M-dwarf stars: properties and shortcomings in stellar modelling

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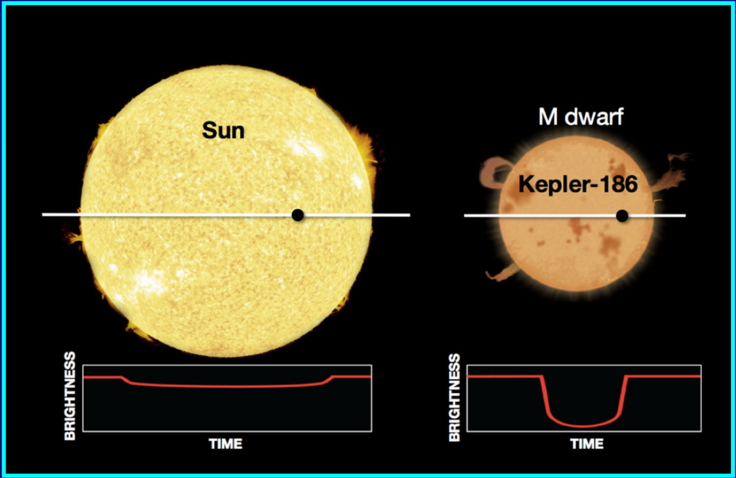
Why M dwarfs in the PLATO context?

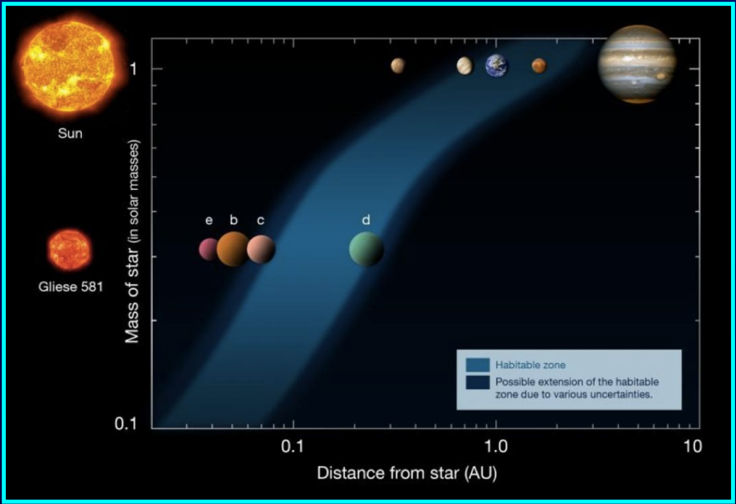
- ✓ M dwarfs comprise **~70% of all stars in the Galaxy** and increase **the chance of finding habitable planets** through their sheer numbers and proximity to the Sun

- ✓ **Small planets are easier to detect orbiting small stars** via the radial velocity and transit techniques, as spectroscopic. Doppler shifts and photometric transit depths are larger due to the smaller star-to-planet mass and size ratios, respectively

- ✓ **Habitable zones are closer** to these stars than those of Sun-like stars, increasing the geometric probability of observing a transit

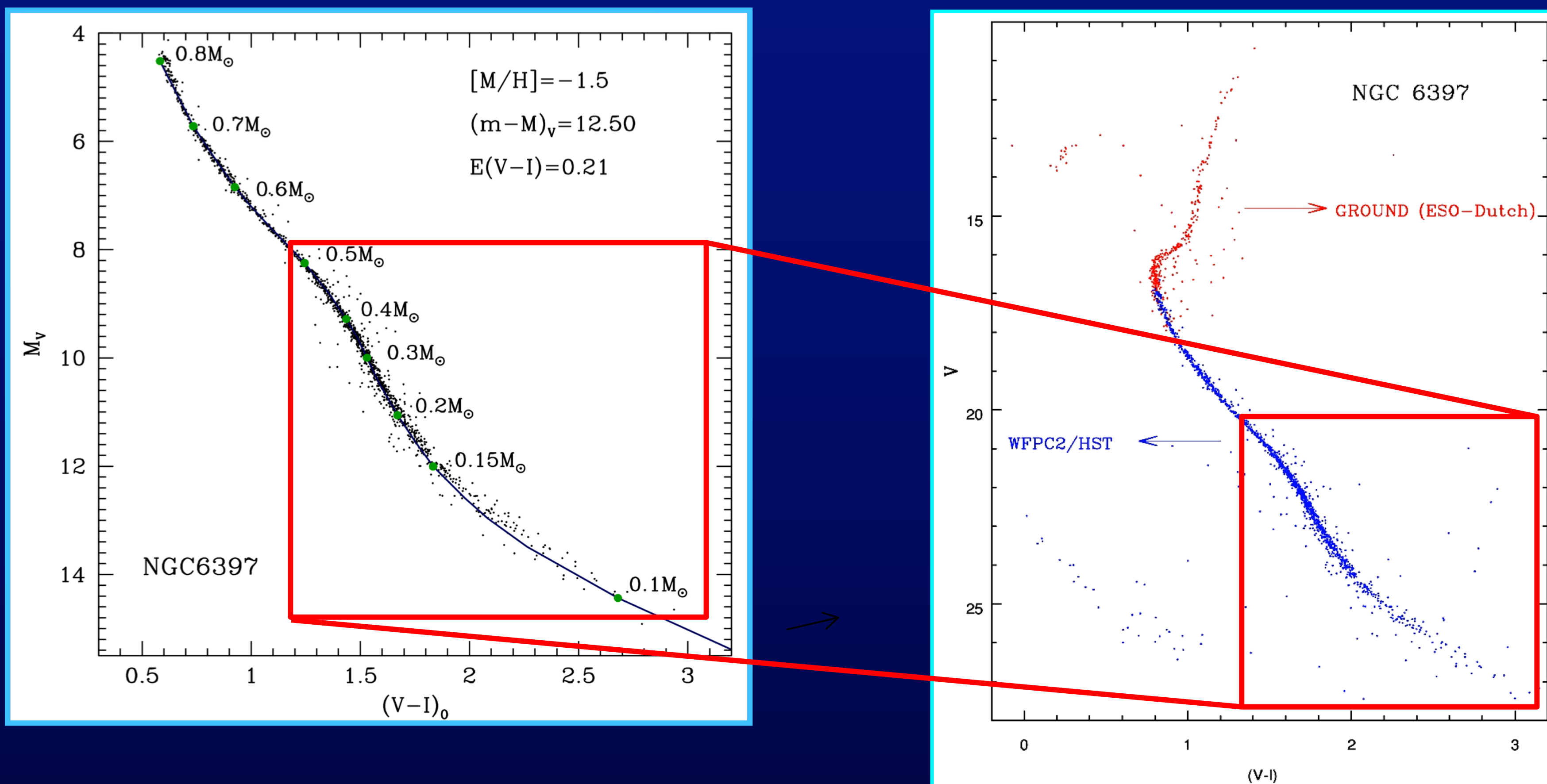
- ✓ Their extremely **long lifetimes ample time for biological development and evolution** on orbiting planets





Who are M dwarfs?

The theoretical counterpart of M-dwarfs are the so-called very-low-mass (VLM) stars, with masses between ~0.5$M_\odot$ (He-ignition limit) and ~0.1$M_\odot$ (H-burning limit). They are fully convective below ~0.35 $M_\odot$



VLM Stars: very intriguing structures…

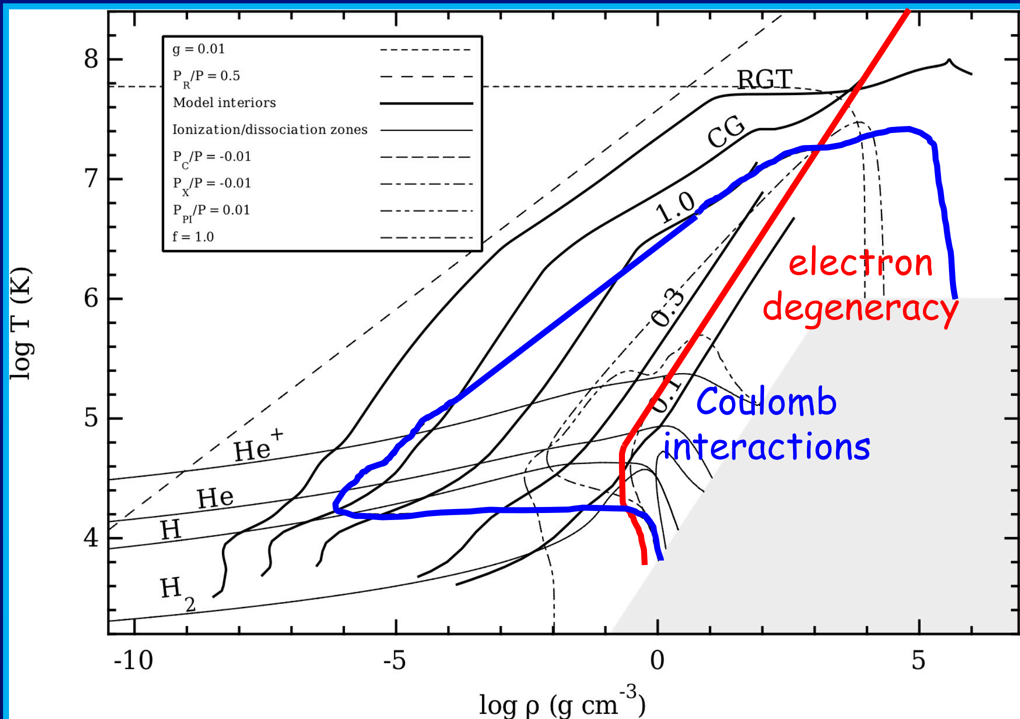
- Extremely dense and cool objects

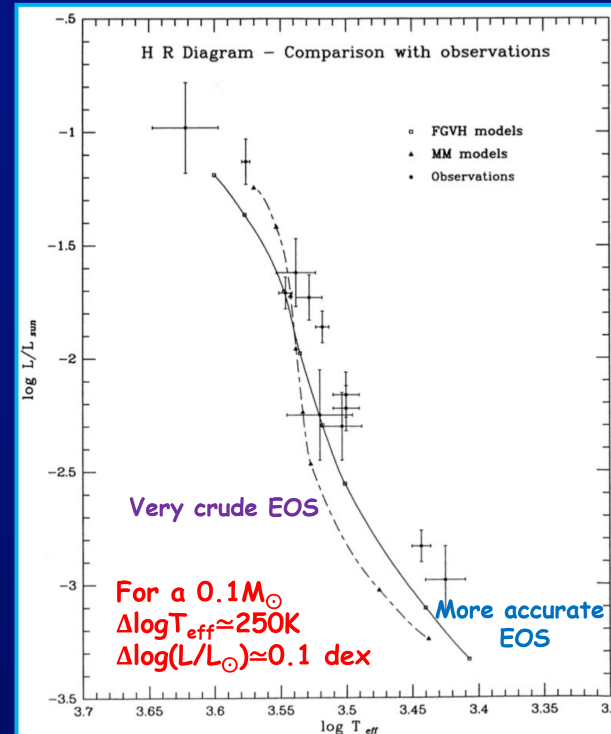
$M/M_\odot$	T_c	ρ_c	T_{phot}	ρ_{phot}
1.0	$\sim 1.6\cdot 10^7$K	$\sim$100g$\cdot$cm^{-3}	~6000K	$\sim 10^{-7}$ g$\cdot$cm^{-3}
0.6	$\sim 10^7$K	$\sim$150g$\cdot$cm^{-3}	~4000K	$\sim 10^{-6}$ g$\cdot$cm^{-3}
0.1	$\sim 5\cdot 10^6$K	$\sim$500g$\cdot$cm^{-3}	~2800K	$\sim 10^{-5}$ g$\cdot$cm^{-3}

The evaluation of the thermal properties & opacity is a thorny problem!

- the issue of the outer boundary conditions…
- the problem of accurate model atmospheres…
- @the transition between the stellar regime and brown dwarf one

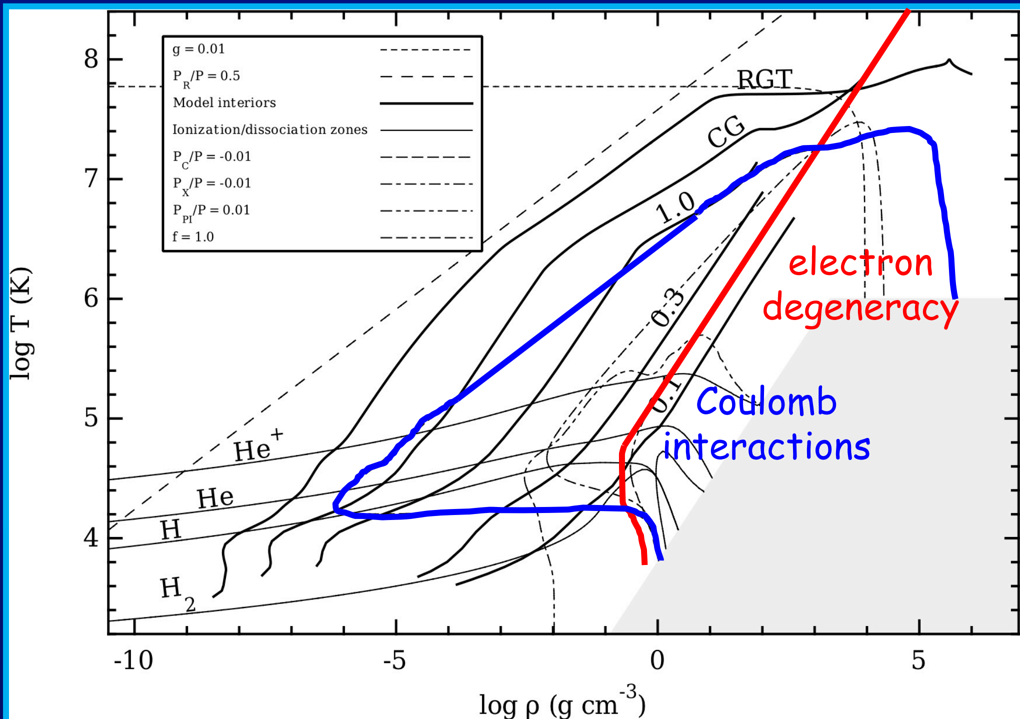
Equation of state

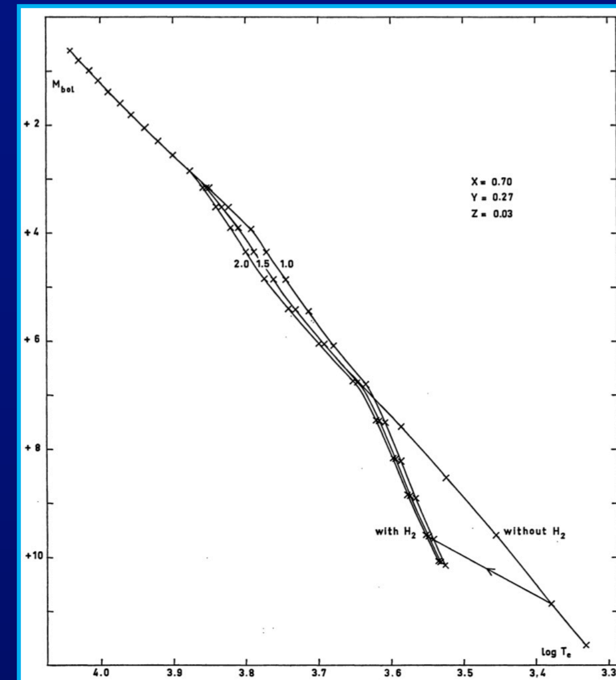




- ✓ The Coulomb parameter Γ reaches values in the range 0.1-30 (as a reference, Γ >180 corresponds to the crystallization regime), meaning that Coulomb interactions among ions are very important
- ✓ Electron degeneracy becomes significant towards the H-ignition limit.
- ✓ Dissociation of the H_2 molecules is crucial…
- ✓ Treatment of pressure ionization is very important and complicted… with a "plasma phase transition"@higher densities…

Equation of state





Copeland et al. (1970)

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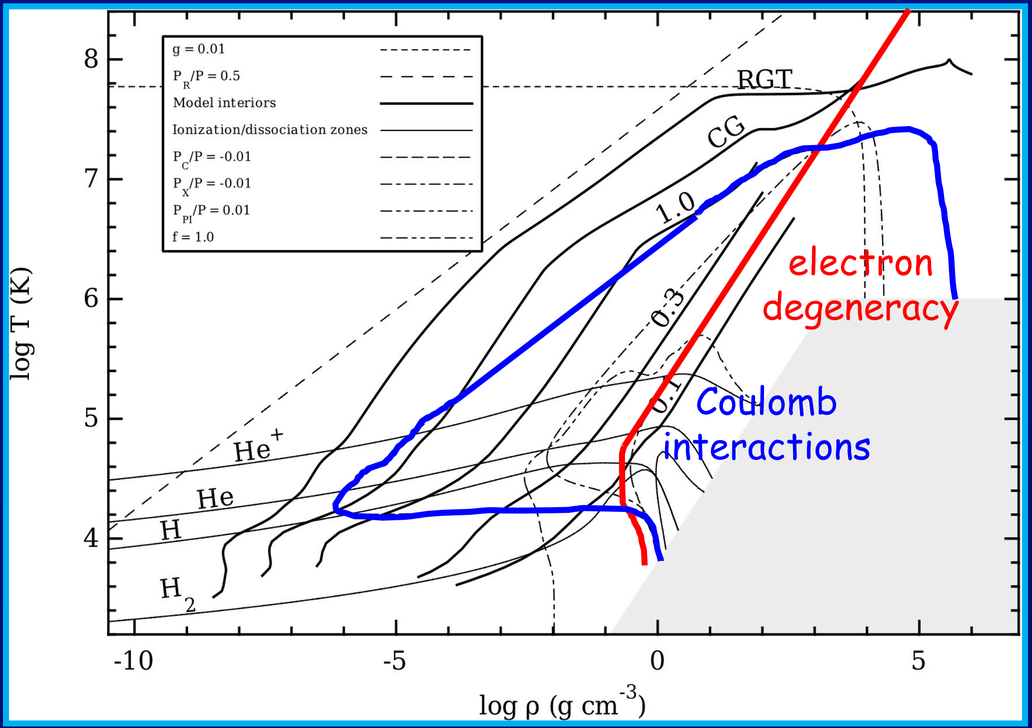

What can we currently use?

- **SCVH95:Saumon, Chabrier & Van Horn (1995)**

Pro: very detailed treatment of all physical processes for a pure H mixture;

Cons: available only for pure H & He cases; a simplified model is used for the treatment of the EOS of the pure He mixture;

- **FreeEOS: Cassisi, Irwin, & Salaris (2003), Irwin (2008)**

Pro: it fully covers the whole thermodynamical range in a wide mass range; it is designed to provide a nice match to the OPAL EOS and SCVH95

Cons: not fully independent from the SCVH95;

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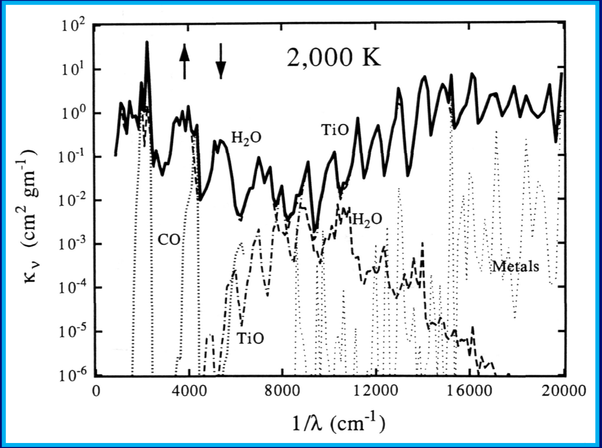
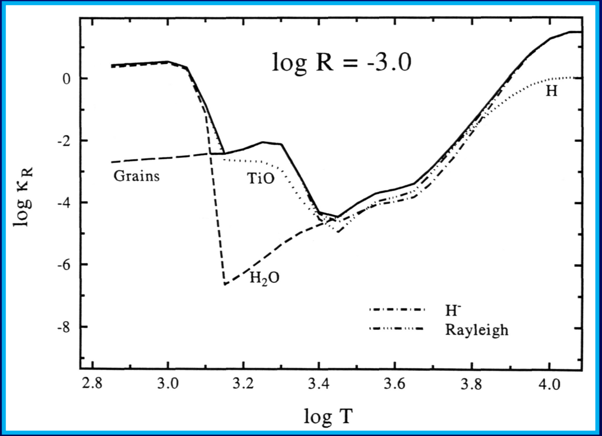
Radiative opacity

In the atmospheres of VLM and Brown dwarfs, almost all H is present as H_2, the larger part of carbon as CO, while oxygen contributes to form molecules of TiO, VO and H_2O





- ✓ the lack of detailed line lists (TiO, H_2O, metal hybrides…) forces to use some approximations (e.g., SM, OS methods) for estimating κ in specific wavelenght ranges…
- ✓ For T_{eff}<2800K, the formation of grains (iron, Al_2O_3, $CaTiO_3$, etc) can not be neglected and this causes relevant complications (size? Spatial distribution?)…
- ✓ An (almost) exclusive opacity source is the H_2 CIA (collisional induced absorption) one…

Huge recent improvements in:
- Molecular opacities (ExoMol project, Yurchenko+13);
- Model atmospheres (Allard+12, Rajpurohit+13);

The state-of-the-art of opacity tables for stellar modelling:

Low-T regime:
- the unique available tabulations are those by Ferguson et al. (2005); No recent updates; estimated uncertainty ~10/15%, larger in the grain regime;

High-T regime:
- various tabulations: OPAL (Rogers+05), OP (Badnell+05), OPAS (Mondet+05); estimated uncertainty ~±5% in the range relevant for VLM models;

Outer boundary conditions: a fundamental issue

To solve stellar structure equations, the pressure at the base of the atmosphere, i.e. at a reference optical depth τ has to be fixed (talk by Silva-Aguirre)

A commonly adopted approach relies on the use of a functional relation $T(\tau)$ describing the atmospheric thermal stratification

$$T^4 = \frac{3}{4} T_{eff}^4 (\tau + q(\tau))$$

If $q(\tau)=2/3$

$$T^4(\tau) = \frac{3}{4} T_{eff}^4 \left(\tau + \frac{2}{3} \right)$$

Eddington (grey) approximation

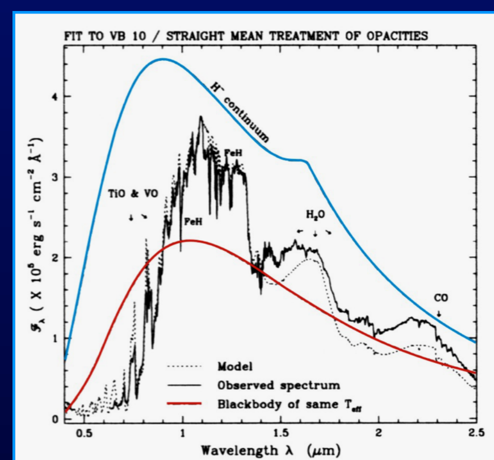
This approach is reliable if:

- ✓ **Pure radiative energy transport**
- ✓ **Isotropic radiation field**
- ✓ **Absorption independent on the frequency**

FALSE for VLM stars!

Convection reaches also the optically thin layers in the atmosphere (τ~10^{-3})

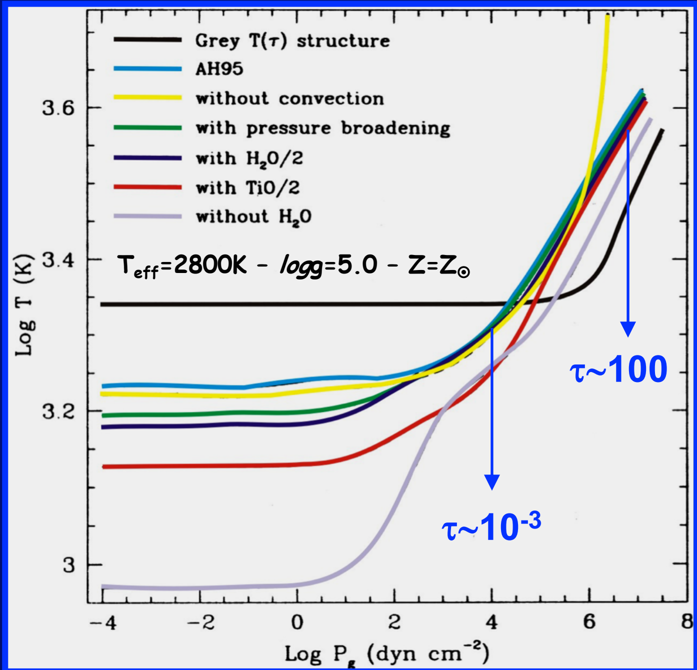
"Absorption" strongly dependent on the radiation frequency:



Extensively investigated by:

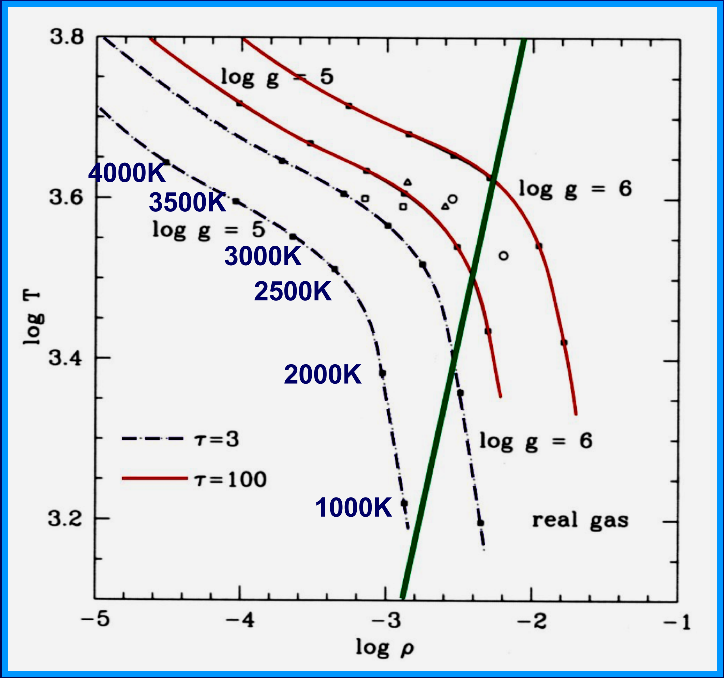
- Chabrier & Baraffe (1997)
- Baraffe et al. (1998)

Boundary conditions (BC) from model atmosphere are crucial (Chabrier & Baraffe 1997)



Allard et al. (1997)

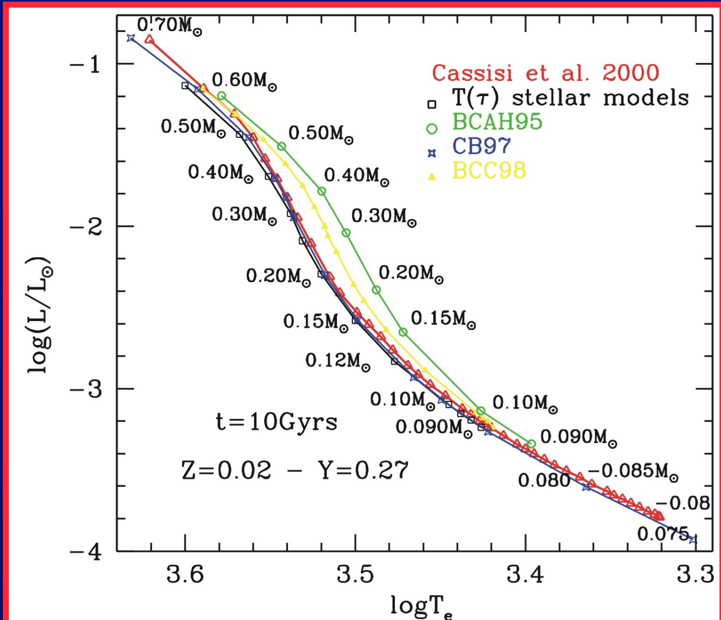
- ✓ The thermal stratification predicted by models atmospheres largely depends on the molecular and atomic opacities adopted in the computations
- ✓ In the less massive VLM structures, non-ideal effects could be also relevant in the outer layers….



As for the uncertainty due to the adopted BCs, we need to consider:

1. the used model atmosphere set;
2. the adopted optical depth to match atmosphere/interior structure;
3. The selected metal mixture…

1. The impact of different BCs

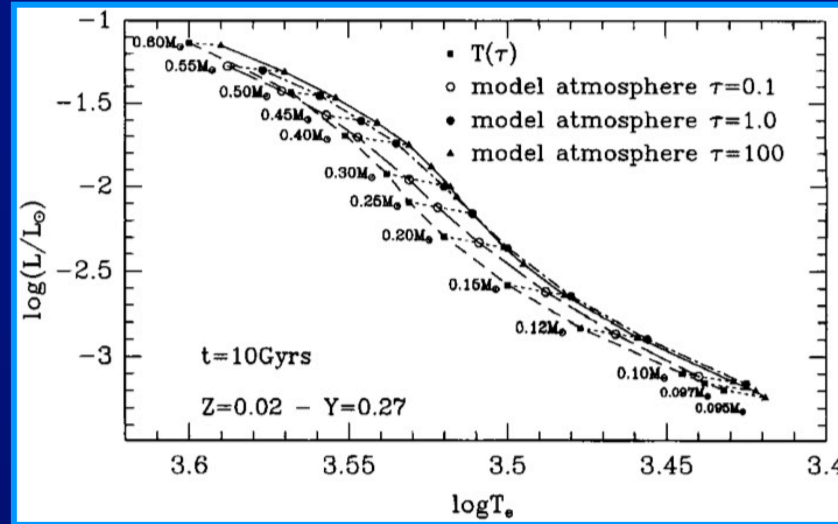


BCAH95 = Baraffe, Chabrier, Allard, Haushildt (1995)

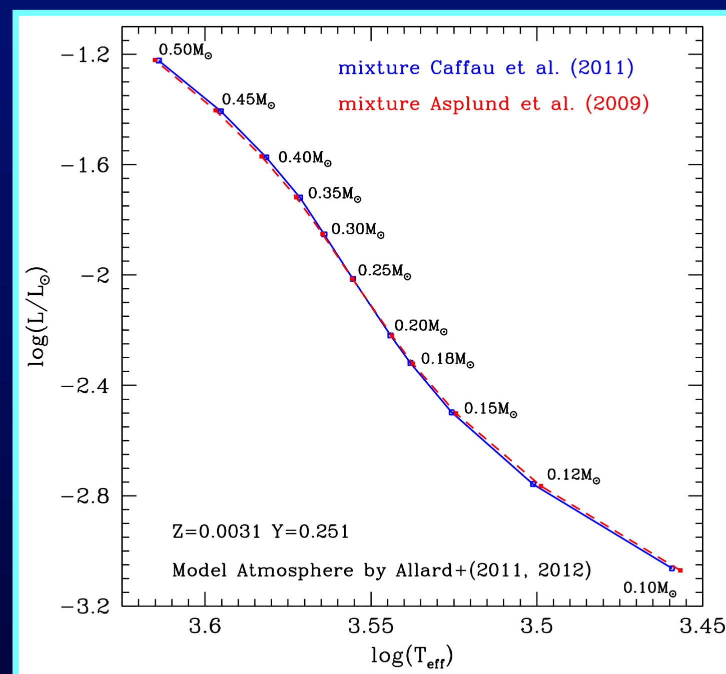
BCC98 = Brocato, Cassisi, Castellani (1998) – BCs by Brett (1995)

CB97 = Chabrier & Baraffe (1997)

2. The impact of different τ

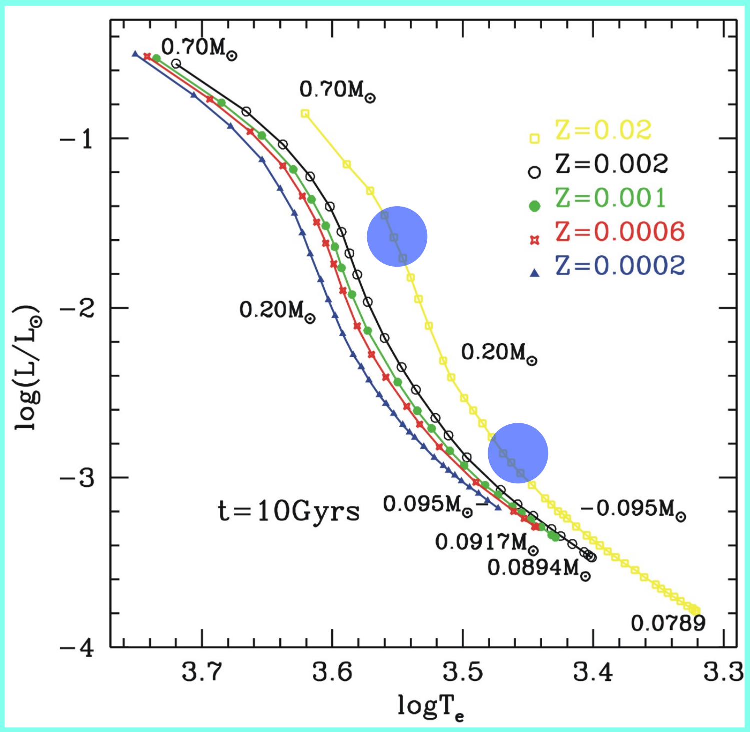


3. The impact of metal mixtures



Hidalgo, Pietrinferni, Cassisi+18

VLM stars in the H-R diagram: lensing the reliability of the physical framework



The I° bending point (T_{eff}~4300K – M~0.5M_o) is due to the H_2 ricombination

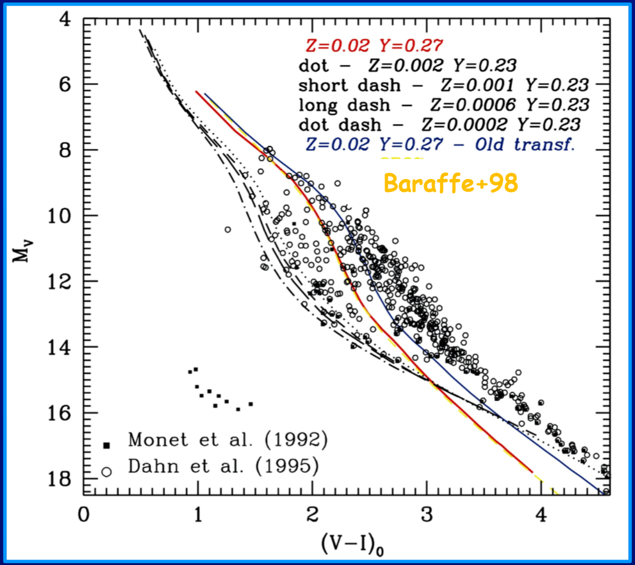
The II° bending point (T_{eff}~3000K – M~0.15M_o) is due to the fact that, when the stellar mass decreases, the electron degeneracy increases and the H-R location of the structures tends towards a constant radius tracks ($R \propto M^{-1/3}$)

Comparison with suitable empirical benchmarks provides strong constraints on the adopted physical scenario: EOS, opacity, boundary conditions, etc.

…but… to do this we need to rely on color-T_{eff} relations and a bolometric correction scale…

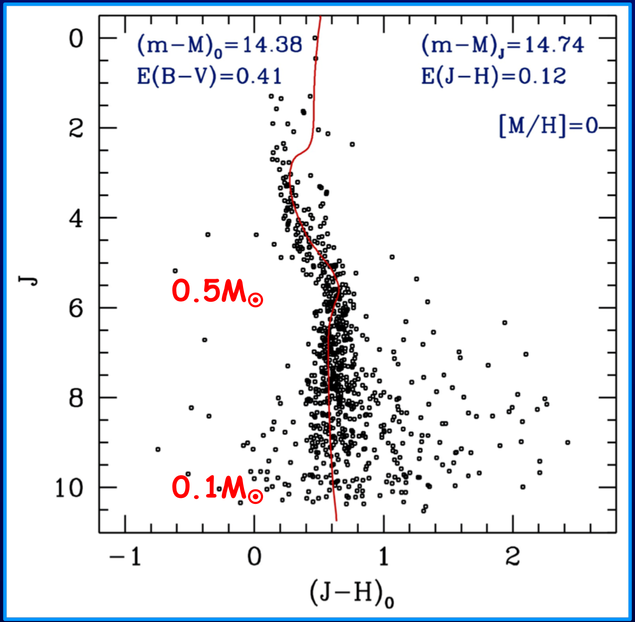
The role of model atmosphere is crucial and critical

Bolometric correction scale(s) for VLM stars



<u>The disagreement in the optical bands due to a wrong evaluation of the opacity for $\lambda < 1\mu m$;</u>

Being TiO molecules the most important opacity source in this spectral range, the adopted TiO lines list was responsible for this problem (but also CaOH …);



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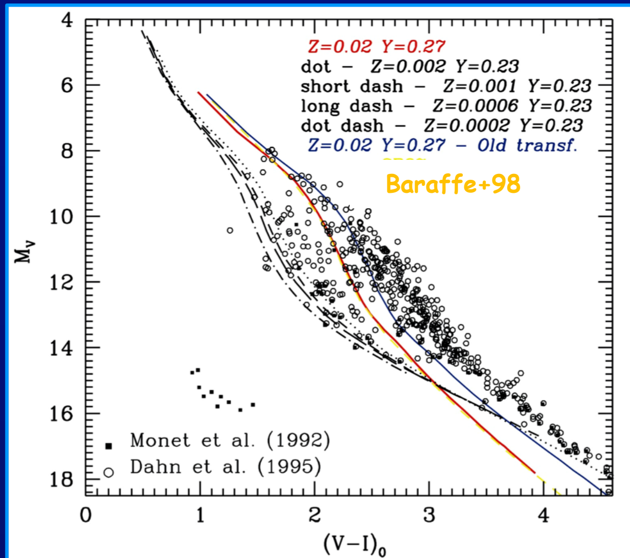

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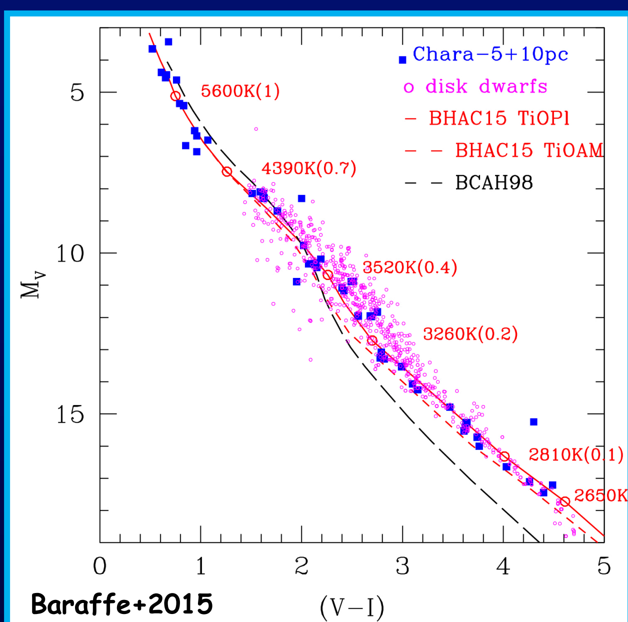
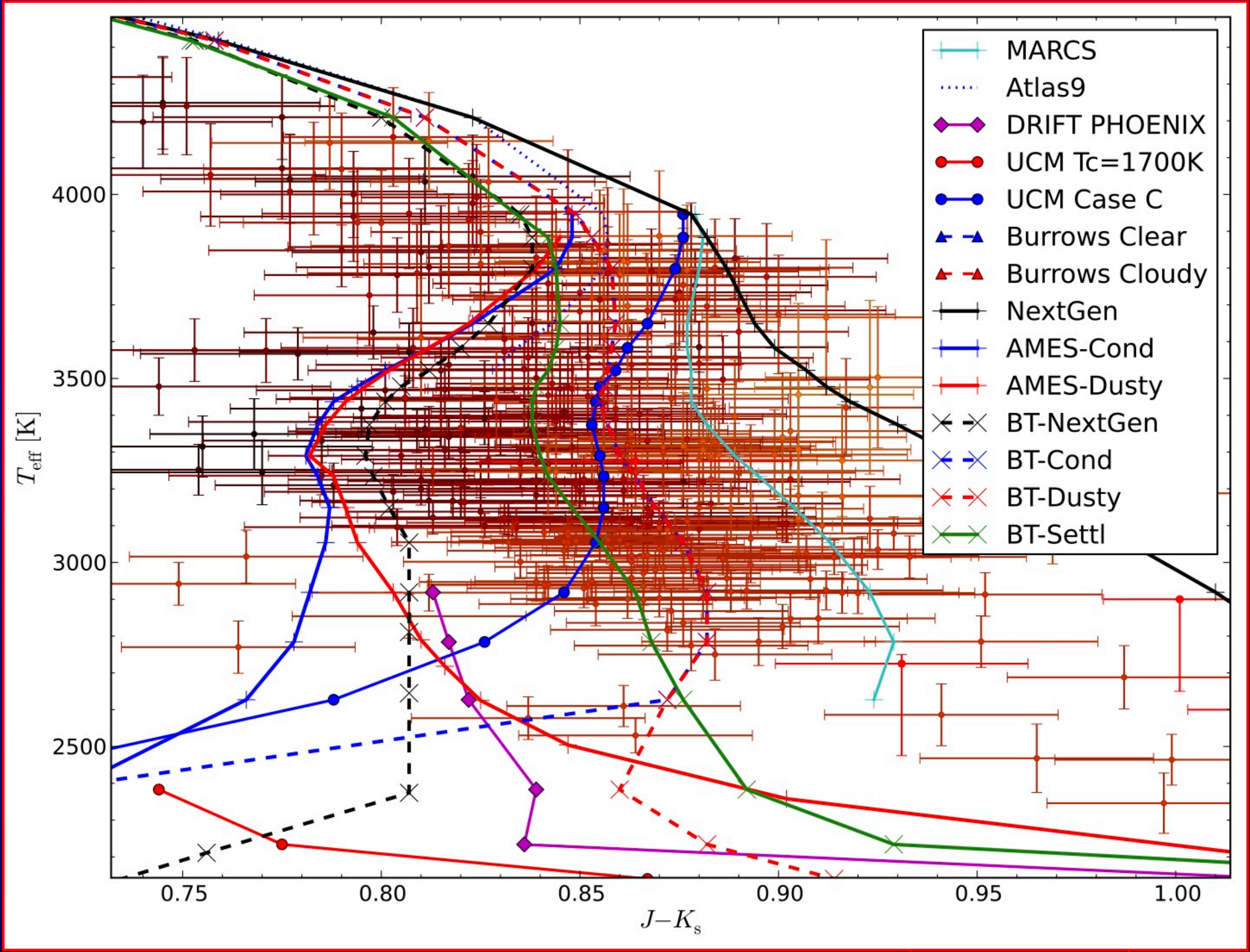


Based on more updated model atmospheres (BT-Settl) by Allard+12 including:

- ✓ ***A more accurate and reliable TiO linelist** (Plez 1998);*
- ✓ ***A decreased Oxygen abundance (by ≈20%) with respect previous models***

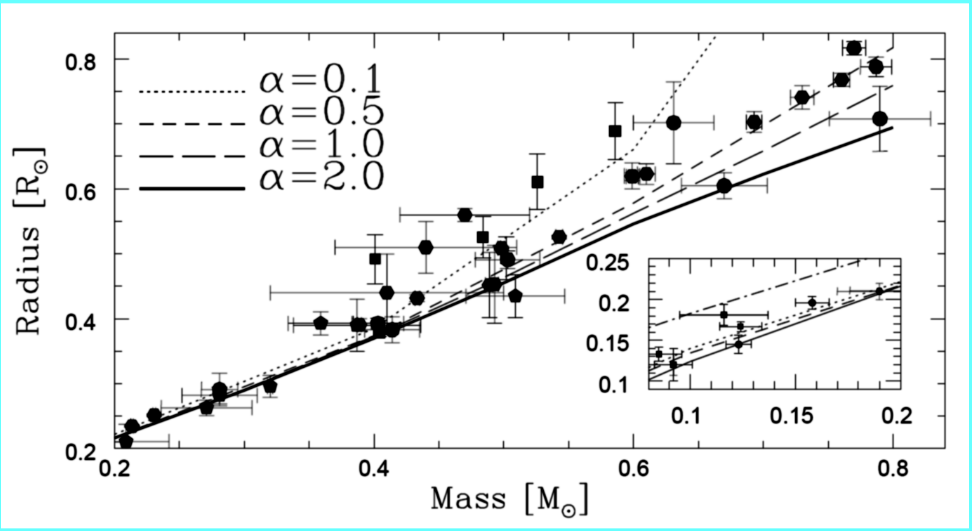
Color-T_{eff} relations: a (still) un-settled issue



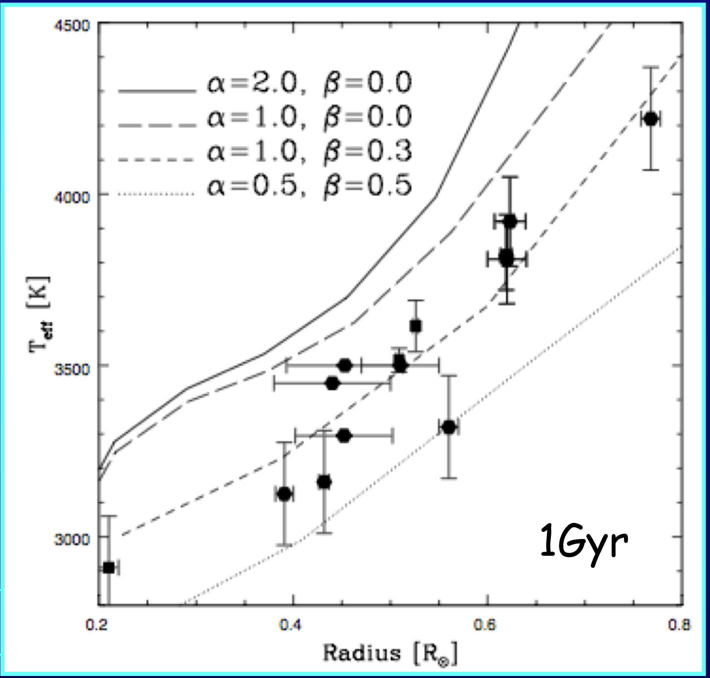
Allard+2013

Large scale magnetic fields

Due to the absence of a proper treatment of heat transport in a magnetised medium for conditions, a "minimalist approach" is commonly adopted that is focused on the reduced efficiency of global thermal convection due to the presence of strong magnetic fields



Chabrier, Gallardo & Baraffe (2007)



$\beta = S_{spot}/S_{\star}$

The strong chromospheric and coronal emission in LMS of spectral types >~M2-M3 can be associated with an average large fraction of the radiating surface being covered with magnetic spots.

WP121 300: M dwarfs

Task: to provide an extended/updated grid of state-of-the-art models for VLM stellar structures for any specified chemical composition;

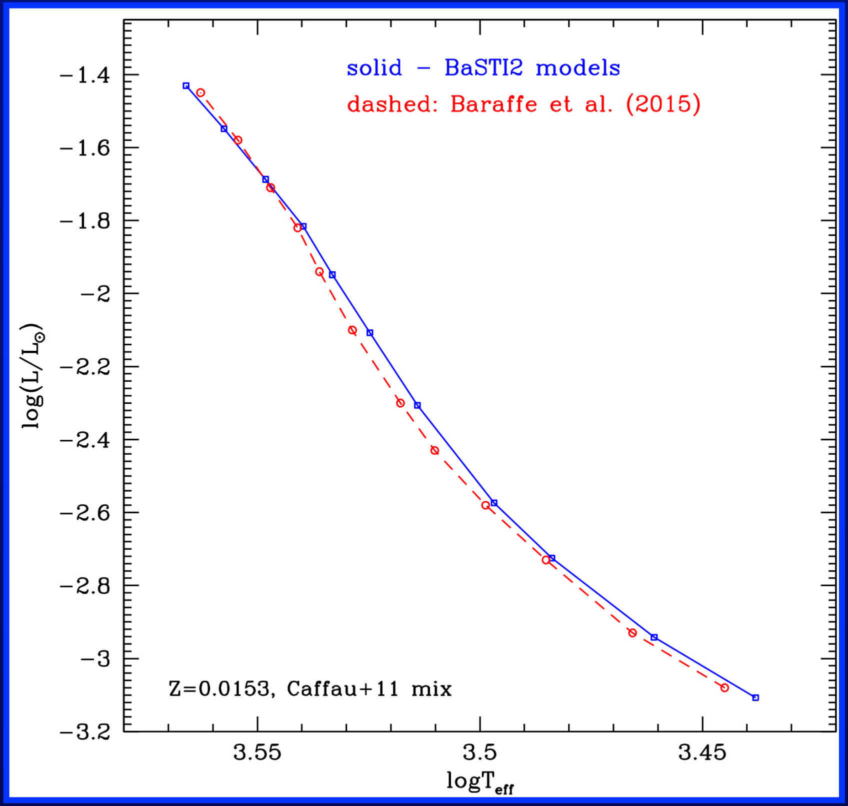
Ith step:

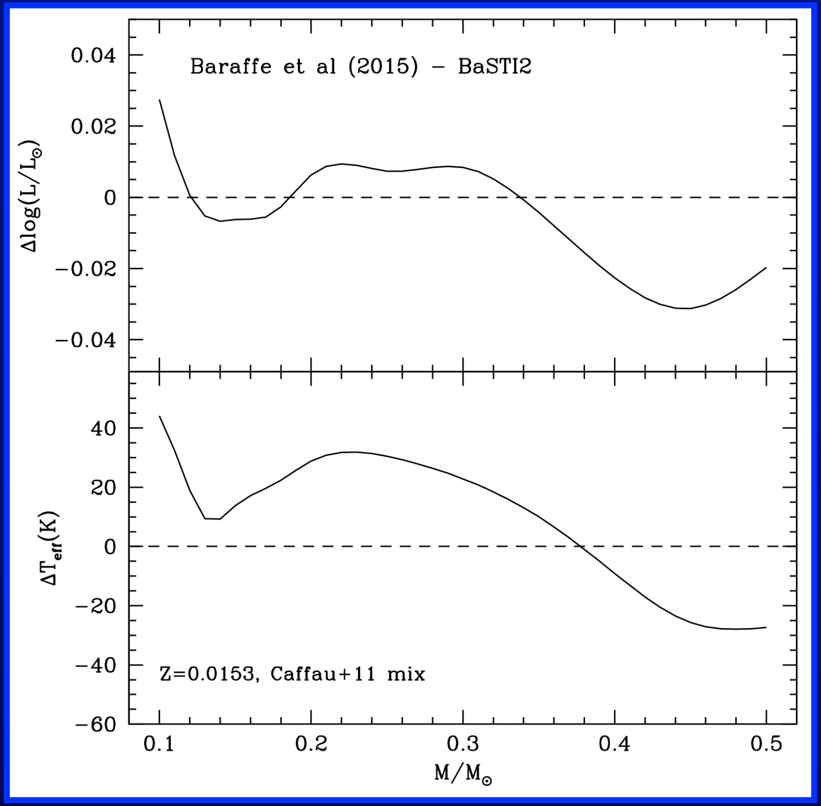
- Check the availability of updated physical inputs (EOS, opacity, boundary conditions, etc.);
- Compute stellar model grids for various assumptions on the chemical composition;
- Interactions with the WP121 xxx – issues: different physical inputs/assumptions, "smooth transition", inclusion in the existing and future database;

A first baseline state-of-the-art set of standard (no-rotation, no magnetic fields) VLM models, from the pre-MS until ages of the order of 15 Gyr, for a large range of initial metallicities (scaled-solar metal mixture) has been just finished.

This is part of the wider scope new BaSTI project (URL: basti-iac.oa-abruzzo.inaf.it)

Model comparisons

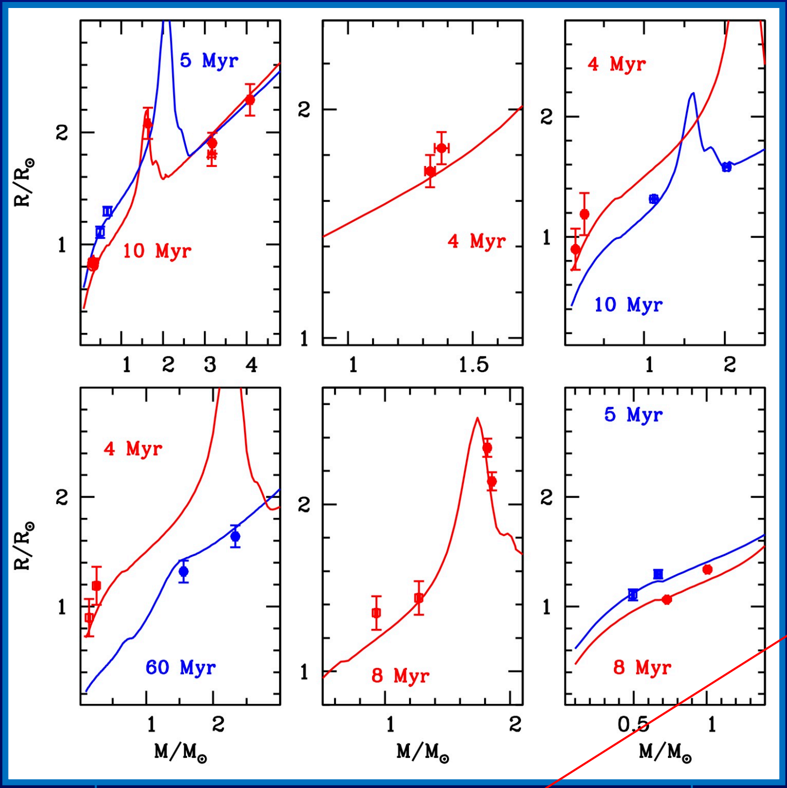




Comparison with empirical benchmarks

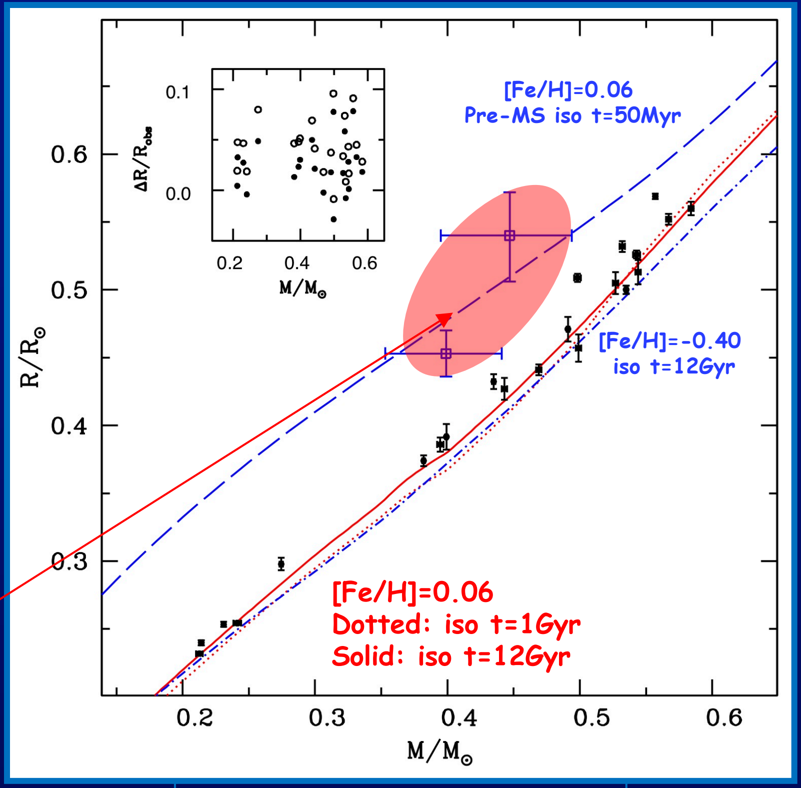
Mass – Radius diagram for detached eclipsing binaries

Pre-Main Sequence



Data by Stassun+14, Simon & Toraskar (2017)

Zero Age Main Sequence



Data by Feiden & Chaboyer (2012)

This is not the whole story for a few cases there are clear mismatches (up to 20%)… an effect of large scale magnetic fields (Lubin+17)

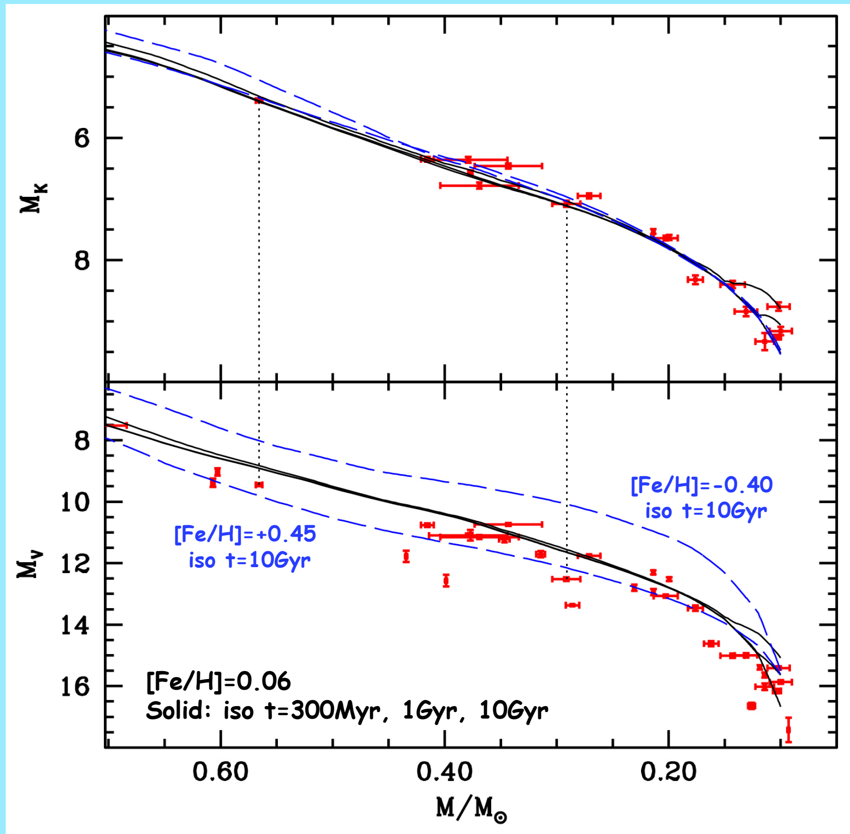
ΔR(obs-theory)/R_{obs}

- ✓ 0.02 ± 0.03 for age of 12Gyr
- ✓ 0.04 ± 0.03 for age of 1Gyr

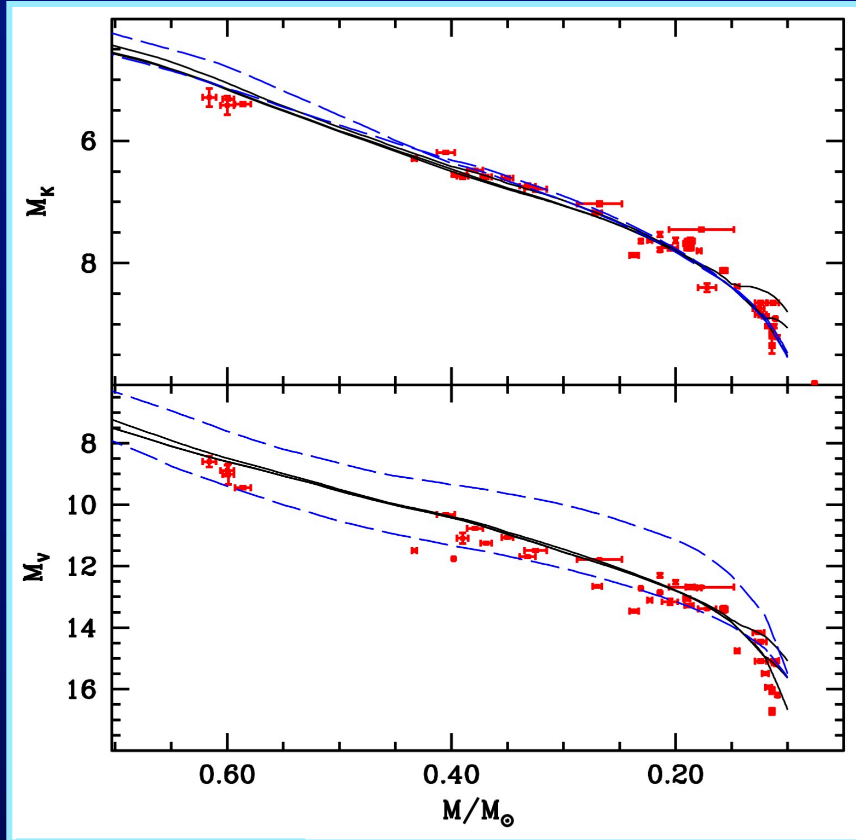
Typical systematic errors on R_{obs} ~ 2-3% (Windmiller+10)

Comparison with empirical benchmarks

Mass – Luminosity diagram for visual and interferometric binaries



Data by Delfosse+00

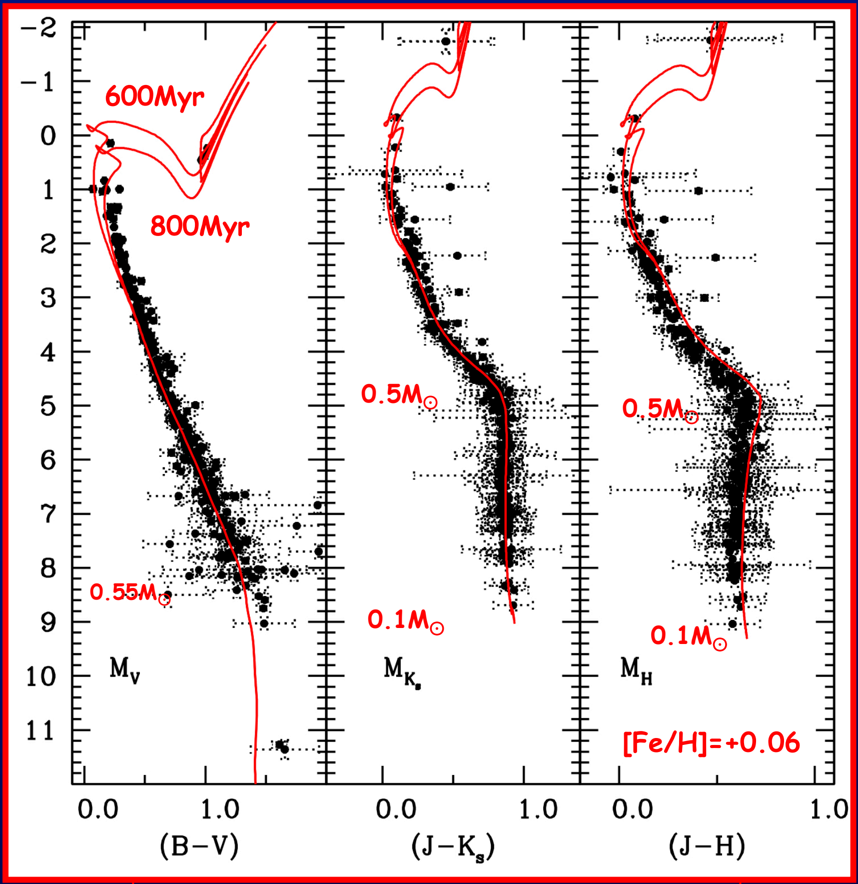


Data by Benedict+16

Comparison with empirical benchmarks

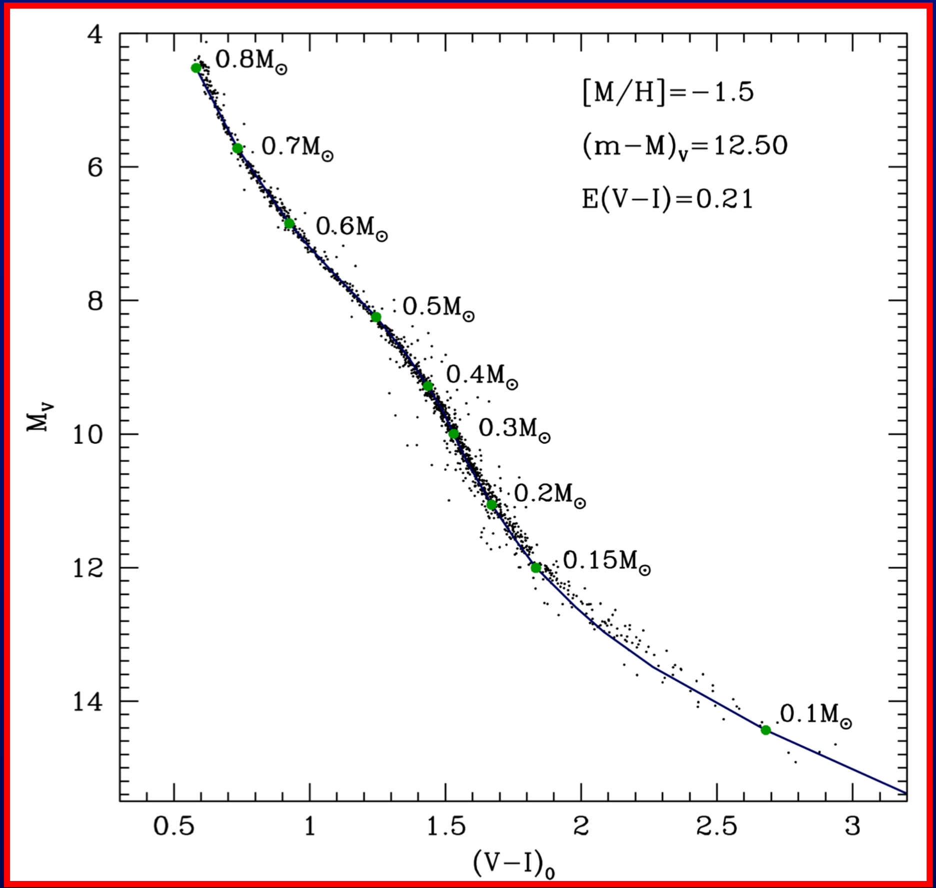
Color - Magnitude Diagram of Star Clusters

Hyades



Parallaxes by Röser+11 & GAIA DR1 collab.+17

NGC6397



WP121 300: roadmap

IIth step:

•Continue to update the physical framework, in particular concerning Boundary Conditions and color-T_{eff} relations;

• inclusion of non-canonical physical mechanism(s);

• develop numerical algorithms for a direct estimate of the structural and evolutionary properties of a given stellar target on the basis of its main "observables" (magnitudes, g, T_{eff}, chemical composition) and an extended grid of stellar models covering the whole parameter space (mass, chemical composition, evolutionary stages);