The Toulouse Geneva Evolution Code (TGEC)

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Main features of TGEC

- TGEC is a 1-D stellar evolution code
- originates from the Geneva code in the early 90's, hence the name
- used as a testbed for non-standard physics (at that time) -> radiative diffusion, accretion of planets, fingering mixing, rotational mixing, etc.
- to date, one the few codes implementing self-consistent radiative diffusion modelling (with CESTAM and MESA)

Main features of TGEC

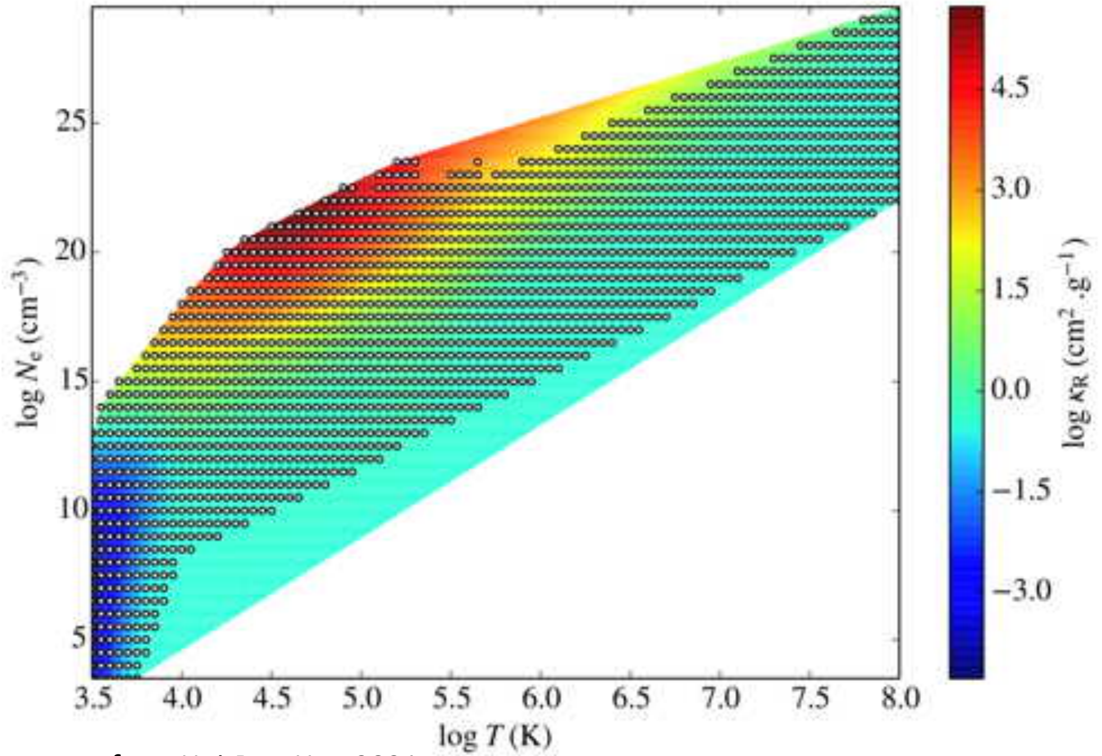
- Summary of the implemented microphysics:
  - nuclear reaction network according to the NACRE compilation + LUNA rate for the $^{14}N(p,\gamma)^{15}O$ reaction
  - OPAL 2001, OPAL 2005 or MHD equations of state
  - Rosseland opacities computed on-the fly with the Opacity Project (OP) cross-sections (OPAL tables also available, Wichita opacs @ low T)
  - revised opacity for Ni
  - atomic diffusion with the Chapman & Cowling approach (test atom approximation in a buffer medium)
  - diffusion coefficients from Paquette et al. (1986)
  - radiative accelerations computed with the Singled Valued Parameters (SVP) method of G. Alecian & F. LeBlanc. On-the-fly calculations from the Opacity Project monochromatic opacities in progress...

Main features of TGEC

- Summary of the implemented macrophysics:
  - convection with either the MLT, Canuto & Mazzitelli (1991) or Canuto et al. (1996) formalisms
  - fingering ("thermohaline") mixing with the prescription of Brown et al. (2013)
  - rotational mixing through meridional circulation:
    - Zahn (1992) -> self-consistent differential rotation, μ-gradient effects omitted
    - Vauclair (1999) -> solid rotation, μ-gradient effects included
  - other parametric turbulent mixing prescriptions (e.g., full mixing down to the Z-bump, etc.)
  - effect of engulfment of planets
  - mass loss (removal of the outermost layers at each time step)

Some implementations in more details

- On-the-fly computation of the Rosseland mean opacities (RMO):
  - mandatory when the chemical composition varies with depth
  - computing time too huge with OPCD routines (computation from scratch at each call, including the reading of the data)
  - new strategy needed:
    ① RMOs computed at the beginning of the evolution run for all the OP (T, N_e) grid points with the initial abundances and stored in memory



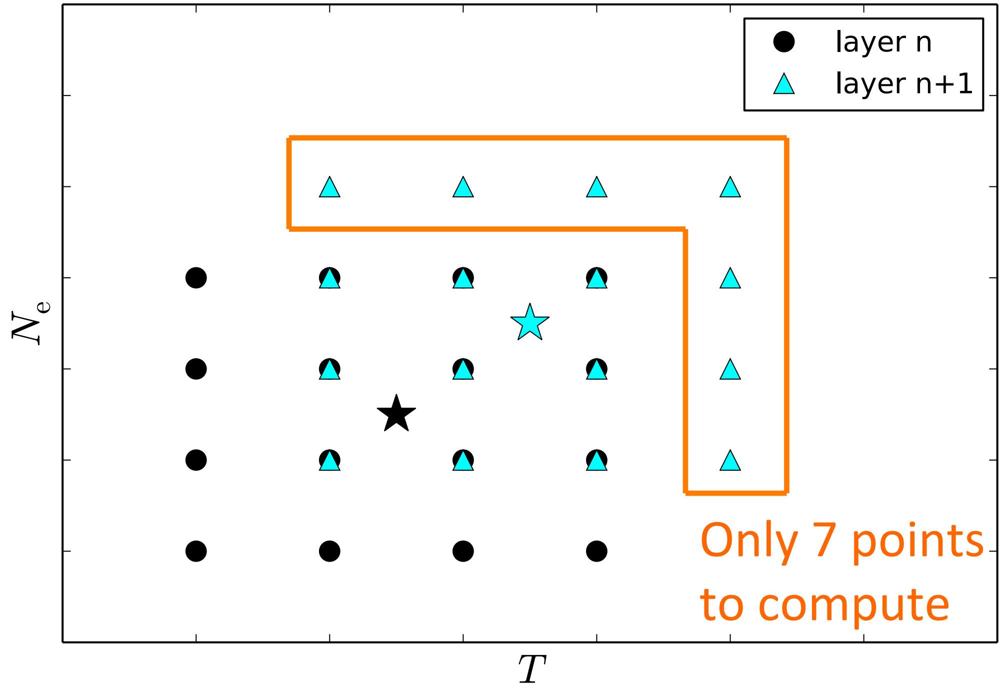
from Hui-Bon-Hoa 2021

Some implementations in more details

② for a layer having the initial abundances, pick the RMOs of the 16 points surrounding the (T, N_e) of the layer + bi-cubic interpolation

③ if the abundances depart from the initial ones, (parallelised) computation of the RMOs for the 16 points surrounding the (T, N_e) values of interest + bi-cubic interpolation

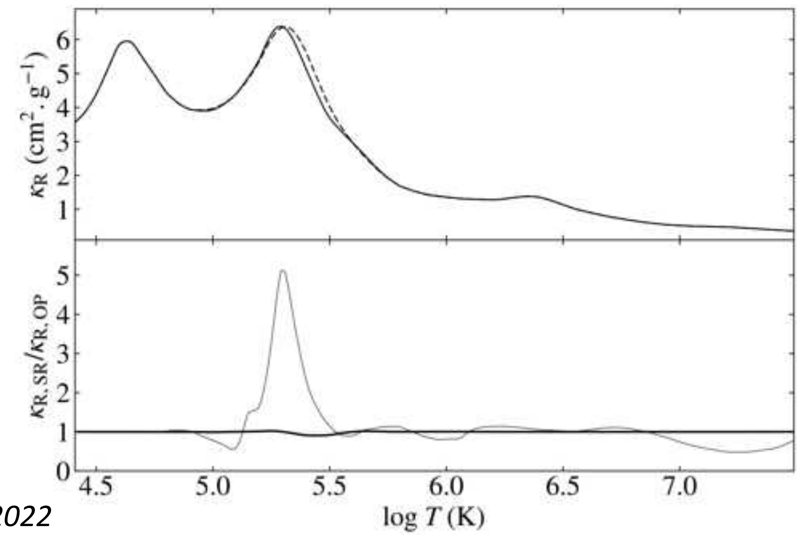
④ if the next layer of the model has the same abundances (e.g., convective zone), compute the RMOs only for the points not considered in the previous layer

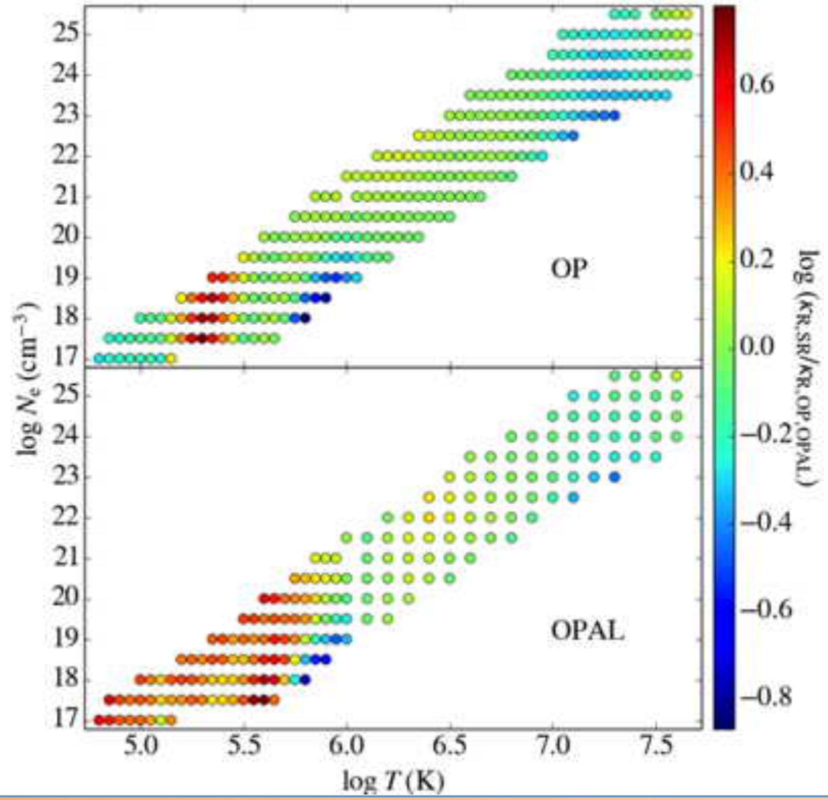


- these new routines are also implemented in CESTAM ! (also, same approach recently in MESA)

Some implementations in more details

- New nickel opacities:
  - OP cross-sections for Ni extrapolated from Fe -> underestimated in the Z-bump (e.g., Turck-Chièze et al. 2016)
  - replaced in the OP files by detailed computations with the SCO-RCG code (Hui-Bon-Hoa, Pain & Richard 2022)
  - Ni RMOs enhanced up to 6 times in the *Z*-bump, but global RMOs weakly changed





from Hui-Bon-Hoa et al. 2022

Some implementations in more details

➢ Radiative accelerations:

- express the momentum transfert through photon absorptions for each chemical species
- SVP, a parametric method using analytic functions and pretabulated coefficients (to avoid the integration over frequencies ➔ save time!)
  - ✧ ex.: absorption by spectral lines ...

instead of

$$g_{il} = (n_{ik}/A_i m_p c n_i) \int_0^\infty \sigma_{i,km} \phi_\nu \mathrm{d}\nu$$

radiative flux (stellar structure)

cross-section (chemical elem.)

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let's write

$$g_{i,\mathrm{line}} = q\varphi_i^* \left(1 + \xi_i^* C_i\right) \left(1 + \frac{C_i}{b\psi_i^{*2}}\right)^{\alpha_i}$$

C_i=concentration of element *i*

Stellar structure

SVP parameters (chemical elem.)

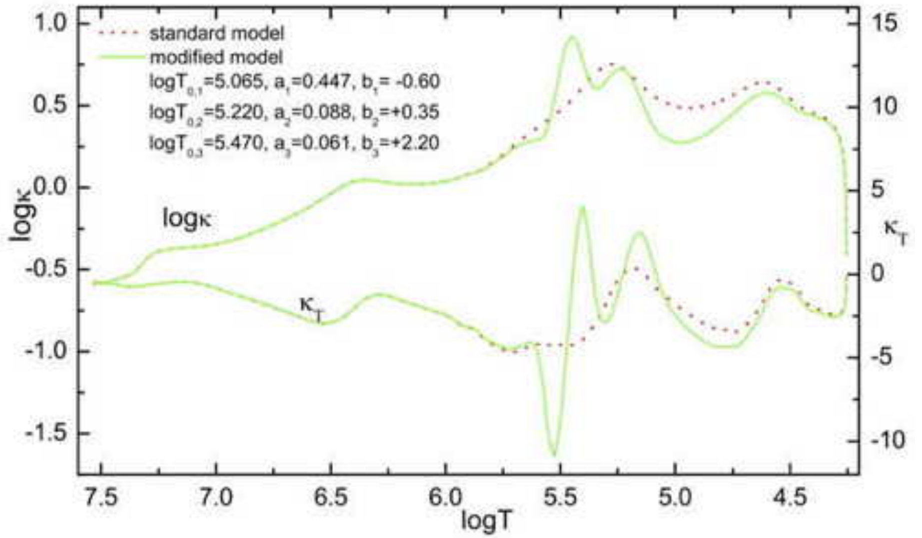
Some implementations in more details

with $q = 5.575 \times 10^{-5} \frac{T_{\rm eff}^4}{T} \left(\frac{R}{r}\right)^2 \frac{1}{A}$ and $b = 9.83 \times 10^{-23} \frac{N_{\rm e} T^{-1/2}}{X_{\rm H}}$.

- SVP parameters from 1 to 5 $M_\odot$ in TGEC (LeBlanc & Alecian 2004), now available for 17 masses from 1 to 10 $M_\odot$ (Alecian & LeBlanc 2020)
- weak and smooth variation of the SVP params vs. mass ➔ interpolations if needed
- 12 (+1) elements considered: C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, and Fe, + Sc (1.5 and 2 $M_\odot$, LeBlanc & Alecian 2013)
- publicly available: http://gradsvp.obspm.fr

Recent studies with TGEC

- Role of atomic diffusion in massive Main Sequence pulsators:
  - oscillation modes not satisfactorily reproduced with models having homogeneous abundances (lack of opacity in the Z-bump, where the pulsations are driven through κ-mechanism)

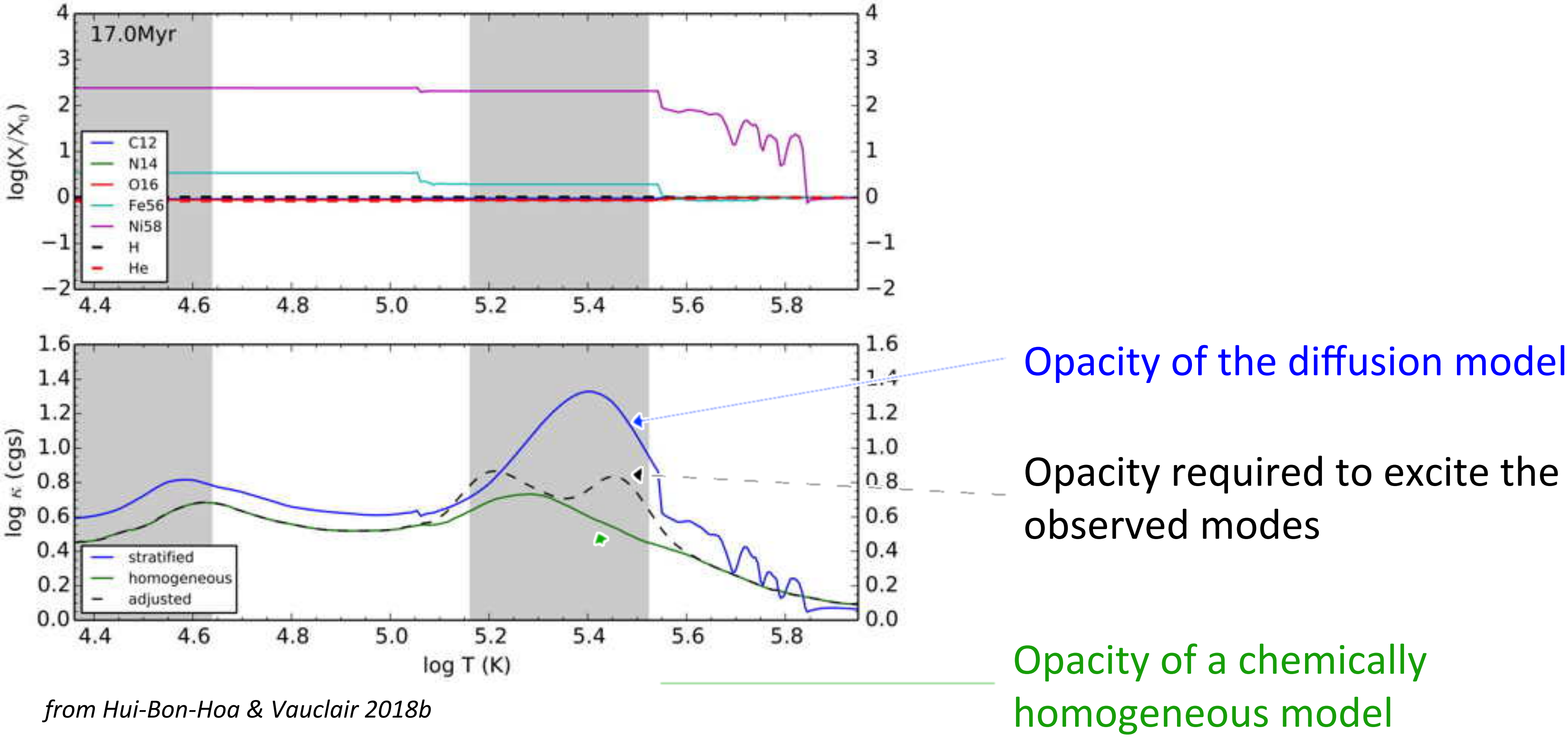


from Daszynska-Daszkiewicz et al. 2017

  - to have the required opacity
    - ✧ available opacities underestimated (e.g., Bailey et al. 2014)
    - ✧ accumulation of Fe-peak elements in the Z-bump (e.g., Pamyatnykh et al. 2004)

Recent studies with TGEC

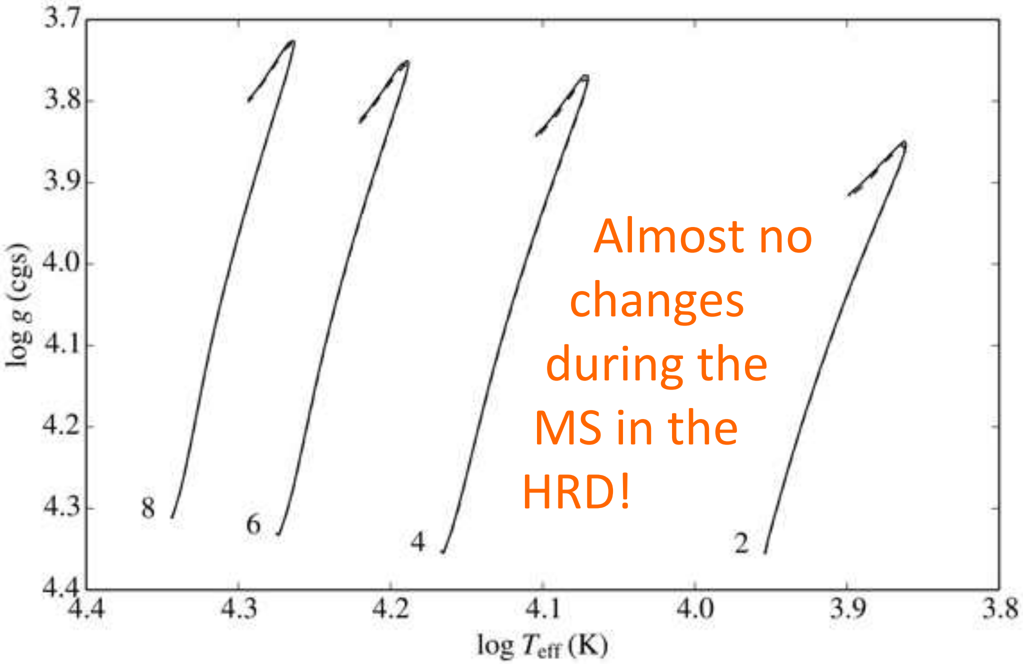
- Role of atomic diffusion in massive Main Sequence pulsators:
  - evolution of a 9.5 $M_{\odot}$ model with atomic diffusion, fingering mixing and mass loss (Hui-Bon-Hoa & Vauclair 2018a,b)

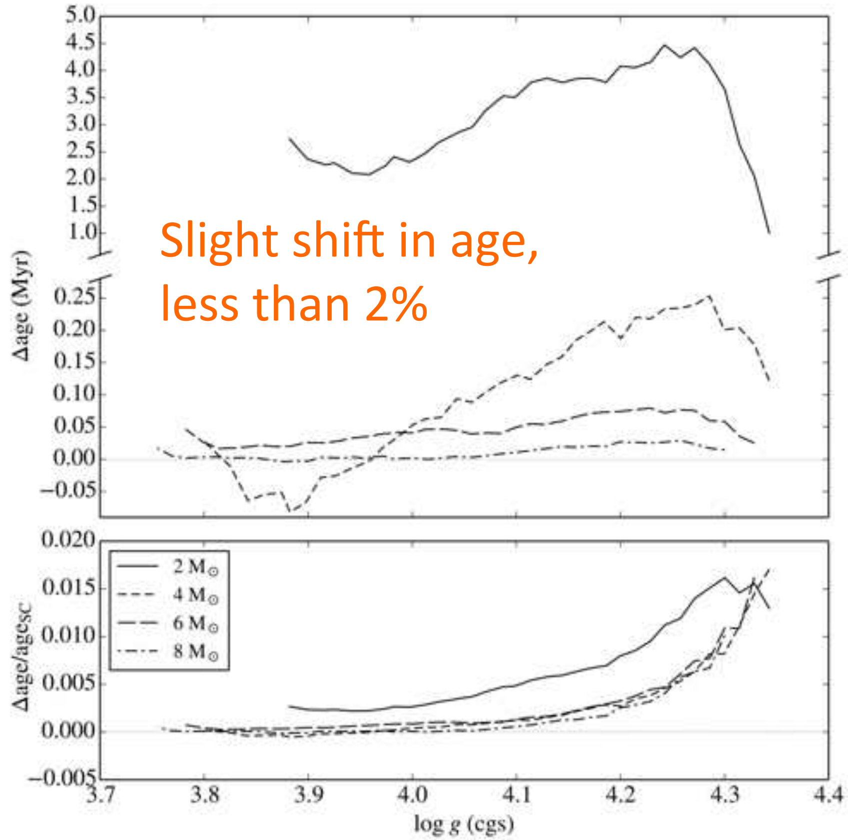


from Hui-Bon-Hoa & Vauclair 2018b

Recent studies with TGEC

- Influence of fully consistent opacities on fundamental parameters:
  - evolution codes often use tabulated Rosseland opacities (not always consistent with the detailed chemical composition in Z)
  - when RMOs are computed consistently with the abundances ➔ age changes

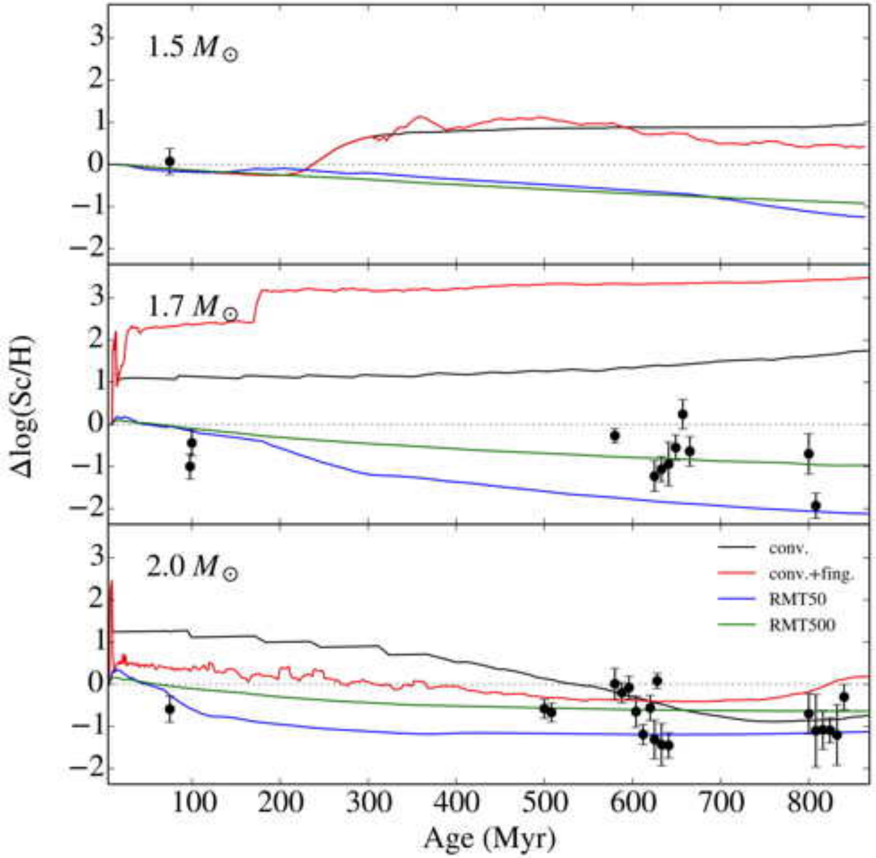




from Hui-Bon-Hoa 2021

Recent studies with TGEC

- Modelling of the Sc abundance evolution in Am stars:
  - Am stars (aka metallic-line stars) show surface abundance anomalies (Ca and Sc underabundant, heavy elements overabundant)
  - various transport process scenarii:
    - without mass loss (convection only, convection + fingering mixing, full mixing down to the Z-bump, "RMT")
    - RMT models give the best overall agreement

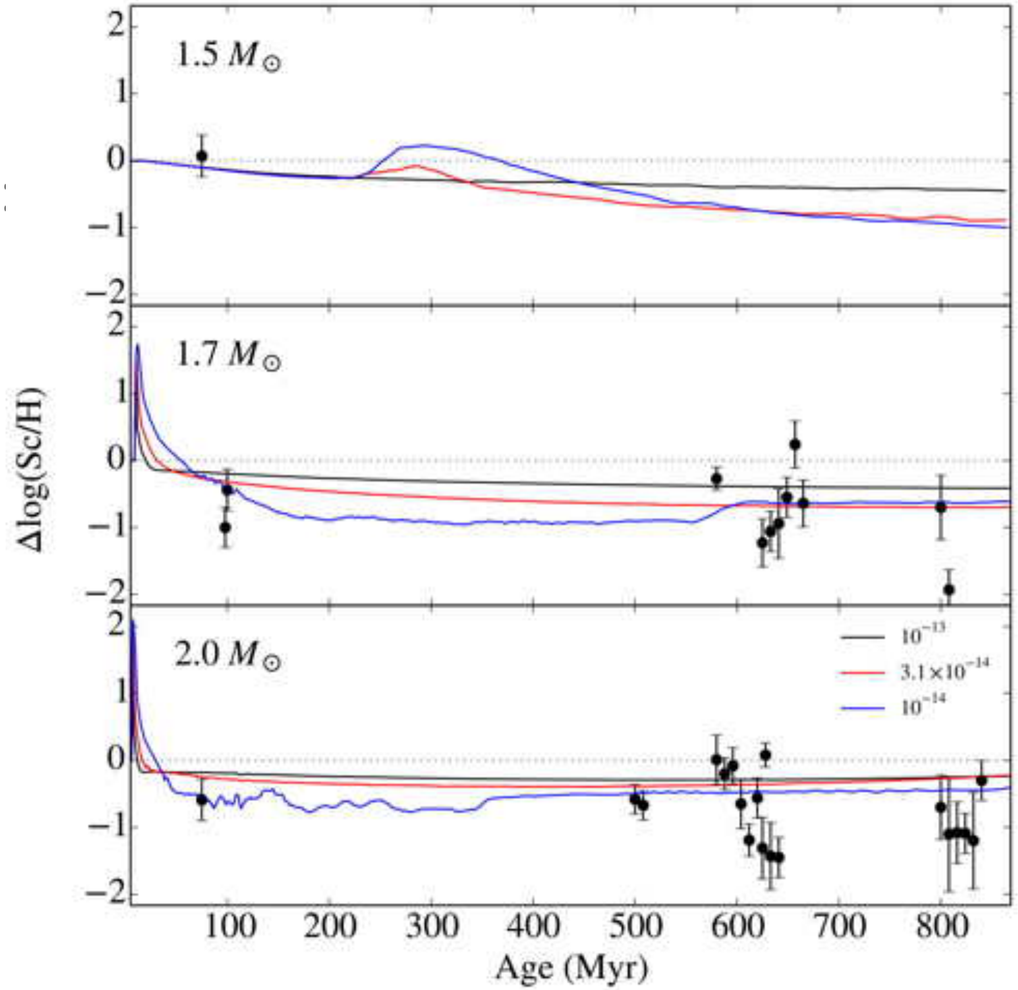


from Hui-Bon-Hoa et al. 2022, submitted

Recent studies with TGEC

➢ Modelling of the Sc abundance evolution in Am stars:

- various transport process scenarii:
  - ✧ with mass loss (and convective mixing only)
  - ✧ mass-loss rates in [10^{-14};10^{-13}] $M_\odot$/yr (consistent with observed values)
  - ✧ all the rates considered consistent with observed abundances



from Hui-Bon-Hoa et al. 2022, submitted

Merci de votre attention, à vos questions !