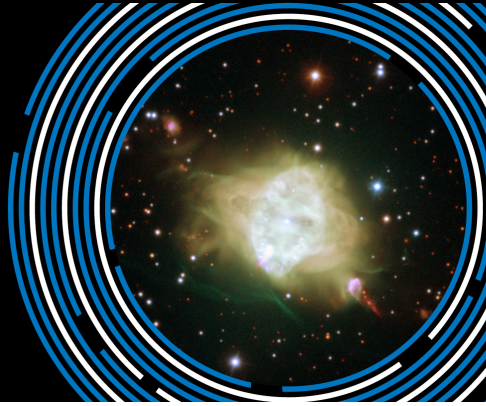
An ESO Workshop on
THE IMPACT OF BINARIES ON STELLAR EVOLUTION
03 – 07 July 2017 I ESO HQ, Garching, Germany



Optical companions to MSPs in GCs

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Bologna University

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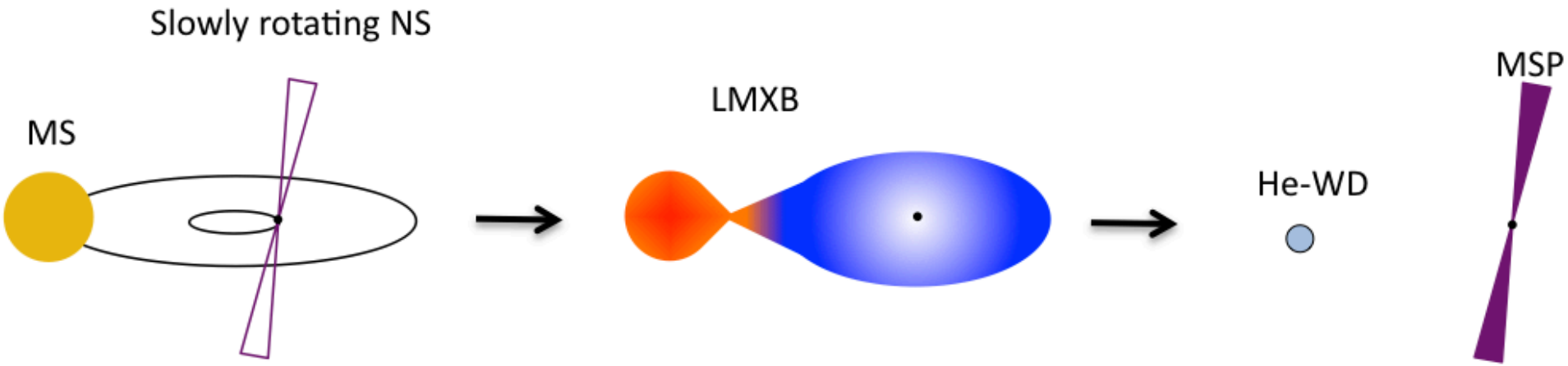
G. Beccari, M. Burgay, P. Freire, R. Mignani, A. Possenti, S. Ransom, I. Stairs

Cosmic-Lab

erc

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)

The optical approach

Radio

Optical

Photometry

Very Accurate position

Orbital parameters

Orbital period
Time ascending node

PSR Mass function

Total mass

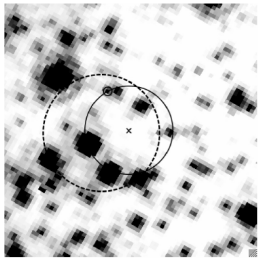
The optical approach

Radio

Optical

Photometry

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 ↔ $M_{PSR}=M_{TOT}-M_{COM}$

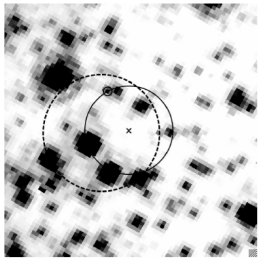
The optical approach

Radio

Optical

Photometry

Astrometry



Very Accurate position → High resolution

!!! Positional coincidence !!!

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} → !!! Orbital variability !!!

Total mass ↔ $M_{PSR}=M_{TOT}-M_{COM}$

A "mass/type" classification of MSPs

High mass

$M_{COM} > 1\ M_{\odot}$

NSs

Intermediate mass

$0.5\ M_{\odot} < M_{COM} < 1\ M_{\odot}$

CO/ONe-WDs

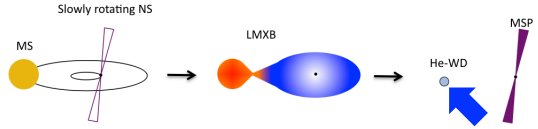
Low mass

$M_{COM} < 0.5\ M_{\odot}$

Canonicals

$0.1\ M_{\odot} < M_{COM} < 0.5\ M_{\odot}$

He-WDs



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Intermediate mass
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CO/ONe-WDs

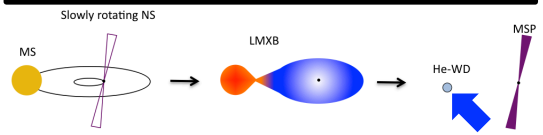
Low mass
$M_{COM} < 0.5\ M_\odot$

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

10 in GCs

?

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



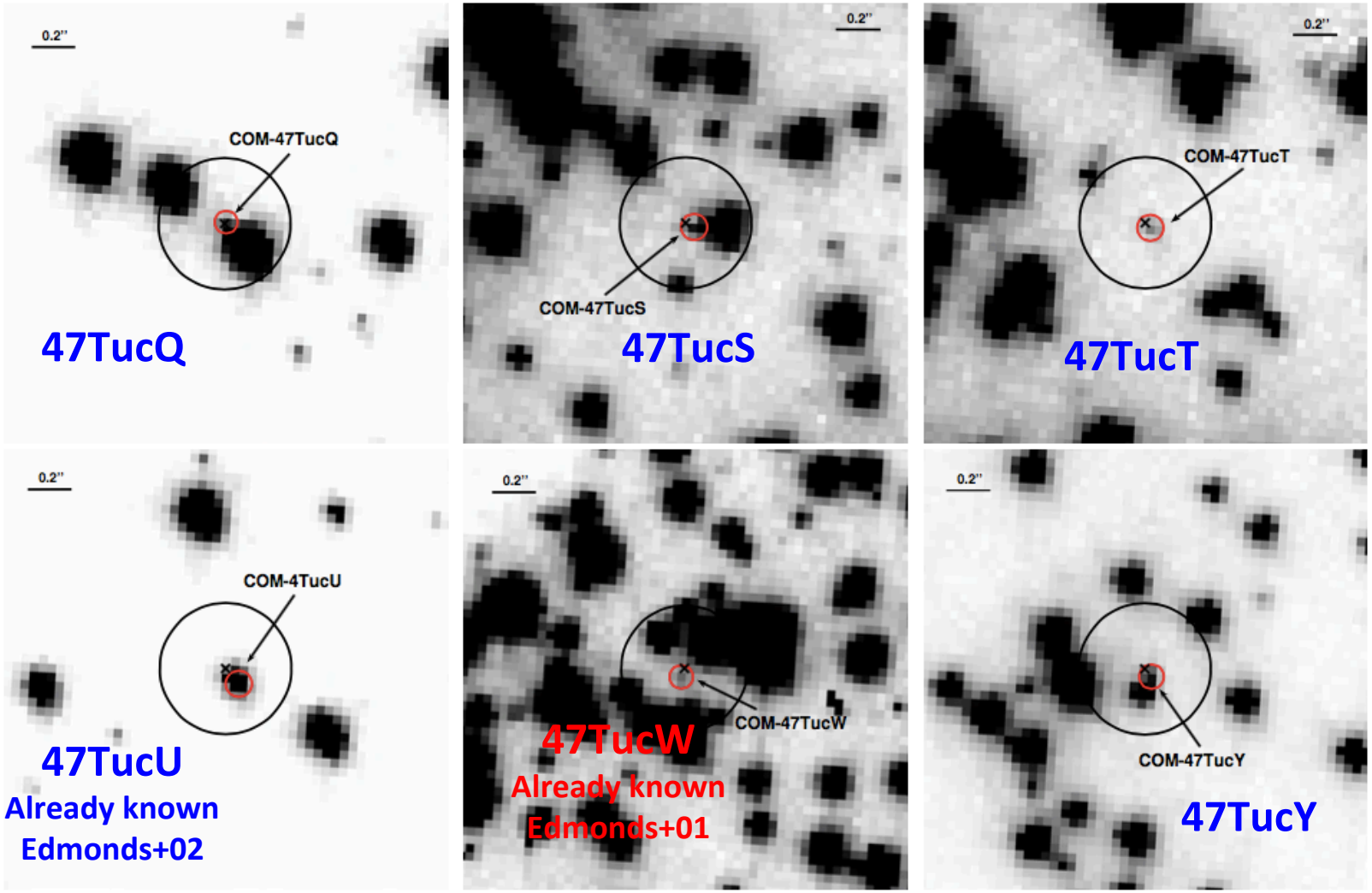
Black widows
$M_{COM} < 0.1\ M_\odot$
MSs/BDs

?

18 in GCs

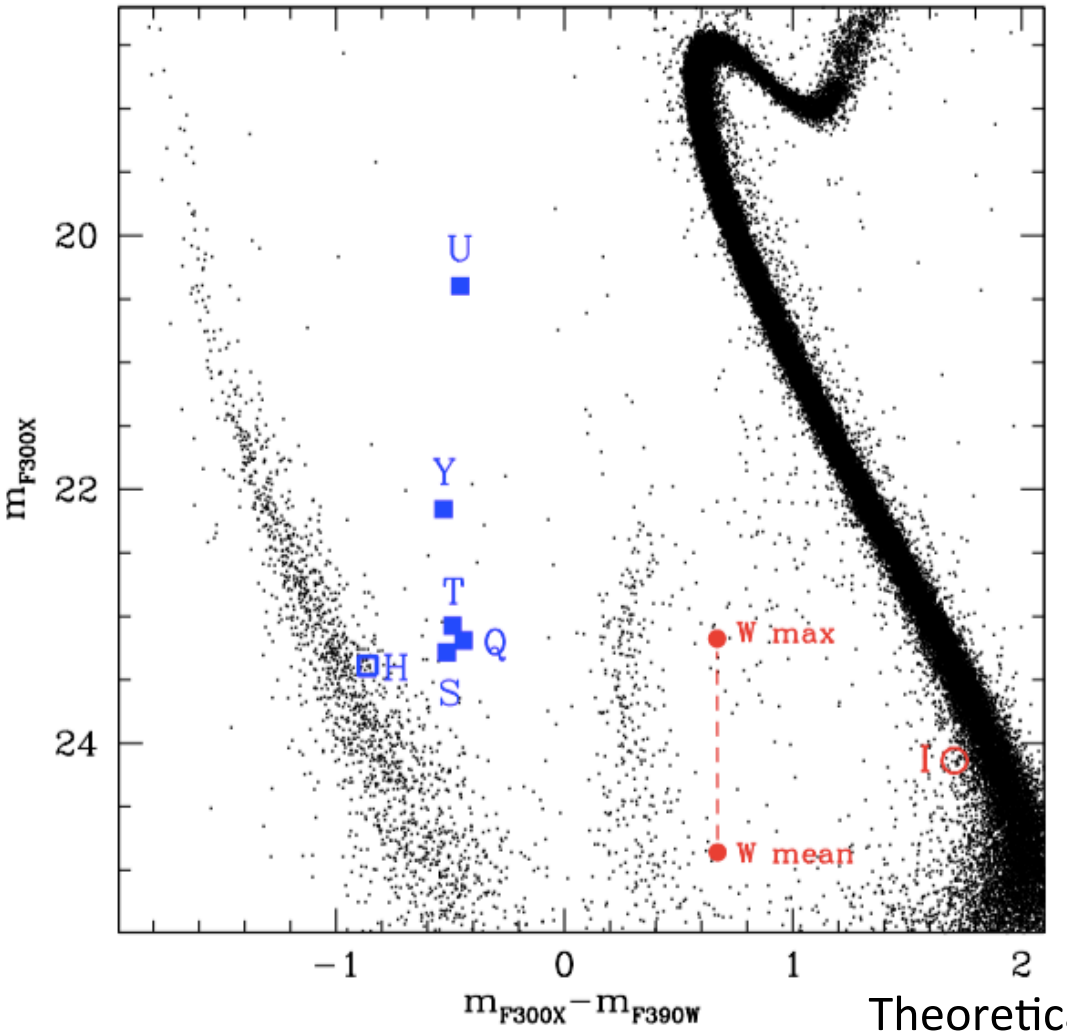
Companions to Canonical MSPs

The He-WDs in 47Tuc



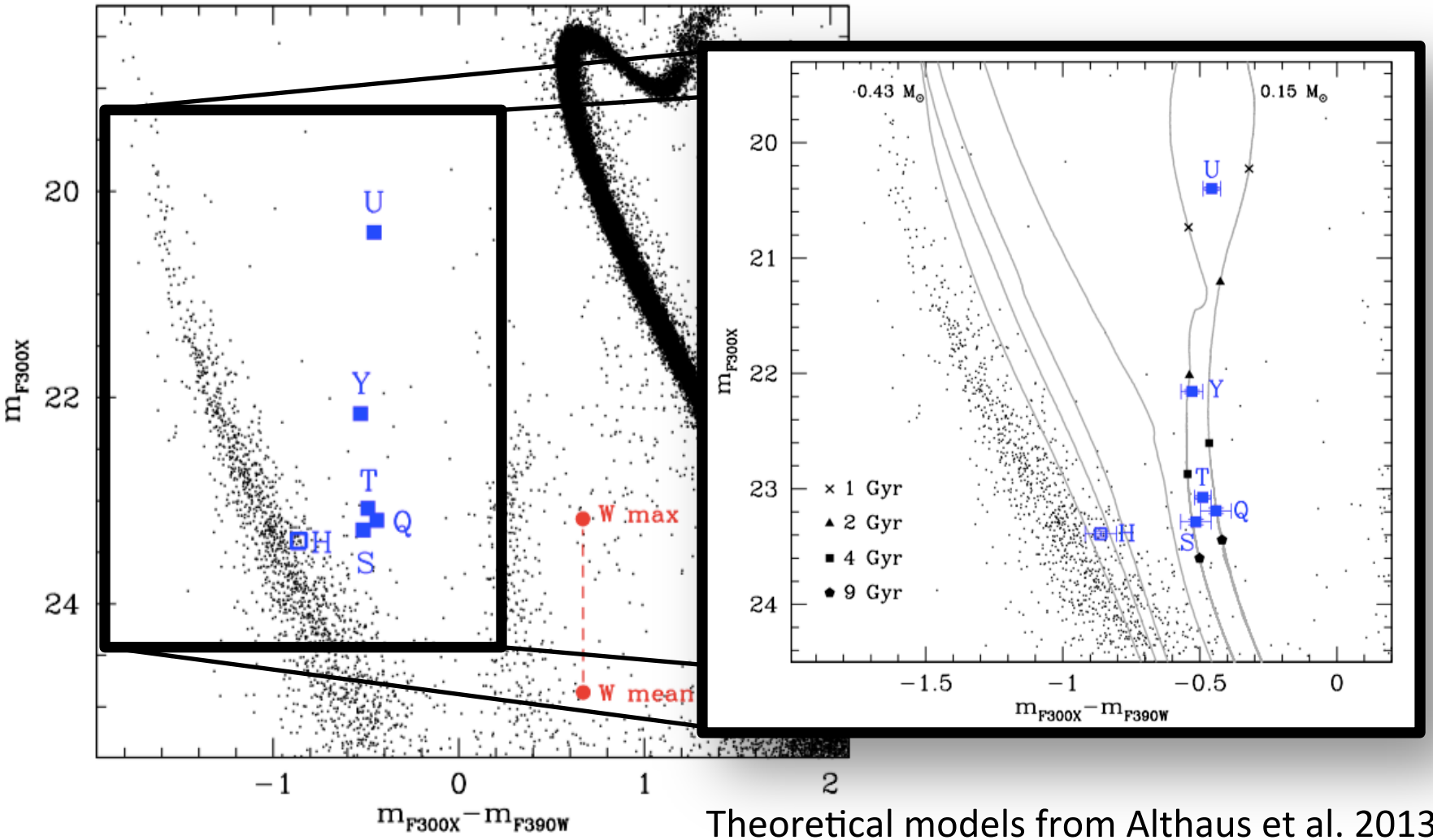
(Cadelano et al. 2015, see also Rivera Sandoval et al. 2015)

The He-WDs in 47Tuc



Theoretical models from Althaus et al. 2013

The He-WDs in 47Tuc



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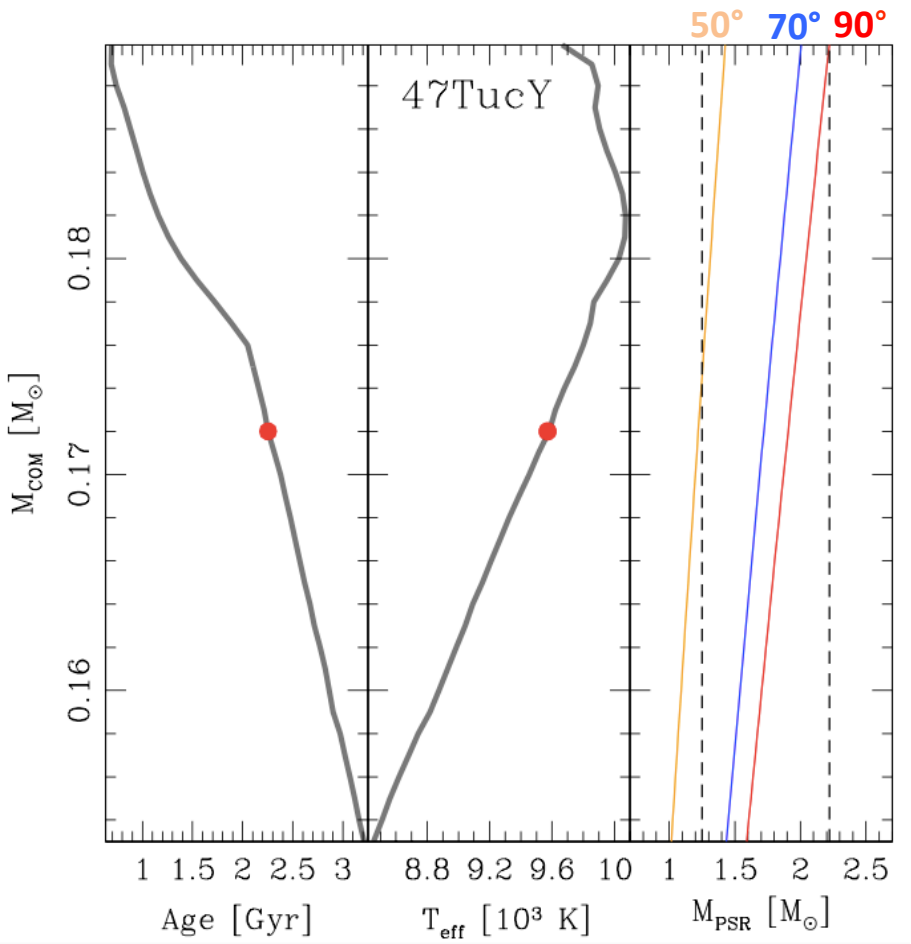
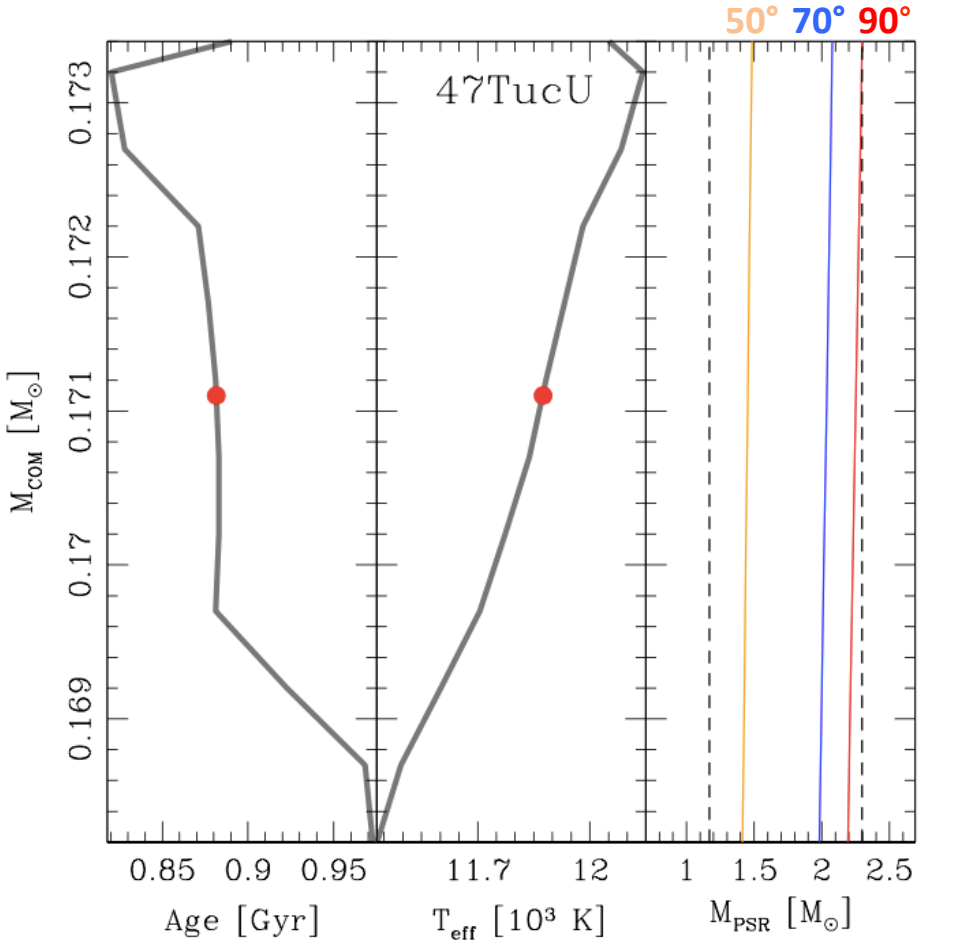


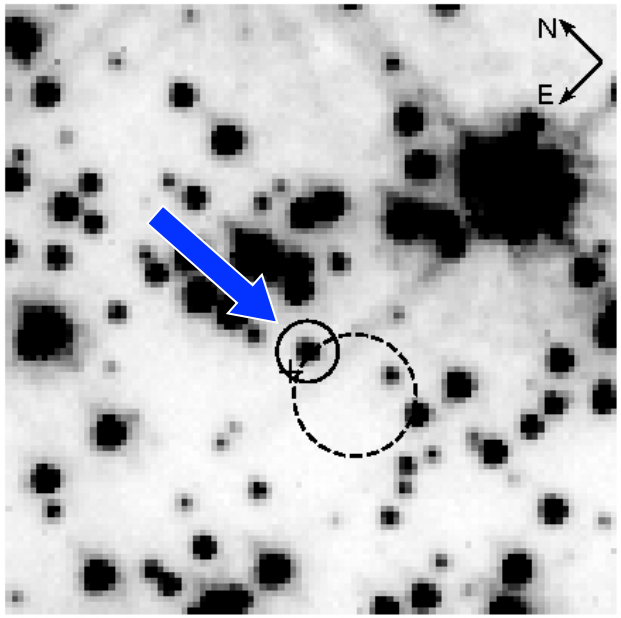


- Companion masses between **0.15 Msun and 0.2 Msun**
- **Cooling ages significantly younger** than the cluster stellar population age
- No massive NSs for **47TucQ** and **47TucT** (**M_{NS}<1.6 Msun**)
- **47TucU** past accretion stages likely proceeded in a **Sub-Eddington rate** (M/Medd~0.02)

Companions to RedBacks

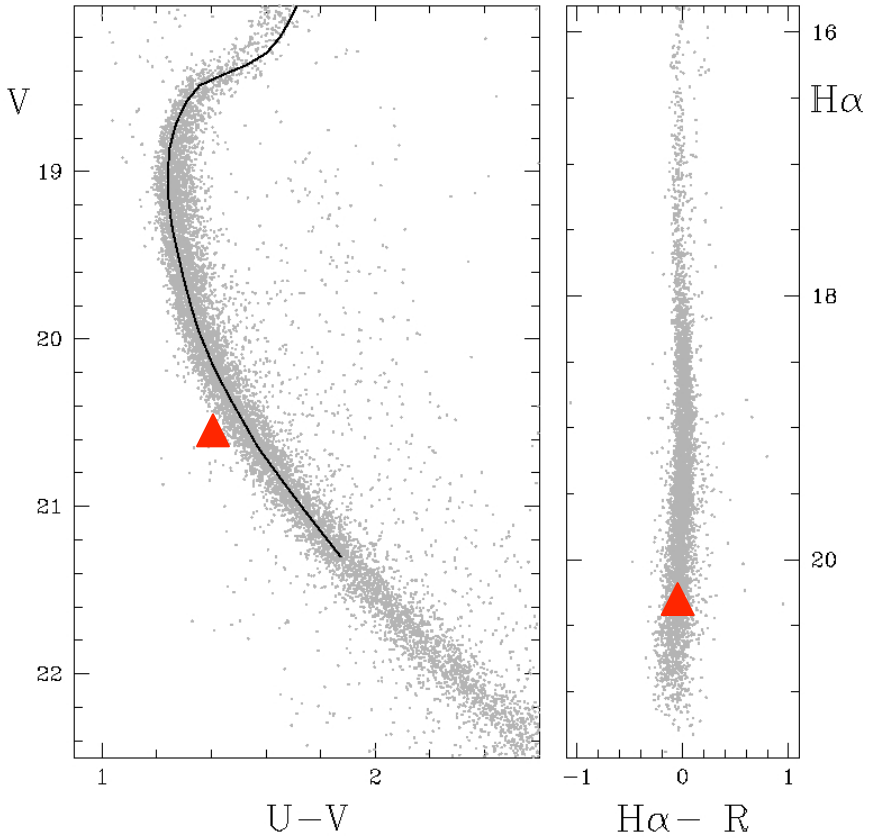
The RB PSR J1824-2452H in M28

WFC3/UVIS@HST



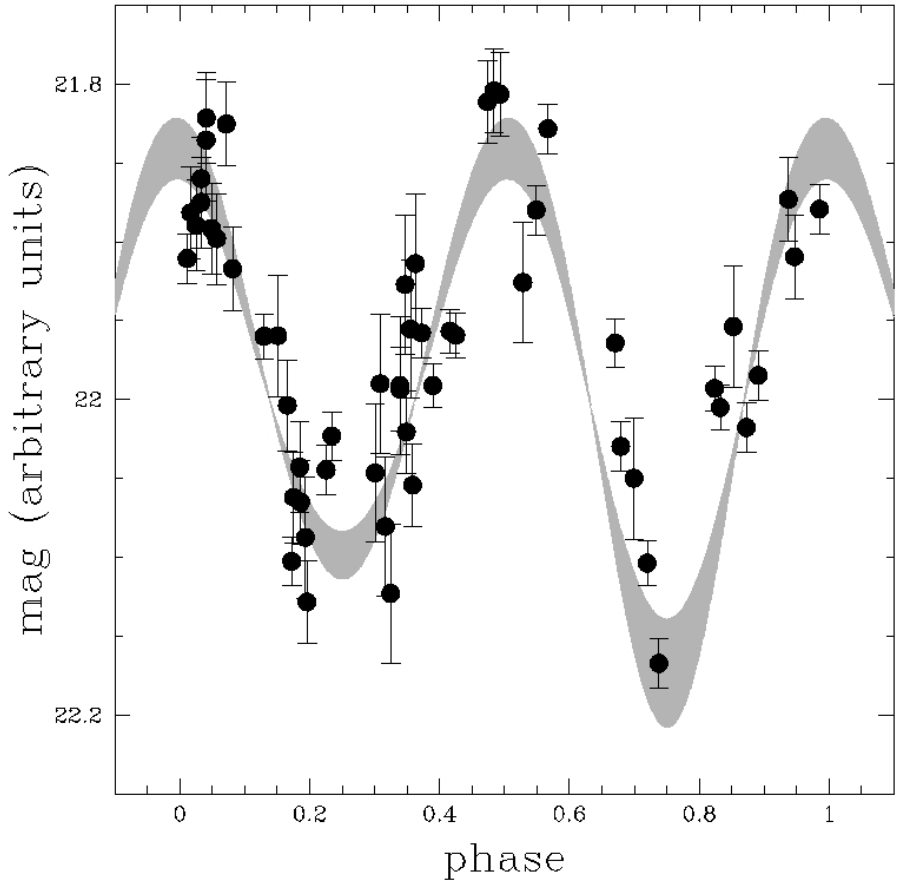
A NON-DEGENERATE companion

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



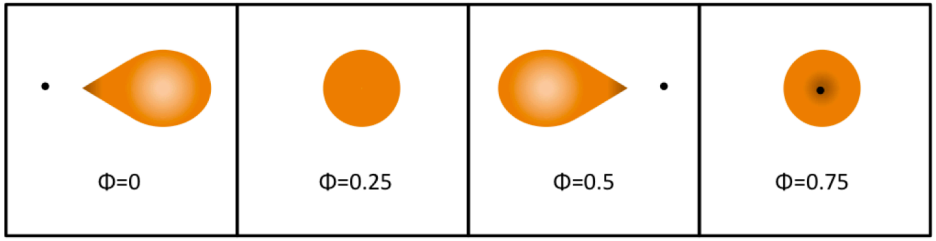
The RB PSR J1824-2452H in M28

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



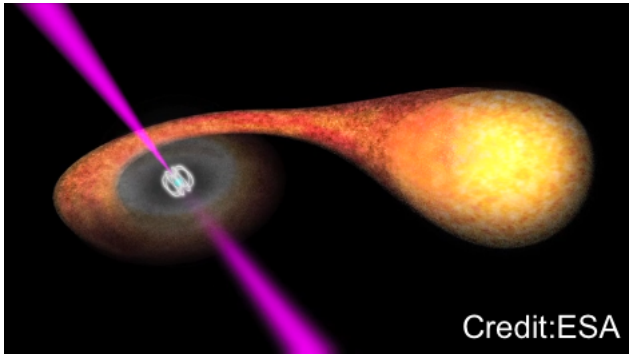
IGR J18245-2452/PSR J1824-2452I

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

doi:10.1038/nature12470

Swings between rotation and accretion power in a binary millisecond pulsar

A. Papitto[1], C. Ferrigno[2], E. Bozzo[2], N. Rea[1], L. Pavan[2], L. Burderi[3], M. Burgay[4], S. Campana[5], T. Di Salvo[6], M. Falanga[7], M. D. Filipović[8], P. C. C. Freire[9], J. W. T. Hessels[10,11], A. Possenti[4], S. M. Ransom[12], A. Riggio[3], P. Romano[13], J. M. Sarkissian[14], I. H. Stairs[15], L. Stella[16], D. F. Torres[1,17], M. H. Wieringa[18] & G. F. Wong[8,14]



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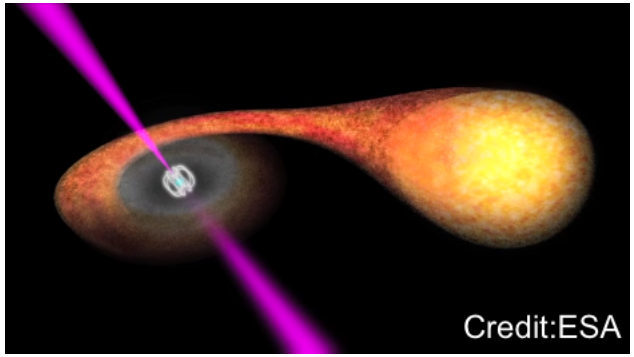
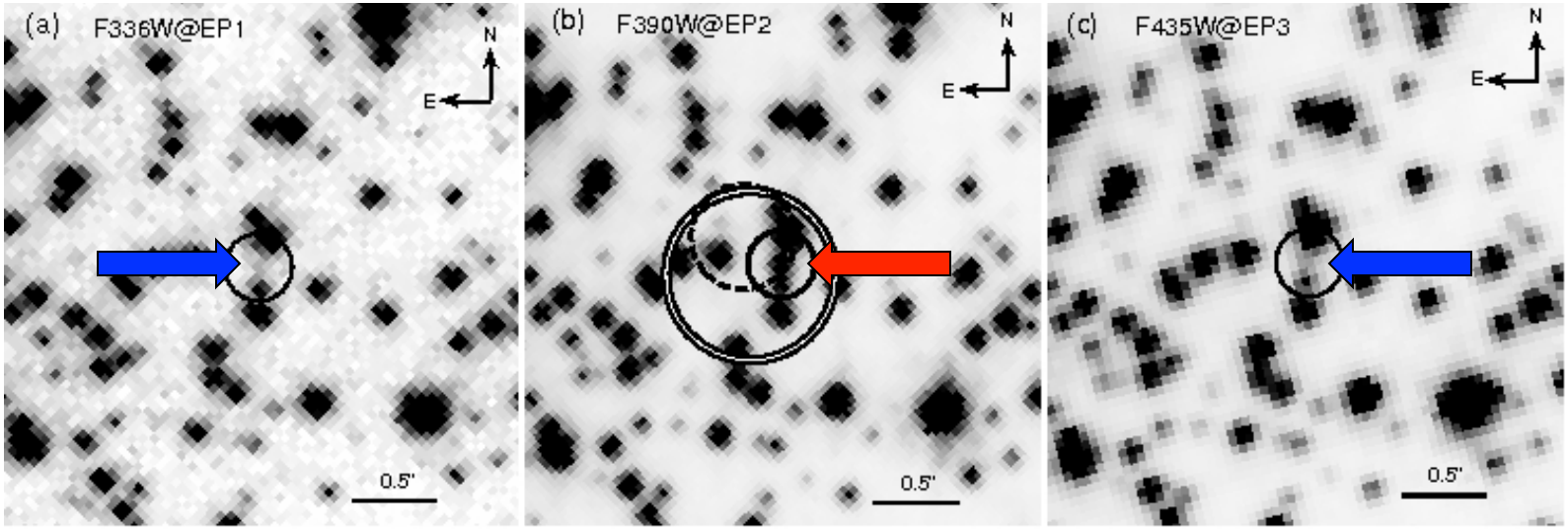
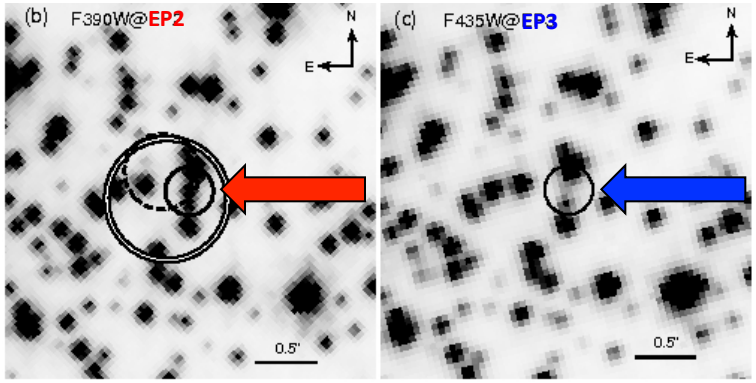


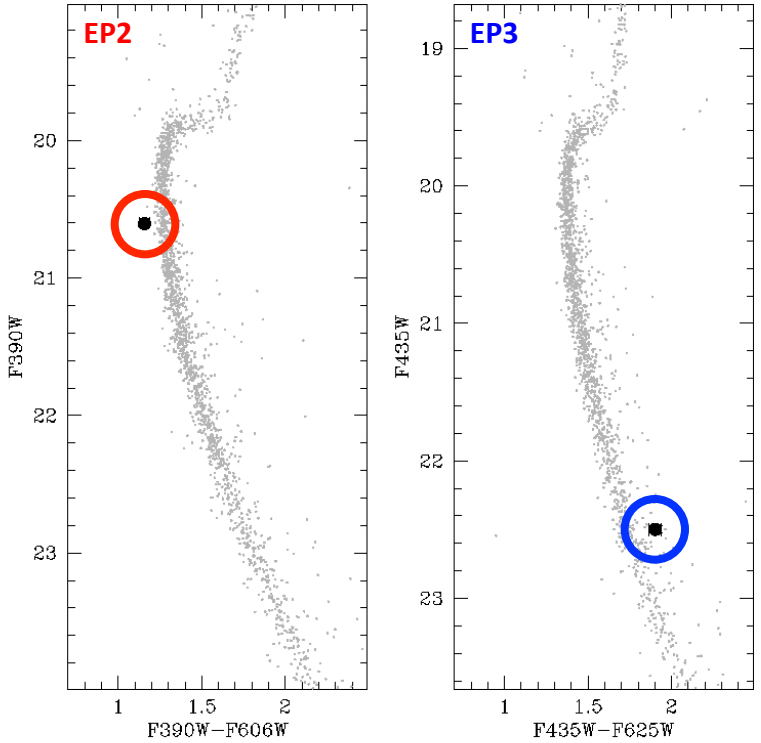
Apr 2009 Aug 2009 Apr 2010



✓We detected the optical counterpart (Atel #5003, Pallanca et al., 2013)

IGR J18245-2452/PSR J1824-2452I





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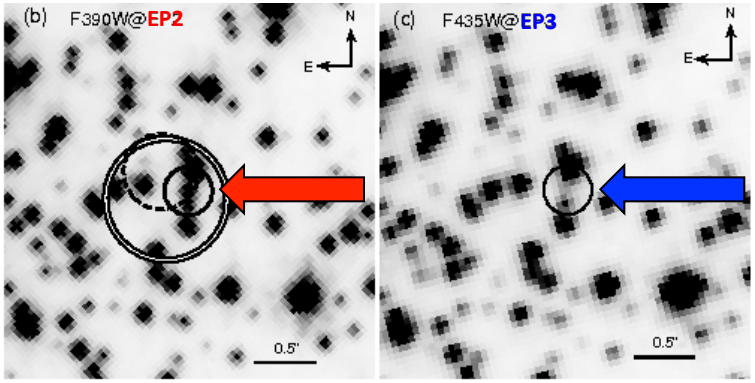
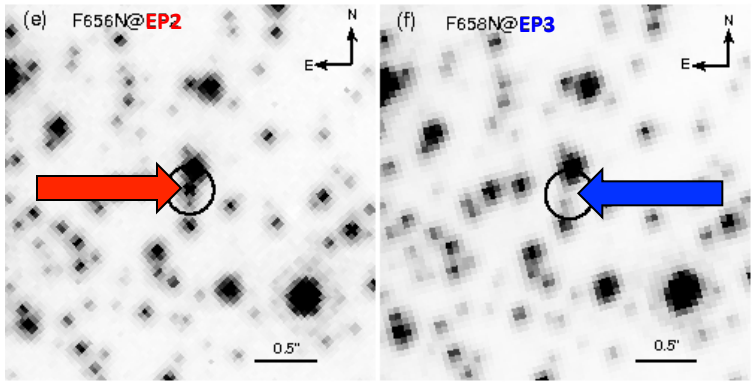
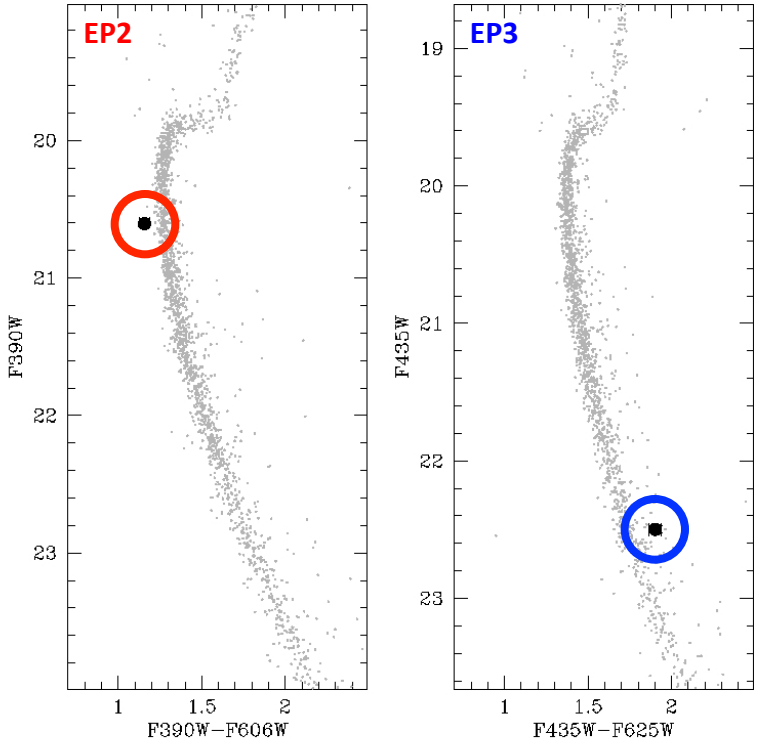
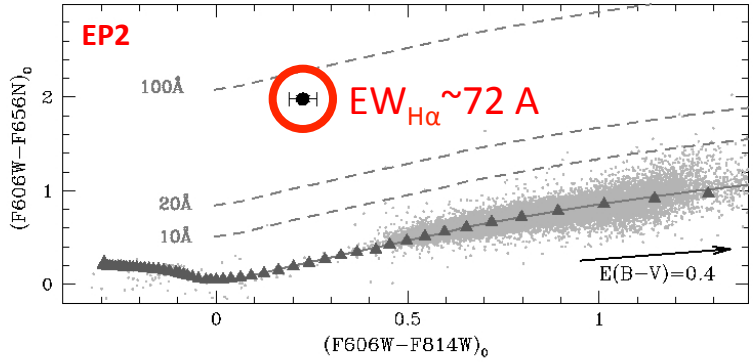
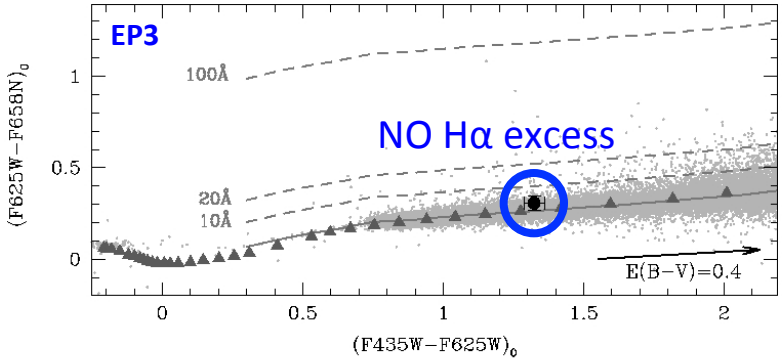










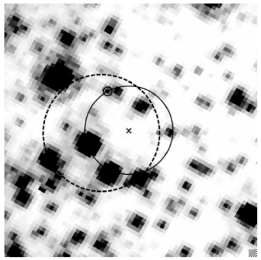
The optical approach

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 ↔ $M_{PSR}=M_{TOT}-M_{COM}$

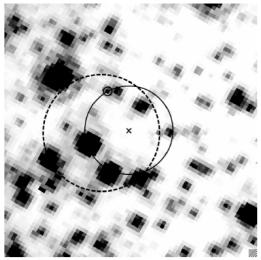
The optical approach

Radio

Optical

Photometry

Astrometry



Very Accurate position →

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Nature and physical parameters

Orbital parameters

Orbital period
Time ascending node ↔ Light curve
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PSR Mass function ↔ i, M_{COM}, M_{PSR}

Total mass ↔ $M_{PSR}=M_{TOT}-M_{COM}$

IF
BRIGHT
ENOUGH

The optical approach

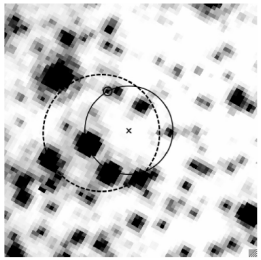
Radio

Optical

Photometry

Spectroscopy

Astrometry



Very Accurate position

CMD position
(Out of sequence)

Radial Velocity

COM mass function

+

PSR mass function

Orbital parameters

Orbital period
Time ascending node

PSR Mass function

Nature and physical parameters

Light curve
(Variability in agreement with the orbital motion)

i, M_{COM}, M_{PSR}

Mass ratio

System solved

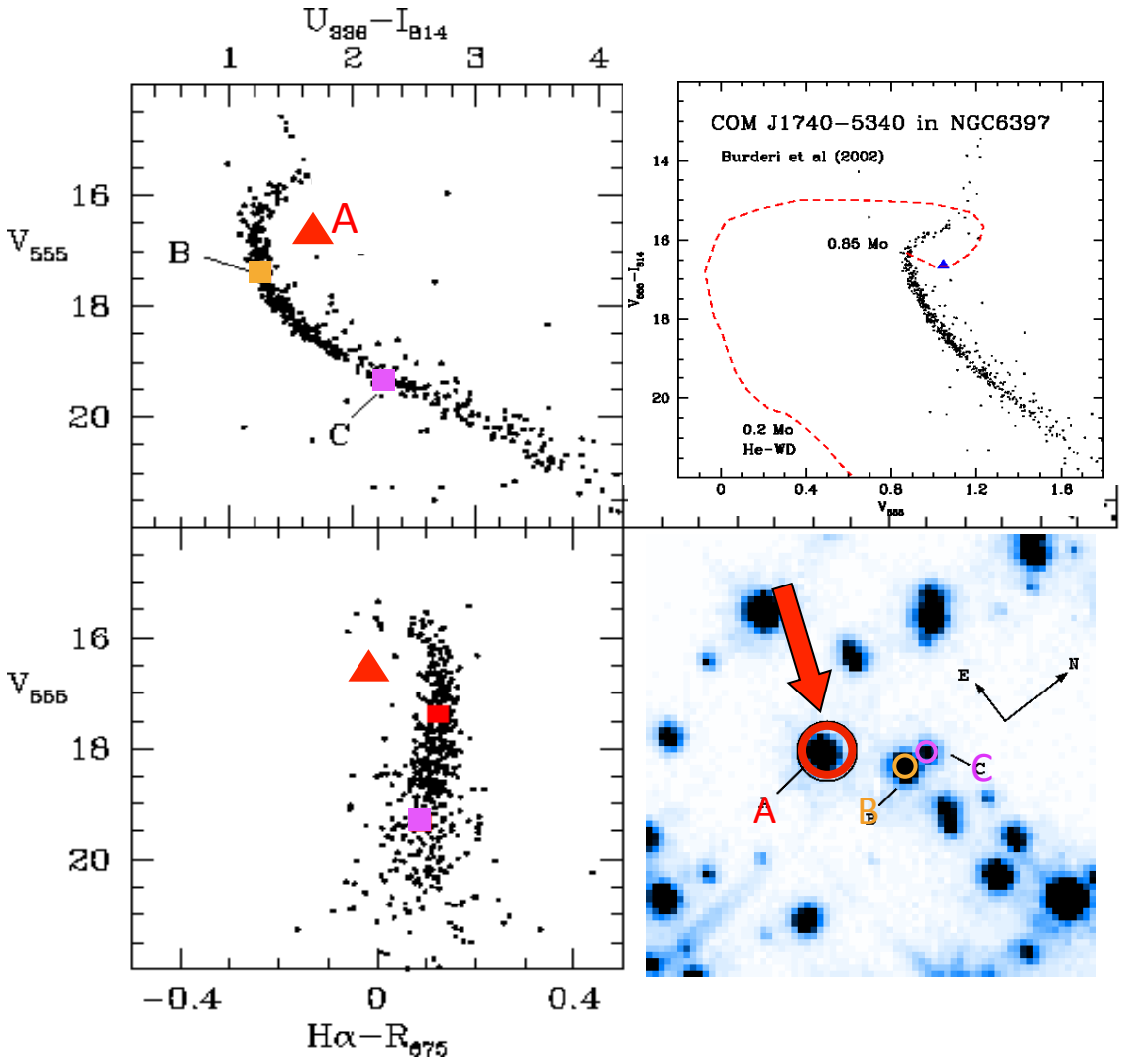
Total mass

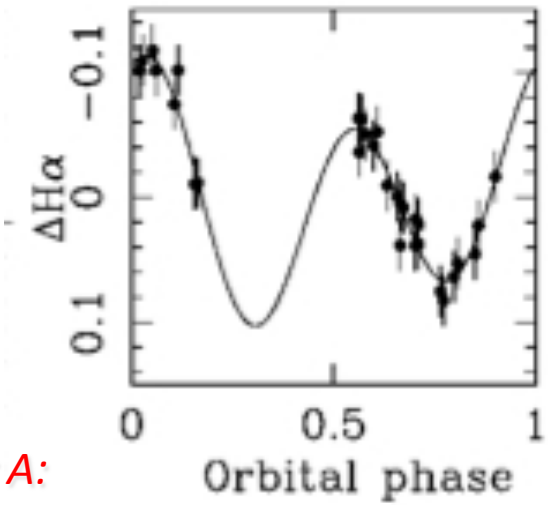
$M_{PSR}=M_{TOT}-M_{COM}$

Chemical abundances

Measure of the mass of a peeled star

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)

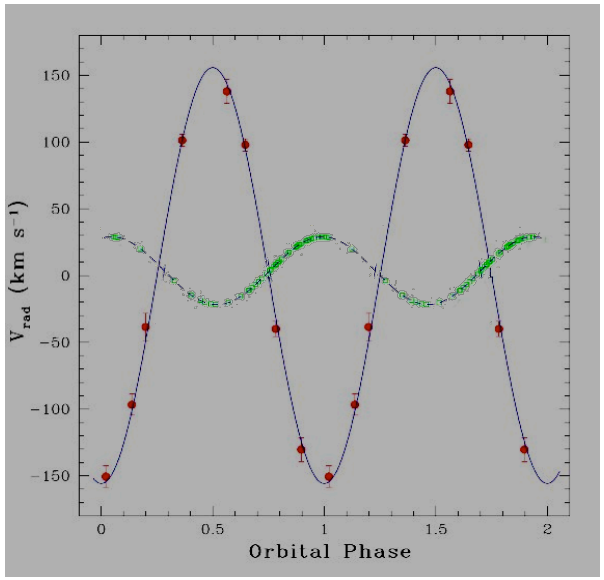
COM J1740-5340A: literature

*B*right object (V=16.5) => High-resolution spectroscopy with UVES/VLT

Lines doppler shift

↓

Measure of the radial velocity



↕ P (Radio)
Pulse delay (X-ray)
Rad. vel. (Optical)

$$\frac{f_{COM} = \frac{4\pi^2 c^3 x_c^3}{G M_\Theta P_b^2} = \frac{\left(m_p \sin i\right)^3}{\left(m_c + m_p\right)^2}}{f_{PSR} = \frac{4\pi^2 c^3 x_p^3}{G M_\Theta P_b^2} = \frac{\left(m_c \sin i\right)^3}{\left(m_c + m_p\right)^2}} \Rightarrow \frac{m_p}{m_c}$$

↔ Orbital period
Ascending node

Mass ratio $\frac{m_p}{m_c}$**=5.85±0.13**
V_{rad} amplitude of Star A: 155.8±3.6 km/s

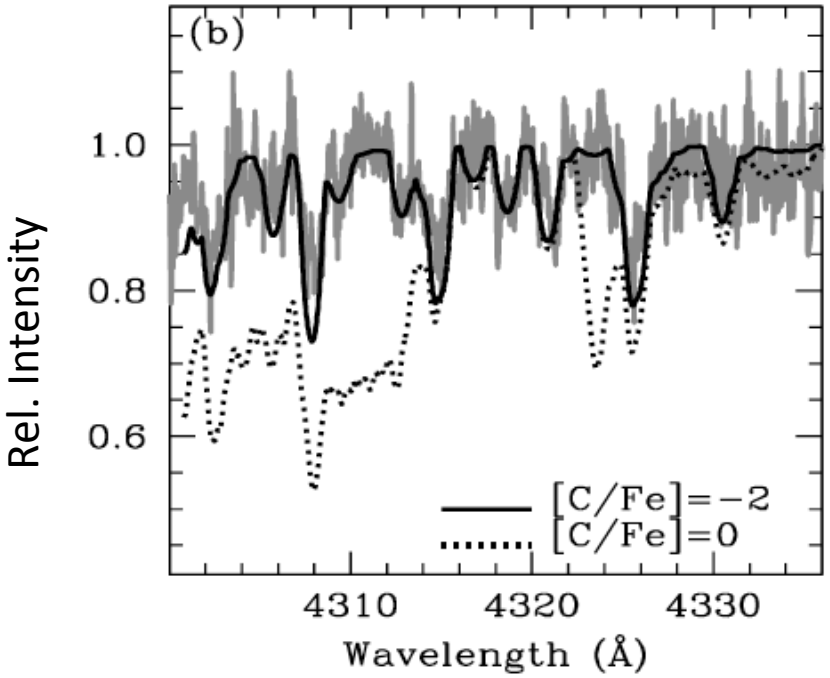
Mass of MSP	**1.30 : 1.90 $M_\odot$**
Mass of Star A	**0.22 : 0.32 $M_\odot$**
Inclination angle	**56 : 47 deg**
Orbital separation	**6.1 : 7.0 $R_\odot$**
Roche lobe radius	**1.5 : 1.7 $R_\odot$**

(Ferraro et al., 2003

COM J1740-5340A: spectroscopic follow-up

Bright object (V=16.5)

High-resolution with UVES/VLT



High resolution

XSHOOTER spectra

No C in its atmosphere

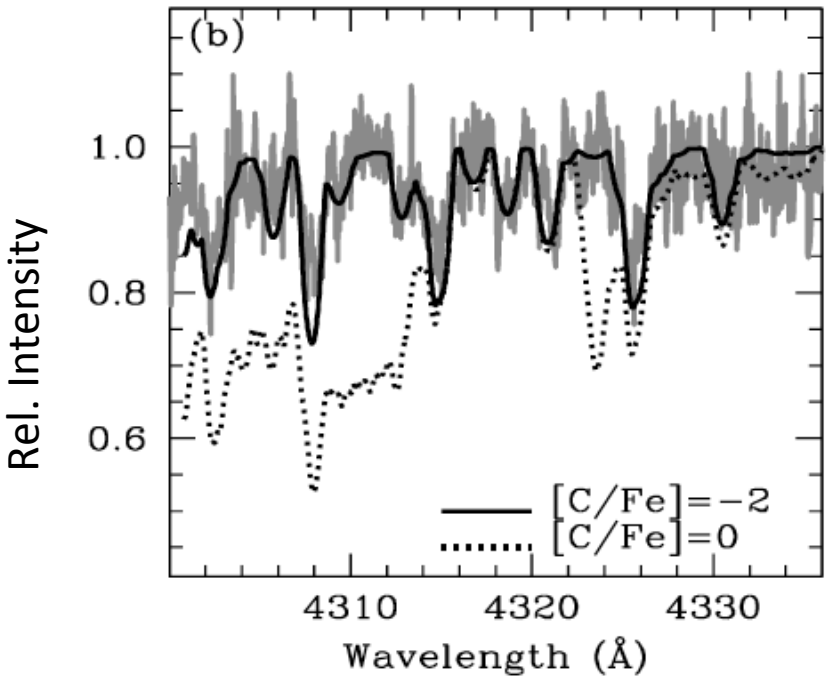
N enhanced

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

COM J1740-5340A: spectroscopic follow-up

Bright object (V=16.5)

High-resolution with UVES/VLT



High resolution

XSHOOTER spectra

No C in its atmosphere

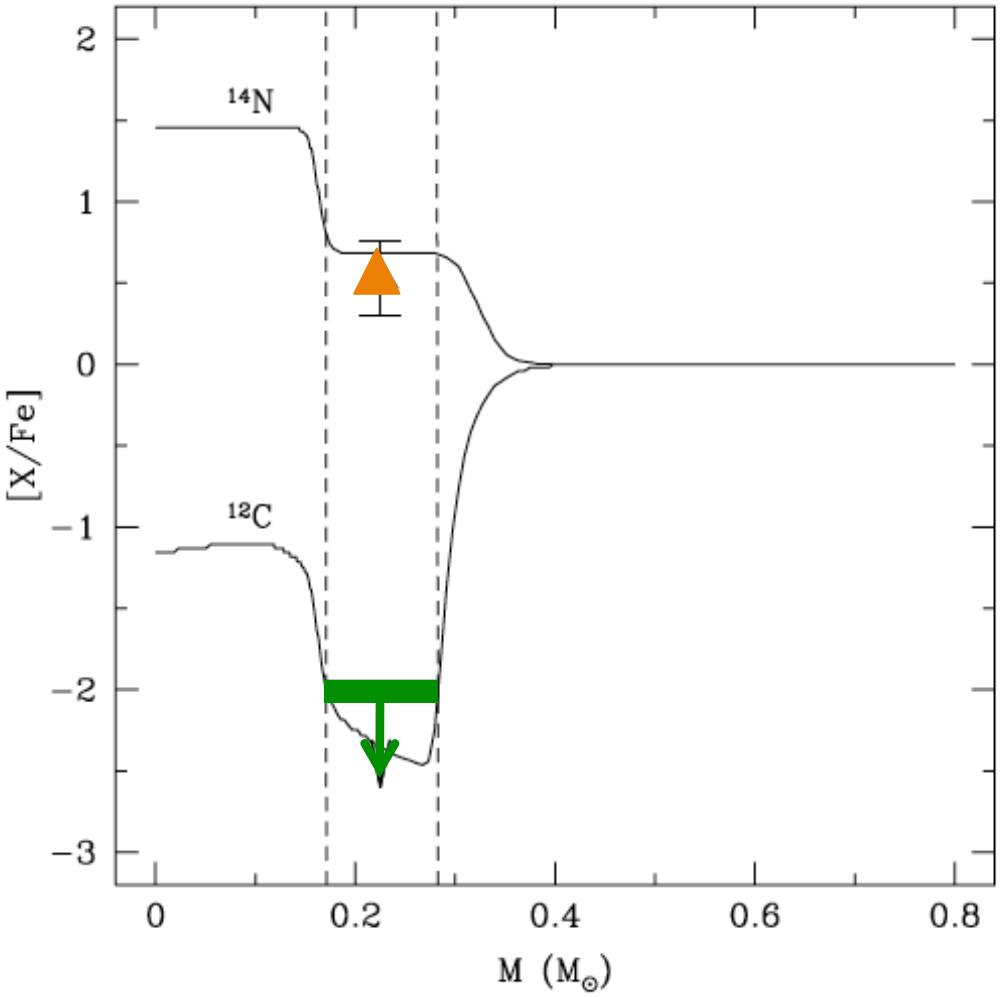
Material processed by CNO-burning

Deeply peeled star

N enhanced

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

COM J1740-5340A: spectroscopic follow-up

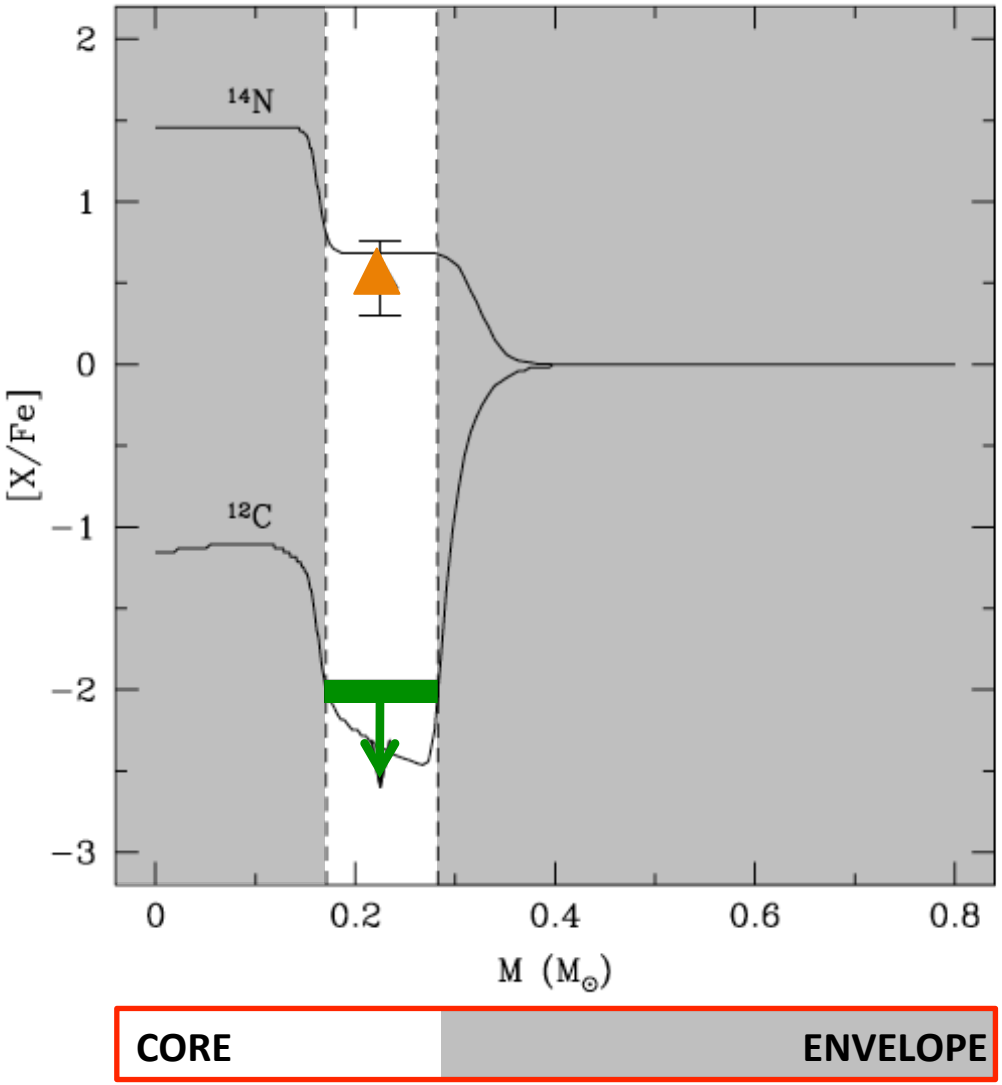


N abundance

C upper limit

CORE **ENVELOPE**

COM J1740-5340A: spectroscopic follow-up



N abundance

C upper limit

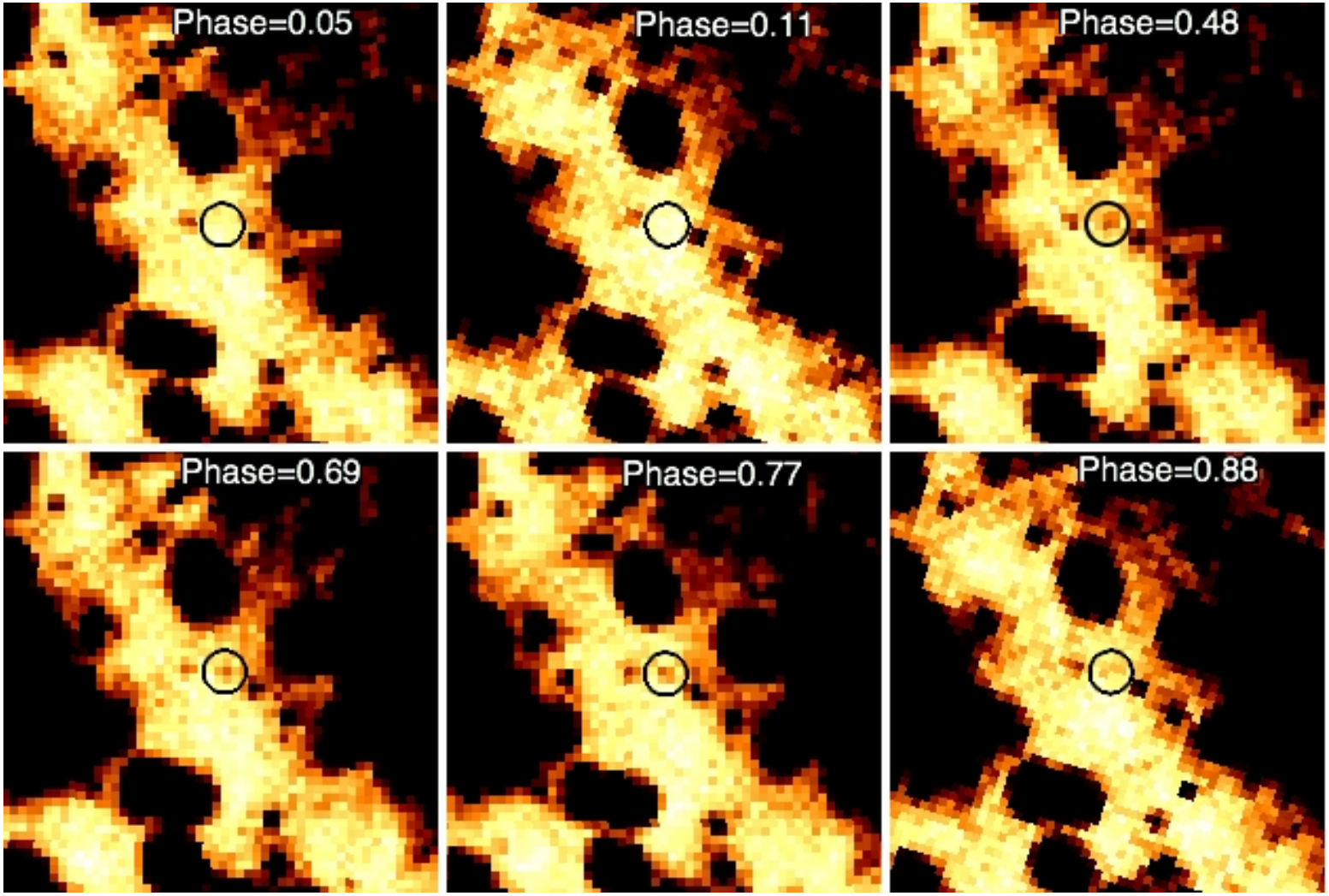
$0.17\ M_\odot < M_{com} < 0.28\ M_\odot$

Mass of MSP
Mass of Star A 0.22 : 0.32 $M_\odot$
Inclination angle

Deeply peeled star because of mass transfer

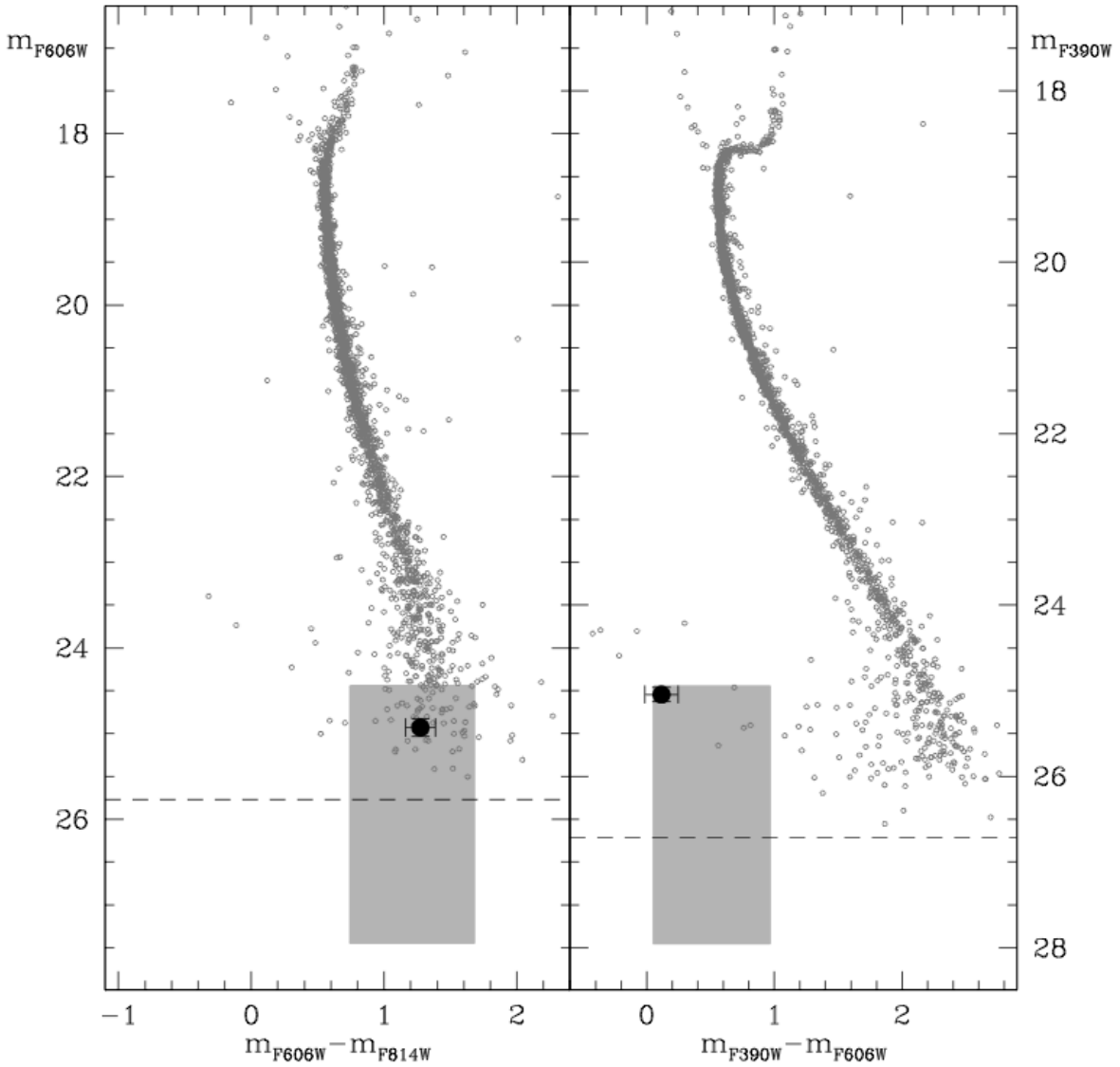
Companions to Black widows

The BW PSR J1518+0204C in M5



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

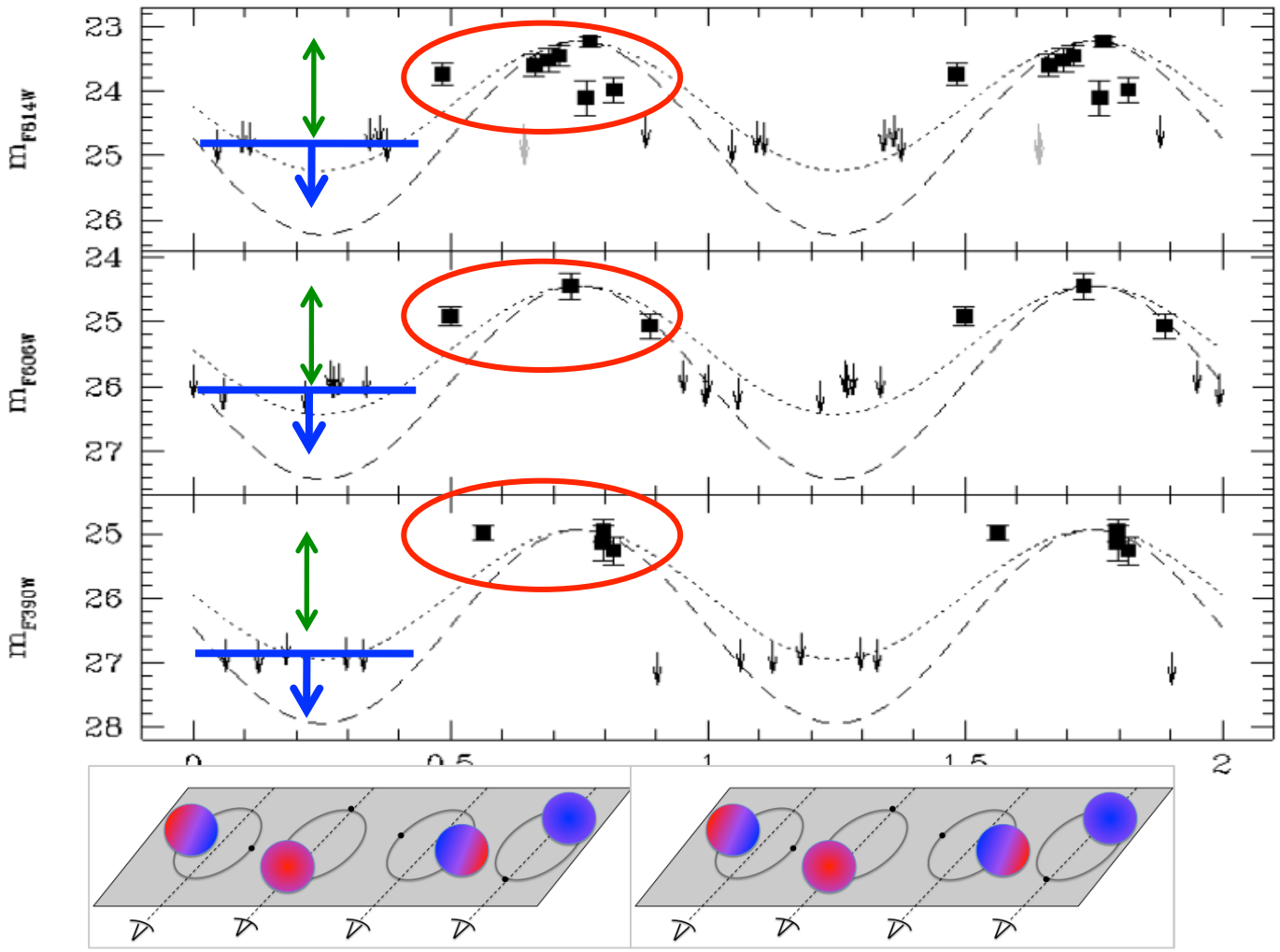
The BW PSR J1518+0204C in M5



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

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

The BW PSR J1518+0204C in M5



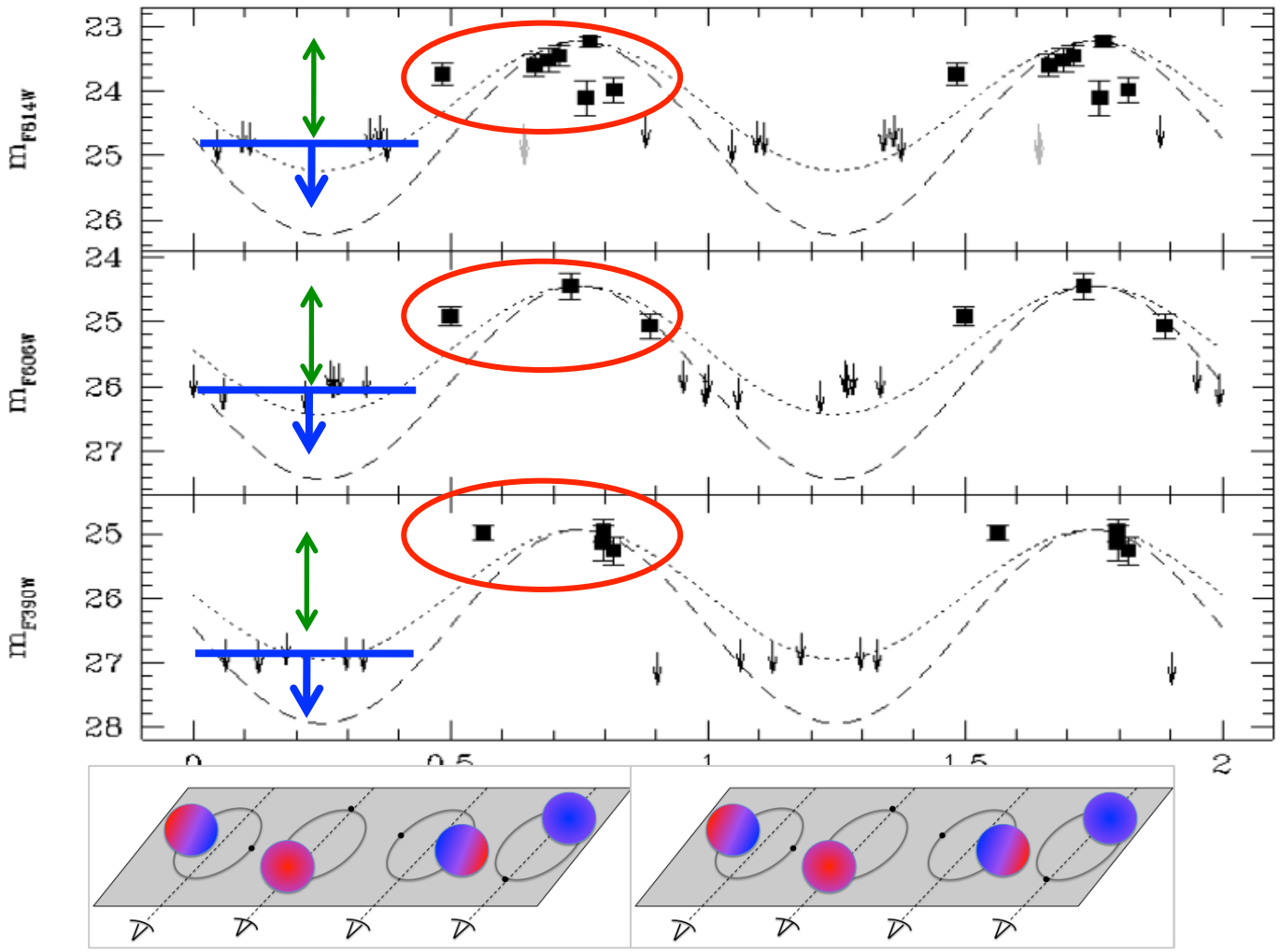
Orbital modulation in agreement with the orbital period

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 M5

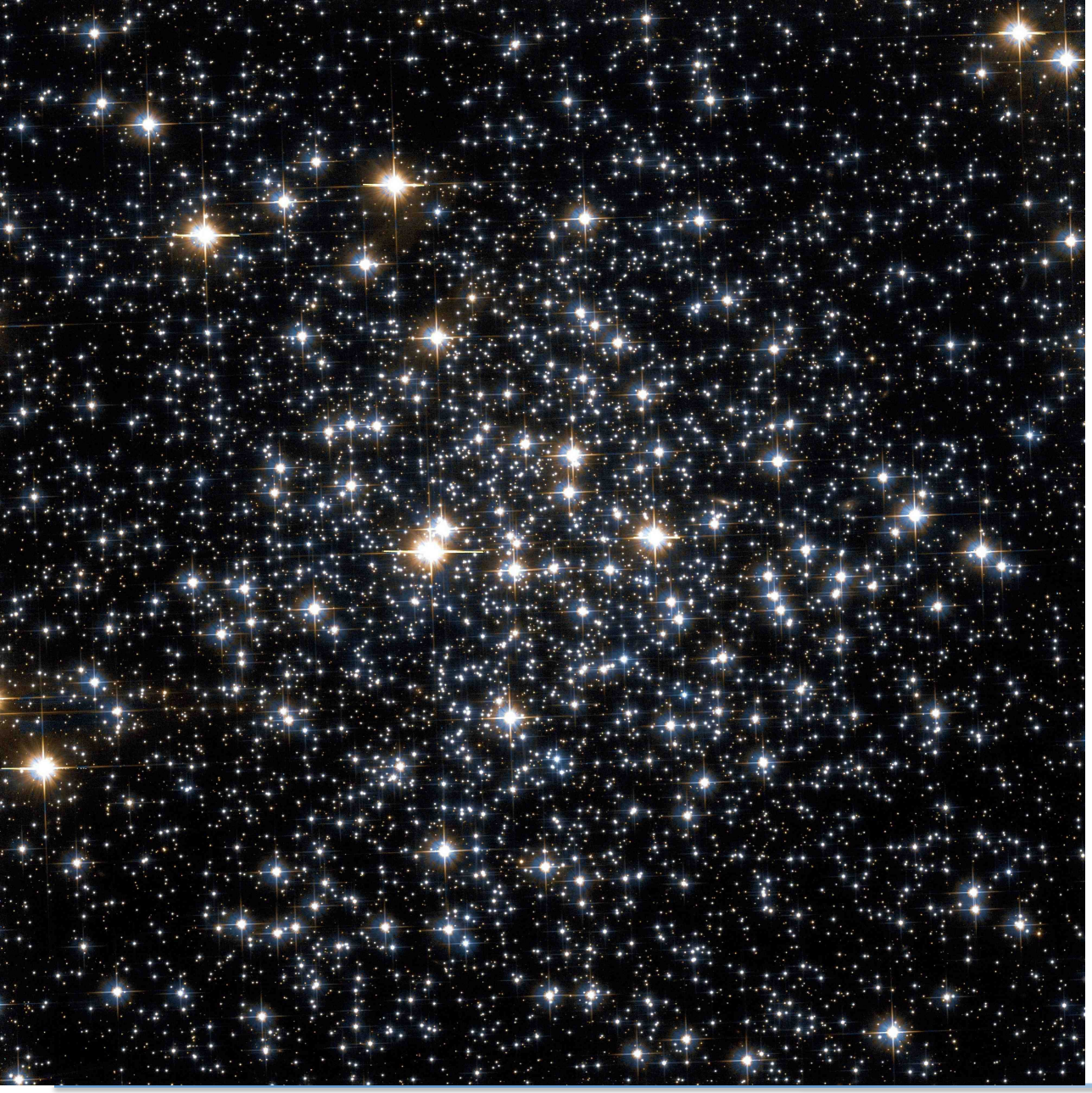


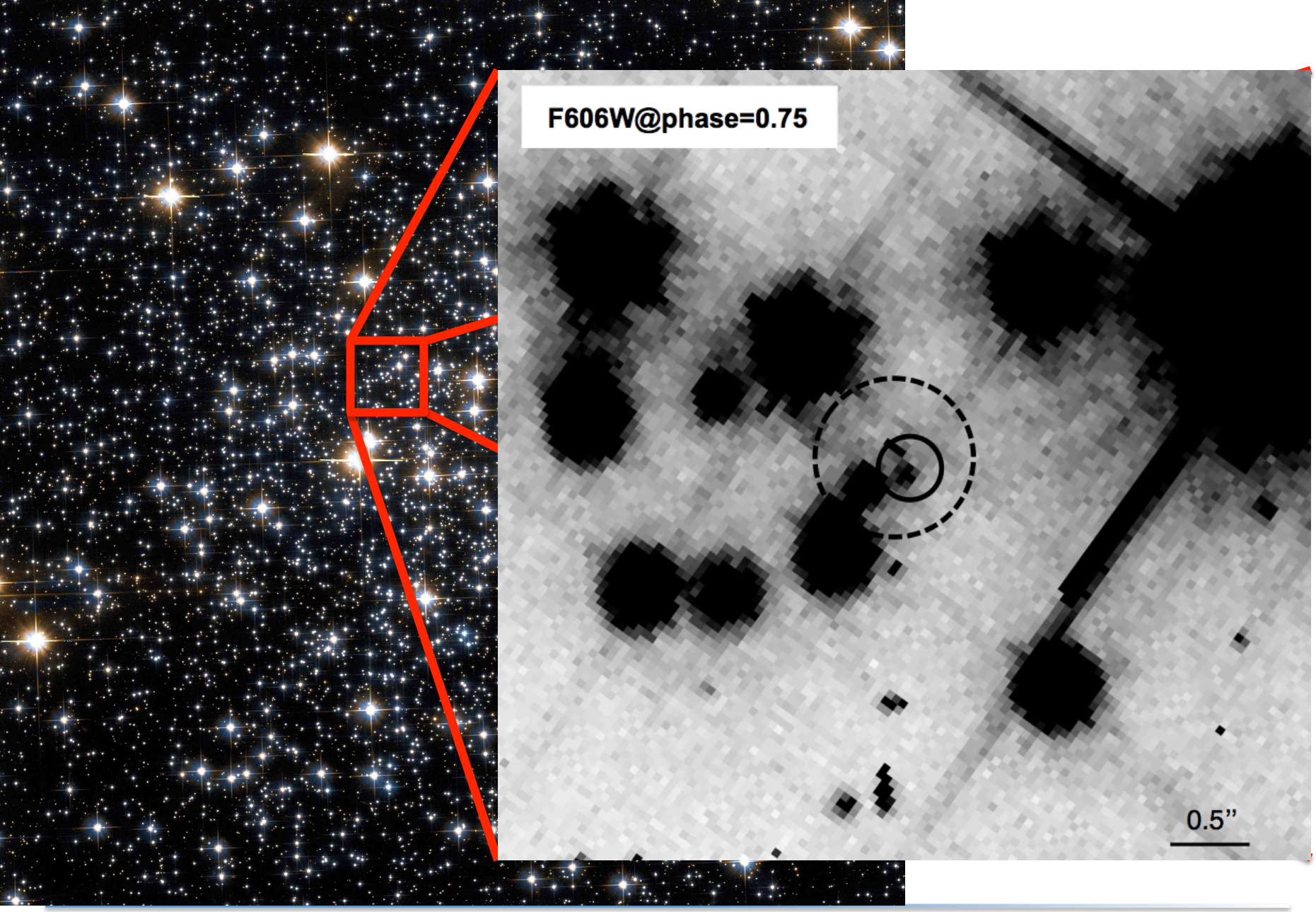
Orbital modulation in agreement with the orbital period

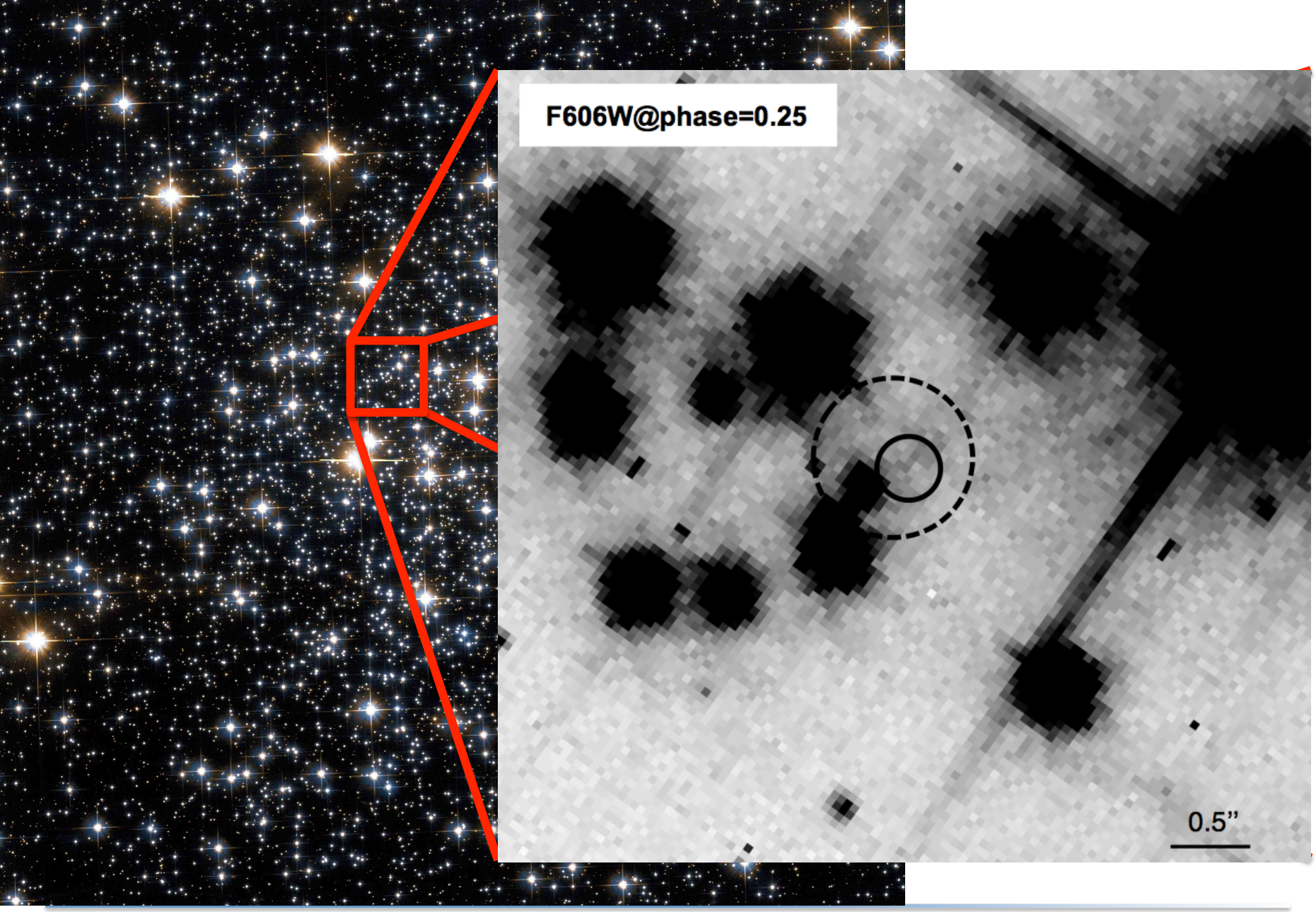
Detected at the PSR inferior conjunction

Under the detection limit at the PSR superior conjunction

Δmag>1.5 mag




F606W@phase=0.75
0.5”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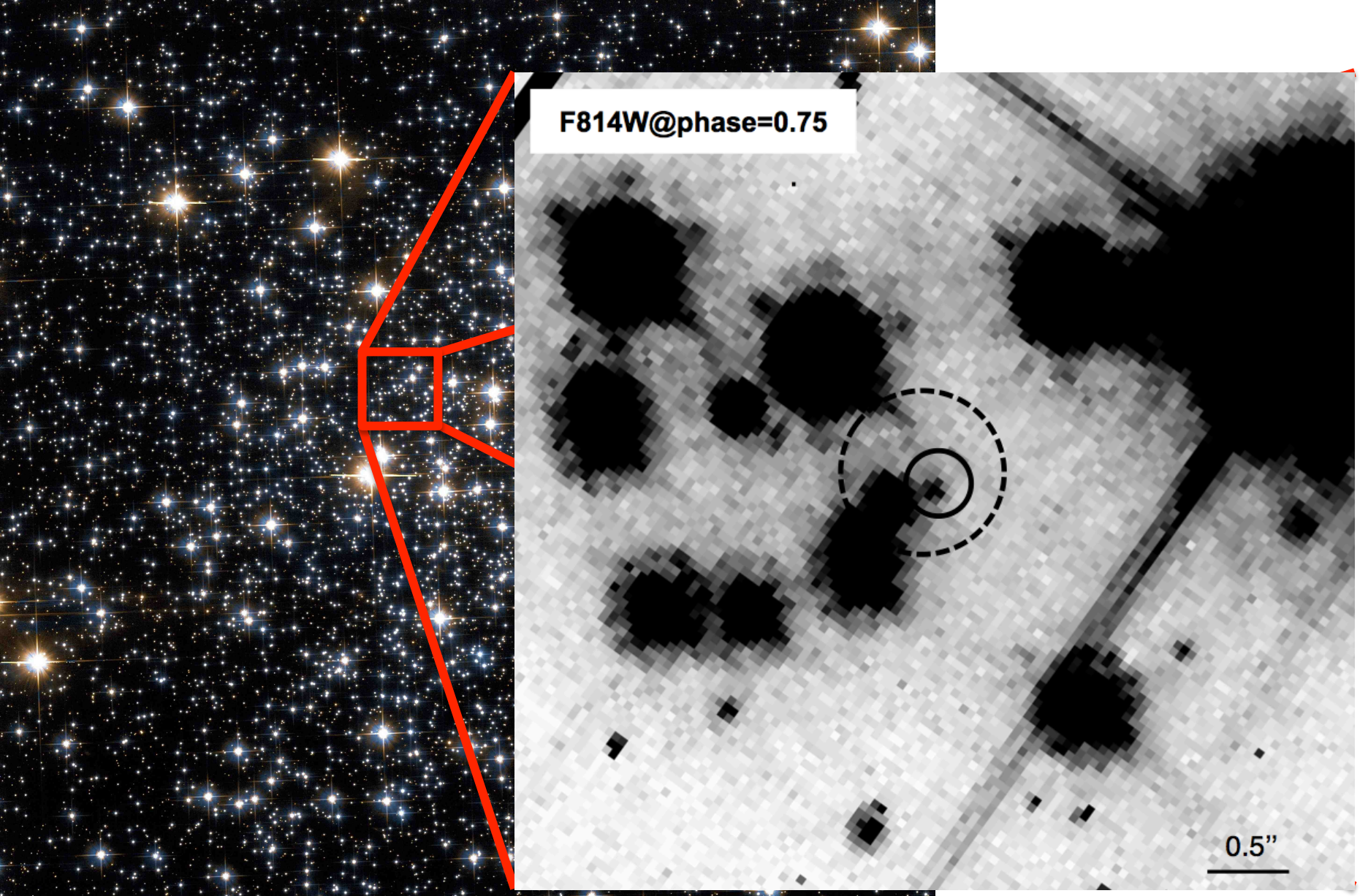
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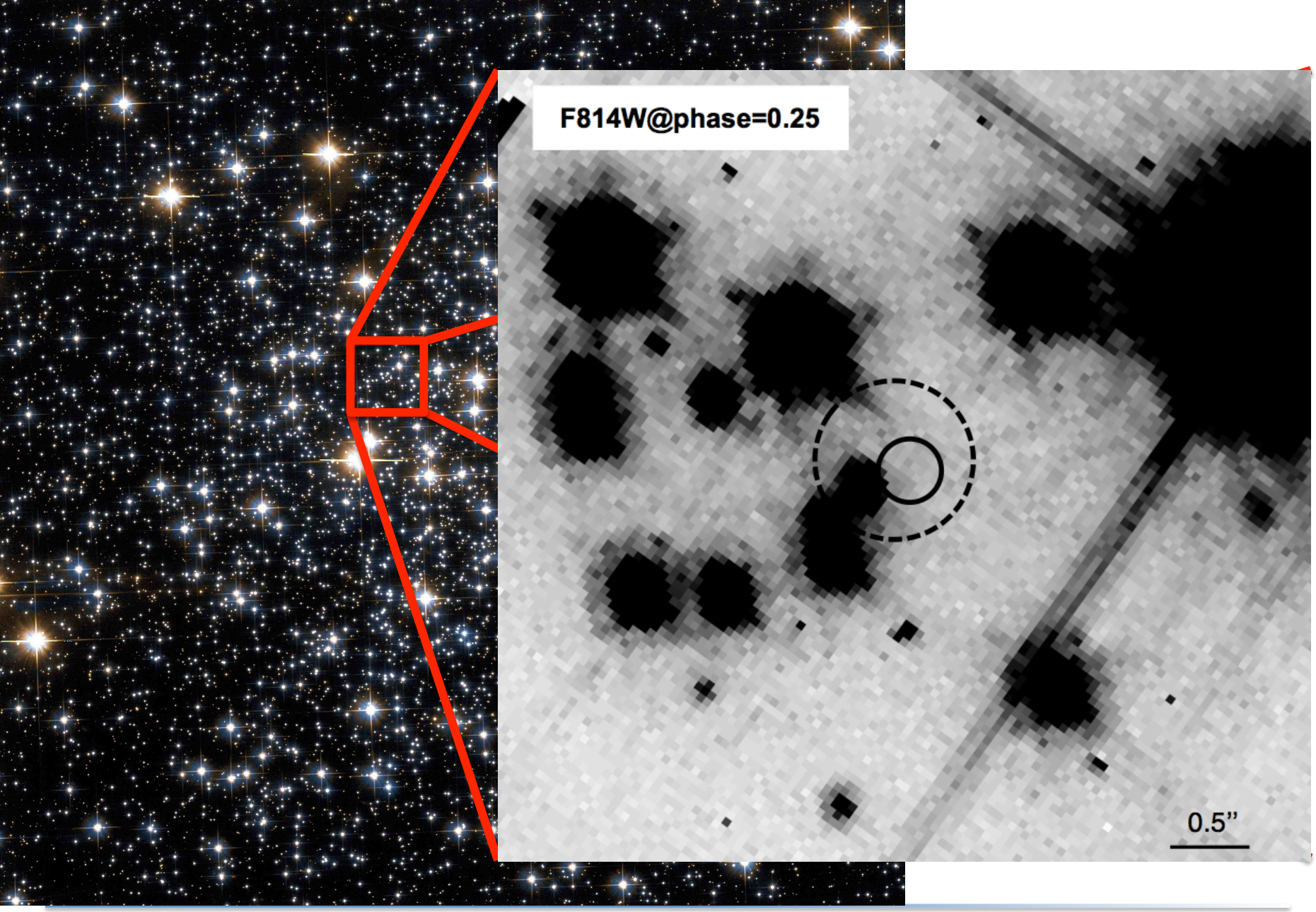
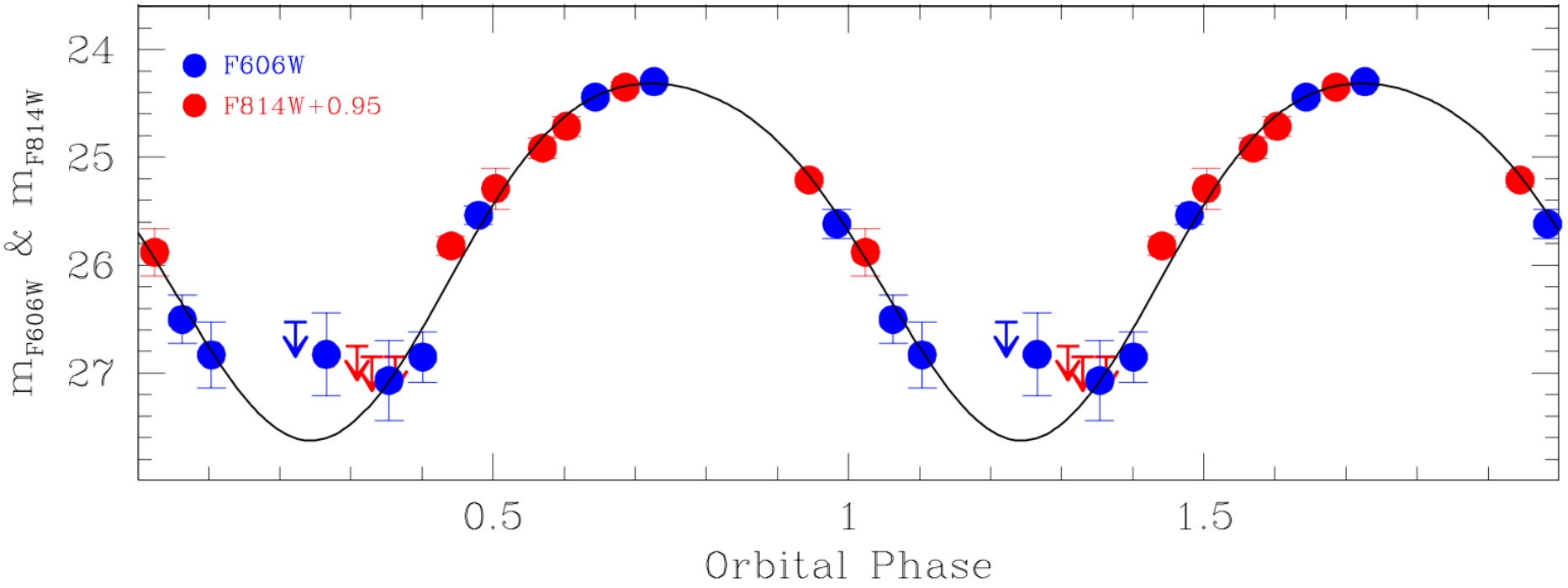
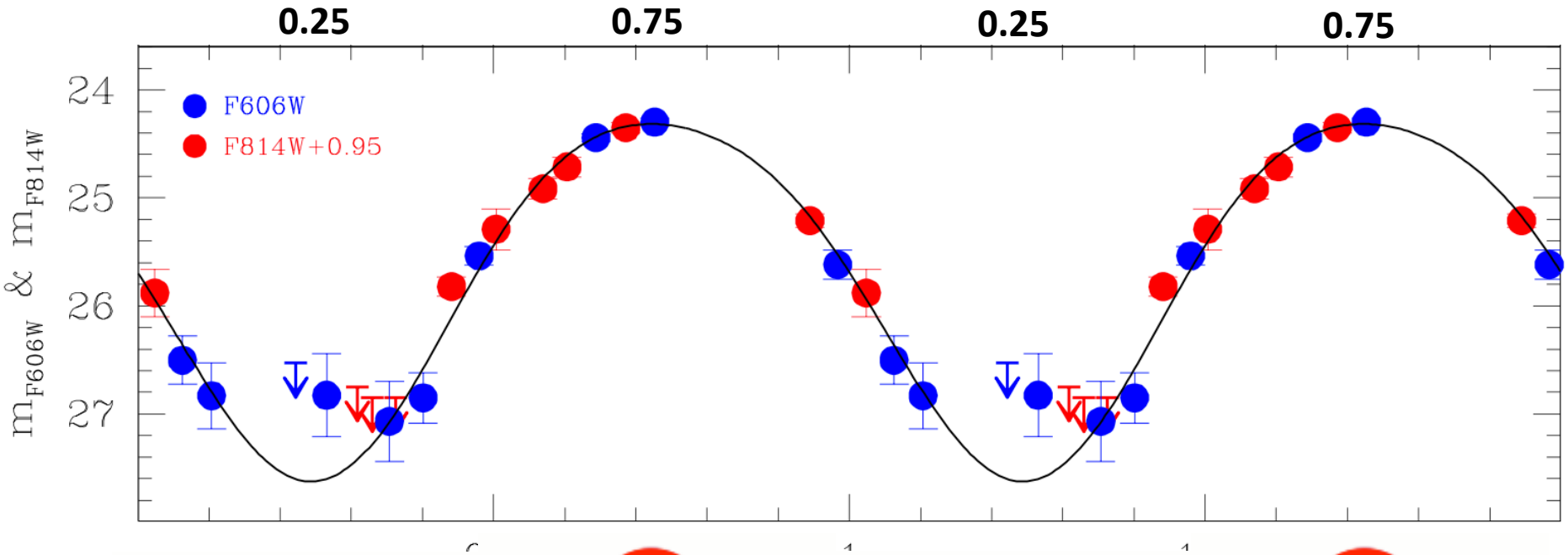

F814W@phase=0.25
0.5”

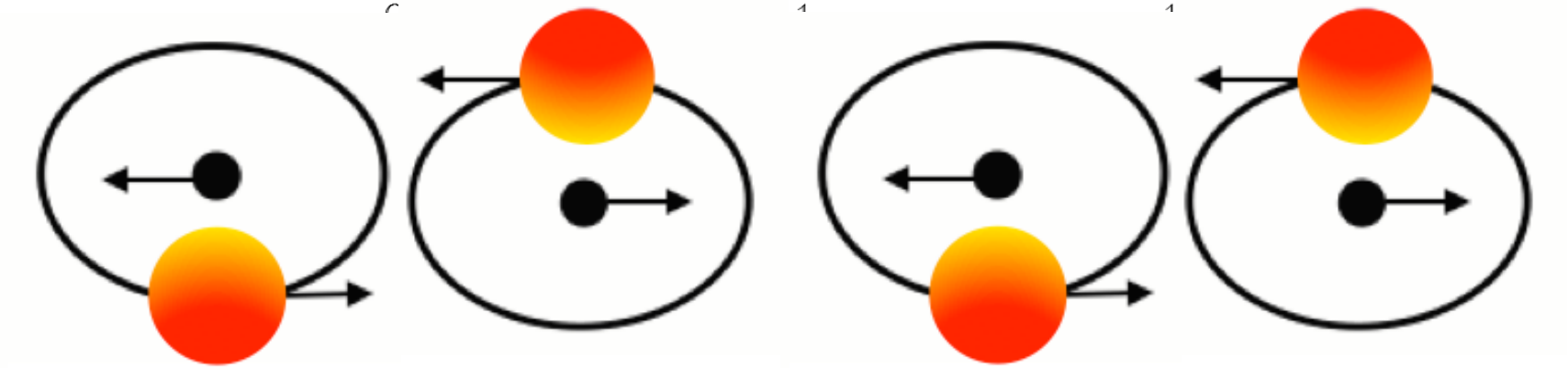
COM-M71A light curve



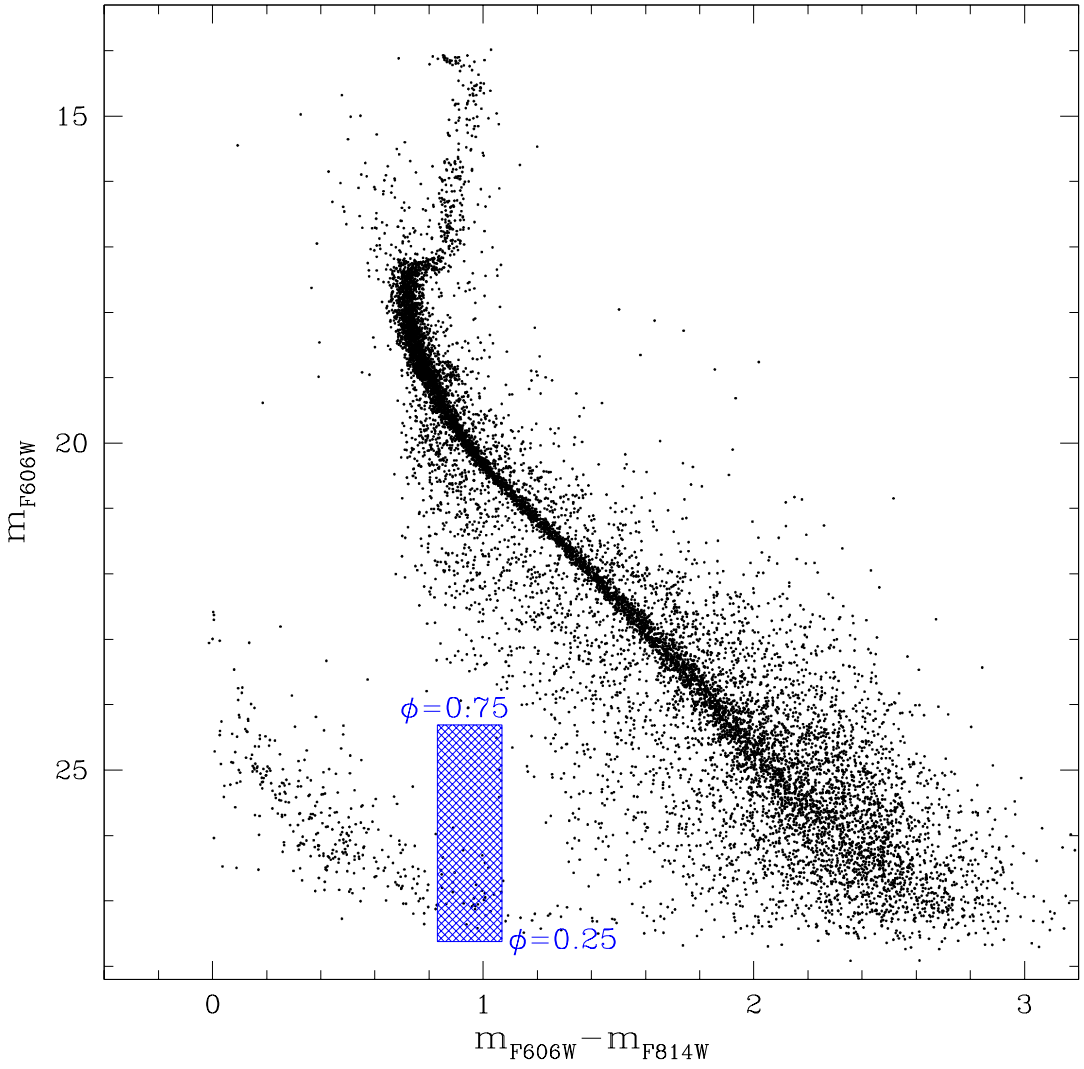
Cadelano et al., 2015a

COM-M71A light curve

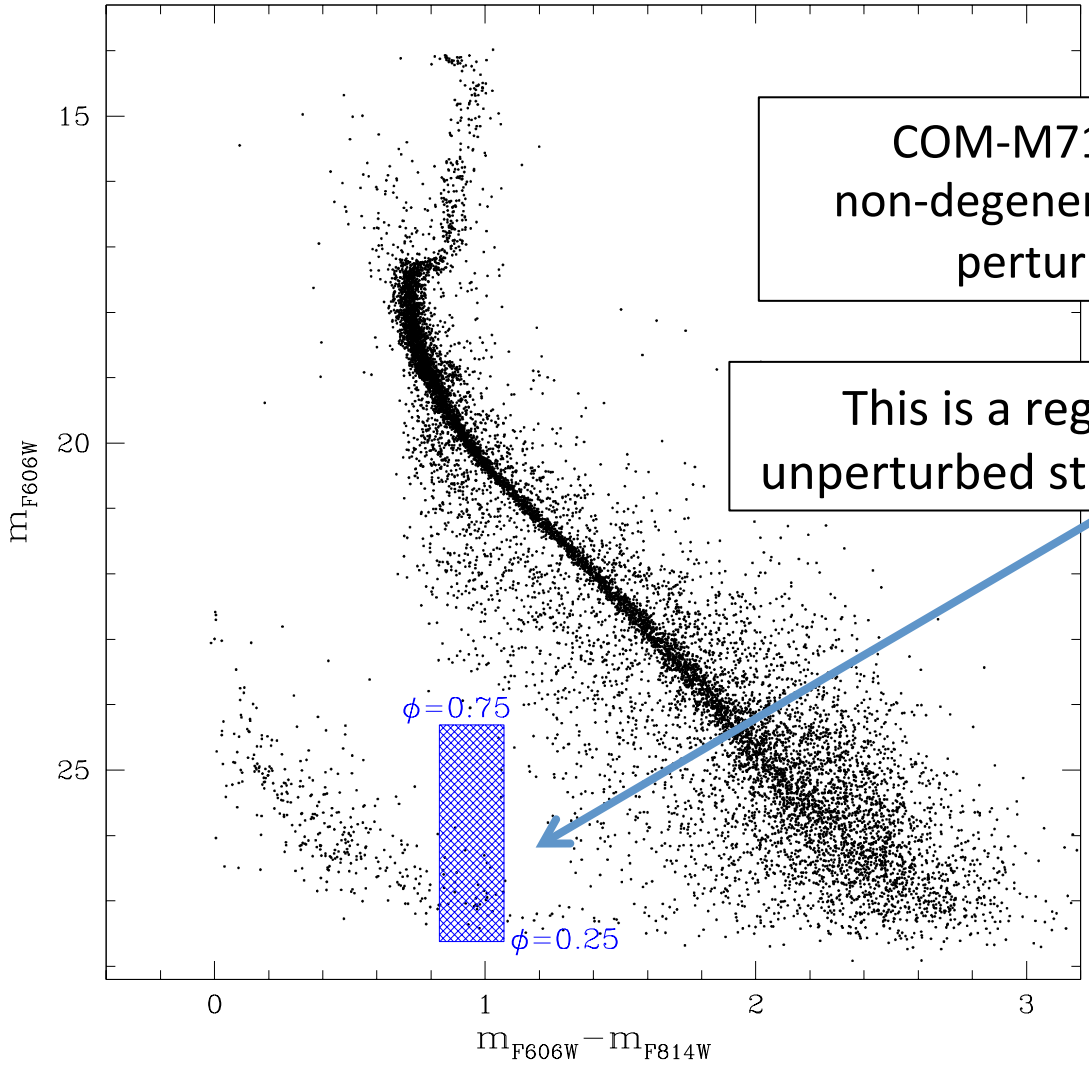




CMD Position



CMD Position

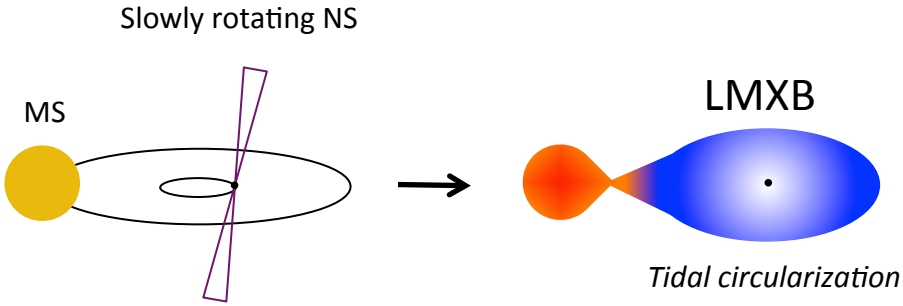


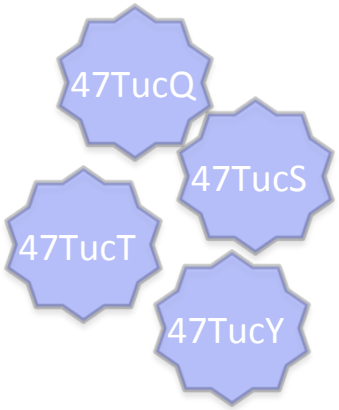
COM-M71A is likely a non-degenerate and highly perturbed star.

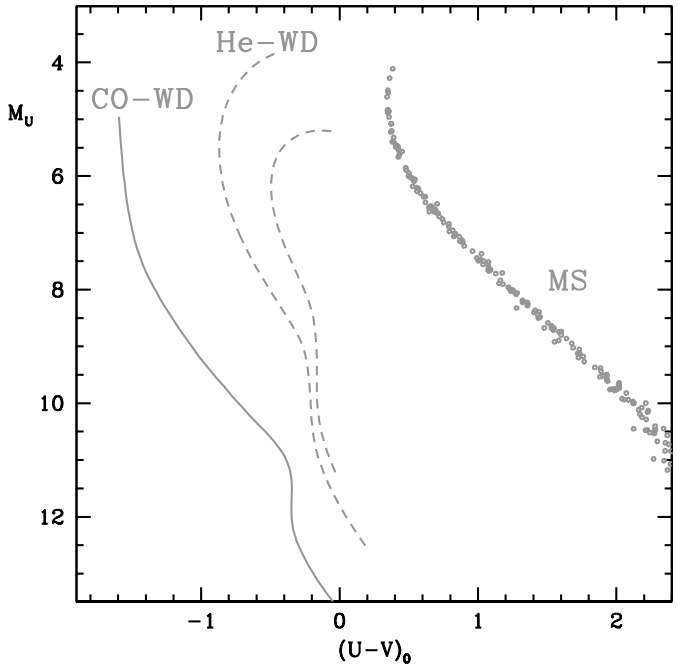
This is a region where no unperturbed stars are expected!

A cartoon of the evolutionary scenario

Canonical recycling scenario ...

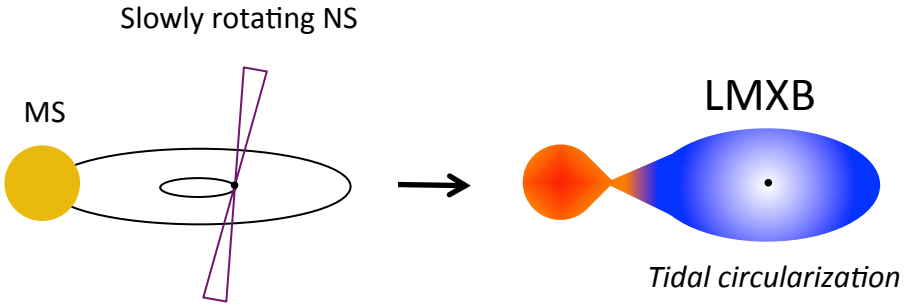




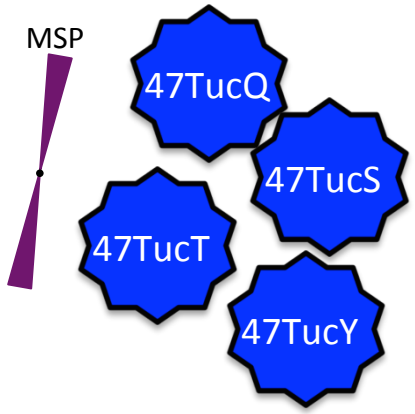


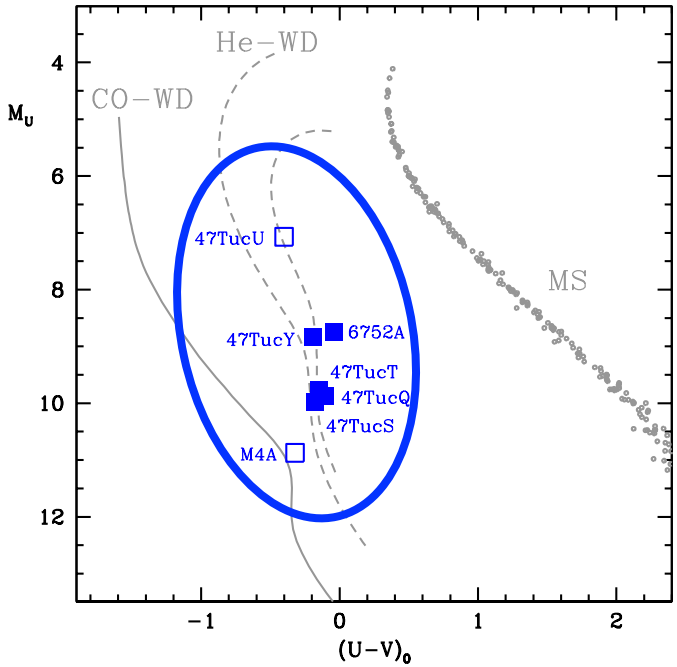
A cartoon of the evolutionary scenario

Canonical recycling scenario ...



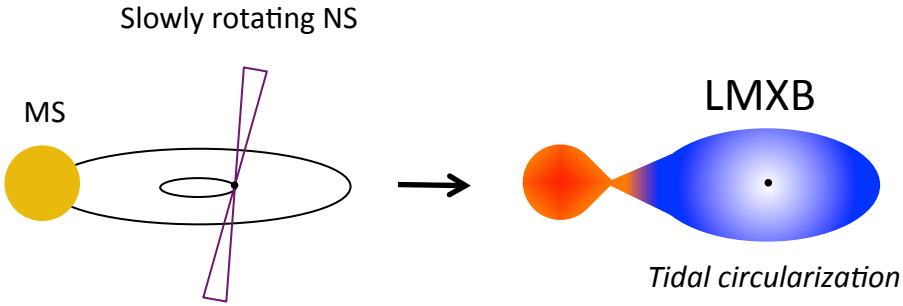
... and deviations

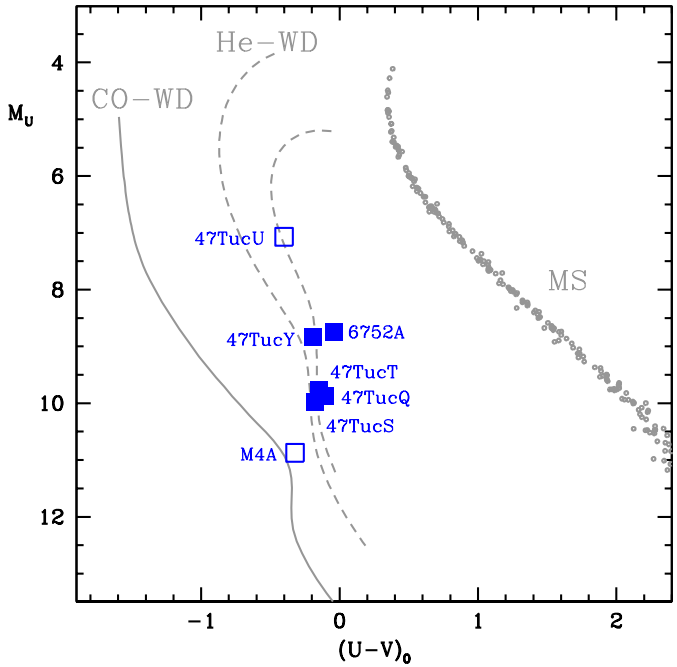




A cartoon of the evolutionary scenario

Canonical recycling scenario ...





... and deviations

M28I

M28H

6397A

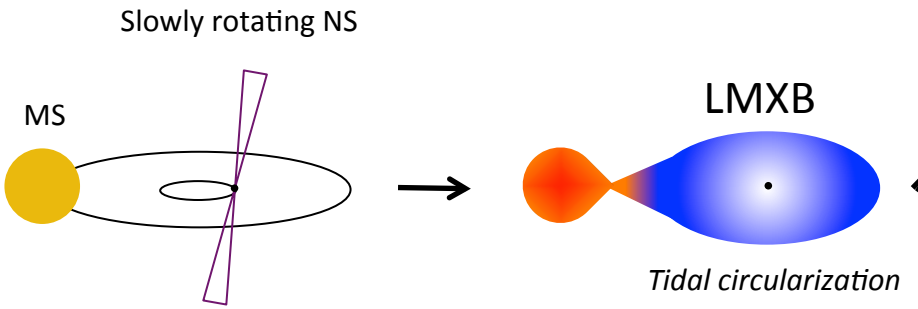
M5C

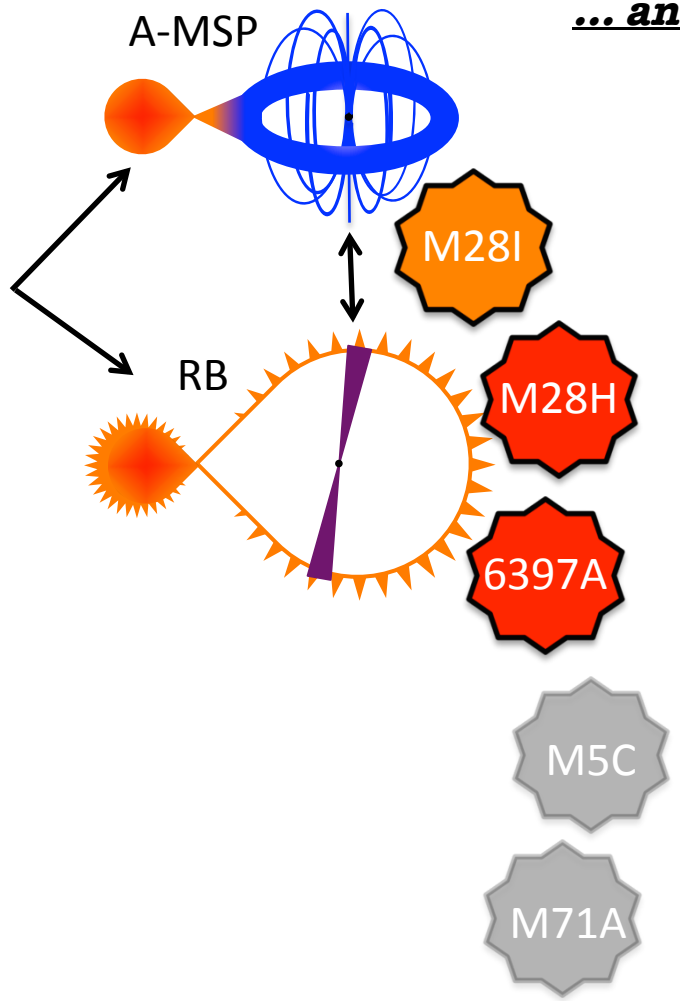
M71A

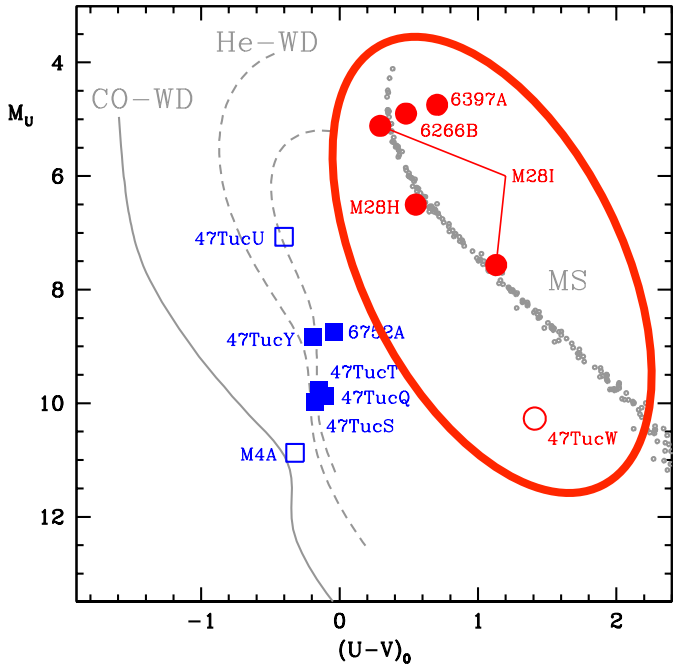
A cartoon of the evolutionary scenario

Canonical recycling scenario ...

... and deviations



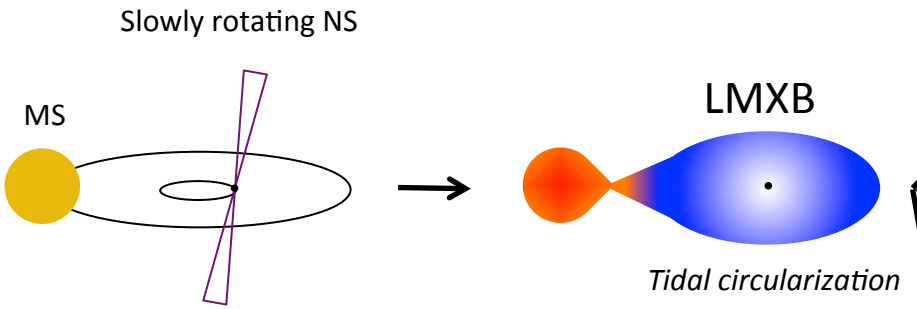


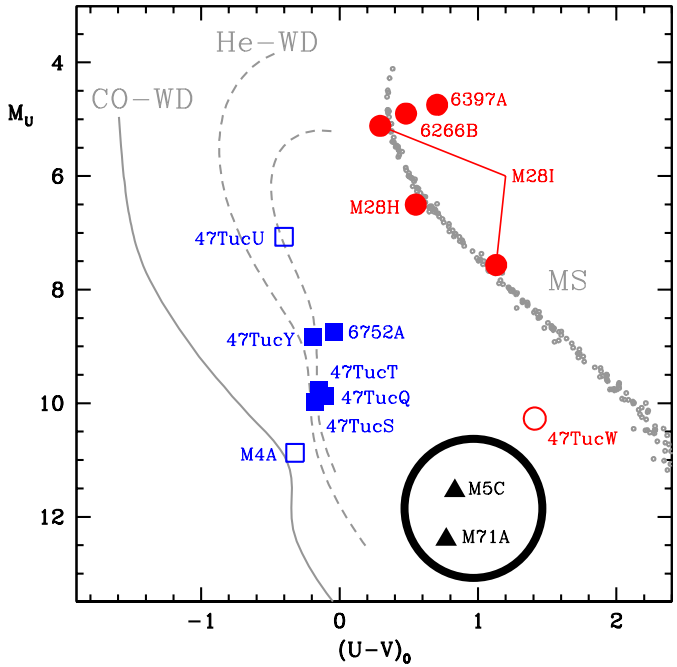


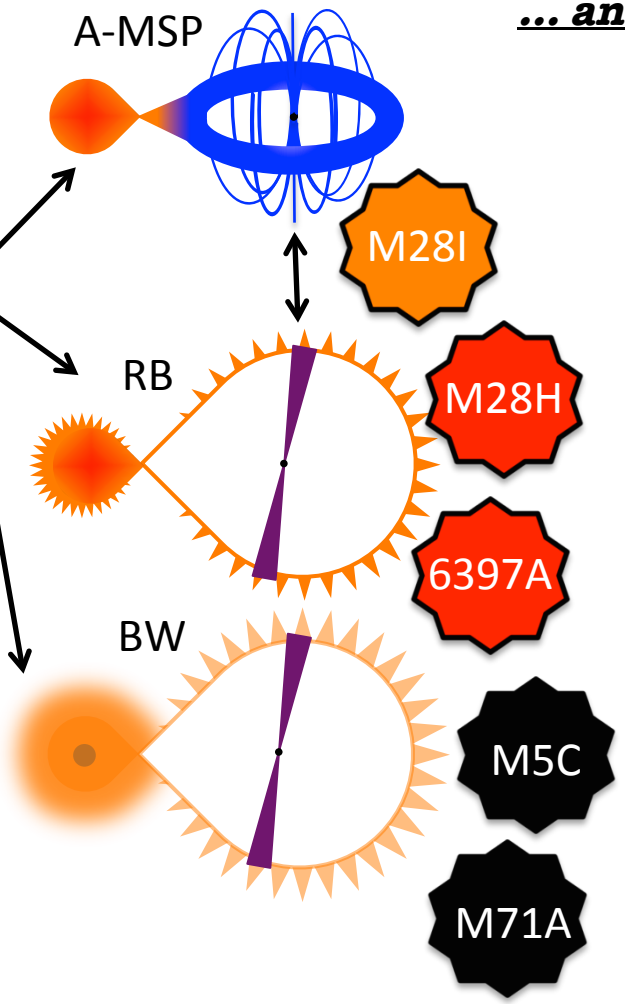
A cartoon of the evolutionary scenario

Canonical recycling scenario ...

... and deviations



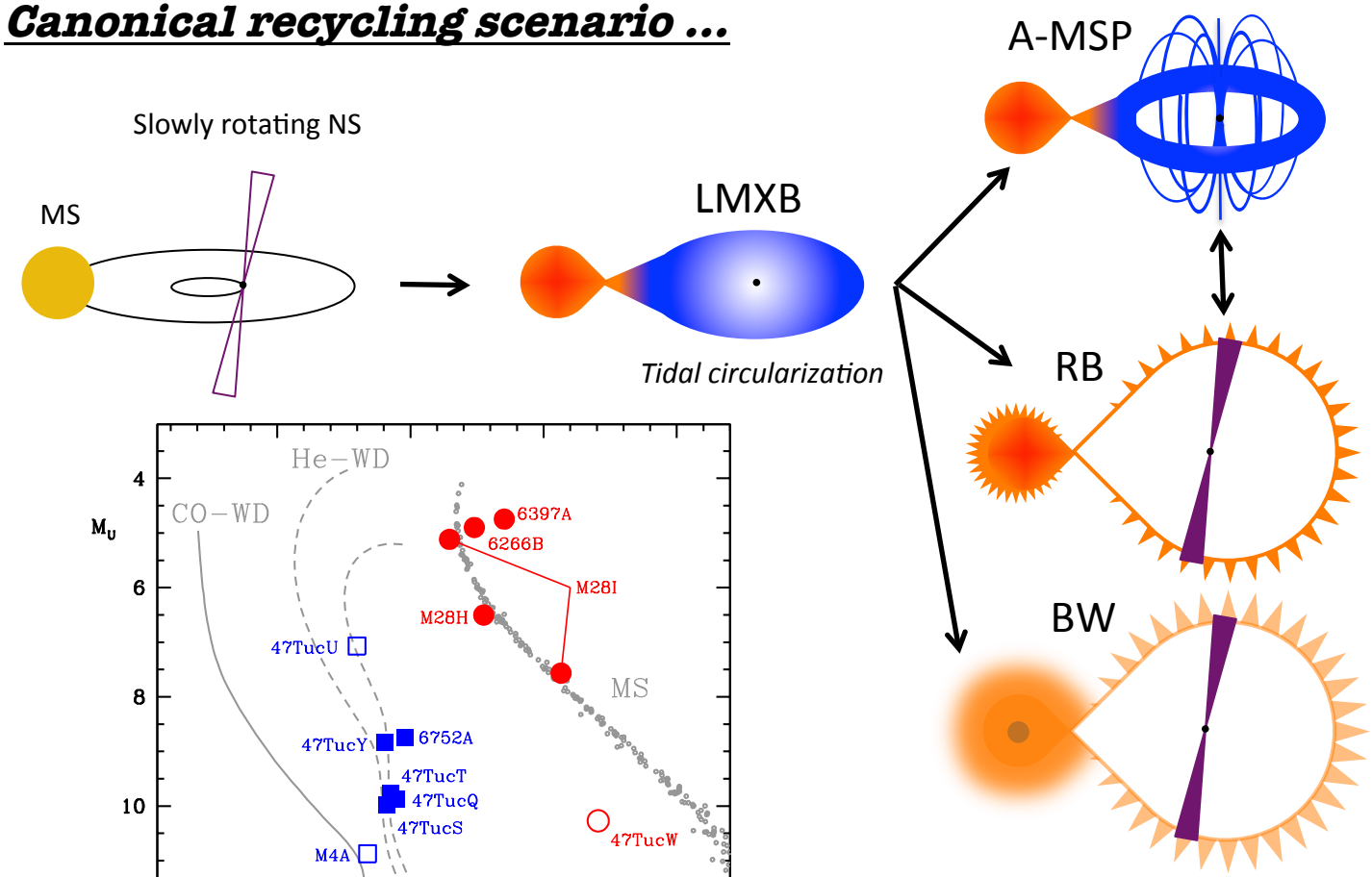




A cartoon of the evolutionary scenario

Canonical recycling scenario ...

... and deviations



A cartoon of the evolutionary scenario

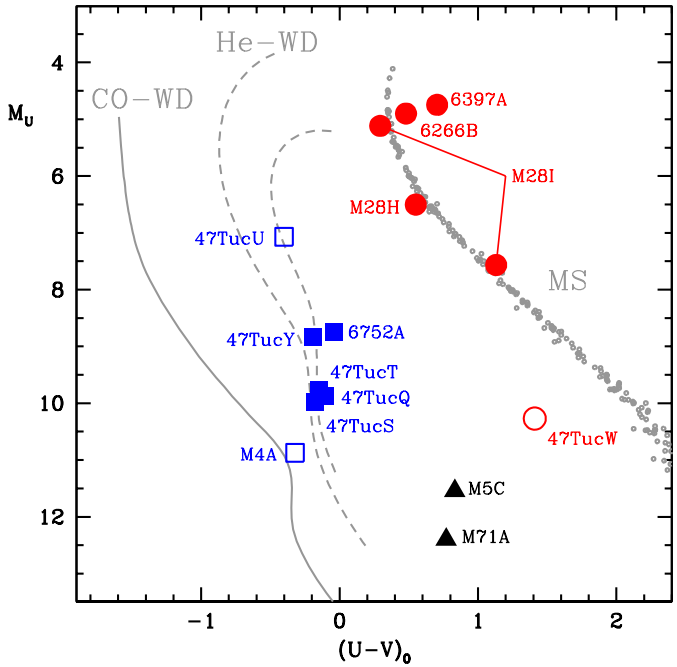
Canonical recycling scenario ...

Slowly rotating NS

MS

LMXB

Tidal circularization



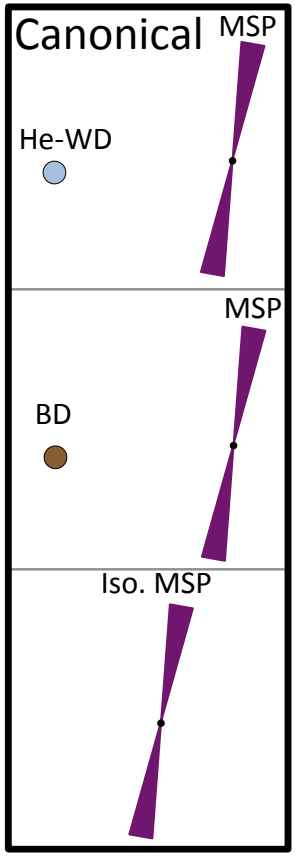
A-MSP

RB

BW

?

... and deviations



A cartoon of the evolutionary scenario

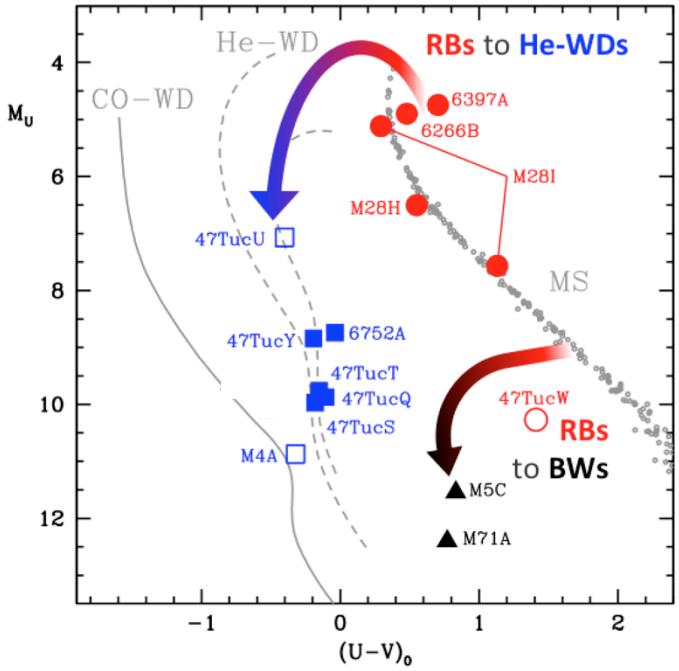
Canonical recycling scenario ...

Slowly rotating NS

MS

LMXB

Tidal circularization



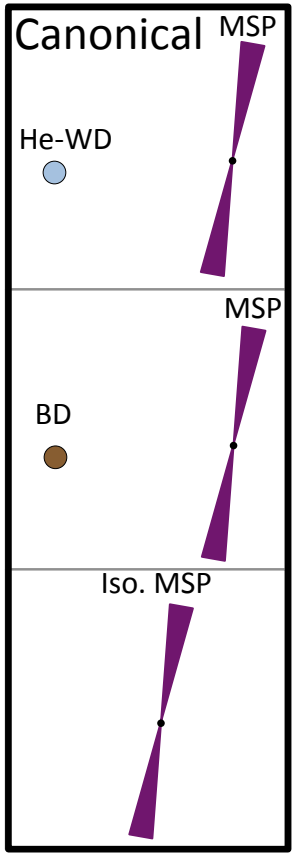
A-MSP

RB

BW

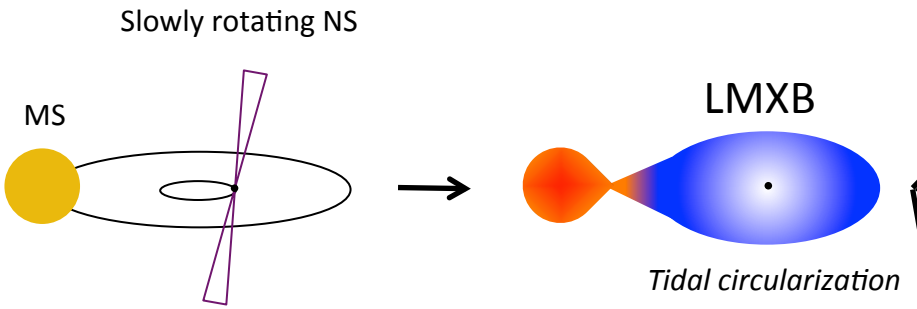
?

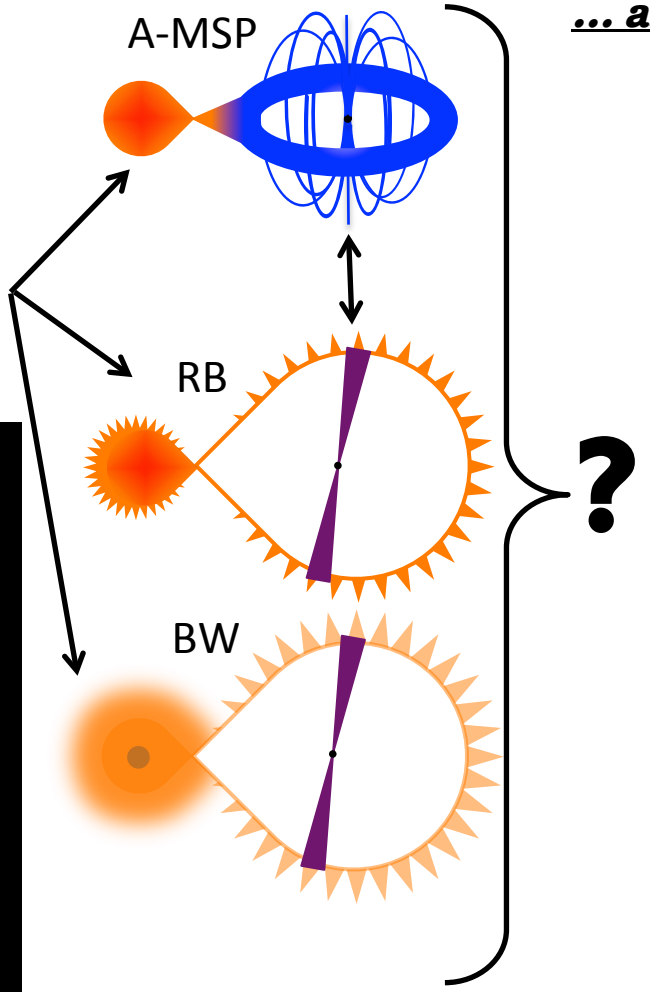
... and deviations



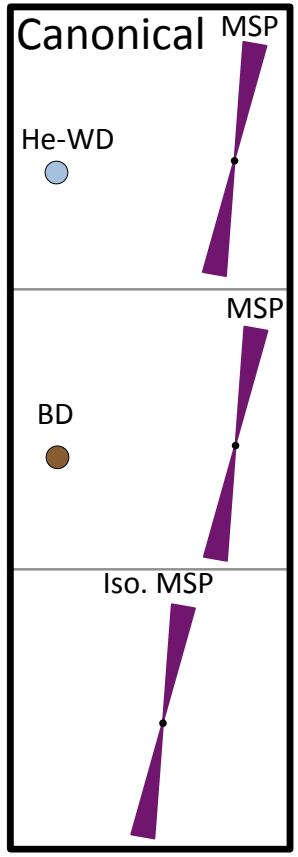
A cartoon of the evolutionary scenario

Canonical recycling scenario ...

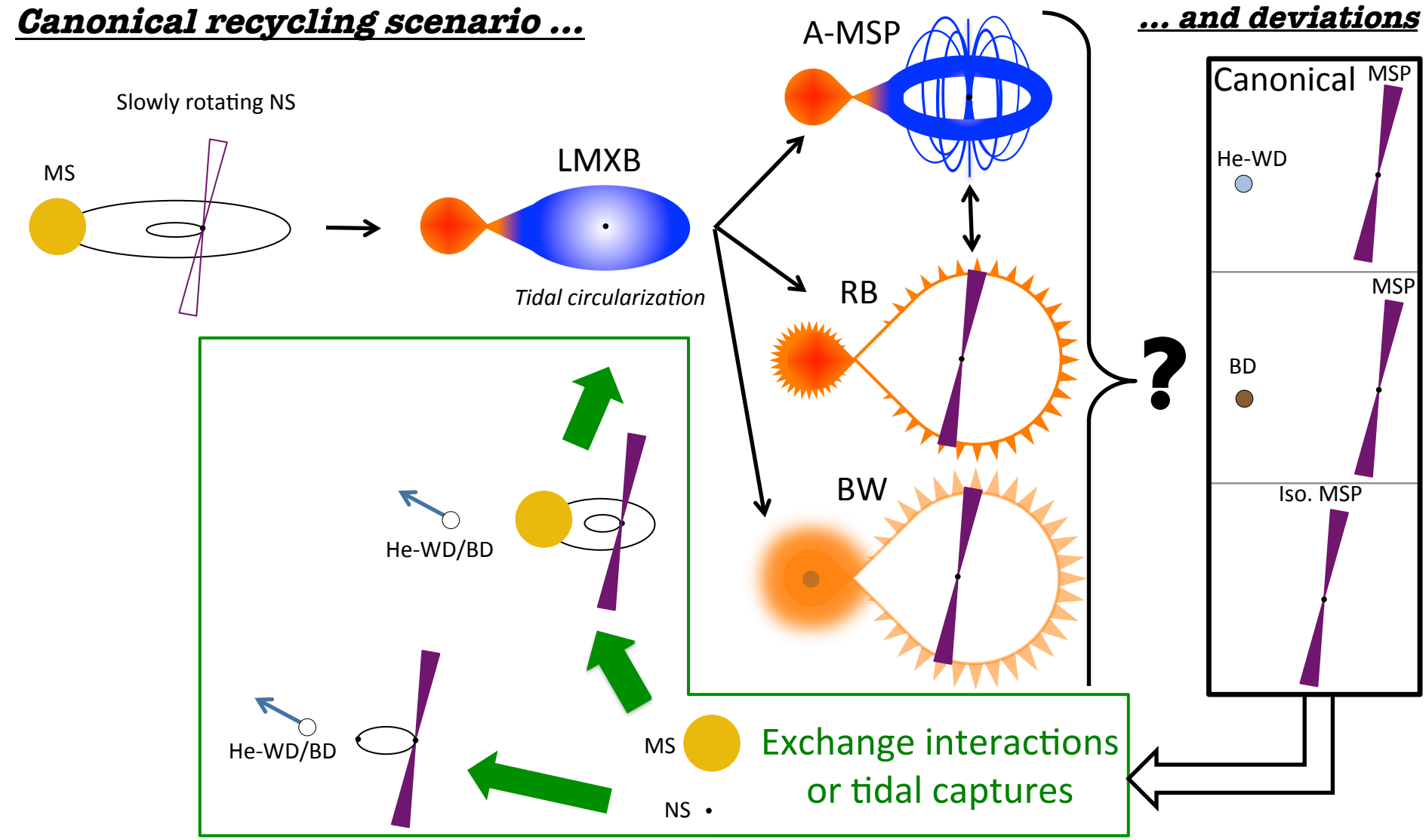




... and deviations



A cartoon of the evolutionary scenario



Thanks for your attention