# Radio MSPs as probes of binary evolution

John Antoniadis
Max-Planck Institut für Radioastronomie

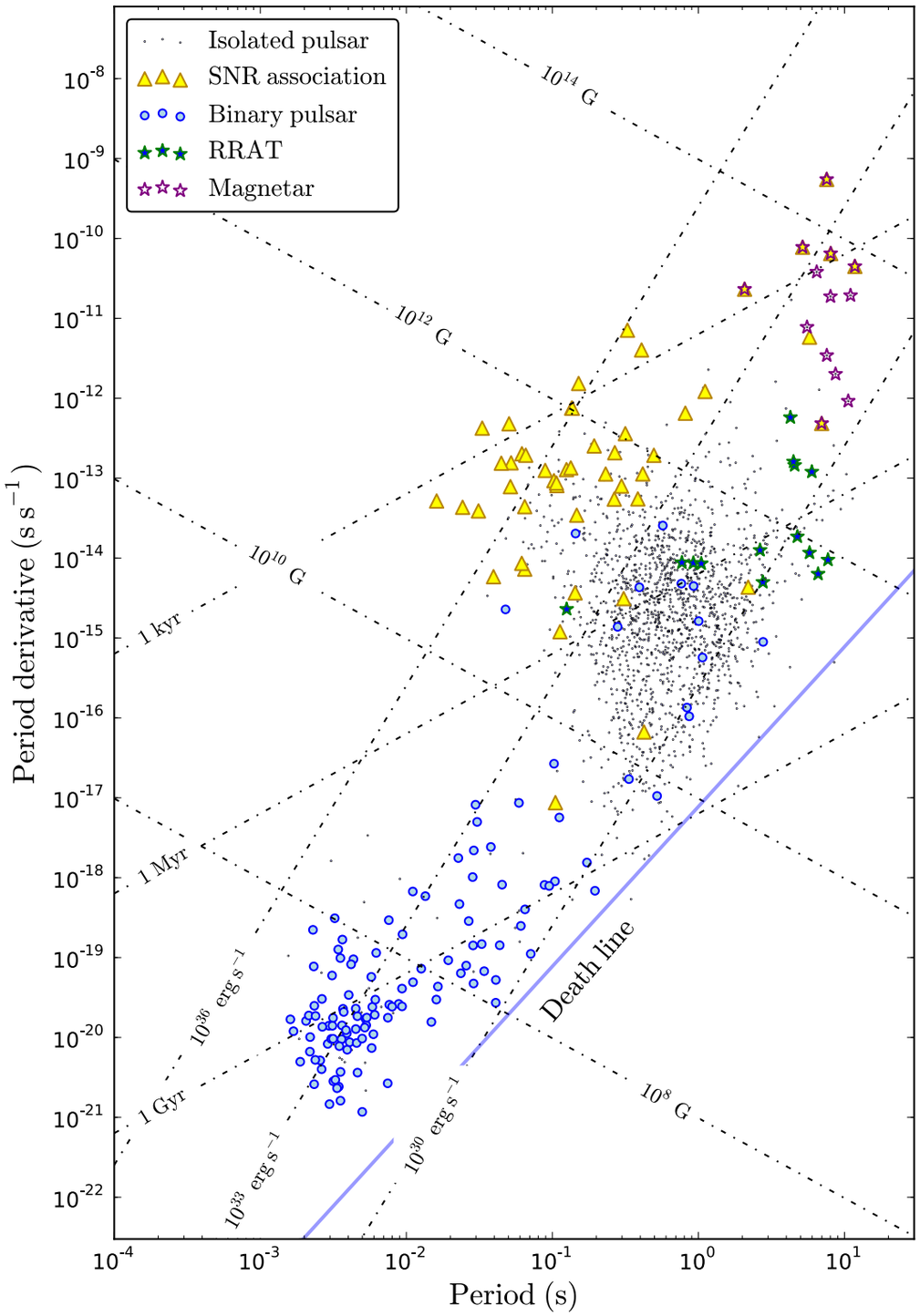
XI Bonn Neutron Star Workshop

# Overview

**See also talk by Amruta**

- Overview of millisecond pulsars
- How millisecond pulsars (don't) form
- compact binaries, tMSPs, eMSPs and other mysteries
- elusive formation channels
- MSP evolution in future research

# Formation of Millisecond Pulsars — A Primer




## Millisecond pulsars in the ATNF catalogue

- **372** radio pulsars with P < 40 ms
- Shortest spin period: **1.39 ms**
- **233** in binaries + **1** triple
- Orbital periods: **1.56 h — 200 yr**
- eccentricities: **1e-7 — 0.8(?)**
- **42+** with “ultra-light” companions
- **3** orbiting planets
- **115+** with He WD companions
- **28** with CO WD companions
- **13+** with MS-like companions
- **5+** with NS companions

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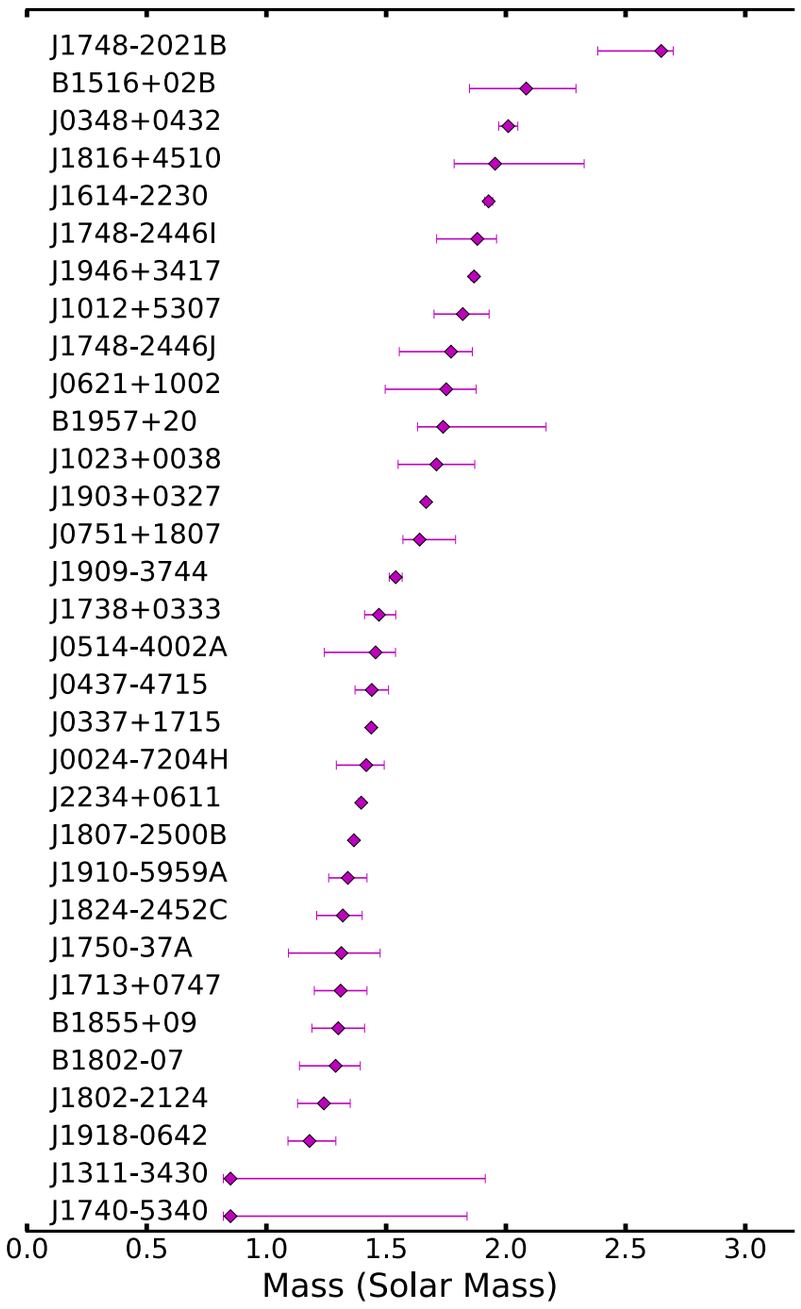
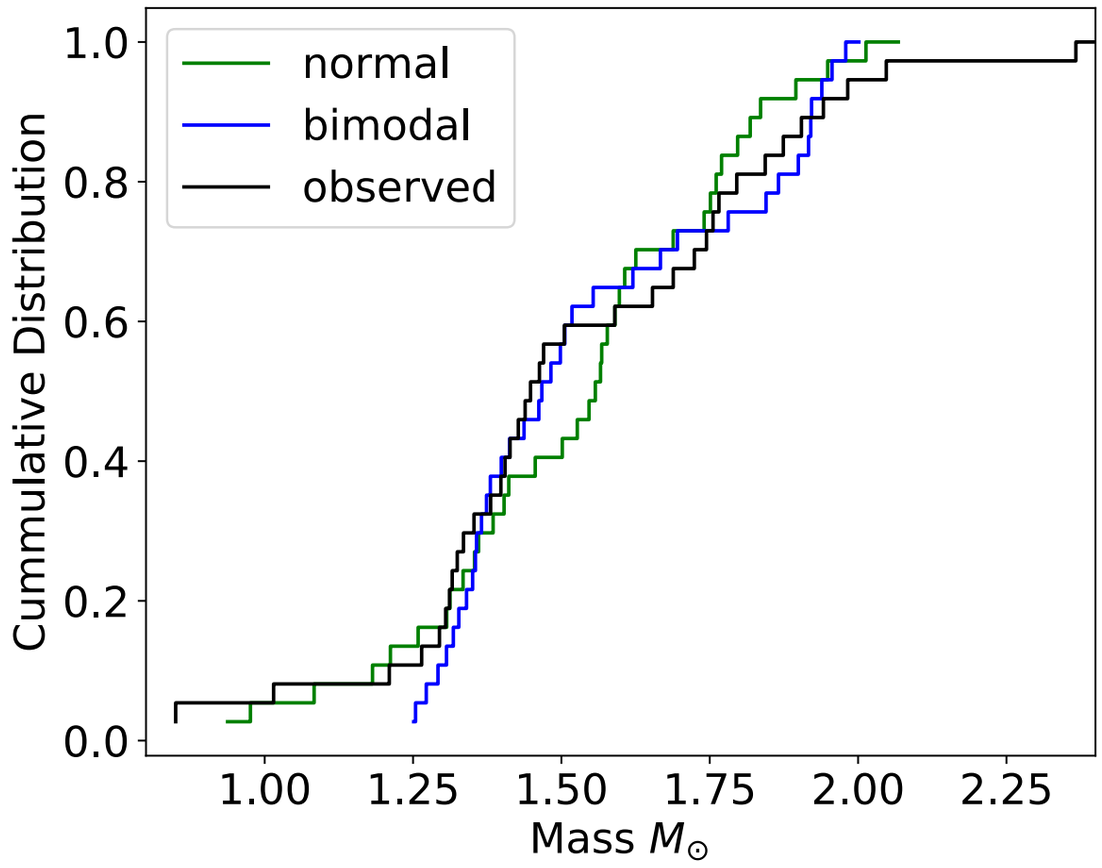



- **Masses from 1.18 Msol to 2.01 Msol**

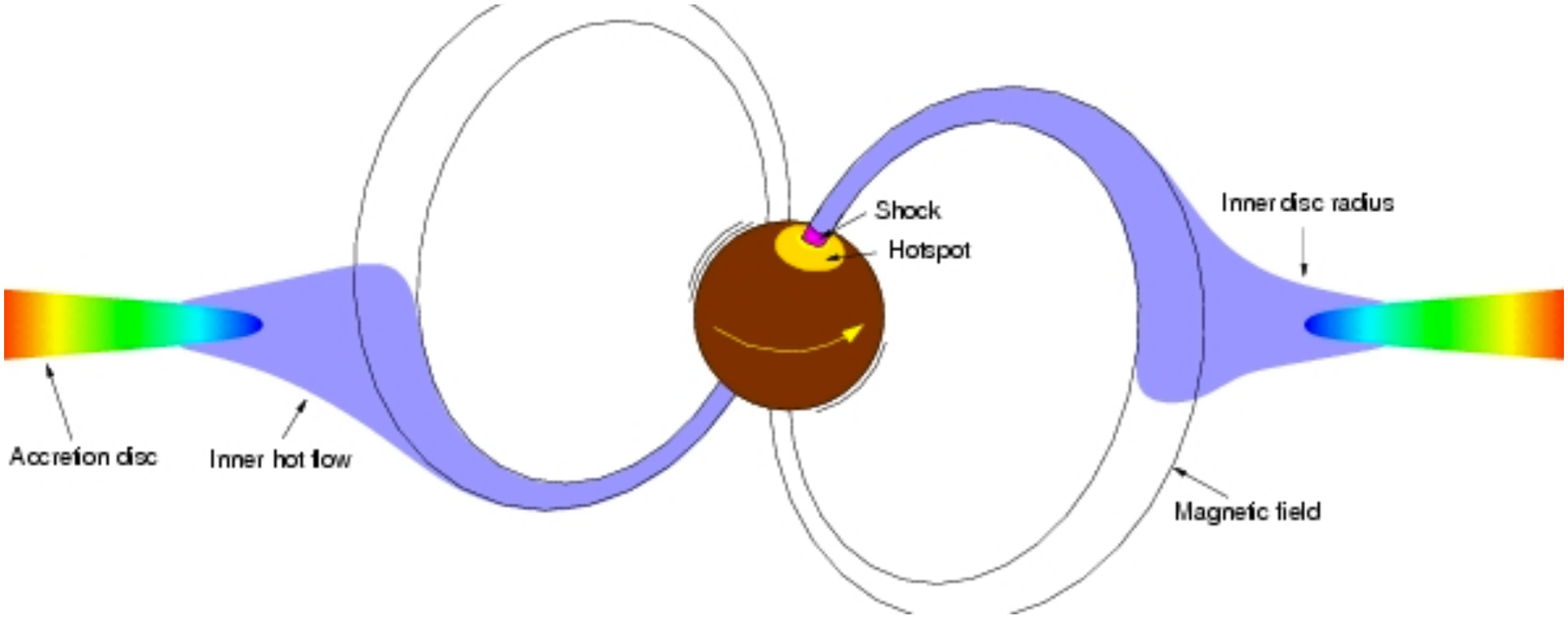



**There may be two clusters at ~1.35 and 1.75 Msol**

Figures from JA et al. 2016; arXiv:1605:.01665

# Formation of Millisecond Pulsars — A Primer

**The majority (if not all) of millisecond pulsars are formed in binaries, always from the first star that goes SN**



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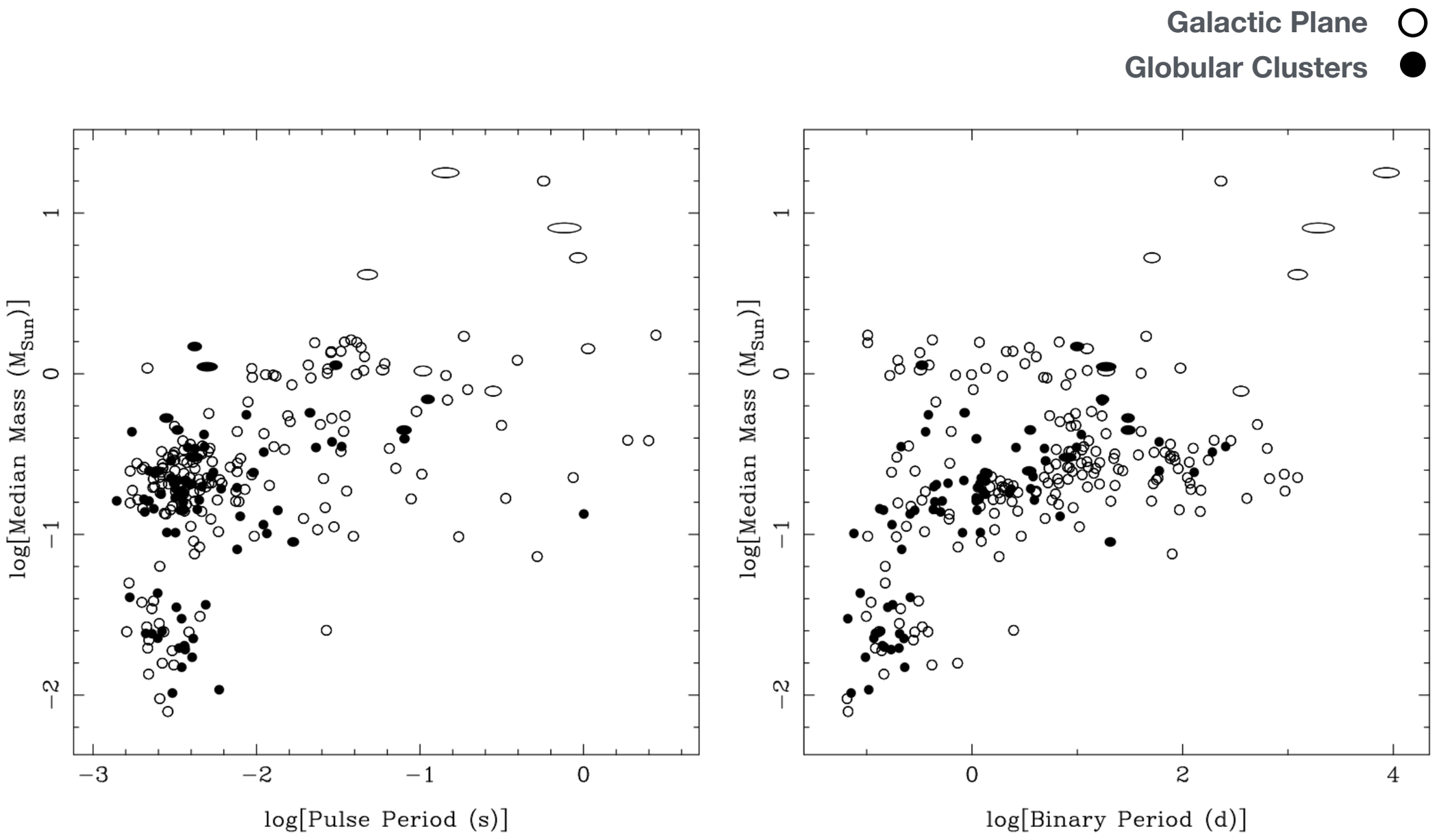
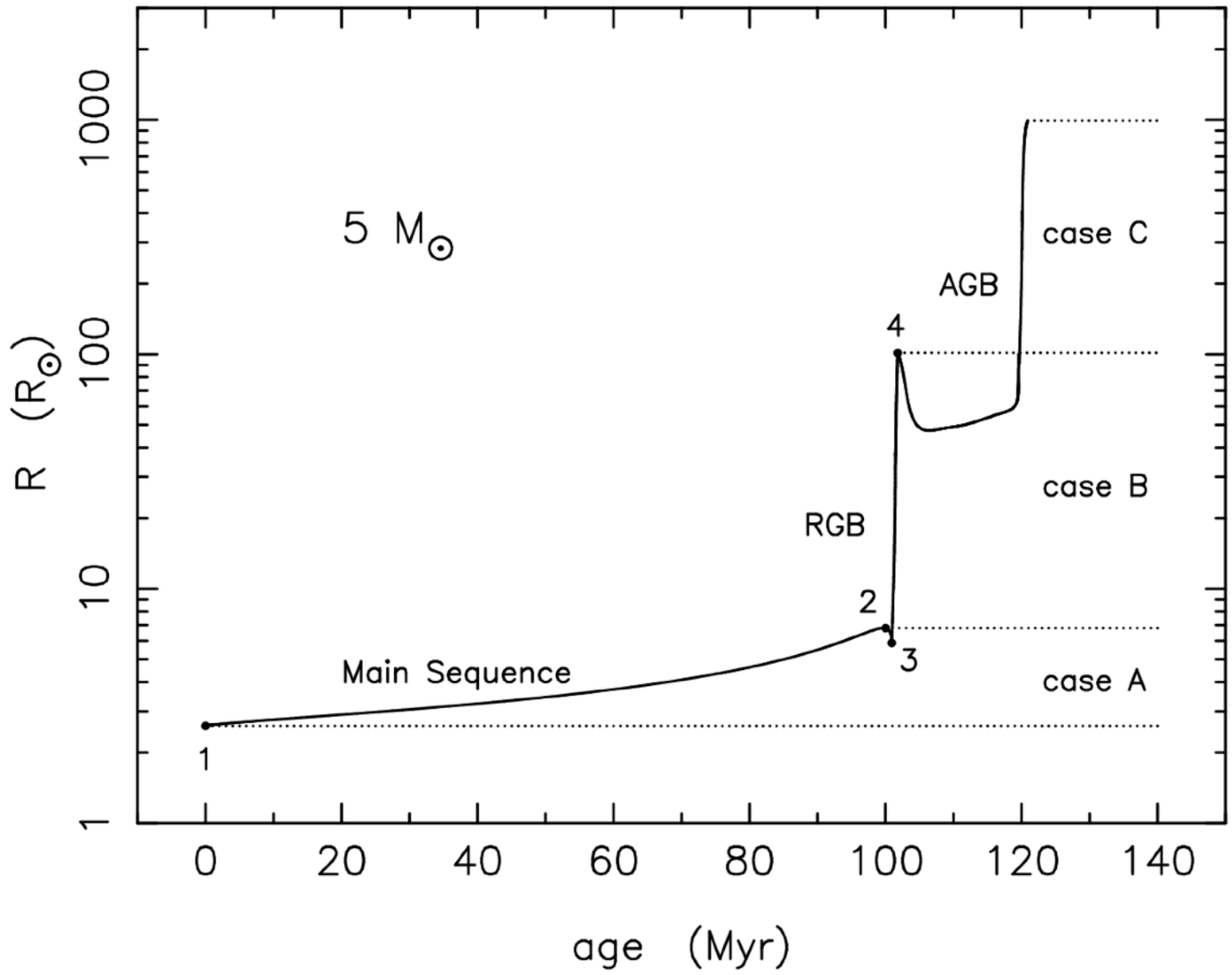



Manchester (2017), ArXiv: 1709.09434

# How MSPs are (not) formed — Recycling theory 1.0.1

**Spin-up requires long-term (nuclear or thermal timescale) accretion from a donor**




**Outcome depends on: initial separation, ZAMS mass (+composition) and evolution state**

Tauris (2011) arXiv: 1106.0897v1

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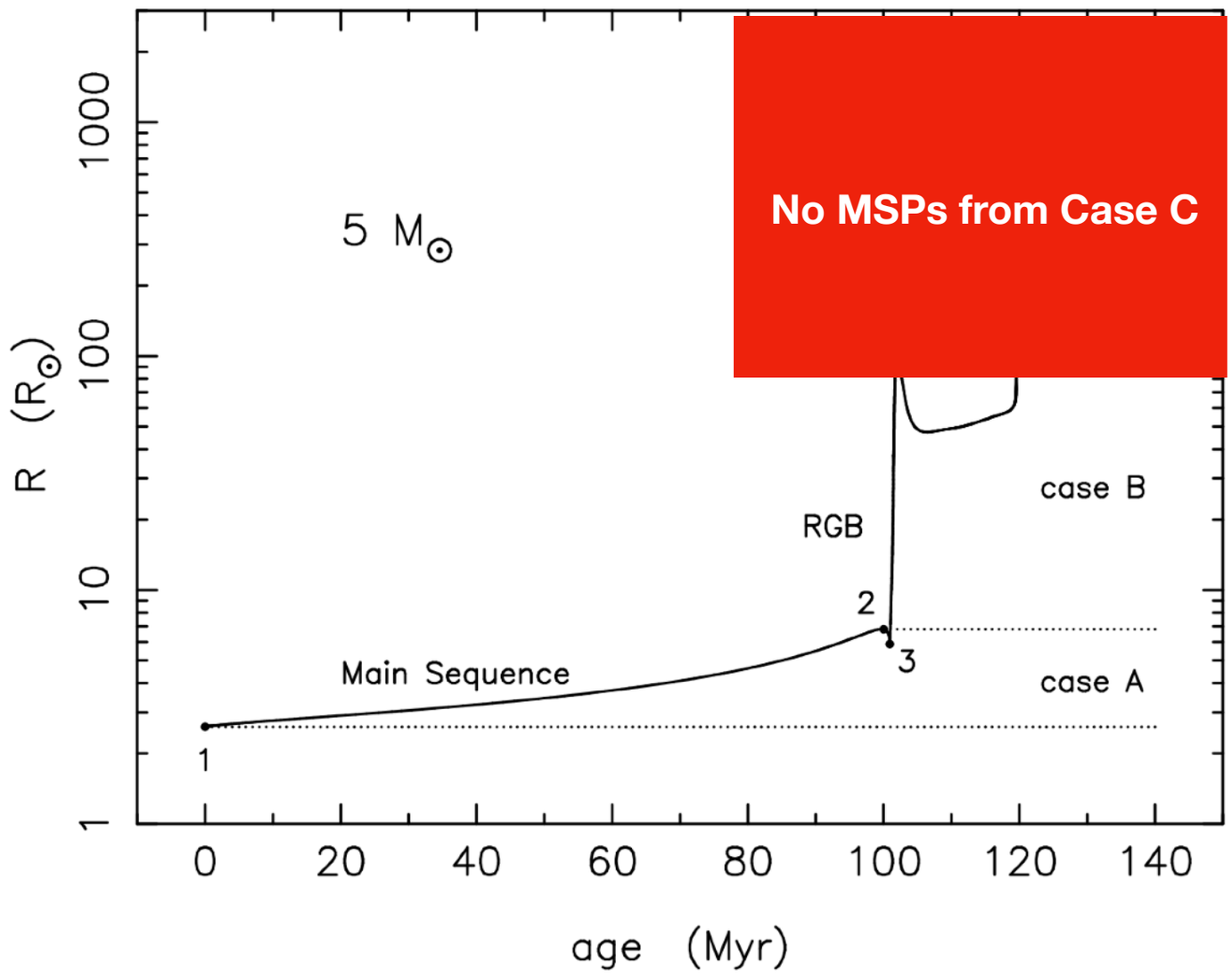


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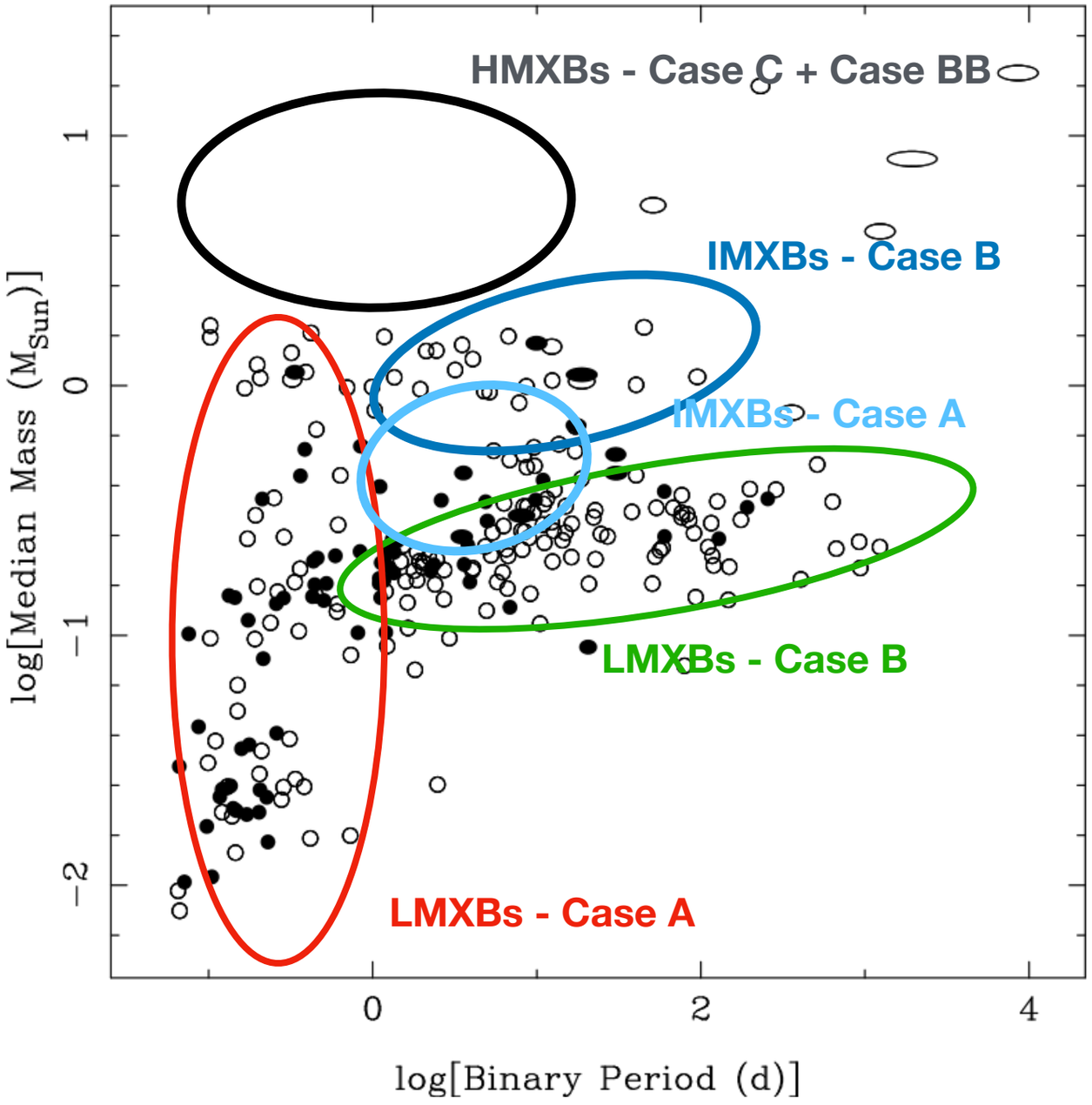
# How MSPs are (not) formed — Recycling theory 1.0.1

**The mapping between initial mass/orbital configuration to final state is not well understood**

**Outcome of mass transfer depends on masses, separation, evolutionary state, accretion physics**

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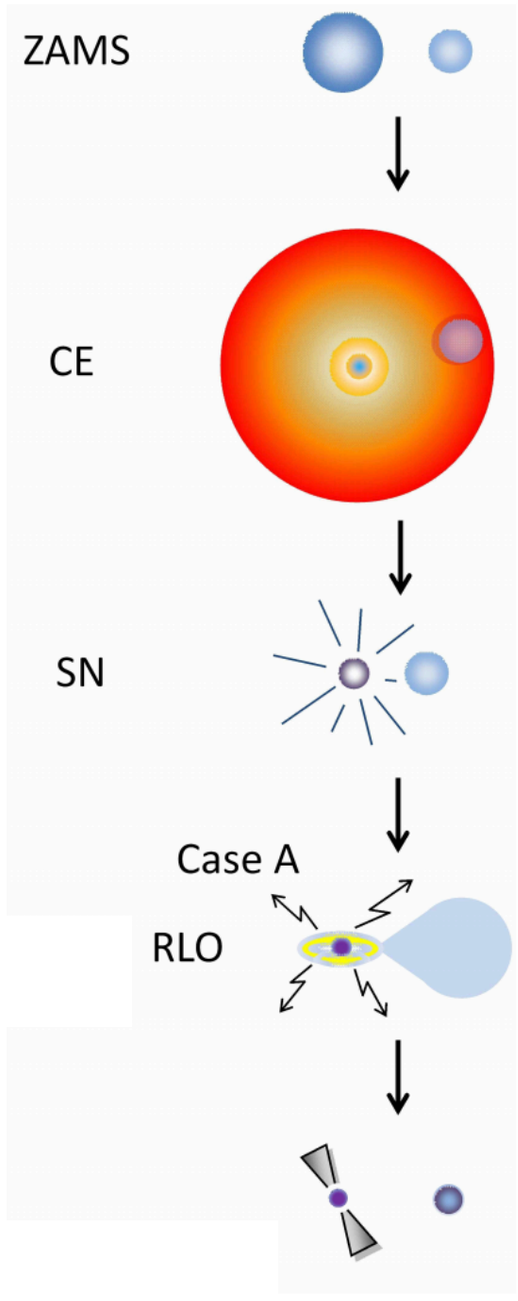
# Case A RLO in IMXBs

## Accretion in Intermediate X-ray binaries may also lead to fully recycled pulsars



# MSPs with CO white-dwarf companions

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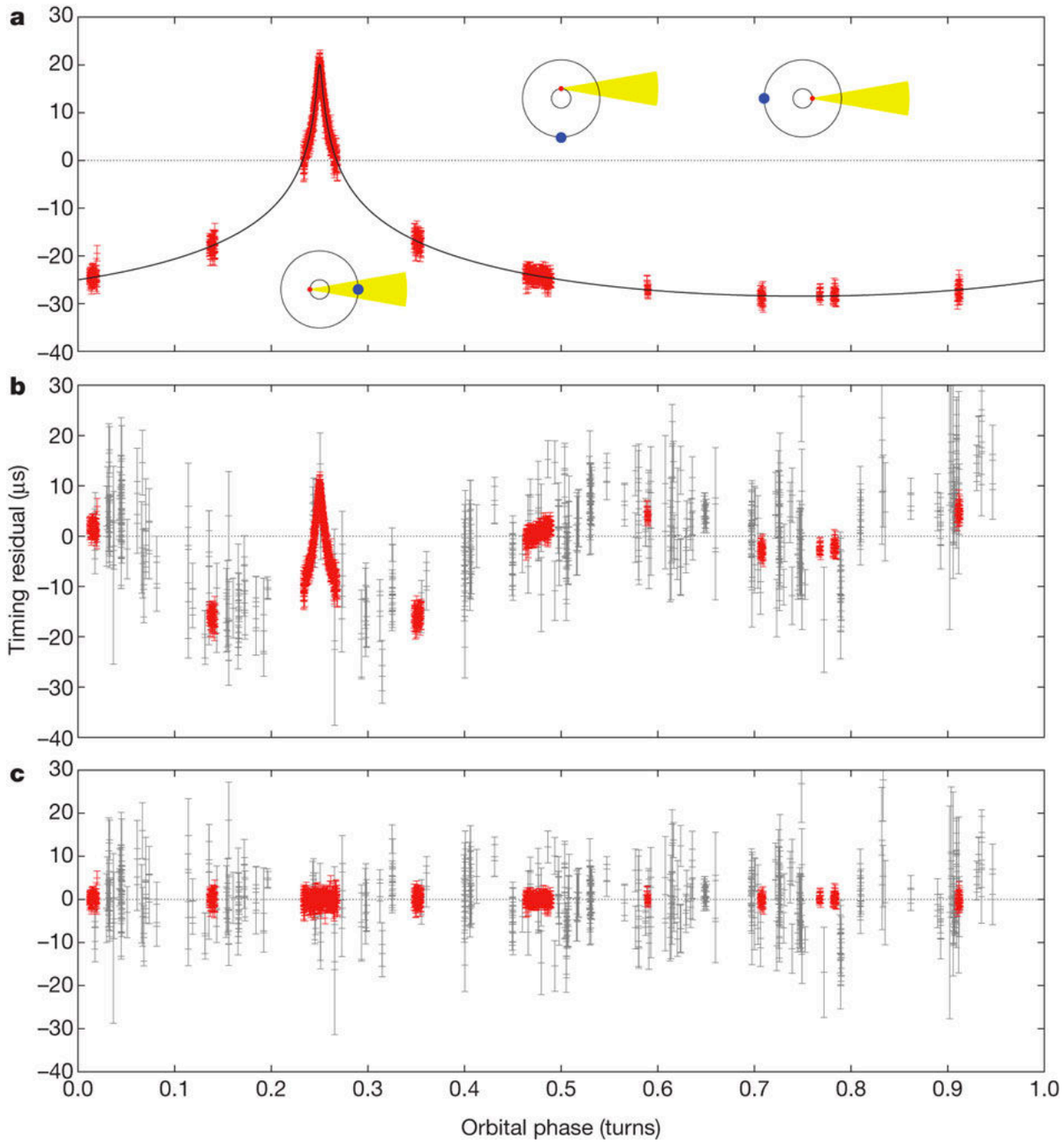
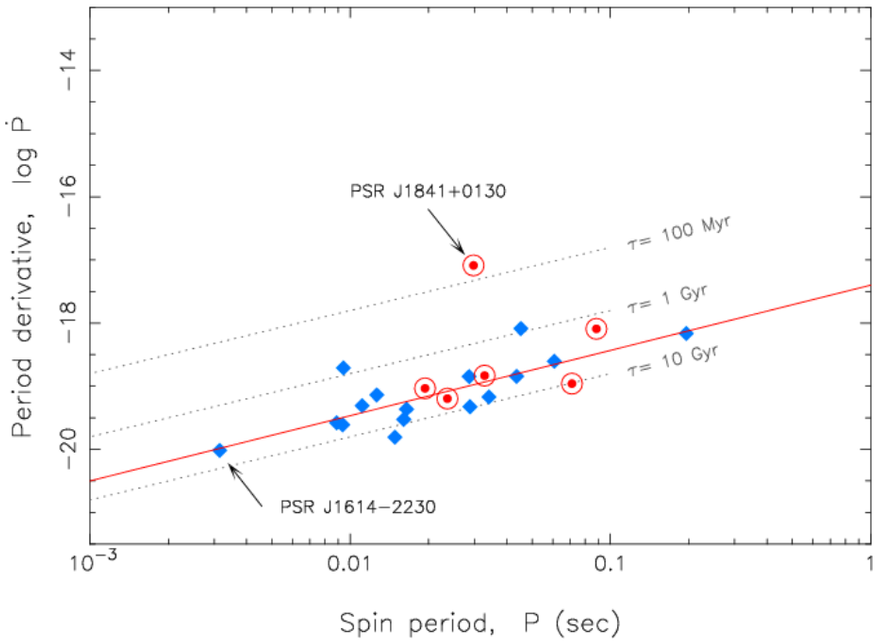



**PSR J1614—2230**

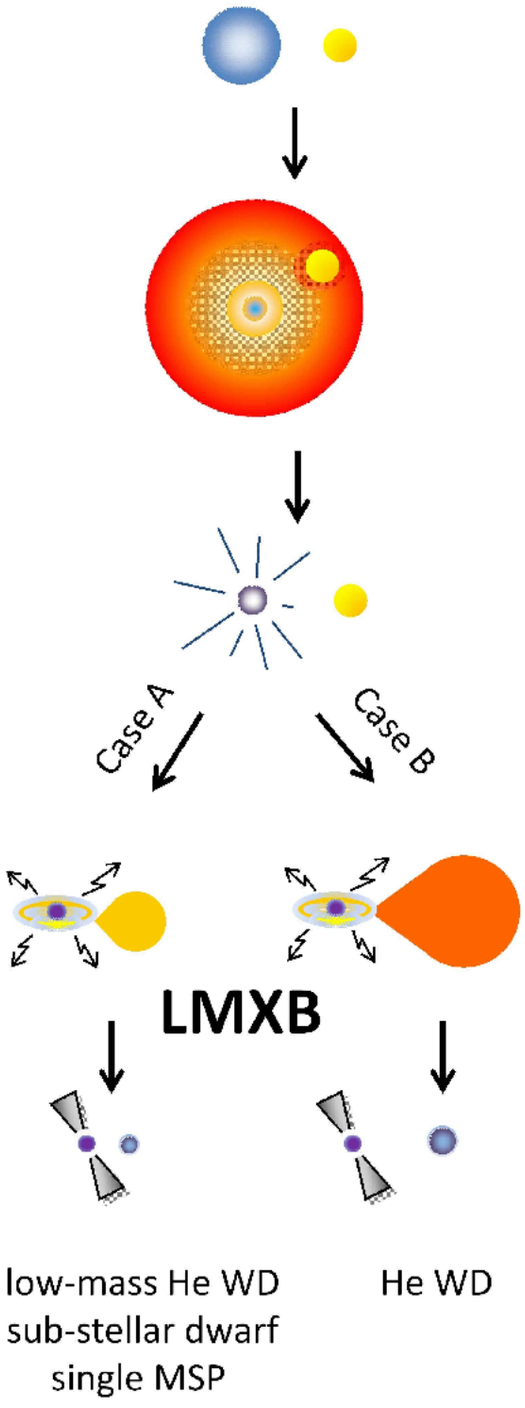
Demorest et al. 2010




Tauris et al. 2011

see also Graikou et al. 2017

# Case A in LMXBs — Some interesting cases




## Compact binaries

**Similar orbital periods**

**companions that differ my > 2 orders of magnitude**

**planets, white dwarfs, black widows, stripped stars (redbacks)**

- **Pulsar — helium white dwarf binaries**

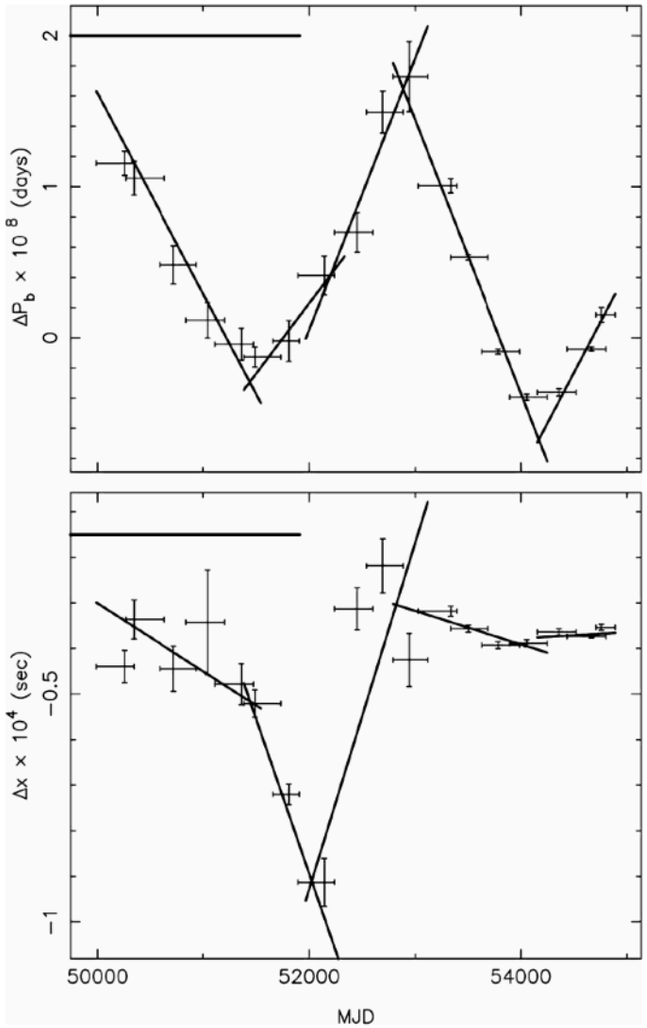
- Mass transfer initiates relatively late on the main sequence
- Orbital evolution driven by magnetic braking and GW emission
- Evolution is understood but size of the population is challenging to explain **[Istrate et al. 2014a, b, 2016]**
- Gravity tests **[see talk by Lijing]**

Tauris (2011) arXiv: 1106.0897v1

# Case A RLO in LMXBs — Some interesting cases

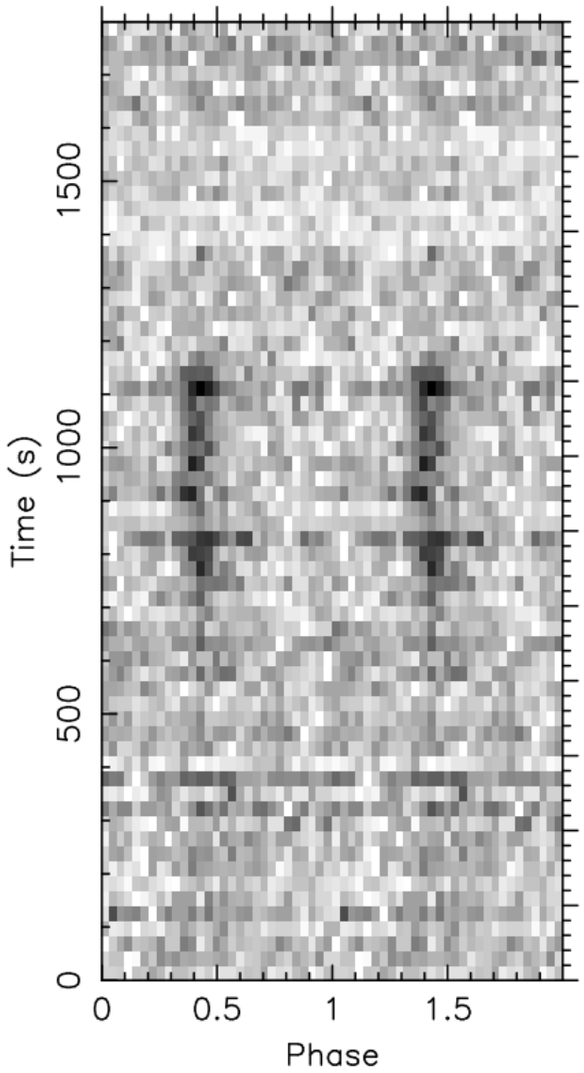
## Black widows as probes of binary evolution

### Spin-orbit coupling



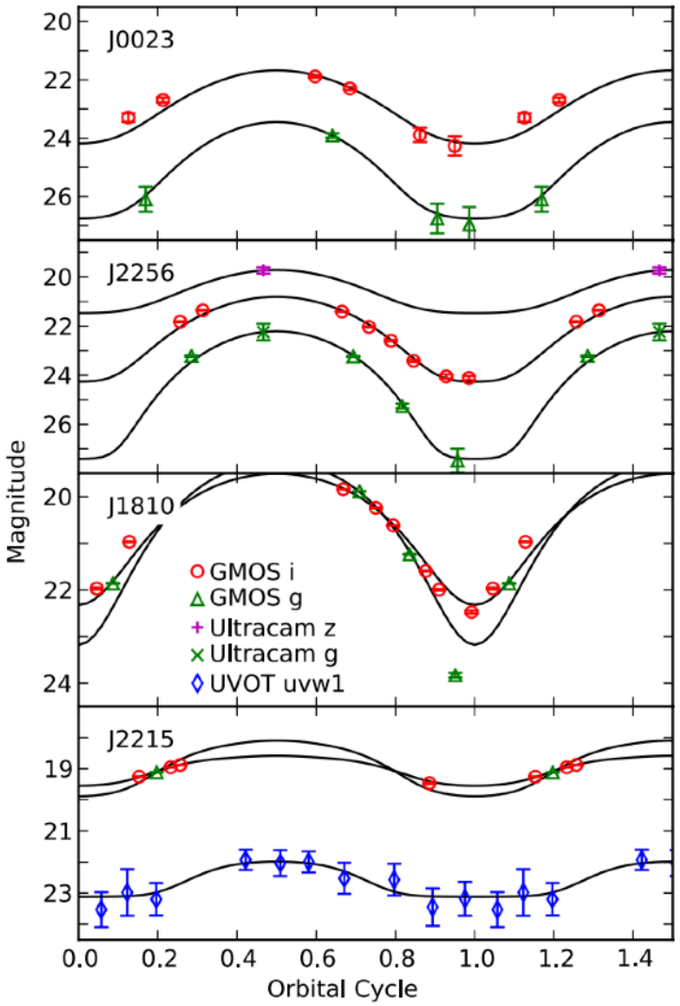

Lazaridis et al. (2011)

### Winds - Evaporation - Eclipses




Crawford et al (2013)

### Irradiation / Tidal Heating




Breton et al. (2013)

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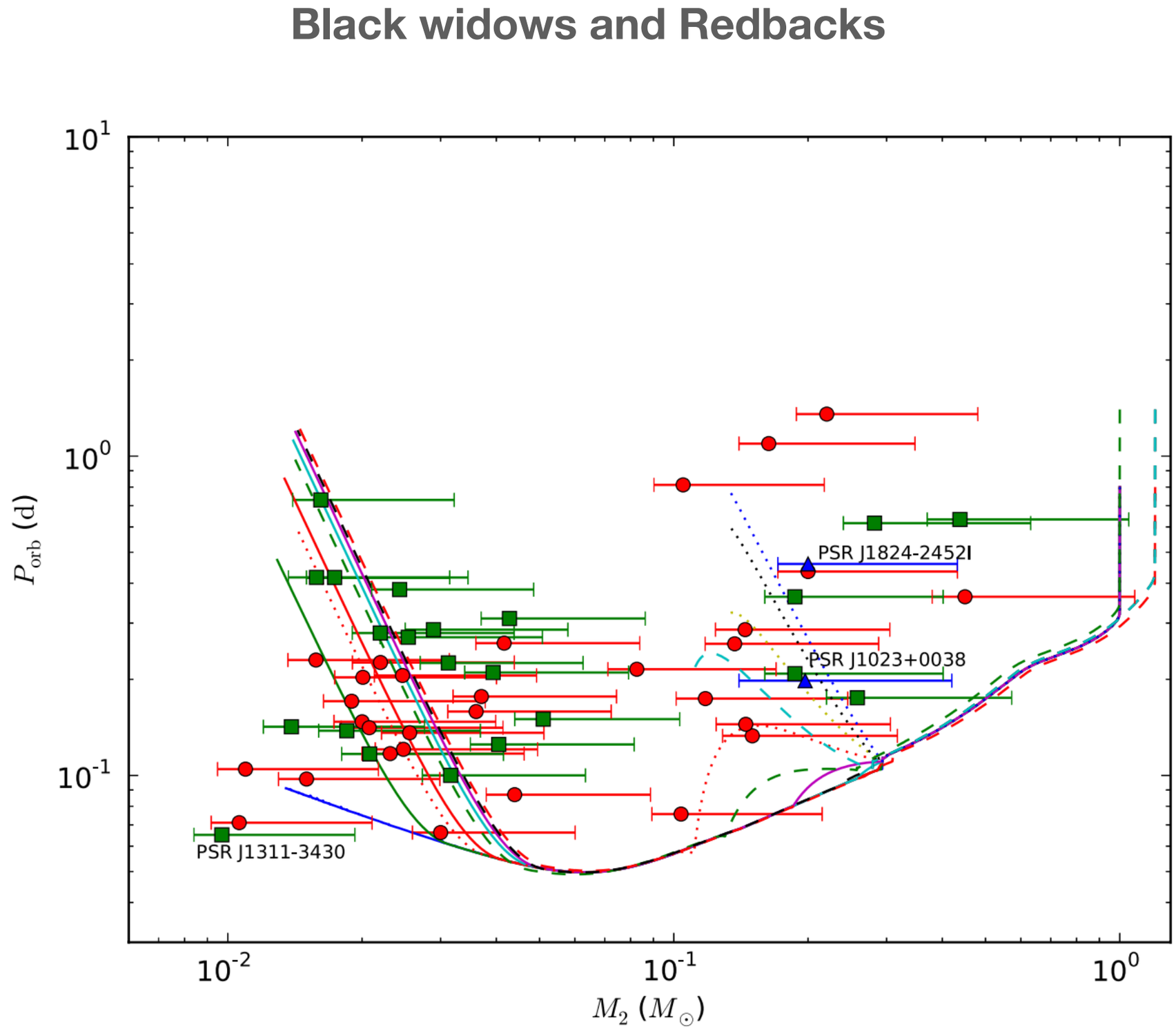


Chen et al. (2013) ApJ, 775, 27

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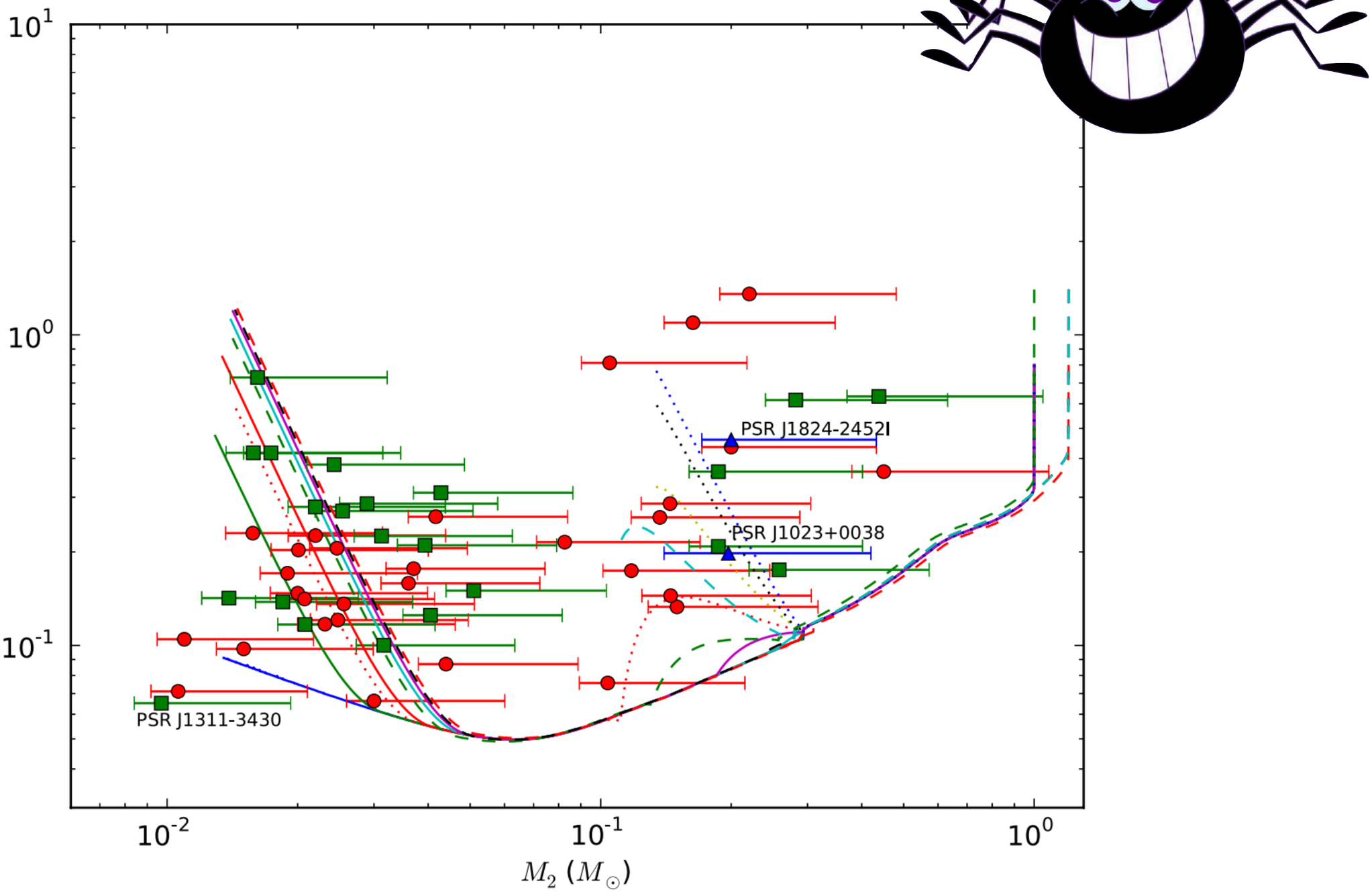


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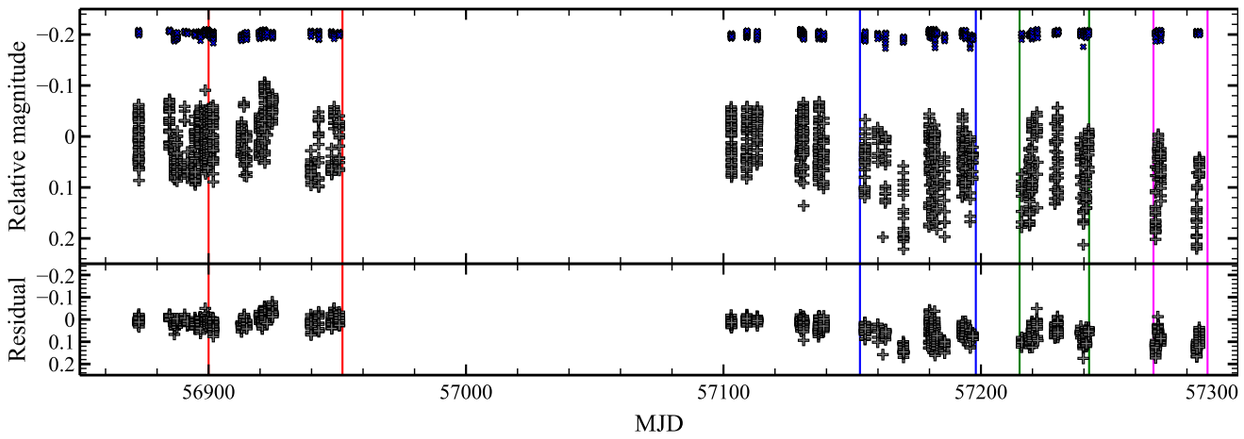
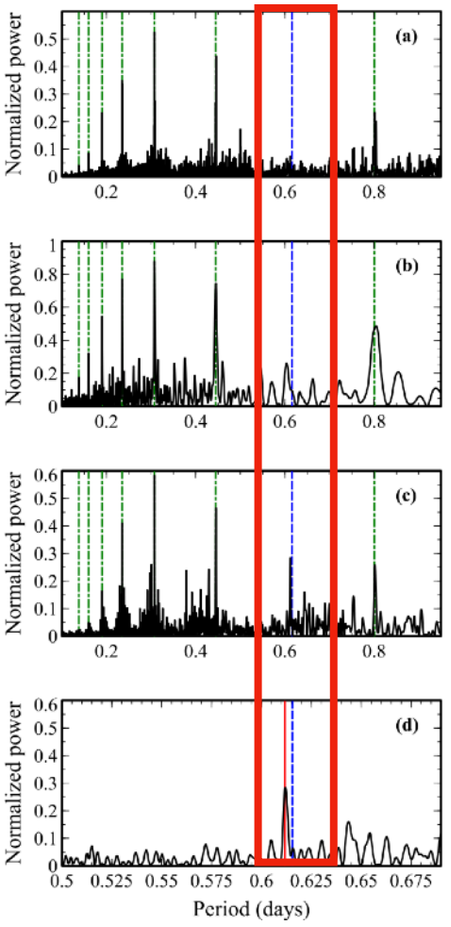
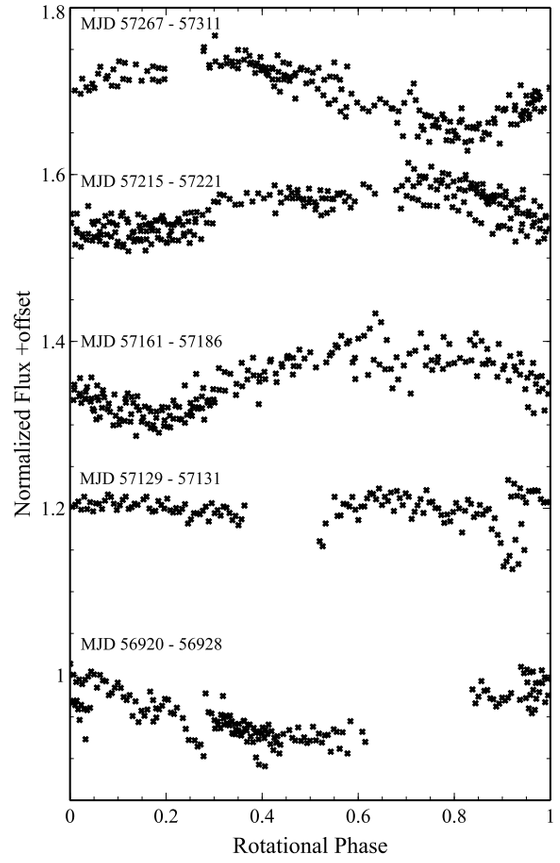
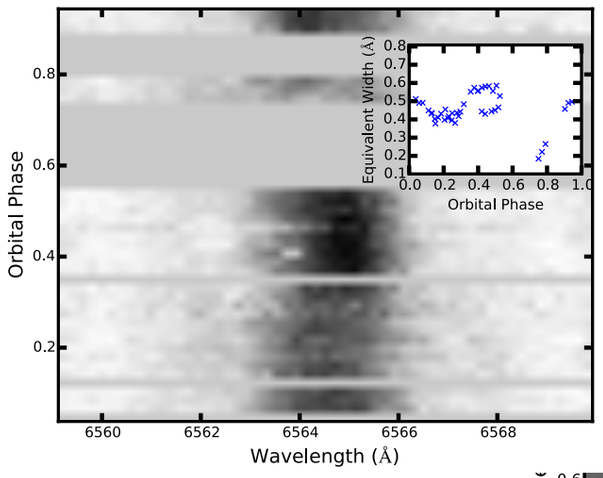
## Redbacks
### Irradiation or Magnetism?

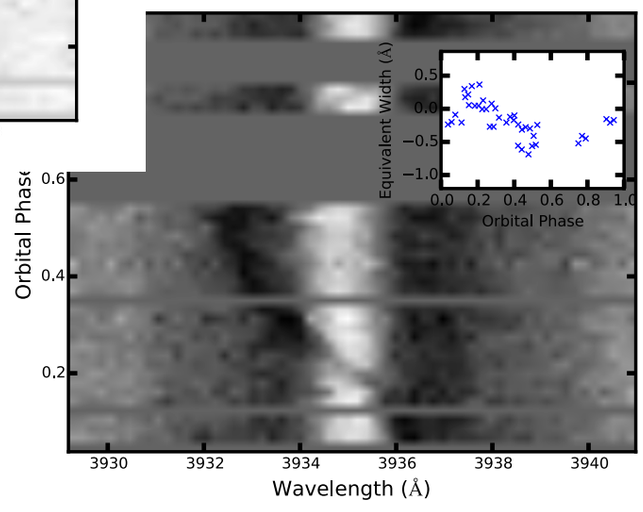
**PSR J1723-2837**




**Not tidally locked!**

van Staden & JA (2016), JA et al., in prep

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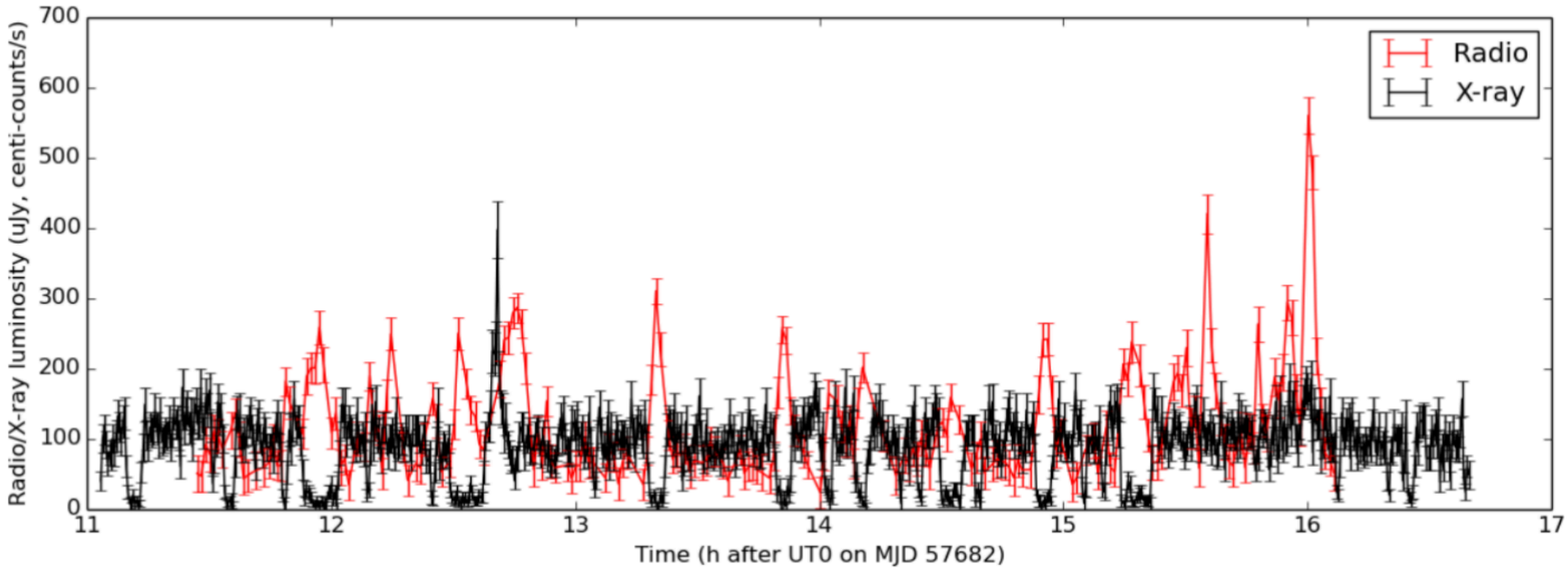
## Transitional millisecond pulsars

LMXB ⟷ Radio MSP



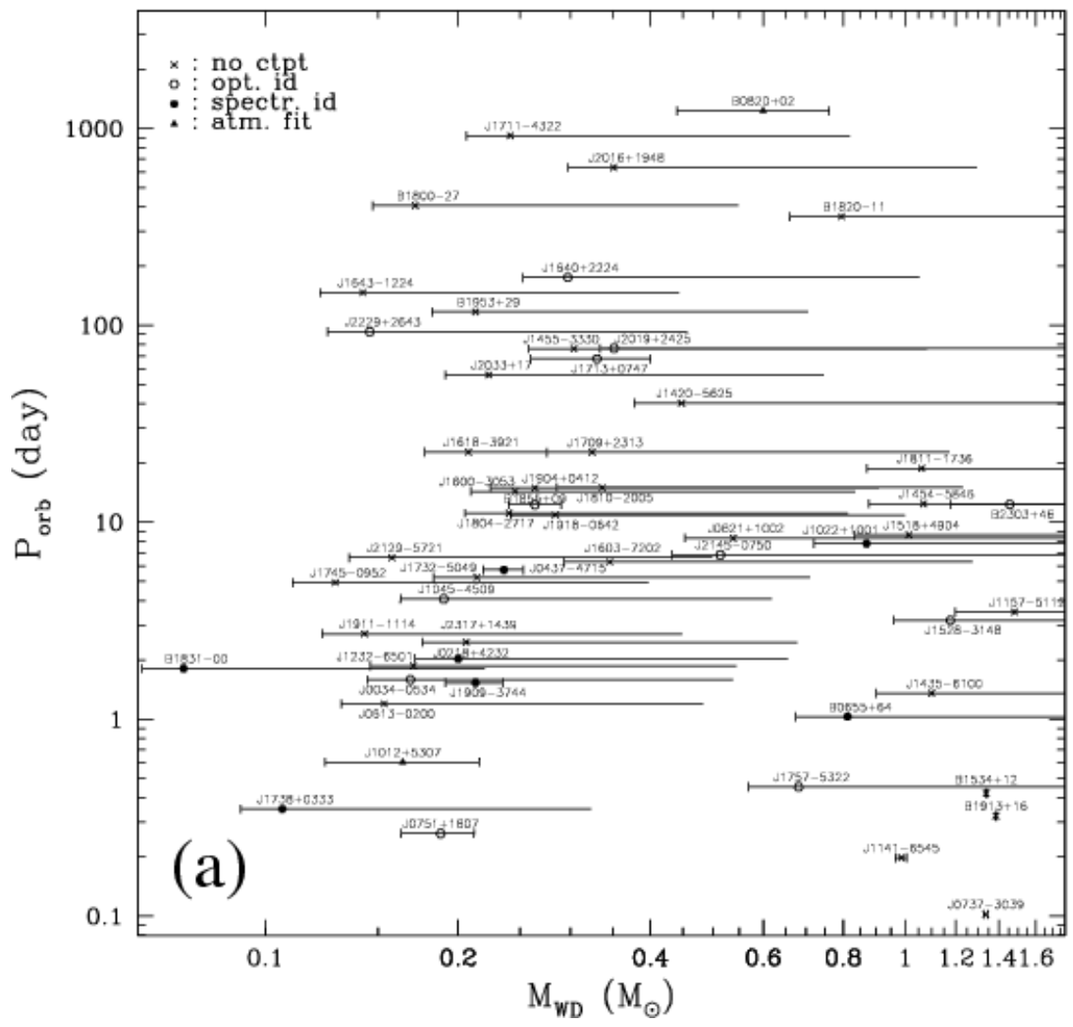

**Excellent probes of binary dynamics and accretion physics in compact binaries**

See talk by Amruta Jaodand

# Case B RLO in LMXBs — Some Interesting Cases

## Pulsar — Helium WDs: Fossils of binary evolution

### Companion mass — Orbital Period correlation




van Kerkwijk et al. (2005) — Tauris & Savonije 1999

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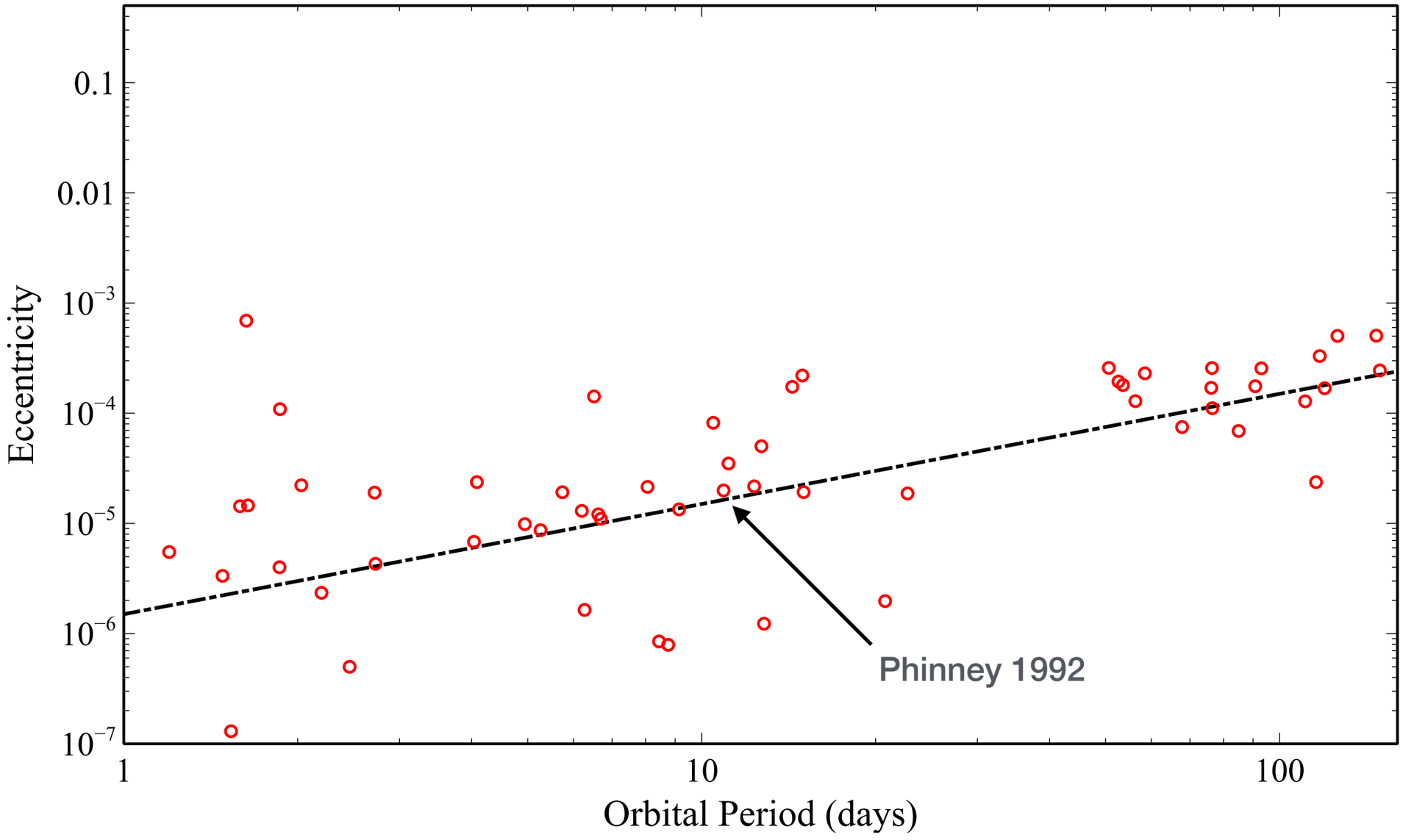
## Orbital period — eccentricity correlation




JA (2014) / JA et al. (2016a)

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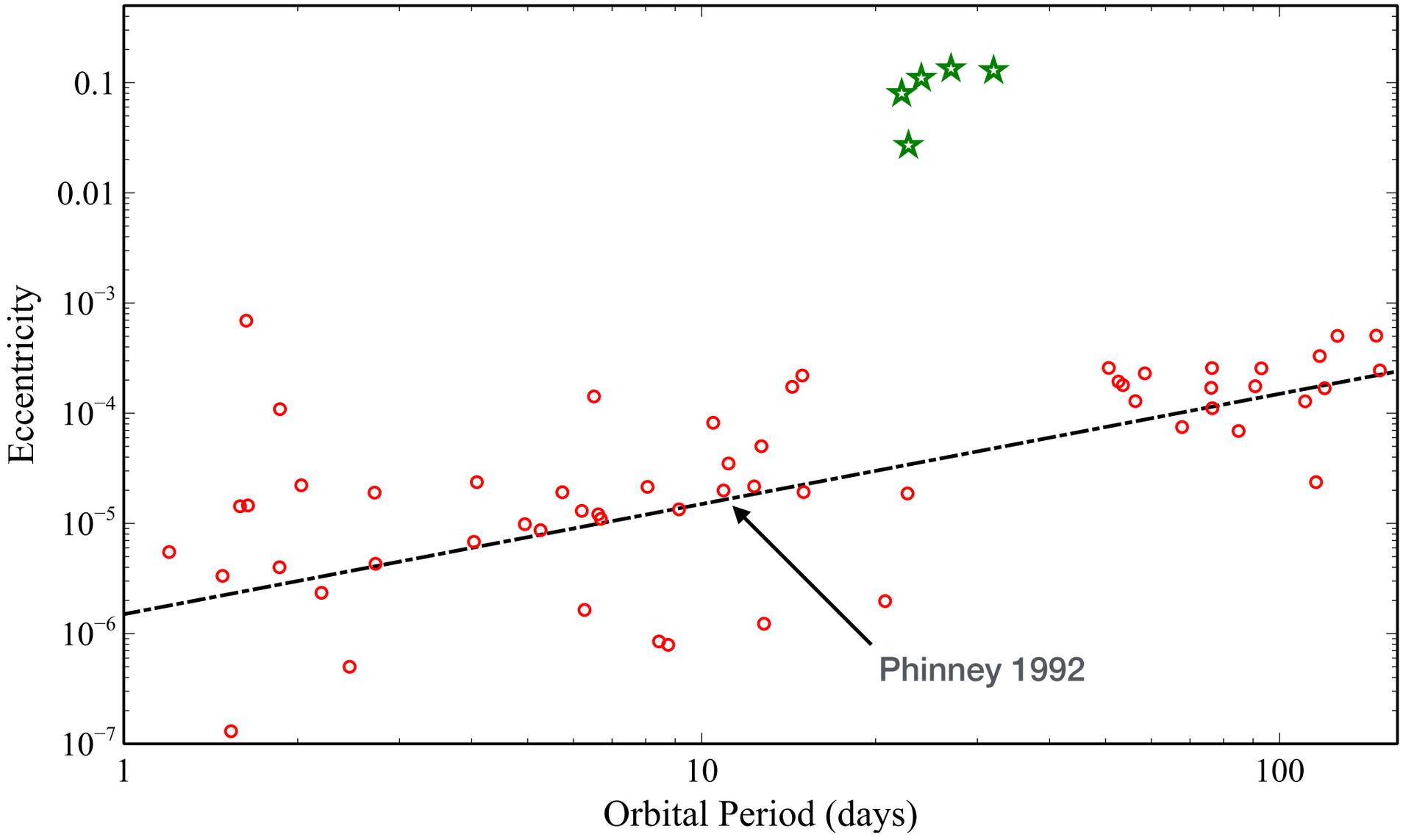


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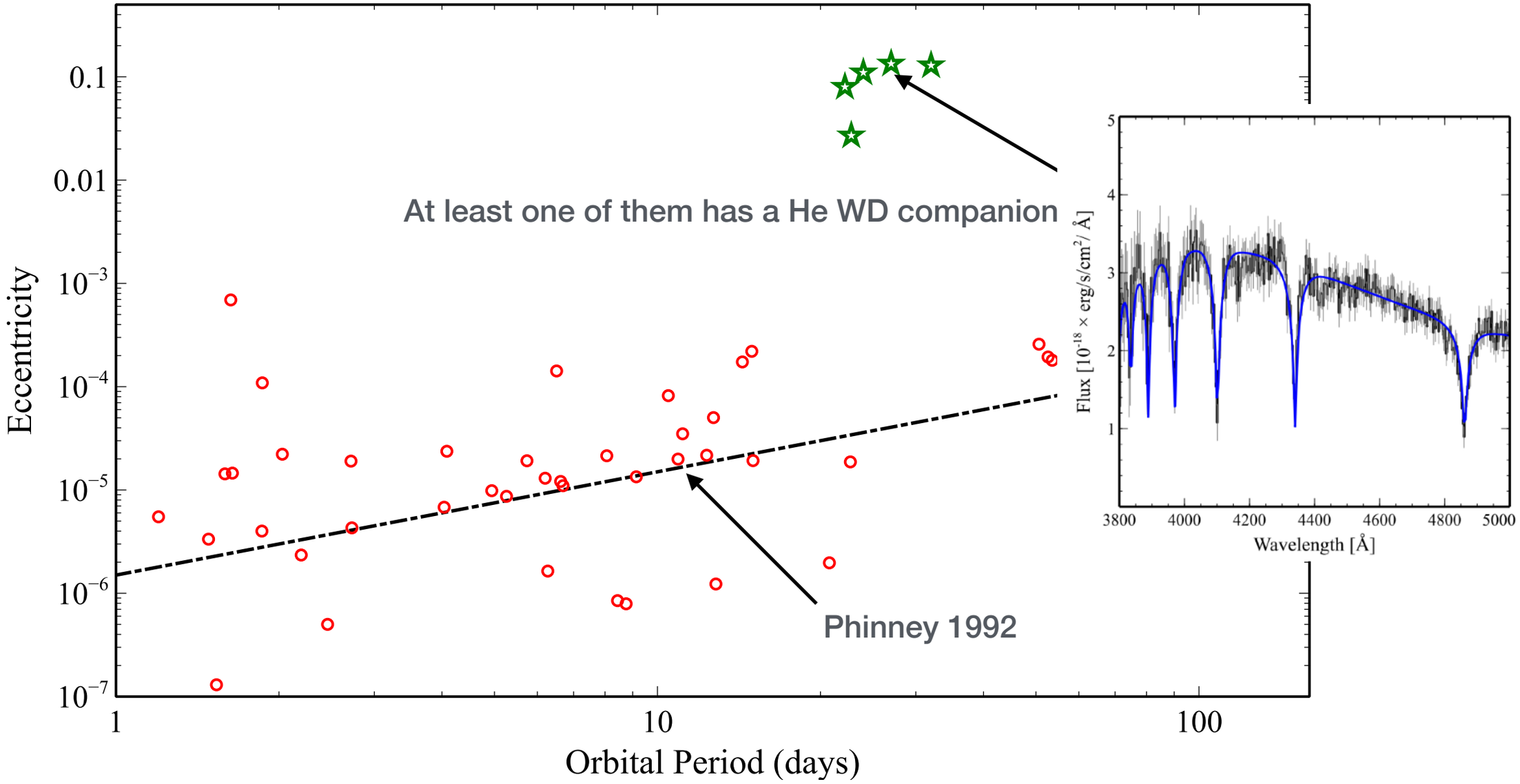


JA (2014) / JA et al. (2016a)

## Eccentric millisecond pulsars
## A new class of binary MSPs

| Pulsar | P (ms) | $P_{orb}$ [days] | $M_c$ [$M_{sol}$] | eccentricity | Companion | Ref. |
|---|---|---|---|---|---|---|
| J2234+0611 | 3.6 | 32 | 0.23 | 0.13 | WD | JA et a. 2016 |
| J1946+3417 | 3.1 | 27 | 0.24 | 0.13 | ? | Barr et al. 2013 |
| J1950+2414 | 4.3 | 32 | 0.24 | 0.08 | ? | Knispel et al. |
| J1618-3921 | 12 | 23 | 0.20 | 0.027 | ? | Bailes et al. 2010 |
| J0955-6150 | 1.99 | 24 | 0.23 | 0.11 | ? | Camilo et al. 2015 |

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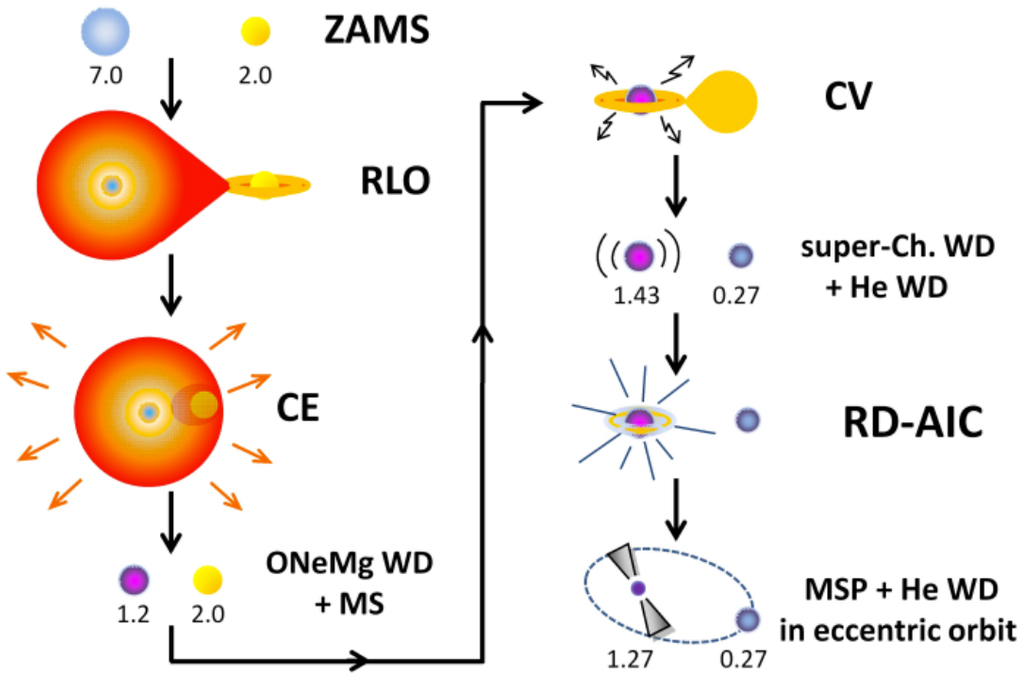
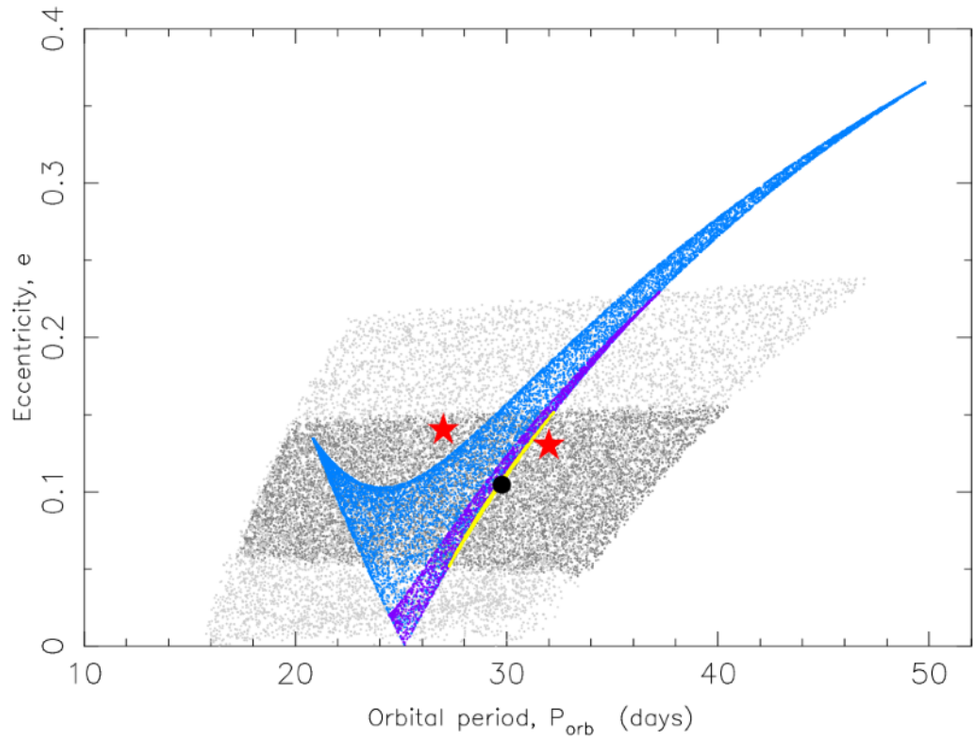
## eccentric MSPs — Possible Formation Scenarios

### Rotationally-delayed accretion-induced collapse of a massive white dwarf




Similar masses, orbital periods between 20-50 days

Freire & Tauris (2014)

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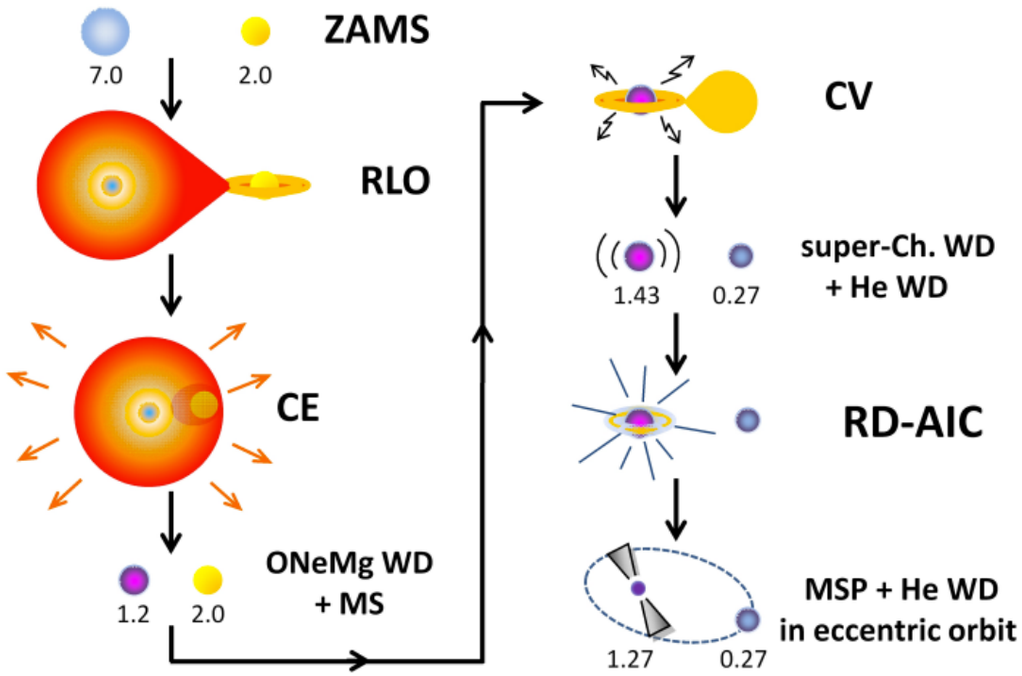


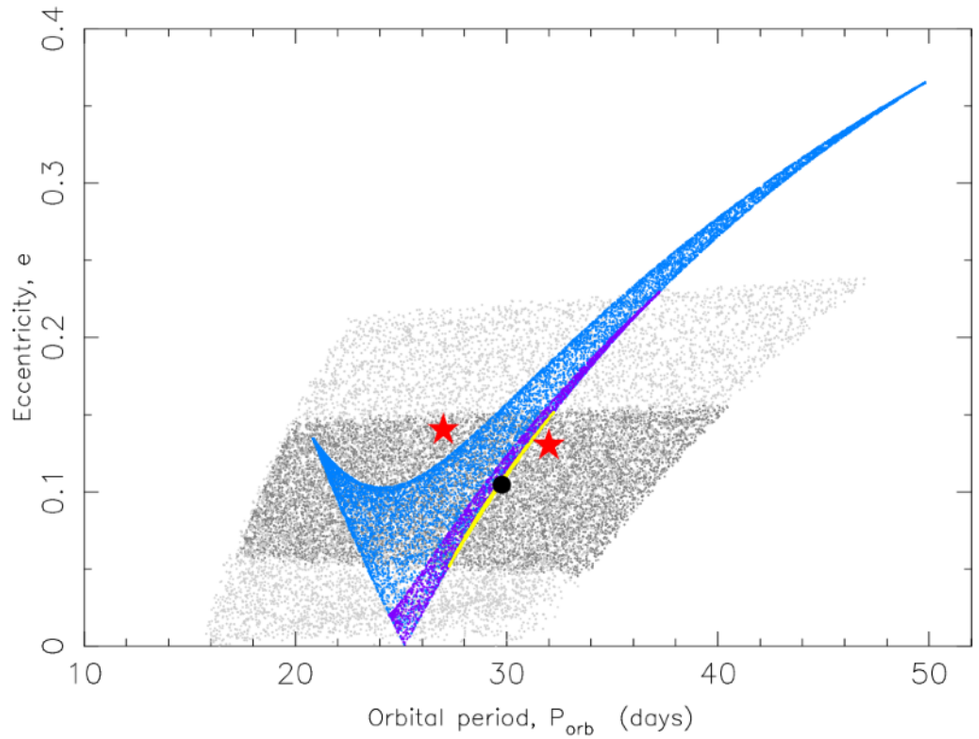


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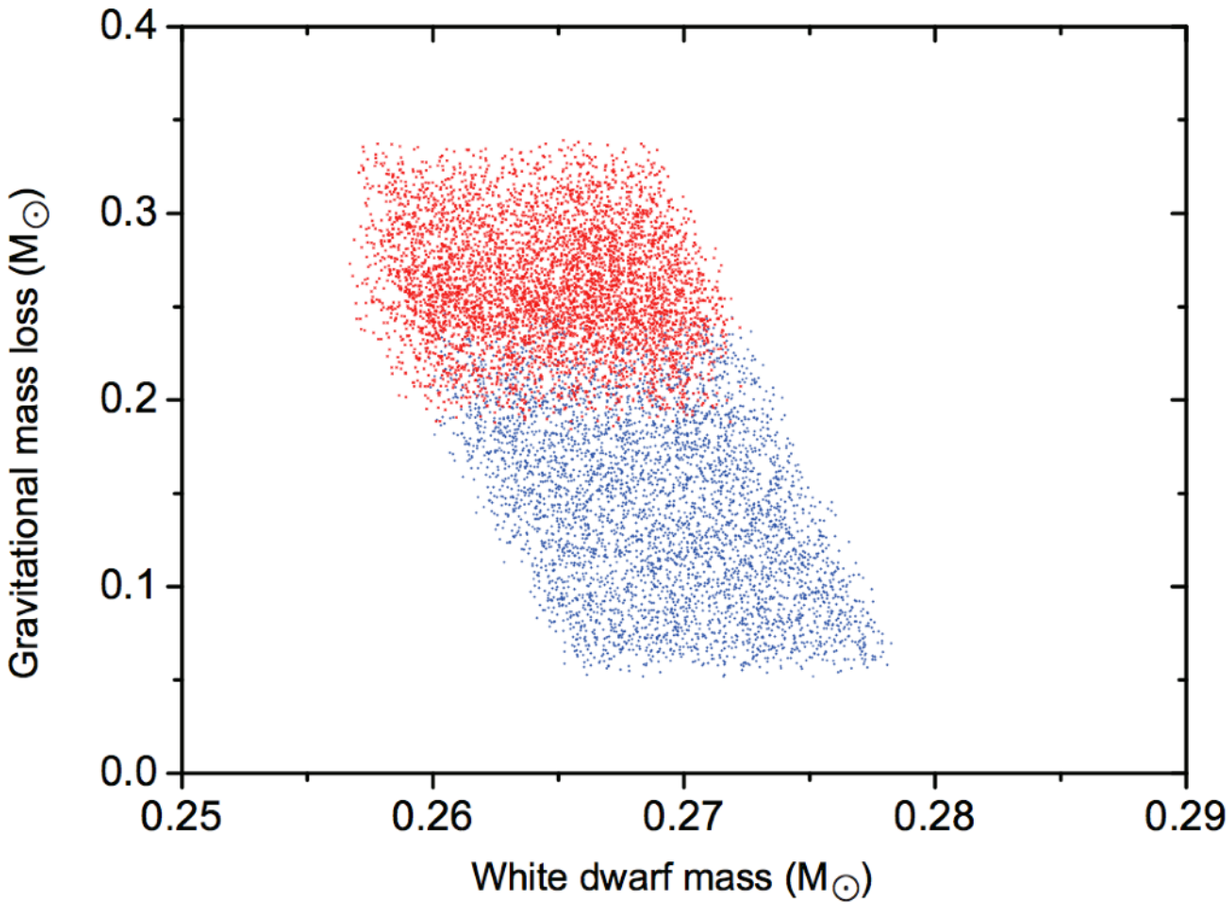


Core Density in LMXBs reaches threshold for quark deconfinement —> Transformation to Strange Quark Star

Similar masses(?)
Constraints on binding energy and the EoS

Fig. 1.— Required gravitational mass loss of the NS vs. the WD mass in the phase transition scenario to reproduce the properties of PSR J2234+06. The red and blue dots represent the cases for the eccentricity in the range of $0.11 - 0.15$ and $0.027 - 0.11$, respectively.

Jiang et al. (2015)

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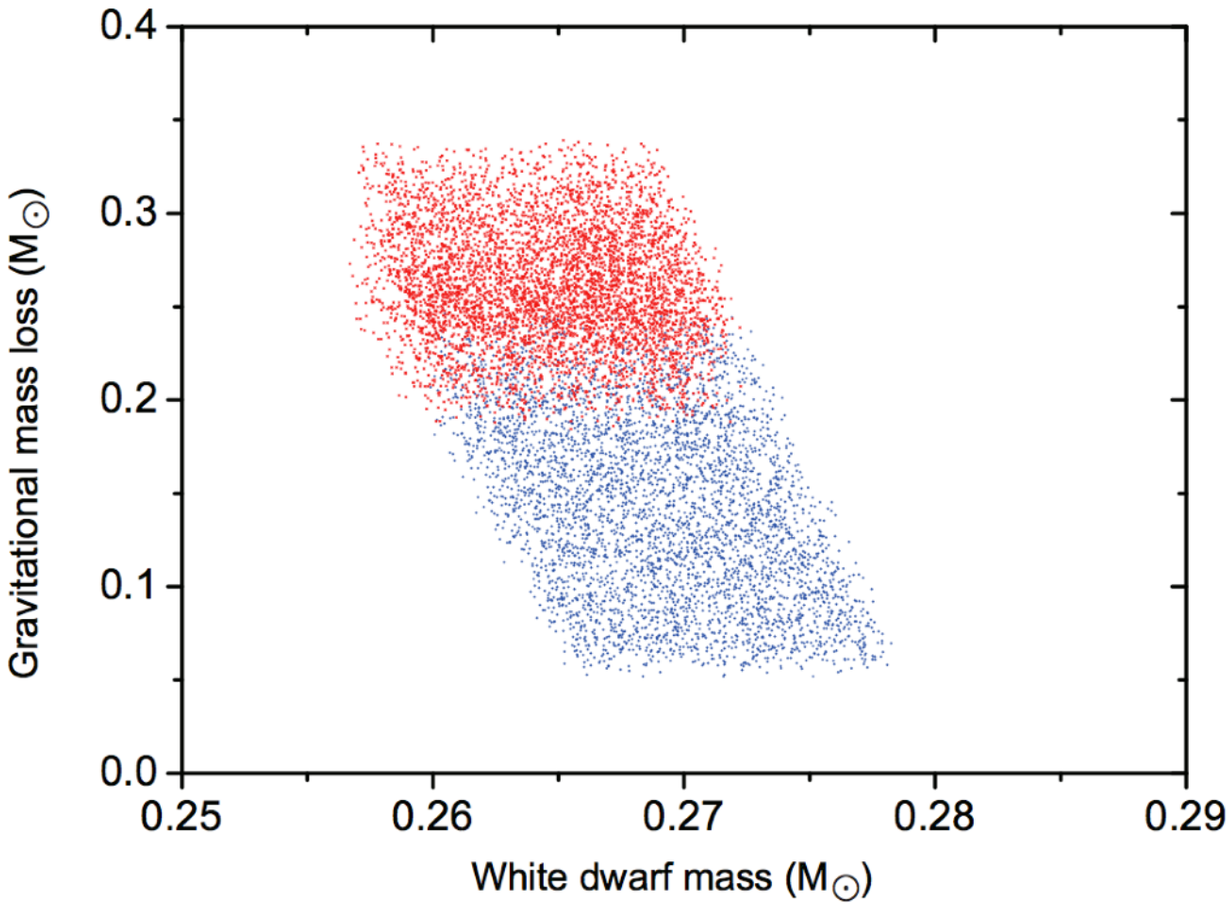


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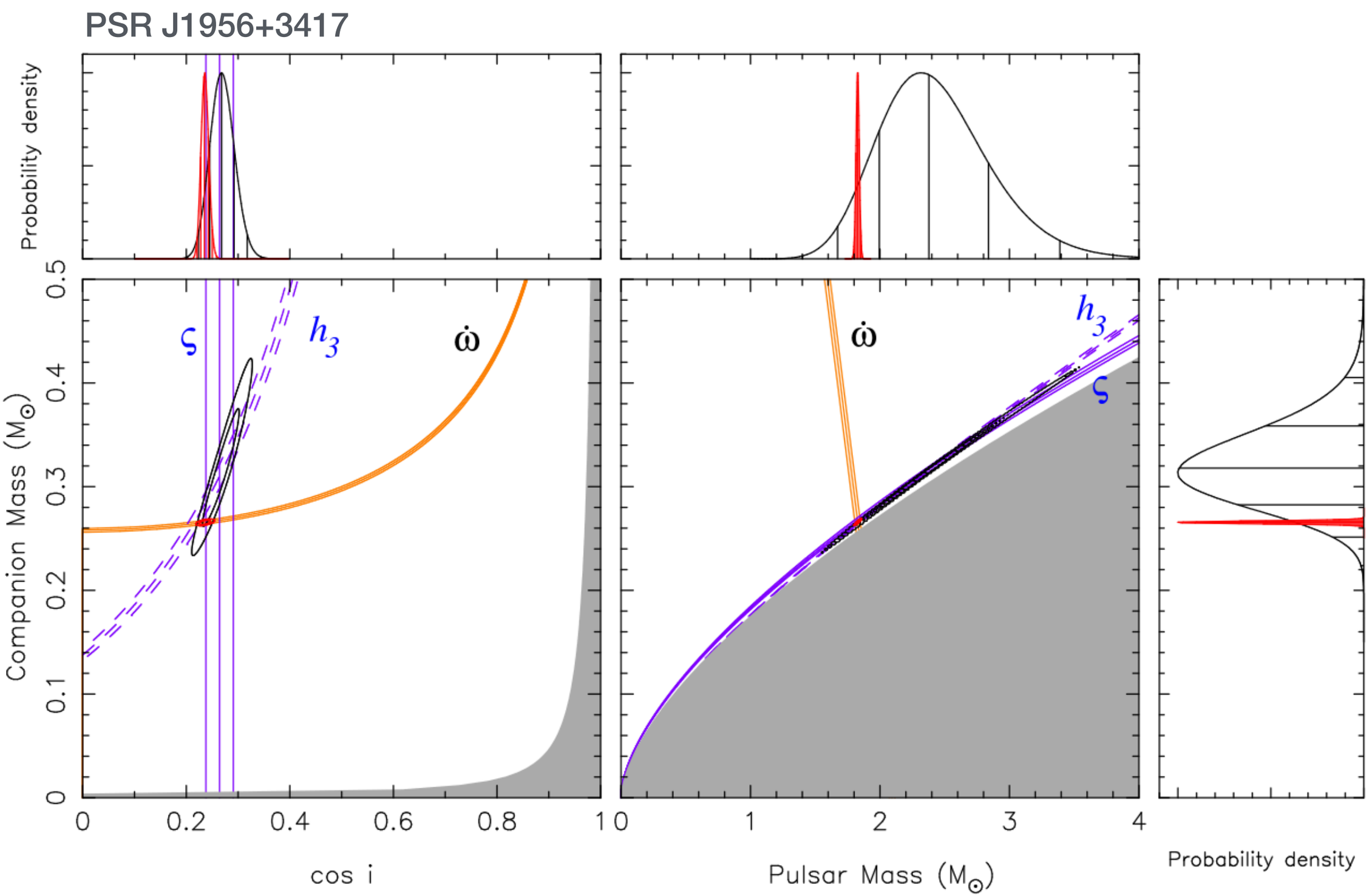
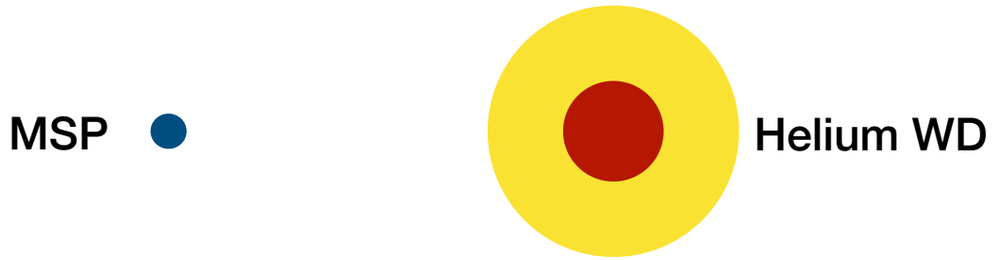



Barr et al. (2016)

# Eccentric MSPs




JA (2014)

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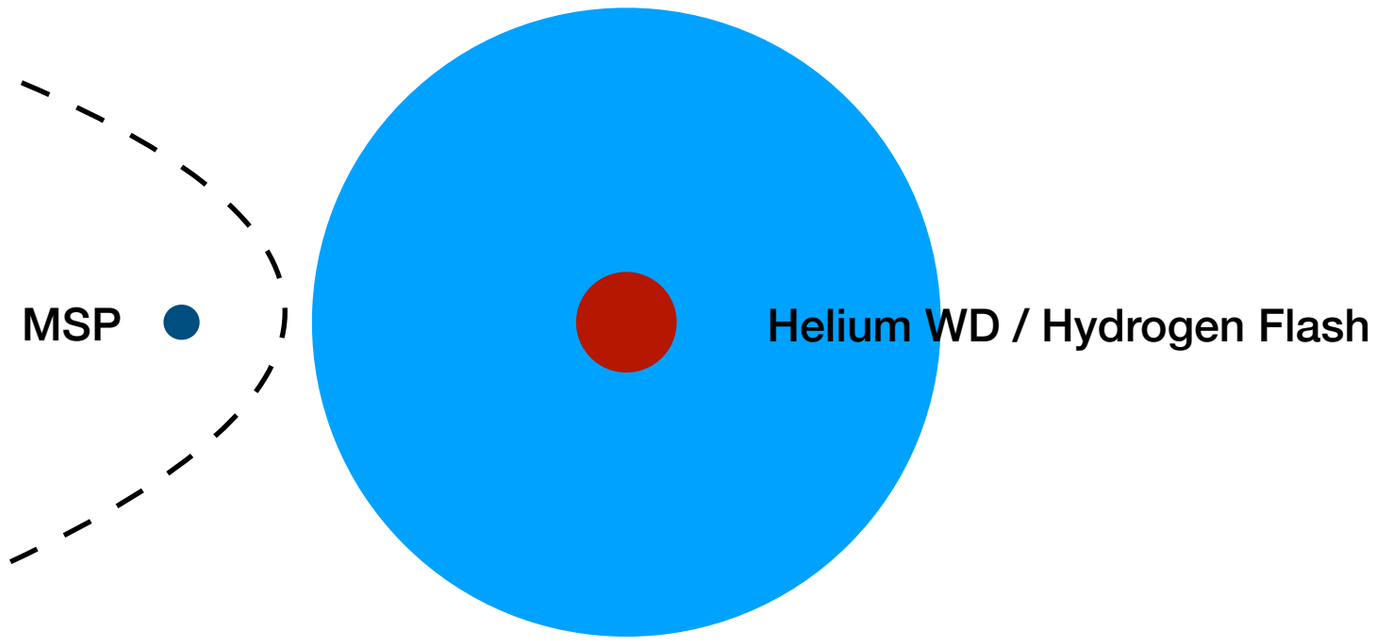


JA (2014)

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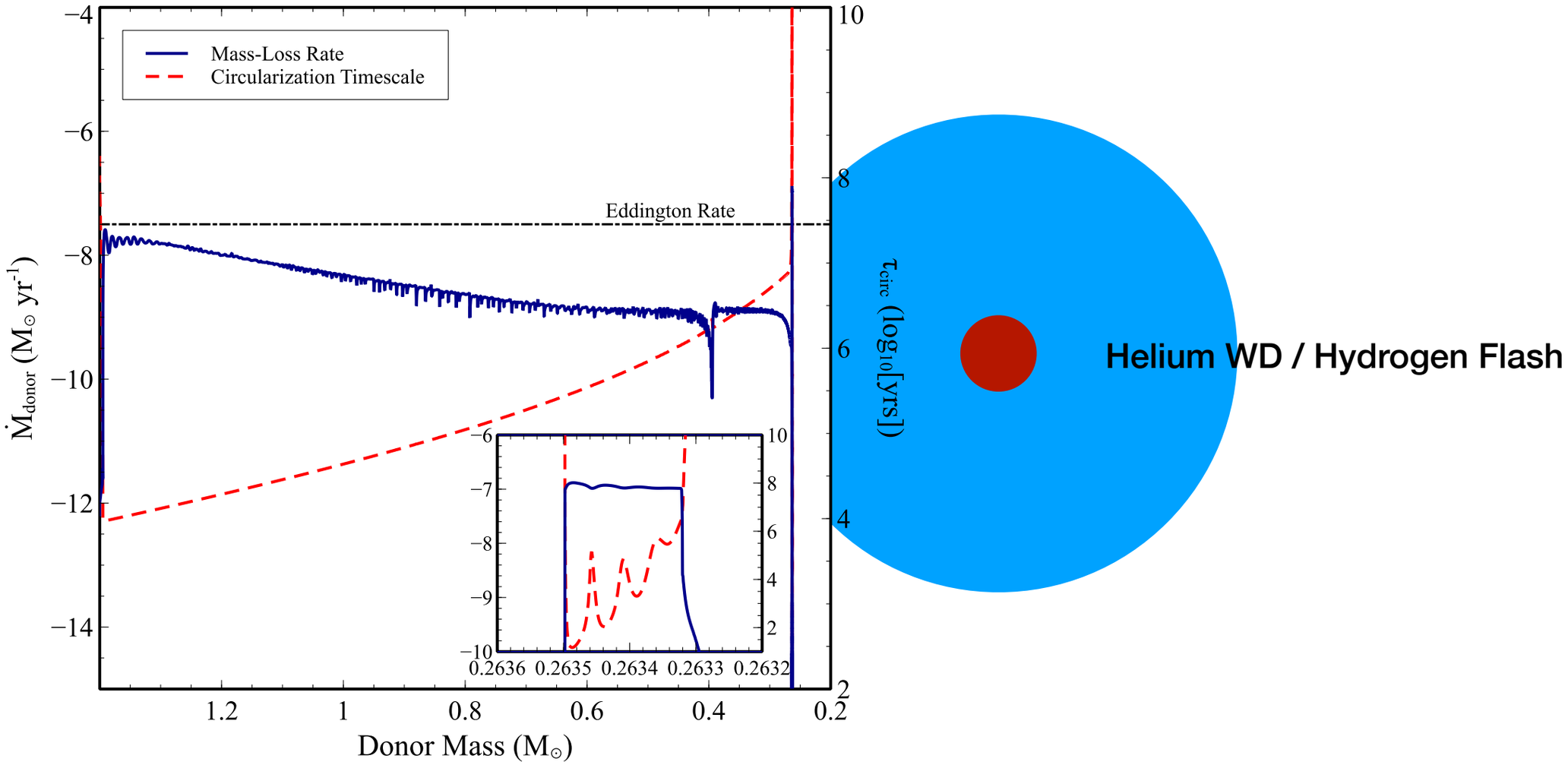


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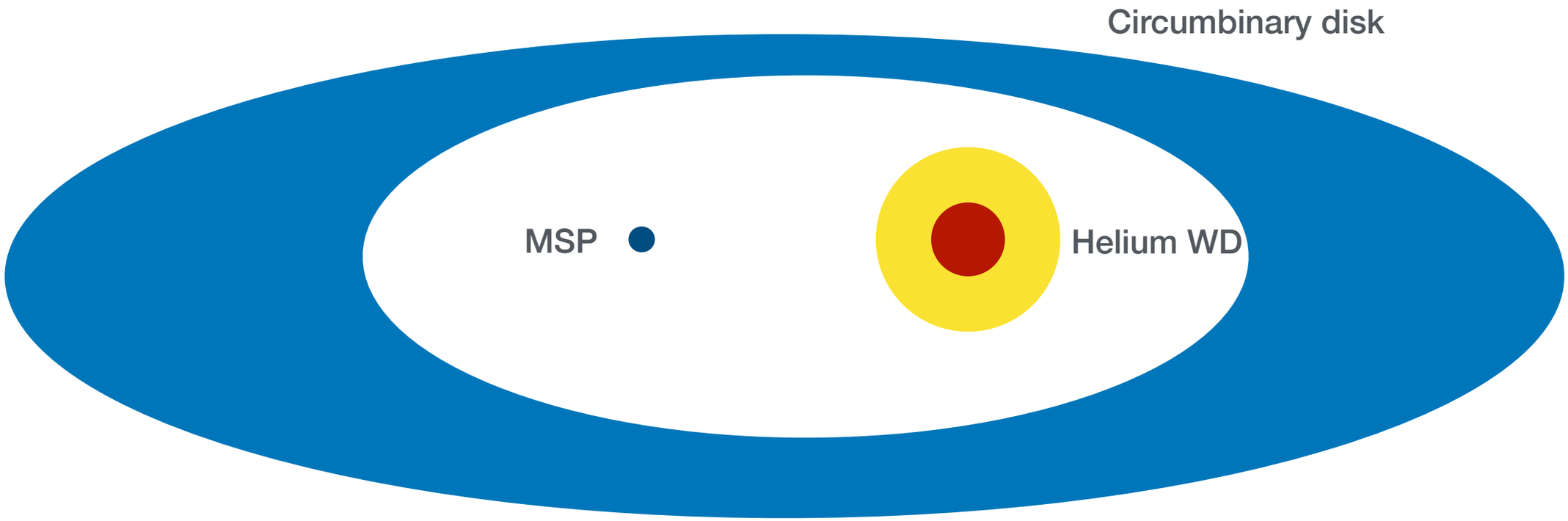


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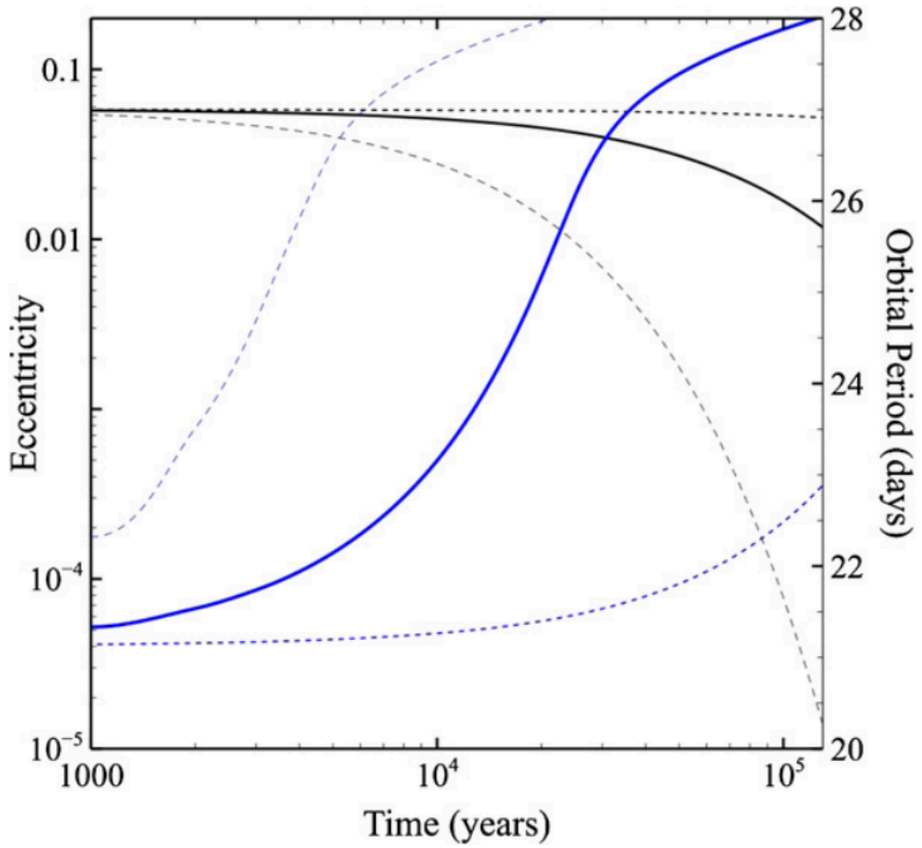


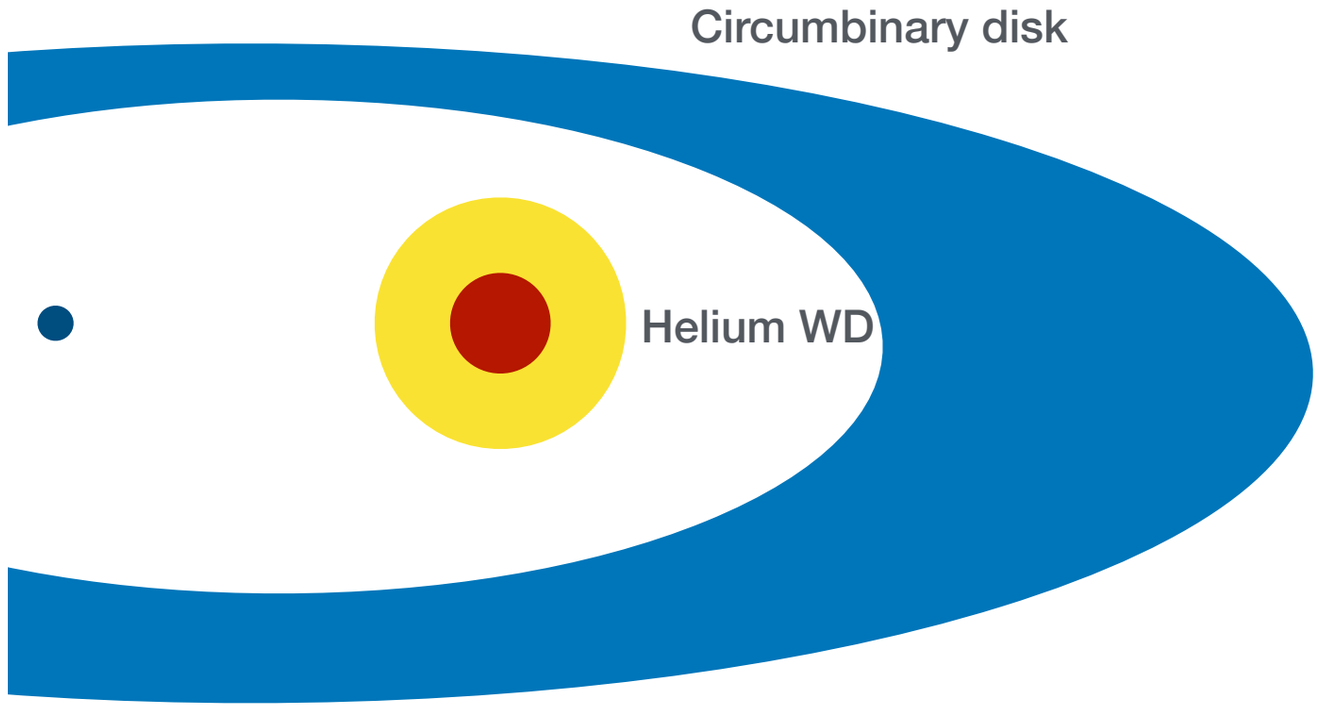


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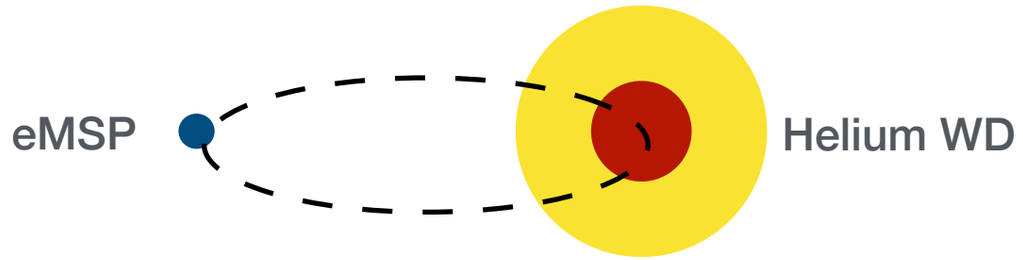


JA (2014), ApJ Letters, 7947 L24

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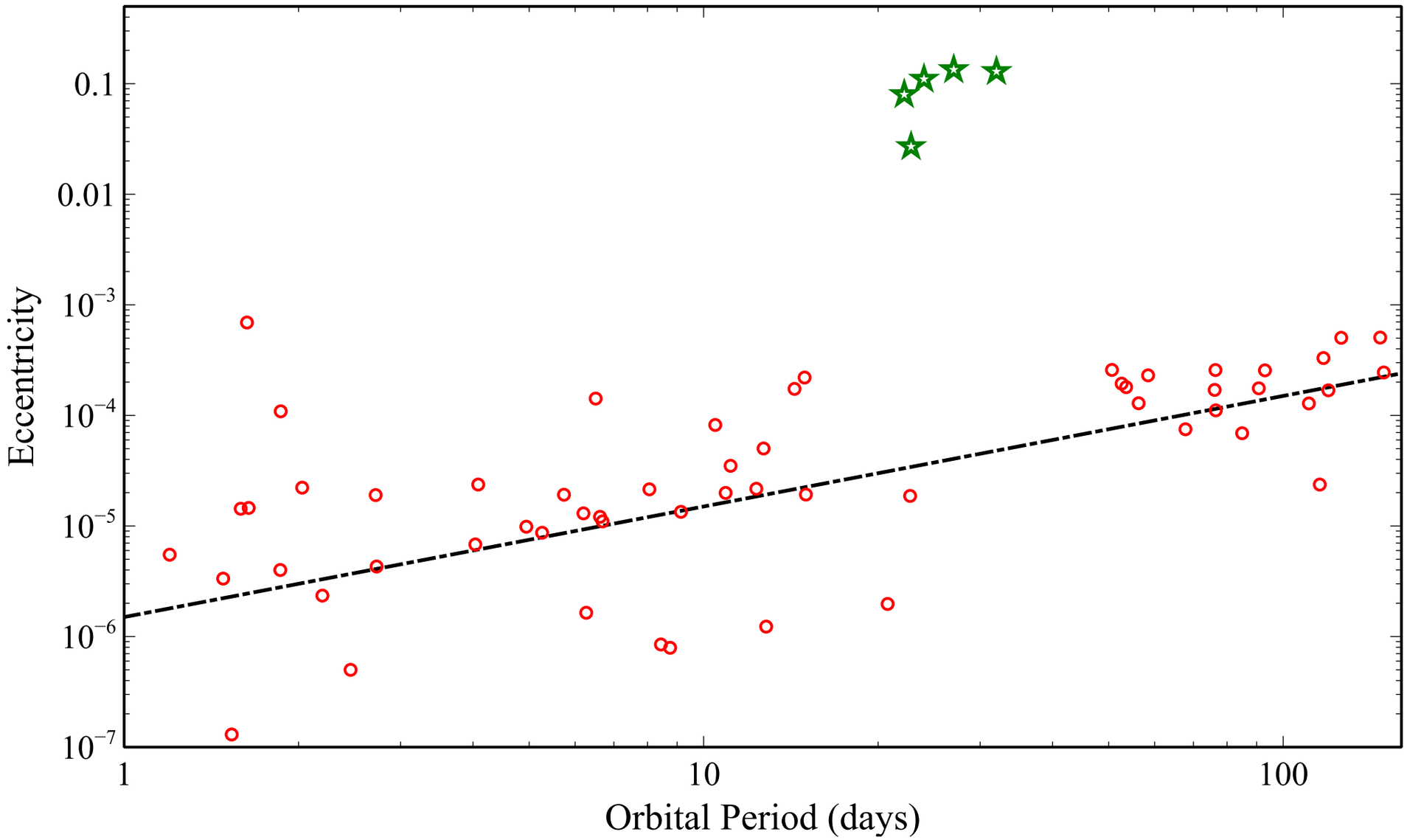

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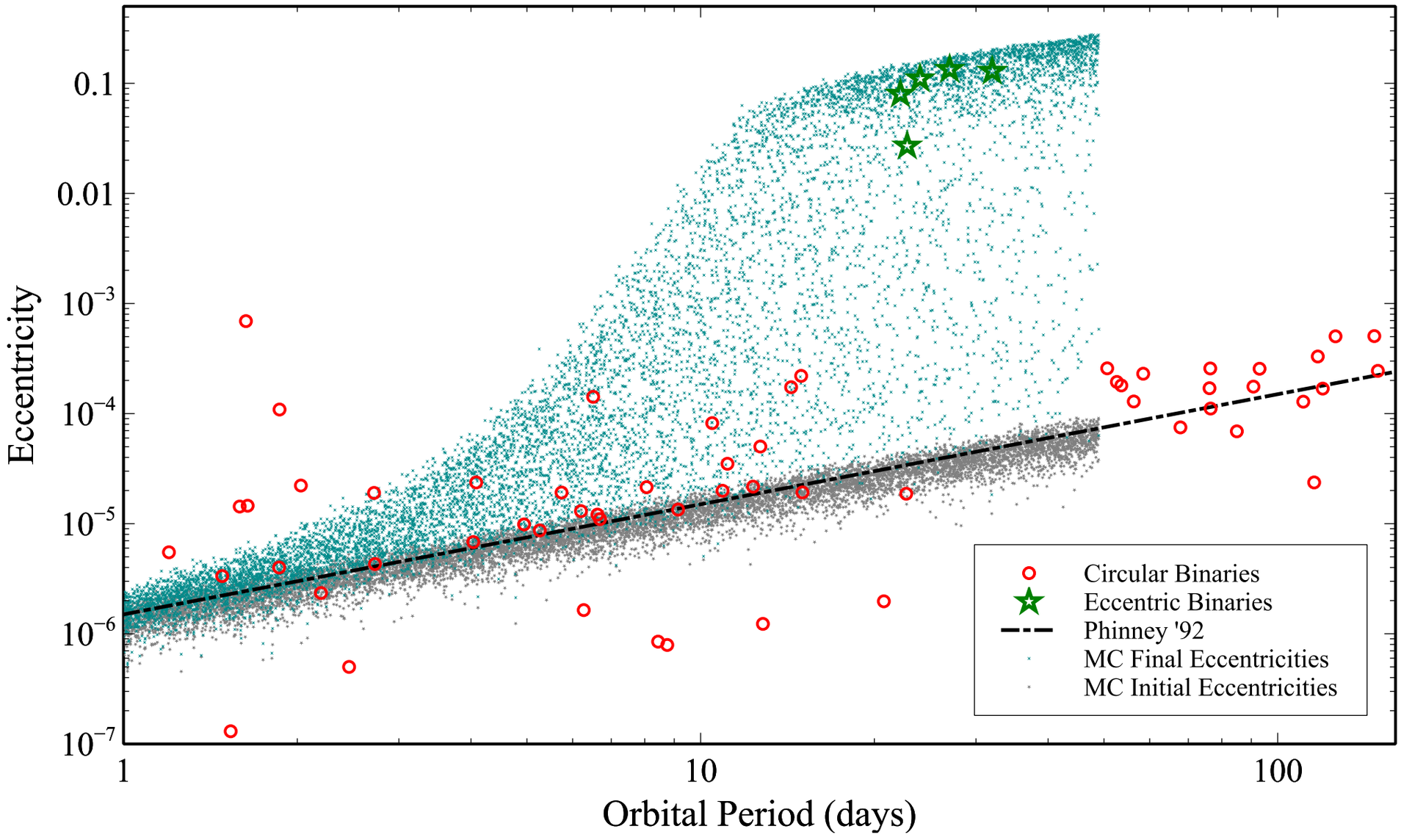
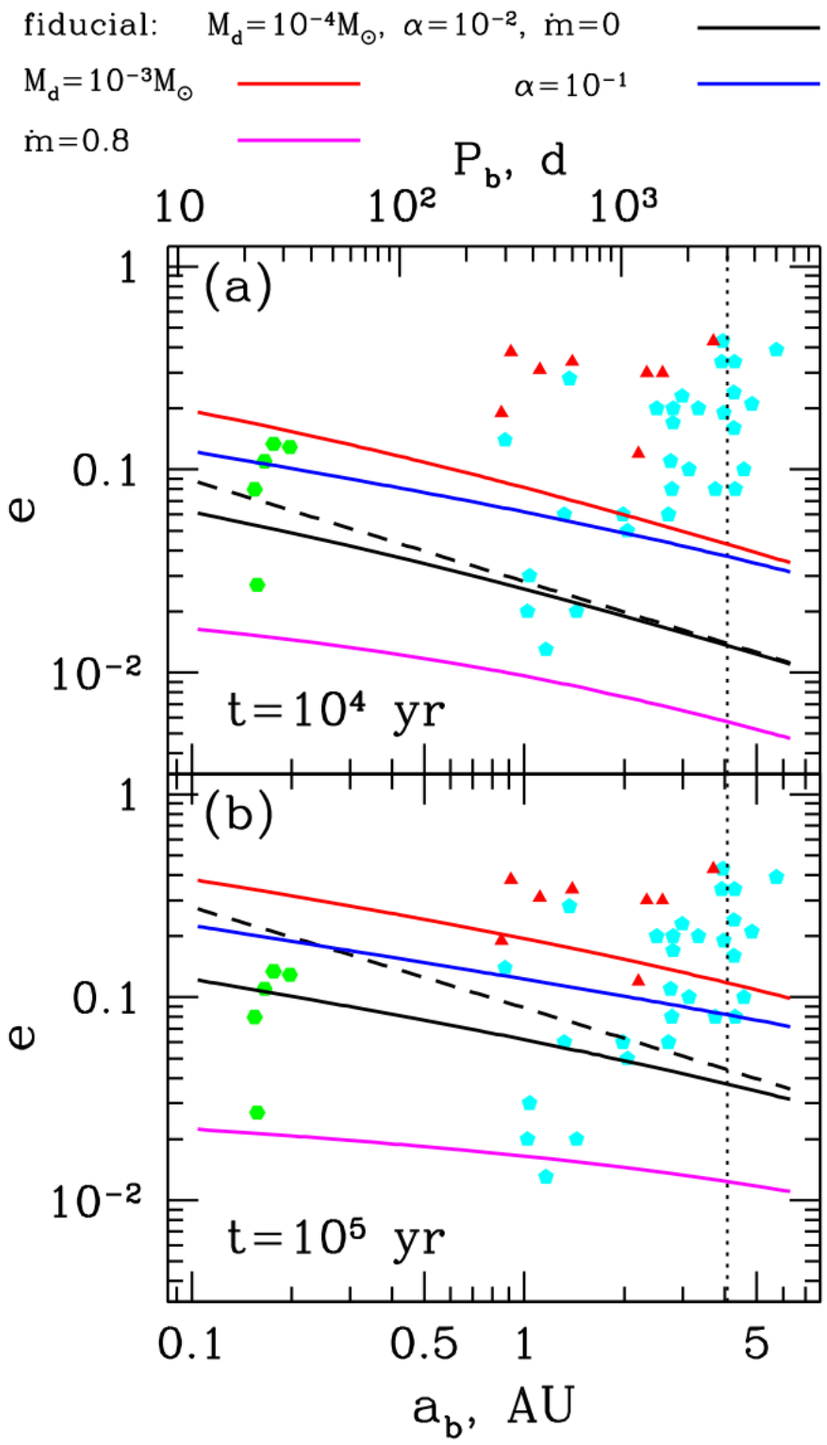


# Eccentric MSPs — What are they?




**eMSPs also descend from LMXBs**

**should obey Pb — Mwd relation**

**Similarities to post-AGBs**

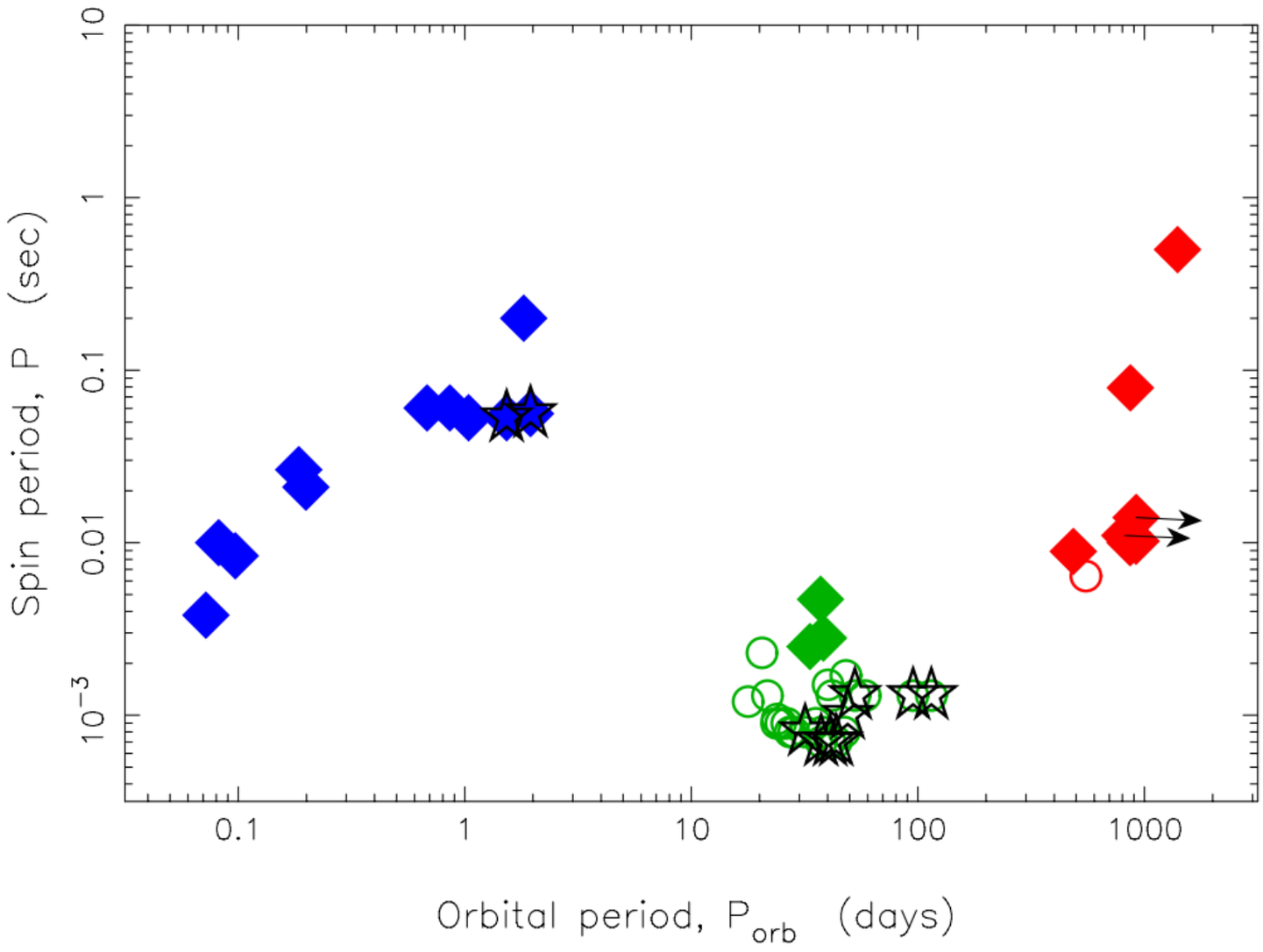
**Mechanism to suppress pumping at short periods**

**Re-accretion may be a problem**

Rafikov (2016a, b), ApJ

# Elusive formation channels

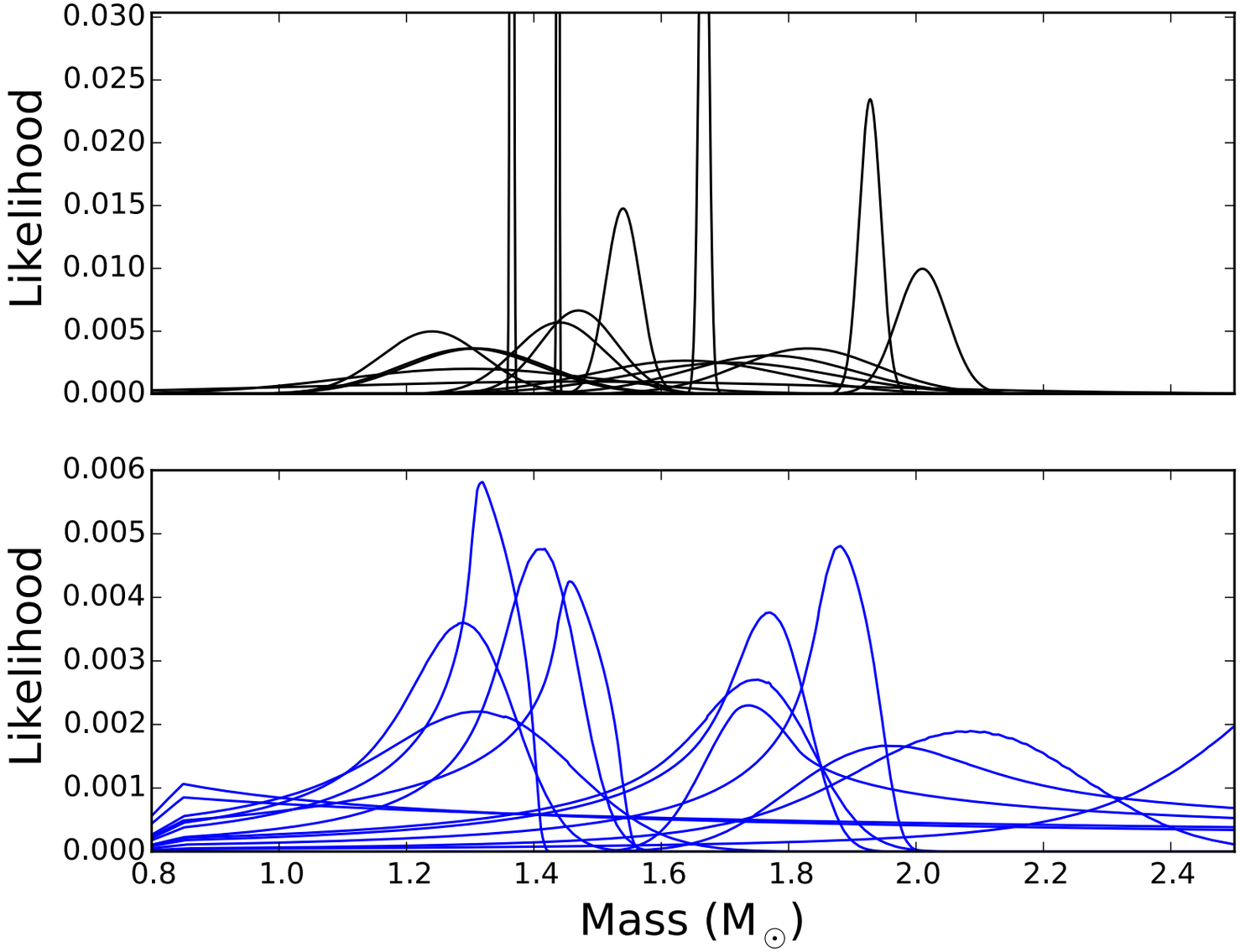
**MSPs can still form via AIC if the mass transfer rate is just right**



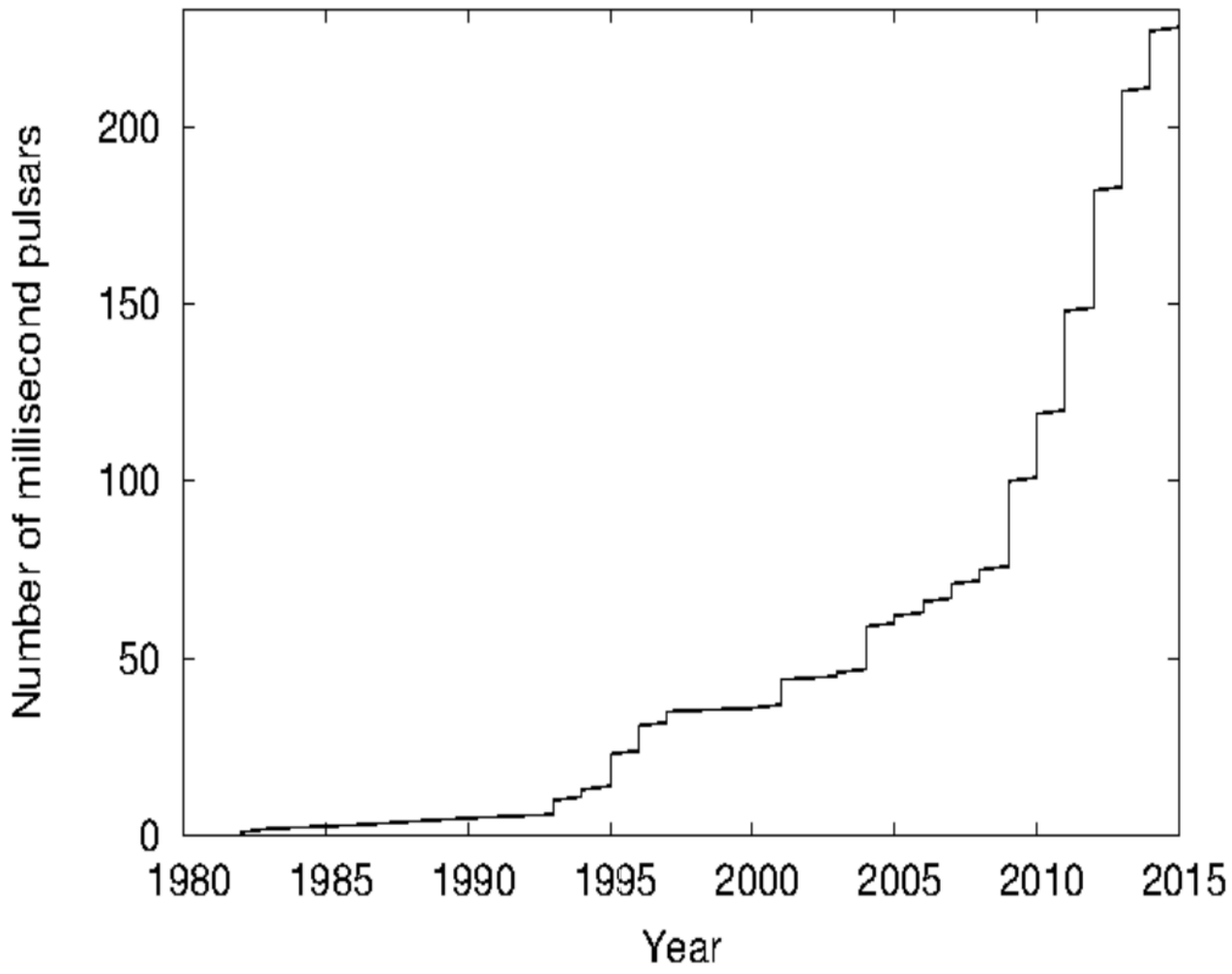

Tauris et al. 2013 Nomoto et al. 1979a

# Elusive formation channels

## AIC MSPs should show up as a distinct population in the MSP mass distribution

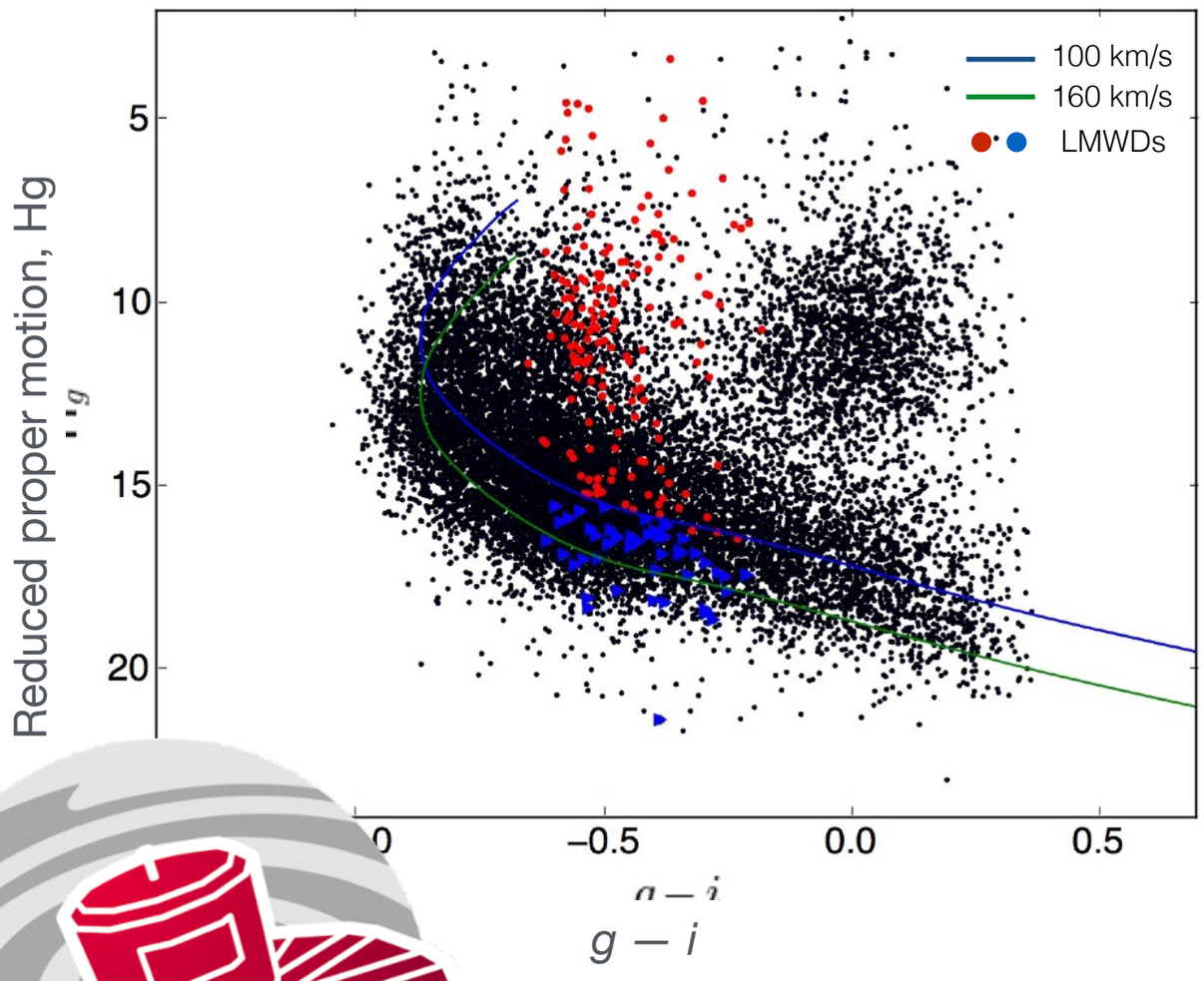


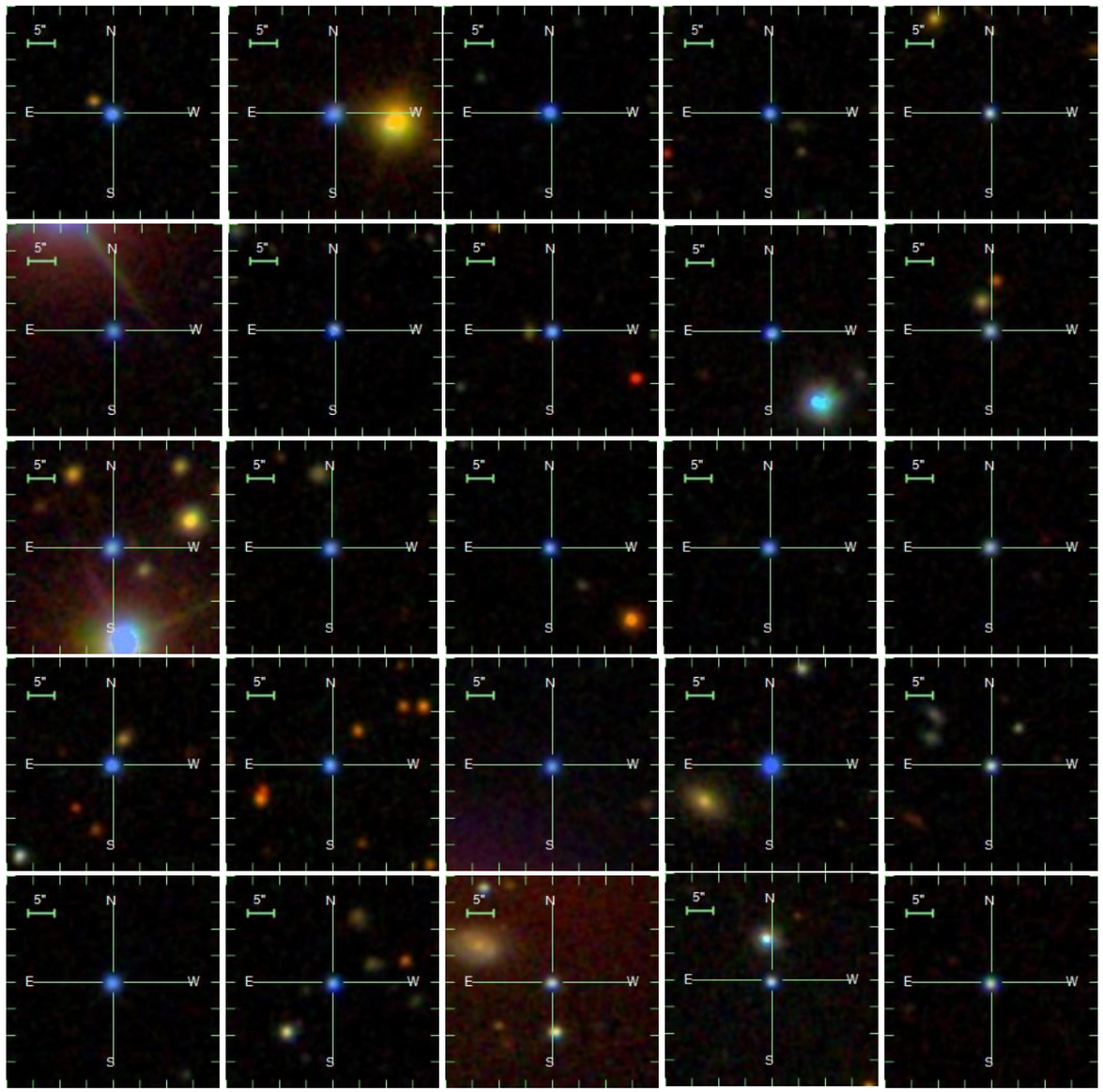
## Surveys with new instruments like the uGMRT, MeerKAT, FAST, SKA will increase the number of exotic systems



# The Future

- 20,000 GAIA low-mass white dwarfs with compact companions
- ~2000 WDs with high transverse velocities
- NSs receive kicks when born. **Hence much higher ratio of pulsars among fast moving binaries**



- Talk to Tilemachos Athanasiadis

# Unsolved mysteries — A look into the future

## Open questions that are probably more interesting than what I just covered

- Magnetic field decay
- Accretion efficiency during mass transfer
- Mass distribution, maximum mass and differences with non-recycled pulsars
- 3D velocities and kick distribution
- Formation of planets
- Isolated millisecond pulsars [30% of the population!]
- MSPs in dense environments (Galactic centre and its γ-ray excess/ GCs)
- MSPs + black holes
- Spin distribution, maximum spin, braking, propeller effect
- Radio-quiet millisecond pulsars
- Population statistics, LISA GW background and connection to double degenerates
- Transients related to binary MSPs [Accretion induced collapse to BH/Mergers?]