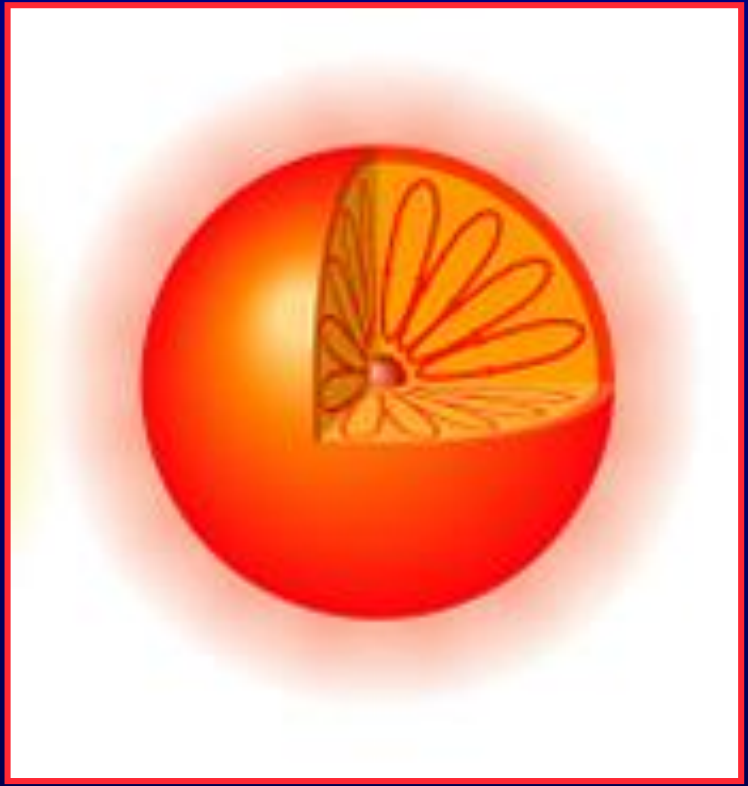
Structure and evolution of M-dwarfs



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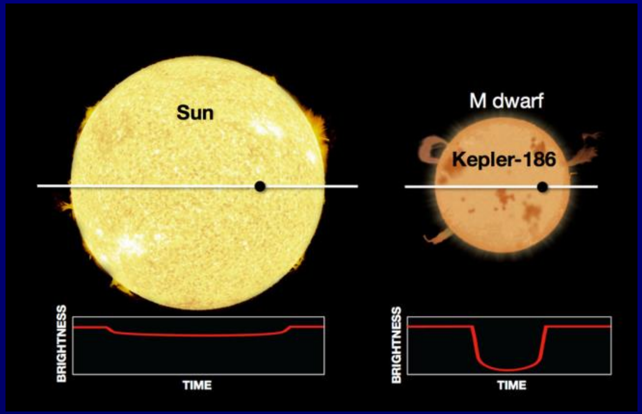
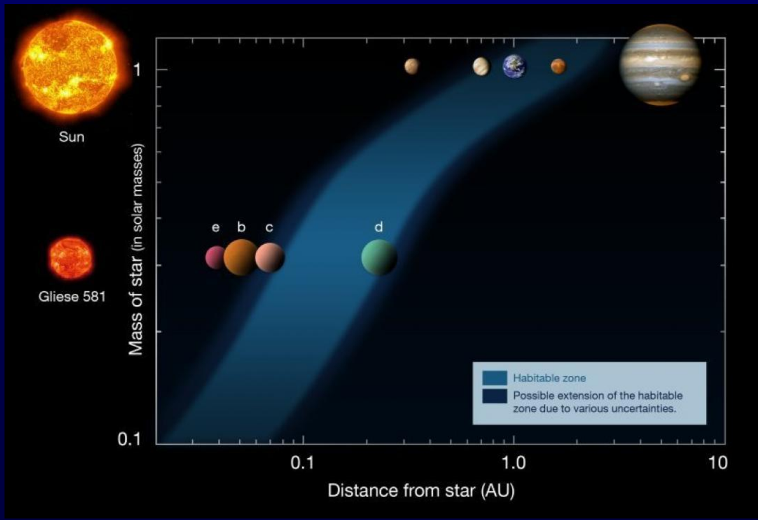
M-dwarfs comprise ~70% of all stars in the Galaxy and increase the chance of finding habitable planets through their sheer numbers and proximity to the Sun



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



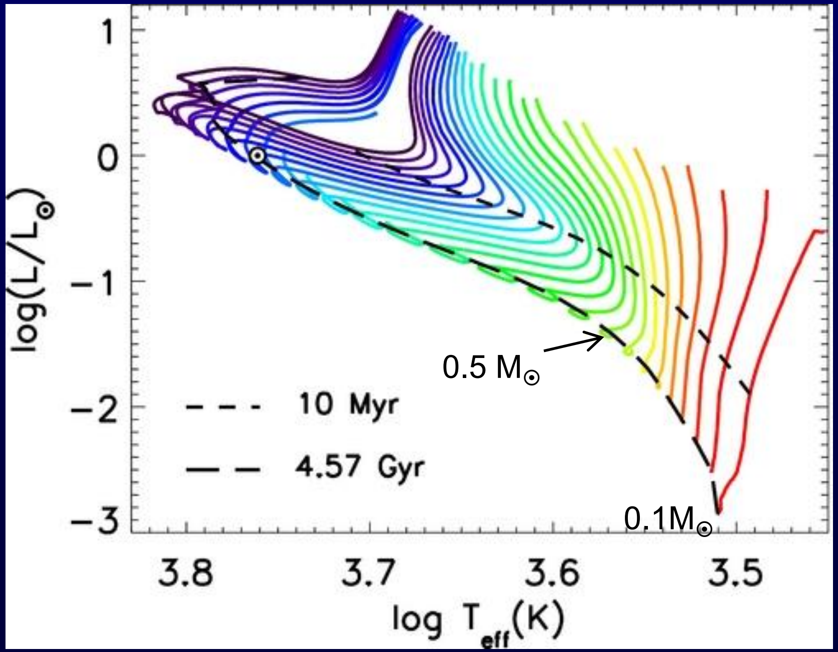
Habitable zones are closer to the stars than those of Sun-like stars, increasing the probability to observe a transit

The extremely long lifetimes give ample time for biological development and evolution on orbiting planets

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 are very dense, 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.
Treatment of pressure ionization is crucial.

Molecular H, atomic He and several molecular species (e.g. H_2O, CO, VO, TiO) are stable in the atmosphere and outer envelope layers.



$0.1 \le M/M_\odot \le 1.25$ (in steps of 0.05 $M_\odot$)

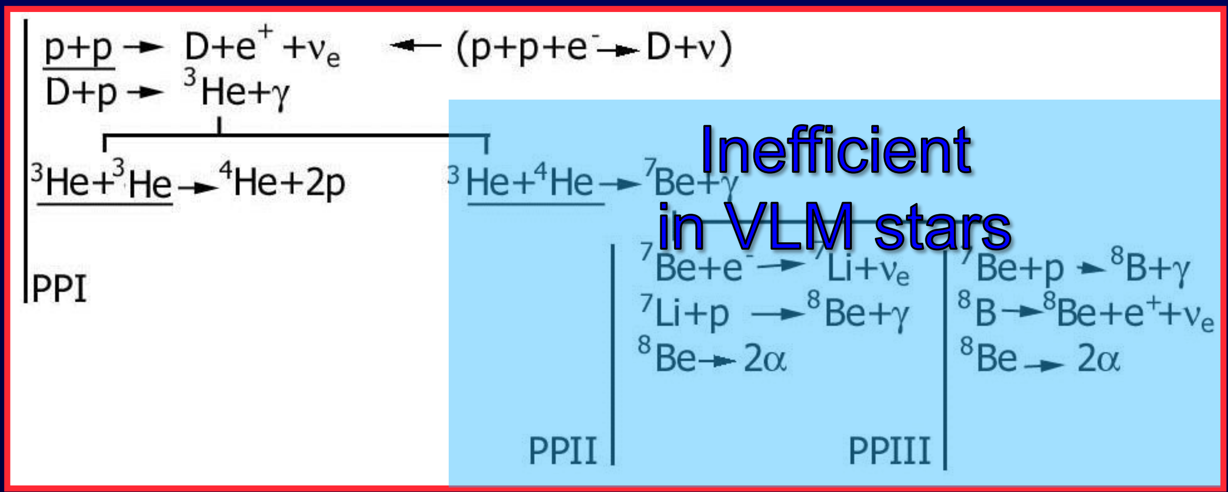
Spada et al. (2013)

- Extremely dense and cool objects

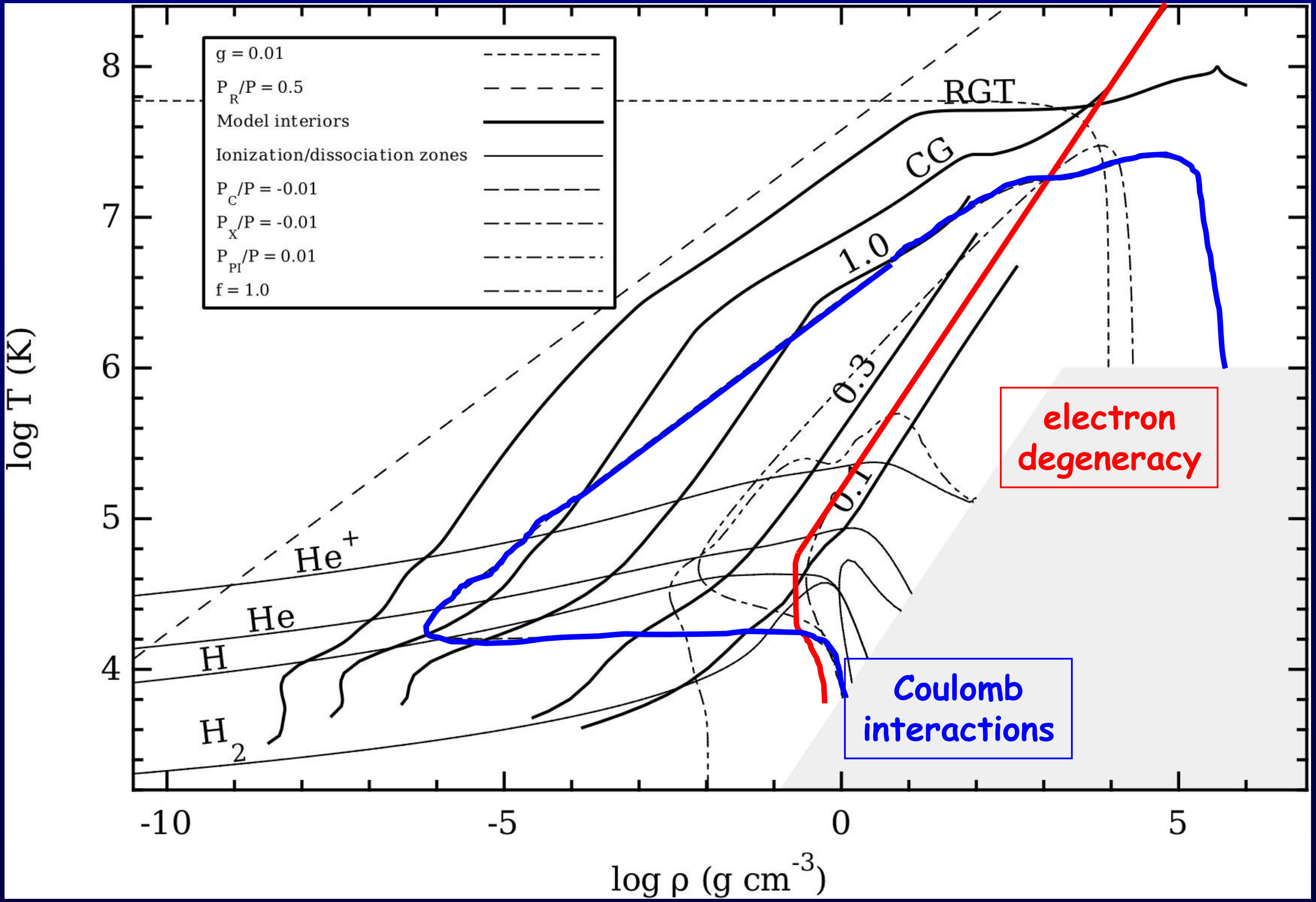
$M/M_\odot$	T_c	ρ_c	T_{phot}	ρ_{phot}
1.0	$\sim 1.6\cdot 10^7$K	~ 100g$\cdot$cm^{-3}	~6000K	$\sim 10^{-7}$ g$\cdot$cm^{-3}
0.6	$\sim 10^7$K	~ 150g$\cdot$cm^{-3}	~4000K	$\sim 10^{-6}$ g$\cdot$cm^{-3}
0.1	$\sim 5\cdot 10^6$K	~ 500g$\cdot$cm^{-3}	~2800K	$\sim 10^{-4}$ g$\cdot$cm^{-3}

EOS & opacity calculations in VLM regimes are complicated

- Models very sensitive to outer boundary conditions

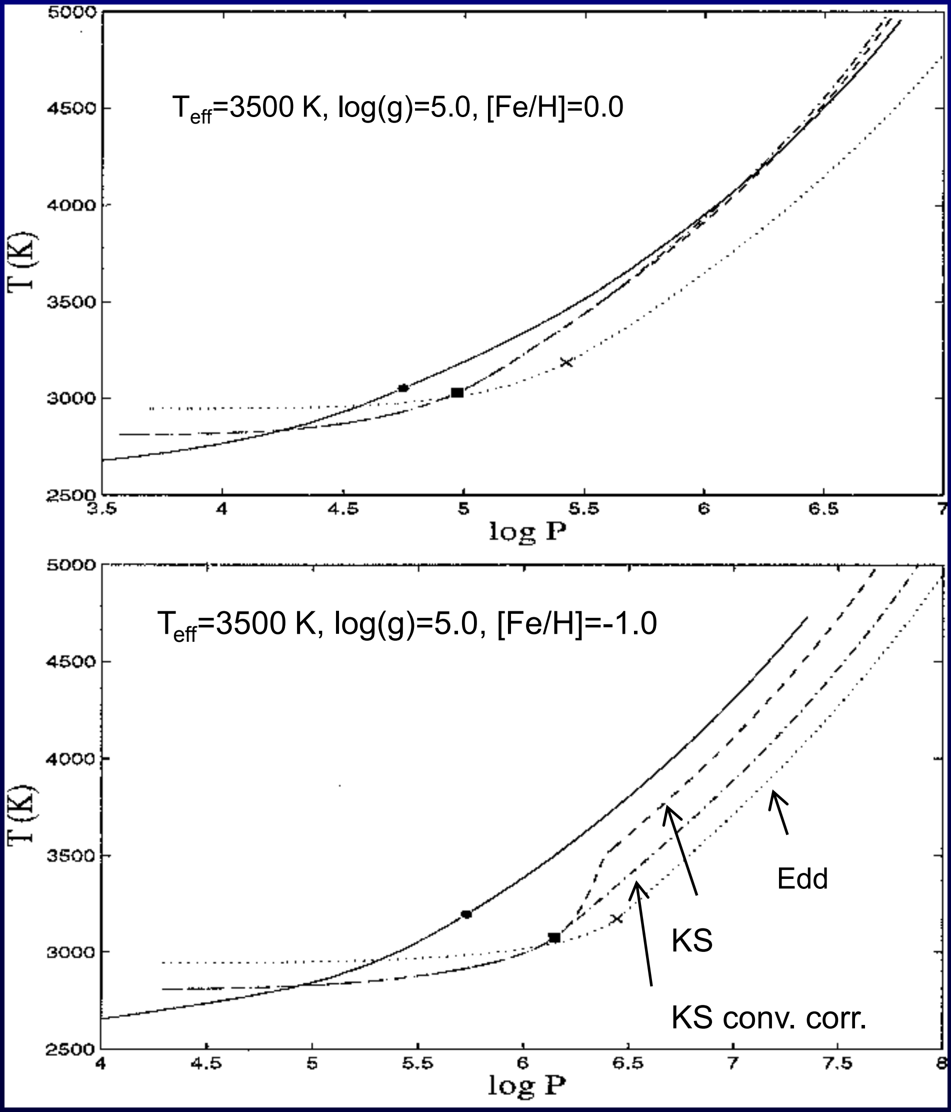


Equation of state



Outer boundary condition → Pressure (and T) at a reference optical depth τ

Chabrier & Baraffe (1997)



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

q(τ)=2/3 → Eddington grey

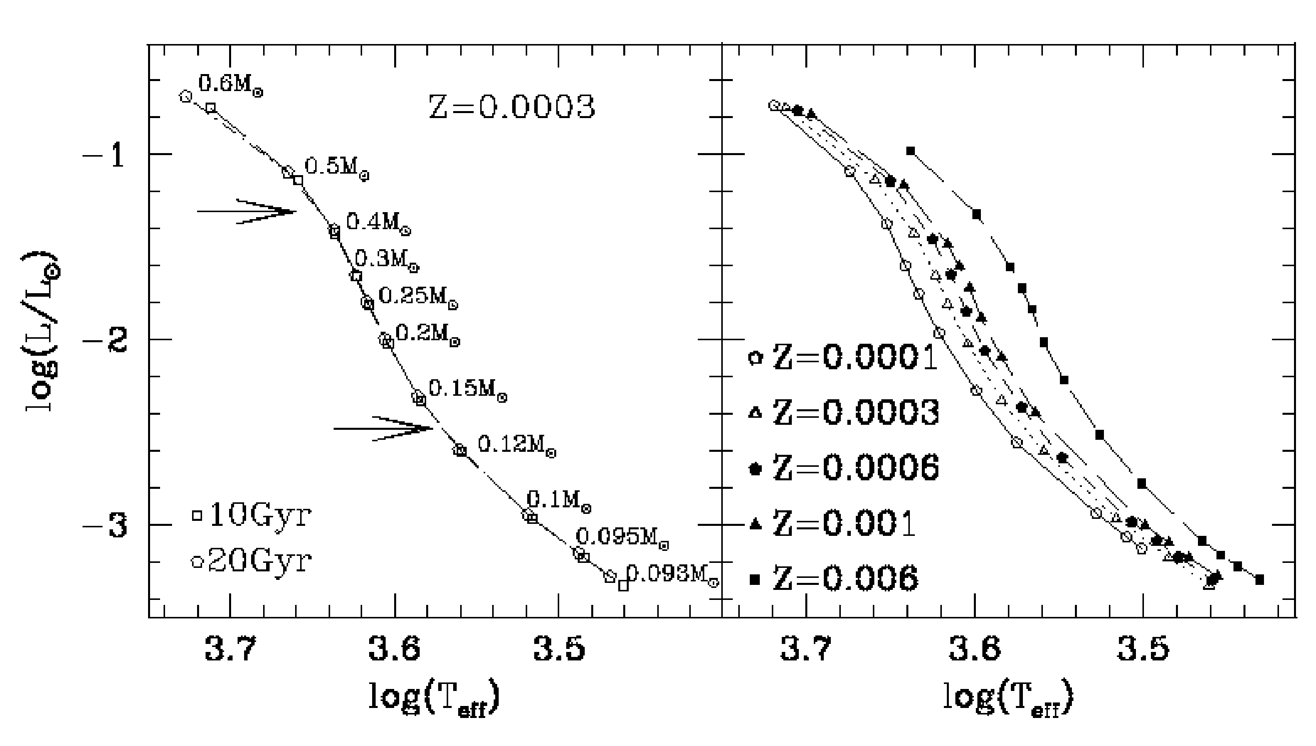
Krishna-Swamy (1966) gives a more complex q(τ) based on the Sun to account for non-greyness

Henyey et al. (1965) provide corrections for convection on T(τ) relationships

The values of (P_0, T) affect the interior thermal structure of VLM stellar models

The thermal stratification predicted by theoretical model atmospheres largely depends on the molecular and atomic opacities adopted in the computations

The VLM stars' main sequence



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

The II bending point (T_{eff}~3000K – M~0.15M_o) is due to the increase of electron degeneracy. As a consequence, models approach their degenerate equilibrium radius ($R \propto M^{-1/3}$)

Effect of boundary conditions on the H-R diagram

Cassisi and V. Castellani

mation, in order both to investigate ting model atmospheres in stellar btain an indication of the value of $T_{\rm eff}^{\rm crit}$. Figs 2 and 3 show the results of expected, even a quick inspection of t at effective temperatures around is achieved between the different e extension of B95 with Kurucz when $Z = 0.002$ one may notice in transition, between the $T(\tau)$ stellar es, which occurs at $T_{\rm eff} \approx 4400$ K for he same smooth transition occurs B95 models at $T_{\rm eff} \approx 4000$ K for a finding appears to be in good agree- Brett (1995a, his fig. 8) when com- spheres with the ATLAS9 results. $_{\rm ff} < 4000$ K the K93 model sequence $T(\tau)$ models is simply a result of the the Kurucz (1993) model atmo- odels computed by adopting the on are hotter and brighter than the rger discrepancy is present at

B95 models agree with K93 ones at $T_{\rm eff}$ mum discrepancy between the $T(\tau)$ structures computed by adopting acc spheres appears at $T_{\rm eff} \approx (4100\text{–}4200)$ differences of the order of ≈ 180 K in T $L_\odot$.

3 STELLAR MODELS

For each given metallicity, we sele sequence of models the one obtained proper range of validity) the $T(\tau)$, K models, ensuring that a fine and smoot between the models computed under di about the outer boundary conditions. Fi of present 'best' MS in the HR diagra assumptions about metallicity. Tables 1 sity, effective temperature, absolute vis predicted colours (in the standard Johns VRI and the CIT system for K) fo models for the various selected metal and colours have been evaluated by a

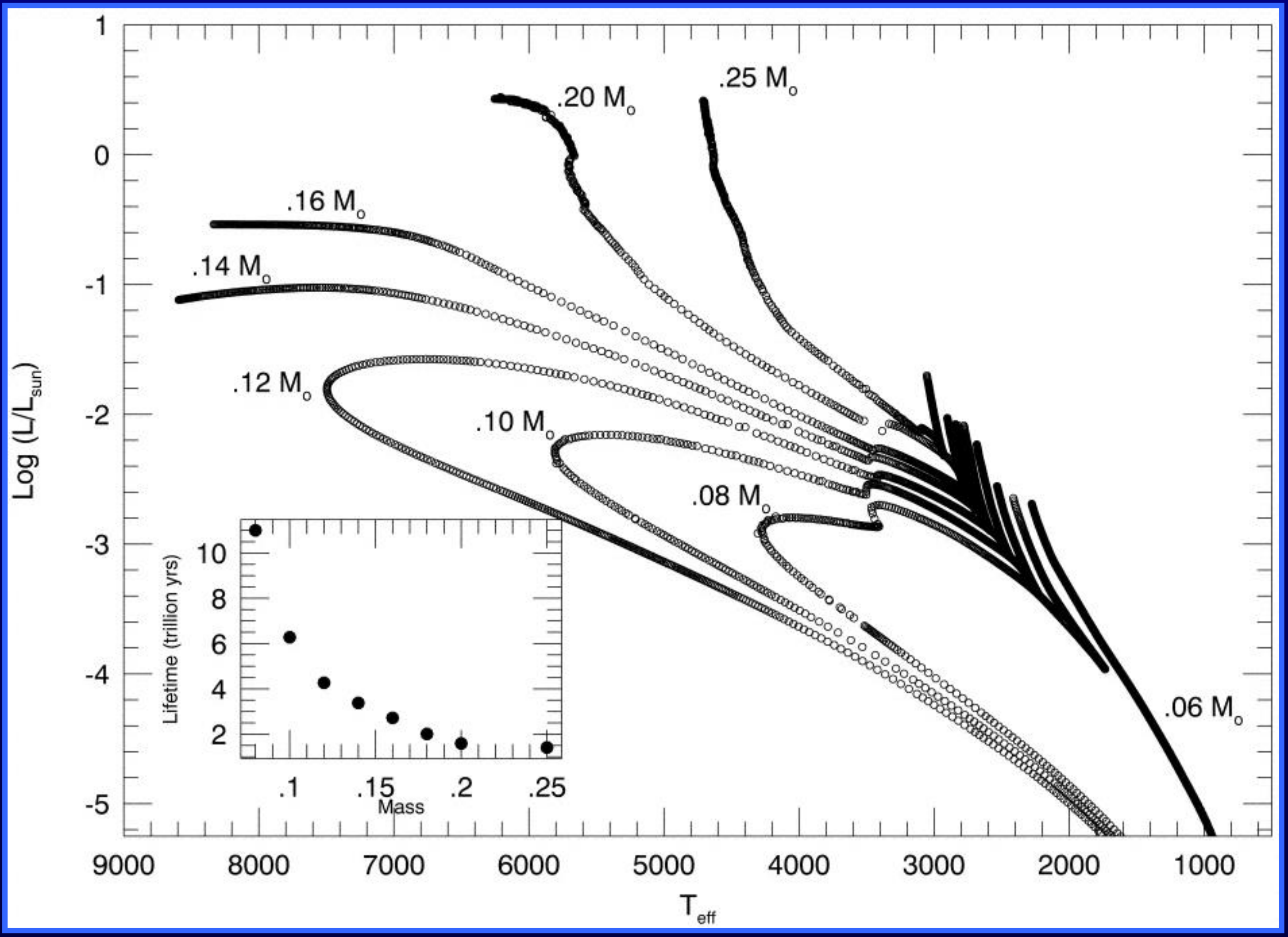
log($T_{\rm eff}$)

and only minor changes for stars with mass around 0.6 $M_\odot$. Since in the present work we are mainly dealing with stellar models with mass $M \le 0.6\ M_\odot$, the results are not affected by the choice of the mixing length parameter. Moreover, as far as concerns the model atmosphere computations, B95 has clearly shown that a variation of the mixing length parameter in the range 1.0 to 2.0 produces only minor effects at effective temperatures around 4000 K, and that these structural effects decrease rapidly, therefore decreas-

log($T_{\rm eff}$)

Brocato et al. (1998)

The long-term evolution of VLM stars



Laughlin et al. (1997)

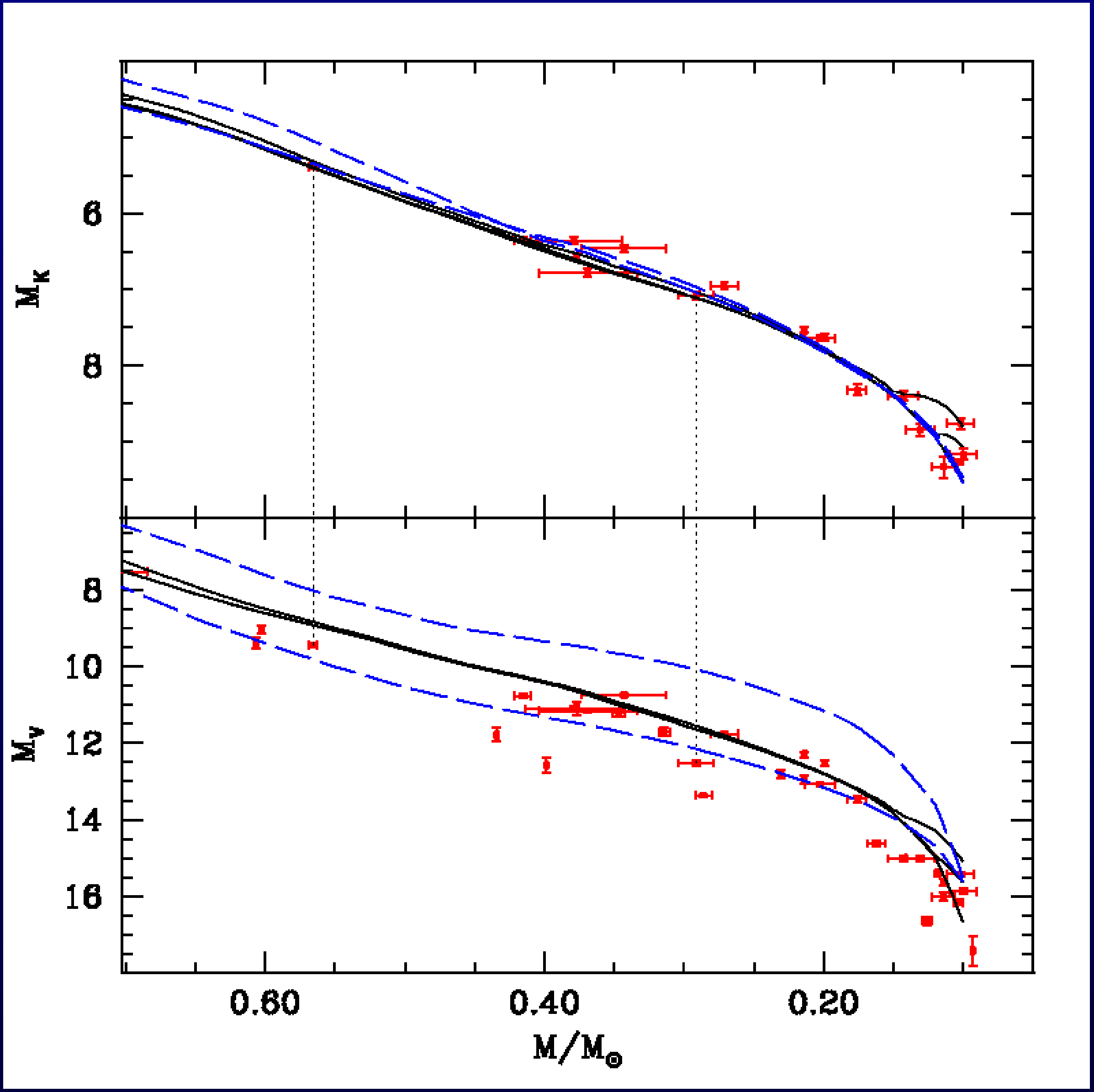
We have just completed the calculation of a first baseline, state-of-the-art set of standard (no-rotation, no magnetic fields) VLM models, from the pre-MS until ages ~15 Gyr, for a large range of initial metallicities (scaled-solar metal mixture). This is part of the wider scope new BaSTI project

People directly involved (WP121 110):

- **Santi Cassisi (INAF – Collurania Astronomical Observatory – Italy)**
- **Maurizio Salaris (ARI, Liverpool John Moores University - UK)**
- **Adriano Pietrinferni (INAF – Collurania Astronomical Observatory – Italy)**

Are current VLM stellar models reliable?

Mass-luminosity relationships

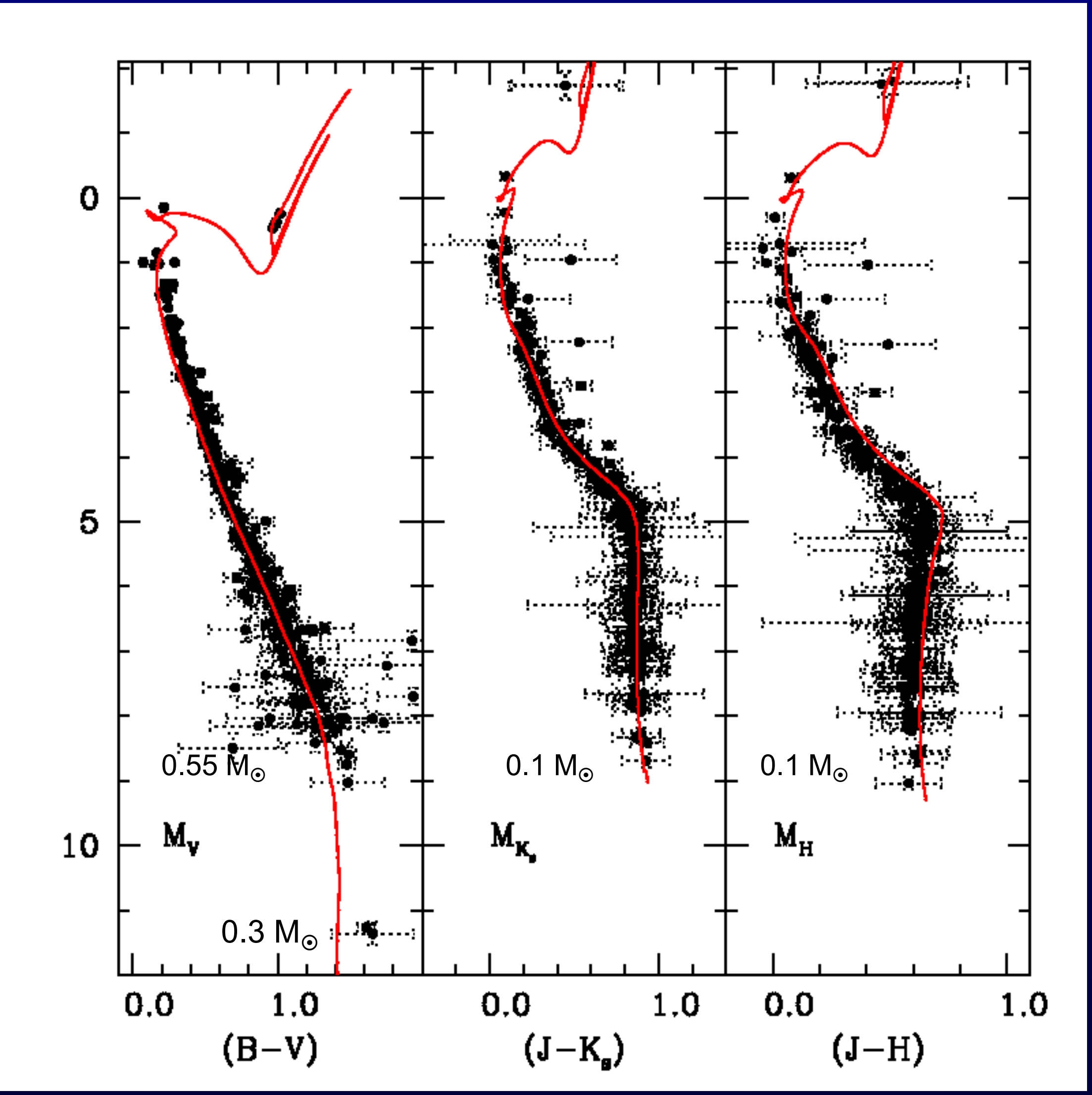


[Fe/H]=0.06
300 Myr, 1Gyr, 10 Gyr (black)

[Fe/H]=−0.4, +0.4
10 Gyr (blue dashed)

Data from Delfosse et al. (2000)

VLM stars in the Hyades



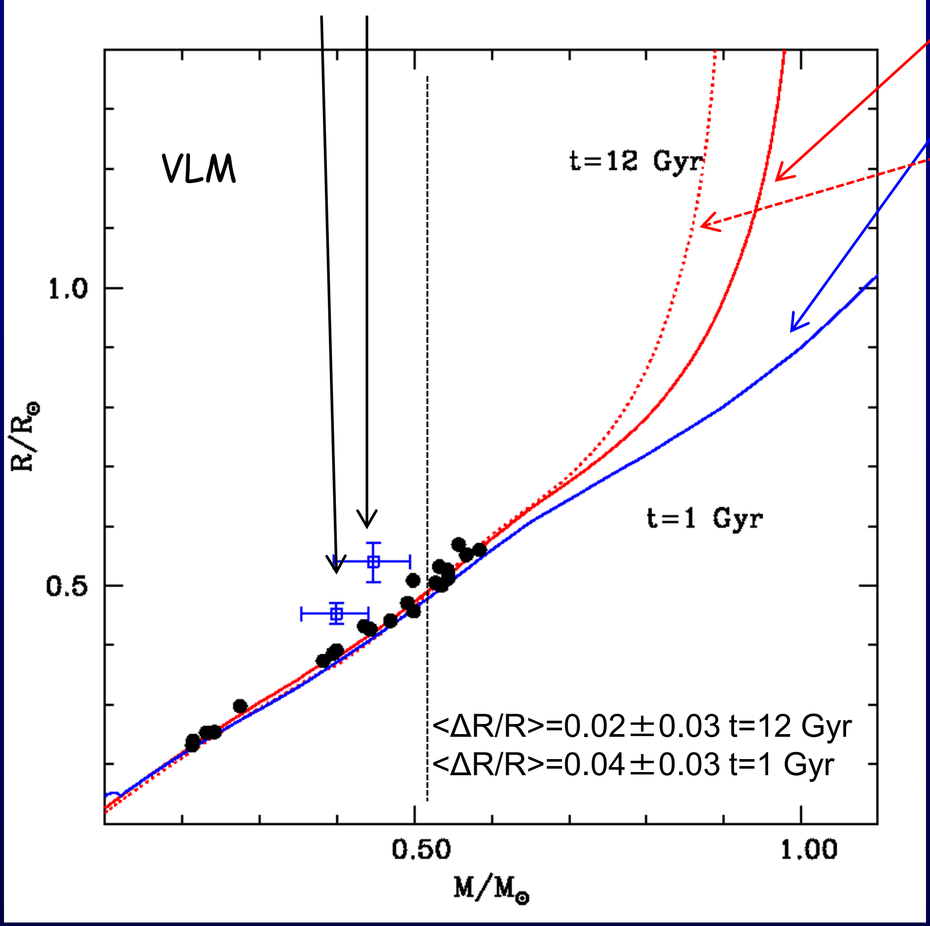
2MASS data from Kopytova et al. (2016)
Optical data from Röser et al. (2011)

900 Myr, [Fe/H]=0.06

Mass-radius relationship

Unevolved components

KELT J041621-620046

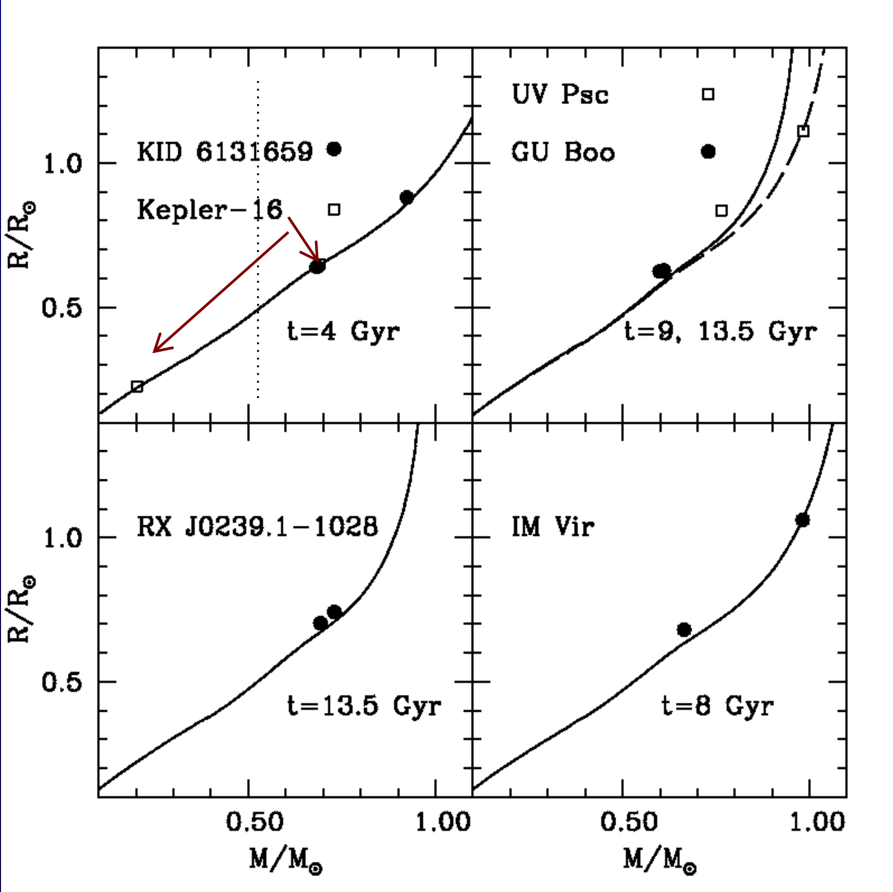


[Fe/H]=0.06

[Fe/H]=-0.40

At least one evolved component

[Fe/H]=0.06

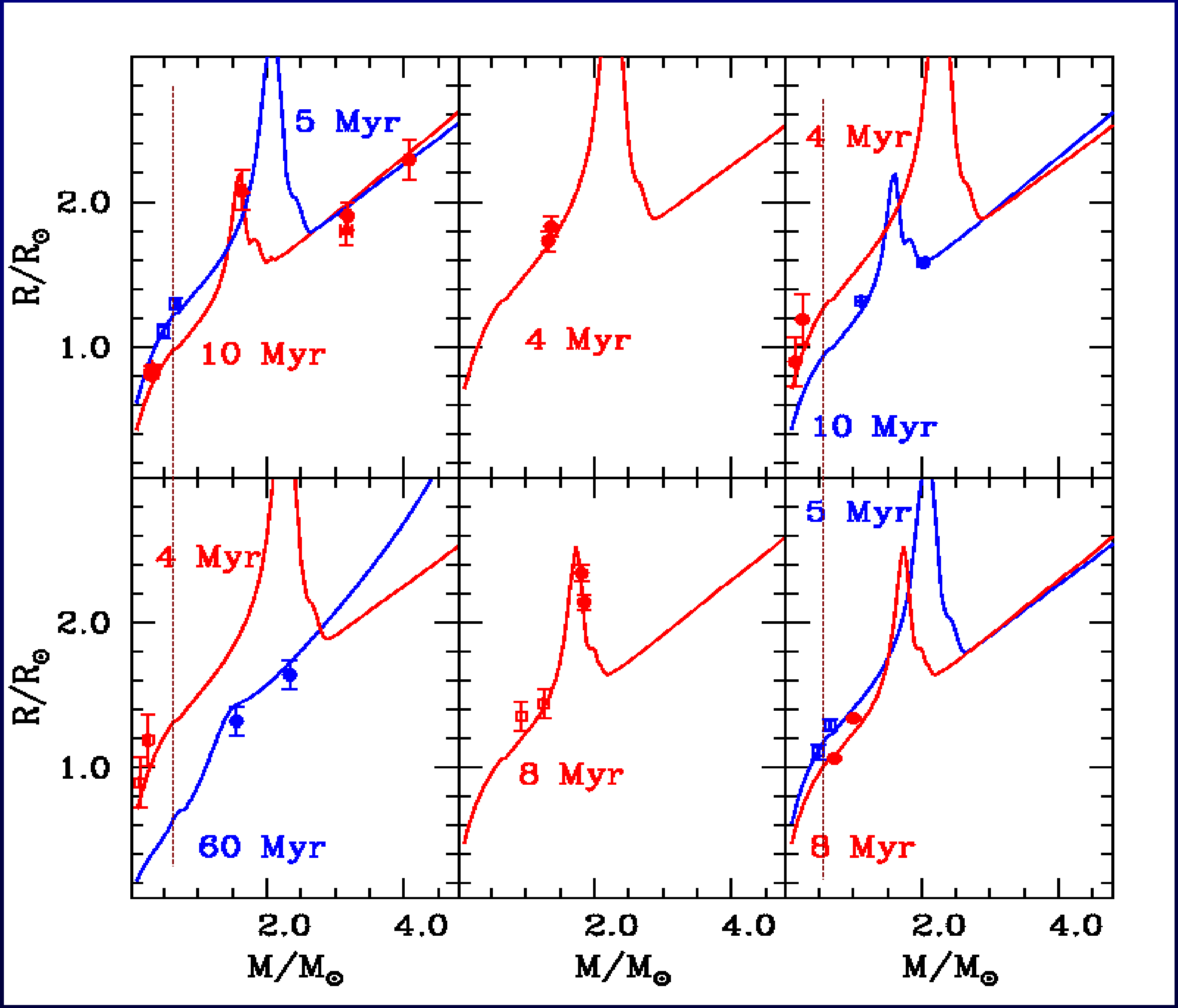


DEB data compiled by Feiden & Chaboyer (2012 – random mass and radius uncertainties less than 3%) + Lubin et al. (2017)

Systematic uncertainties on determinations of R are likely ~3% (discussion in Feiden & Chaboyer 2012)

Pre-MS VLM

[Fe/H]=0.06



Data from Stassun et al. (2014)

Conclusions and WP121 110 roadmap

For several observed VLM stars there isn't a clear discrepancy with radii predicted by our baseline models. In other cases systematics do appear clearly. They are likely correlated with the strength of magnetic activity (Spada et al 2013)

Extend comparisons of our baseline models to additional datasets

Calculate baseline α-enhanced model grid

Calculate rotating VLM models (rotation already included in the code)

Include magnetic field effects, following Feiden & Chaboyer (2012) methods