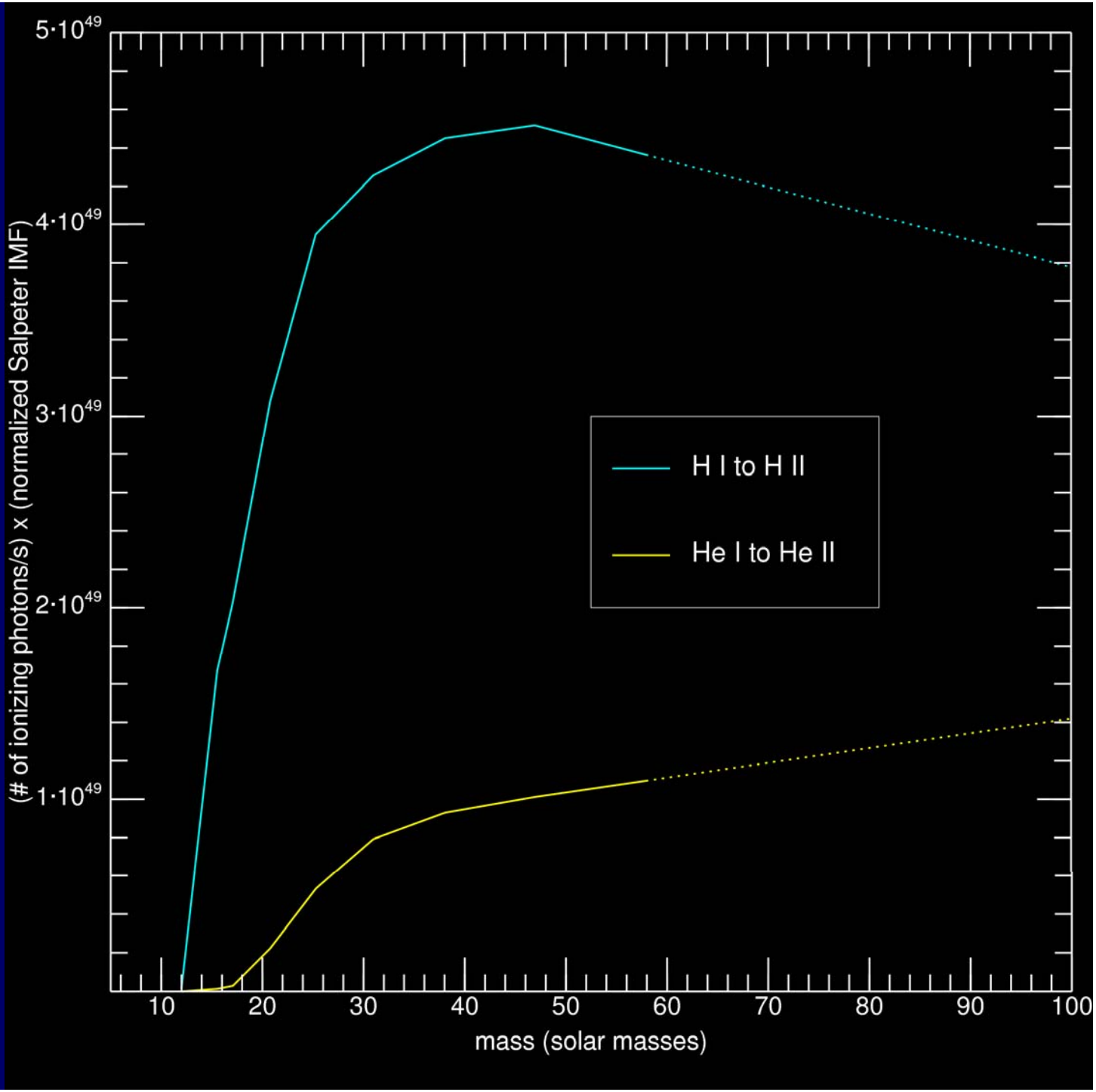
The stellar upper mass limit in the solar neighborhood

Jesús Maíz Apellániz
Instituto de Astrofísica de Andalucía
Granada, 1 March 2007

Is there a stellar upper mass limit?
Is the IMF Salpeter until the end?

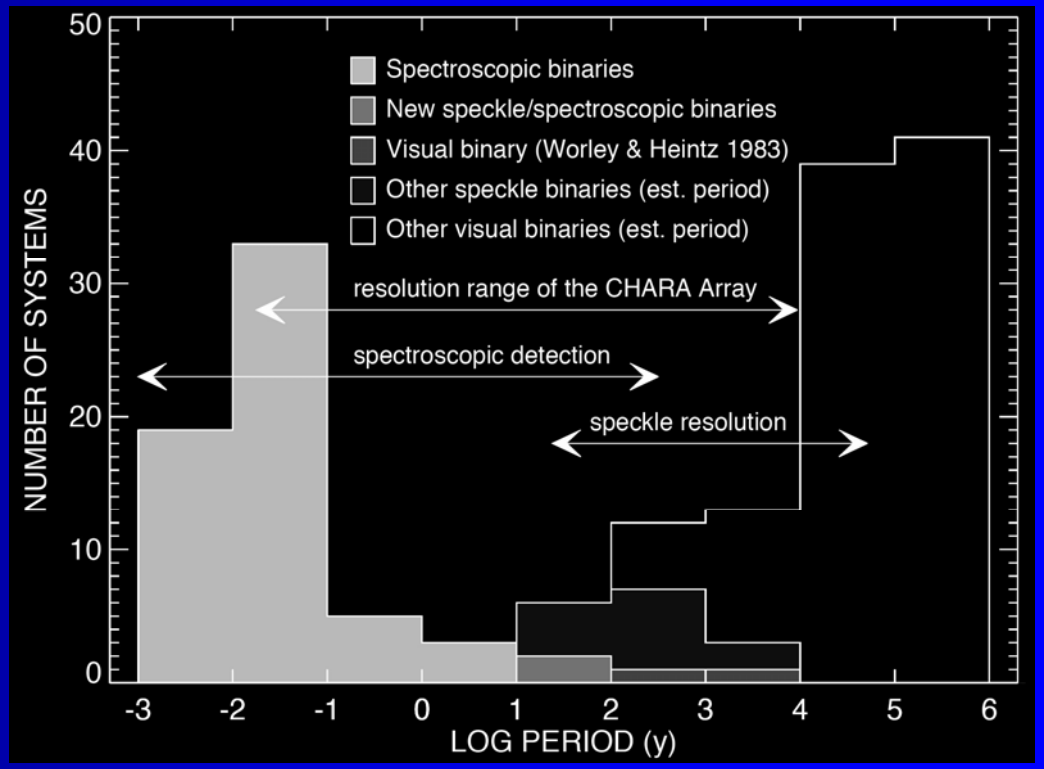
- Previous observational studies
  - Individual stars: O, WR, LBV
  - Clusters
- Theory
  - Massive-star formation mechanisms
- HST GO 10602 (+10205+10898)
  - Program description
  - Pismis 24-1
  - HD 93129A
- Future

Why do we care?



Individual stars: two important restrictions

- Good examples are scarce
  - Number
  - Distance
  - Extinction



- Multiplicity
  - Mason et al. (1998)
  - O stars
  - Are all non-runaway O stars multiple?

Measuring masses

- Keplerian masses
  - Astrometric binaries
  - Eclipsing spectroscopic binaries
  - Spectroscopic binaries with apsidal motion
- Evolutionary masses
  - Comparison between measured $T_{\rm eff}$ + L and evolutionary tracks
- Spectroscopic masses
  - Fitting $T_{\rm eff}$ y log$g$ to atmosphere models

Keplerian masses

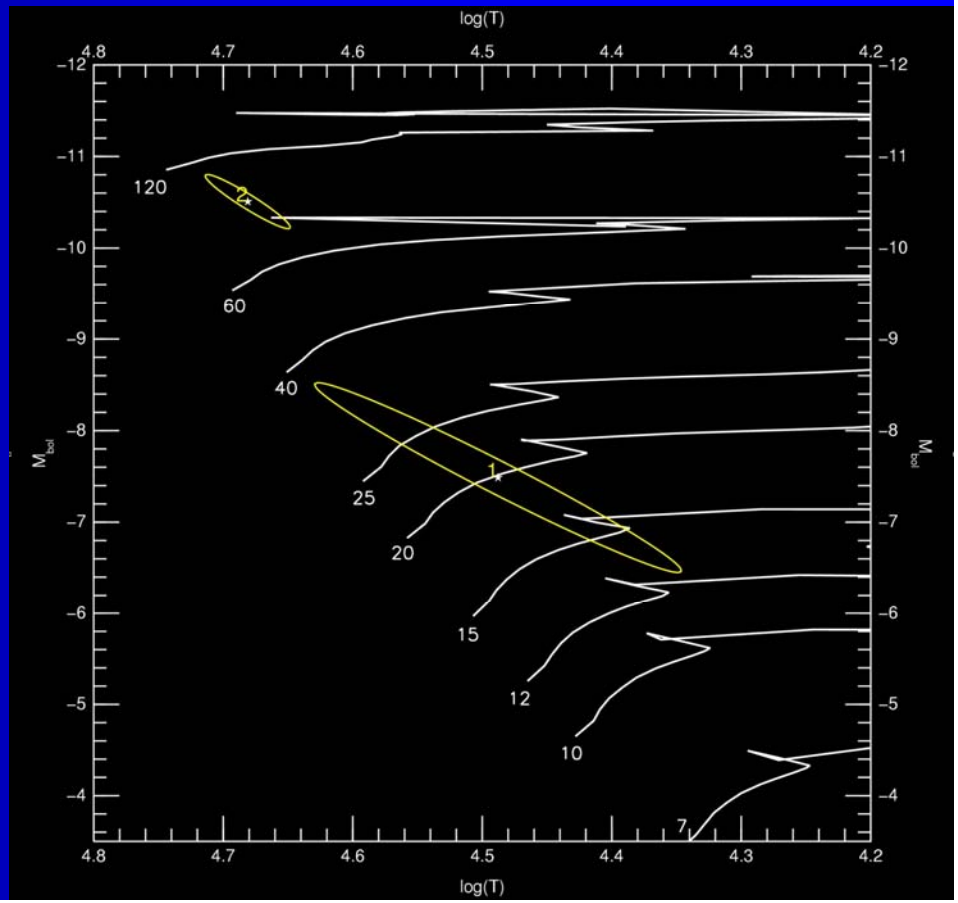
- Only direct method
- Problems:
  - Detection and follow-up
  - Limited sample
    - Astrometric: 3 O systems
    - Apsidal motion: 1 O system
    - Eclipsing binaries: tens of O systems
- ~~And the Oscar goes to~~ And the winner is…

Keplerian masses

- Only direct method
- Problems:
  - Detection and follow-up
  - Limited sample
    - Astrometric: 3 O systems
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- ~~And the Oscar goes to~~ And the winner is…
- … WR 20a (WN6ha+WN6ha)
  - $83 \pm 6\ M_{Sol} + 82 \pm 6\ M_{Sol}$

Evolutionary masses

- Measurable for all stars
- Problems:
  - Distances
  - Extinction
  - T_{eff} scale
  - Tracks
  - Multiplicity
- Cases with > 200 M_{Sol}

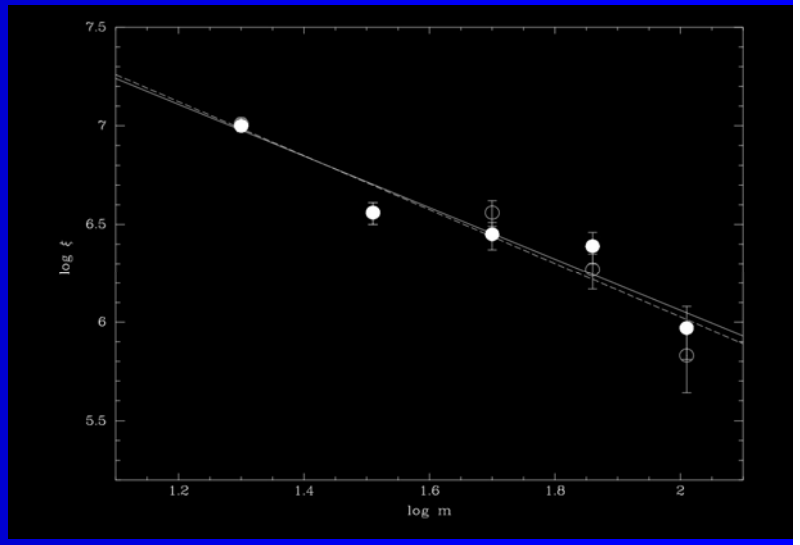


Spectroscopic masses

- Detailed atmosphere modeling
  - $T_{\rm eff}$, $\log g + m_V$, $d \Rightarrow L$, $R \Rightarrow M$
- Less sensitive to multiplicity and observational effects
- Most of 1990s discrepancies have disappeared with new models
- Problems:
  - Detailed modeling effort
  - Model dependency
  - Insensitive to binaries of similar spectral type

Massive stars in massive clusters

- Individual stars: needle in a galactic haystack
- Massive clusters: needle collection
- R136:
  - 2000 M_{Sol} star (1981)
  - Resolved by Weigelt & Baier (1985)
- Massey & Hunter (1998)
  - HST/FOS spectroscopy
  - Stars up to 136-155 M_{Sol}
  - Salpeter IMF until 120 M_{Sol}
  - Consistent with $M_{sup} = \infty$ …
  - … but $M > 120\ M_{Sol}$ stars not included in calculation of M_{sup}



Massive stars in massive clusters

- Weidner & Kroupa (2004), Oey & Clarke (2005), Figer (2005), Koen (2006)
  - R136 (+ Arches and others)
  - M_{sup} ~150 M_{Sol} or IMF very steep for > 120 M_{Sol}
- What happened?
  - New atmosphere models
    - $T_{eff} \downarrow$ for a spectral type $\Rightarrow M_{bol} \downarrow \Rightarrow$ evolutionary mass $\downarrow$
  - Special care for small *N* statistics needed
    - IMF slopes are overestimated if constant bin sizes are employed

How do massive stars form?

- Stellar collisions
  - How do you reach required densities?
  - Predicted flatter IMF, higher M_{sup} in dense clusters
- Disk accretion
  - May avoid Eddington-limit issues
  - Time scales?
  - No disks observed around OB stars yet
  - More uniform IMF, M_{sup} predicted

HST GO 10602 (+10205+10898)

- Observe all known O2/O3/O3.5 stars in the Galaxy
  - ACS/HRC+WFC with multiple filters
  - HRC: 0.028"/píxel, excellent astrometry
  - 7 stars in NGC 3603
  - 13 stars in less-dense clusters
  - Low/moderate extinction: $E(B\text{-}V) < 2.5$
- Objectives:
  - Multiplicity and M_{sup}: unresolved components?
  - IMF calculation

Pismis 24-1

- Brightest star in Pismis 24 (2.5 kpc)
- Cluster in H II region NGC 6357
- Spectral type O3.5 If*
- Main ionizing source with Pismis 24-17, O3.5 III(f*)
- Walborn et al (2002):
  - Evolutionary mass of 210-291 M_{Sol} (old T_{eff} scale)
- Lortet et al. (1984):
  - Radial velocity changes

Pismis 24-1



Pismis 24-1

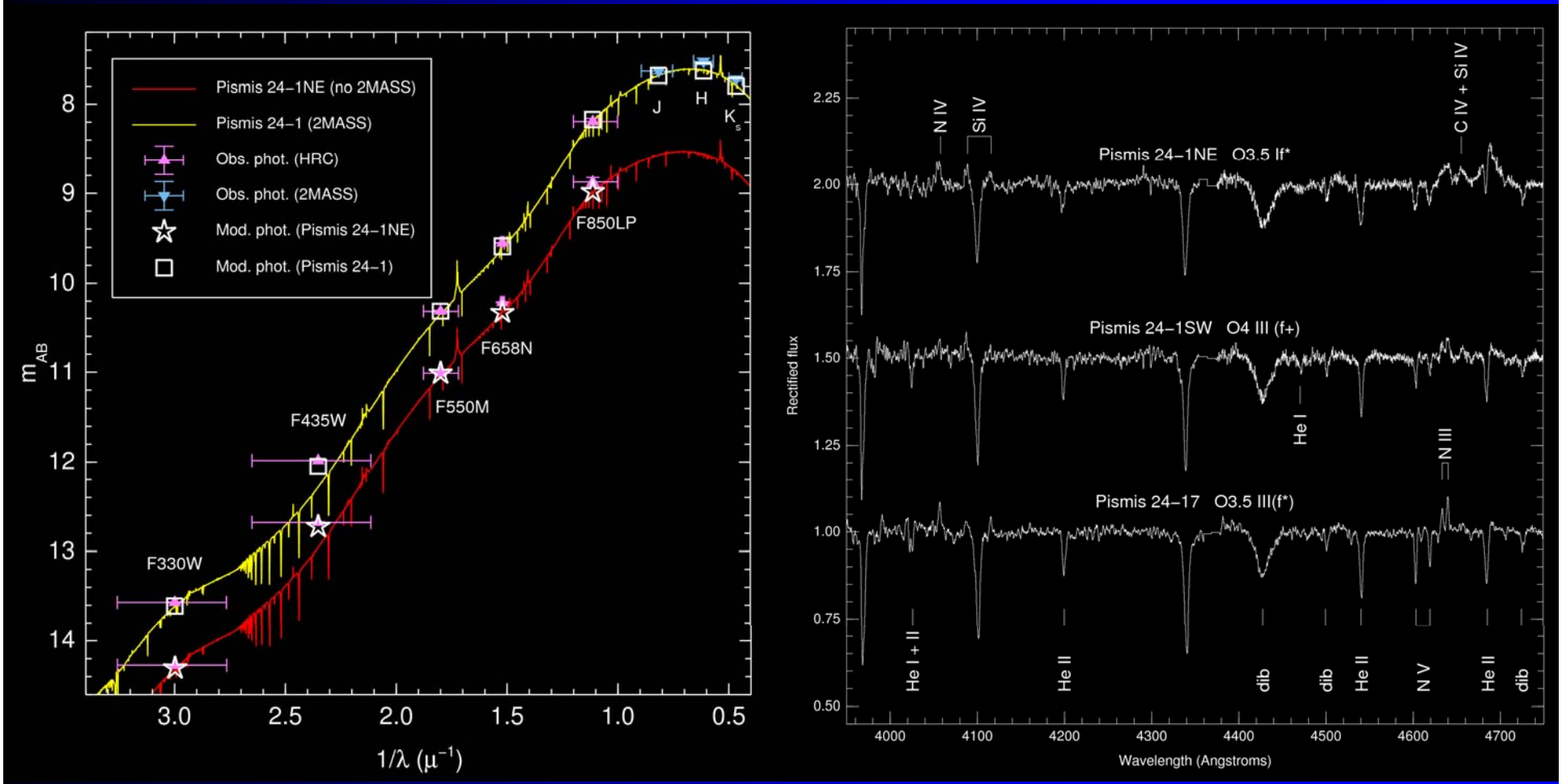
QuickTime™ and a
decompressor
are needed to see this picture.

Pismis 24-1



- Two components separated by 0.36386"
- $\Delta m \sim 0.1$ in NUV and optical
- $A_{F550M} = 5.87 \pm 0.02$ mag
- Resolved spectroscopy from Las Campanas:
  - Pismis 24-1 NE: O3.5 If*
  - Pismis 24-1 SW: O4 III(f+)
- Unresolved spectroscopy from CASLEO:
  - Δv between +20 y -90 km/s
  - N IV λ4058 shifts: NE is the spectroscopic binary
- Photometric variability (Massey et al.):
  - Similar eclipses
  - Period: 2.36088 days

Pismis 24-1


Pismis 24–1NE (no 2MASS)
Pismis 24–1 (2MASS)
Obs. phot. (HRC)
Obs. phot. (2MASS)
Mod. phot. (Pismis 24–1NE)
Mod. phot. (Pismis 24–1)
J
H
K_s
F850LP
F658N
F550M
F435W
F330W
m_AB
1/λ (μ^-1)
Pismis 24–1NE O3.5 If*
Pismis 24–1SW O4 III (f+)
Pismis 24–17 O3.5 III(f*)
N IV
Si IV
C IV + Si IV
He I
N III
He I + II
He II
dib
N V
Rectified flux
Wavelength (Angstroms)

Pismis 24-1

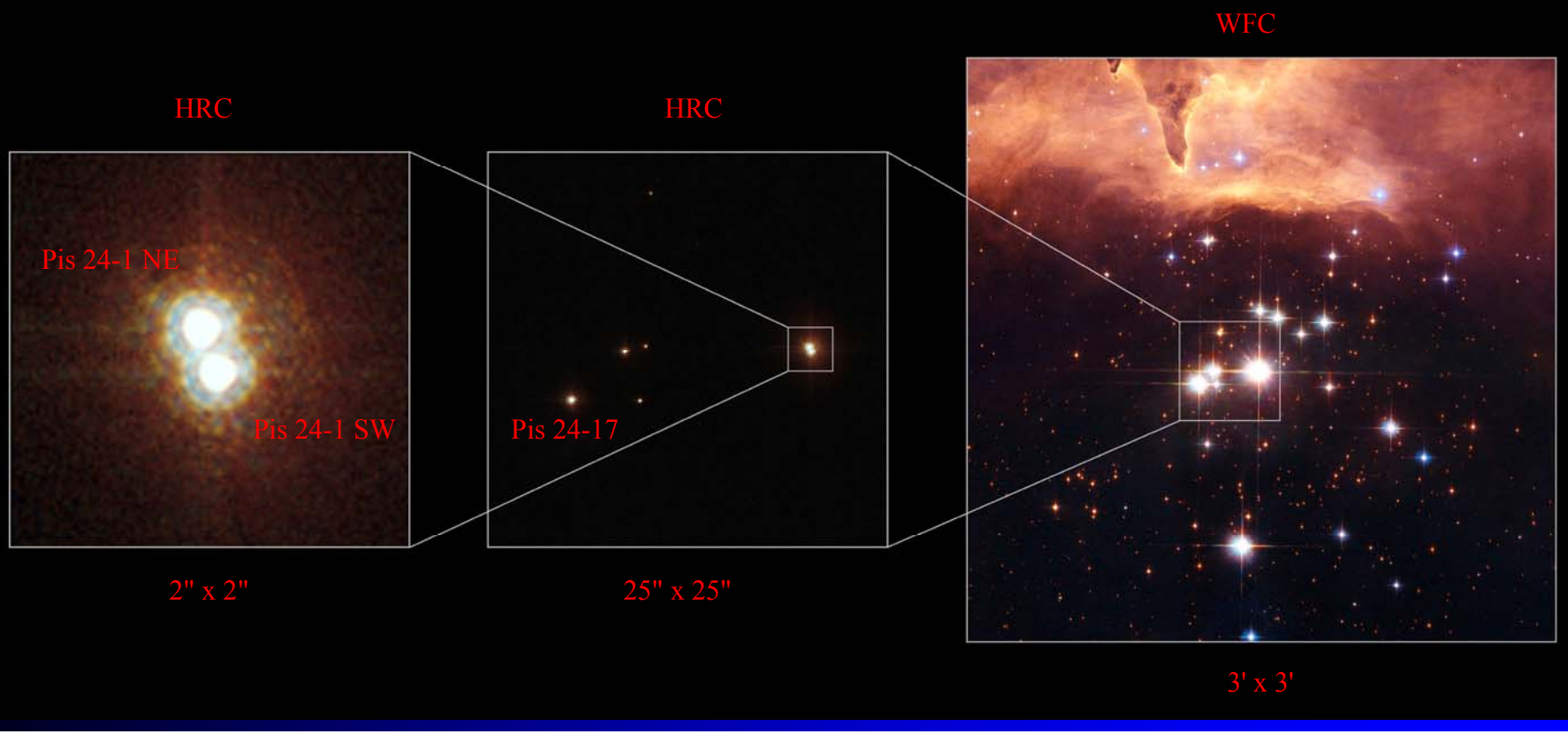


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Pismis 24

- Pis 24-1 SW: 96 ±10 M_{Sol}
- Pis 24-1 NEa: ~ 64 M_{Sol}
- Pis 24-1 NEb: ~ 64 M_{Sol}
- Pis 24-17: 92 ± 9 M_{Sol}
- "Pis 24-1": 155 ± 19 M_{Sol}

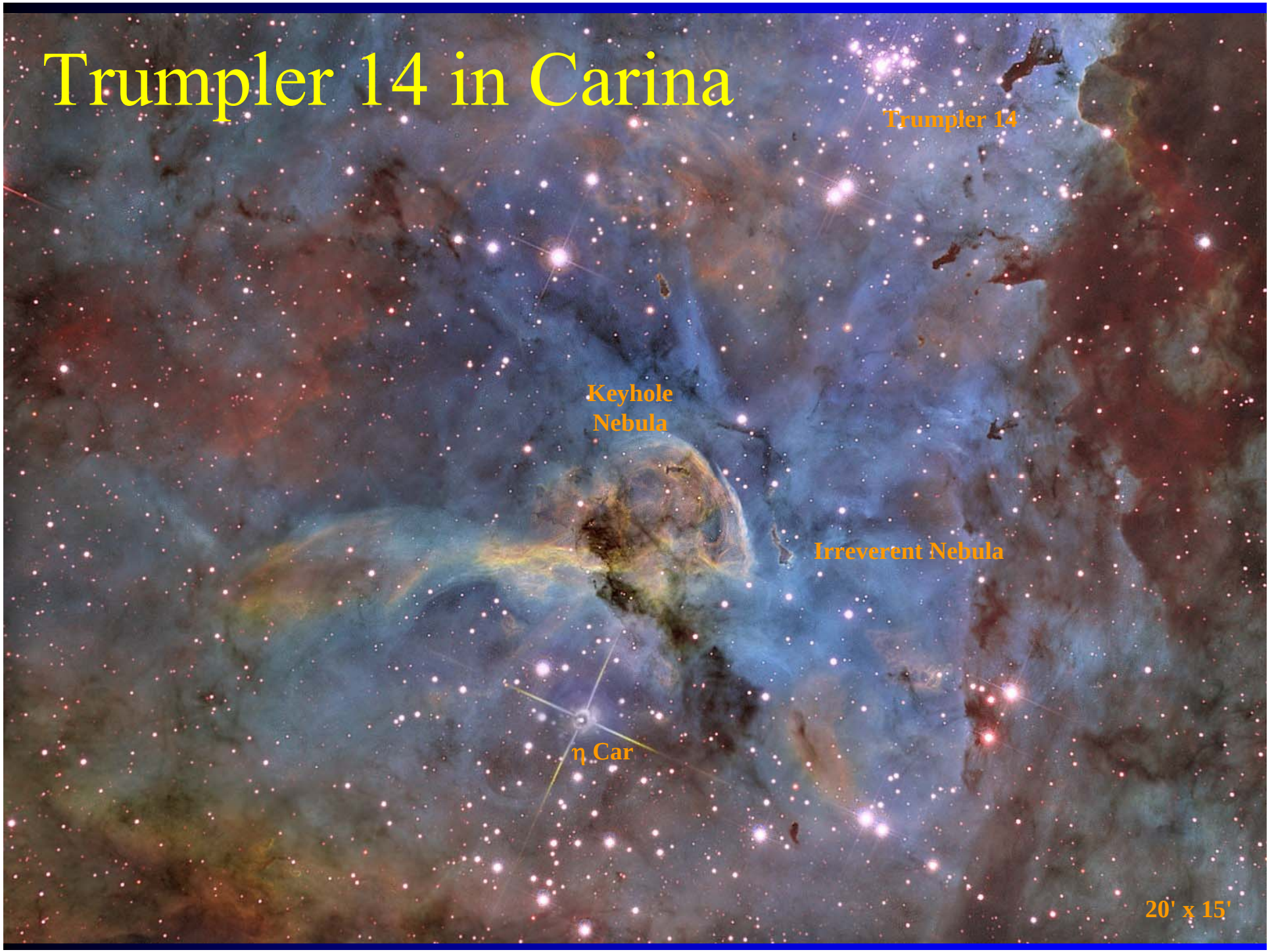
- Medium-sized cluster with 4 very massive stars
- Atypical IMF?
- Favors accretion theories
- Pis 24-1: point source at the distance of 30 Doradus



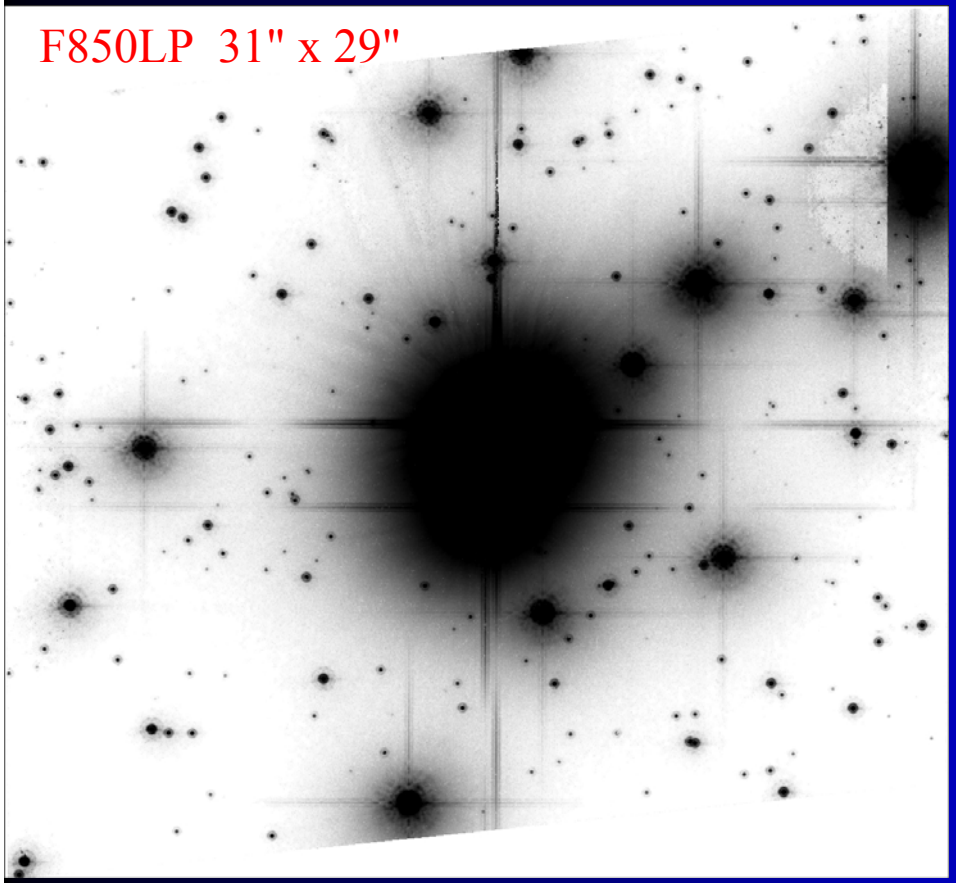
HD 93129A

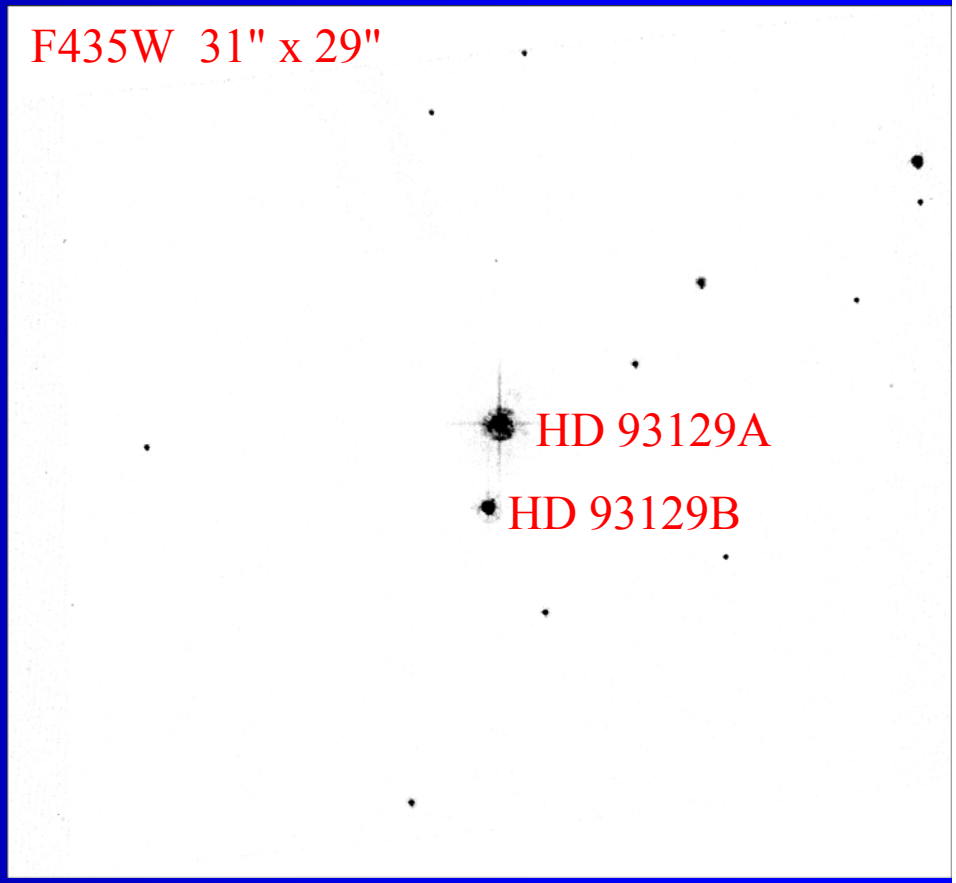
- Prototypical O2 If*
- Closest O2 star (2.3 kpc)
- At the nucleus of Trumpler 14 in the Carina Nebula
  - OB Association with more O stars in the solar neighborhood
- Nelan et al. (2004) resolved it with HST/FGS: $\Delta m \sim 1$, separation of 0.050”
- Observed with HRC in GO 10205 and 10898 and with WFC in 10602

Trumpler 14 in Carina



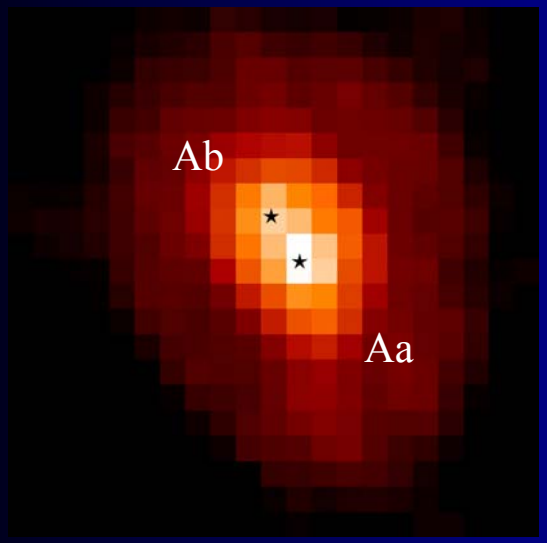
Trumpler 14 with HRC



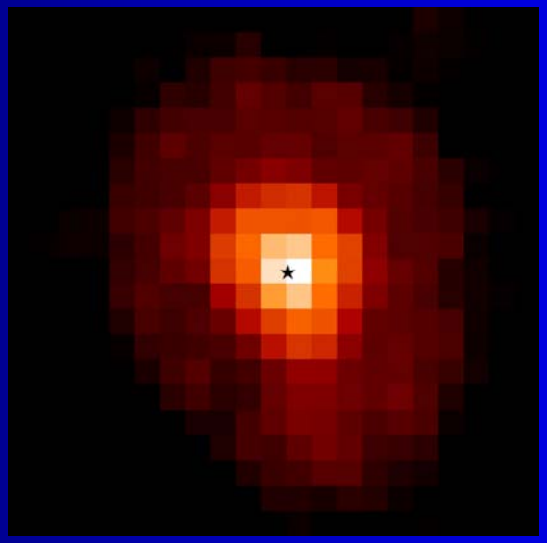


HD 93129 with HRC

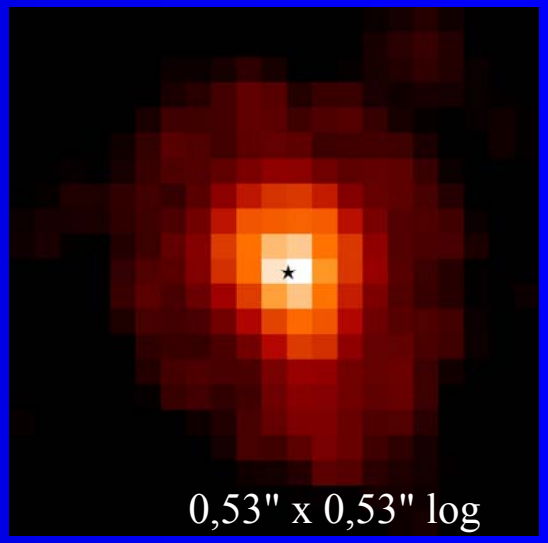
HD 93129A - data



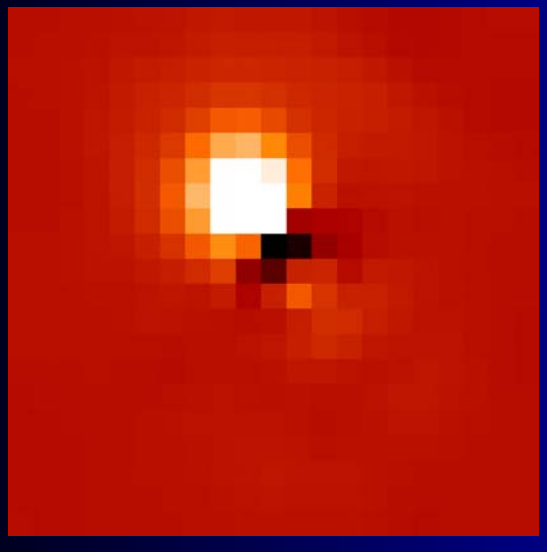
HD 93129B - data



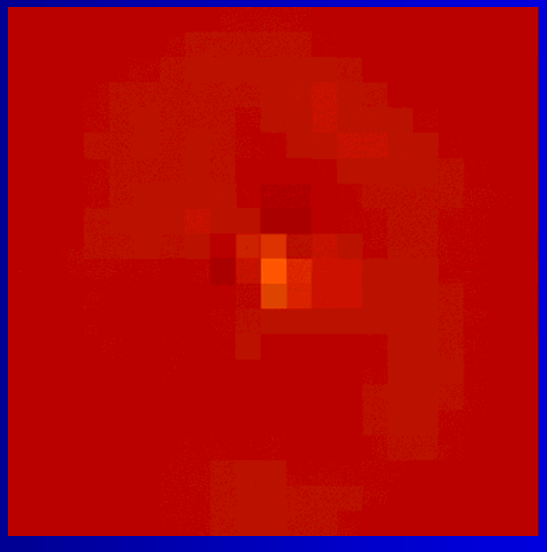
PSF



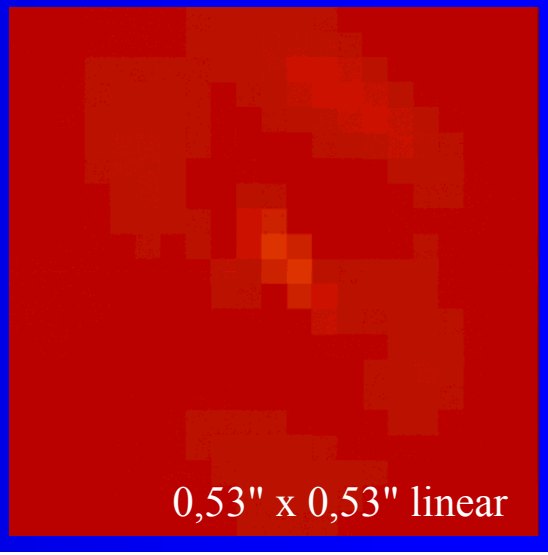
HD 93129A - simple residual



HD 93129B - simple residual

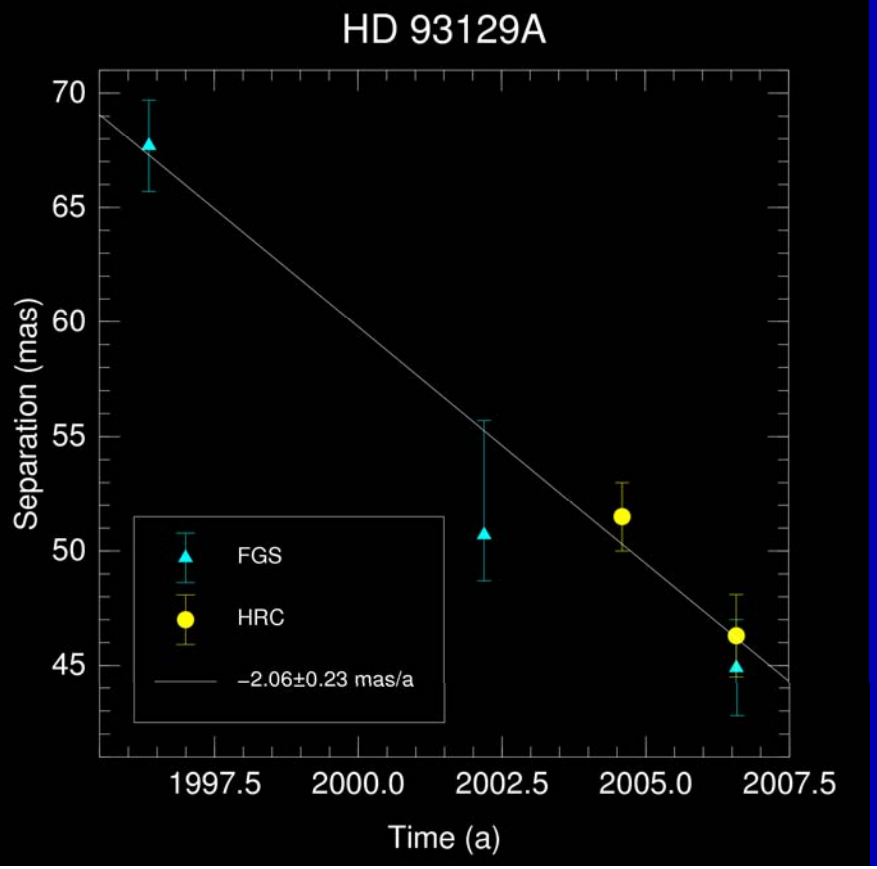


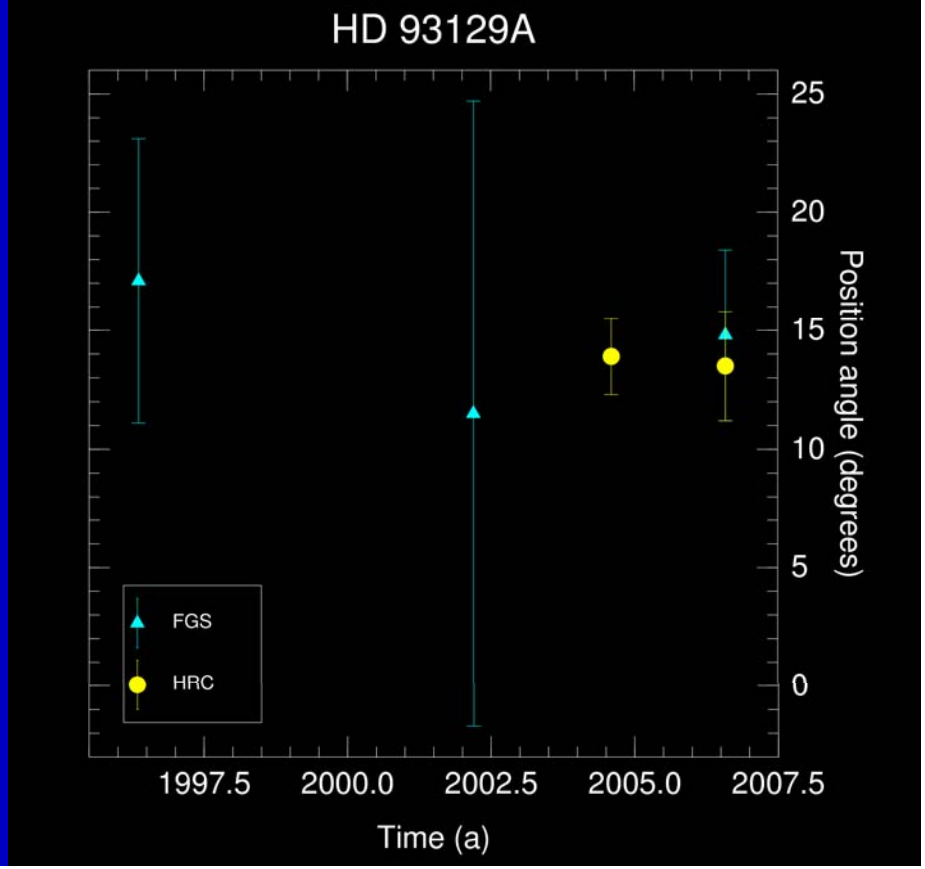
HD 93129A - double residual



HD 93129Aa+b:
The most massive astrometric binary

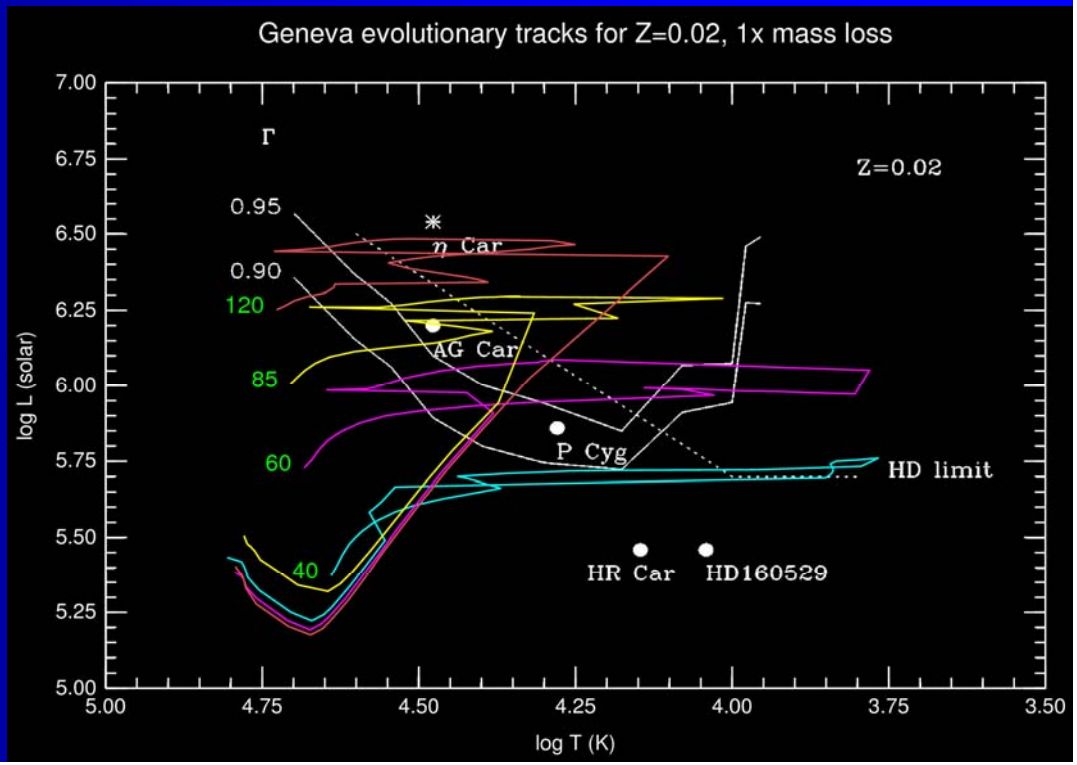
- $M_1 + M_2 \sim 200\ M_{Sol}$ for a circular $i = 90^o$ orbit
- Analyzing M_2 / M_1
- FGS in 2008 and 2009
- Period: 100-200 a
- Δv with STIS?



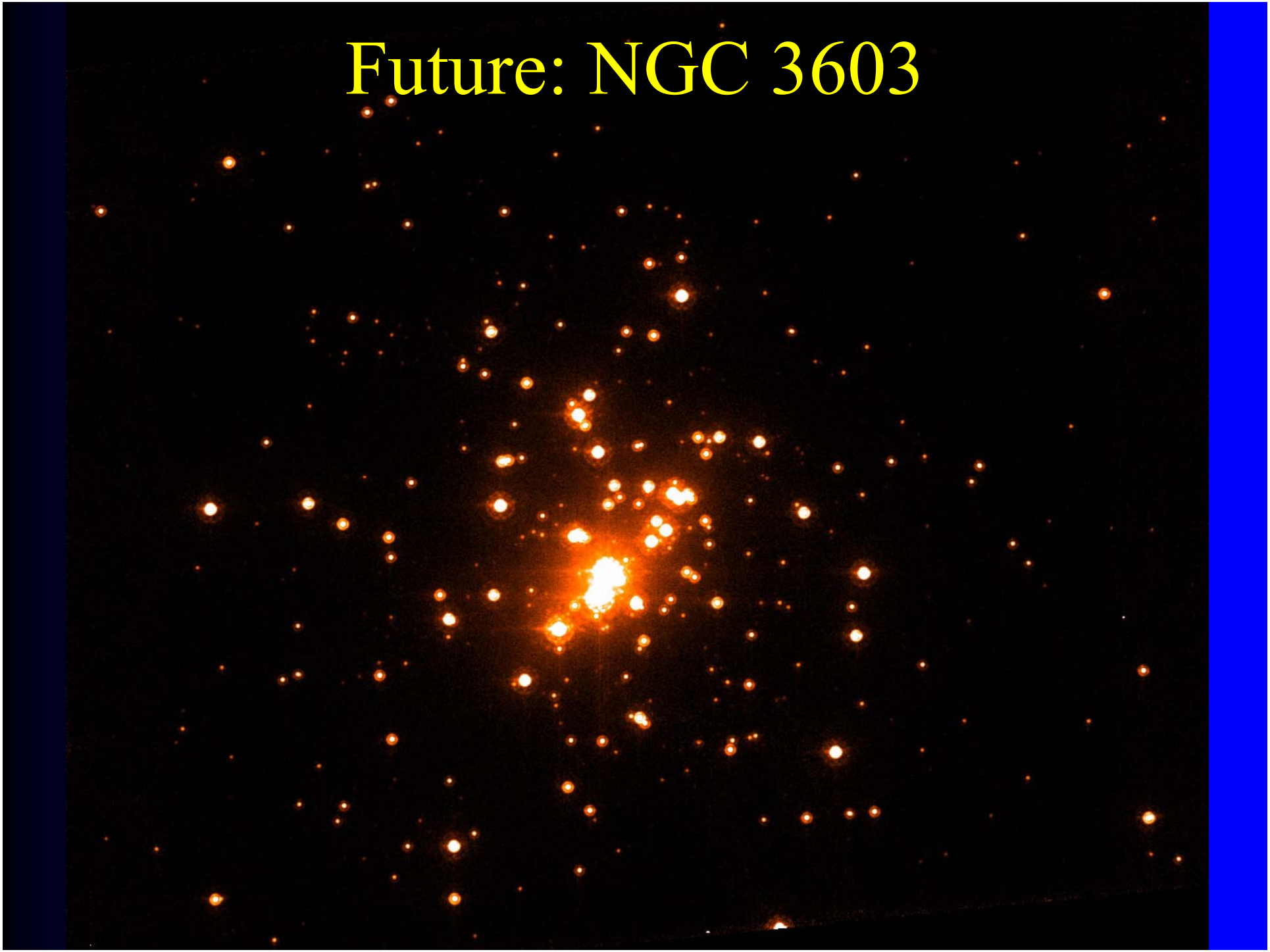


Future: Other candidates to the Galactic heavy weight title

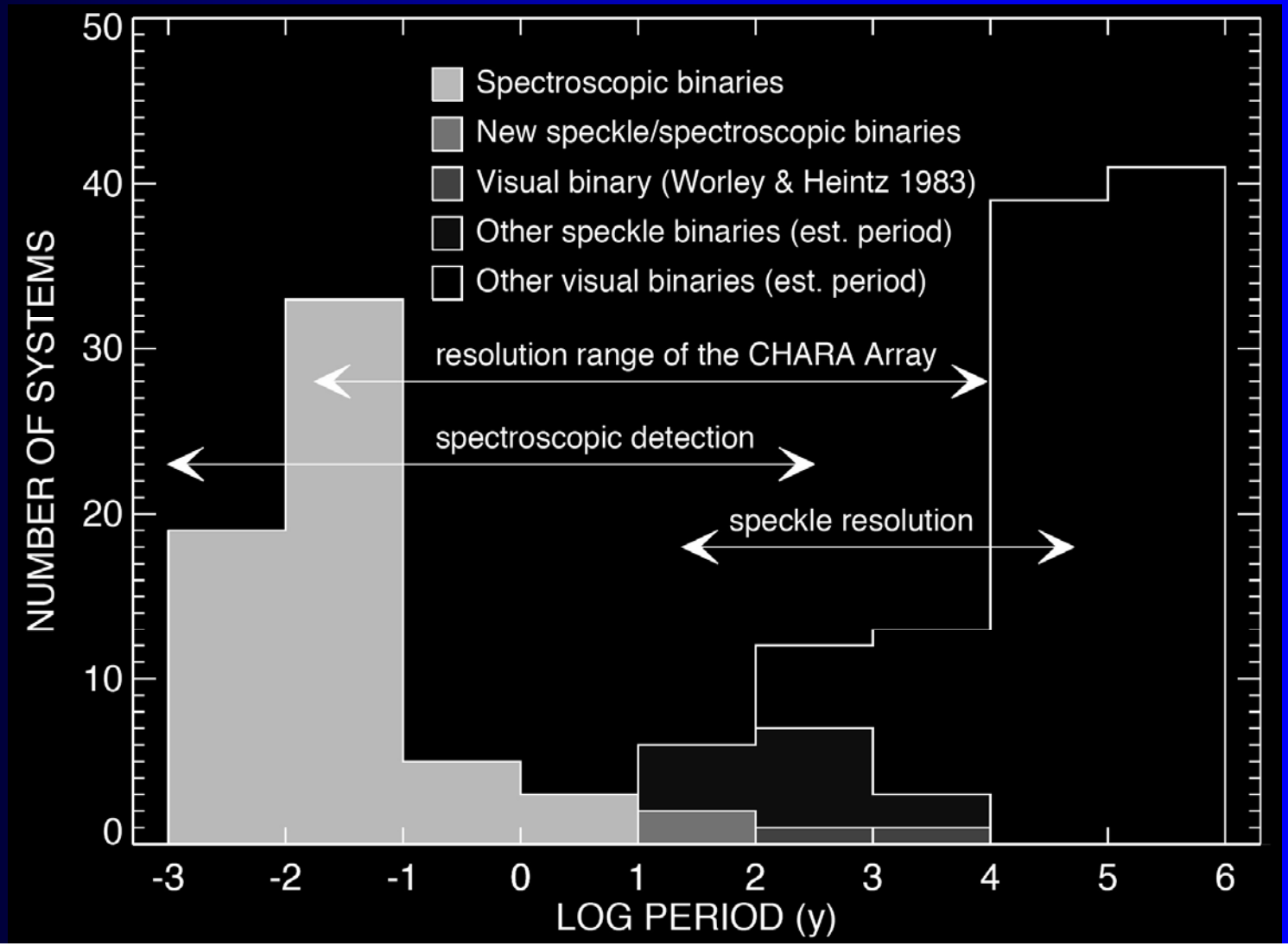
- O2/3 ⇒ WN h ⇒ LBV ⇒ WN ⇒ WC ⇒ SN Ic
  - Cygnus OB2-22A (O3)
  - WN h stars in NGC 3603
  - η Car (LBV)
  - Pistol star (LBV)
- HRC is dead :-(



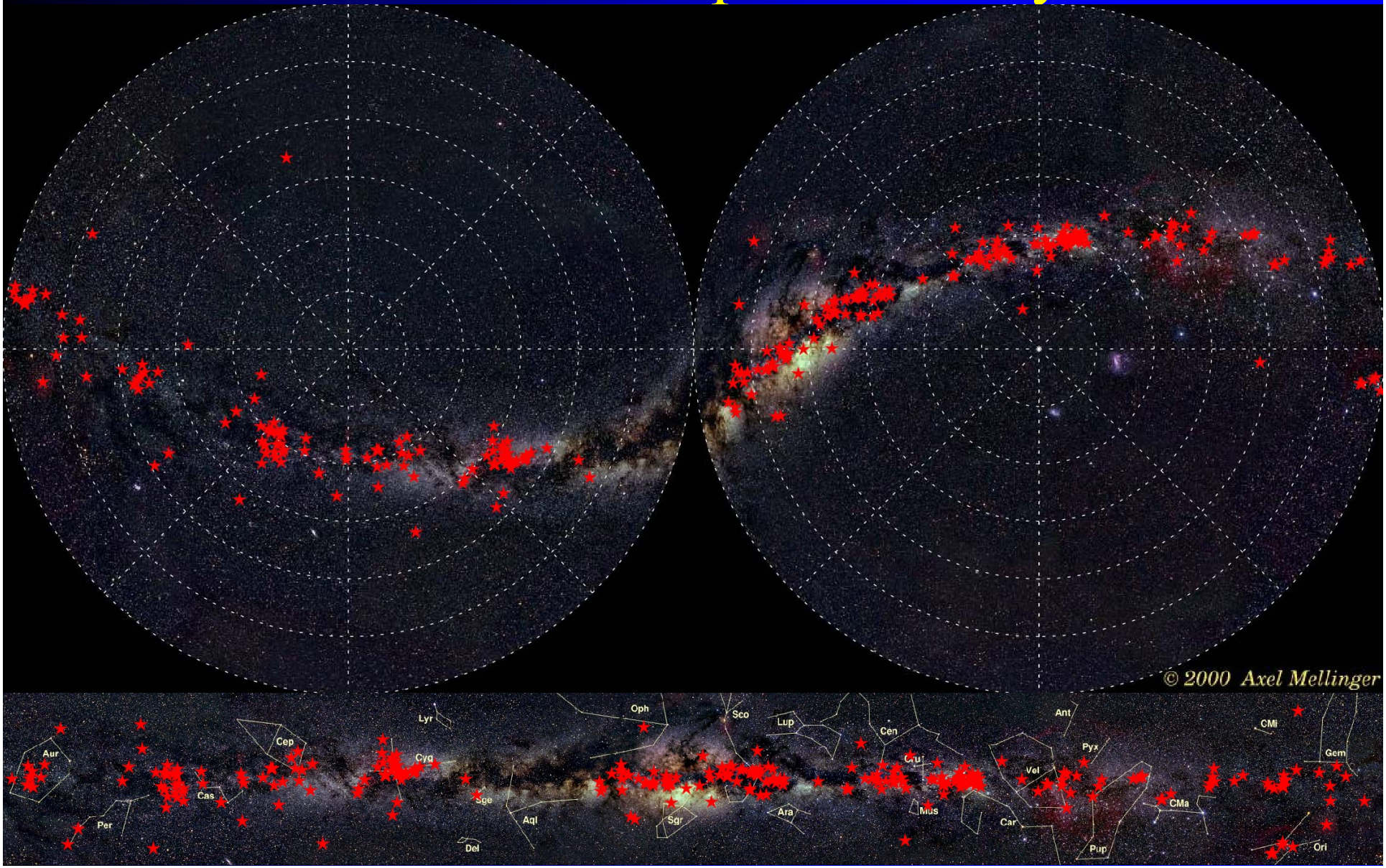
Future: NGC 3603



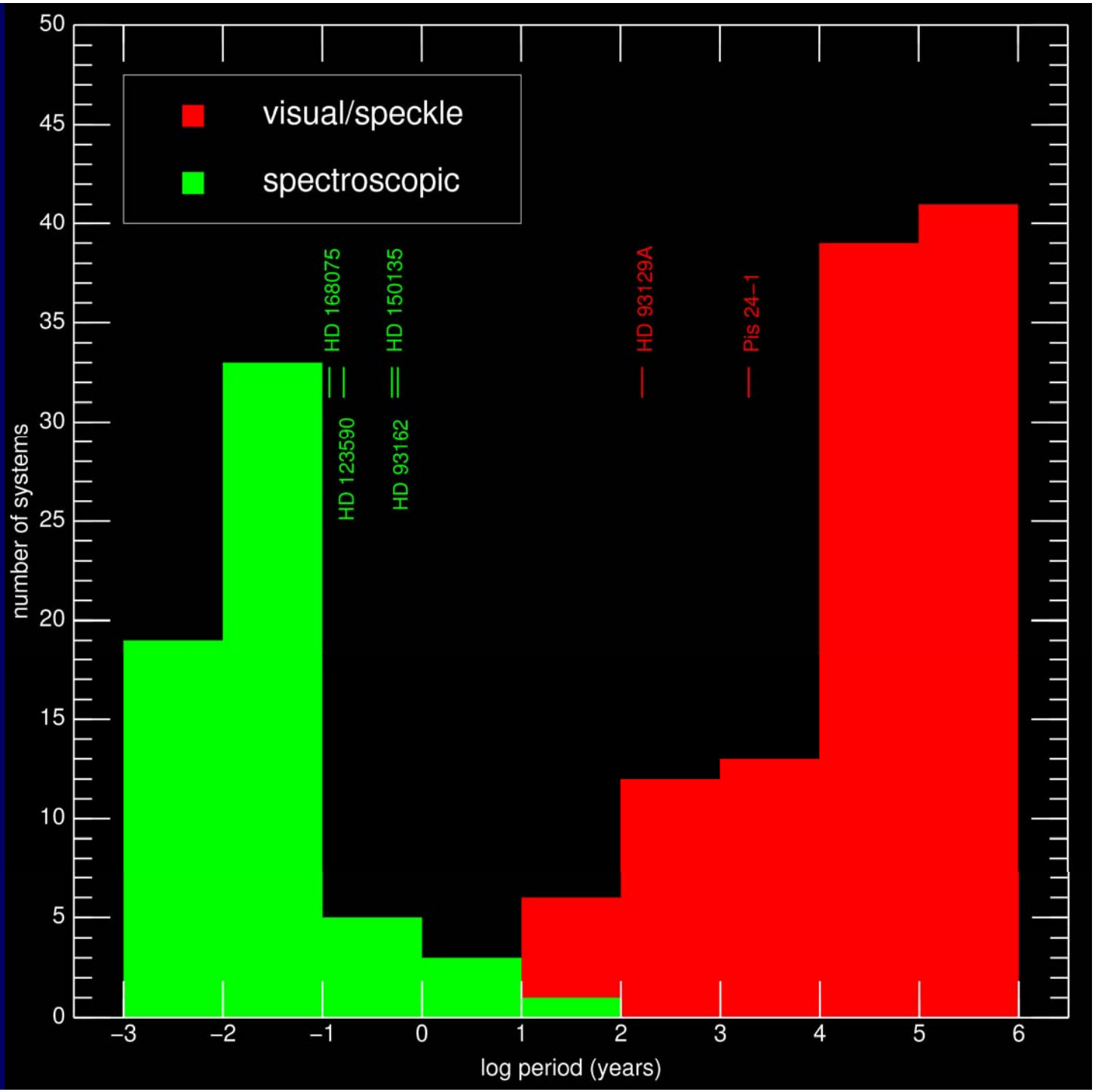
Future: Filling the Mason et al. (1998) gap



Future: OSN and southern hemisphere surveys



Future: OSN and southern hemisphere surveys



Conclusions

- Pismis 24 does not violate $M_{sup} \sim 150\ M_{Sol}$
  - Pis 24-1 is a triple system with ~64-96 M_{Sol} per star
  - Pis 24-17 has $92 \pm 9\ M_{Sol}$
- HD 93129A is the most massive astrometric binary
  - More data needed to calculate its mass
- More objects to analyze
- OSN and southern hemisphere surveys will detect more spectroscopic binaries