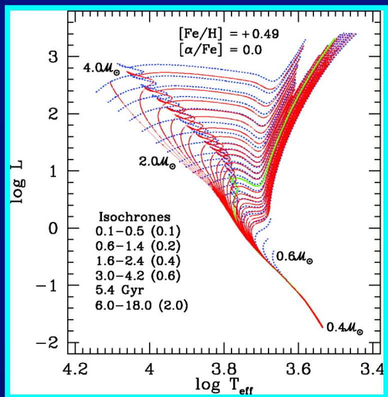
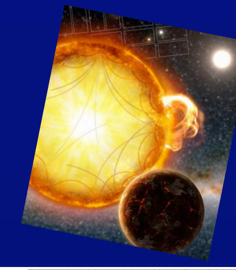
The new challenges for Stellar Evolution

Santi Cassisi

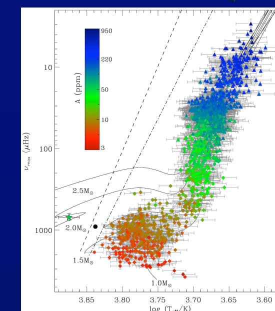
INAF - Astronomical Observatory of Teramo, Italy

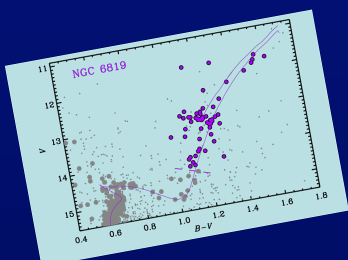
A crucial "tool" for studying:

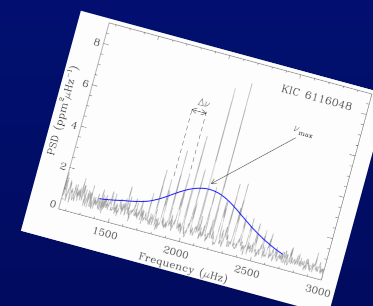


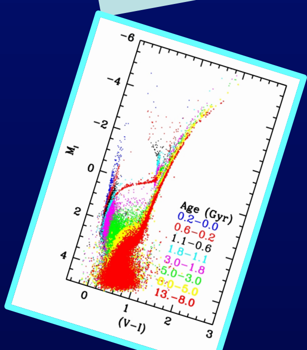


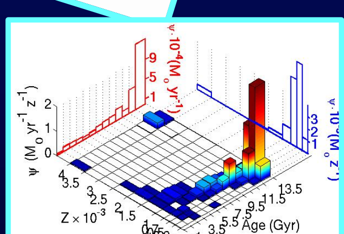
- ✓ Resolved stellar populations…
  - ➢ Galactic field stars;
  - ➢ Asteroseismology;
  - ➢ Exoplanet science…;
  - ➢ Star clusters;
  - ➢ Chemical abundances;
  - ➢ Stellar pulsations;
  - ➢ SN progenitors;
  - ➢ Galactic archeology;
  - ➢ Stellar populations in Local Group galaxies;

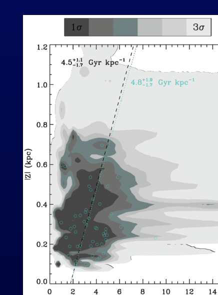












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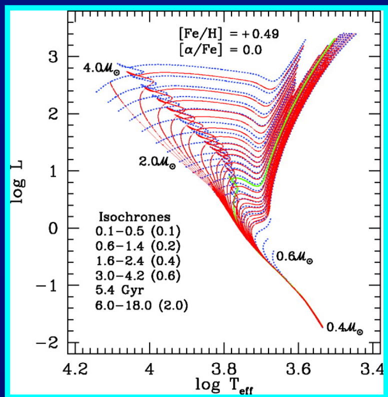

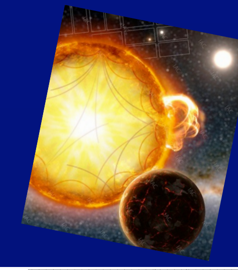

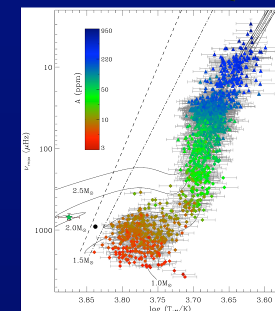

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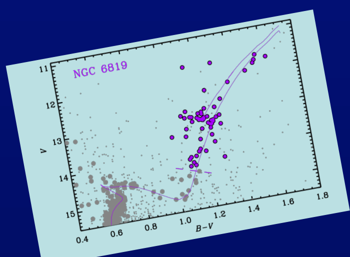
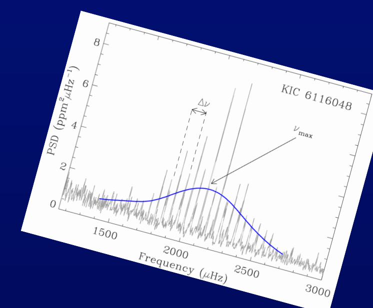
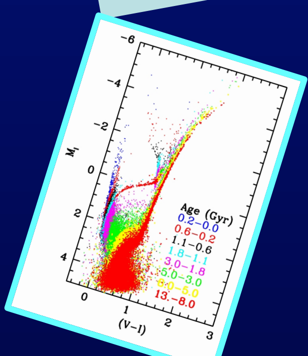
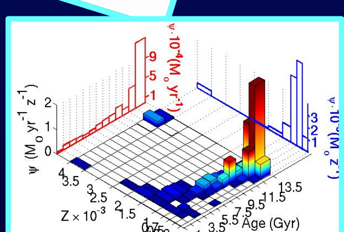
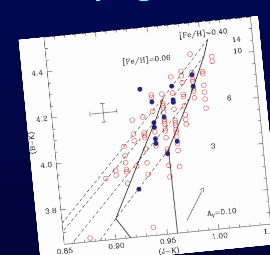


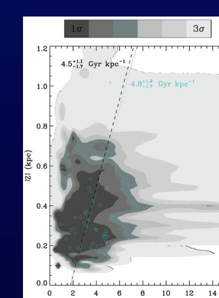






- ✓ Unresolved stellar populations…





Stellar Evolution: the "ingredients"

An evolutionary code

- Numerics
- Boundary conditions
- 1D versus 3D

Physical inputs

- Equation of State
- Radiative opacity
- Conductive opacity
- Nuclear reaction rates
- Neutrino energy losses

Mixing treatment

- Overshooting
- Superadiabatic convection
- Non-canonical processes

Microscopic mechanism

- Atomic diffusion
- Radiative levitation

Additional mechanism

- Mass loss
- Rotation
- Magnetic field
- Internal Gravity waves

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"Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden beneath substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?"

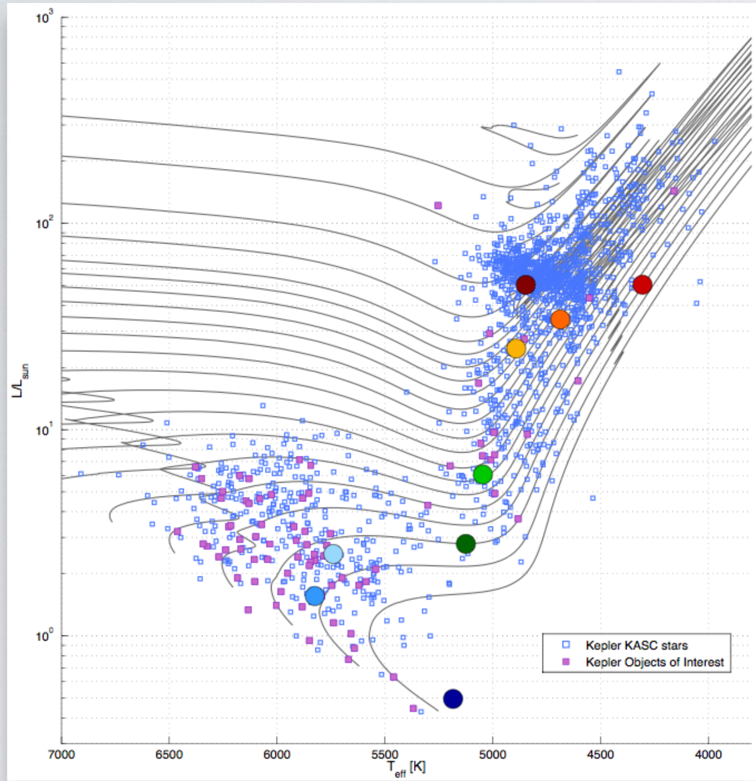
A. S. Eddington, 'The internal constitution of Stars', 1926, "Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden beneath substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?"

A. S. Eddington, 'The internal constitution of Stars', 1926,

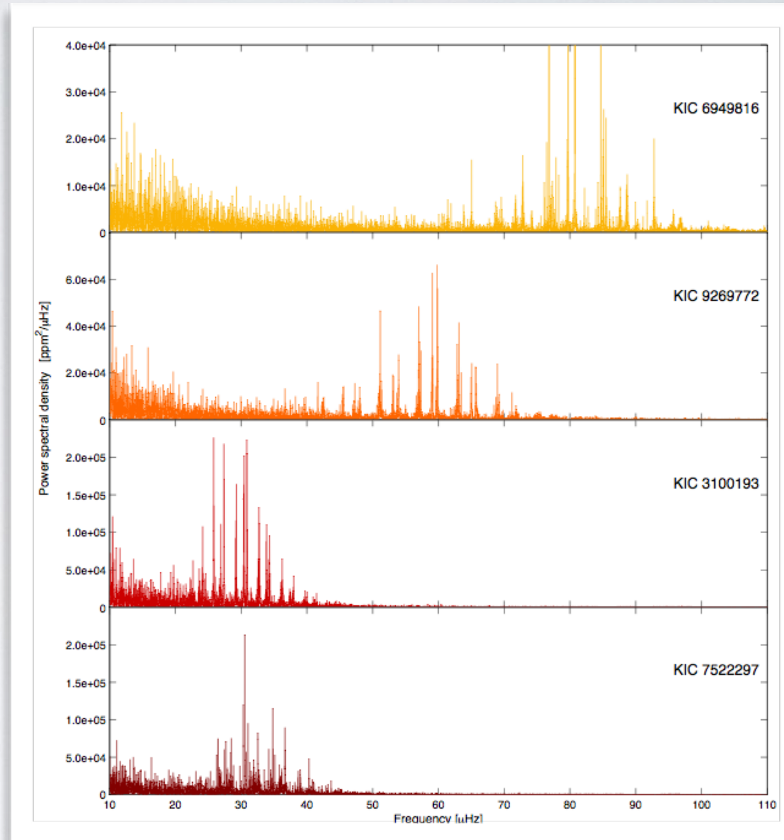
What can we do to overcome this?

Asteroseismology

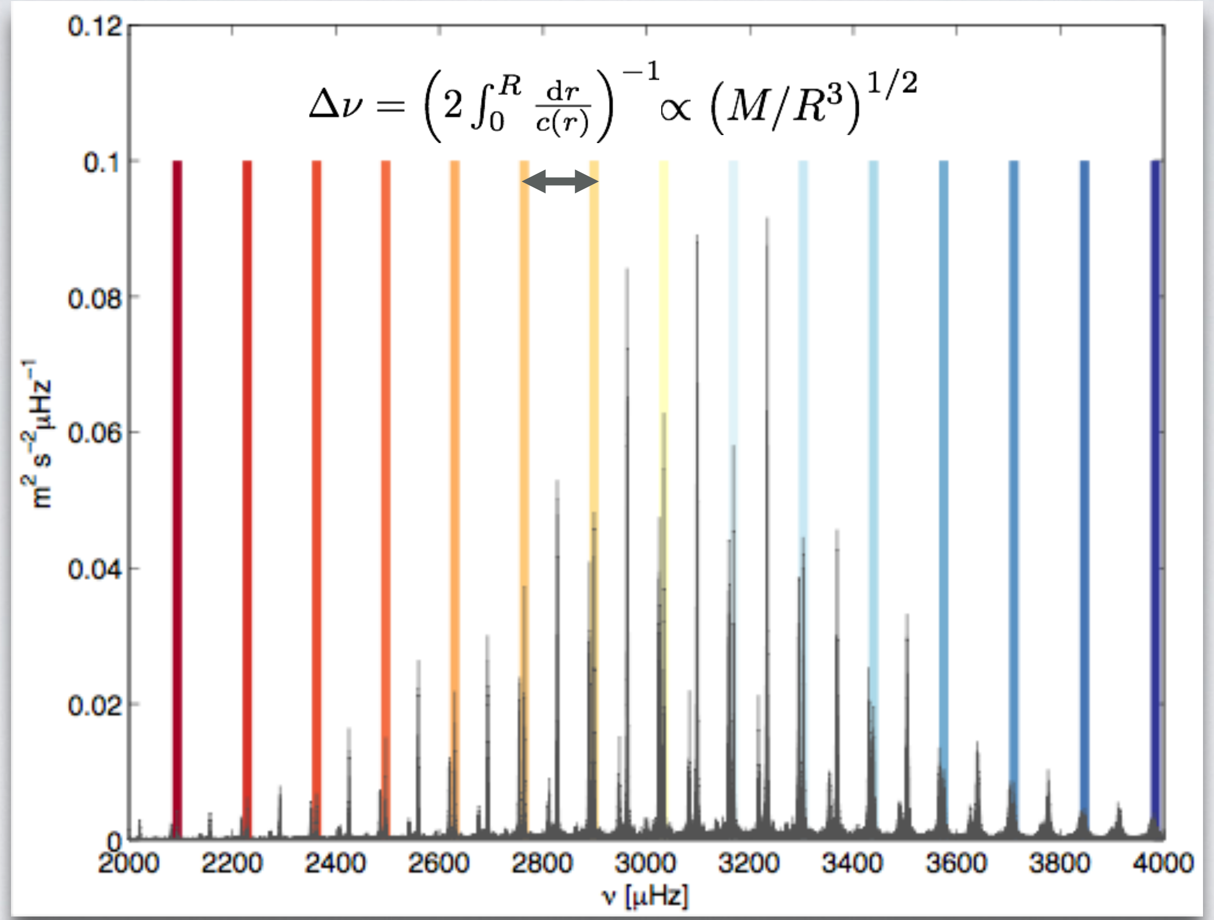
THE SPACE PHOTOMETRY REVOLUTION



Chaplin & Miglio, ARAA, 2013

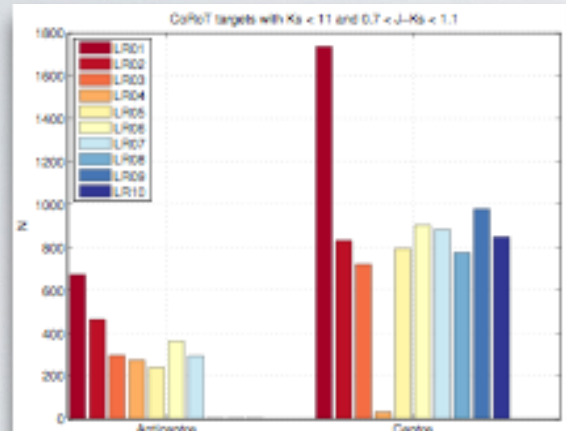


Solar-like Oscillations

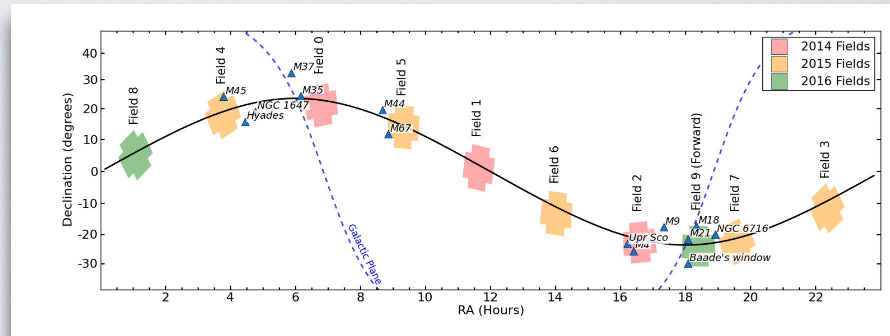


Harvesting Data for Seismology

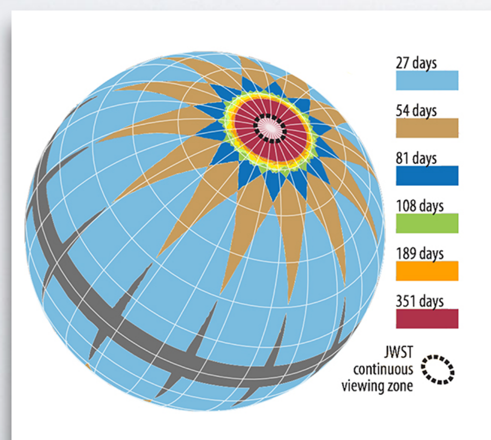
CoRoT

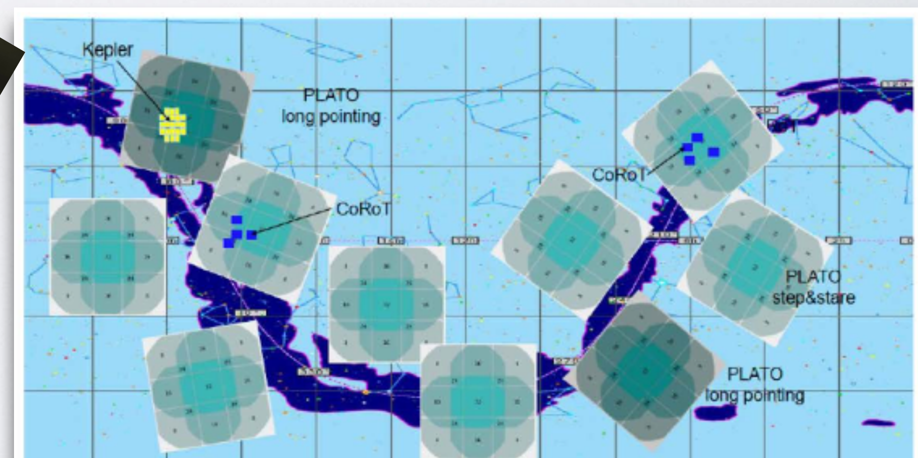


K2



TESS





PLATO

PLATO ⇄ Stellar Evolution

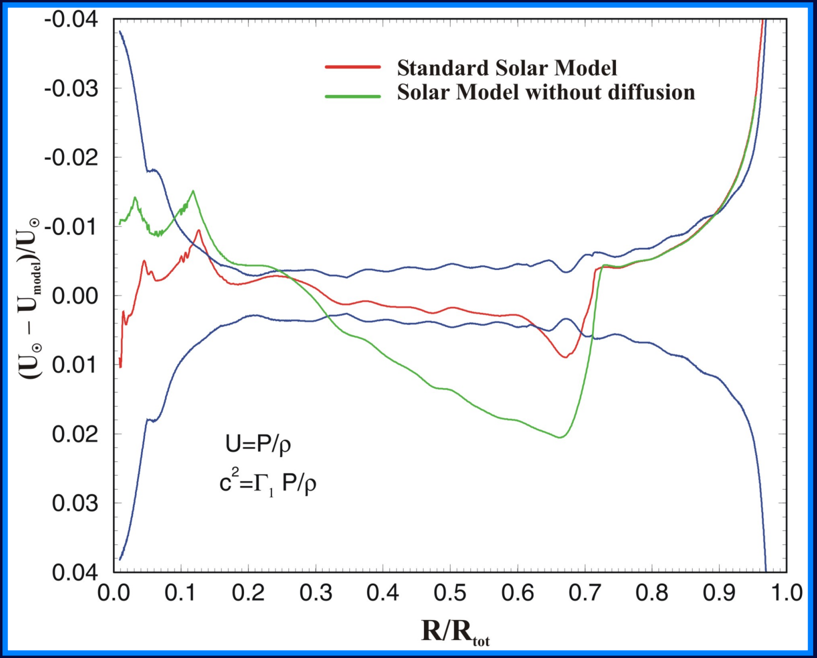
The main focus of the PLATO asteroseismology program will be to support exoplanet science by providing:

- ✓ stellar masses with an accuracy of better than 10%;
- ✓ stellar radii to 1-2%;
- ✓ stellar ages to 10% accuracy; → what is the current uncertainty?

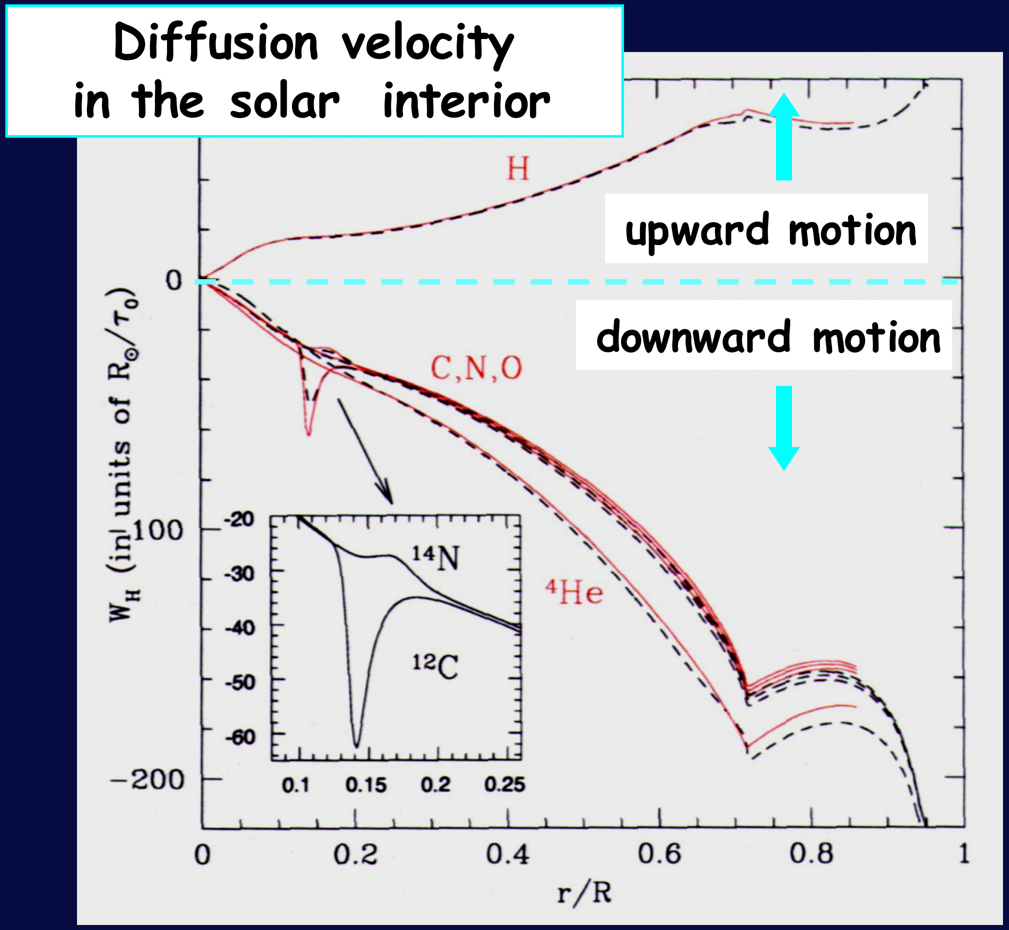
The PLATO mission will provide the observational framework in order to:

- ✓improve understanding of stellar structure/physics;
- ✓identify "missing physics";
- ✓improve our knowledge on stellar evolution;

Atomic diffusion: to be or not to be … at work ?



Helioseismological constraints strongly support the efficiency of this process



More sophisticated models…

A theoretical evidence:

radiative accelerations can be up to 40% of gravity below the solar convection zone… for metal-poor stars, their value should be larger…

Observational suggestions:

Slow extra-mixing at the bottom of convective envelope would improve the agreement concerning:

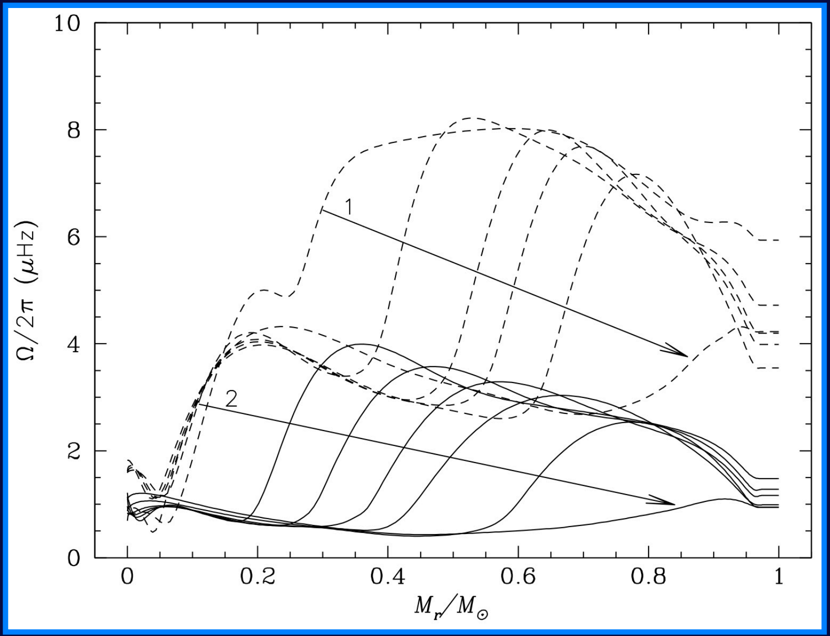
- the observed abundances of Be and Li in the Sun;
- predicted sound speed profile and that derived by helioseismological data…;
- spectroscopical measurements in Globular Cluster Stars;

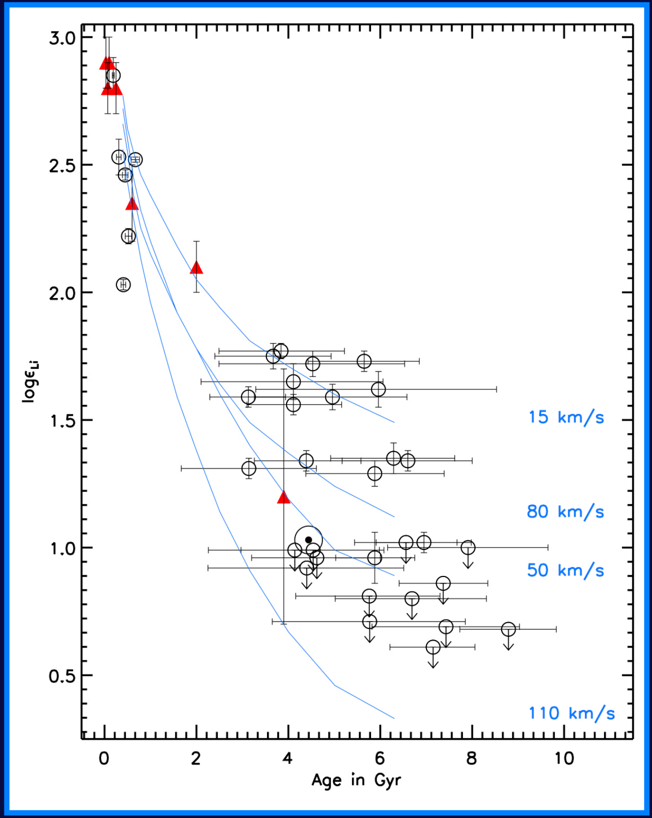
It is necessary to account for
atomic diffusion + radiative levitation + extra-mixing!

Who is responsible for this non-canonical mixing?

Non-canonical "transport mechanisms"

- rotational induced mixings;
- internal gravity waves;





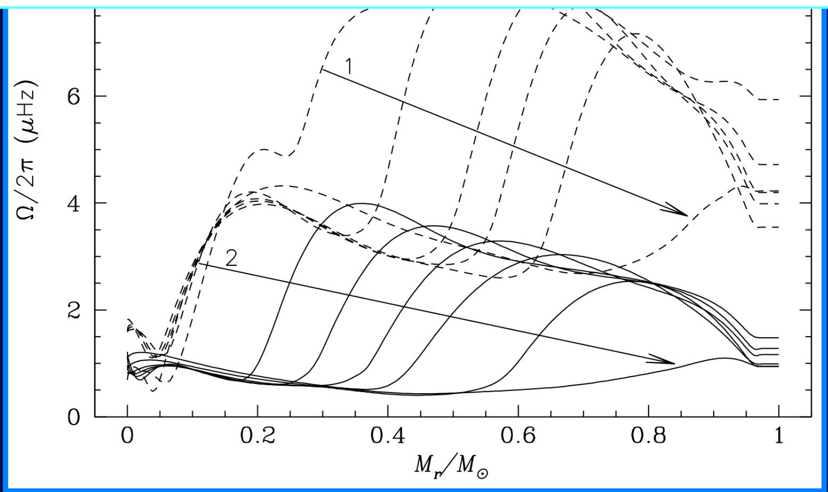
These processes to be included in stellar models require the calibration of free parameters that are poorly constrained by "standard" observations

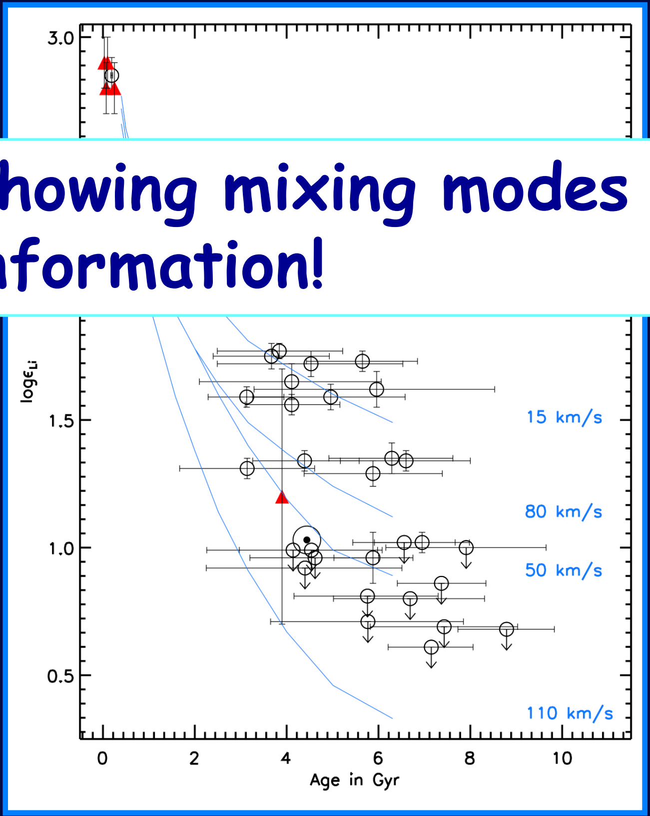
Since rotational mixings affect not only chemicals but also the angular momentum distribution… to retrieve information about internal rotation profiles is mandatory!

Non-canonical "transport mechanisms"

- rotational induced mixings;
- internal gravity waves;

Asteroseismology of stars showing mixing modes can provide this information!





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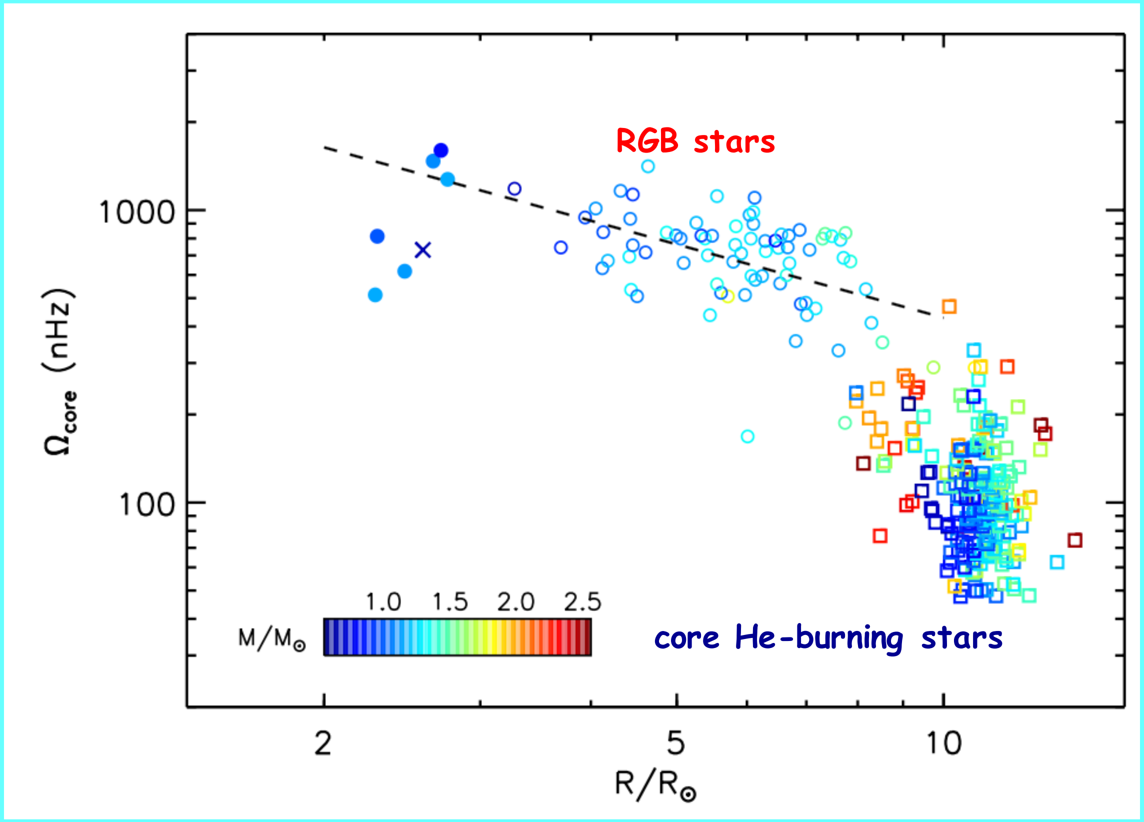
Asteroseismic constraints from observations of RG Stars

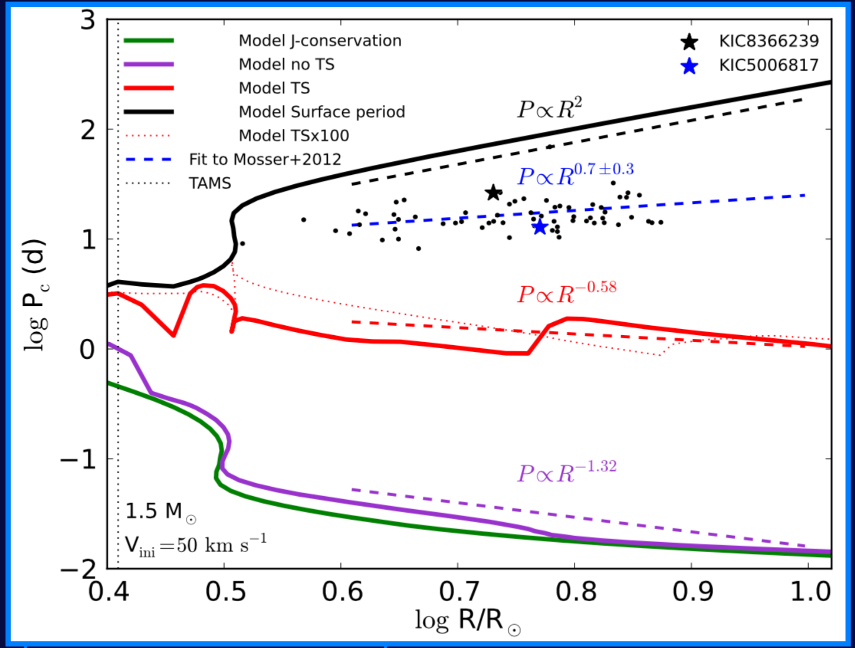
The measurement with KEPLER of the core rotation rates for hundreds of red giants is allowing an unprecedented view in the internal rotation evolution of evolved stars.



Mosser et al. (2013) - Deheuvels et al. (2014)

the inferred rotation periods are 10 - 30 days for ≈ $0.2M_\odot$ He degenerate cores on the RGB and 30 - 100 days for core He-burning stars

The state-of-the-art of theoretical modelling



Cantiello et al. (2014)

Some evidences:

- the envelope slows down as expected due to expansion and AM conservation;
- the core rotates about 10 – 10^3 times faster than the values inferred by asteroseismology;
- the trend of the core rotational rate with the radius is reversed with respect the observed ones;

the amount of torque between the core and envelope is underestimated by RGB stellar models

A query for non canonical physical mechanisms: hot topics

✓ Internal gravity waves

- IGWs could be excited by the convective envelope during the RGB;
- the details of their excitations and propagations are very poorly understood…;

✓ Large scale magnetic field

- if a magnetic field is present at the boundary of He core at the end of the MS stage, it could provide some coupling between core and envelope;
- what is its origin? fossil origin? generated by a convective dynamo during the central H-burning stage? Interaction convection-magnetic field?;

✓ Mass loss along the RGB

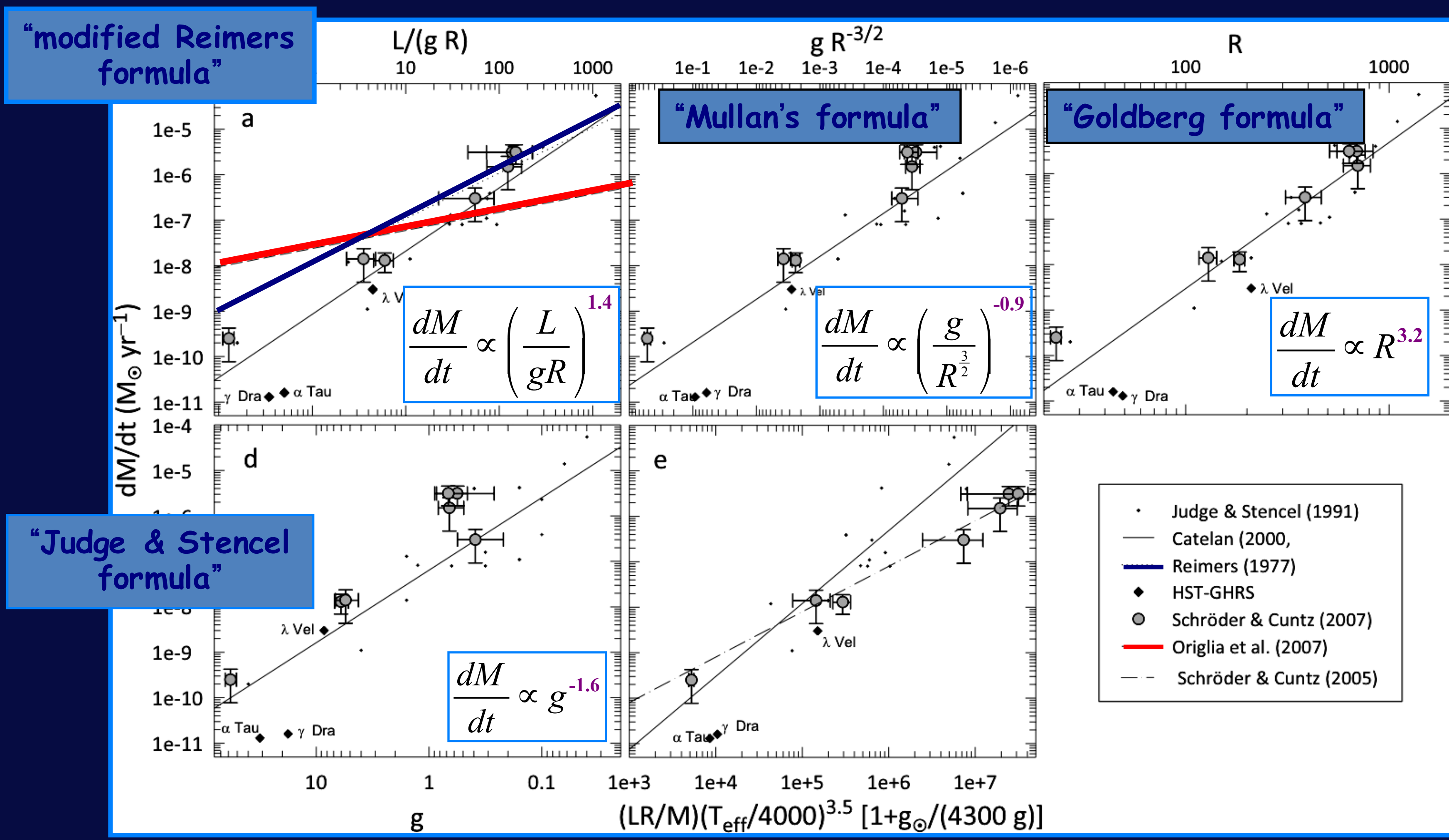
- Mass loss can significantly reduce the total mass and contribute to remove angular momentum;
- a still poorly understood physical mechanisms…;

The bulk of asteroseismic data refers to field stars…

Can we obtain reliable constraints from cluster stars?

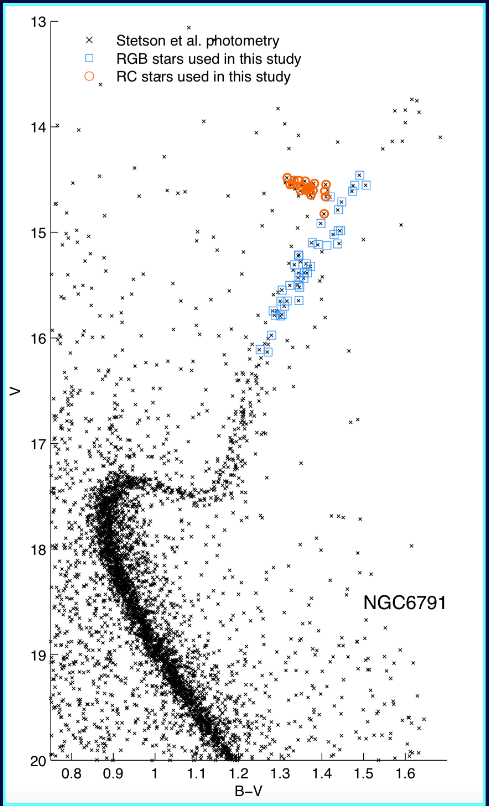
The KEPLER's lesson…

Can we still rely on Reimers' "law"?

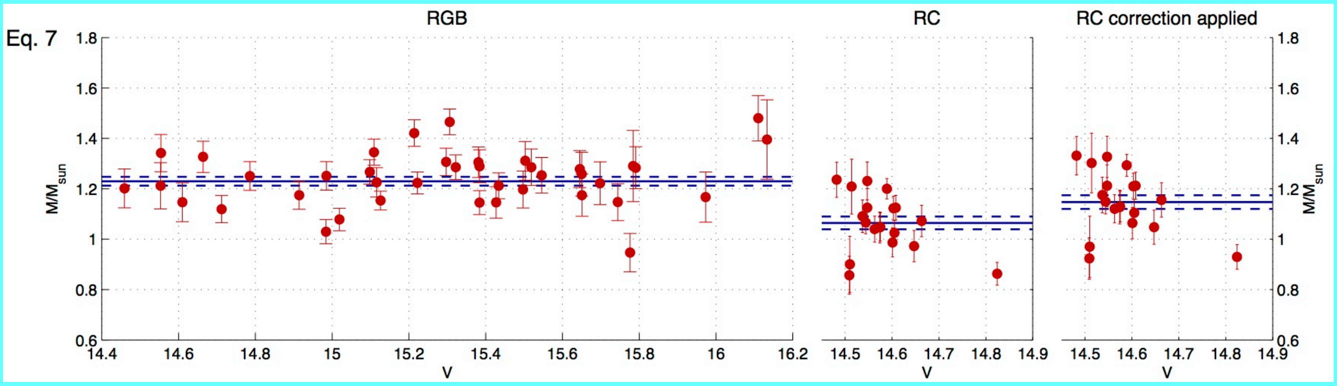


Reimers' law is rejected at the 3σ level…
but we can't distinguish among the alternatives!

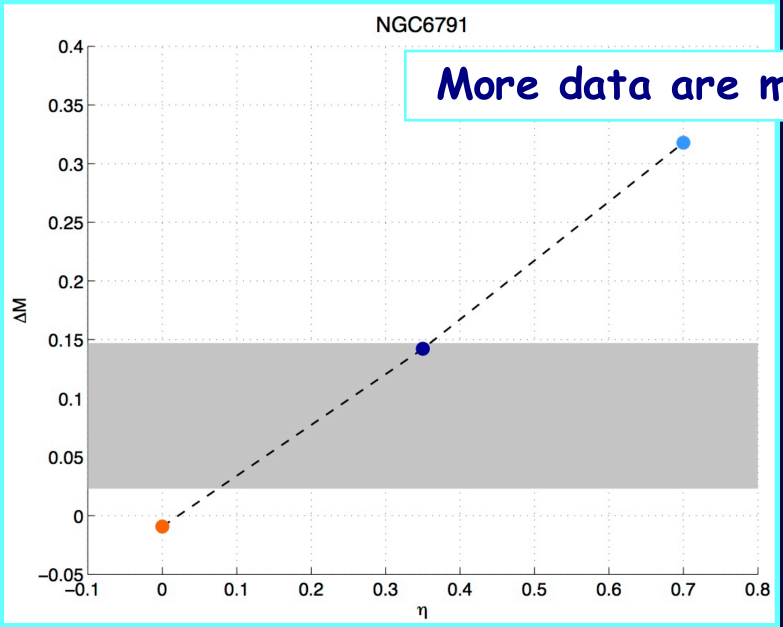
RGB mass loss & Asteroseismology



Miglio et al. (2012)



< ΔM>/$M_{\odot}$=0.09±0.03 (random) ± 0.04 (systematic)

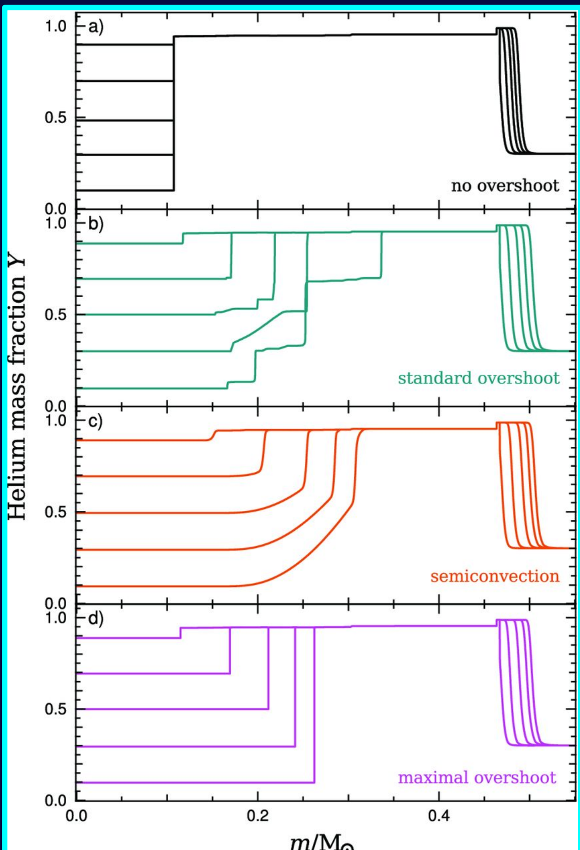


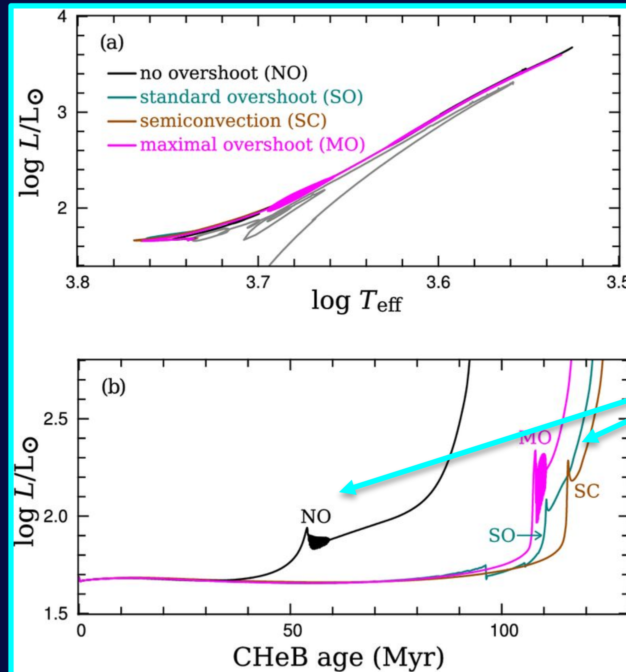
More data are mandatory!

PLATO could lead to a major progress in this area!!!

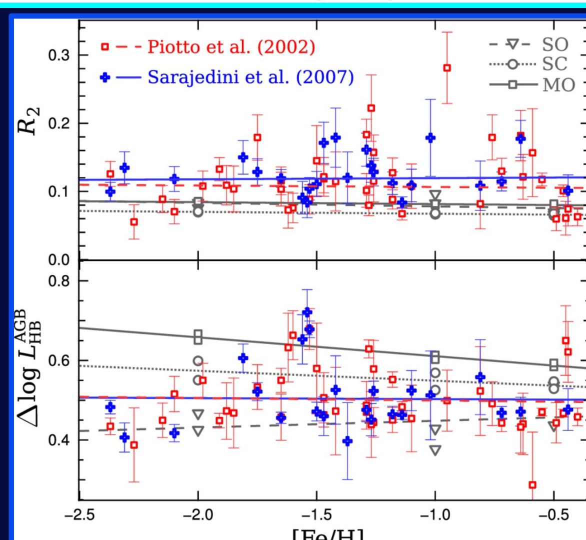
Core Mixing in He-burning stars

Mixing schemes





AGB clump

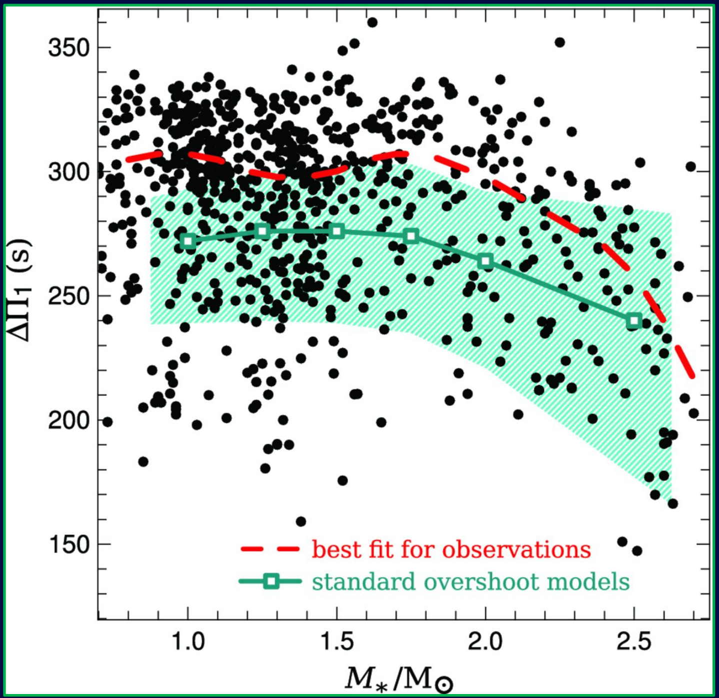


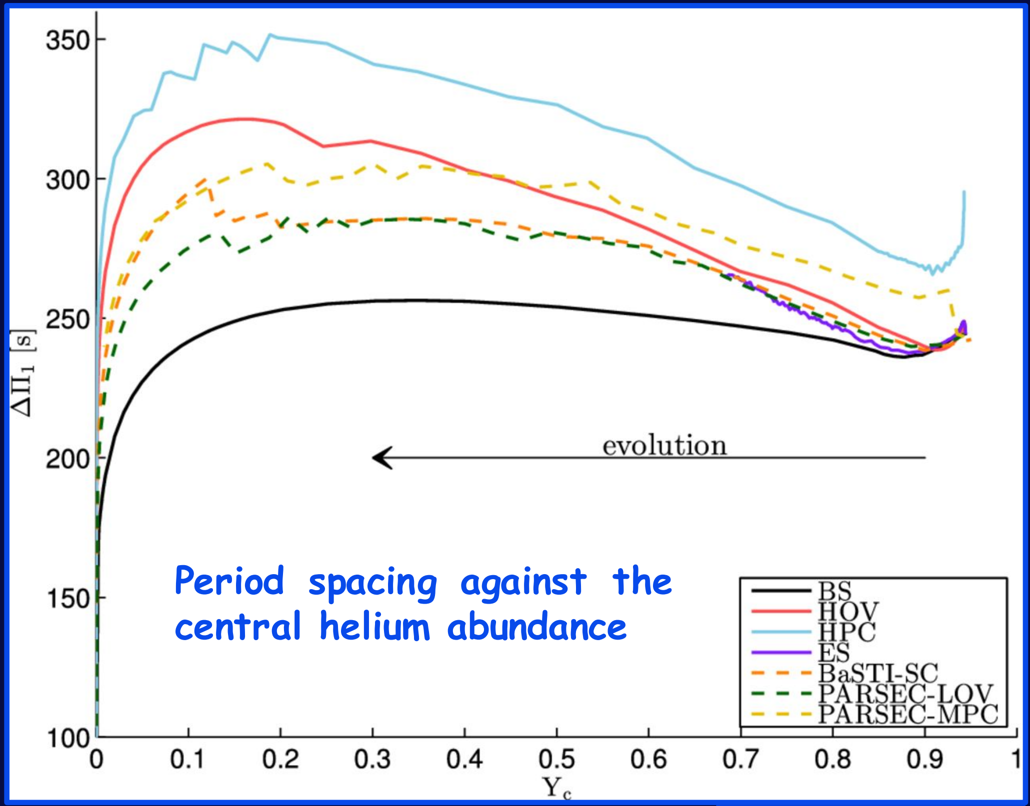
Constantino et al. (2016)

Unconclusive… due to:

- Uncertainty in the (^{12}C + α) rate;
- Breathing pulses suppression method;

A new approach for constraining core mixing efficiency during the central He-burning stage





Bossini et al. (2015)

Preliminary results suggest that asteroseismological constraints can be better reproduced when accounting for a mixed region slightly larger than that predicted by "standard" semiconvective models

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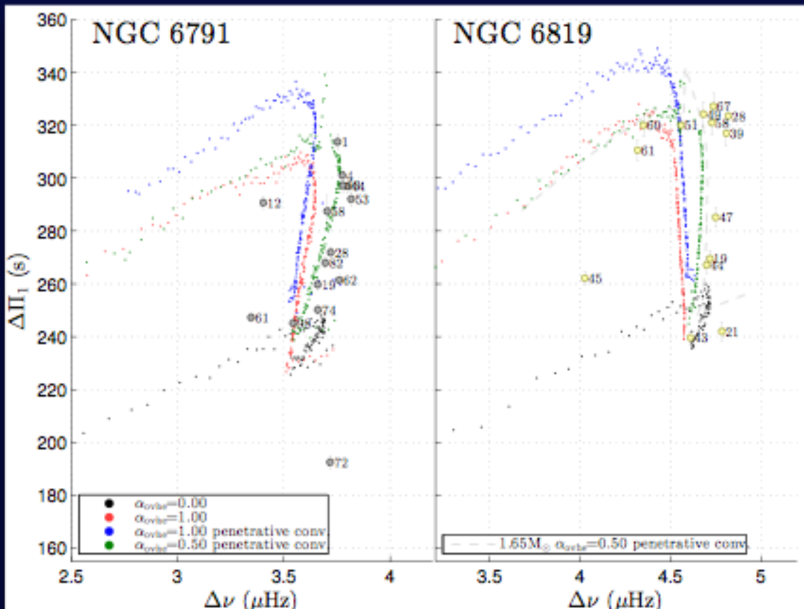

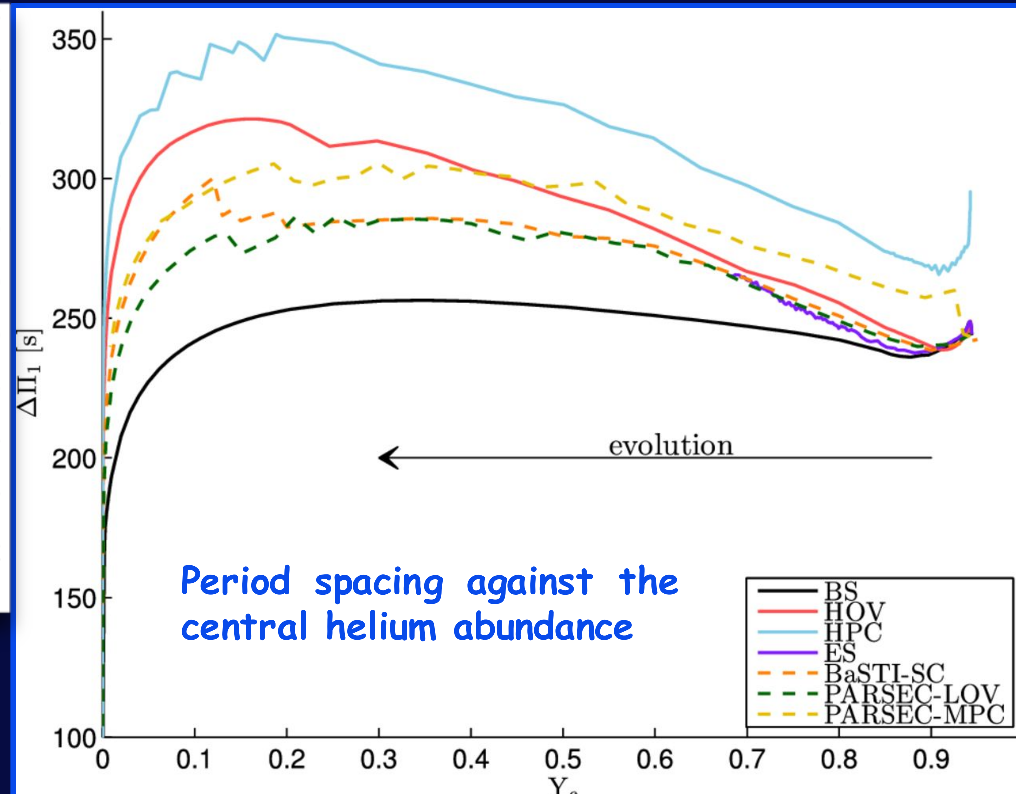

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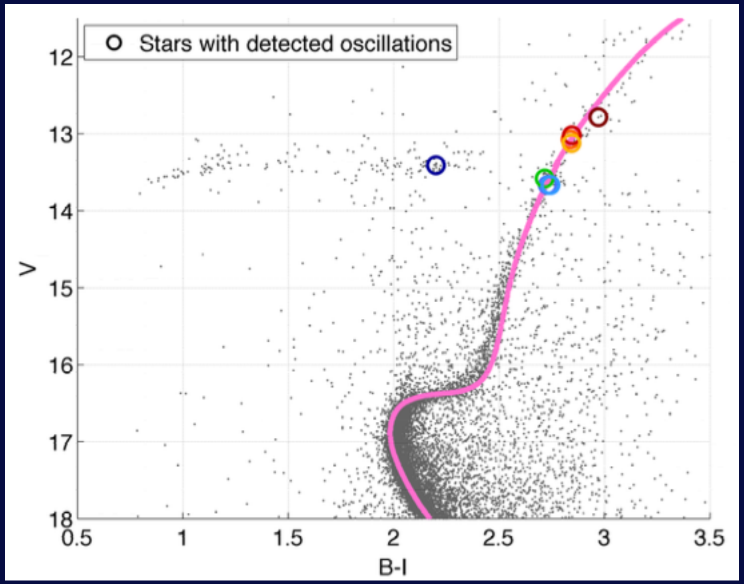
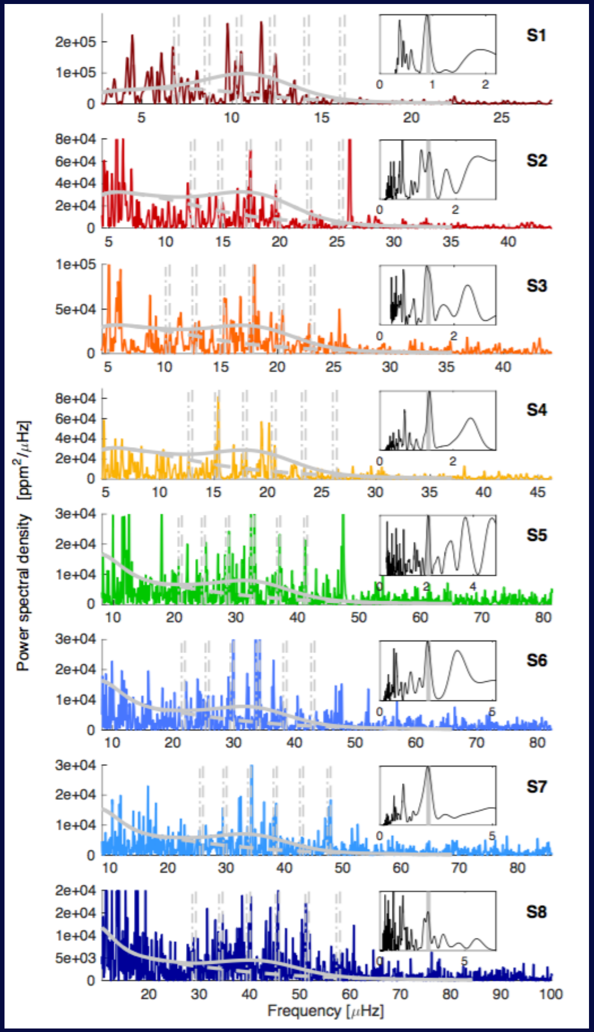
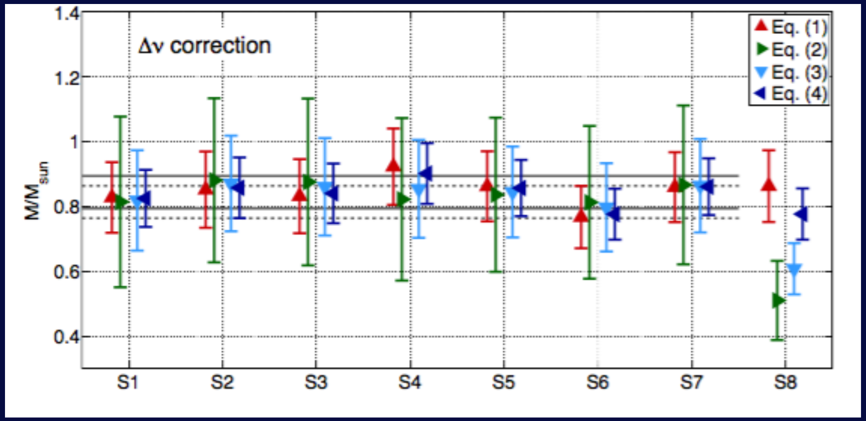
Asteroseismology of Globular Cluster Stars



The unique case of M4: Miglio+16





Theoretical evolutionary framework for low-mass stars in Galactic Globular Clusters

The peculiar chemical patterns of multiple stellar populations

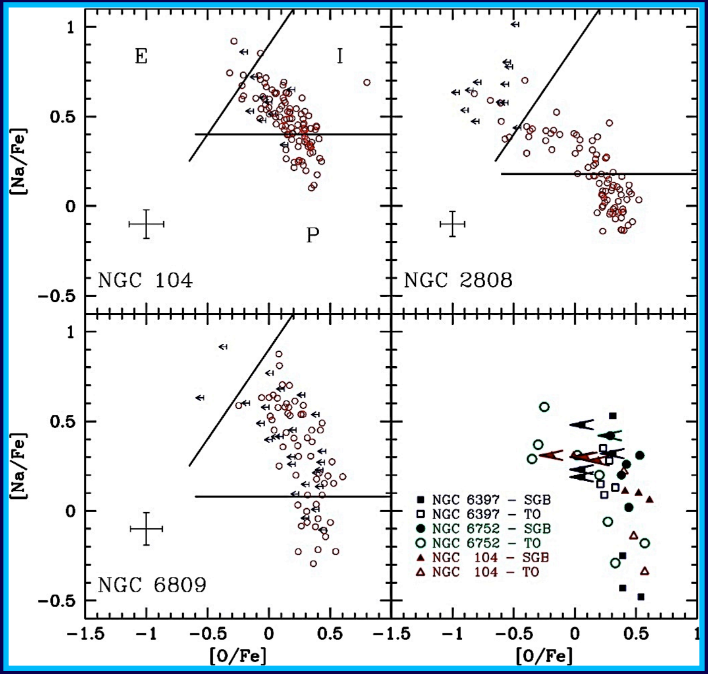
✓ light elements anti-correlations

- Na-O anti-correlation
- Mg-Al anti-correlation
- C-N and N-O anti-correlations

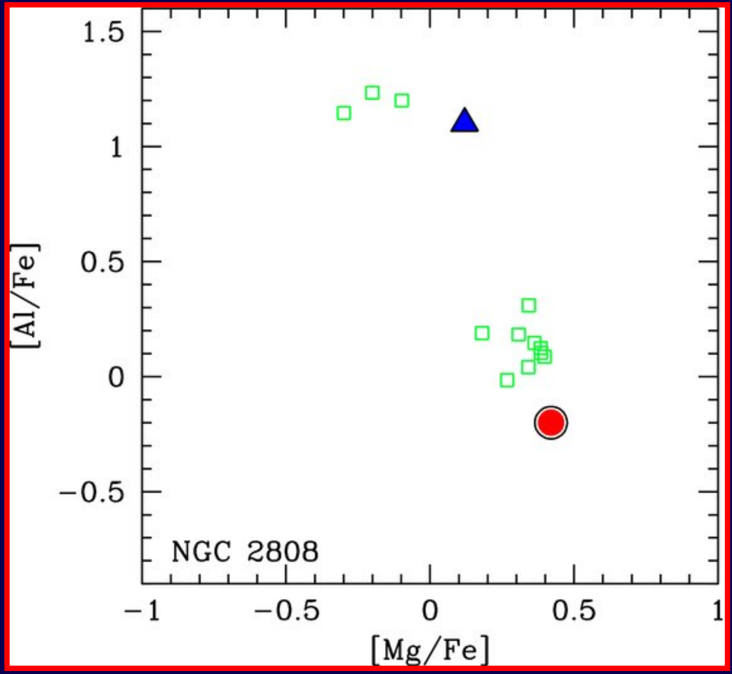
✓ C+N+O enhancement

- in general, the CNO sum is constant but…

✓ Helium enhancement

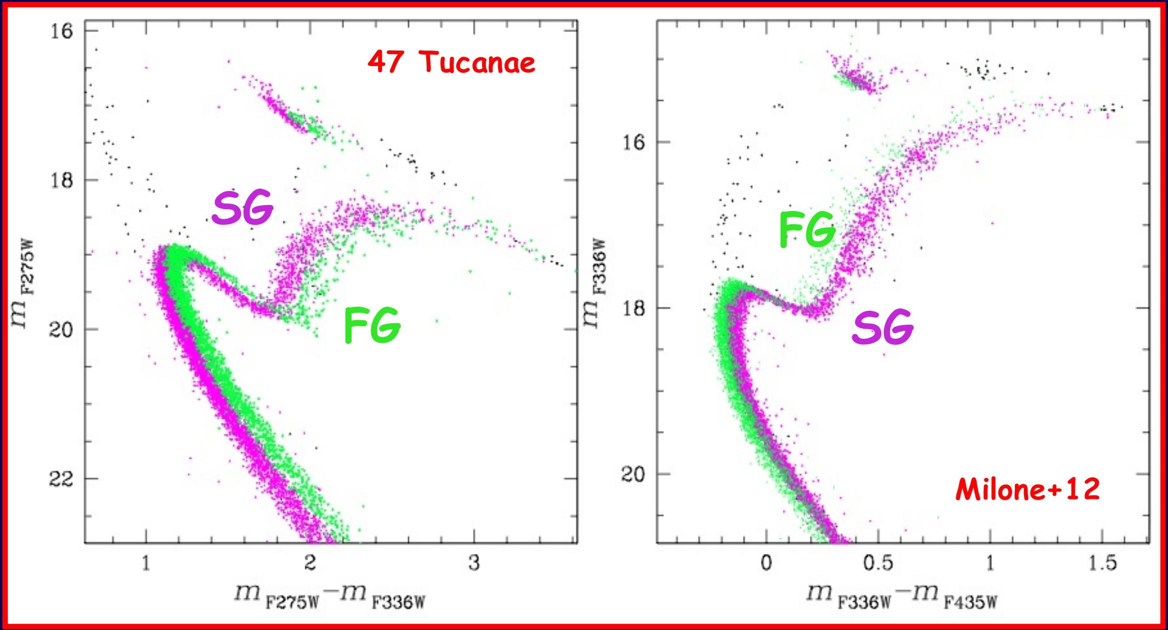


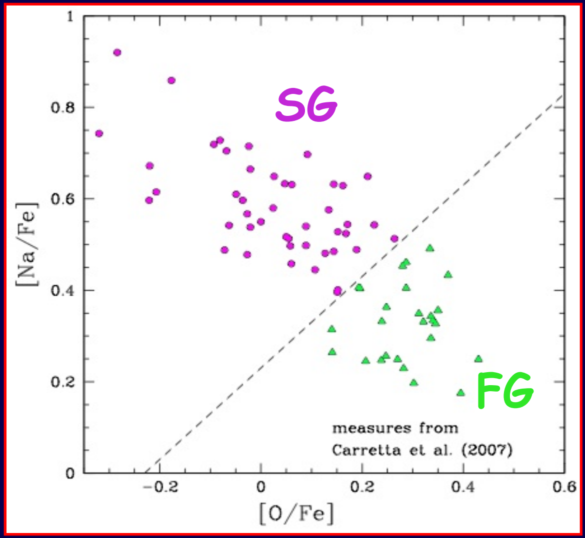
Carretta (2012)



Bragaglia+2010

Multi-band photometric surveys:
the Pandora's box or the Rosetta stone?

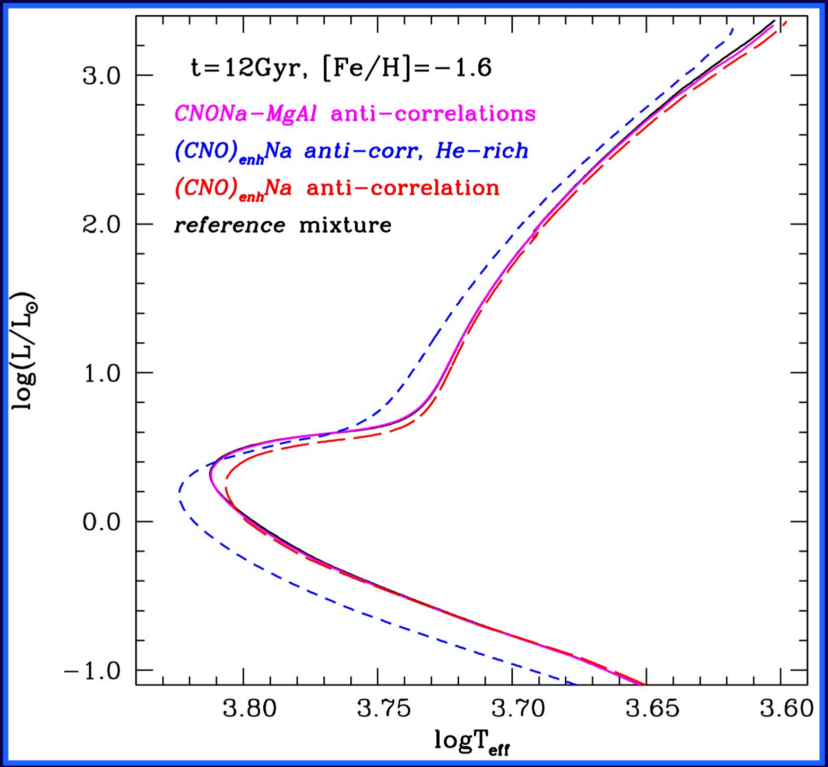




Photometric evidence:

- distinct sequences from the MS up to the AGB stage…
- …also in GCs with no "significant" He enhancement…
- "swapping" sequences…
- … a clear correlation with the chemical abundances…

MPs peculiar chemical patterns: Stellar models and Spectral Energy Distribution

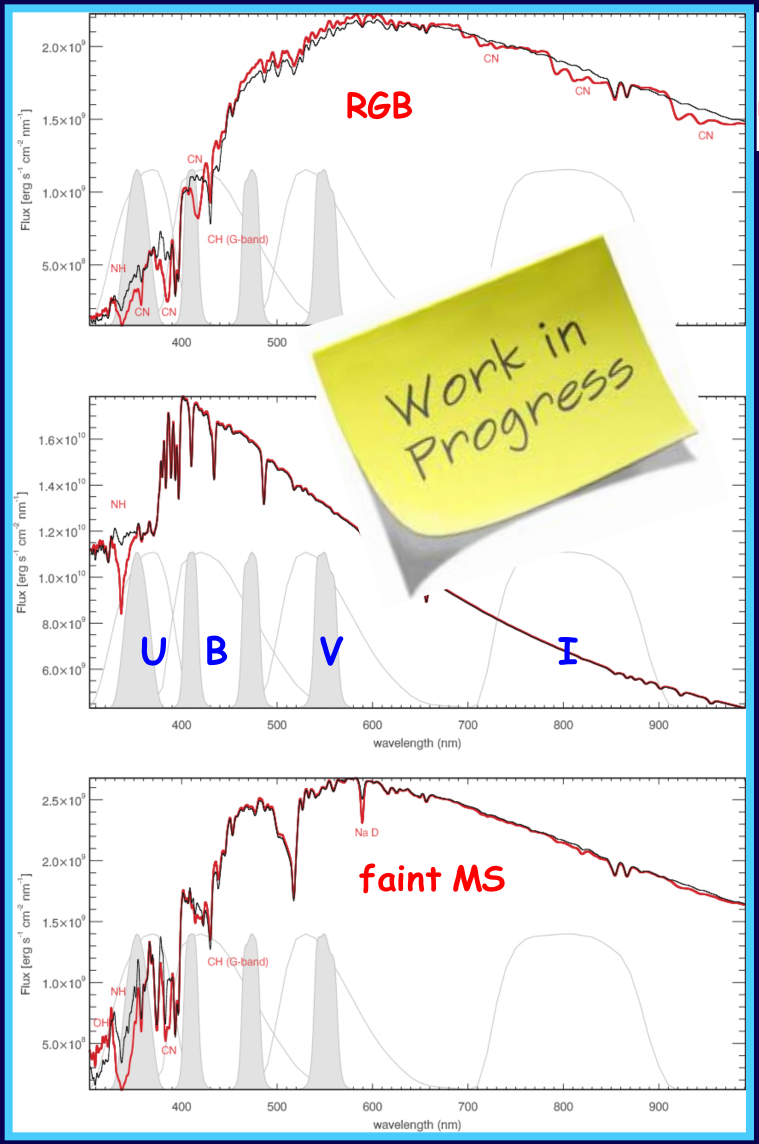


In the H-R diagram, at fixed [Fe/H], a splitting of an evolutionary sequence can be obtained:

- for the MS, only as a consequence of a huge He-enhancement;
- for the SGB, only as a consequence of an increase of the (C+N+O) sum;
- in the case of the RGB, only as a consequence of an He increase;

...but multi-band observations suggest that the changes in the stellar Spectral Energy Distribution induced by the peculiar chemical patterns are important...;

First Stellar Generation SEDs versus Second Generation ones



black: reference mixture
red: (CNO)$_{ext}$Na anti-correlation

what did we learn? (Sbordone+11, Cassisi+13)

- ✓ CNO abundance changes affect mainly the portion of the spectra short of about 400 nm ;
- ✓ changes in absorption features related with NH, CN, and OH molecular bands;
- ✓ the effect is relevant regardless if the CNO sum is changed or not;
- ✓ Mg/Al anti-correlation does not produce significant effects, if any;
- ✓ He enhancement is quite irrelevant in this context;

Stellar Evolution: What future?

- ✓ Italians do it better…

- ✓ The "aging problem"…

- ✓ The "money problem"…

- ✓ The "Black & Decker" problem…

Stellar Evolution: What can we do?

- Extended sets of "standard models"...
- The challenges...
  - Transport properties (convection, turbulence, accretion···)
  - Rotation & related mixing processes;
  - Magnetic field (dynamo generation, interaction convection-magnetic field;
  - Atmospheric processes in cool atmospheres;
- To look for new synergies with important research topics such as dynamical and chemical evolution of stellar systems;
- To look for new (and unprecedent ...) collaborations among the various groups...
- Stellar Evolution "within" INAF...