Alternative Pathways of Stellar Evolution (in Open Clusters)

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M67 (4 Gyr)

NGC 188 (7 Gyr)

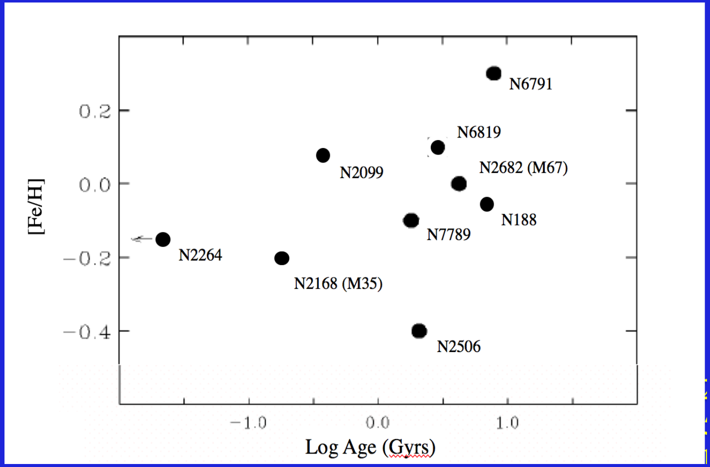
A. Geller, N. Gosnell, E. Leiner,
K. Milliman, M. Pollack,
B. Tofflemire

J. Hurley, C. Knigge, D. Latham
N. Leigh, S. Schuler, A. Sills

Setting the Stage

Solar-type Binary Populations in Open Clusters

WIYN Open Cluster Study

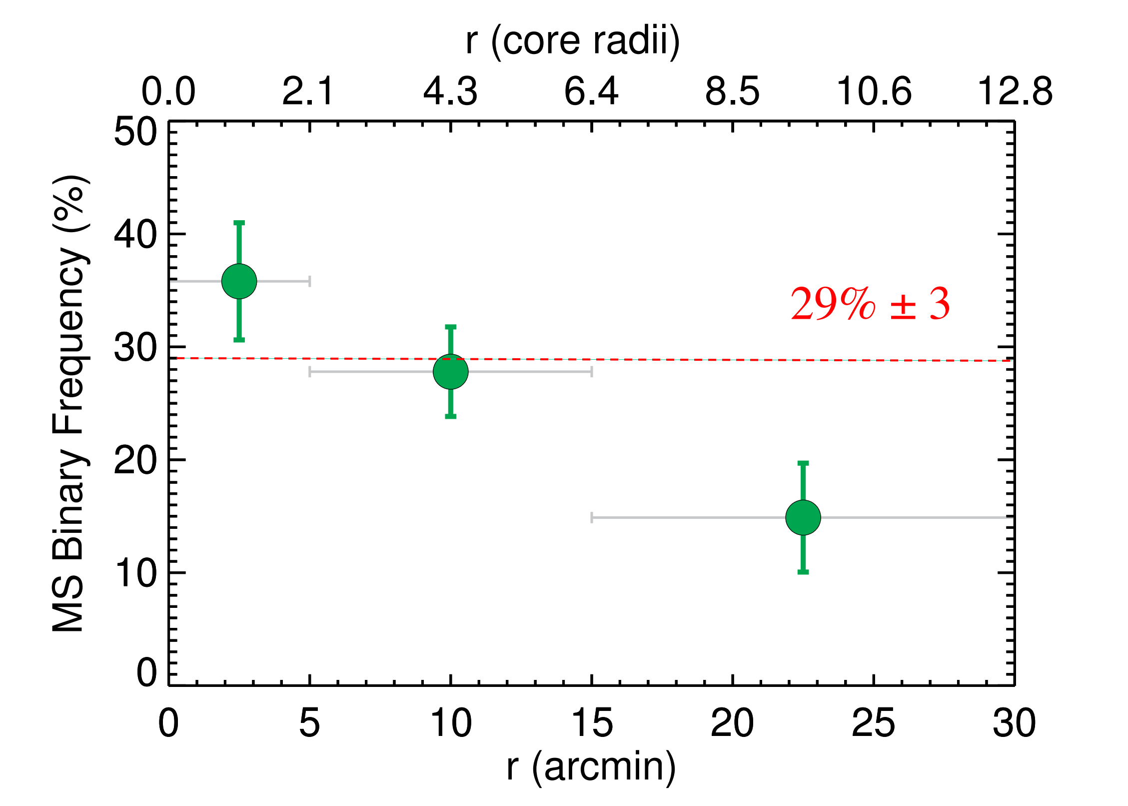


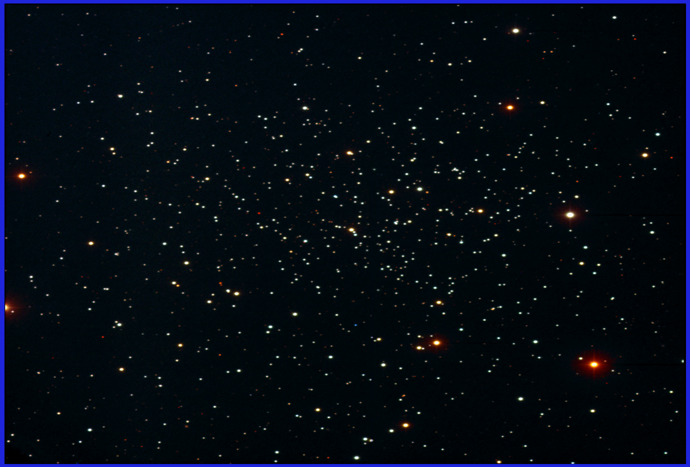
NGC 188	Geller et al. 2012
NGC 2168 (M35)	Leiner et al. 2015
NGC 2682 (M67)	Pollack et al. 2017
NGC 6819	Milliman et al. 2014
NGC 7789	Milliman et al. 2017

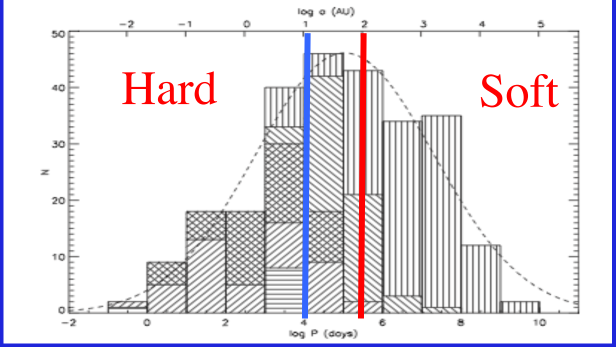
Binary Frequency

NGC 188

7 Gyr





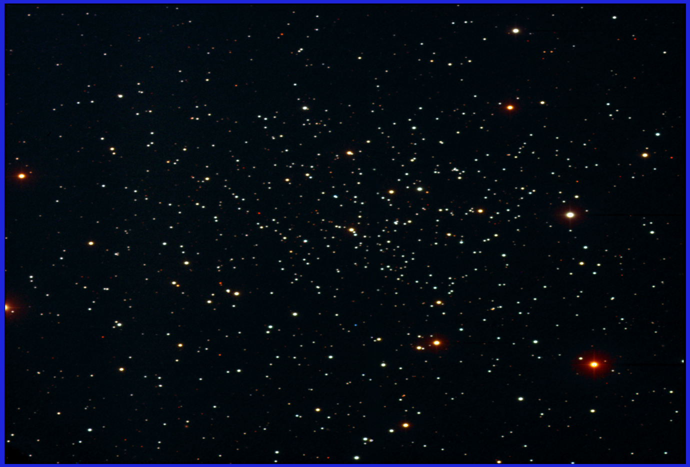


$P < 10^4$ days

Field

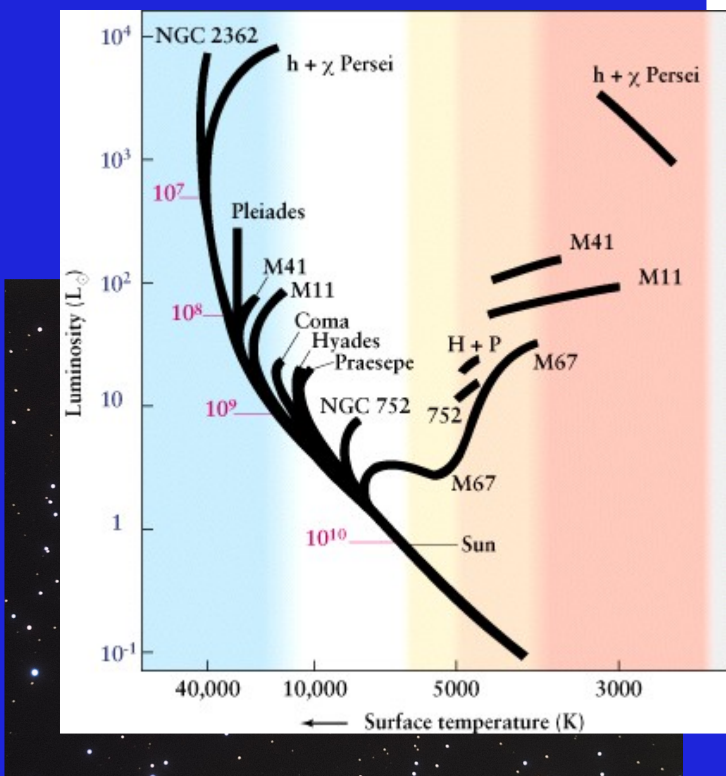
The Landscape

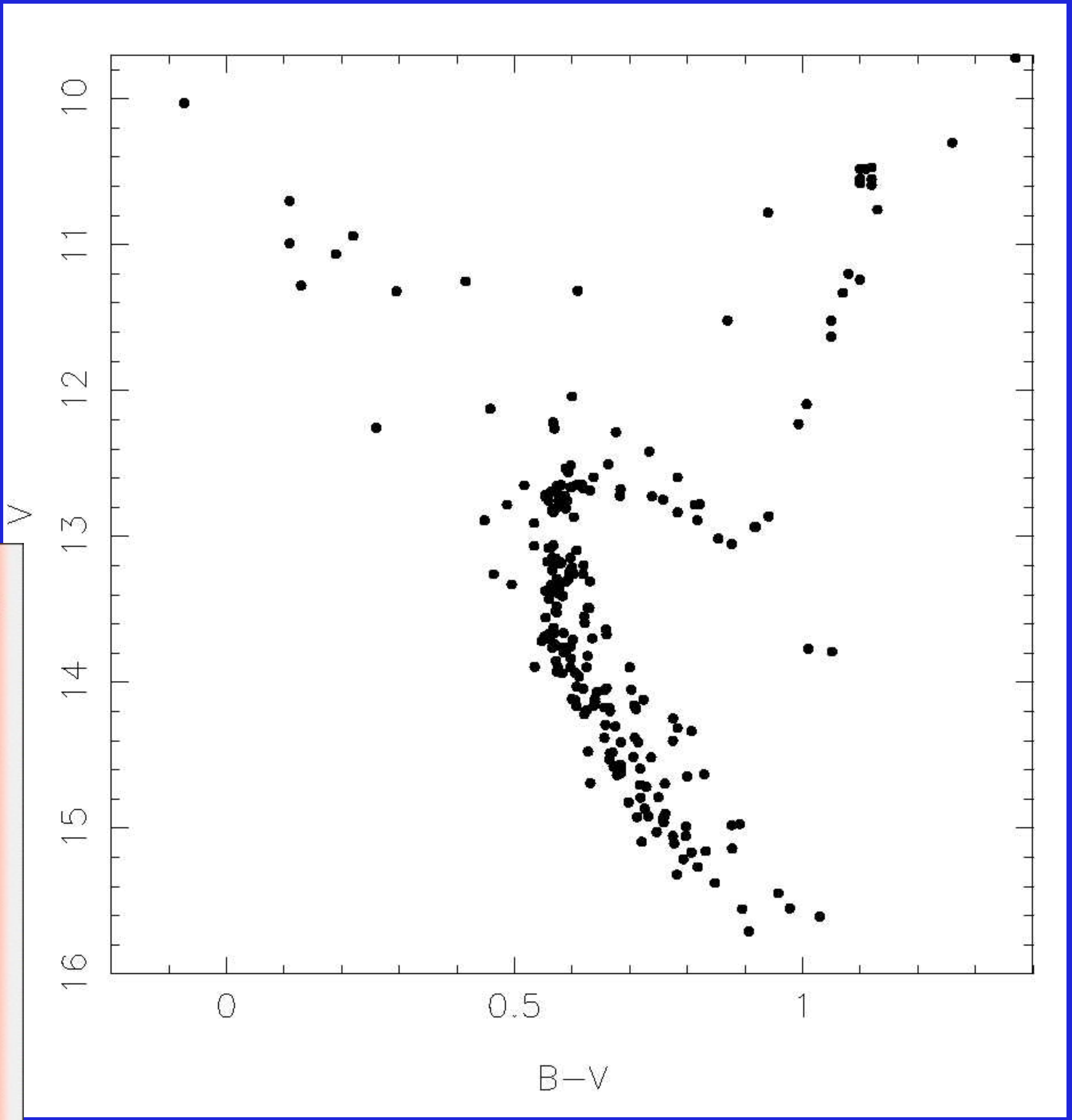
The Color-Magnitude Diagram of M67 (4 Gyr)



M67

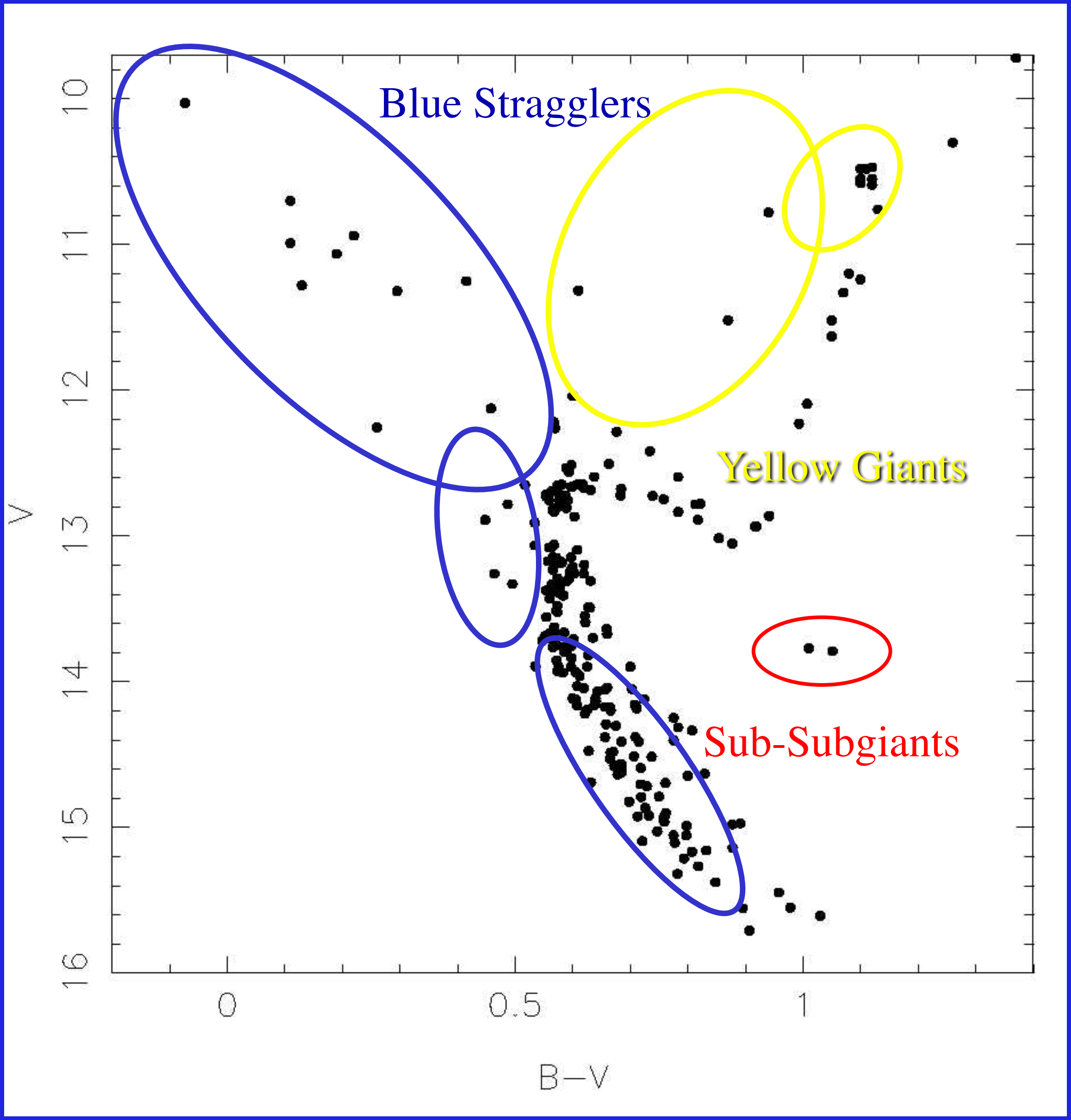
4 Gyr


Luminosity ($L_\odot$)
10^{-1}
1
10
10^2
10^3
10^4
NGC 2362
h + χ Persei
h + χ Persei
10^7
10^8
10^9
10^{10}
Pleiades
M41
M11
M41
M11
Coma
Hyades
Praesepe
H + P
M67
NGC 752
752
M67
Sun
40,000
10,000
5000
3000
Surface temperature (K)


V
10
11
12
13
14
15
16
0
0.5
1
B−V

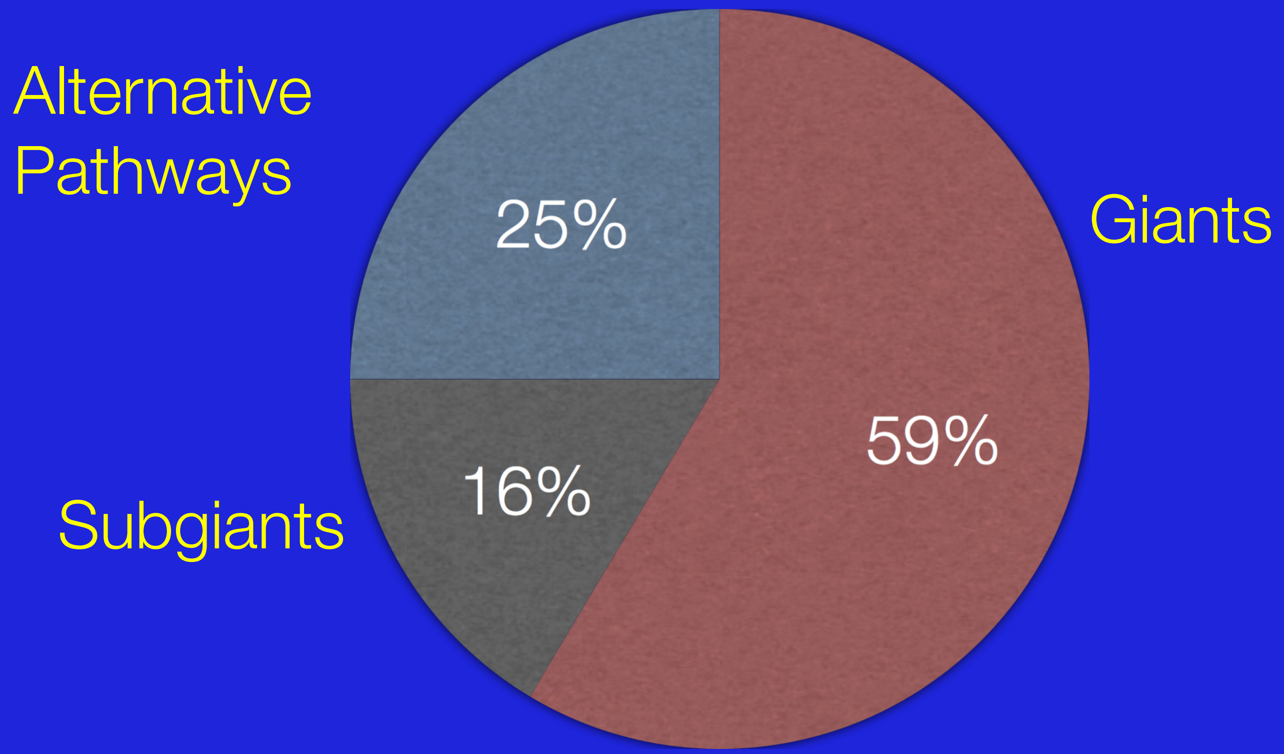
M67

4 Gyr



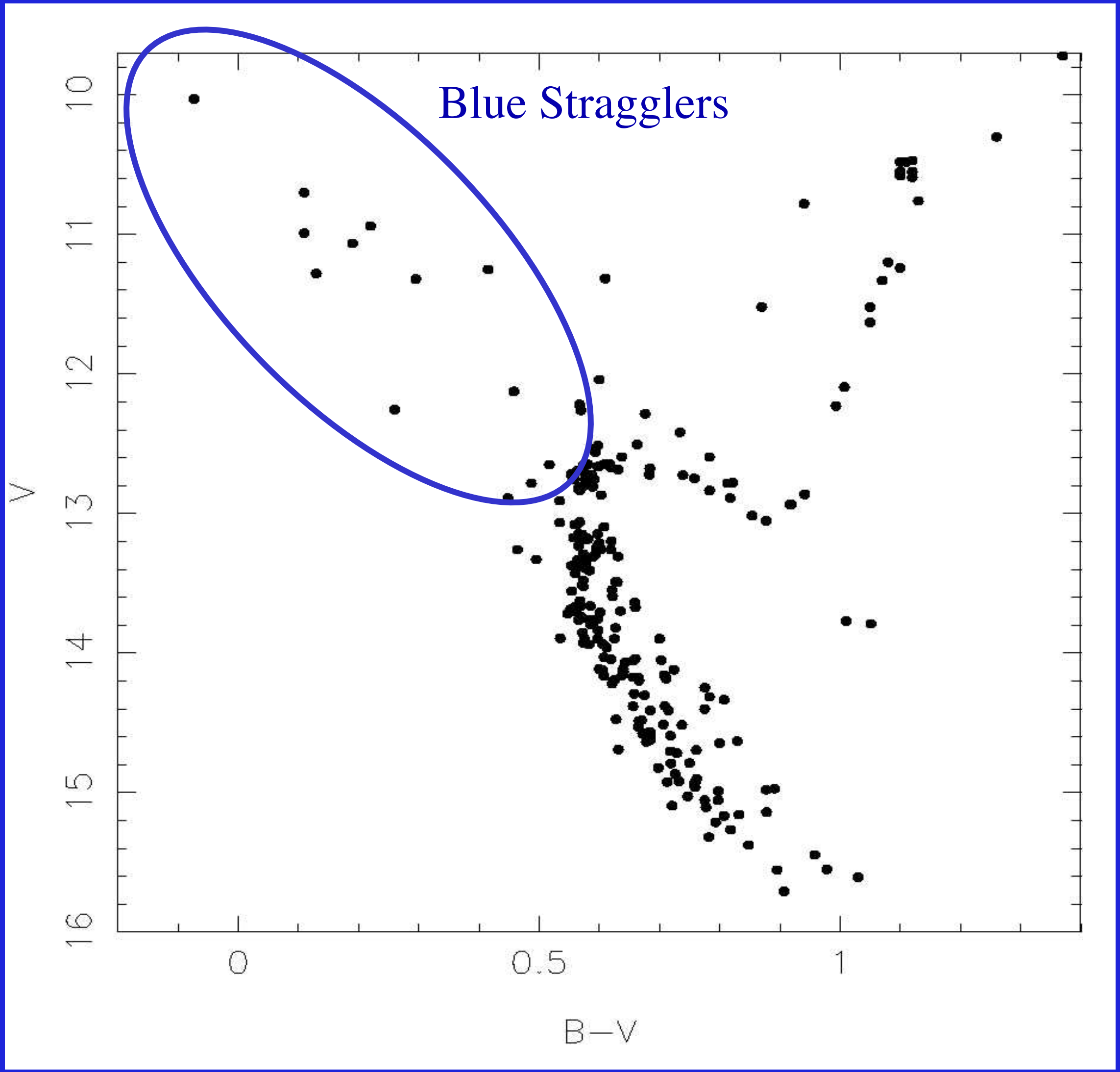
Blue Stragglers
Yellow Giants
Sub-Subgiants
V
10
11
12
13
14
15
16
B−V
0
0.5
1

25% of evolved stars are not on single-star evolutionary paths

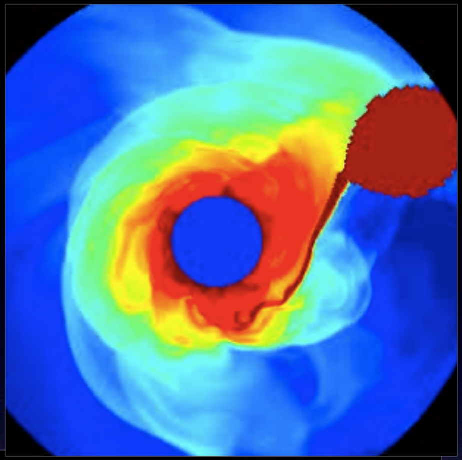


Alternative stellar evolution products are neither anomalous nor rare

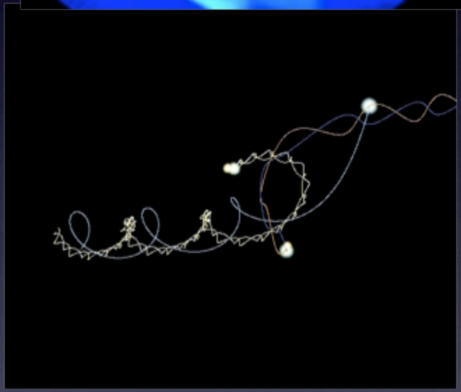
Blue Stragglers



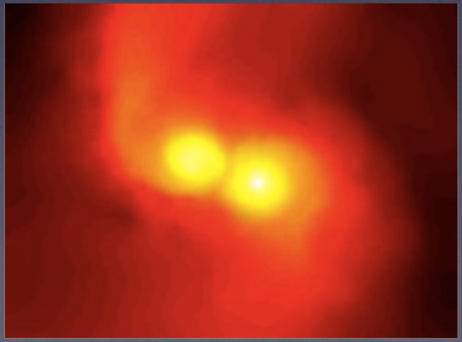
Blue Straggler Formation Scenarios



1. Mass transfer

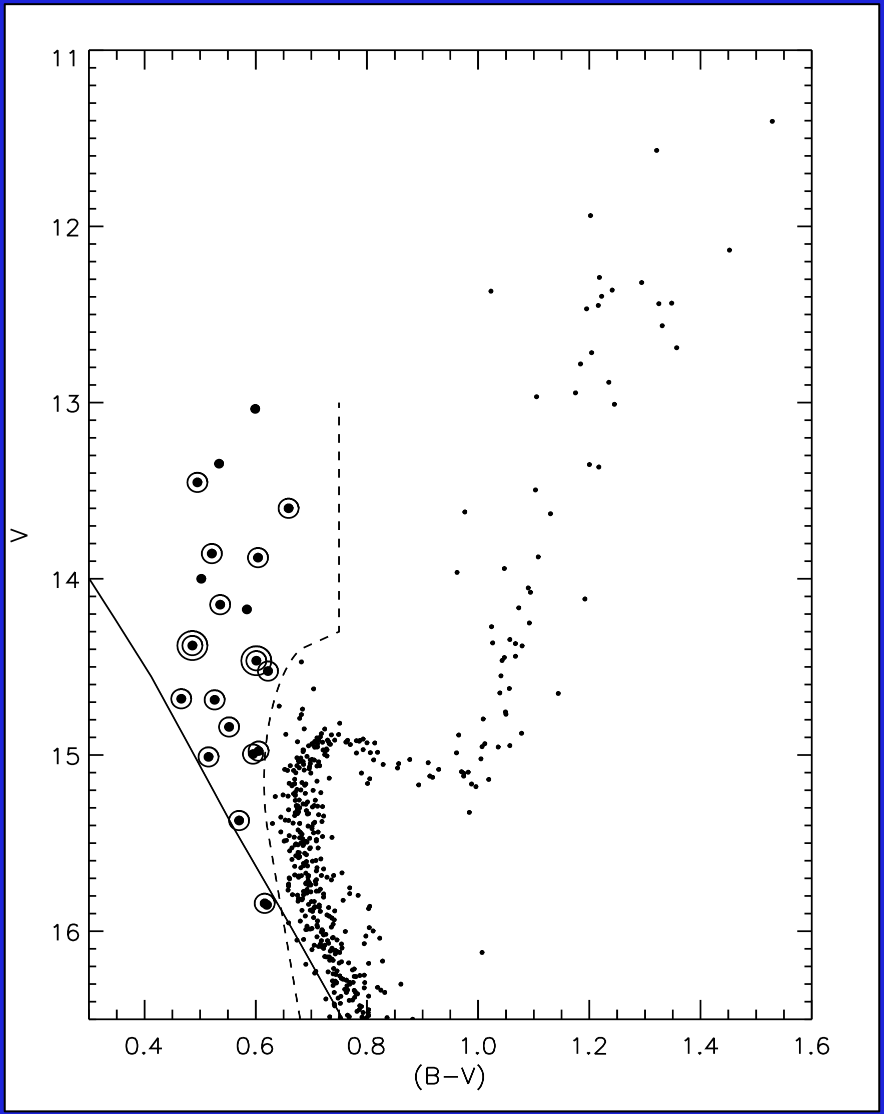


2. Stellar collision during dynamical encounter



3. Inner binary merger (Kozai)

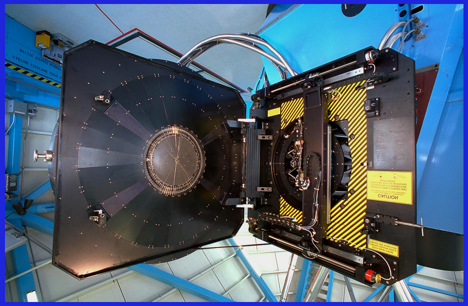
NGC 188 Blue Stragglers



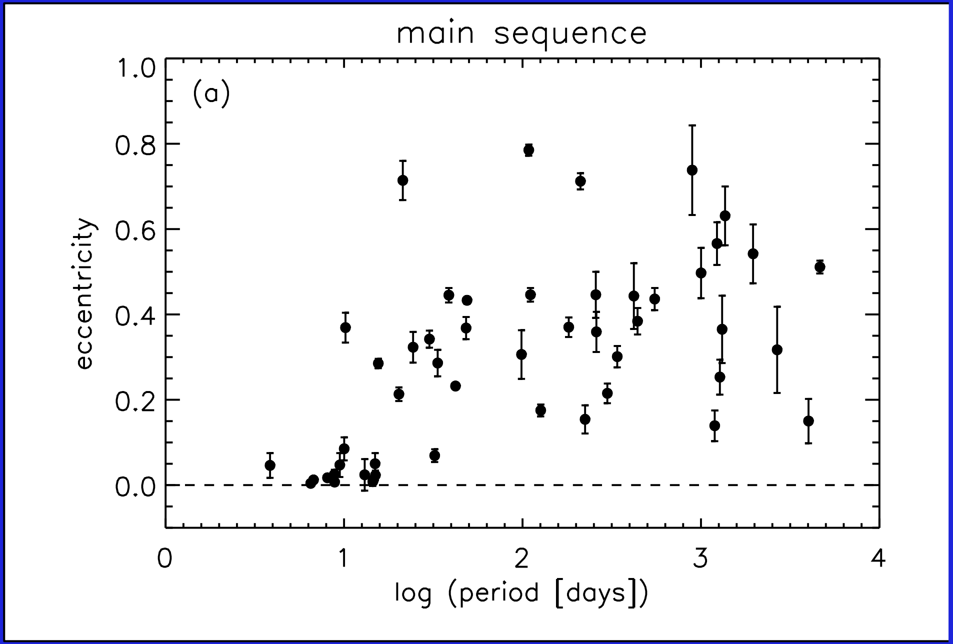
Binary Frequency
76% ± 21%

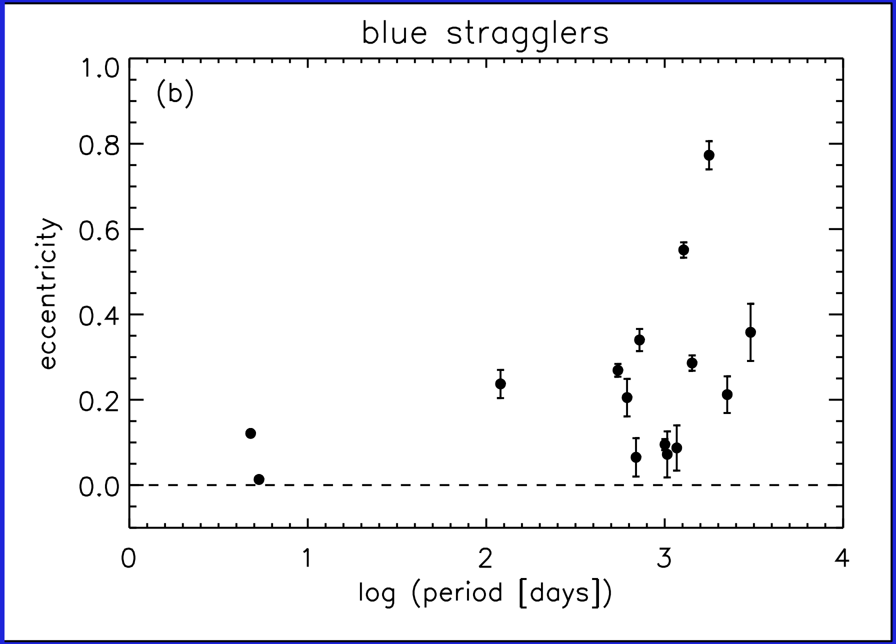
Main Sequence
29% ± 3

Mathieu & Geller 2009

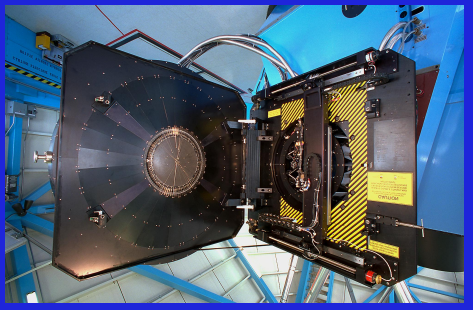


NGC 188 Blue Stragglers



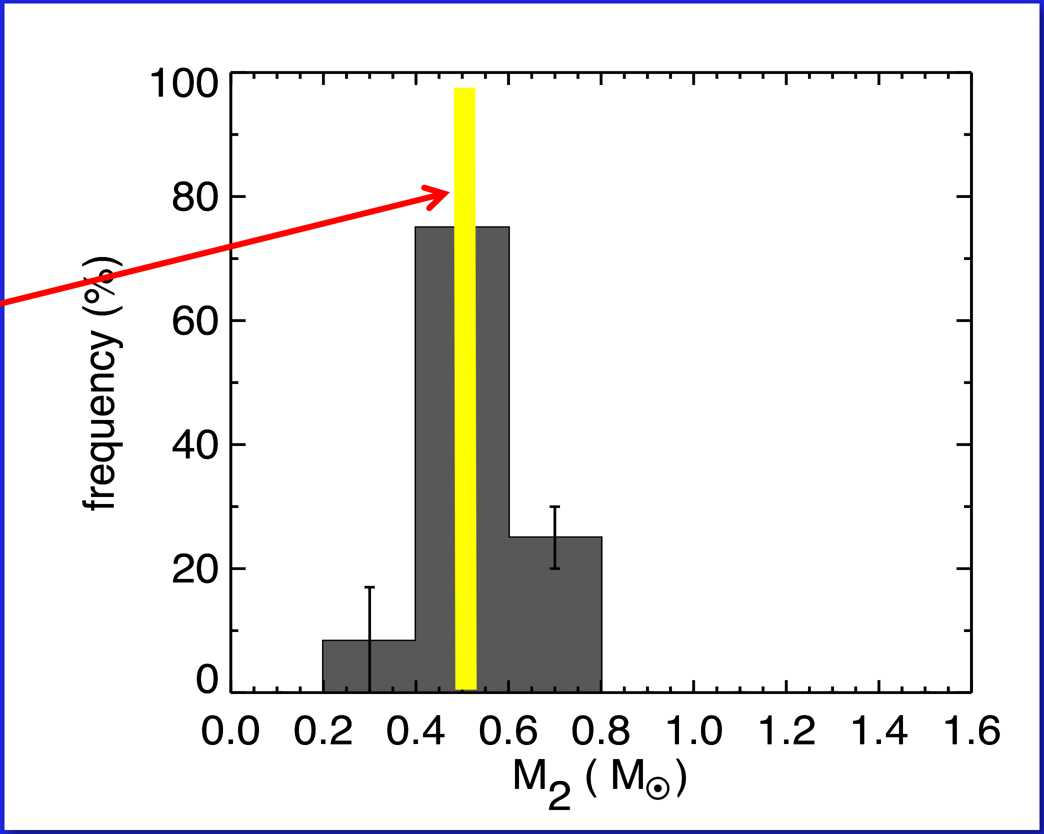


Eccentricity - Period Distribution



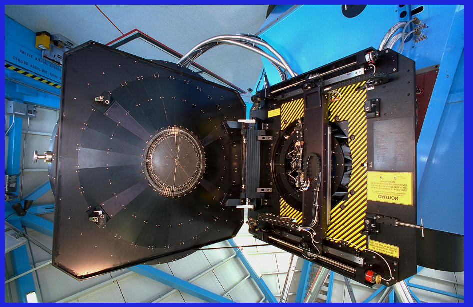
NGC 188 Blue Stragglers

0.55 $M_\odot$
CO WDs



Geller & Mathieu 2011

Secondary Mass Distribution
(Statistical)

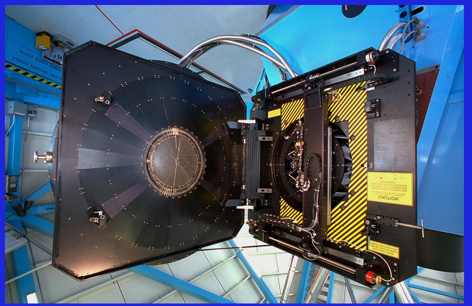


NGC 188 Blue Stragglers

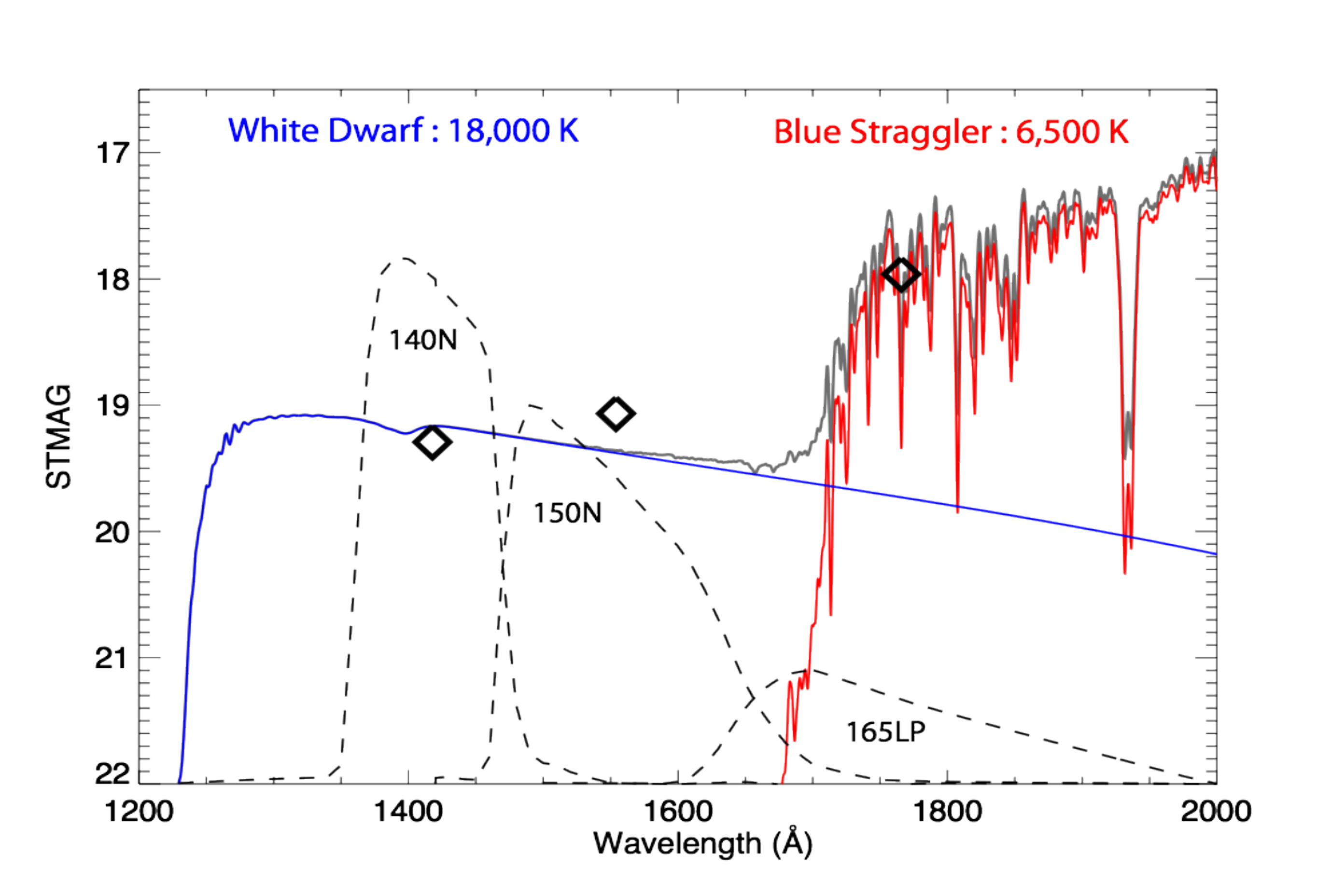
- Hard binary frequency 76%
- Typical orbital period ≈ 1000 days
- Typical secondary mass $0.5\ M_o$
- Abundance variations
- Rapidly rotating (modestly)
- Bimodal spatial distribution
- Dynamical mass < Standard evolution mass

Mass Transfer Formation ?

Confirm the WD companions

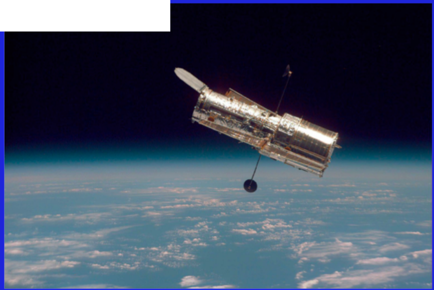


NGC 188 Blue Stragglers – Long Period

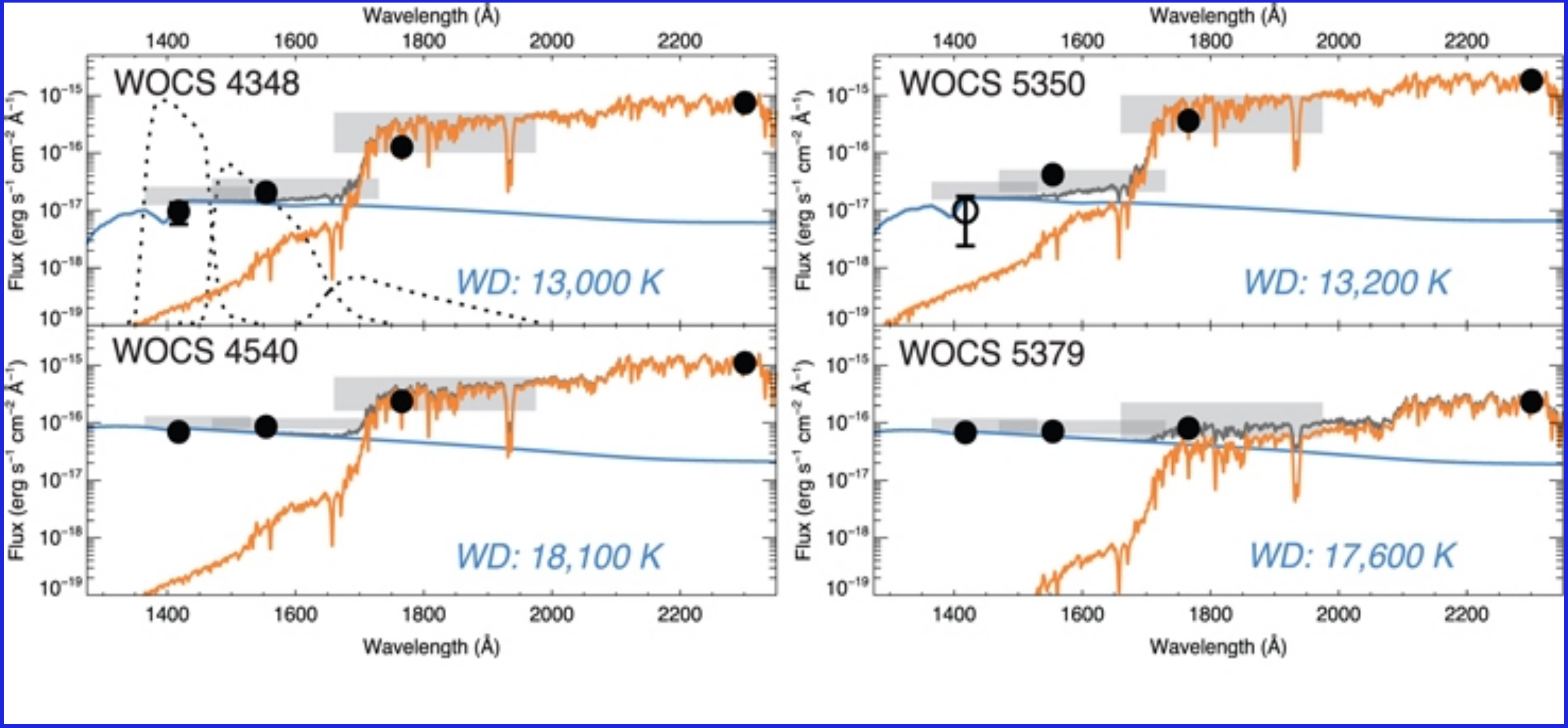


ACS/SBC far-UV photometry

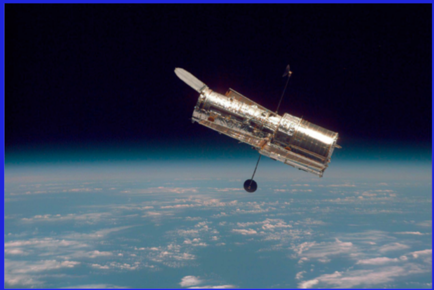
Gosnell et al. 2014



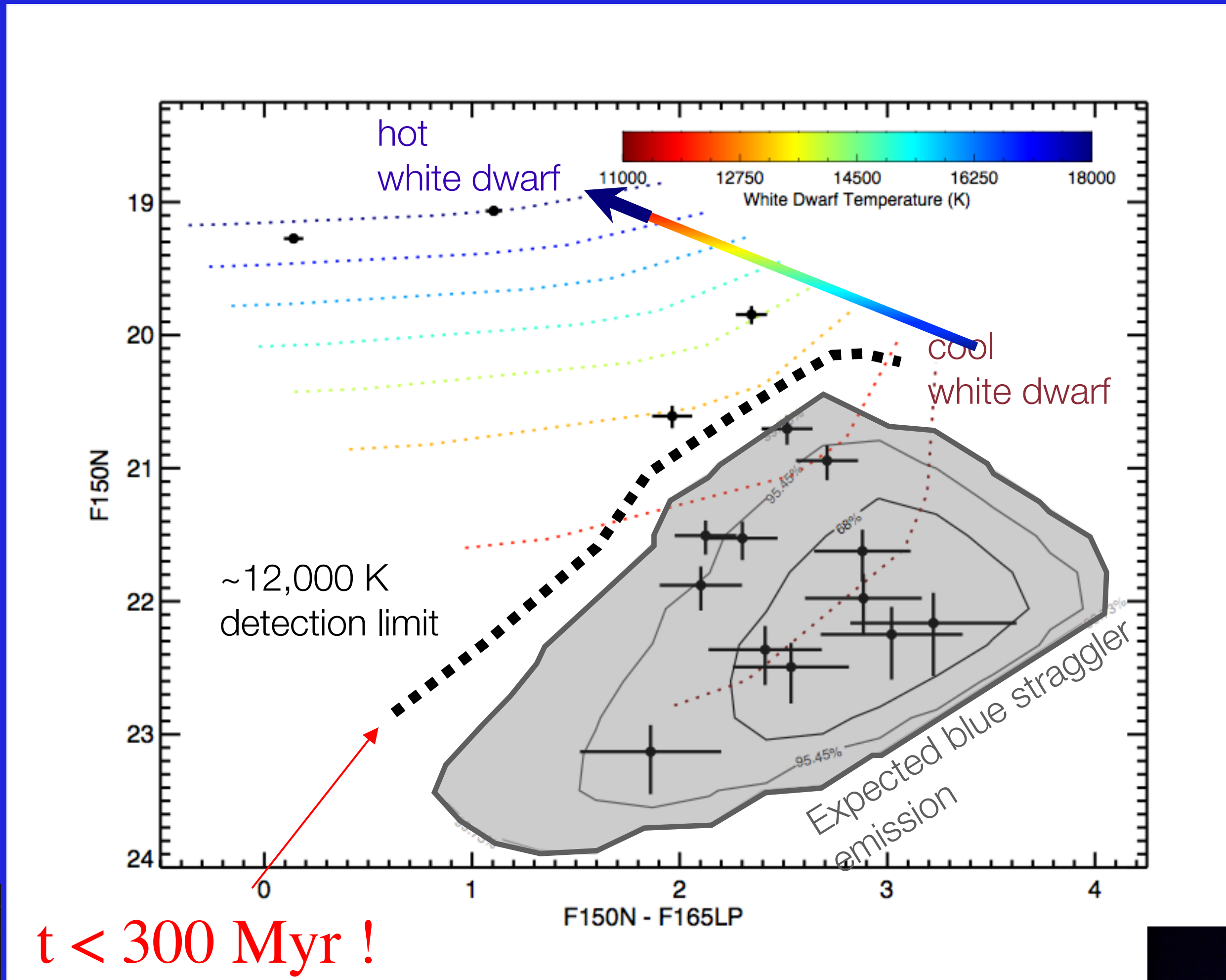
NGC 188 Blue Stragglers – Long Period

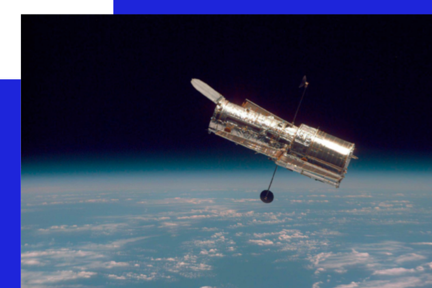


Gosnell et al. 2015



NGC 188 Blue Stragglers – Long Period

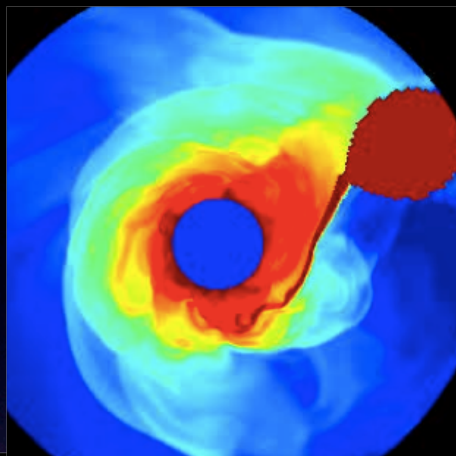


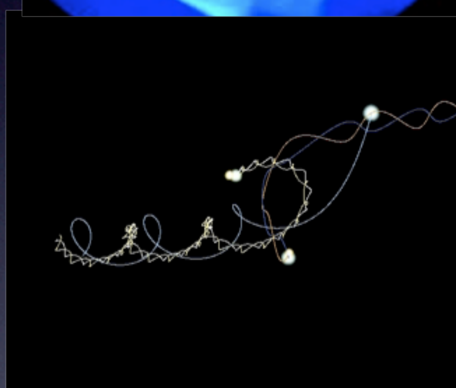


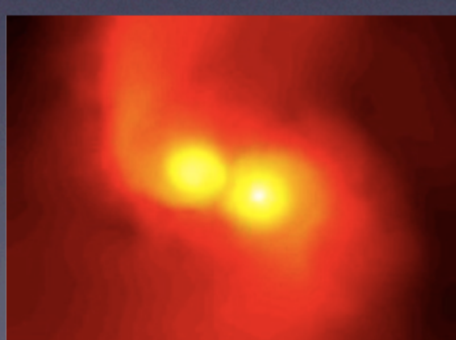
Gosnell et al. 2014, 2015

Blue Straggler Formation in NGC 188

Summary







21 blue stragglers:

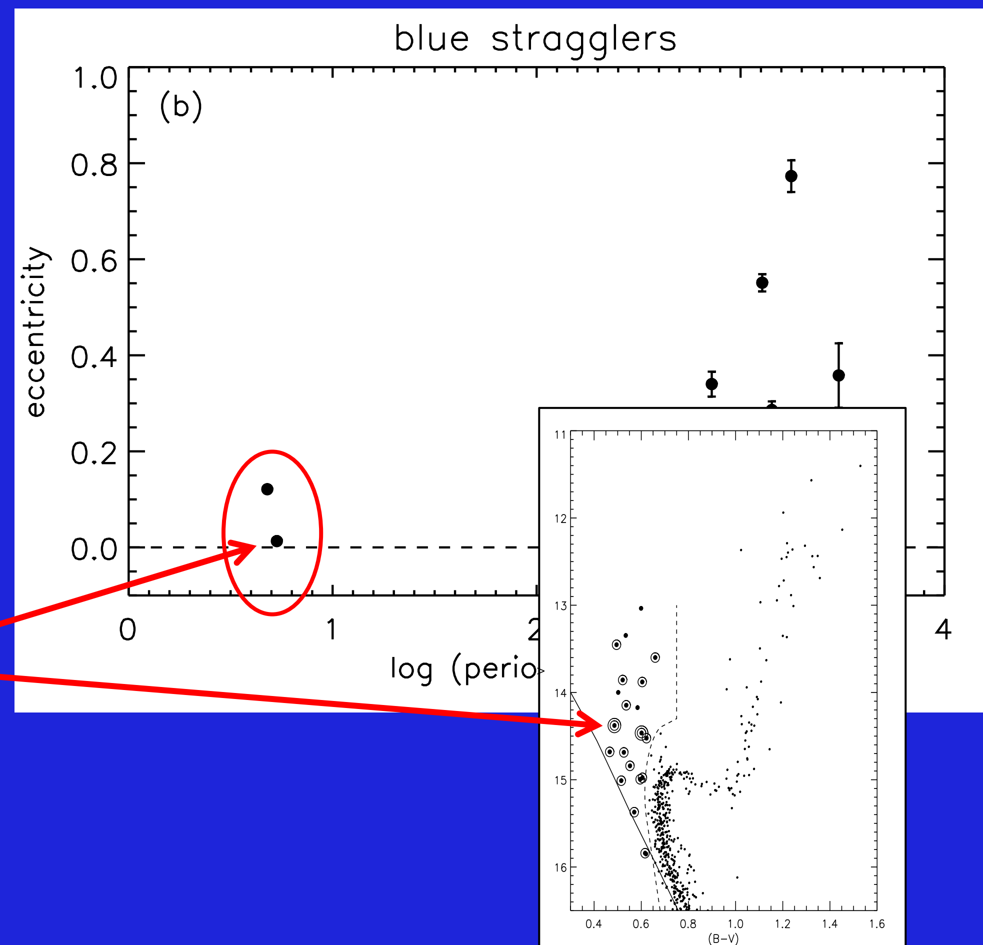
15 long period binaries

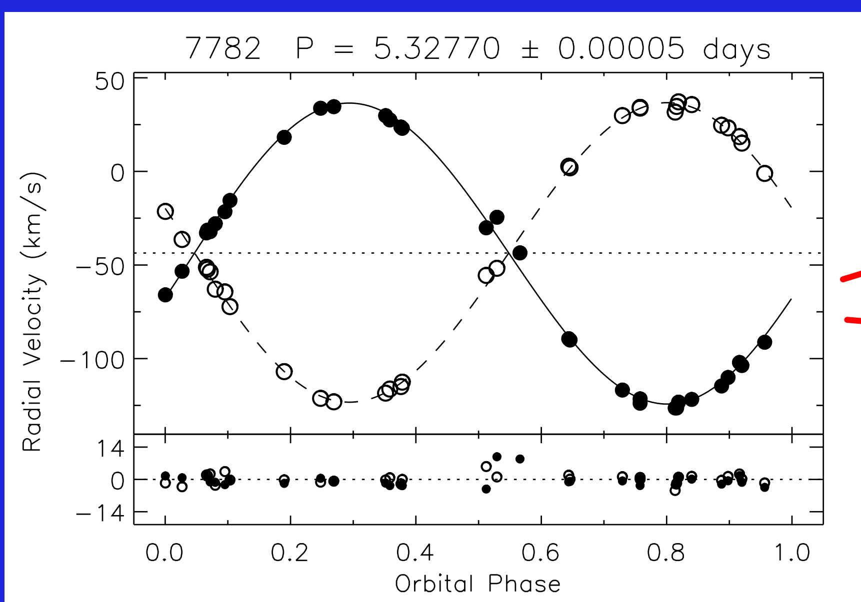
14 formed through mass transfer
~1 formed via Kozai mechanism

Gosnell et al. 2014, 2015

NGC 188 Blue Stragglers – Short Period

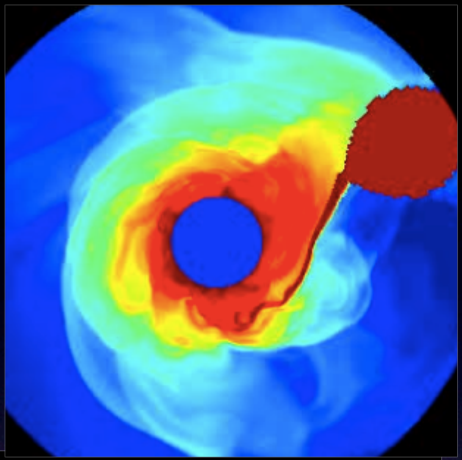
- SB2 => q ~ 1
- Two blue stragglers!
- Must be cluster dynamics and binary exchange involved

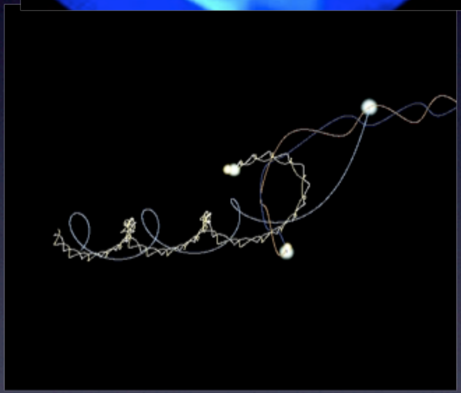


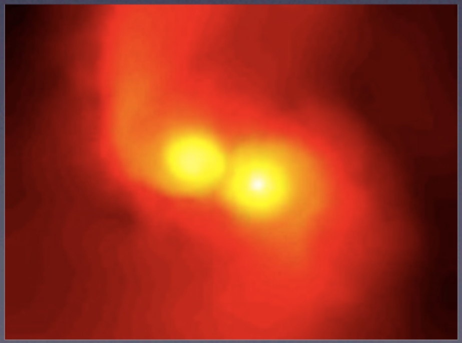


Blue Straggler Formation in NGC 188

Summary







21 blue stragglers:

15 long period binaries

14 formed through mass transfer
~1 formed via Kozai mechanism

2 short-period binaries

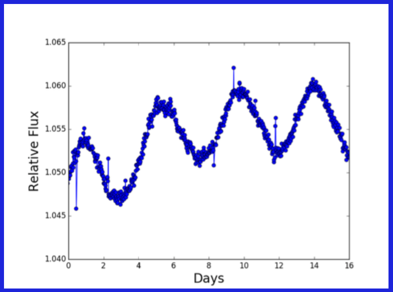
Likely dynamical binary formation
Undetermined BS origin

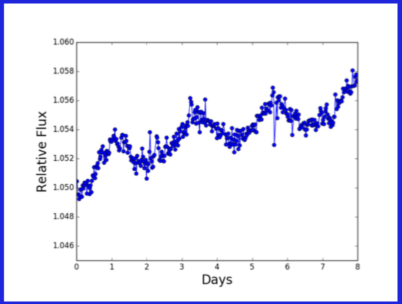
4 non-velocity variable

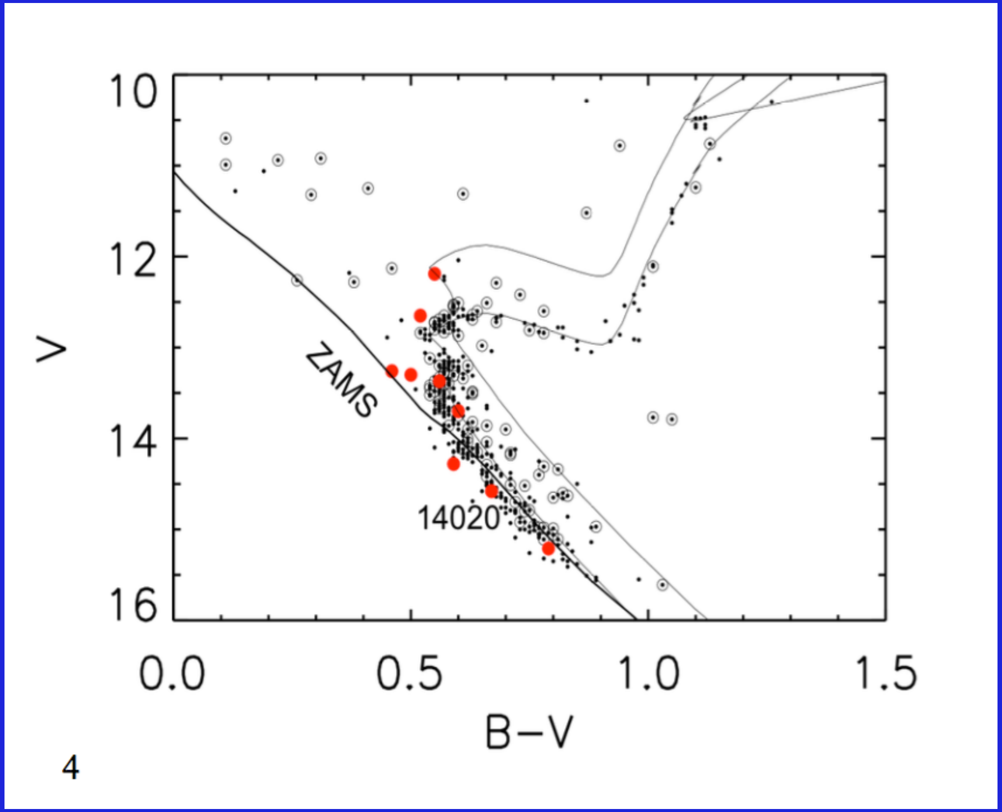
Collisions or mergers

Gosnell et al. 2014, 2015

M67 Blue Stragglers – Main Sequence



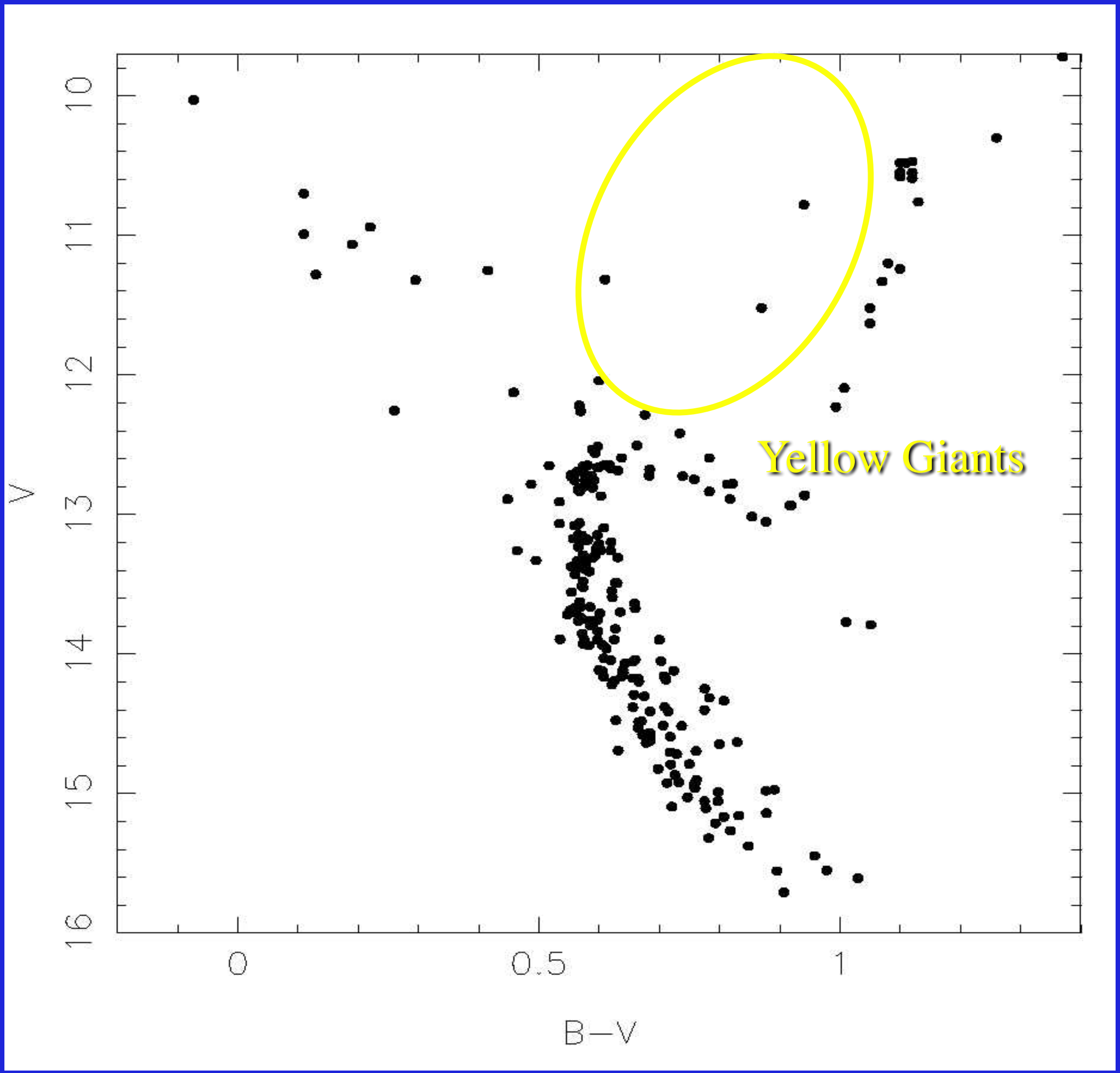




- K2 $P_{rot} < 10$ days
- WOCS $P_{orb} > 500$ days

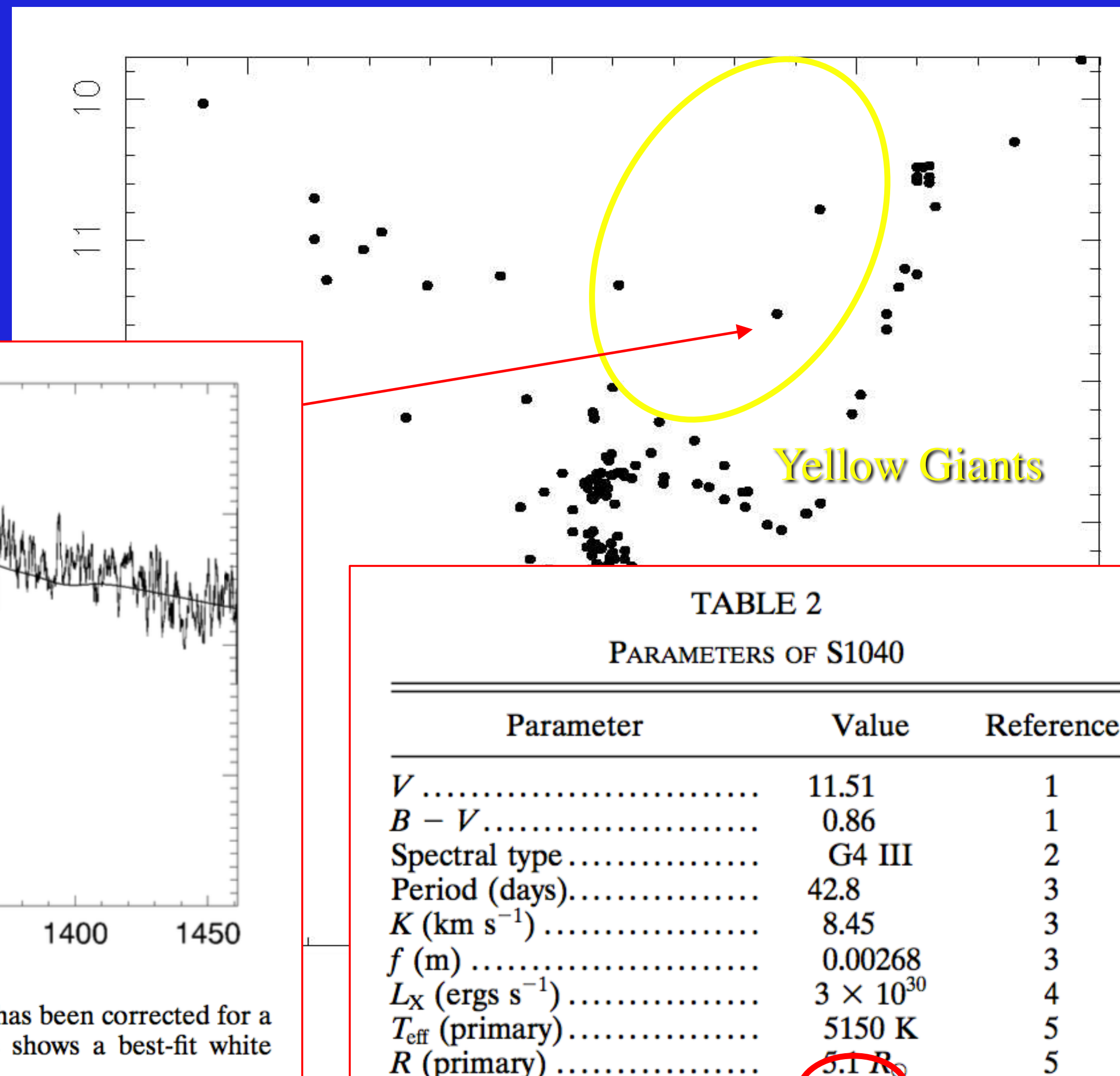
Leiner & Mathieu 2017

Yellow Giants



M67 Yellow Giants

RGB Mass Transfer
Blue Straggler Evolution



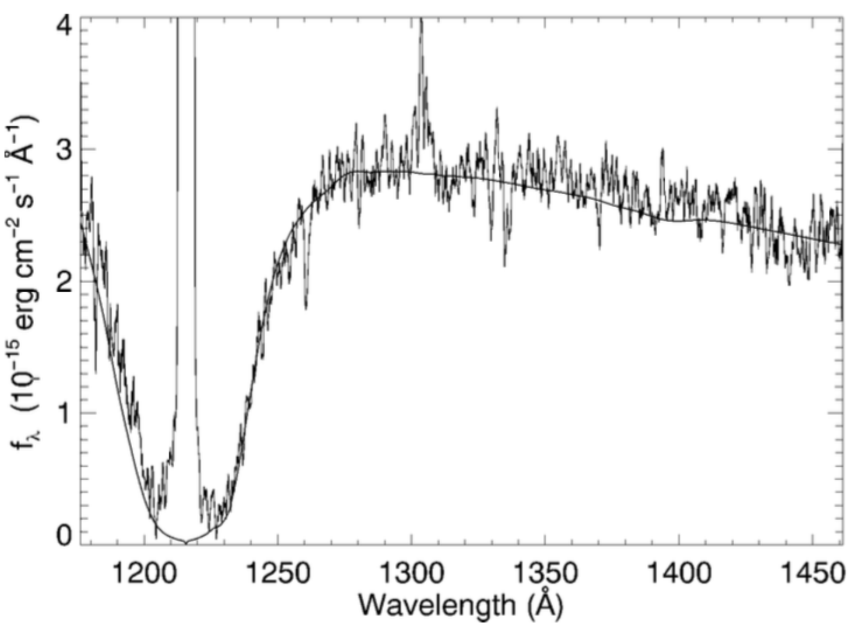


FIG. 1.—GHRS spectrum of S1040. The spectrum has been corrected for a reddening of $E(B-V) = 0.02$. The thick solid line shows a best-fit white dwarf model with $T_{\rm eff} = 16{,}900$ K and $\log g = 7.0$.

TABLE 2

PARAMETERS OF S1040

Parameter	Value	Reference
V	11.51	1
$B-V$	0.86	1
Spectral type	G4 III	2
Period (days)................	42.8	3
K (km s^{-1})	8.45	3
f (m)	0.00268	3
L_X (ergs s^{-1})	3×10^{30}	4
$T_{\rm eff}$ (primary)...............	5150 K	5
R (primary)	5.1 $R_\odot$	5
M (WD)......................	0.22 $M_\odot$	5
$T_{\rm eff}$ (WD)....................	16,160 K	5

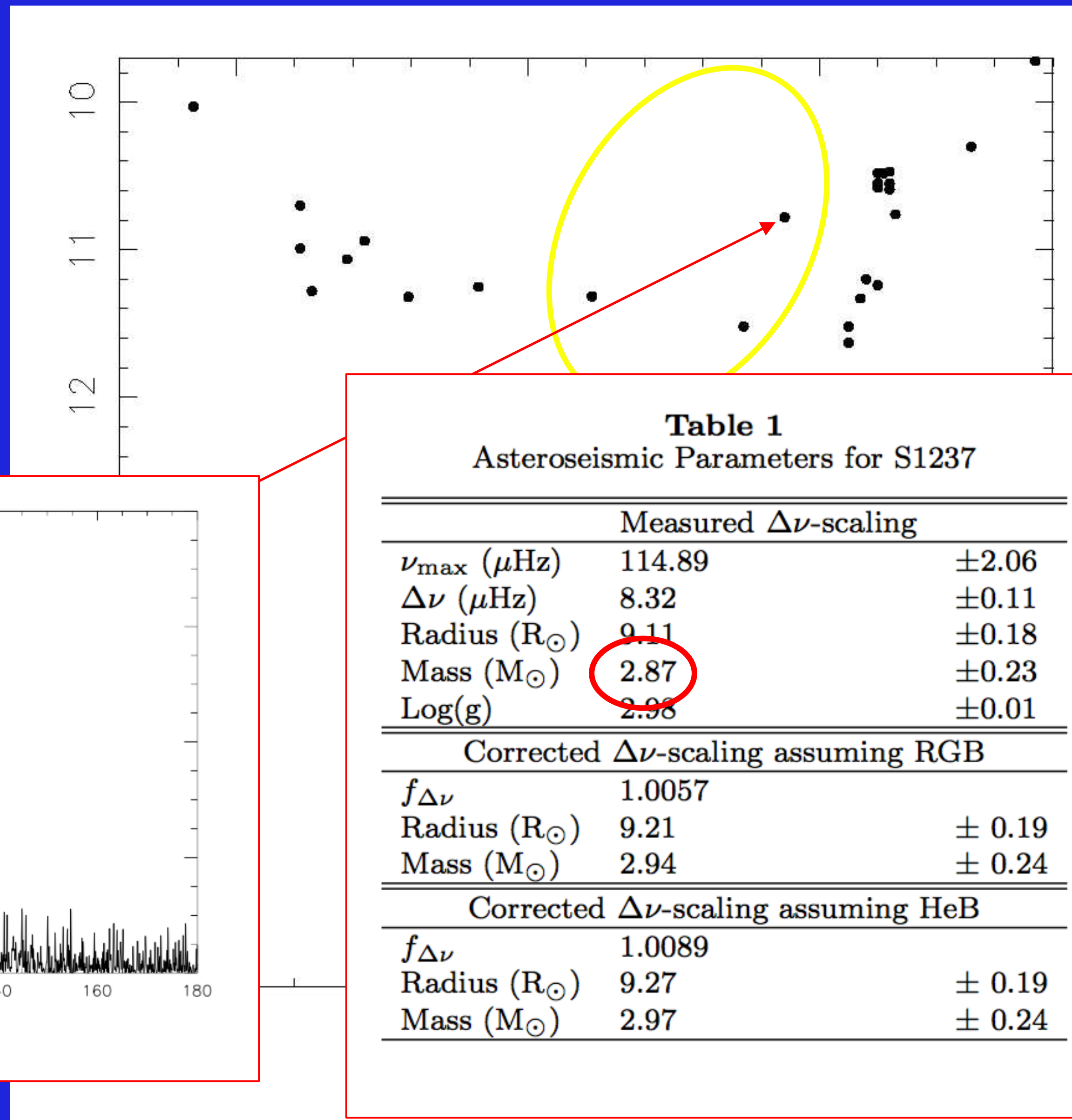
Landsman et al. 1997

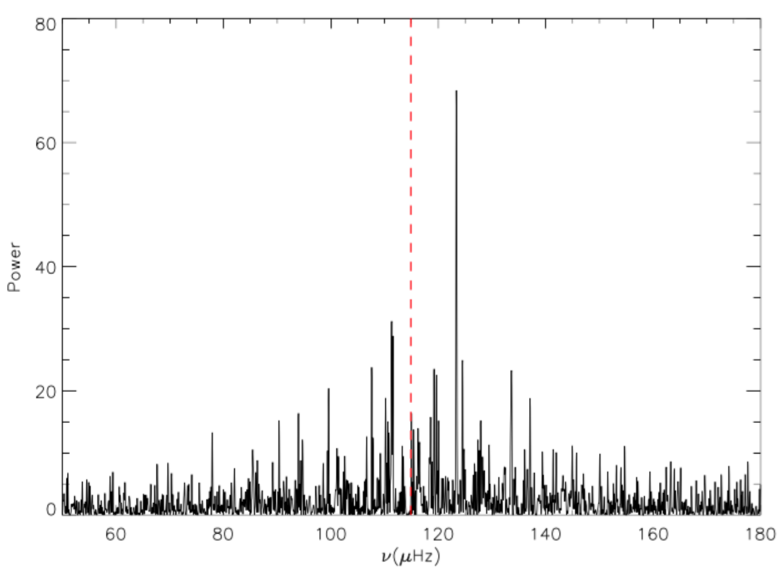
M67 Yellow Giants

M67

4 Gyr

Blue Straggler Evolution





(a)

Table 1
Asteroseismic Parameters for S1237

	Measured $\Delta\nu$-scaling	
ν_{max} (μHz)	114.89	$\pm$2.06
$\Delta\nu$ (μHz)	8.32	$\pm$0.11
Radius ($R_\odot$)	9.11	$\pm$0.18
Mass ($M_\odot$)	2.87	$\pm$0.23
Log(g)	2.98	$\pm$0.01
	Corrected $\Delta\nu$-scaling assuming RGB	
$f_{\Delta\nu}$	1.0057	
Radius ($R_\odot$)	9.21	$\pm$ 0.19
Mass ($M_\odot$)	2.94	$\pm$ 0.24
	Corrected $\Delta\nu$-scaling assuming HeB	
$f_{\Delta\nu}$	1.0089	
Radius ($R_\odot$)	9.27	$\pm$ 0.19
Mass ($M_\odot$)	2.97	$\pm$ 0.24

Leiner et al. 2016

NGC 188 Yellow Giants

NGC 188

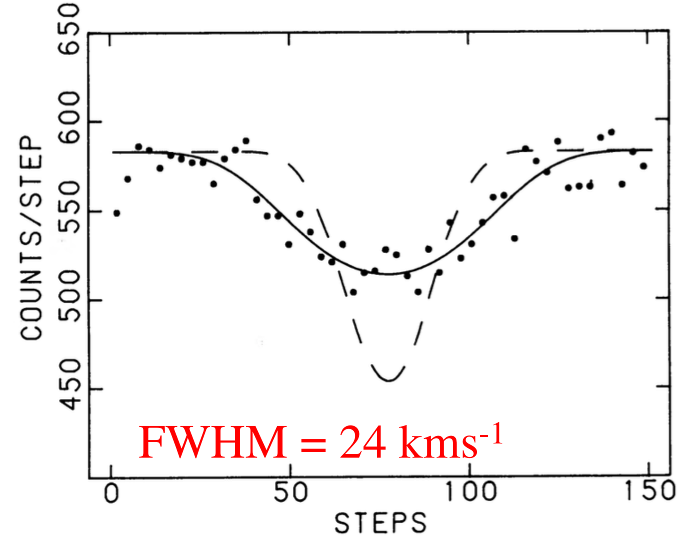
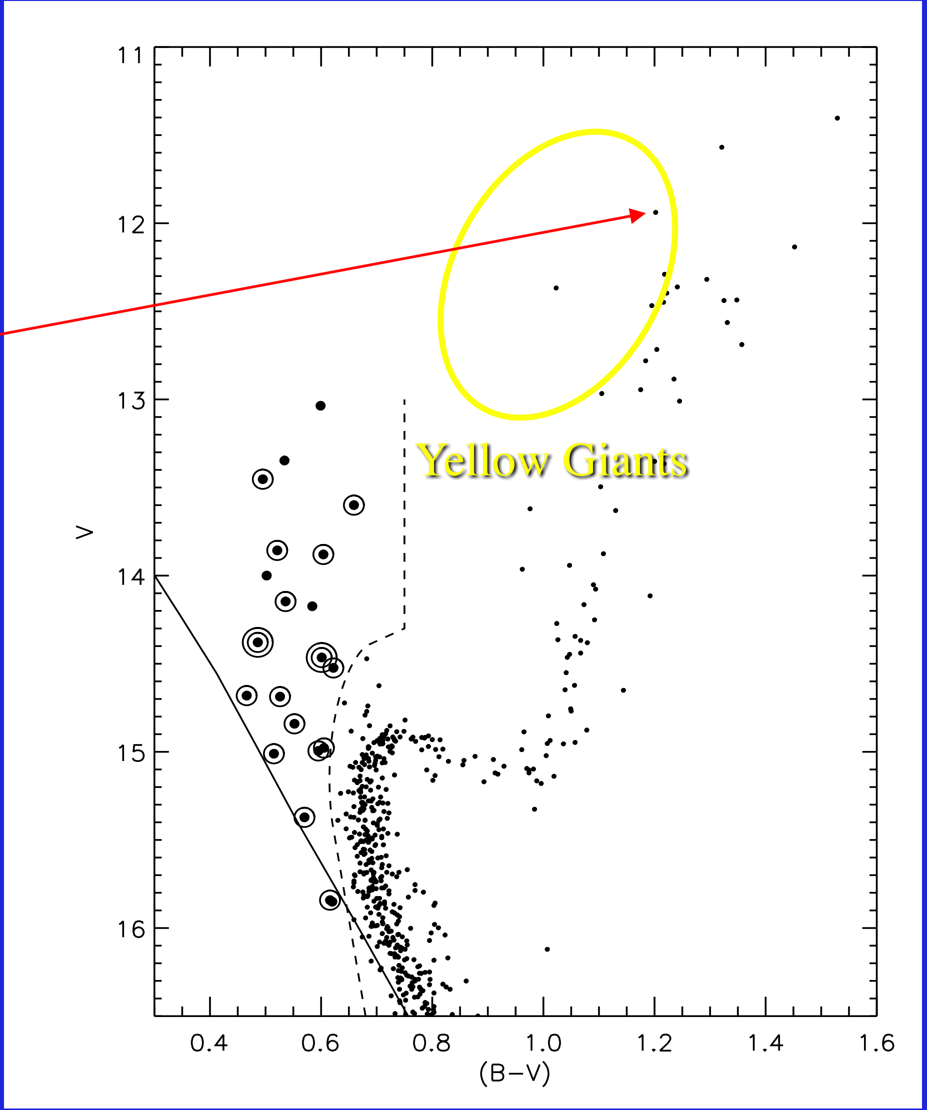


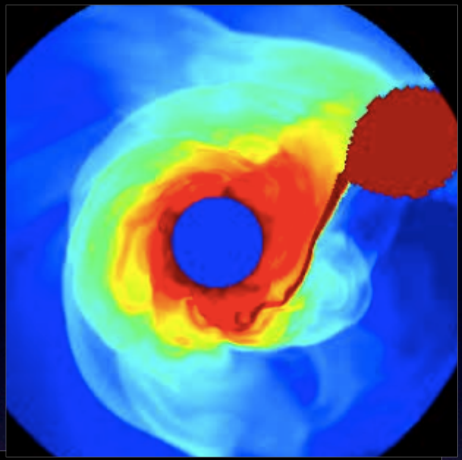
FIG. 1—The cross-correlation profile of I-1 observed on 1982 August 20. The data are binned into three steps per point, each step corresponds to 0.6 km s^{-1}. The solid line shows the least-squares fit to the data. The dashed line shows the profile for the sharp-lined star γ Aql.

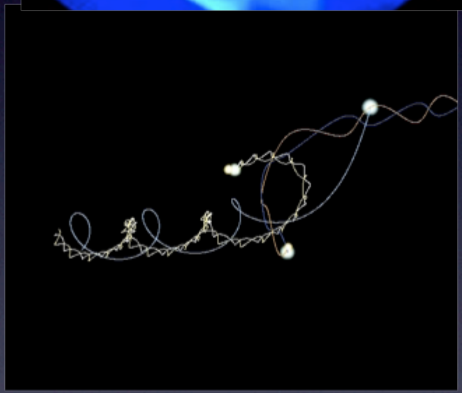


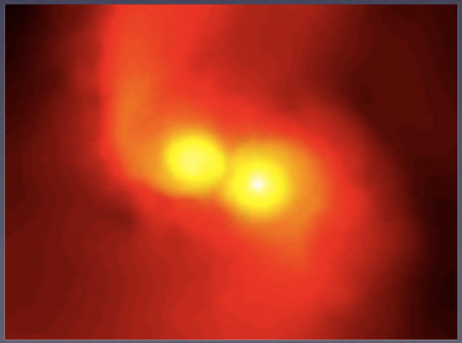
Harris & McClure 1985

Blue Straggler Evolution or Merger ?

Yellow Giant Formation

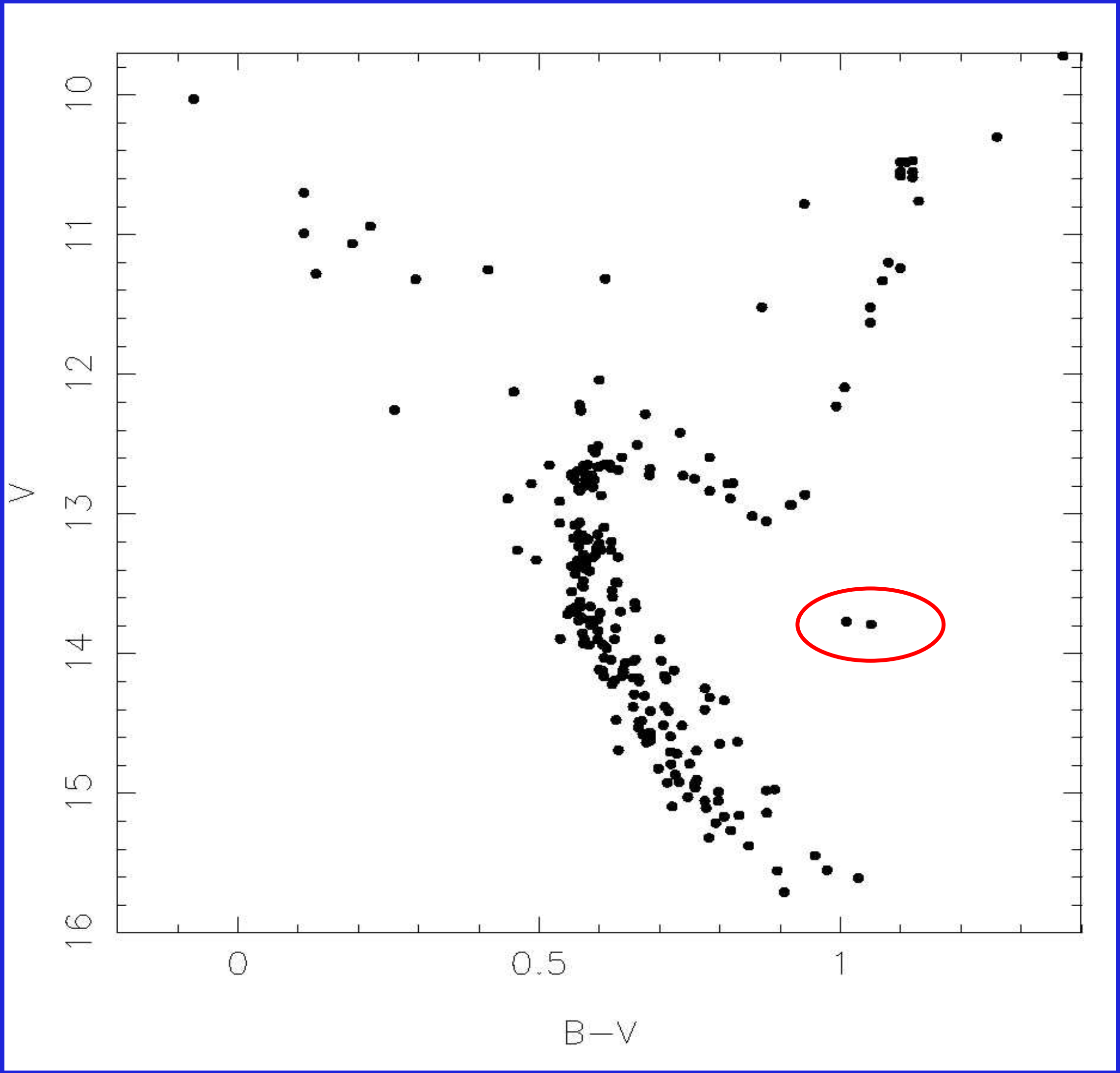




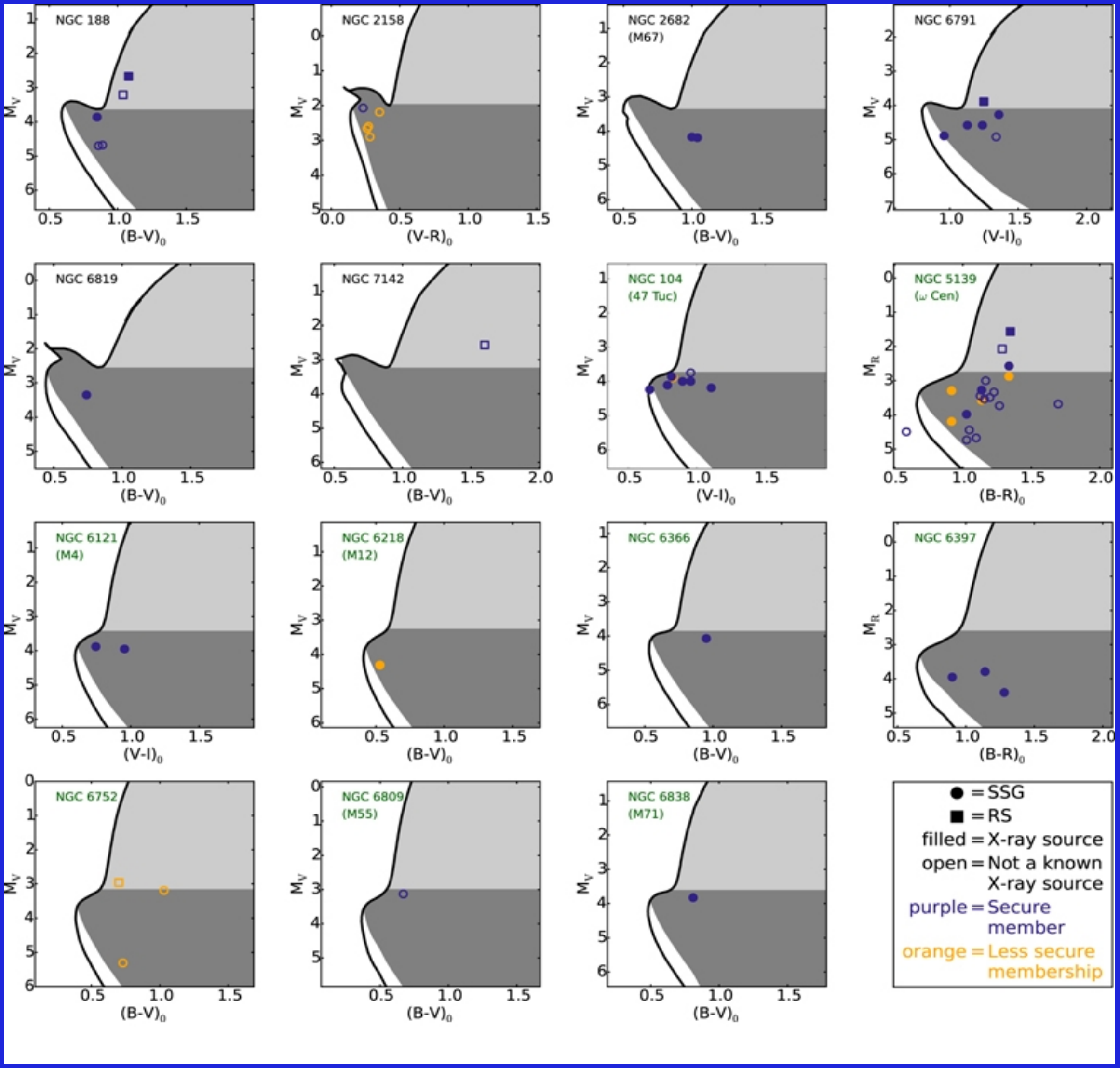


Blue Straggler Evolution

Sub-Subgiants



Sub-Subgiants

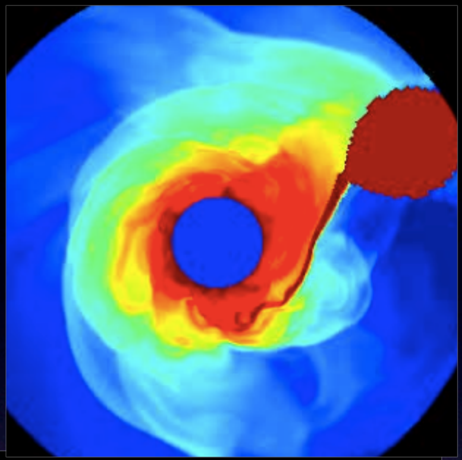


- > 50% $L_x \approx 10^{30\text{-}31}$
- > 33% Hα emission
- > 67% Photometric variables with P < 15^d
- > 50% RV variable
- 73% Short-period binaries in open clusters
- Highest specific frequency in open clusters

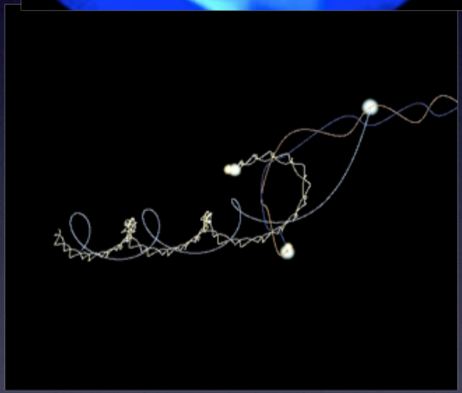
56 Sub-Subgiants (and 8 Red Stragglers)

Geller et al. 2017a

Sub-Subgiant Formation Scenarios



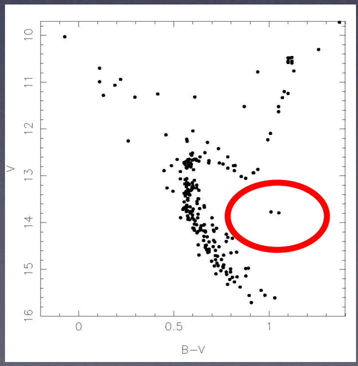
1. Subgiant mass transfer



2. Envelope stripping (during dynamical encounter or common envelope?)

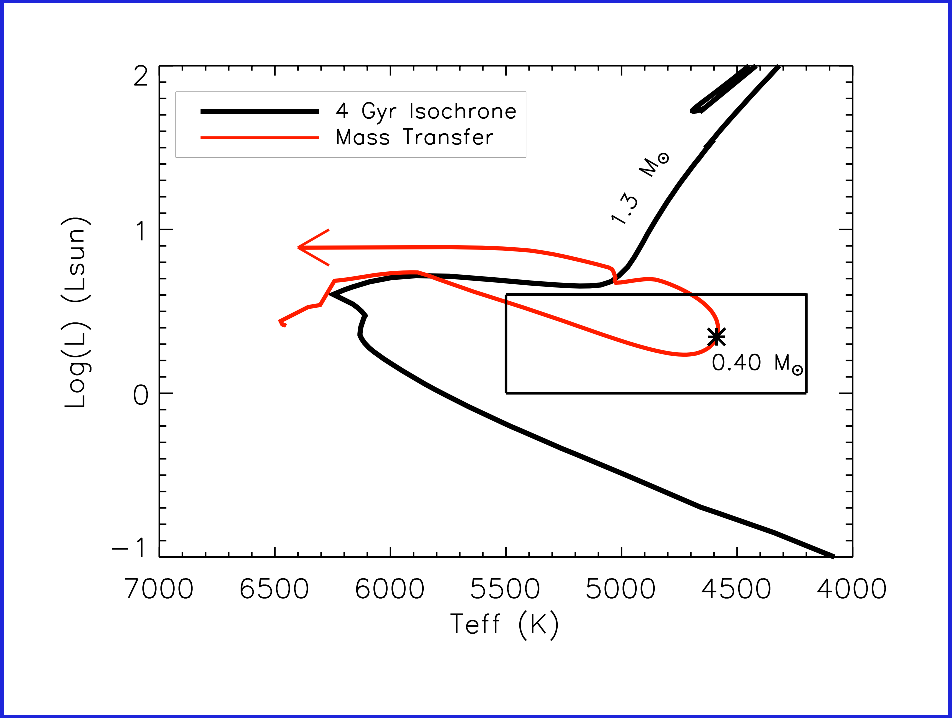
3. Suppression of convection by strong magnetic fields

Leiner, Mathieu and Geller 2017

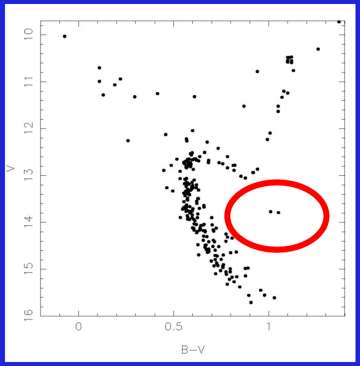


Sub-Subgiant Formation Scenarios

1. Binary mass transfer on the subgiant branch

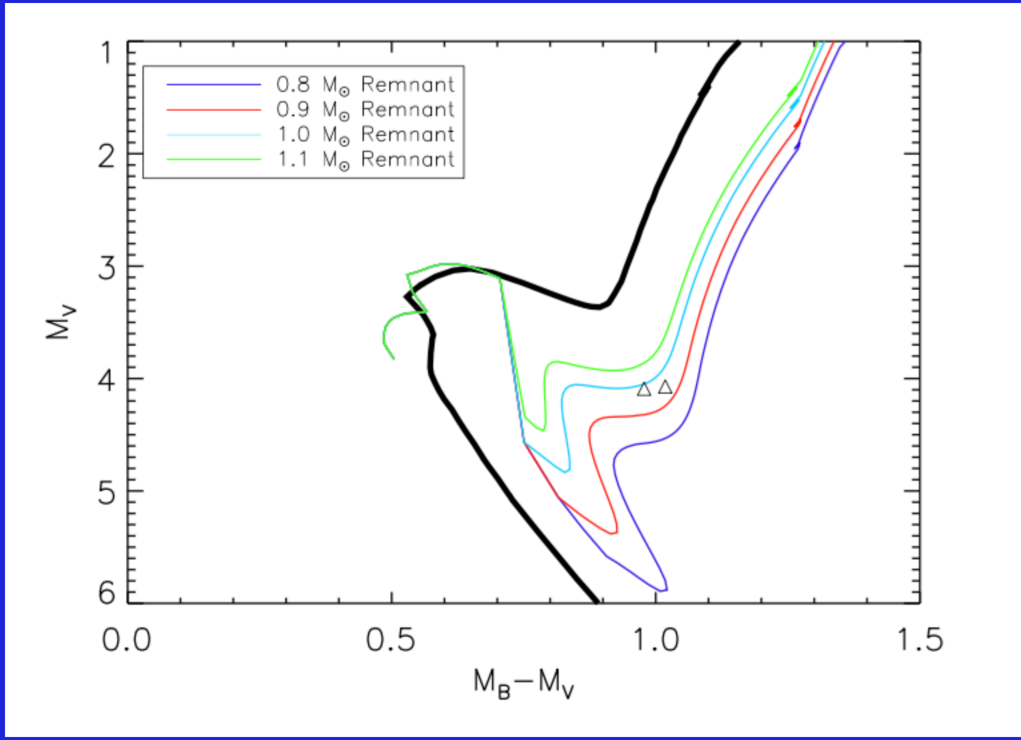


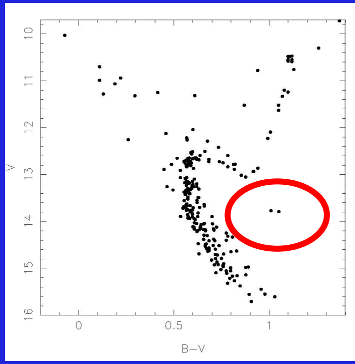
But orbital periods are too short (P < 1^d) …
And often accretor outshines donor …



Sub-Subgiant Formation Scenarios

2. Envelope stripping, e.g. during dynamical encounter



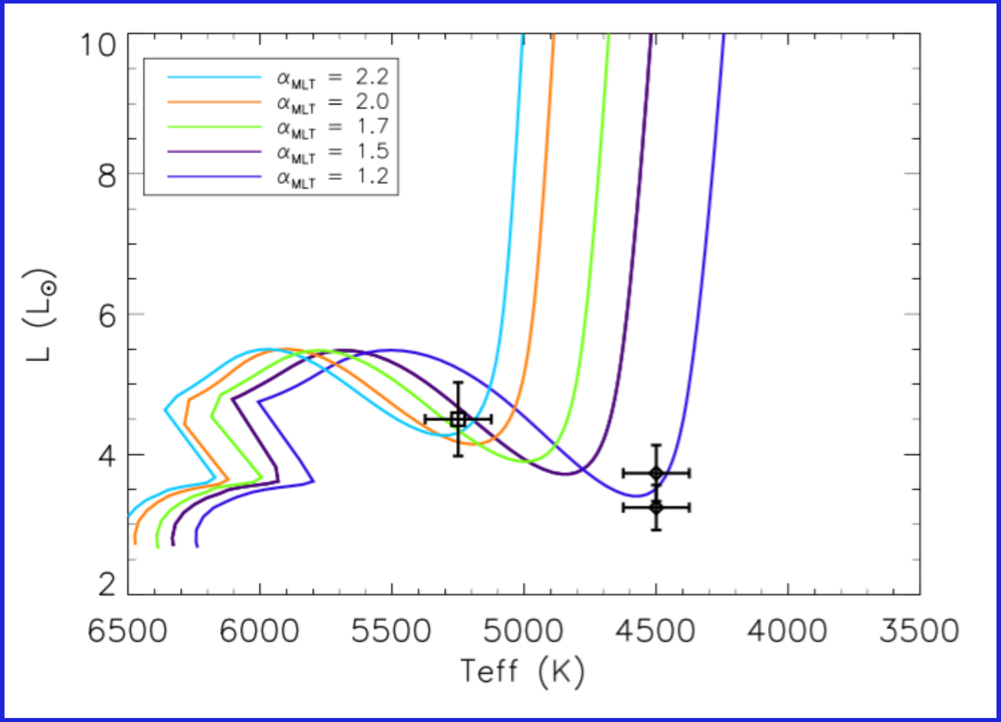


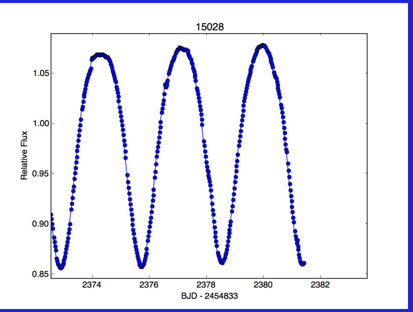
But encounter frequency is too low …

(… in open clusters; see Geller et al. 2017b, Ivanova et al. 2017)

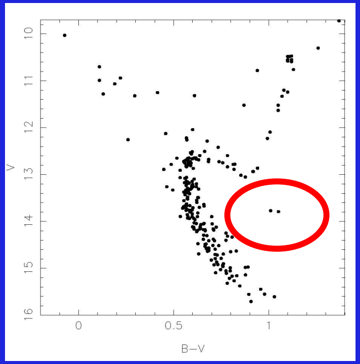
Sub-Subgiant Formation Scenarios

3. Magnetic suppression of convection (tidal-driven rapid rotation)



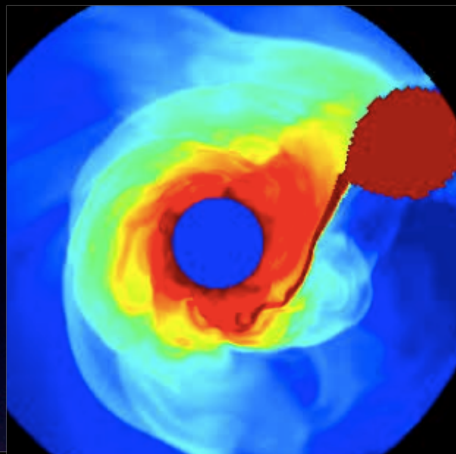


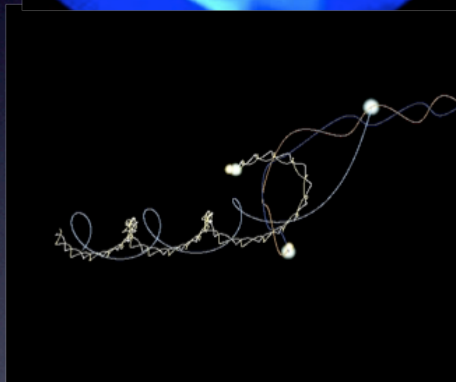
K2 $P_{rot} = 2.8^d$

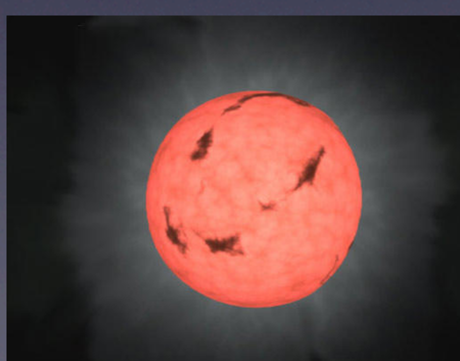


Frequency OK; but physics is not done …

Sub-Subgiant Formation Scenarios







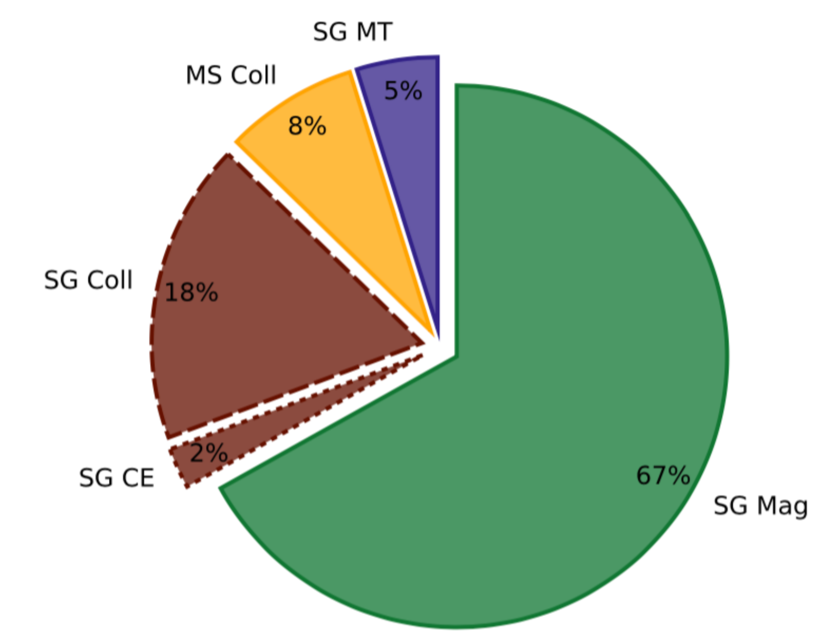
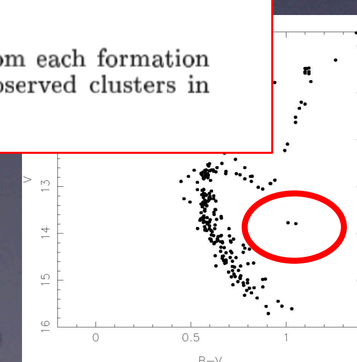


FIG. 3.— Percent of total SSGs predicted from each formation mechanism (see Sections 2 and 3) in all the observed clusters in Table 1.



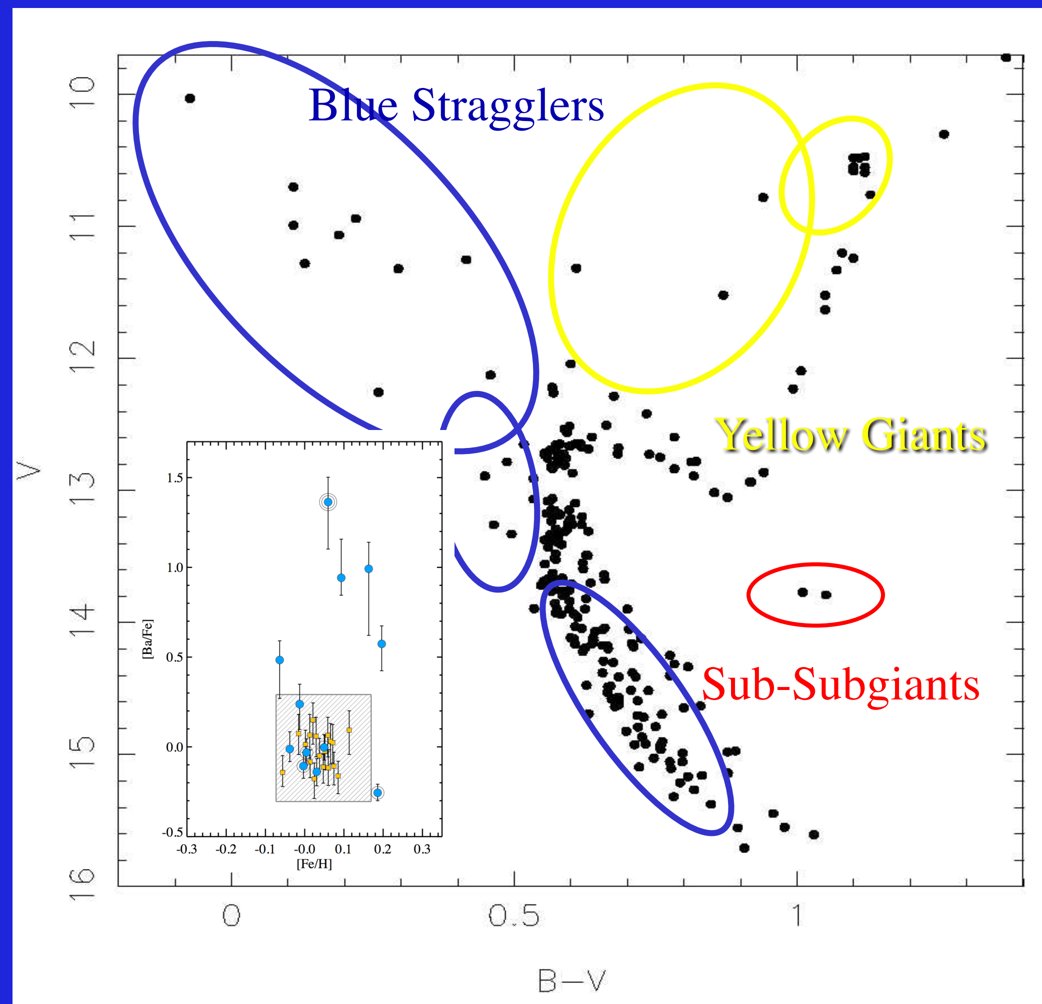
Geller et al. 2017b

The Next Play

Tying It All Together

Accretion on MS Stars in Binaries

+ Barium Stars
+ Carbon Stars
+ CEMP-s
+ post-AGB
+ PN cores
+ ?

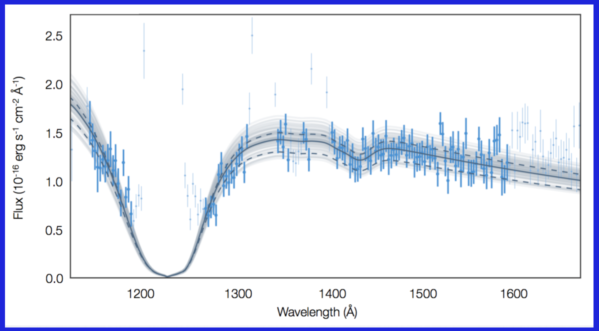


The Next Play

Detailed Modeling

For NGC 188 blue stragglers, we know …

HST COS spectrum



Progenitor donor mass
Progenitor core mass and evolutionary state
Progenitor donor radius
Roche lobe => Progenitor orbit (f (a,e,q))
Progenitor accretor mass < turnoff mass
Progenitor accretor mass > BS mass – Donor mass

Final orbit (p,e,q)
Final accretor luminosity and effective temperature
Final WD mass and temperature
Formation time

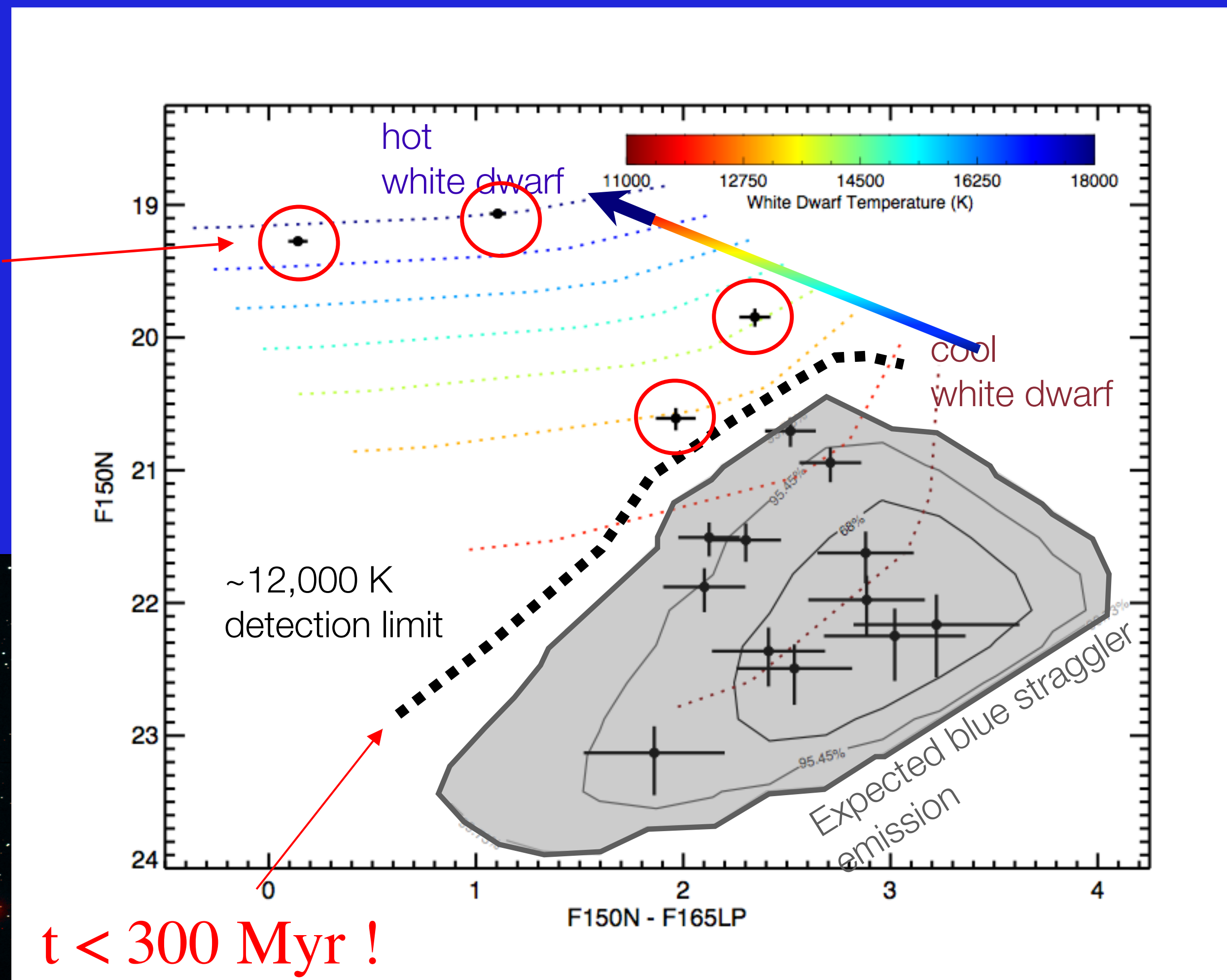
Gosnell, Leiner et al. 2017

The Next Play

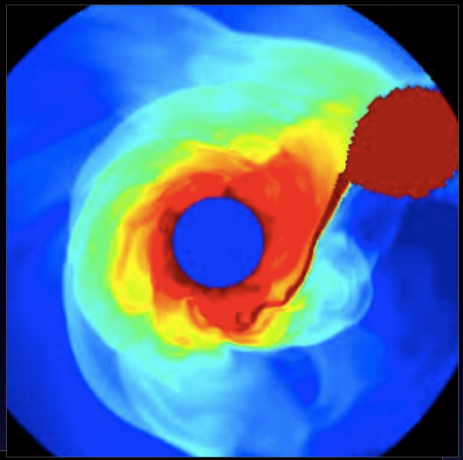
Angular Momentum

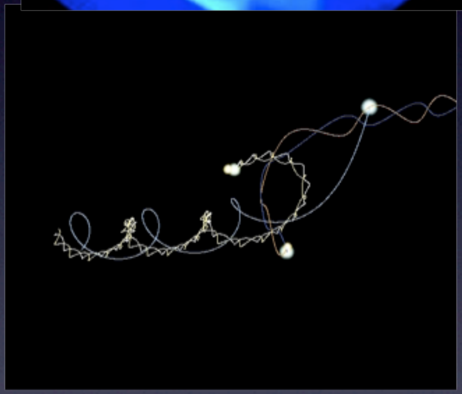
Most rapidly rotating

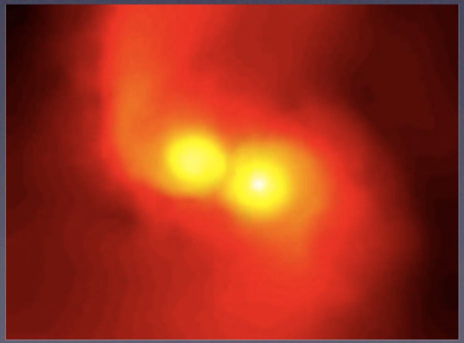
Pollack, Leiner et al. 2018

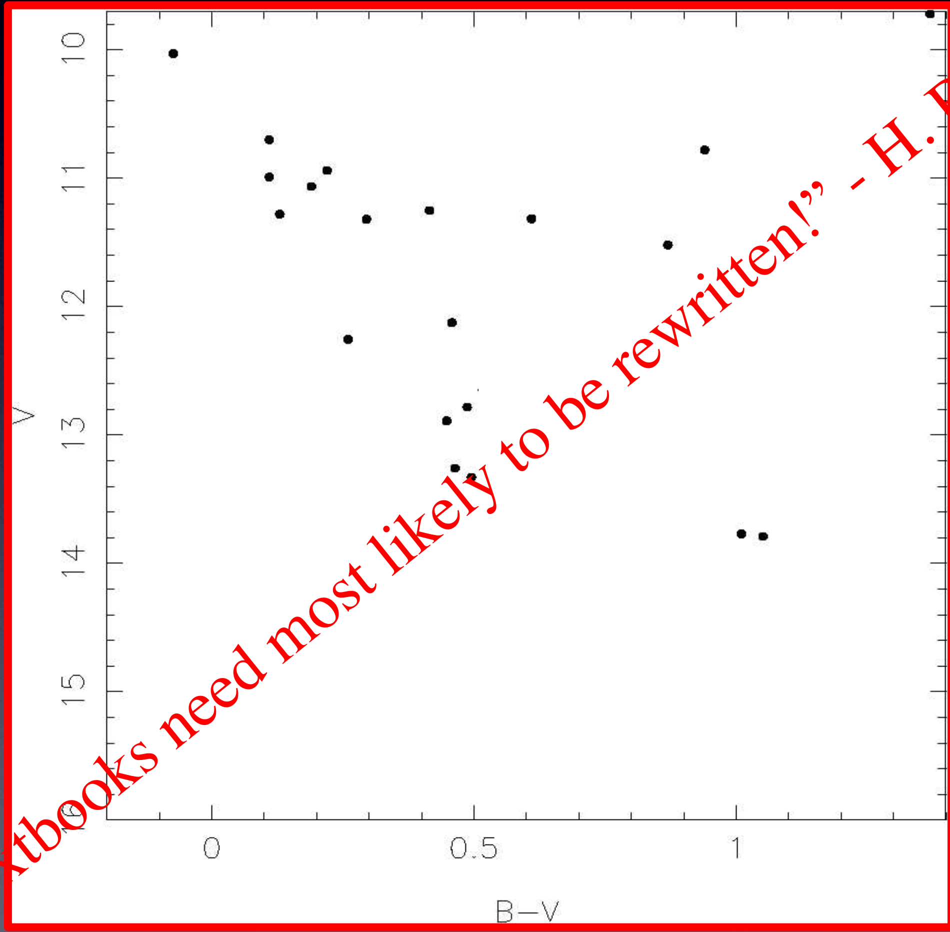


This too is normal stellar evolution!



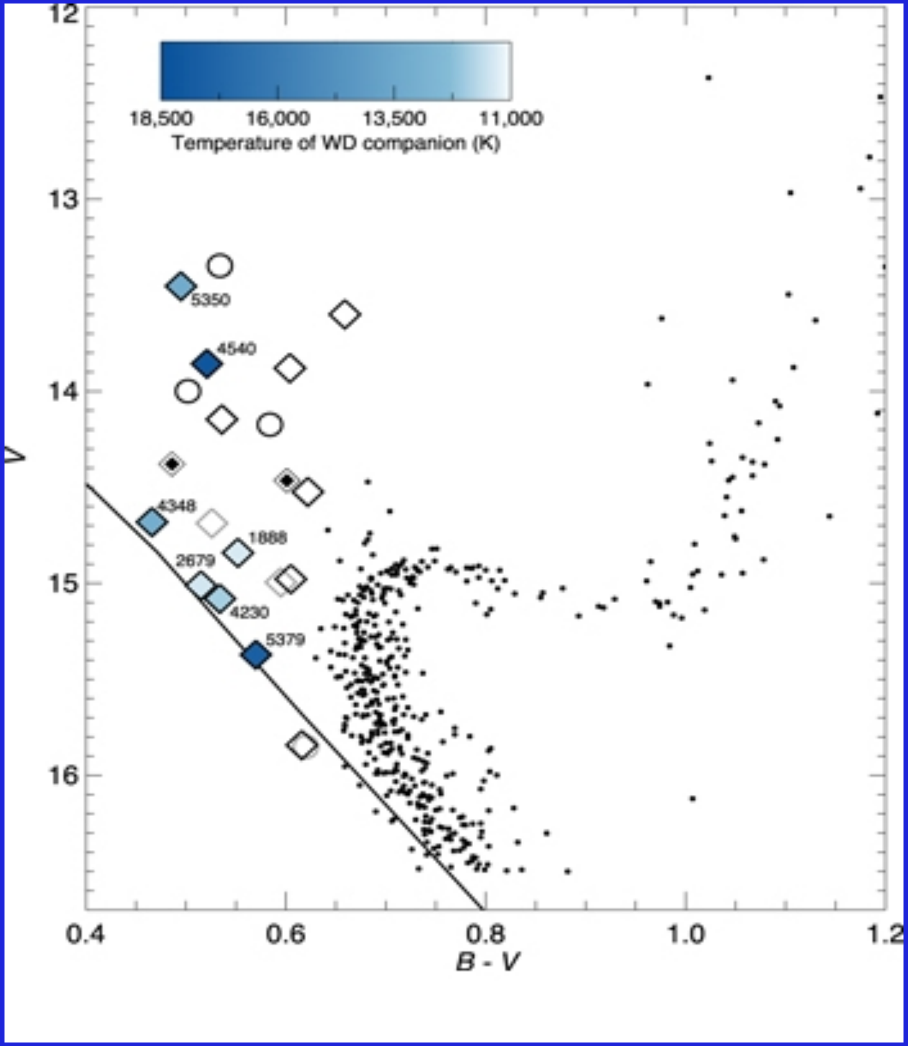




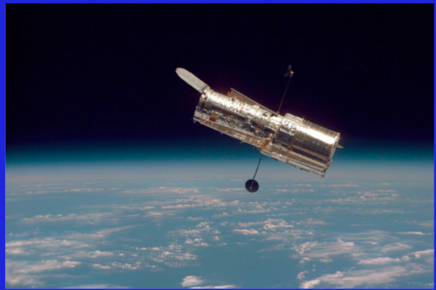


“Textbooks need most likely to be rewritten!” - H. Boffin

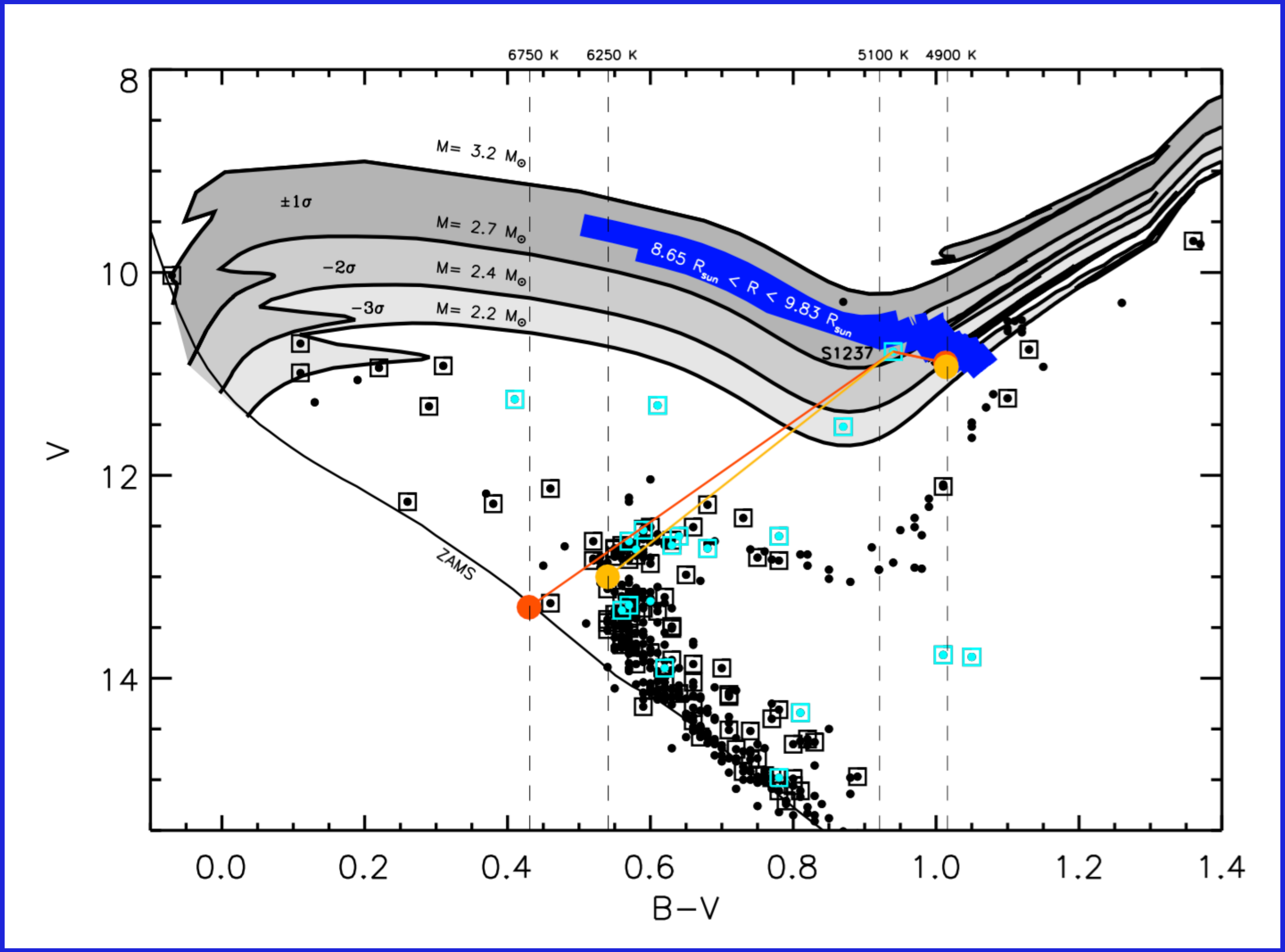
NGC 188 Blue Stragglers – Long Period

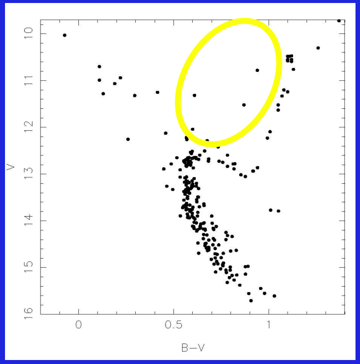


Gosnell et al. 2015



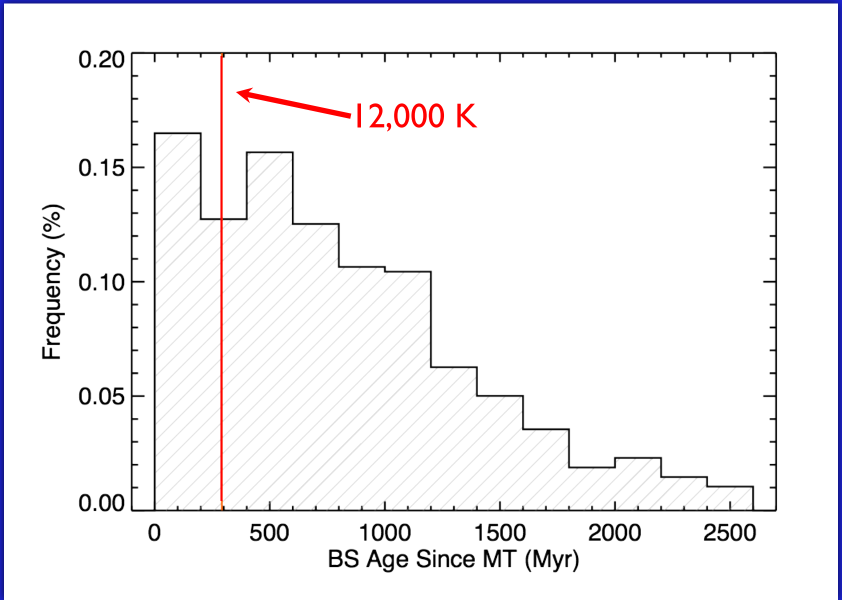
M67 Yellow Giants

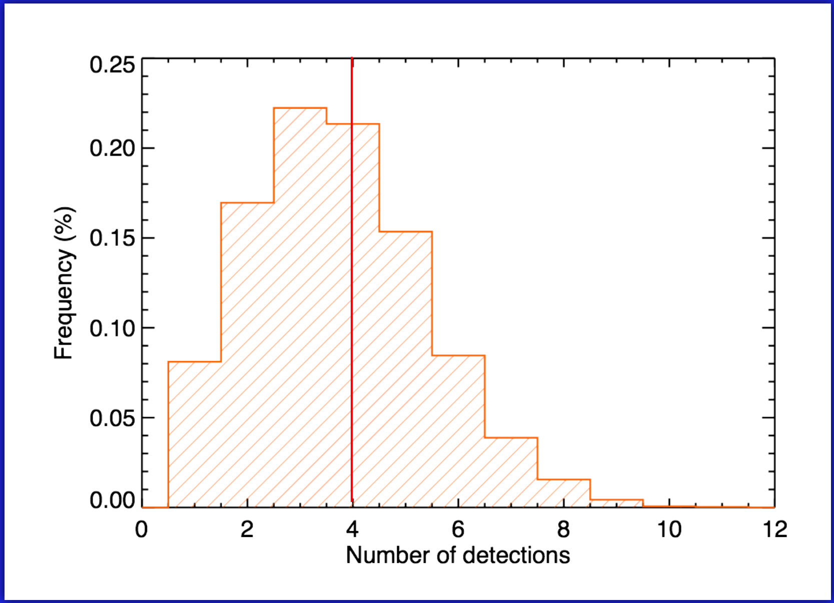




Blue Straggler Evolution

NGC 188 Blue Stragglers – Long Period

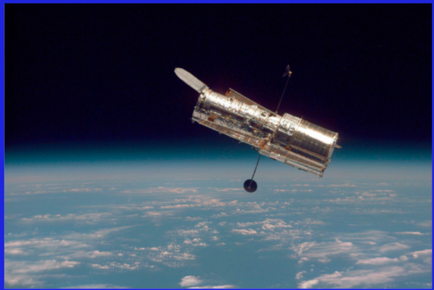




Age distribution of mass transfer-formed blue stragglers from *N*-body model of NGC 188

Monte Carlo sampling of WD age distribution

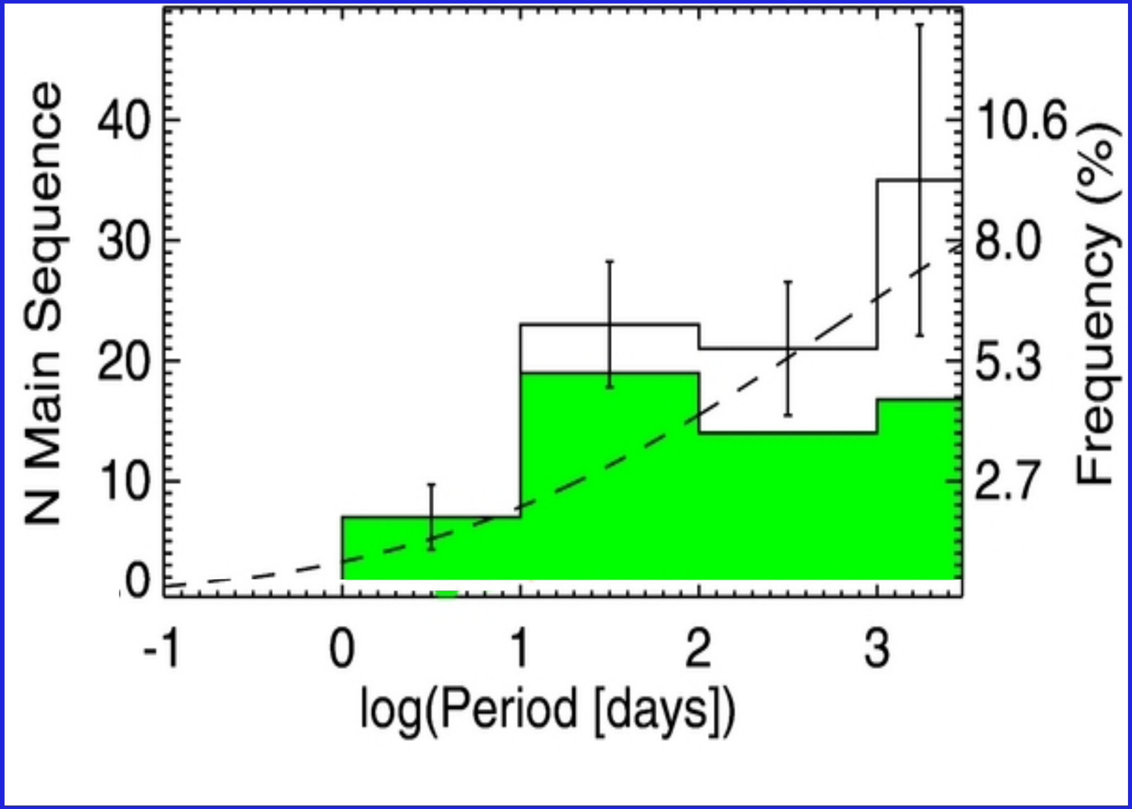
Gosnell et al. 2014, 2015

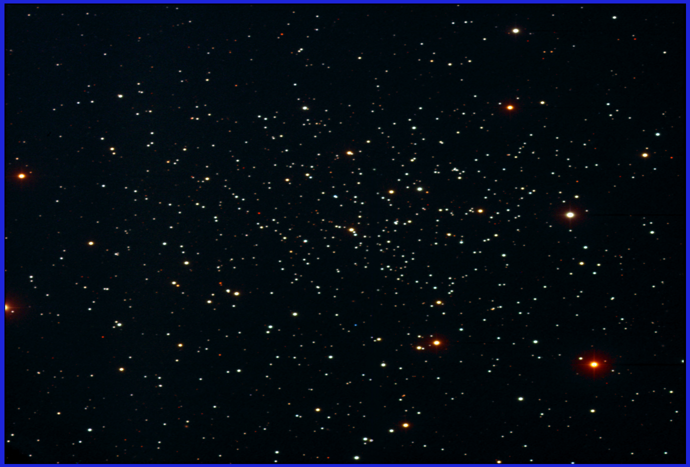


Period Distribution

NGC 188

7 Gyr



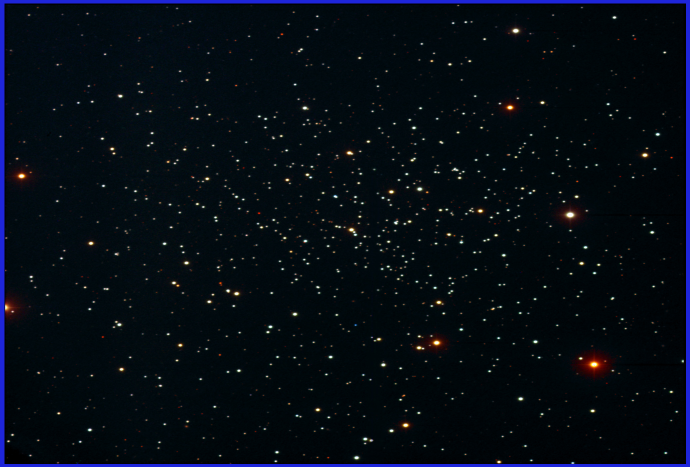


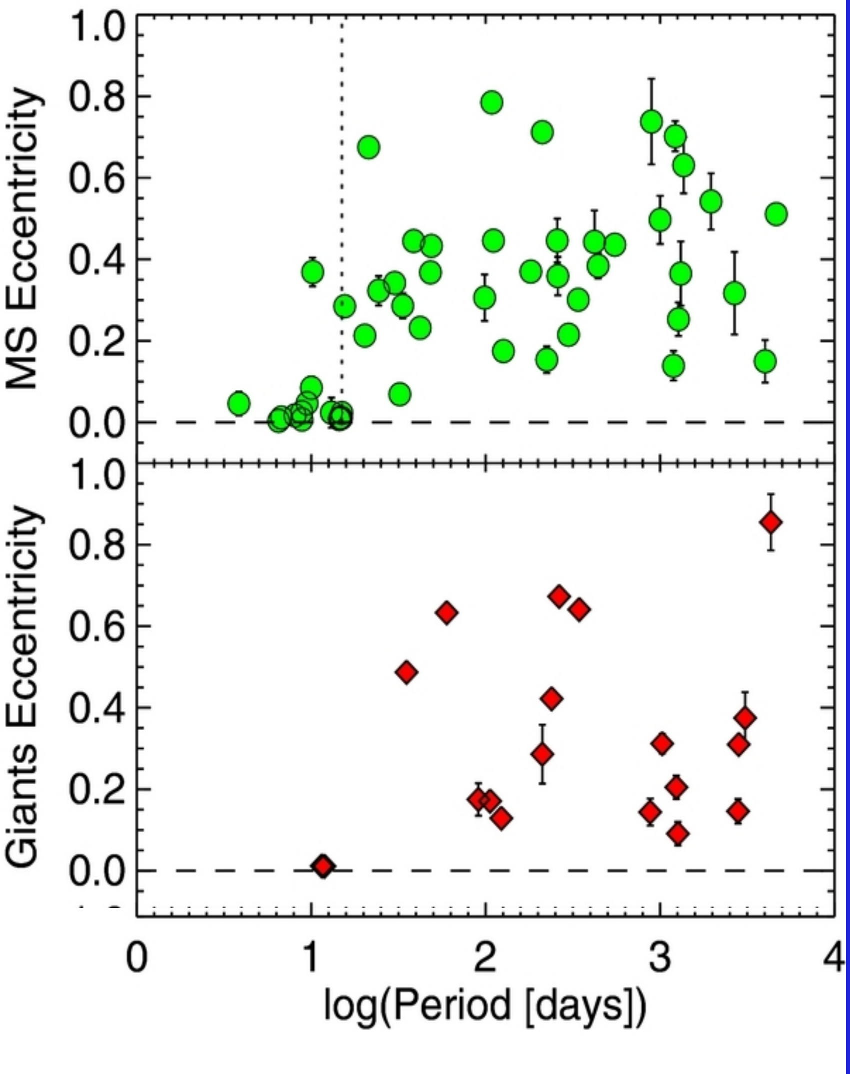
Geller & Mathieu 2012

Eccentricity Distribution

NGC 188

7 Gyr

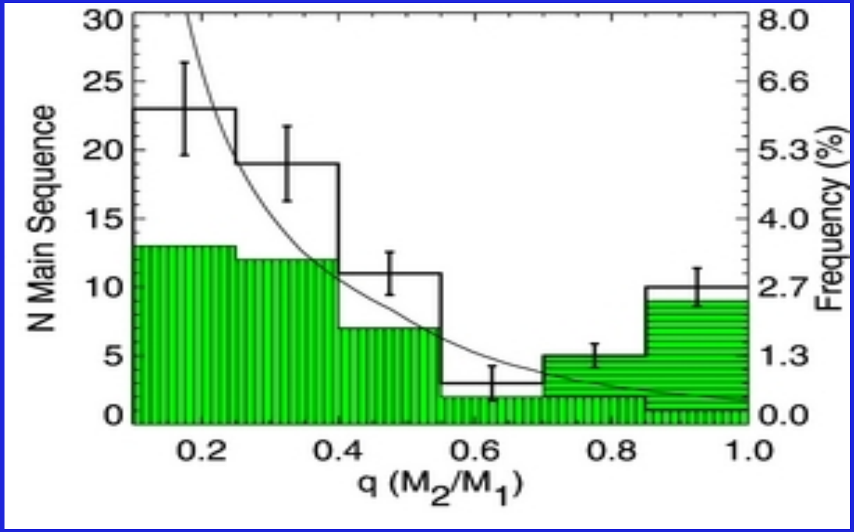


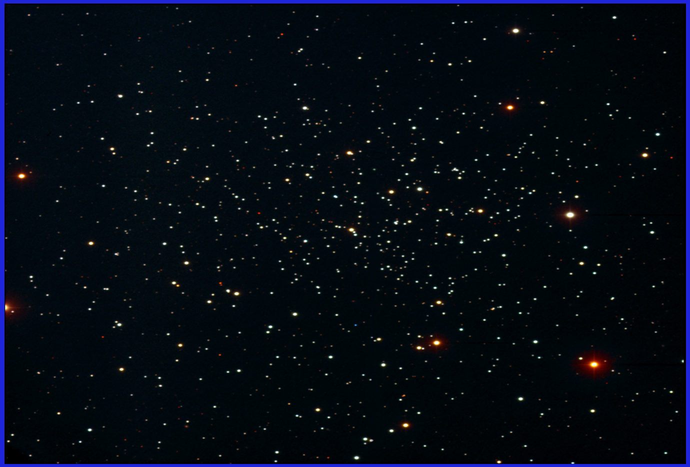


Secondary Mass Distribution

NGC 188

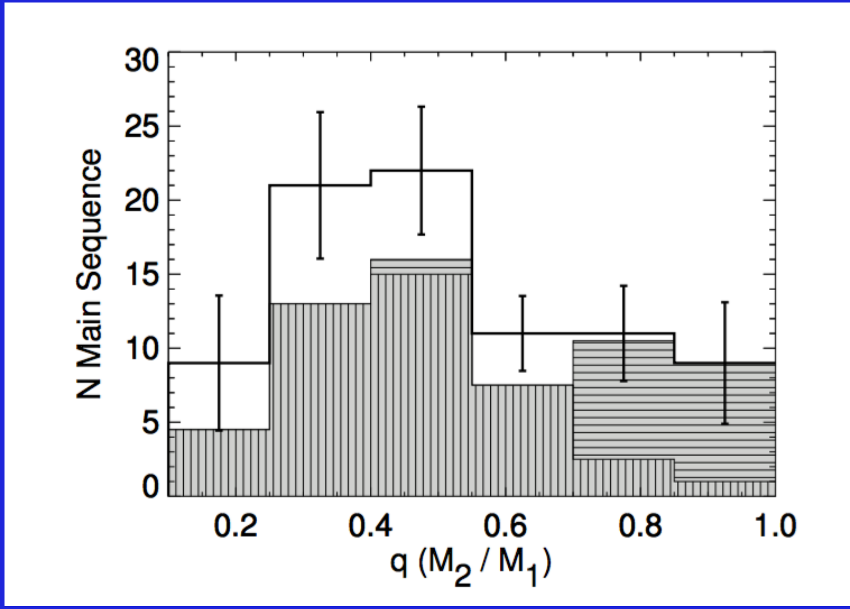
7 Gyr



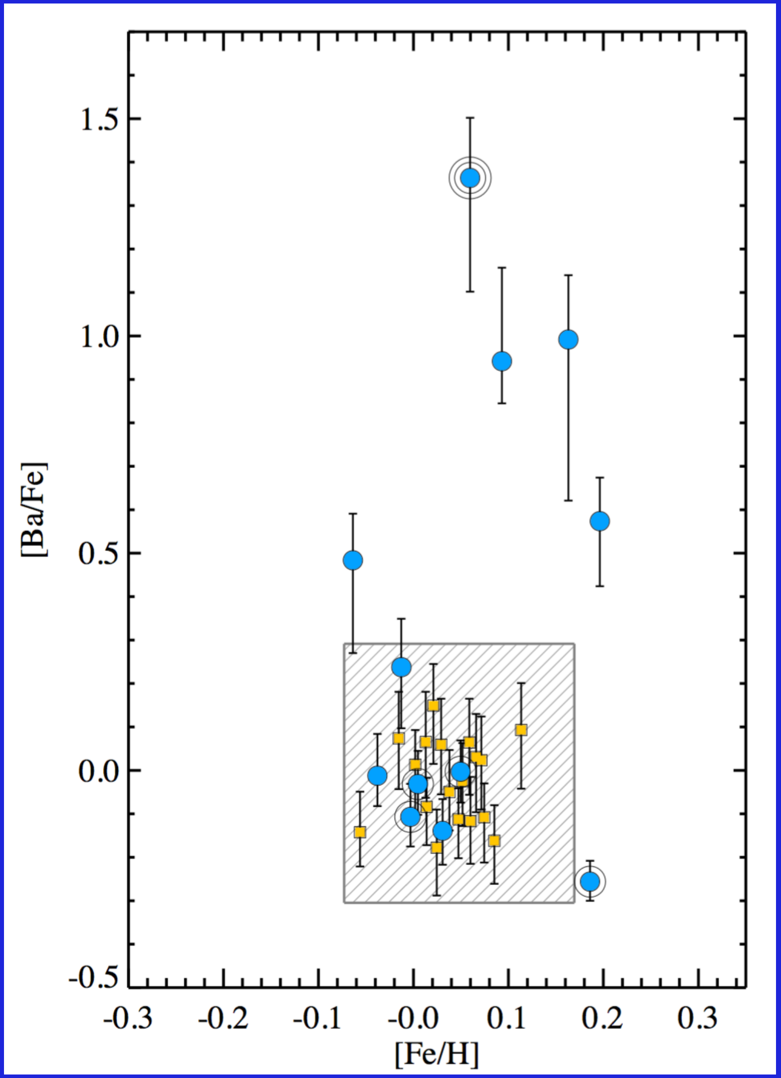


M67

4 Gyr



NGC 6819 Blue Stragglers



Milliman et al. 2015