Evolution of low- and intermediate mass stars

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thermohaline mixing

mass loss and opacities

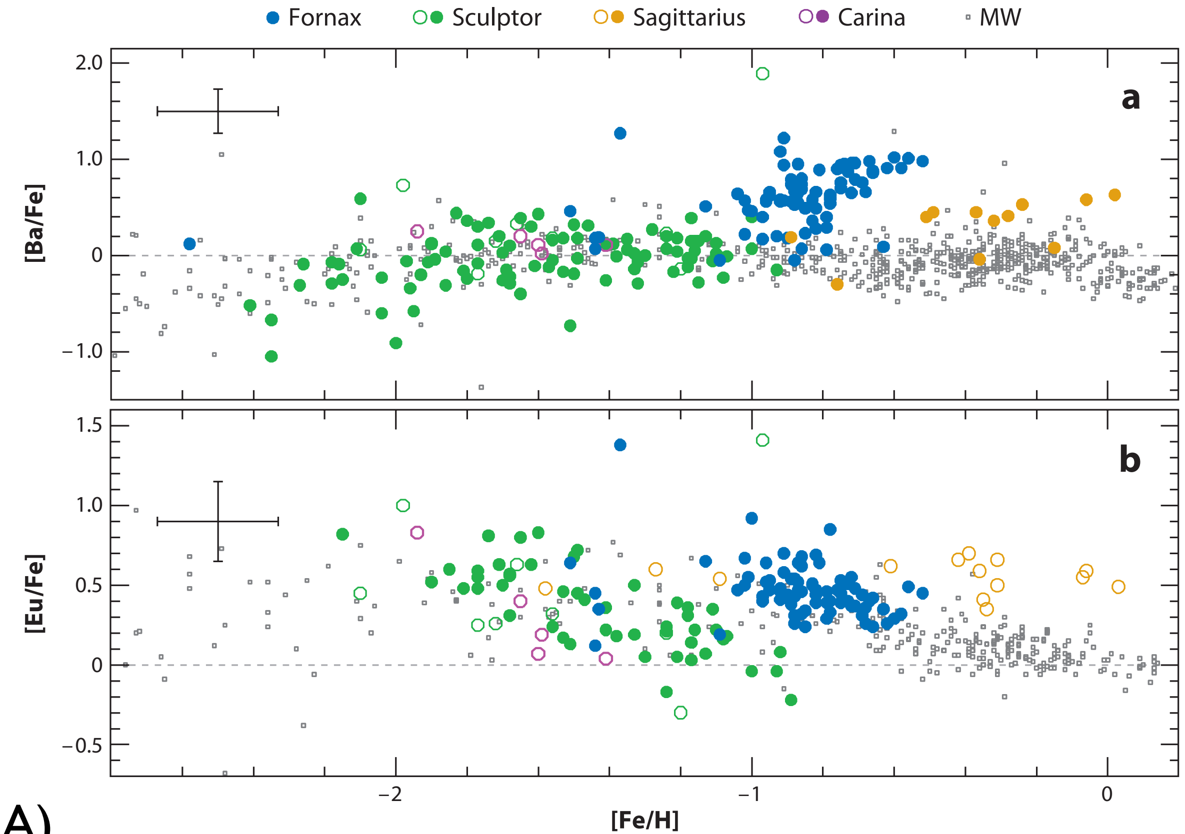
rotation

convection

- ^{13}C-pocket
- proton-^{12}C combustion

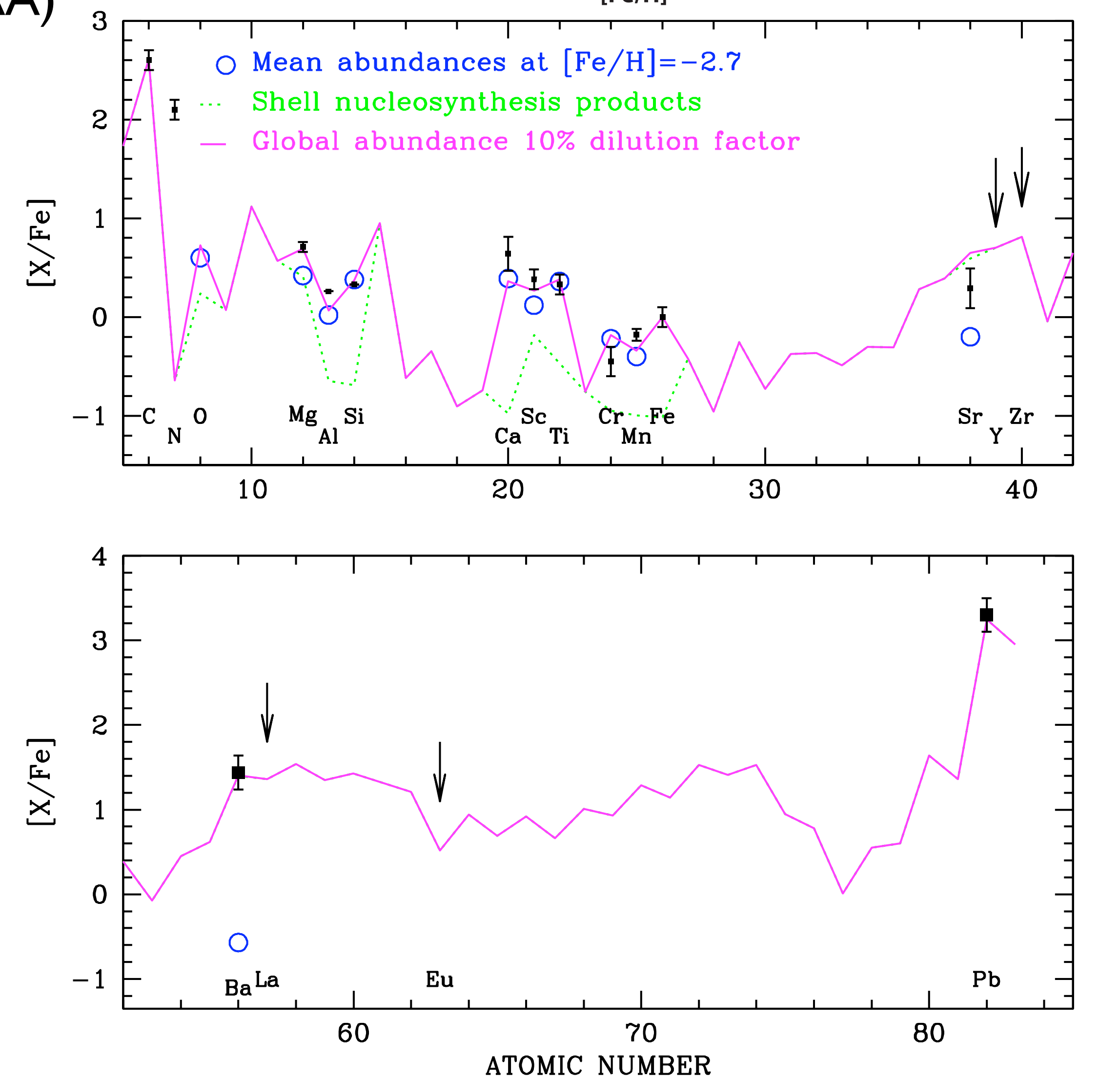
Motivation

- understanding SFH and chemical evolution in dSph galaxies
- constrain nucleosynthesis processes, e.g. Eu vs α-elements
- near-field cosmologie: identify the building blocks of our galaxy



Tolstoy etal 2009 (ARAA)

- abundances in extremely enriched very metal-poor stars
- stellar archeology: find the nucleosynthetic signature of the first stars in the Universe



Lucatello etal 2004

how?

Multi-physics and multi-scale simulations:

Multi-physics:

- nuclear physics, nucleosynthesis
- evolution of the star: atomic, plasma, hydro, EOS under extreme conditions
- stellar explosion

Multi-scale (e.g. time):

Evolution time: 10^0 to 10^3yrs (log t/s = 7 … 11)
Flash-burning (combustion) times: hours to days (log t/s = 3 … 5)
Convective mixing/Nuclear reaction time: minutes (log t/s = 1 … 2)
Sound crossing time: seconds (log t/s = 0 … 1)
n-capture time scale: < seconds (log t/s < 0)

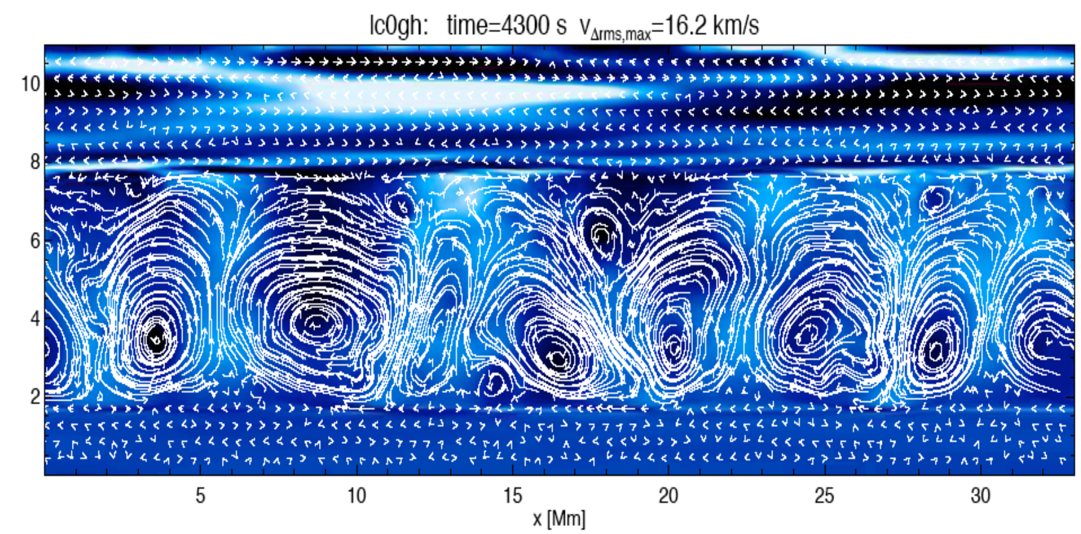
How to respond?

Combine different simulation approaches for different components ...

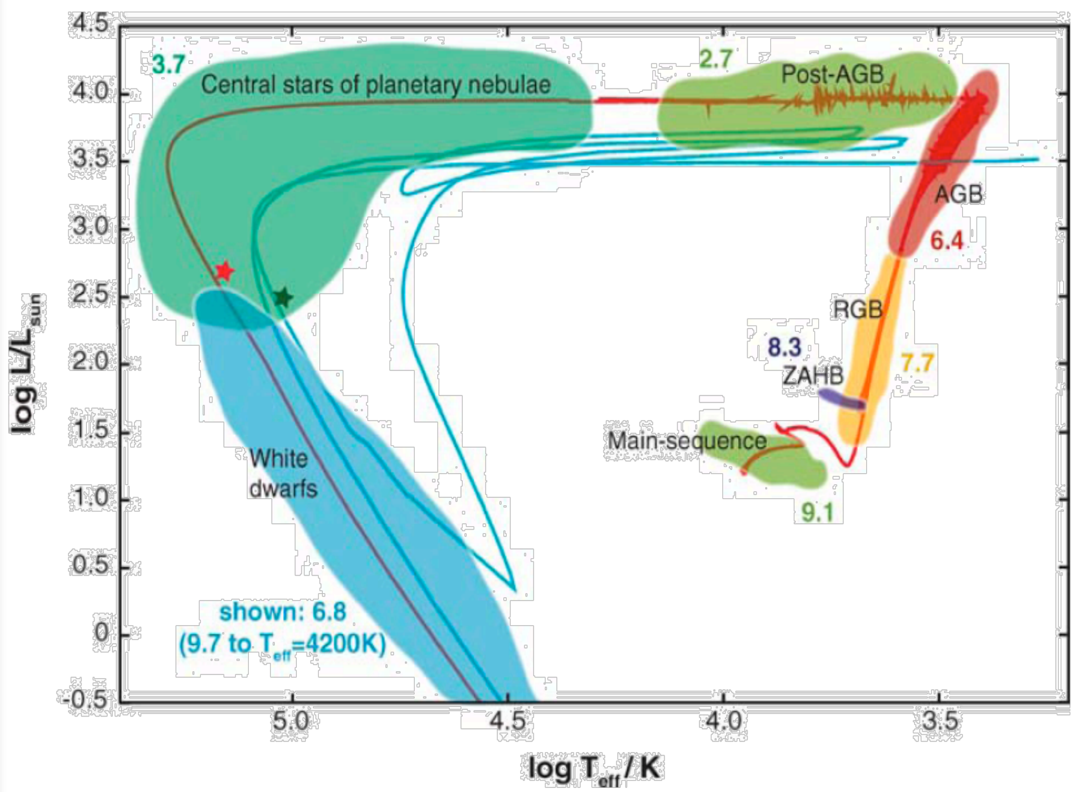
how?

The three simulation components

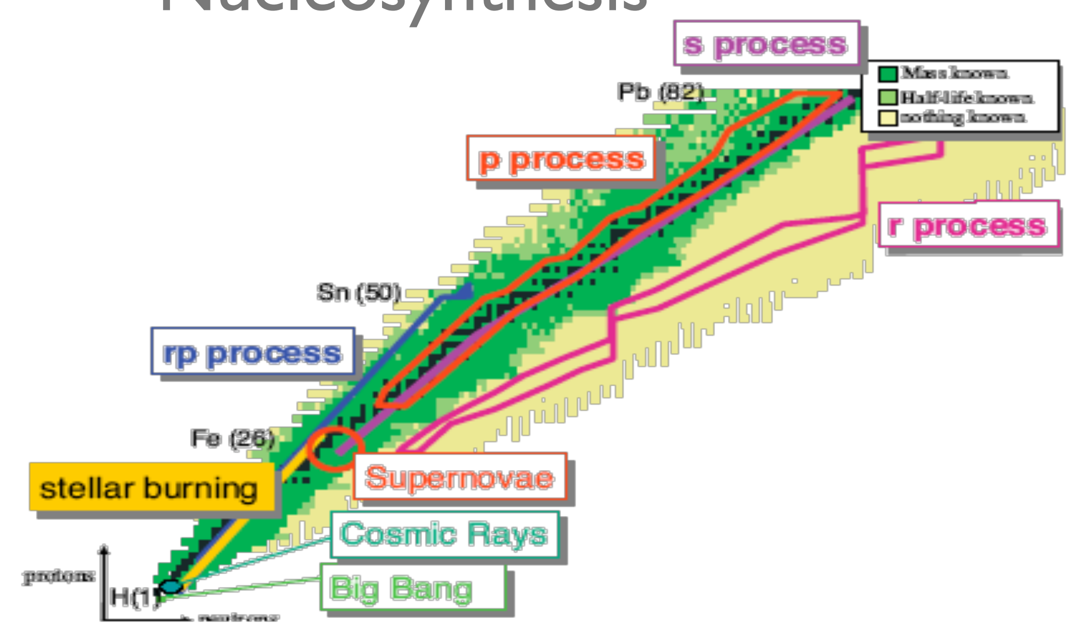
Stellar hydrodynamics



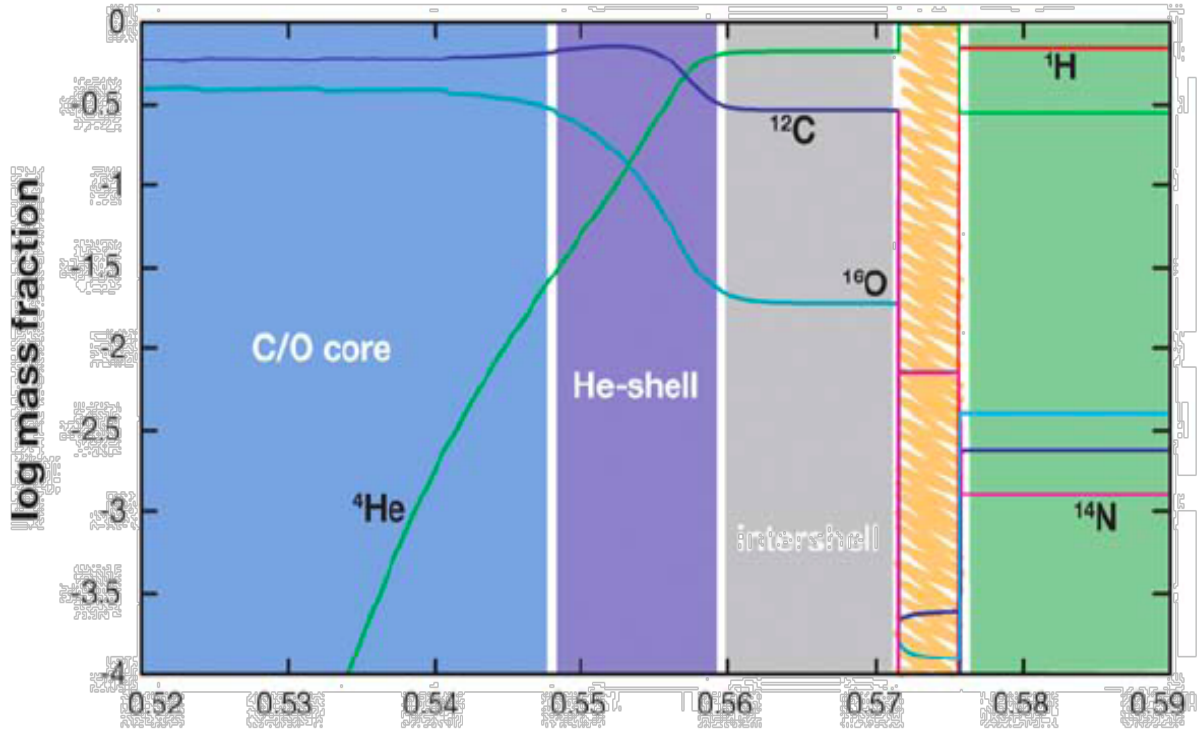
Stellar evolution

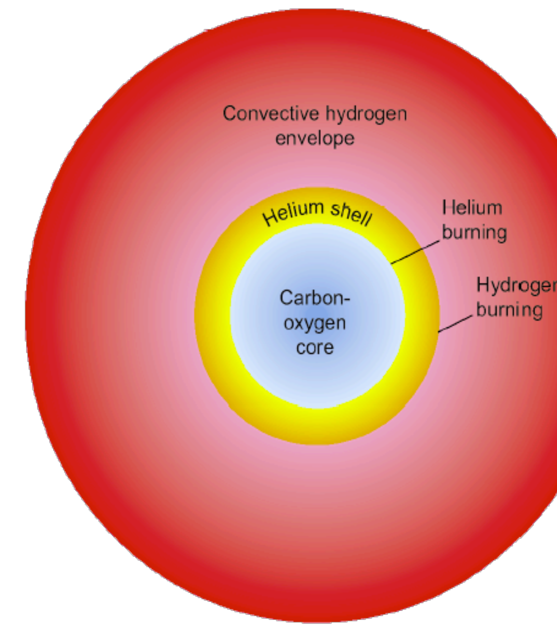


Nucleosynthesis



Stellar evolution: macroscopic/global evolution of stars





Assumptions:
- Spherical symmetry
- Hydrostatic equilibrium (u=0)

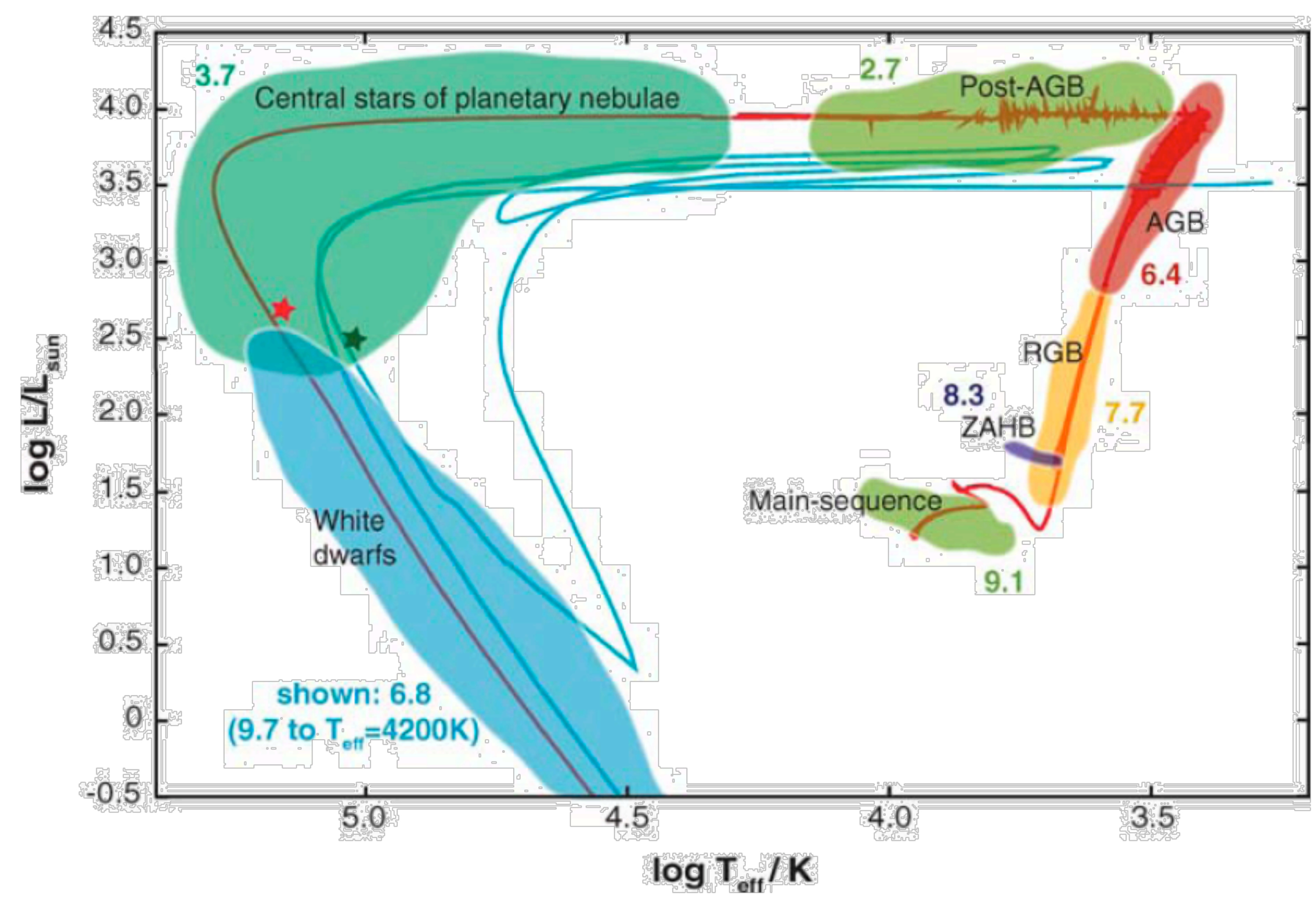
Complete evolution of intermediate mass star

Conservation laws:

$$\frac{d\mathcal{M}}{dr} = 4\pi r^2 \rho(r)$$ mass

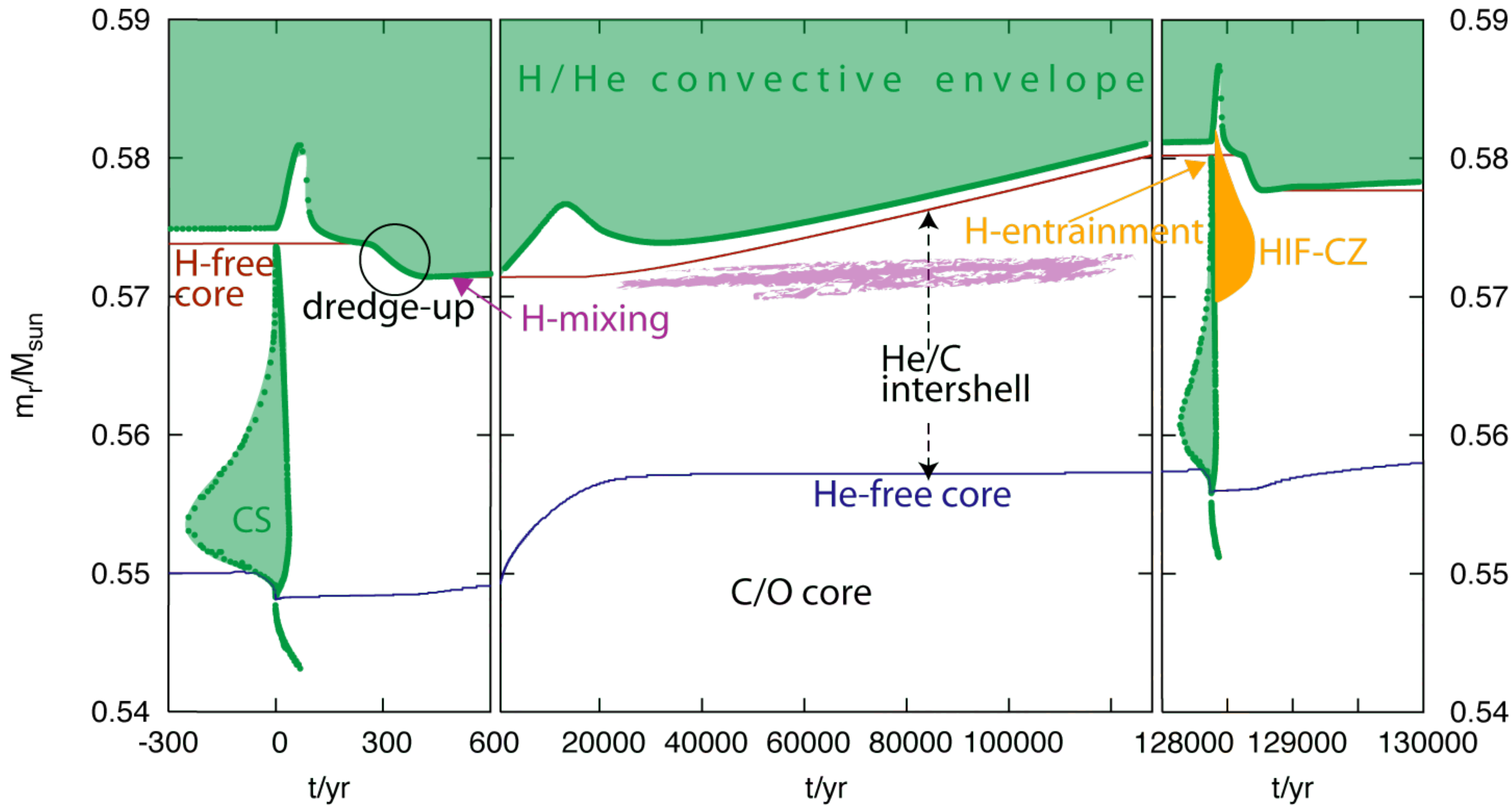
$$\frac{dP}{dr} = -\frac{G\mathcal{M}(r)}{r^2}\rho$$ momentum

$$\frac{d\mathcal{L}}{dr} = 4\pi r^2 \rho\, \epsilon$$ energy



plus material properties: atomic, nuclear, thermodynamic physics.

He-shell flashes in AGB stars



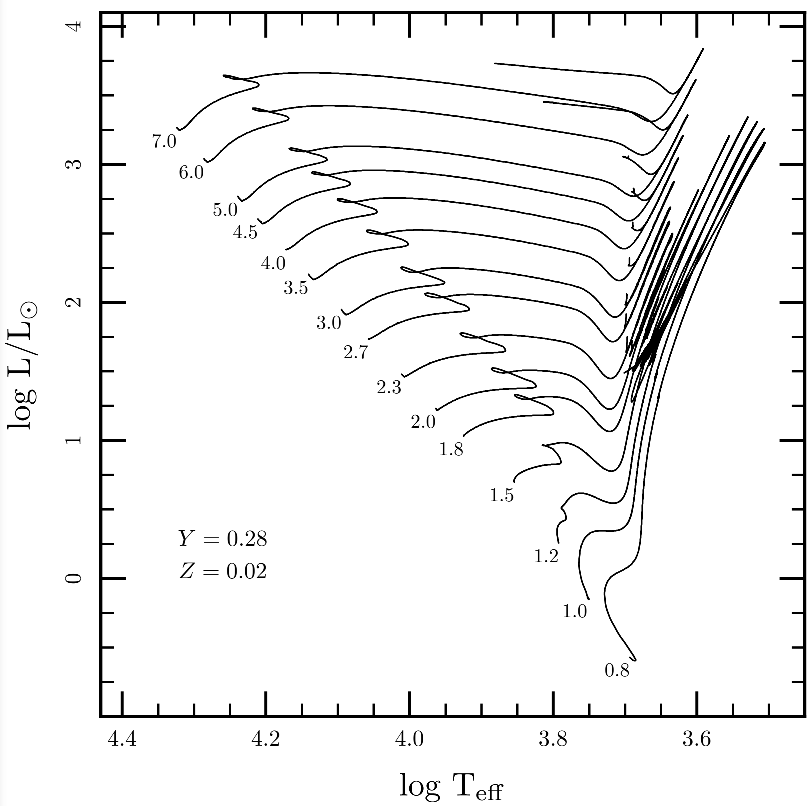
Adopted from Herwig, 2005, ARAA, 43.

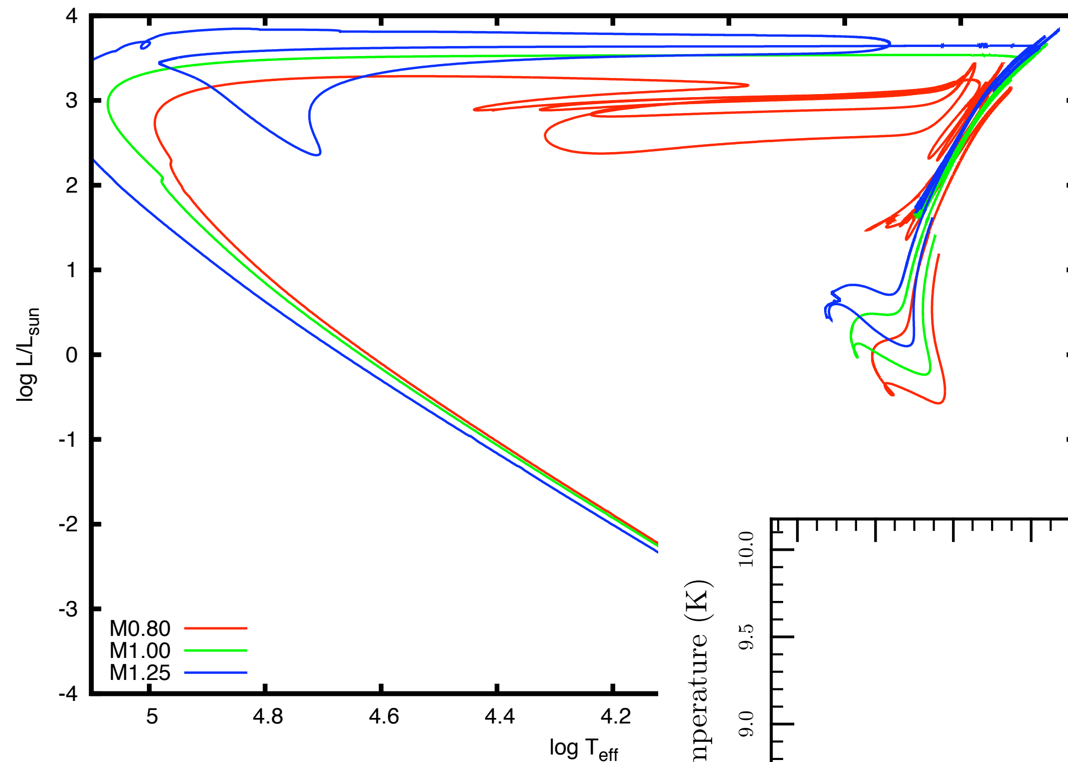
MESA: modules for experiments in stellar evolution

A new, modern, modular, open, fast community stellar evolution code

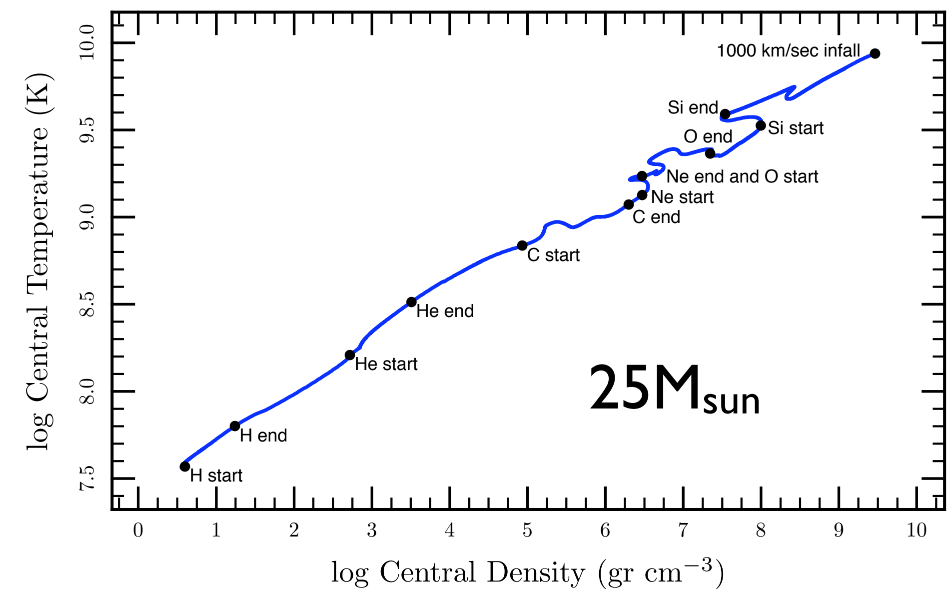
Evolution of low- & intermed. mass stars

low-/intermediate mass evolution

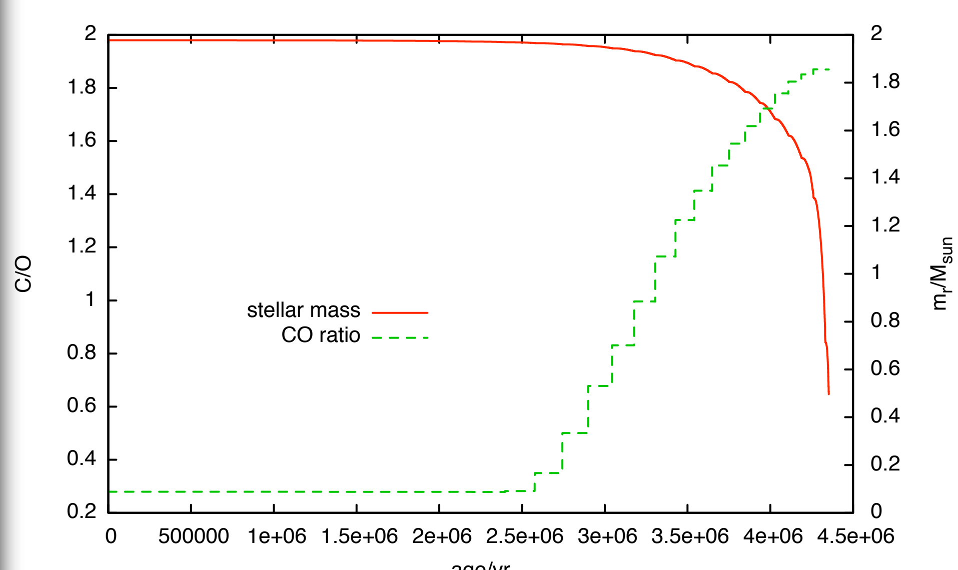




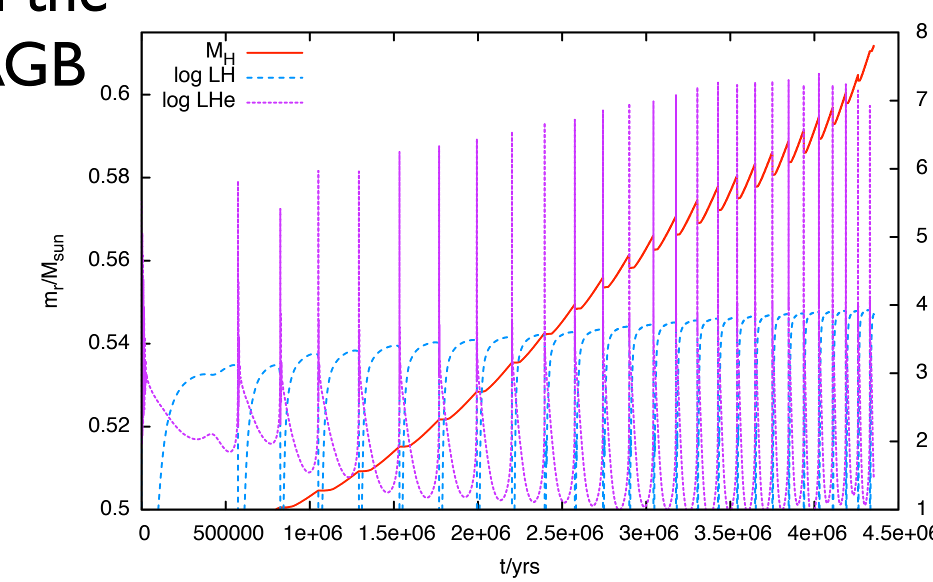
MS to WD through He-core flash



massive star evolution

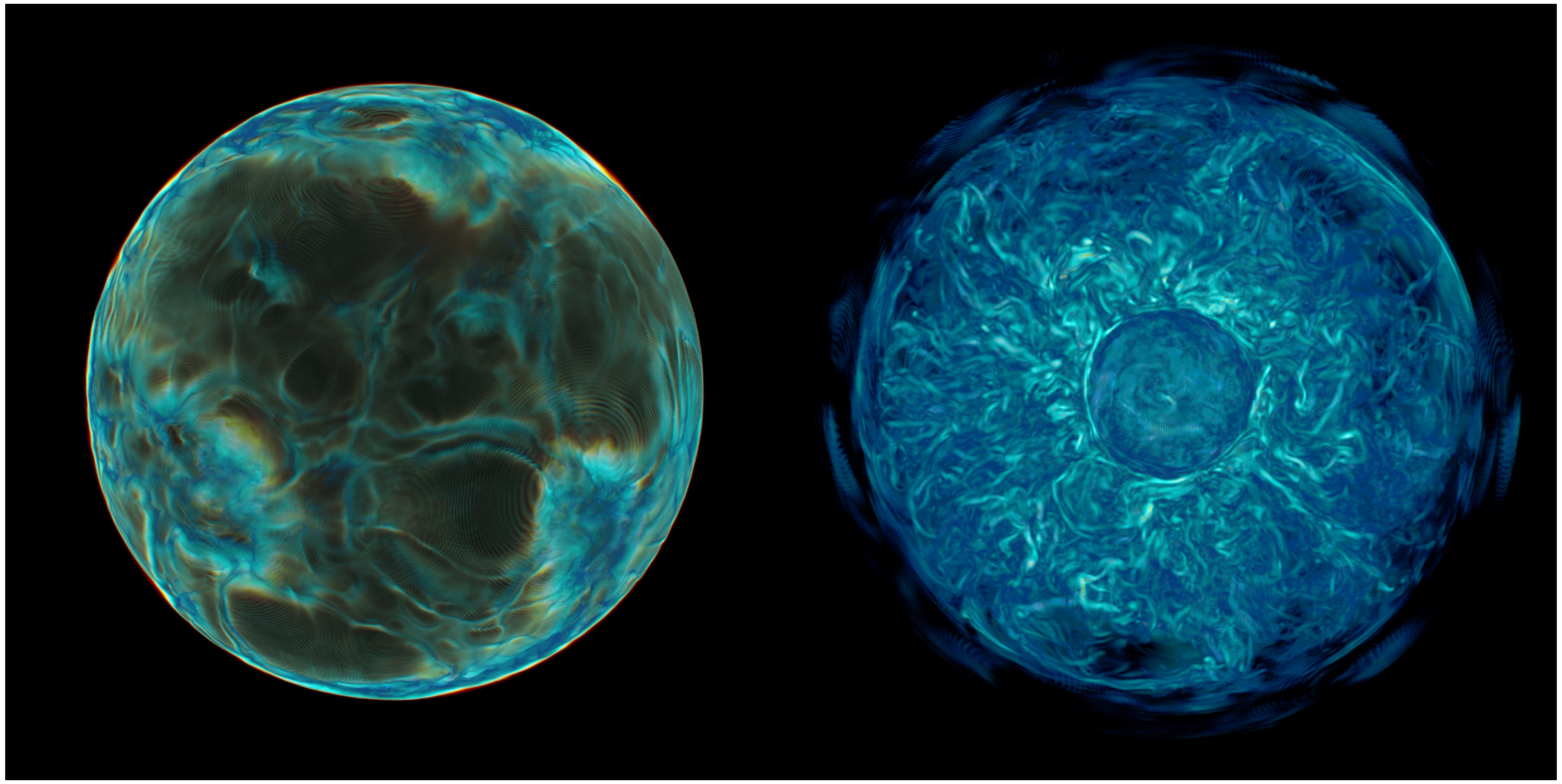


C-star formation on the AGB



Paxton etal 2010, in prep. read the Manifesto before using!!!

Local 3D simulations of hydrodynamic processes on shorter time scales



The fluid equations of motion

Conservation laws:

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0 \,,$$ mass

$$\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{\nabla P}{\rho} - g\hat{z} \,,$$ momentum

$$\partial_t(\rho E) + \nabla \cdot (\boldsymbol{u}\rho E) = -\nabla \cdot (\boldsymbol{u}P - \kappa \nabla T) \,,$$ energy

where the total energy density per unit mass is given by

$$E = \tfrac{1}{2}u^2 + \epsilon + gz \,.$$

Stellar interior convection:
Hydrodynamics and Mixing of He-shell Flash Convection
(Paul Woodward, LCSE, Minnesota)

Plus nuclear burn: $$\left(\frac{\mathrm{d}Y_i}{\mathrm{d}t}\right)_{\mathrm{burn}} = \sum_{\mathrm{l}} <\sigma v>_{\mathrm{li}} Y_{\mathrm{l}} Y_{\mathrm{i}} - \sum_{\mathrm{k}} <\sigma v>_{\mathrm{ik}} Y_{\mathrm{i}} Y_{\mathrm{k}},$$

Extra-mixing aka "cool-bottom processing"

Several observations on the AGB as well as on the RGB indicate that a certain amount of mixing between the bottom of the giant convection envelope and the H-burning shell is needed, e.g.

- large [N/Fe] in C-rich extremely metal poor stars
- lower $^{12}C/^{13}C$ on the AGB then expected from standard models
- abundance correlations with L in RGB GC stars, e.g. C/N
- Li enhancements in RGB GC stars

Proposed scenarios include

- "Enhanced Extra Mixing in Low-Mass Red Giants: Lithium Production and Thermal Stability" Denissenkov & Herwig (2004)
- magnetic fields: "Can Extra Mixing in RGB and AGB Stars Be Attributed to Magnetic Mechanisms?" Busso etal (2007)
- "Magneto-Thermohaline Mixing in Red Giants" Denissenkov etal (2009)
- followed finally by "Is Extra Mixing Really Needed in Asymptotic Giant Branch Stars?" Karakas etal (2010) [best reproduction of observations with enhanced ^{16}O intershell abundance]

University of Victoria

Deep Mixing of ^{3}He: Reconciling Big Bang and Stellar Nucleosynthesis

Peter P. Eggleton,[1]* David S. P. Dearborn,[2] John C. Lattanzio[3]

Low-mass stars, ~1 to 2 solar masses, near the Main Sequence are efficient at producing the helium isotope ^{3}He, which they mix into the convective envelope on the giant branch and should distribute into the Galaxy by way of envelope loss. This process is so efficient that it is difficult to reconcile the low observed cosmic abundance of ^{3}He with the predictions of both stellar and Big Bang nucleosynthesis. Here we find, by modeling a red giant with a fully three-dimensional hydrodynamic code and a full nucleosynthetic network, that mixing arises in the supposedly stable and radiative zone between the hydrogen-burning shell and the base of the convective envelope. This mixing is due to Rayleigh-Taylor instability within a zone just above the hydrogen-burning shell, where a nuclear reaction lowers the mean molecular weight slightly. Thus, we are able to remove the threat that ^{3}He production in low-mass stars poses to the Big Bang nucleosynthesis of ^{3}He.

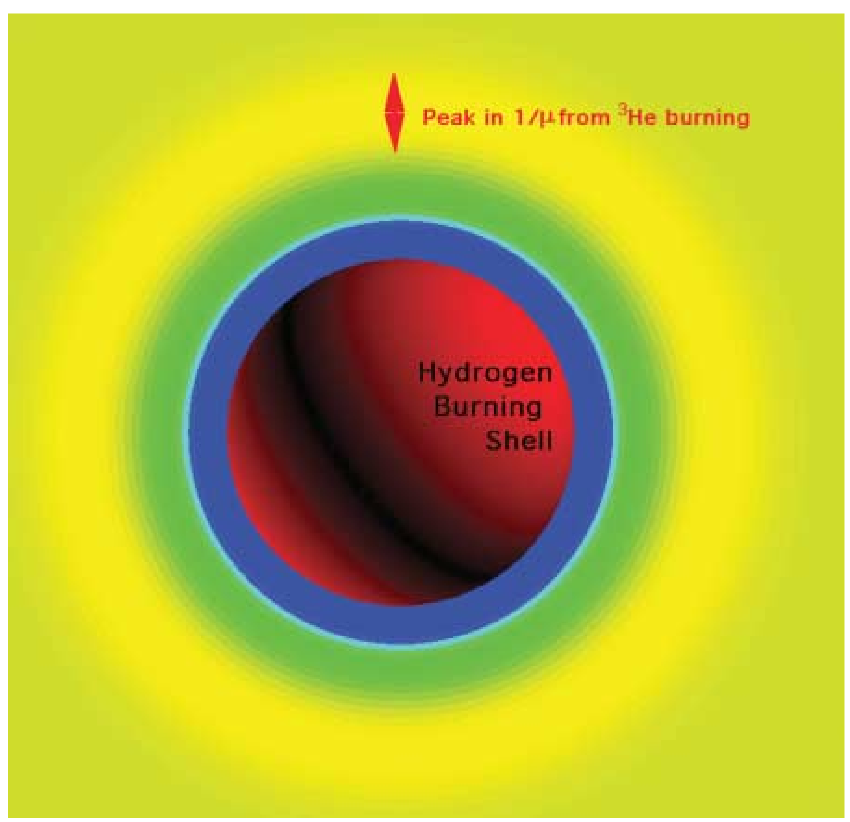


Fig. 4. A color-coded plot of μ on a cross-section through the initial 3D model. The shell where the μ inversion occurs is the yellow region sandwiched between a yellow-green and a darker green. The inversion is at a radius of ~5×10^7 m. The base of the SCZ is at ~2×10^9 m, well outside the frame, and the surface of the star is at ~2×10^{10} m.

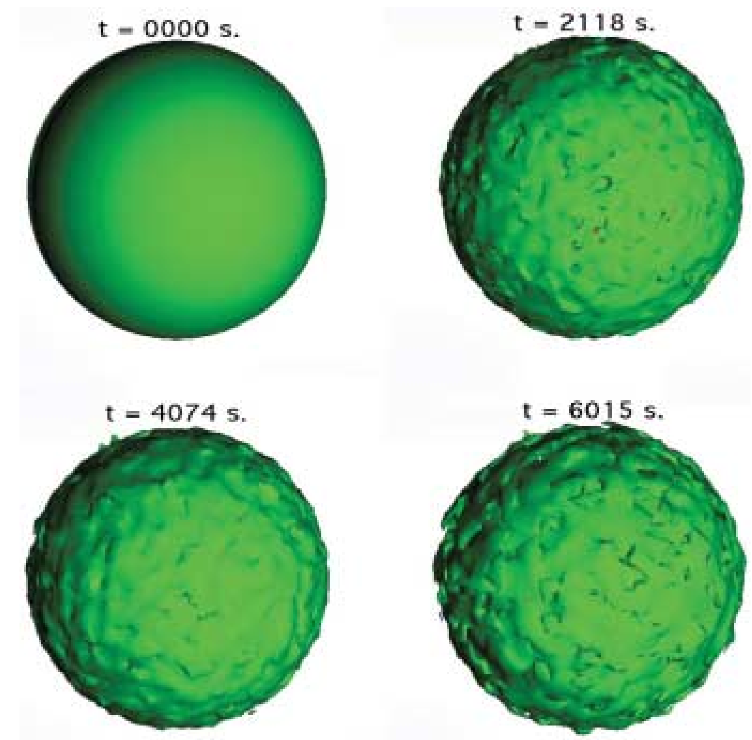


Fig. 5. The development with time of a contour surface of mean molecular weight near the peak in the blue curve of Fig. 3. The contour dimples, and begins to break up, on a time scale of only ~2000 s.

A&A 467, L15–L18 (2007)
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Astronomy & Astrophysics

Letter to the Editor

Thermohaline mixing: a physical mechanism governing the photospheric composition of low-mass giants

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ABSTRACT

Aims. Numerous spectroscopic observations provide compelling evidence for a non-canonical mixing process that modifies the surface abundances of Li, C and N of low-mass red giants when they reach the bump in the luminosity function. Eggleton and collaborators have proposed that a molecular weight inversion created by the ^{3}He(^{3}He, 2p)^{4}He reaction may be at the origin of this mixing, and relate it to the Rayleigh-Taylor instability. We argue that one is actually dealing with a double diffusive instability referred to as thermohaline convection and we discuss its influence on the red giant branch.
Methods. We compute stellar models of various initial metallicities that include thermohaline mixing, which is treated as a diffusive process based on the prescription given originally by Ulrich for the turbulent diffusivity produced by the thermohaline instability in stellar radiation zones.
Results. Thermohaline mixing simultaneously accounts for the observed behaviour of the carbon isotopic ratio and of the abundances of Li, C and N in the upper part of the red giant branch. It significantly reduces the ^{3}He production with respect to canonical evolution models as required by measurements of ^{3}He/H in galactic HII regions.
Conclusions. Thermohaline mixing is a fundamental physical process that must be included in stellar evolution modeling.

Key words. instabilities – stars: abundances – stars: interiors – hydrodynamics

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University of Victoria

Evolution of low- & intermed. mass stars

THERMOHALINE CONVECTION IN STELLAR INTERIORS

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Received 1971 June 14; revised 1971 July 23 and 1971 September 7

ABSTRACT

A quantitative theory of mixing induced by an inverted gradient of mean molecular weight is presented. This theory is applied to three stellar problems, with the following results: (1) during ^{3}He burning in a 2 $M_\odot$ star the change of X_3 between the center and surface is 0.002; (2) the μ-mechanism proposed by Stothers and Simon is too short-lived to explain the β Cephei variables, and (3) after the initial ignition of ^{4}He burning in a degenerate shell flash, the ^{4}He core and the ^{12}C shell mix on a time scale greater than 10^6 years. The theory is checked by comparison with the laboratory experiment by Stommel and Faller quoted by Stern. The agreement is satisfactory. An important uncertainty in the theory is the ratio of length to width of a moving finger of matter.

VI. APPLICATIONS

a) ^{3}He *Burning* (*Case 1*)

The entry for case 1 in the last column of Table 4 indicates that the mixing time is comparable to the time scale for depletion of ^{3}He. Consequently, a detailed discussion of this case is necessary. I assume that the initial ^{3}He abundance is large and ask the question: What is the difference in ^{3}He abundance between the center and the surface of the star required to allow a uniform rate of depletion throughout?

Just prior to the arrival of a pre–main-sequence star on the ^{1}H burning main sequence, the reaction

$$^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2{}^1\text{H} + 12.86\ \text{Mev} \tag{26}$$

can temporarily halt gravitational contraction. Furthermore, this reaction converts two particles into three and thus decreases the mean molecular weight. After the maximum gradient of X_3, the mass fraction of ^{3}He, has been achieved, the thermohaline-convection mechanism discussed above permits X_3 to decrease at a uniform rate throughout the star. Thus,

$$\left(\frac{\partial X_3}{\partial t}\right)_{\text{actual}} = \left(\frac{\partial X_3}{\partial t}\right)_{\text{nuc}} + \left(\frac{\partial X_3}{\partial t}\right)_{\text{diff}} = \frac{L_*}{QM_*} \tag{27}$$

where Q is the energy released per unit mass of ^{3}He which undergoes reaction (26); its value is 2.07×10^{18} ergs per g ^{3}He consumed. Also, L_* and M_* are the total luminosity and mass.

NUMERICAL SIMULATIONS OF THERMOHALINE CONVECTION: IMPLICATIONS FOR EXTRA-MIXING IN LOW-MASS RGB STARS

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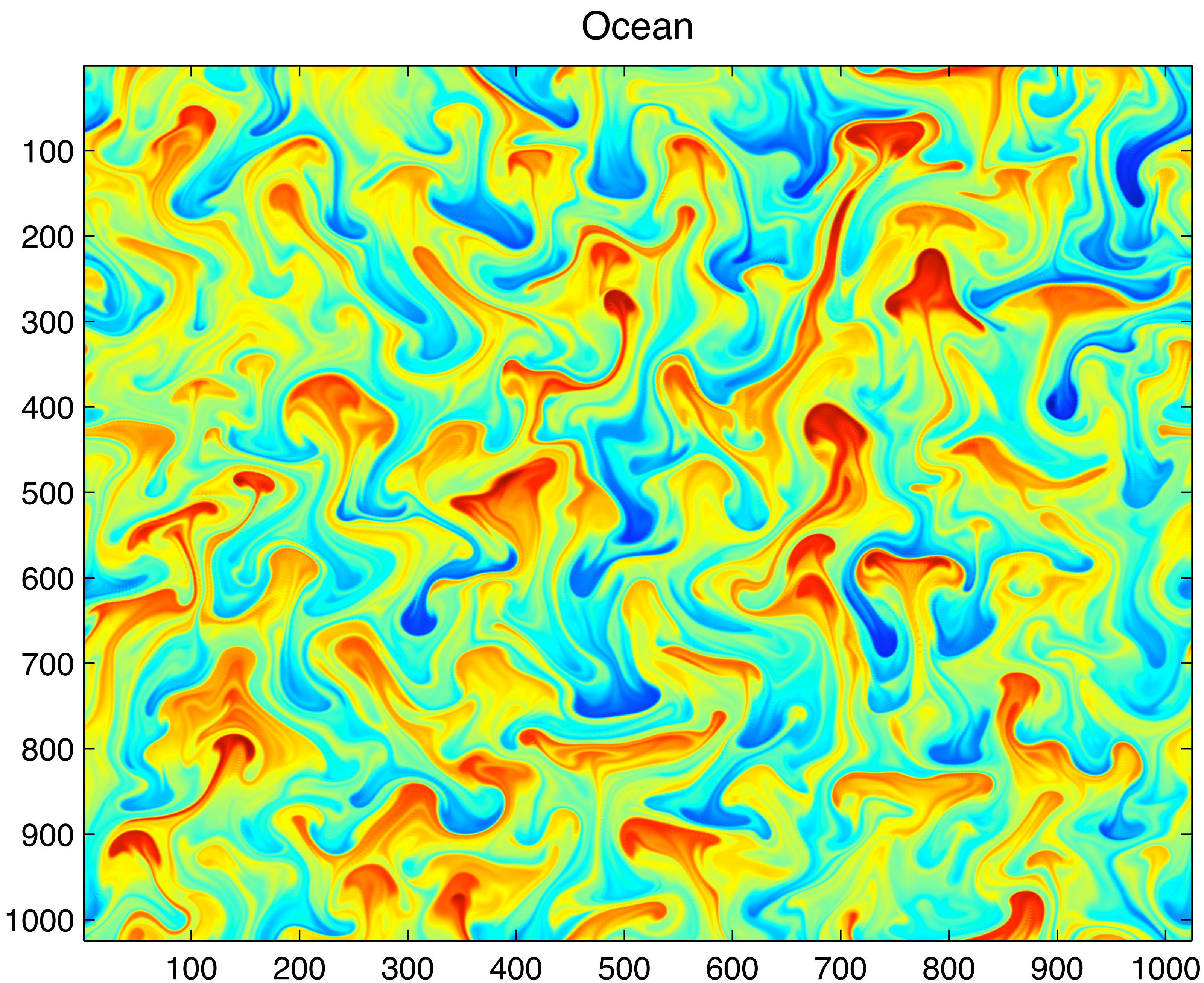
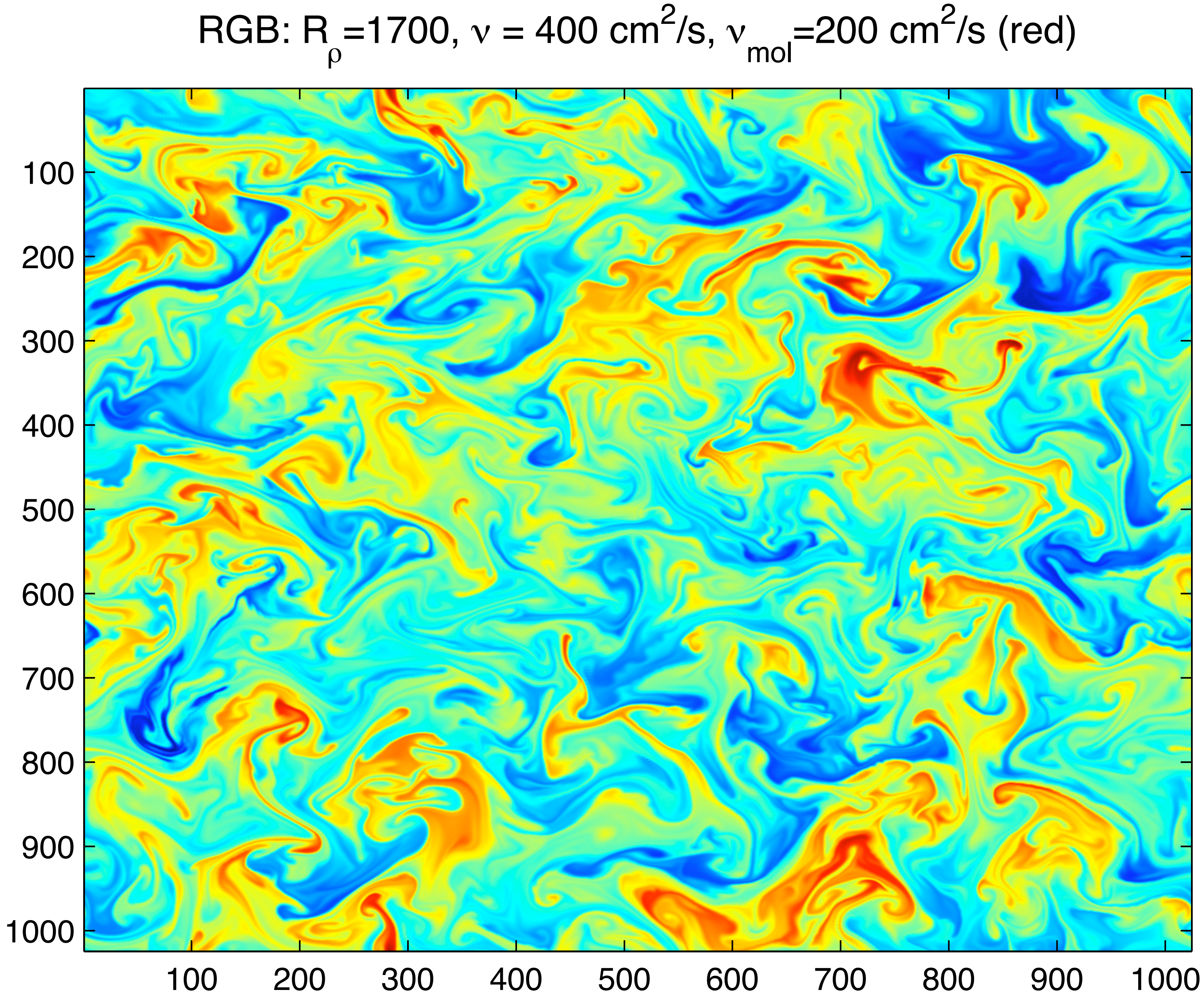
1. study the hydrodynamics of thermohaline mixing
2. apply results in stellar evolution and compare with observations

arXiv:1006.5481



In ocean conditions longish finger structures establish with an aspect ratio (vertical to horizontal) of a few.

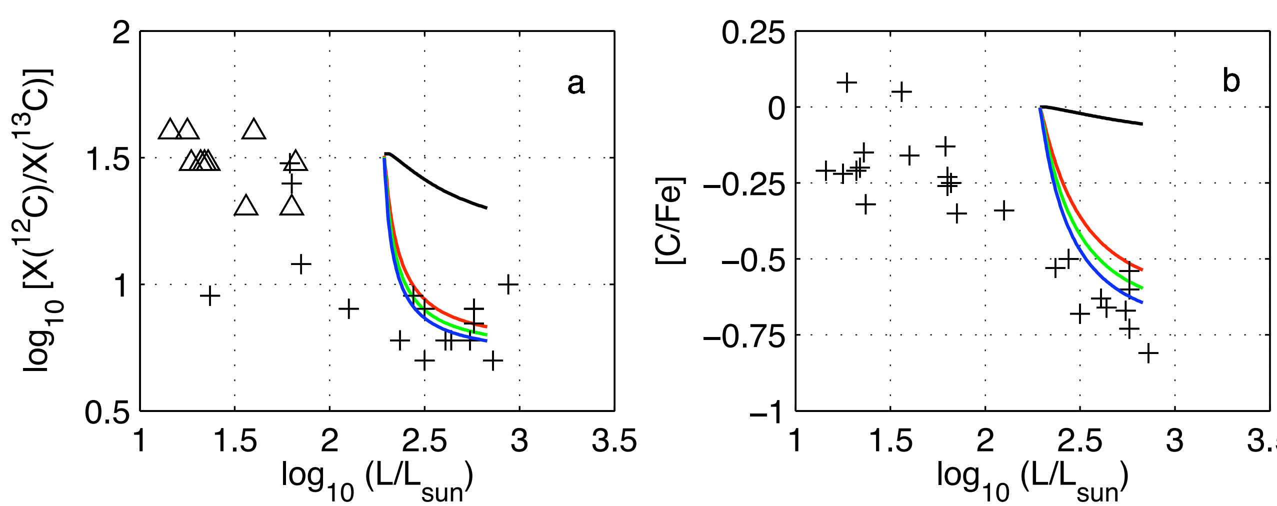


In star conditions the ratio of thermal diffusivity to diffusivity of “salinity” is much greater PLUS the viscosity is much smaller: fingers are shredded, aspect ration < 1.

(3D simulations underway, no dramatic effect expected)

Application to stellar evolution and obs:

- black lines: aspect ration according to hydro
- coloured lines: aspect ratios 5-7 best fitting observations



Mass loss and opacities in AGB stars

An important new ingredient for AGB stellar evolution are new low-T opacities and - ideally matching - mass loss rates, e.g. from hydrodynamic wind models (see Susanne Hoefner's presentation for details).

Goal: correctly and predictively describe the loss of the envelope when the star becomes C-rich through 3rd dredge-up, and the surface temperature evolution.

Routinely employed now, e.g.:

- "New asymptotic giant branch models for a range of metallicities" Weiss & Ferguson, A&A, 2009.
- "Evolution and chemical yields of AGB stars: effects of low-temperature opacities" Ventura & Marigo, MN, 2009.
- "Molecular Opacities for Low-Mass Metal-poor AGB Stars Undergoing the Third Dredge-up" Cristallo etal, ApJ, 2007.
- "Low temperature Rosseland opacities with varied abundances of carbon and nitrogen" Lederer & Aringer, A&A 2009.
- "Asymptotic Giant Branch evolution at varying surface C/O ratio: effects of changes in molecular opacities" Marigo, A&A, 2002.

Mass loss and opacities in AGB stars

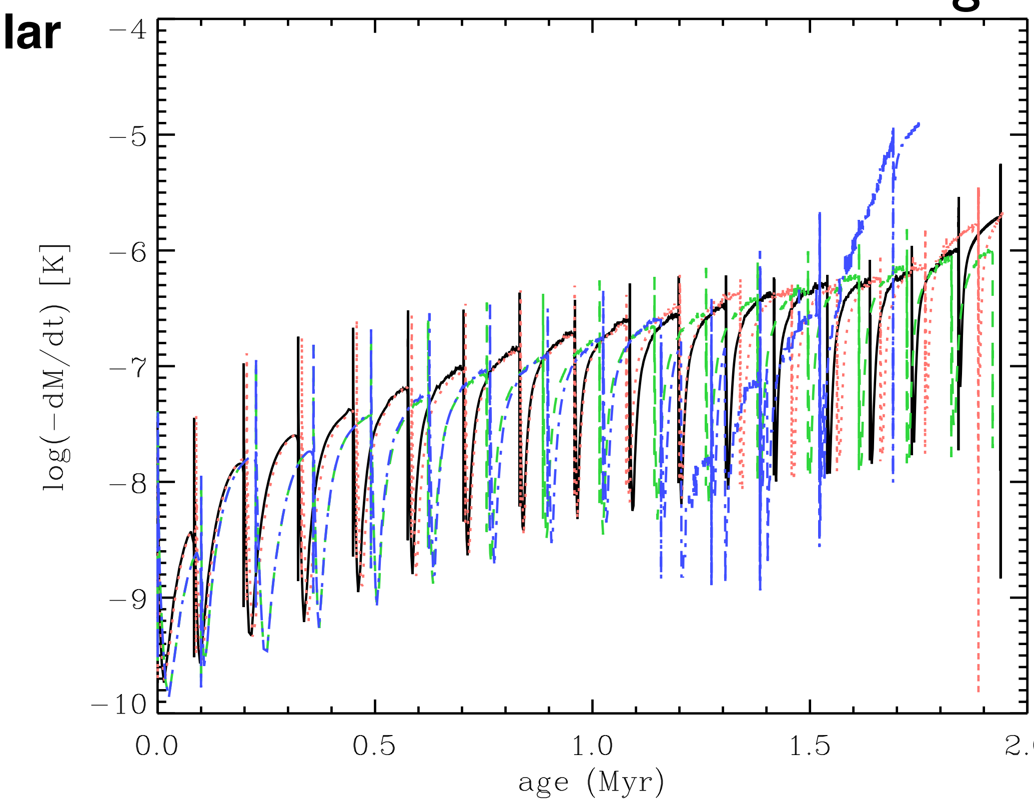
Mattson, Herwig,Hoefner, Wahlin, Lederer, Paxton

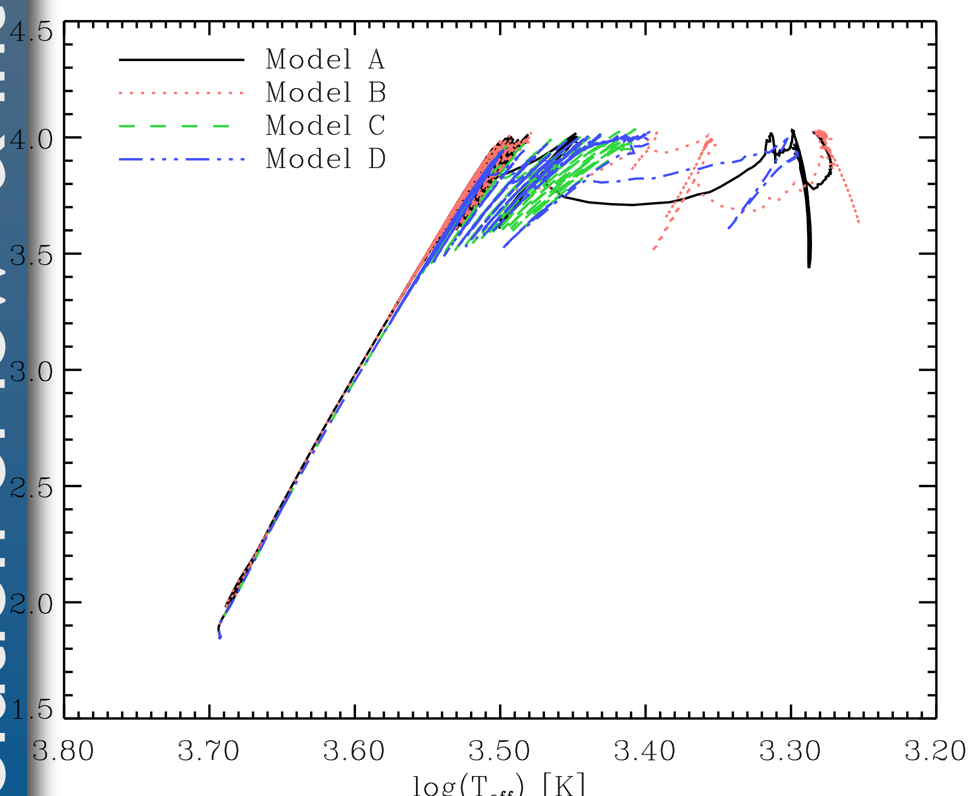
Effects of Carbon-excess Dependent Mass Loss and Molecular Opacities on Models of C-star Evolution

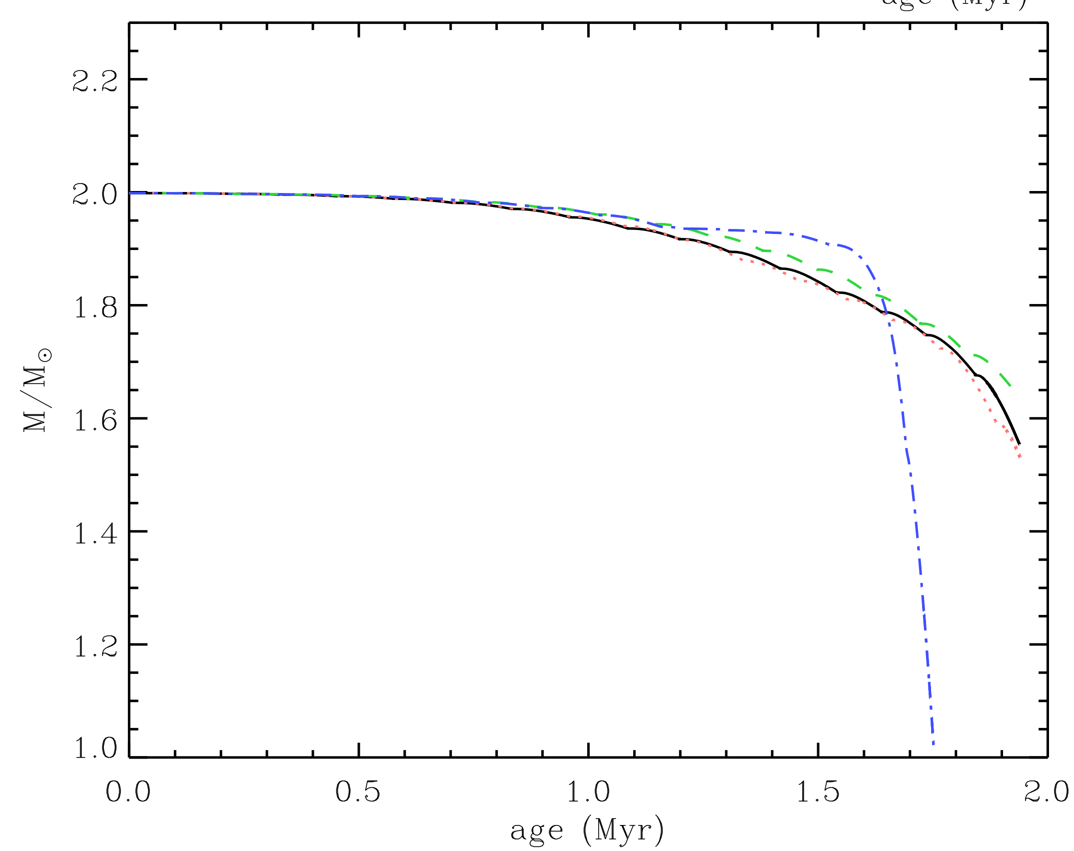
A Mass loss according to Blöcker for both M-star phase and C-star phase. Low-temperature opacities by Alexander & Ferguson (1994) without dependence on the carbon excess.
B Mass loss according to Blöcker for M-star phase and according to Mattsson et al. (2009) for the C-star phase, and low-temperature opacities as in A.
C Mass loss as in A, but the new low-temperature opacities as described in Sect. 2.3.
D Mass loss as in B and low-temperature opacities as in C, i.e., the new opacities and the new mass-loss prescription implemented simultaneously.

"forward-modeling" superwind?!!

mass loss vs. age







total mass vs. age

Evolution of low- & intermed. mass stars

Hydrodynamic simulations of AGB envelopes

Freytag & Hoefner (2008)

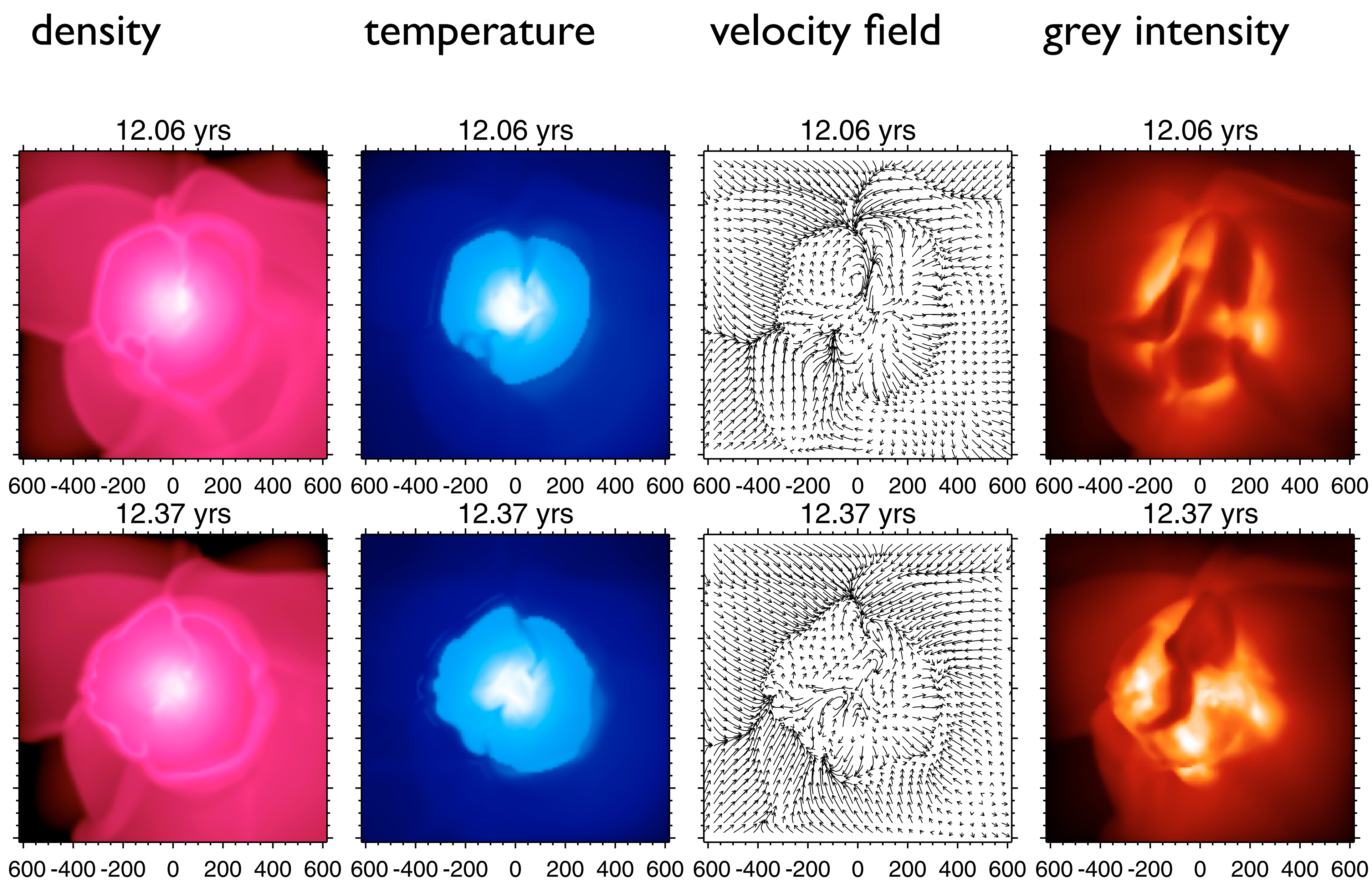
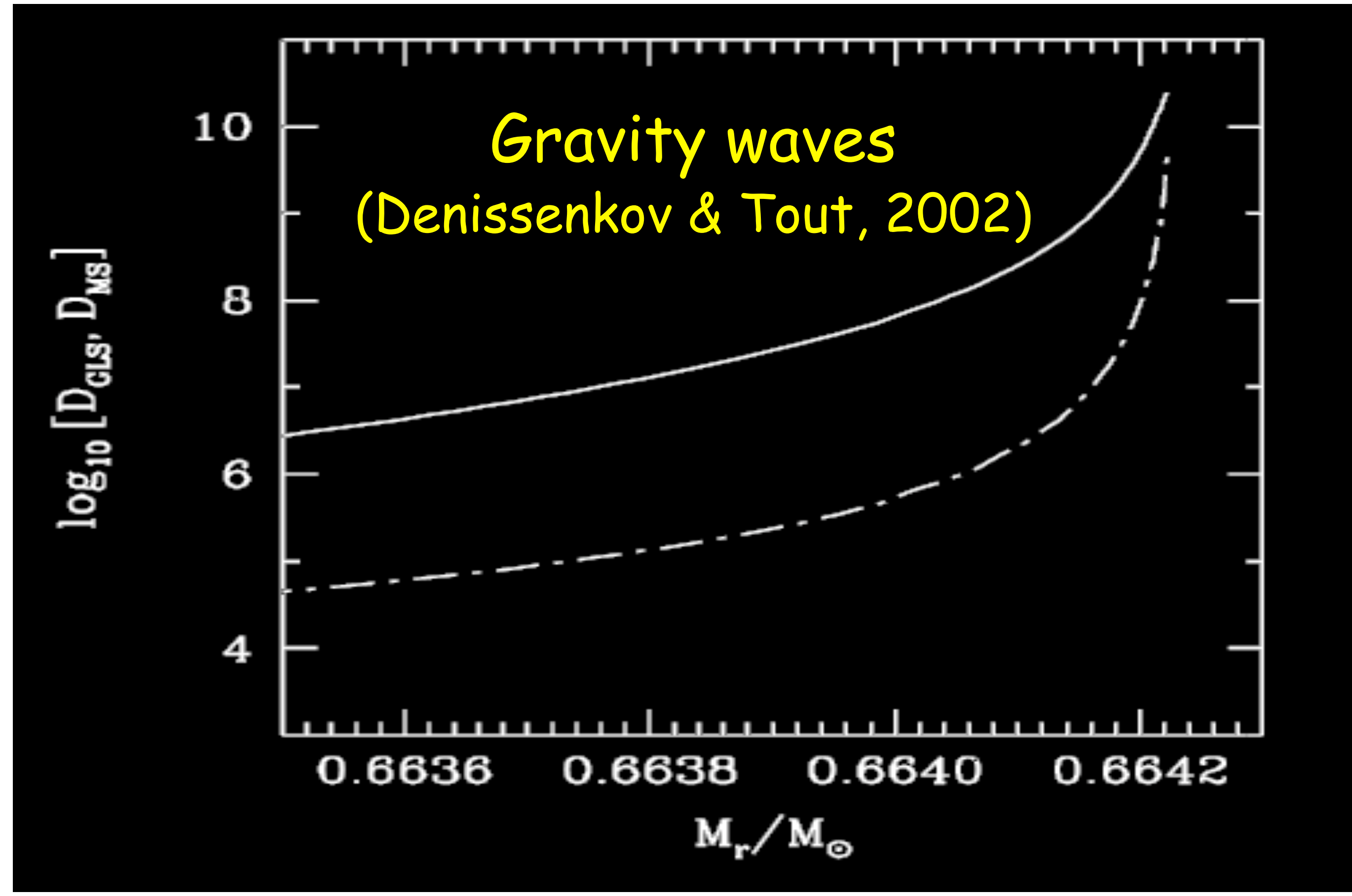
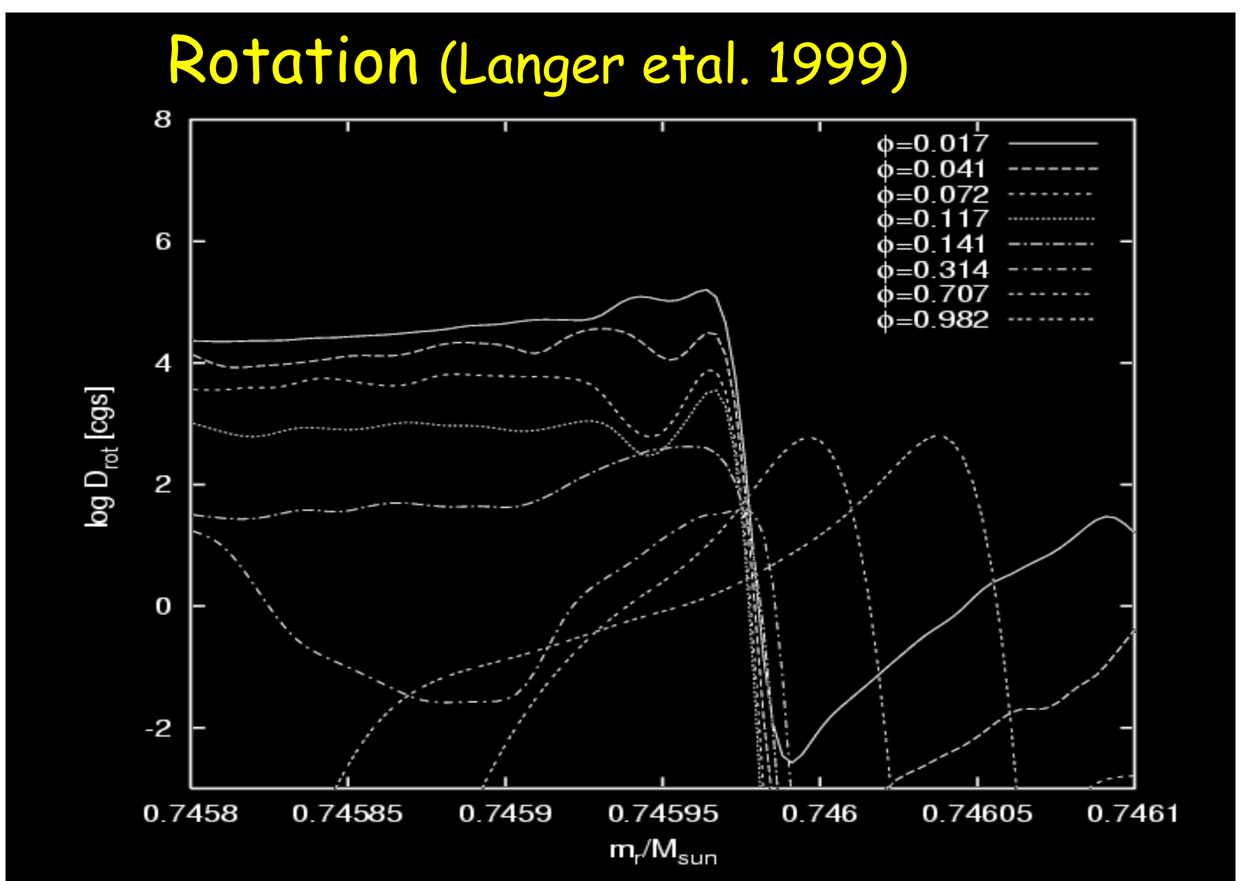


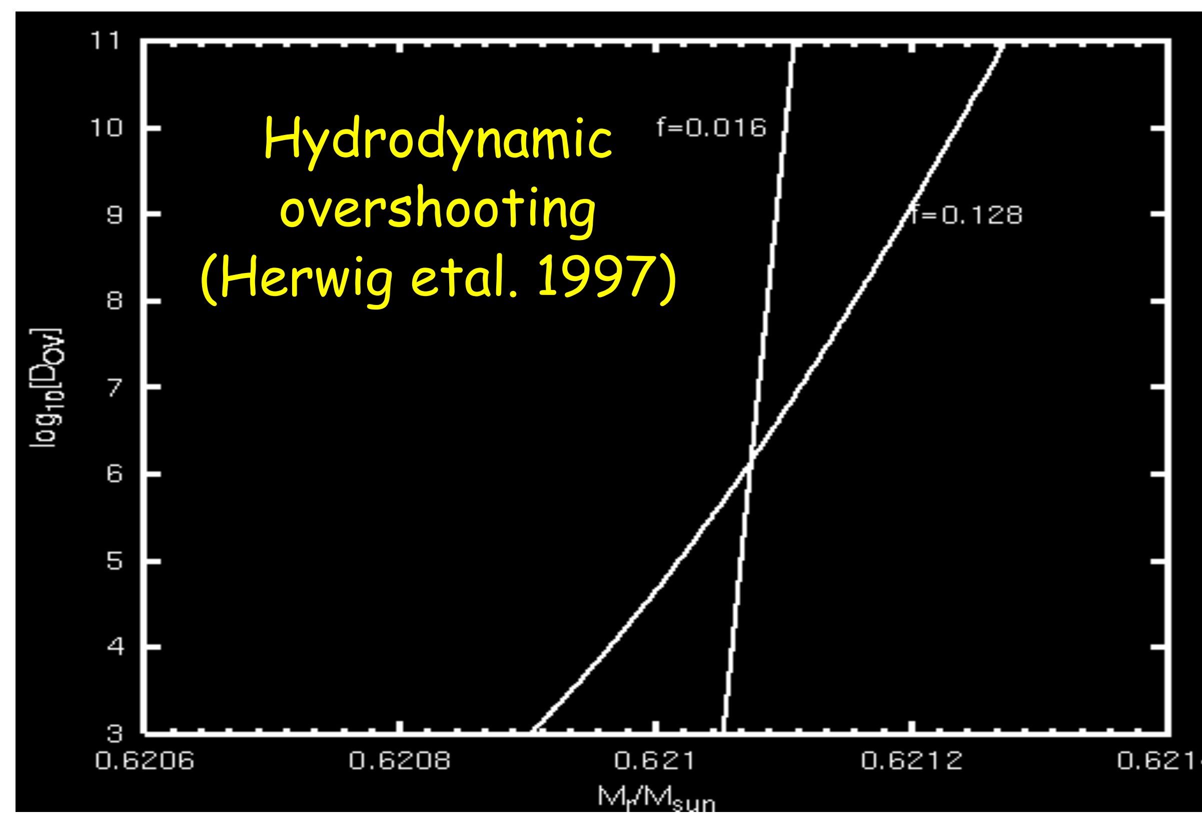
Fig. 1. Time sequence of five snapshots for model S (st28gm06n02). The model age in years is indicated on top of each frame. The axes are in solar radii. Shown from left to right are log density (color range from 10^{-13} to 2×10^{-7} g/cm^3), log temperature (color range from 800 K to 50 000 K), velocity field (pseudo-streamlines of the velocity components within the image plane integrated over 5×10^6 s) and grey intensity.

1. Formation and
2. evolution
of the ^{13}C-pocket

Mixing processes for the radiative s-process (partial mixing of protons with ^{12}C at the base of the convective envelope during/ after 3DUP)



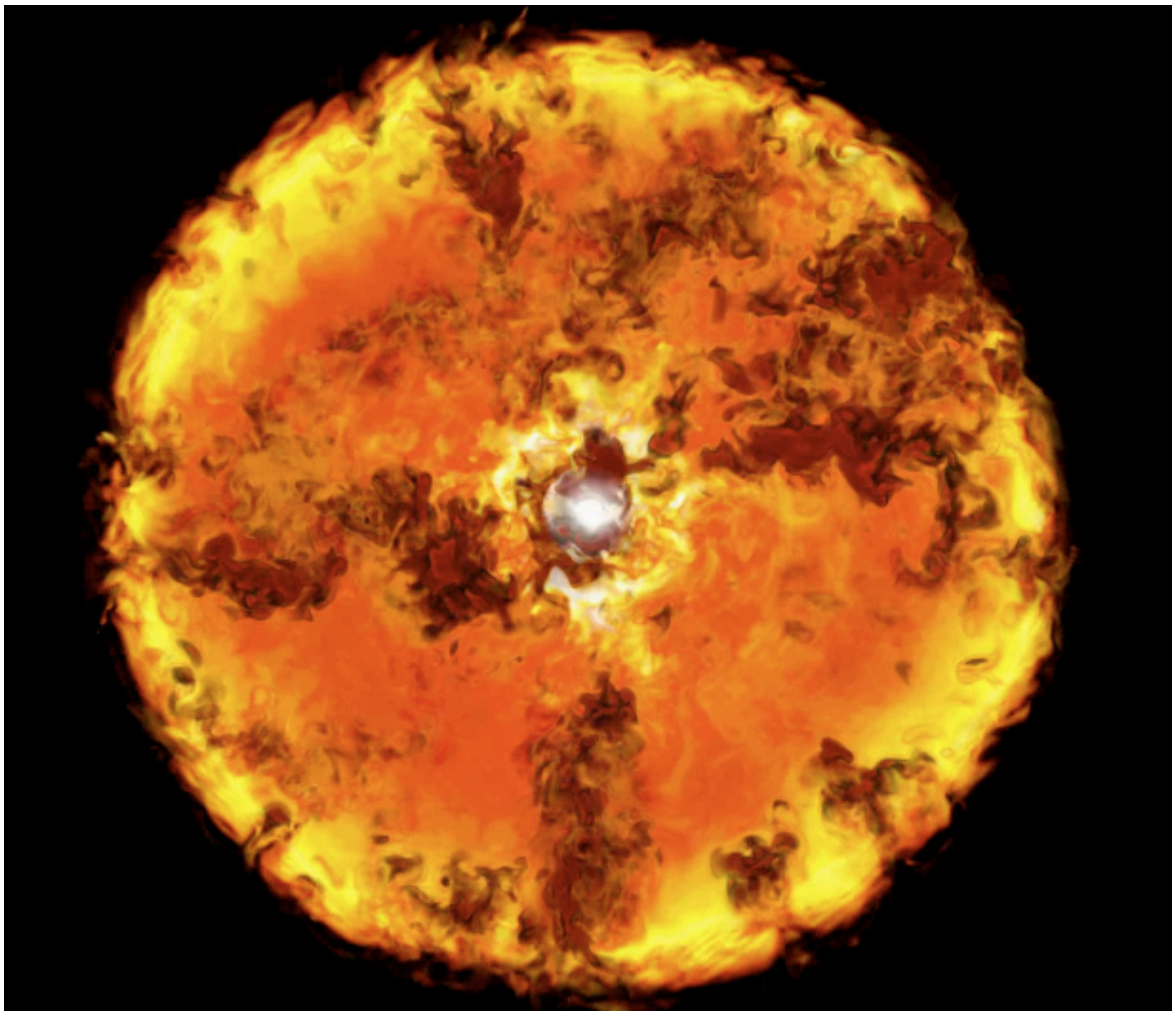




Hydrodynamic simulations of AGB envelope convection

focus on beneath-atmosphere, deeper layers

Woodward & Porter, LCSE, U Minnesota, http://www.lcse.umn.edu



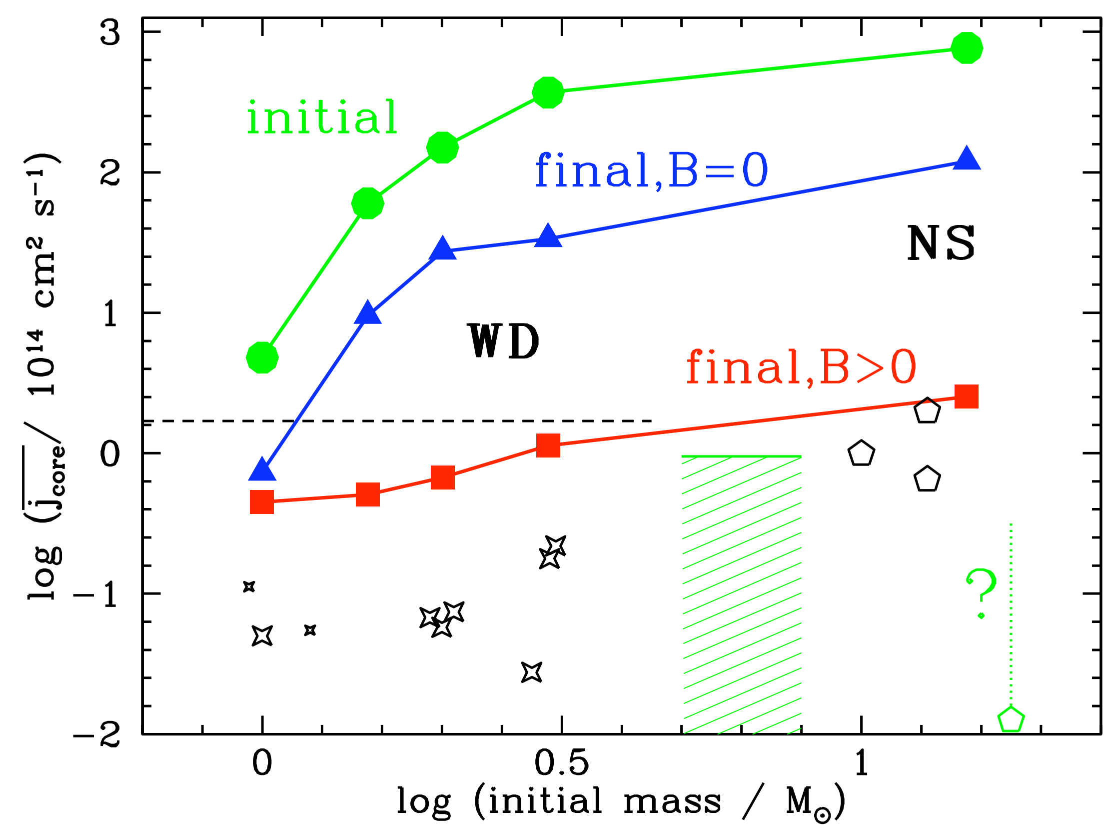
temperature fluctuation

Rotation and magnetic fields

- Rotation in 1D stellar evolution, e.g. Maeder & Meynet, Heger etal, Langer etal.
- plus magnetic fields, e.g. Taylor & Spruit dynamo, questioned by Zahn etal (2007)

Compare to observations in late phases:

- Rotation rates of neutron stars and white dwarfs
- Implications from nucleosynthesis, e.g. s-process in TP-AGB stars (Herwig etal 2003, Siess etal 2004)

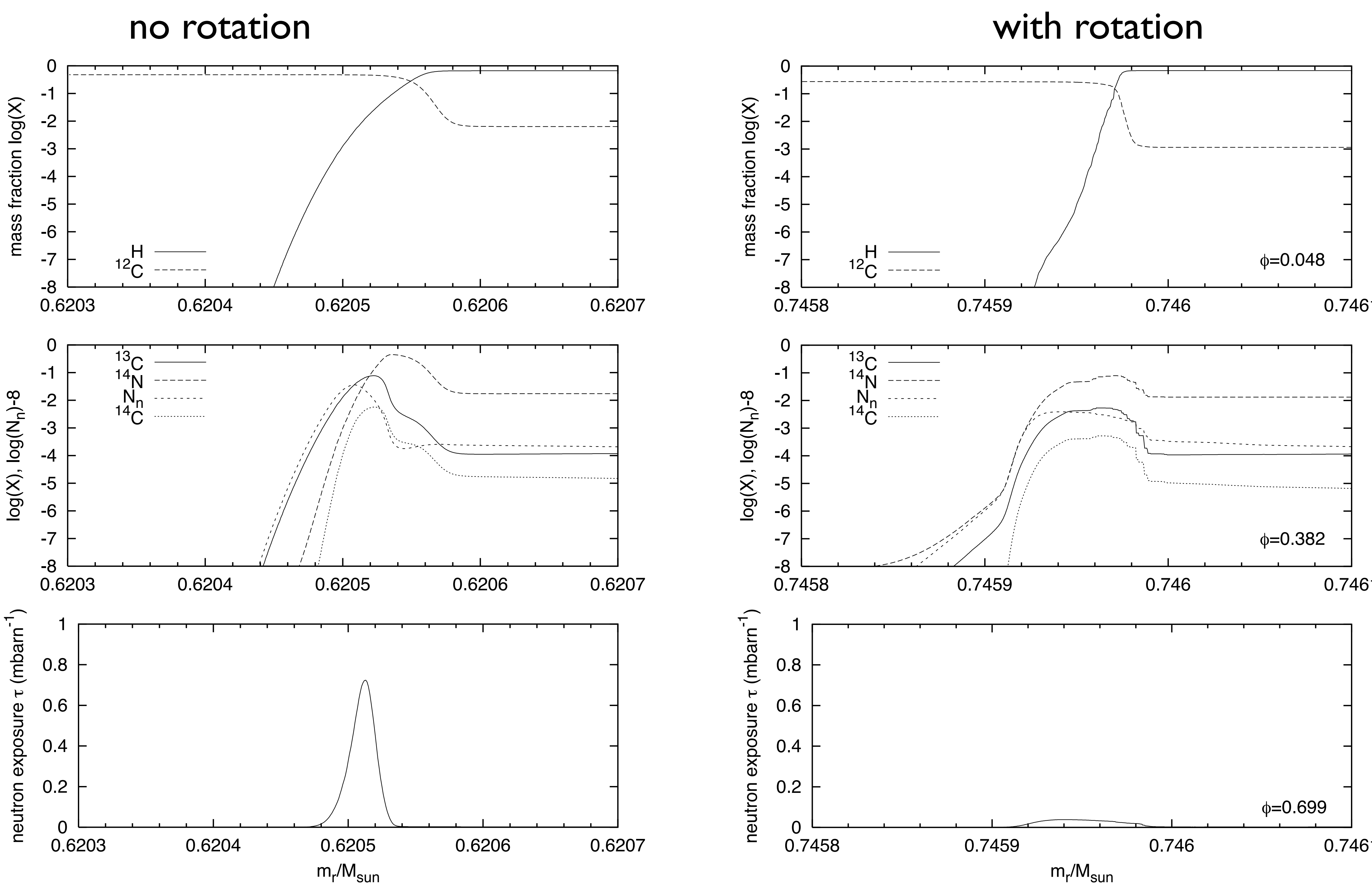


Suijs etal (2008)

“Seismic evidence for the loss of stellar angular momentum before the white-dwarf stage”
Charpinet, S.; Fontaine, G.; Brassard, P., Nature, 2009.

Rotation and magnetic fields

- Implications from nucleosynthesis, e.g. s-process in TP-AGB stars (Herwig etal 2003)



Rotation and magnetic fields

next generation ?!?

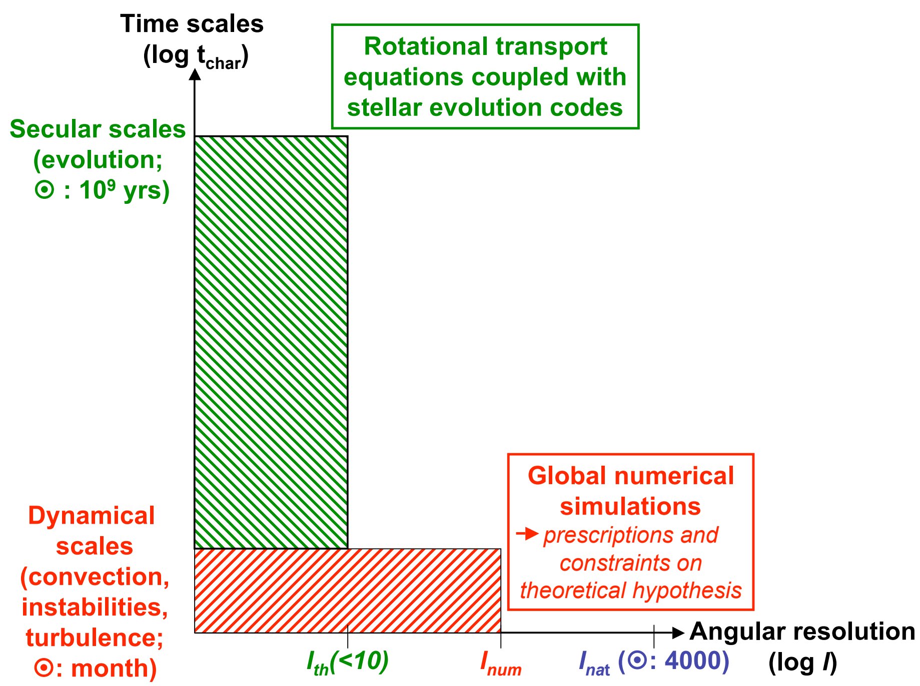


Fig. 1. Modelling strategy to study dynamical stellar evolution. The diagram presents timescales of the typical physical processes as a function of the angular resolution necessary to properly describe these processes. The angular resolution is expressed in terms of the l index of the spherical harmonics $Y_{l,m}(\theta, \phi)$. $l_{\rm num} \simeq 600$ indicates the maximum angular resolution (in term of spherical harmonics nodes) presently achieved in global numerical simulations.

"Secular hydrodynamic processes in rotating stars" Decressin et al (2009)

"A Model of Magnetic Braking of Solar Rotation That Satisfies Observational Constraints" Denissenkov (2010)

- improving on Charbonneau & MacGregor (1993)
- strongly anisotropic rotation-driven turbulent diffusion with dominating horizontal components
- numerical solution of the azimuthal components of the coupled momentum and magnetic induction equations in 2D

"Numerical Simulations of a Rotating Red Giant Star. I. Three-dimensional Models of Turbulent Convection and Associated Mean Flows" Brun & Palacios, 2009

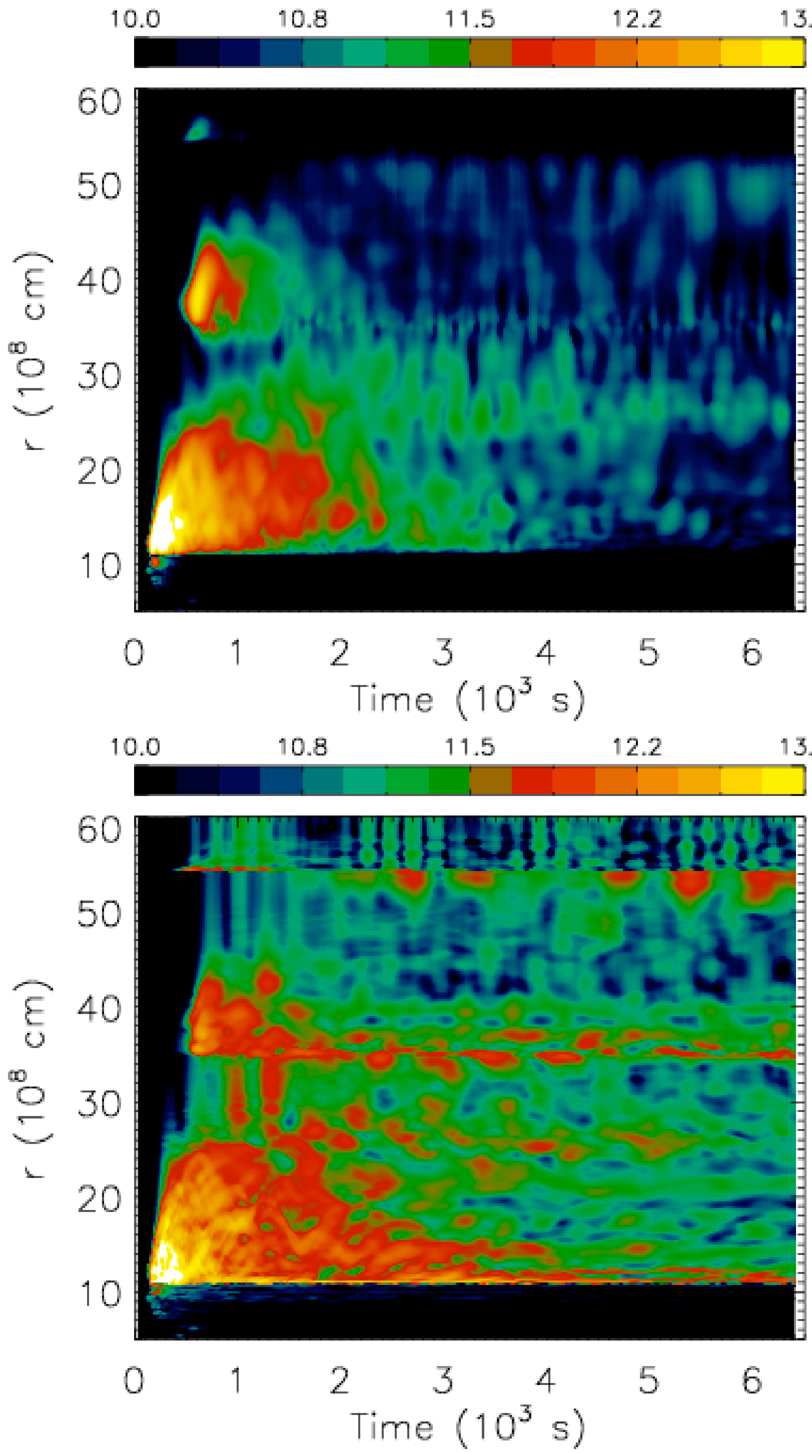


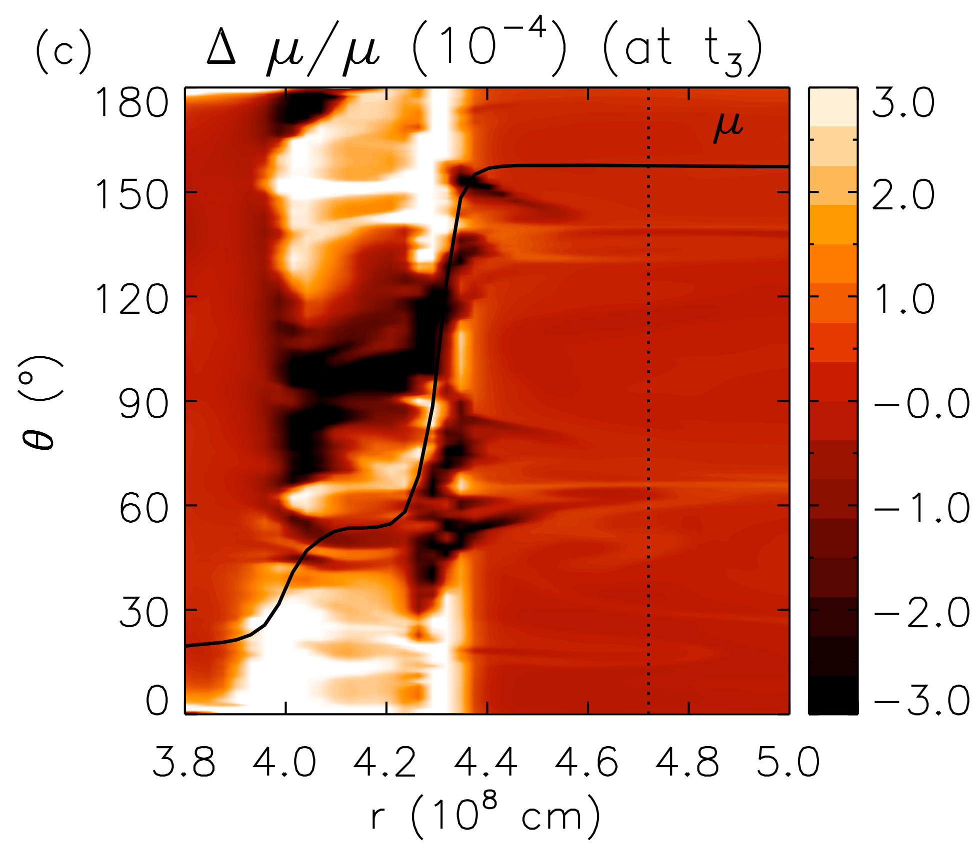
Fig. 12. Temporal evolution of the radial distribution of the (color coded) logarithm of the angular averaged radial ($v_r^2/2$; upper panel) and angular $v_\theta^2/2$; lower panel) component of the specific kinetic energy (in erg g^{-1}) of the 2D model heflpopIII.2d.2.

Mocak etal 2010a,b

He-core flash simulations (here 2D) at low Z show H-ingestion

main results

- hydrodynamic results do not agree with 1D stellar evolution
- entrainment at bottom of He-core flash convection zone (cf. ‘overshooting’ at bottom of He-shell flash convection zone)



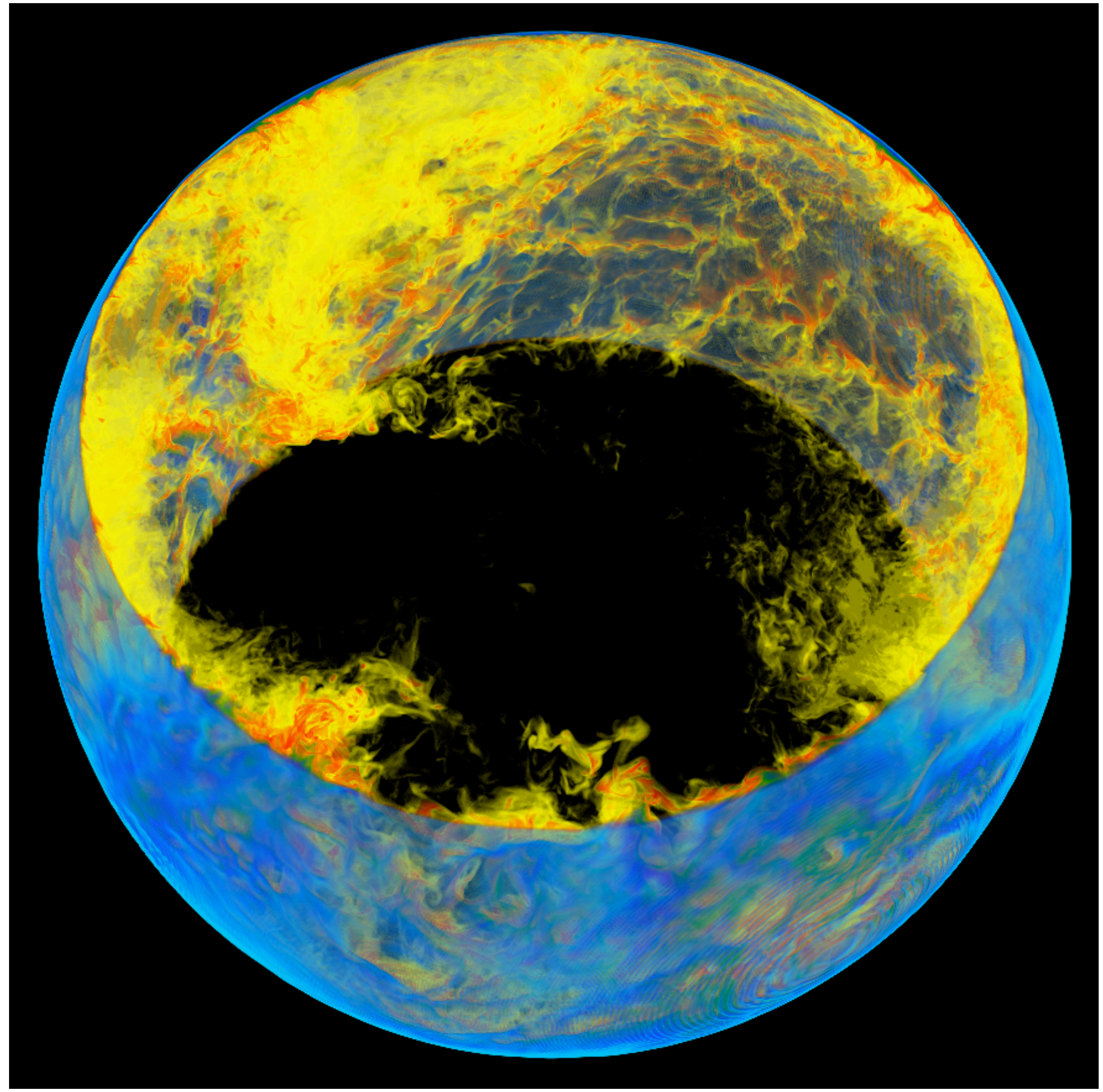
- mixing due to RT finger instabilities at the bottom of convective shells

Multi-dimensional stars

abundance of H-rich material entrained from above into convection zone at ~20ks

Next generation He-shell flash convection

i. 3D 4π star-in-a-box simulations (e.g. Herwig etal 2010, arXiv:1002.2241)
ii. compressible gas dynamics PPM code Paul Woodward (http://www.lcse.umn.edu)
iii. high accuracy PPB advection scheme
iv. 2 fluids, with individual, realistic material densities
v. 576^3 cartesian grid, simulated time total 60ks
vi. Ma ~ 0.03, 11H_p in conv. zone



http://www.lcse.umn.edu/index.php?c=movies

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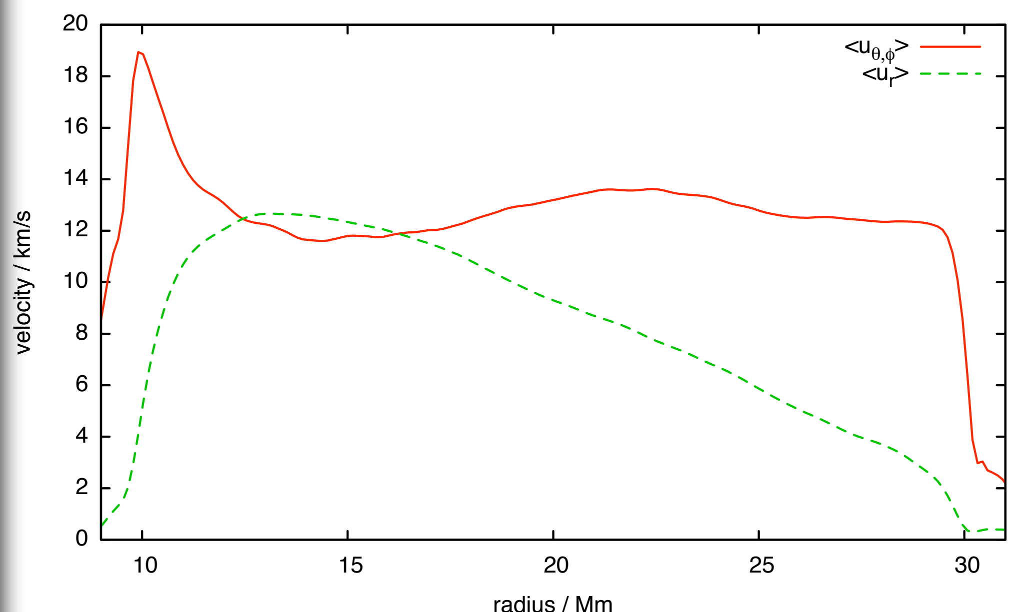
Multi-dimensional stars

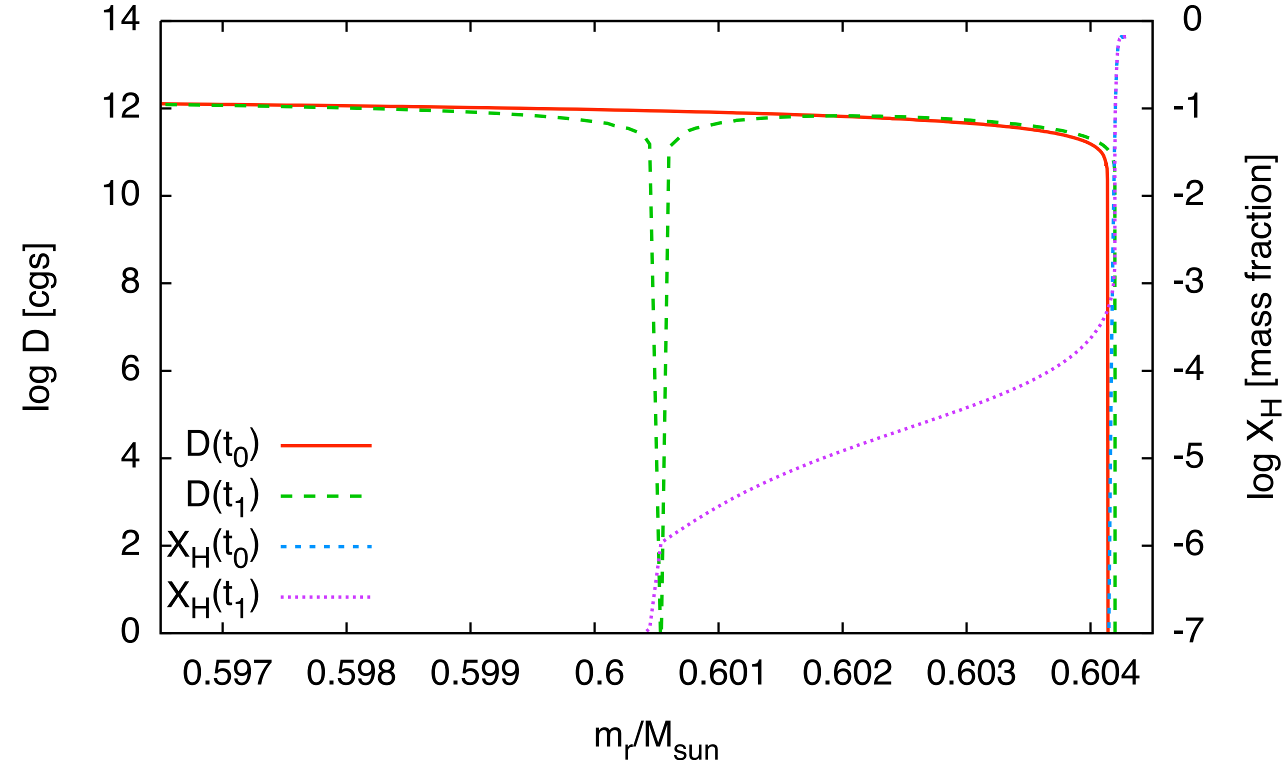
Evolution of low- & intermed. mass stars

3D 4π star-in-a-box simulations

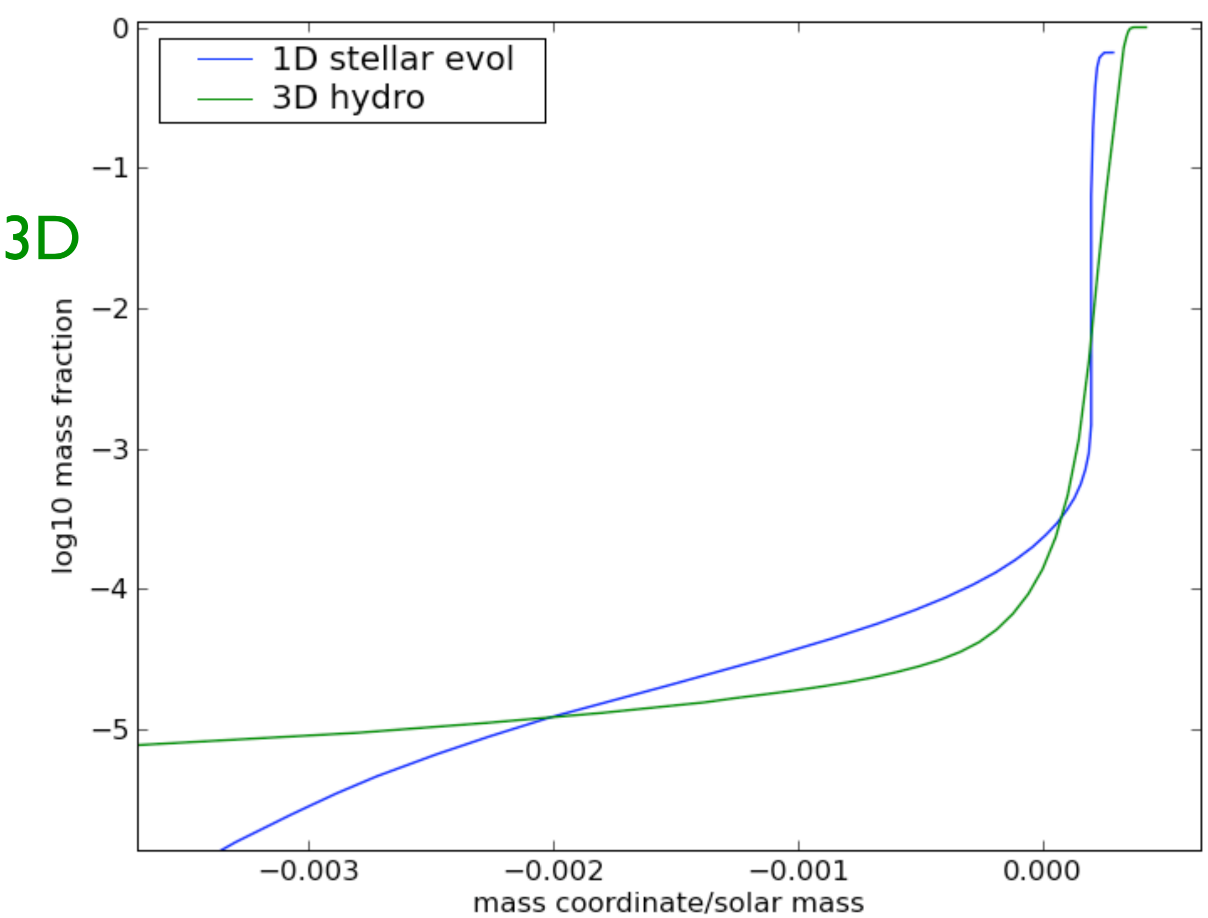
horizontal and vertical v_{rms}



1D mixing profiles



comparison 1D and 3D averaged profiles



See poster for details on nucleosynthesis implications: NIC_XI_224, see also arXiv: 1002.2241

Convective-reactive proton-^{12}C combustion in Sakurai's object (V4334 Sagittarii) and implications for the evolution and yields from the first generations of stars

(arXiv:1002.2241 for details)

The ratio of the mixing time scale and the reaction time scale is called the Damköhler number:

$$D_\alpha = \frac{\tau_{\rm mix}}{\tau_{\rm react}} \ .$$

Dimotakis, P. E. 2005, Annu. Rev. Fluid Mech., 37, 329

- D_α <<1: fully mixed burning, MLT appropriate
- D_α ~1 : combustion regime, MLT and 1D spherical symmetry assumption inappropriate because:
  - ★ MLT describes convection only in a time and spatially averaged sense
  - ★ in combustion fuels are not completely mixed
  - ★ localized energy feedback from nuclear burn feeds back into hydro
- combustion in low- and zero-metallicity stars common, including both low-mass and massive, rotating and non-rotating stars, X-ray bursts, SD SN Ia projenitors, etc

How nucleosynthesis? Different strategies:

- synthetic stellar structures (i.e. fit-formula to full stellar evolution) and more or less complete processing
- Stellar evolution first, then nucleosynthesis post-processing of a few key locations, e.g. the ^{13}C-pocket etc (the Gallino etal approach)
- Stellar evolution with an inlined network
  - ✳ smaller network of charged particles, plus co-processing of heavier elements in separate larger network (e.g. Lattanzio, Karakas etal)
  - ✳ inlining of complete network into stellar evolution code (e.g. Cristallo etal)

- NuGrid approach: stellar evolution first with energy suficient network, write out all strucutre information, complete post-processing of all zones and timesteps for dynamic and complete network of entire evolution (made possible vie parallel computing)

How nucleosynthesis?

Why NUGRID ?

- create a framework that allows to process large, internally consistent and comprehensive yield sets
- facilitate easy and routine production of large sets of observables that allow simultaneous validation of stellar physics in a wide range of situations
- detach (as far as possible) stellar evolution and explosion (SEE library) business from nucleosynthesis business (PPN - post-processing network code suite)

http://nugrid.phys.uvic.ca

http://nugrid.phys.uvic.ca/

NUGRID

Introduction
The NuGrid Web Page
The NuGrid SEE library
The NuGrid mailing lists
Links related to the NuGrid collaboration

Introduction

The NuGrid collaboration works on Computational Nuclear Astrophysics and Stellar Physics to characterize the Origin of the Elements for a range of conditions.

The NuGrid Web Page

Please visit the NuGrid web site, which is a wiki-like Plone page. We use it for our regular collaborative exchange. The internal pages requir login password. But there is already some public information.

The NuGrid SEE library

We are in the process of building up the NuGrid stellar evolution and explosion SEE library. The library already contains a large number of low-mass and massive stellar evolution tracks. Since we are still in the process of working on the publication the library is still password protected. However, please contact us if you would like to have pre-release access to the library.

The NuGrid mailing lists

We have two mailing lists:

- NuGrid list: please sign up to this list. It is meant to inform anyone interested about the progress and development of the NuGrid proj You will receive the occasional message about new data releases, releases of public codes, etc. We will at some point make the arc publicly available. So, we hope that over time this will develop into a great place to ask questions, and search for answers.
- NuGrid-team list: This is a list only for internal collaboration use.

Links related to the NuGrid collaboration

- Joint Institute for Nuclear Astrophysics - an NSF Physics Frontier Center
- MESA stellar evolution and MESA plone
- LCSE at the University of Minnesota
- Raphael Hirschi's home page and his group
- Claudia Travaglio and B^2FH in Italy
- Frank Timmes' cococubed
- Falk Herwig's web page
- NuGrid on ADS

NuGrid Collaboration, Last update: Sat Nov 21 11:55:57 PST 2009 , Back to NuGrid web page

NIC_XI_255 Pignatari M. etal. *Neutron capture processes in stars between the s process and the r process*
NIC_XI_285 Pignatari M. etal. *Nucleosynthesis in the He-burning shell in massive stars*
NIC_XI_244 Bennett M. etal. *The effect of 12C + 12C rate uncertainties on the weak s-process component*

Results: Set 1

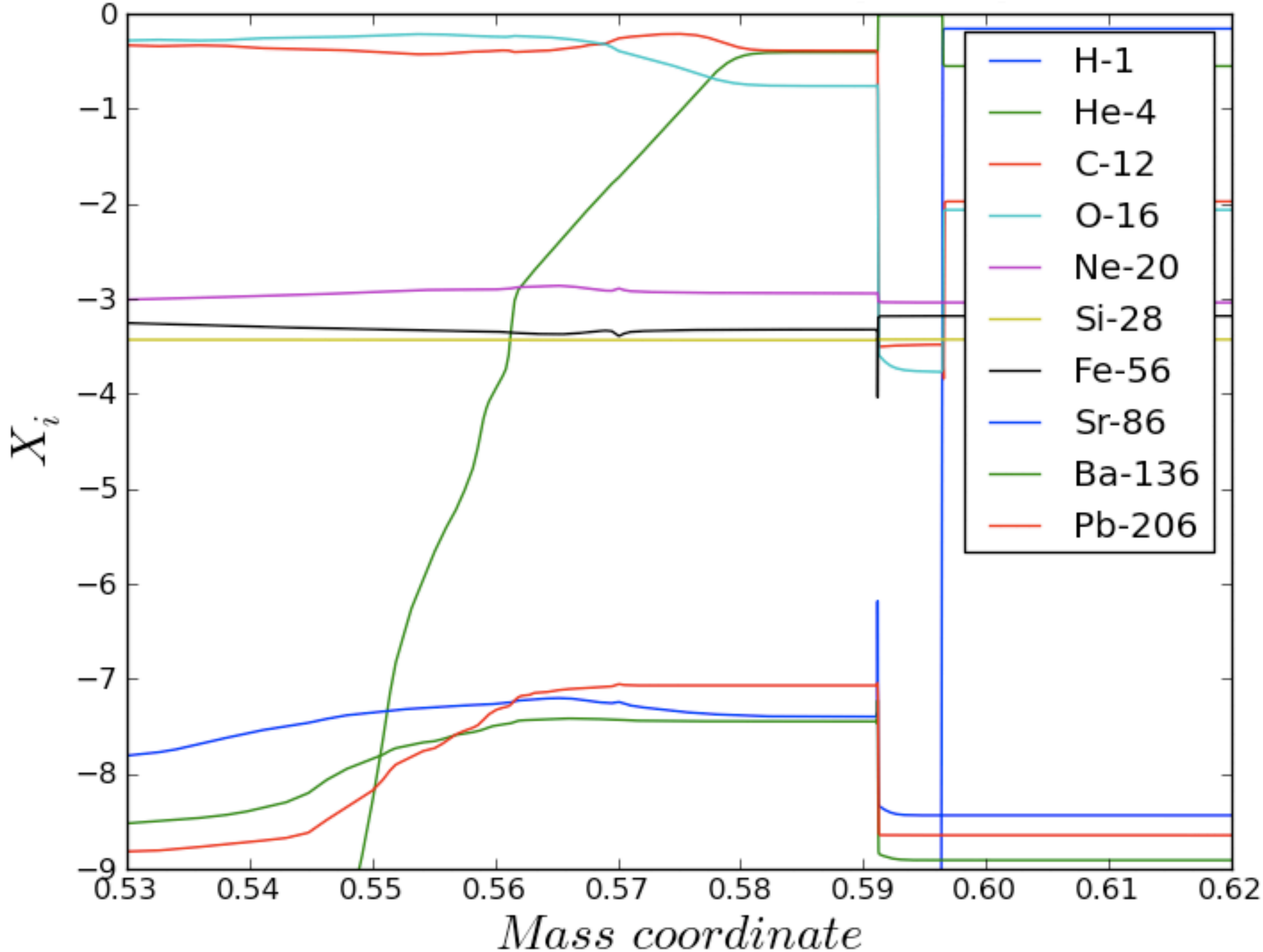
- 2 metallicities: Z=0.02, 0.01
- masses: 1.65, 2, 3, 5, 15, 20, 25 (32 and 60 for Z=0.02 only), massive star tracks with Geneva code, low-mass tracks with MESA code
- all tracks to the end of the AGB or end of Si burning
- synthetic explosions for massive stars
- complete post-processing of all tracks with the NuGrid ppn codes: all reactions and isotopes that could have taken place are considered

Evolution of low- & intermed. mass stars

Results Set 1: 2M_{sun} star

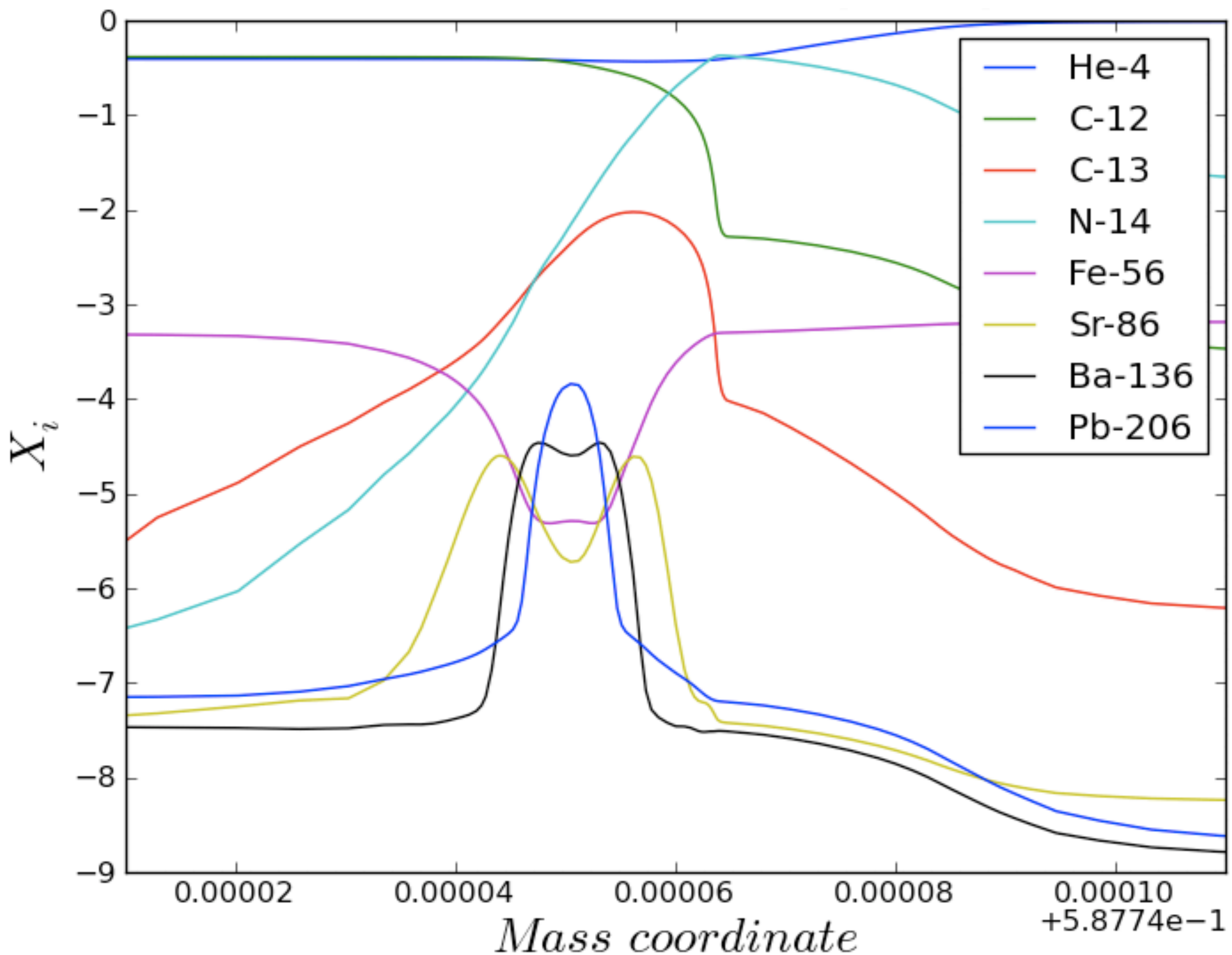
Nucleosynthesis including s-process in the He-shell flash thermal pulses of AGB stars from the NuGrid collaboration

Z=0.01



Results Set 1: 2M_{sun} star

Z=0.01



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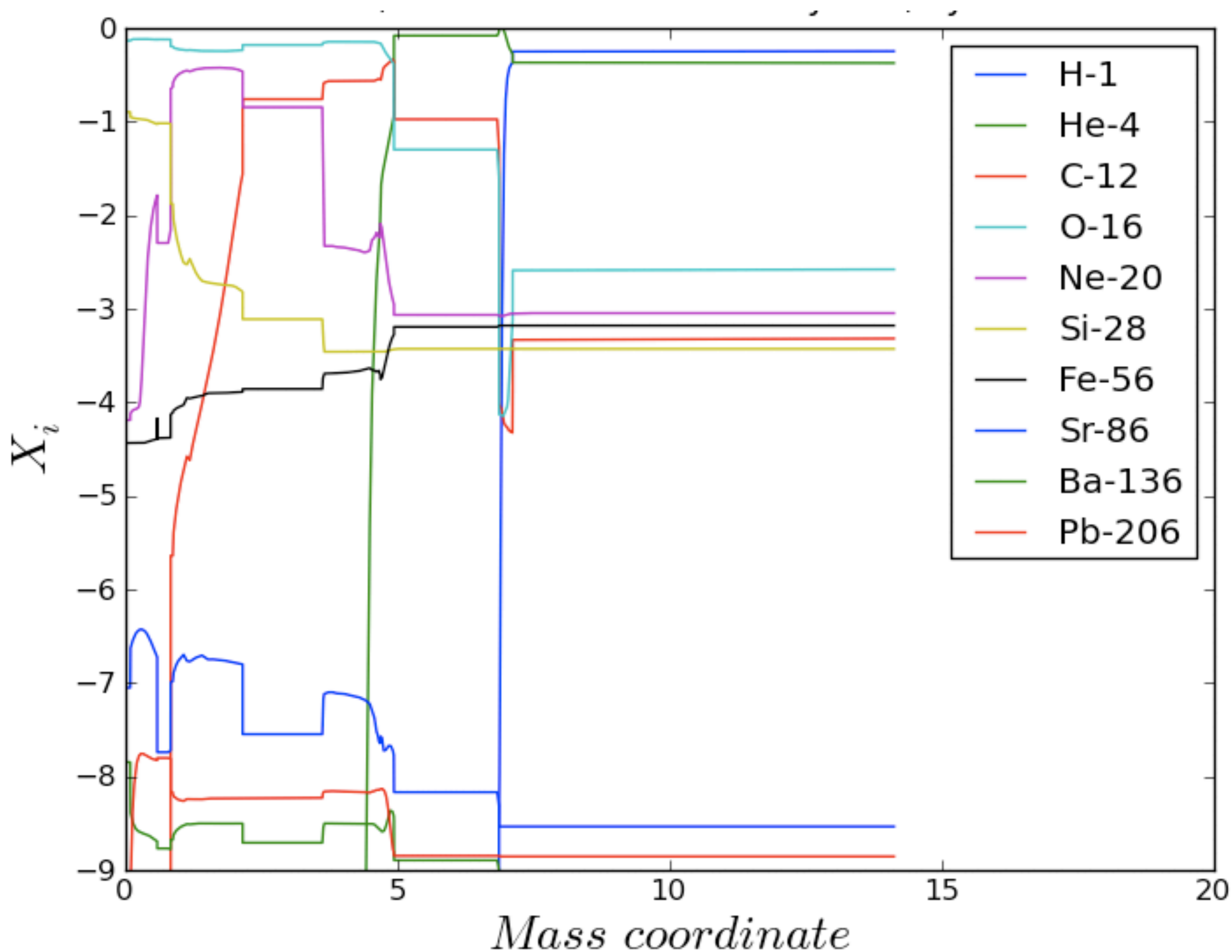
Evolution of low- & intermed. mass stars

Results Set 1: 20M$_{sun}$ star

Nucleosynthesis in a massive star

Z=0.01



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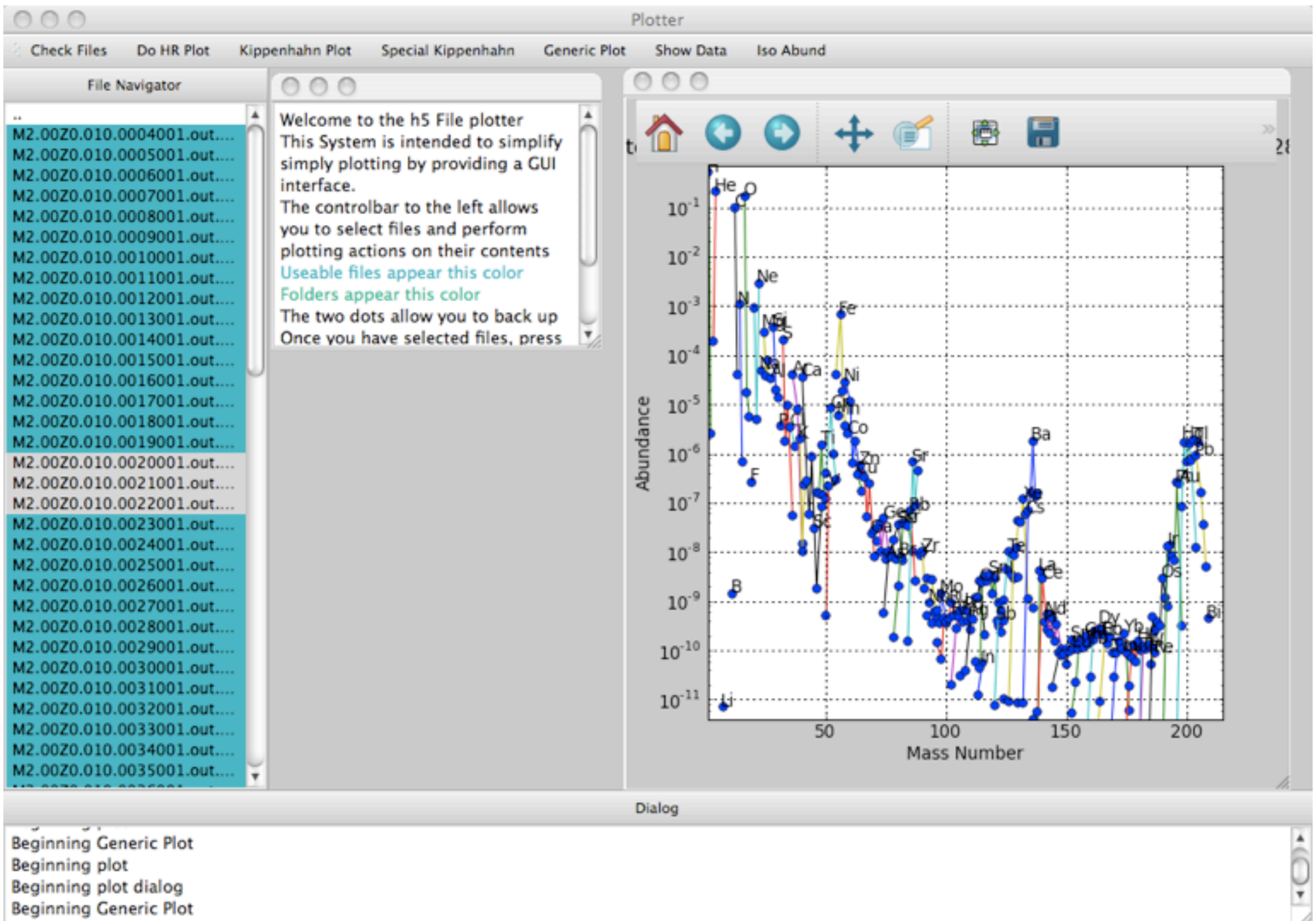
Availability of results

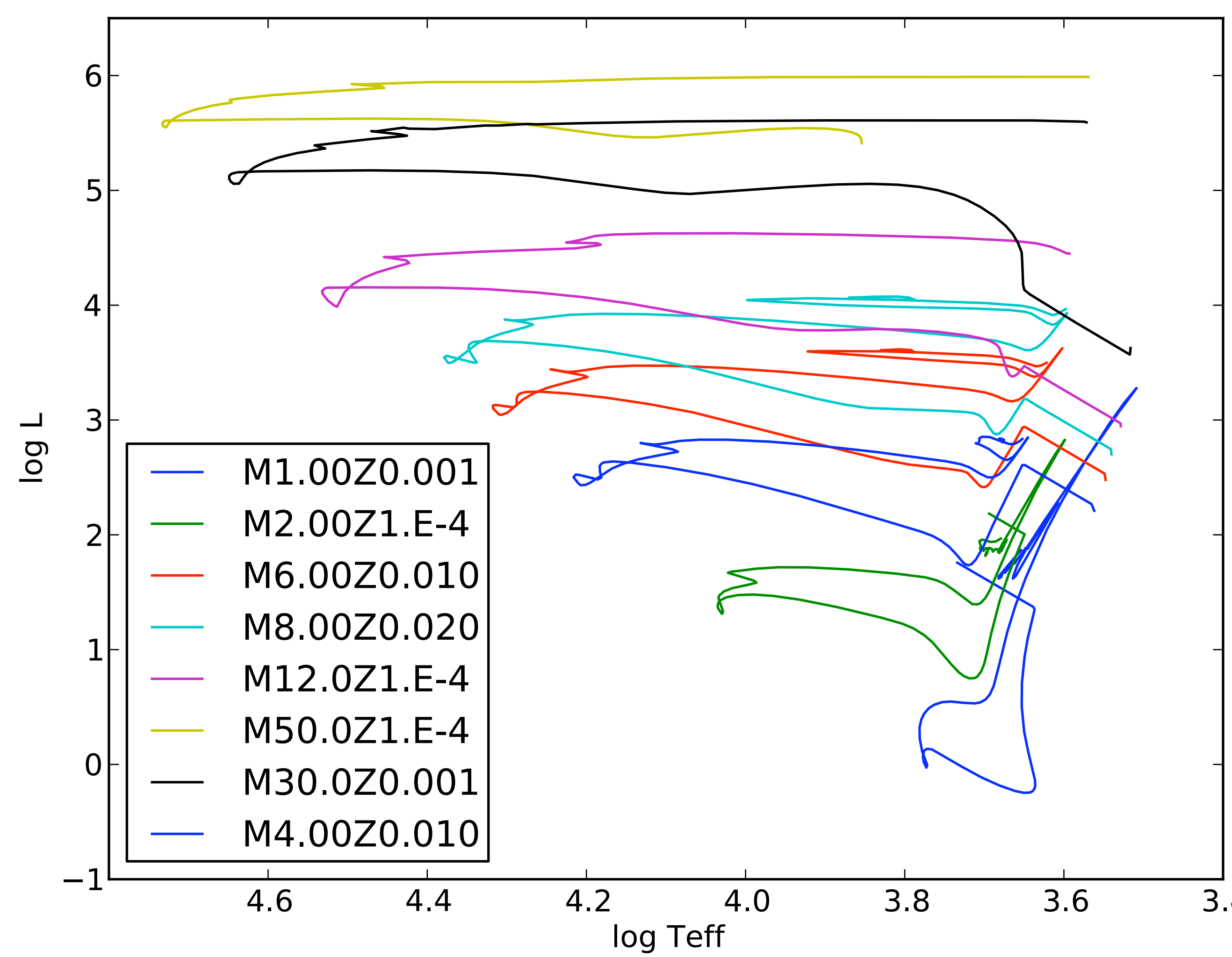
all data will be made available along with convenient tools to explore the data, e.g. SEexplorer: interactive data exploration and visualization as well as Python tools



Next steps: Set2

- 21 masses between 0.8 and 60M_{sun} for 5 metallicities between Z=0.04 and 1.e-4
- again non-rotating, no B-fields
- improved convective boundary mixing, mass loss
- 1D and 3D explosions
- SN Ia contributions
- again complete post-processing data sets of all tracks with the NuGrid ppn codes with all reactions and isotopes that could have taken place

HRD of a subset of preliminary Set 2 calculations to the end of He-core burning



Concluding remarks

- progress is being made in many areas now by investigating multi-dimensional effects in the stellar interior.
- many approaches needed - don't expect the golden bullet
- great opportunities for nuclear astrophysics: as we push to simulate shorter timescales we need new diagnostics sensitive on shorter time scales -> branchings, radiaoctive beams, nuclear physics of radioactive targets