Five and a half roads to from a millisecond pulsar

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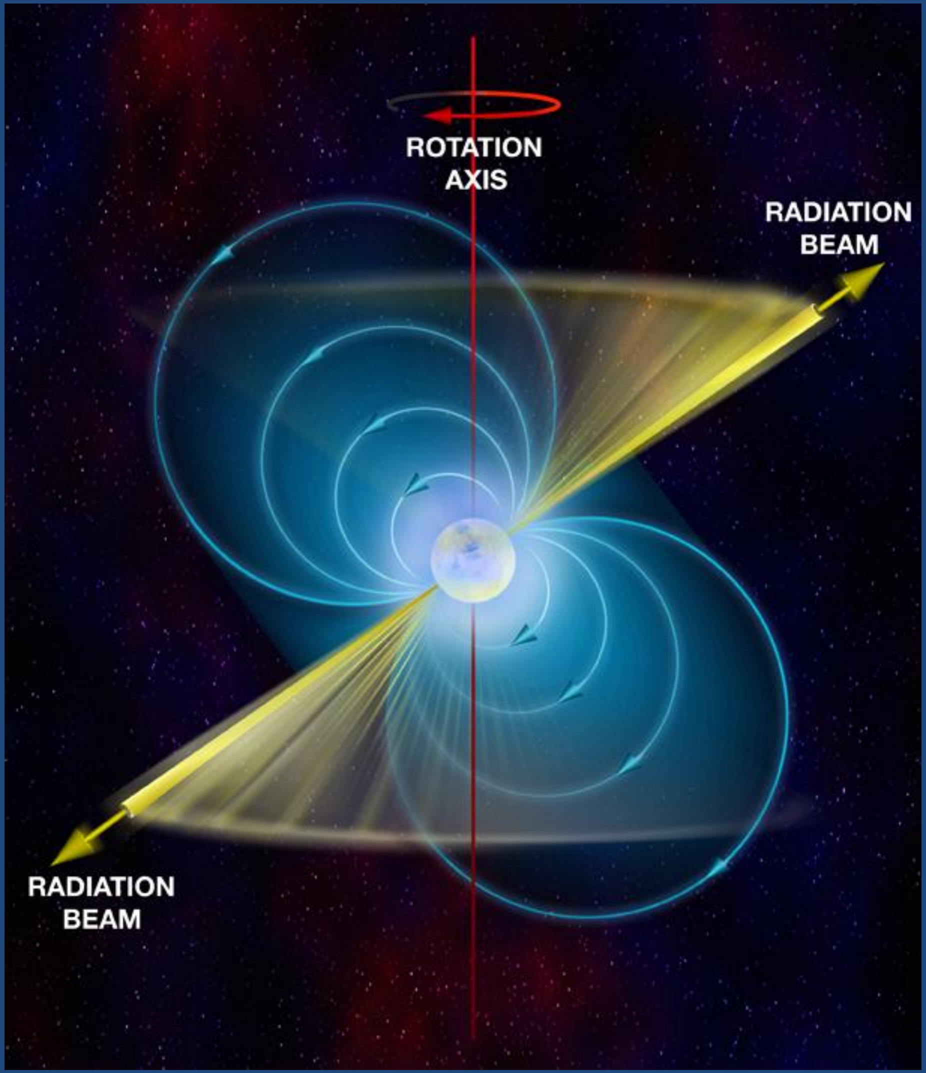
Evolution of Compact Binaries, ESO Chile, March 6-11, 2011

- Millisecond pulsars - an introduction
- Mass transfer in X-ray binaries
  - Stability
  - Modes of mass transfer / loss
- Formation of millisecond pulsars
  1) LMXB $P_{orb} > P_{bif}$
  2) LMXB $P_{orb} < P_{bif}$
  3) IMXB Common Envelope
  4) IMXB Early case B
  5) IMXB Case A - PSR J1614-2230
- Summary

For a review: Tauris & van den Heuvel (2006)

Pulsars are key probes of fundamental physics



Particle physics

Nuclear physics

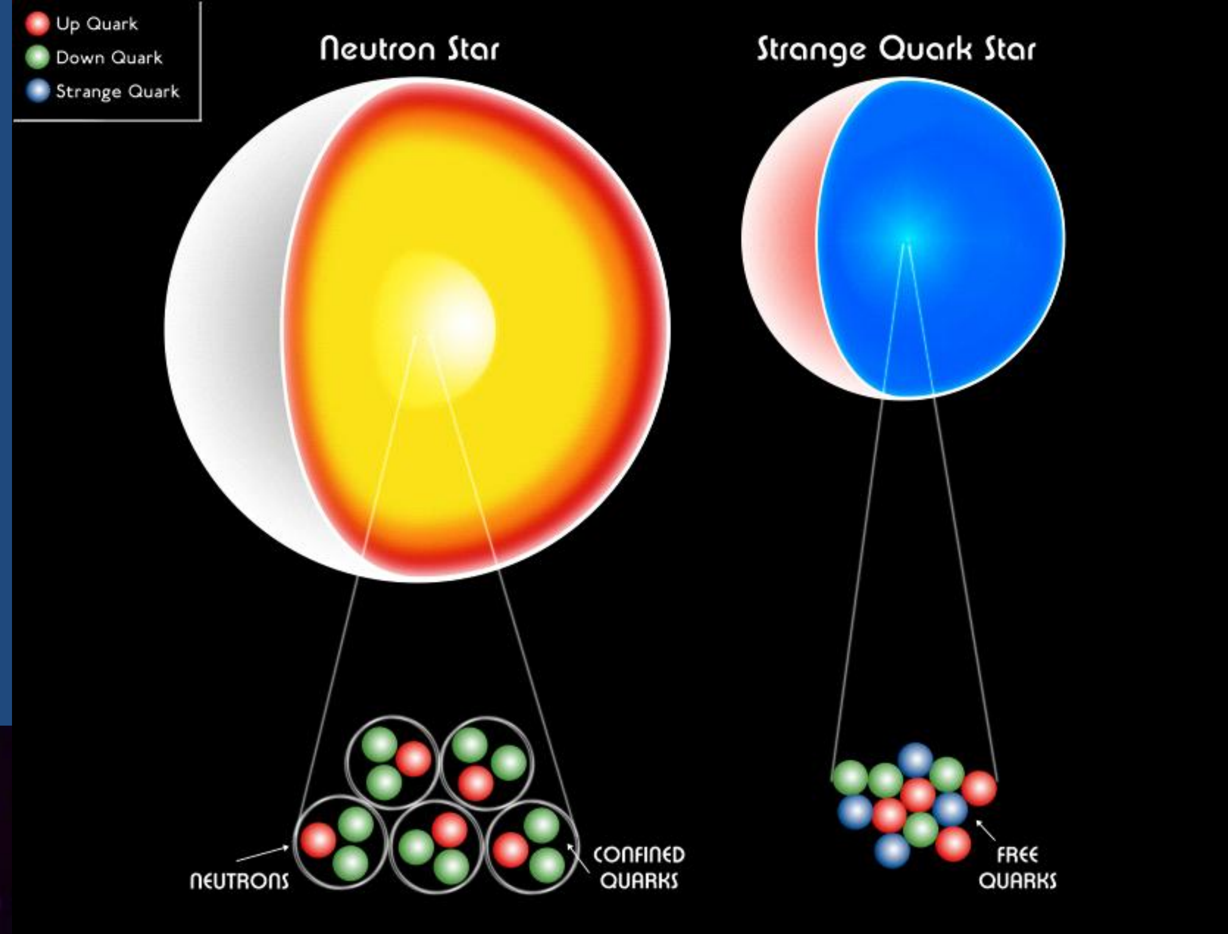
Condense matter physics

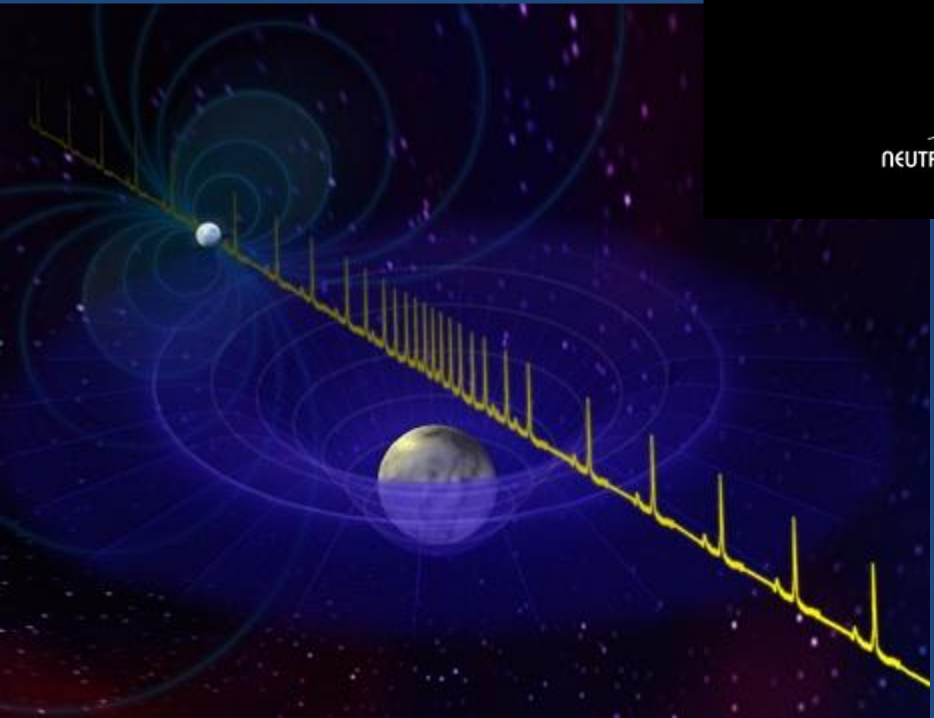
Atom physics

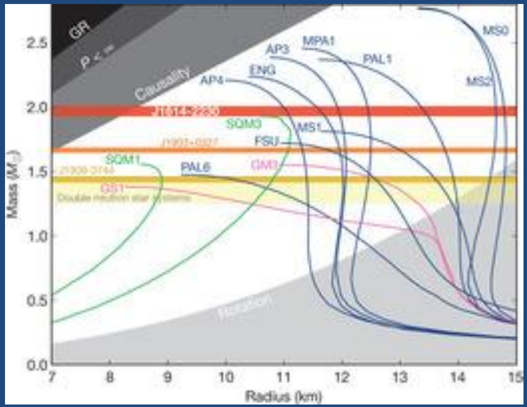
Plasma physics

Relativity

Equations-of-state for
high density nuclear matter







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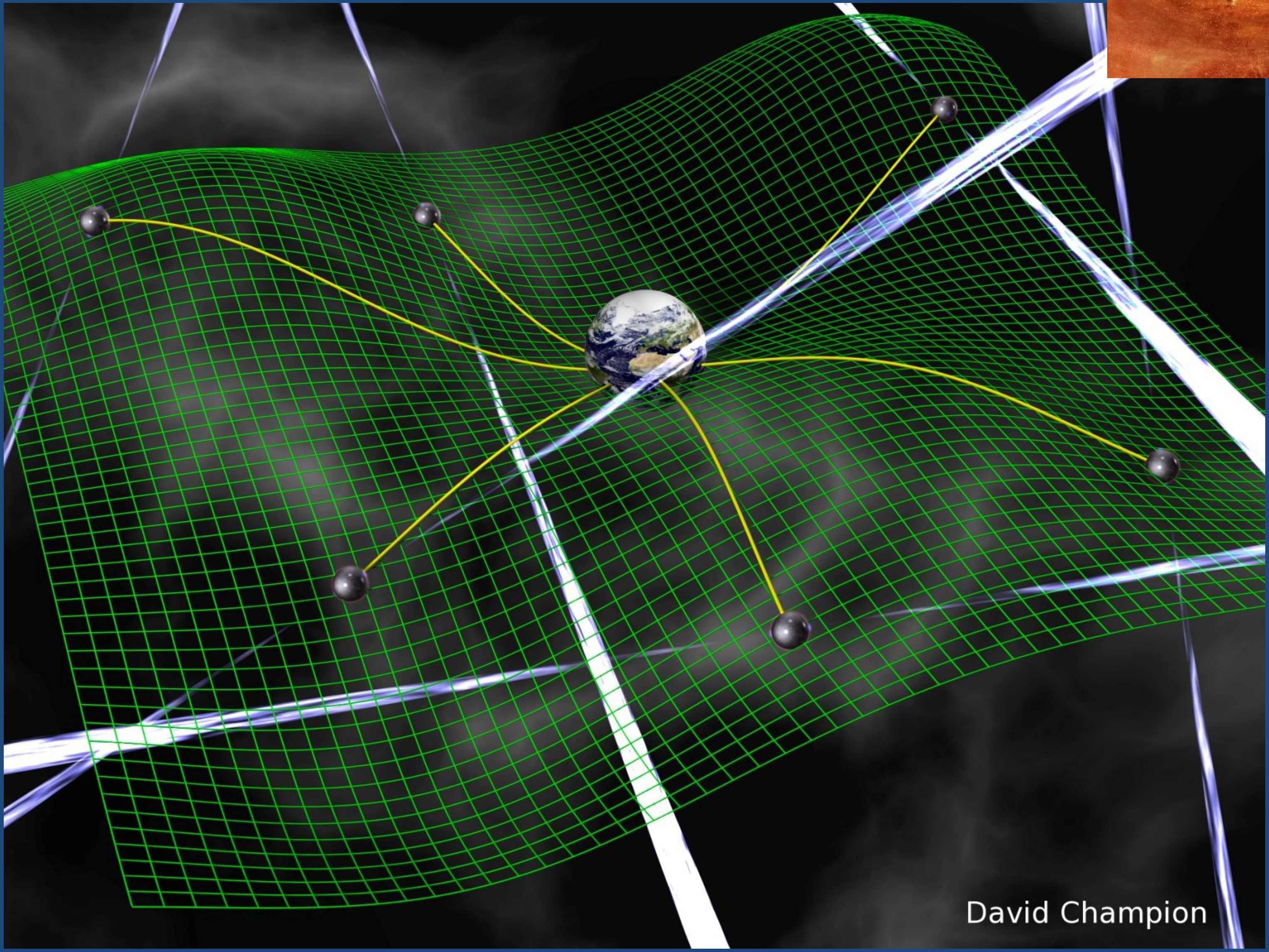
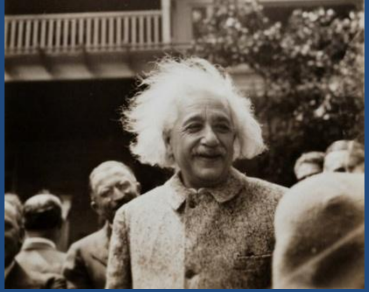
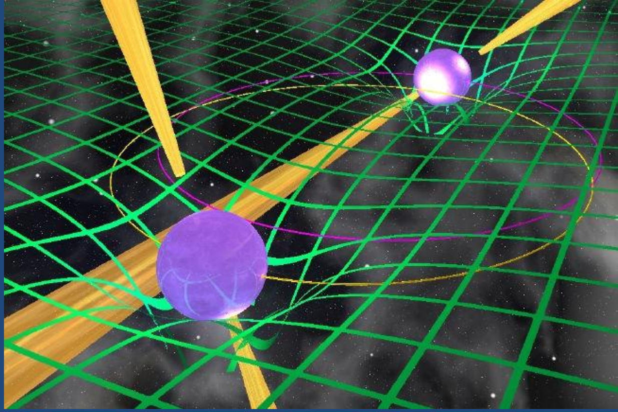
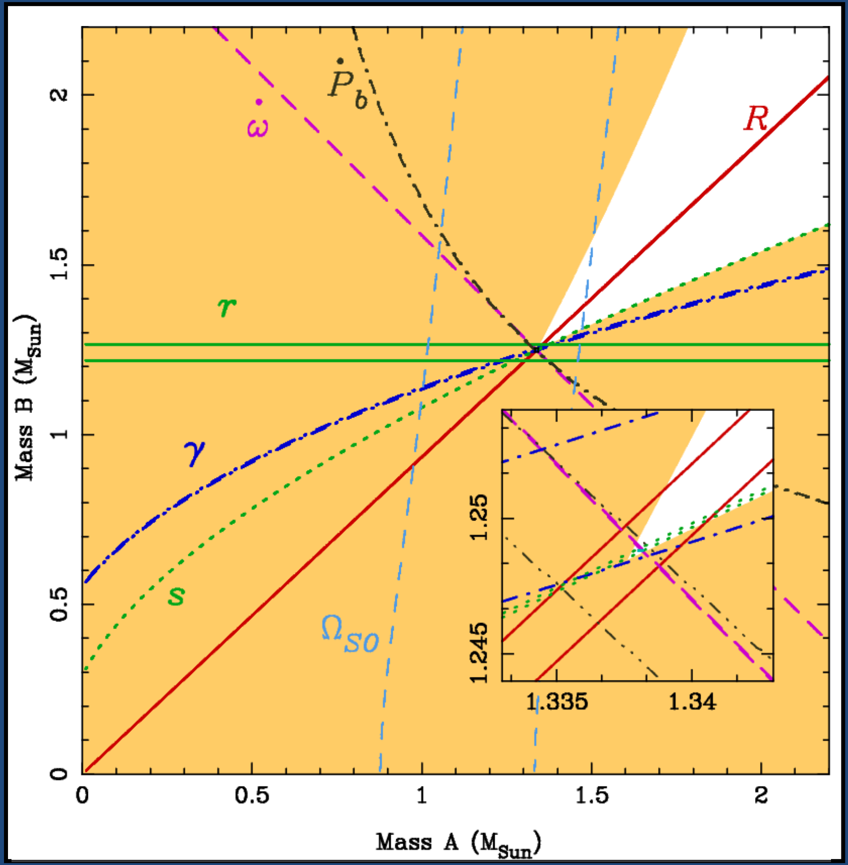
Detection of low frequency gravitational waves using pulsars



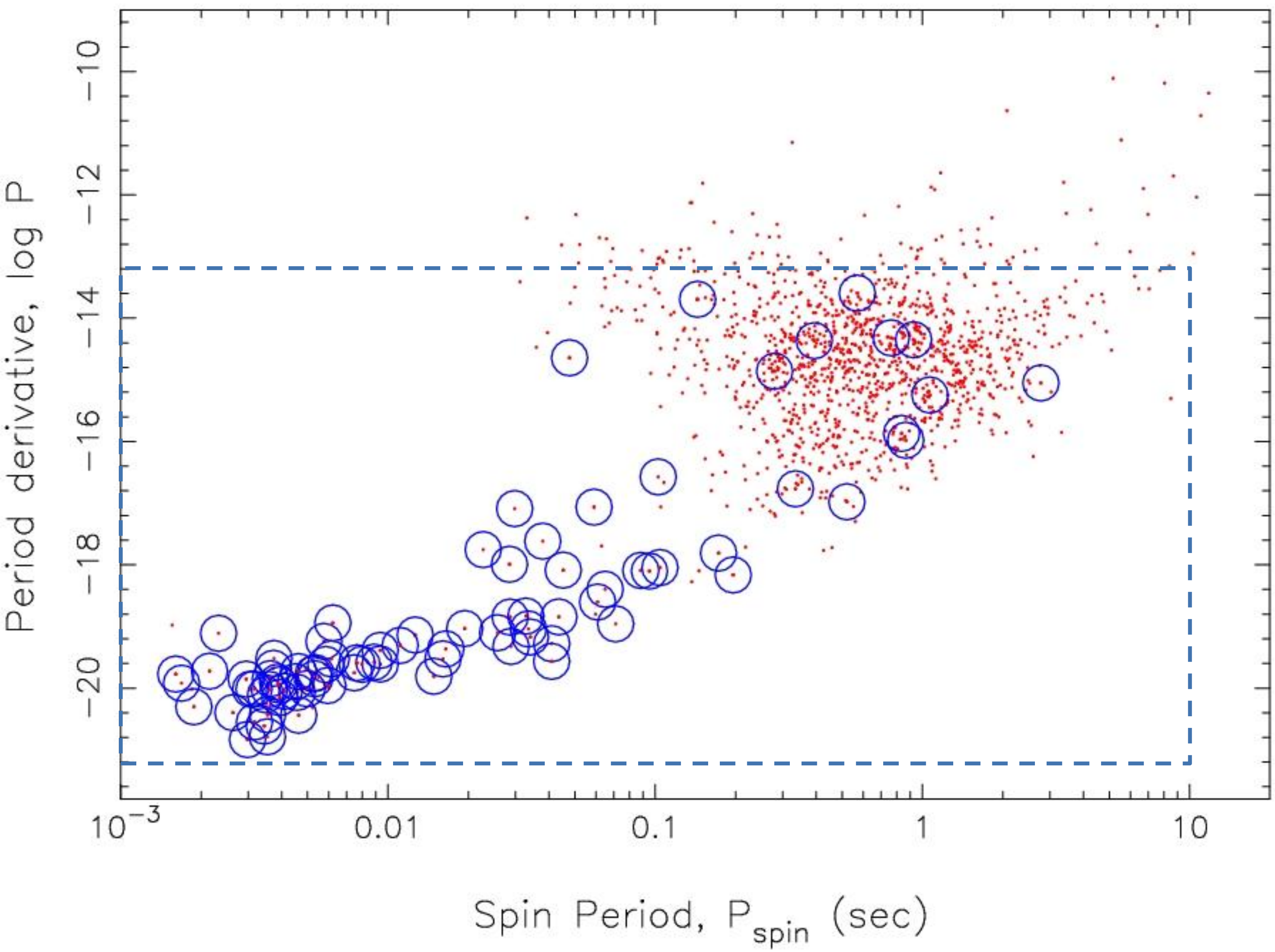
Tests of theories of gravity

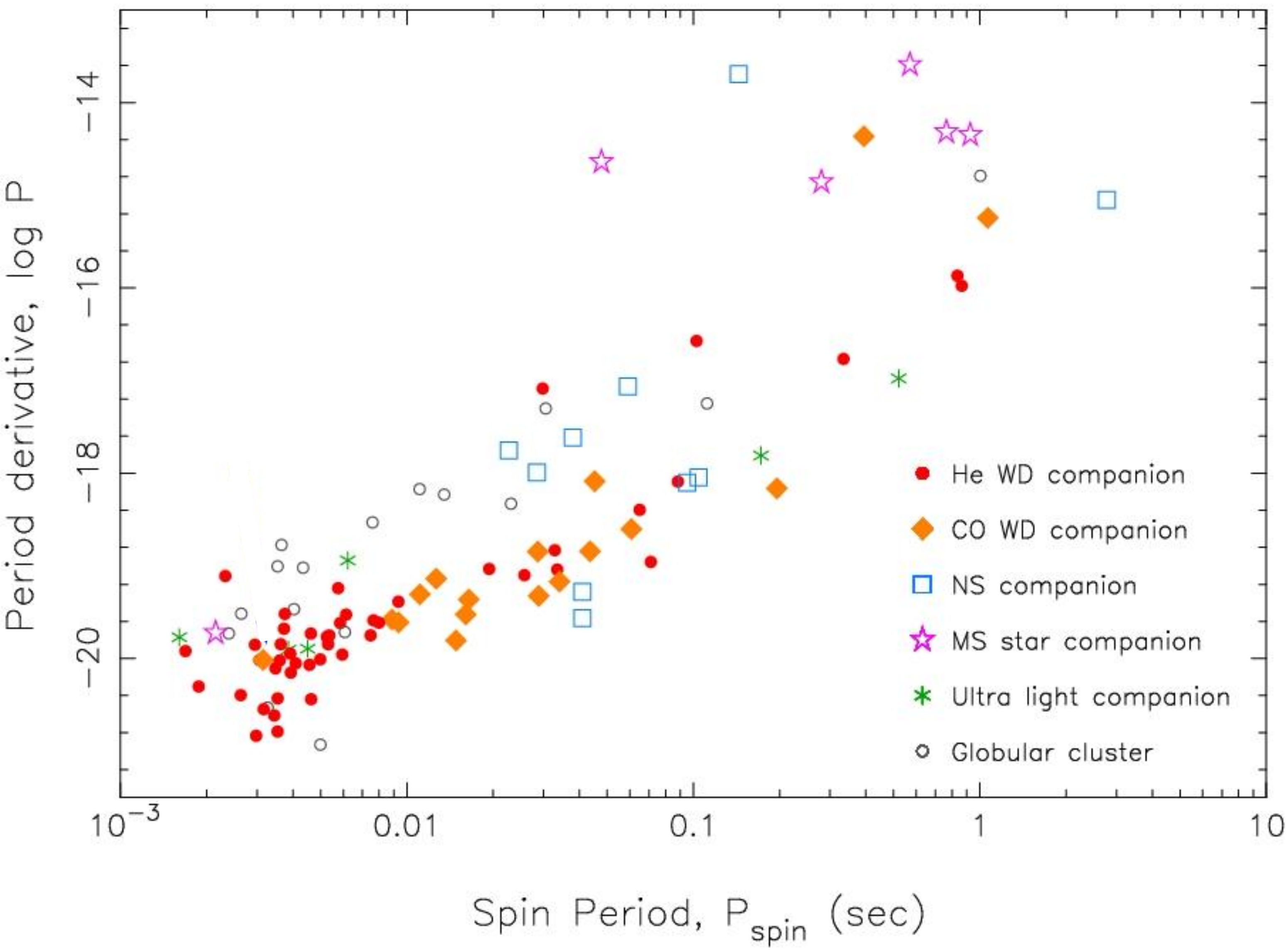




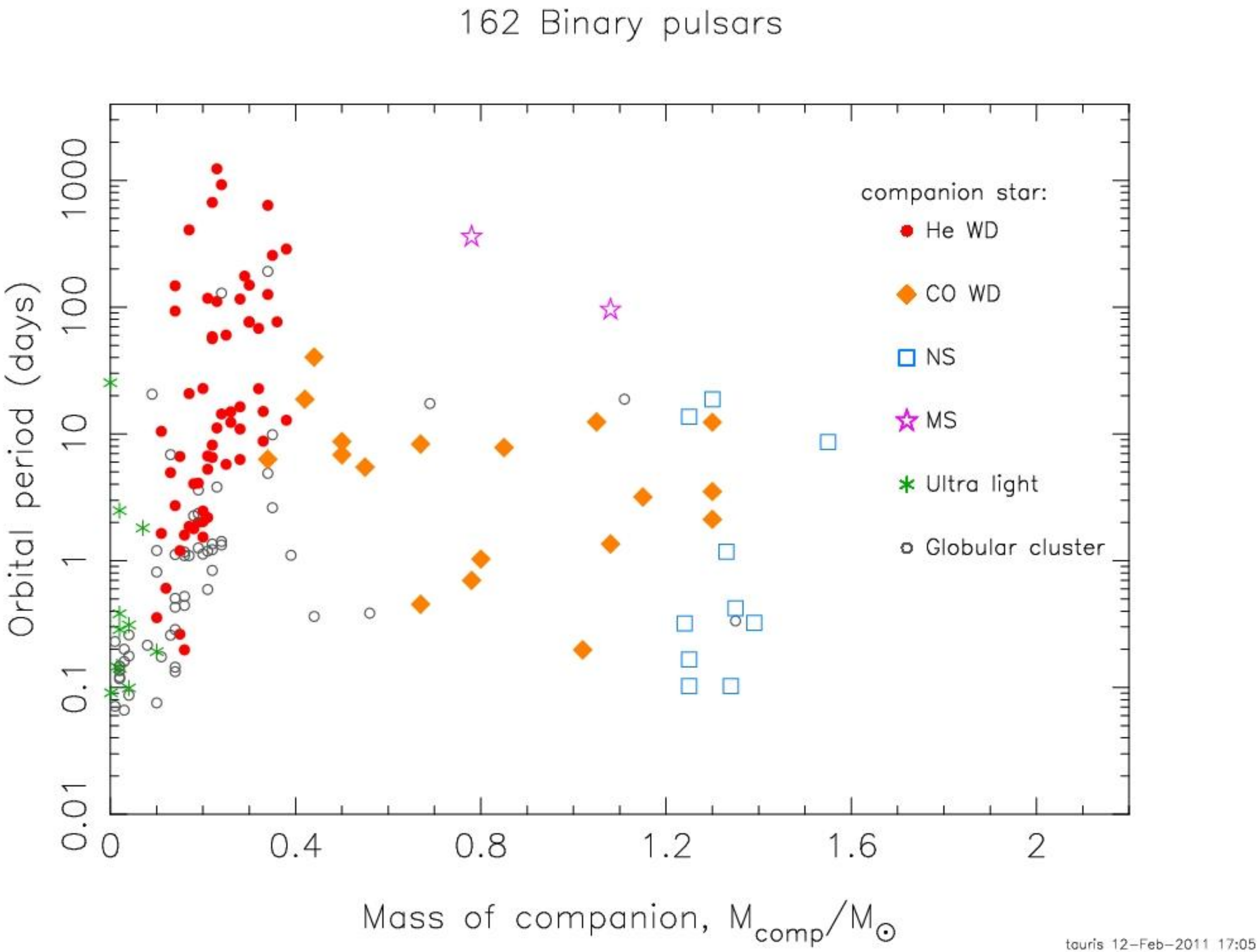


1669 radio pulsars





Period derivative, log Ṗ
−14
−16
−18
−20
10^{-3}
0.01
0.1
1
10
Spin Period, P_{spin} (sec)
He WD companion
CO WD companion
NS companion
MS star companion
Ultra light companion
Globular cluster

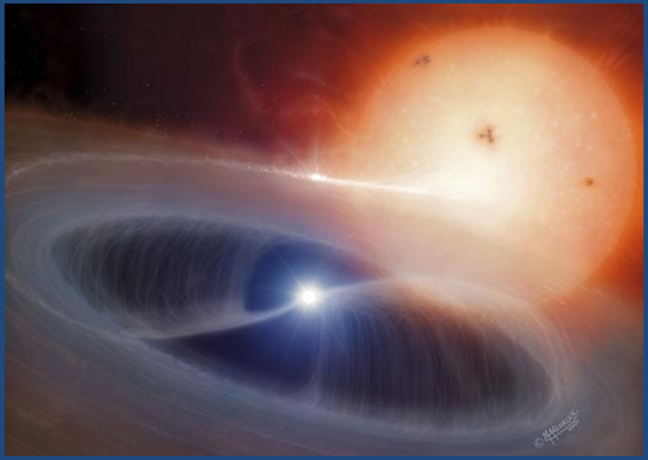

162 Binary pulsars
Orbital period (days)
0.01
0.1
1
10
100
1000
0
0.4
0.8
1.2
1.6
2
Mass of companion, $M_{comp}/M_{\odot}$
companion star:
He WD
CO WD
NS
MS
Ultra light
Globular cluster
tauris 12-Feb-2011 17:05

Characteristics of a binary millisecond pulsar (BMSP):

- Rapid spin: $P_{spin} < 50$ ms
- Small period derivative: $dP/dt < 10^{-18}\ \mathrm{s\ s^{-1}}$

Ingridients needed for spin-up:

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



Solution:

- Accretion of mass

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

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

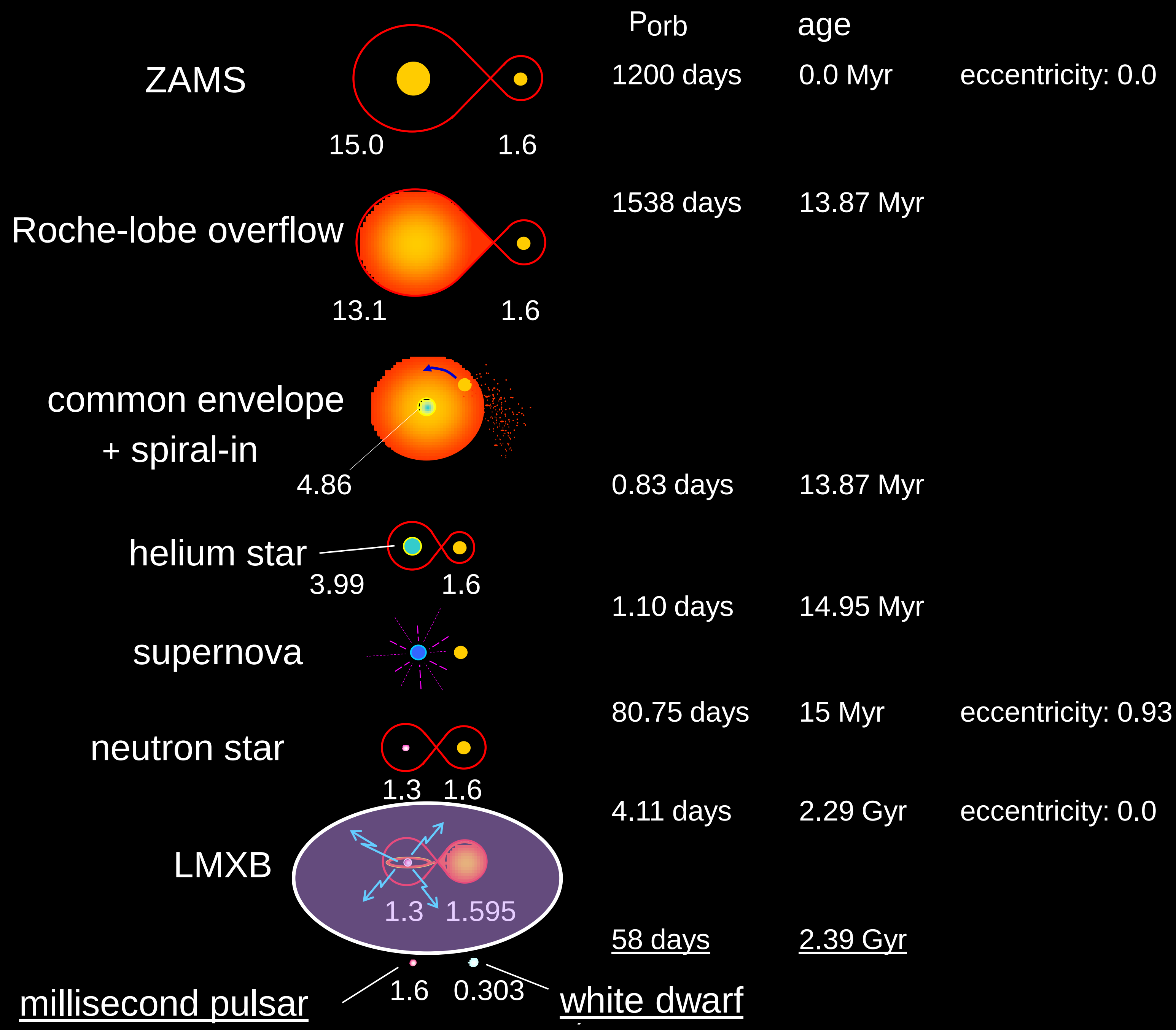
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{v} \times \vec{B}\right) - \frac{c^2}{4\pi} \nabla \times \left(\frac{1}{\sigma} \times \nabla \times \vec{B}\right)$$

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

Formation of a BMSP



Porb
age
ZAMS
15.0
1.6
1200 days
0.0 Myr
eccentricity: 0.0
Roche-lobe overflow
13.1
1.6
1538 days
13.87 Myr
common envelope
+ spiral-in
4.86
0.83 days
13.87 Myr
helium star
3.99
1.6
1.10 days
14.95 Myr
supernova
80.75 days
15 Myr
eccentricity: 0.93
neutron star
1.3
1.6
4.11 days
2.29 Gyr
eccentricity: 0.0
LMXB
1.3
1.595
58 days
2.39 Gyr
millisecond pulsar
1.6
0.303
white dwarf

The evolution of compact binaries

Stability ?

response of donor star ?

response of Roche-lobe ?

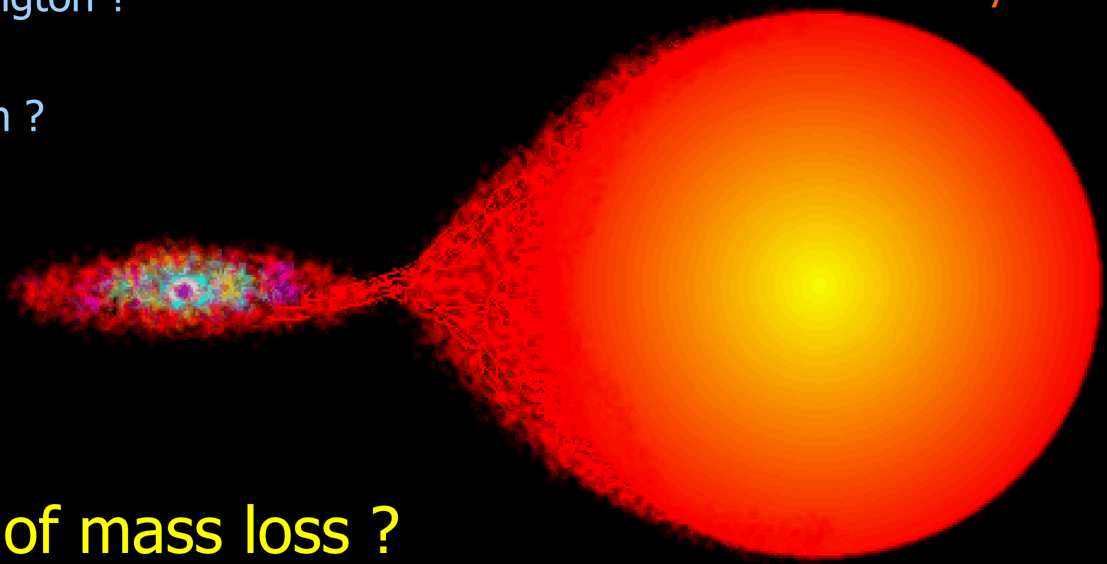
dynamically stable ?

Accretion ?

super-Eddington ?

jet ?

B-field, spin ?



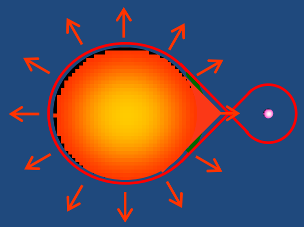
Mode of mass loss ?

specific orbital angular momentum ?

The evolution of compact binaries

Stability criteria for mass transfer

exponents of radius to mass: $R \propto M^{\zeta}$



$$\zeta_{donor} \equiv \frac{\partial \ln R_2}{\partial \ln M_2} \quad \wedge \quad \zeta_L \equiv \frac{\partial \ln R_L}{\partial \ln M_2}$$

adiabatic or thermal response of the donor star to mass loss

initial stability criteria: $\zeta_L \leq \zeta_{donor}$

$$\dot{R}_2 = \frac{\partial R_2}{\partial t}\bigg|_{M_2} + R_2\,\zeta_{donor}\frac{\dot{M}_2}{M_2}$$

nuclear burning

$$\dot{R}_L = \frac{\partial R_L}{\partial t}\bigg|_{M_2} + R_L\,\zeta_L\frac{\dot{M}_2}{M_2}$$

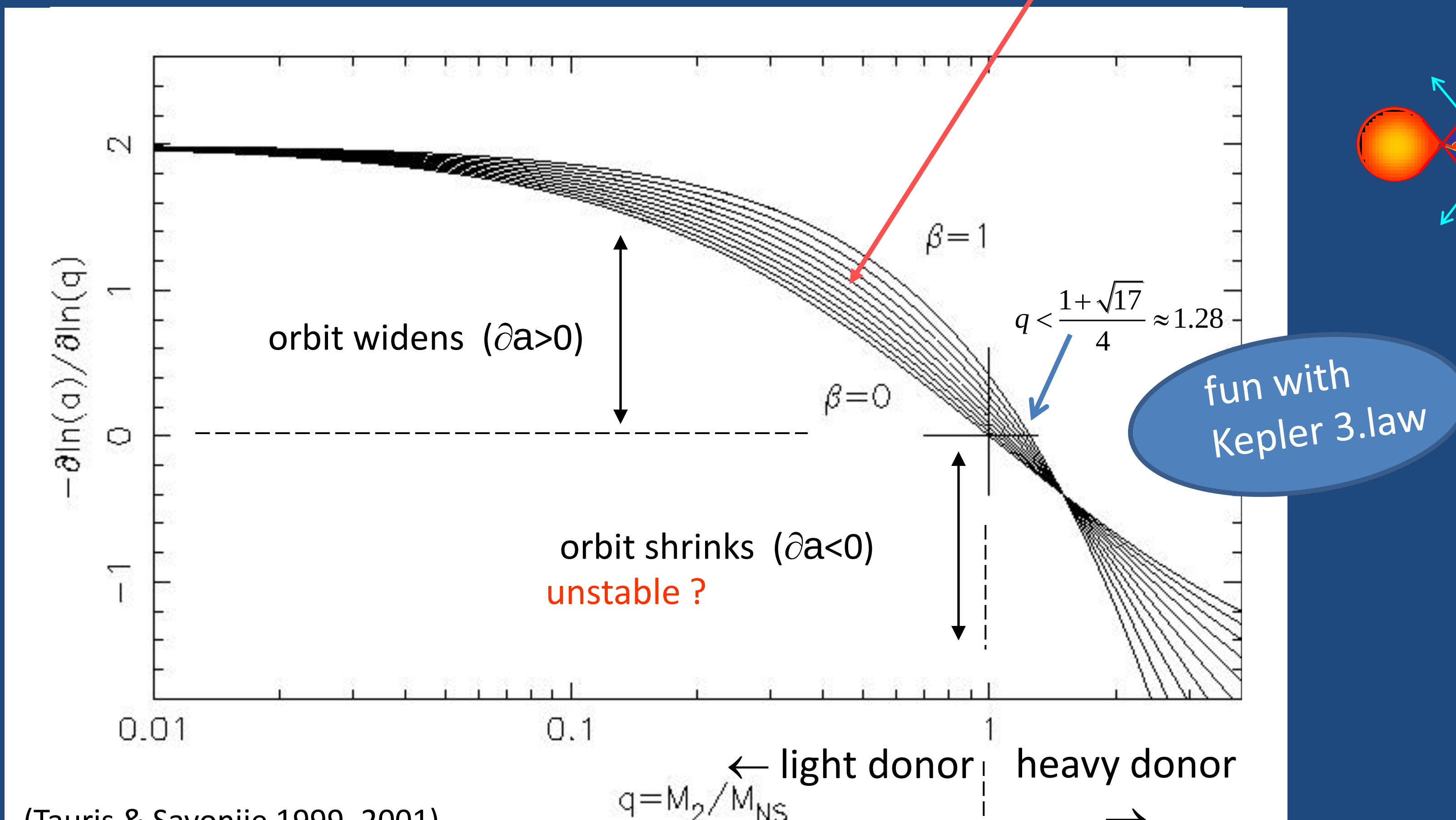
tidal spin-orbit couplings
gravitational wave radiation

$\dot{R}_2 = \dot{R}_L$ yields mass loss rate!

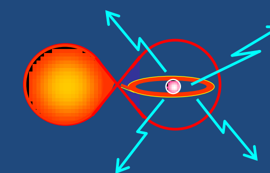
Stability criteria for mass transfer II - Isotropic re-emission model

Orbital evolution: $-\dfrac{\partial \ln a}{\partial \ln q} \quad \wedge \quad q = \dfrac{M_2}{M_{NS}} \quad (\partial q < 0)$

$$\beta = \max\left(\frac{|\dot{M}_2| - \dot{M}_{Edd}}{|\dot{M}_2|}, 0\right) \quad \alpha = 0 \quad \delta = 0$$



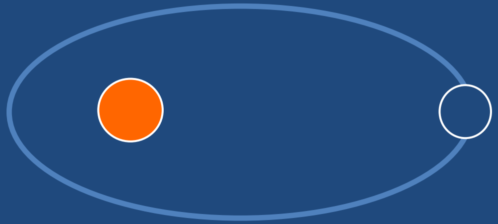
(Tauris & Savonije 1999, 2001)



The Orbital Angular Momentum Balance Equation

$$J_{orb} = \frac{M_1 M_2}{M}\,\Omega\, a^2 \sqrt{1-e^2}$$

orbital angular momentum



$$J_{orb} = |\vec{r} \times \vec{p}|$$

logarithmic differentiation

(e=0, tidal circularization)

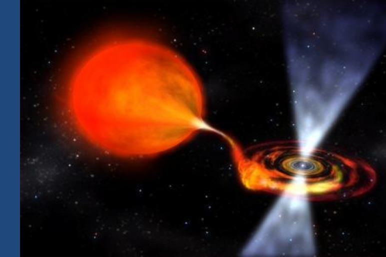
$\Downarrow$

$$\frac{\dot{a}}{a} = 2\frac{\dot{J}_{orb}}{J_{orb}} - 2\frac{\dot{M}_1}{M_1} - 2\frac{\dot{M}_2}{M_2} + \frac{\dot{M}_1 + \dot{M}_2}{M}$$

$$\frac{\dot{J}_{orb}}{J_{orb}} = \frac{\dot{J}_{gwr}}{J_{orb}} + \frac{\dot{J}_{mb}}{J_{orb}} + \frac{\dot{J}_{ls}}{J_{orb}} + \frac{\dot{J}_{ml}}{J_{orb}}$$

$$\frac{\dot{J}_{ml}}{J_{orb}} = \frac{\alpha + \beta q^2 + \delta\gamma(1+q)^2}{1+q}\,\frac{\dot{M}_2}{M_2}$$

$$\frac{a}{a_0} = \Gamma_{ls}\left(\frac{q}{q_0}\right)^{2(\alpha+\gamma\delta-1)}\left(\frac{q+1}{q_0+1}\right)^{\frac{-\alpha-\beta+\delta}{1-\varepsilon}}\left(\frac{\varepsilon q+1}{\varepsilon q_0+1}\right)^{3+2\frac{\alpha\varepsilon^2+\beta+\gamma\delta(1-\varepsilon)^2}{\varepsilon(1-\varepsilon)}}$$



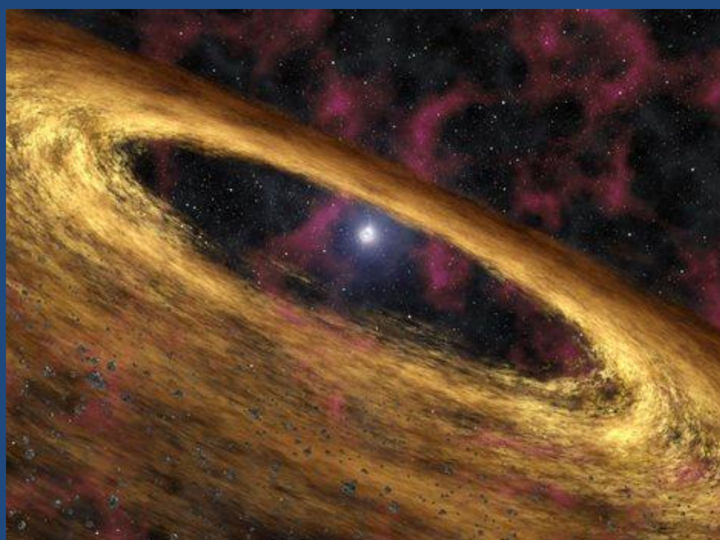
LMXB bifircation period

$P_{orb} < P_{bif}$: Converging

→ LMXB **shorten** their orbital period

Donor star still on main sequence

RLO driven by loss of J_{orb} (gwr, mb)



”Black widow” millisecond pulsars:

$$P_{orb} < 10\ hrs \qquad M_{comp.} < 0.1\, M_{\odot}$$

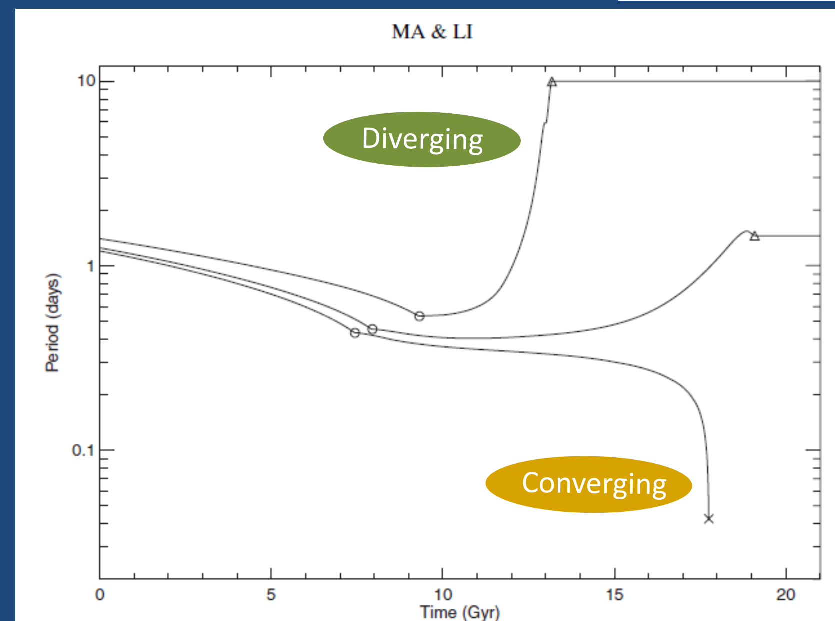
EoS?

Evaporation → single millisecond pulsars

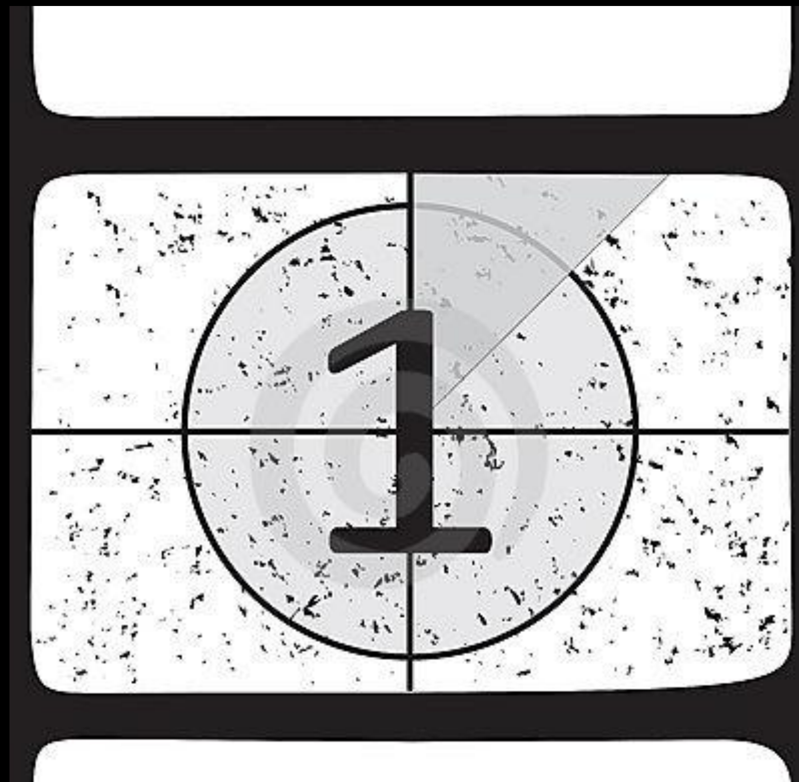
Problem?

Tutukov et al. (1985)
Pylyser & Savonije (1988, 1989)
Ma & Li (2009)

$$P_{bif} \approx 1\ day$$



Lazaridis, Verbiest, Tauris, et al. (2011)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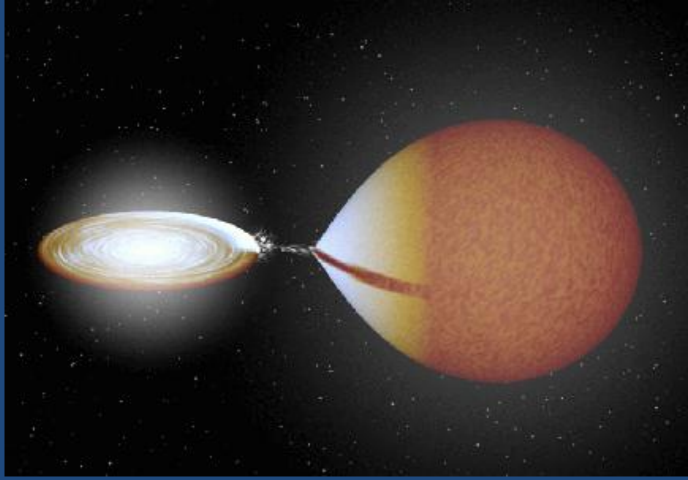
LMXB → BMSPs with He-WD



$P_{orb} > P_{bif}$: Diverging

→ LMXB **widen** their orbital period

Donor star is a (sub)giant

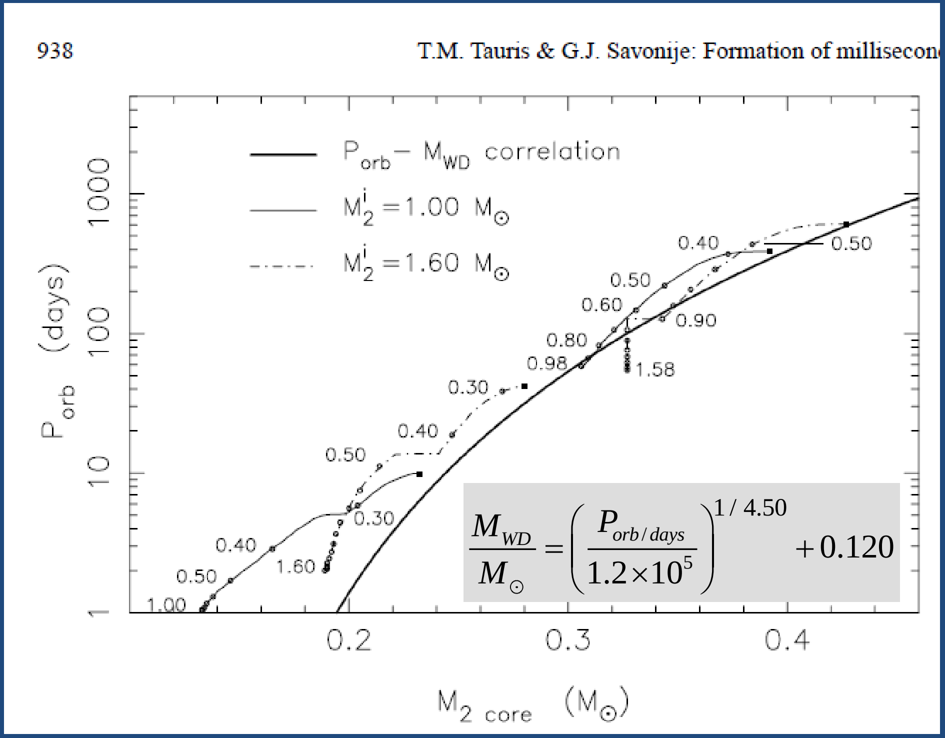
RLO driven by nuclear expansion

Formation of BMSPs with He-WD:

$$P_{orb} > 1\,day$$
$$0.18 < M_{WD} < 0.46\,M_\odot$$

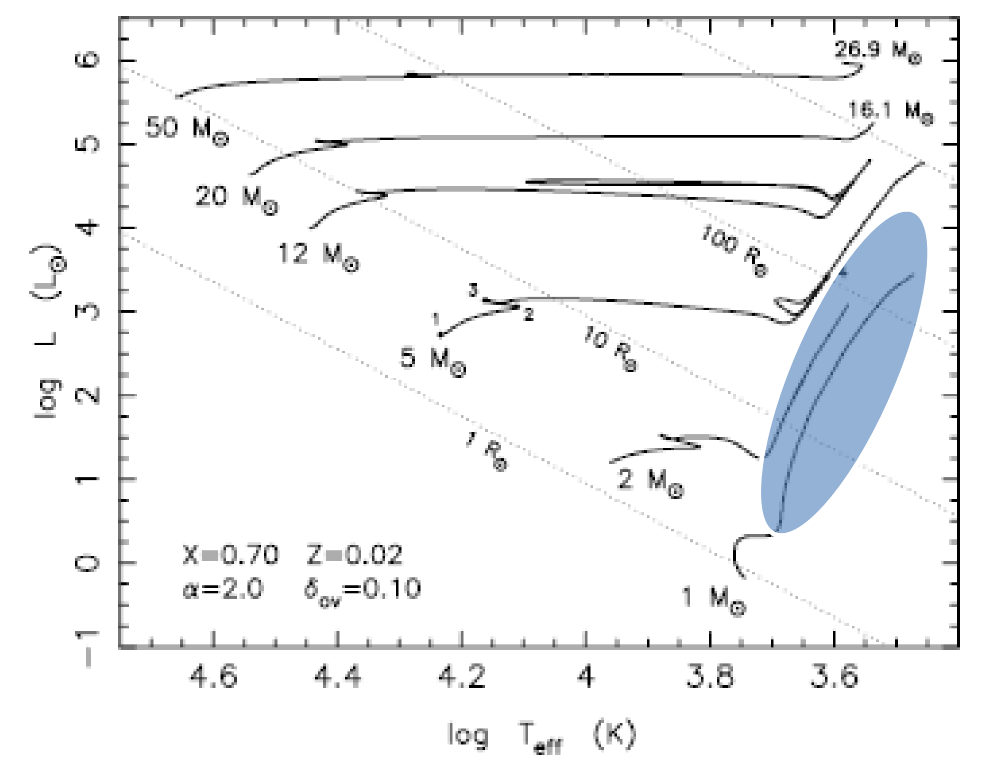
Unique relation between P_{orb} and M_{WD}

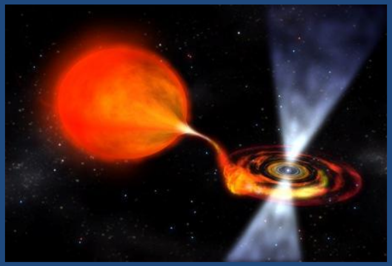
Savonije (1987)
Joss, Rappaport & Lewis (1987)
Rappaport et al. (1995)
Tauris & Savonije (1999)



Orbital period – white dwarf mass correlation

- On the red giant branch (hydrogen shell burning) the growth of the degenerate core mass is directly related to the luminosity of the star
- Temperature is almost constant on the Hyashi track $\Rightarrow$ $L \propto R^2$ $\quad L = 4\pi R^2 \sigma T_{eff}^4$
- Hence there is a relation between M_{core} and R
- The donor star fills its Roche-lobe during the mass transfer $\Rightarrow$ R is correlated with P_{orb}

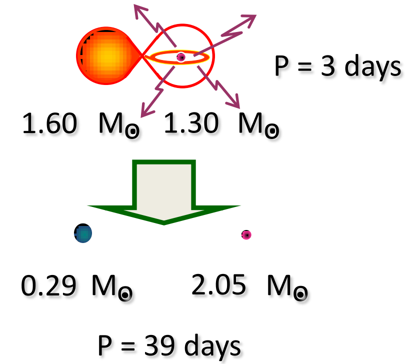


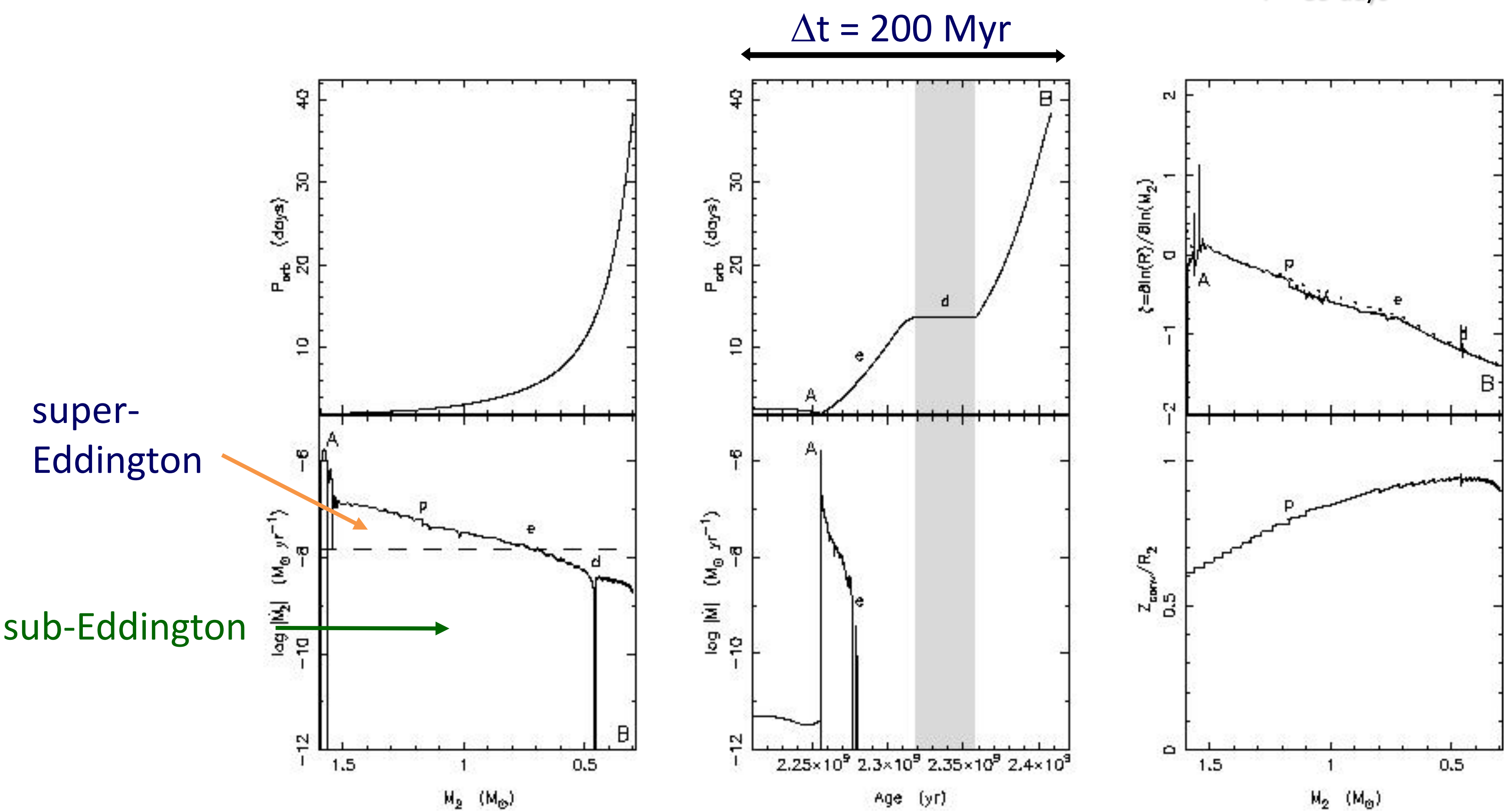


correlation between (P_{orb} , M_{WD})

Detailed evolution of LMXBs
- formation of MSPs

Tauris & Savonije (1999)

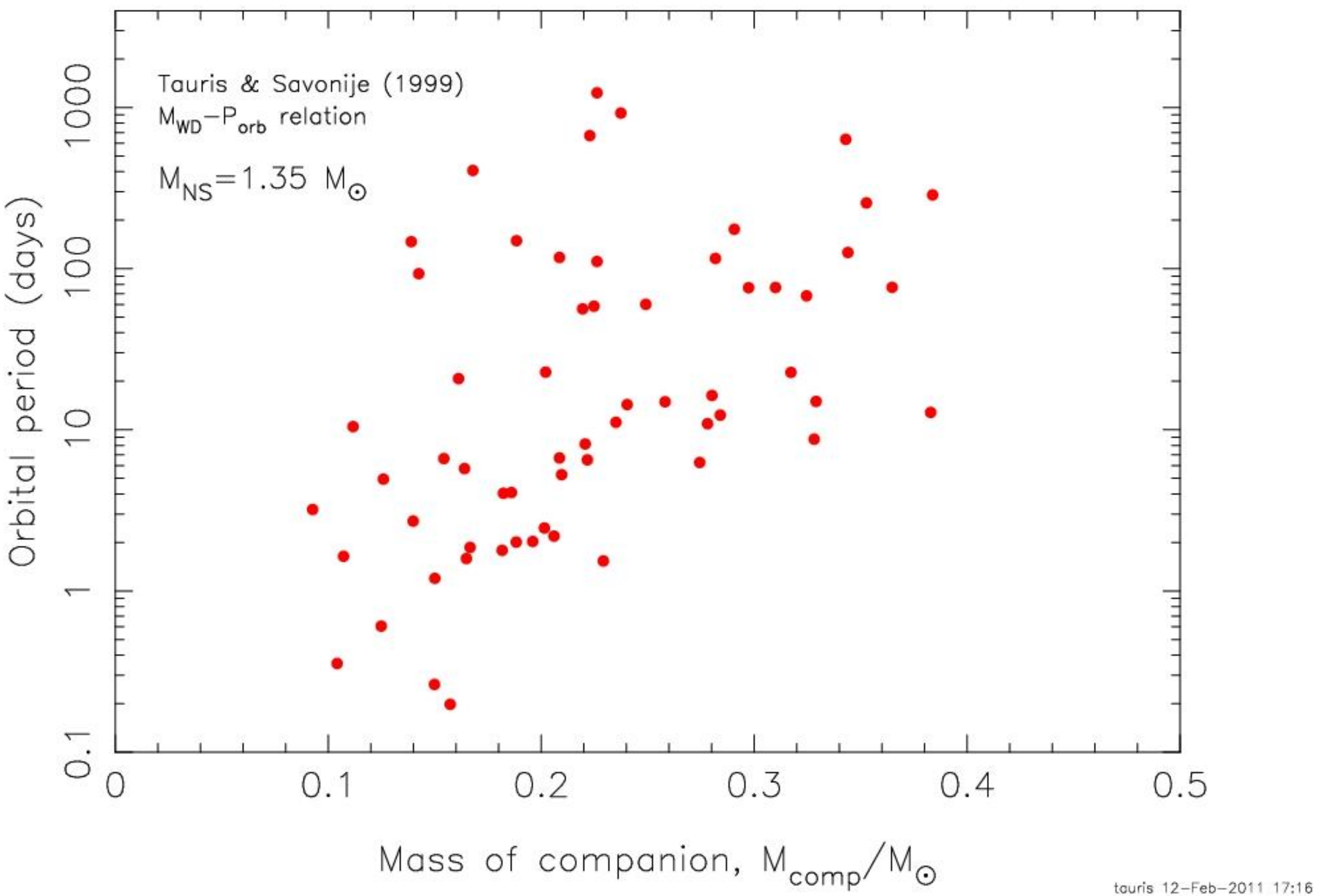




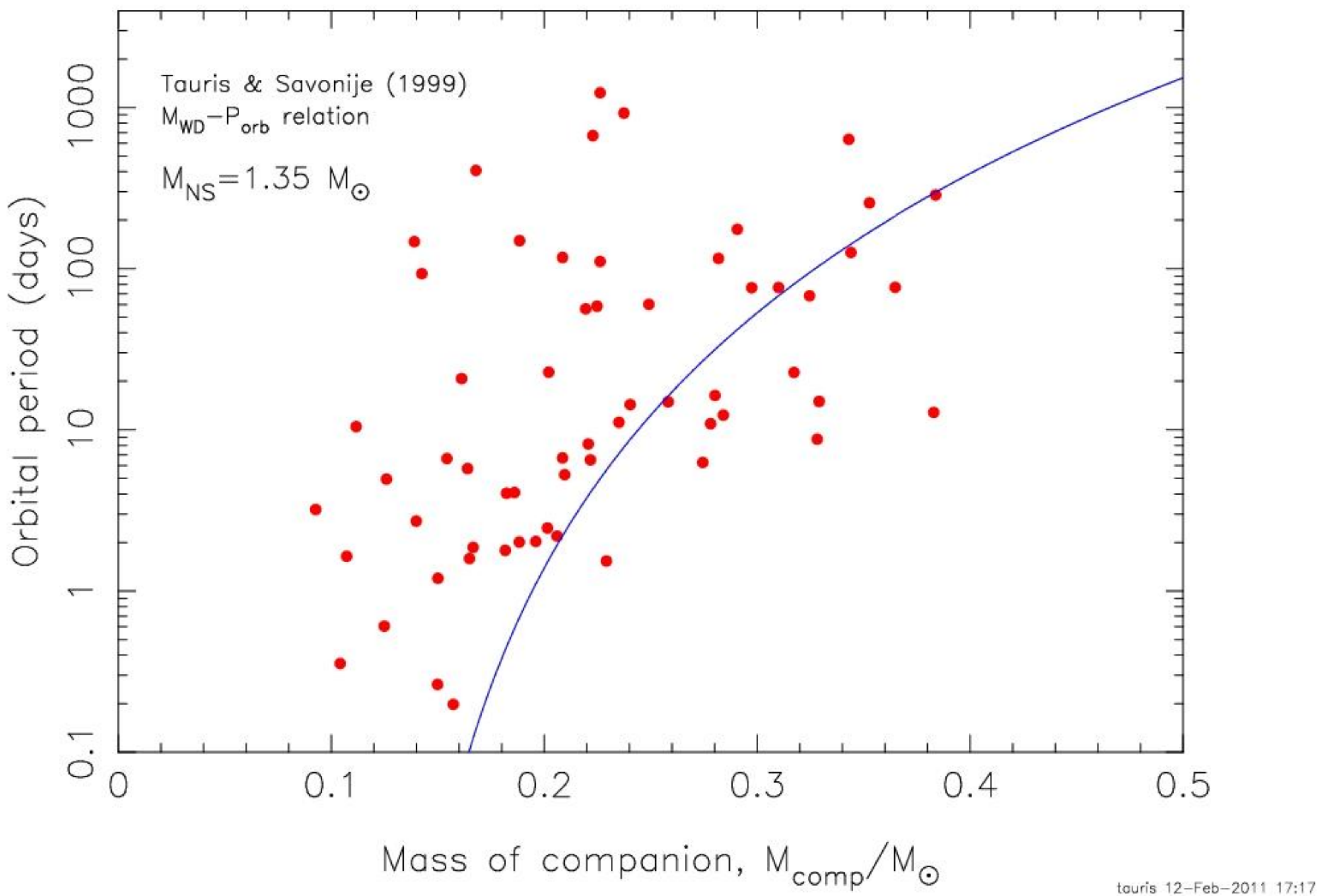
Orbital period – white dwarf mass correlation

At first sight the theoretical relation looks really crappy when compared with observations……….

60 Binary pulsars



60 Binary pulsars



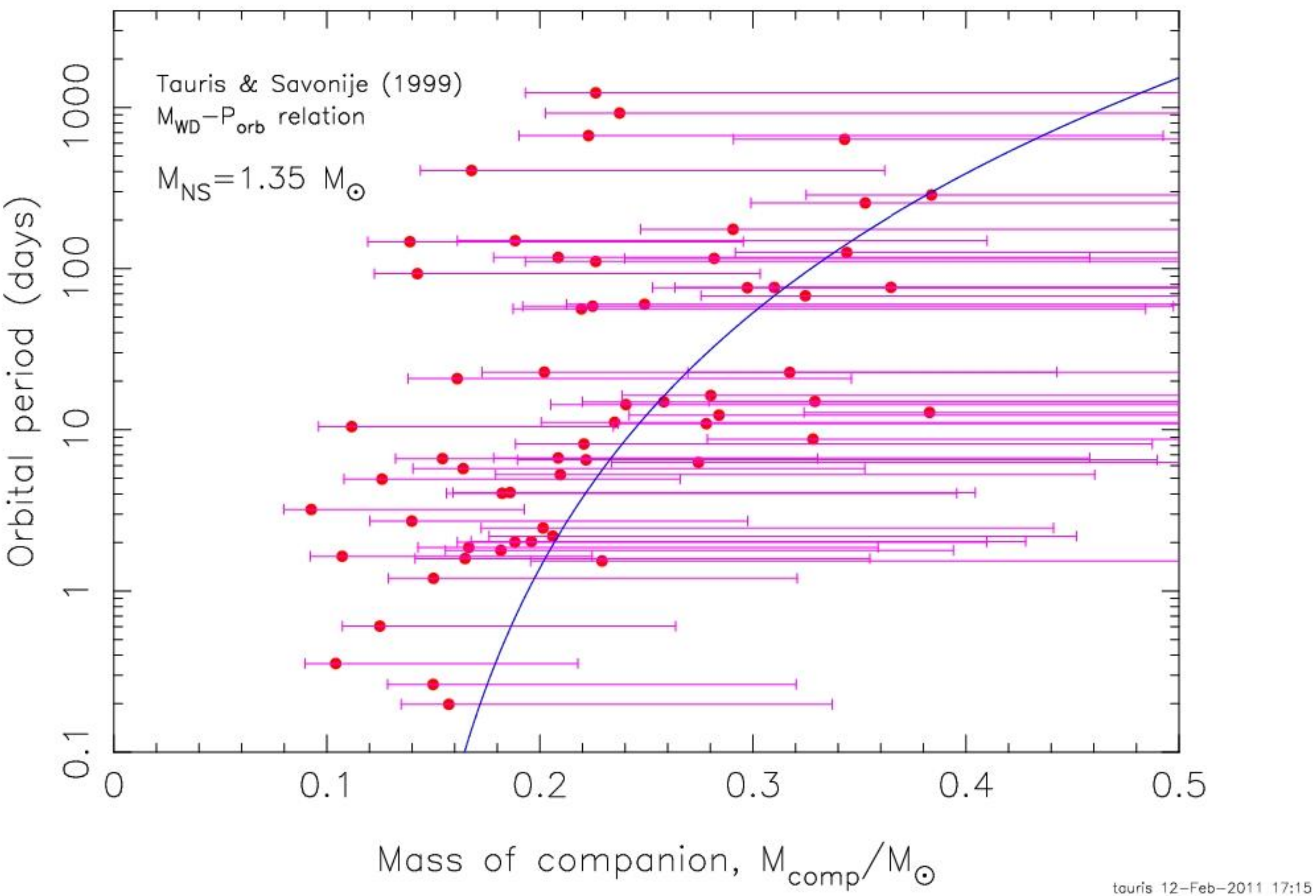
Orbital period – white dwarf mass correlation

At first sight the theoretical relation looks really crappy when compared with observations……...

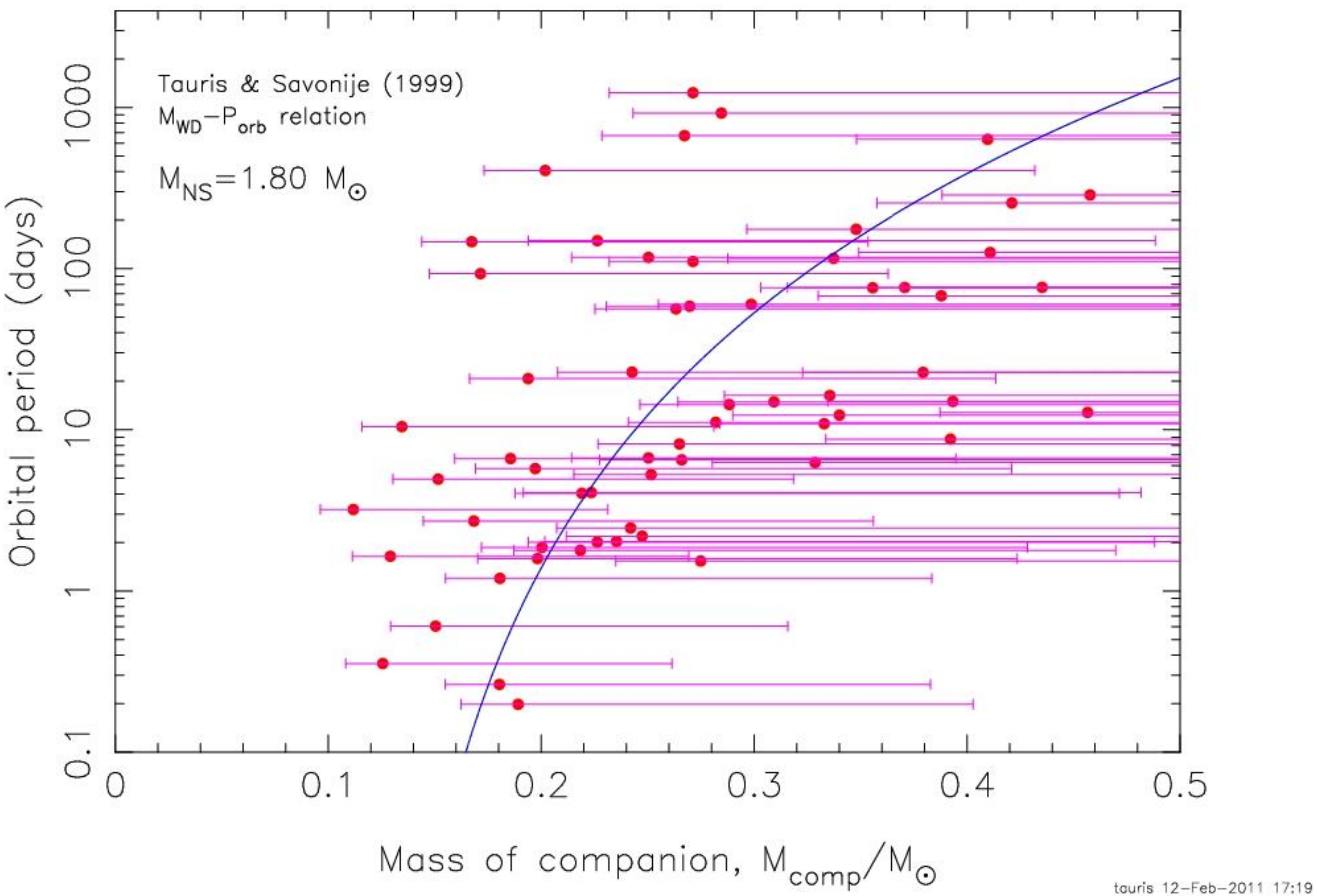
But for each *individual* binary one must take into account:

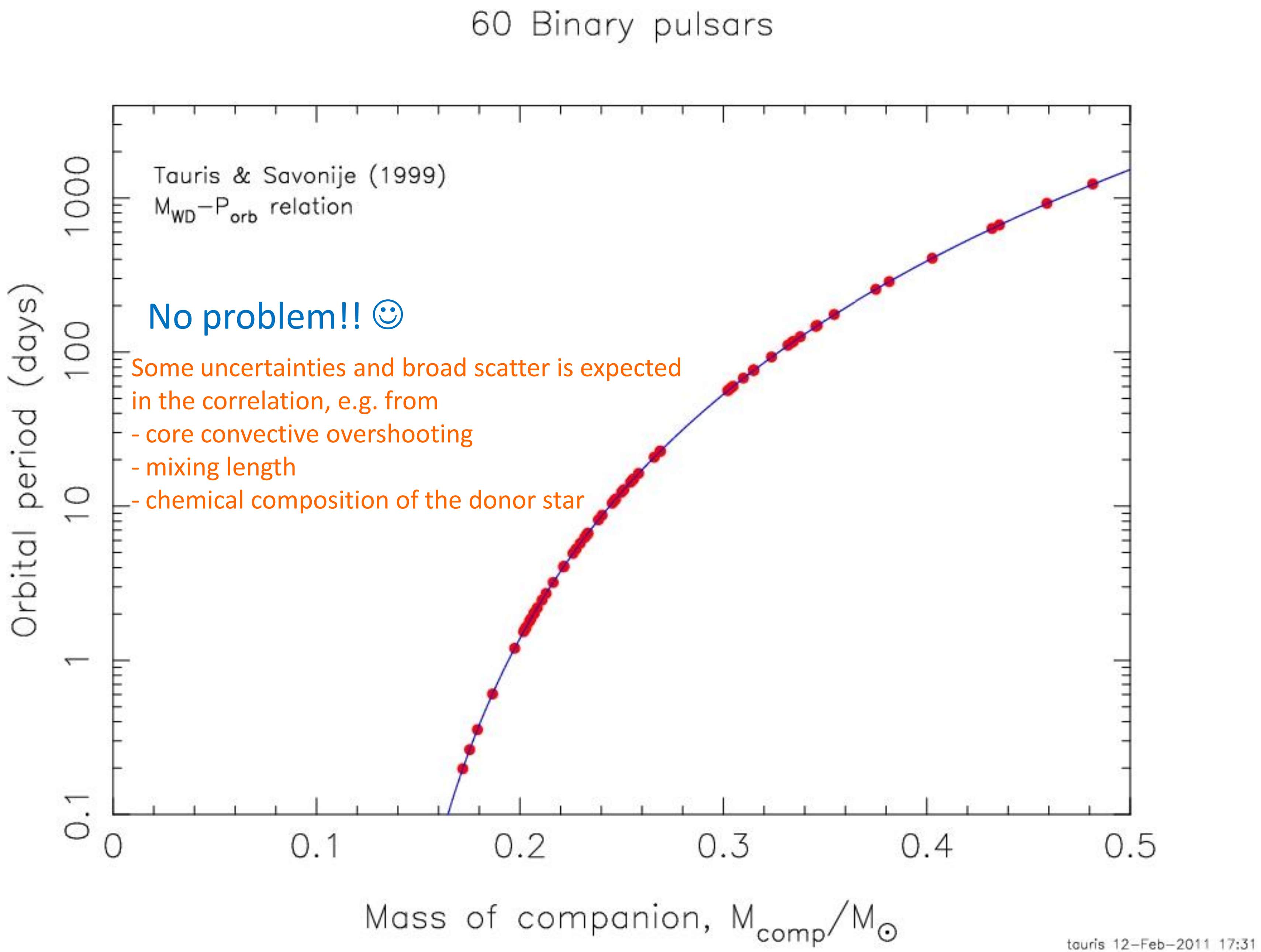
1) Unknown orbital inclination angle
2) The mass of the pulsar (*not* always 1.35 M_{sun} -- LMXBs allow for accretion!)

60 Binary pulsars



60 Binary pulsars





60 Binary pulsars
Tauris & Savonije (1999)
M_WD–P_orb relation
No problem!! ☺
Some uncertainties and broad scatter is expected
in the correlation, e.g. from
- core convective overshooting
- mixing length
- chemical composition of the donor star
Orbital period (days)
0.1
1
10
100
1000
0
0.1
0.2
0.3
0.4
0.5
Mass of companion, M_comp/M⊙
tauris 12–Feb–2011 17:31

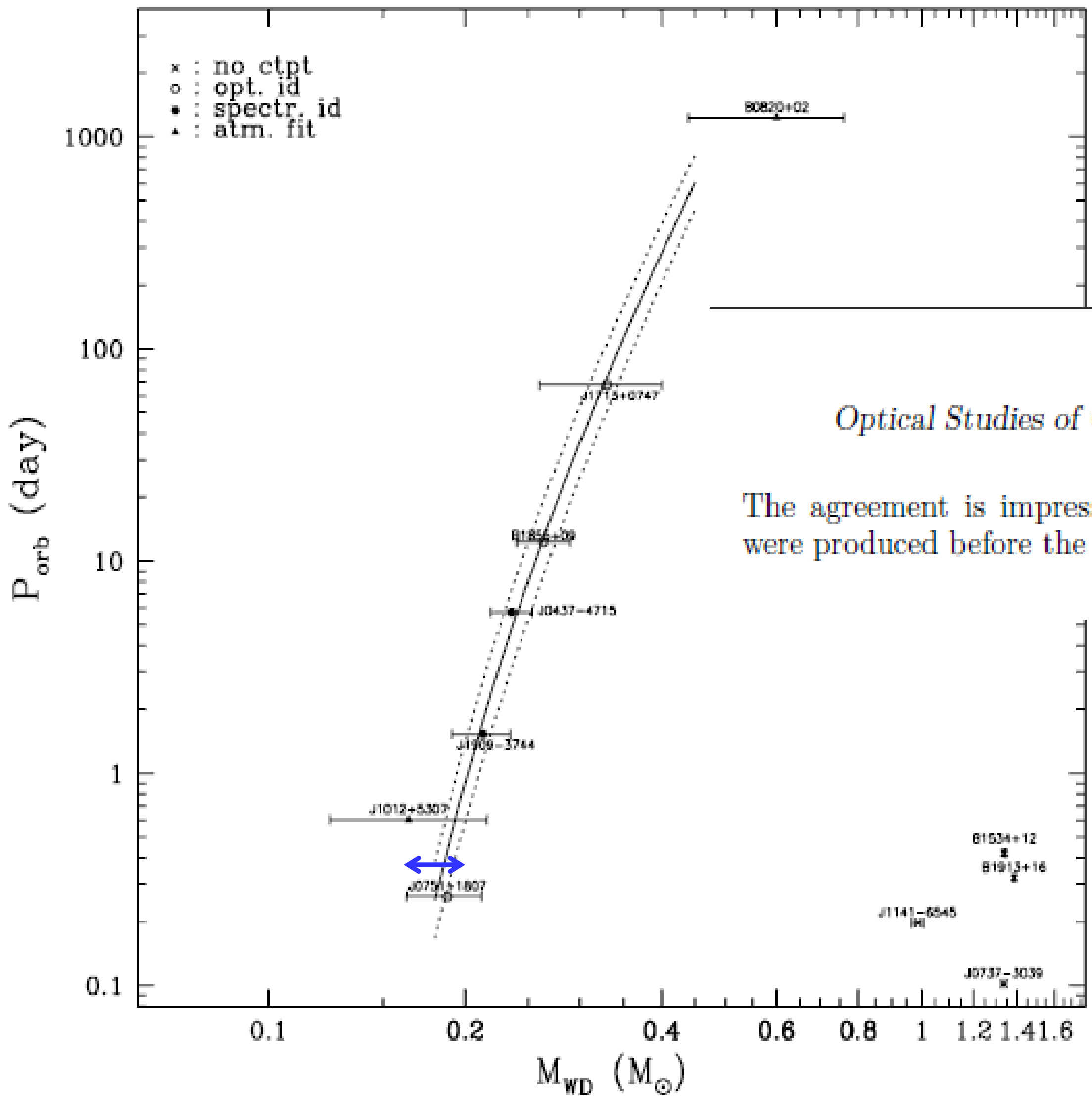


Figure 2. Orbital period as a function of companion mass for all binary pulsars with measured masses (shown with 95% confidence error bars). Overdrawn are predictions from the evolutionary calculations of Tauris & Savonije (1999). The different lines are for different progenitor metallicities; there is some additional uncertainty related to the mixing-length parameter.

The agreement is impressive, especially when one considers that the models were produced before the accurate masses became available.

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2

IMXB case C (B) RLO → BMSPs with CO/ONeMg-WD via Common Envelope and spiral-in phase

Dynamically unstable mass transfer if:

- deep convective envelope of donor star

  (rapid expasion in response to mass loss)

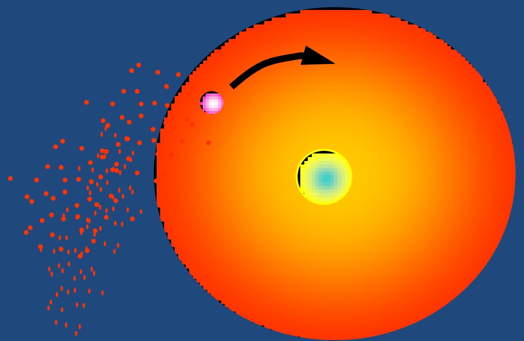
- $M_{donor} > M_{accretor}$

  (orbit shrinks in response to mass loss)

Run-away process !

⇓

common envelope



drag force → dissipation of orb. ang. mom.

+ deposition of E_{orb} in the envelope

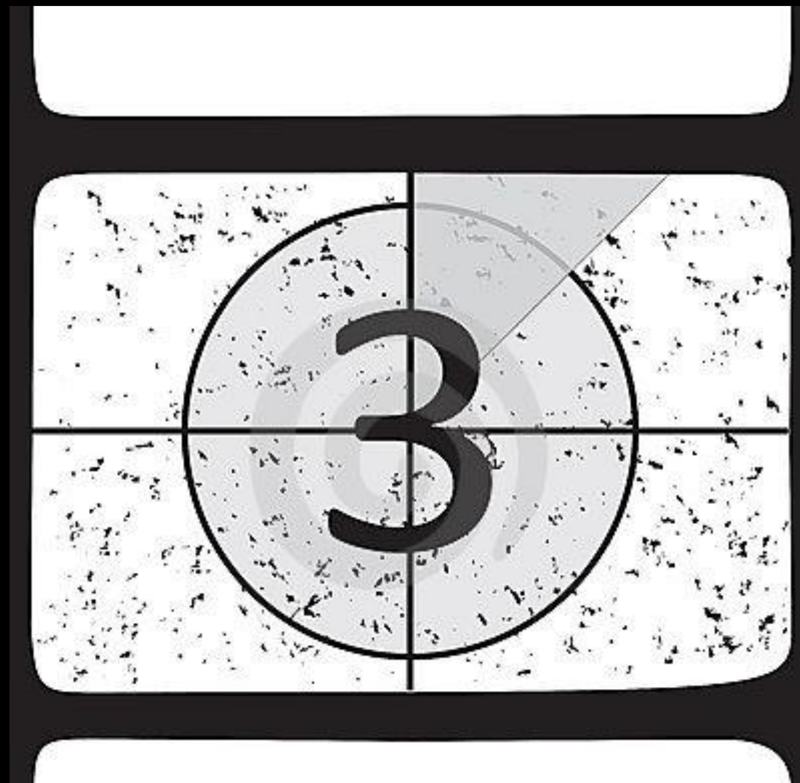
Outcome:

- huge reduction of orbital separation

→ rejection of stellar envelope
(NS orbiting a naked helium star)

→ merging of NS + core
(Thorne-Zytkow object / black hole)

Explain tight BMSPs, P_{orb} < 3 days!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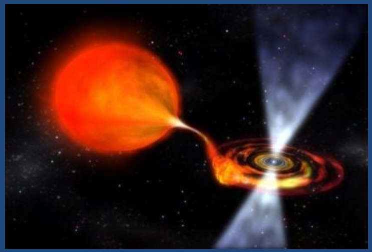
IMXB Early case B RLO → BMSPs with CO-WD (He-WD)

Alternative to CE-phase:
- thermal timescale mass transfer
- isotropic re-emission model



Cyg X-2:
King & Ritter (1999)
Podsiadlowski & Rappaport (2000)

Tauris, van den Heuvel & Savonije (2000)

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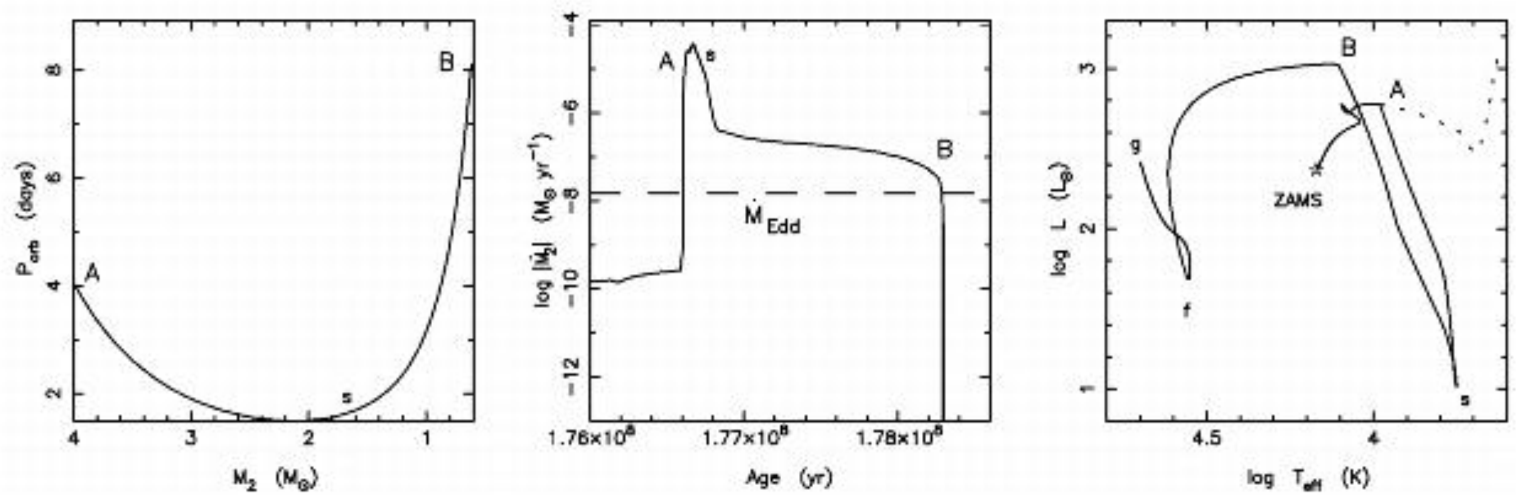


FIG. 1.—Evolution of an X-ray binary with $M_2 = 4.0\ M_\odot$ and $P_{orb} = 4.0$ days. *Left:* Evolution of P_{orb} as a function of M_2 (time is increasing to the right). *Middle:* Mass-loss rate of the donor as a function of its age since the ZAMS. *Right:* Evolution of the mass-losing donor (*solid line*) in an H-R diagram. The dotted line represents the evolutionary track of a single 4.0 $M_\odot$ star. The letters in the different panels correspond to one another at a given evolutionary epoch—see text for further explanation.


4

IMXB case A RLO → BMSPs with CO/He-WD

Podsiadlowski, Rappaport & Pfahl (2002)

Tauris, Langer & Kramer (2011a,b), Tauris & Langer (2011)

nature International weekly journal of science

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts & J. W. T. Hessels

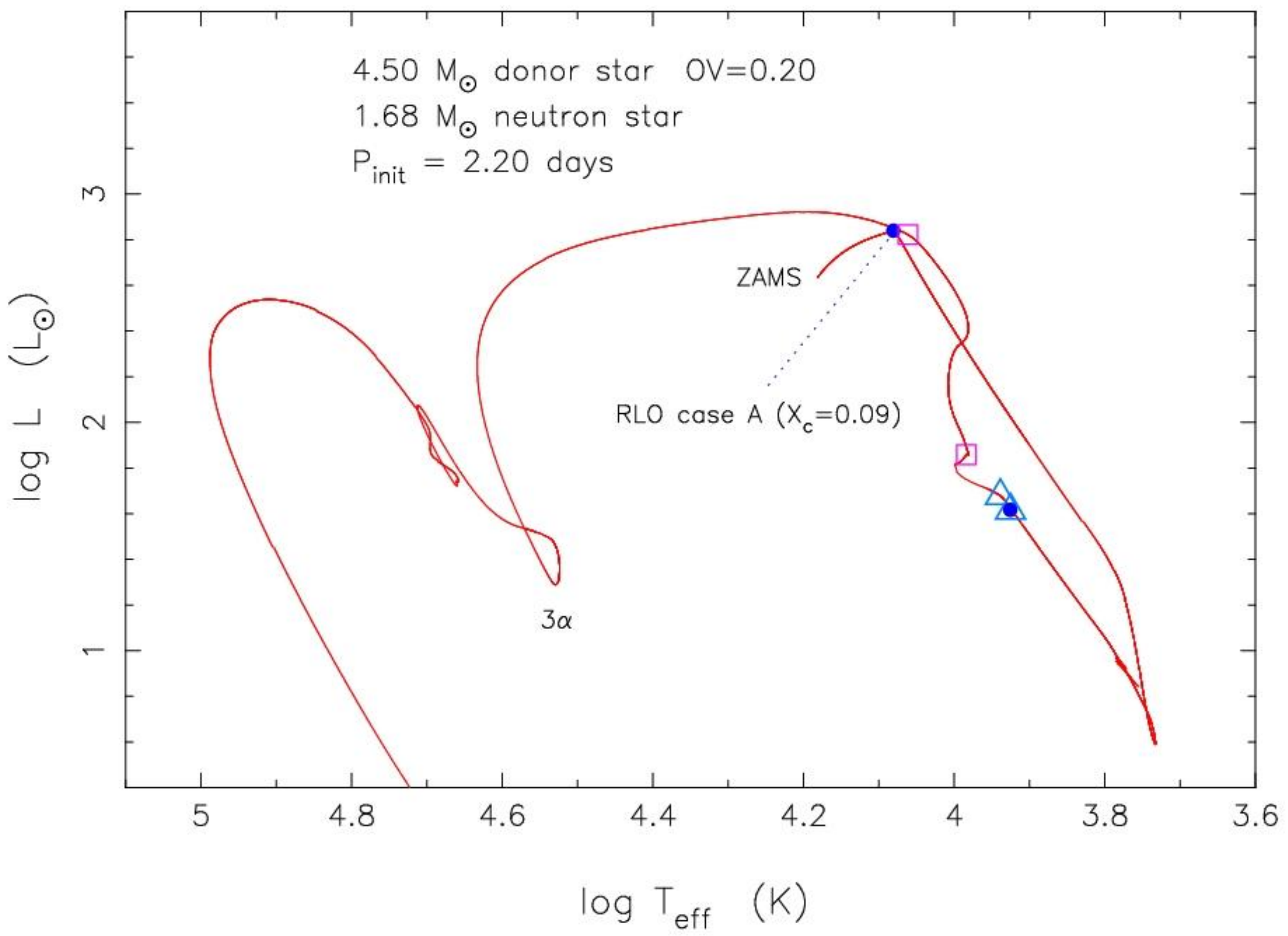
PSR J1614-2230

Pulsar mass:	1.97±0.04 M_o
WD mass:	0.500±0.006 M_o
Orbital period:	8.69 days
Projected a_{psr}:	11.29 light s
Eccentricity:	1.30±0.04 × 10^{-6}
Inclination angle:	89.17±0.02 deg.
DM distance:	1.2 kpc

Was this pulsar born massive?

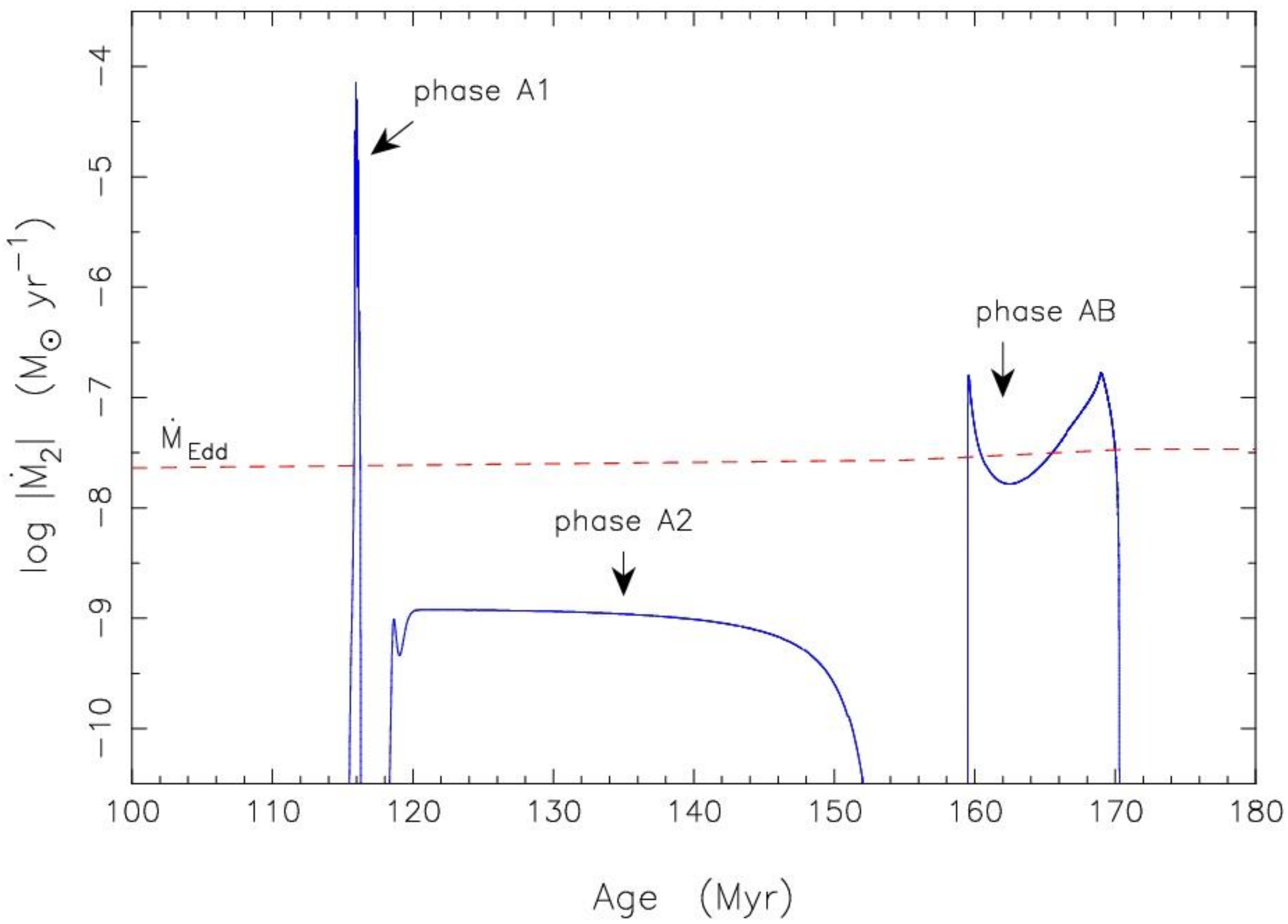
Nature of progenitor binary ?

IMXB case A

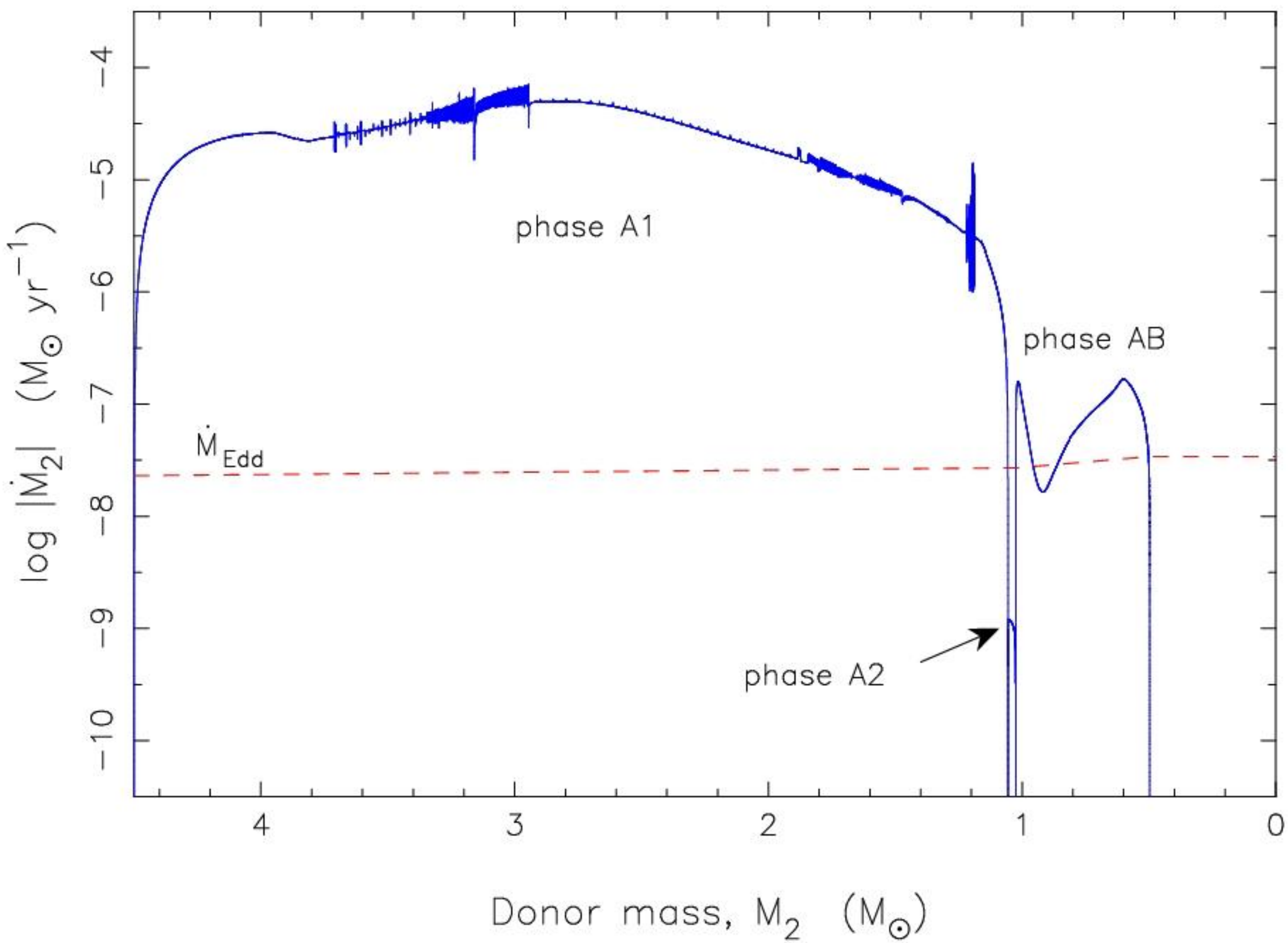


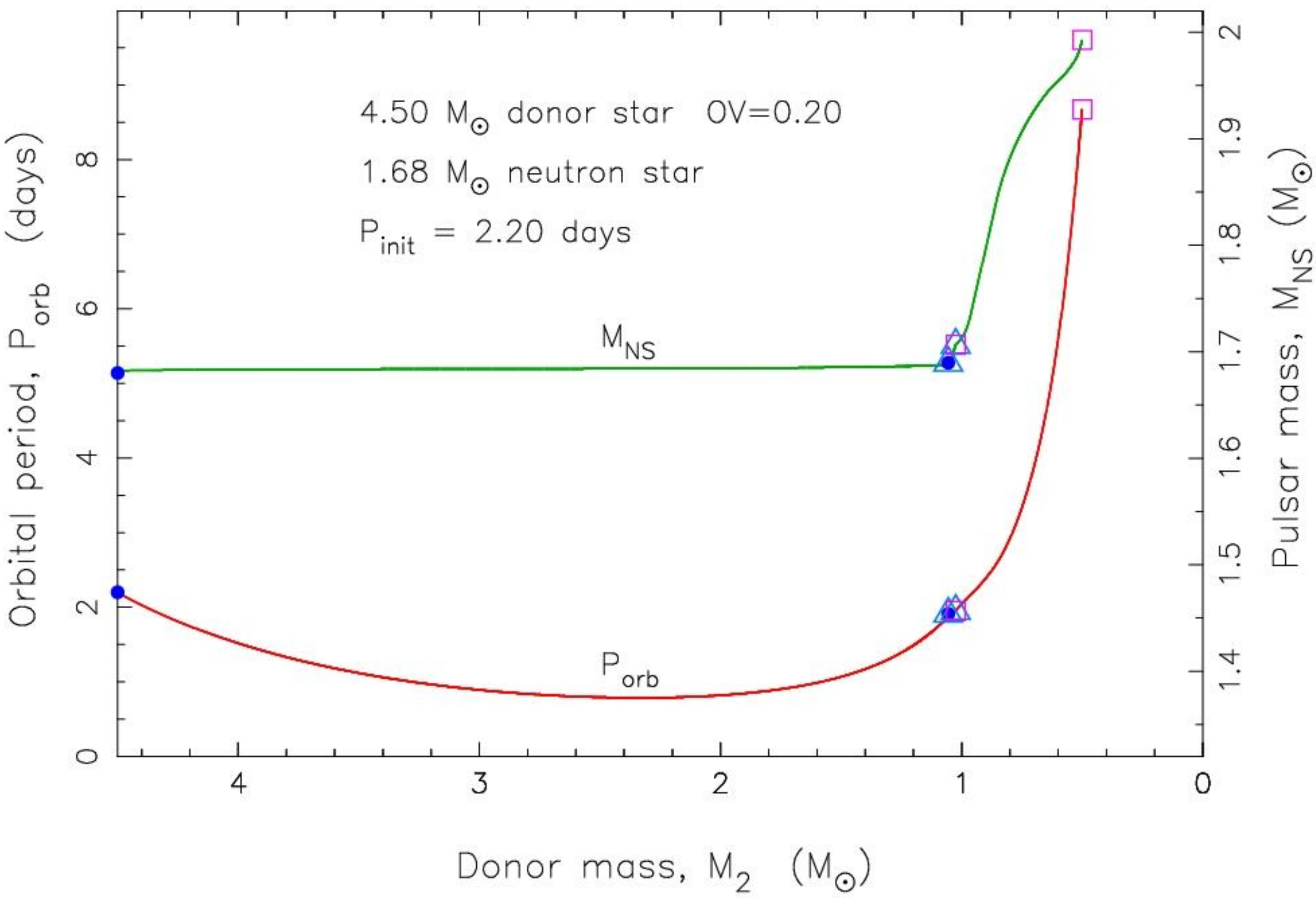
4.50 M⊙ donor star OV=0.20
1.68 M⊙ neutron star
P_init = 2.20 days
ZAMS
RLO case A (X_c=0.09)
3α
log L (L⊙)
log T_eff (K)
5
4.8
4.6
4.4
4.2
4
3.8
3.6
1
2
3

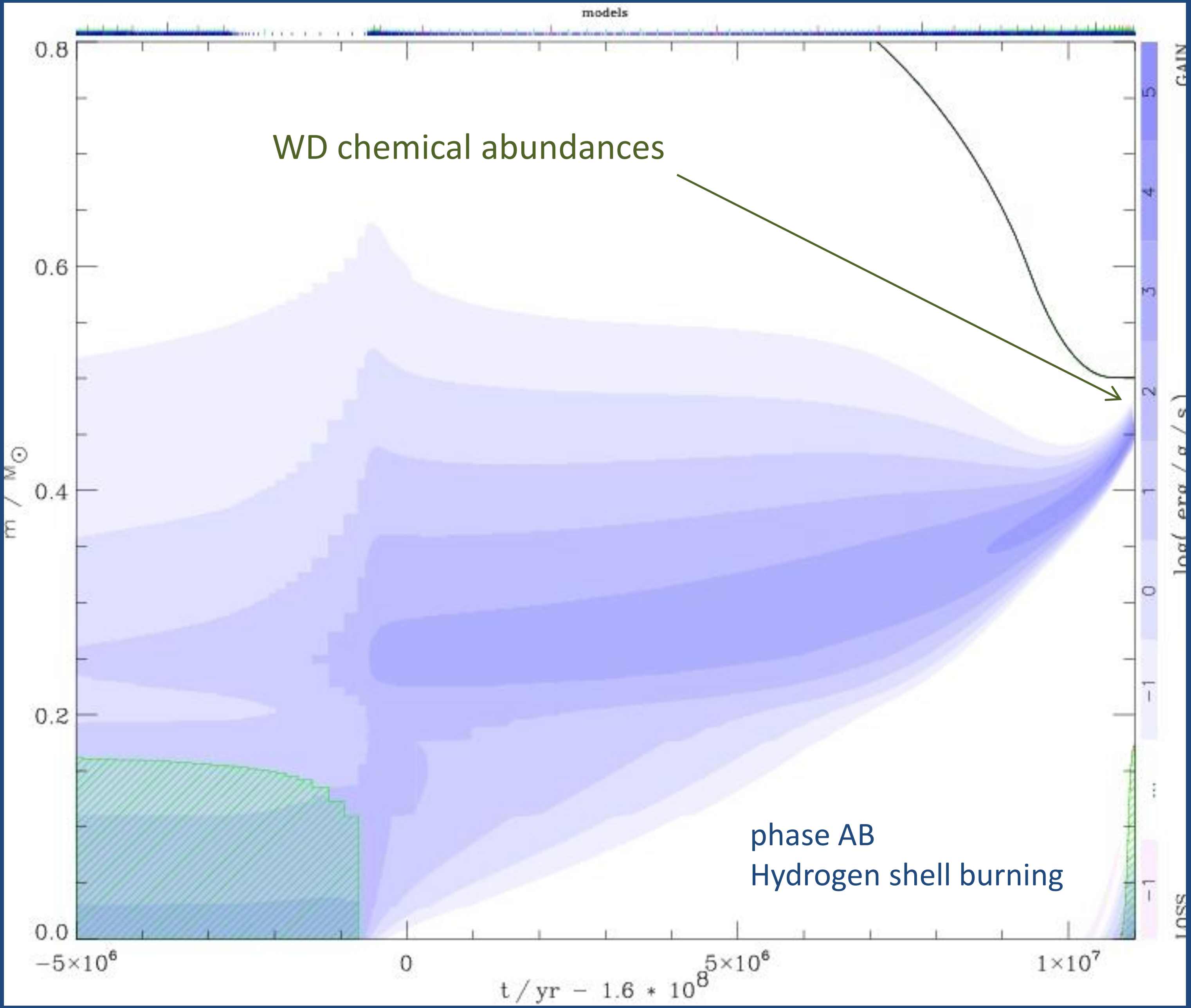
IMXB case A: thermal + nuclear timescale mass transfer

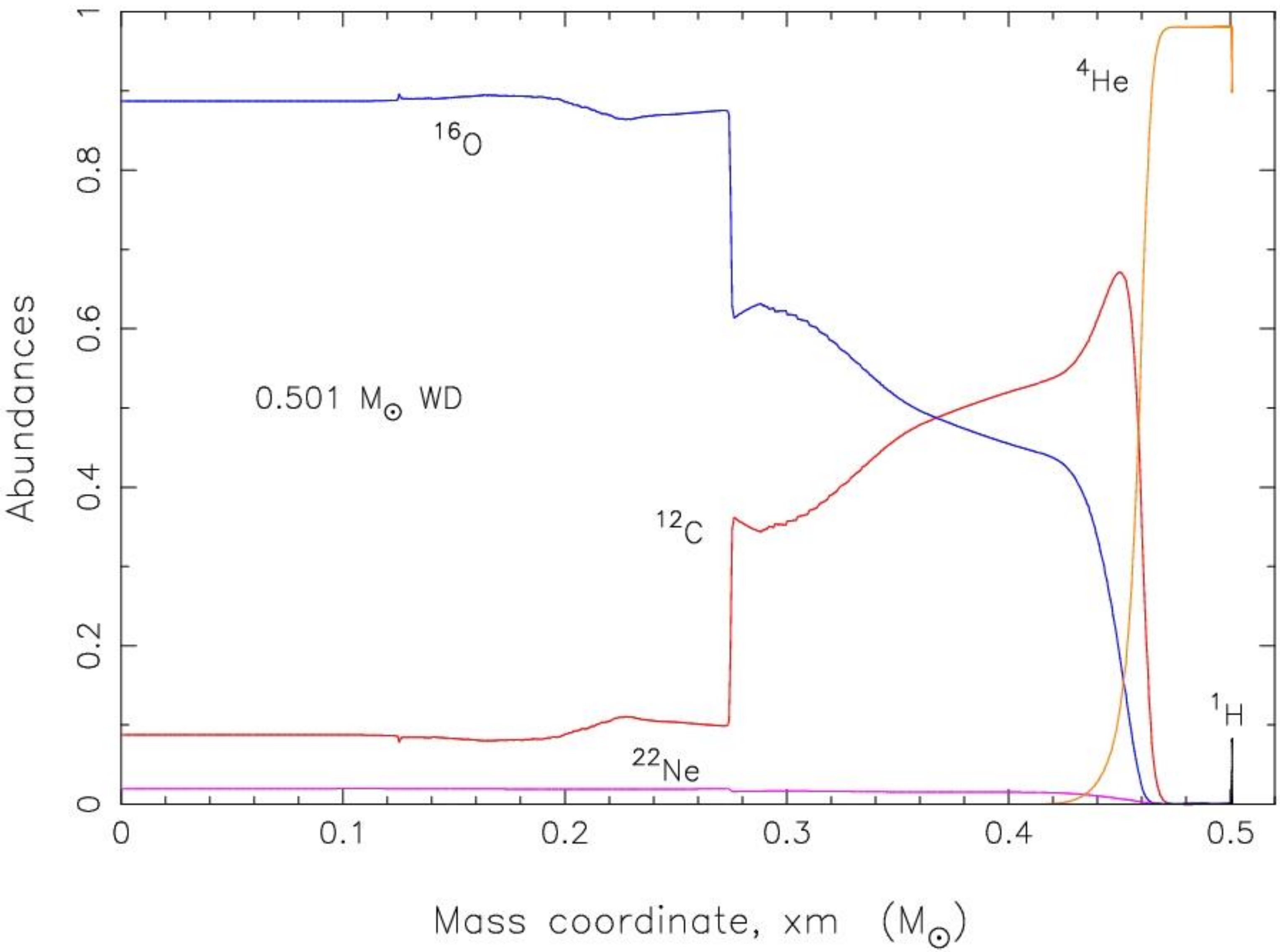


IMXB case A: thermal + nuclear timescale mass transfer



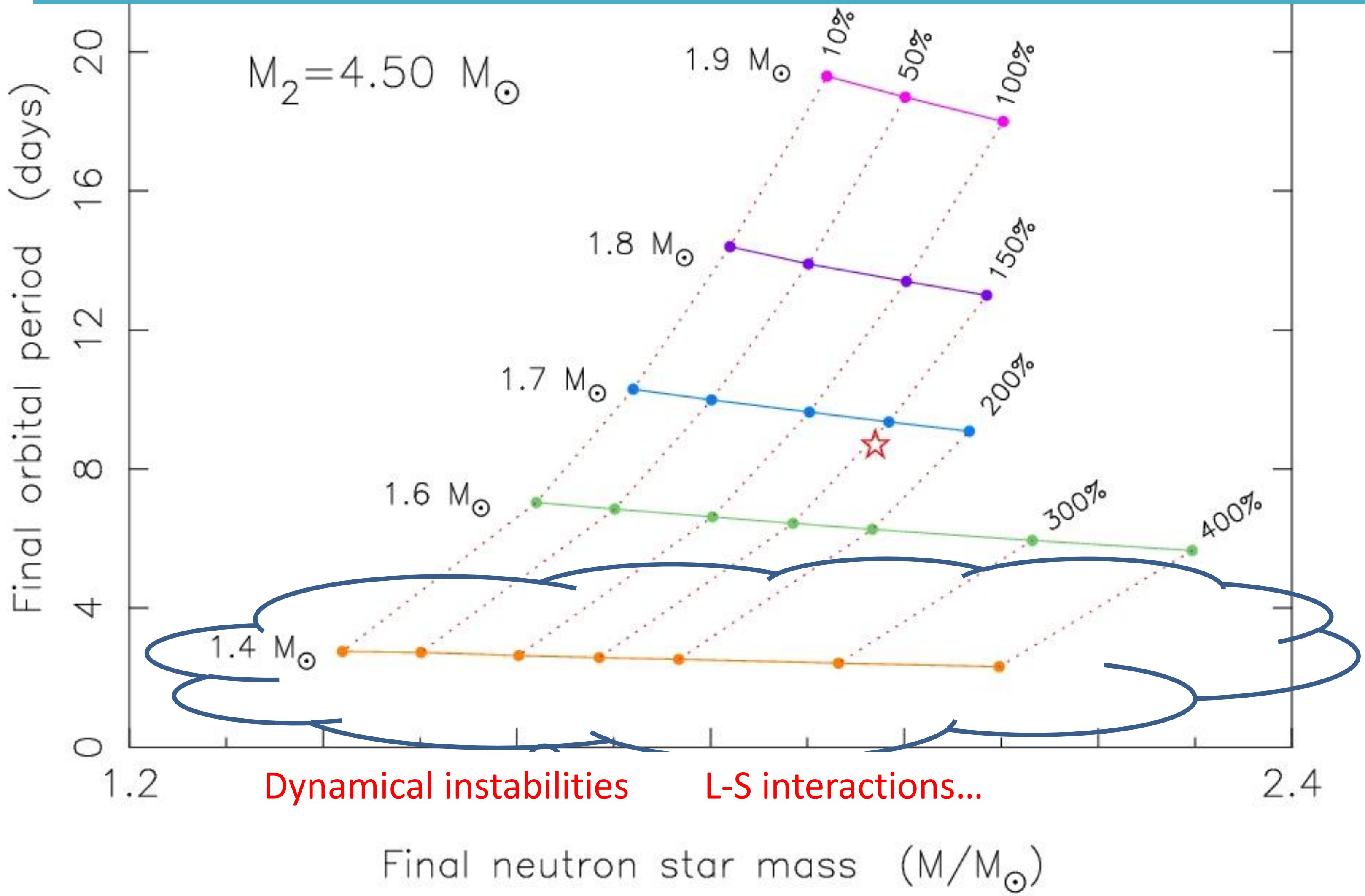

4.50 $M_\odot$ donor star OV=0.20
1.68 $M_\odot$ neutron star
P_{init} = 2.20 days
M_{NS}
P_{orb}
Orbital period, P_{orb} (days)
Pulsar mass, M_{NS} ($M_\odot$)
Donor mass, M_2 ($M_\odot$)
0
2
4
6
8
1.4
1.5
1.6
1.7
1.8
1.9
2
4
3
2
1
0

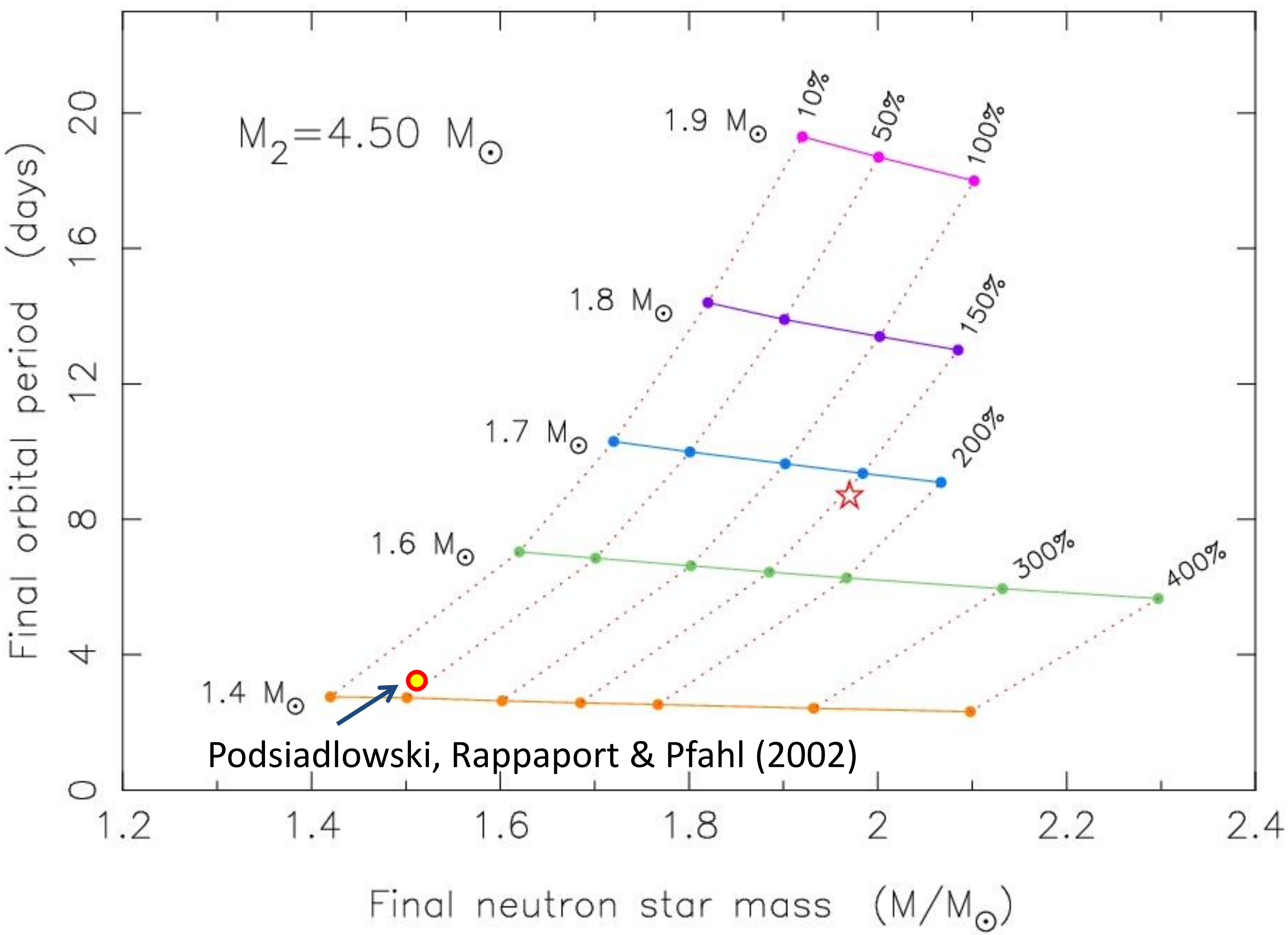

models
WD chemical abundances
phase AB
Hydrogen shell burning
m / M⊙
t / yr − 1.6 * 10^8
log(erg / g / s)
GAIN
LOSS
0.8
0.6
0.4
0.2
0.0
−5×10^6
0
5×10^6
1×10^7



1
0.8
0.6
0.4
0.2
0
Abundances
^{16}O
^{4}He
0.501 $M_\odot$ WD
^{12}C
^{1}H
^{22}Ne
0
0.1
0.2
0.3
0.4
0.5
Mass coordinate, xm ($M_\odot$)

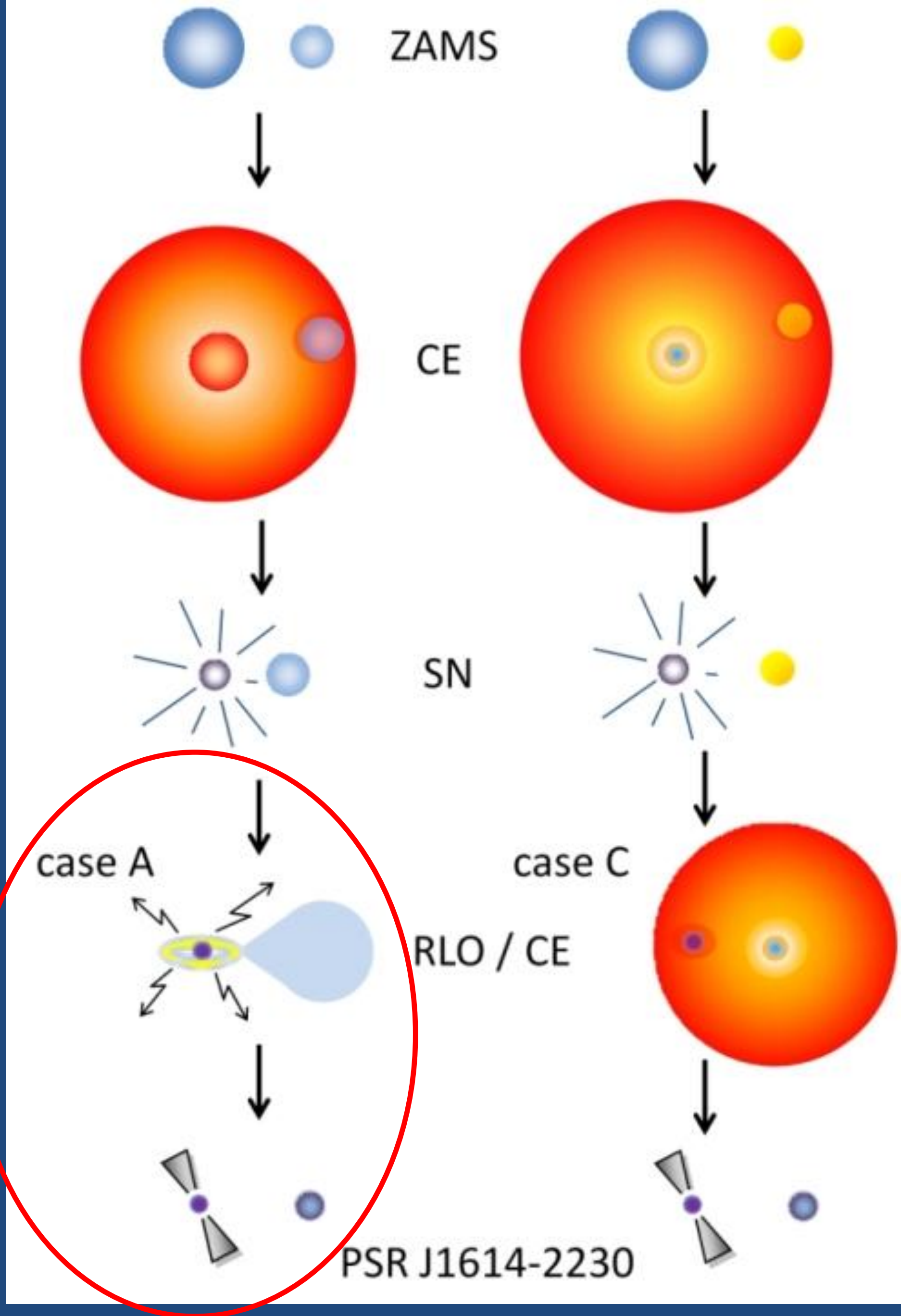
	PSR J1614-2230	Tauris, Langer & Kramer (2011)
Pulsar mass:	$1.97 \pm 0.04\ M_{\odot}$	$1.99\ M_{\odot}$
WD mass:	$0.500 \pm 0.006\ M_{\odot}$	$0.501\ M_{\odot}$
Orbital period:	8.69 days	8.67 days



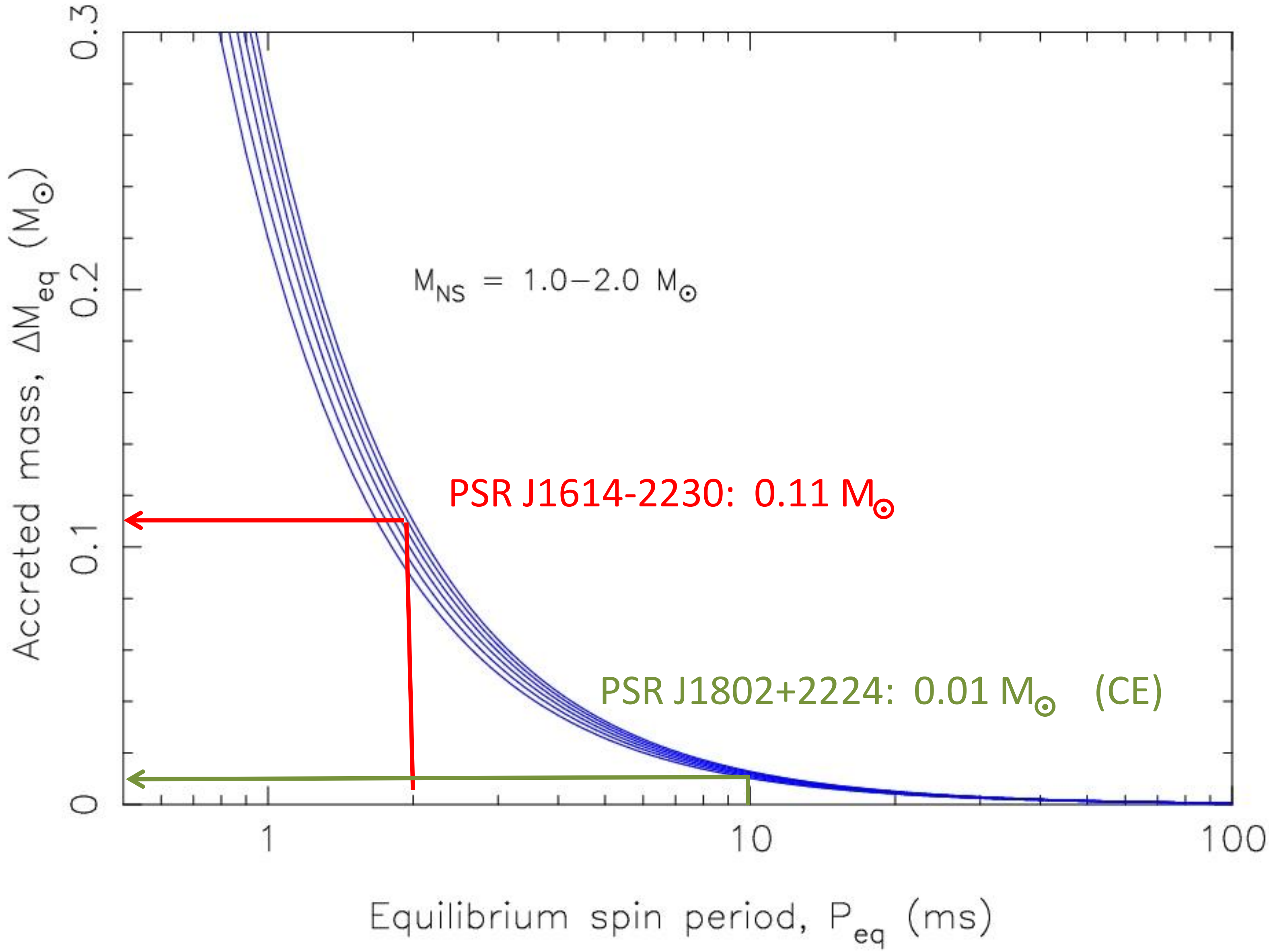


M_2=4.50 $M_\odot$
1.9 $M_\odot$
1.8 $M_\odot$
1.7 $M_\odot$
1.6 $M_\odot$
1.4 $M_\odot$
10%
50%
100%
150%
200%
300%
400%
Podsiadlowski, Rappaport & Pfahl (2002)
Final orbital period (days)
Final neutron star mass ($M/M_\odot$)
0
4
8
12
16
20
1.2
1.4
1.6
1.8
2
2.2
2.4

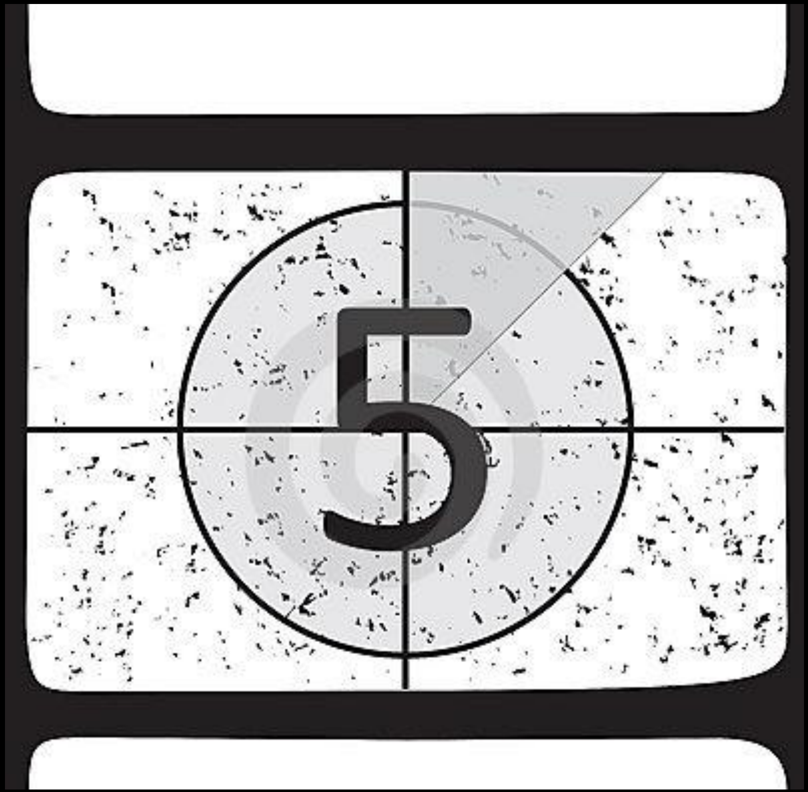
PSR J1614-2230

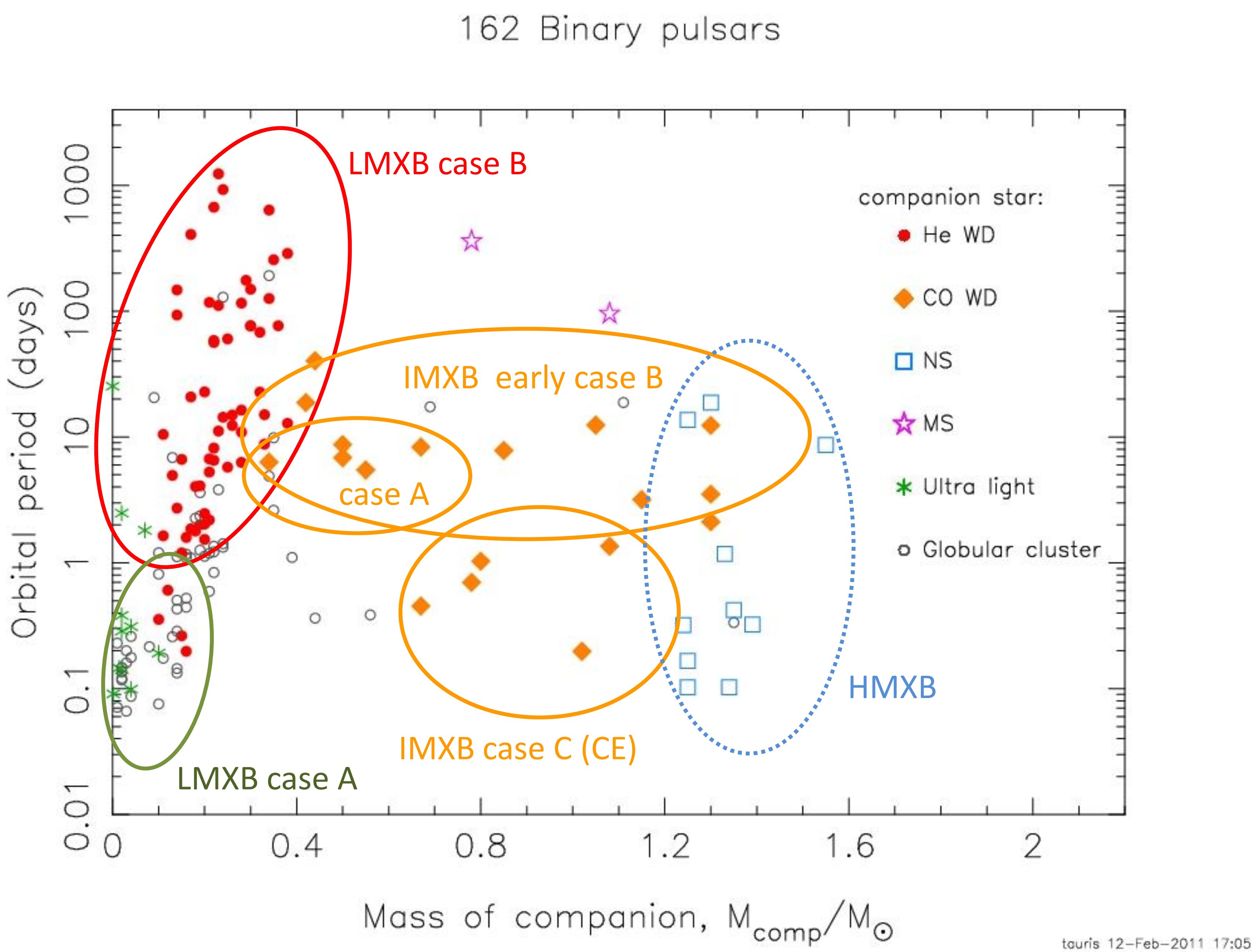


Spin of the recycled pulsar?



0.3
0.2
0.1
0
Accreted mass, ΔM_{eq} ($M_\odot$)
M_{NS} = 1.0–2.0 $M_\odot$
PSR J1614-2230: 0.11 $M_\odot$
PSR J1802+2224: 0.01 $M_\odot$ (CE)
1
10
100
Equilibrium spin period, P_{eq} (ms)


5

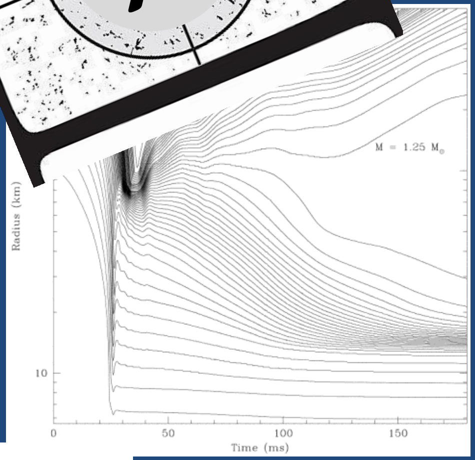

162 Binary pulsars
Orbital period (days)
0.01
0.1
1
10
100
1000
0
0.4
0.8
1.2
1.6
2
Mass of companion, $M_{comp}/M_{\odot}$
companion star:
He WD
CO WD
NS
MS
Ultra light
Globular cluster
LMXB case B
IMXB early case B
case A
IMXB case C (CE)
LMXB case A
HMXB
tauris 12-Feb-2011 17:05

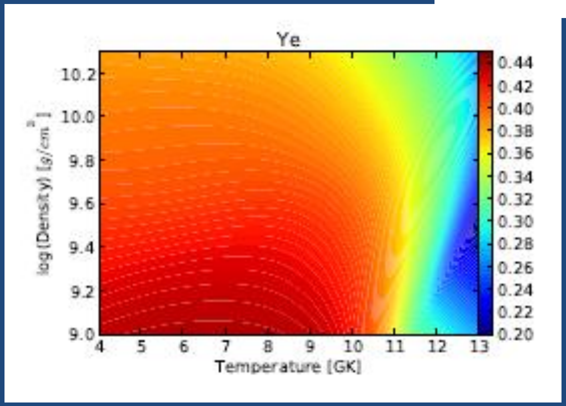
AIC – accretion induced collapse of a white dwarf

Half road?

J. Hurley et al. (2010):
"AIC route cannot be ignored"

- Theory / simulations (√)
- Attractive for GC MSPs √
- Population synthesis ?
- Exact outcome P_{spin} , B (?)
- No observational evidence †
  (although probably candidates…)





Summary

Formation of millisecond pulsars

1) LMXB $P_{orb} > P_{bif}$ (case B)
2) LMXB $P_{orb} < P_{bif}$ (case A)
3) IMXB Common Envelope (case C)
4) IMXB Early case B
5) IMXB Case A (PSR J1614-2230: neutron star was born massive)
5½) AIC

Great diversity in MSP zoo since discovery in 1982
Challenges remain intact!

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