# MESA – INTRODUCTION AND CAPABILITIES

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# Introduction

- Main author: Bill Paxton
- Paxton et al. 2011, ApJSS, 193, 3
- Paxton et al. 2013, ApJSS, 208, 4
- MESA – Modules for Experiments in Stellar Astrophysics
- New stellar evolution code
- 1-D code

# Introduction

Photo by F. X. Timmes

# Introduction

- http://mesa.sourceforge.net/
- http://www.astro.wisc.edu/~townsend/static.php?ref=mesasdk
- http://mesastar.org

# Introduction

- MESA – very versatile tool
- Wide applicability
- Modern microphysics
- Modern techniques
- Modularity
- Performance
- Openess

# Modules

Paxton et al. 2011

**Table 2**
MESA Module Definitions and Purposes

| Name | Type | Purpose | Section |
|---|---|---|---|
| alert | Utility | Error handling | 3 |
| atm | Microphysics | Gray and non-gray atmospheres; tables and integration | 5.3 |
| const | Utility | Numerical and physical constants | 4.1 |
| chem | Microphysics | Properties of elements and isotopes | 4.1 |
| diffusion | Macrophysics | Gravitational settling and chemical and thermal diffusion | 5.4 |
| eos | Microphysics | Equation of state | 4.2 |
| interp_1d | Numerics | One-dimensional interpolation routines | 3 |
| interp_2d | Numerics | Two-dimensional interpolation routines | 3 |
| ionization | Microphysics | Average ionic charges for diffusion | 5.4 |
| jina | Macrophysics | Large nuclear reaction nets using reaclib | 4.5 |
| kap | Microphysics | Opacities | 4.3 |
| karo | Microphysics | Alternative low-$T$ opacities for C and N enhanced material | 4.3 |
| mlt | Macrophysics | Mixing length theory | 5.1 |
| mtx | Numerics | Linear algebra matrix solvers | 3 |
| net | Macrophysics | Small nuclear reaction nets optimized for performance | 4.5 |
| neu | Microphysics | Thermal neutrino rates | 4.5 |
| num | Numerics | Solvers for ordinary differential and differential-algebraic equations | 3 |
| package_template | Utility | Template for creating a new MESA module | 2 |
| rates | Microphysics | Nuclear reaction rates | 4.4 |
| screen | Microphysics | Nuclear reaction screening | 4.5 |
| star | Evolution | One-dimensional stellar evolution | 6 |
| utils | Utility | Miscellaneous utilities | 3 |
| weaklib | Microphysics | Rates for weak nuclear reactions | 4.5 |

- And the new ones: binary, colors

# EOS

- OPAL (Rogers & Nayfonov 2002) + SCVH (Saumon et al. 1995)

- X = (0.0, 0.2, 0.4, 0.6, 0.8, 1.0)
- Z = (0.0, 0.02, 0.04)

- HELM (Timmes & Swesty 2000), PC (Potekhin & Chabrier 2010)

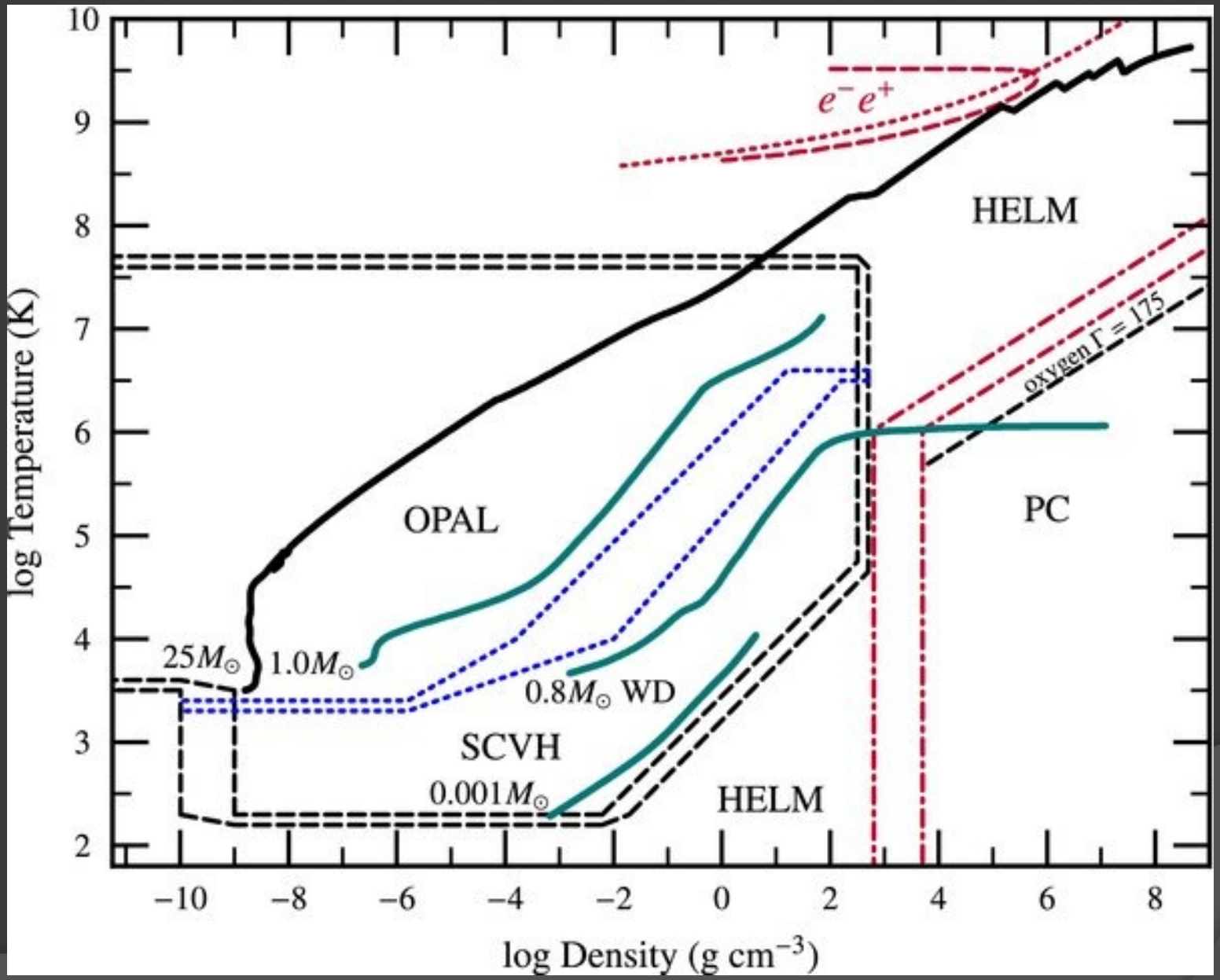
- Assumed complete ionization

- HELM – up to $\log T = 13$, $\log \rho = 15$
- Accounts for the onset of pair production

- PC – lower temperatures, high densities – perfect for white dwarfs, incorporates crystallization

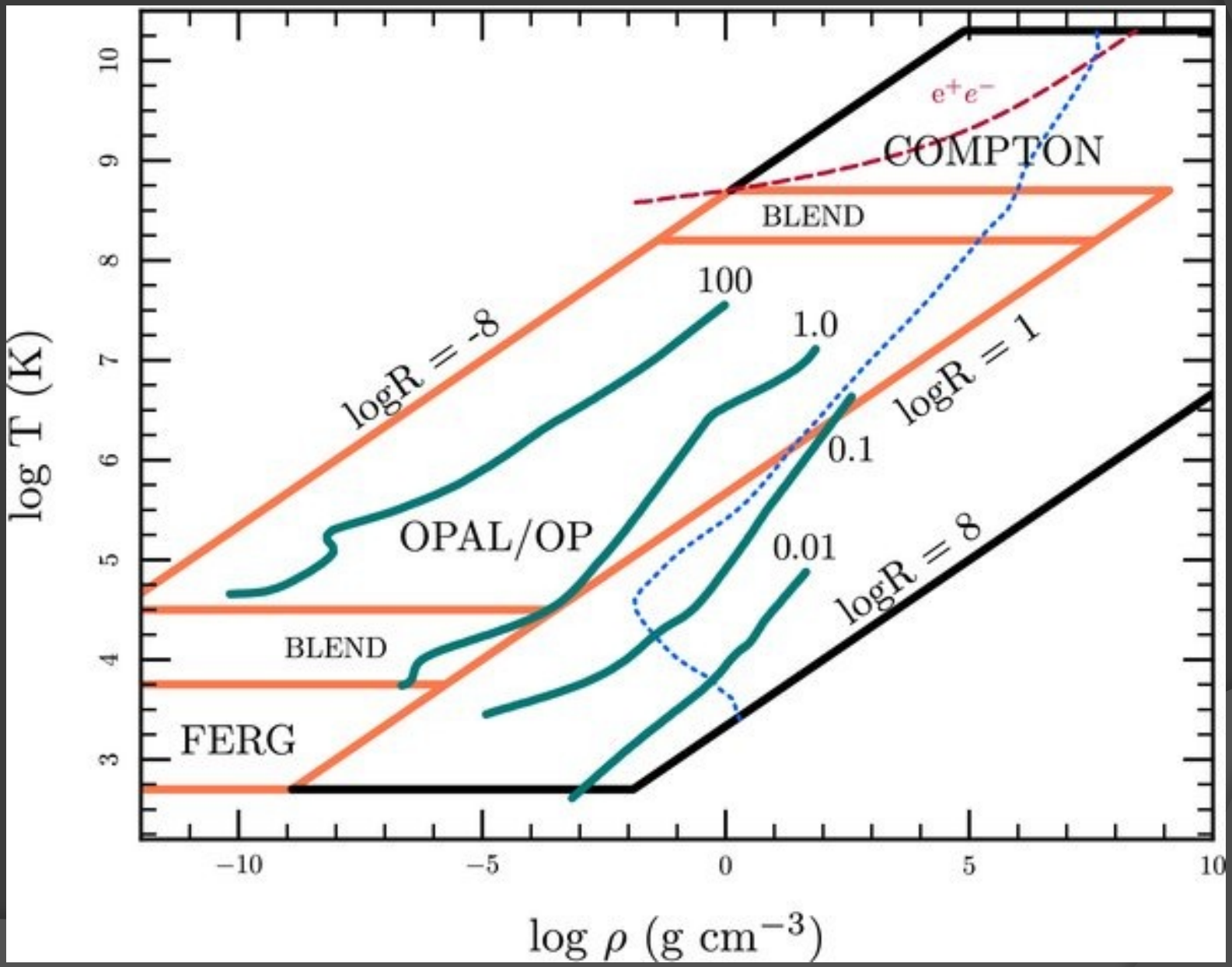
# EOS

Paxton et al. 2011



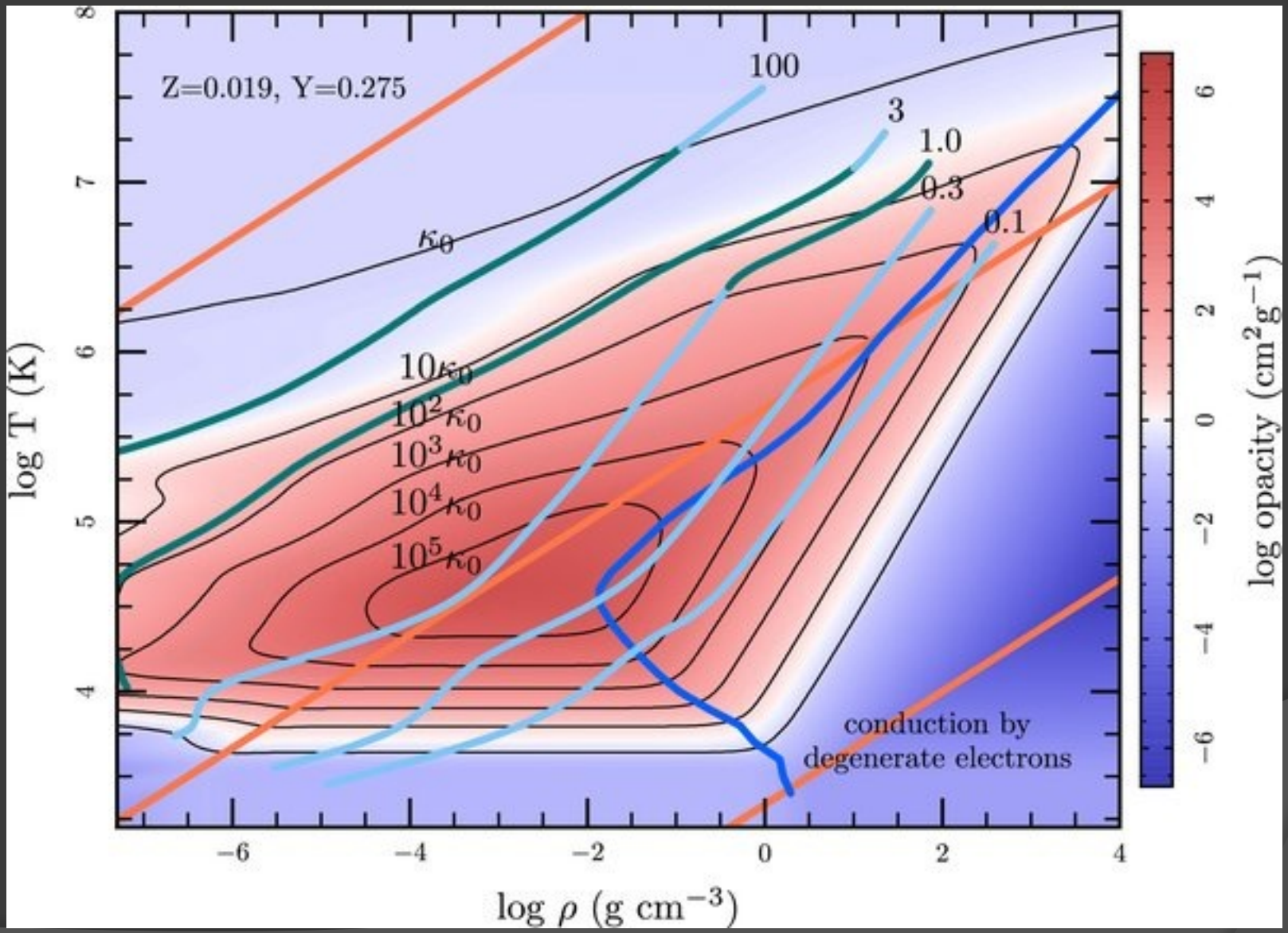
# Opacities

Paxton et al. 2011



# Opacities

$\kappa_0 = 0.2(1+X)\ cm^2\ g^{-1}$




Paxton et al. 2011

# Nuclear reaction rates

- CF88 (Caughlan & Fowler 1988)
- NACRE (Angulo et al. 1999) – preferred when available

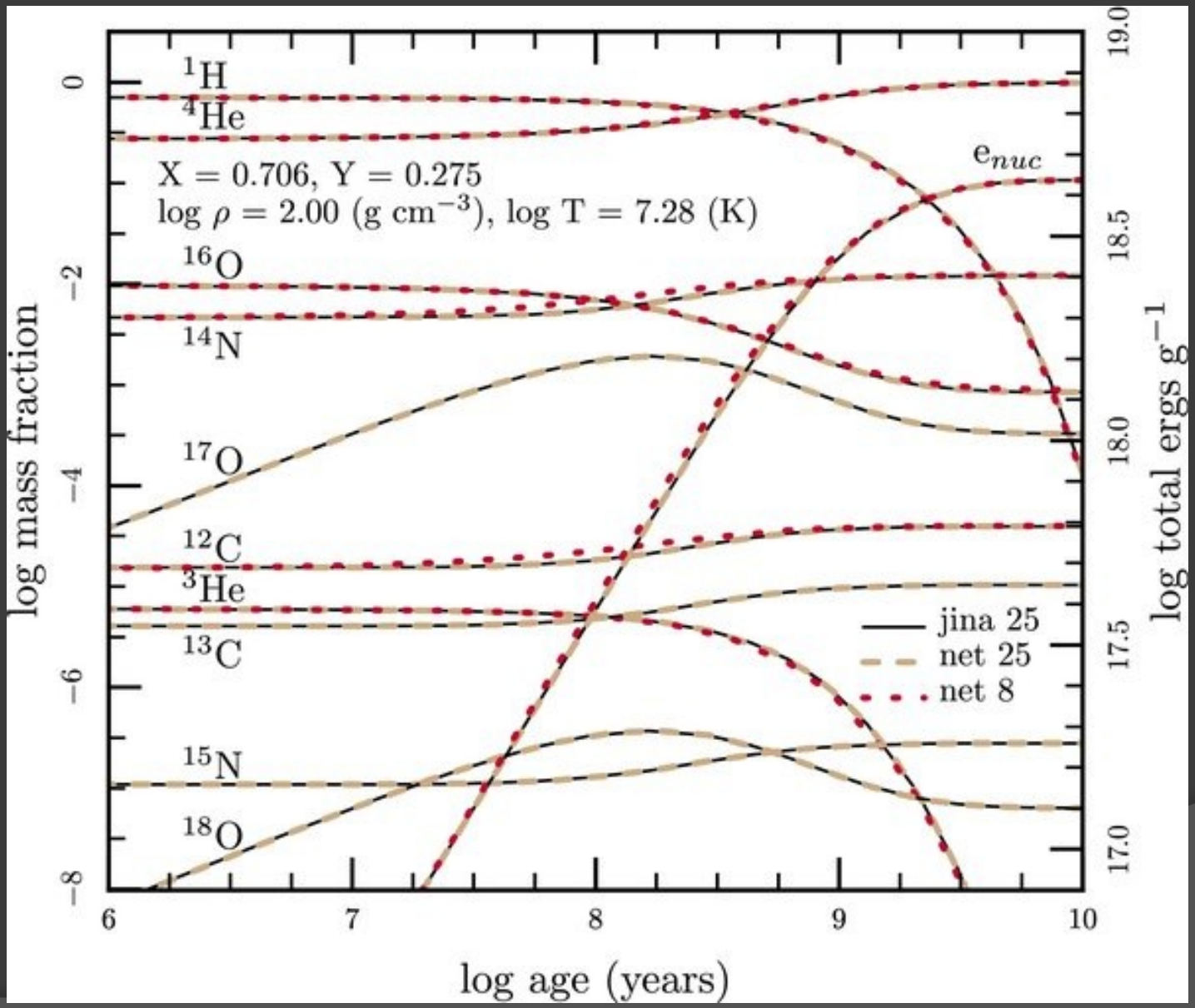
- Rates for over 300 reactions (weak reactions included, e.g. positron emissions, electron captures)

# Nuclear reaction networks

- net – small networks
- basic – $^{1}H$, $^{3}He$, $^{4}He$, $^{12}C$, $^{14}N$, $^{16}O$, $^{20}Ne$, $^{24}Mg$
- 350 reactions

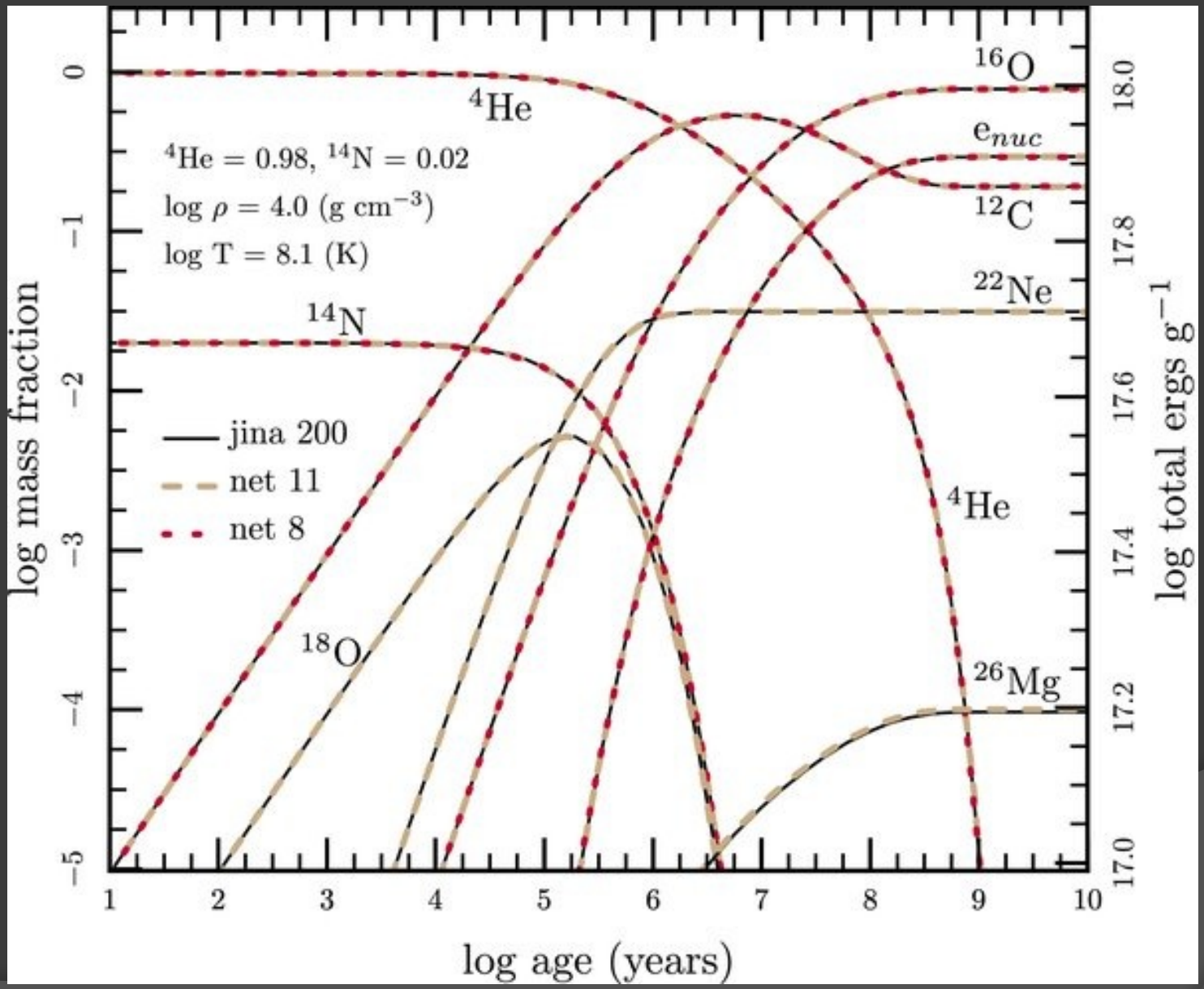
- reaclib (previously: jina) – large networks
- JINA reaclib database (Rauscher & Thielemann 2000; Sakharuk et al. 2006)
- 76000 reactions
- 4500 isotopes

# Nuclear reaction networks




Paxton et al. 2011

# Nuclear reaction networks




Paxton et al. 2011

# Macrophysics

- mlt – mixing length theory
- atm – atmosphere boundary conditions
- diffusion – diffusion, gravitational settling and radiative levitation

# MESA star

1) Preparing to make a new step by remeshing the model (if necessary)

2) Adjusting the model and solving for the new stucture and composition

3) Estimation of the new timestep

4) Generating output files

# Mass loss and gain

- Variety of models
- Coverage of many types of star
- Great versatility
- Possibility of setting constant mass accretion or mass loss

# Multithreading

**Table 9**
Execution Times (s) with Multiple Threads

| Task | Number of Threads | | | |
|---|---|---|---|---|
| | 1 | 2 | 4 | 8 |
| Total[a] | 12.2146 | 8.0099 | 5.8963 | 5.0634 |
| Ratio | ... | 1.53 | 1.36 | 1.16 |
| Threaded tasks | | | | |
| `net` | 6.2602 | 3.1721 | 1.6047 | 0.8182 |
| `eos` | 1.7185 | 0.8897 | 0.4539 | 0.2399 |
| `mlt` | 0.2479 | 0.1384 | 0.0704 | 0.0357 |
| `kap` | 0.2285 | 0.1386 | 0.1044 | 0.0875 |
| `neu` | 0.0240 | 0.0209 | 0.0139 | 0.0098 |
| Subtotal | 8.4791 | 4.3597 | 2.2473 | 1.1911 |
| Ratio | ... | 1.95 | 1.94 | 1.89 |
| Fraction of total | 0.69 | 0.54 | 0.38 | 0.24 |
| Serial tasks | | | | |
| File output | 1.1848 | 1.0301 | 1.0036 | 1.1679 |
| Matrix linear algebra | 0.6569 | 0.7654 | 0.7885 | 0.7926 |
| Miscellaneous | 1.8938 | 1.8547 | 1.8569 | 1.9118 |
| Subtotal | 3.7355 | 3.6502 | 3.6490 | 3.8723 |
| Fraction of total | 0.31 | 0.46 | 0.62 | 0.76 |

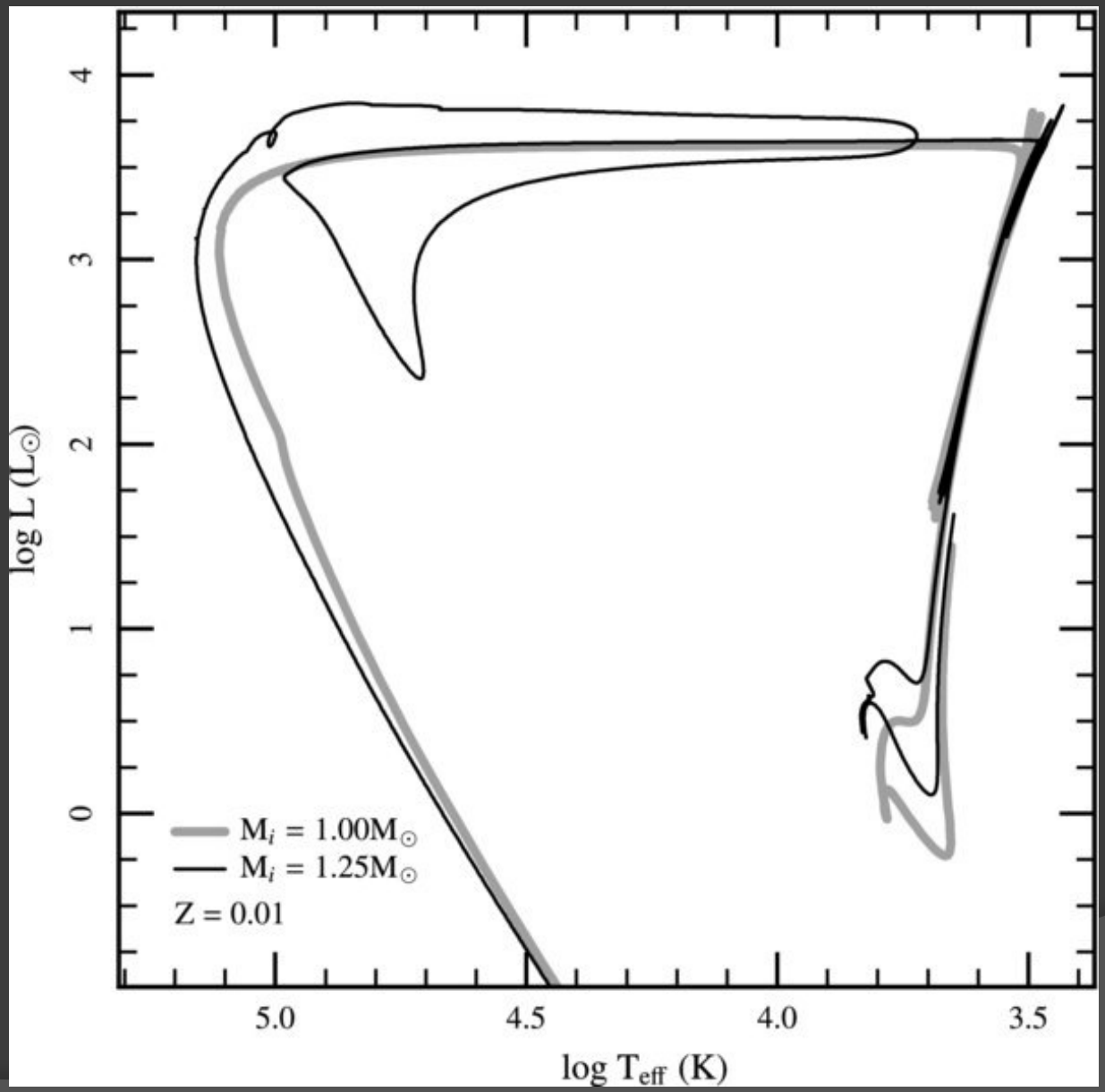
**Note.** [a] These numbers do not include initialization, e.g., loading of data tables.

Paxton et al. 2011

# Verification and validation

- Is it solving the equations correctly?
- Does it solve the right equation?
- Time for some results…

# Low-mass stellar structure and evolution




Paxton et al. 2011

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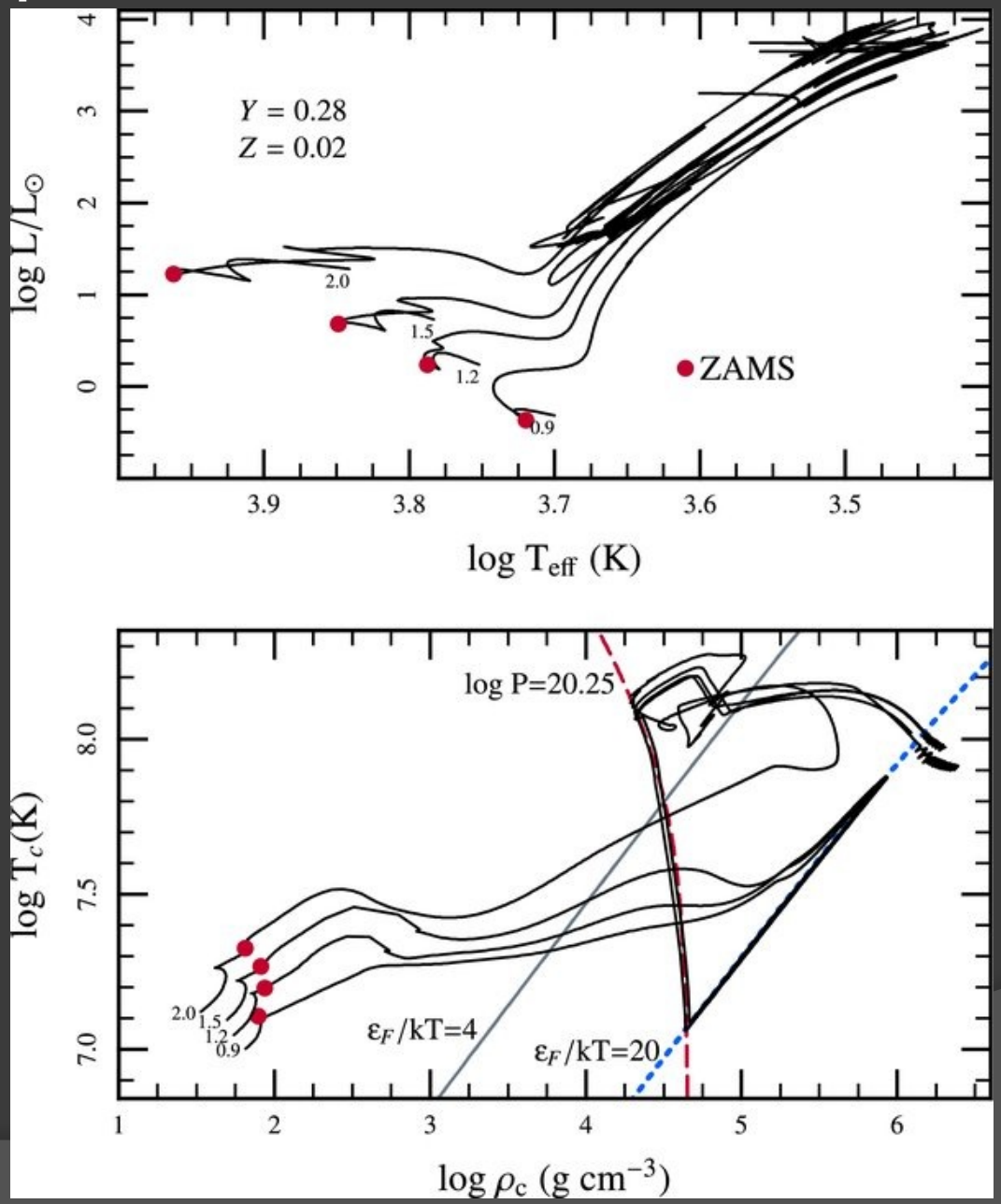


Paxton et al. 2011

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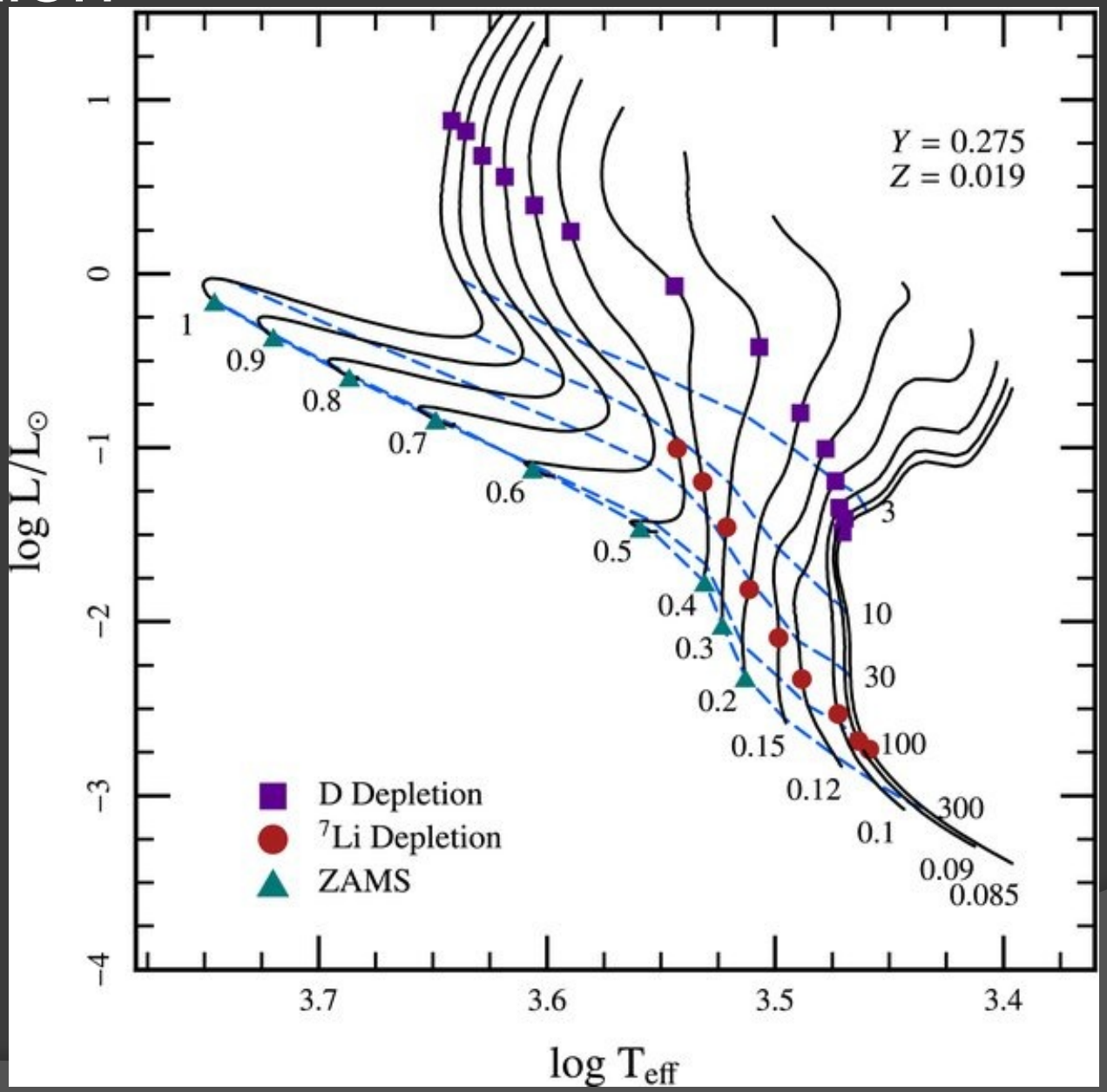


Paxton et al. 2011

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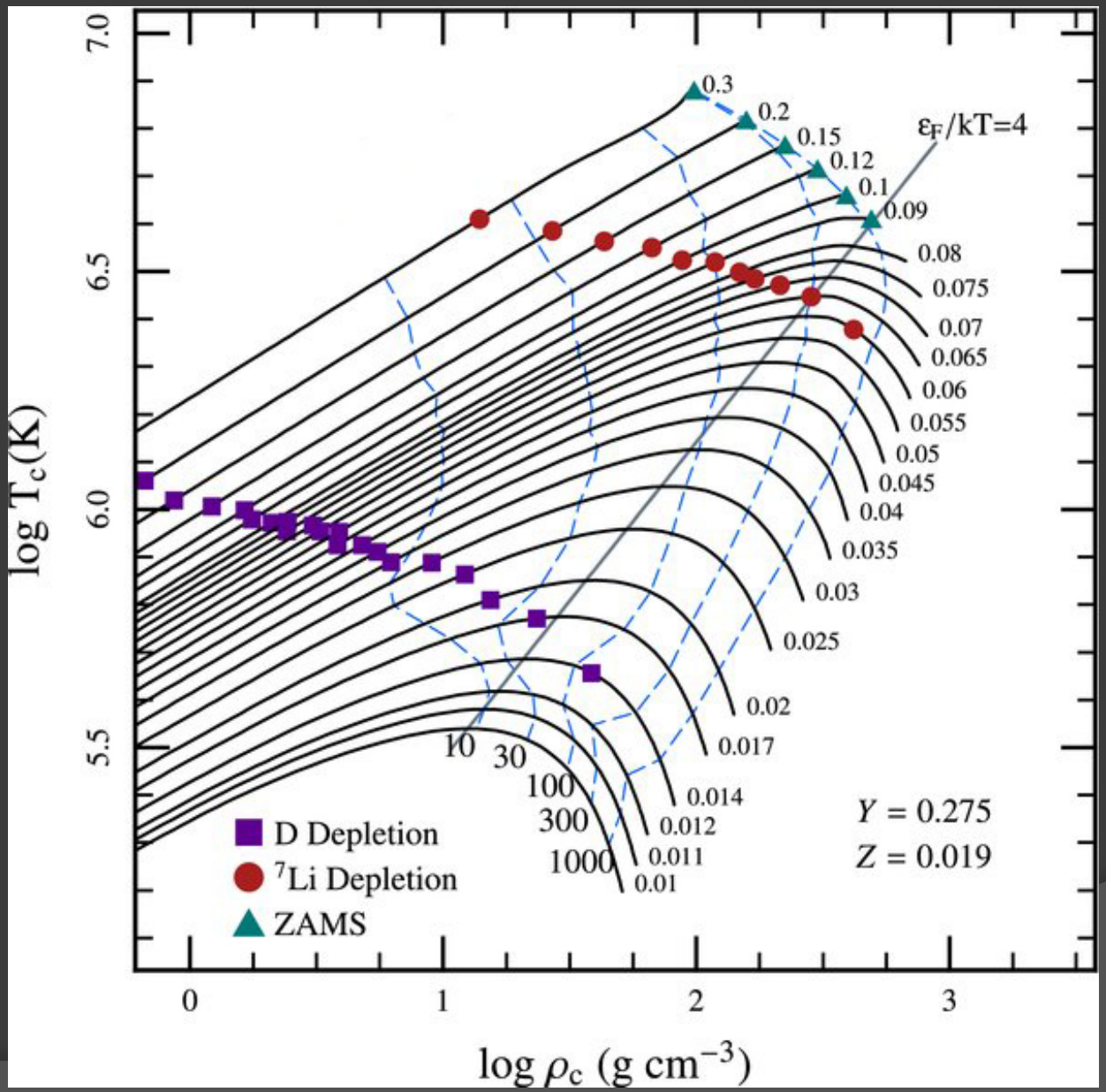


Paxton et al. 2011

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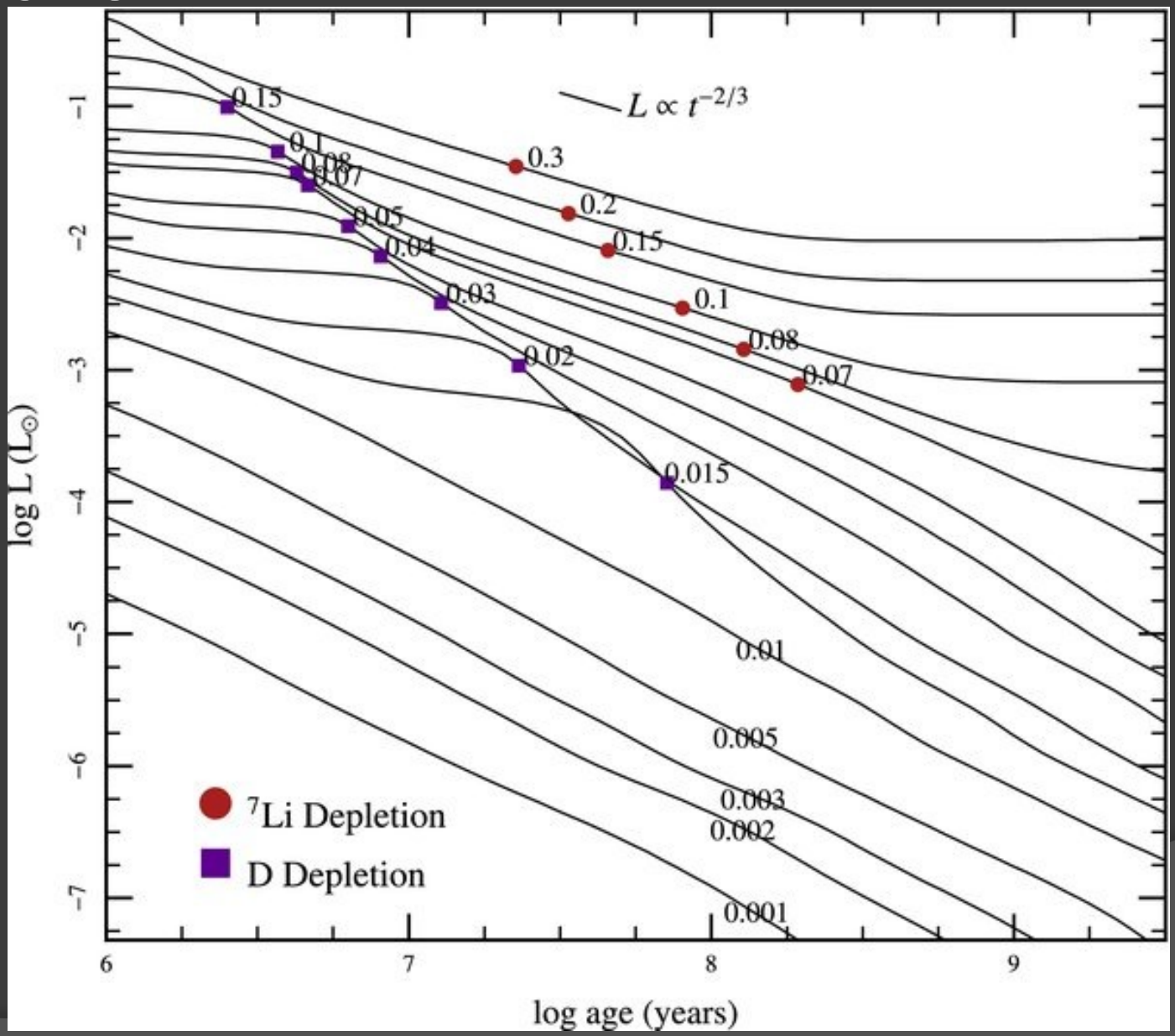
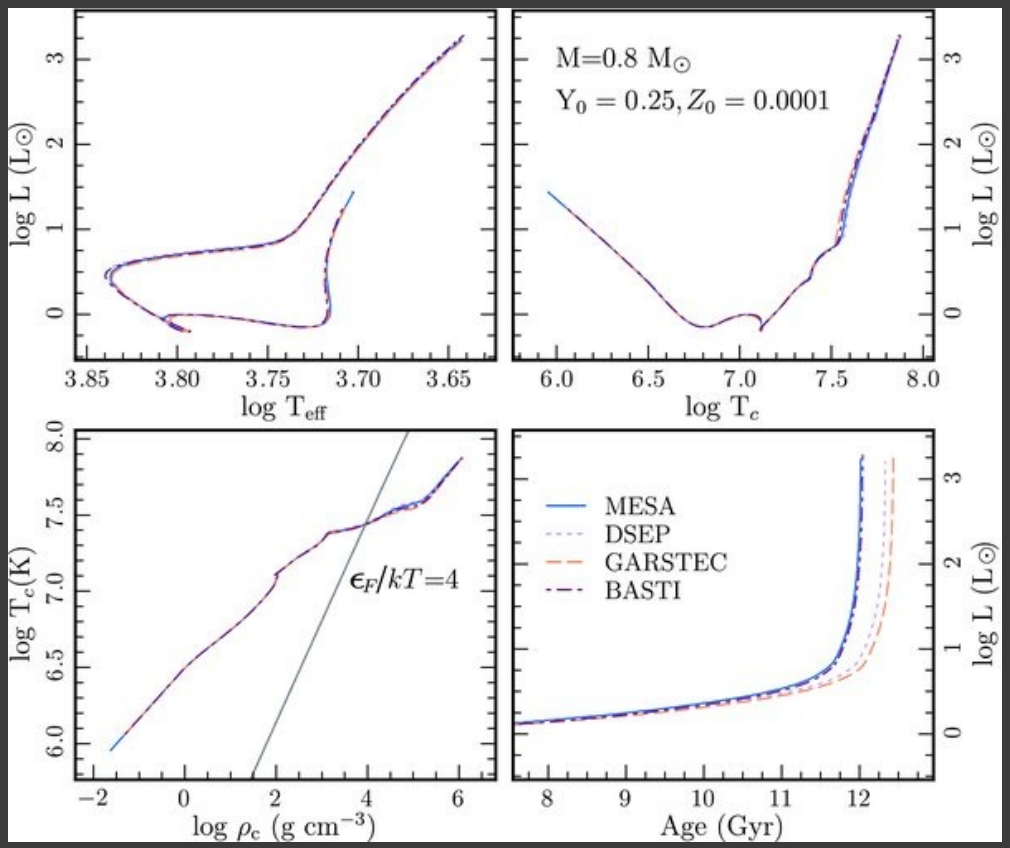
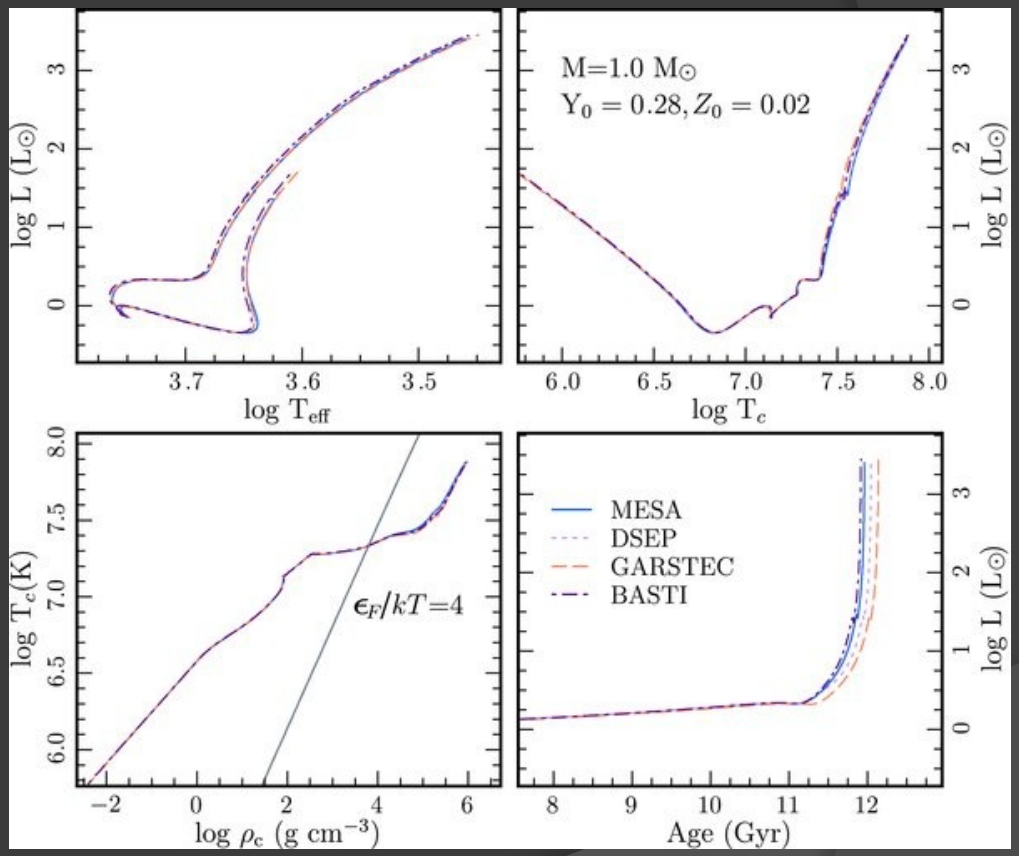



Paxton et al. 2011

# Comparison with other codes




Paxton et al. 2011

# Solar model

- $L_\odot = 3.8418 \times 10^{33}$ erg $s^{-1}$
- $R_\odot = 6.9598 \times 10^{10}$ $cm^{-2}$
- t = 4.57 Gy
- GS98

- Bahcall et al. 2005 (BBP98)
- Serenelli et al. 2009 (S09)

- Iteratively varying $\alpha_{MLT}$, $Y_i$, $Z_i$

# Solar model

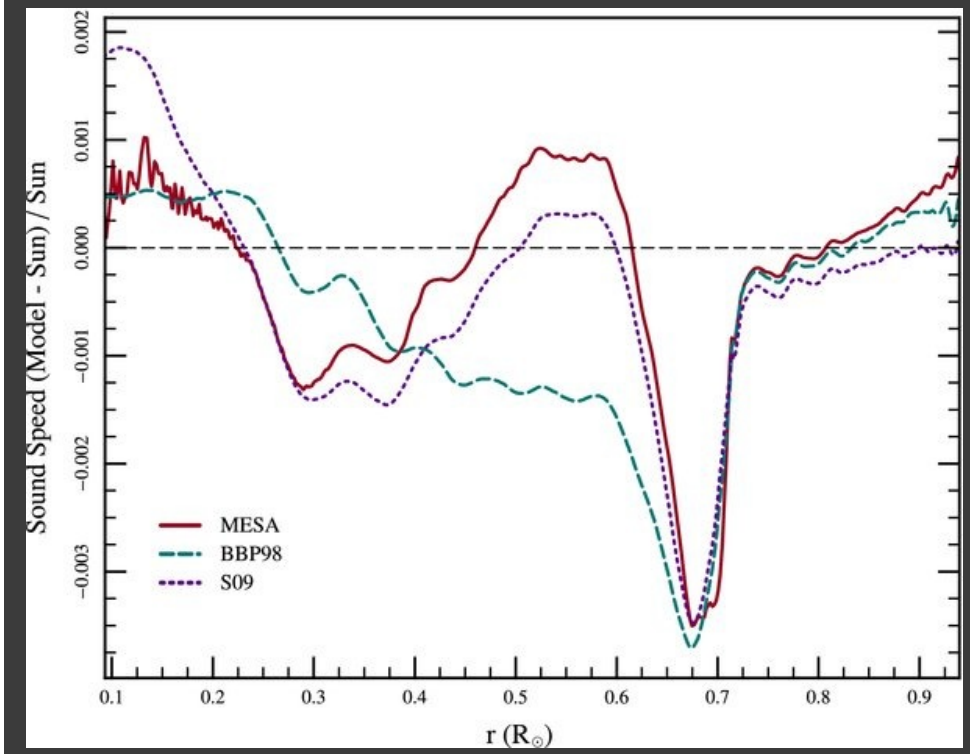
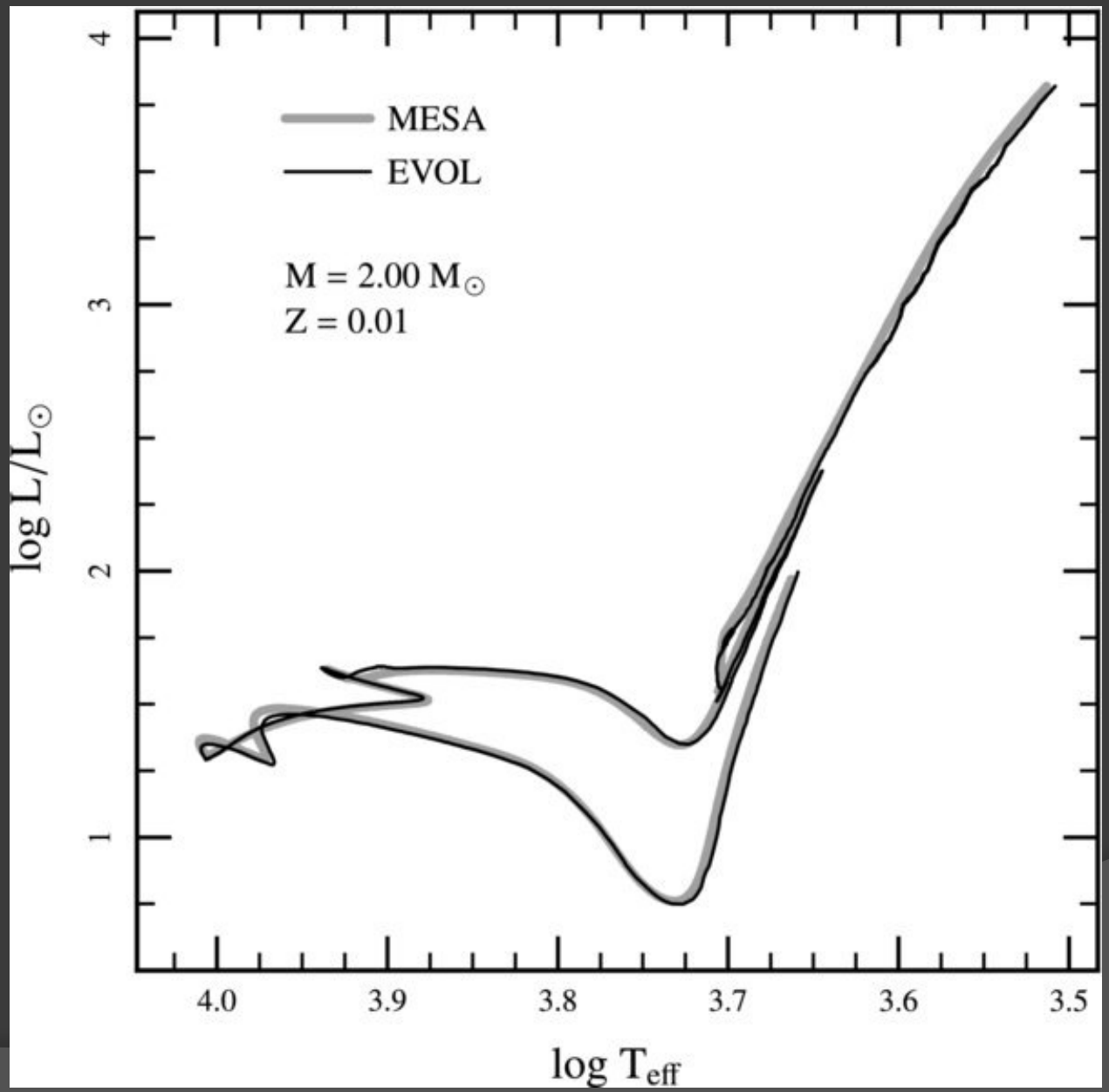



**Table 10**
MESA `star` Standard Solar Model at 4.57 Gyr

| Quantity | Value |
|---|---|
| Converged input parameters | |
| $\alpha_{\rm MLT}$ | 1.9179113764 |
| $Y_i$ | 0.2744267987 |
| $Z_i$ | 0.0191292323 |
| Properties of converged model | |
| $(Z/X)_s$ | 0.02293 |
| $X_s$ | 0.73973 |
| $Y_s$ | 0.24331 |
| $Z_s$ | 0.01696 |
| $X_c$ | 0.33550 |
| $Z_c$ | 0.02125 |
| $R_{\rm CZ}/R_\odot$ | 0.71398 |
| $\log \rho_c$ | 2.18644 |
| $\log P_c$ | 17.3695 |
| $\log T_c$ | 7.19518 |
| $\mathrm{rms}[(c_{\rm Model} - c_\odot)/c_\odot]$ | 0.00093 |

# Intermediate-mass structure and evolution




Paxton et al. 2011

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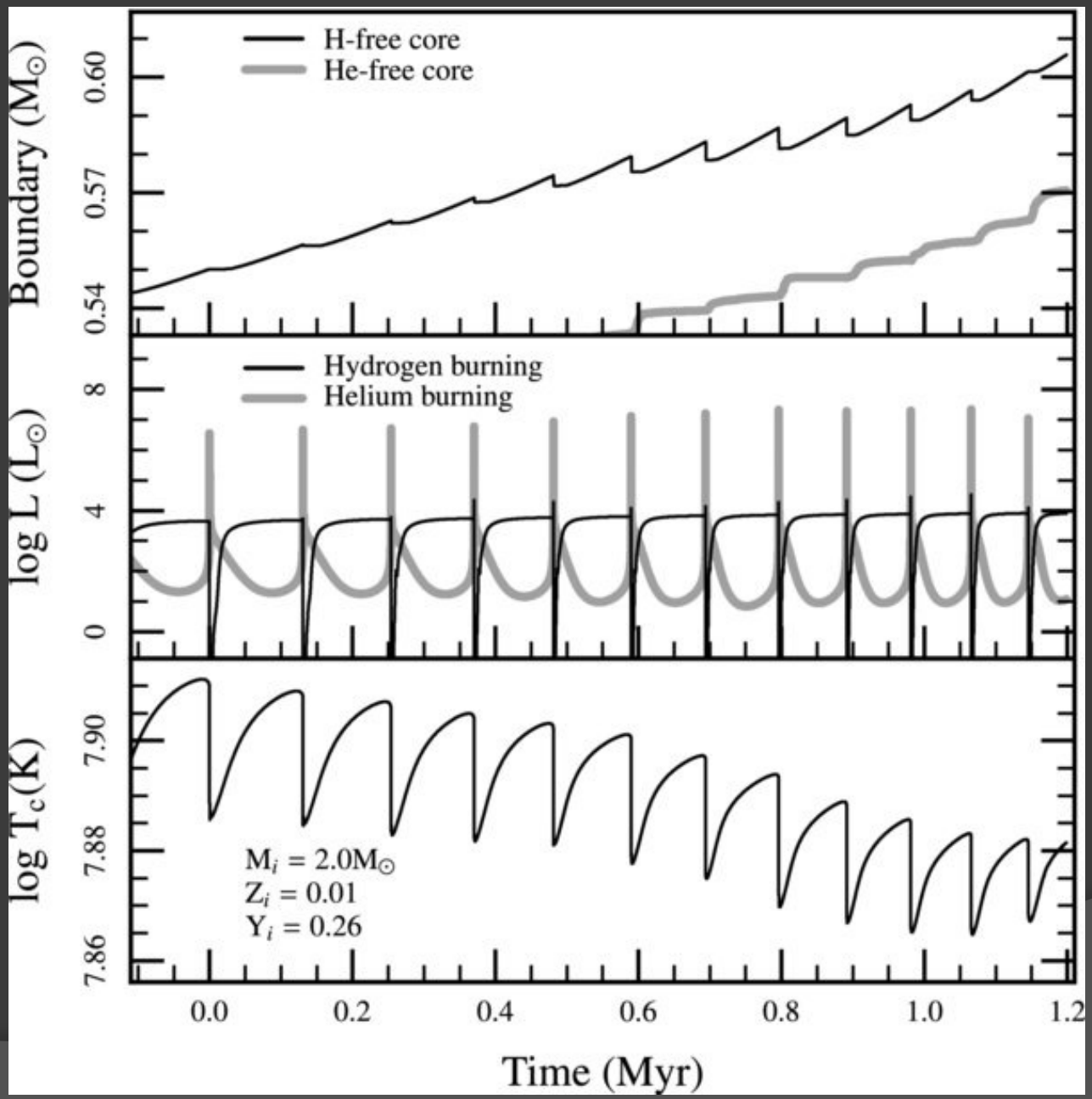


Paxton et al. 2011

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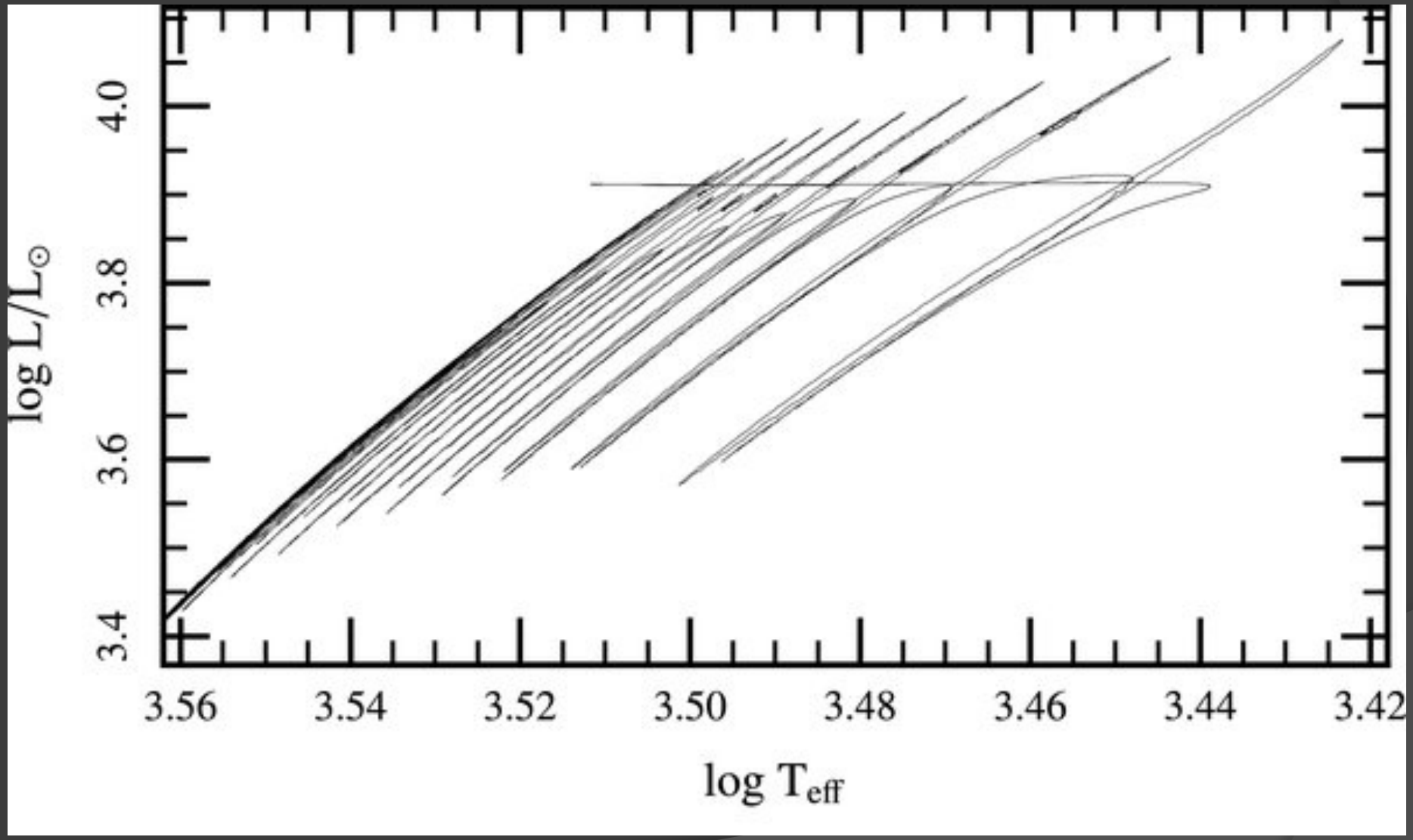
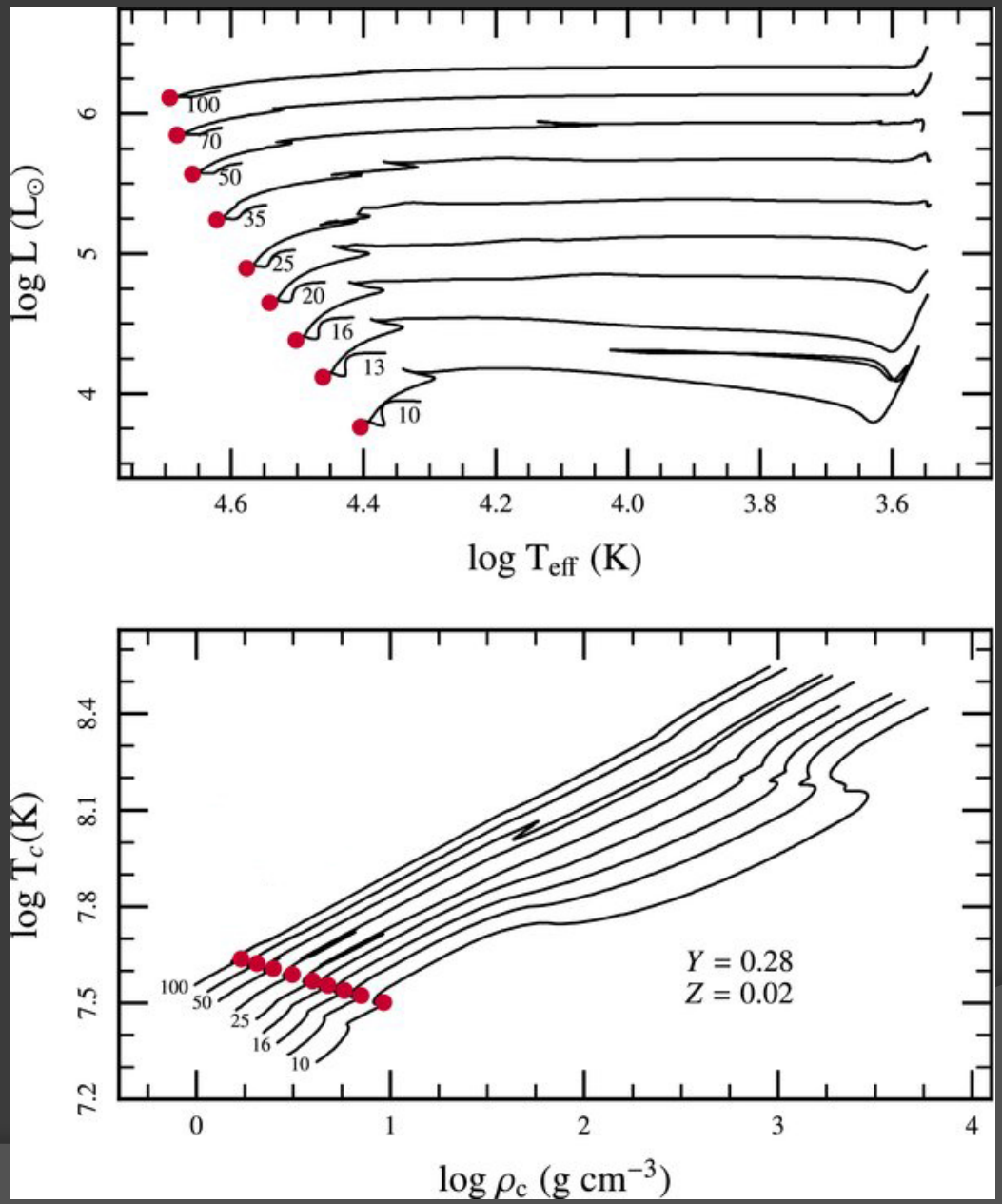



Paxton et al. 2011

# Massive stars




Paxton et al. 2011

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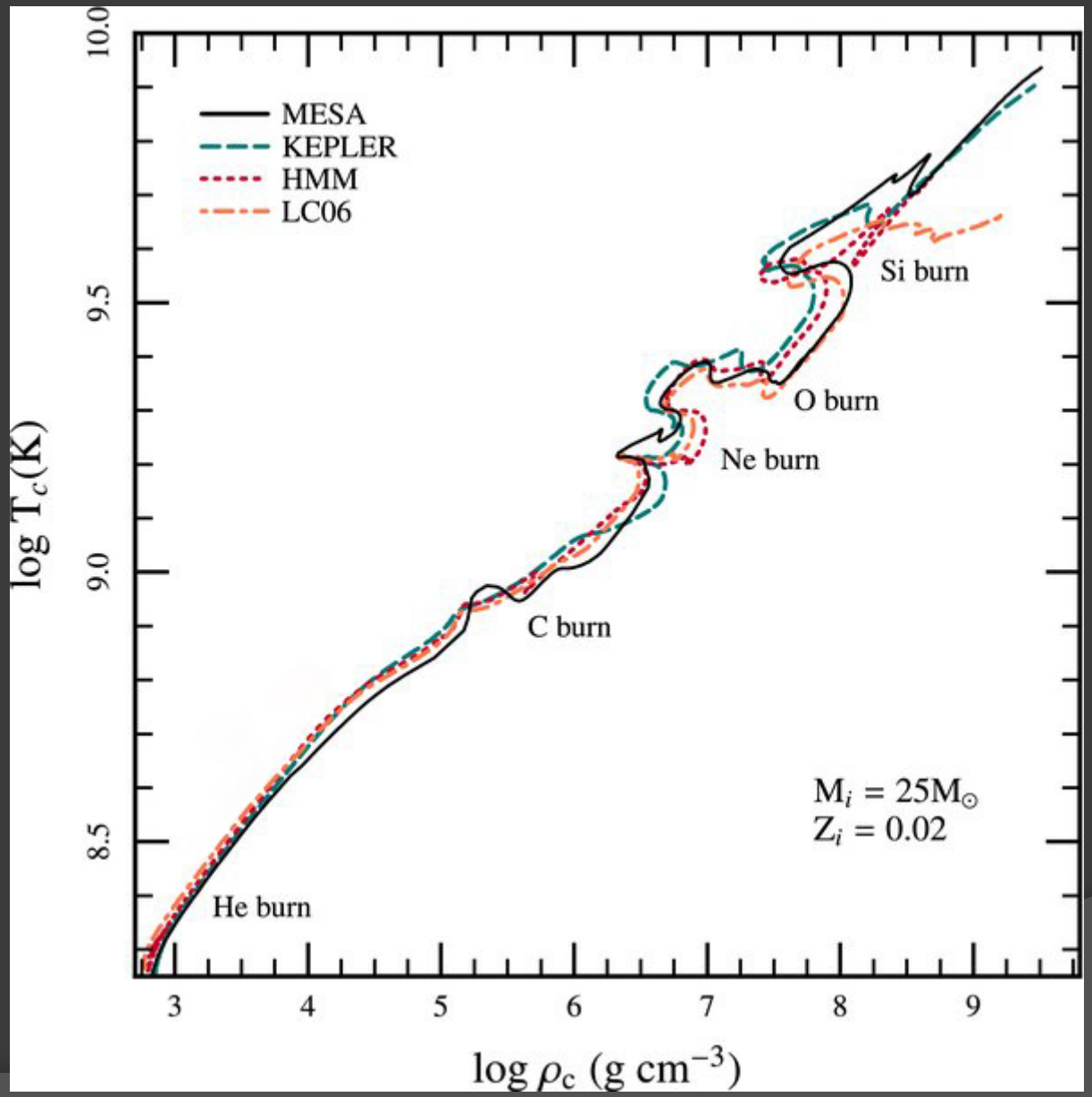


Paxton et al. 2011

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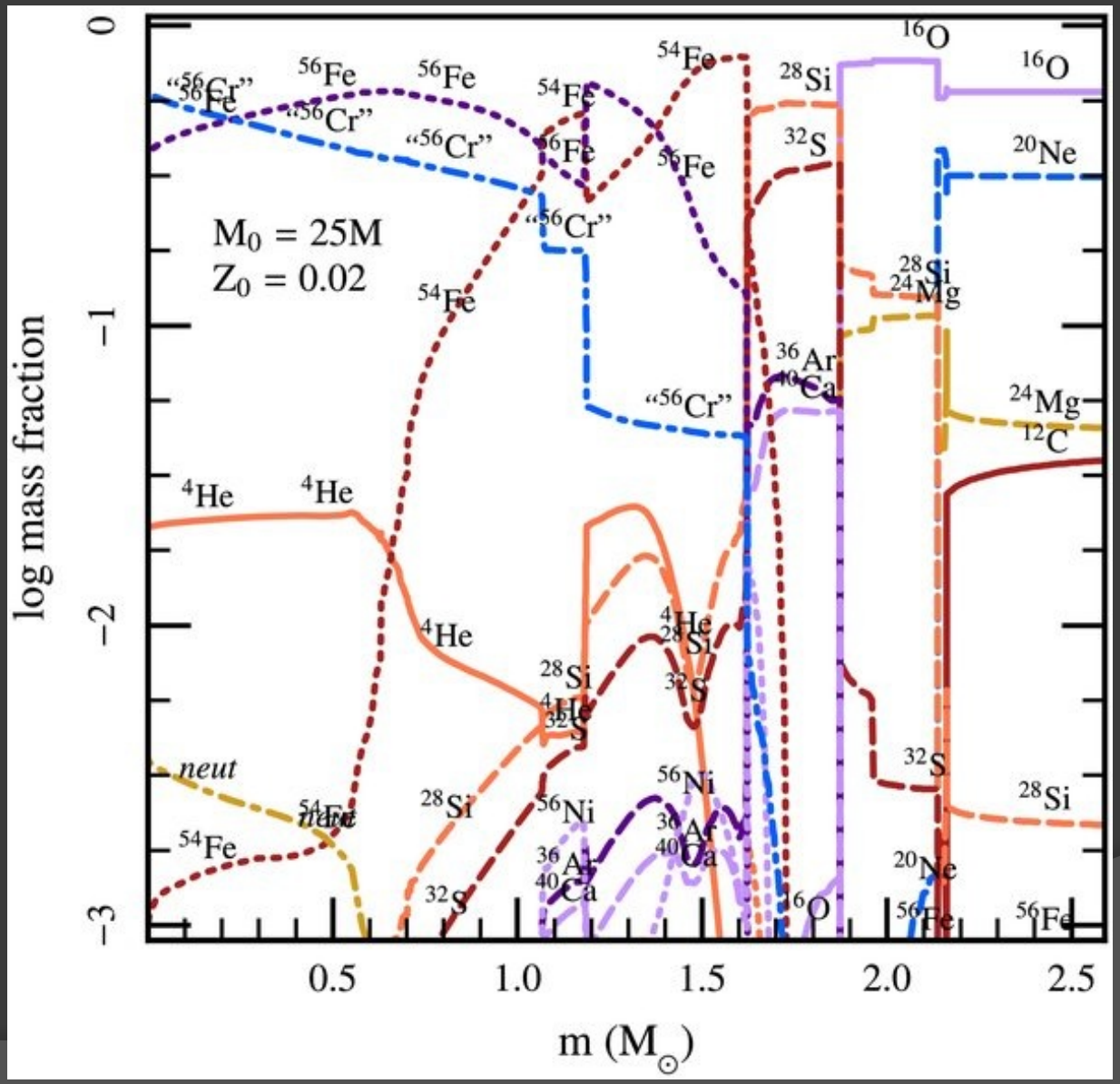


Paxton et al. 2011

# Conclusions

- Excellent stellar evolution code
- Wide applicability
- Results in agreement with other codes
- Openness and excellent licensing policies