Open Clusters: Open Windows on Stellar Dynamics

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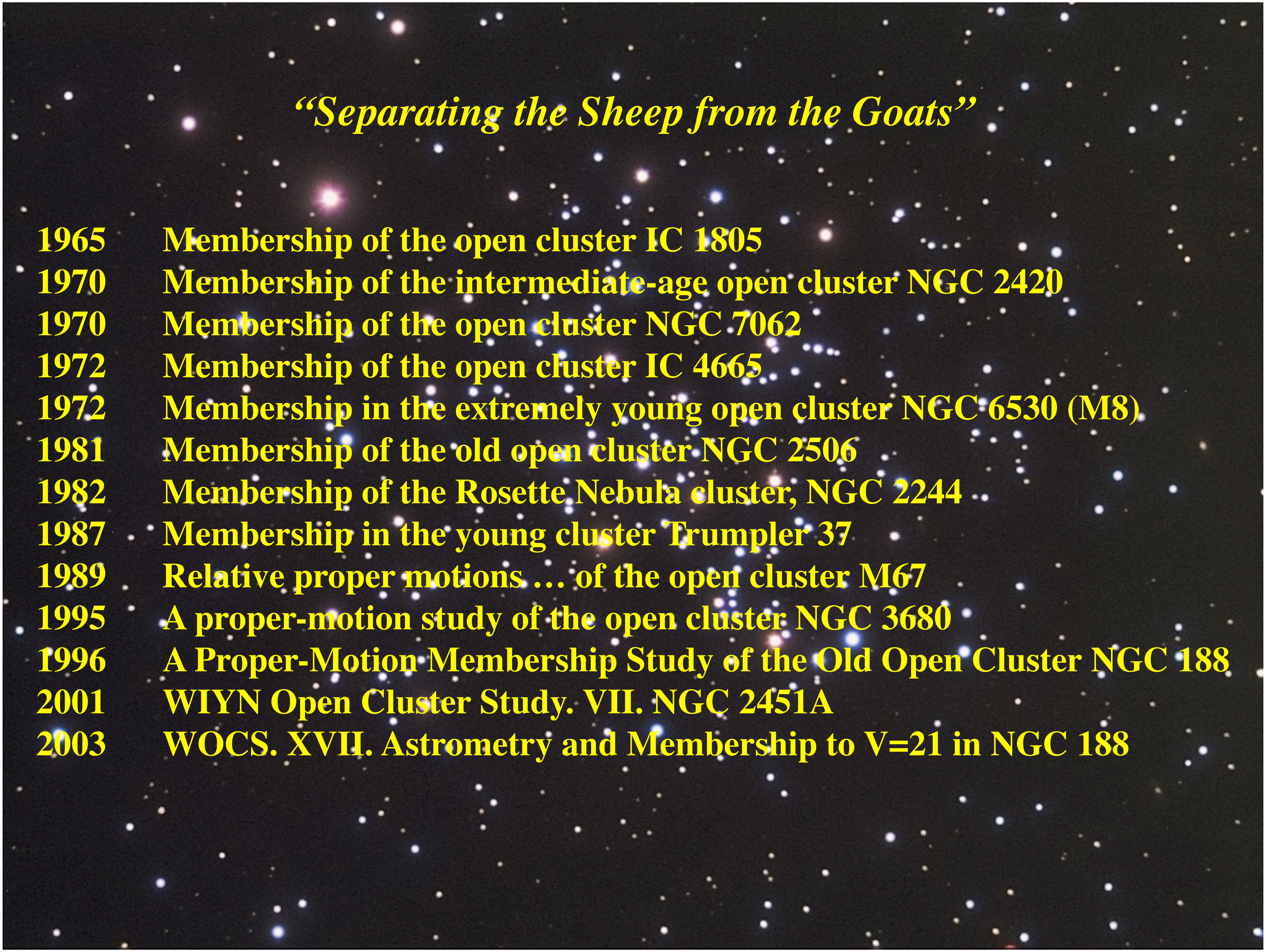
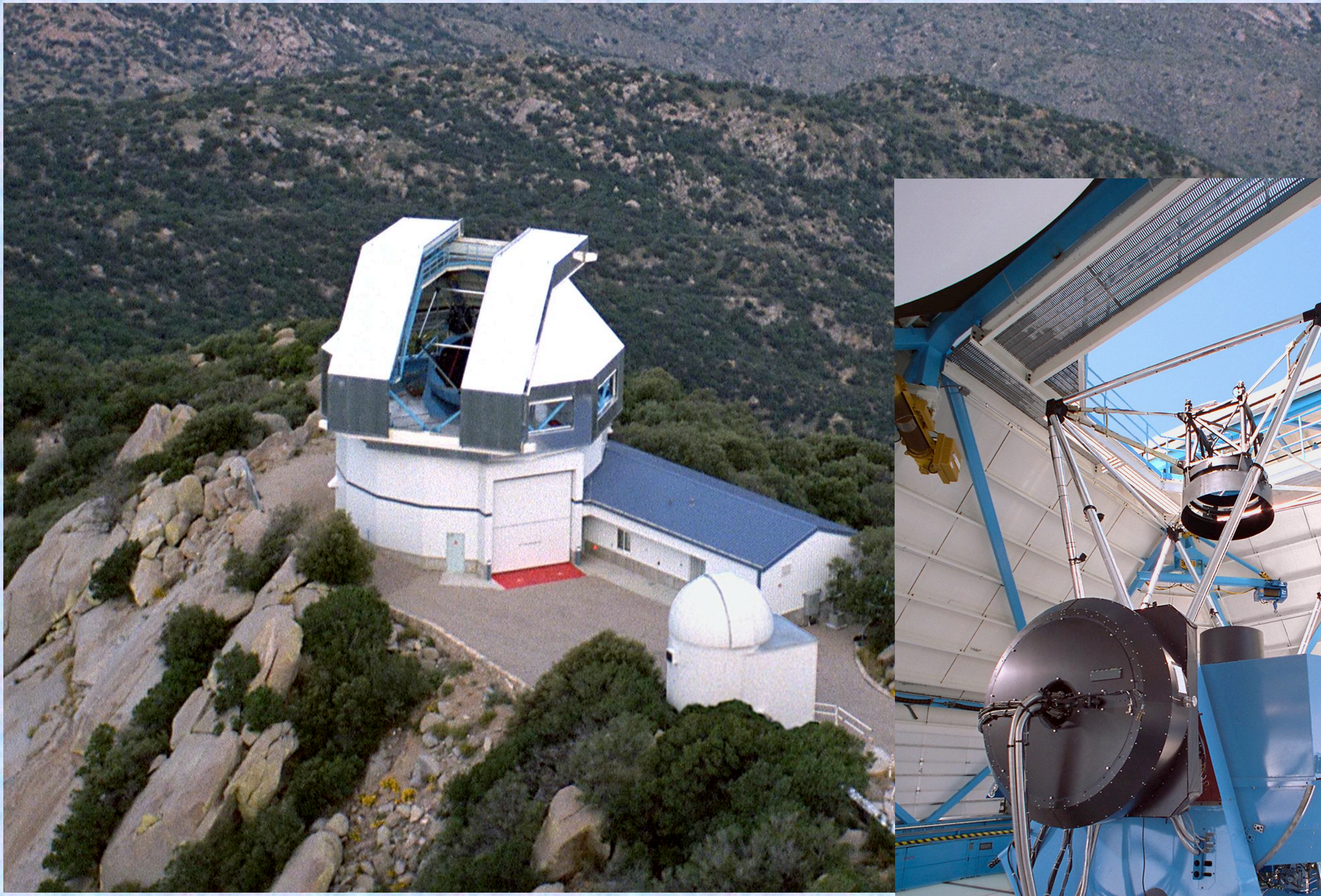
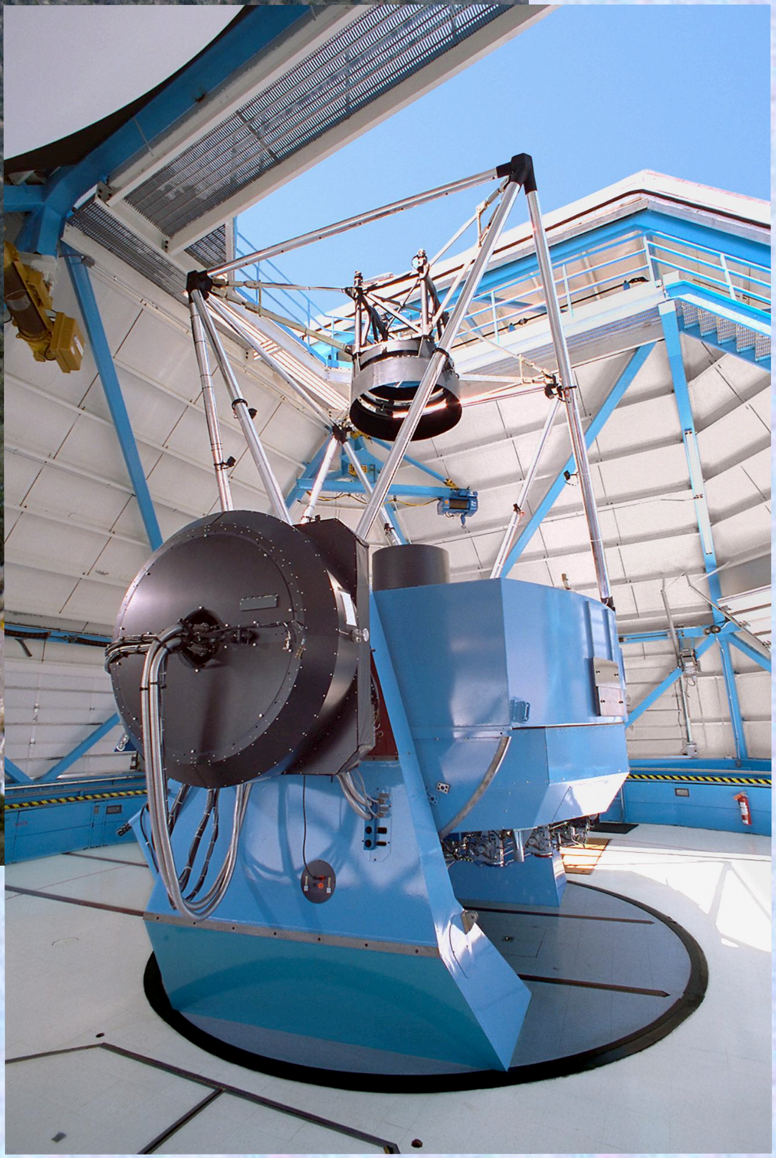
Overview

- WIYN Open Cluster Study
- 30,000 Radial Velocity Measurements
- Stellar Dynamics, Binaries, and Stellar Collisions
- Blue Stragglers, Sub-Subgiants, and Stars that Shouldn’t Be
- Conclusions



"Separating the Sheep from the Goats"
1965 Membership of the open cluster IC 1805
1970 Membership of the intermediate-age open cluster NGC 2420
1970 Membership of the open cluster NGC 7062
1972 Membership of the open cluster IC 4665
1972 Membership in the extremely young open cluster NGC 6530 (M8)
1981 Membership of the old open cluster NGC 2506
1982 Membership of the Rosette Nebula cluster, NGC 2244
1987 Membership in the young cluster Trumpler 37
1989 Relative proper motions … of the open cluster M67
1995 A proper-motion study of the open cluster NGC 3680
1996 A Proper-Motion Membership Study of the Old Open Cluster NGC 188
2001 WIYN Open Cluster Study. VII. NGC 2451A
2003 WOCS. XVII. Astrometry and Membership to V=21 in NGC 188





The WIYN Observatory

WIYN Open Cluster Study

- Comprehensive and definitive astrometric, photometric, and spectroscopic databases for new fundamental open clusters.

- A body of investigations which address critical astrophysical problems through study of open clusters.

WOCS Senior Scientists

• C. Deliyannis	IU	photometry, spectroscopy, abundances
• P. Demarque	Yale	theoretical stellar evolution
• T. Girard	Yale	astrometry, proper motions
• K. Honeycutt	IU	photometric monitoring, compact binaries
• S. Kafka	SSC	photometric monitoring, compact binaries
• D. Latham	CfA	radial velocities, photometric monitoring
• R. Mathieu	UW	radial velocities, binary populations
• S. Meibom	CfA	photometric monitoring, radial velocities
• I. Platais	JHU	astrometry, proper motions, photometry
• A. Sarajedini	Florida	photometry, stellar evolution
• W. van Altena	Yale	astrometry, proper motions
• T. von Hippel	Siena	photometry, luminosity functions

WOCS Publications

….

Giampapa, M. S., Hall, J. C., Radick, R. R., & Baliunas, S. L. 2006, "A Survey of Chromospheric Activity in the Solar-Type Stars in the Open Cluster M67," ApJ, 651, 444 (WIYN Open Cluster Study XXVIII)

Meibom, S., Mathieu, R. D., Stassun, K. G. 2006, "An Observational Study of Tidal Synchronization in Solar-Type Binary Stars in the Open Clusters M35 and M34," ApJ, 653, 621 (WIYN Open Cluster Study XXIX)

Jeffery, E. J.; von Hippel, T.; Jefferys, W. H.; Winget, D. E.; Stein, N.; DeGennaro, S. 2007, "New Techniques to Determine Ages of Open Clusters Using White Dwarfs," ApJ, 658, 391 (WIYN Open Cluster Study XXX)

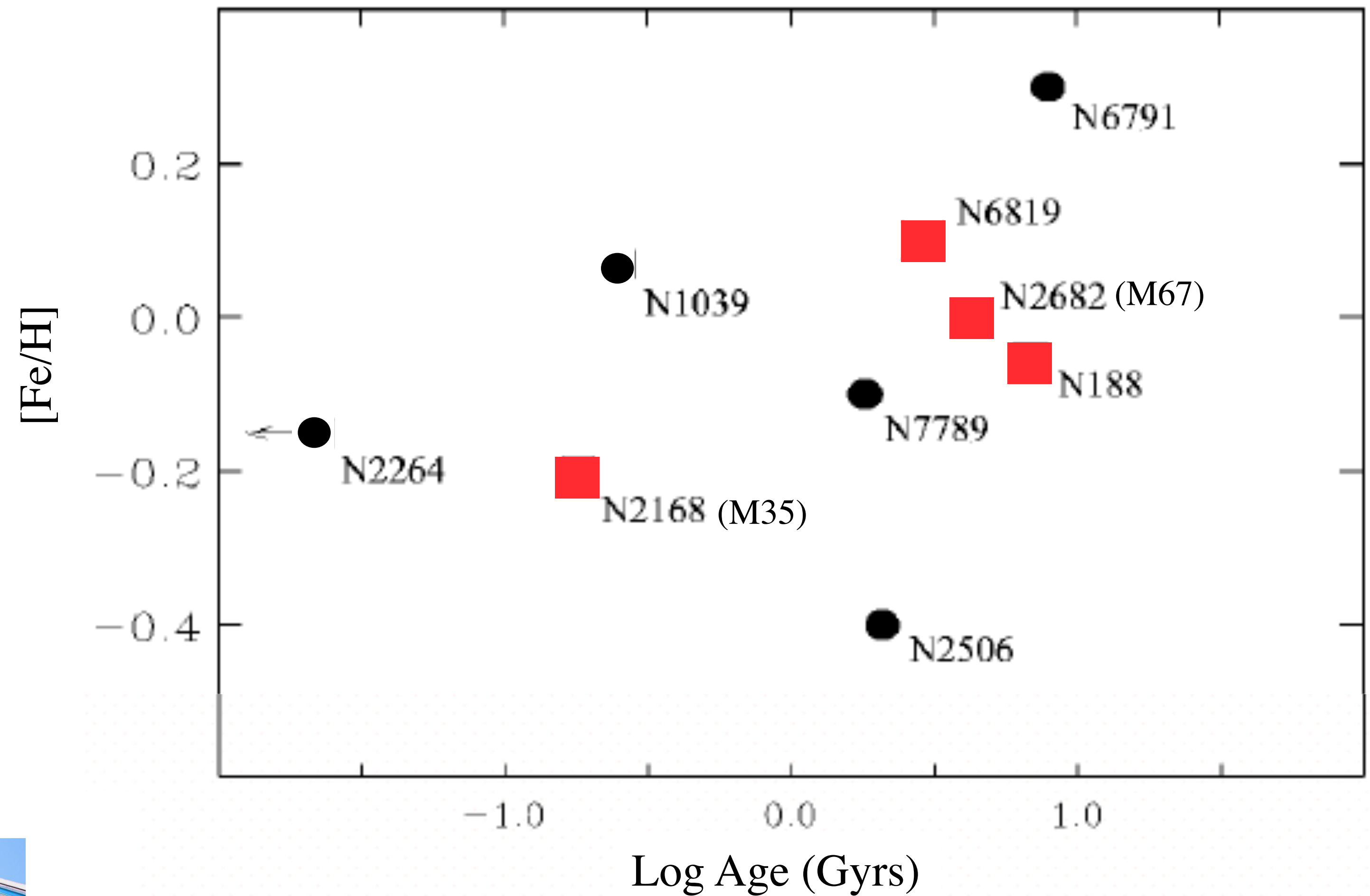
Meibom, S., Mathieu, R. D., & Stassun, K. G. 2007, "The Effect of Binarity on Stellar Evolution - Beyond the Reach of Tides," ApJ, 655, L155 (WIYN Open Cluster Study XXXI)

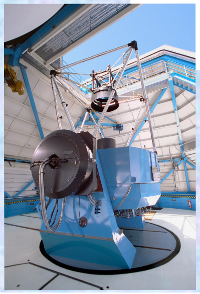
Geller, A., Mathieu, R. D., Harris, H. C. & McClure, R. D., 2008, "WIYN Open Cluster Study. XXXII. Stellar Radial Velocities in the Old Open Cluster NGC 188", AJ, 135, 2264

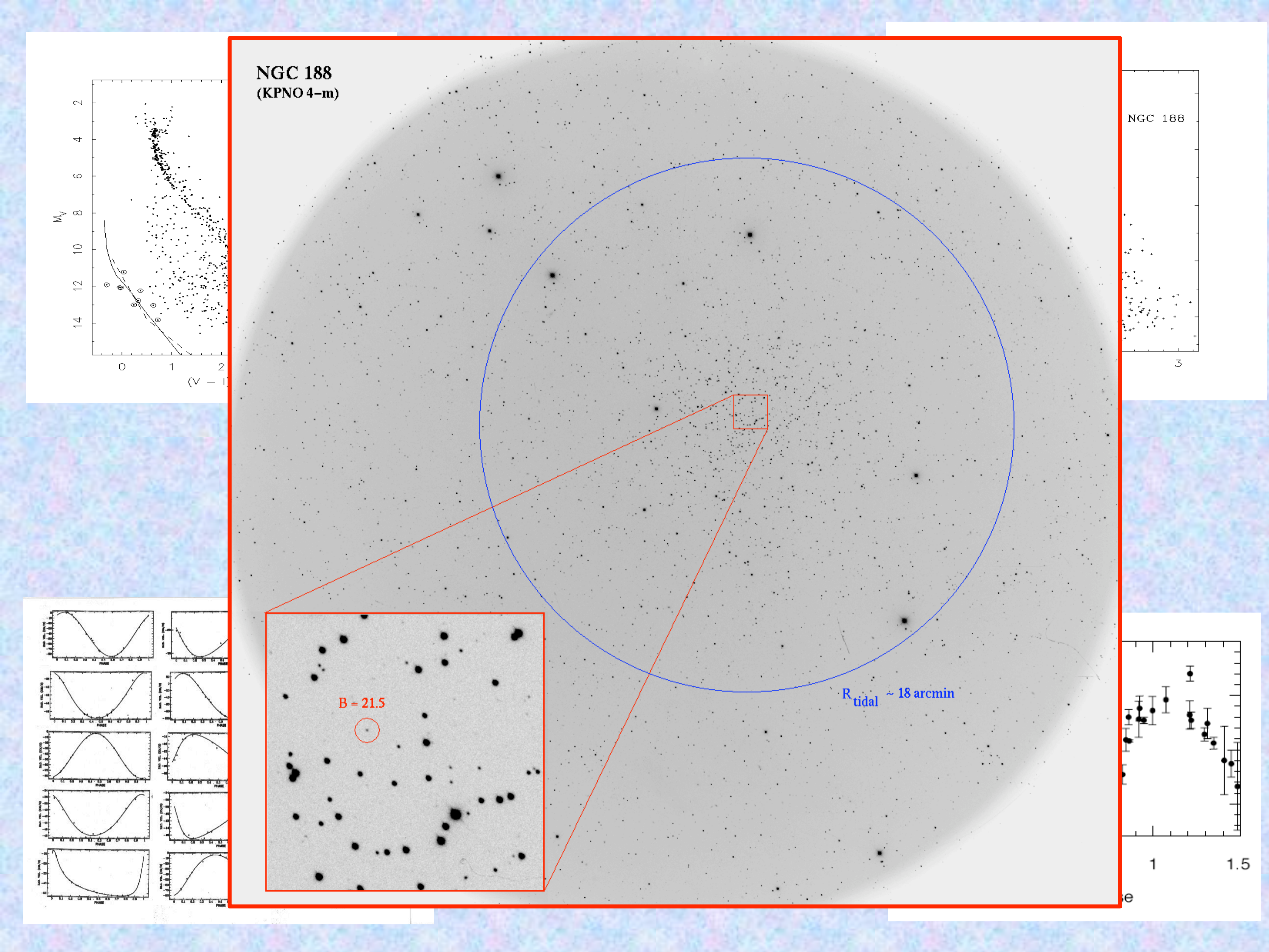
Meibom, S., Mathieu, R. D., & Stassun, K. G. 2007, "Stellar Rotation in M35: Mass-Period Relations, Spin-Down Rates, and Gyrochronology," ApJ, in press (WIYN Open Cluster Study XXXIII

Geller, A., Mathieu, R. D., Harris, H. C. & McClure, R. D., 2008, "WIYN Open Cluster Study**. XXXIV**. Spectroscopic Binary Orbits in NGC 188, AJ, submitted

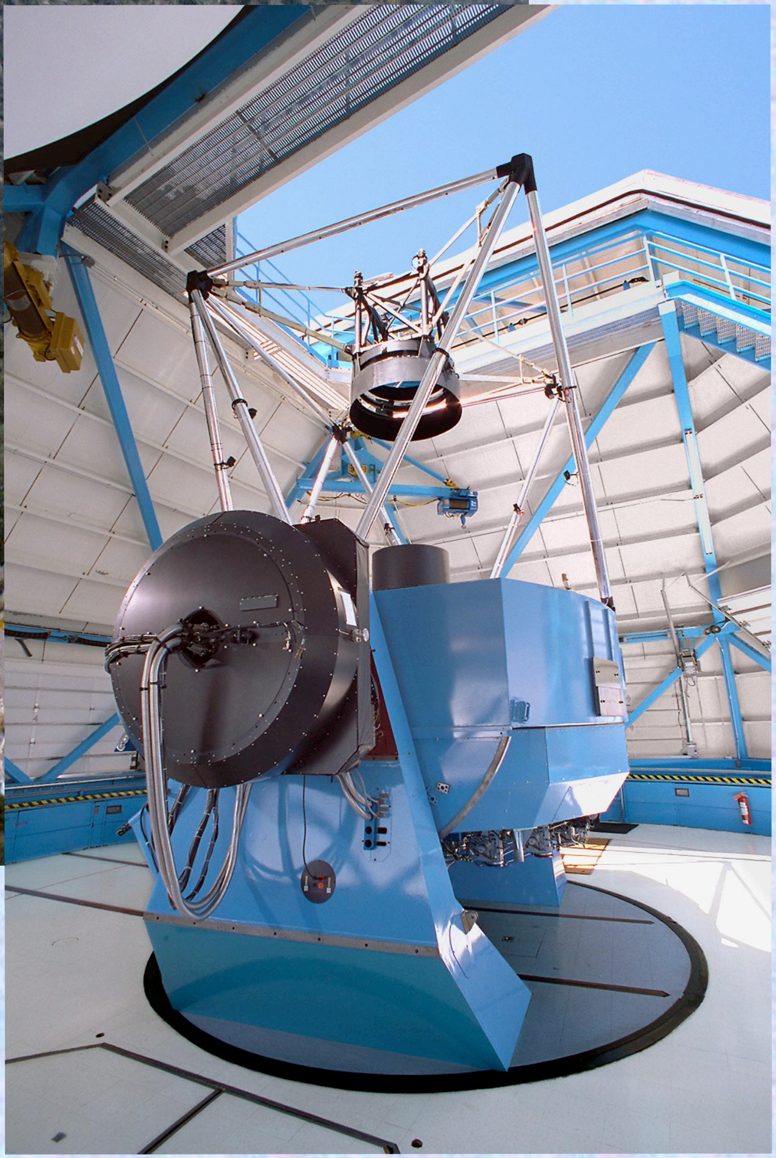
WIYN Open Cluster Study







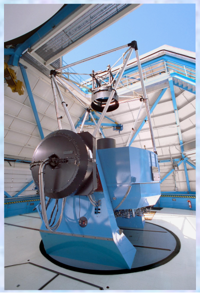
NGC 188
(KPNO 4–m)
B = 21.5
R tidal ~ 18 arcmin
NGC 188
M V

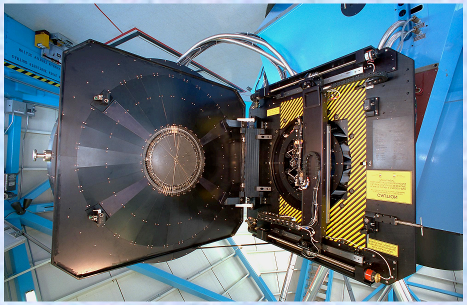


Radial Velocities

Stellar Radial Velocities

- *NGC 2168* (0.15 Gyr)
  - 1597 stars ($0.8\ M_o < M_* < 1.2\ M_o$) ($V < 16.5$, $B\text{-}V > 0.4$)
  - 7104 measurements ($\sigma = 0.4$ km s^{-1})
  - 102 binaries ($P < 1000^d$)
- *NGC 6819* (2 Gyr)
  - 1517 stars
  - 7698 measurements
  - 133 binaries
- *NGC 188* (7 Gyr)
  - 1092 stars
  - 8570 measurements
  - 124 binaries





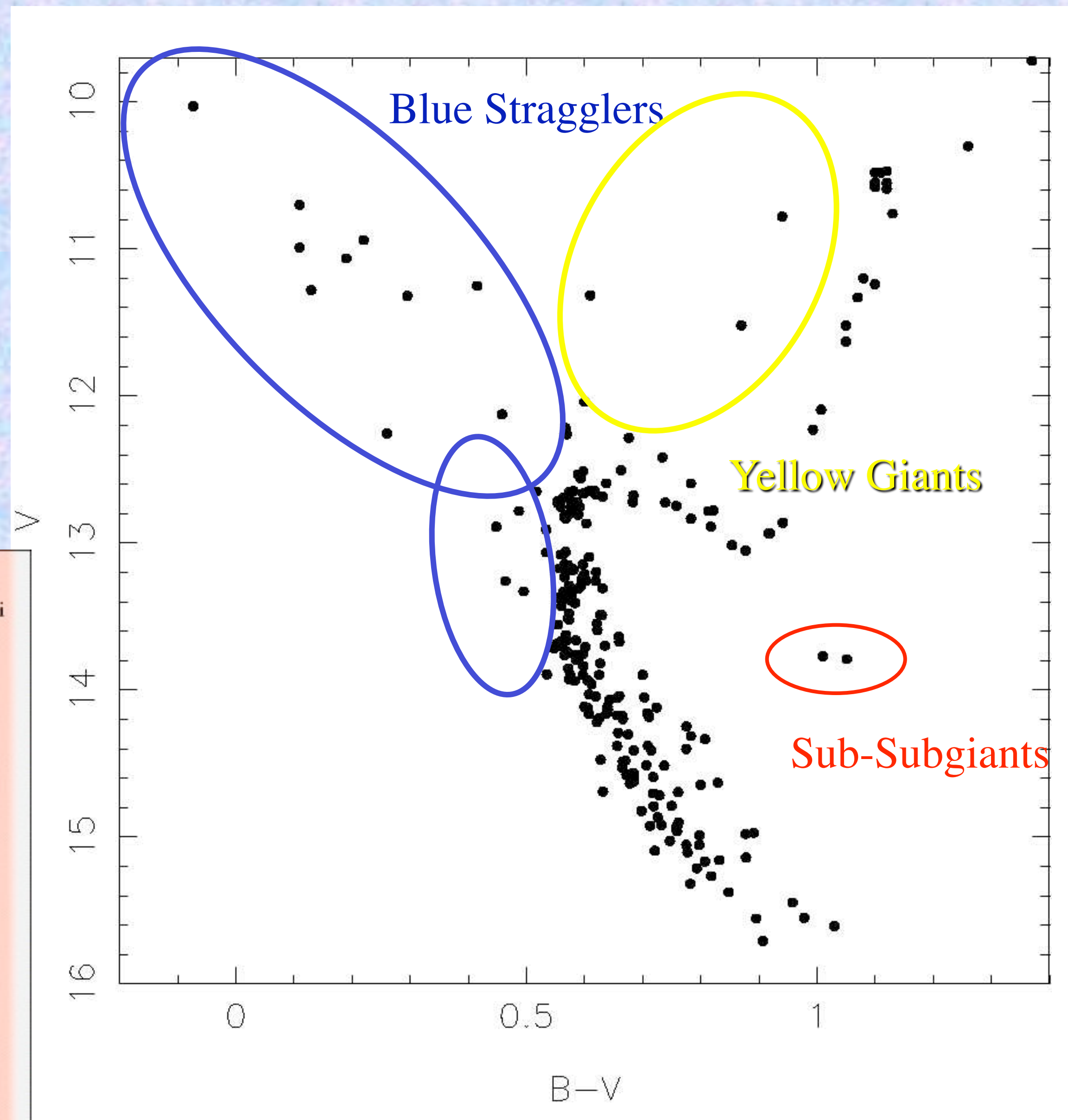
The Open Star Cluster M67

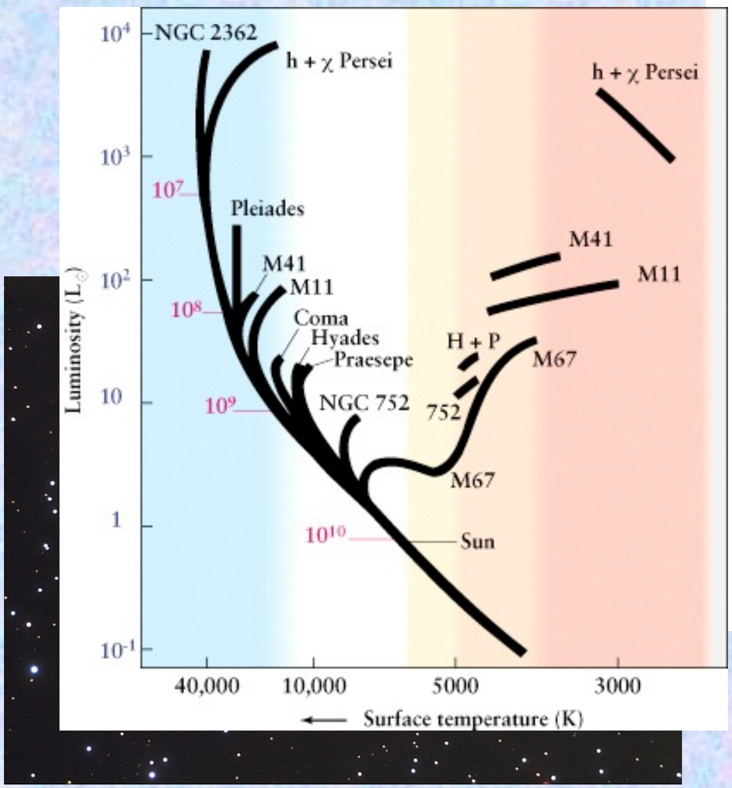
Stellar Dynamics, Binaries, and Stellar Collisions

M67

4.5 Gyr

$\approx 1000\ M_o$

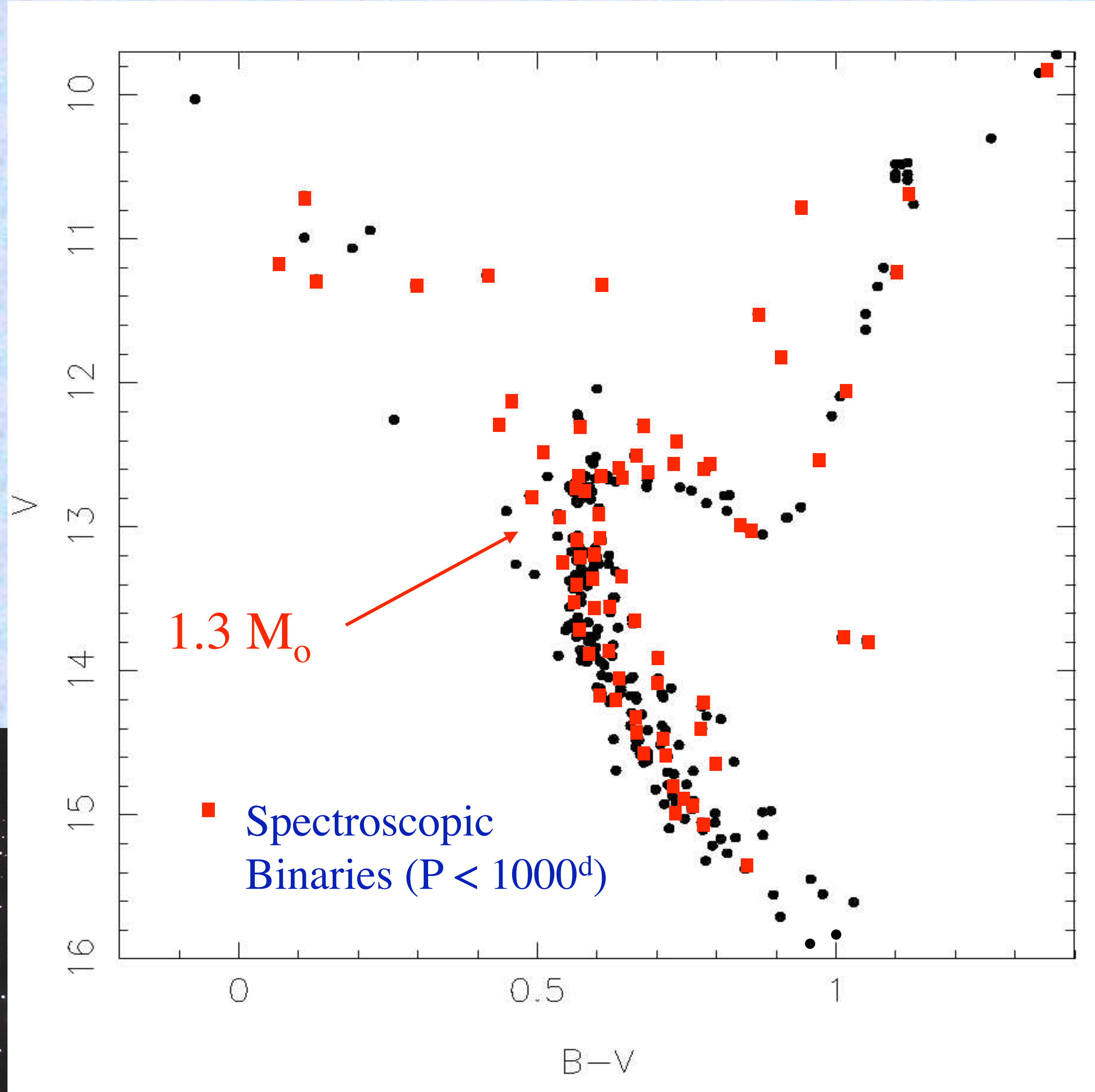


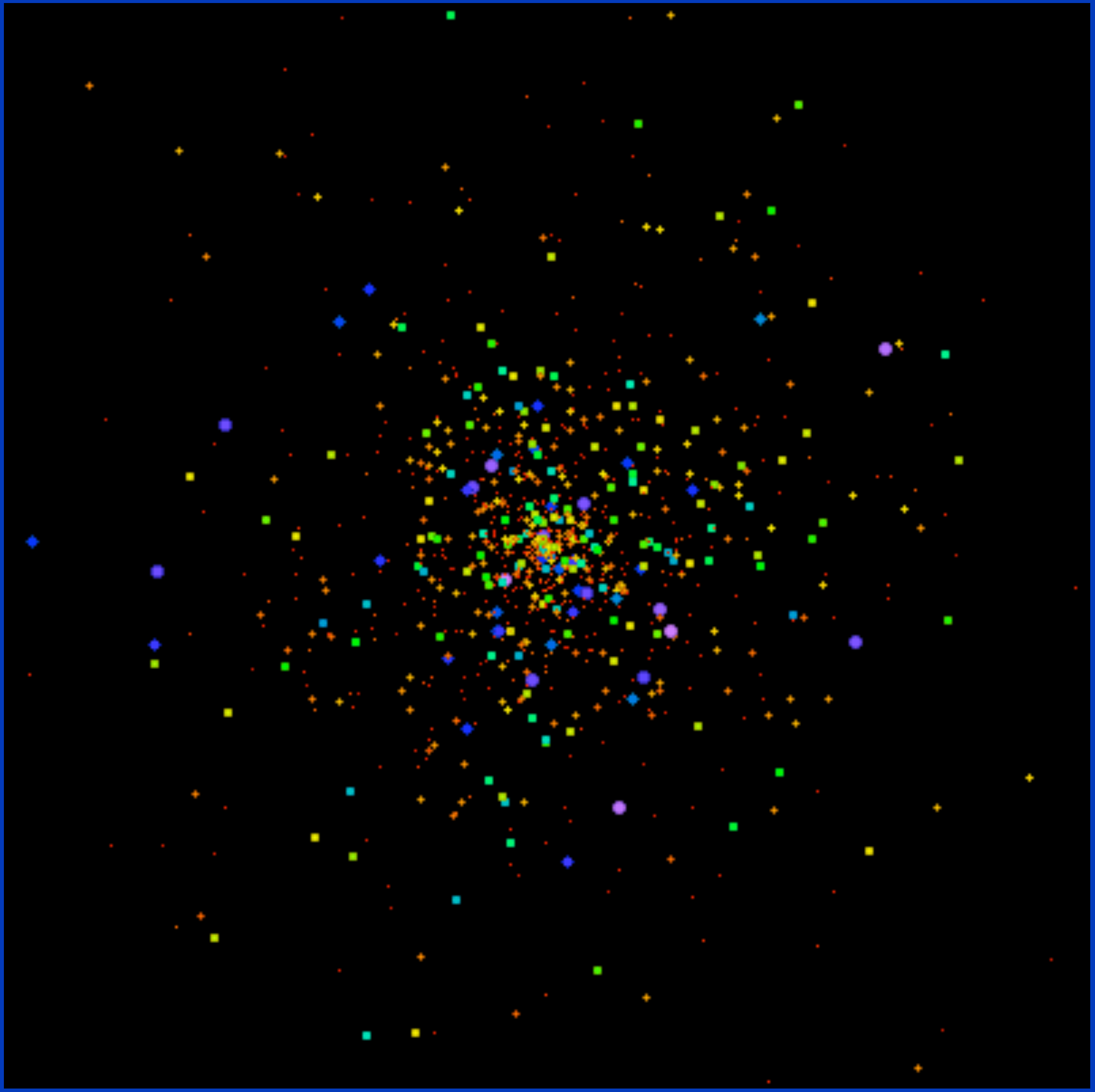


M67

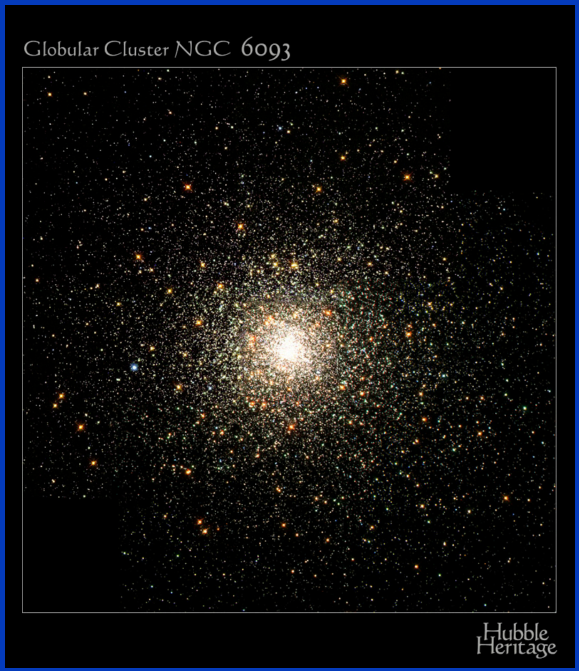
4.5 Gyr

≈ 1000 M_o

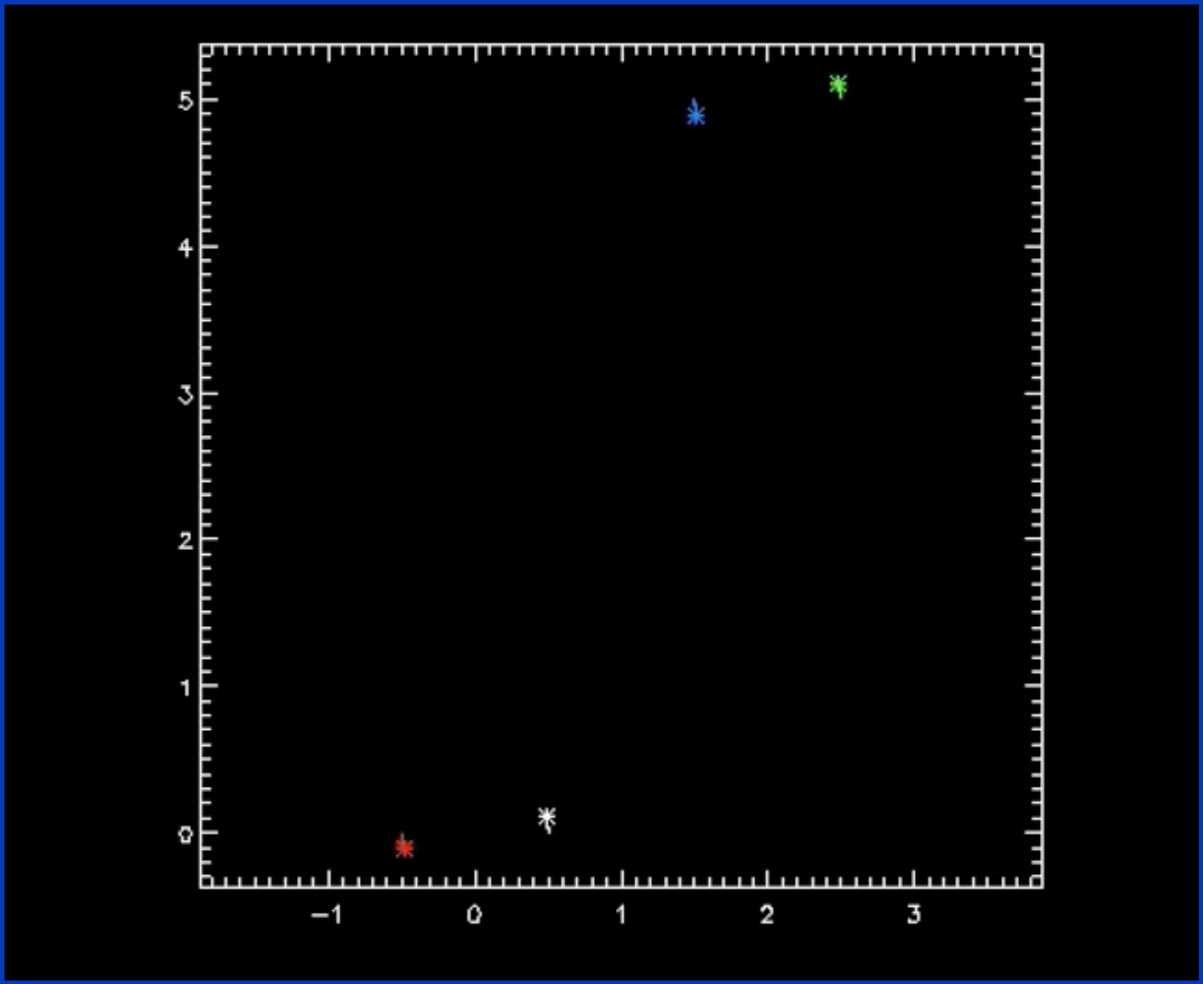




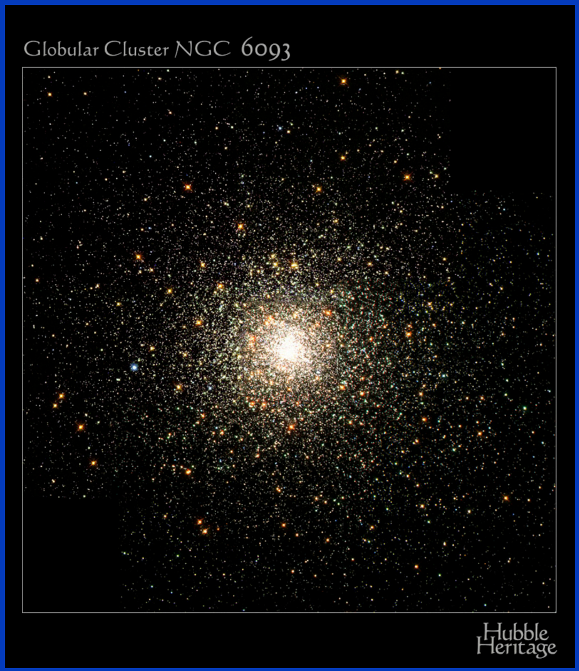
Stellar Dynamics

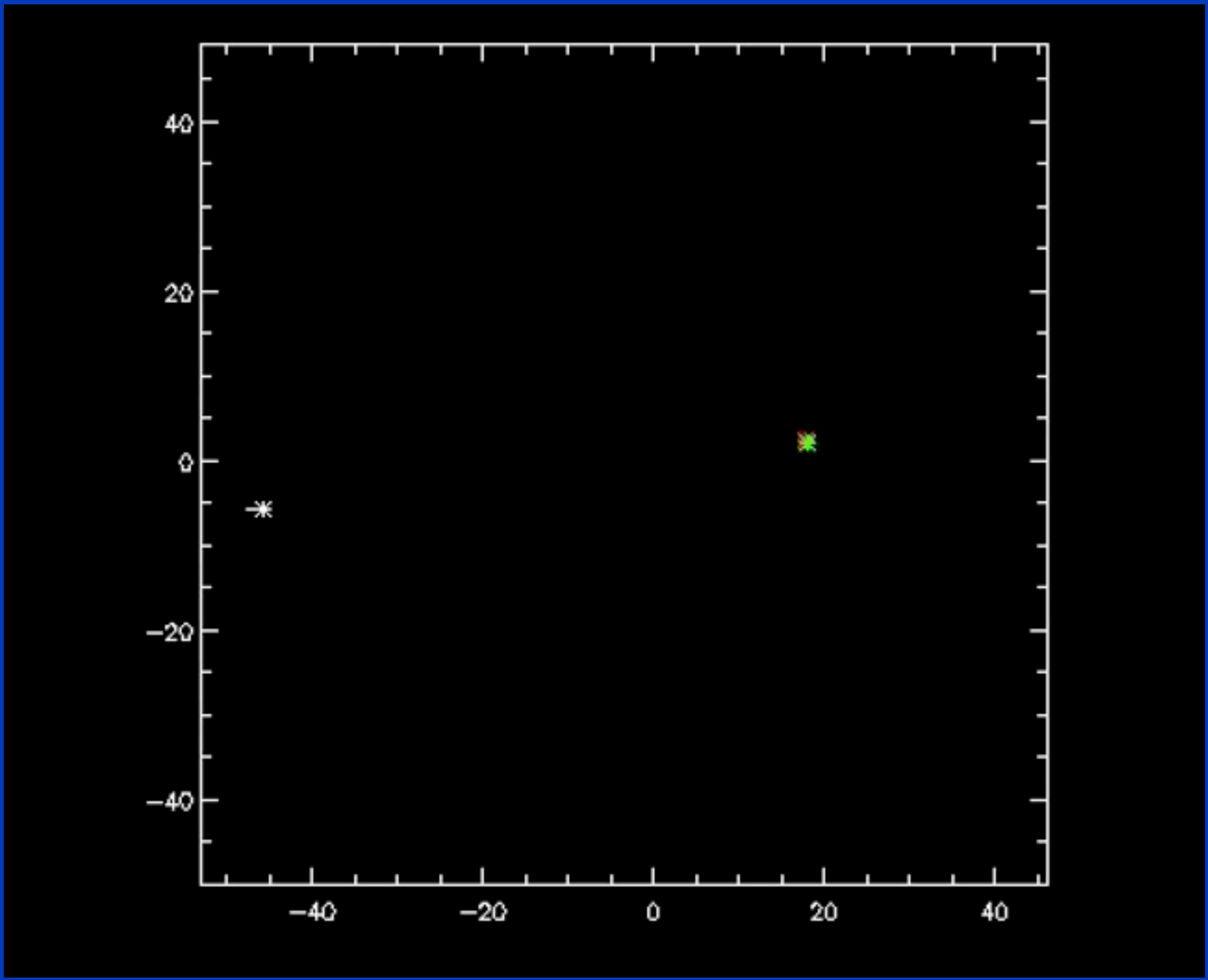


Binary Stars

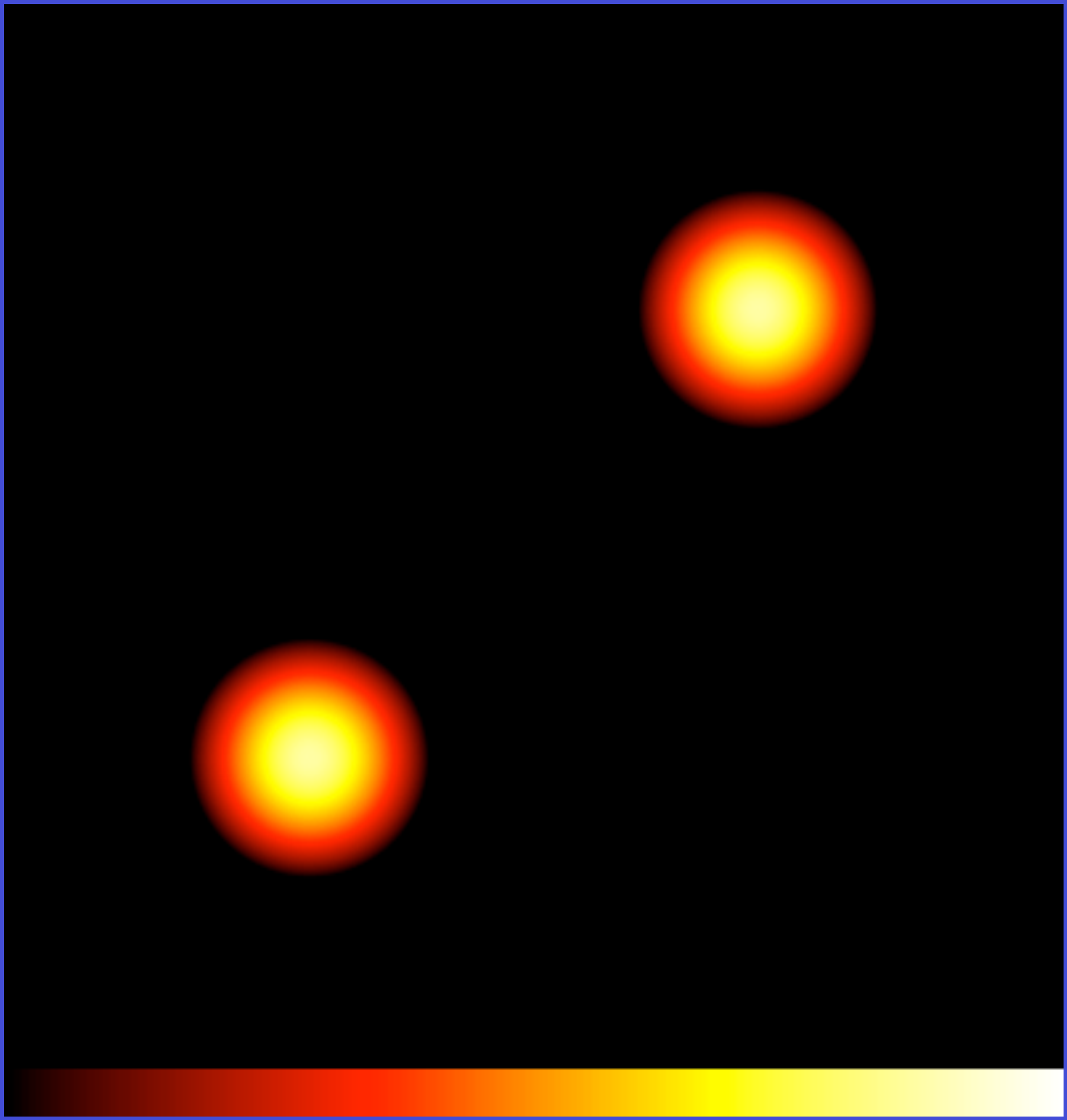


Stellar Dynamics





Stellar Dynamics



Sills et al. 2006

Theoretical Simulation of M67

Initial Conditions

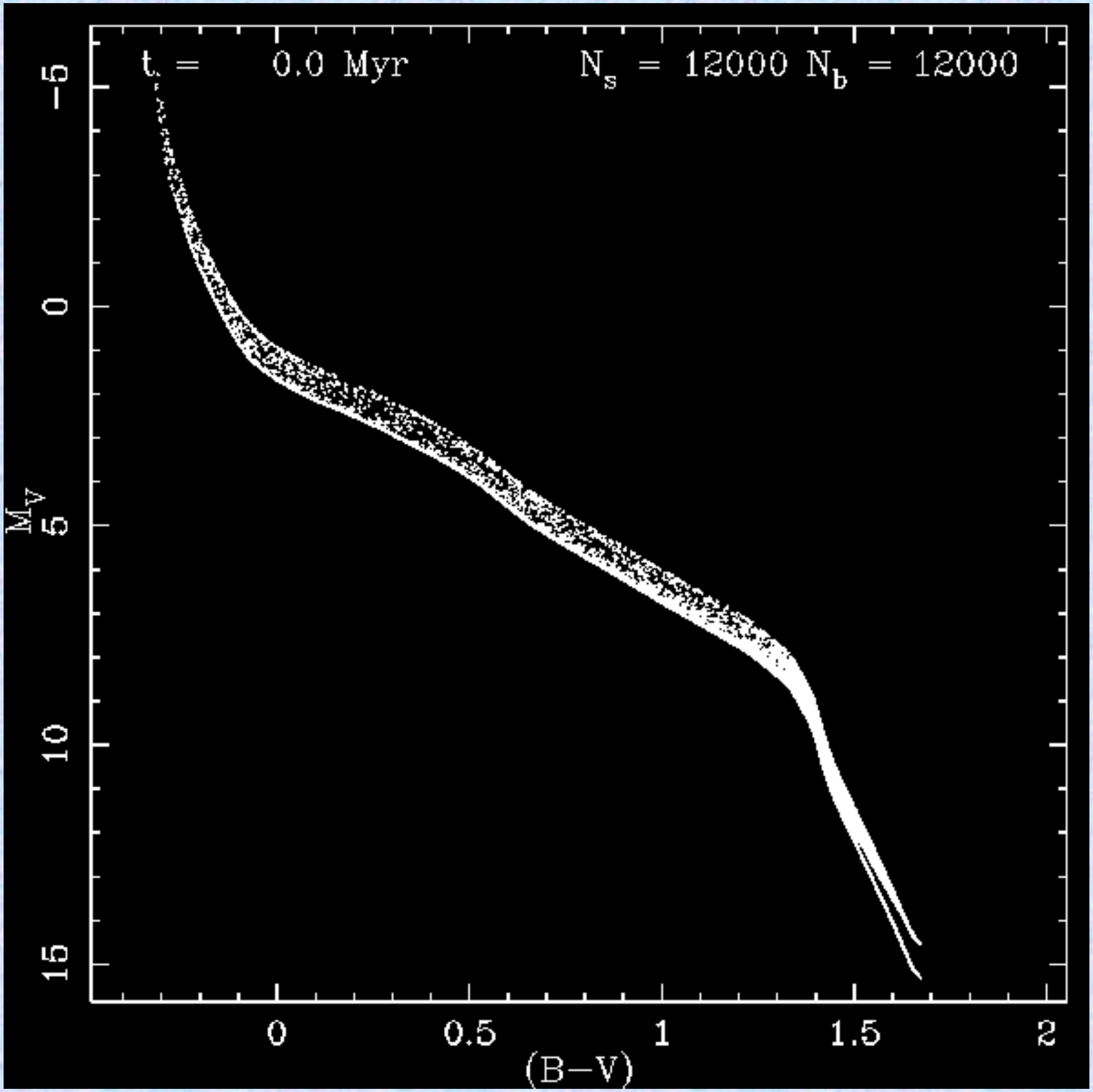
- 12,000 single stars (0.1 - 50 $M_{\odot}$)
- 12,000 binaries (*a*: flat-log, *e*: thermal, *q*: uniform)
- Solar metallicity ($Z = 0.02$)

- Plummer sphere in virial equilibrium
- Circular orbit at R_{gc}= 8 kpc

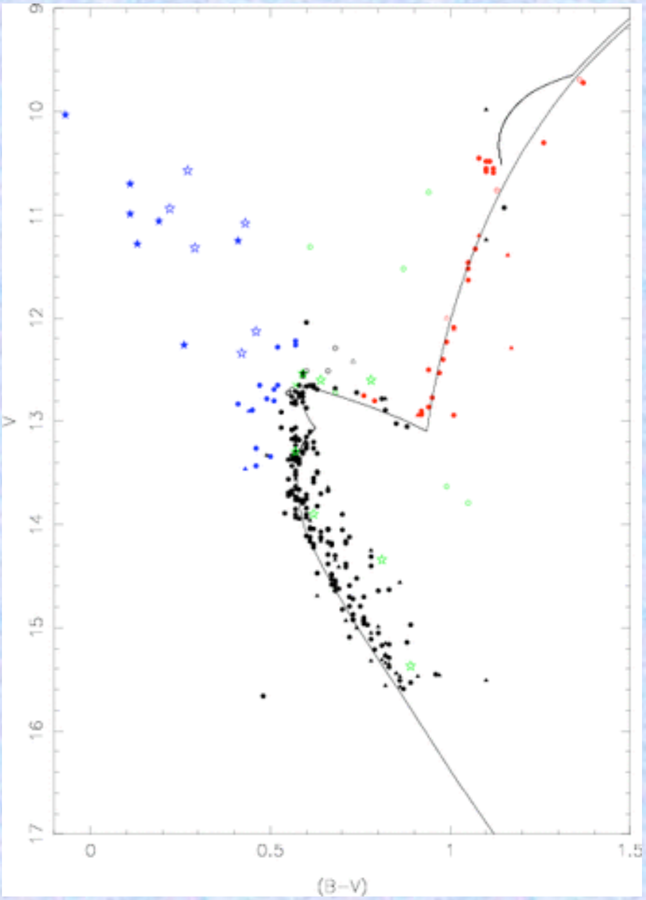
- M ~ 18700 $M_{\odot}$
- tidal radius 32 pc
- T_{rh} ~ 400 Myr
- σ ~ 3 km/s
- n_c ~ 200 stars/pc^3

Hurley *et al*. 2005

Theoretical Simulation of M67

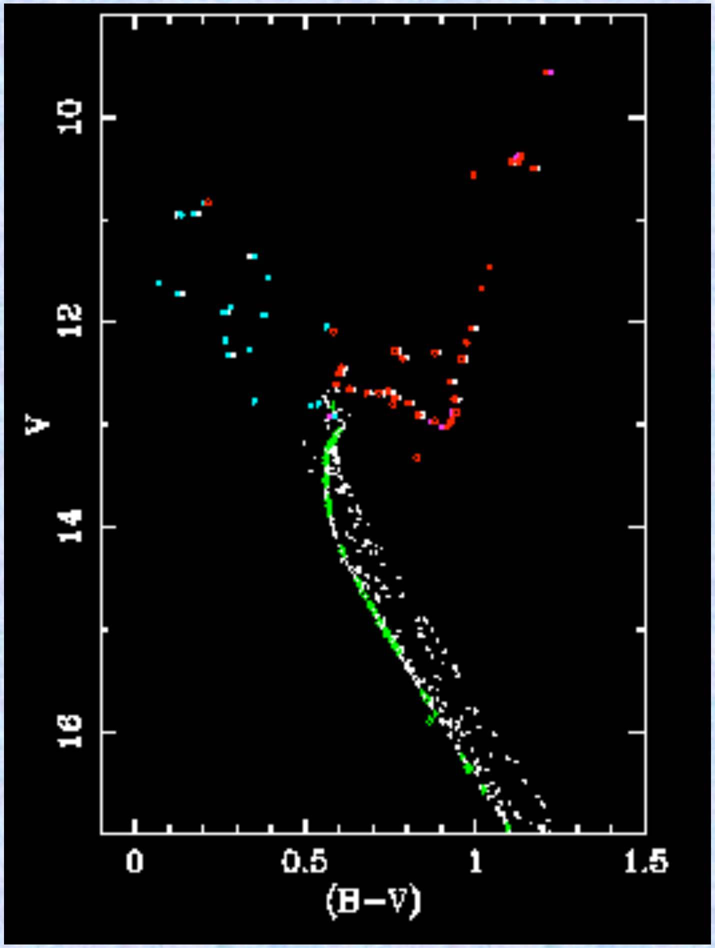


M67 Observed CMD



- 29 blue stragglers
- $N_{BS}/N_{ms,2to} = 0.15$
- $R_{h,BS} = 1.6pc$

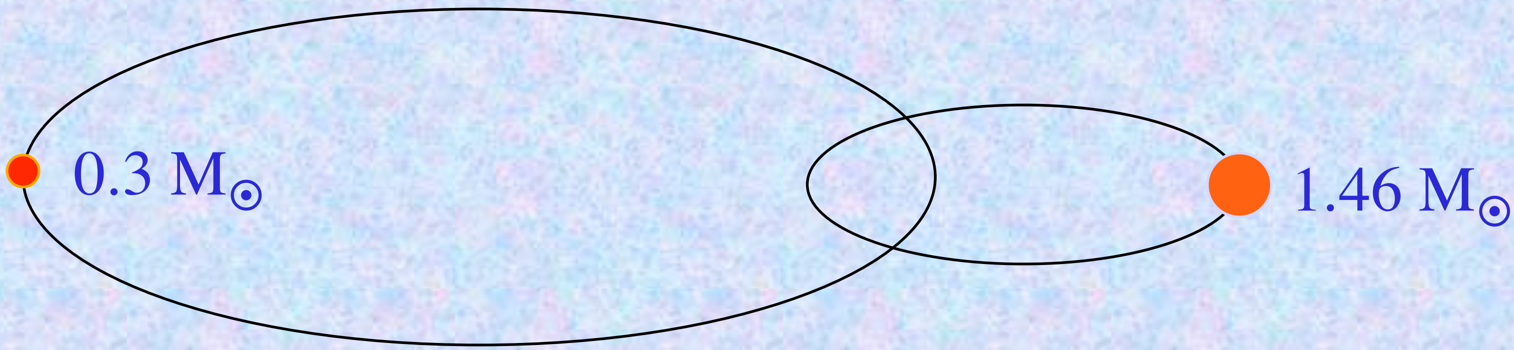
N-body Model CMD



- 25 blue stragglers
- $N_{BS}/N_{ms,2to} = 0.18$
- $R_{h,BS} = 1.1pc$

Theoretical Simulation of M67

Primordial Binary
Period: 47,860 days
Eccentricity: 0.8

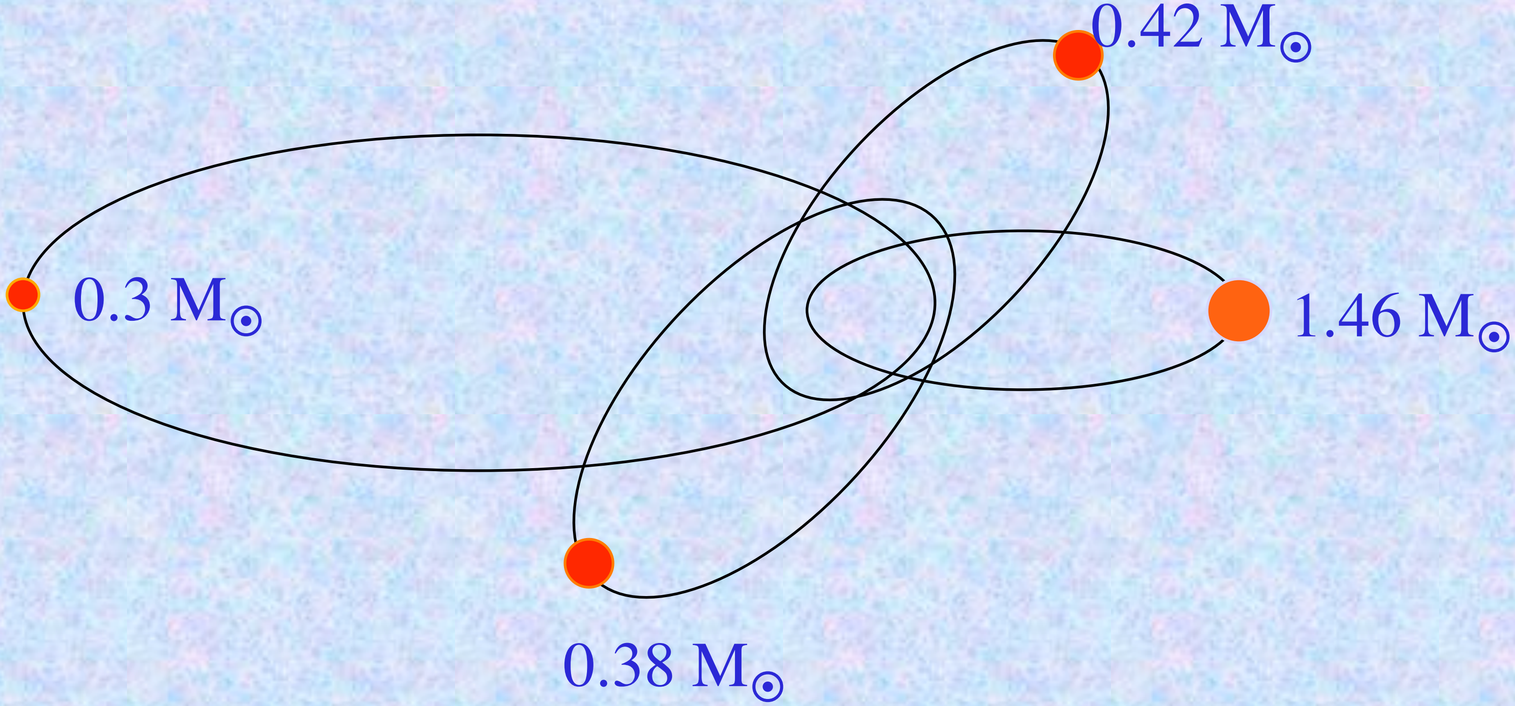


Theoretical Simulation of M67

2.089 Gyr later

Theoretical Simulation of M67

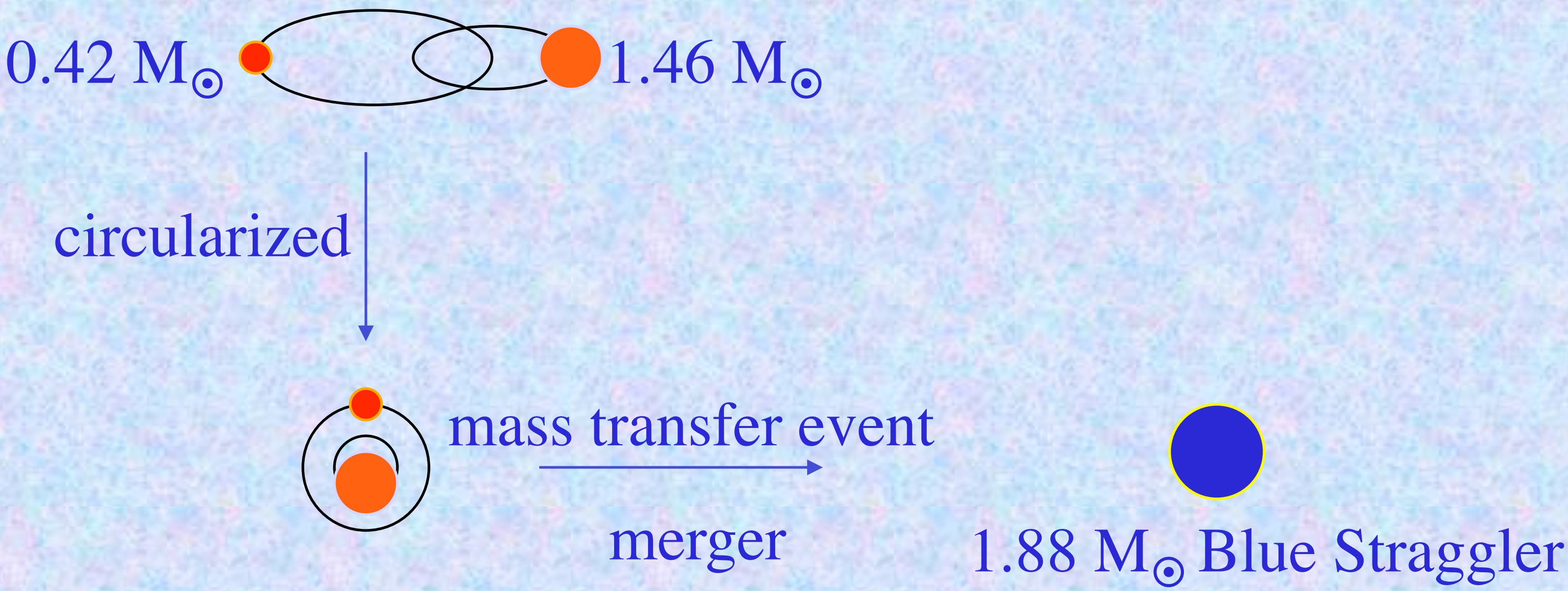
4-body interaction



Theoretical Simulation of M67

Period: 1.1 days

Eccentricity 0.8

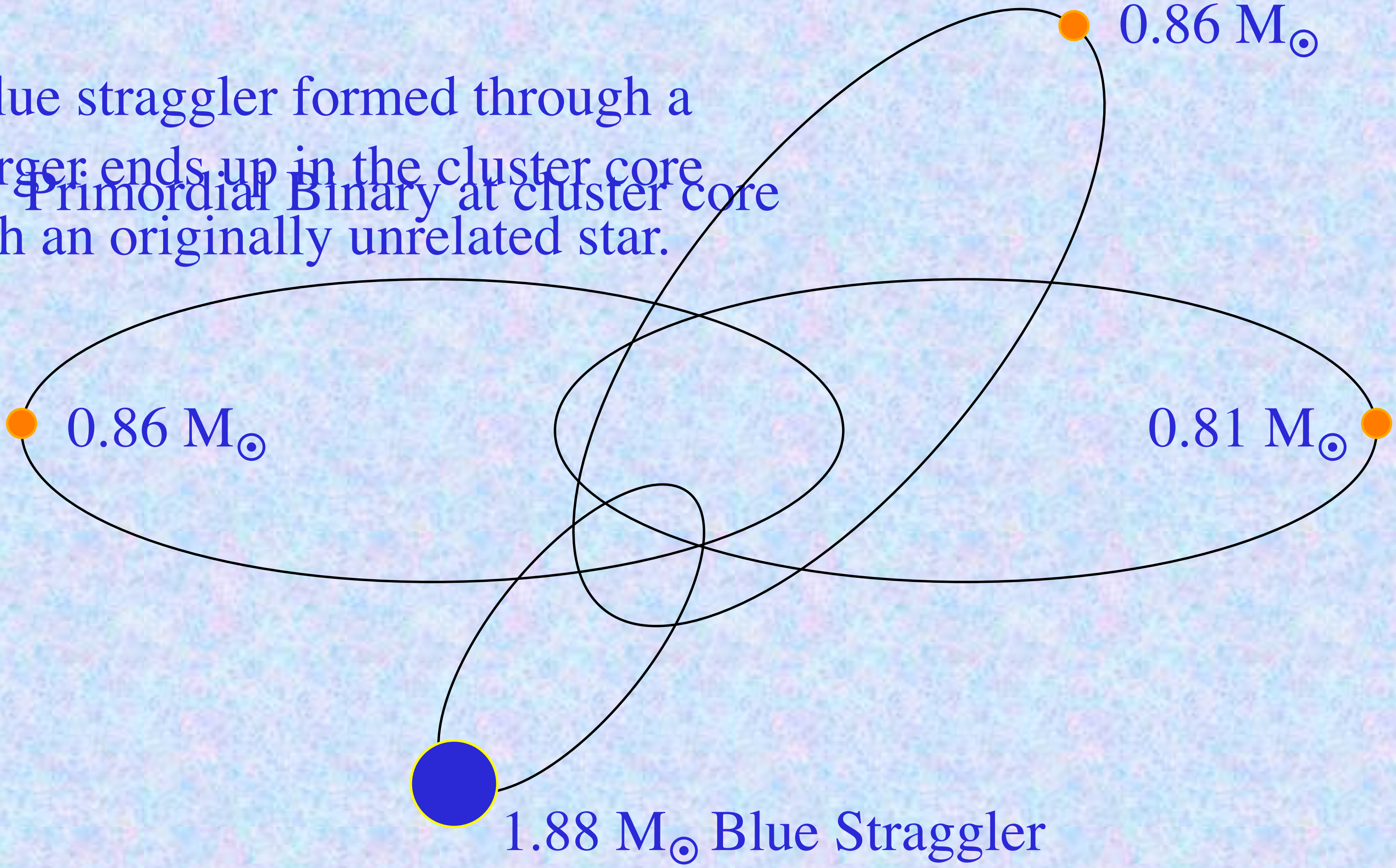


Theoretical Simulation of M67

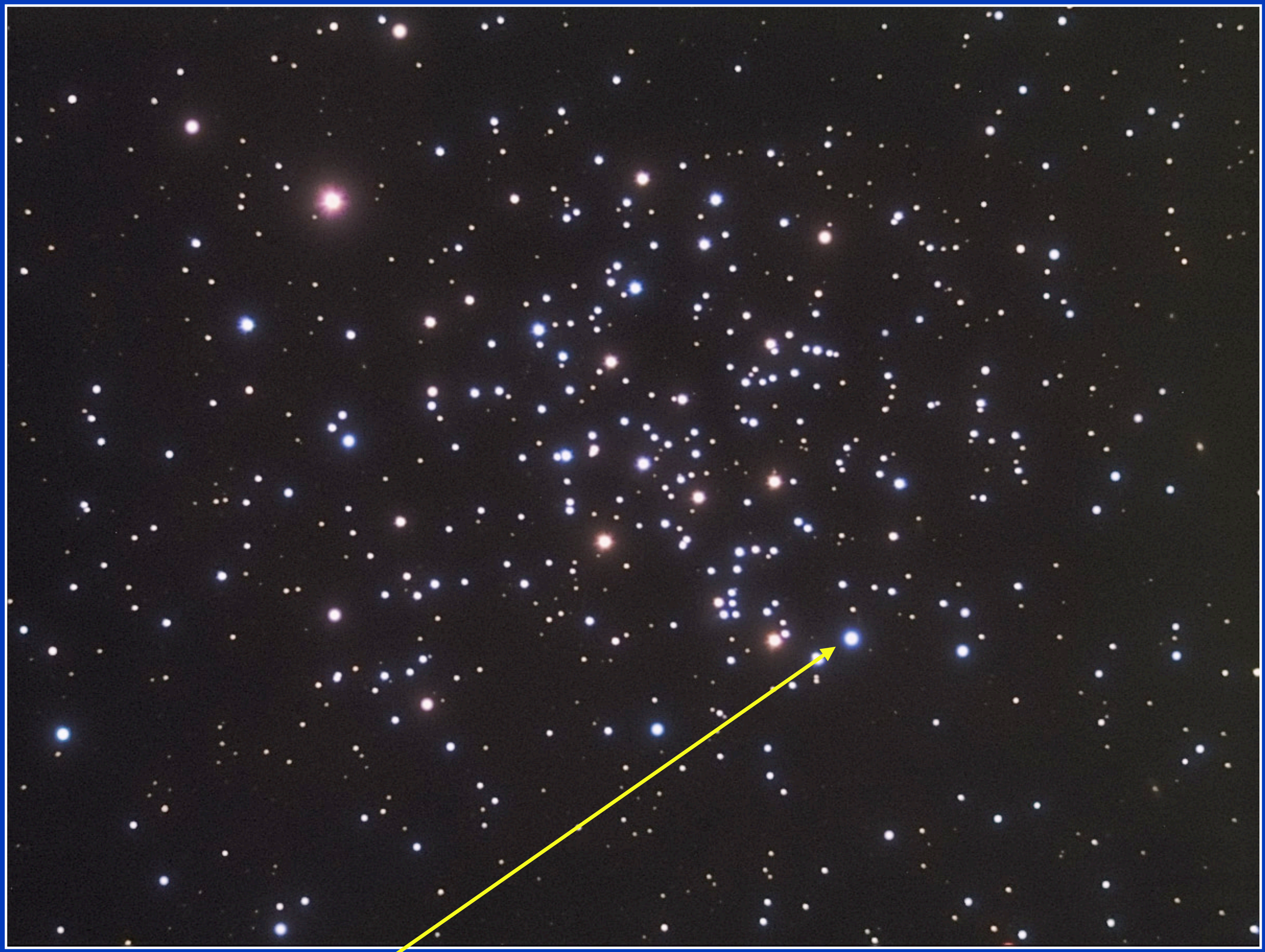
But wait…there's more

Theoretical Simulation of M67

A blue straggler formed through a merger ends up in the cluster core with an originally unrelated star.

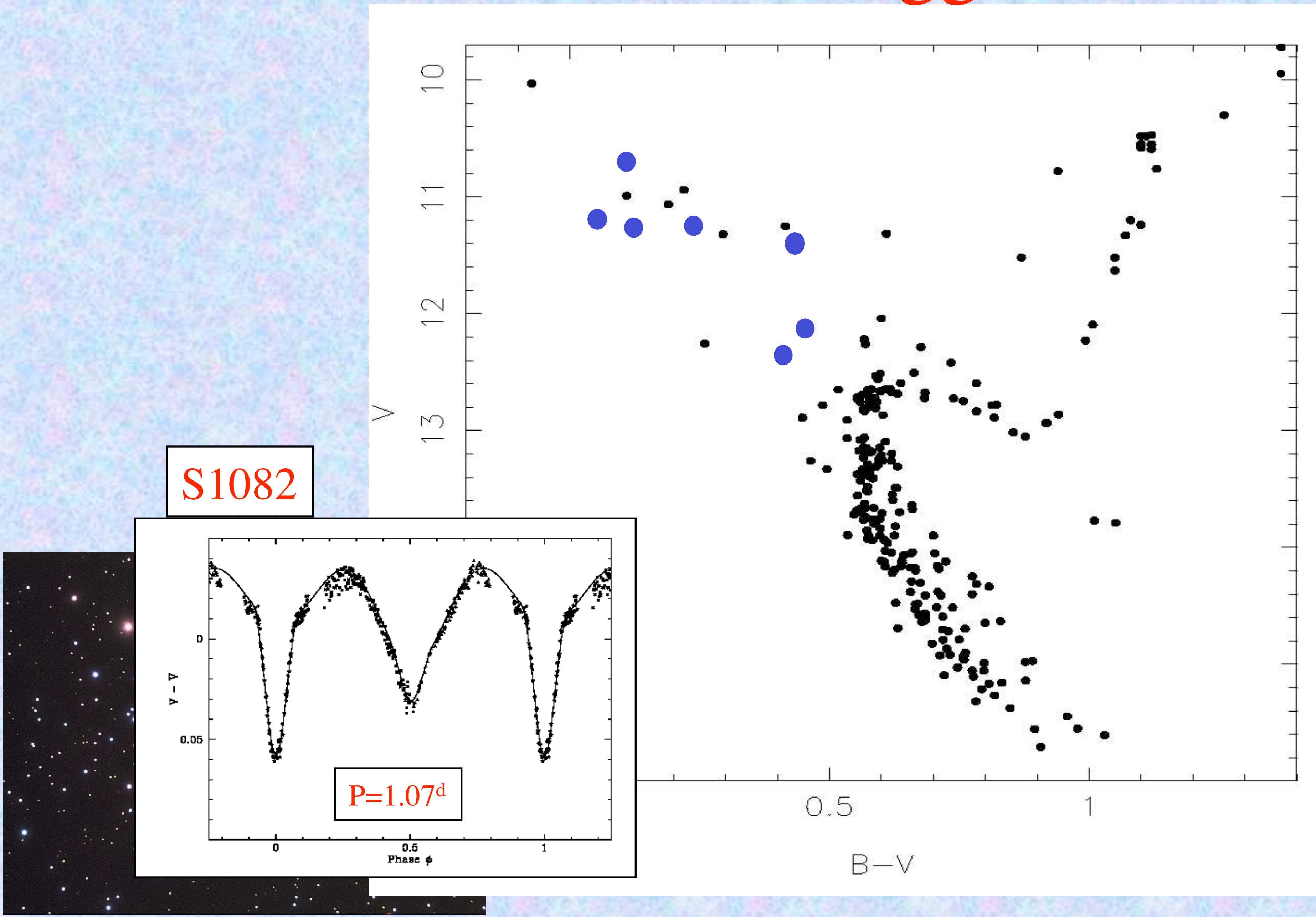


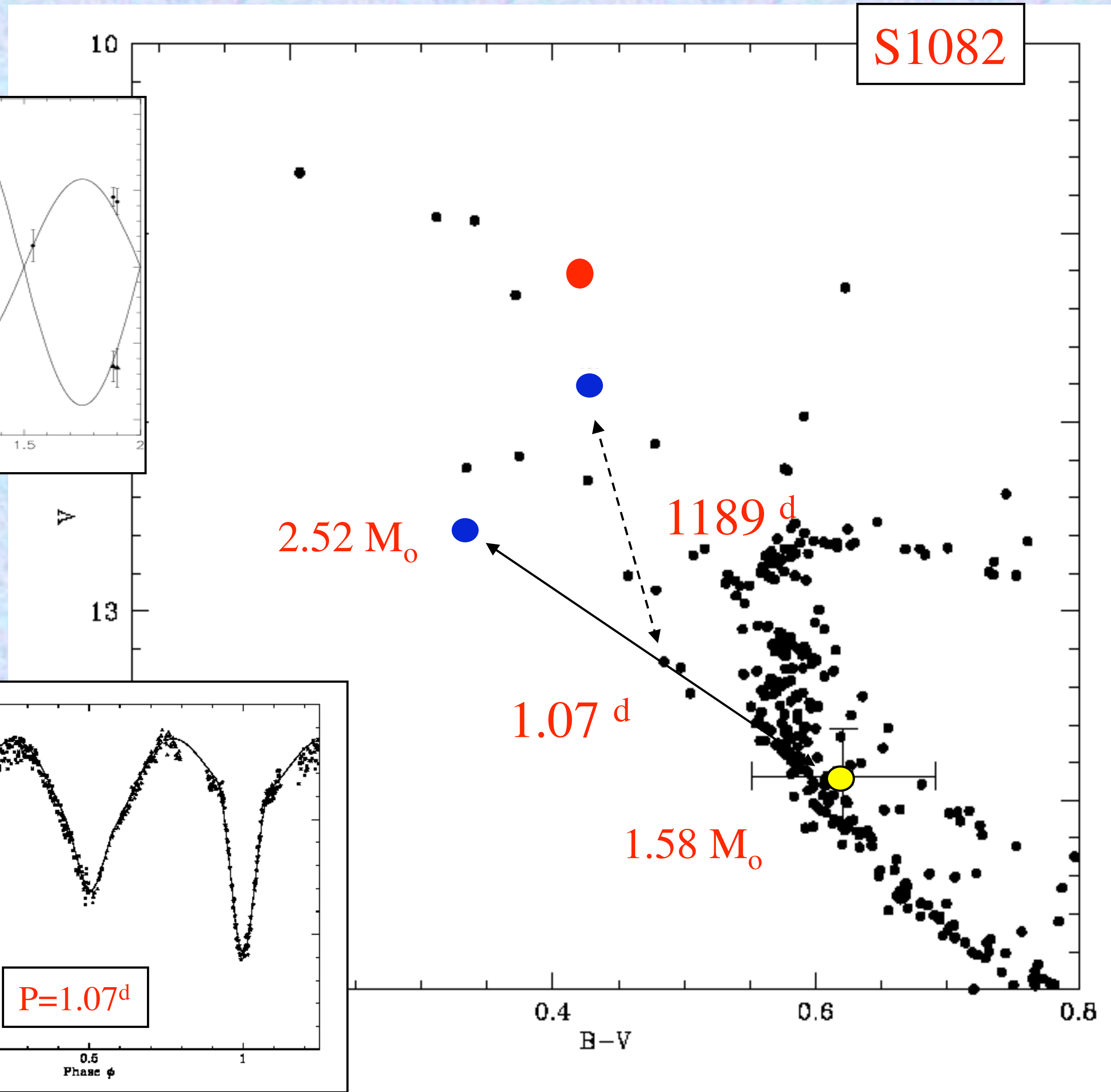
The Open Star Cluster M67

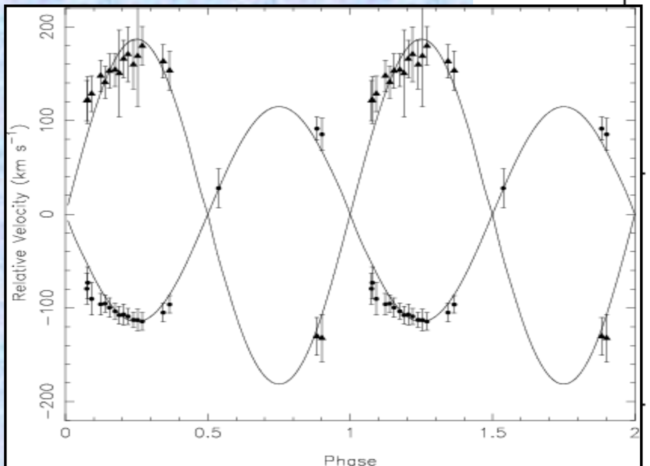


Stars that Shouldn't Be

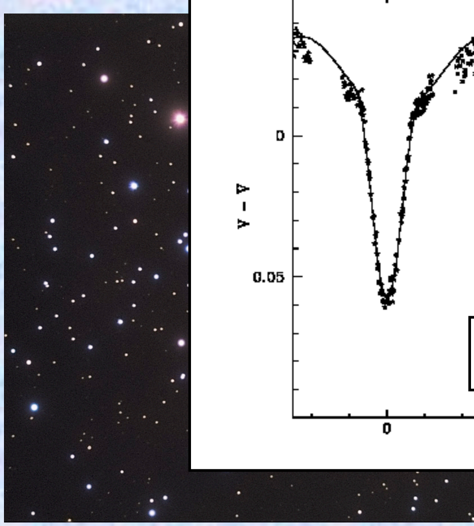
S1082 Blue Straggler







Van den Berg *et al*. 2001
Sandquist *et al*. 2003



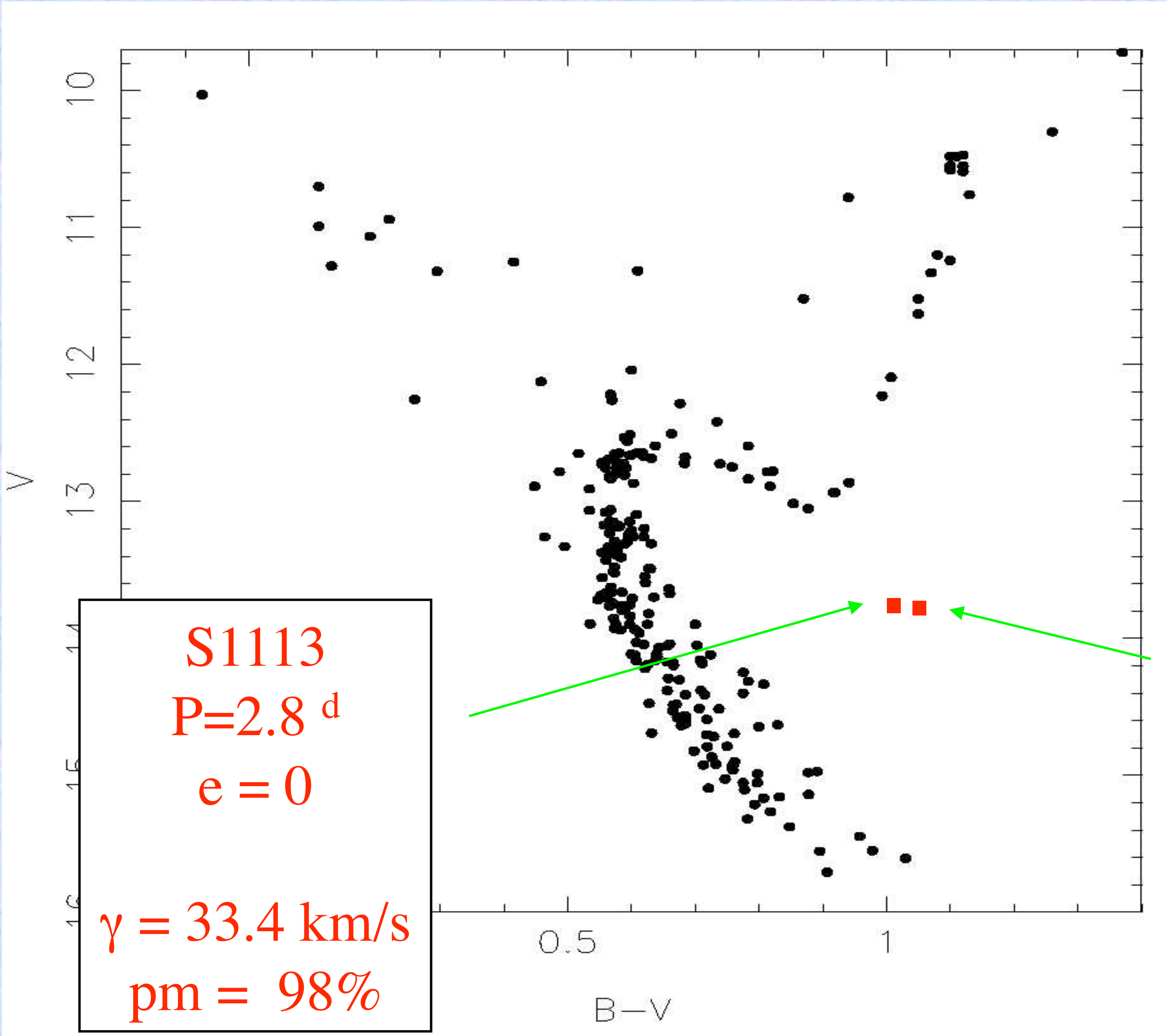
S1082 Evolutionary Scenario

4 M_o in the close binary suggests a collisional scenario
At least 3 stars involved, likely 4 or more

Binary-Binary encounter
1. Two stars collide and merge into the secondary
2. Third star becomes the primary
3. Fourth star becomes the tertiary in wide orbit

Challenges
1. Primary and tertiary are blue stragglers
    a) Already present in the binaries?
    b) Subsequently exchanged into the system?
2. The secondary of the close binary is not in thermal equilib.
    a) Can only be subluminous for a thermal timescale

S1113 Sub-Subgiant



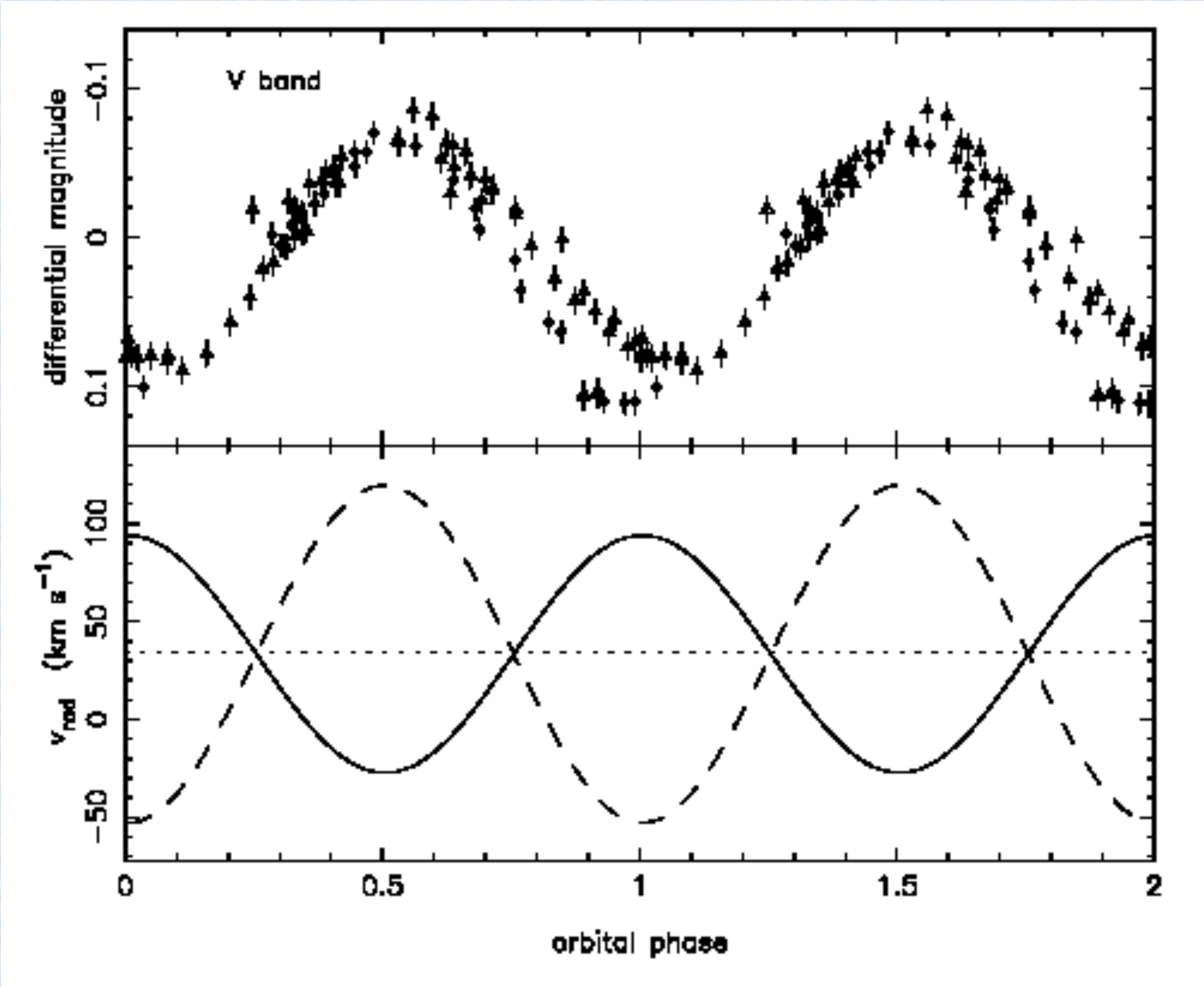
S1113
P=2.8 ^{d}
e = 0

γ = 33.4 km/s
pm = 98%

S1063
P=18.4 ^{d}
e = 0.21

γ = 34.3 km/s
pm = 97%

S1113 Sub-Subgiant

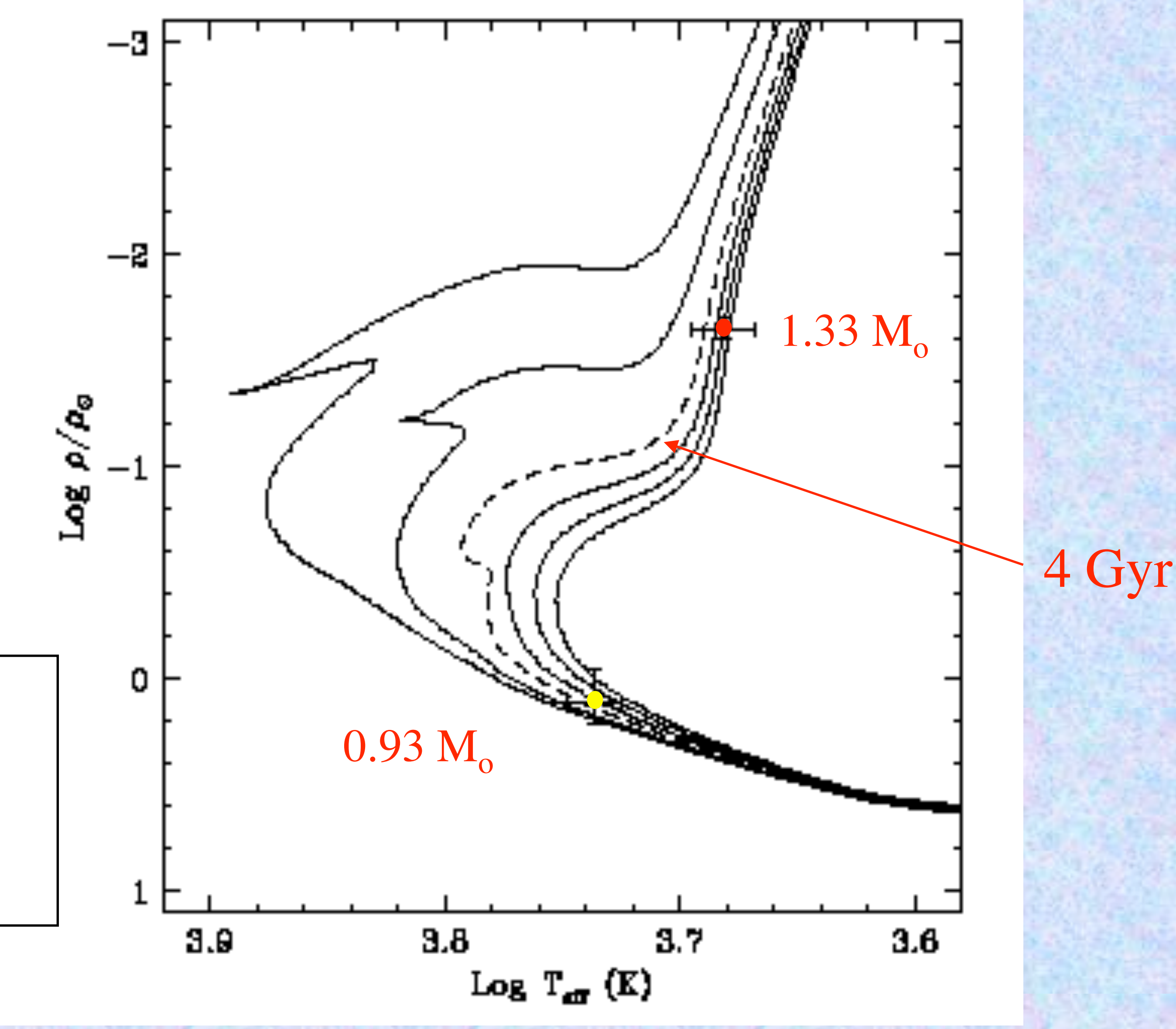


Mathieu *et al*. 2003

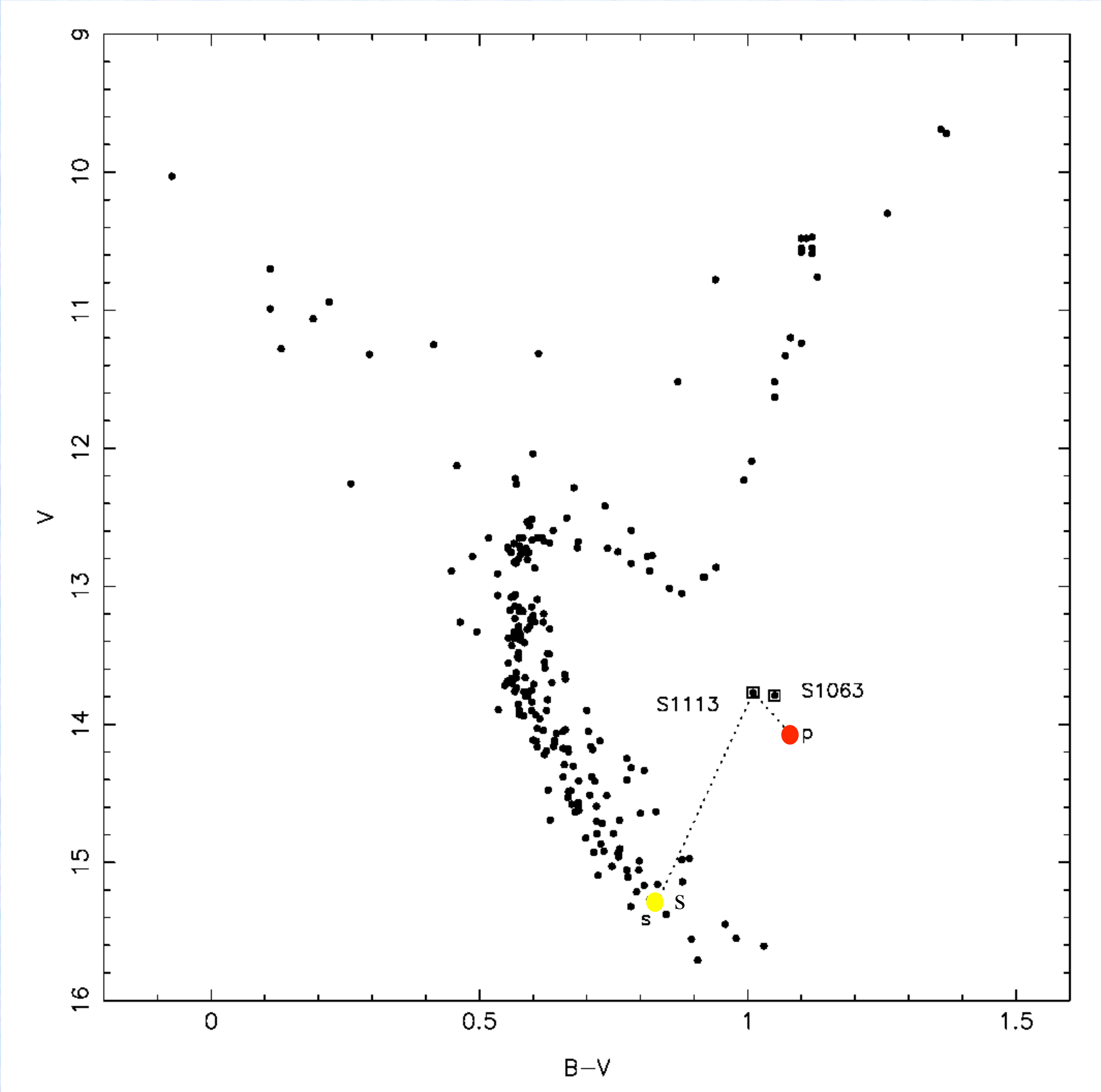
Sub-Subgiant S1113 - Geometric

$$\rho \propto \frac{\left(M \sin^3 i\right)}{\left(P_t v \sin i\right)^3}$$

$L_{V,2} / L_{V,1} = 0.11$



Sub-Subgiant S1113 - Photometric



$L_{V,2} / L_{V,1} = 0.11$

vs.

$L_{V,2} / L_{V,1} = 0.35 \pm 0.02$

Mid-Course Conclusions

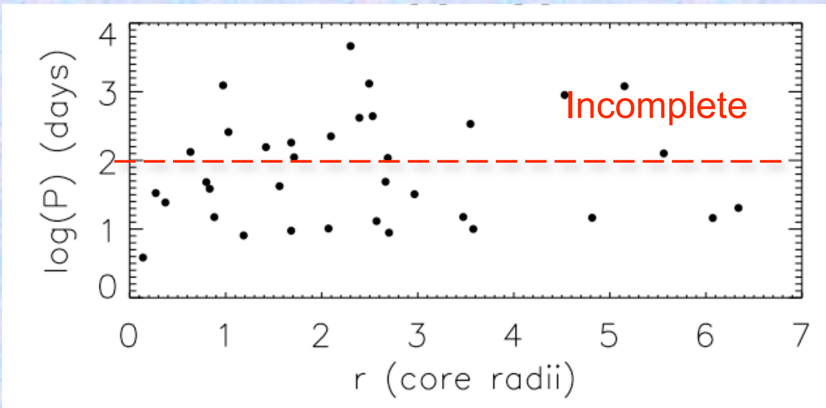
1. N-body simulations with initial binary populations predict stellar collisions.

3. N-body simulations with initial binary populations reproduce open cluster CMDs, including anomalous stars.

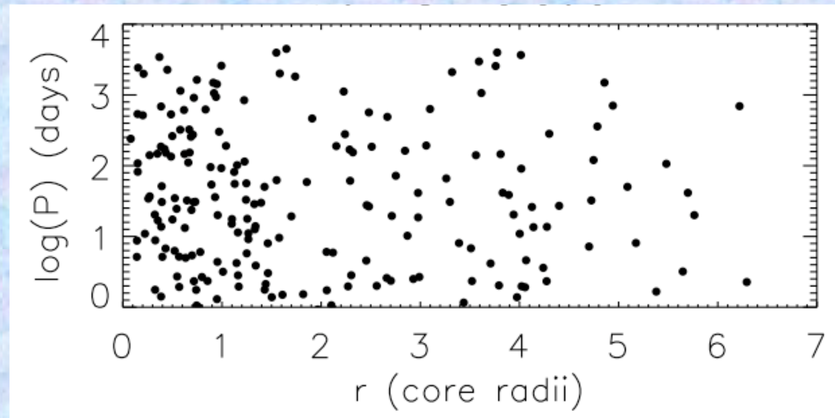
4. Evidence for encounter and collision products are being found in open clusters; require non-equilibrium stellar models.

Evolved Hard-Binary Population Periods

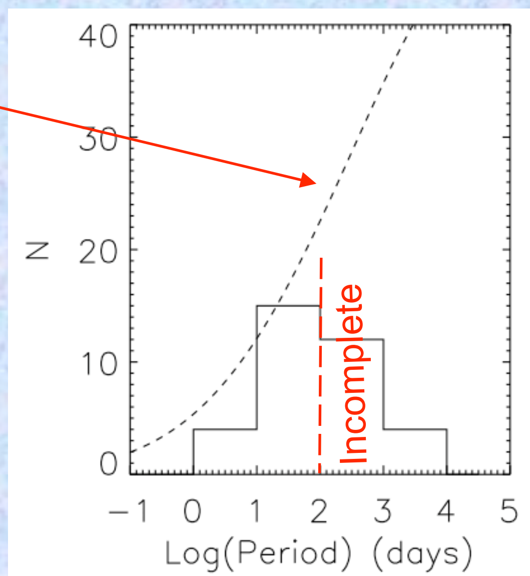
NGC 188 **(7 Gyr)**

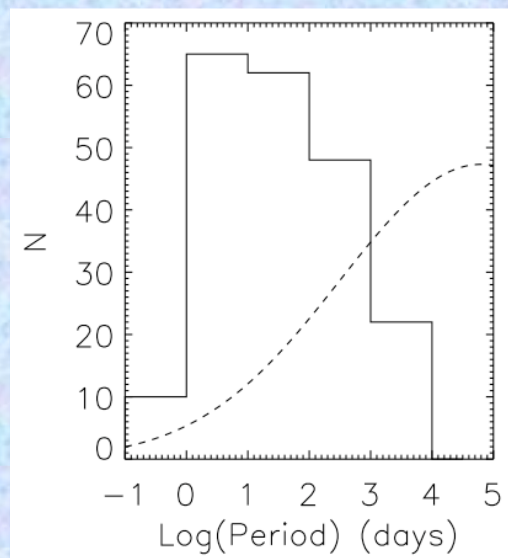


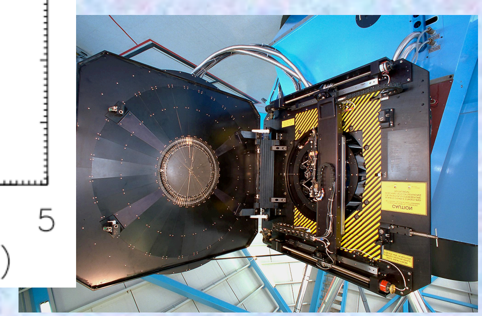
M67 simulation **(4.5 Gyr)**



Field (DM)

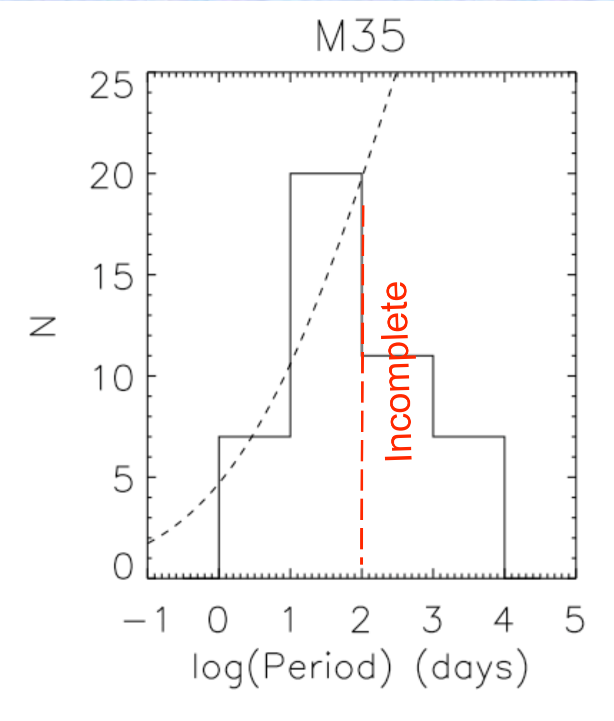




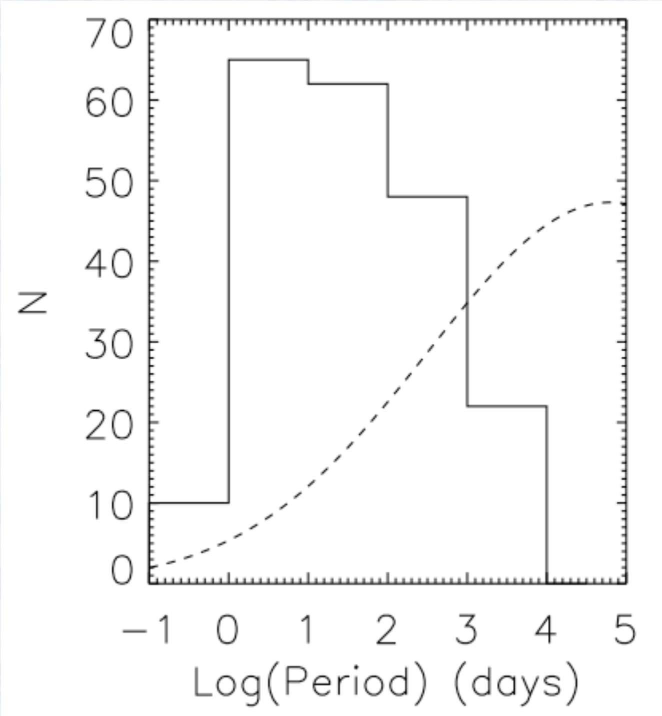


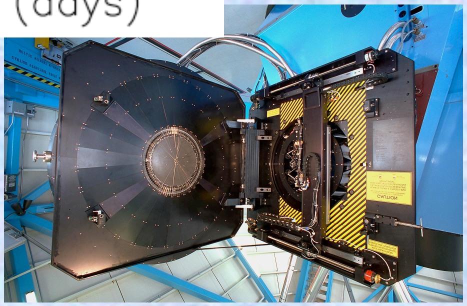
Initial Hard-Binary Population Periods

NGC 2168 **(0.15 Gyr)**



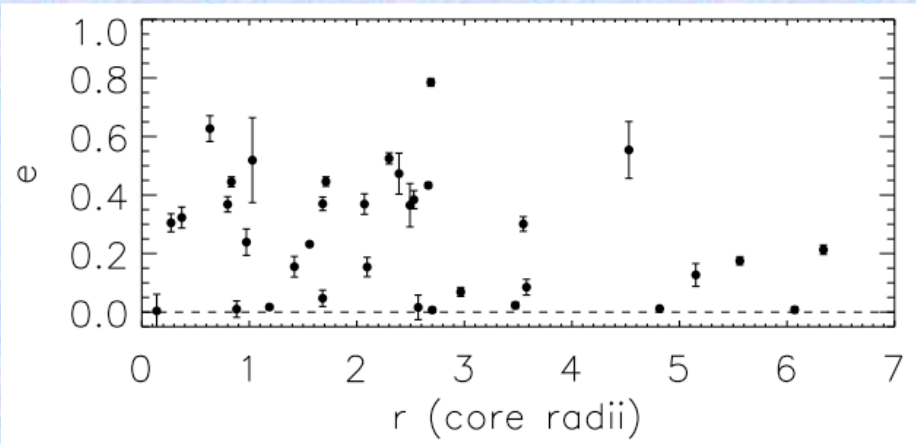
M67 simulation **(4.5 Gyr)**



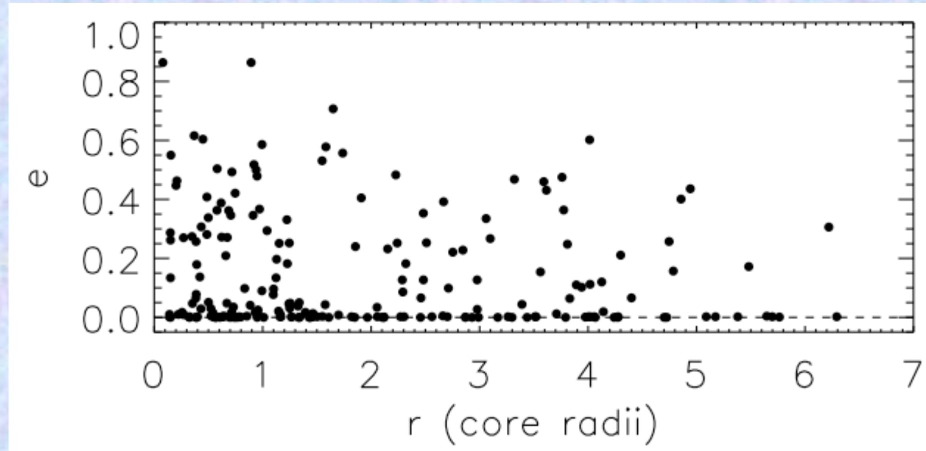


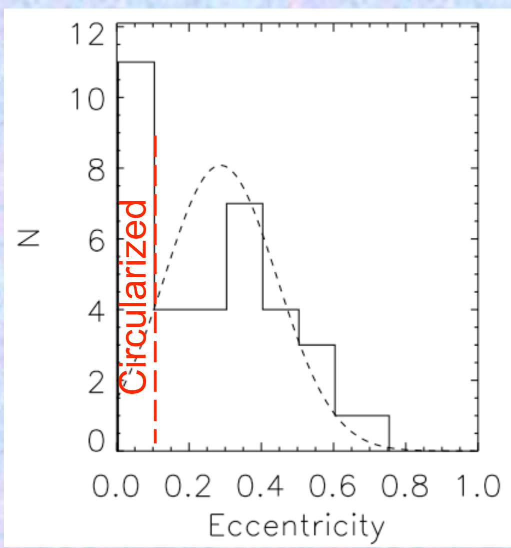
Evolved Hard-Binary Population Eccentricities

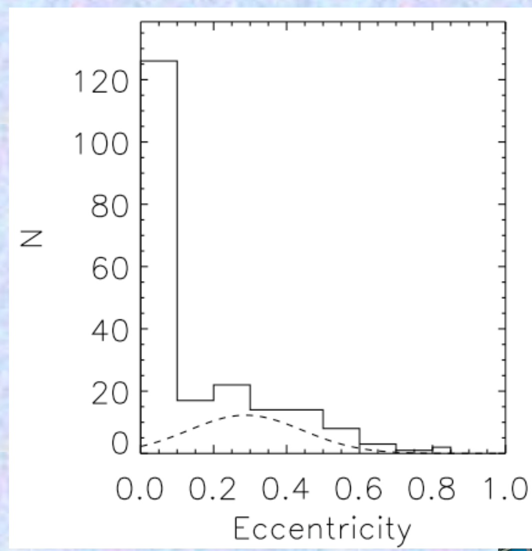
NGC 188 **(7 Gyr)**

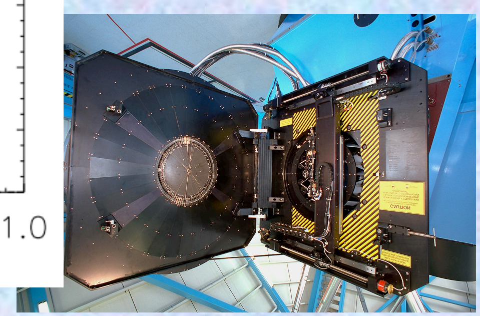


M67 simulation **(4.5 Gyr)**



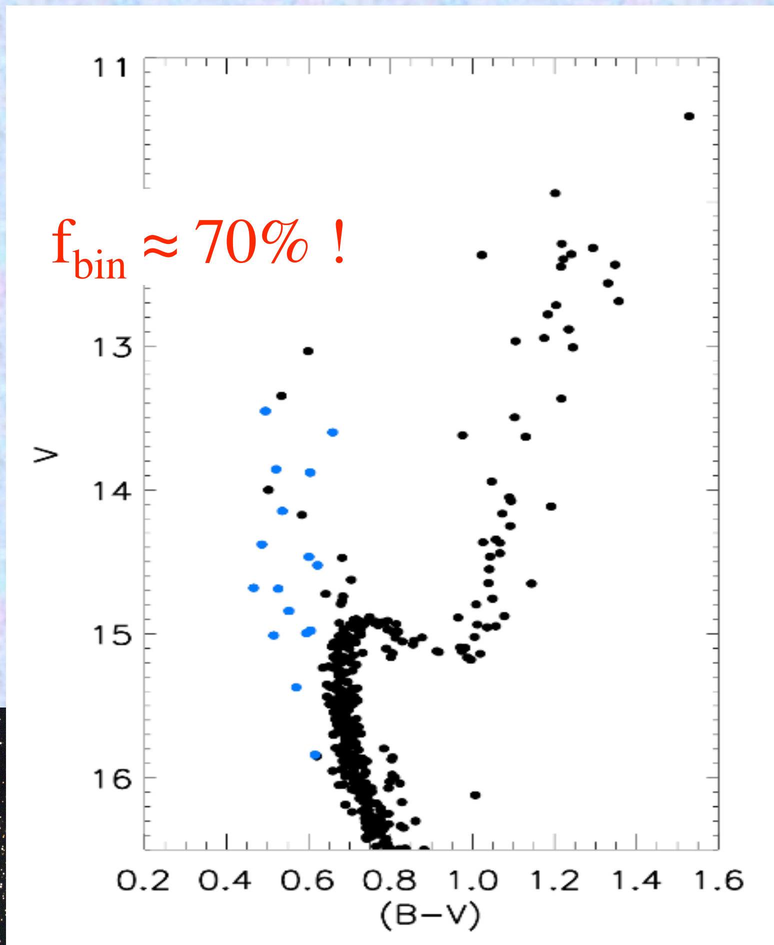




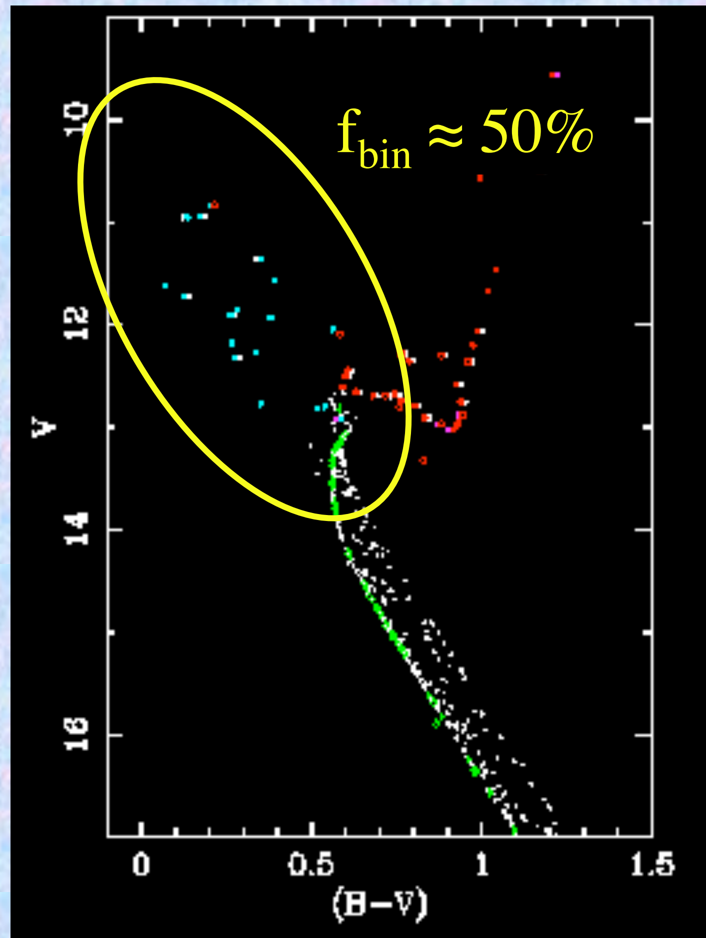


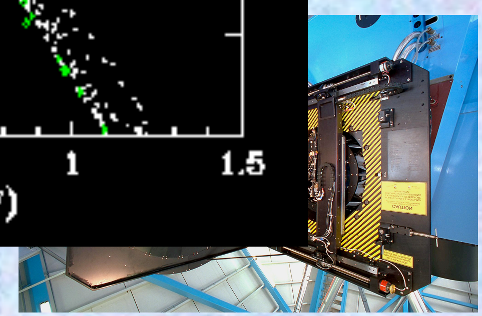
Evolved Hard-Binary Population
Blue Stragglers

NGC 188 **(7 Gyr)**

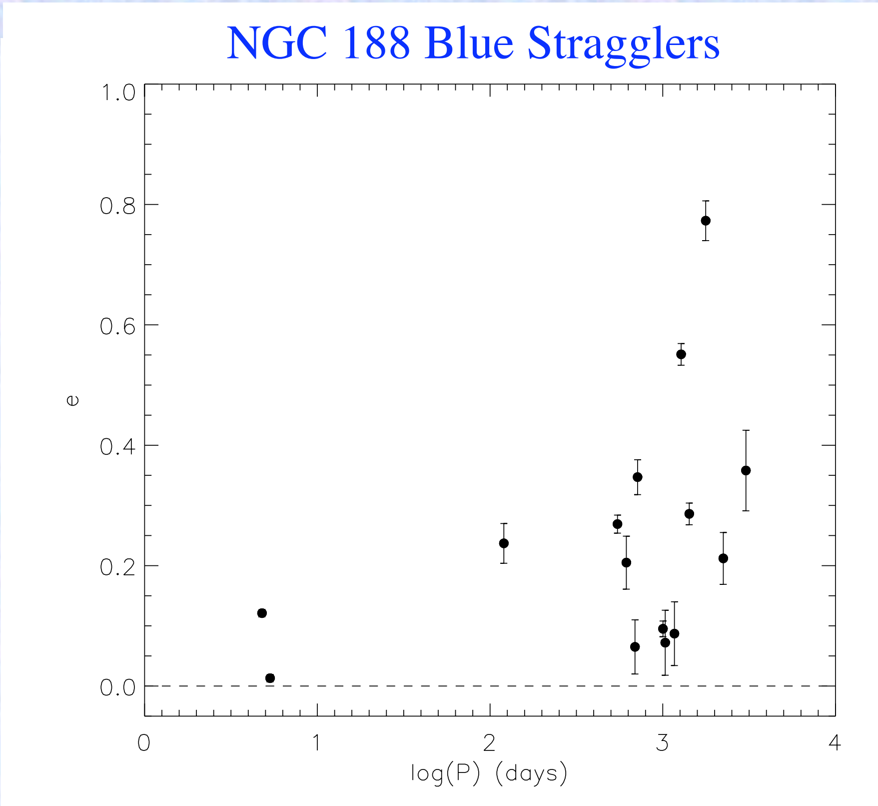


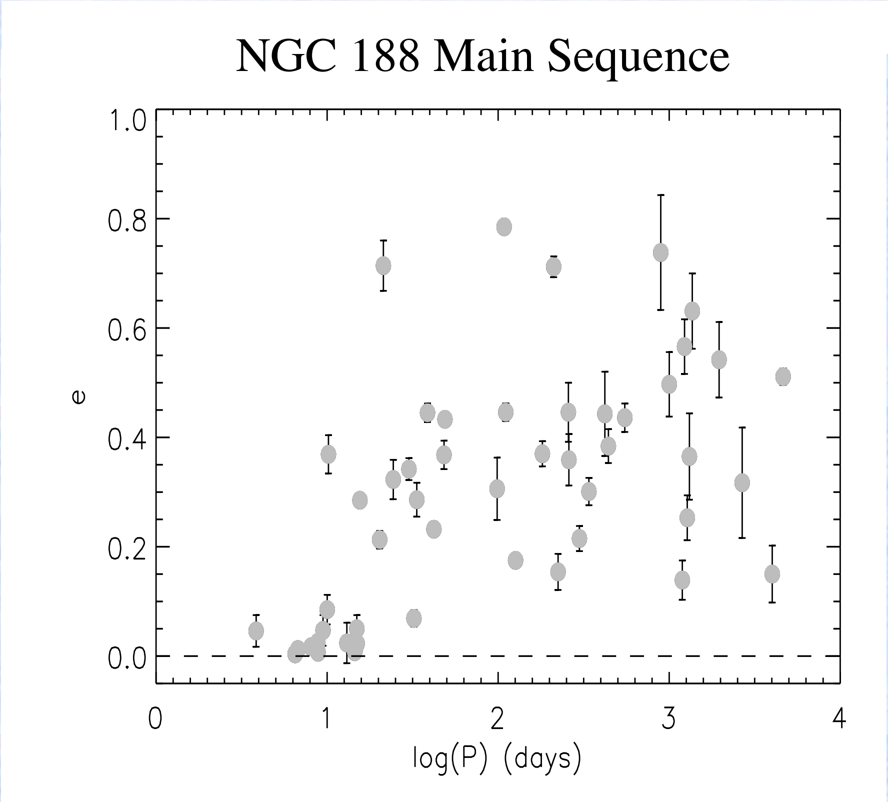
M67 simulation **(4.5 Gyr)**

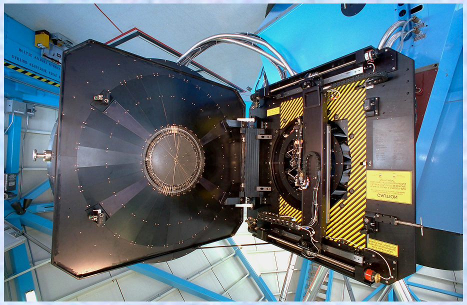




Angular Momentum of Blue Stragglers

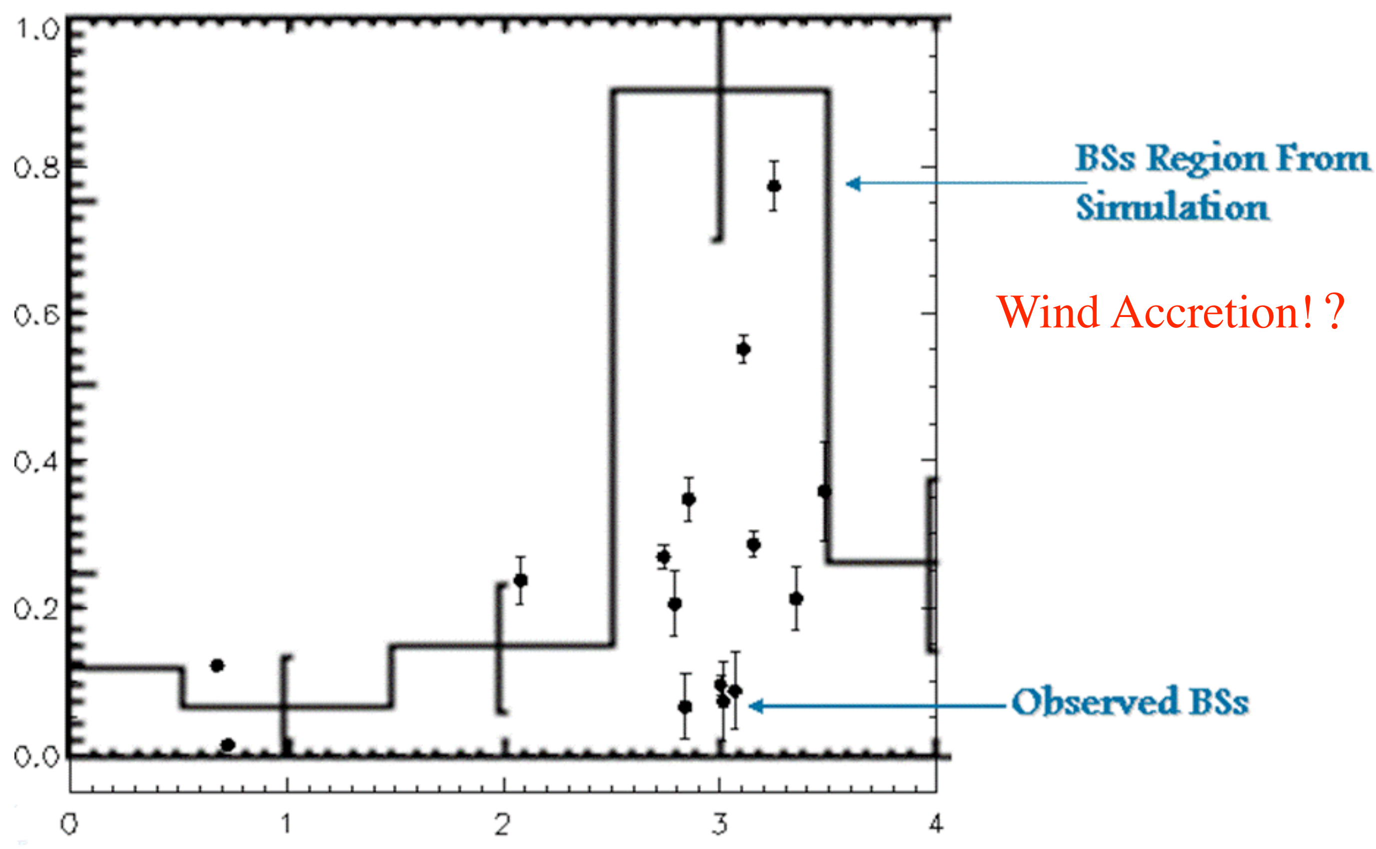




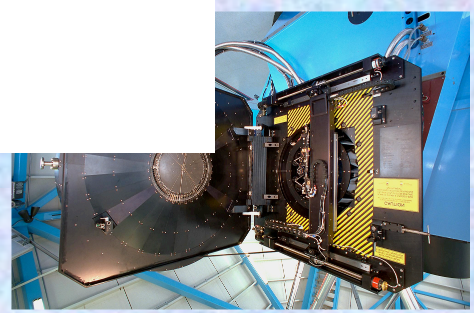


Angular Momentum of Blue Stragglers

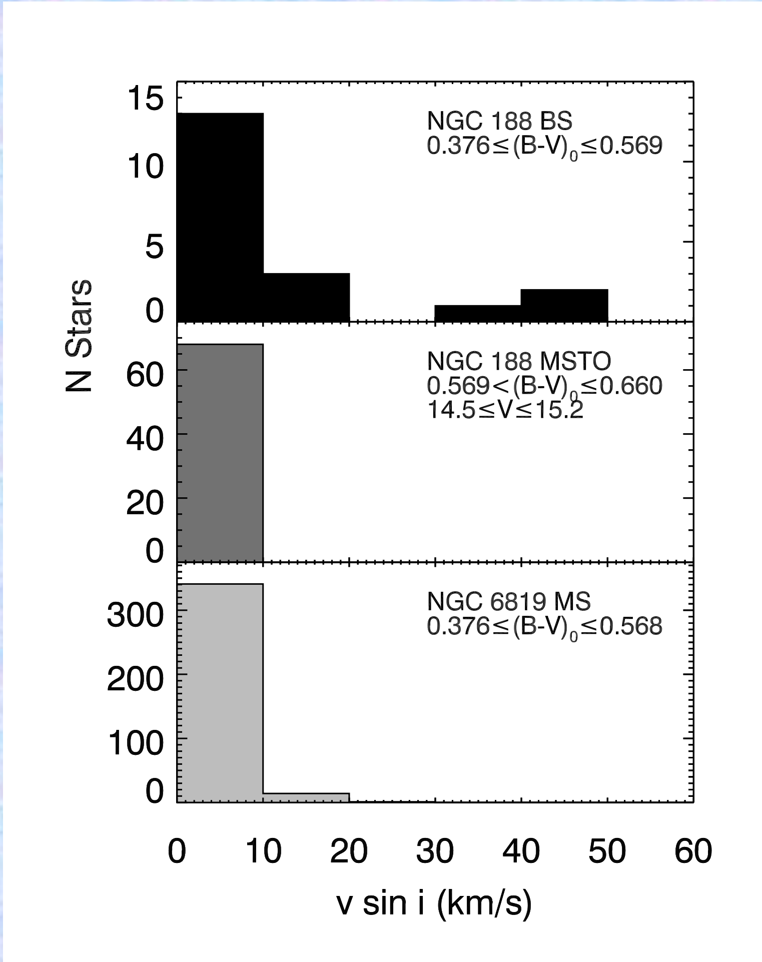
Observed e vs. log p Plot with Simulated BSs Period Distribution

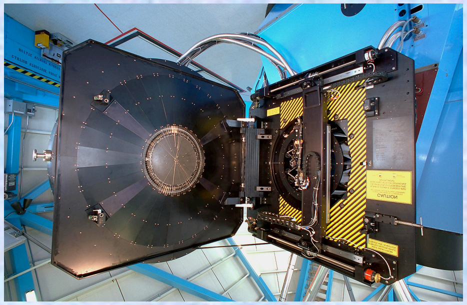


Wind Accretion! ?

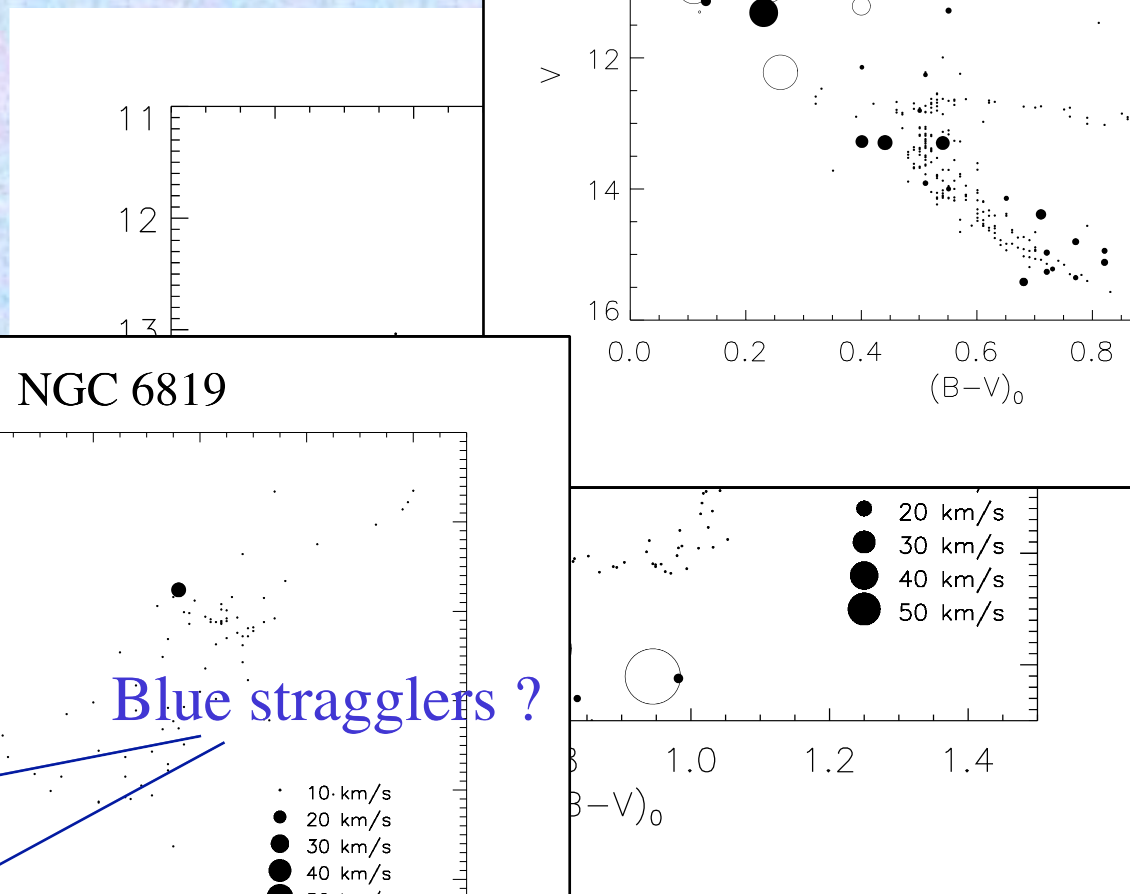


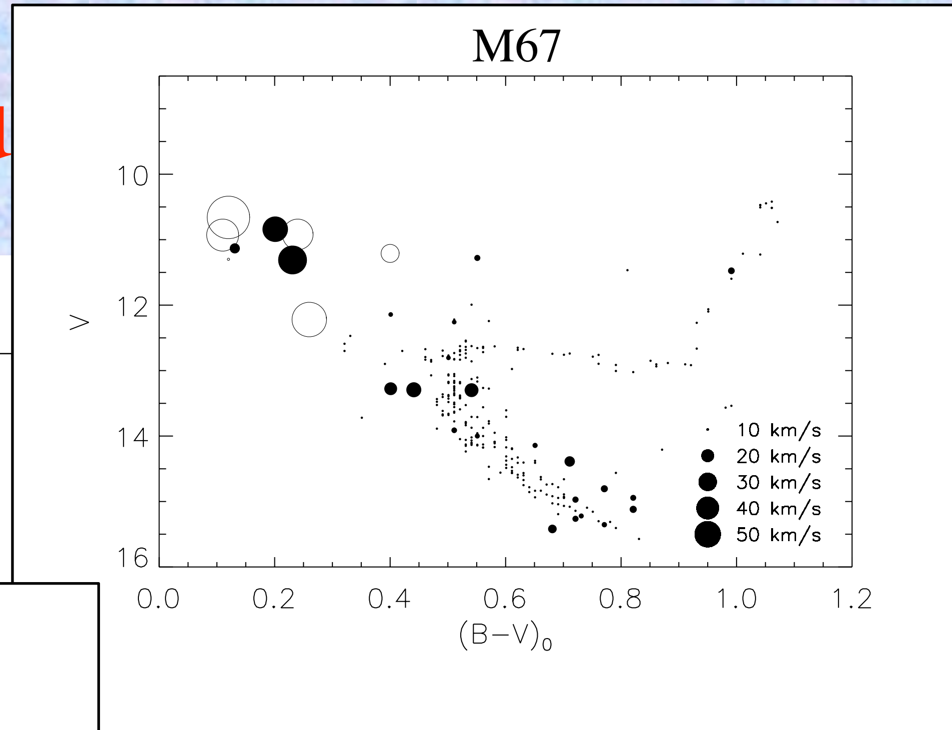
Angular Momentum of Blue Stragglers

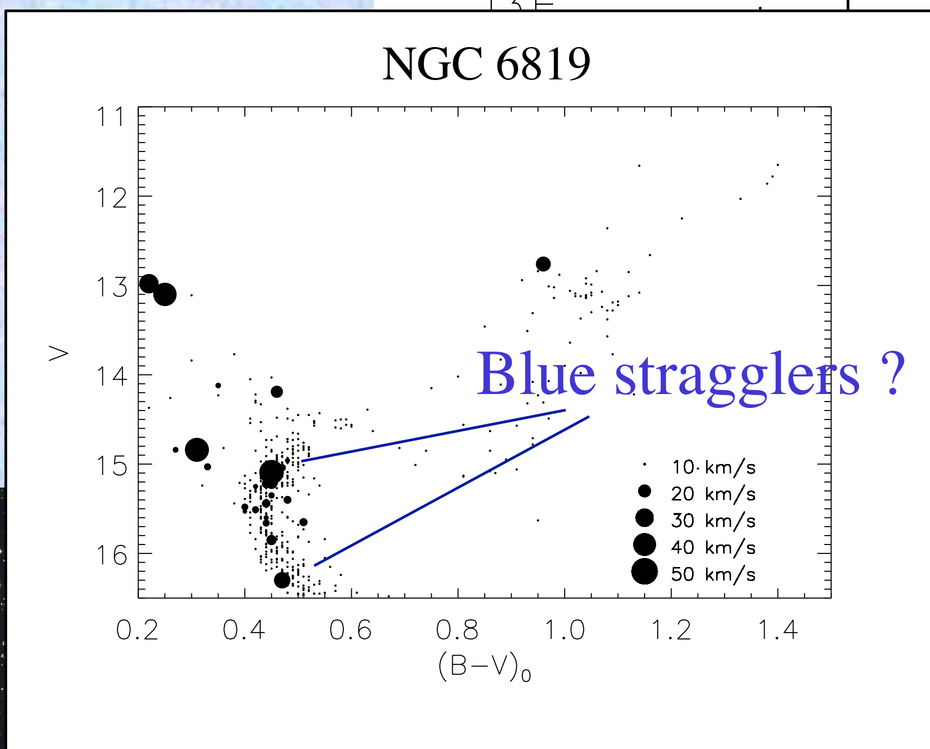


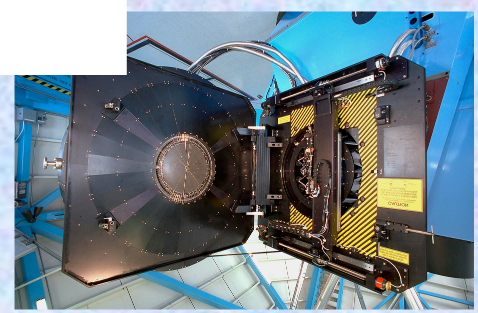


Angular Momentu









Conclusions

1. Evidence for encounter and collision products are being found in open clusters.

2. N-body simulations with initial binary populations reproduce open cluster CMDs, including anomalous stars, but with initial and final binary populations much too high.

3. Blue straggler angular momenta distributions – orbital and rotational – are distinguishing clues to formation process.

Concluding Thoughts

We are on the verge of *detailed* comparisons of N-body simulations and open clusters, *including binaries*.

Given the significance of dissipative processes between stars, we already may be limited by physics rather than computing power.

Fundamental stellar astrophysics still to be understood: blue stragglers, sub-subgiants, non-equilibrium stellar evolution? - an exciting time for students!