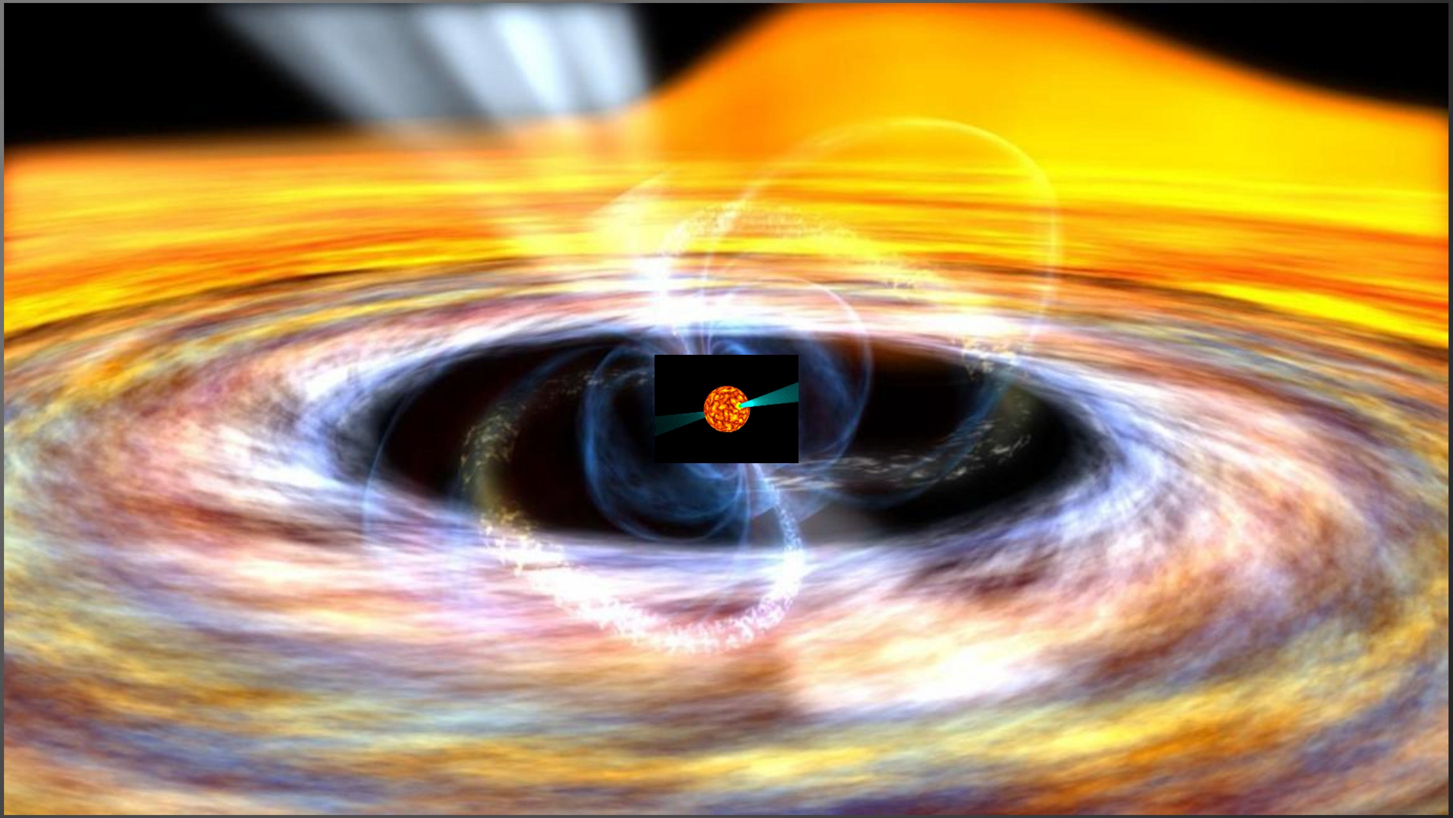
FORMATION OF MILLISECOND PULSARS AND DOUBLE NEUTRON STARS

EWASS 2015



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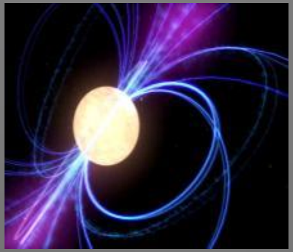
(T. Belloni)

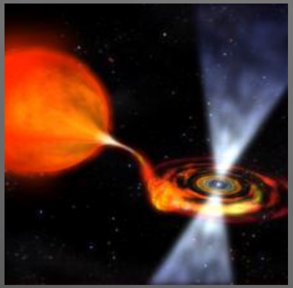
MSP: press > 100 Hz

Do not try this!

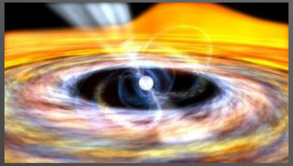
Agenda



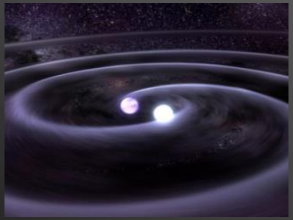
- Overview of the MSP population



- Formation scenarios of MSP subclasses
- Probing Stellar Evolution using MSPs



- The recycling phase and accretion physics



- Formation of double neutron star systems

The NS population

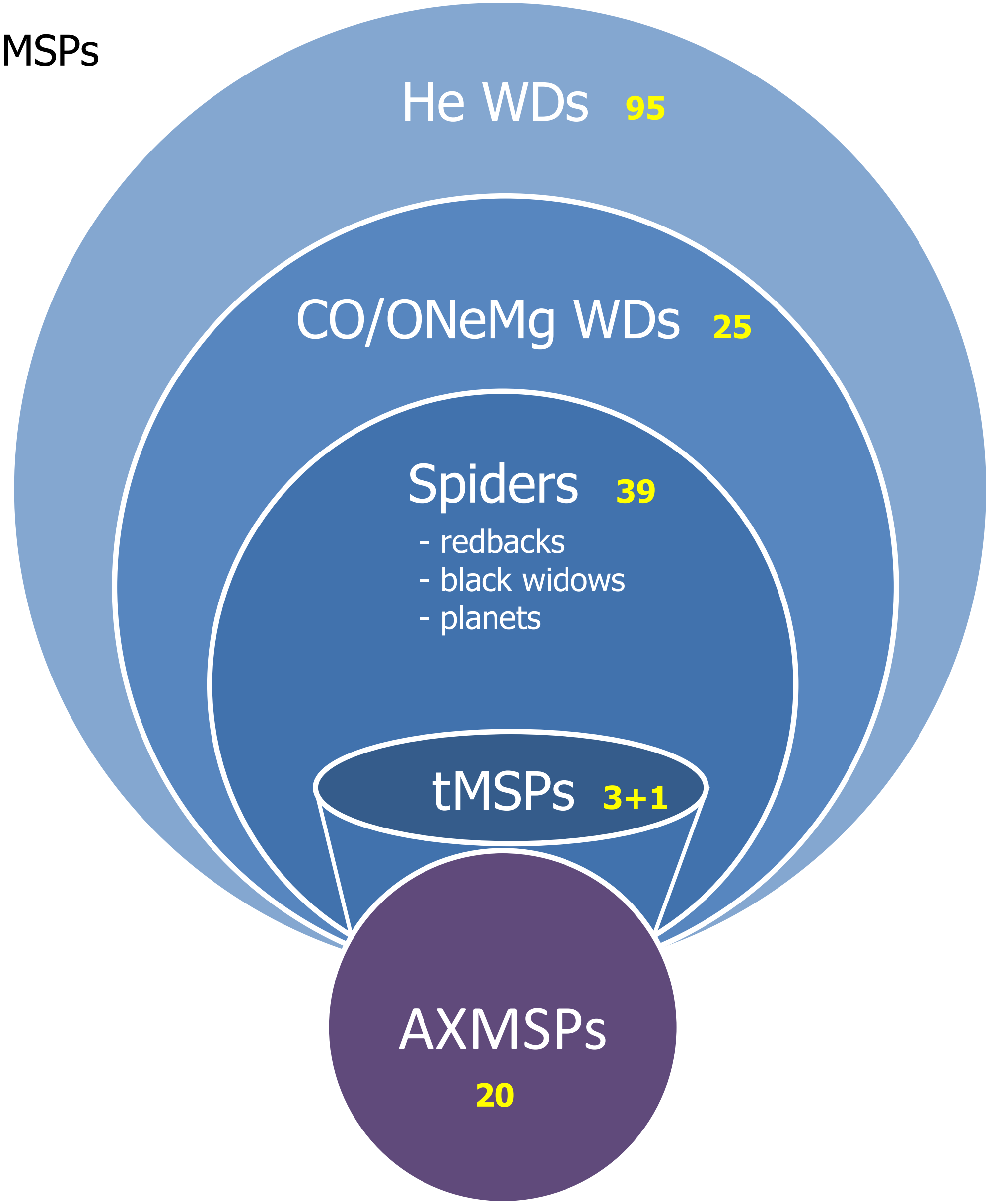
100.000.000 NSs in Milky Way

tip of the iceberg:

- strong B-fields
- rapid spin
- accreting
- hot (newborn)

The MSP population – companion stars

~200 binary MSPs



He WDs **95**

CO/ONeMg WDs **25**

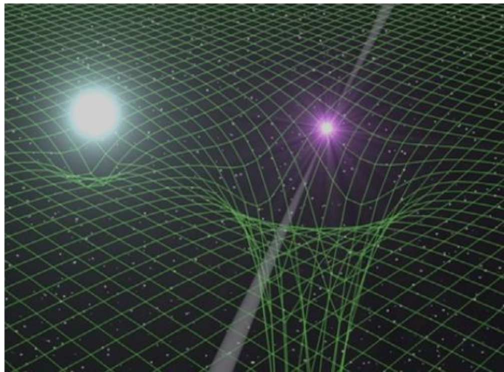
Spiders **39**

- redbacks
- black widows
- planets

tMSPs **3+1**

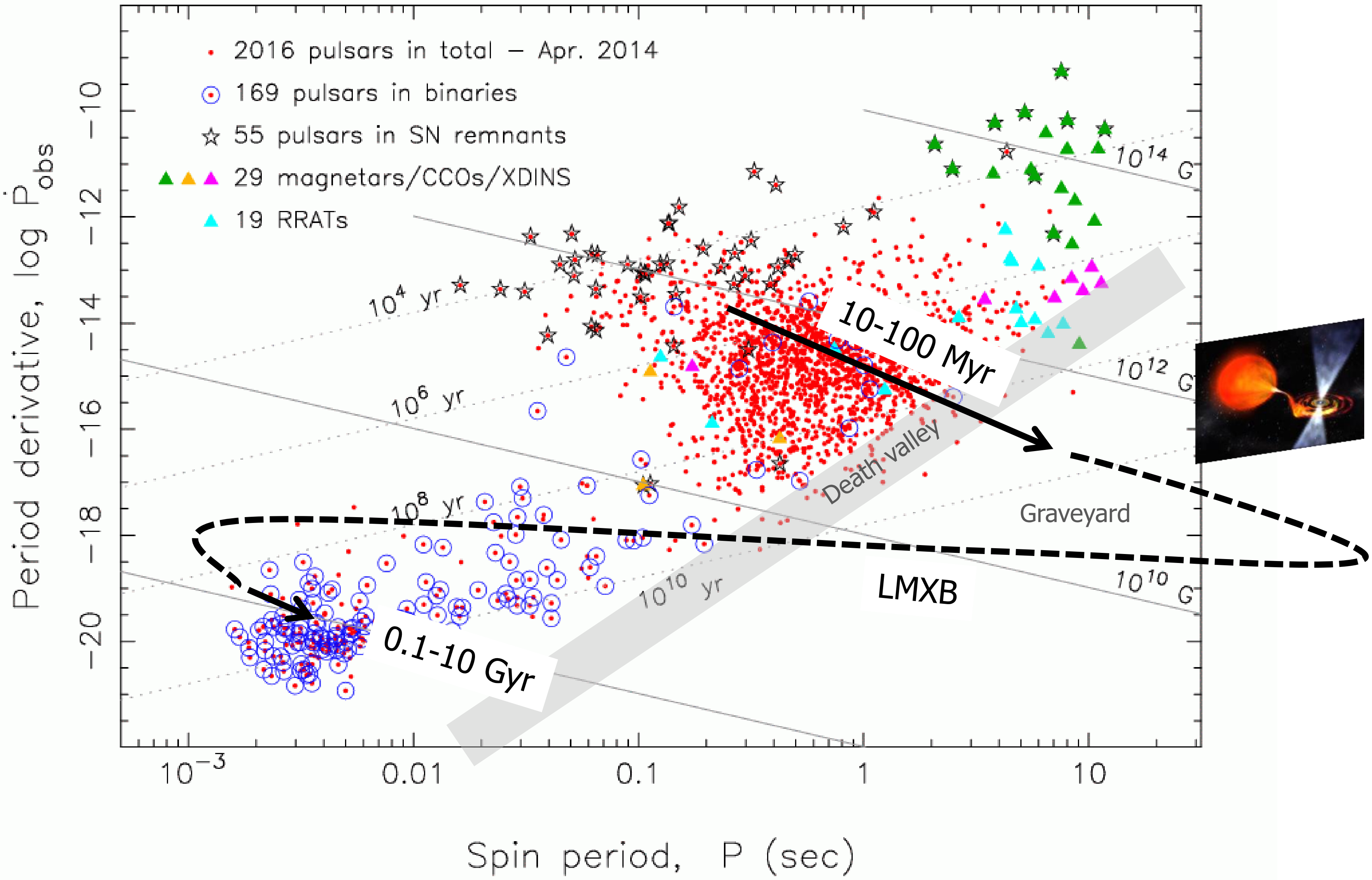
AXMSPs

20

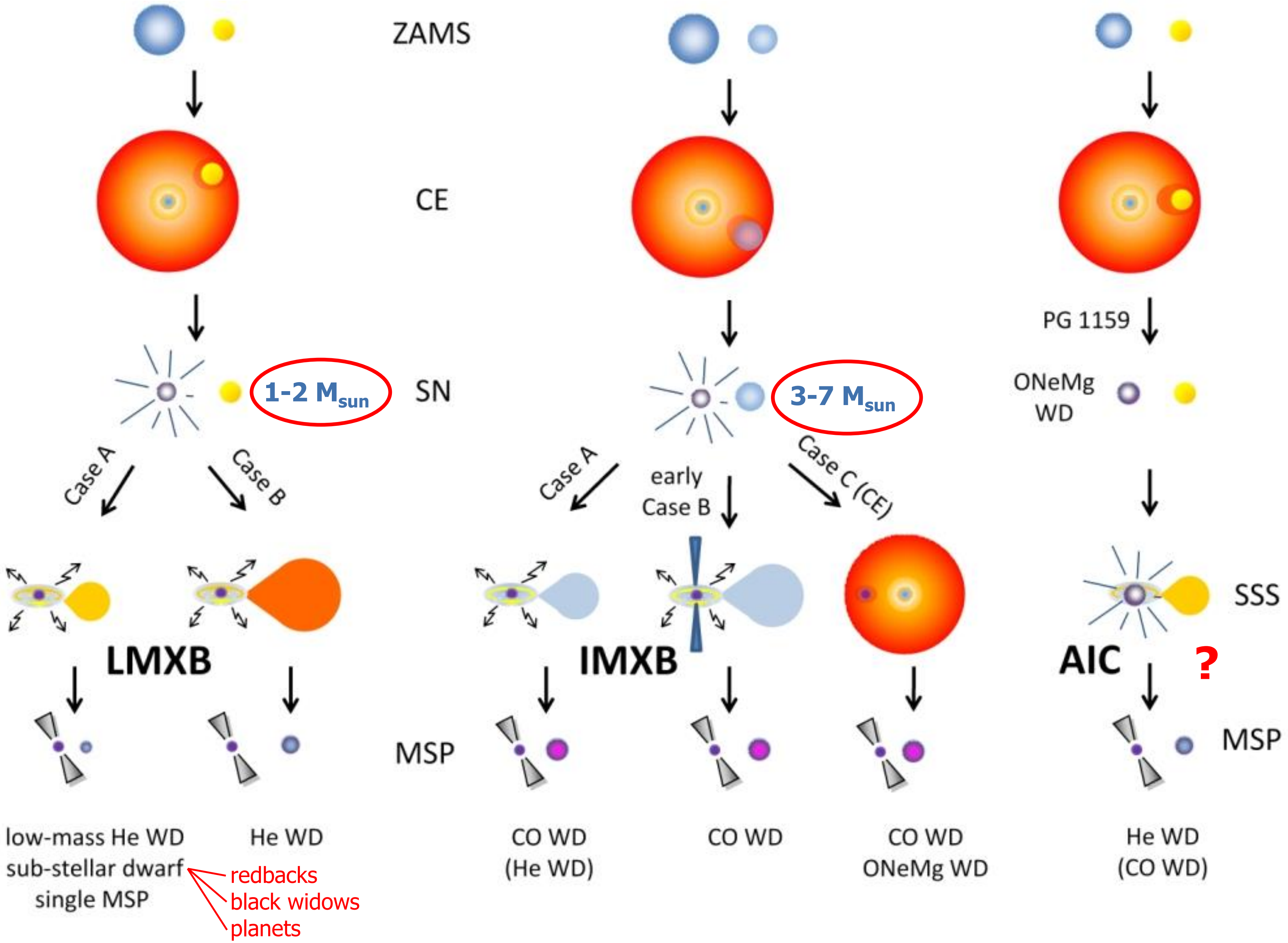


The MSP population - The P-P_{dot} diagram

Tauris, Kaspi, Breton, Deller, et al. (2014)



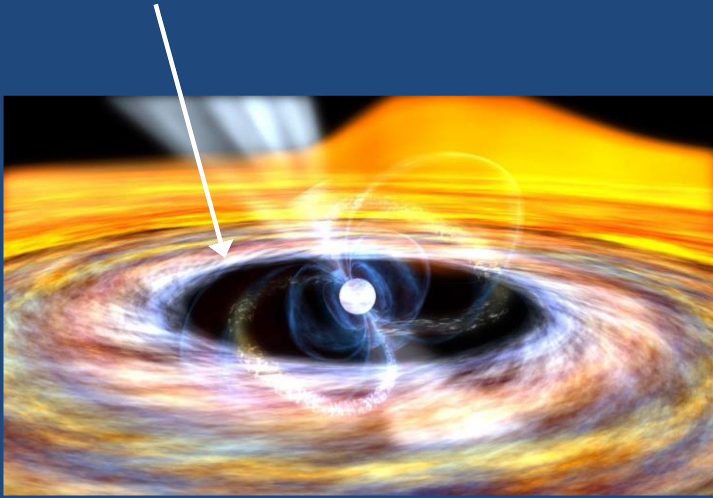
Tauris (2011)


ZAMS
CE
PG 1159
SN
1-2 M_{sun}
3-7 M_{sun}
ONeMg WD
Case A
Case B
Case A
early Case B
Case C (CE)
SSS
LMXB
IMXB
AIC
?
MSP
MSP
low-mass He WD
sub-stellar dwarf
single MSP
redbacks
black widows
planets
He WD
CO WD
(He WD)
CO WD
CO WD
ONeMg WD
He WD
(CO WD)

The MSP population - The standard formation scenario

- Rapid spin: $P < 50\ ms$
- Small period derivative: $\dot{P} < 10^{-17}\ s\,s^{-1}$

$\dot{J} = |\vec{r} \times \vec{p}|$



Ingridients needed for recycling:

- Increase of spin ang. mom.
- Decrease of period derivative

Solution:

- Accretion of mass

$$\boxed{N = \dot{J}_* \equiv \frac{d}{dt}(I\Omega_*) = \dot{M}_* \sqrt{GM_* r_A}\ \xi}$$

Lamb, Pethick & Pines (1973)
Ghosh & Lamb (1979, 1992)

How?

$$\boxed{\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) - \frac{c^2}{4\pi} \nabla \times \left(\frac{1}{\sigma} \times \nabla \times \vec{B} \right)}$$

Geppert & Urpin (1994); Konar & Bhattacharya (1997)

$$\boxed{B = \sqrt{\frac{3c^3 I_{NS}}{8\pi^2 R_{NS}^6} P\dot{P}}}$$

Magnetic-dipole model

The MSP population - The B-field decay

e.g. Bhattacharya (2002)

Why do MSPs have small B-fields?

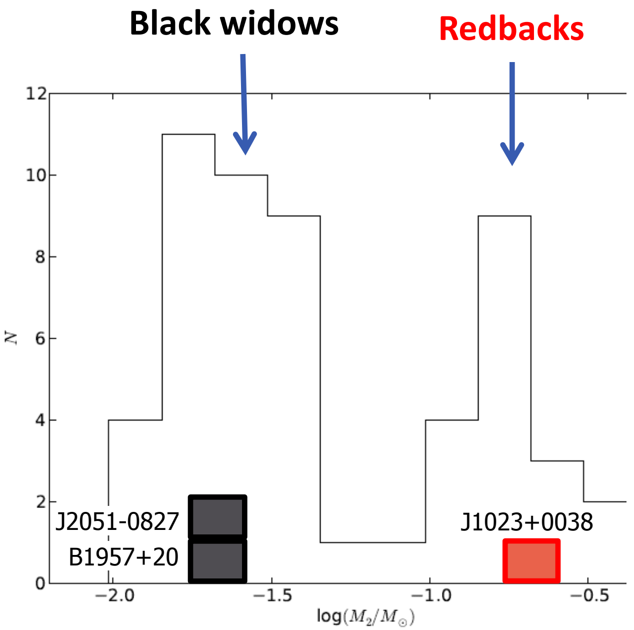
1) Because of accretion:

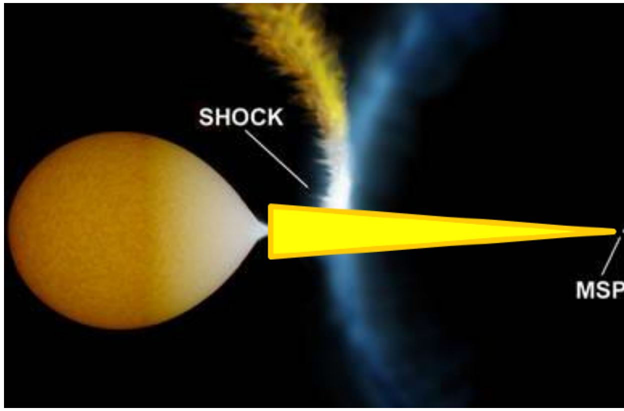
?

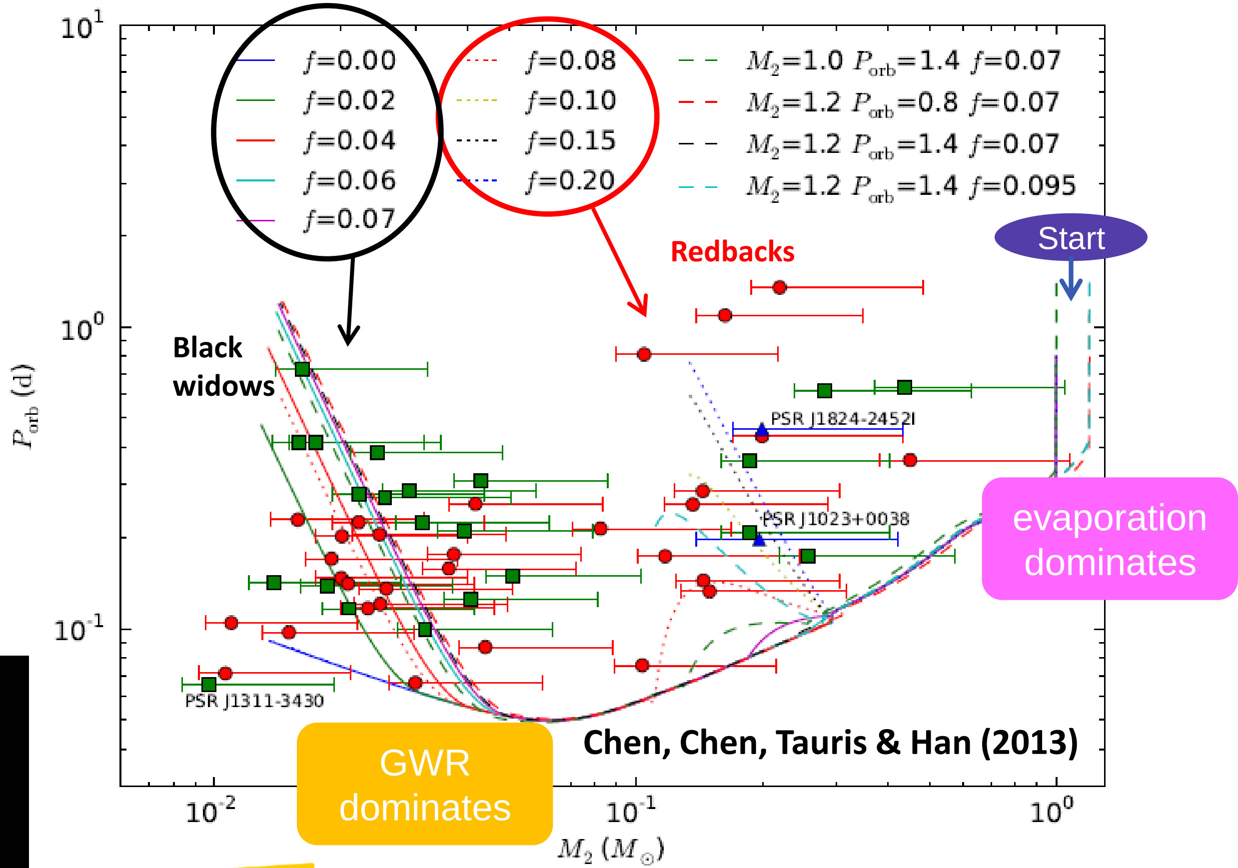
- Ohmic dissipipation and diffusion (crustal heating)
- B-field burial (screening)
- Rotational slow-down → outward motion of votices drag along B-field flux tubes from the core to the curst

2) Because they are old! **(Marilyn Cruces' poster on ambipolar diffusion)**

The MSP population - The Spiders







Chen, Chen, Tauris & Han (2013)

”It’s simply a matter of beaming and geometry…”

The MSP population - The Spiders

- Geometric beaming is likely to be causing the difference between Black widows and Redbacks
  (Chen, Chen, Tauris & Han, 2013, ApJ 775, 27)
- Redbacks do **not** evolve into black widows
  (two distinct populations) but see also Benvenuto et al. (2014) Talk by Horvath
- Do Redbacks eventually produce WDs? Probably not…
  (competition between evaporation and burning of hydrogen)
- **Problem:** poor understanding of magnetic braking
- **Problem:** how/when the radio MSP turns on?
- **Problem:** understanding the accretion and the mechanism of transitional MSPs

Archibald et al. (2009)
Papitto et al. (2013)
Stappers et al. (2014)
Bassa et al. (2014)

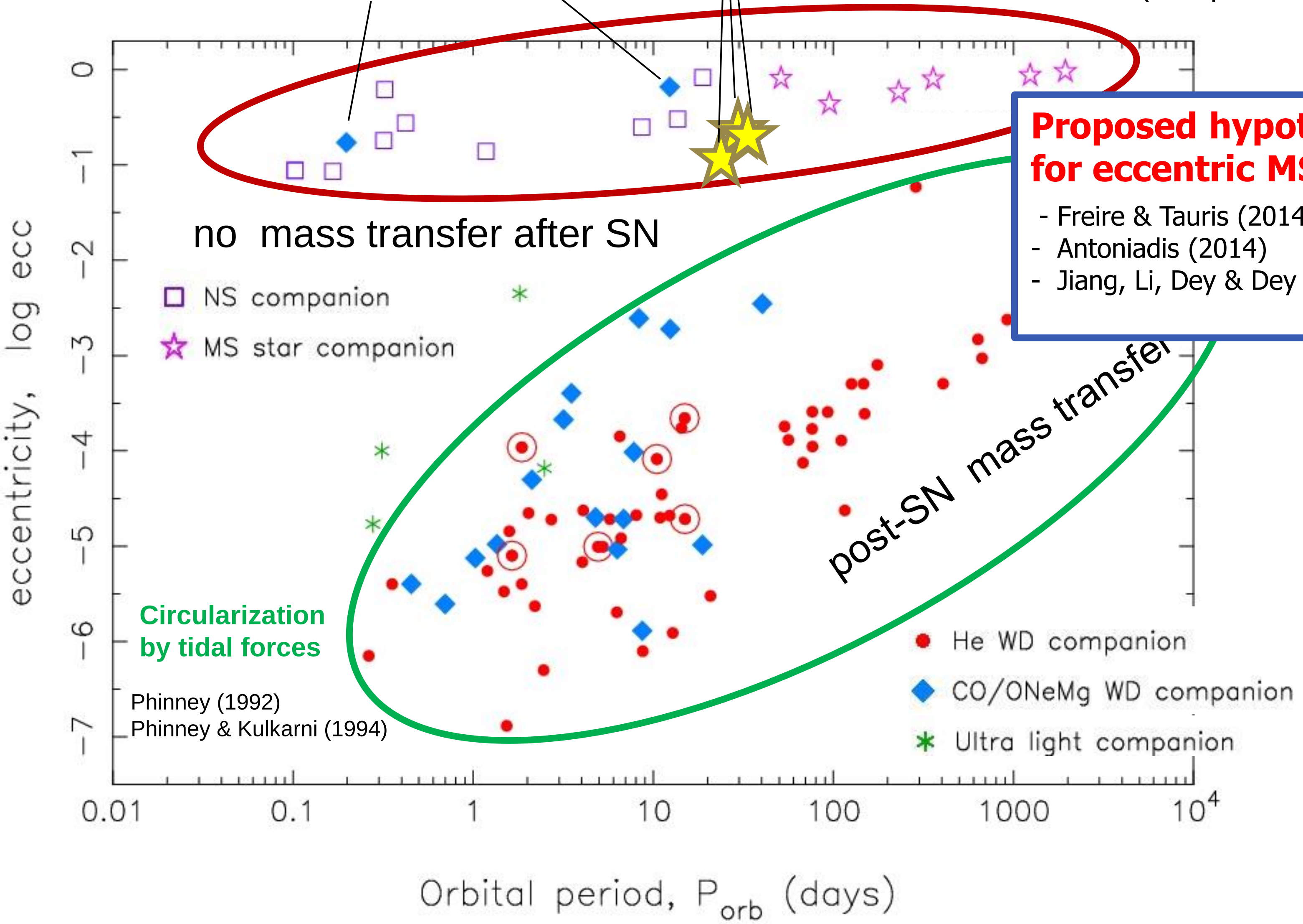
and review by Jason Hessels (2015, BONN VII. NS workshop)

The MSP population - The eccentric MSPs

WDNS systems: PSR B2303+46
(Tauris & Sennels, 2000) PSR J1141-6545

Eccentric MSPs:

PSR J2234+06	(Deneva et al. 2013)
PSR J1946+3417	(Barr et al. 2013)
PSR J1950+2414	(Knispel et al. 2015)



no mass transfer after SN

post-SN mass transfer

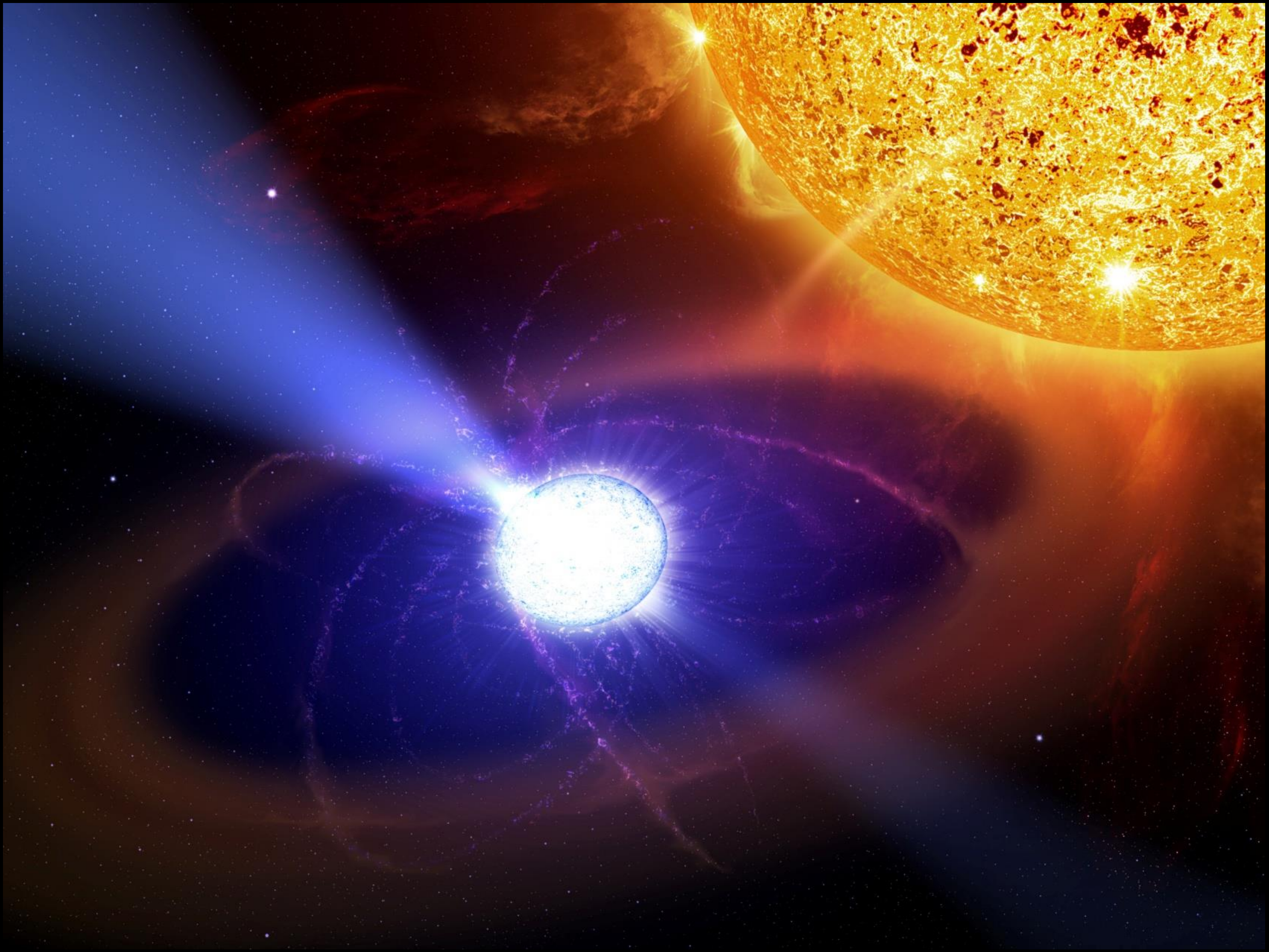
Circularization by tidal forces

Phinney (1992)
Phinney & Kulkarni (1994)

Proposed hypothesis for eccentric MSPs:

- Freire & Tauris (2014)
- Antoniadis (2014)
- Jiang, Li, Dey & Dey (2015)

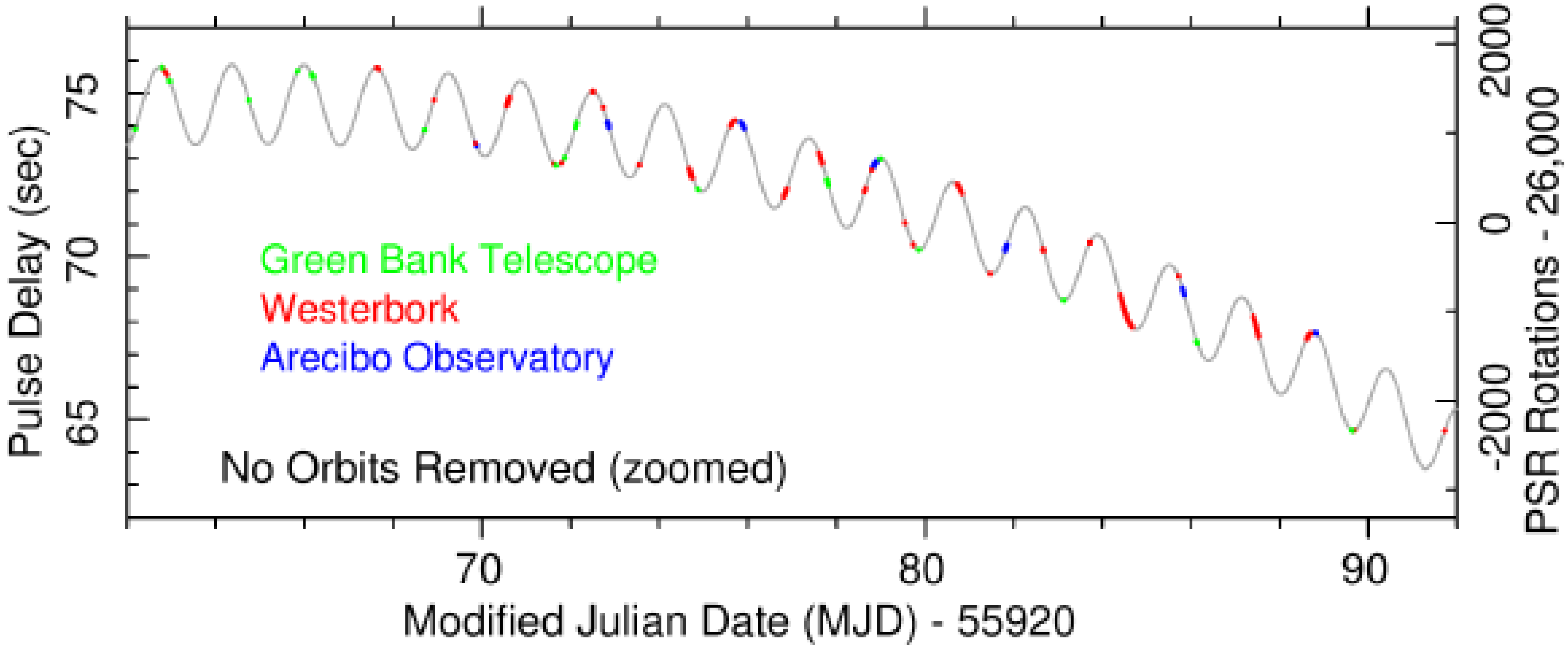
Probing Stellar Evolution using MSPs

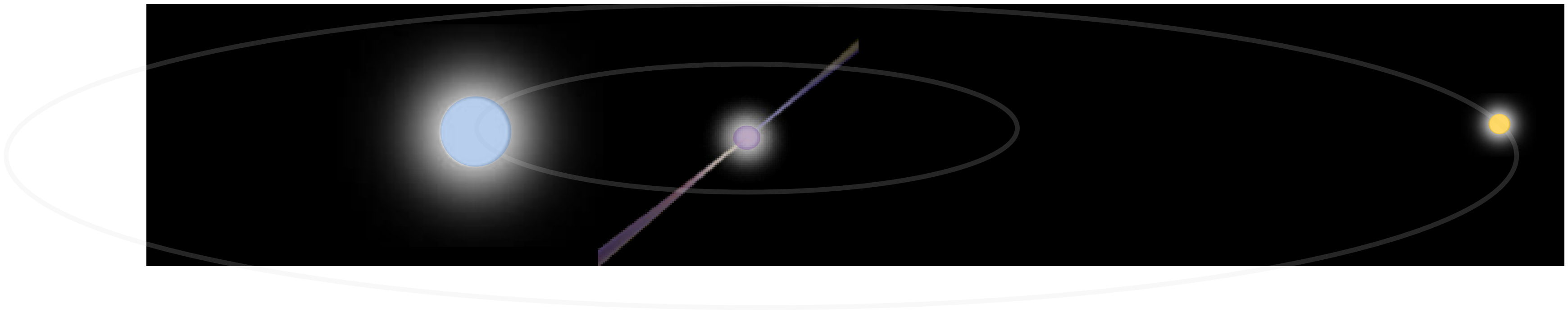


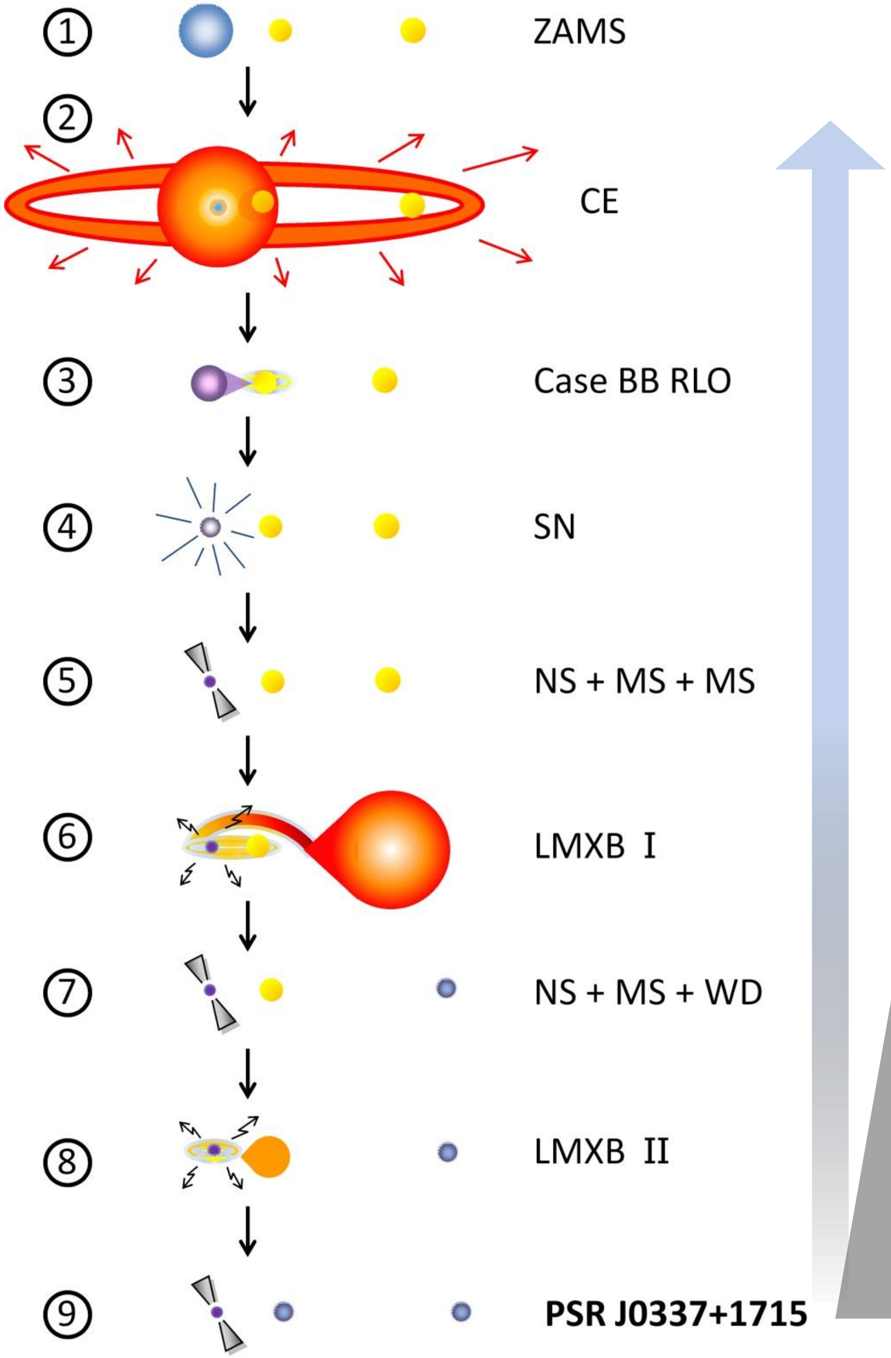
Stellar Evolution and MSPs - The Triple MSP!!!

PSR J0337+1715, a remarkable Galactic triple millisecond pulsar

Discovered by Ransom, Stairs, Archibald, Hessels,... Ransom et al. (2014), Nature 505, 520







① ZAMS

② CE

③ Case BB RLO

④ SN

⑤ NS + MS + MS

⑥ LMXB I

⑦ NS + MS + WD

⑧ LMXB II

⑨ **PSR J0337+1715**

Tauris & van den Heuvel (2014)

Stellar Forensics

Tracing the evolution backwards

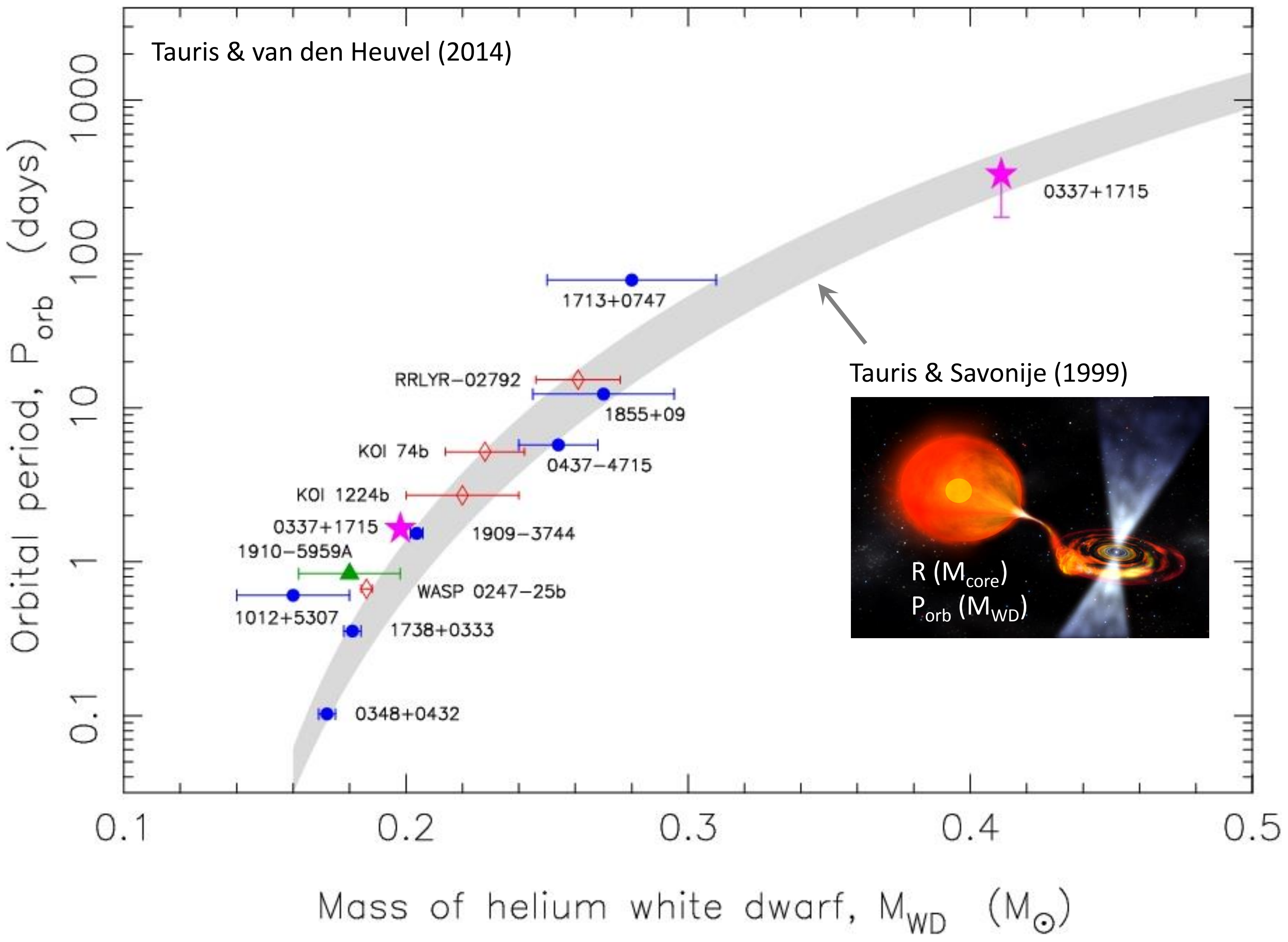
see also Sabach & Soker (2015)

- Applying constraints from knowledge of stellar evolution and mass tranfer (RLO).
- Simulations of the dynamical effects of the supernova explosion.
- At all stages ensuring that the triple remains dynamically *stable* on a long timescale.

Millisecond pulsar mass:	$1.438\ M_\odot$
inner WD mass:	$0.197\ M_\odot$
inner WD temp:	$15\,800\ K$
inner P_{orb}:	1.63 days
inner ecc:	0.00069
outer WD mass:	$0.410\ M_\odot$
outer P_{orb}:	327 days
outer ecc:	0.035
angle between orb. planes:	0.01°

Ransom et al. (2014), Kaplan et al. (2014)

Stellar Evolution and MSPs - The M_{WD} – P_{orb} correlation



Tauris & van den Heuvel (2014)

Tauris & Savonije (1999)

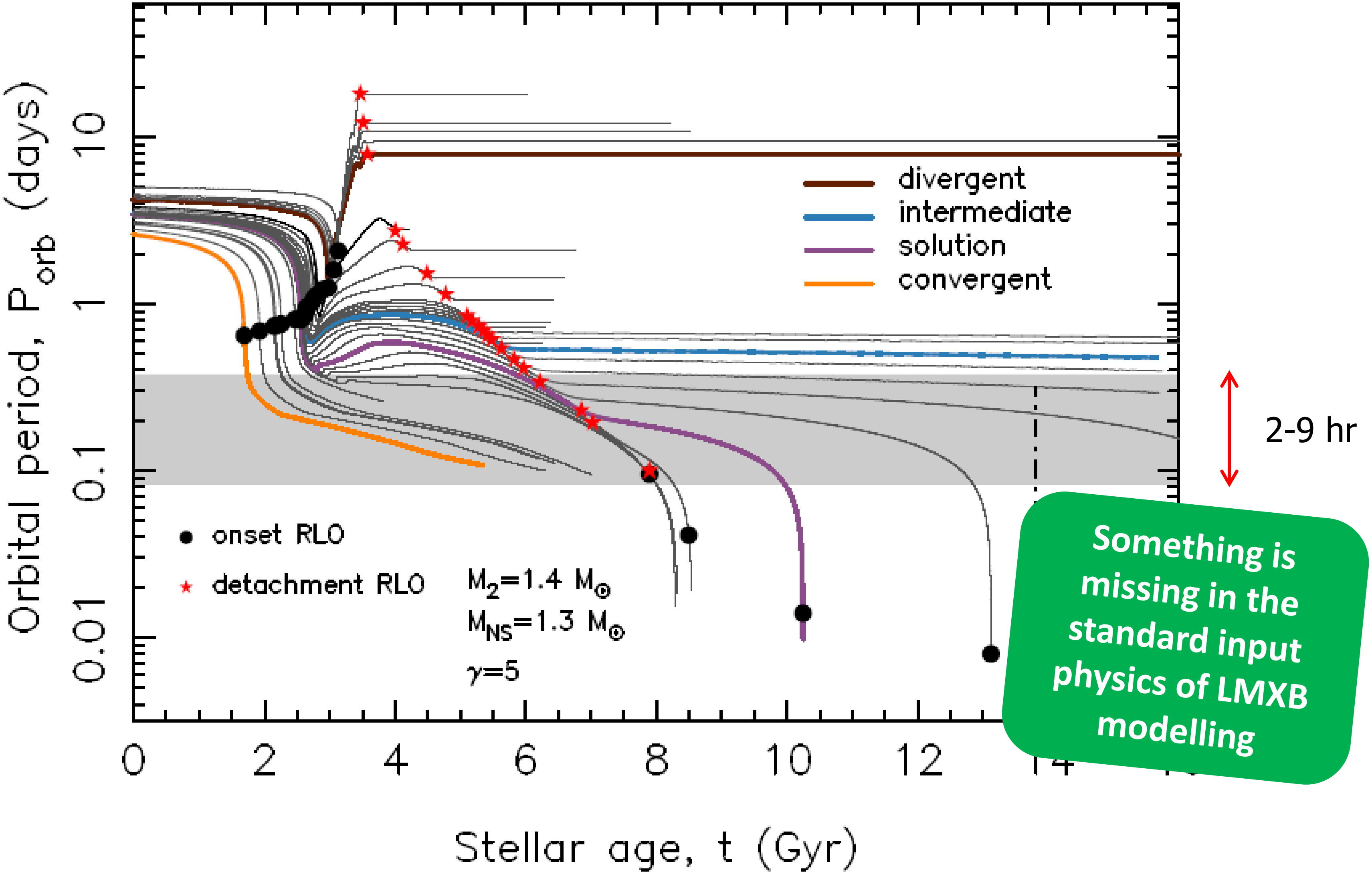
R (M_{core})

P_{orb} (M_{WD})

Puzzles: bifurcation period of LMXBs / tight binary MSPs with He-WDs

Pylyser & Savonije (1988, 1989), van den Sluys, Verbunt & Pols (2005), Ma & Li (2009)

Istrate, Tauris & Langer (2014)



Something is missing in the standard input physics of LMXB modelling

Puzzles: Observational evidence for AIC ?

Tauris, Debashis, Yoon & Langer (2013)

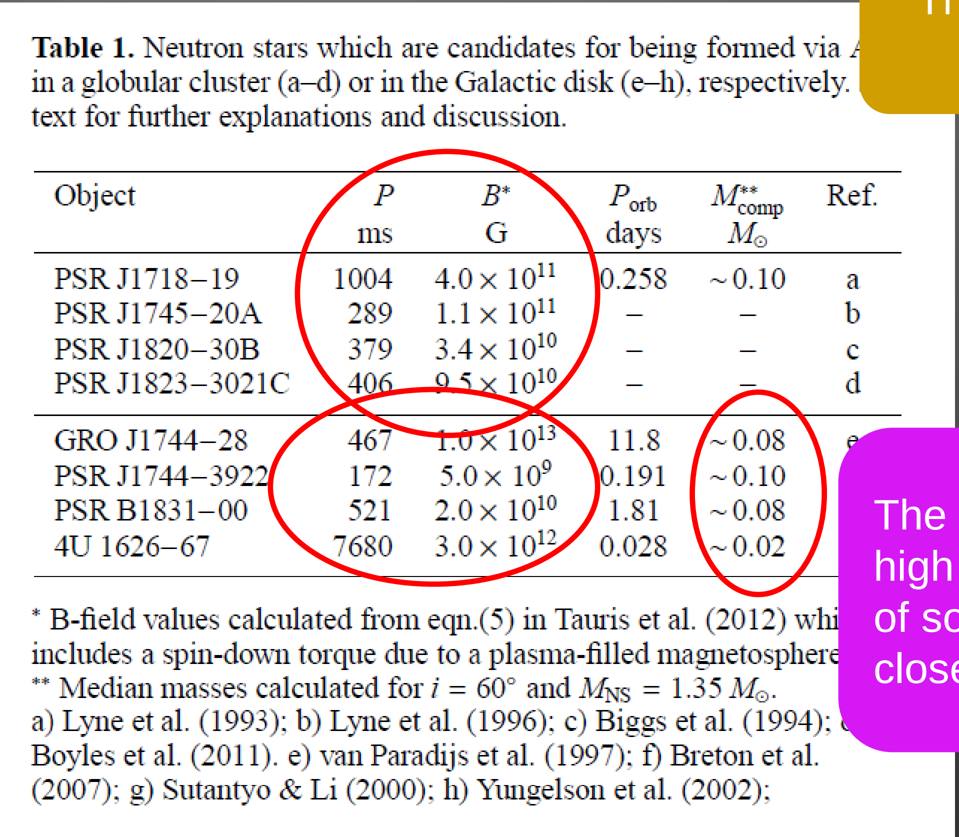


Table 1. Neutron stars which are candidates for being formed via in a globular cluster (a–d) or in the Galactic disk (e–h), respectively. text for further explanations and discussion.

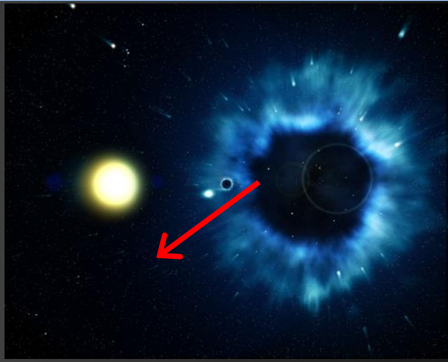
Object	P ms	B^* G	$P_{\rm orb}$ days	$M_{\rm comp}^{**}$ $M_\odot$	Ref.
PSR J1718–19	1004	4.0×10^{11}	0.258	~0.10	a
PSR J1745–20A	289	1.1×10^{11}	–	–	b
PSR J1820–30B	379	3.4×10^{10}	–	–	c
PSR J1823–3021C	406	9.5×10^{10}	–	–	d
GRO J1744–28	467	1.0×10^{13}	11.8	~0.08	e
PSR J1744–3922	172	5.0×10^{9}	0.191	~0.10	
PSR B1831–00	521	2.0×10^{10}	1.81	~0.08	
4U 1626–67	7680	3.0×10^{12}	0.028	~0.02	

* B-field values calculated from eqn.(5) in Tauris et al. (2012) whi includes a spin-down torque due to a plasma-filled magnetosphere

** Median masses calculated for $i = 60°$ and $M_{\rm NS} = 1.35\ M_\odot$.

a) Lyne et al. (1993); b) Lyne et al. (1996); c) Biggs et al. (1994); Boyles et al. (2011). e) van Paradijs et al. (1997); f) Breton et al. (2007); g) Sutantyo & Li (2000); h) Yungelson et al. (2002);

Low space velocities
of some NS binaries
\+ the retention of NS
in globular clusters



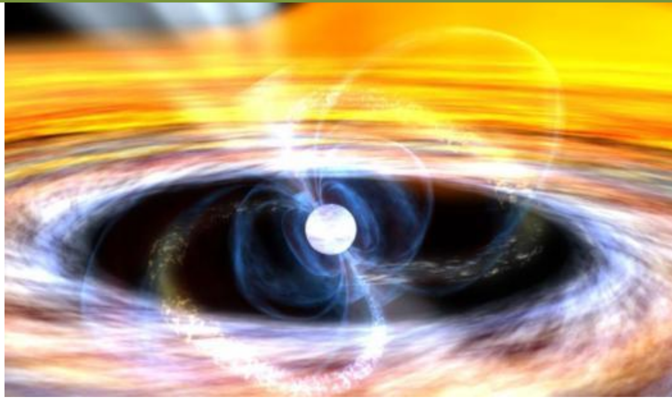
The apparently *young* NS
in globular clusters

÷ SN II, I b/c, EC

\+ AIC

The peculiar, relatively
high B-fields and slow spins
of some Galactic NS in
close binaries

Pulsar Recycling - accretion physics



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

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

spin-up line in $P\dot{P}$ – diagram

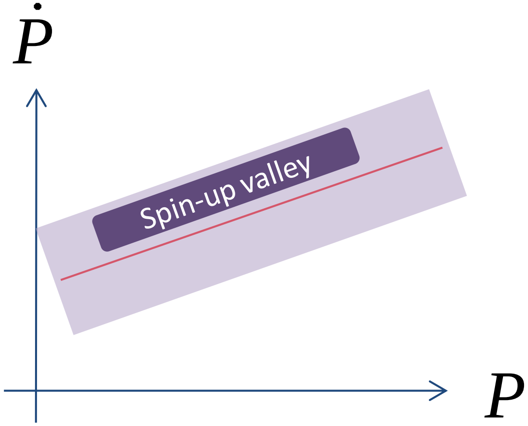
Tauris, Langer & Kramer (2012)

Important!

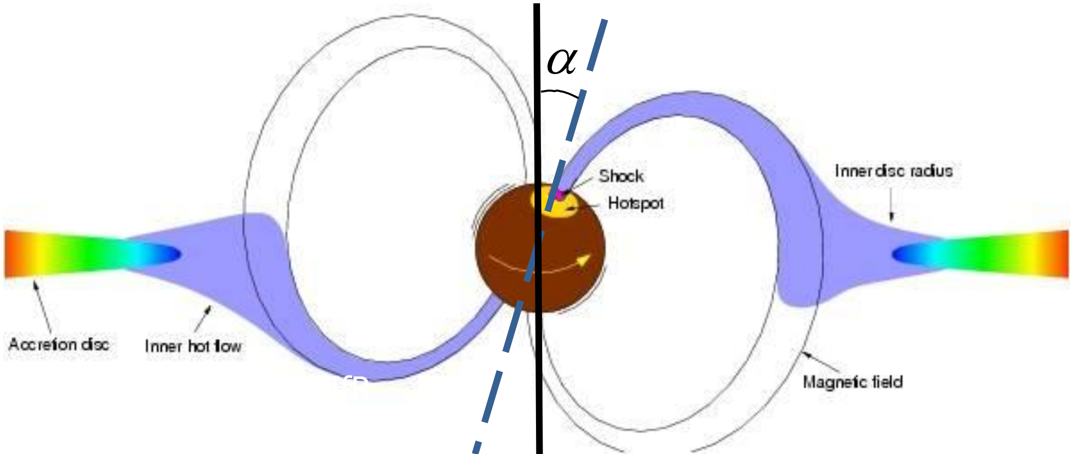
disk –magnetosphere parameters:

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

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



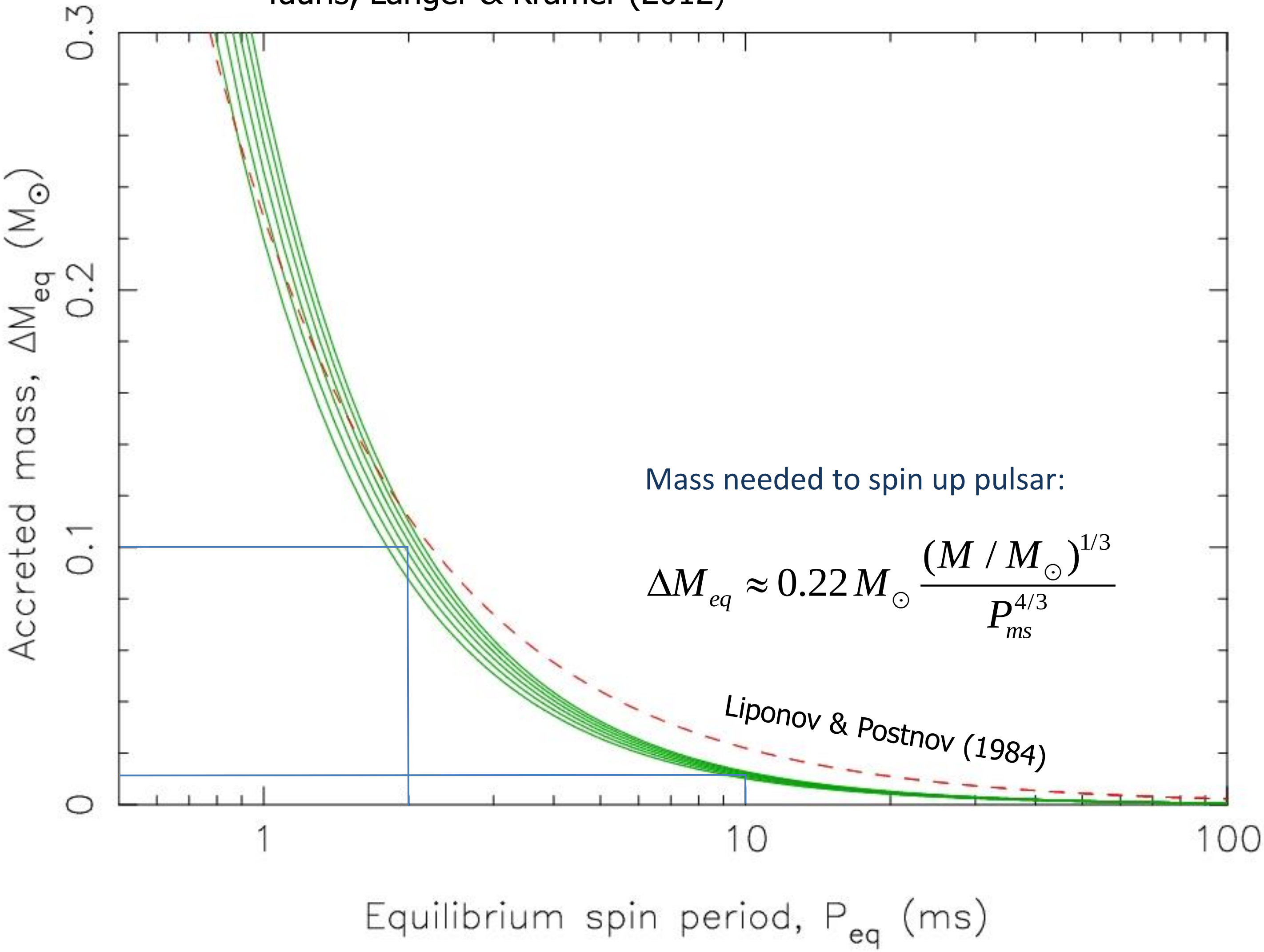
Classical spin-up line
e.g. Bhattacharya & van den Heuvel (1991)



Pulsar Recycling - amount of accreted mass

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

Tauris, Langer & Kramer (2012)



Mass needed to spin up pulsar:

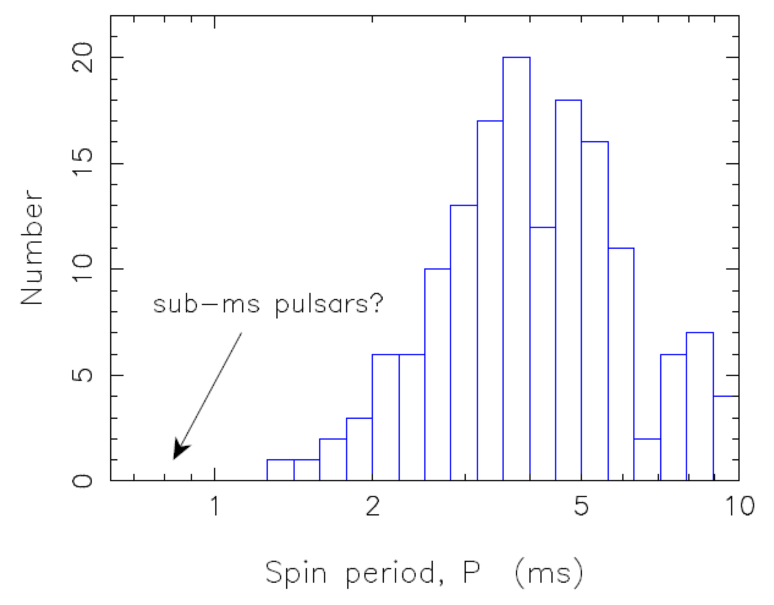
$$\Delta M_{eq} \approx 0.22\,M_\odot \frac{(M/M_\odot)^{1/3}}{P_{ms}^{4/3}}$$

P (ms)	**M** (M_{sun})
0.7	0.40
2	0.10
5	0.03
10	0.01
50	0.001

Puzzles: missing sub-ms MSPs

Where are the sub-ms MSPs?

- Speed limit caused by GW
  (Bildsten 1998, Chakrabarty et al. 2003)
  - however, see also Patruno et al. (2012)
- RLDP (Tauris 2012)
- Observational selection effects (….no)
- Magnetospheric conditions are not satisfied
  (Lamb & Yu 2005)



Tauris et al. (2014)
SKA Science Book

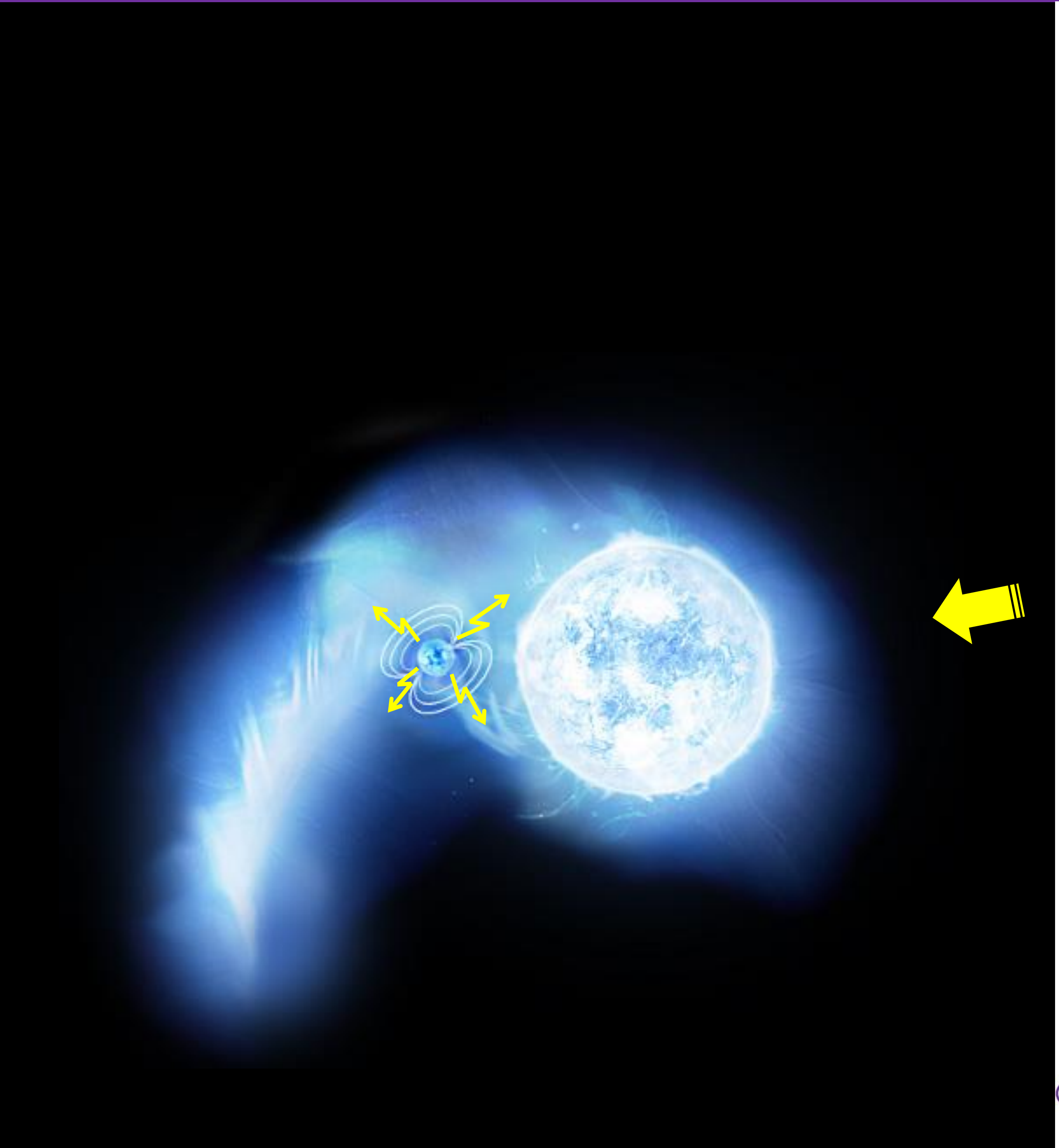
$$P_{eq} \approx 1.40\,ms \cdot B_8^{6/7} \left(\frac{\dot{M}}{0.1\dot{M}_{Edd}} \right)^{-3/7} \left(\frac{M}{1.4\,M_\odot} \right)^{-5/7} R_{13}^{18/7}$$

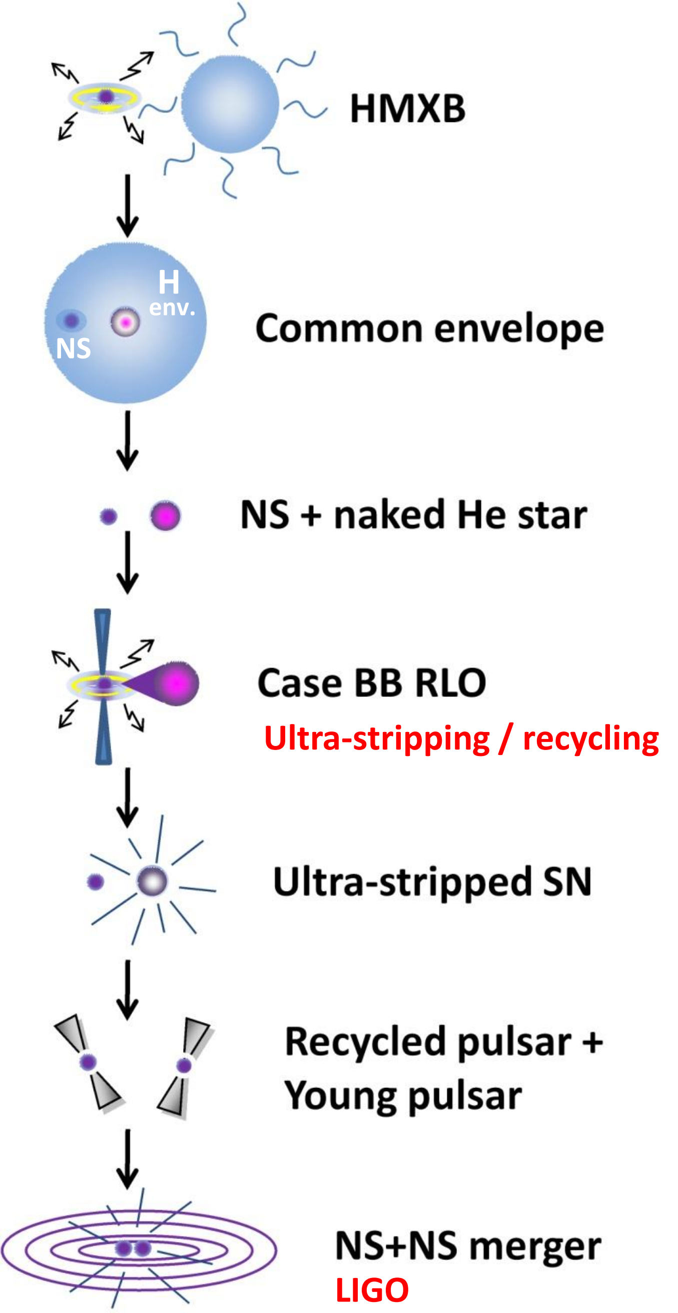
Problem: those LMXB systems which experience the largest values of M_{dot} are short lived → B high and less net accretion onto NS → no sub-ms MSP

and vice versa: those LMXB systems in which the NSs have small B-fields had a long lived RLO → low-mass donors → small values of M_{dot} → no sub-ms MSP

+ torque is small for a magnetosphere close to the NS → requires a long spin-up timescale

Ultra-stripped SNe – Double NS systems





HMXB

Common envelope

NS + naked He star

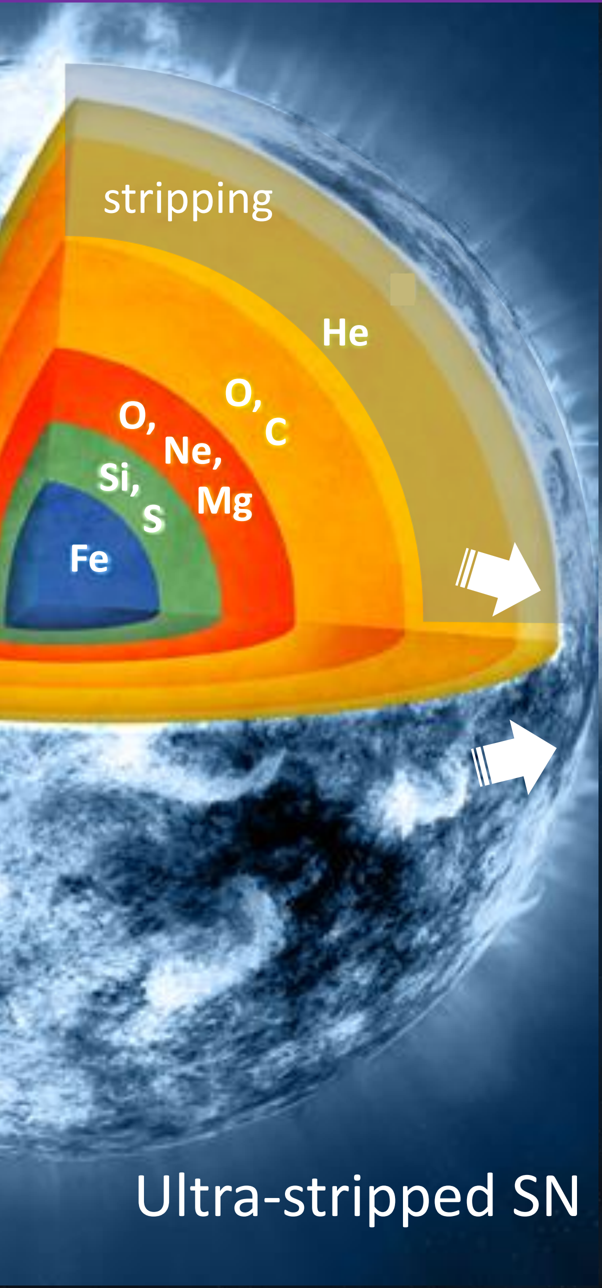
Case BB RLO
Ultra-stripping / recycling

Ultra-stripped SN

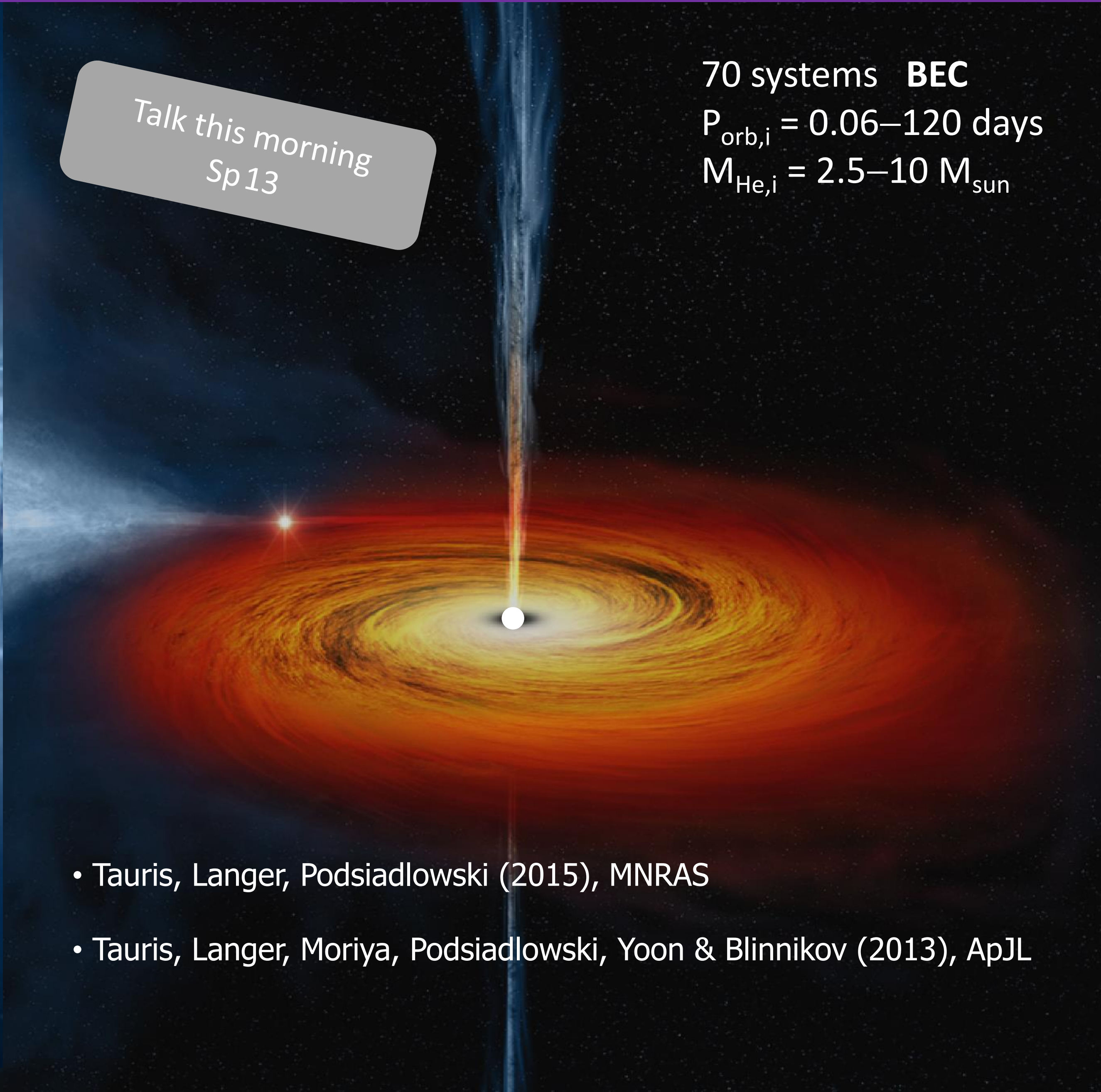
Recycled pulsar +
Young pulsar

NS+NS merger
LIGO

Ultra-stripped SNe – Double NS systems



Ultra-stripped SN



Talk this morning
Sp 13

70 systems **BEC**

$P_{orb,i}$ = 0.06–120 days

$M_{He,i}$ = 2.5–10 M_{sun}

- Tauris, Langer, Podsiadlowski (2015), MNRAS
- Tauris, Langer, Moriya, Podsiadlowski, Yoon & Blinnikov (2013), ApJL

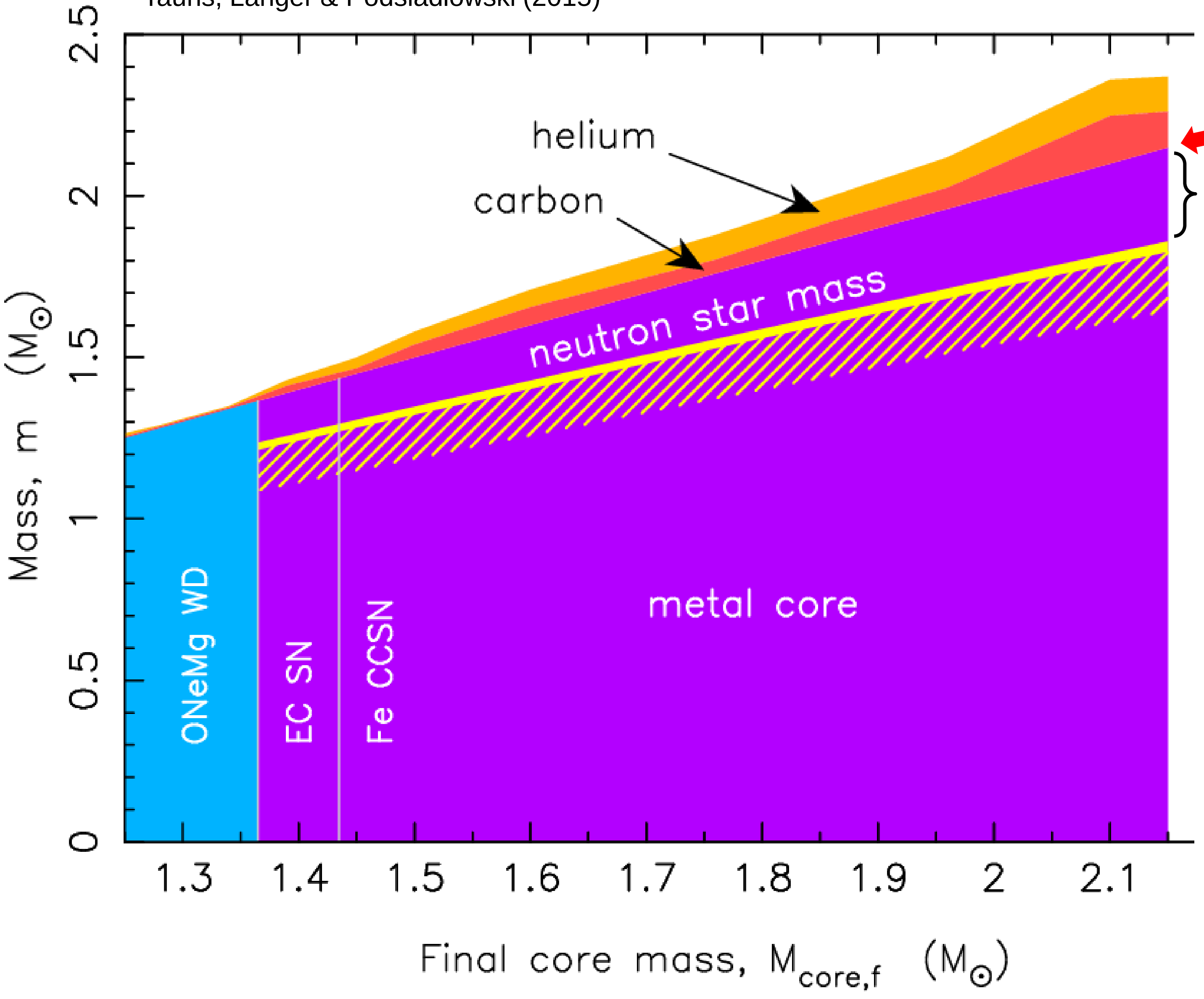
Double Neutron Star Systems

🟪 = ultra-stripped EC / Fe CCSN
candidates

		P (ms)	P_{dot} (10^{-18})	P_{orb} (d)	ecc	M_{psr} / M_{comp}	M_{total}
recycled	J0453+1559	45.8	0.19	4.07	0.11	1.61 / 1.17	2.78
recycled young	J0737-3039 A B	22.7 2773.5	1.8 892	0.10	0.09	1.34 1.25	2.59
recycled	J1518+4904	40.9	0.022	8.63	0.25	? / ?	2.72
recycled	B1534+12	37.9	2.4	0.42	0.27	1.33 / 1.35	2.68
recycled	J1753-2240	95.1	0.79	13.64	0.30	?	?
young	J1755-25? **Cherry**	315.2	2470	9.70	0.09	? / >0.40	?
recycled	J1756-2251	28.5	1.0	0.32	0.18	1.34 / 1.23	2.57
recycled	J1811-1736	104.2	0.90	18.78	0.83	<1.64 / >0.93	2.60
recycled	J1829+2456	41.0	0.053	1.18	0.14	<1.38 / >1.22	2.59
young	J1906+0746	144.1	20300	0.17	0.09	1.29 / 1.32	2.61
recycled	New **PALFA** Lazarus et al.	27.3	0.15	0.20	0.09	?	2.86
recycled	B1913+16	59.0	8.6	0.32	0.62	1.44 / 1.39	2.83
recycled	J1930-1852	185.5	18.0	45.06	0.40	<1.29/ >1.30	2.59
GC	J1807-2500B	4.2	8.2*	9.96	0.75	1.37 / 1.21	2.57
GC	B2127+11C	30.5	5.0	0.34	0.68	1.36 / 1.35	2.71

Ultra-stripped SNe – Pre-SN cross-sections

Tauris, Langer & Podsiadlowski (2015)

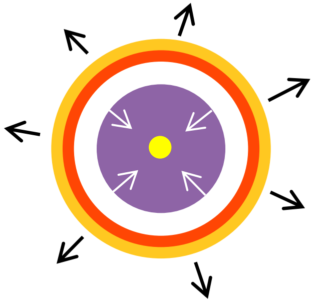


If SN mass cut is here…

E_{bind}

Lattimer & Yahil (1989)

$$M_{NS} \approx 1.10 - 1.80\ M_{\odot}$$

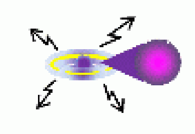


Small kicks? (yes)

$$P_{orb,i} = 0.1\ \text{days}$$

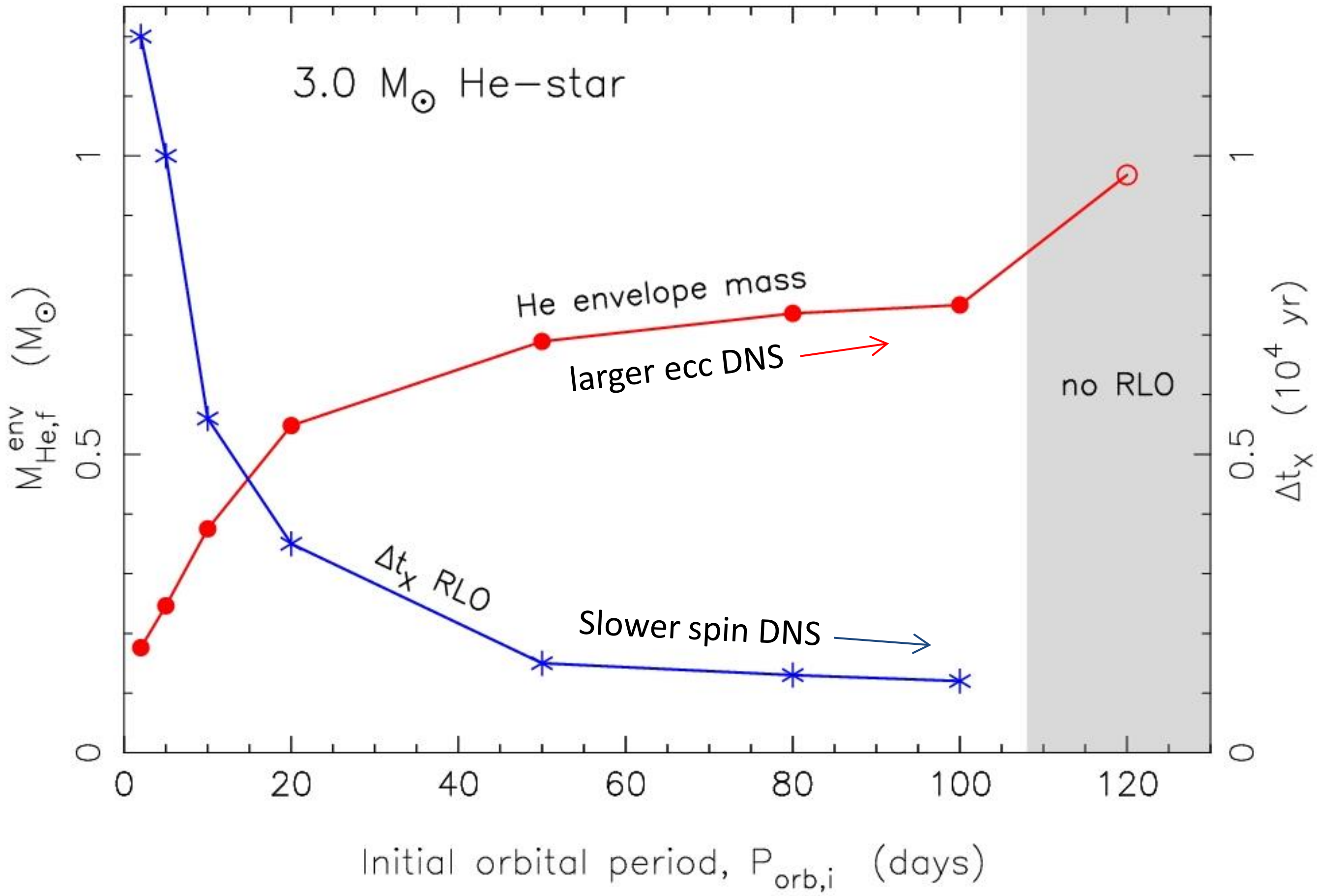
$$M_{He,i} = 2.5 - 6.0\ M_{\odot}$$

DNS (P$_{orb}$ – P$_{spin}$) and (P$_{orb}$ – ecc) correlations



$$P_{orb}\uparrow \;\Rightarrow\; \Delta t_X\downarrow \;\Rightarrow\; \Delta M_{NS}\downarrow \;\Rightarrow\; P_{spin}\uparrow$$

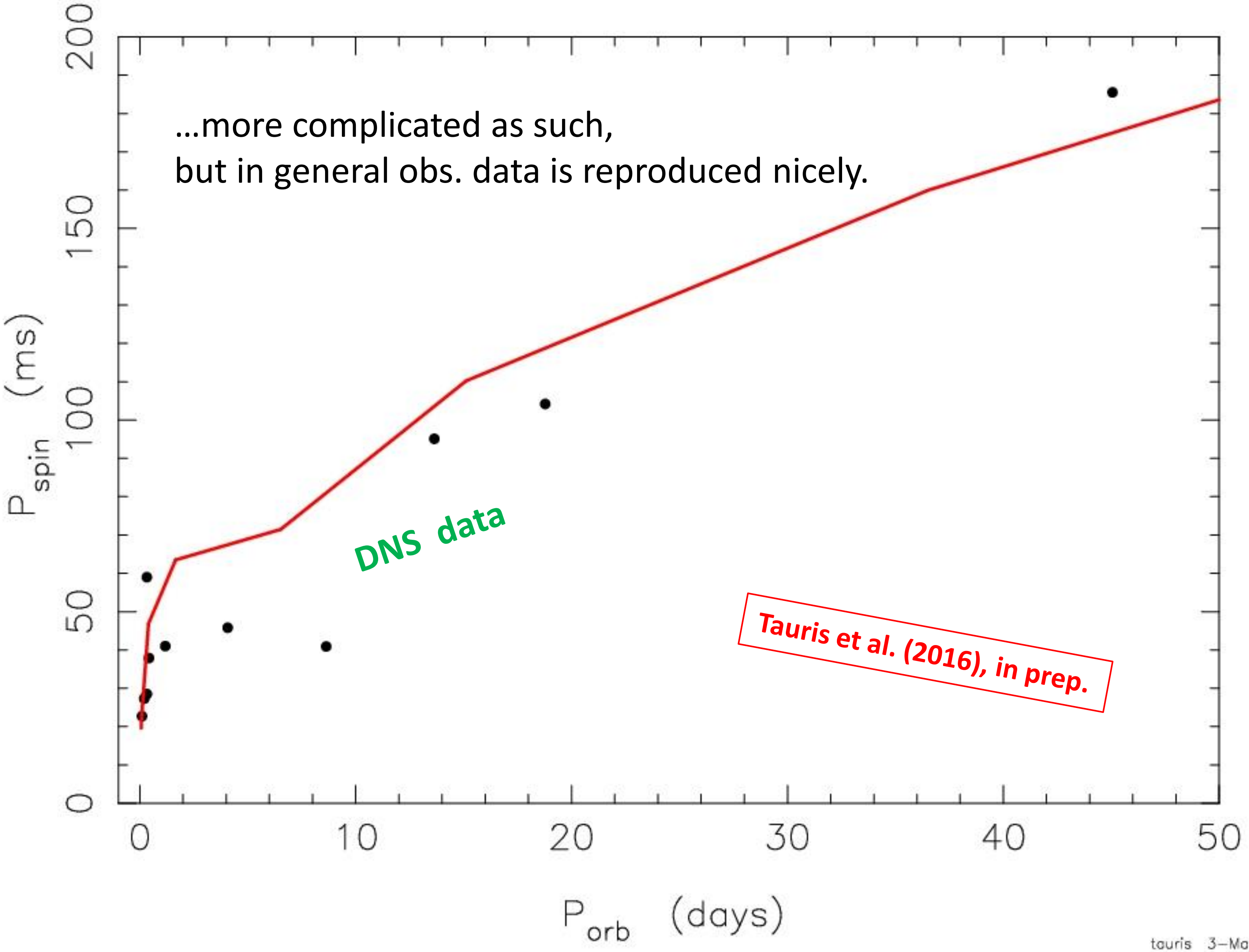
Tauris, Langer & Podsiadlowski (2015)



larger ecc DNS

Slower spin DNS

DNS $P_{orb} - P_{spin}$ correlation



…more complicated as such,
but in general obs. data is reproduced nicely.

Tauris et al. (2016), in prep.

tauris 3–May–2015 13:36

Merging Neutron Stars - LIGO detection rate

DFG project
Matthias Krukow

RECIPE

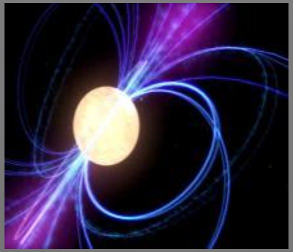
- Binary stellar evolution
  - Stellar rotation
  - WR-stars (winds)
  - CE evolution
  - SN kicks
- Population synthesis
  (input distributions and stellar grids)
- Galactic star formation rate
  (formation history of massive binaries)
- Galactic potentials
  (to probe location of mergers in host galaxies)
- Extrapolation to local Universe
  (scaling-law of galaxy number density)

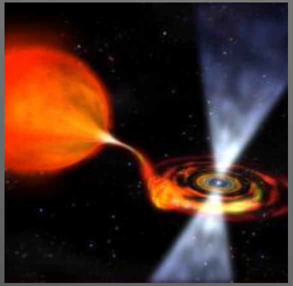
Range:
NSNS merger 200 Mpc
NSBH merger 450 Mpc
BHBH merger 0.7 Gpc
(Z=0.2)

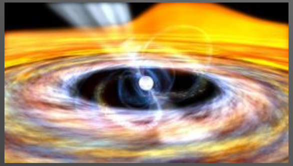
LIGO event rate:
1 per week
(Milky Way: 1 Myr $^{-1}$)

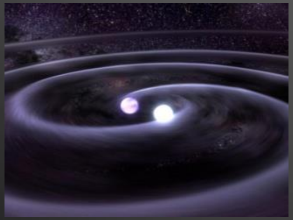
Highly uncertain

Conclusions









- **The last decade has revealed new interesting MSPs**
  - **The spiders, The transitional MSPs (tMSPs), The eccentric MSPs**
- **New MSPs keep challenging Stellar Evolution**
  - **The Triple MSP ….and other puzzling MSP systems**

But also well-constrained behaviour...

  - **The (M_{WD}, P_{ORB}) - correlation**
- **The recycling phase revisited**
  - **The spin-up line should be replaced with a ’spin-up valley’**
  - **Characteristic ages of MSPs are pretty useless as age estimators**
  - **The non-existence of sub-ms MSPs is perhaps not surprising**
- **Formation of double neutron star (DNS) systems**
  - **Ultra-stripped SNe often lead to small kicks**
  - **(P_{orb},P_{spin}) and (P_{orb},ecc) - correlations in DNS systems**
- **LIGO/VIRGO merger rates**
  - **DNS: 1 Myr^{-1} $MWGal^{-1}$ → Detection of 1 $week^{-1}$ (~ factor 100)**