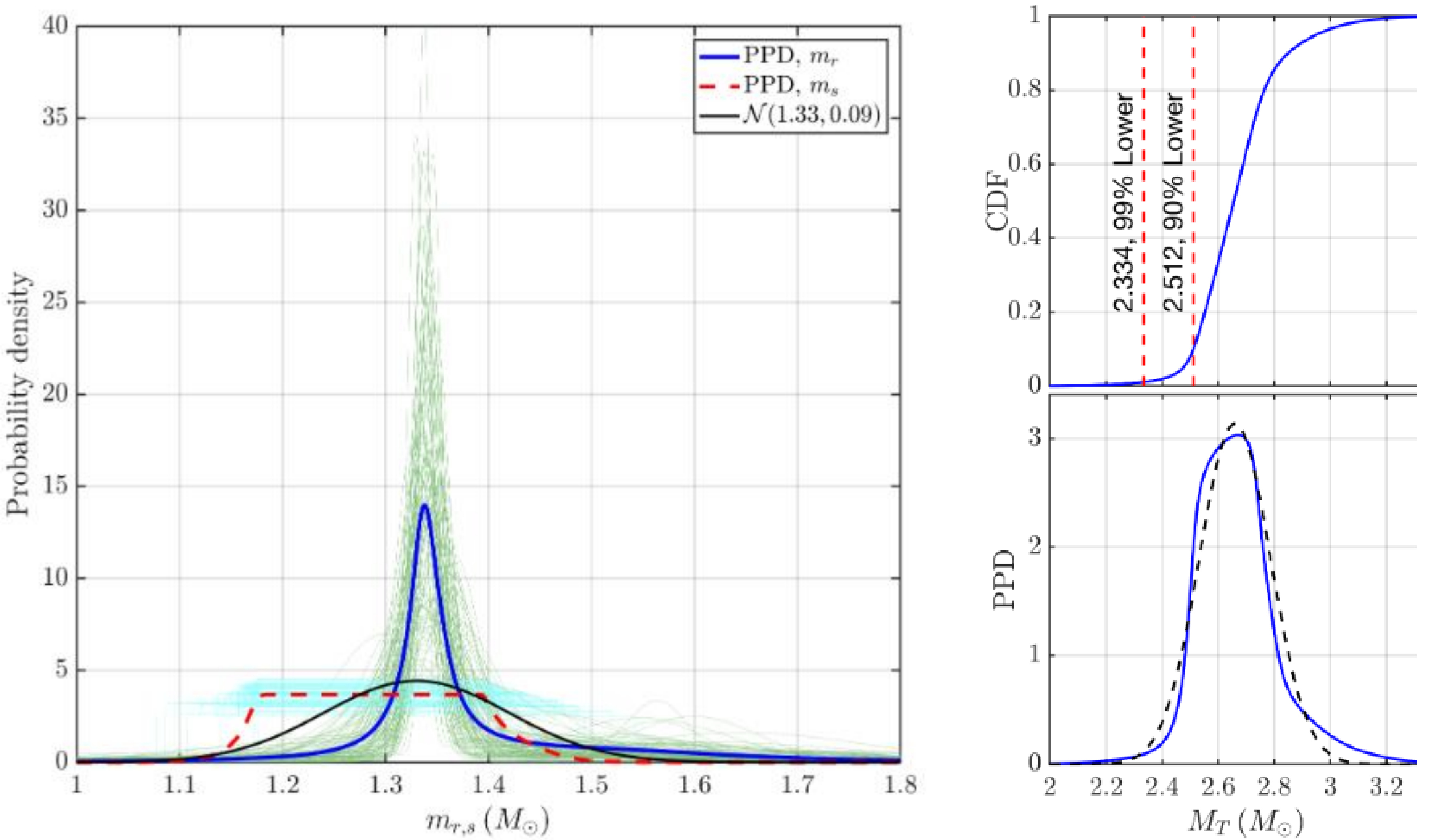
1902.03300

Individual masses of DNS



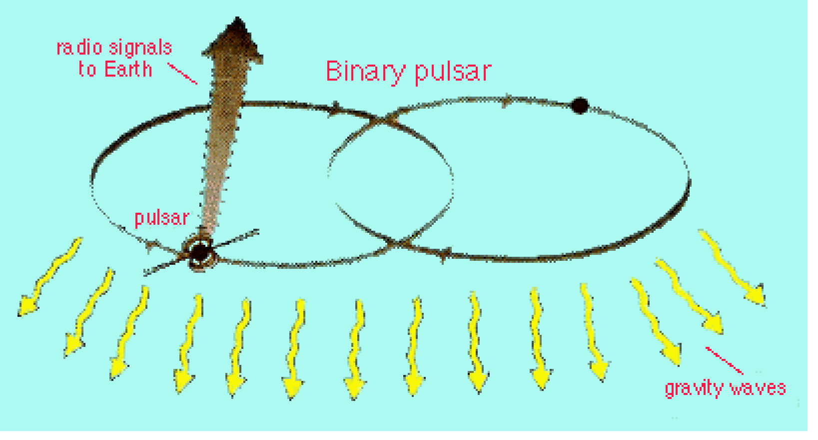
1902.03300

DNS mass distributions



1902.03300

Binary pulsars



$$\frac{d\Delta_{E\odot}}{dt} = \sum_i \frac{Gm_i}{c^2 r_i} + \frac{v_\oplus^2}{2c^2} - \text{constant} \,.$$

$$\Delta_{S\odot} = -\frac{2GM_\odot}{c^3} \log(1 + \cos\theta) \,,$$

$$\begin{aligned} T = {} & t_{\text{obs}} - t_0 + \Delta_C - D/f^2 + \Delta_{R\odot}(\alpha, \delta, \mu_\alpha, \mu_\delta, \pi) \\ & + \Delta_{E\odot} - \Delta_{S\odot}(\alpha, \delta) \\ & - \Delta_R(x, e, P_b, T_0, \omega, \dot{\omega}, \dot{P}_b) - \Delta_E(\gamma) - \Delta_S(r, s) \end{aligned}$$

See 1502.05474 for a recent detailed review

Relativistic corrections and measurable parameters

$$\dot{\omega}=3\left[\frac{P_b}{2\pi}\right]^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1}\ ,$$

$$\gamma=e\left[\frac{P_b}{2\pi}\right]^{1/3}T_\odot^{2/3}M^{-4/3}m_2(m_1+2m_2)\ ,$$

$$\dot{P}_b=-\frac{192\pi}{5}\left[\frac{P_b}{2\pi}\right]^{-5/3}\left[1+\frac{73}{24}e^2+\frac{37}{96}e^4\right]$$
$$\times(1-e^2)^{-7/2}T_\odot^{5/3}m_1 m_2 M^{-1/3}\ ,$$

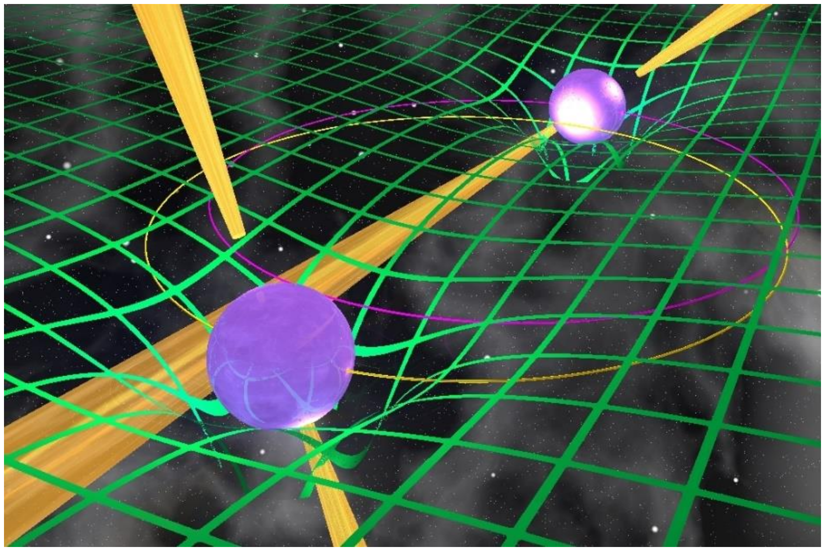
$$r=T_\odot m_2\ ,$$

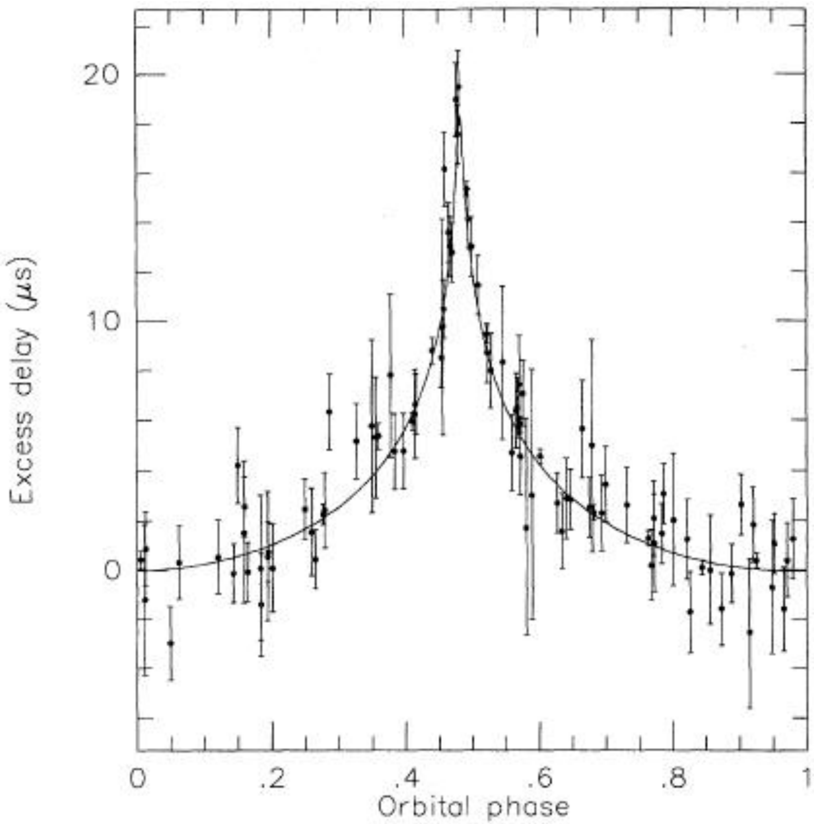
$$s=x\left[\frac{P_b}{2\pi}\right]^{-2/3}T_\odot^{-1/3}M^{2/3}m_2^{-1}\ .$$

For details see
Taylor, Weisberg 1989
ApJ 345, 434

Shapiro delay

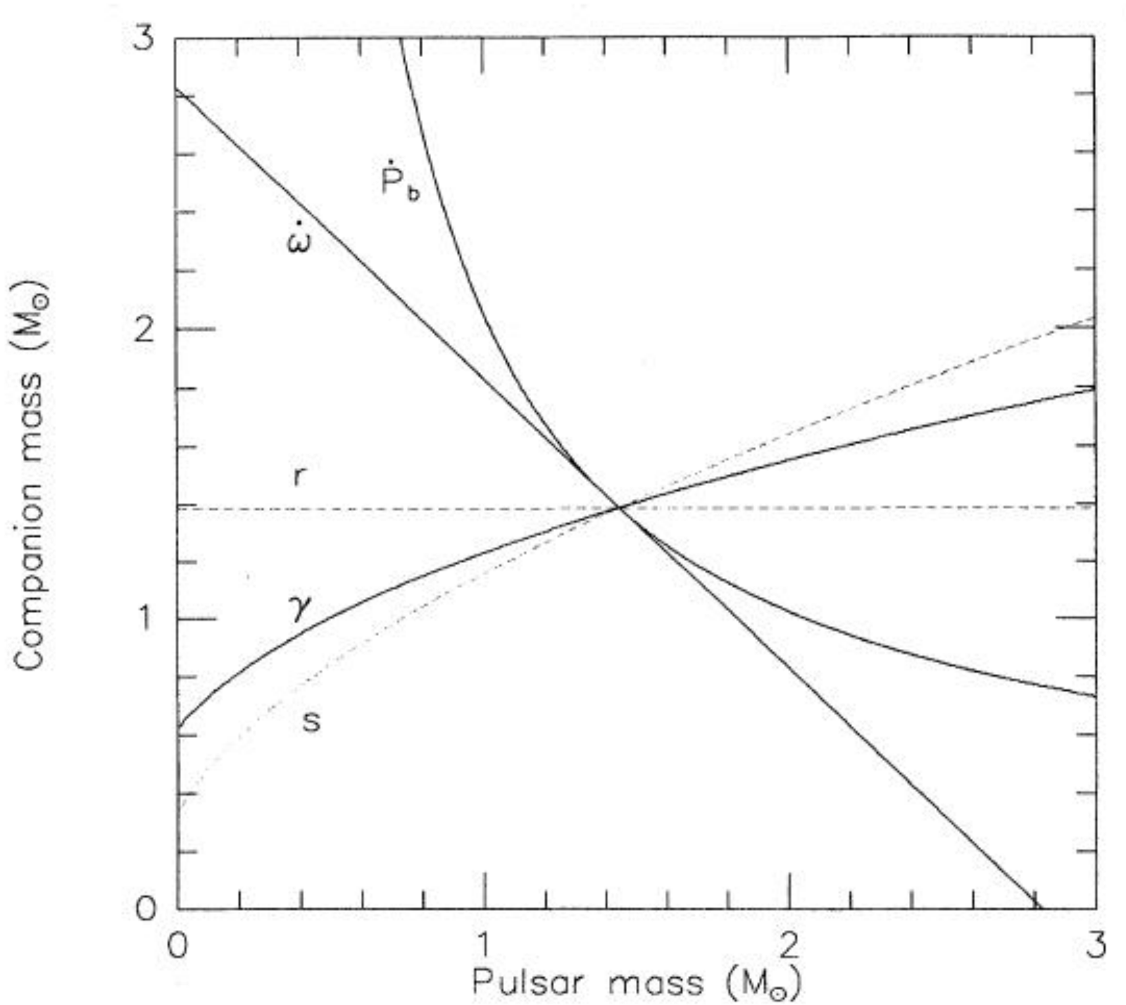
$$\Delta_S = -2r\log(1 - s\cos[2\pi(\phi - \phi_0)])$$





PSR 1855+09 (Taylor, Nobel lecture)

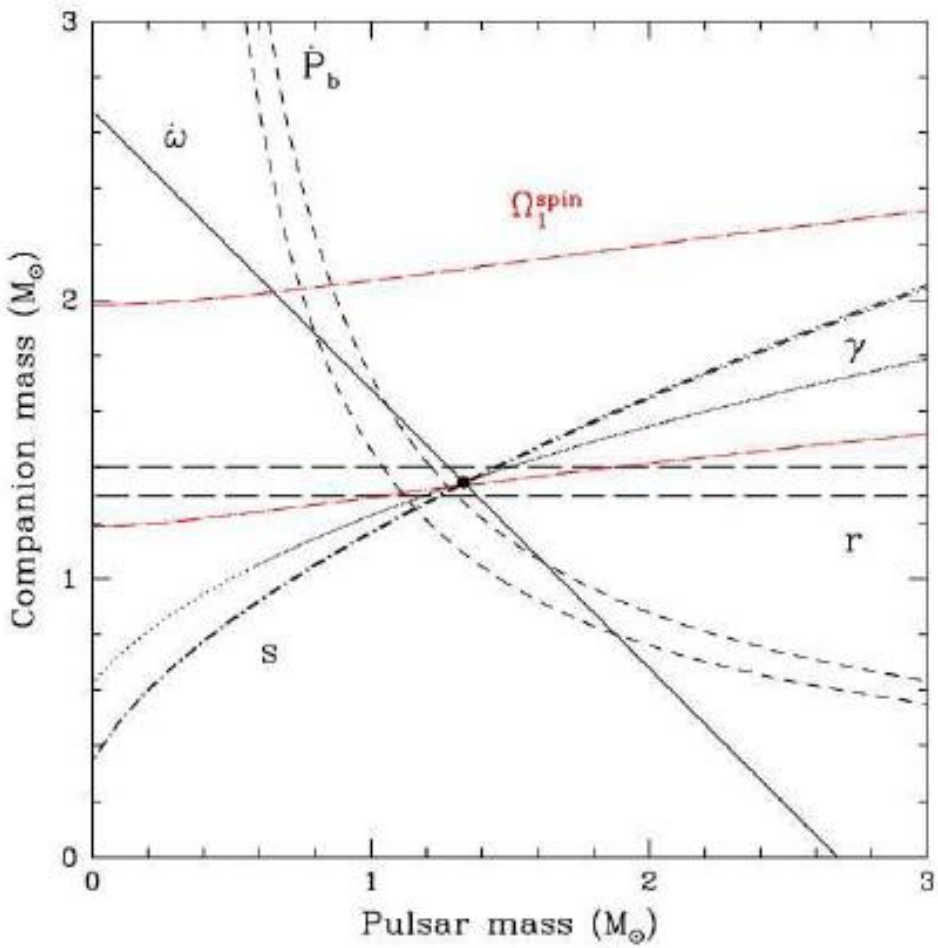
Mass measurements



PSR 1913+16

Taylor

Uncertainties and inverse problems



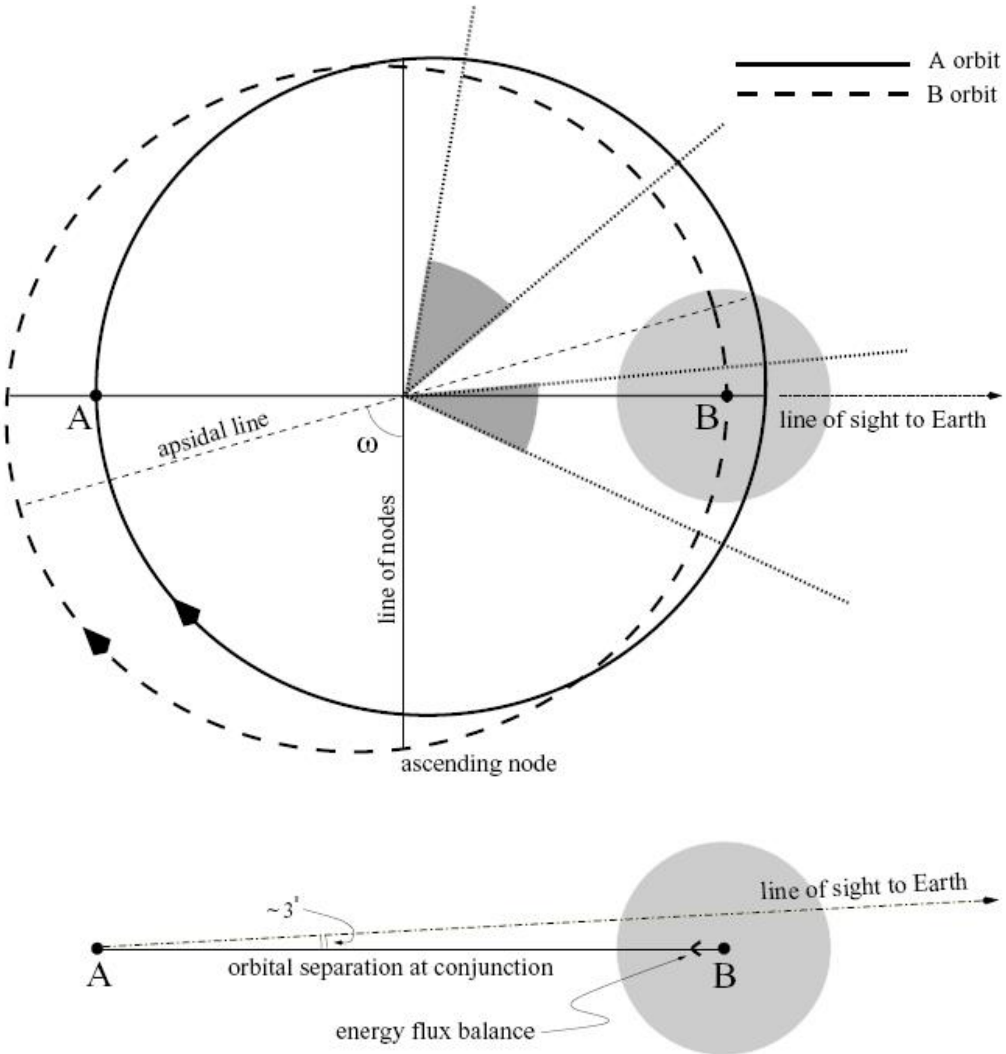
PSR B1534+12.

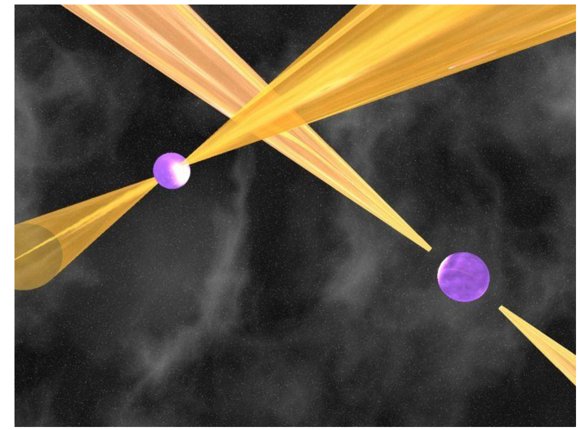
$P_b$dot depends on the Shklovskii effect. So, if distance is not certain, it is difficult to have a good measurement of this parameter.

It is possible to invert the problem. Assuming that GR is correct, one can improve the distance estimate for the given source.

1502.05474

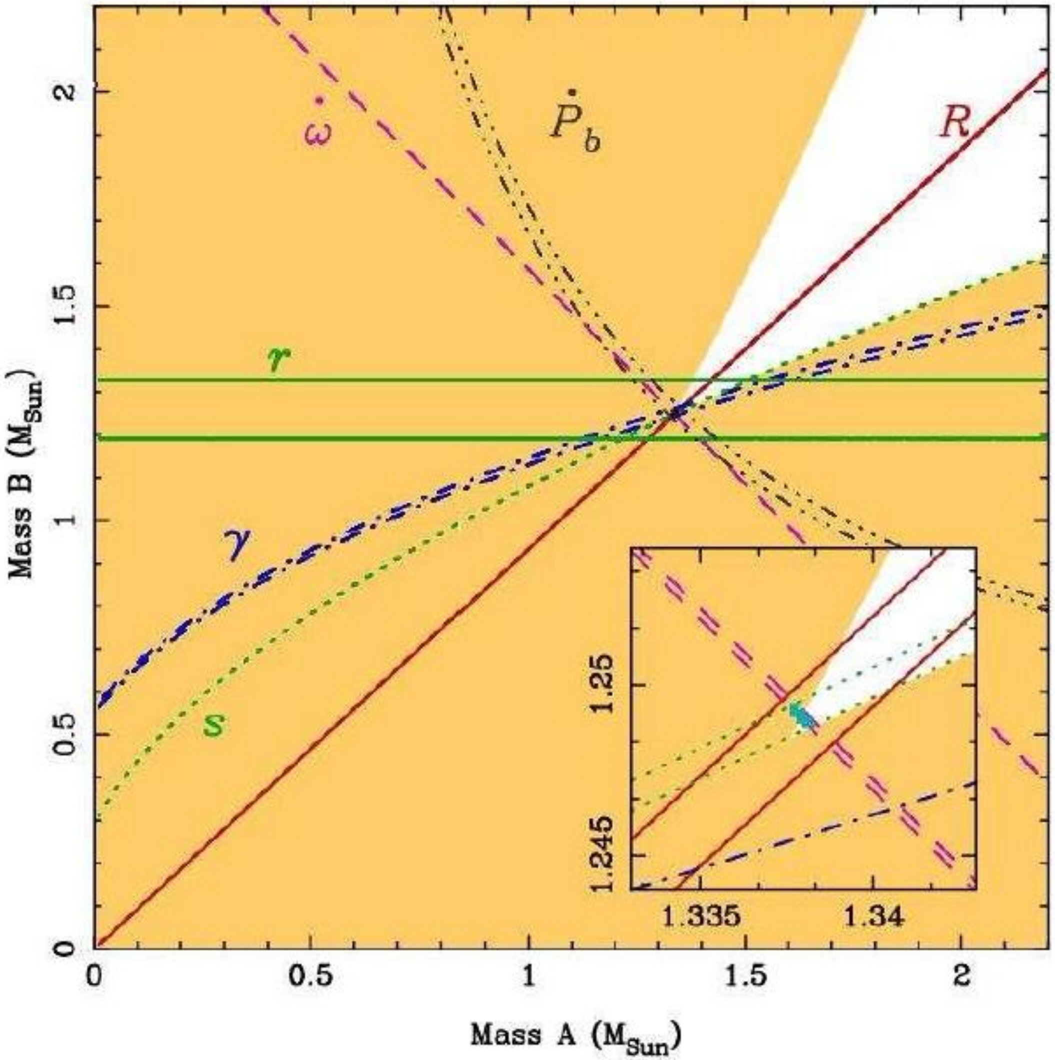
Double pulsar J0737-3039





Lyne et al. astro-ph/0401086

Masses for PSR J0737-3039

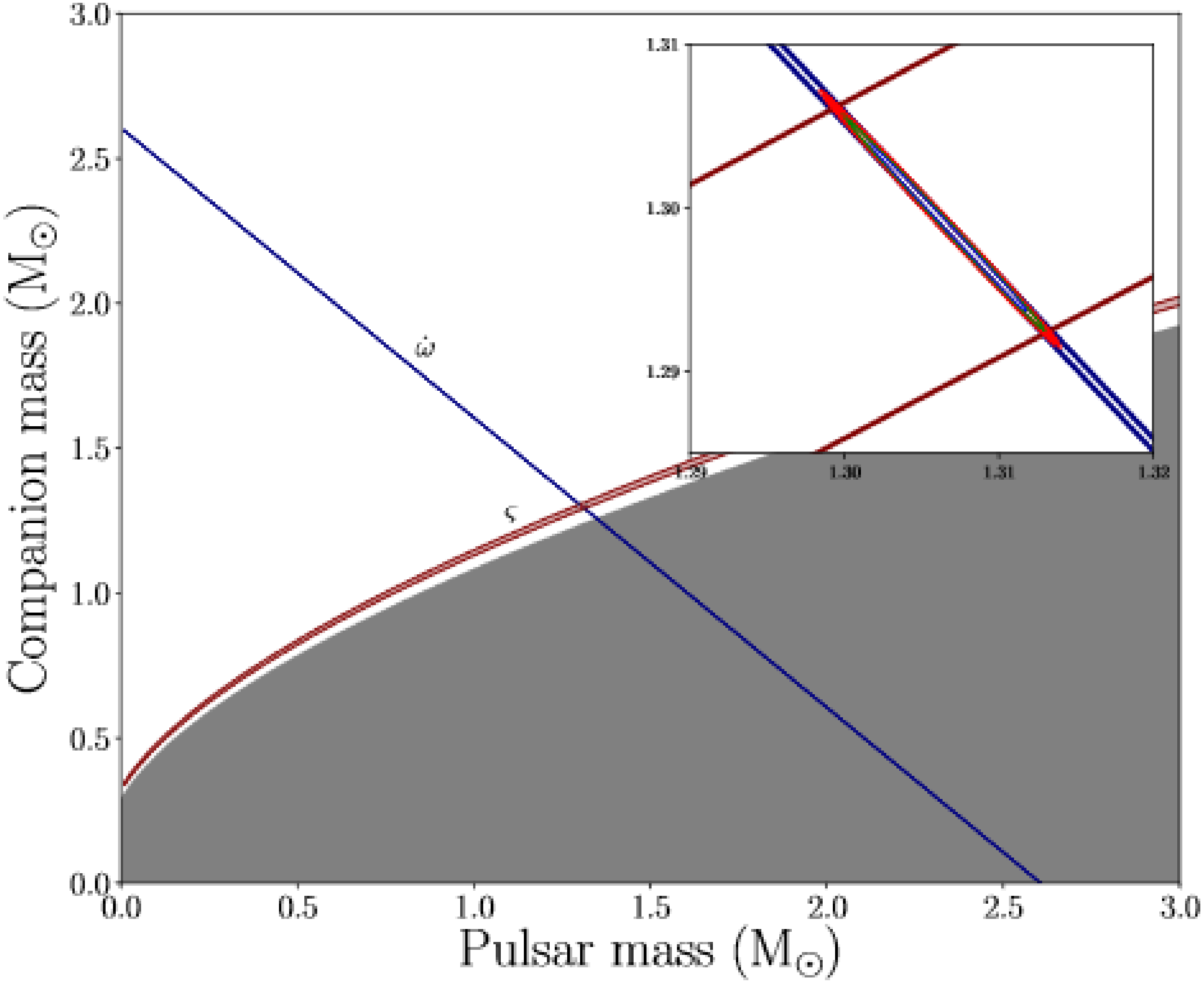


The most precise values.

New mass estimates have uncertainties <0.001

Kramer et al. astro-ph/0609417

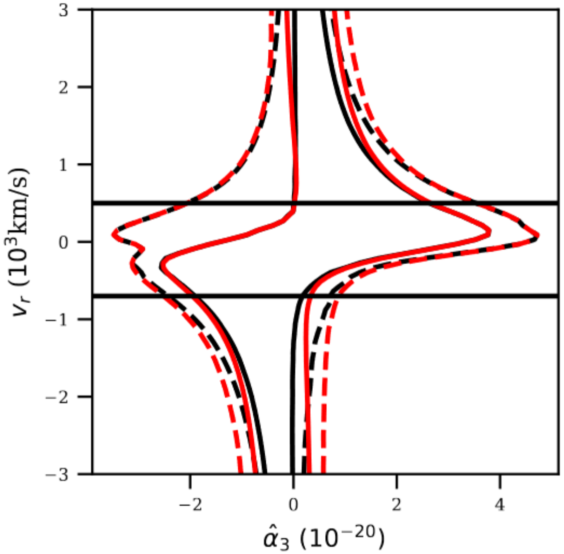
DNS J1829+2456 mass measurements

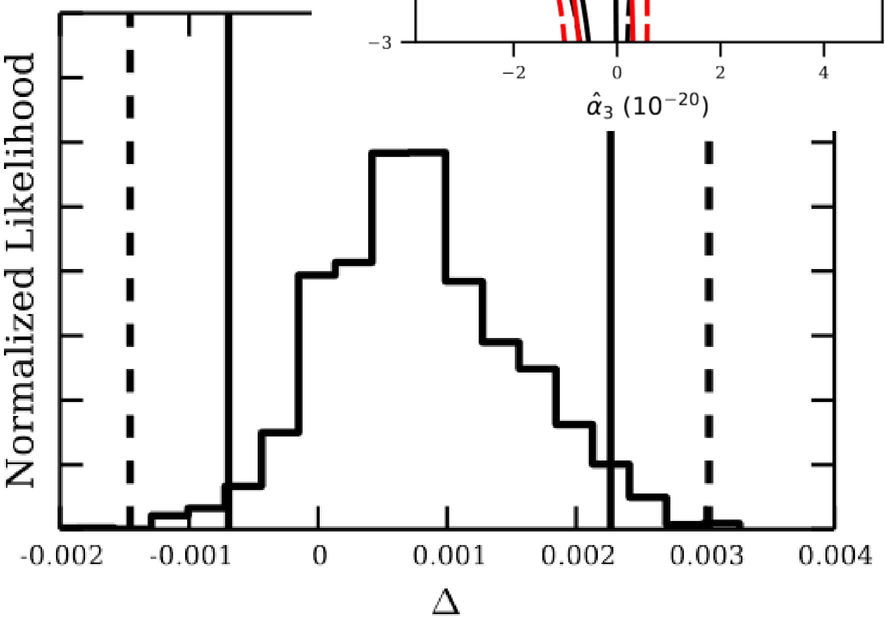


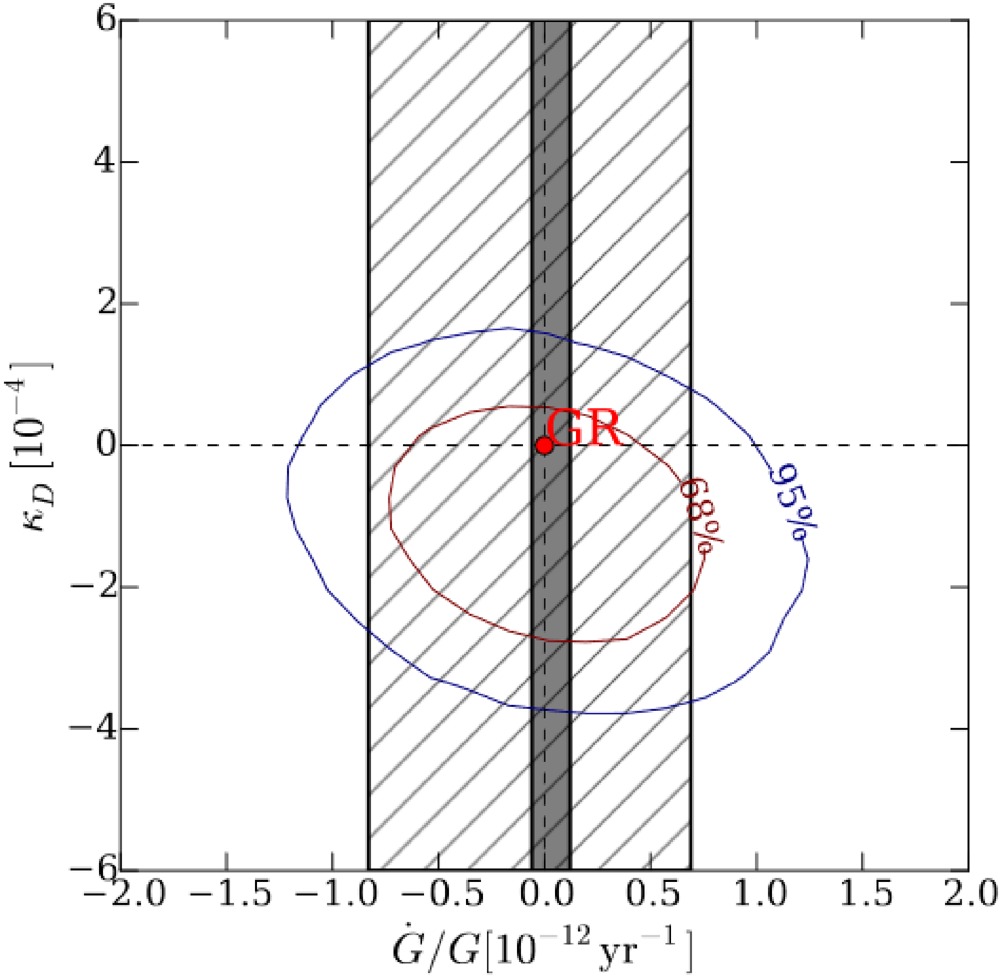
2007.07565

Tests of theories of gravity

J1713+0747

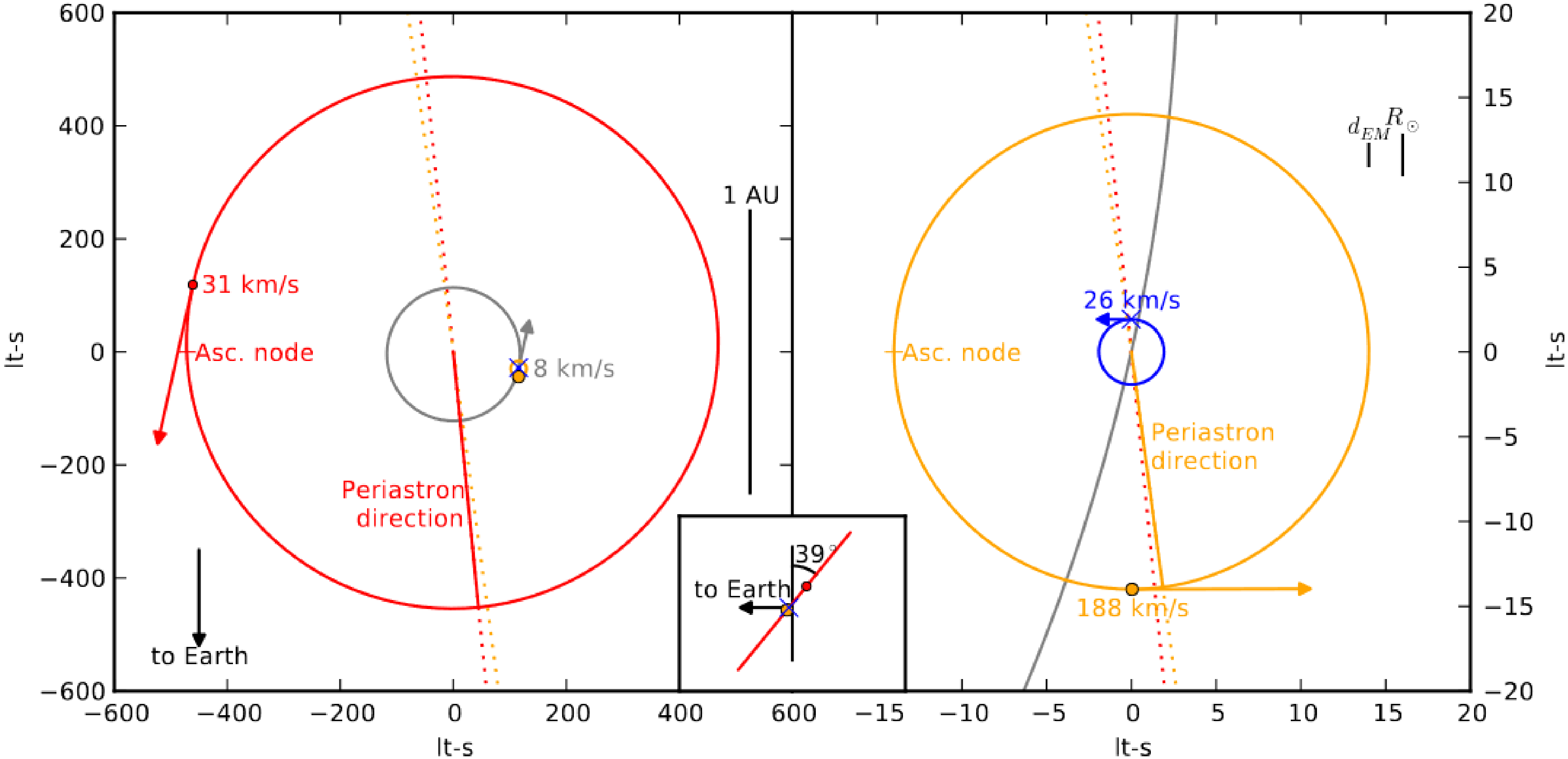






1802.09206

Testing strong equivalence principle with triple pulsar PSR J0337+1715



NS+WD+WD

1401.0535

NS+WD binaries

Some examples

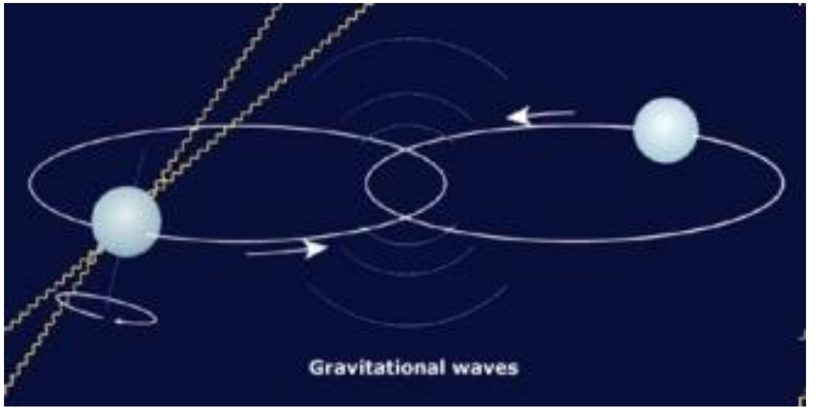
PSR J0437-4715. WD companion [0801.2589, 0808.1594].
The closest millisecond PSR. M_{NS}=1.76+/-0.2 solar.

The case of PSR J0751+1807.
Initially, it was announced that it has a mass ~2.1 solar [astro-ph/0508050].
However, then in 2007 at a conference the authors announced that the result was incorrect. Actually, the initial value was 2.1+/-0.2 (1 sigma error).
New result: 1.26 +/- 0.14 solar
[Nice et al. 2008, Proc. of the conf. "40 Years of pulsars"]

It is expected that most massive NSs get their additional "kilos" due to accretion from WD companions [astro-ph/0412327].

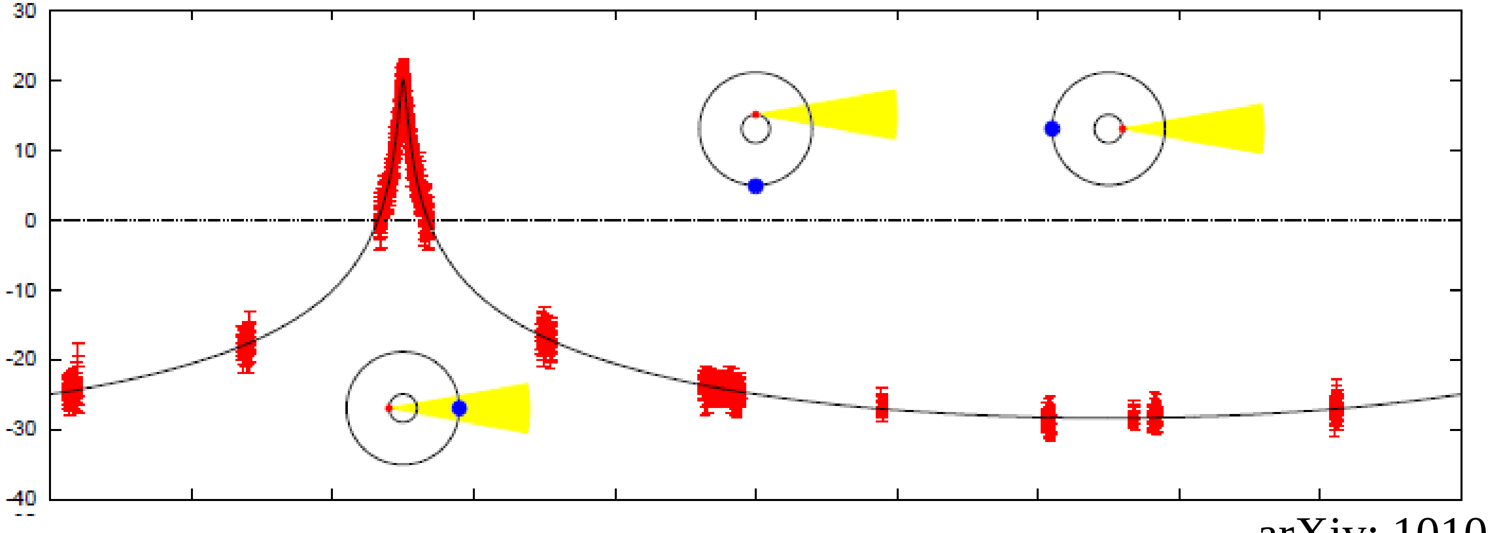
Very massive neutron star

Binary system: pulsar + white dwarf
PSR 1614-2230



Mass ~ 2 solar

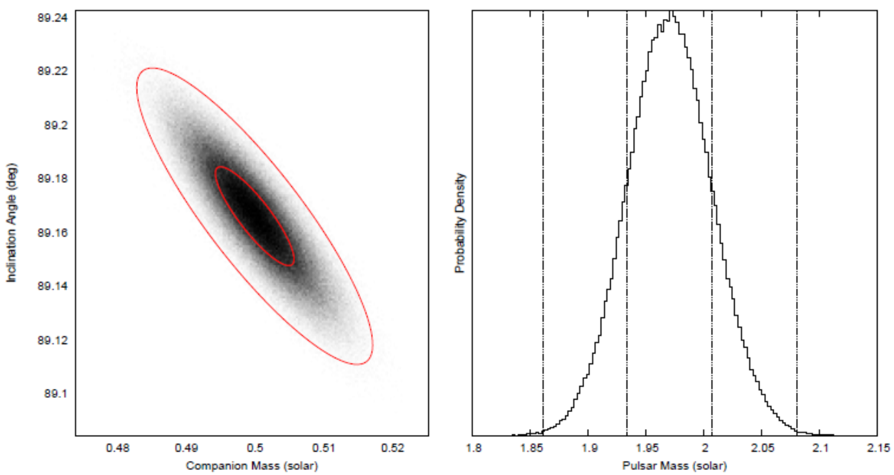
About the WD see 1106.5497.
The object was identified in optics.



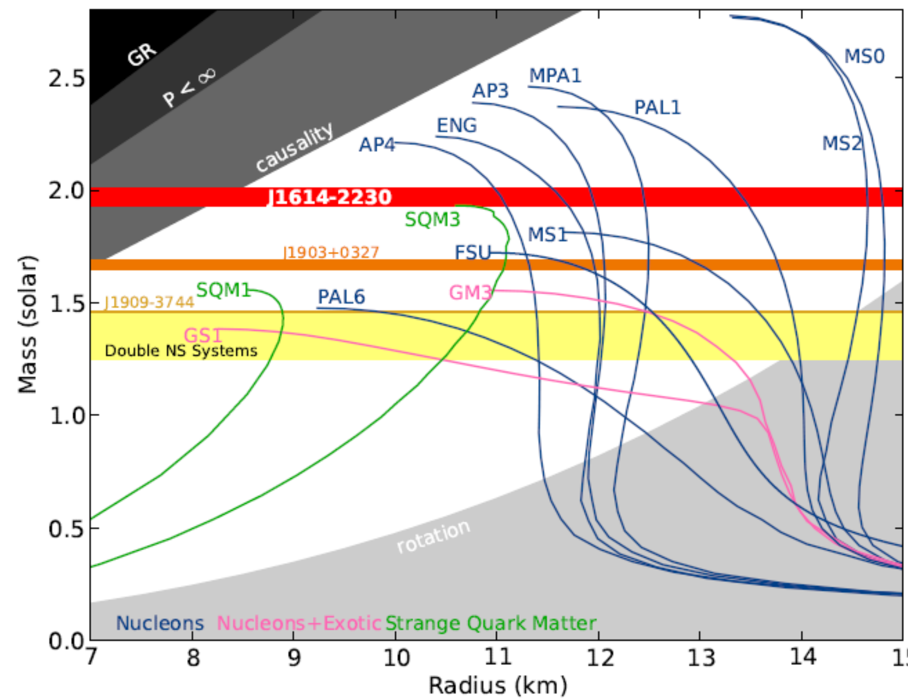
arXiv: 1010.5788

About formation of this objects see 1103.4996

Why is it so important?



The maximum mass is a crucial property of a given EoS



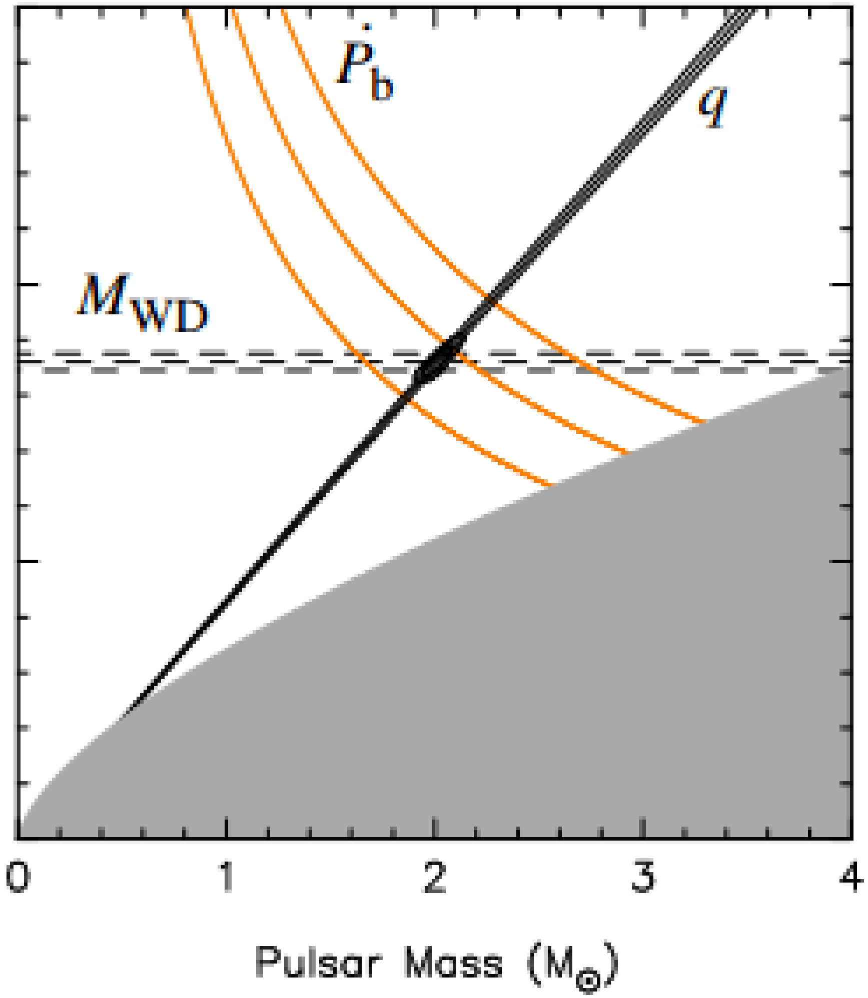
Collapse happens earlier for softer EoSs, see however, 1111.6929 about quark and hybrid stars to explain these data.

Interestingly, it was suggested that just <0.1 solar masses was accreted (1210.8331)

arXiv: 1010.5788

In the future specific X-ray sources (eclipsing msec PSR like SWIFT J1749.4−2807) can show Shapiro delay and help to obtain masses for a different kind of systems, see 1005.3527 , 1005.3479 .

2.01 solar masses NS



PSR J0348+0432
39 ms, 2.46 h orbit
WD companion

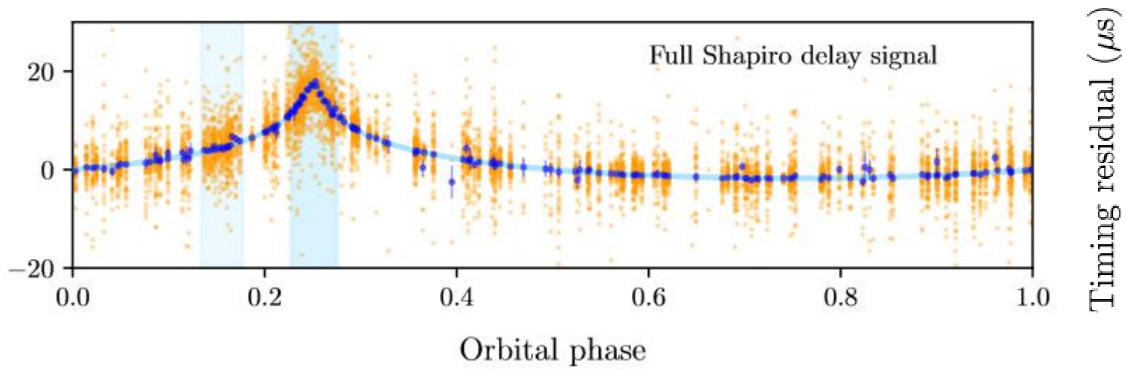
The NS mass is estimated to be:
1.97 – 2.05 solar mass at 68.27%
1.90 – 2.18 solar mass at 99.73%
confidence level.

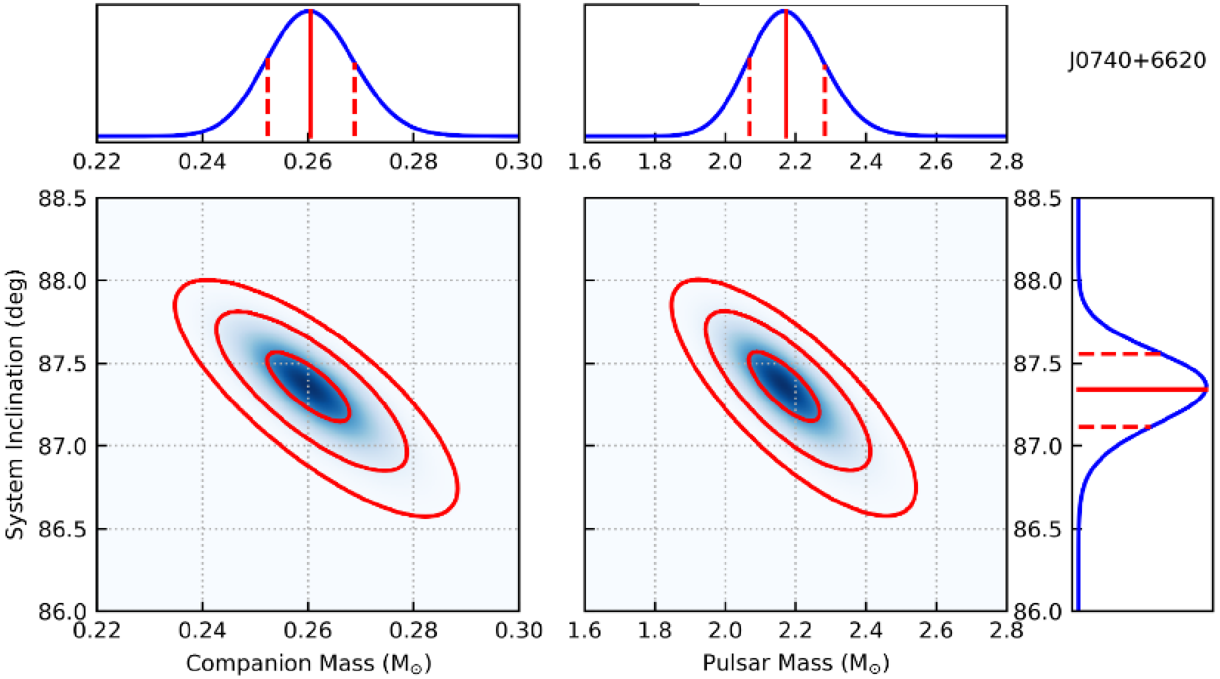
System is perfect for probing
theories of gravity as it is very compact.

1304.6875

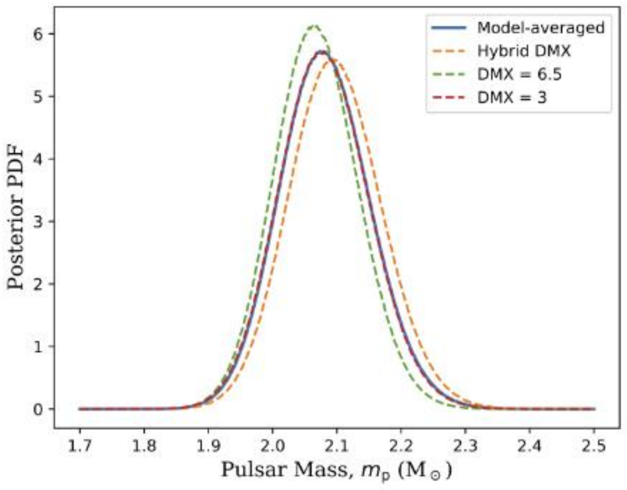
2.14 solar mass NS

J0740+6620
2.14 solar masses





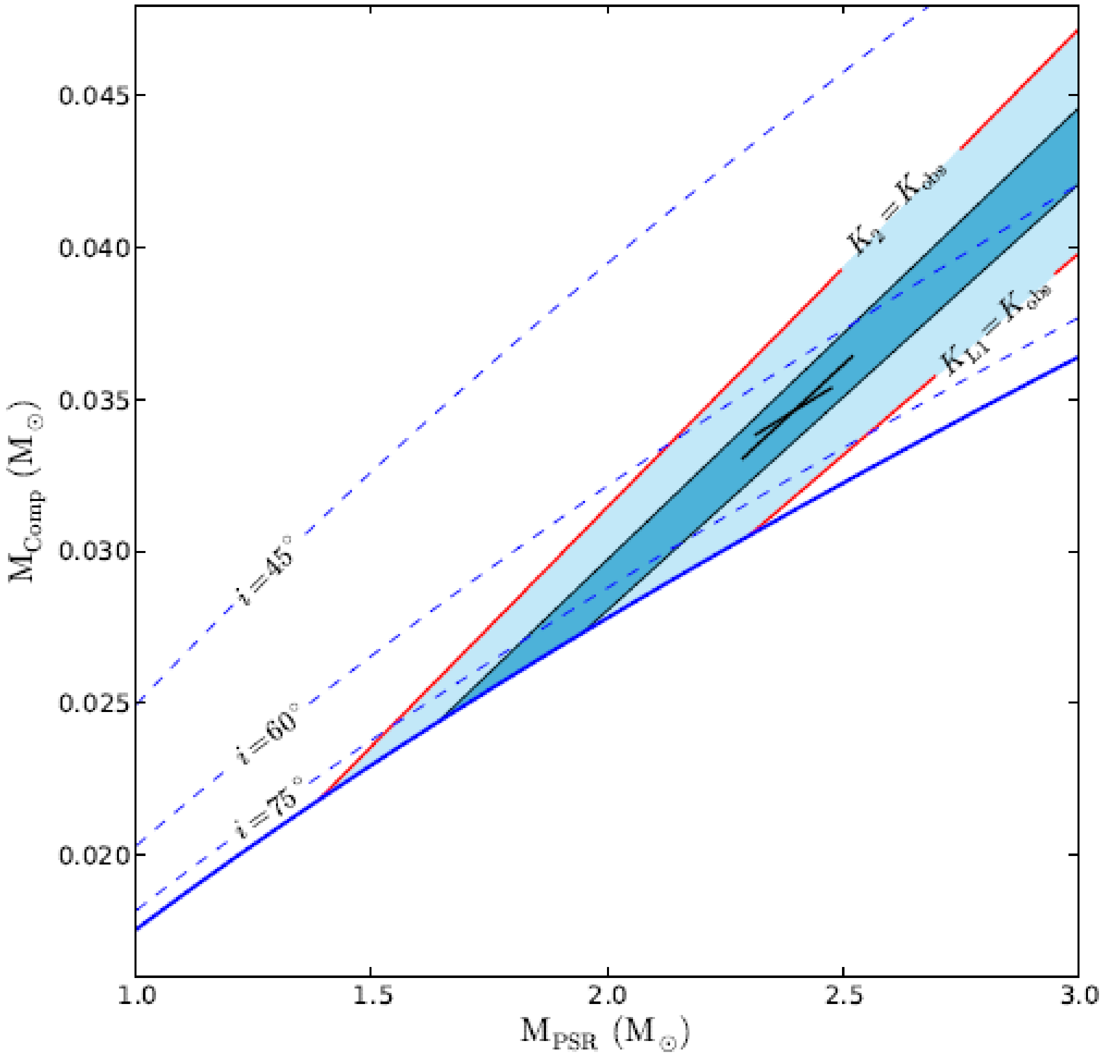
New data confirm it:
2.01-2.17 Msun (1-sigma)



1904.06759

2104.00880

The most extreme (but unclear) example

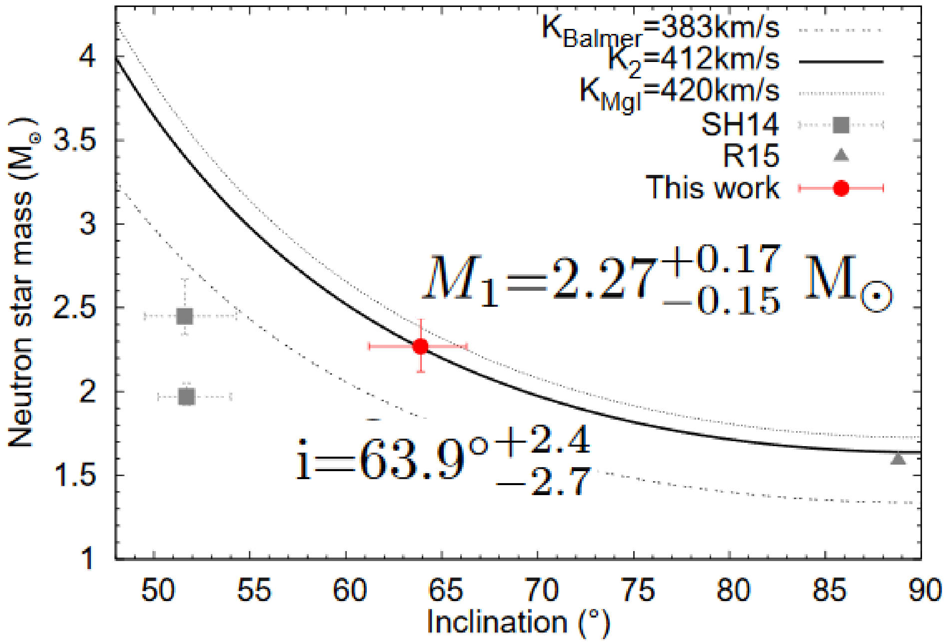


BLACK WIDOW PULSAR
PSR B1957+20

2.4+/-0.12 solar masses

1009.5427

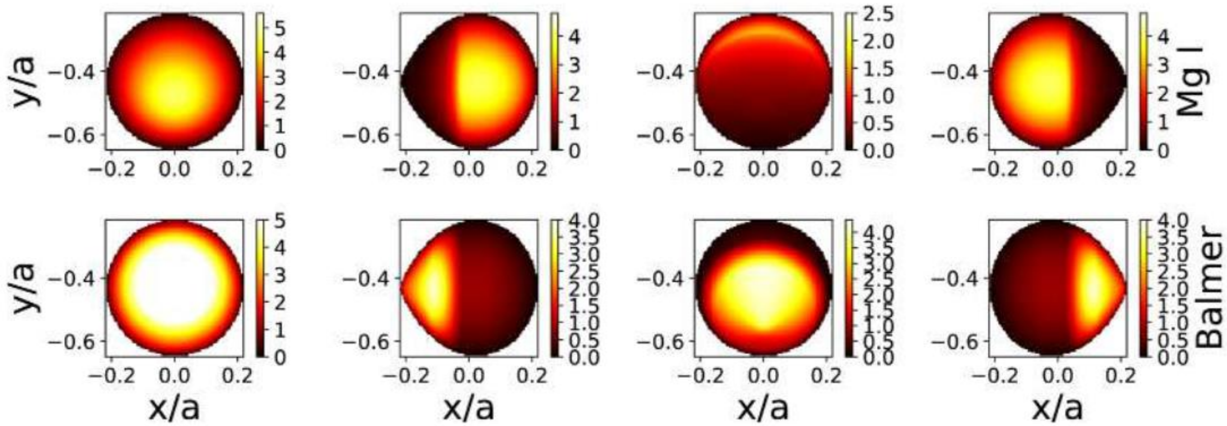
A massive NS in PSR J2215+5135



Different lines provide different velocity as they are emitted from different sides of the companion.

Different sides of the companion move with different velocity.

Thus, a correct model provides new mass determination.



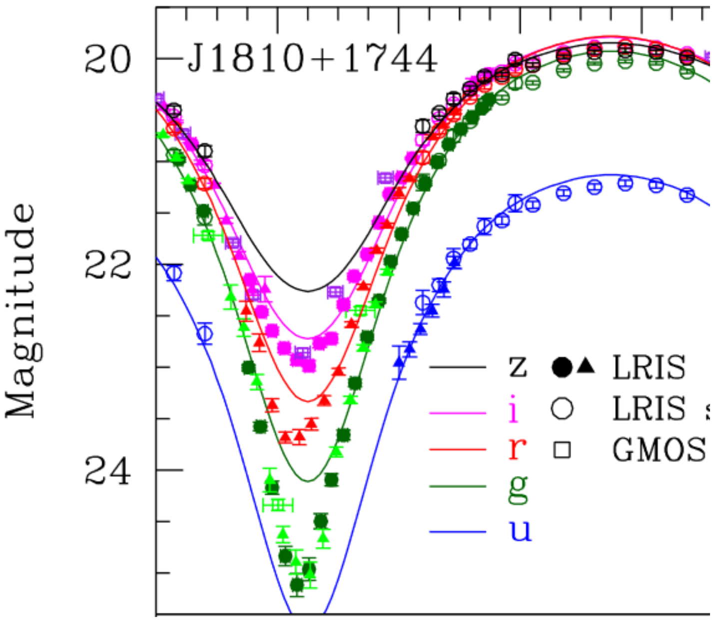
New calculations confirm high mass of the NS (2002.12483).

1805.08799

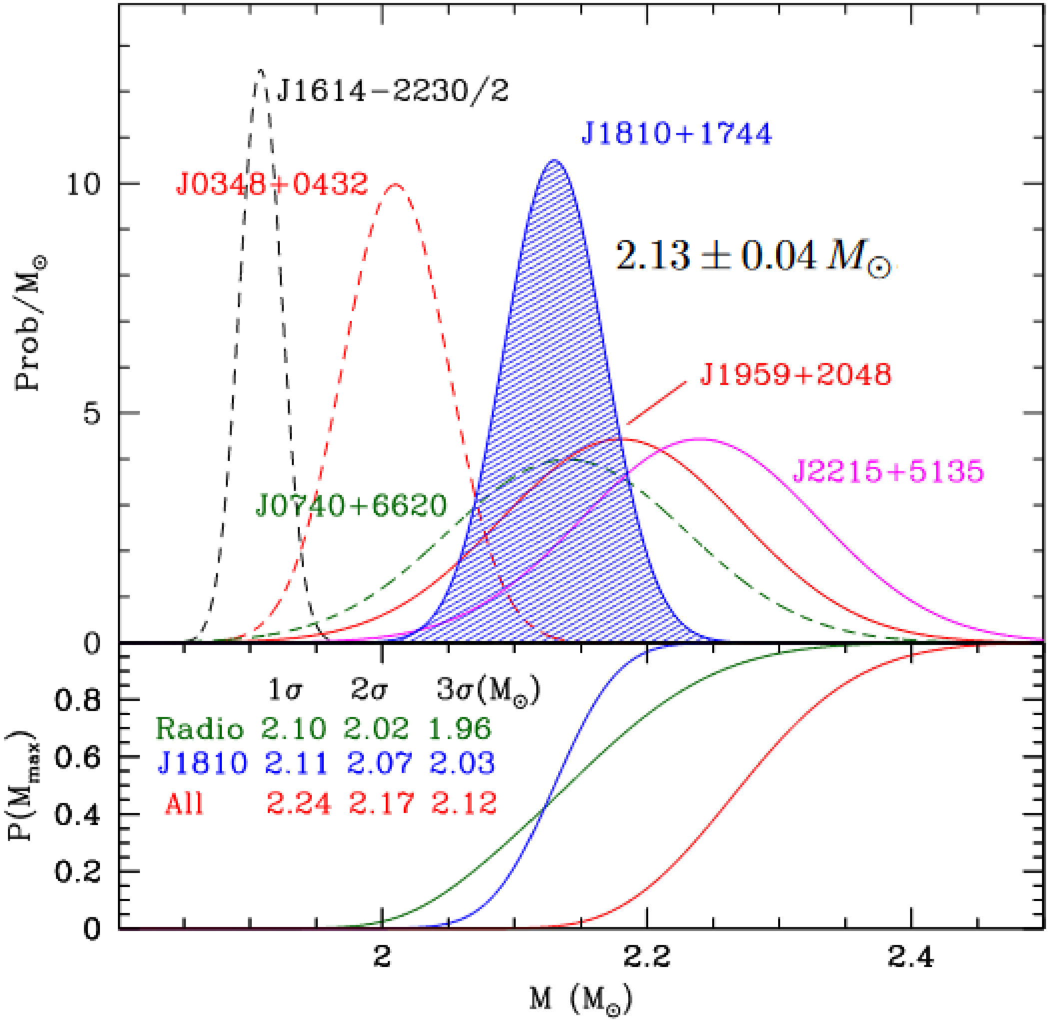
High mass of PSR J1810+1744

Black widow – like system

Detailed studies of companion are necessary to measure mass.

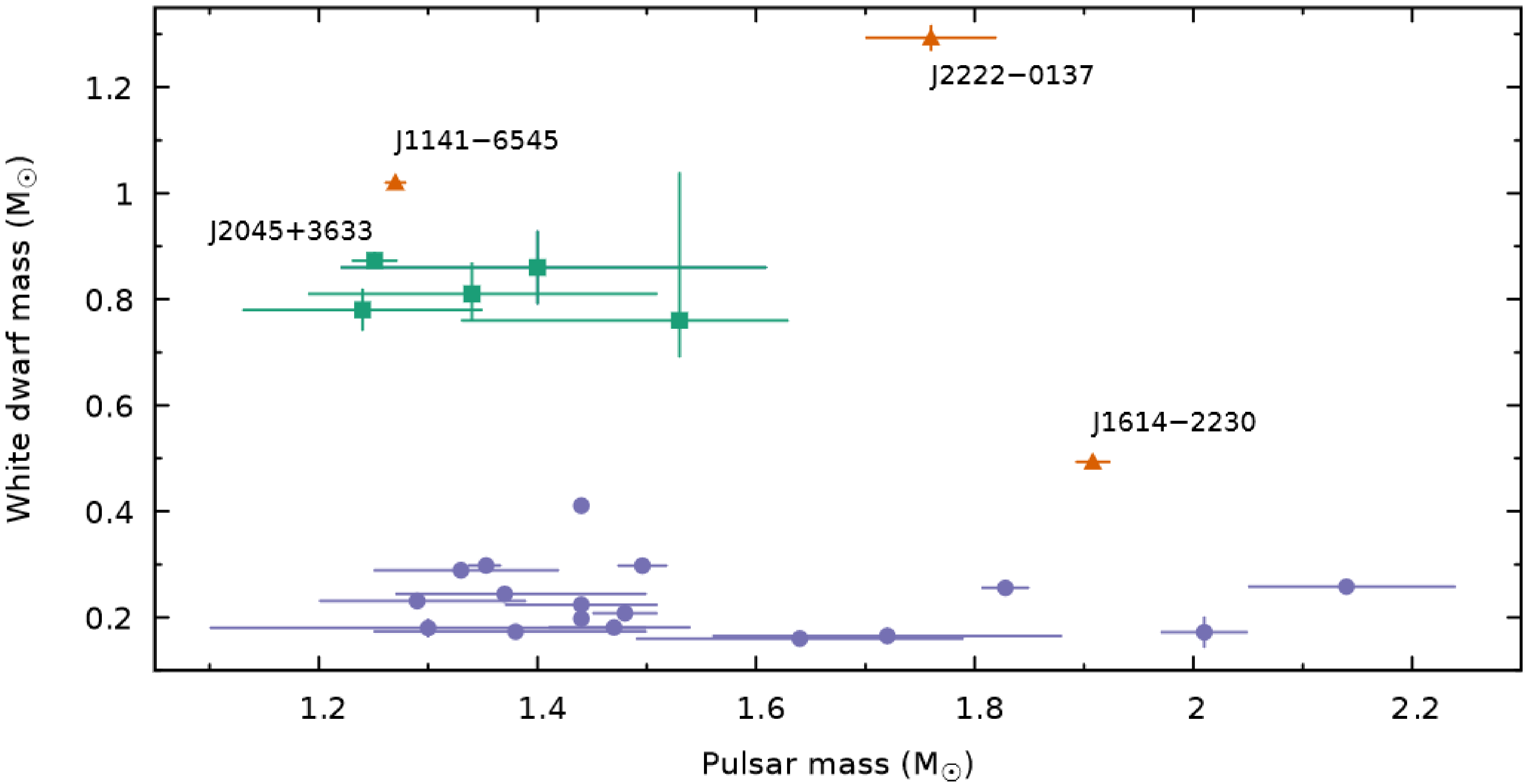


Keck light curves



2101.09822

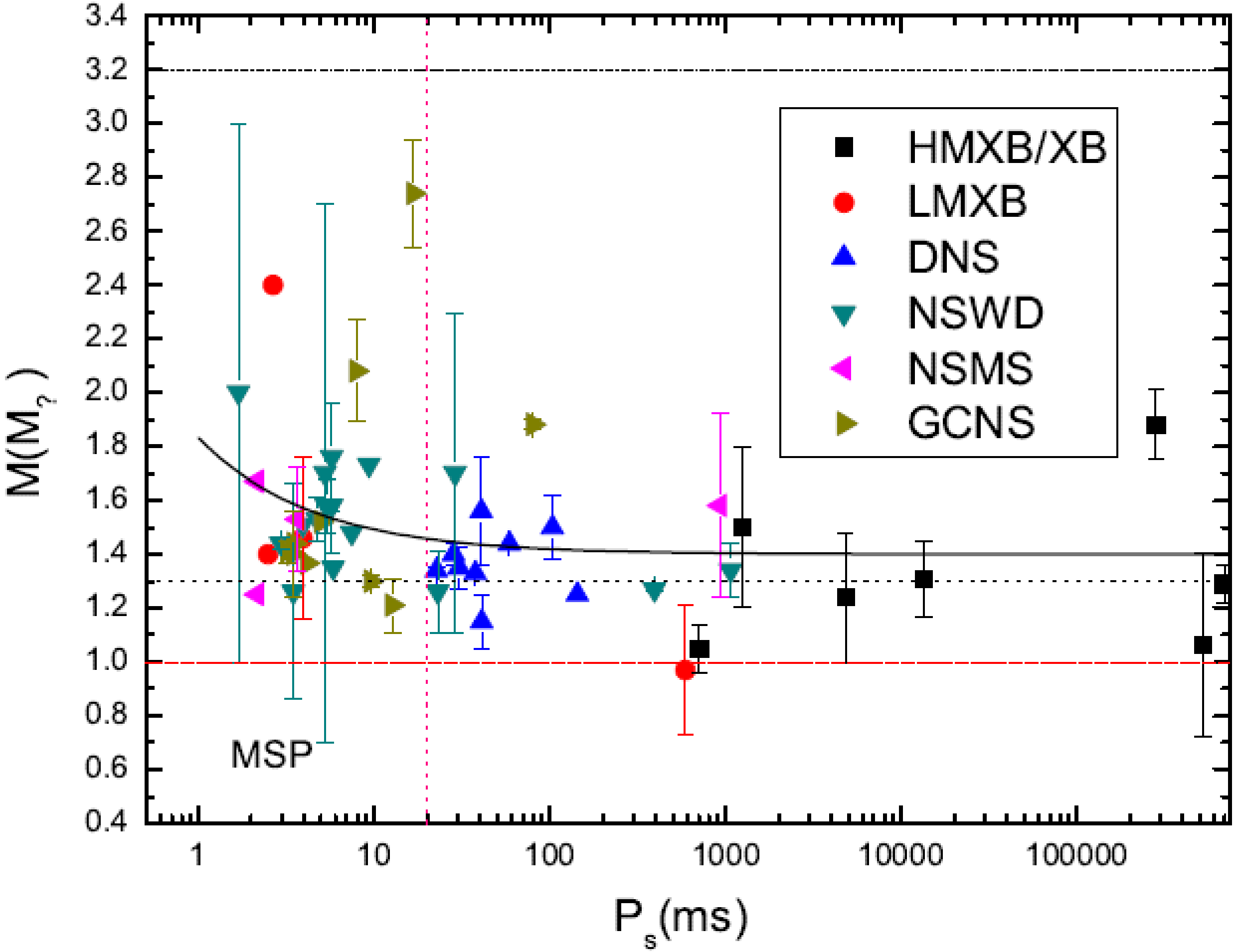
PSR-WD masses



Light helium white dwarf companions are shown as purple circles, and the systems with massive white dwarf (CO WD) companions are shown as green squares. Triangles – non-recycled PSRs (WD formed first).

2009.12283

How much do PSRs accrete?

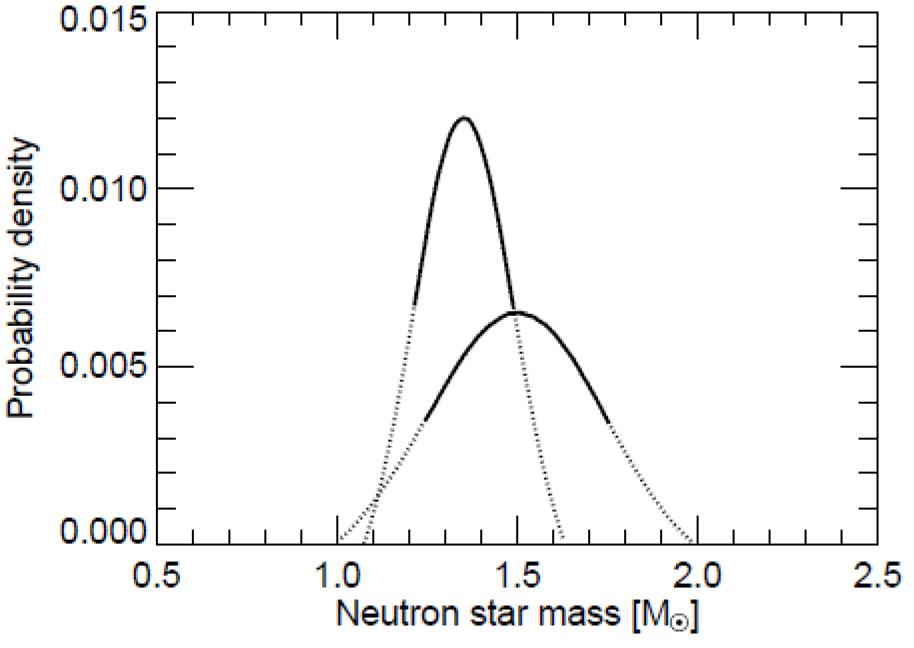


$M=1.4+0.43(P/ms)^{-2/3}$

Millisecond pulsars are ~0.2 solar masses more massive than the rest ones.

1010.5429

DNS and NS+WD binaries



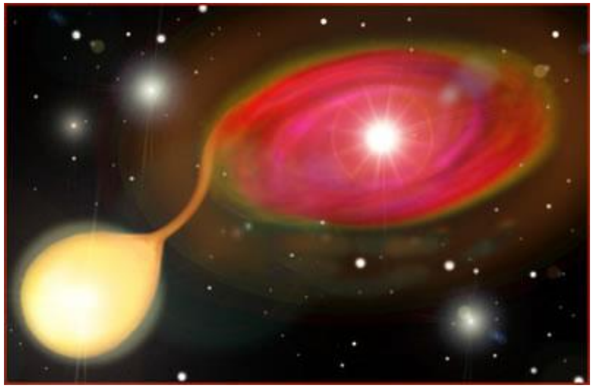
1.35+/-0.13 and 1.5+/-0.25

Cut-off at ~2.1 solar masses can be mainly due to evolution in a binary, not due to nuclear physics (see 1309.6635)

1011.4291

Neutron stars in binaries

Study of close binary systems gives an opportunity to obtain mass estimate for progenitors of NSs (see for example, Ergma, van den Heuvel 1998 A&A 331, L29).
For example, an interesting estimate was obtained for GX 301-2.
The progenitor mass is >50 solar masses.
On the other hand, for several other systems with both NSs and BHs progenitor masses a smaller: from 20 up to 50.
Finally, for the BH binary LMC X-3 the progenitor mass is estimated as >60 solar.
So, the situation is tricky.
Most probably, in some range of masses, at least in binary systems, stars can produce both types of compact objects: NSs and BHs.



Mass determination in binaries: mass function

$$f_v(m)\frac{m_x^3 \sin i^3}{(m_x+m_v)^2} = 1,038 \cdot 10^{-7} K_v^3 P (1-e^2)^{3/2},$$

m_x, m_v - masses of a compact object and of a normal star (in solar units),
K_v – observed semi-amplitude of line of sight velocity of the normal star (in km/s),
P – orbital period (in days), e – orbital eccentricity, i – orbital inclination
(the angle between the orbital plane and line of sight).

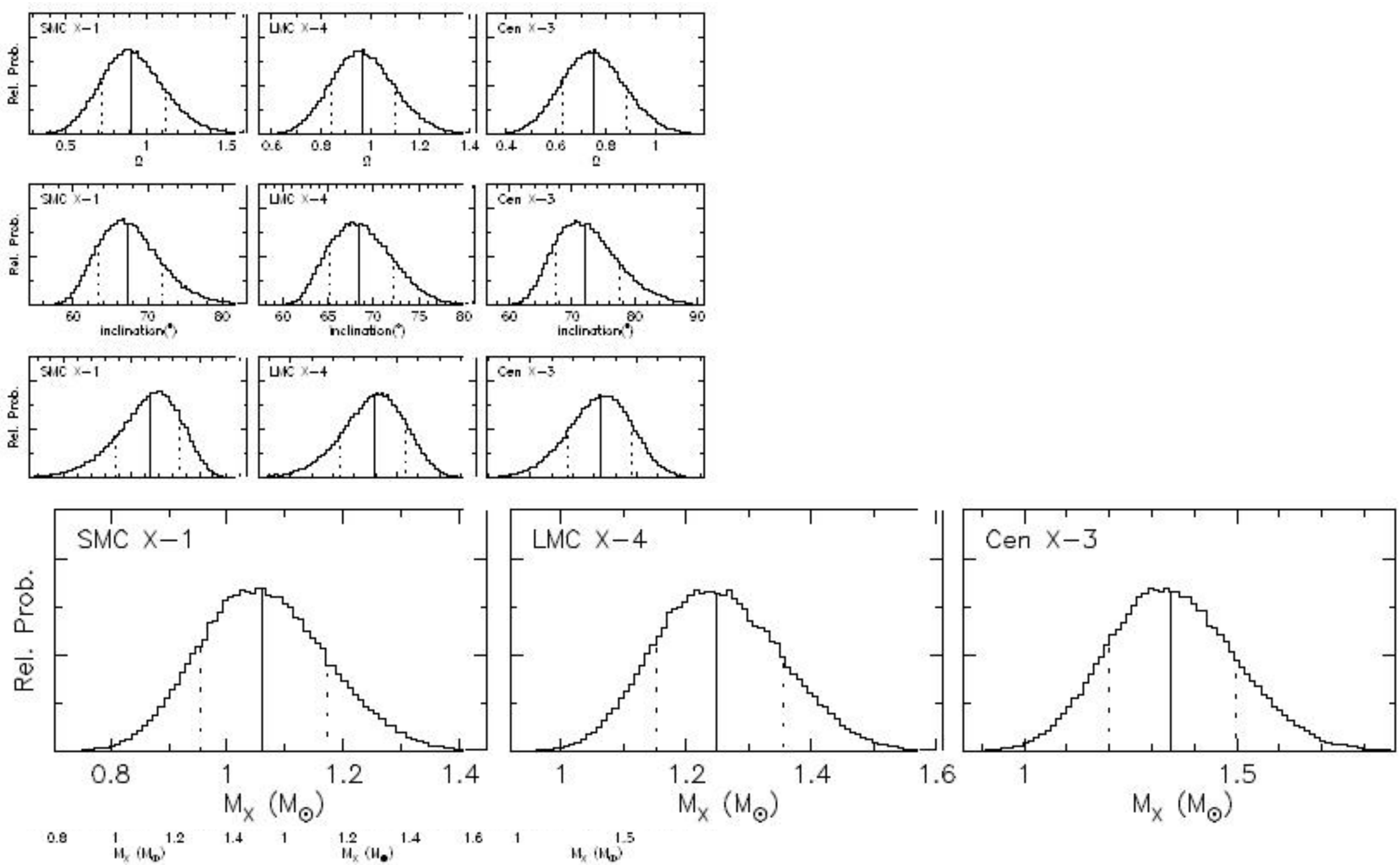
One can see that the mass function is the lower limit for the mass of a compact star.

The mass of a compact object can be calculated as:

$$m_x = f_v(m)\left(1+\frac{m_v}{m_x}\right)^2 \frac{1}{\sin i^3}.$$

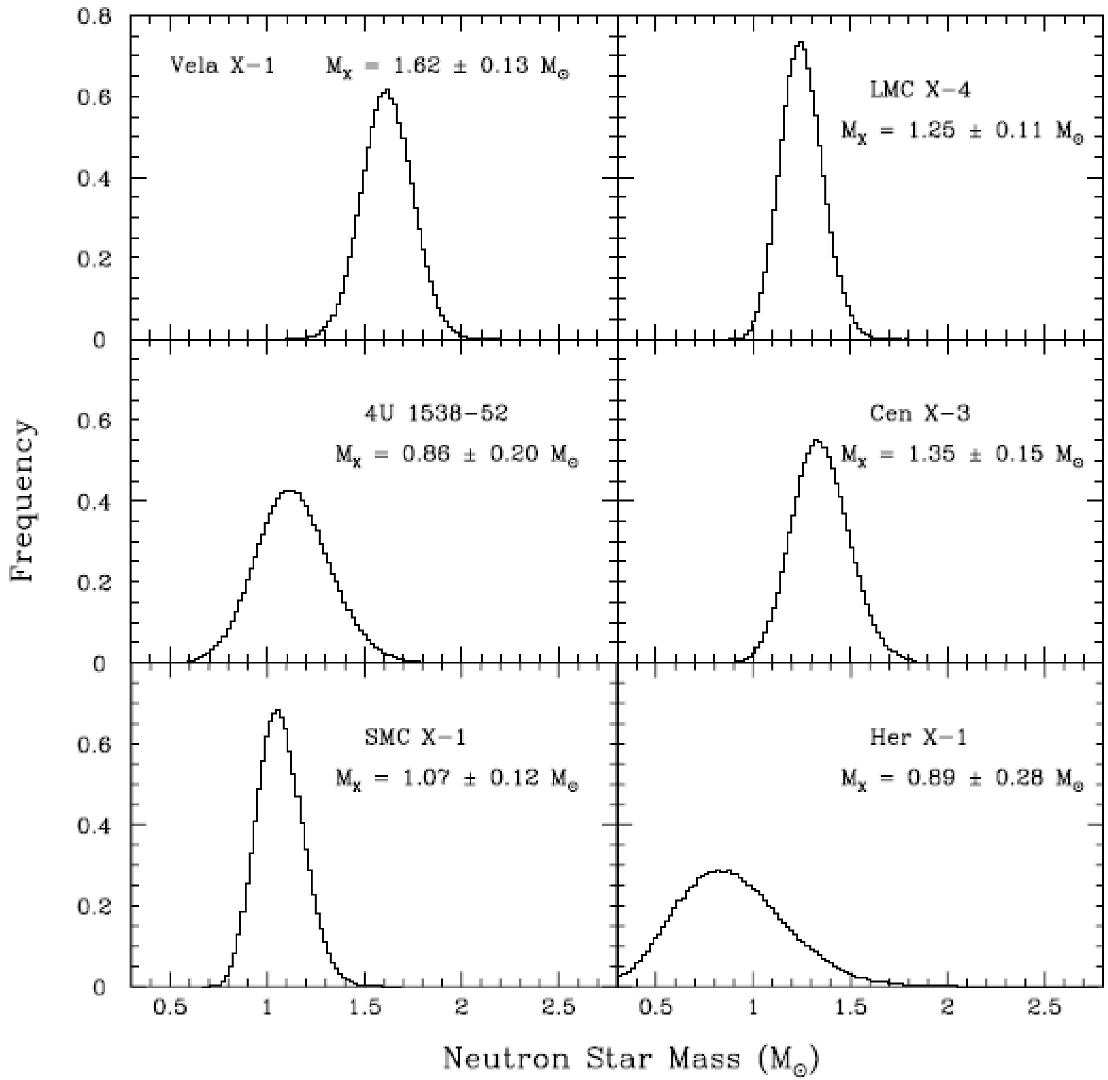
So, to derive the mass it is necessary to know (besides the line of sight velocity) independently two more parameters: mass ration $q=m_x/m_v$,
and orbital inclination i.

Some mass estimates



ArXiv: 0707.2802

More measurements



Six X-ray binary systems.
All are eclipsing pulsars.

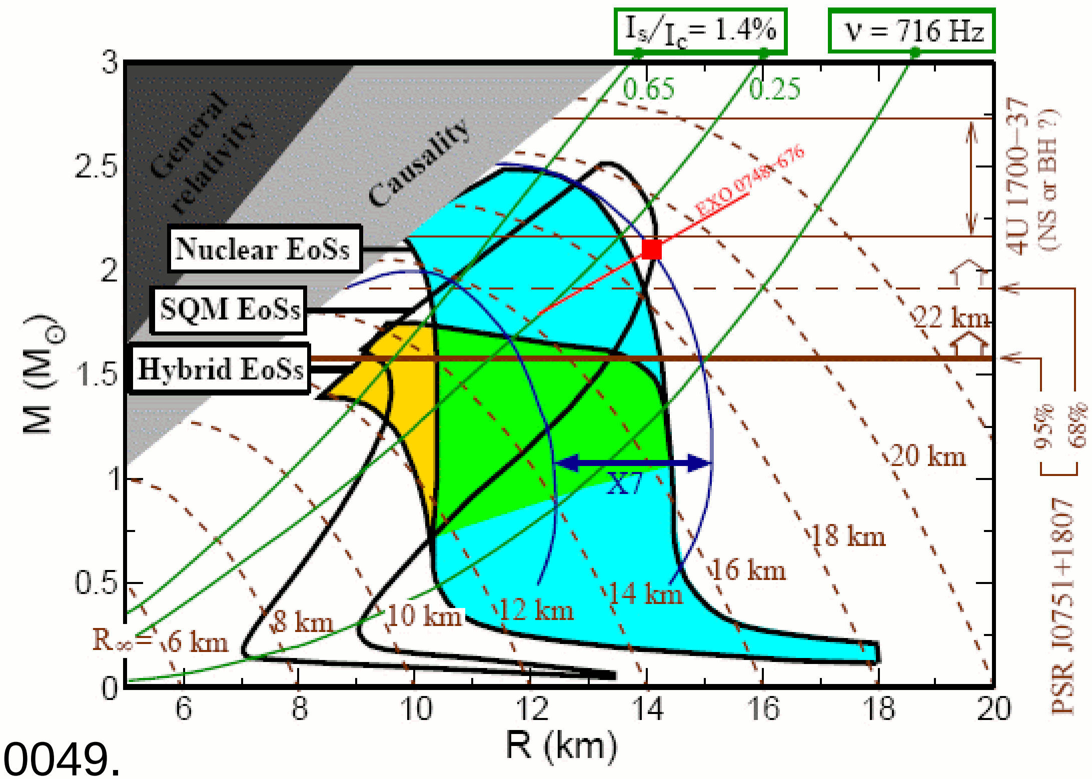
1101.2465

Mass-radius diagram and constraints

Unfortunately, there are no good data on independent measurements of masses and radii of NSs.

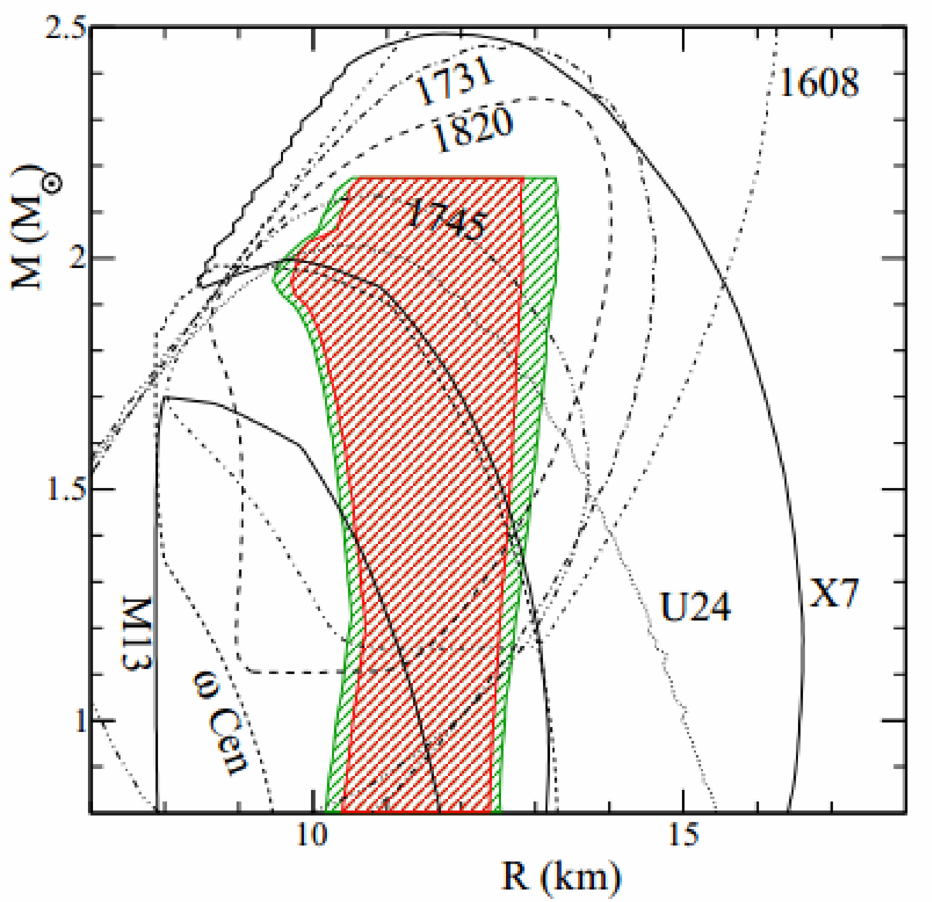
Still, it is possible to put important constraints.
Most of recent observations favour stiff EoS.

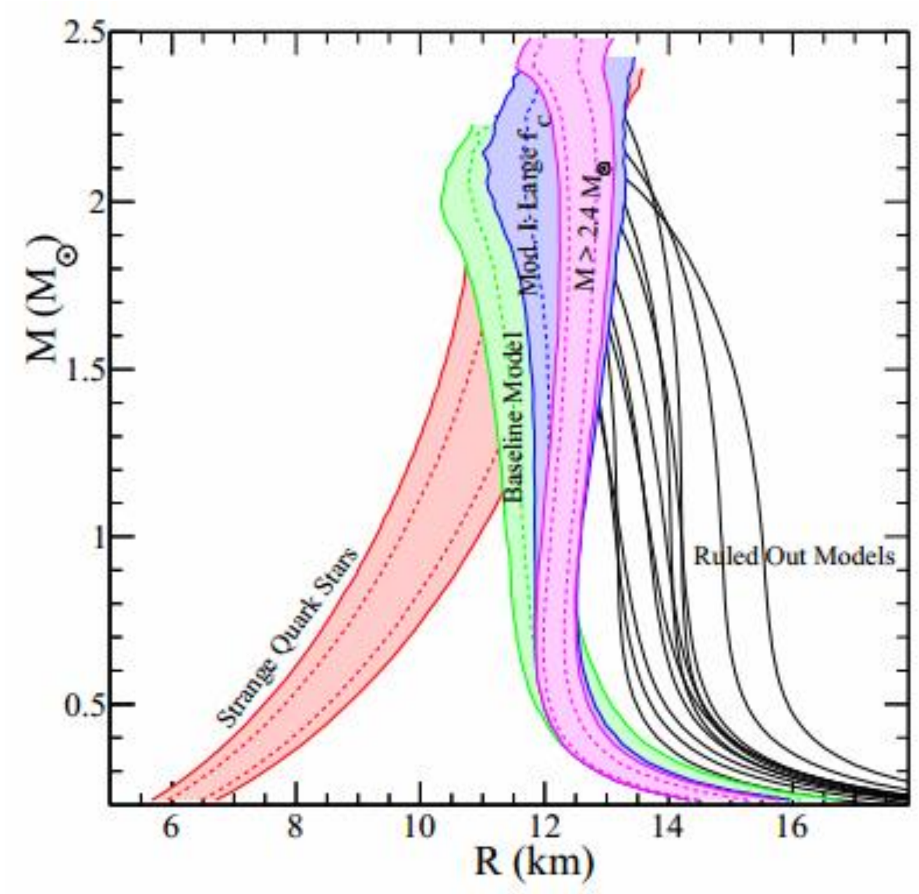
Useful analytical estimates for EoS can be found in 1310.0049.



astro-ph/0608345, 0608360

Observations vs. data





1205.6871 Some newer results by the same group are presented in 1305.3242

Mass and radius for a pulsar!

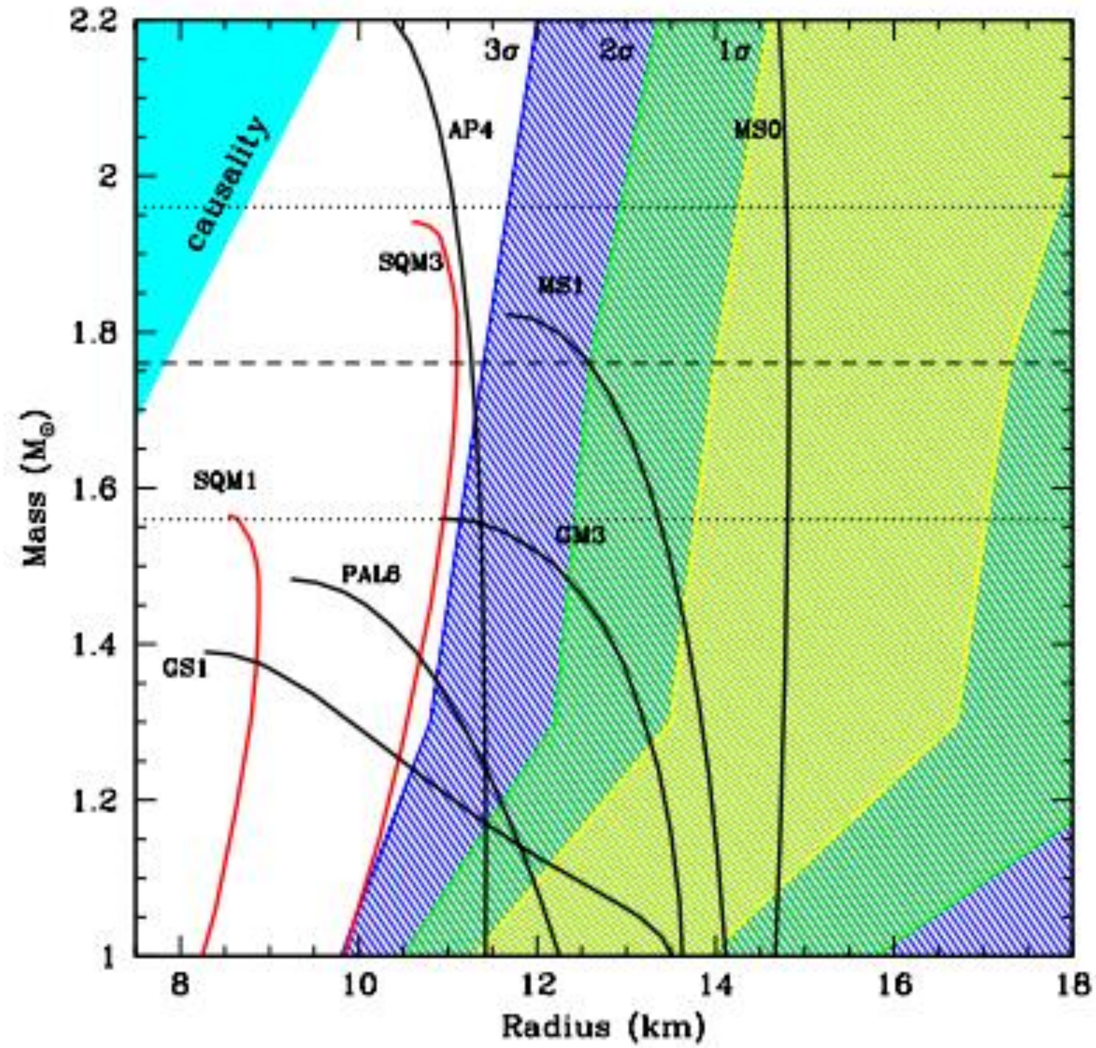
PSR J0437–4715 NS+WD

The nearest known mPSR
155-158 pc

XMM-Newton observations showed thermal emission.

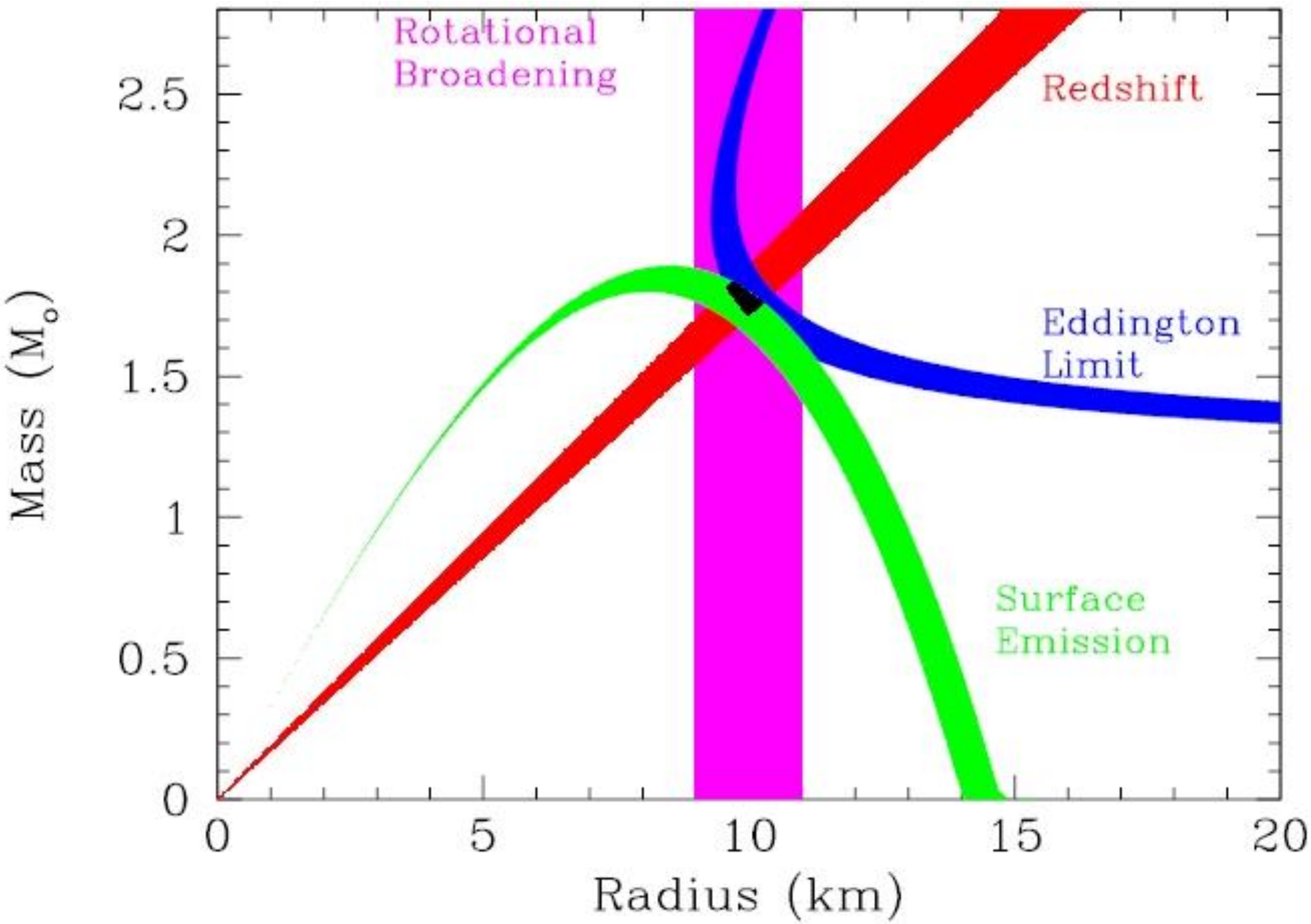
H-atmosphere model fits.

Hot caps are non-antipodal.



1211.6113

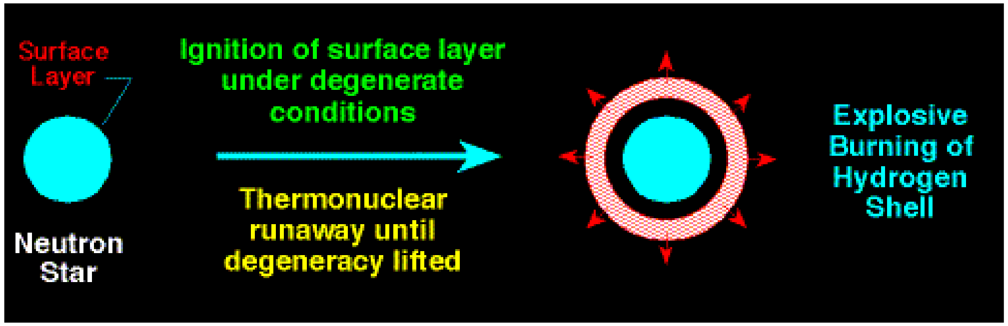
Combination of different methods



EXO 0748-676

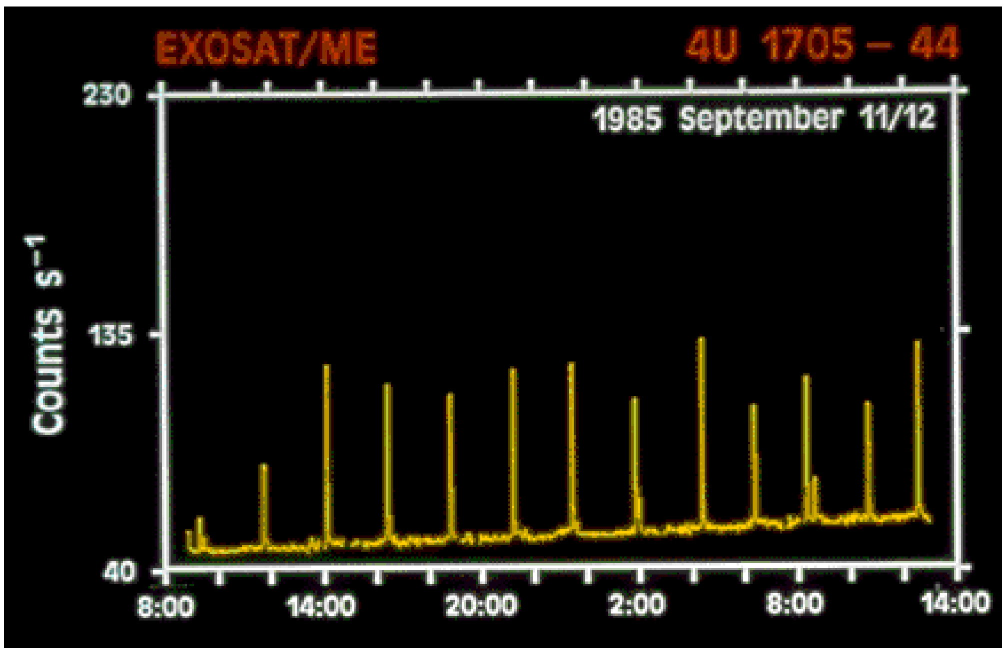
Ozel astro-ph/0605106

Radius determination in bursters



Explosion with a ~ Eddington liminosity.

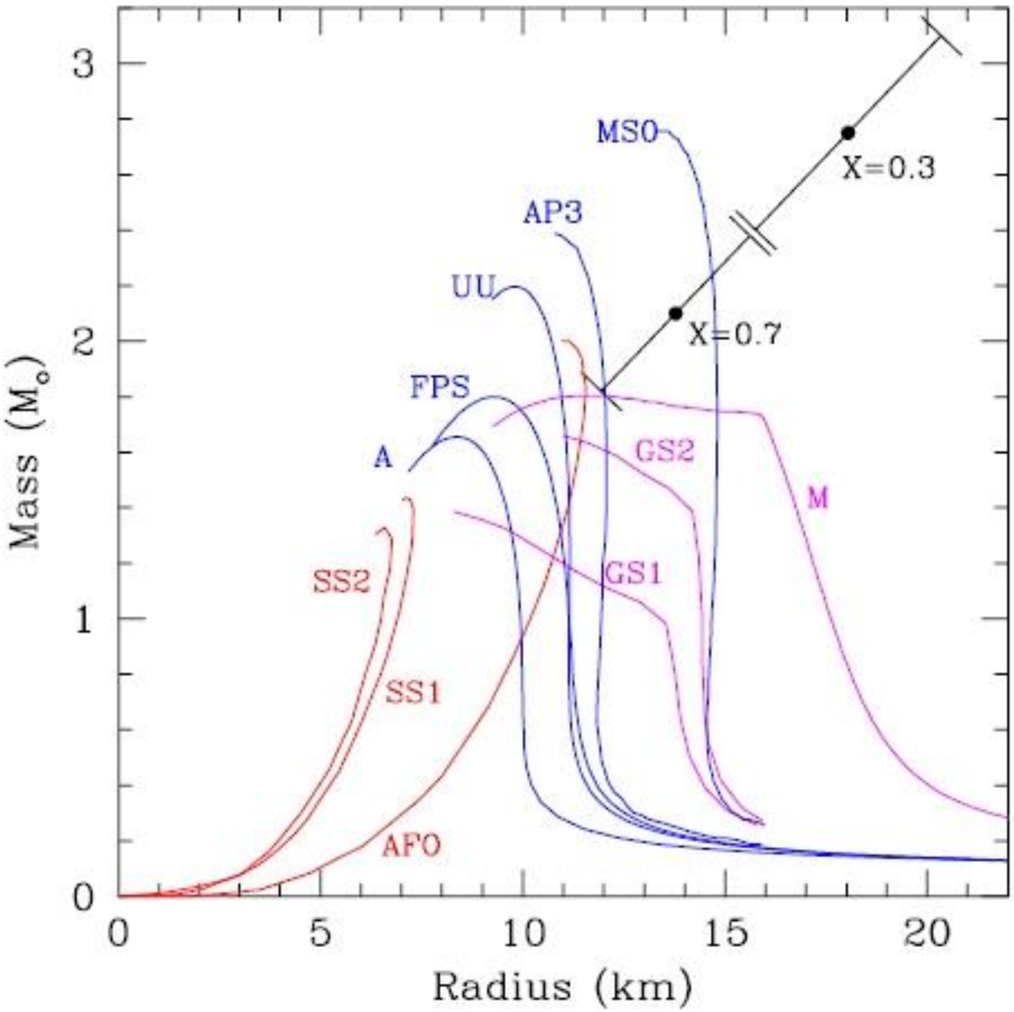
Modeling of the burst spectrum and its evolution.



See, for example,
Joss, Rappaport 1984,
Haberl, Titarchuk 1995

http://www.astro.washington.edu/ben/a510/NSTARS.new.html

Limits on the EoS from EXO 0748-676

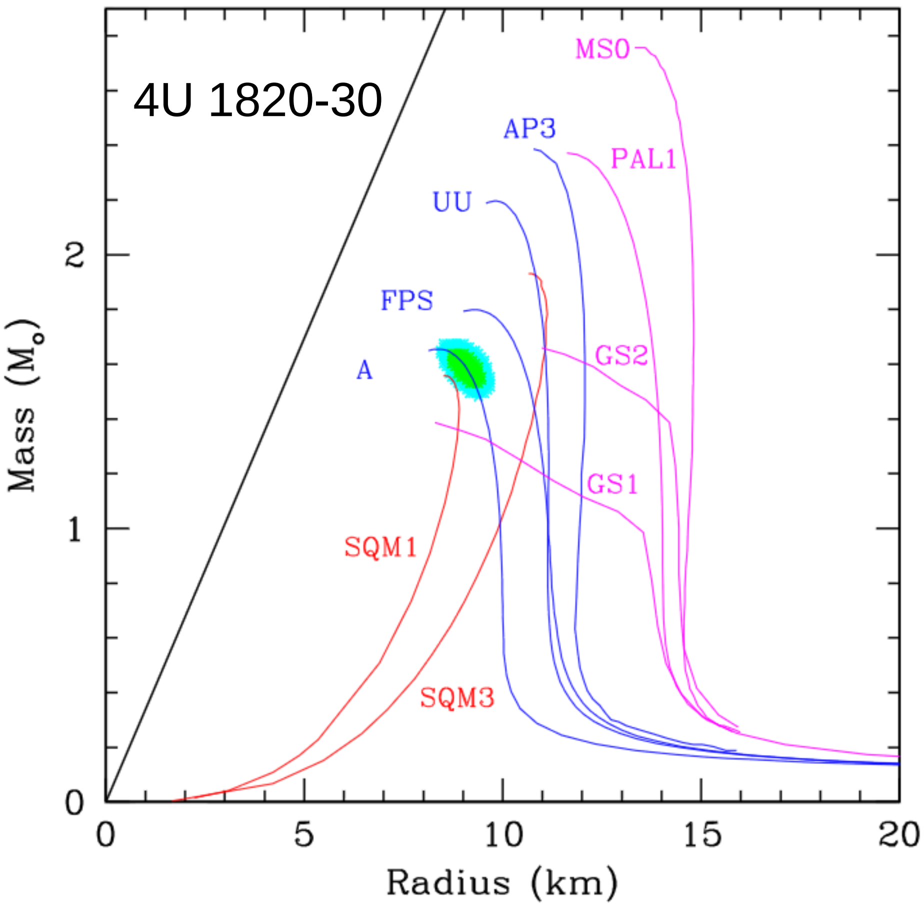


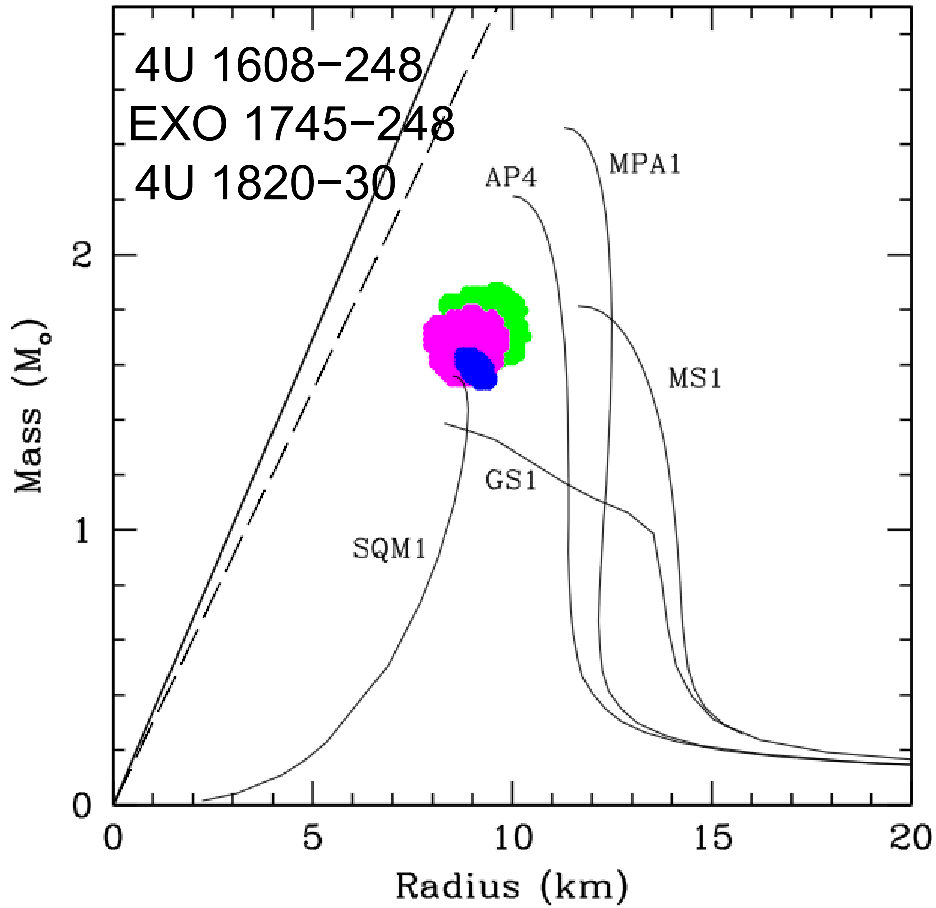
Stiff EoS are better.
Many EoS for strange matter are rejected.
But no all! (see discussion in Nature).

X- hydrogen fraction in the accreted material

Ozel astro-ph/0605106

Some optimistic estimates

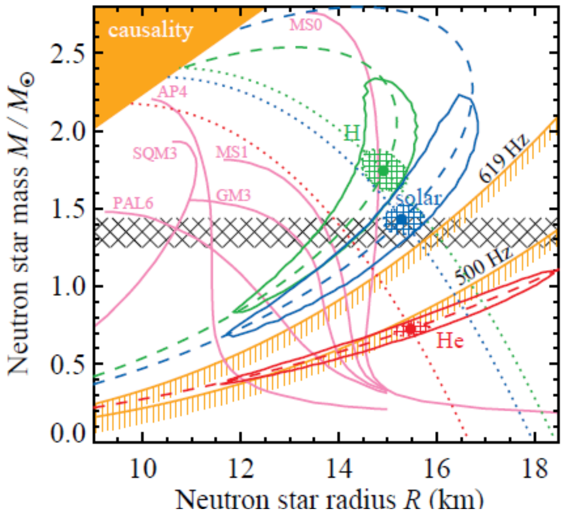




1002.3825

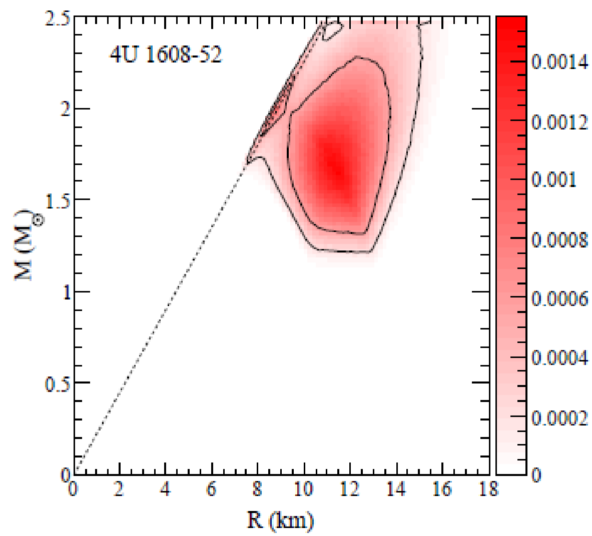
1002.3153

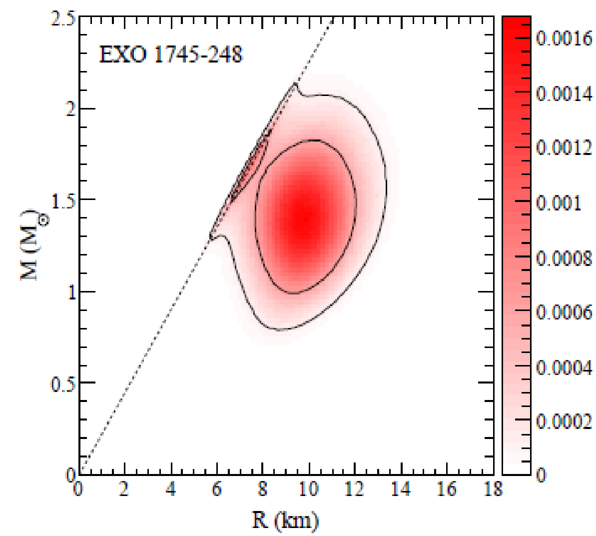
Pessimistic estimates

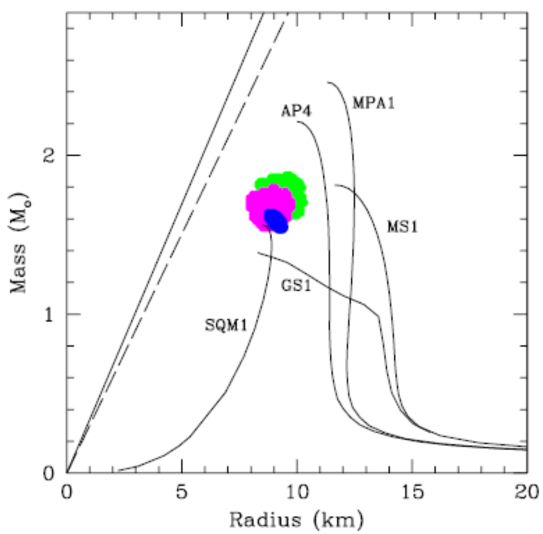


1004.4871

1005.0811





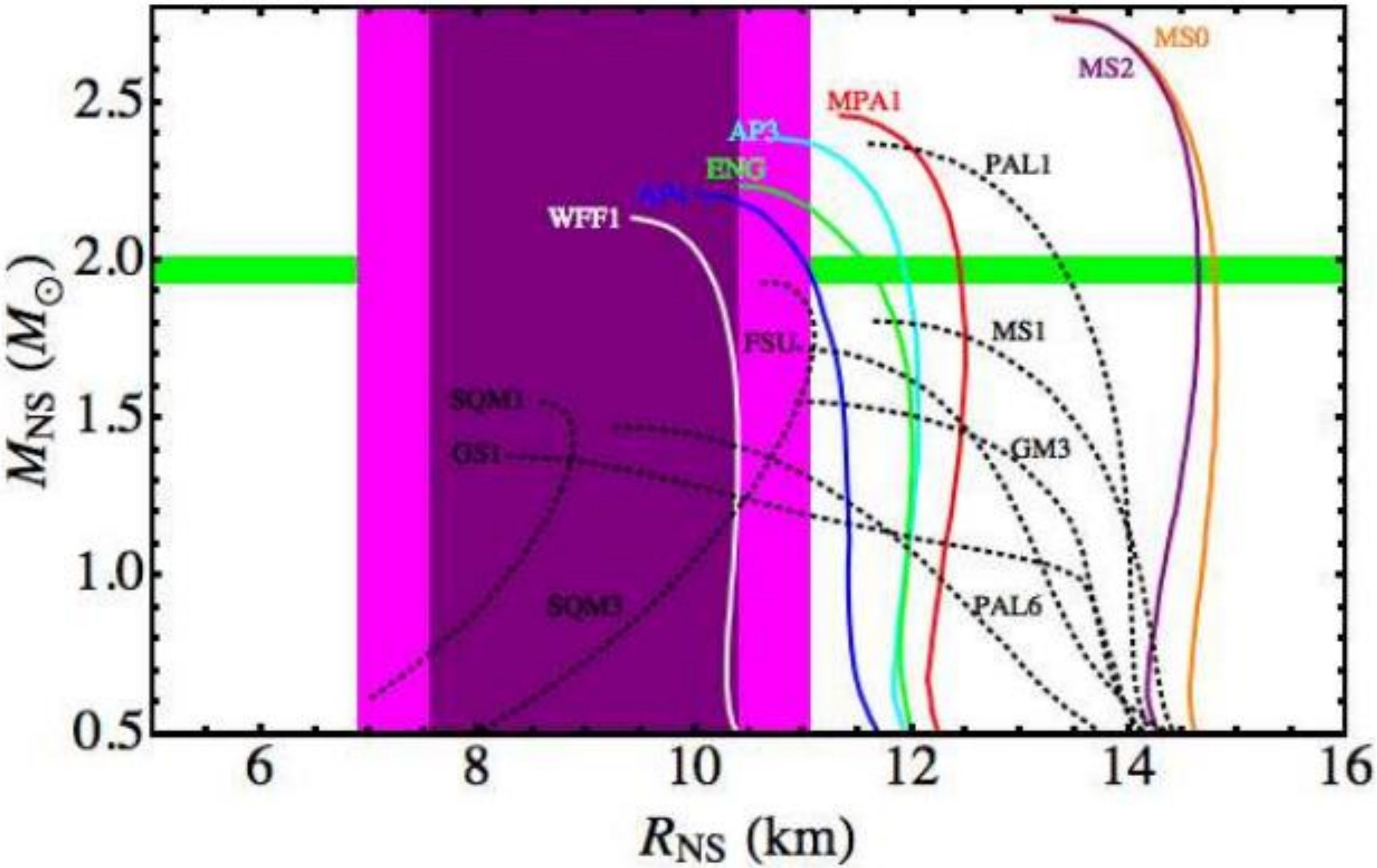


It seems that Ozel et al. underestimate different uncertainties and make additional assumptions.

1002.3153

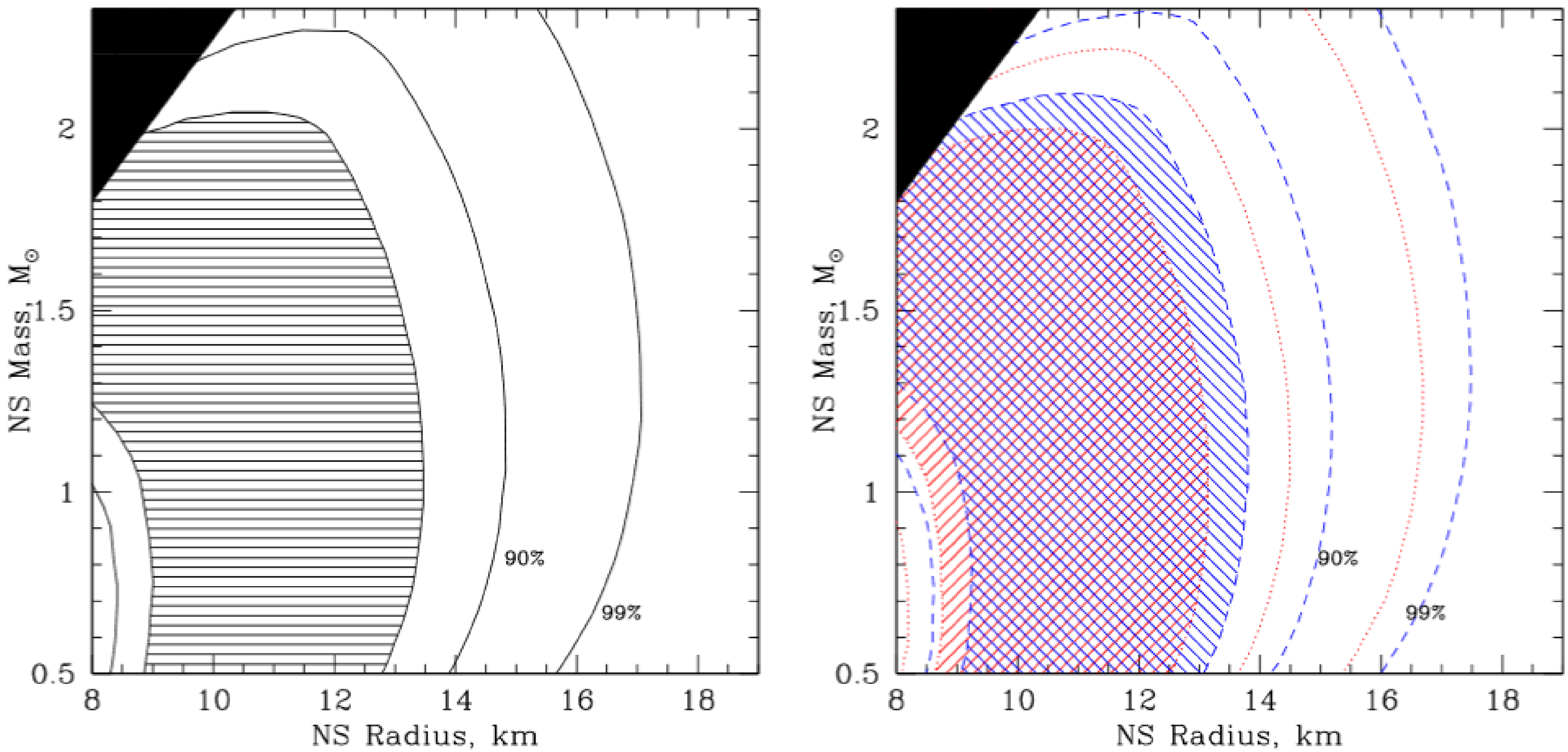
Radii measurements for qLMXBs in GCs

5 sources



1302.0023, see new results in 1905.01081

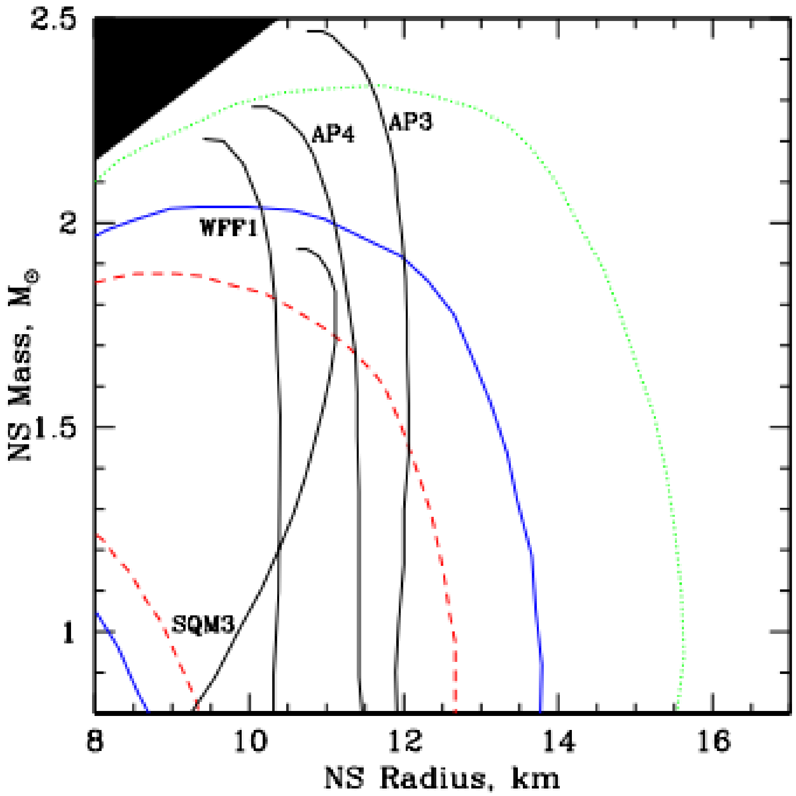
Distance uncertainty



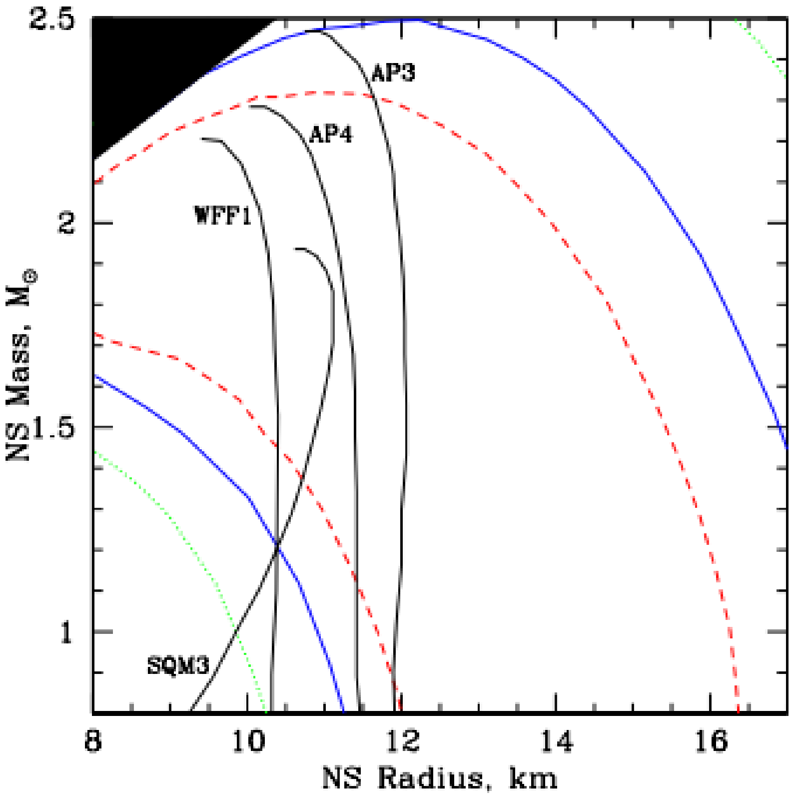
1406.1497

Atmospheric uncertainties

qLMXB in M13



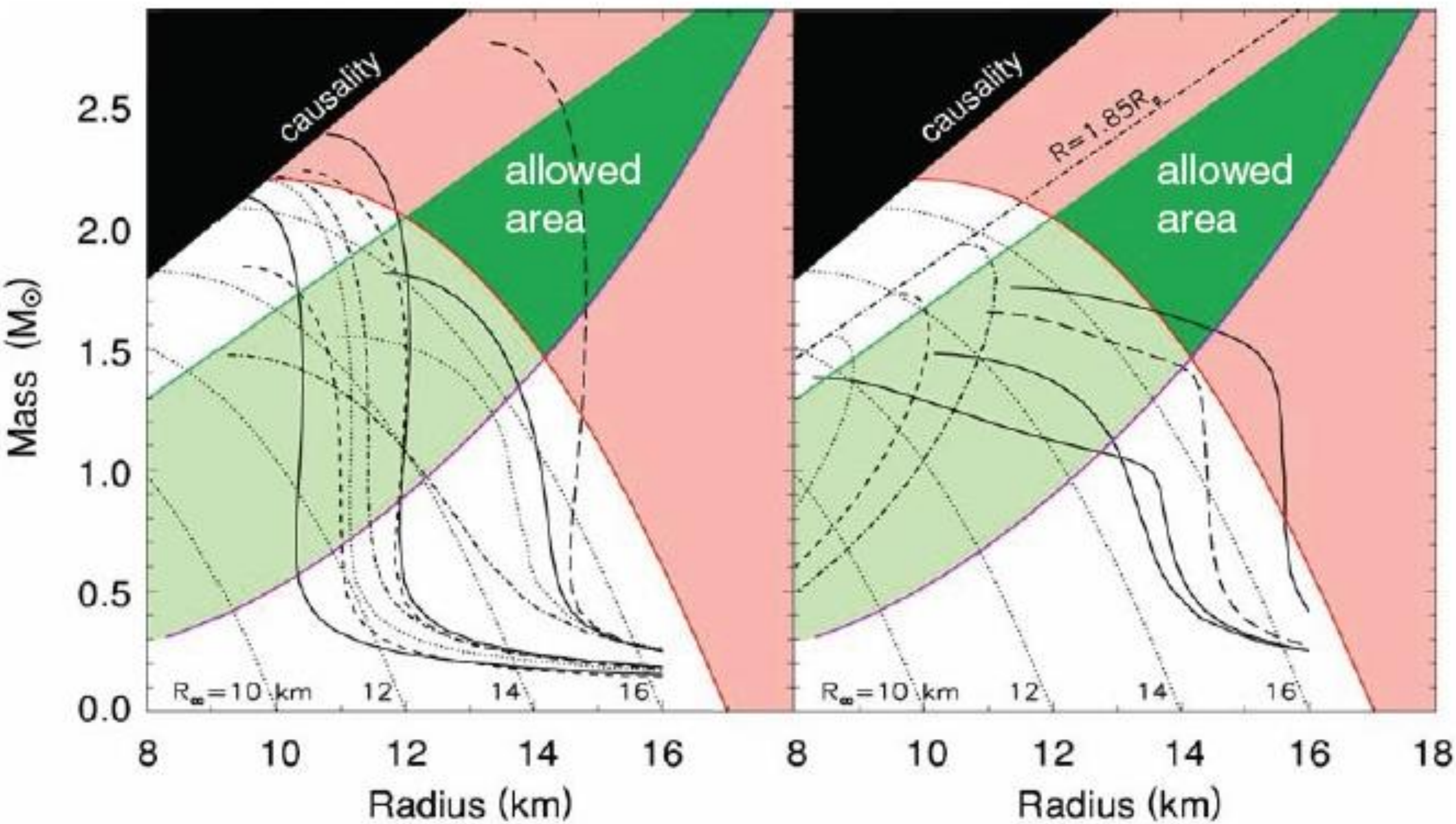
Hydrogene



Helium

1301.3768

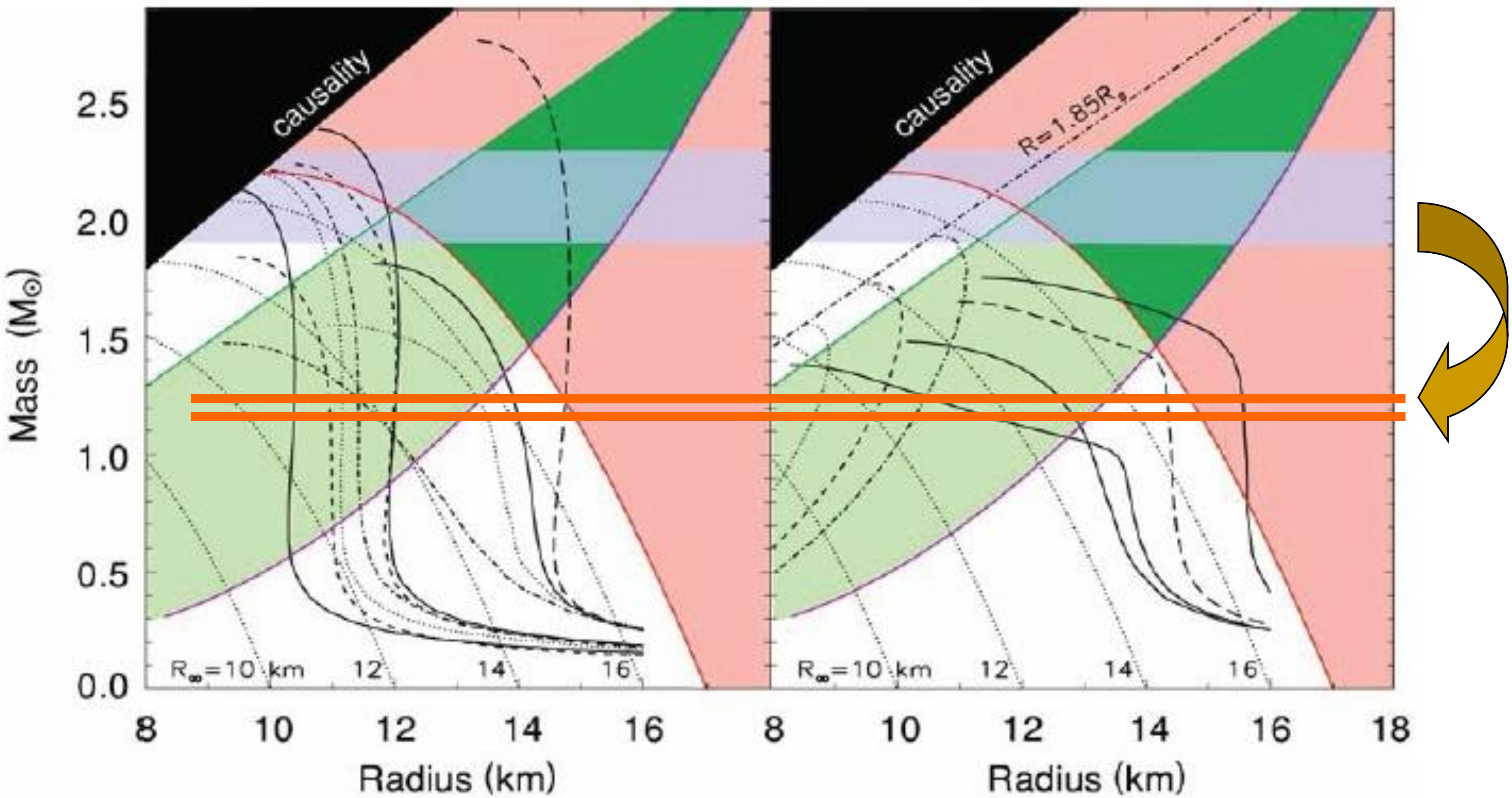
Limits from RX J1856



Trumper

About M7 for constraints on the EoS see 1111.0447

PSR 0751+1807



Massive NS: 2.1+/-0.3 solar masses – later shown to be wrong (!)

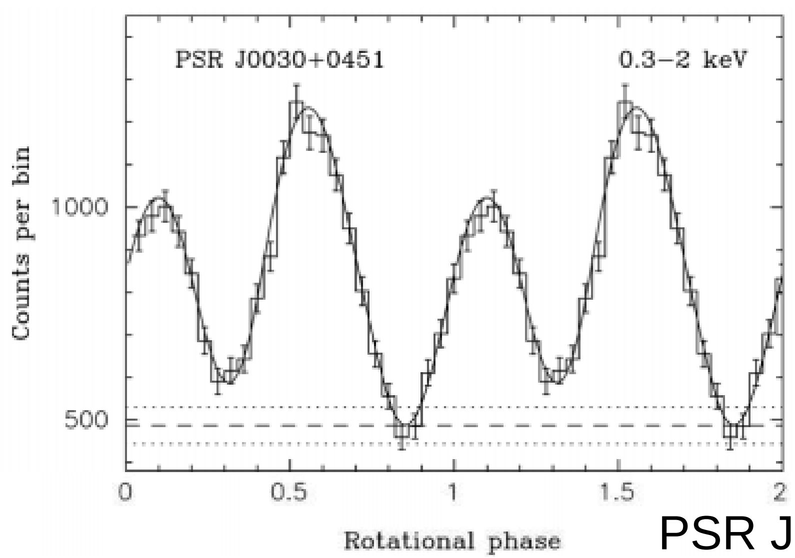
[see Nice et al. 2008]

Trumper

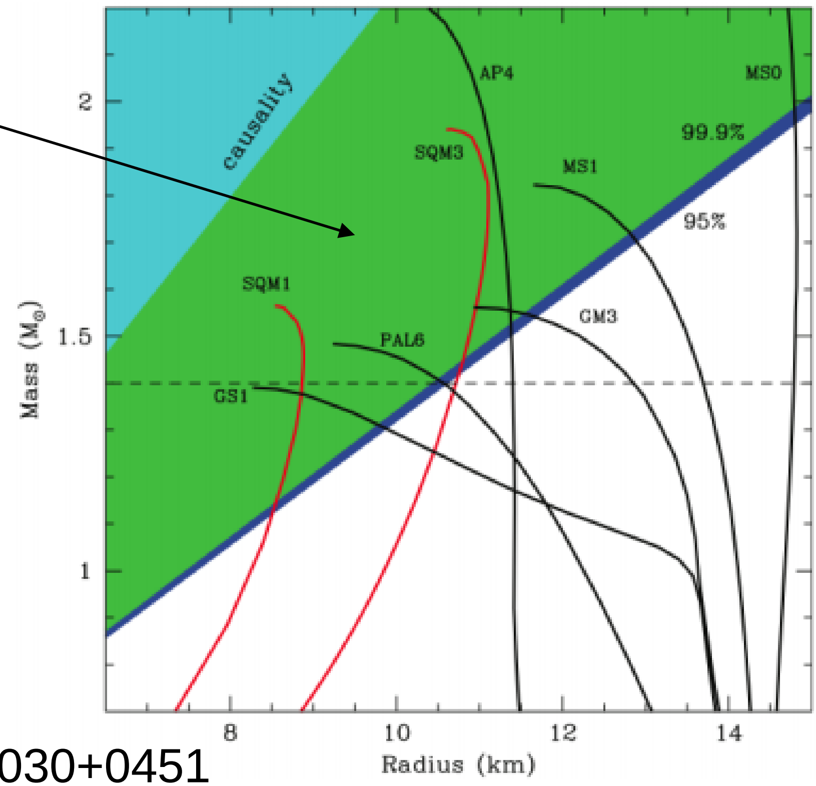
Pulse profile constraints

The idea is that: sharp pulses are possible only in the case of a large star.

Green – excluded region



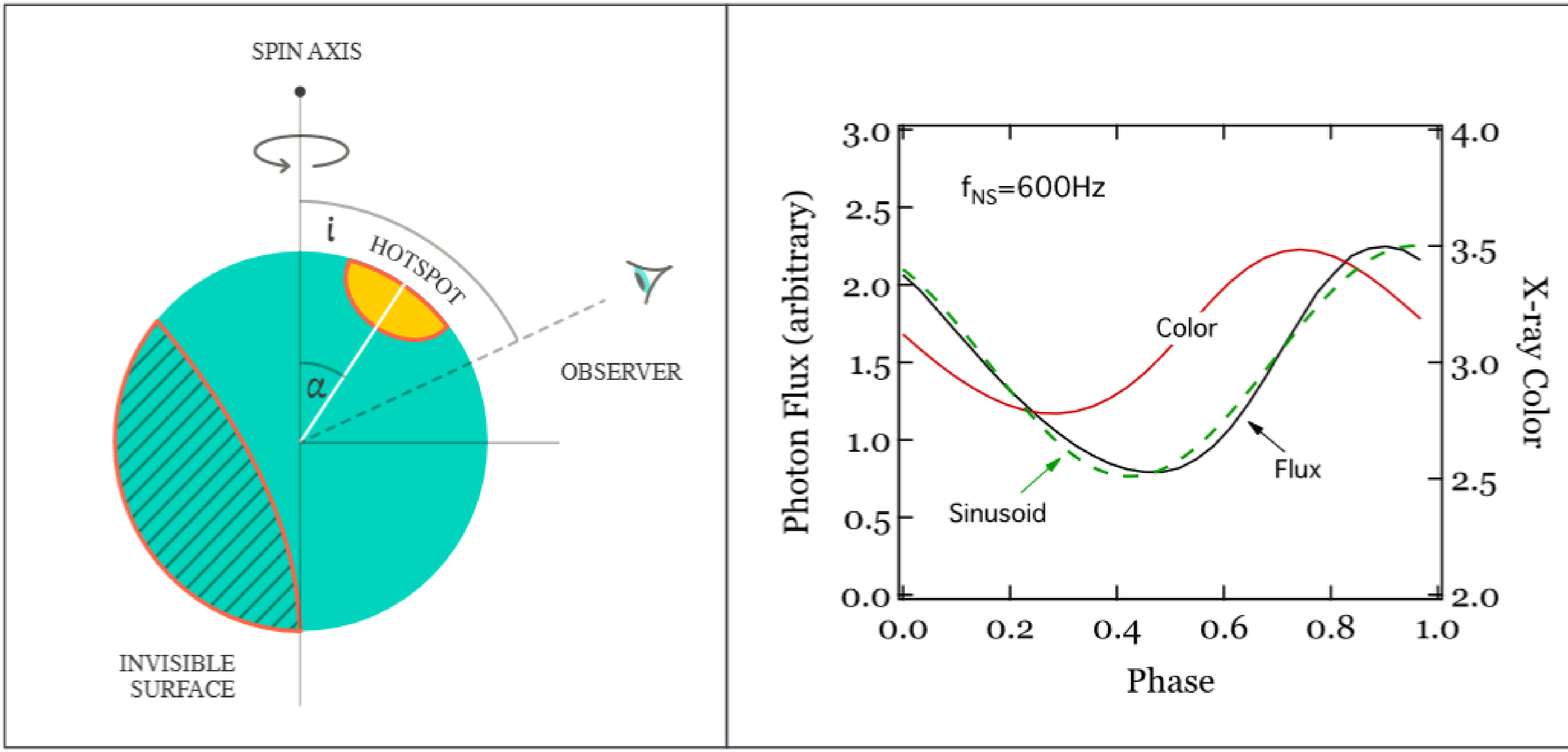
PSR J0030+0451



Based on Bogdanov, Grindlay 2009

1303.0317

Hot spots and pulse profiles



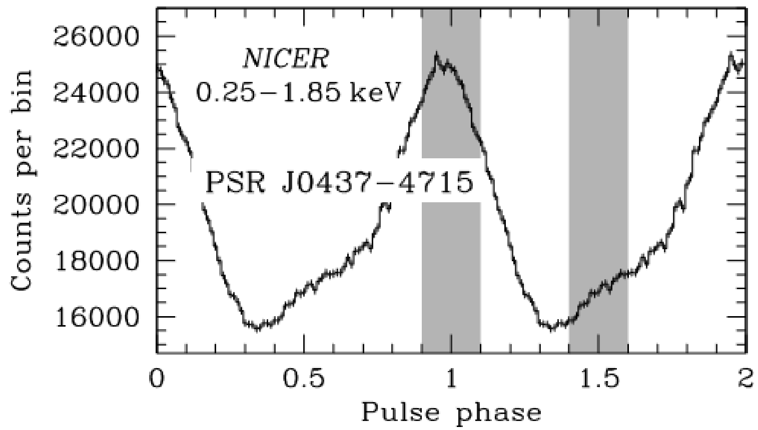
As the neutron star rotates, emission from a surface hotspot generates a pulsation. The figure shows observer inclination i, and hotspot inclination α. The invisible surface is smaller than a hemisphere due to relativistic light-bending.

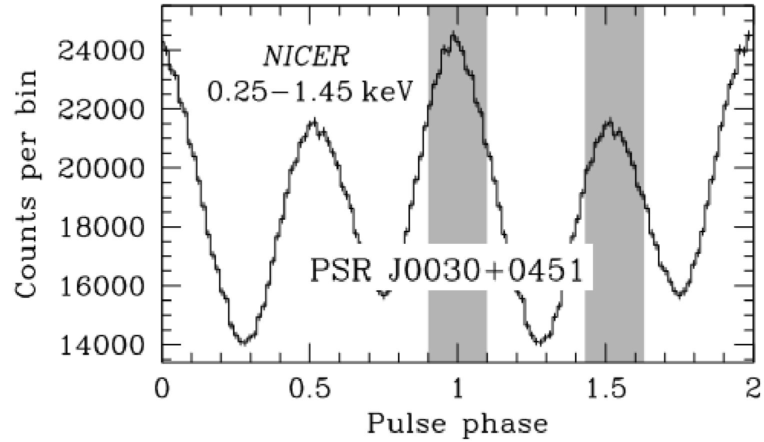
1602.01081

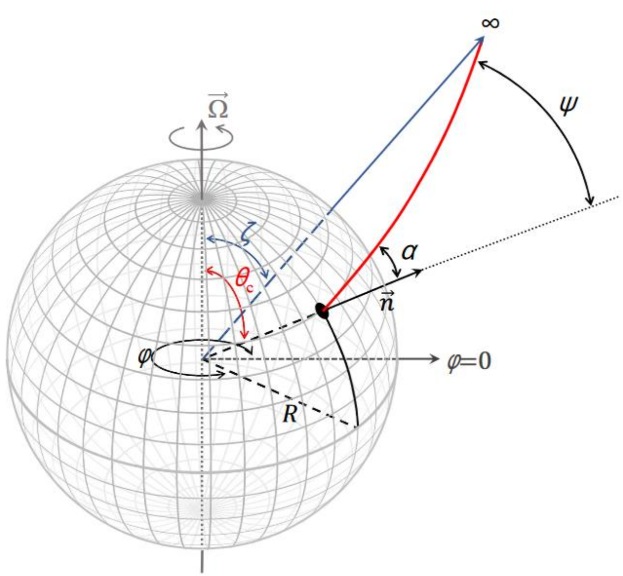
Detailed model description in 2104.06928.

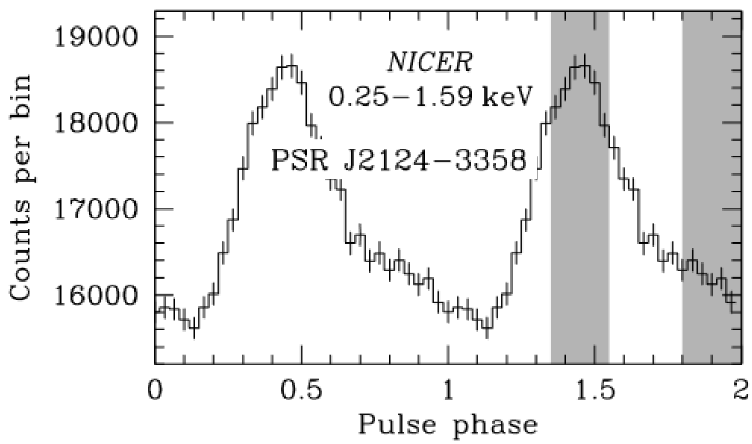
NICER's mPSRs

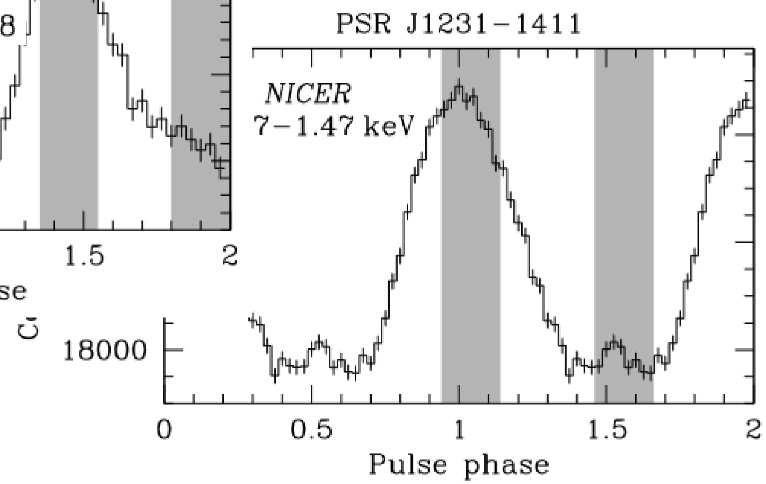
Four near-by millisecond radio pulsars:
J0437−4715
J0030+0451
J1231−1411
J2124−3358











1912.05707, 1912.05706

Results from NICER. PSR J0030+0451

$1.34^{+0.15}_{-0.16}\ \mathrm{M}_\odot$

$12.71^{+1.14}_{-1.19}$ km

For the ST-PST model

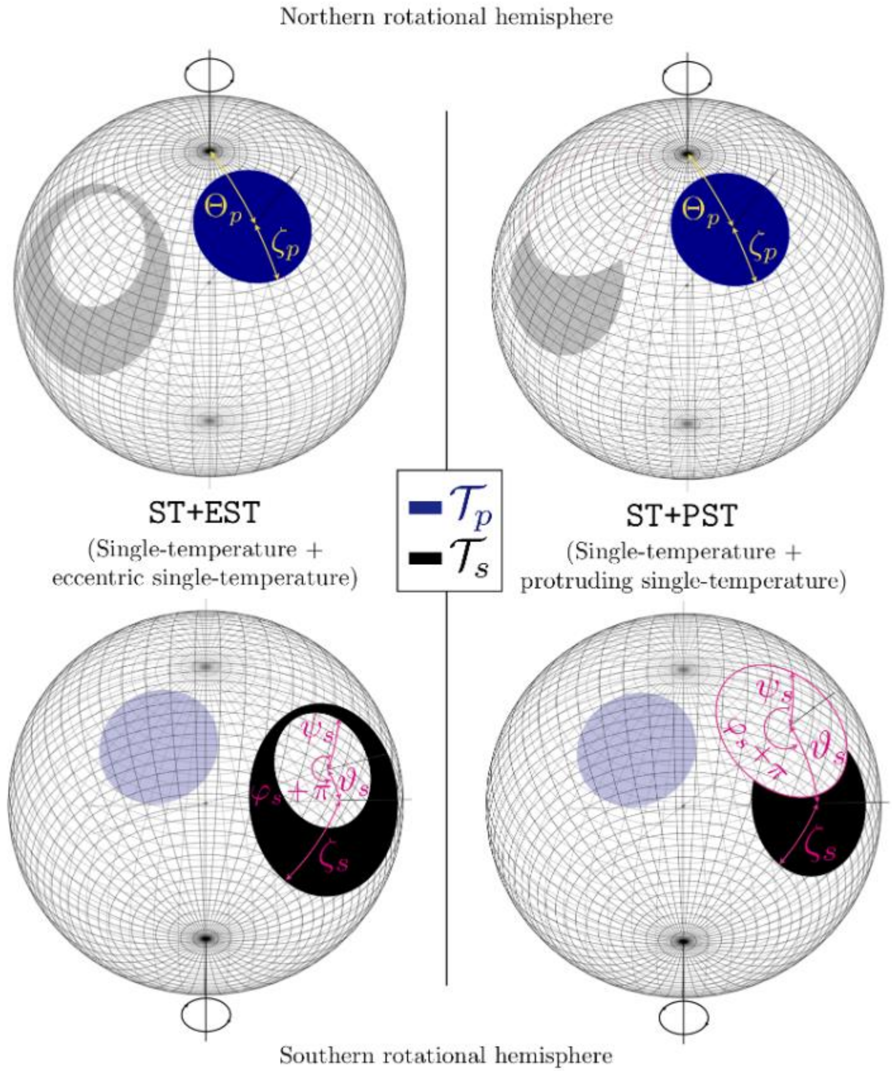
Single temperature+Protruding single temp.
No antipodal symmetry.

But several other tried models
are not ruled out.

For example, in the ST-CST model

$$M = 1.44^{+0.18}_{-0.19}\ \mathrm{M}_\odot$$

$$R_{\mathrm{eq}} = 13.89^{+1.22}_{-1.39}\ \mathrm{km}$$

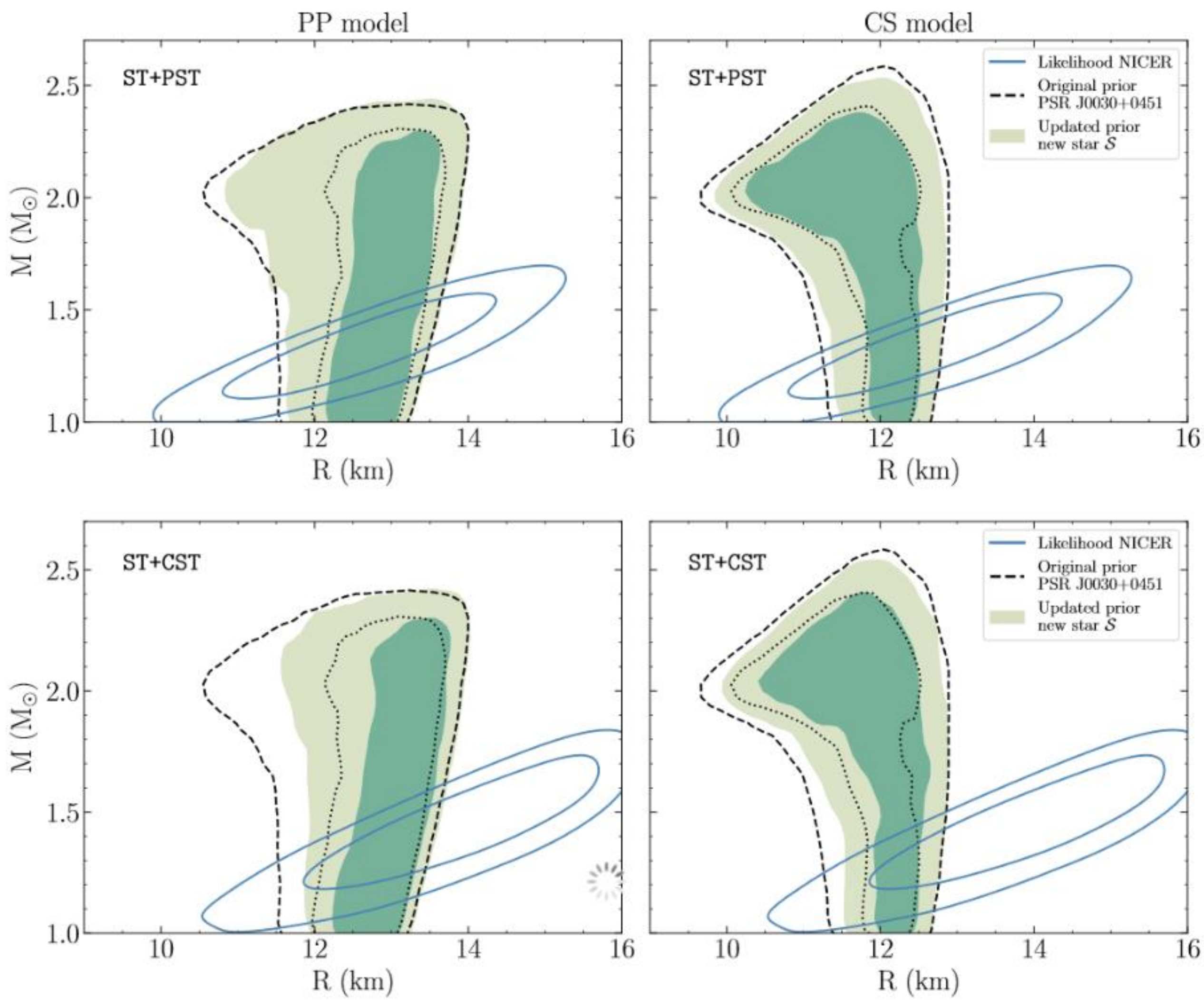


1912.05702

Results from NICER. PSR J0030+0451

Two types of EoS models are considered:

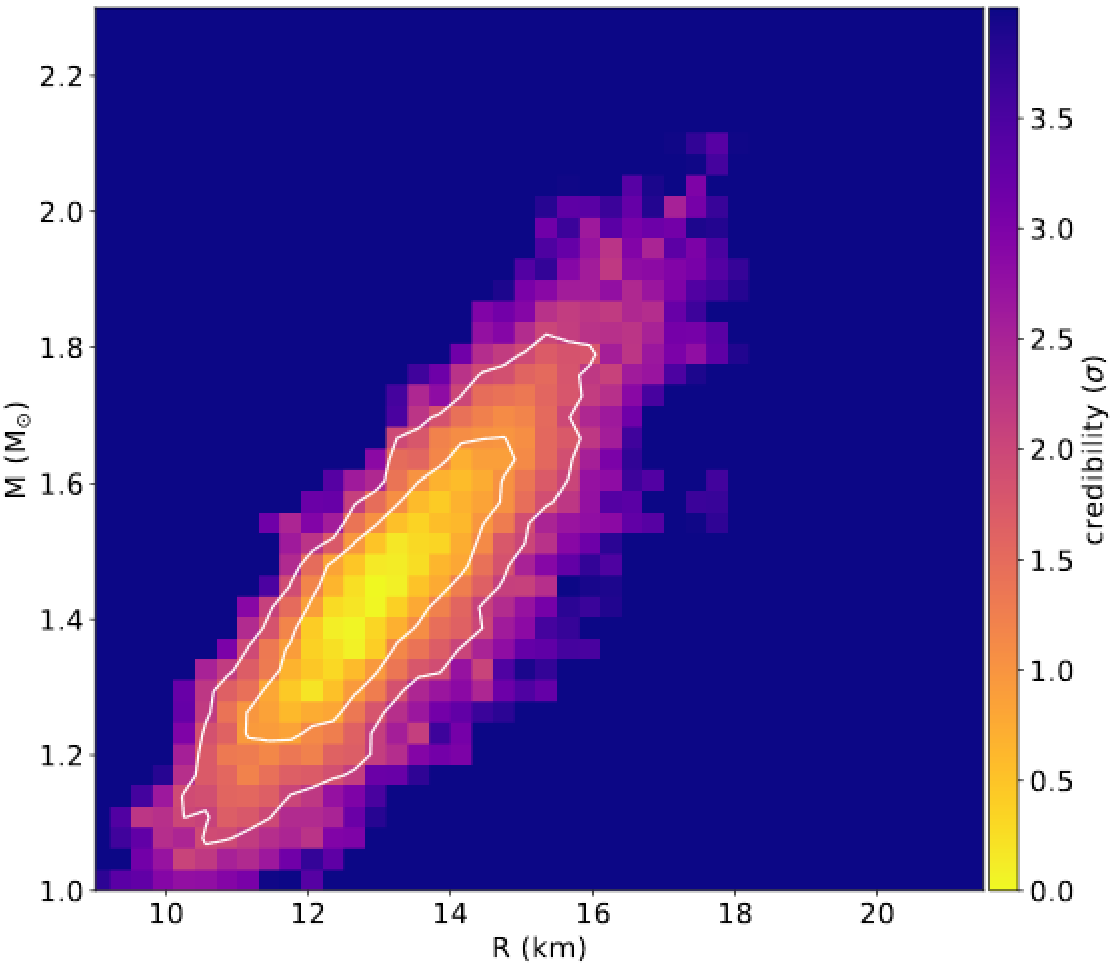
- PP (piecewise-polytropic);
- CS (speed of sound).

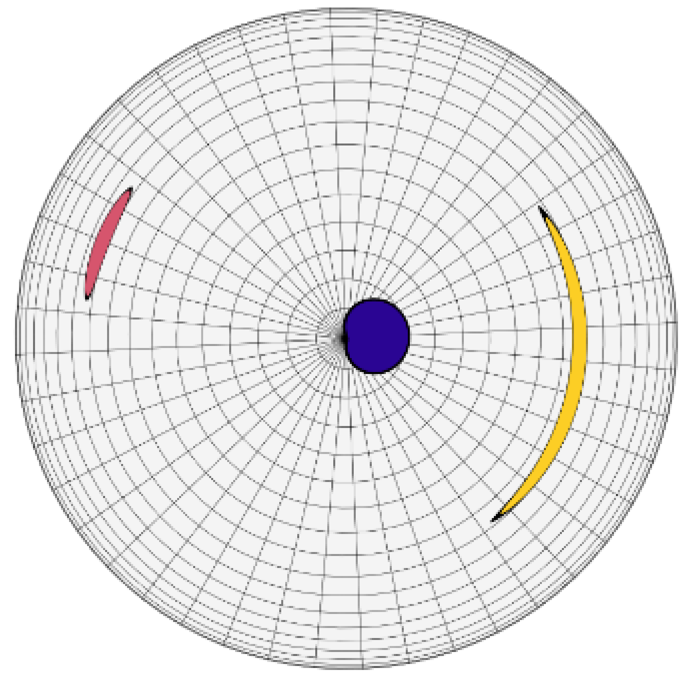


1912.05703

Results from NICER. PSR J0030+0451

Three oval spots model.
Non-trivial field structure.



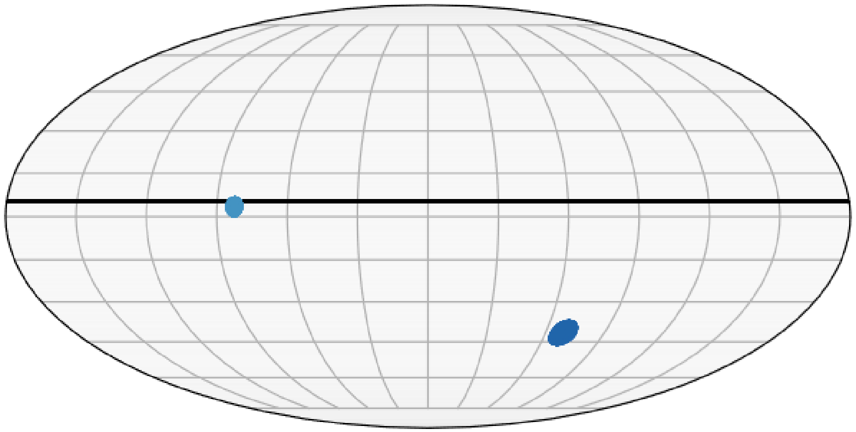


$$R_e = 13.02^{+1.24}_{-1.06} \text{ km}$$

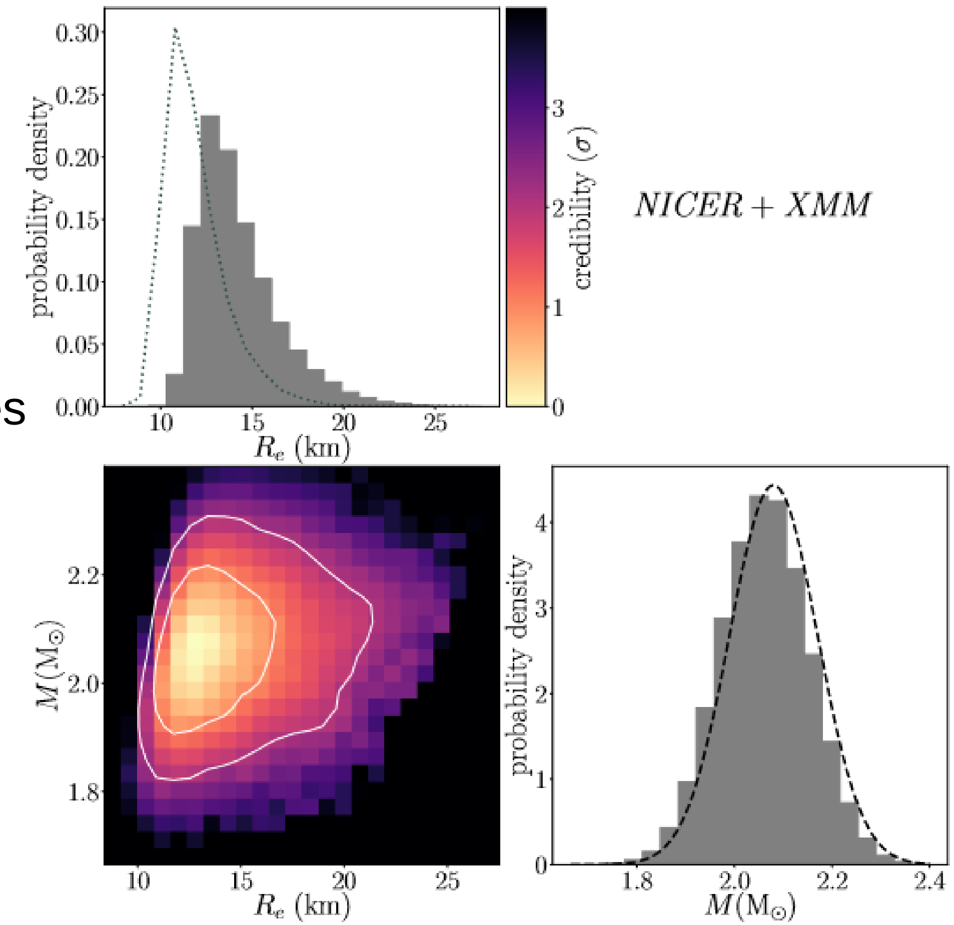
$$M = 1.44^{+0.15}_{-0.14} \ M_\odot$$

1912.05705

Results from NICER. PSR J0740+6620



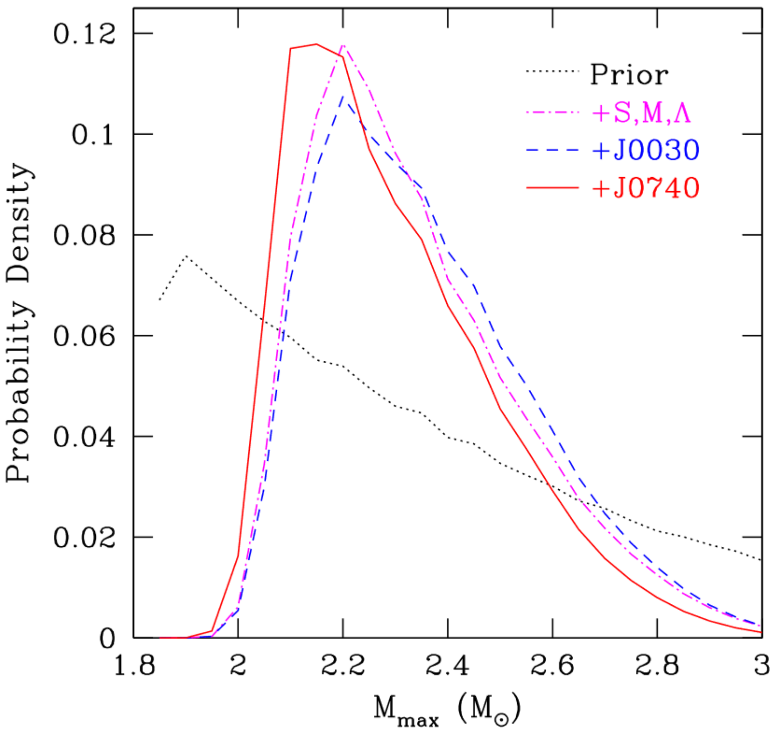
Without XMM data the radius is smaller.

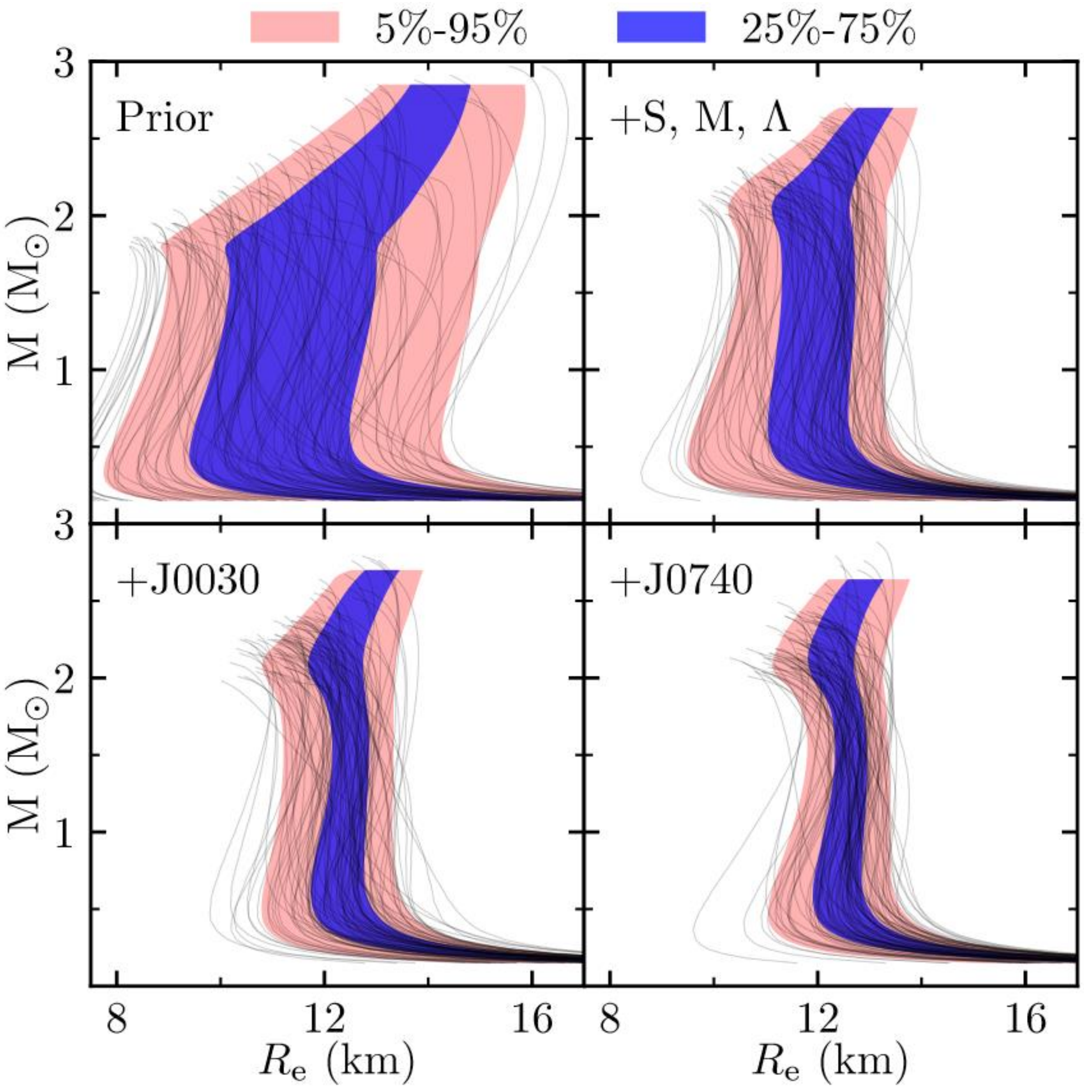


Model: two circular spots,
pure hydrogen model atmospheres
that allow for the possibility
of partial ionization.

2105.06979

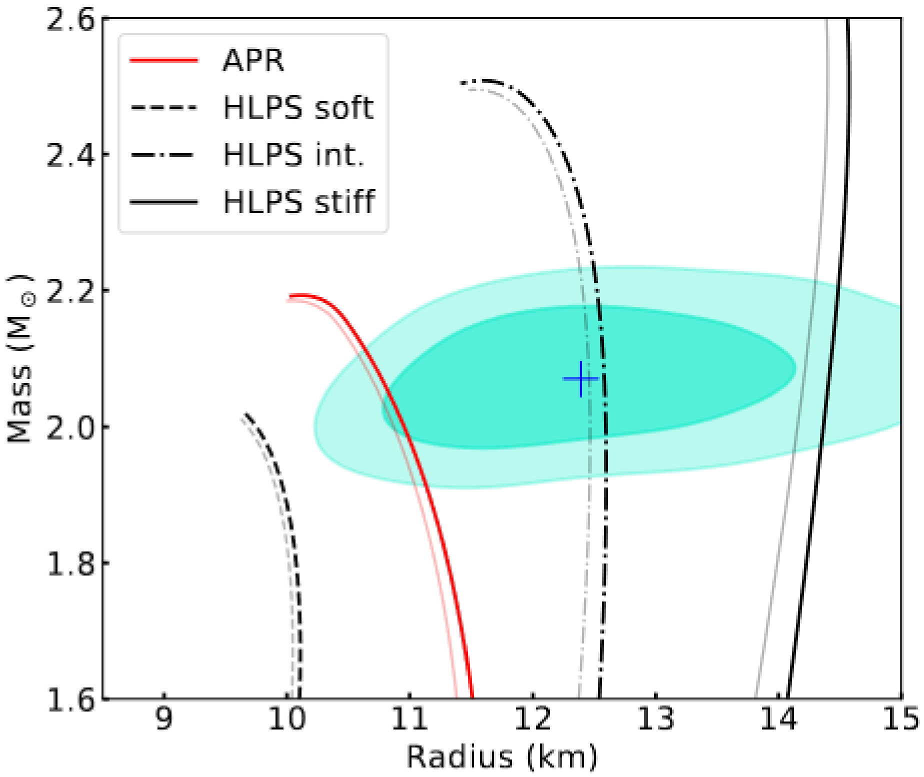
PSR J0740+6620 and EoS

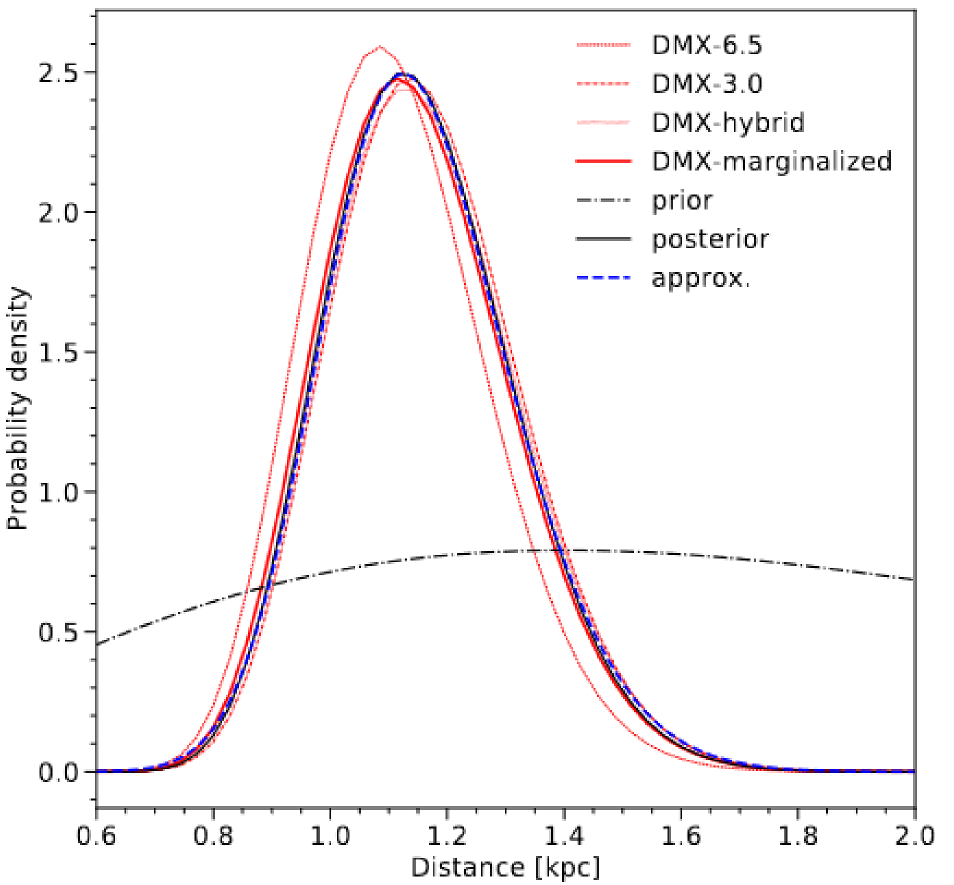




2105.06979

PSR J0740+6620. X-ray+radio data

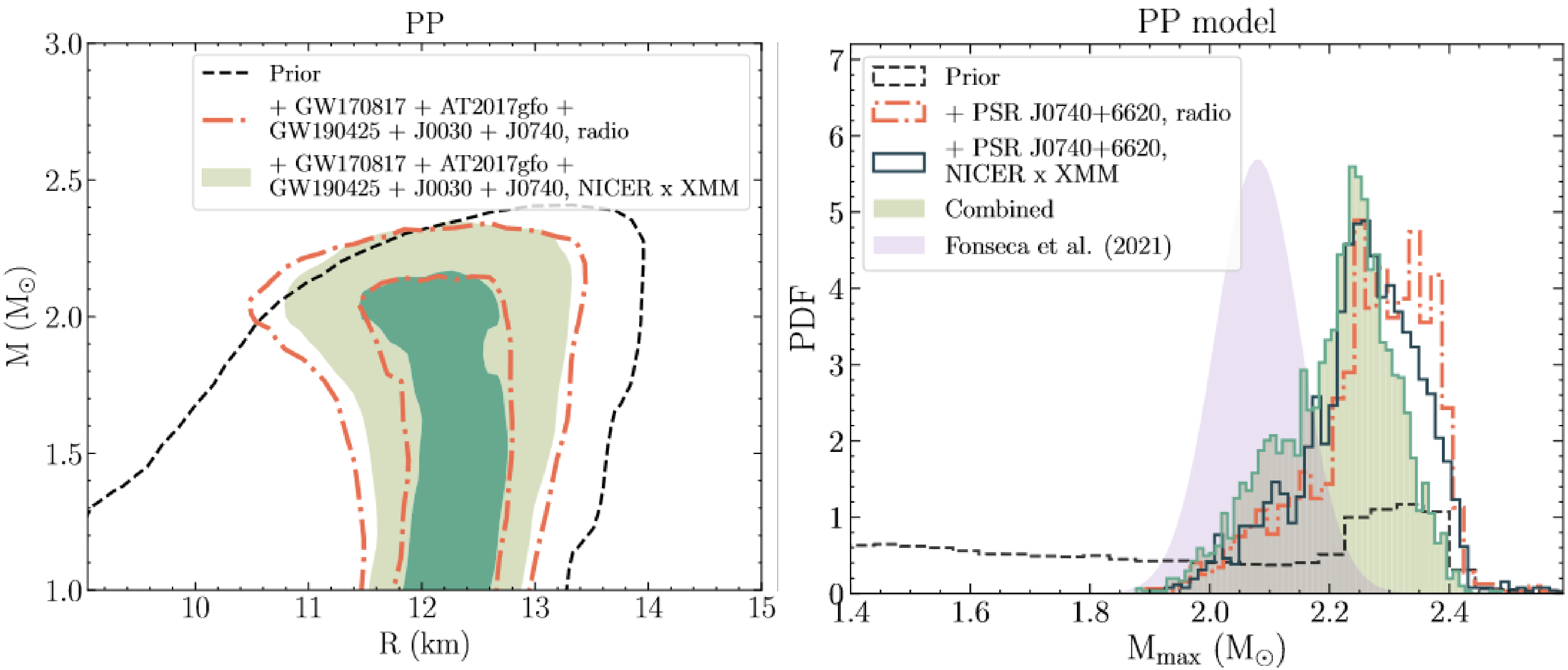




Based on radio (NANOGrav+CHIME)

2105.06980

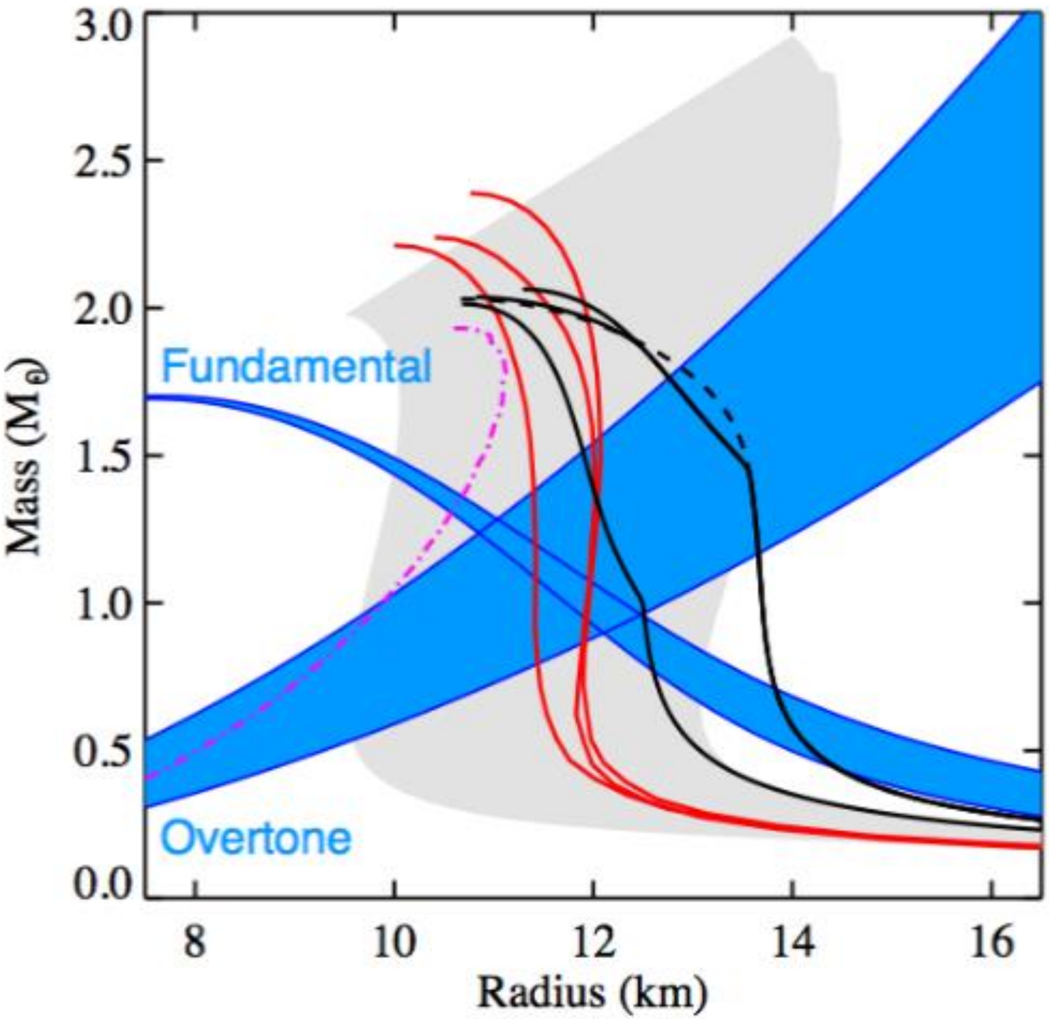
Altogether now



Joint constraints based on NICER, GW, etc.

2105.06981

Astroseismology



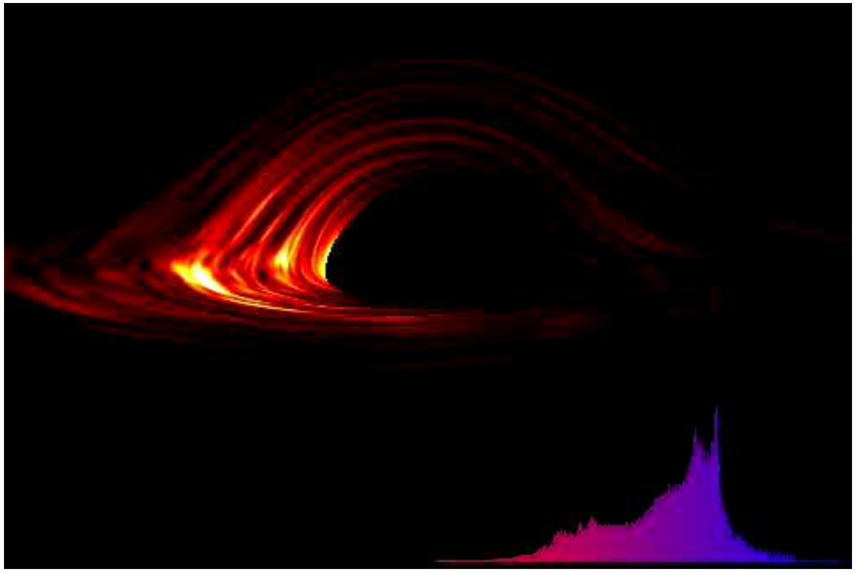
M – R diagram showing the seismological constraints for the soft gamma-ray repeater SGR 1806–20 using the relativistic torsional crust oscillation model of Samuelsson and Andersson (2007), in which the 29 Hz QPO is identified as the fundamental and the 625 Hz QPO as the first radial overtone. The neutron star lies in the box where the constraints from the two frequency bands overlap.

This is a simplified model.

1602.01081

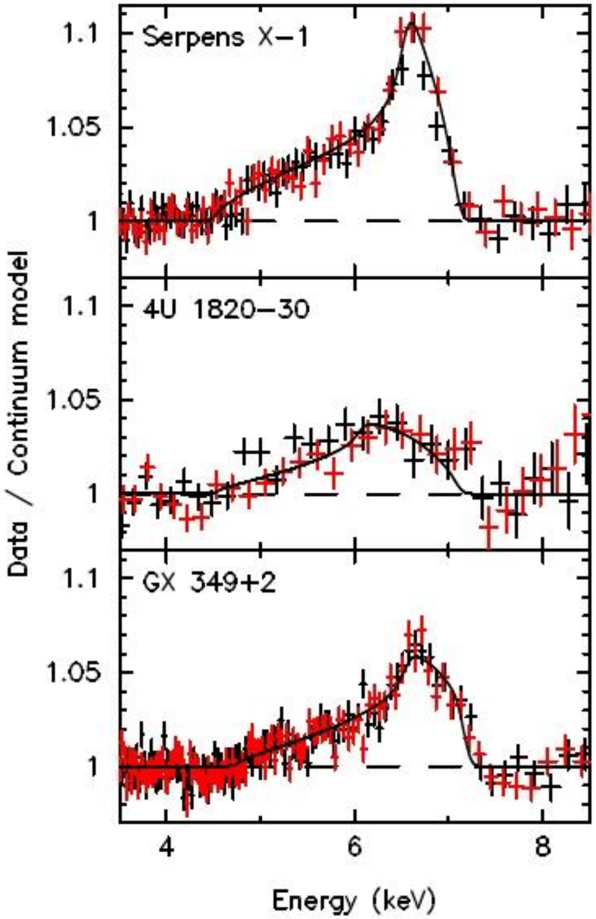
Fe K lines from accretion discs

Measurements of the inner disc radius provide upper limits on the NS radius.



Ser X-1 <15.9+/-1
4U 1820-30 <13.8+2.9-1.4
GX 349+2 <16.5+/-0.8
(all estimates for 1.4 solar mass NS)

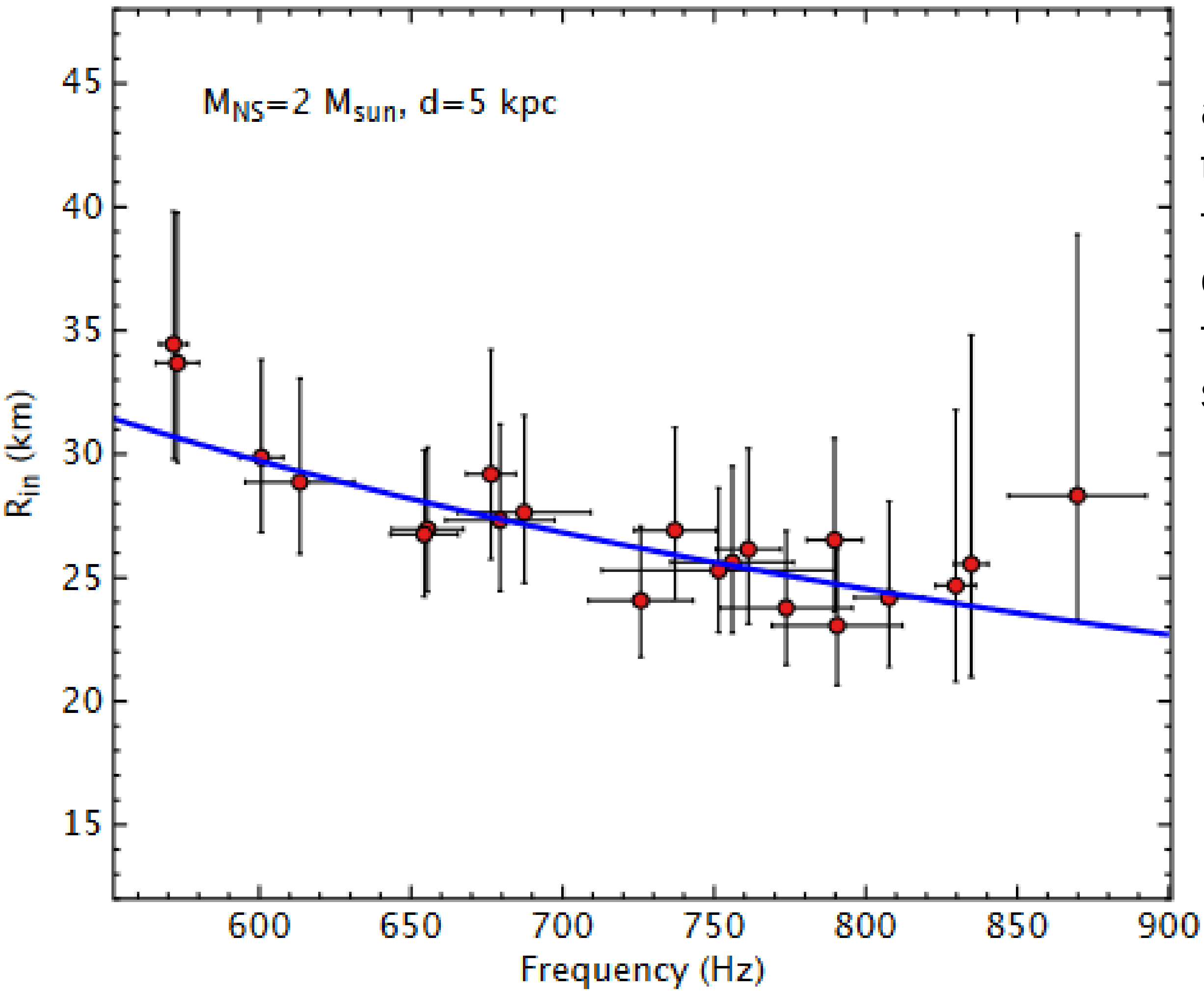
[Cackett et al. arXiv: 0708.3615]



Suzaku observations

See also Papito et al. arXiv: 0812.1149,
a review in Cackett et al. 0908.1098, and theory in 1109.2068.

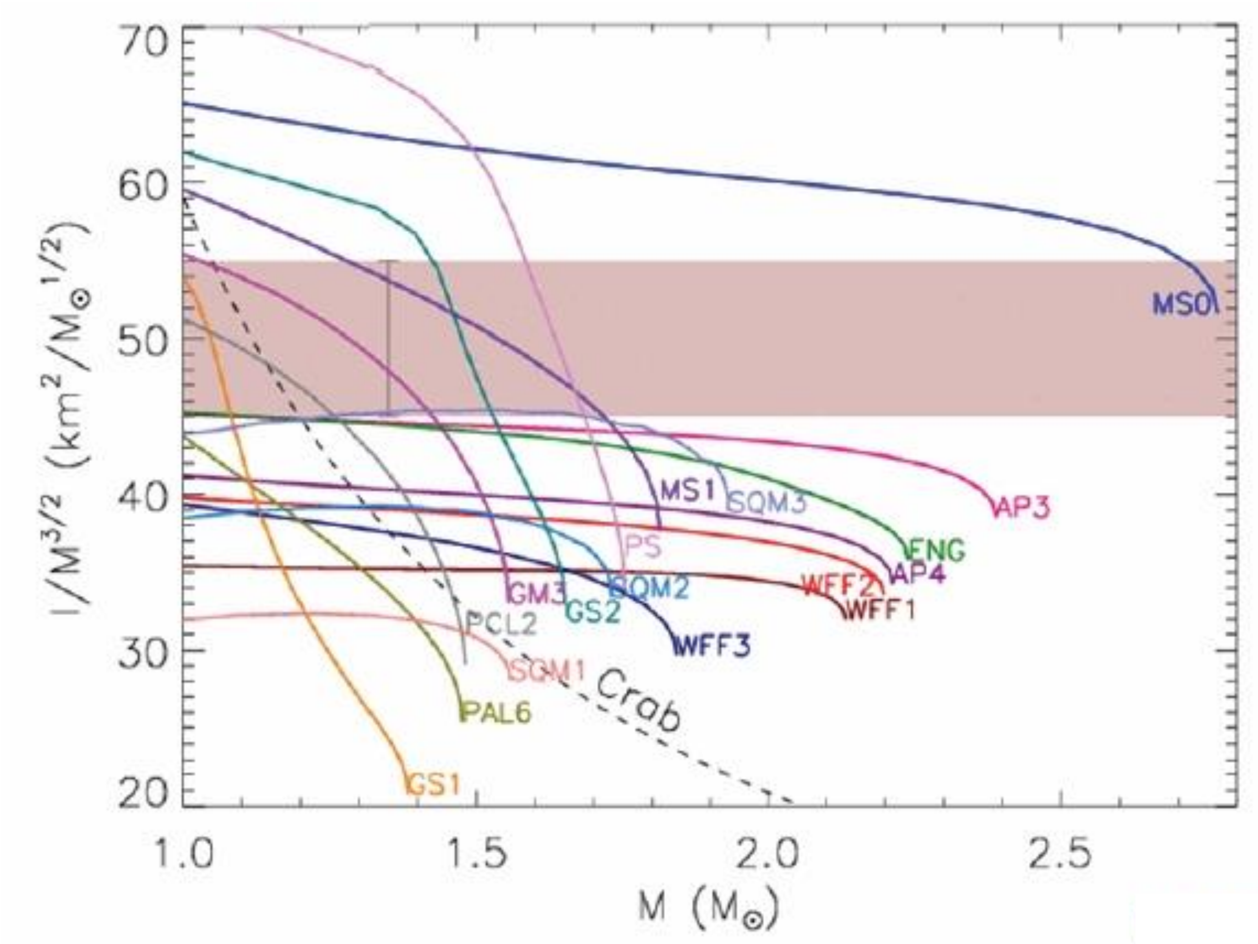
Fits from QPOs



Inner radius of the accretion disc, from fits to the energy spectra, as a function of the frequency of the lower kHz QPO, from fits to the power spectra, in 4U 1608–52

2010.08291

Limits on the moment of inertia



Spin-orbital interaction

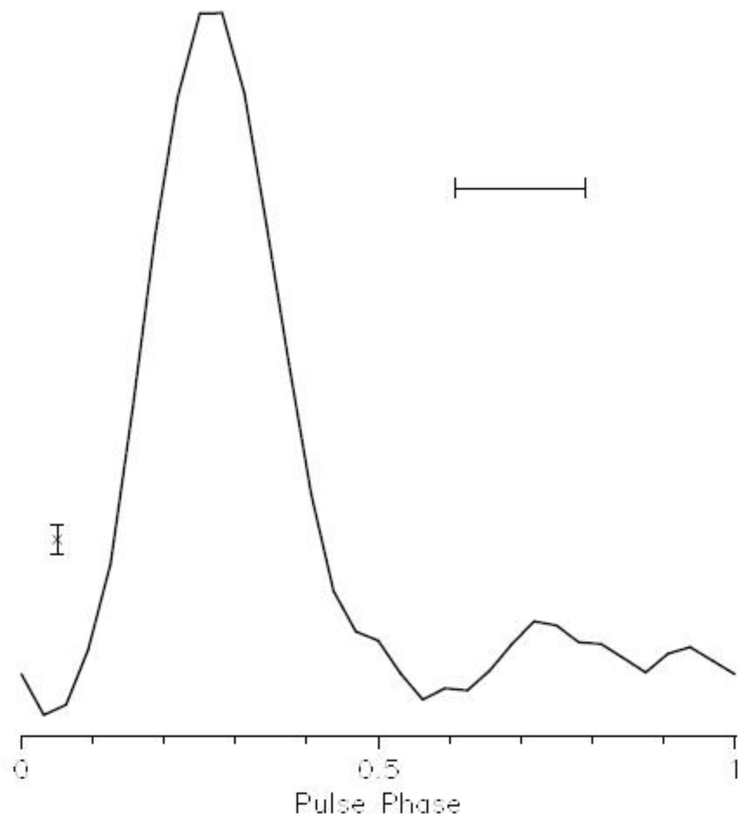
PSR J0737-3039
(see Lattimer, Schutz
astro-ph/0411470)

The band refers to a *hypothetical* 10% error. This limit, hopefully, can be reached in several years of observ.

See a more detailed discussion in 1006.3758

Most rapidly rotating PSR

716-Hz eclipsing binary radio pulsar in the globular cluster Terzan 5

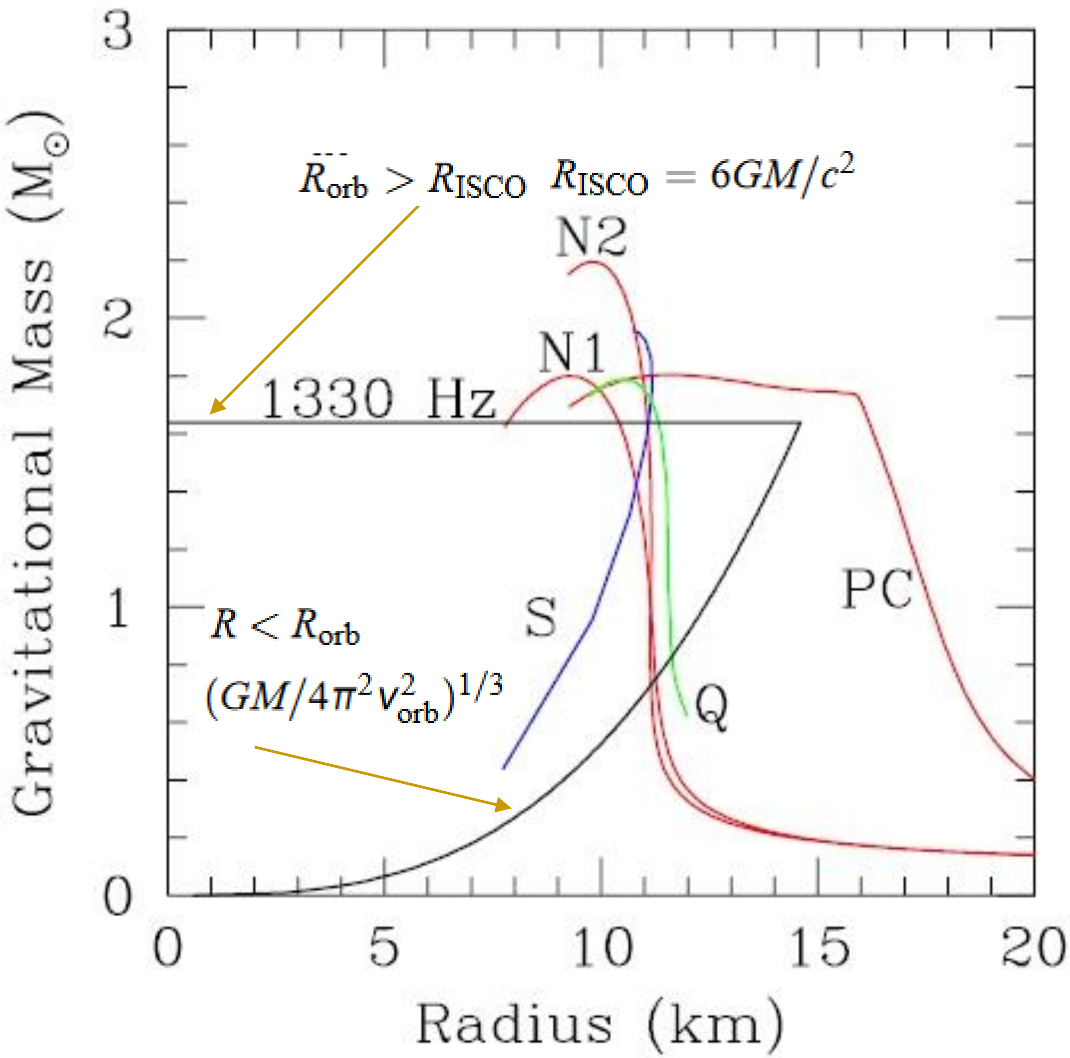


Previous record
(642-Hz pulsar B1937+21)
survived for more than 20 years.

Rotation starts to be important
from periods ~3 msec.

Jason W.T. Hessels et al. astro-ph/0601337

QPO and rapid rotation



XTE J1739-285
1122 Hz
P. Kaaret et al.
astro-ph/0611716

1330 Hz – one of the highest QPO frequency

The line corresponds to the interpretation, that the frequency is that of the last stable orbit, $6GM/c^2$

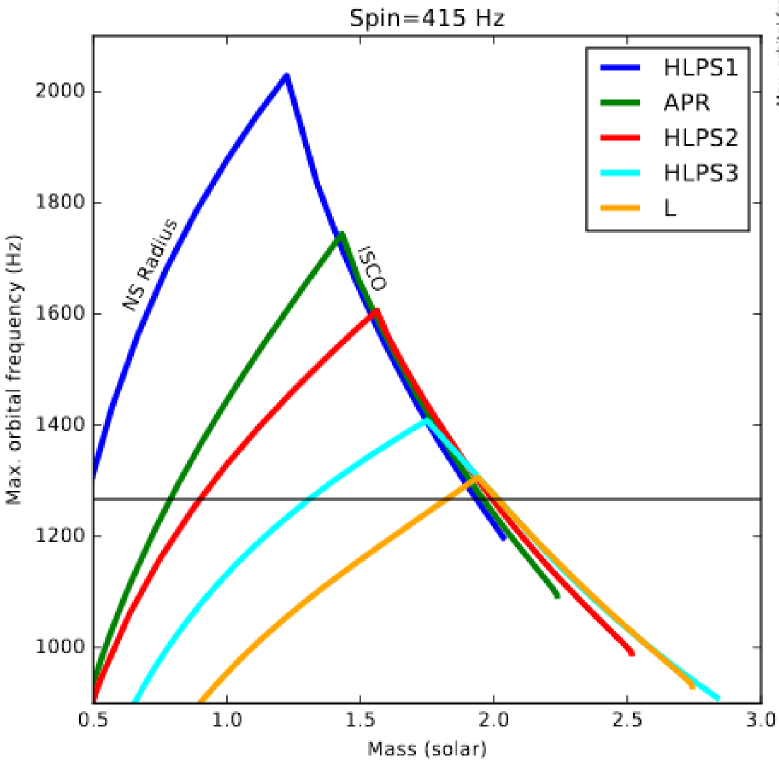
Miller astro-ph/0312449

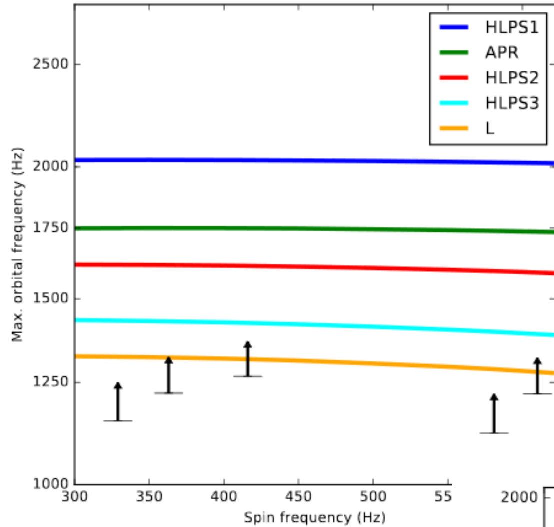
New measurements for 4U 0614+09

$$M \leq 2.2(\nu_{orb}/1000\ \mathrm{Hz})^{-1}(1+0.75j)M_\odot$$

$$R \leq 19.5(\nu_{orb}/1000\ \mathrm{Hz})^{-1}(1+0.2j)\mathrm{km}$$

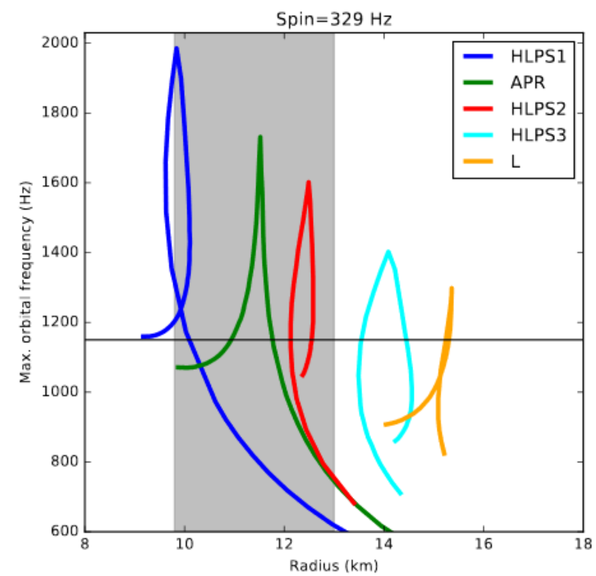
$$j \equiv cJ/GM^2$$





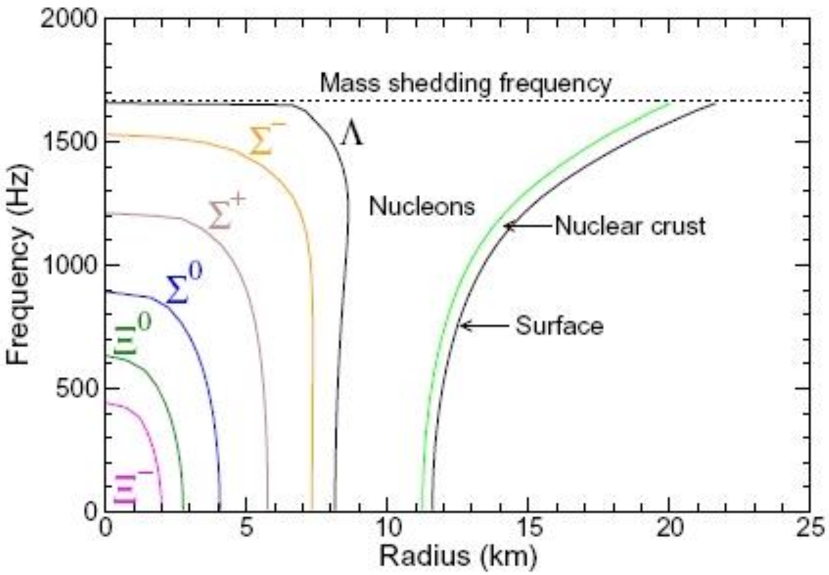
$$r_{min} = \begin{cases} 6GM/c2, & r_{ISCO} > R_{NS} \\ R_{NS}, & r_{ISCO} < R_{NS} \end{cases}$$

1267 Hz

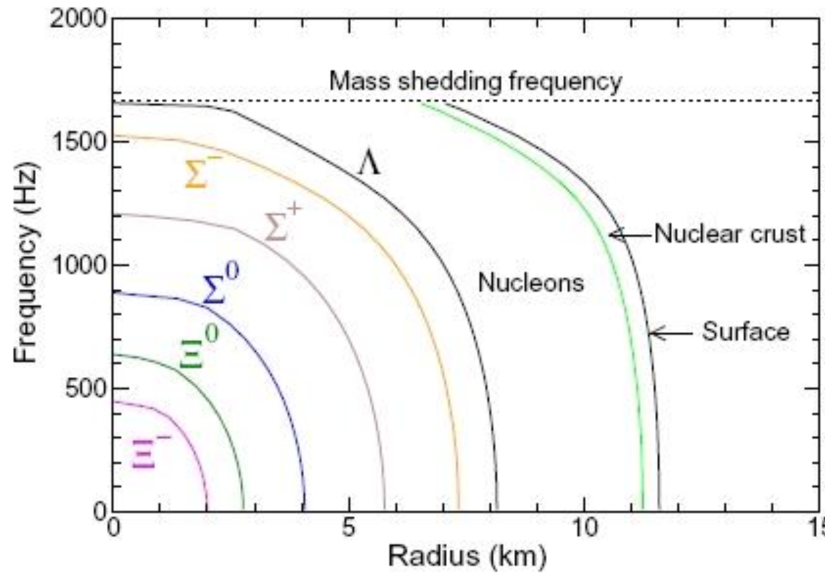


1805.11361

Rotation and composition



(equatorial)



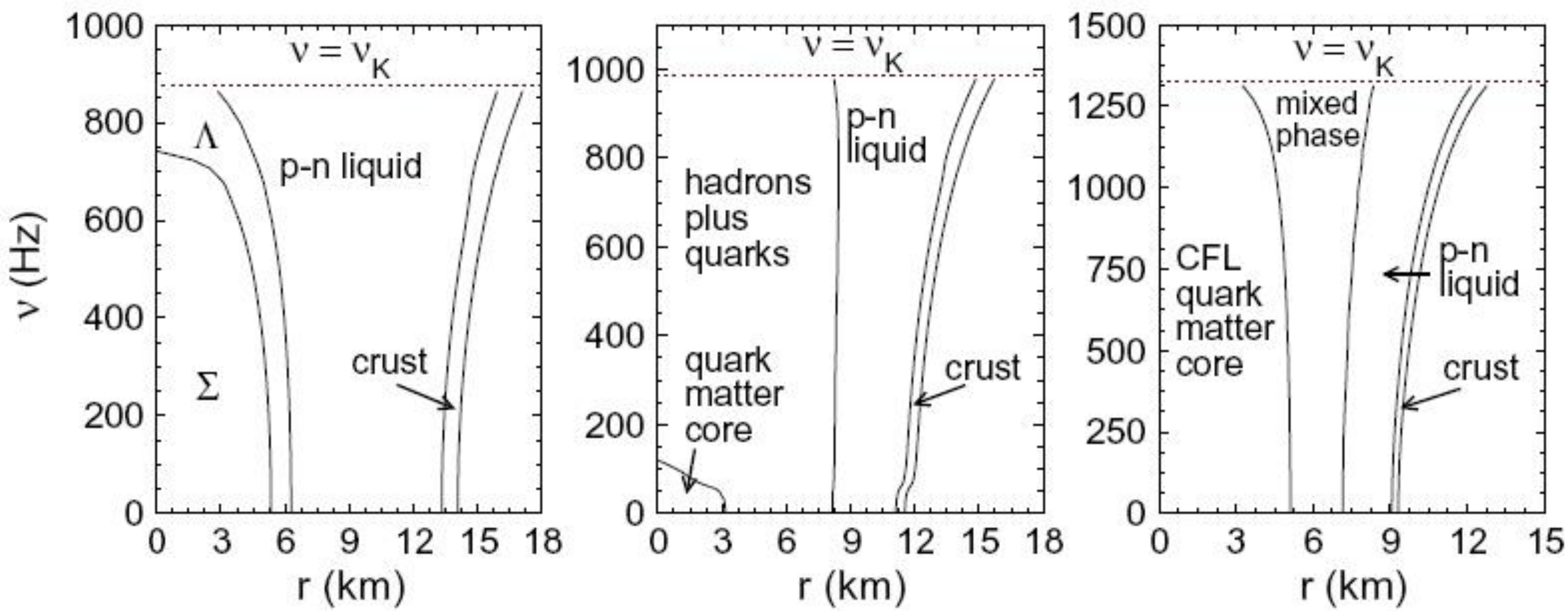
(polar)

Computed for a particular model:
density dependent relativistic Brueckner-Hartree-Fock (DD-RBHF)

(Weber et al. arXiv: 0705.2708)

Detailed study of the influence of rotation onto structure and composition is given in 1307.1103

Rotation and composition



hyperon **quark-hybrid** **quark-hybrid (quarks in CFL)**

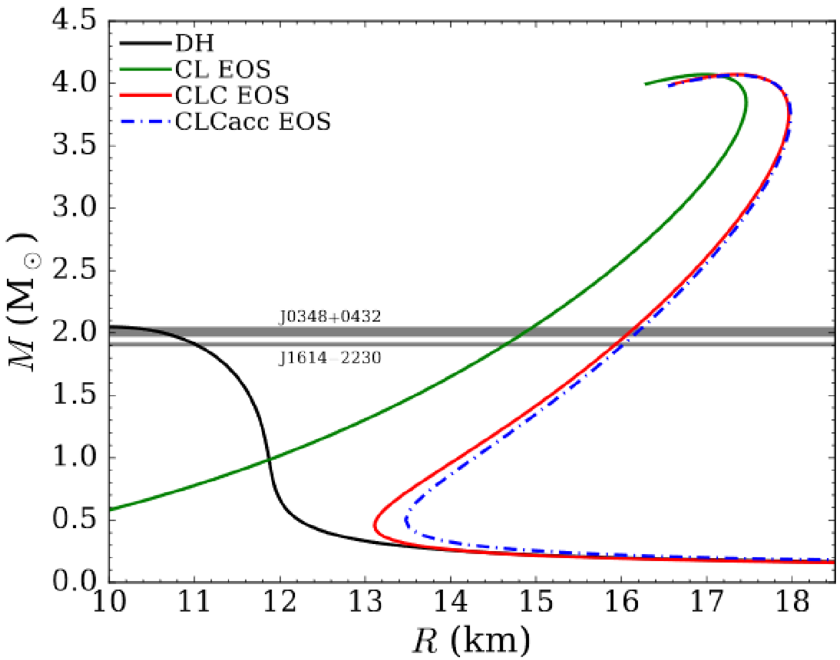
(Weber et al. arXiv: 0705.2708) 1.4 solar mass NS (when non-rotating)

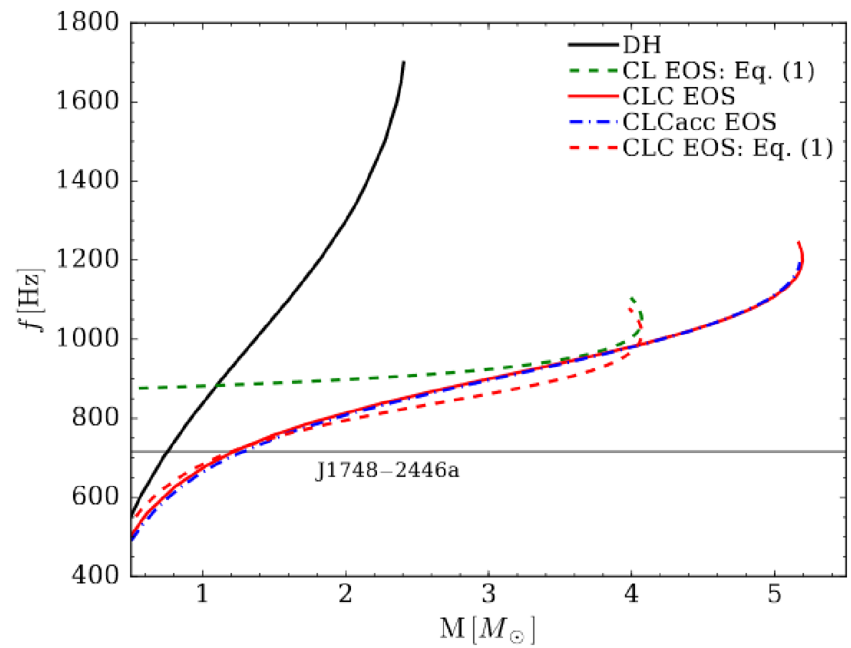
Limiting rotation

$$f_{\max}^{\mathrm{EOS}} = C_{\max}\left(\frac{M_{\max}^{\mathrm{stat}}}{M_{\odot}}\right)^{1/2}\left(\frac{R_{M_{\max}}^{\mathrm{stat}}}{10\ \mathrm{km}}\right)^{-3/2}$$

$$C_{\max} = 1.22\ \mathrm{kHz}$$

Without additional assumptions for realistic EoS it is expected that NS can rotate faster than f=716 Hz for masses close to the limiting value.





1805.11277

Parameters of extremely rotating NSs

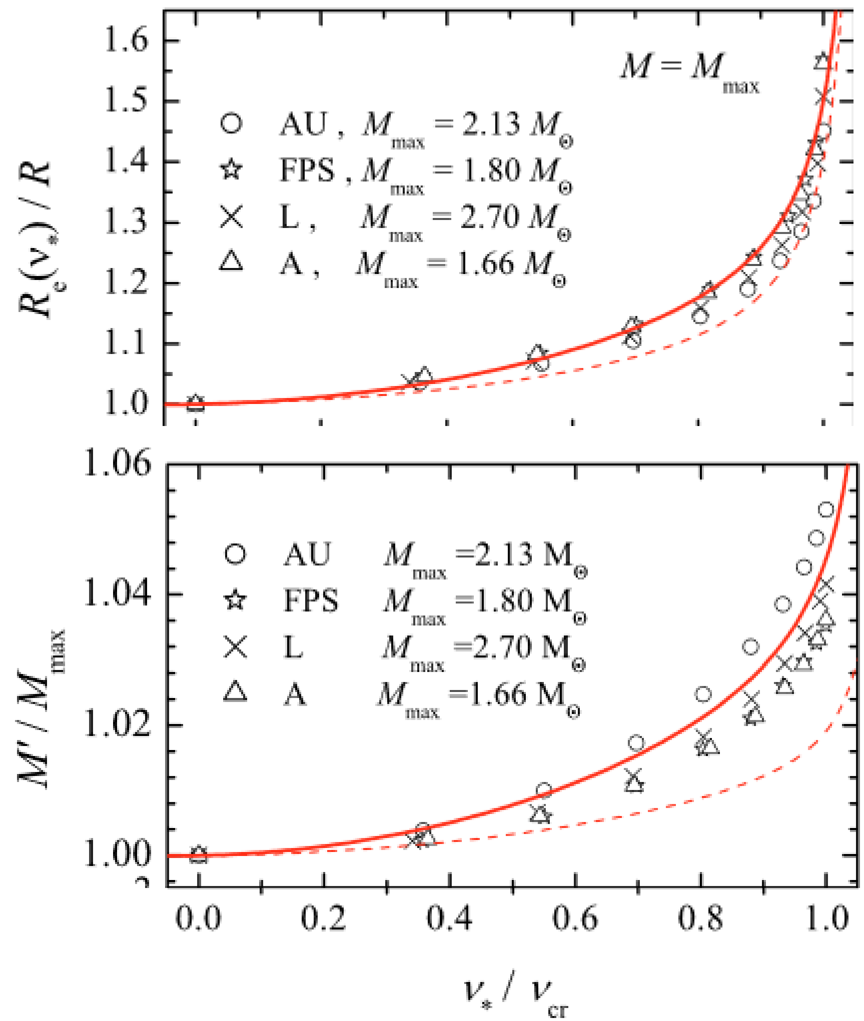
$$\nu_{\rm cr} = 1278\, M_{1.4}^{1/2} \left(\frac{10\ \mathrm{km}}{R}\right)^{3/2}\ \mathrm{Hz}$$

$$R_{\rm e} = R \left[0.9766 + \frac{0.025}{1.07 - \bar{\nu}} + 0.07\, M_{1.4}^{3/2}\, \bar{\nu}^2\right]$$

Gravitational mass changes due to rotation:

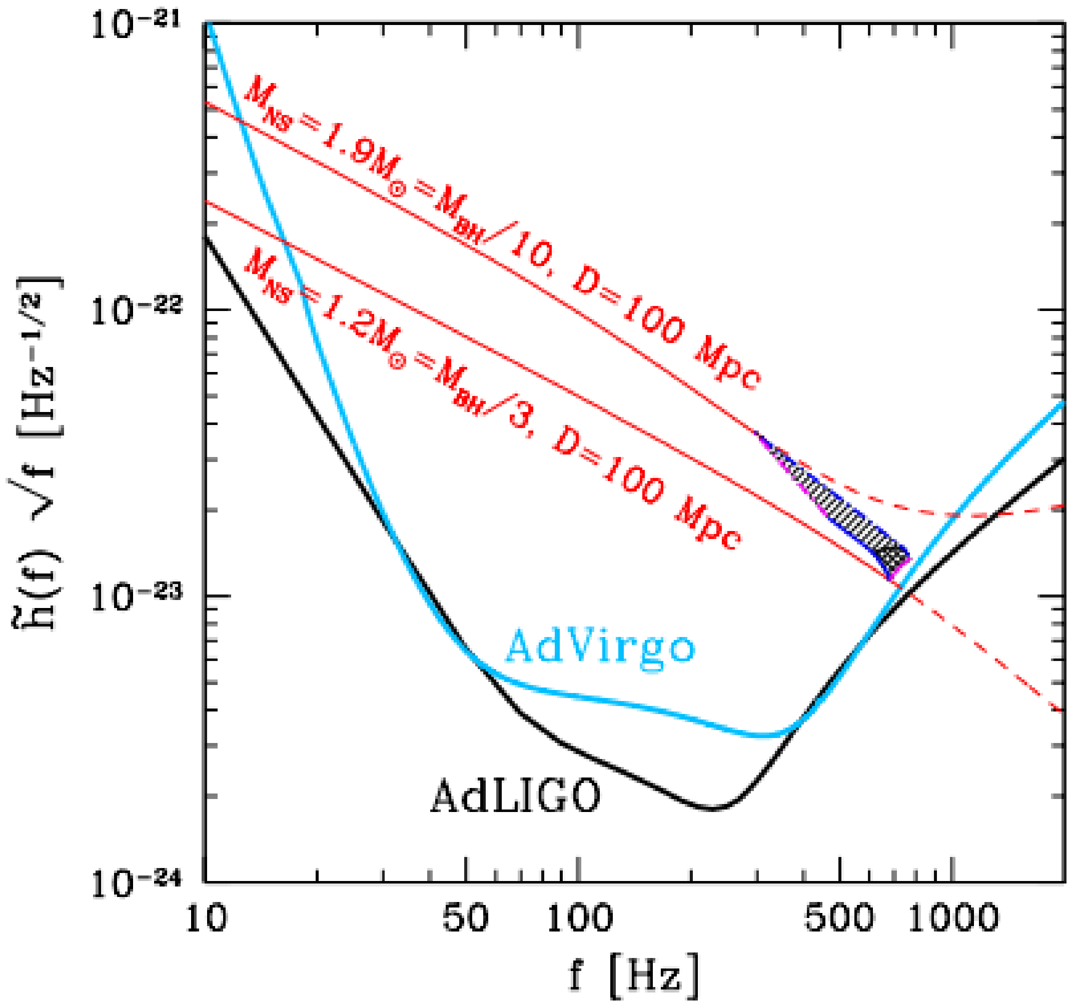
$$M' = M \left[a_0 + \frac{a_1}{1.1 - \bar{\nu}} + a_2\, \bar{\nu}^2\right]$$

$$a_0 = 1 - a_1/1.1,\ a_1 = 0.001 M_{1.4}^{3/2},\ a_2 = 10 a_1$$

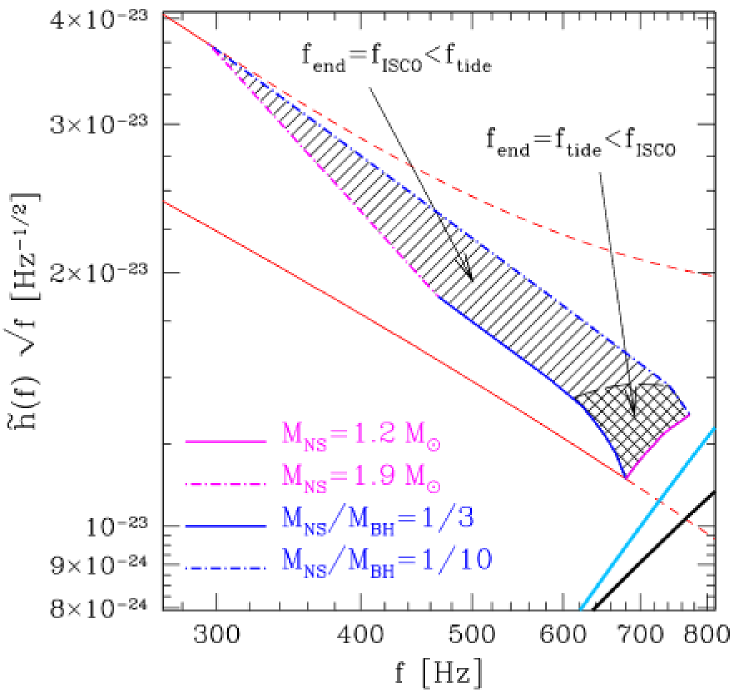


2005.09759

Limits on the EoS from GW observations

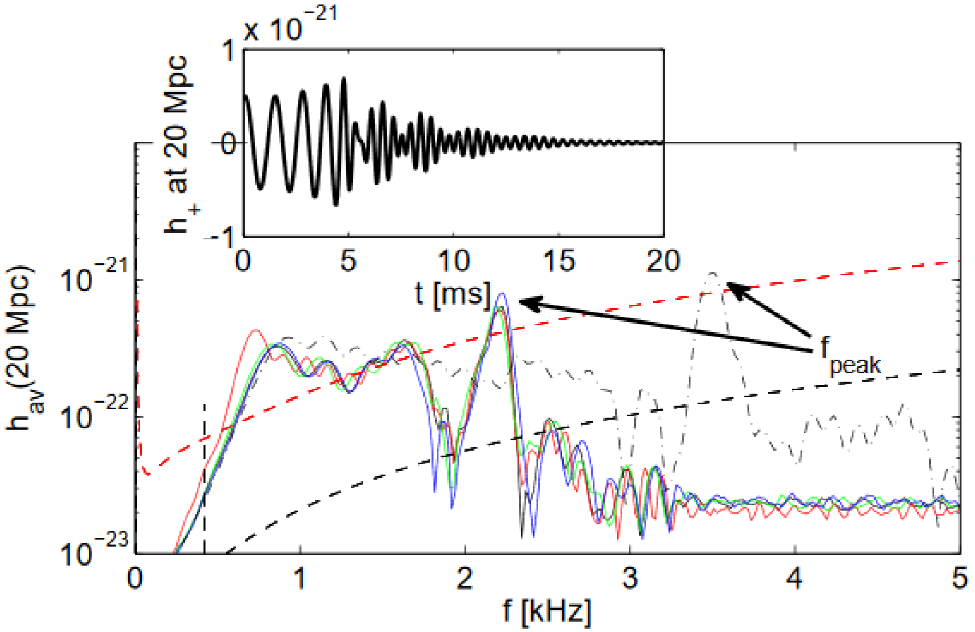


For stiff EoS
AdLIGO and AdVIRGO
can detect signatures
in the GW signal
during BH-NS mergers.



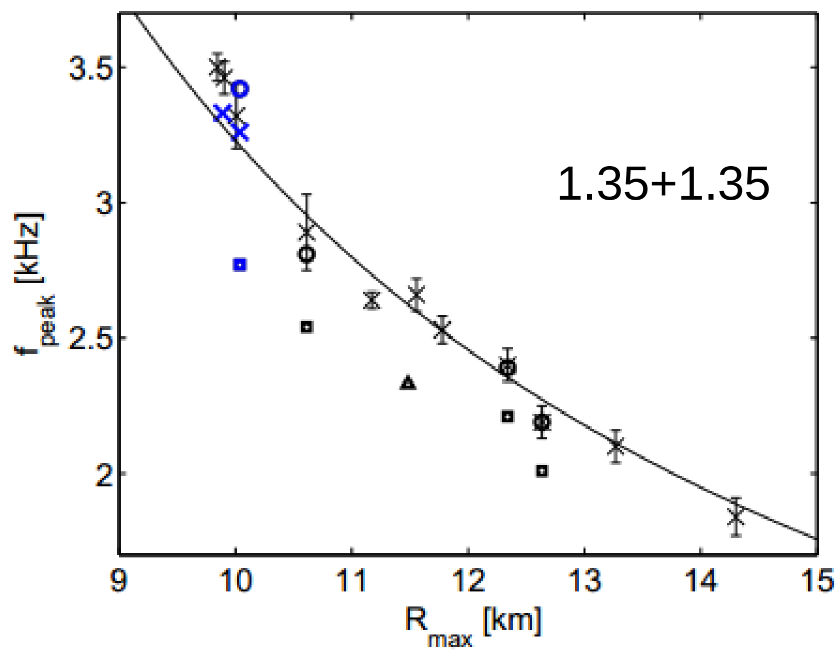
1103.3526, see a review in 2103.16371

Another constraint



Orientation-averaged spectra of the GW signal for the Shen (solid) and the eosUU (black dashed-dotted) EoSs and the AdvLIGO (red dashed) and ET (black dashed) unity SNR sensitivities. The inset shows the GW amplitude with +polarization at a polar distance of 20 Mpc for the Shen EoS

Measuring NS-NS mergers
one can better constraint the EoS.



1106.1616

GW170817: deformability Λ

Many papers are published based on detection of GW signal from GW170817: 1803.00549, 1804.08583, 1805.09371, 1805.11579, 1805.11581, 1901.04138.

$$\tilde{\Lambda} = \frac{16}{13}\frac{(12q+1)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5},$$

$$q = m_2/m_1 \leq 1$$

$$\Lambda_{1,2} = \frac{2}{3}k_2\left(\frac{R_{1,2}c^2}{Gm_{1,2}}\right)^5$$

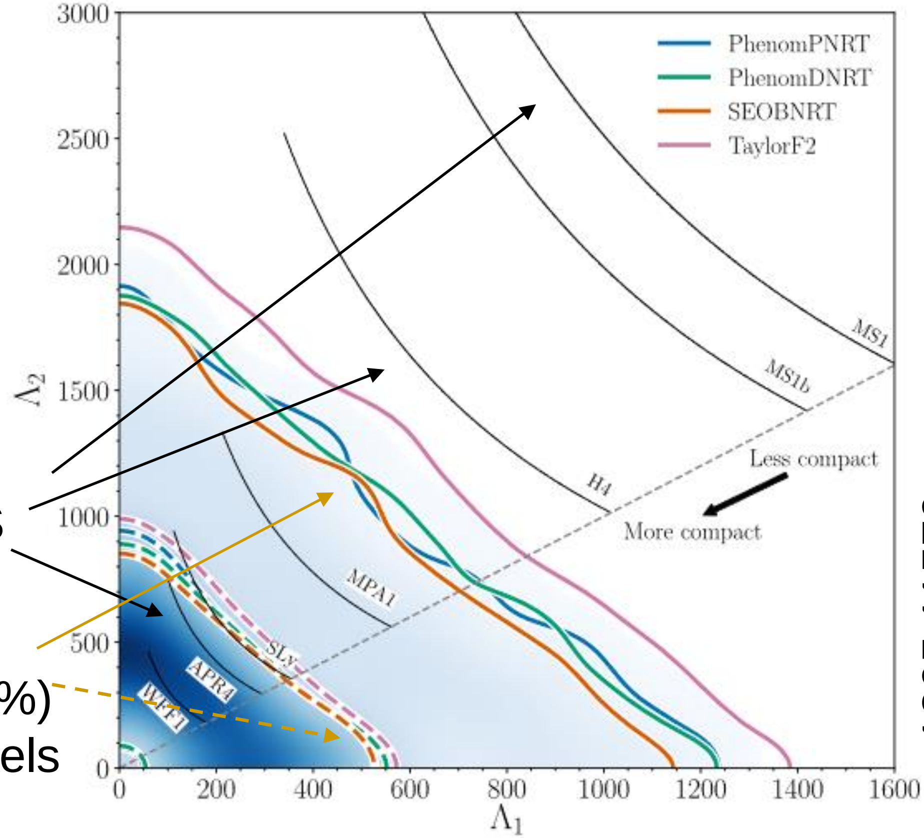
$$\beta = Gm/(Rc^2)$$

$k_2 \sim \beta^{-1}$
$\Lambda \sim \beta^{-6}$

Low spin priors

Solid – theoretical EoS

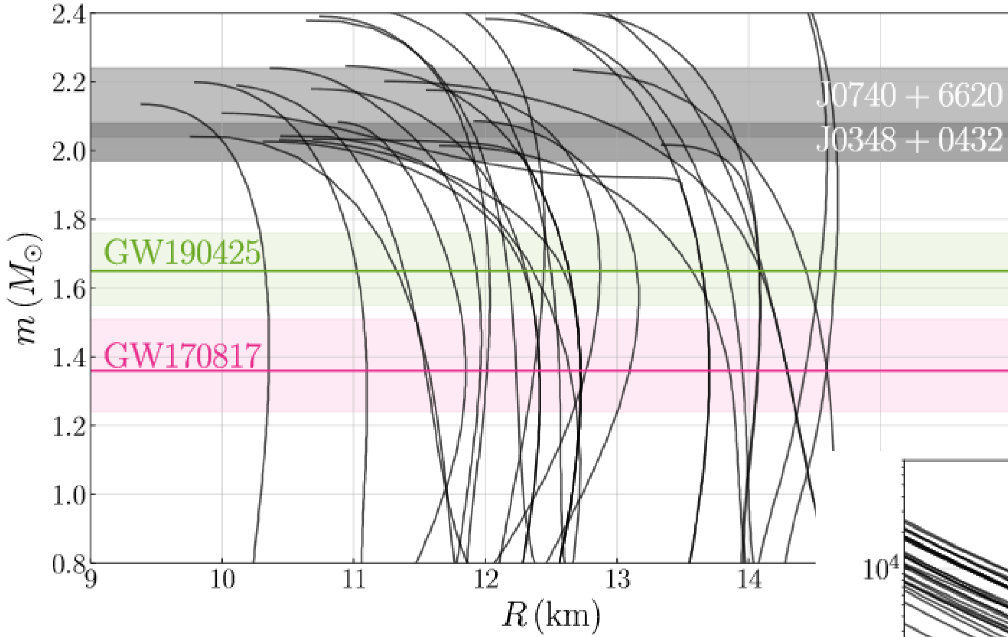
Colored – limits
(dashed 50%, solid 90%)
for four waveform models



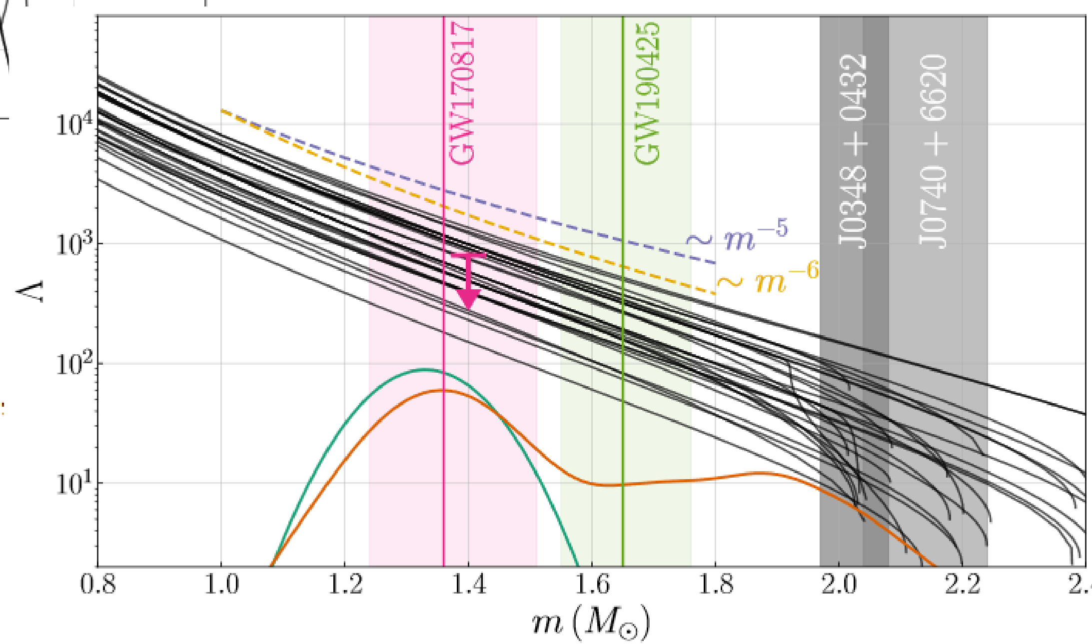
1805.11579

Collapse to a BH after ~1 sec? (1901.04138)

Parameters of NSs in known coalescences

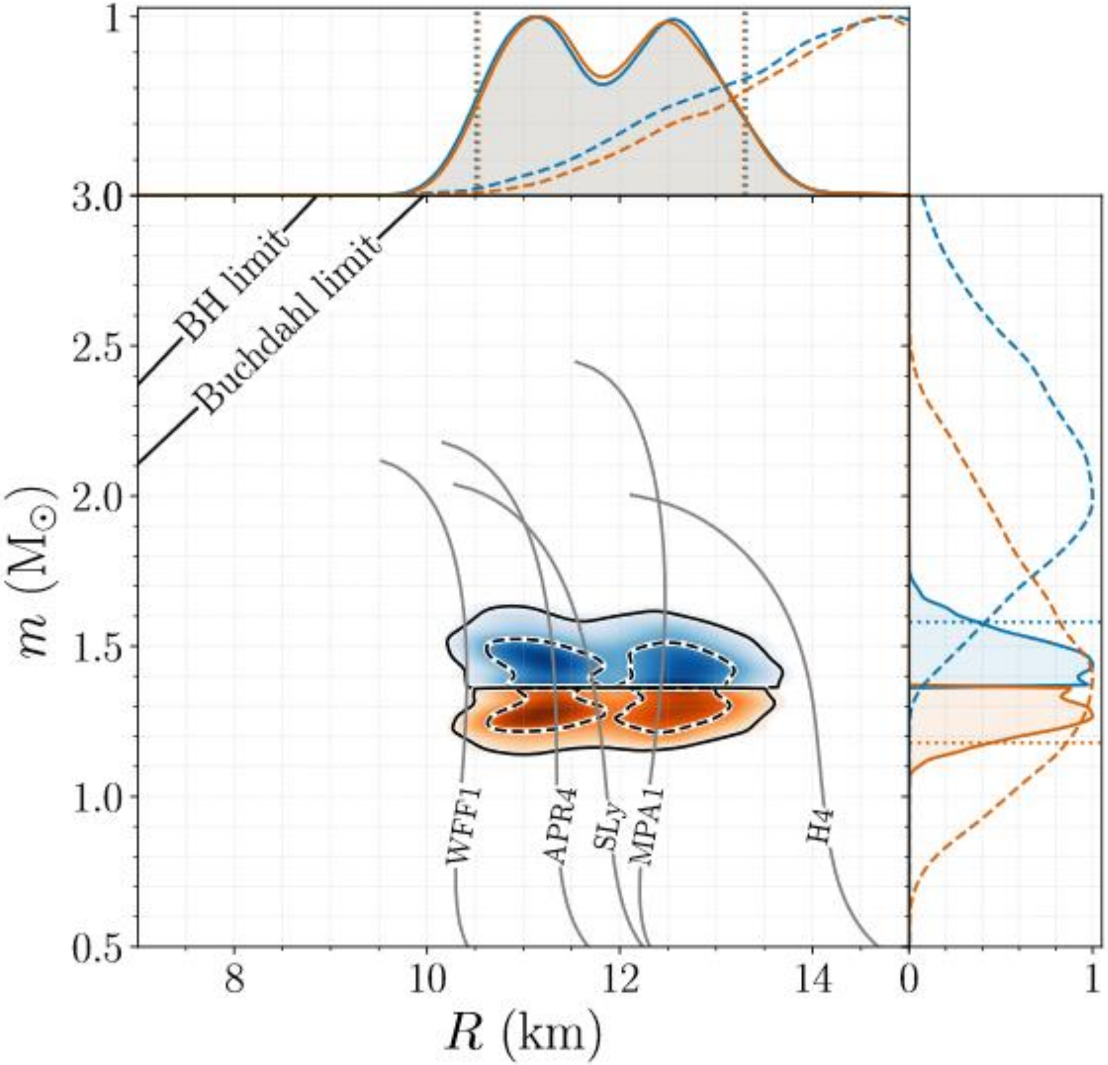


$$\Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3}k_2\frac{R^5}{m^5} = \frac{2}{3}k_2 C^{-5},$$



2006.03168

GW170817: M-R



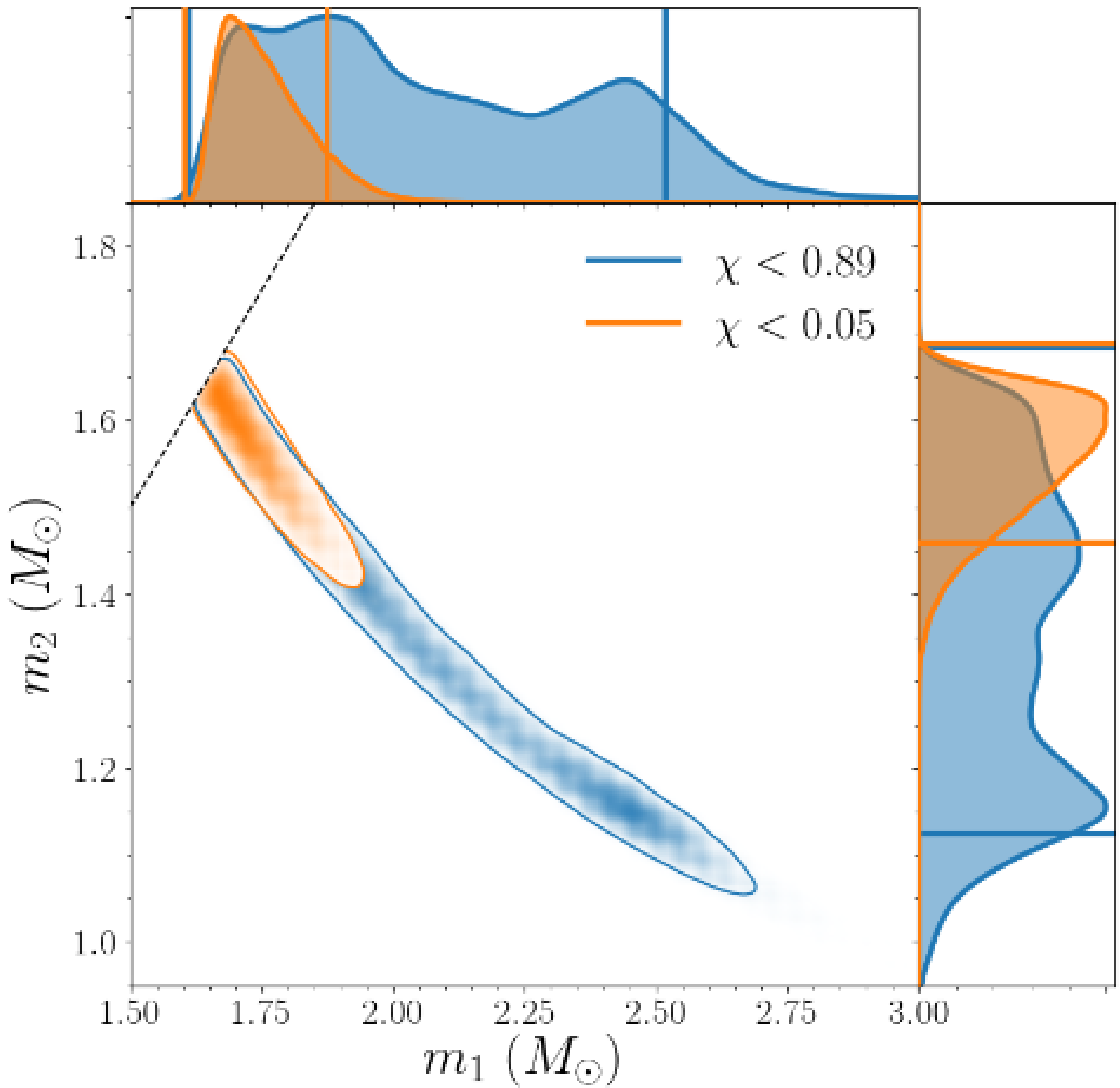
$$R_1 = 11.9^{+1.4}_{-1.4}\,\mathrm{km}$$

$$R_2 = 11.9^{+1.4}_{-1.4}\,\mathrm{km}$$

1805.11581

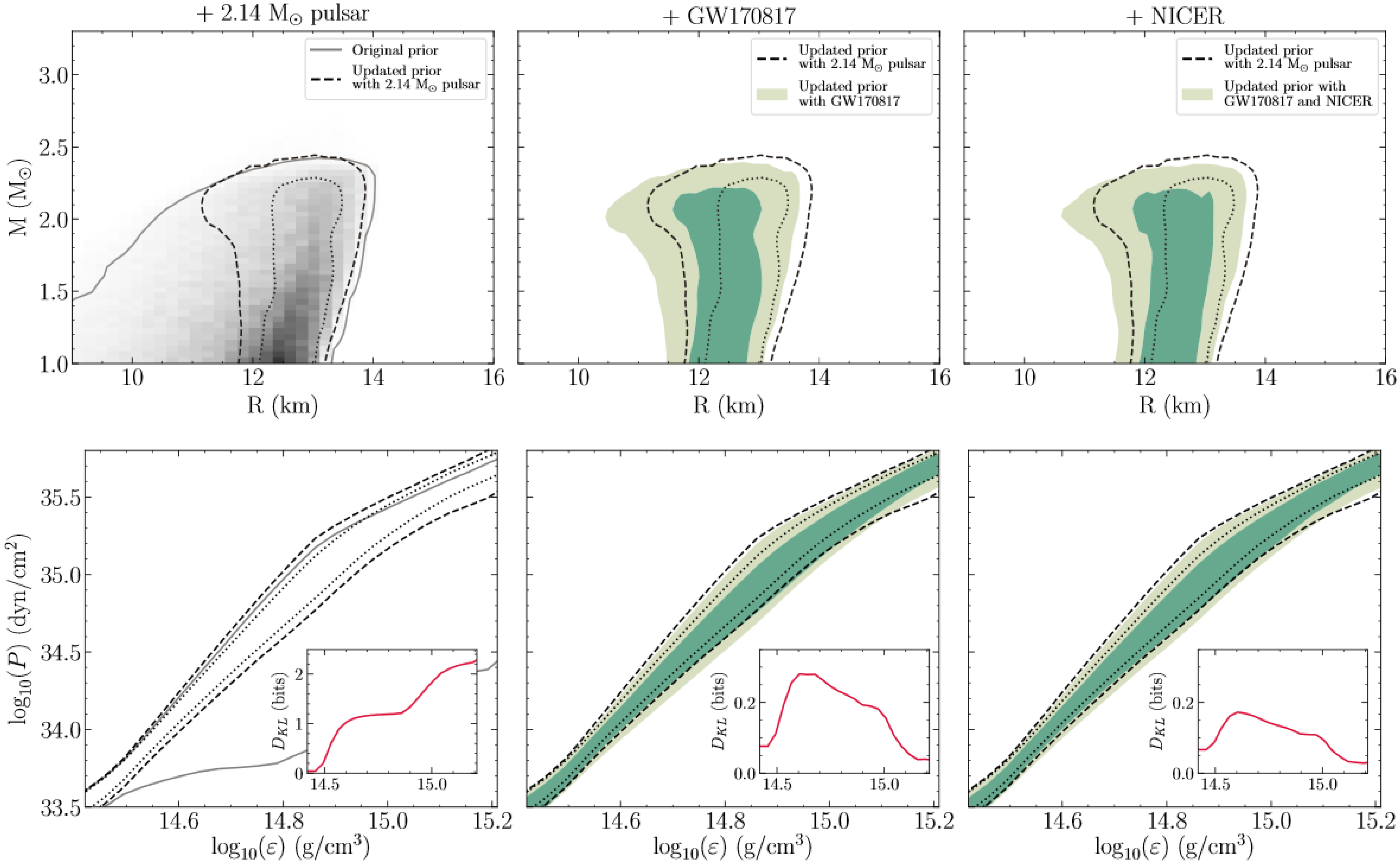
GW190425

Primary mass m_1
Secondary mass m_2
Chirp mass $\mathcal{M}$
Detector-frame chirp mass
Mass ratio m_2/m_1
Total mass $m_{\rm tot}$
Effective inspiral spin parameter $\chi_{\rm e}$
Luminosity distance $D_{\rm L}$
Combined dimensionless tidal defor



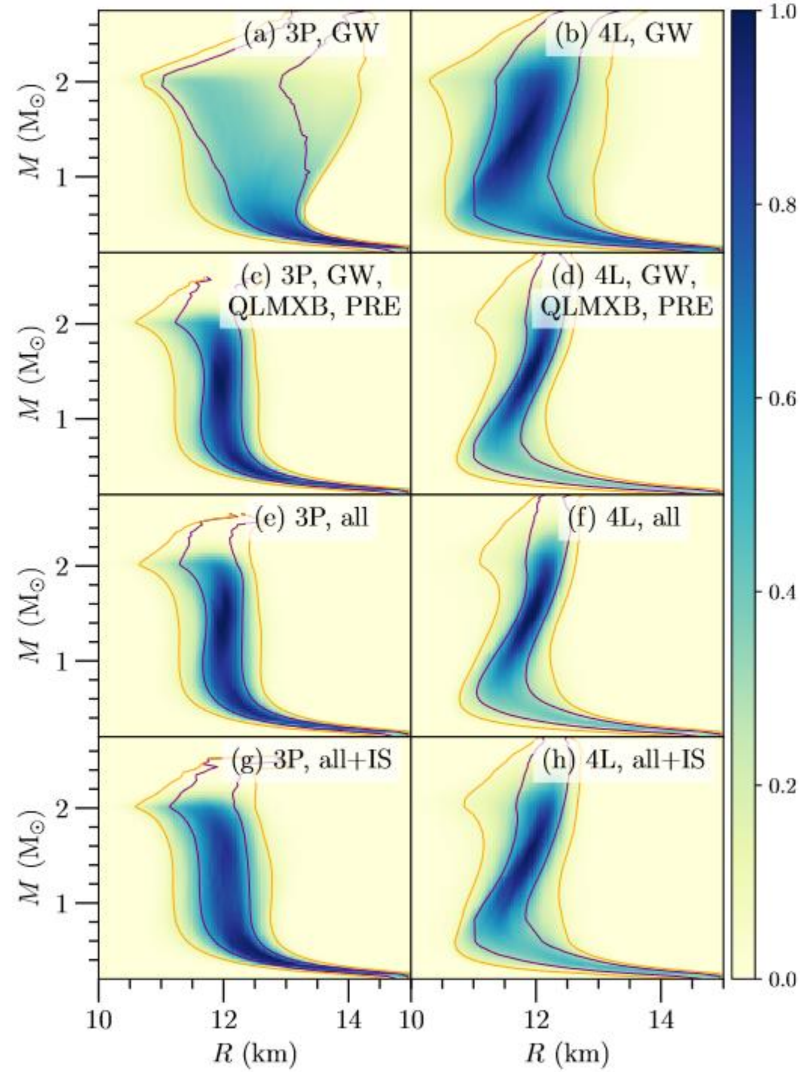
2001.01761

LIGO+NICER=EoS ?



1912.11031

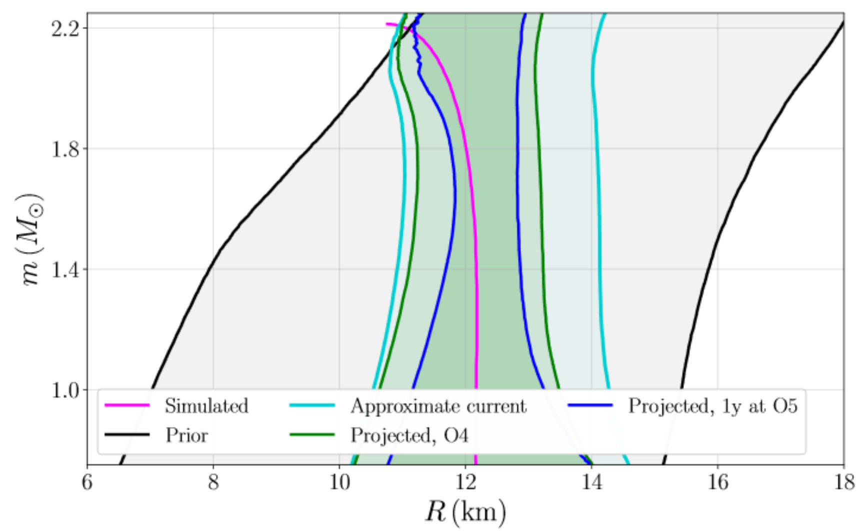
GW+binaries+EoS parametrization



It is important how to parametrize an EoS. Two columns correspond to different approaches to parametrize the EoS.

The last line included effect if systematic uncertainties (IS – intrinsic scattering)

PRE – photospheric radius expansion



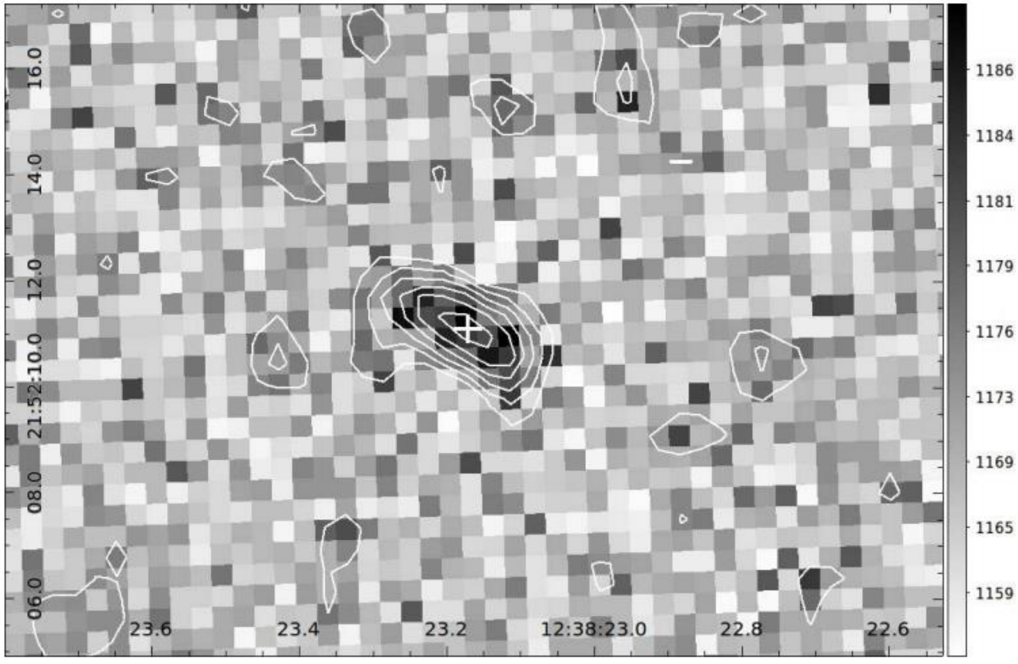
2006.03168

2008.12817, see also 2009.06441

Microlensing and weak lensing

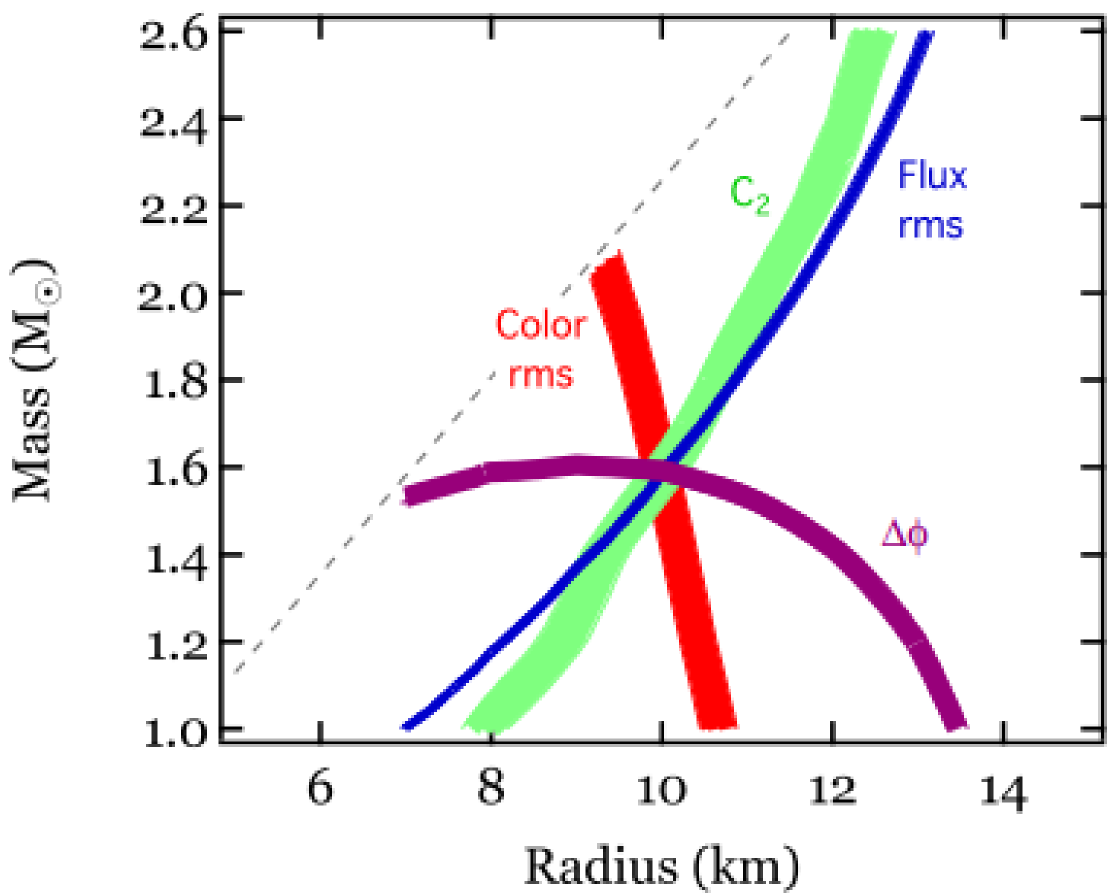
In the future (maybe already with Gaia)
it can possible to determine NS mass with lensing.
Different techniques can be discussed:
photometric (normal) microlensing (1009.0005),
astrometric microlensing, weak lensing (1209.2249).

See recent studies
in 2107.13697, 2107.13701



1209.2249

Future X-ray measurements



Valid for future observations aboard NICER and LOFT space projects.

Data based on pulse profile.

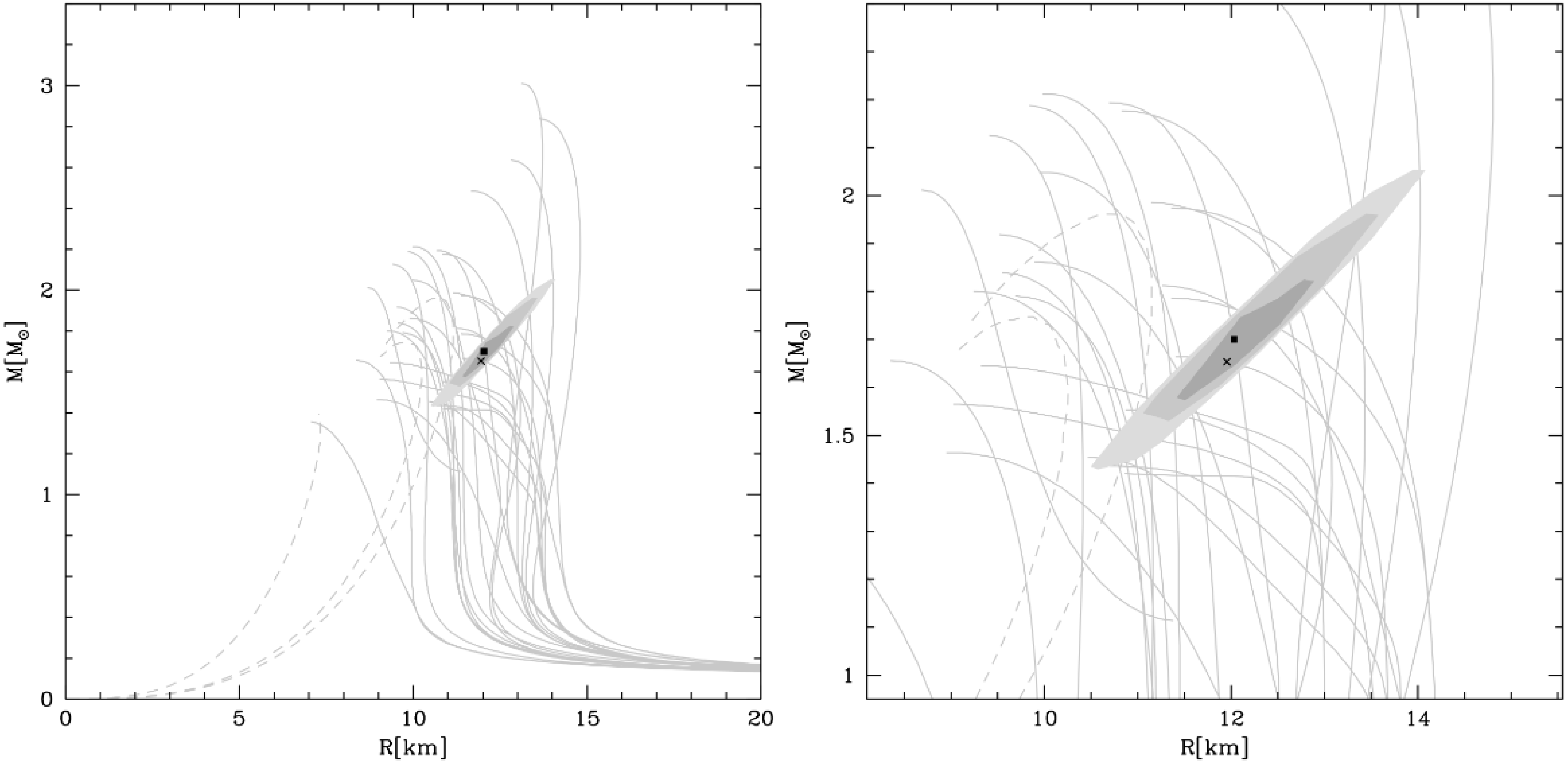
The idea is to observe X-ray pulsars with spin periods ~few msec and to collect about 10^6 counts.

It allows to derive from the pulse profile a lot of info about a NS.

1311.1571

ATHENA

Using only spectra M and R can be determined within 3-10% and 2-8%, respectively.



1912.01608

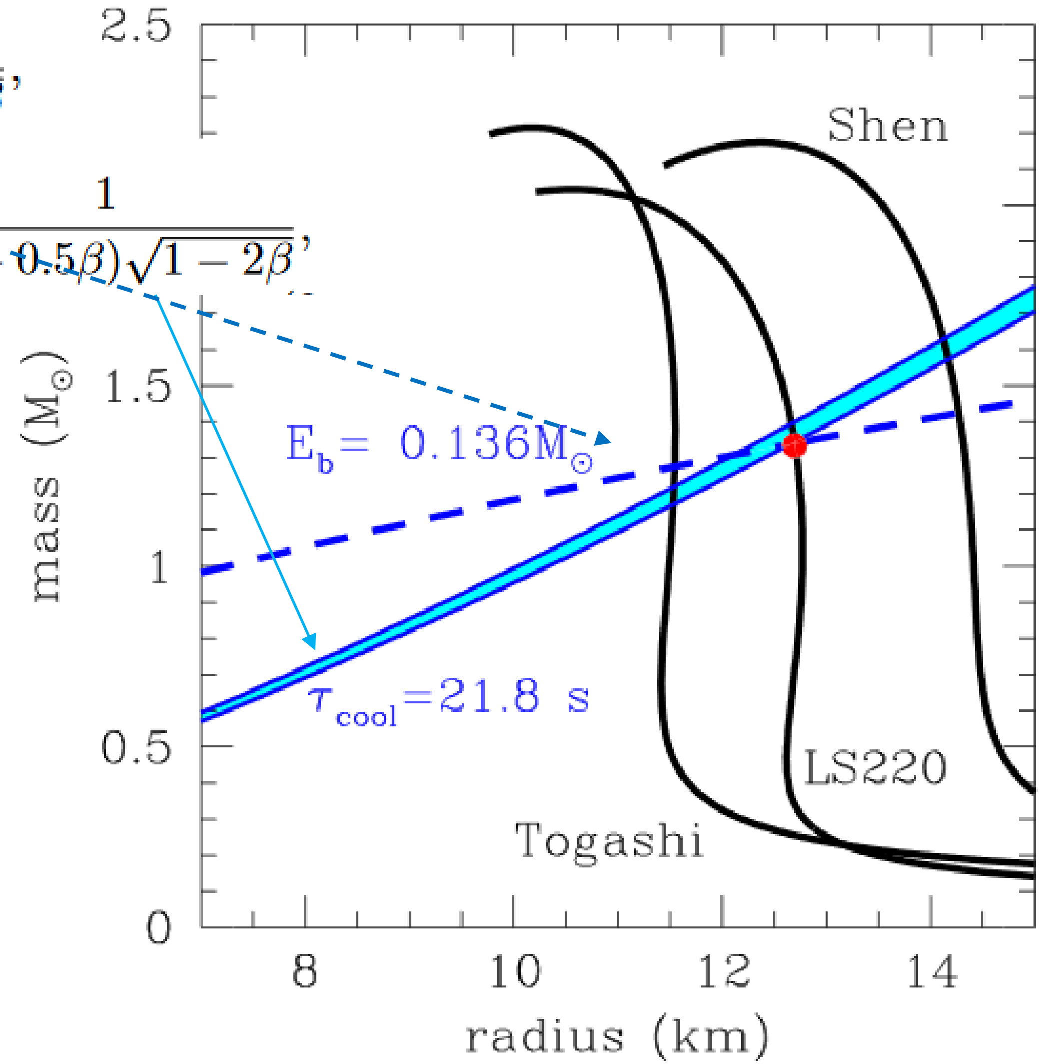
Exotics: neutrino signal

$$\frac{E_b}{m} = \frac{0.6\beta}{1-0.5\beta}. \qquad \tau_{\rm cool} \propto \frac{E_b}{r^2\sqrt{1-2\beta}},$$

$$\tau_{\rm cool} = \tau^* \left(\frac{m}{1.4M_\odot}\right)^2 \left(\frac{r}{10\,{\rm km}}\right)^{-3} \frac{1}{(1-0.5\beta)\sqrt{1-2\beta}},$$

$$\beta = Gm/rc^2$$

Cooling timescale is longer
for a model with
a larger neutron star mass
and a smaller neutron star radius.

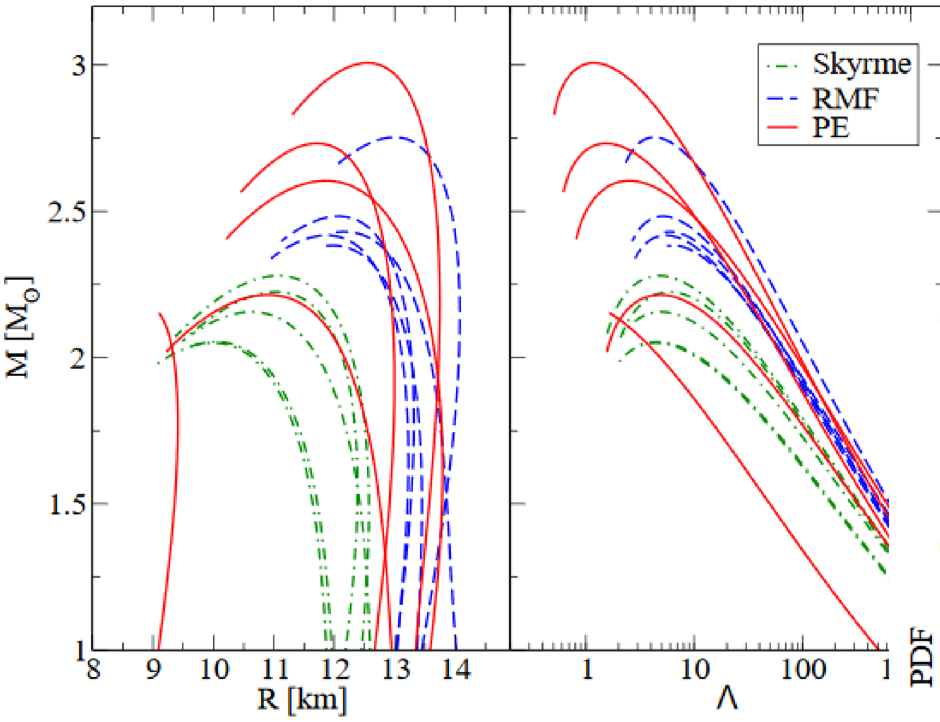


2002.03300

References

- Observational Constraints on Neutron Star Masses and Radii 1604.03894
  The review is about X-ray systems
- Mass, radii and equation of state of neutron stars 1603.02698
  The review about different kinds of measurements, including radio pulsars. Recent lists of mass measurements for different NSs.
- Measuring the neutron star equation of state using X-ray timing 1602.01081
  The review about EoS and X-ray measurements
- The masses and spins of neutron stars and stellar-mass black holes 1408.4145
  The review covers several topics. Good brief description of radio pulsar mass measurements.
- Properties of DNS systems. 1706.09438
  The review covers all aspects of observations, formation and evolution.
- Testing the equation of state of neutron stars with electromagnetic observations. 1806.02833 The BIG review describes observational tests of the EoS.
- Birth events, masses and the maximum mass of Compact Stars. 2011.08157 The review covers mass measurements and birth rates.

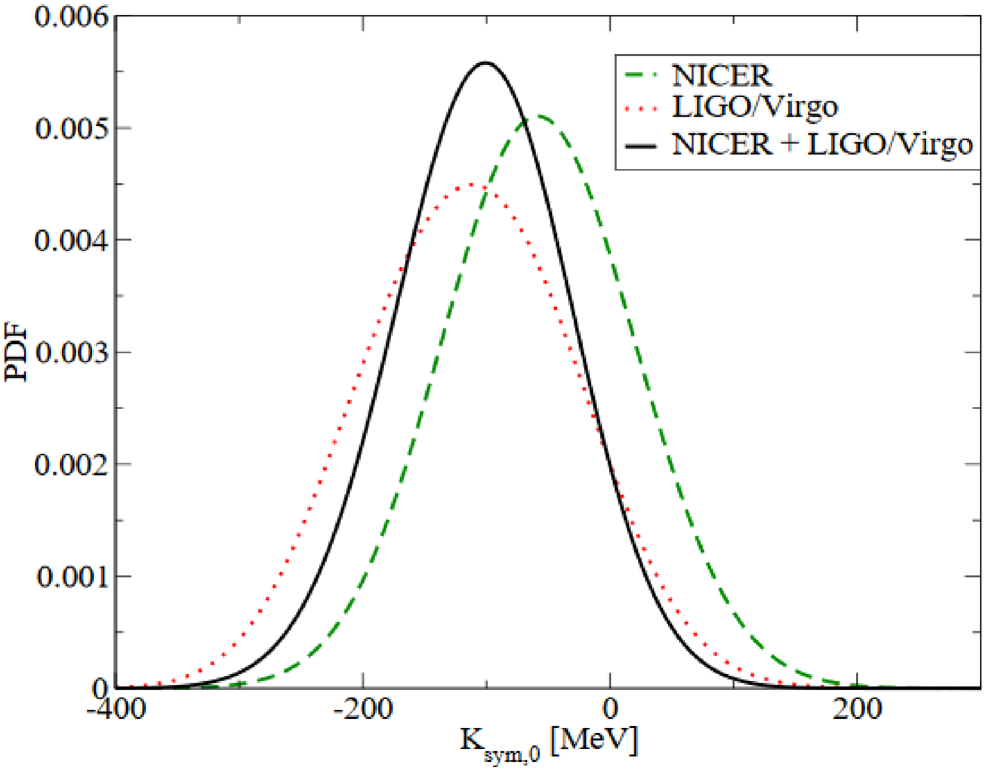
LIGO+NICER=EoS ?



$$e(n,\delta) = e(n,0) + S_2(n)\delta^2 + \mathcal{O}(\delta^4).$$

$$e(n,0) = e_0 + \frac{K_0}{2}y^2 + \frac{Q_0}{6}y^3 + \mathcal{O}(y^4),$$

$$S_2(n) = J_0 + L_0 y + \frac{K_{\mathrm{sym},0}}{2}y^2 + \mathcal{O}(y^3),$$



$$Q_{ij} = -\lambda\, \mathcal{E}_{ij}.$$

$$\Lambda \equiv \lambda/M^5.$$

$$\tilde{\Lambda} = \frac{16}{13}\frac{(1+12q)\Lambda_1 + (12+q)q^4\Lambda_2}{(1+q)^5}$$

2002.03210

NS+NS binaries

Secondary companion in double NS binaries can give a good estimate of the initial mass if we can neglect effects of evolution in a binary system.

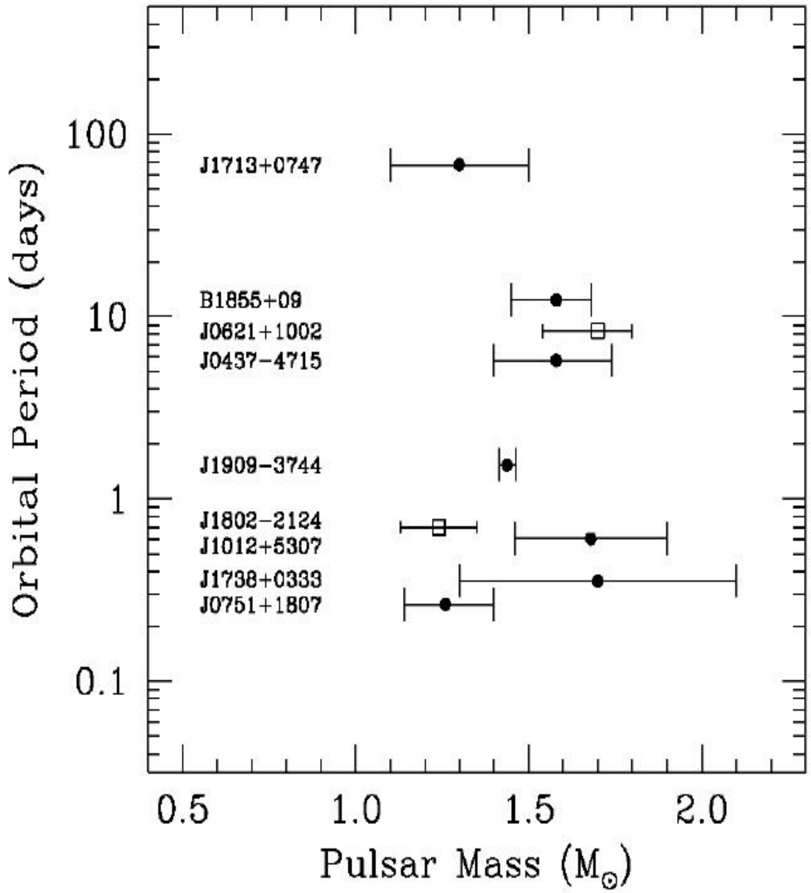
	Pulsar	Pulsar mass	Companion mass	
	B1913+16	1.44	1.39	
GC →	B2127+11C	1.36	1.35	
	B1534+12	1.33	1.35	
	J0737-3039	1.34	1.25	
	J1756-2251	1.40	1.18	
	J1518+4904	<1.17	>1.55	→ 0808.2292
Non-recycled →	J1906+0746	1.25	1.37	
	J1811-1736	1.56	1.12	
	J1829+2456	1.2	1.4	

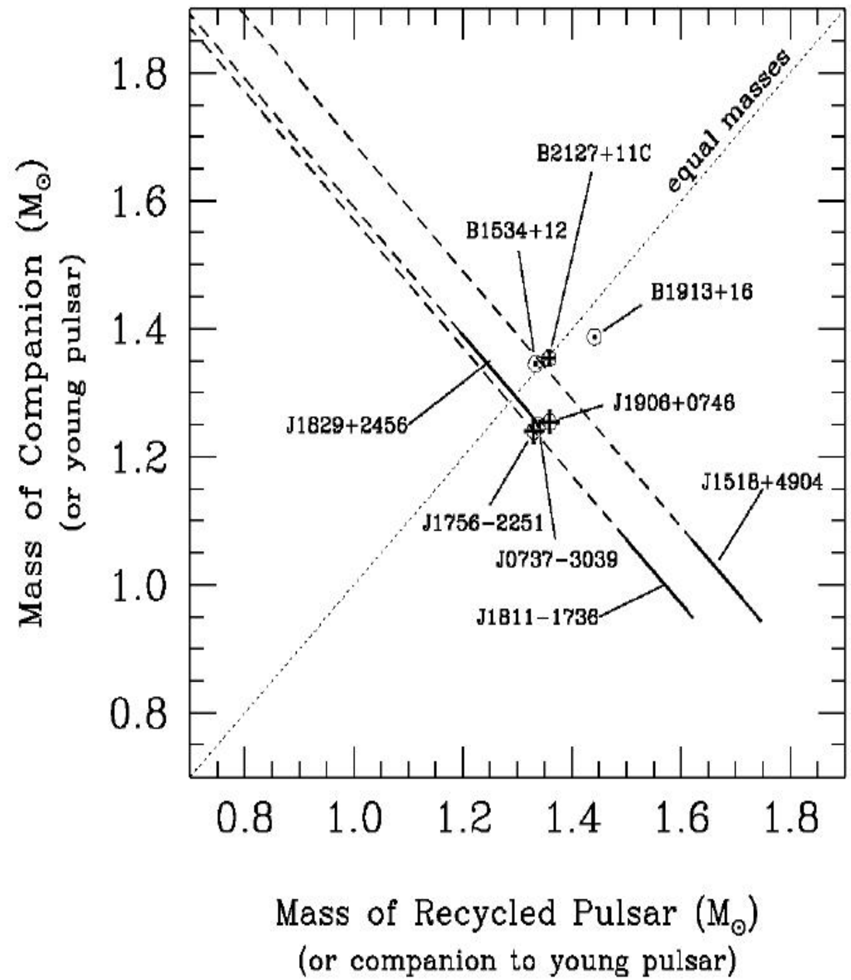
Also there are candidates, for example PSR J1753-2240 arXiv:0811.2027

In NS-NS systems we can neglect all tidal effects etc.

See a review on formation and evolution of DNS binaries in 1706.09438

Pulsar masses



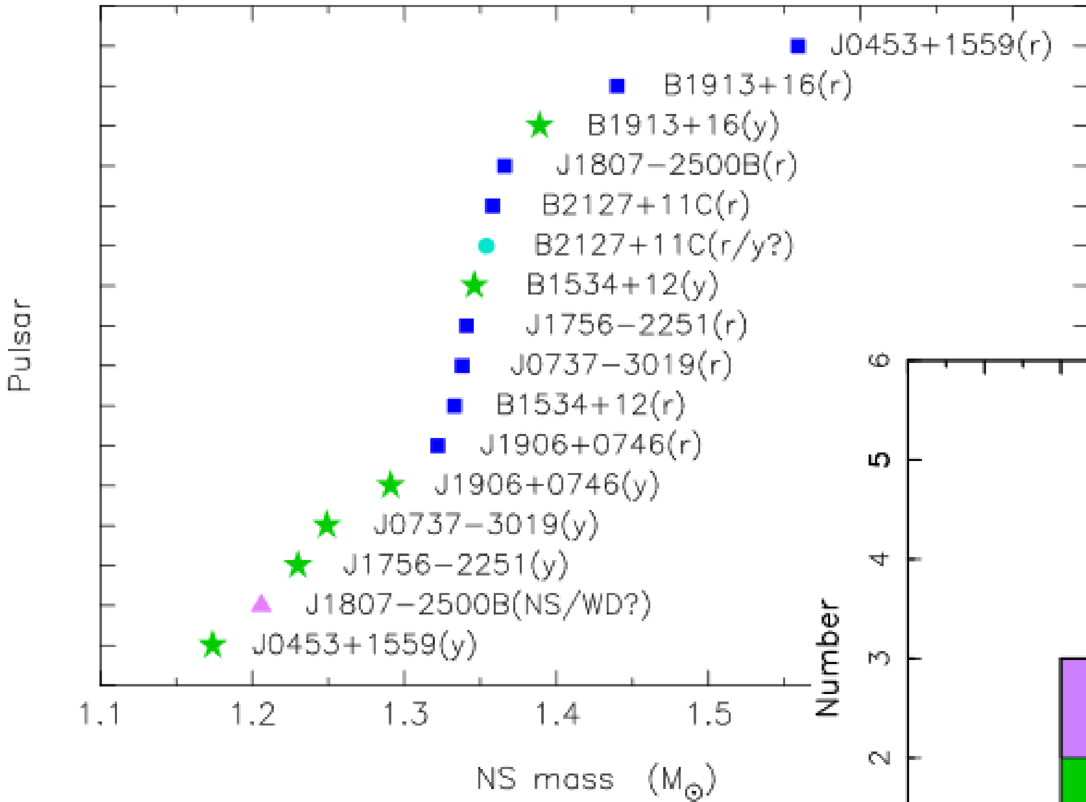


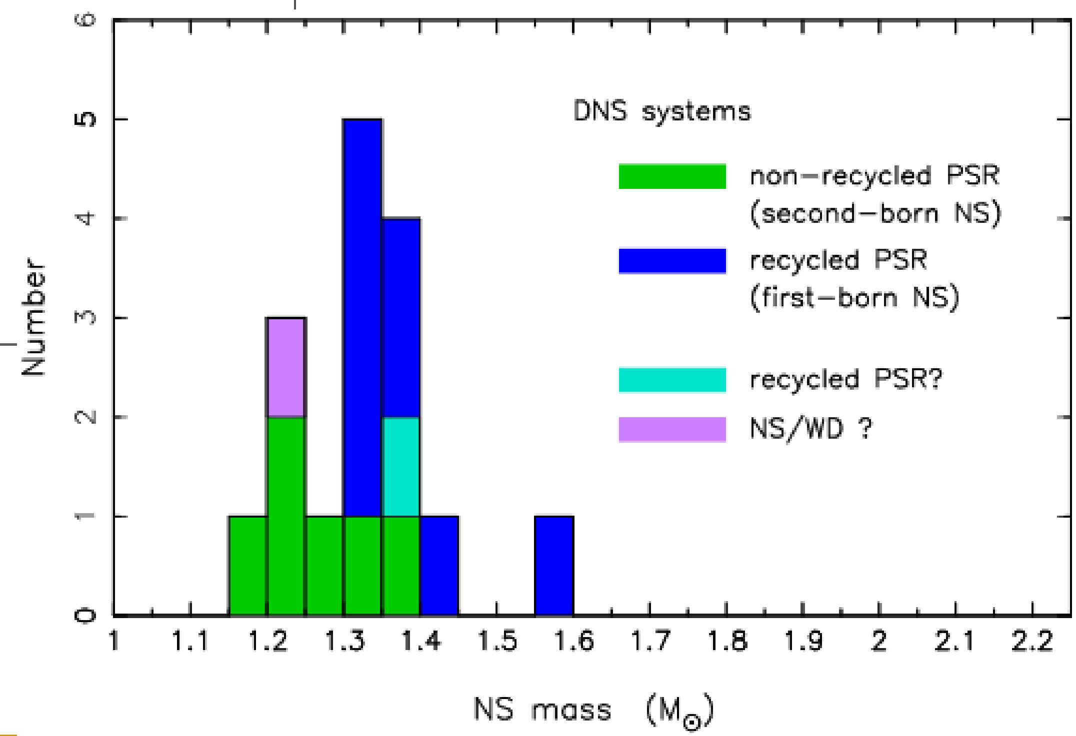
With WD companions

With NS companions

[Nice et al. 2008]

Mass distribution





1706.09438

PSR J1518+4904

[Janssen et al. arXiv: 0808.2292]

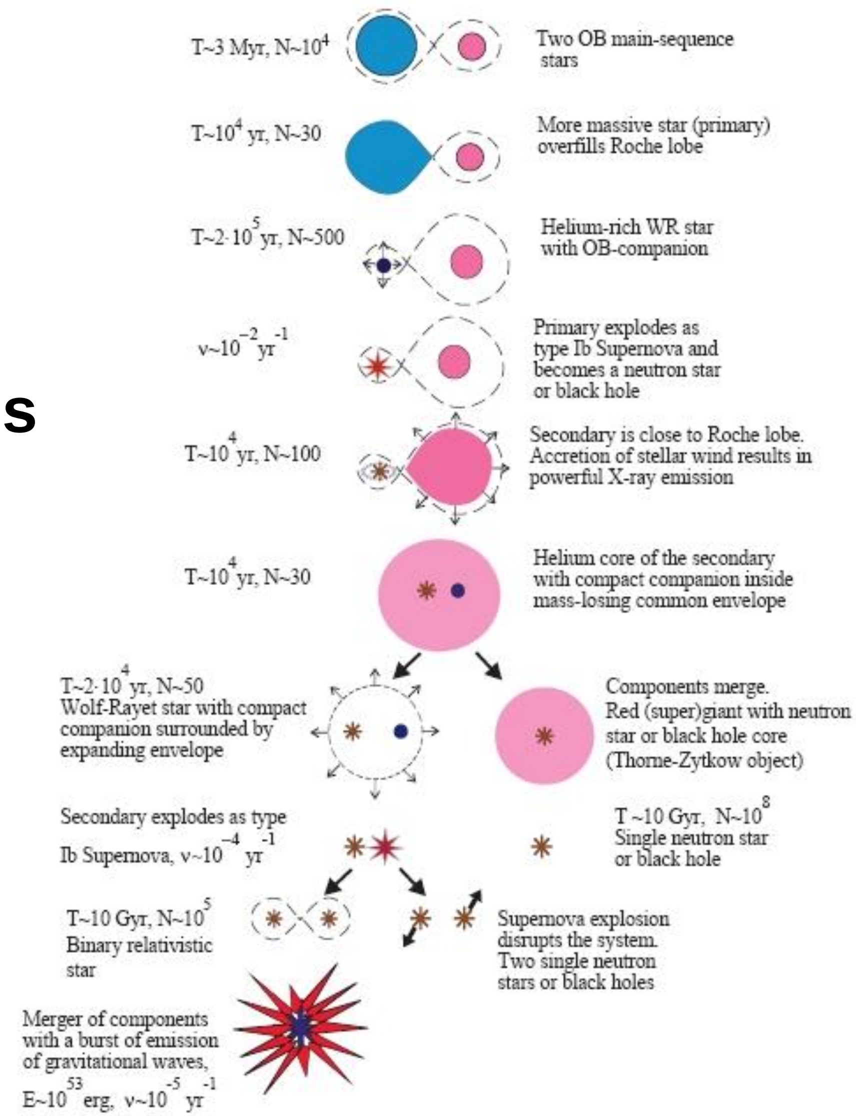
Surprising results !!!

Mass of the recycled pulsar is
<1.17 solar masses
Mass of its component is
>1.55 solar masses

<u>Central values are even more shocking:</u>

$0.72^{+0.51}_{-0.58}$ and $2.00^{+0.58}_{-0.51}$

V~25 km/s, e~0.25
The second SN was e^--capture?

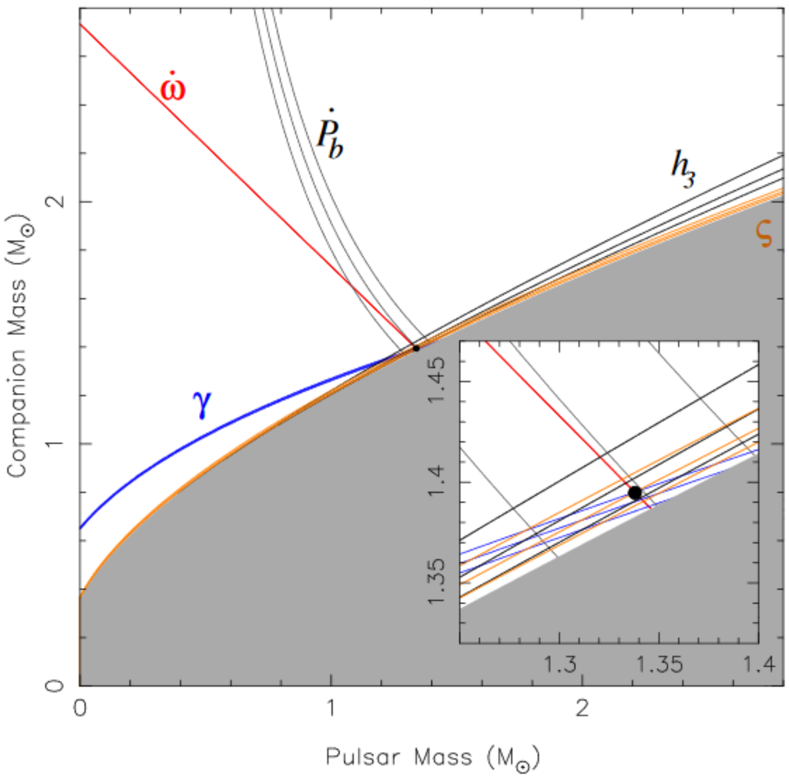


New measurements show less extreme values, see table 1 in 1603.02698:
<1.768 and >0.95 solar masses. Total mass is the same 2.7183 solar masses.

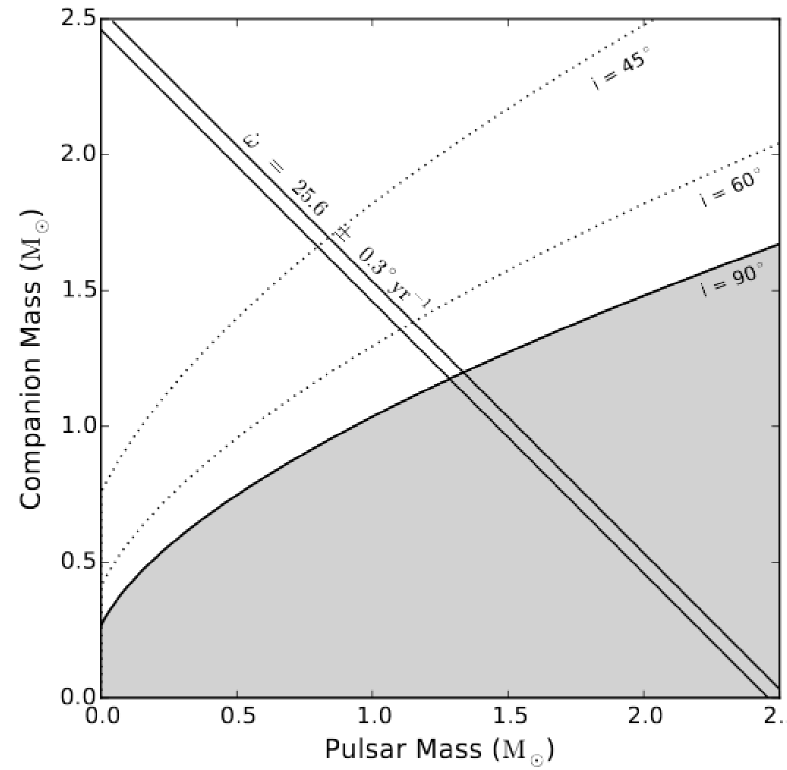
Recent discoveries with records

PSR J1757−1854
4.4 hours

PSR J1946+2052
1.88 hours



$$\dot{\omega} \simeq 10.37\,^\circ\,\mathrm{yr}^{-1},$$



$$\dot{\omega} = 25.6 \pm 0.3 \,\deg\,\mathrm{yr}^{-1},$$

1711.07697

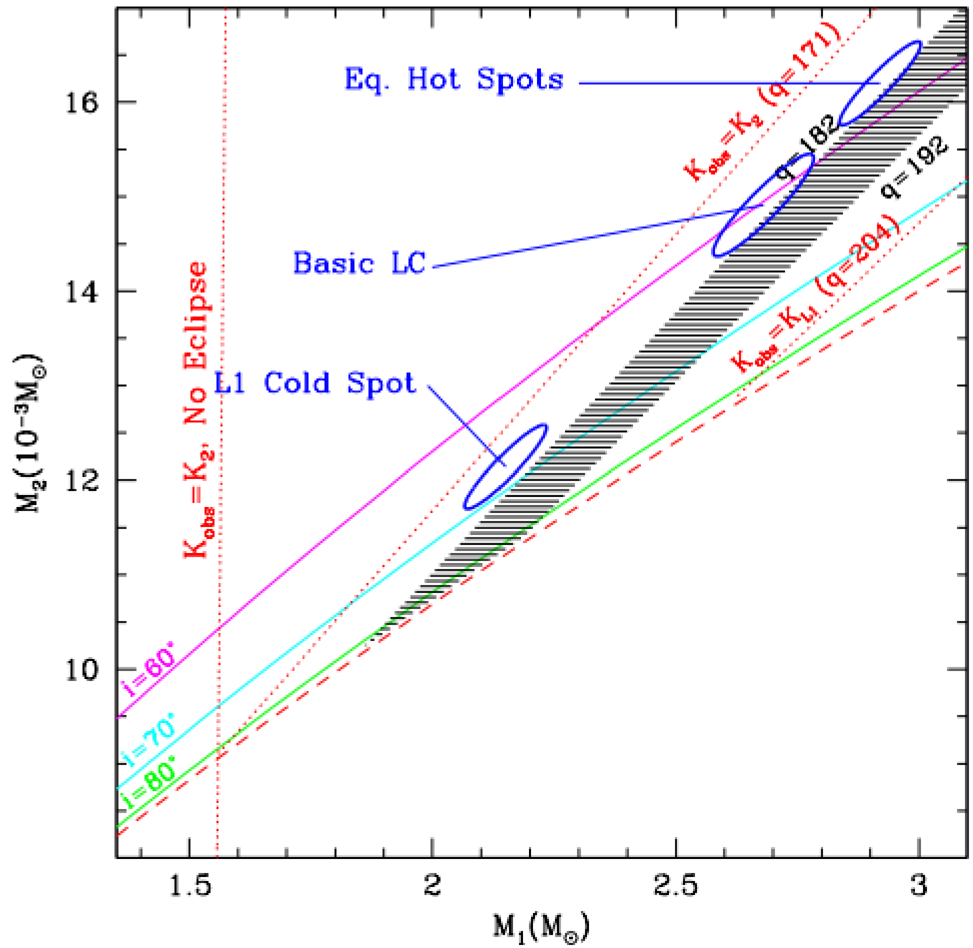
1802.01707

More measurements

PSR J1738+0333 NS+WD   arXiv: 1204.3948

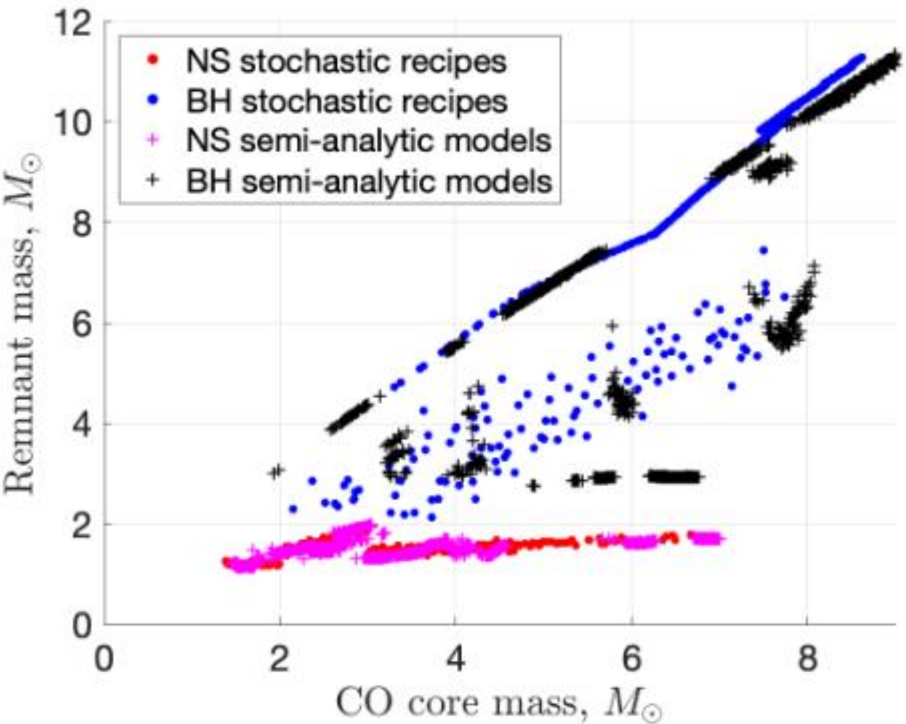
$M_{WD} = 0.181{+0.007}{-0.005}\ M_O$
$M_{PSR} = 1.47{+0.07}{-0.06}\ M_O$

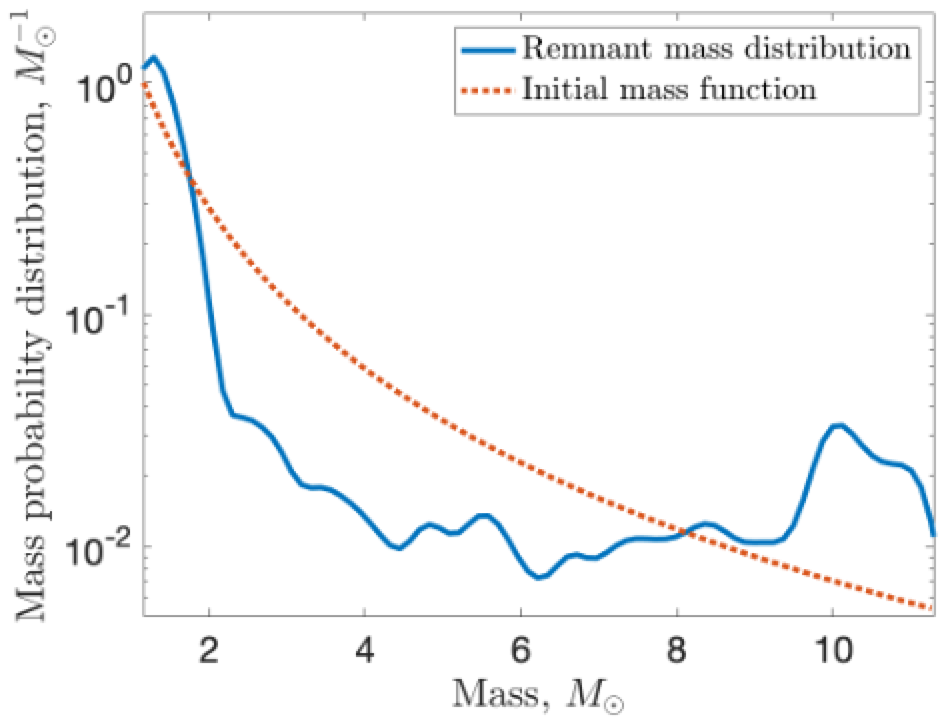
PSR J1311−3430
arXiv: 1210.6884
MPSR>2.1 at least!



Stochastic predictions

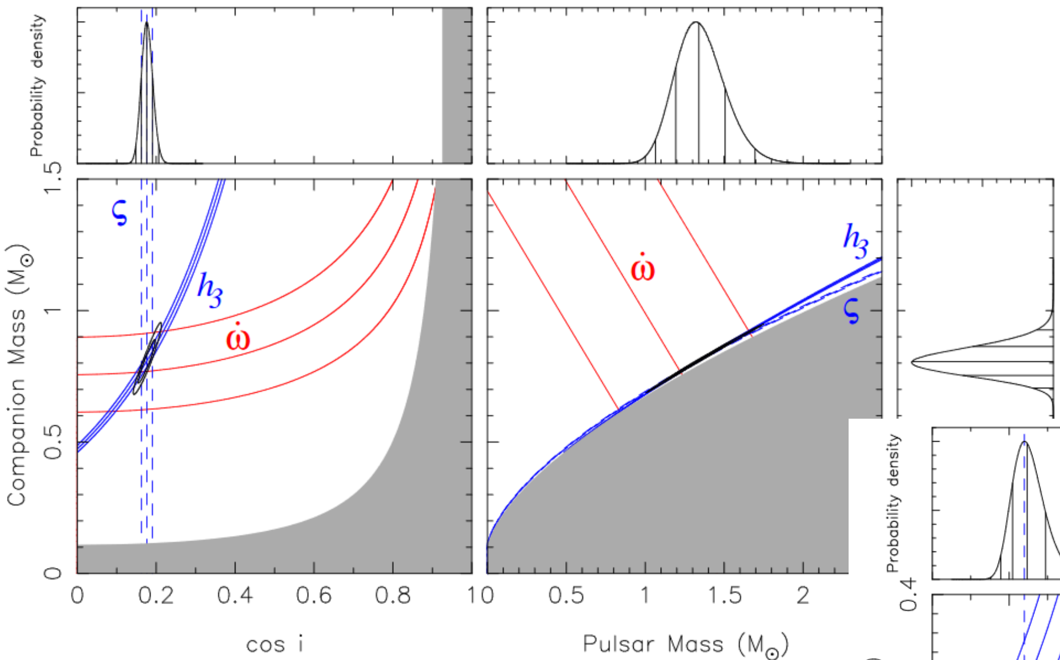
Prediction (semi-analytic) is based on detailed 3D models of single stars SN explosions.
Stochastic recipe just assumes some general properties of pre-SN and SN applied to COMPAS stellar population synthesis code.





2006.08360

Two more measurements: PSR+WD



PSR J1950+2414

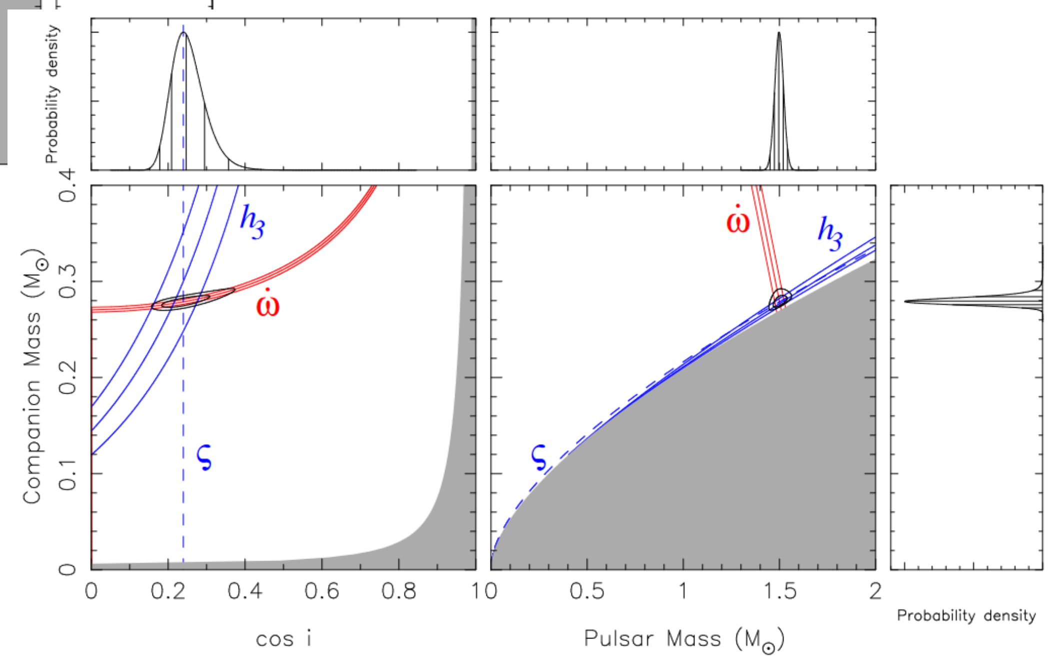
$$M_c = 0.2795^{+0.0046}_{-0.0038}\,M_\odot$$

$$M_p = 1.496 \pm 0.023\,M_\odot$$

PSR J1949+3106

$$M_c = 0.81^{+0.06}_{-0.05}\,M_\odot$$

$$M_p = 1.34^{+0.17}_{-0.15}\,M_\odot$$



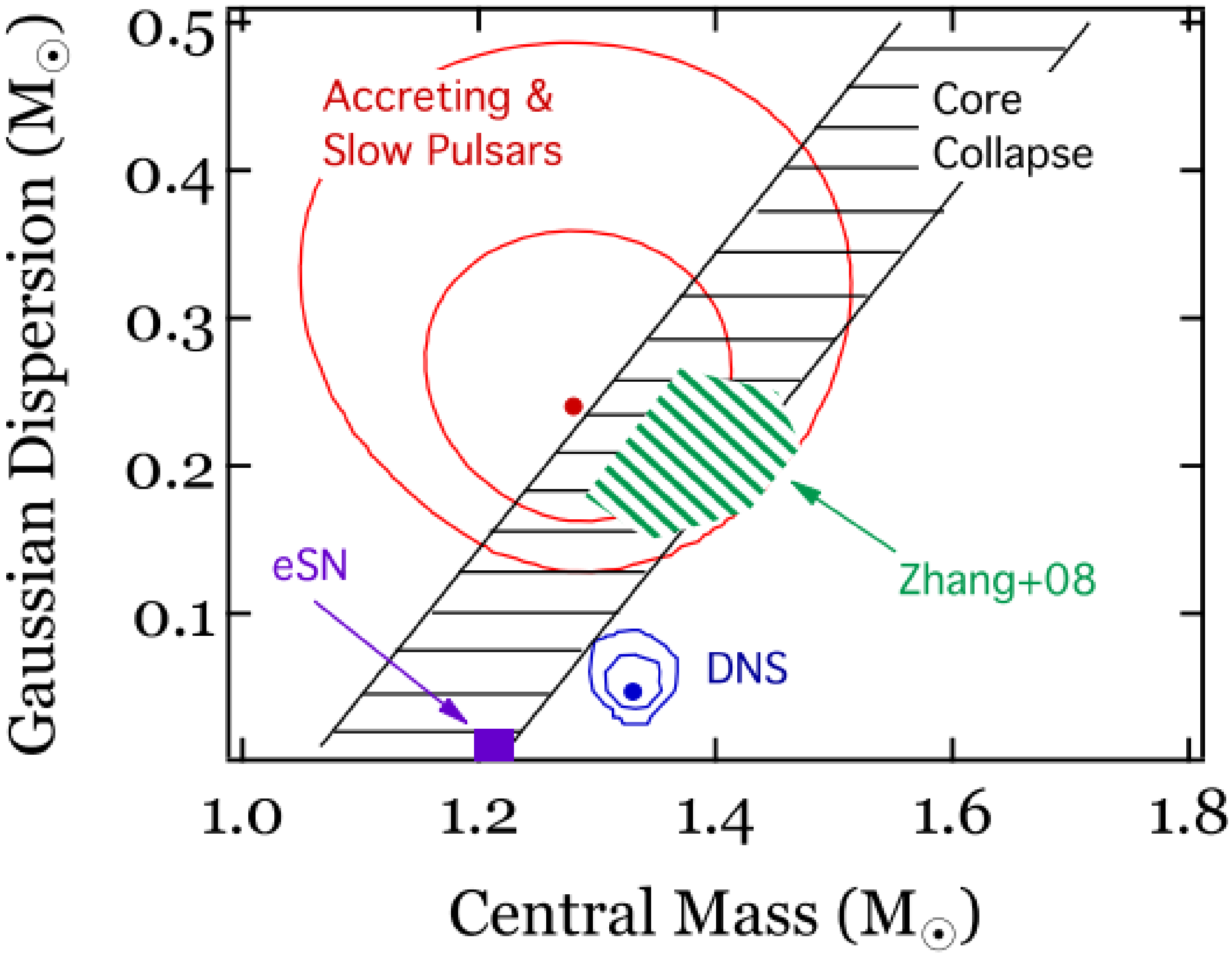
1907.05046

More measurements

<u>Continuously new measurements, critics and discussion appears</u>

- 1104.2602 Systematic Uncertainties in the Spectroscopic Measurements of Neutron-Star Masses and Radii from Thermonuclear X-ray Bursts. II. Eddington Limit
- 1104.5027 The Mass and Radius of the Neutron Star in the Bulge Low-Mass X-ray Binary KS 1731-260
- 1103.5767 Systematic Uncertainties in the Spectroscopic Measurements of Neutron-Star Masses and Radii from Thermonuclear X-ray Bursts. I. Apparent Radii
- 1105.1525 Mass and radius estimation for the neutron star in X-ray burster 4U 1820-30
- 1105.2030 New Method for Determining the Mass and Radius of Neutron Stars
- 1106.3131 Constraints on the Mass and Radius of the Neutron Star XTE J1807-294
- 1111.0347 Constraints on neutron star mass and radius in GS 1826-24 from sub-Eddington X-ray bursts
- 1201.1680 On the consistency of neutron-star radius measurements from thermonuclear bursts
- 1204.3627 Constraints on the mass and radius of the accreting neutron star in the Rapid Burster
- 1301.0831 The mass and the radius of the neutron star in the transient low mass X-ray binary SAX J1748.9-2021

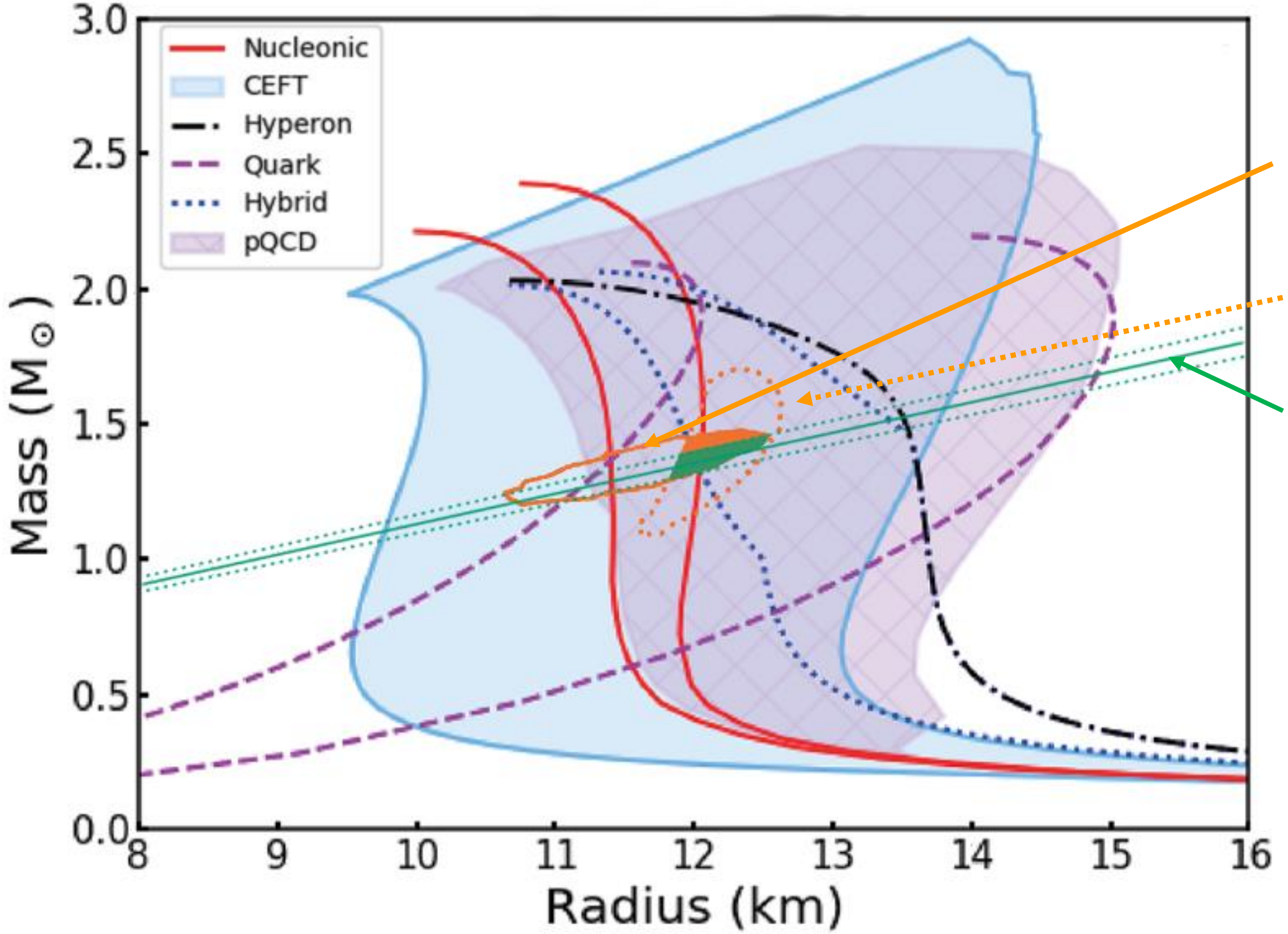
Altogether



1201.1006

Occultation of the disc by the NS

Results of modeling are shown. Large area detectors are necessary.



Pulse profile measurements

Atmospheric modeling

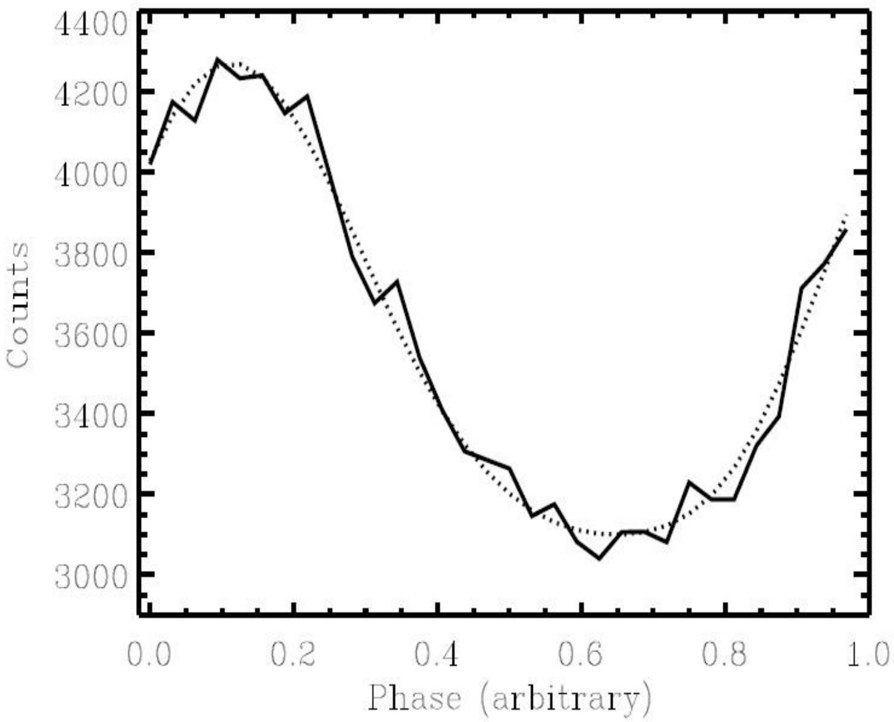
Kalpha line with shading

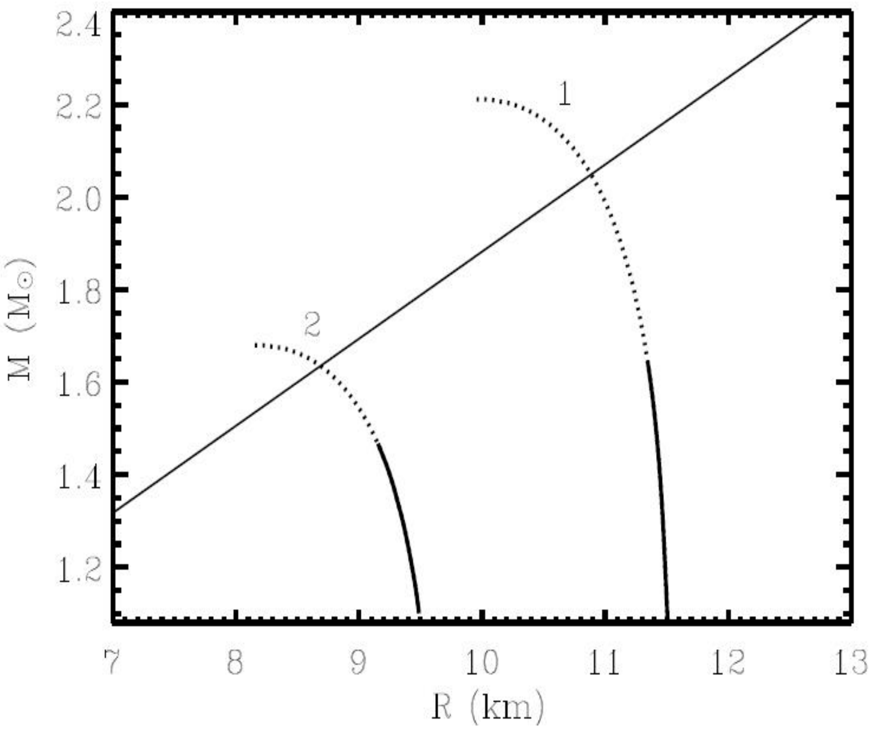
The authors tested a new method to measure R/M by observations of variations of the Kalpha line profile due to occultations of part of a disc by a NS.
Not effective, yet.

2003.07659

Burst oscillations

Fitting light curves of X-ray bursts.
Oscillations due to rotation of a NS.
$Rc^2/GM > 4.2$ for the neutron star in XTE J1814-338.





Bhattacharyya et al. astro-ph/0402534

Radius measurement

Fitting X-ray spectrum of a low-mass X-ray binary in quiescent state.

Mostly sources in globular clusters.

For 4 objects ~10% precision. But this is for fixed mass.

For U24 in NGC 6397 $R_{NS}=8.9^{+0.9}_{-0.6}$ km for 1.4 solar masses.
For the radius observed from infinity: $11.9^{+2.2}_{-2.5}$ km

1007.2415