Optical companions to MSPs in GCs

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Star Clusters as Cosmic Laboratories for Astrophysics, Dynamics and Fundamental Physics - MODEST 16

April 18-22 2016, Bologna (Italy)

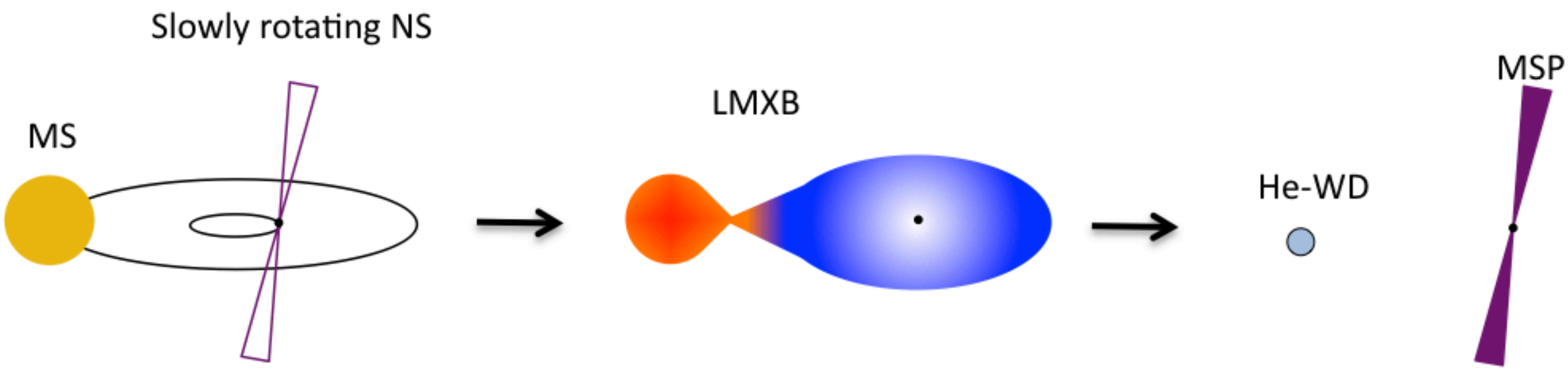
Cosmic-Lab

- 5-year project (web site at **www.cosmic-lab.eu**)
- *Advanced Research Grant* funded by the European Research Council (ERC)
- PI: Francesco R. Ferraro (Dip. of Physics & Astronomy – Bologna University)
- AIM: **to understand the complex interplay between dynamics & stellar evolution**
- HOW: using **globular clusters** as cosmic laboratories and

Blue Straggler Stars
Millisecond Pulsars
Intermediate-mass Black Holes

as probe-particles

The canonical recycling scenario



Binary system:
Neutron star (NS)
+ evolving companion

mass accretion from an
evolving companion
spin up the NS

fast rotating pulsar (MSP)
+ an exhausted star

the core of a peeled star = WD

(Bhattacharya et al. 1991)

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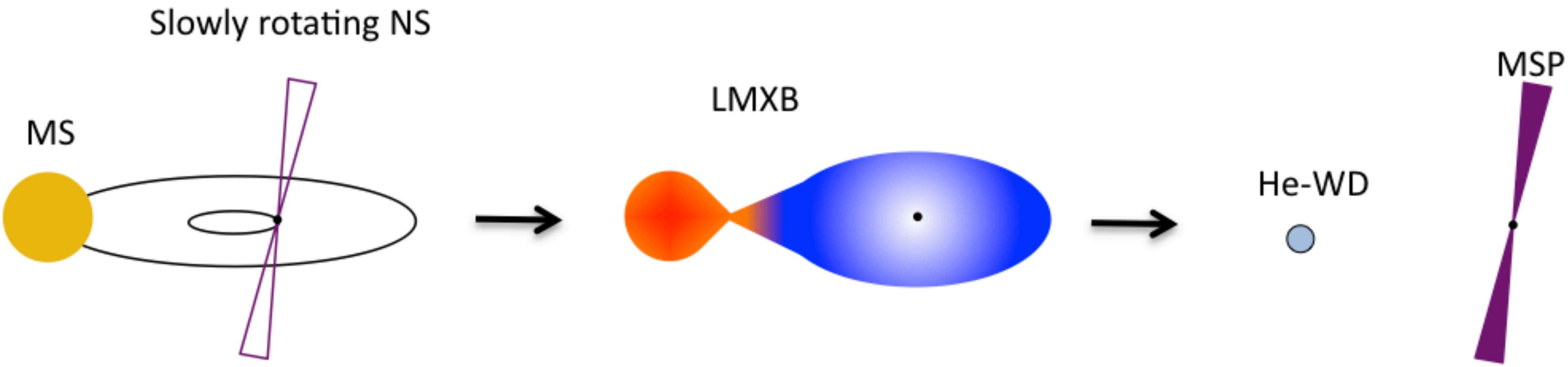

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...but there are a few exceptions...

(Bhattacharya et al. 1991)

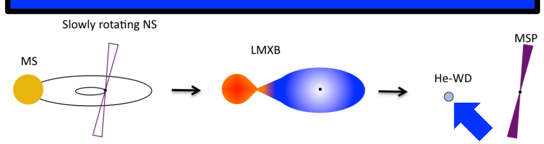
A “mass/type” classification of MSPs

<u>High mass</u>
$M_{COM} > 1\ M_\odot$
NSs

<u>Intermediate mass</u>
$0.5\ M_\odot < M_{COM} < 1\ M_\odot$
CO/ONe-WDs

<u>Low mass</u>
$M_{COM} < 0.5\ M_\odot$

<u>Canonicals</u>
$0.1\ M_\odot < M_{COM} < 0.5\ M_\odot$
He-WDs



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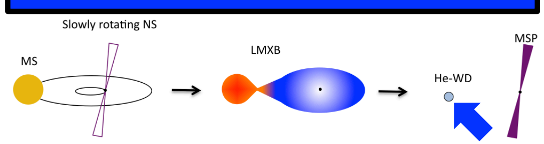
Red-backs
$0.1\ M_\odot < M_{COM} < 0.5\ M_\odot$
MSs

Canonicals
$0.1\ M_\odot < M_{COM} < 0.5\ M_\odot$
He-WDs

Black widows
$M_{COM} < 0.1\ M_\odot$
MSs/BDs

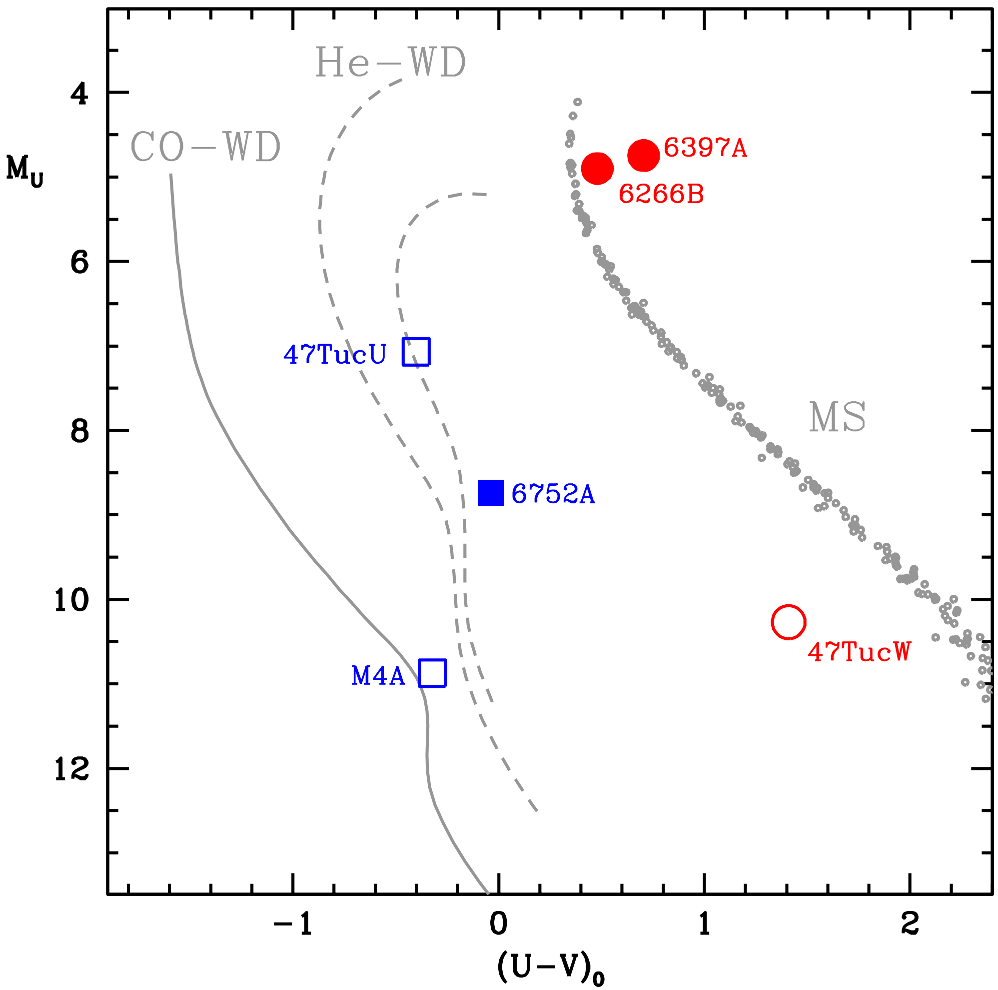
10 in GCs ?



?

18 in GCs

The state of the art in GCs (before Cosmic-lab project)



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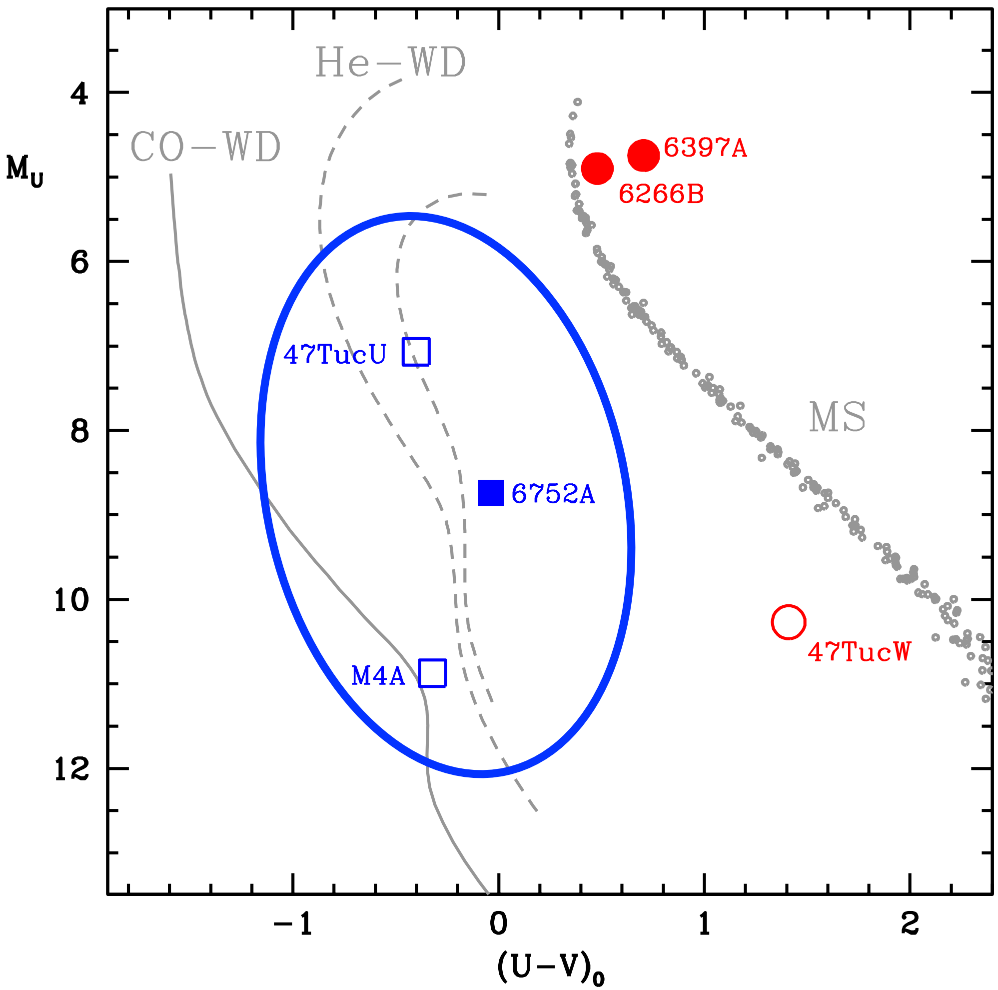
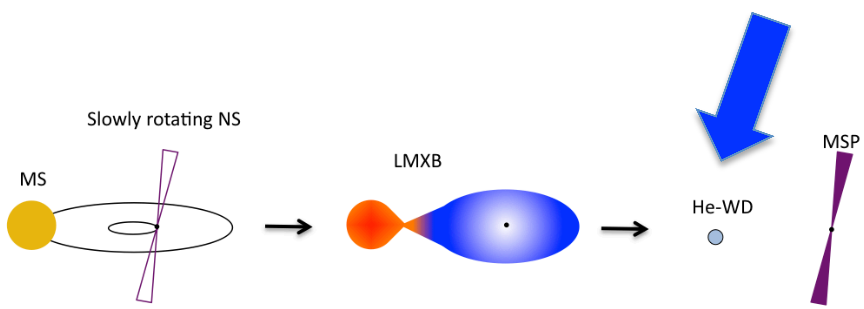


3 WDs
(Edmonds et al. 2001; Ferraro et al. 2003; Sigurdsson et al 2003)

CONFIRMATION OF THE RECYCLING SCENARIO:

Low mass WDs:
The "final stage" of the pulsar recycling process



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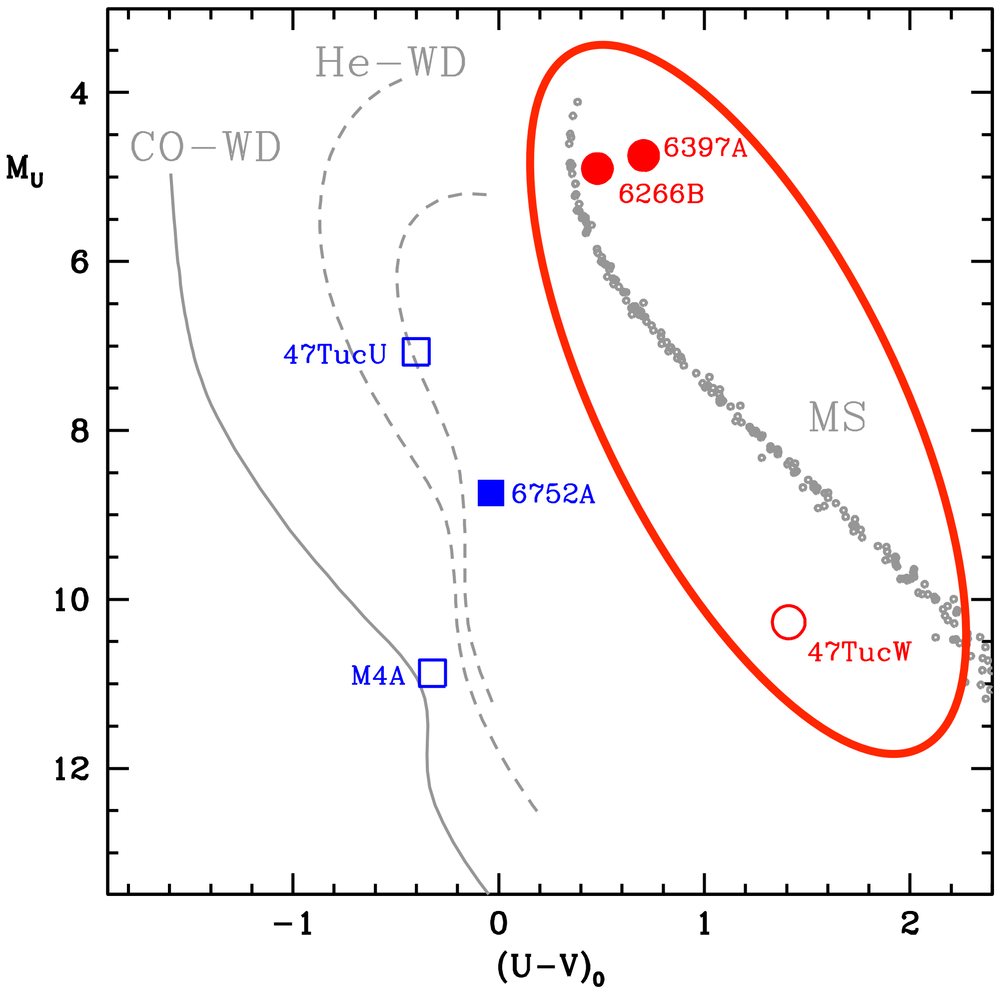
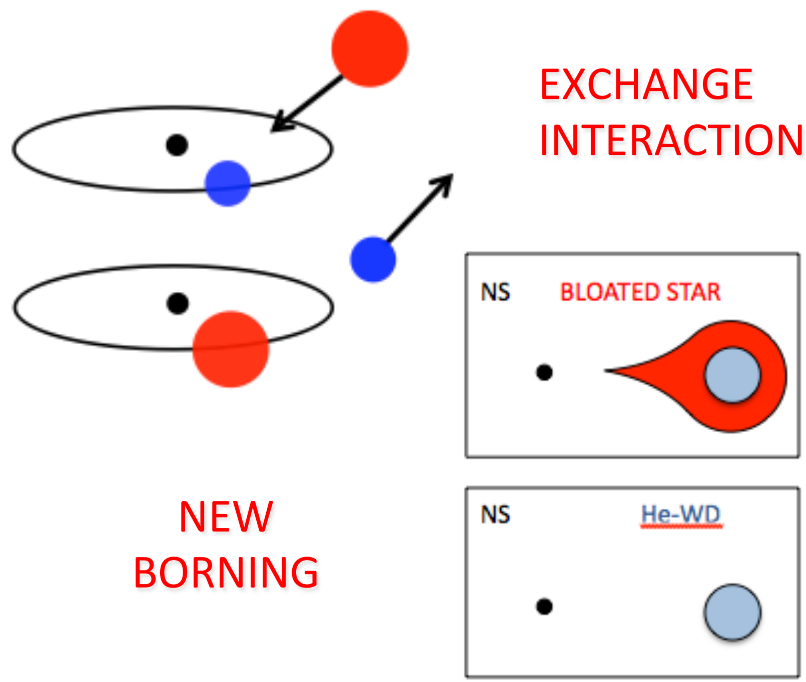


3 NON Degenerate Objects
(Ferraro et al. 2001; Edmonds et al 2002; Cocozza et al 2008).



The new identified companions

Photometric identification of:

- The "Canonical" PSR J0024-7204Q in 47Tuc
- The "Canonical" PSR J0024-7204S in 47Tuc
- The "Canonical" PSR J0024-7204T in 47Tuc
- The "Canonical" PSR J0024-7204Y in 47Tuc
- The Red-Back PSR J1824-2452H in M28
- The Transitional PSR J1824-2452I in M28
- The Black-widow PSR J1518+0204C in M5
- The Black-widow PSR J1953+1846A in M71

Spectroscopic follow-up of:

- The Red-Back COM J1740-5340A in NGC 6397

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The optical approach

Radio

Optical

Photometry

Very Accurate position

Orbital parameters

Orbital period
Time ascending node

PSR Mass function

Total mass

The optical approach

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Optical

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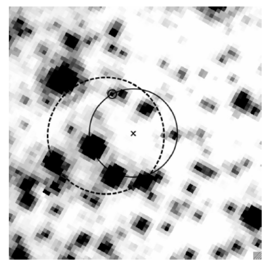
Astrometry



Very Accurate position

High resolution

CMD position
(Out of sequence)

Deep

Nature and physical parameters

Orbital parameters

Orbital period
Time ascending node

Light curve
(Variability in agreement with the orbital motion)

Multiple epochs

PSR Mass function

i, M_{COM}, M_{PSR}

Total mass

$M_{PSR}=M_{TOT}-M_{COM}$

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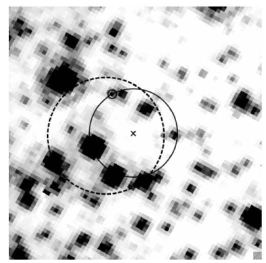

High resolution

!!! Positional coincidence !!!

CMD position

(Out of sequence)

Deep

Nature and physical parameters

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Orbital period
Time ascending node

Light curve

(Variability in agreement with the orbital motion)

Multiple epochs

PSR Mass function

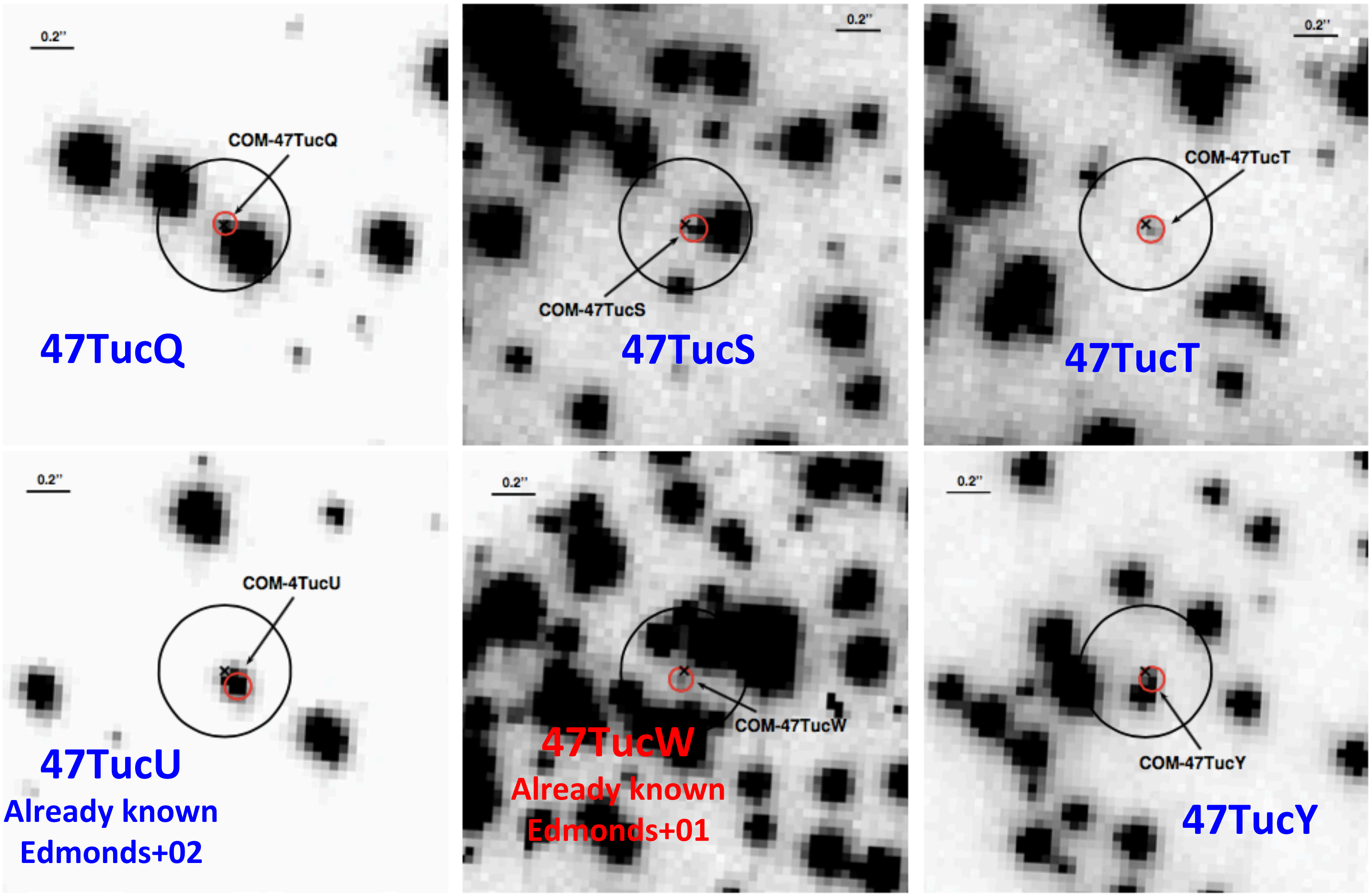
i, M_{COM}, M_{PSR}

!!! Orbital variability !!!

Total mass

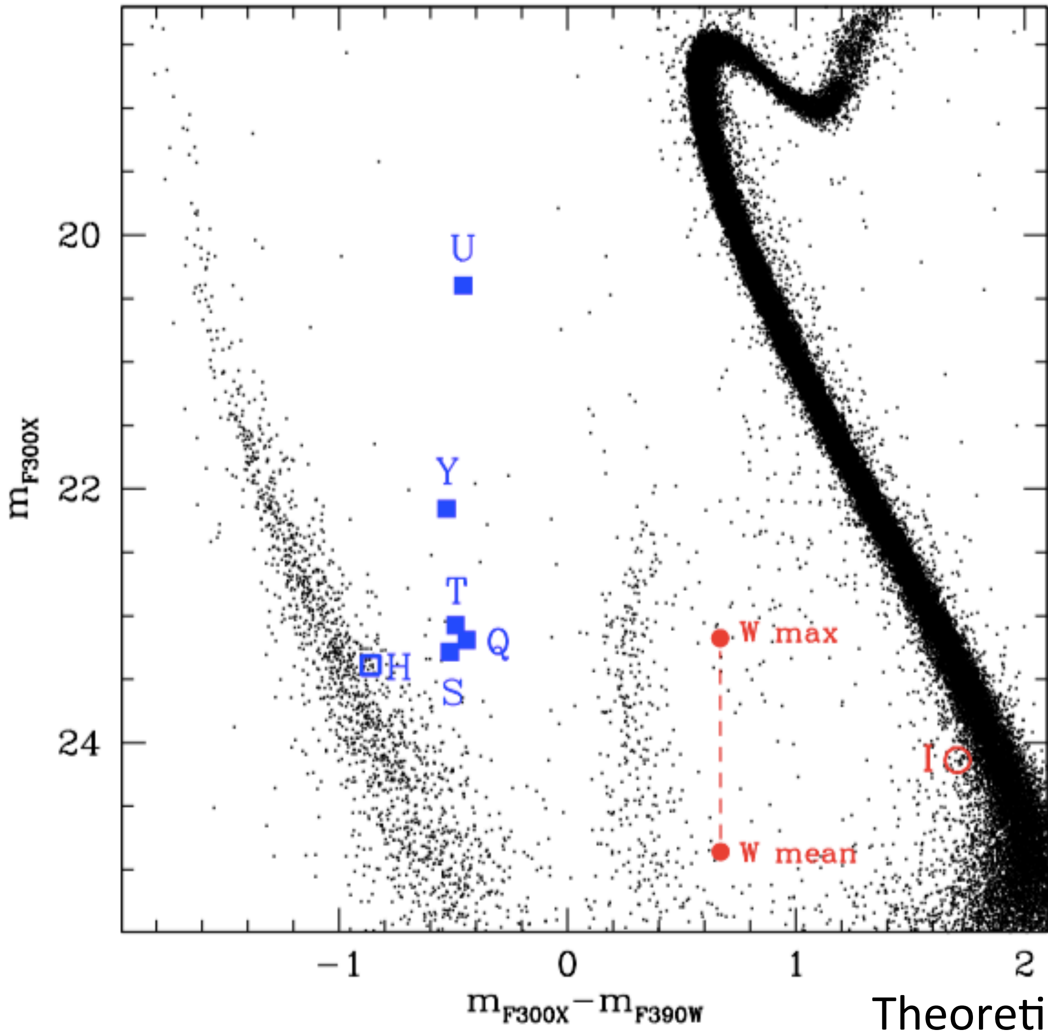
$M_{PSR}=M_{TOT}-M_{COM}$

The He-WDs in 47Tuc



(Cadelano et al. 2015, see also Rivera Sandoval et al. 2015)

The He-WDs in 47Tuc



Theoretical models from Althaus et al. 2013

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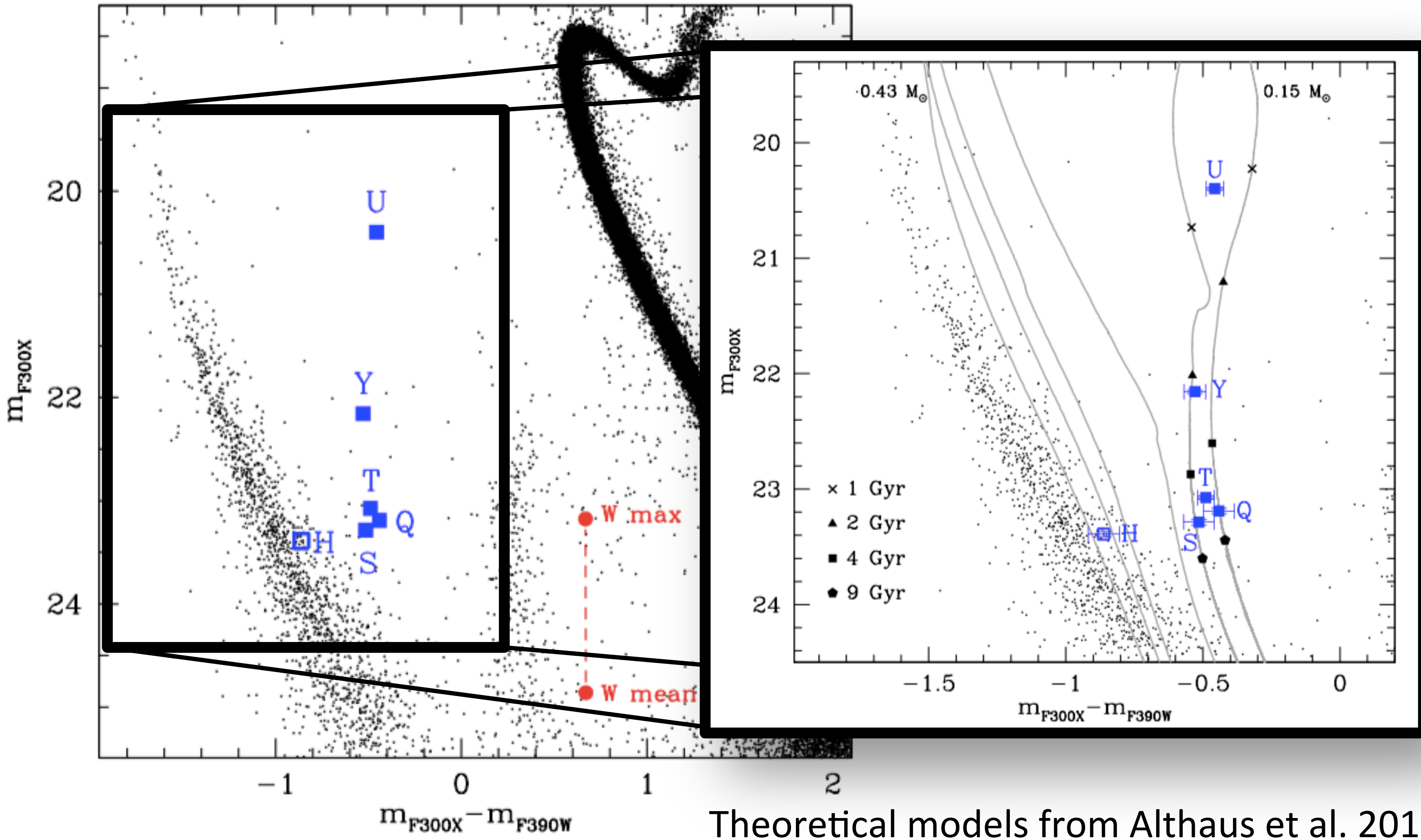

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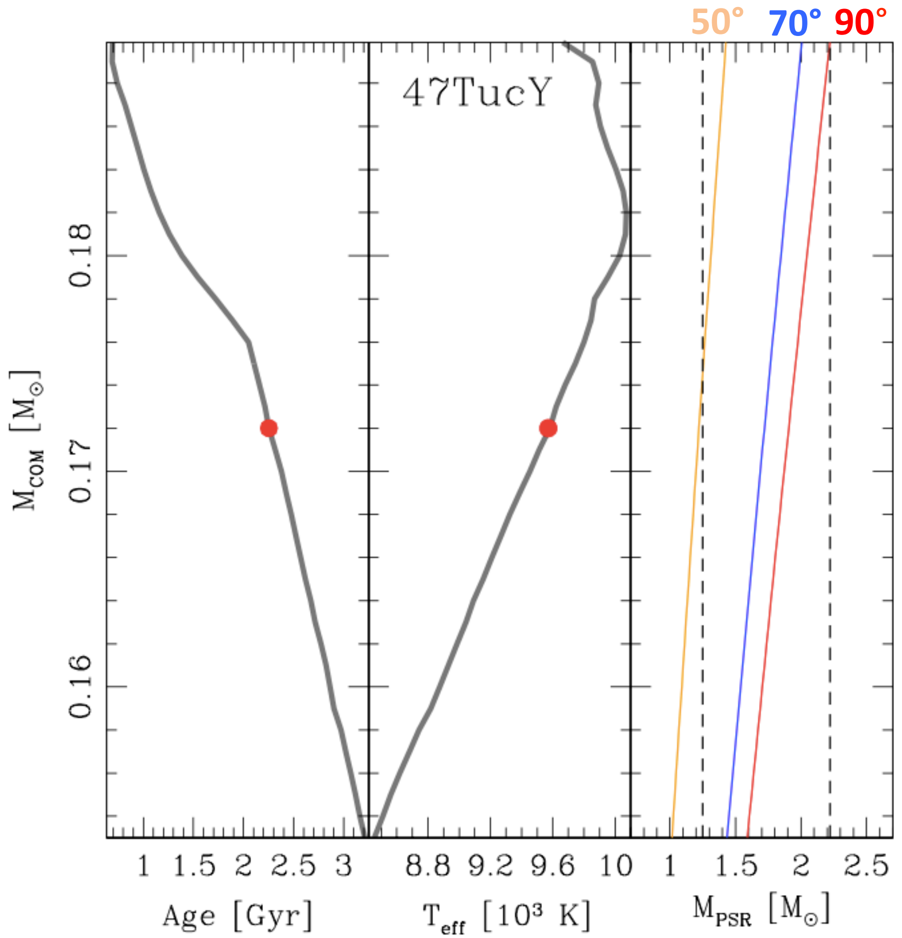
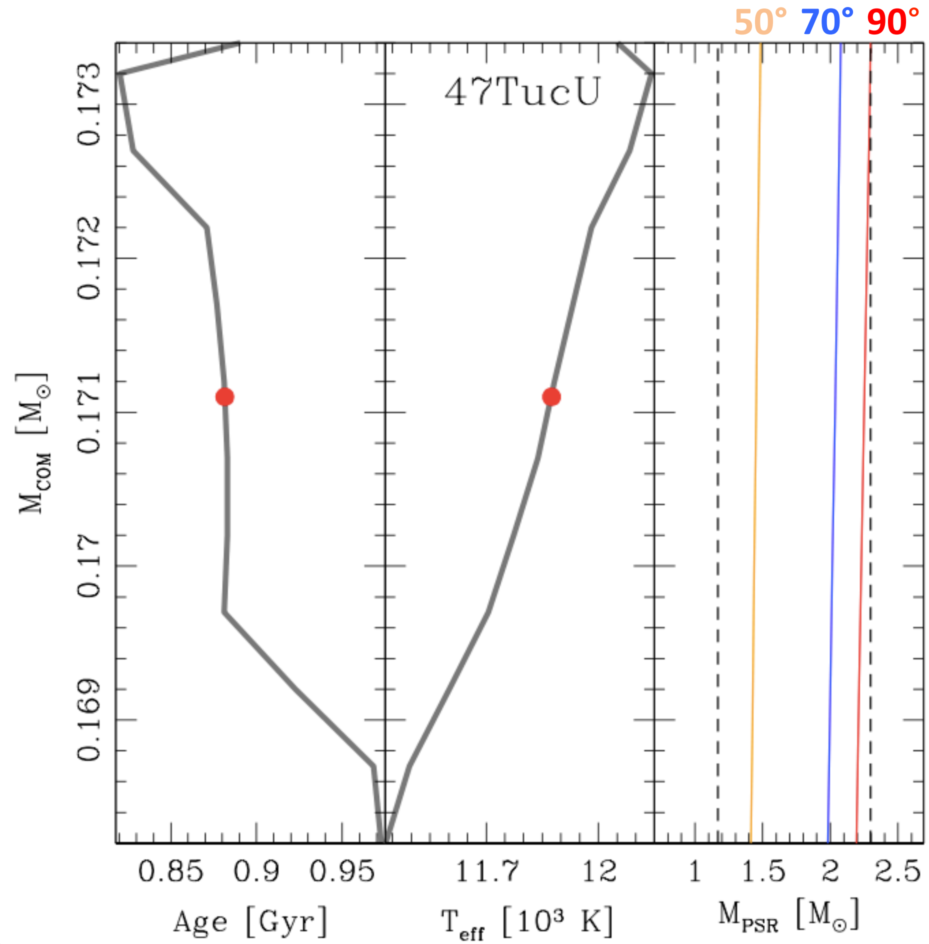


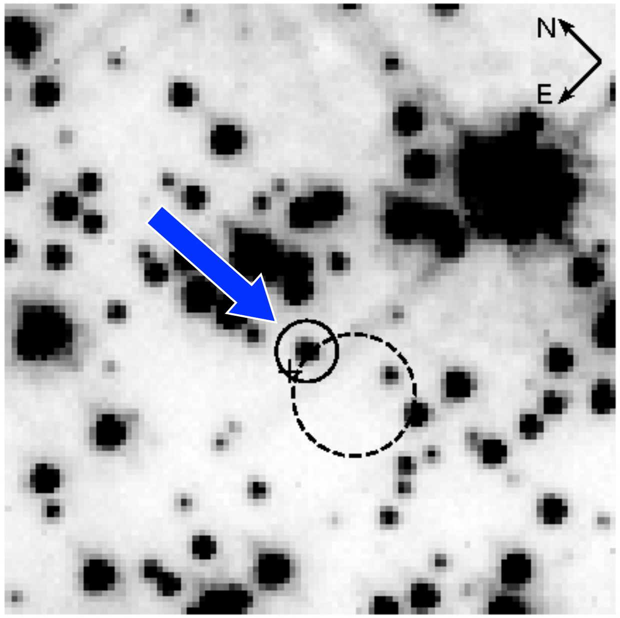


Conclusions:

- Companion masses between **0.15 Msun and 0.2 Msun**
- **Cooling ages significantly younger** than the cluster stellar population age
- No massive NSs for **47TucQ** and **47TucT** (**M_{NS}<1.6 Msun**)
- **47TucU** past accretion stages likely proceeded in a **Sub-Eddington rate** (M/Medd~0.02)

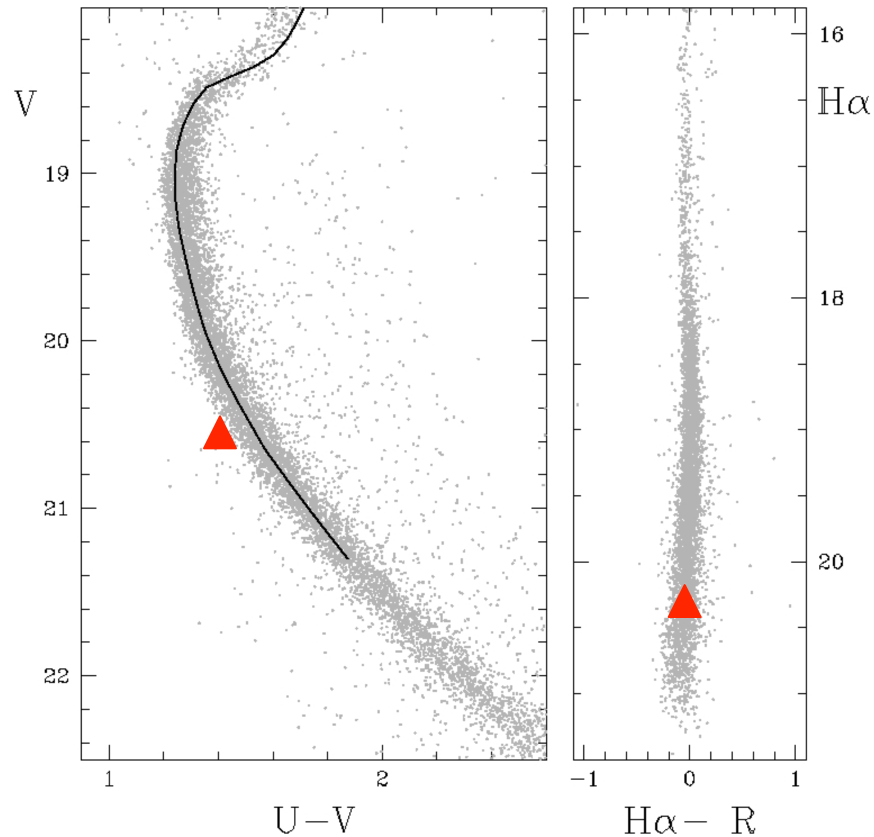
The RB PSR J1824-2452H in M28

WFC3/UVIS@HST



A NON-DEGENERATE companion

The companion star is located at *0.17" from the radio source* (+) and ~0.4" from the X-ray source (dashed circle)



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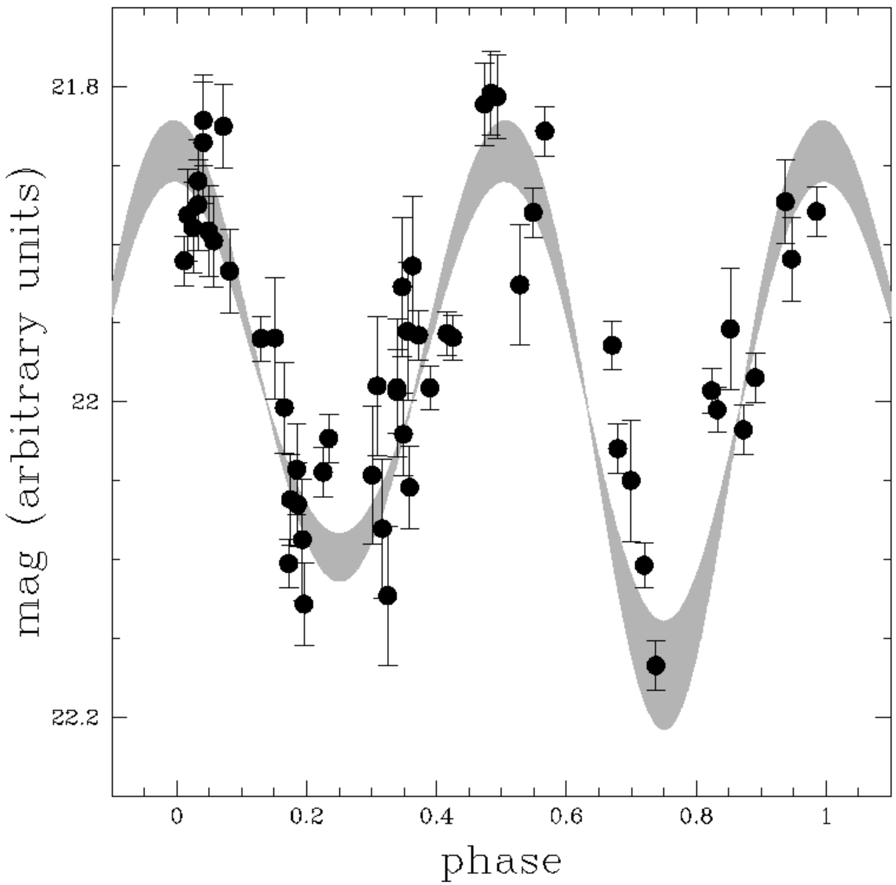
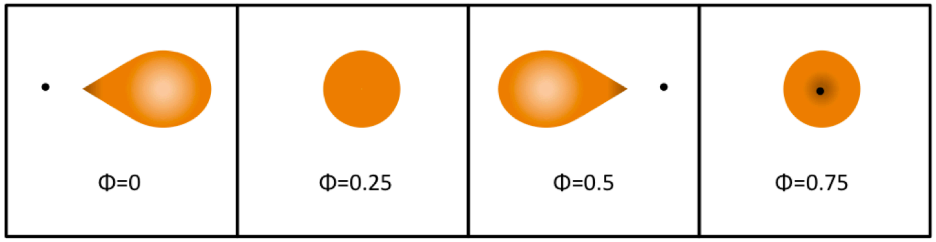
The variability is associated with the pulsar binary motion



Two distinct and asymmetric minima

Clear signature
of ellipsoidal variations
induced by the NS tidal field
on a highly perturbed
bloated star



IGR J18245-2452/PSR J1824-2452I

LETTER (Papitto et al. 2014, Nature 501,517)

doi:10.1038/nature12470

Swings between rotation and accretion power in a binary millisecond pulsar

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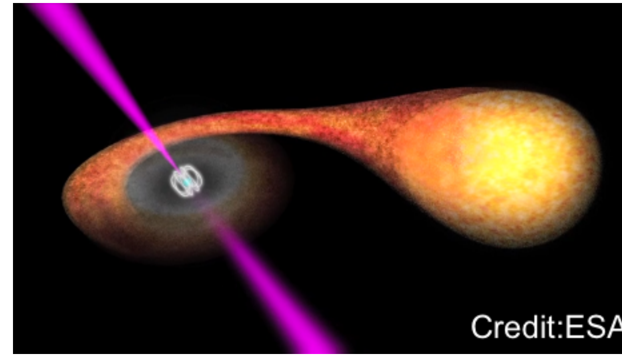

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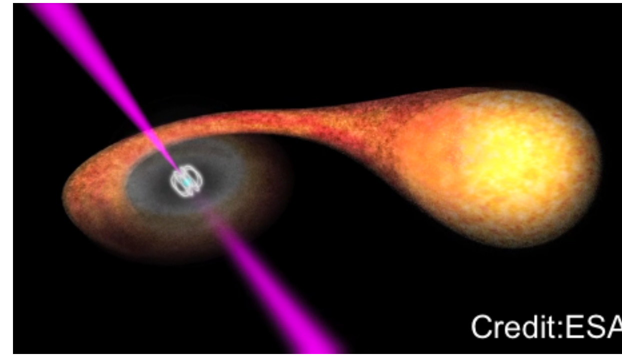
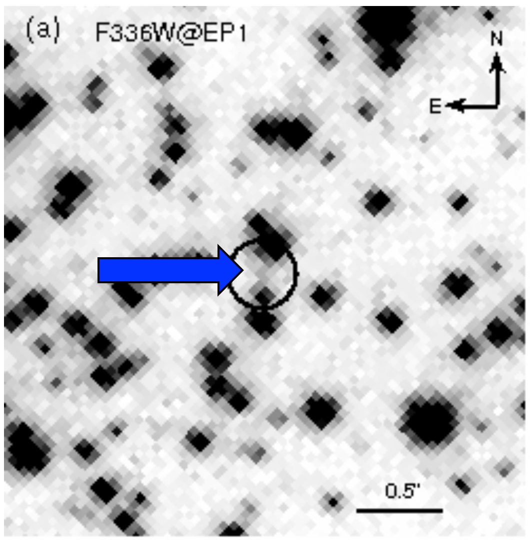


Apr 2009



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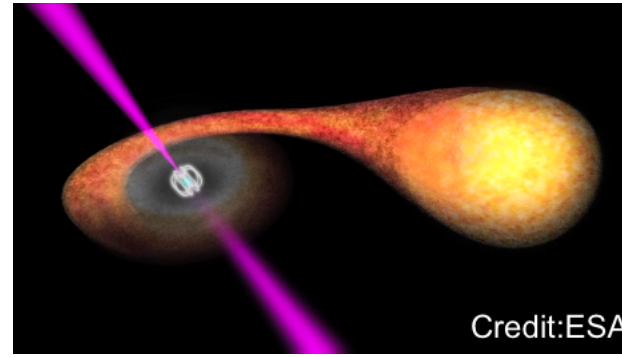

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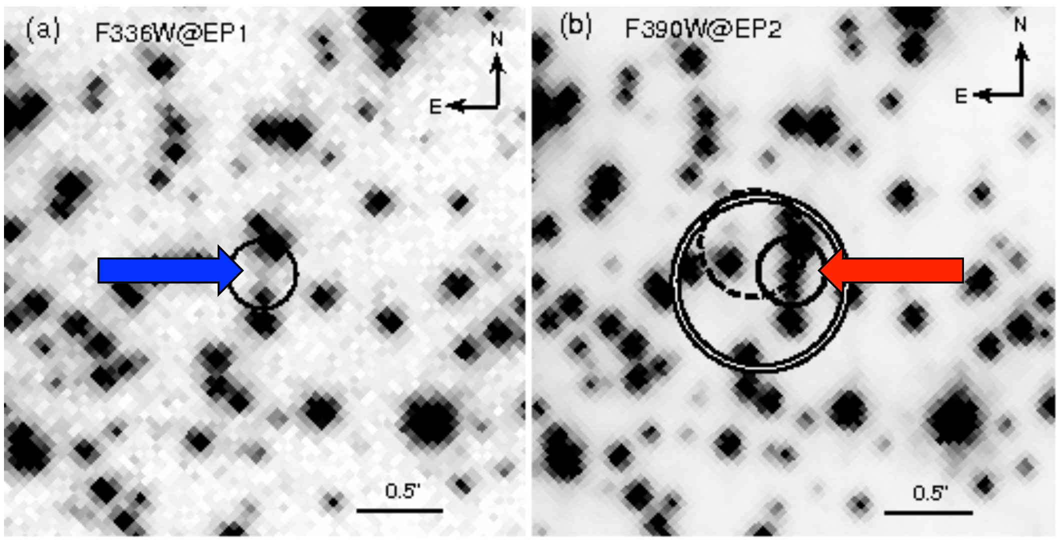

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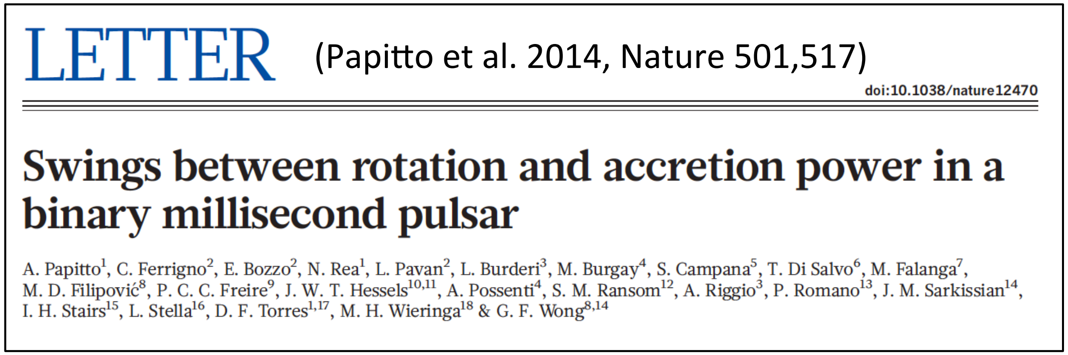

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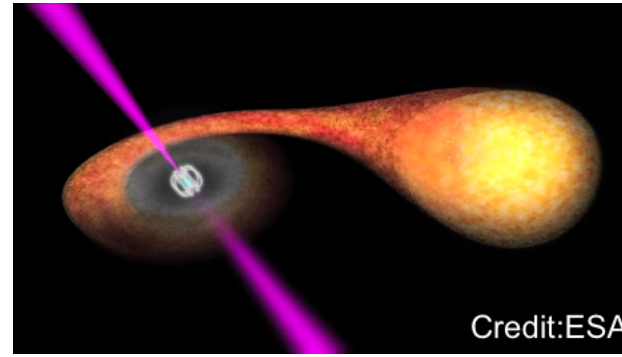

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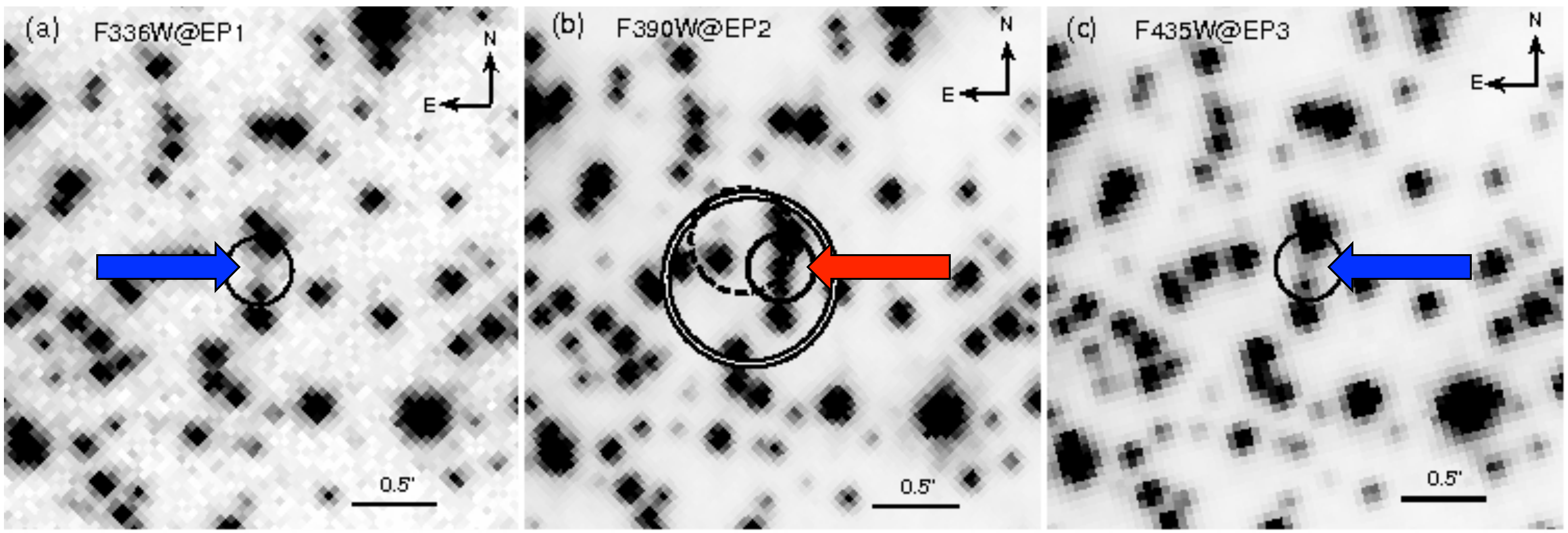

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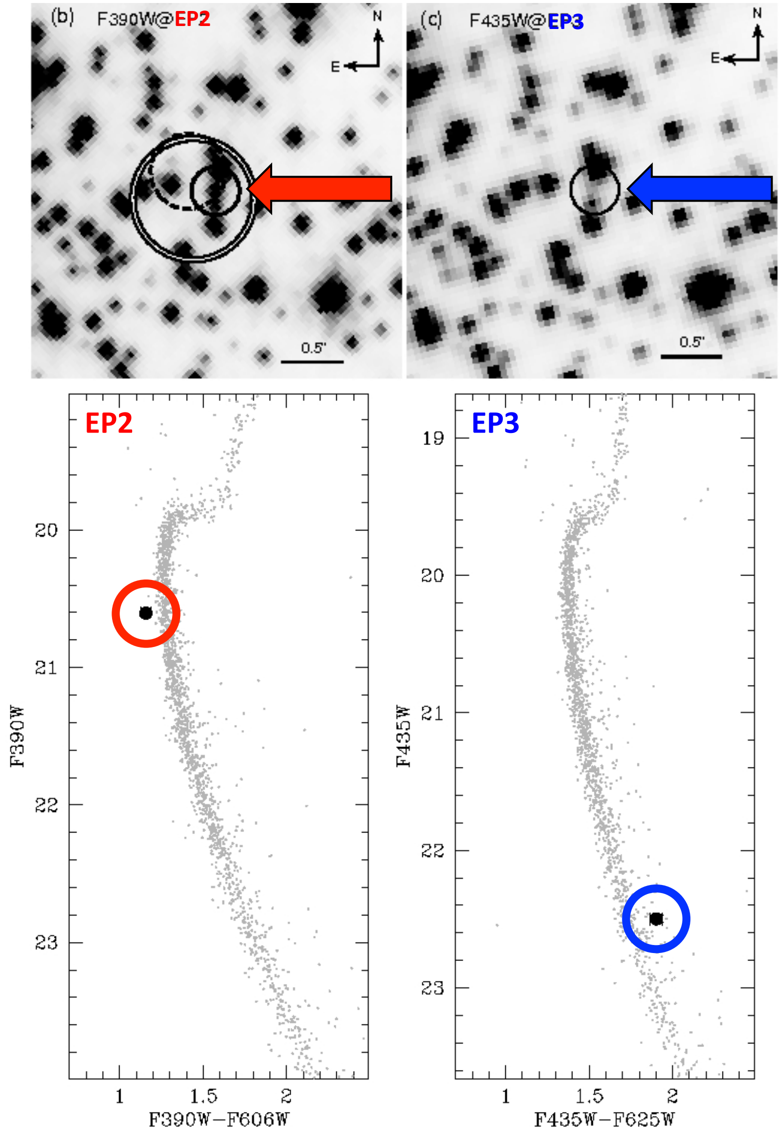

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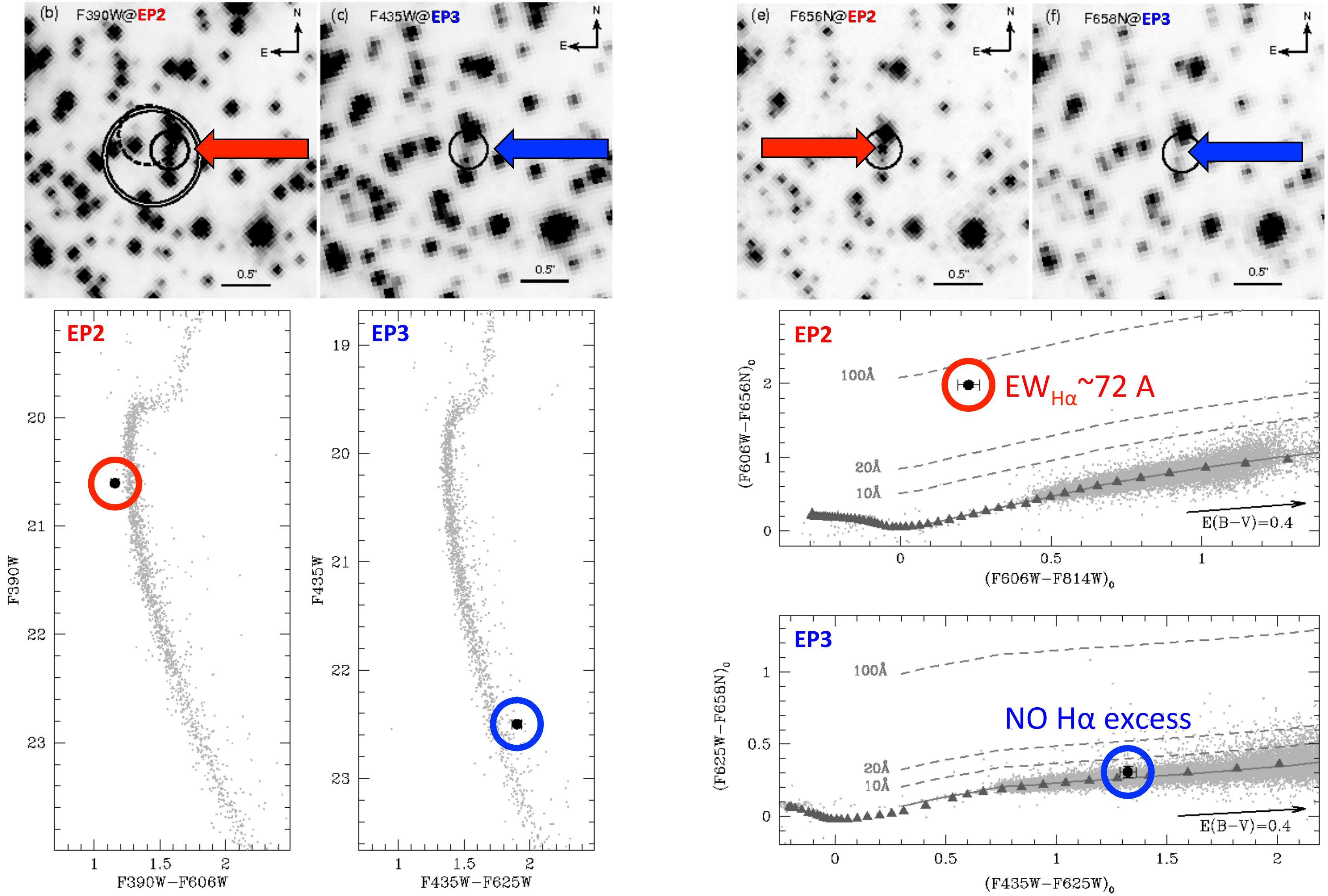


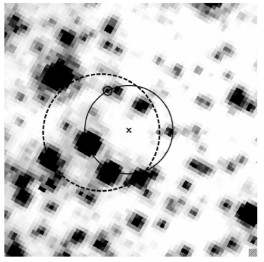
The optical approach

Radio

Optical

Photometry

Astrometry



Very Accurate position

CMD position
(Out of sequence)

Nature and physical parameters

Orbital parameters

Orbital period
Time ascending node

Light curve
(Variability in agreement with the orbital motion)

PSR Mass function

i, M_{COM}, M_{PSR}

Total mass

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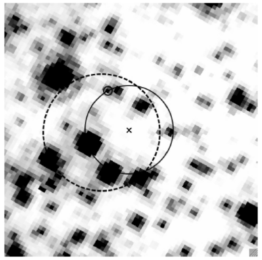

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IF BRIGHT ENOUGH

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Photometry

Spectroscopy

Astrometry

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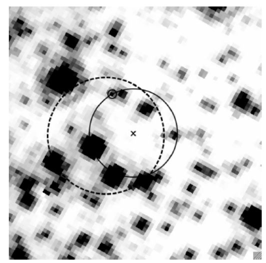

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Radial Velocity

COM mass function

+
PSR mass function

Mass ratio

System solved

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Optical

Photometry

Spectroscopy

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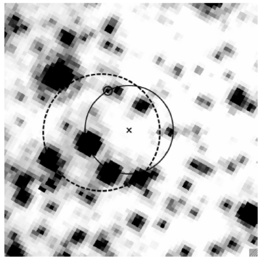

Radial Velocity

COM mass function

+

PSR mass function

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Mass ratio

System solved

PSR Mass function

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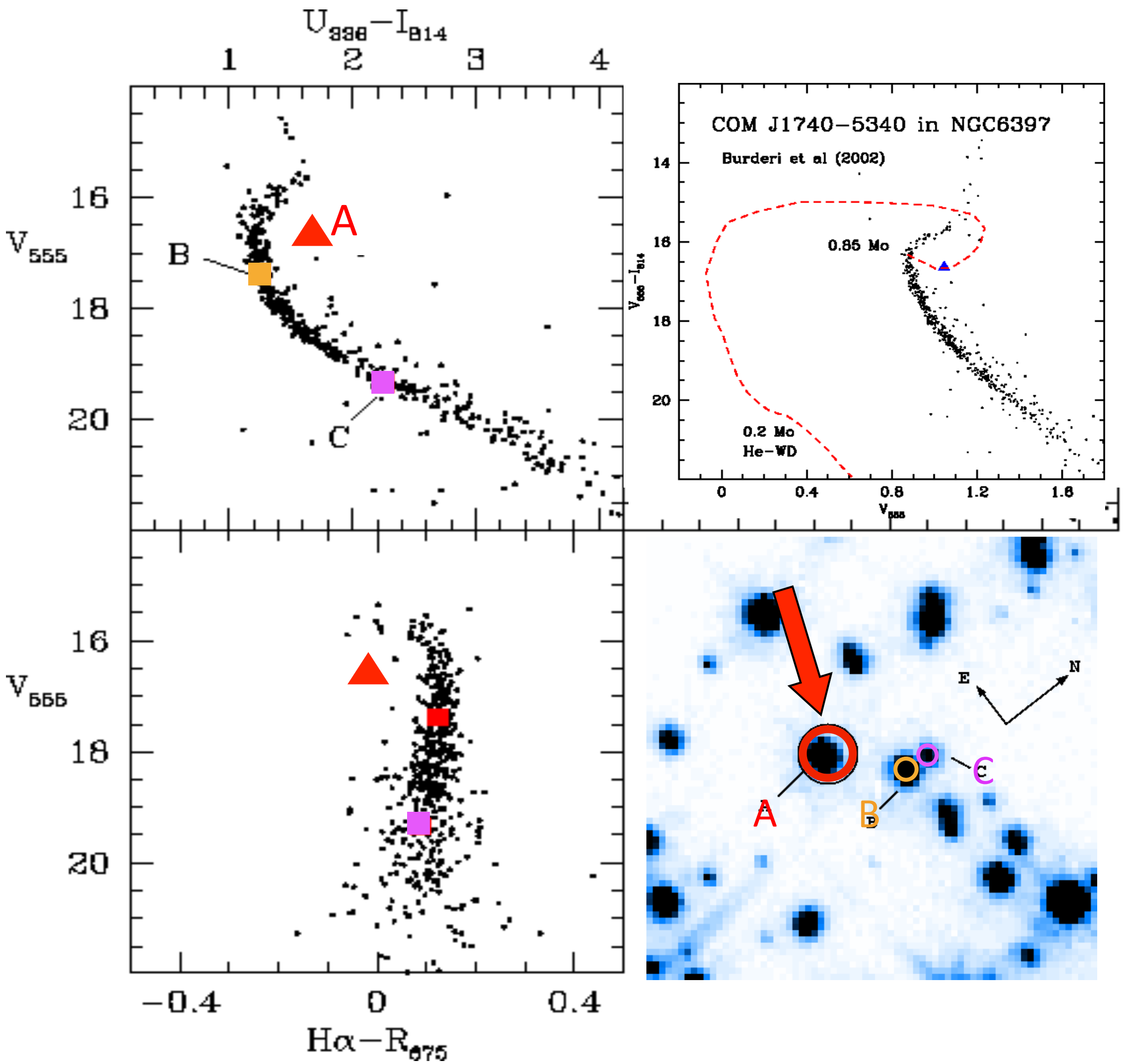
Chemical abundances

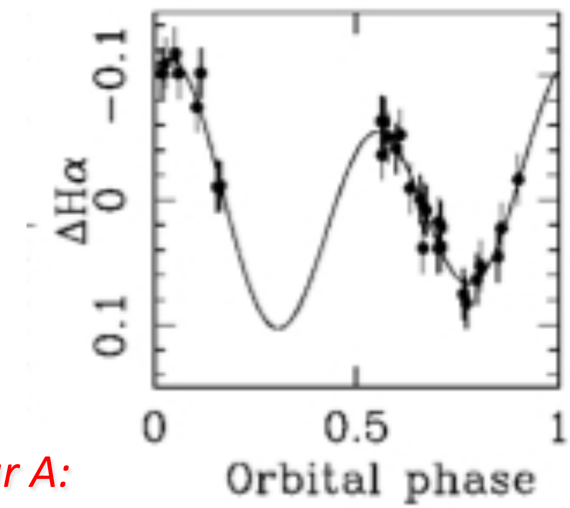
Measure of the mass of a peeled star

Total mass

$M_{PSR}=M_{TOT}-M_{COM}$

COM J1740-5340A: literature





Star A:

- **has an anomalous position in the CMD**
- **shows *Hα* emission**
- **is *NOT* a WD !!**
- **shows variability consistent with the P_b**

(Ferraro et al. 2001)

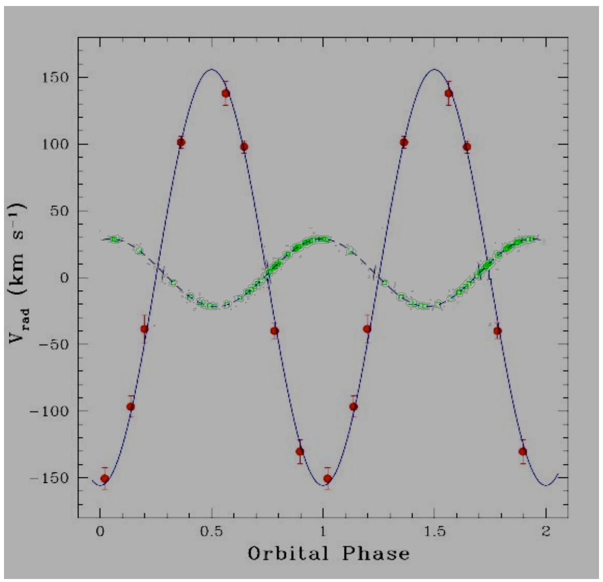
COM J1740-5340A: literature

Bright object (V=16.5) => High-resolution spectroscopy with UVES/VLT

Lines doppler shift

↓

Measure of the radial velocity



Orbital period

Ascending node

P (Radio)

Pulse delay (X-ray)

Rad. vel. (Optical)

$$\frac{\boxed{f_{COM} = \dfrac{4\pi^2 c^3 x_c^3}{G M_\odot P_b^2} = \dfrac{(m_p \sin i)^3}{(m_c + m_p)^2}}}{\boxed{f_{PSR} = \dfrac{4\pi^2 c^3 x_p^3}{G M_\odot P_b^2} = \dfrac{(m_c \sin i)^3}{(m_c + m_p)^2}}} \Longrightarrow \frac{m_p}{m_c}$$

Mass ratio q=5.85±0.13

V_{rad} amplitude of Star A: 155.8±3.6 km/s

Mass of MSP	1.30 : 1.90 $M_\odot$
Mass of Star A	0.22 : 0.32 $M_\odot$
Inclination angle	56 : 47 deg
Orbital separation	6.1 : 7.0 $R_\odot$
Roche lobe radius	1.5 : 1.7 $R_\odot$

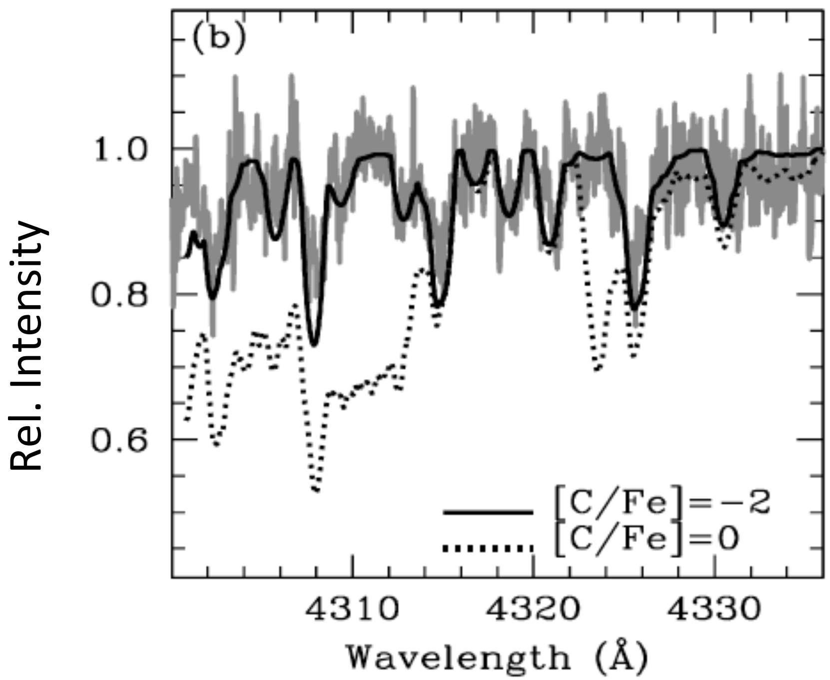
(Ferraro et al., 2003

COM J1740-5340A: spectroscopic follow-up

Bright object (V=16.5)

High-resolution with UVES/VLT

No C in its atmosphere



(Sabbi et al., 2003; Mucciarelli et al., 2013)

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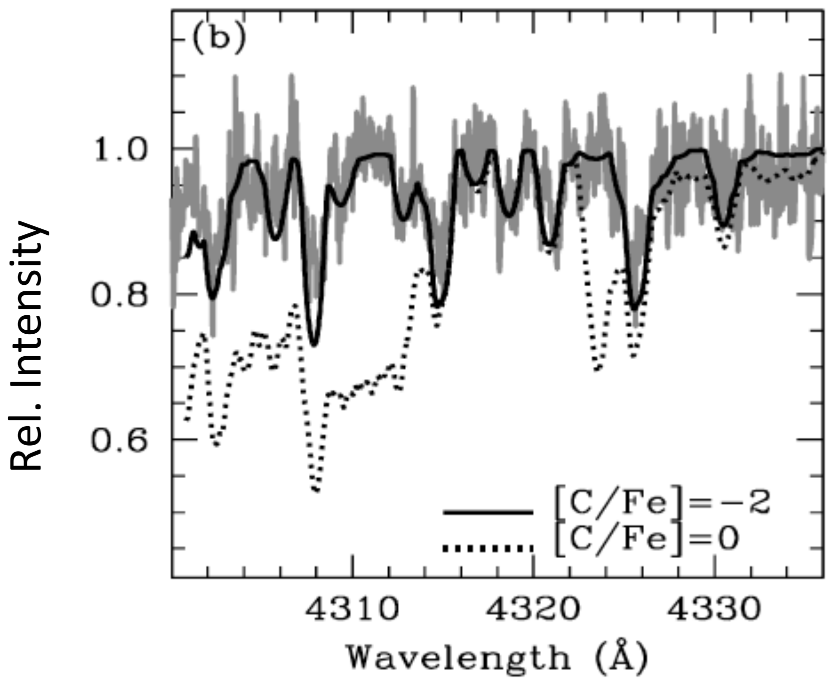

New high resolution XSHOOTER spectra

N enhanced

(Sabbi et al., 2003; Mucciarelli et al., 2013)

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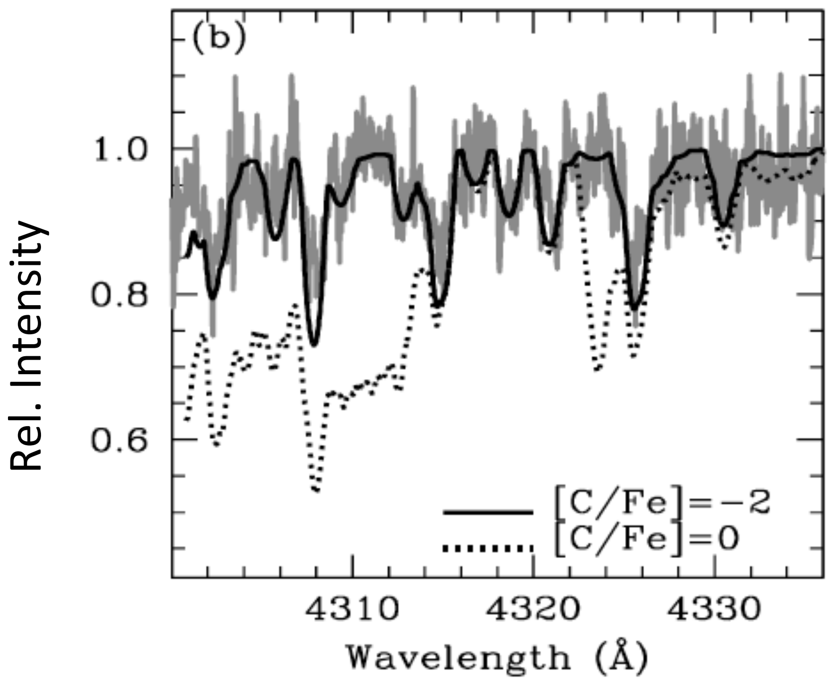


Material processed by CNO-burning

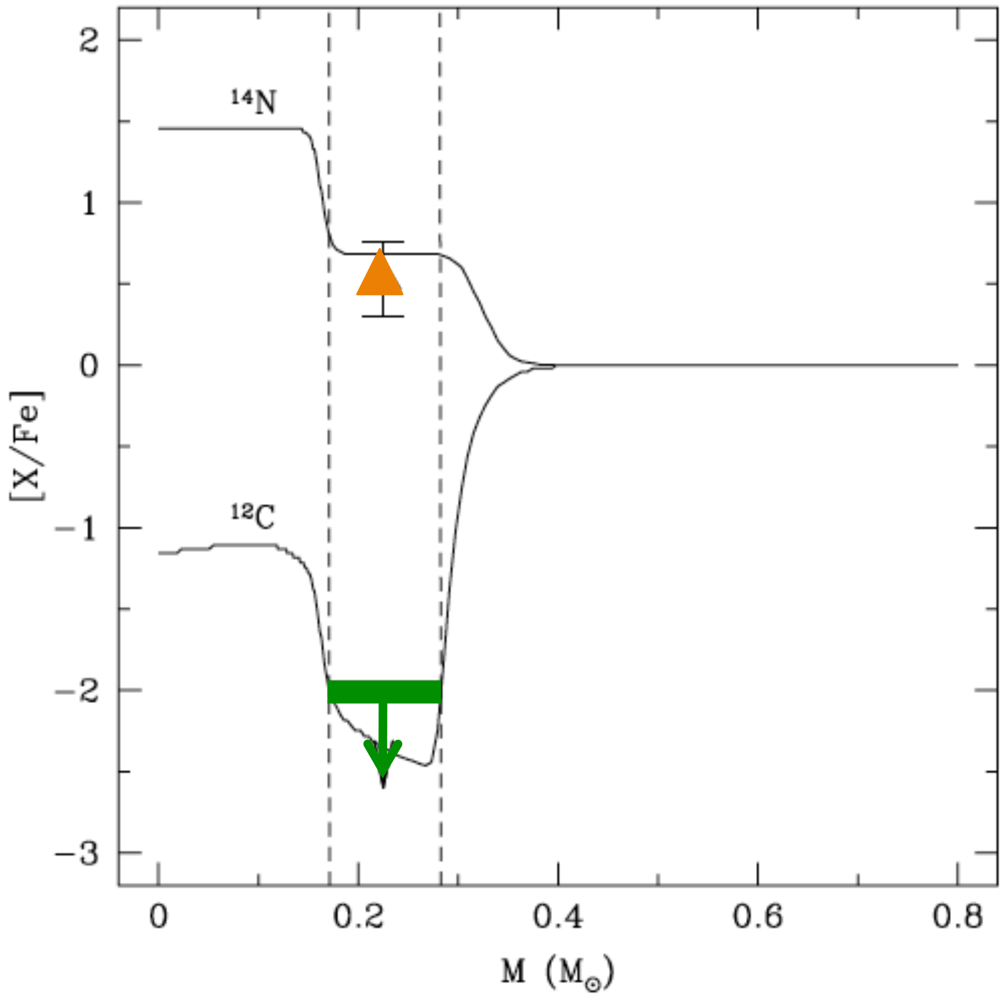
Deeply peeled star

New high resolution XSHOOTER spectra

N enhanced

(Sabbi et al., 2003; Mucciarelli et al., 2013)

COM J1740-5340A: spectroscopic follow-up



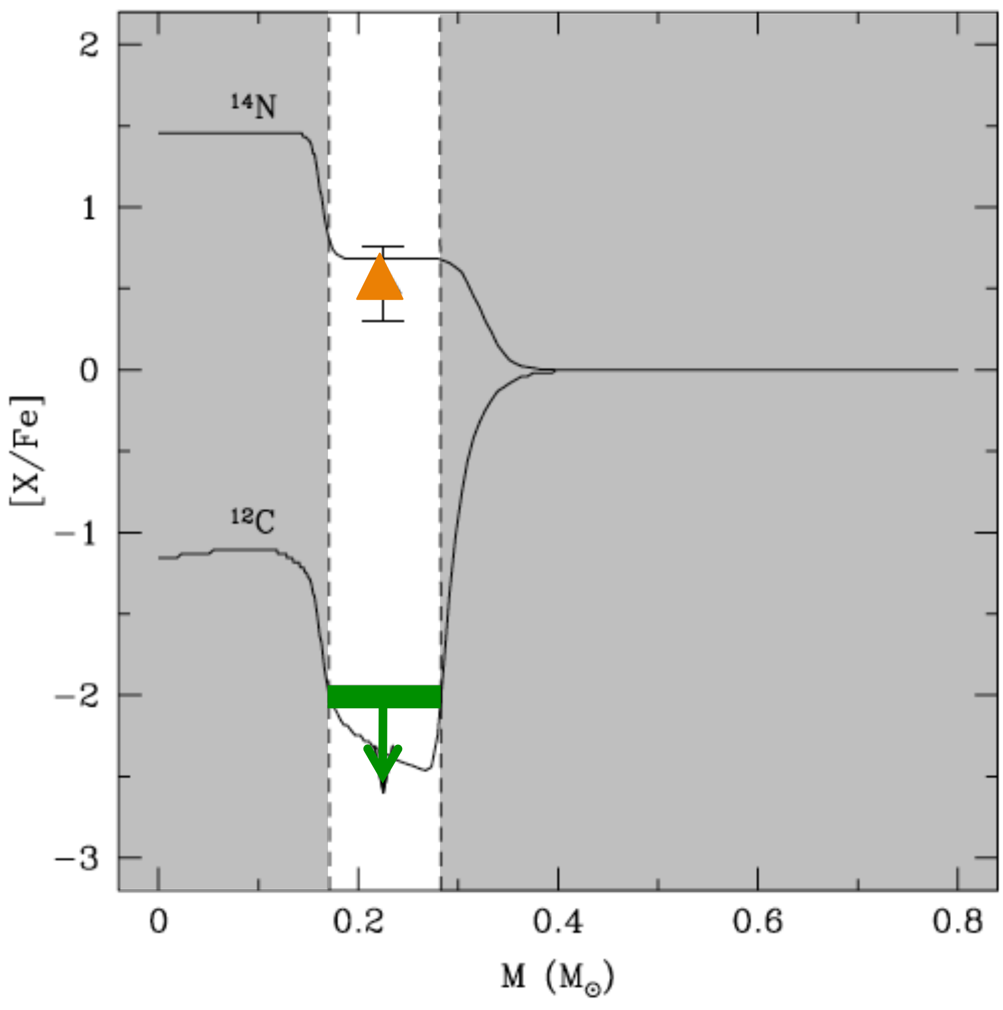
CORE

ENVELOPE

N abundance

C upper limit

COM J1740-5340A: spectroscopic follow-up



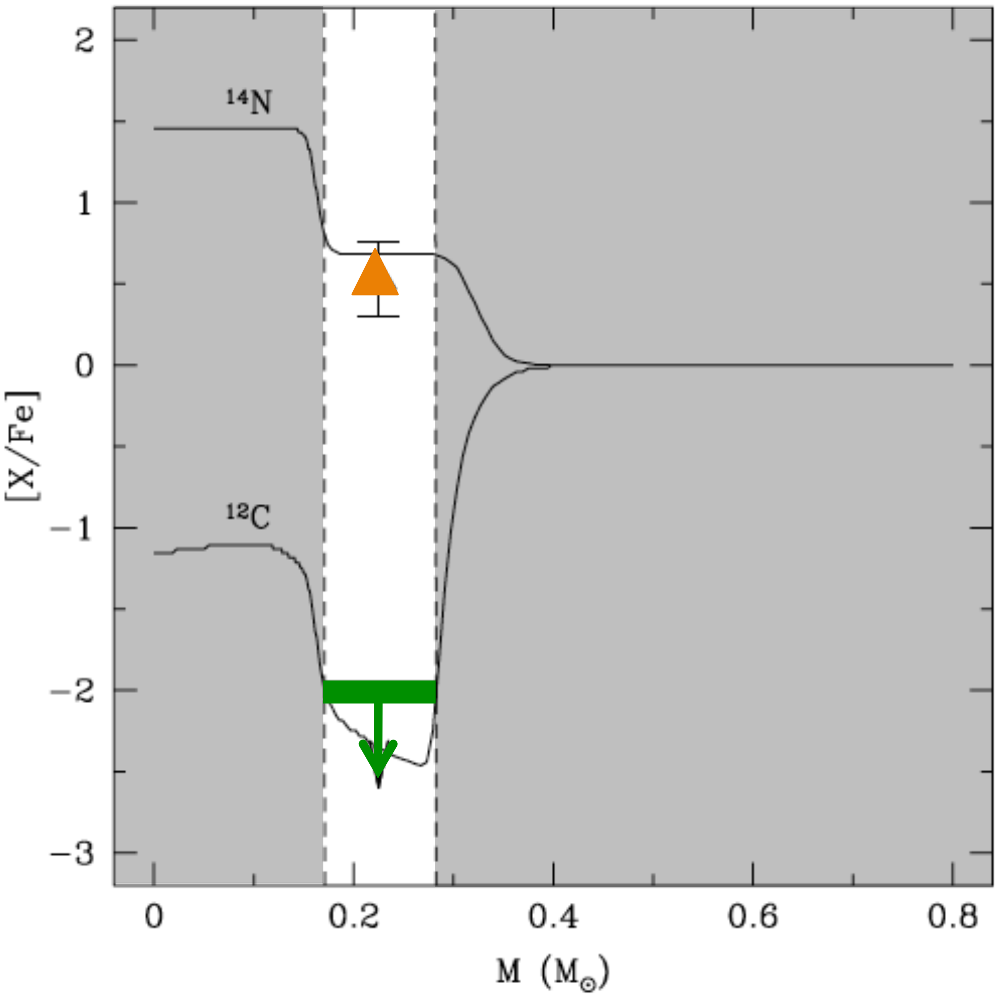
CORE **ENVELOPE**

N abundance

C upper limit

$0.17\ M_\odot < M_{com} < 0.28\ M_\odot$

COM J1740-5340A: spectroscopic follow-up



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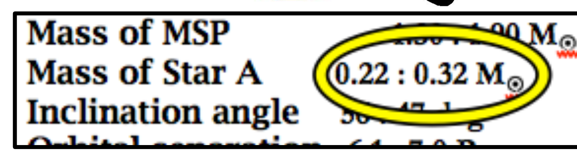
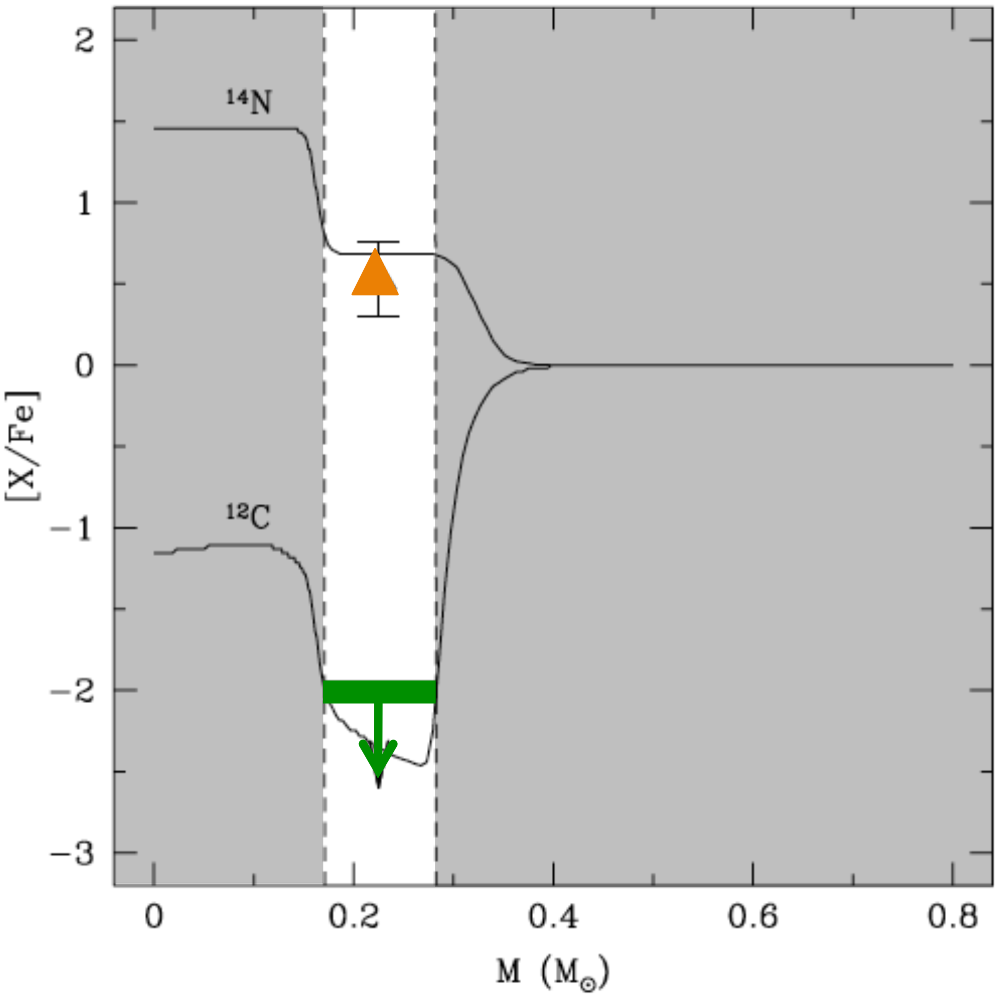


COM J1740-5340A: spectroscopic follow-up



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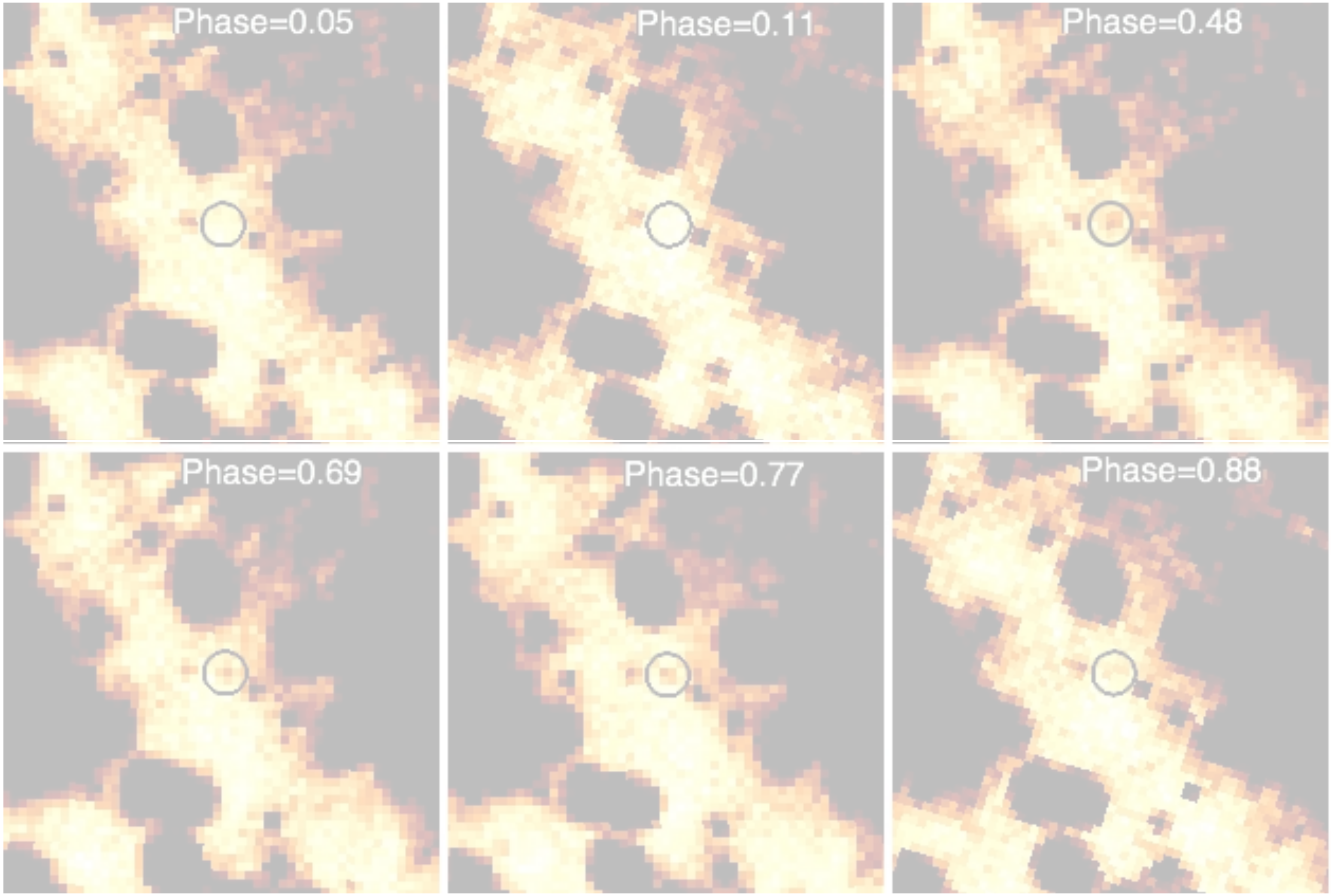
Inclination angle	

Deeply peeled star because of mass transfer

The BW PSR J1518+0204C in M5



WFC3/UVIS@HST images in the F814W at different epochs

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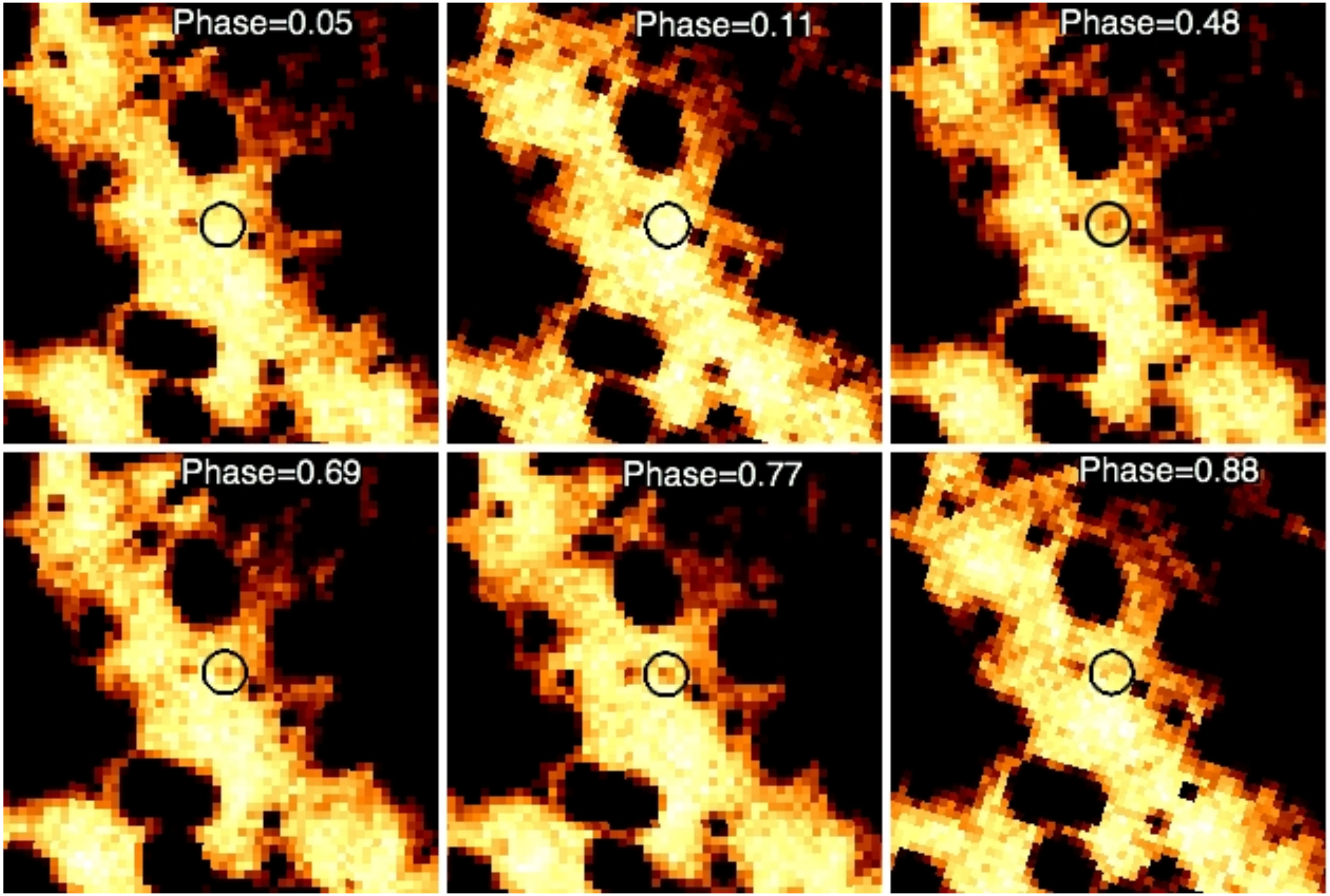

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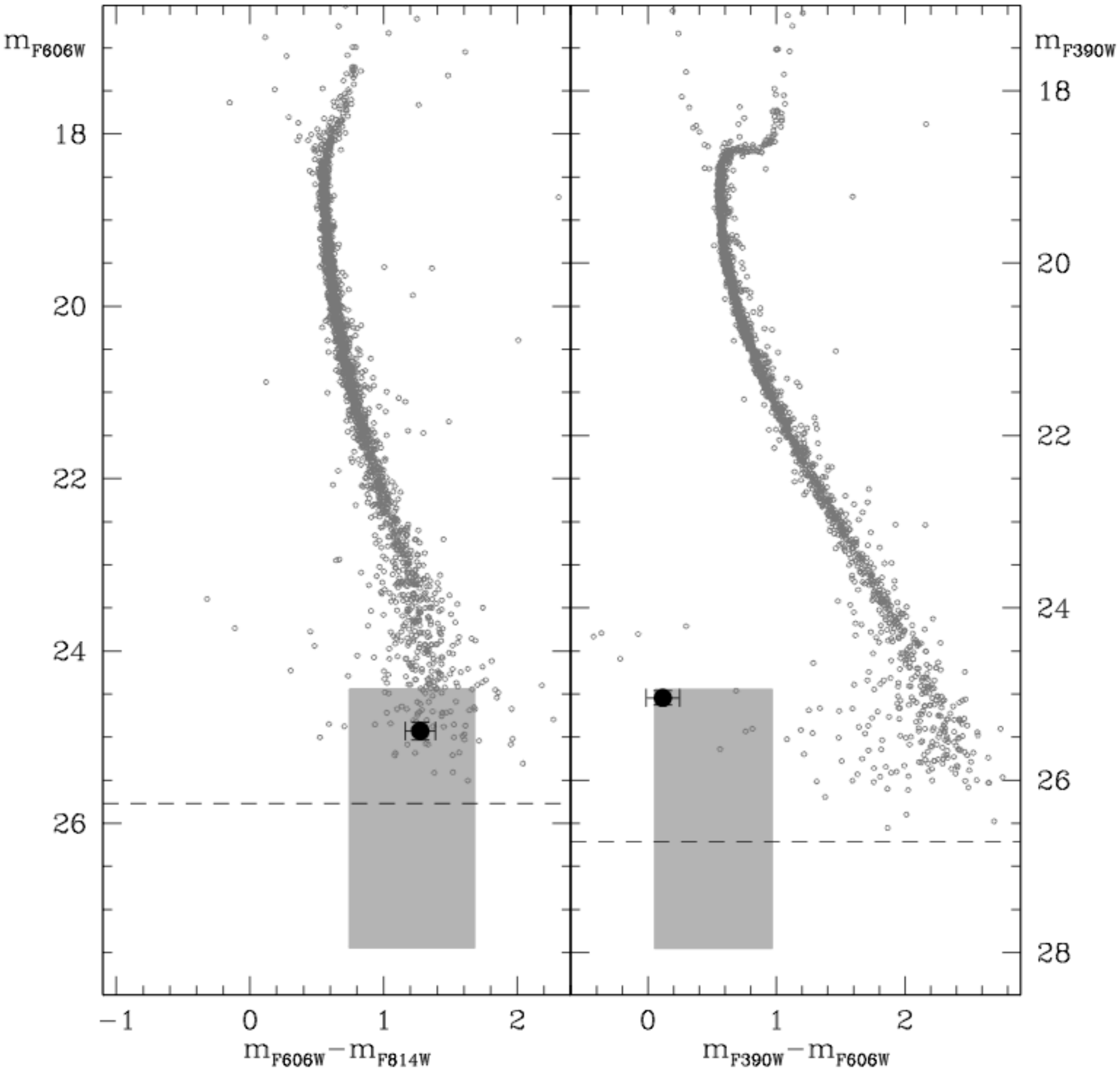
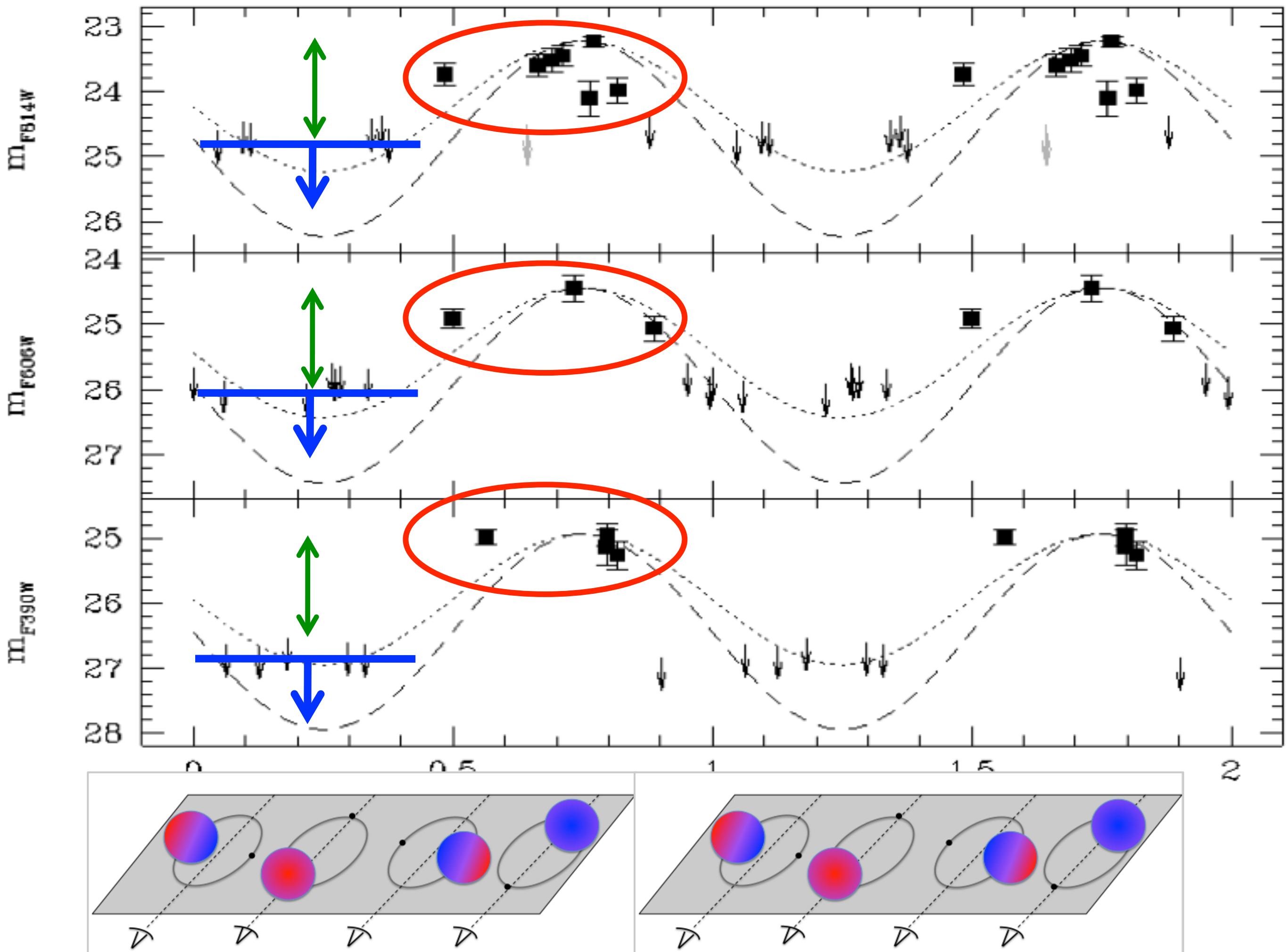


CMD position consistent with a location between the WDs and the MS

$M_{COM}<0.2M_{\odot}$

The BW PSR J1518+0204C in M5



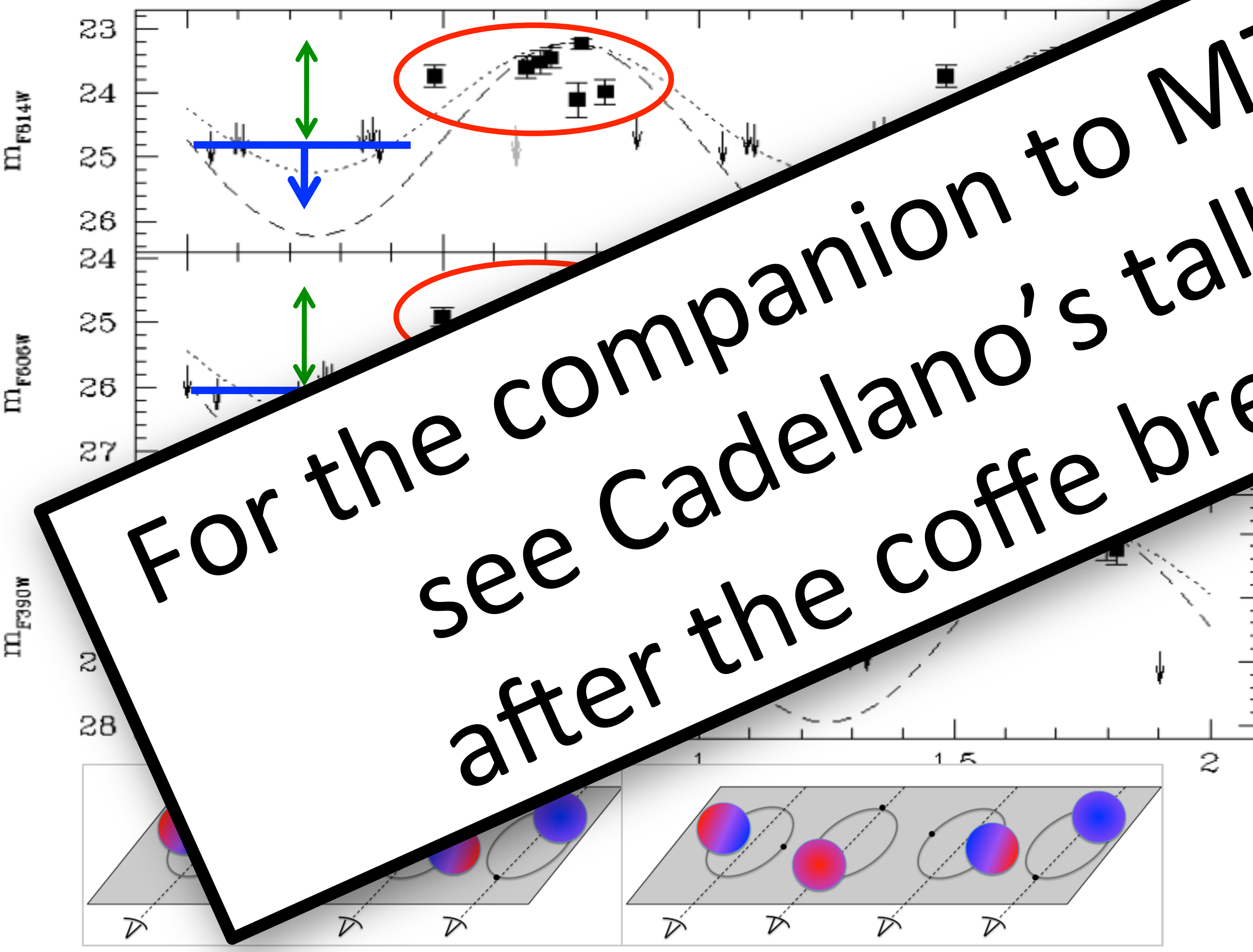
Orbital modulation in agreement with the orbital period

Detected at the PSR inferior conjunction

Under the detection limit at the PSR superior conjunction

Δmag>1.5 mag

The BW PSR J1518+0204C in



For the companion to M71A,
see Cadelano's talk
after the coffe break

l
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R inferior
conjunction

Under the detection limit at the PSR superior conjunction

Δmag>1.5 mag

Summary

We used multi-wavelength and multi-epoch observations:

The association with the PSRs has been based on:

-the ***positional coincidence***

-the ***position in the color-magnitude diagram***

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- ***The companions to RBs are 0.2 $M_{\odot}$ perturbed MS stars***
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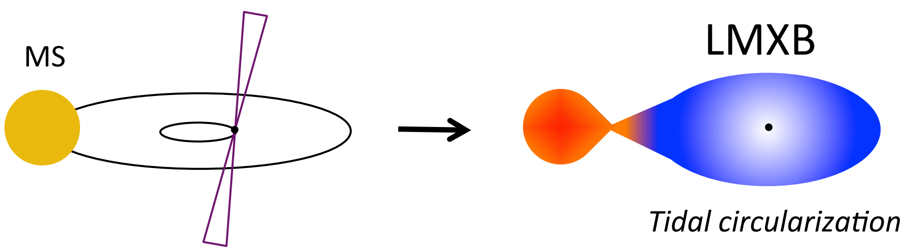
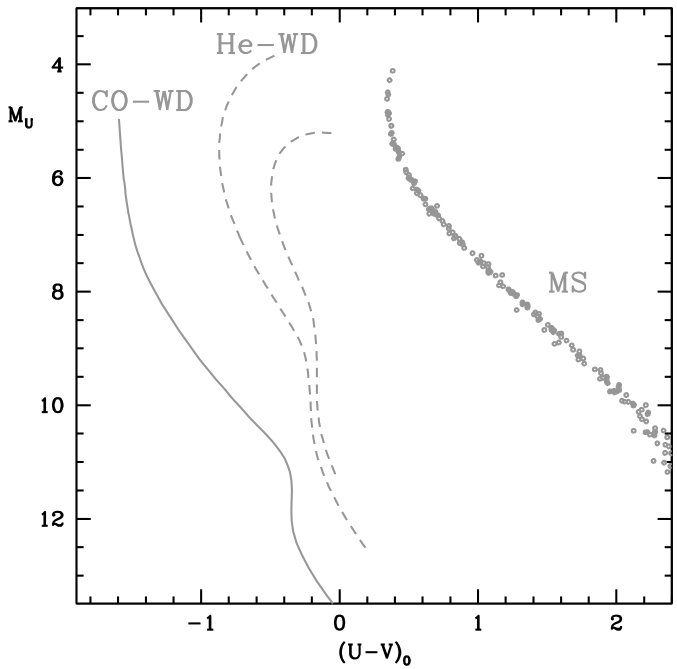
We performed a spectroscopic follow-up of 1 companion:

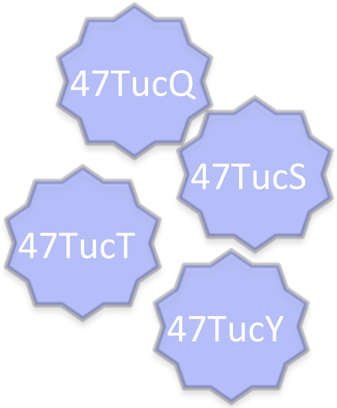
- ***The chemical analysis confirmed that it is an evolved deeply peeled star***

A cartoon of the evolutionary scenario

Canonical recycling scenario …

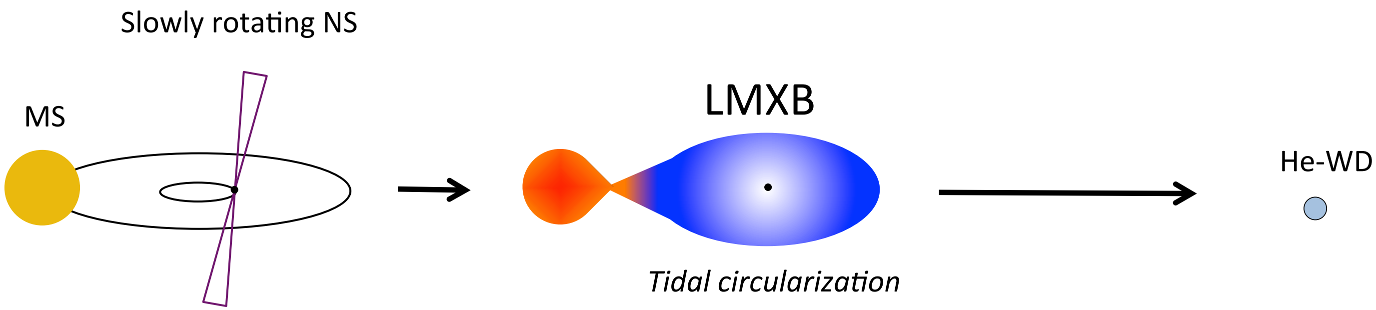


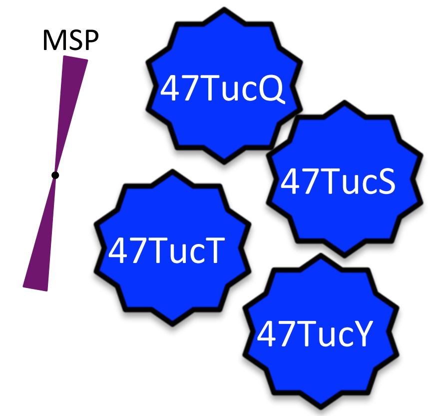


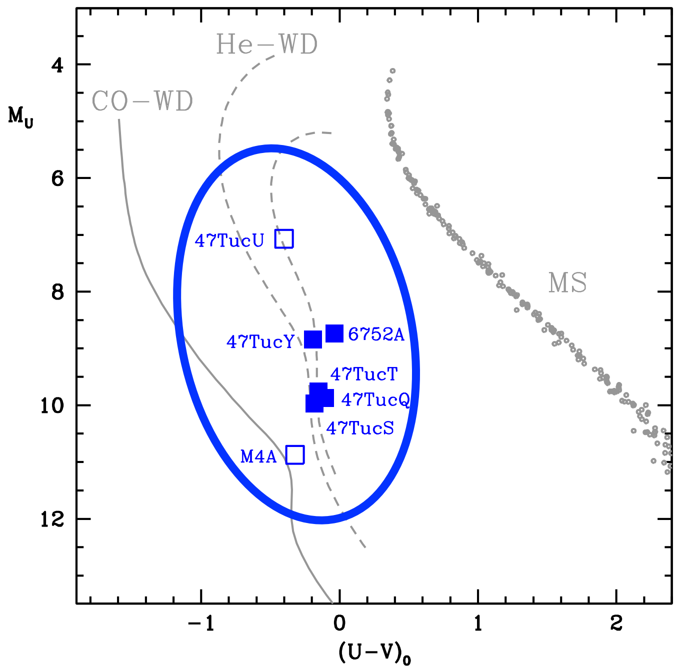


A cartoon of the evolutionary scenario

Canonical recycling scenario ... **... and deviations**







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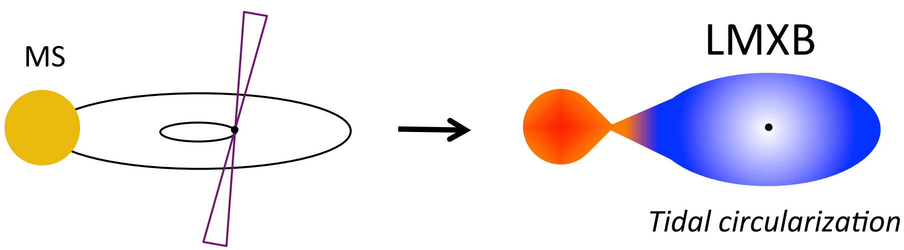

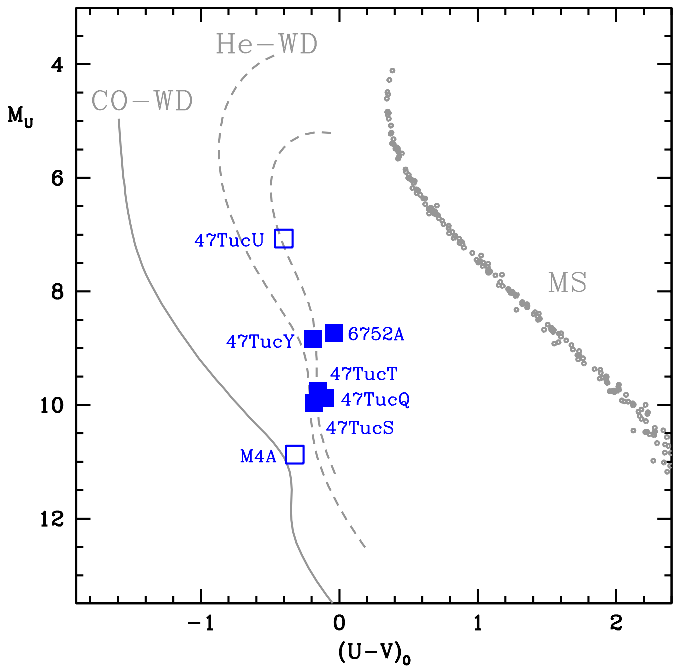

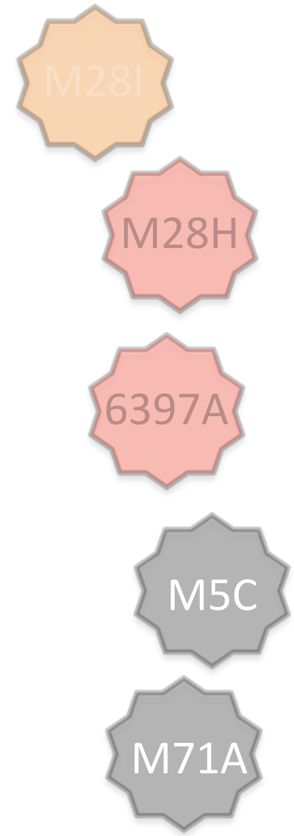

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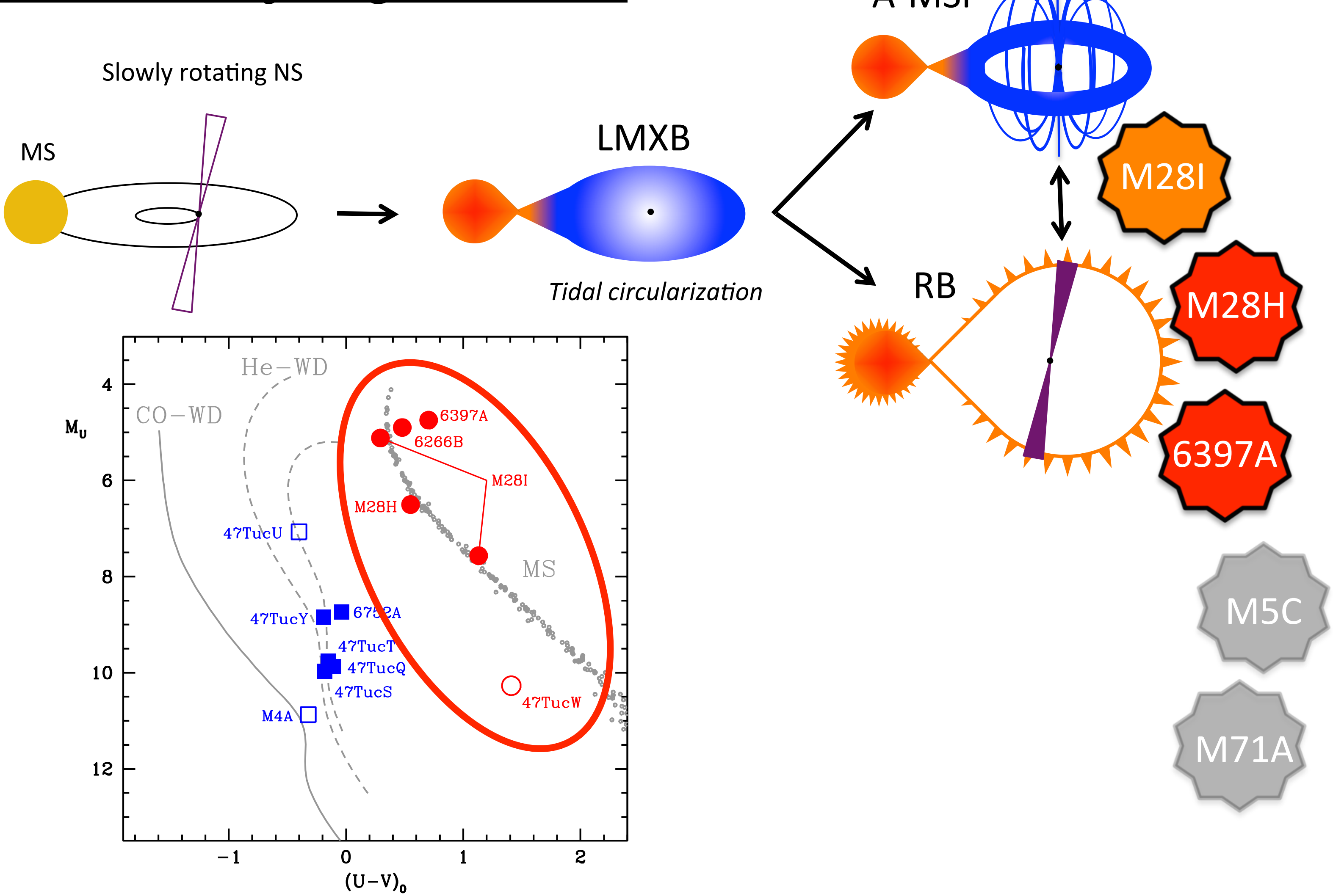

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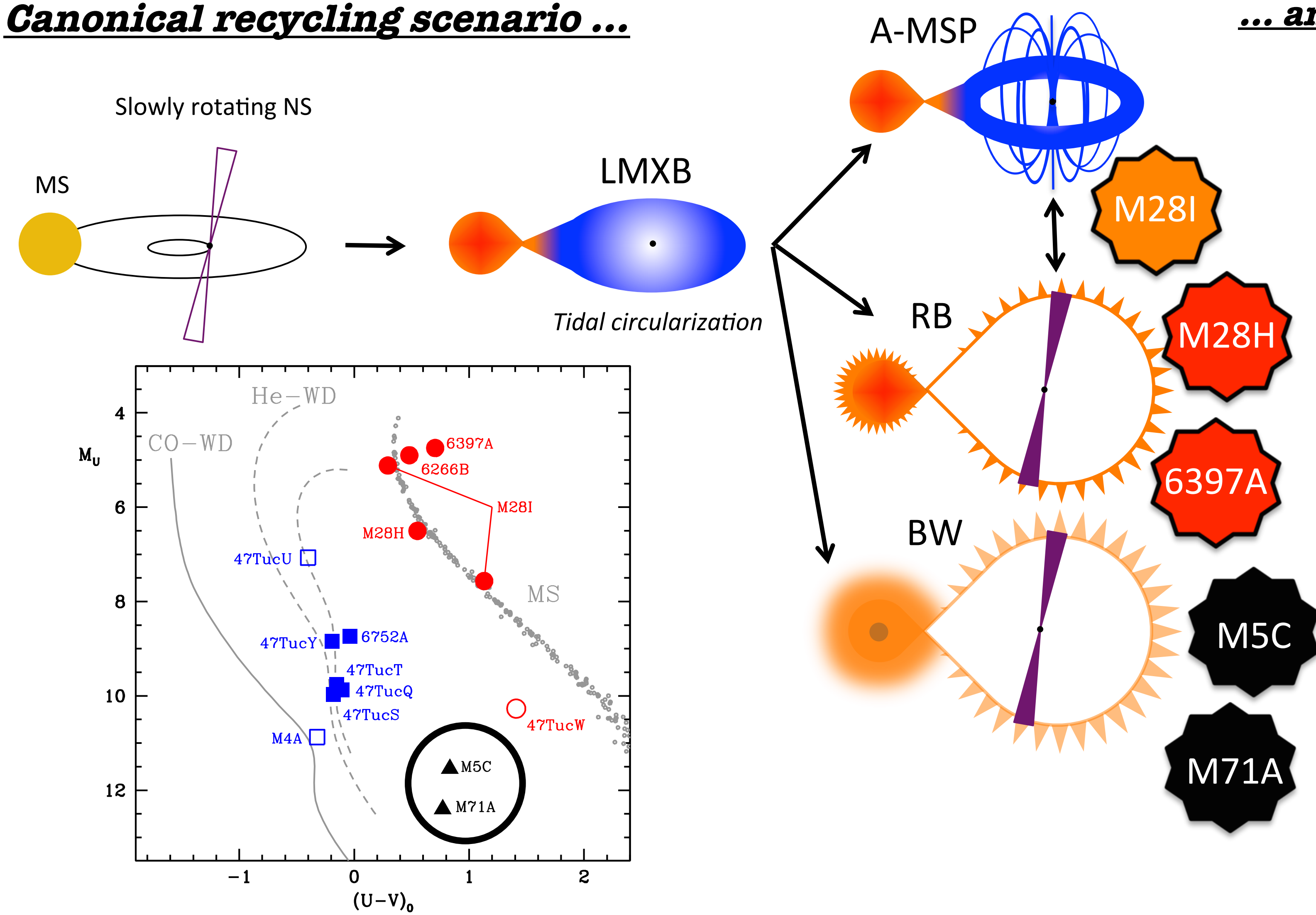

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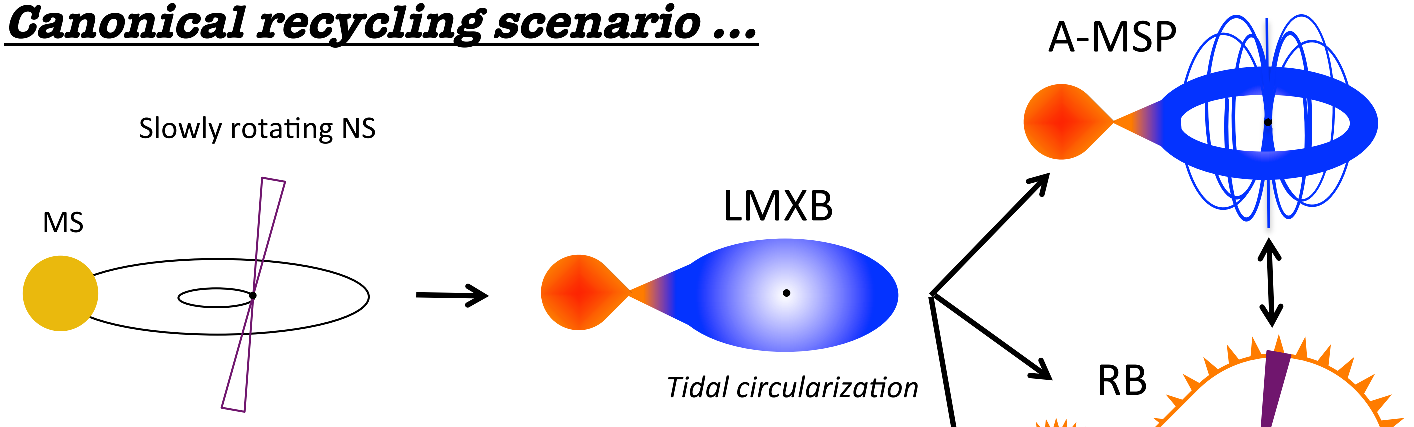

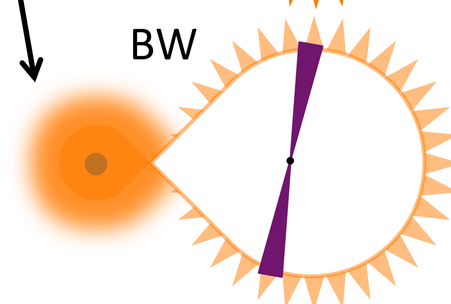

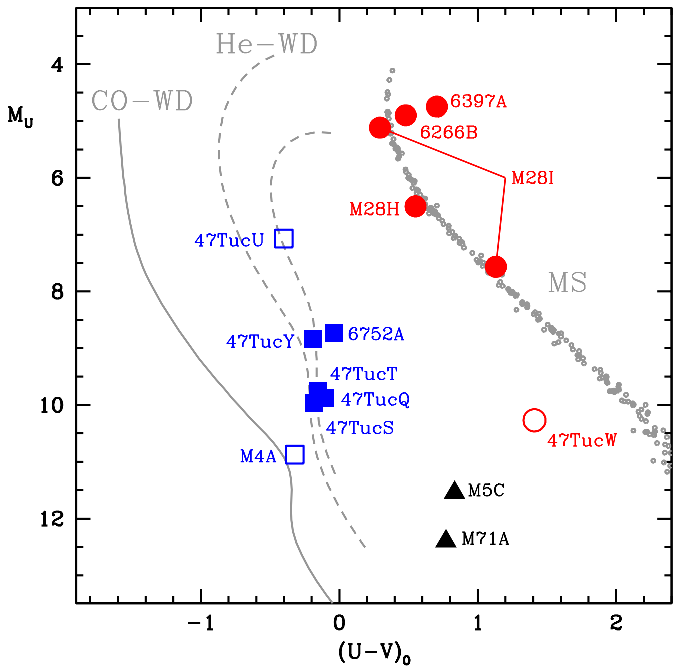

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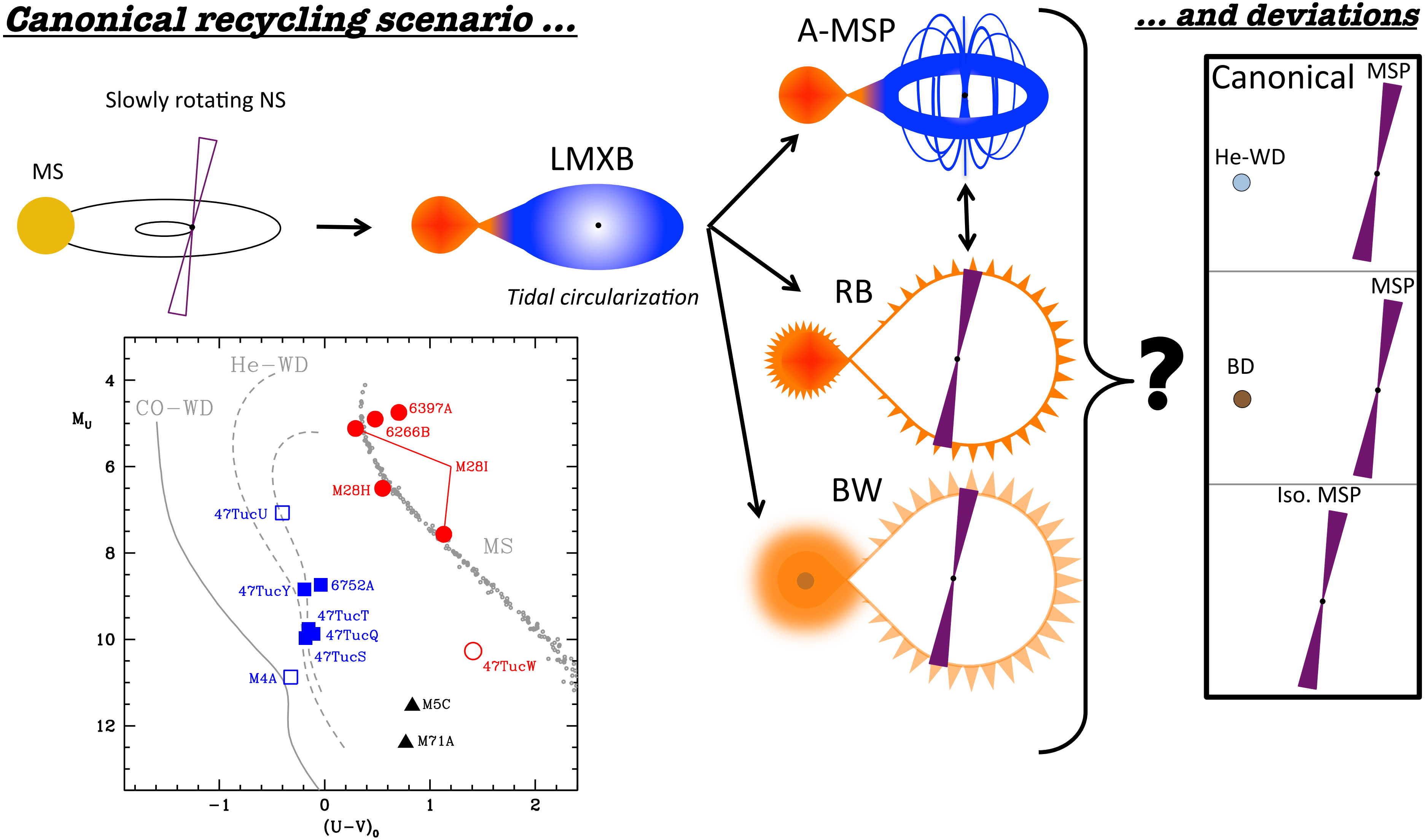

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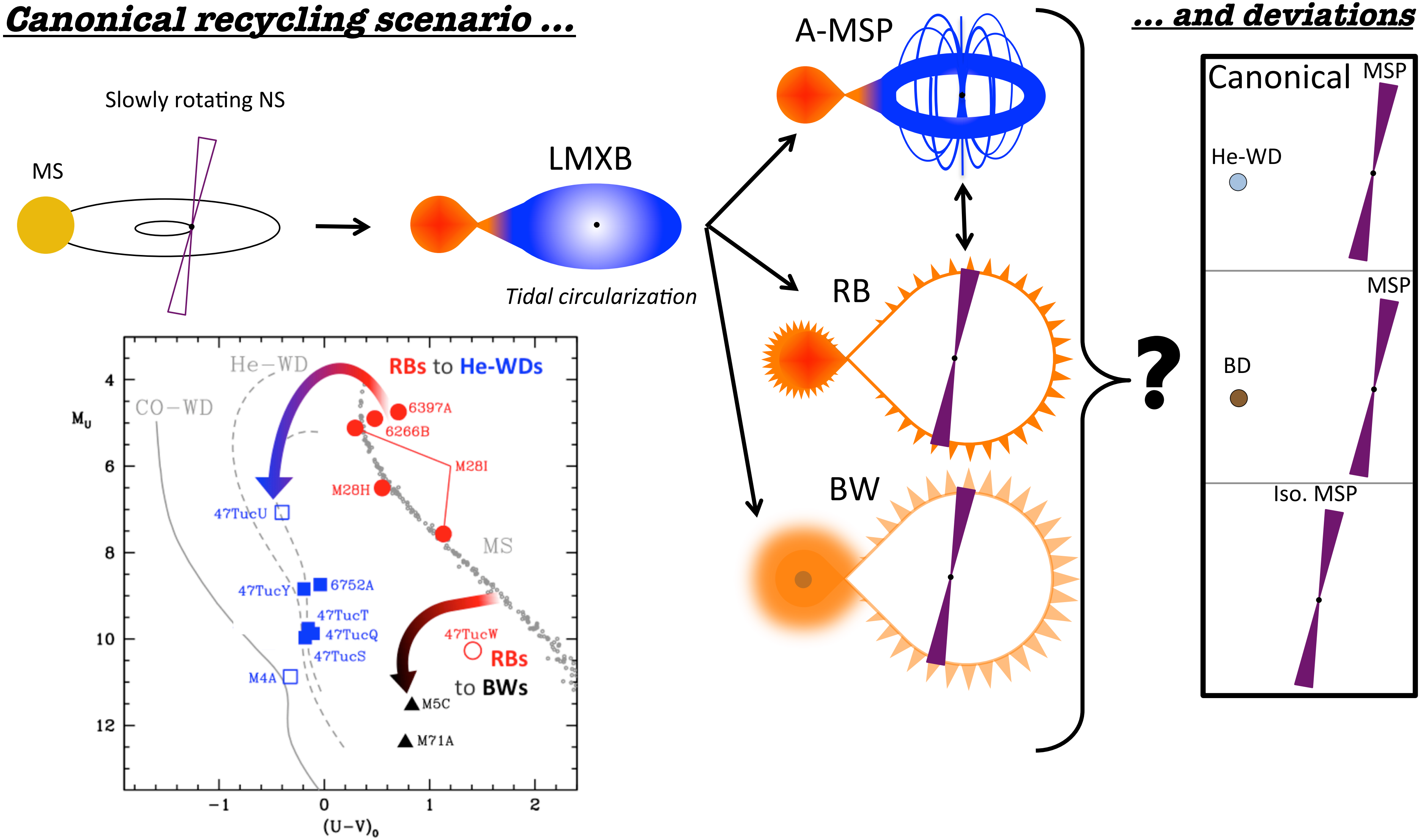

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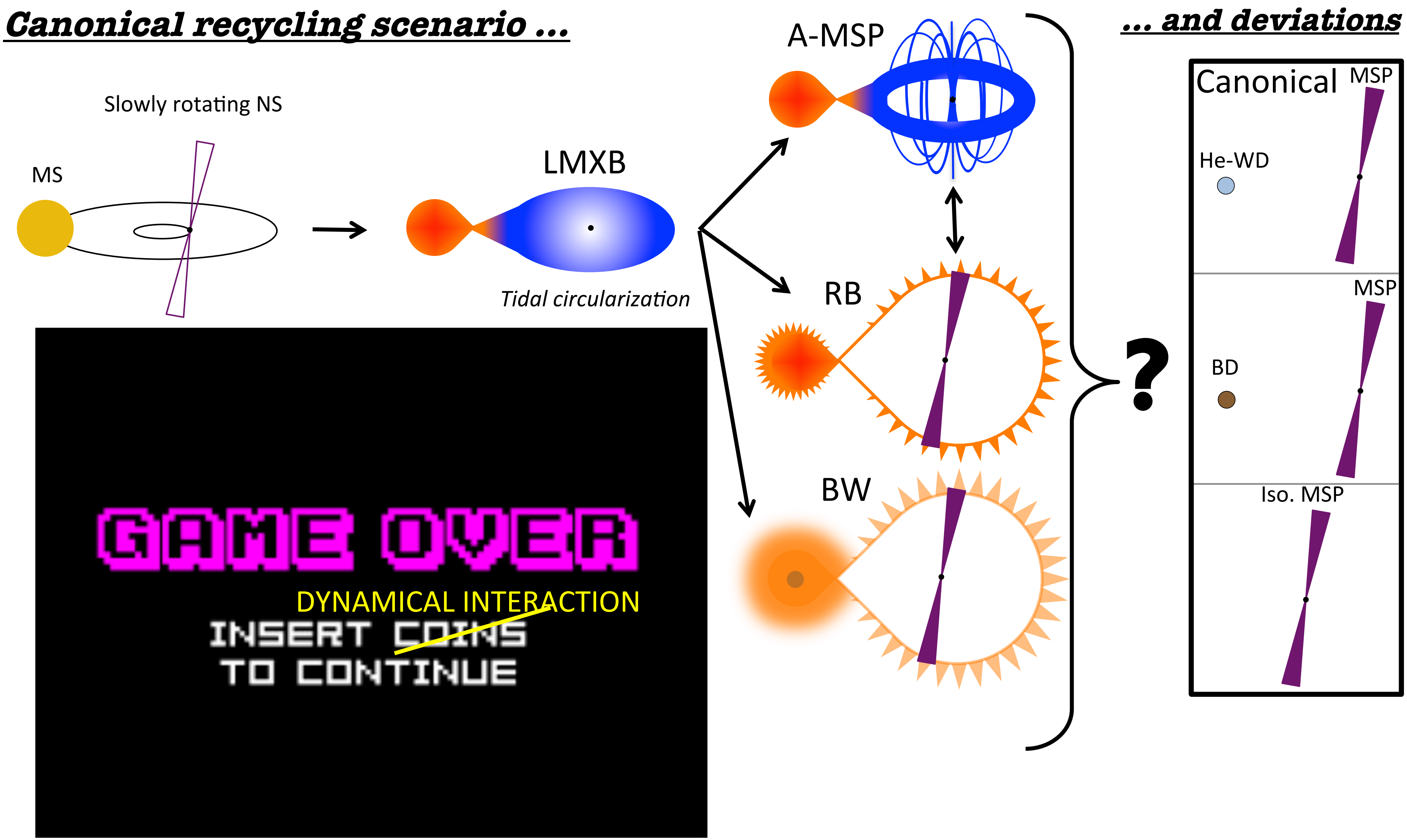

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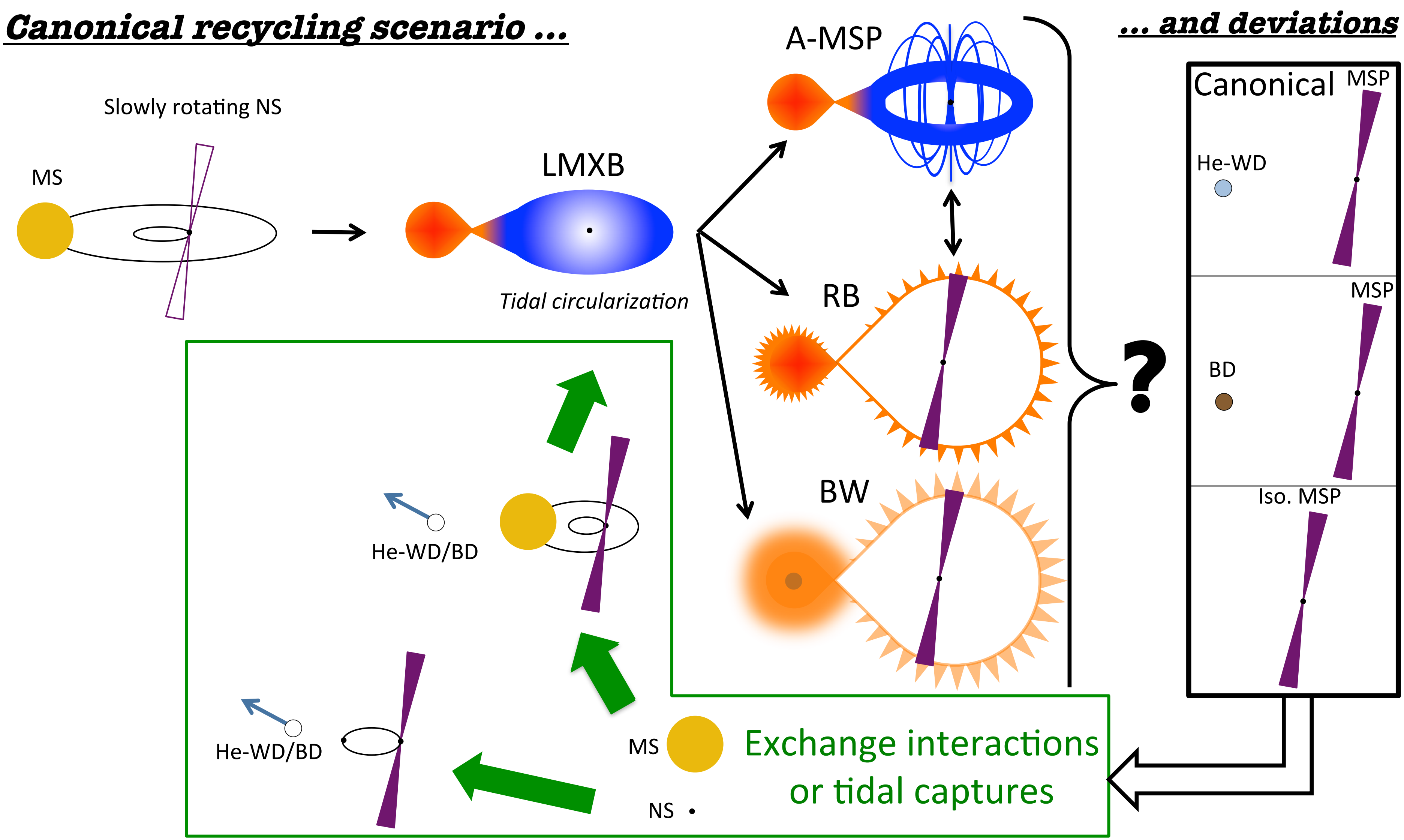

Thanks for your attention