Star clusters –
laboratories of stellar structure theory

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Motivation

- Stars are complex objects
- Stellar evolution theory tries to treat the problem with as simple assumptions as possible
- Complicated physics often simplified and/or parametrized
- Assumptions and implemented physics need to be tested for accuracy
- valuable test/calibration objects
    - The Sun
    - Detached eclipsing binaries
    - Star clusters
    - Oscillating stars
    - ....

Advantages of Stellar Clusters

- same distance → accurate relative HRD-positions
- same age (not true for young massive clusters)
- same composition (but multiple populations in globulars)
- only mass varies
- cover pre-MS to WD evolution
- different branches sensitive to different parameters
- range of ages, compositions → different sensitivities
- examples:
  - M67: convection
  - globular clusters: bump (convection), tip (neutrinos, axions), HB (mass loss),
  - WD in clusters: mass loss
  - young open clusters: rotation and gravity waves

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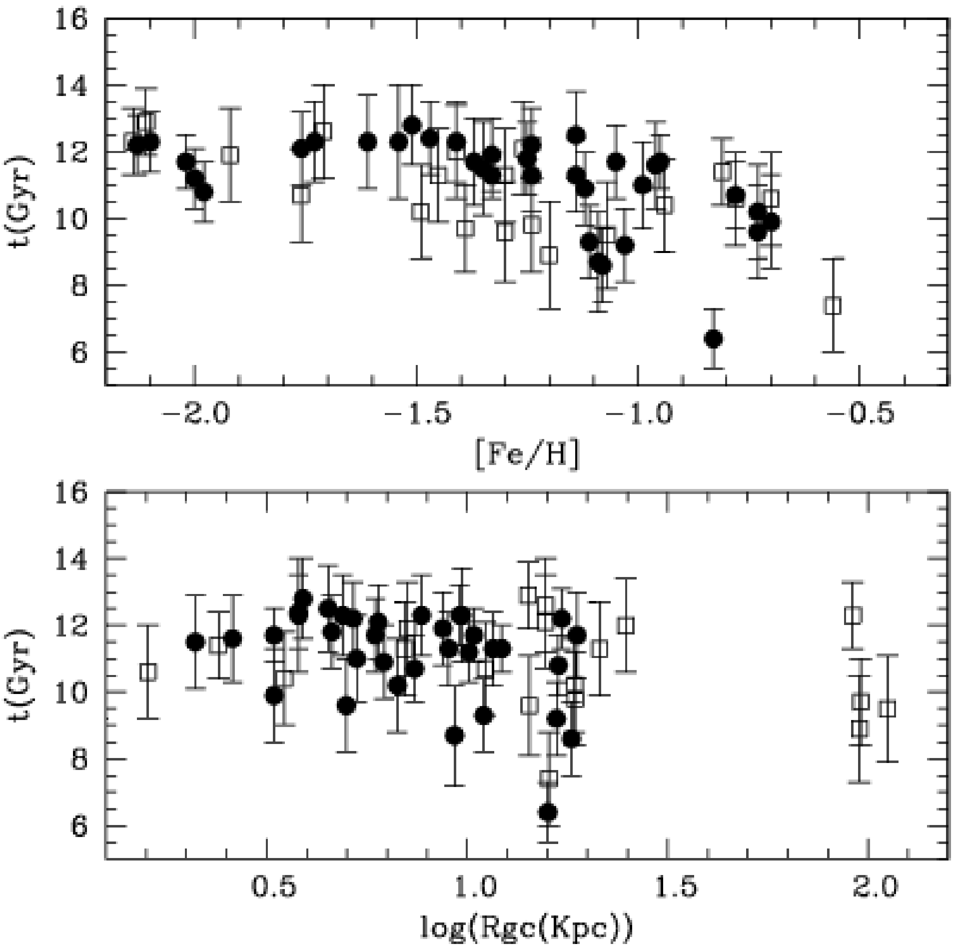
GC ages and constitutional physics

- Chaboyer (1995): influence of physics uncertainties on turn-off ages of GC
  - Debye-Hueckel approx. for EOS: −6.6%
  - He-diffusion : −7.1%
  - He increase (Y=0.26): −3.8%
  - 3σ decrease in nuc. reaction rates: +4.9%
  - α-elements (+0.2/+0.6) +6.6/−6.0%
- Salaris et al. (1997): (age from ΔV_{TO-HB}; distance-independent!)
  - OPAL-EOS, Y=0.23/0.24, [α/Fe]≈0.4
  - no diffusion, standard nuclear reactions
  - (coeval) ages for M15, M68, M92: reduced by 1-2 Gyr (≈12 Gyr)
  - in agreement with cosmic age!

GC ages and constitutional physics



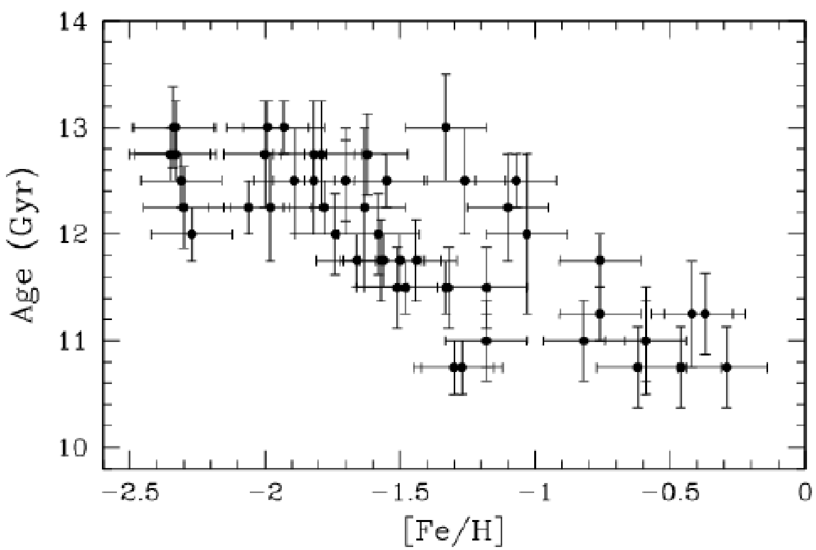
Salaris & Weiss (2002):

result from 55 GCs

- coeval population of GC over wide metallicity range

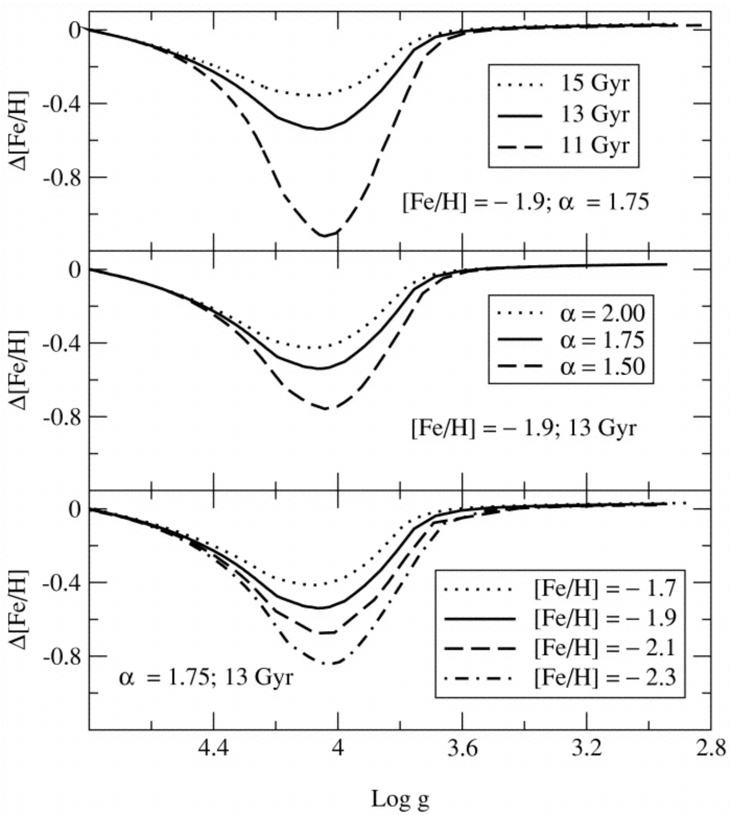
- additional younger clusters with increasing metallicity

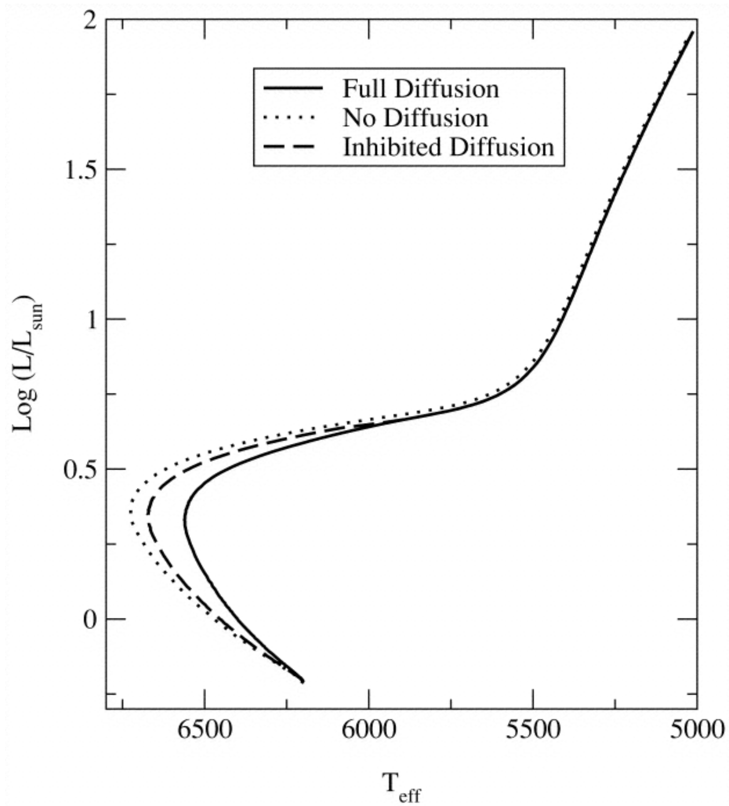
(global result confirmed by ...
Marin-Franch et al. 2009,
Dotter et al. 2011,
VandenBerg et al. 2013)



GC ages and constitutional physics

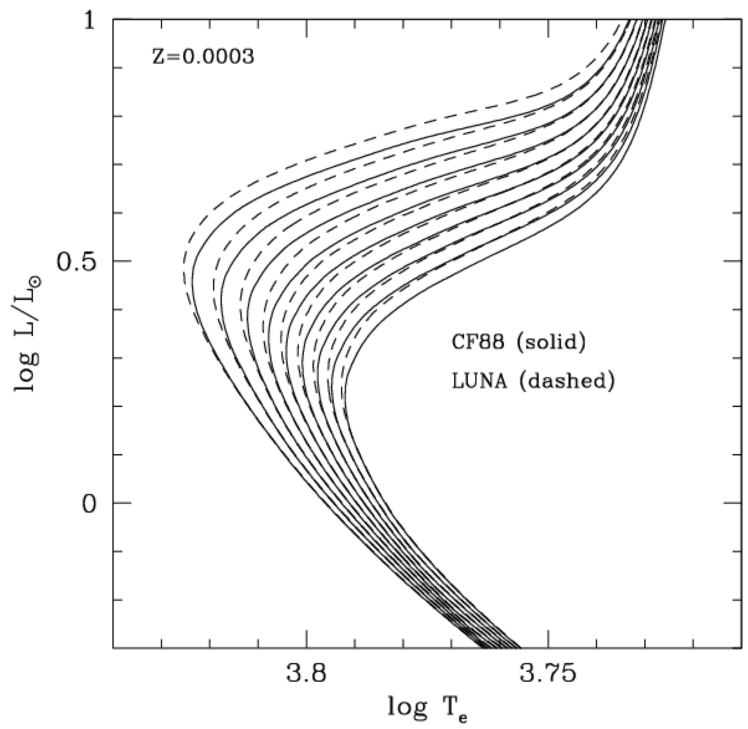
- How much diffusion?
  - straightforward application of sedimentation leads to strong depletion of heavy elements (He, ..., Fe) from atmosphere; Δ[Fe/H] ≤ −0.23 dex
  - "inhibited diffusion" in outer layers; reduced age by 4% (Chaboyer 2001)
  - cf. "turbulent diffusion" (Richard et al. 2005, ...)





GC ages and constitutional physics

- CNO-burning: nuclear reaction rates and CNO-abundances
  - $^{14}N(p,\gamma)^{15}O$ bottleneck reaction; new – and lower – reaction rate from LUNA experiments (Formicola et al. 2004, Marta et al. 2008) by ≈40-50%
  - leads to higher ages from TO-luminosity by up to 1 Gyr

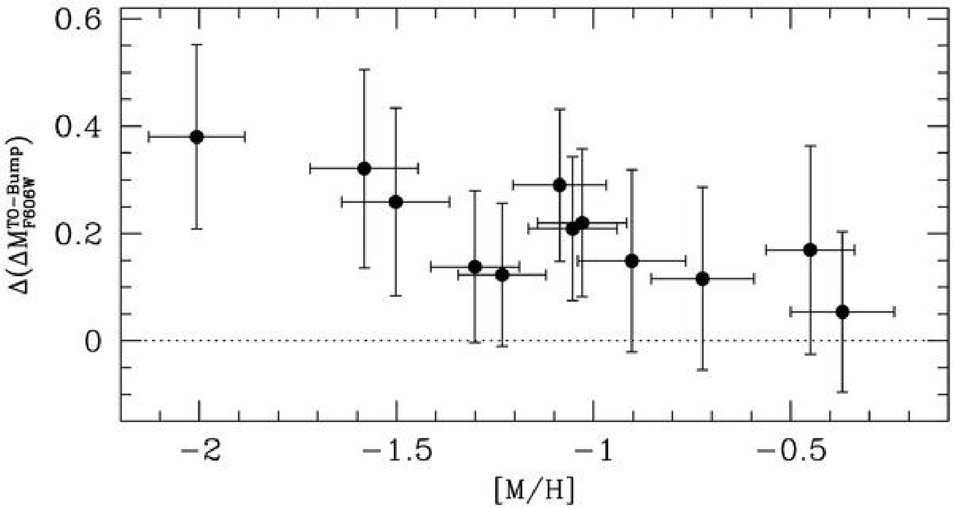


- similar effect due to C+N+O-abundance (Marin-Franch et al. 2011); see NGC 1851

The Bump and convective overshooting

- theoretical isochrones predict a too bright RGB-bump (Cassisi & Salaris 1997; Meissner & Weiss 2006; Cassisi et al. 2011; Troisi et al. 2011)

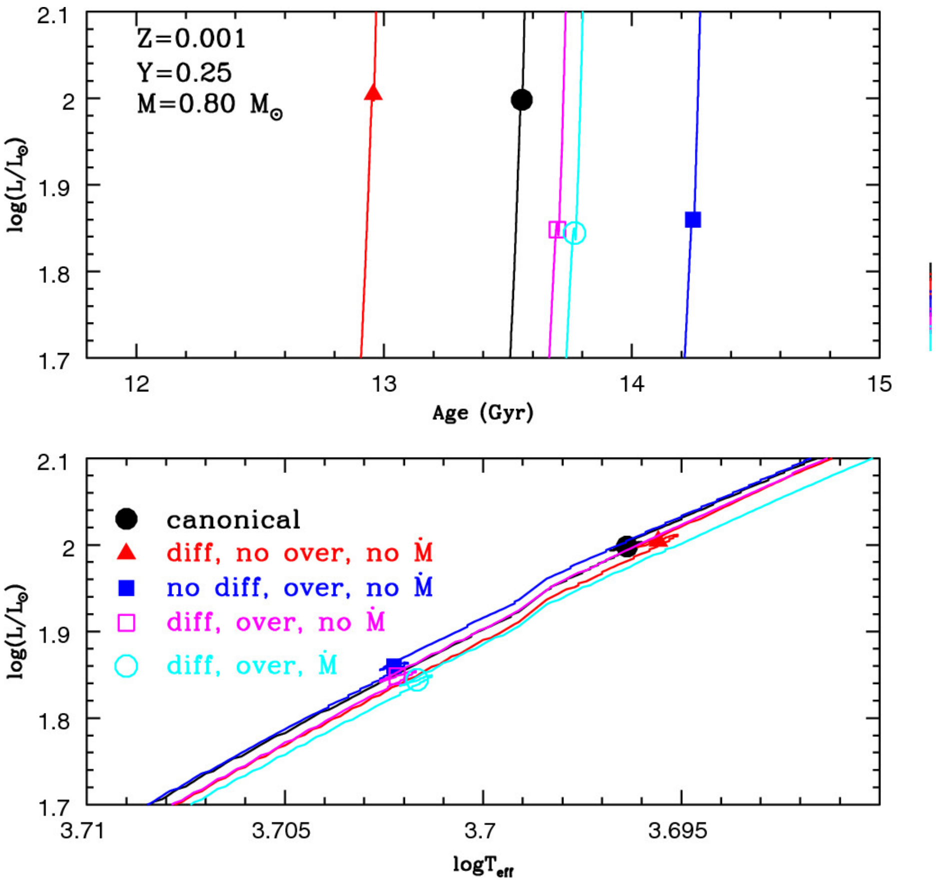
- possible solutions: everything that increasing maximum penetration of convective envelope during lower RGB evolution
  - higher opacity
  - lower helium content (see later)
  - overshooting



bump bringhtness discrepancy from $\Delta V_{TO\text{-}bump}$ (Cassisi et al. 2011)

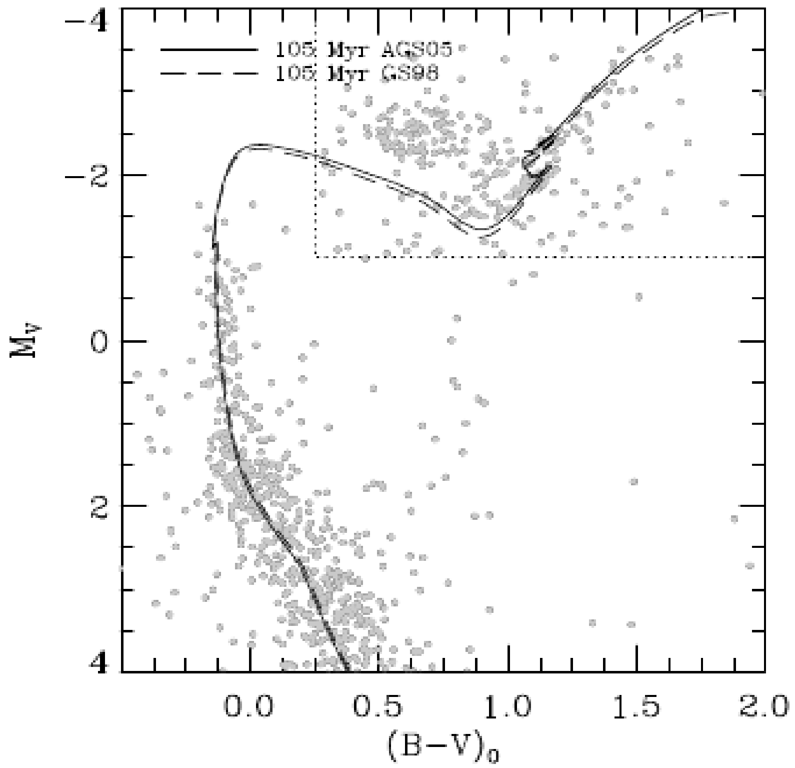
Convective overshooting from envelope

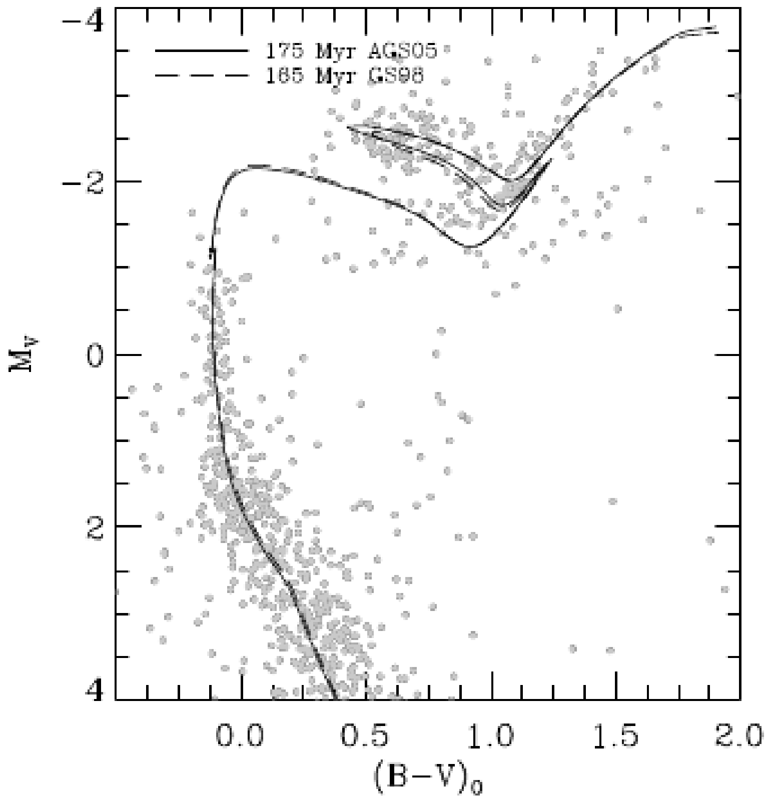
- (required opacity increase: ≈ 30%, unreasonably large)
- convective overshooting from bottom of envelope promising
- parameter similar to that required for core overshooting in main-sequence stars
- consequences for
  - loops of intermediate-mass stars (Cepheids)
  - third dredge-up and nucleosynthesis in AGB stars



influence of various processes on bump brightness; convective overshooting most promising (Troisi et al. 2011)

More overshooting – NGC 1866





Magic (master thesis 2010): NGC 1866 (LMC; [Fe/H]=-0.35; 100-200 Myr)
left: no overshooting, **right**: overshooting (from all convective boundaries, including bottom of convective envelope

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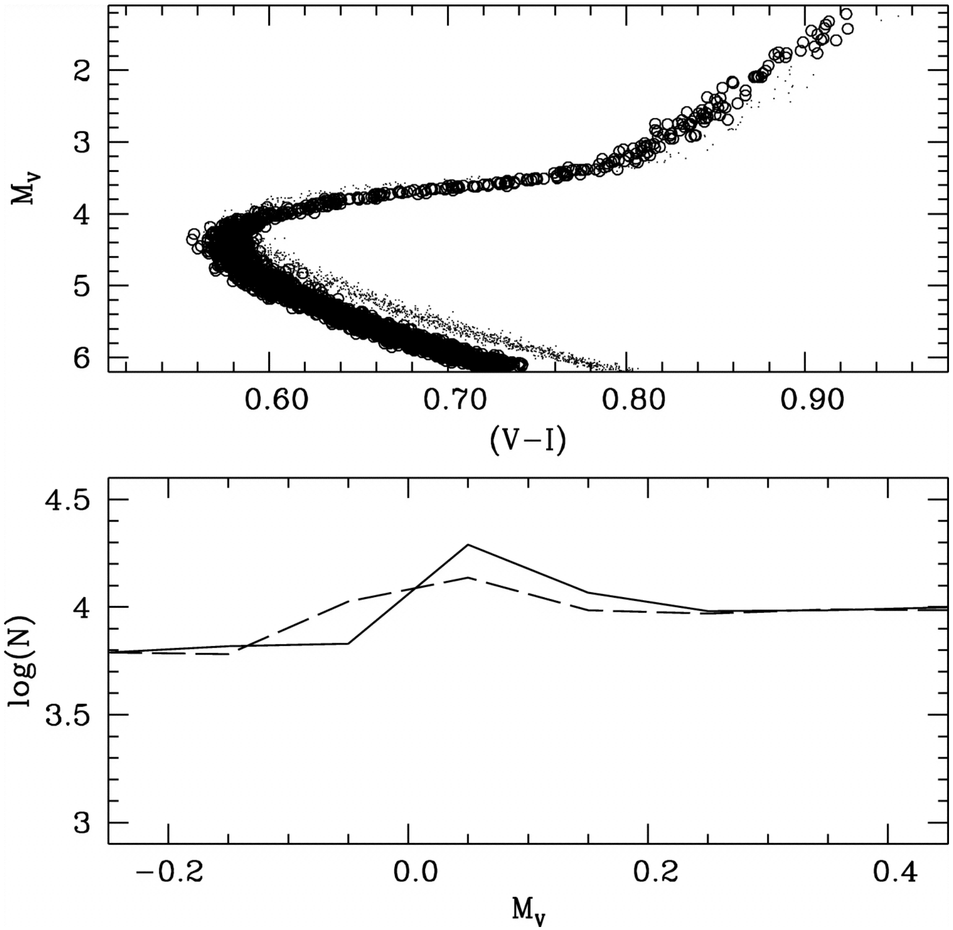
Bump substructure

- Salaris et al. (2006): multiple populations in GC may show up in substructure of the bump



upper panel:

simulation of GC ([Fe/H]=−1.6)
with normal (points; 13 Gyr)
and "extreme" (Y=0.35, CNONa-anomaly)
population (circles, 12.5 Gyr)

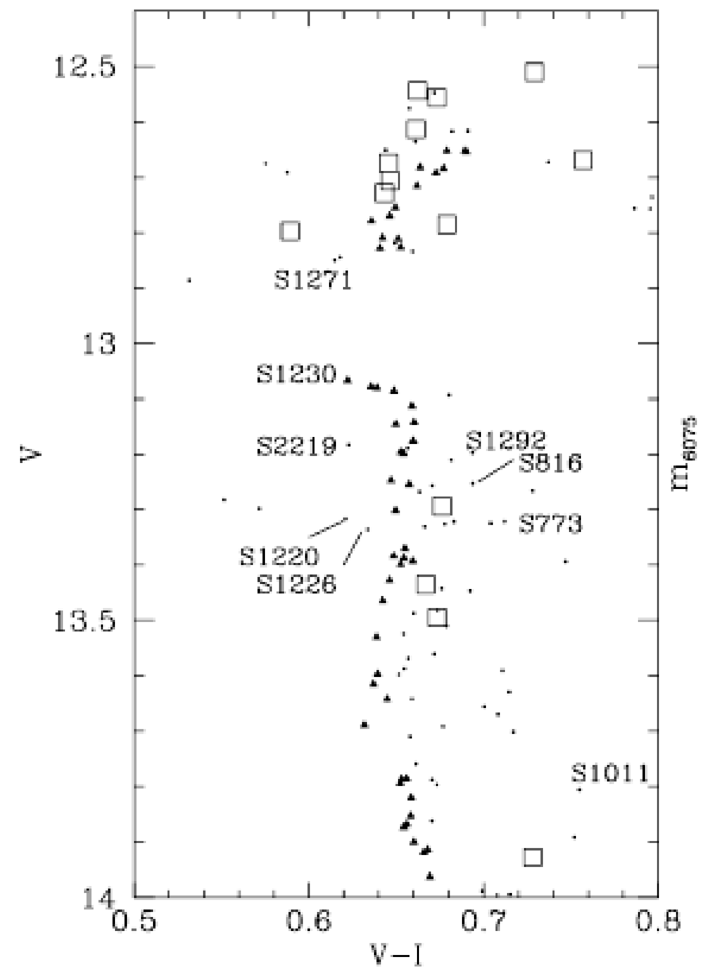
lower panel:

luminosity function in the bump region for this simulation (dashed) compared to only-normal population (solid)

(obs. evidence for brighter bump of second generation stars (He-enriched) by Bragaglia et al. 2010)

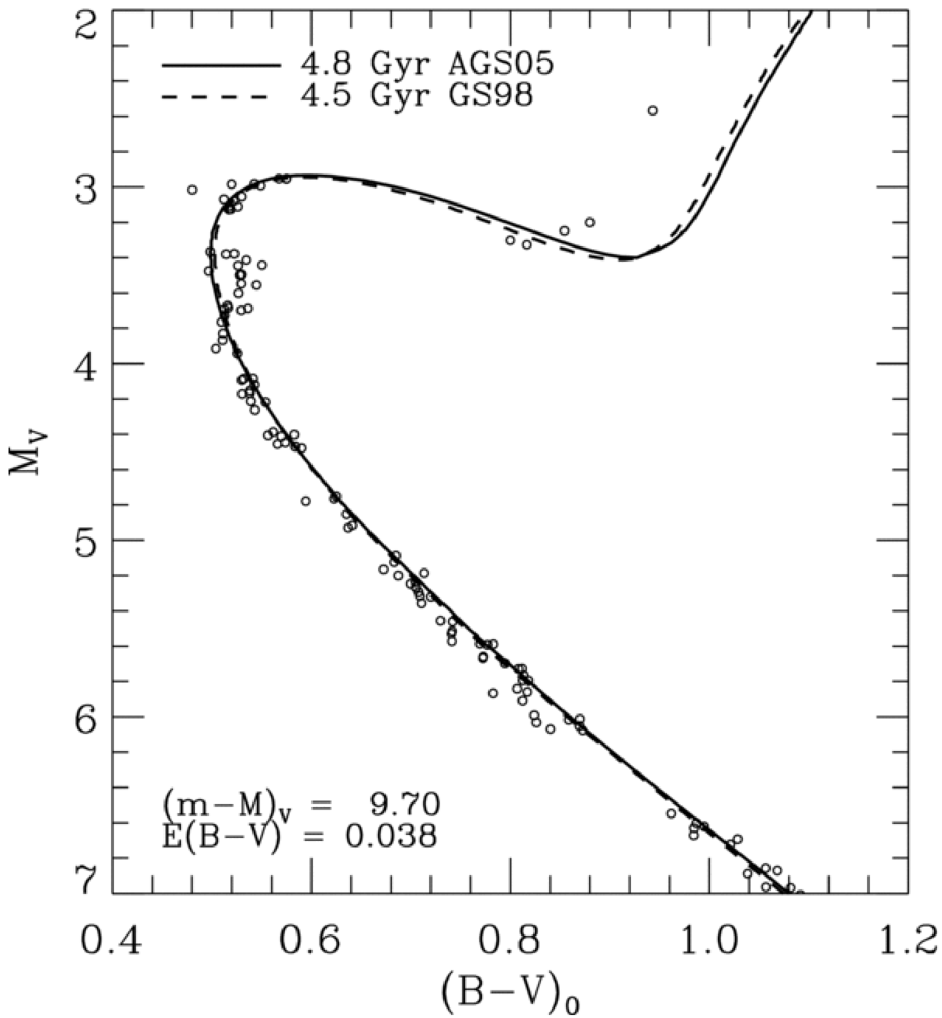
Convective core overshooting

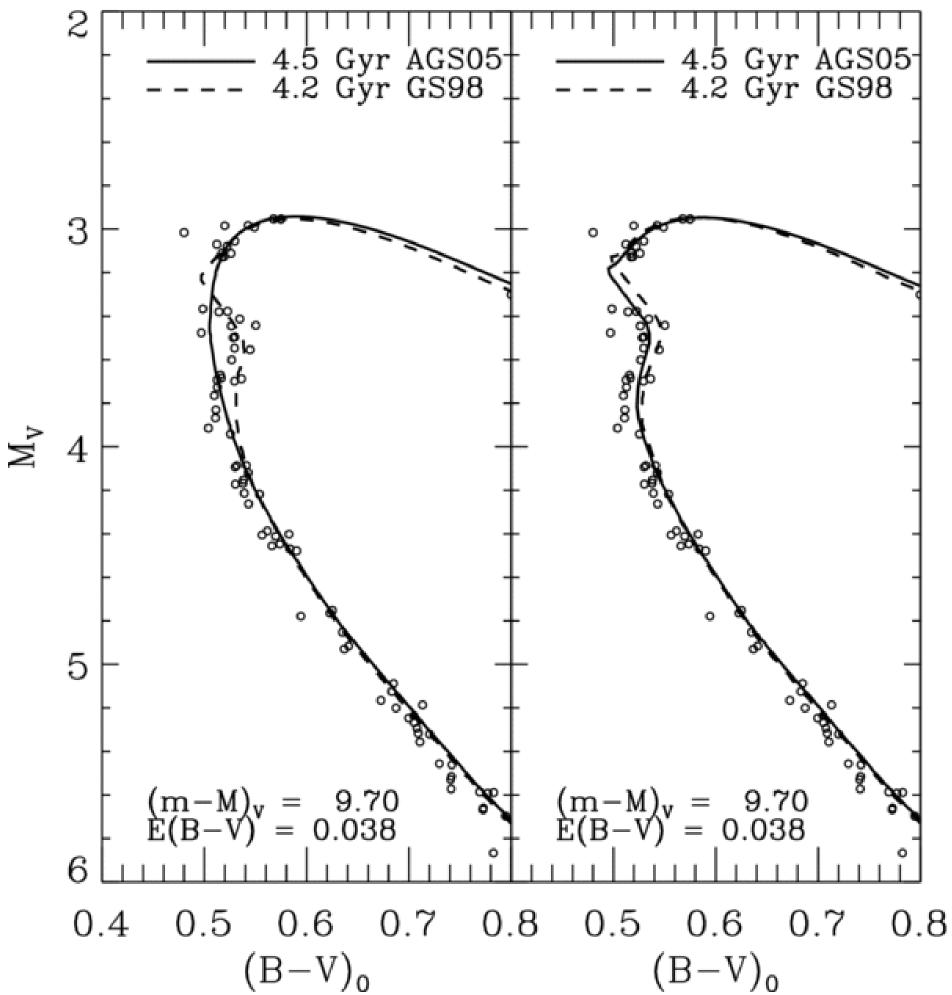
- clusters up to a few Gyr harbour MS stars with (small) convective cores ($M/M_\odot \gtrsim 1.1$; age $\lesssim$ 5 Gyr)
- TO-stars with convective cores result in "hook" at TO of CMDs
- appearance and size of convective core depends (also) on overshooting assumptions
- Note: c.c. depends on CNO-burning efficiency, thus on $^{14}N(p,\gamma)^{15}O$ reaction, but also on C+N+O-abundance; used by VandenBerg et al. (2007) in an attempt to discriminate between Grevesse/Sauval and Asplund *solar metal abundance scales*



TO-region of M67 (Sandquist 2004)

Conv. core overshooting – M67 (Magic et al. 2010)

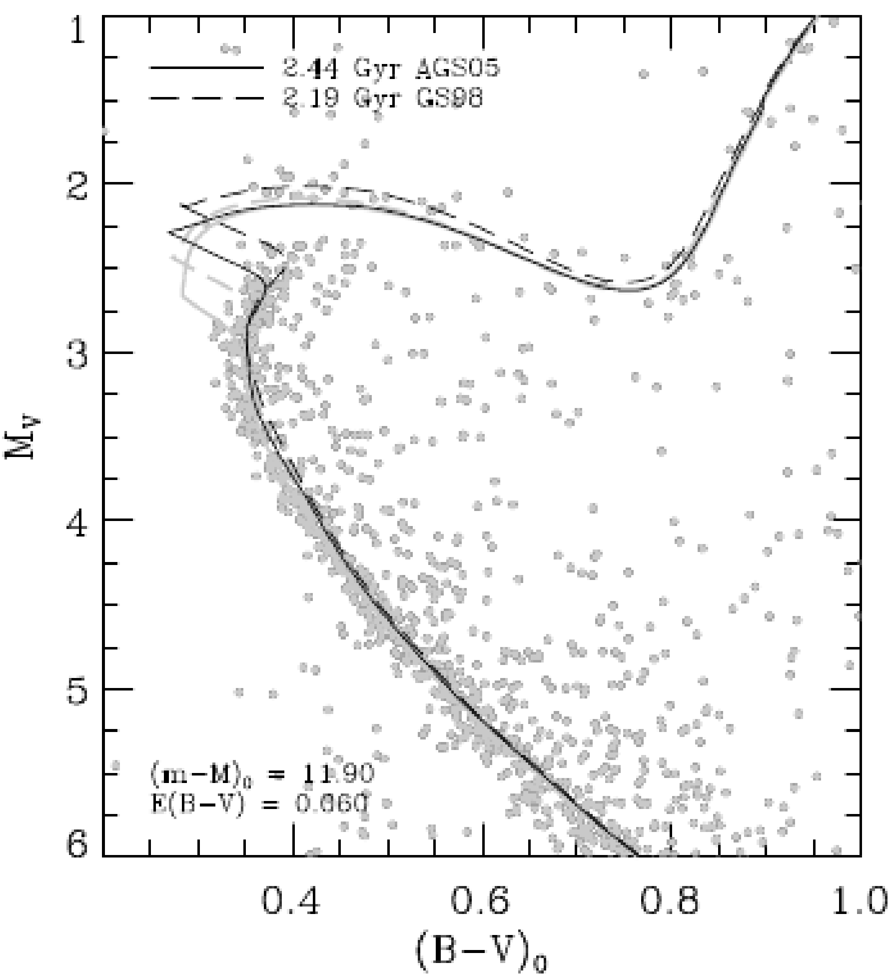




tracks without overshooting and diffusion for two solar abundance scales (using Marta-rate for $^{14}C(p,\gamma)^{15}O$)

left: overshooting with geometric size restriction;
right: with mass-dependent restriction (in both cases diffusion is included)

Conv. core overshooting – NGC 2420



age 2.2–2.4 Gyr; [Fe/H]=–0.44

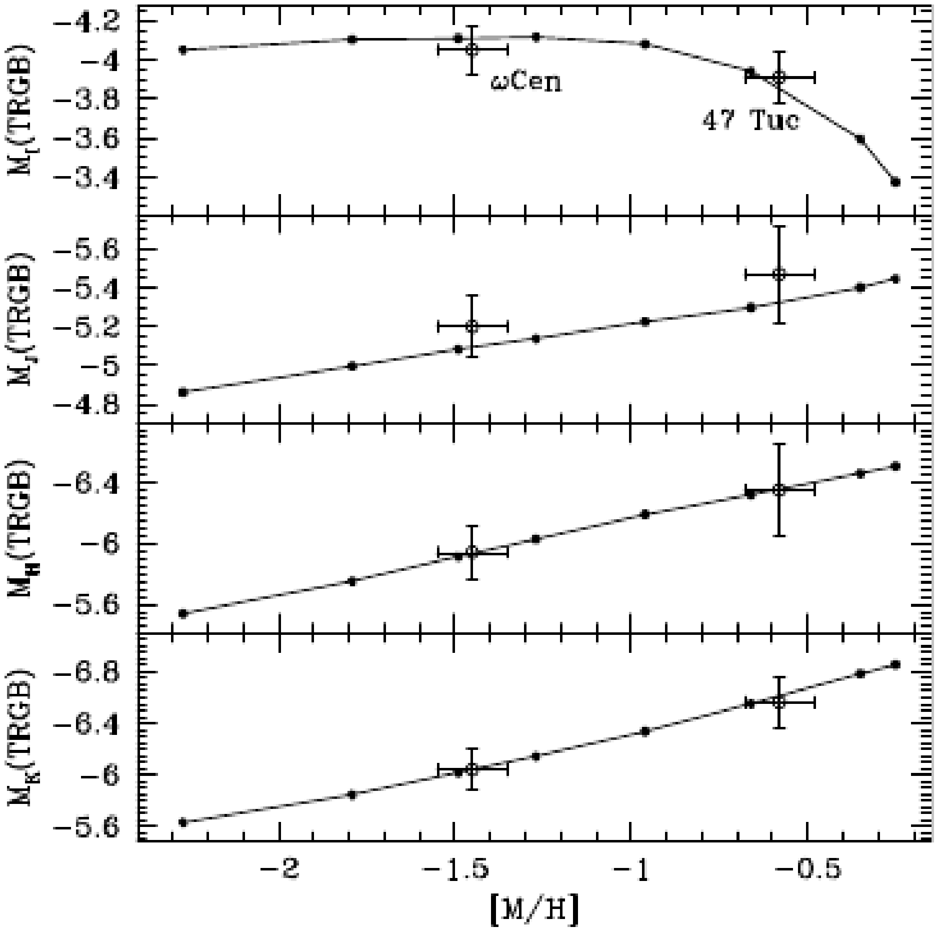
grey lines: no overshooting

black lines: with overshooting

Tip of the Red Giant Branch

predicted brightness of Red Giant Branch tip in old clusters (≳ 1 Gyr) agrees well with observations

<u>here</u>: ω Cen and 47 Tuc in comparison with BaSTi models (Salaris 2013)



TRGB brightness depends on

- conductive opacities
- cooling by neutrinos and ....
- very weakly on M and [Fe/H] (in particular in I–band)

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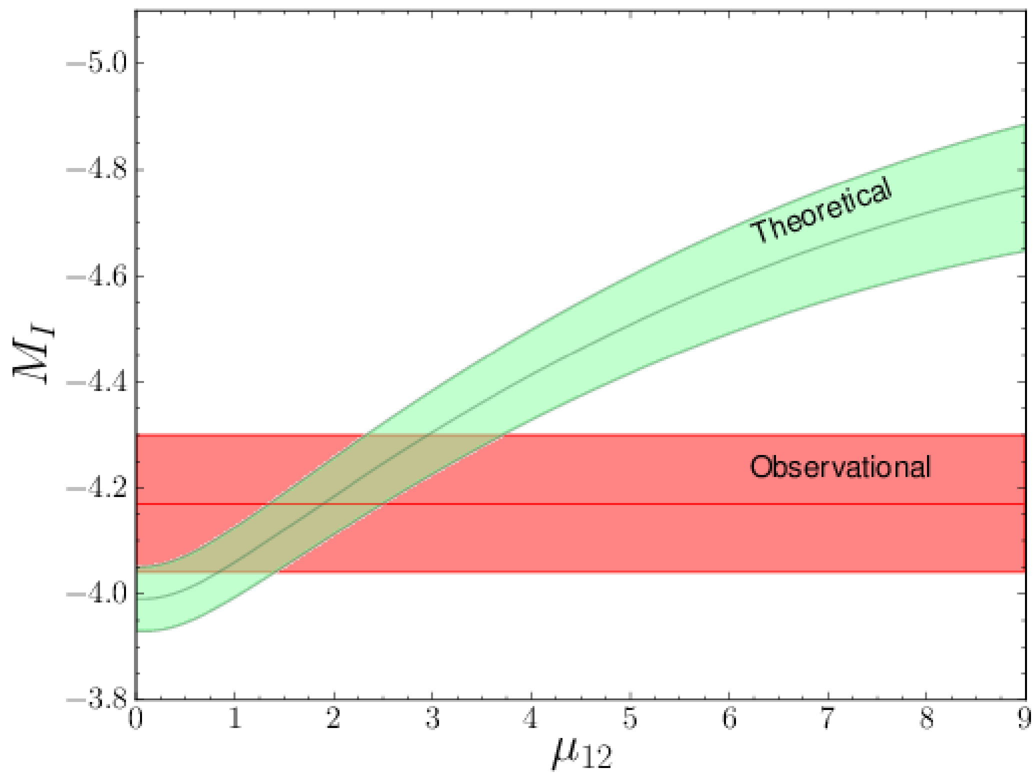
TRGB brightness and particle physics

- neutrino emission rates and non-standard cooling mechanisms affect TRGB brightness
  - test for standard plasma/pair/photo-neutrino cooling
  - astrophysical limit for neutrino properties (electromagnetic dipole moment), axion masses, or other postulated emission channels (Raffelt, Catelan, ...)
- needed:
  - well populated RGB-tip
  - cleaning from contaminating AGB stars
  - excellent cluster distance

TRBG brightness



GC M5 (Viaux et al. 2013):

[Fe/H] = −1.33; [α/Fe]=0.30
$(m-M)_0$ = 14.45±0.11 (Layden et al. 2005)

green:
stellar model predictions including variable size of electromagnetic dipole moment of neutrino, expressed by scaling parameter μ_{12} (Raffelt & Weiss 1992; MDM in 10^{-12} Bohr magnetons)

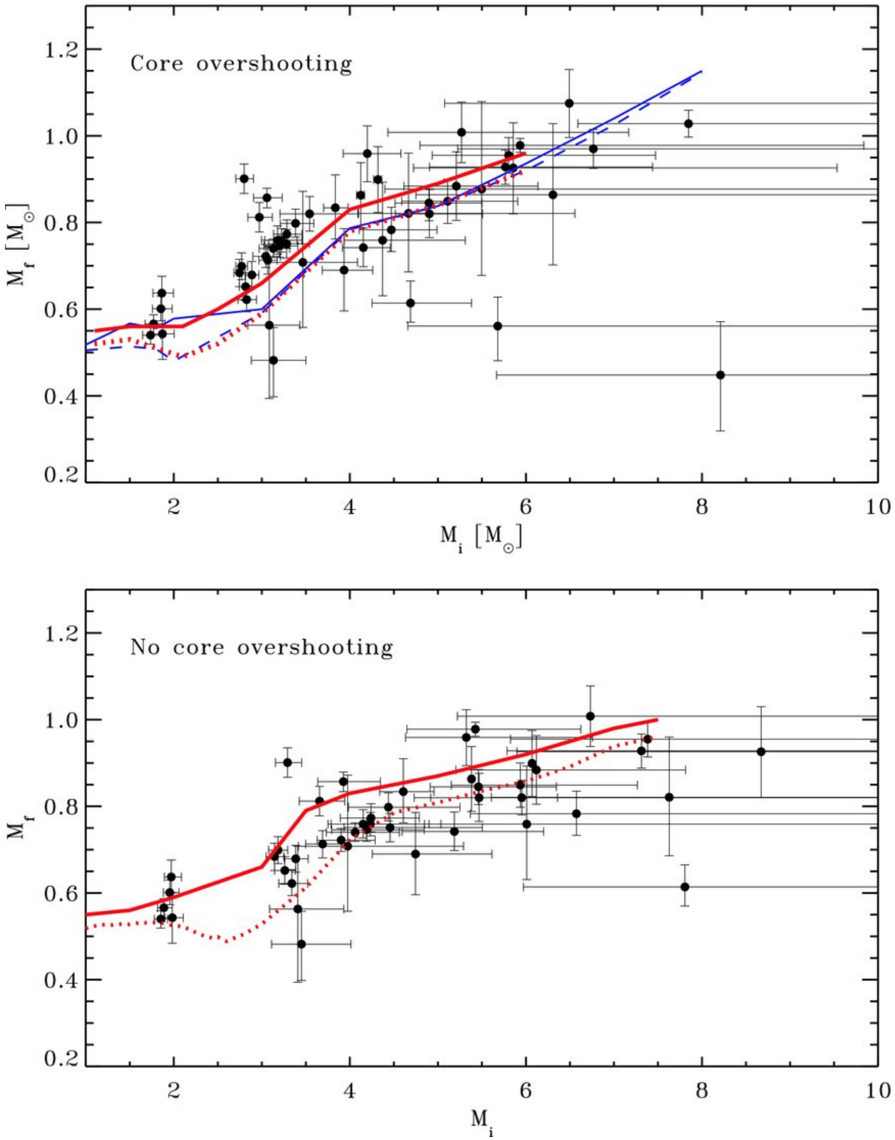
ranges include all possible errors

laboratory limit: $\mu_{12} < 32$
here: $\mu_{12} < 4.4$ at 95% C.L.

by similar procedure postulating axion−electron coupling:
axion−mass restricted to < 16.8 meV

largest observational uncertainty: **distance**!

Initial–final mass relation



needs:
- cluster CMD for cluster age
- cluster WDs (spectra, T_{eff})
- WD cooling tracks
- isochrones

depends on:
- physics for isochrones
- WD cooling physics
- cluster distance

delivers information about:
- MS lifetimes (overshooting!)
- total mass loss (mainly AGB)
- convection on AGB (growth of core, efficiency of 3rd dredge-up)

solid red: BaSTi prediction; dotted red: M_c at 1st thermal pulse
blue lines: same for LPCODE (Salaris et al. 2009)

White Dwarf sequences – NGC6791

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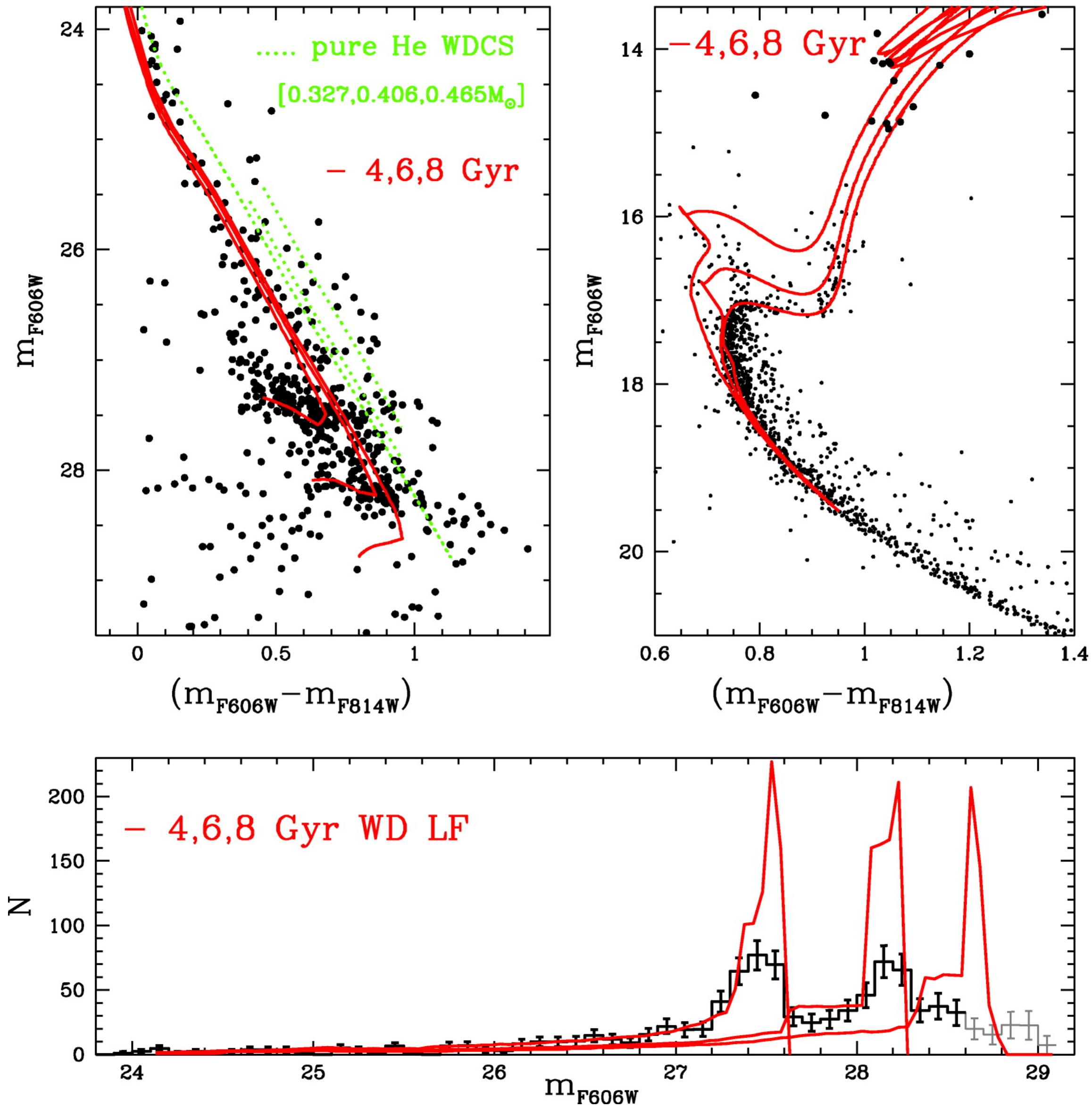

Bedin et al (2005, 2008):

- NGC6791: [Fe/H]=0.3

- end of WD cooling sequence reached
- two distinct WD LF peaks

- brighter peak: 30% unresolved WD+WD binaries

- age discrepancy between lower peak (at 6 Gyr) and TO-age of 8 Gyr

- explanation for age discrepancy:

additional energy from ^{22}Ne diffusion in liquid phase

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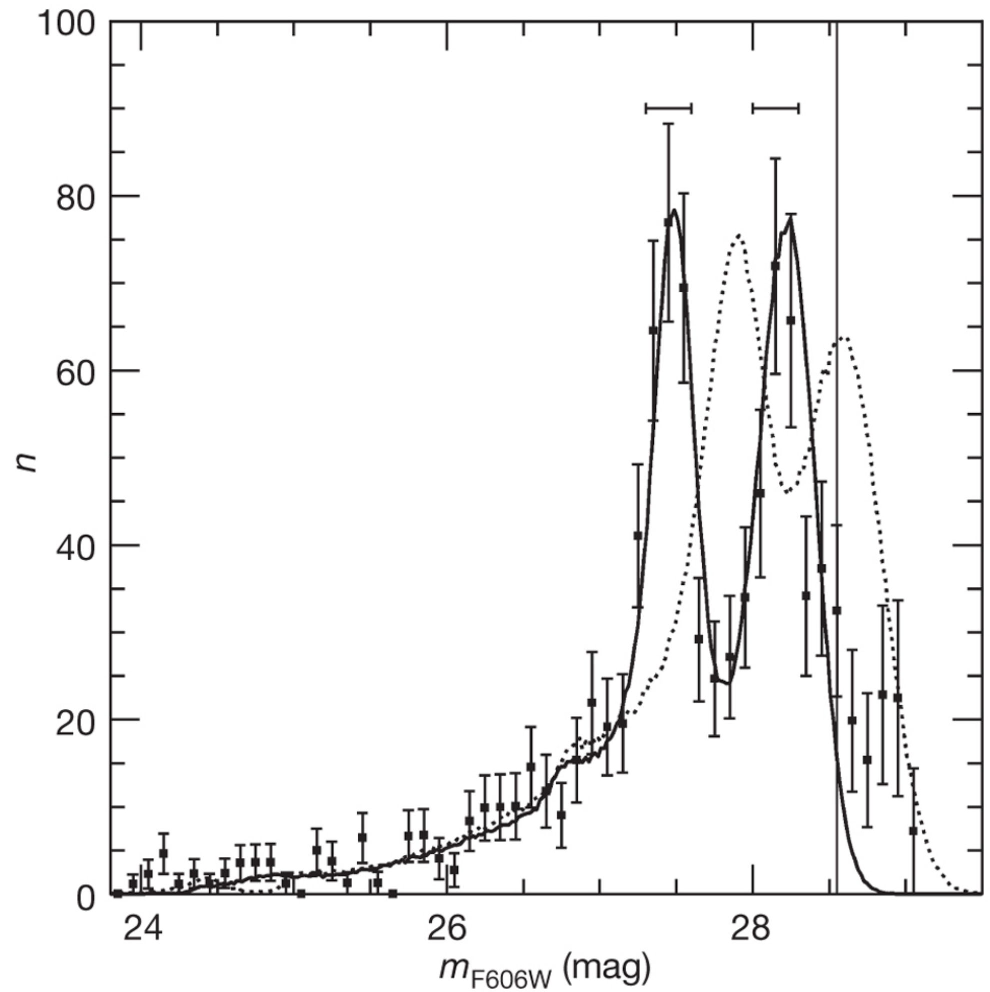
^{22}Ne-settling effect in NGC6791

- ^{22}Ne from α-captures on ^{14}N
- relevant in metal-rich stars
- 2 excess neutrons (rel. to average A/Z=2) leads to downward force and diffusion
- diffusion in liquid phase, down to crystallization limit
- energy release
- slow-down of cooling
- higher age at given luminosity

<u>Figure</u>:

- solid line: prediction from models with ^{22}Ne-settling
- dotted: without
- both for 8 Gyr and MC simulations to account for unresolved binaries

(Garcia-Berro et al., 2010)



Helium vs. metallicity

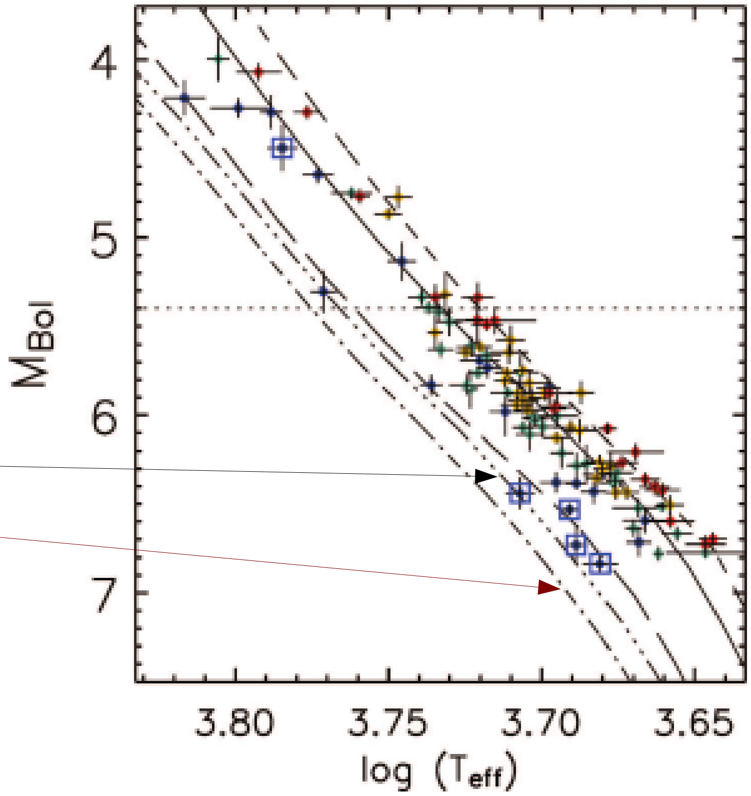
Casagrande et al. (2007) and Portinari et al. (2010):

from CMD position comparison of *Hipparcos*-K-dwarfs to isochrones conclude that match requires sub-BBN helium abundance at lowest metallicities, but generally $\Delta Y/\Delta Z=2.1\pm0.9$ around solar metallicity

(known since Lebreton et al. 1999)

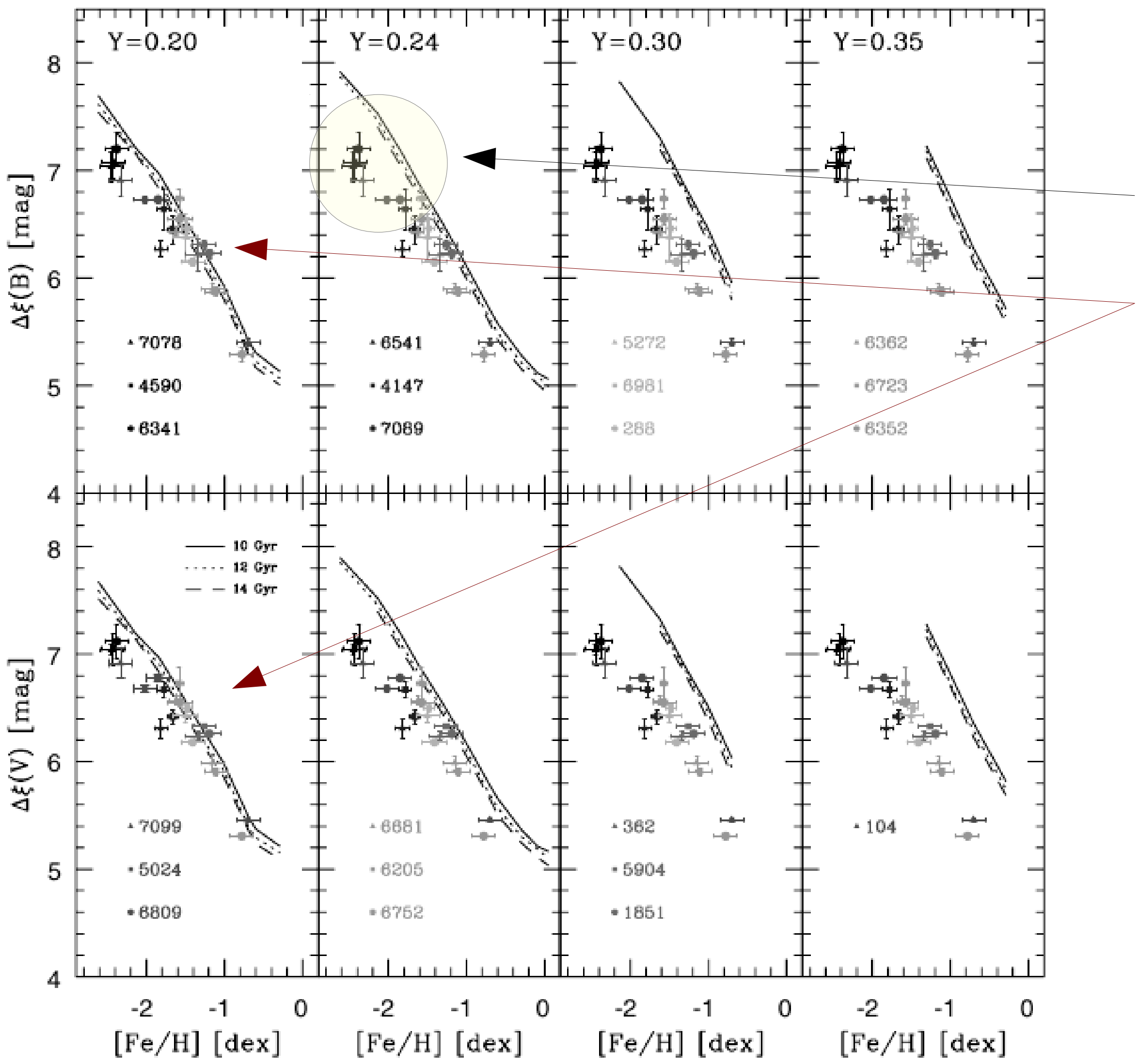
Casagrande et al. (2007):
symbols:
stars with $Z \approx 0.001$ to ≥ 0.022
lines:
expectations from models
$Z=0.001$, $Y=0.167$
$Z=0.001$, $Y=0.246$

corresponds to $\Delta Y/\Delta Z \approx 10$!



(but see Gennaro et al. 2010 and Valcarce et al. 2013 for other explanations)

More on low helium at low Z



Troisi et al (2011):

bump brightness problem could be solved with low initial Y for metal-poor clusters

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Helium vs. metallicity: a suggestion

- Recall ω Cen MS: bluest MS is **not** most metal-poor
  → must have higher helium content ($Y \geq 0.3$)
- Use clusters with well-defined distances and accurate metallicity determinations
- compare lower main-sequences
- use appropriate theoretical isochrones
- derive Y for each cluster and get $\Delta Y/\Delta Z$

<u>advantages</u>:

- better coverage, more data
- accurate ages

Additional possibilities ...

- CNO and Li abundance variations above the bump:

  → hints for additional mixing processes (thermohaline mixing)
- Li on upper MS, SGB and lower RGB:

  → primordial Li determination
- RGB effective temperatures:

  → "calibration" of α_{MLT}
- HB morphology:

  → multiple populations, He–variations
- HB/RGB number counts (R–parameter):

  → primordial He estimate
- ....

Conclusions

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- clusters at various ages and metallicities trace various physical effects
- ideally suited to verify stellar models (e.g. nuclear reaction rates)
- and to identify crucial physics (e.g. diffusion, gravity waves)
- has been done so far extensively
- to exploit potential even more, we need ....
    - accurate distances
    - accurate chemical composition
- but then the prospects are enormous

Final comment

- globular clusters host multiple populations
- cover similar CMD positions (depending on colour), but differ in properties (compositions, mass, age)

  → GC are no longer the ideal laboratory

- this may require
  - more complicated models (population synthesis) and isochrones
  - revisit what we thought we have learnt to far from GC!
  - some results may have misled us so far due to the too simple assumption of "simple stellar populations"!