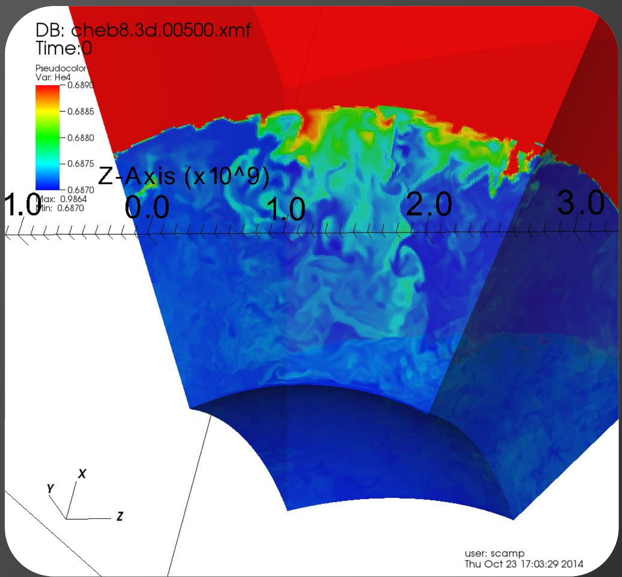
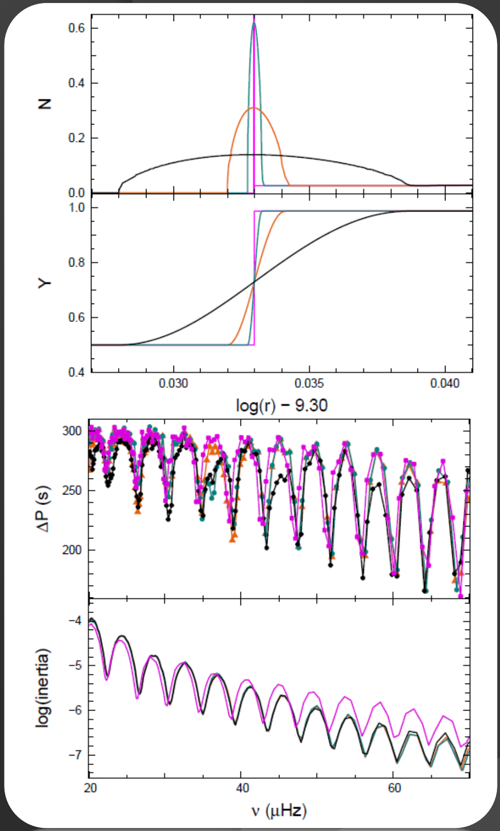
Towards 21st Century Stellar Models:

Star Clusters, Supercomputing, & Asteroseismology





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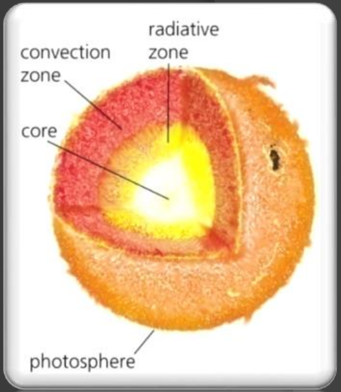
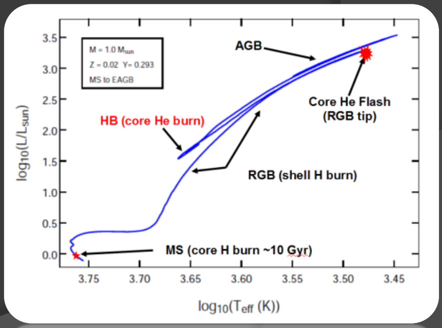
MoCA Monash Centre for Astrophysics → Max-Planck-Institut für Astrophysik

On the Importance of Stellar Models

- Stars contribute to the Universe in a number of ways:
  - Emit radiation - which we can detect.
  - Modify the chemical make-up of the gas from which they formed, through nucleosynthesis.
  - Lock up matter in stellar remnants.

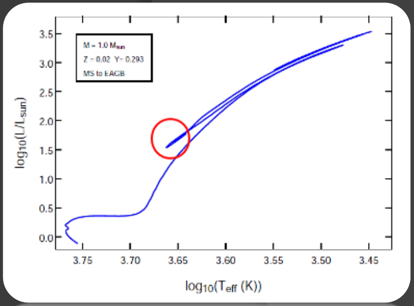


- Stellar models provide various predictions:
  - Stellar lifetimes: Of each phase of a star's life – to be compared to star counts.
  - Surface properties: Temperature, Luminosity, chemical abundances – to be compared to photometry and spectroscopy.
  - Contributions to ISM versus time: Stellar mass-loss via winds and explosions = mass returned/locked up in remnants, chemical enrichment; EM radiation.
  - Internal properties: Thermal structure, chemical profiles, asteroseismic properties, etc.



All of these outputs are used in models of the Milky Way and other galaxies!

Background on Core Helium Burning (CHeB) Stars

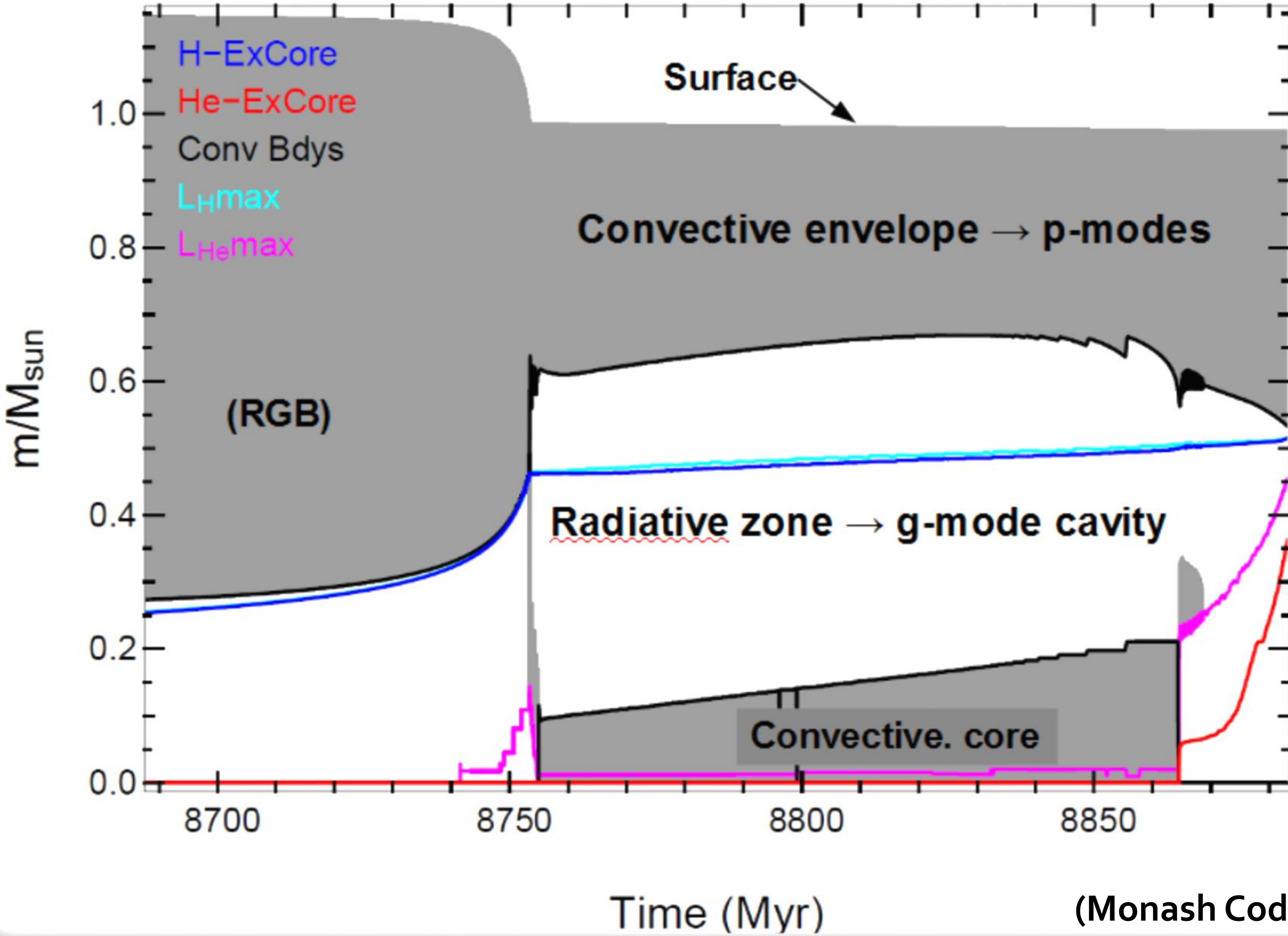


- Phase of evolution after the RGB, just before the (early) AGB.
- CHeB lifetimes are ~1 to 10% of MS → Numerous (& luminous)
- Dense core, initially ~98% helium.
- Helium burning occurs under highly turbulent conditions = 'convective core'.
- He burnt to C and O (becomes CO core of AGB star ⟶ WD).
- Observationally known as red clump (RC), second clump (SC), horizontal branch (HB), subdwarf B (sdB) or RR Lyrae stars (!) – depending on metallicity, envelope mass, and total mass.
- If the envelope is large enough (approx > 0.25 Msun) then they are photometrically similar to RGB stars.

Subsequent evolution – eg. AGB, supernovae – depends on the results of this phase ⟶ need to simulate well!

Unfortunately CHeB is where stellar code results really start to diverge..

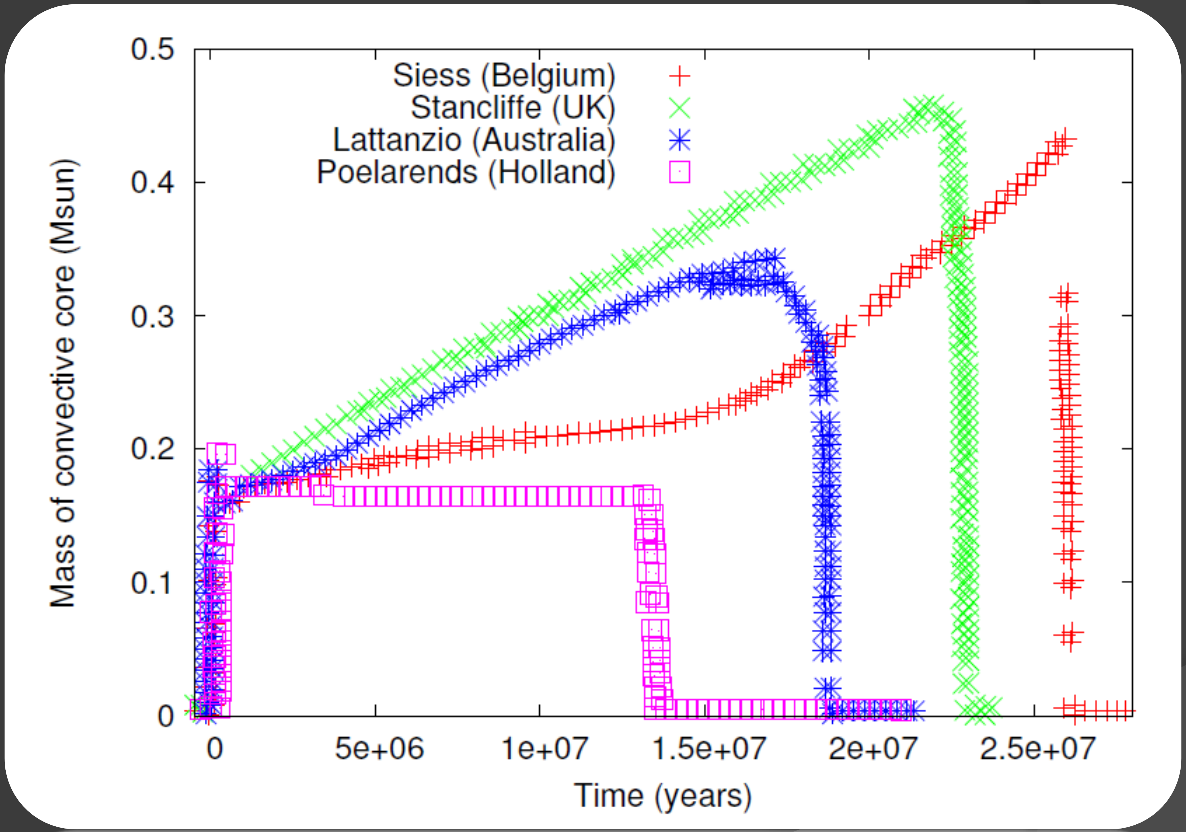
CHeB: Internal evolution



(Monash Code)

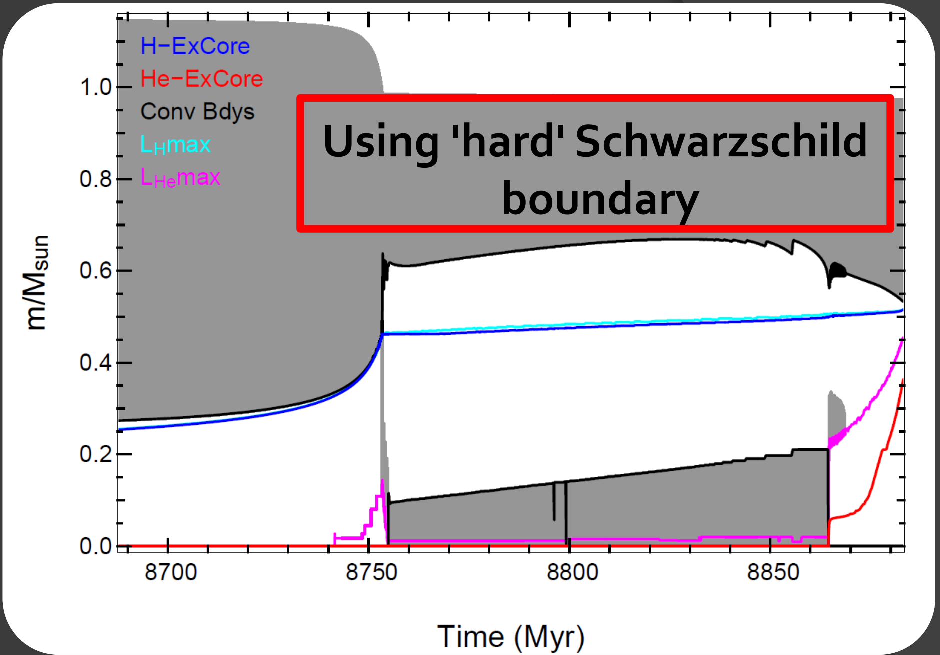
CHeB Problem #1: Models are a Mess!

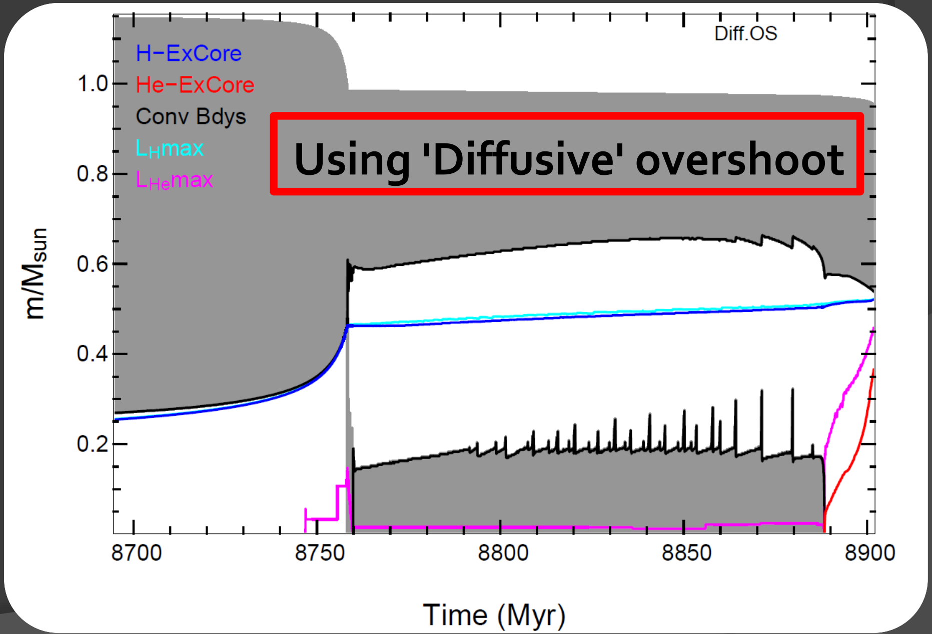
- Stellar codes give wildly varying evolution for core helium burning.
- In this comparison between 4 stellar codes we found:
  - Factor of 2 difference in lifetime!
  - More than a factor of 2 difference in final core size!
- This is also true of massive star models (M > 10 Msun, eg. Langer 1991, A&A, 248,531)
  - So will affect (pre)supernova models!



Why such a mess?

- A difficult case to model because as helium burning converts He to C and O the opacity disparity between convective core and radiative zone above increases.
- Results are heavily dependent on treatment of mixing at edge of convective core.
- Monash models shown here, for just 2 different treatments of convective boundaries.
- Spikes in lower panel show 'core breathing pulses' → sudden ingestion of helium from radiative zone due to instability of convective boundary.
- Actually reduces size of fully mixed core → affects oscillation frequencies…





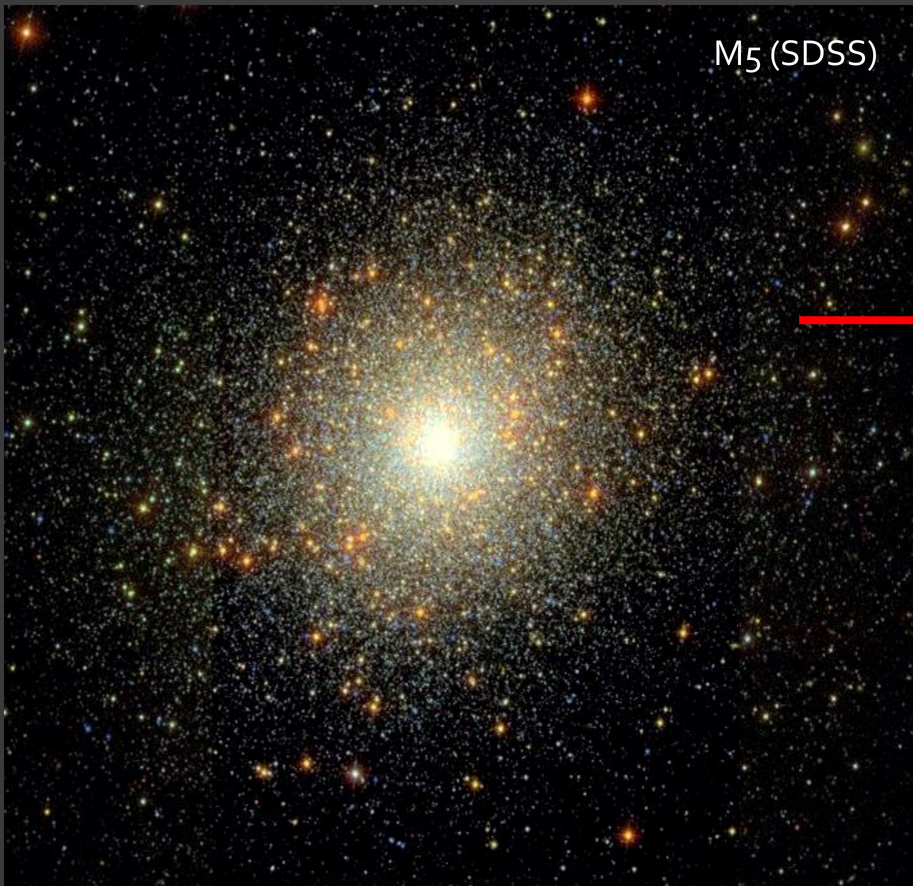
The Way Forward: How to Advance the Models?

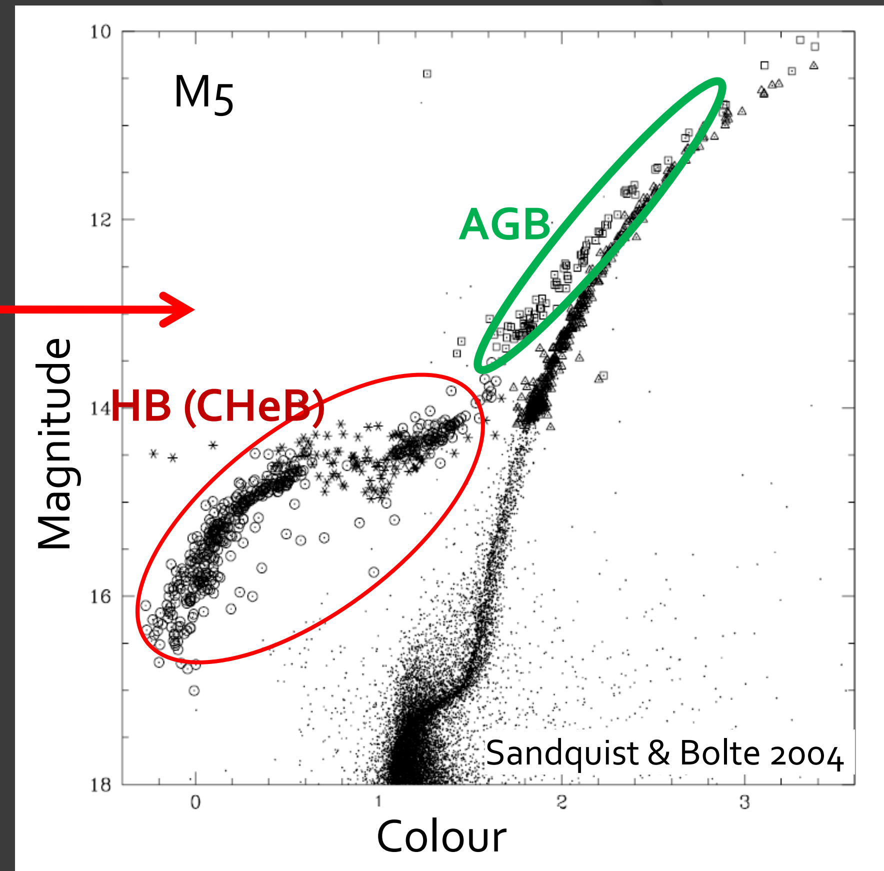
1) Take advantage of the current convergence of various high-quality observations:
   - Spectroscopy & Photometry of Star Clusters: Chemical tagging of evolutionary phases, stellar parameters. Also huge databases of stars coming online (eg. GALAH, GAIA-ESO, SAGA..)
   - Asteroseismology: ‘Seeing’ inside stars; eg. Kepler, CoRoT, PLATO..

2) Gain physical insights from hydrodynamic simulations:
   - 3D simulations of stars: Stellar interior hydrodynamics on supercomputers (Magnus, Raijin)

Improving the Models I: Spectroscopic Observations of Globular Cluster Stars

Globular Clusters as Stellar Testbeds



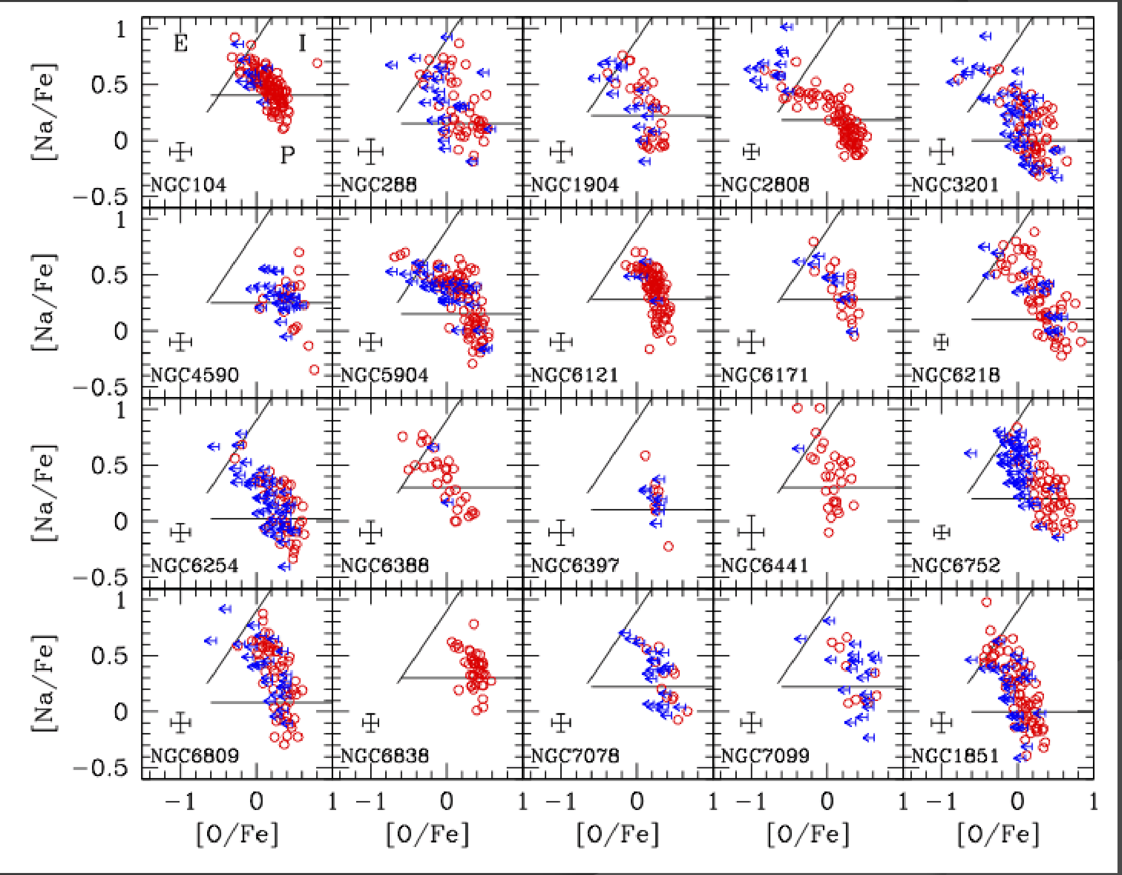


- $10^4 \sim 10^6$ stars
- About 150 GCs orbit the Milky Way
- Initially thought to be simple stellar populations

- Colour-Magnitude diagrams show tight evolutionary sequences!
- **Great for comparing with our stellar models :)**

GC Multiple Populations → Mini versions of Galactic-scale Problem(s): Chemical Space

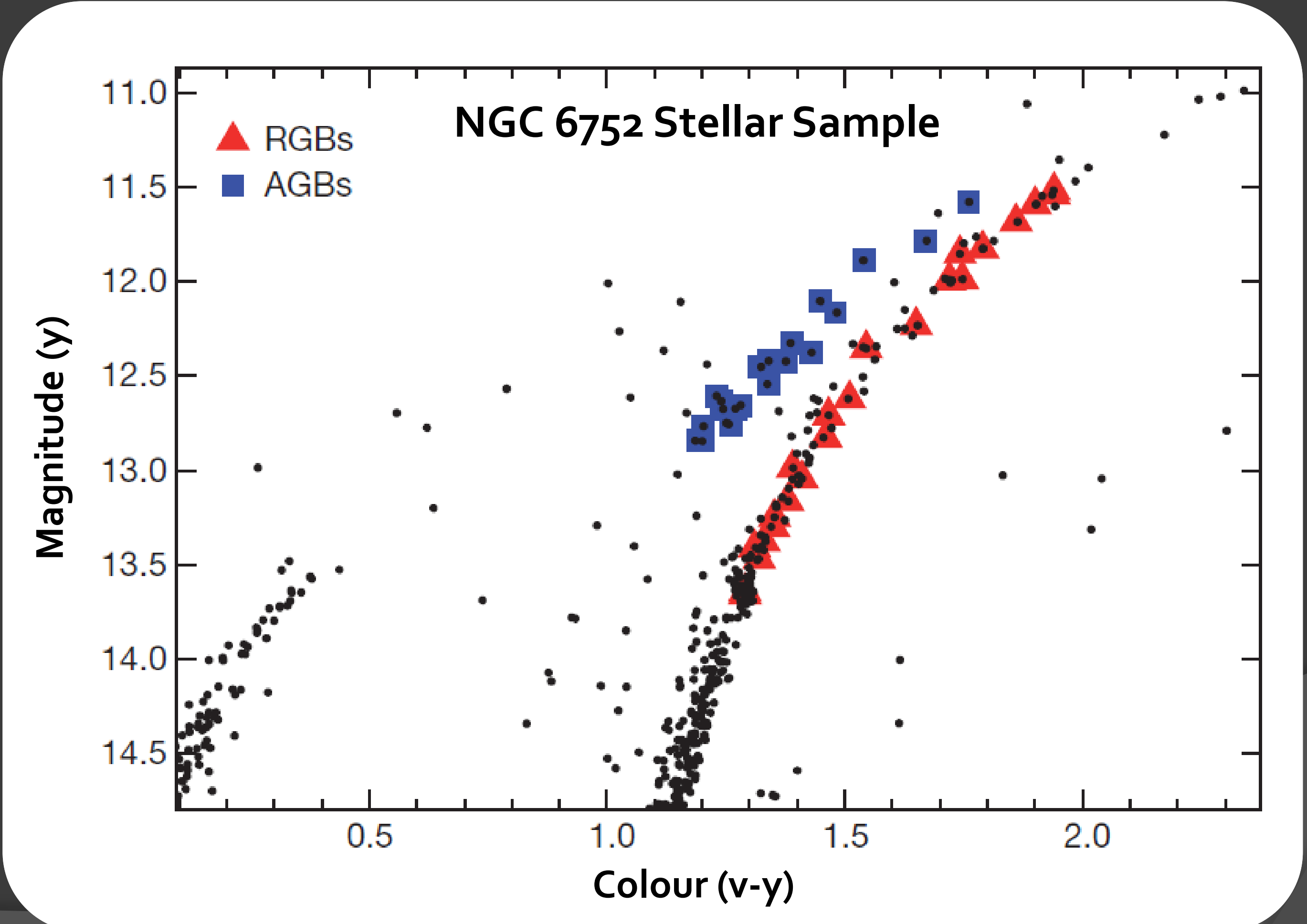
- With the advent of multi-object, high-resolution spectrographs we now have a huge amount of information on chemical abundances in GC stars.
- Basically all GCs have multiple populations with varying Na, O along with C,N and sometimes Mg, Al, and probably He
- Note: These samples primarily contain RGB stars.



The Na-O anticorrelation in 20 MW GCs
Gratton, Carretta & Bragaglia 2012, A&ARv, 20, 50

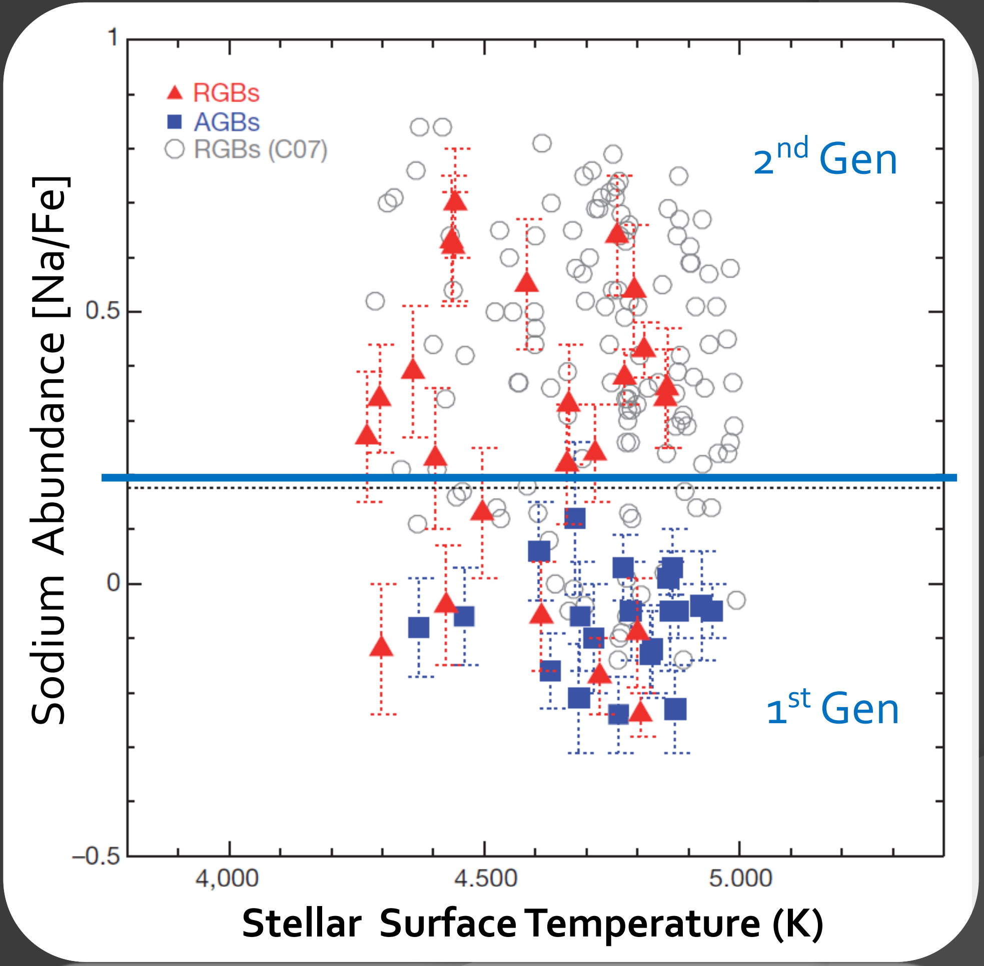
Chemical Tagging of Subpopulations + Evolutionary Phases in NGC 6752

What is happening to the CHeB stars??



Stars Failing to get to AGB!

- VLT observations to get O, Na, Mg, Al abundances in 20 AGB stars and 30 RGB stars.
- Amazingly the *entire* AGB sample turned out to be Na-poor!
- What does this mean??
- It appears the Na-rich second generation are failing to get to AGB
- This implies 70% of the cluster stars are failing to become AGBs… Can models reproduce this?

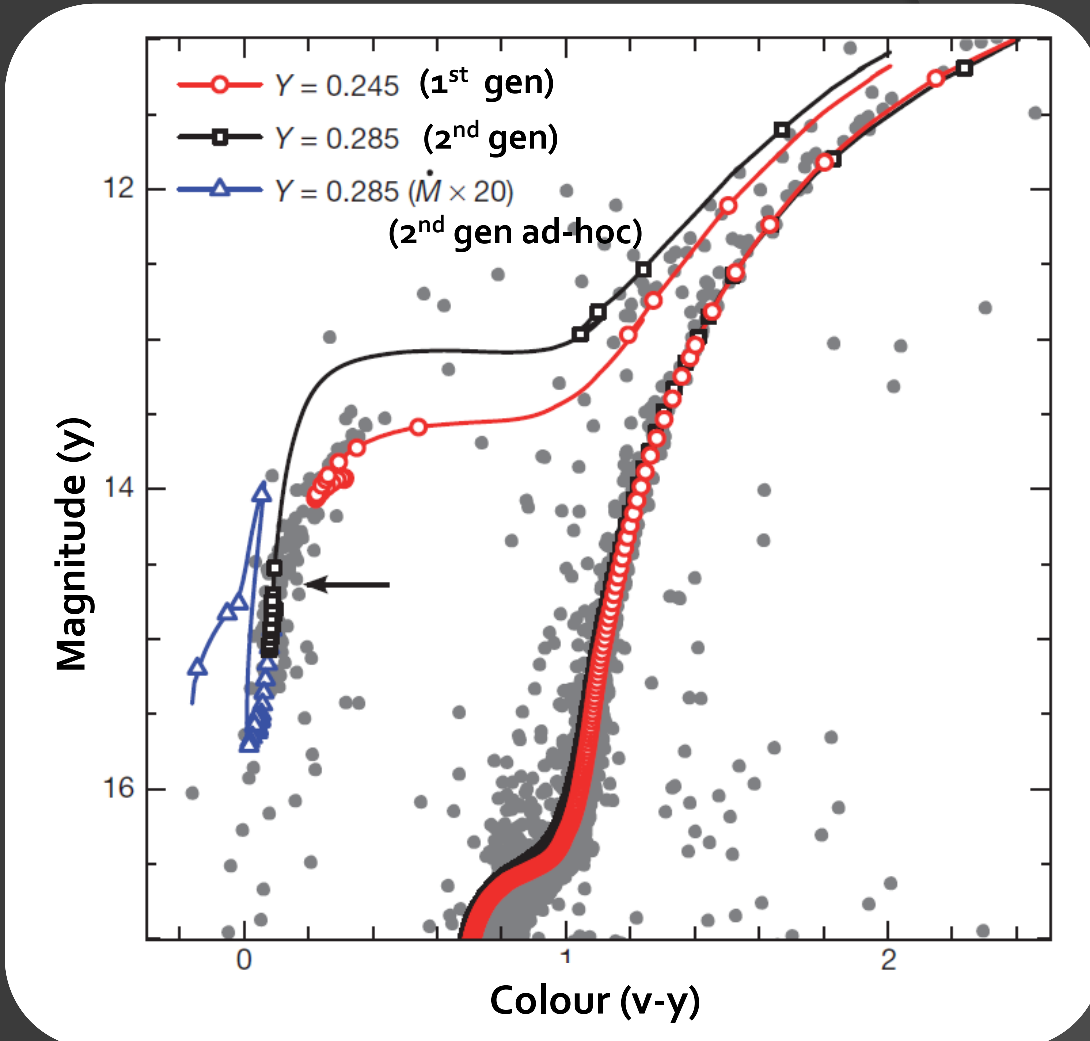


Campbell, D'Orazi, Yong, Constantino et al. 2013, Nature, 498, 198.

Core He burning Problem #2: Cannot match CHeB Failure Rate

- Extra helium content in 2nd generation stars shortens their lifetimes, so they have lower mass (+ bluer HB).
- Extra mass loss on RGB also gives a bluer ZAHB star. However it is the red(er) HB stars that fail to reach AGB, so this can't be the solution.
- **→ Standard stellar models cannot reproduce this phenomenon.**
- The only model that fits is one with artificially boosted mass-loss on the HB

→ Problem with core helium burning models?? Missing physics?

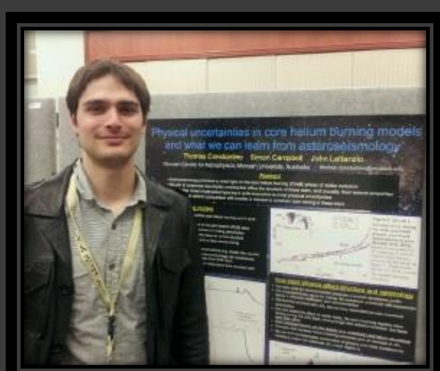


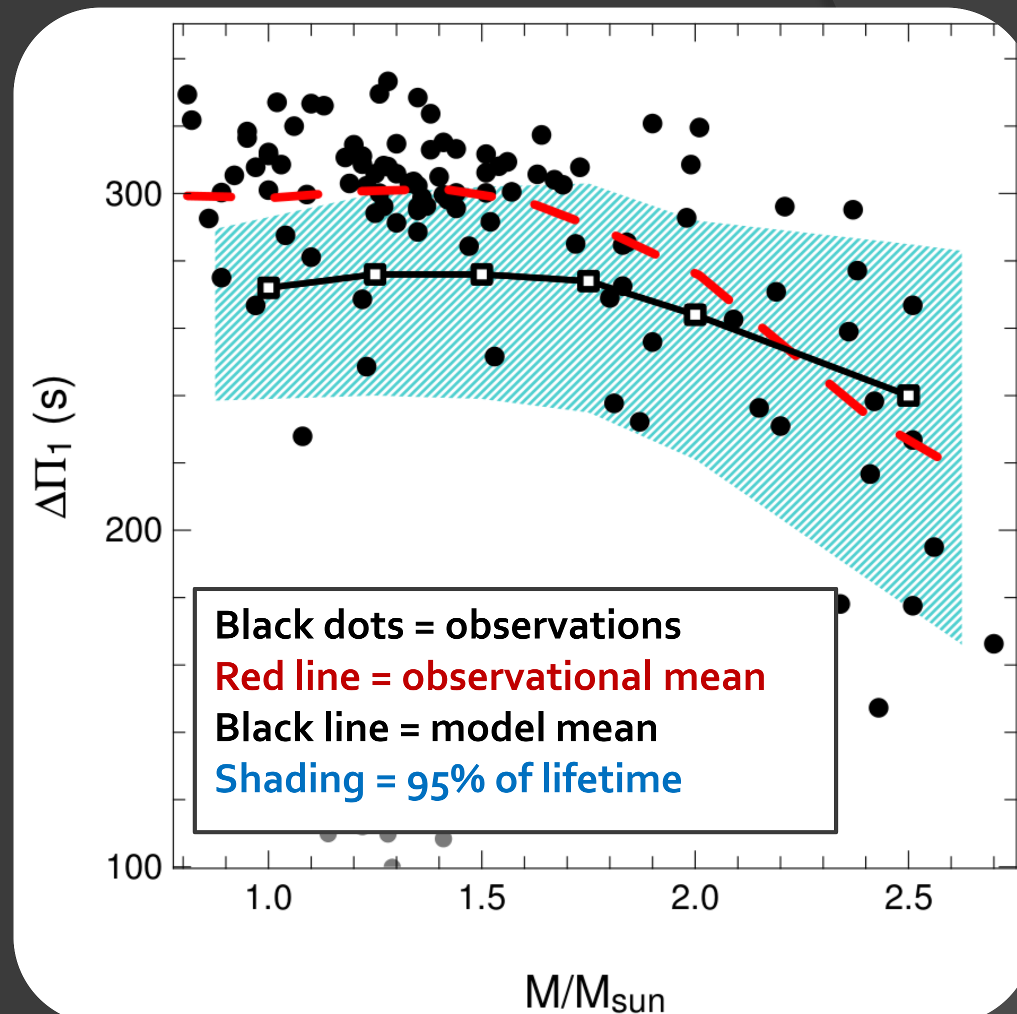
Campbell, D'Orazi, Yong, Constantino et al. 2013, Nature, 498, 198.

Improving the Models II: Asteroseismology of Field CHeB Stars

Asteroseismology = CHeB Problem #3!

- Turns out that 1D models cannot reproduce the recent asteroseismology observations either! (Kepler data, Mosser+ 2012, 2014)
- $\Delta\Pi_1$ = mixed-mode period spacing, gives information on core radius.
- Our PhD student Thomas Constantino is working on this problem:

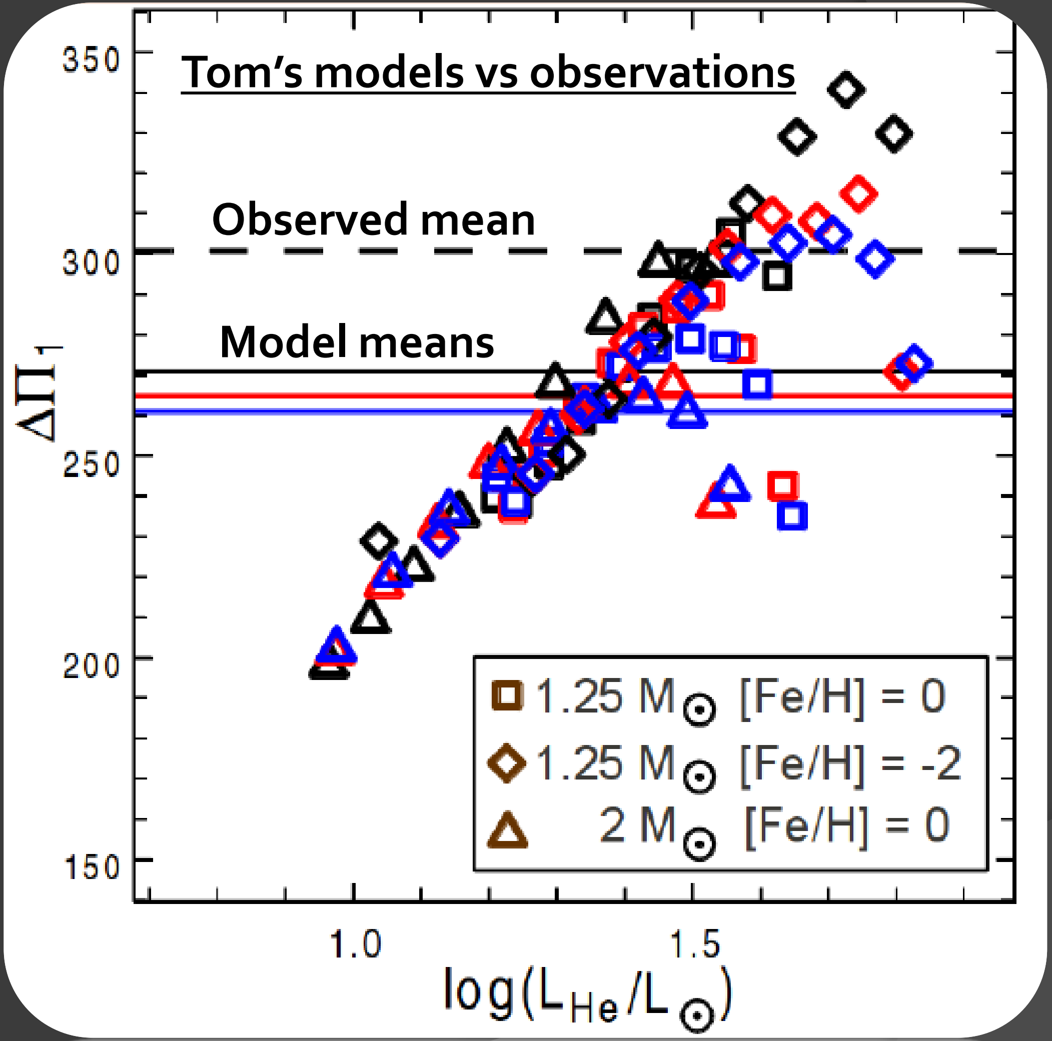




Constantino, Campbell, Christensen-Dalsgaard, Lattanzio, Stello, 2015, submitted.

Asteroseismology = CHeB Problem #3

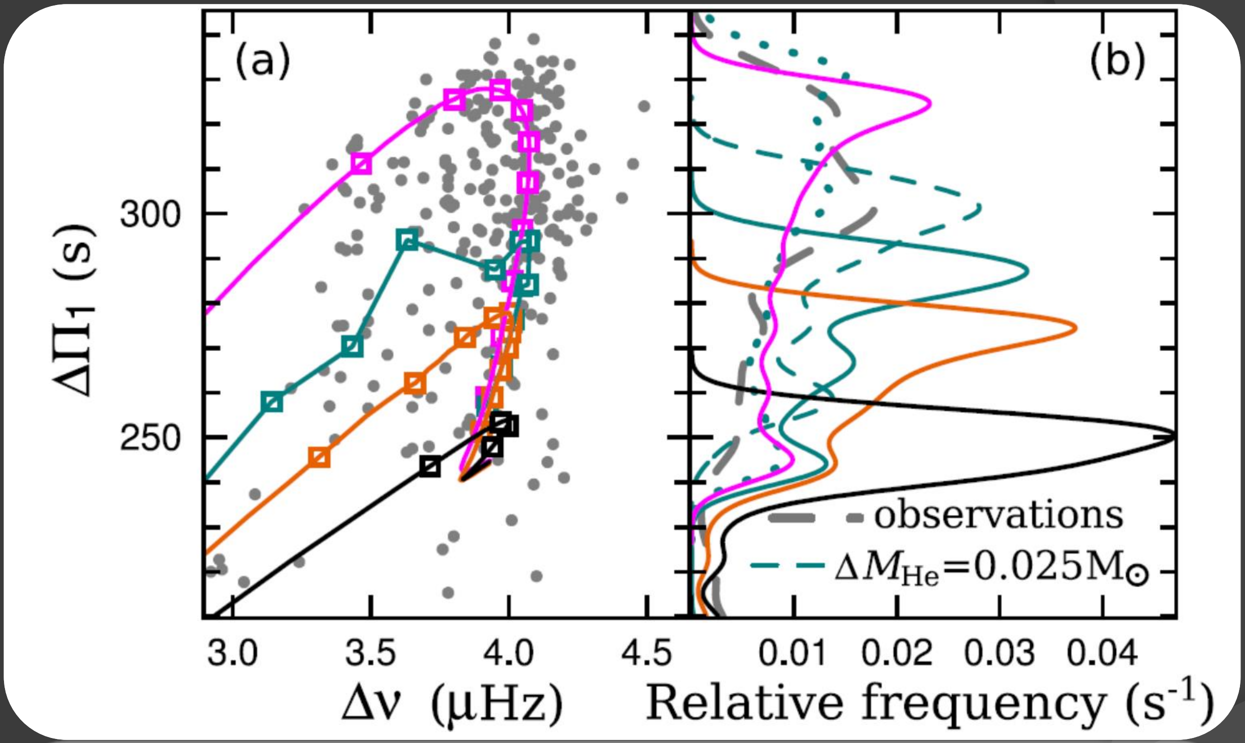
- Each colour represents a model with a different treatment of mixing at convective boundary.
- Can't shift models substantially with standard mixing schemes.



Constantino, Campbell, Christensen-Dalsgaard, Lattanzio, Stello, 2015, submitted.

CHeB Problem #3: Our Findings

- Can match the peak of the $\Delta\Pi_1$ distribution, albeit without a physical basis for such an overshoot scheme ('Maximal Overshoot')
- High $\Delta\Pi_1$ may also be due to assumptions in observationally-determined values (mode trapping)
- All models predict too many stars at low $\Delta\Pi_1$
- Biases in sample could be behind problem(s)?
- To the observers: We really need to know sample biases to make strong conclusions on stellar structure.

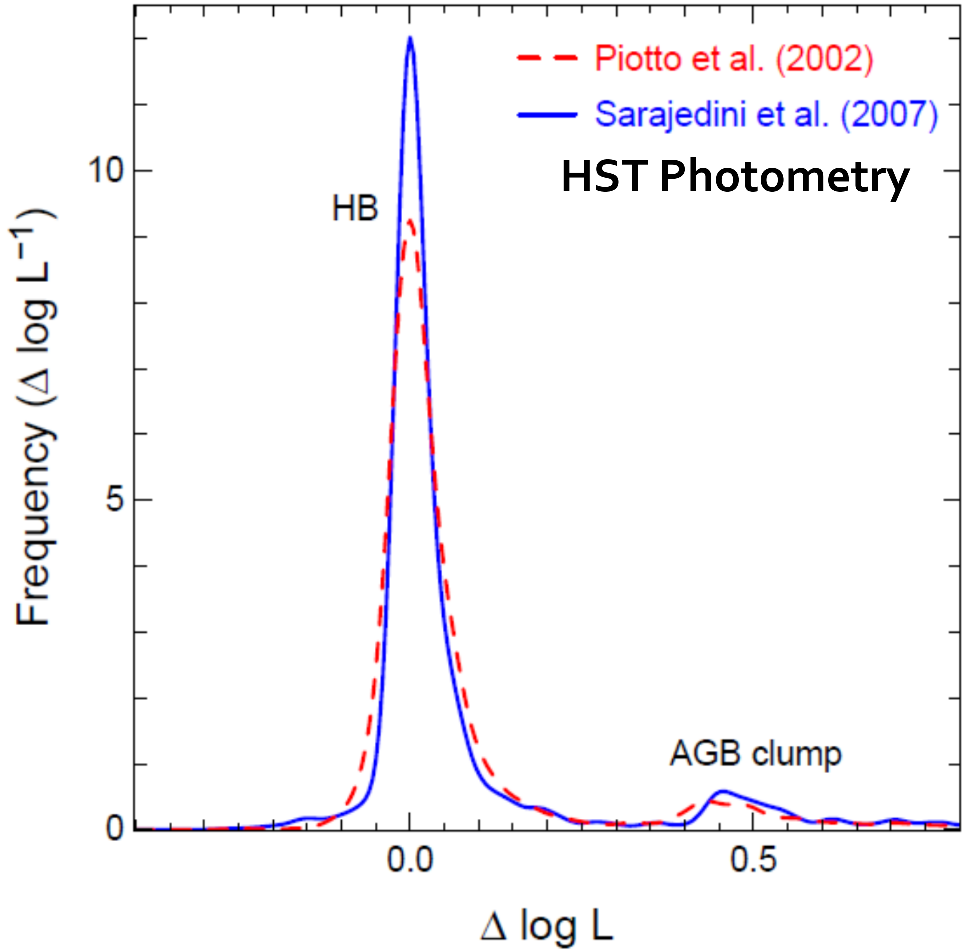


Constantino, Campbell, Christensen-Dalsgaard, Lattanzio, Stello, 2015, submitted.

Improving the Models III: Photometry of GC Stars

Photometry of GCs 1: CHeB/EAGB Luminosity Function

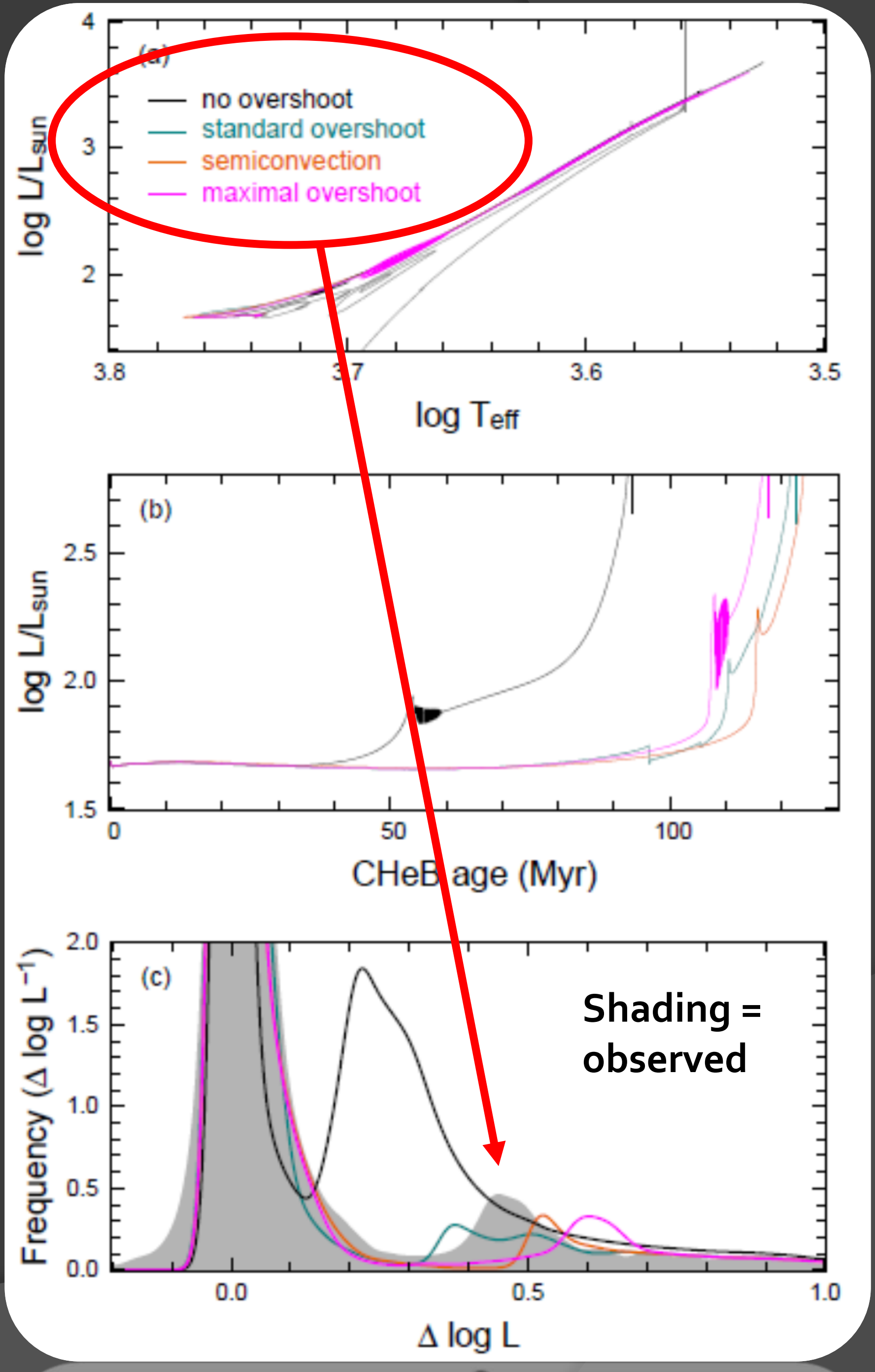
- Average luminosity distribution for 13 GCs that do not have an extreme blue extension of HB.
- Remarkably sharp peaks given that this is a mix of GCs and that there is a range of observational that would widen the peaks.
- Puts strong constraints on the models!



Constantino, Campbell, Lattanzio, 2015, in prep.

Photometry of GCs = CHeB Problem #4!!

- 4 different mixing schemes tested.
- None can match the Luminosity distribution function of the EAGB.
- Can definitely rule out 'hard' Schwarzschild boundary (or Ledoux).

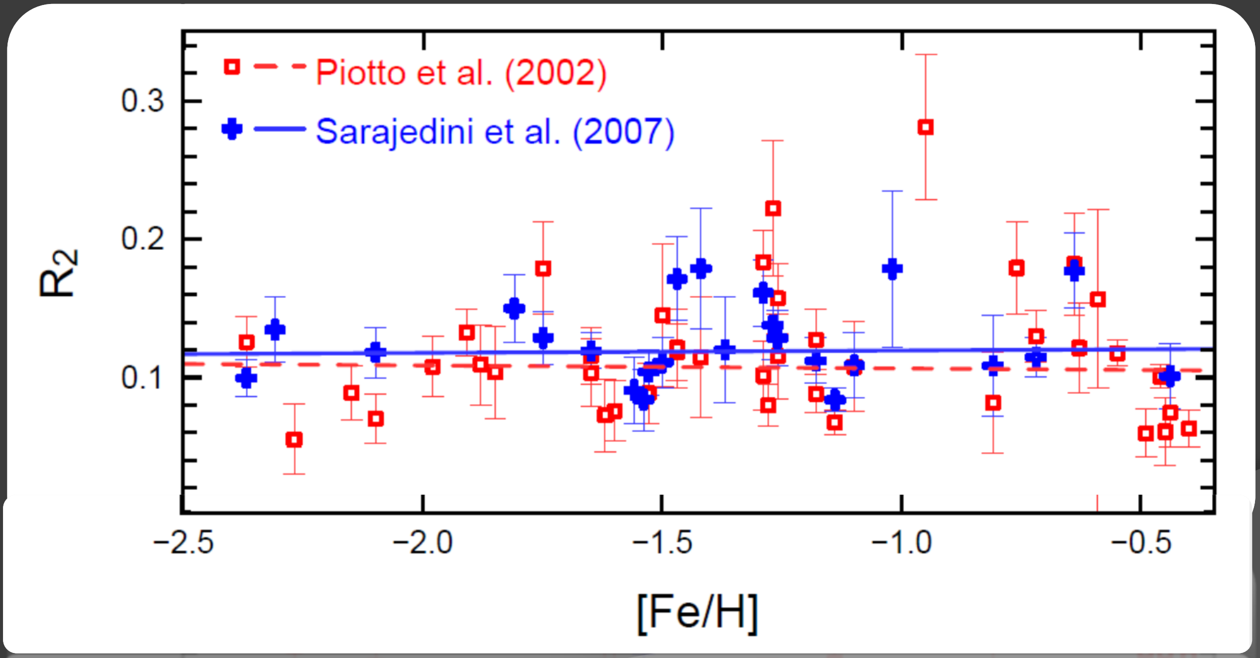


Constantino, Campbell, Lattanzio, 2015, in prep.

Photometry of GCs 2: Relative Lifetimes from Star counts

- $R2 = N_{AGB}/N_{HB} = t_{AGB}/t_{HB}$
- Using HST data of 48 GCs we find that R2 = 0.118 +- 0.005 (substantially lower than typical previous determinations, consistent with a single value)
- This value appears to be more consistent with (certain) models in literature.
- Scatter in R2 is probably mainly driven by finite sampling statistics (few AGBs..)

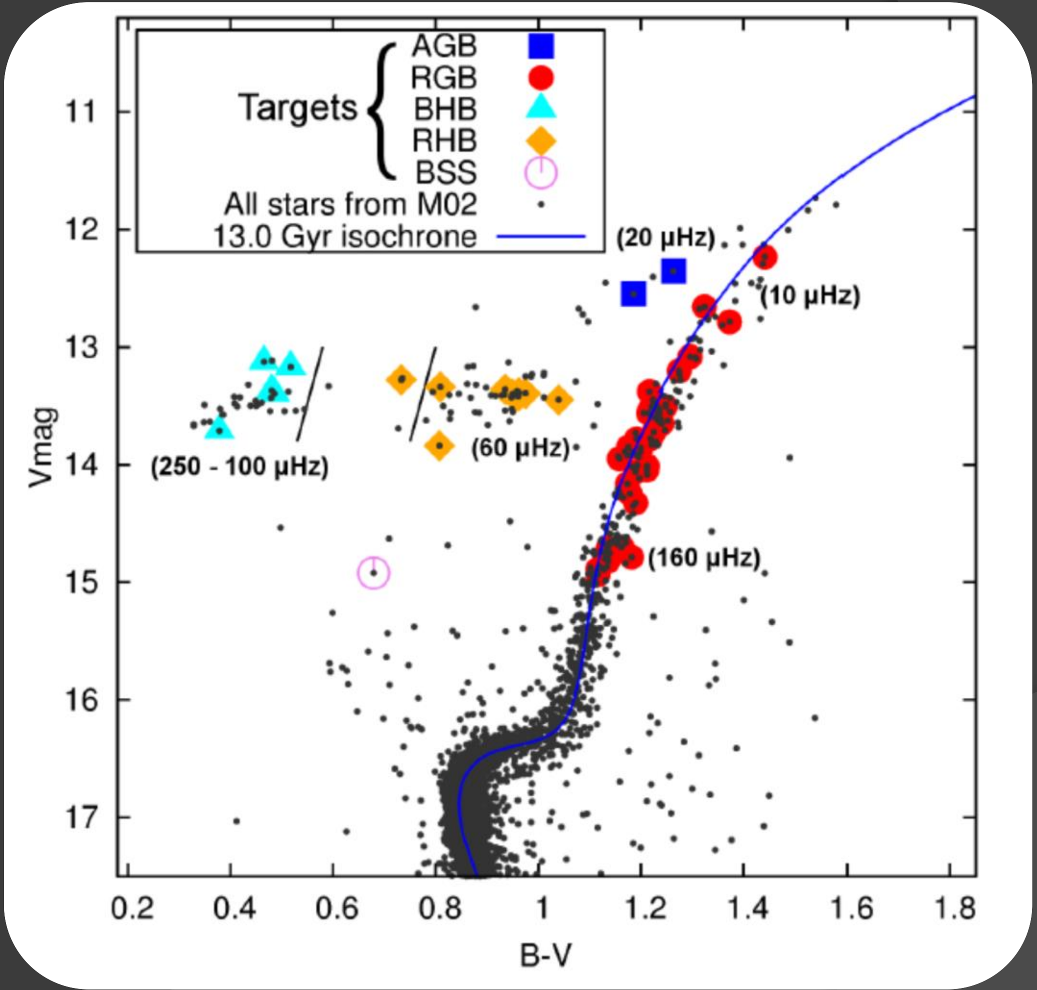
However the models with correct R2 do not match the other constraints…!!



Constantino, Campbell, Lattanzio, 2015, in prep.

Coming Soon: Combining Photometry, Spectroscopy & Asteroseismology in a Globular Cluster!

- A unique opportunity
- + HERMES spectra
  + K2 Asteroseismology
  + Wide field Photometry



Campbell, Kuehn, Stello, 2015, in prep.

IMPROVING THE MODELS IV: 3D SIMULATIONS OF STELLAR INTERIORS

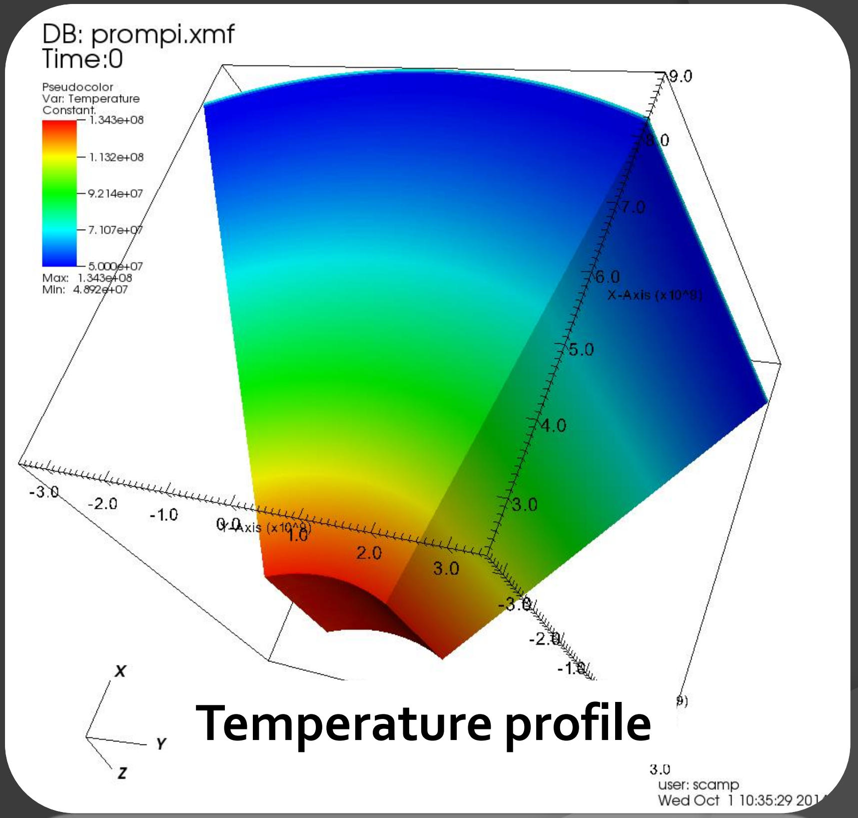
Mental note for jetlagged brain:
If running short on time, skip most of this :)

3D Stellar Interior Simulations

- The details of the 1D problems with CHeB are related to the treatment of convection and convective boundaries – both crudely modelled in 1D at the moment.
- We are now working on these problems using 3D hydrodynamics.
- 3D models are still hugely computationally expensive but we can now simulate a few convective turnover times at reasonable resolution.
- 3D models of short timeframes can give physical insight into these regions.
- **This new knowledge can then be used in the 1D models which are still necessary for simulating the whole lifetime of a star.**

3D Stars: Wedge Simulations

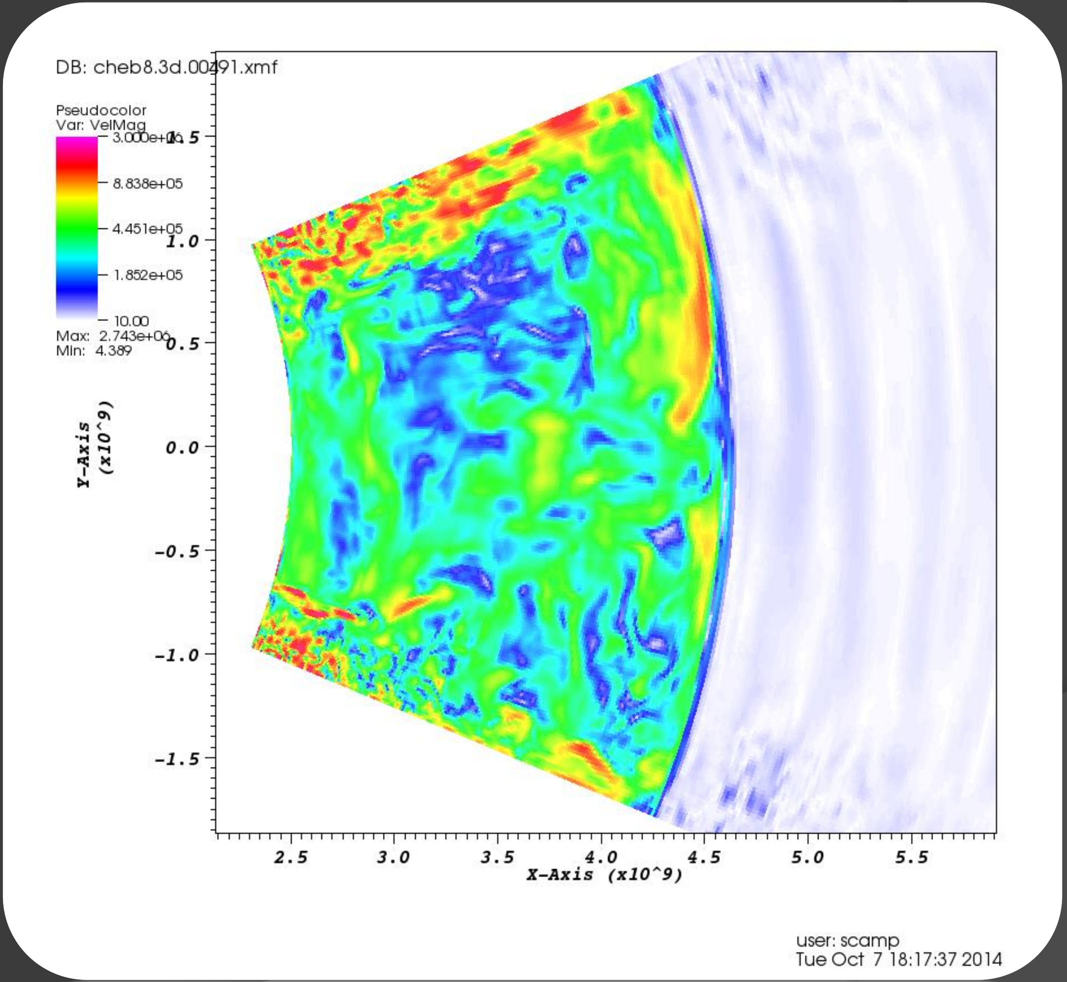
- Stellar Hydro Code:
  - PROMPI (Meakin & Arnett 2007, 2008) is a parallel version of the Prometheus code (Fryxell, Arnett & Muller 1991), related to FLASH.
  - PPM hydro code
  - Nuclear network
  - Timmes & Swesty EOS
  - OPAL opacity



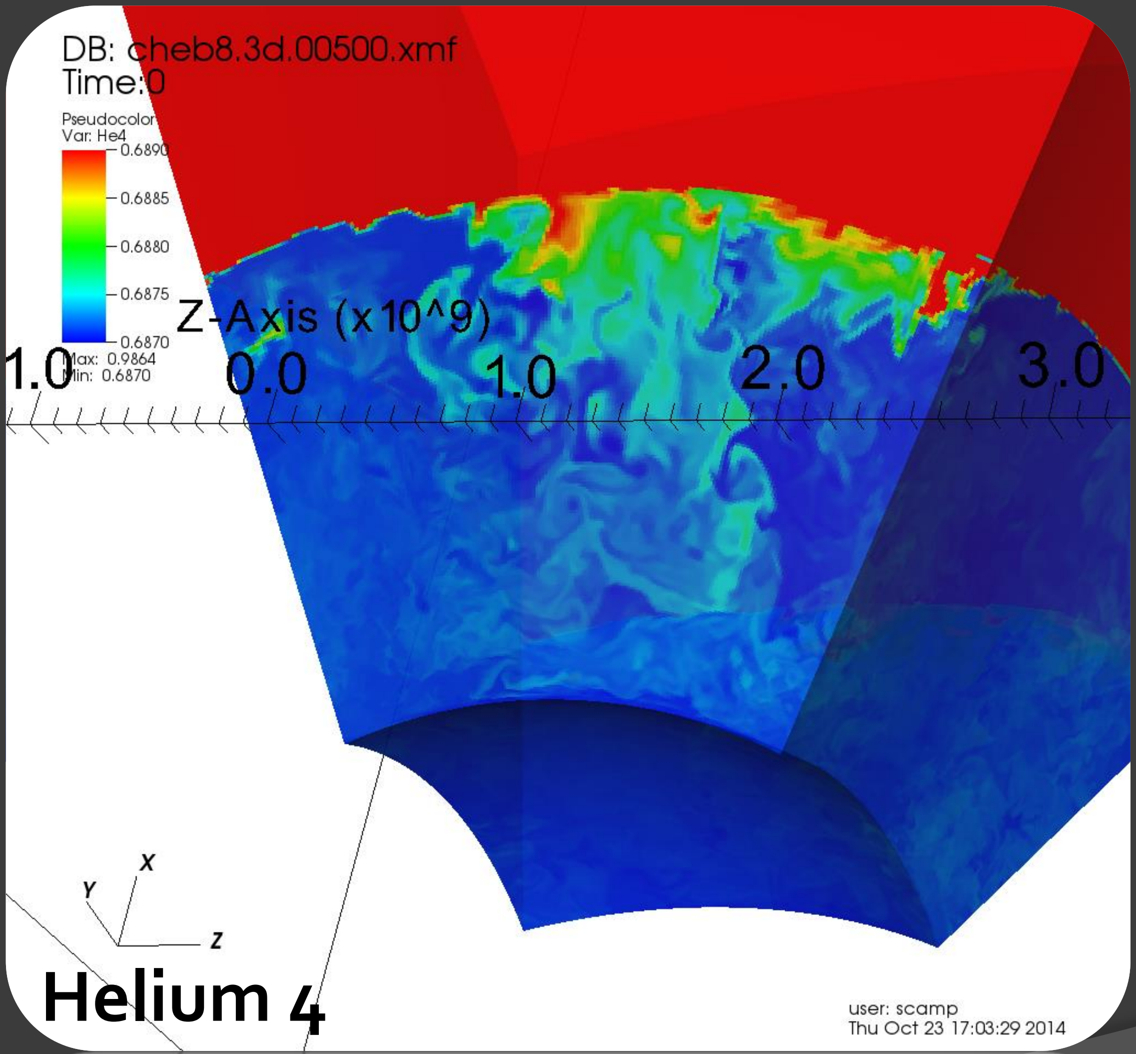
Temperature profile

3D Stellar Interiors: 2D Slice Movie

- Colours shows magnitude of velocity (red > yellow > blue)
- 5 turn-over times
- Note gravity waves in stable region above convective core.

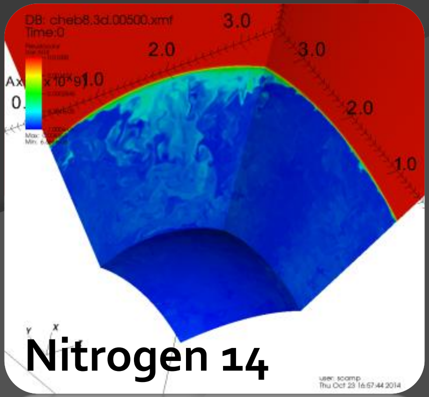


Helium Entrainment!



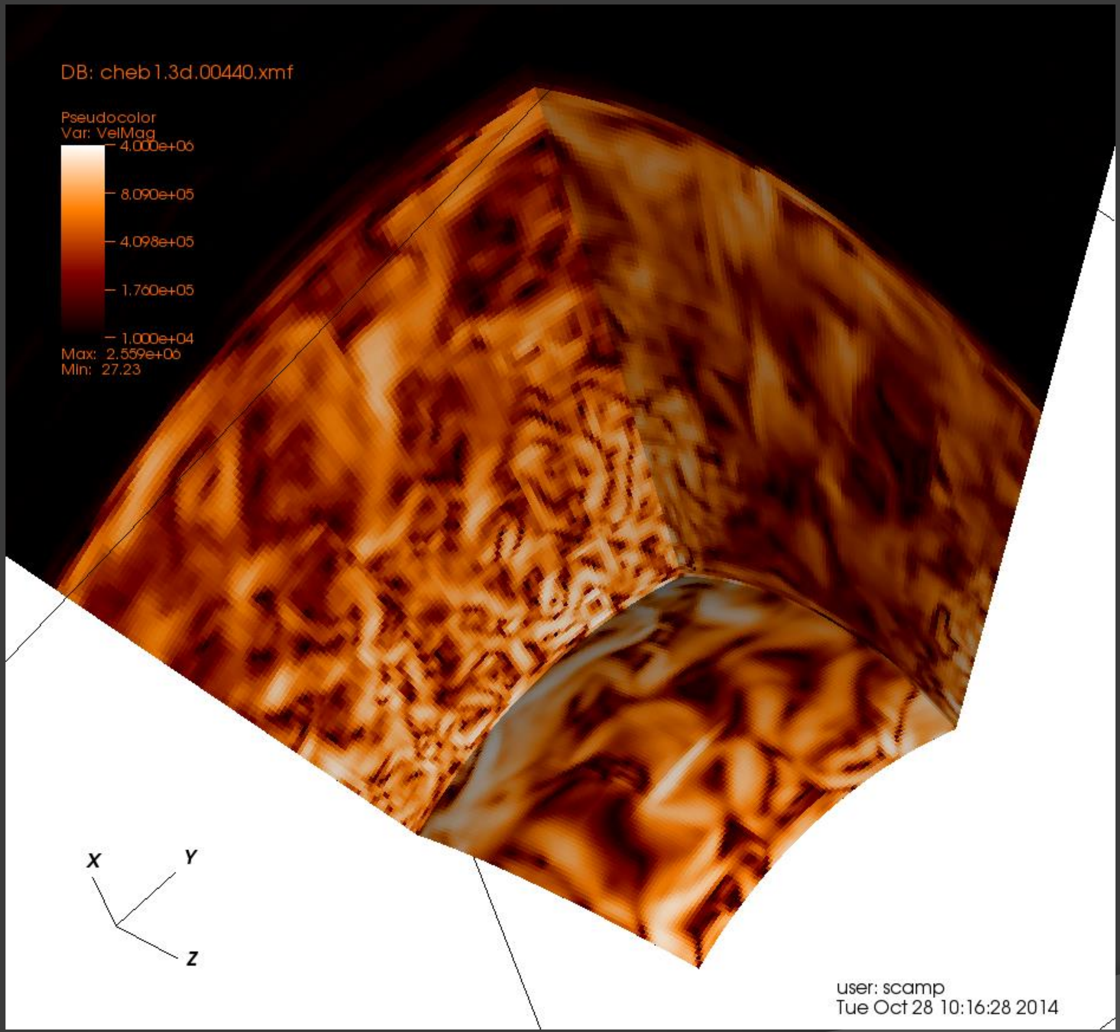
Helium 4

- Answer to previous question = not a stable configuration, at least for this low-resolution simulation.
- Helium mixed down, will burn in convective core and extend CHeB lifetime.



Nitrogen 14

Stop Press:
Sun during CHeB in 3D

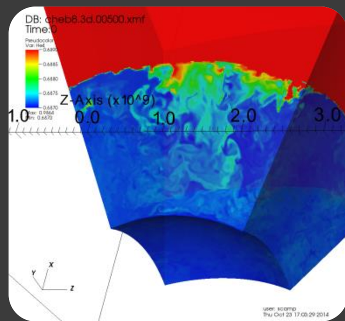


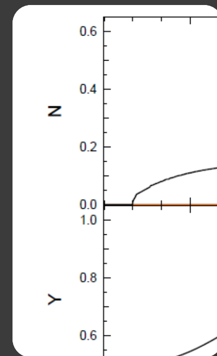
- Very low resolution, but proof of concept simulation.
- Boundary issues more extreme at this mass.

Summary

- Vital to model stars well!
- Achtung!: Be careful of results from stellar codes if you use them as input for your Galactic modelling – particularly if they involve late stages of evolution. This includes stellar chemical yields.
- At least 4 different problems identified for core He burning stars
- Ways to advance stellar evolution modelling:
  - Combine observational constraints from star clusters (photometry, star counts, spectroscopy) with asteroseismology observations that give information on interiors.
  - Initial work is revealing that:
    1. *It is very difficult to simultaneously match multiple observational constraints*.
    2. *Biases in observational samples need to be reported so we can use the data to constrain models.*
- Ongoing Work:
  - Use 3D hydrodynamical simulations of stars to pin down the key physics in convection zones and, vitally, at convective boundaries
  - Combine the excellent stellar test bed of globular clusters with asteroseismology (+ chemical tagging, photometry).

The End :)





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