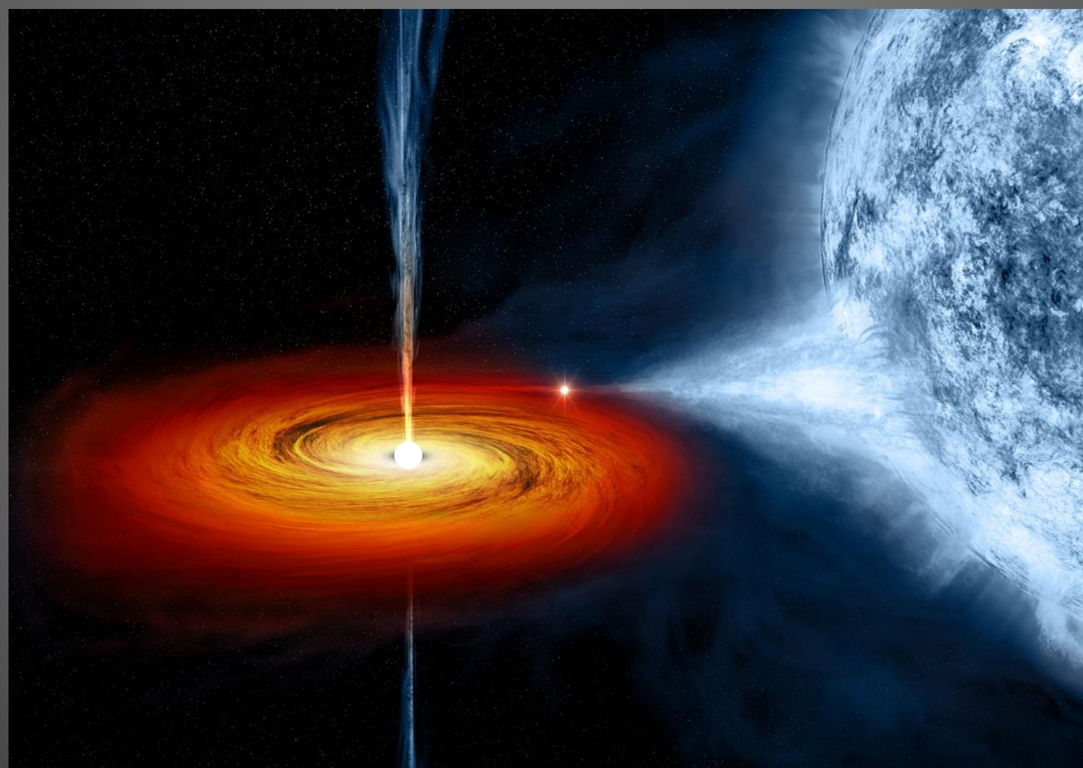
FORMATION OF BINARY NEUTRON STARS / BLACK HOLES

AEI IMPRS GW LECTURES 5+6



Thomas Tauris – IFA, Aarhus University

Note: These lectures will be recorded and posted onto the IMPRS website

Dear participants,

We will record all lectures on “The Astrophysics of Compact Objects”, including possible Q&A after the presentation, and we will make the recordings publicly available on the IMPRS lecture website at:

https://imprs-gw-lectures.aei.mpg.de

By participating in this Zoom meeting, you are giving your explicit consent to the recording of the lecture and the publication of the recording on the course website.

Albert-Einstein Institute Lectures 2021

Thomas Tauris @ Aarhus University

Lectures 1+2: Wednesday May 12, 10:00 – 12:00
X-ray Binaries and Recycling Millisecond Pulsars

Lectures 3+4: Friday May 14, 10:00 – 12:00
Spin and B-field Evolution of Neutron Stars (+ Black Hole Spins)

Lectures 5+6: Wednesday May 19, 10:00 – 12:00
Formation of Binary Neutron Stars/Black Holes

Lectures 7+8: Friday May 21, 10:00 – 12:00
Binary Neutron Stars and Gravitational Waves at Low and High Frequencies

You are most welcome to ask questions any time ☺

FORMATION OF BINARY NEUTRON STARS / BLACK HOLES

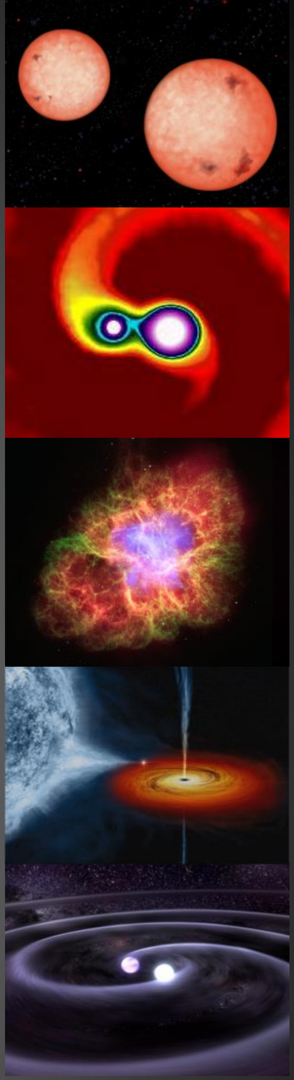
AEI LECTURES 5+6

- Resumé of the formation of double NS binaries
  - Case BB RLO
  - Ultra-stripped SNe
  - Impact of SN kicks
  - NS masses, spins and B-fields

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

a personal bias

- Formation of double BH binaries
  - BH masses and spins
  - BHNS binaries



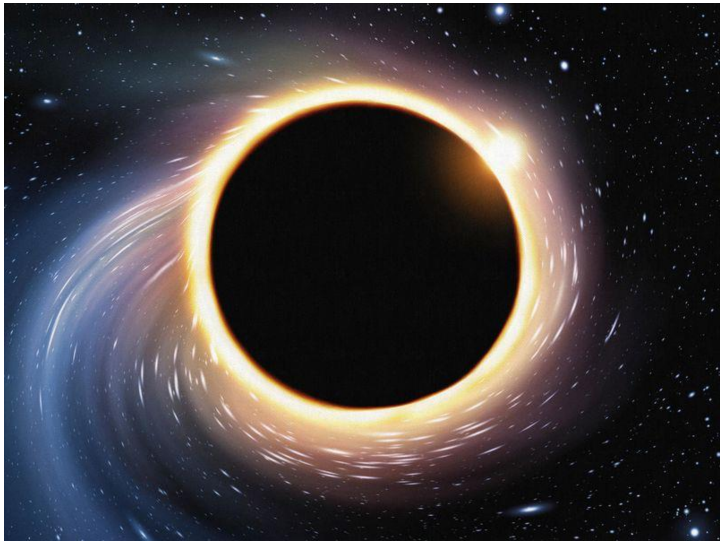
For a review:
Tauris & van den Heuvel (2022)
New textbook from Princeton Uni. Press

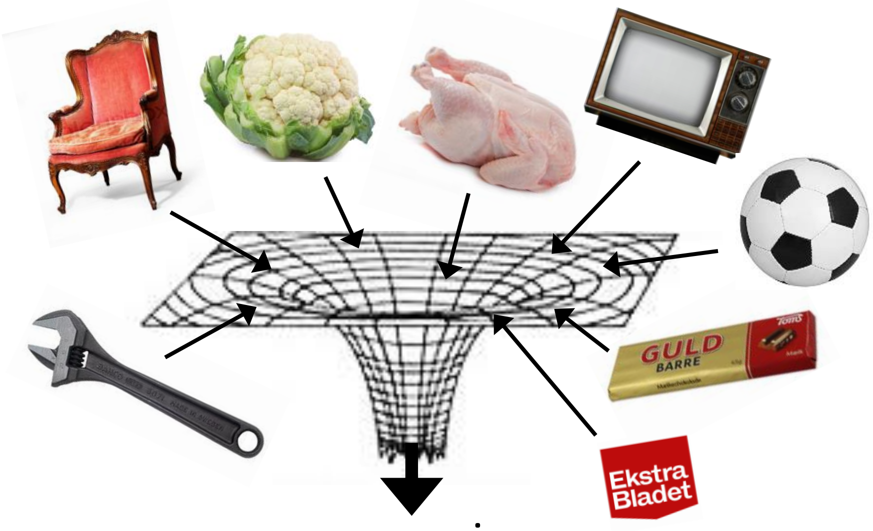
Neutron Stars and Black Holes

Unique **physics labs**.

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

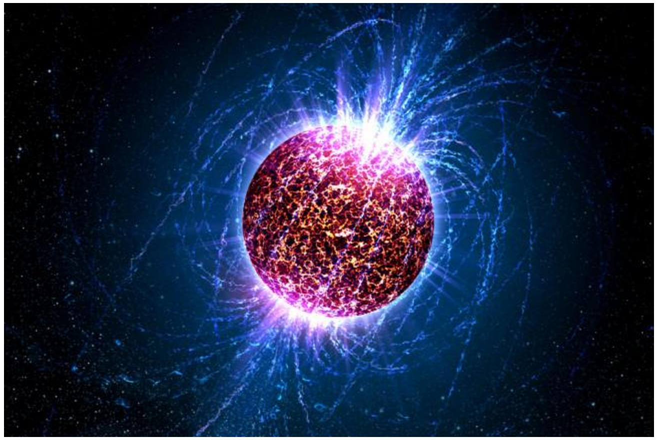
Many **astrophysical phenomena** are related to **NSs** and **BHs** in **binaries**:
X-ray sources, radio pulsars, jets, Type Ib/c SNe, GRBs and **GWs and mergers**

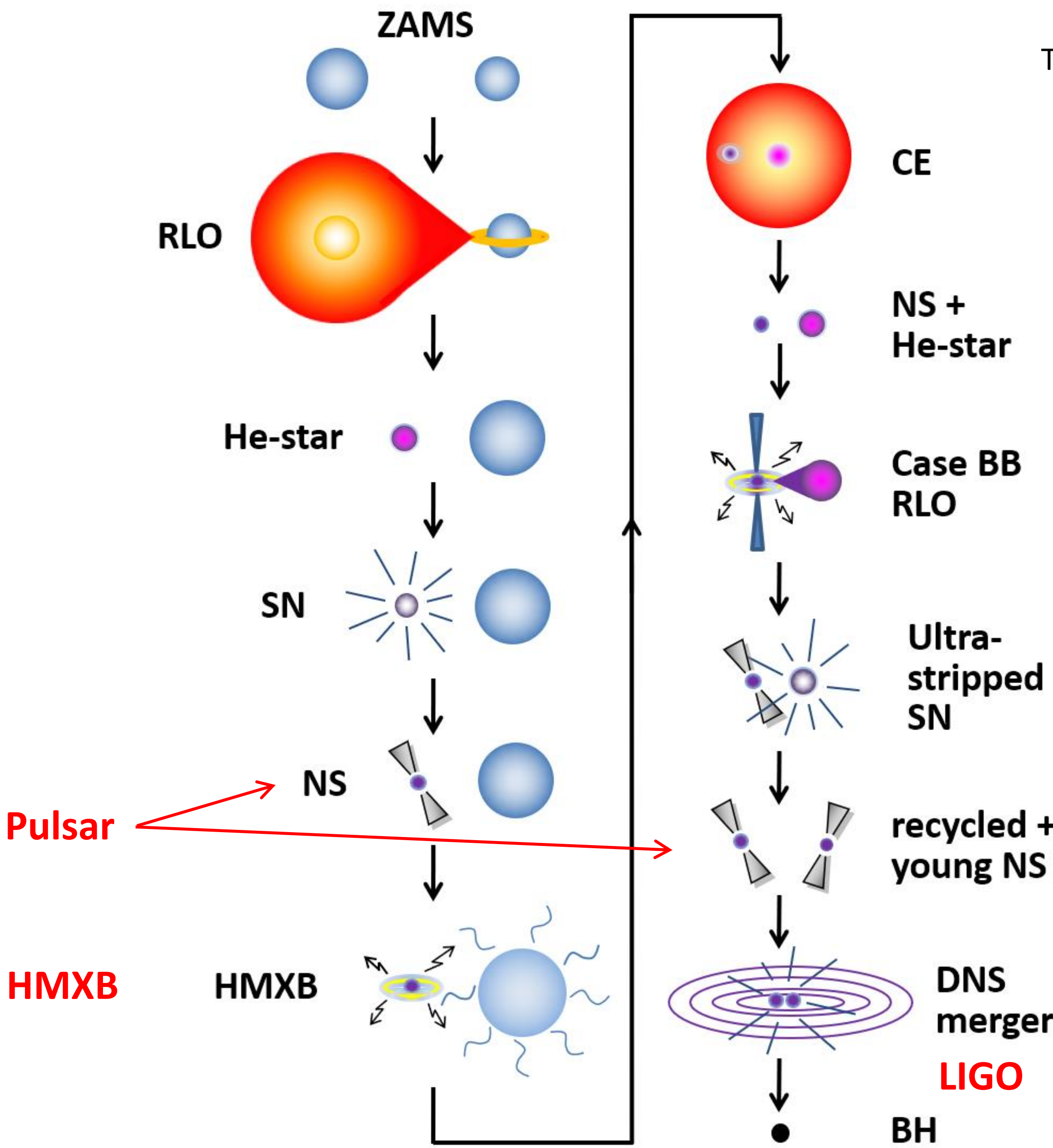




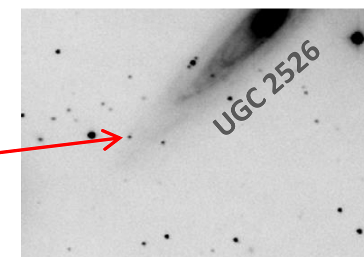
mass, spin,
~~electric charge~~

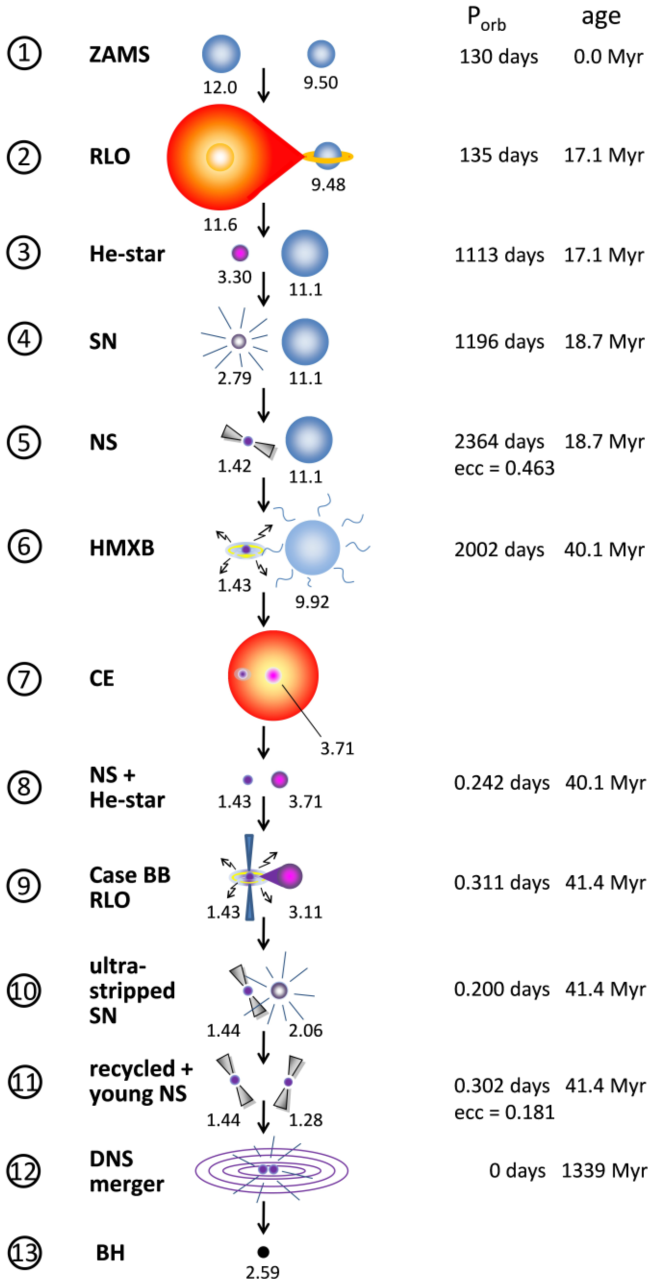
Black holes have no hair…
… Neutron stars have lots of hair!





Tauris et al. (2017), ApJ

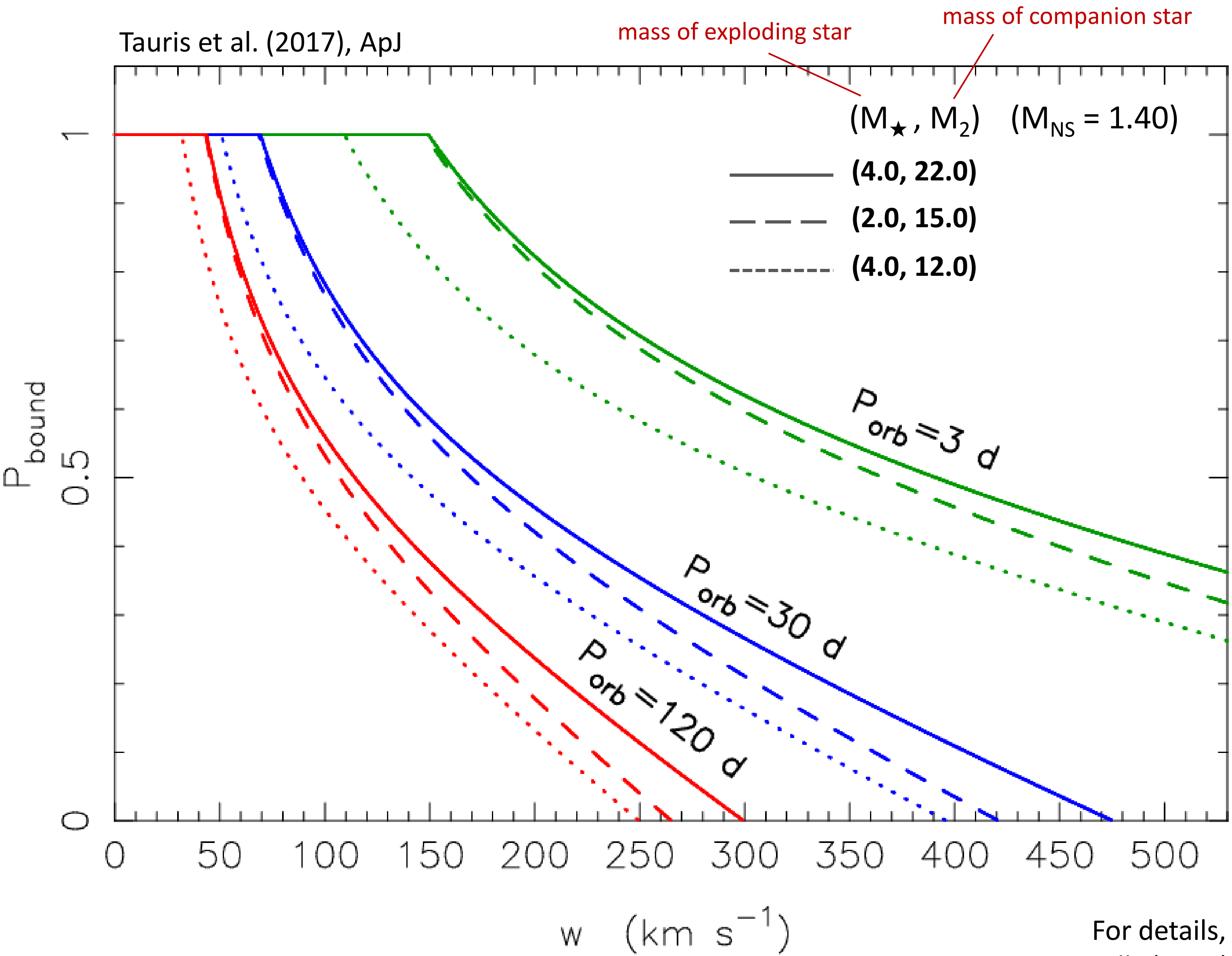


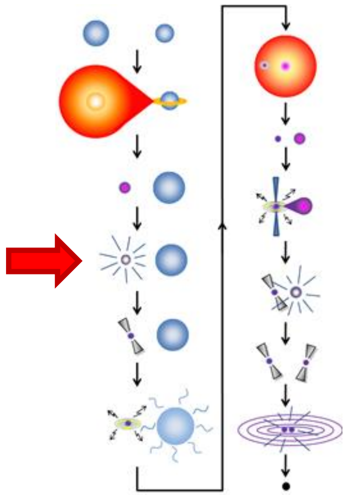


Tauris & van den Heuvel (2022)

Physics of Binary Star Evolution

PROBABILITY OF SURVIVING 1st SUPERNOVA





For details, see e.g:
Hills (1983)
Tauris & Takens (1998)

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

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

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

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:

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

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

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

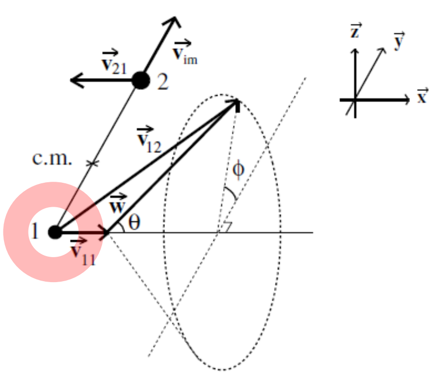
and for the companion star:

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

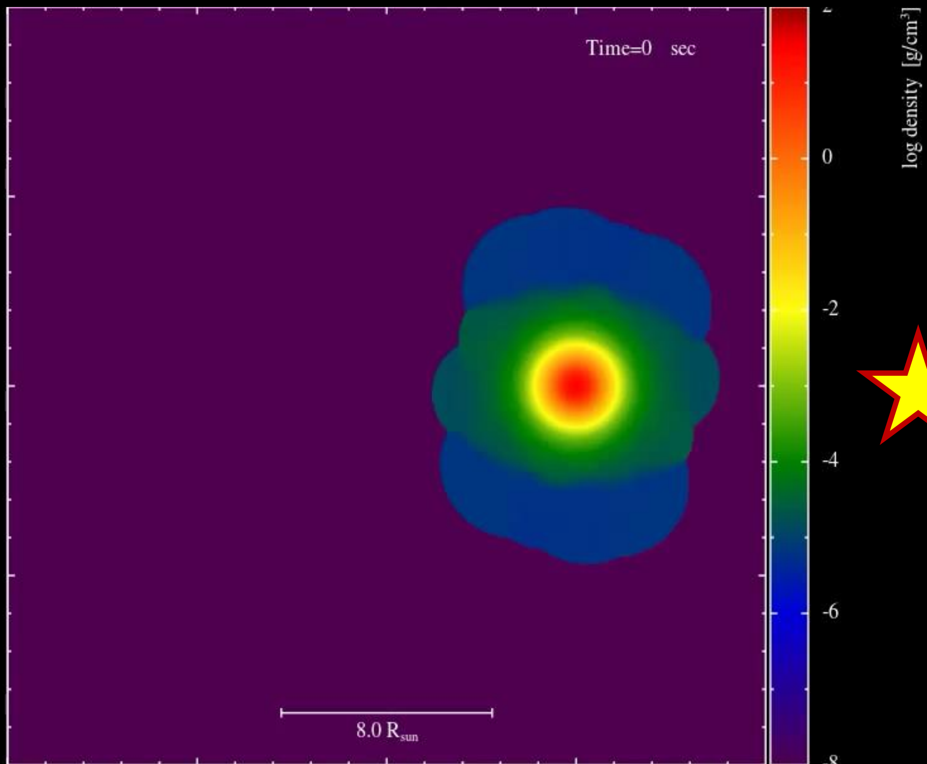
$$v_{2y} = \frac{w\sin\vartheta\cos\varphi}{m_{2f}S} + \left(1 - \frac{1}{m_{2f}S}\right)v_{\rm im} - \frac{Q\sqrt{P}}{m_{2f}S}v \quad (55)$$

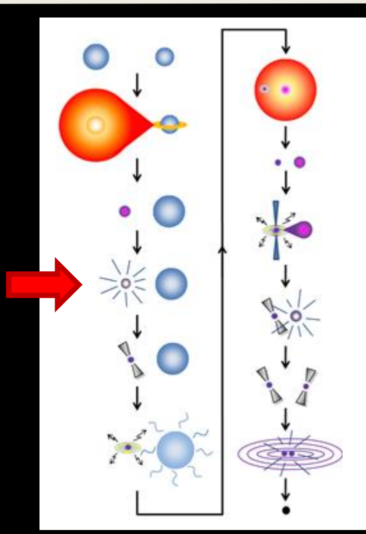
$$v_{2z} = \frac{-w\sin\vartheta\sin\varphi}{m_{2f}R} \quad (56)$$

Tauris & Takens (1998), A&A



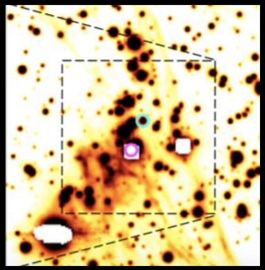
Liu, Tauris, Röpke et al. (2015), A&A   3D hydrodynamical sim.

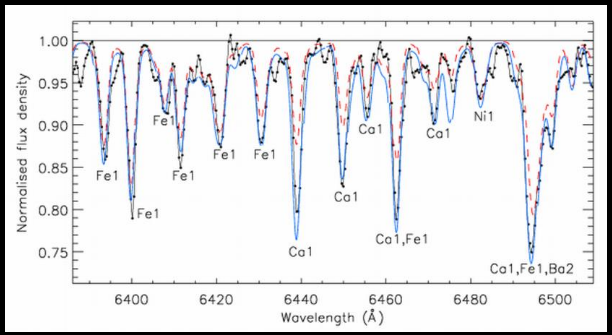




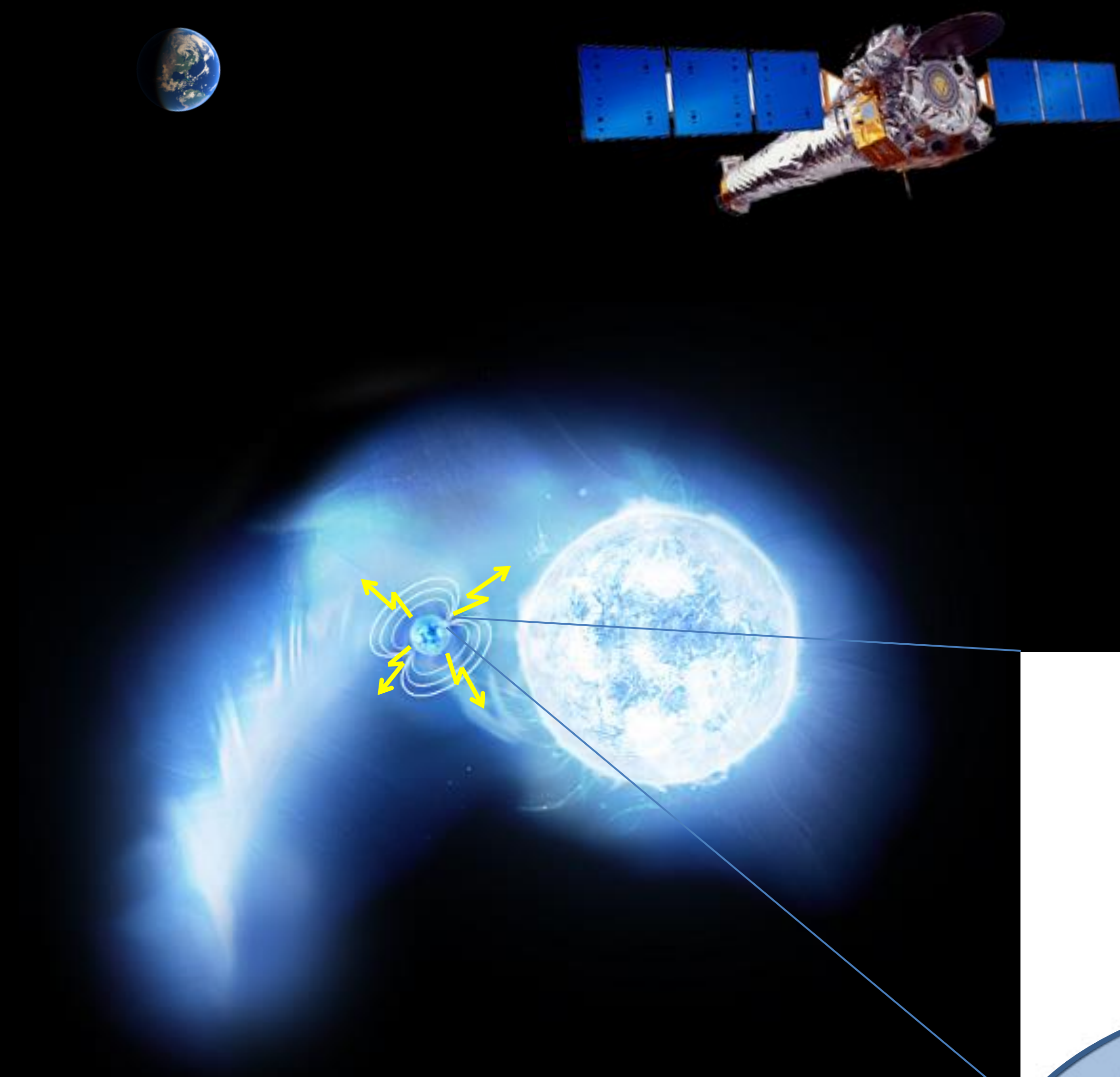
evaporation / ablation and pollution

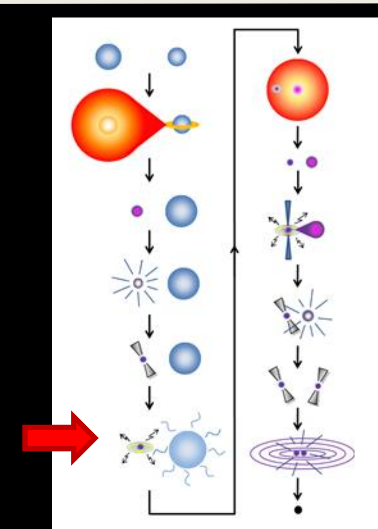
RCW 86

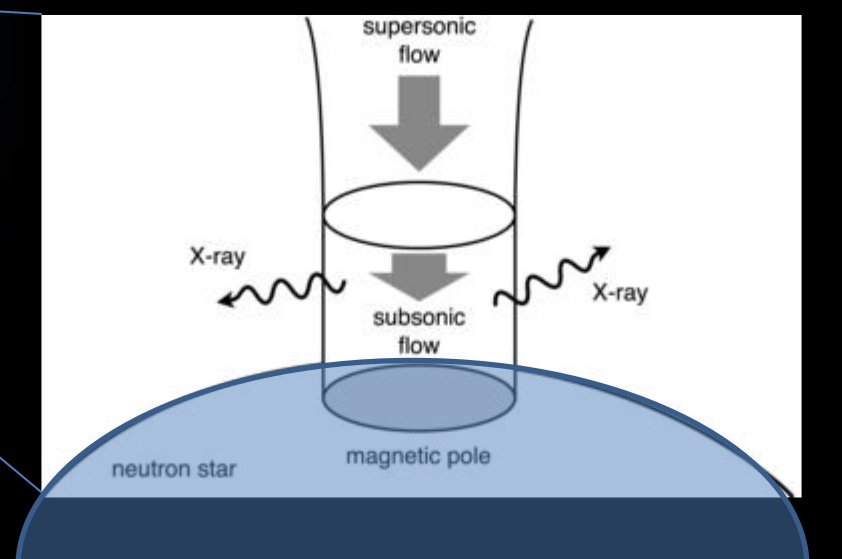




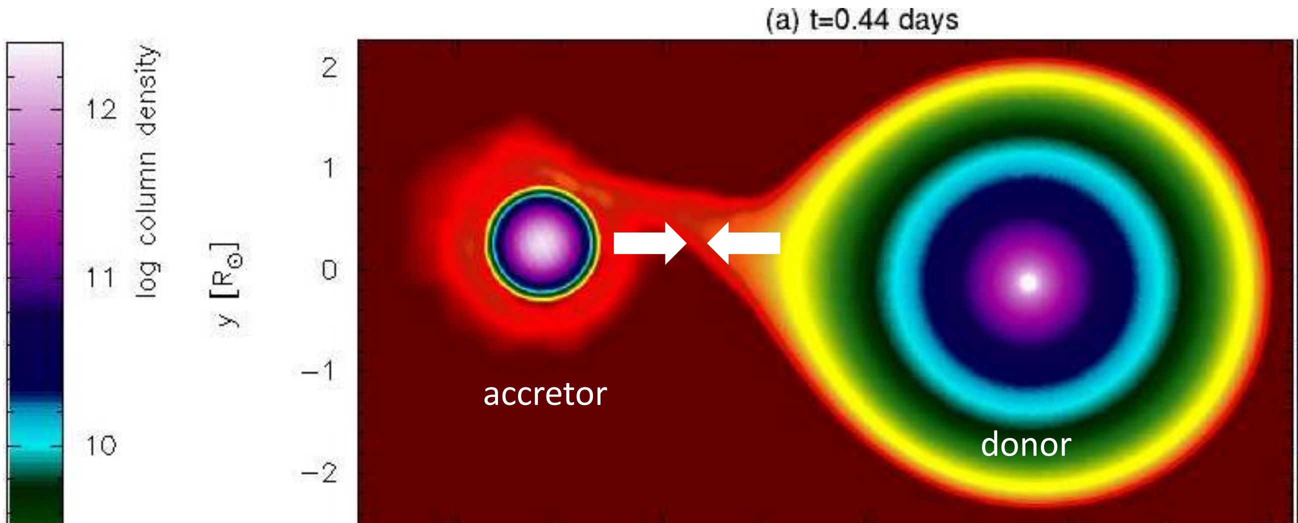
See also
Gvaramadze et al. (2017), Nature Astronomy

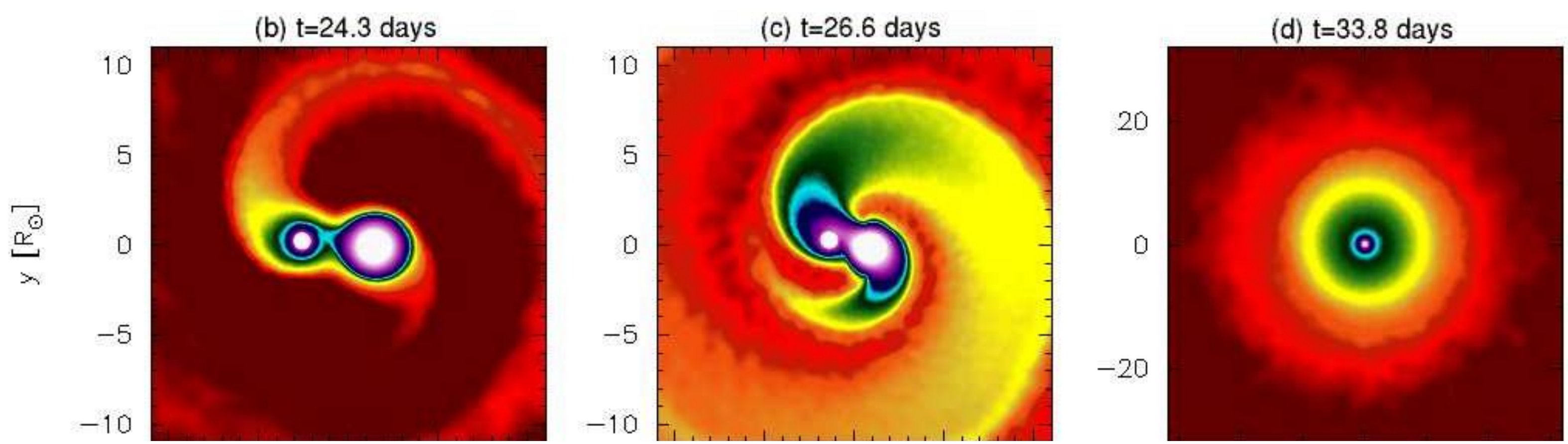


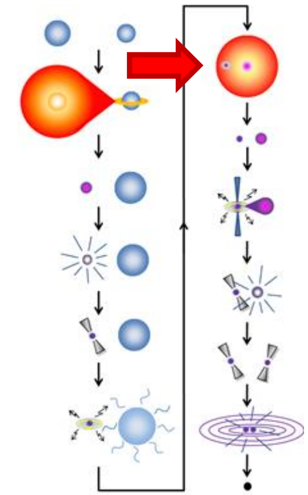



supersonic
flow
X-ray
X-ray
subsonic
flow
neutron star
magnetic pole

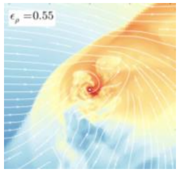
Run-away mass transfer → common envelope





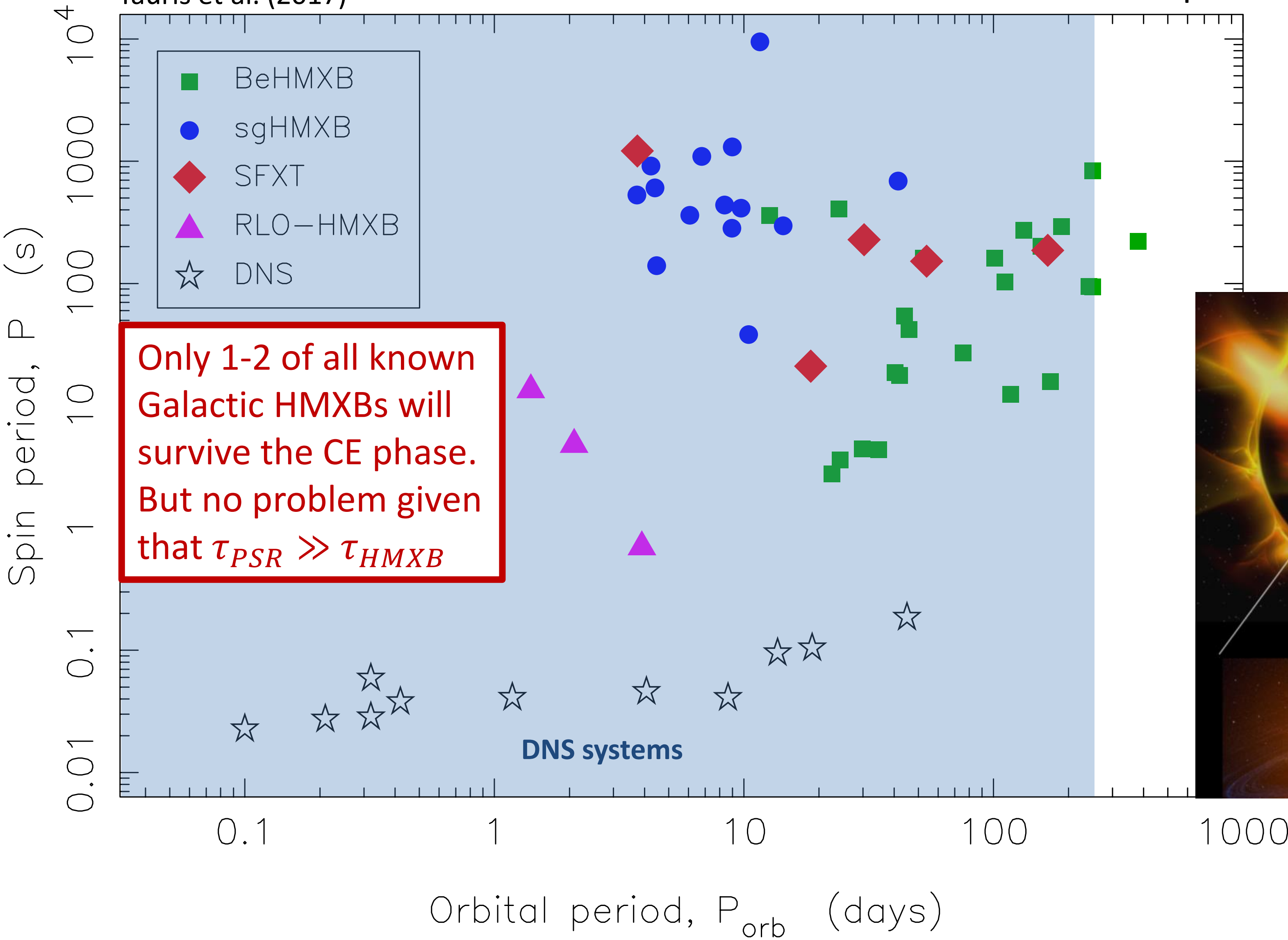


Lombardi & Scruggs, in Ivanova et al. (2013)
MacLeod & Ramirez-Ruiz (2015)
Kruckow, Tauris et al. (2016)
Fragos et al. (2019)
Marchant et al. (2021)



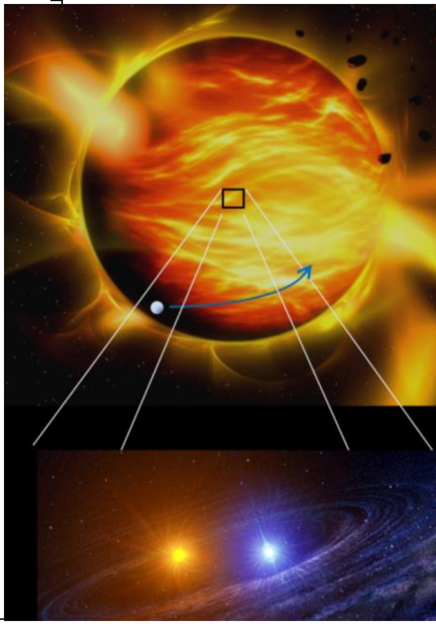
stellar merger
(*cannibalism*)

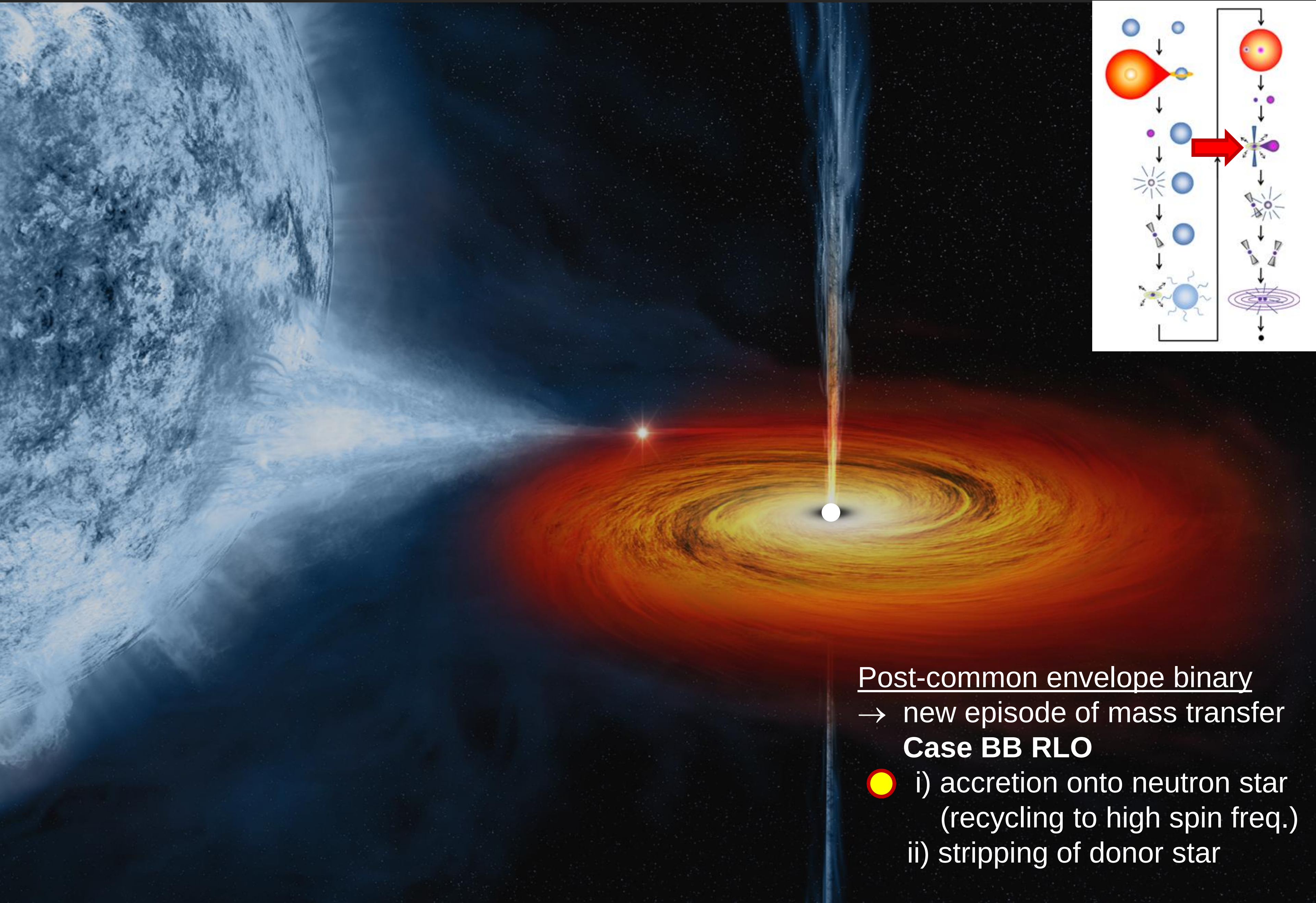
DNS systems: connections to their HMXB progenitor systems?



Only 1-2 of all known Galactic HMXBs will survive the CE phase. But no problem given that $\tau_{PSR} \gg \tau_{HMXB}$

HMXB → CE





<u>Post-common envelope binary</u>

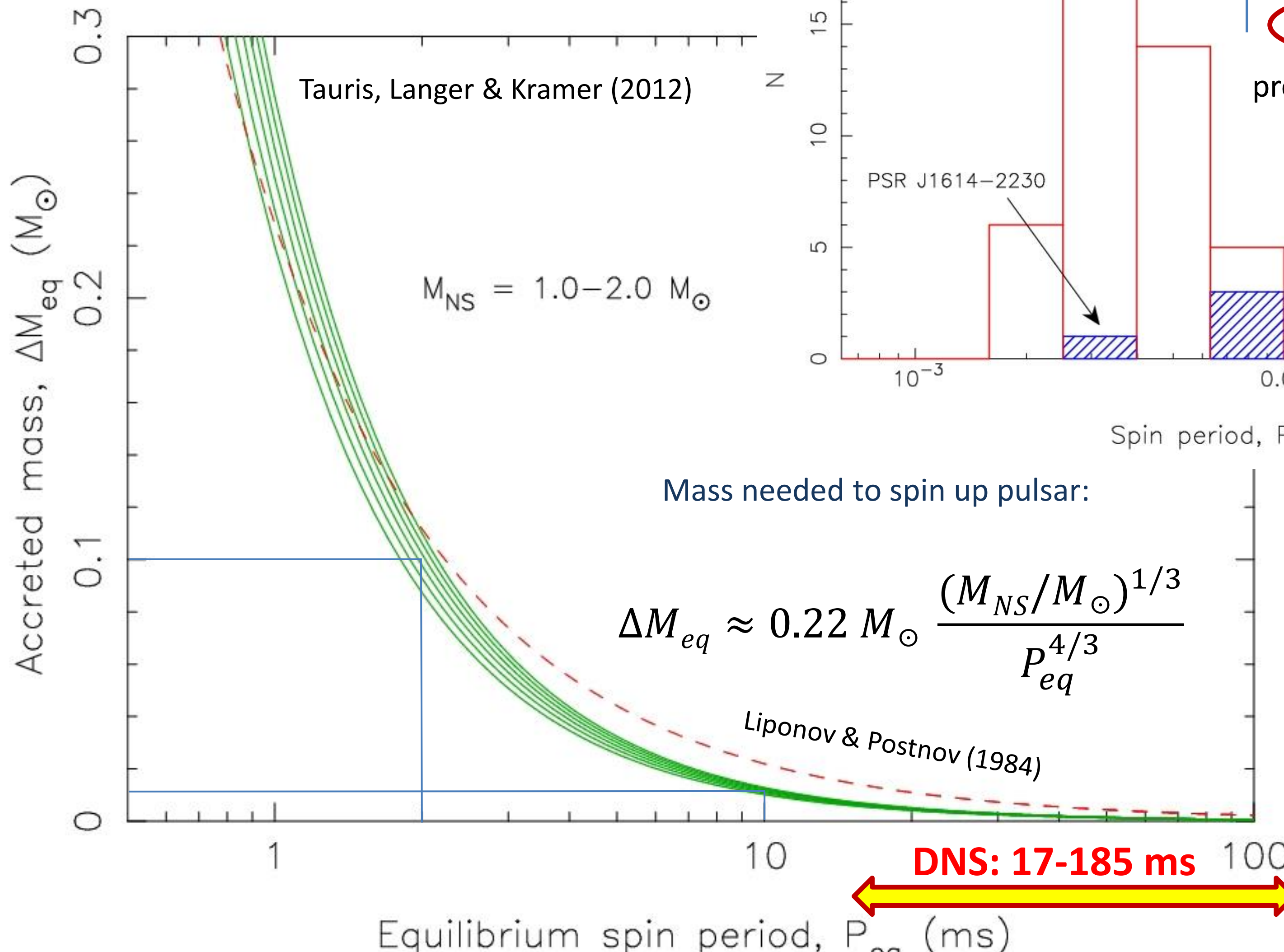
→ new episode of mass transfer

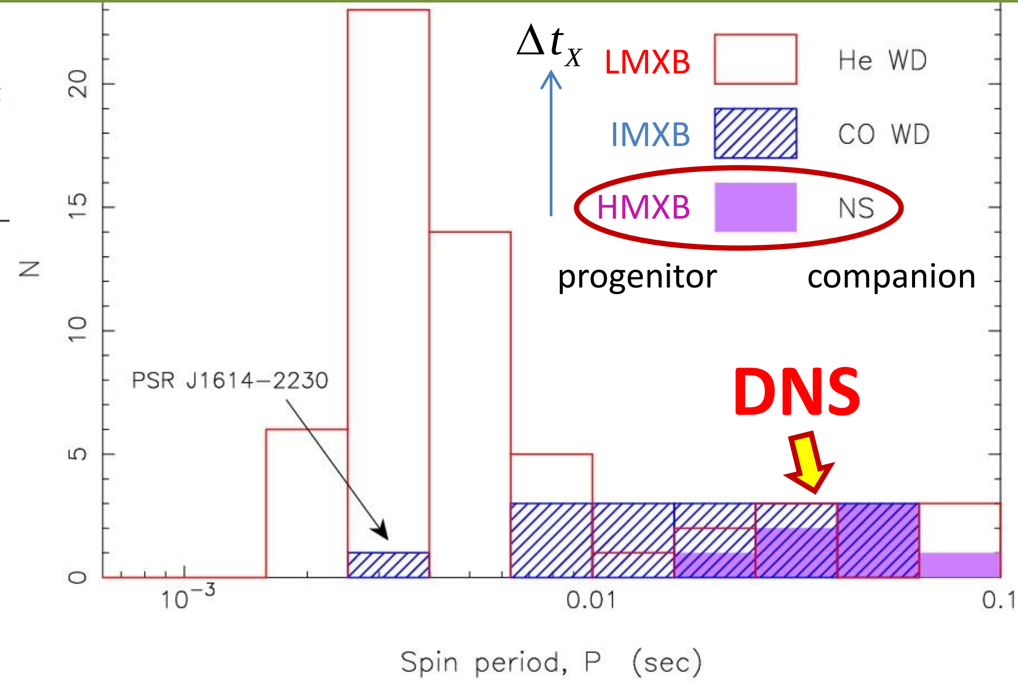
Case BB RLO

- i) accretion onto neutron star
  (recycling to high spin freq.)
- ii) stripping of donor star

Recycled Pulsars in DNS systems - amount of accreted mass

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





Mass needed to spin up pulsar:

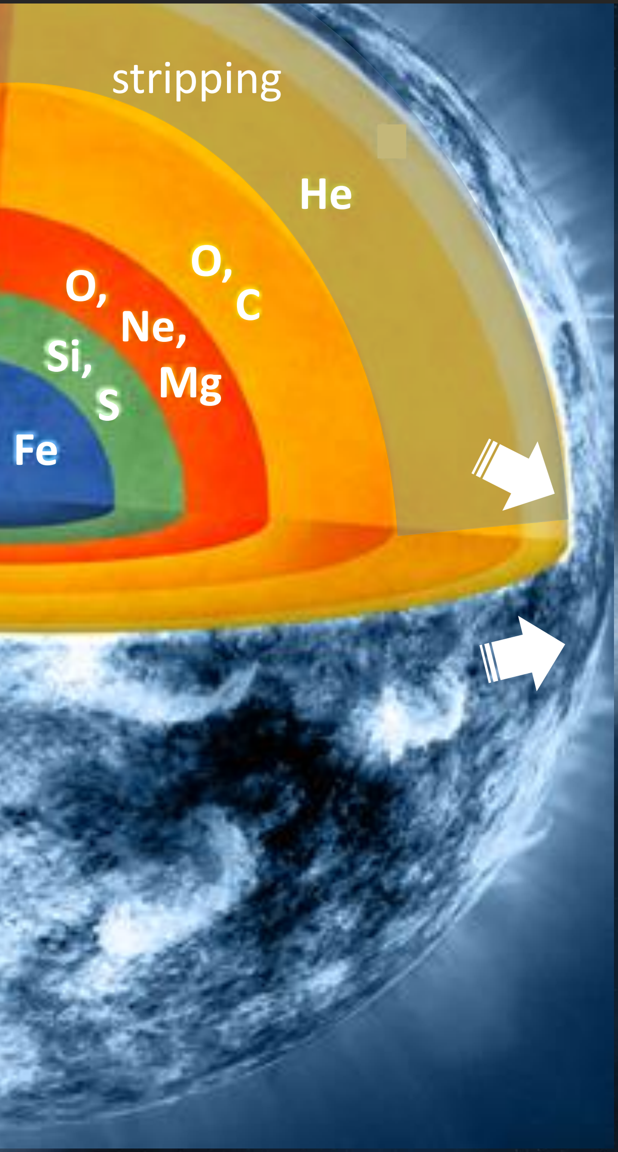
$$\Delta M_{eq} \approx 0.22\, M_\odot \frac{(M_{NS}/M_\odot)^{1/3}}{P_{eq}^{4/3}}$$

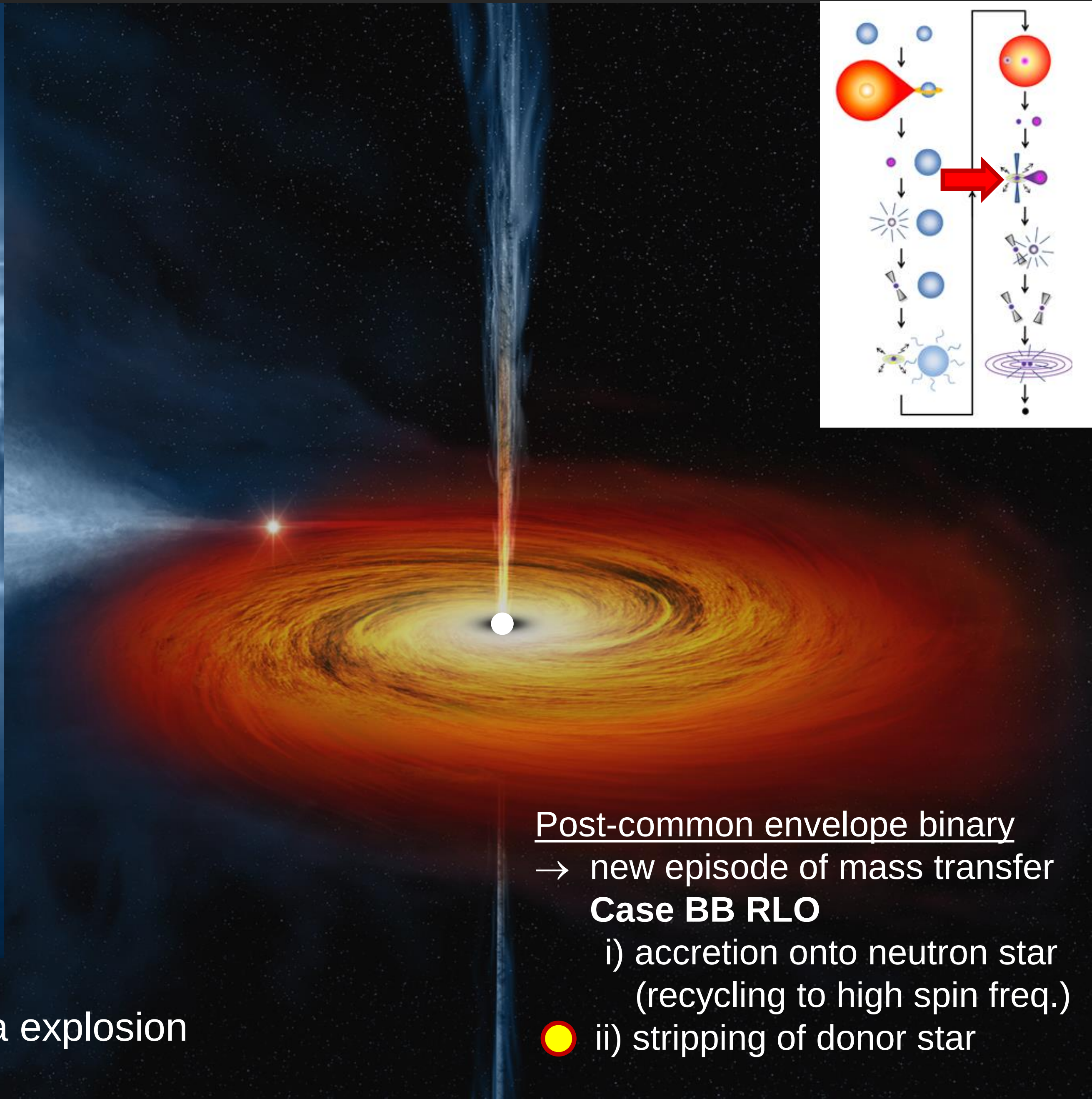
P (ms)	**M** ($M_\odot$)
0.7	0.40
2	0.10
5	0.03
10	0.01
50	0.001

Accreted just a few 0.001-0.01 $M_\odot$

Radio Pulsar	Type	P (ms)	$\dot{P}$ (10^{-18})	B (10^9 G)	P_{orb} (days)	e	M_{psr} ($M_\odot$)	M_{comp} ($M_\odot$)	M_{total} ($M_\odot$)
J0453+1559[a]	recycled	45.8	0.186	1.1	4.072	0.113	1.559	1.174	2.734
J0509+3801[b]	recycled	76.5	7.93	7.2	0.380	0.586	~ 1.34	~ 1.46	2.805
J0737−3039A[c]	recycled	22.7	1.76	1.8	0.102	0.088	1.338	1.249	2.587
J0737−3039B[c]	young	2773.5	892	410	−‖−	−‖−	1.249	1.338	−‖−
J1411+2551[d]	recycled	62.5	0.0956	0.66	2.616	0.170	< 1.62	> 0.92	2.538
J1518+4904[e]	recycled	40.9	0.0272	0.33	8.634	0.249	***	***	2.718
B1534+12[f]	recycled	37.9	2.42	2.8	0.421	0.274	1.333	1.346	2.678
J1753−2240[g]	recycled	95.1	0.970	2.5	13.638	0.304	—	—	—
J1755−2550[h]*	young	315.2	—	270	9.696	0.089	—	> 0.40	—
J1756−2251[i]	recycled	28.5	1.02	1.6	0.320	0.181	1.341	1.230	2.570
J1757−1854[j]	recycled	21.5	2.63	2.2	0.184	0.606	1.338	1.395	2.733
J1811−1736[k]	recycled	104.2	0.901	2.7	18.779	0.828	< 1.64	> 0.93	2.57
J1829+2456[l]	recycled	41.0	0.0495	0.42	1.176	0.139	1.306	1.299	2.606
J1906+0746[m]*	young	144.1	20300	470	0.166	0.085	1.291	1.322	2.613
J1913+1102[n]	recycled	27.3	0.157	0.83	0.206	0.090	1.62	1.27	2.889
B1913+16[o]	recycled	59.0	8.63	7.3	0.323	0.617	1.440	1.389	2.828
J1930−1852[p]	recycled	185.5	18.0	16	45.060	0.399	< 1.32	> 1.30	2.59
J1946+2052[q]	recycled	17.0	0.92	1.0	0.078	0.064	< 1.31	> 1.18	2.50
J0514−4002A[r]*	GC	5.0	0.00070	0.016	18.79	0.888	~ 1.25	~ 1.22	2.473
J1807−2459B[s]*	GC	4.2	0.0823	0.18	9.957	0.747	1.366	1.206	2.572
B2127+11C[t]	GC	30.5	4.99	3.7	0.335	0.681	1.358	1.354	2.713

Tauris & van den Heuvel (2022)





Ultra-stripped supernova explosion

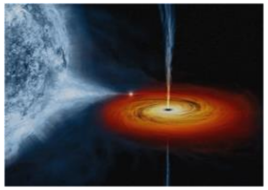
Post-common envelope binary

→ new episode of mass transfer

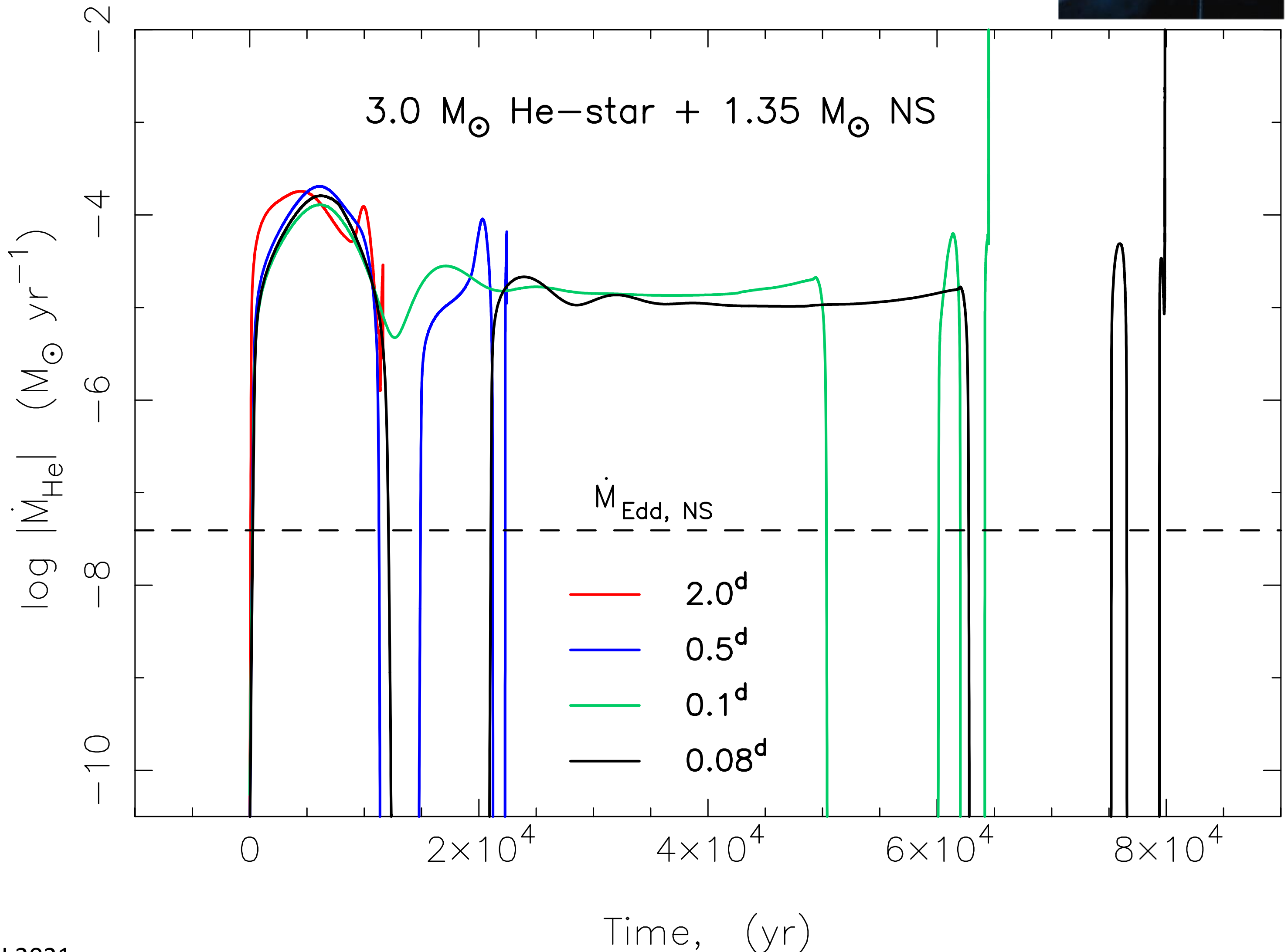
Case BB RLO

i) accretion onto neutron star (recycling to high spin freq.)

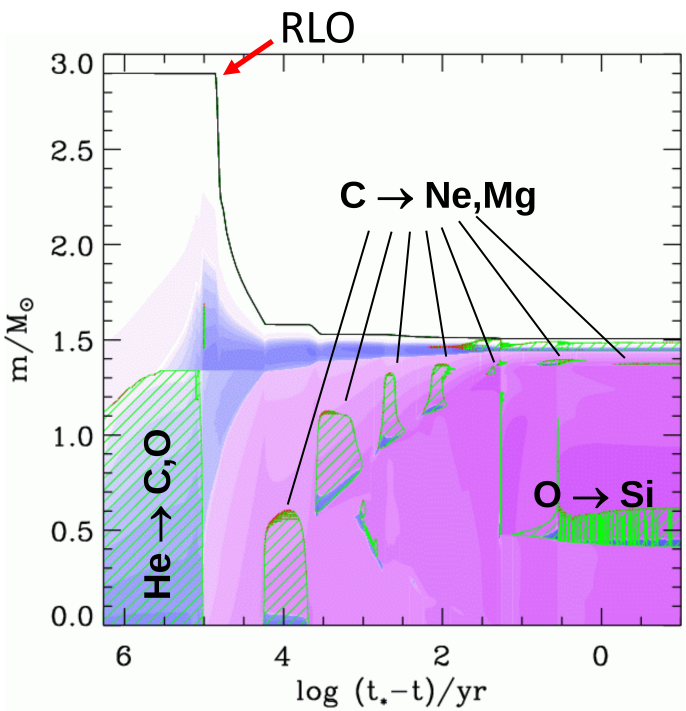
ii) stripping of donor star



Tauris, Langer & Podsiadlowski (2015)



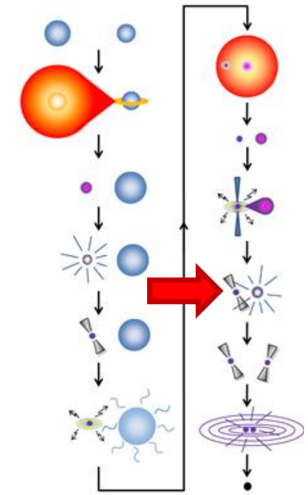
<u>All</u>* LIGO/Virgo double NS mergers are produced via **ultra-stripped SNe**



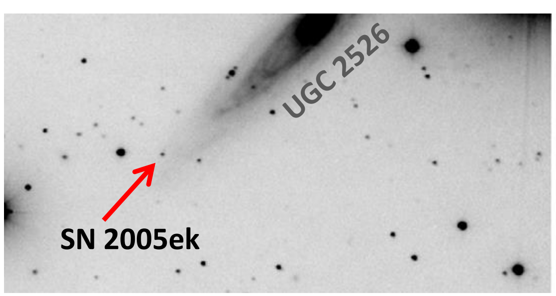
Models calculated for the first time.
We predict a new subclass of SNe
ultra-stripped SNe
with ejecta masses of ~ 0.1 M_{sun}

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

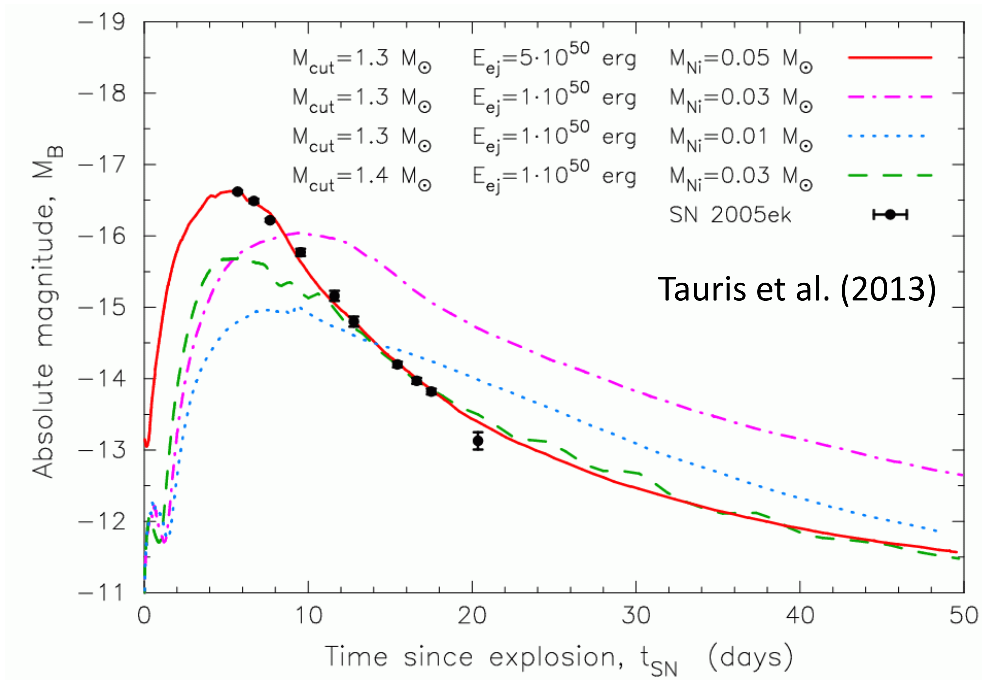
Suwa et al. (2015), MNRAS
Moriya et al. (2017), MNRAS — LCs + spectra
Newton, Steiner & Yagi (2018), ApJ
Müller et al. (2018, 2019), MNRAS — 3D explosion modelling



Observational evidence for ultra-stripped SNe…



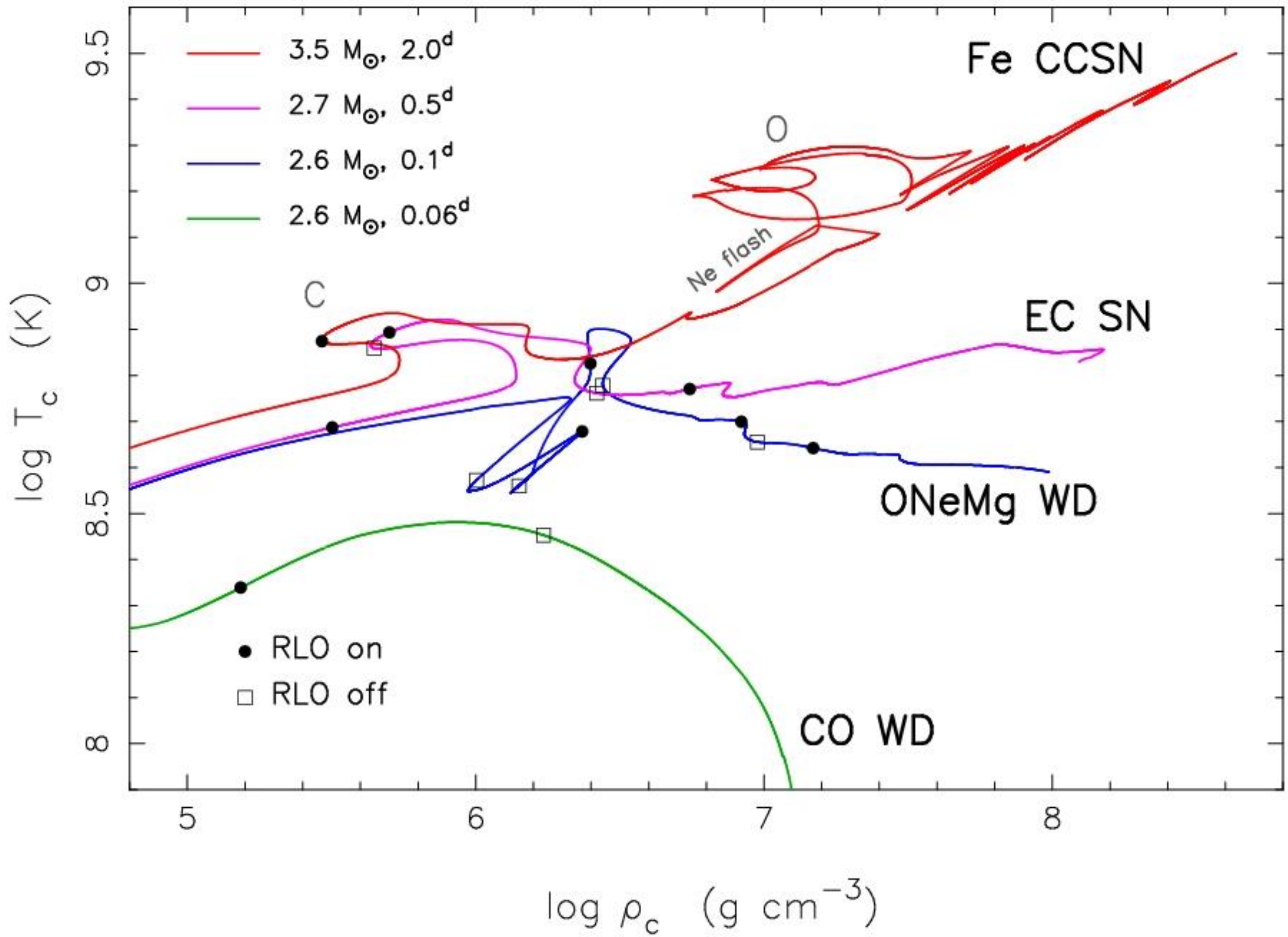
Drout et al. (2013), ApJ
De et al. (2018), Science



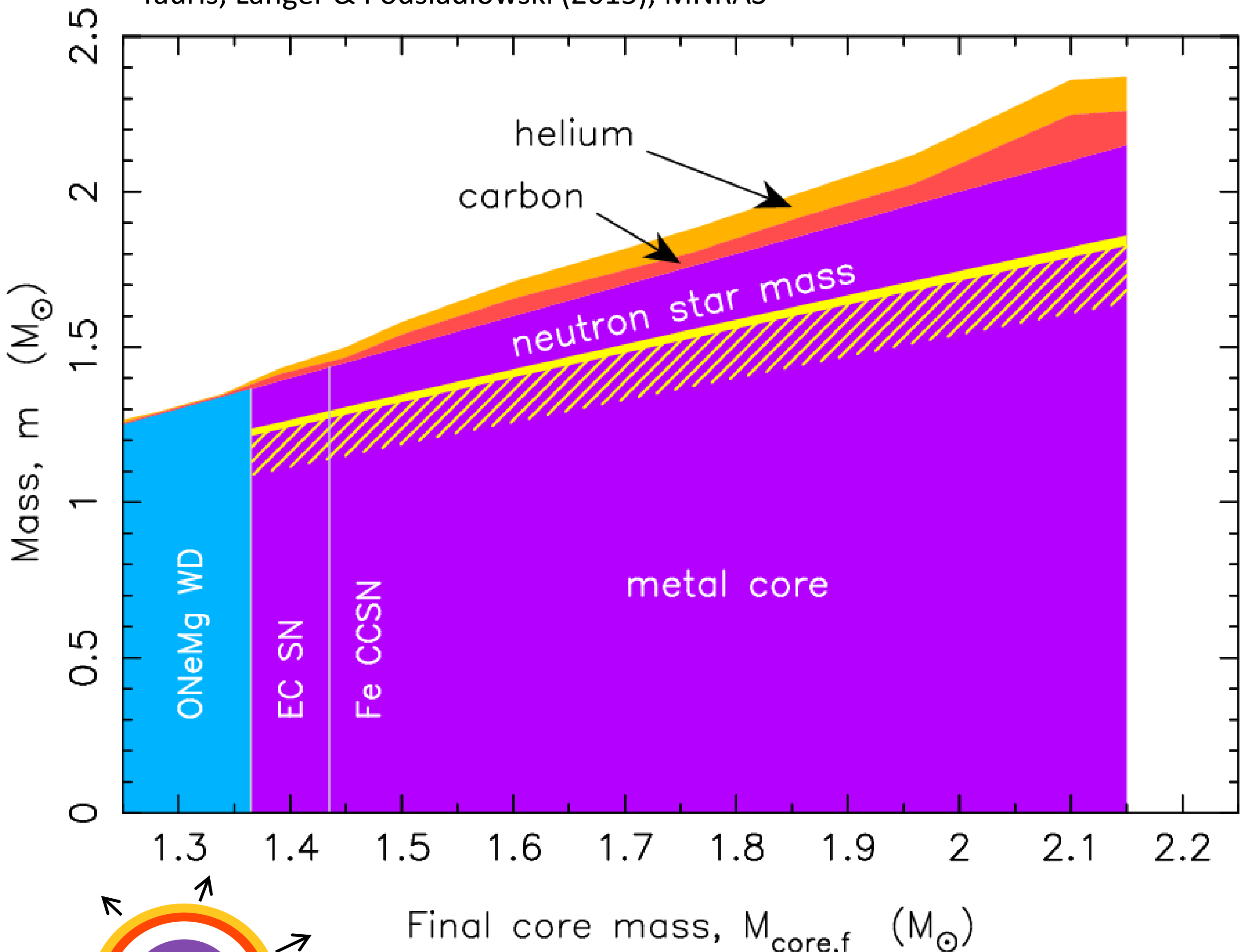
Fe CCSN versus EC SN

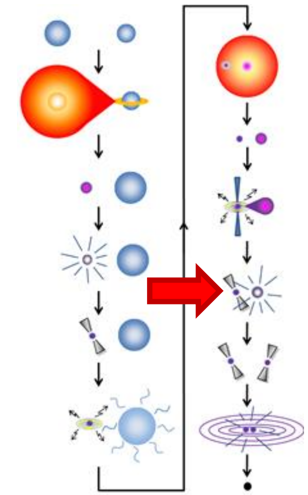
Takahashi et al. (2013)
Umeda et al. (2012)
Jones et al. (2013)

Tauris, Langer & Podsiadlowski (2015), MNRAS

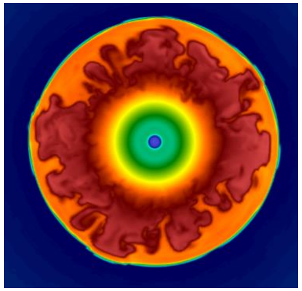


Tauris, Langer & Podsiadlowski (2015), MNRAS

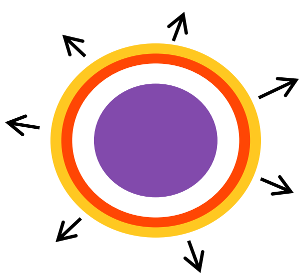




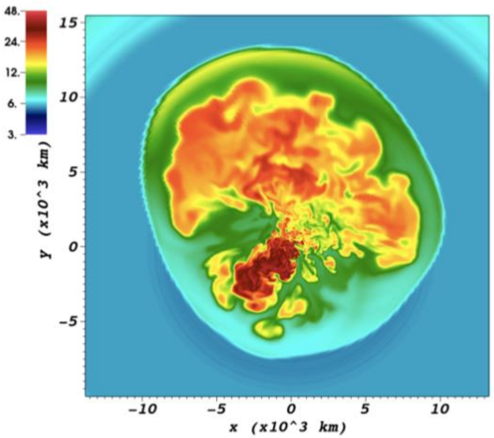
3-D simulations



Müller et al. (2018)
Müller et al. (2019)



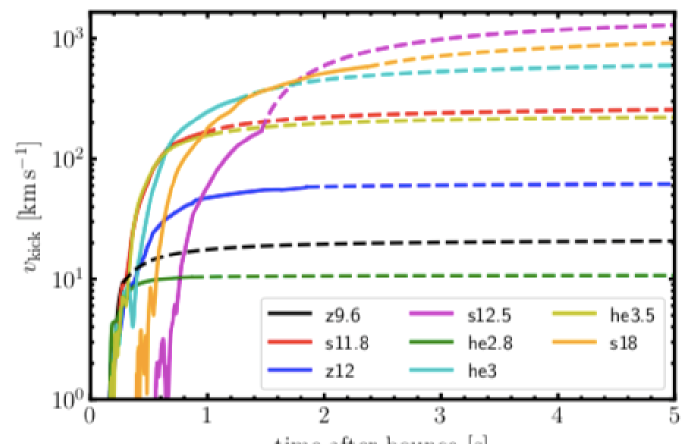
Tiny envelopes (loosely bound, little mass) often yield small SN kicks!



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

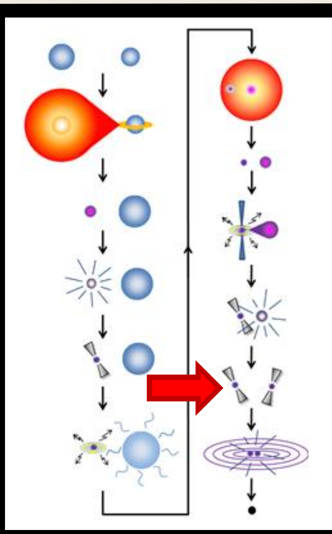


Example of **Ultra-stripped SN**
2.80 M_{sun} He-star stripped down to 1.49 M_{sun} prior to explosion (DNS progenitor)

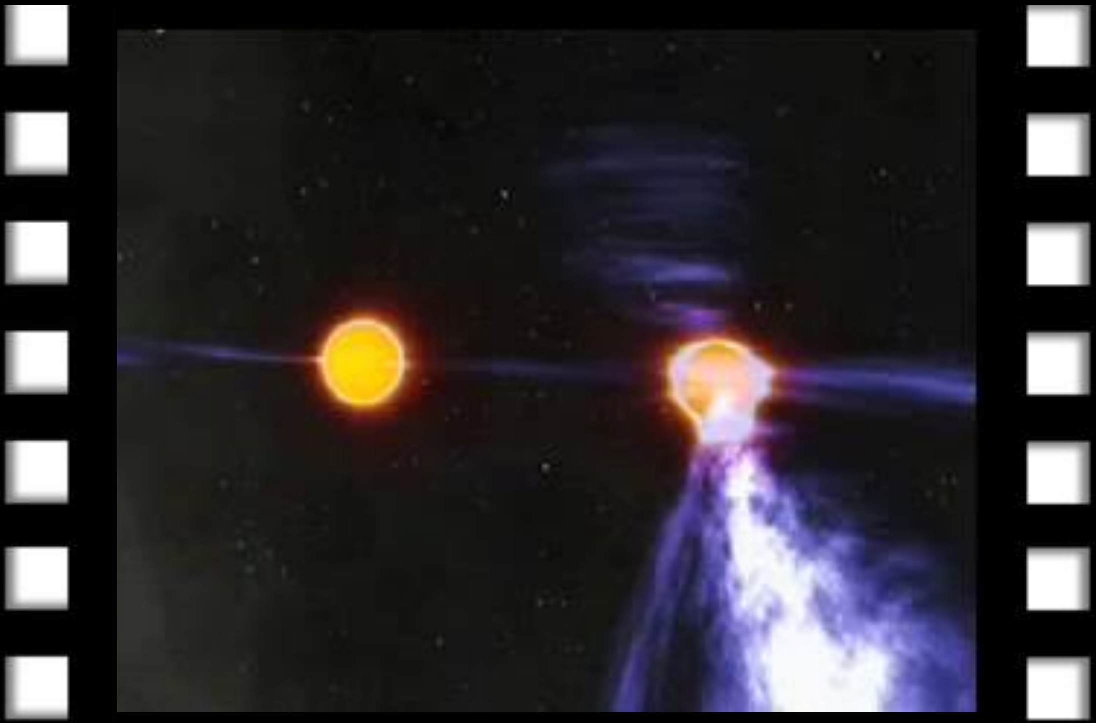
Model	t_{fin} (ms)	E_{expl} (10^{50} erg)	M_{IG} ($M_\odot$)	M_{by} ($M_\odot$)	M_{grav} ($M_\odot$)	v_{PNS} (km s^{-1})	$v_{PNS,ex}$ (km s^{-1})	P_{PNS} (ms)	α
z9.6	273	1.32	0.014	1.35	1.22	9.2	21	1060	48°
s11.8	963	1.99	0.024	1.35	1.23	164	278	152	64°
z12	1847	4.10	0.039	1.35	1.22	58	64	205	62°
s12.5	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°

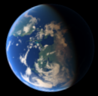
small kick

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.

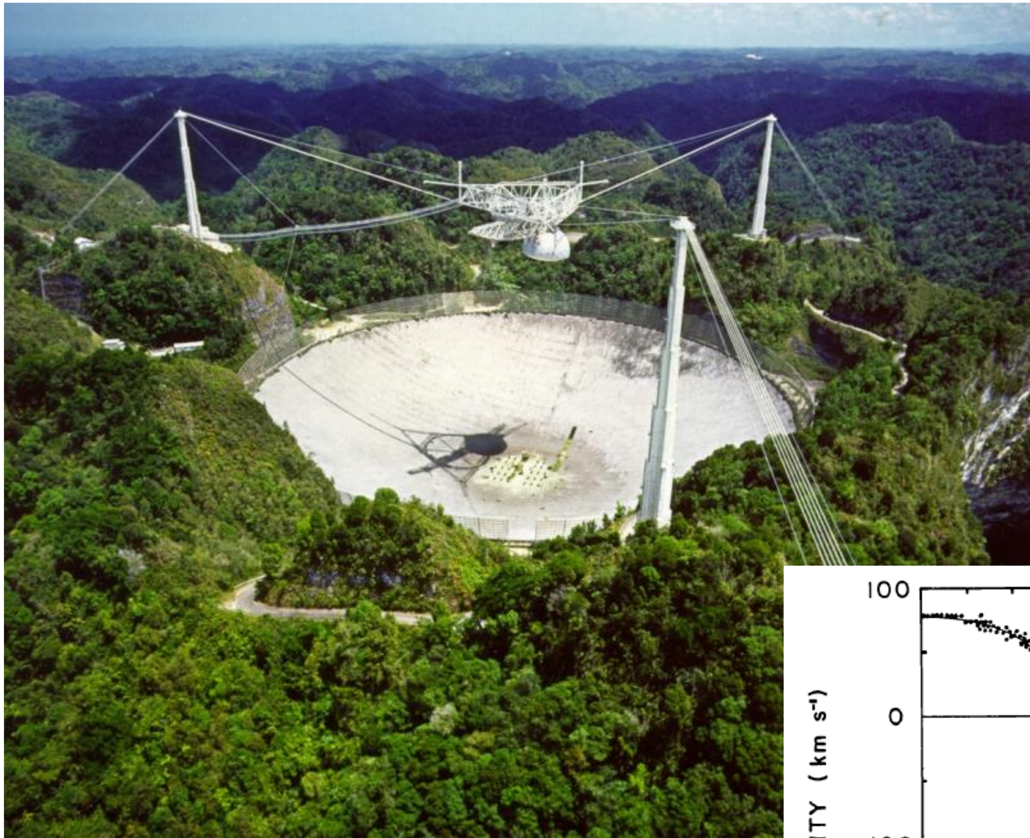


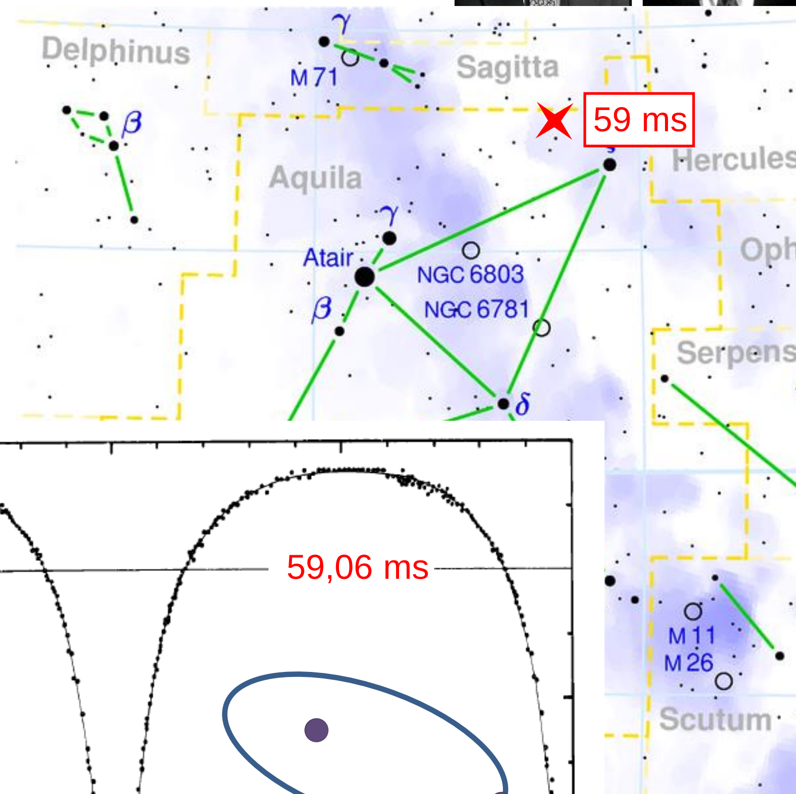
Burgay et al. (2003), Lyne et al. (2004), Kramer et al. (2006)

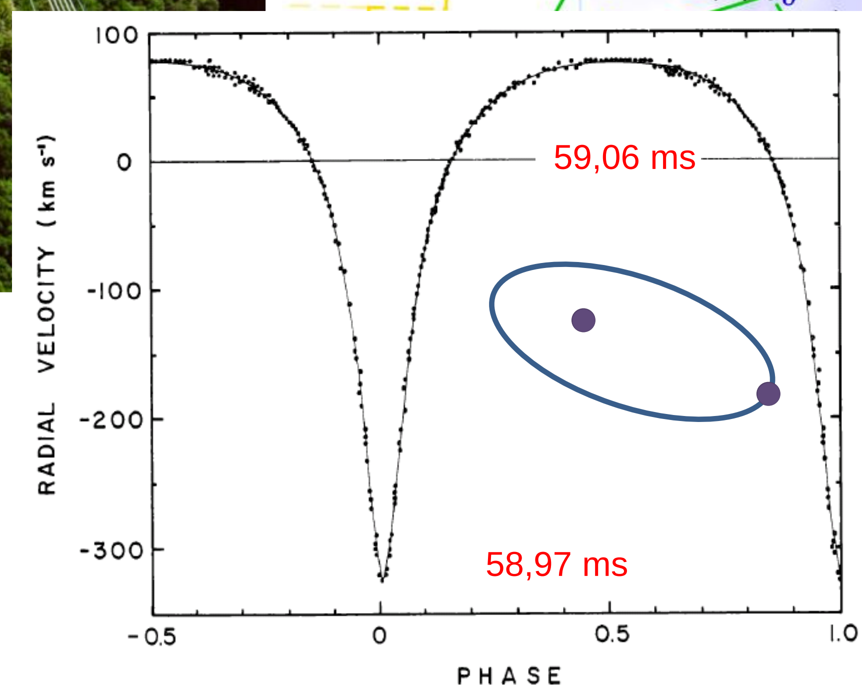




Pulsar J0737-3039A: P=22.7 ms
Pulsar J0737-3039B: P=2.77 sec







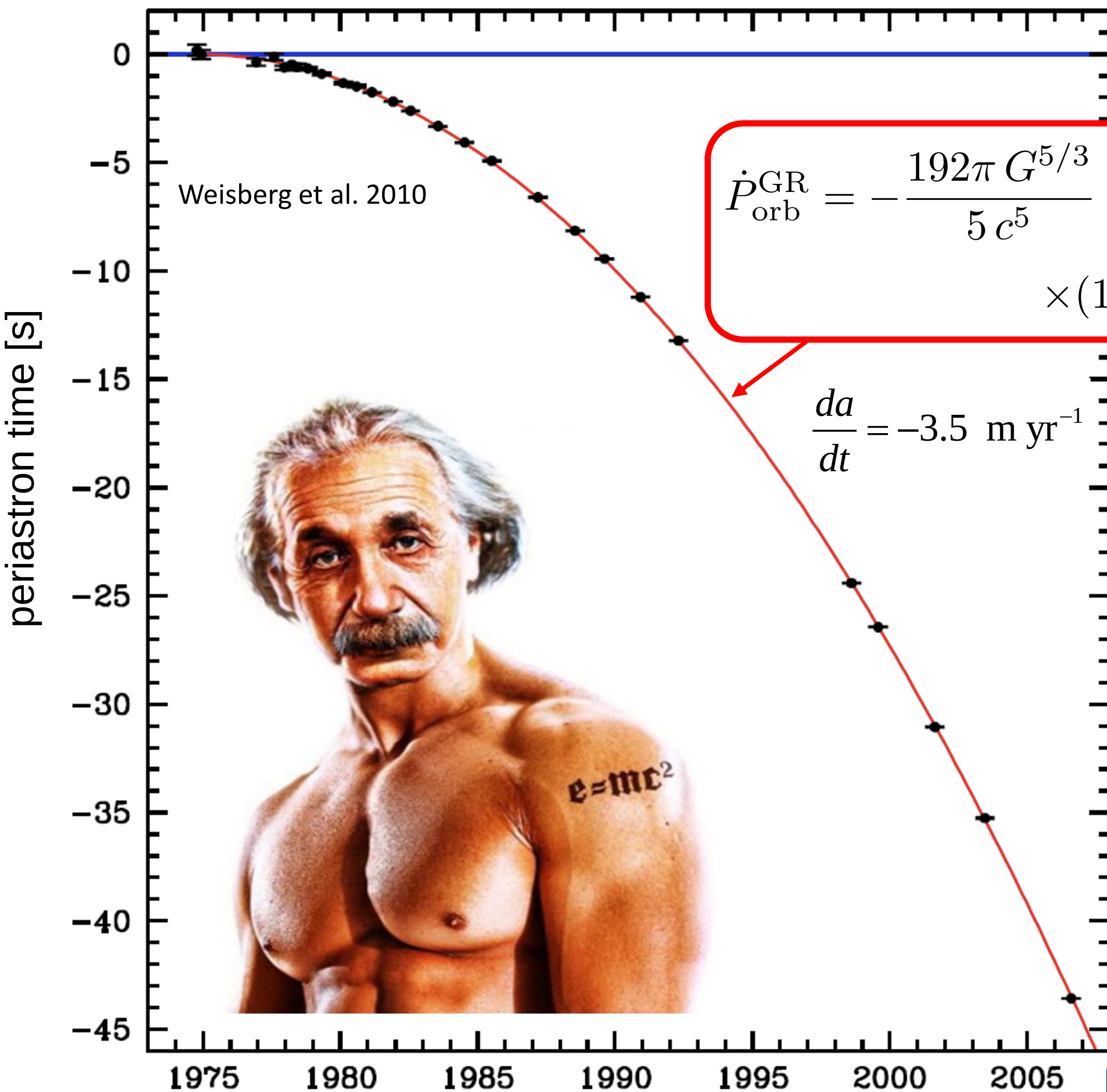
Pulse period: 59.0 ms

Orbital period: 7.75 h

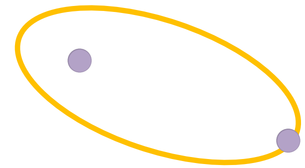
Eccentricity: 0.617

Companion: neutron star

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



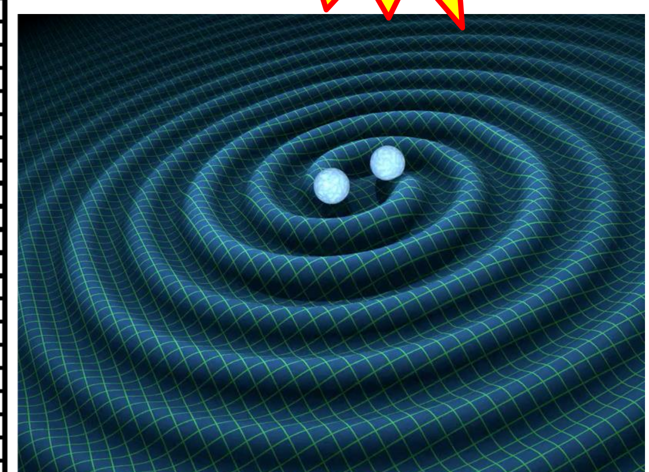
$$\frac{da}{dt} = -3.5 \text{ m yr}^{-1}$$



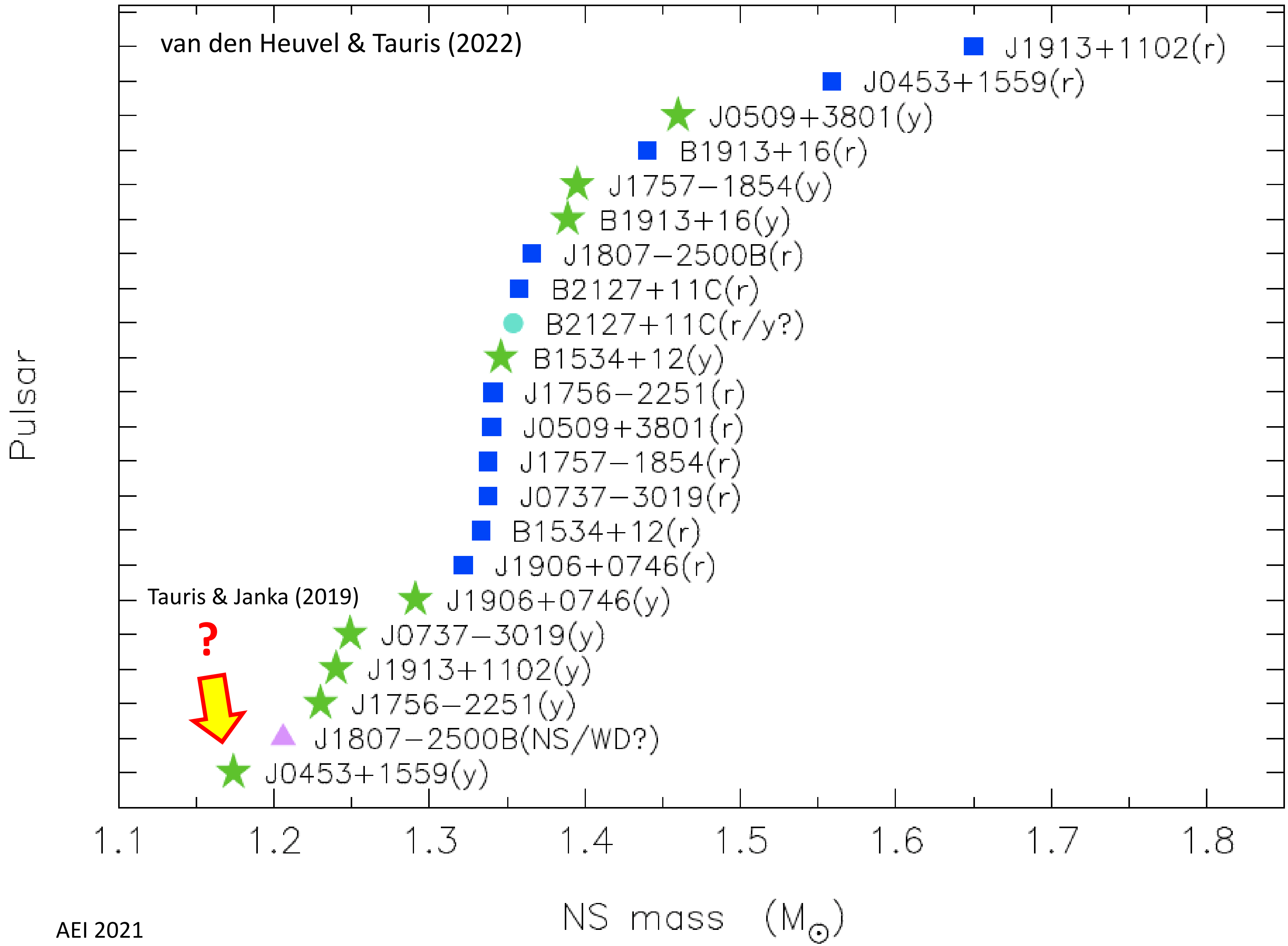
Peters (1964)

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

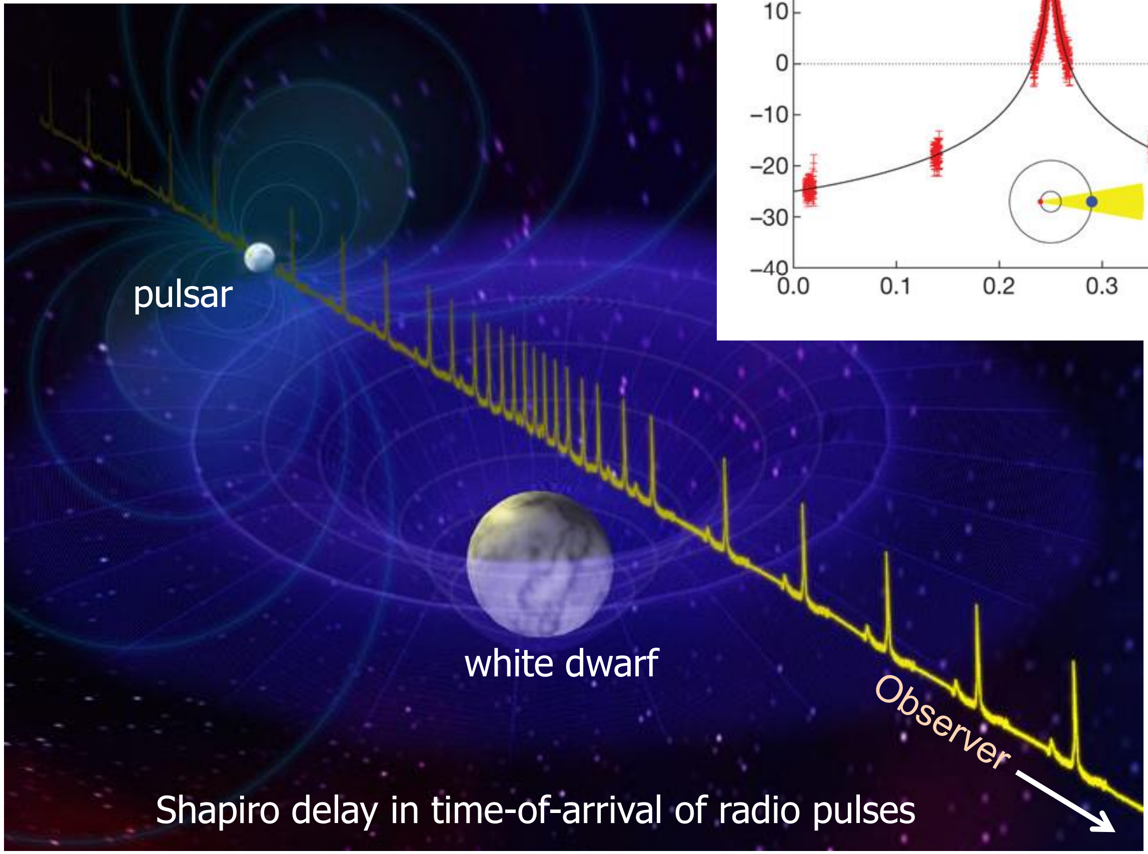
Merge in
τ = 301 Myr

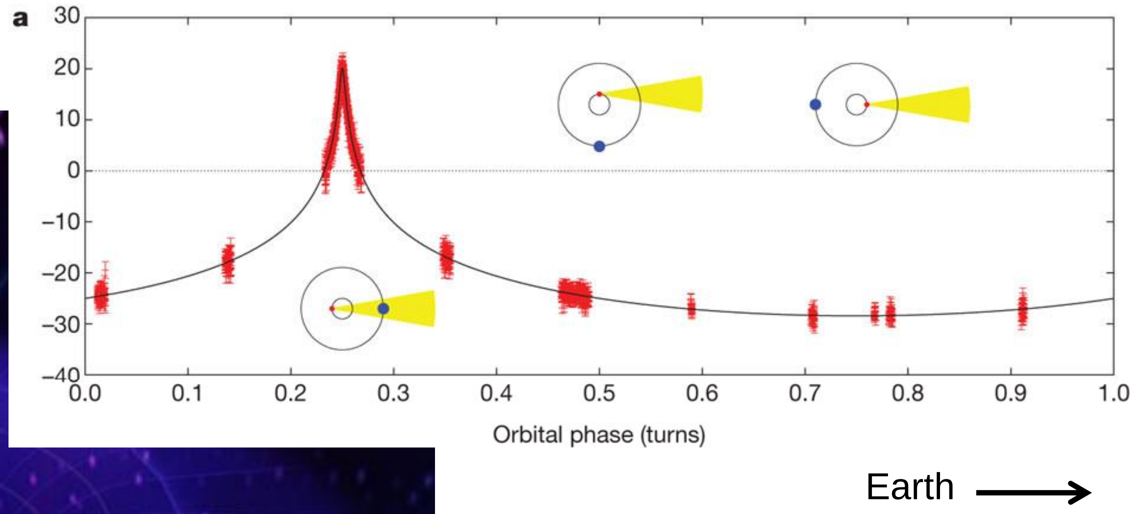


$L_{\rm GW} = 7\times 10^{24}$ W ($L_{{\rm GW},\odot} = 5000$ W)


van den Heuvel & Tauris (2022)
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)
Tauris & Janka (2019)
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☉)

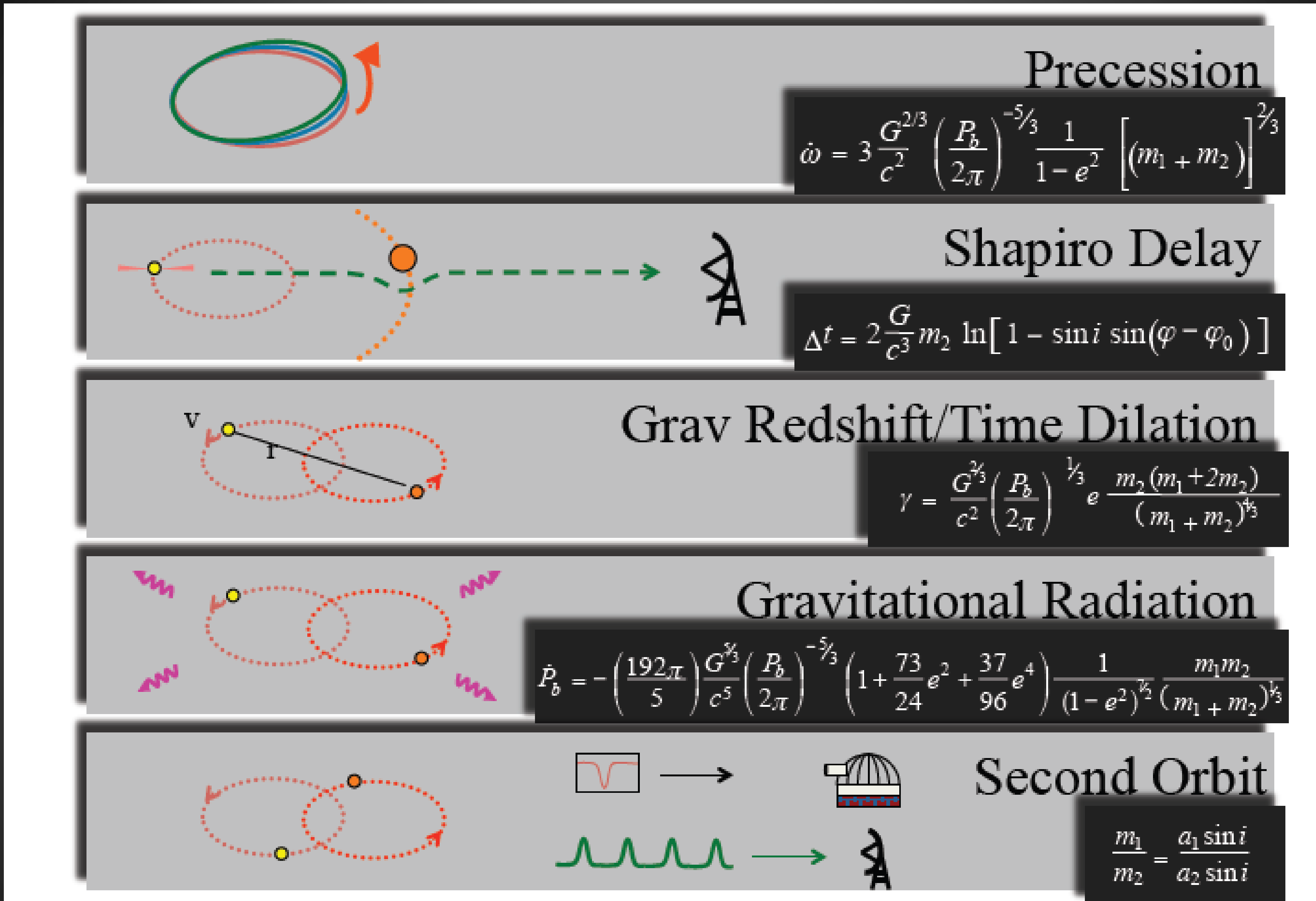
Moving atomic clocks in space!





Demorest et al. (2010)

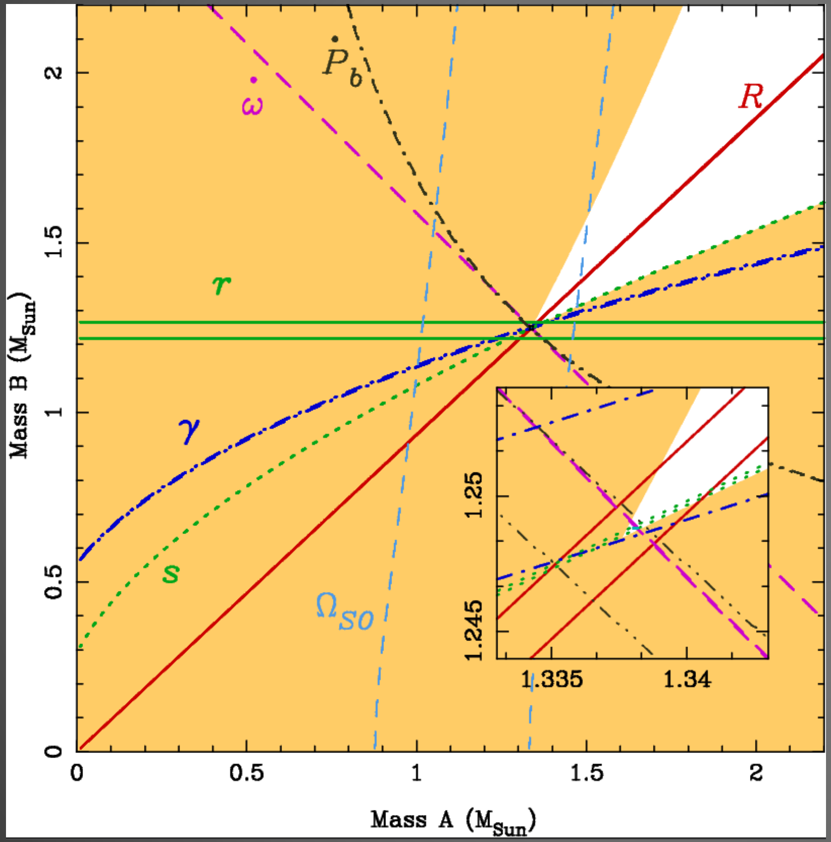
Pulsar mass:	1.97±0.04 M_{sun}
White dwarf mass:	0.500±0.006 M_{sun}
Orbital period:	8.69 days
Pulsar spin period:	3.15 ms

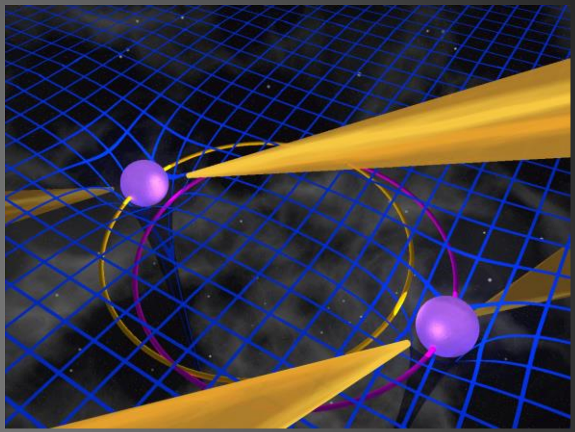


Any PK measurement yields a line in the (m_1,m_2)-plane.
Hence, two PK parametres determines m_1 and m_2 uniquely.

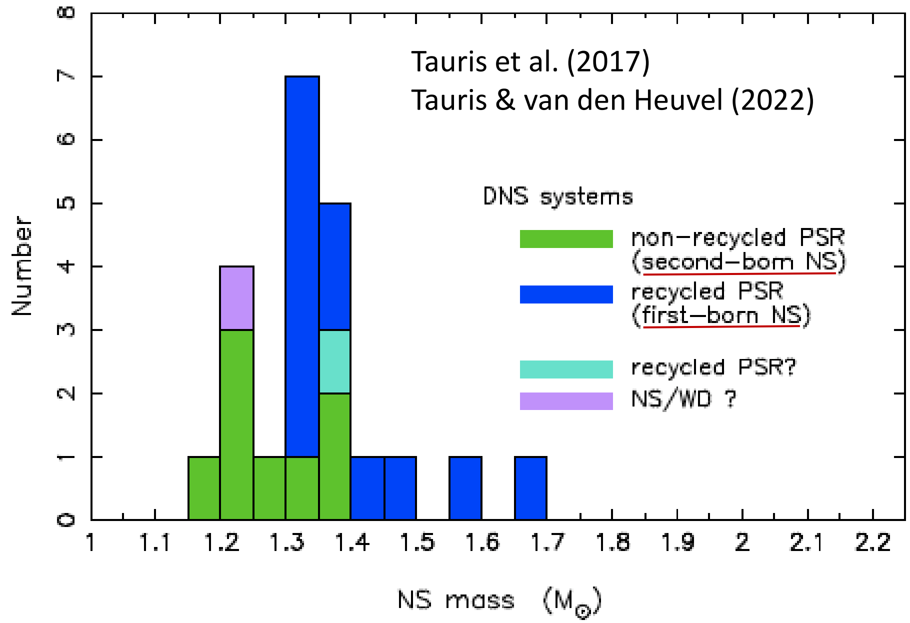
Neutron star masses

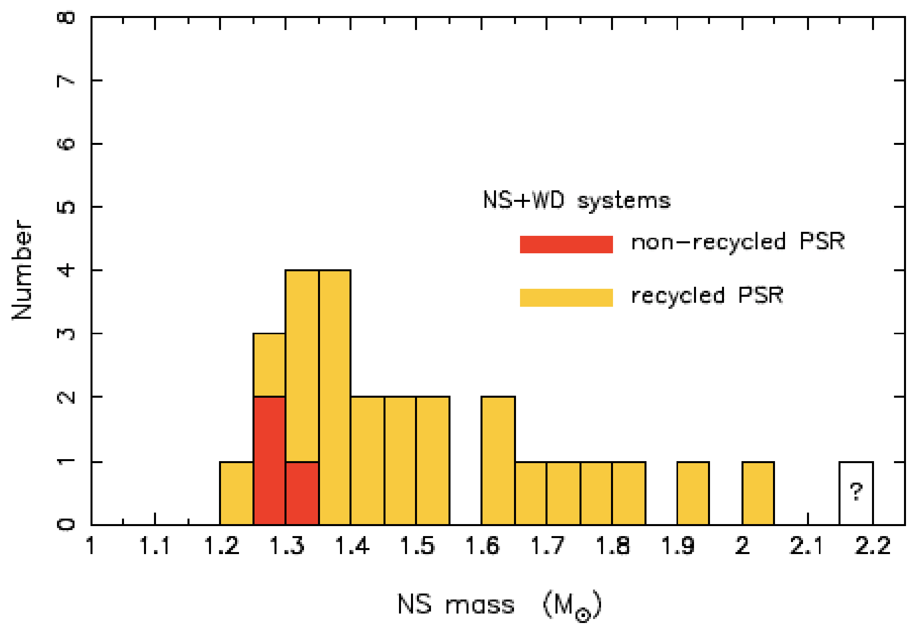
- The double pulsar PSR J0737-3039





Kramer et al. (2006)





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

⇓

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

There is a difference in birth masses of 1st and 2nd born NSs.

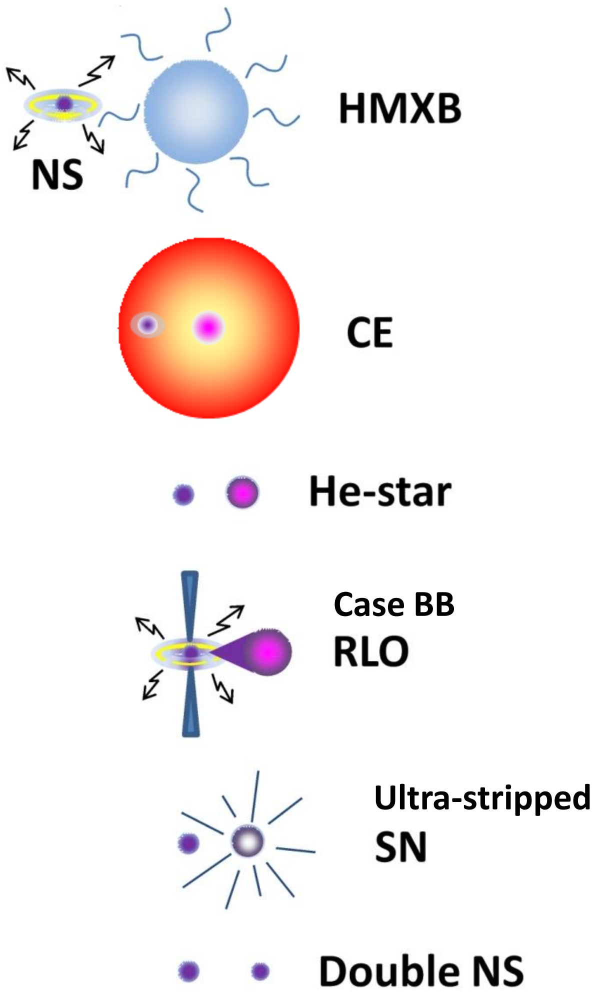
In NS+WD sytems produced via LMXBs, the accretion phase is much longer (up to several Gyr)

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

⇓

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

Observed mass distribution reflects spread in NS birth masses.



Accretion I — $\Delta M_{acc} \approx 3\times10^{-3}\ M_{\odot}$ Tauris et al. (2017)

+

Accretion II — $\Delta M_{acc} \ll 0.1\ M_{\odot} \quad (\sim 0.01\ M_{\odot})$ MacLeod & Ramirez-Ruiz (2015a,b)

+

Accretion III — $\Delta M_{acc} \approx 4\times10^{-4}\ M_{\odot}$ Tauris et al. (2017)

+

Accretion IV — $\Delta M_{acc} \approx 5\times10^{-5} - 3\times10^{-3}\ M_{\odot}$ Tauris, Langer & Podsiadlowski (2015)

+

Accretion V — $\Delta M_{acc} \ll 10^{-3}\ M_{\odot}$ Fryer et al. (2014)

In total $\Delta M_{acc} \leq 0.02\ M_{\odot}$

Wind accretion from (WR) He-stars

$$\dot{M}_{NS} \approx \pi R_{acc}^2 \rho v_{rel}$$

$$R_{acc} = \frac{2GM_{NS}}{v_{rel}^2 + c_s^2} \quad \wedge \quad v_{rel}^2 = v_{orb}^2 + v_{vind}^2$$

$$v_{wind} \approx v_{esc} = \sqrt{2GM_{He} / R_{He}} > 10^3 \; km\, s^{-1} \quad (v_{wind} \gg v_{orb})$$

$$v_{wind} > c_s \quad c_s = \sqrt{\gamma \frac{P}{\rho}} \approx 10 \left(\frac{T}{10^4 \; K} \right)^{1/2} km\, s^{-1}$$

$$\dot{M}_{He} \approx 4\pi a^2 \rho v_{rel}$$

$$\Rightarrow \quad \dot{M}_{NS} = \frac{(GM_{NS})^2}{a^2 v_{wind}^4} \dot{M}_{He}$$

$$\dot{M}_{NS} \approx 10^{-5} - 10^{-4} \dot{M}_{He}$$

$$M_{He} = 3.5 \, M_\odot \quad M_{NS} = 1.35 \, M_\odot$$

$$P_{orb} = 2.0 \, d \quad (a = 11.3 \, R_\odot)$$

$$v_{wind} = 500 - 1600 \, km\, s^{-1} \quad (10^3 \; km\, s^{-1})$$

$$\Rightarrow \quad \dot{M}_{He} \approx 5 \times 10^{-7} \; M_\odot \, yr^{-1}$$

$$\Rightarrow \quad \dot{M}_{NS} \approx 3 \times 10^{-10} \; M_\odot \, yr^{-1}$$

$$\Rightarrow \quad \Delta M_{NS} \approx 4 \times 10^{-4} \; M_\odot$$

Pejcha & Thompson (2015)

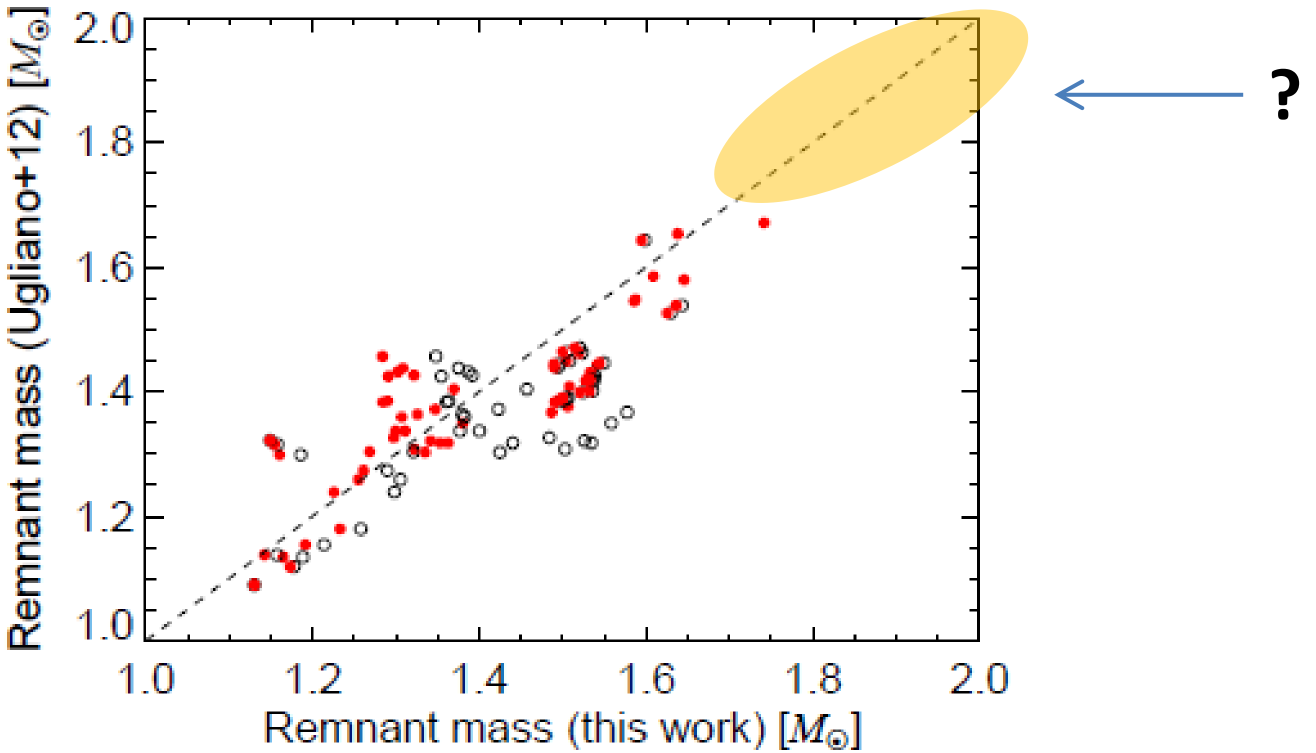
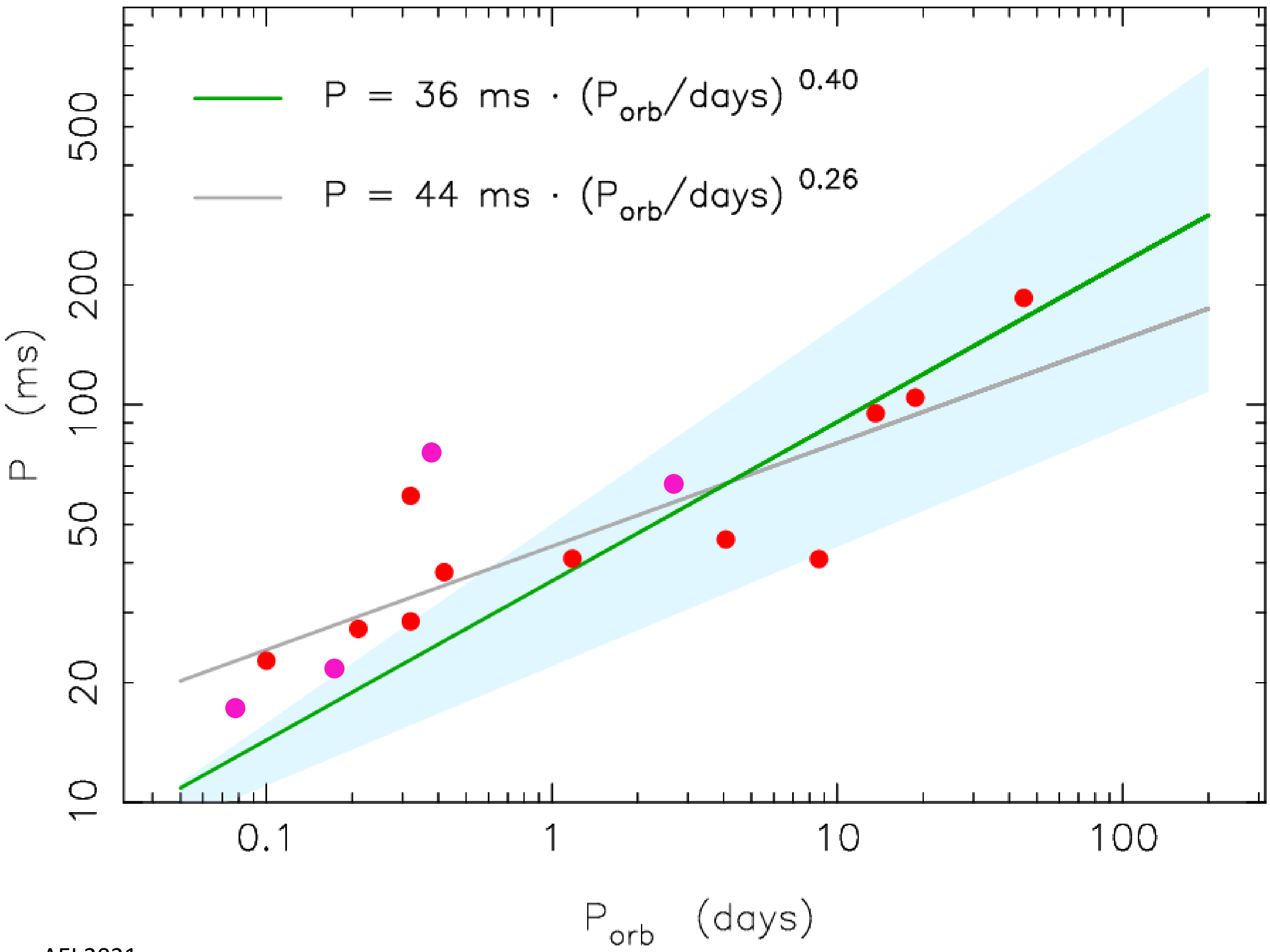


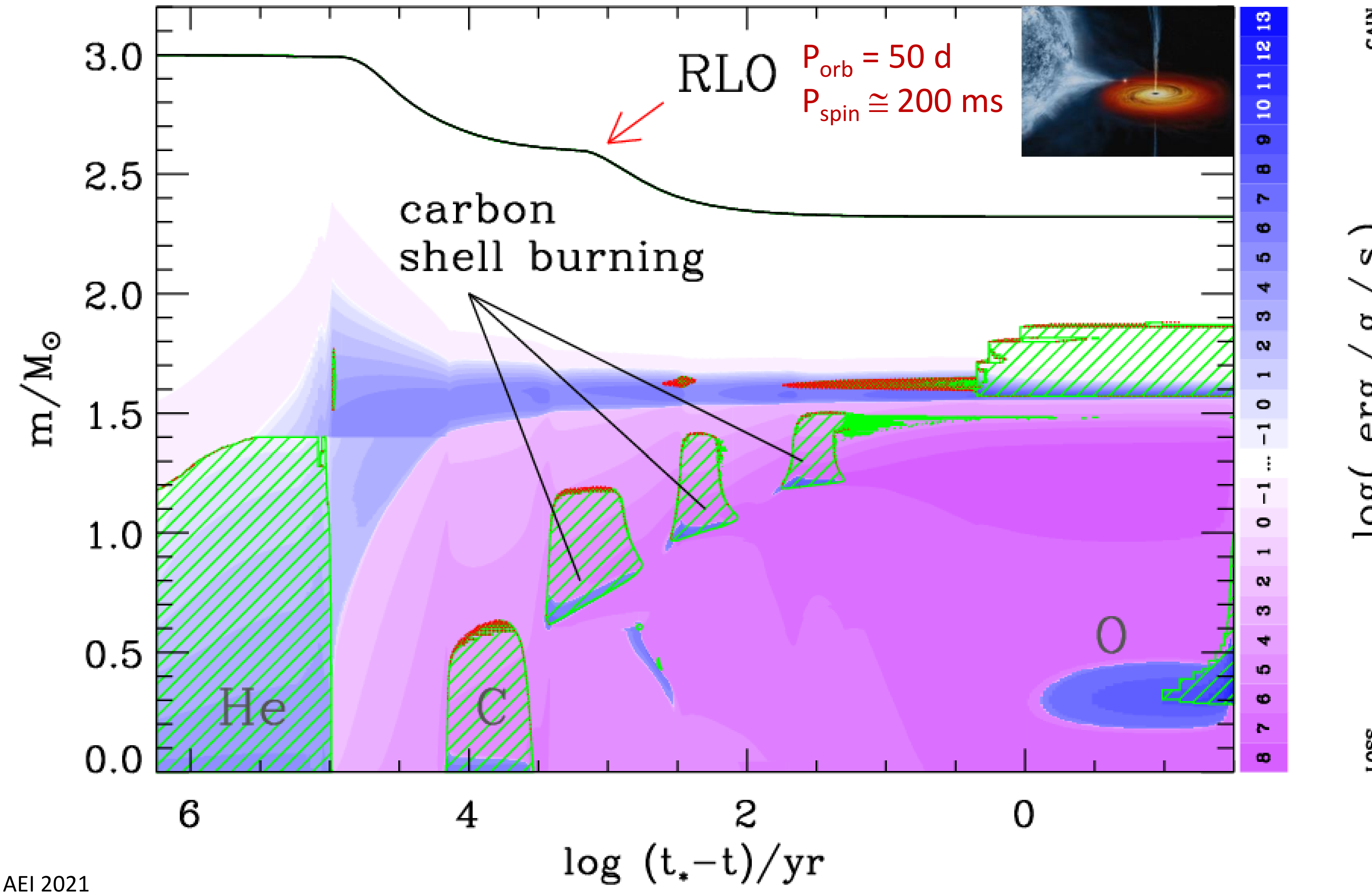
FIG. 18.— Comparison of gravitational neutron star masses without fall-back from Ugliano et al. (2012) and for our neutrino mechanism parameterizations (a) and (b) shown with open black and solid red circles, respectively.

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



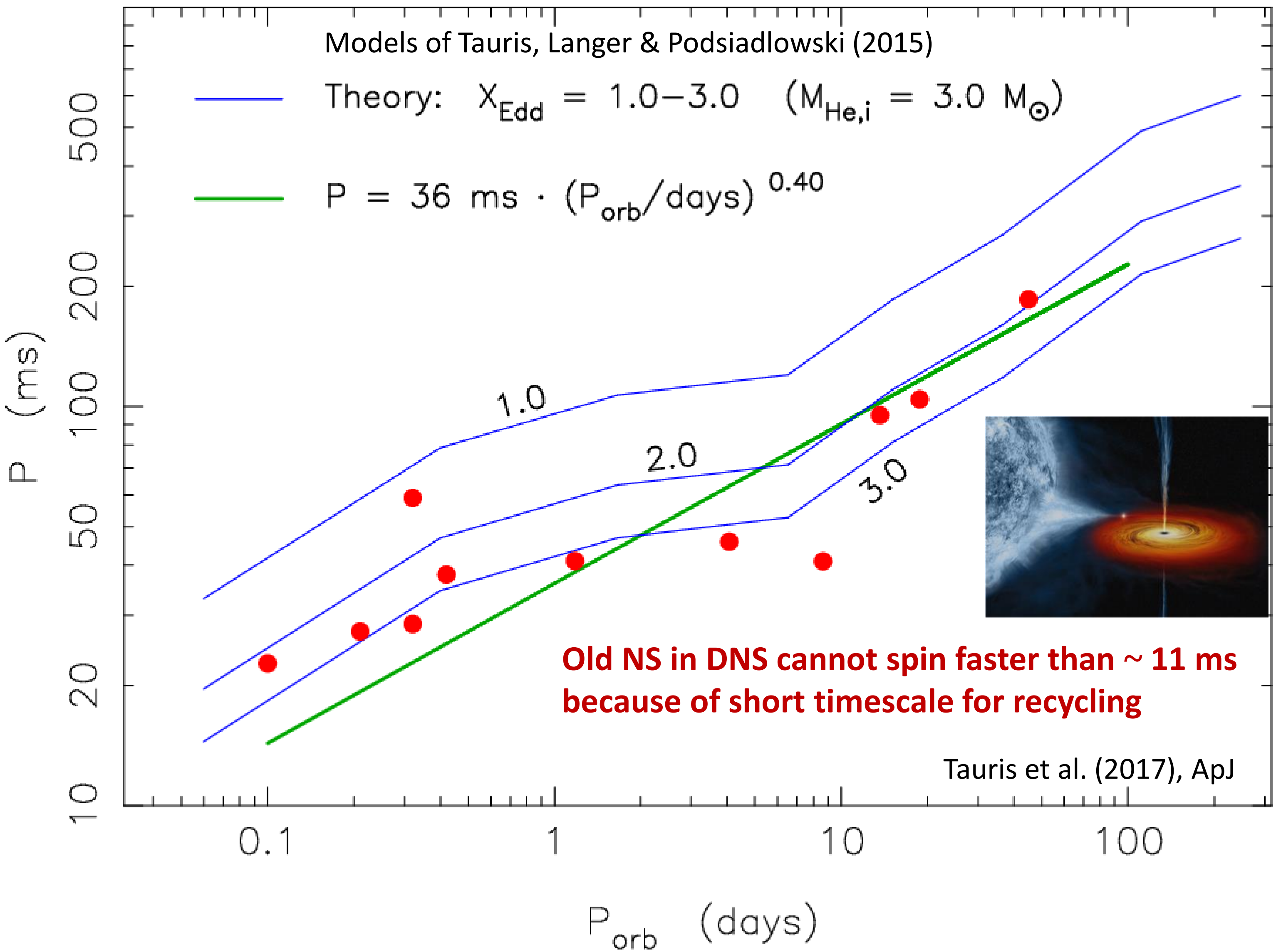
Tauris et al. (2017), ApJ

wide orbits start RLO very late → little recycling



Theoretical DNS correlations: P_{orb} and P_{spin}

Assuming <u>symmetric</u> SNe and <u>same</u> initial helium star donor

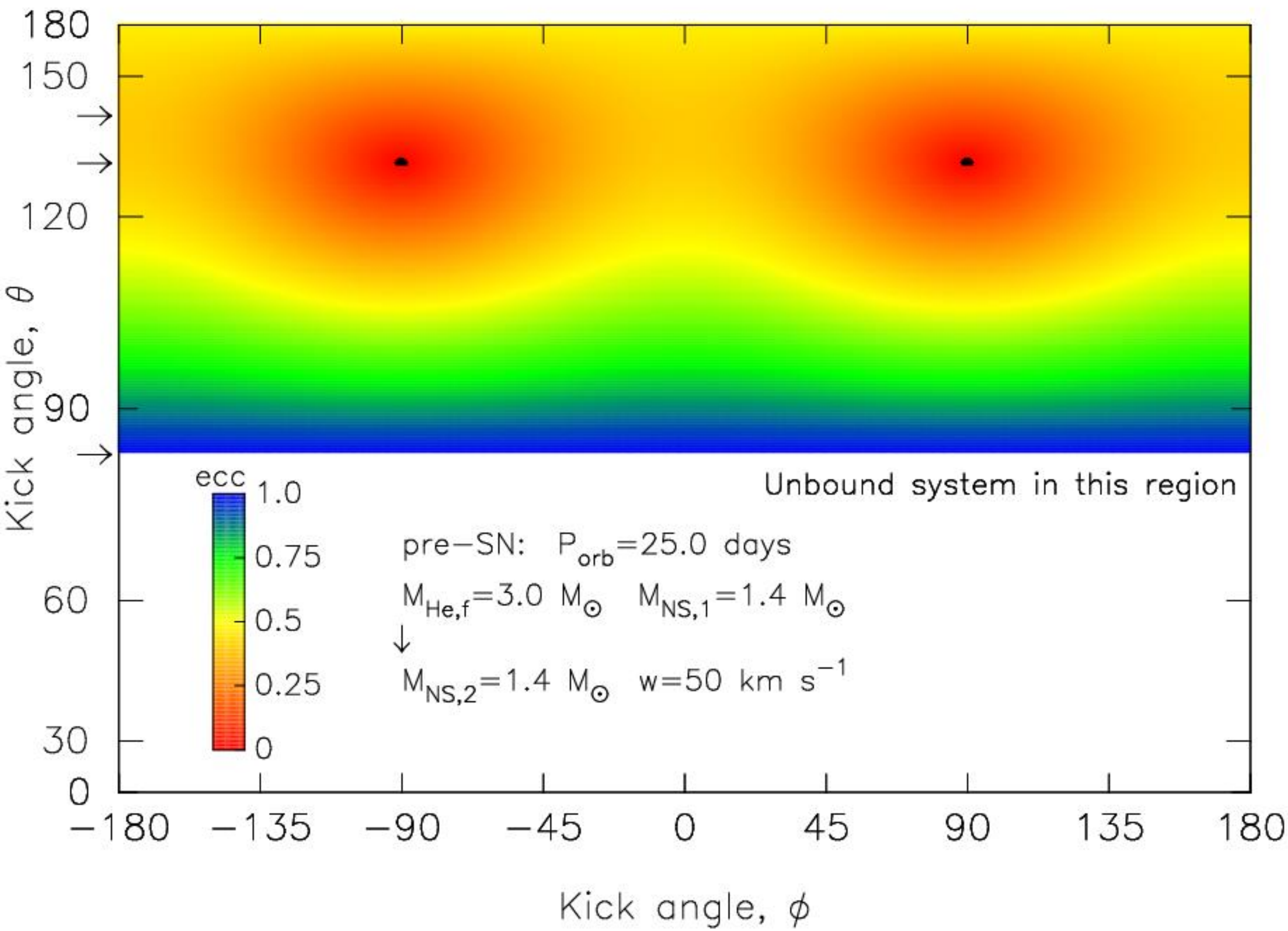


Tauris & van den Heuvel (2022)

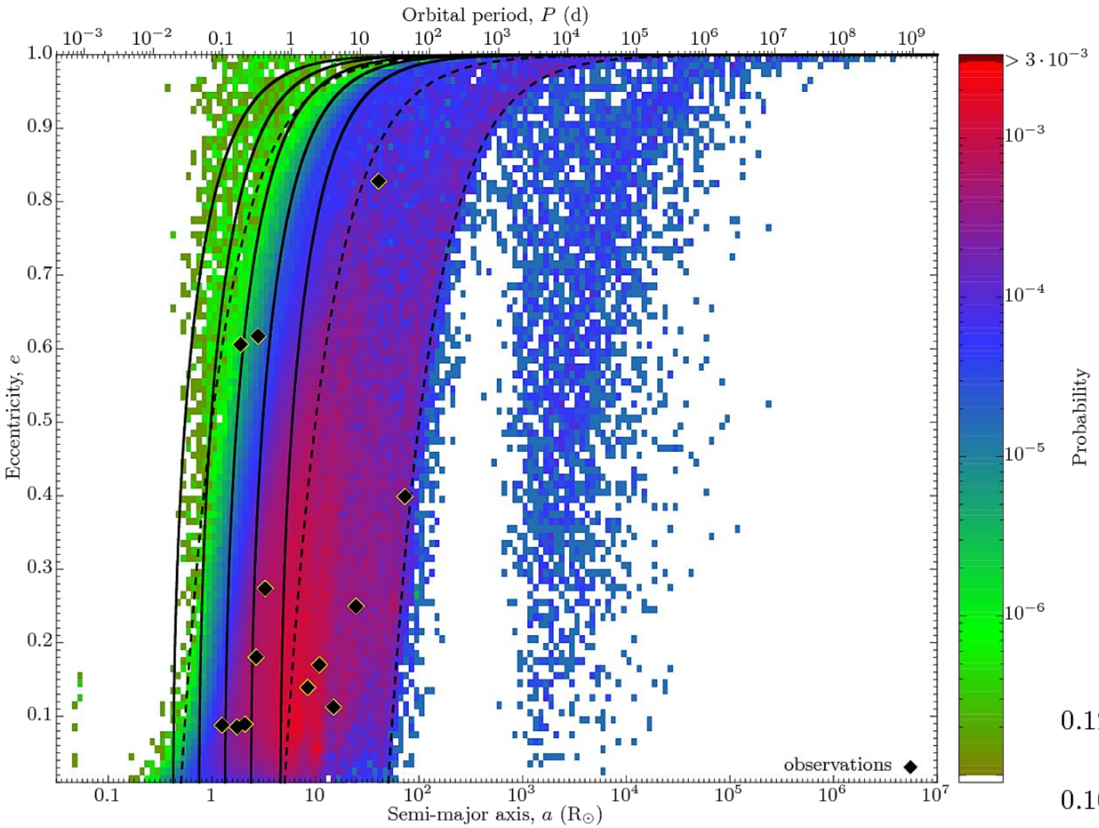
Table 14.5: Properties of 20 DNS systems with published data (including a few unconfirmed candidates).

Radio Pulsar	Type	P (ms)	$\dot{P}$ (10^{-18})	B (10^9 G)	P_{orb} (days)	e	M_{psr} ($M_\odot$)	M_{comp} ($M_\odot$)	M_{total} ($M_\odot$)	δ (deg)	Dist. (kpc)	v^{LSR}** (km s^{-1})	τ_{gwr} (Myr)
J0453+1559[a]	recycled	45.8	0.186	1.1	4.072	0.113	1.559	1.174	2.734	—	1.07	82	∞
J0509+3801[b]	recycled	76.5	7.93	7.2	0.380	0.586	∼ 1.34	∼ 1.46	2.805	—	1.56	—	579
J0737−3039A[c]	recycled	22.7	1.76	1.8	0.102	0.088	1.338	1.249	2.587	< 3.2	1.15	32	86
J0737−3039B[c]	young	2773.5	892	410	−‖−	−‖−	1.249	1.338	−‖−	130 ± 1	−‖−	−‖−	−‖−
J1411+2551[d]	recycled	62.5	0.0956	0.66	2.616	0.170	< 1.62	> 0.92	2.538	—	1.13	—	∞
J1518+4904[e]	recycled	40.9	0.0272	0.33	8.634	0.249	***	***	2.718	—	0.63	30	∞
B1534+12[f]	recycled	37.9	2.42	2.8	0.421	0.274	1.333	1.346	2.678	27 ± 3	1.05	143	2730
J1753−2240[g]	recycled	95.1	0.970	2.5	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	1.6	0.320	0.181	1.341	1.230	2.570	< 34	0.73	39****	1660
J1757−1854[j]	recycled	21.5	2.63	2.2	0.184	0.606	1.338	1.395	2.733	—	19.6	—	76
J1811−1736[k]	recycled	104.2	0.901	2.7	18.779	0.828	< 1.64	> 0.93	2.57	—	5.93	—	∞
J1829+2456[l]	recycled	41.0	0.0495	0.42	1.176	0.139	1.306	1.299	2.606	—	0.91	49	∞
J1906+0746[m]*	young	144.1	20300	470	0.166	0.085	1.291	1.322	2.613	—	7.40	—	309
J1913+1102[n]	recycled	27.3	0.157	0.83	0.206	0.090	1.62	1.27	2.889	—	—	—	471
B1913+16[o]	recycled	59.0	8.63	7.3	0.323	0.617	1.440	1.389	2.828	18 ± 6	9.80	241	301
J1930−1852[p]	recycled	185.5	18.0	16	45.060	0.399	< 1.32	> 1.30	2.59	—	1.5	—	∞
J1946+2052[q]	recycled	17.0	0.92	1.0	0.078	0.064	< 1.31	> 1.18	2.50	—	1.5	—	46
J0514−4002A[r]*	GC	5.0	0.00070	0.016	18.79	0.888	∼ 1.25	∼ 1.22	2.473	—	12.1	—	∞
J1807−2459B[s]*	GC	4.2	0.0823	0.18	9.957	0.747	1.366	1.206	2.572	—	3.0	—	∞
B2127+11C[t]	GC	30.5	4.99	3.7	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


180
150
120
90
60
30
0
Kick angle, θ
ecc
1.0
0.75
0.5
0.25
0
Unbound system in this region
pre−SN: P_orb=25.0 days
M_He,f=3.0 M⊙ M_NS,1=1.4 M⊙
↓
M_NS,2=1.4 M⊙ w=50 km s^−1
−180 −135 −90 −45 0 45 90 135 180
Kick angle, ϕ

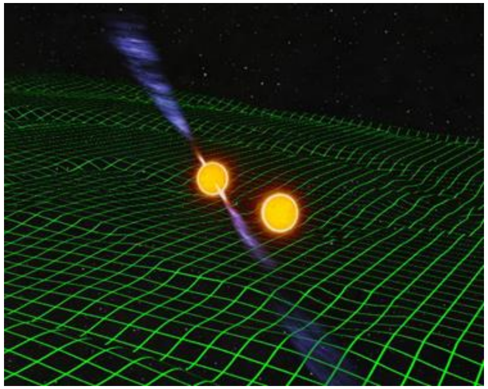
Eccentricity, e



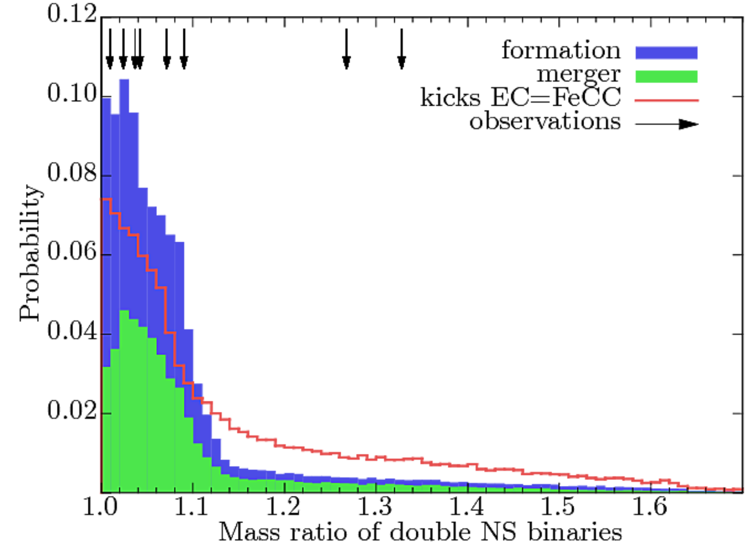
Semi-major axis, a (R_{sun})

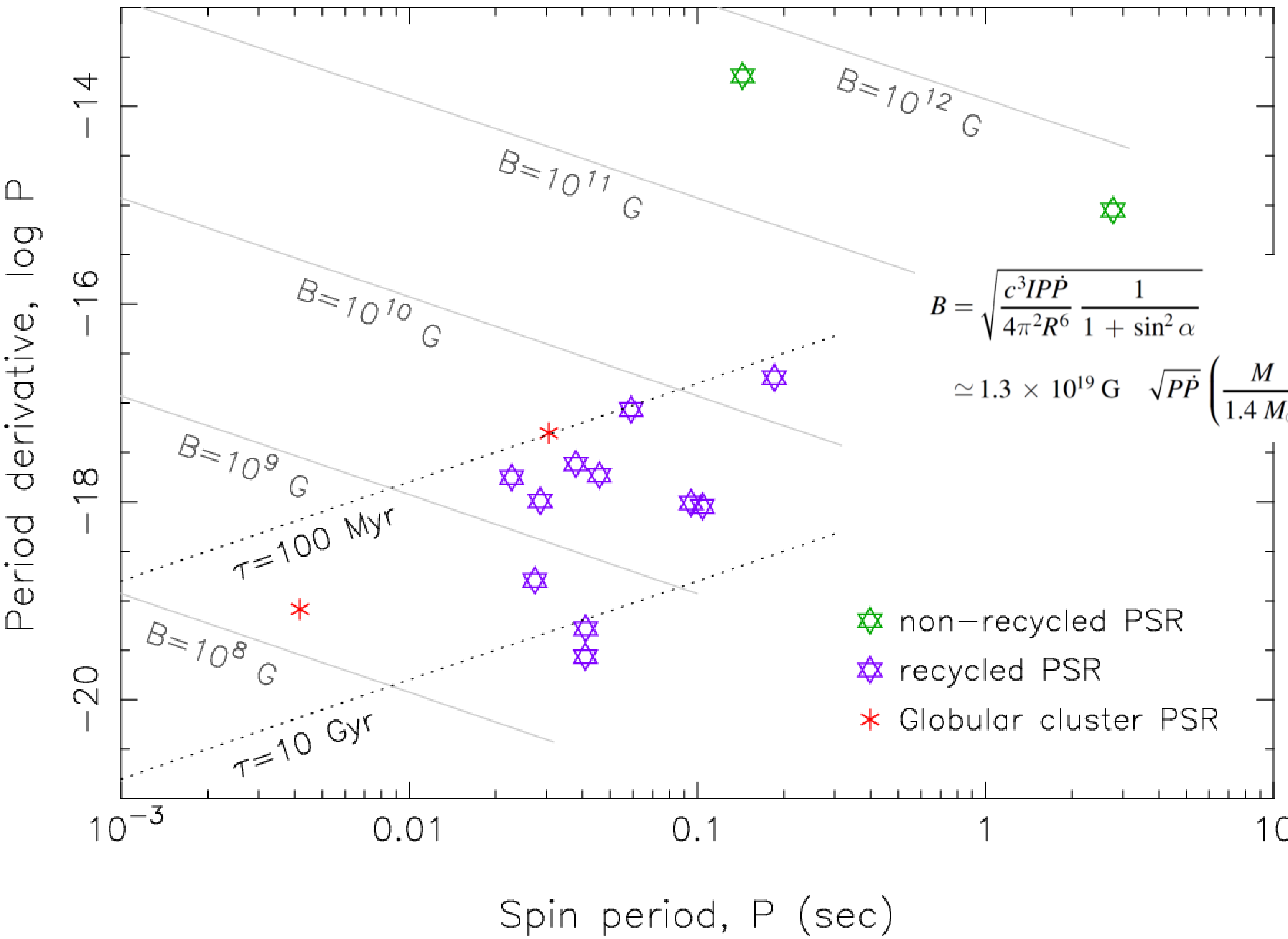
Kruckow, Tauris, et al. (2018), MNRAS

Important calibration data for population synthesis!!!



NS mass ratios





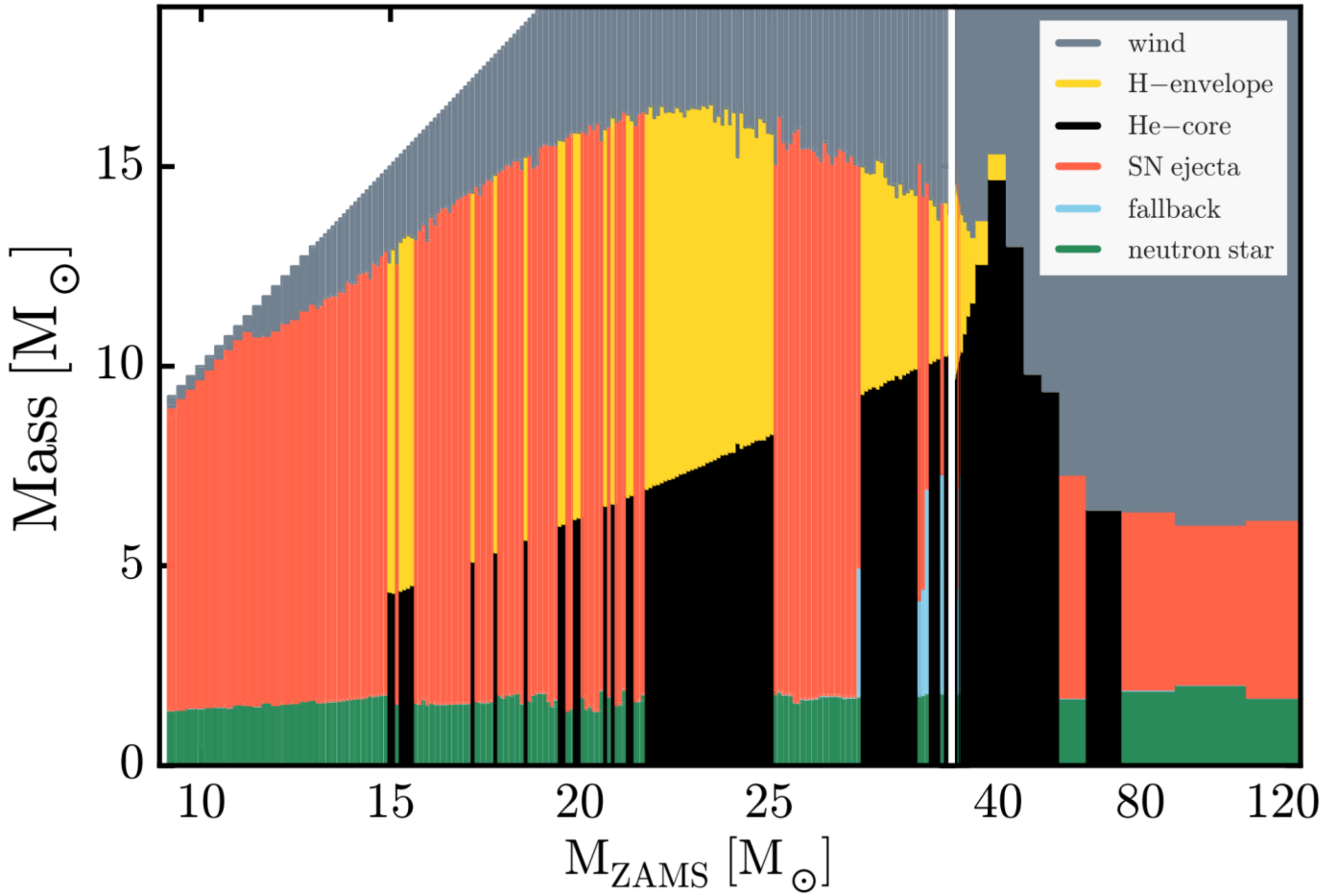
$$B = \sqrt{\frac{c^3 I P \dot{P}}{4\pi^2 R^6} \frac{1}{1+\sin^2\alpha}}$$

$$\simeq 1.3 \times 10^{19}\,\mathrm{G} \quad \sqrt{P\dot{P}} \left(\frac{M}{1.4\,M_\odot}\right)^{3/2} \sqrt{\frac{1}{1+\sin^2\alpha}}$$

FORMATION OF BHBH / BHNS BINARIES

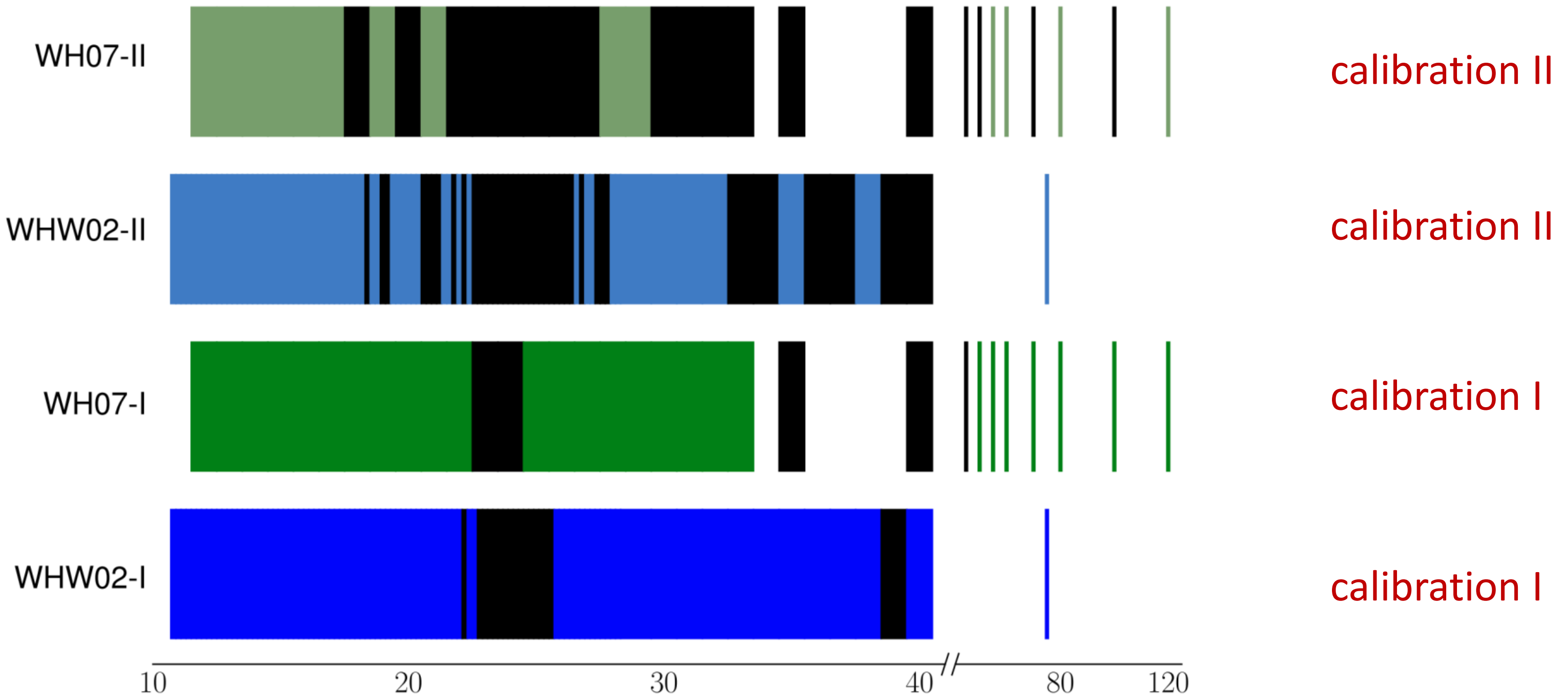
The final outcome of stellar core collape is **not** monotonic
(non-trivial to determine beforehand if the outcome will be a NS or a BH)

Sukhbold et al. (2016)



Metallicity and SN "calibrations" plays a role as well for the NS vs BH outcome:

Ebinger et al. (2019)



The **differences** in stellar evolution between **single** and **binary stars** have been highlighted in a number of papers, e.g. Podsiadlowski et al. (1992); Brown et al. (2001); Podsiadlowski et al. (2004) and more recently by Woosley (2019).

Five formation channels for BHBH mergers (see e.g. Tauris & van den Heuvel 2022)

i) The CE channel (i.e. the traditional or "standard" channel).
(This is the high-mass analogue of the formation channel of DNSs.)

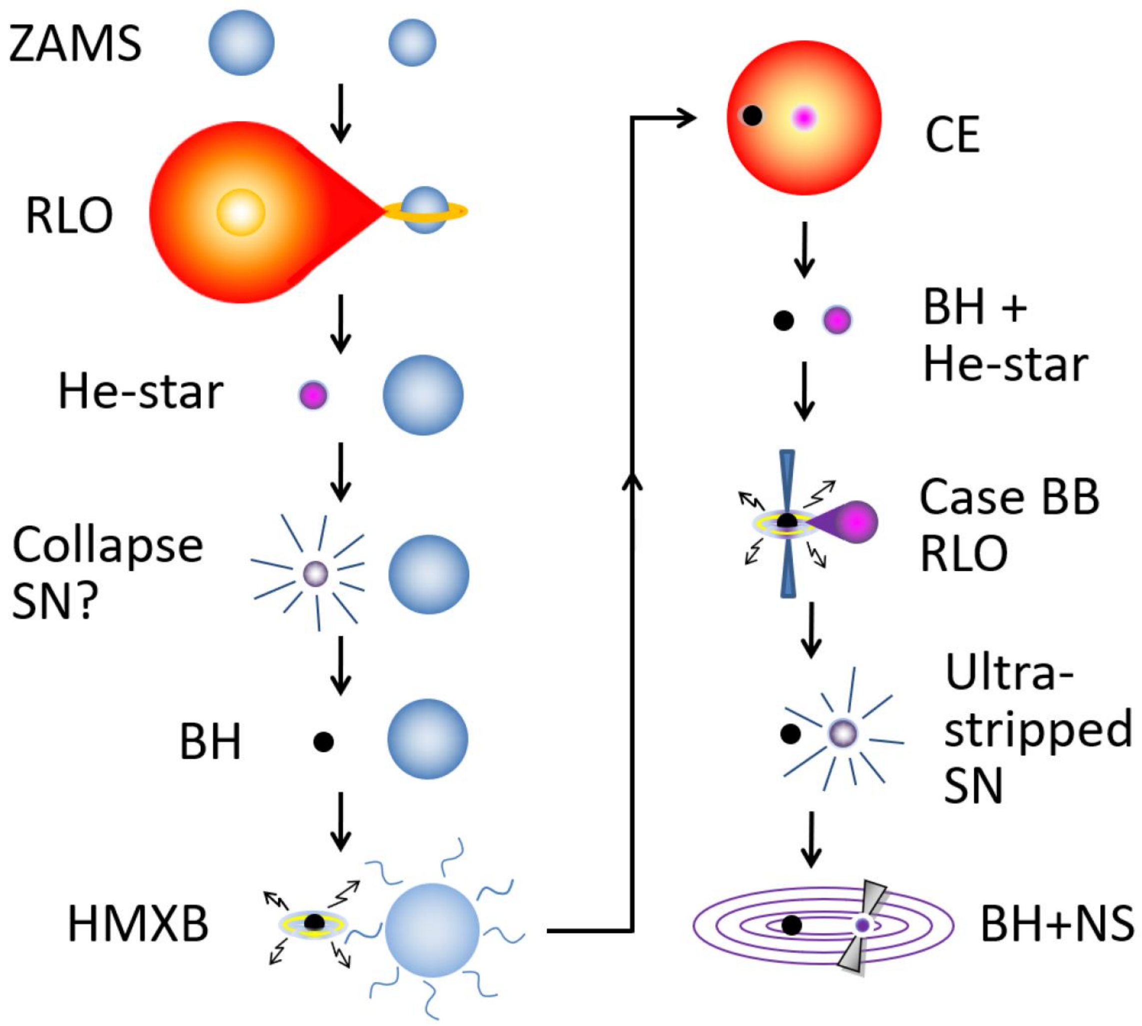
ii) The stable RLO channel (i.e. the SS433-like channel).

iii) The chemically homogeneous evolution (CHE) channel
with or without a massive overcontact binary.

iv) The dynamical channel (applicable only in dense stellar environments).

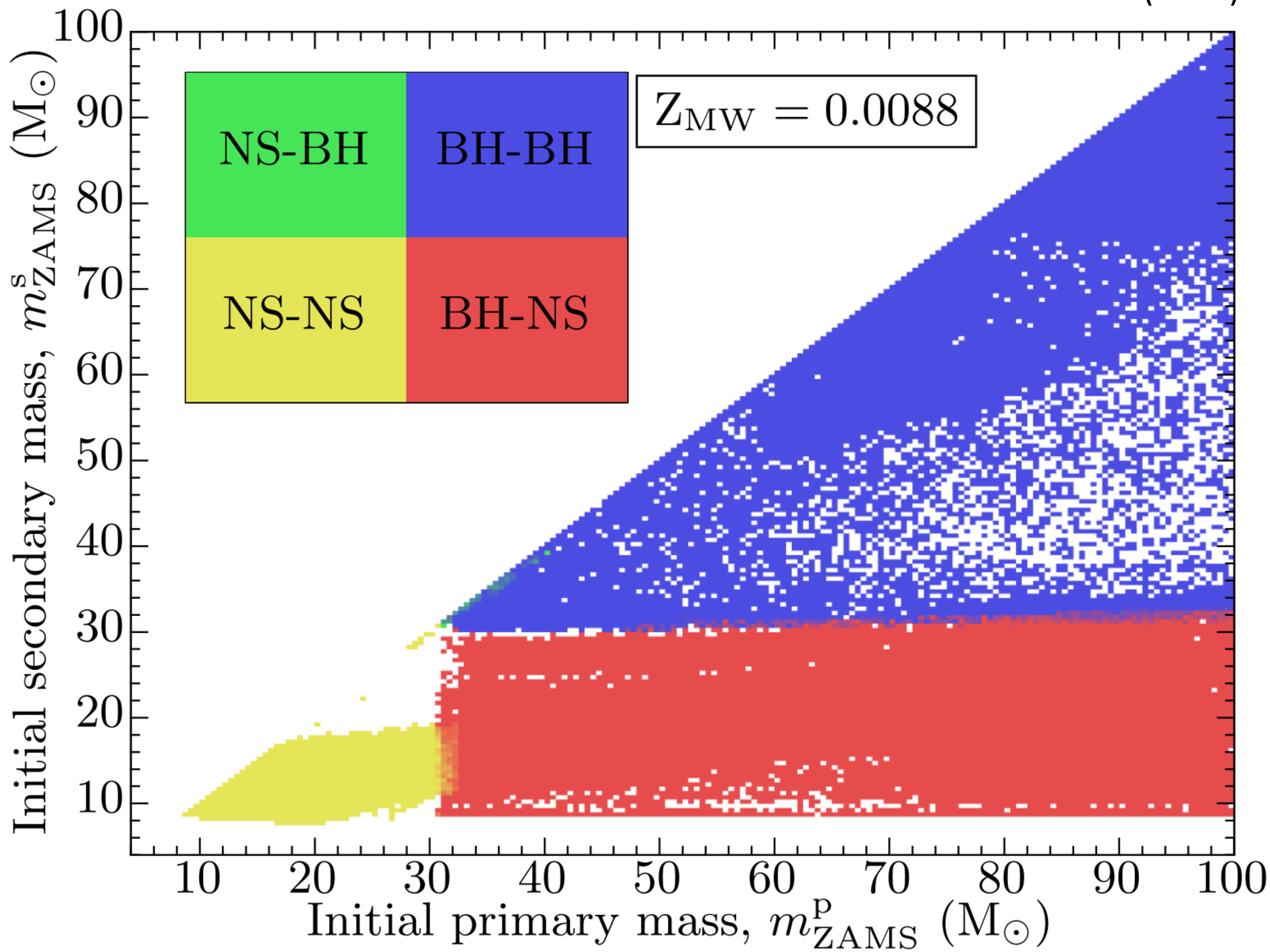
v) The hierarchical triple system channel.

NSNS / BHNS / BHBH systems form very similarly in isolation via the CE channel.



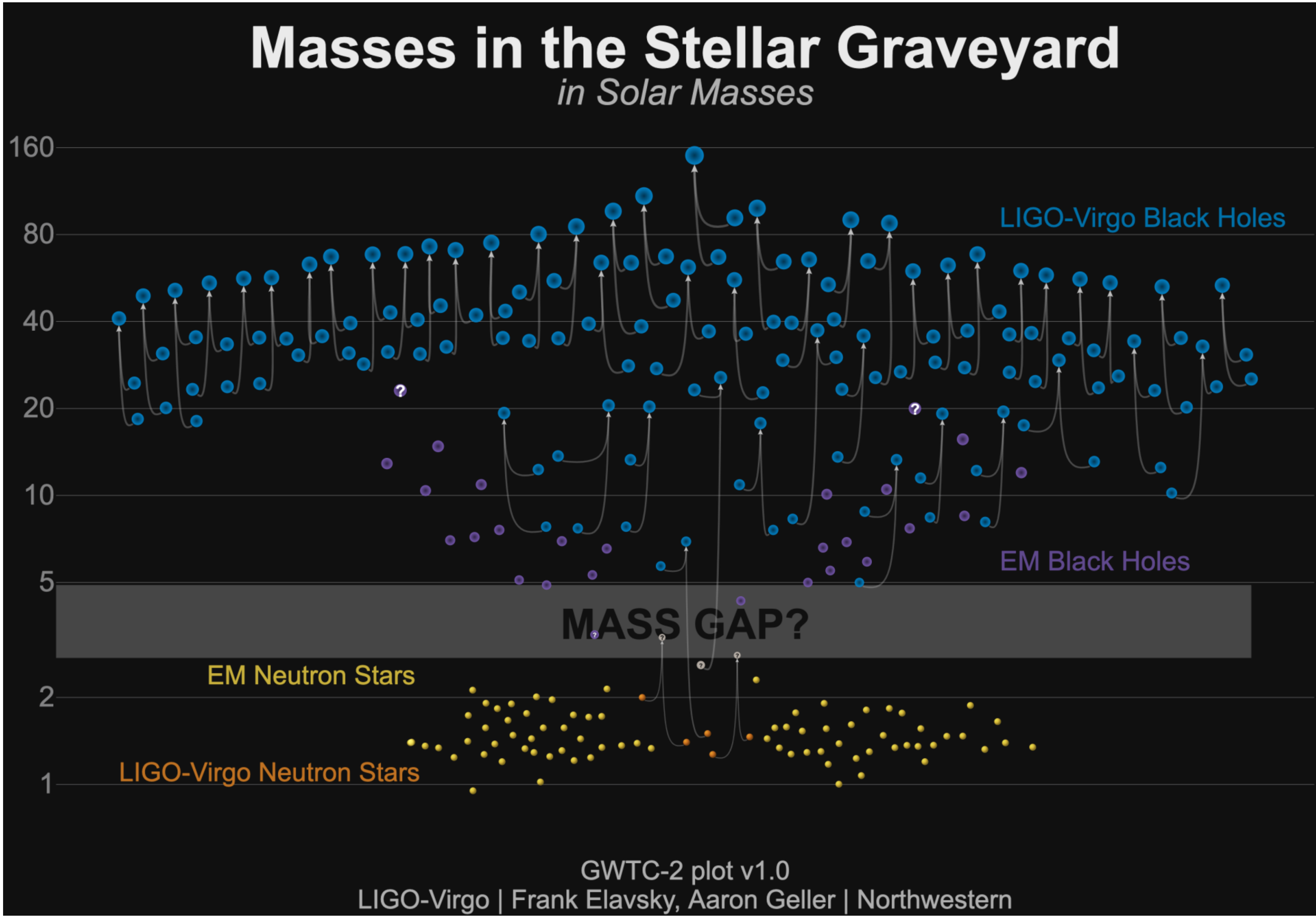
Tauris & van den Heuvel (2022)

Kruckow et al. (2018)



BH-BH Class	Chirp mass, $\mathcal{M}/M_\odot$	Example
very-low mass	$3 - 10$	GW170608
low mass	$10 - 20$	GW151012
intermediate mass	$20 - 40$	GW150914
massive	$40 - 60$	GW190602
extremely massive	> 60	GW190521

Different origins?


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
MASS GAP?
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Chemically Homogeneous Evolution (CHE)

CHE:
Maeder (1987), Langer (1992)
Heger & Langer (2000)
de Mink+ (2009)
Mandel & de Mink (2016)
de Mink & Mandel (2016)

A new route towards merging massive black holes

Astronomy & Astrophysics
A&A 588, 50 (2016)

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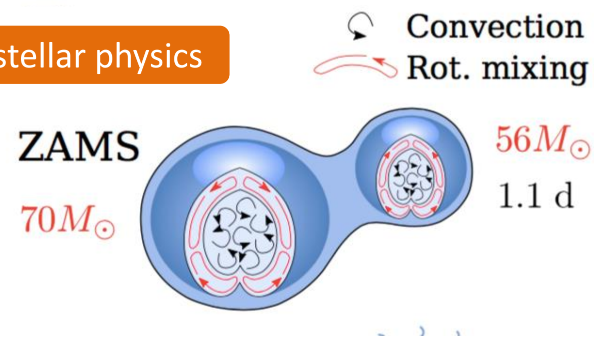
New stellar physics

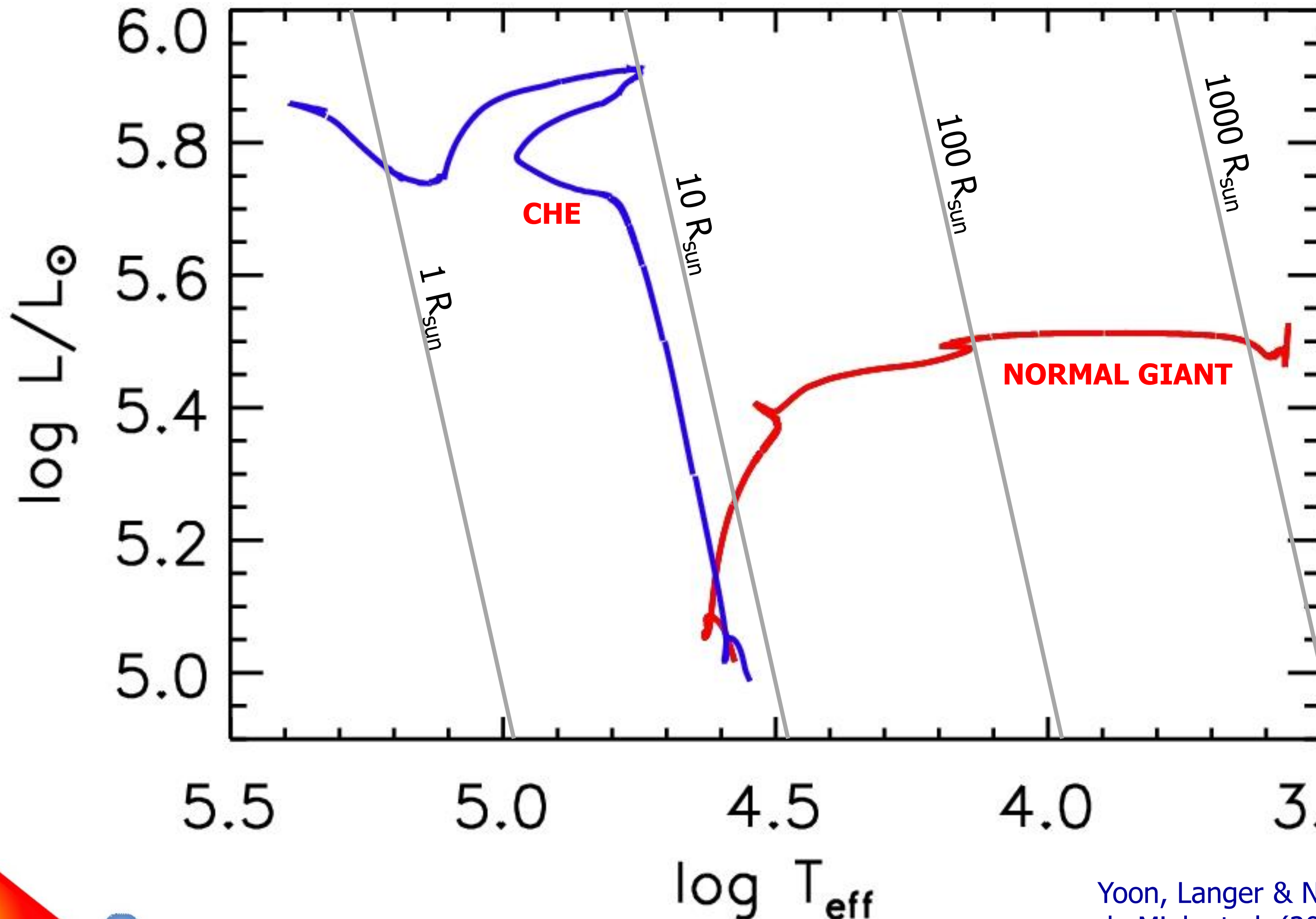


tight binary
↓ tidal forces
rapid rotation
↓ meridional currents
effective mixing
↓ no composition gradients
star remains compact
↓
no common envelope!

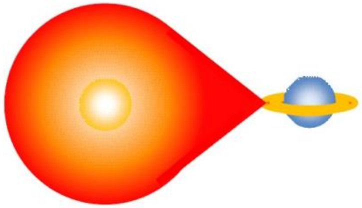
Requires:
- massive stars (high radiation pressure helps mixing)
- low-metallicity (weak stellar winds): remove little spin.ang.mom. / preventing orbital widening

Chemically Homogeneous Evolution of a 30 M_{sun} star with Z=0.002

These **rotating stars** remain blue and compact, and avoid RLO and mergers in close-orbit binaries

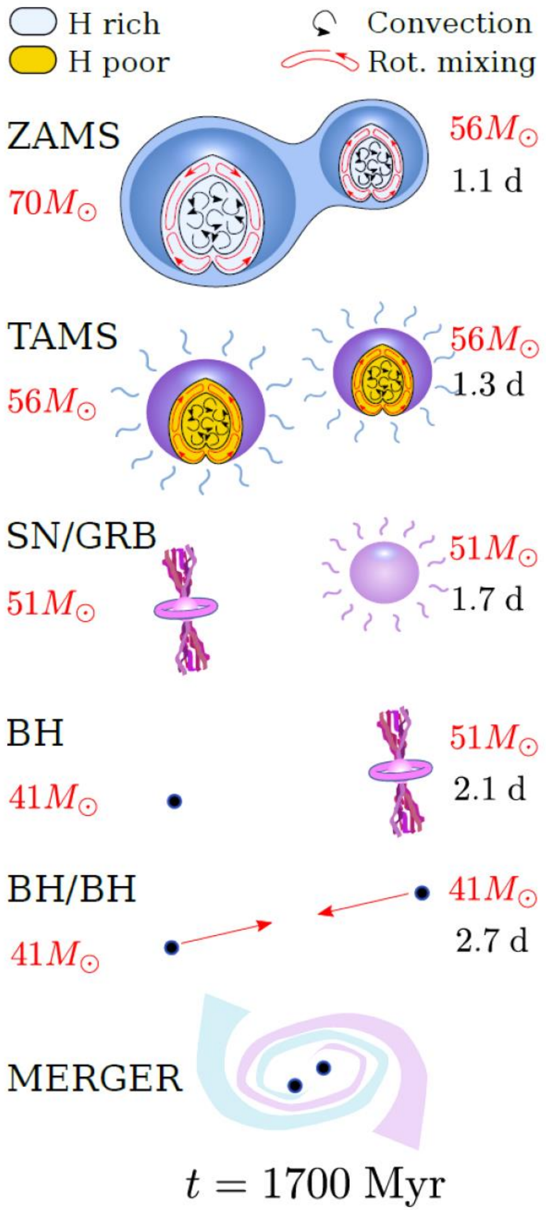


Important for BHBH merger rate!



Yoon, Langer & Norman (2006)
de Mink et al. (2009)

Different recipes for mixing processes (e.g. ang.mom. transport by B-fields)

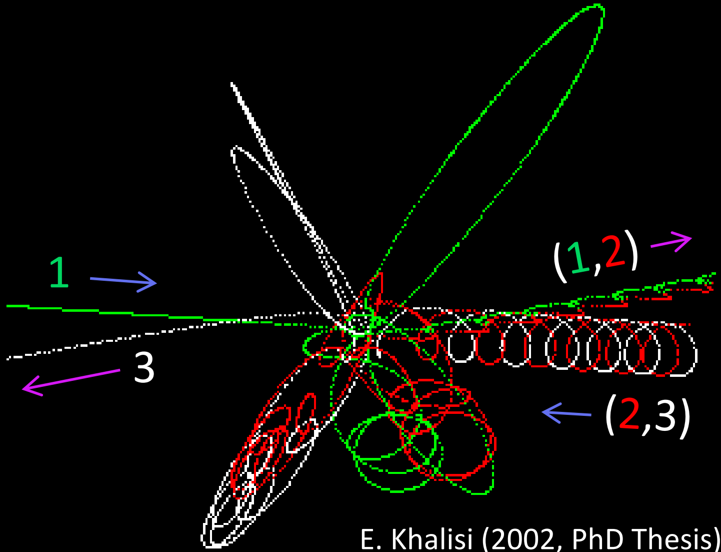


Chemically homogeneous evolution (CHE) of a very massive and close binary (initial orbital period, P_{orb} = 2–3 d), into a tight double BH which merges within a Hubble time.

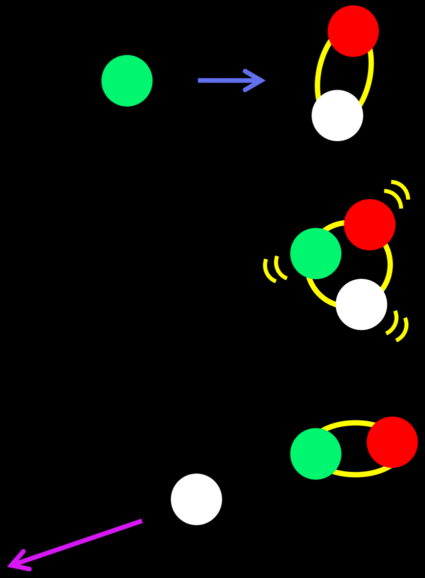
Marchant et al. (2017)

Dynamical interactions in dense stellar clusters

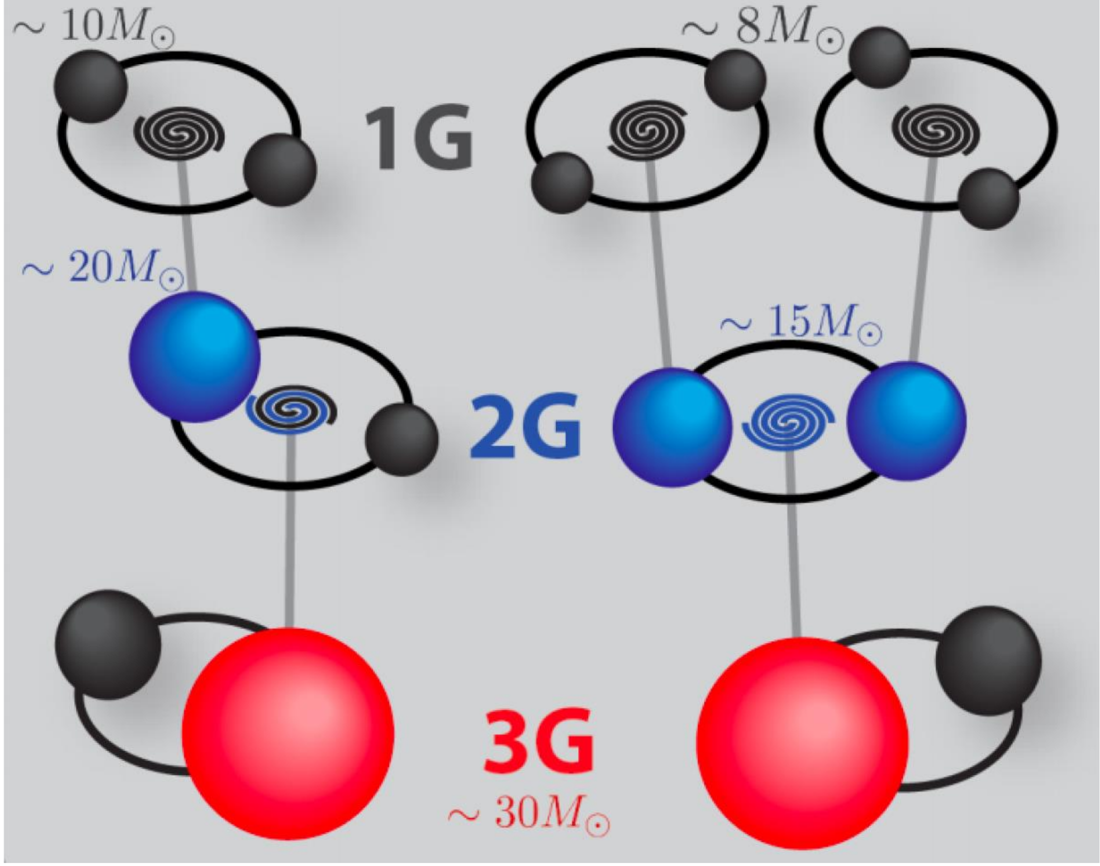
Three-body interactions :
(e.g. exchange encounters between binaries and a third star)



E. Khalisi (2002, PhD Thesis)

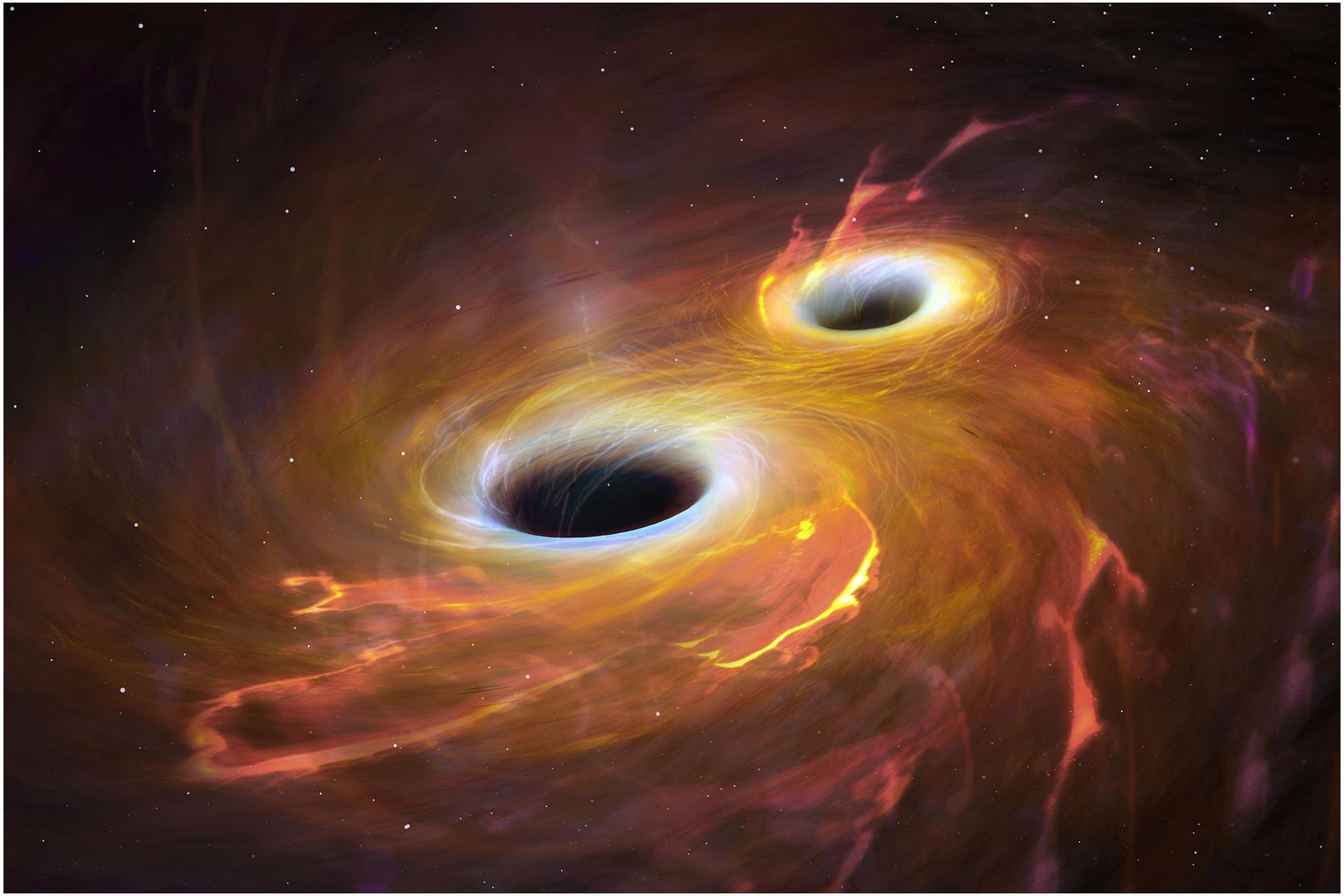


Hierarchical mergers in dense environments may lead to second (2G) and third (3G) generation mergers, thus producing very massive BHs (e.g. GW190521: 95 + 69 M_{sun} BHBH merger).



Rodriguez et al. (2020)

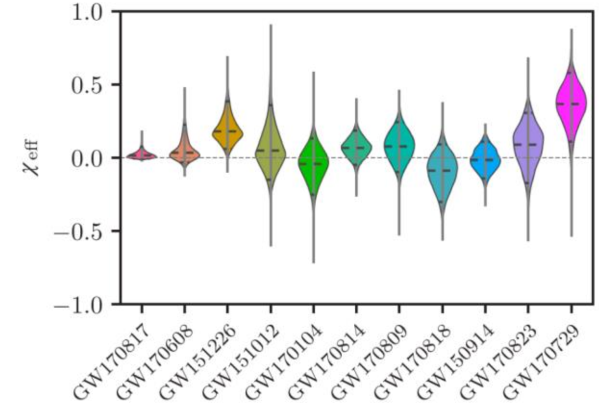
BHBH SPINS



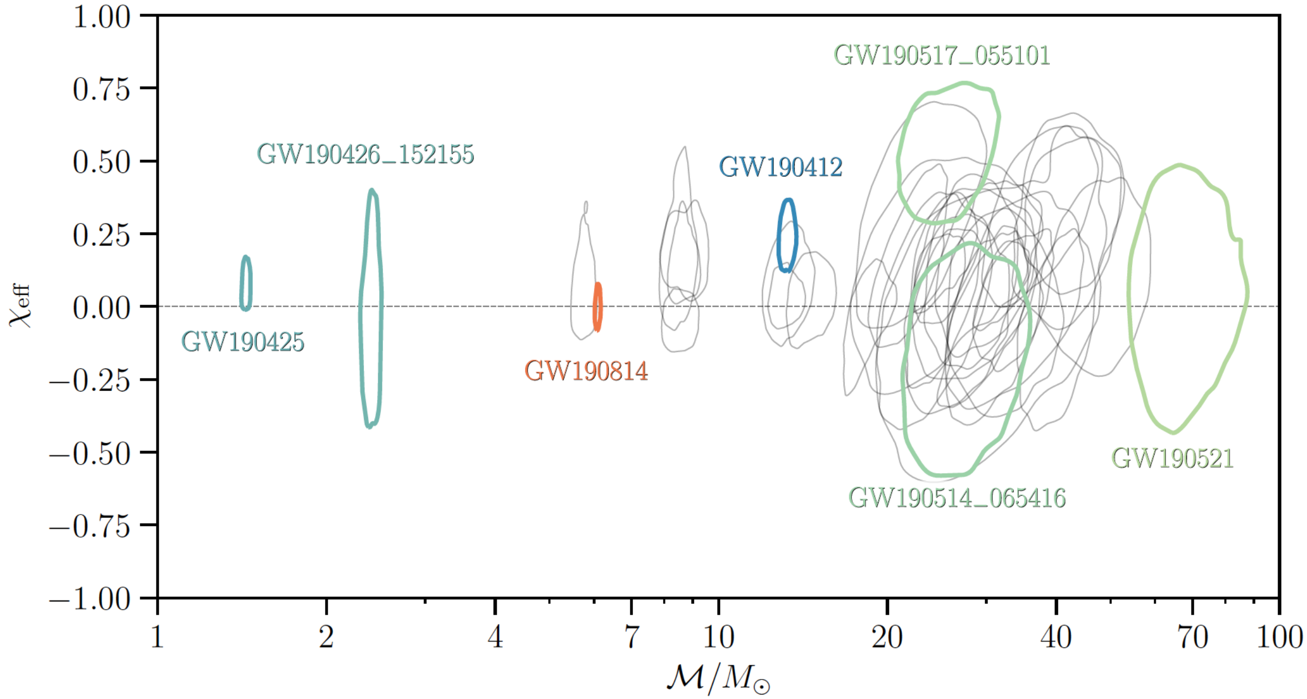
LIGO network measurements:

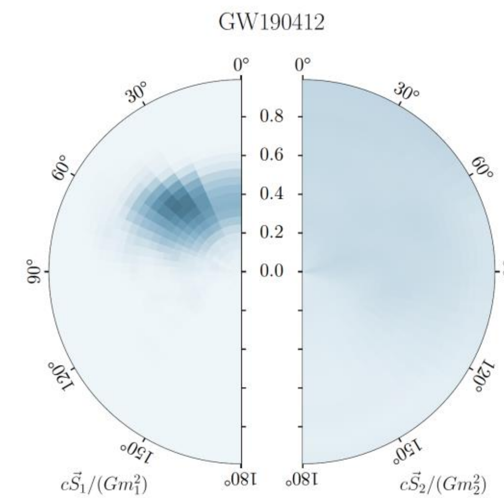
$$\chi_{\mathrm{eff}} \equiv \frac{(M_1\vec{\chi}_1 + M_2\vec{\chi}_2)}{M} \cdot \frac{\vec{L}}{|\vec{L}|} = \frac{\chi_1 \cos\theta_1 + q\,\chi_2 \cos\theta_2}{1+q}$$

LIGO run O1+O2:



LIGO run O3a:





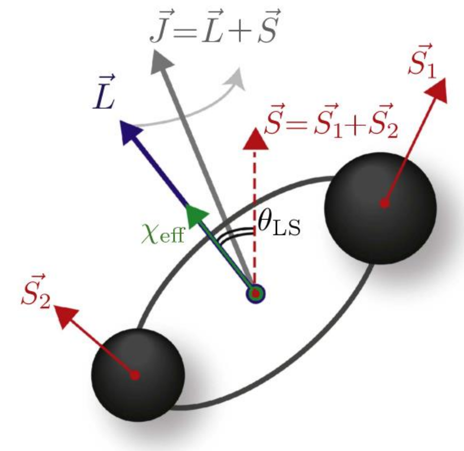
Intrepretation of BHBH mergers spins

Given that the far majority of all BH-BH mergers reported so far have near-zero effective spins leads to only three potential explanations (e.g. Belczynski et al., 2020):

<u>If the individual BH spin magnitudes are large, then:</u>
(i) Either both BH spin vectors must be nearly in the orbital plane, or
(ii) the spin angular momenta of the BHs must be oppositely directed and similar in magnitude.

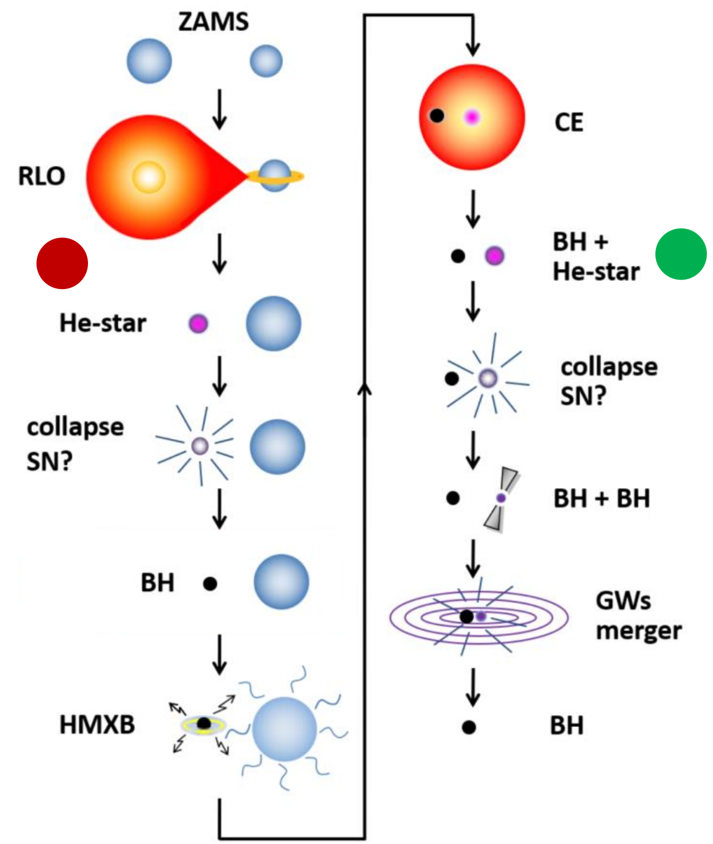
Finally, there is also the possibility that:
(iii) the BH spin magnitudes are small.

Belczynski et al. (2020) demonstrate that they can reproduce the observed distribution of low $\chi_{\rm eff}$ values within the classical isolated binary evolution scenario (the CE channel) of BH-BH formation assuming effcient angular momentum transport.



Expectations from stellar evolution:

See e.g.: Kushnir et al. (2016), Hotokezaka & Piran (2017), Zaldarriaga et al. (2018), Fuller & Ma (2019), Qin et al. (2019), Belczynski et al. (2020), Bavera et al. (2020)



- First-born BH will be spinning rather slow
- Second-born BH will be spinning rather fast

1. Efficient angular momentum transport by viscosity will couple the stellar core to its envelope, thereby slowing the spin of the core as the envelope expands when it becomes a giant star. Contradiction *

2. Tidal interactions between the first-born BH and the close-by naked-core WR-star (progenitor of the second-born BH) causes the latter to spin up efficiently.

* In clear tension with observations of BH spins in HMXBs (see Lecture 4)

Albert-Einstein Institute Lectures 2021

Thomas Tauris @ Aarhus University

Lectures 1+2: Wednesday May 12, 10:00 – 12:00
X-ray Binaries and Recycling Millisecond Pulsars

Lectures 3+4: Friday May 14, 10:00 – 12:00
Spin and B-field Evolution of Neutron Stars (+ Black Hole Spins)

Lectures 5+6: Wednesday May 19, 10:00 – 12:00
Formation of Binary Neutron Stars/Black Holes

Lectures 7+8: Friday May 21, 10:00 – 12:00
Binary Neutron Stars and Gravitational Waves at Low and High Frequencies

You are most welcome to ask questions any time ☺

FORMATION OF BINARY NEUTRON STARS / BLACK HOLES

AEI LECTURES 5+6

Summary

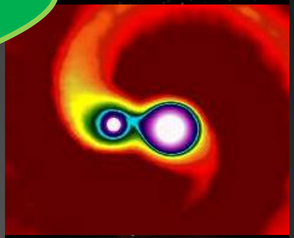
- Resumé of the formation of double NS binaries
  - Case BB RLO
  - Ultra-stripped SNe
  - Impact of SN kicks
  - NS masses, spins and B-fields

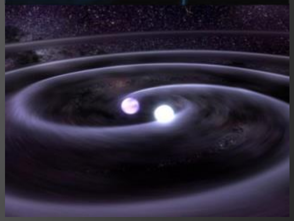
Tauris et al. (2017), ApJ 846, 170

a personal bias

- Formation of double BH binaries
  - BH masses and spins
  - BHNS binaries

For a review:
Tauris & van den Heuvel (2022)
New textbook from Princeton Uni. Press

Self study!

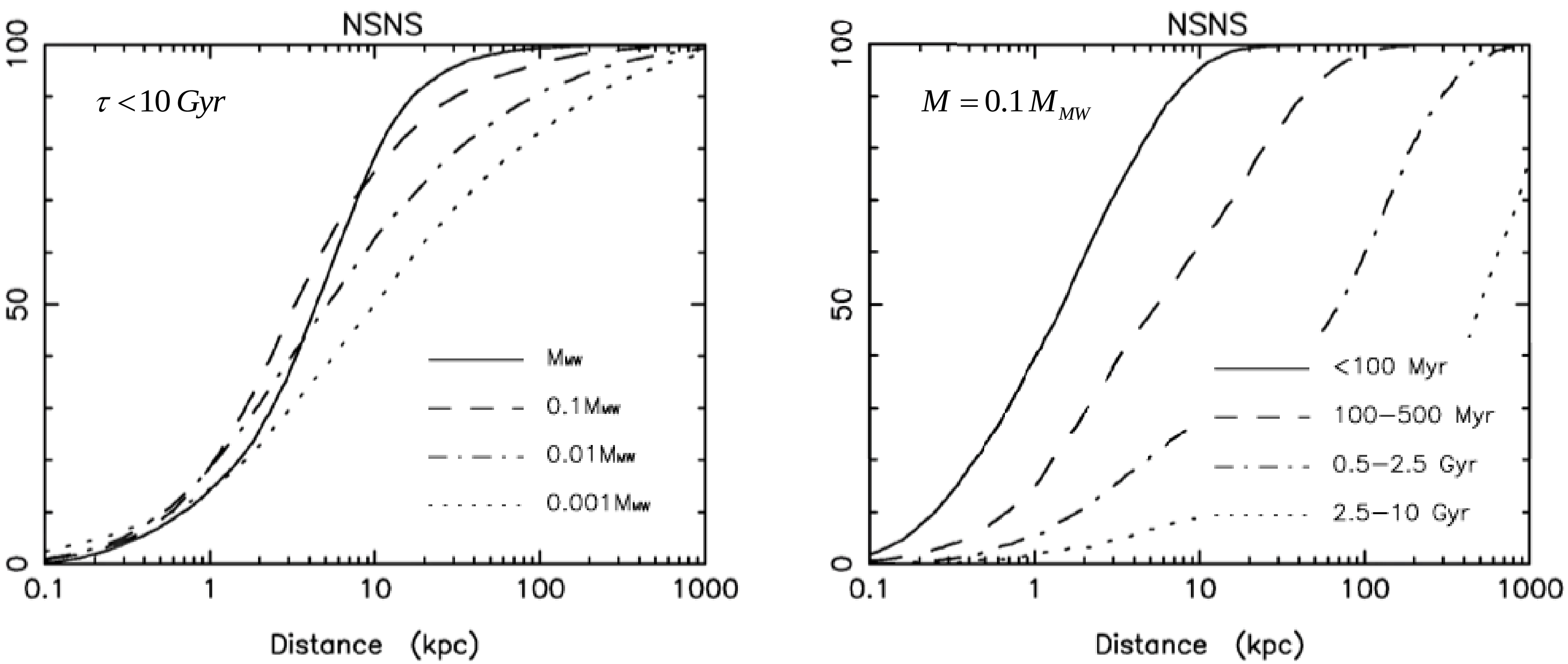
KICKS (2^{nd} SN)

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

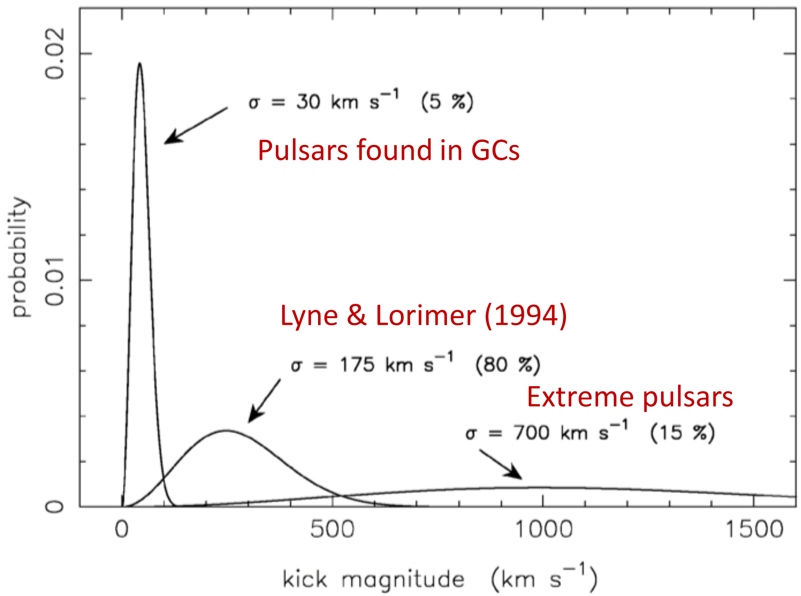
Galactic distribution of merging neutron stars and black holes – prospects for short gamma-ray burst progenitors and LIGO/VIRGO

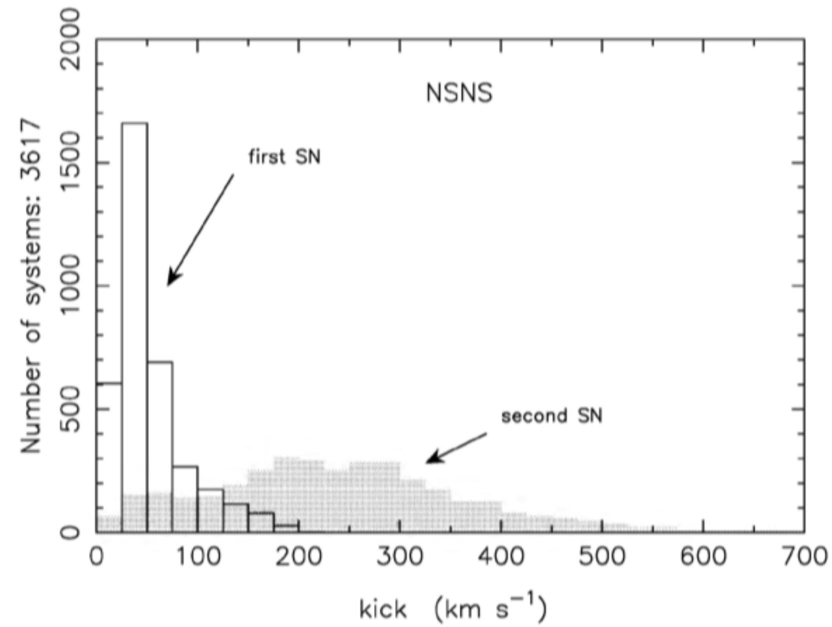
R. Voss★ and T. M. Tauris★

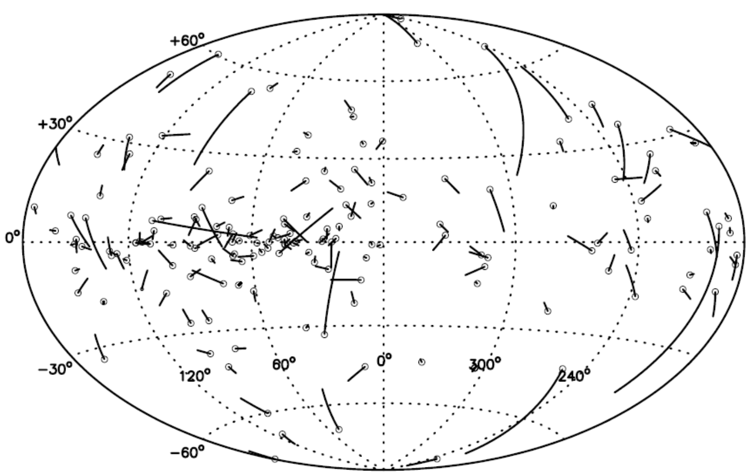
★*Astronomical Observatory, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark*

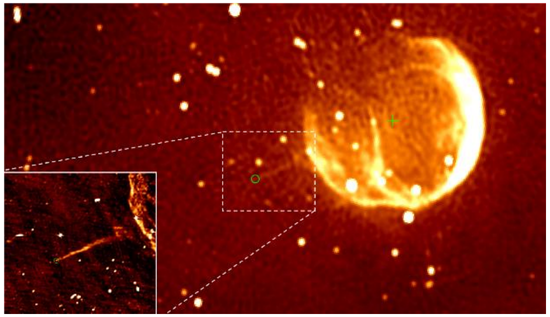


Voss & Tauris (2003), MNRAS



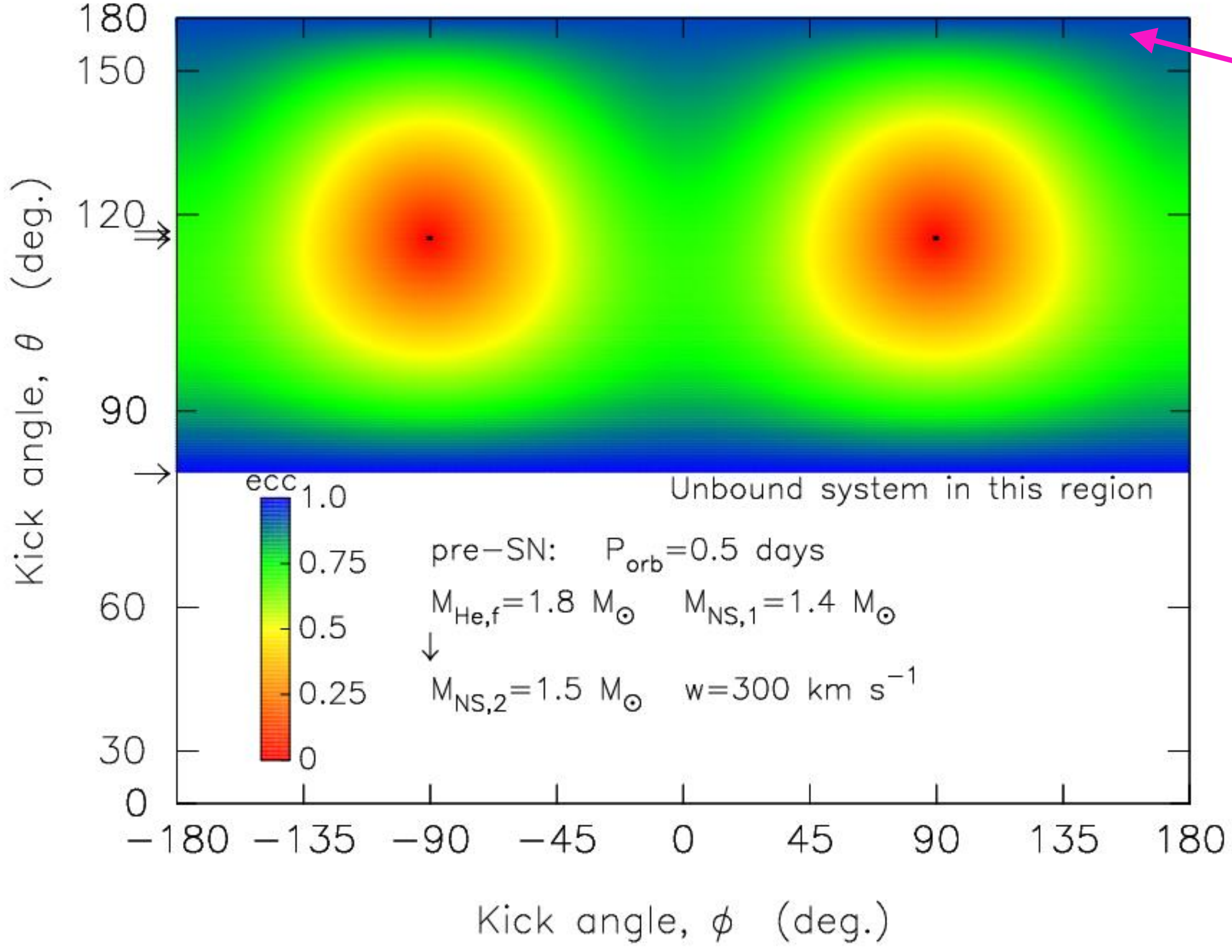




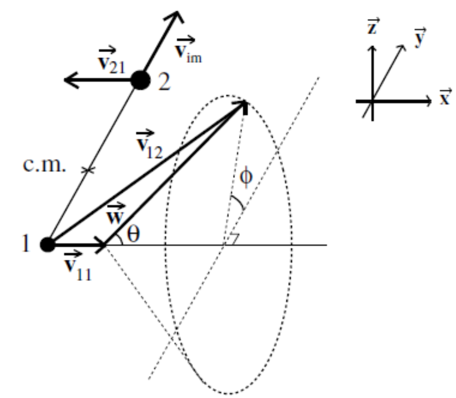


Radio proper motions show evidence for average 3D velocities of ~ 400 km s^{-1} (Hobbs et al. 2005).

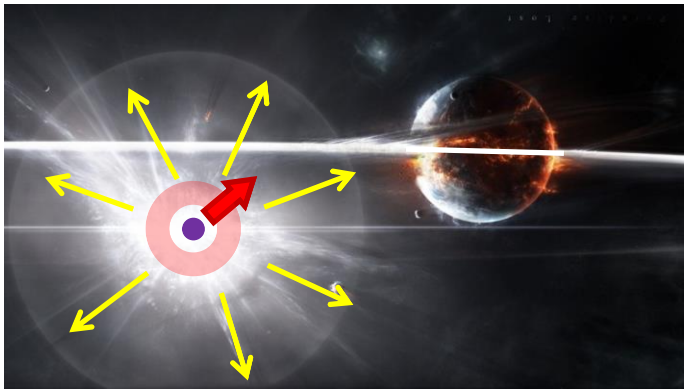
Tauris et al. (2017), ApL

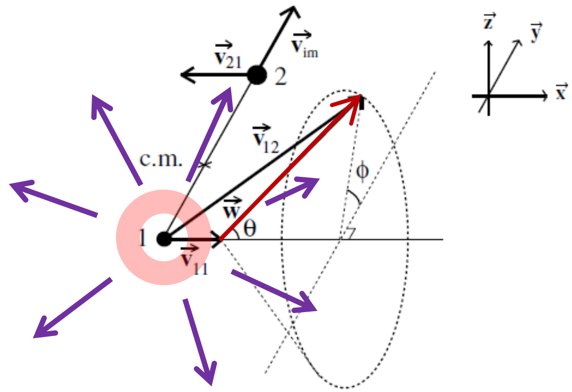


$\tau_{GW} < 1$ Myr!
(short sGRB delay time)



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

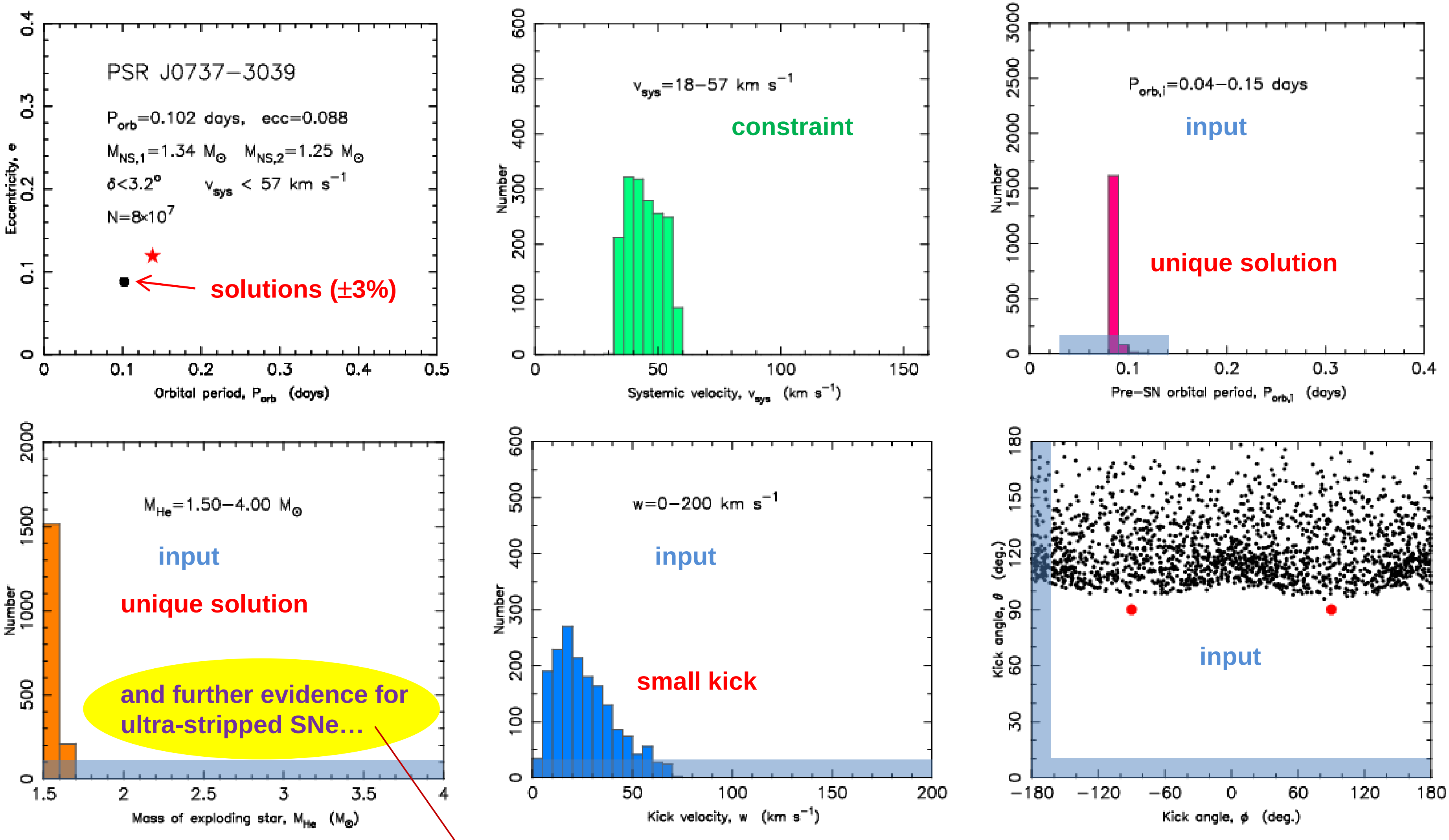




Our simulations take their basis in a five dimensional phase space.
The **input parameters** are:

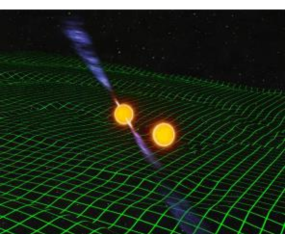
- the pre-SN orbital period
- the final mass of the (stripped) exploding star
- the magnitude of the kick velocity imparted onto the newborn NS
- the two angles defining the direction of the kick velocity, θ and φ.

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

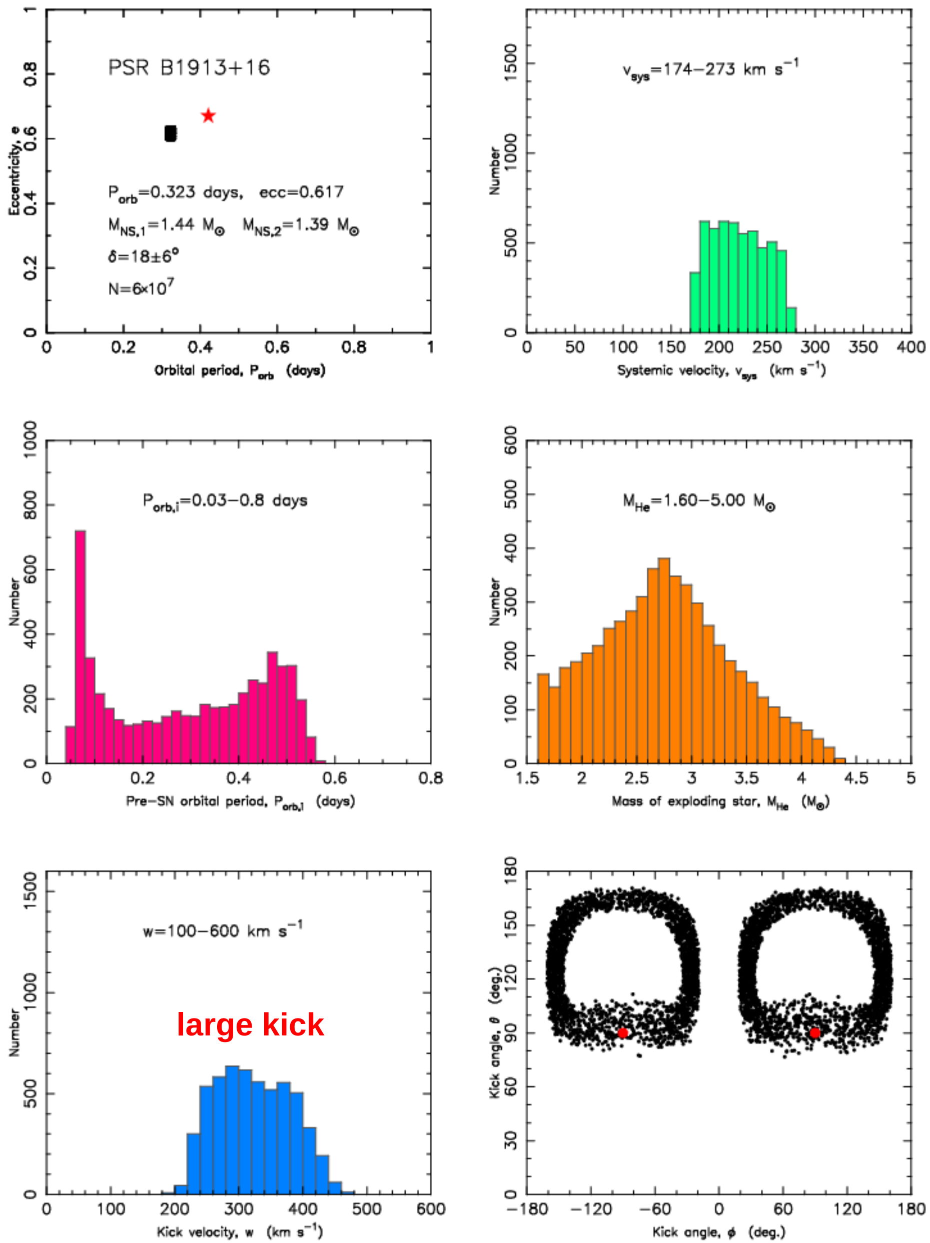


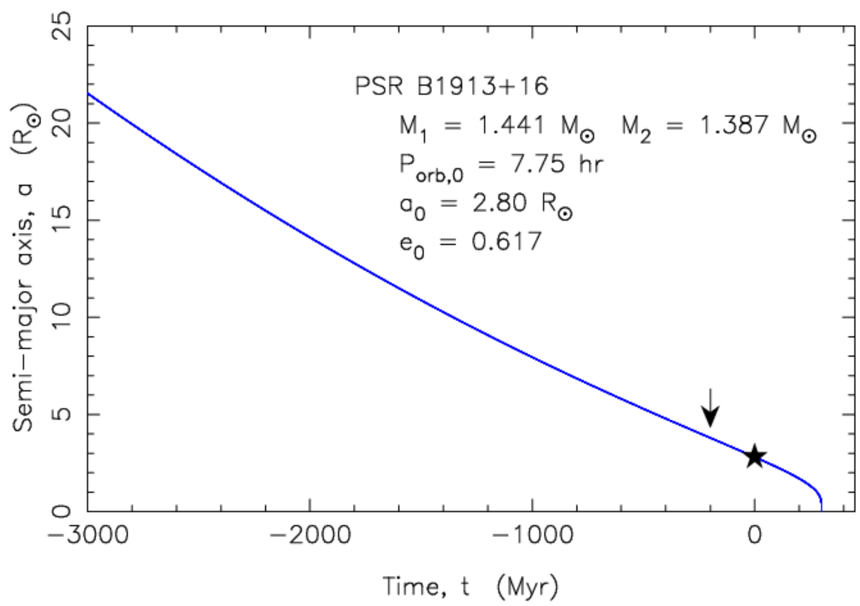
See also Piran & Shaviv (2005)

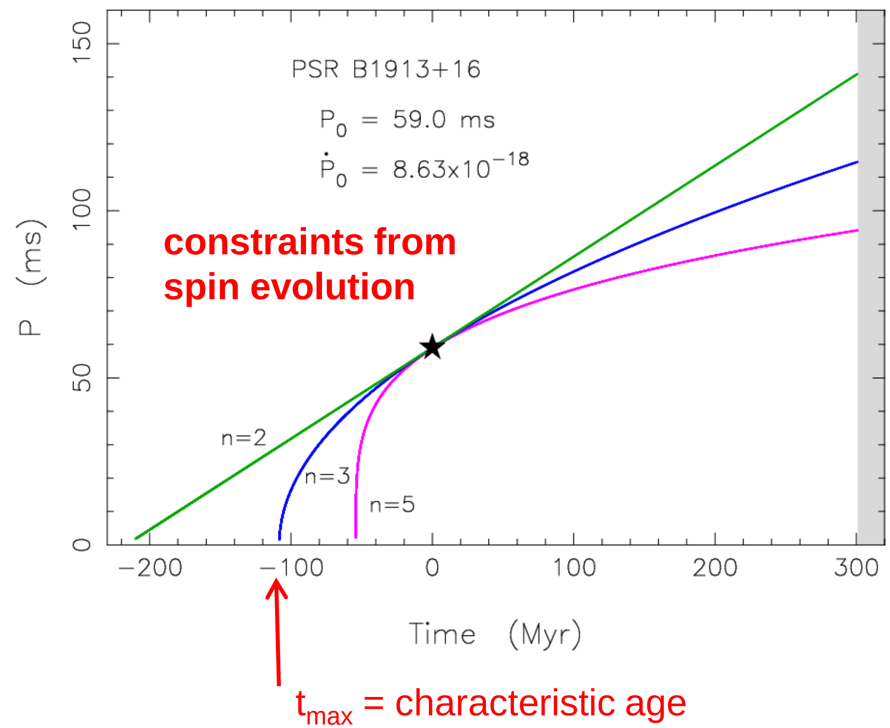
Tauris et al. (2017)

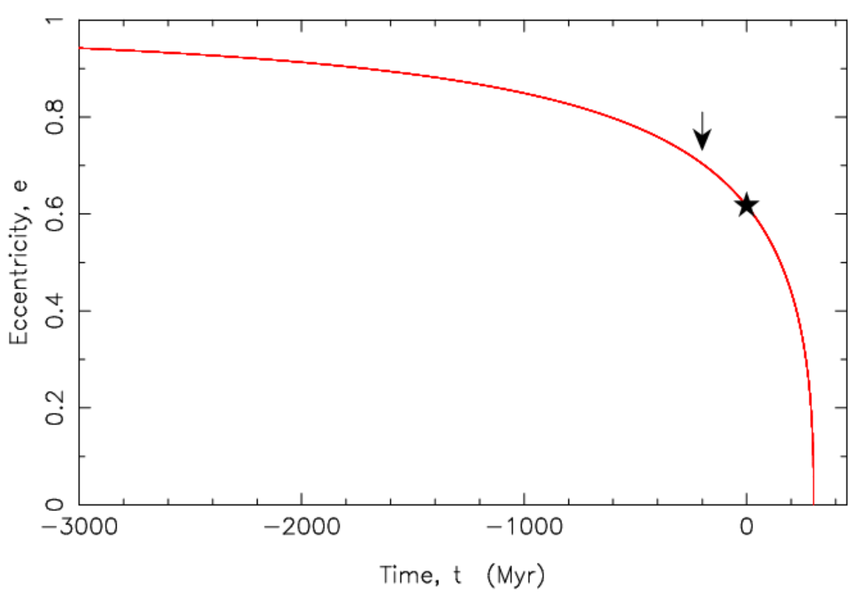


★ Based on proper motion and distance measurements (Deller et al. 2009) combined with MC simulations of the 3rd velocity component and a Galactic potential.


PSR B1913+16
P_orb=0.323 days, ecc=0.617
M_NS,1=1.44 M_⊙ M_NS,2=1.39 M_⊙
δ=18±6°
N=6×10^7
Eccentricity, e
Orbital period, P_orb (days)
v_sys=174−273 km s^−1
Number
Systemic velocity, v_sys (km s^−1)
P_orb,i=0.03−0.8 days
Number
Pre−SN orbital period, P_orb,i (days)
M_He=1.60−5.00 M_⊙
Number
Mass of exploding star, M_He (M_⊙)
w=100−600 km s^−1
large kick
Number
Kick velocity, w (km s^−1)
Kick angle, θ (deg.)
Kick angle, φ (deg.)

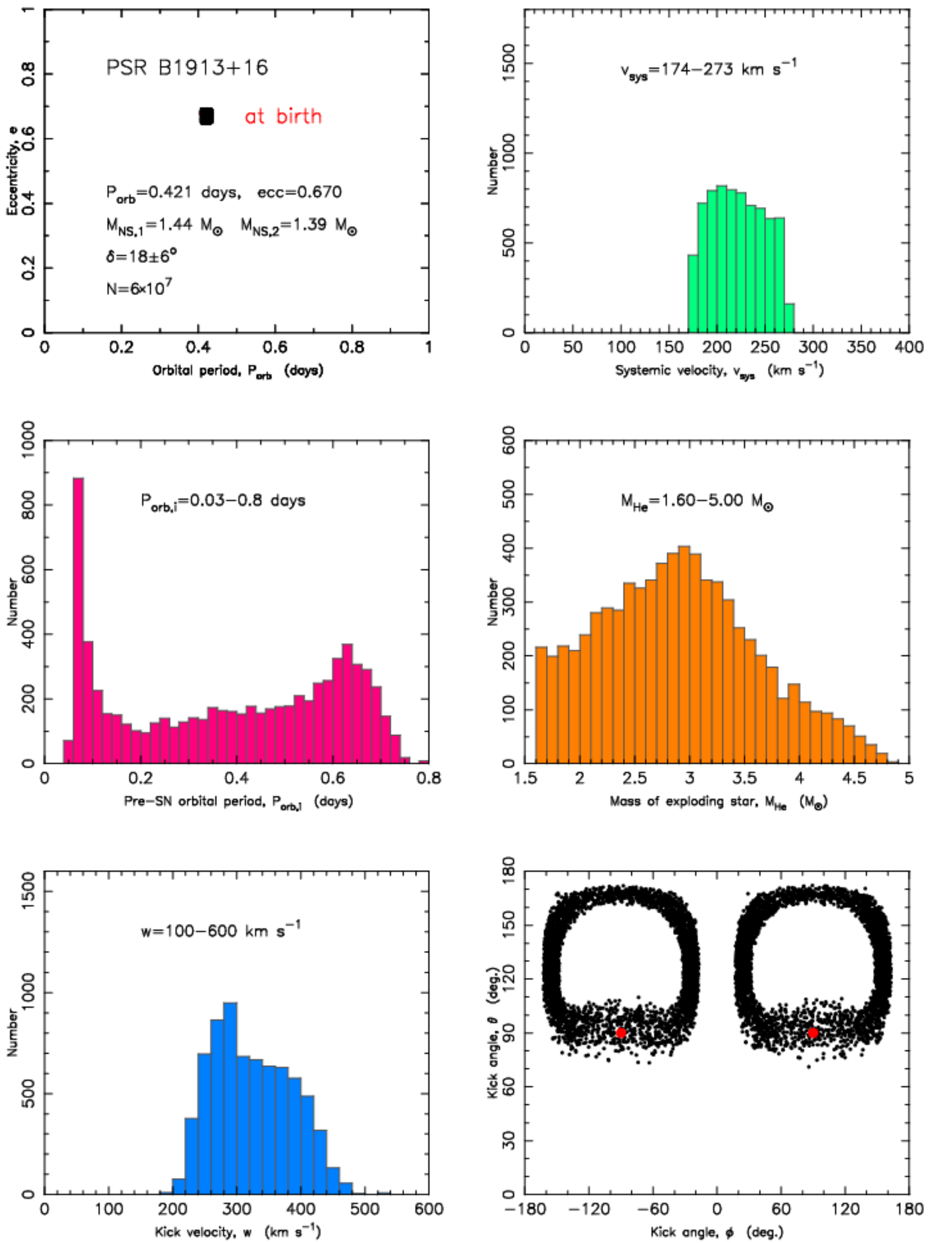






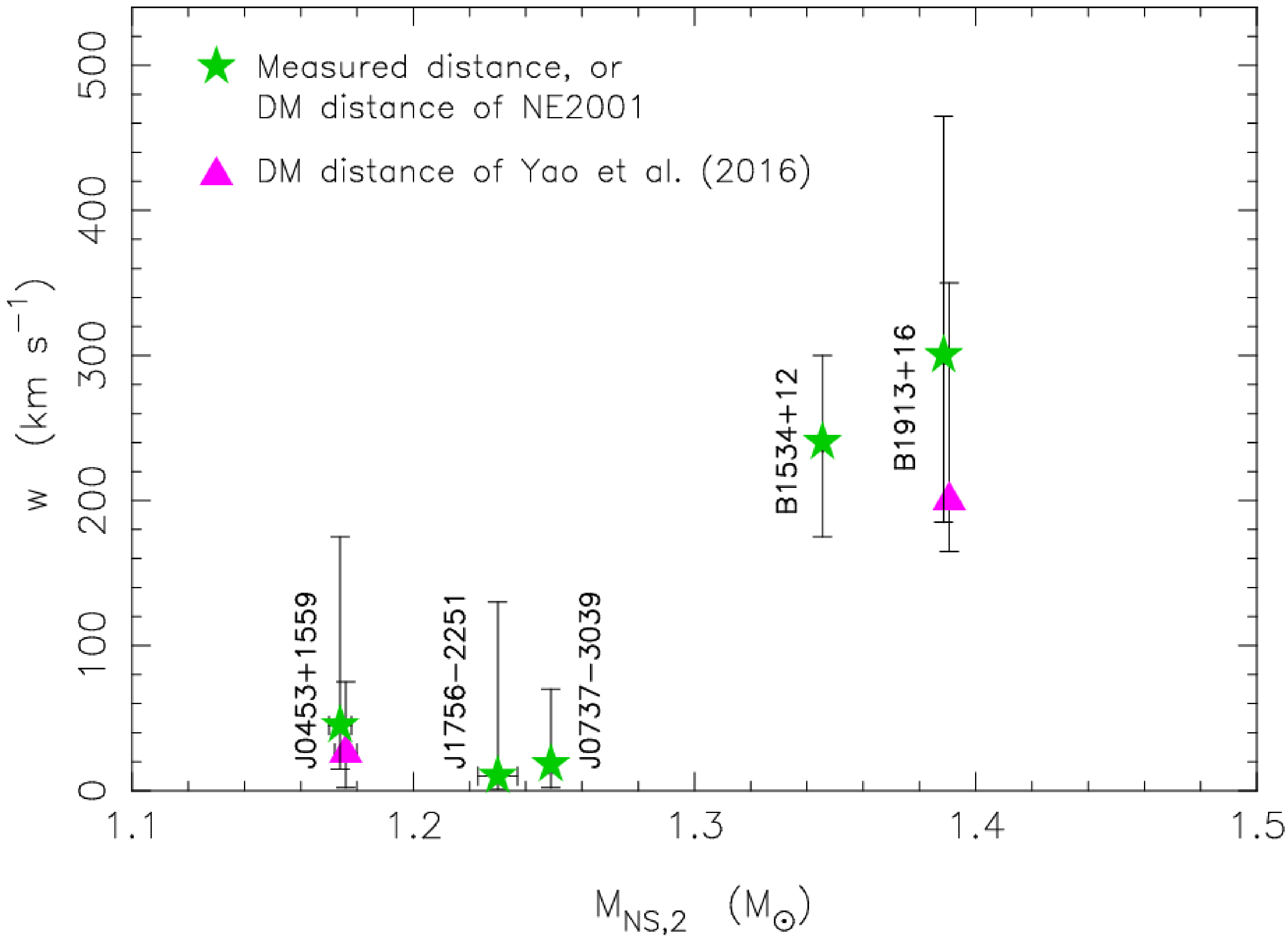
For **PSR 1913+16**, this yields upper limits of the post-SN parameters of $a = 3.34\ R_\odot$ (corresponding to $P_{orb} = 10.1$ hr) and $e = 0.670$. This only leads to *very* marginal changes in the pre-SN solutions for this system.

Results for PSR B1913+16 (at birth)

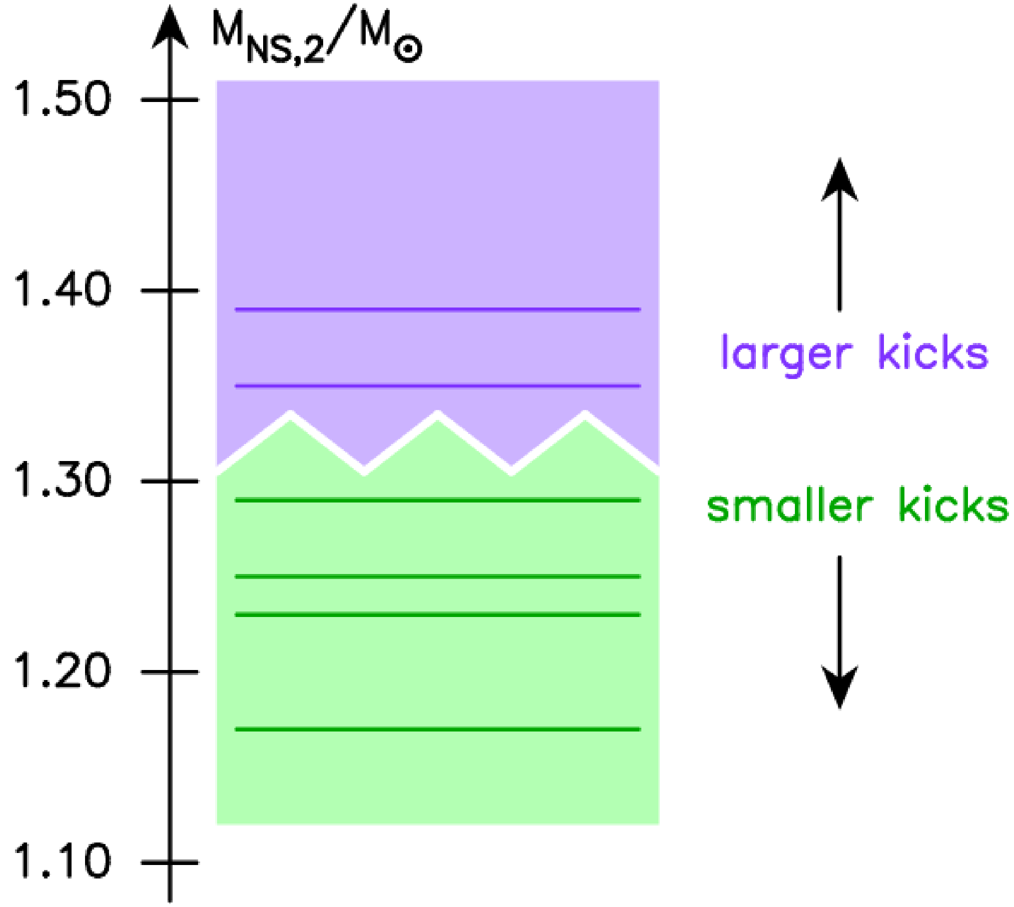


A NS mass-kick correlation ?

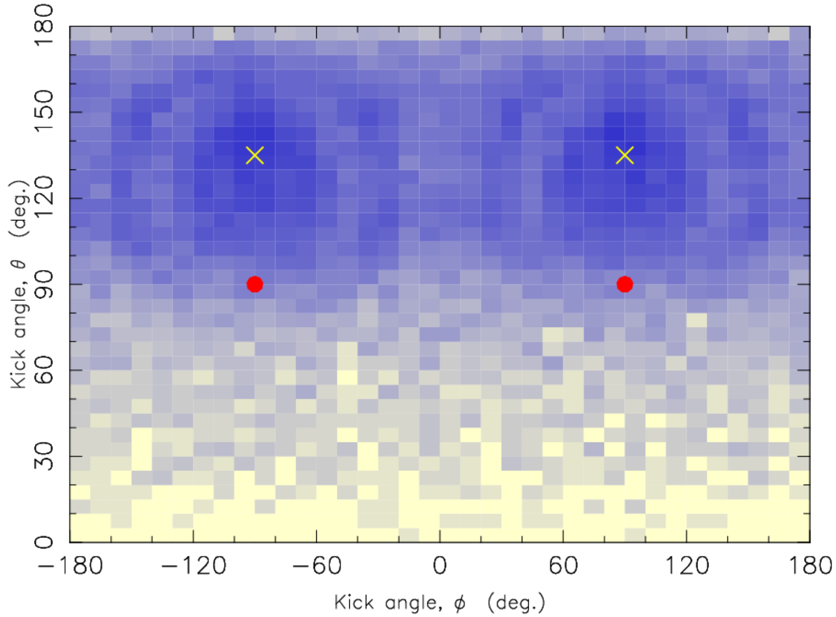
Tauris et al.(2017), ApJ



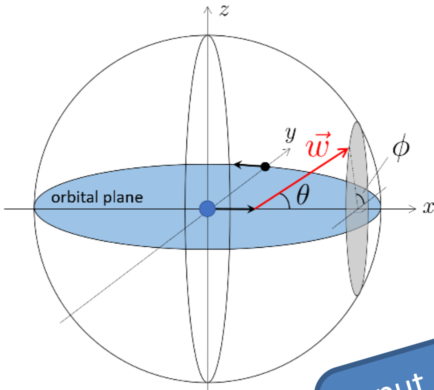
Kick – NS mass relation? Empirical evidence from current data

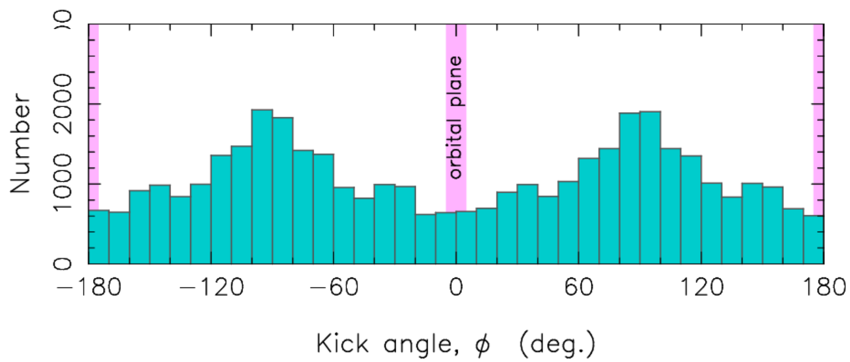


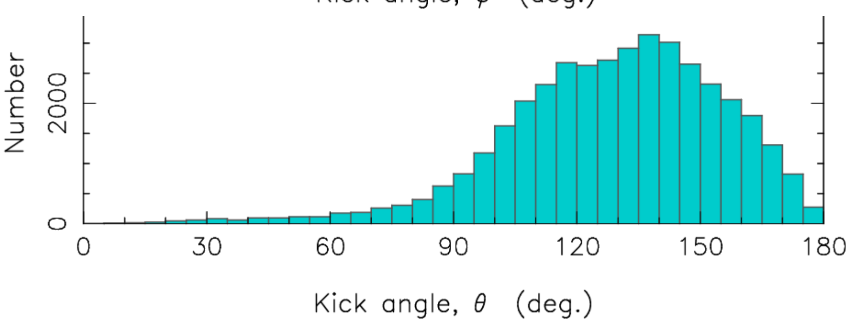
SN kick angle anisotropy?



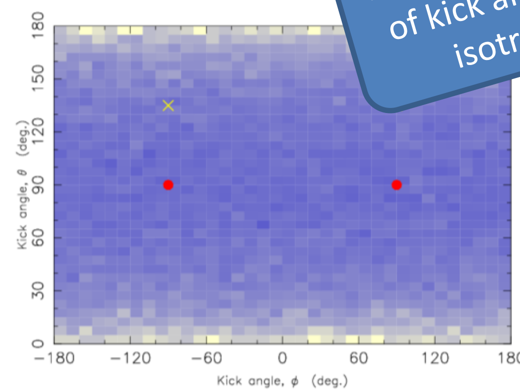
Why?

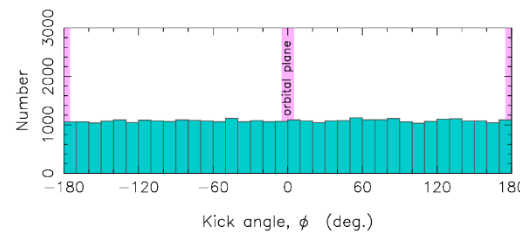


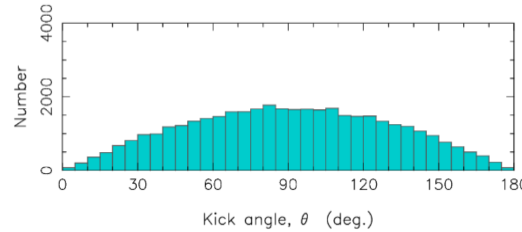


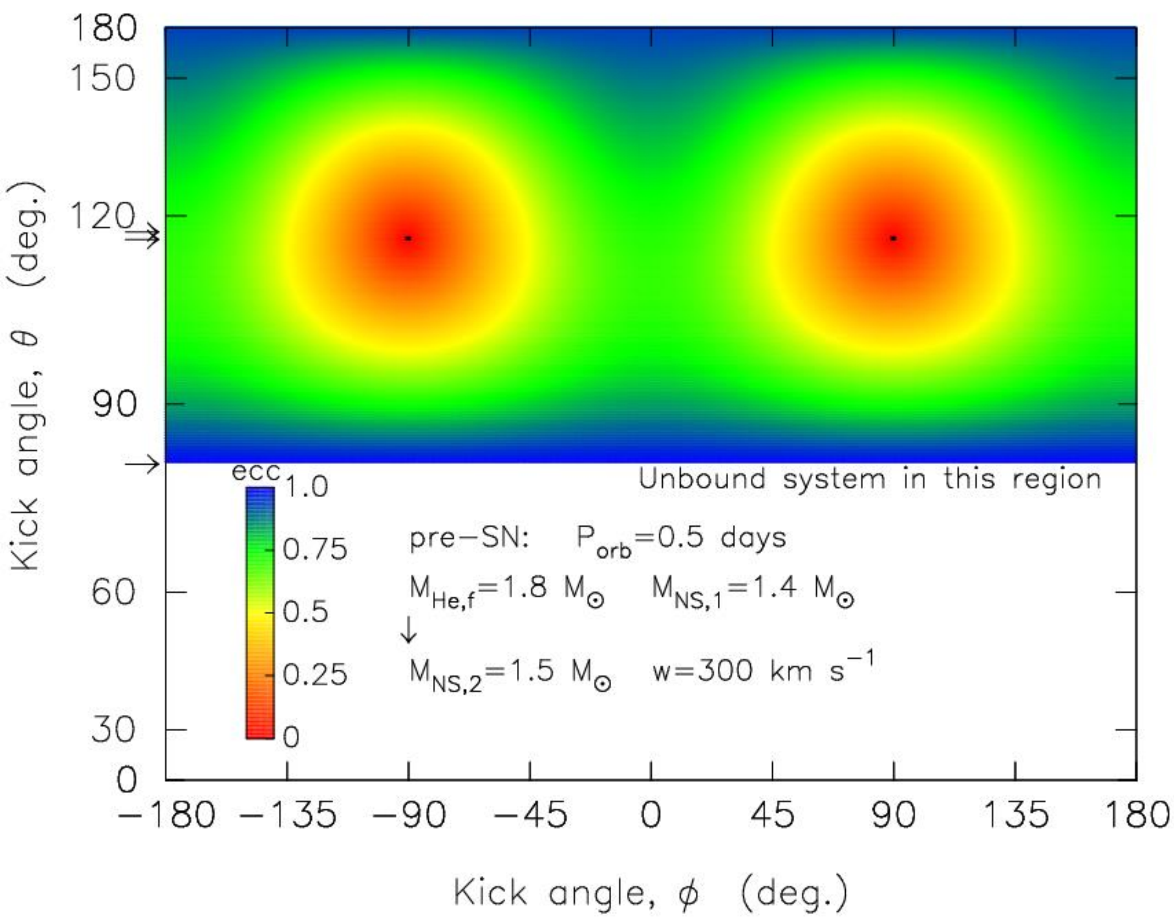


Input distribution of kick angles is isotropic

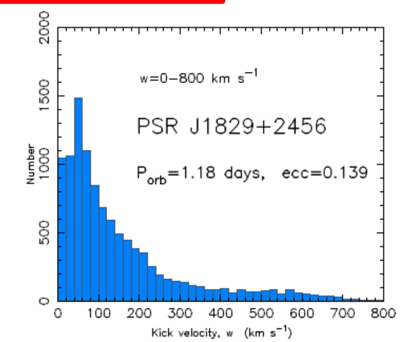


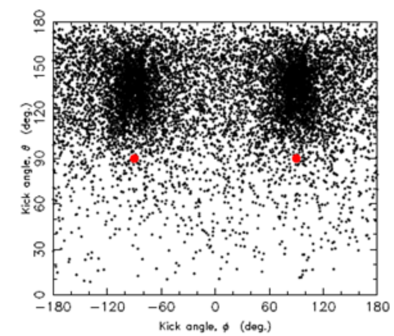






Kick angle anisotropy is only an apparent effect

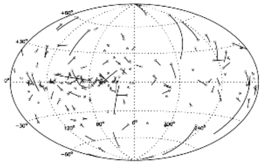
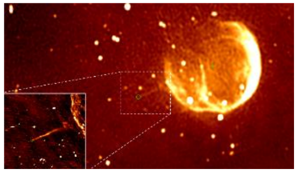




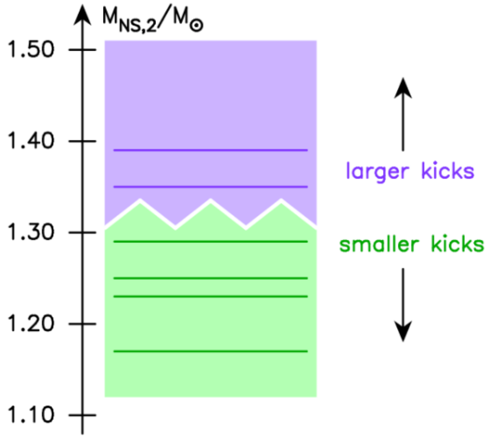
1. The **input** kick distribution allows for **too large kick magnitudes**
   - to reproduce obs. DNS systems (often with small ecc) only a certain angle region is allowed

2. **Observational selection effects**
   - tight, eccentric DNS systems are removed from obs. sample b/c GW damping

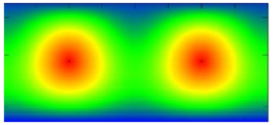
Tauris, Langer & Podsiadlowski (2015); Tauris et al. (2017)

- Multi component kick distribution (e.g. GC sources, isolated pulsars, +1000 km/s)
- Kick magnitude depends on: mass of iron core; and also (less) on envelope mass (early discussion in Tauris & Bailes 1996)

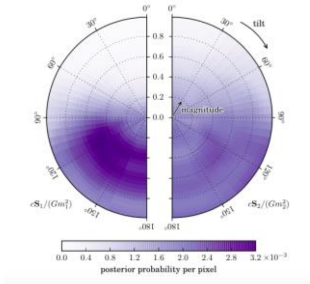


- All* DNS mergers undergo an ultra-stripped SN as 2nd SN
- Correlation between kick magnitude and NS mass
- Kicks may produce DNS merger times of < 1 Myr (sGRBs in star-forming regions!)



- Spin tossing occurs in 2 out of 2 known DNS systems where the young NS is observed. Also applies to double BH mergers? (→ misaligned spins from isolated binaries)

$$\chi_{eff} \equiv \frac{1}{M}\left(m_1\chi_1 + m_2\chi_2\right)$$



- No evidence for a preferred kick directions