Stellar Evolution
&
issues related to the post Turn-Off evolution

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The point of view of Population Synthesis users

What do they want?

Magnitudes & Colors
Spectral indices
Integrated spectra
Surface Brightness fluctuations

What do you need?

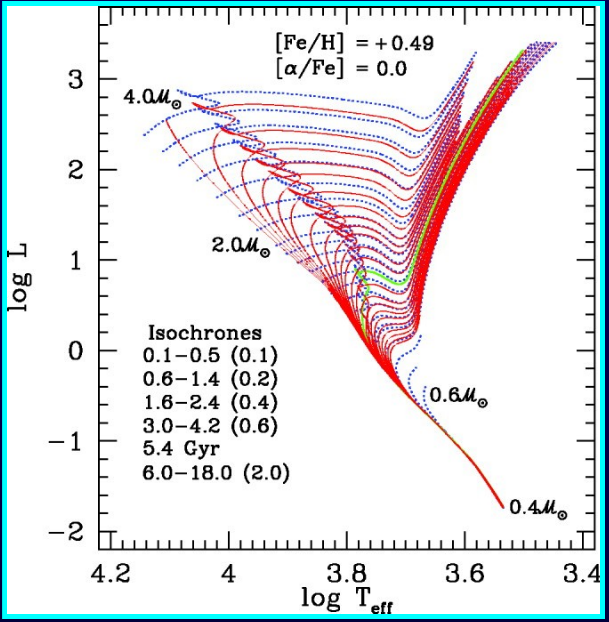
Bolometric corrections
+
color-T_{eff} relations
+
spectral library

+

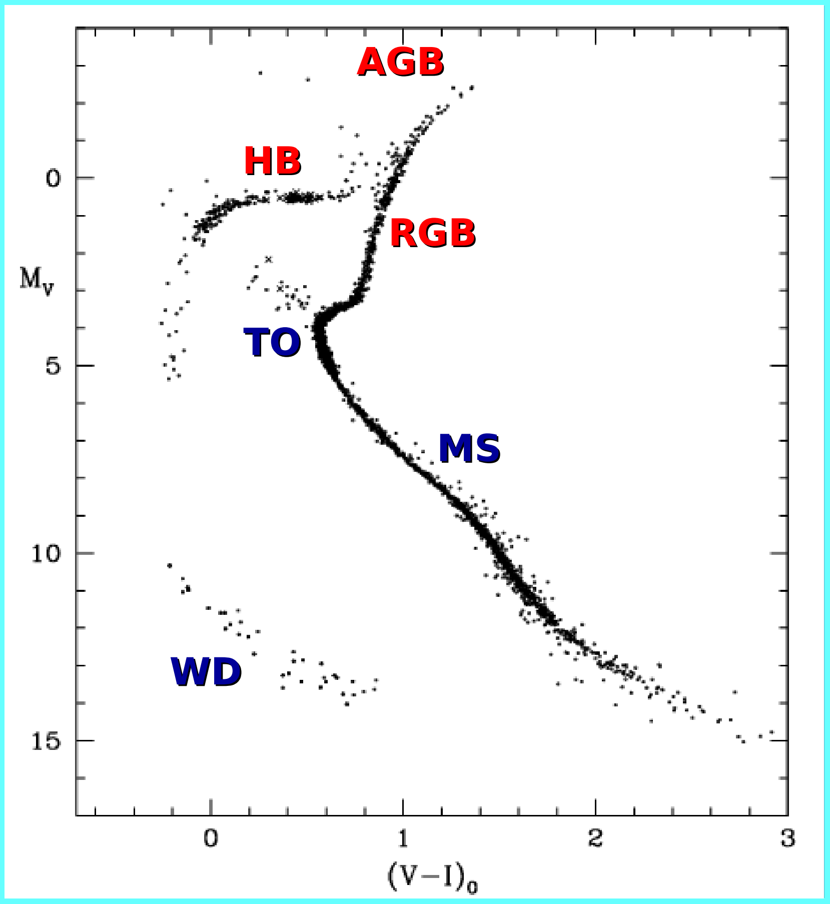
Stellar model library

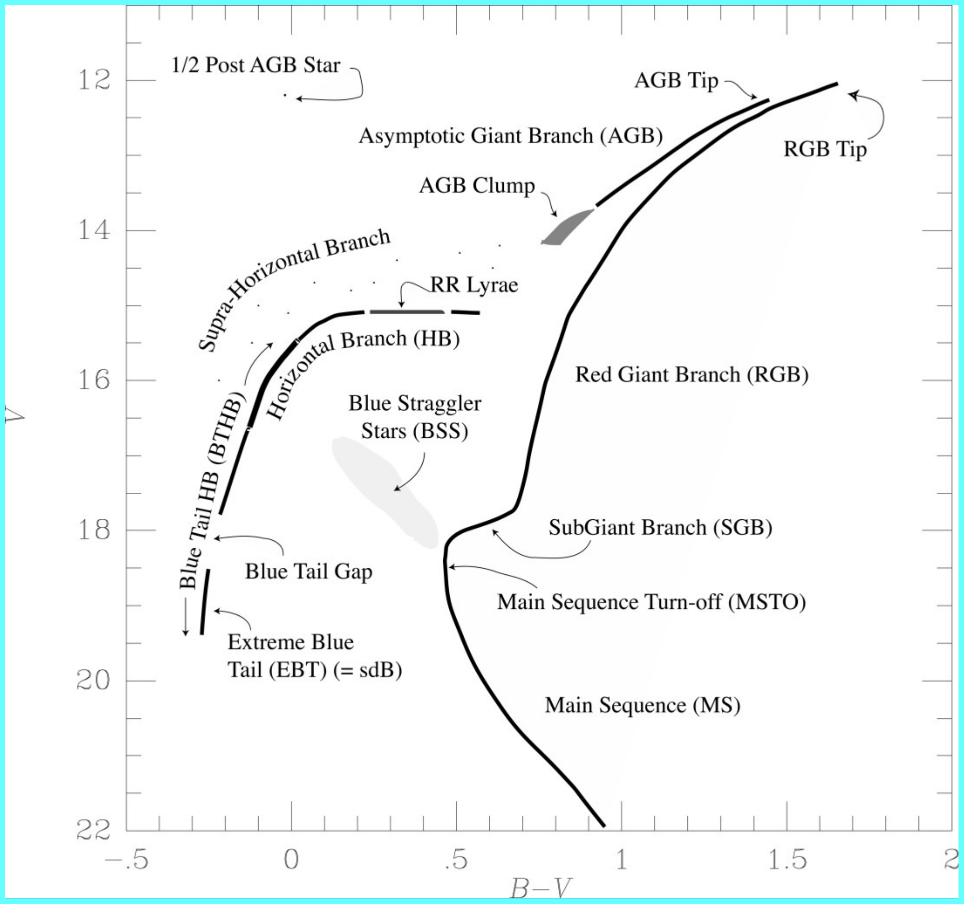
Stellar models provide:

- Evolutionary lifetimes
- Bolometric luminosity
- Effective temperature
- Actual Mass



Color-Magnitude diagrams of star clusters:
laboratories of low- & intermediate mass stellar evolution





Rood et al. (1998)

Issues related to post-TO evolution

- What is a “realistic” estimate of the uncertainty affecting SMs in advanced evolutionary stages?

- How do these uncertainties affect the Pop. Synthesis predictions and the calibration of distance indicators?

- The most critical issues…:

  - **Mass loss efficiency during the RGB and AGB stages;**
  - **Extremely Hot HB stars;**
  - **The reliability of AGB stellar models;**

Input physics affecting the RGB models

Input

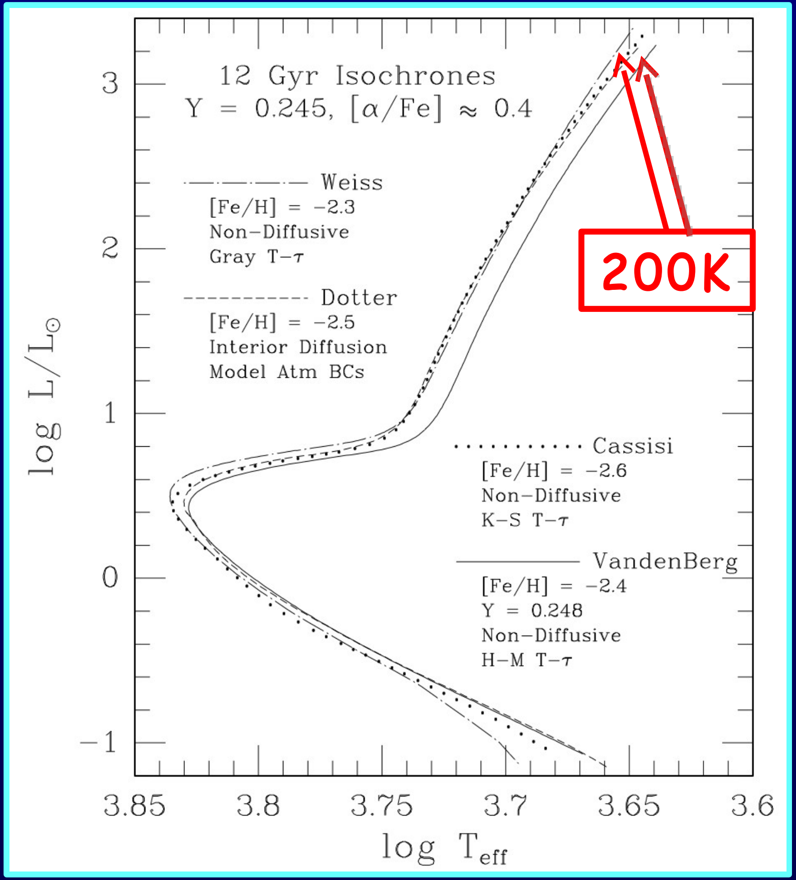
- Equation of State — ΔT_{eff}~100K
- Low Temperature Radiative Opacity — ΔT_{eff}~150K
- Efficiency of the convective energy transport — **Solar calibrated *ml***
- Boundary conditions — $\Delta T_{eff} \lesssim 80K$
- Abundances (He, Fe & α-elements)
- Conductive Opacity
- Neutrino energy losses
- Atomic diffusion efficiency

Evolutionary properties

T_{eff} ⇕ RGB location & shape

He core mass@RGB Tip ⇕ RGB Tip brightness

Red Giant Branch models: the state-of-the-art



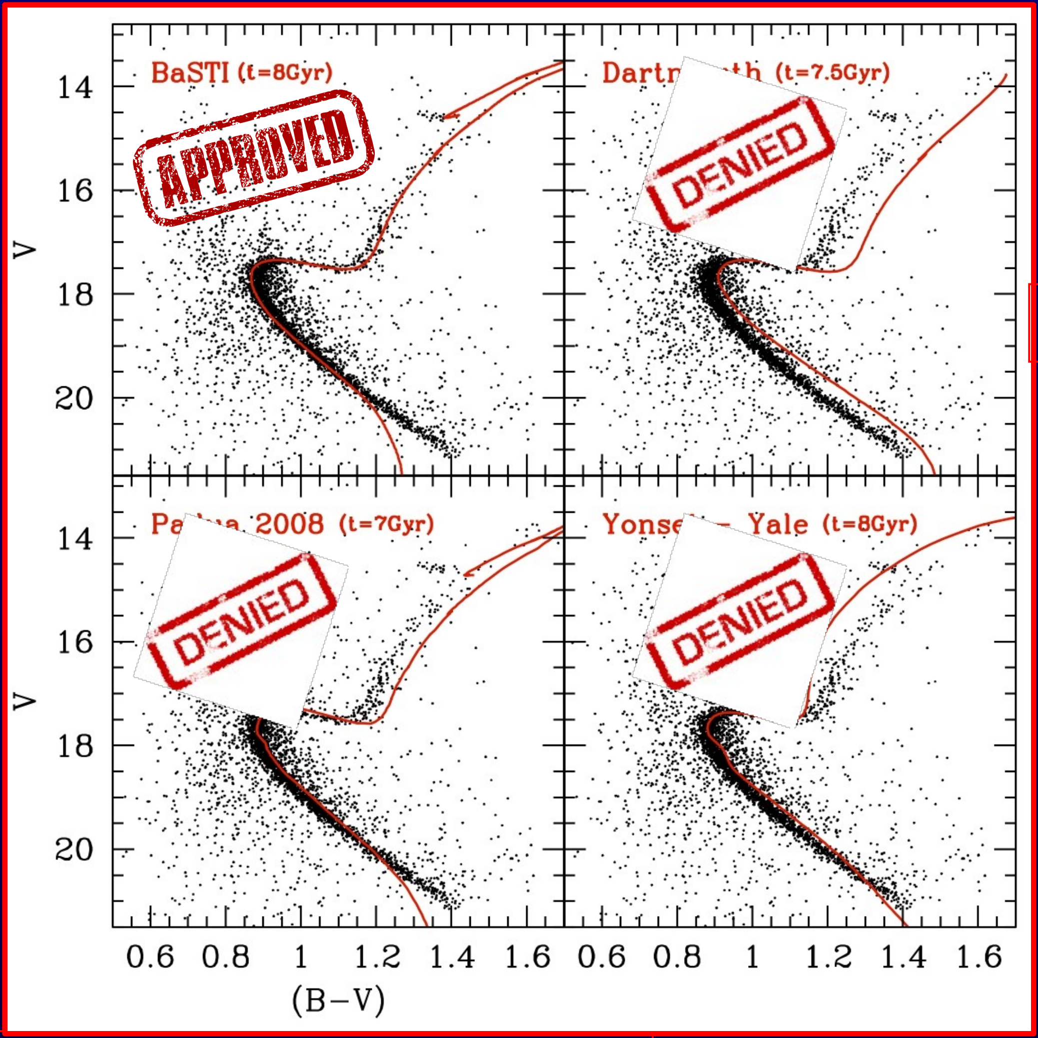
Models from different libraries, <u>based on a solar-calibrated *ml*,</u> can show different RGB effective temperatures

The difference can be also larger (up to 400K) when accounting for "old" stellar models

Is there any way to check the reliability of RGB stellar models?

Eclipsing binary: an important benchmark

When the distance & the metallicity are known the degrees of freedom in the fitting procedure are drastically reduced…

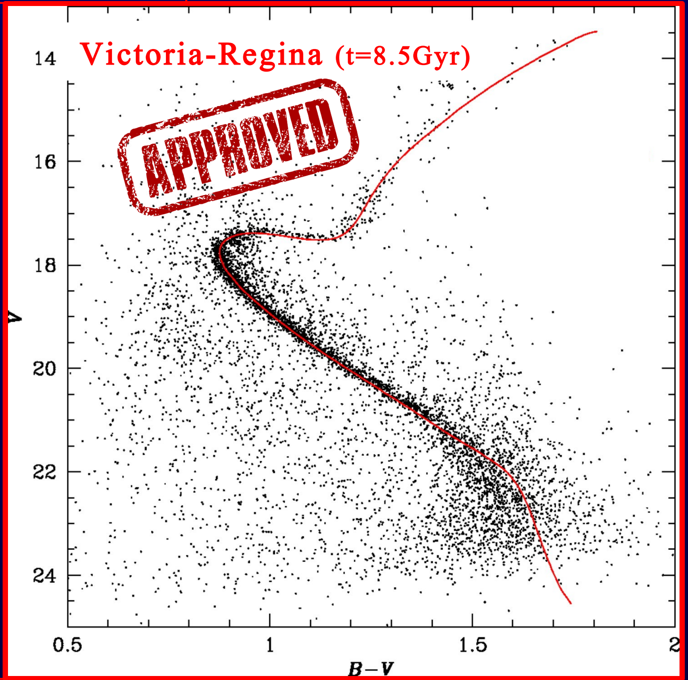


Photometry by Stetson et al. (2003)

$(m\text{-}M)_V = 13.46 \pm 0.10$

$E(B\text{-}V) = 0.15 \pm 0.02$

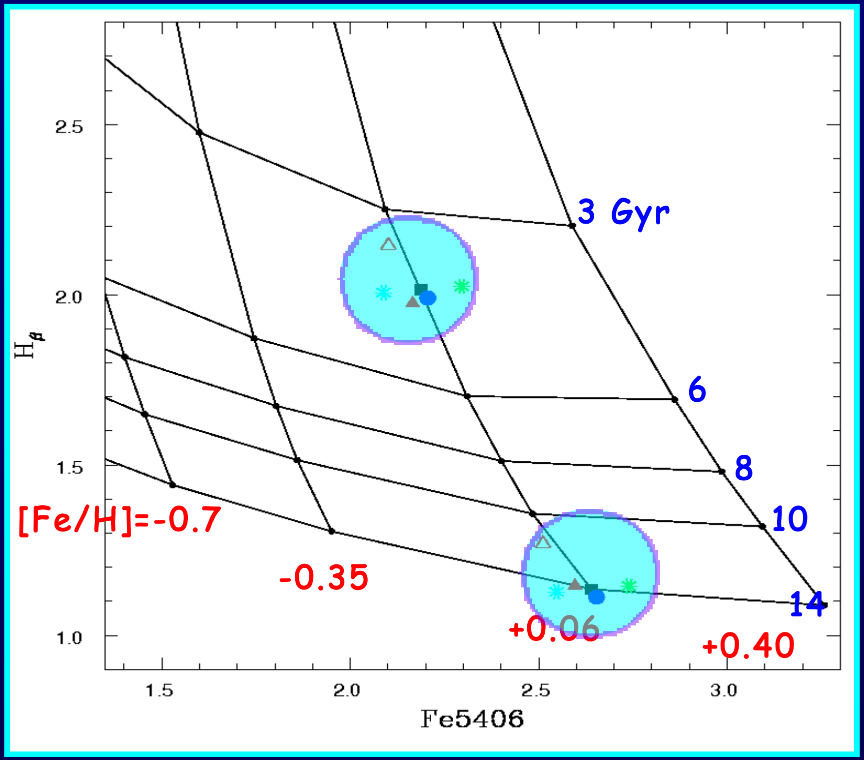
NGC6791

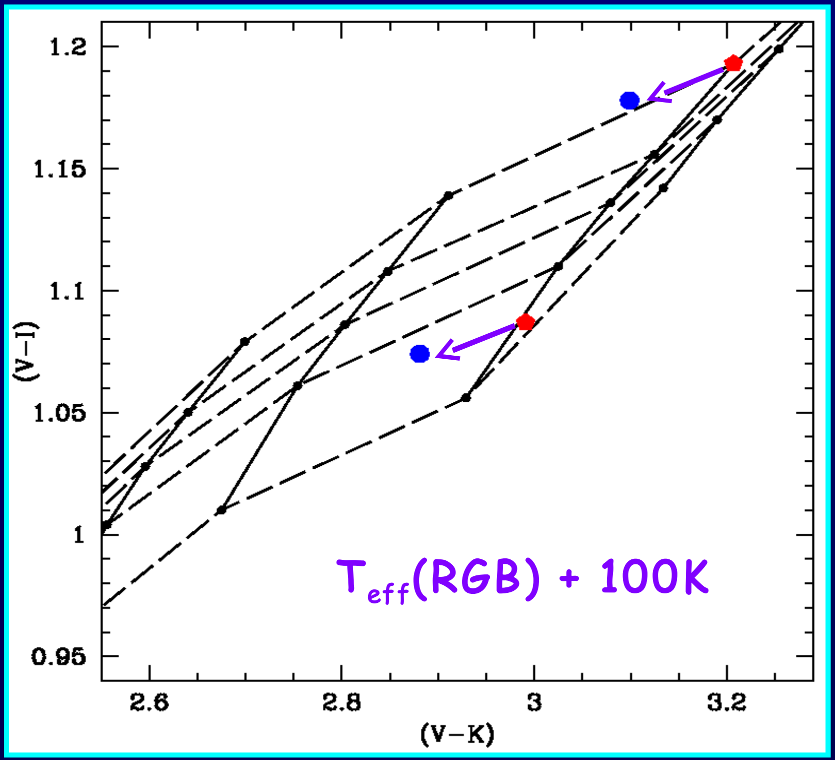


Kalirai et al.(2007)

What is the impact on PS predictions?

Some quantitative tests of the sensitivity to RGB/AGB stars



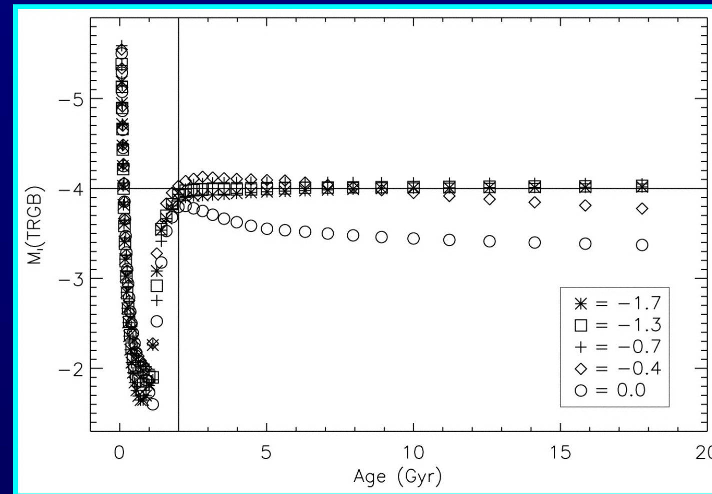


- Red triangles ➔ T_{eff} + 100 K (only the AGB & RGB)
- Blue circles ➔ log(g) + 0.25 dex
- Asterisks ➔ [Fe/H]±0.15 dex
- Open triangles ➔ T_{eff} + 100 K (whole isochrone)

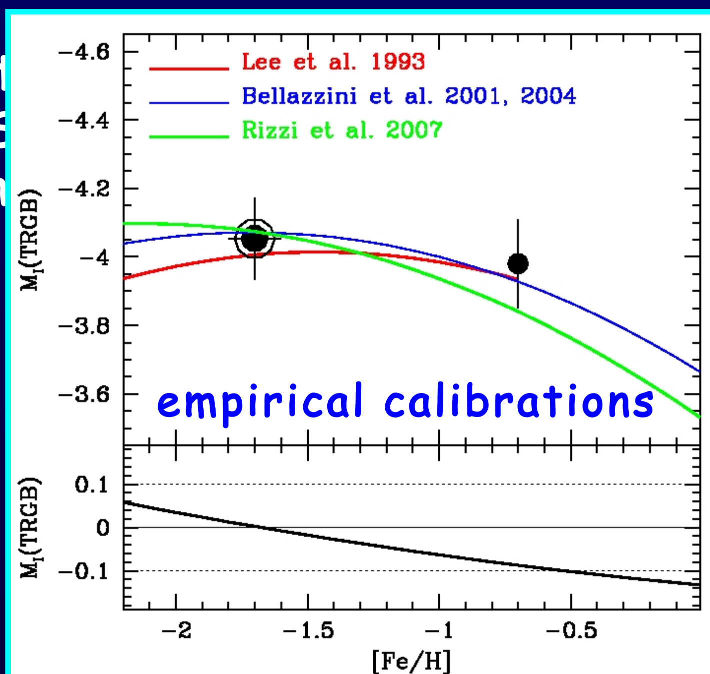
The RGB Tip brightness: a standard candle

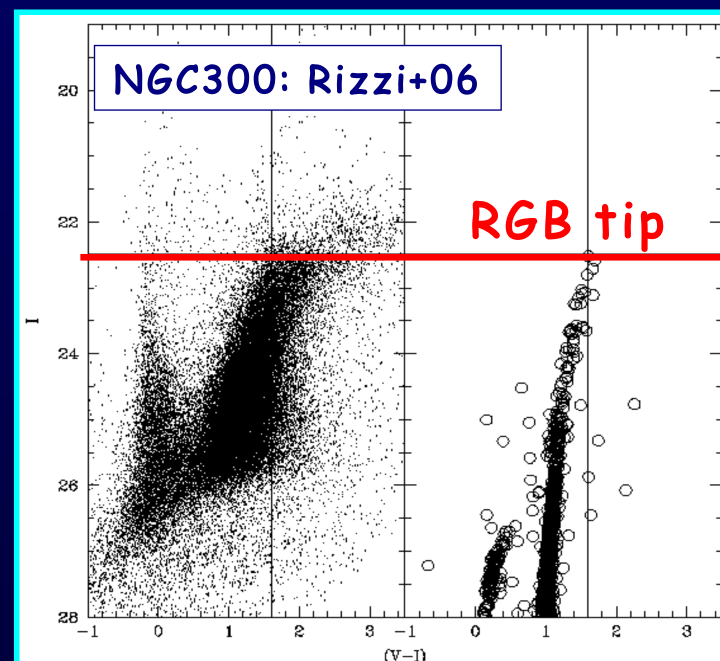
<u>The I-Cousins TRGB magnitude </u>is one of the most important primary distance indicators (Tamman+08):

- age independent for t>2-3Gyrs;
- metallicity independent for [M/H]<-0.9

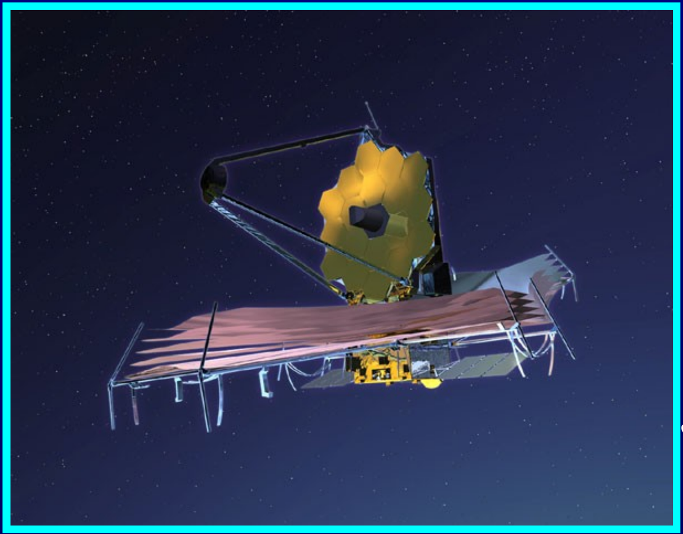


In t… to the ACS… red in man… Local Gro… ger+08, …)



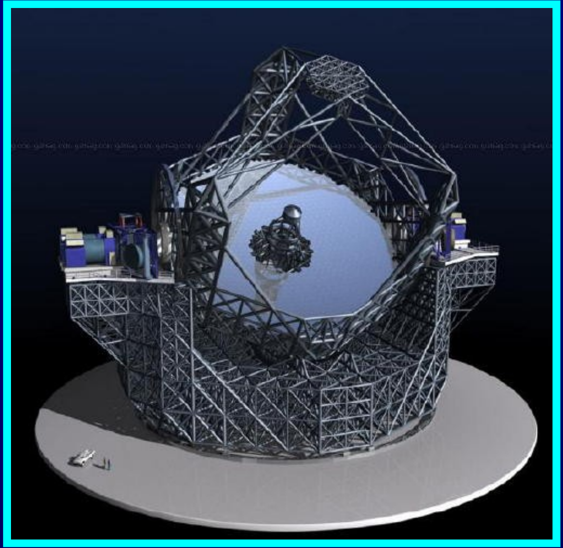


The future: JWST and/or ELT+AO



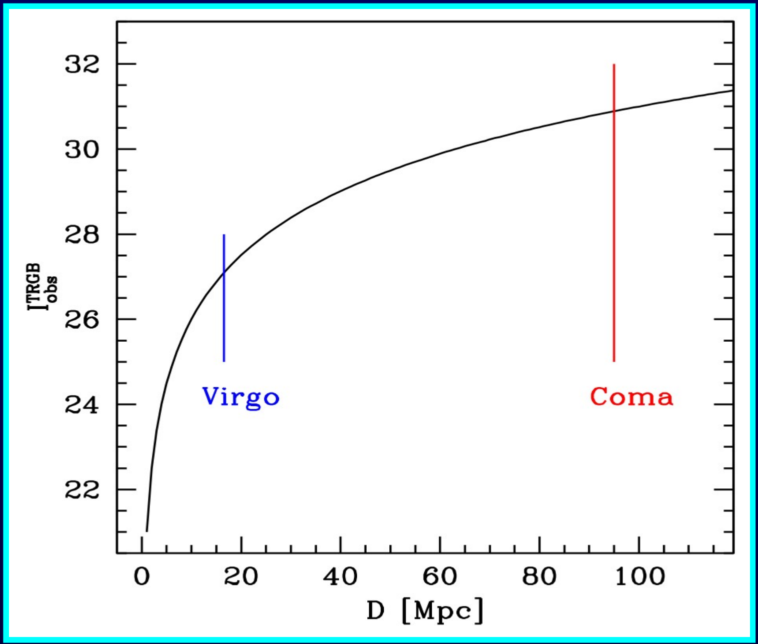
Both the best observational facilities of the future will be optimized for the near infrared

JWST should "see" also the I band

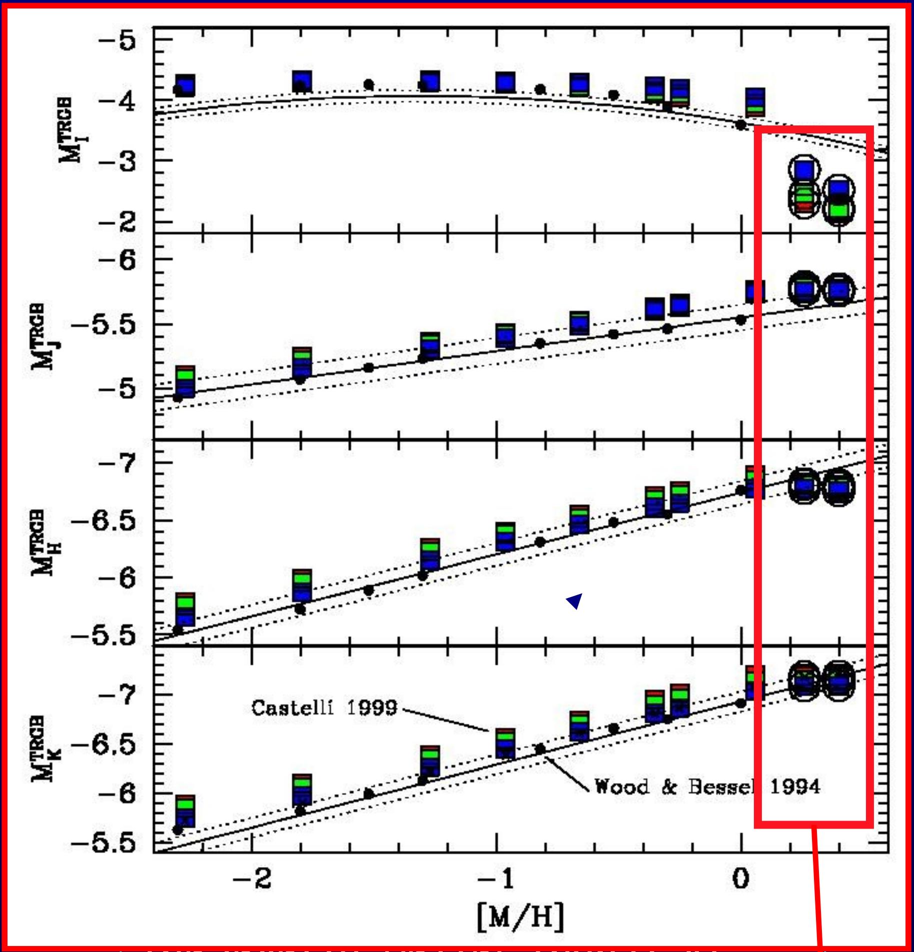


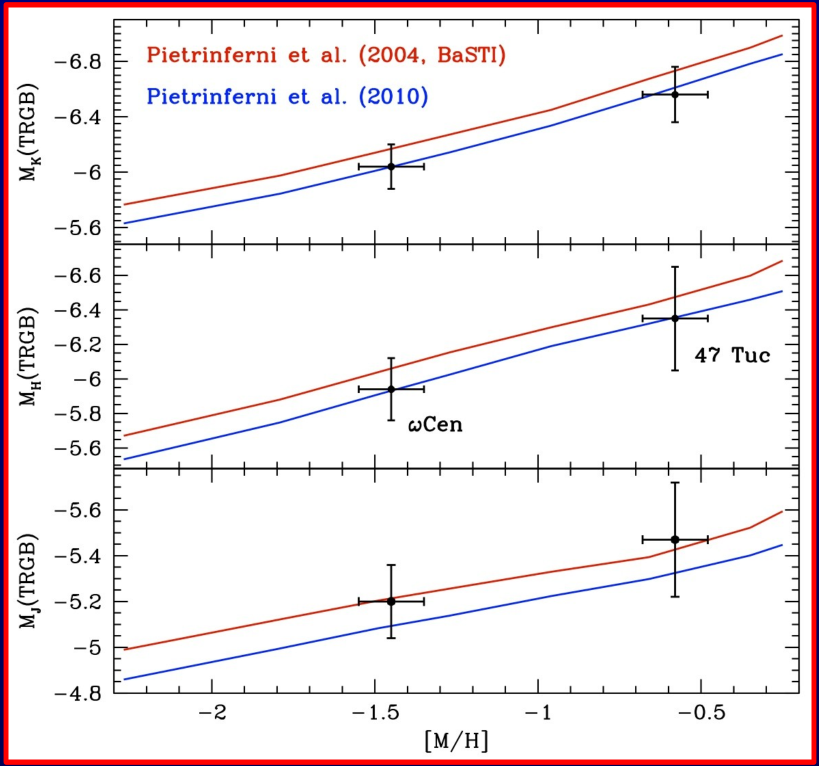
The Red Giant Branch is what we will see of resolved giant ellipticals!

Is its calibration still a critical issue?



The TRGB brightness: theoretical calibration





The level of better than 0.30

In the near-IR bands, the same calibration seems to be in fine agreement with empirical constraints (but in the J-band…)

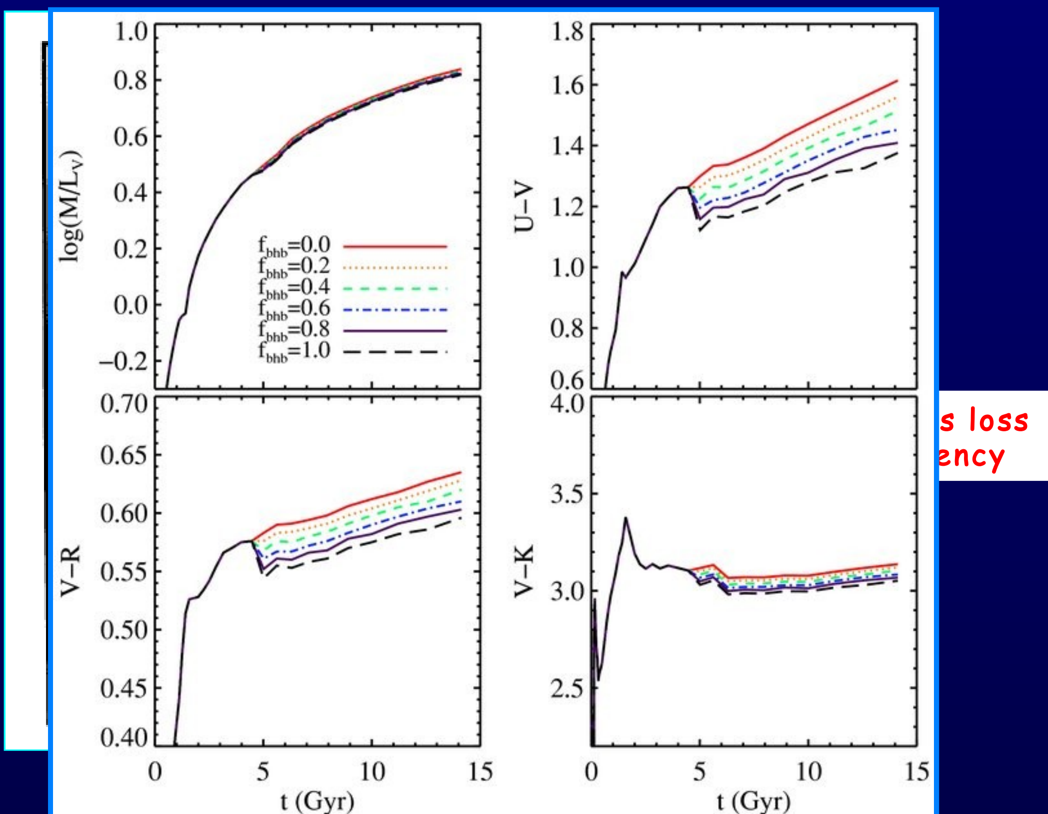
If you want to use the Tip as a distance indicator for elliptical galaxies it is better to use NIR passbands

Input physics affecting the HB models

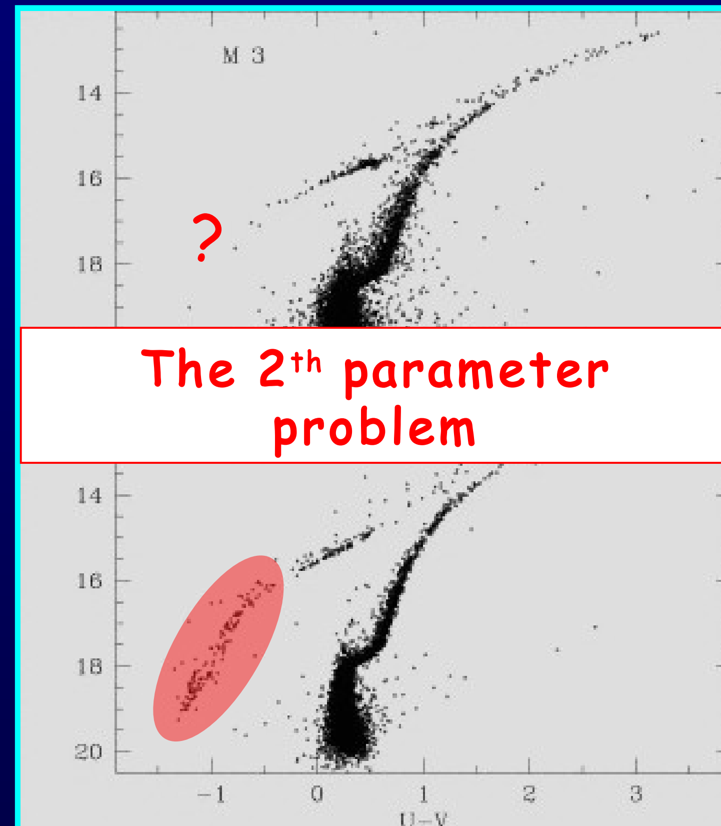
Input	Evolutionary properties
• Equation of State • Low Temperature Radiative Opacity • Efficiency of the convective energy transport • Boundary conditions	T_{eff} ⇕ RGB location & shape
• Abundances (He, Fe & α-elements) • Conductive Opacity • Neutrino energy losses • Atomic diffusion efficiency	He core mass@RGB Tip ⇕ RGB Tip brightness
• Mass loss efficiency	Envelope mass

The impact on the Horizontal Branch morphology

Mass loss has negligible (…not always…!) effects on the evolutionary properties of RGB stars, but it strongly controls the color distribution of stars along the Horizontal Branch



Conroy et al. 2009

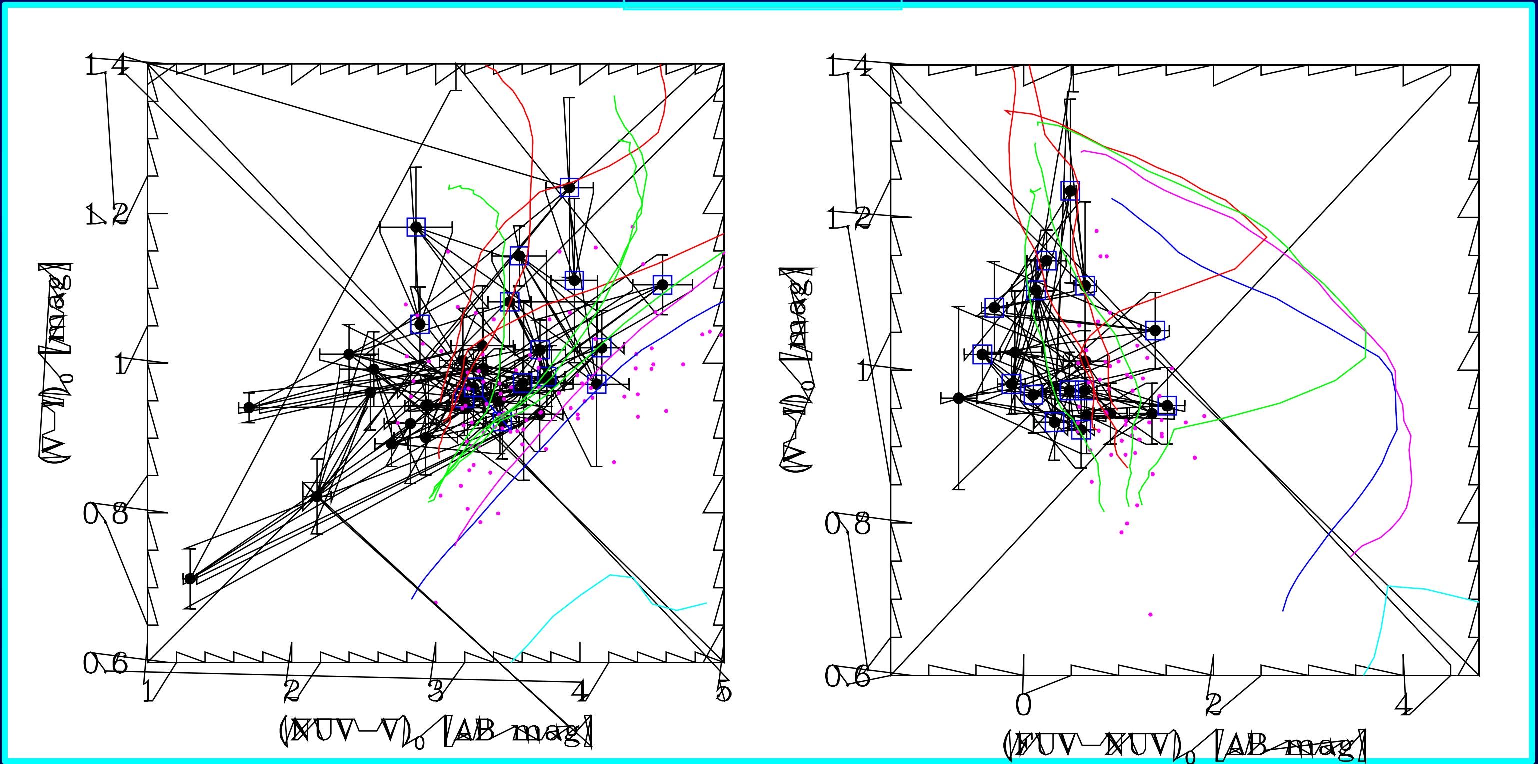


Warning: we can not predict "a priori" the HB morphology for a given metallicity!!!!

The HB morphology versus Population Synthesis tools

The "HB type" strongly affects the integrated colors and magnitudes. This should be seriously taken into account when interpreting color differences among GCs in the same galaxy as "just" due to a metallicity differences ➔ color bimodality, color-(UV) color diagram, "integrated" GCs CMD

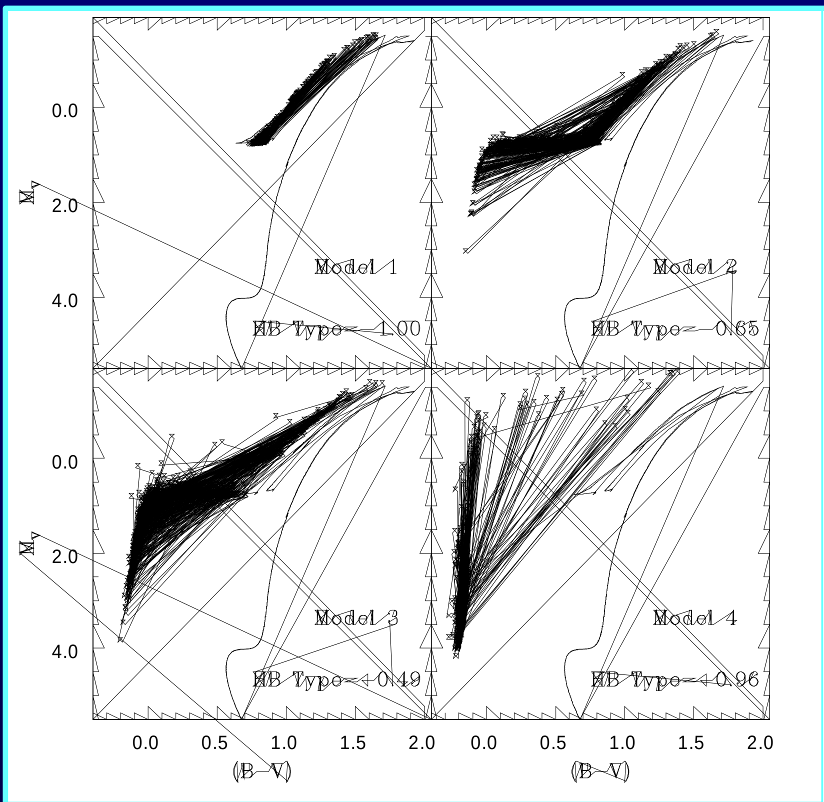
GCs in Fornax



Mieske et al.(2008)

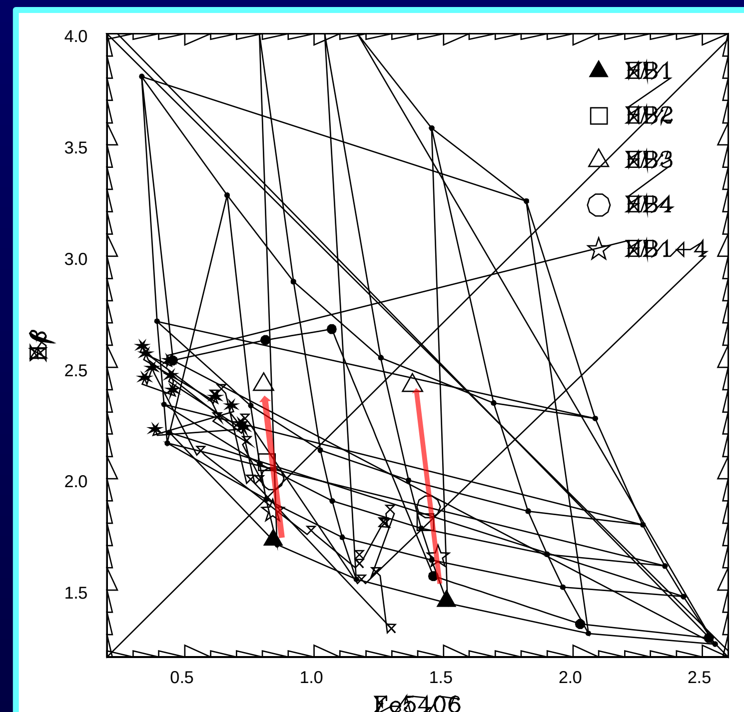
The HB morphology versus Spectral indices

An "hot" HB increases the strength of the Balmer lines and can make an old population looks spuriously young (Lee+00, De Propris 00)!



Percival & Salaris (2011)

In their seminal work, Lee et al (00) assume that the change of the HB type is driven by age…but…

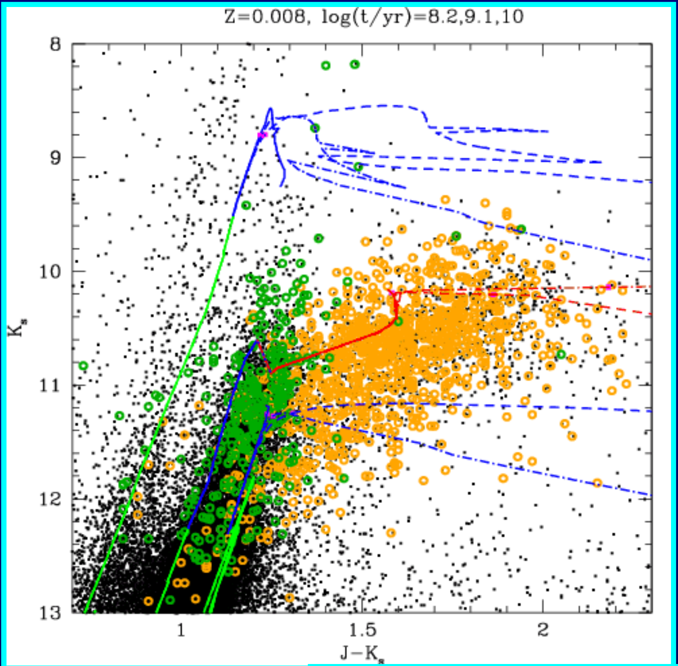


The Asymptotic Giant Branch

The AGB evolutionary stage is crucial:

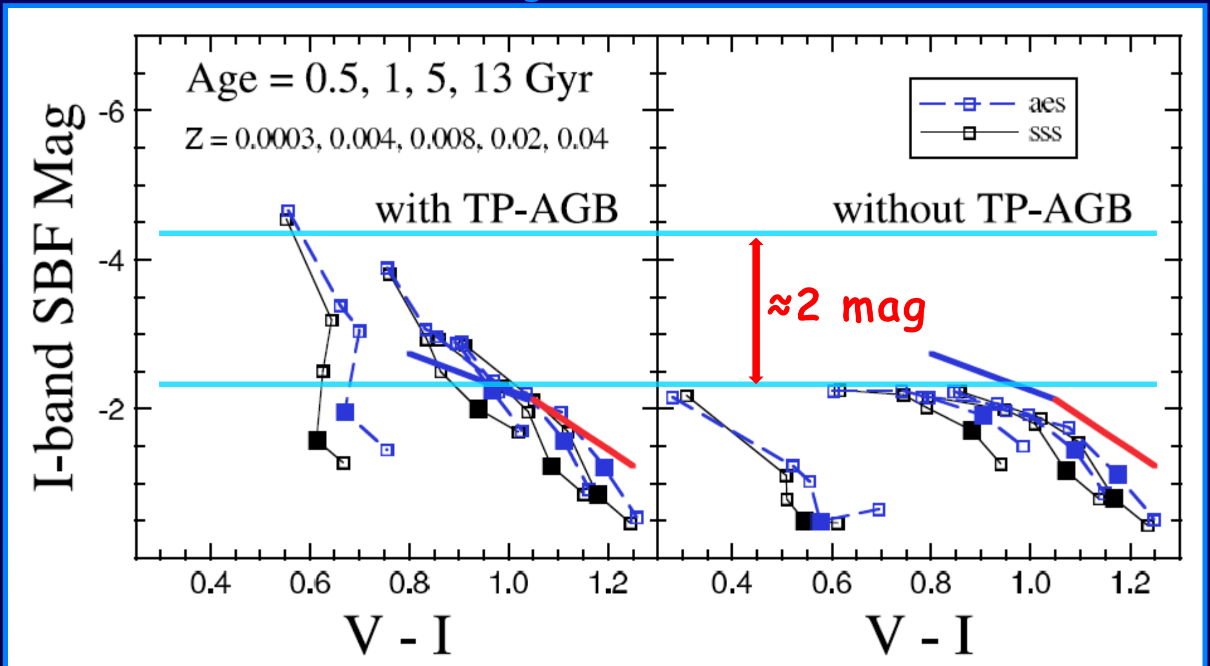
- Population tracers

- Integrated properties of resolved & unresolved stellar populations



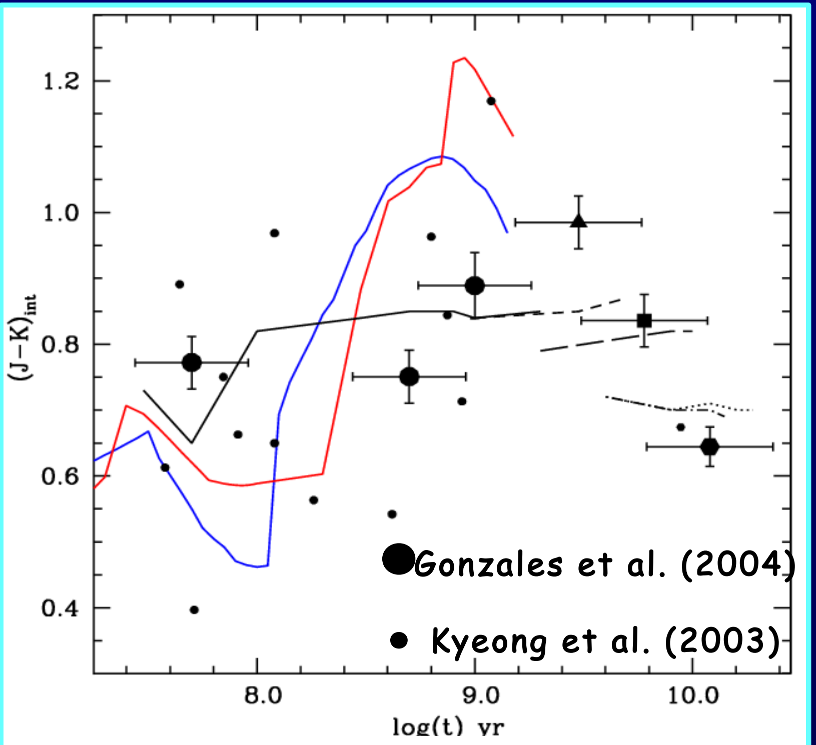
Marigo et al. (2008)

Surface Brightess Fluctuations



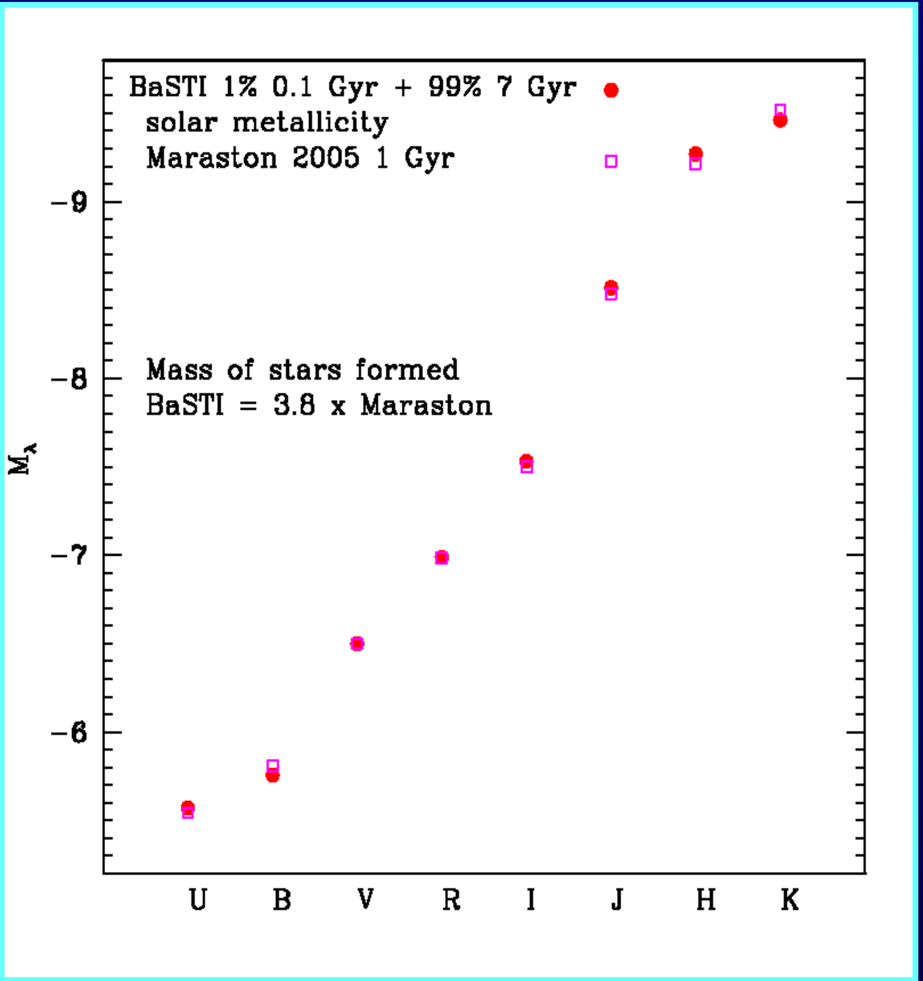
Lee, Worthey & Blakeslee (2009)

The AGB stage treatment in Pop. Synthesis Tools



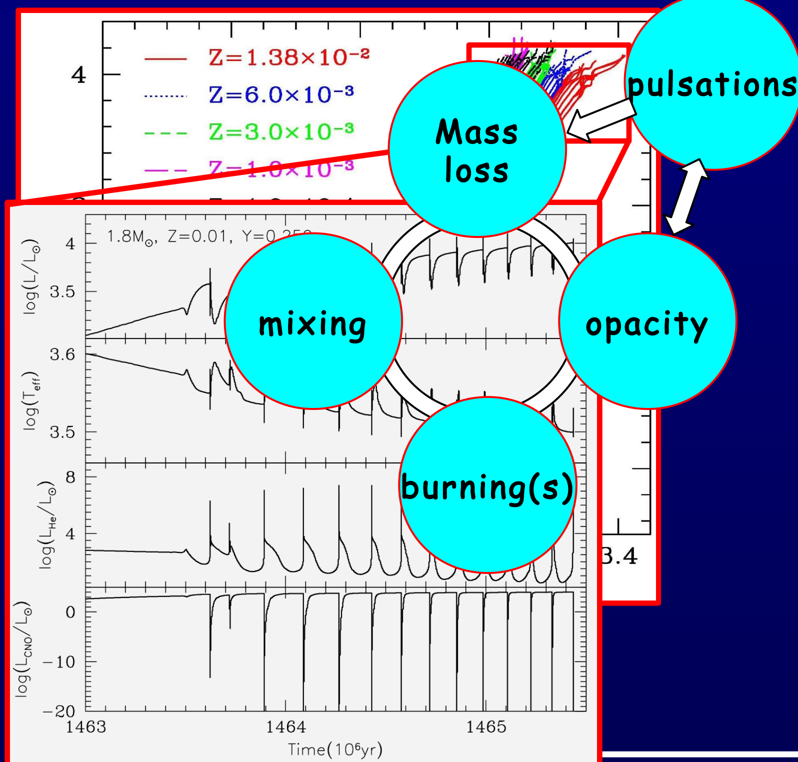
Models (for Z=0.01) by:

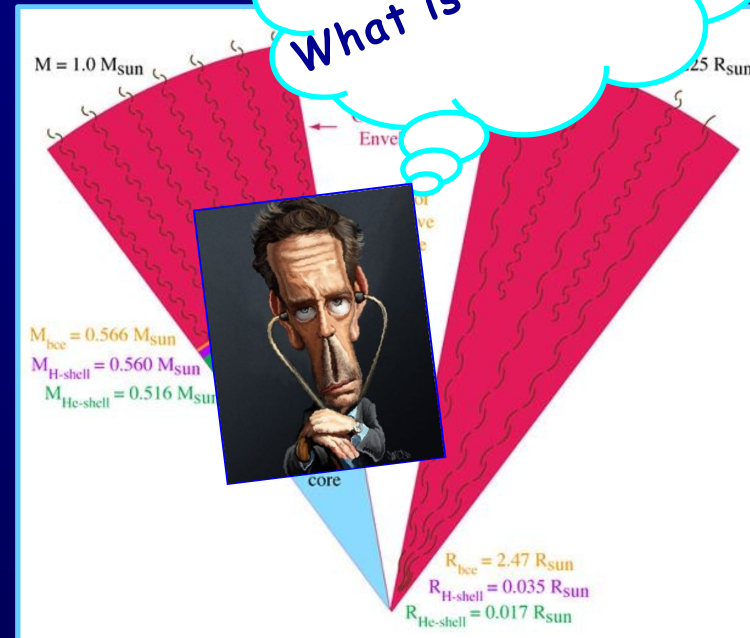
✓Maraston (2005)
✓Marigo & Girardi (2008, Padua)
✓Percival et al. (2009, BaSTI) (also for Z=0.008, 0.004, 0.0008)



AGB stellar models

What is the problem?





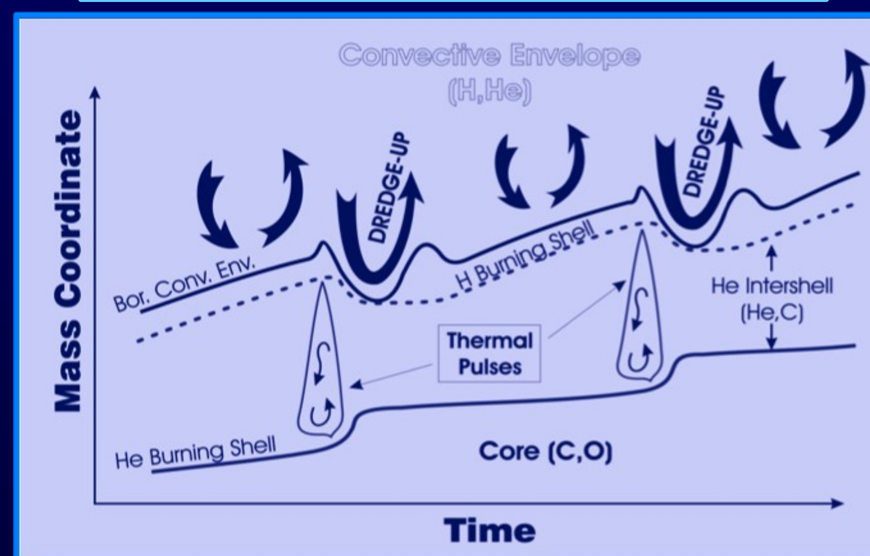
Nucleosynthesis

Brightness

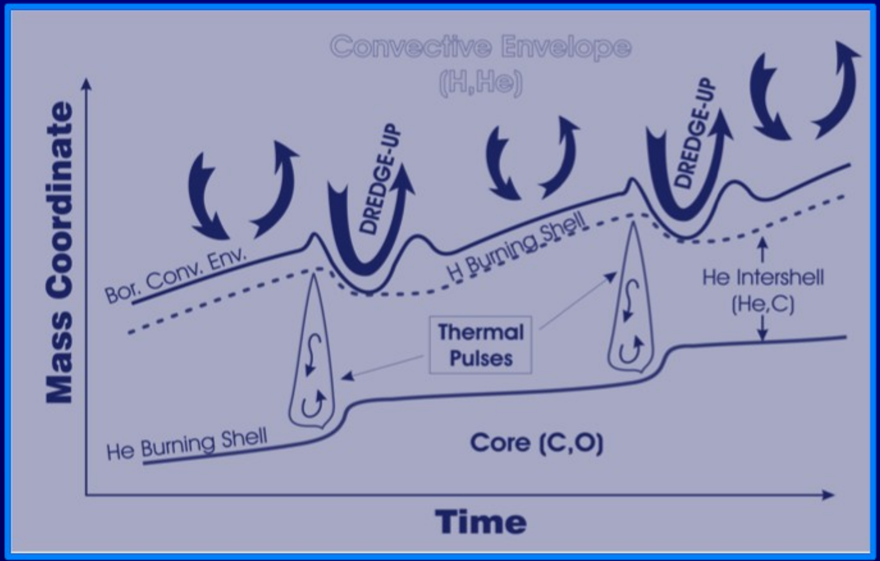
Effective temperature scale → colors

Evolutionary lifetime

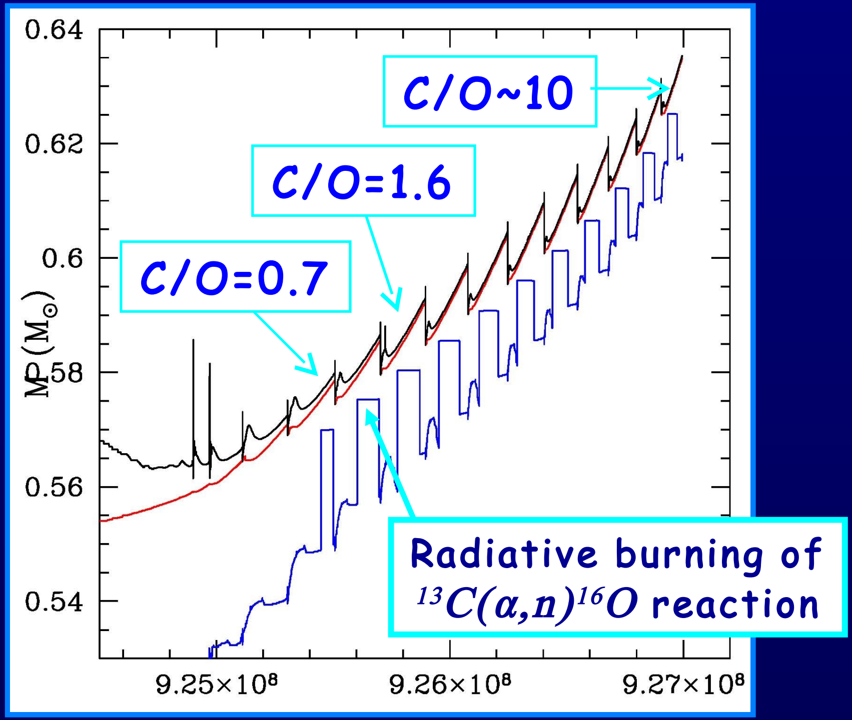
Initial - Final mass relation



The efficiency of the Third Dredge Up



Helium, Carbon, s-elements ↑



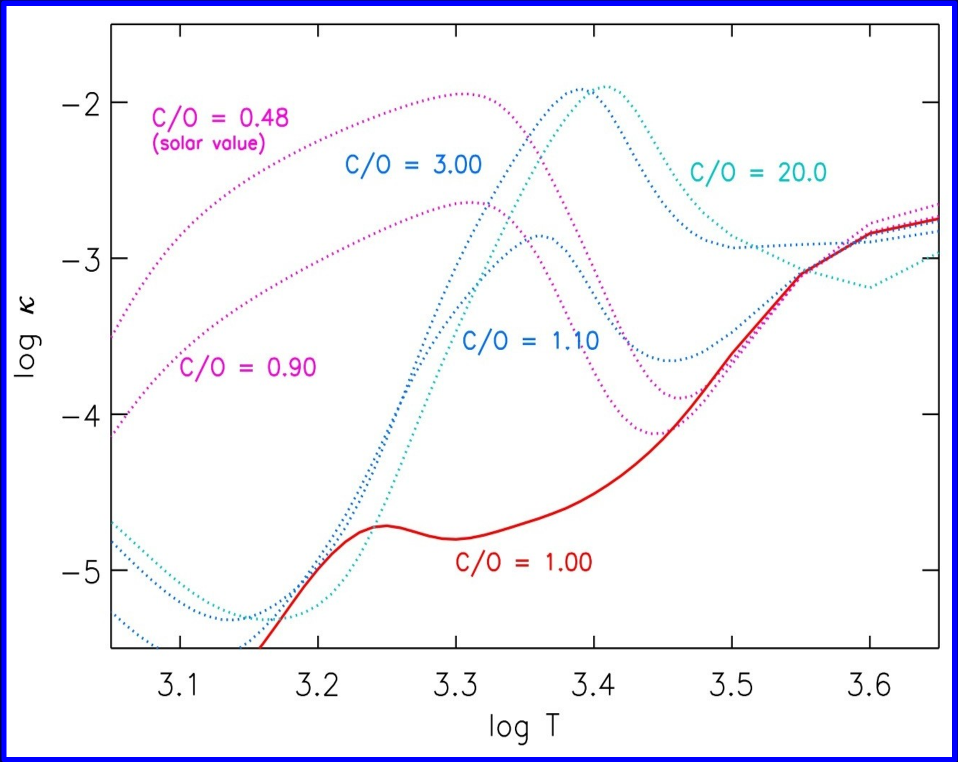
The mixing efficiency during the TDU has important effects on:

- the rate of surface C-enhancement;
- the effective temperature scale and colors;
- the mass loss efficiency and, in turn, the TP stage lifetime;
- the nucleosynthesis;

The opacitive effects of the C-enhancement

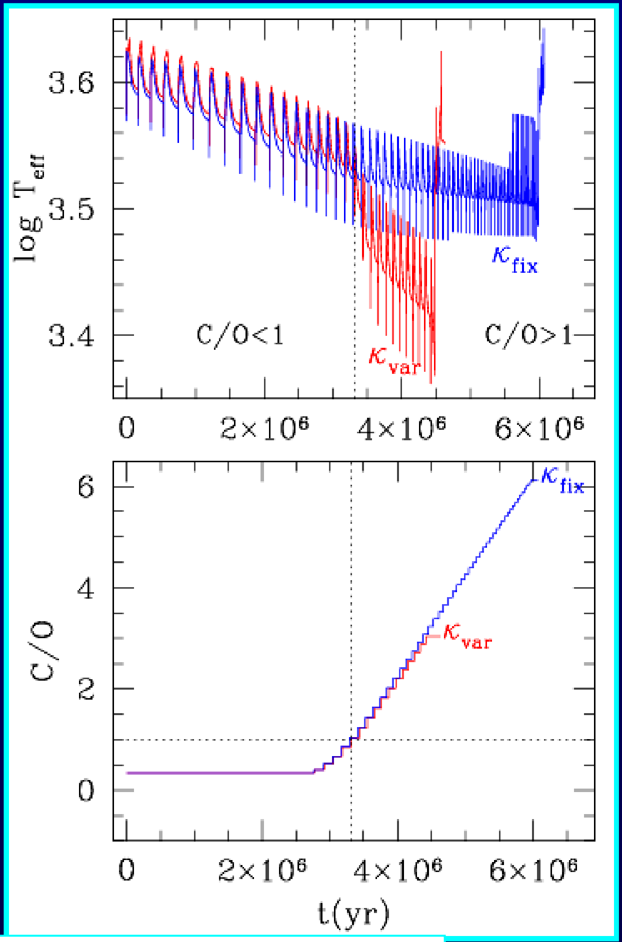
Scalo & Ulrich (1975) and Marigo (2002) showed that: TiO and H_2O are the most important molecules in the oxygen-rich regime (C/O<1), while carbon-bearing molecules (C_2, CN, C_2H_2 and C_3) dominate the opacity for C/O>1

Fundamental further steps ahead have been now made by Lederer & Aringer (2008), Marigo & Aringer (2009) and by Weiss & Ferguson (2009)



What is the impact on the effective temperature scale?

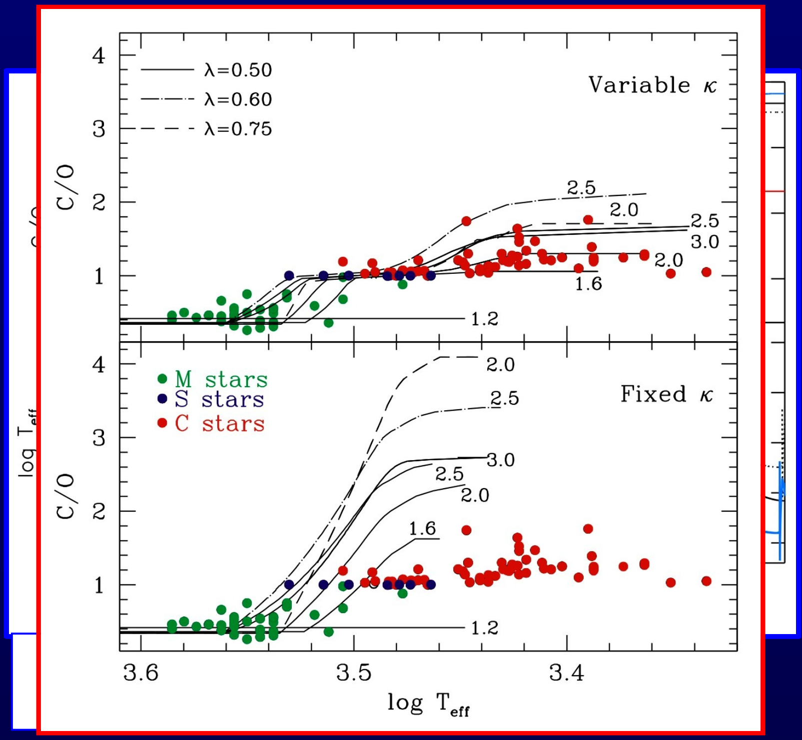
The importance of an appropriate treatment of C-rich mixture opacity



Marigo & Girardi (2007)

Direct effect:

- huge decrease of the effective temperature



Indirect effect:

- strong increase of the mass loss efficiency…
- reduction of the Hot Bottom Burning efficiency…

AGB stellar models: the neverending story…

AGB models are based on the fine-tuning of many free parameters!

So they have not to be taken as a "dogma": an illustrative case…

- The new "Padua" (MG07) AGB models were announced as quite reliable and accurate…;
- So many groups have recomputed their pop. Syn. Models by using these updated prescriptions;
- BUT, after a while, it was evident that such models overestimate the AGB flux contribution, due to the too long evolutionary lifetimes…