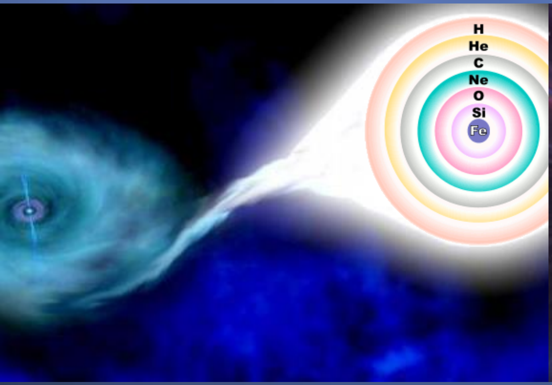
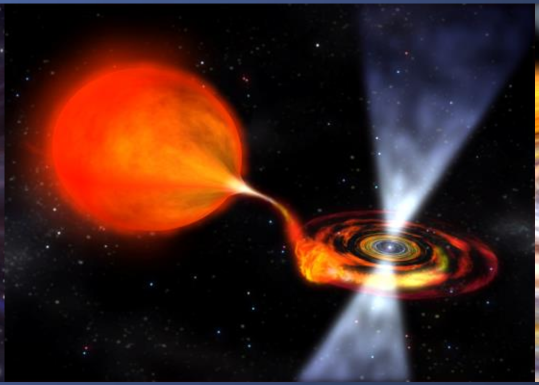
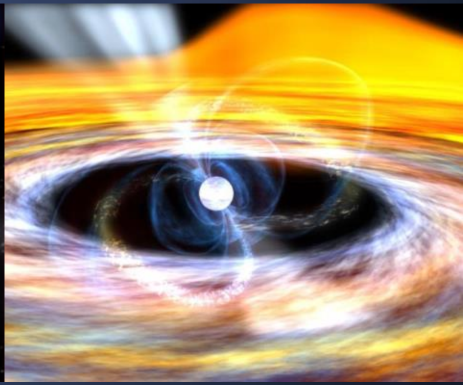
FORMATION OF MILLISECOND PULSARS AND DOUBLE NEUTRON STARS



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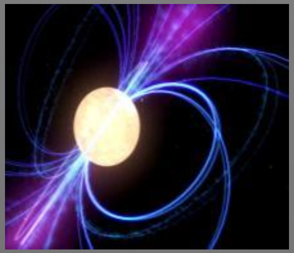
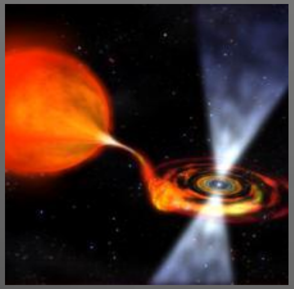
Max-Planck-Institut für Radioastronomie

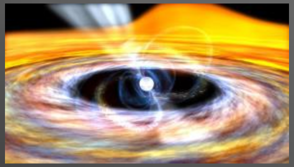
Agenda



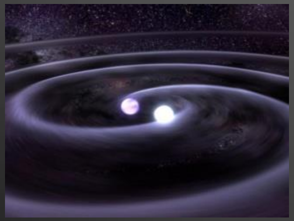
- Overview of the MSP population



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



- The recycling phase and accretion physics



- Formation of double neutron star systems

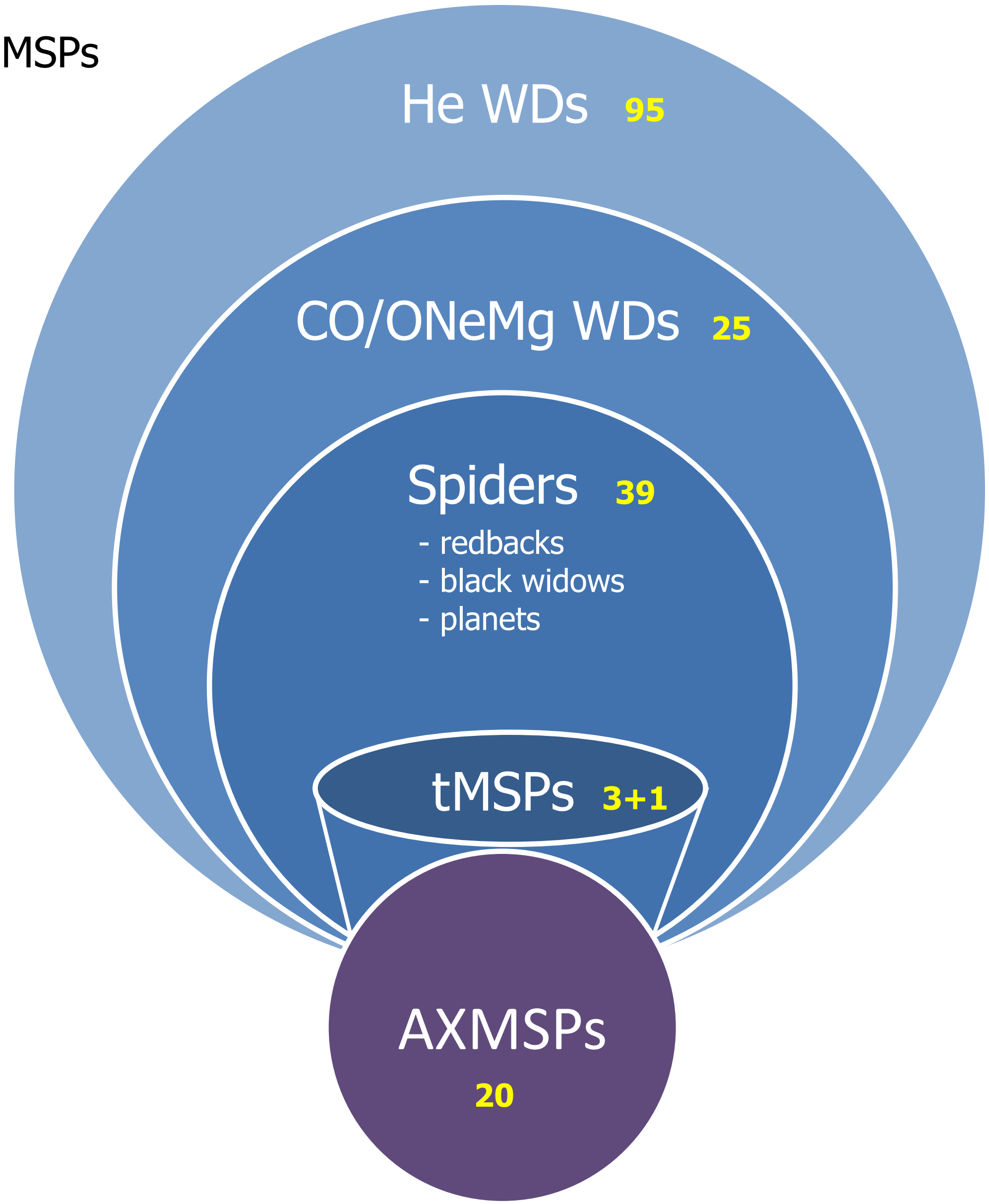
The NS population

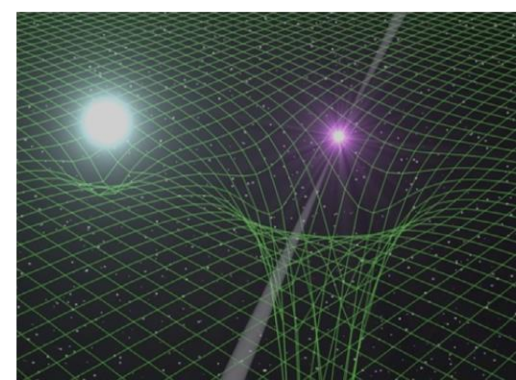
tip of the iceberg:

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

The MSP population – companion stars

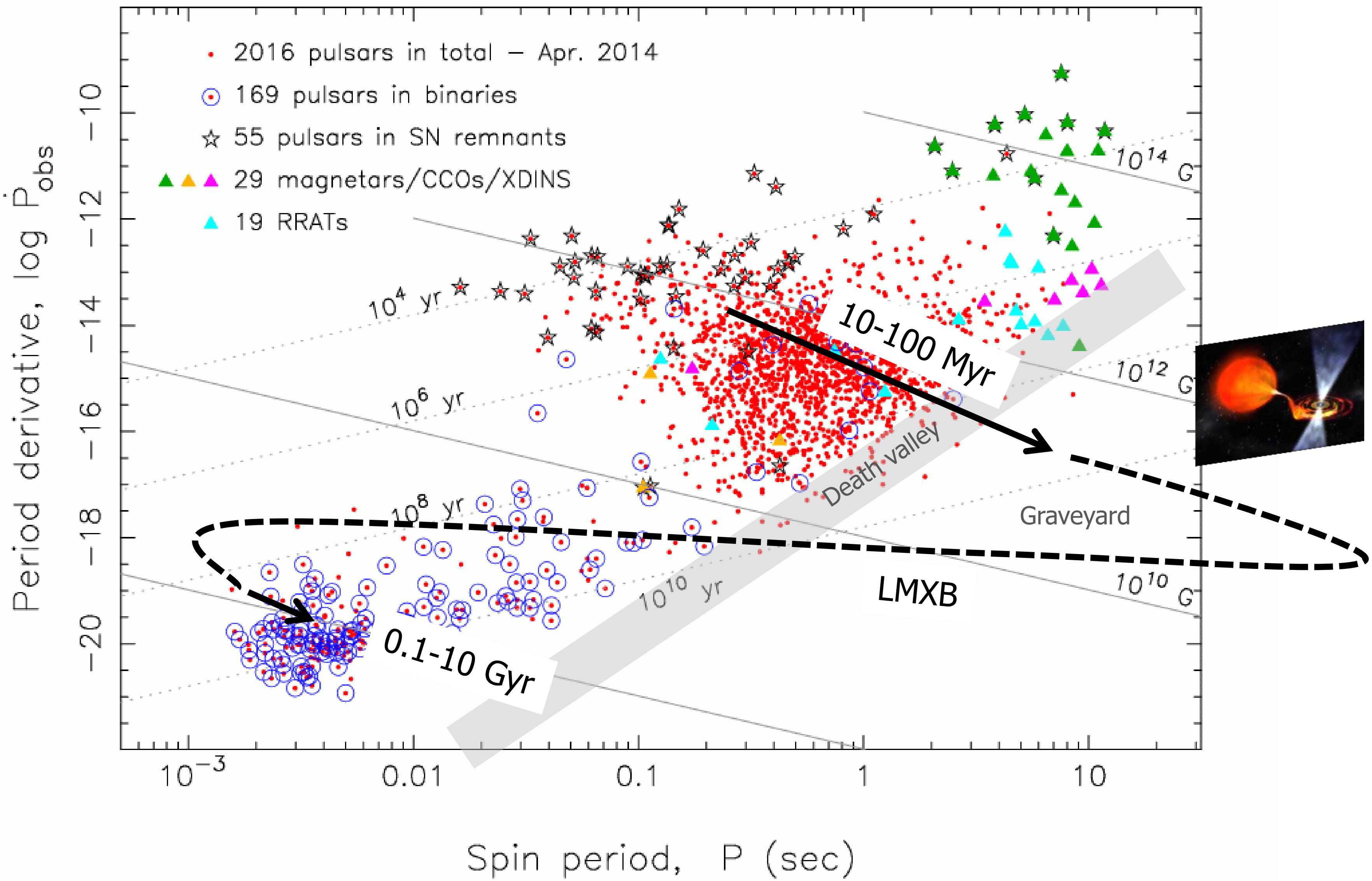
~200 binary MSPs

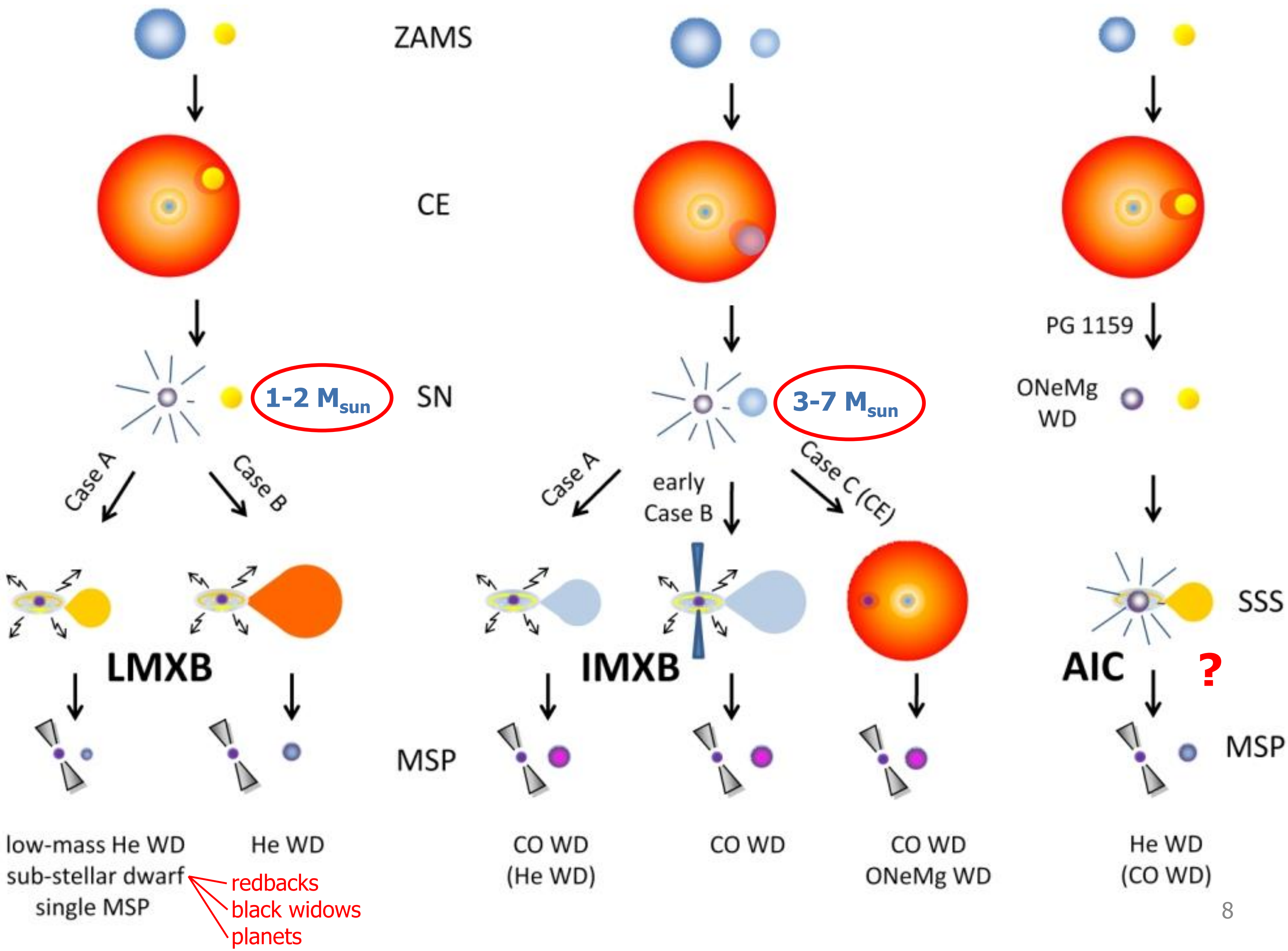




The MSP population - The P-P_{dot} diagram

Tauris, Kaspi, Breton, Deller, et al. (2015)

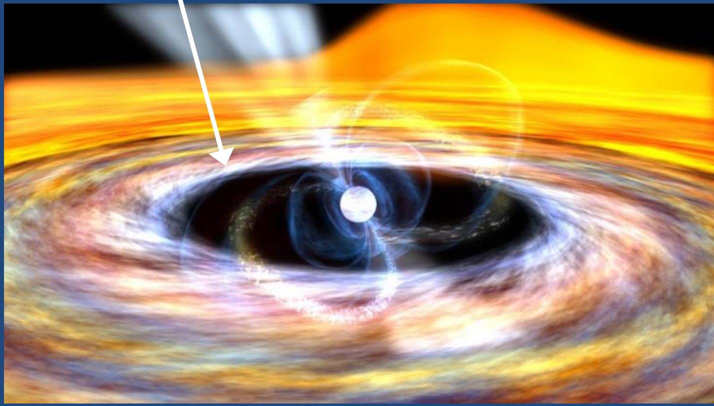



ZAMS
CE
PG 1159
SN
$1\text{-}2\ M_{sun}$
$3\text{-}7\ M_{sun}$
ONeMg WD
Case A
Case B
Case A
early Case B
Case C (CE)
SSS
LMXB
IMXB
AIC
?
MSP
MSP
low-mass He WD
sub-stellar dwarf
single MSP
redbacks
black widows
planets
He WD
CO WD (He WD)
CO WD
CO WD ONeMg WD
He WD (CO WD)

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

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

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

B-decay
How?
M. Cruces' talk

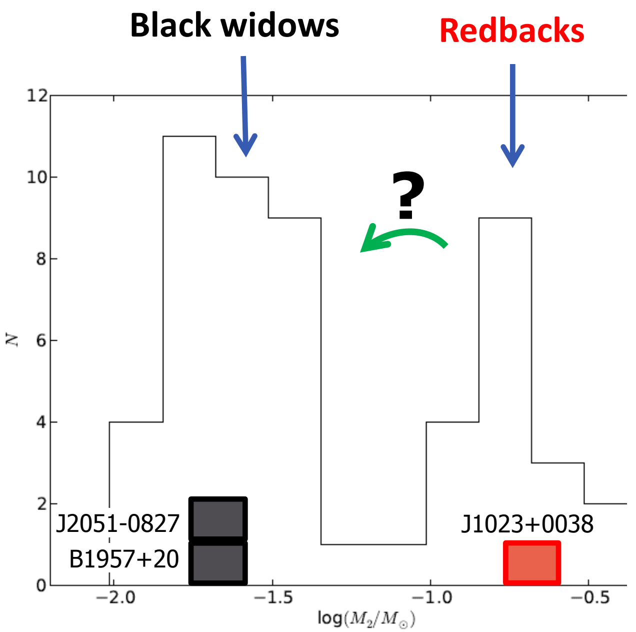
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) - \frac{c^2}{4\pi} \nabla \times \left(\frac{1}{\sigma} \times \nabla \times \vec{B} \right)$$

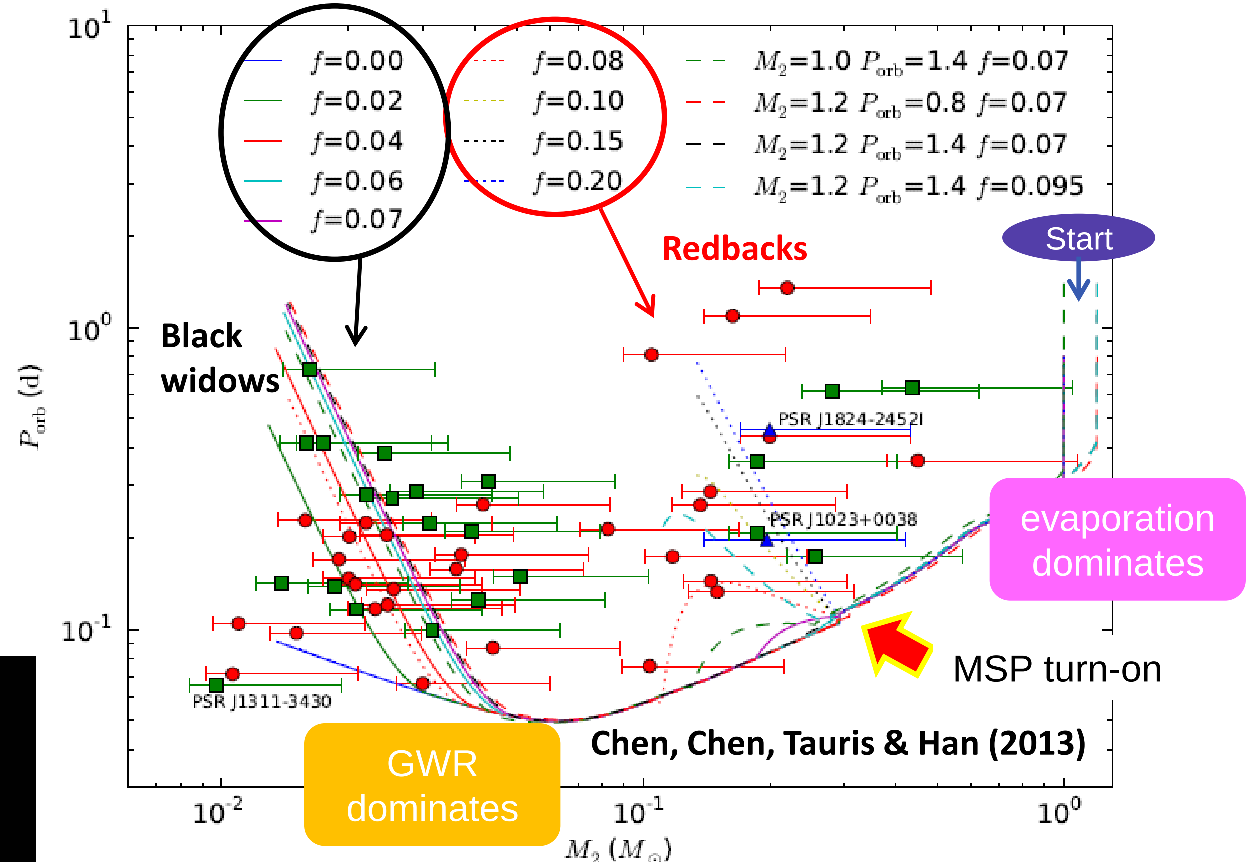
Geppert & Urpin (1994); Konar & Bhattacharya (1997)

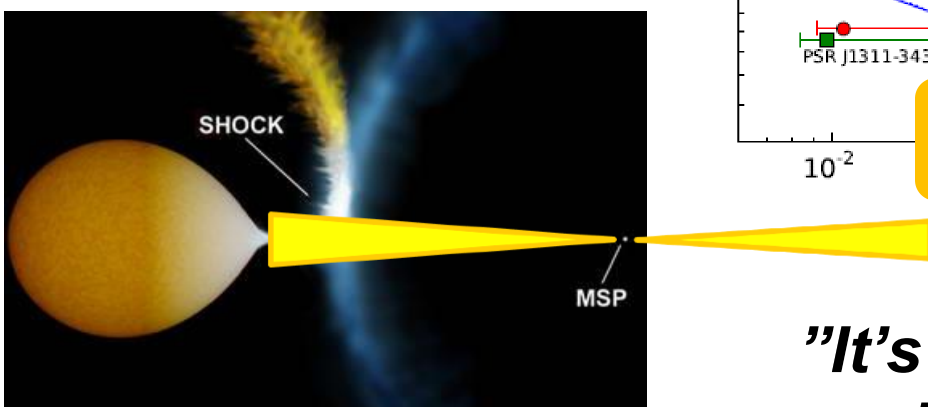
$$B = \sqrt{\frac{3c^3 I_{NS}}{8\pi^2 R_{NS}^6} P\dot{P}}$$

Magnetic-dipole model

The MSP population - The Spiders







"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).
  Other recent papers: Ablimit & Li (2014), Smedley et al. (2015).
- 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)

3FGL J1417.5-4402 The first Red-Bump Spider?

The 'Huntsman' spider: 1FGL J1417.7-4407 (Strader et al. 2015)

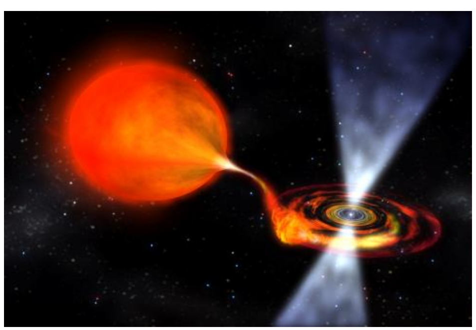
Camilo et al. (2016):

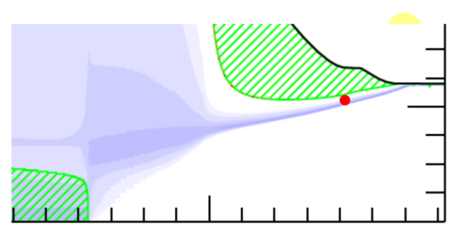
P_{orb} = 5.4 days
M_2 = 0.33 +/- 0.03 M_{sun} (M_{NS} = 1.77–2.13 M_{sun})
P = 2.66 ms

Discovery of the first **Red-Bump Spider?**

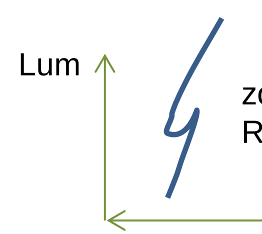
Their existence was predicted theoretically in 1999....

Red-bump MSPs decouple from RLO because of a **chemical discontinuity.**
(Tauris & Savonije 1999, see also D'Antona et al. 2006). Only for P_{orb} > 3 days.



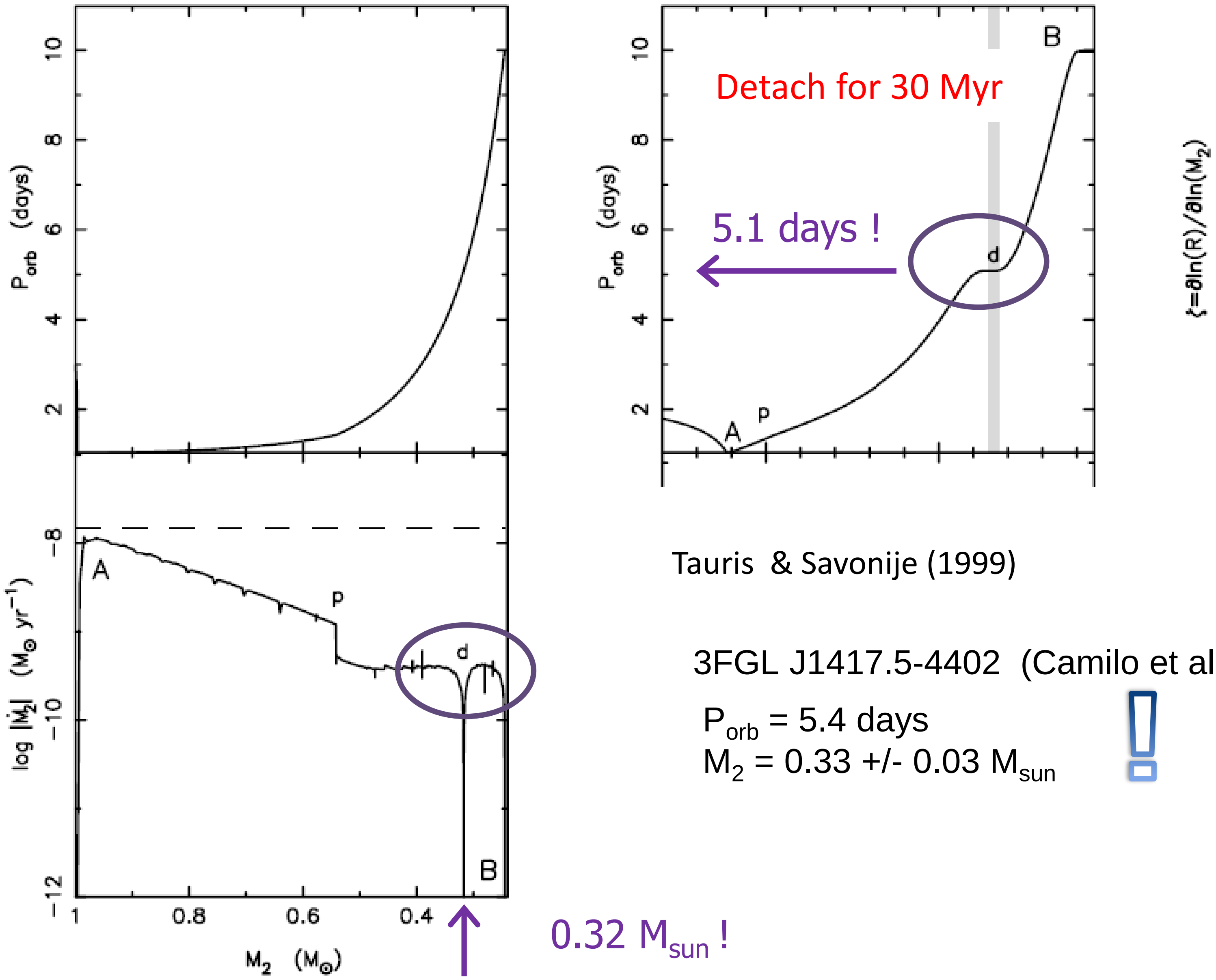


Istrate, Tauris & Langer (2014)



3FGL J1417.5-4402 The first Red-Bump Spider?

T.M. Tauris & G.J. Savonije: Formation of millisecond pulsars.

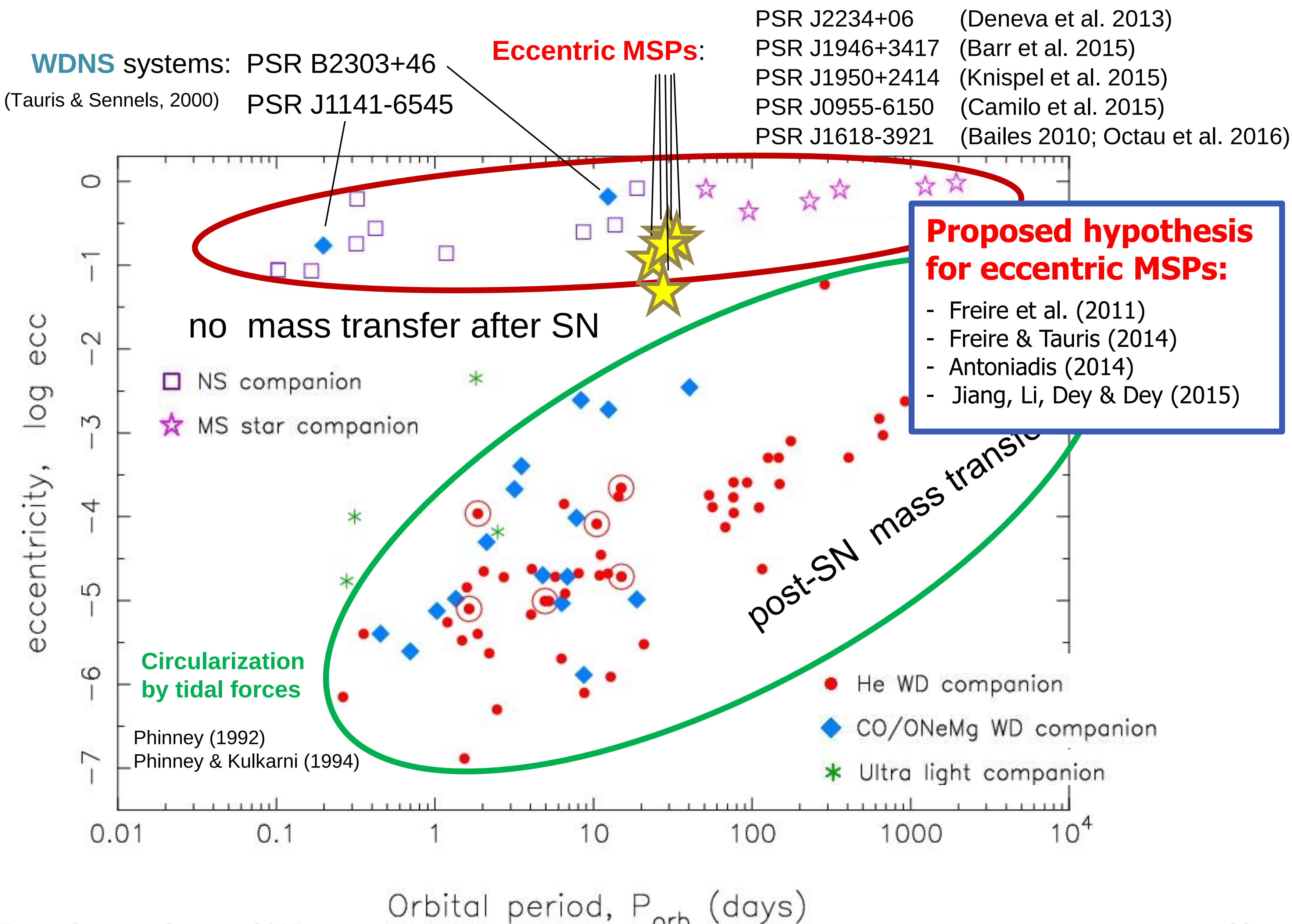


Tauris & Savonije (1999)

3FGL J1417.5-4402 (Camilo et al. 2016):

P_{orb} = 5.4 days
M_2 = 0.33 +/- 0.03 M_{sun} !

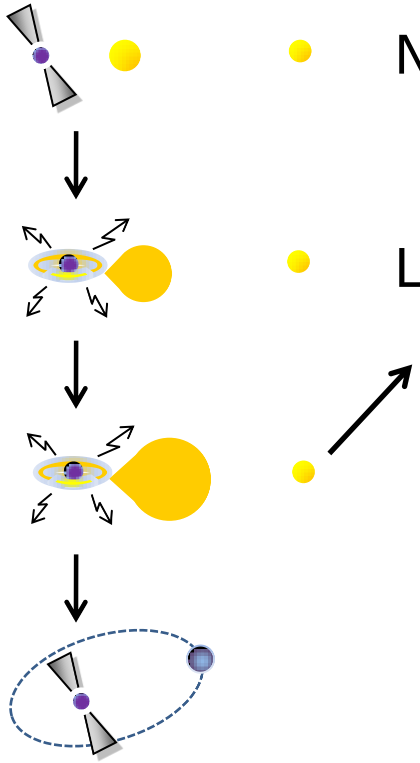
The MSP population - The eccentric MSPs



Proposed hypothesis for eccentric MSPs:

- Freire et al. (2011)
- Freire & Tauris (2014)
- Antoniadis (2014)
- Jiang, Li, Dey & Dey (2015)

Do eccentric MSPs have a triple origin? ....difficult



NS + MS + MS

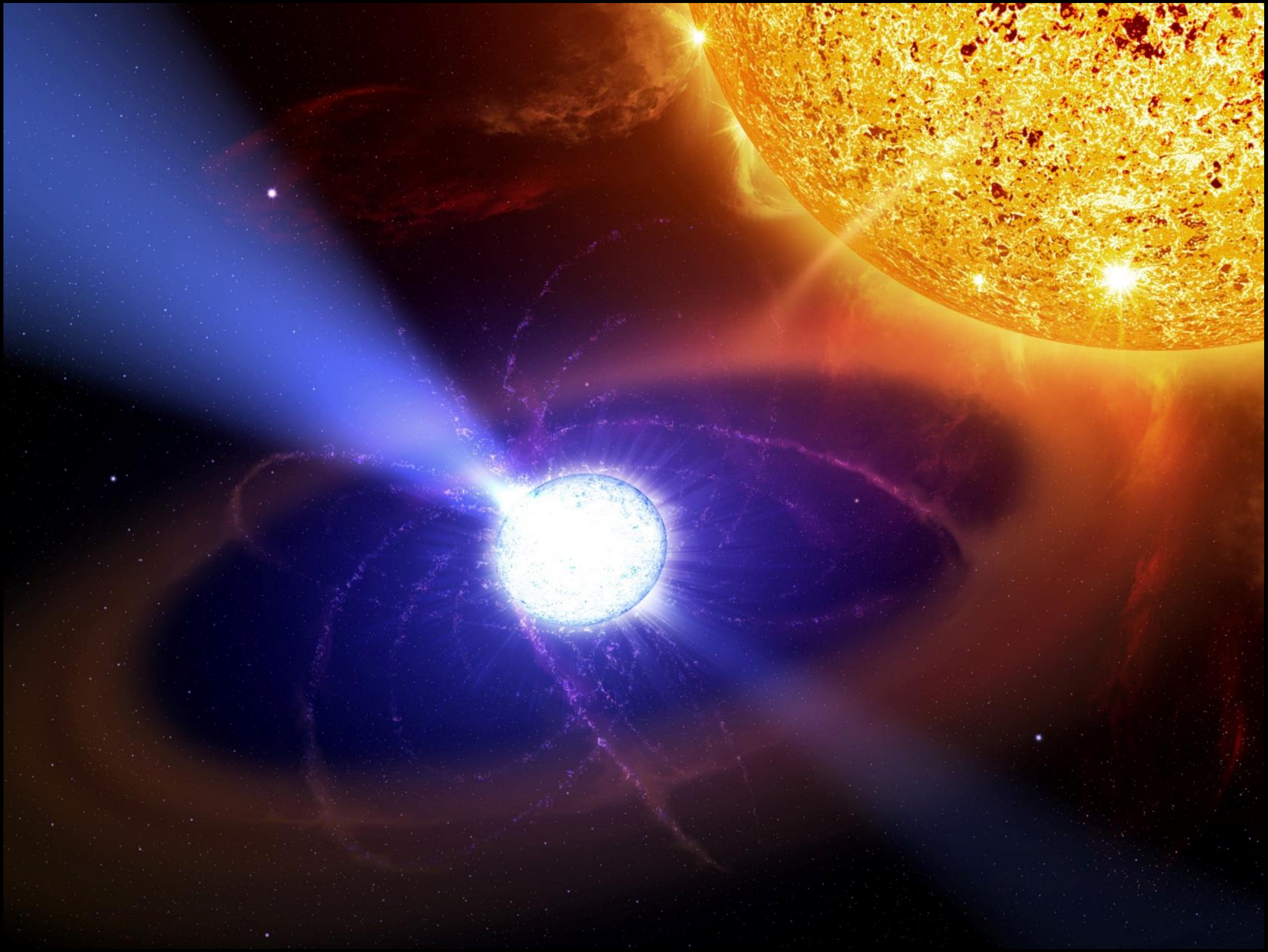
LMXB

MS ejected
→ ecc MSP + WD

PSR J2234+06
PSR J1946+3417
PSR J1950+2414
PSR J0955-6150
PSR J1618-3921

Puzzles:
1) Why always near end of RLO?
   (so orbit doesn't circularize again)
2) Why is ecc. always ~0.1?
3) Why do all systems have P_{orb}=20–30 days?

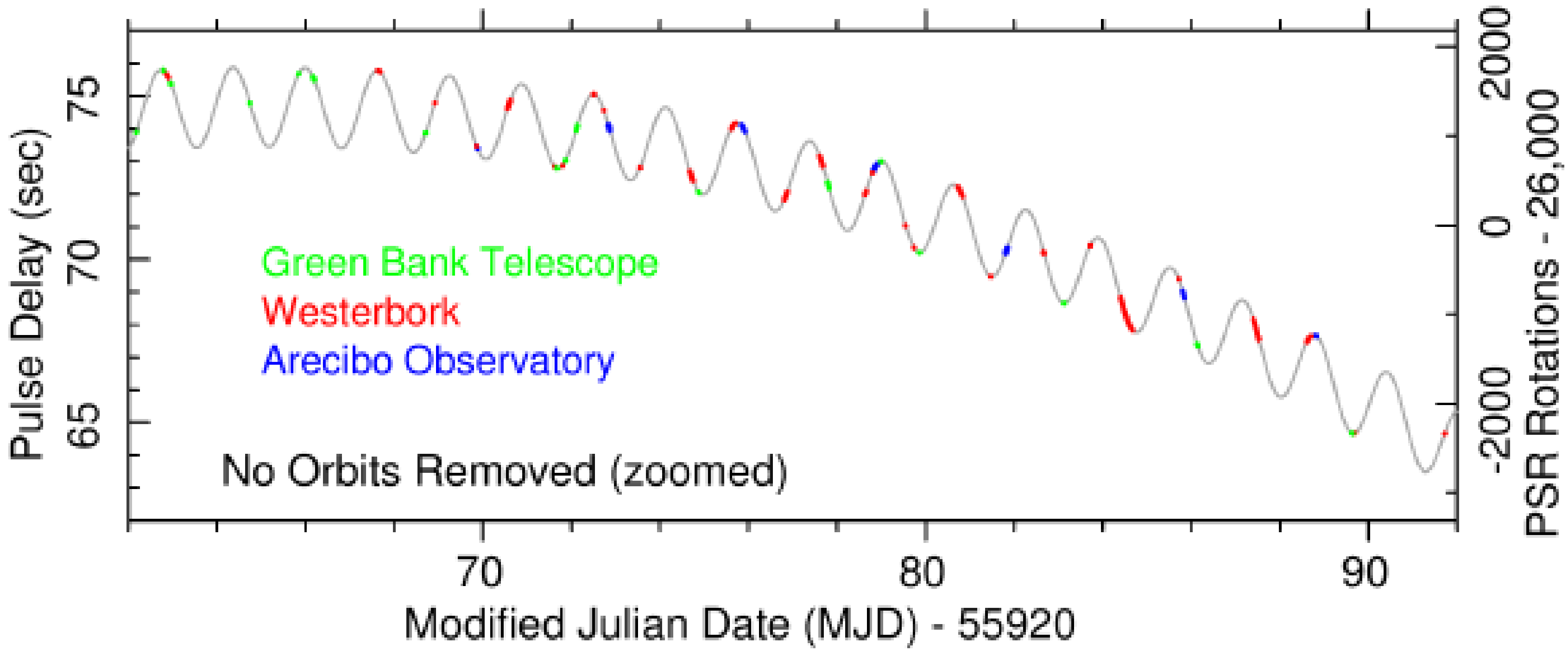
Probing Stellar Evolution using MSPs

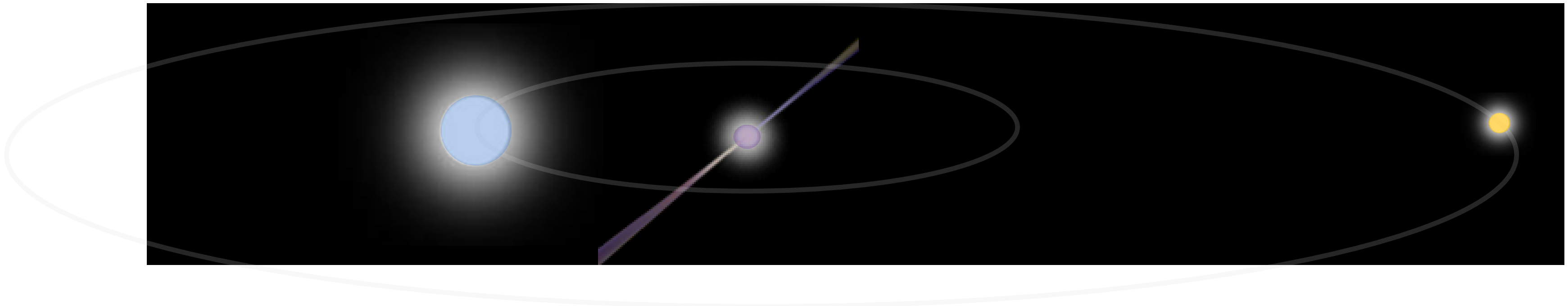


Stellar Evolution and MSPs - The Triple MSP!!!

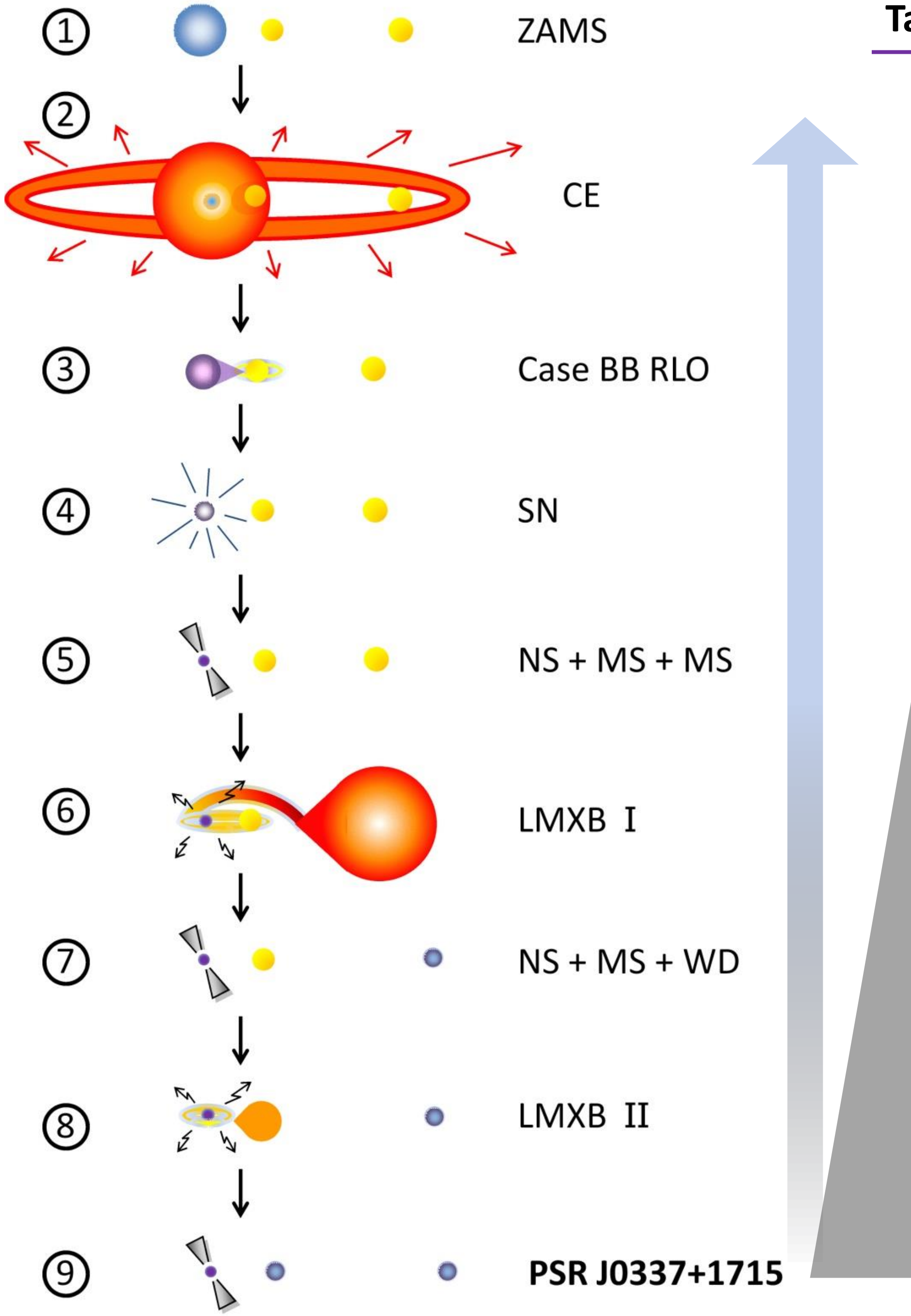
PSR J0337+1715, a remarkable Galactic triple millisecond pulsar

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





Tauris & van den Heuvel (2014), ApJL



Stellar Forensics

Tracing the evolution backwards

see also Sabach & Soker (2015)

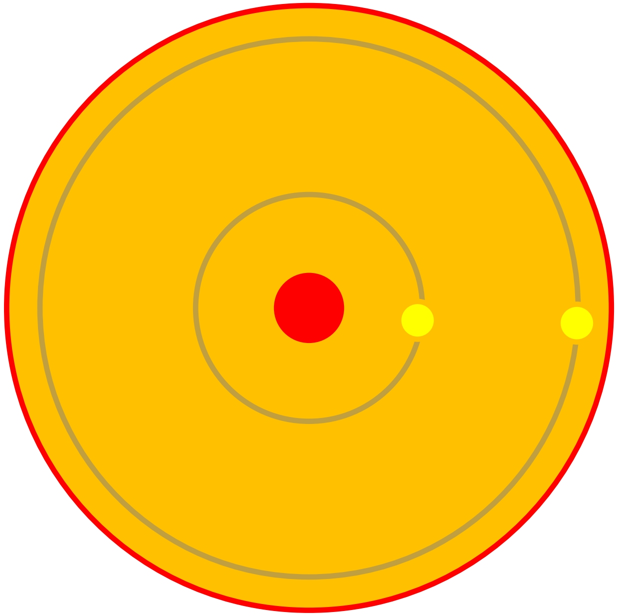
- Applying constraints from knowledge of stellar evolution and mass tranfer (RLO).
- Simulations of the dynamical effects of the supernova explosion.
- At all stages ensuring that the triple remains dynamically *stable* on a long timescale.

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°

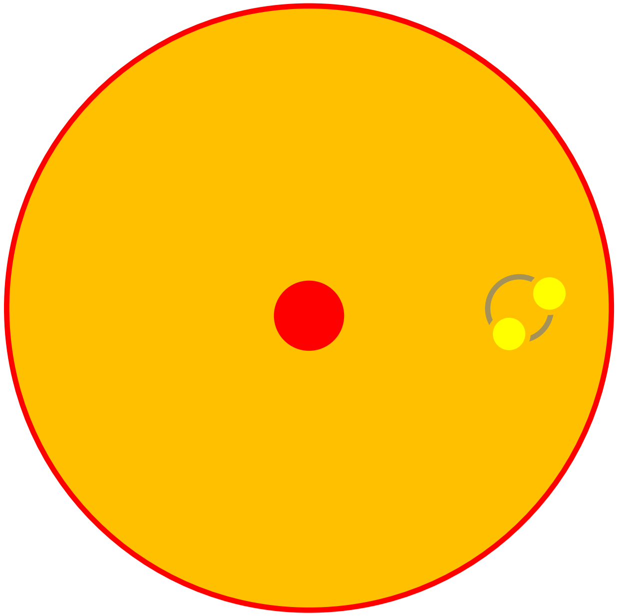
Ransom et al. (2014), Kaplan et al. (2014)

Pre-CE configuration ? Hierarchical structure?

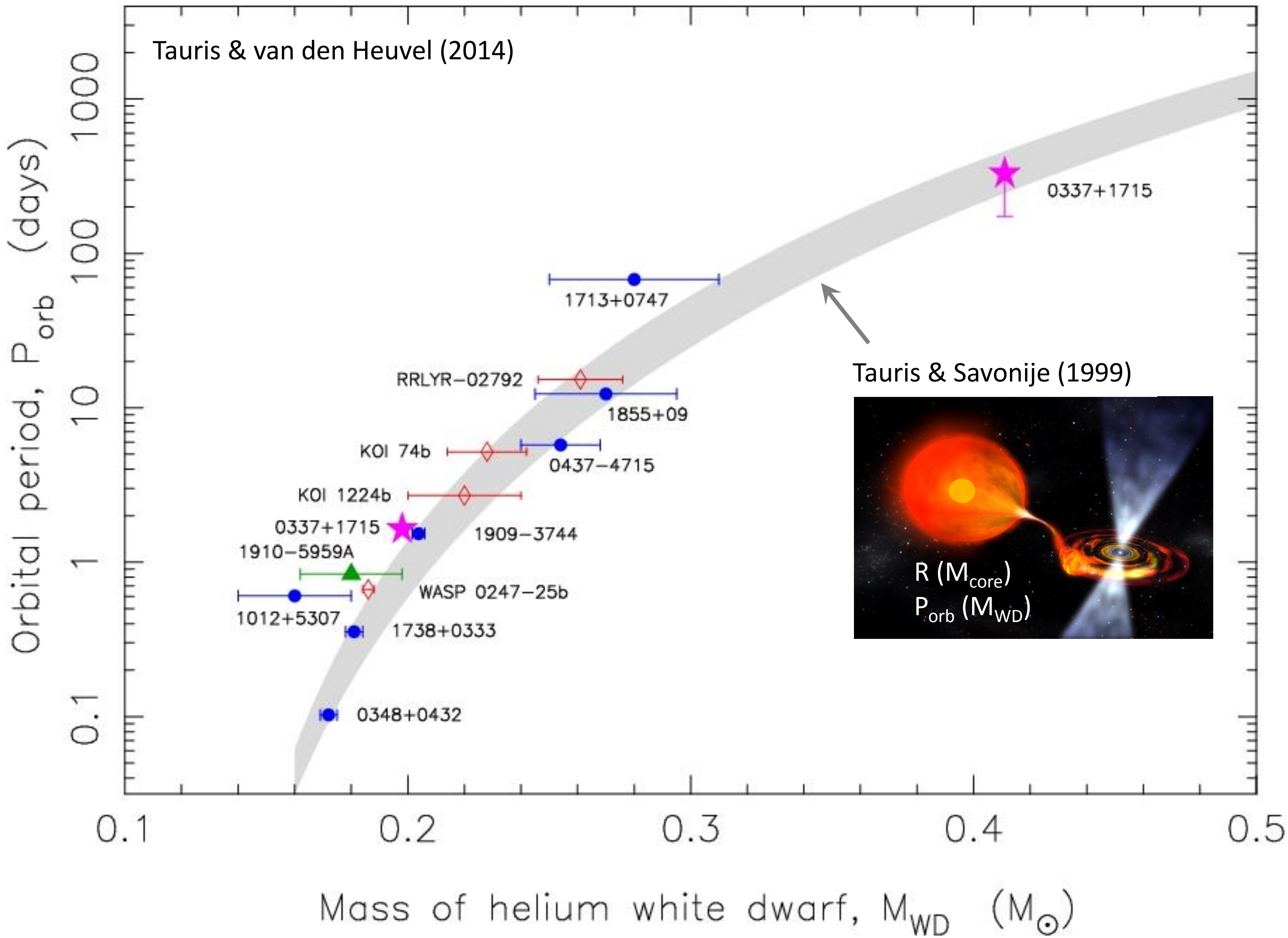
1)



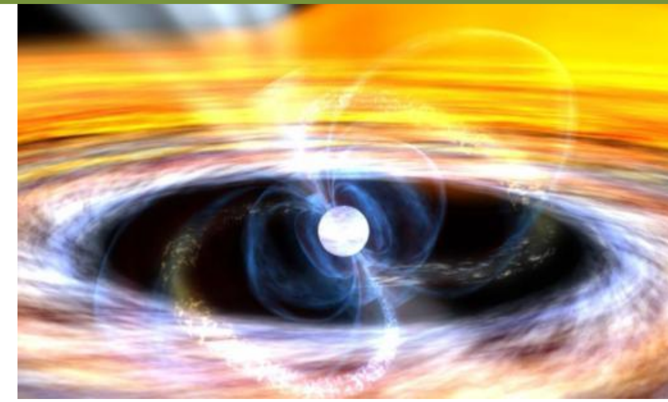
2)



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



Pulsar Recycling - accretion physics



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

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

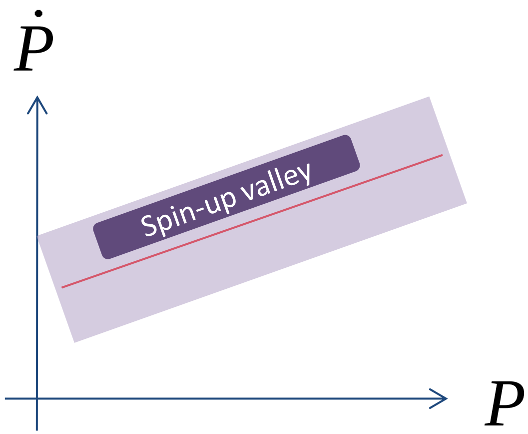
Tauris, Langer & Kramer (2012)

Important!

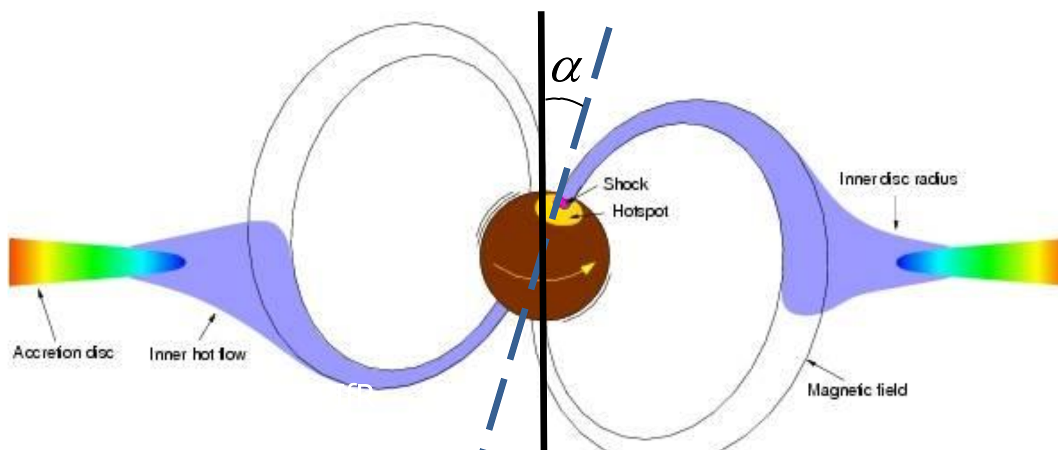
disk –magnetosphere parameters:

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

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

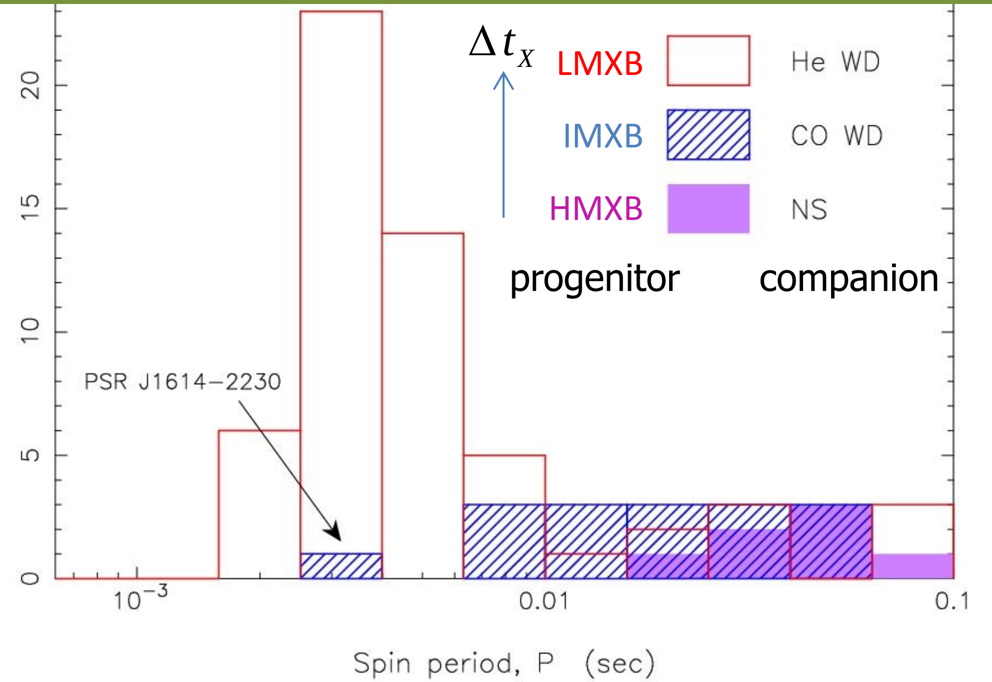


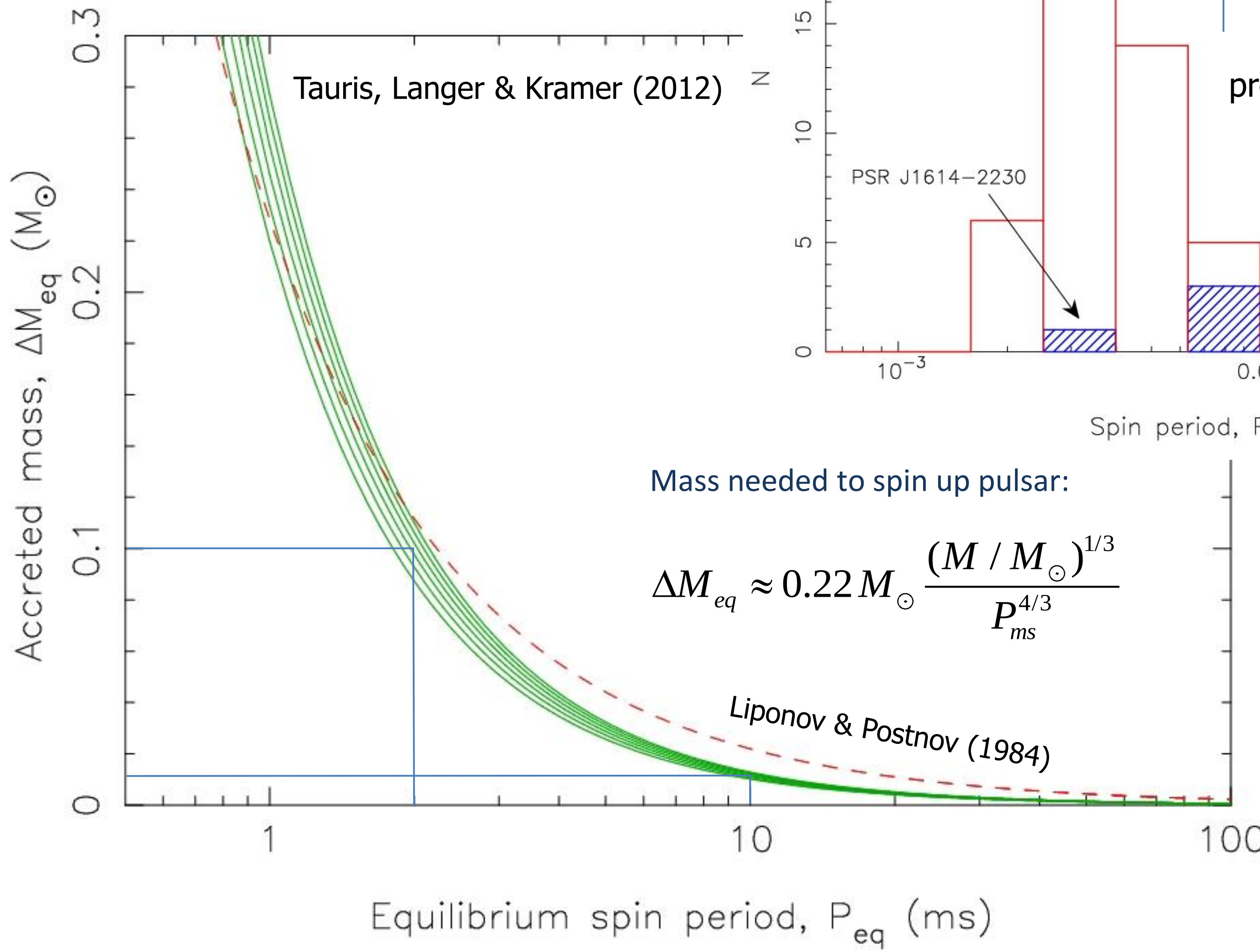
Classical spin-up line
e.g. Bhattacharya & van den Heuvel (1991)



Pulsar Recycling - amount of accreted mass

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



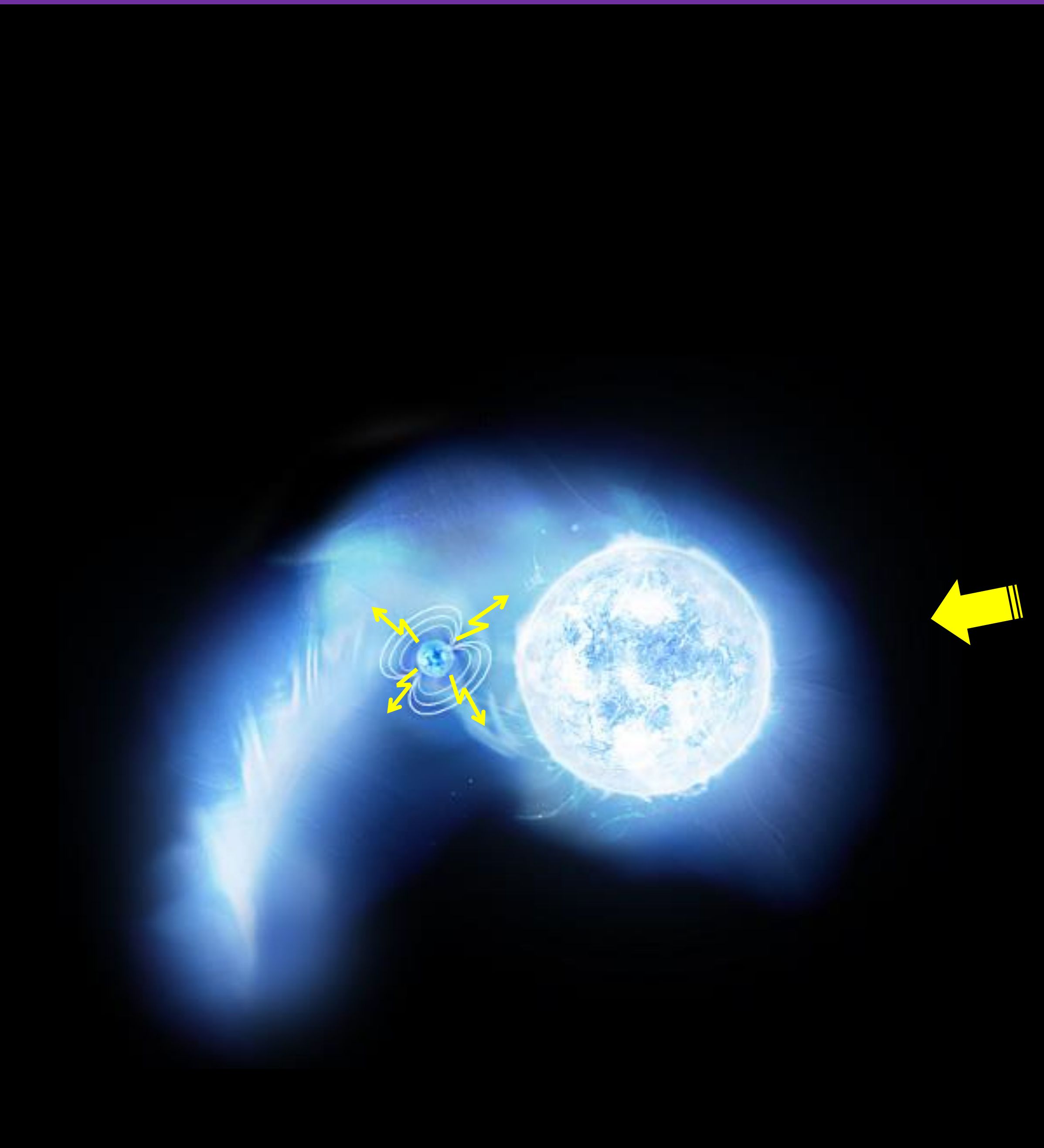


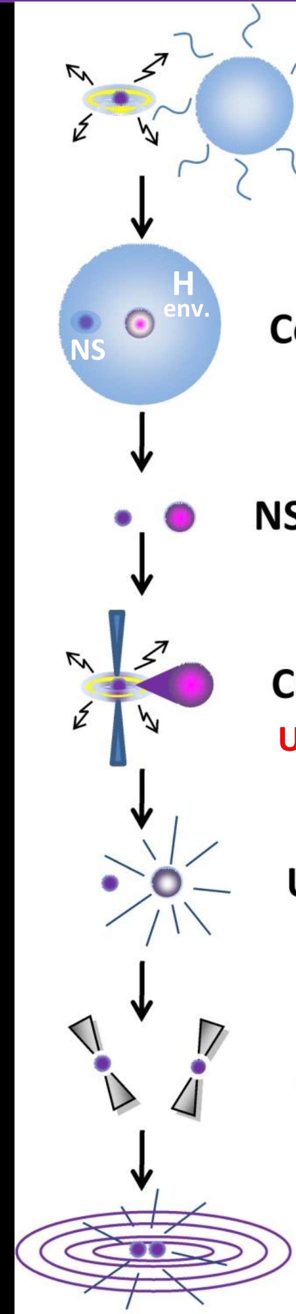
Mass needed to spin up pulsar:

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

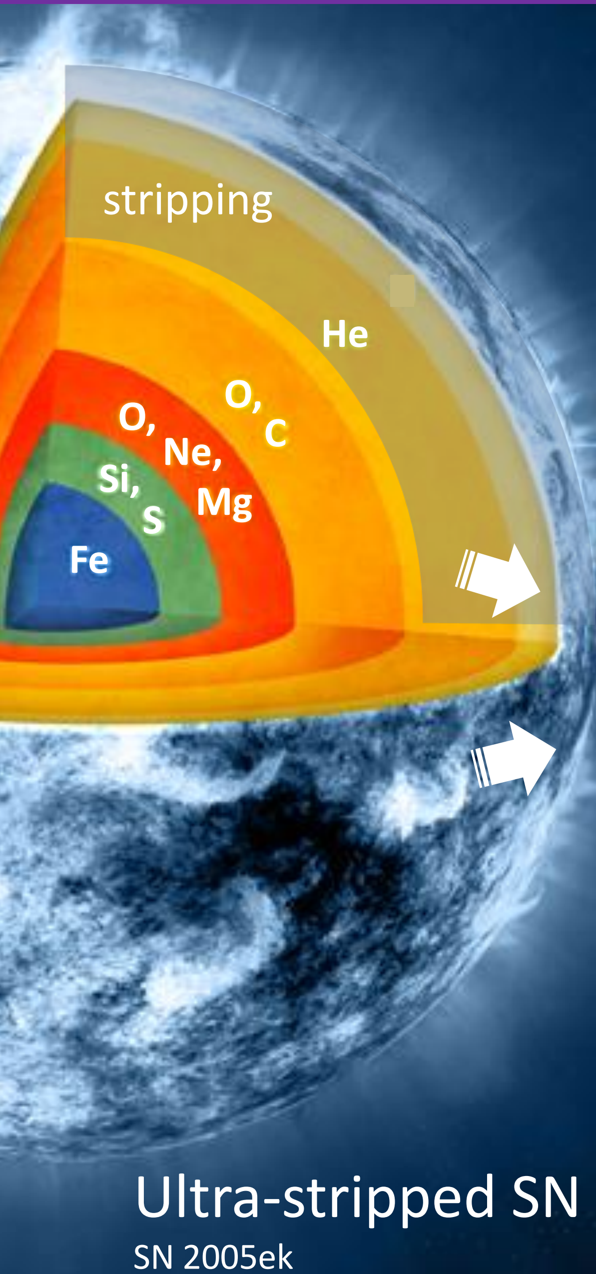
P (ms)	M (M_{sun})
0.7	0.40
2	0.10
5	0.03
10	0.01
50	0.001

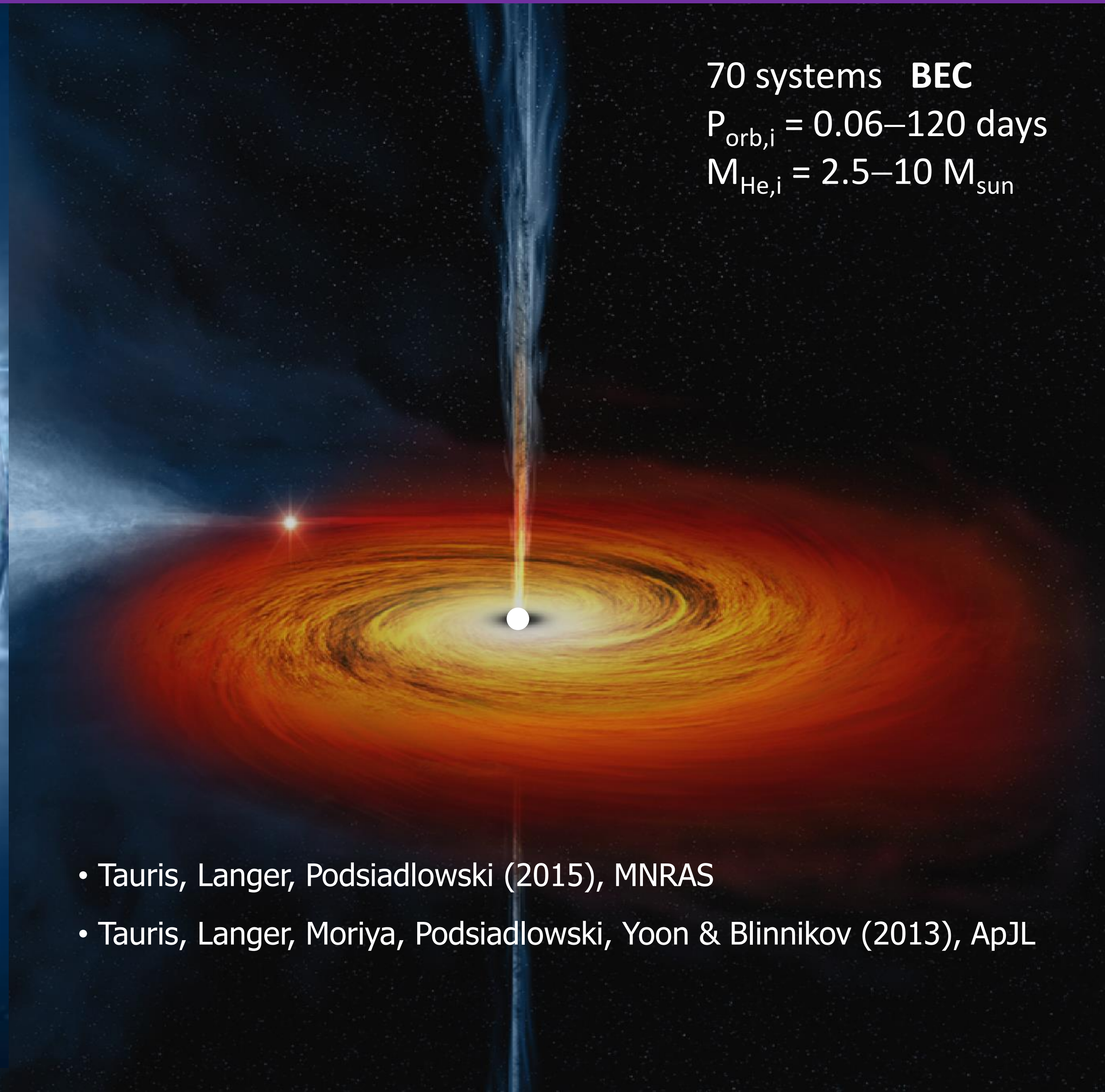
Ultra-stripped SNe – Double NS systems





Ultra-stripped SNe – Double NS systems





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

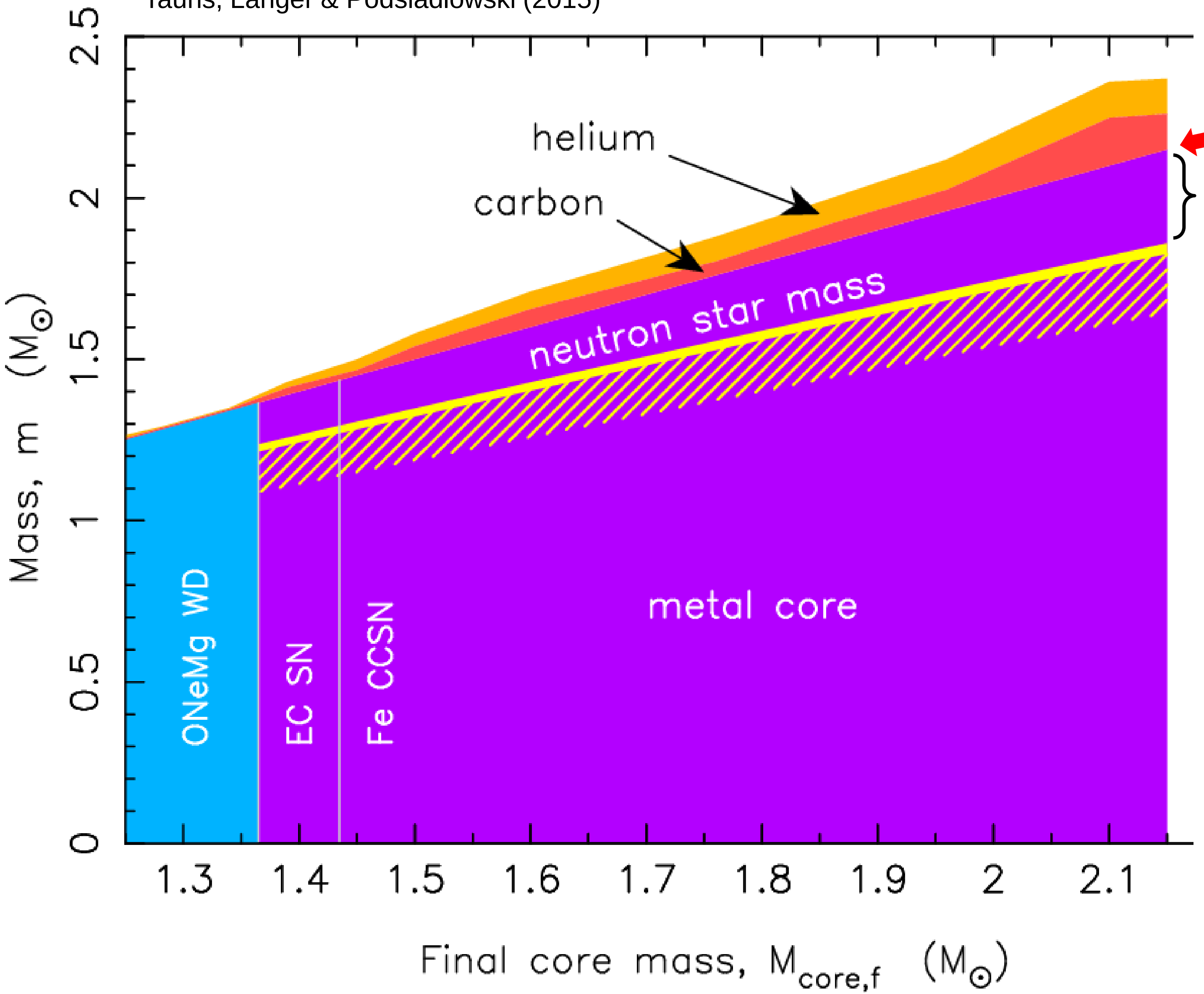
Double Neutron Star Systems

(shaded) = 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	1.56 / 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)

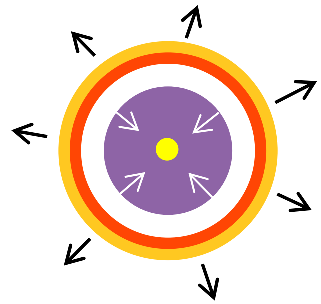


If SN mass cut is here…

E_{bind}

Lattimer & Yahil (1989)

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



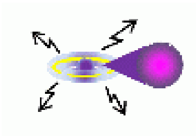
Small kicks? (yes)

Suwa et al. (2015)

$P_{orb,i} = 0.1$ days

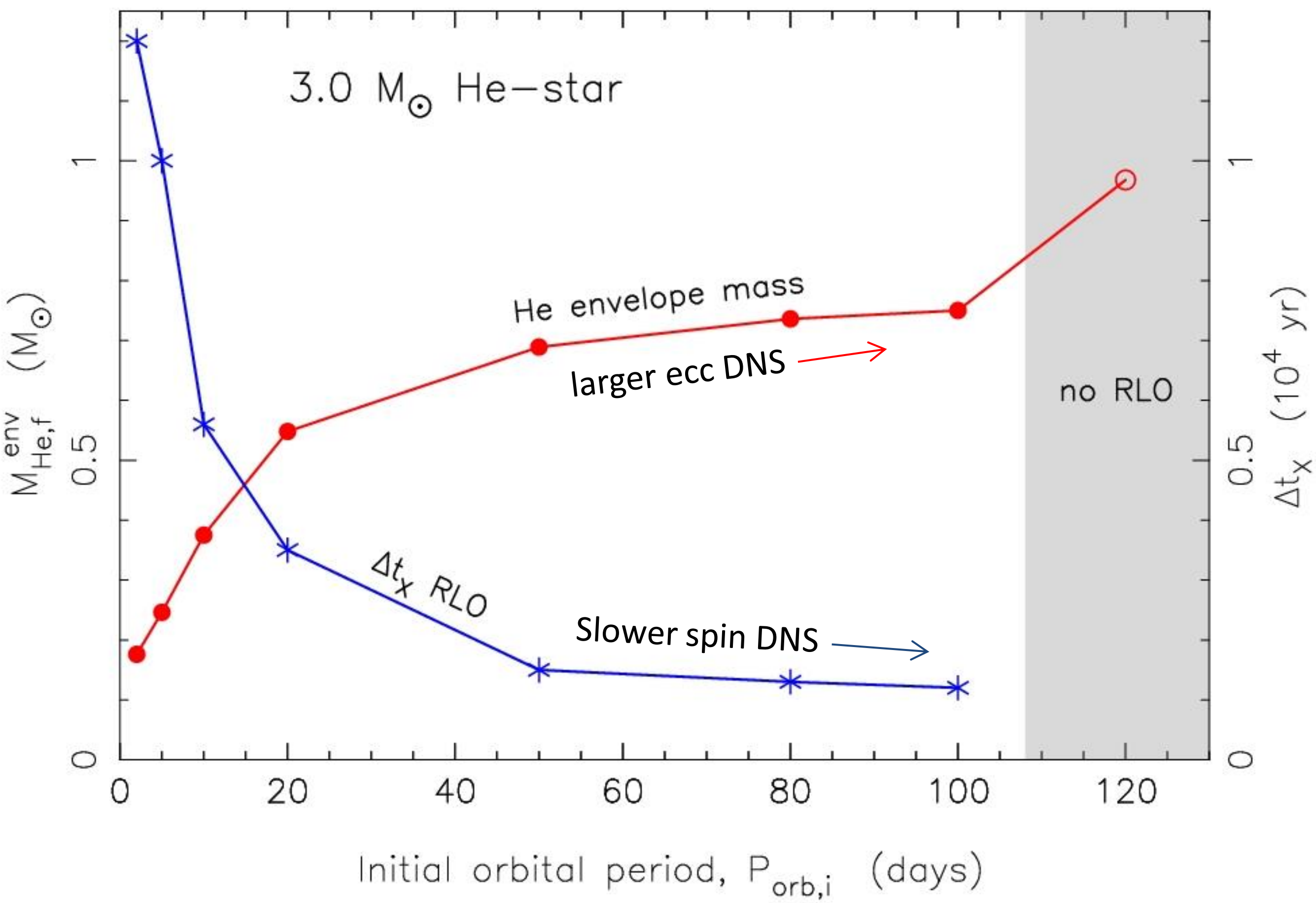
$M_{He,i} = 2.5 - 6.0\, M_{\odot}$

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

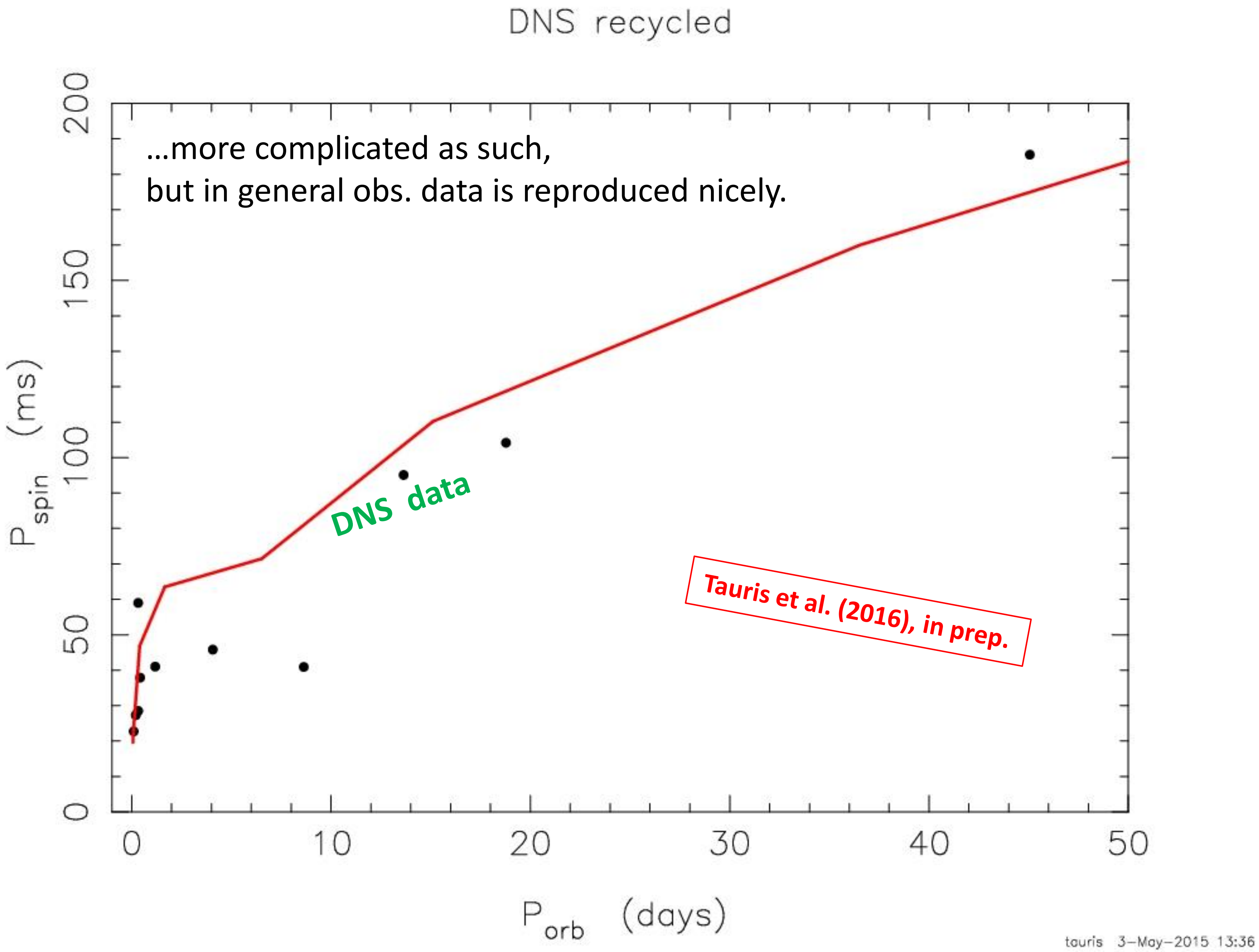


$$P_{orb}\uparrow \;\Rightarrow\; \Delta t_X \downarrow \;\Rightarrow\; \Delta M_{NS}\downarrow \;\Rightarrow\; P_{spin}\uparrow$$

Tauris, Langer & Podsiadlowski (2015)



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



Merging Neutron Stars - LIGO detection rate

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)

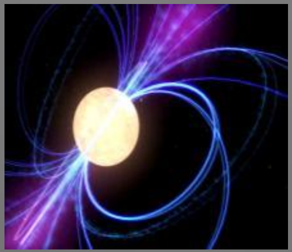
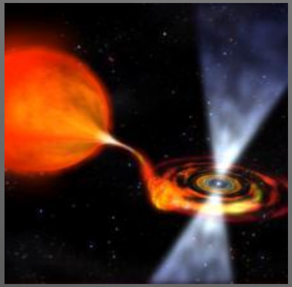
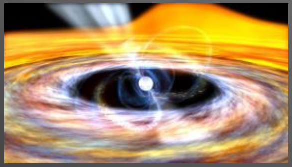
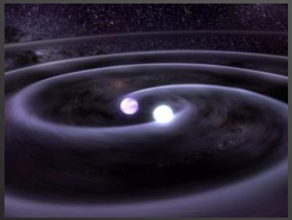
DFG project
Matthias Krukow

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: 1-10 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 (3FGL 1417.5...)**

But also well-constrained behaviour...
  - **The (M_{WD}, P_{ORB}) – correlation, MSP spin periods vs companion types**
- **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**
- **Formation of double neutron star (DNS) systems**
  - **All DNS systems formed via an ultra-stripped SN**
  - **Ultra-stripped SNe often (but not always) lead to small kicks**
  - **(P_{orb},P_{spin}) and (P_{orb},ecc) - correlations in DNS systems**
- **LIGO/VIRGO merger rates**
  - **DNS: 1-10 Myr^{-1} $MWGal^{-1}$ → Detection of 1 $week^{-1}$ (~ factor 100)**