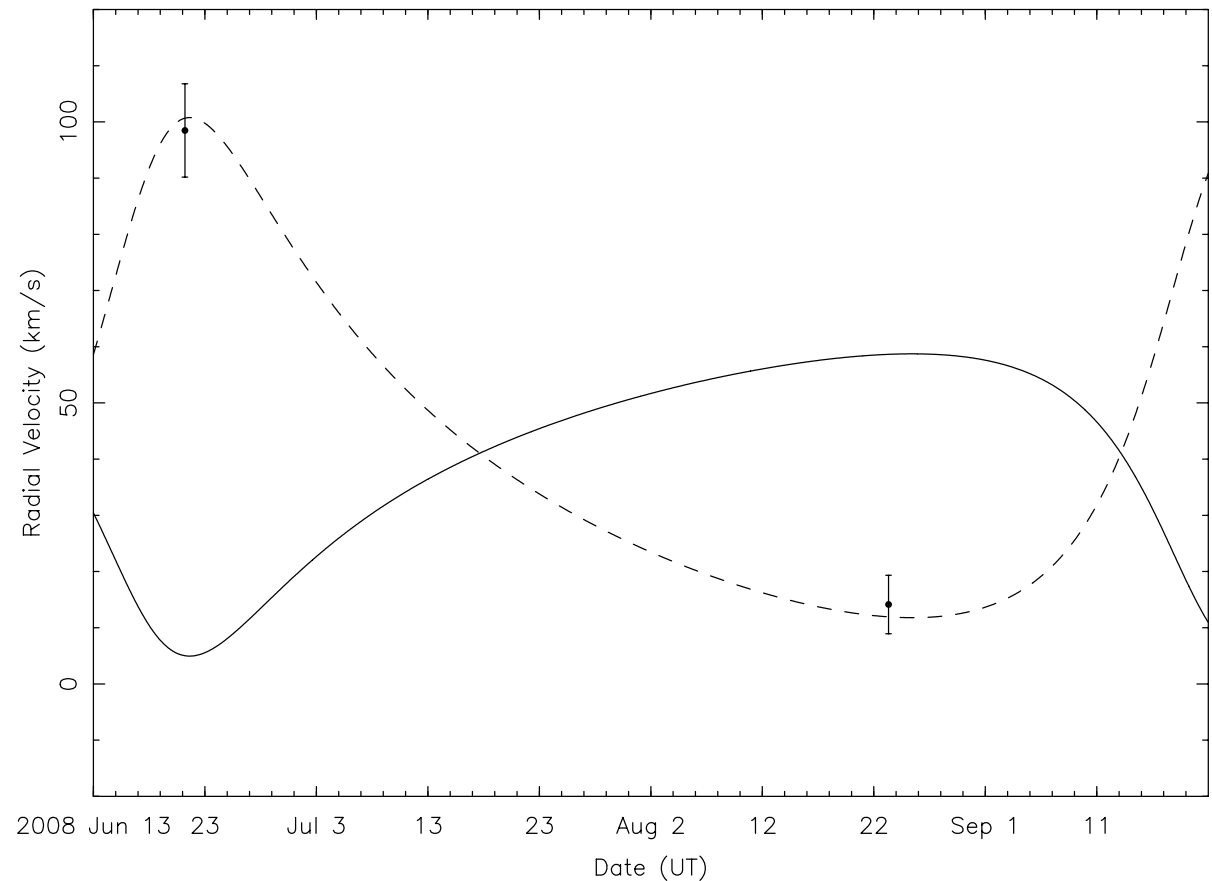

Paulo C. Freire (MPIfR)
Thomas Tauris (MPIfR/AlfA)

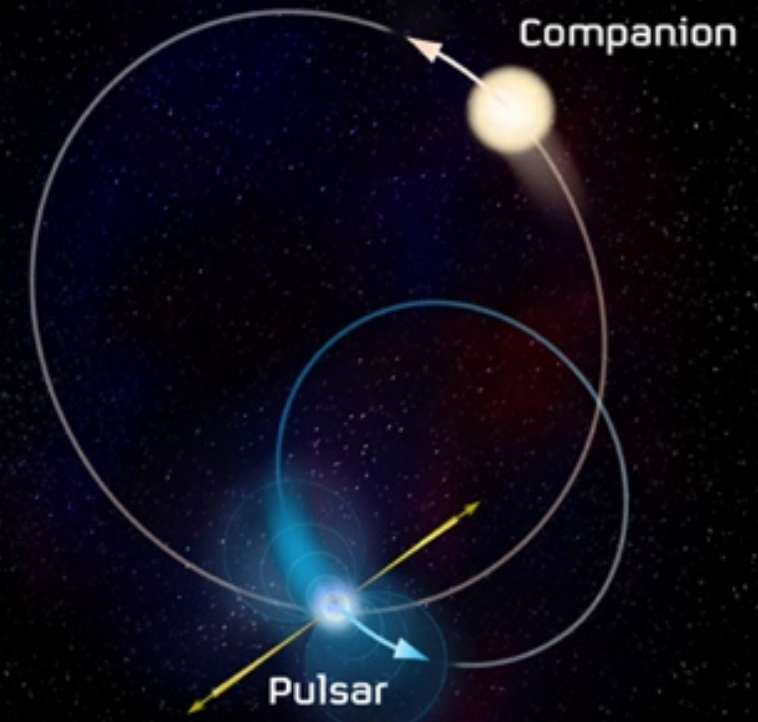
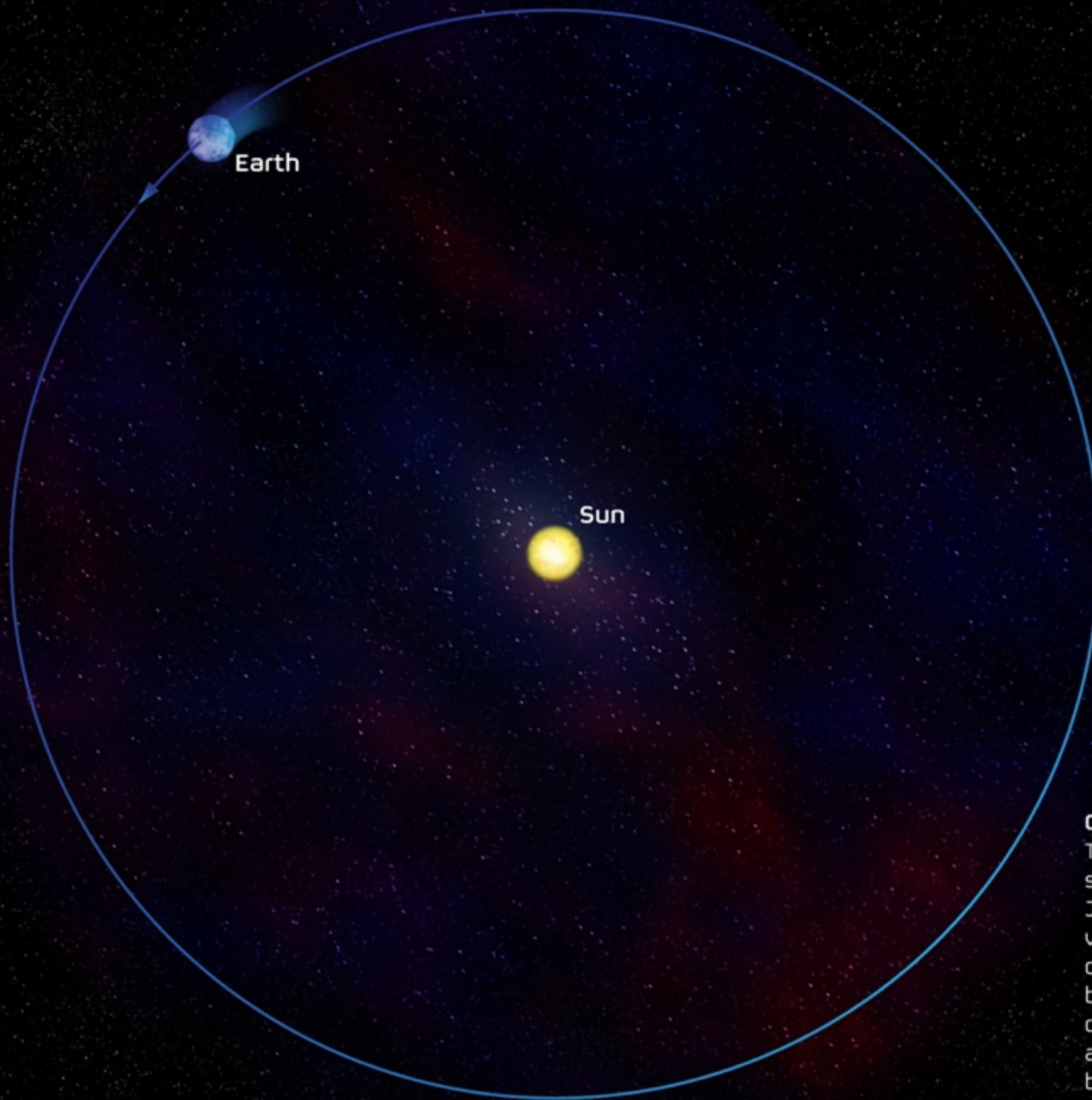
Rotationally-Delayed AIC,

and direct formation of MSPs

Millisecond pulsars with elliptical orbits

- MSP: pulsar with a spin period < 20 ms
- Until 2008, all had been found in orbits with very low eccentricities (< 0.002) and WD or low-mass companions.
- PSR J1903+0327 was the first exception...
- $e = 0.43!$
- Companion is a 1.03 solar mass MS star!!!
- System formed in triple! (Freire et al. 2011, Portegies-Zwart et al. 2011)



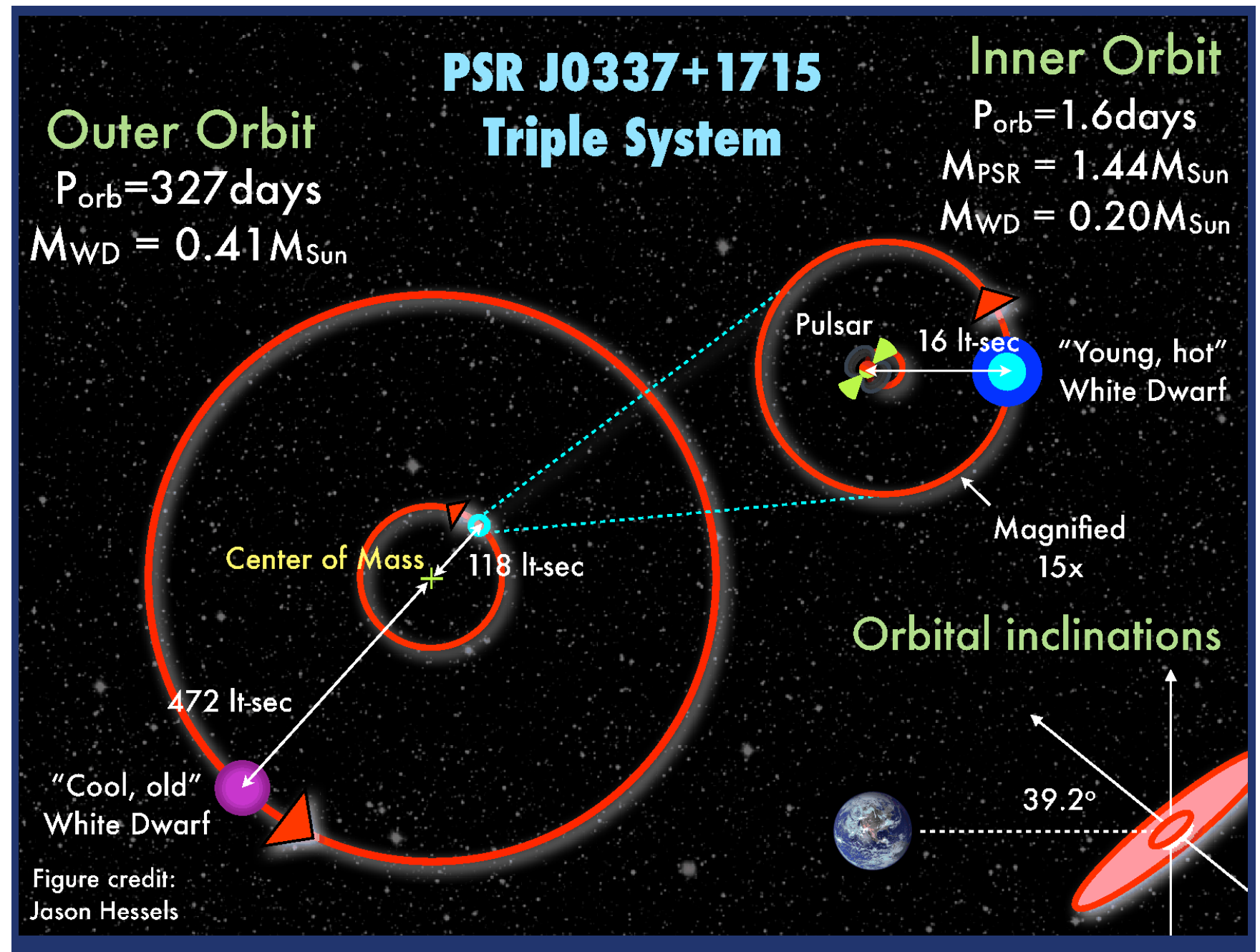


Orbital Comparison With the Solar System:

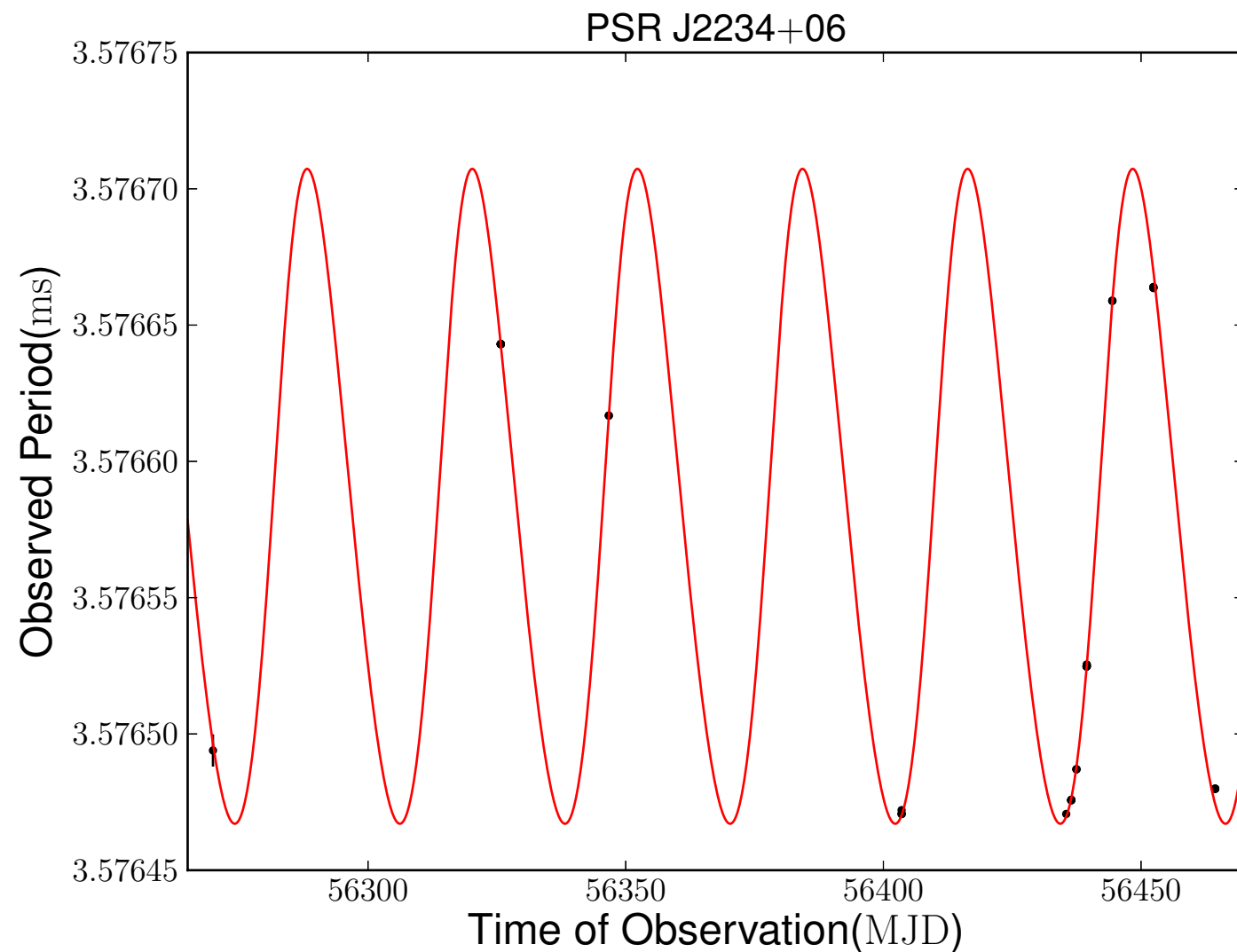
This diagram shows a comparison of the sizes and strangely elliptical shapes of the orbits of the pulsar J1903+0327 and its possible Sun-like companion star with the orbit of the Earth around the Sun. The sizes of the Sun and the possible companion star have been exaggerated by a factor of about 10, while that of the Earth has been exaggerated by a factor of about 1000. The pulsar, with its magnetic field and beams of radiation, is too large by a factor of about 100,000.

The triple system

- The GBT 350-MHz drift-scan survey found a MSP in a hierarchical triple! (Ransom et al., Nature, 2014).
- The system has one MSP and two WDs
- This shows clearly that evolution in triple systems is not impossibly rare.
- Evolution was different than for J1903+0327: the system remained stable through many episodes of mass transfer!



More discoveries



- Three different surveys (HTRU-N, PALFA and AO327) have recently discovered *three* more MSPs with eccentric orbits. An example of striking beauty is PSR J2234+0611, which has timing precision of 218 ns (in 1.5 minute pointings!) and is relatively nearby – thus allowing for good optical follow-up.

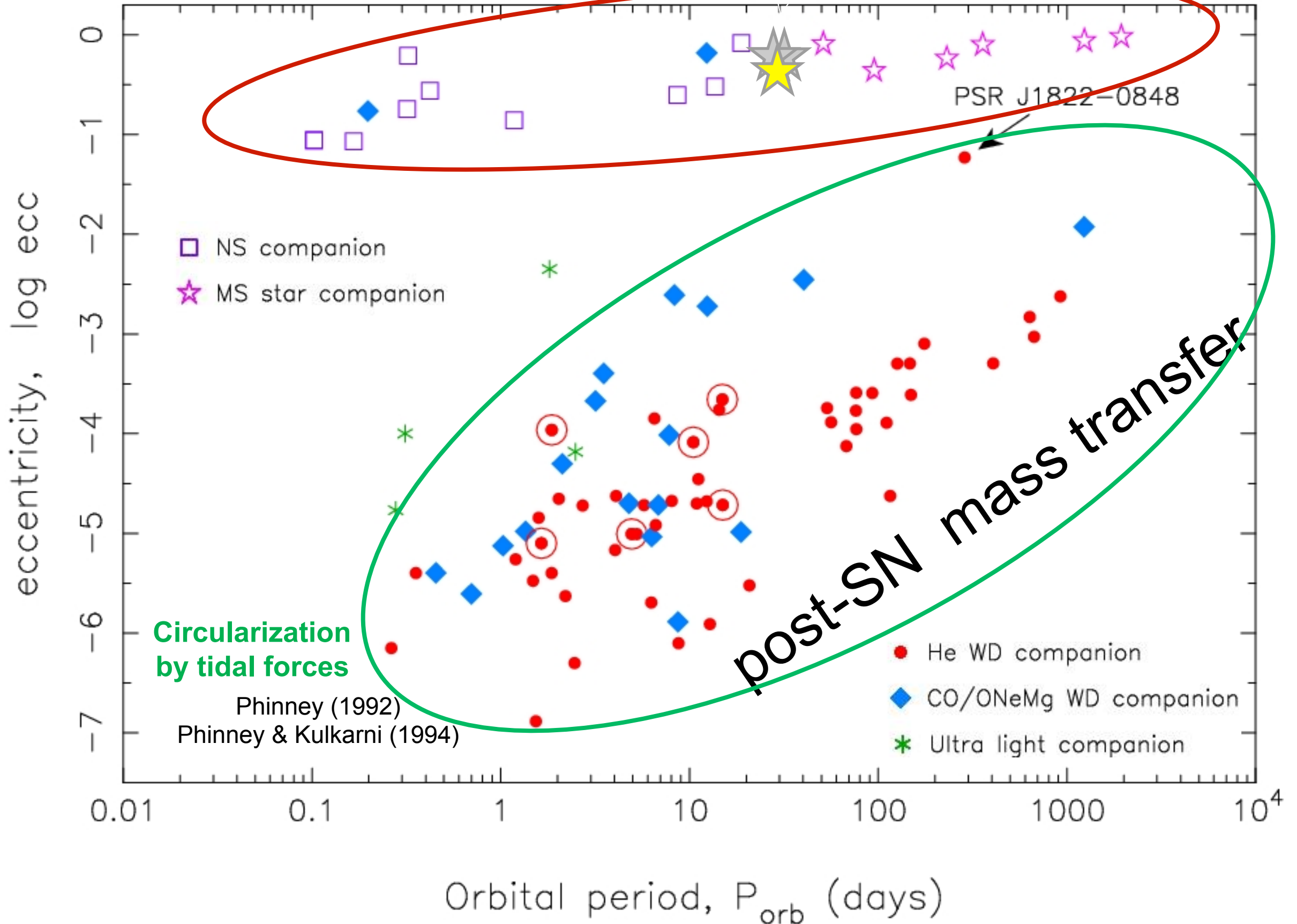
More discoveries

The new systems are:

	P (ms)	P_b (days)	e	M_c (M_\odot)	Survey
PSR J1946+3417	3.1	27	0.13	0.24	HTRU-N
PSR J1950	4.3	22	0.08	0.24	PALFA (NEW!)
PSR J2234+0611	3.6	32	0.13	0.23	AO327
PSR J1903+0327	2.2	95	0.44	1.03	PALFA
PSR J0337+1715	2.7	1.6/327	0.00/0.035	0.19/0.41	GBT 350MHz Drift scan

Eccentric MSPs: PSR J2234+06 (Deneva et al. 2013)
 PSR J1946+3417 (Barr et al. 2013)
 PSR J1950+2414 (Knispel et al. 2014)

no mass transfer after SN



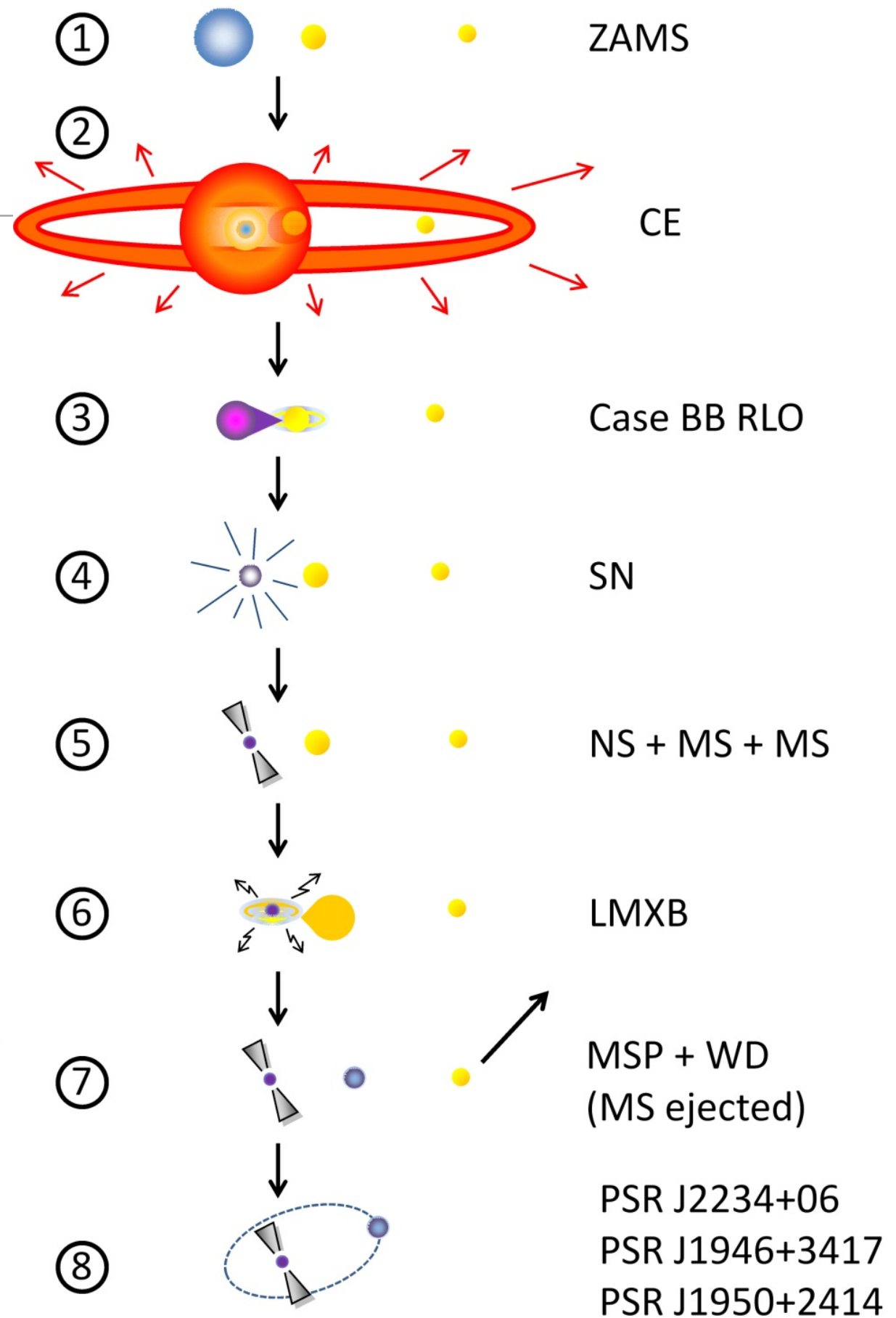
Did they form in triples?

Kozai-mechanism:

$$L_z = \sqrt{1 - e^2} \cos i$$

$L_z < L_z^{crit} \rightarrow$ Kozai oscillations

Inclination can be "traded" for eccentricity



More discoveries

... but then, why the regularity in the orbital parameters?

	P (ms)	P_b (days)	e	M_c (M_\odot)	Survey
PSR J1946+3417	3.1	27	0.13	0.24	HTRU-N
PSR J1950+2414	4.3	22	0.08	0.24	PALFA
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PSR J0337+1715	2.7	1.6/327	0.00/0.035	0.19/0.41	GBT 350MHz Drift scan

Direct formation of millisecond pulsars from rotationally delayed accretion-induced collapse of massive white dwarfs

Paulo C. C. Freire^{1★} and Thomas M. Tauris^{1,2★}

¹*Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*

²*Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany*

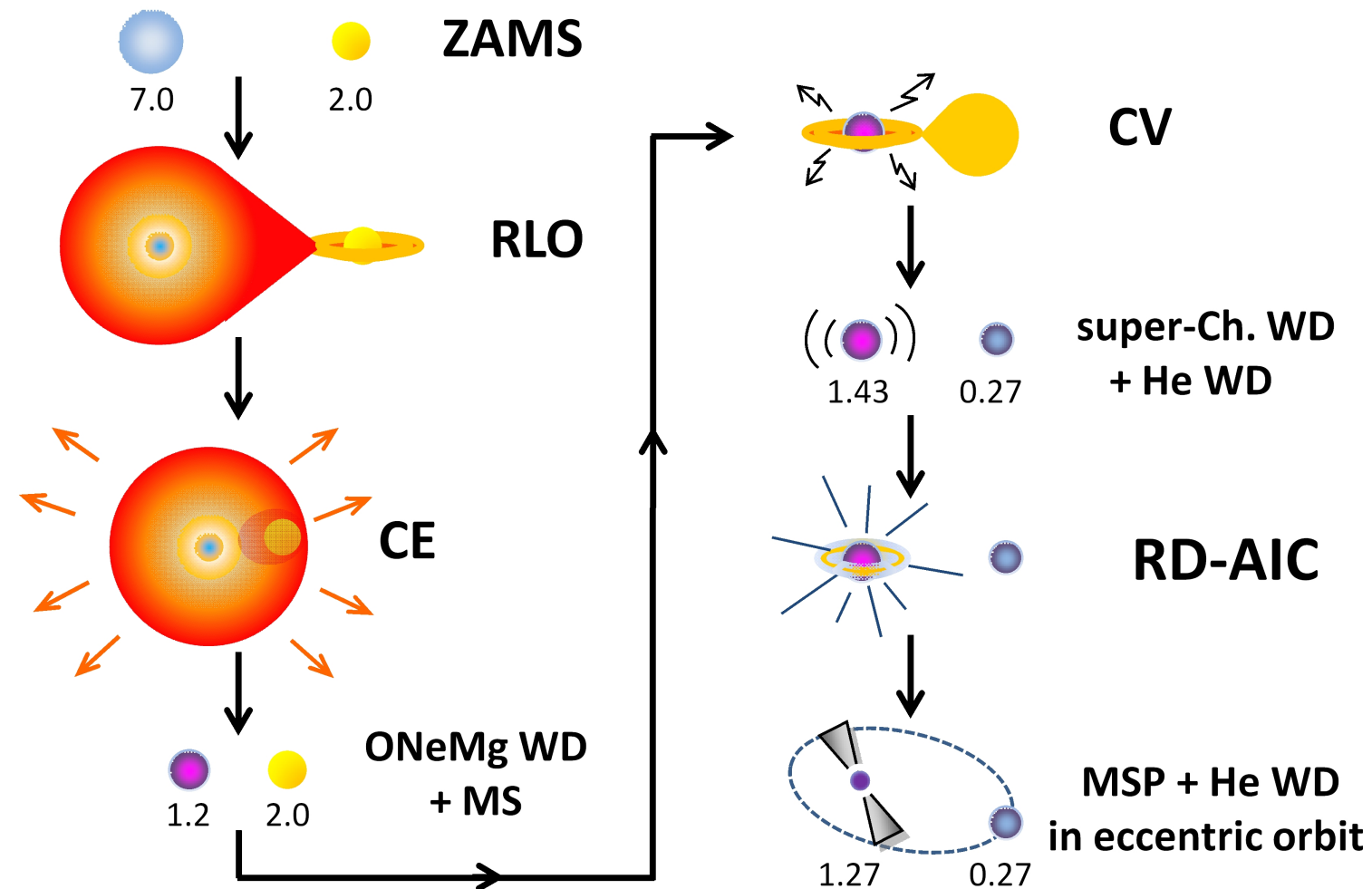
Accepted 2013 November 13. Received 2013 November 13; in original form 2013 September 26

ABSTRACT

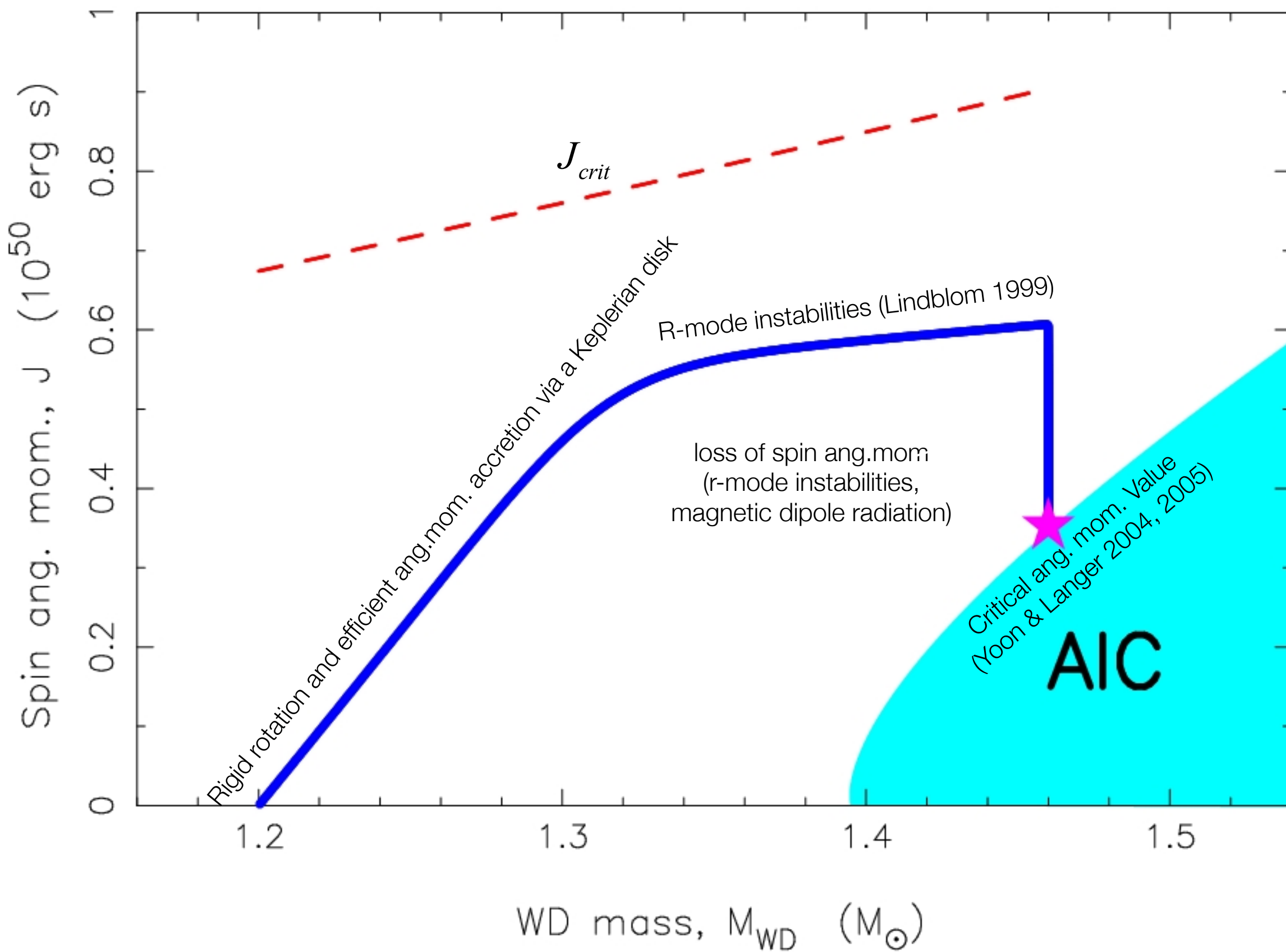
Millisecond pulsars (MSPs) are believed to be old neutron stars, formed via Type Ib/c core-collapse supernovae, which have subsequently been spun up to high rotation rates via accretion from a companion star in a highly circularized low-mass X-ray binary. The recent discoveries of Galactic field binary MSPs in eccentric orbits, and mass functions compatible with that expected for helium white dwarf companions, PSR J2234+06 and PSR J1946+3417, therefore challenge this picture. Here, we present a hypothesis for producing this new class of systems, where the MSPs are formed directly from a rotationally delayed accretion-induced collapse of a super-Chandrasekhar mass white dwarf. We compute the orbital properties of the MSPs formed in such events and demonstrate that our hypothesis can reproduce the observed eccentricities, masses and orbital periods of the white dwarfs, as well as forecasting the pulsar masses and velocities. Finally, we compare this hypothesis to a triple-star scenario.

Key words: stars: neutron – pulsars: general – stars: rotation – supernovae: general – white dwarfs – X-rays: binaries.

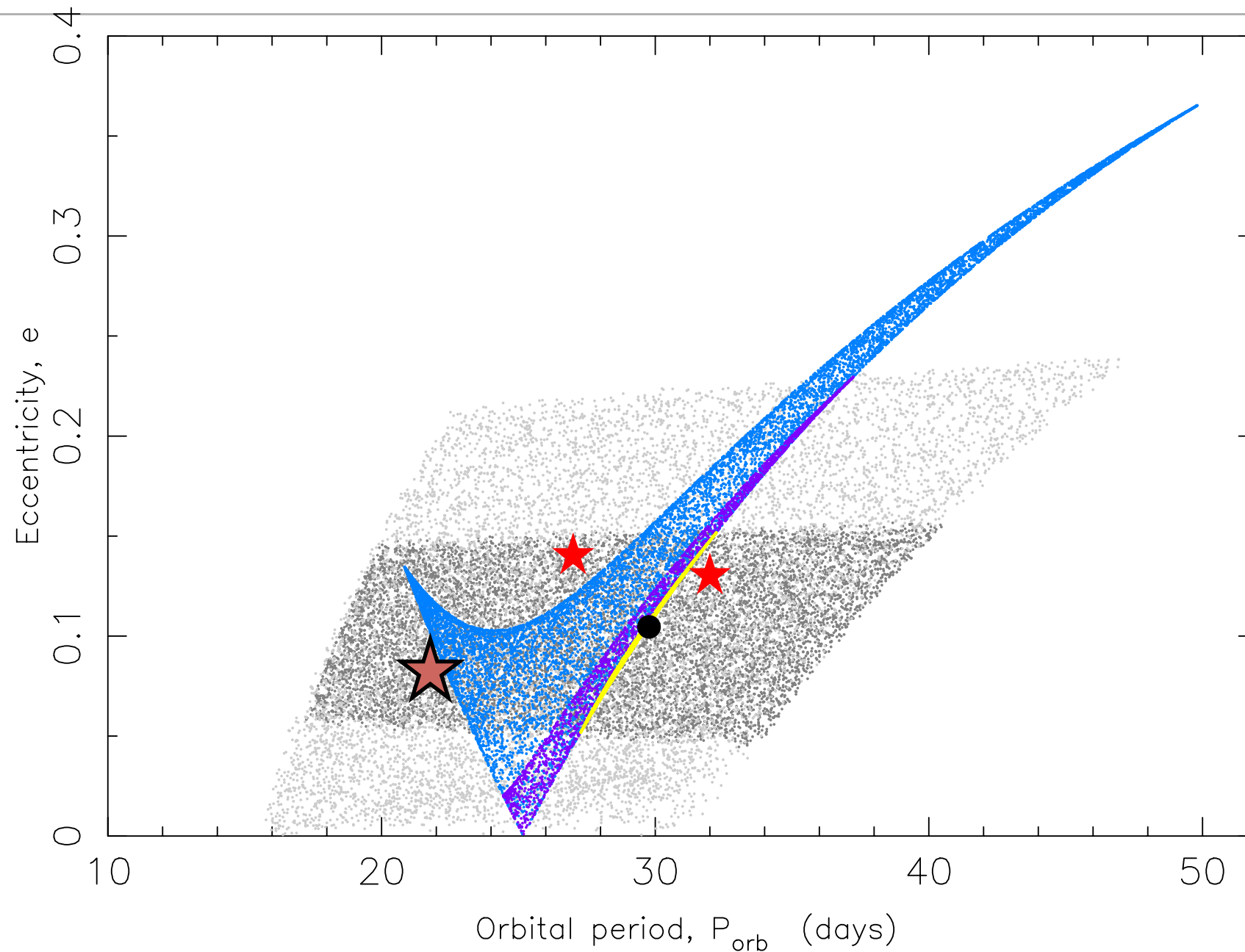
A new evolutionary scenario



We suggest the possibility that MSPs might form *directly* from the collapse of a fast-rotating WD. Previous work by Tauris et al. 2013, *A&A*, 558, A39 assumes that accretion goes on, creating a circular system. In this work, accretion ceases *before* AIC.



A new evolutionary scenario



Our scenario can reproduce the features of these systems very neatly – particularly the eccentricities, which are given by $e = \Delta m / M_t \sim 0.1$.

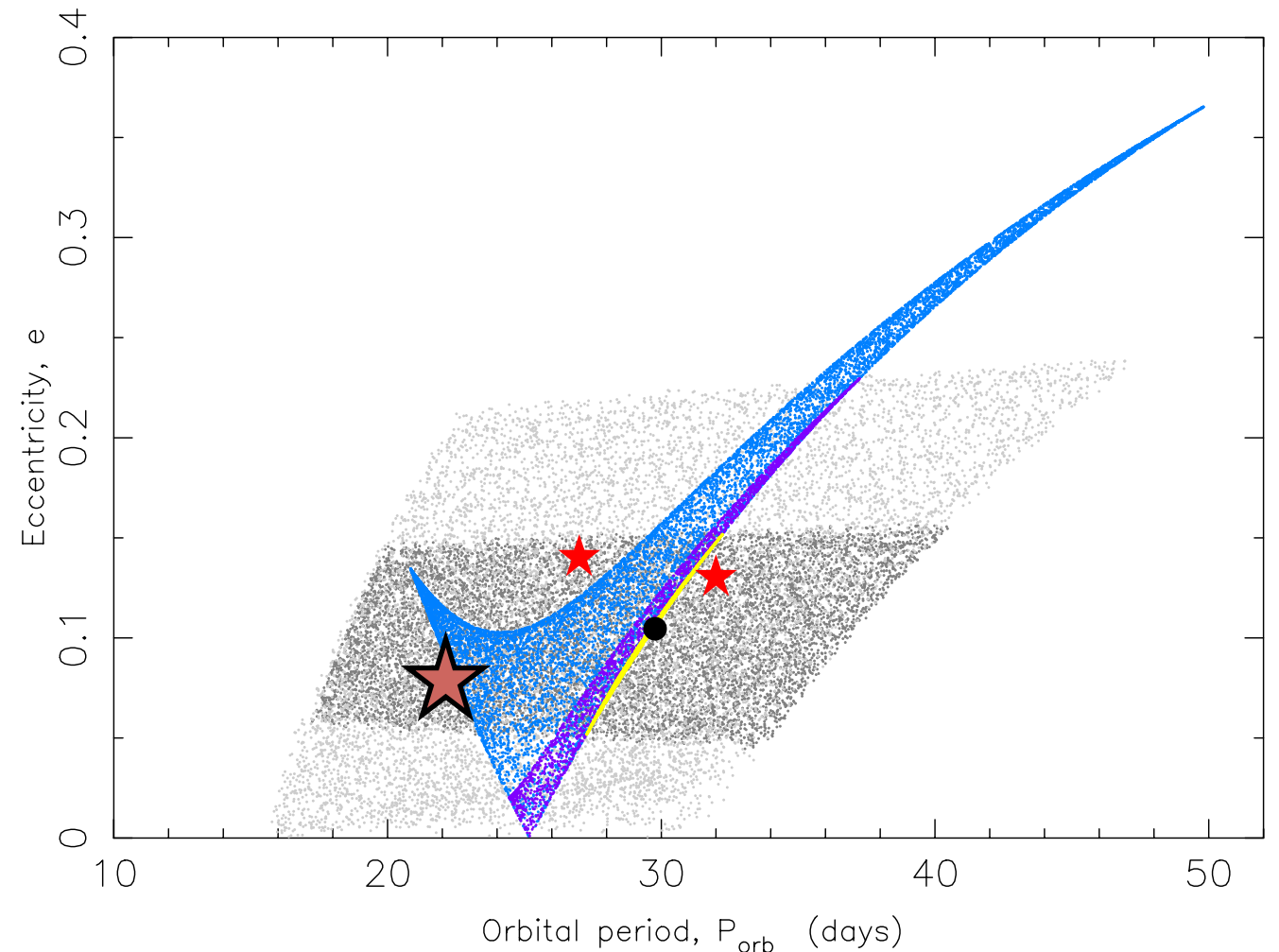
Tests

We predict that:

- Companions should be faint WDs
 1. One confirmed: PSR J2234+0611.
- They should have masses as given by the Tauris & Savonije (1999, A&A, 350, 928) relation.
- The MSP masses should be low, between 1.24 and 1.31 M_{\odot} (These will be measured precisely very soon! Systems are eccentric, which makes it very easy), *IF pre-collapse WD rotation is rigid.*
- The spatial velocities of these systems should be very small. Proper motions easily measurable, 3-D velocities only possible when radial velocity of companion WD is measured.

What we will learn if this scenario is correct:

- Average mass loss in AIC SNe, which should give us a strict upper bound on the gravitational binding energy of NSs – important for the study of the equation of state!
- Average kicks of EC SNe – these must be small (~ 2 km/s), otherwise we should not see this concentration at eccentricities of ~ 0.1 .



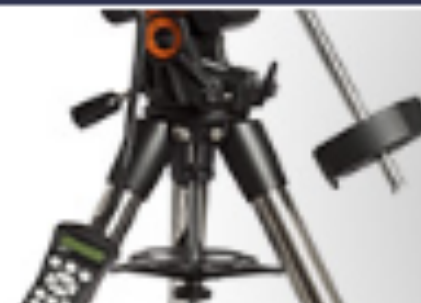
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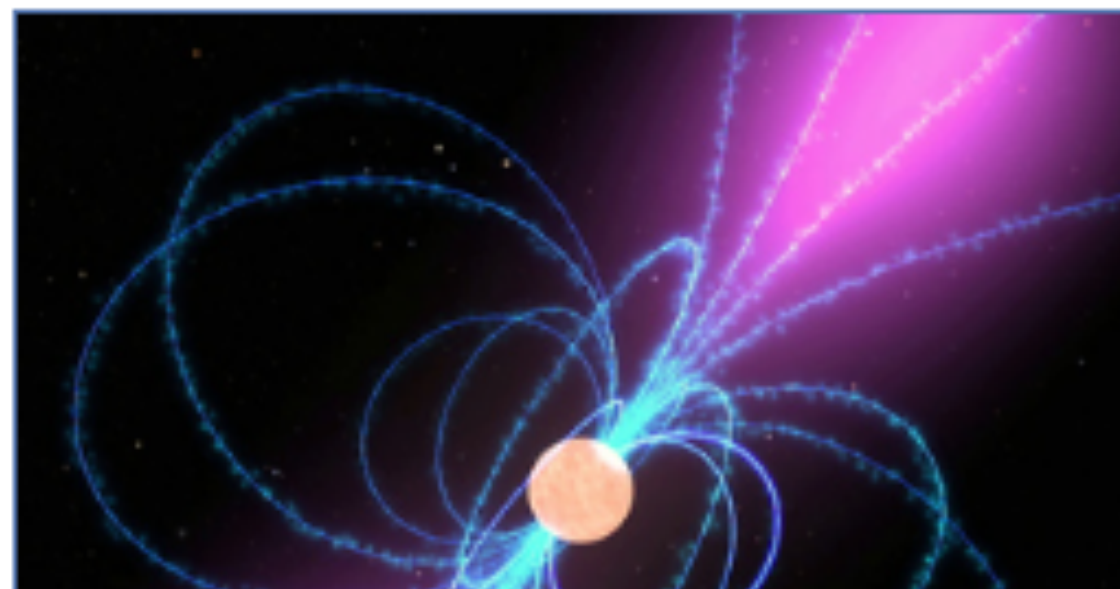
NEWS by Camille Carlisle



Oddball Pulsar Origin?

A few whirling neutron stars might get their start as very different objects, at least if this new analysis is correct.

White dwarfs usually only make a blazing stellar mark one way: by dying as a Type Ia supernova. But a new analysis suggests that white dwarfs might also be responsible for a particular type of stellar lighthouse: a small club of millisecond pulsars that don't fit the mold.

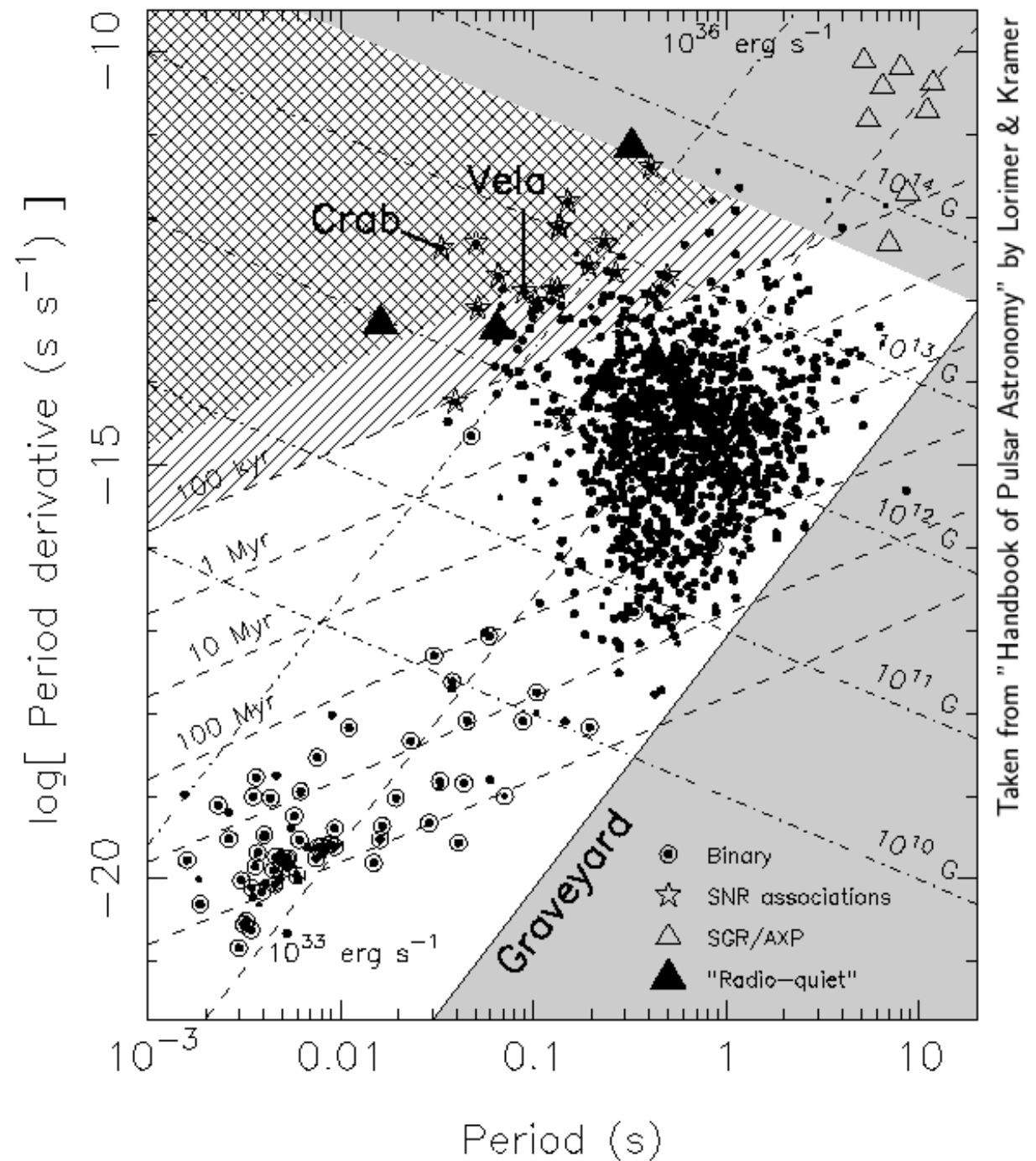


The end

Reference slides

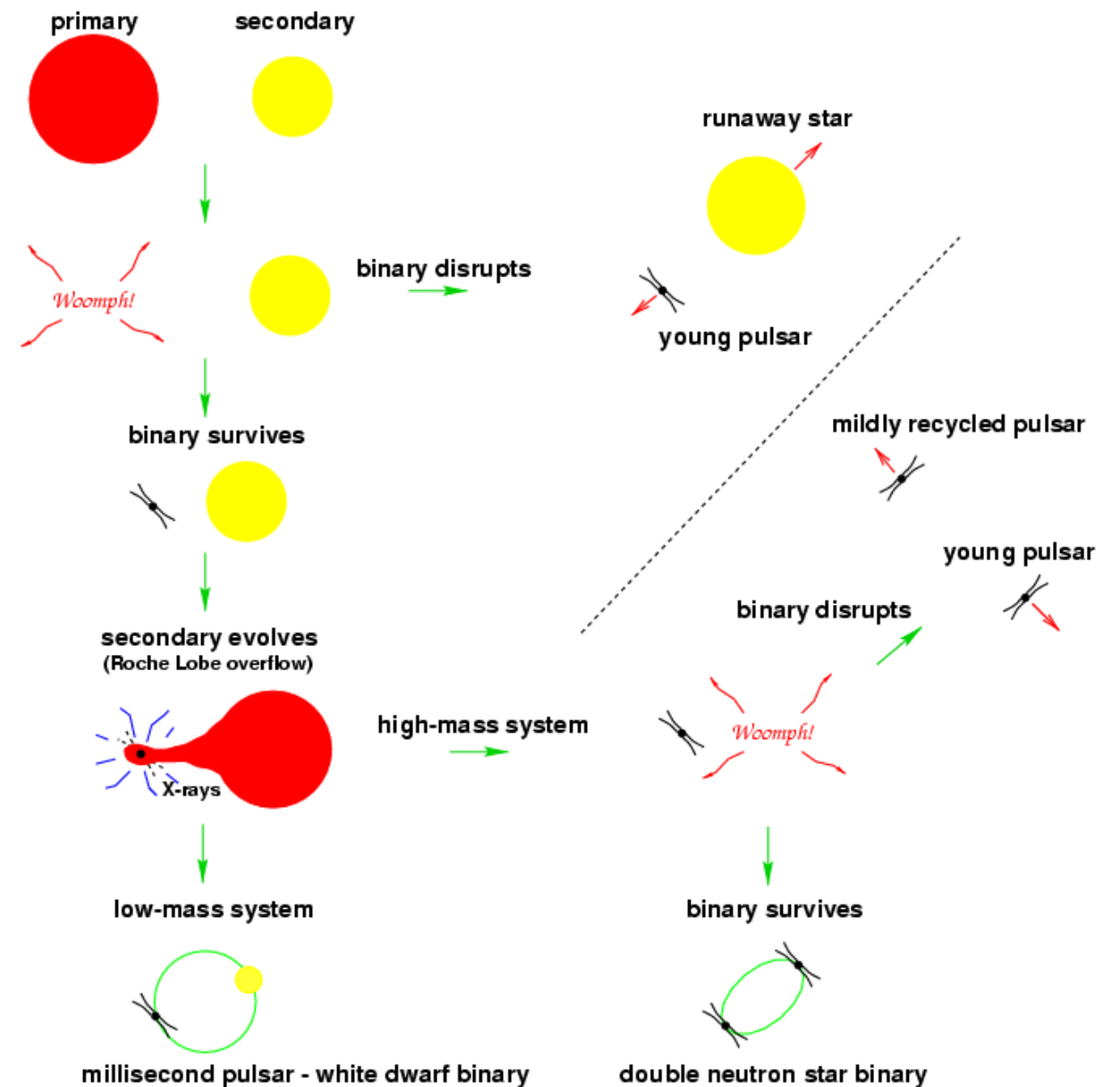
“Centisecond” and Millisecond Pulsars

- The main difference between normal and recycled pulsars is not merely the spin period, which is faster for the second class. Recycled pulsars also spin down much more slowly.
- Furthermore, many more of them are in binary systems!
- The fast-spinning objects ($P < 8$ ms) - the millisecond pulsars (MSPs) are either isolated or have light white dwarf companions and low-eccentricity orbits.
- Some of the slower-spinning recycled pulsars ($8 < P < 110$ ms) - the “centisecond” pulsars (CSPs) are either isolated, or they have a massive white dwarf or a neutron star companion. The orbits for these systems are generally eccentric!



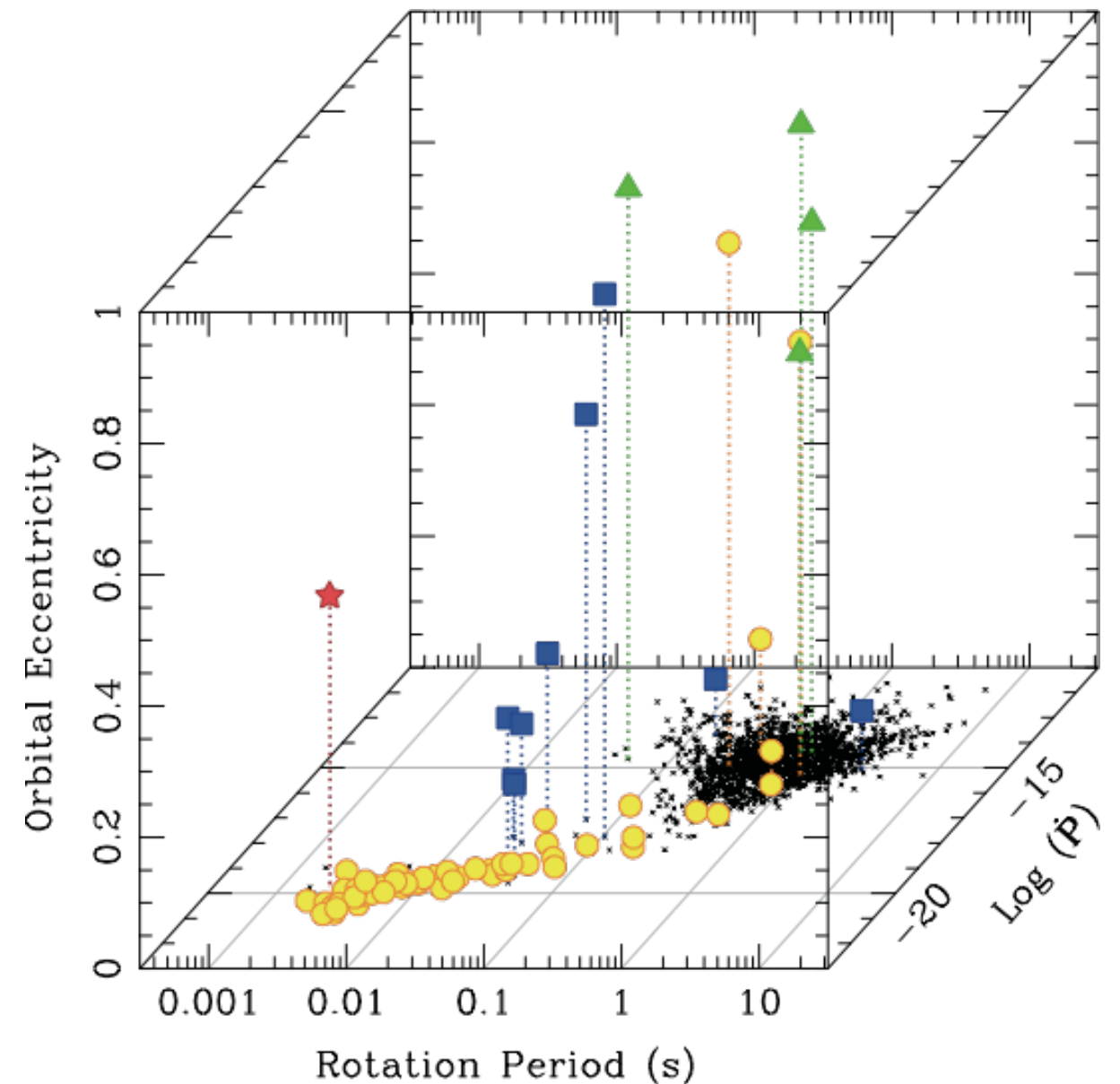
Normal Pulsars and Millisecond Pulsars

- The differences among the recycled pulsars reflect different evolution scenarios!
- If the companion is massive, accretion won't last long - mildly recycled pulsar (CSP). The massive companion then goes supernova, producing a double neutron star system (DNS) with an eccentric orbit.
- If companion is not so massive, it will evolve to a white dwarf. In this case, accretion lasts much longer! Resulting pulsar should spin much faster and **it should be much more massive**. Resulting orbit should be very circular, as observed for the vast majority of MSPs in the Galaxy.



A strange binary system

- With a spin period of 2.15 ms, PSR J1903+0327 was the first millisecond pulsar (MSP) discovered in Arecibo's ALFA pulsar survey.
- It is in a 95-day binary system. Its $m_c \sim 1.0 M_\odot$ companion is by far the most massive of any MSP with a similar spin period.
- It is the first millisecond pulsar in the disk of the Galaxy to have an eccentric orbit: $e = 0.44$. All other MSPs in binary systems have $e < 0.002$ (Champion et al., Science, 320, 1309).
- It is very difficult to explain the formation of such a binary system with previous stellar evolution theory. Even more because the companion is a MS star! (Freire et al. 2011, MNRAS, 412, 2763).



From: Champion et al., Science, 320, 1309 (2008)

The origin of PSR J1903+0327

- Galactic motion of PSR J1903+0327 excludes an exchange interaction origin, which can only happen in an environment with a very high stellar density (like globular clusters or the Galactic centre)
- Timing and optical observations exclude the possibility of a complex system at present.
- System likely originated as a triple (Freire et al. 2011, MNRAS, 412, 2763, Portegies-Zwart et al. 2011, ApJ, 734, 55).

Previous donor was accreting into proto-MSP. Orbit widened, and system became dynamically unstable. Eventually, donor star (being the lightest in the system) was ejected.

