Quo vadis stellar evolution

Themes for this talk

1. Stellar evolution: present state
2. The multi-dimensional star
3. Application of stellar evolution

Falk Herwig
University of Victoria
Beautiful British Coloumbia

University of Victoria

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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]

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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.

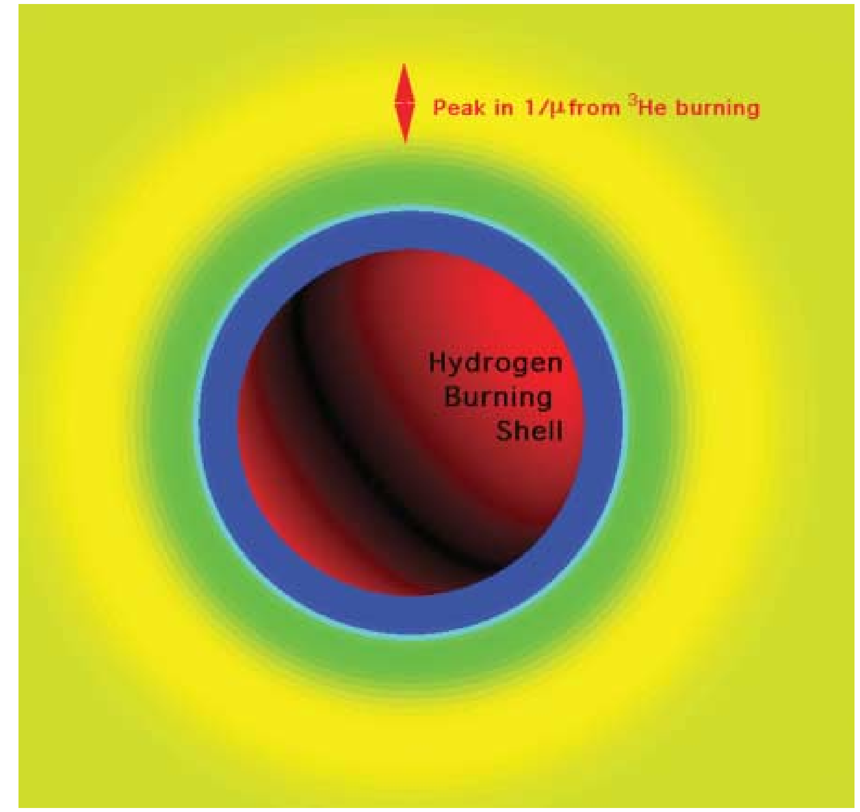

Fig. 4. A color-coded plot of μ on a cross-section through the initial 3D model. The shell where the μ inversion occurs is the yellow region sandwiched between a yellow-green and a darker green. The inversion is at a radius of ~5 × 10^7 m. The base of the SCZ is at ~2 × 10^9 m, well outside the frame,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

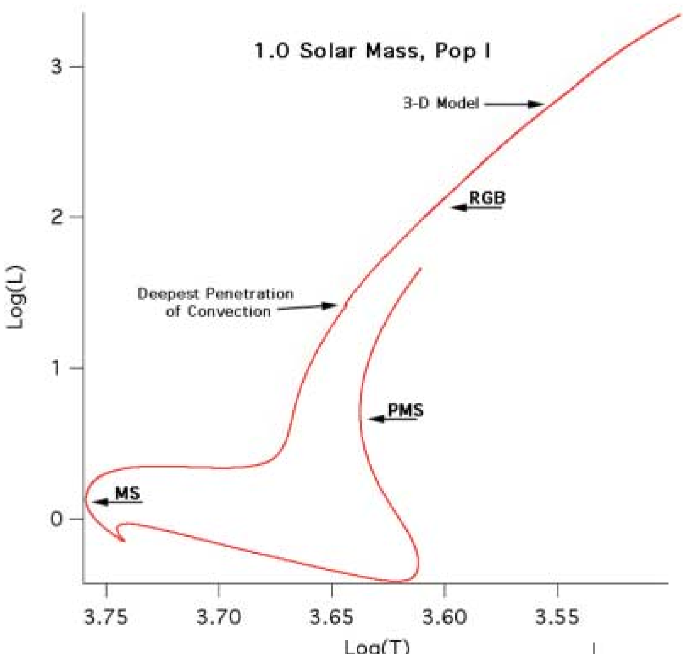

Fig. 1. Evolution of a low-mass Pop I star in a luminosity-temperature diagram. The model was computed in 1D, that is, spherical symmetry was assumed, using the code of (*20*, *21*) with updated equation of state, opacity, and nuclear reaction rates (*22*). Surface temperature is in kelvins, luminosity in solar units.

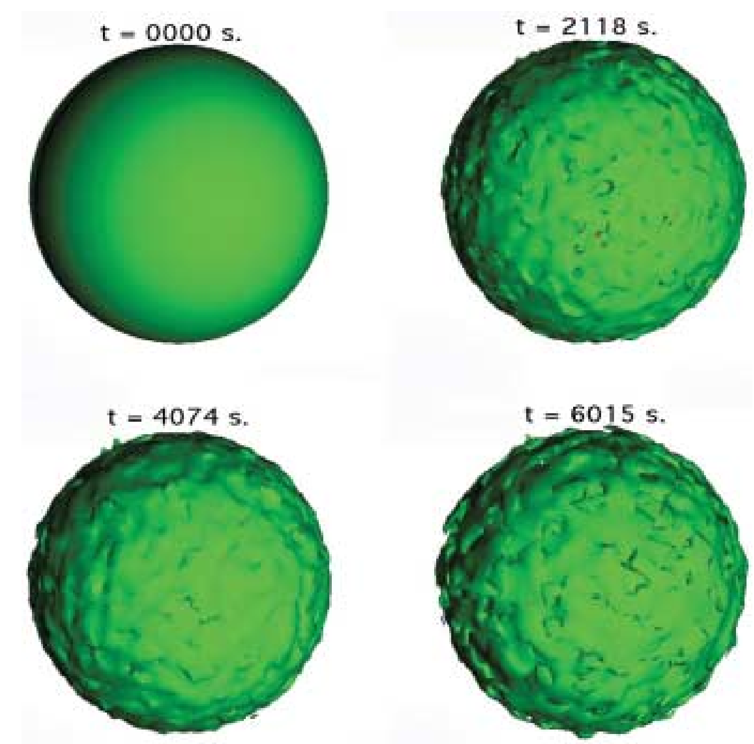

Fig. 5. The development with time of a contour surface of mean molecular weight near the peak in the blue curve of Fig. 3. The contour dimples, and begins to break up, on a time scale of only ~2000 s.

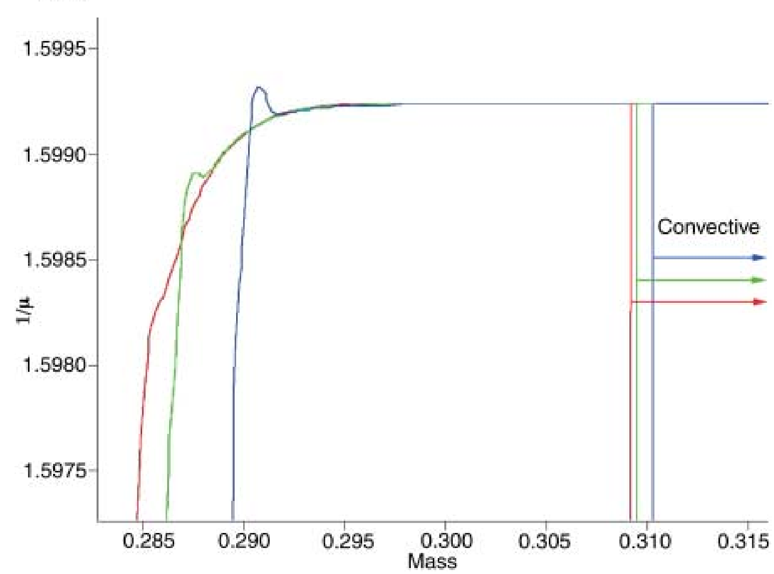

Fig. 3. The profile of reciprocal molecular weight (1/μ), as a function of mass in solar units, at three successive times (red, then green 2 million years later, then blue 2 million years later still).

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Wednesday, March 31, 2010

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

THE ASTROPHYSICAL JOURNAL, 172:165–177, 1972 February 15

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

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

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,

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

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.

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THE ASTROPHYSICAL JOURNAL, 677:581–592, 2008 April 10

COMPULSORY DEEP MIXING OF ^{3}He AND CNO ISOTOPES IN THE ENVELOPES OF LOW-MASS RED GIANTS

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Received 2007 January 17; accepted 2007 December 20

ABSTRACT

Three-dimensional stellar modeling has enabled us to identify a deep-mixing mechanism that must operate in all low-mass giants. This mixing process is not optional, and is driven by a molecular weight inversion created by the ^{3}He(^{3}He,2*p*)^{4}He reaction. In this paper we characterize the behavior of this mixing, and study its impact on the envelope abundances. It not only eliminates the problem of ^{3}He overproduction, reconciling stellar and big bang nucleosynthesis with observations, but solves the discrepancy between observed and calculated CNO isotope ratios in low-mass giants, a problem of more than three decades standing. This mixing mechanism, which we call "$\delta\mu$ mixing," operates rapidly (relative to the nuclear timescale of overall evolution, $\sim 10^8$ yr) once the hydrogen-burning shell approaches the material homogenized by the surface convection zone. In agreement with observations, Population I stars between 0.8 and 2.0 $M_\odot$ develop ^{12}C/^{13}C ratios of 14.5 ± 1.5, while Population II stars process the carbon to ratios of 4.0 ± 0.5. In stars less than 1.25 $M_\odot$, this mechanism also destroys 90%–95% of the ^{3}He produced on the main sequence.

Subject headings: hydrodynamics — stars: abundances — stars: chemically peculiar — stars: evolution — stars: interiors — stars: Population II

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.

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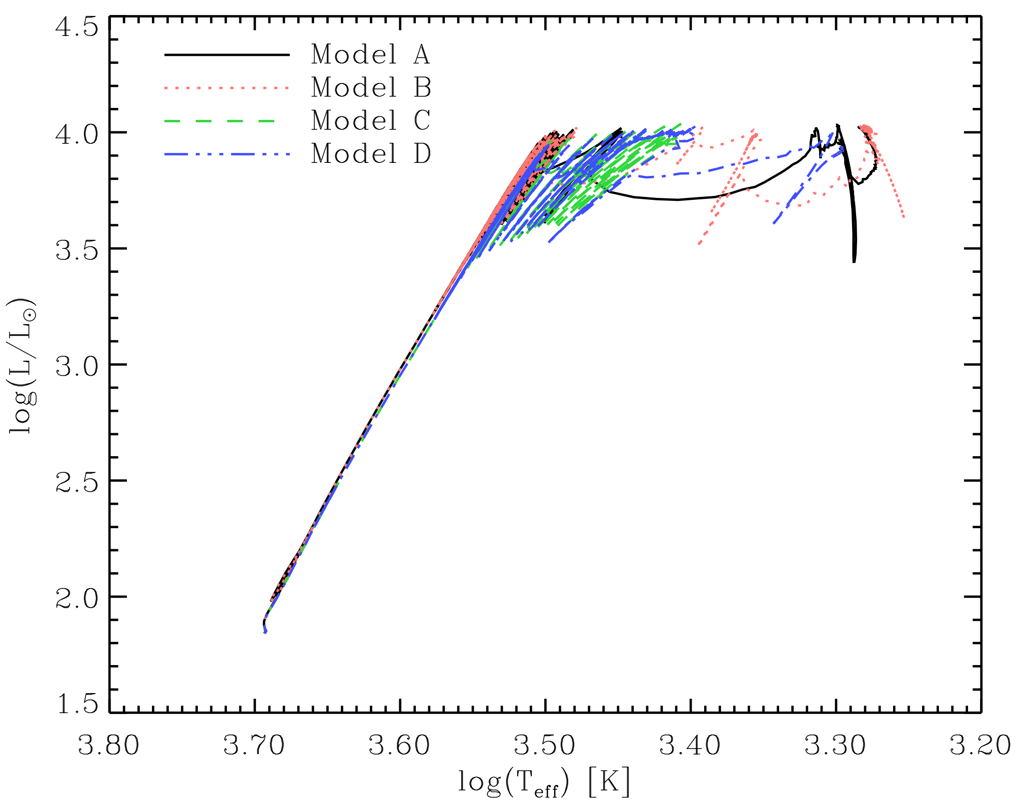
Mass loss and opacities in AGB stars

Mattson, Herwig, Hoefner, Wahlin, Lederer, Paxton

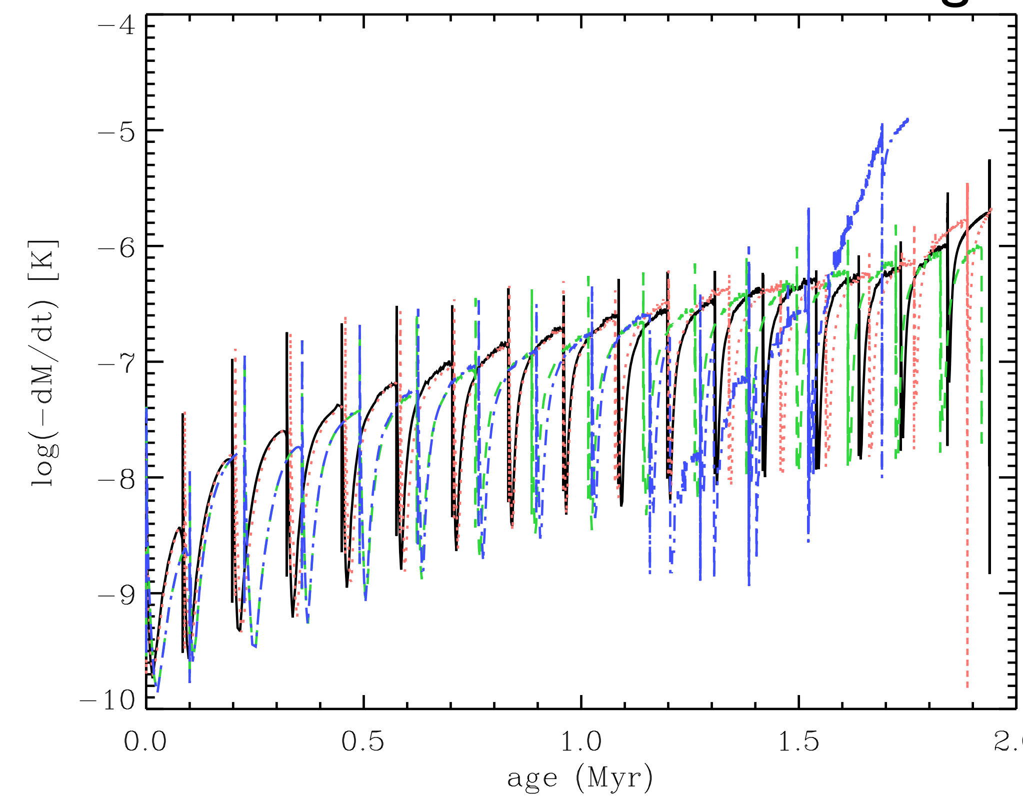
Effects of Carbon-excess Dependent Mass Loss and Molecular Opacities on Models of C-star Evolution

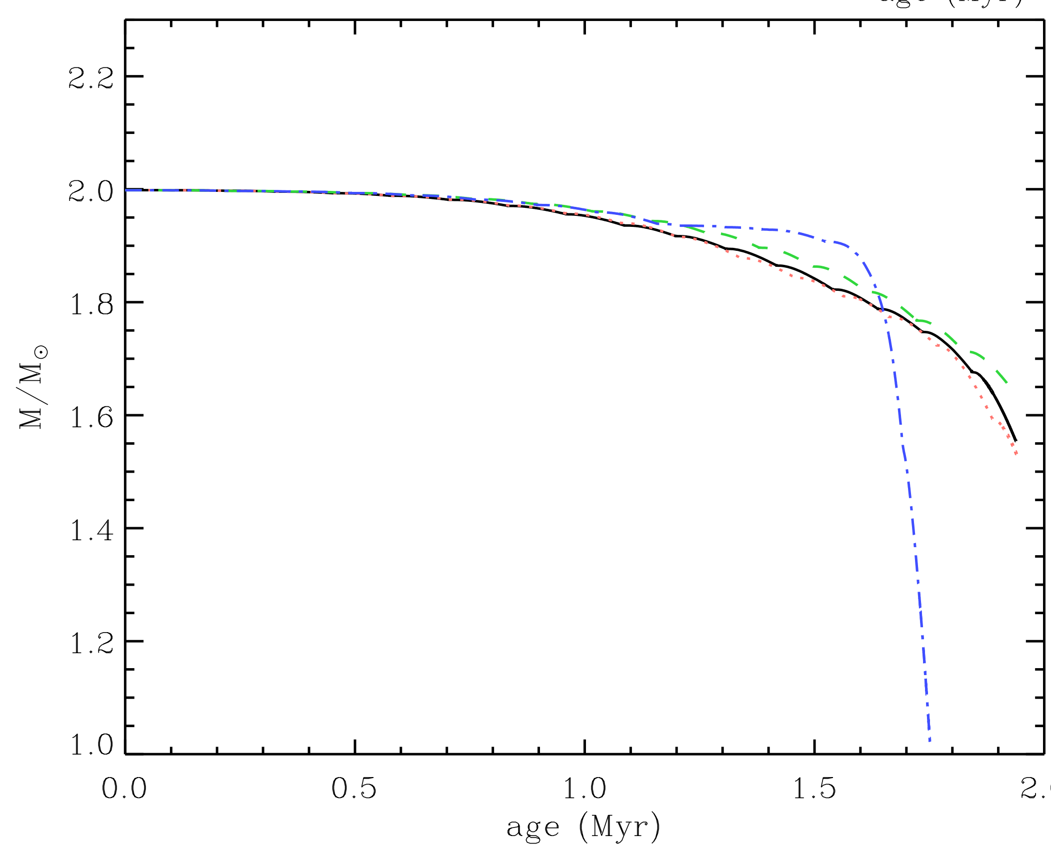
A Mass loss according to Blöcker for both M-star phase and C-star phase. Low-temperature opacities by Alexander & Ferguson (1994) without dependence on the carbon excess.
B Mass loss according to Blöcker for M-star phase and according to Mattsson et al. (2009) for the C-star phase, and low-temperature 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

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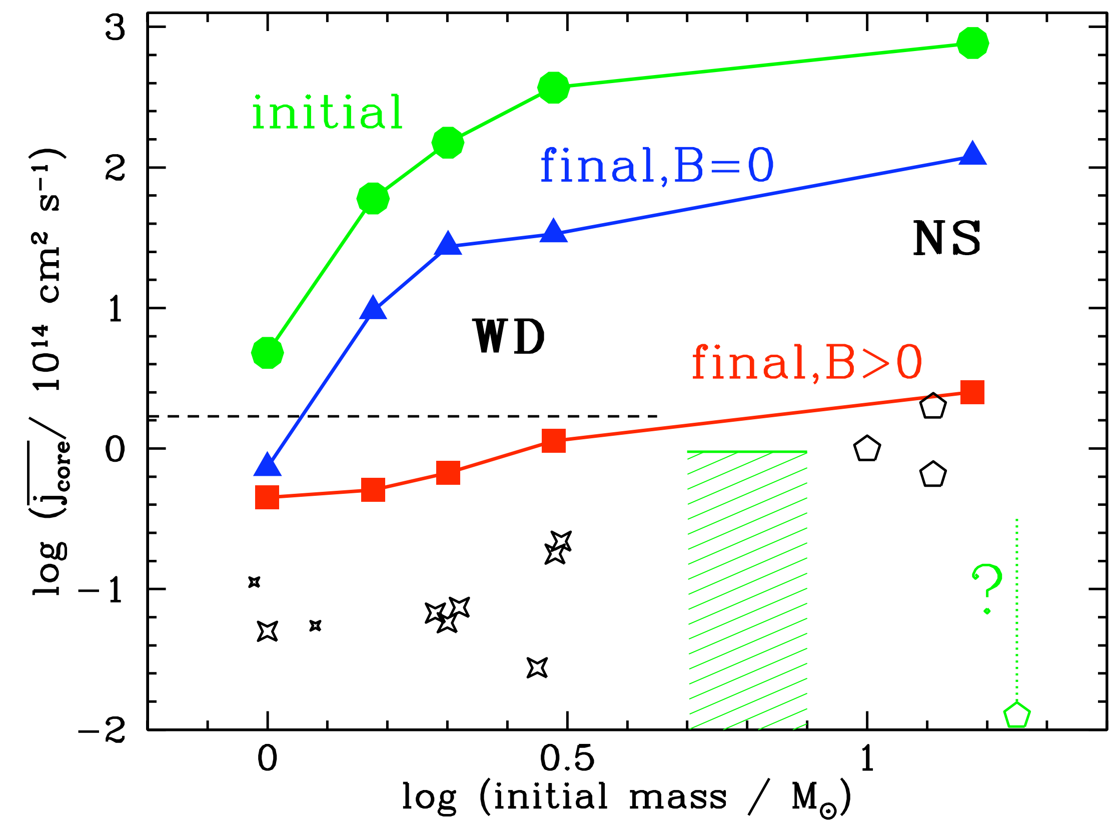
Rotation and magnetic fields

- 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)



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.

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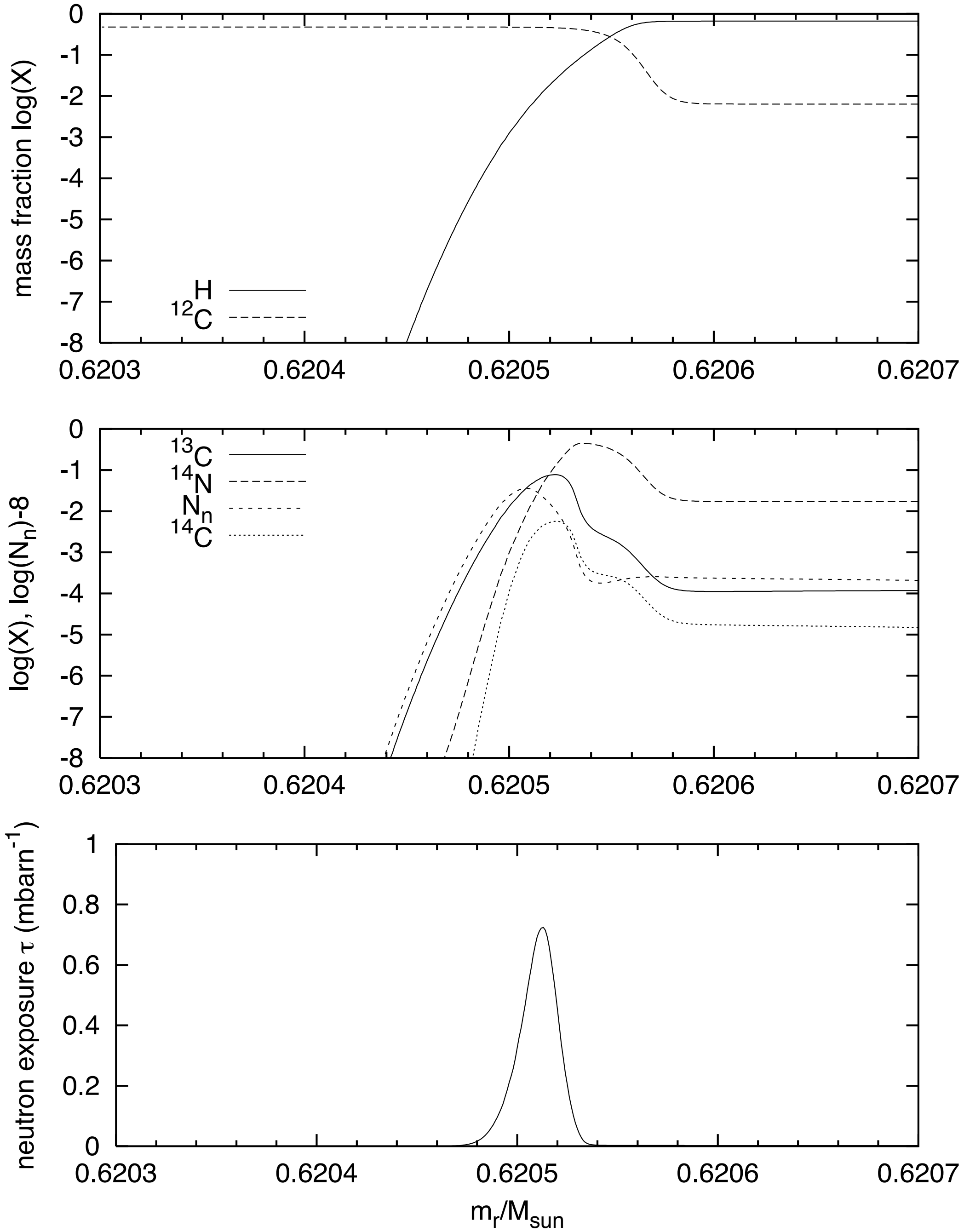
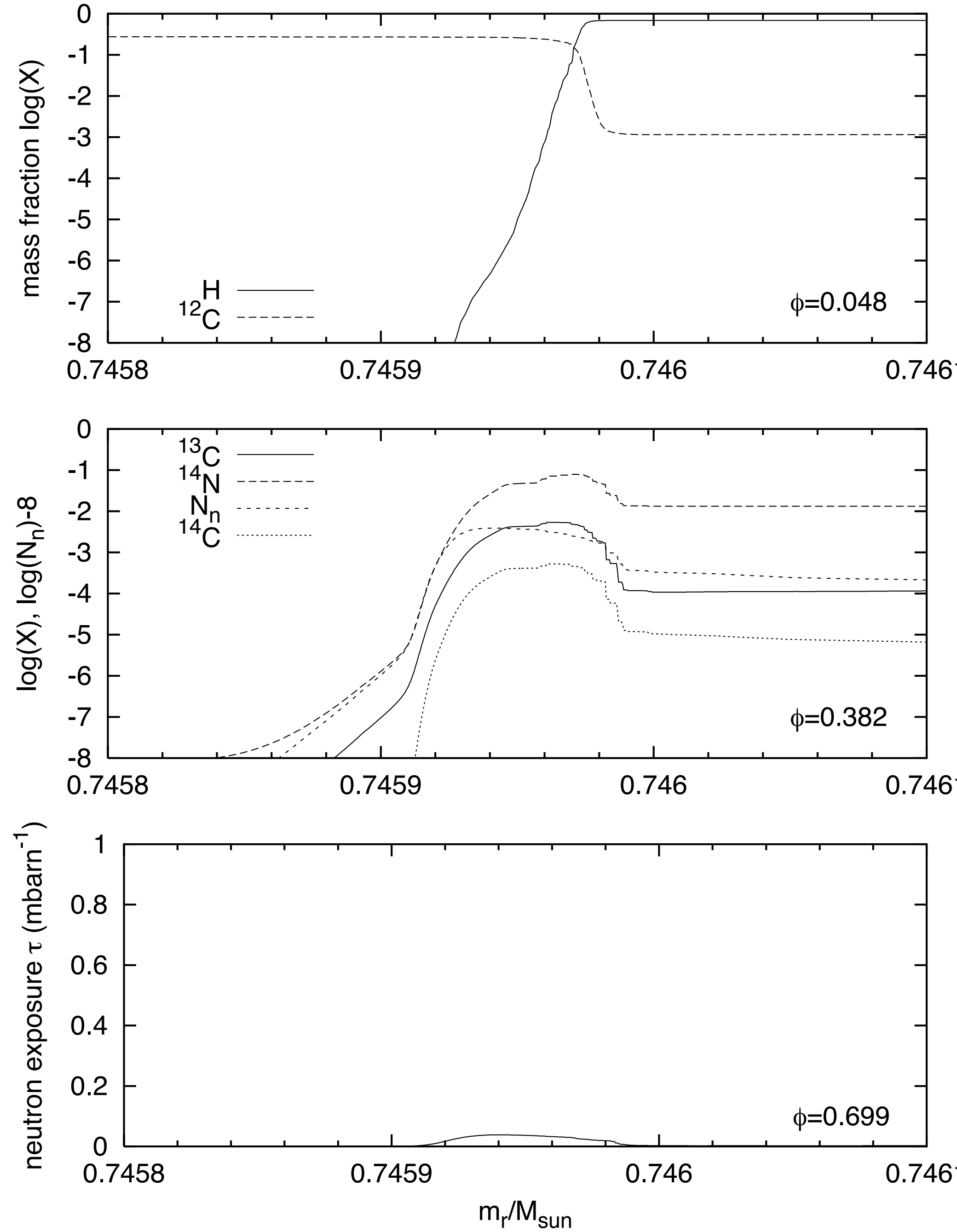
Rotation and magnetic fields

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

no rotation



with rotation



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Rotation and magnetic fields

next generation ?!?

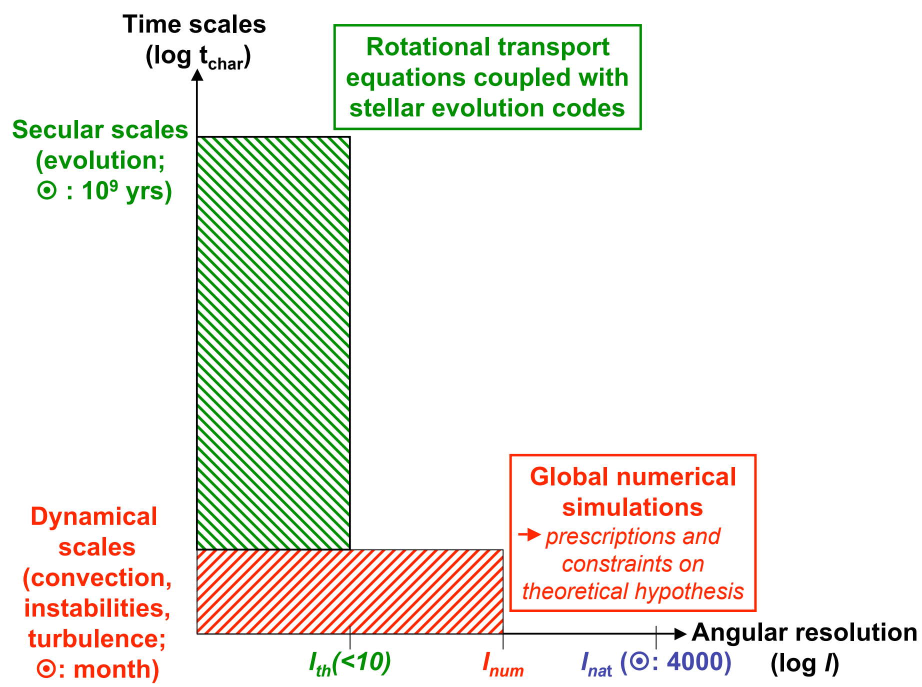

Fig. 1. Modelling strategy to study dynamical stellar evolution. The diagram presents timescales of the typical physical processes as a function of the angular resolution necessary to properly describe these processes. The angular resolution is expressed in terms of the l index of the spherical harmonics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

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Stellar evolution in the early universe

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
- combustion in low- and zero-metallicity stars common, inlcuging both low-mass and massive, rotating and non-rotating stars
- examples of papers which have not observed this physics requirement: e.g. Herwig etal 1999, Herwig 2001 plus ca. 10-20 since then.
- check our poster and arXiv:1002.2241 for details

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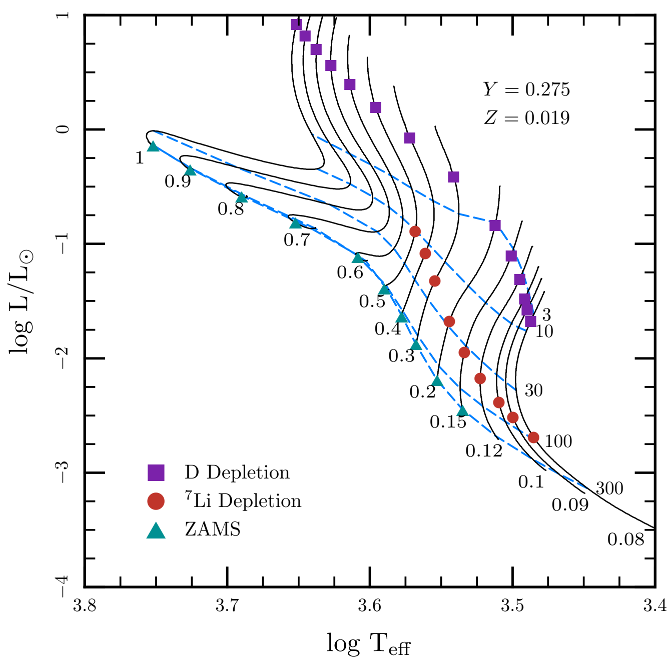
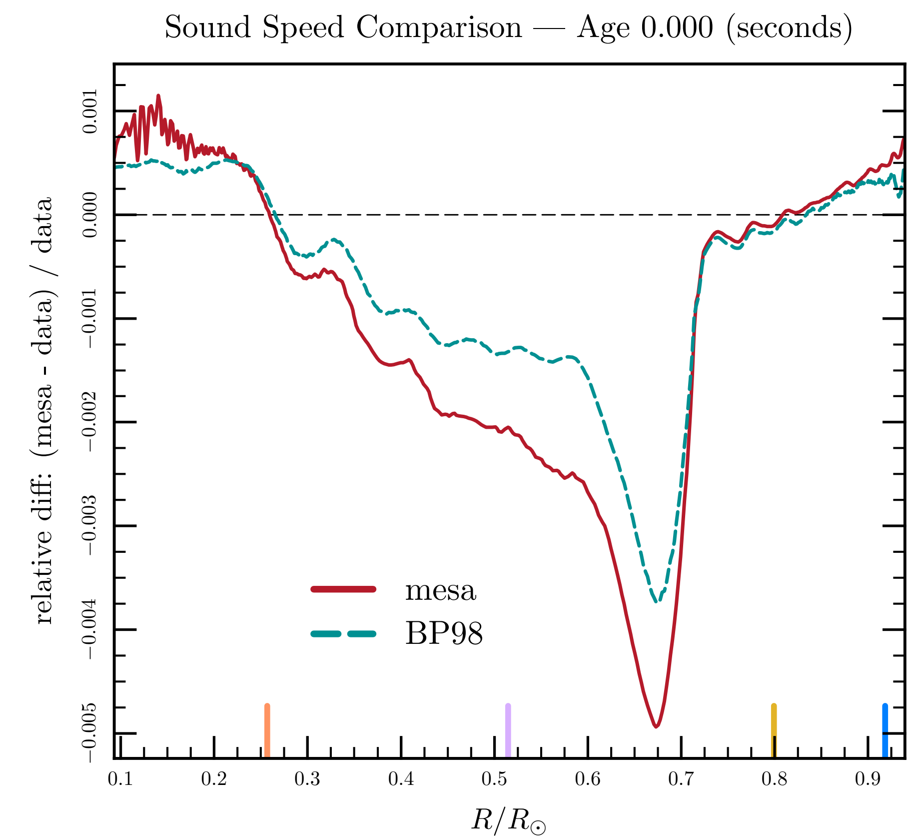
MESA: modules for experiments in stellar evolution

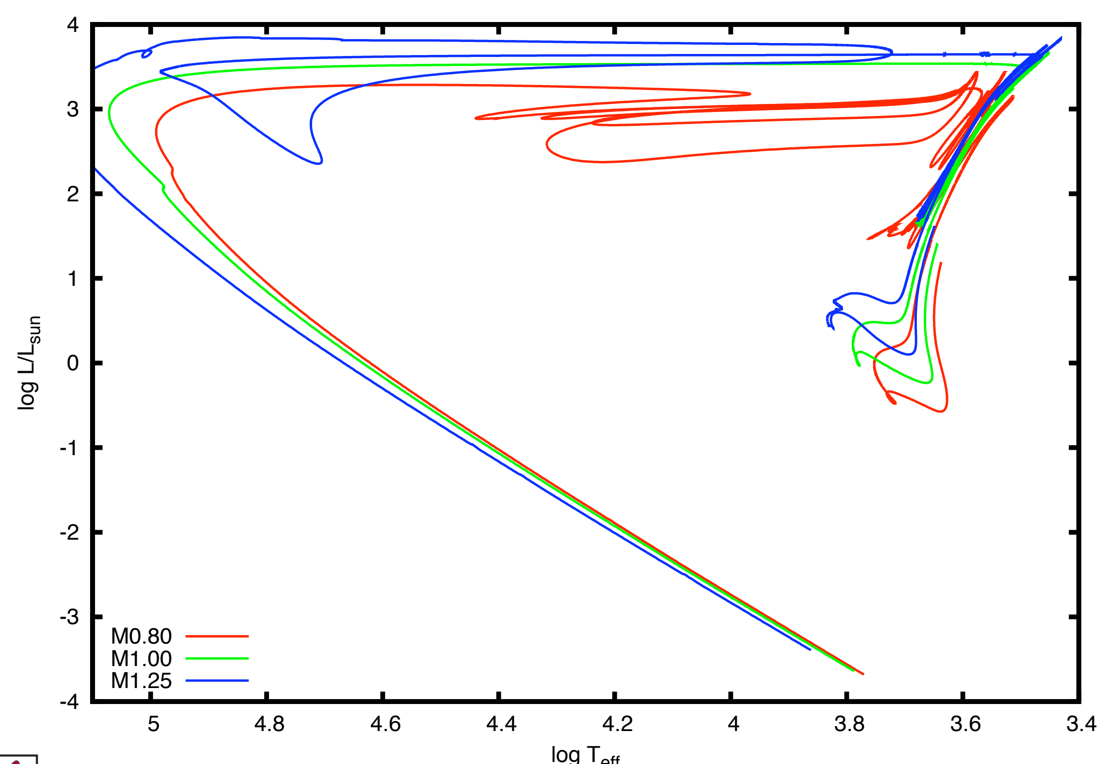
A new, modern, modular, open, fast community stellar evolution code

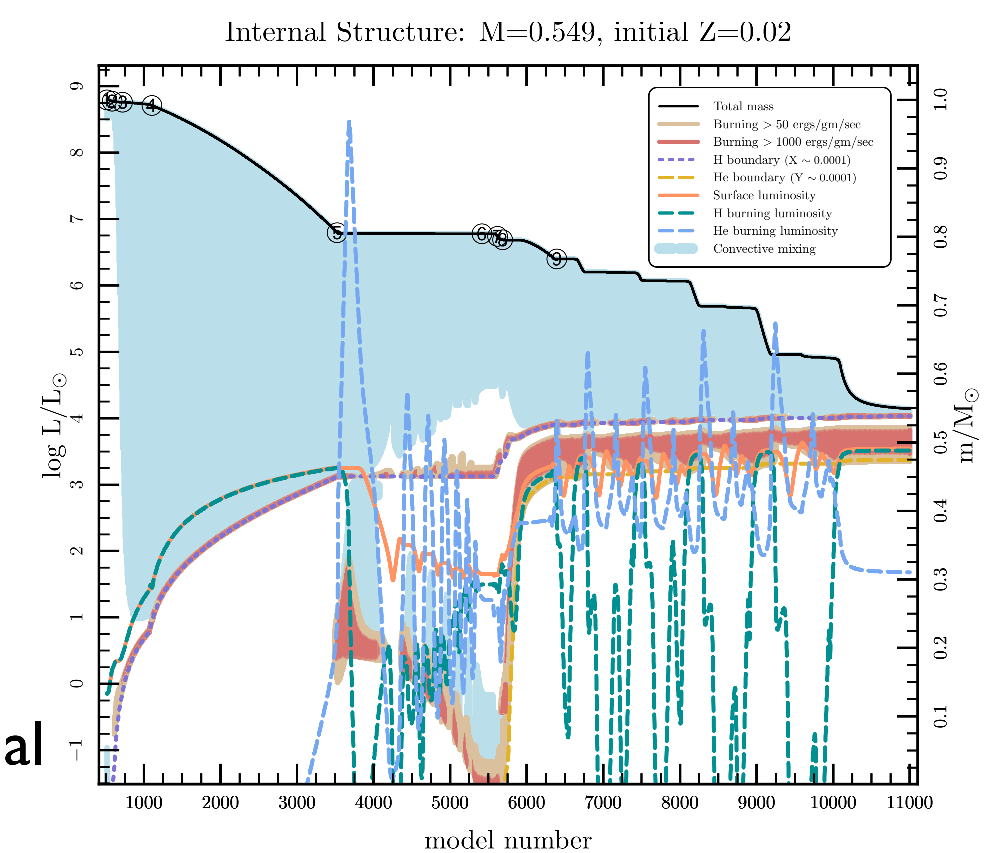


PMS of Brown dwarfs, VLM and LM stars



MS to WD through He-core flash < 1day on my laptop





1M$_{sun}$ internal evolution

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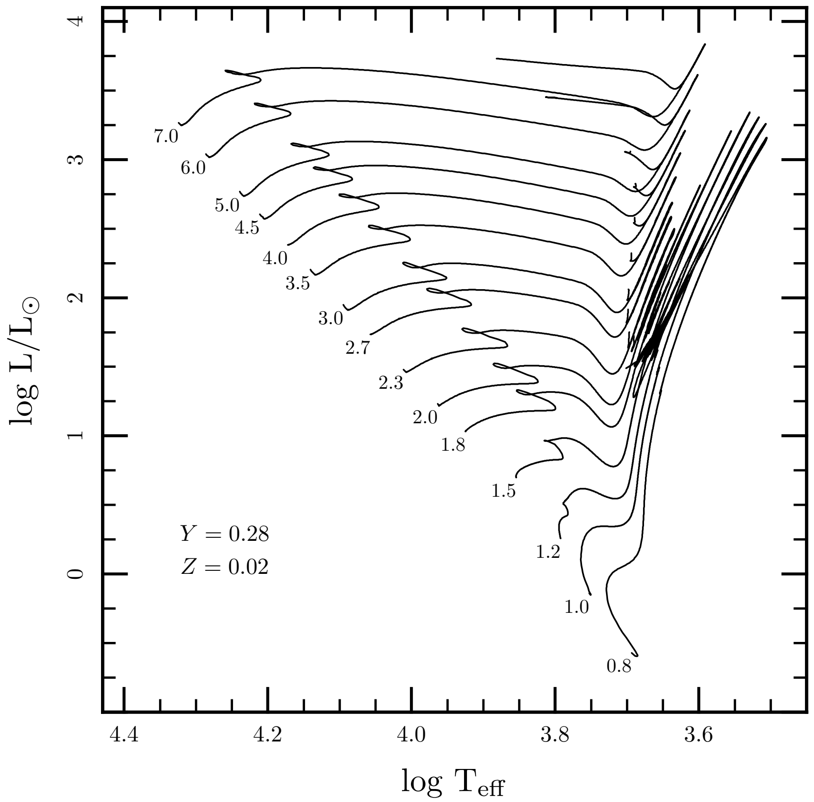
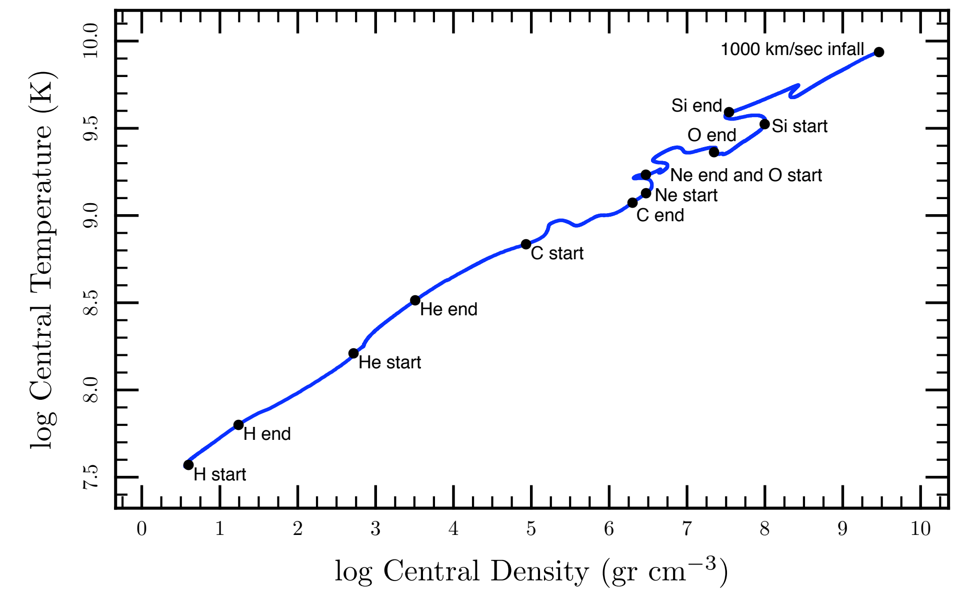
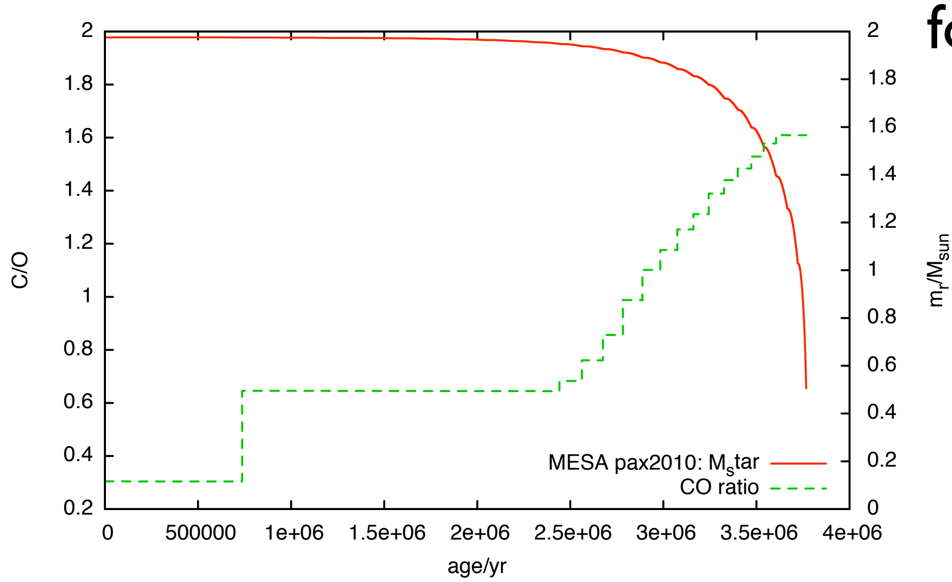


low-/intermediate mass evolution

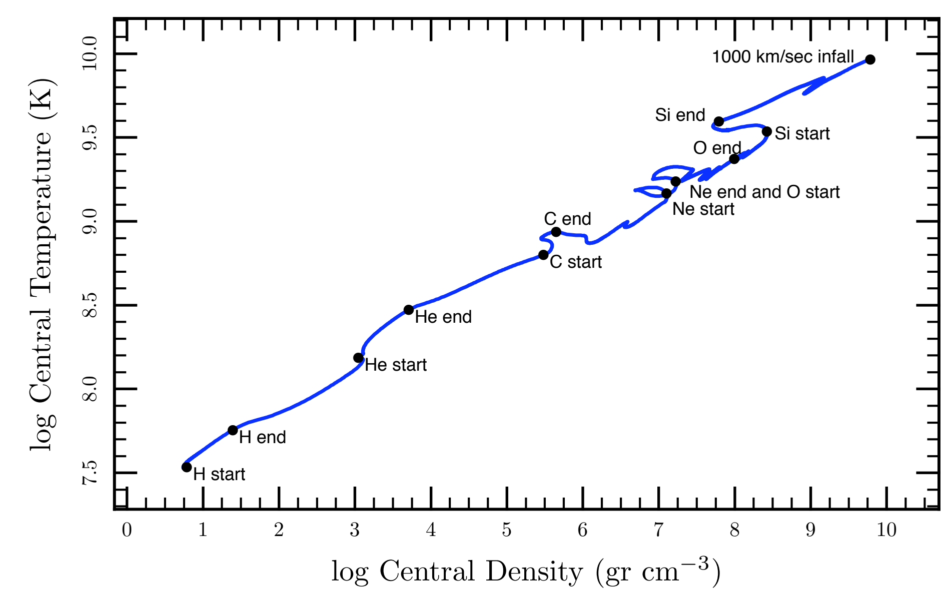
massive star evolution



$25M_{sun}$



C-star formation on the AGB



$15M_{sun}$

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MESA: modules for experiments in stellar evolution

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

http://mesa.sourceforge.net/

MESA
Modules for Experiments in Stellar Astrophysics

MESA home
getting started
news
numerics
microphysics
macrophysics
evolution
how to use MESA/STAR
mailing lists

Links

Bill Paxton

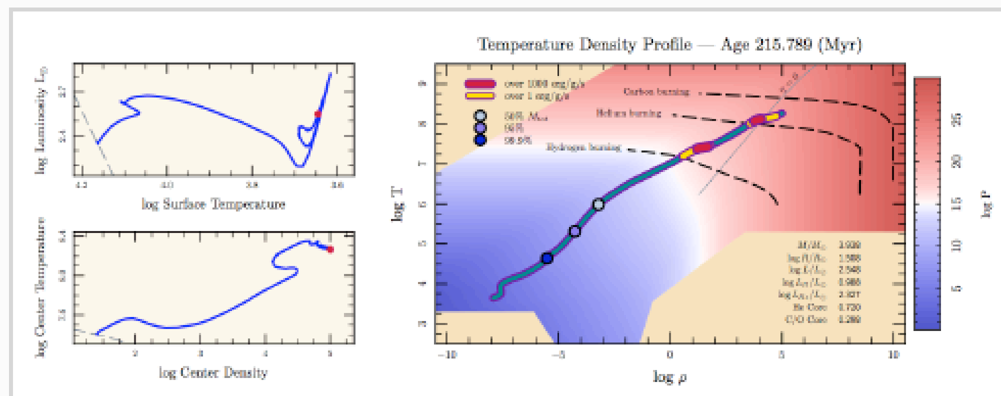
Lars Bildsten
Frank Timmes
Lorne Nelson
Pierre Lesaffre
Falk Herwig
Aaron Dotter
Don VandenBerg
Steinn Sigurðsson
Raphael Hirschi
Jon Tomshine

tioga for plots
MESA at sourceforge

Welcome

... to the homepage of ***MESA***, modules for experiments in stellar astrophysics.

- Overview
- Background
- How do you say that?
- What does thread-safe mean?
- Why Fortran? Isn't C++ better?
- Which Fortran 95 Compiler?



This plot is a hint of the sort of experiments in stellar astrophysics that MESA will support. It shows the state of a 4 Msun star during a second ascent of the Red Giant Branch computed with MESA modules. Included are the HR track, the time history of the central temperature vs density, and the profile of the star in the temperature and density plane with the background colored to show the pressure.

Overview

The software project MESA, Modules for Experiments in Stellar Astrophysics, aims to provide state-of-the-art, robust, and efficient open source modules, usable singly or in combination for a wide range of applications in stellar astrophysics. It includes modules for various aspects of the physics, such as nuclear networks, opacities, and

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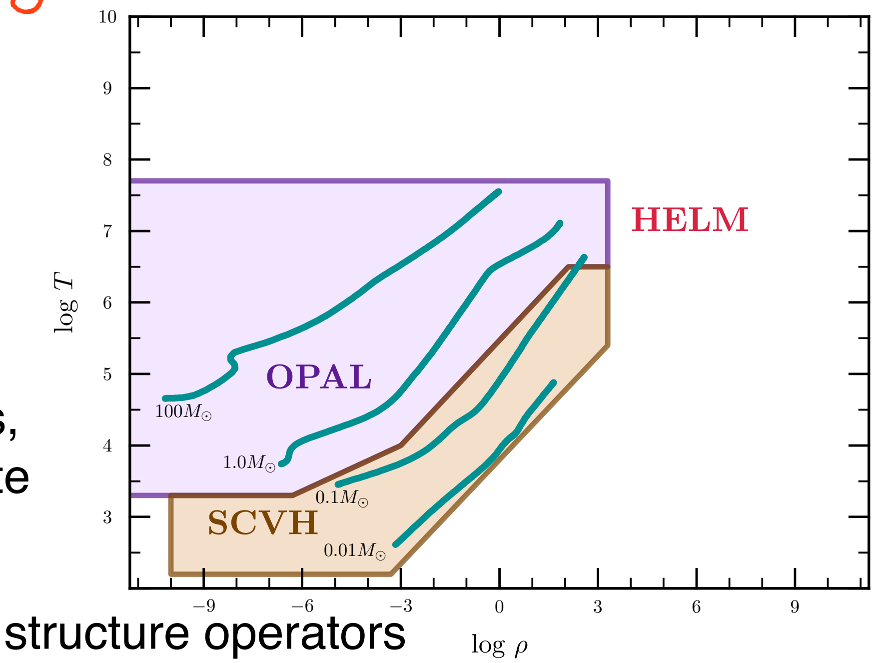
MESA: modules for experiments in stellar evolution

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



MESA acknowledgements:
MESA was written from scratch by **Bill Paxton** (KITP/UCSB) with major support from **Lars Bildsten** as well as the following individuals:

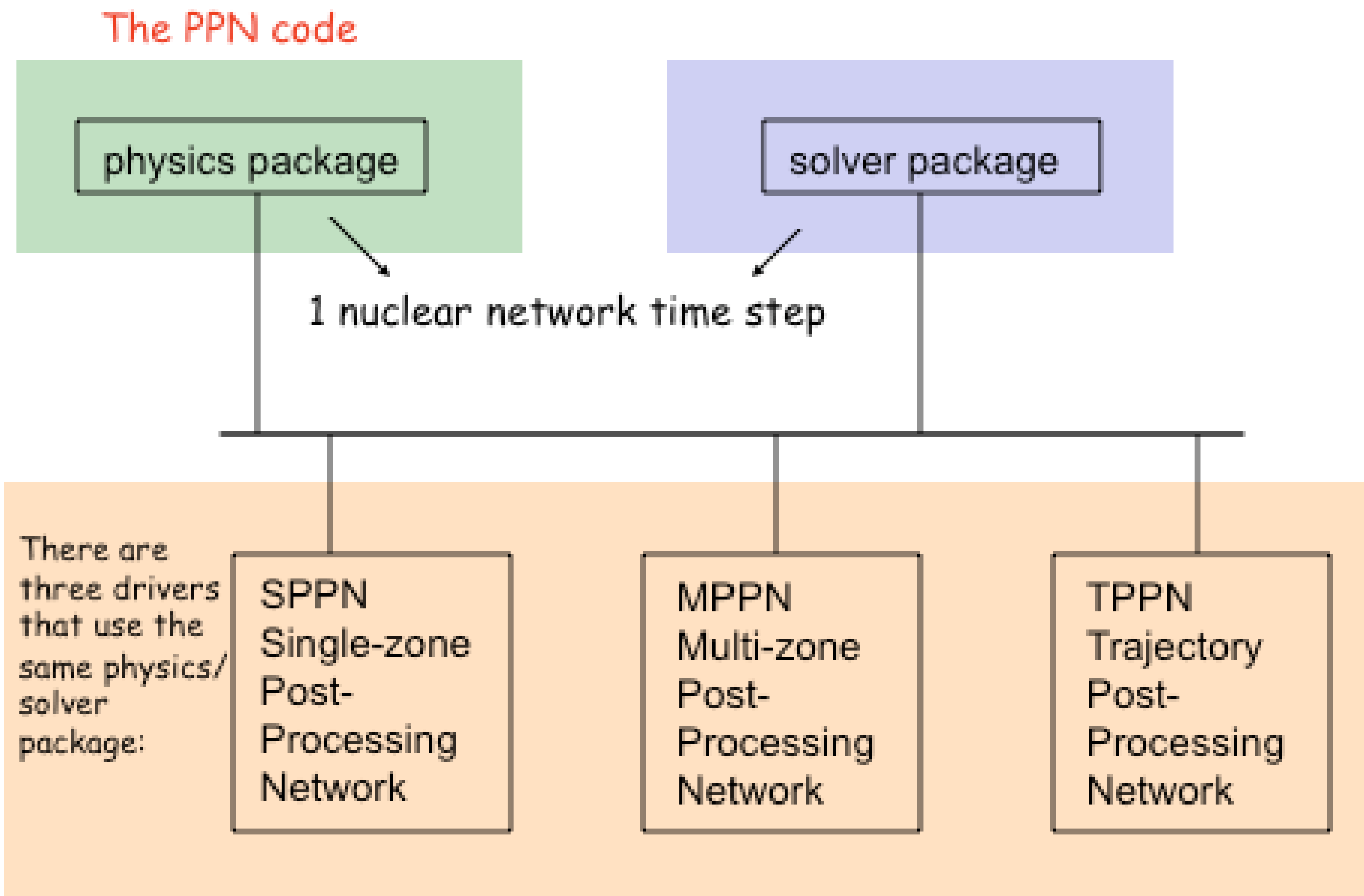
- ★ Frank Timmes
- ★ Lorne Nelson
- ★ Pierre Lesaffre
- ★ Falk Herwig
- ★ **Aaron Dotter**
- ★ Don VandenBerg
- ★ Steinn Sigurðsson
- ★ Raphael Hirschi
- ★ Jon Tomshine
- ★ Ed Brown

Some features:

- versatile compilation of EOS, allowing VLM stars, brown dwarfs, degenerate stars
- full coupling of mixing, burning and structure operators
- both hydrodynamic and hydrostatic option
- range of networks, including those needed for massive star collapse
- convection MLT (different versions), overshooting, Ledoux criterion, semi-convection
- mass transfer, accretion, mass loss, binary stars (Roche Lobe overflow)
- several atmosphere options, including atmosphere tables, e.g. from Phoenix code
- verified (as in code comparison with established research codes) for low mass stars, the sun, advanced phases (AGB), massive stars, including nucleosynthesis predictions
- passed Stellar Code Calibration (Achim Weiss etal) project test cases
- individual module level verification for eos, kap, atm, mlt by running in DSEP code and EVOL code
- diffusion/gravitational settling via Thoul et al. (1994); recently verified against VandenBerg's code with diffusion treated according to Michaud & Proffit.
- pulsation module (LAWE according to Jørgen Christensen-Dalsgaard's ADIPLS, 1997)
- thermohaline mixing
- compatible with NuGrid nucleosynthesis codes.

NuGrid: Nucleosynthesis for a wide range of (M,Z)

A new, parallel, comprehensive nucleosynthesis code for large-scale post-processing computations



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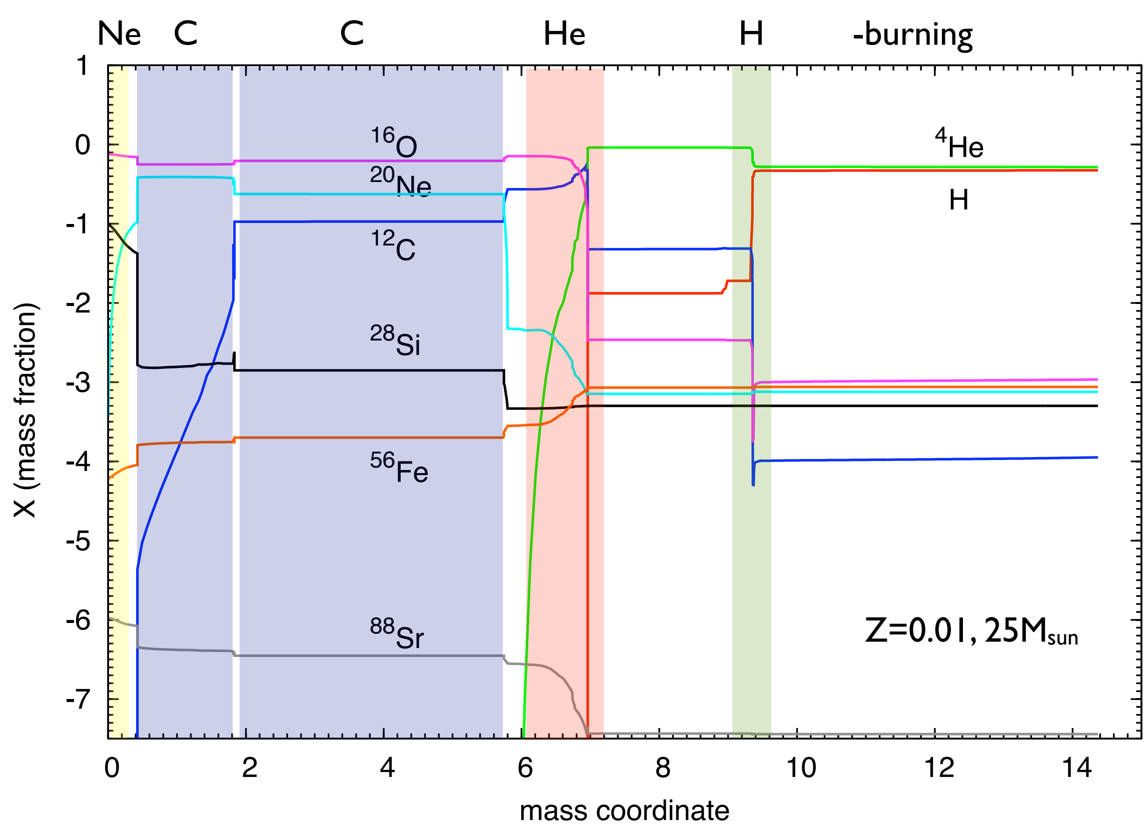
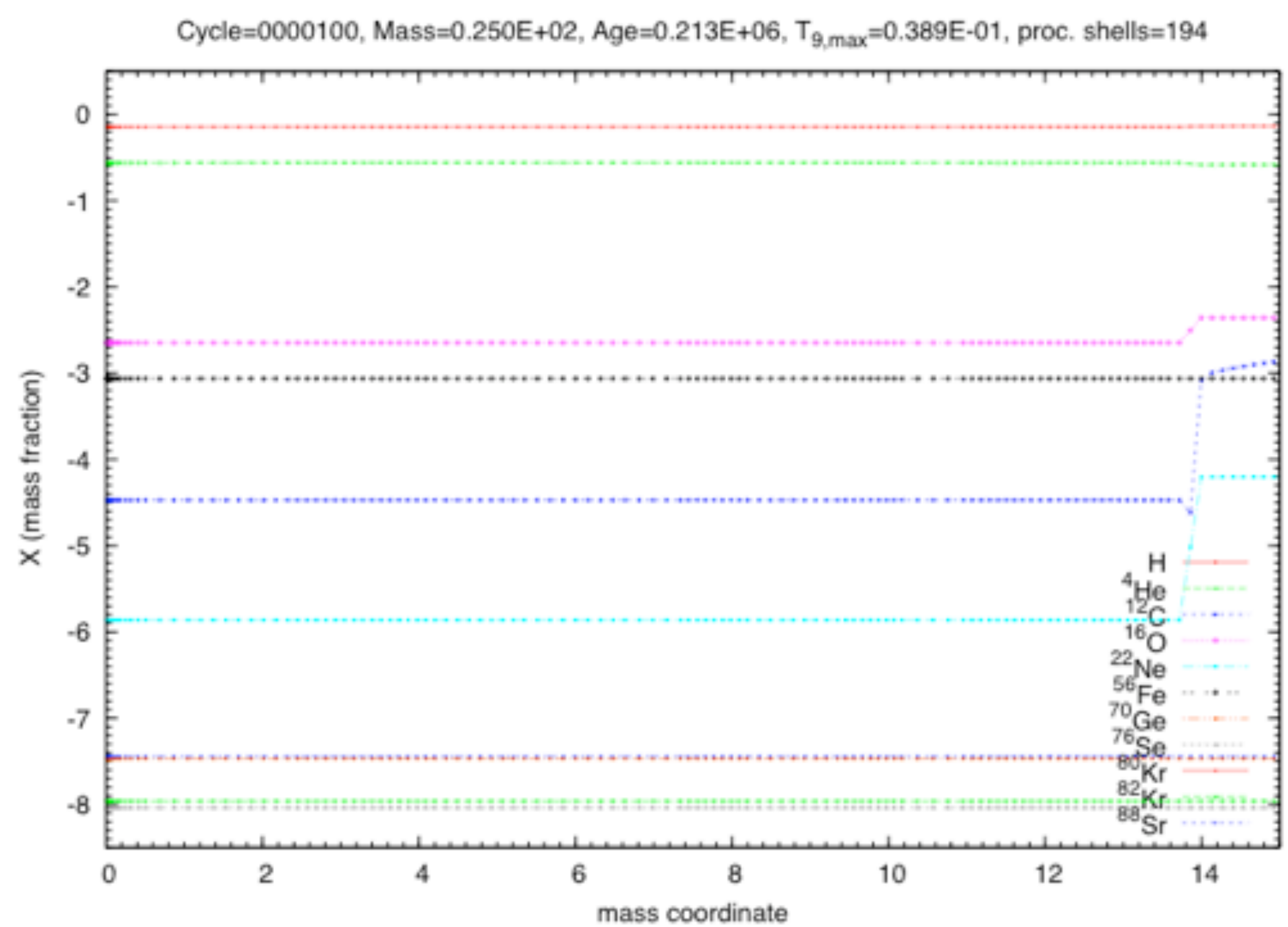
NuGrid: Nucleosynthesis for a wide range of (M,Z)

Application examples

$25M_{sun}$ nucleosynthesis





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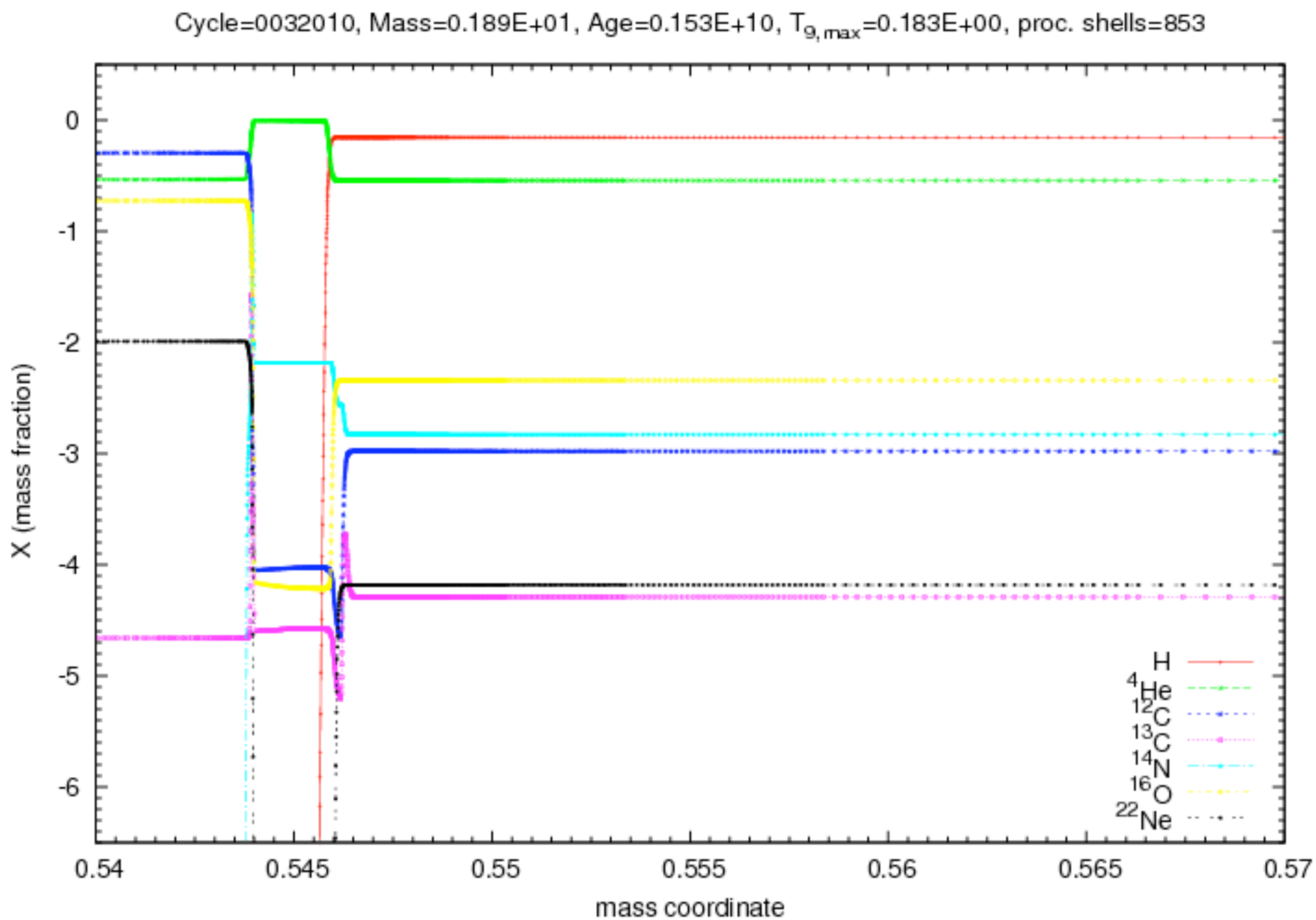
NuGrid: Nucleosynthesis for a wide range of (M,Z)

Application examples

$2.0M_{sun}$ nucleosynthesis



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NUGRID

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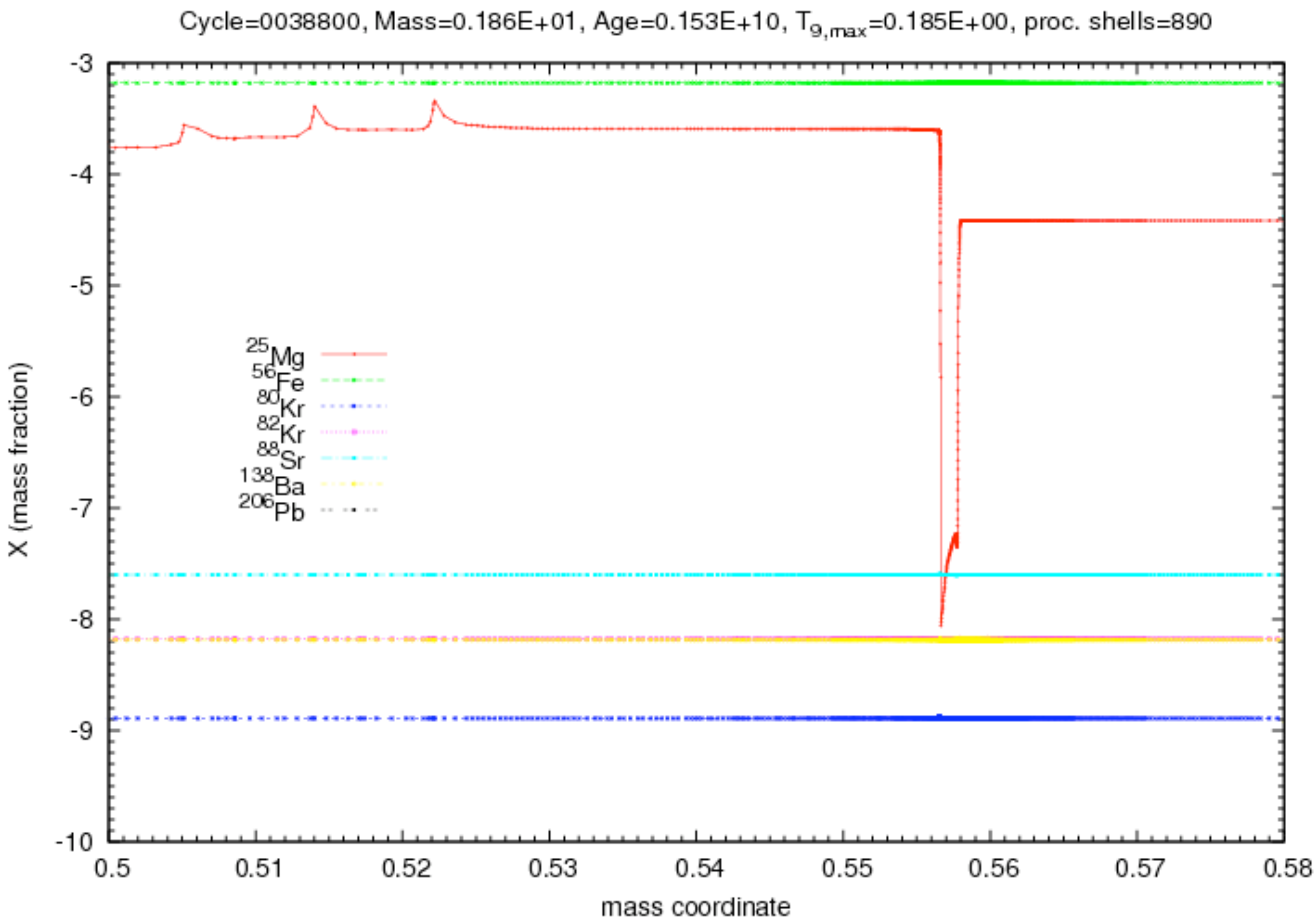
NuGrid: Nucleosynthesis for a wide range of (M,Z)

Application examples

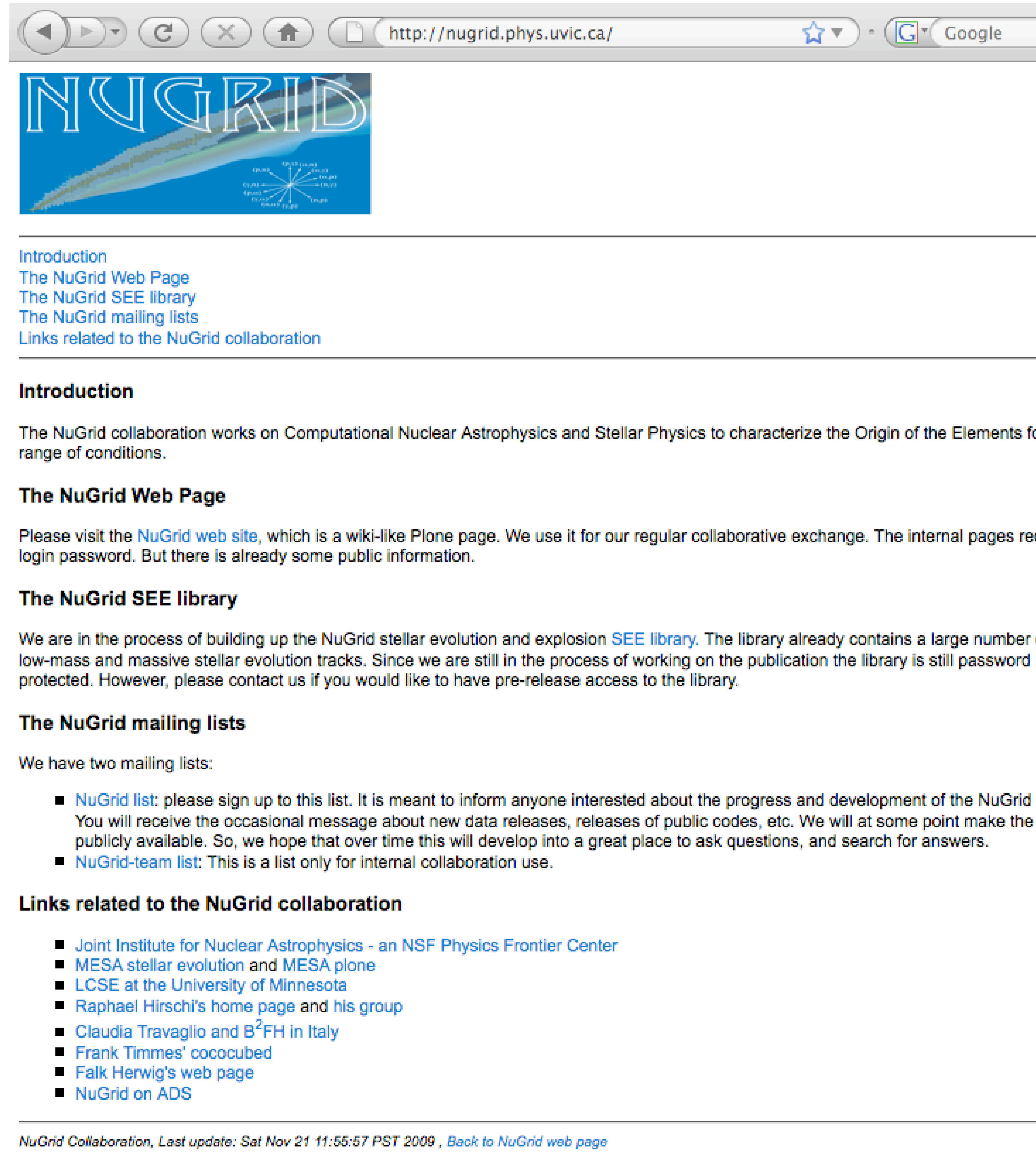
2.0M_{sun} nucleosynthesis



NuGrid: Nucleosynthesis for a wide range of (M,Z)

NuGrid acknowledgements:

- ★ R. Hirschi, M. Bennett (Keele University, UK)
- ★ F. Herwig, M. Pignatari, William Hillary, Debra Richman, Aaron Dotter (University of Victoria, BC, Canada)
- ★ C. L. Fryer, G. Rockefeller, A. Hungerford, Aaron Courture (Los Alamos National Laboratory, NM, USA)
- ★ F. X. Timmes, P. A. Young (Arizona State University)
- ★ Claudia Travaglio (Observatory of Torino, INAF)
- ★ Bill Paxton (KITP, UC Santa Barbara)
- ★ JINA


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 fo 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 re 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 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:

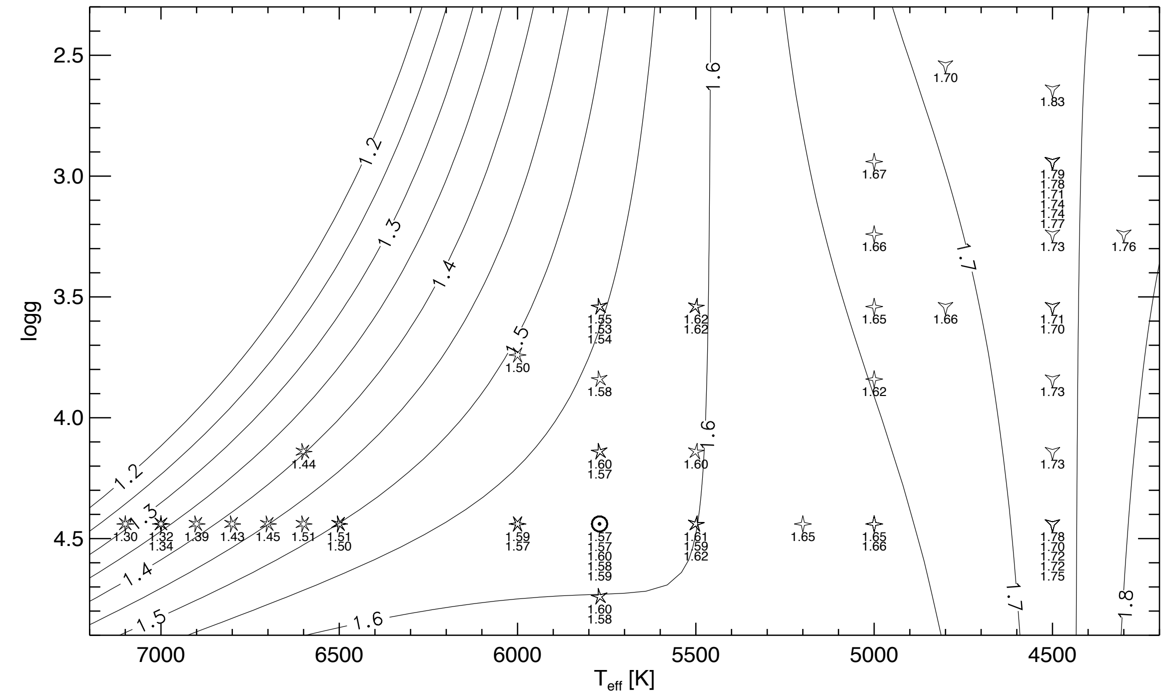
- NuGrid list: please sign up to this list. It is meant to inform anyone interested about the progress and development of the NuGrid You will receive the occasional message about new data releases, releases of public codes, etc. We will at some point make the publicly available. So, we hope that over 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

Multi-dimensional stars



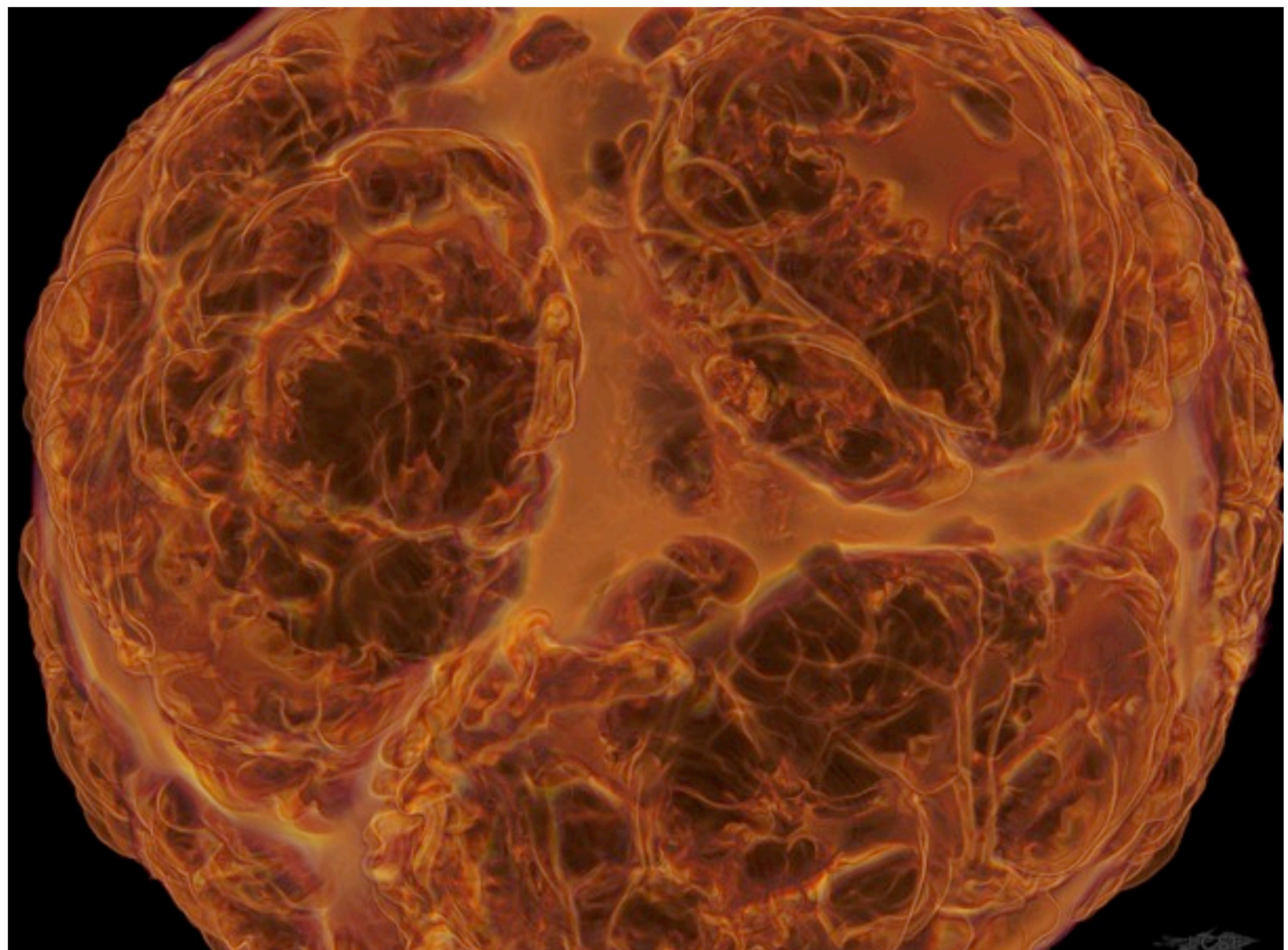
Convection (vs. secular instabilities) of the stellar interiors:

α_{MLT} is different in different convection zones

i. "A calibration of the mixing-length for solar-type stars based on hydrodynamical simulations", Ludwig, Freytag & Steffen, A&A (1999)

ii. "Abundances in intermediate-mass AGB stars undergoing third dredge-up and hot-bottom burning" McSaveney, J. A.; Wood, P. R.; Scholz, M.; Lattanzio, J. C.; Hinkle, K. H., MN (2007) $\alpha_{MLT} \sim 2.3 - 2.6$

iii. "Three-dimensional Simulations of Turbulent Compressible Convection", Porter & Woodward (2000) $\alpha_{MLT} \sim 2.68$



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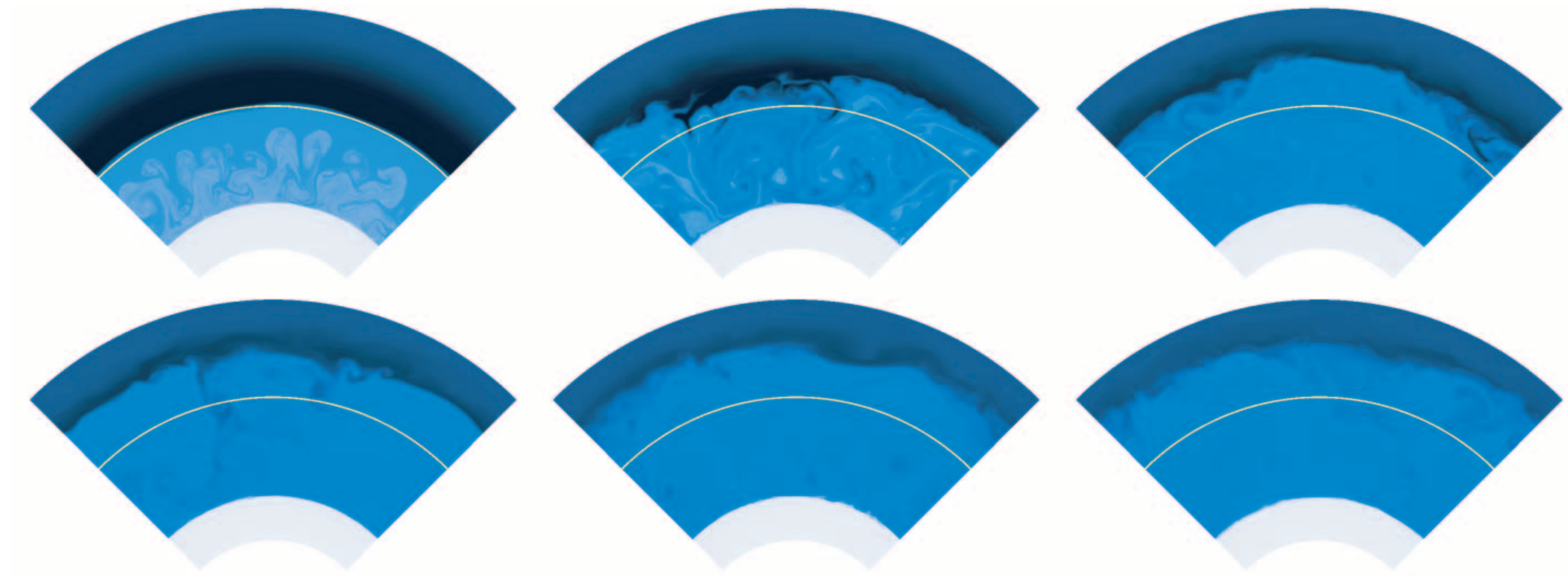
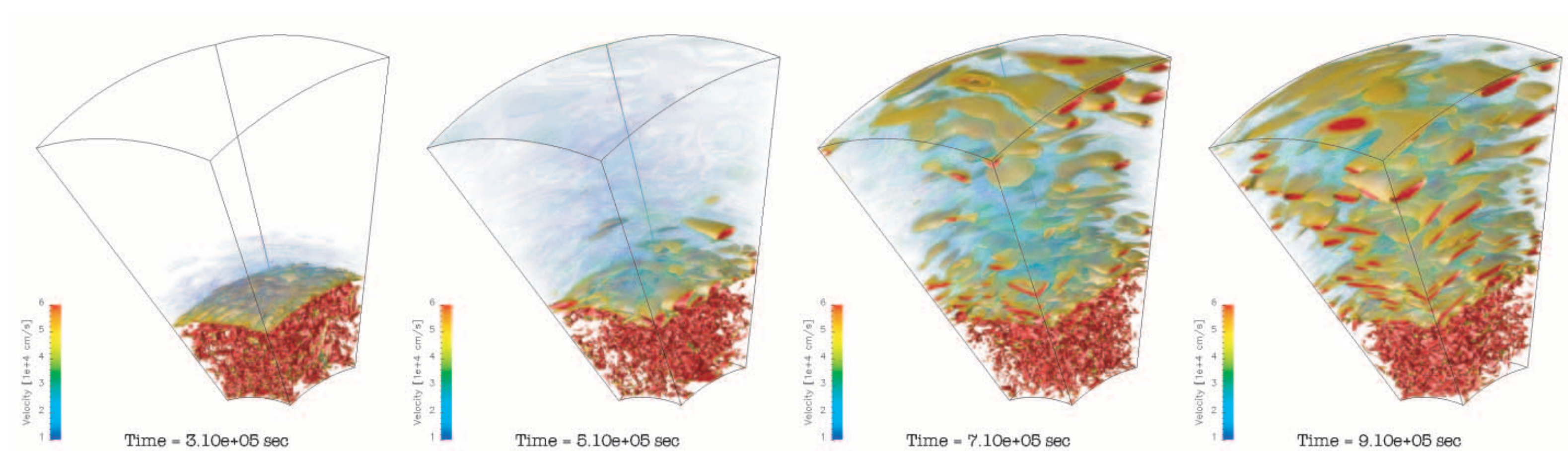
Multi-dimensional stars

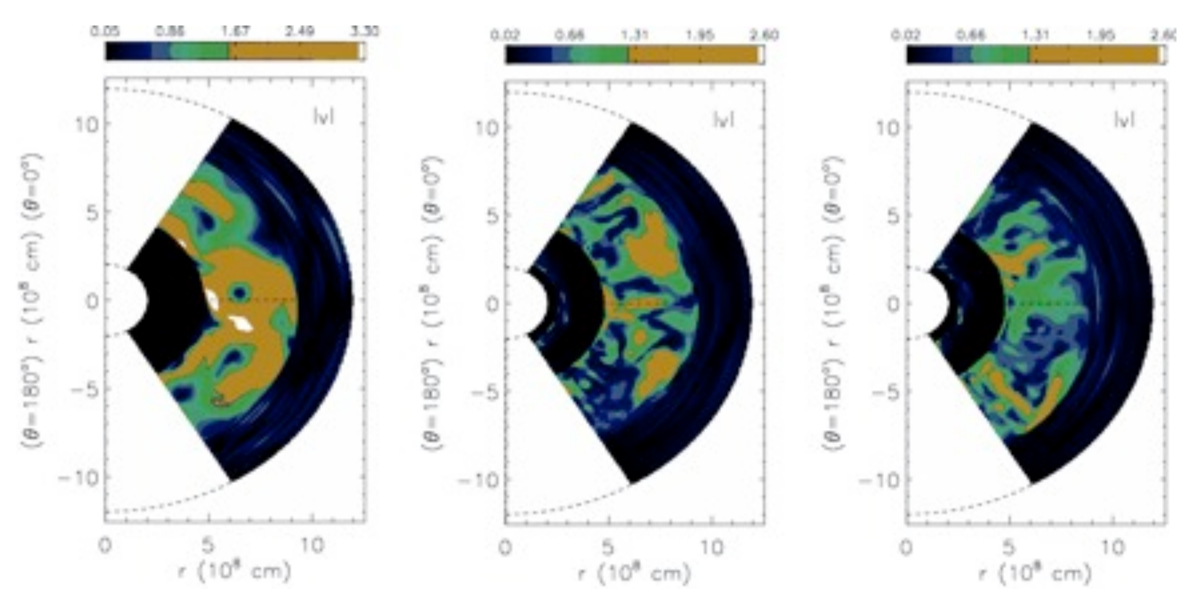


Stellar interior simulations:

i. massive stars: "Turbulent convection in stellar interiors" Meakin & Arnett (2007)



ii. "The core helium flash revisited" Mocák etal A&A (2009)



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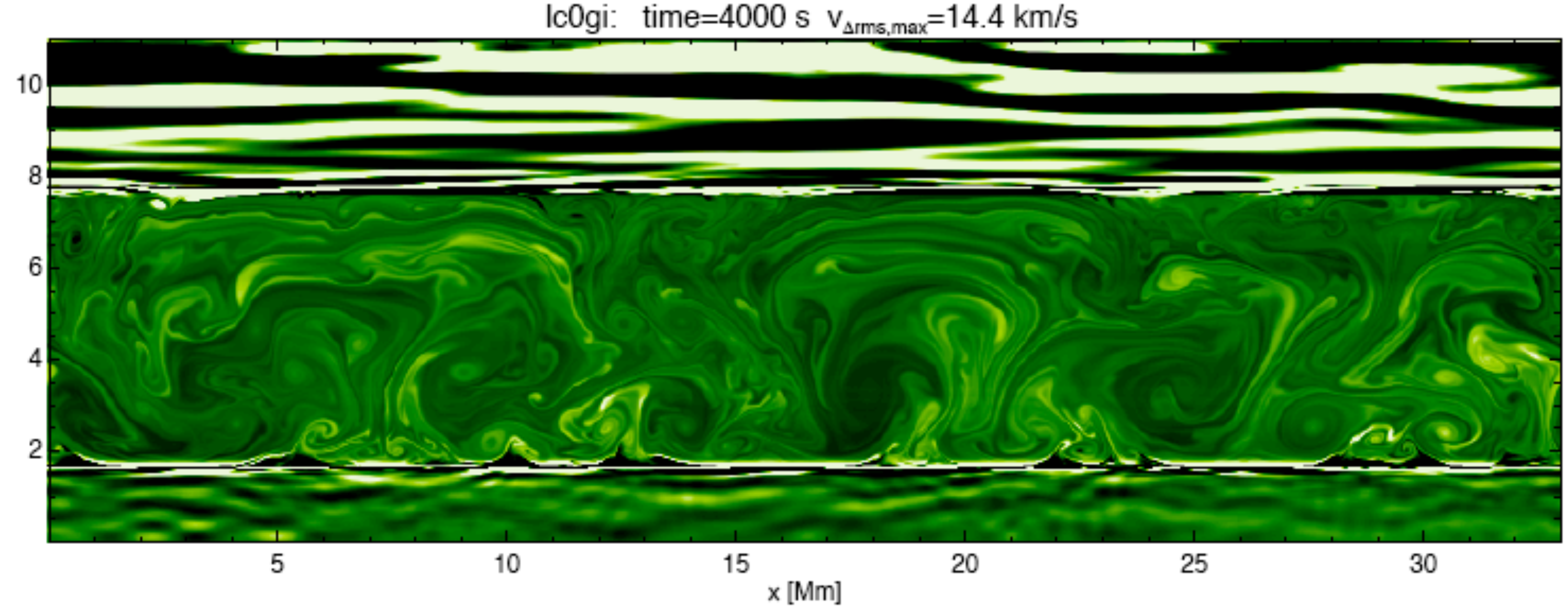
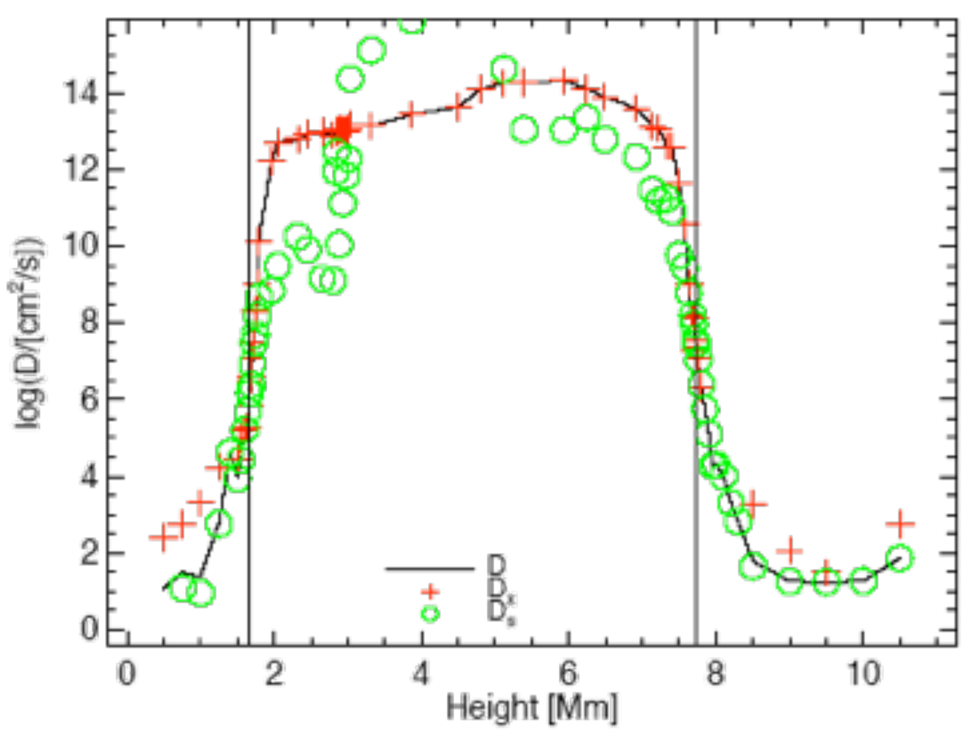
Multi-dimensional stars

2D entropy fluctuations (2400x800), realistic heating rate
Courant time scale at this resolution: ~3*10^{-3}sec -> 1.6M cycles

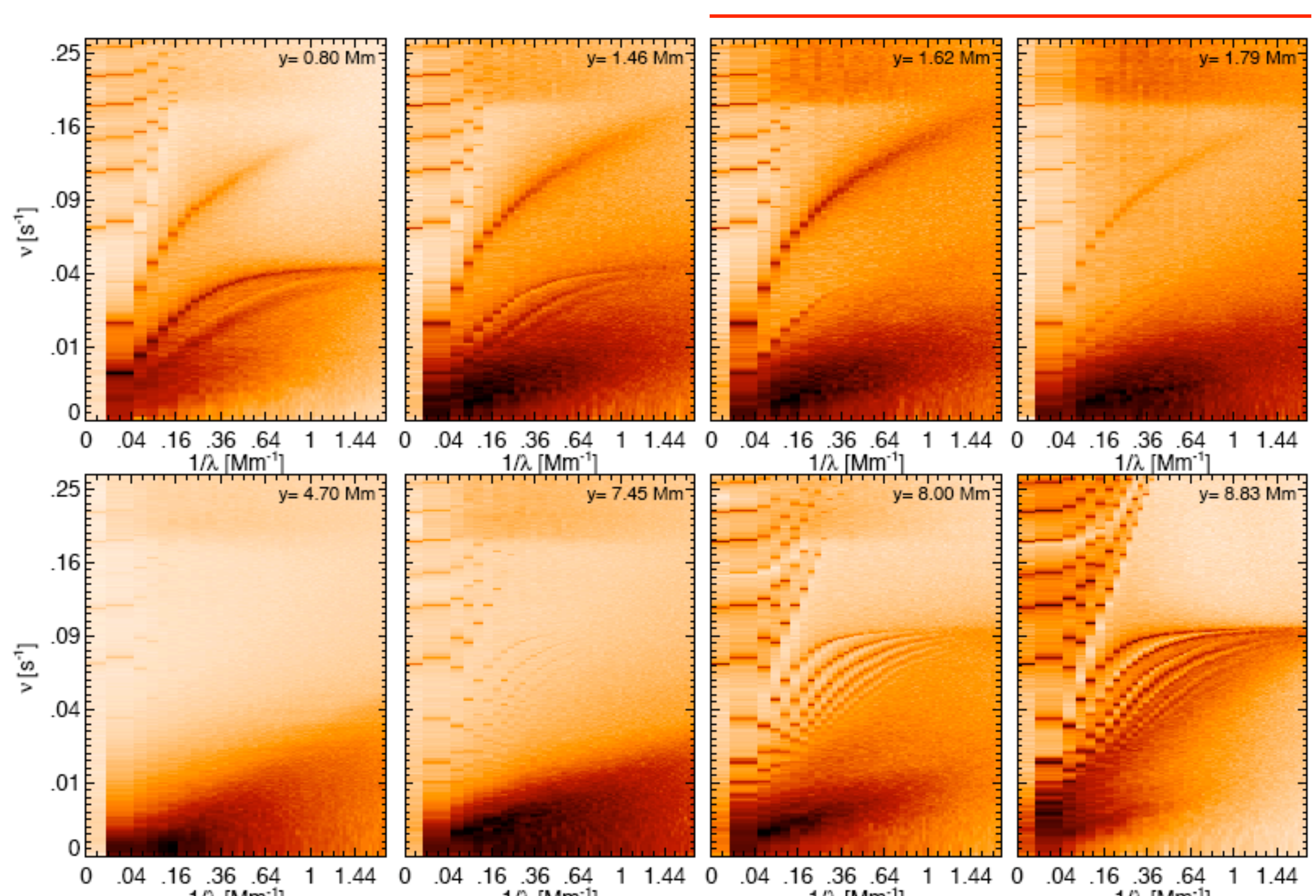


He-shell flash convection

i. 2D and 3D plane-parallel box-in-a-star (Herwig etal 2006)



quantify "overshooting" - develop models for 1D stellar evolution (cf. Karakas etal 2010.)



k-ω diagrams for various heights of benchmark run lc0gg

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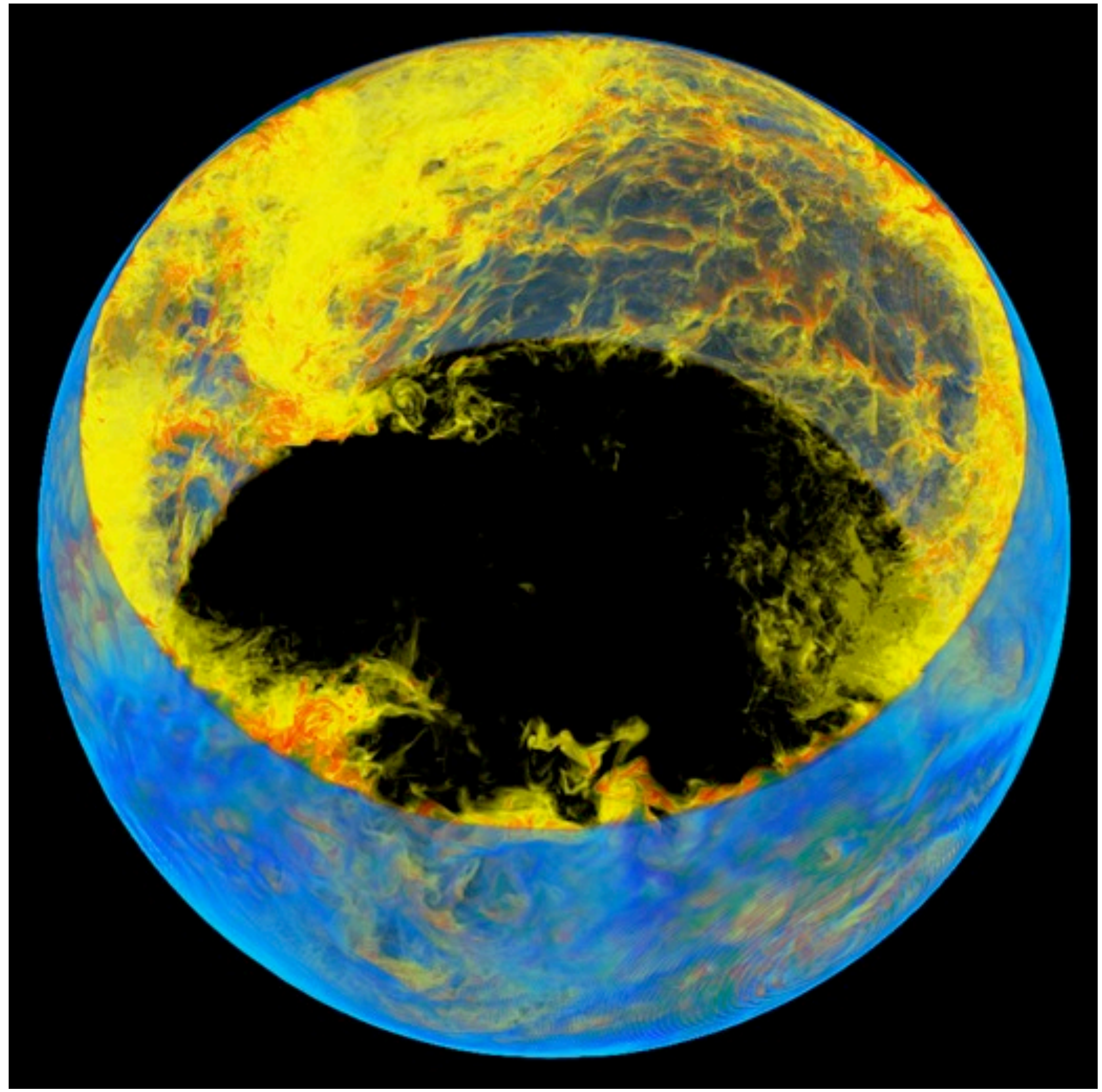
Multi-dimensional stars

Next generation He-shell flash convection

i. 3D 4π star-in-a-box simulations (e.g. Herwig etal 2010, poster outside)
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

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



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

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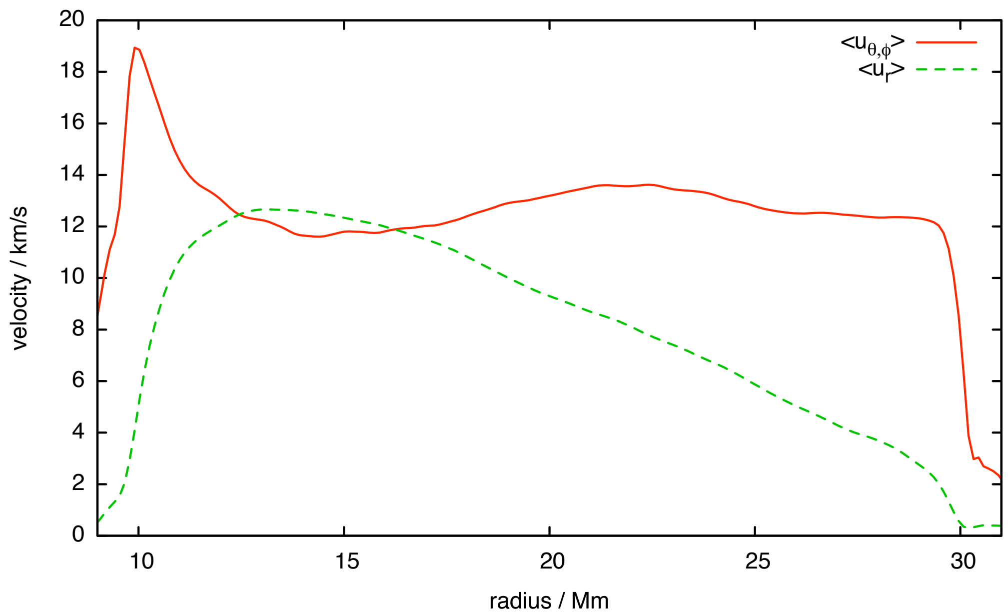
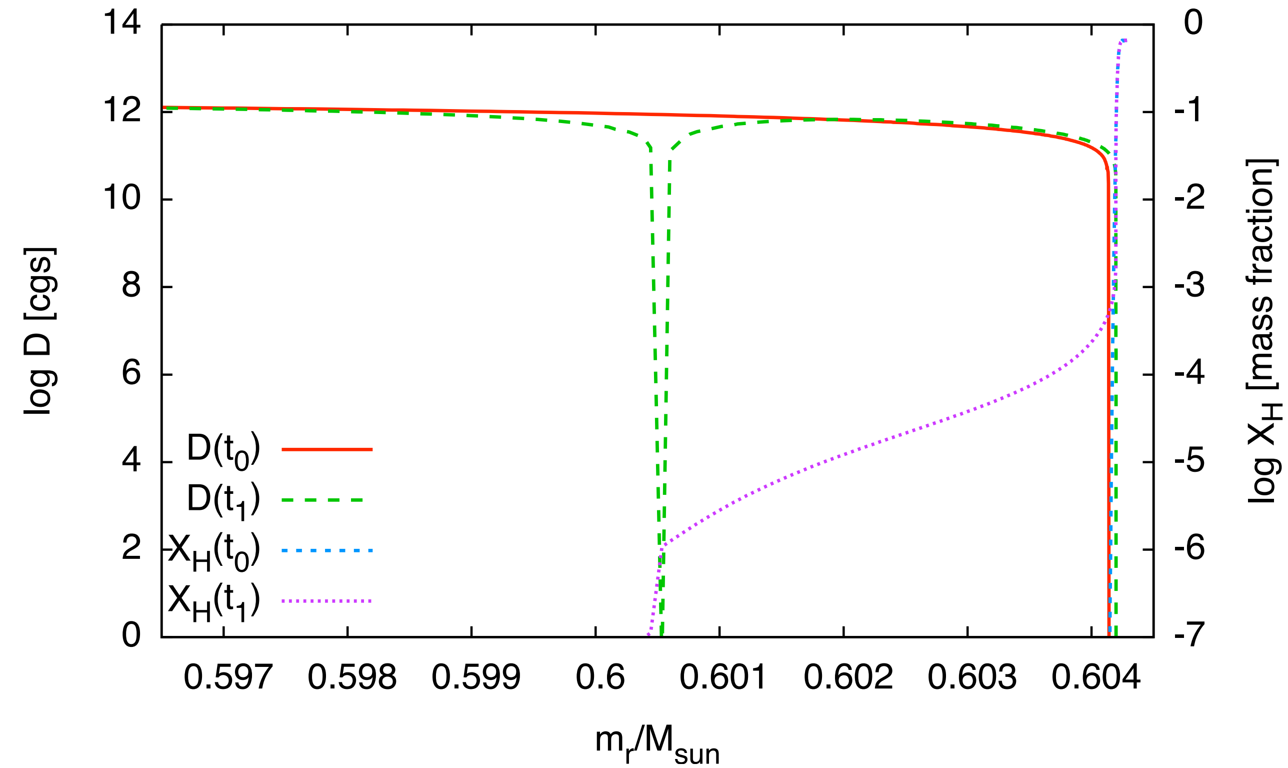
3D 4π star-in-a-box simulations

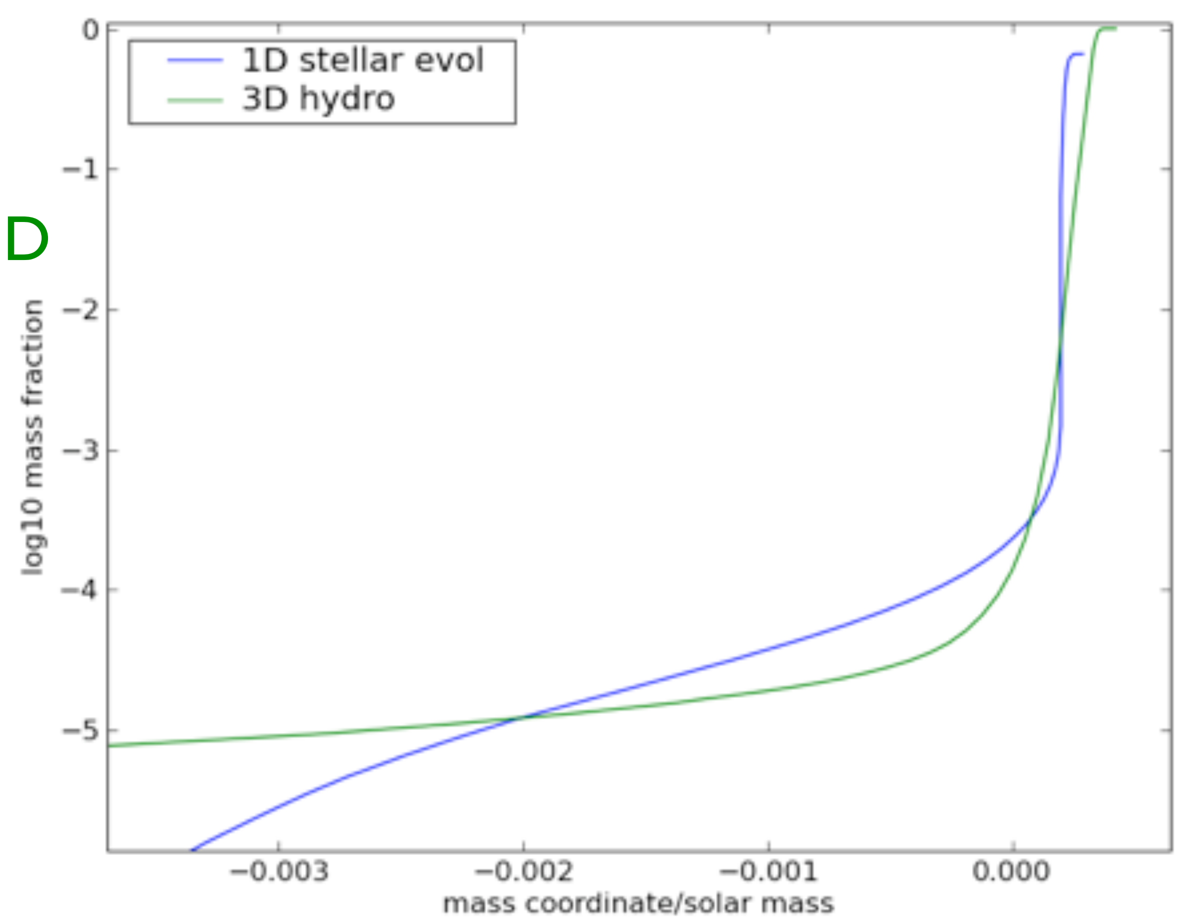
horizontal and vertical v_{rms}



1D mixing profiles



comparison 1D and 3D averaged profiles



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Multi-dimensional stars

3D 4π star-in-a-box simulations

How expensive is it? 576^3 for 60ks (several M cycles):

- 18*8*10*24 ~ 34,000 CPU hrs
- factor 2 up in resolution = factor 8 in effort: ~270,000 CPU hrs for 1152^3
- another factor 2 up: 2.2M CPU hrs
- another one up 17M CPU hrs (4608^3, corresponding to Δr=6km, Δr_{eff}=3km)

How does this compare to availability?

- 256 cluster: 2.2M CPU hrs
- regional facilities: > dozen CPU hrs
- peta-scale computing now deployed: ~1,500 M CPU hrs

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Applications of stellar evolution

- stellar populations
- first stars/near-field cosmology
- high-z Universe, especially AGB stars (e.g. how well can we describe C-star formation?)
- grains, nucleosynthesis
- SN progenitors

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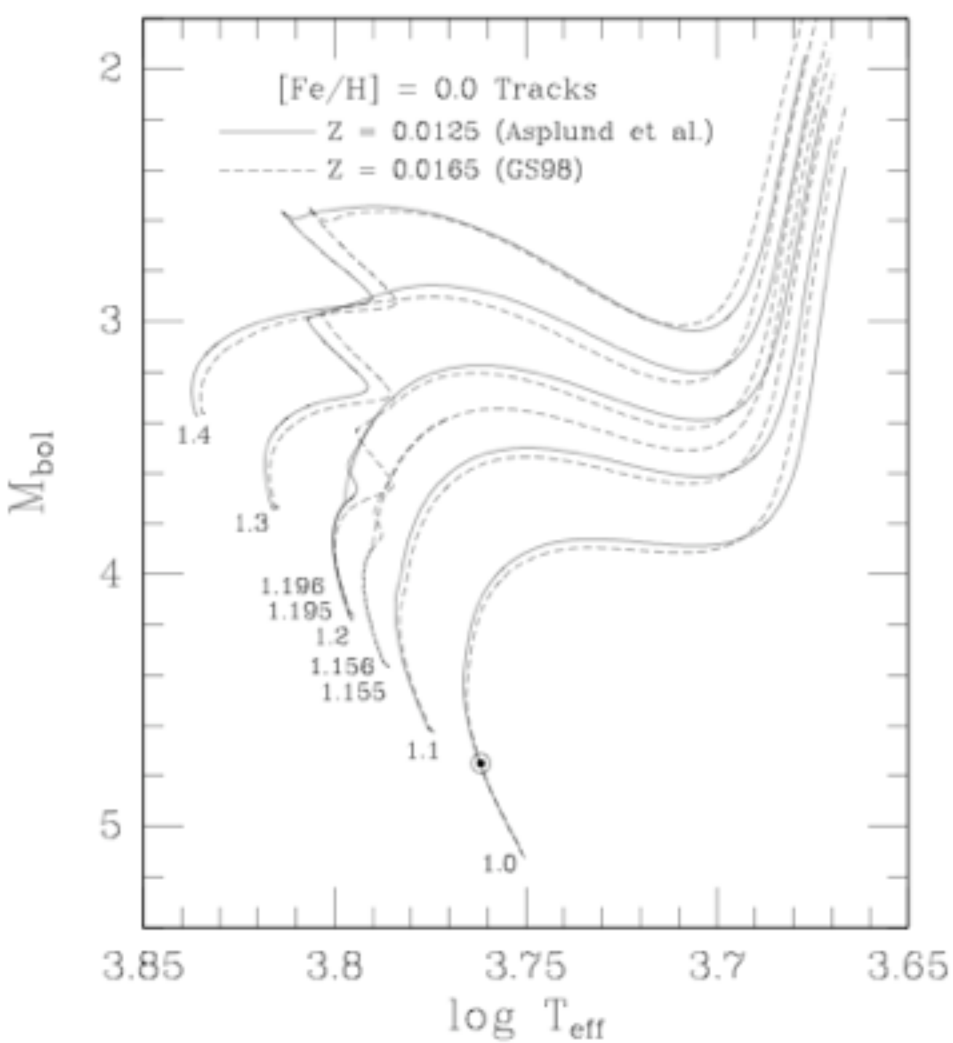
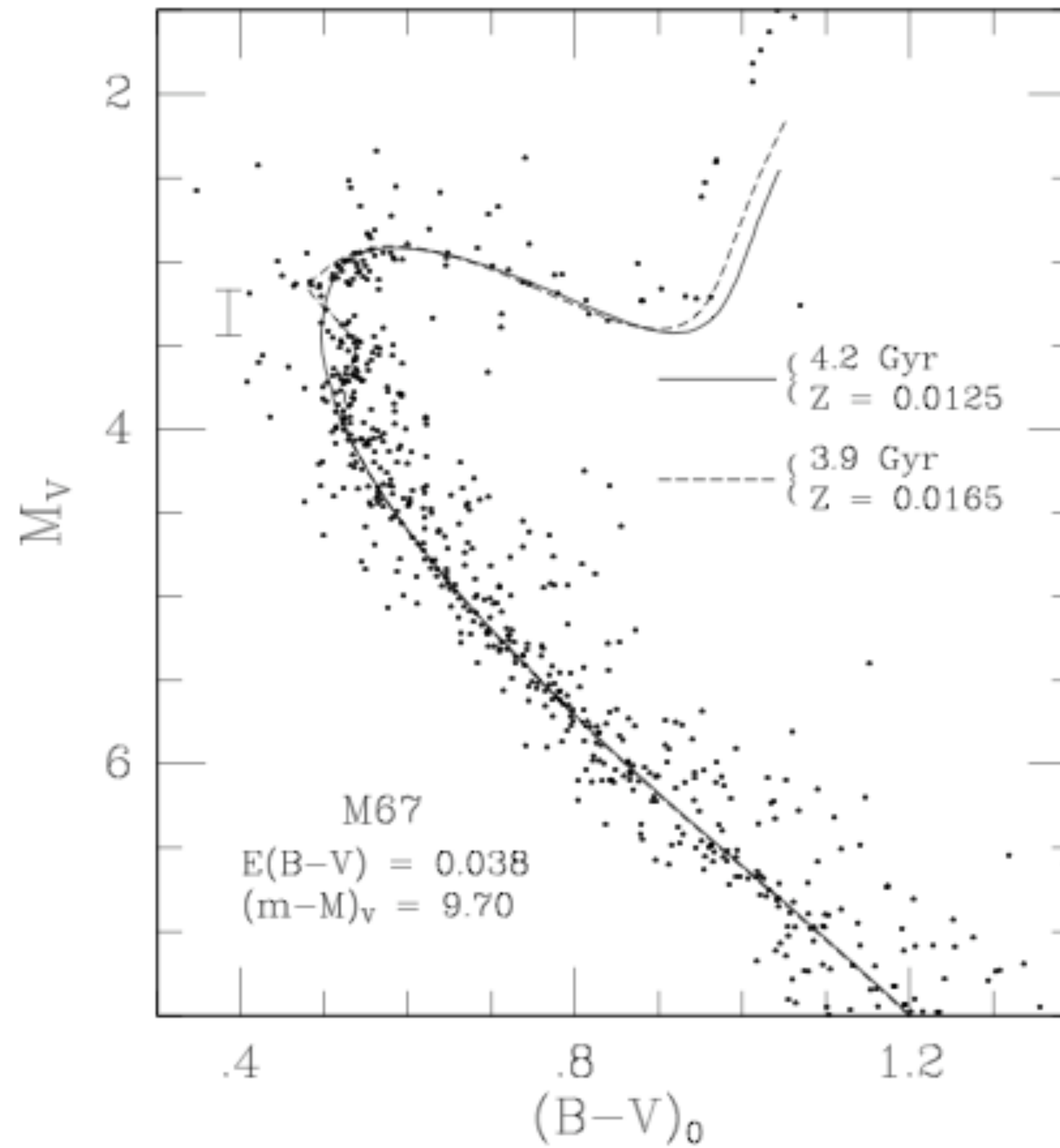
A Constraint on $Z_\odot$ From Fits of Isochrones to the Color-Magnitude Diagram of M 67

Don A. VandenBerg[1], Bengt Gustafsson[2], Bengt Edvardsson[2], Kjell Eriksson[2], and Jason Ferguson[3]

Adding another argument to the solar abundance puzzle:





VandenBerg etal. 2007

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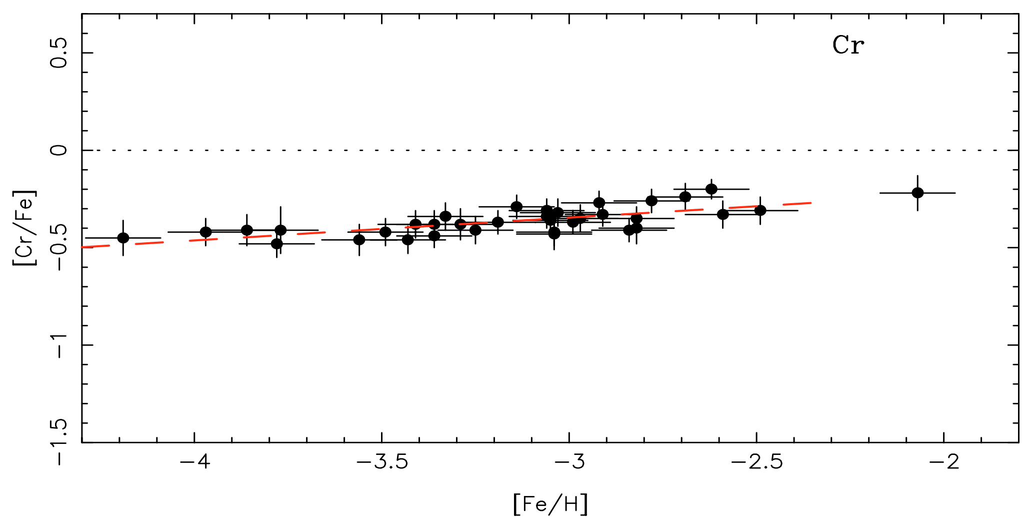
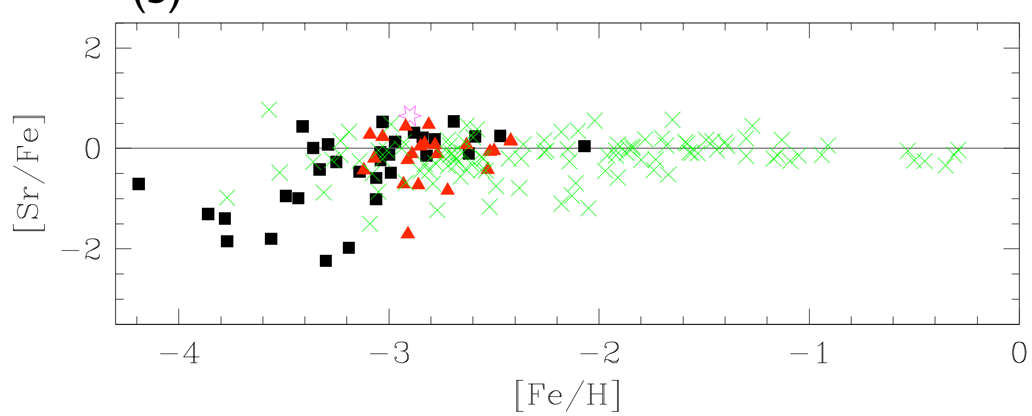
Applications of stellar evolution

- first stars/near-field cosmology

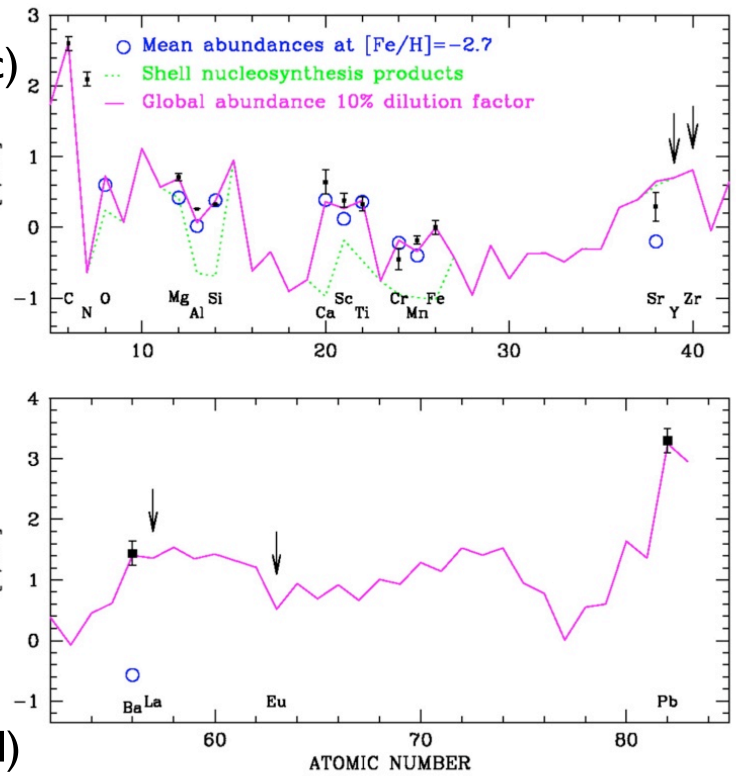
(a)



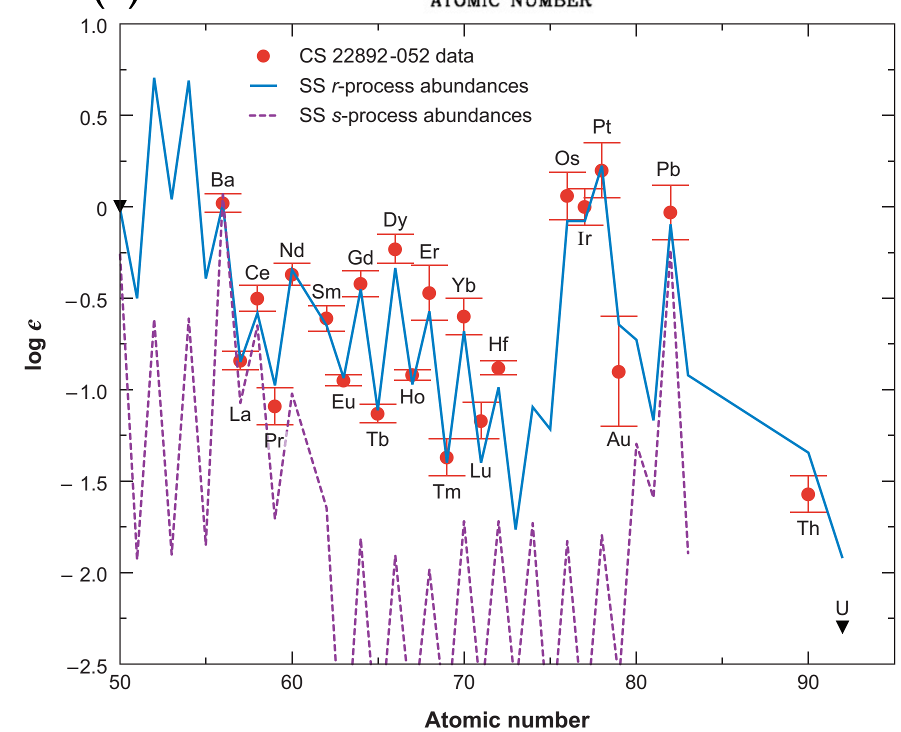
(b)



(c)



(d)



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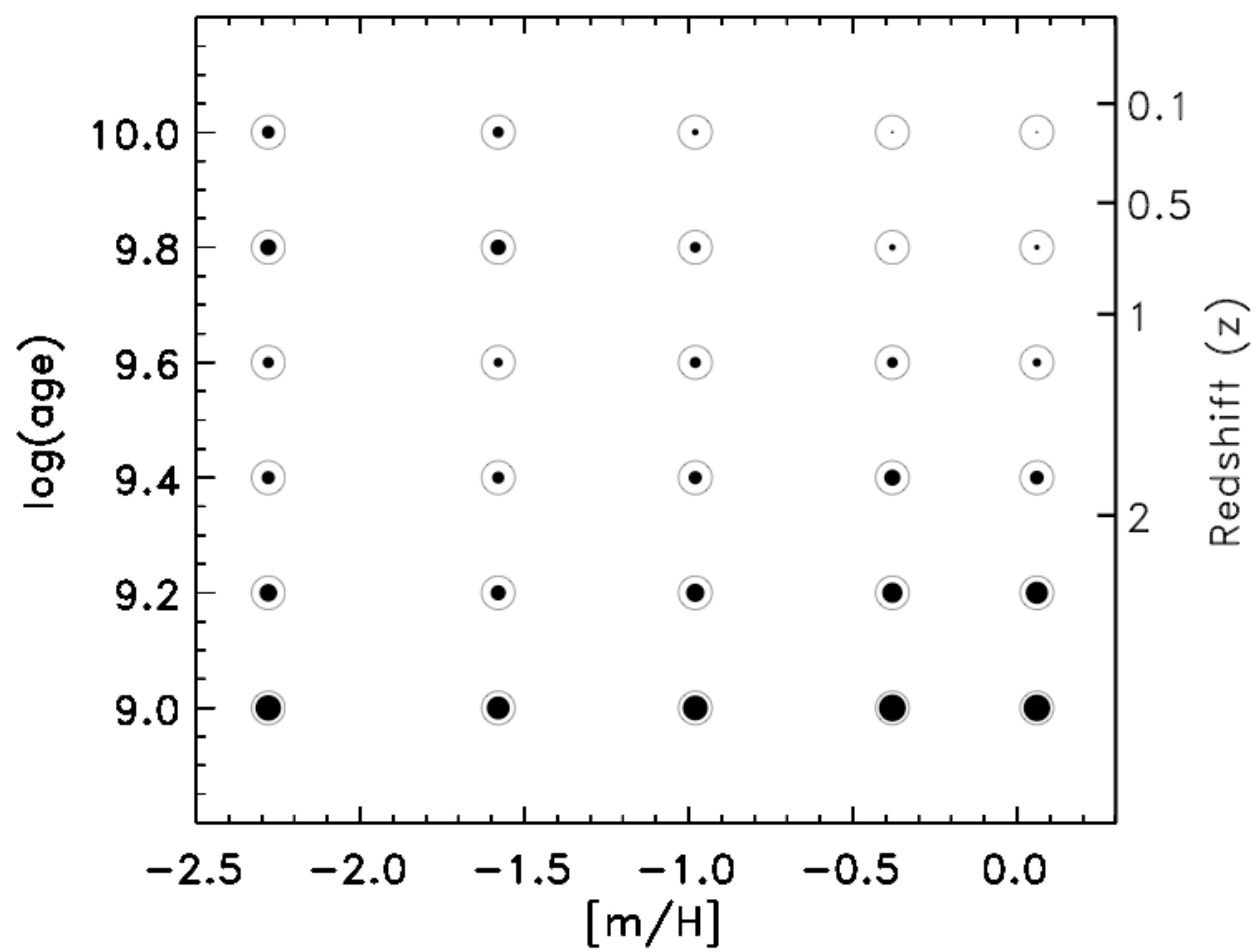
Applications of stellar evolution

- high-z universe, especially AGB stars (e.g. how well can we describe C-star formation?)

AGB Stars Have Huge Implications for Measuring Masses of High-z Galaxies

Melbourne etal (2010)
Marasont etal (2009)
Tonini etal (2009)



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