Stellar models for modeling stellar populations

Léo Girardi (Oss. Ast. Padova, Italy)

with <u>incomplete</u> list of collaborators:

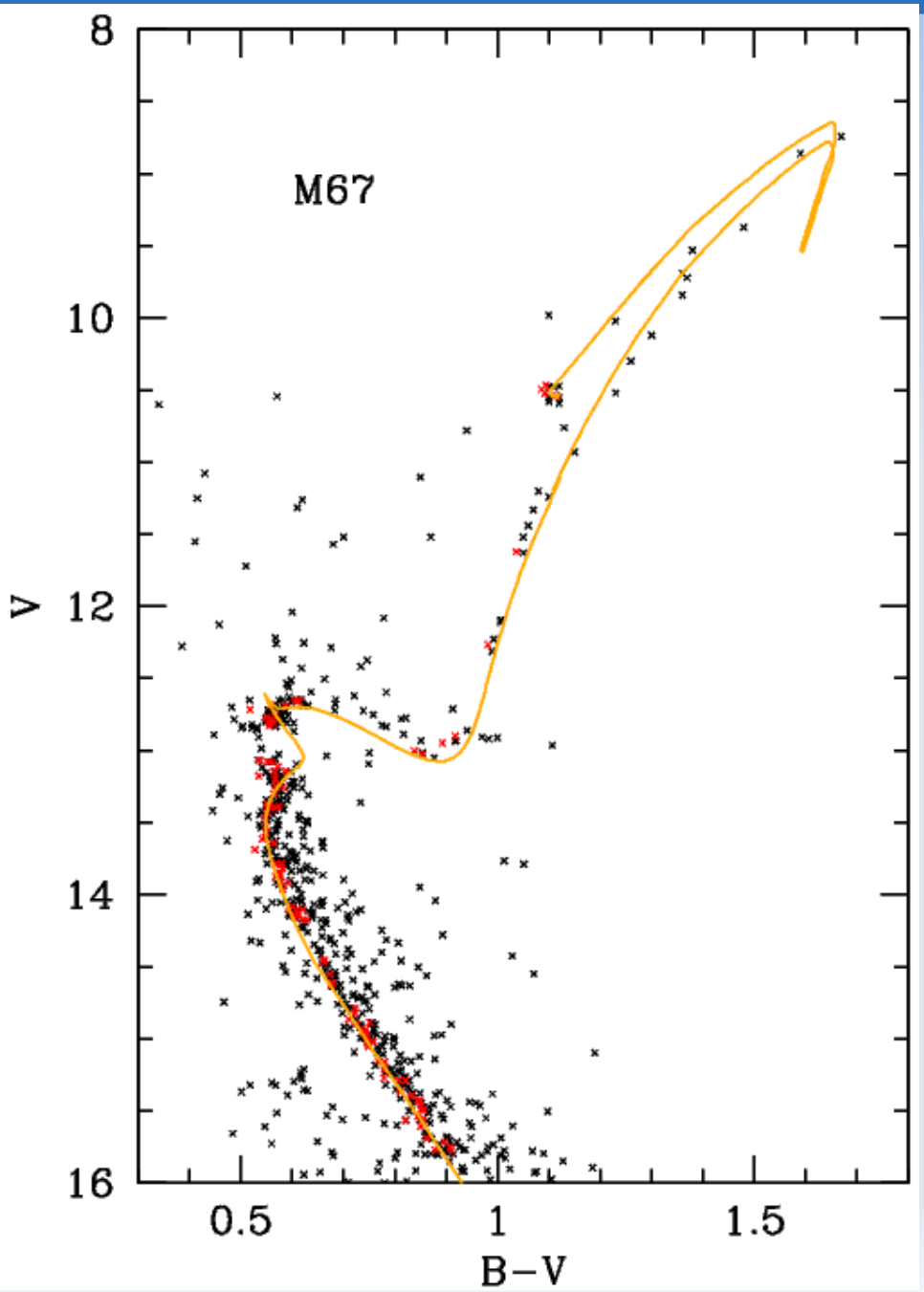
- Alessandro Bressan, Paola Marigo, Phil Rosenfield, Yang Chen, Bernhard Aringer, ANGST + PHAT teams (PARSEC evolutionary tracks, spectra of cool stars, STARKEY project)
- Stefano Rubele, Leandro Kerber, Paul Goudfrooij, Vera Kozhurina-Platais, Patrick Eggenberger, Andrea Miglio, et al. Intermediate-age star clusters in the MCs
- KASC, APOKASC, SDSS-III + DES Brazil (modeling the Milky Way, its asteroseismology data, and TRILEGAL optimization)

Overview

- Available tracks and isochrones (mainly PARSEC)
- Some present challenges:

1. Radii/colors of very low mass stars
2. Intermediate-age star clusters in Magellanic Clouds
3. Helium burning sequences
4. The mixing length theory
5. TP-AGB stars

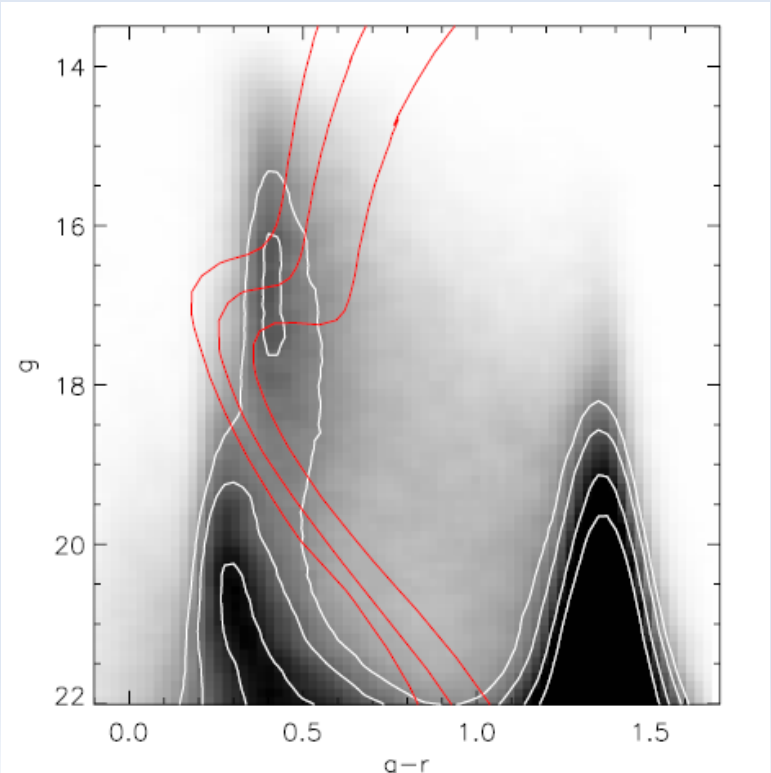
If one simply wants to interpretate CMDs:



M67
(Bressan+12)

- CMDs of ”normal stars” in Milky Way field, nearby galaxies, star clusters
- Stellar models do exist, complete enough in age/metallicity, and adapted to many population synthesis codes

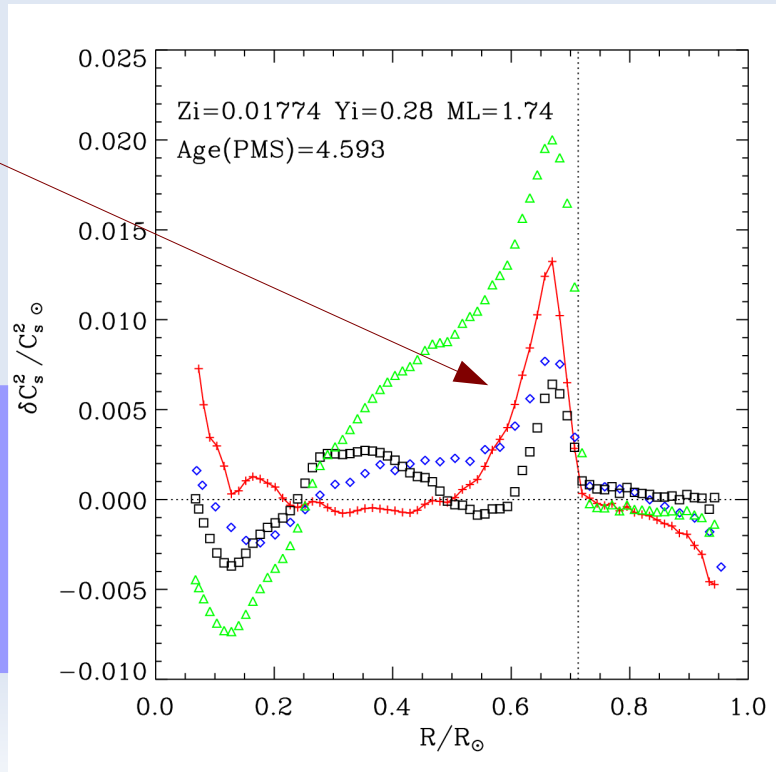
MW field from SDSS (de Jong)

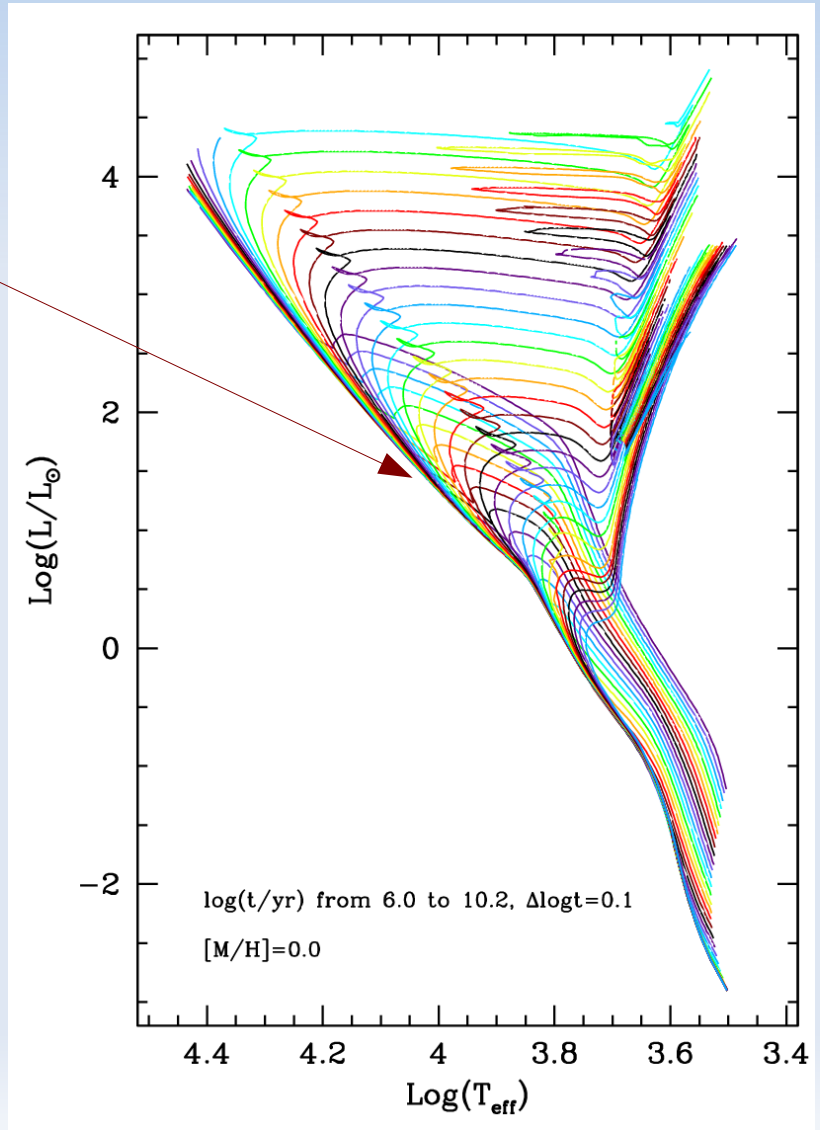


Evolutionary tracks / isochrones

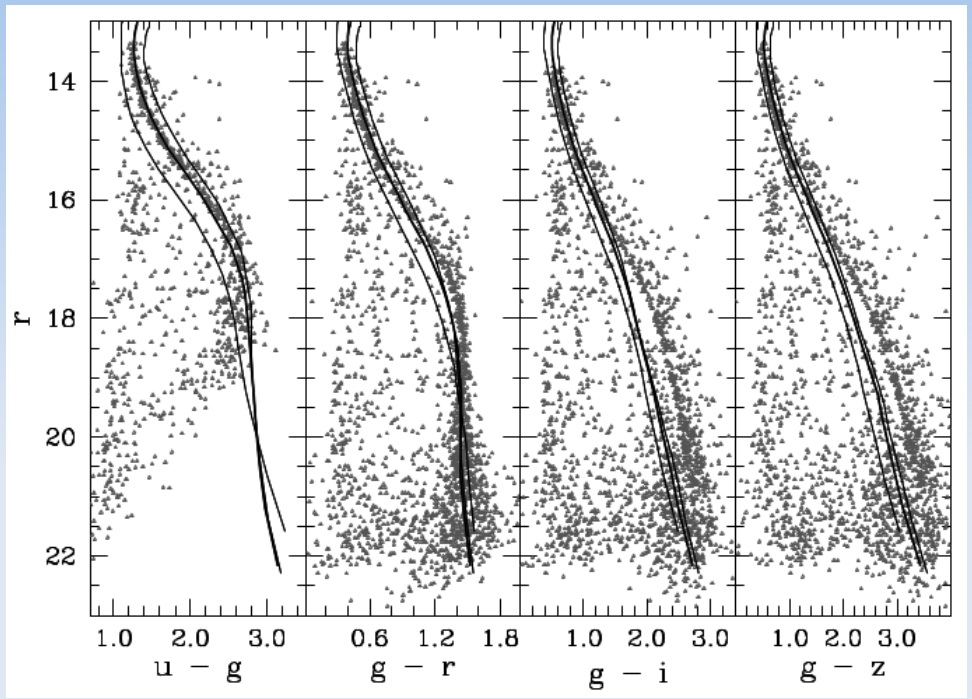
- e.g. PARSEC – Padova-Trieste Stellar Evolutionary Code (Bressan+12 + Tang+14): -2.2<[M/H]<2.4, 0.1<M/Msun<250
- Pre-main sequence evolution
- Microscopic diffusion, varying opacities
- Primordial helium from WMAP
- Solar composition from Caffau+11
- Well-performing Solar Model
- ...

Next: A list of embarassments, pending problems and urgent issues in such grids

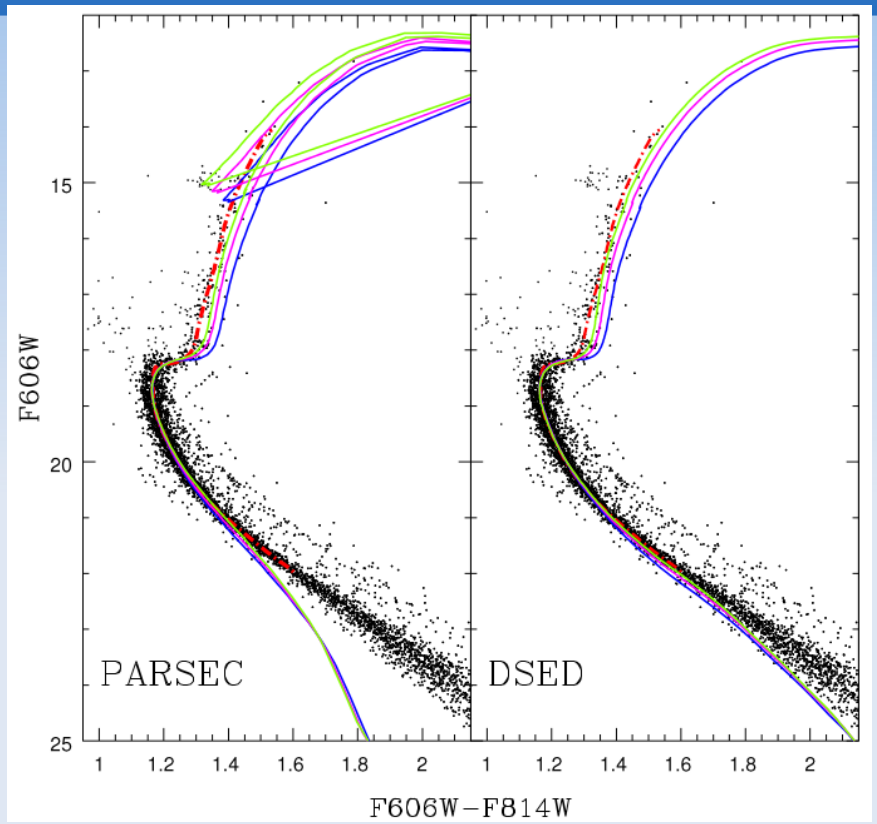




Very low mass stars: the color discrepancy



An+07 (SDSS photometry of M67)



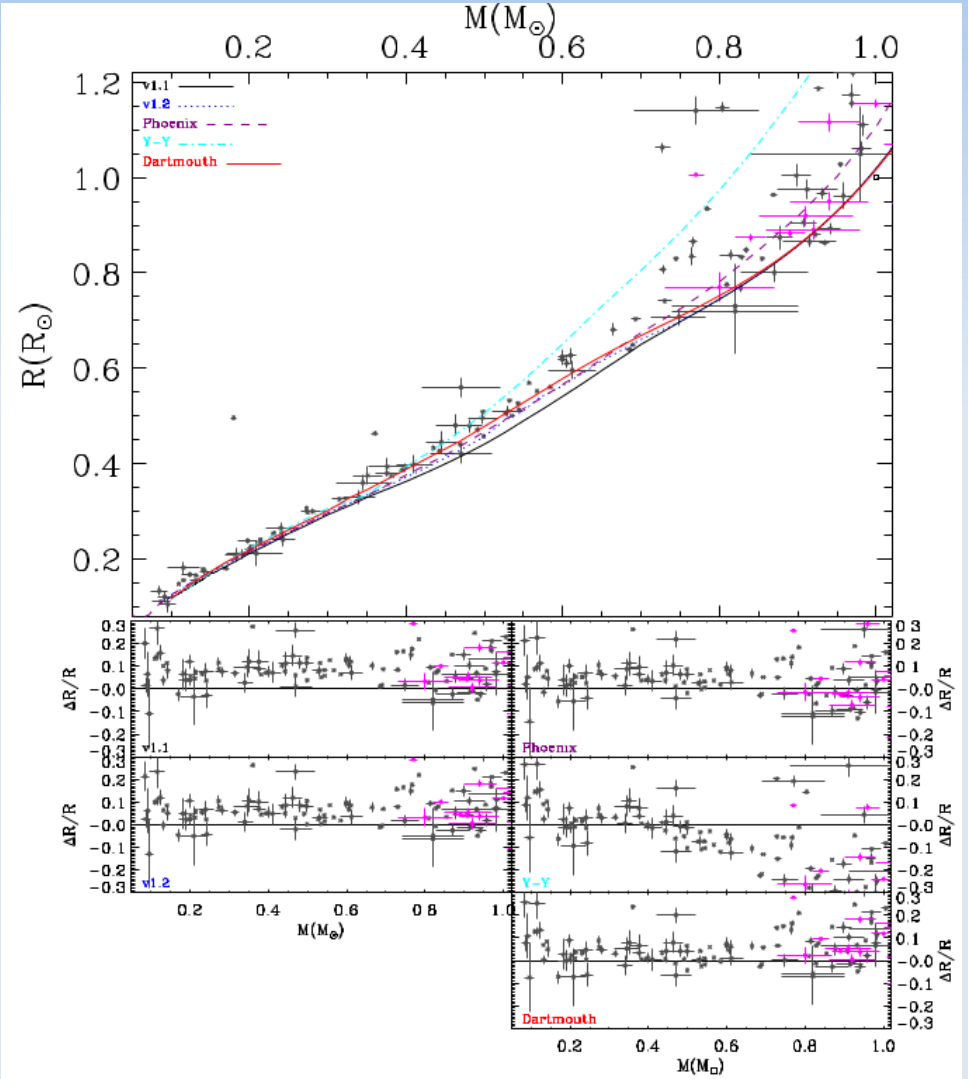
Campos+13 (HST photometry of NGC 6366)

Models applying ”standard” tables of BC and Teff–color relations do not fit the lower main sequence, for all masses smaller than ~0.5 Msun

Very low mass stars: the mass-radius discrepancy

- Eclipsing binaries with accurate masses+radii (e.g. Torres+10) :

Models applying ”standard” ingredients and boundary conditions, produce radii ~5 to 10 % too small, for all masses smaller than ~0.6 Msun



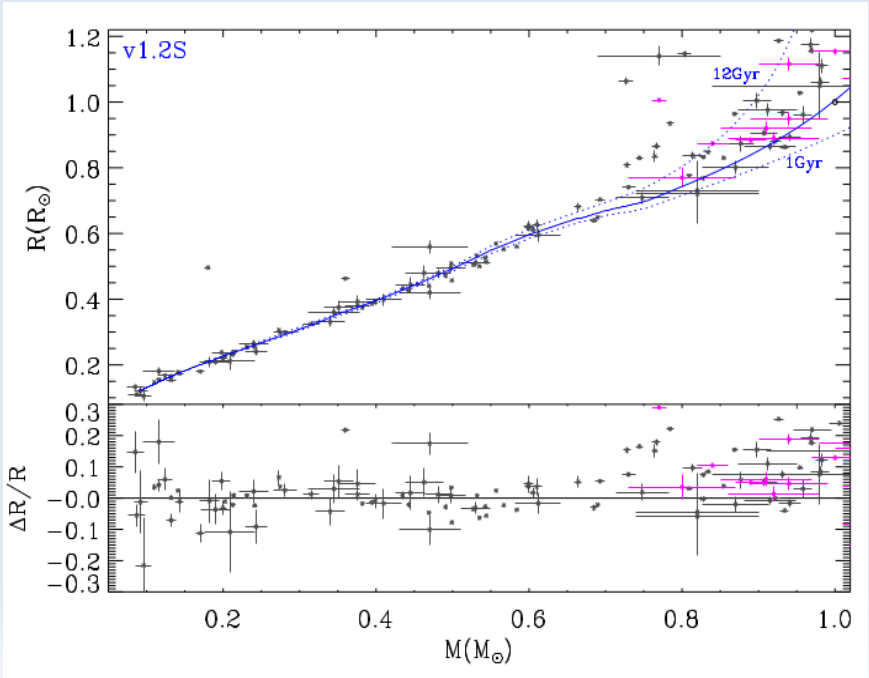
Chen+14

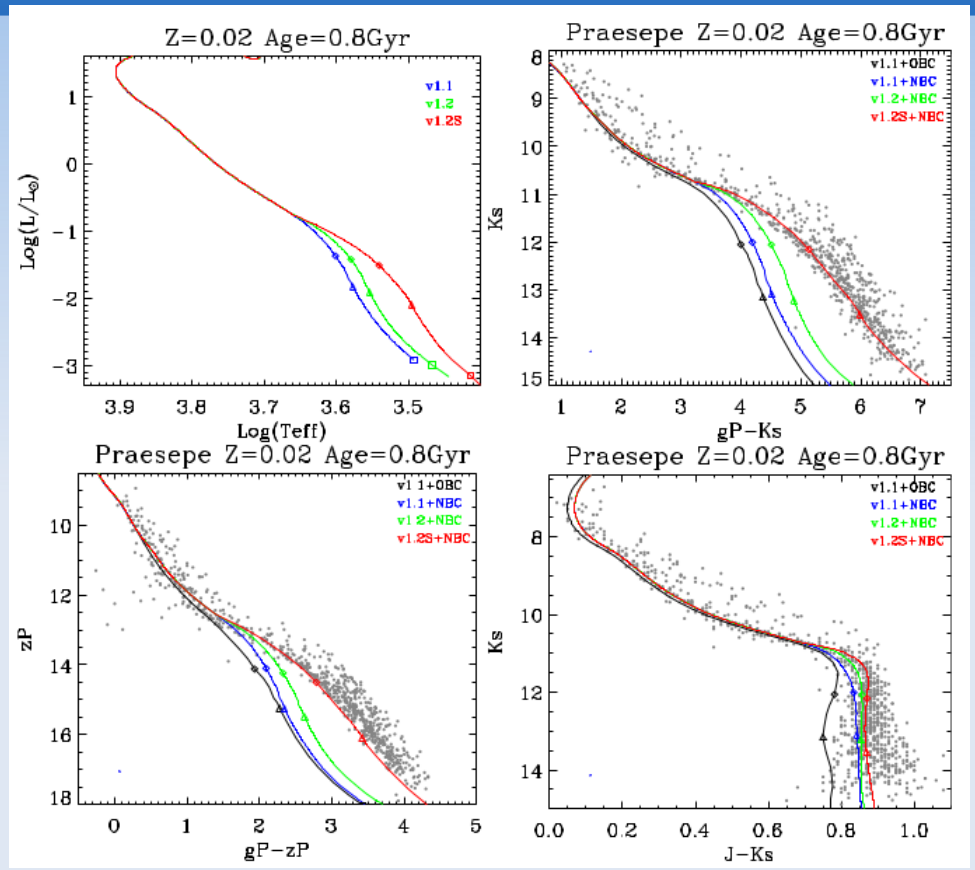
Very low mass stars: maybe just 1 problem

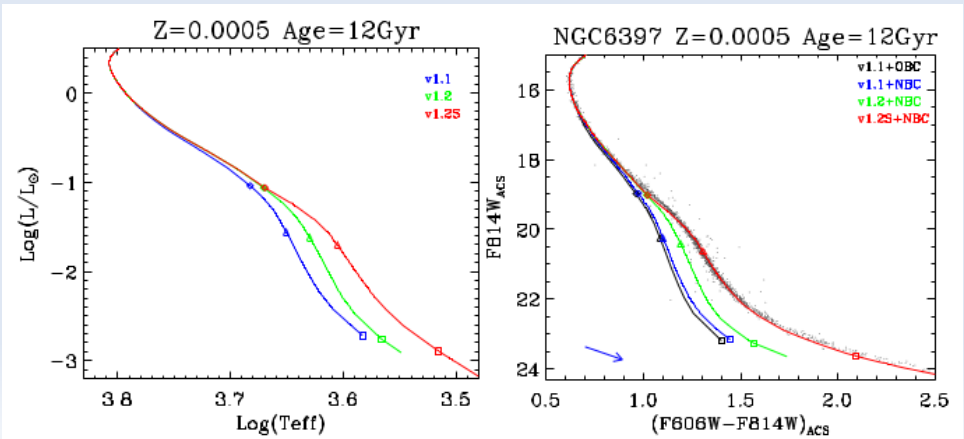
- Chen+14: if you shift atmospheric T-tau relation upward in T so that radii are reproduced, model colors+magnitudes do also turn out right (using PHOENIX spectra)

- This is no solution, but indicates a common origin to both problems

- What's the solution? Starspots (Spruit & Weiss 06)? Stars inflated by magnetic fields (Feyden & Chaboyer 13)?



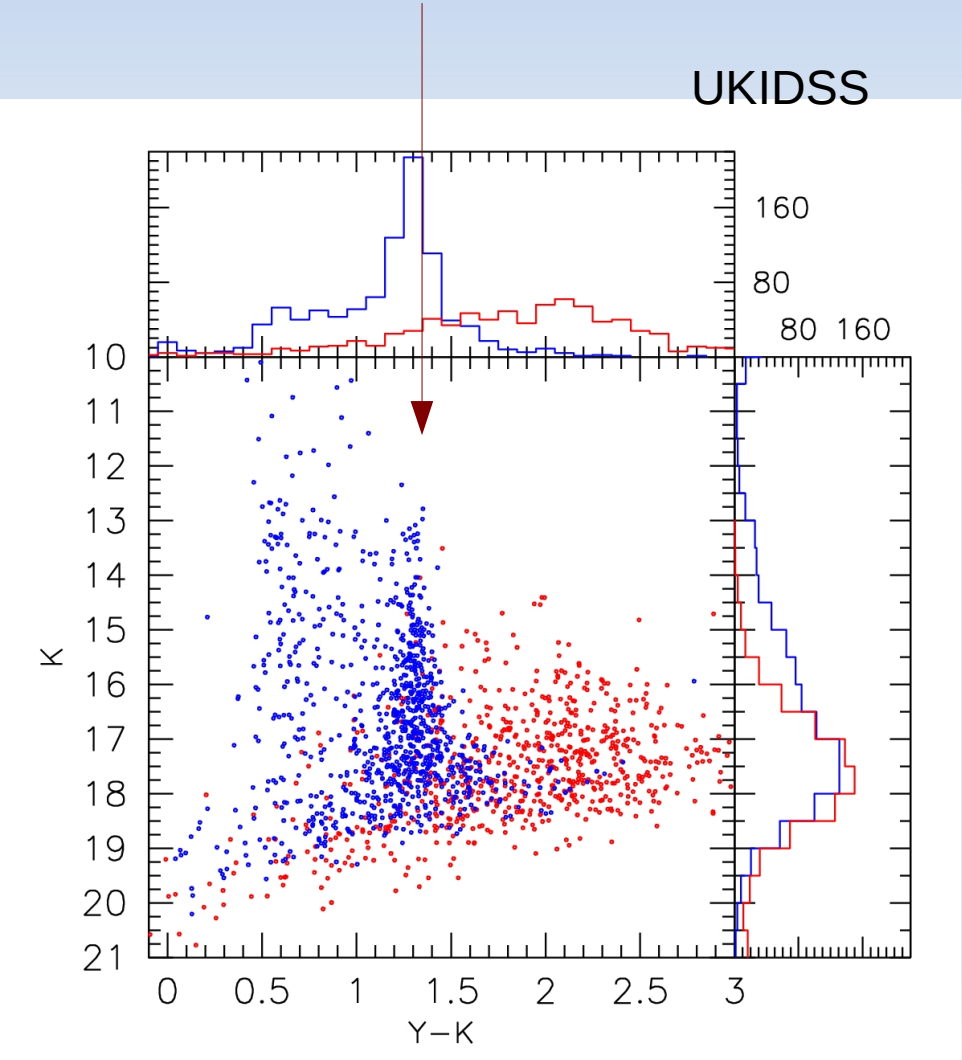




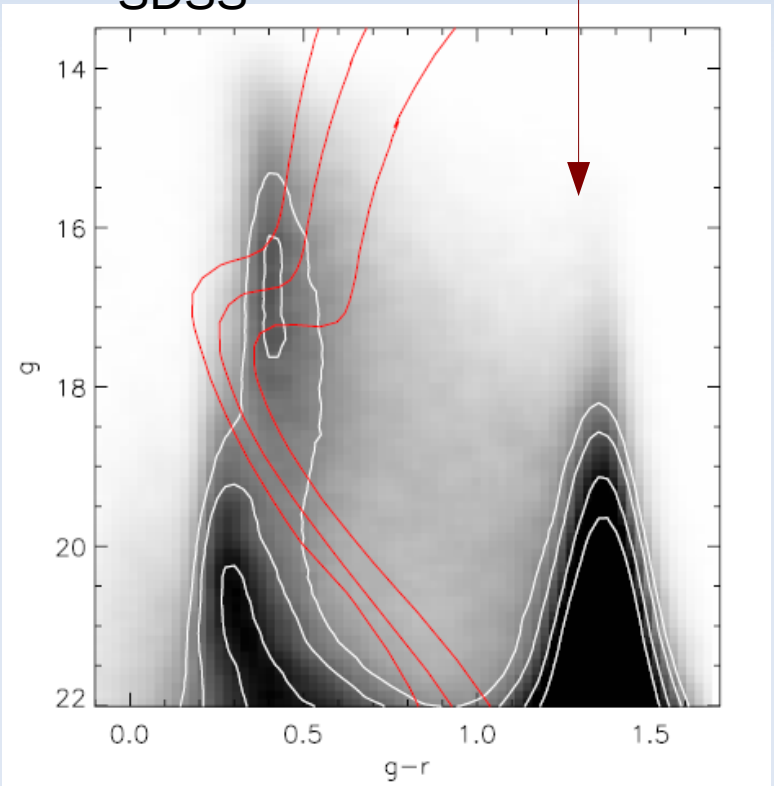
Very low mass stars: maybe just 1 problem

- Are these VLMS important at all?
- In deep surveys, they make most of the observed MW stars (mainly thin disk within 500 pc)

UKIDSS



SDSS



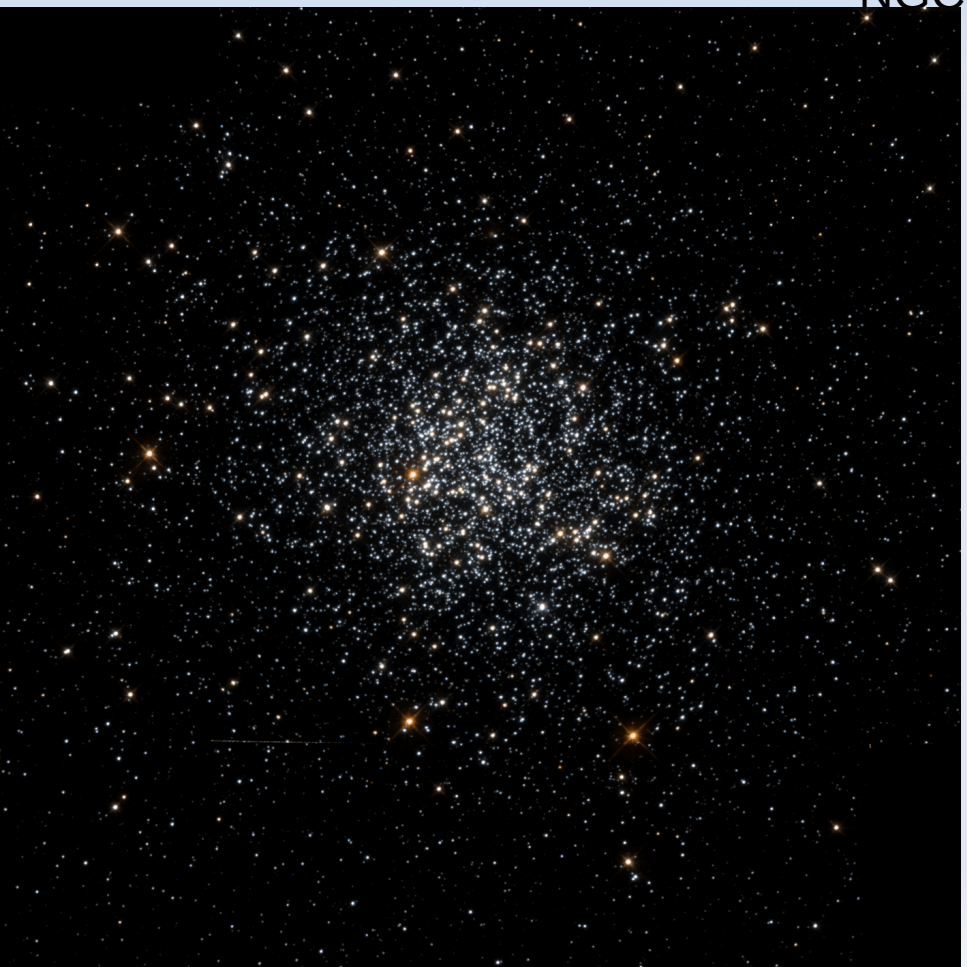
Star clusters in Magellanic Clouds

The best calibrators of stellar evolution for young-to-intermediate ages:

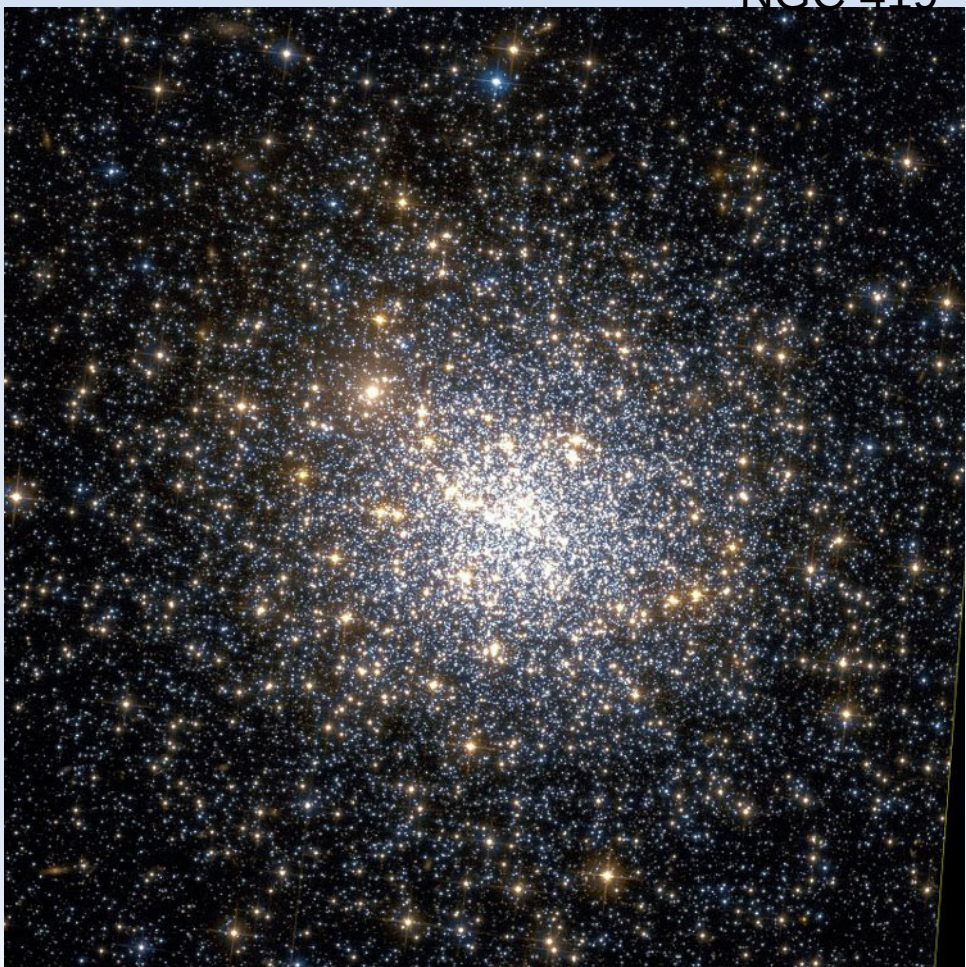
With HST photometry and a simple radial cut, one can easily get memberships >99%.

Populous! (e.g. a few with hundreds of red clump stars, one with ~10 Cepheids, a couple with 20 TP-AGB stars...)

NGC 1866



NGC 419

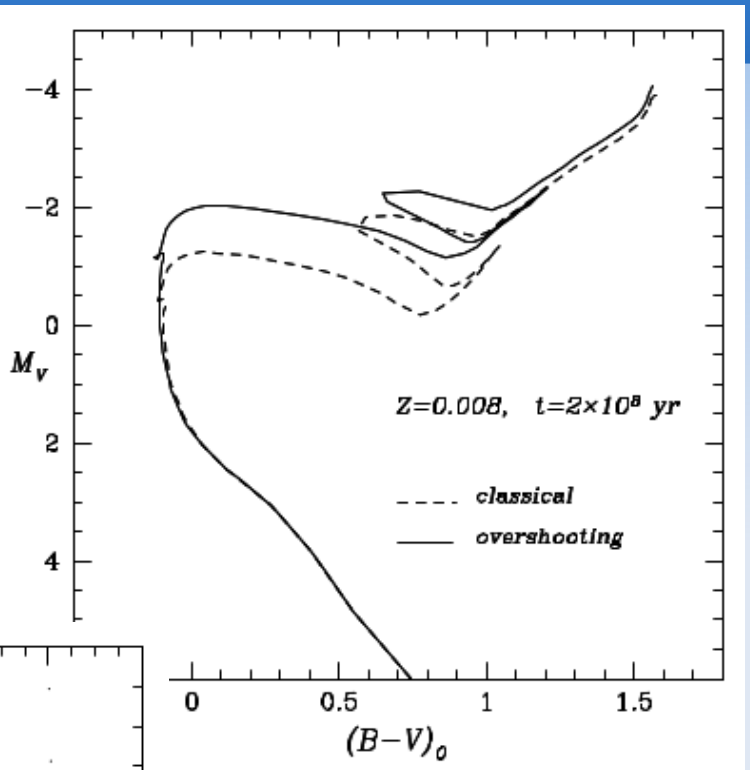


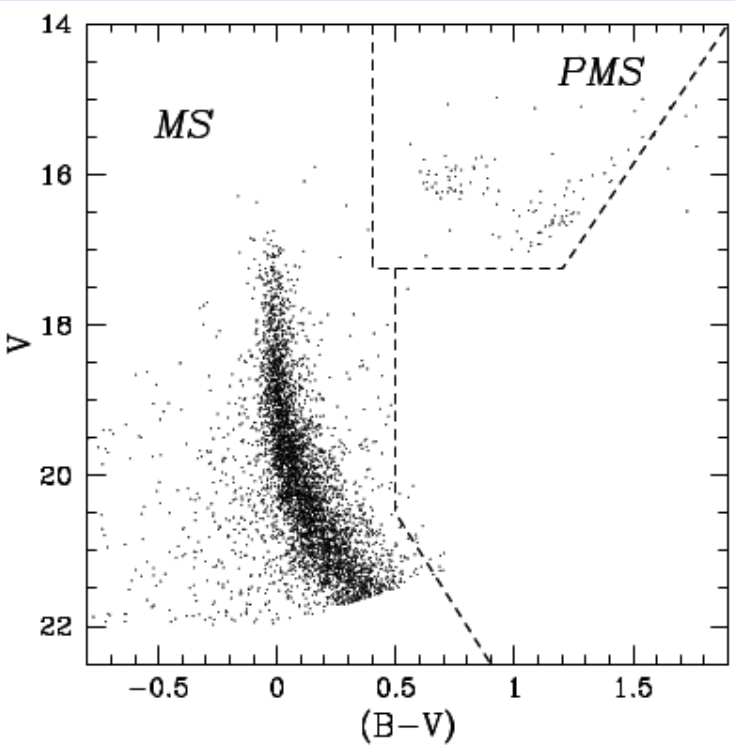
Star clusters in Magellanic Clouds

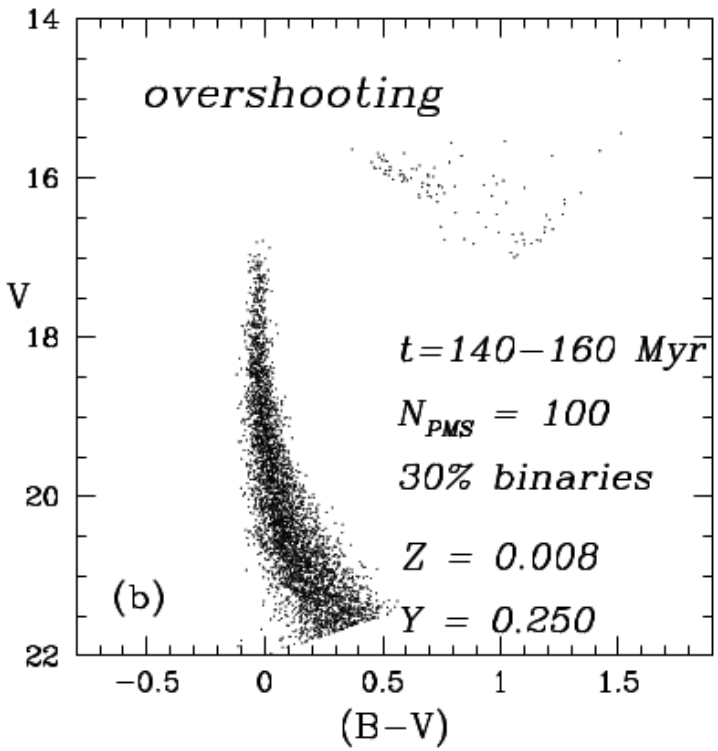
Ideal to test convective core overshooting, using either:

1. LF (of ratio between H and He-burning lifetimes) in younger clusters
2. MSTO position at ages in which clusters start to develop the RGB and RC

Why is this important? → *absolute calibration of age scale*







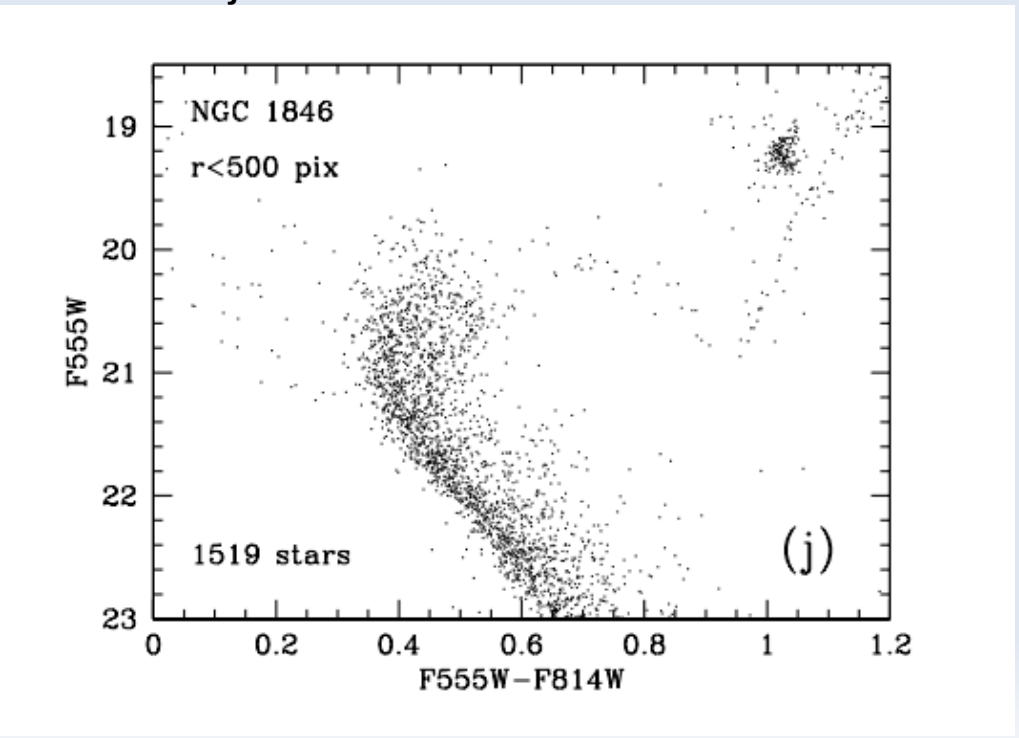
NGC1866 (Barmina+08)

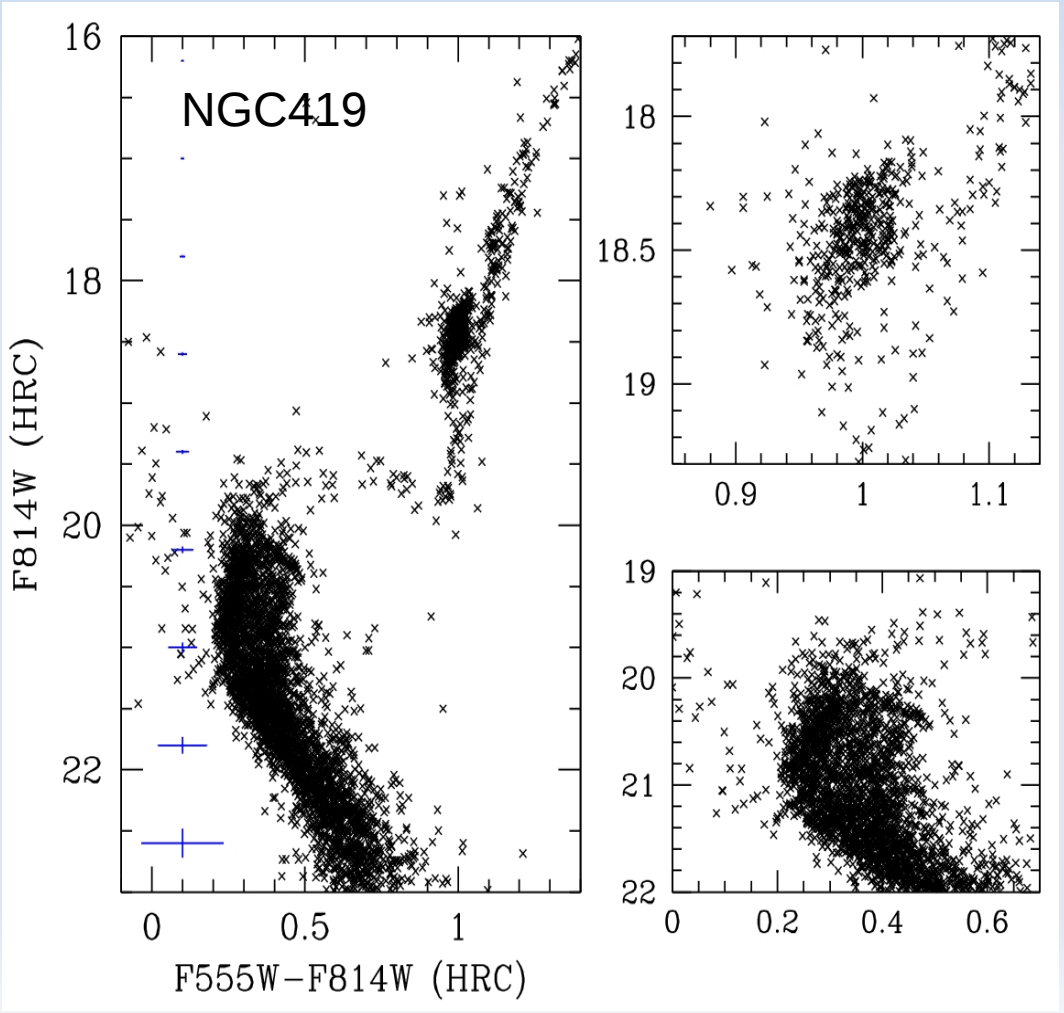
Intermediate-age star clusters in Magellanic Clouds

Intermediate-age clusters (1-2 Gyr) may be even better: the most massive ones exhibit extended main sequence turn-offs (eMSTOs; Bertelli+03; Mackey+07,08; Milone+09; Goudfrooij+09; Glatt+08, ...)

Some do also exhibit dual red clumps (Girardi+09)

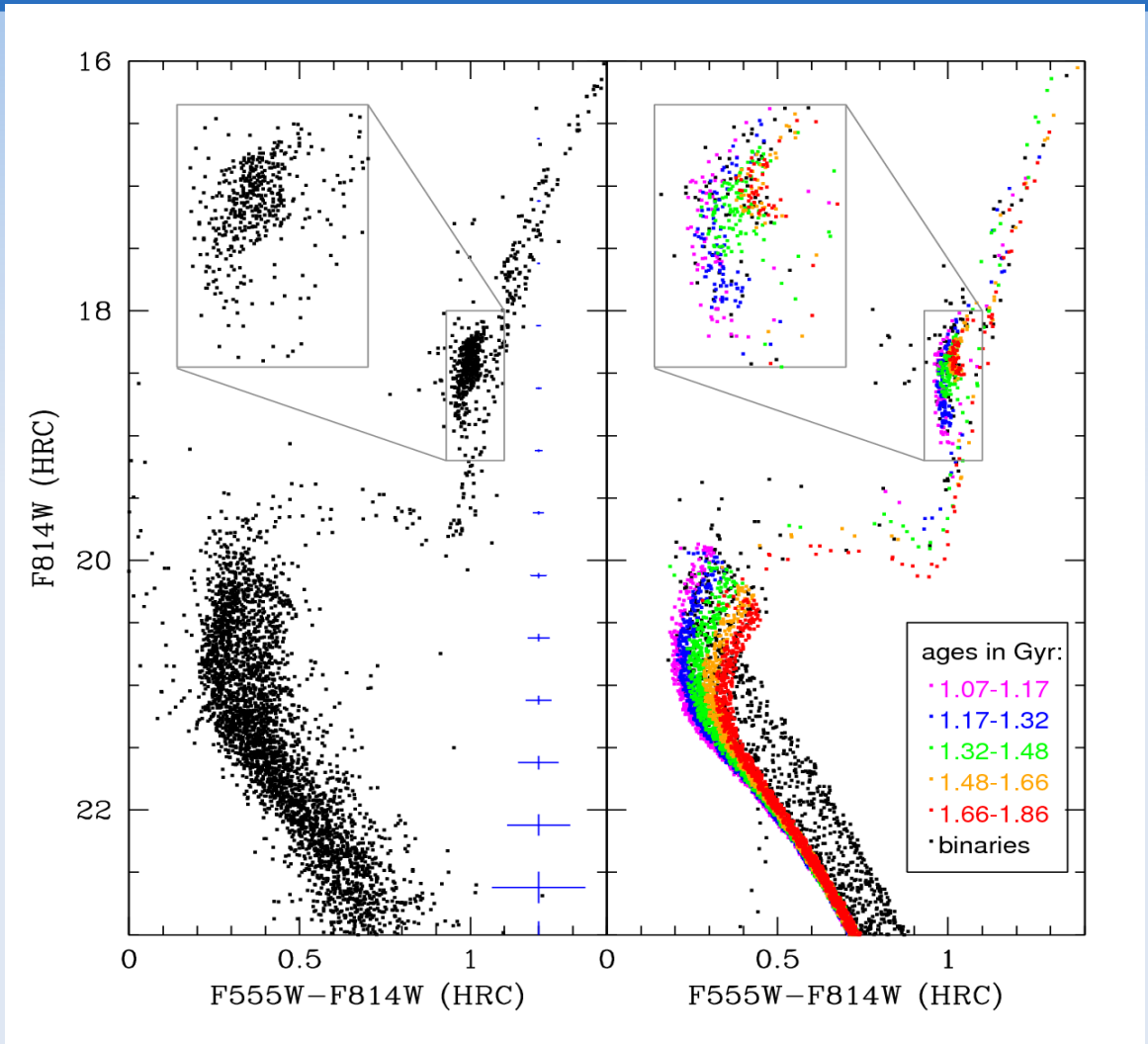
Goudfrooij+09

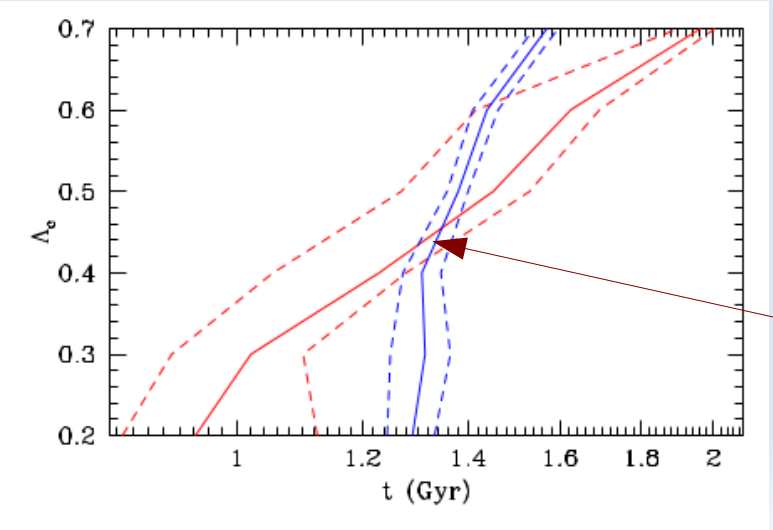




The simplest explanation

- eMSTOs are the signature of extended star formation, spanning a few 100 Myr
- Dual red clumps: a snapshot of the fast transition from post-MS non-degenerate to degenerate cores → hence ensure core masses being ~0.33 Msun

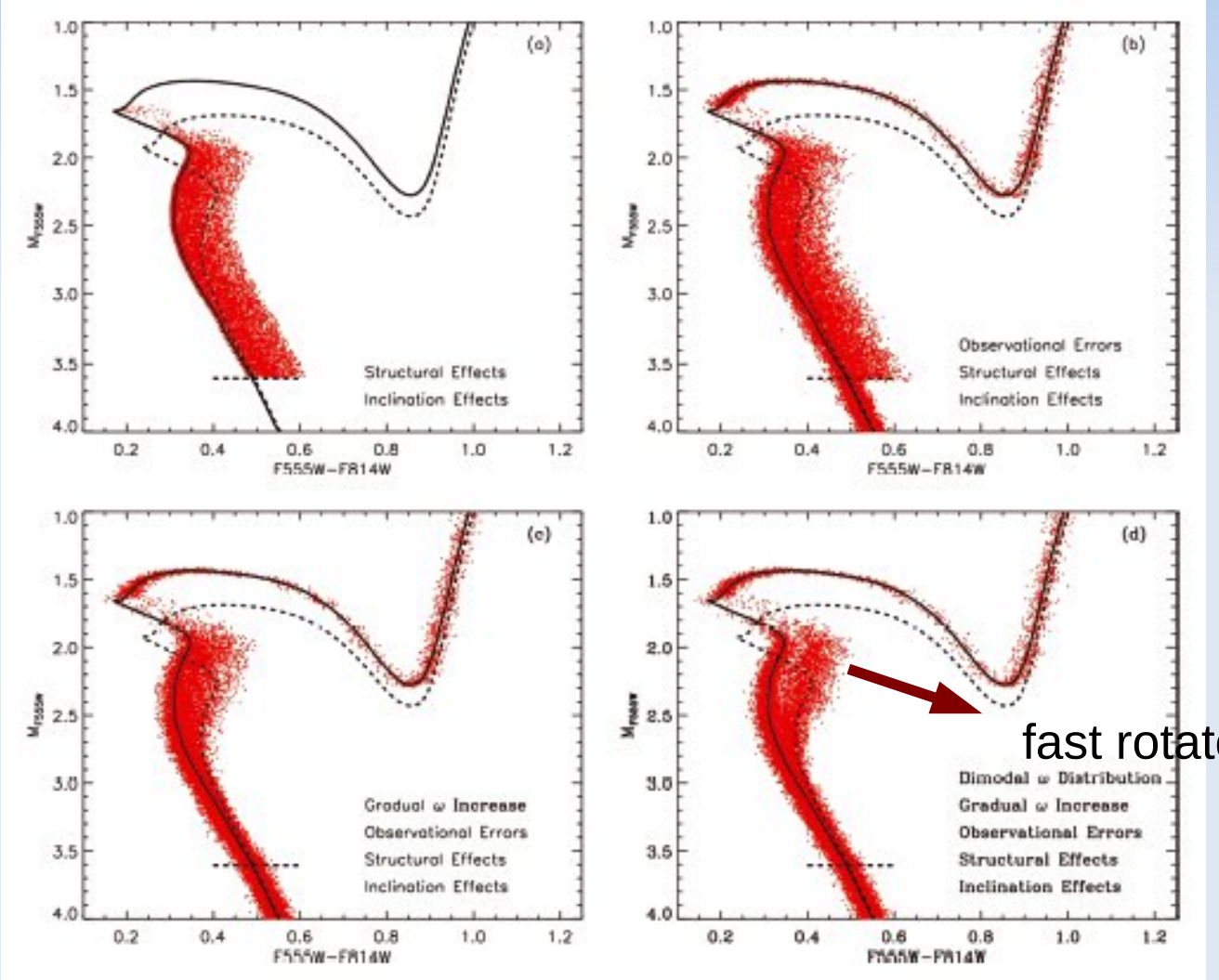




Coupled to MSTO mean position → a measure of both overshooting and absolute mean age

The alternative explanation: spread caused by rotation?

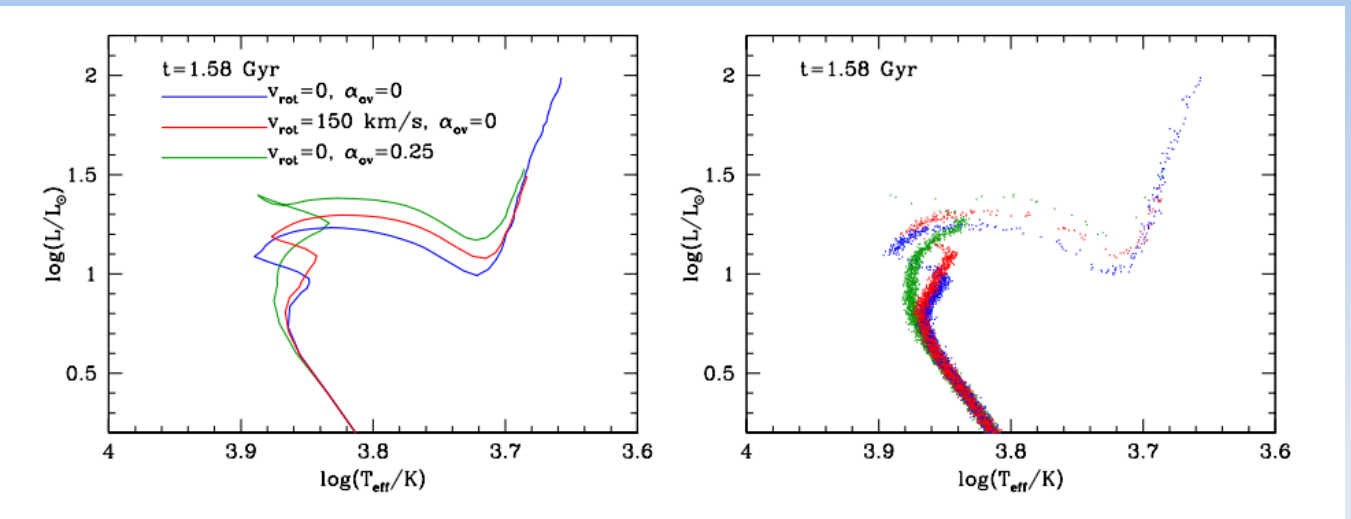
- Fast rotators have a redder TO than non-rotators of same mass



fast rotators

Bastian & de Mink (2009)

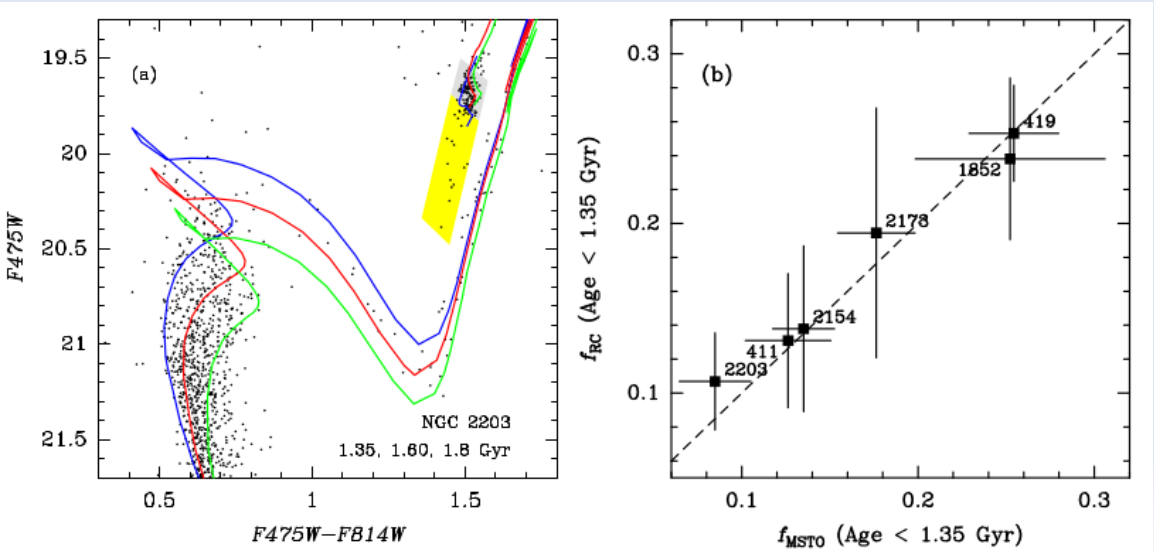
The alternative explanation: spread caused by rotation?



Girardi+11

- To simulate rotation, needs to consider not only the changes in shapes of tracks, but also the changes in lifetimes (see e.g. Eggenberger+09)
- → Effect small and opposite to what claimed by Bastian & de Mink

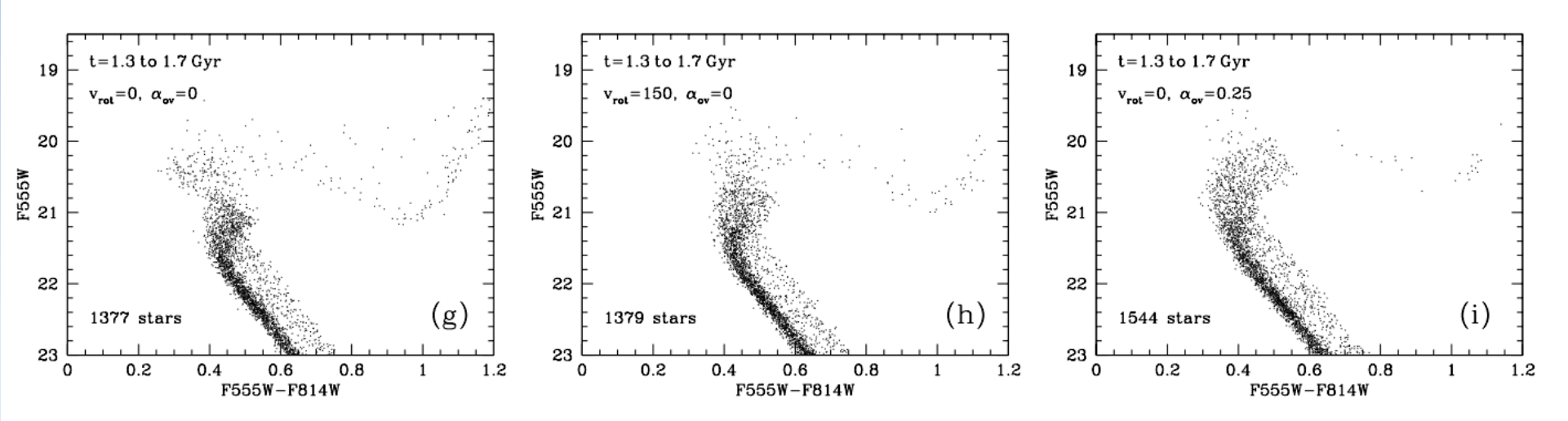
Goudfrooij+14



• In addition, rotation does not explain tight relation between number of secondary (faint) red clump stars and fraction of MSTO younger than 1.4 Gyr

Spread caused by rotation?

For a prolonged period of star formation:



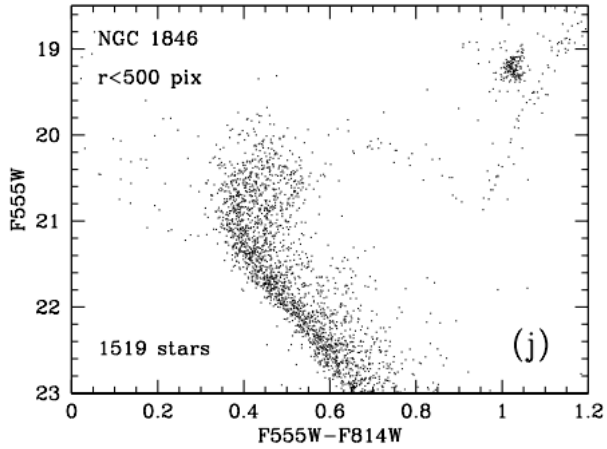
No rotation, no overshoot

Rotation, no overshoot

No rotation, overshoot

Real models that best describe the shape of eMSTO are still those with age spread+overshooting.

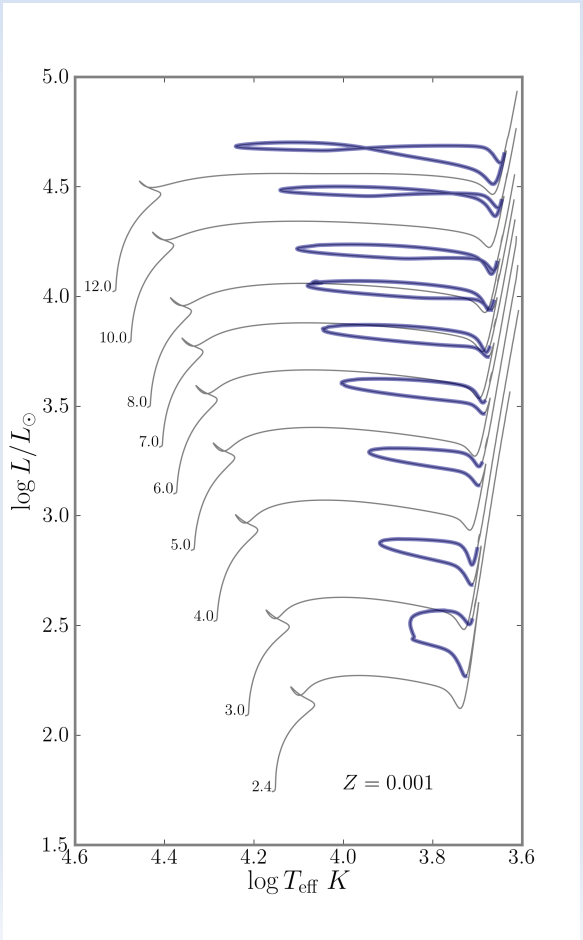
Rotation models that do the same are not real(istic)! – either use tracks instead of isochrones (Bastian & de Mink, Li+14), or rotate with minimum induced mixing (Yang+13).

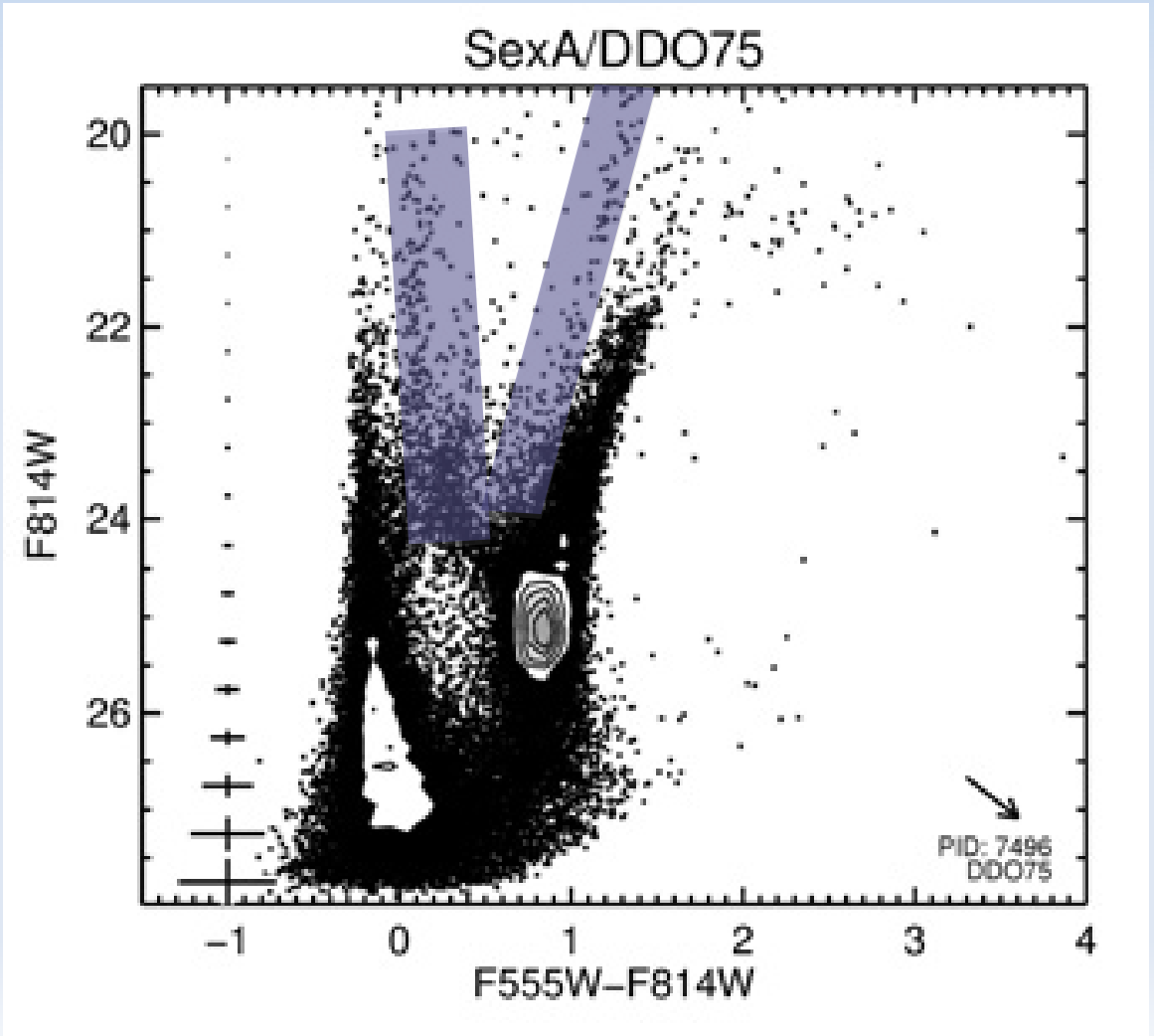


NGC1846
(Groudfrooij et al.)

He-burning sequences of intermediate-to-high mass stars

- For [M/H]<~0.3, they split in red and blue sequences, frequently seen in CMDs of nearby galaxies (probing ages of 25 – 300 Myr)
- Color of blue sequence strongly varying with metallicity (and crossing the Cepheids instability strip)

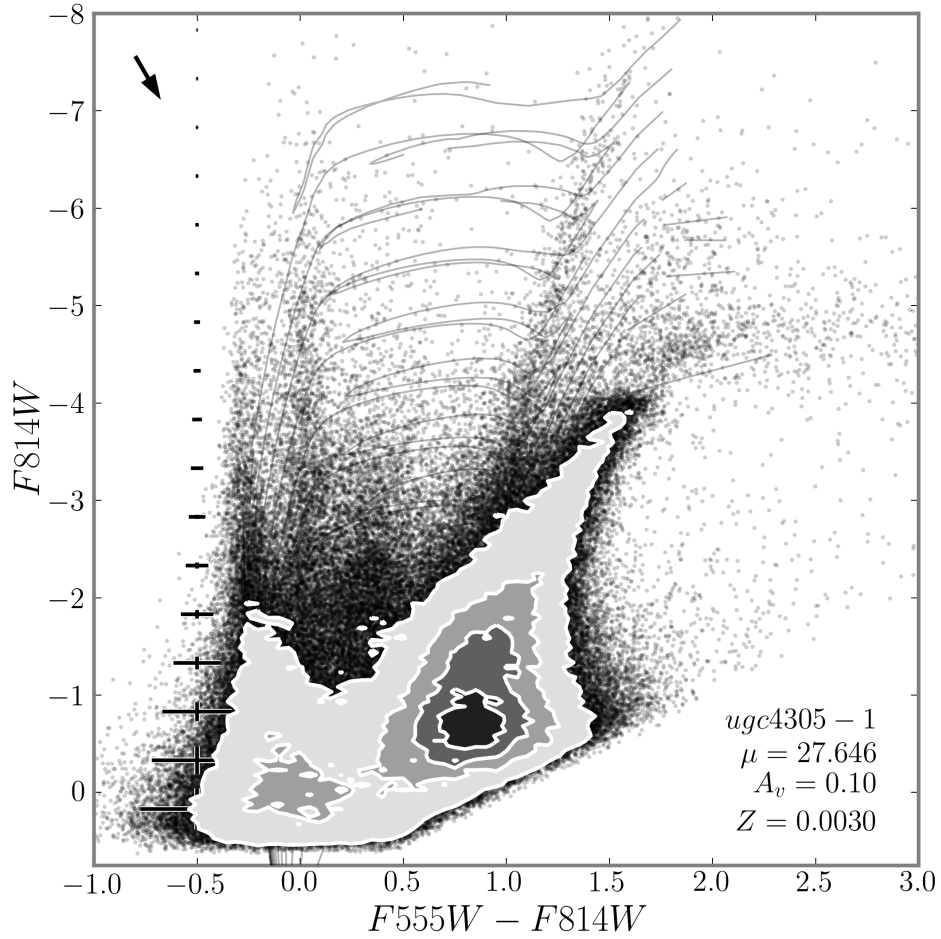




He-burning sequences of intermediate-to-high mass stars

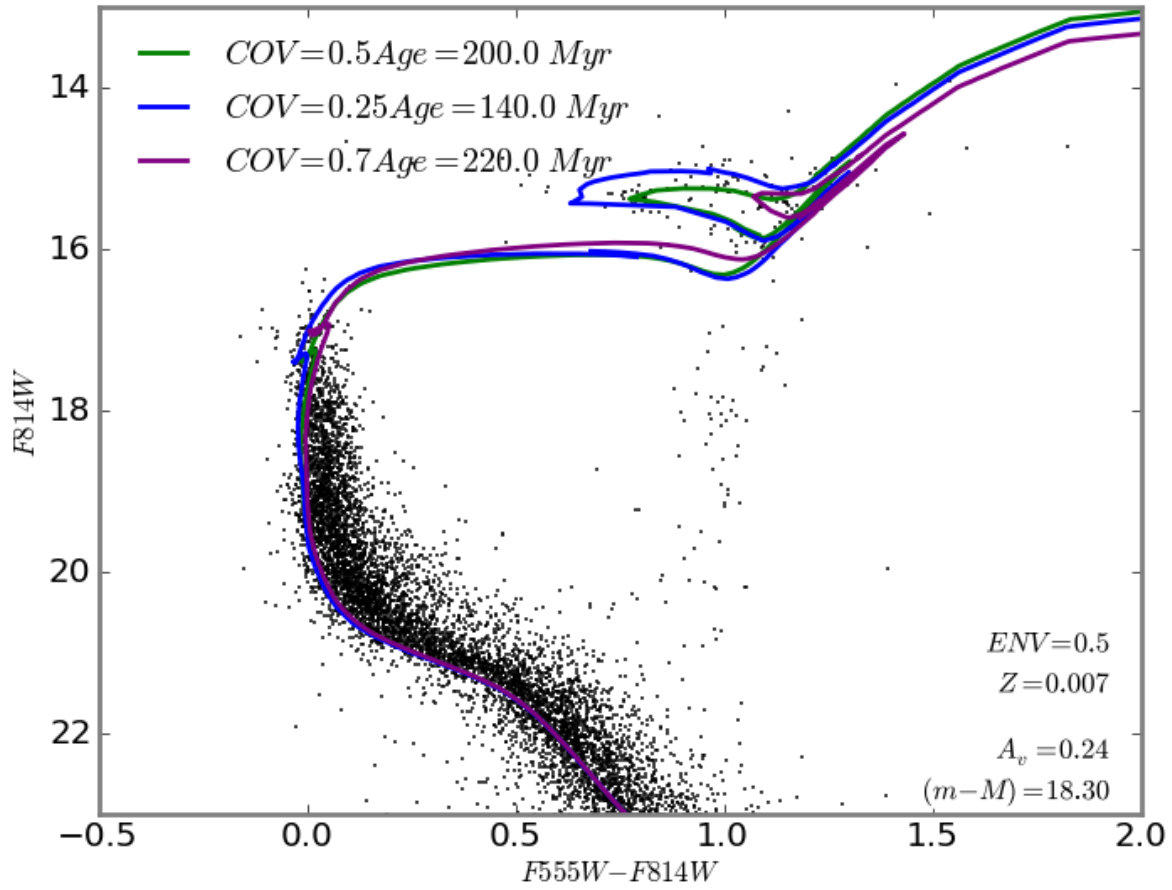
The problem: models ~describe the data but don't fit it, e.g. for ANGST data for nearby galaxies (McQuinn+11):

- offsets in color between the observations and theoretical isochrones of order 0.15 mag (0.5 mag) for the blue (red) HeB populations brighter than Mv ~ −4 mag, which cannot be solely due to differential extinction;
- blue HeB stars fainter than Mv ~ −3 mag are bluer than predicted;
- the slope of the red HeB sequence is shallower than predicted by a factor of ~3; and
- the models overpredict the ratio of the most luminous blue to red HeB stars corresponding to ages 50 Myr.



He-burning sequences of intermediate-to-high mass stars

- Obvious parameters to change: core overshooting and envelope overshooting.

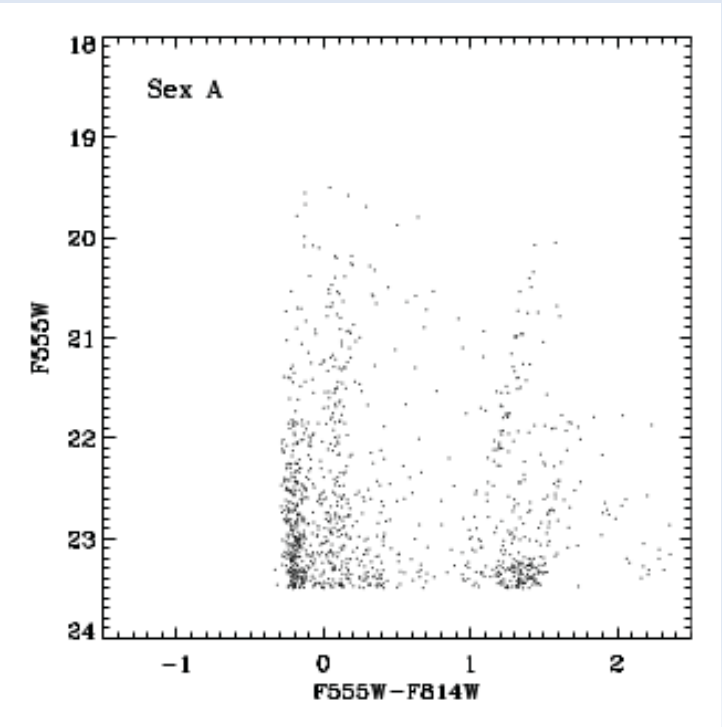


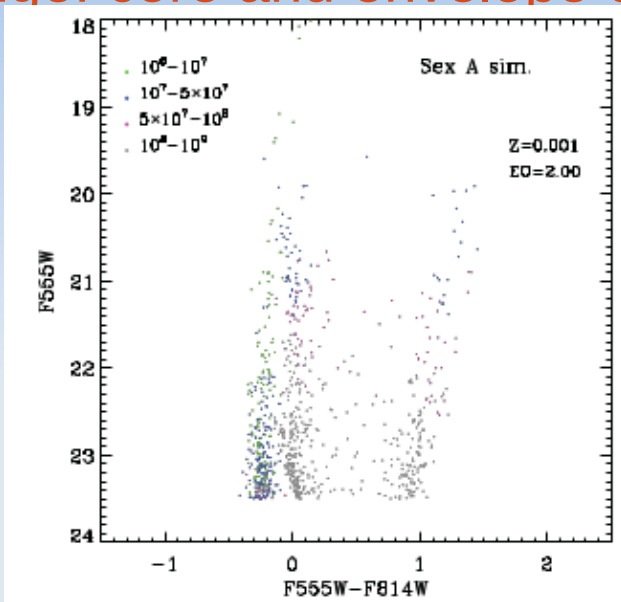
NGC1866 X core overshoot (Rosenfield+15)

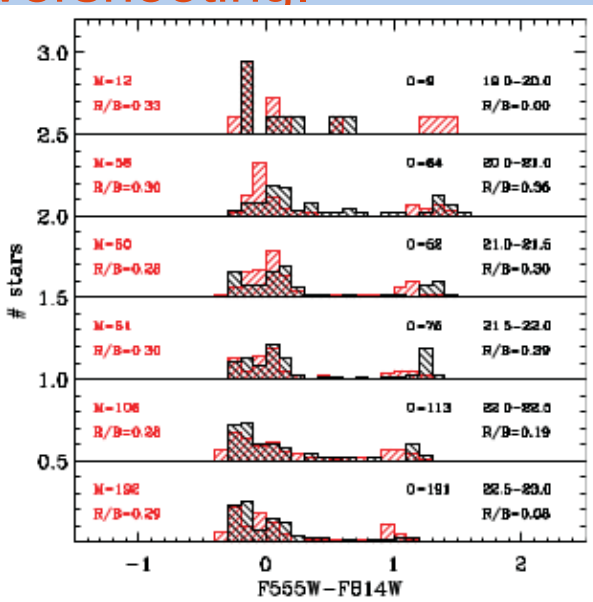
He-burning sequences of intermediate-to-high mass stars

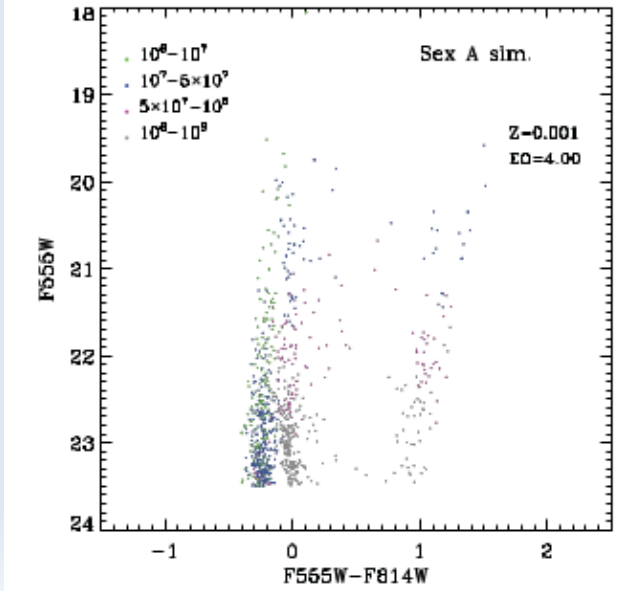
Obvious parameters to change: core and envelope overshooting.

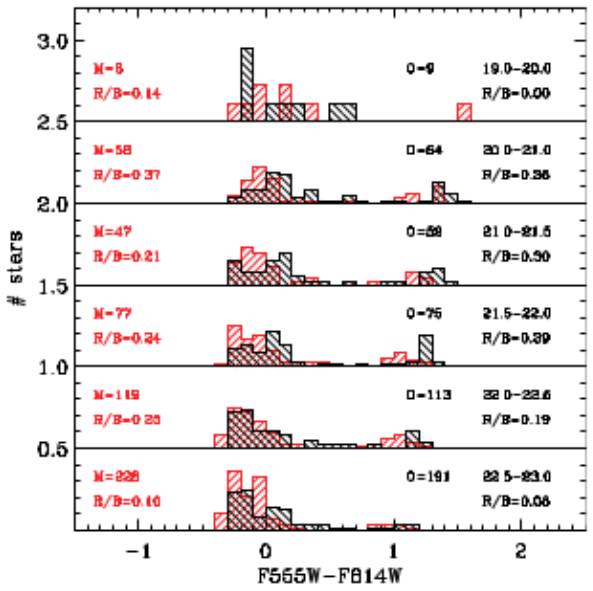
- Tang+14: with latest physical ingredients, quite strong envelope overshooting (2 to 4 Hp) needed to reproduce observed HeB sequences in metal-poor galaxies







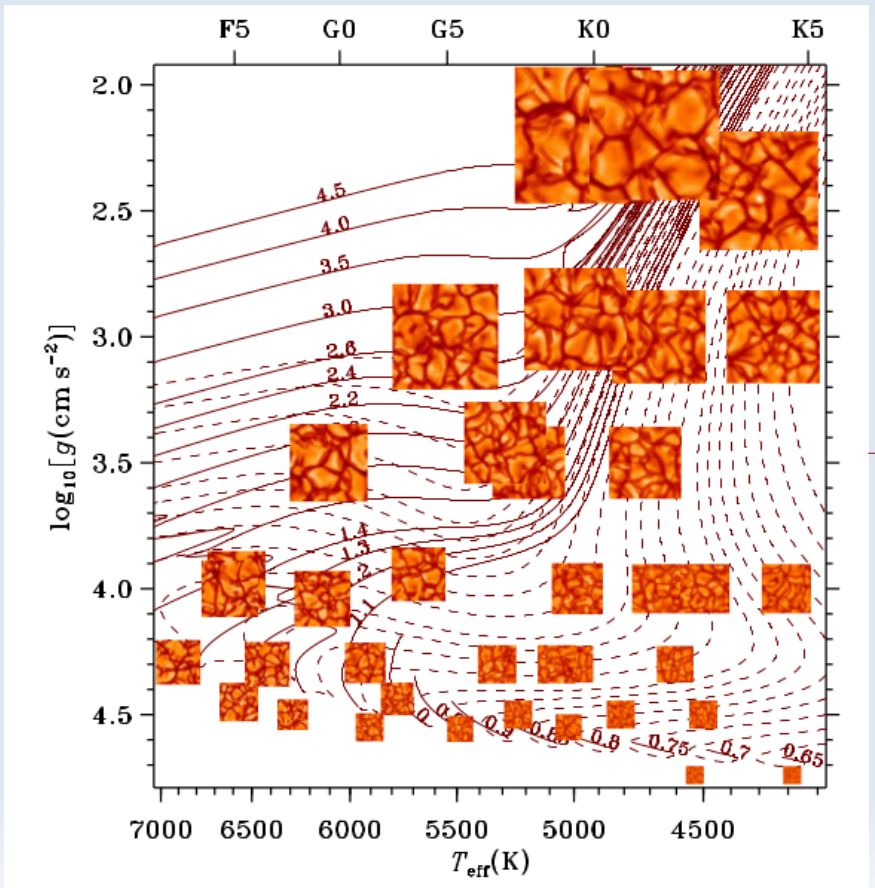


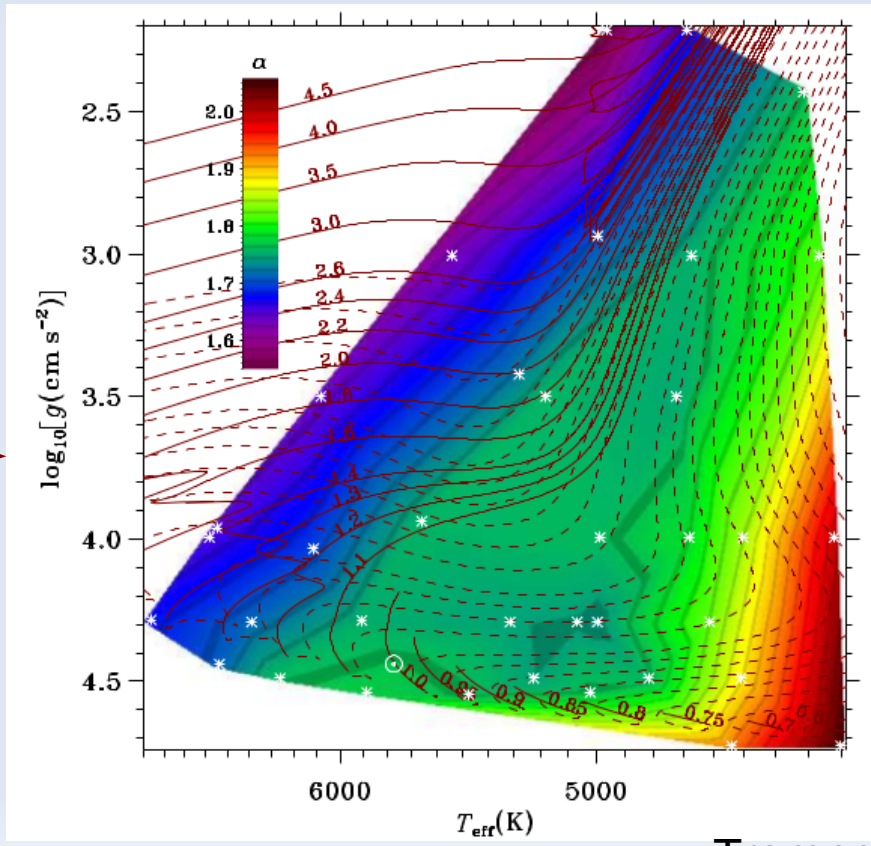


The mixing length theory

Should we get rid of a theory that worked so well for >40 years?

- To be replaced soon by full 3D dynamical models of convection
- Trampedach+14: shows that a ~constant alpha(MLT) for Sun+all red giants was just fortune.
- Expected small variations across HRD → important in the Gaia era of ultra-precise CMDs

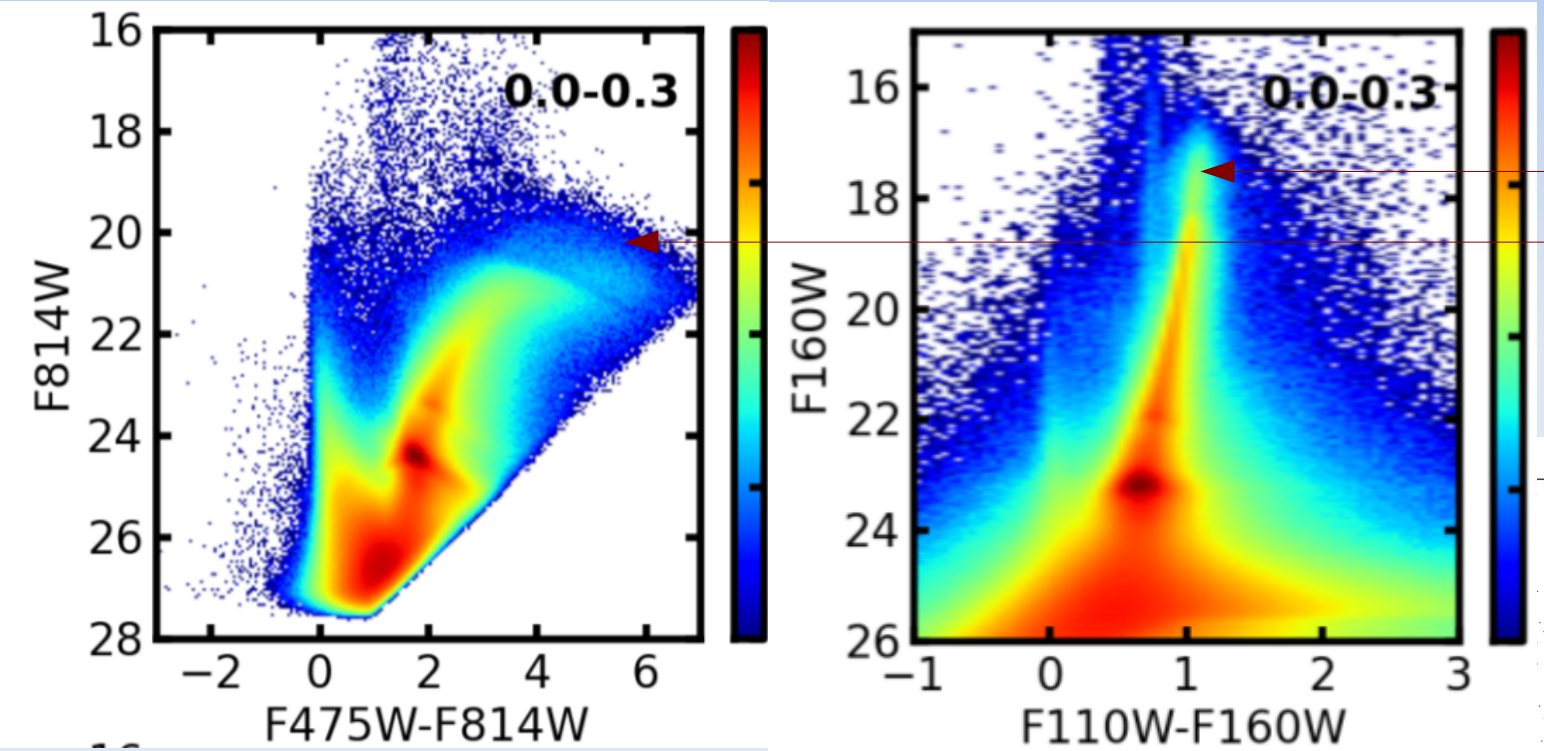




Trampedach+14

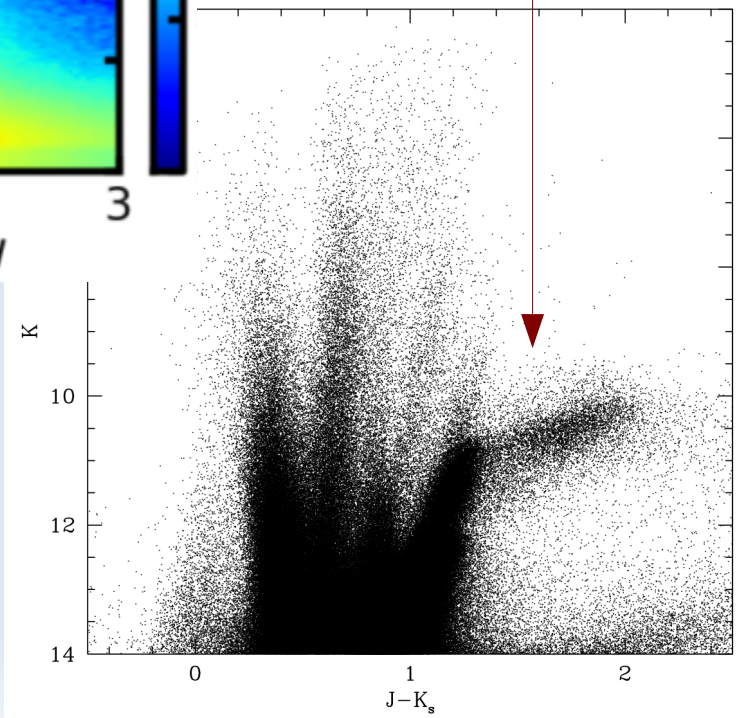
TP-AGB stars

Short-lived but luminous, sizeable fraction of IR sources and integrated light



TP-AGB

M31 from PHAT (Williams+14)

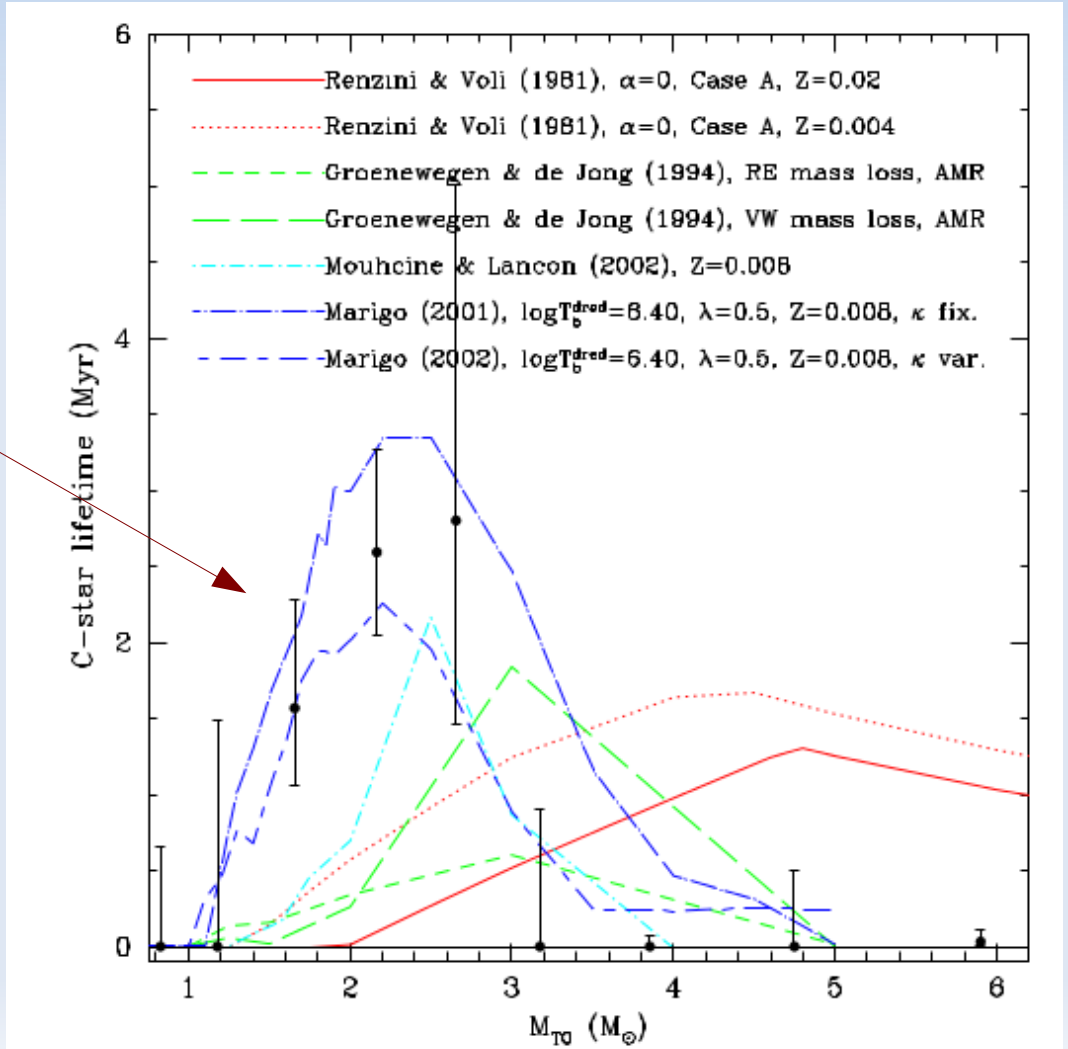


LMC from 2MASS
(Nikolaev Weinberg 02)

TP-AGB stars

Short-lived but luminous, sizeable fraction of IR light and sources

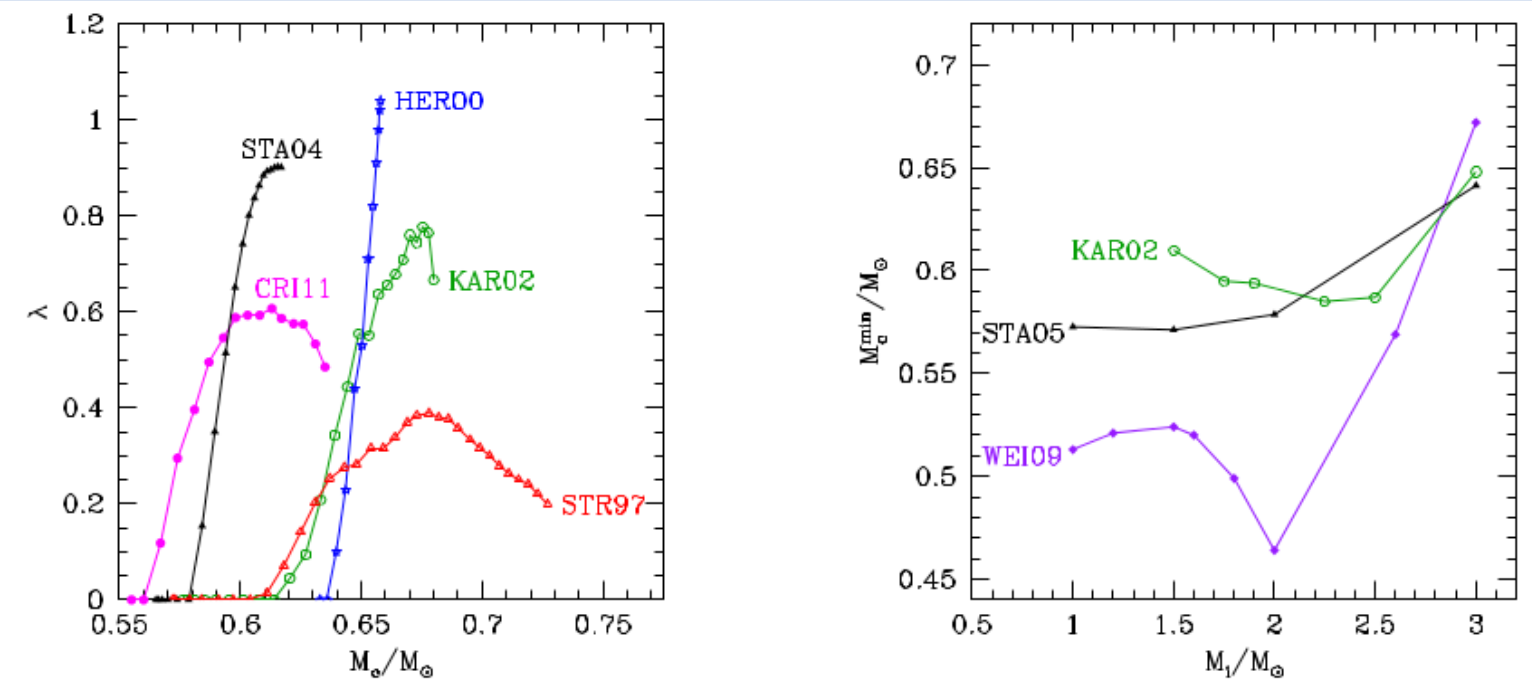
- List of embarassments is too long, starting from the C-star mistery (Iben+81): with Schwarzschild criterion, third dredge-up makes C stars only at too large masses / too young ages
- Lifetimes change by factors of many between authors
- Scarcity of calibrating data: even the classical calibrators (Magellanic Cloud clusters) might have been giving the wrong answers by factors of 2 (Girardi+13).



TP-AGB stars

Even worst: no agreement about onset of dredge up and hot-bottom burning

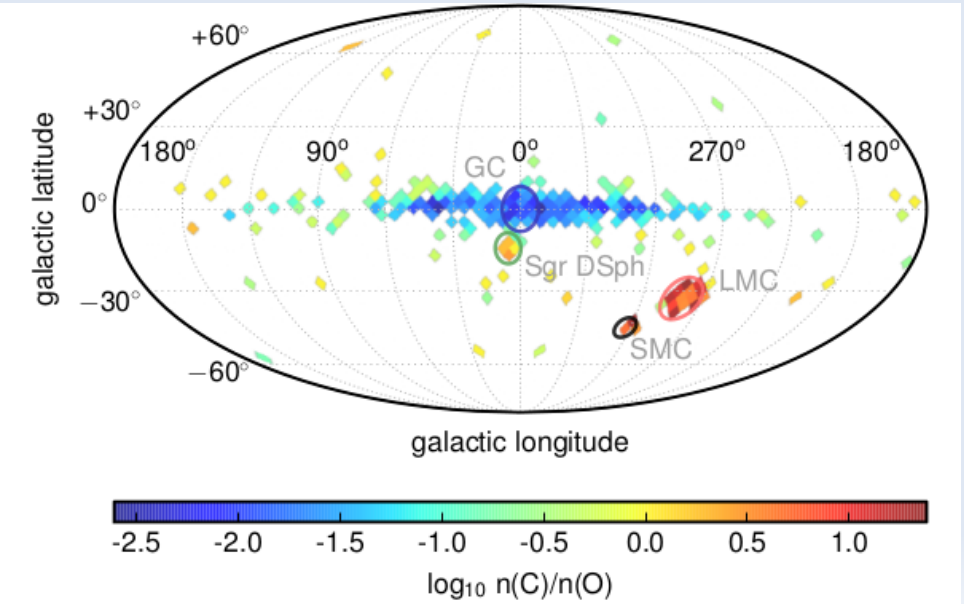
- → affects chemistry
- → affects Teff and mass loss
- → affects lifetimes... which affects chemistry
- Complex network of dependencies



TP-AGB stars

The COLIBRI code and STARKEY project:

- Accept that some parameterization is still necessary
- To constrain parameters by reproducing TP-AGB properties (numbers, photometry, chemical types, periods...) in nearby resolved galaxies with reliable SFHs
- Early examples: Girardi+10 and Rosenfield+14 application to ANGST galaxies
- Will be essential to interpreting upcoming IR surveys (WISE, JWST, AO in large telescopes)



WISE (Nikutta+13)

Summary

- Large grids of stellar models are available, everybody knows it
- They hide a number of problems/approximations mostly related with convection
  - Mixing length theory is about to retIre!
  - Next big thing: a theory for overshooting that works everywhere (hopefully from 3D models)
  - Role of rotation in intermediate masses has to be clarified
- In TP-AGB, situation likely to remain uncertain for long, first goal is to get numbers (i.e. lifetimes) accurate to within ~10%

Stellar evolution models

Questions from a modeller:

- Are you comfortable with present large grids of stellar models? What else would you like to have available for your work?
- What do you prefer: (1) models with (few) ajustable parameters that fit everything, or (2) models without parameters that don't fit anything? We are aiming at option (1), and that should be clear to everybody!
- Do you agree that the next big thing is to deal with overshooting in a more consistent way? Or, based on your data, you believe that modeling rotation is more urgent?
- Observational stellar astronomy will be shaked by ultra-precise CMDs from Gaia, are we prepared for that?
- Are we prepared for K2, TESS, PLATO and LSST light curves? And for the gradual shift to infrared observations?