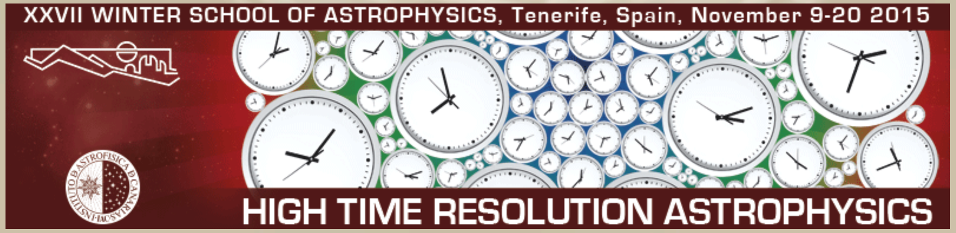
2.

Binary Pulsars and their evolution



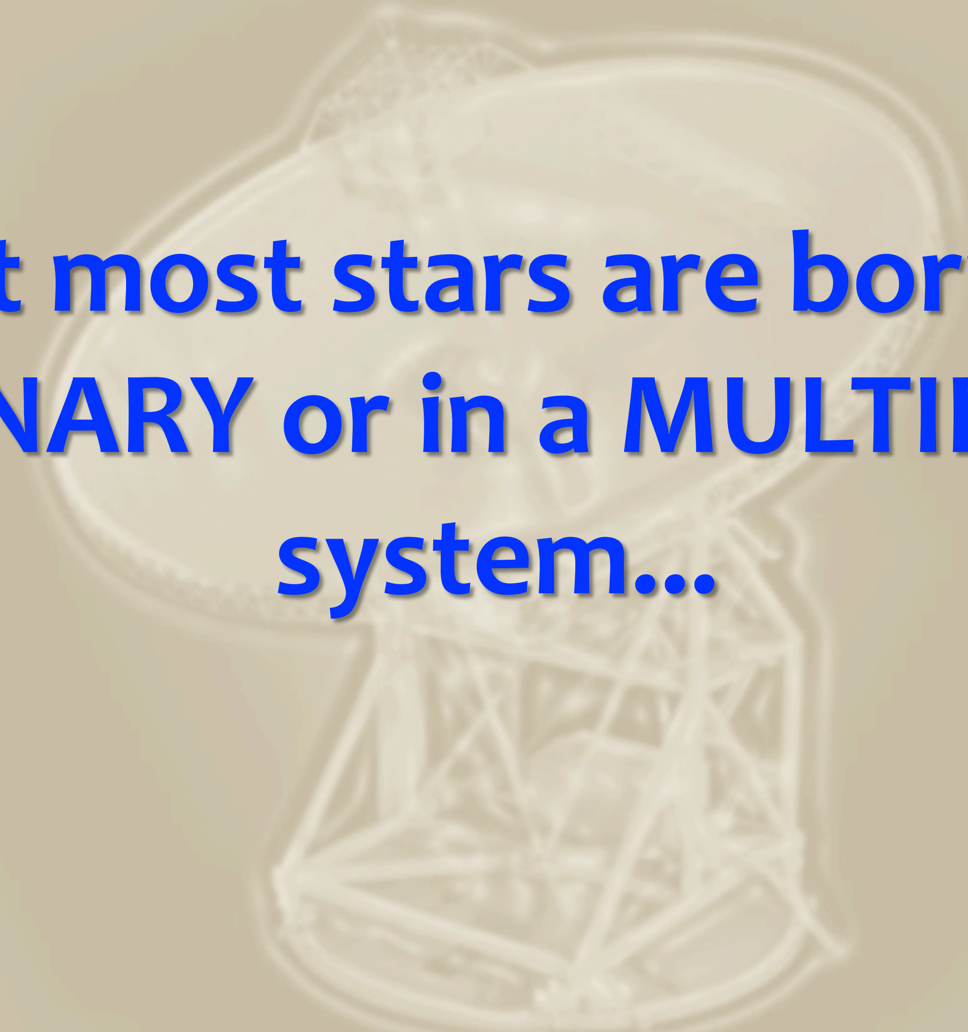
XXVII WINTER SCHOOL OF ASTROPHYSICS, Tenerife, Spain, November 9-20 2015

HIGH TIME RESOLUTION ASTROPHYSICS

Outcome of the evolution of a "Single" star

0.08 - 3	White Dwarf	Planetary Nebula
3 - 8	Disintegration (?)	Supernova
8 - 19	Neutron Star	Supernova
19 - 25	Neutron Star or Black Hole	Supernova
25 - 40	Black Hole	Supernova
40 - 120	Black Hole	Direct Collapse

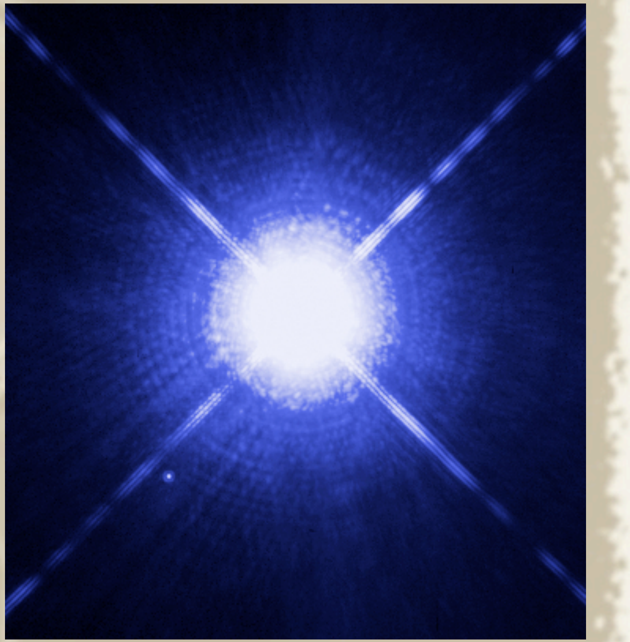
M/M_{sun}

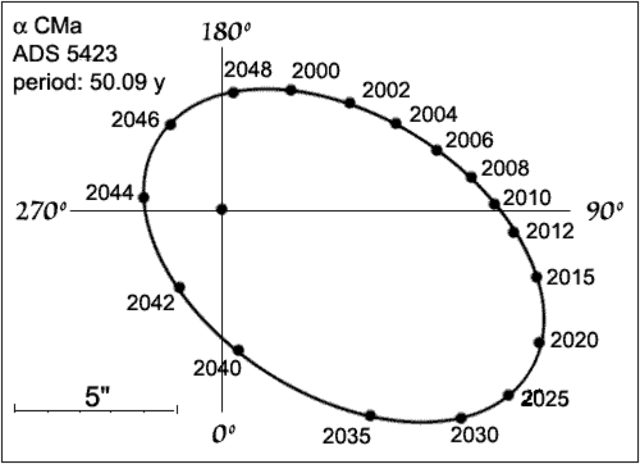


...but most stars are born in a BINARY or in a MULTIPLE system...

Ordinary Star + White Dwarf

Sirius : α Canis Maior

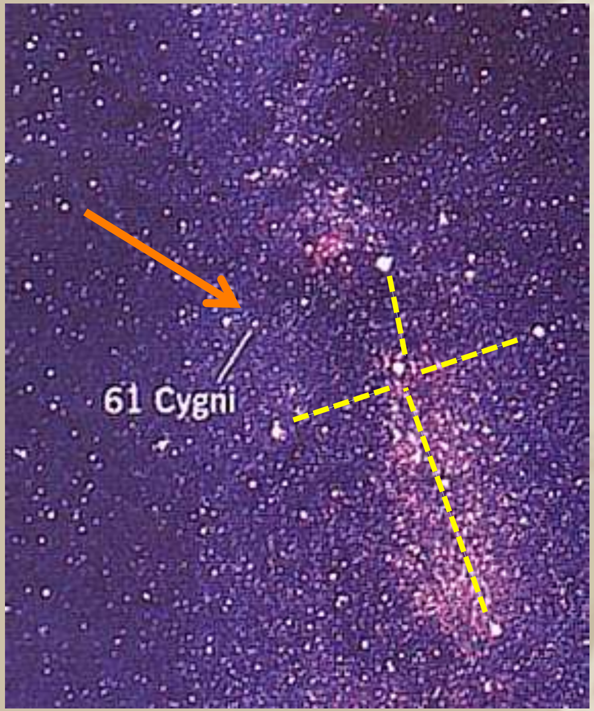




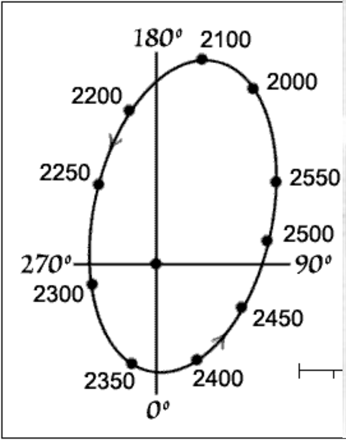
Located at about 9 a.l. with an orbital period of about 50 yrs

Ordinary Star + Ordinary Star:

The ”flying star” of Piazzi: 61 Cygni in Cygnus



Located at about 11.4 a.l. with orbital period of about 680 years

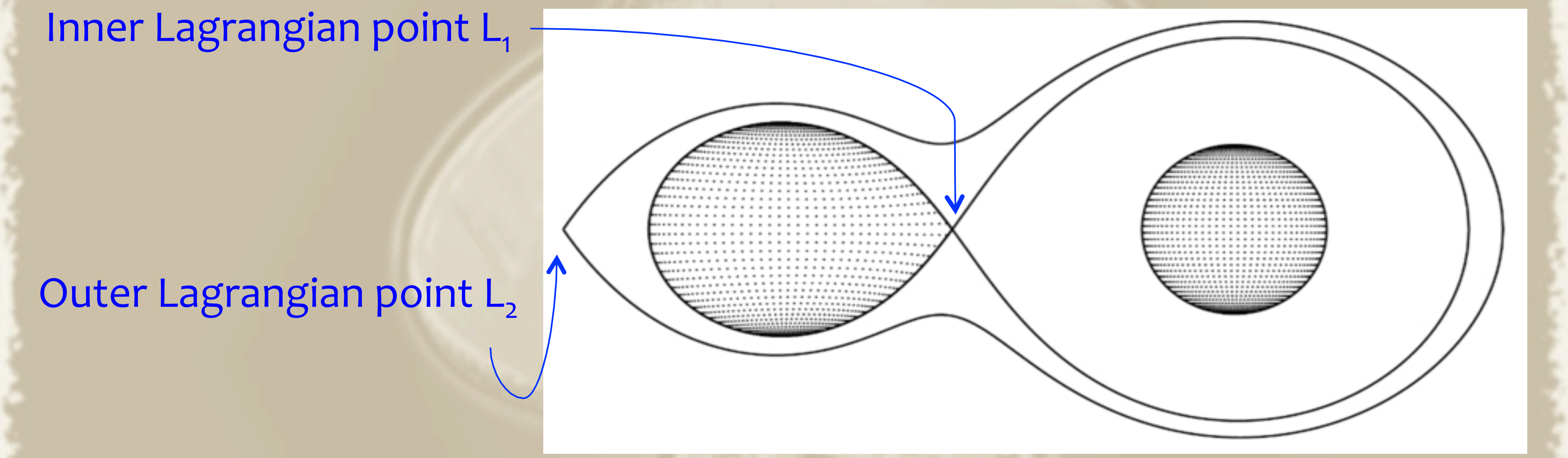


In most cases, the life in a couple strongly modify the evolution of the single stars as a consequence of mass exchange

In this way, the involved stars can have features at variance with those of the stars evolving in isolation and pathways are available to produce exotic stars and binary systems

Some general concepts

Roche lobe geometry



In a fully conservative system:

redistribution of mass closer to the centre of mass → **orbit widens**

redistribution of mass farther from the centre of mass → **orbit shrinks**

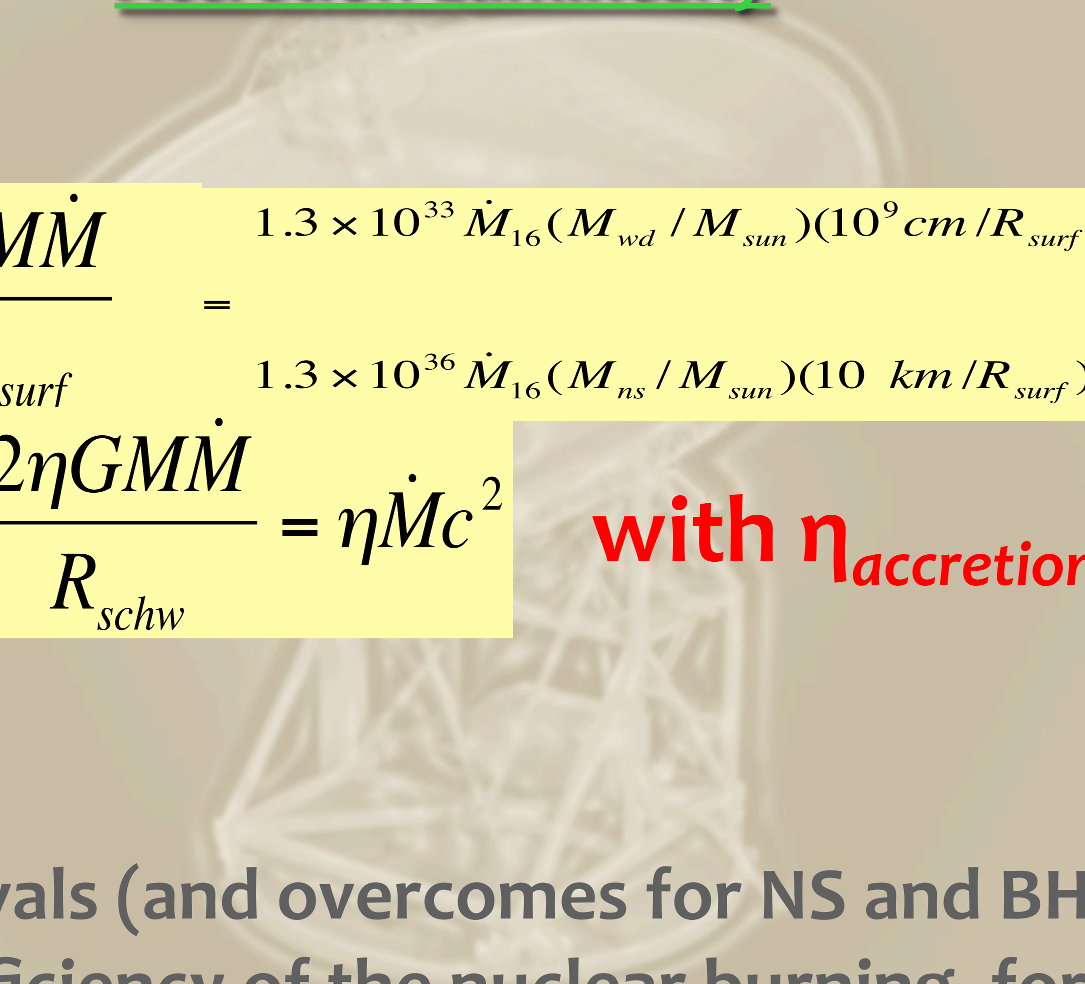
However there are at least two additional mechanisms for close orbits:

magnetic braking → **orbit shrinks**

gravitational waves quadrupole emission → **orbit shrinks**

Some general concepts

Accretion Luminosity



$$L_{accretion} = \frac{GM\dot{M}}{R_{surf}} = \begin{matrix} 1.3\times 10^{33}\,\dot{M}_{16}(M_{wd}/M_{sun})(10^{9}\,cm/R_{surf})\,erg/s \\ \\ 1.3\times 10^{36}\,\dot{M}_{16}(M_{ns}/M_{sun})(10\ \ km/R_{surf})\,erg/s \end{matrix}$$

$$L^{BH}{}_{accretion} = \frac{2\eta GM\dot{M}}{R_{schw}} = \eta\dot{M}c^{2}$$

with $\eta_{accretion} \approx 0.1$

That rivals (and overcomes for NS and BH) the efficiency of the nuclear burning, for which $\eta_{nuclear} \approx 0.007$

Some general concepts

Accretion Luminosity

1) Steady accretion
2) Spherical symmetric accretion

$$\left[(GMm_p - L_{accretion}\,\sigma_T/(4\pi c))\right]\frac{1}{r^2}$$

$$L_{Edd} = 4\pi GcMm_p/\sigma_{Th} = 1.3\times 10^{38}\left[\frac{M}{M_{sun}}\right]erg/s$$

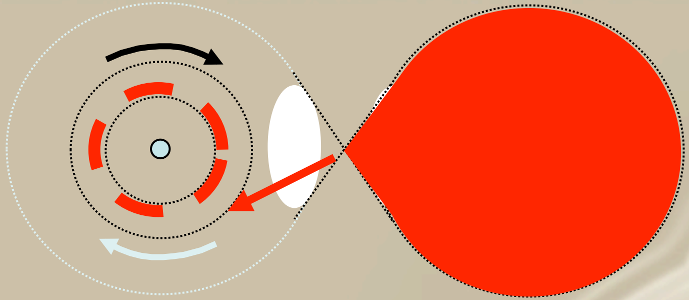
Accretion spectrum

$$h\nu_{bb} \approx k_B T_{bb} = k_B\left(\frac{L_{accretion}}{4\pi\sigma_{SB}R_{surf}^2}\right)^{0.25}$$

$$h\nu_{th} \approx k_B T_{th} = k_B\left(\frac{GMm_p}{3k_B R_{surf}}\right)$$

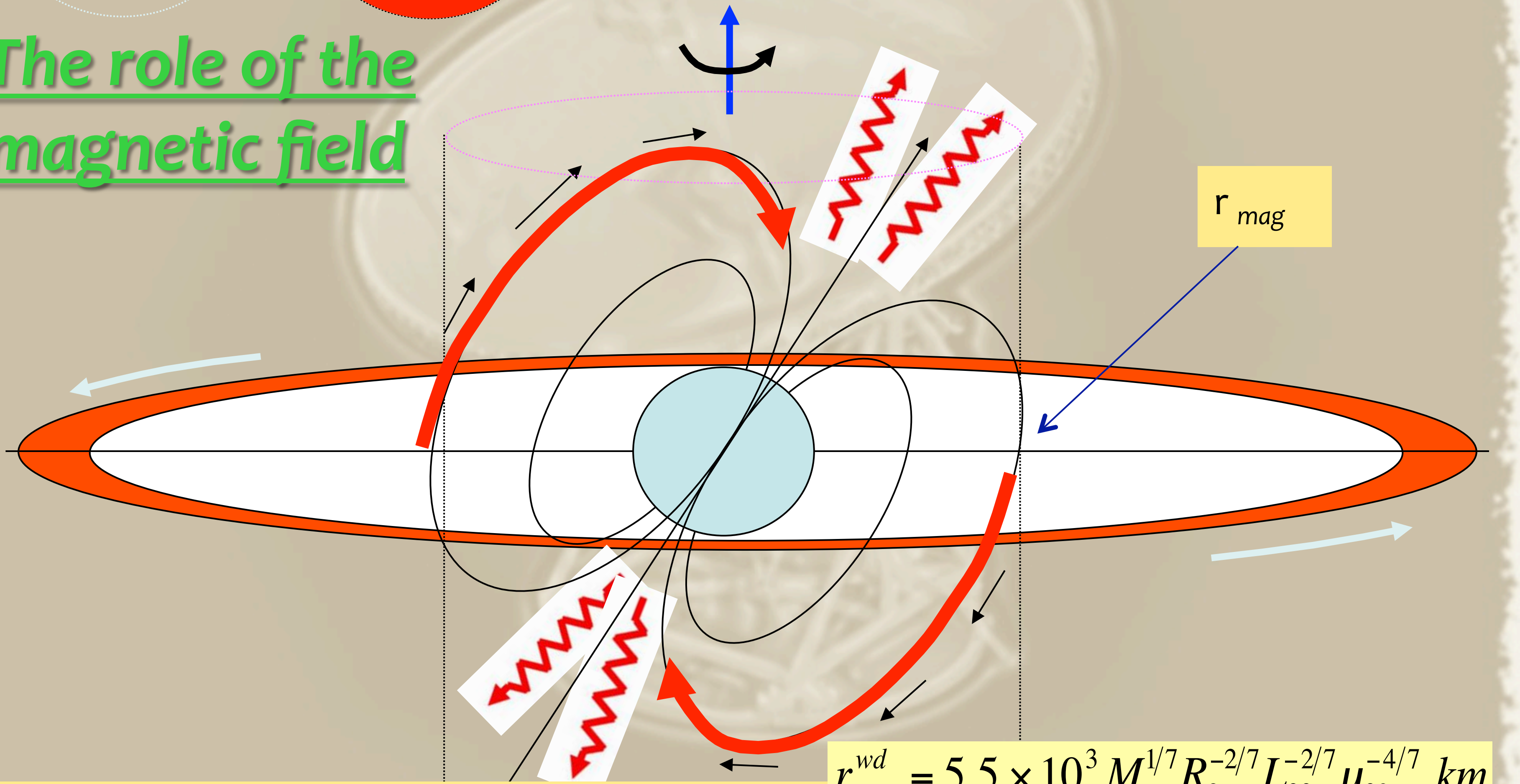
$$1\ keV \le h\bar{\nu}_{ns} \le 50\ MeV$$

$$6\ eV \le h\bar{\nu}_{wd} \le 10\ keV$$



In order for the matter to get rid of part of its angular momentum and then approach the compact star, an accretion disk must form

The role of the magnetic field



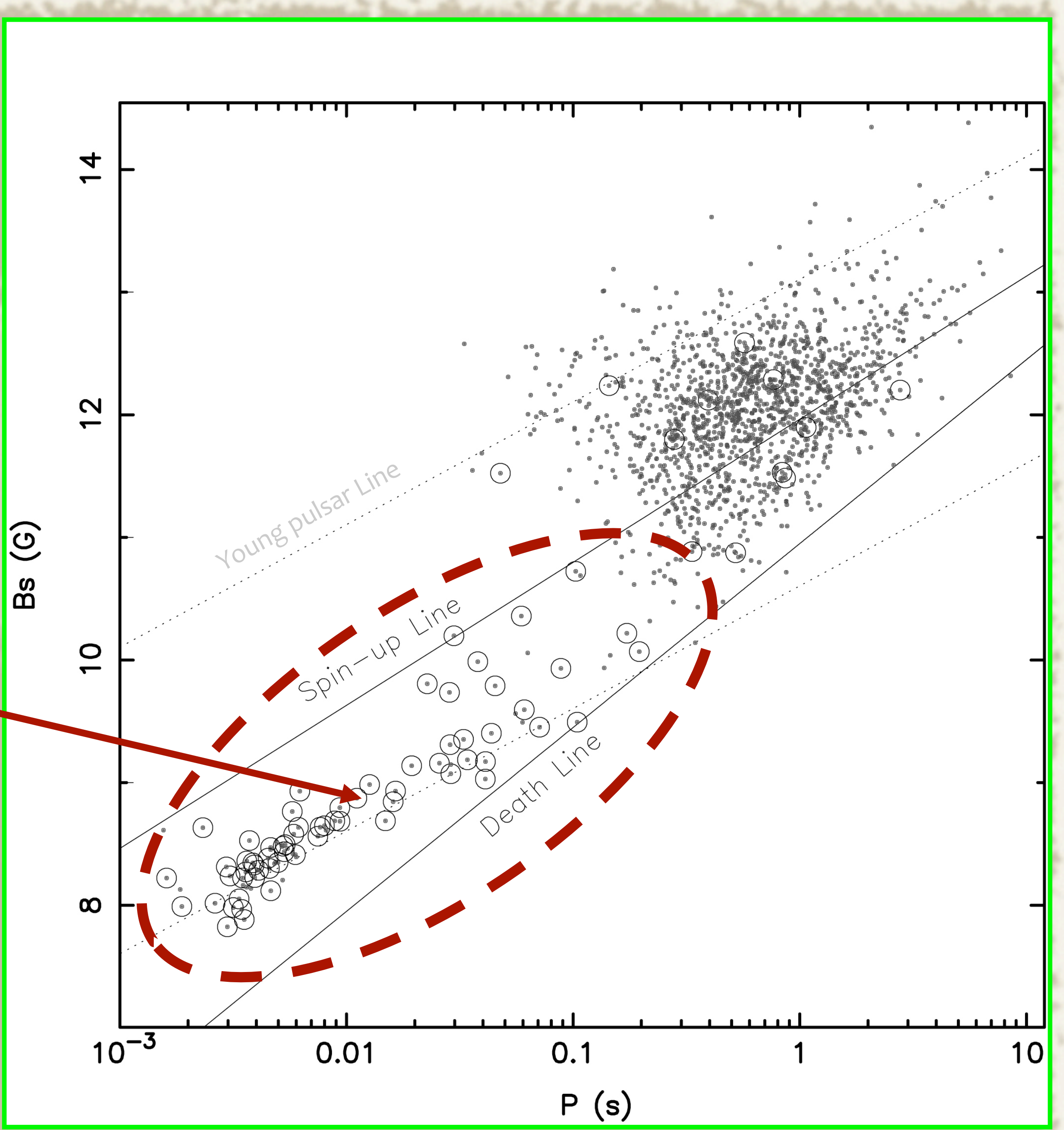
The B-field starts dominating at r_{mag}

$$r_{mag}^{wd} = 5.5 \times 10^{3}\, M^{1/7} R_{9}^{-2/7} L_{33}^{-2/7} \mu_{30}^{-4/7}\ km$$

$$r_{mag}^{ns} = 2.9 \times 10^{3}\, M^{1/7} R_{6}^{-2/7} L_{37}^{-2/7} \mu_{30}^{-4/7}\ km$$

A dichotomy in the population

How to explain this group of pulsars ?



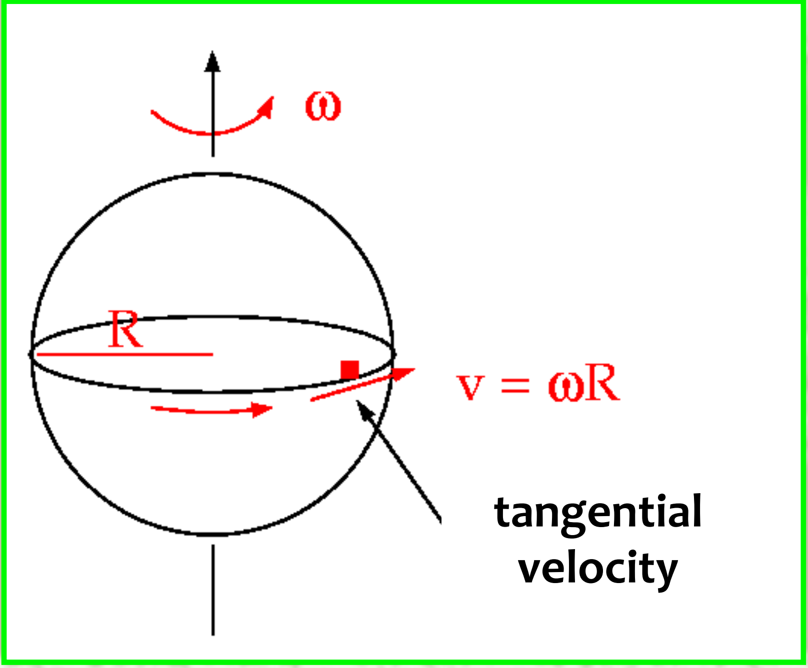
ATNF Pulsar Catalogue

Discovery of the first millisecond pulsar
B1937+21 (1982)

[Backer et al. 1982]

P = 1.557 ms

V_{tang} = 0.13 C !!

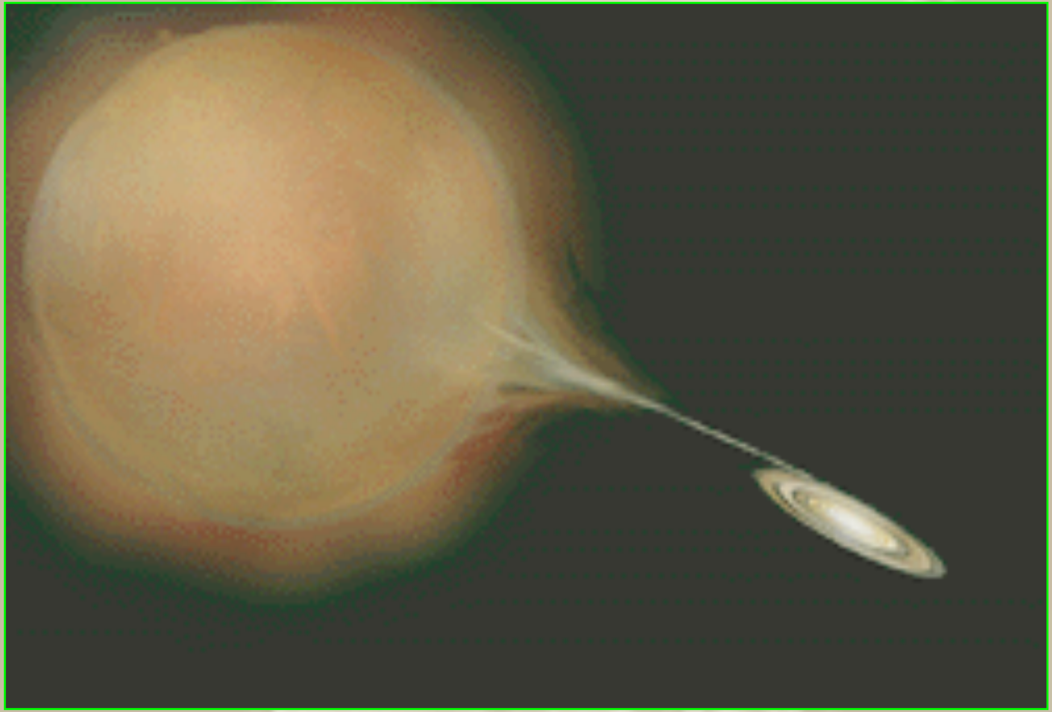


tangential velocity

Extreme physical conditions occur in millisecond pulsars

First promise of putting constraints to the Equation of State for nuclear matter !

The formation paradigm: the recycling scenario



Recycled pulsars are old neutron stars spun up by accretion of matter and angular momentum from a companion star in a multiple system [Bisnovati-Kogan & Kornberg 1974, Alpar et al. 1982]

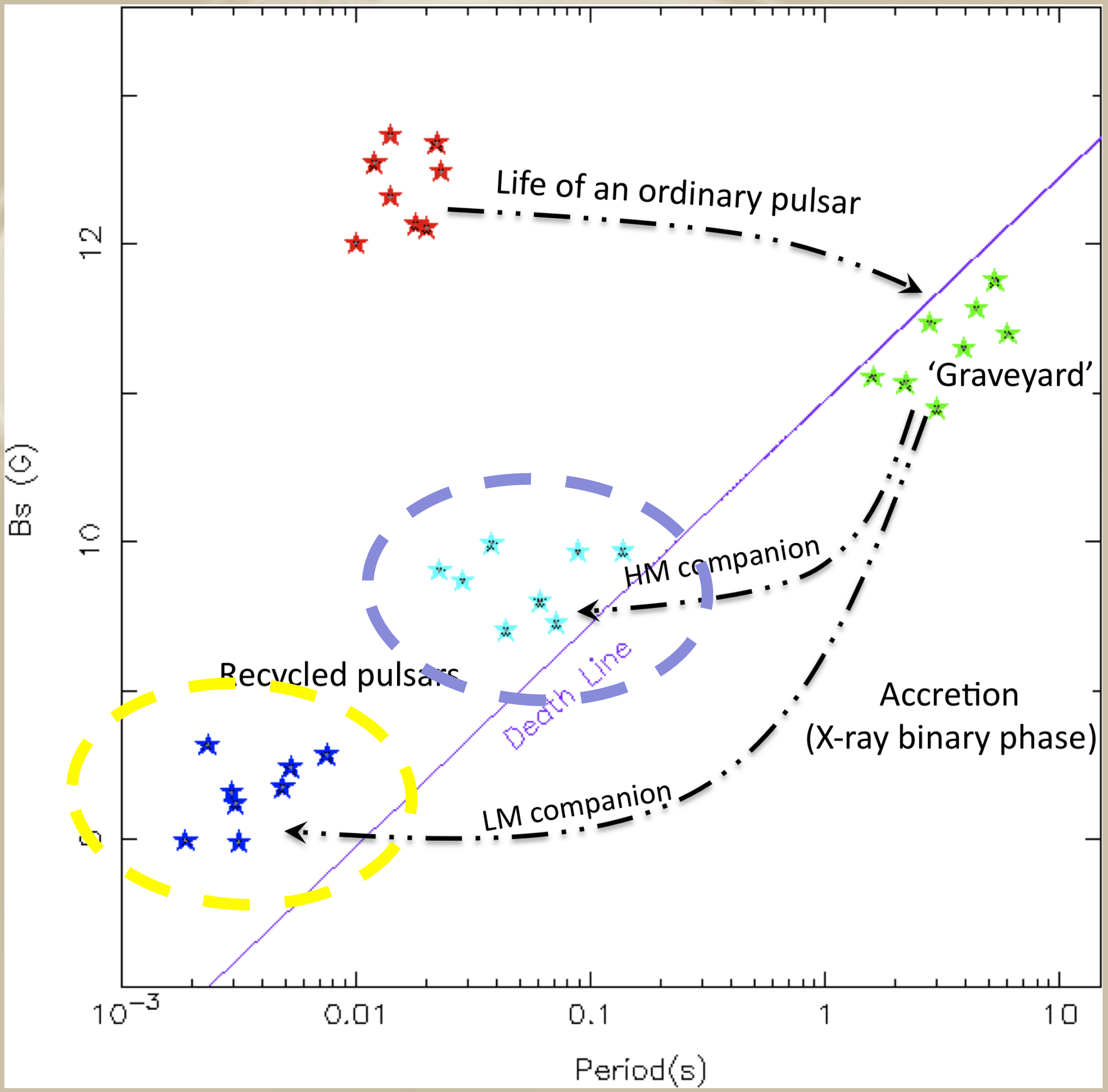
Recycled pulsars: which evolution originates which?

Mildly recycled pulsars:

e.g. double neutron stars via NS-HMXB stage

Fully recycled pulsars:

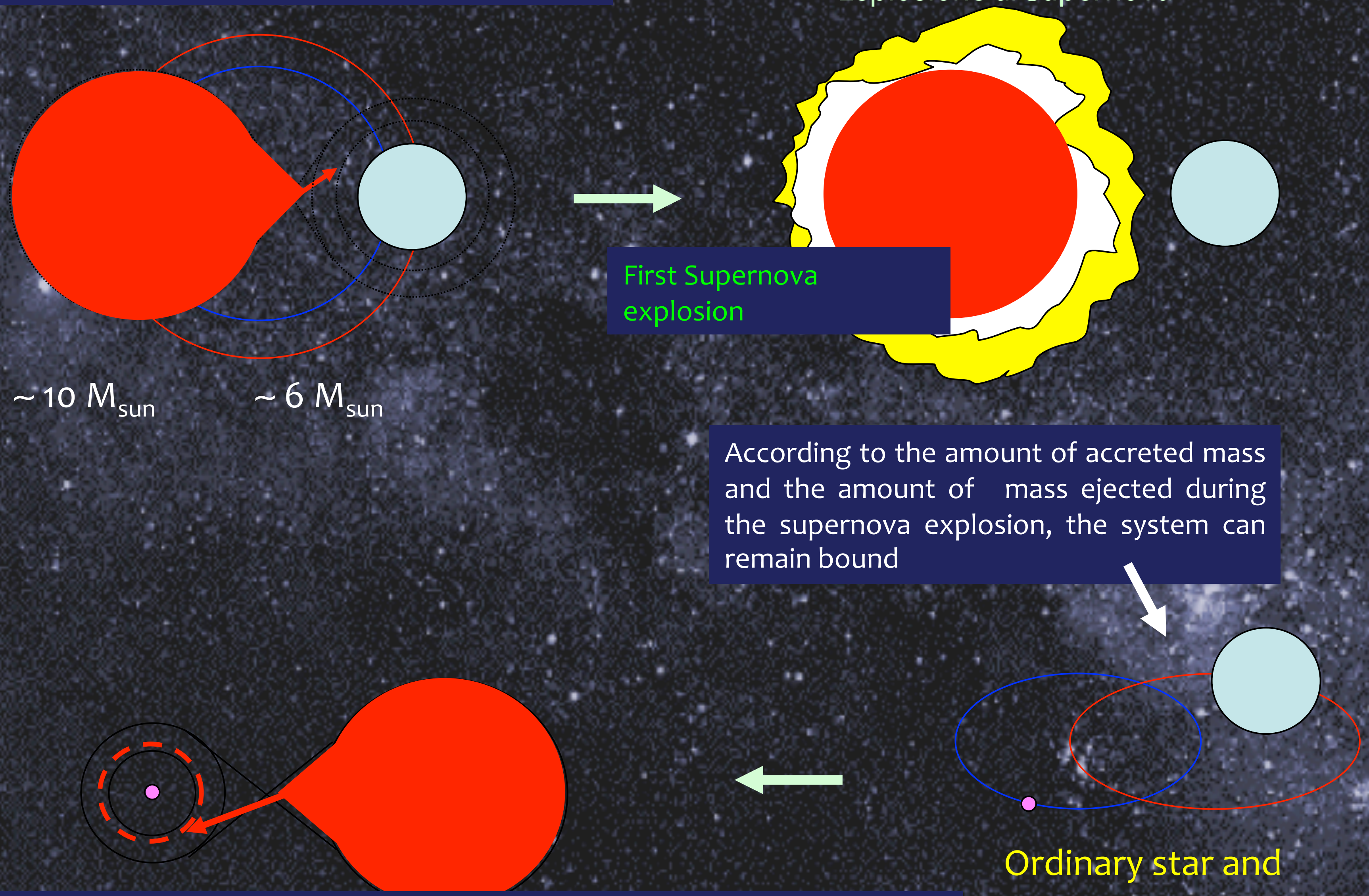
in most cases millisecond pulsars **+ White Dwarfs via NS-LMXB stage**



[@ Burgay 2011]

Evolution of 2 initially massive stars: stage I

The most massive star evolves first and could transfer mass to the companion star



First Supernova explosion

According to the amount of accreted mass and the amount of mass ejected during the supernova explosion, the system can remain bound

Ordinary star and Neutron star in an eccentric orbit

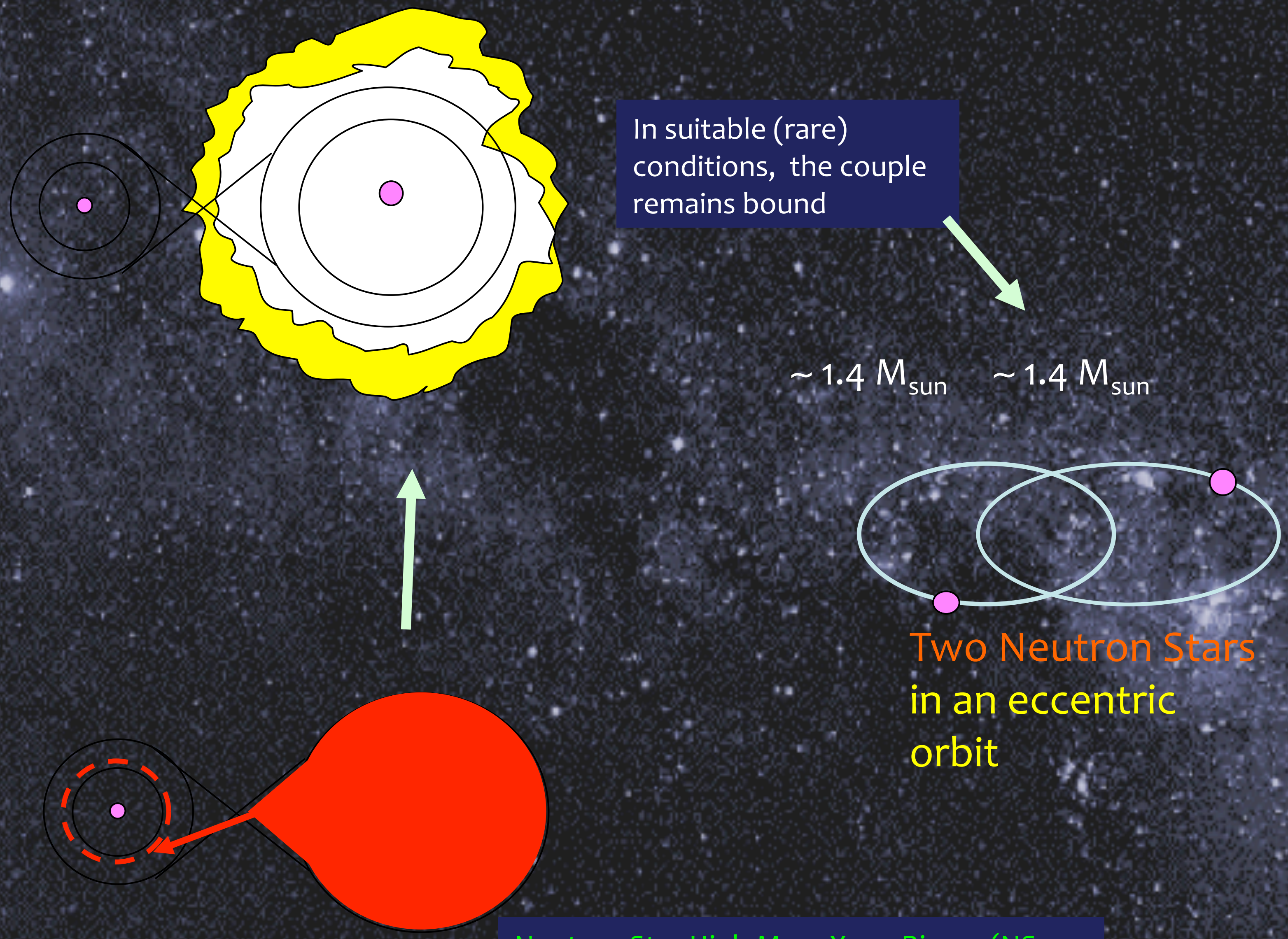
Rapid evolutionary timescale of the Donor star : small ri-acceleration of the Neutron star: Neutron Star High Mass X-ray Binary (NS-HMXB) stage

Neutron star + Supergiant star

Centaurus X-3 in Centaurus

At about 18000 a.l.: X-ray binary with an orbital period of about 2 days

Evolution of 2 initially massive stars: stage II



Second supernova explosion

In suitable (rare) conditions, the couple remains bound

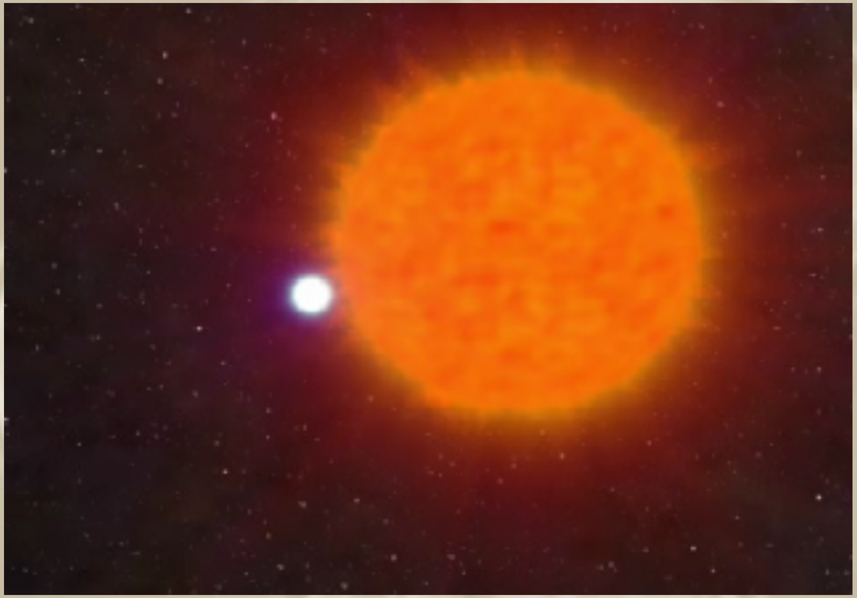
~ 1.4 M_{sun} ~ 1.4 M_{sun}

Two Neutron Stars in an eccentric orbit

Neutron Star High Mass X-ray Binary (NS-HMXB) stage

Neutron star + Neutron star:

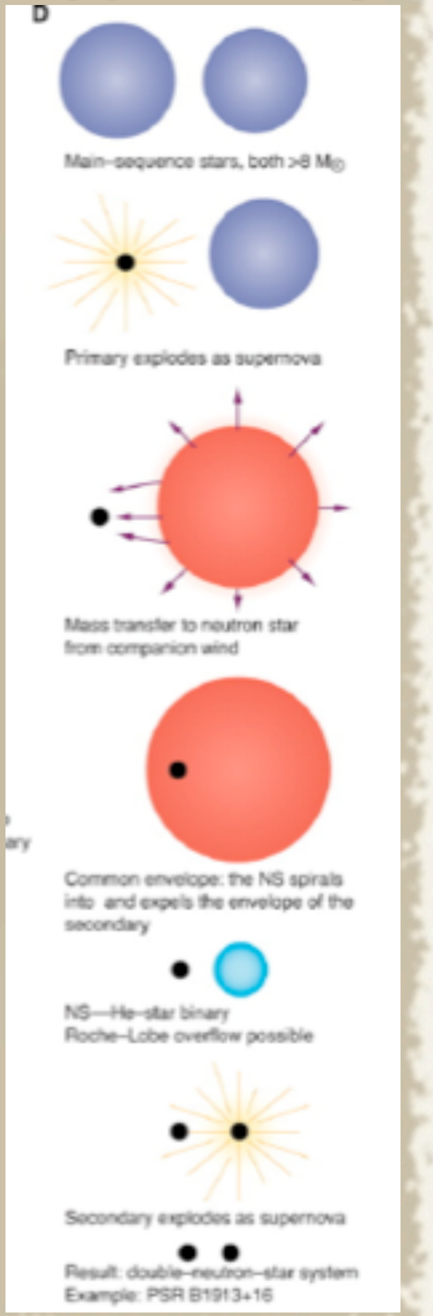
J0737-3039A/B (the Double Pulsar)



© Howe at ATNF

At about 2000 a.l.: two neutron stars orbiting each other in about 2.5 hours

[@ Stairs 2004]

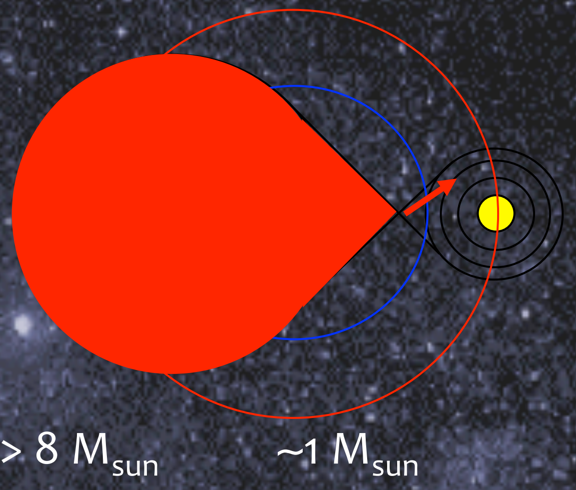


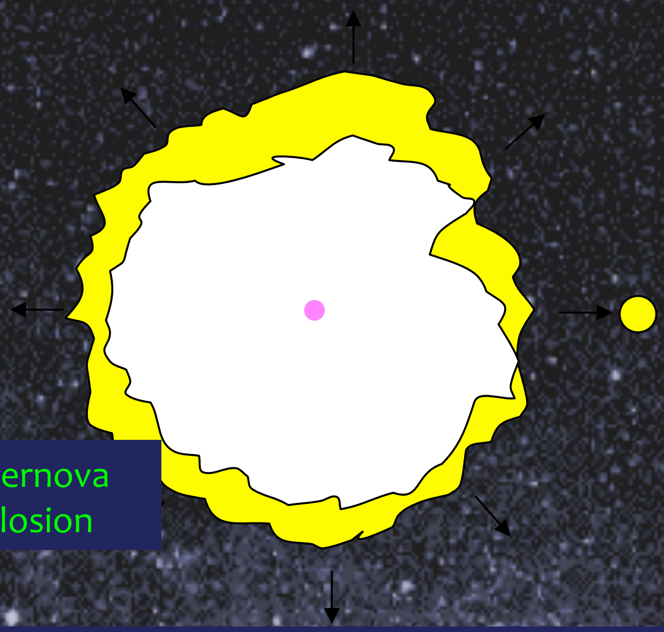
- van den Heuvel & DeLoore 1975
- Piran & Shaviv 2005
- Podsiadlowski et al 2005
- Willems et al 2005
- van den Heuvel
- Willems et al 2006
- Stairs 2006
- Dewi 201
- ven den Heuvel 2010
- Oslowski et al 2011
- Farr et al 2011
- Belczynski et al 2010, 2011, 2012

\+ ...

Evolution of a massive and a light star

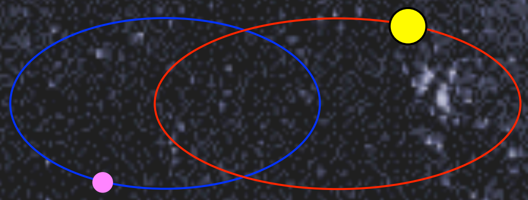
The most massive star evolves first and could transfer mass to the companion star



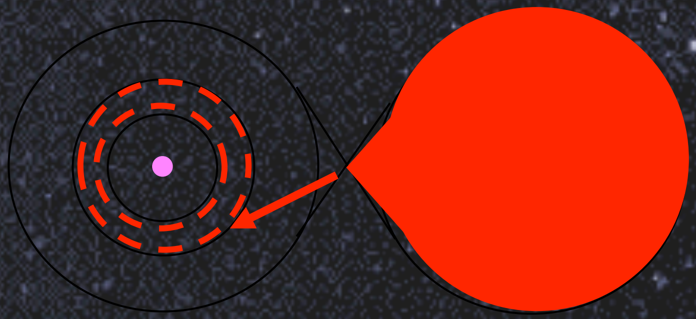


In a supernova explosion, the system can remain bound if the ejected mass < ½ M_{tot}. This is possible if there was enough accretion onto the secondary.

Otherwise, the binary is preserved by the occurrence of a suitably directed "kick" imparted to the new born neutron star in the supernova explosion

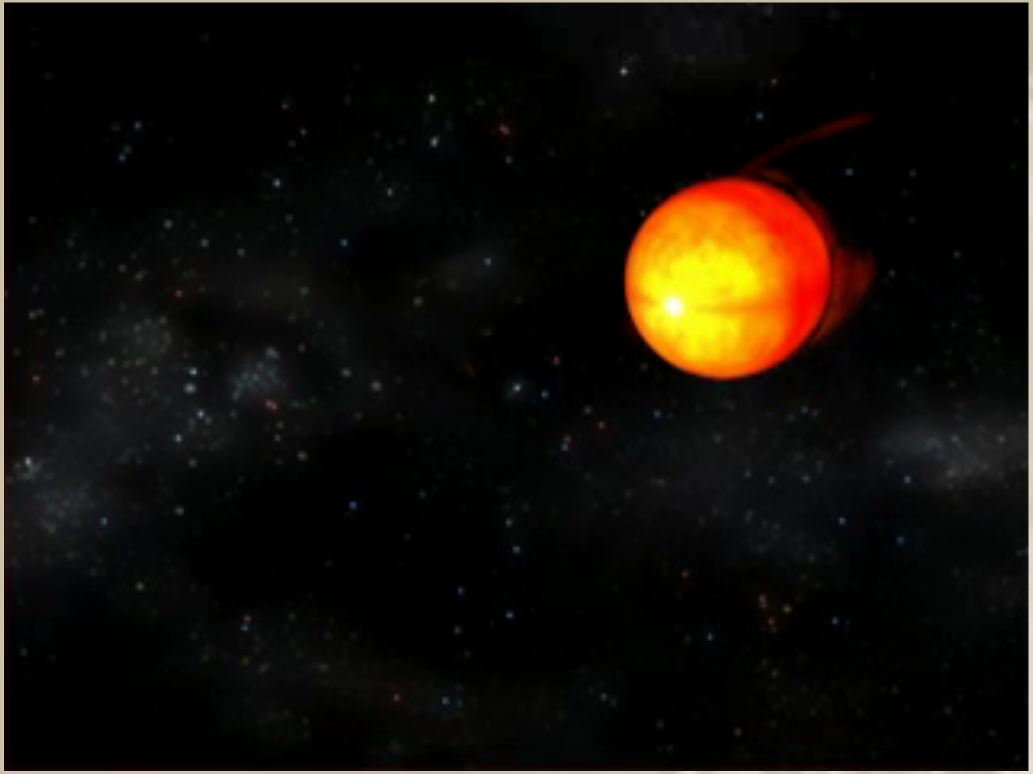


Ordinary relatively light star and a Neutron star in an eccentric orbit

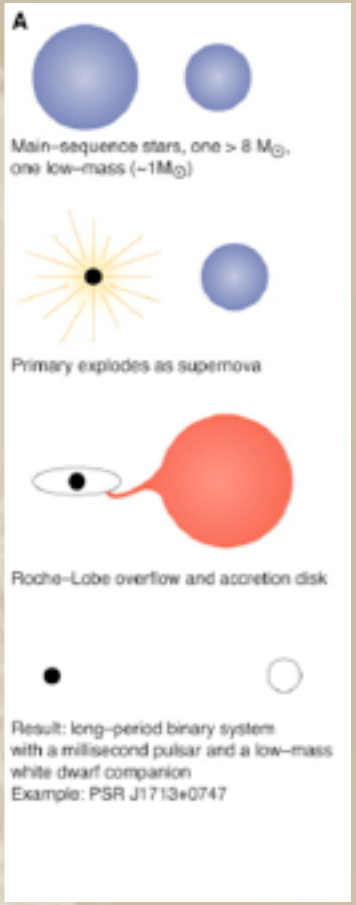


Long lasting evolutionary timescale of the Donor star : strong ri-acceleration of the Neutron star reaching Millisecond spin period: Neutron Star Low-Mass X-ray Binary (NS-LMXB) stage

Dana Berry @ NASA



[@ Stairs 2004]



Main–sequence stars, one > 8 $M_\odot$, one low–mass (~1$M_\odot$)

Primary explodes as supernova

Roche–Lobe overflow and accretion disk

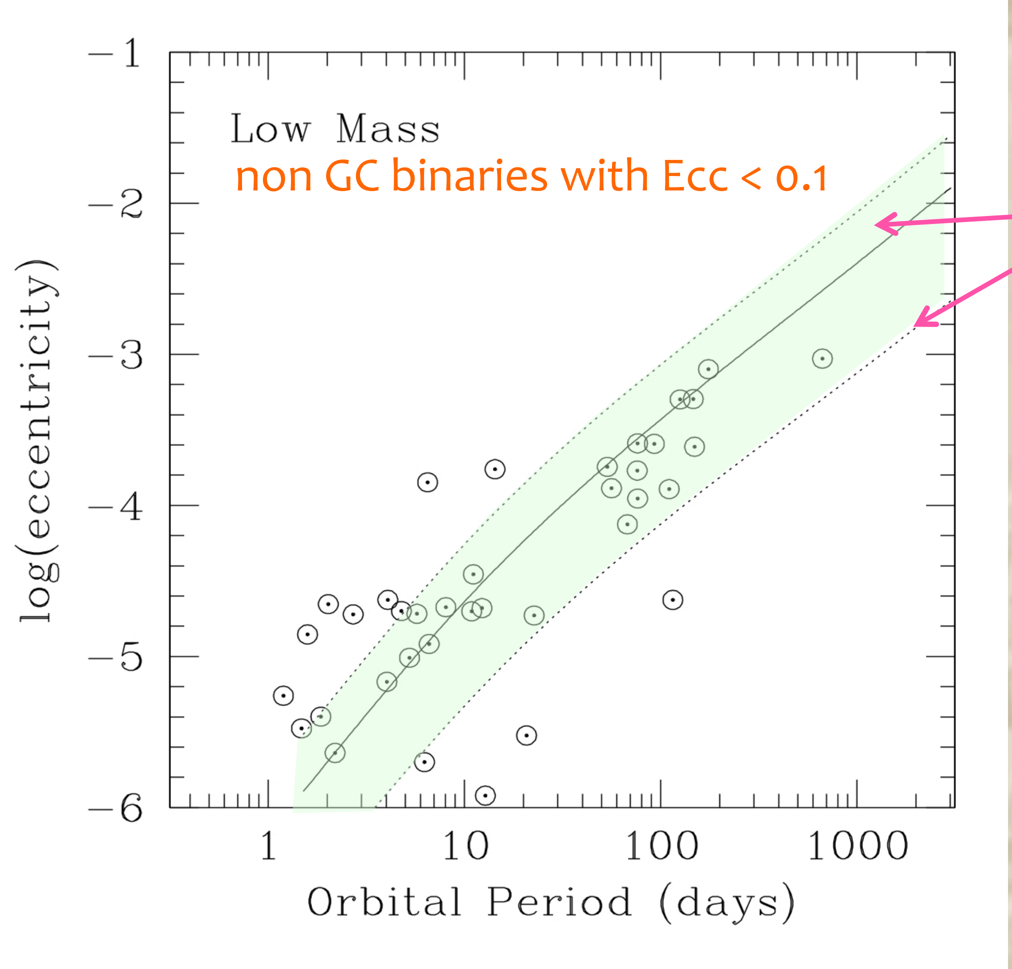
Result: long–period binary system with a millisecond pulsar and a low–mass white dwarf companion
Example: PSR J1713+0747

X-ray Accreting Millisecond Pulsar (AXMSP)

Rotation Powered Radio Millisecond Pulsar (MSP)

A system unambiguously linking Accreting X-ray millisecond pulsars and Radio millisecond pulsars was unsuccessfully sought for 3 decades...

Thus, other tests were proposed to support the recycling model for radio MSP



[Phinney & Kulkarni, 1994]

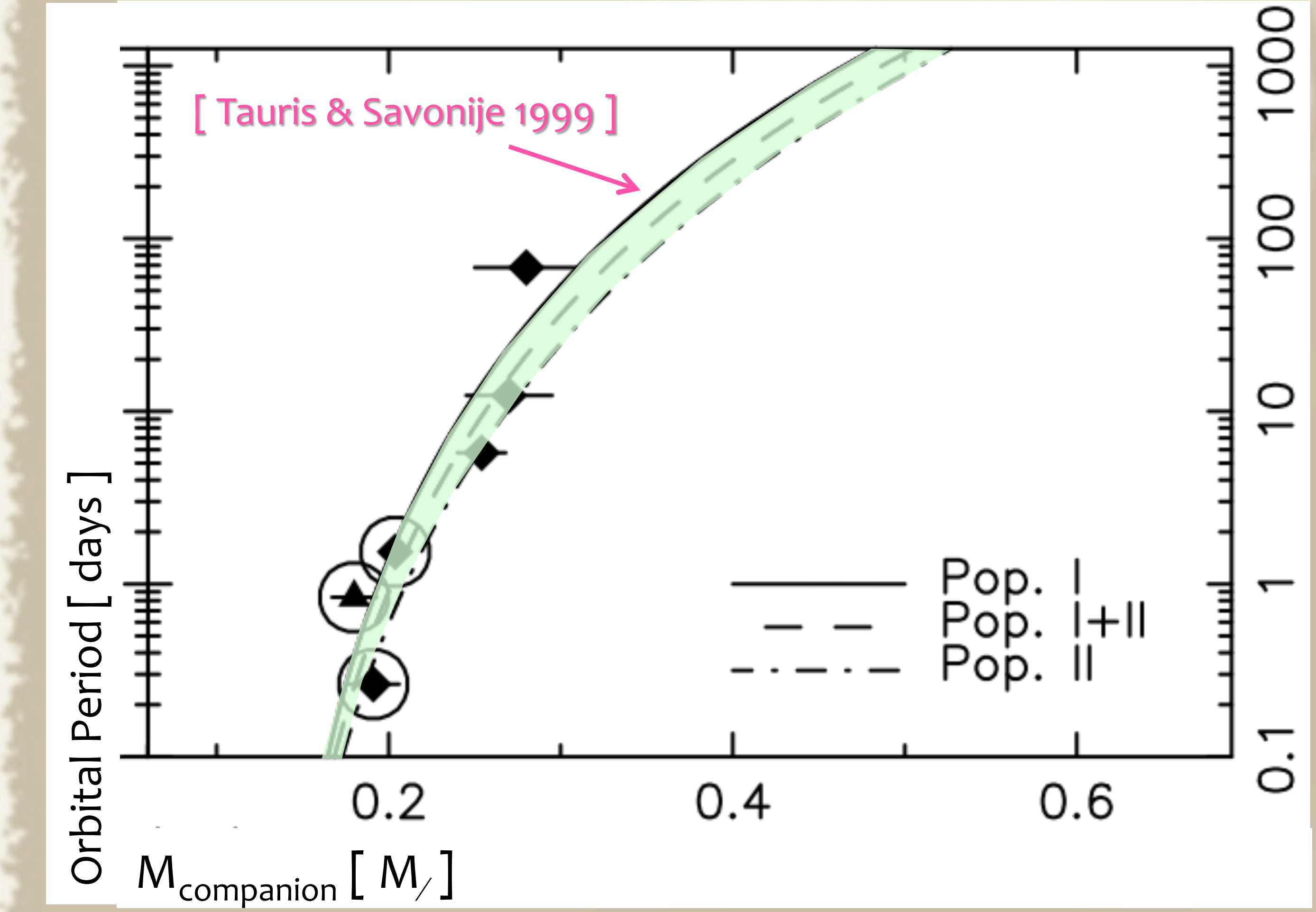
27 over 36 LMBPs ok with prediction

⊙ Low Mass Binary Pulsars (LMBP) with He-WD companion

[adapted from Burgay et al, 2013]

The “classic tests” of the evolutionary picture for LMBPs: Eccentricity vs Orbital Period

The “classic tests” of the evolutionary picture for LMBPs: Orbital Period vs Companion Mass for He-WD companions



[Tauris & Savonije 1999]

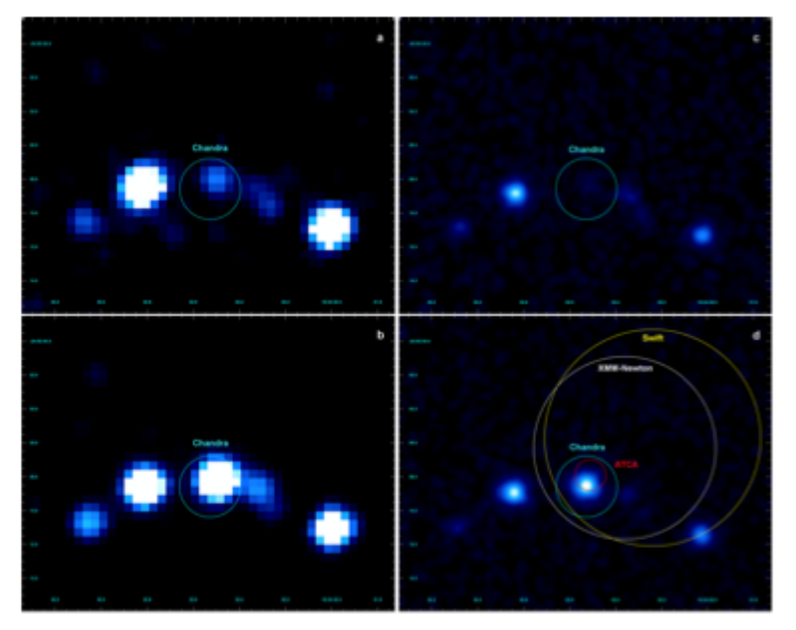
[Corongiu, Possenti et al 2013]

A more constraining test

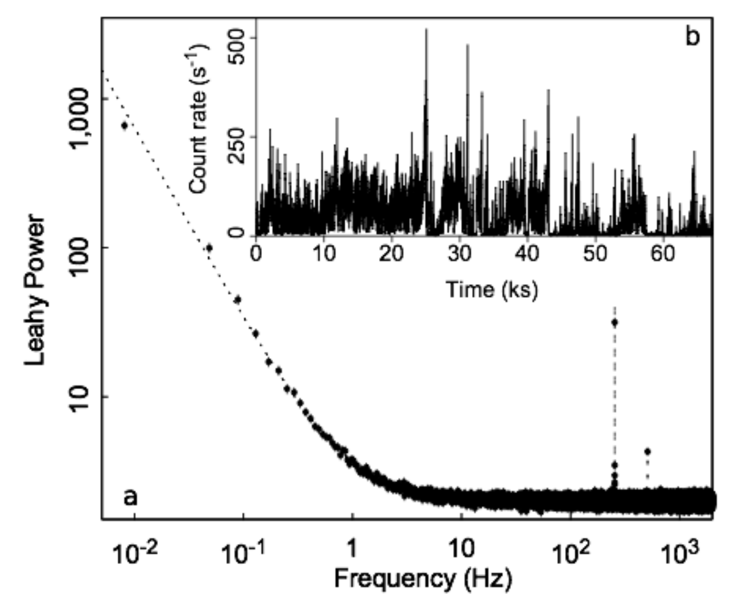
The 6 LMBPs for which the Companion Mass has been determined using the measurement of the Shapiro delay

And finally: A binary swinging btw X-ray and radio MSP

PSR J1824-2452I / IGR J18245-2452 in M28 : the long sought link btw LMXPs and the largest family of LMBPs



[Papitto et al Sept 2013]

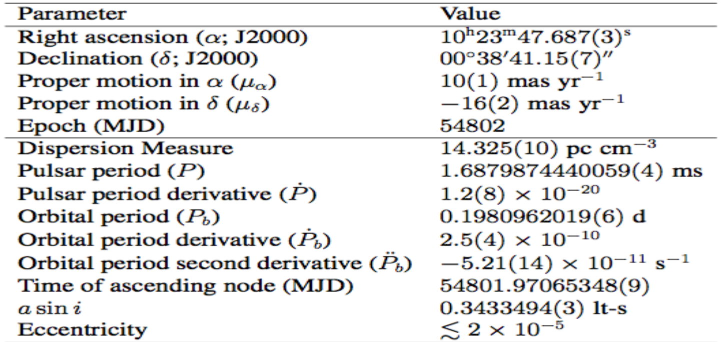


Nowadays a 3.93-ms MSP in a 11.0-hr circular orbit with a ≈0.17 M_{sun} companion, displaying extended radio eclipses, and which experienced few phases of accretion with emission of millisecond X-ray pulsations, the last of them around April 2013

The switching btw radio and X-ray pulsations is very rapid, or order days at most

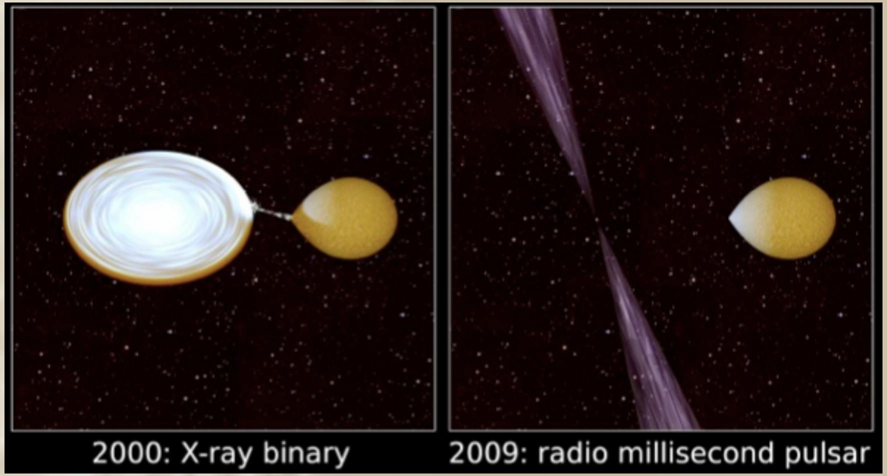
..and another example: J1023+0038

[Archibald et al 2009, Zhang et al 2009]



Parameter	Value
Right ascension (α; J2000)	$10^h23^m47.687(3)^s$
Declination (δ; J2000)	$00^\circ38'41.15(7)''$
Proper motion in α (μ_α)	$10(1)$ mas yr^{-1}
Proper motion in δ (μ_δ)	$-16(2)$ mas yr^{-1}
Epoch (MJD)	54802
Dispersion Measure	$14.325(10)$ pc cm^{-3}
Pulsar period (P)	$1.6879874440059(4)$ ms
Pulsar period derivative ($\dot{P}$)	$1.2(8) \times 10^{-20}$
Orbital period (P_b)	$0.1980962019(6)$ d
Orbital period derivative ($\dot{P}_b$)	$2.5(4) \times 10^{-10}$
Orbital period second derivative ($\ddot{P}_b$)	$-5.21(14) \times 10^{-11}$ s^{-1}
Time of ascending node (MJD)	$54801.97065348(9)$
$a \sin i$	$0.3433494(3)$ lt-s
Eccentricity	$\lesssim 2 \times 10^{-5}$

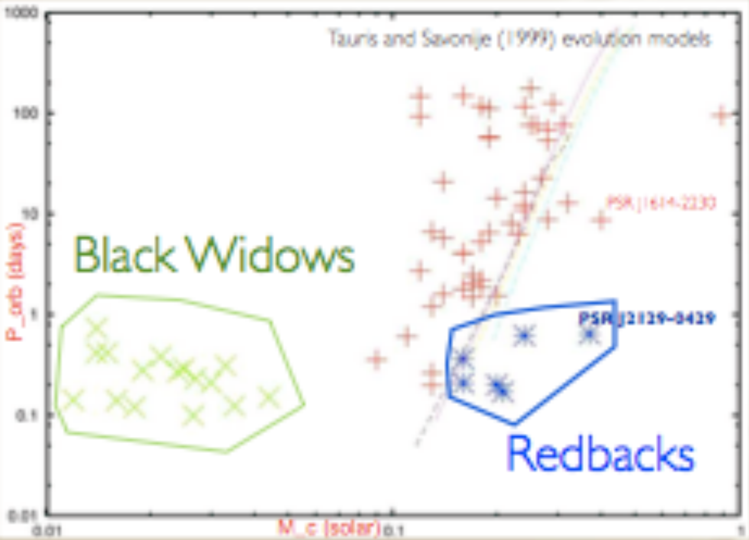
A 1.69-ms MSP in a 4.75-hr circular orbit with a ≈0.25 M_{sun} MS companion, displaying extended radio eclipses, X-ray orbital modulation and gamma-ray emission and showing to have had an accretion disk until around 2001 [Archibald et al 2010: Tam et al 2010; Bogdanov et al 2011]



.... and counting: J1227-4859, ...

Thus established the new family of the TRANSITIONAL binary pulsars

The TRANSITIONAL binary pulsars belong to the larger category of the ECLIPSING pulsars



RED BACKs: $M_c > 0.1\text{-}0.2\ M_{sun}$

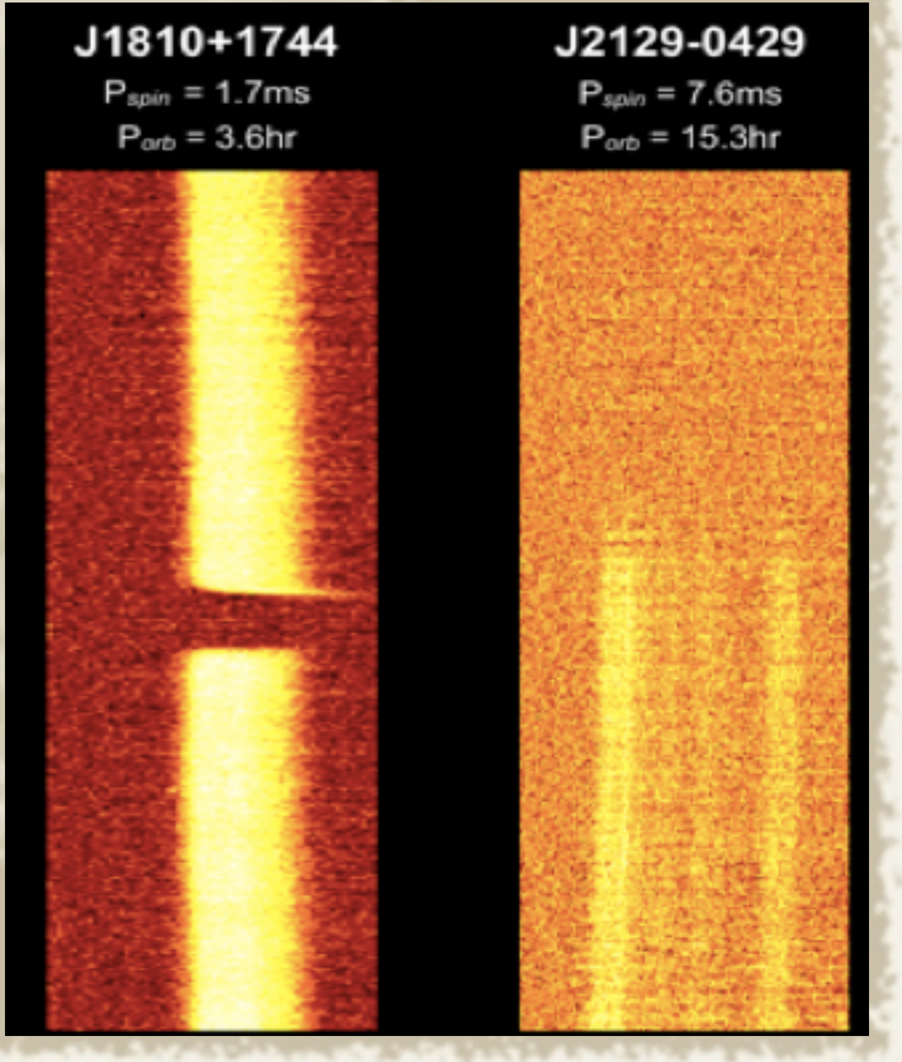
Not degenerate companion

Small ablation

BLACK WIDOWs: $M_c < 0.1\ M_{sun}$

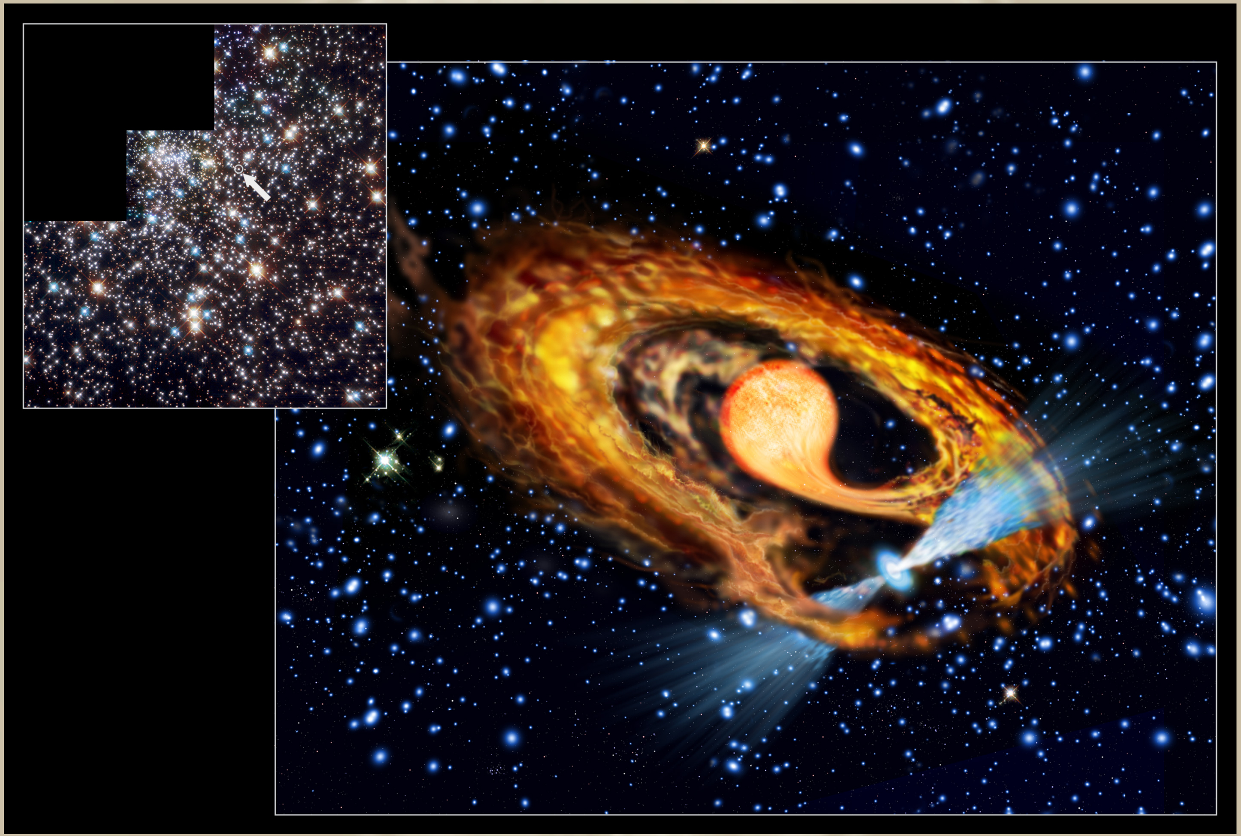
Short orbital period

Evidences of ablation



Neutron star + Roche lobe filling “pear-shaped” star

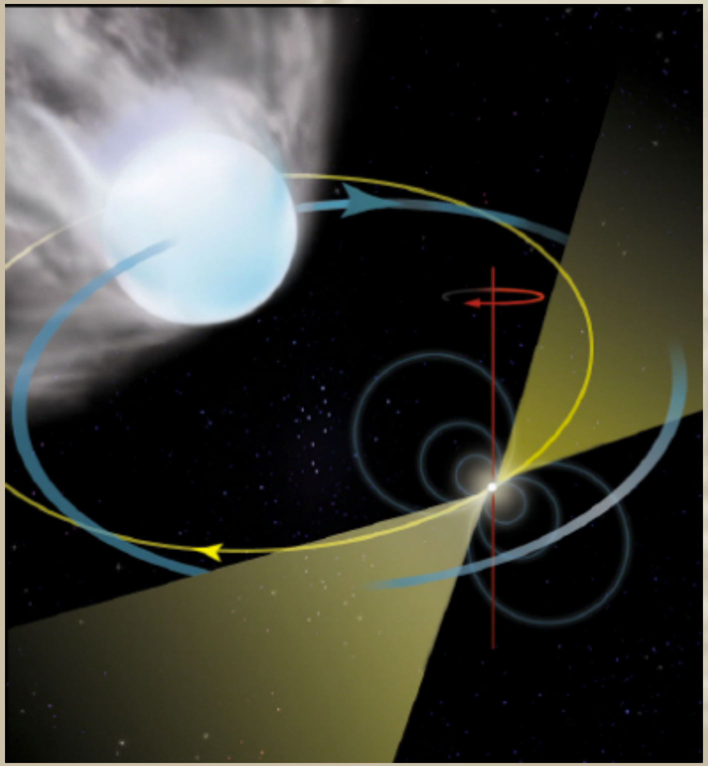
PSR 6397A + COM 6397A



At about 7000 a.l.: eclipsing binary pulsar in the globular cluster NGC 6397

The RED BACK stereotype

until recently the vast majority of the eclipsing pulsars were found in globular clusters, but now…

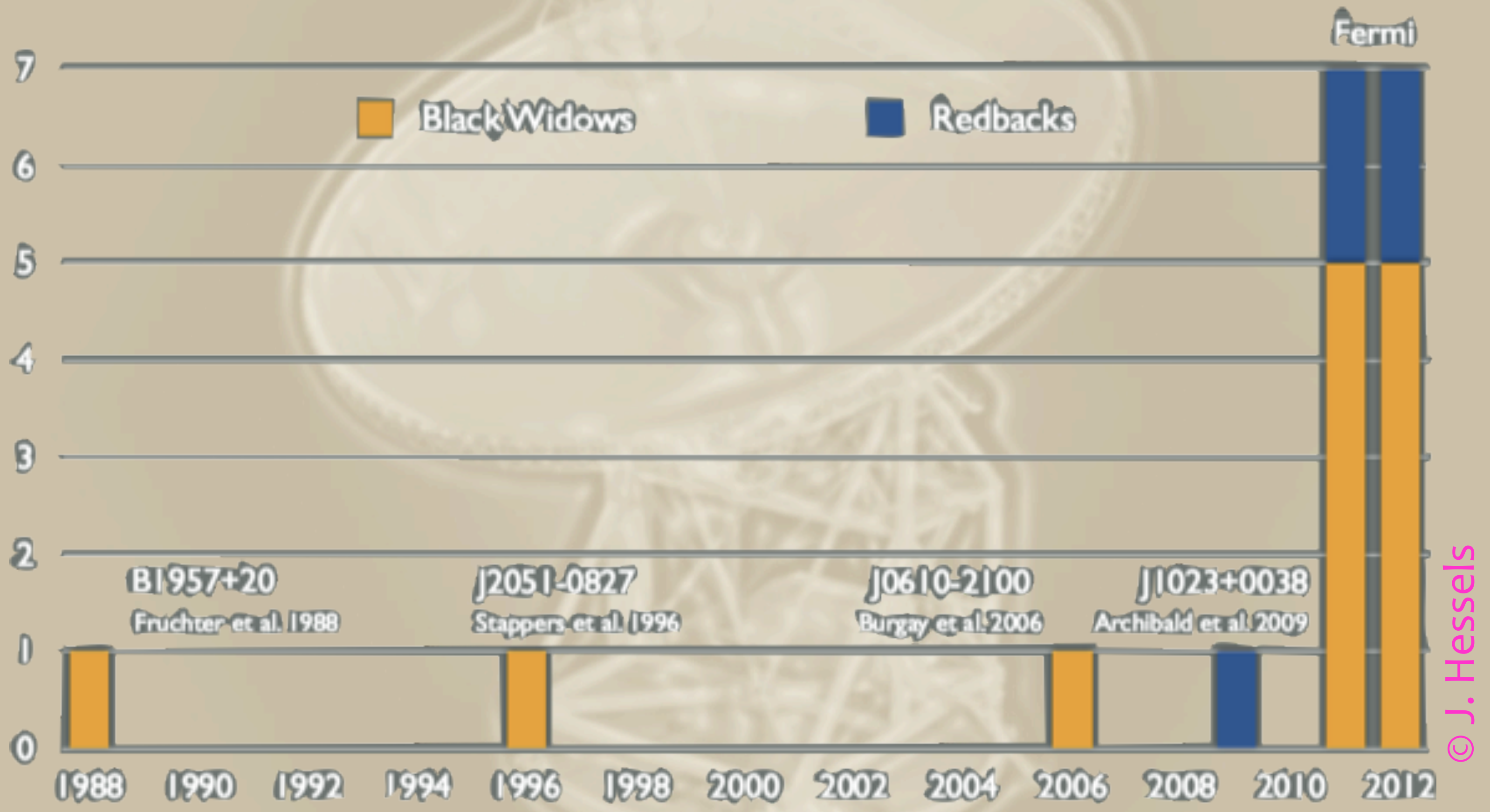


Fermi 'spiders'

Black Widow and Redback pulsar binaries.

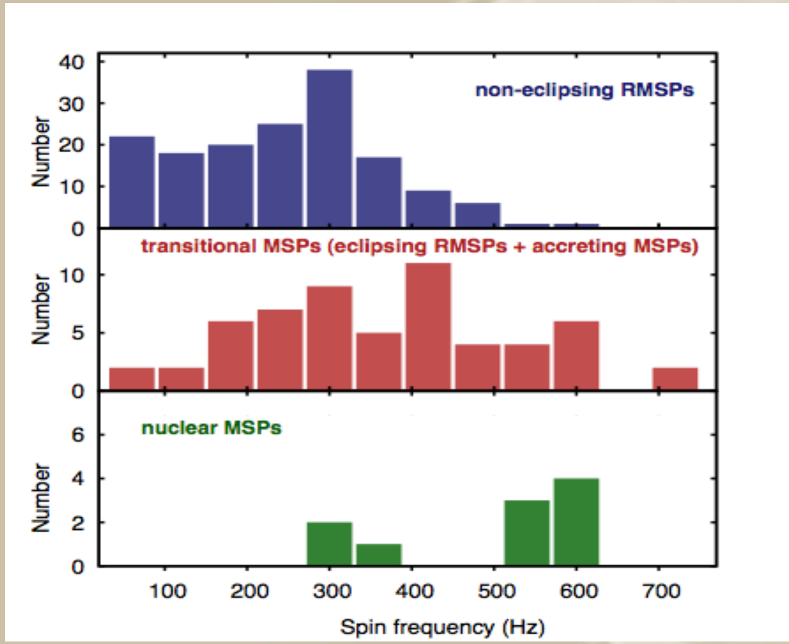
So named because they 'devour' (ablate) their companions

Fermi 'spiders' in the Galactic field

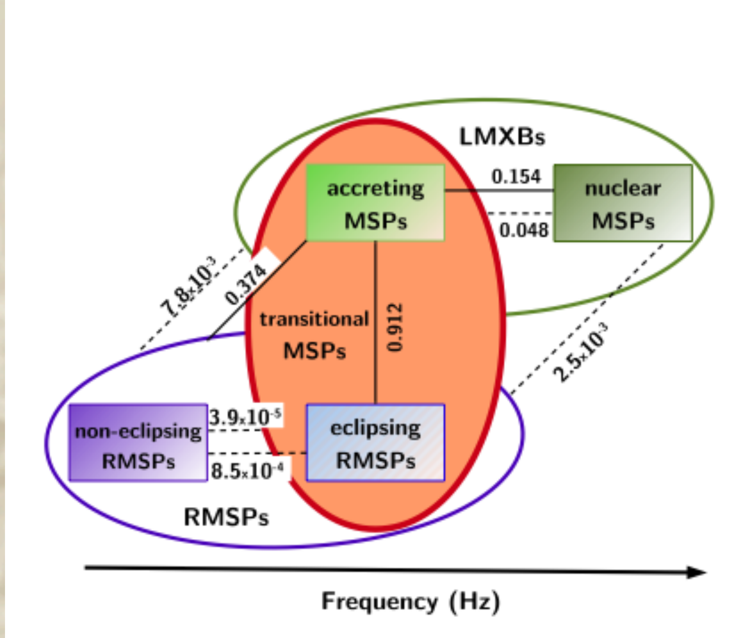


In the Galactic field
3 BW, 1 RB pre-Fermi
16 BW, 9 RB post-Fermi

NOT all is explained in the recycling scenario, though: e.g. spin discrepancy btw Accreting X-ray Millisecond Pulsars (AXMSPs) and MSPs



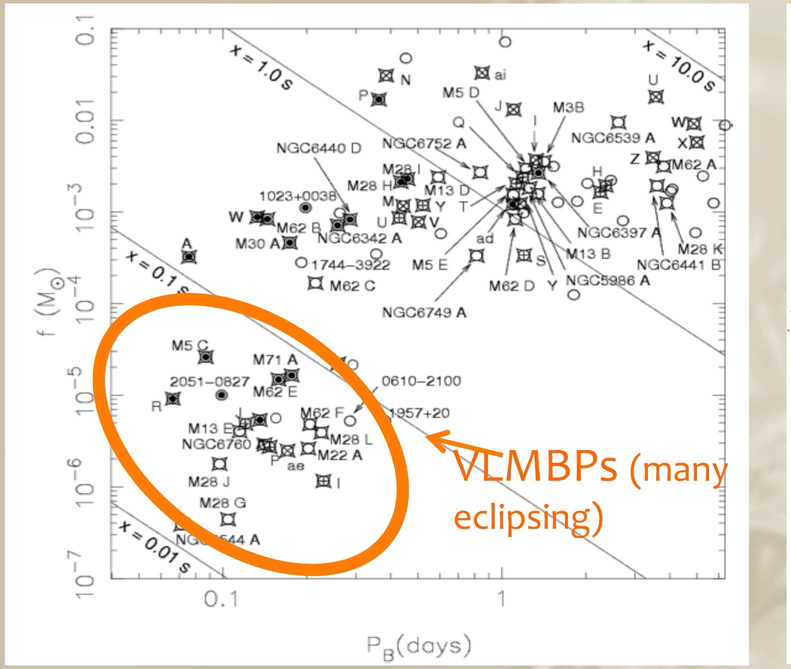
[Papitto et al 2013]



reconciled via Propeller effect and other effects ?

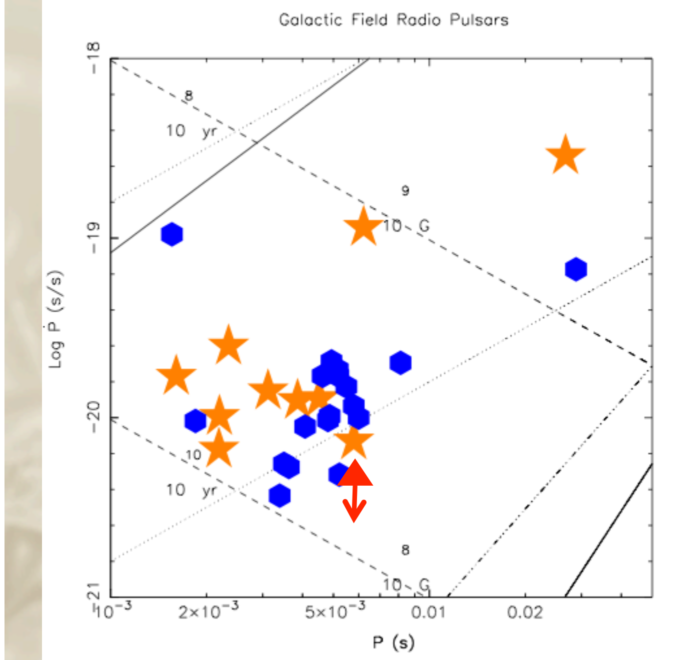
P.S. Be careful – even more than before – when considering spin-down age of the MSPs

NOT all is explained in the recycling scenario, though:
e.g. formation of ISOLATED RECYCLED PULSARs



VLMBPs (many eclipsing)

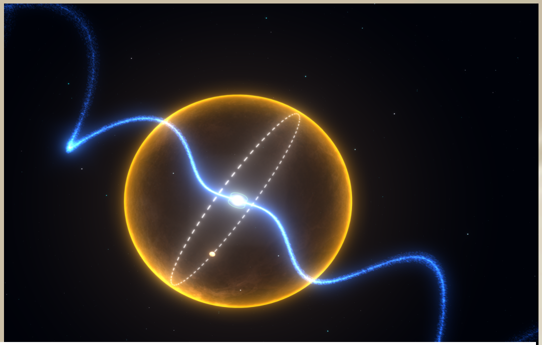
[© P. Freire]

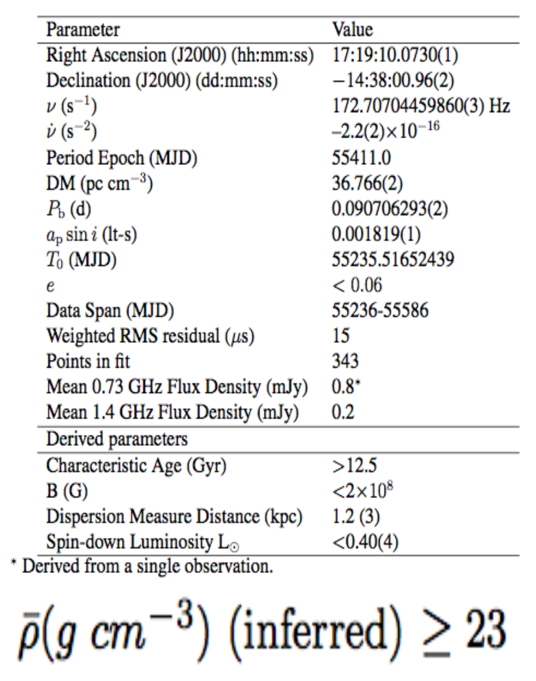


[Possenti et al, in prep]

are they descendants of Very Low Mass Binary Pulsars (VLMBPs)
as well as of Ultra Low Mass Binary Pulsars (ULMBPs) ?

the recent new population of the
ULTRA LOW MASS BINARY PULSARs (ULMBPs): e.g. J1719-1438



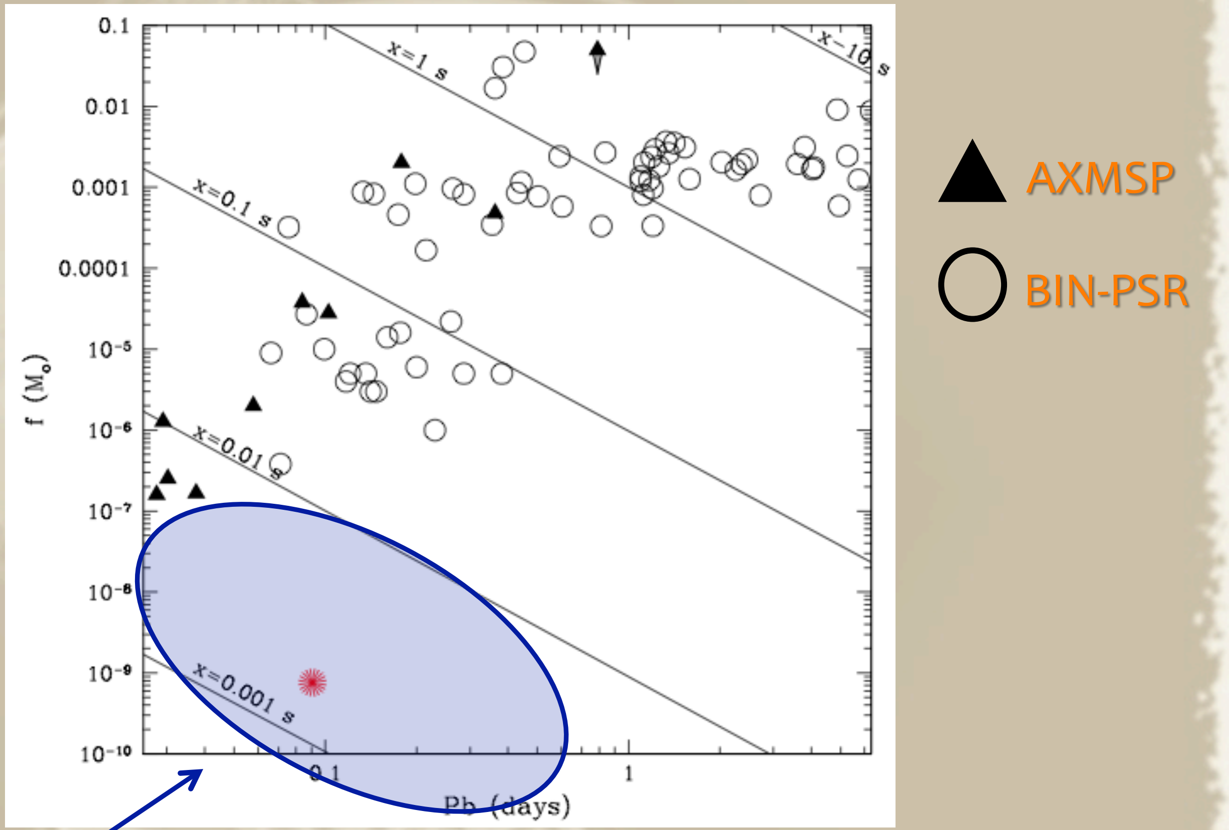


Parameter	Value
Right Ascension (J2000) (hh:mm:ss)	17:19:10.0730(1)
Declination (J2000) (dd:mm:ss)	−14:38:00.96(2)
ν (s^{-1})	172.70704459860(3) Hz
$\dot{\nu}$ (s^{-2})	$-2.2(2)\times10^{-16}$
Period Epoch (MJD)	55411.0
DM (pc cm^{-3})	36.766(2)
P_b (d)	0.090706293(2)
$a_p \sin i$ (lt-s)	0.001819(1)
T_0 (MJD)	55235.51652439
e	< 0.06
Data Span (MJD)	55236-55586
Weighted RMS residual (μs)	15
Points in fit	343
Mean 0.73 GHz Flux Density (mJy)	0.8*
Mean 1.4 GHz Flux Density (mJy)	0.2
Derived parameters	
Characteristic Age (Gyr)	>12.5
B (G)	$<2\times10^{8}$
Dispersion Measure Distance (kpc)	1.2 (3)
Spin-down Luminosity $L_\odot$	<0.40(4)

* Derived from a single observation.

$$\bar{\rho}(g\ cm^{-3})\ (\text{inferred}) \geq 23$$

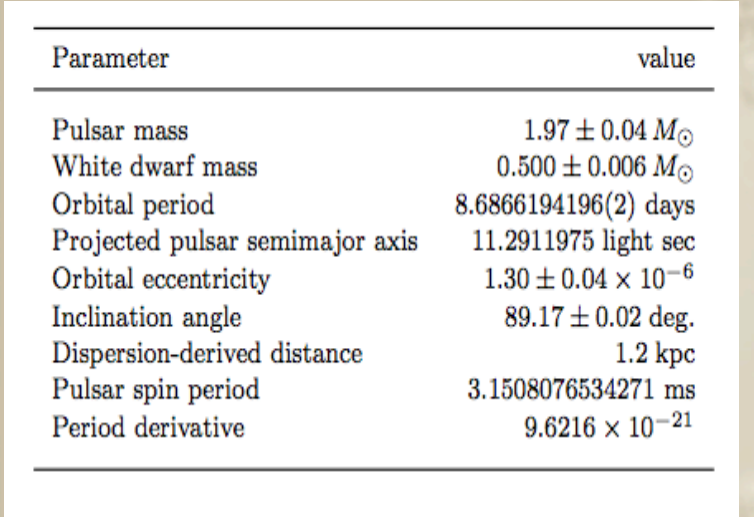
[Bailes et al 2011]



Jovian-like mass companions for ULMBPs

the previously missing descendants of the Ultra Compact Accreting X-ray Millisecond Pulsars (UC-AXMSPs) ?

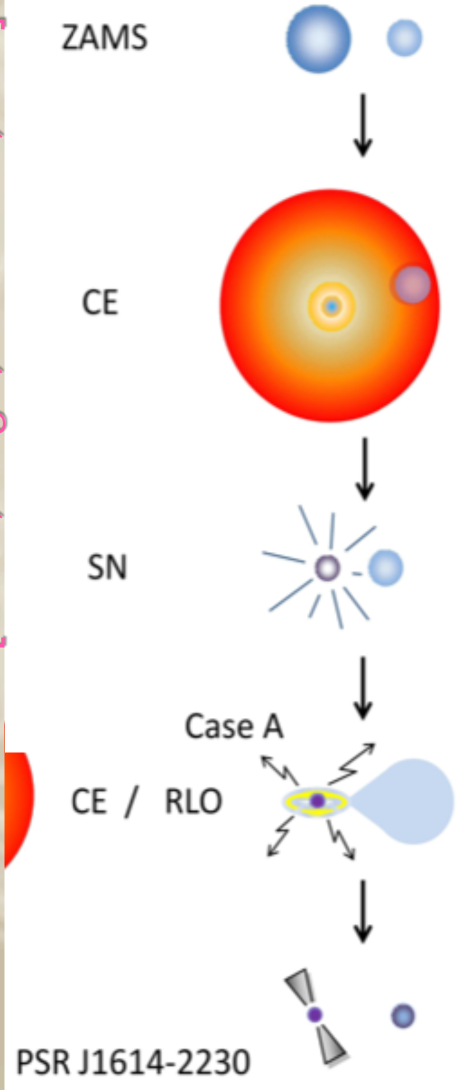
A new evolutionary path (case A RLO) for Intermediate Mass Binary Pulsars (IMBPs) : e.g. the massive pulsar J1614-2230



Parameter	value
Pulsar mass	$1.97 \pm 0.04\, M_{\odot}$
White dwarf mass	$0.500 \pm 0.006\, M_{\odot}$
Orbital period	8.6866194196(2) days
Projected pulsar semimajor axis	11.2911975 light sec
Orbital eccentricity	$1.30 \pm 0.04 \times 10^{-6}$
Inclination angle	89.17 ± 0.02 deg.
Dispersion-derived distance	1.2 kpc
Pulsar spin period	3.1508076534271 ms
Period derivative	9.6216×10^{-21}

[Demorest et al. 2010]

[Tauris, Langer, Kramer 2011, 2012]



The most likely pulsar mass at birth was 1.7±0.15 M

See also [Lin et al. 2011] and [Bhalerao & Kulkarni 2011] for alternate scenarios

and the first triple system: NS + WD + WD

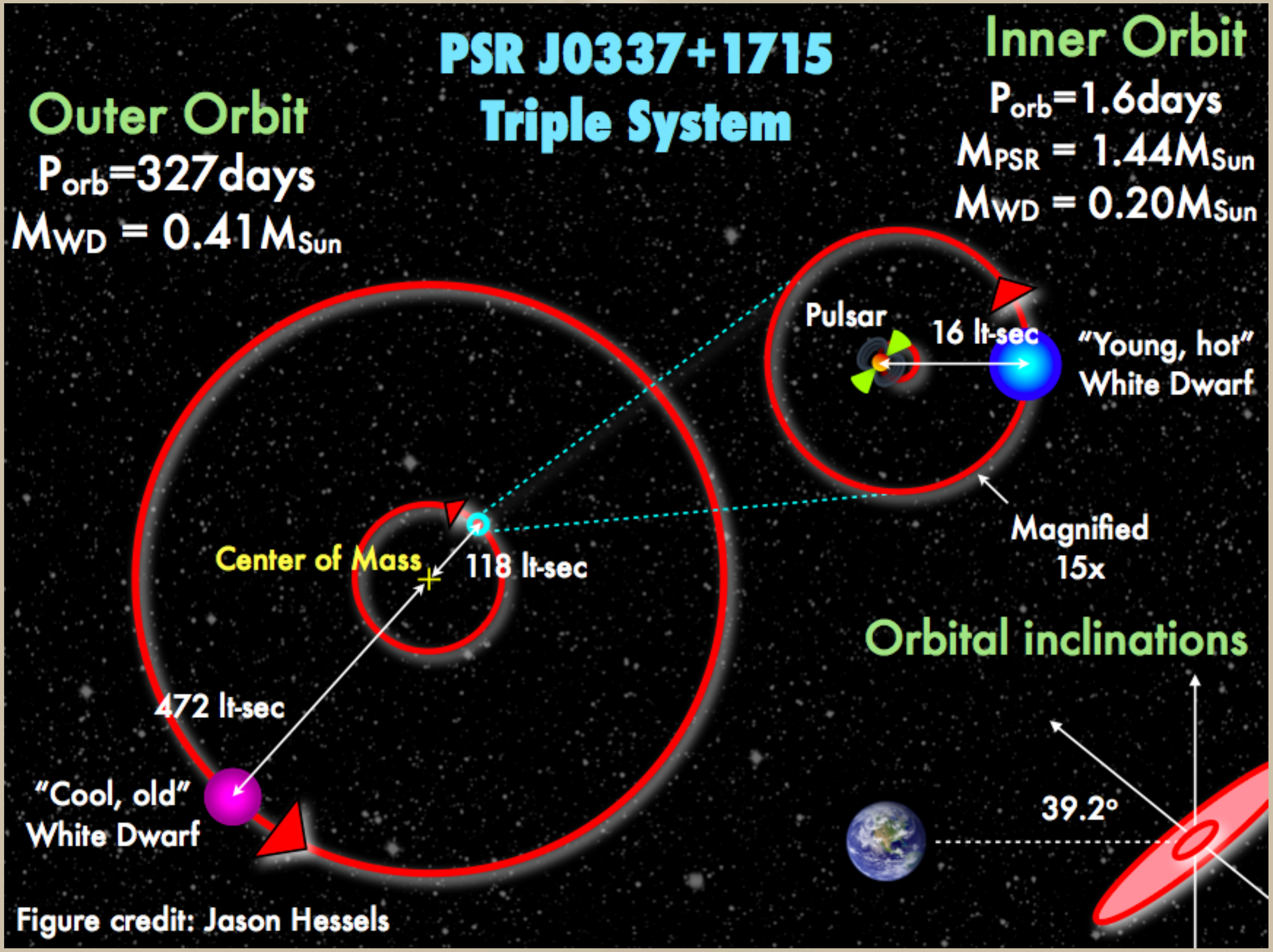
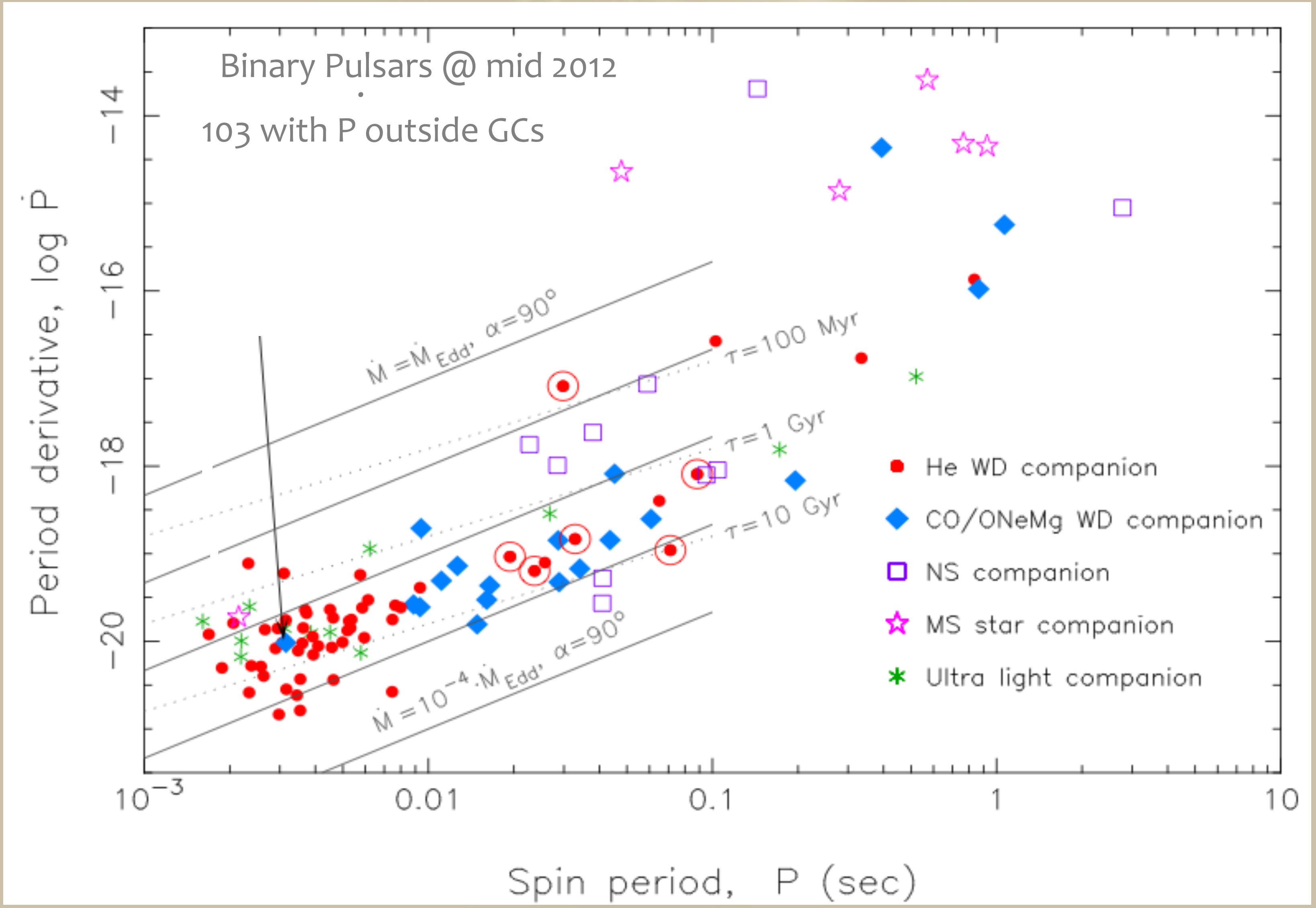


Figure credit: Jason Hessels

A variety of pulsar companions



Binary Pulsars @ mid 2012

103 with $\dot{P}$ outside GCs

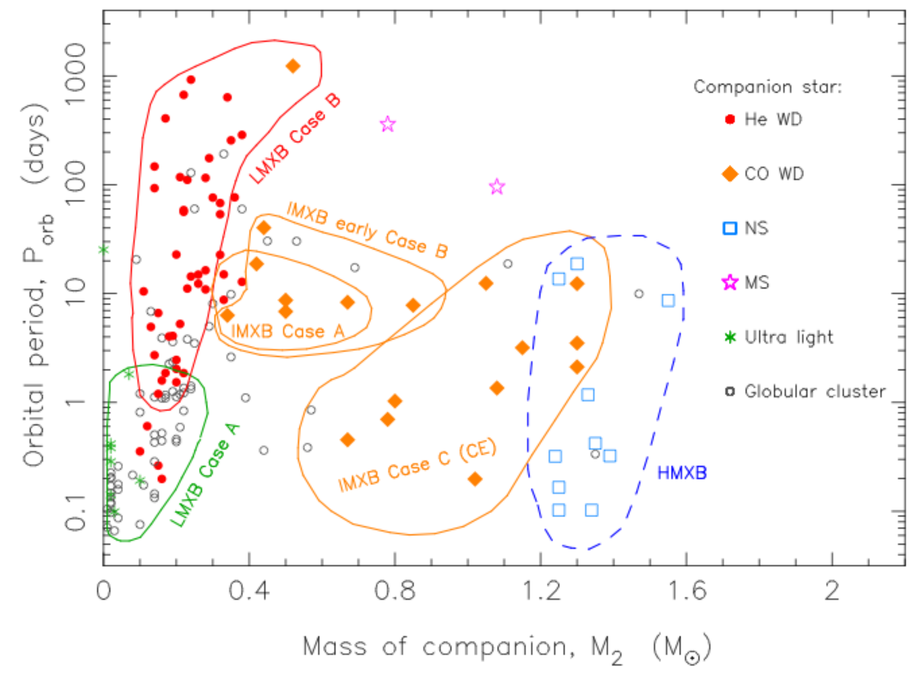
[from Tauris, Langer, Kramer 2012]

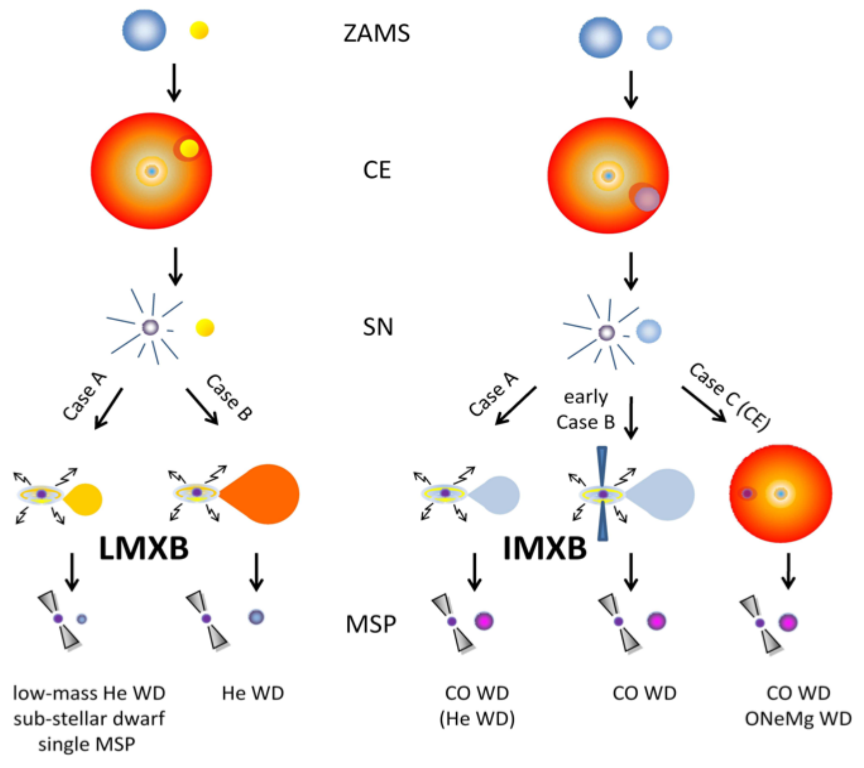
Finding Charts for the nature of a pulsar companion

Companion type	Conditions
MS	$M_2^* > 0.5\,M_\odot$ and $P_{\rm orb} > 50^{\rm d}$
NS	$P_{\rm orb} < 50^{\rm d}$ and $ecc > 0.05$
CO	$M_2^* > 0.335\,M_\odot$ and $P_{\rm orb} < 75^{\rm d}$ and $ecc < 0.05$ and $P > 8$ ms
He	$M_2^* > 0.08\,M_\odot$ and $\{(P_{\rm orb} < 75^{\rm d}$ and $M_2^* < 0.335\,M_\odot)$ or $(P_{\rm orb} > 75^{\rm d}$ and $M_2^* < 0.46\,M_\odot)\}$
*UL***	$M_2^* < 0.08\,M_\odot$

* The median companion mass M_2 is calculated for an orbital inclination angle $i = 60^\circ$ and an assumed pulsar mass $M_{\rm NS} = 1.35\,M_\odot$.

** Many pulsars with unmeasured values of a_1 are also expected to host an ultra-light companion if $P_{\rm orb} < 2$ days and $P < 8$ ms.





[Tauris 2011; Tauris, Langer, Kramer 2012]