The Origin of Low-Luminosity Carbon Stars

Rob Izzard, June 2003

V713 Mon (2MASS)

What is a Carbon Star?

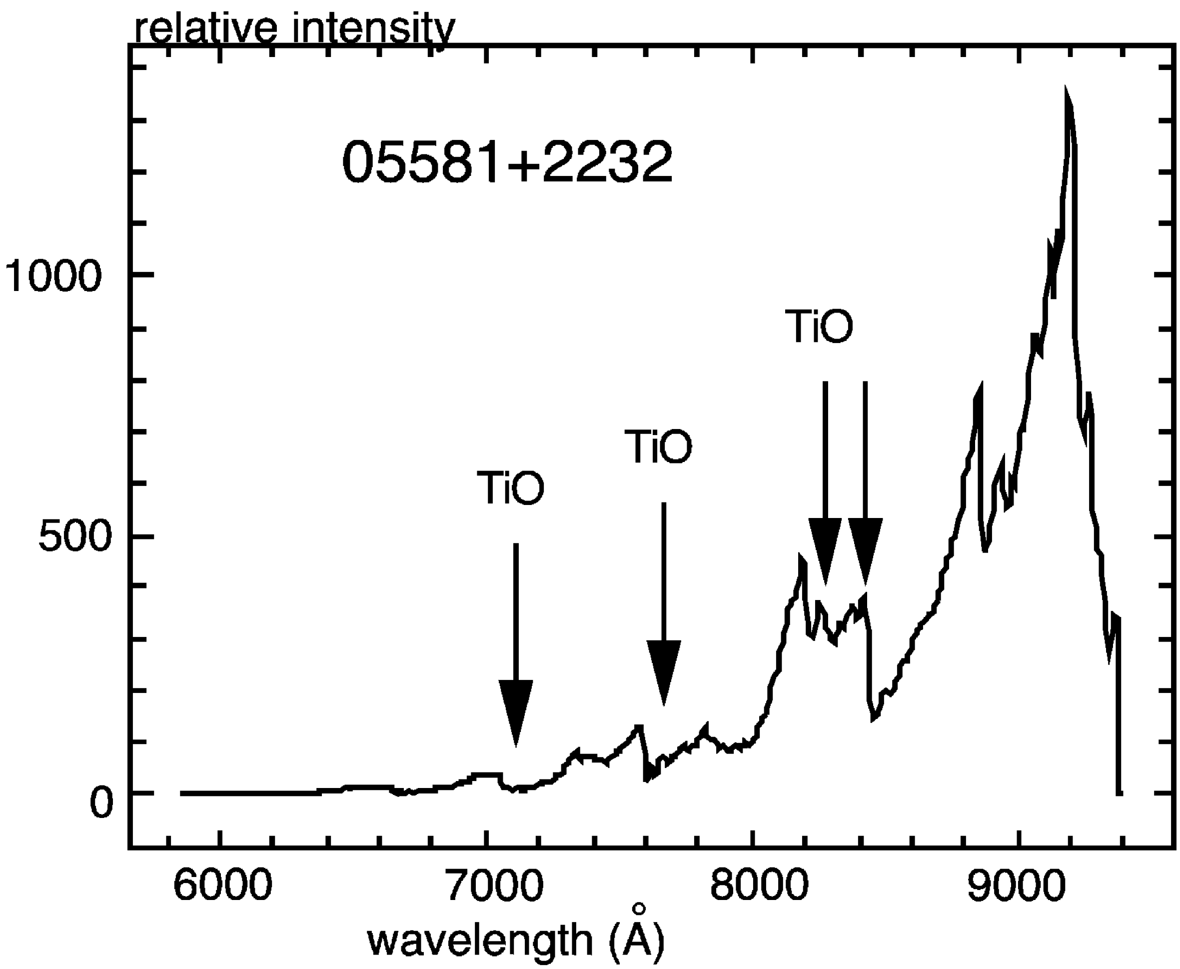
Observations

- M-Type Red Giant with Carbon>Oxygen
- Carbon rich molecular (CN) bands obvious in spectrum
- Easily distinguished from regular M-star with Carbon<Oxygen (TiO bands)

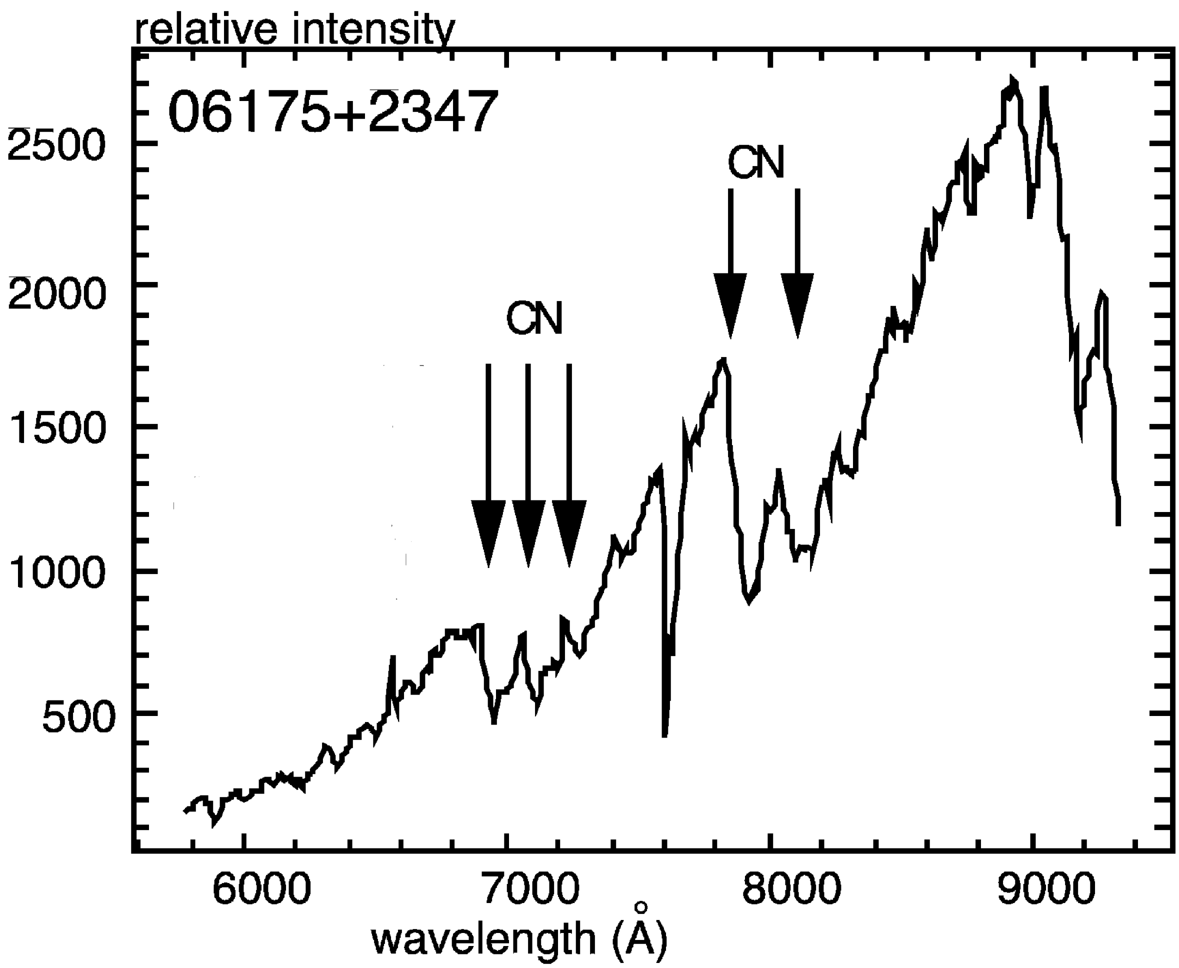
Theory

- TPAGB star undergoing Third Dredge-Up

M-Star Spectrum



C-Star Spectrum



Photometric Observations

- Calibrated by spectra
- R,I colours $\rightarrow m_{\rm bol}$
  "The Rosetta Stone of Stellar Evolution" Costa and Frogel (1996)
- Magellanic Clouds: Little reddening, "complete" surveys
- Compilation of Groenewegen (2002)
- $N_{\rm LMC} = 7750$; $N_{\rm SMC} = 2497$

Observations 2

- Distance modulus + $m_{\rm bol} \rightarrow M_{\rm bol}$
- Completeness $> 70\%$ in crowded regions
- $> 90\%$ elsewhere

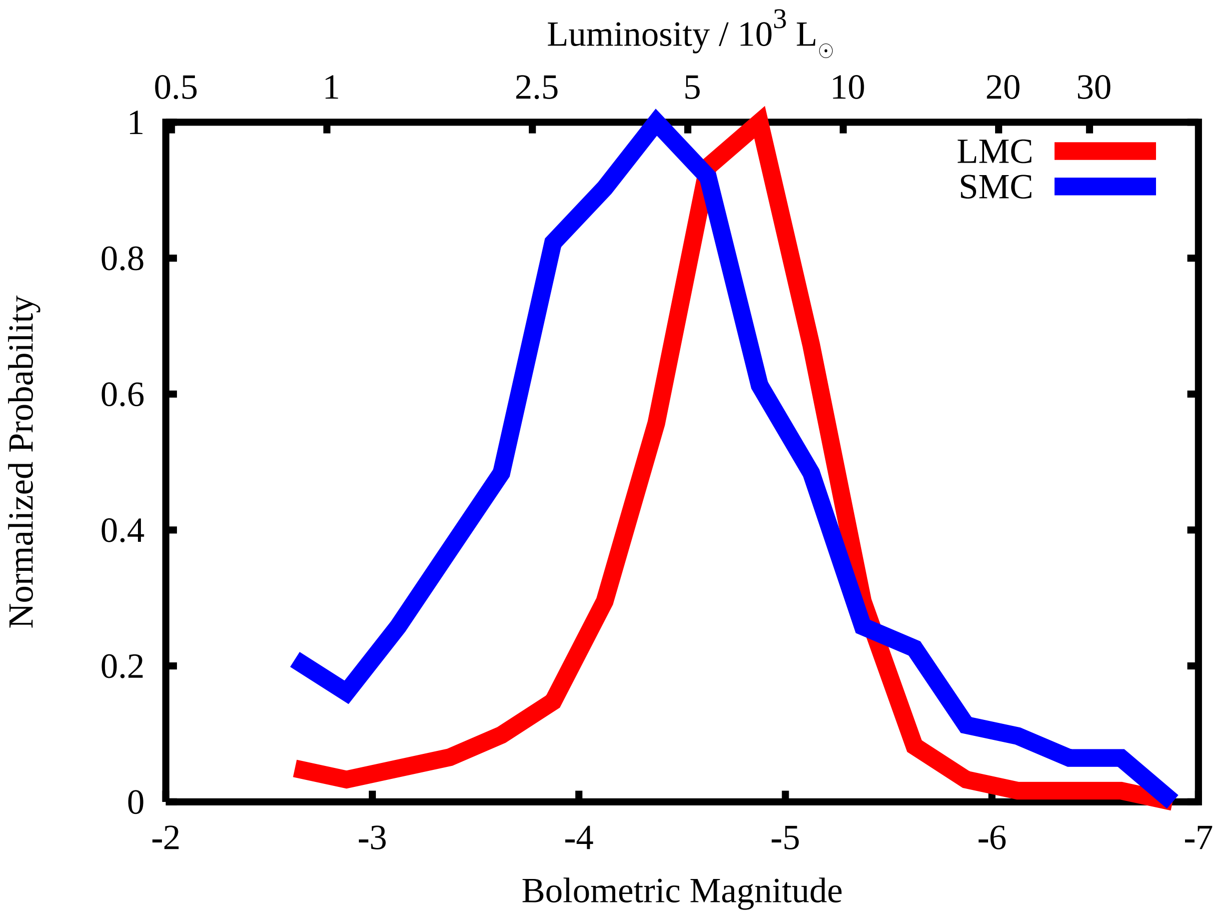
Errors:

- Distance modulus $\pm 0.2\,{\rm mag}$
- $m_{\rm bol}(R, I) \pm 0.34\,{\rm mag}$
- Worst case $\pm 0.5\,{\rm mag}$

Carbon Star Luminosity Func.

- From $M_{\rm bol}$ for many carbon stars we construct a luminosity function
- Distribution shows an obvious peak, bright tail and dim tail
- Peak position function of Z (LMC $Z = 0.008$, SMC $Z = 0.004$) brighter for higher Z
- Bright tail dep. on recent SF
- Dim tail - why?

MC CSLFs

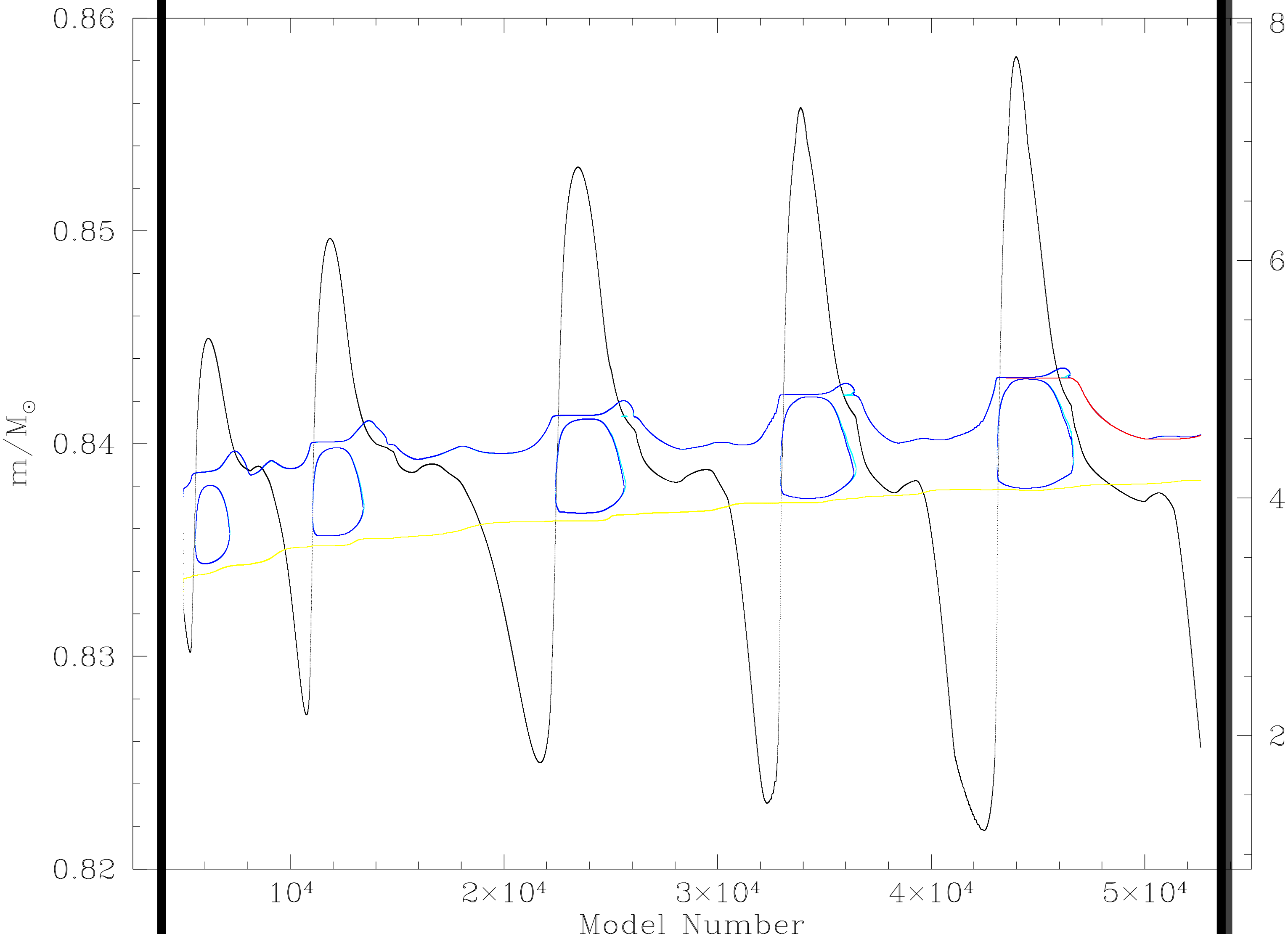


Luminosity / 10^3 $L_\odot$
0.5
1
2.5
5
10
20
30
1
0.8
0.6
0.4
0.2
0
Normalized Probability
LMC
SMC
-2
-3
-4
-5
-6
-7
Bolometric Magnitude

Theoretical Carbon Stars

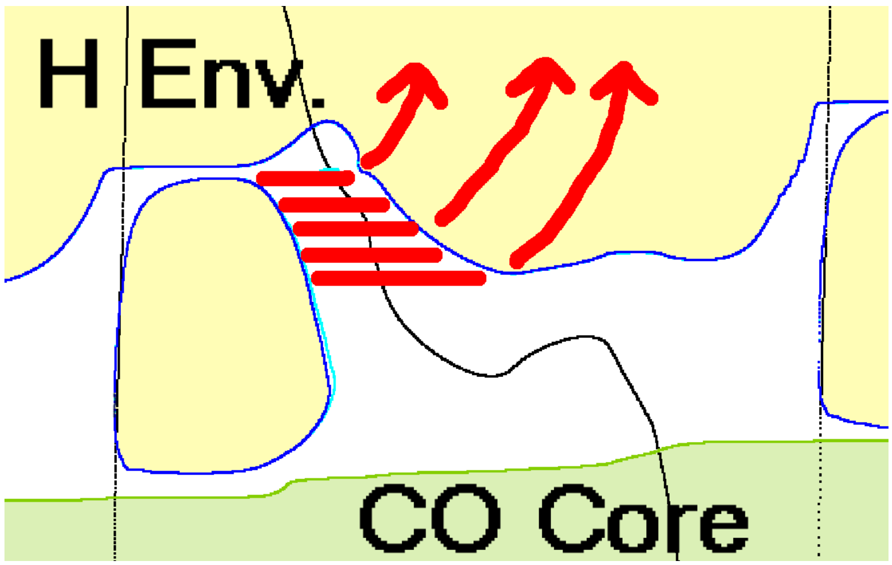
- Thought to be Thermally-Pulsing Asymptotic Giant Branch stars undergoing third dredge-up.
- Twin burning shells : H and He
- triple $-\ \alpha$ reactions process He to C in intershell region
- C brought to surface in series of pulses by convective mixing in envelope
- Single stars

Detailed Model



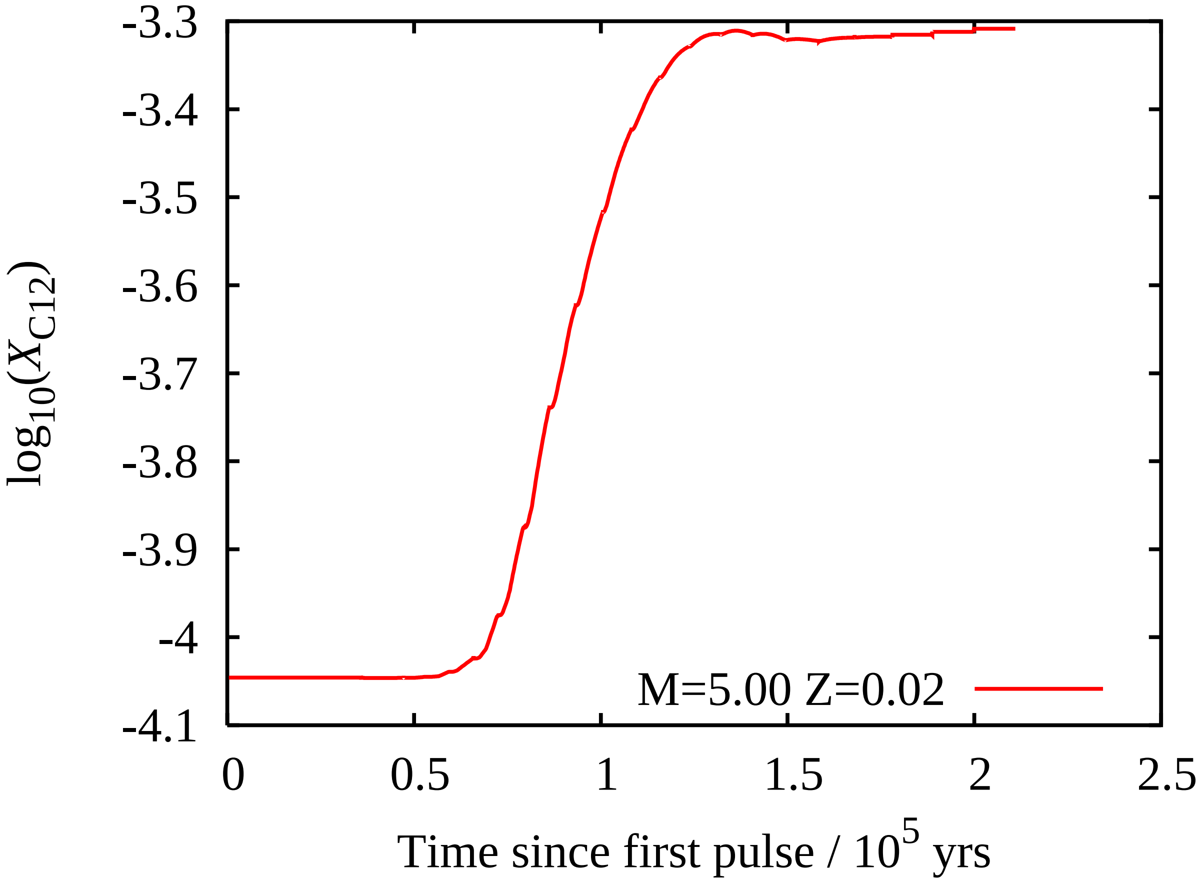
Richard Stancliffe's $5\,M_\odot$ model

Close Up on Dredge Up



- Core mass increases at each pulse
- Dredged-up material is approx. 22% C, 75% ^{4}He, 2% ^{22}Ne, 1% ^{16}O + traces of s-process (Ba, La, Y, Tc etc.)

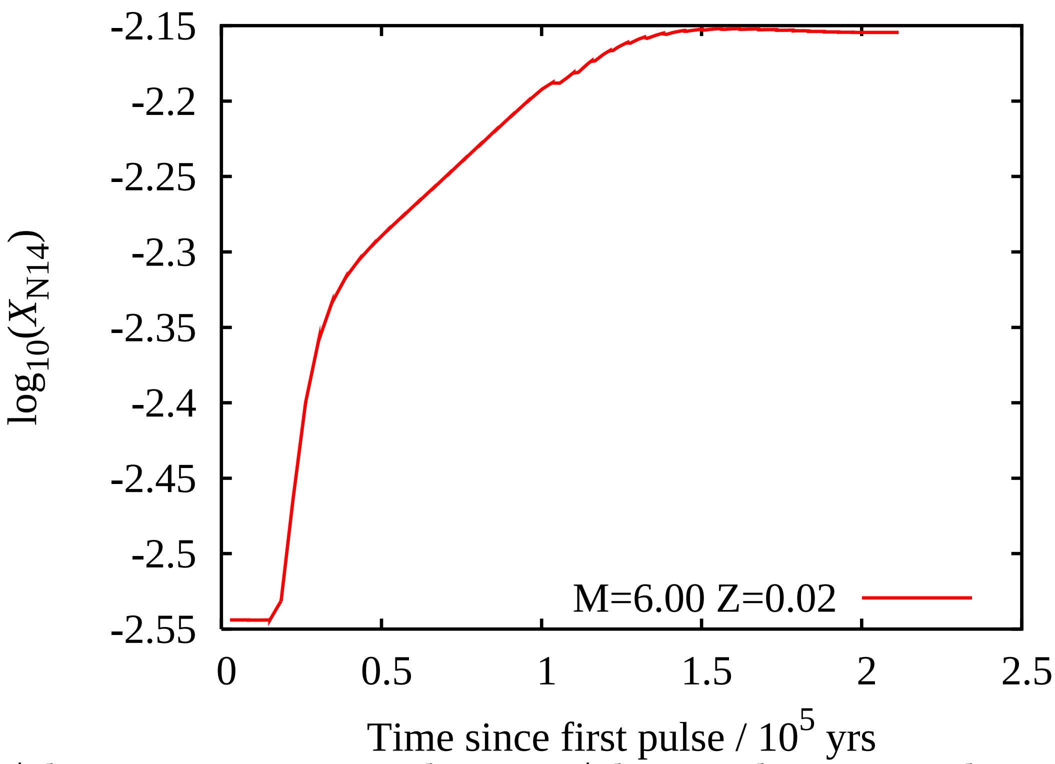
Surface Carbon



Data from Monash group's models (Karakas et al., 2002)

Hot Bottom Burning

- For $M \gtrsim 5\,\mathrm{M}_\odot$ HBB converts ^{12}C to ^{14}N via CNO cycle
- Removes high luminosity C-stars



Also NeNa and MgAl cycles, Lithium burning etc.

How Much DUP

Parameterize dredge-up by two (semi-free) parameters

WHEN : $M_{\mathrm{c,min}}$– minimum core mass for dredge-up

HOW MUCH : λ - ratio of amount dredged-up to core growth during interpulse time

Detailed models (Karakas et al.) predict $M_{\mathrm{c,min}}$ and λ

. . . *but they are wrong.*

Synthetic TPAGB Models

Detailed models of TPAGB stars are difficult and time consuming to construct, so make synthetic models.

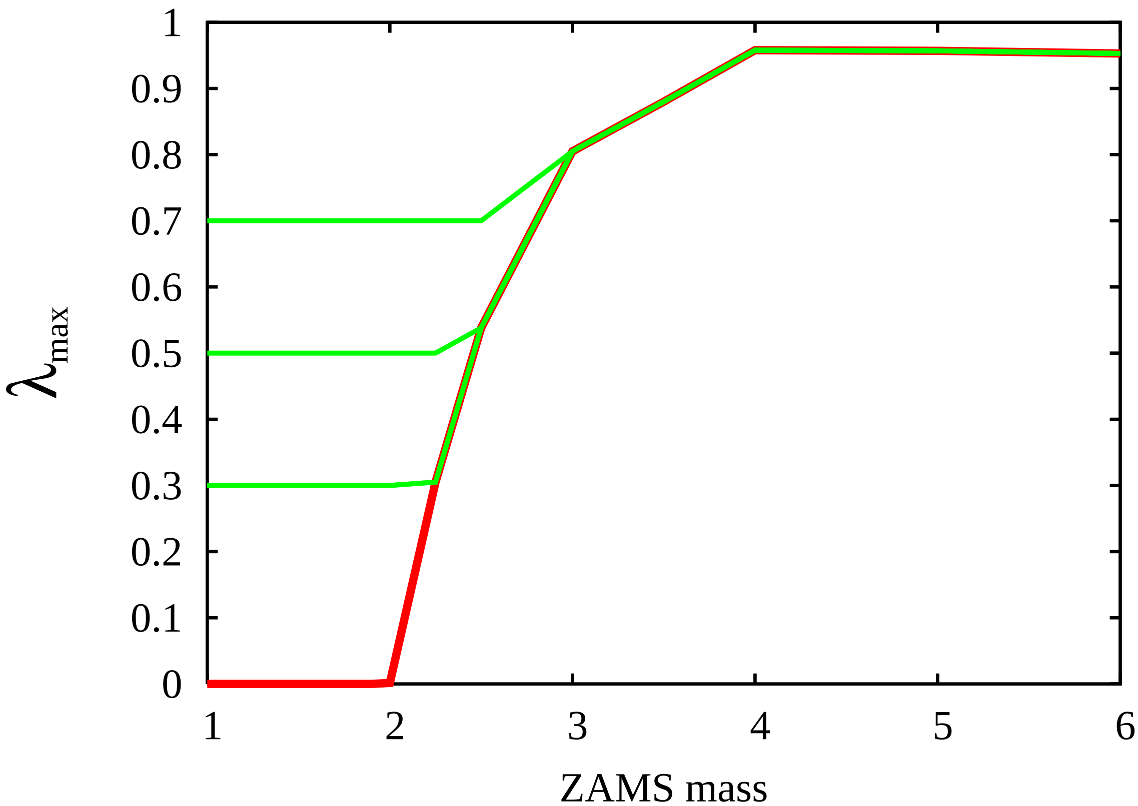
- Based on fits to detailed (Monash) models
- Much faster! ($t_{\mathrm{CPU}} \lesssim 1\,\mathrm{s}$ c.f. days)
- Features DUP and HBB
- Coupled to Hurley et al. (2002) single/binary population synthesis code
- Calibrate λ and $M_{\mathrm{c,min}}$ to observations of carbon stars

Vary λ using $\lambda_{\rm min}$

λ exponentially reaches a maximum value $\lambda_{\rm max}$ so after N pulses:

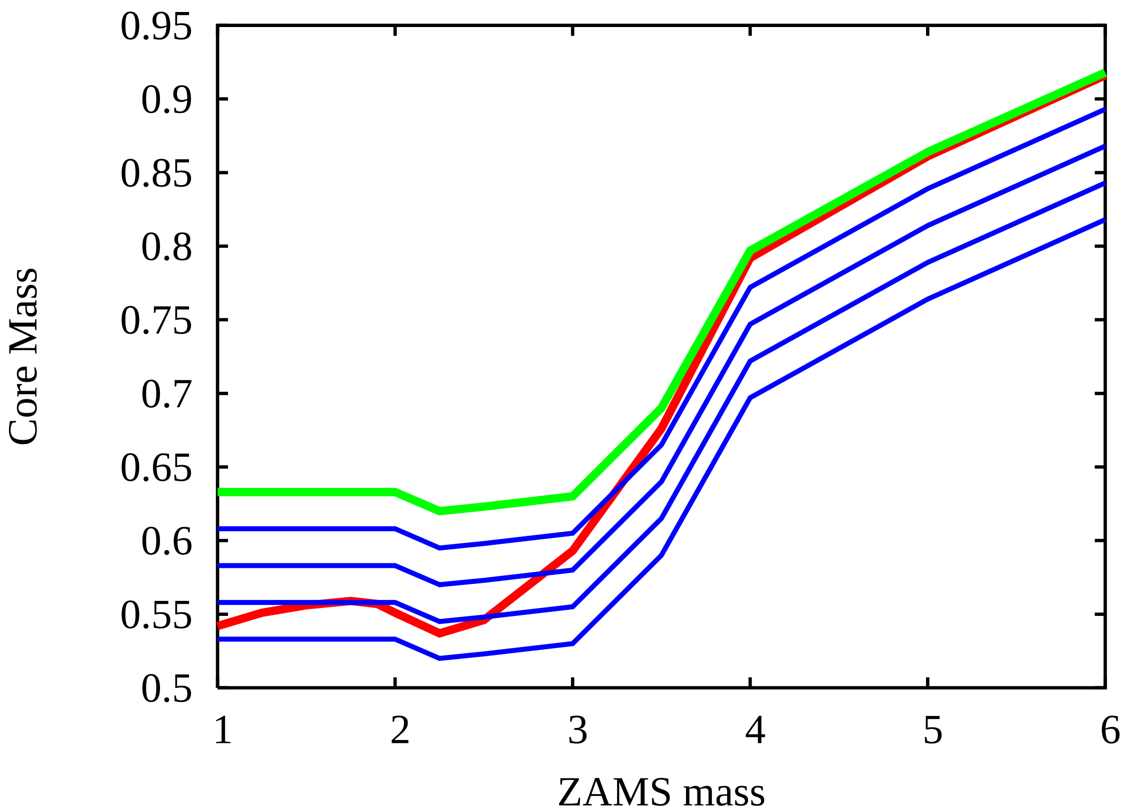
$$\lambda = \lambda_{\rm max}^{\rm fit}(M, Z) \times (1 - \exp(-N/N_0))$$

with $N_0 \approx 3$. Set $\lambda_{\rm max} = \max(\lambda_{\rm max}^{\rm fit}, \lambda_{\rm min})$ to force more dredge-up in low mass stars.



Vary $M_{\mathbf{c,min}}$ using $\Delta M_{\mathbf{c,min}}$

Add a constant $\Delta M_{\mathrm{c,min}}$ (< 0) to the fit for $M_{\mathrm{c,min}}$ to force dredge-up to start at a lower core mass.



Other “free” parameters

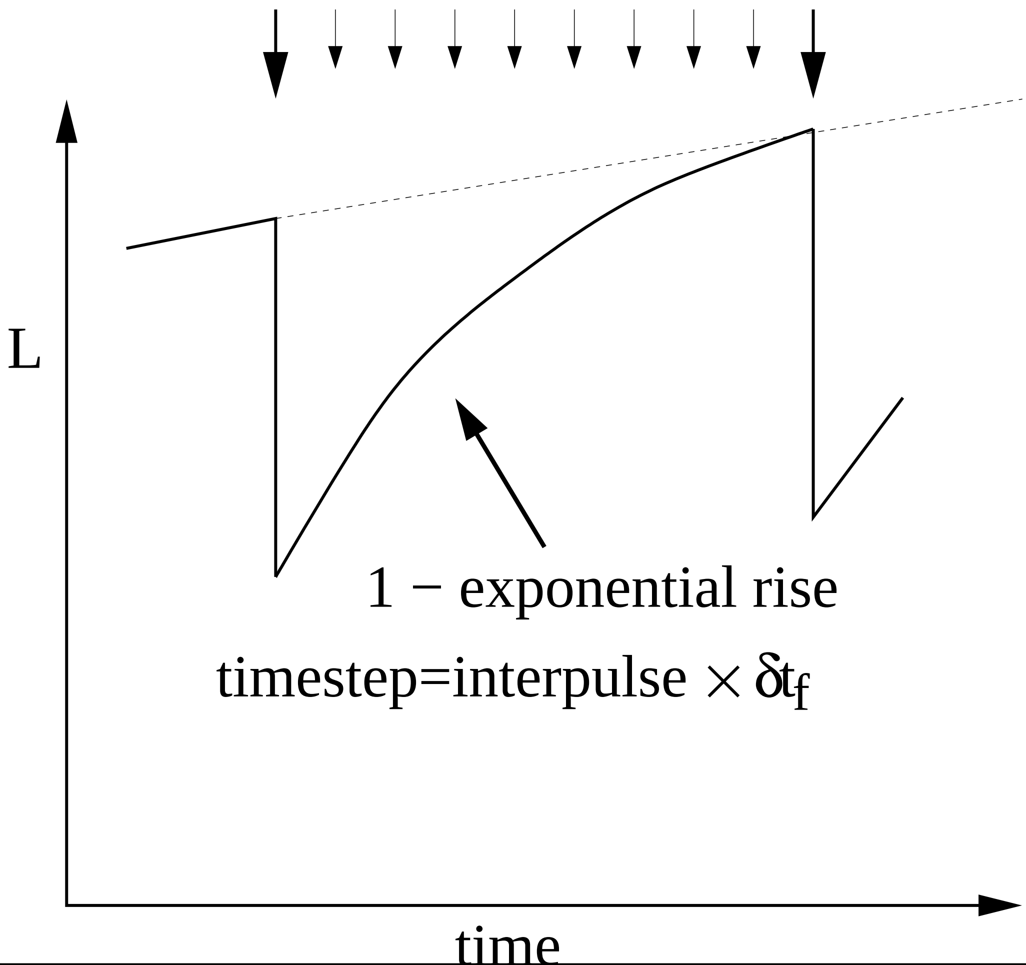
Mass loss prescription. Either

- Vassiliadis and Wood (1993) with a superwind when Mira pulsation period exceeds 500 days
- original Vassiliadis and Wood (1993) as used by Hurley et al. (2002) or
- Reimers (1975) mass loss rate (modulated by a constant η)

Assume constant star formation rate and $t_{\rm gal} = 14\,{\rm Gyr}$.

Post-Flash Luminosity

Dips due to extinction of H-shell during pulse. Included in approximate way in synthetic model by reducing the luminosity for the first ten pulses. Effect is small after that, according to detailed models.



Intrinsic/Extrinsic

For the first time it is possible to include binary stars in this type of study. "Typical" binary star distribution

- $0.1 \leq M_1 \leq 8.0$
- $q = M_2/M_1$ flat distribution
- separation $3 < a/\,\mathrm{R}_\odot < 10^4$ flat distribution in $\ln a$, $e = 0$

Mass transfer from TPAGB stars may lead to carbon enriched *pre-TPAGB (GB or EAGB) stars*. These are *extrinsic* carbon stars (McClure, 2000). TPAGB carbon-stars are *intrinsic*.

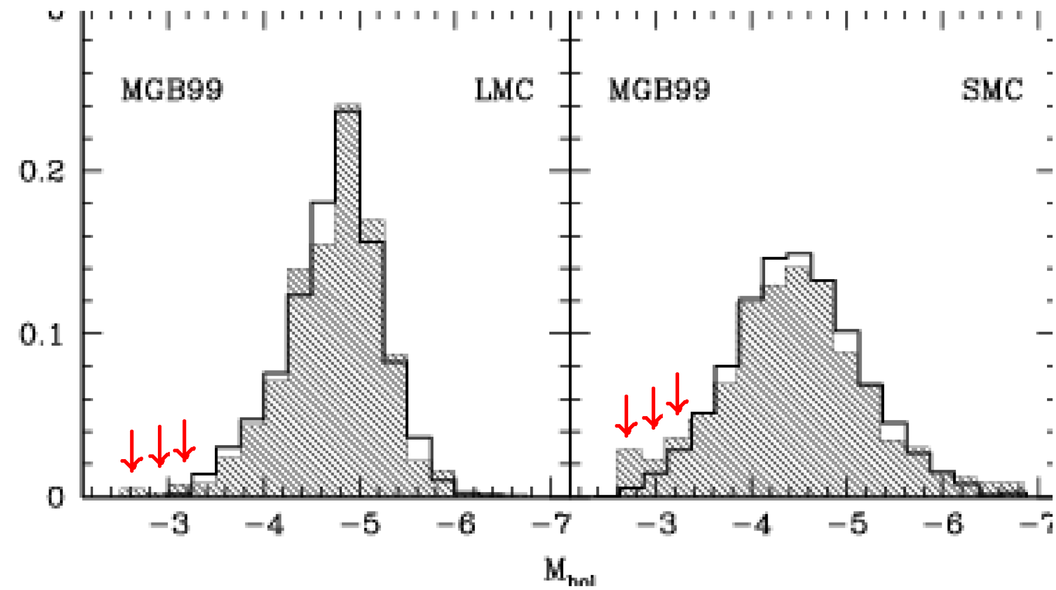
Models meet Observations

Past attempts to match TPAGB models to observed CSLFs have been quite successful e.g.

- Iben and Renzini (1983) introduced "Synthetic" models
- Groenewegen and de Jong (1993) refined this to include HBB
- Marigo (1999, 2001) "Envelope burning" models
- Marigo (2002) Molecular Opacities

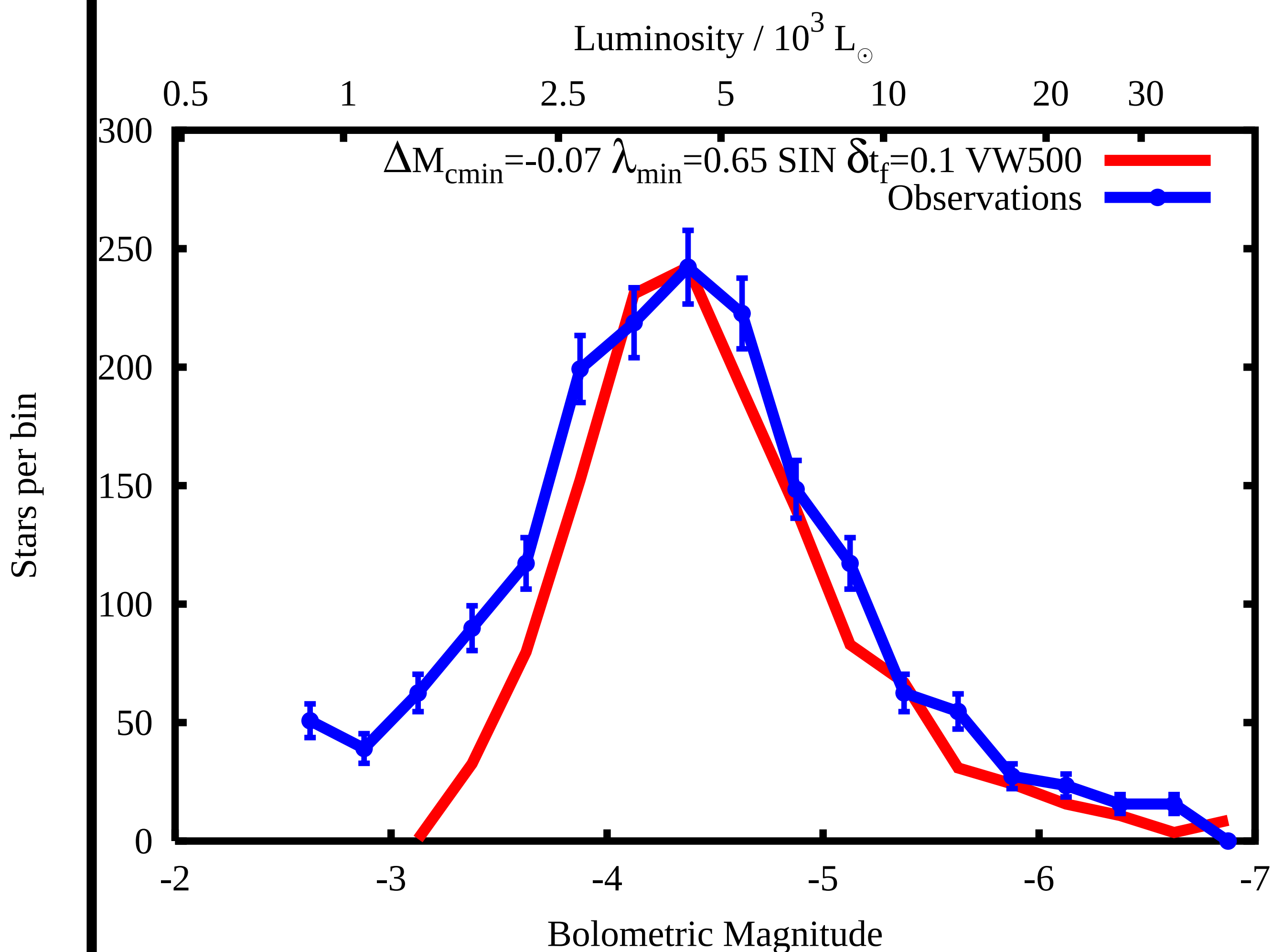
. . . but all fail to reproduce the dim tail of the luminosity function.

Marigo's best effort



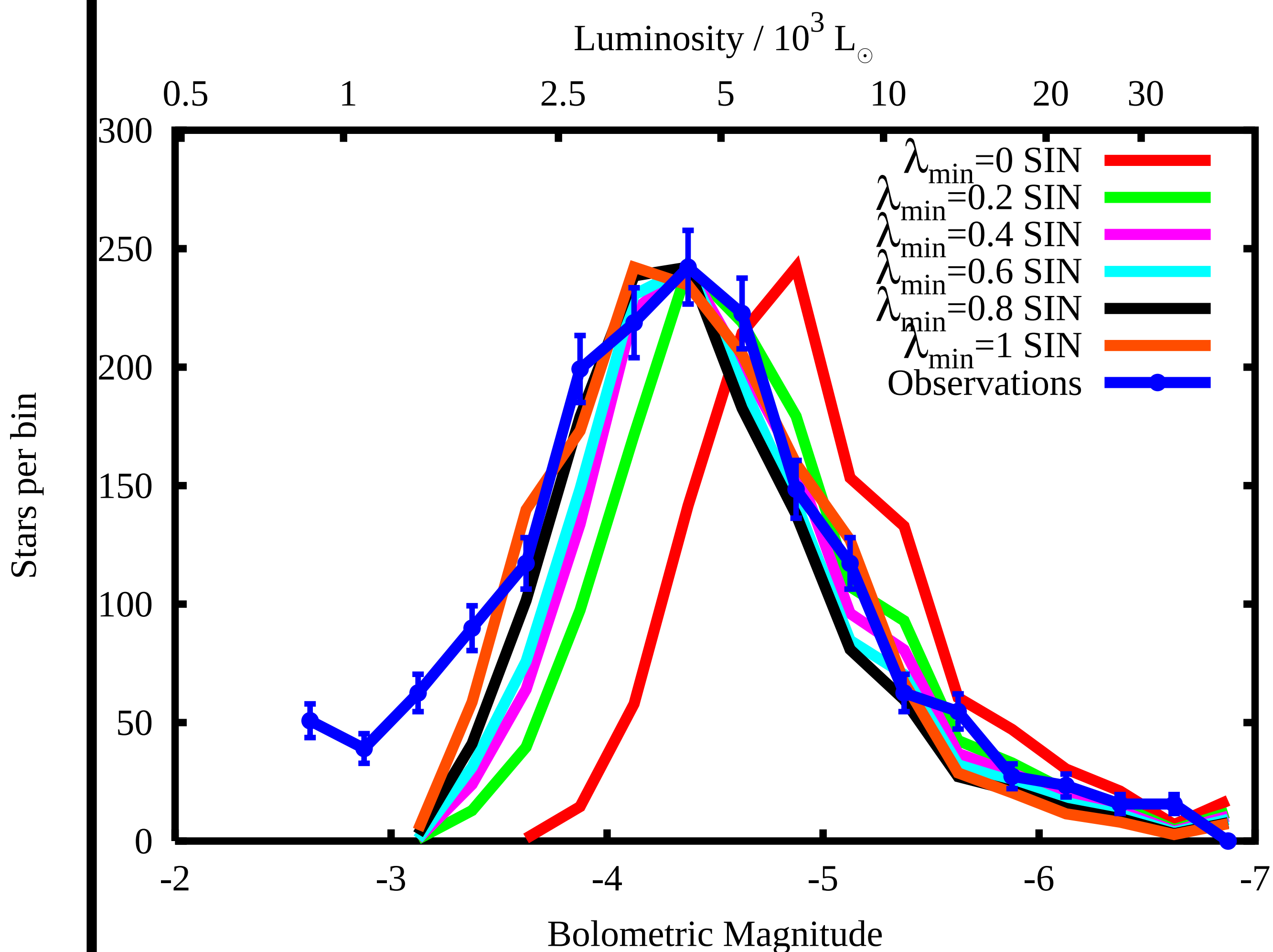
"Missing" dim stars from theoretical distribution ($N \sim 150$ for SMC and LMC) even with magical molecular opacities *and* inclusion of post-flash luminosity dips. What do our synthetic models suggest?

Standard Synthetic Model (SMC)



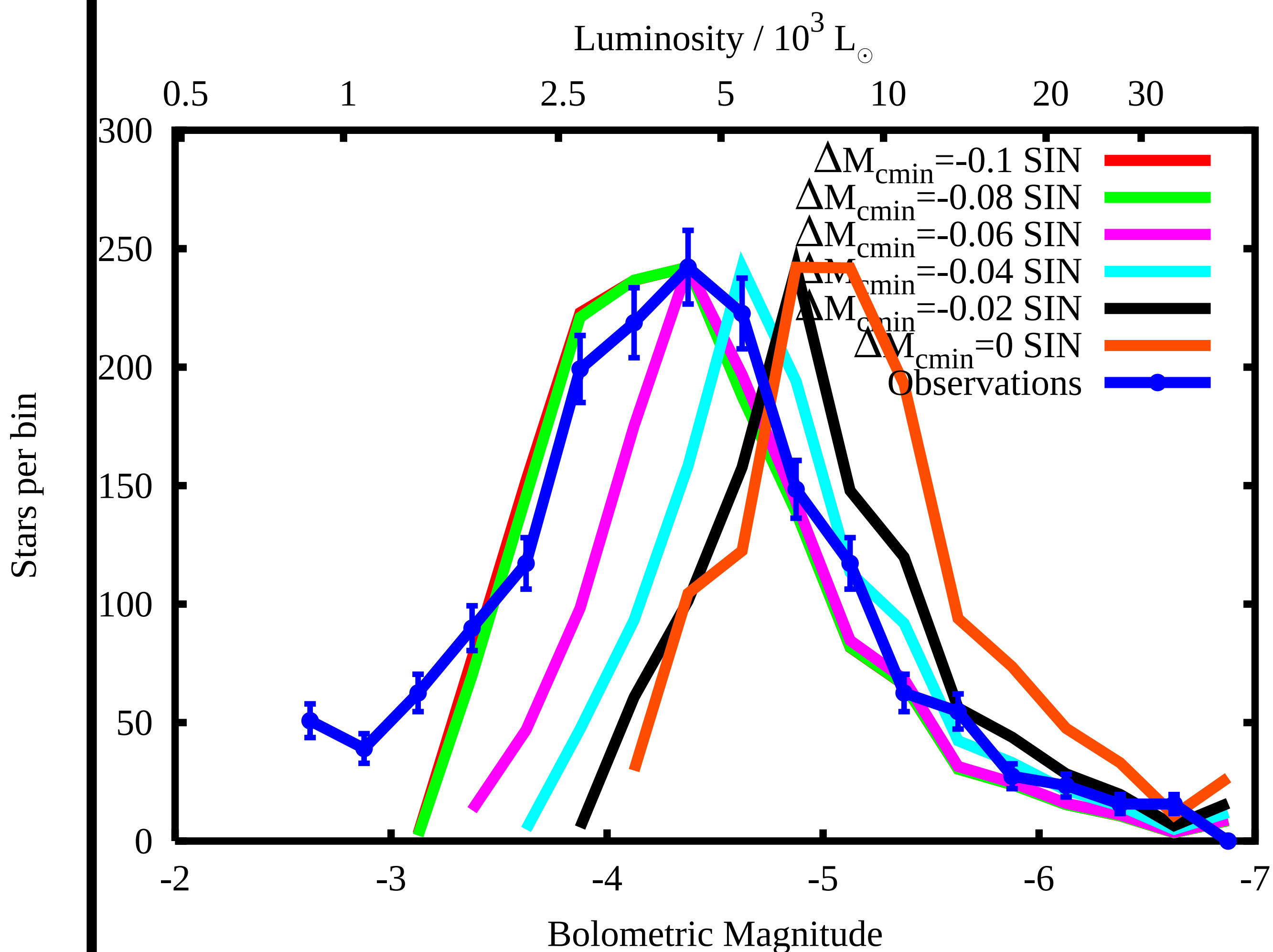
Calibration (best χ^2): $\Delta M_{\rm c,min} = -0.07$, $\lambda_{\rm min} = 0.65$, $\delta t_f = 0.1$, $\dot{M}$=VW500, single stars.

Vary λ_{min} to obtain dim stars?



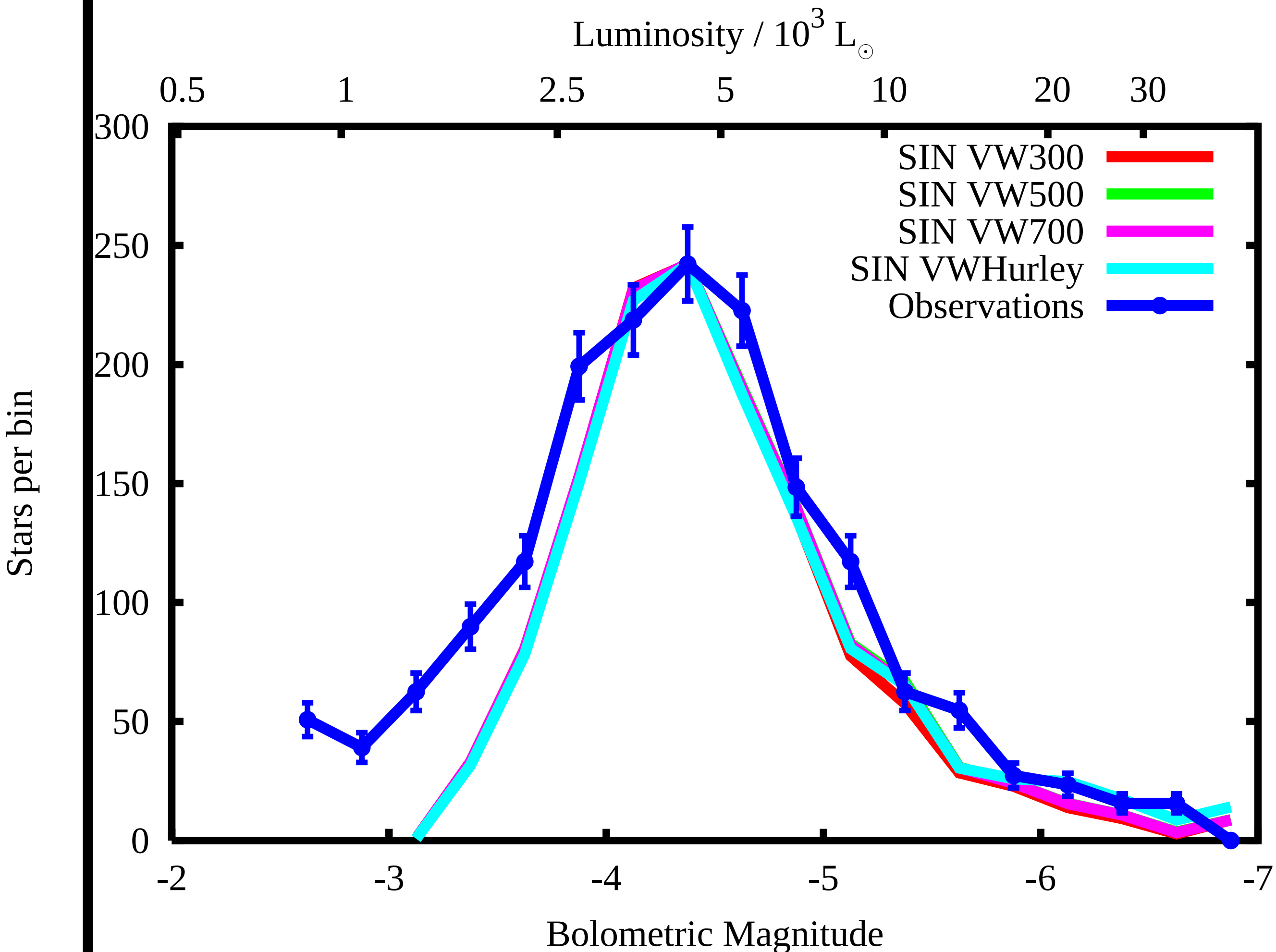
No dim stars.

Vary $\Delta M_{\mathbf{c,min}}$ to obtain dim stars?



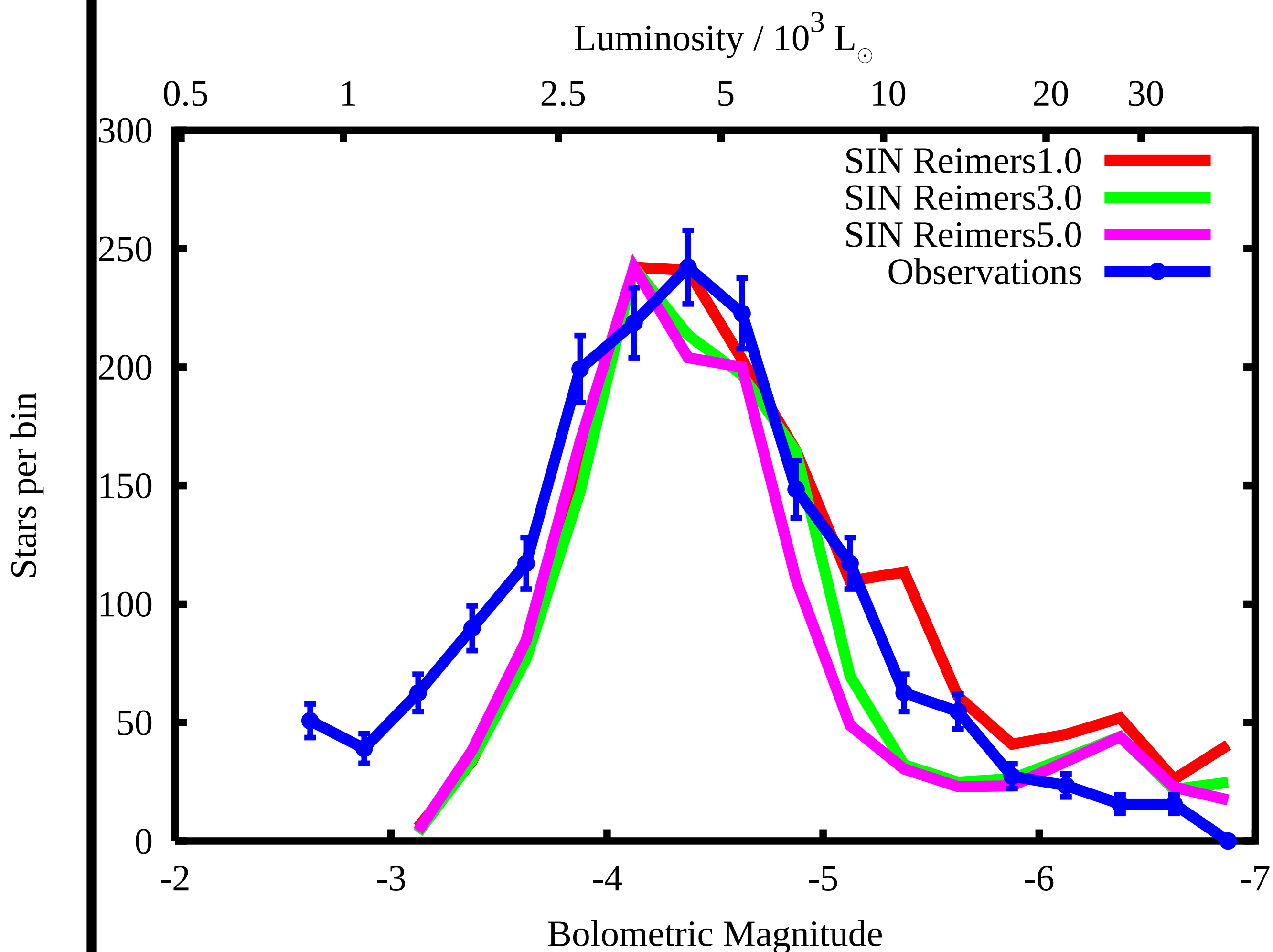
Still no dim stars.

Vary wind loss (VW)



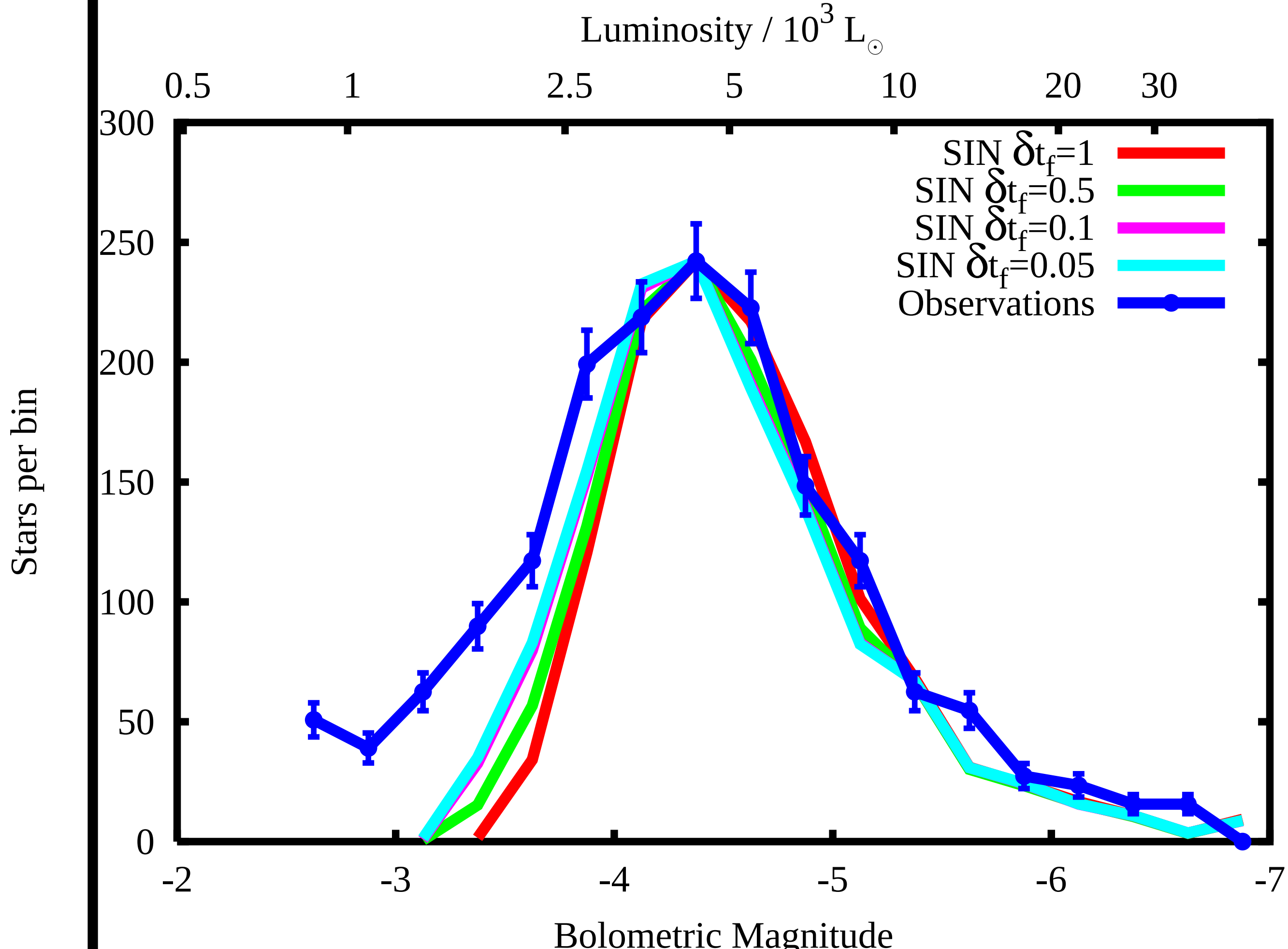
Still no dim stars.

Vary wind loss (Reimers)



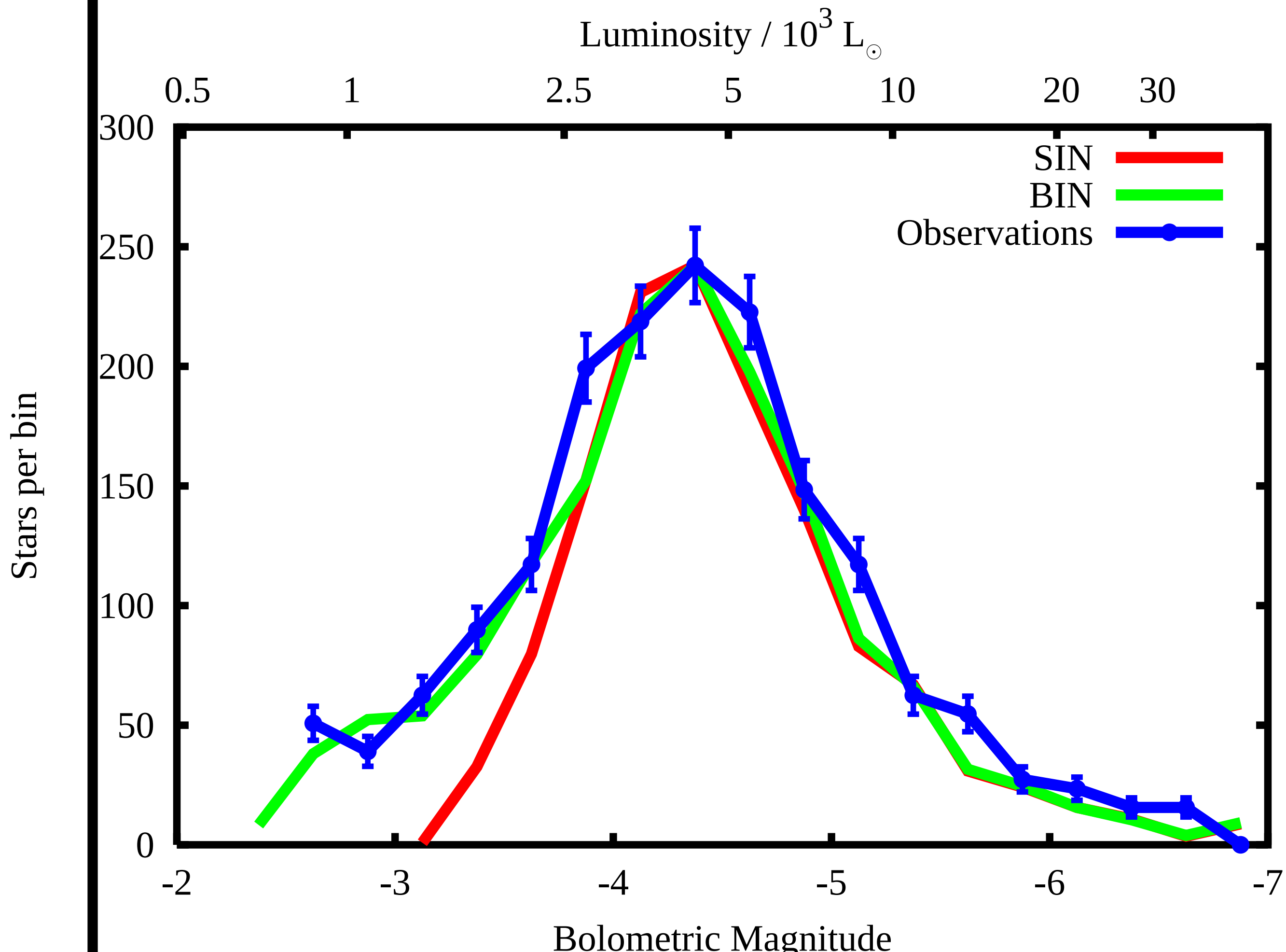
Still no dim stars.

Vary timestep



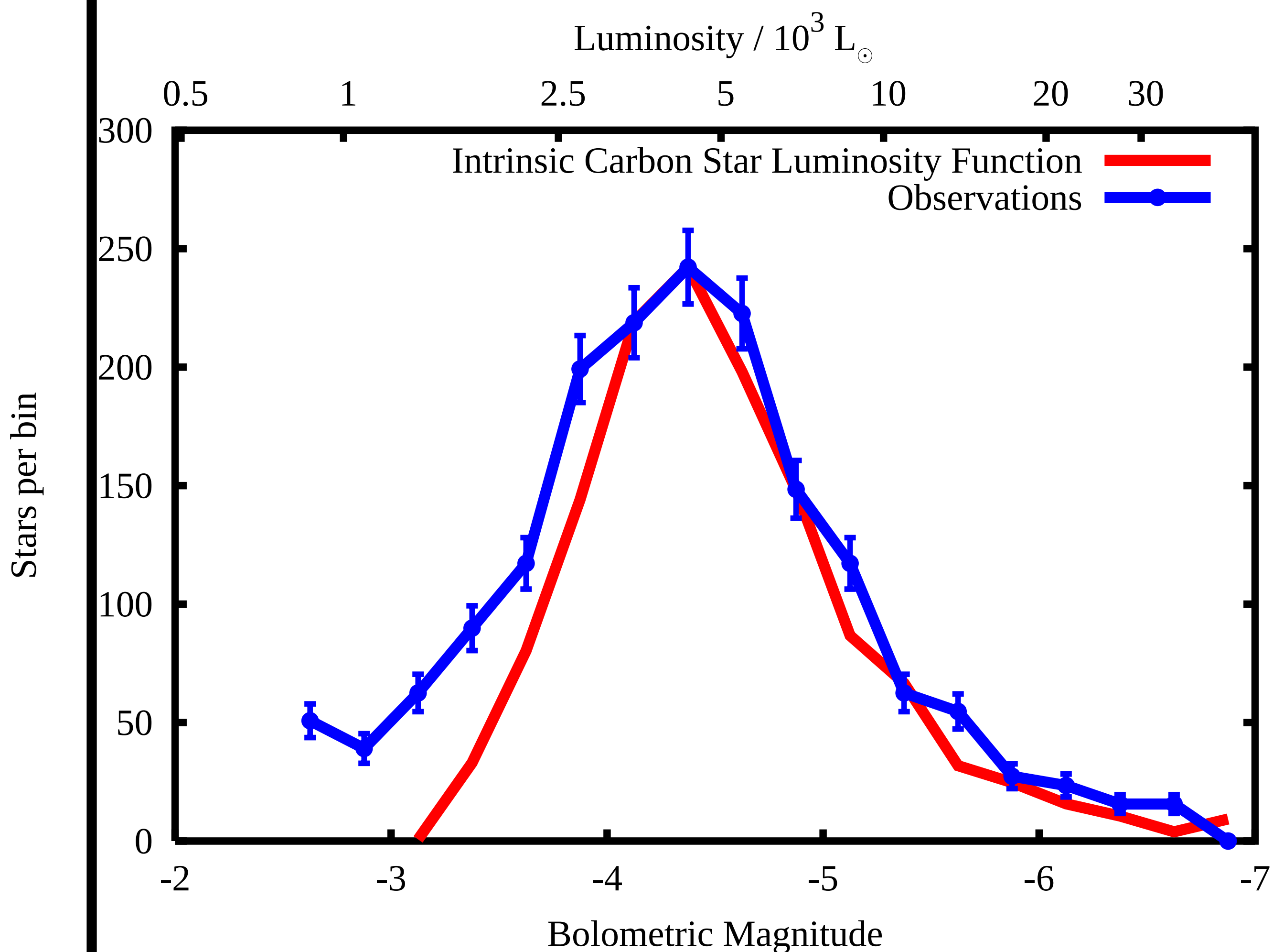
Still no dim stars.

Include binaries

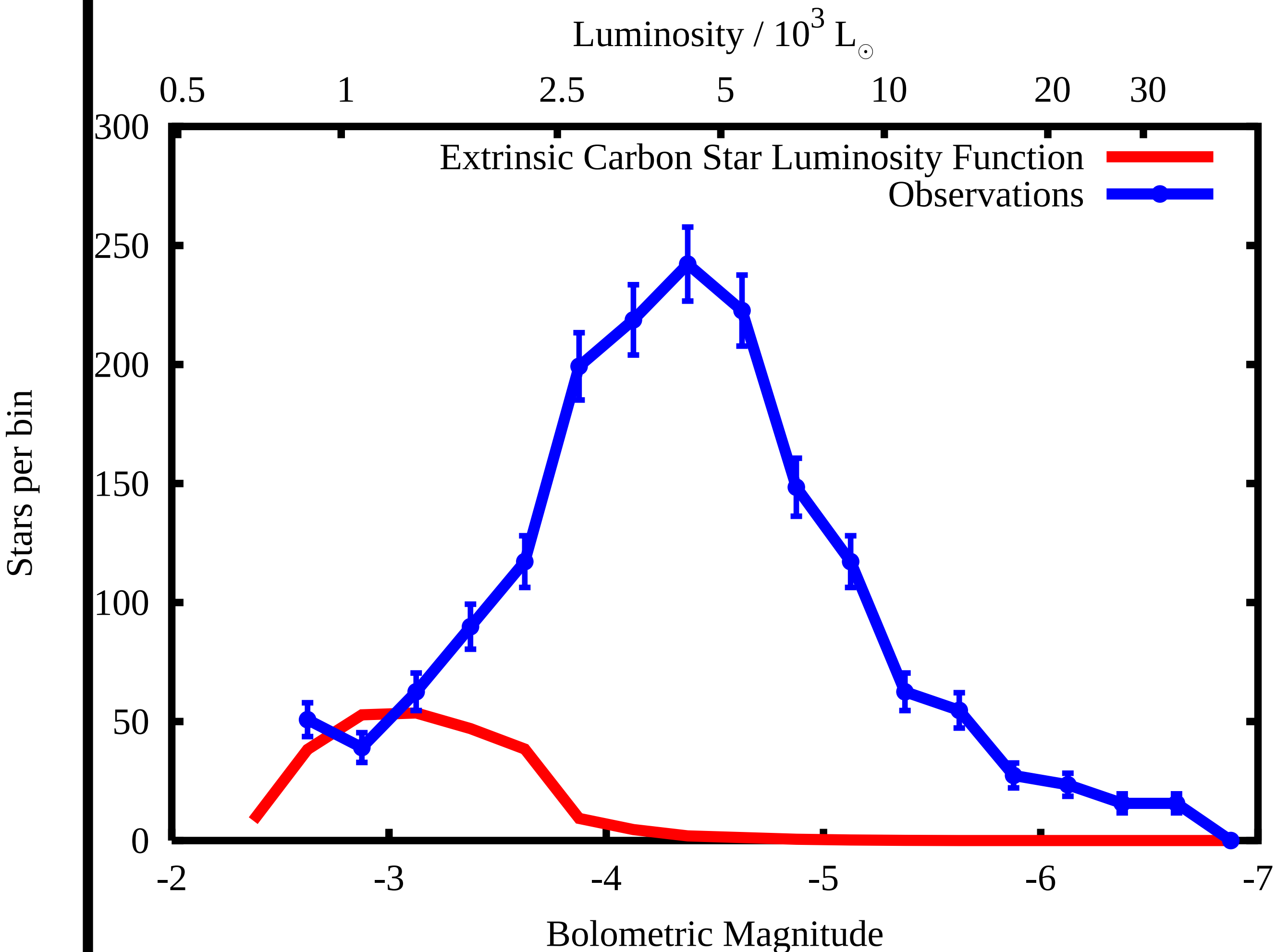


Many dim stars! What are they?

Intrinsic Luminosity Function

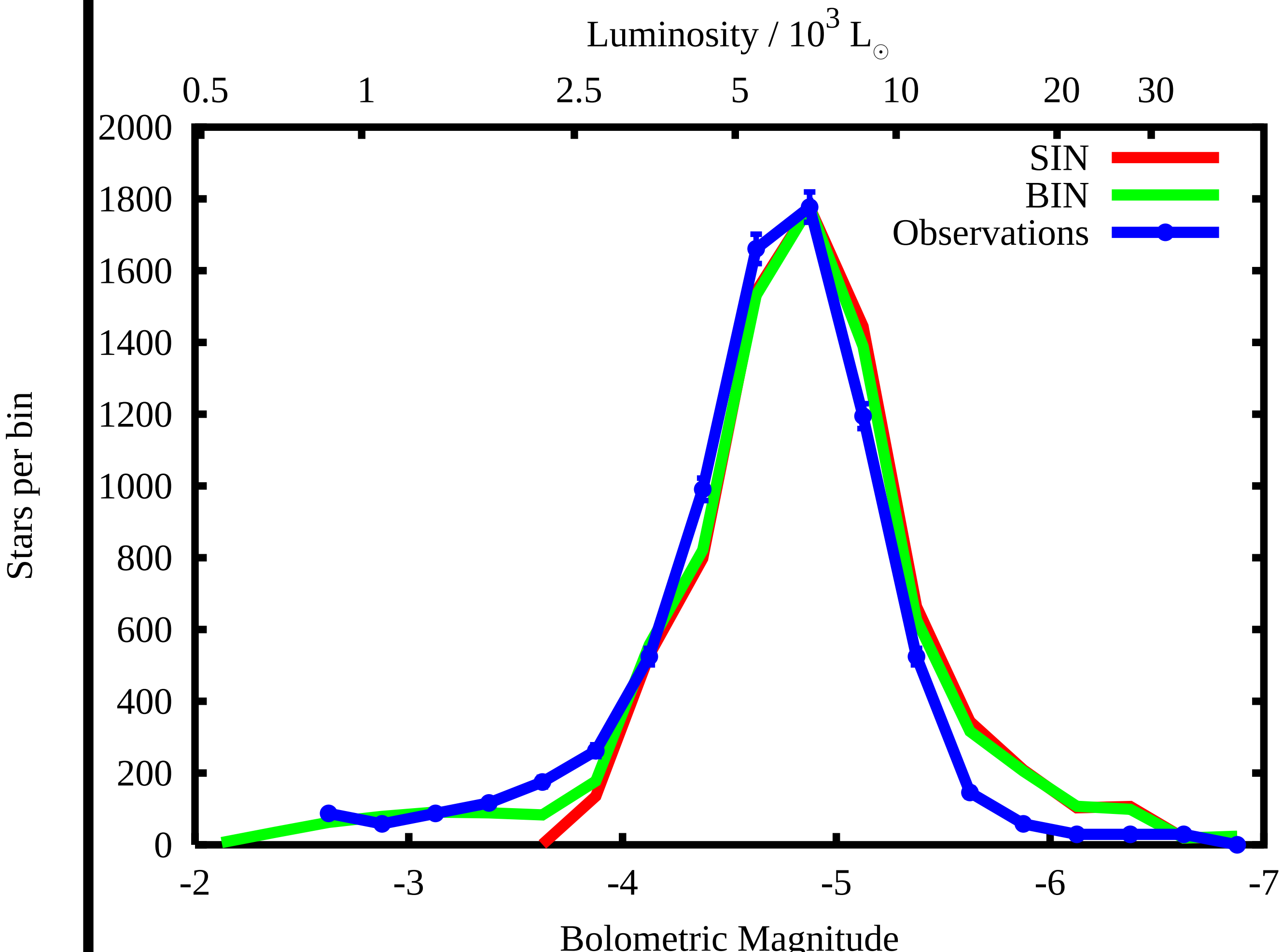


Extrinsic Luminosity Function



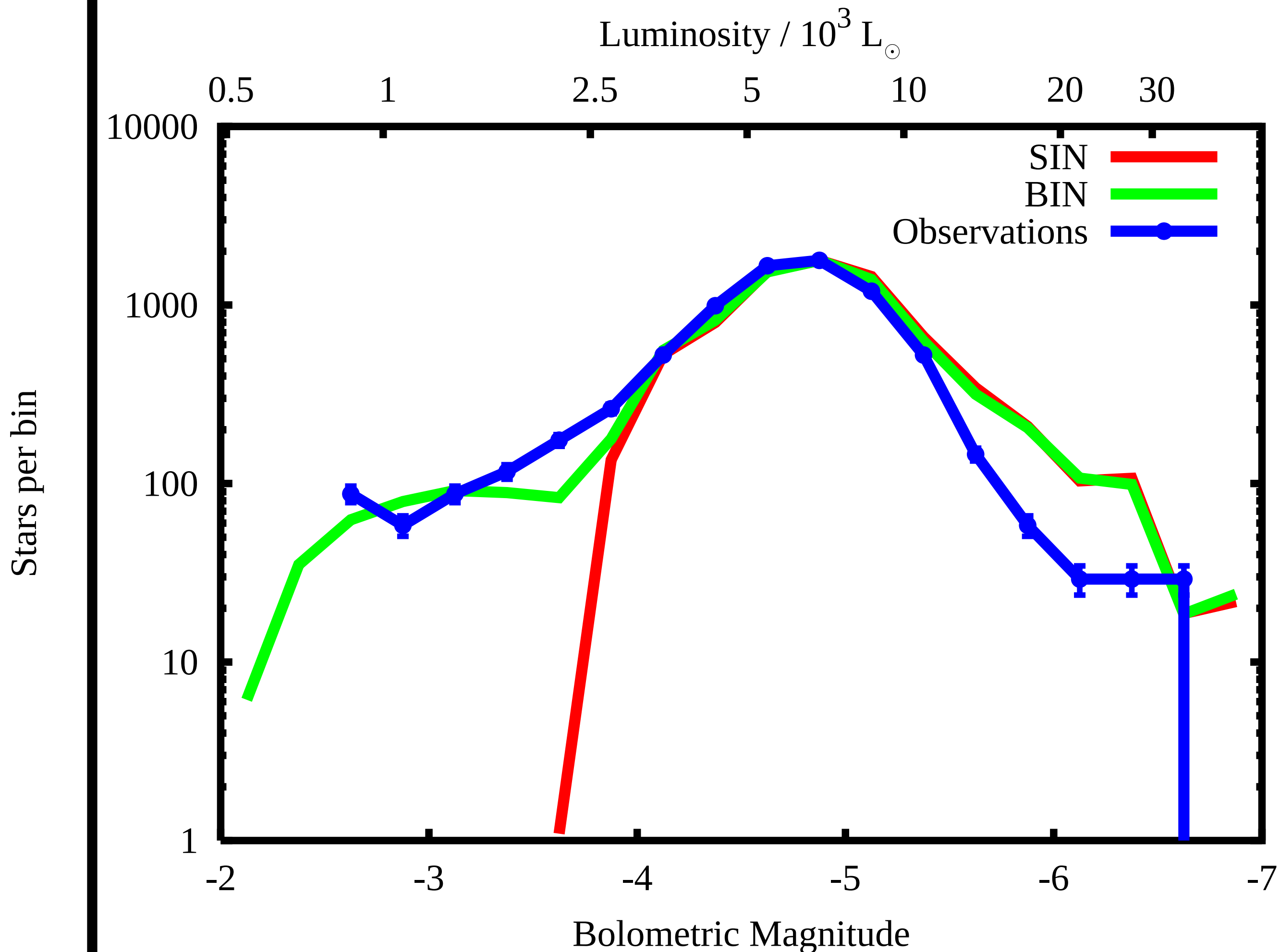
The new stars are *extrinsic* carbon stars, i.e. pre-TPAGB giants.

LMC CSLF



The effect of binaries is evident in the LMC as well, but not so marked (due to higher metallicity).

LMC CSLF (log scale)



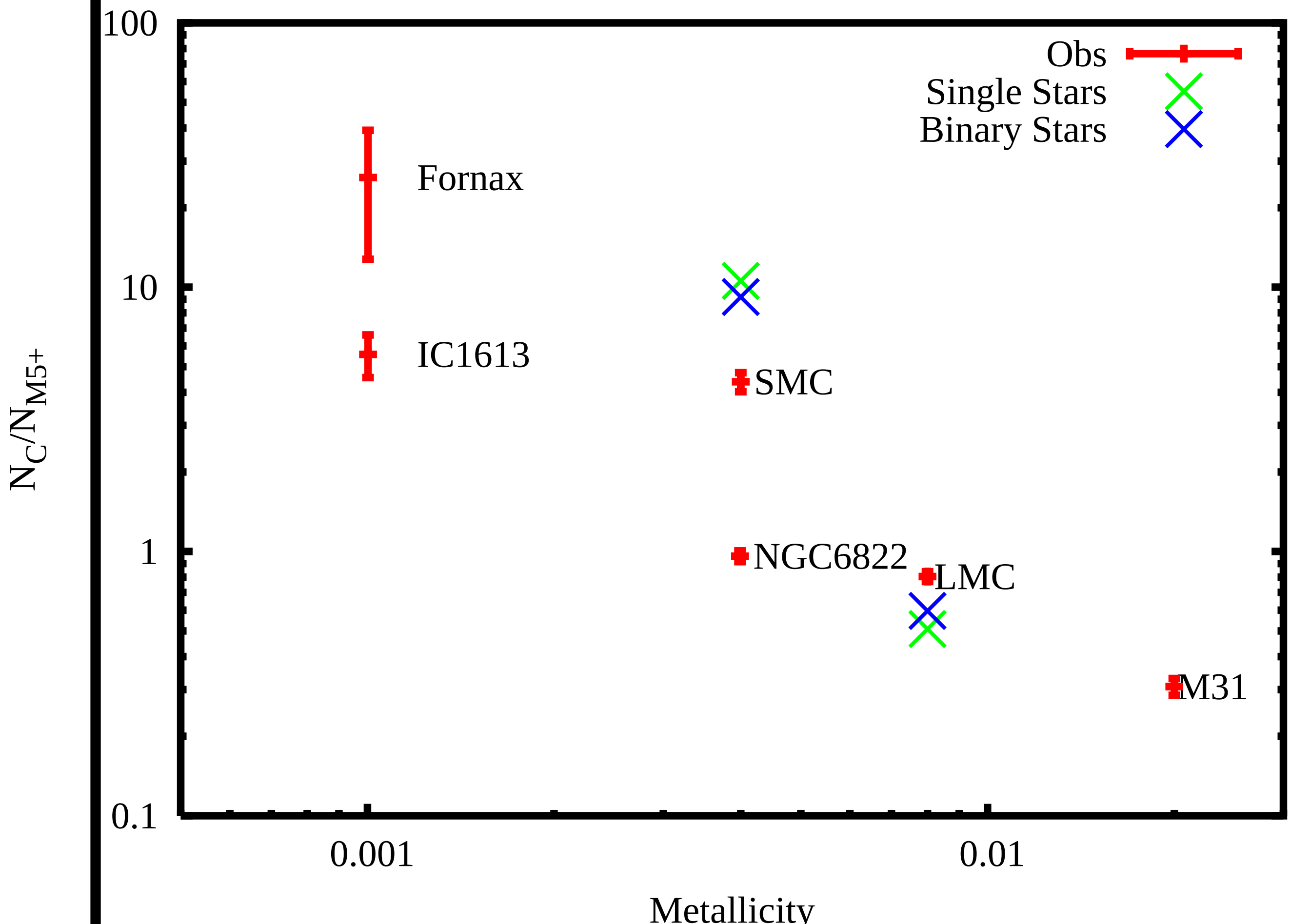
Future Tests – Theory

- The introduction of binary stars naturally explains the presence of low-luminosity carbon stars in the Magellanic Clouds.
- A real study of this problem requires the calculation of many grids of models covering the entire binary star parameter space as well as a more realistic star formation history and binary fraction. Better detailed models would help.

Future Tests – Theory 2

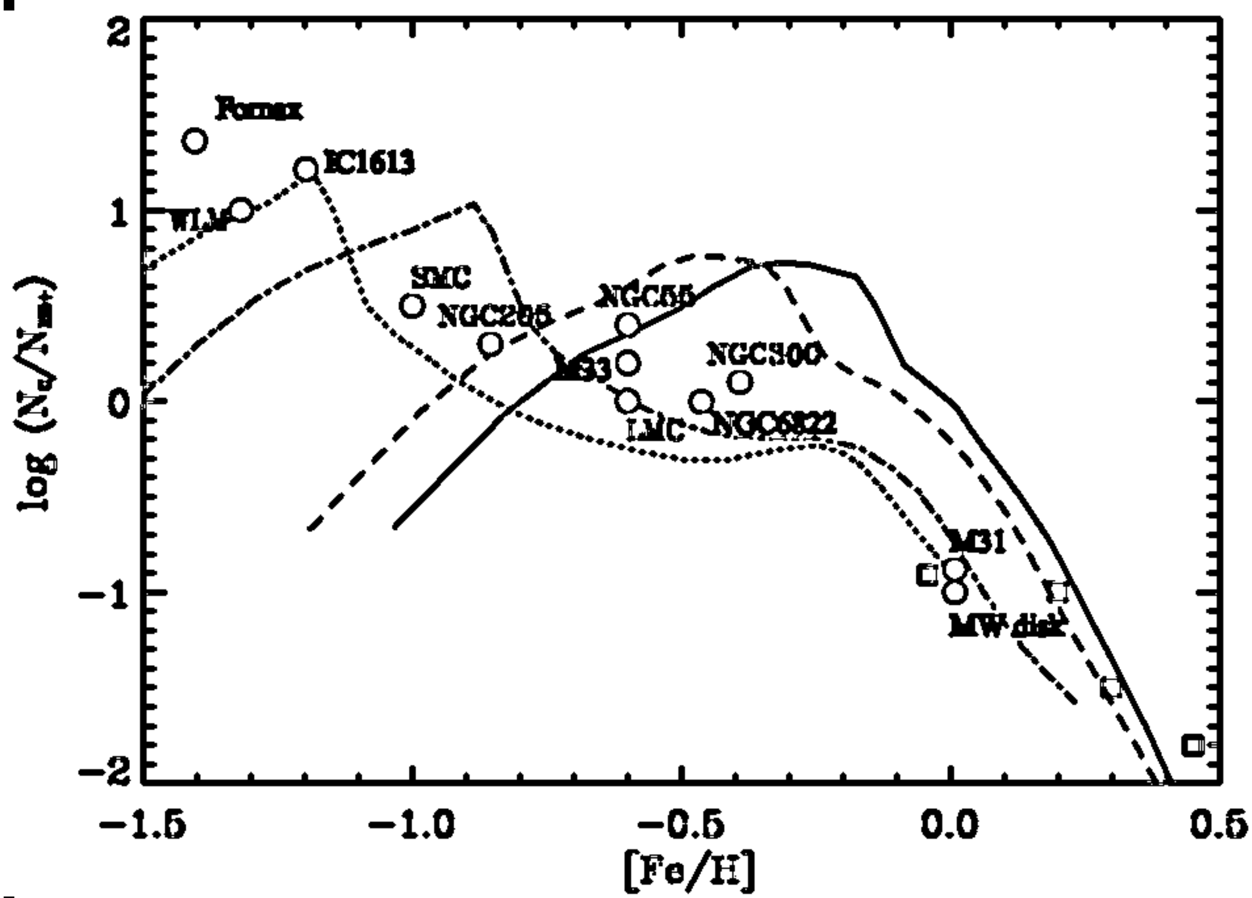
- Extension to other Local Group galaxies will become possible as surveys approach sufficient completeness. Doubtless the models will not fit the observations!
- Other statistical tests are possible e.g. $N_{\mathrm{C}}/N_{\text{late-M}}$ number counts.

$N_{\mathrm{C}}/N_{\mathrm{M5+}}$ in Local Group Galaxies



All featured galaxies have $N_{\mathrm{C}} > 100$.

$N_{\mathrm{C}}/N_{\mathrm{M5+}}$ varying SF history



From Mouhcine and Lançon (2003).

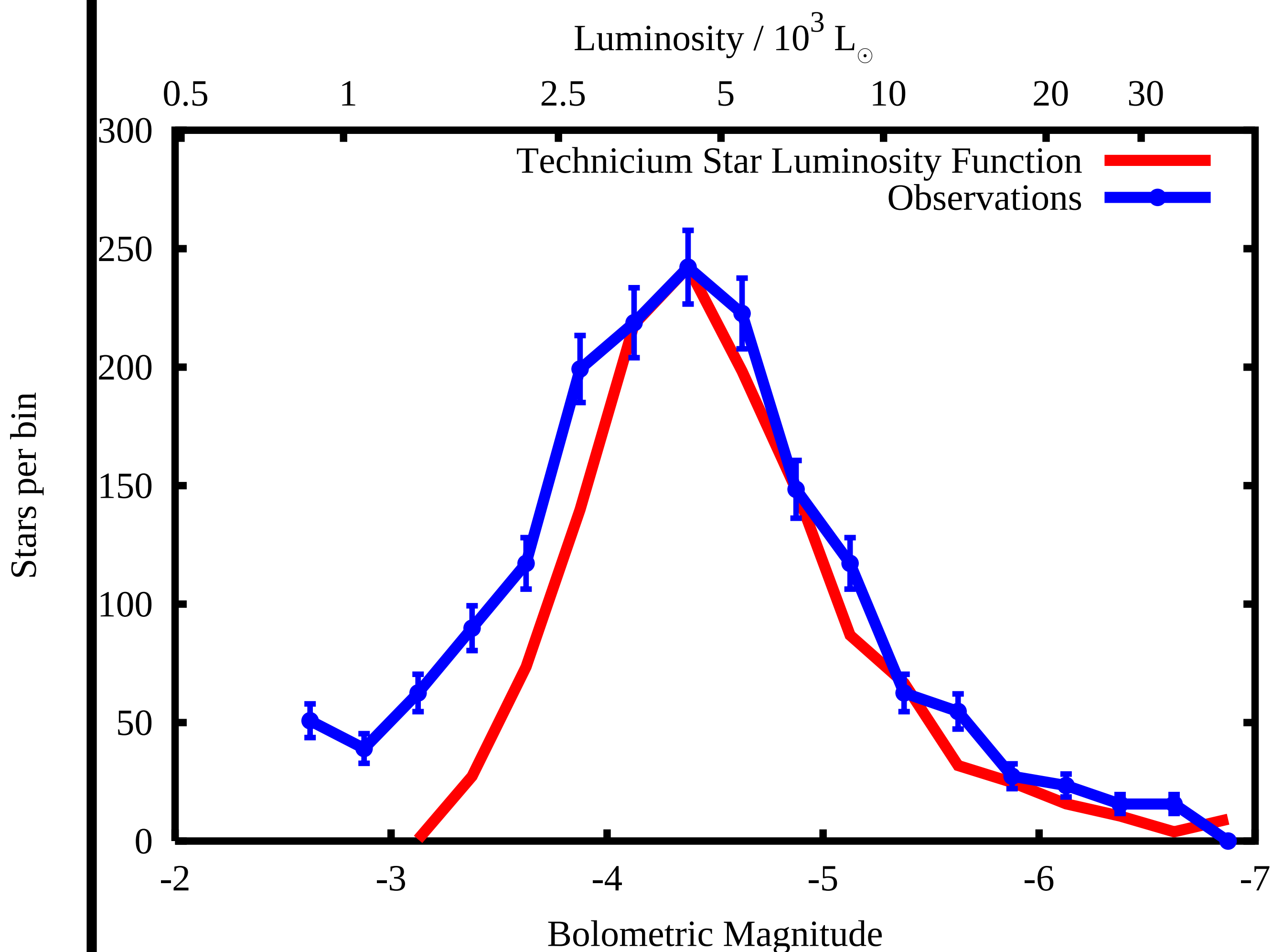
Future Tests – Obs

One relatively easy way to determine the nature of the dim carbon stars is through the radioactive s-process element Technetium. This is produced in the interpulse region by neutron capture reactions and has a lifetime of 2.5×10^5 years.

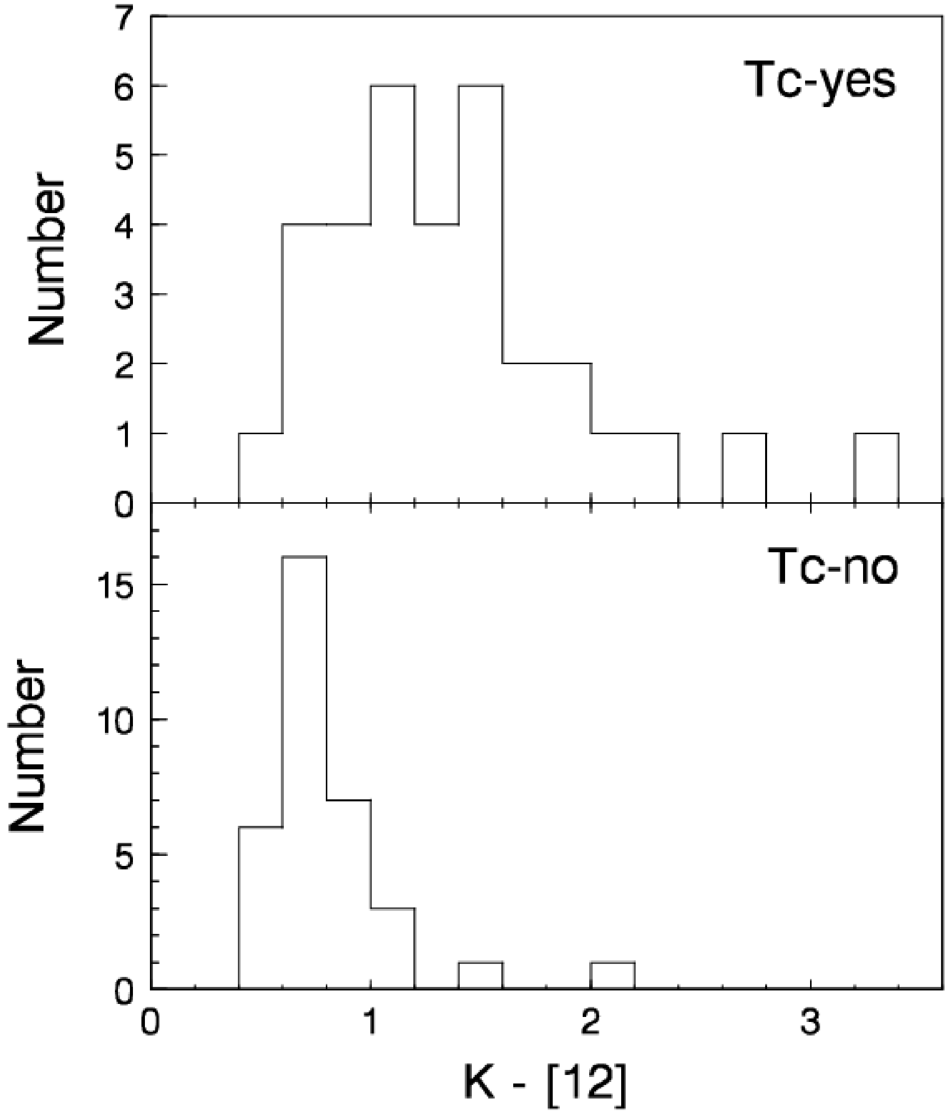
An *extrinsic* carbon star should be *rich in carbon but devoid of Tc.*

The rapid binary code includes s-process elements.

Theoretical Tc-star LF (SMC)

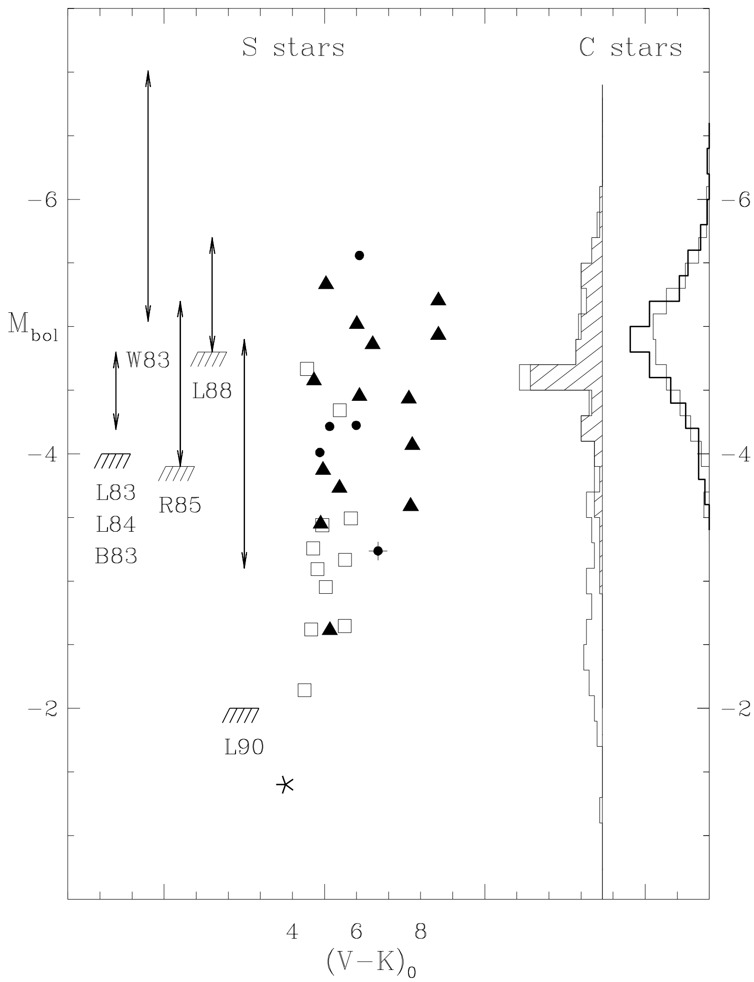


Galactic Tc Stars are dim



Wang and Chen (2002) (IRAS)

A few L/SMC Tc star obs



Van Eck et al. (1998) MC compliation - poor stats, need more stars!

Conclusions

- Binaries naturally explain the dim tail of the LMC and SMC CSLFs as pre-TPAGB giants enriched by a companion.
- In future Tc can be used to determine if binarity is more important than other parameters (e.g. molecular opacities).
- Need to calibrate dredge-up for more metallicities in other galaxies.
- Need our own detailed models.
- Good that new binary model survives first test.

the end

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