Keele University

Brainstorming

KAVLI IPMU

Stellar Evolution Modelling: 1D to 3D to 1D (convection)

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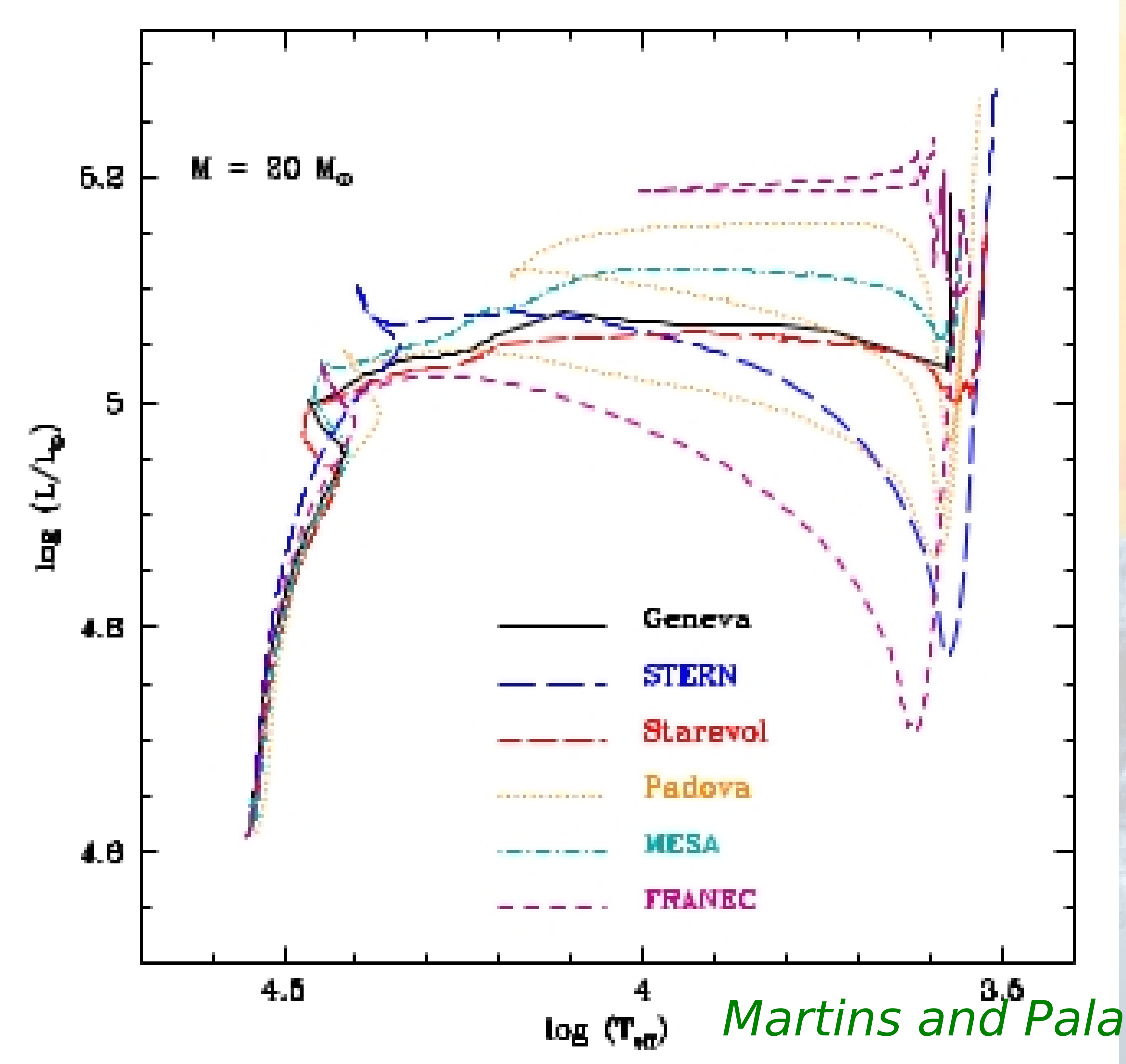
NUGRID: F. Herwig, S. Jones (Victoria, Canada), C. Fryer (LANL), Laird (York), UChicago, UFrankfurt, …

Convective Boundaray Mixing (CBM) impact on post-MS

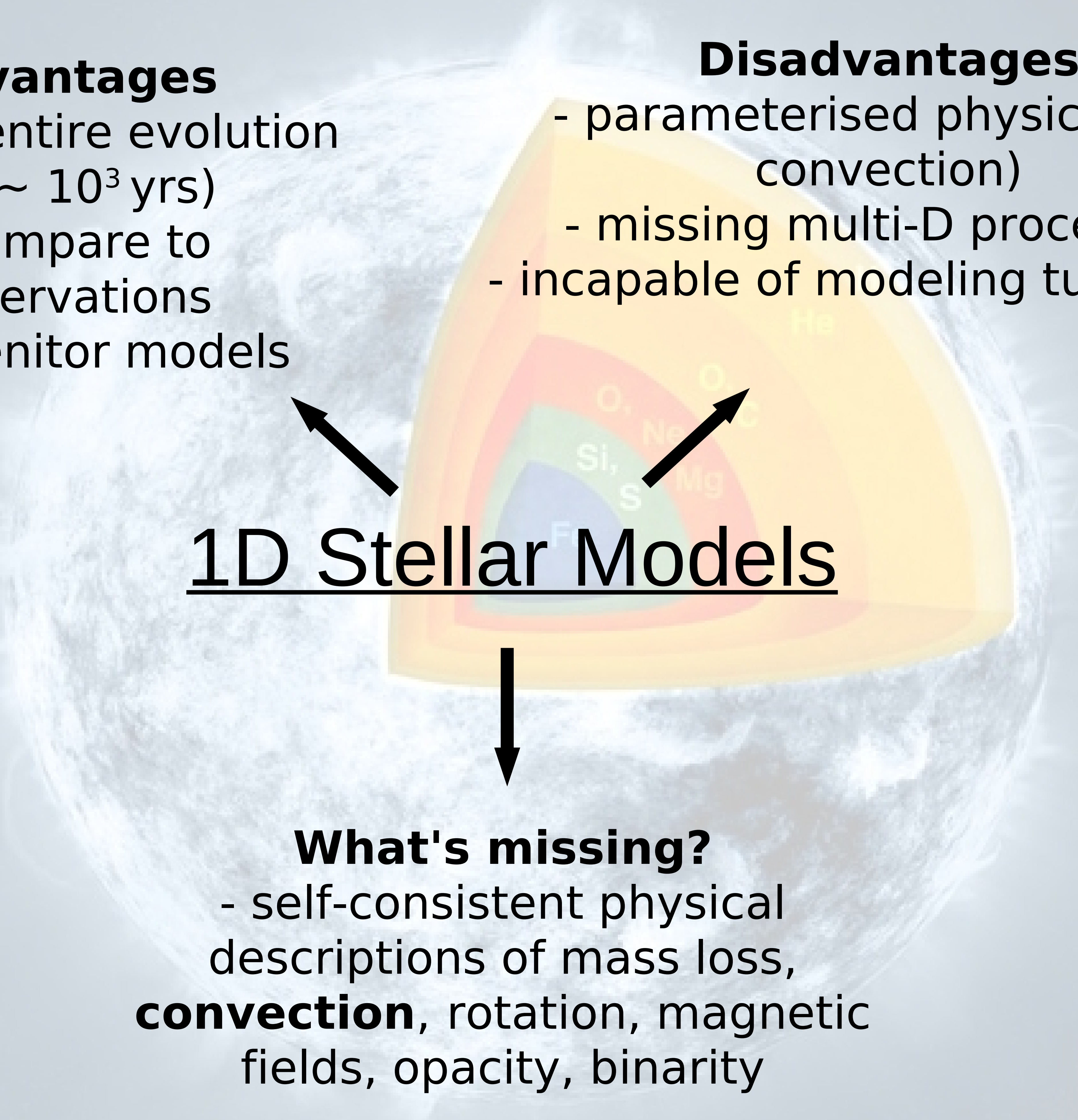


Different prescriptions for mixing, CBM and free parameters affects extent of MS and post-MS evolution.

Martins and Palacios (2013)

Advantages
- model entire evolution ($\Delta t \sim 10^3$ yrs)
- compare to observations
- progenitor models

Disadvantages
- parameterised physics (e.g. convection)
- missing multi-D processes
- incapable of modeling turbulence



1D Stellar Models

What's missing?
- self-consistent physical descriptions of mass loss, **convection**, rotation, magnetic fields, opacity, binarity

Advantages

- model fluid instabilities (e.g. Rayleigh-Taylor)
- modeling 3D processes
- model diffusive and advective processes

Disadvantages

- resolution dependent?
- initial condition dependent?
- computational cost
- limited to dynamical timescales (t_{ct} ~ 100s)

3D Stellar Models

What's missing?

- full star simulations
- Large scale (LES) and small scale (DNS) cannot be followed simultaneously

Current Implementation: Convection

Multi-D processes

Major contributor to turbulent mixing

Turbulent entrainment at convective boundaries

Internal gravity waves

1D prescriptions

Mixing length theory, boundary placement, convective boundary mixing

Bohm-Vitense (1958)

Impact on models

Mixing rates

Advanced evolution

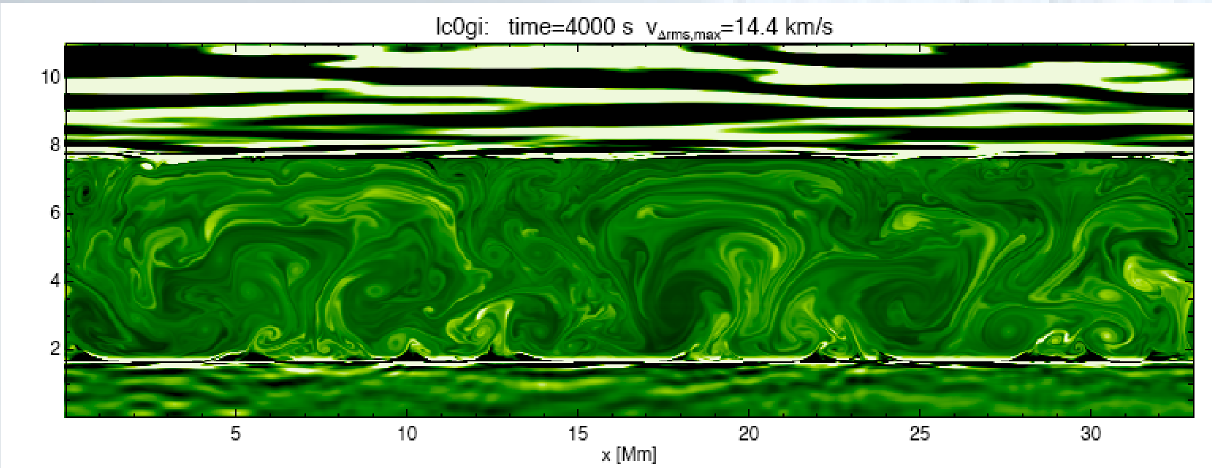
Convective core size

Surface abundances

Mass loss

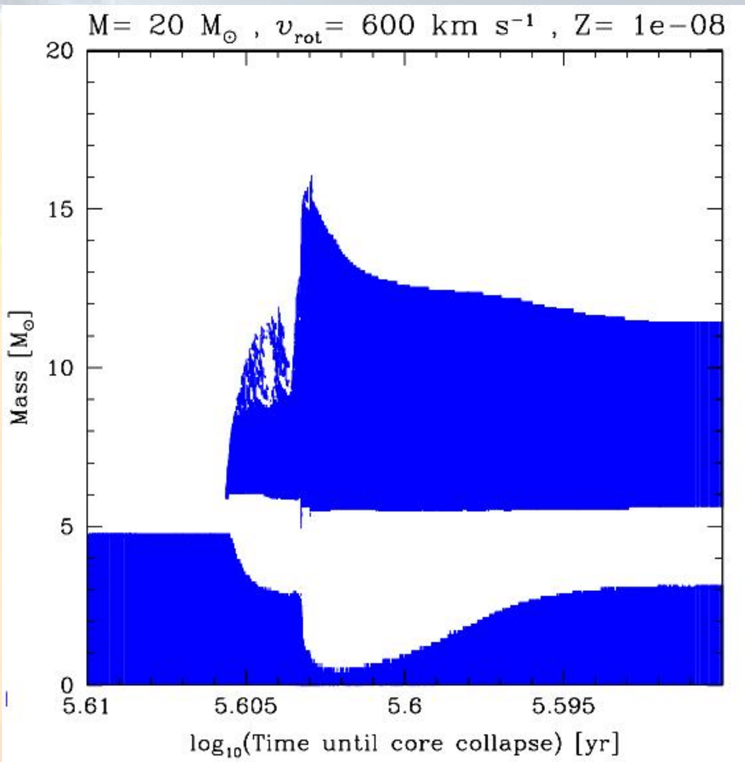
Way Forward

3D simulations

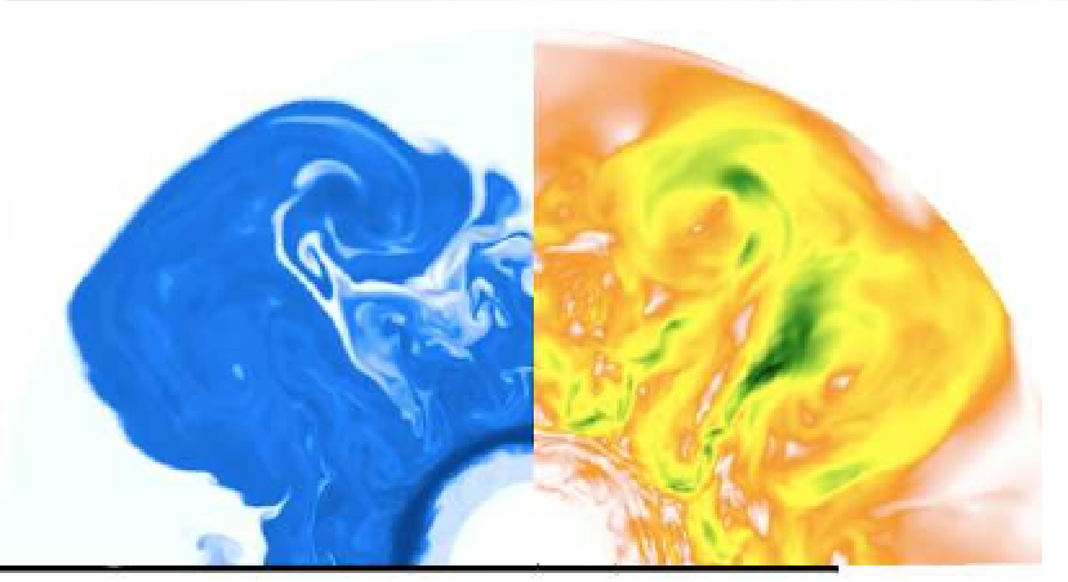


Herwig et al 06

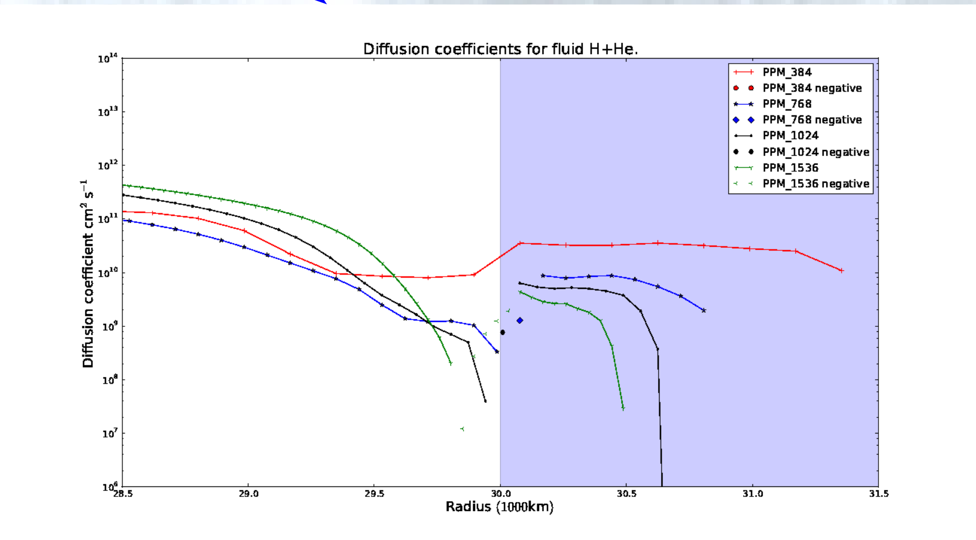
Uncertainties in 1D



e.g. Hirschi 07



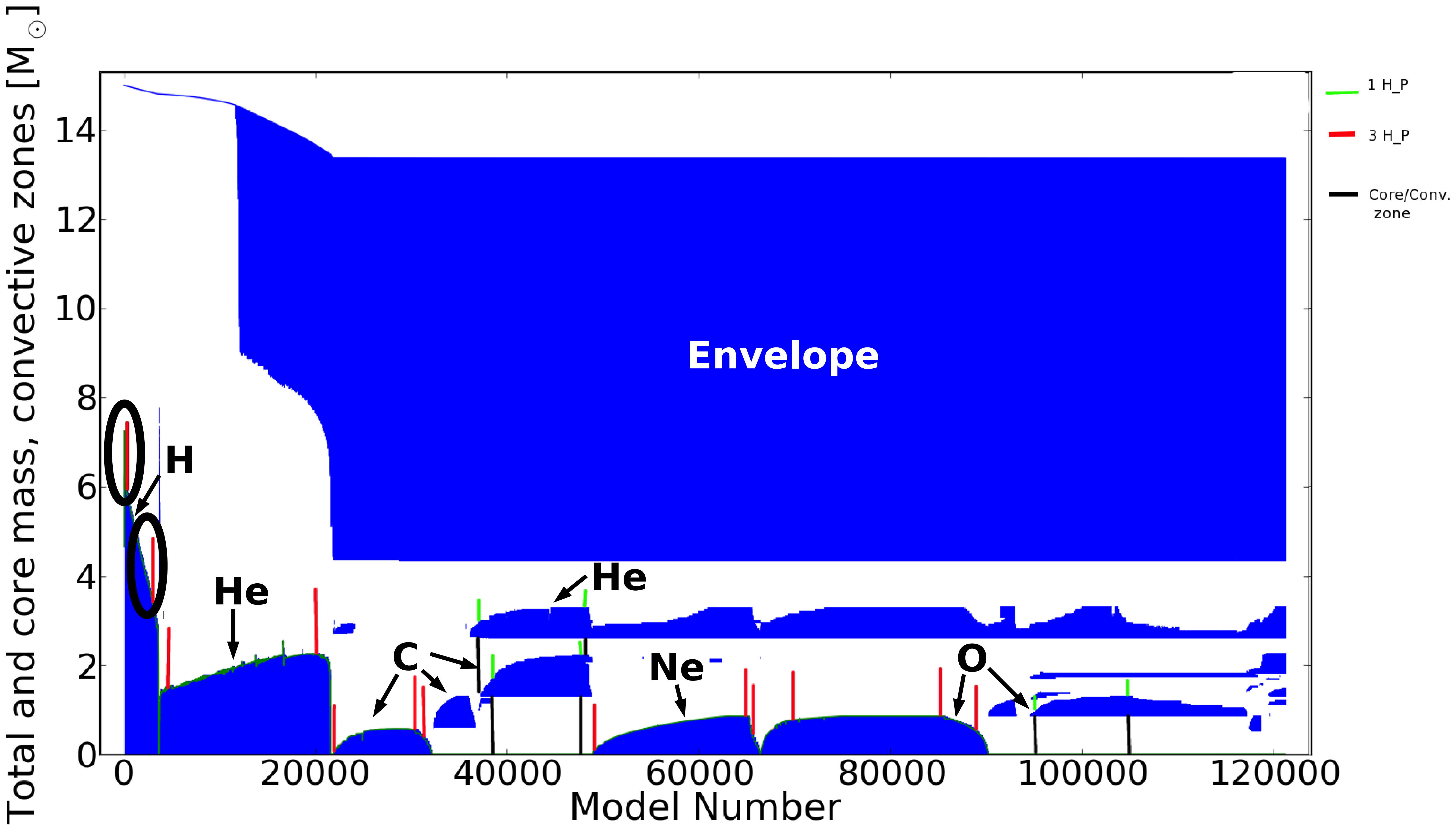
e.g. Arnett & Meakin 2011
Mocak et al 2011,
Viallet et al 2013, ...



Meakin et al 2009 ; Bennett et al PhD thesis

Determine effective diffusion (advection?) coefficient

Many Different Convective Zones in Stars!



1D to 3D: Priority List

* Convective boundary mixing during core hydrogen burning:
 +: many constraints (HRD, astero, ...)
 -: difficult to model due to important thermal/radiative effects
 -: long time-scale

* Silicon burning:
 +: important to determine impact on SNe of multi-D structure in progenitor (Couch & Ott, aph1408.1399, Mueller & Janka aph1409.4783)
 +: possible shell mergers occurring after core Si-burning (e.g. Tur et al 2009ApJ702.1068; Sukhbold & Woosley 2014ApJ783.105) strongly affect core compactness
 +: radiative effects small/negl.
 -: ~ 10^9 CPU hours needed for full silicon burning phase will be ok soon;
 -: might be affected by convective shell history

* AGB thermal pulses/H-ingestion:
 +: already doable (e.g. Herwig et al 2014ApJ729.3, 2011ApJ727.89, Mocak et al 2010A&A520.114)
 +: thermal/radiative effects not dominant
 ?: applicable to other phases?

* Oxygen shell: (Meakin & Arnett 2007ApJ667.448/665.448, Viallet et al 2013ApJ769.1)
 +: similar to silicon burning but smaller reaction network needed
 -: might be affected by convective shell history

* Carbon shell: (PhD A. Cristini)
 +: not affected by prior shell history
 +: first stage for which thermal effects become negligible

* Envelope of RSG (e.g. Viallet et al. 2013, Chiavassa et al 2009-2013),

3D to 1D: Convective boundary mixing (CBM)

CBM → Entrainment...?

Penetrative

exp-D

Extend convective region

$$d_{ov} = \alpha_{ov} \, min[H_P, r_c]$$

Zahn 1991

$$D = D_0 \exp\left[\frac{-2z}{f_{CBM} H_P}\right]$$

Freytag et al 1996

Same degree of mixing

Extended by fraction of pressure scale height

Mixing reduced exponentially

Mixing continued until cutoff reached

Convective boundary mixing (CBM)

CBM → Entrainment...?

CBM → Penetrative

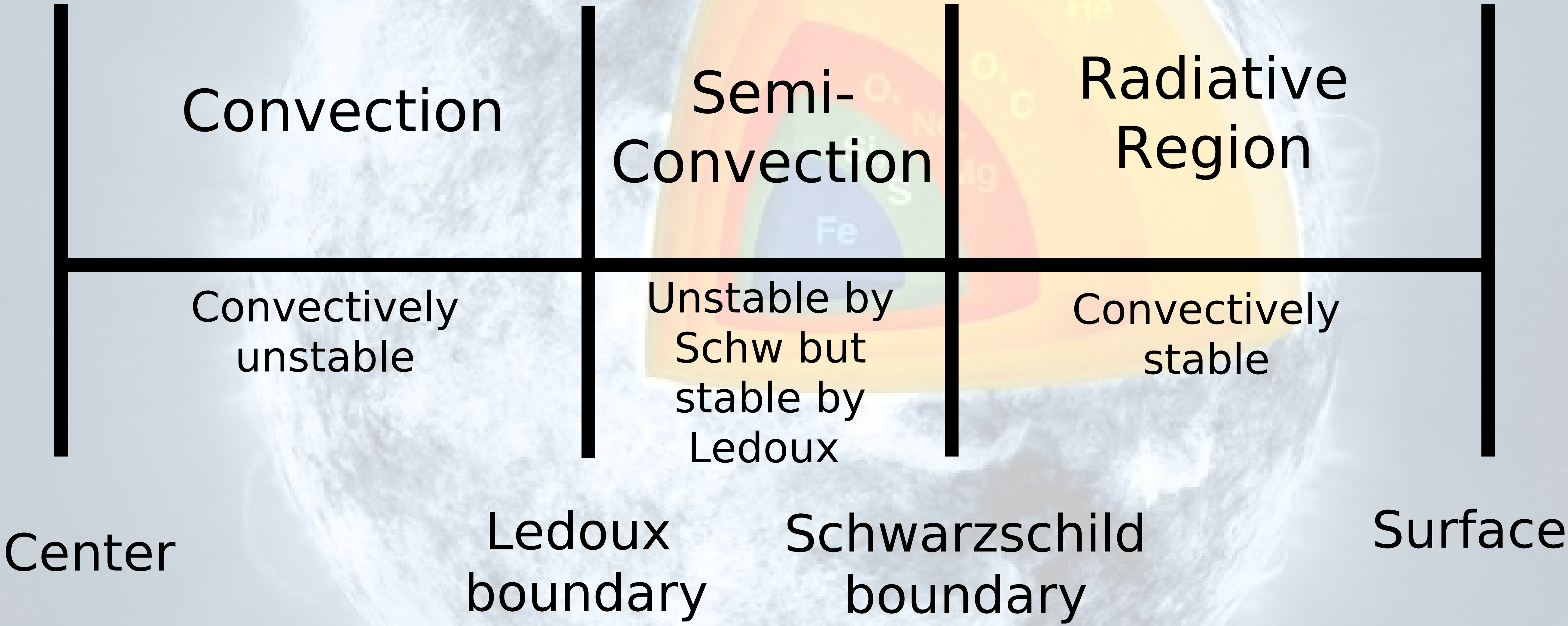
CBM → exp-D

Prescriptions inspired by multi-D hydrodynamic simulations

↓

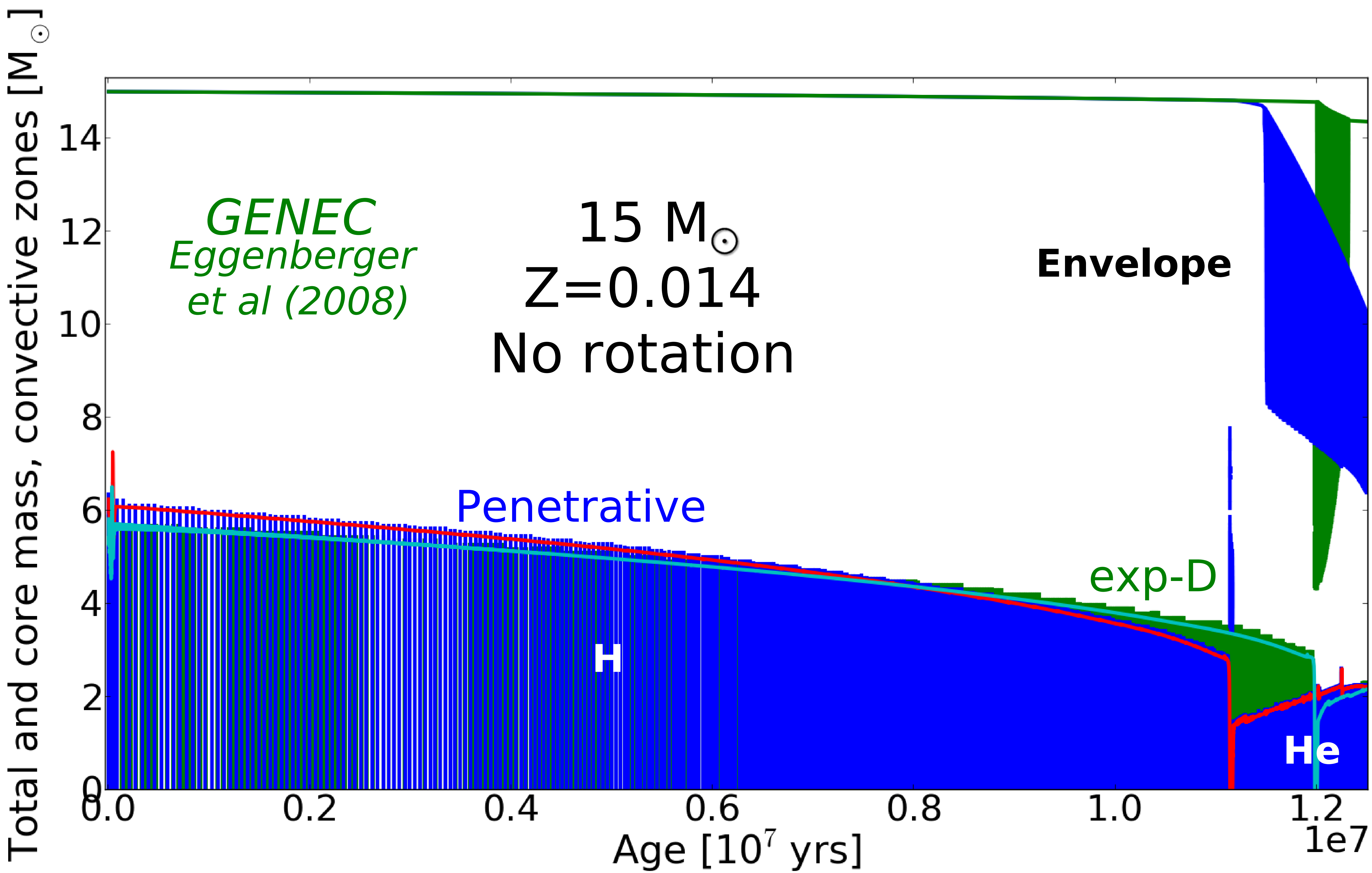
More simulations will help to test these prescriptions

Regions of instability



All stars ~>$1.8 M_\odot$ have this structure on MS

Penetrative vs exp-D CBM



Penetrative vs exp-D CBM

- Both GENEC and MESA have included penetrative and exp-D prescriptions.

- CBM prescription changes slope of core boundary

- This can greatly affect the post-MS evolution

Convective boundary mixing

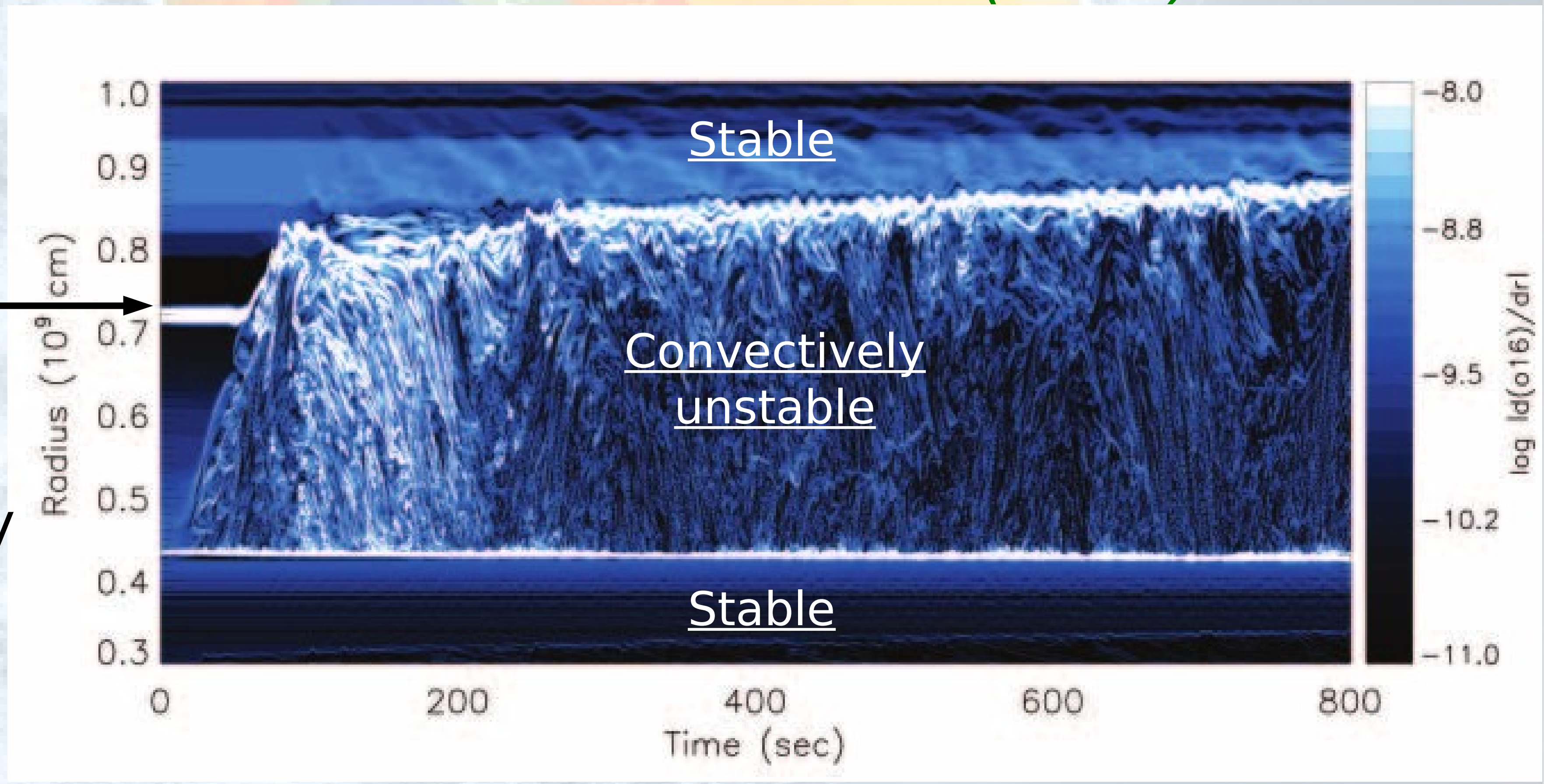
- Convective flux and velocity zero at the boundary
- Convective boundary mixing (CBM) observed in 3D hydrodynamical simulations.

O burning shell of 23 $M_{\odot}$ star simulated using PROMPI

Meakin and Arnett (2007)

Mass entrainment beyond boundary

Ledoux boundary



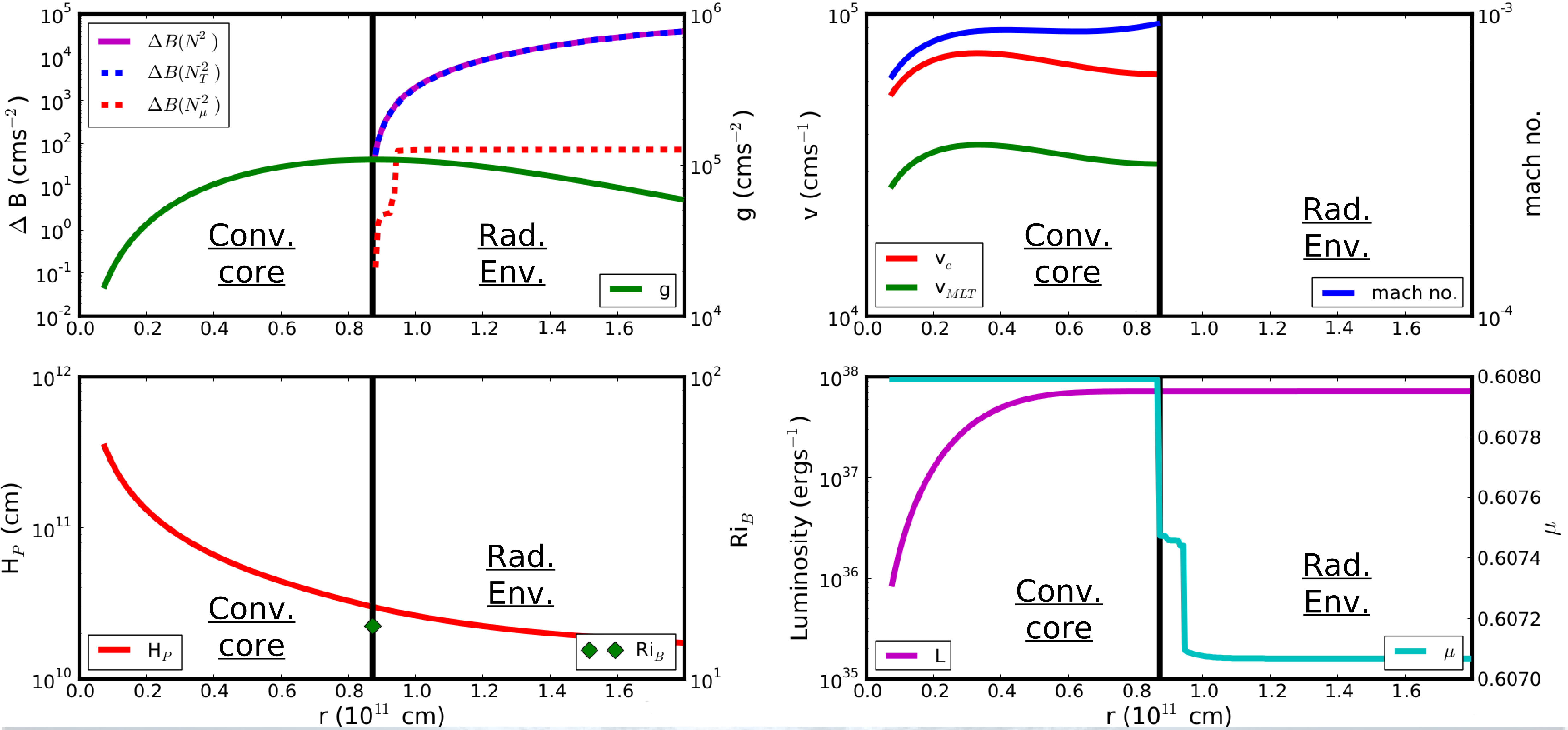
New processes needed in 1D to capture CBM

Due to free parameters in MLT and CBM in 1D further multi-D simulations needed to understand CBM

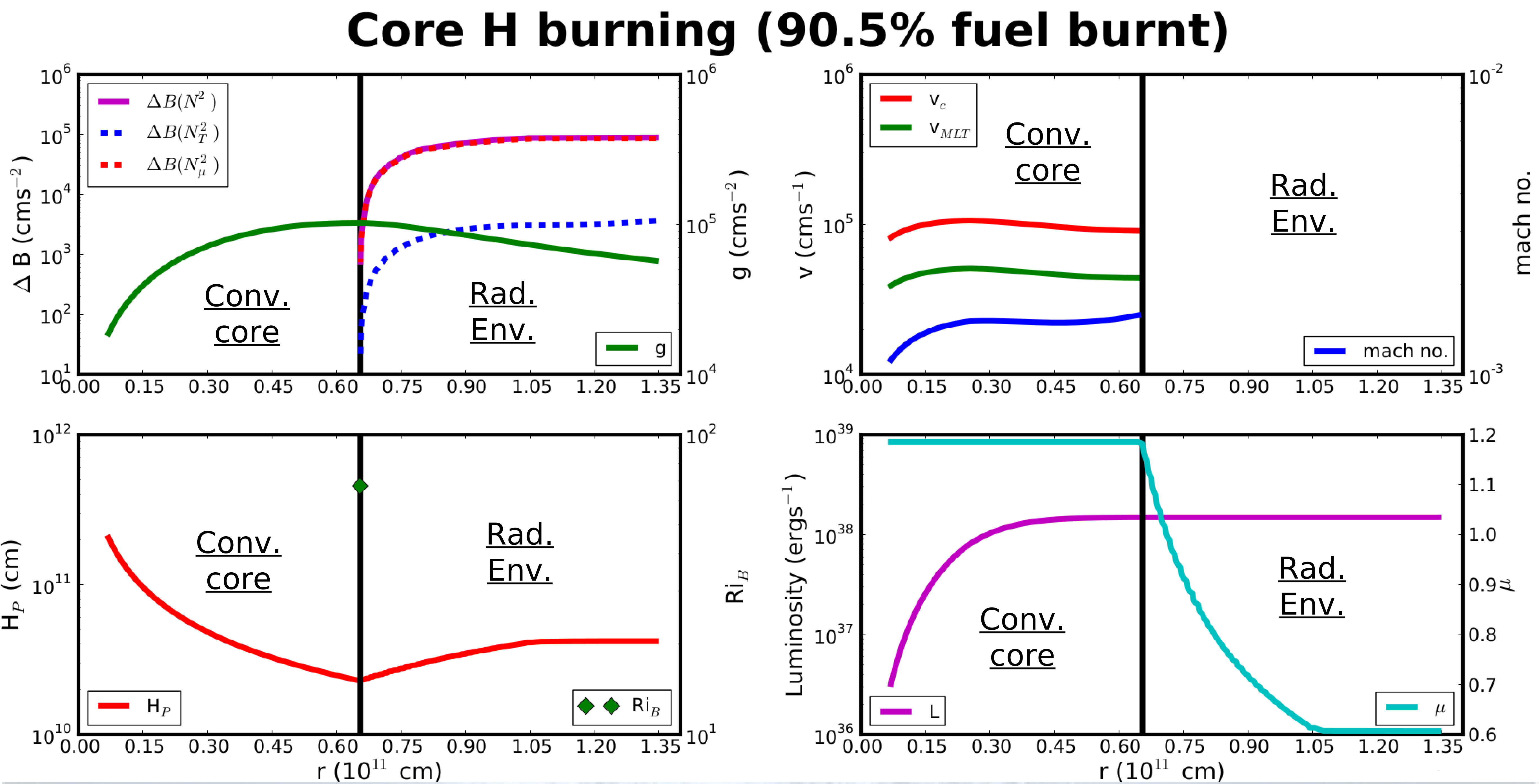
See also e.g. Woodward, Herwig et al 2013

Burning zones

Core H burning (0.3% fuel burnt)



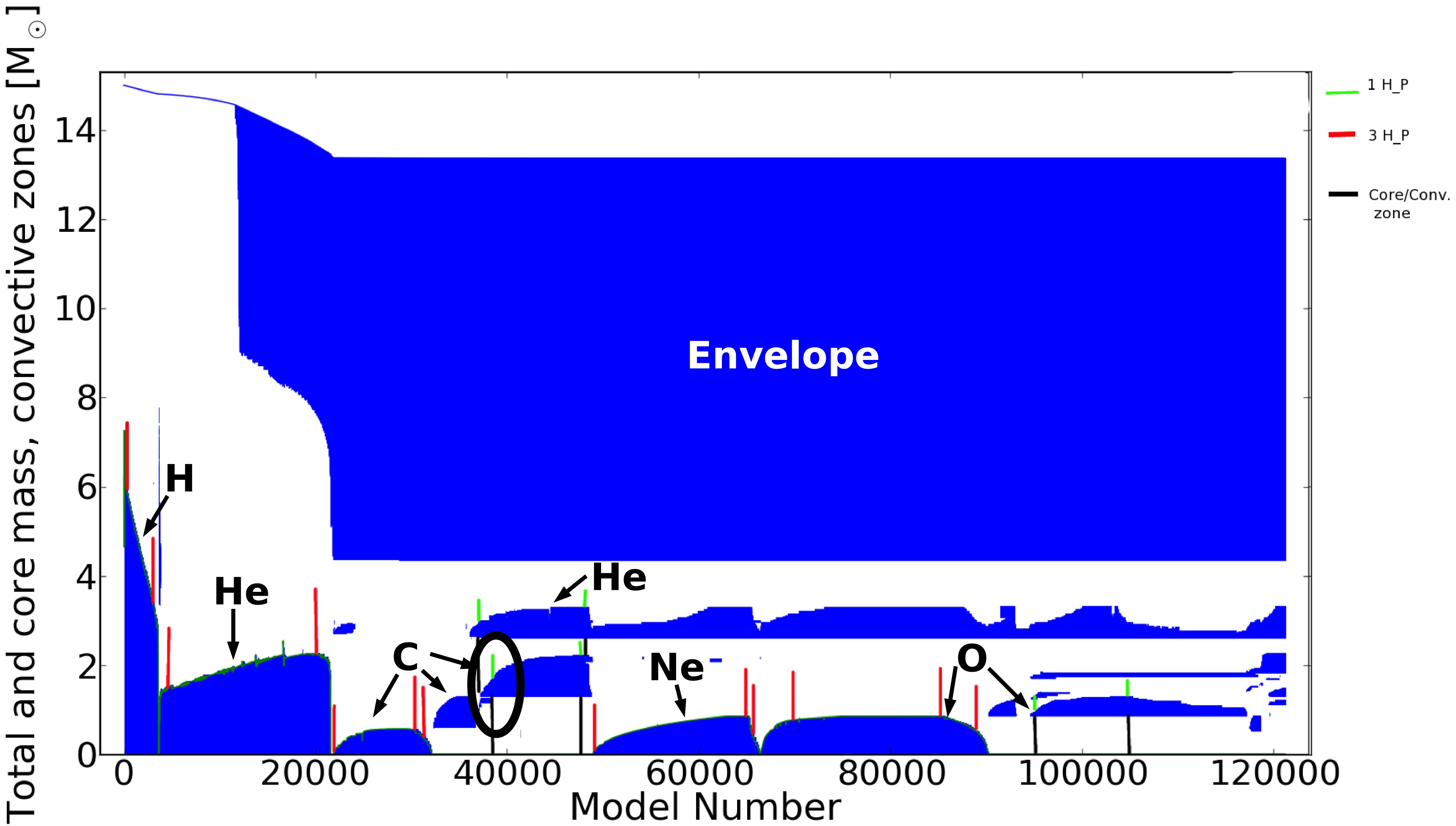
Burning zones



Remarks

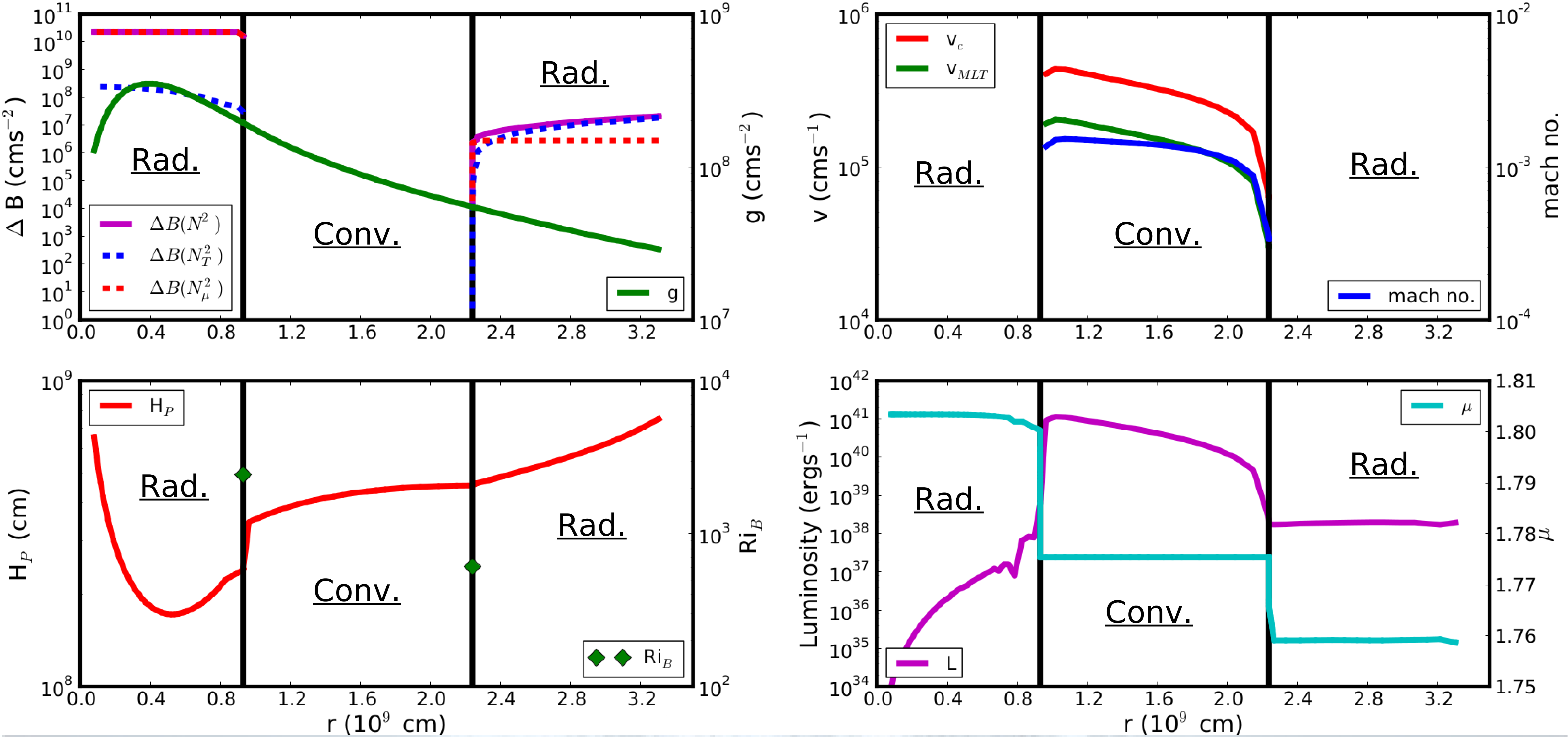
- Contribution to buoyancy jump changes
- Thermal gradient dominates at the start
- Molecular weight gradient dominates at the end

Burning zones

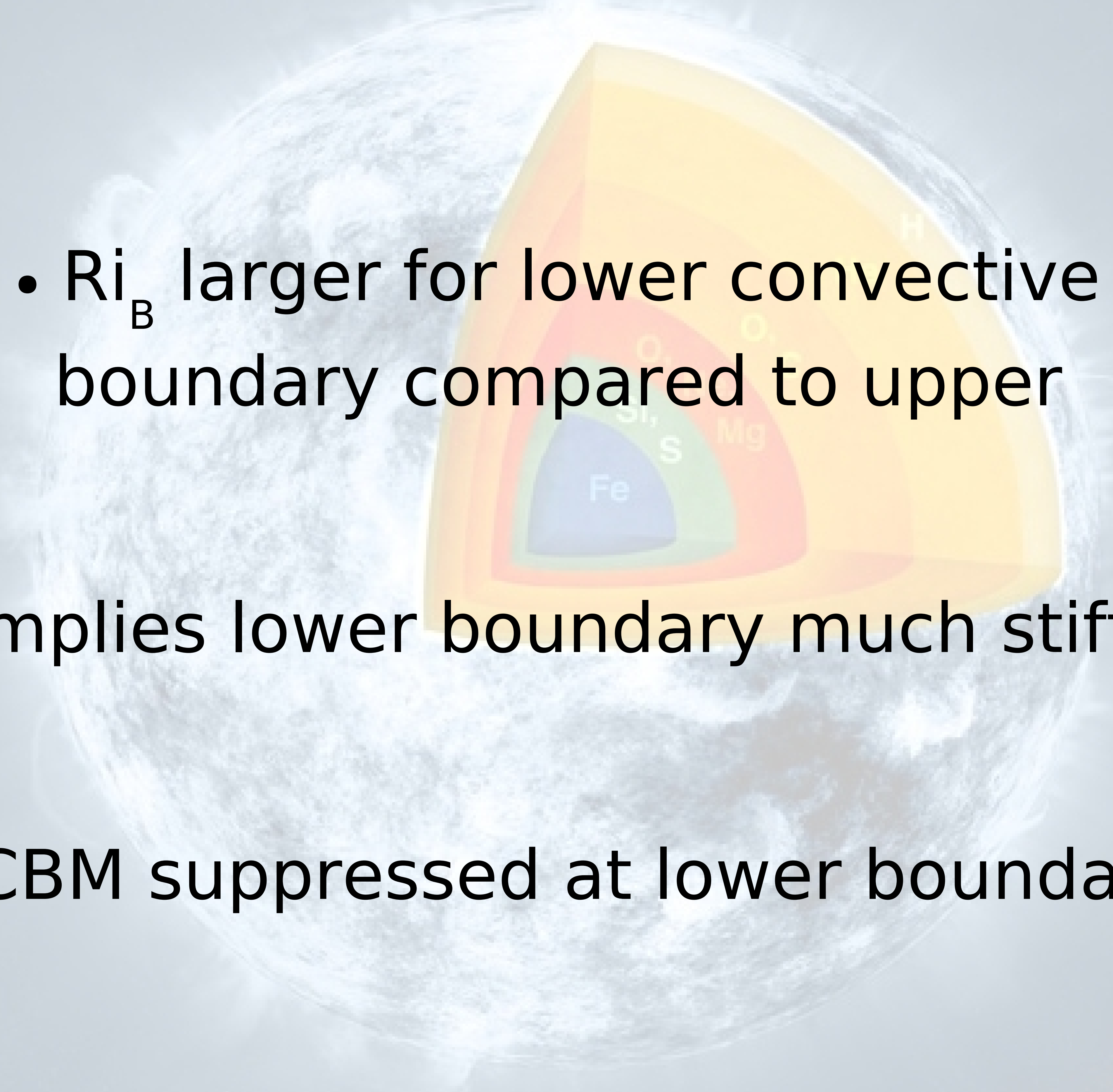


Burning zones

Shell C burning (31% of shell lifetime)



Remarks



- Ri_B larger for lower convective boundary compared to upper

- Implies lower boundary much stiffer

- CBM suppressed at lower boundary

Conclusions thus far

- exp-D CBM changes slope of core boundary

- Thermal and mu gradients dominate buoyancy jump at the start and end of MS, respectively

- Lower boundary of convective shells are stiffer than upper boundaries

1D to 3D: Key Uncertainties

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    -

- Carbon shell: (Cristini et al in prep)
- +: not affected by prior shell history
- Envelope convection for RSG, low-mass stars, ... ?