Fundamental Parameters of Four Massive Eclipsing Binaries in Westerlund 1

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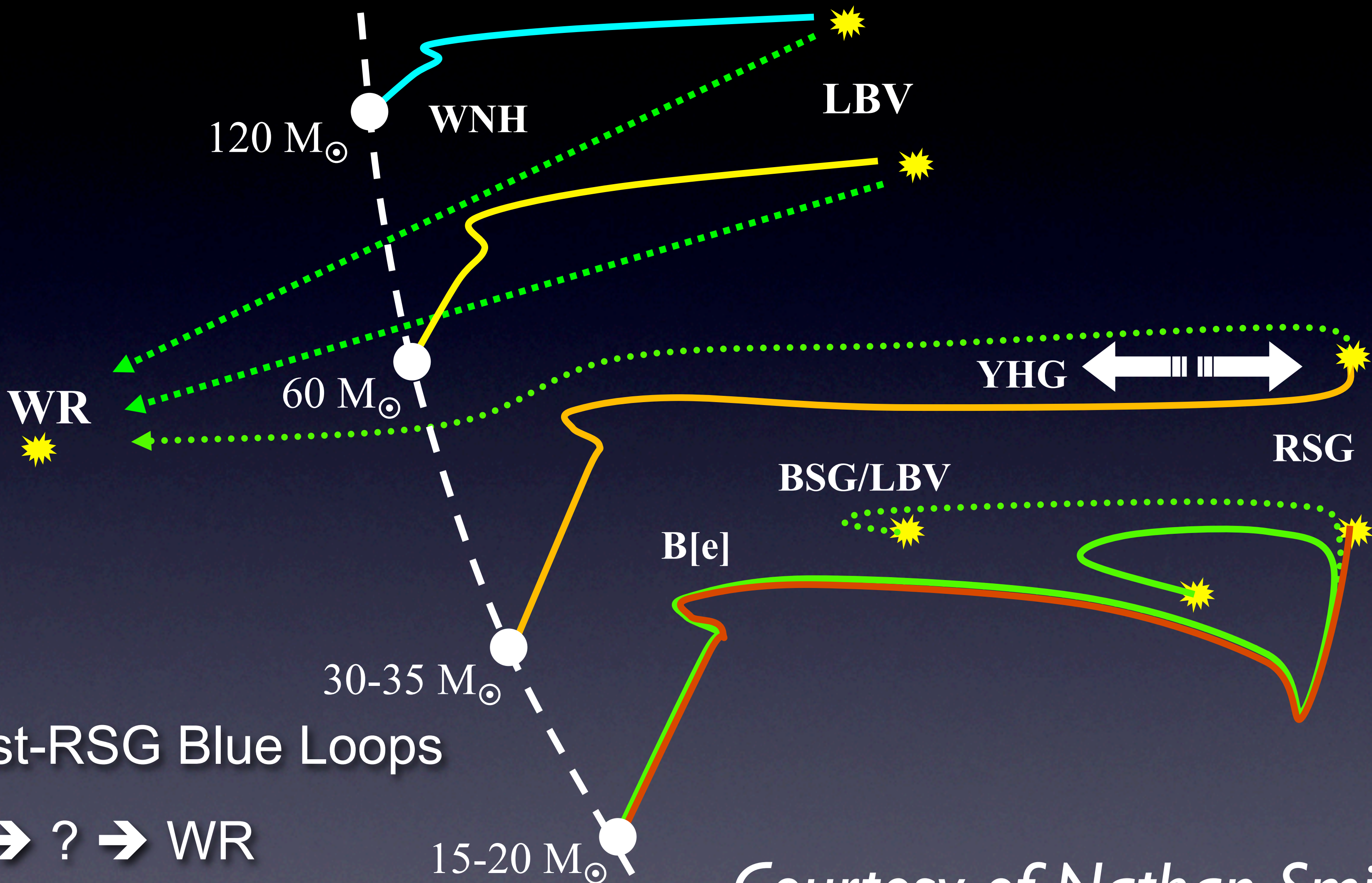
Hot & Cool: Bridging Gaps in Massive Star Evolution

(November 2008, Caltech)

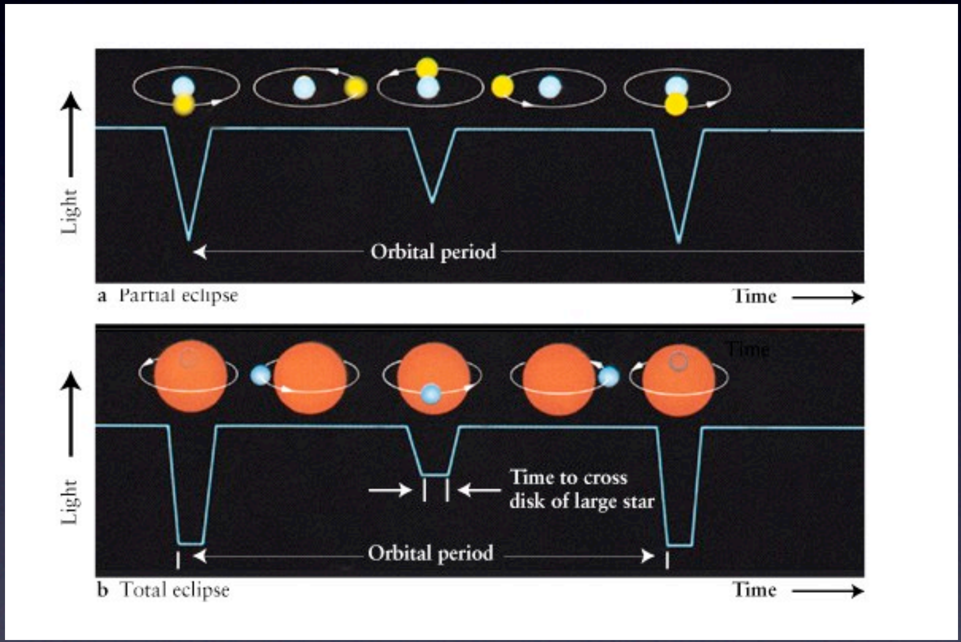


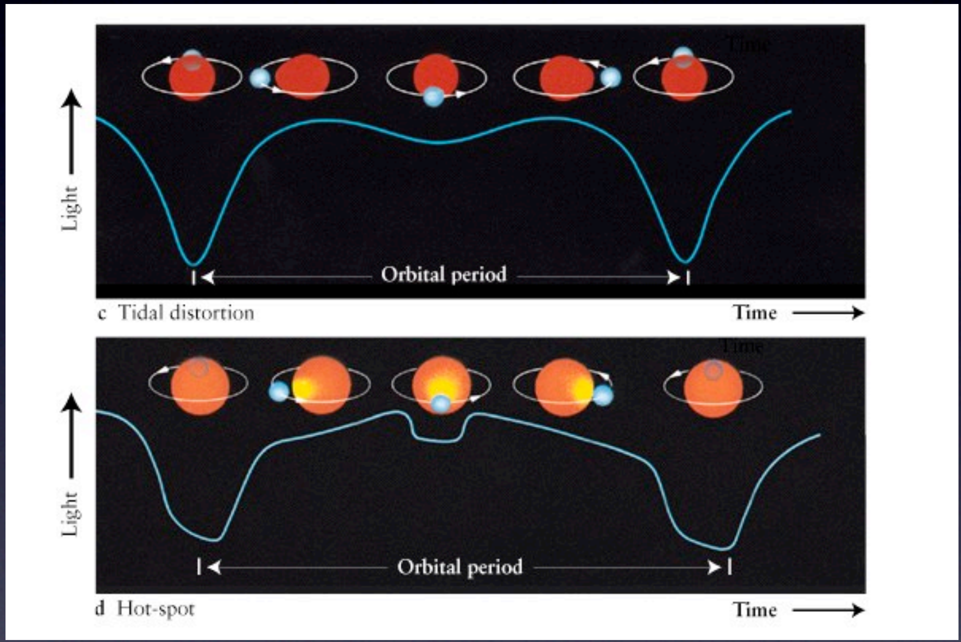
1. Post-RSG Blue Loops
2. O → ? → WR
3. Binary Evolution
4. Instabilities & Mass Loss

Courtesy of Nathan Smith

Eclipsing Binaries

Light curves: period, inclination, eccentricity, longitude of periastron (ω), fractional radii, flux ratio ($Teff_2/Teff_1$)





Spectra: radial velocity semi-amplitudes, eccentricity, ω ($Teff_1$, $Teff_2$, intrinsic color, reddening)

Kepler's law: semi-major axis of orbit, radii, masses

Most Massive Stars in Binaries

- $>116 \pm 33\ M_\odot$, $>48 \pm 20\ M_\odot$ — R145 (WN6ha)
  (Schnurr, Moffat et al. 2009)
- $116 \pm 31\ M_\odot$, $89 \pm 16\ M_\odot$ — NGC 3603-A1 (WN6ha)
  (Schnurr, Moffat et al. 2008)
- $>87 \pm 6\ M_\odot$, $>53 \pm 4\ M_\odot$ — WR 21a (O3f*/WN6ha)
  (Niemela et al. 2008)
- $83 \pm 5\ M_\odot$, $82 \pm 5\ M_\odot$ — WR 20a (WN6ha)
  (Rauw et al. 2004, Bonanos et al. 2004)
- $>78 \pm 8\ M_\odot$, $>66 \pm 7\ M_\odot$ — R139 (O6.5 Iafc + O6 Iaf)
  (Taylor et al. 2011)
- $70.0 \pm 6.9\ M_\odot$ — M33 X-7 (O7 III + BH)
  (Orosz et al. 2007)
- $60 \pm 5\ M_\odot$ — Cyg OB2-B17 (O7 Iaf$^+$ +O9 Iaf)
  (Stroud et al. 2010)
- $56.9 \pm 0.6\ M_\odot$ — R136-38 (O3V+O6V)
  (Massey et al. 2002)

Most Massive Stars in Binaries

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Smith & Conti (2008)

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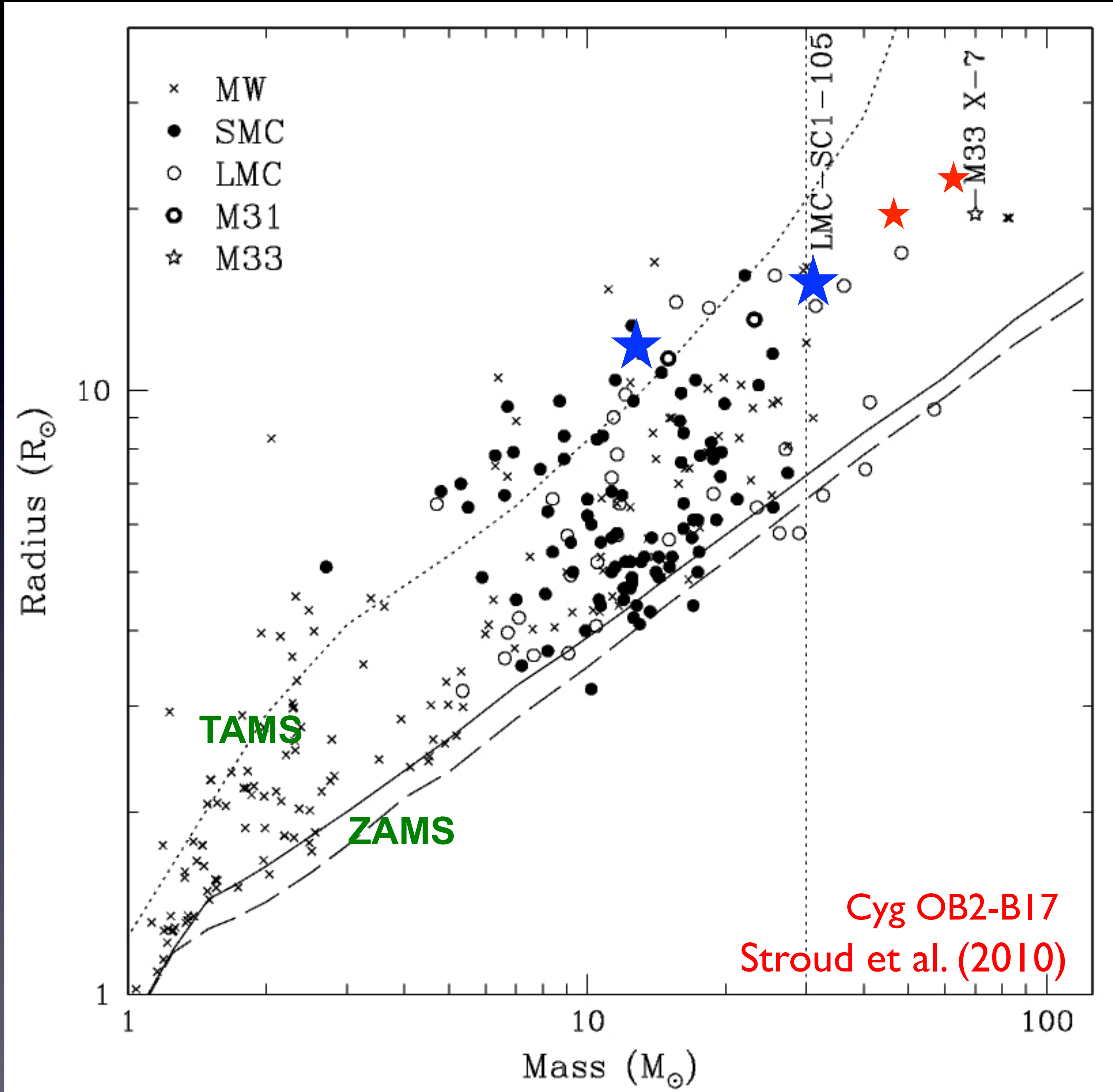
Fundamental parameters for massive stars

σ < 10%



Bonanos (2009)

Young Massive Clusters

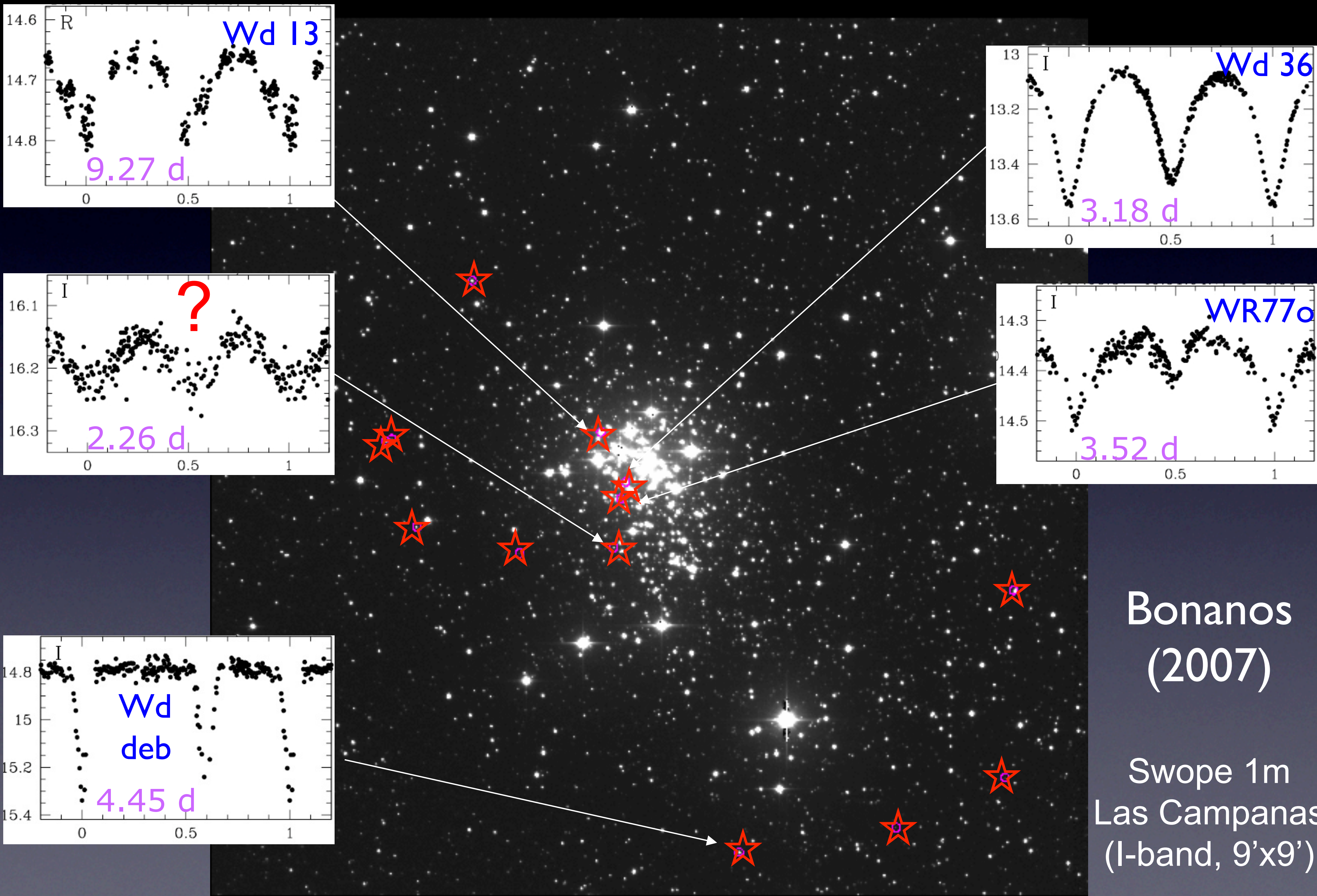
Cluster	log $M1$ ($M_\odot$)	log $M2$ ($M_\odot$)	Radius (pc)	Age (Myr)
Wd 1	3.8	4.75	0.6	3.5-5
Quintuplet	3.0	3.8	1.0	3-6
Arches	3.7	4.3	0.19	2-3
Center	3.0	4.0	0.23	3-7
NGC 3603	3.1	3.7	0.23	2.5
R136	3.4	4.5	1.6	$< 1 - 2$

Clark & Negueruela (2005)

M1: mass in visible stars

M2: total mass assuming Salpeter IMF

Eclipsing Binaries in Westerlund 1



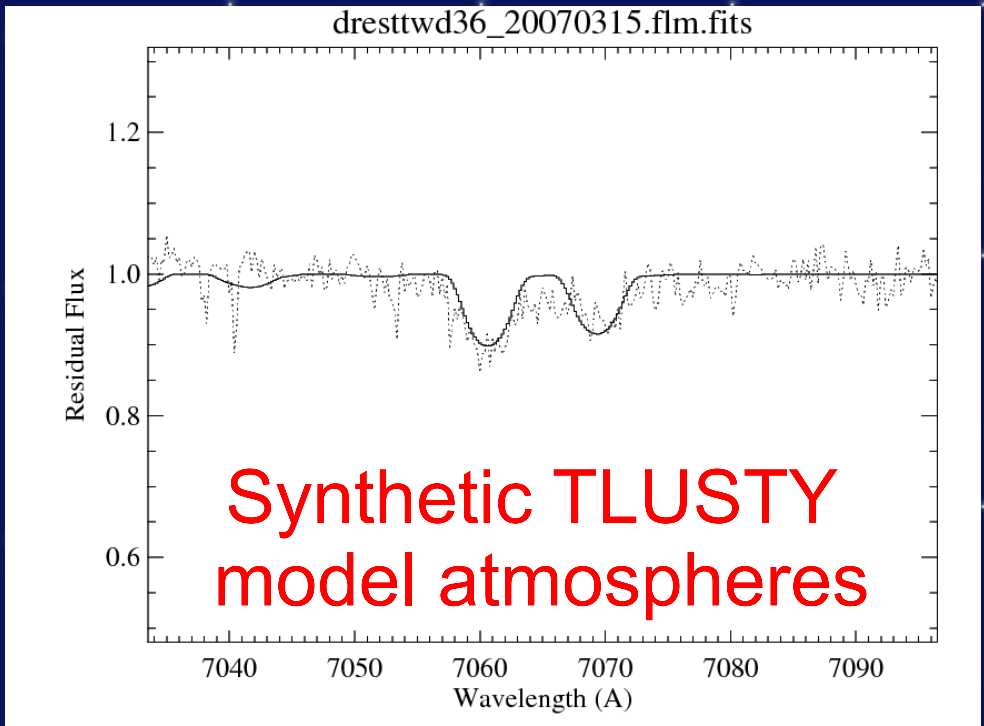
Bonanos (2007)

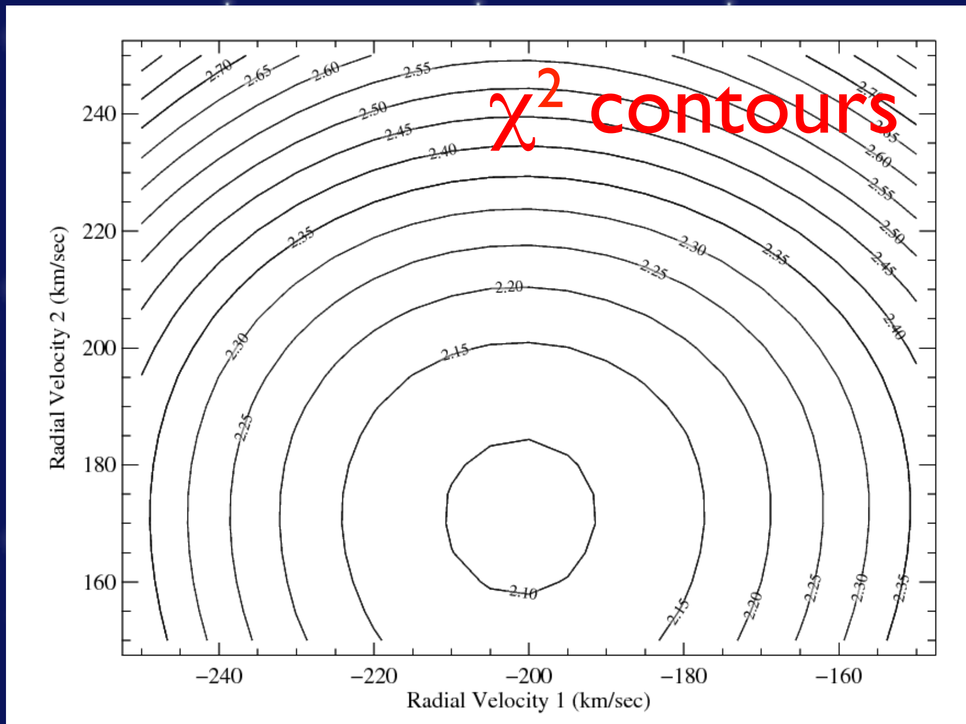
Swope 1m
Las Campanas
(I-band, 9'x9')

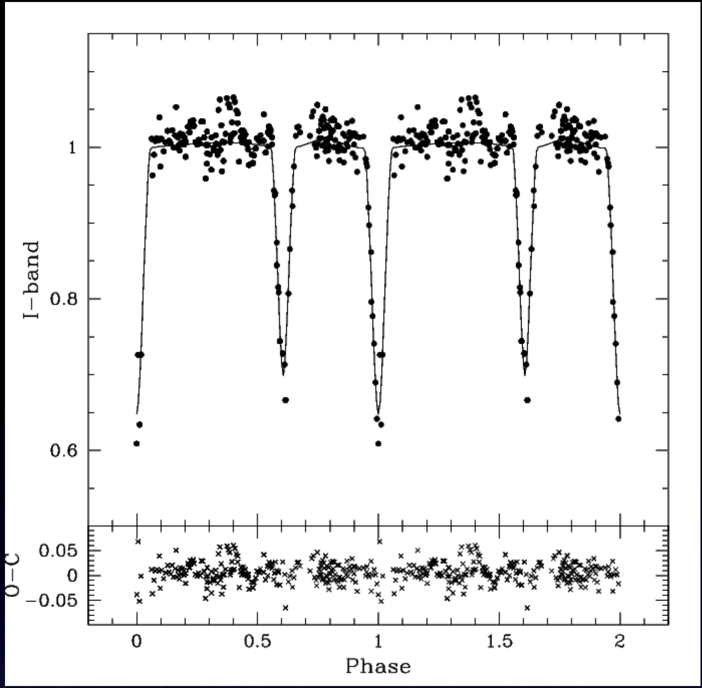
Reduction & Analysis

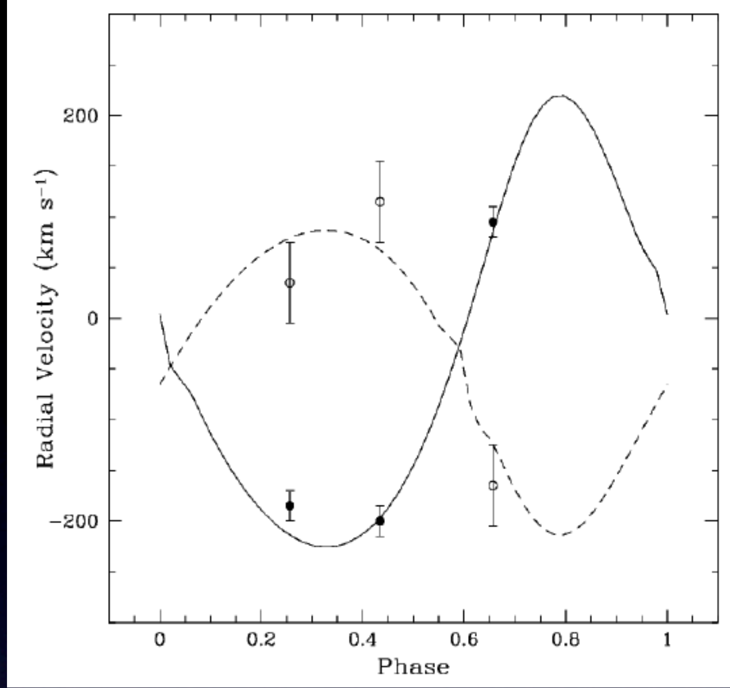
by Eugenia Koumpia

Magellan/MIKE & IMACS+MOE spectra
9 nights in 2007-2008
HeI λλ6678, 7065









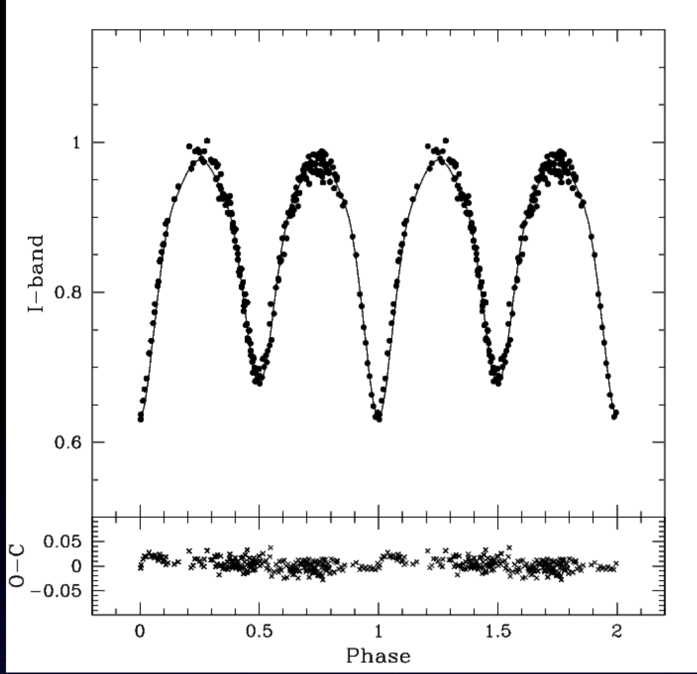
PHOEBE
(Prsa & Zwitter 2005)

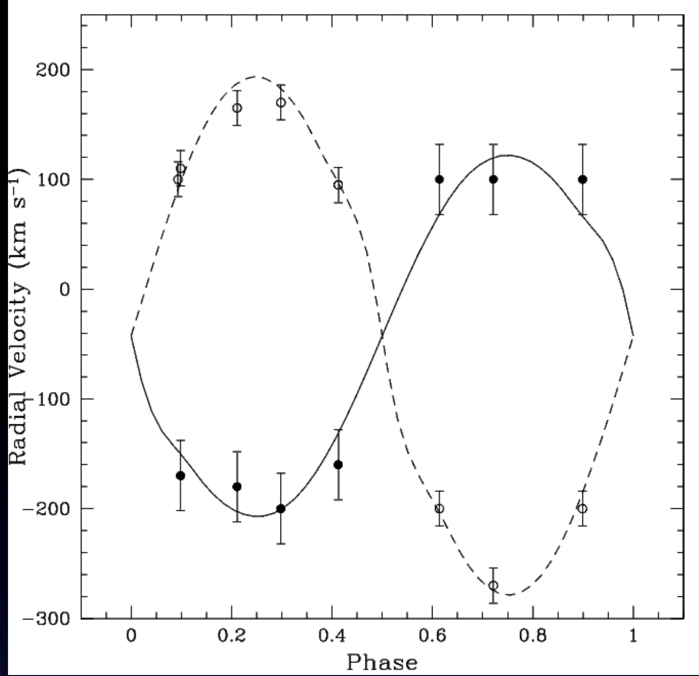
Wd deb

Binary	P (days)	$M_1(M_o)$	$M_2(M_o)$	$R_1(R_o)$	$R_2(R_o)$	$\log g_1$	$\log g_2$	Ecc.	Inclin. (°)
Wddeb	4.447	15.4	11.1	6.8	4.8	3.96	4.12	0.1742	89
Wd36	3.181	15±2	11±2	11±1	9±1	3.55	3.55	0 (fixed)	73.3±0.2
WR77o	3.518	40.2	14.75	17.38	7.7	3.56	3.83	0 (fixed)	56.9
Wd13	9.266	28±1	38±2	24±2	28±2	3.00	3.38	0 (fixed)	56±1

detached system

Koumpia & Bonanos
(in prep)





Wd 36

Binary	P (days)	$M_1(M_o)$	$M_2(M_o)$	$R_1(R_o)$	$R_2(R_o)$	$\log g_1$	$\log g_2$	Ecc.	Inclin. (°)
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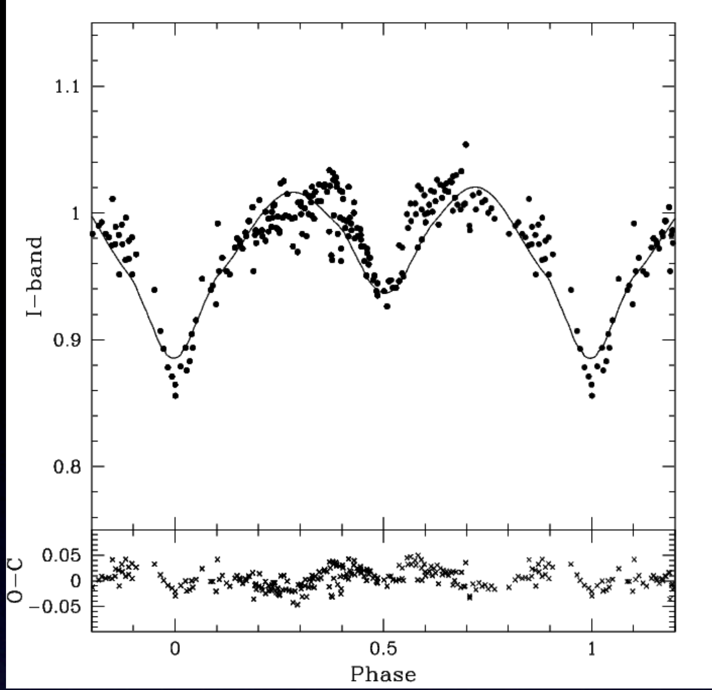
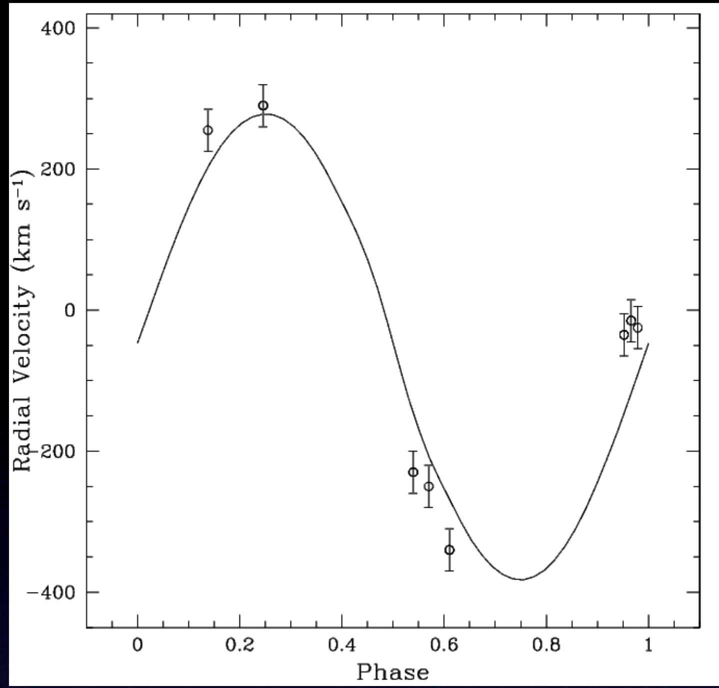
contact system

Koumpia & Bonanos
(in prep)





WR77o (WN6-7)

Binary	P (days)	$M_1(M_o)$	$M_2(M_o)$	$R_1(R_o)$	$R_2(R_o)$	$\log g_1$	$\log g_2$	Ecc.	Inclin. (°)
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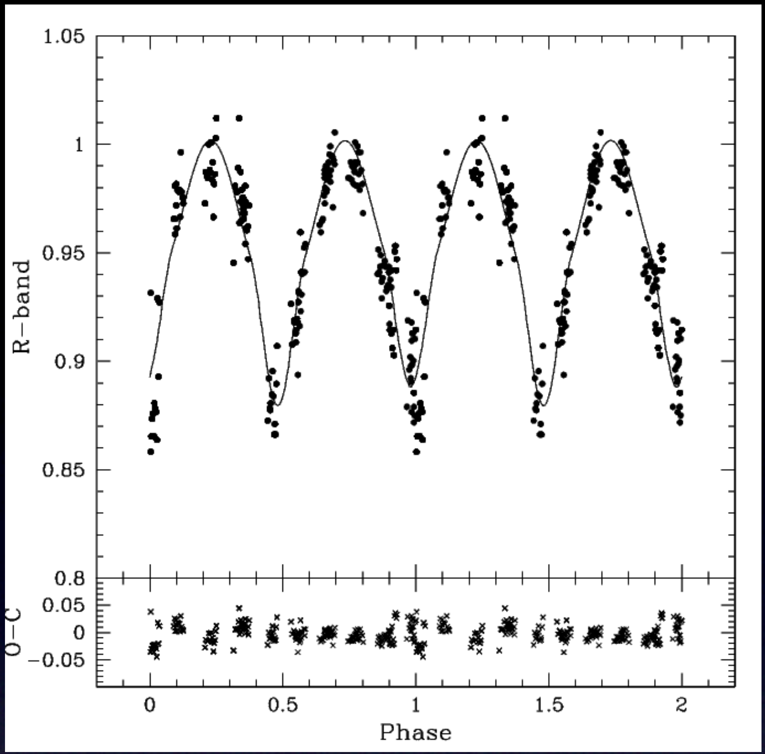
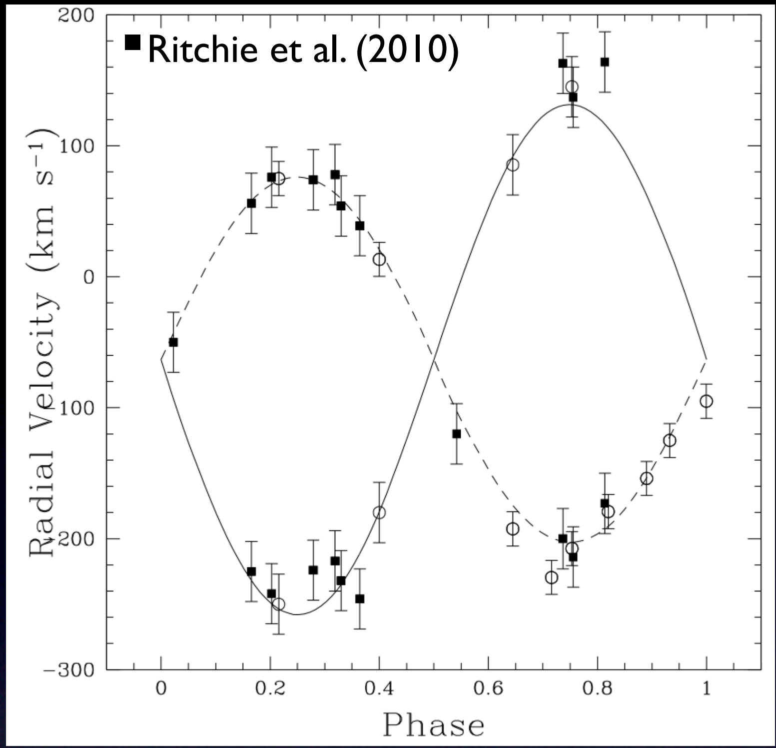
Wd13	9.266	28±1	38±2	24±2	28±2	3.00	3.38	0 (fixed)	56±1

$f(M_1, M_2) = (M_2 \sin i)^3/(M_1+M_2)^2 = 21\ M_o$

Koumpia & Bonanos (in prep)





Wd 13 (B0Ia$^+$/WNVL+O9.5-B0.5I)

Binary	P (days)	$M_1(M_o)$	$M_2(M_o)$	$R_1(R_o)$	$R_2(R_o)$	$\log g_1$	$\log g_2$	Ecc.	Inclin. (°)
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Wd13	9.266	28±1	38±2	24±2	28±2	3.00	3.38	0 (fixed)	56±1

near contact system

Koumpia & Bonanos
(in prep)

Wd 13

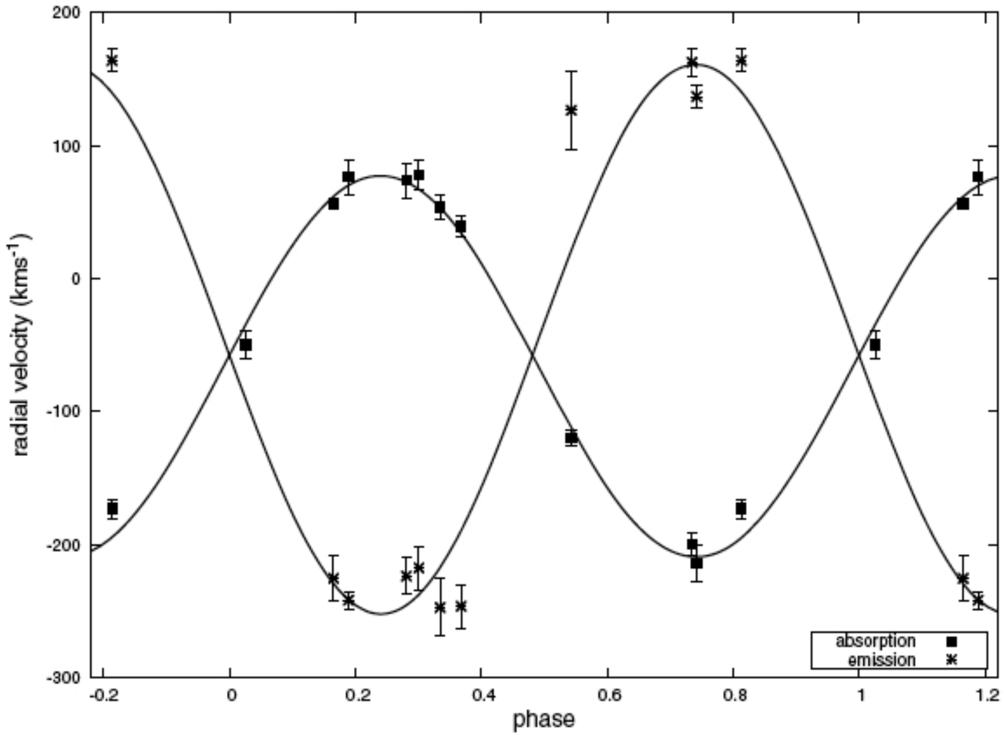


Fig. 3. Radial velocity curve for W13.

Table 2. Summary of orbital and physical parameters of W13[a] .

Parameter	Value	
T_0 (MJD)[a]	54 643.080	
P (days)	9.2709 ± 0.0015	
$q = m_{abs}/m_{em}$	1.53 ± 0.10	
a ($R_\odot$)	72 ± 3	
e	0 (fixed)	
i	$62^{+3\circ}_{-4}$	
	Emission	Absorption
Filling factor	0.93 ± 0.05	0.74 ± 0.1
T_{eff} (K)	25 000 (fixed)	$25\,000 \pm 2000$
R ($R_\odot$)	22 ± 2	21 ± 2
γ (km s^{-1})	-48.2 ± 3.1	-65.9 ± 2.4
K (km s^{-1})	210.2 ± 8.7	137.3 ± 6.7
$M\sin^3 i$ ($M_\odot$)	15.9 ± 1.9	24.4 ± 3.0
$M(i = 65^\circ)$ ($M_\odot$)	21.4 ± 2.6	32.8 ± 4.0
$M(i = 62^{+3\circ}_{-4})$ ($M_\odot$)	$23.2^{+3.3}_{-3.0}$	$35.4^{+5.0}_{-4.6}$

Notes. [(a)] Note that T_0 corresponds to the eclipse of the B0.5Ia$^+$ emission-line star.

Ritchie et al. (2010)

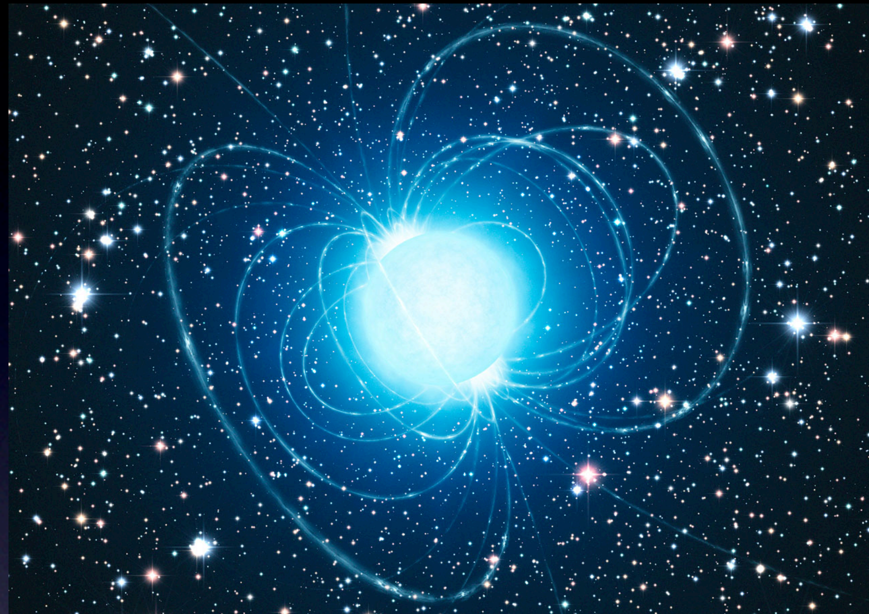
Magnetar: CXOU J164710.2-455216

(Muno et al. 2006)

"How Much Mass Makes a Black Hole?"

(ESO PR #1034, August 2010)

Ritchie et al. (2010) found progenitor > 40 $M_{\odot}$

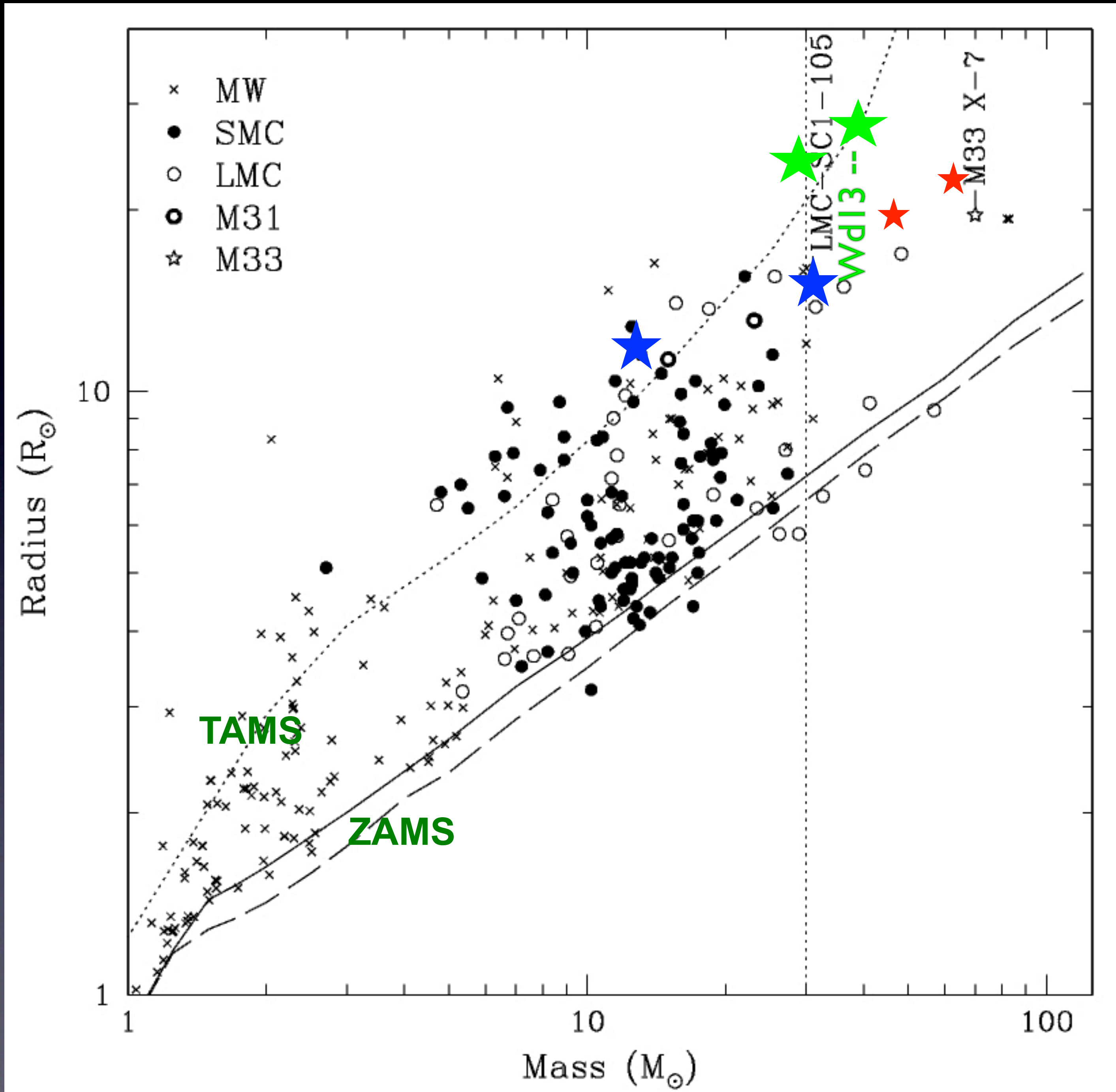


ESO/L. Calçada

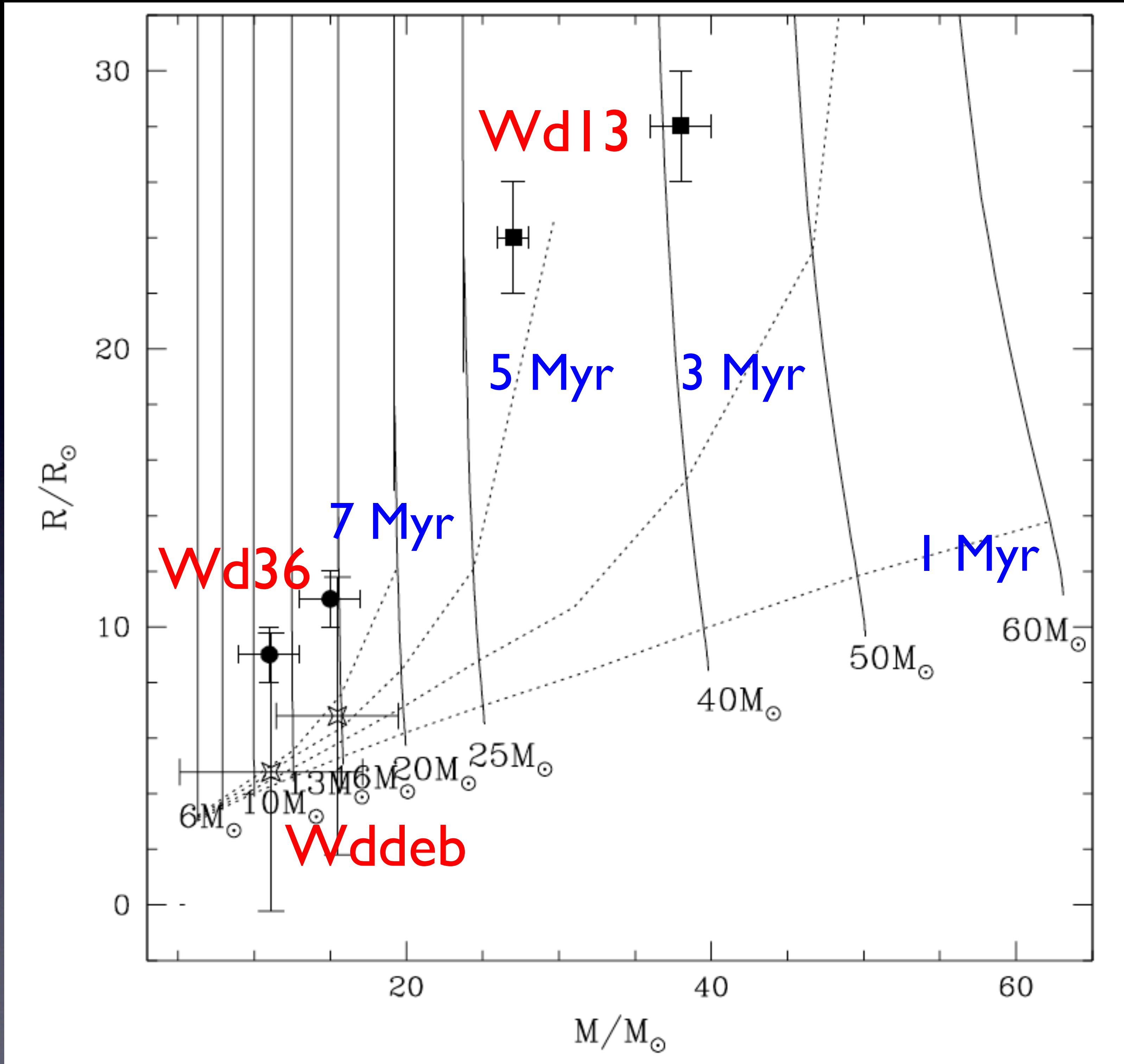
Object [+ Cluster]	$M_{prog}/M_{\odot}$	Remnant	B ($\times 10^{14}$ G)	Ref.
SGR 1806 – 20	48^{+20}_{-8}	Magnetar	2-8	1,2
CXO J164710.2-455216 [Wd 1]	40 ± 5	Magnetar	<1.5	3
IGR J18135-1751 [Cl 1813 – 18]	20-30	Pulsar Wind Nebula	0.03	4,5,6
AX J1838-0655 [RSGC1]	18 ± 2	Pulsar Wind Nebula	0.02	7,8
SGR 1900+14	17 ± 1	Magnetar	2-8	This work, 9

References. (1) Bibby et al. 2008; (2) Kouveliotou et al. 1998; (3) Muno et al. 2006; (4) Helfand et al. 2007; (5) Messineo et al. 2008; (6) Gotthelf & Halpern 2009; (7) Davies et al. 2008; (8) Gotthelf & Halpern 2008; (9) Kouveliotou et al. 1999.

Davies et al. (2009)



MW
SMC
LMC
M31
M33
LMC−SC1−105
Wd13 --
M33 X−7
TAMS
ZAMS
Radius (R⊙)
Mass (M⊙)
1
10
100



Wd13
Wd36
Wddeb
7 Myr
5 Myr
3 Myr
1 Myr
6M⊙
10M⊙
13M⊙
16M⊙
20M⊙
25M⊙
40M⊙
50M⊙
60M⊙
R/R⊙
M/M⊙
0
10
20
30
20
40
60

Conclusions

- Lack of accurate fundamental parameters
- Eclipsing binaries provide model constraints
- Westerlund 1 results:
  - Wd13 (28 +38 $M_{\odot}$): confirm & extend high mass for magnetar progenitor (>40 $M_{\odot}$)
  - WR77o: very massive companion (~40 $M_{\odot}$)
- Future: independent distance to Wd1 (3.5-5kpc)
- Stay tuned: Arches & Quintuplet clusters, G305, LMC, SMC, M33, IC 1613, NGC 6822