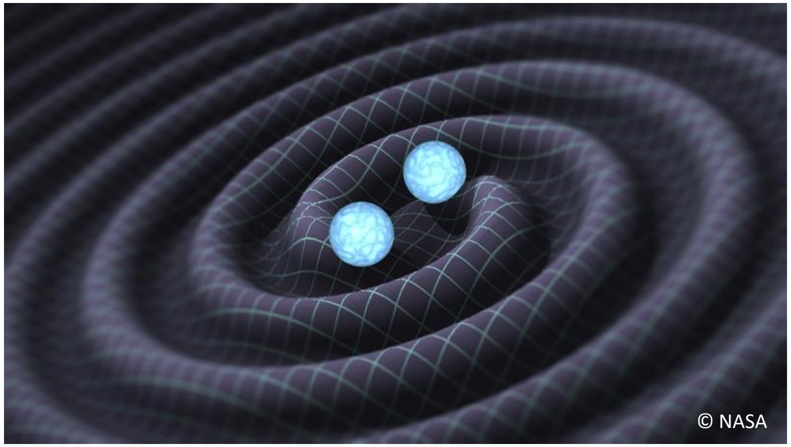
THOMAS TAURIS



PROPERTIES OF BINARY NEUTRON STARS AS GRAVITATIONAL WAVE SOURCES

August 19, 2019 NBIA Copenhagen

AARHUS UNIVERSITET

AARHUS INSTITUTE OF ADVANCED STUDIES

INSTITUT FOR FYSIK OG ASTRONOMI IFA

Neutron Stars and Black Holes

Unique **physics labs**.

- Densest matter in obs. Uni.
  (testing supranuclear matter) Pethick, Andersson
- Strongest E/B-fields
  (testing plasma physics)
- Atomic clock precision
- Testing theories of gravity
  (unite quantum theory and gravity) Damour, Berti Cardoso
- Probes of stellar evolution and supernovae Burrows

...and all the rest of you!

Many **astrophysical phenomena** are related to **NSs** and **BHs** in **binaries**:
X-ray sources, radio pulsars, jets, Type Ib/c SNe, GRBs and **GWs and mergers**

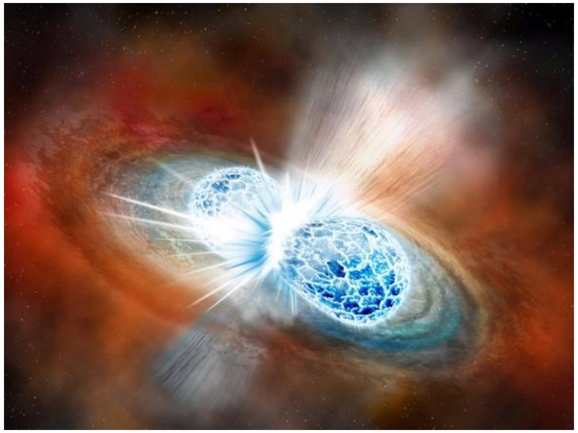
Triples: Samsing Brown, Papa Tamborra, Greiner

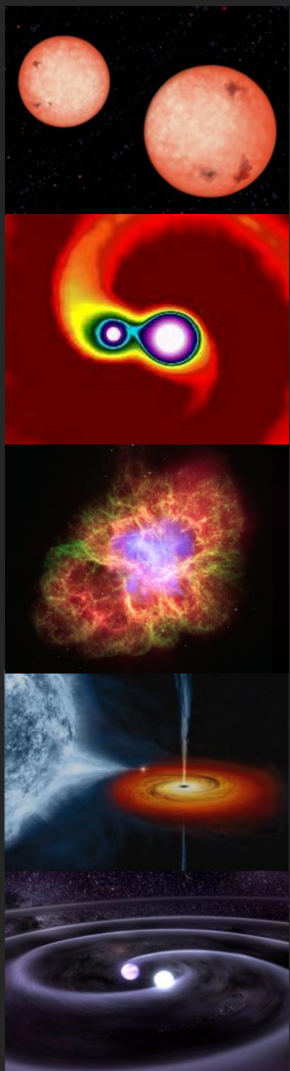
Central questions:

How do these BH/NS binaries form?

And how can we understand their properties (i.e. masses and spins)?

What are the GW spectra for LISA?





PROPERTIES OF BINARY NEUTRON STARS AS GRAVITATIONAL WAVE SOURCES

- **Resume of the formation of double NS mergers**
  - **Case BB X-ray binaries / Ultra-stripped SNe**
- **NS masses, spins and B-fields expected in GW sources**
- **GW170817: properties and GW merger rates**

\+

or

- **Kicks: evidence for (mainly) small kicks in 2nd SN**
- **LISA GW sources: mass transfer from a white dwarf to a NS**

a personal bias

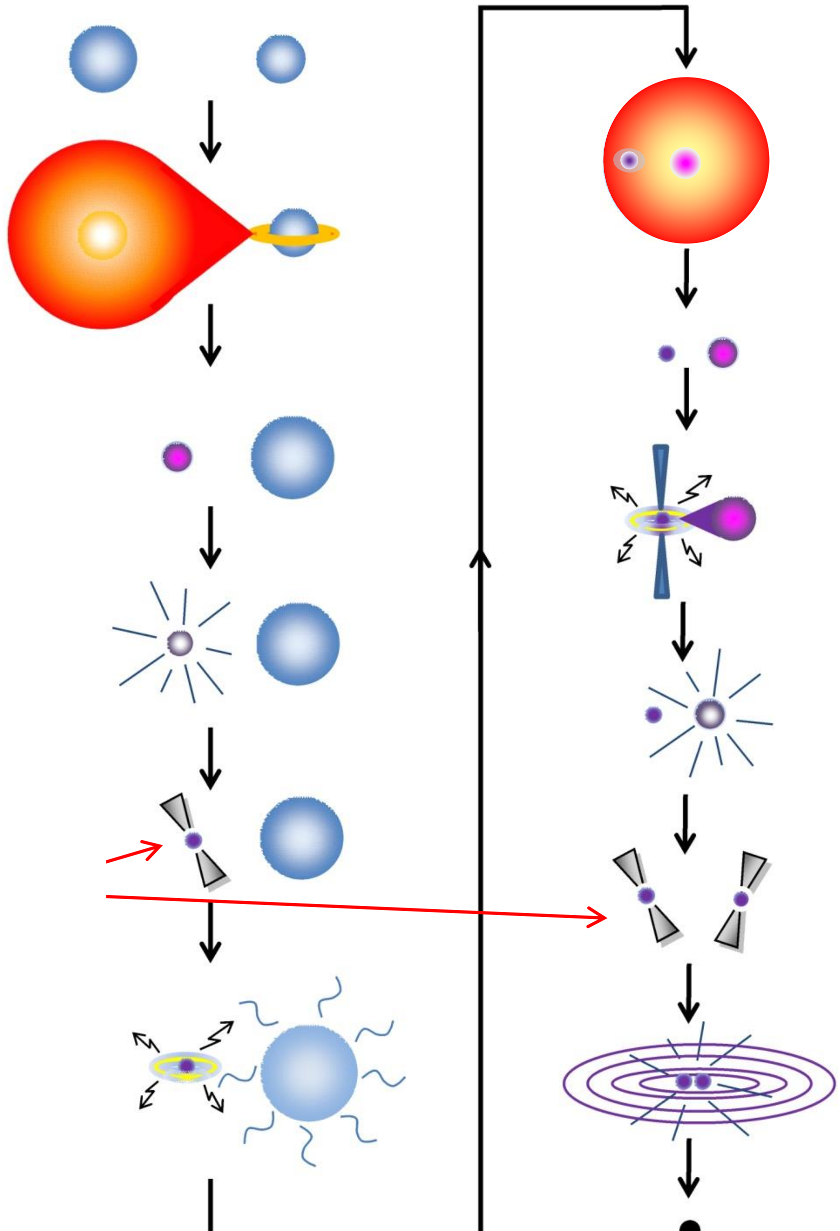
Tauris (2018), Phys. Rev. Lett. 121, 131105

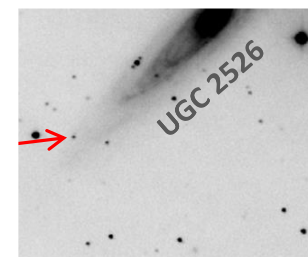
Kruckow, Tauris et al. (2018), MNRAS 481, 1908

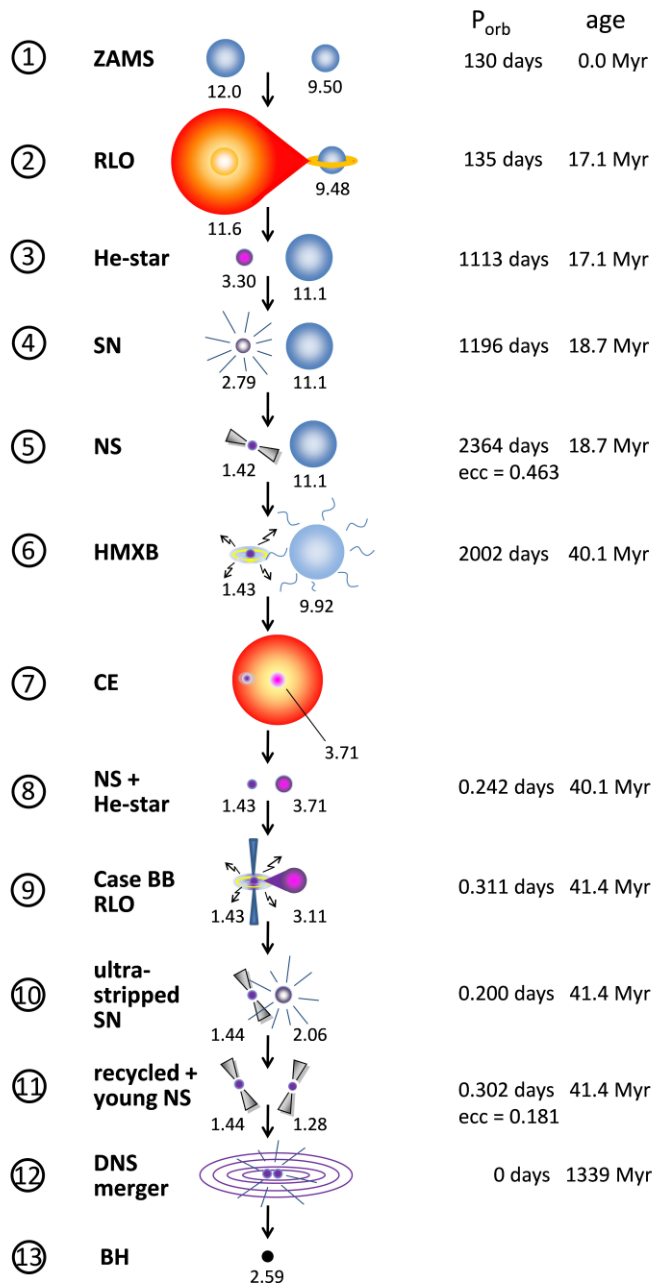
Tauris et al. (2017), ApJ, 846, 170

Sengar, Tauris et al. (2017), MNRAS Letters 470, L6

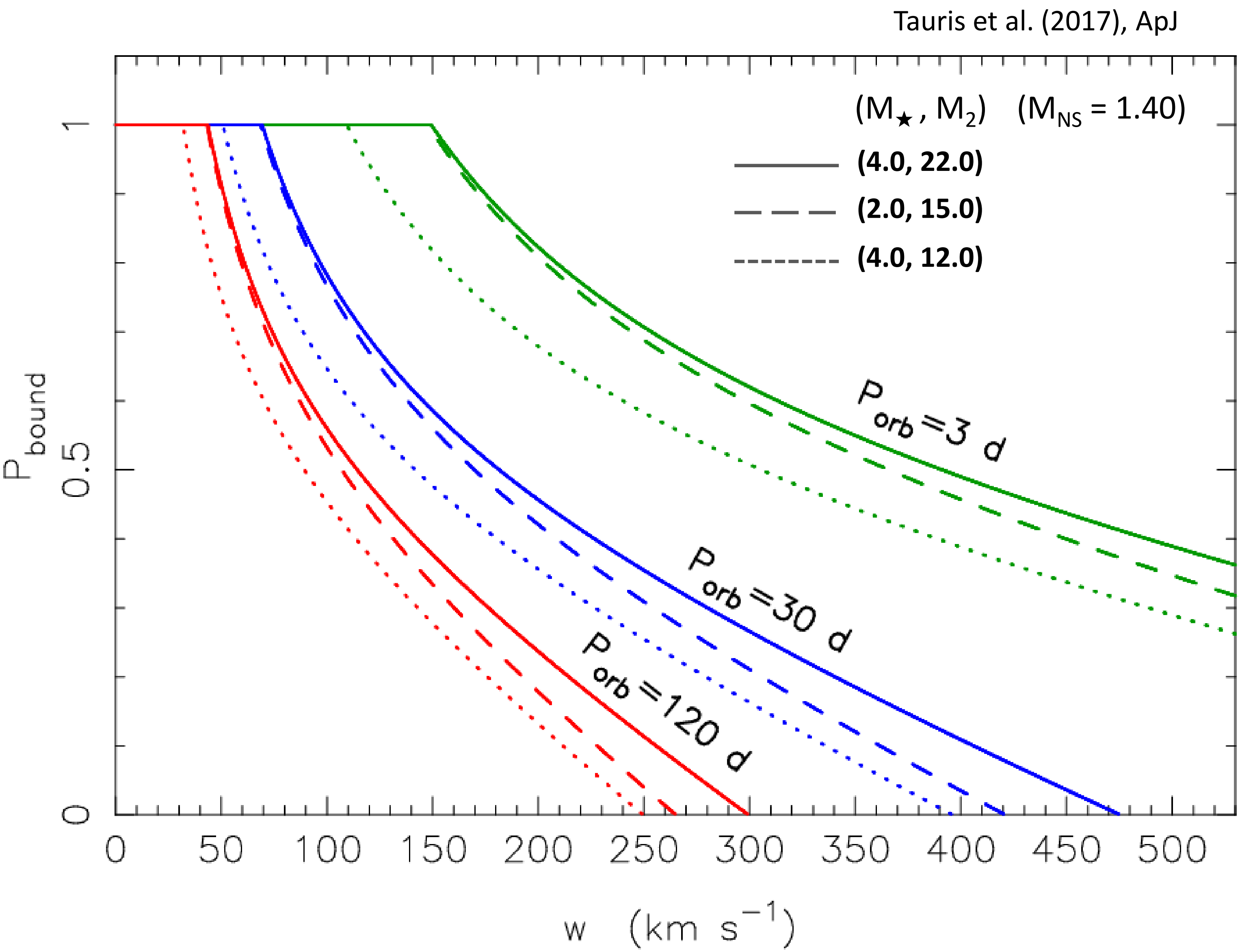
Tauris et al. (2017), ApJ



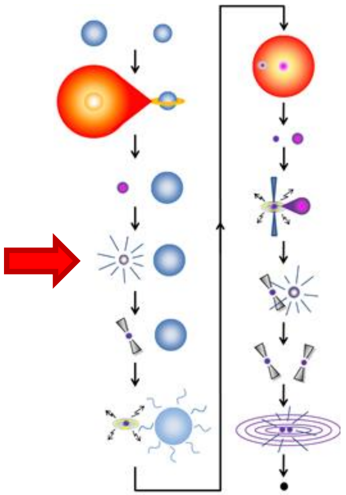




van den Heuvel & Tauris (2020)
Physics of Binary Star Evolution
Princeton University Press



Tauris et al. (2017), ApJ
$(M_\star, M_2)$ $(M_{NS} = 1.40)$
(4.0, 22.0)
(2.0, 15.0)
(4.0, 12.0)
P_{orb} =3 d
P_{orb} =30 d
P_{orb} =120 d
P_{bound}
0
0.5
1
0 50 100 150 200 250 300 350 400 450 500
w (km s^{-1})



$$\frac{X_+}{A} = -\cos\beta\left[\xi\sin\gamma + (\xi-1)\sqrt{\frac{\xi}{\xi-2}}\right] \quad (38)$$

$$\frac{Y_+}{A} = \xi\cos^2\gamma - 1 - \sin\gamma\sqrt{\frac{\xi}{\xi-2}} \quad (39)$$

$$\frac{Z_+}{A} = -\sin\beta\sin\lambda\left[\xi\sin\gamma + (\xi-1)\sqrt{\frac{\xi}{\xi-2}}\right] \quad (40)$$

where we have used $u_\infty = A\,e^2$ and $u_0 = u_\infty\sqrt{\xi/(\xi-2)}$.

We now proceed to express β, γ and λ in the true input angles ϑ and φ. We cannot reach $\sin\lambda$ directly, but that doesn't matter, from Fig. 1 (bottom) we have: $u_0\sin\beta\sin\lambda = w\sin\vartheta\sin\varphi$. Intermediate results are:

$$X_+ = \frac{v + w\cos\vartheta}{1 - \xi + \sqrt{\xi(\xi-2)}\sin\gamma} \quad (41)$$

$$Y_+ = \frac{\sqrt{\xi(\xi-2)}}{1+\xi(\xi-2)\cos^2\gamma}\times\left[u_0\left(1-\frac{1}{\xi}\right) - \frac{1}{u_0}(w\sin\vartheta\cos\varphi - v_{\rm im})^2\right] - \frac{(w\sin\vartheta\cos\varphi - v_{\rm im})}{1+\xi(\xi-2)\cos^2\gamma} \quad (42)$$

$$P \equiv 1 - 2\tilde{m} + \frac{w^2}{v^2} + \frac{v_{\rm im}^2}{v^2} + 2\frac{w}{v^2}(v\cos\vartheta - v_{\rm im}\sin\vartheta\cos\varphi) \quad (44)$$

$$Q \equiv 1 + \frac{P}{\tilde{m}} - \frac{(w\sin\vartheta\cos\varphi - v_{\rm im})^2}{\tilde{m}v^2} \quad (45)$$

$$R \equiv \left(\frac{\sqrt{P}}{\tilde{m}v}(w\sin\vartheta\cos\varphi - v_{\rm im}) - \frac{P}{\tilde{m}} - 1\right)\frac{1+m_{2f}}{m_{2f}} \quad (46)$$

Inserting Eqs. (48)–(50) into Eqs. (12) and (13) gives the final velocities of the stellar components in the original reference frame.

We find for the neutron star:

$$v_{\rm NS,x} = w\cos\vartheta\left(\frac{1}{R}+1\right) + \left(\frac{1}{R} + \frac{m_2}{1+m_{\rm shell}+m_2}\right)v \quad (51)$$

$$v_{\rm NS,y} = w\sin\vartheta\cos\varphi\left(1-\frac{1}{S}\right) + \frac{1}{S}v_{\rm im} + \frac{Q\sqrt{P}}{S}v \quad (52)$$

$$v_{\rm NS,z} = w\sin\vartheta\sin\varphi\left(\frac{1}{R}+1\right) \quad (53)$$

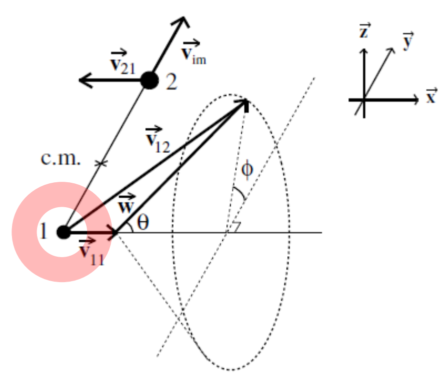
and for the companion star:

$$v_{2x} = \frac{-w\cos\vartheta}{m_{2f}R} - \left(\frac{1}{m_{2f}R} + \frac{1+m_{\rm shell}}{1+m_{\rm shell}+m_2}\right)v \quad (54)$$

$$v_{2y} = \frac{w\sin\vartheta\cos\varphi}{m_{2f}S} + \left(1 - \frac{1}{m_{2f}S}\right)v_{\rm im} - \frac{Q\sqrt{P}}{m_{2f}S}v \quad (55)$$

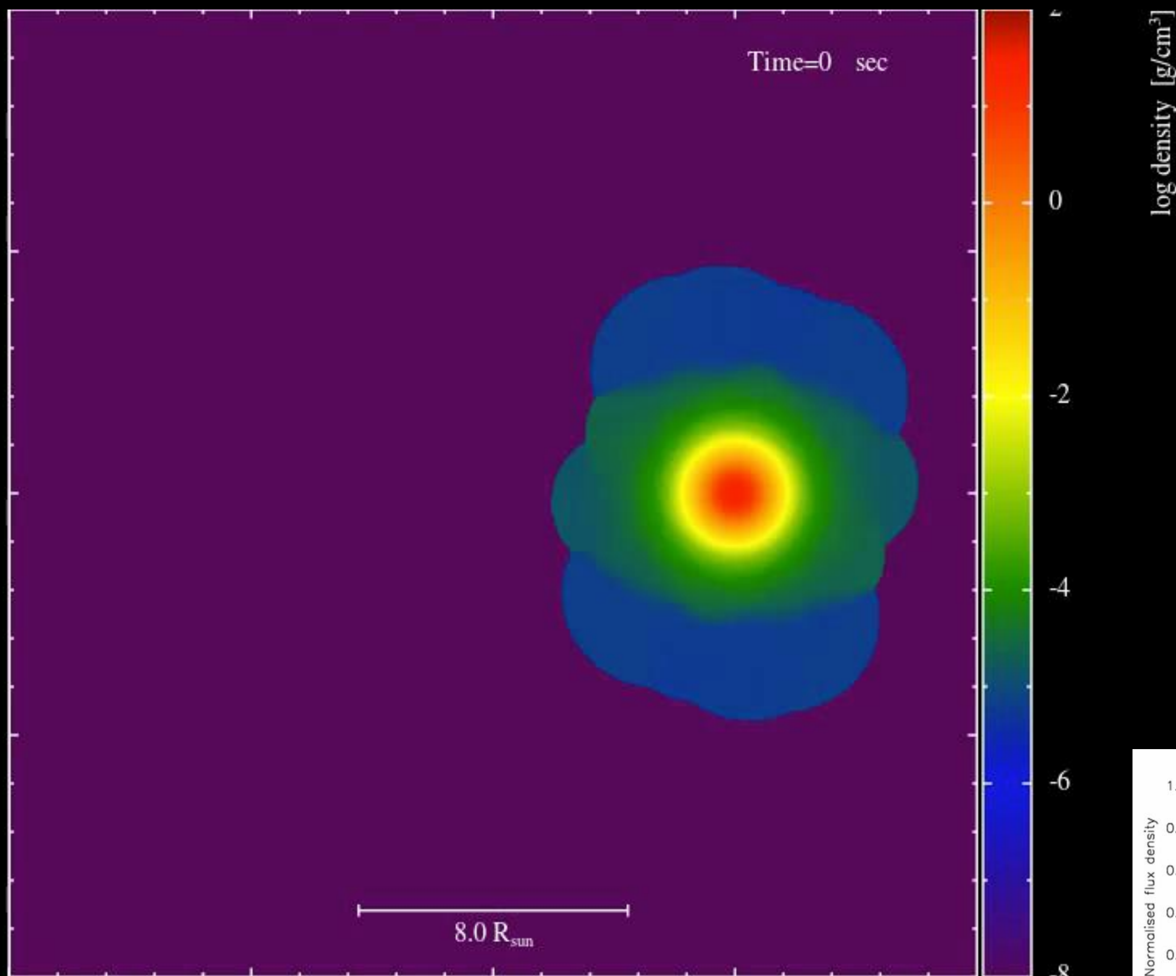
$$v_{2z} = \frac{-w\sin\vartheta\sin\varphi}{m_{2f}R} \quad (56)$$

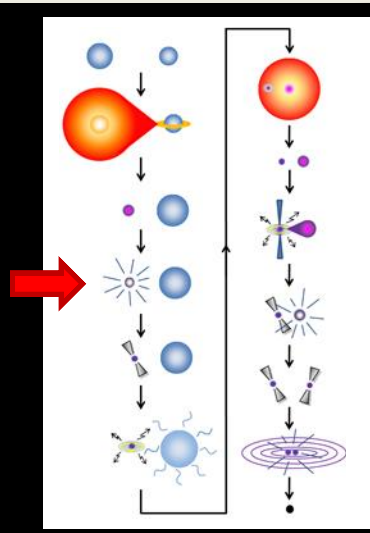
Tauris & Takens (1998), A&A



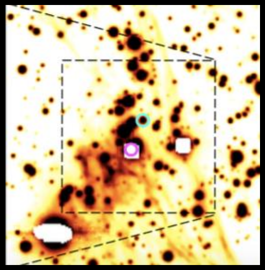
SUPERNOVA SHELL IMPACT

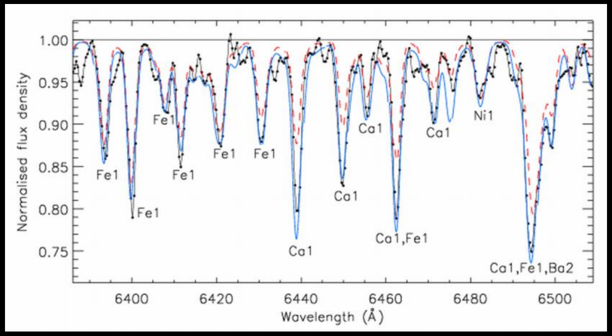
Liu, Tauris, Röpke et al. (2015), A&A





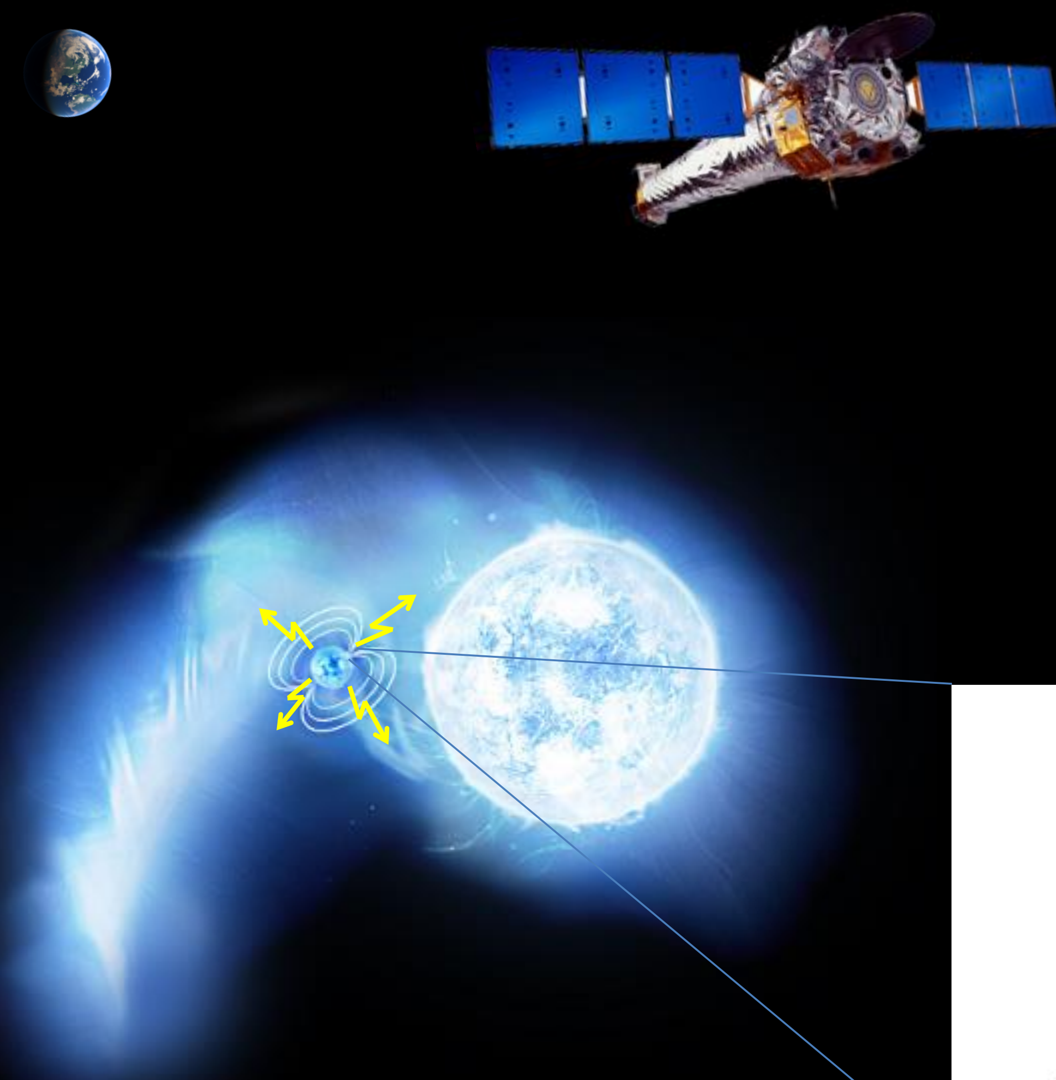
RCW 86

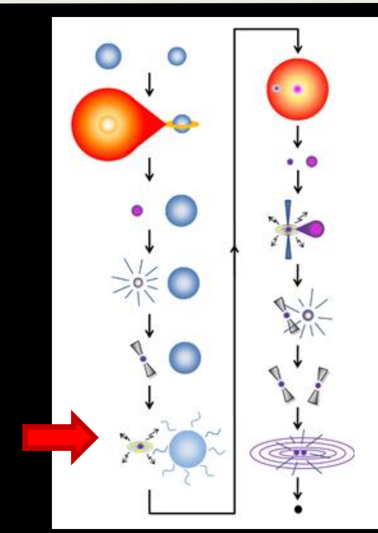


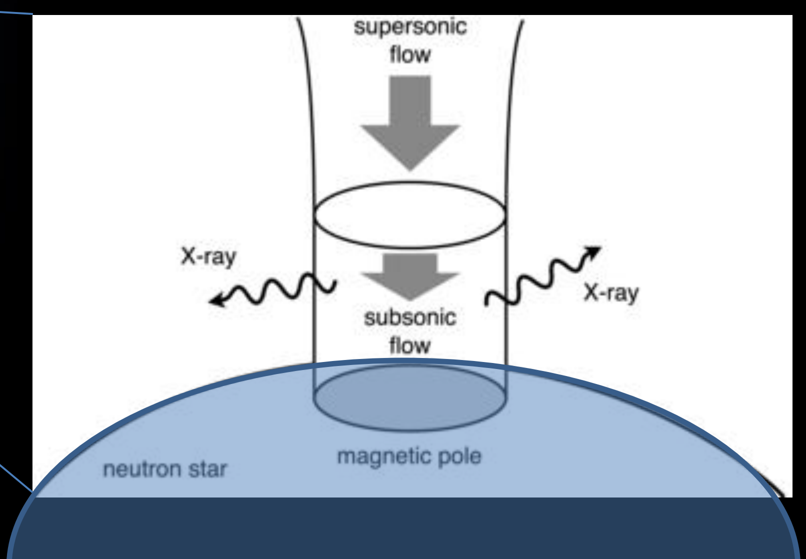


See also

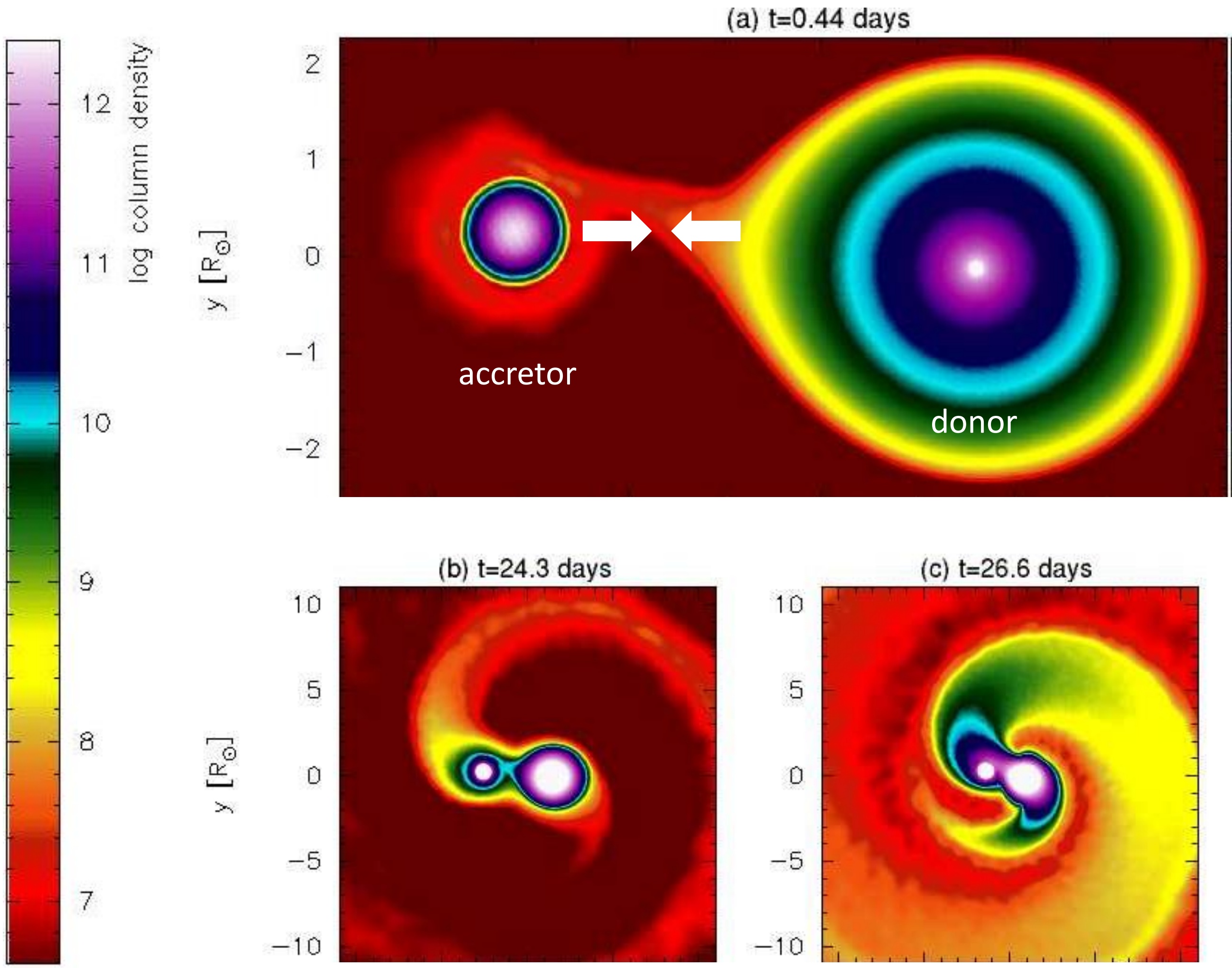
Gvaramadze et al. (2017), Nature Astronomy

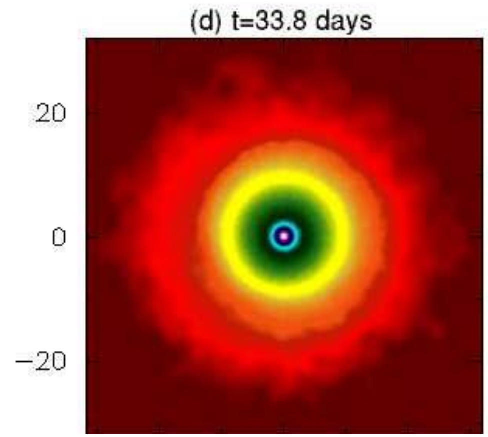


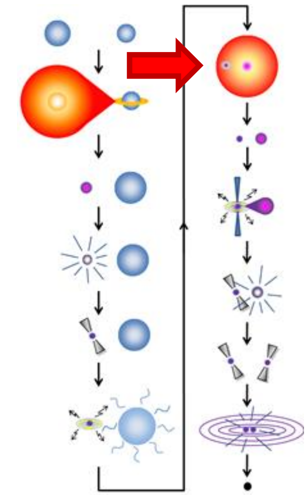



supersonic
flow
X-ray
X-ray
subsonic
flow
neutron star
magnetic pole

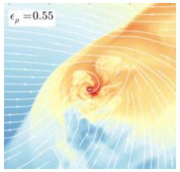
Run-away mass transfer → common envelope







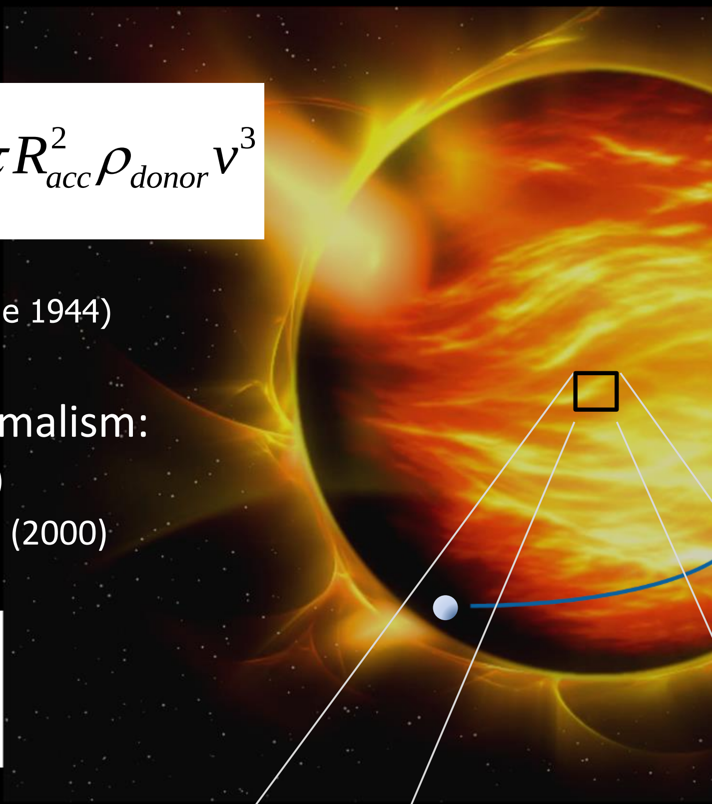
Lombardi & Scruggs in Ivanova et al. (2013)
MacLeod & Ramirez-Ruiz (2015)
Kruckow, Tauris et al. (2016)
Fragos et al. (2019)

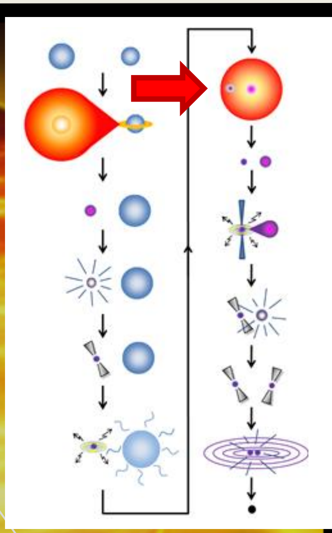


stellar merger
(*cannibalism*)

$$\left(\frac{dE_{orb}}{dt}\right) = -\frac{GM_{donor}M_X}{2a^2}\frac{da}{dt} = \xi(\mu)\pi R_{acc}^2 \rho_{donor} v^3$$

Dissipation of E_{orb} by drag force (Bondi & Hoyle 1944)





Energy budget (α, λ)-formalism:

Webbink (1984), de Kool (1990)

Han et al. (1994), Dewi & Tauris (2000)

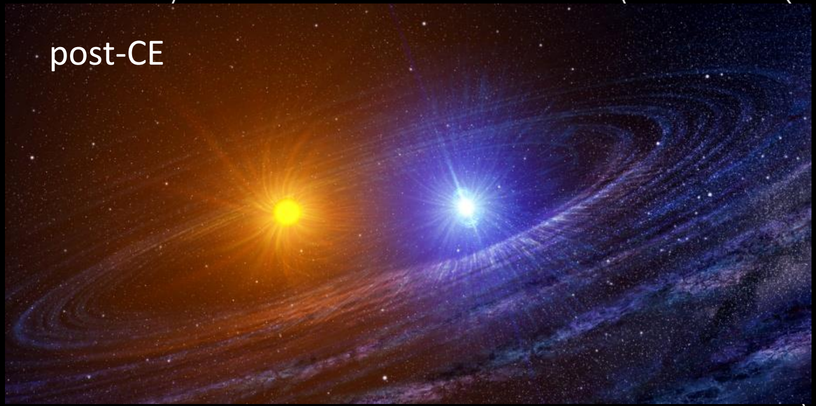
$$E_{env} \equiv \alpha \, \Delta E_{orb}$$

$$E_{env} = \int_{M_{core}}^{M_{donor}} \left(-\frac{GM(r)}{r} + \eta_{th} \, U \right) dm$$

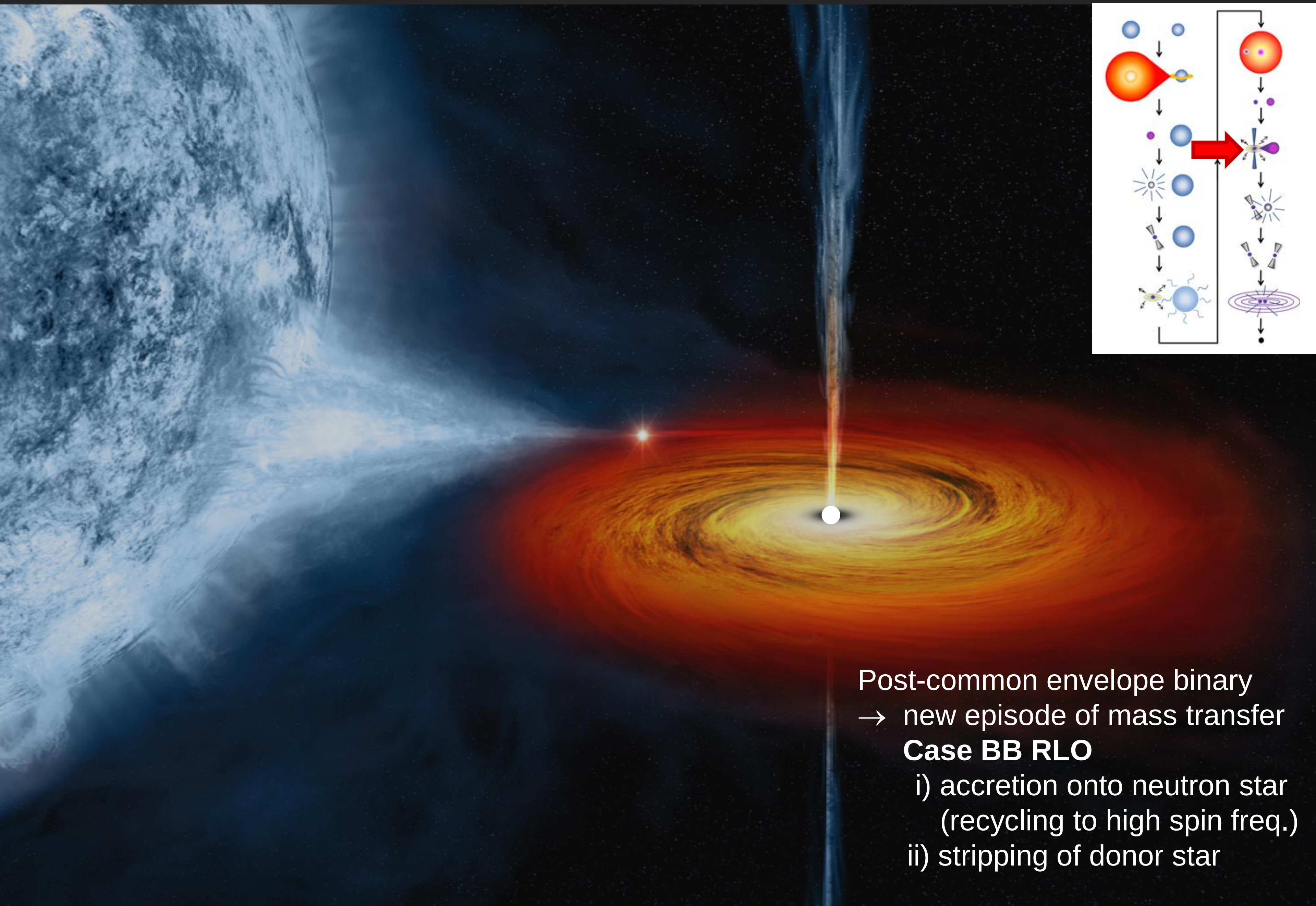
gravitational binding energy

internal thermodynamic energy

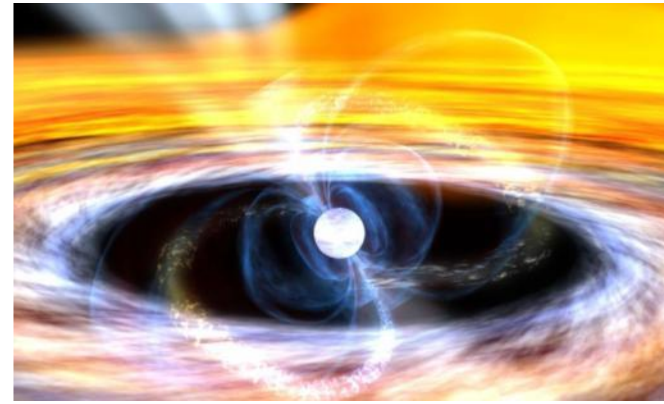
- thermal energy
- energy of radiation
- recombination energy



Review by Ivanova et al. (2013)



Post-common envelope binary
→ new episode of mass transfer
Case BB RLO
i) accretion onto neutron star
(recycling to high spin freq.)
ii) stripping of donor star



$$P_{eq} = 2\pi\sqrt{\frac{r_{mag}^{3}}{GM}}\,\frac{1}{\omega_c} \quad \wedge \quad r_{mag}(\dot{M}, B) \quad \wedge \quad B(P, \dot{P})$$

$$\dot{P} = \frac{2^{1/6}\,G^{5/3}}{\pi^{1/3}c^{3}}\,\frac{\dot{M}M^{5/3}P_{eq}^{4/3}}{I}\cdot(1+\sin^{2}\alpha)\cdot\varphi^{-7/2}\cdot\omega_c^{7/3}$$ spin-up line in $P\dot{P}$ – diagram

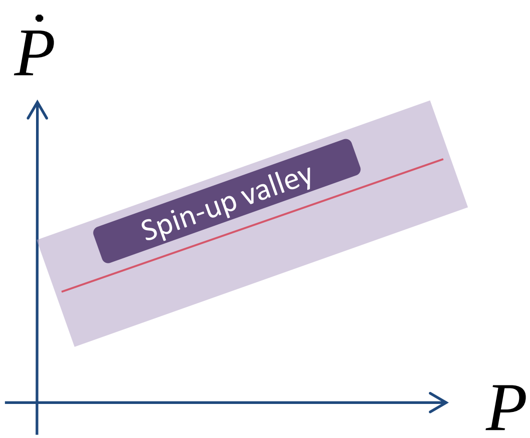
Tauris, Langer & Kramer (2012)

Important!

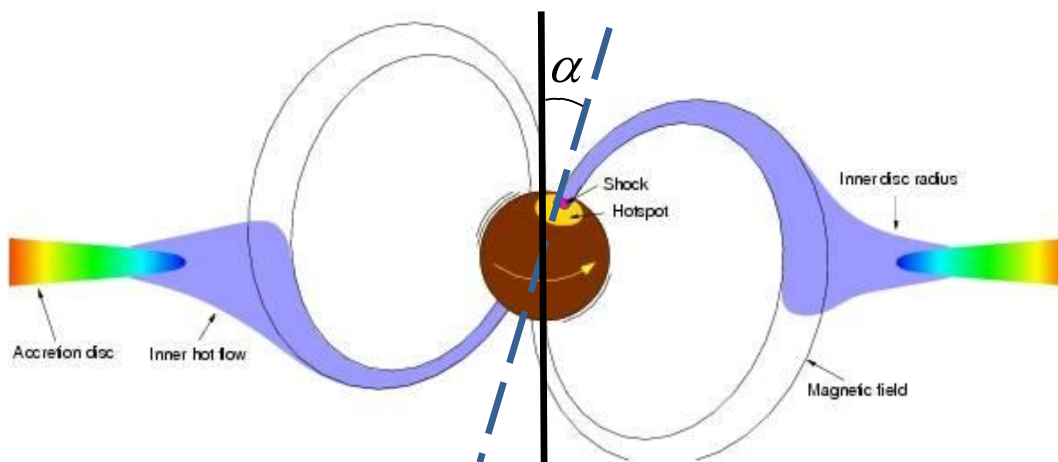
disk –magnetosphere parameters:

$$R_{mag} = \varphi\, R_{Alfven}$$

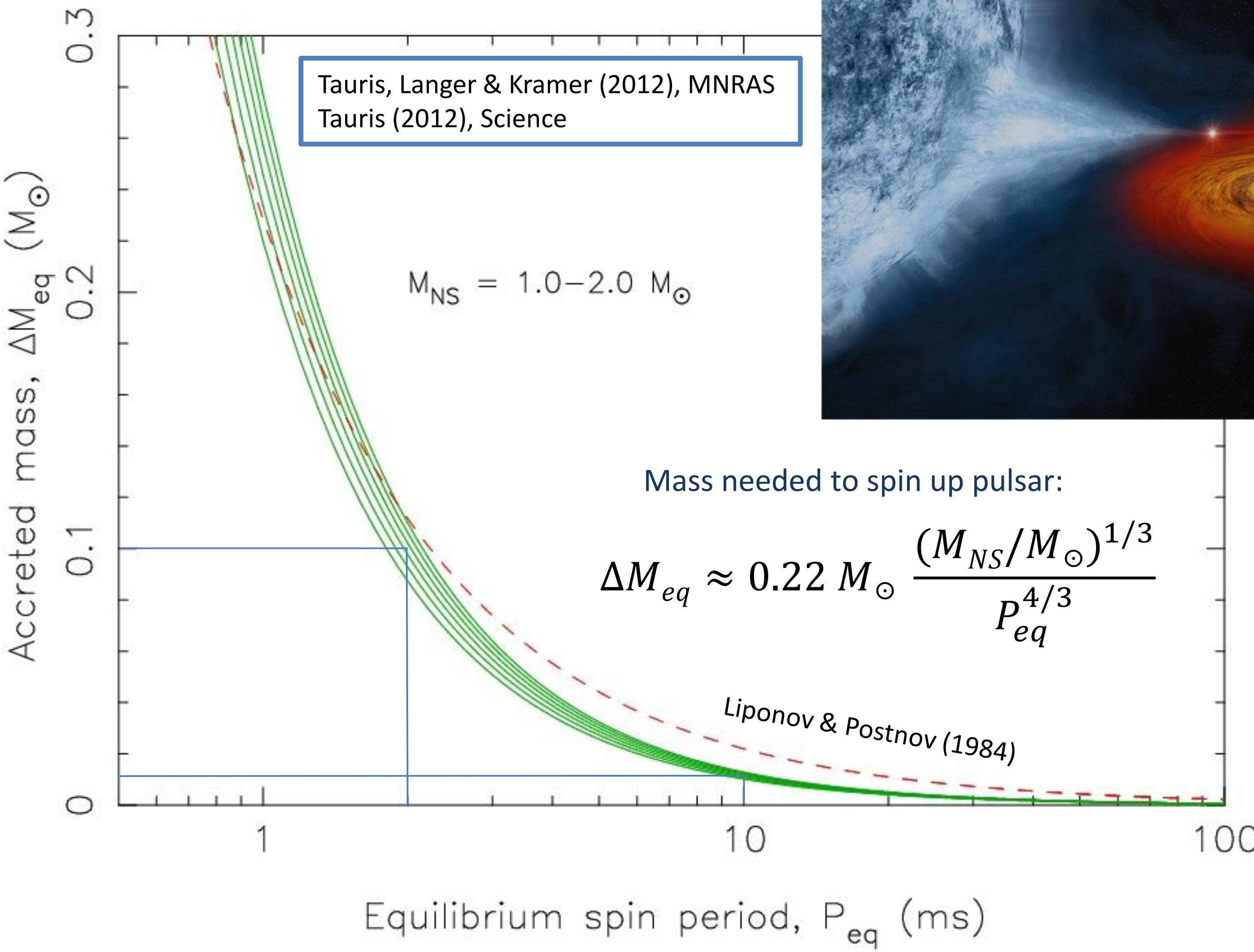
$$\Omega_{NS} = \omega_c\,\Omega_{mag}^{Kep.}$$

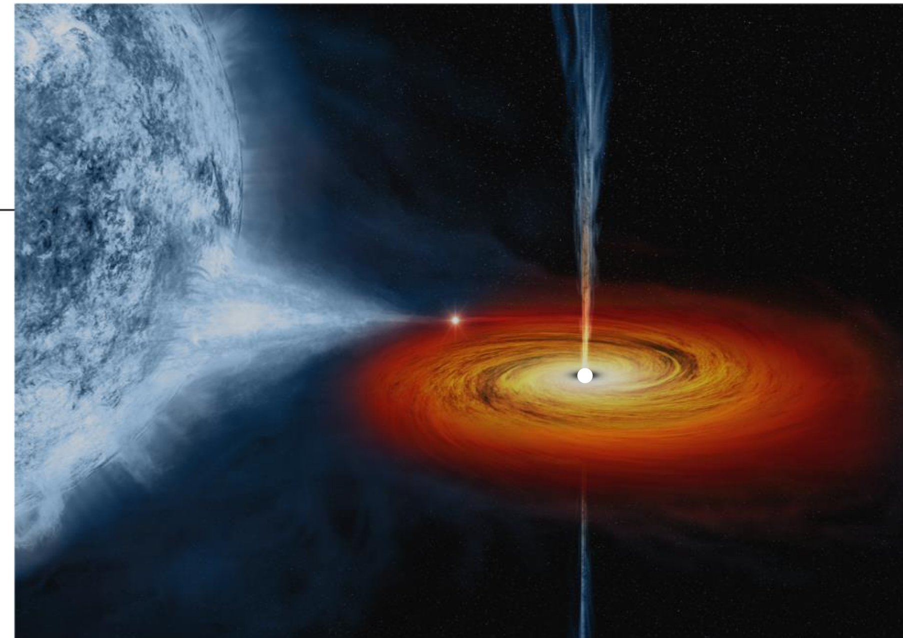


Classical spin-up line
e.g. Bhattacharya & van den Heuvel (1991)



$$\Delta J_\star = \int n(\omega,t)\,\dot{M}(t)\,\sqrt{GM(t)r_{\mathrm{mag}}(t)}\,\xi(t)\,dt$$

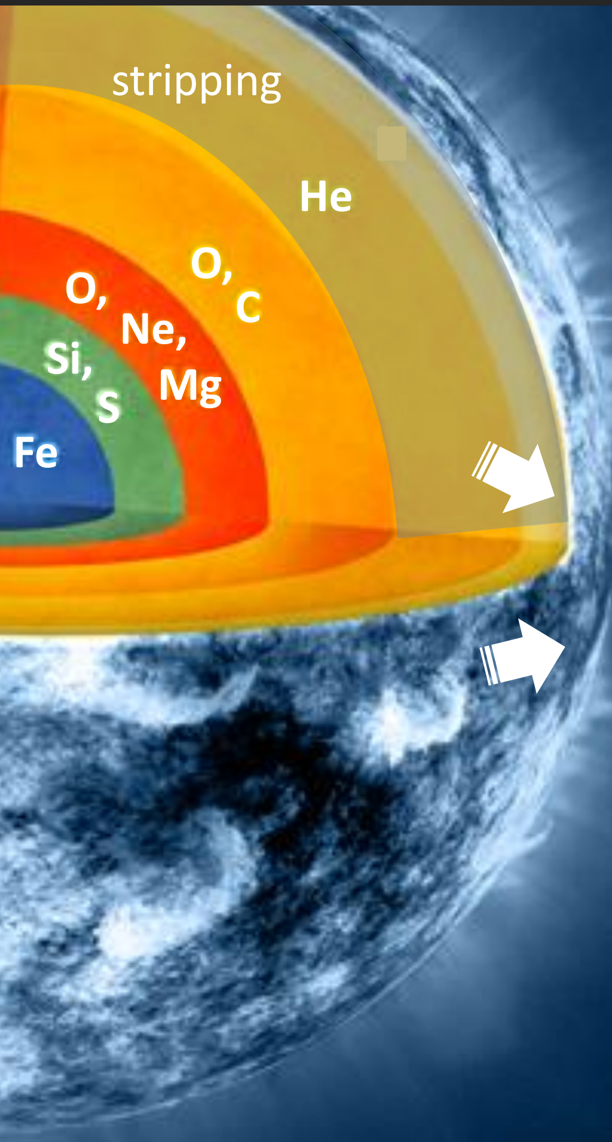




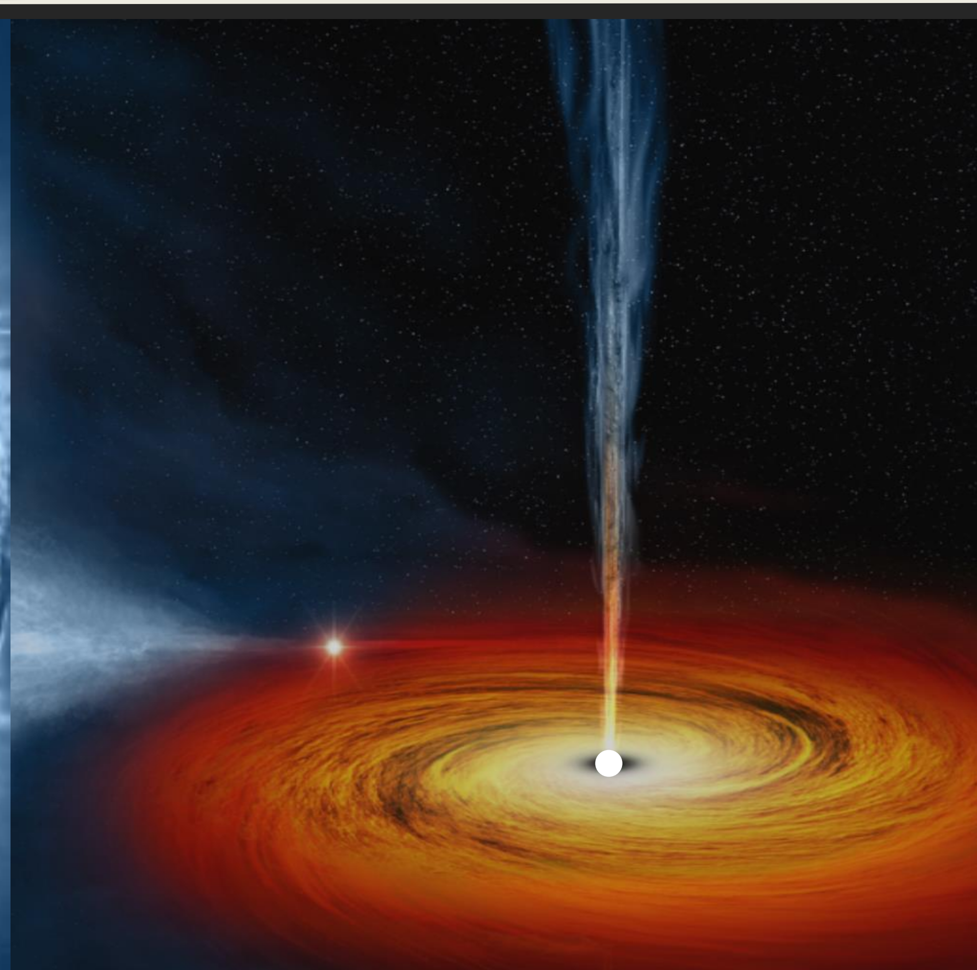
Mass needed to spin up pulsar:

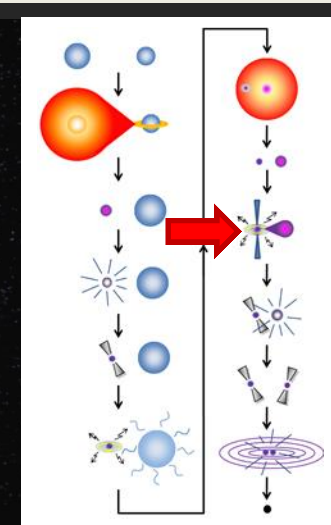
$$\Delta M_{eq} \approx 0.22\,M_\odot\,\frac{(M_{NS}/M_\odot)^{1/3}}{P_{eq}^{4/3}}$$

P (ms)	**M** ($M_\odot$)
0.7	0.40
2	0.10
5	0.03
10	0.01
50	0.001



Ultra-stripped supernova explosion





Post-common envelope binary
→ new episode of mass transfer
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i) accretion onto neutron star
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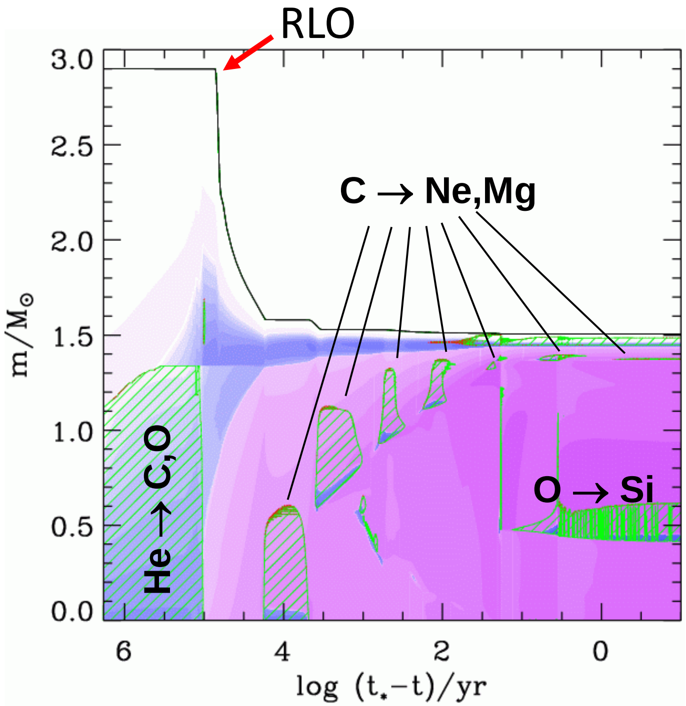
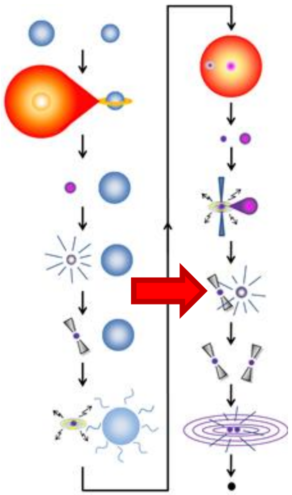


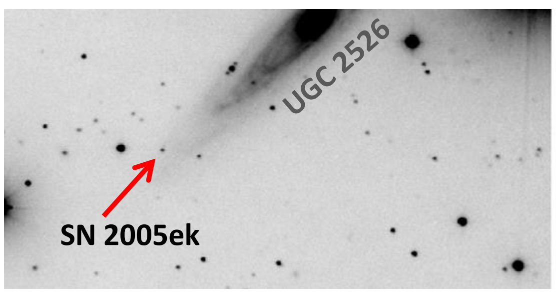
Models calculated for the first time.
We predict a new subclass of SNe
ultra-stripped SNe
with ejecta masses of ~ 0.1 M_{sun}

Tauris et al. (2013), ApJL
Tauris, Langer & Podsiadlowski (2015), MNRAS

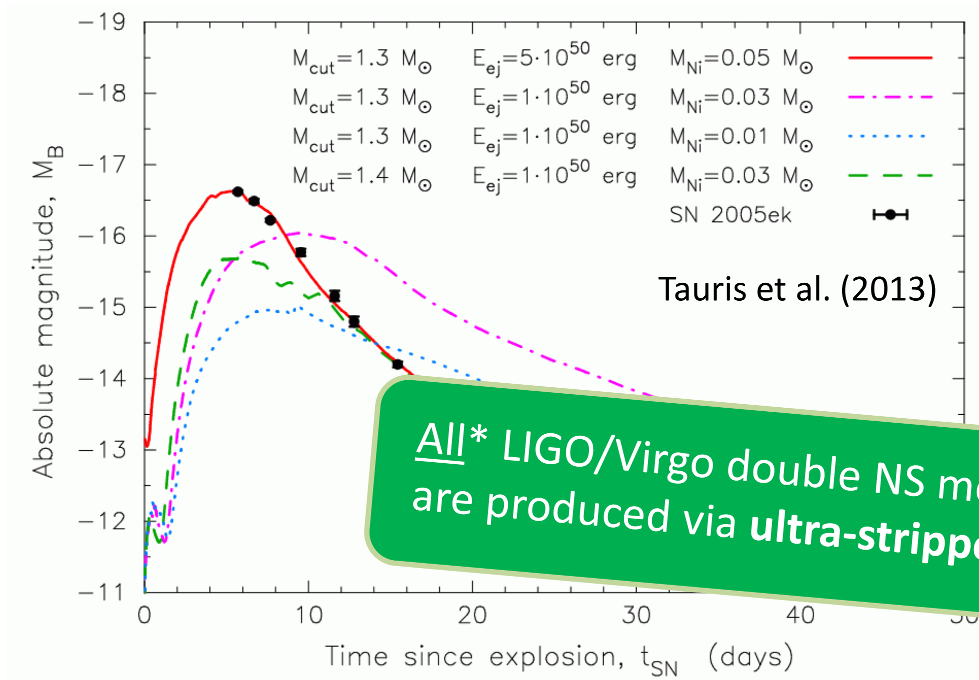
Suwa et al. (2015), MNRAS
Moriya et al. (2017), MNRAS — LCs + spectra
Newton, Steiner & Yagi (2018), ApJ
Müller et al. (2018, 2019), MNRAS — 3D explosion modelling



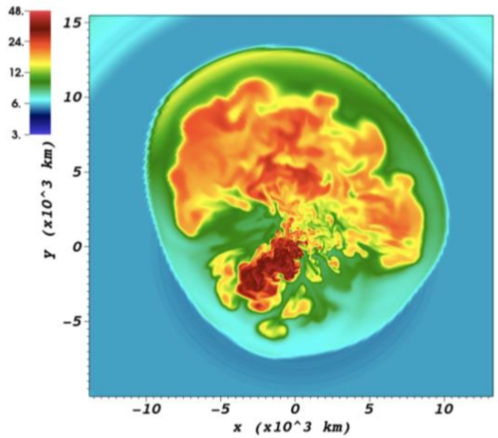
Observational evidence for ultra-stripped SNe…



Drout et al. (2013), ApJ
De et al. (2018), Science



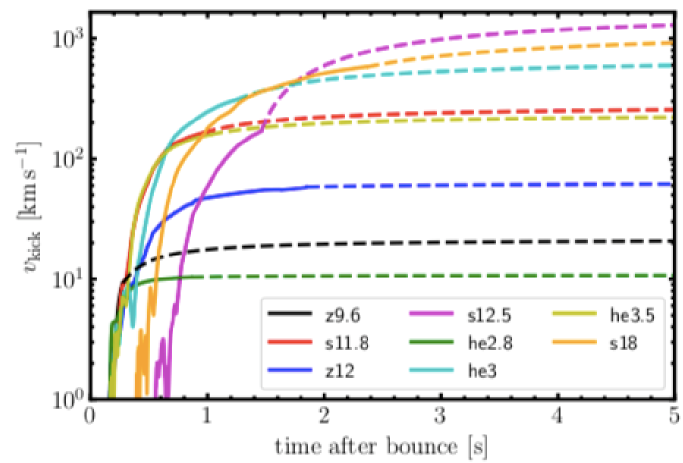
All* LIGO/Virgo double NS mergers are produced via **ultra-stripped SNe**



Three-Dimensional Simulations of Neutrino-Driven Core-Collapse Supernovae from Low-Mass Single and Binary Star Progenitors

Bernhard Müller[1★], Thomas M. Tauris[2], Alexander Heger[1,3], Projjwal Banerjee[4], Yong-Zhong Qian[5,3], Jade Powell[6], Conrad Chan[1], Daniel W. Gay[7,1], Norbert Langer[8,9]

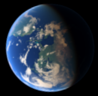
Müller et al. (2019), MNRAS



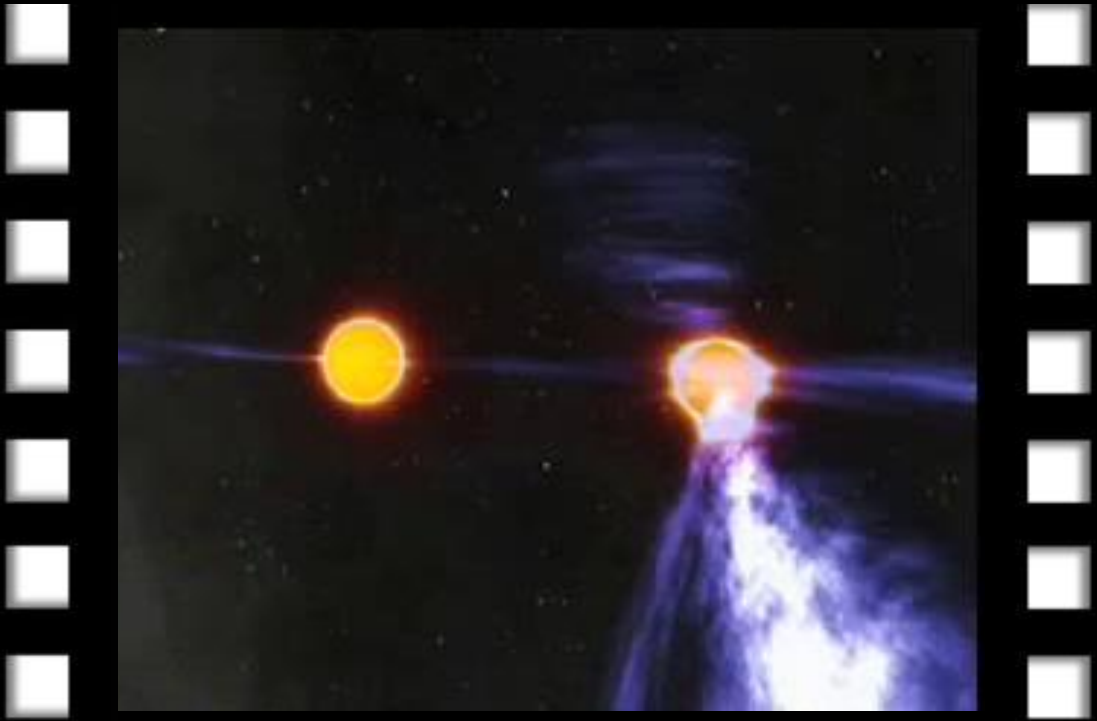
Example of **<u>Ultra-stripped SN</u>**
2.80 M_{sun} He-star stripped down to 1.49 M_{sun} prior to explosion (DNS progenitor)

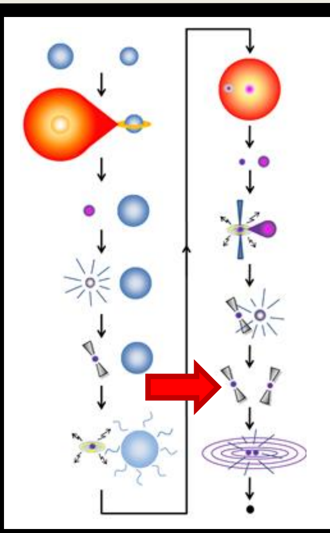
Model	t_{fin} (ms)	E_{expl} (10^{50} erg)	M_{IG} ($M_\odot$)	M_{by} ($M_\odot$)	M_{grav} (km s^{-1})	v_{PNS} (km s^{-1})	$v_{PNS,ex}$ (ms)	P_{PNS}	α
z9.6	273	1.32	0.014	1.35	1.22	9.2	21	1060	48°
s11.8	963	1.99	0.024	1.35	1.23	164	278	152	64°
z12	1847	4.10	0.039	1.35	1.22	58	64	205	62°
s12.5	1461	1.56	0.013	1.61	1.44	170	> 170	20	55°
he2.8	860	1.12	0.010	1.42	1.28	10.4	11	2749	55°
he3.0	1242	3.66	0.035	1.48	1.33	308	695	93	76°
he3.5	1023	2.78	0.031	1.57	1.41	159	238	98	80°

t_{fin} is the final post-bounce time reached by each simulation, E_{expl} is the final diagnostic explosion energy at the end of the simulations, M_{IG} is the mass of iron-group ejecta, M_{grav} is the gravitational neutron star mass, v_{PNS} is the kick velocity at the end of the run, $v_{PNS,ex}$ is the extrapolated kick obtained from Equation (6), P_{PNS} is the estimated neutron star spin period, and α is the angle between the spin and kick vector at the end of the simulations.



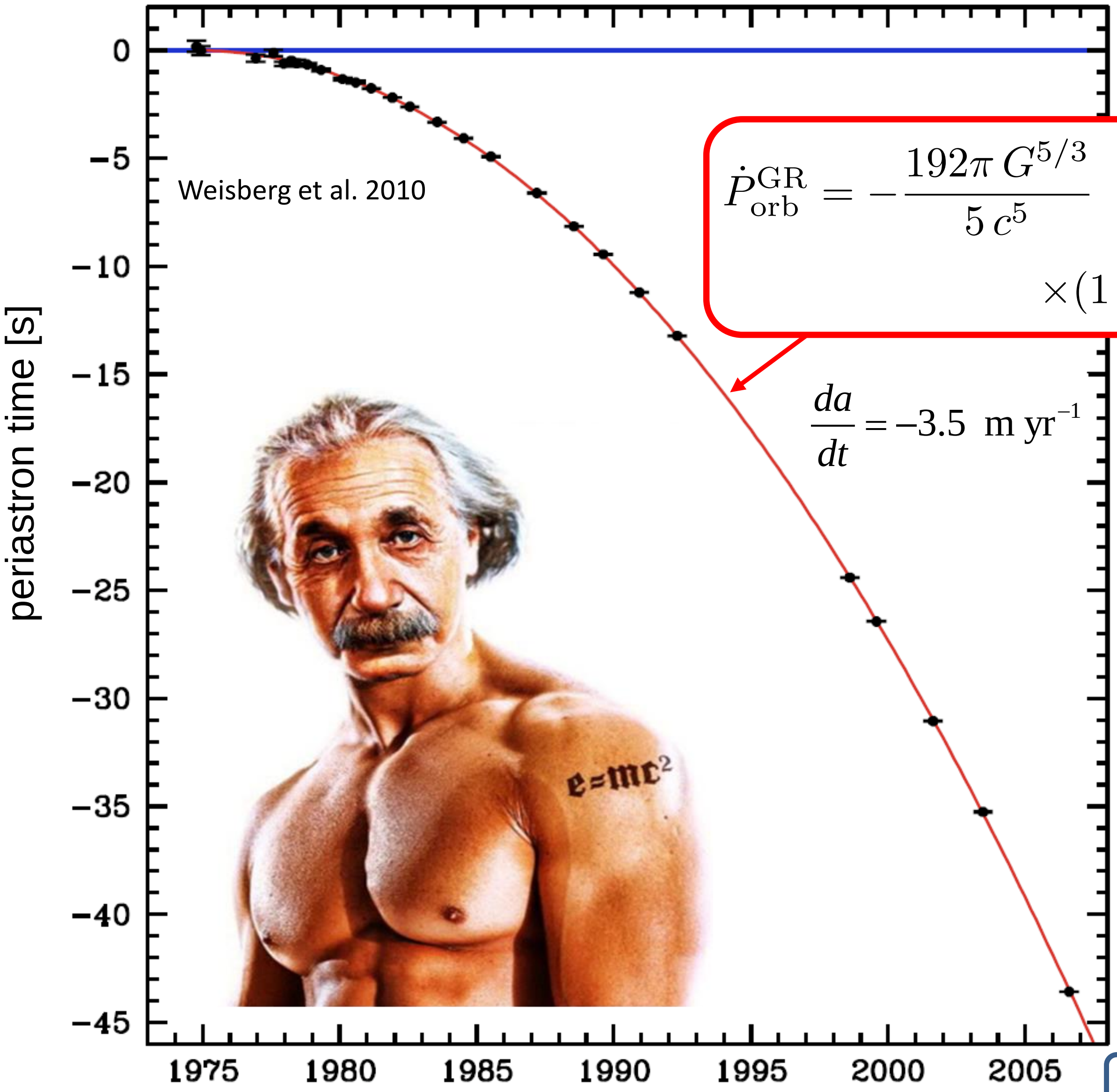
Burgay et al. (2003), Lyne et al. (2004), Kramer et al. (2006)

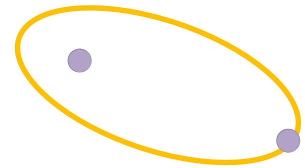




Pulsar J0737-3039A: P=22.7 ms
Pulsar J0737-3039B: P=2.77 sec

PSR B1913+16 (Hulse-Taylor pulsar, P_{orb}=7.75 hr, ecc=0.61)

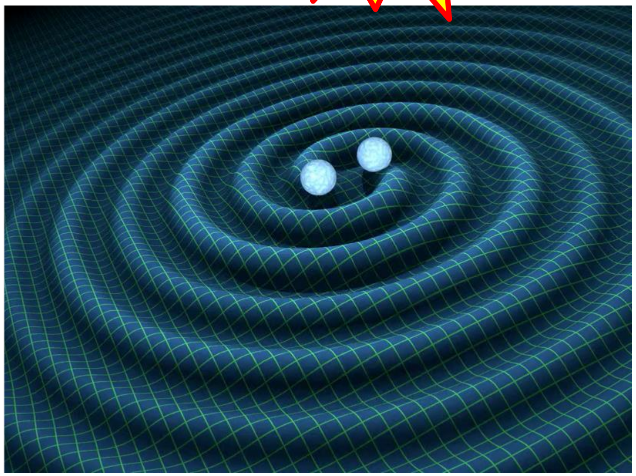




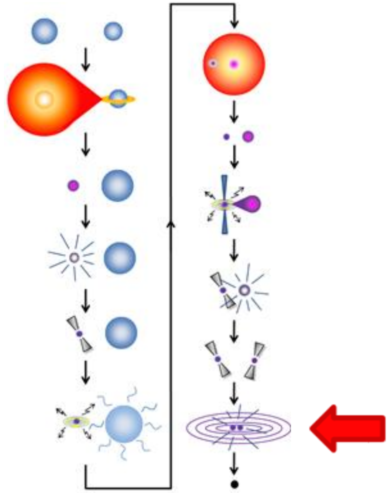
Peters (1964)

$$\dot{P}_{\rm orb}^{\rm GR} = -\frac{192\pi\, G^{5/3}}{5\, c^5} \left(\frac{P_{\rm orb}}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) \times (1-e^2)^{-7/2}\, M_1 M_2\, (M_1 + M_2)^{-1/3}$$

Merge in
τ = 300 Myr



$L_{\rm GW} = 7 \times 10^{24}$ W $\quad (L_{\rm GW,\odot} = 5000$ W$)$



Double neutron star mergers: GW170817

$\rightarrow$ gravitational wave burst

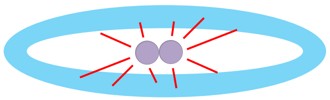
$\rightarrow$ short γ-ray burst

$\rightarrow$ ejection of a few $0.01\ M_\odot$ heavy r-process elements

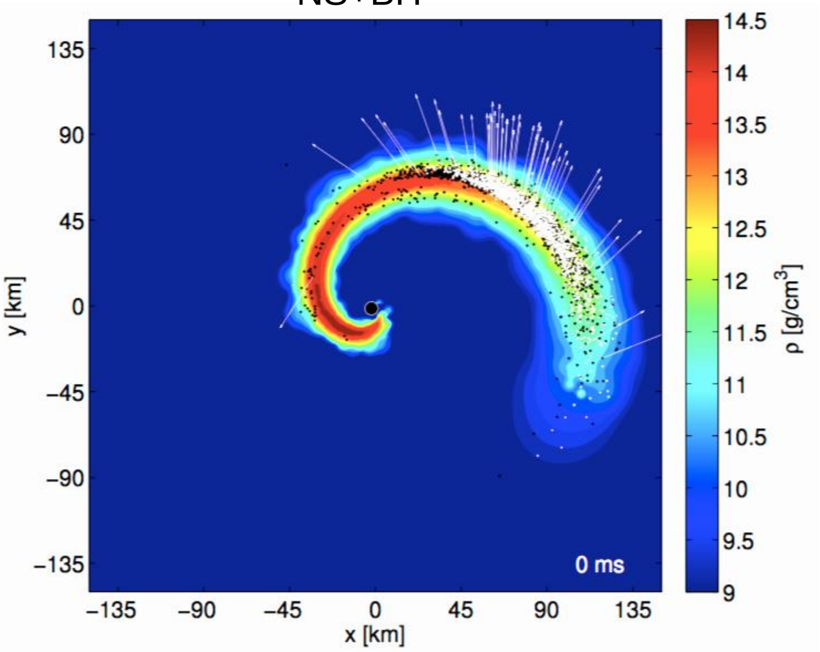
$\rightarrow$ macro/kilonovae (EM follow-up)

Abbott et al. (2017), Coulter et al. (2017), Soares-Santos et al. (2017), Smartt et al. (2017), Drout et al. (2017)

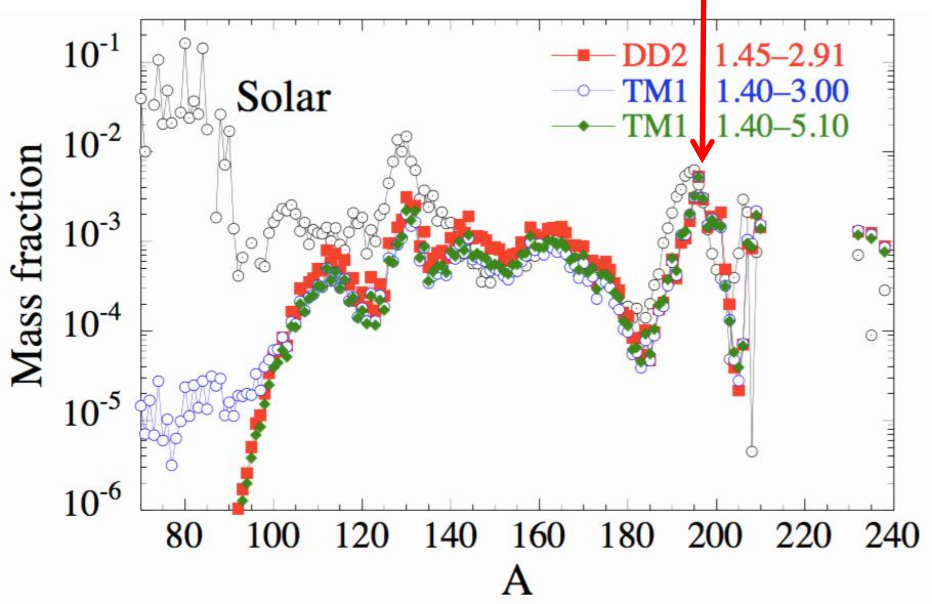
Giacomazzo et al. (2019)

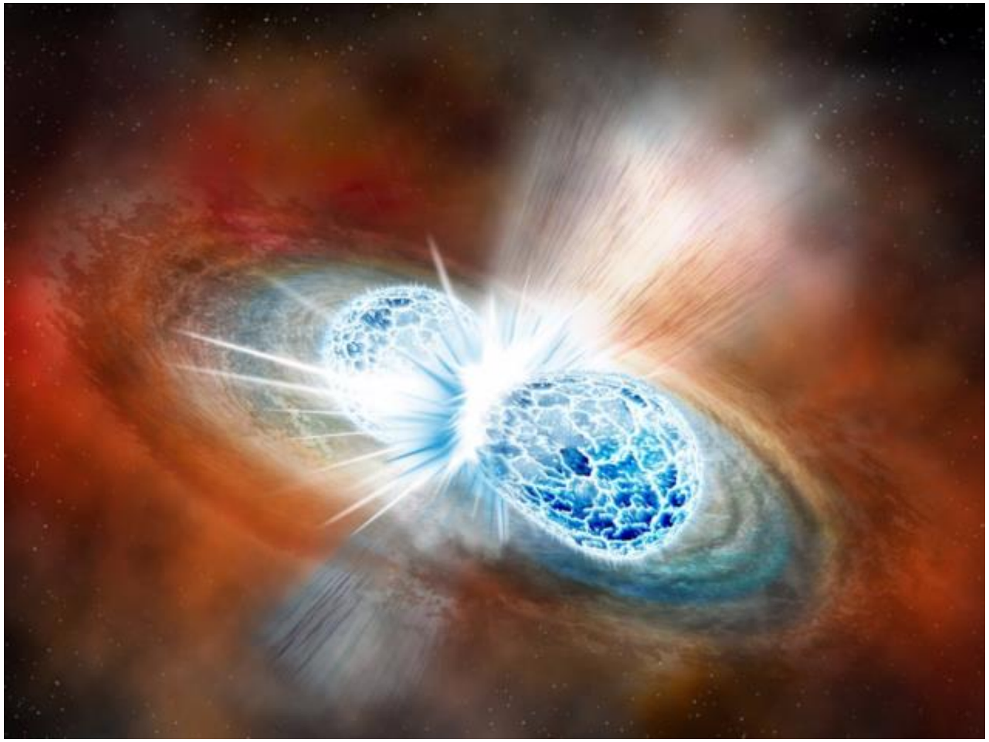


NS+BH



Just et al. (2015)



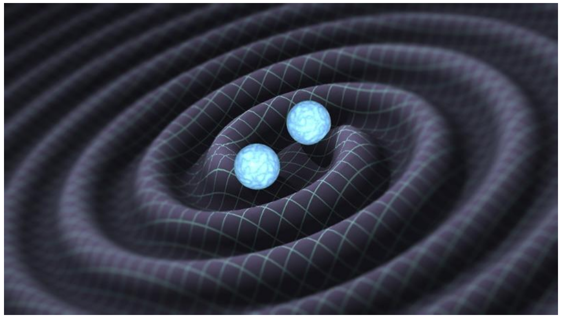


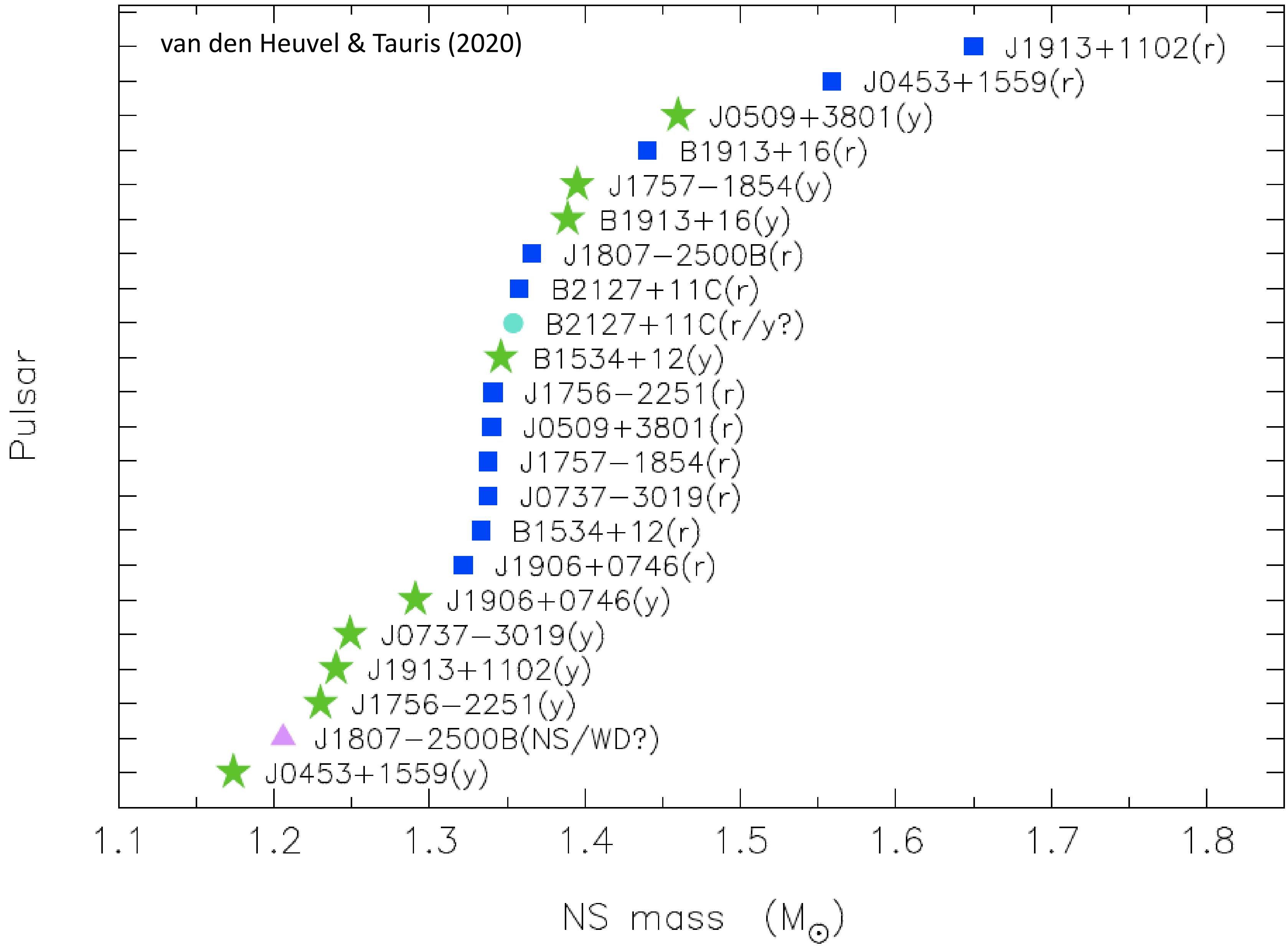
- Masses
- Spins
- B-fields

- Orbital period
- Eccentricity

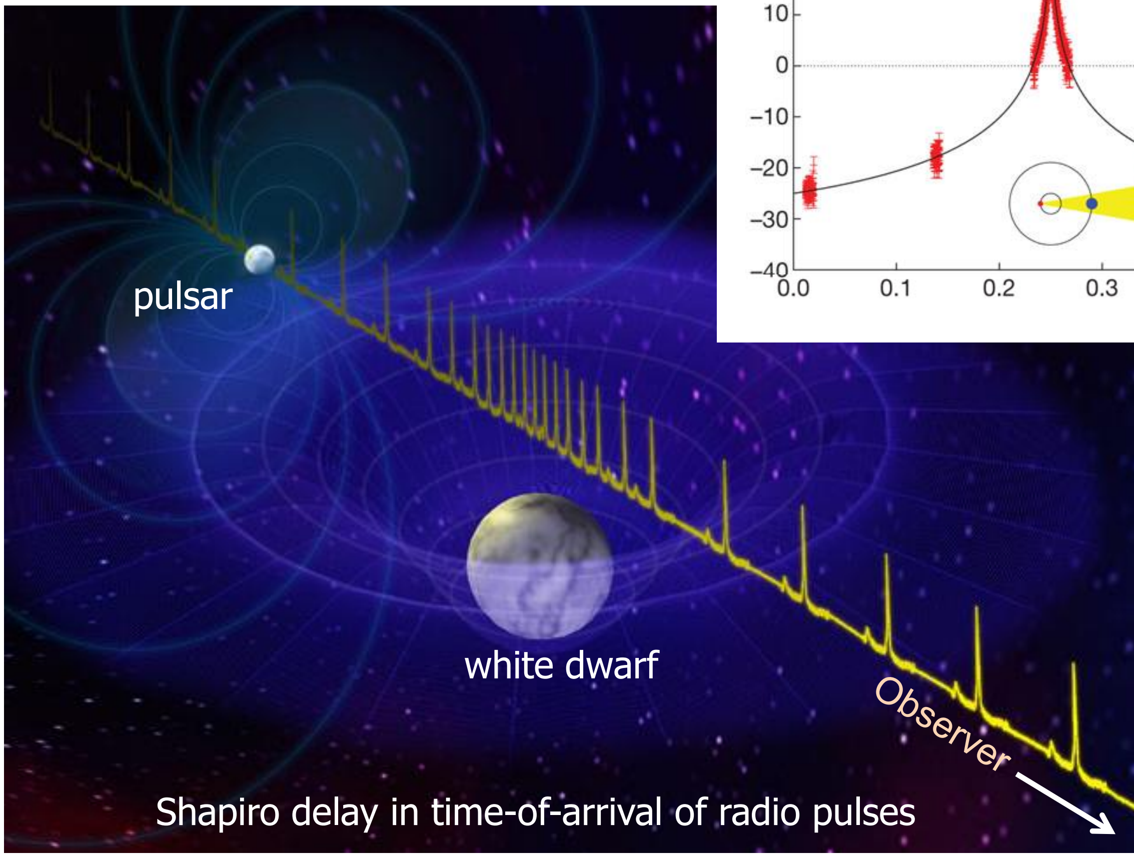
- Age at merger time
- Location relative to host galaxy
- Kicks

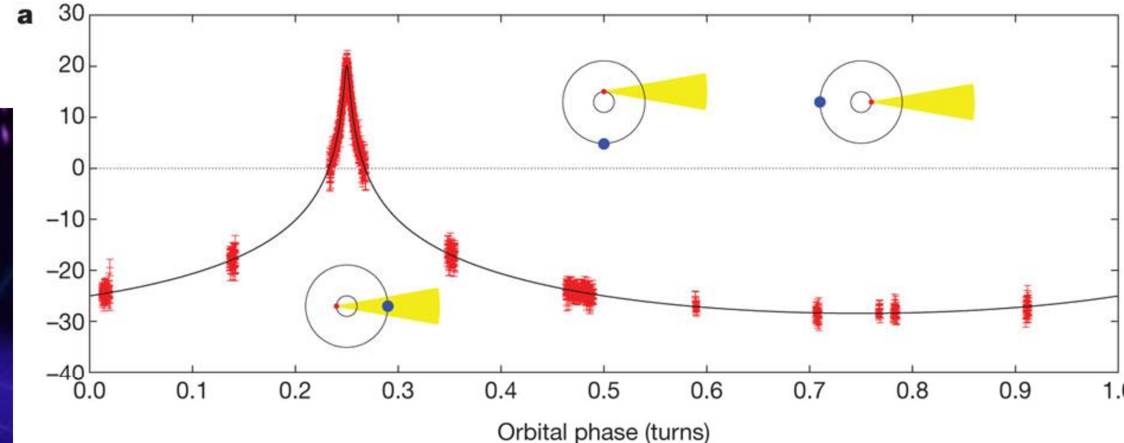
- Merger rates




van den Heuvel & Tauris (2020)
J1913+1102(r)
J0453+1559(r)
J0509+3801(y)
B1913+16(r)
J1757−1854(y)
B1913+16(y)
J1807−2500B(r)
B2127+11C(r)
B2127+11C(r/y?)
B1534+12(y)
J1756−2251(r)
J0509+3801(r)
J1757−1854(r)
J0737−3019(r)
B1534+12(r)
J1906+0746(r)
J1906+0746(y)
J0737−3019(y)
J1913+1102(y)
J1756−2251(y)
J1807−2500B(NS/WD?)
J0453+1559(y)
Pulsar
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
NS mass (M⊙)

Moving atomic clocks in space!





Earth →

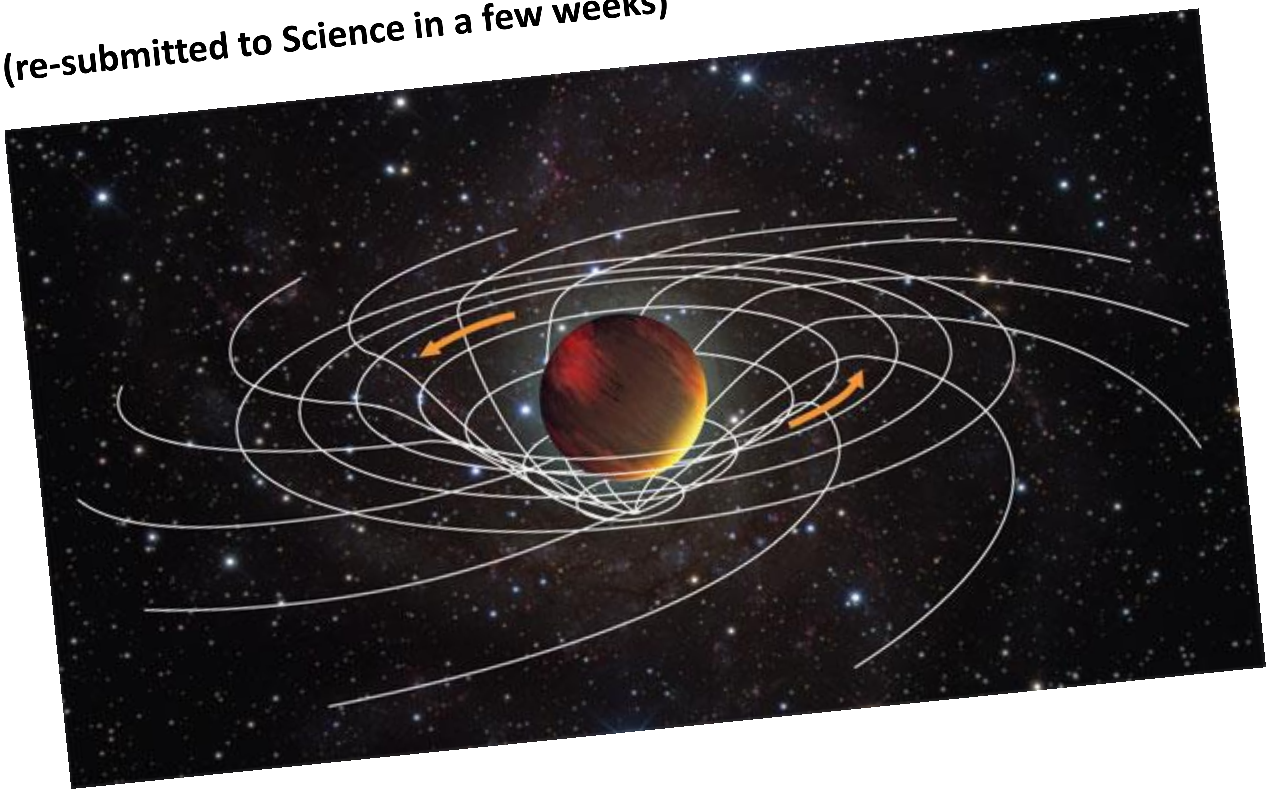
<u>Demorest et al. (2010)</u>

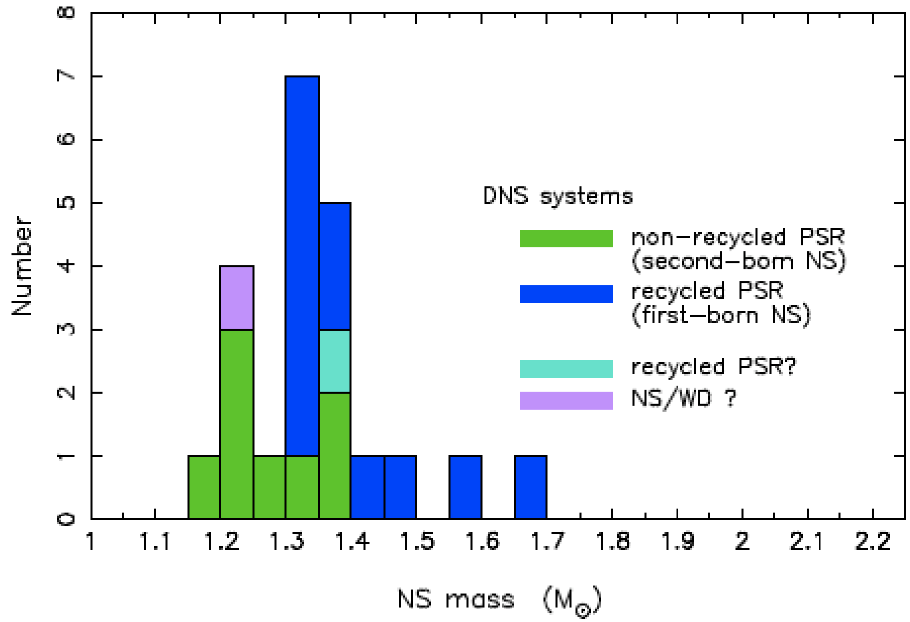
Pulsar mass:	1.97±0.04 M_{sun}
White dwarf mass:	0.500±0.006 M_{sun}
Orbital period:	8.69 days
Pulsar spin period:	3.15 ms

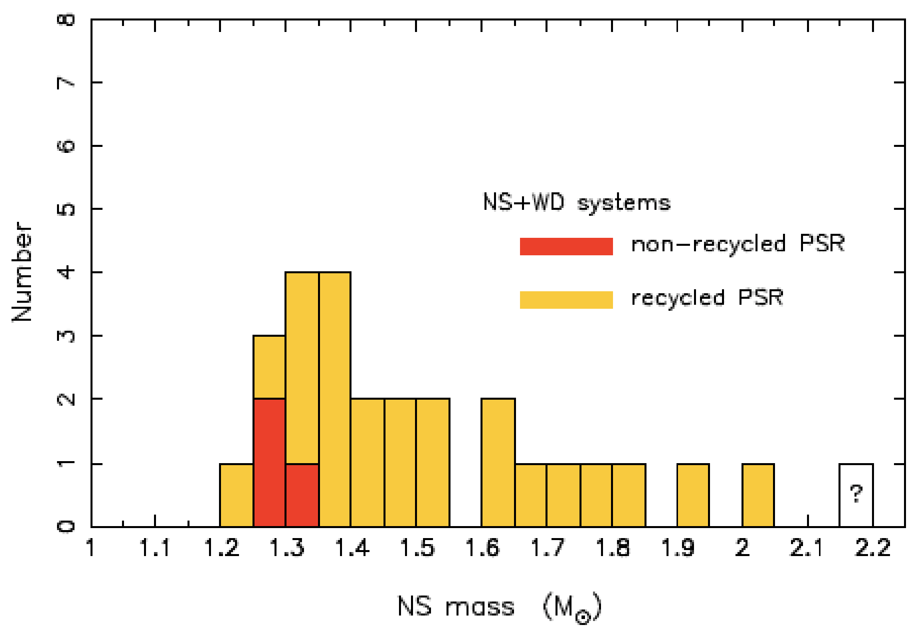
FIRST EVER

MEASUREMENT OF LENSE-THIRRING PRECESSION (FRAME DRAGGING)

(re-submitted to Science in a few weeks)







van den Heuvel & Tauris (2020)

In DNS systems, the first-born NS accretes max. 0.02 M_{sun}

⇩

Measured masses of recycled NSs are close to their birth masses!

In NS+WD sytems produced via LMXBs, the accretion phase is much longer (up to several Gyr)

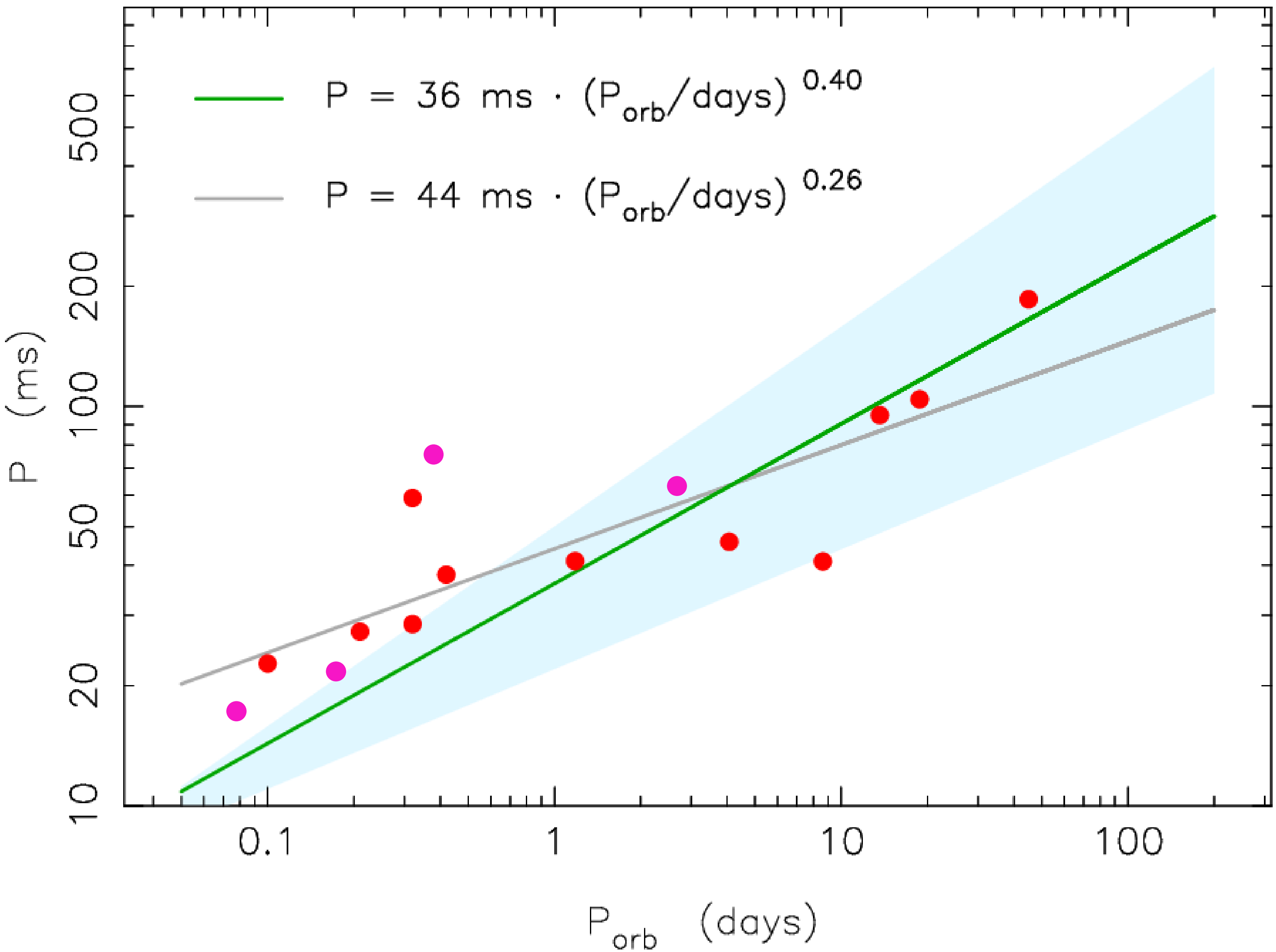
However, some fully recycled NSs only have masses of ~1.3 M_{sun}.

⇩

Accretion is very *inefficient* even at sub-Eddington accretion levels.

Distribution reflects spread in NS birth masses.

Tauris et al. (2017), ApJ + updated data

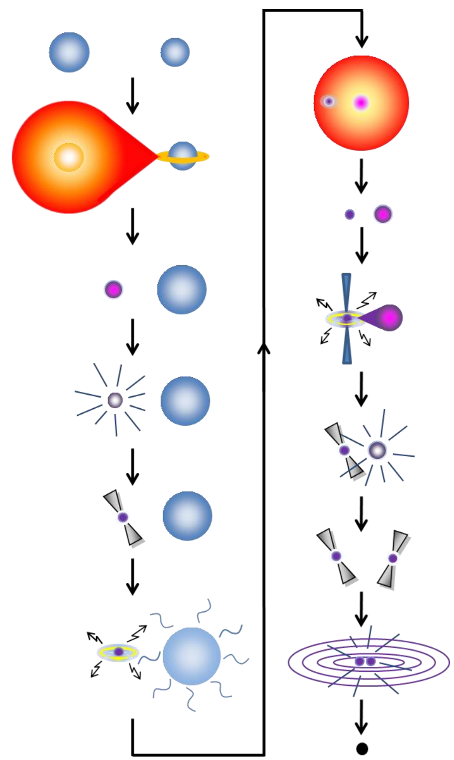


Tauris et al. (2017), ApJ 846, 170

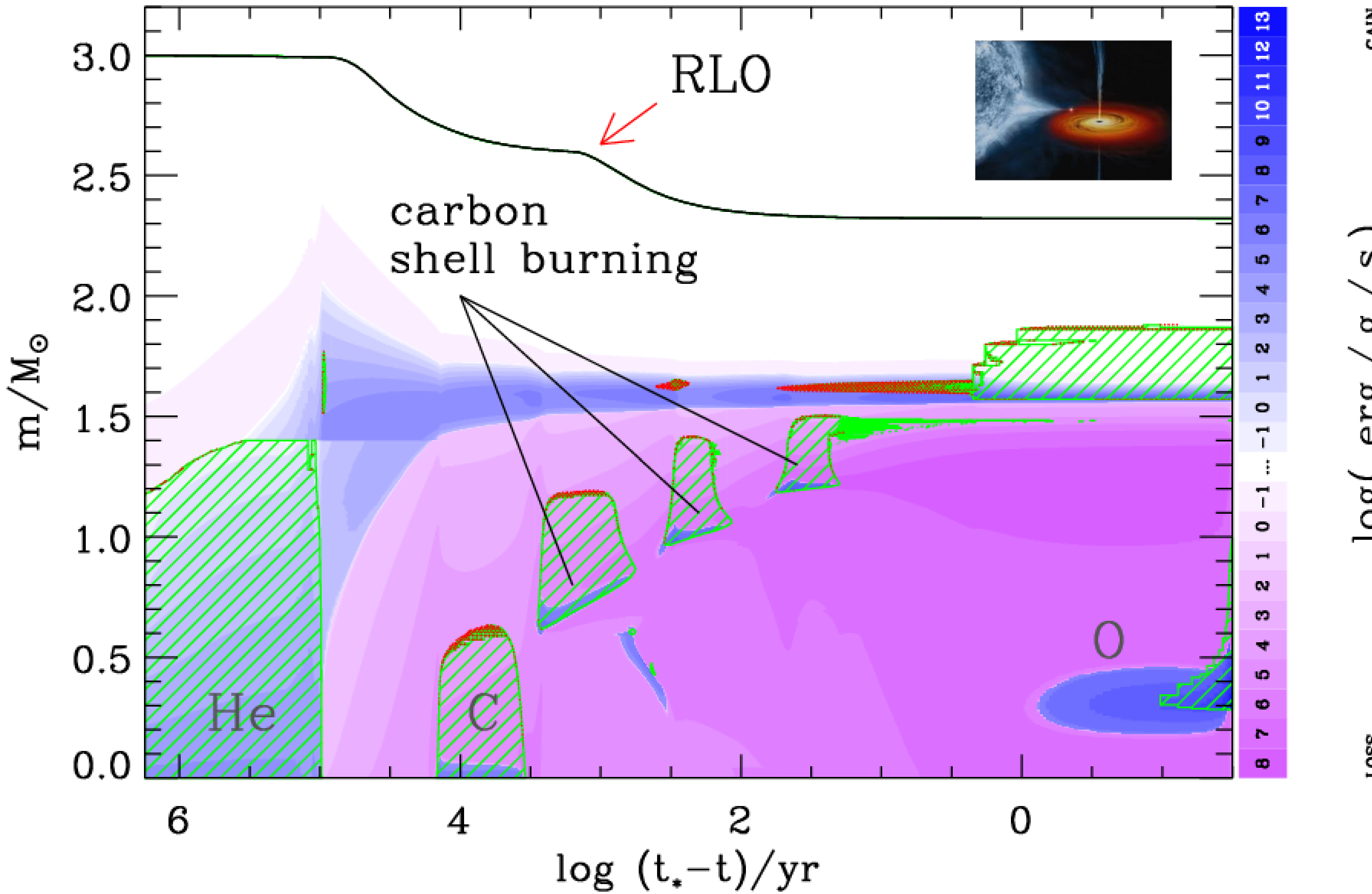
The Astrophysical Journal, 846:170 (58pp), 2017 September 10 https://doi.org/10.3847/1538-4357/aa7e89

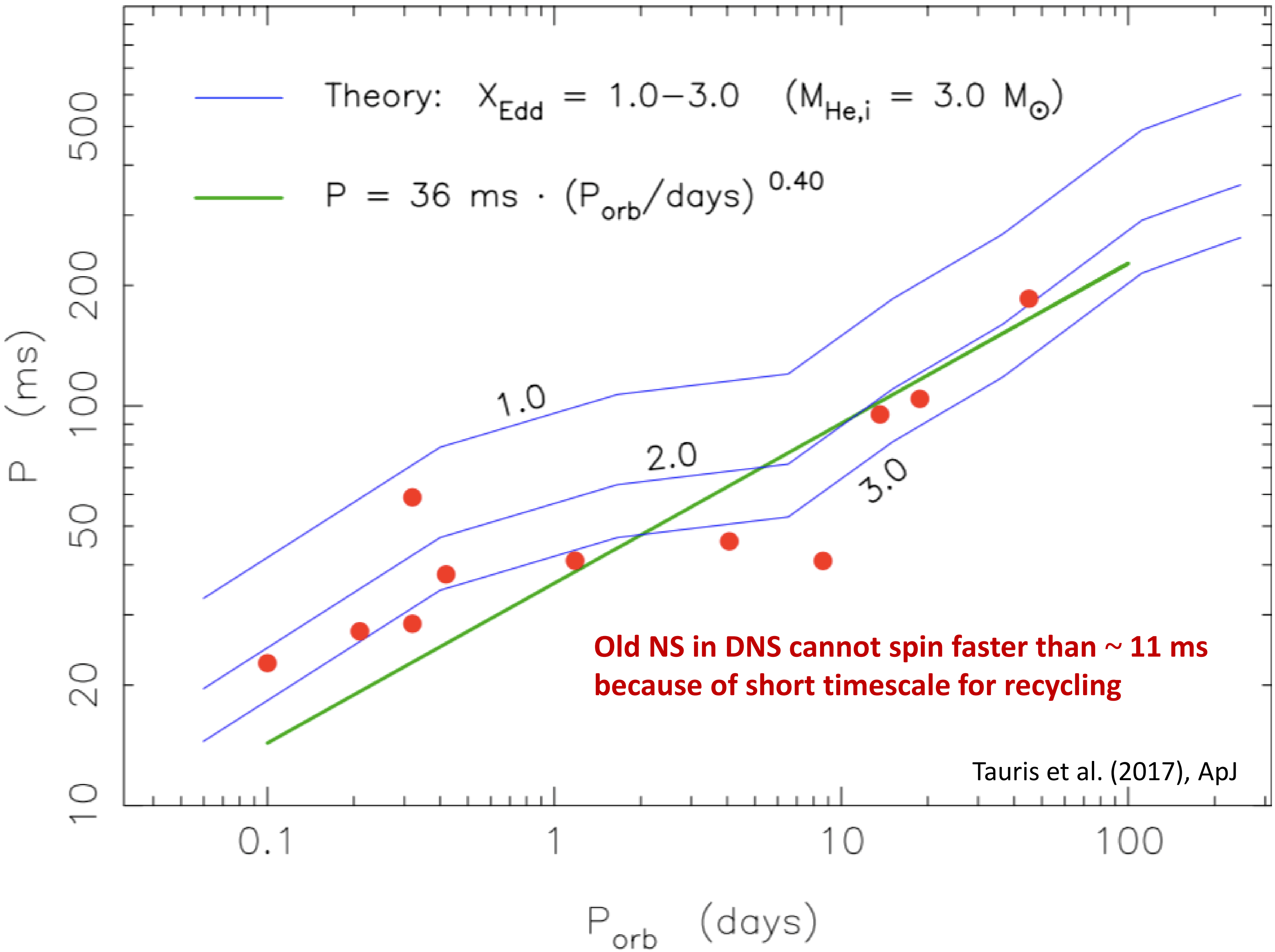
Formation of Double Neutron Star Systems

T. M. Tauris[1,2], M. Kramer[1], P. C. C. Freire[1], N. Wex[1], H.-T. Janka[3], N. Langer[2], Ph. Podsiadlowski[2,4], E. Bozzo[5], S. Chaty[6,7], M. U. Kruckow[2], E. P. J. van den Heuvel[8], J. Antoniadis[1,9], R. P. Breton[10], and D. J. Champion[1]



Tauris et al. (2017), ApJ





Old NS in DNS cannot spin faster than ~ 11 ms because of short timescale for recycling

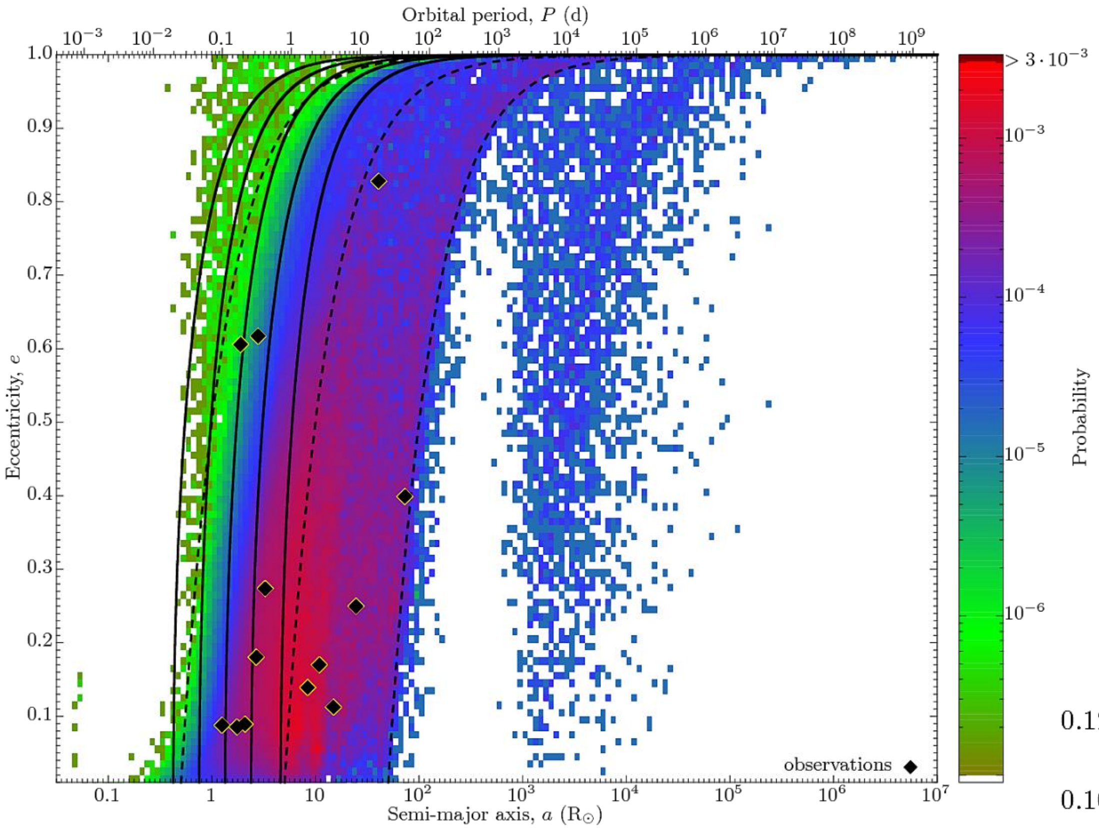
Tauris et al. (2017), ApJ

Table 1.4: Properties of 19 DNS systems with published data (including a few unconfirmed candidates).

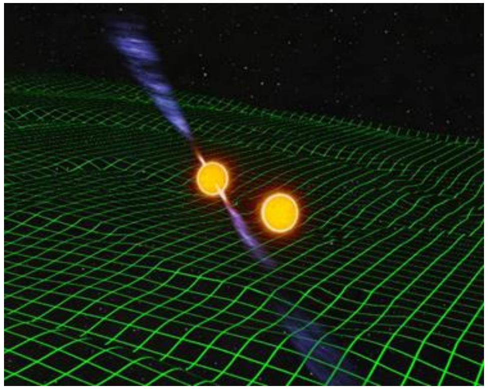
Radio Pulsar	Type	P (ms)	$\dot{P}$ (10^{-18})	B (10^9 G)	$P_{\rm orb}$ (days)	e	$M_{\rm psr}$ ($M_\odot$)	$M_{\rm comp}$ ($M_\odot$)	$M_{\rm total}$ ($M_\odot$)	δ (deg)	Dist. (kpc)	$v^{\rm LSR}$ ** (km s^{-1})	$\tau_{\rm gwr}$ (Myr)
J0453+1559[a]	recycled	45.8	0.186	0.92	4.072	0.113	1.559	1.174	2.734	–	1.07	82	∞
J0509+3801[b]	recycled	76.5	7.93	7.8	0.380	0.586	$\sim$ 1.34	$\sim$ 1.46	2.805	–	1.56	–	579
J0737−3039A[c]	recycled	22.7	1.76	2.0	0.102	0.088	1.338	1.249	2.587	$<$ 3.2	1.15	32	86
J0737−3039B[c]	young	2773.5	892	490	−‖−	−‖−	1.249	1.338	−‖−	130 $\pm$ 1	−‖−	−‖−	−‖−
J1411+2551[d]	recycled	62.5	0.0956	0.77	2.616	0.170	$<$ 1.62	$>$ 0.92	2.538	–	1.13	–	∞
J1518+4904[e]	recycled	40.9	0.0272	0.29	8.634	0.249	***	***	2.718	–	0.63	30	∞
B1534+12[f]	recycled	37.9	2.42	3.0	0.421	0.274	1.333	1.346	2.678	27 $\pm$ 3	1.05	143	2730
J1753−2240[g]	recycled	95.1	0.970	2.7	13.638	0.304	–	–	–	–	3.46	–	∞
J1755−2550[h]*	young	315.2	–	270	9.696	0.089	–	$>$ 0.40	–	–	10.3	–	∞
J1756−2251[i]	recycled	28.5	1.02	1.7	0.320	0.181	1.341	1.230	2.570	$<$ 34	0.73	39****	1660
J1757−1854[j]	recycled	21.5	2.63	2.4	0.184	0.606	1.338	1.395	2.733	–	19.6	–	76
J1811−1736[k]	recycled	104.2	0.901	3.0	18.779	0.828	$<$ 1.64	$>$ 0.93	2.57	–	5.93	–	∞
J1829+2456[l]	recycled	41.0	0.0525	0.46	1.176	0.139	$<$ 1.38	$>$ 1.22	2.59	–	0.74	–	∞
J1906+0746[m]*	young	144.1	20300	530	0.166	0.085	1.291	1.322	2.613	–	7.40	–	309
J1913+1102[n]	recycled	27.3	0.161	0.63	0.206	0.090	$\sim$ 1.65	$\sim$ 1.24	2.89	–	–	–	$\sim$ 470
B1913+16[o]	recycled	59.0	8.63	7.0	0.323	0.617	1.440	1.389	2.828	18 $\pm$ 6	9.80	241	301
J1930−1852[p]	recycled	185.5	18.0	18	45.060	0.399	$<$ 1.32	$>$ 1.30	2.59	–	1.5	–	∞
J1946+2052[q]	recycled	17.0	0.92	1.3	0.078	0.064	$<$ 1.31	$>$ 1.18	2.50	–	1.5	–	46
J1807−2500B[r]*	GC	4.2	0.0823	0.18	9.957	0.747	1.366	1.206	2.572	–	3.0	–	∞
B2127+11C[s]	GC	30.5	4.99	3.8	0.335	0.681	1.358	1.354	2.713	–	12.9	–	217

Globular cluster source! This NS was most likely recycled in a LMXB (WD progenitor as donor star) which was afterwards disrupted and the recycled NS was paired with another NS

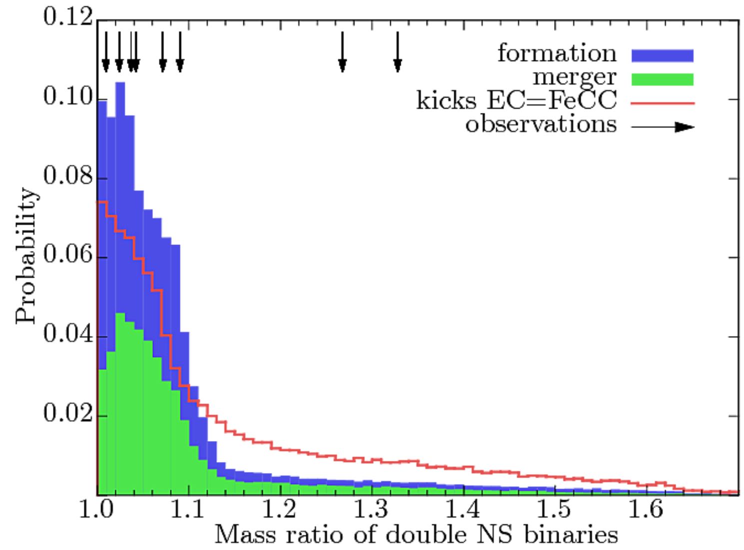
Eccentricity, e



Semi-major axis, a (R_{sun})

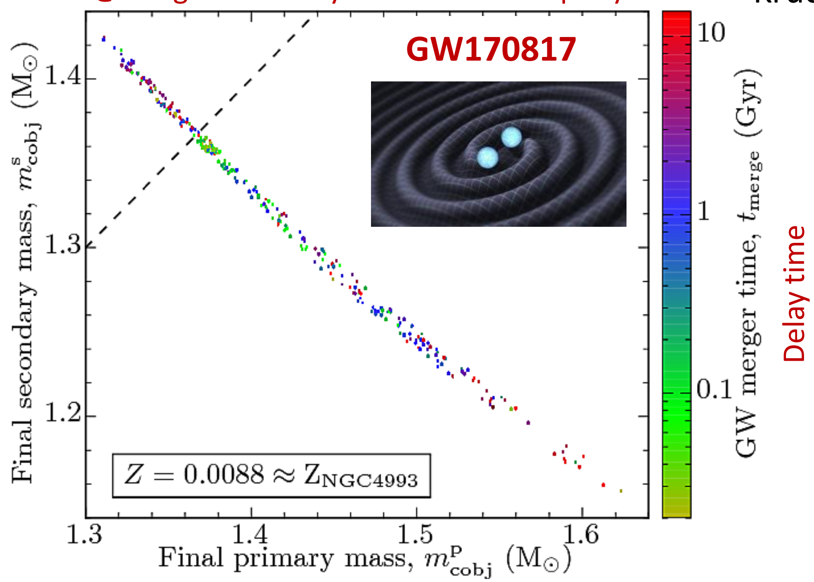


NS mass ratios

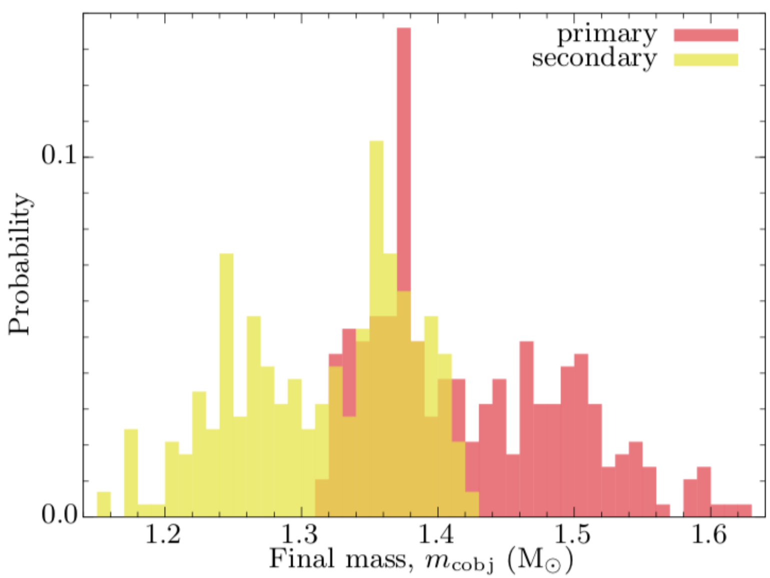


Kruckow, Tauris, et al. (2018), MNRAS

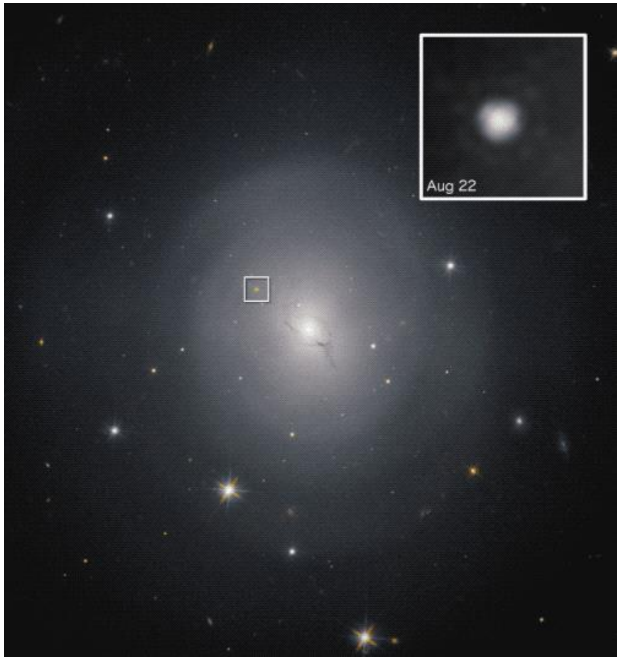
Important calibration data



Kruckow, Tauris, et al. (2018), MNRAS

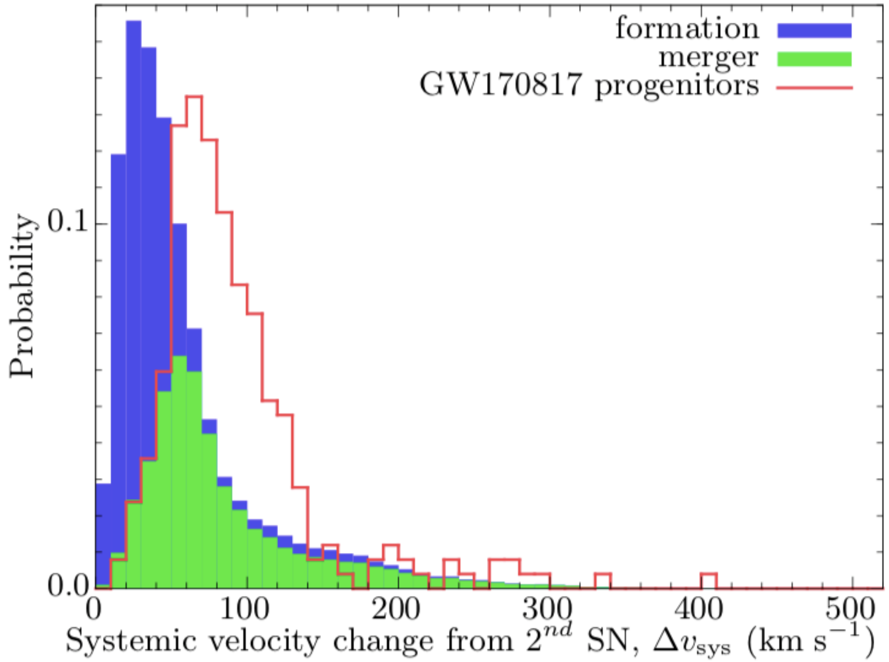


Our NS mass solutions for GW170817 are typical for Galactic DNS systems



NGC 4993

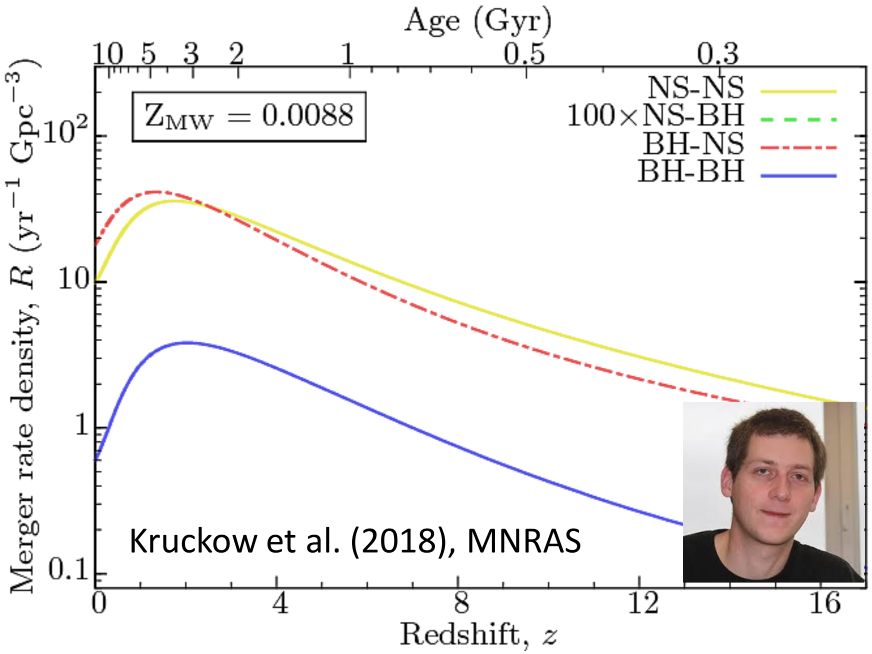
Kruckow et al. (2018), MNRAS

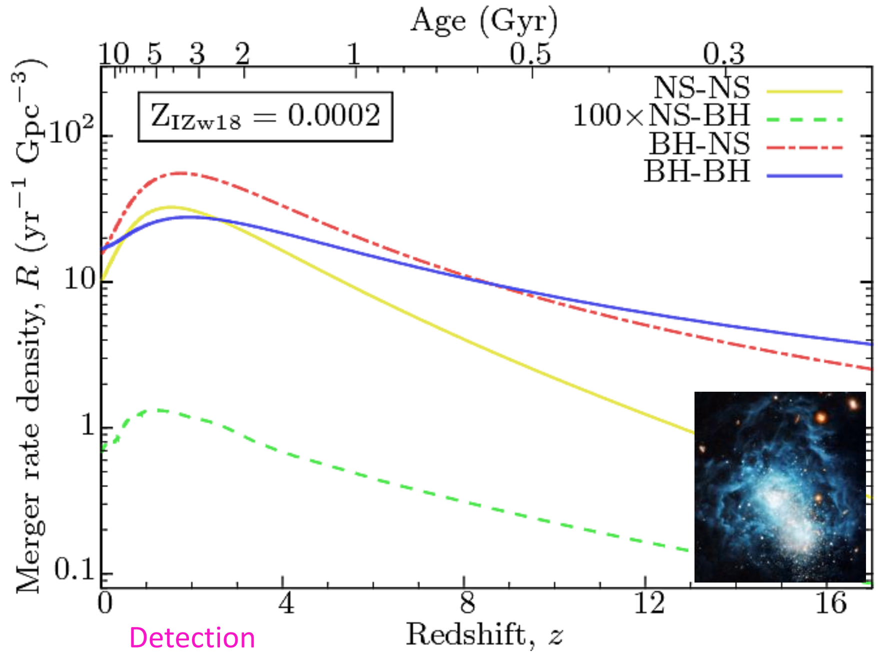


We find age solutions from <100 Myr to >10 Gyr.

For NGC 4393, the escape velocity at the location of GW170817 is about 350 km s^{-1} (Pan et al. 2017), much larger than the typical systemic velocities we obtain in our simulations.

MERGER-RATE DENSITY



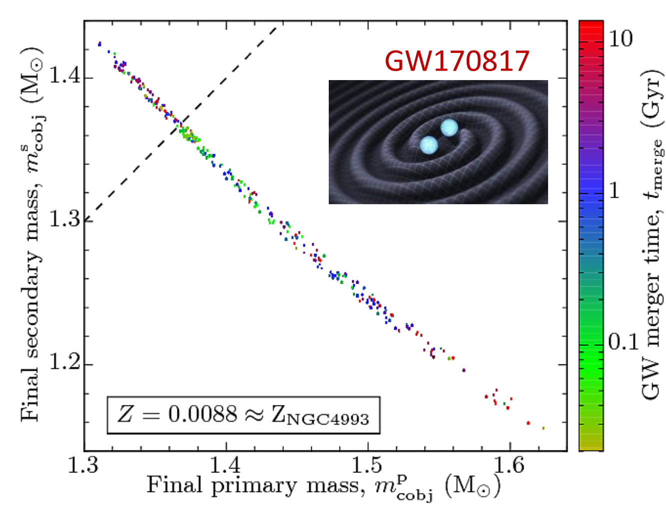


Detection rates

local Universe

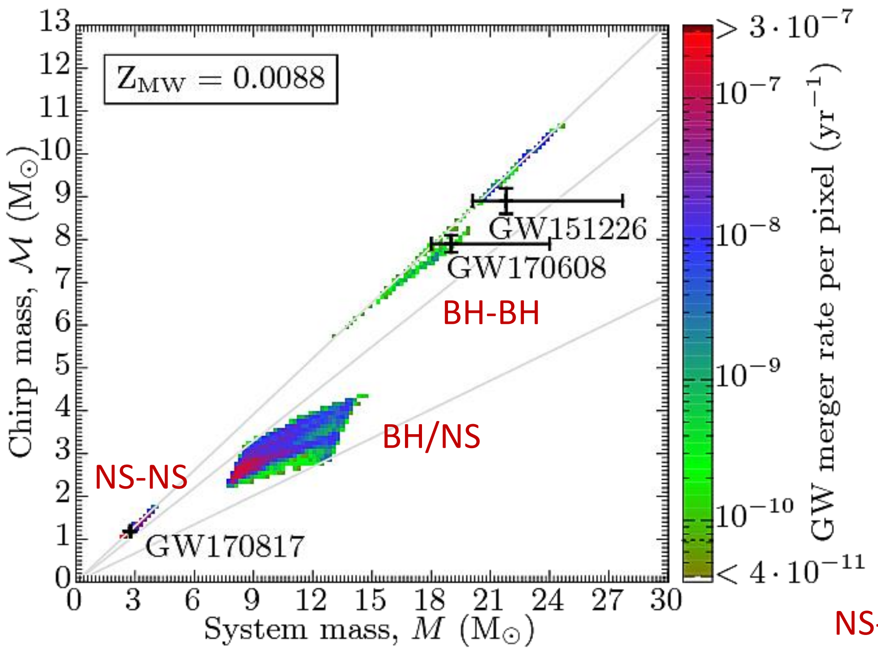
Z_{MW}	$\langle \mathcal{M}^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.36 $M_\odot^{2.5}$	9.85×10^0 yr^{-1} Gpc^{-3}	0.28 yr^{-1}	3.47×10^1 yr^{-1} Gpc^{-3}	0.98 yr^{-1}
NS-BH	20.0 $M_\odot^{2.5}$	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}
BH-NS	15.7 $M_\odot^{2.5}$	1.80×10^1 yr^{-1} Gpc^{-3}	5.88 yr^{-1}	4.72×10^1 yr^{-1} Gpc^{-3}	15.43 yr^{-1}
BH-BH	233 $M_\odot^{2.5}$	6.01×10^{-1} yr^{-1} Gpc^{-3}	2.92 yr^{-1}	3.08×10^0 yr^{-1} Gpc^{-3}	14.95 yr^{-1}
Z_{IZw18}	$\langle \mathcal{M}^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.27 $M_\odot^{2.5}$	1.00×10^1 yr^{-1} Gpc^{-3}	0.27 yr^{-1}	3.28×10^1 yr^{-1} Gpc^{-3}	0.87 yr^{-1}
NS-BH	32.3 $M_\odot^{2.5}$	6.61×10^{-3} yr^{-1} Gpc^{-3}	0.00 yr^{-1}	1.55×10^{-2} yr^{-1} Gpc^{-3}	0.01 yr^{-1}
BH-NS	35.5 $M_\odot^{2.5}$	1.54×10^1 yr^{-1} Gpc^{-3}	11.40 yr^{-1}	5.32×10^1 yr^{-1} Gpc^{-3}	39.34 yr^{-1}
BH-BH	1720 $M_\odot^{2.5}$	1.68×10^1 yr^{-1} Gpc^{-3}	603.02 yr^{-1}	3.45×10^1 yr^{-1} Gpc^{-3}	1235.27 yr^{-1}
optimistic	$\langle \mathcal{M}^{2.5} \rangle$	$R_{z=0}$	R_D	R_{cSFR}	$R_{D,cSFR}$
NS-NS	1.31 $M_\odot^{2.5}$	7.09×10^1 yr^{-1} Gpc^{-3}	1.94 yr^{-1}	1.59×10^2 yr^{-1} Gpc^{-3}	4.37 yr^{-1}
NS-BH	19.4 $M_\odot^{2.5}$	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}	0.00×10^0 yr^{-1} Gpc^{-3}	0.00 yr^{-1}
BH-NS	21.9 $M_\odot^{2.5}$	1.34×10^1 yr^{-1} Gpc^{-3}	6.11 yr^{-1}	2.44×10^1 yr^{-1} Gpc^{-3}	11.17 yr^{-1}
BH-BH	275 $M_\odot^{2.5}$	4.34×10^1 yr^{-1} Gpc^{-3}	248.34 yr^{-1}	1.09×10^2 yr^{-1} Gpc^{-3}	623.03 yr^{-1}

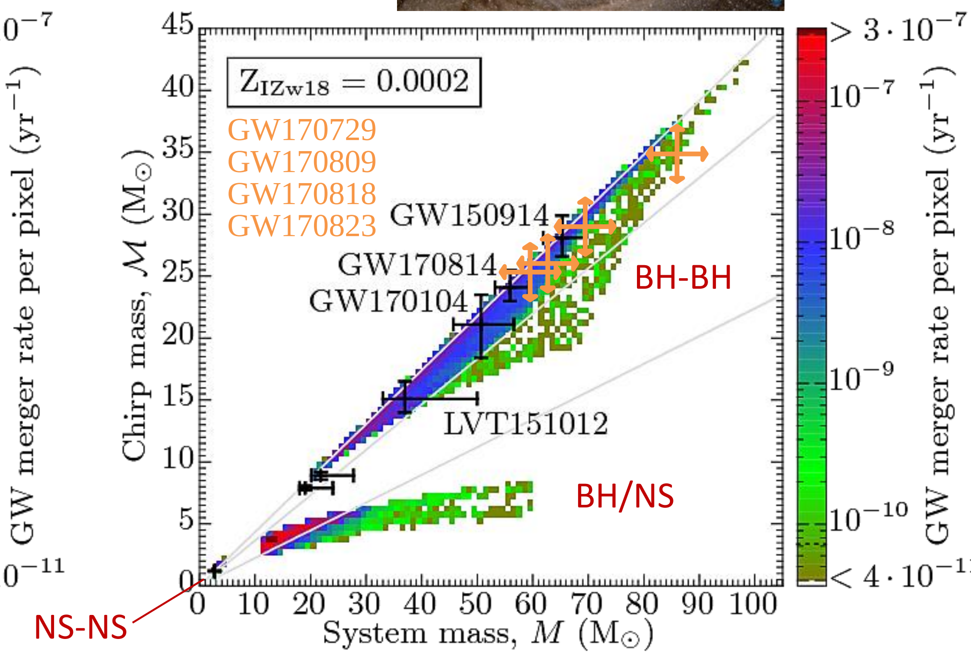
@design sensitivity: 1–5 detections per yr



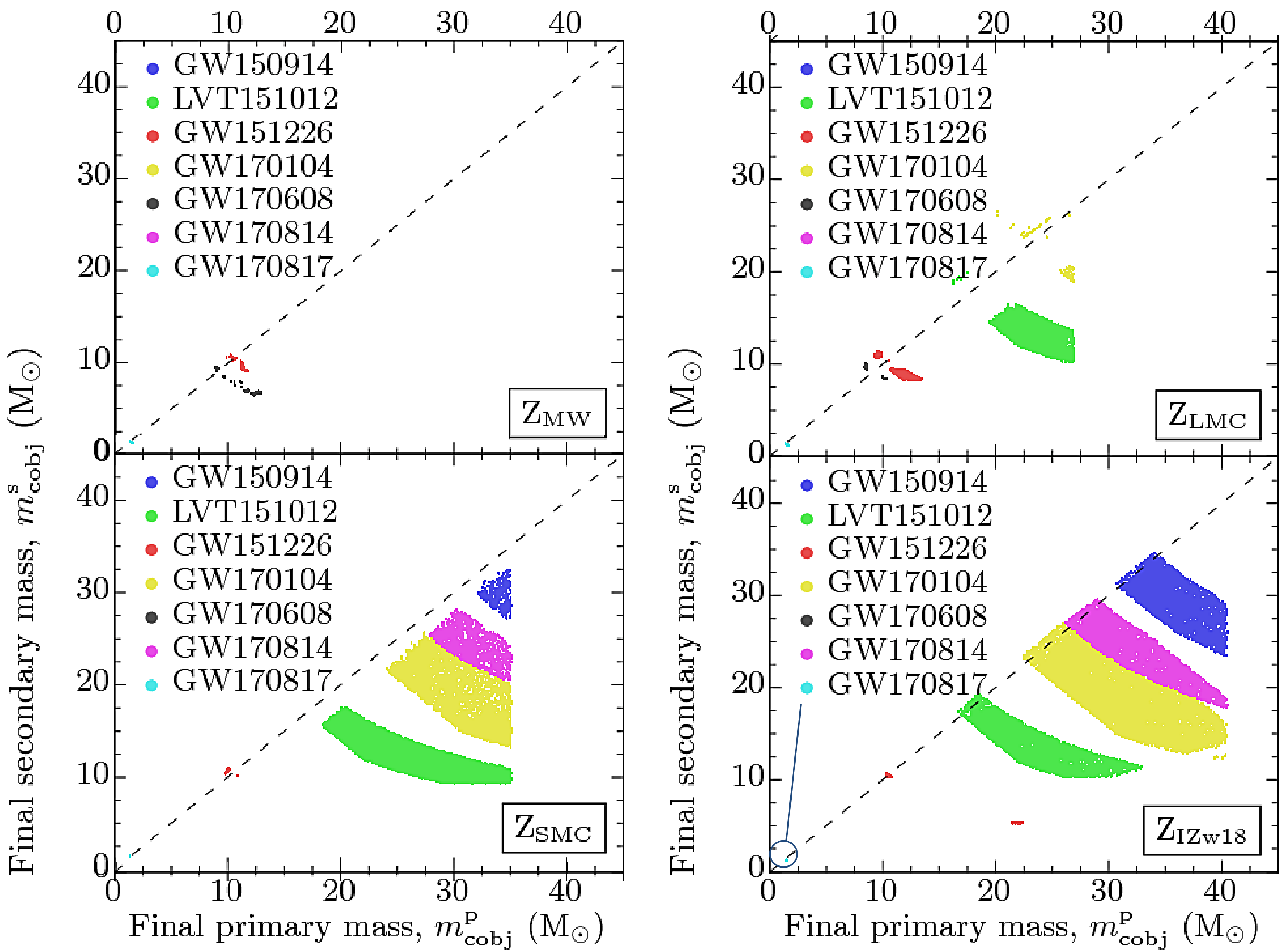
PROGENITORS OF FIRST 11 LIGO-VIRGO EVENTS

Kruckow et al. (2018), MNRAS





PROGENITORS OF LIGO-VIRGO EVENTS: METALLICITY



Kruckow et al. (2018), MNRAS

11 events in O1 and O2

10 BH+BH mergers
1 NS+NS merger

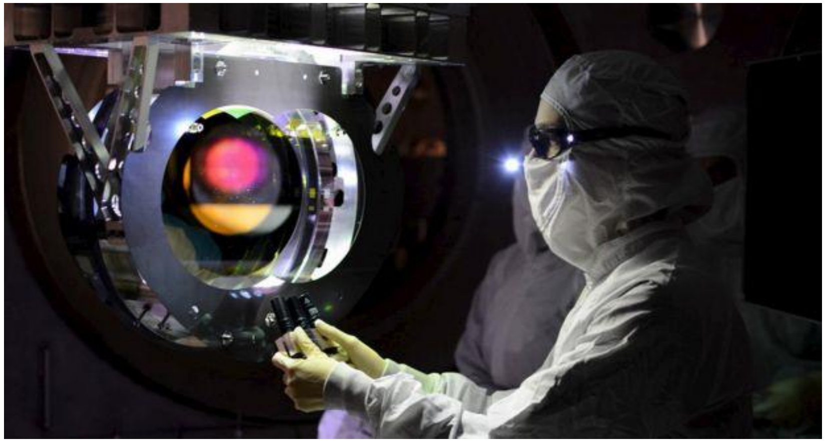
2019 (now!)

~40 events in O3 (if sensitivity ↑ x 1.5 and ΔT_{obs} remains the same)

?	x	BH+BH mergers	2
	y	NS+NS mergers	1
	z	BH+NS mergers	

- We predict 10-15 times more detections of mixed BH/NS mergers compared to double NS mergers

Observational selection bias against?



KICKS (2nd SN)

or

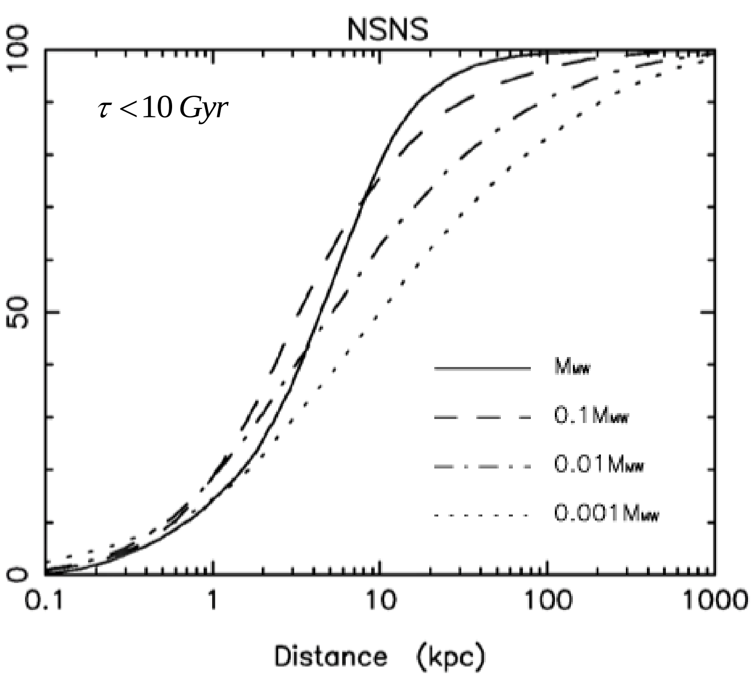
NS+WD LISA SOURCES

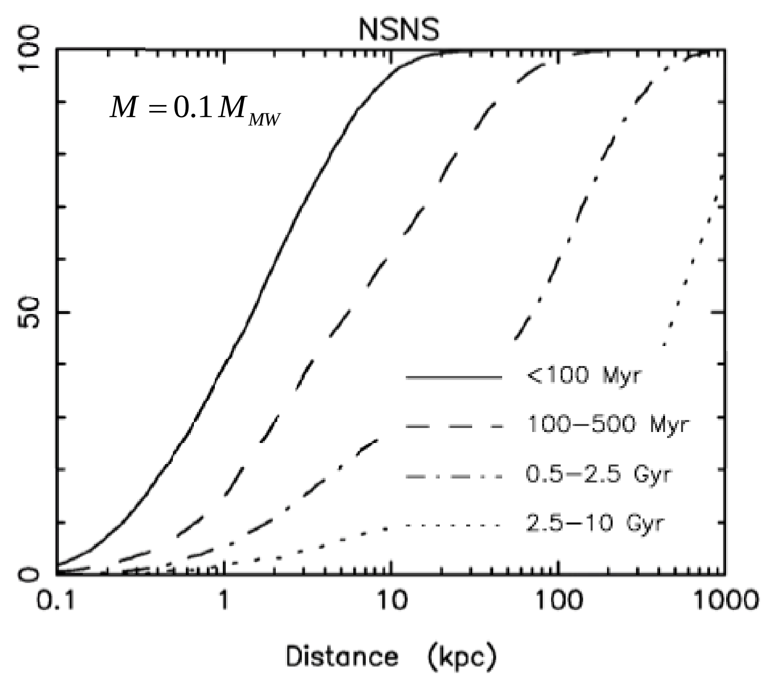
?

Mon. Not. R. Astron. Soc. **342,** 1169–1184 (2003)

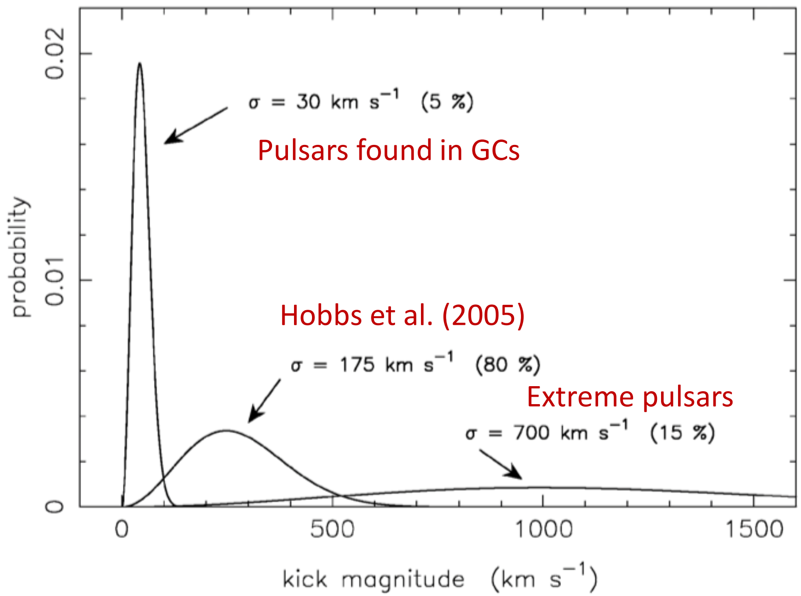
Galactic distribution of merging neutron stars and black holes – prospects for short gamma-ray burst progenitors and LIGO/VIRGO

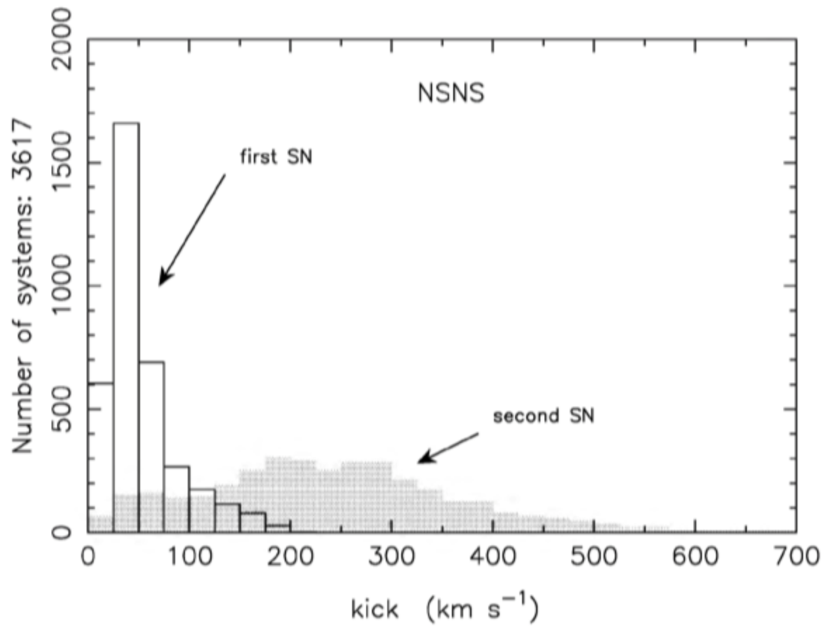
R. Voss★ and T. M. Tauris★
★*Astronomical Observatory, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark*

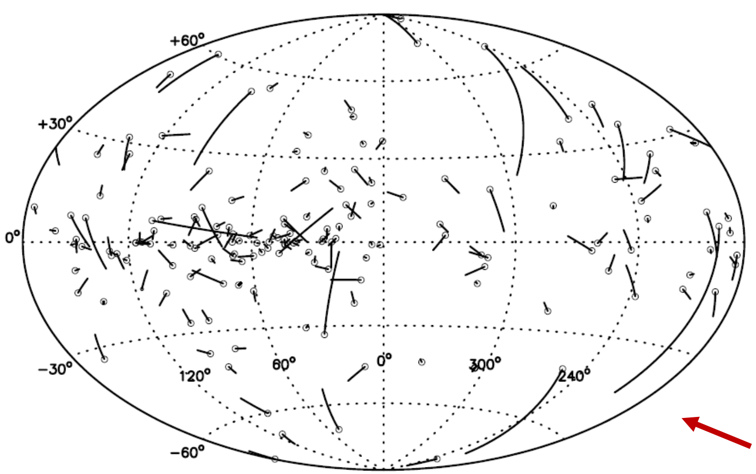


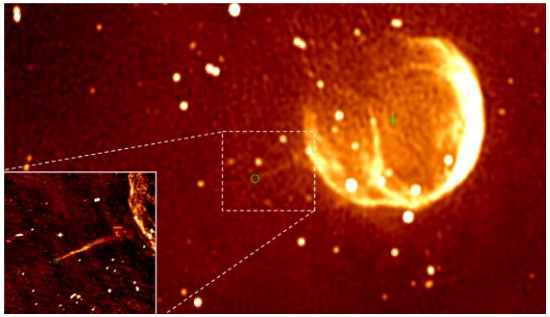


Voss & Tauris (2003), MNRAS



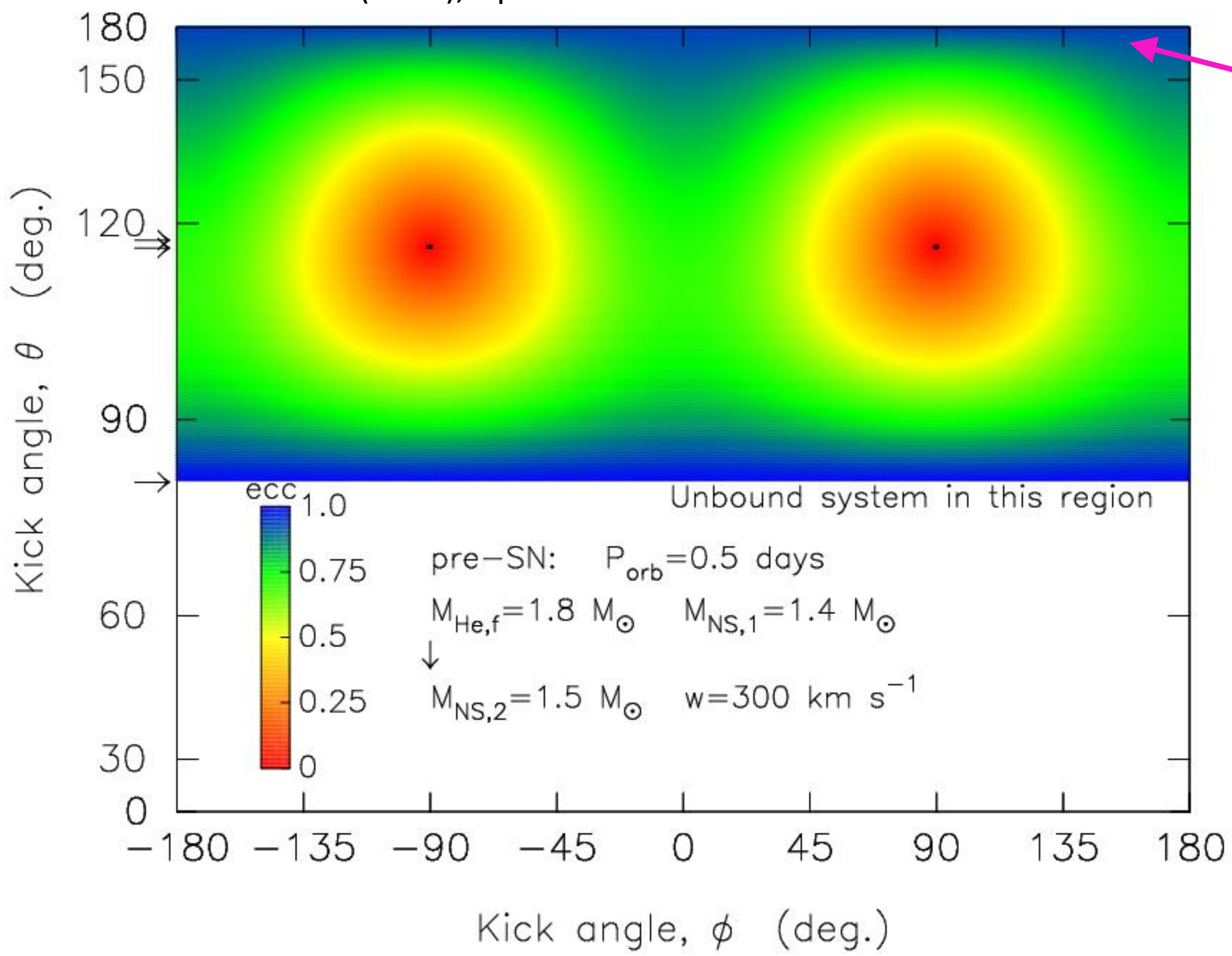




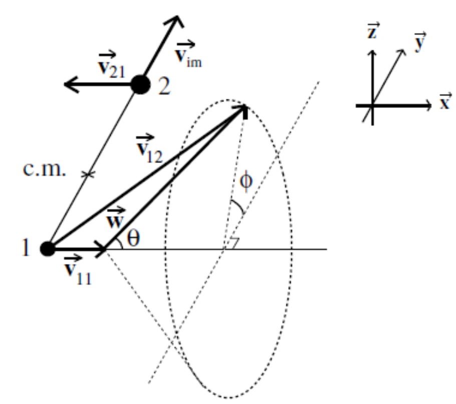


Radio proper motions show evidence for average 3D velocities of ~ 400 km s^{-1} (Hobbs et al. 2005).

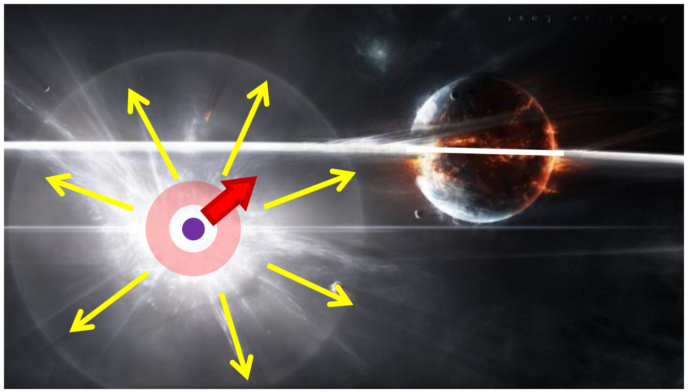
Tauris et al. (2017), ApL

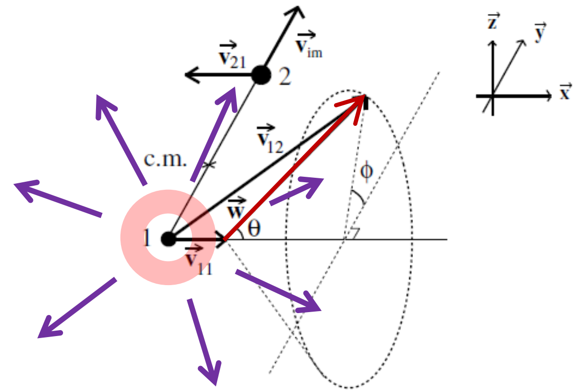


τ_{GW} < 1 Myr!
(short sGRB delay time)



Consider the **kinematics** from the **2nd SN explosion**

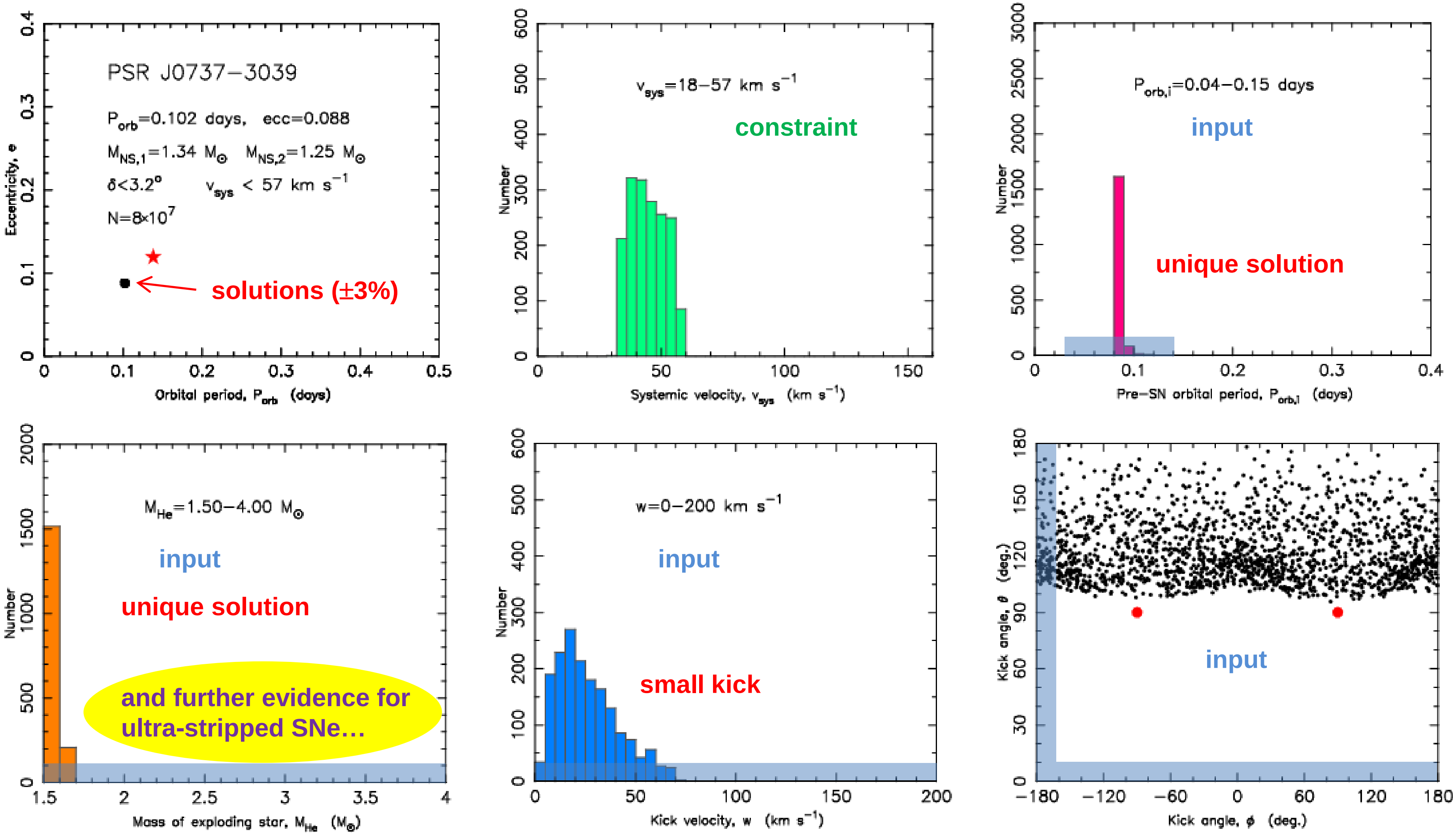




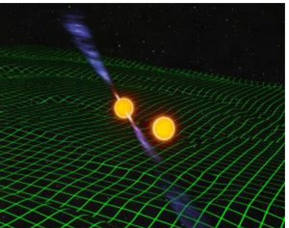
Our simulations take their basis in a five dimensional phase space.
The **input parameters** are:

- the pre-SN orbital period
- the final mass of the (stripped) exploding star
- the magnitude of the kick velocity imparted onto the newborn NS
- the two angles defining the direction of the kick velocity, θ and φ.

A sixth input parameter is the mass of the first-born NS, However, the SN simulation results are not very dependent on this parameter.

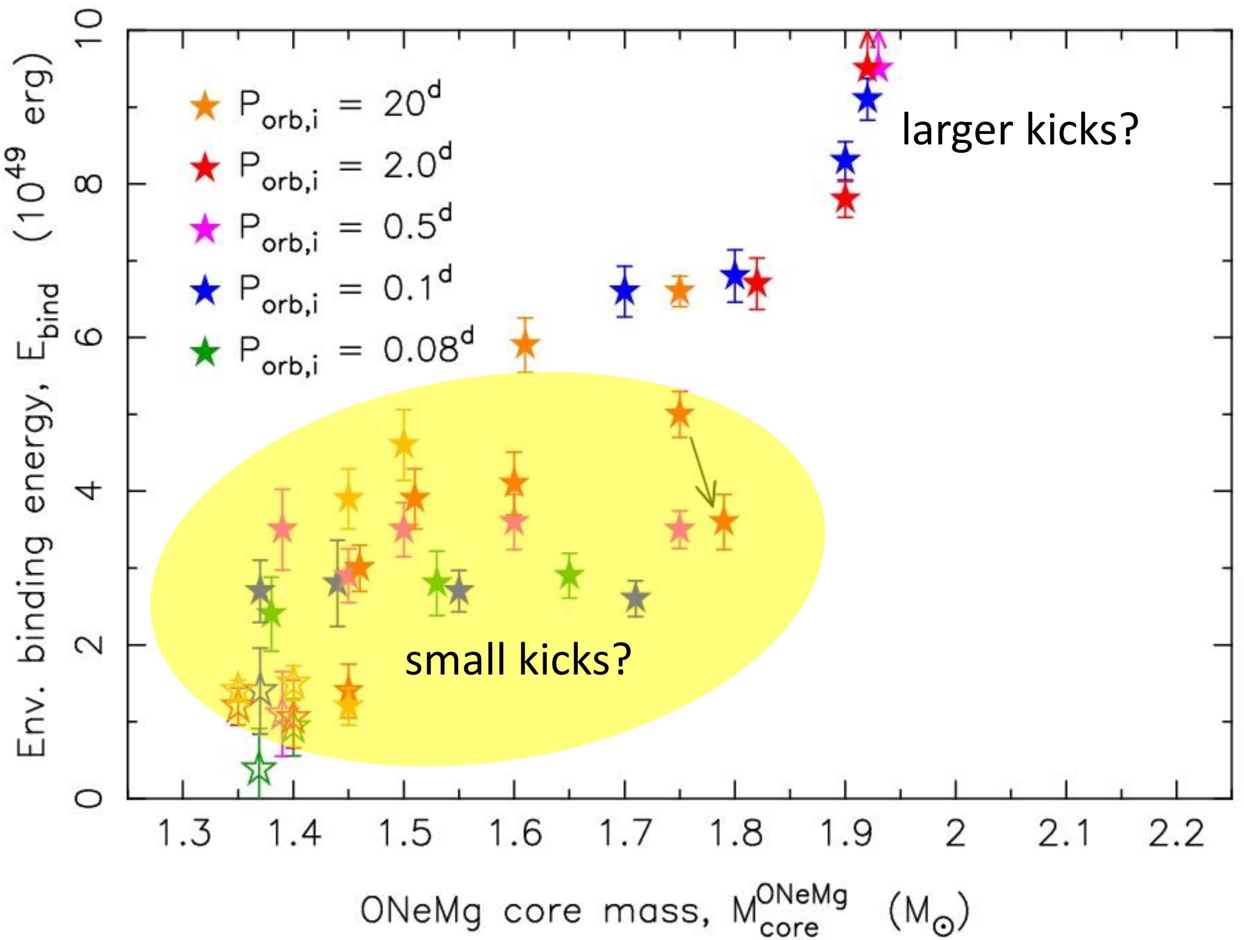


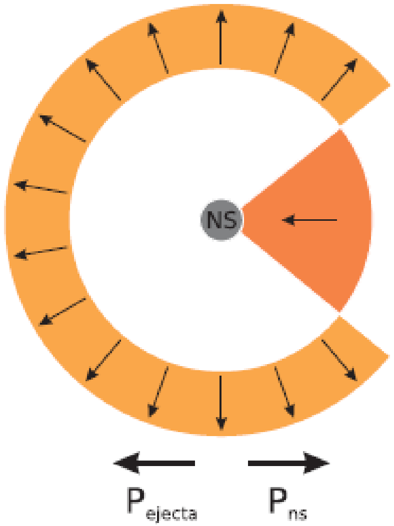
Tauris et al. (2017)

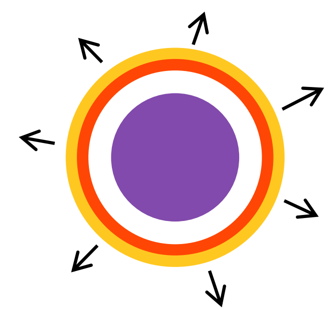


★ Based on proper motion and distance measurements (Deller et al. 2009) combined with MC simulations of the 3rd velocity component and a Galactic potential.

Tauris, Langer & Podsiadlowski (2015), MNRAS

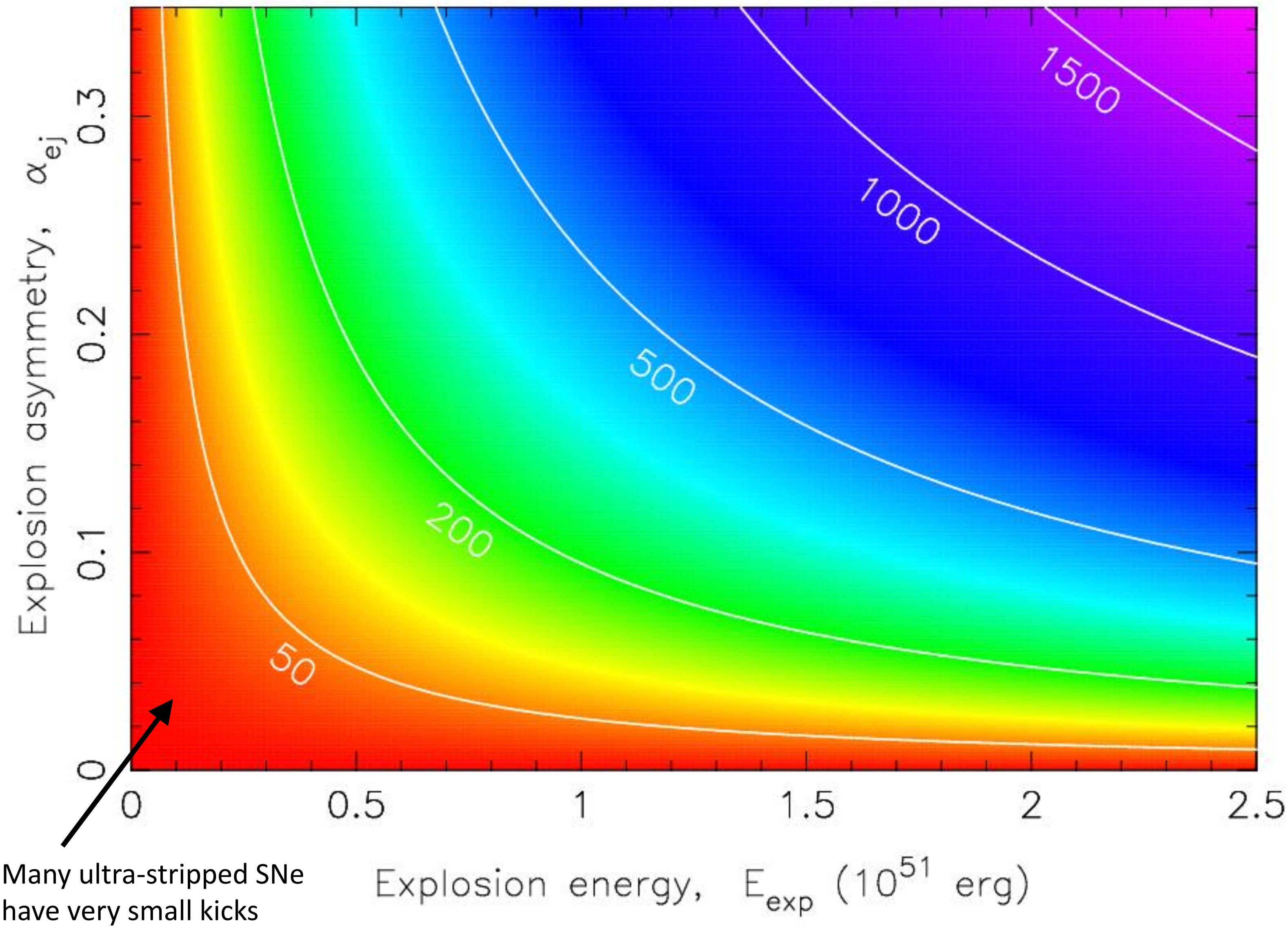






* Non-radial hydrodynamical instabilities, e.g. Standing Accretion Shock Instabilities (SASI) or neutrino driven convection bubbles (Janka 2012).

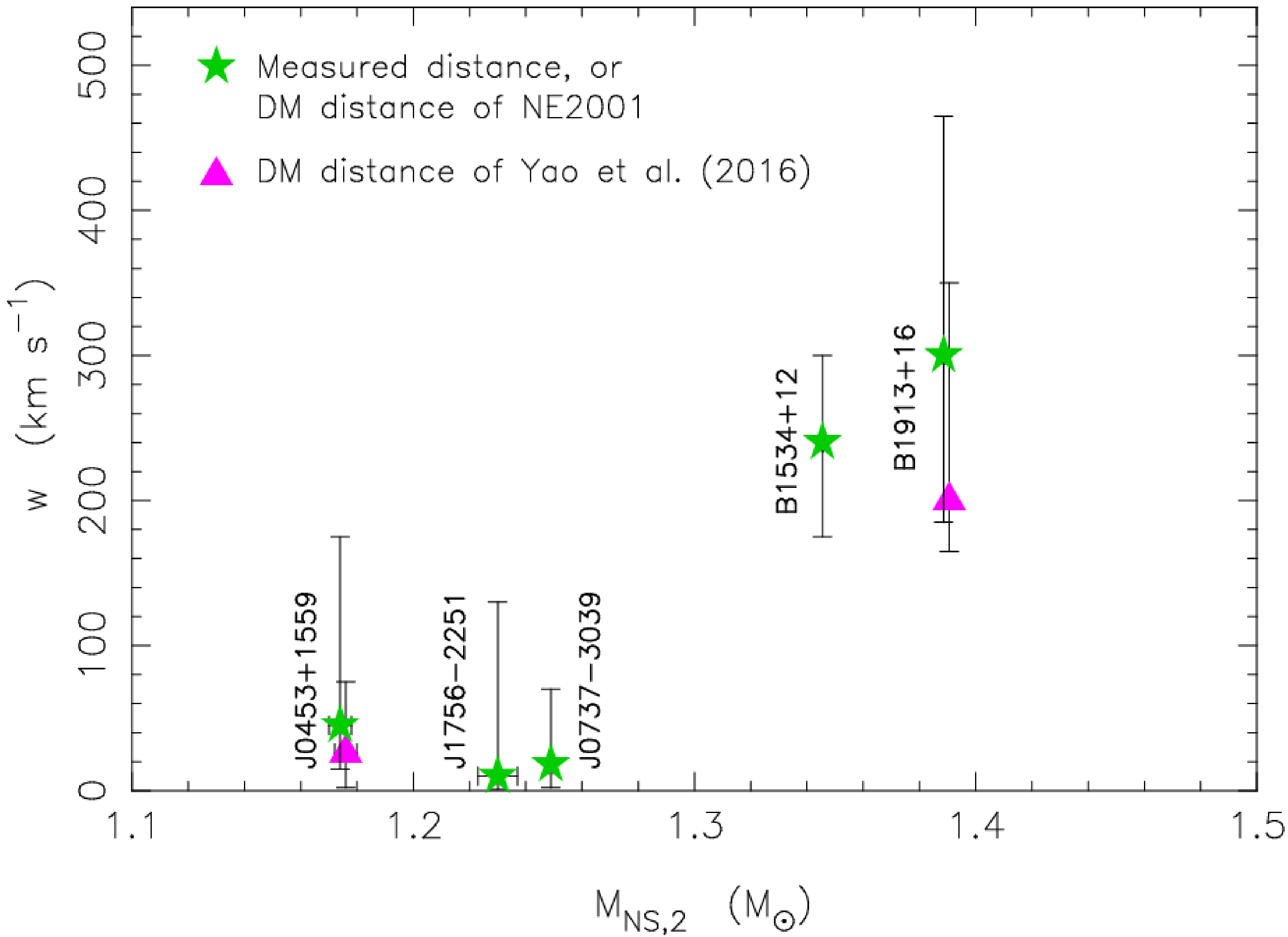
Theoretical kick magnitudes (following Janka 2017)



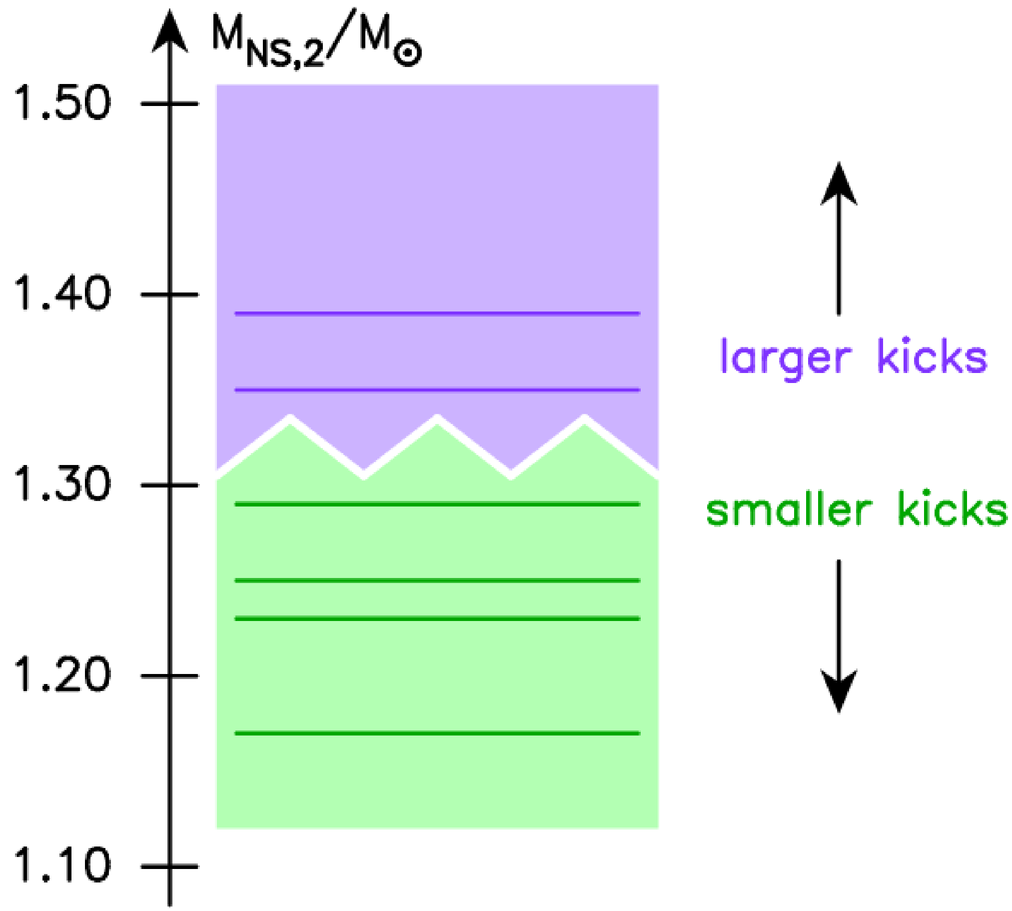
Many ultra-stripped SNe have very small kicks (although not all!)

A NS mass-kick correlation ?

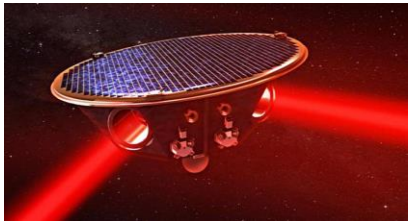
Tauris et al.(2017), ApJ

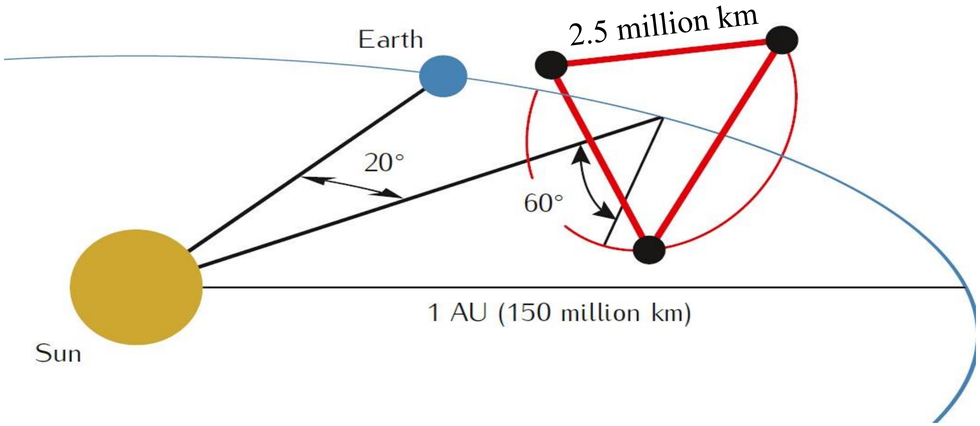


Kick – NS mass relation? Empirical evidence from current data

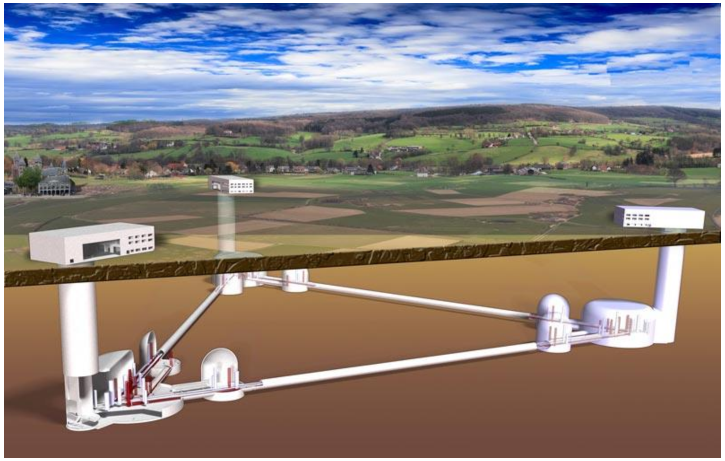


LISA
~2034

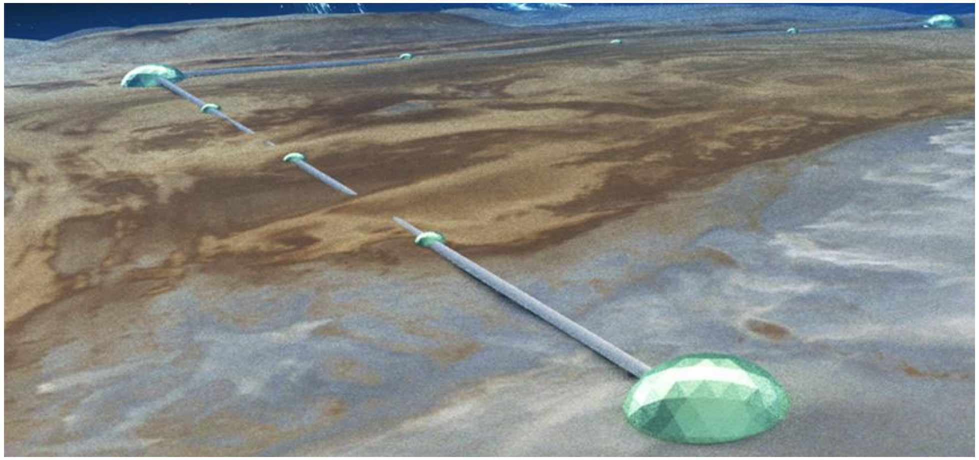




3G
~ ?

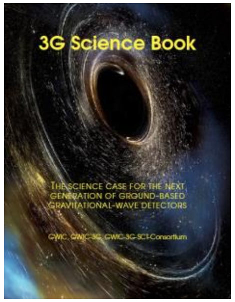


EINSTEIN TELESCOPE



COSMIC EXPLORER

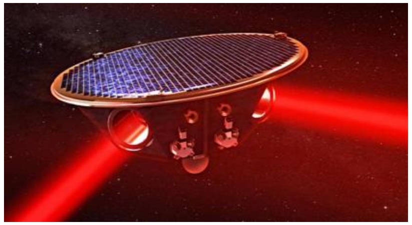
Ask for 3 detectors
(~ 1 billion € each)



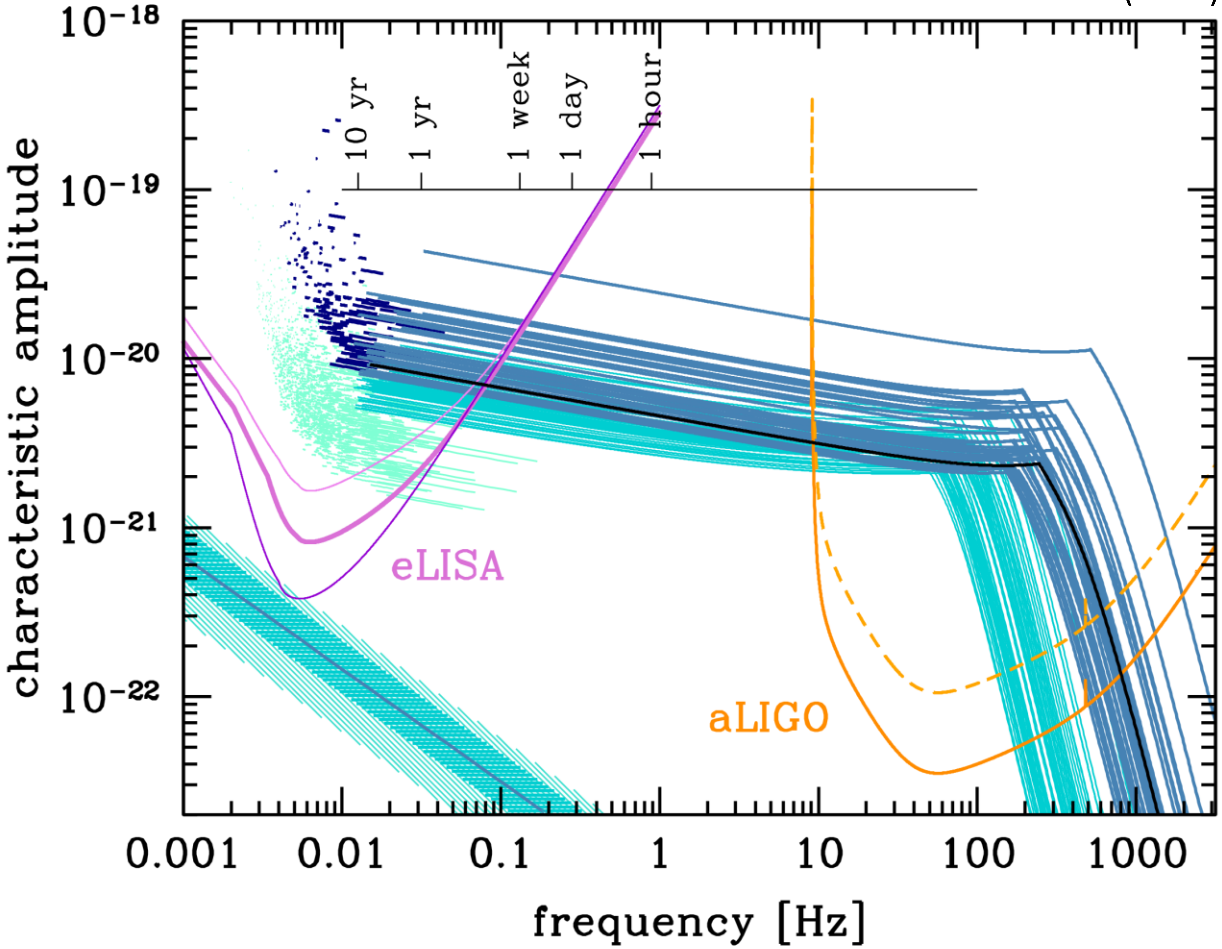
- Detect all BH-BH mergers out to z~20
- Detect the BH seeds evolving into SMBHs
- Possibly detect primordial BHs
- Determine the NS EoS to extreme precision
- etc.

The space-born observatory **LISA** (2034)
will detect thousands of resolvable **Galactic GW sources**
(besides millions of signals below the confusion limit)

WD, NS, BH

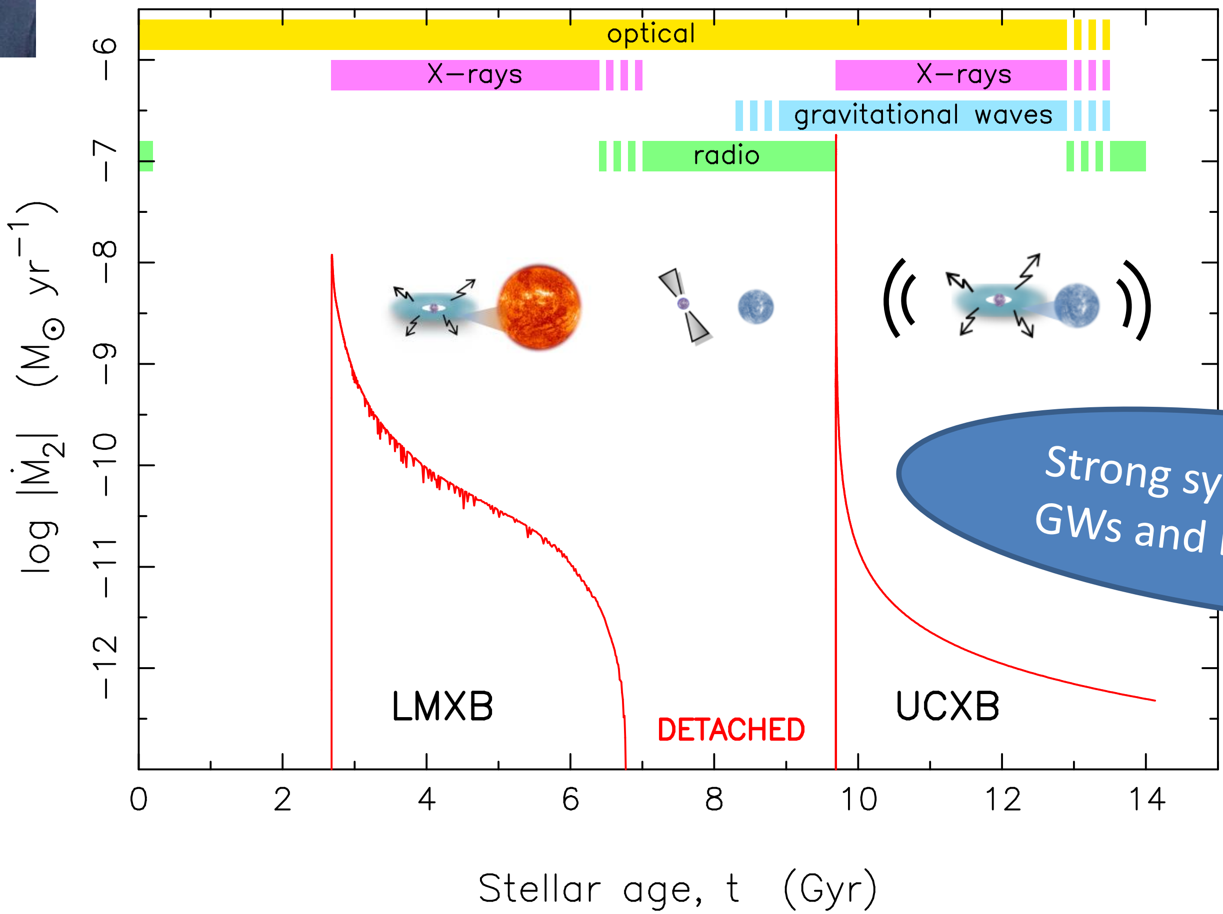


Sessana (2016)



First calculations of stable mass transfer from a WD to a NS
(Sengar, Tauris, Langer & Istrate 2017), MNRAS Letters

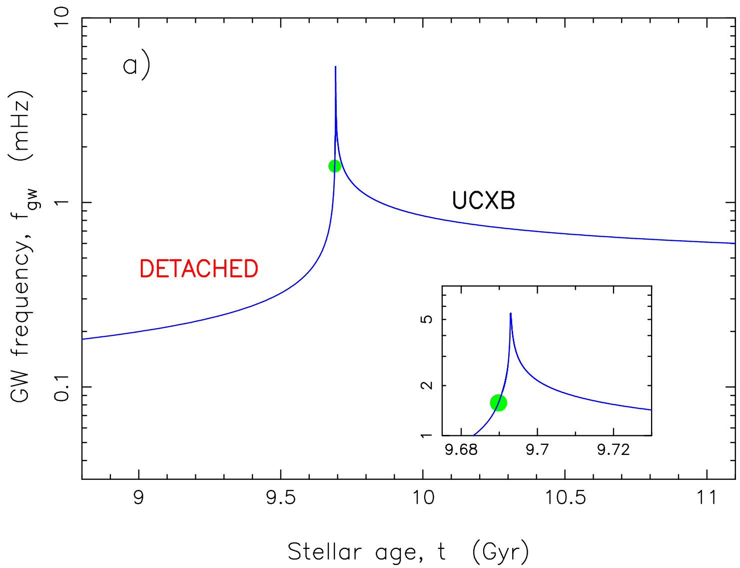
Tauris (2018), PRL



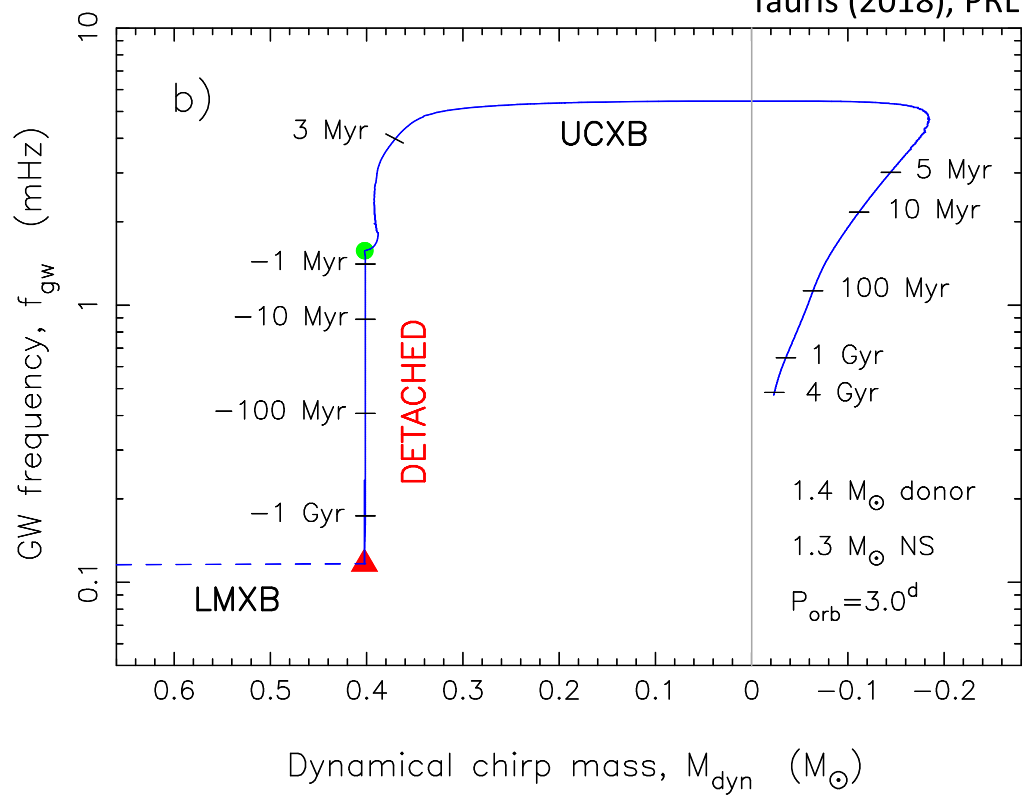
Strong synergies between GWs and EM observations

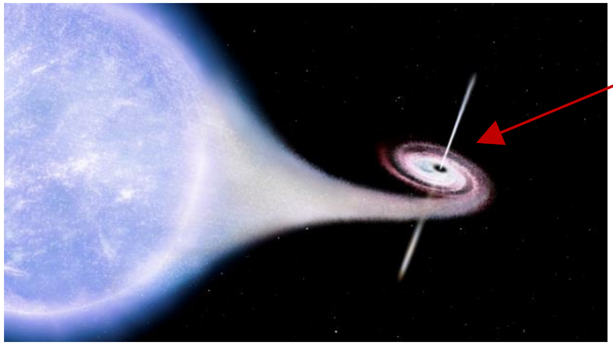
GW spectrum evolution

with finite-temperature effects
(specific entropy) of the WD donor

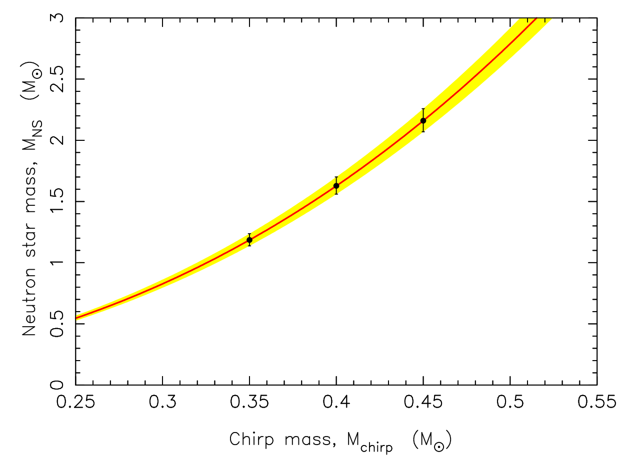


Tauris (2018), PRL

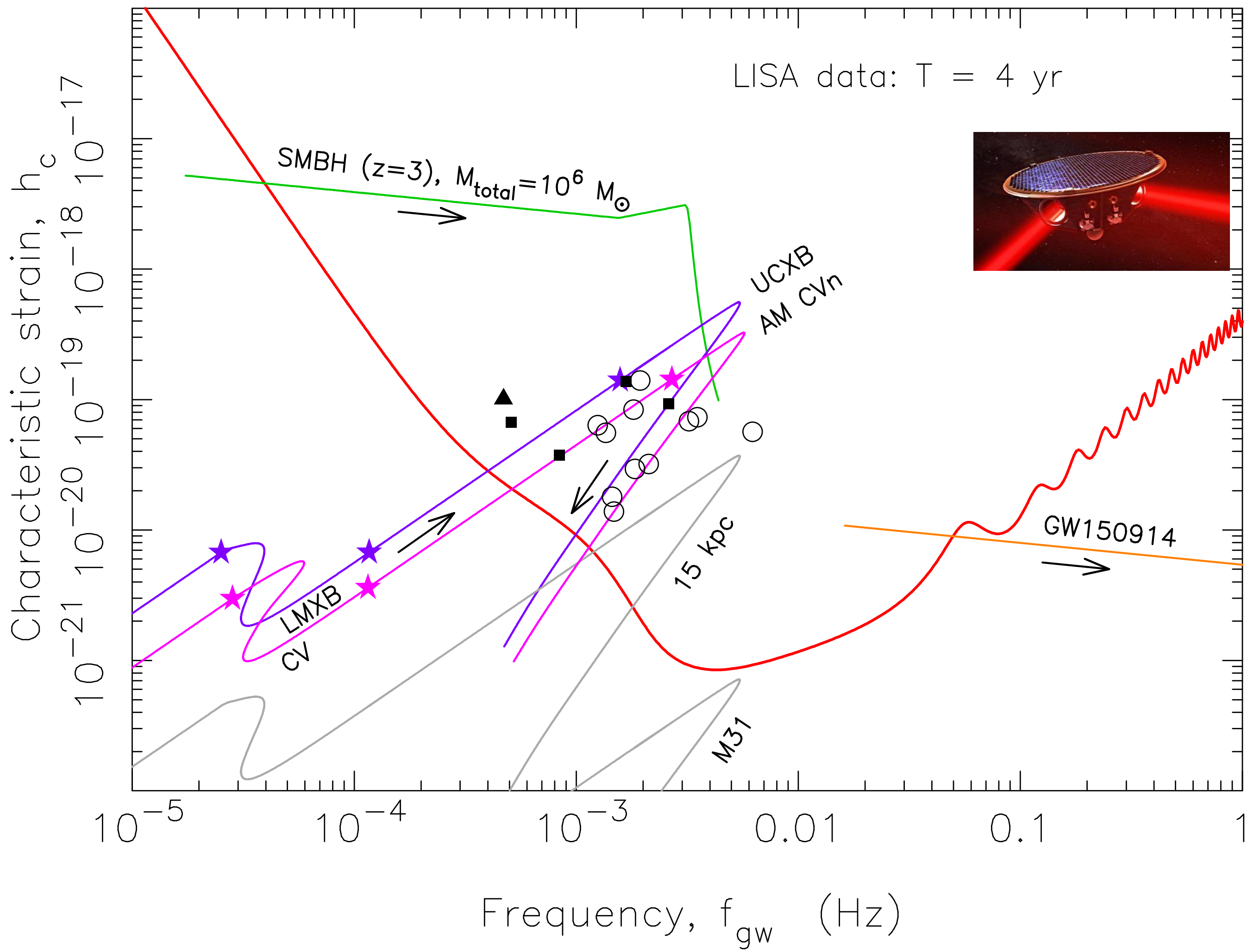




Determine NS the mass to a high accuracy via a new method



Tauris (2018), PRL



$$h_c \approx \sqrt{N_{cycles}}\,\sqrt{2}\,h_0 = \sqrt{2\,f_{gw}T_{obs}}\,h_0 \qquad h_0 = \sqrt{\frac{32}{80}}\;\frac{\pi^{2/3}G^{5/3}\,f_{gw}^{\,2/3}M_{chirp}^{\,5/3}}{c^4\,d_L}$$

Discovery of a ***<u>dual-line</u>*** GW binary

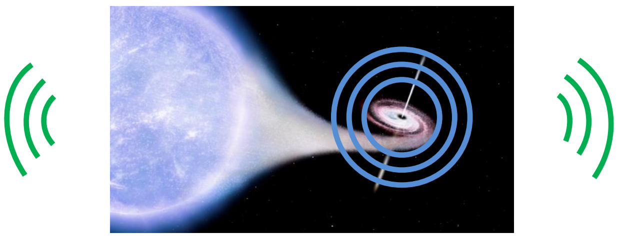
Tauris (2018), PRL

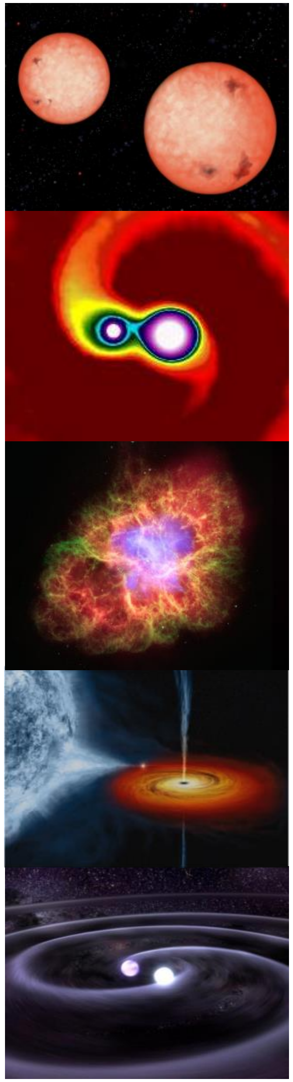
$$I_{zz}\,\varepsilon = \sqrt{\frac{32}{80}}\;\pi^{-4/3} G^{2/3} f_{gw}^{-4/3} M_{chirp}^{5/3} \left(\frac{h_{spin}}{h_{orb}}\right)$$

LIGO

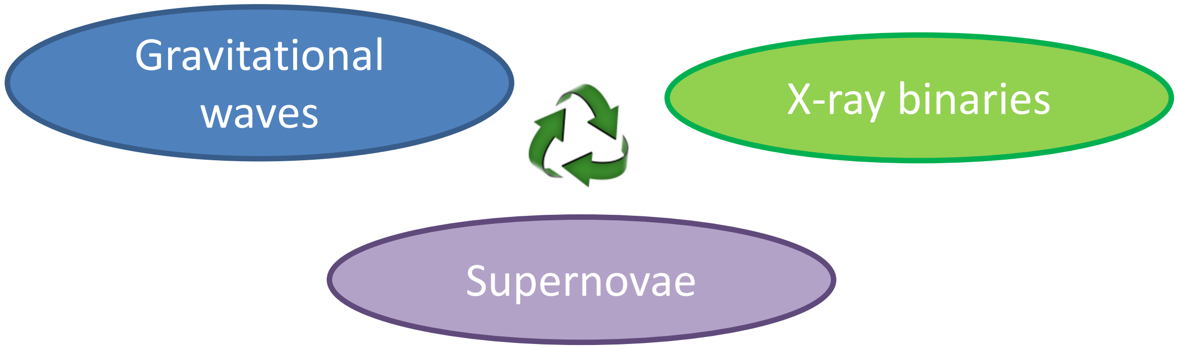
LISA

Independent on the distance to the binary





SYNERGIES OF MULTIDISCIPLINARY RESEARCH



A RICH AVENUE FOR THE NEXT DECADES

… a big grant is needed!

- Formation and evolution of compact binary stars **self-consistently** …. until gravitational collapse and apply these models as **realistic** SN input
- Computations of accretion to obtain final NS/BH **masses** and **spin rates**
- Numerical modelling of **LISA sources** including finite-temperature effects

Thank you

I look forward to learn from you