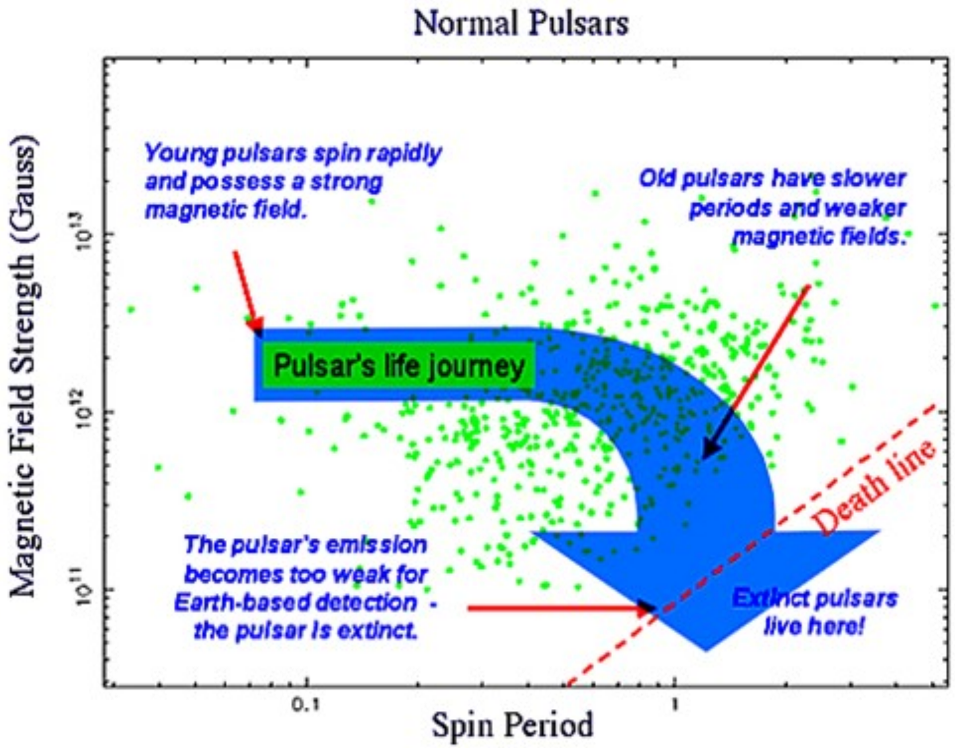
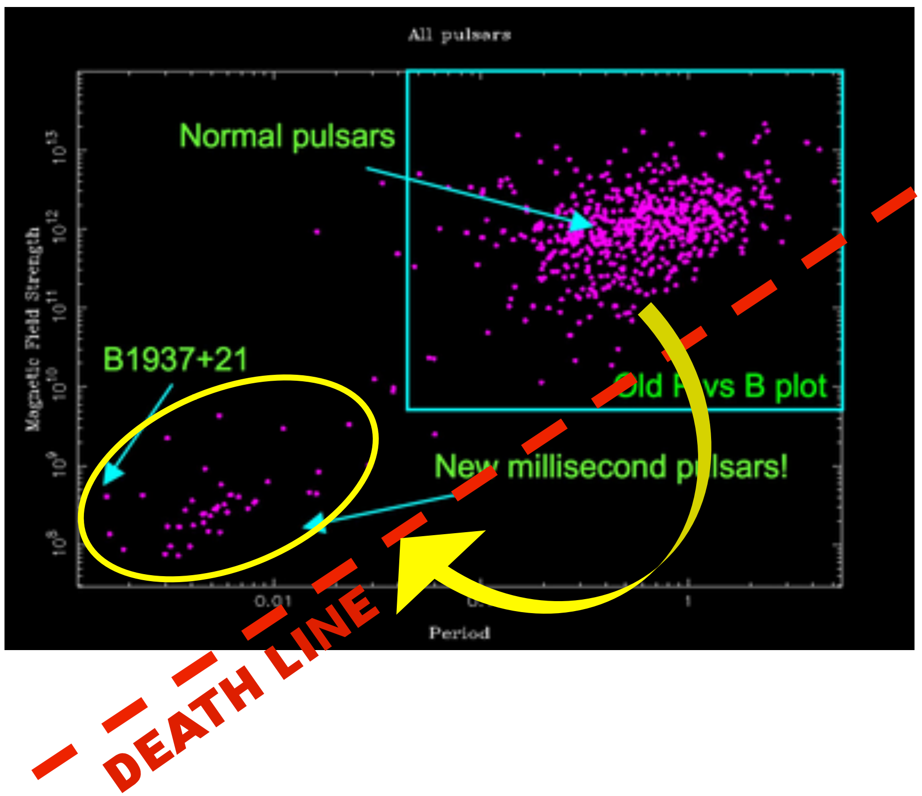
Companions to binary MSPs in GCs

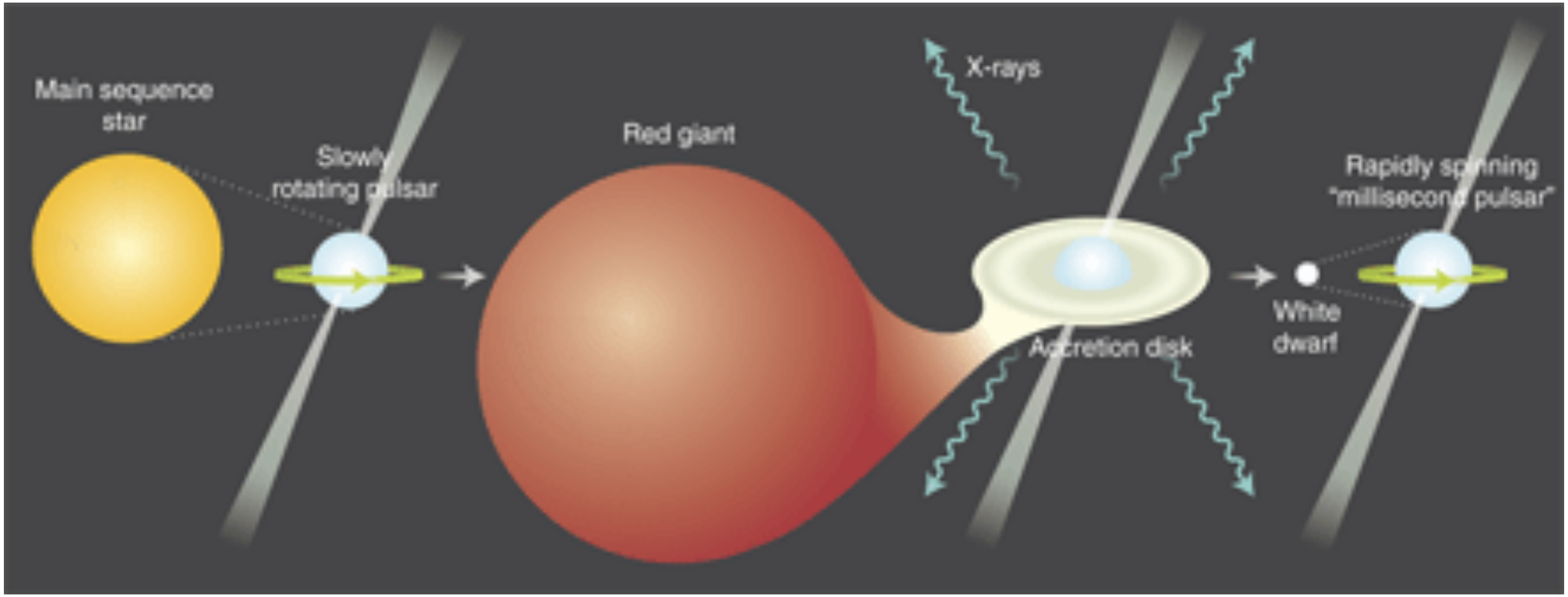
MSPs (recycled-pulsars):

pulsars with dP/dt < 10^{-17} (OLD) and P ~ 10^{-3} sec (RE-ACCELERATED)





RECYCLING -SCENARIO (Bhattacharya et al. 1991):



Binary system: NS + evolving companion

mass accretion from the evolving companion spin up the pulsar

fast rotating pulsar (MSP) + an exhausted star

the core of a peeled star = WD

MSPs in globular clusters

Galactic disc is 100 times more massive than the GGC system.

However.... **more than 50% of known MSPs is found in GCs!!**

Galactic Field

Globular Clusters

Evolution of primordial binaries

Dynamical interactions can promote the formation of binaries suitable for recycling NSs into MSPs

GCs are efficient MPS "furnaces"

Optical companions to binary MSPs

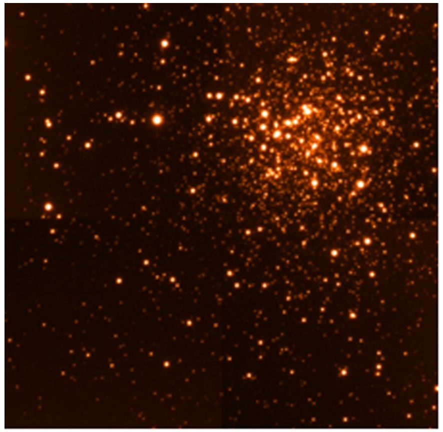
Why important?

To investigate the recycling mechanism

(WD or not?)

To measure the NS mass

upper limit to the NS mass & tight constraints to the equation of state of the matter at the nuclear equilibrium density



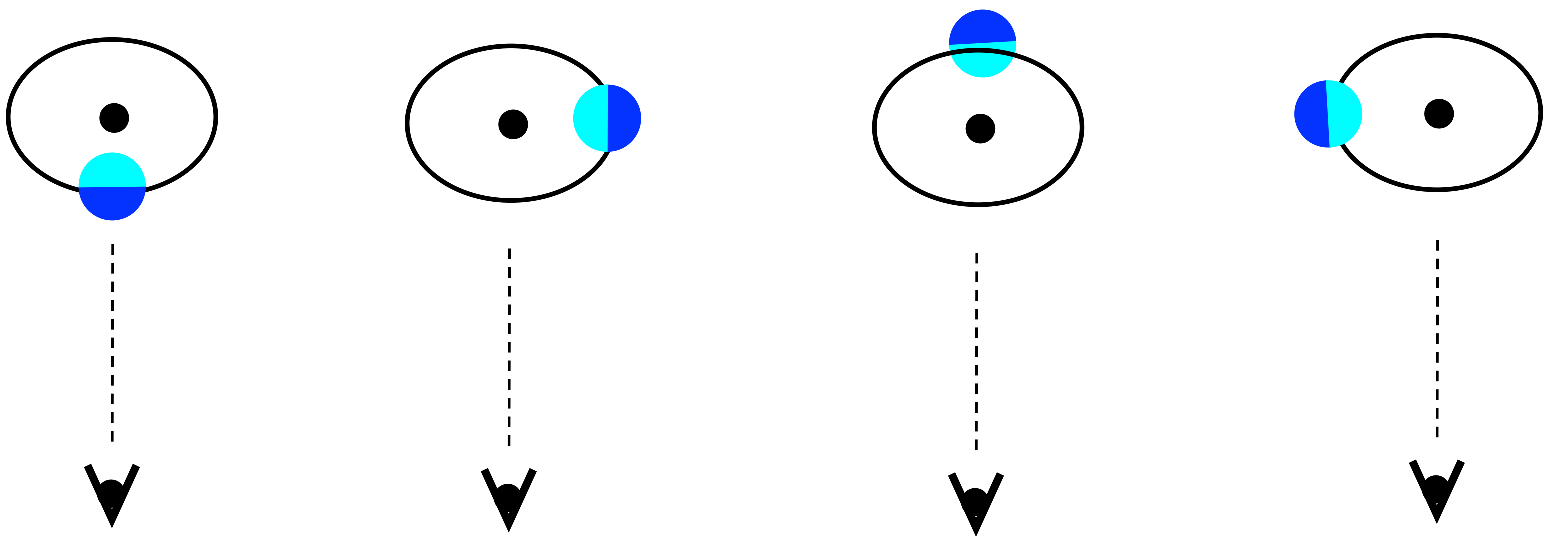
To clarify the effects of crowded stellar environments on the evolution of binaries

Optical companions to binary MSPs

How to search for them?

COM is (expected to be):

- **located close to the PSR (=> in the very central regions of GCs)**
- **an almost exhausted star (WD)**
- **orbiting the PSR (=> showing periodical eclipses and/or heating from the PSR flux => optical variability)**



Searching for optical companions to binary MSPs

Radio

Very accurate position of the PSR

Orbital parameters

Orbital period: P_b

Projected semi-major axis: $a_p \sin i$

PSR Mass function: $f\,(M_{MSP}, M_{COM})$

Total mass: $M_{PSR}+M_{COM}$

$$f(M_{MSP}, M_{COM}) = \frac{(M_{COM} \sin i)^3}{(M_{MSP} + M_{COM})^2} = \frac{4\pi^2 (a_p \sin i)^3}{G\, P_b^{\;2}}$$

Searching for optical companions to binary MSPs

Radio

Optical

Photometry

Very accurate position of the PSR → **search for a star close to the PSR**

Orbital parameters

Orbital period

PSR Mass function

→ **search for variability corresponding to orbital motion (P_b)**

Total mass:
$M_{PSR}+M_{COM}$

high-resolution
(GCs very dense, MSPs in the centre)

deep
(COM expected to be a WD => faint)

high-precision astrometry
(for a precise location with respect to PSR)

multi-epoch

Searching for optical companions to binary MSPs

Radio

Very accurate position of the PSR

Orbital parameters

Orbital period

PSR Mass function

Total mass: $M_{PSR}+M_{COM}$

Optical

Photometry

- **positional coincidence**
- **CMD**

(nature -WD or not, Teff, luminosity & mass of COM)

- **light curve**

(orbital inclination i)

→ M_{PSR}

$$f(M_{MSP}, M_{COM}) = \frac{(M_{COM}\sin i)^3}{(M_{MSP}+M_{COM})^2} = \frac{4\pi^2(a_p \sin i)^3}{G\,P_b^{\,2}}$$

Searching for optical companions to binary MSPs

Radio

Optical

Photometry

Spectroscopy

Very accurate position of the PSR

Orbital parameters

Orbital period

PSR Mass function

Total mass: $M_{PSR}+M_{COM}$

- **positional coincidence**
- **CMD**

  (nature -WD or not, Teff, luminosity & mass of COM)

- **light curve**

  (orbital inclination i)

... if bright enough...

Searching for optical companions to binary MSPs

Radio

Very accurate position of the PSR

Orbital parameters

Orbital period

PSR Mass function

Total mass: $M_{PSR}+M_{COM}$

Optical

Photometry

- positional coincidence
- CMD

  (nature -WD or not, Teff, luminosity & mass of COM)
- light curve

  (orbital inclination i)

Spectroscopy

- radial velocity curve

COM mass function
\+
PSR mass function

↓

mass ratio
(M_{PSR}/M_{COM})

↓

system solved:
$(M_{PSR},\ M_{COM})$

- chemical abundances

$$f(M_{MSP}, M_{COM}) = \frac{(M_{COM}\sin i)^3}{(M_{MSP}+M_{COM})^2} = \frac{4\pi^2(a_p \sin i)^3}{G\,P_b^{\,2}}$$

The state of the art

~80 binary MSPs in GCs (http://www.naic.edu/~pfreire/GCpsr.html)

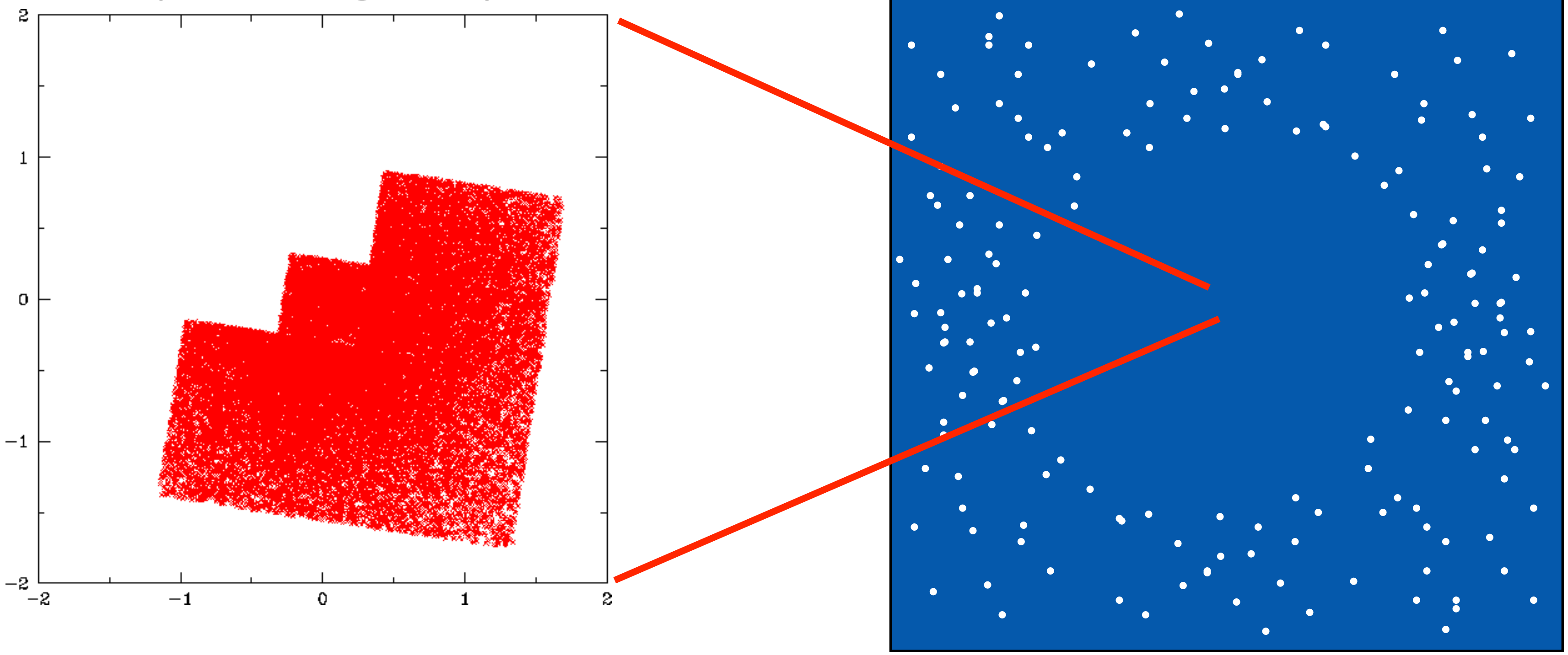
only 7 (<10%) identified companions!

PSR J0024-7203U – Edmonds et al. 2001
PSR B1620-26 – Sigurdsson et al. 2003
PSR J1911-5958A – Ferraro et al. 2003; Bassa et al. 2003

PSR J1740-5340A – Ferraro et al al. 2001
PSR J0024-7204W – Edmonds et al. 2002
PSR J1701-3006B – Cocozza et al. 2008
PSR J1824-2452H – Pallanca et al. 2010

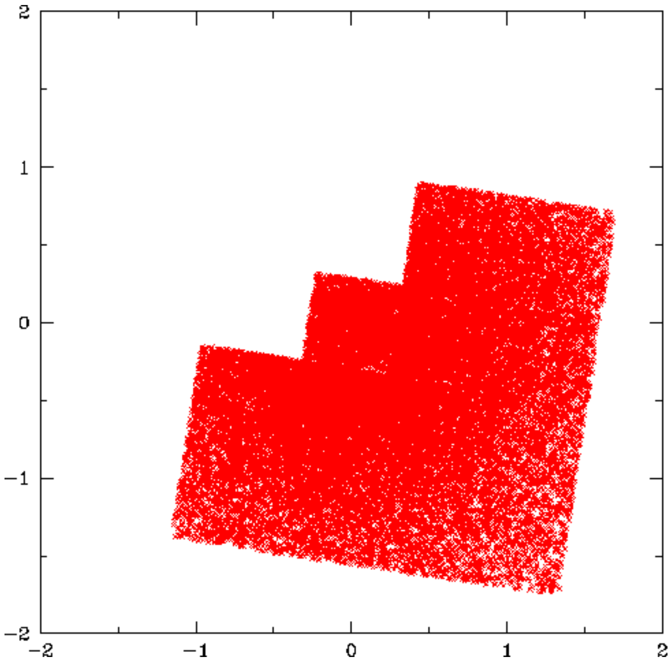
High resolution images
(WFPC2@HST)

primary astrometric standard catalog (GSC2)

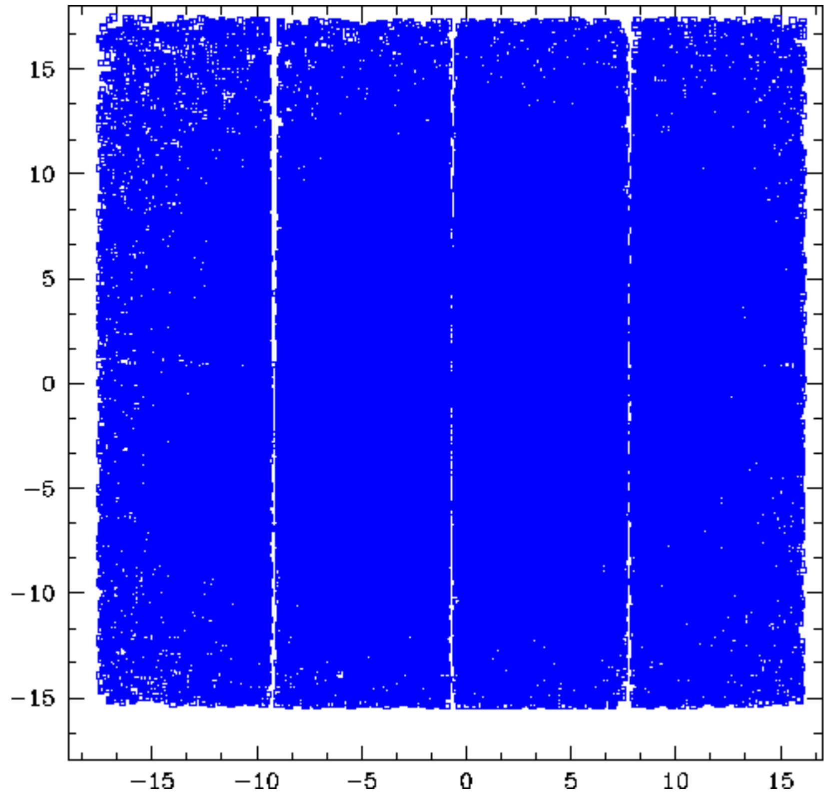


How to astrometrize it ?
(i.e., put on the absolute astrometric system)

High resolution images
(WFPC2@HST)

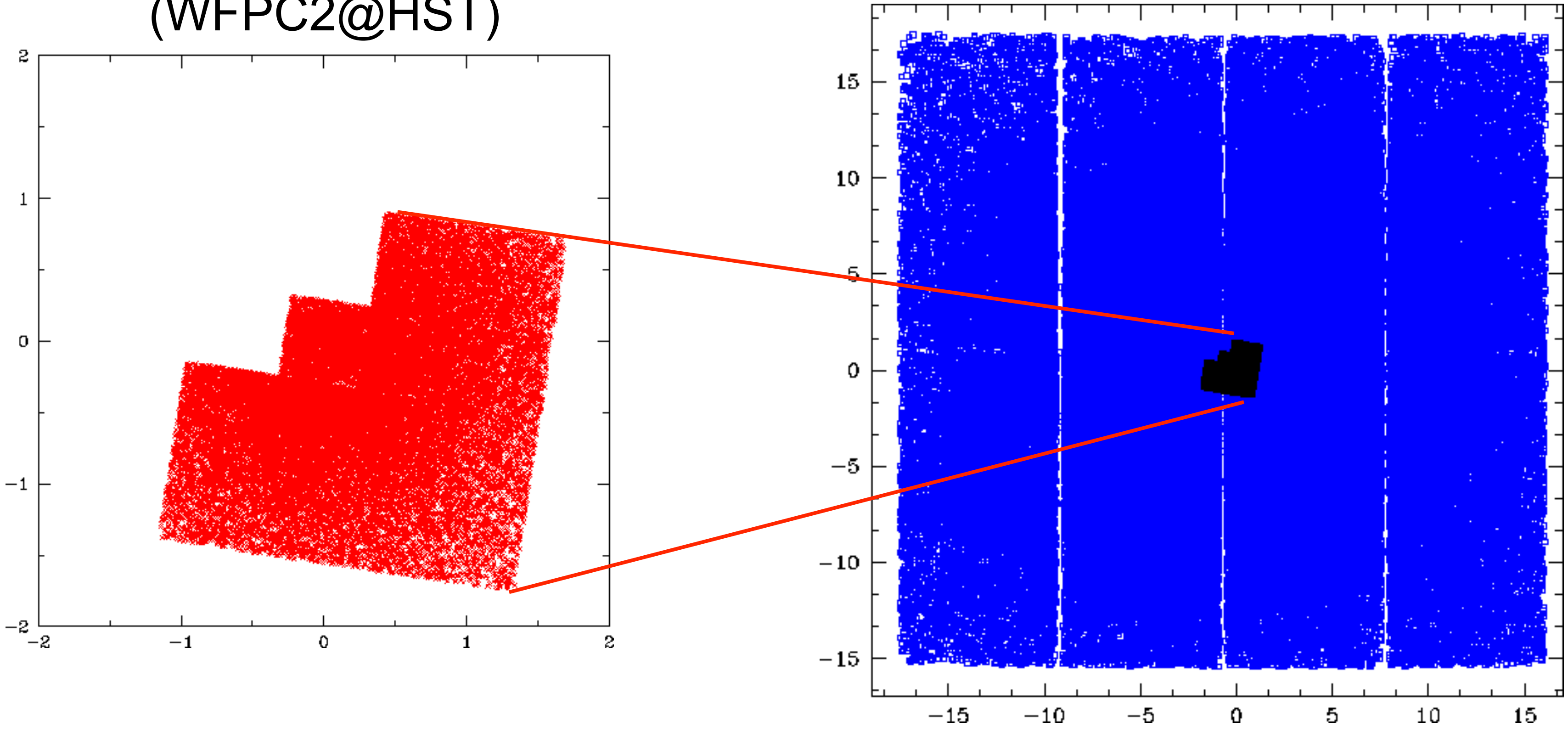


Wide-Field images
(WFI@ESO-2.2m: FoV 30'x30')



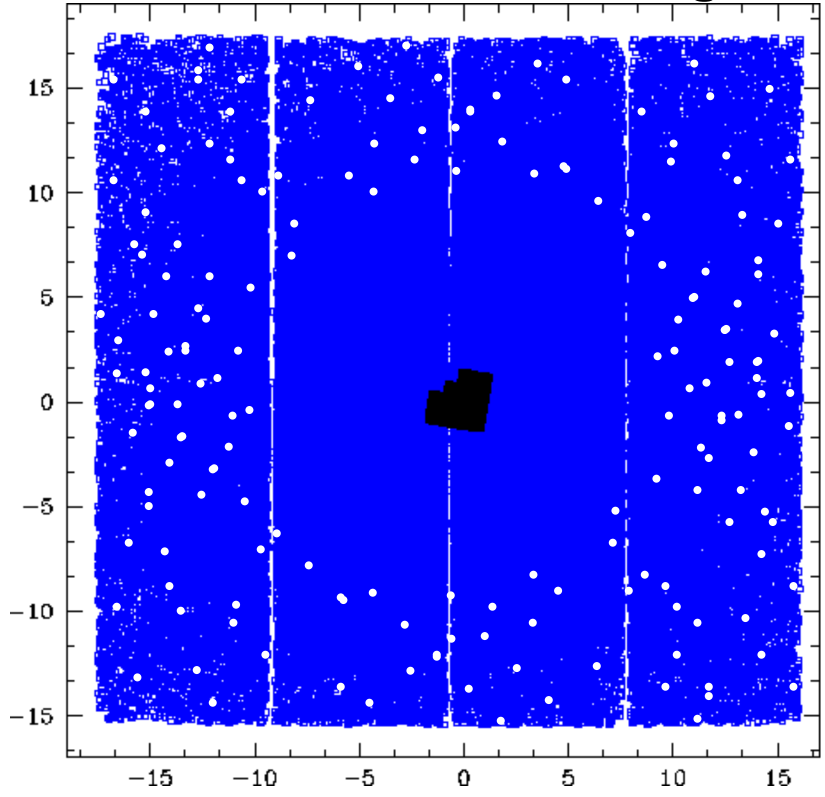
High resolution images
(WFPC2@HST)

combined catalog
(high-res + wide-field)



find the stars in common between
high-resolution & wide-field samples

combined catalog
& astrometric catalog



Put the combined catalog onto the absolute astrometric system, by using the (wide-field) stars in common with the astrometric catalog

fully astrometrized catalog (σ<0.2”)

high-resolution

(to search for MSP companions in highly crowded stellar fields)

HST/ACS-HRC:

pixel scale = 0.027”

FoV = 26”x 25”

wide-field

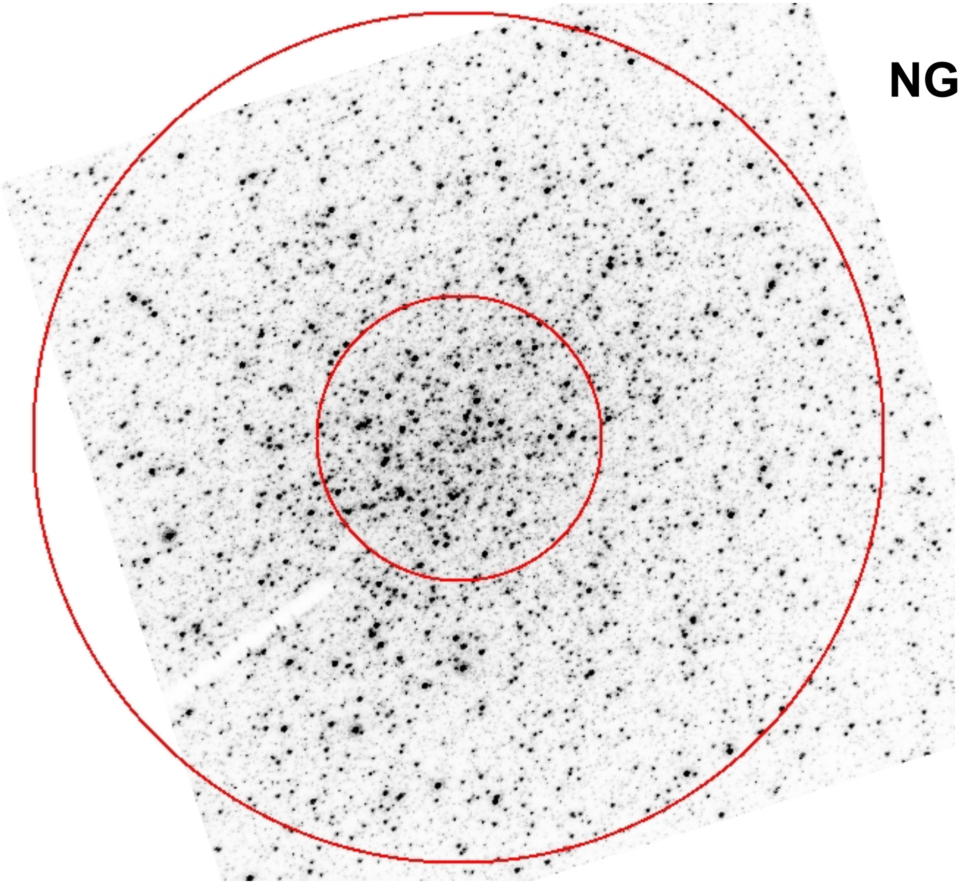
(for a very accurate astrometry of the high-resolution catalog)

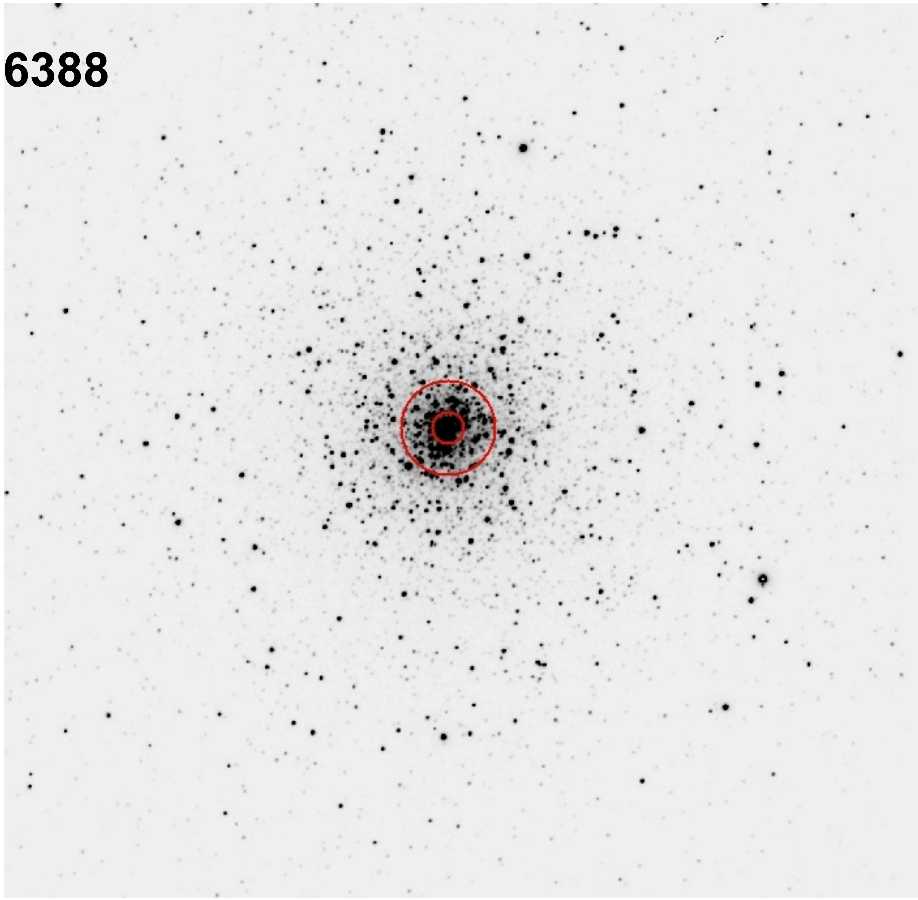
ESO/SOFI:

pixel scale = 0.28” (+ seeing!!)

FoV = 294” x 294”

NGC 6388

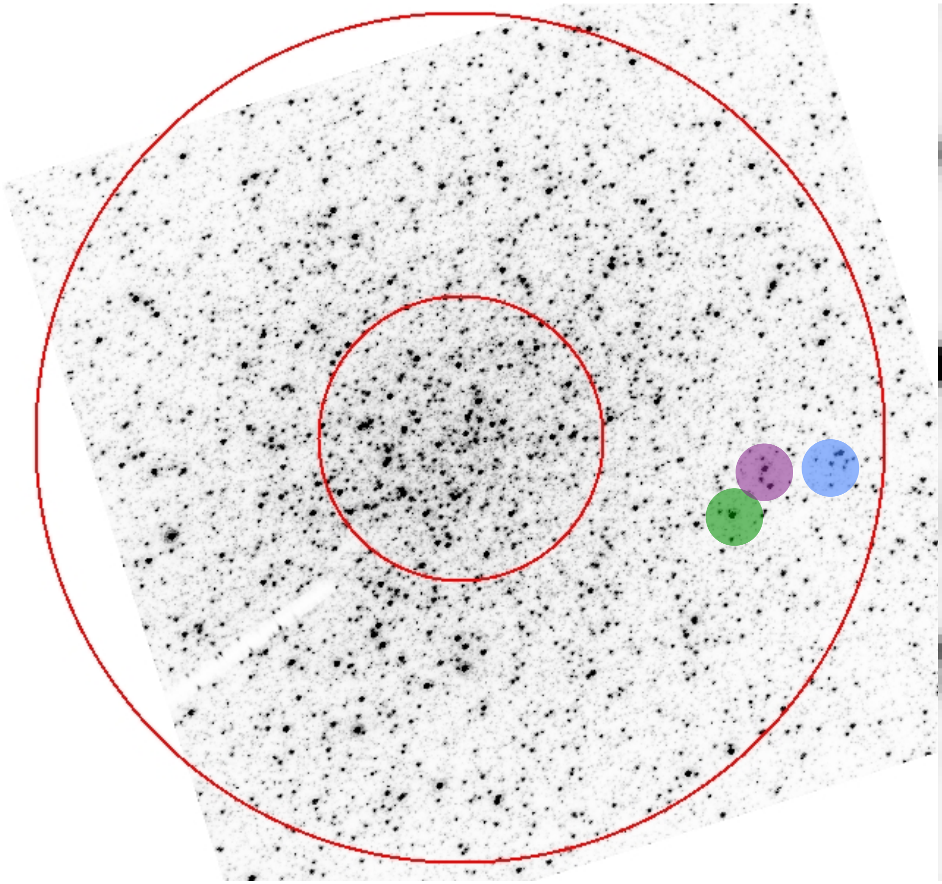




HST/ACS-HRC:

pixel scale = 0.027”

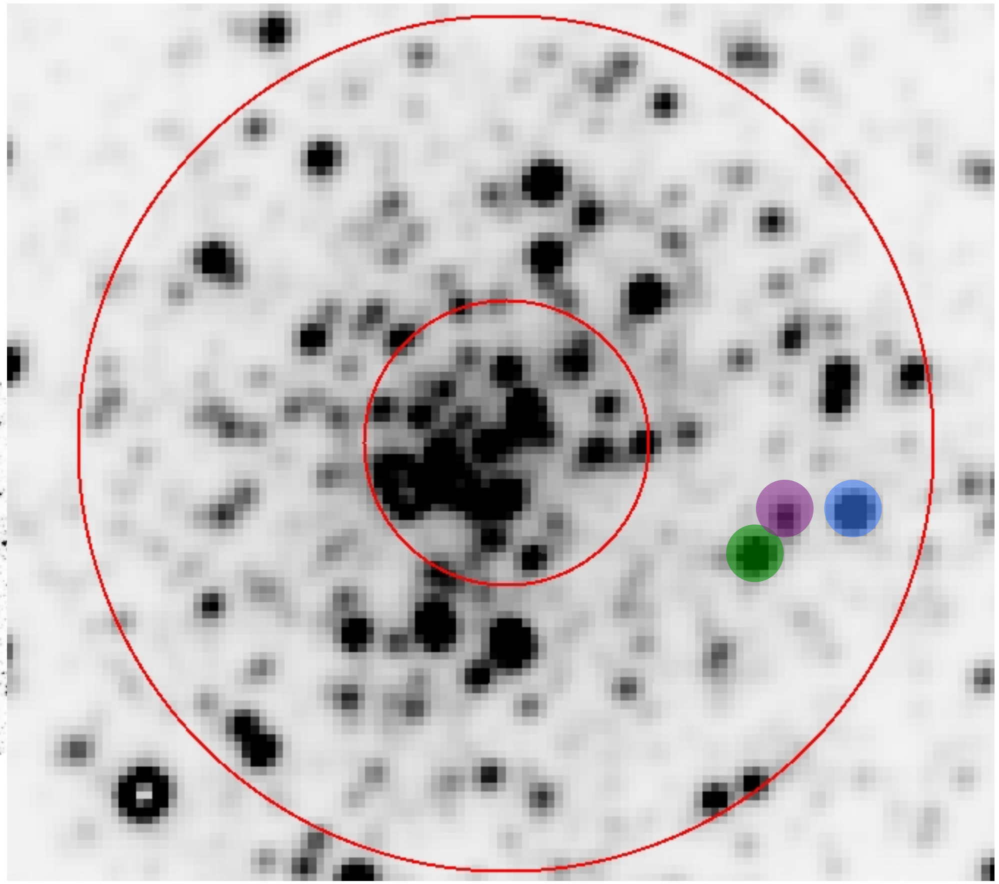
FoV = 26”x 25”



ESO/SOFI:

pixel scale = 0.28” (+ seeing!!)

FoV = 4.9’x 4.9’



inner circle: r=5”

outer circle: r=15”

HST/ACS-WFC:

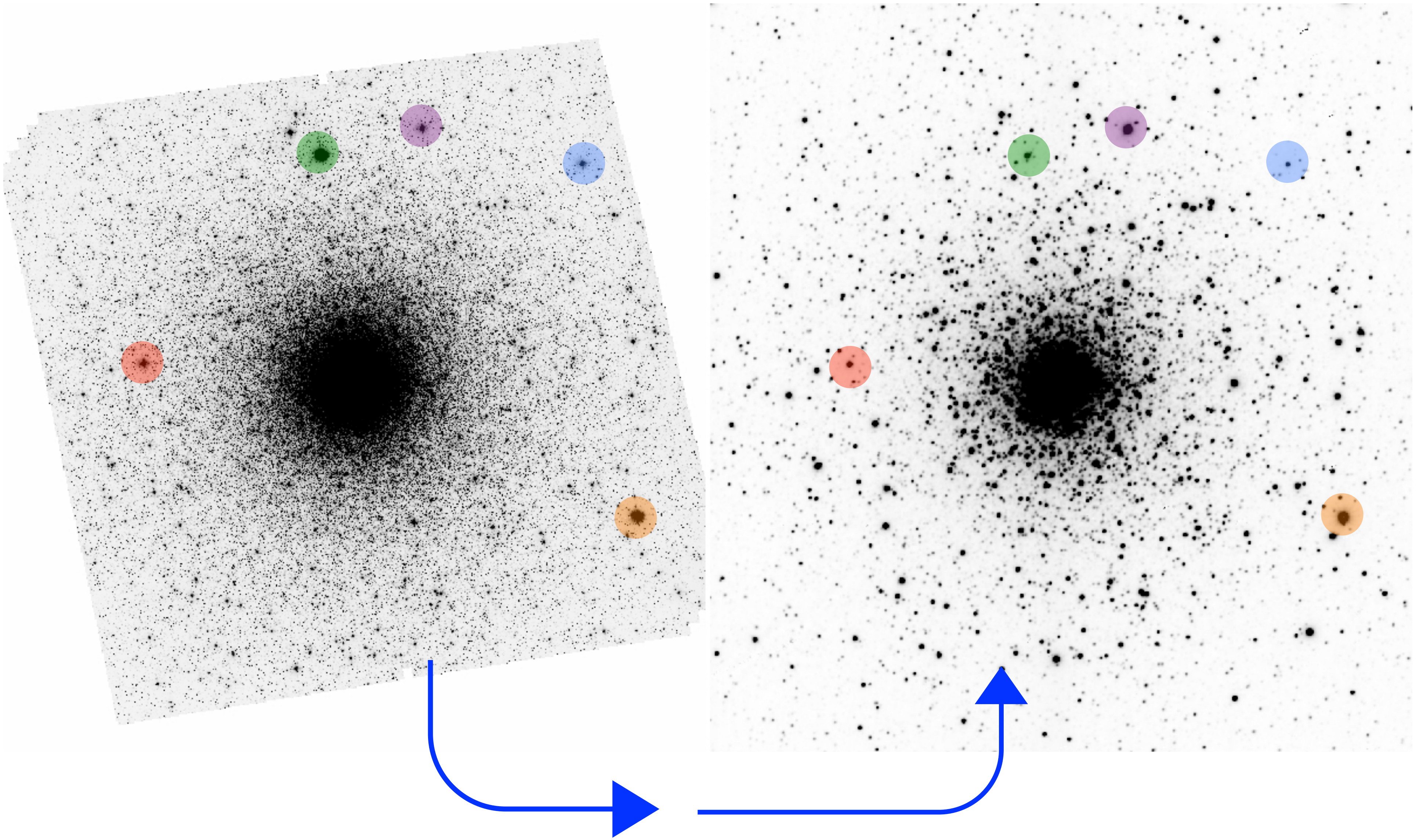
pixel scale = 0.05”

FoV = 202”x 202”

ESO/SOFI:

pixel scale = 0.28” (+ seeing!!)

FoV = 294” x 294”



HST/ACS-WFC:

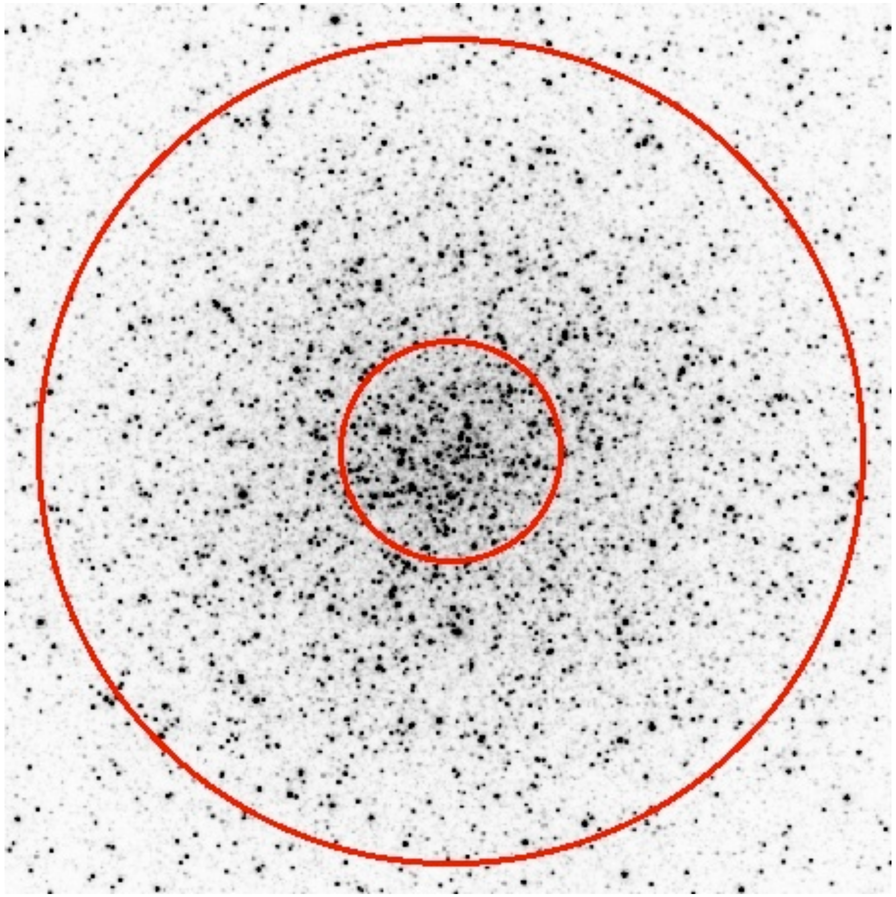
pixel scale = 0.05”

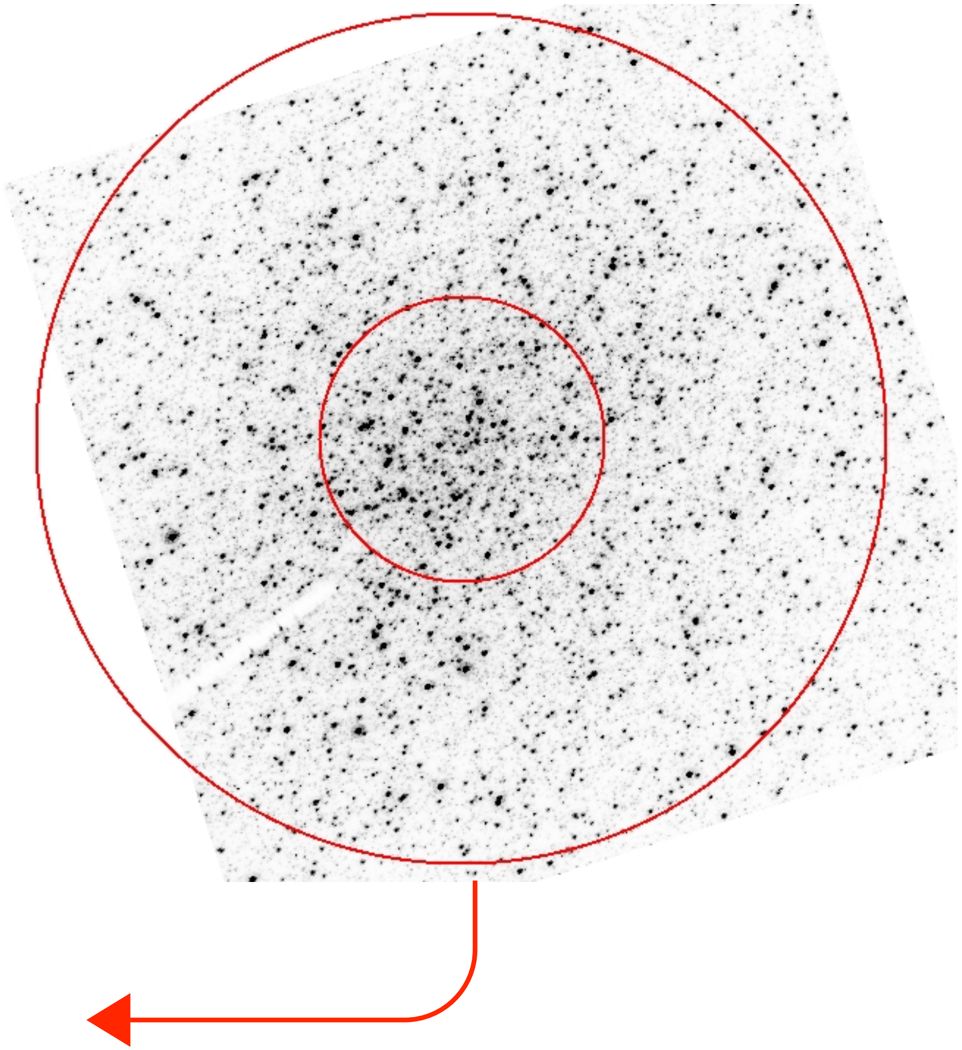
FoV = 202”x 202”

HST/ACS-HRC:

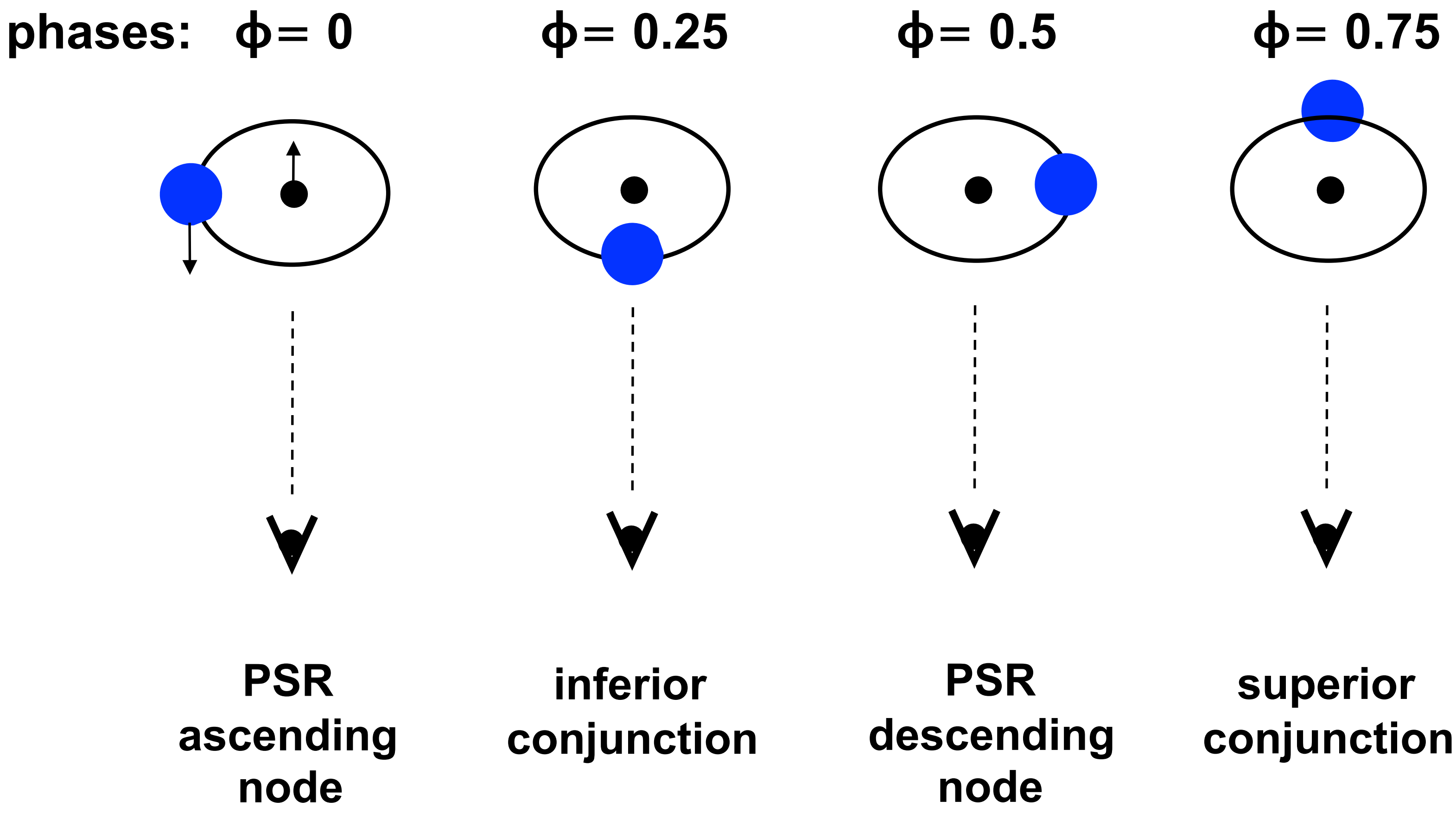
pixel scale = 0.027”

FoV = 26”x 25”

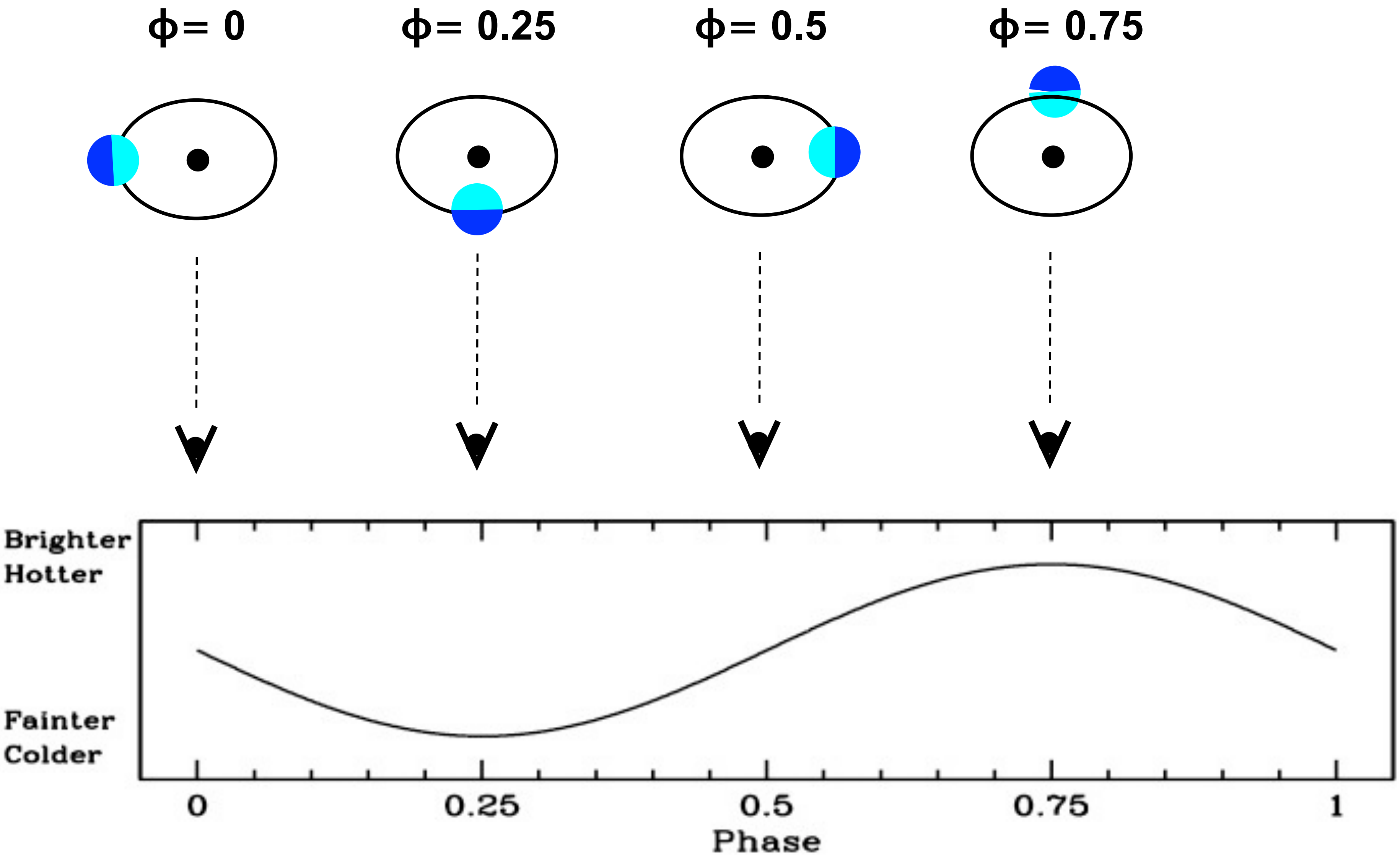




Light curves



Light curves: heating



Heating: 1 minimum (at $\phi = 0.25$) and 1 maximum (at $\phi = 0.75$)

Light curves: tidal distortion

the companion is deformed by the tidal field of the NS

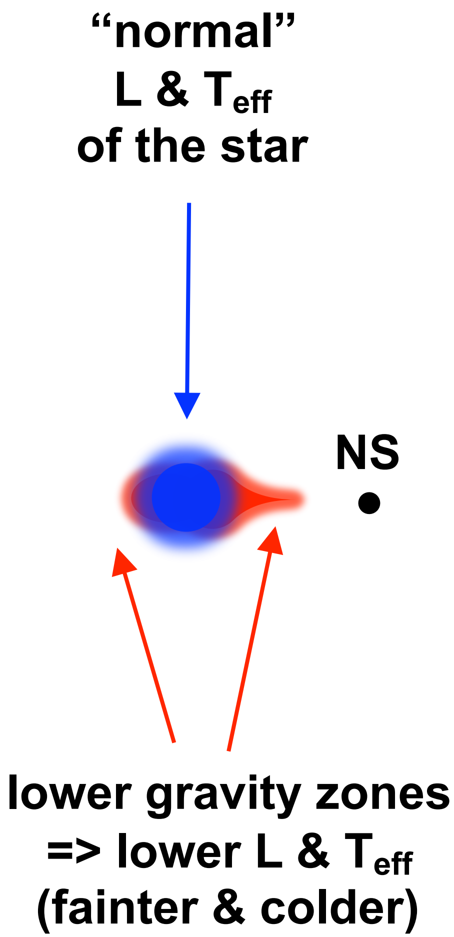
→ gravity varies on the surface

For radiative atmospheres, the emergent intensity and the flux at each point on the surface (assuming hydrostatic equilibrium) is proportional to the local gravity (von Zeipel (1924):

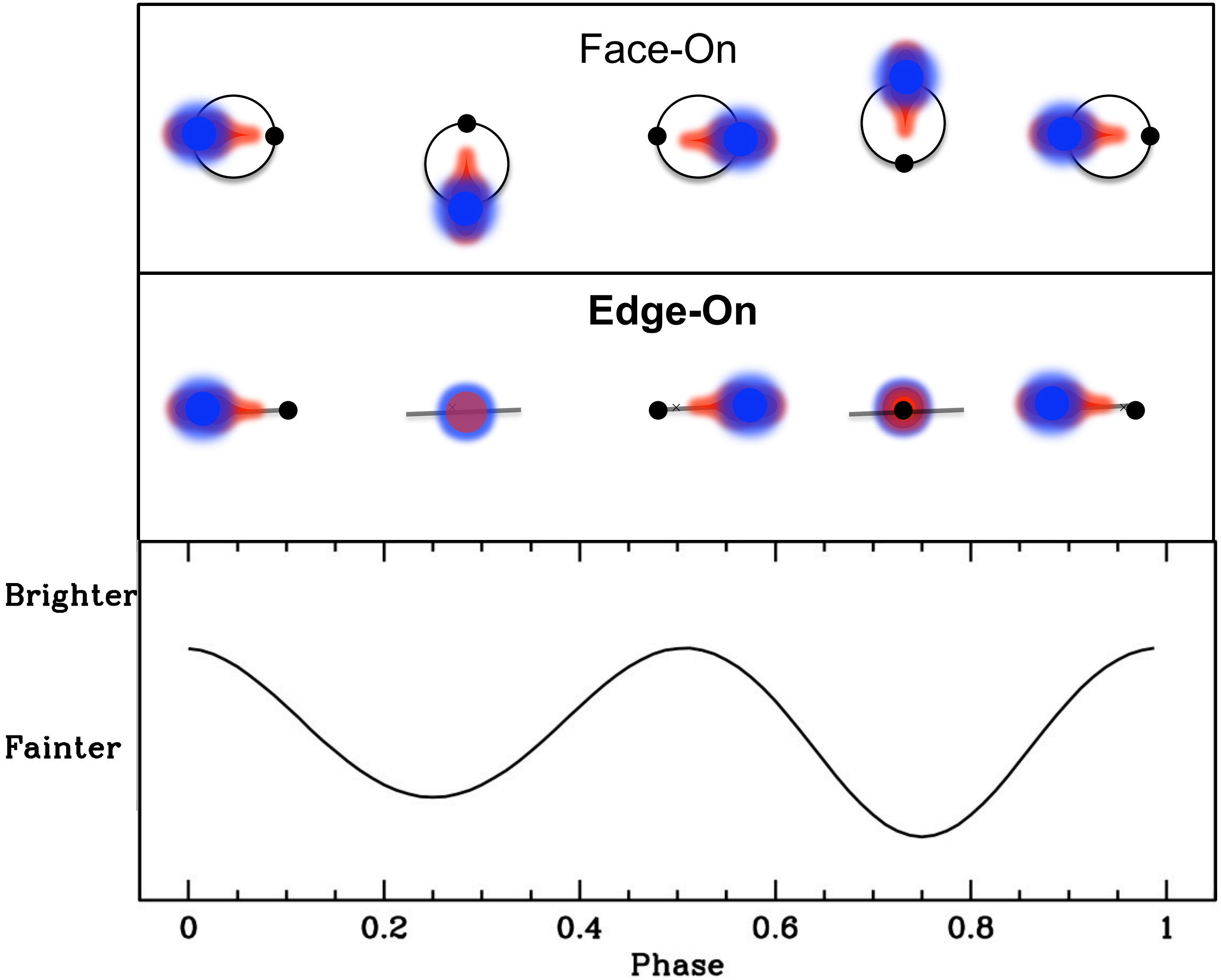
$$\boldsymbol{F \propto g}$$

Furthermore, since $F \propto T^4$ => $\mathbf{T \propto g^{1/4}}$

For convective atmospheres, similar results hold.

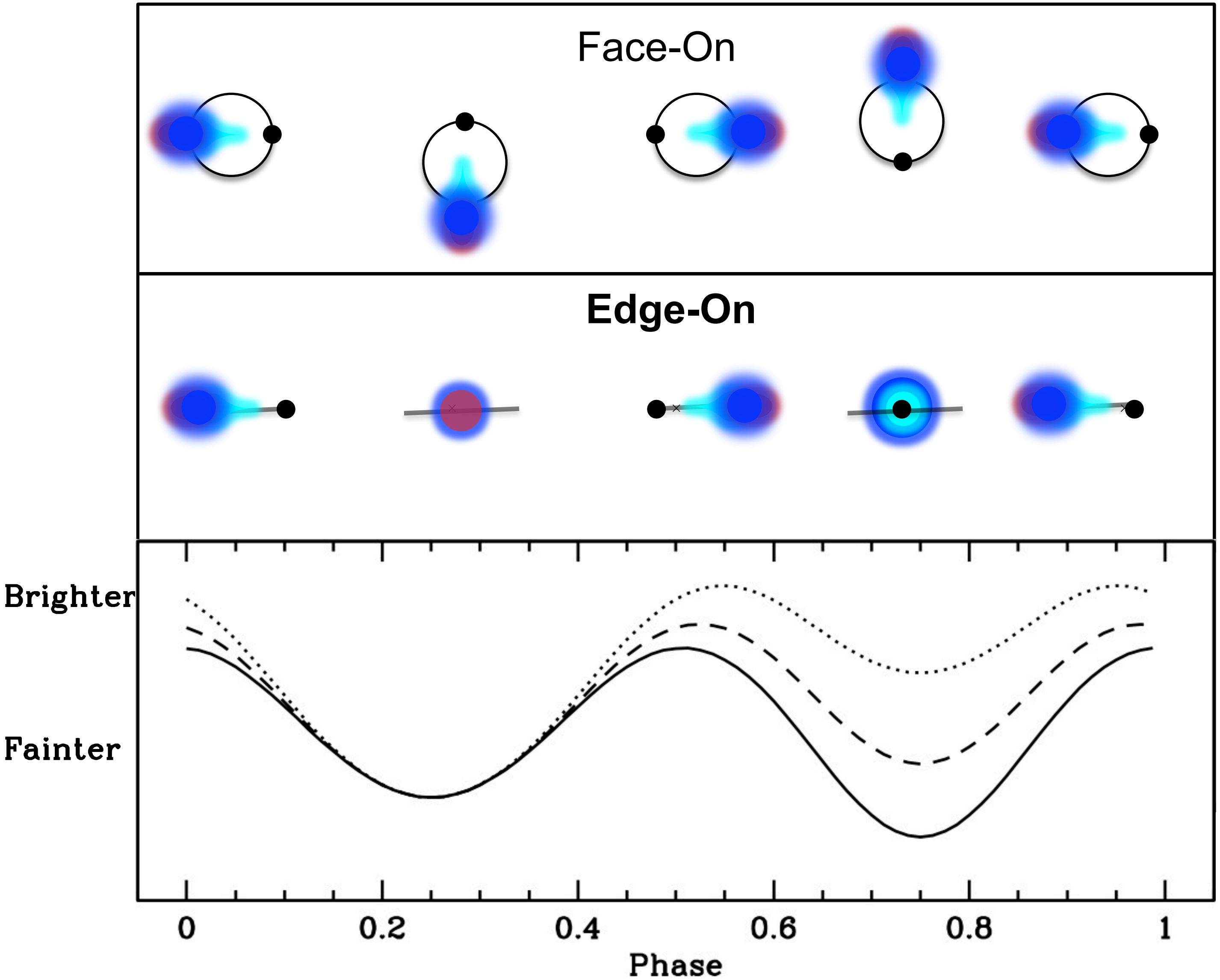


Light curves: tidal distortion



Tidal distortion: 2 maxima ($\phi = 0, 0.5$) and 2 asymmetric minima ($\phi = 0.25, 0.75$)

Light curves: heating + tidal distortion

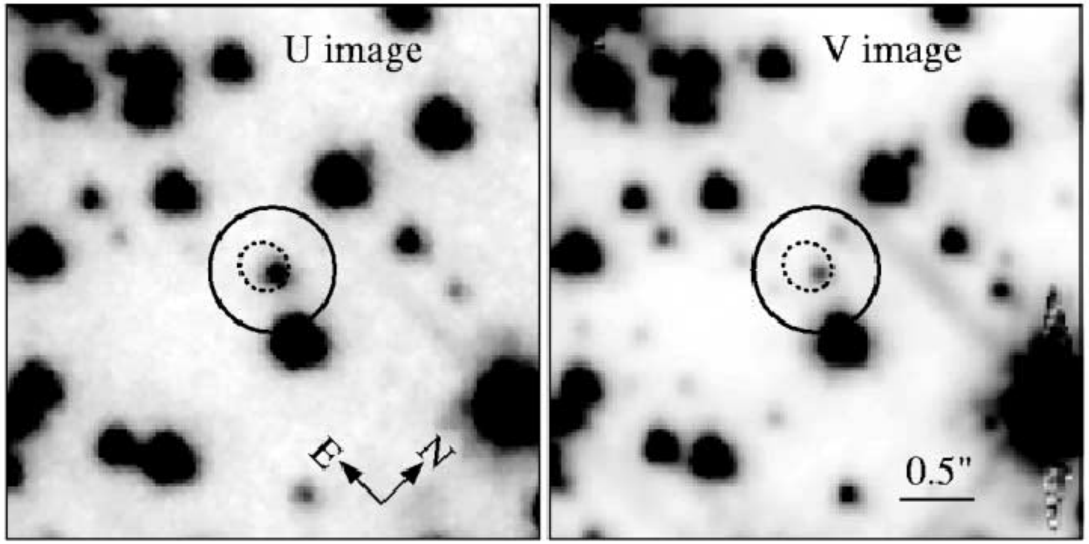


Heating + tidal distortion: 2 asymmetric maxima (ϕ= 0, 0.5) and 2 asymmetric minima (ϕ= 0.25, 0.75)

Optical companions to MSPs: the first identification

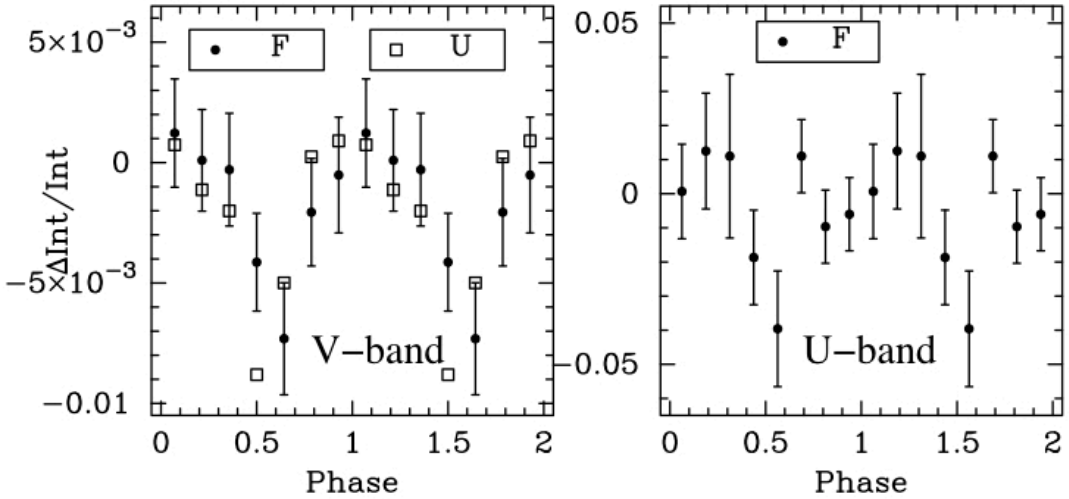
47 Tuc-U

HST/WFPC2 data



→ **positional coincidence**

- dashed : 3σ RADIO error circle
- solid : 3σ X-ray error circle

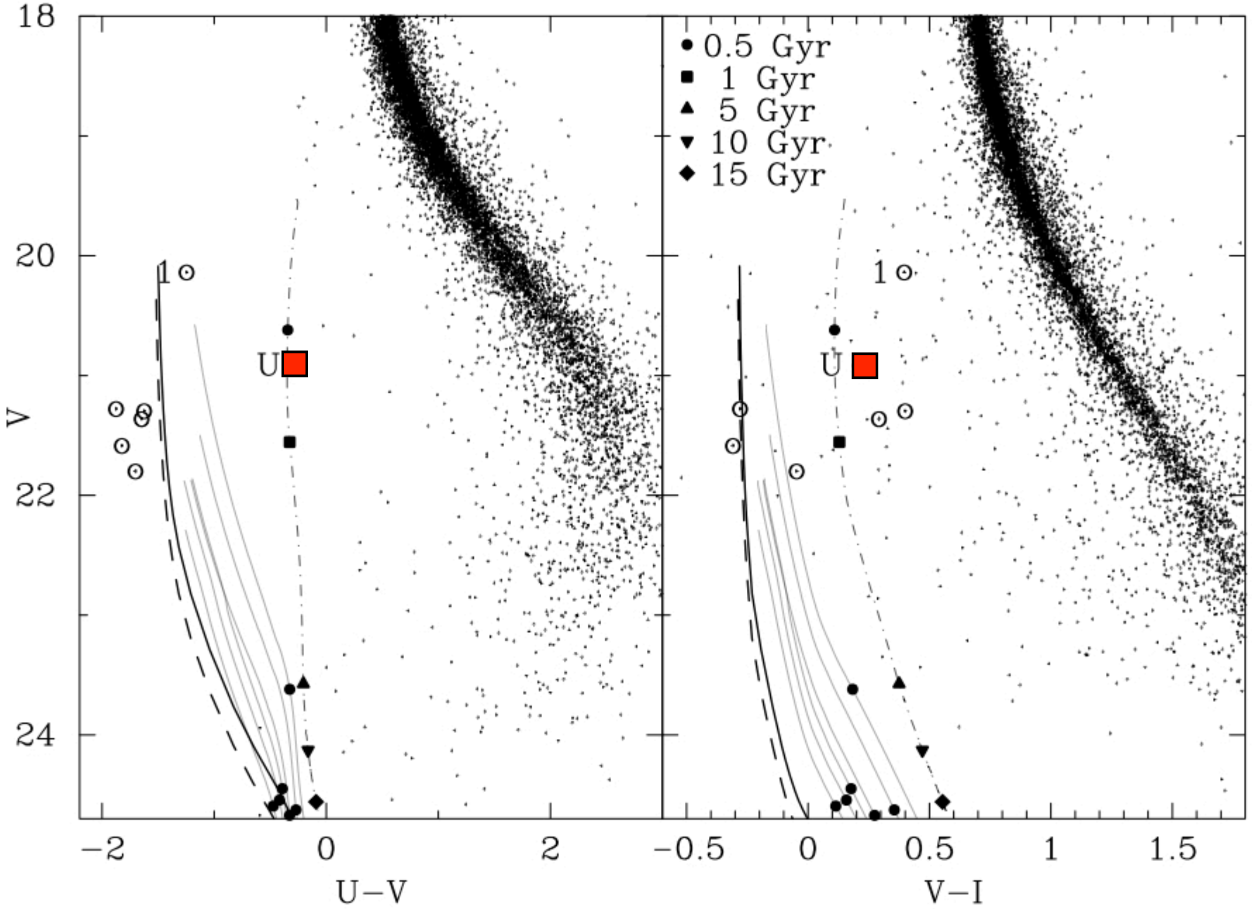


→ **optical variability**

with period in agreement with the orbital period of the system (from RADIO)

(Edmonds et al. 2001)

Optical companions to MSPs: 47 Tuc-U



→ a He-WD

fully in agreement
with the canonical
recycling scenario

(Edmonds et al. 2001)

NGC 6397-A: the first surprise

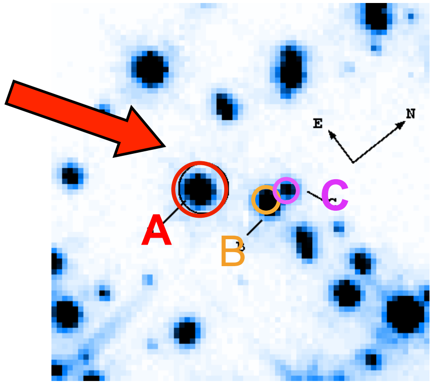
PSR J1740-5340 **in NGC6397** *(D'Amico+01)*:

- **member of a binary system with P_{orb} = 1.35 days**
- **eclipse of the radio signal for about 40% of the orbit**

⬇

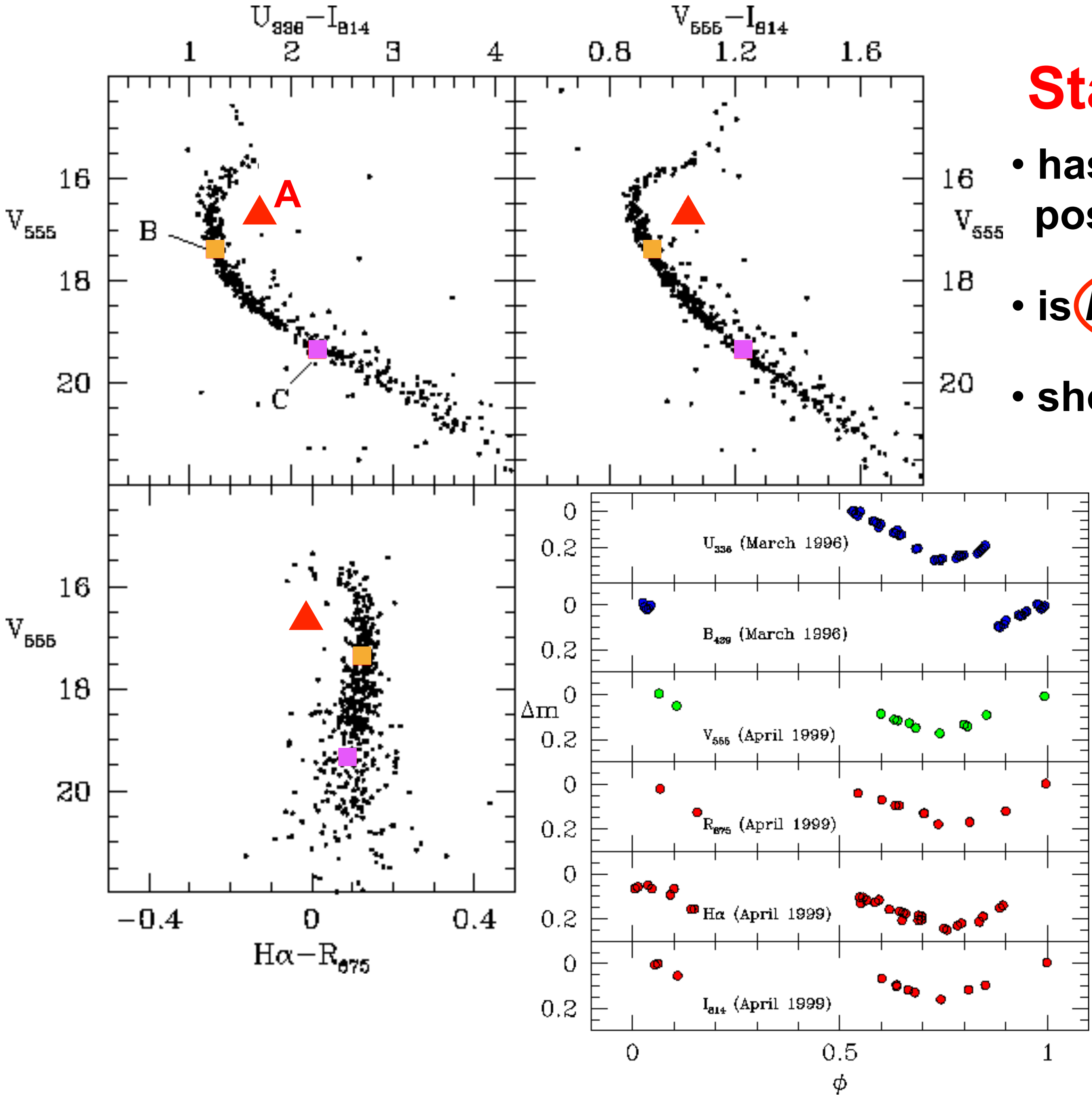
NS orbiting within a large envelope of matter released by the companion

WFPC2/HST images



***Star A*:**
a bright variable star nearly coincident with the MSP nominal position
(Ferraro et al. 2001)

NGC 6397-A



Star A:

- has an anomalous position in the CMD
- is *NOT* a WD !!
- shows $H\alpha$ emission
- shows variability consistent with MSP P_b
- 2 asymmetric minima

NGC 6397-A

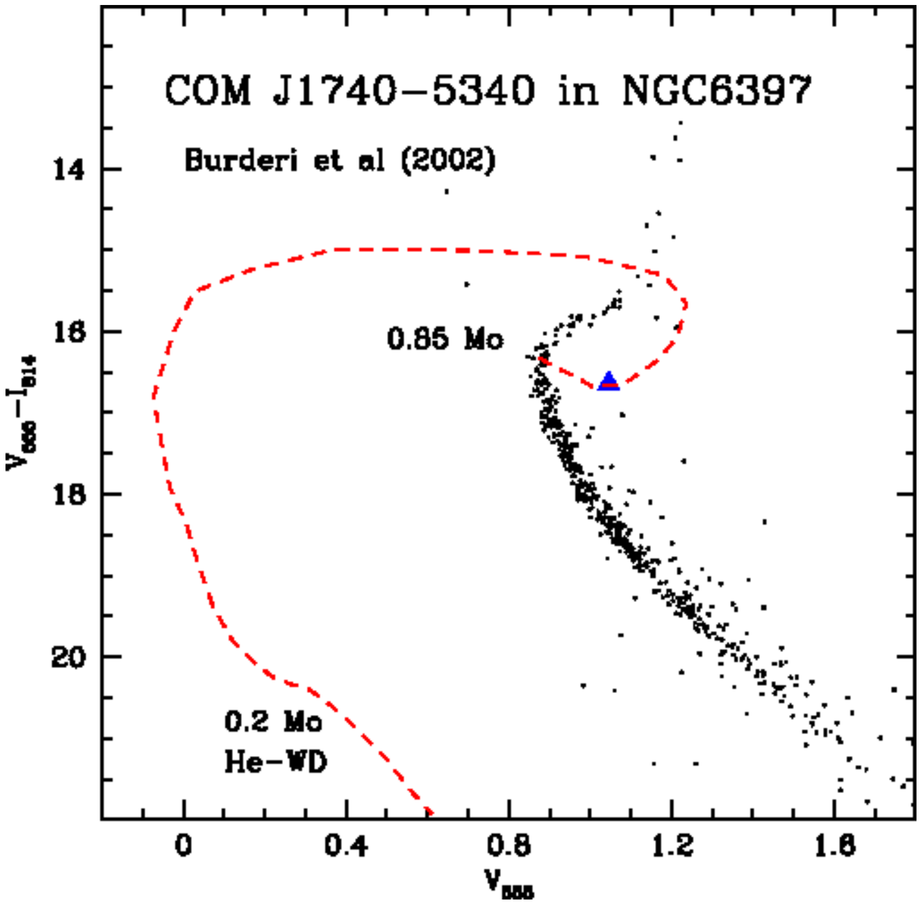
- <u>optical light curve shape</u>:

Star A is tidally distorted

- <u>anomalies in the radio signals + Hα emission</u>:

presence of *ionized matter* along the light of sight

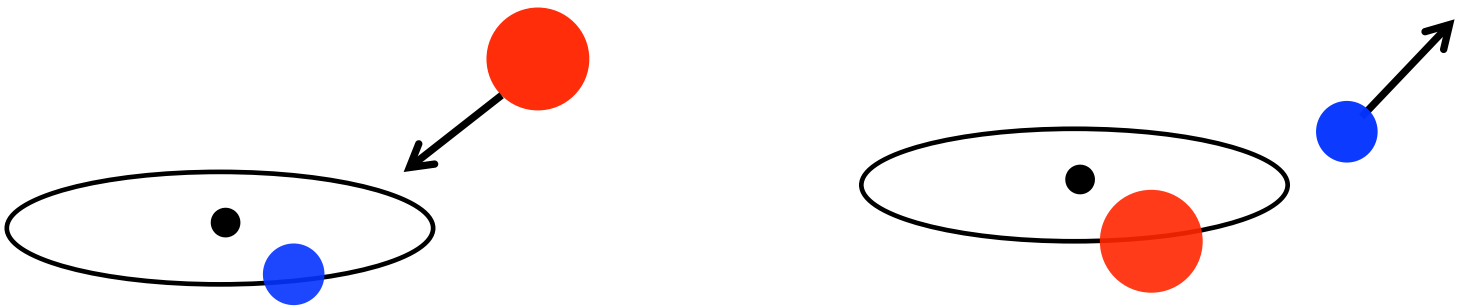
Star A consistent with a slightly evolved TO star orbiting the NS and loosing mass.
The evolution will generate a He-WD.
(Burderi et al. 2002)



Is Star A the star that spun up the MSP ?
(if so, we are observing a JUST-BORN MSP!!!)

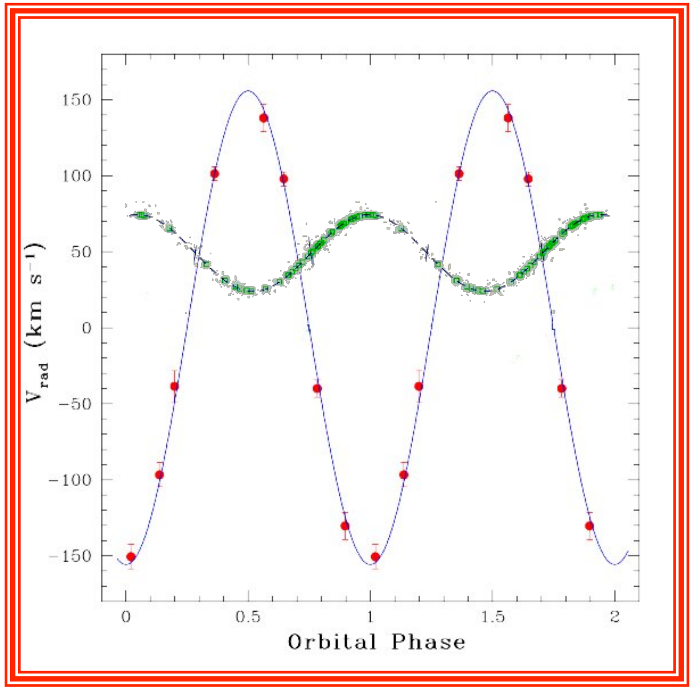
or

Is this peculiar system the end-product
of an exchange interaction
between the original binary & an isolated MS star ?



High-resolution spectroscopy with UVES/VLT

(***Star A***: **bright object => ideal for spectroscopic follow-up)**



Vsin i = 49.6 ± 0.9

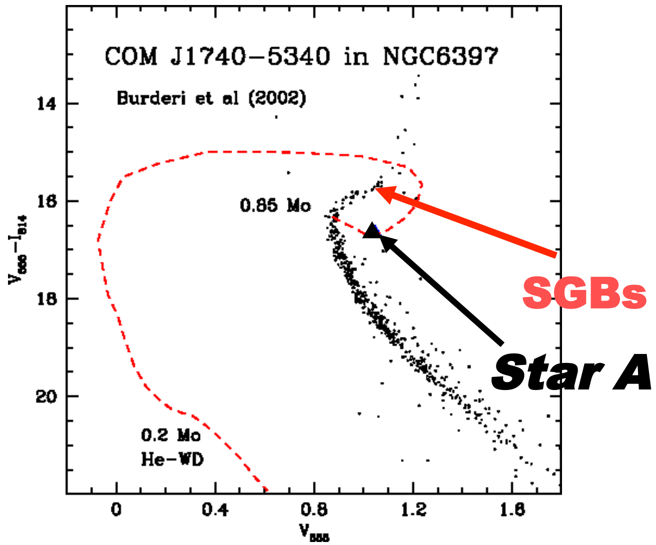
Mass ratio q=5.85±0.13

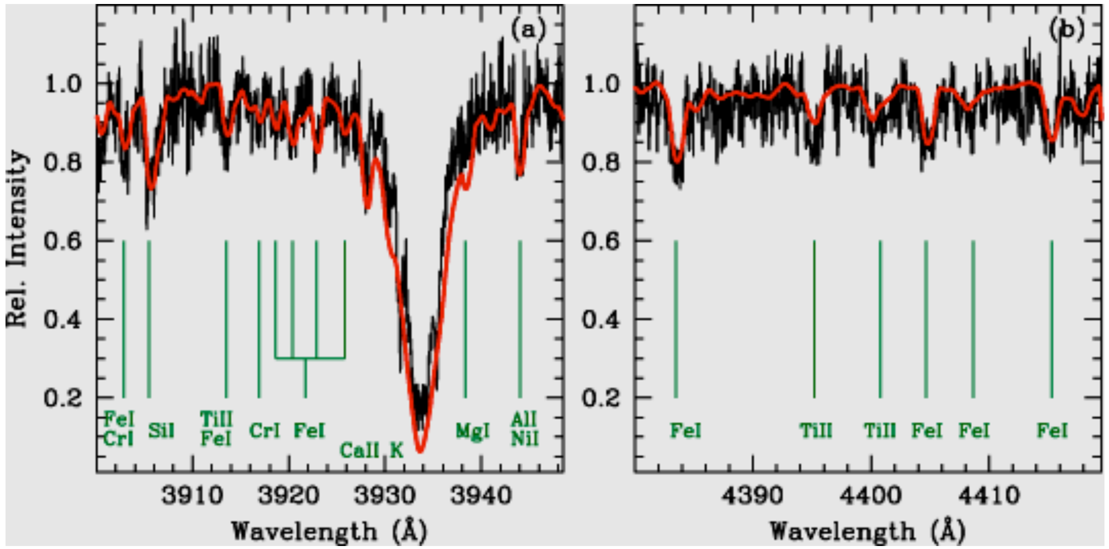
V_{rad} amplitude of Star A: 155.8±3.6 km/s

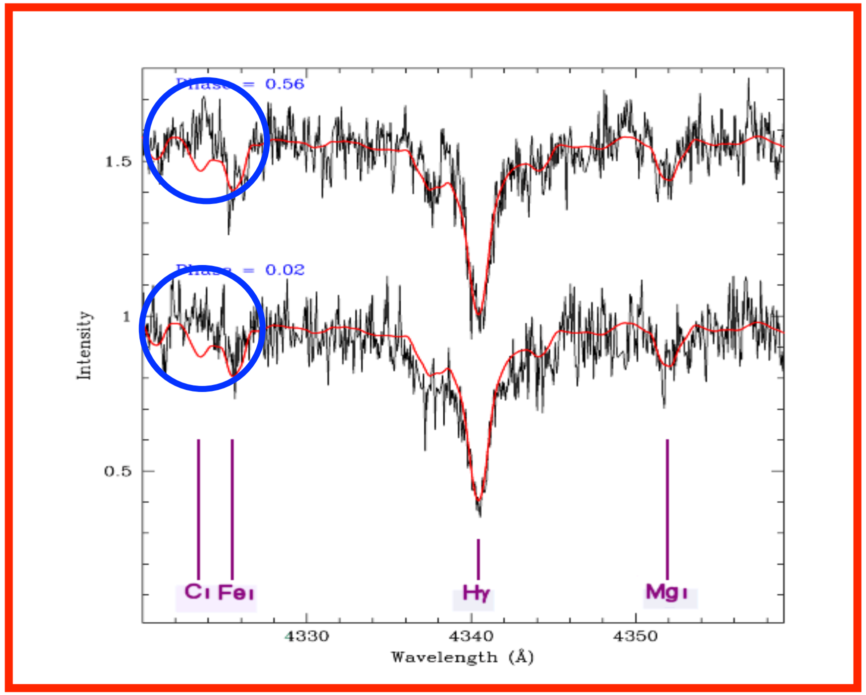
Mass of MSP	**1.30 : 1.90 $M_{\odot}$**
Mass of Star A	**0.22 : 0.32 $M_{\odot}$**
Inclination angle	**56 : 47 deg**
Orbital separation	**6.1 : 7.0 $R_{\odot}$**
Roche lobe radius	**1.5 : 1.7 $R_{\odot}$**

(Ferraro et al. 2003;
Sabbi et al. 2003)

High-resolution spectroscopy with UVES/VLT





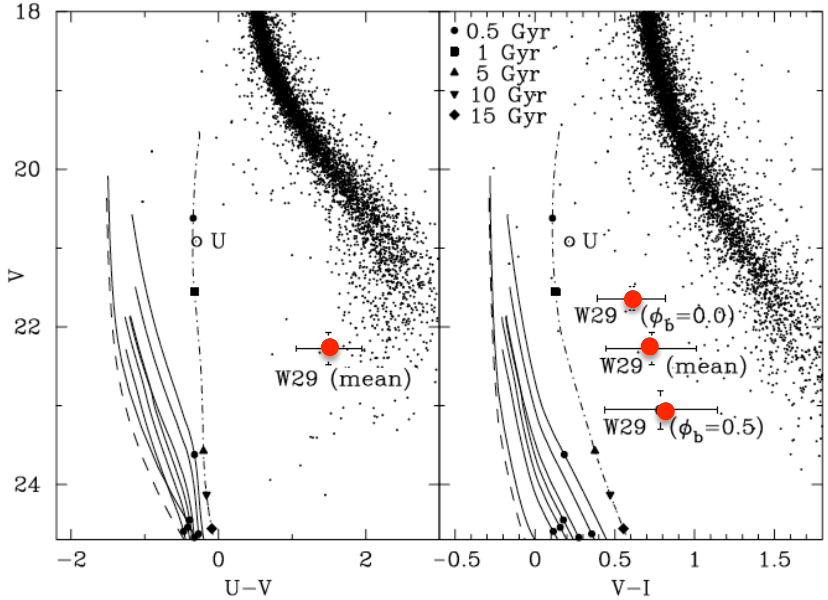


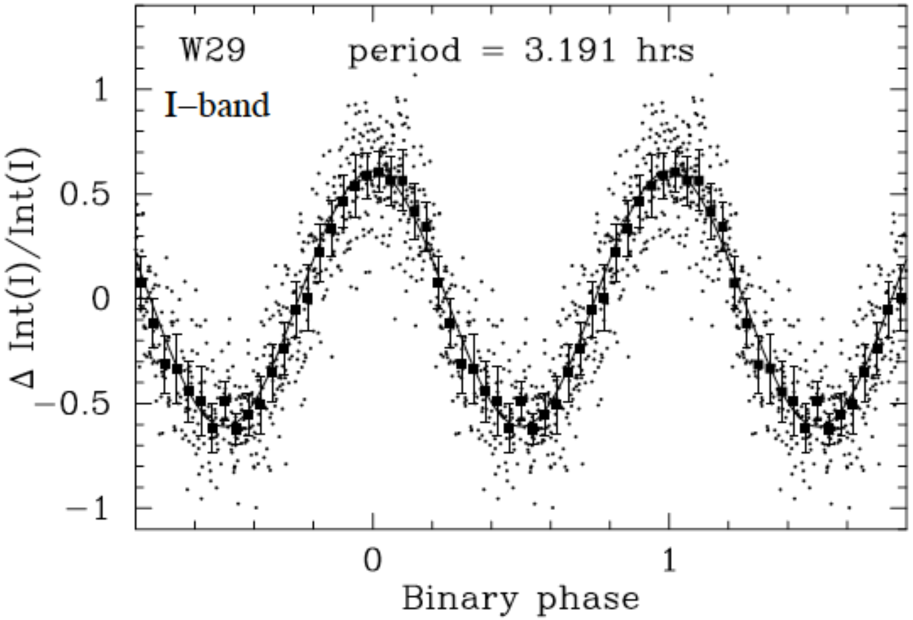
STAR A:

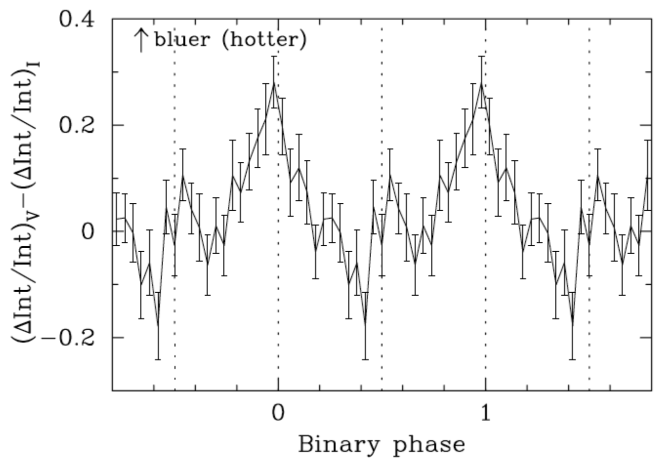
- same overall chemical composition of SGB stars
- no C in its atmosphere => material processed by CNO-burning => deeply peeled star (Ergma & Sarna 2003)

The bright companion to the MSP in NGC6397

47 Tuc-W: a heated MS star







Faint MS star

Large sinusoidal variations

The observed variations are thought to be caused by the heating from the pulsar flux

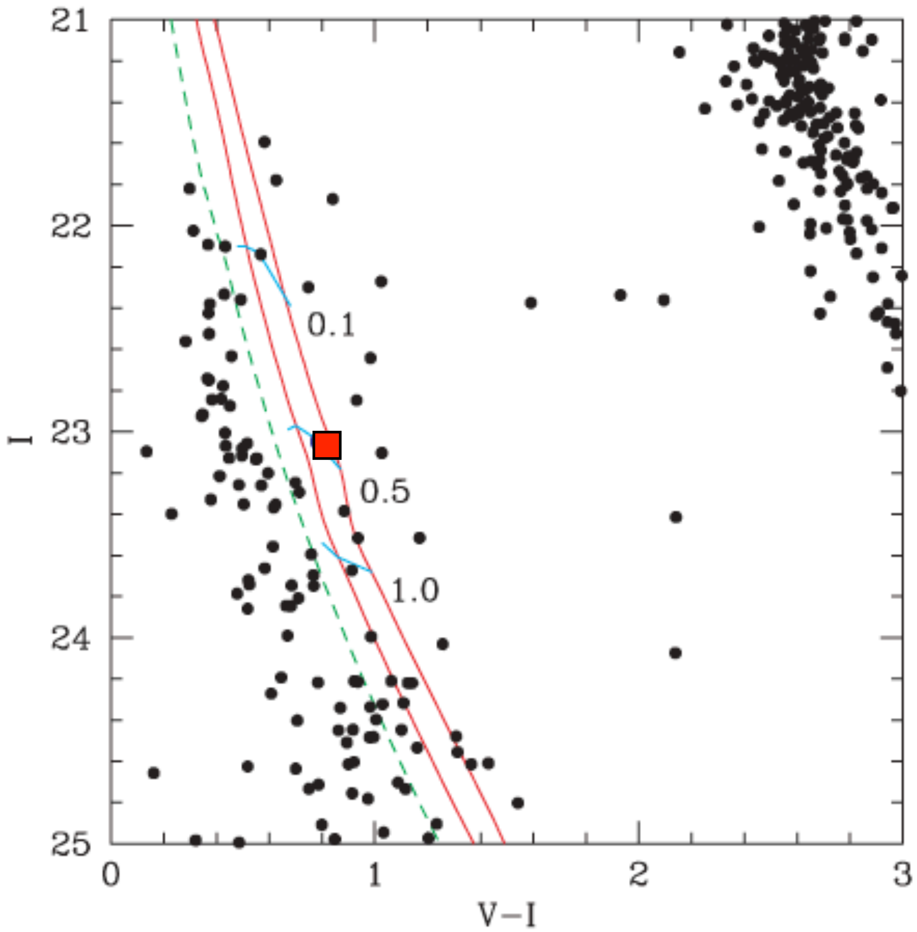
Edmonds et al. (2002)

M4-A: a triple system

PSR B1620−26 **in M4** (*Lyne+88*)**:**

– **member of a long orbit (P_b ~ 191 d), triple system**
(with a **planet** in moderate/low ε orbit, or with a star in a wide & high-ε orbit)

– **at the edge of the core radius**



HST/WFPC2 obs (Sigurdsson+2003):

→ **undermassive (~0.34 $M_\odot$) WD with t_{cool} ~ 500 Myr**

Proposed scenario:

RECENT exchange interaction ~1Gyr ago
between NS +WD & MS +planet

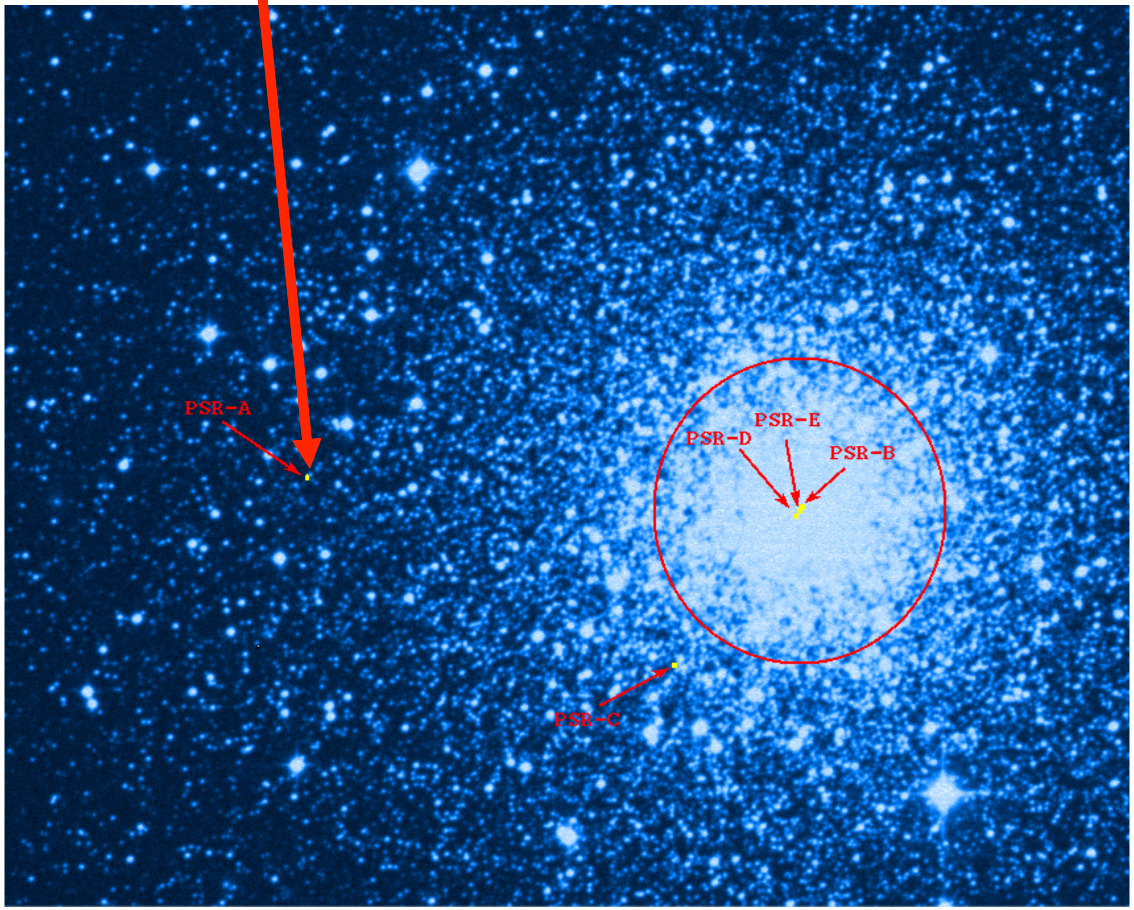
→ **NS +MS +planet**

Then MS lost mass to the NS (which accelerated) and became a WD.

Recoil => off-centre position.

NGC 6752-A: the most off-centred MSP

- **5 MSPs in total**
- **3 (isolated) in the centre**
- **anomalously large acceleration for 2 of the central three**
- ***PSR-A*: the most off-centre ever observed in a cluster !!**



Ejected from the core?

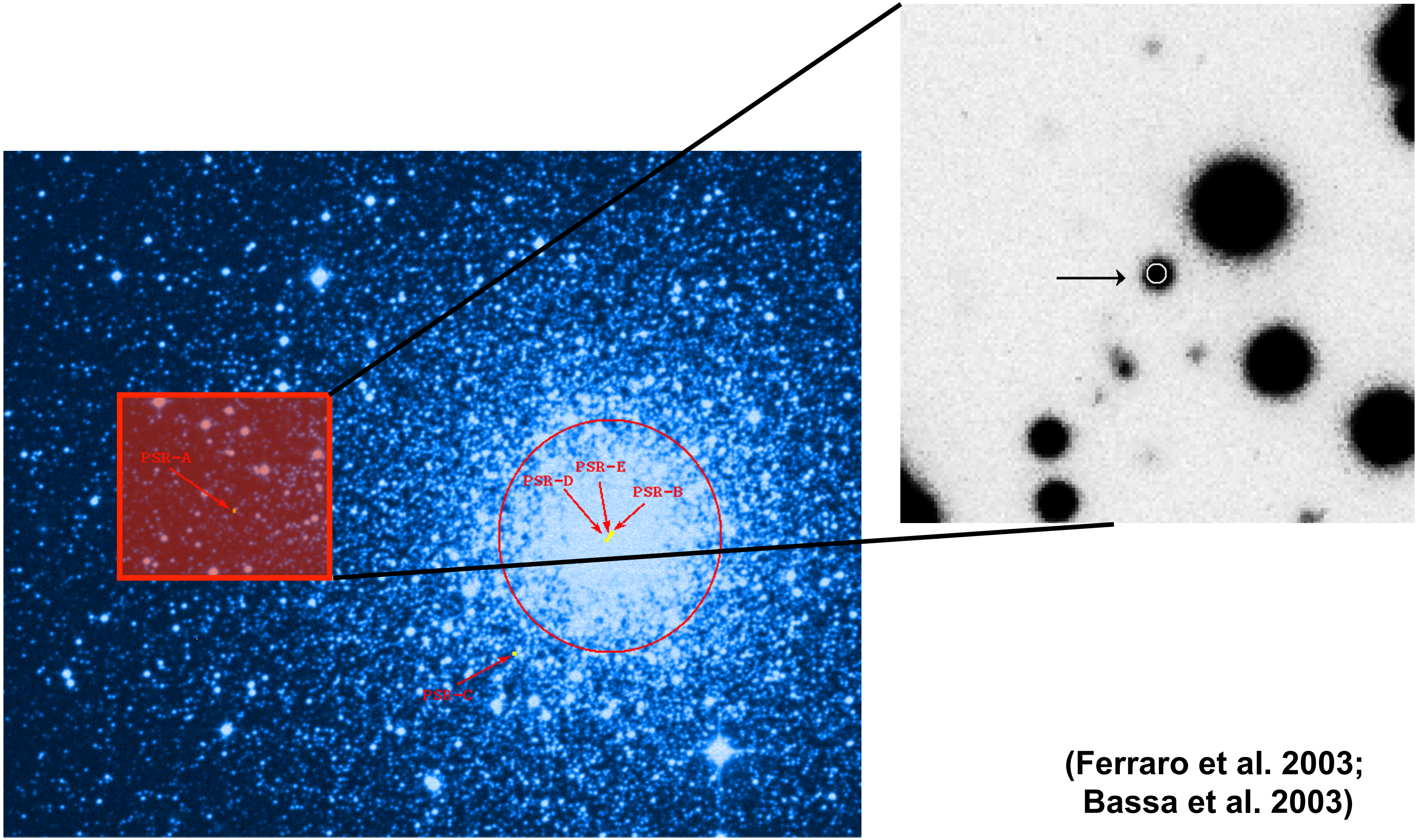
1000-2000 $M_\odot$ of under-luminous matter within 0.08 pc from the centre!!

binary/single BH?

(Colpi et al. 2002, 2003)

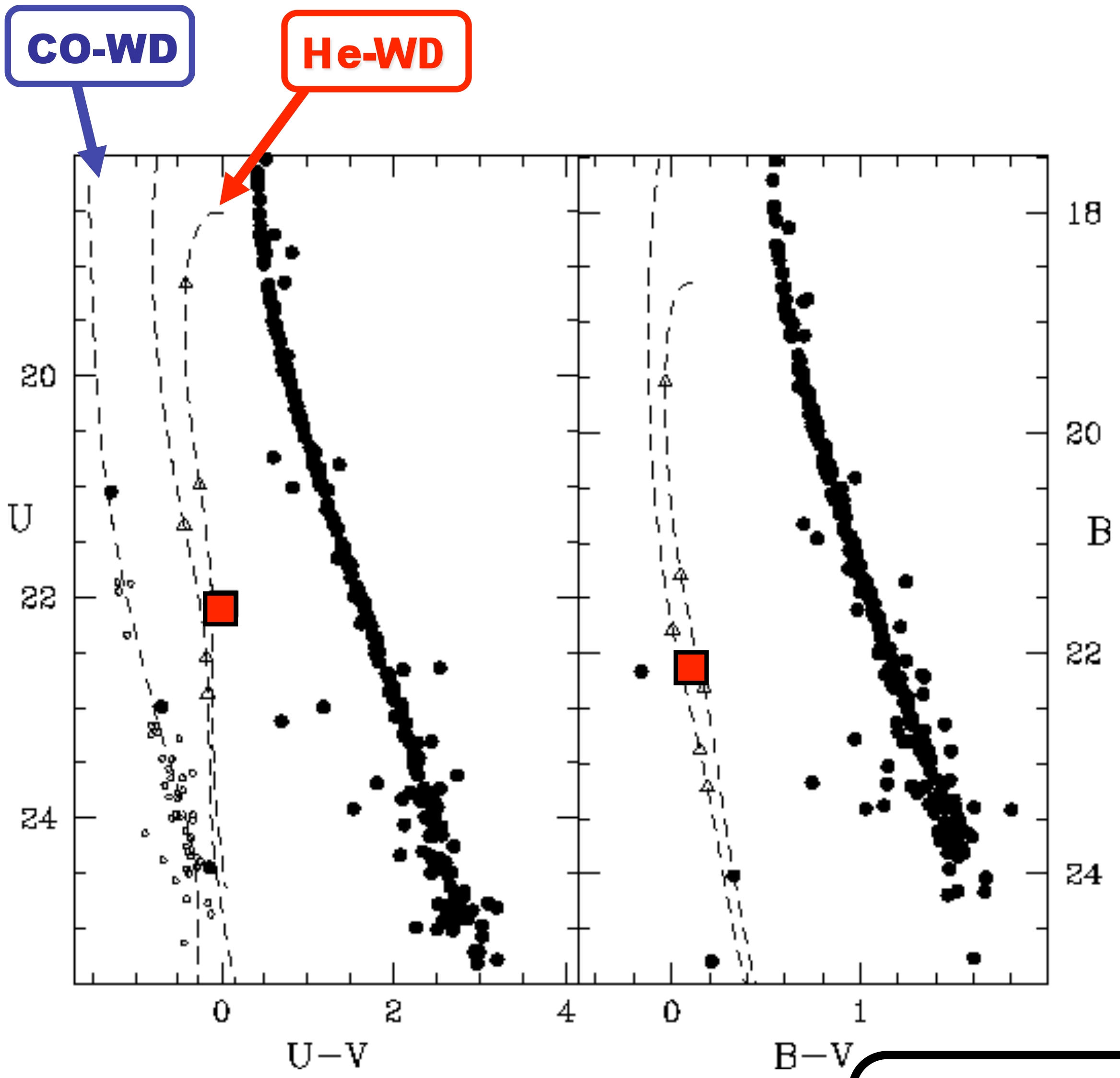
NGC 6752-A

VLT-FORS1 multi-λ (U,B,V) high-resolution imaging



(Ferraro et al. 2003;
Bassa et al. 2003)

NGC 6752-A



He-WD

$M = 0.17\text{-}0.19\ M_{\odot}$

$t_{cool} = 1.2\text{-}2.8$ Gyr

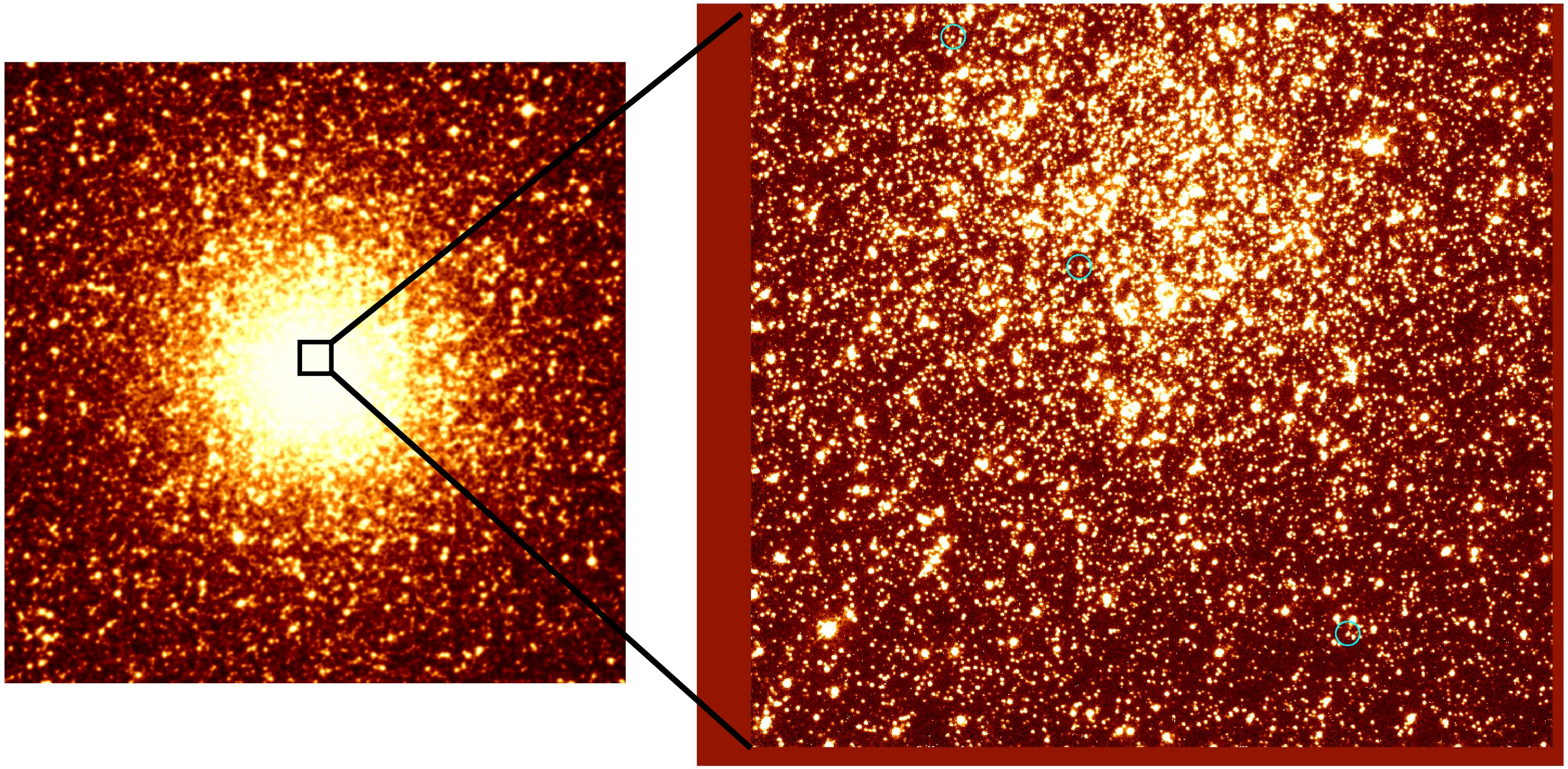
$t_{df}\,(r_{MSP}) < 1$ Gyr

(time needed to drive the system back into the core)

the ejection acted on an already formed MSP

(Ferraro et al. 2003; Bassa et al. 2003)

NGC 6266-B: another puzzle…

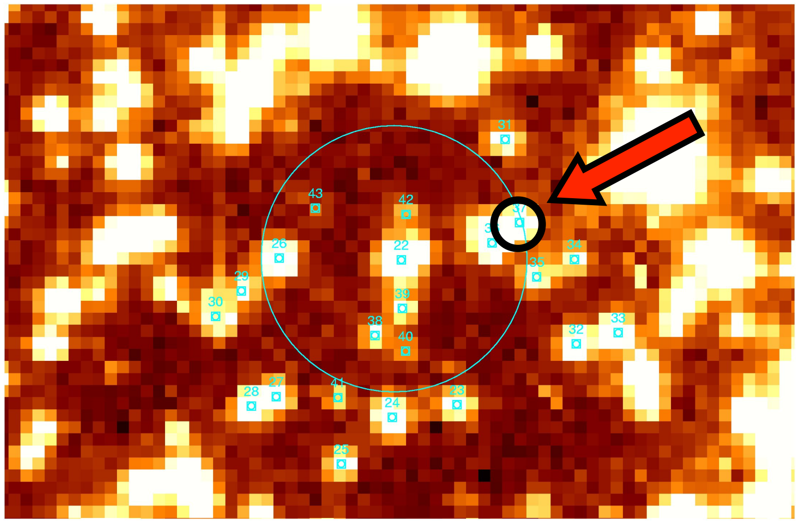


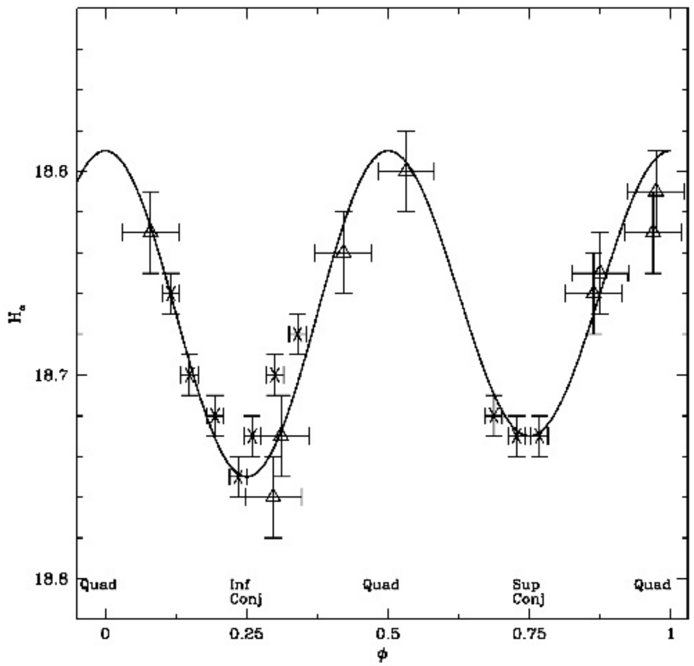
- **6 MSPs in total** **(D'Amico et al. 2001a,b; Jacoby et al.2002)**
- **ALL are in binary systems**
- **MSP-B: partial/total eclipses of the radio signal**

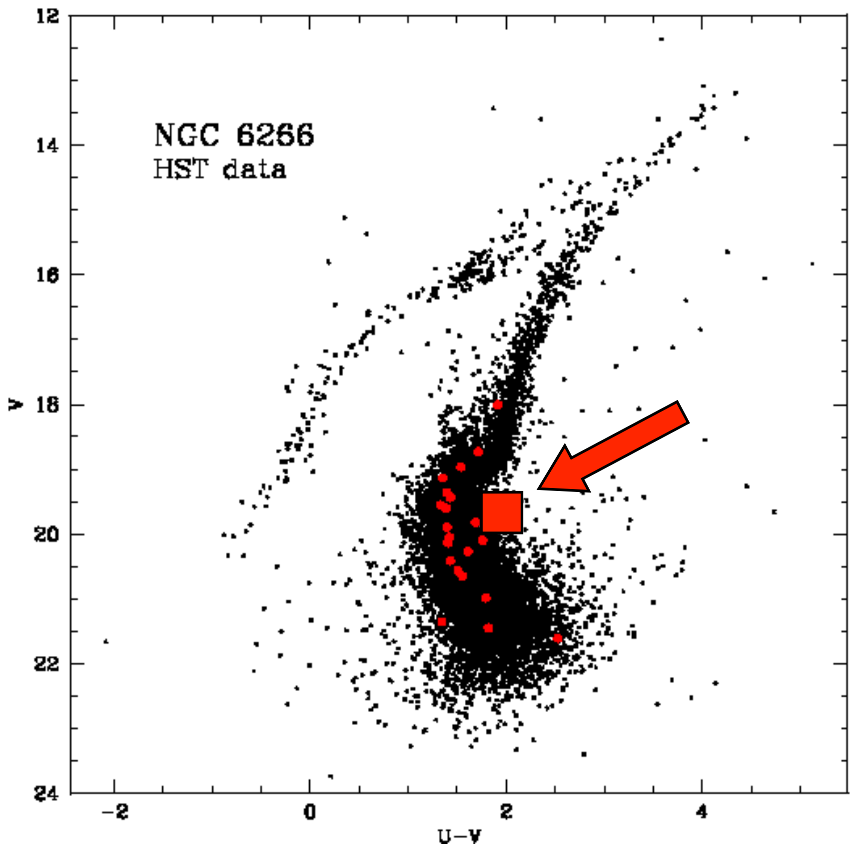
  (gas streaming off the companion)

NGC 6266-B

WFPC2 & ACS data







MSP-B companion:

- bright star
- anomalous red color
- optical variability correlated with P_{orb}
- 2 asymmetric minima

(Cocozza et al. 2008)

MSP-B companion:

• **shape of light curve**
(+ red color, Hα excess,
X-ray emission) → **tidally distorted, bloated star that filled its Roche Lobe (R_{RL}) and is loosing mass**
(similar tp NGC 6397-A)

From projection onto the isochrone:

$L_{bol} \approx 1.9\ L_\odot$
$R_{COM} \approx 1.2\ R_\odot$
$T_{COM} \approx 6000$ K

From tidal deformation → $R \sim R_{RL}$
From radio eclipses → $i \geq 20°$
Assuming $M_{PSR} = 1.4\ M_\odot$

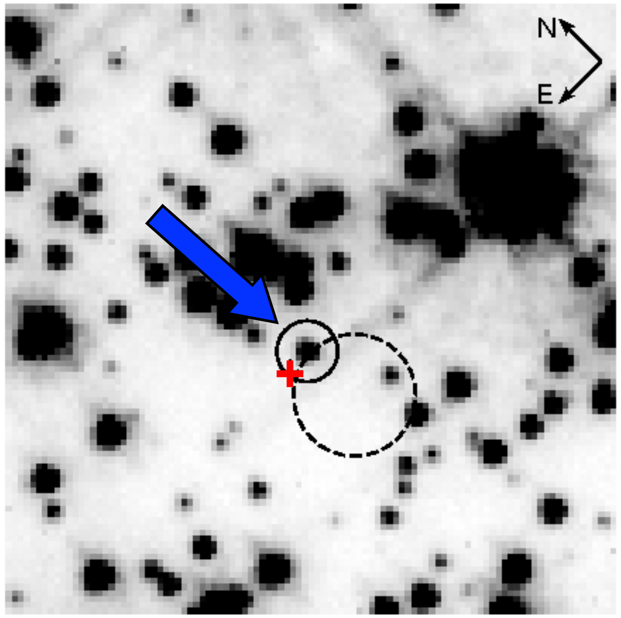
$M_{COM} \approx 0.15 - 0.41\ M_\odot$ for $i = 90°, 20°$
→ $R_{RL} \approx 0.26\text{-}0.40\ R_\odot$

$R_* \sim 2.5\ R_L$??!

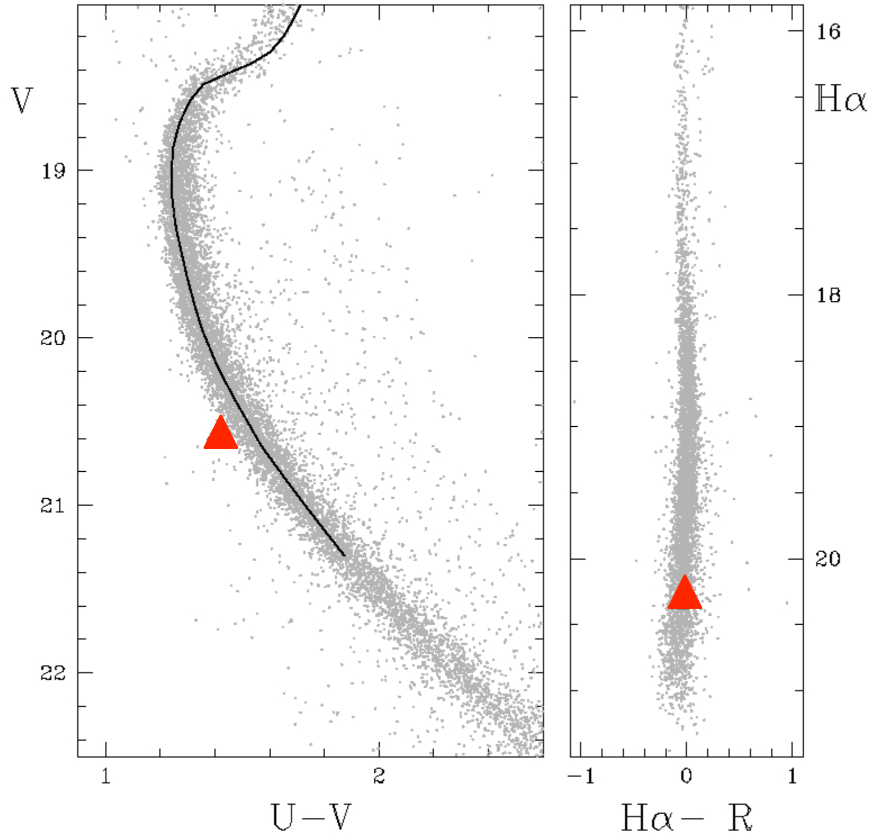
- binary NOT belonging to the cluster (wrong dist)
- optical lum dominated by non-thermal processes

... spectroscopic follow-up could help....

M28-H: another exchange interaction?

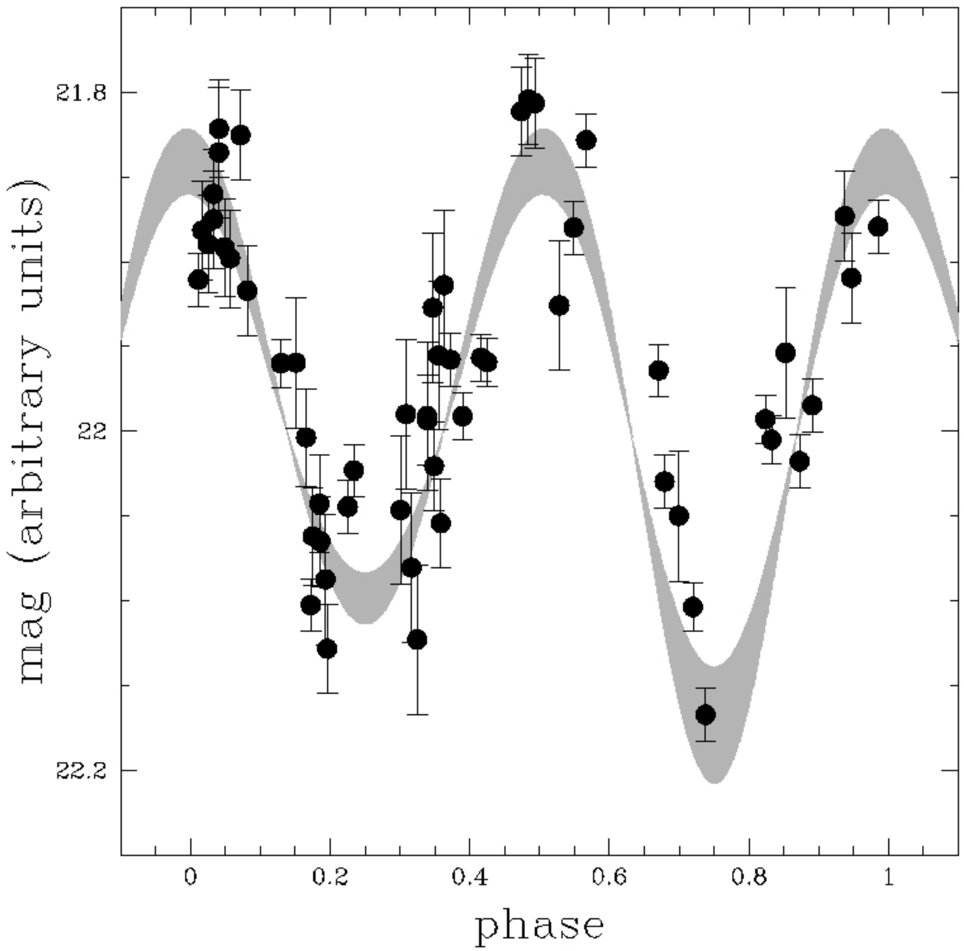


The companion star is located at 0.17" from the radio source (+) and ~0.4" from the X-ray source (dashed circle)



another
NON-DEGENERATE
companion!

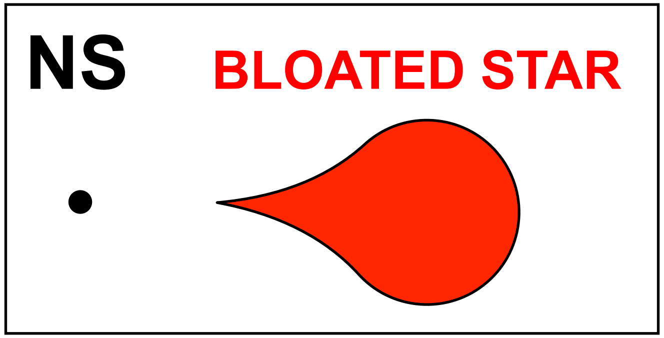
M28-H: another exchange interaction?



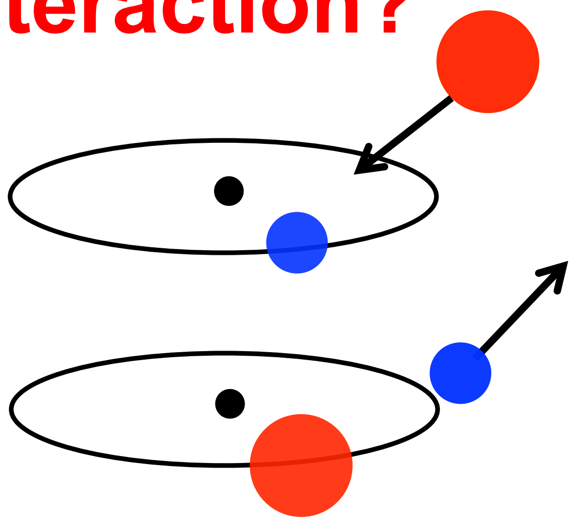
→ optical variability

- with period in agreement with the orbital period of the system (from RADIO)
- with 2 asymmetric minima

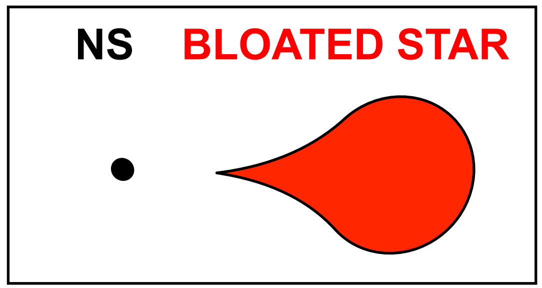
clear signature of ellipsoidal variations induced by the NS tidal field on a highly perturbed bloated star



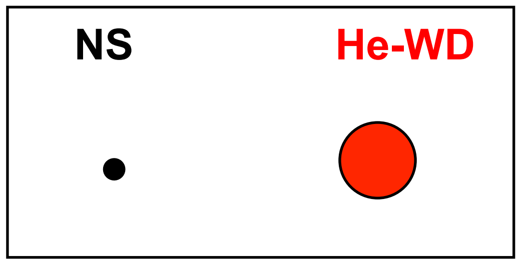
M28-H: another exchange interaction?



M28H is outside the cluster core.
Such an offset position may suggest that the NS was recycled by another companion



The new companion started to suffer heavy perturbations (bloating, mass loss…) induced by the MSP and we currently observe it as COM-M28H

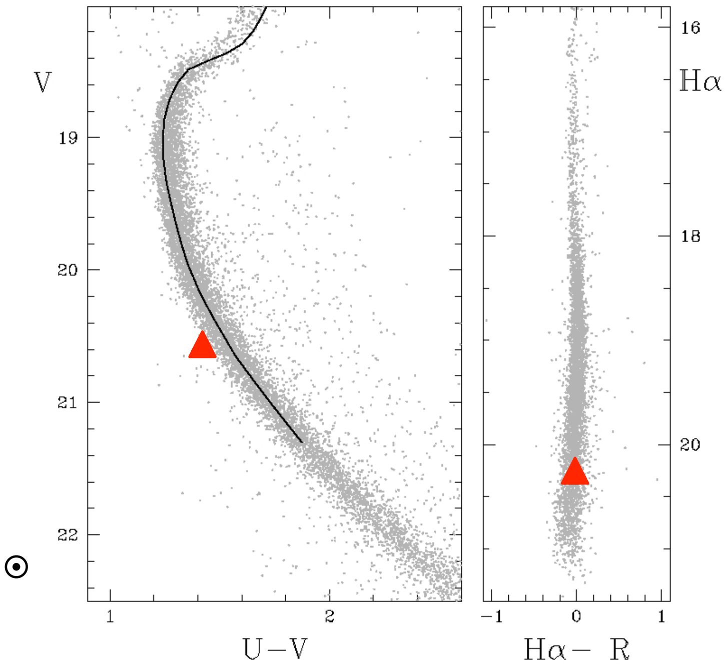


It eventually will become a helium WD

M28-H: estimate of physical parameter

From projection onto the isochrone:

$M_{COM} \approx 0.68\ M_\odot$
$R_{COM} \approx 0.64\ R_\odot$
$T_{COM} \approx 6000$ K



- **PSR mass function** (Begin 2006):

$$f = \frac{(M_{COM}\sin i)^3}{(M_{MSP}+M_{COM})^2} = \frac{4\pi^2(a_p \sin i)^3}{G\,P_b^{\,2}} = 0.00211277\ M_\odot$$

- **III Kepler Law:**

$$P^2 = \frac{4\pi^2 a^3}{G\,(M_{MSP}+M_{COM})}$$

- **Roche Lobe radius:**

$$\frac{R_{LR}}{a} = 0.462\left(\frac{M_{COM}}{M_{MSP}+M_{COM}}\right)^{\frac{1}{3}}$$

=> by assuming:

$M_{PSR} \approx 1.4\ M_\odot$
$M_{COM} \approx 0.68\ M_\odot$
} => $i \sim 18°$

→ **NO optical modulations should be observable!**

M28-H: estimate of physical parameter

Indeed **eclipses and optical light curve suggest i ~ 60°**

=> $M_{COM} \approx 0.2\ M_{\odot}$

=> $M_{TOT} \approx 1.6\ M_{\odot}$ and $a \sim 2.8\ R_{\odot}$

To verify if such a configuration reproduces the observed light curve
→ software **NIGHTFALL**, by assuming:

- P_b, T=6000 K
- i = [0°, 90°]
- M_{PSR}/M_{COM} = [1, 20]
- Roche Lobe filling factor = [0,1]

M28-H: estimate of physical parameter

χ^2 test:

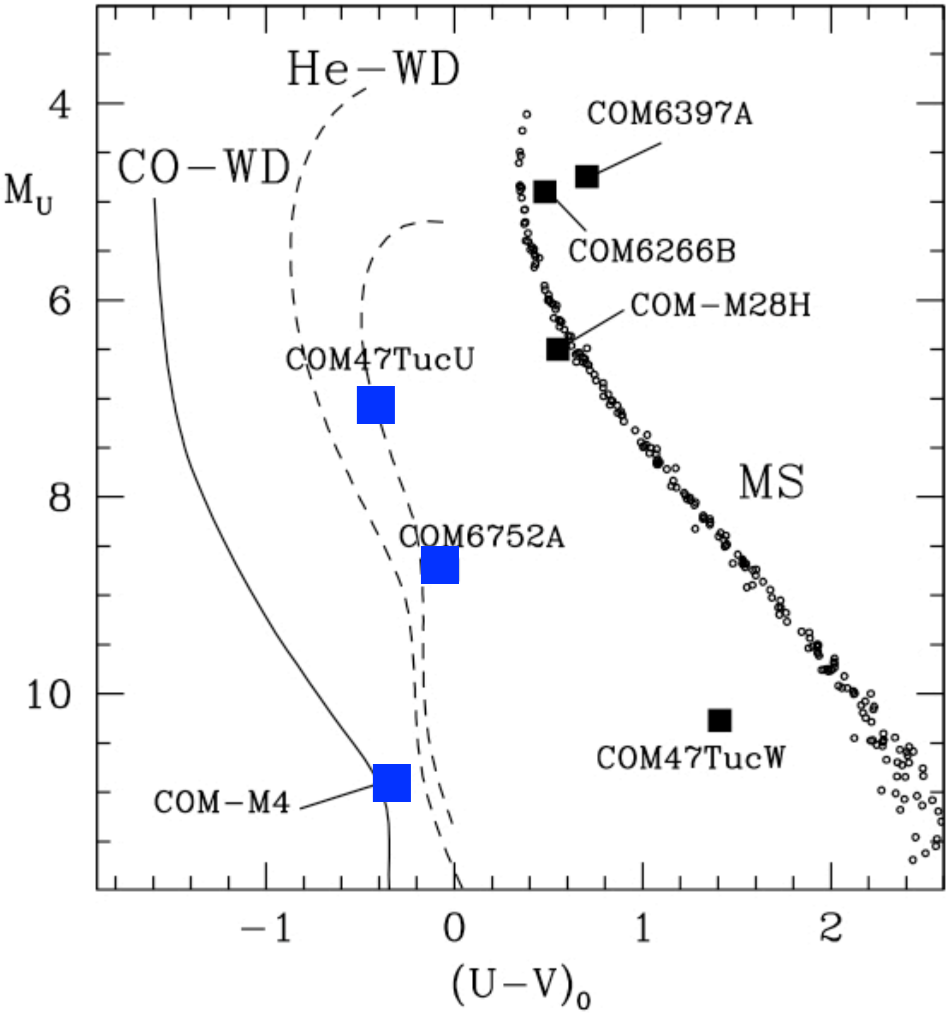
i = 65°
M_{PSR}/M_{COM} = 1
Roche Lobe filling factor = 1

=> if $M_{PSR} \approx 1.4\ M_\odot$ => $M_{COM} \approx 0.2\ M_\odot$

NB: $R_{RL} \approx 0.65\ R_\odot$ → consistent with observed luminosity of COM, but NOT consistent with radio eclipses (20% of P_b => size of eclipsing region ~3.3 $R_\odot$)

=> system surrounded by large clouds of gas

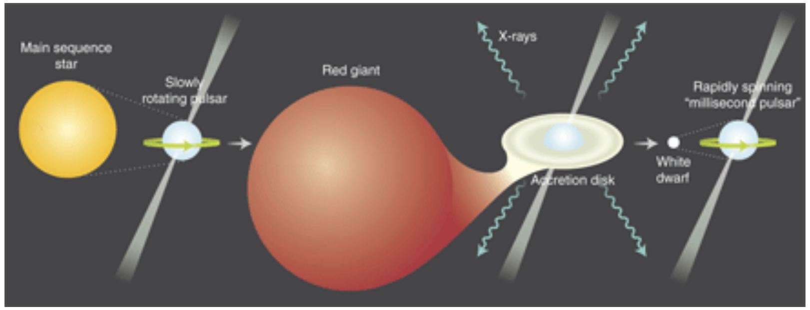
The state of the art



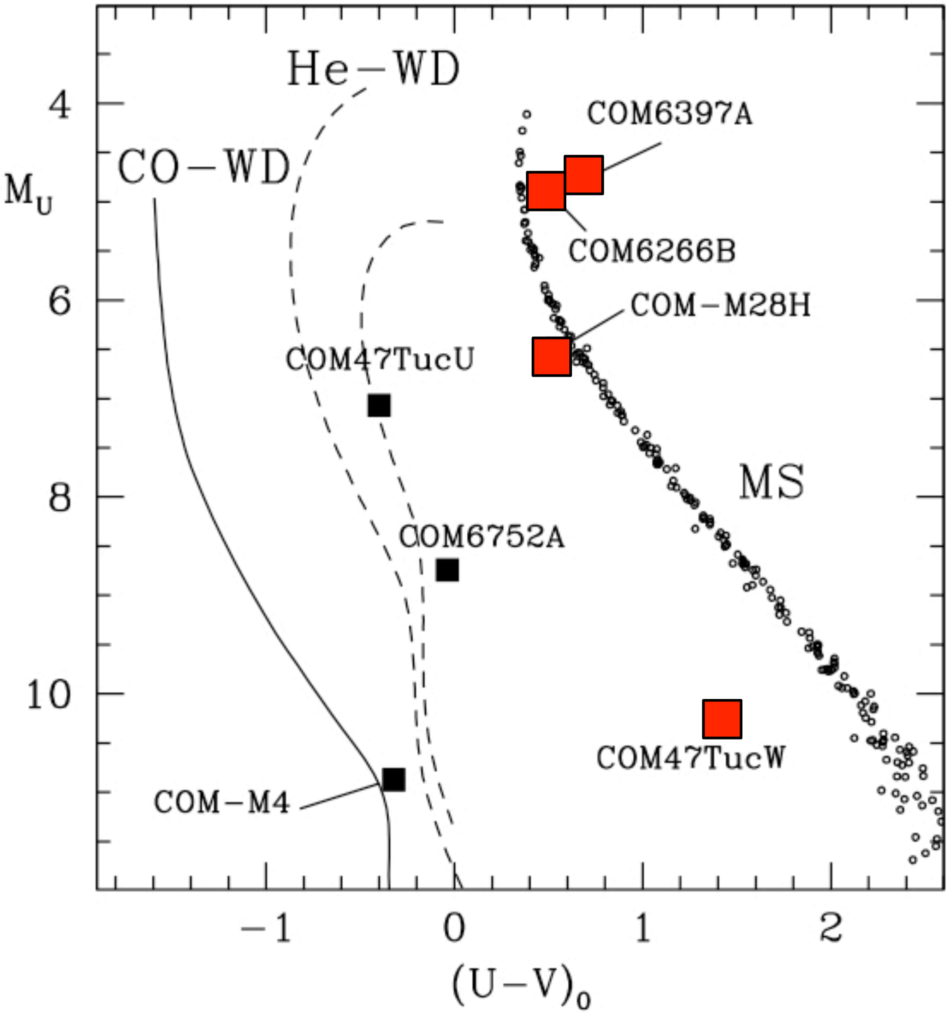
3 He WD
(Edmonds et al. 2001; Ferraro et al. 2003; Sigurdsson et al 2003)

CONFIRMATION OF THE RECYCLING SCENARIO:

low mass He-WD is the "final stage" of the pulsar recycling process



The state of the art

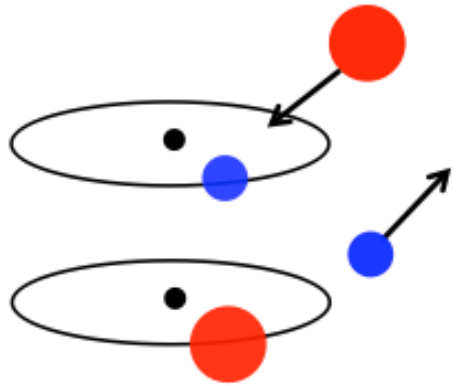


4 NON-degenerate Objects

(Ferraro et al. 2001; Edmonds et al 2002; Cocozza et al 2008; Pallanca et al. 2010).

EXCHANGE INTERACTION?

(GC dynamics)

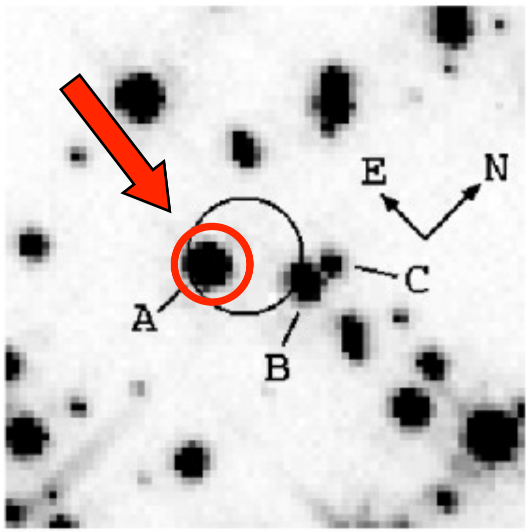


Positional coincidence

In order to look for a companion it is mandatory to obtain an accurate astrometric solution.

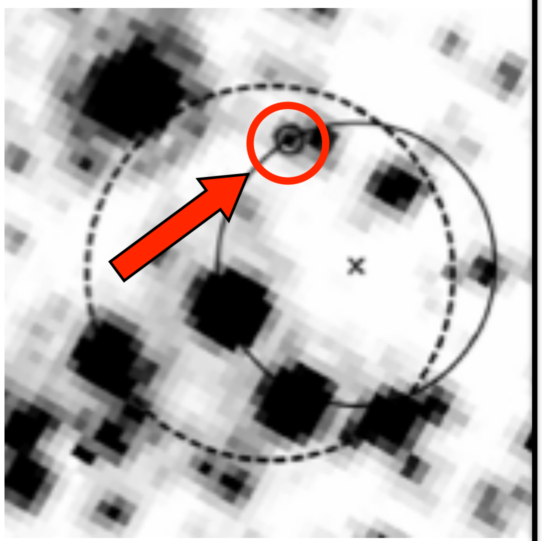
In previous identifications we found an agreement between radio and optical positions with an accuracy < 0.3”

COM 6397A



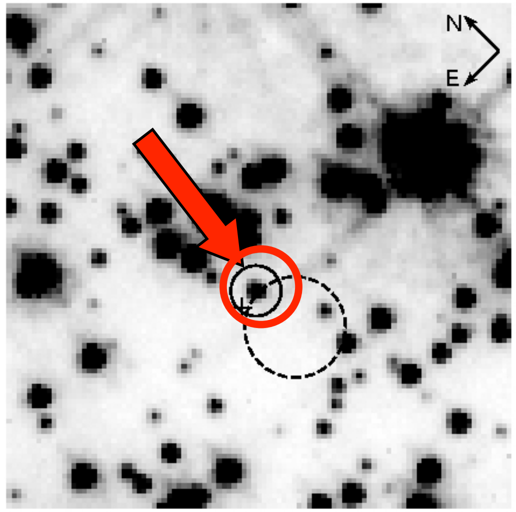
(Ferraro et al. 2001)

COM 6266B



(Cocozza et al. 2008)

COM-M28H



(Pallanca et al. 2010)

COM M28-I

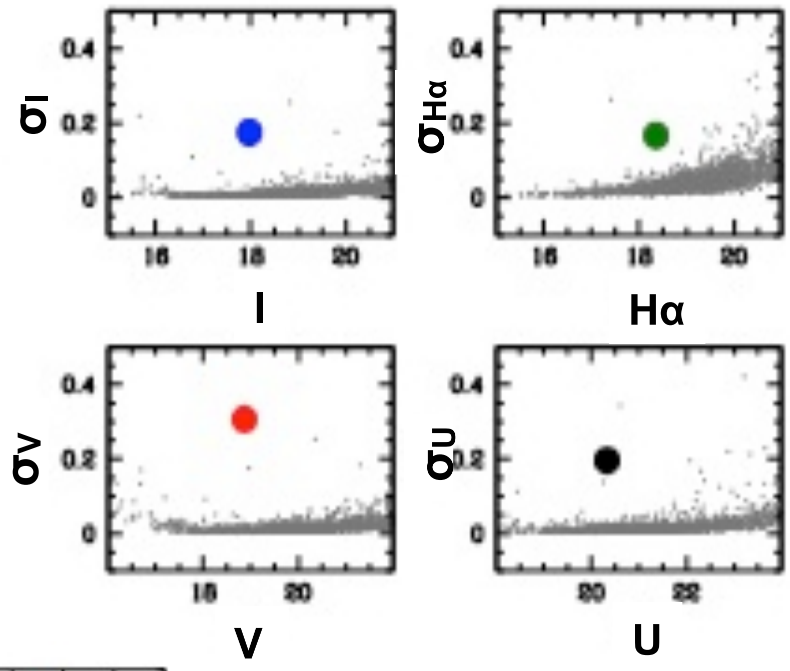
RADIO:

- eclipsing system
- P_b~0.459 d
- only PRELIMINARY position

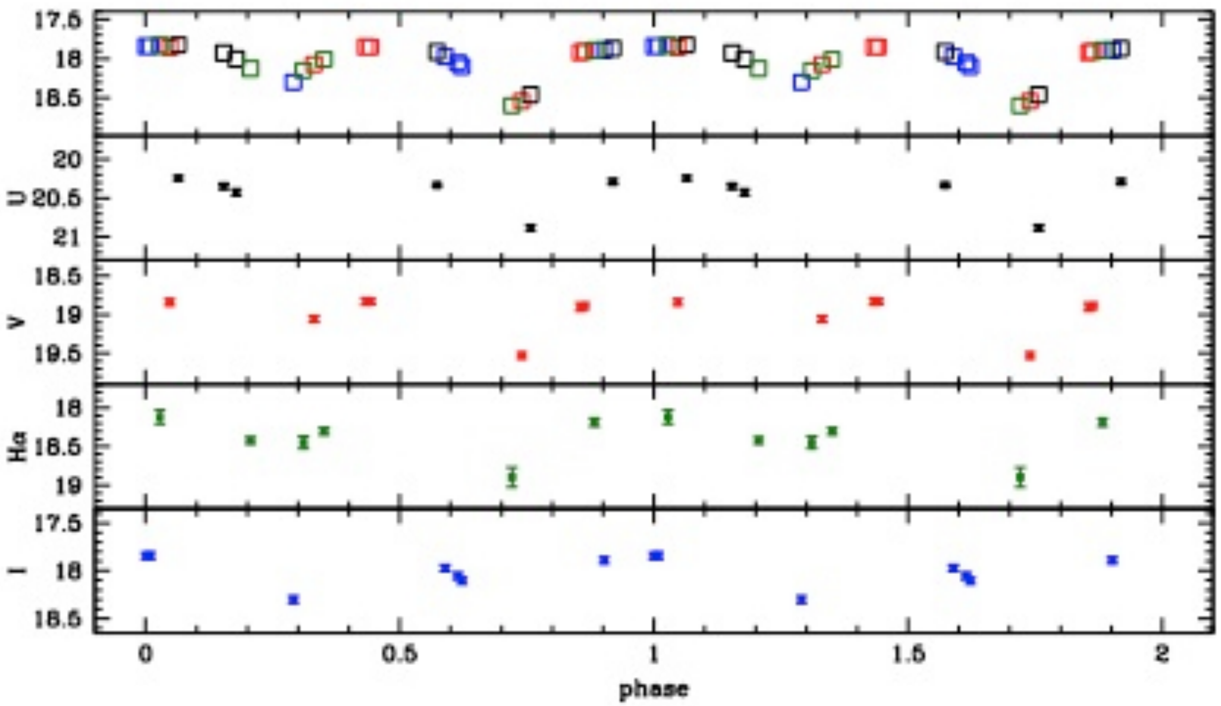
=> how to find the companion??!

Look for objects (in the PSR "vicinity") with optical variability compatible with the orbital motion!

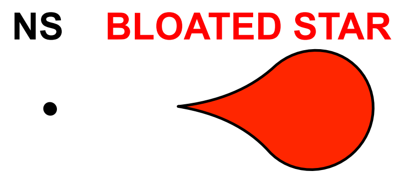
1) search for variable objects



2) build the light curve
& compare the period

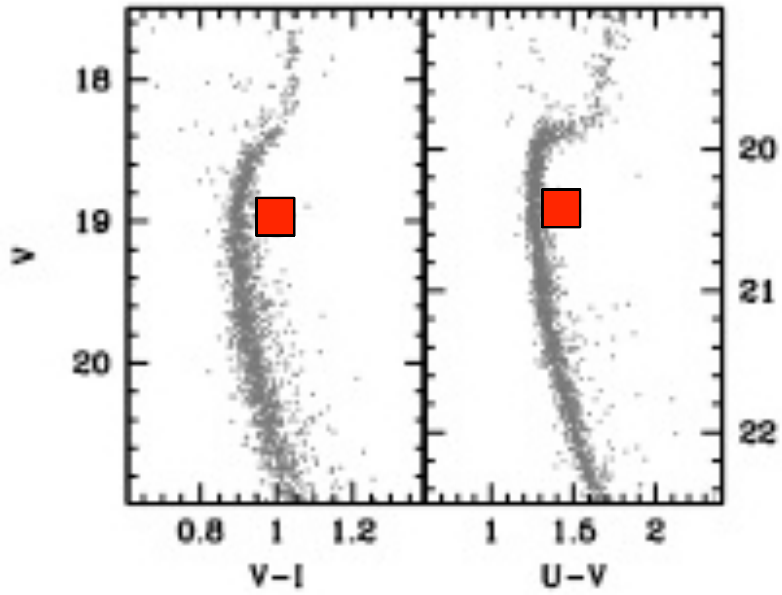


=> good agreement with P_b !



CMD: NON-degenerate star

(position is similar to that of COM6397A and COM6266 B)



1) position in agreement with the radio PRELIMINARY PSR position

2) optical variability in agreement with orbital period

=> LIKELY companion to PSR M28-I !!

For a solid confirmation:

- improve radio timing
- spectroscopic follow-up (=> radial velocity curve)?
- search for X-ray counterpart?

The optical identification to PSR companions could help constraining their location!