

Challenges in Massive Star Evolution: Convection and Mass Loss

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Plan

- Importance and evolution of (massive) stars:

Radiative, kinetic and chemical feedback!

Evolutionary tracks, progenitor structures (SNe, GW),
nucleosynthesis production

- 1D vs 3D modelling
- Convective boundaries
- Current and future computing platforms
- Conclusions & outlook



Evolution of Surface Properties

Main sequence:

hydrogen burning

After Main Sequence:

Helium burning

Low and intermediate-mass stars:

MS → RG → HB/RC → AGB → WD

Single massive stars:

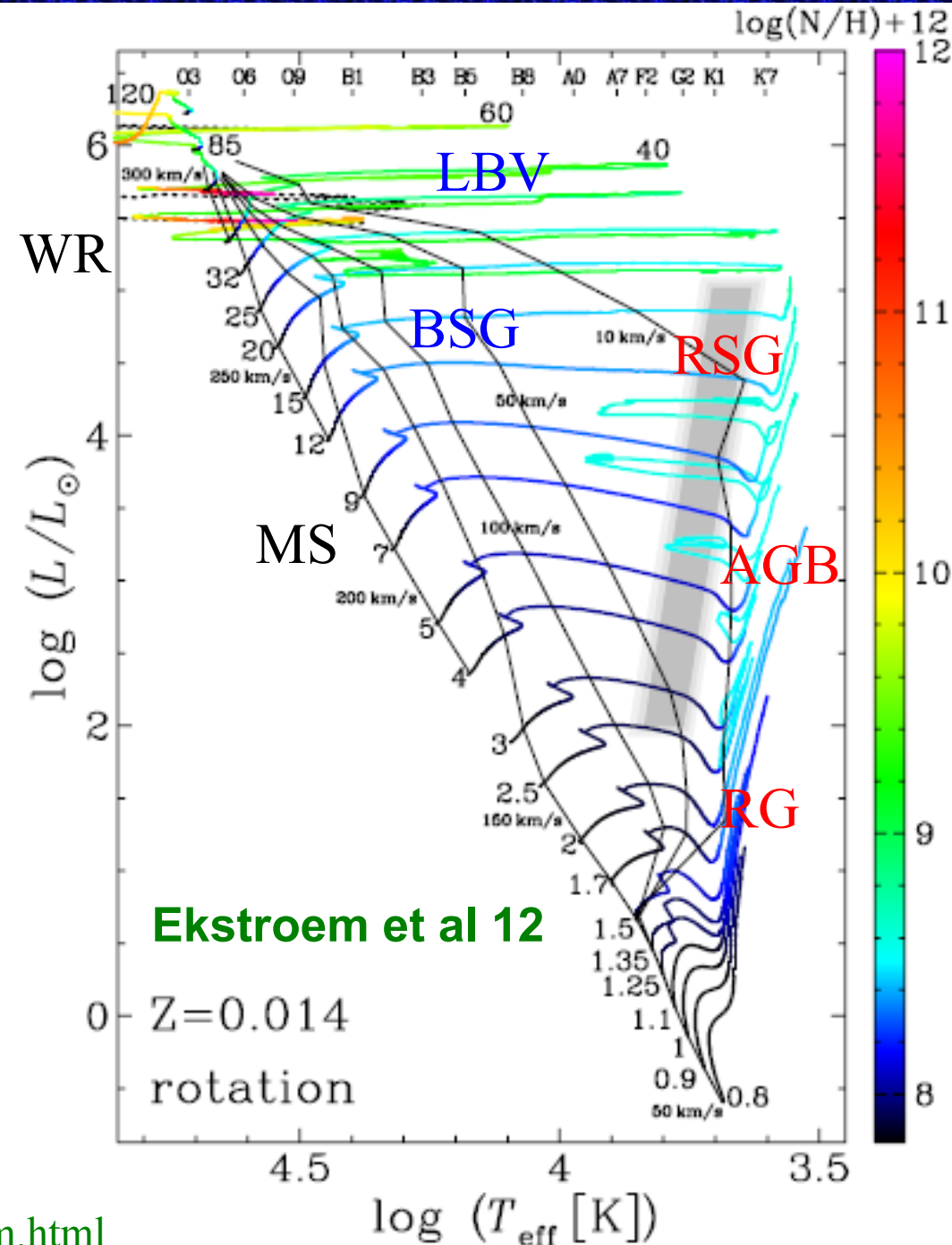
Supergiant stage (red or blue)

Wolf-Rayet (WR): $M > 20\text{-}25 M_{\odot}$

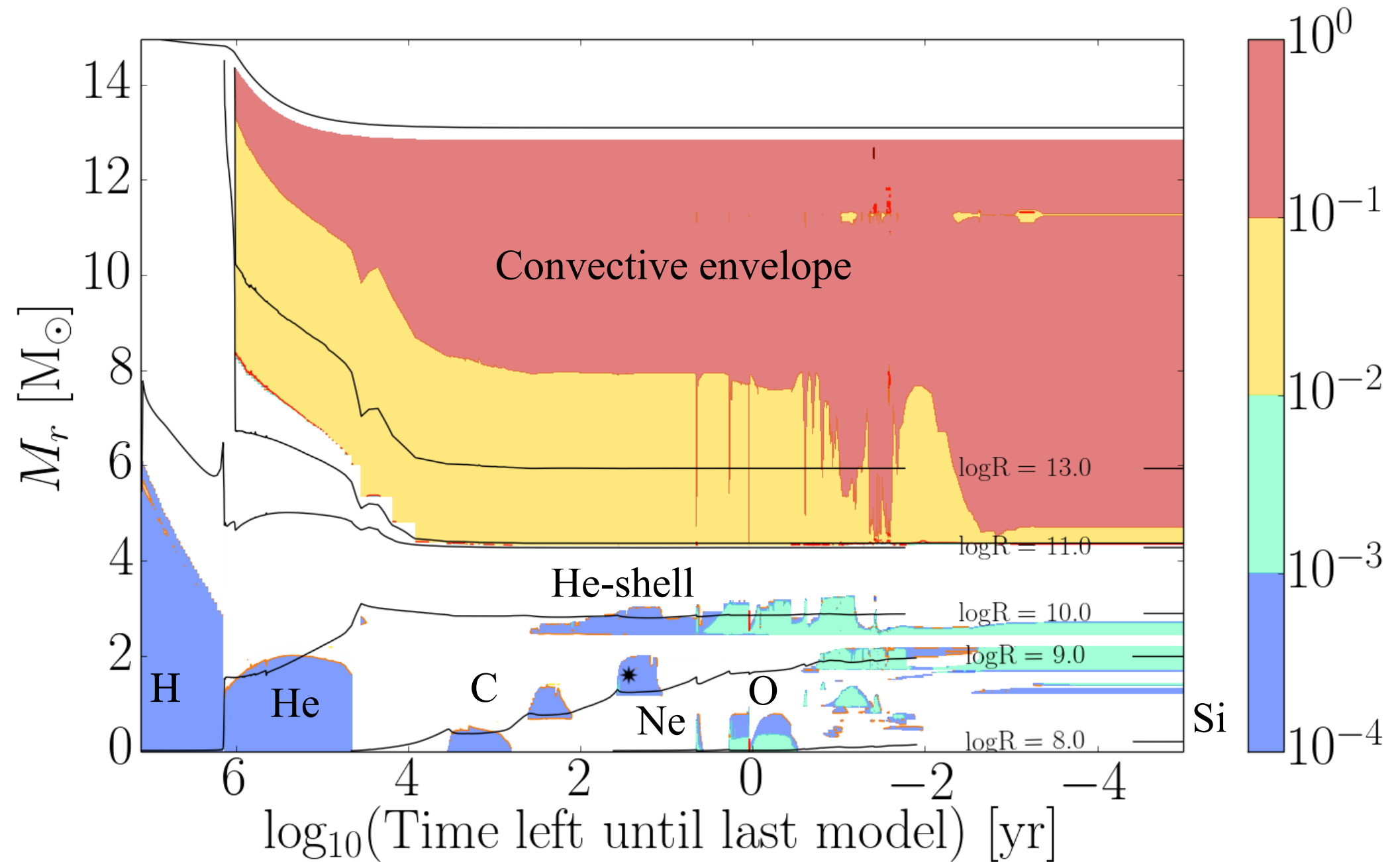
WR without RSG: $M > 40 M_{\odot}$

Advanced stages: C, Ne, O, Si

→ iron core → SN/NS/BH



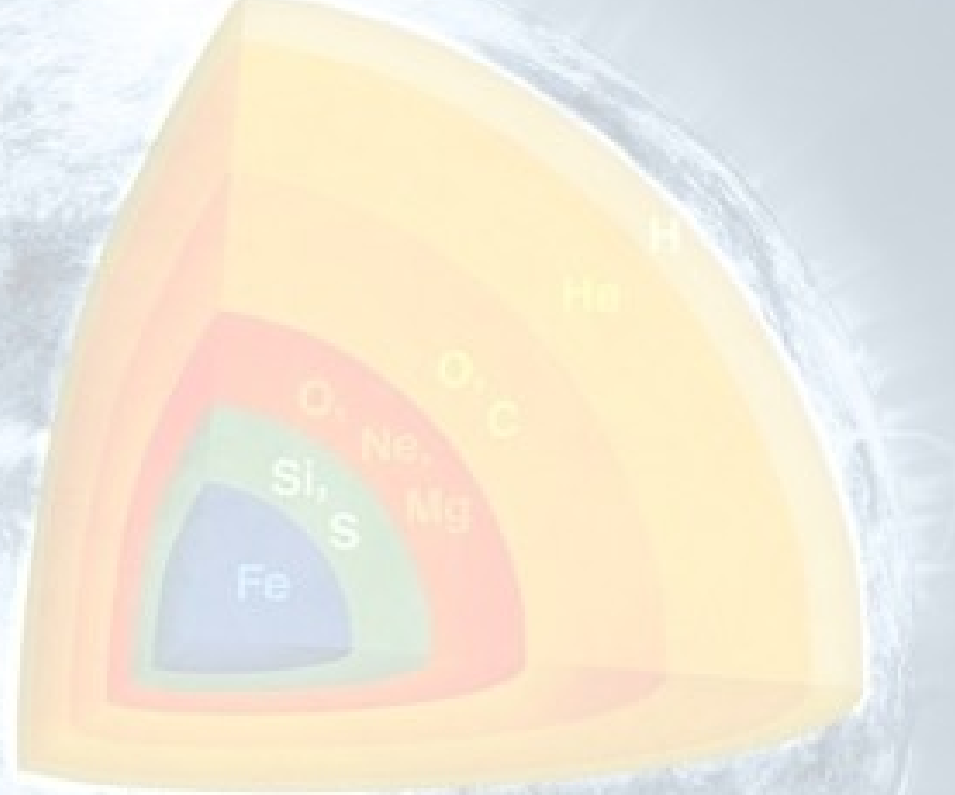
Evolution of Massive Stars



Convection takes place during most burning stages

Physical Ingredients

- Nuclear reactions
- Rotation
- Mass loss
- Convection
- Magnetic fields
- Binarity (following talks)
- Equation of state, opacities & neutrino losses
including metallicity dependence



Mass Loss: Types, Driving & Recipes

Mass loss driving mechanism and prescriptions for different stages:

- O-type & “LBV” stars (bi-stab.): line-driven Vink et al 2000, 2001
- WR stars (clumping effect): line-driven Nugis & Lamers 2000, Gräfener & Hamann (2008)
- RSG: Pulsation/dust? de Jager et al 1988
- RG: Pulsation/dust? Reimers 1975,78, with $\eta \sim 0.5$
- AGB: Super winds? Dust Bloeker et al 1995, with $\eta \sim 0.05$
- LBV eruptions: continuous driven winds? Owocki et al
- ...

What changes at low Z?

- Stars are **more compact**: $R \sim R(Z_0)/4$ (lower opacities) at $Z=10^{-8}$
- Rotation at low Z: stronger shear, weaker mer. circ.
- Mass loss weaker at low Z: \rightarrow faster rotation

$$\dot{M}(Z) = \dot{M}(Z_0) \left(Z/Z_0 \right)^\alpha$$

- $\alpha = 0.5-0.6$ (Kudritzki & Puls 00, Ku02)

(Nugis & Lamers, Evans et al 05)

- $\alpha = 0.7-0.86$ (Vink et al 00,01,05)

$$Z(\text{LMC}) \sim Z_0/2.3 \Rightarrow \dot{M}/1.5 - \dot{M}/2$$

$$Z(\text{SMC}) \sim Z_0/7 \Rightarrow \dot{M}/2.6 - \dot{M}/5$$

Mass loss at low Z still possible?

RSG (and LBV?): no Z-dep.; CNO? (Van Loon 05, Owocky et al)

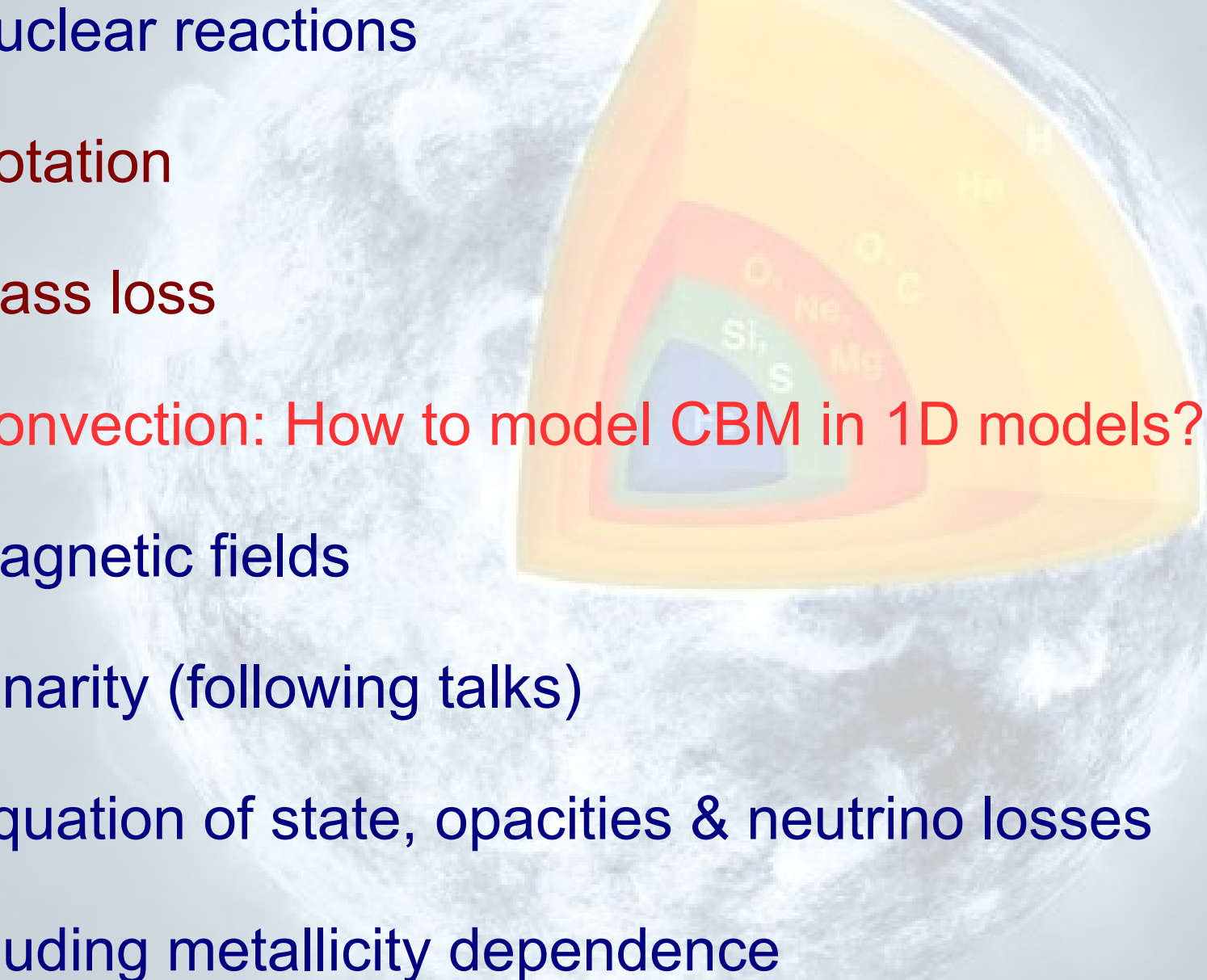
Mechanical mass loss \leftarrow critical rotation/ Eddington limit

(e.g. Hirschi 2007, Ekstroem et al 2008, Yoon et al 2012)

Key Open Questions Concerning Mass Loss

- Mass loss in cool parts of HRD: LBV & RSG, especially at low Z
- Position in & evolution across HRD: effects of rotation-induced mixing, feedback from mass loss Yusof et al 13, Langer 07, Sanyal et al 15, Kohler et al 15...
- Mass loss near Eddington limit Graefener & Hamann 08, Vink et al 11, ...
- Importance of clumping, porosity, inflation Fullerton et al 06, Graefener et al. 12, Vink et al, ...
- Which stars may explode in the LBV phase? Smith et al 11, ... ,Vink et al, ...
- Look of WR stars: radius, spectra Graefener et al. 2012, Groh et al 2013-...
- Additional mass loss mechanisms? Critical rotation at low Z? Shell mergers in late phases of evolution? ... Hirschi 2007, Meynet et al 2006, ... , Smith & Arnett 2014, ...
- ...

Physical Ingredients

- Nuclear reactions
 - Rotation
 - Mass loss
 - Convection: How to model CBM in 1D models?
 - Magnetic fields
 - Binarity (following talks)
 - Equation of state, opacities & neutrino losses
including metallicity dependence
- 

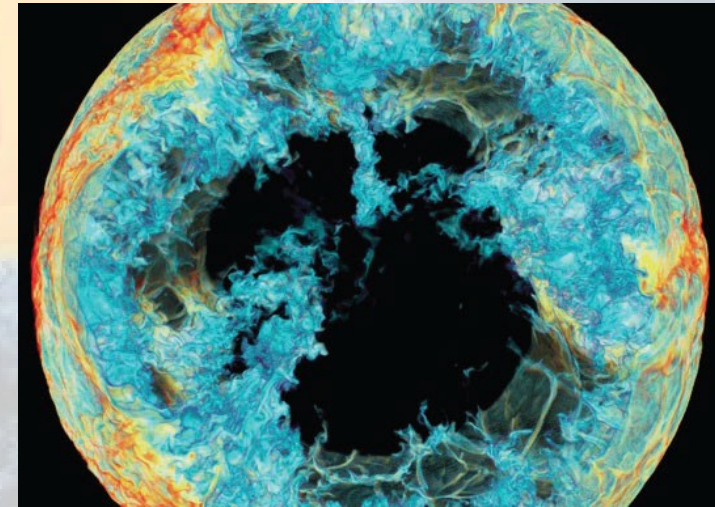
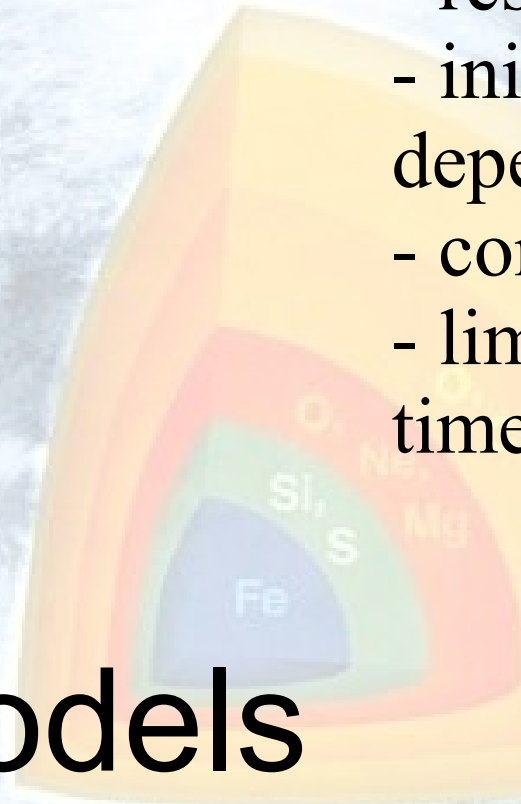
Advantages:

- 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 ($t_{\text{conv}} \sim 1\text{s} - \text{days}$)

3D stellar models



Herwig, Woodward et al 2013

What's missing?

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

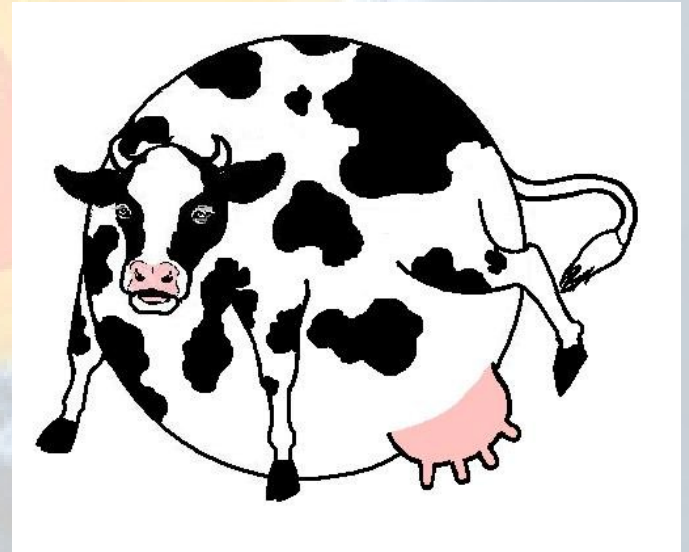
Advantages:

- model entire evolution ($\Delta t \sim 10^3$ yrs)
- compare to observations
- progenitor models
- large grids (M, Z)

Disadvantages:

- parametrized physics (e.g. convection)
- missing multi-D processes
- incapable of modelling turbulence

1D stellar models



What's missing?

- self-consistent physical descriptions of mass loss, **convection**, **rotation**, magnetic fields, opacity, binarity

Convection: Current Implementation in 1D Codes

Multi-D processes:

Major contributor to turbulent mixing

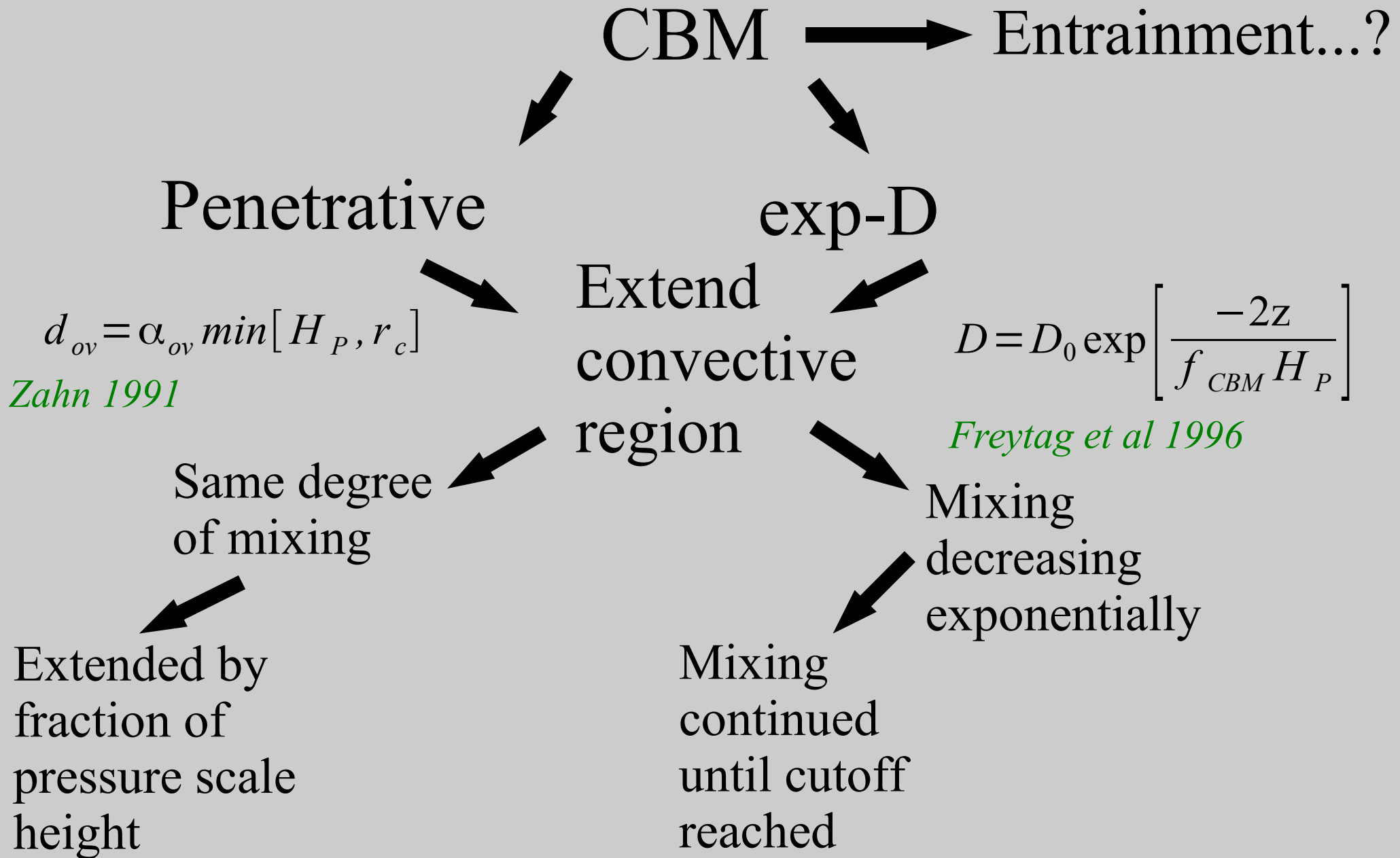
Turbulent entrainment at convective boundaries

Internal gravity waves

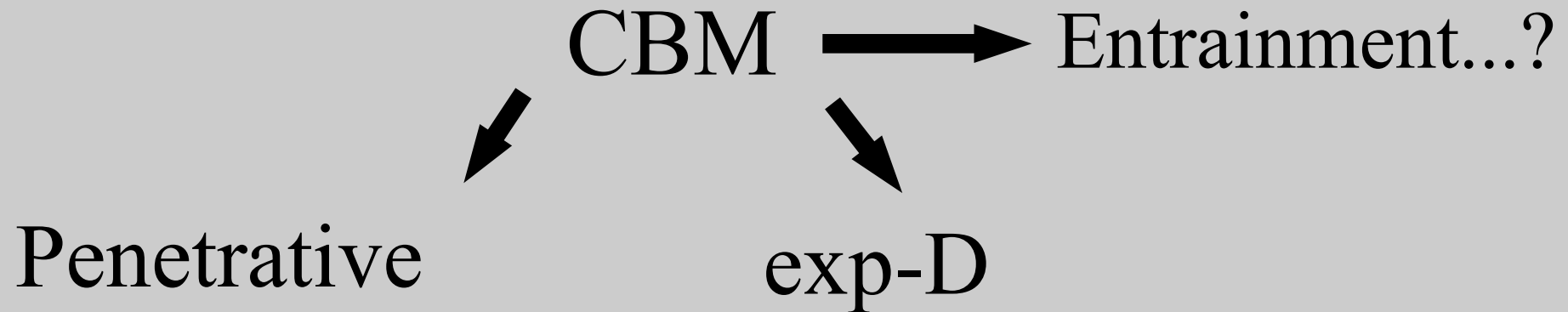
1D prescriptions:

- Energy transport in convective zone: **mixing length theory (MLT)** *Bohm-Vitense (1957,58)*, or updates, e.g. FST: *Canuto & Mazitelli (1991)*
- Boundary location: Schwarzschild criterion OR Ledoux (+semi-convection)
- Convective boundary mixing (CBM, also composition dependent)

Convective Boundary Mixing (CBM)



Convective Boundary Mixing (CBM)

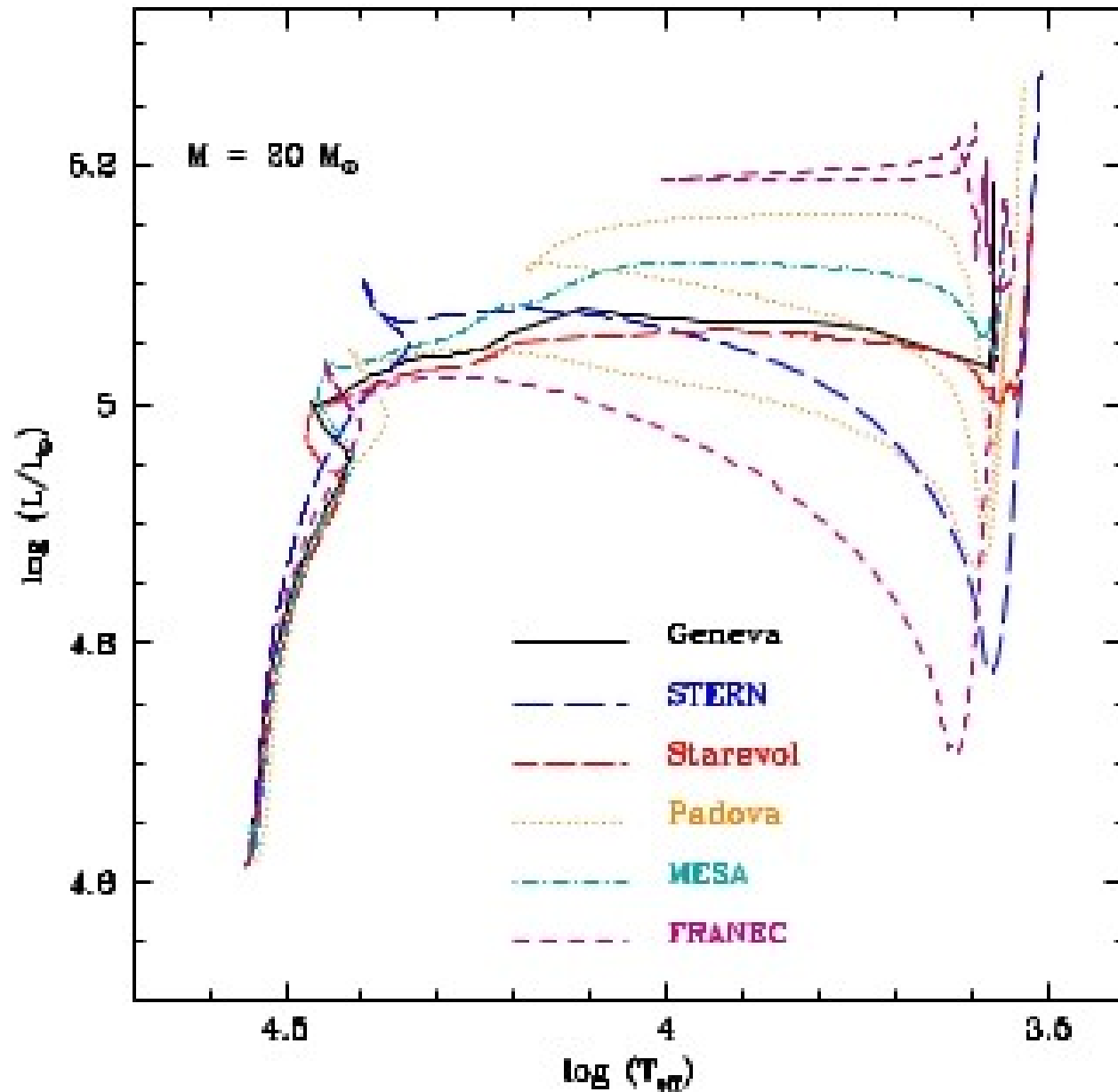


- Inspired by multi-D hydro simulations
- More simulations and **their interpretation in a theoretical framework** will help improve these prescriptions

Viallet, Meakin, Prat, Arnett 2015, Arnett et al 2015

1D Model Uncertainties

Martins and Palacios (2013)



Different prescriptions for convective mixing and free parameters **strongly affect** post-MS evolution.

See also Jones et al 2015, *MNRAS*, 447, 3115

1D Model Uncertainties: Complex Convective History

Detailed convective shell history affects fate of models: strong/weak/failed explosions!!!

Sukhbold & Woosley, 2014ApJ...783...10S

Sukhbold, Ertl et al, 2016ApJ...821...38S,

Ugliano et al 2012, Ertl et al 2015

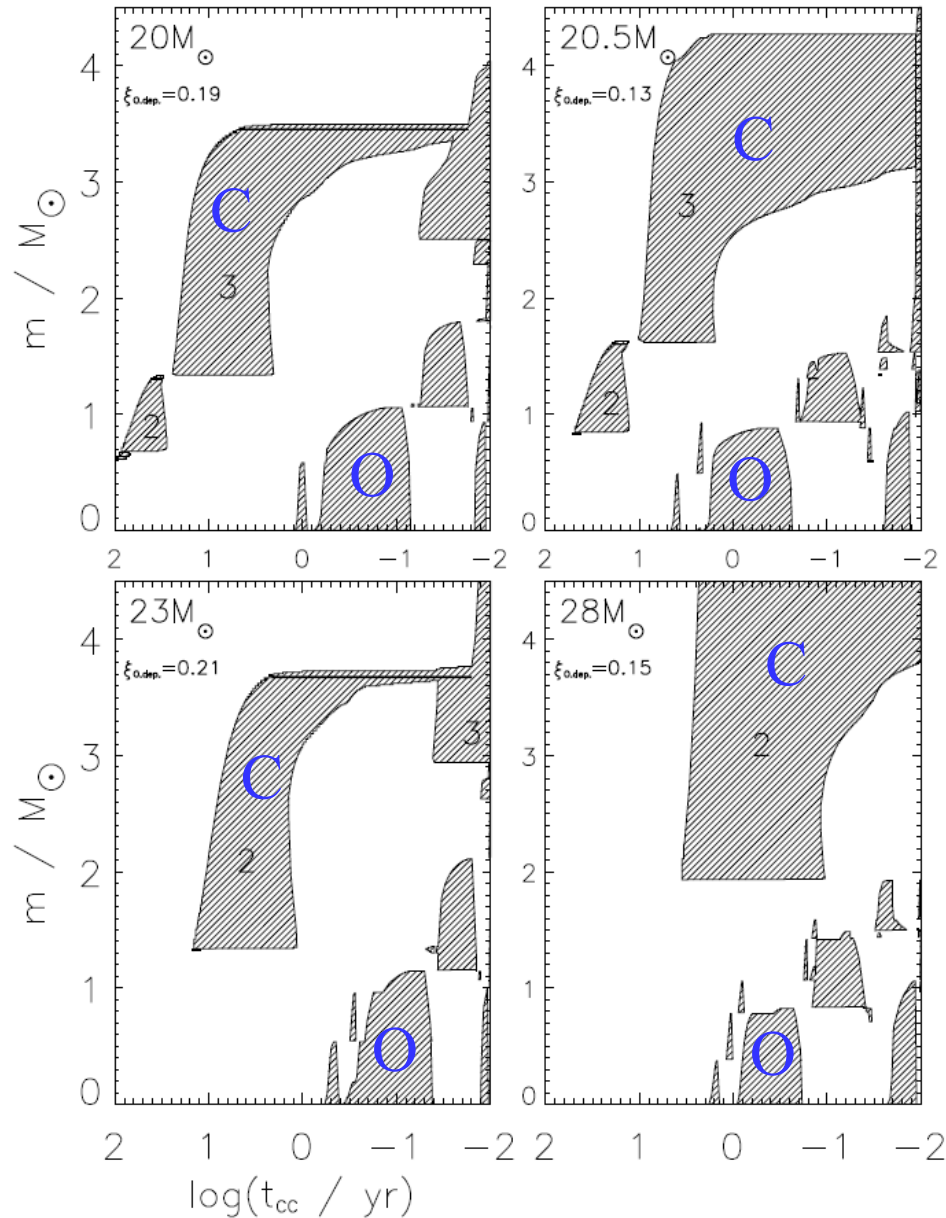


FIG. 13.— Convective history of four models showing the major

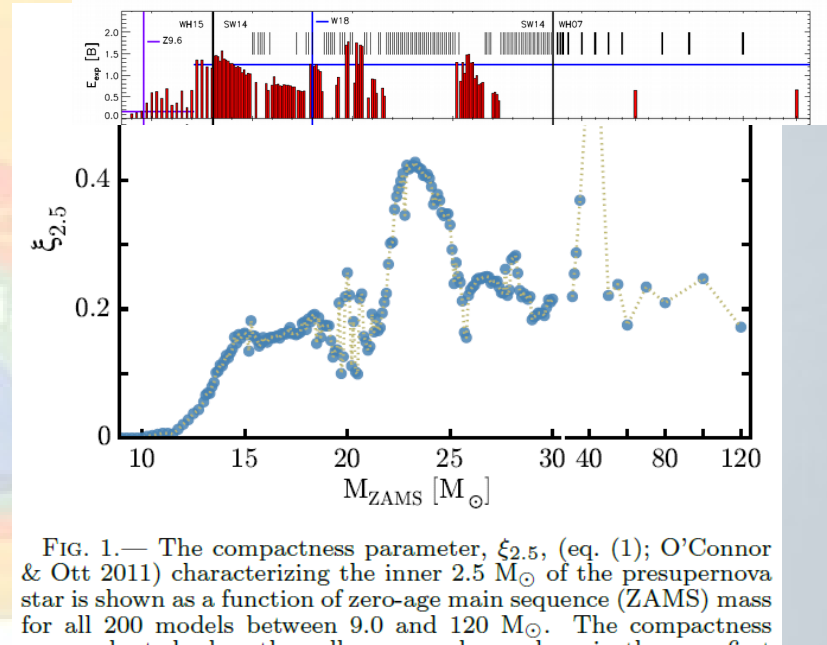


FIG. 1.— The compactness parameter, $\xi_{2.5}$, (eq. (1); O'Connor & Ott 2011) characterizing the inner 2.5 M_{\odot} of the presupernova star is shown as a function of zero-age main sequence (ZAMS) mass for all 200 models between 9.0 and 120 M_{\odot} . The compactness

Non-monotonic behaviour!

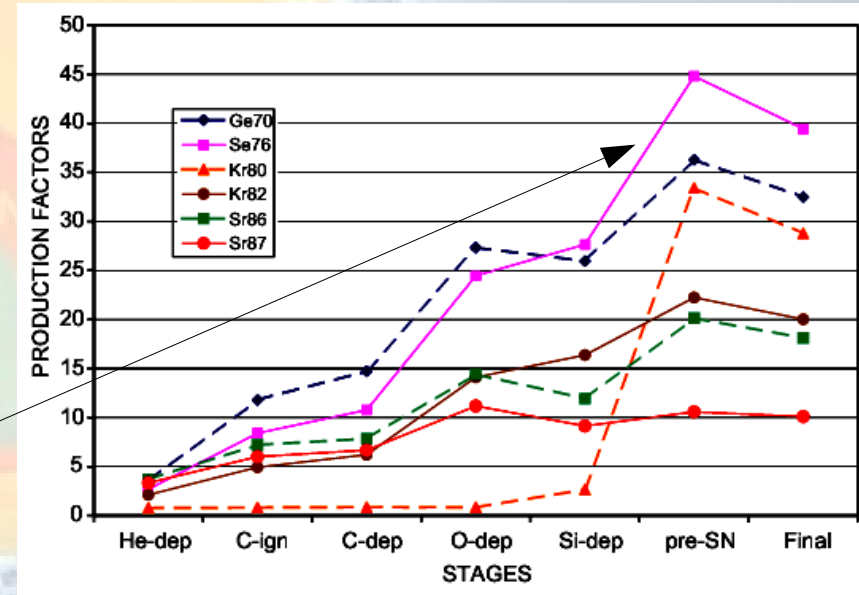
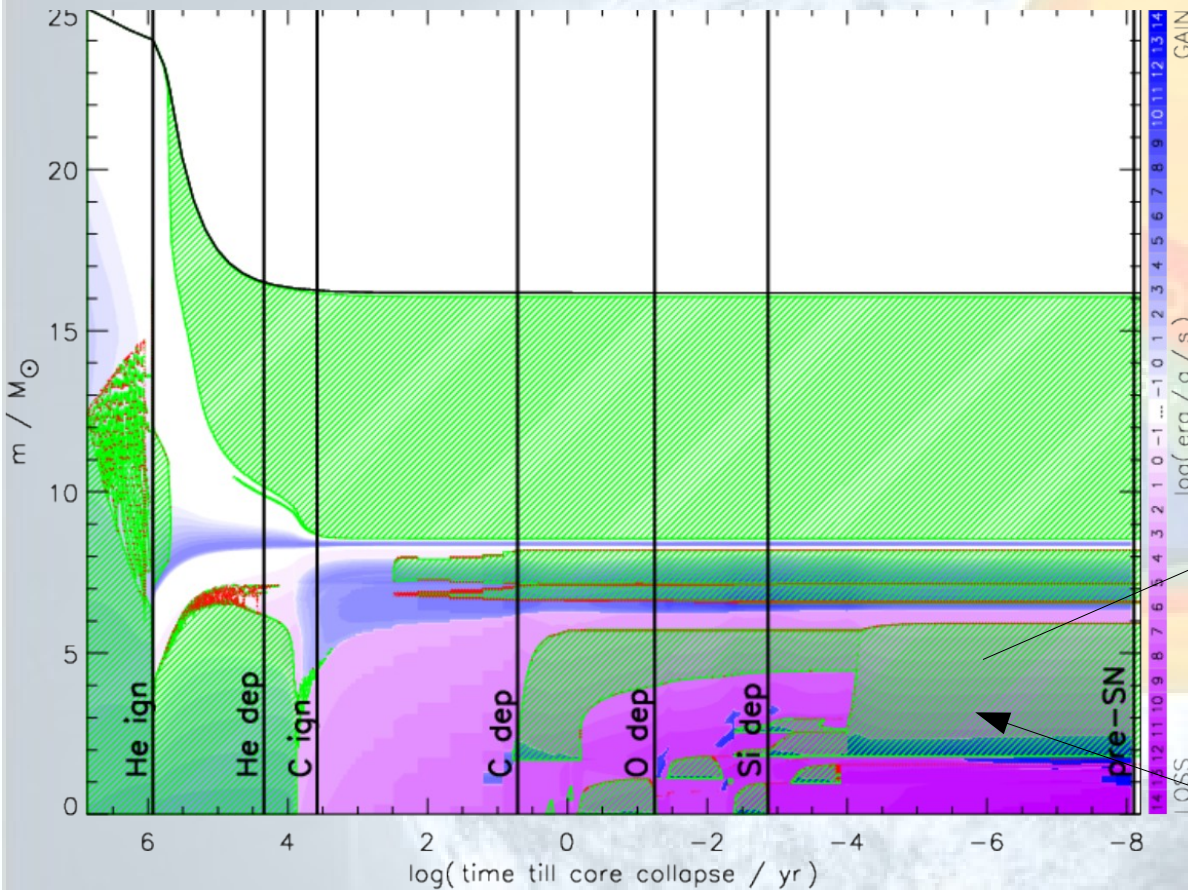
We are particularly interested in how the “explodability” of the presupernova models and their observable properties correlate with their “compactness” (Fig. 1; O'Connor & Ott 2011)

$$\xi_M = \frac{M/M_{\odot}}{R(M)/1000 \text{ km}} \Big|_{t_{\text{bounce}}}, \quad (1)$$

and other measures of presupernova core structure (§ 3.1.3; Ertl et al. (2015)). Using a standard central engine in presupernova models of variable compactness, a significant correlation in outcome is found (§ 4). As pre-

1D Model Uncertainties: Possible Shell Mergers

Tur, Heger et al 07/09/10



C/Ne/O shell mergers

Rauscher, Heger and Woosley 2002: "Interesting and unusual nucleosynthetic results are found for one particular 20M model as a result of its special stellar structure."

Shell mergers also affect compactness

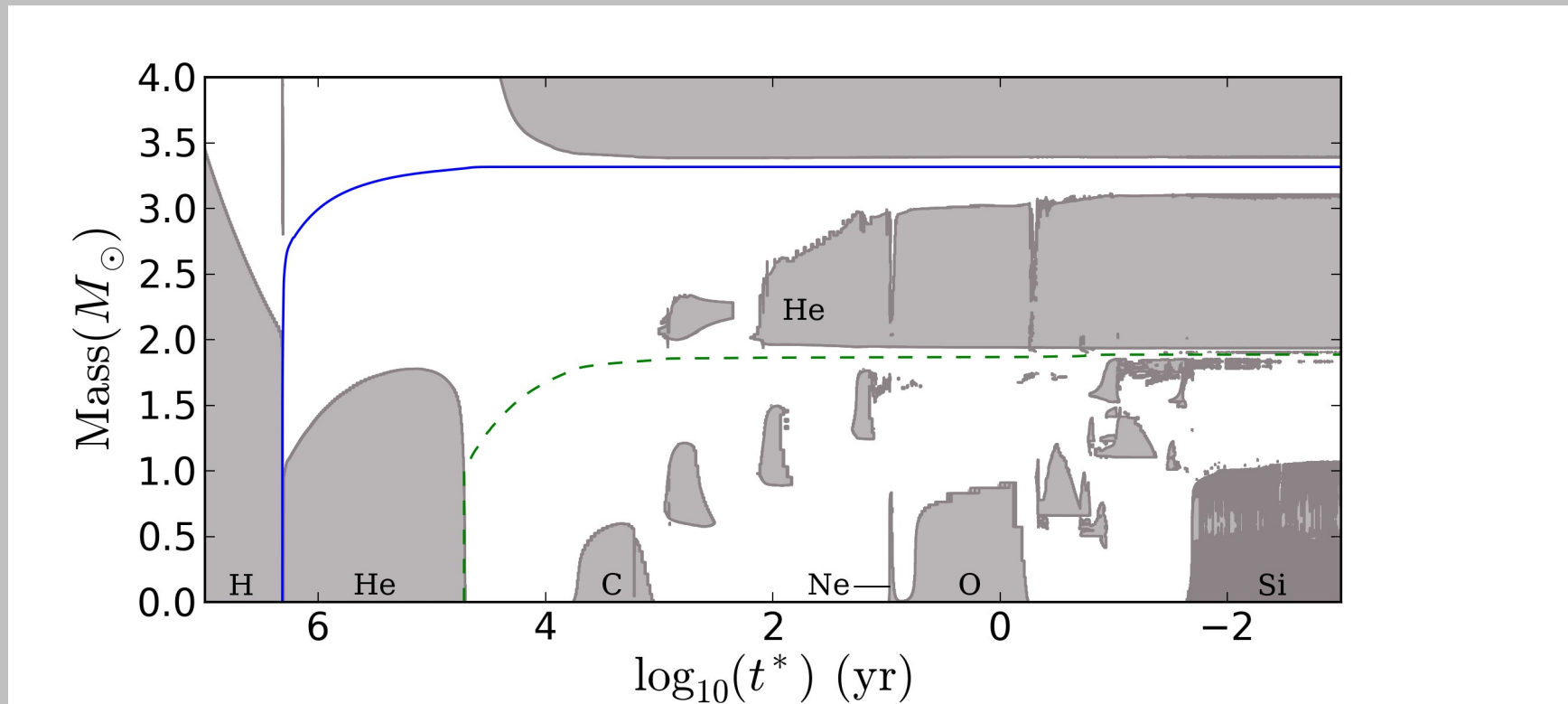
Convection physics uncertainties affect fate of models: strong/weak/failed explosions!!!

Fate of Least-Massive MS: EC SN/Fe-CCSN?

7-15 M_{\odot} models ← MESA stellar evolution code: <http://mesa.sourceforge.net/>

Paxton et al 10,12

12 M_{\odot} is a typical massive star:

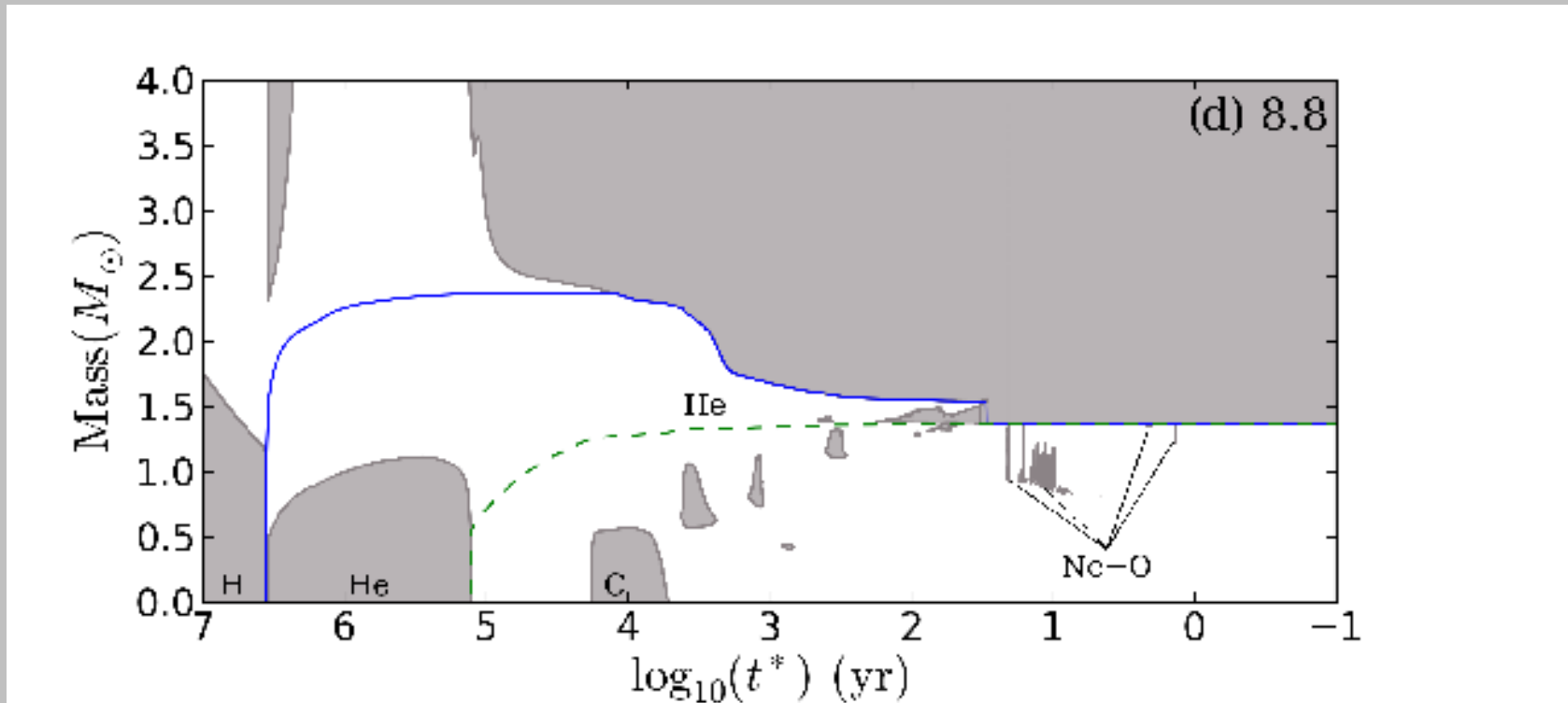


All burning stages ignited centrally. Fate: Fe-CCSN

Jones et al. (2013), ApJ 772, 150;
see also Mueller et al 12, Umeda et al 12, Takahashi et al 13

Fate of Least-Massive MS: ECSN/Fe-CCSN?

8.8 M_{\odot} failed massive star:



Ne-b. starts off-centre but does not reach the centre.
MESA \rightarrow Oxygen deflagration

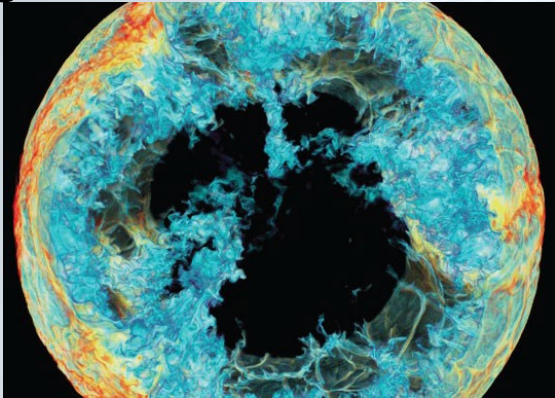
Jones et al. (2013), ApJ 772, 150
See also Nomoto 84: case 2.6
Timmes et al 92,94
Eldridge & Tout 04
Heger et al ...

Fate: ECSN!

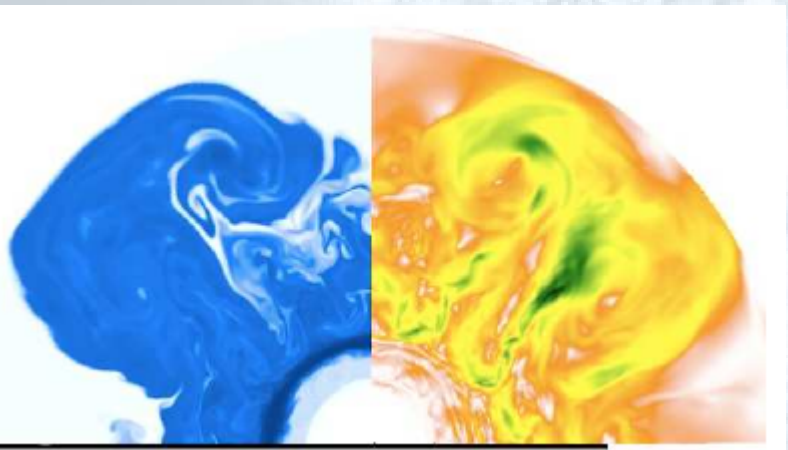
Key uncertainties: convective boundary mixing, mass loss

Way Forward: 1 to 3 to 1D link

Targetted 3D simulations

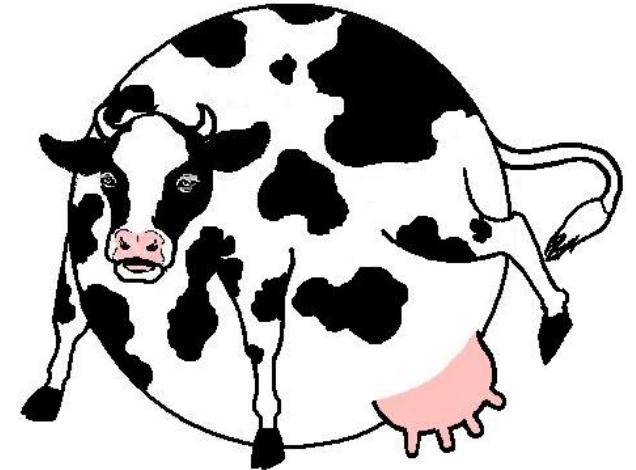


Herwig et al 06, Herwig, Woodward et al 2013

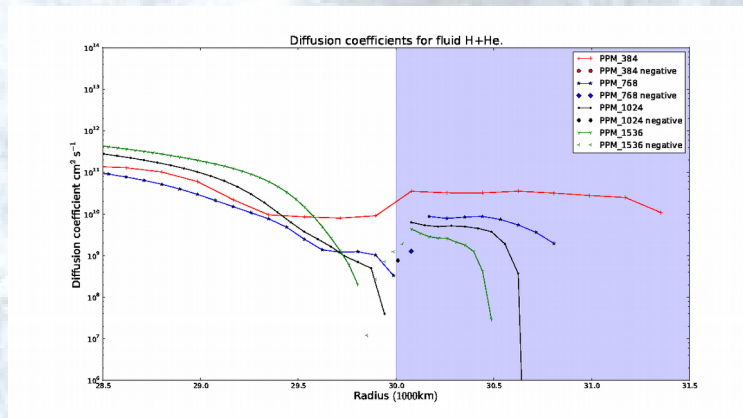


e.g. Arnett & Meakin 2011, ...
Mocak et al 2011,
Viallet et al 2013, ...

Uncertainties in 1D



+asteroseismology



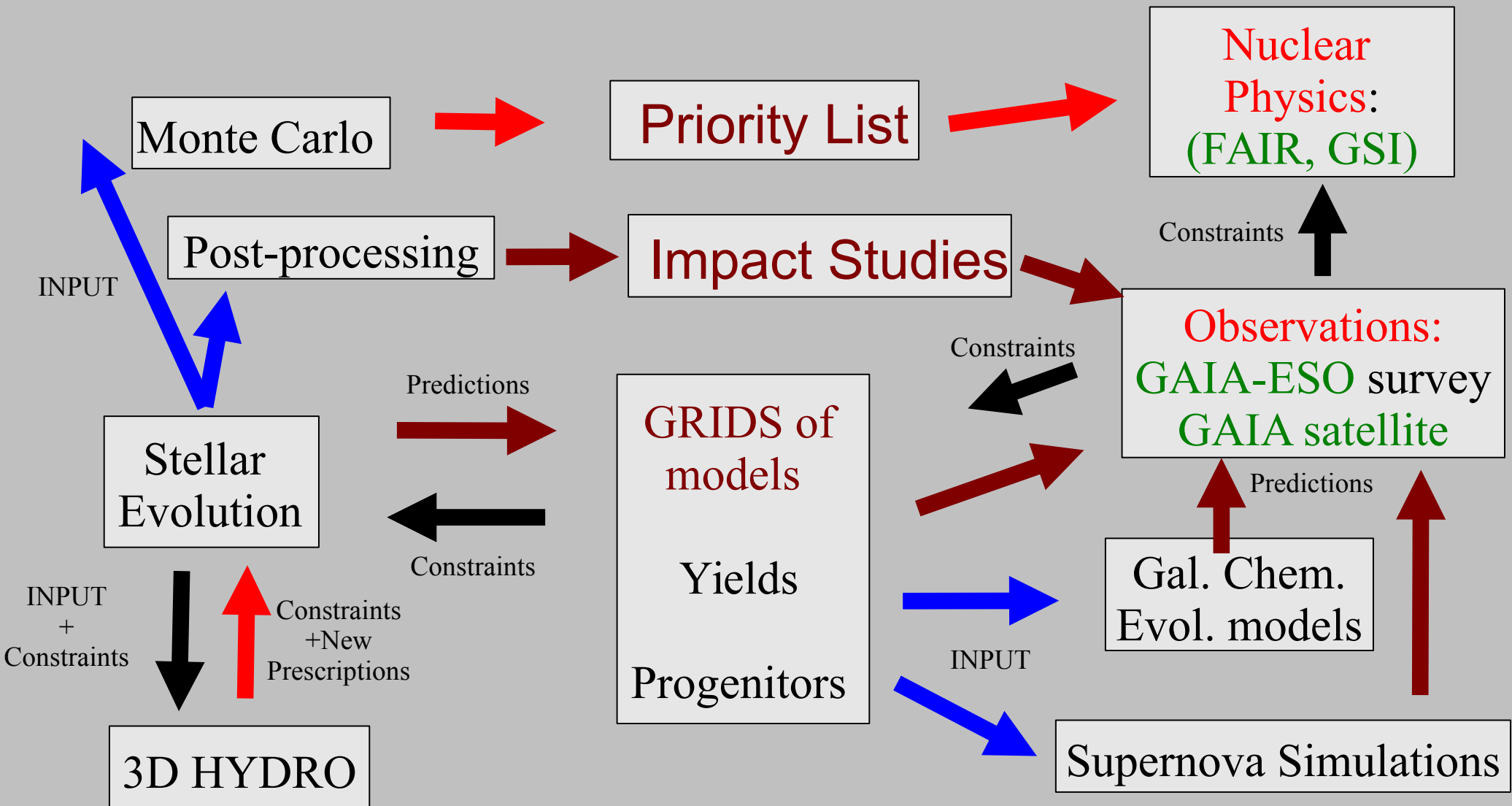
Meakin et al 09 ; Bennett et al (thesis), Jones et al 16

→ Determine effective coefficient / improve theoretical prescriptions

Stellar Hydrodynamics Nucleosynthesis & Evolution (SHYNE) Project

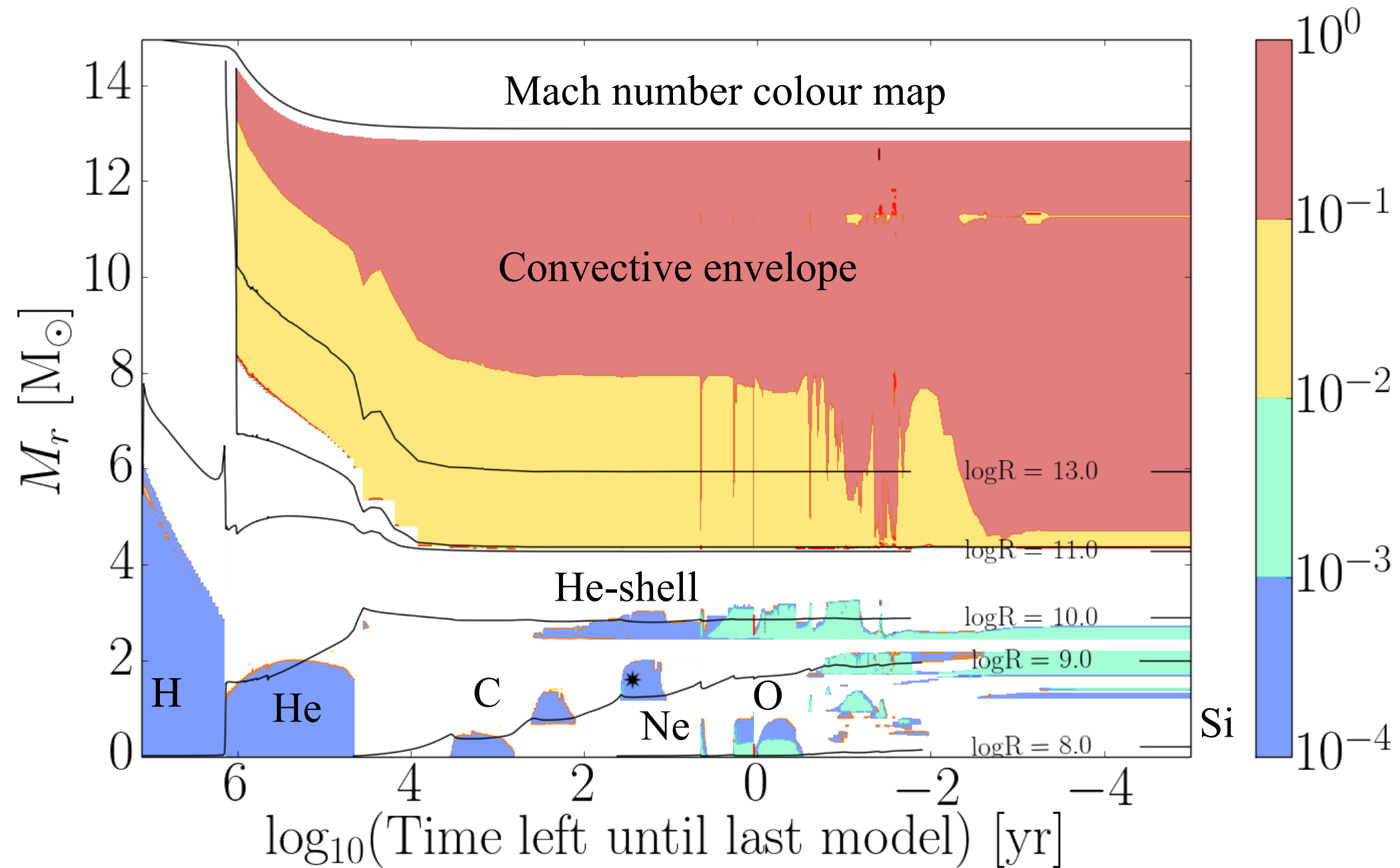
ERC Starting grant: 2012-2017

TOOL SUITE → DATASETS → IMPACT



• Efficient pipeline: nuclear/hydro/astro

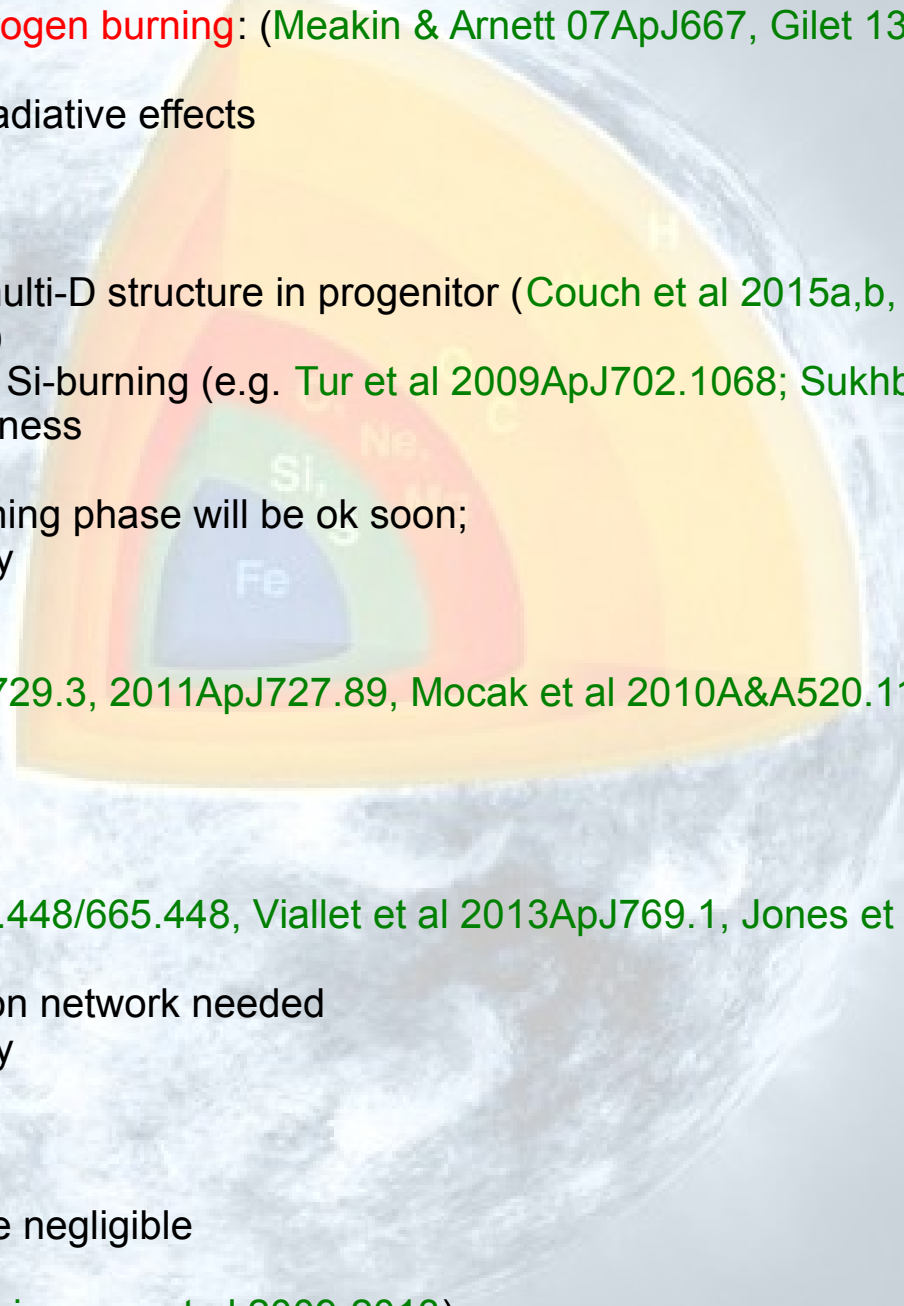
Where to Start?



Convection takes place during most burning stages

Priority List + Existing Efforts

- * **Convective boundary mixing during core hydrogen burning:** (Meakin & Arnett 07ApJ667, Gilet 13)
 - +: 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 et al 2015a,b, Mueller & Janka aph1409.4783, Mueller et al ArXiv1605.01393)
 - +: 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.
 - -: $\sim 10^9$ 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, Woodward et al 2015)
 - +: thermal/radiative effects not dominant
 - ?: applicable to other phases?
 -
- * **Oxygen shell:** (Meakin & Arnett 2007ApJ667.448/665.448, Viallet et al 2013ApJ769.1, Jones et al ArXiv1605.03766)
 - +: 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),
- * Solar-type stars (e.g. Magic et al. 2013A&A557.26, ...)
-



Approximations/Choices in 3D simulations

- Star in a box vs box in a star (+ geometry)

Global modes vs local resolution

- Treatment of radiation: envelope (crucial), H/He cores (needed), advanced phases (small to negligible)
- Nuclear reaction network: envelope (negligible), H/He cores (small), Si-burning (crucial)
- Initial conditions
- Shortcuts

Where to Start? Carbon burning shell

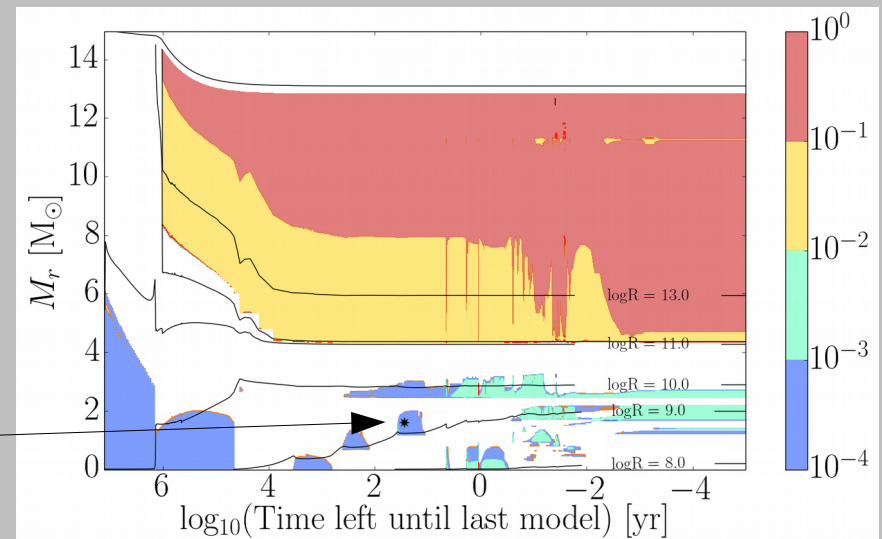
- “Simple” convective history before C-shell
- Cooling dominated by neutrinos: 1) radiative diffusion can be neglected, 2) “fast” timescale
- O-shell done before *Meakin & Arnett 2007-...*
- H/He burning lifetime much longer + *radiative effects*

important

- Si-burning: complex

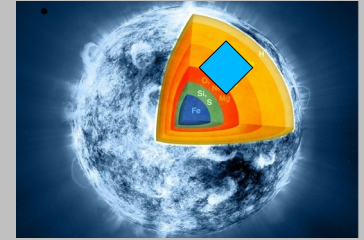
reaction network

C-shell



C-shell Setup & Approximations

- PROMPI code Meakin, Arnett et al 2007-...
- Initial conditions provided by stellar model from GENEC:
15M_☉, non-rotating at solar metallicity (see previous slide)
- “Box in a star” (plane-parallel) simulation using Cartesian co-ordinates
- Parameterised gravitational acceleration and ¹²C+¹²C energy generation rate
(energy rate boosted by a factor of 1000 for parameter study)
- Radiative diffusion neglected
- Turbulence initiated through random low-amplitude perturbations in temperature and density
- Constant abundance of ¹²C fuel over simulation time
- 4 resolutions: lrez: 128³, mrez: 256³, hrez: 512³, vhrez: 1024³

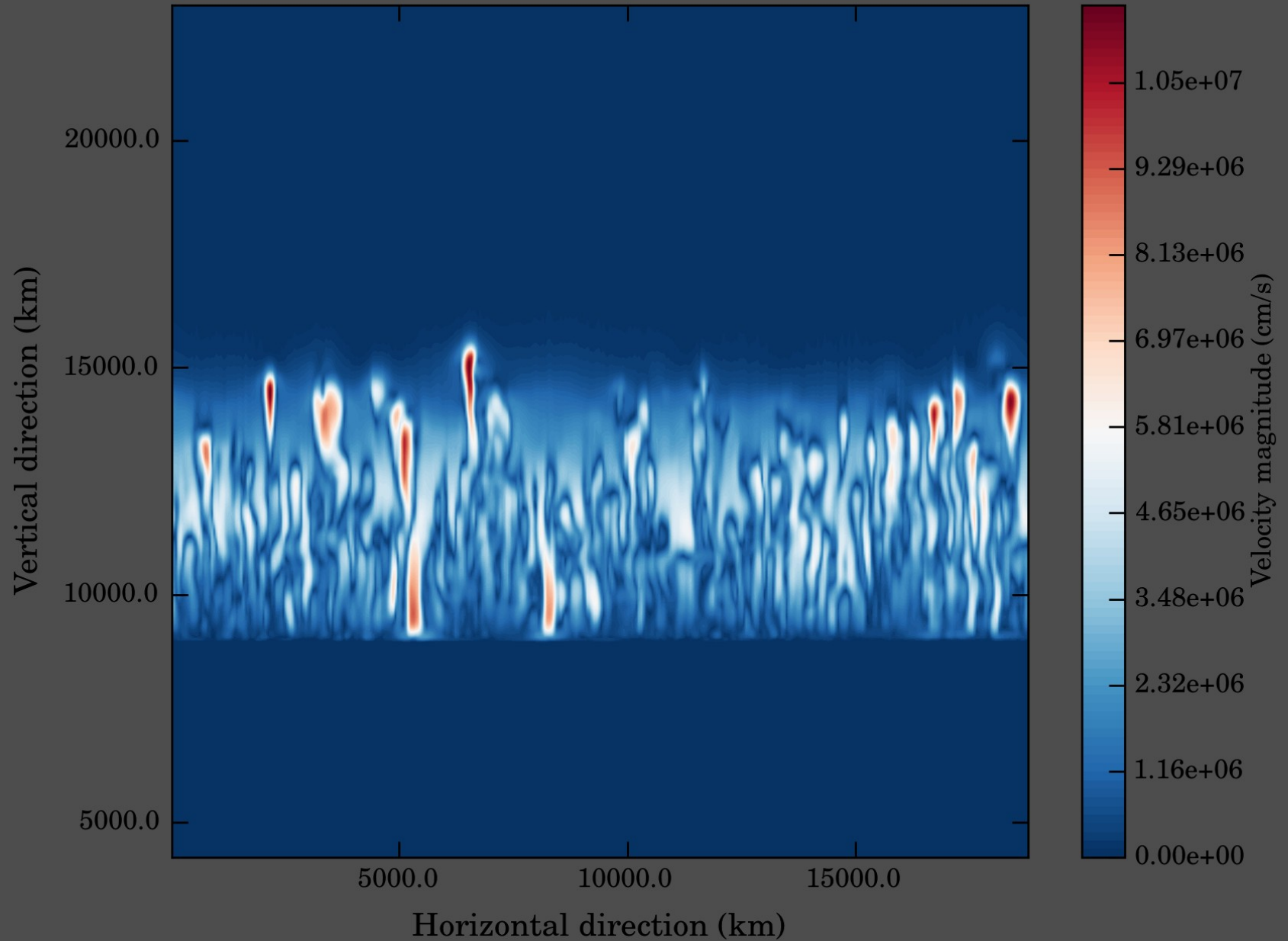


C-shell Simulations

384³ res.

Gas Velocity: $\|v\|$, $t = 300.1$ s (dump 31)

run

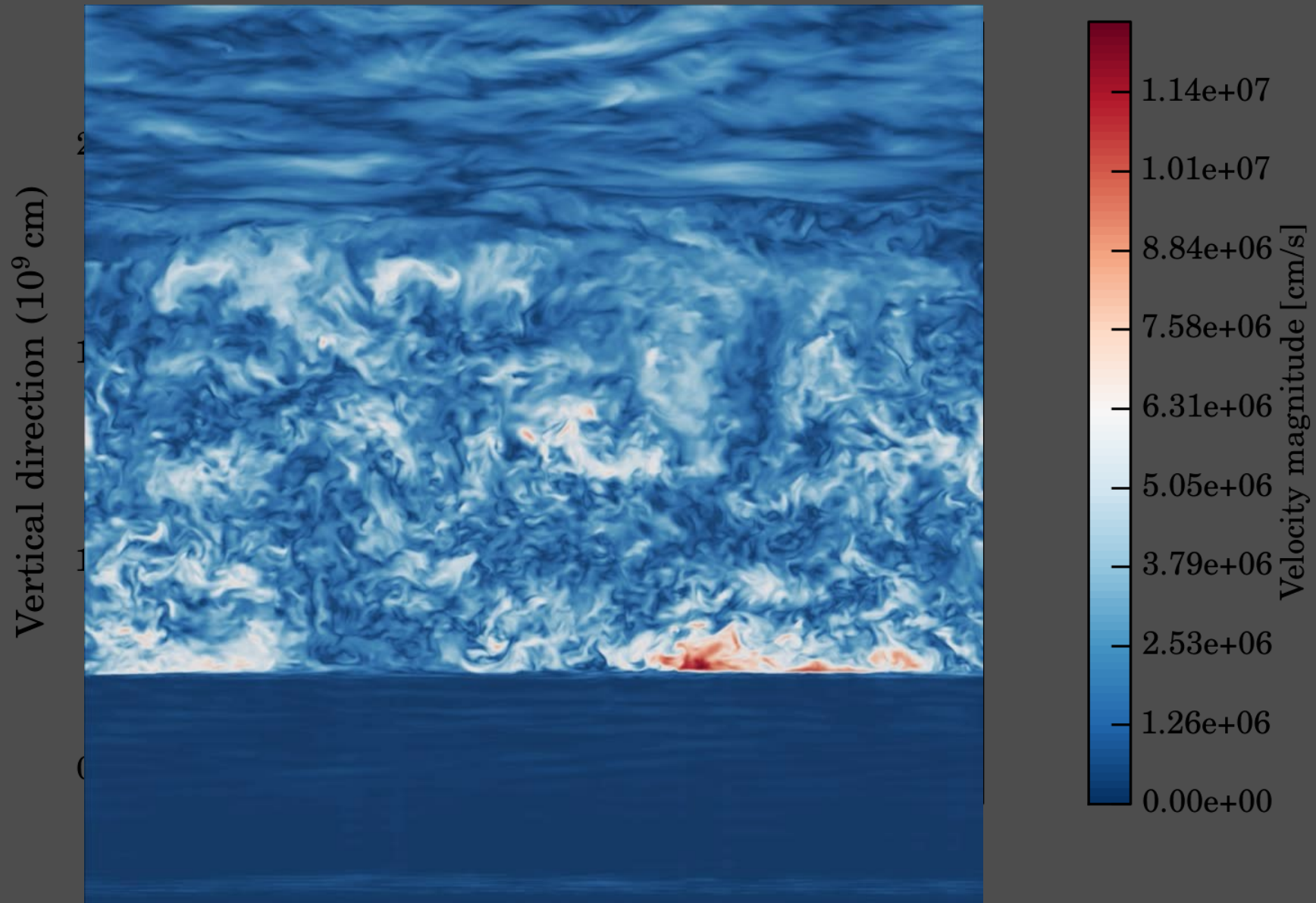


Cristini et al
in 2017

C-shell Simulations: $|v|$ movie

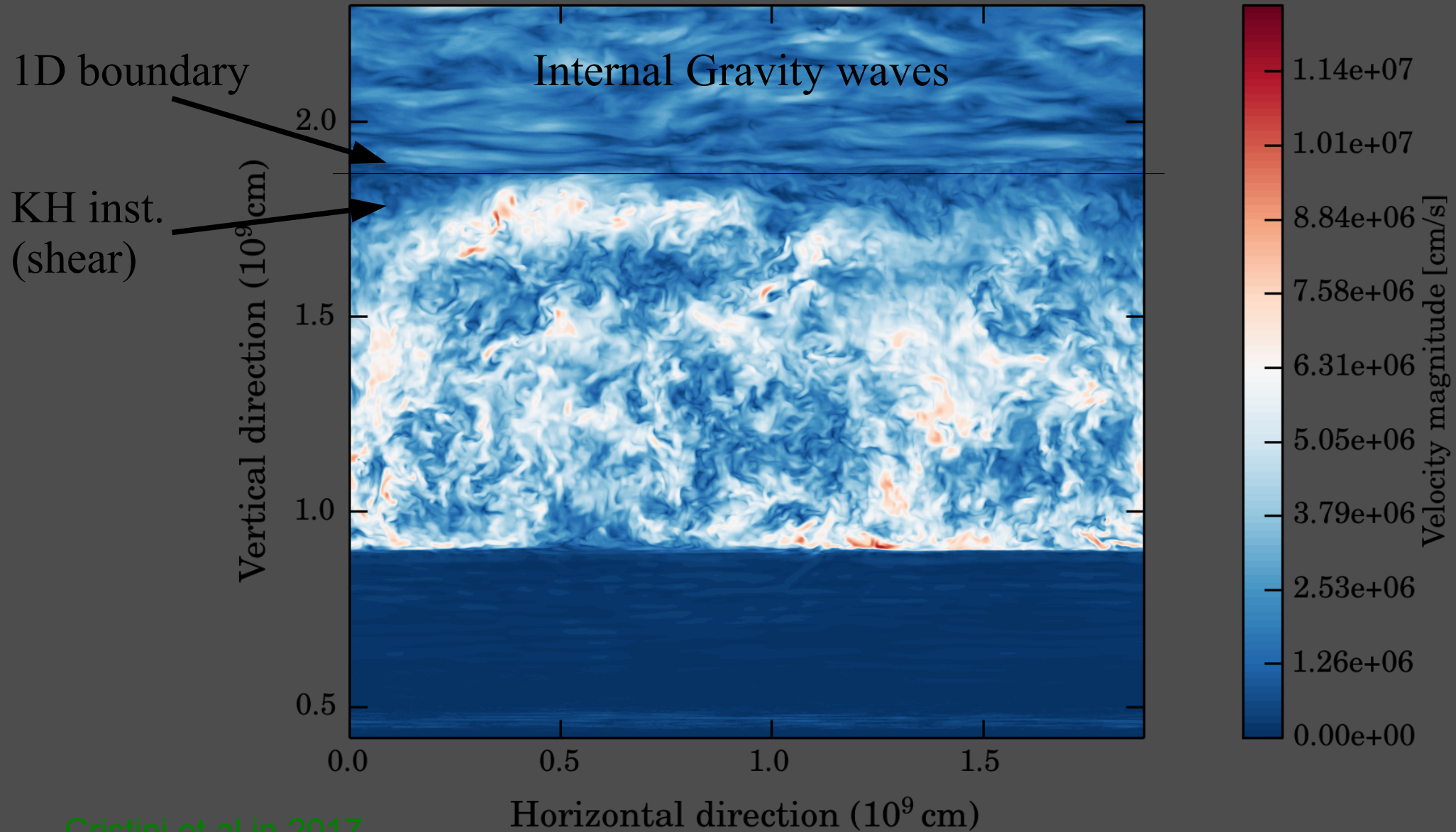
Cristini et al in 2017

Gas Velocity $\|v\|$



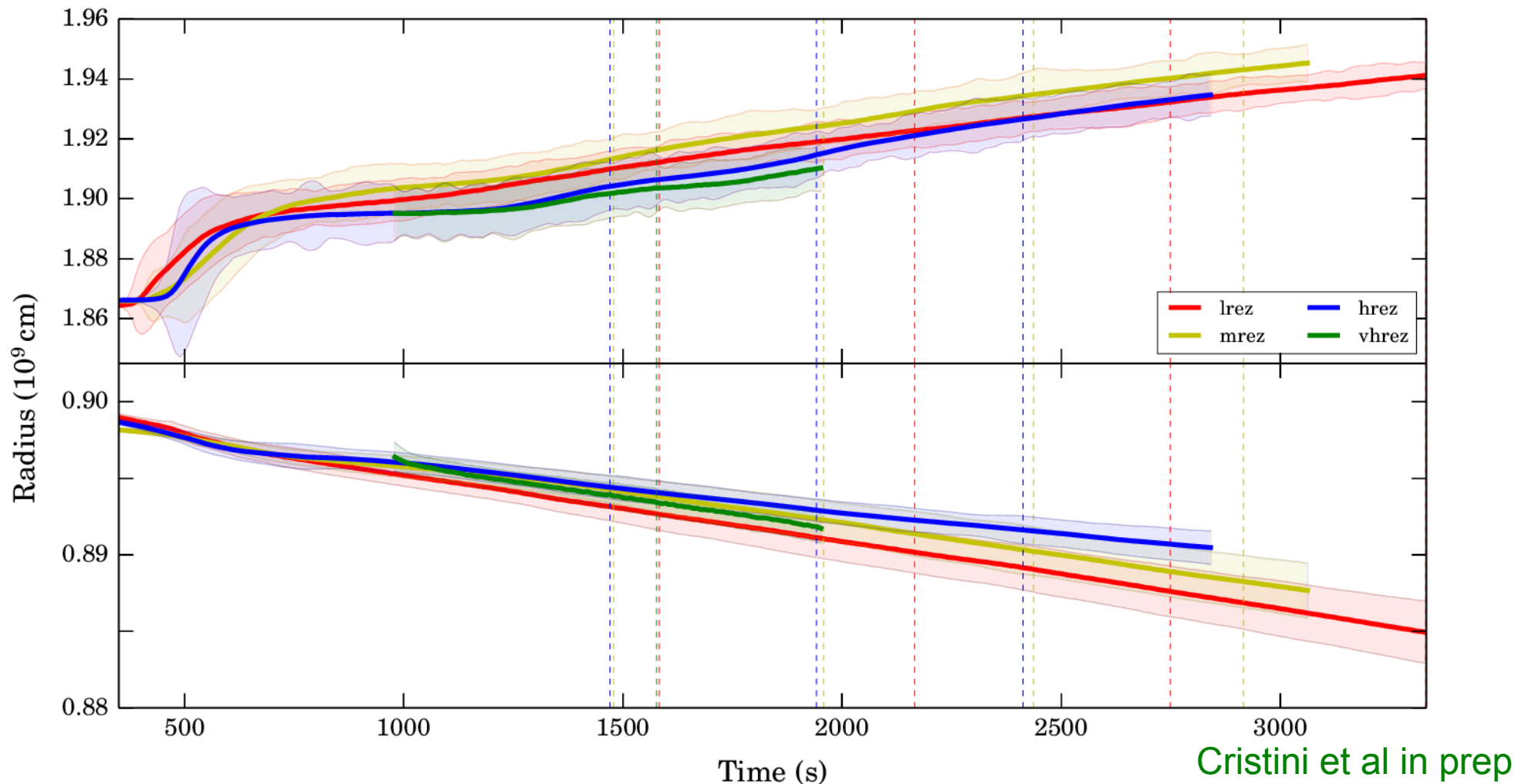
C-shell Simulations

Snapshot from 1024^3 resolution run: Gas Velocity $\|\mathbf{v}\|$



Cristini et al in 2017

Boundary Entrainment



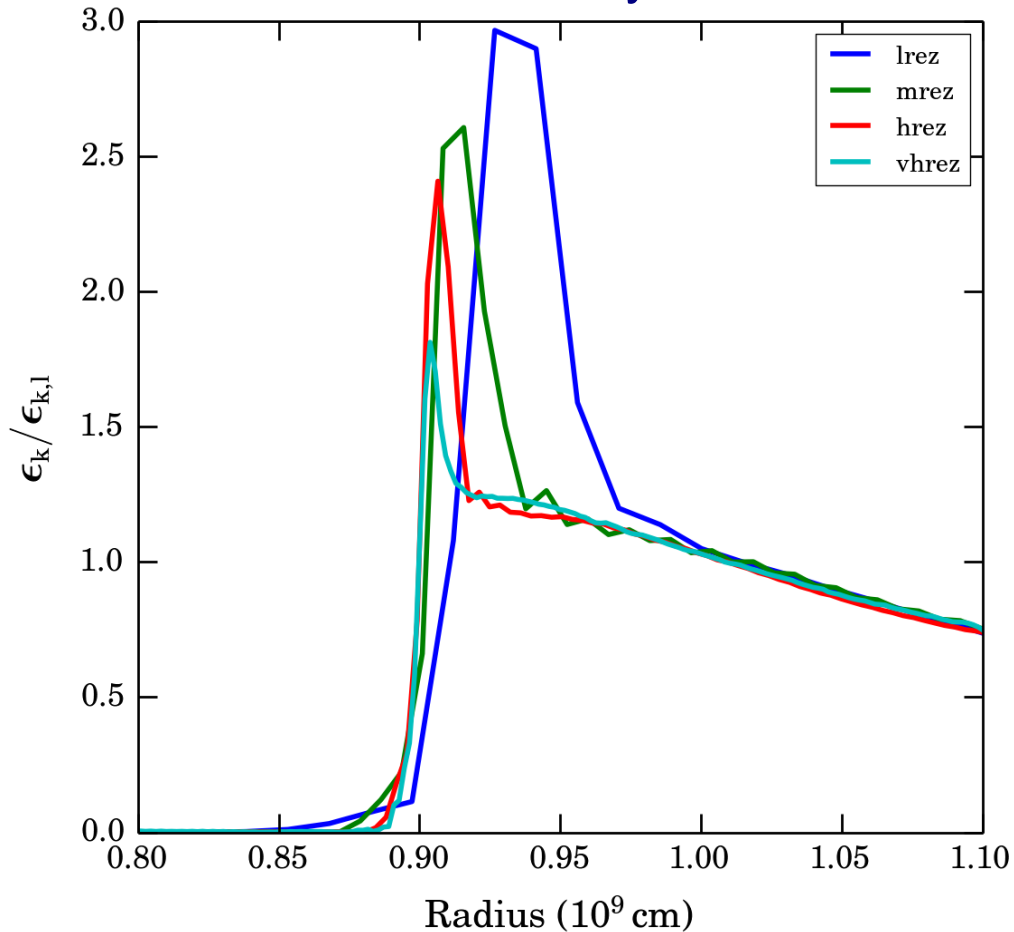
Top: $u_e \sim 20,000$ cm/s; Bottom: $u_e \sim 3,000$ cm/s. *Rescaled for ϵ_{burn} boosting (1/1000)*
→ In 1 year, top: $\Delta R \sim 6 \times 10^8$ cm, bottom: $\Delta R \sim 10^8$ cm: large but reasonable

Consistent with oxygen-shell results and entrainment law.

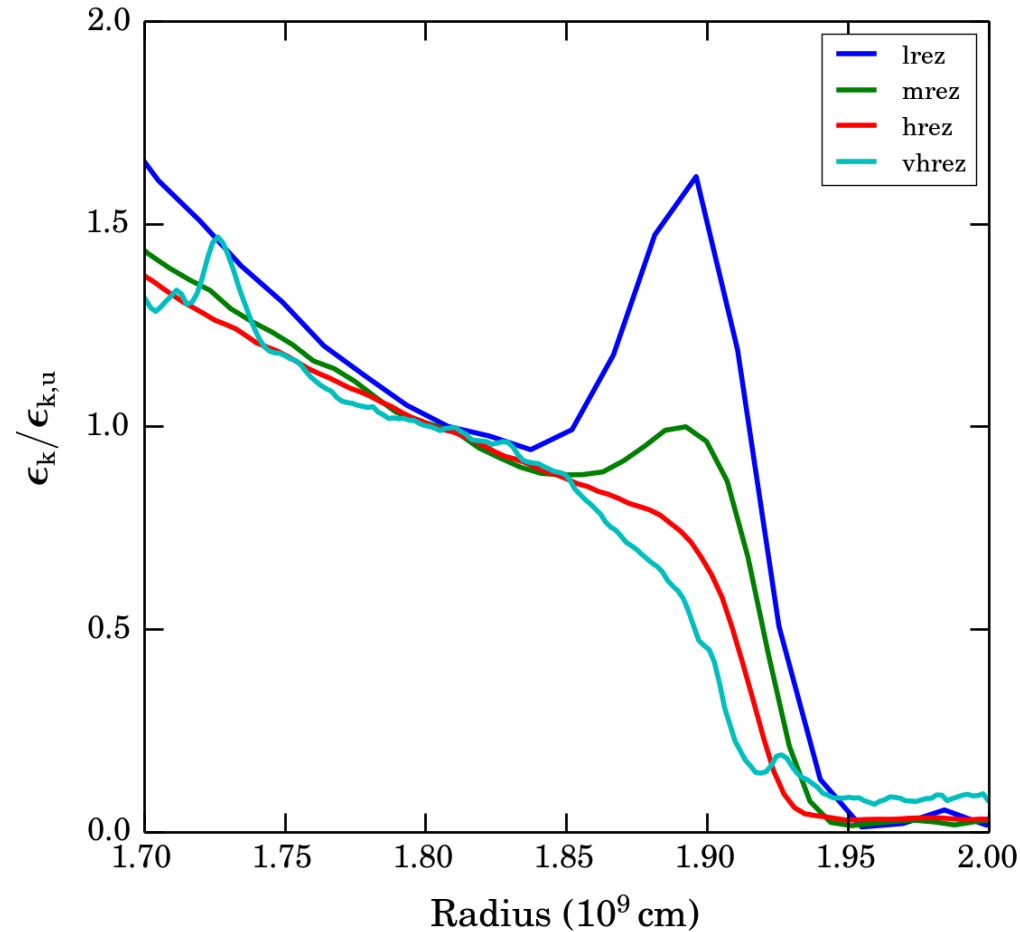
RANS Analysis: Reaching Convergence?

Turbulent kinetic energy residual dissipation, ϵ_k (Viallet et al 2013)

Bottom boundary



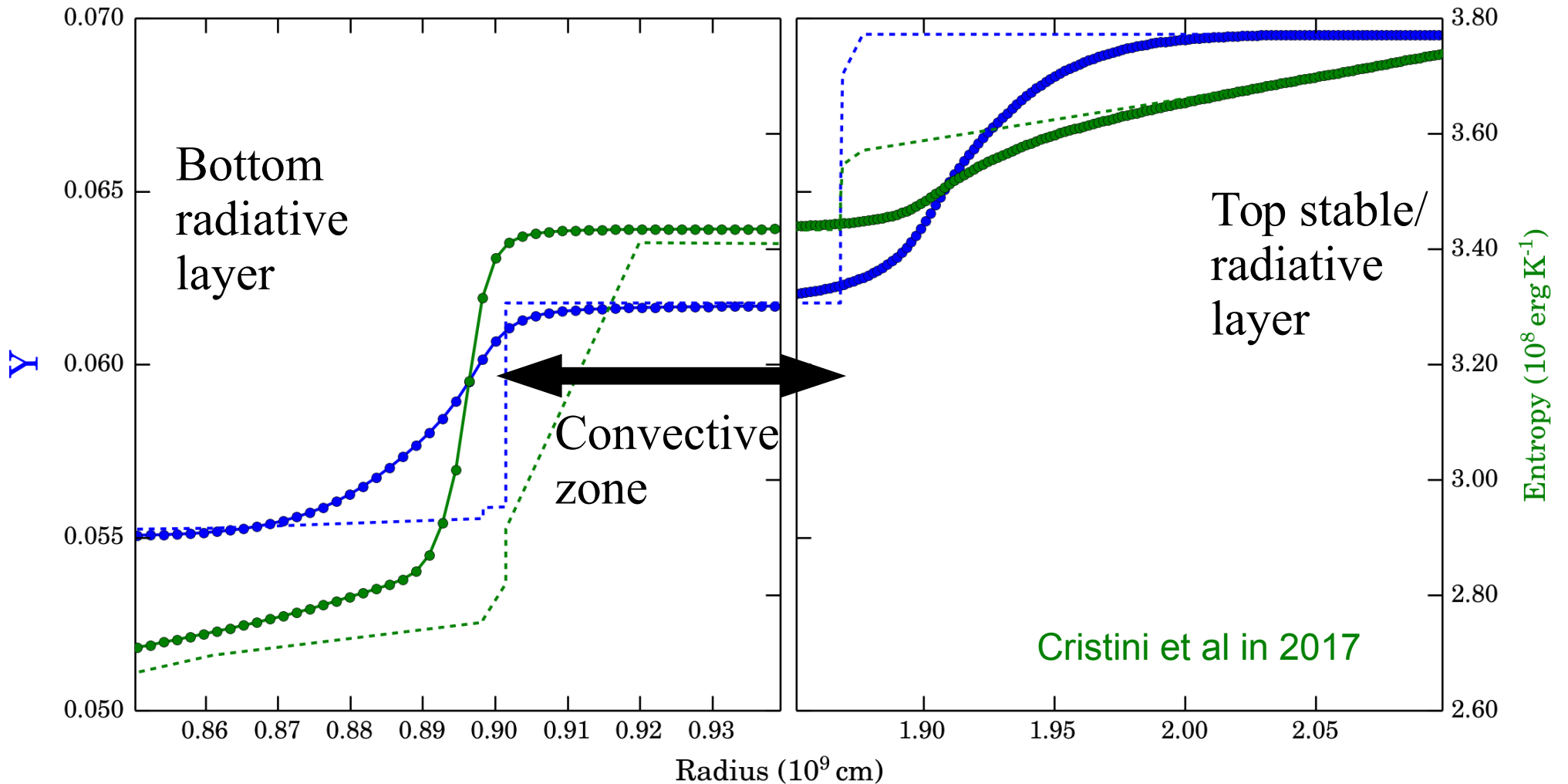
Top boundary



Cristini et al in prep

Top boundary resolved, bottom almost resolved!

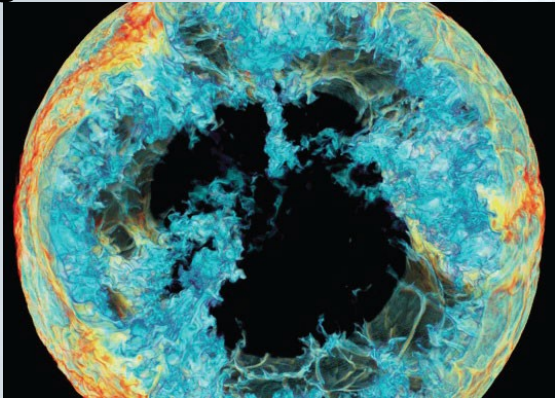
3D versus 1D



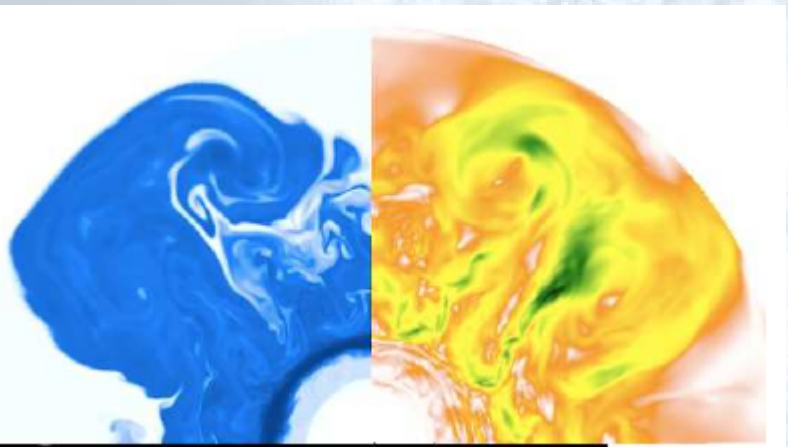
- Improved prescriptions for CBM needed!

Way Forward: 1 to 3 to 1D link

Targetted 3D simulations

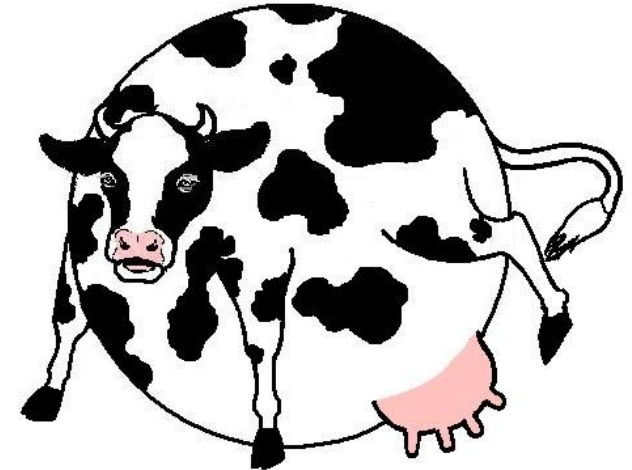


Herwig et al 06, Herwig, Woodward et al 2013

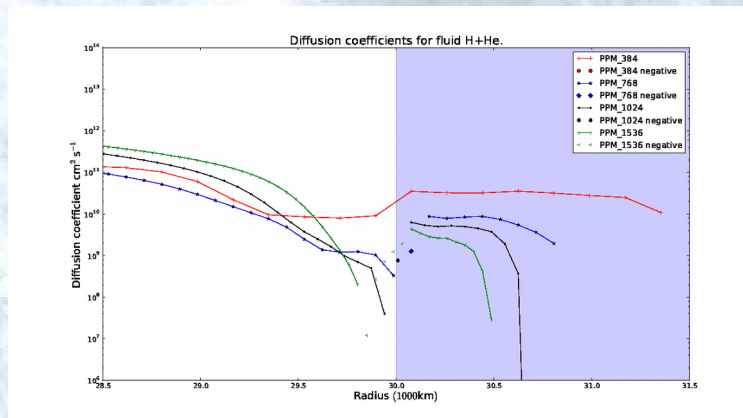


e.g. Arnett & Meakin 2011, ...
Mocak et al 2011,
Viallet et al 2013, ...

Uncertainties in 1D



+asteroseismology



Meakin et al 09 ; Bennett et al (thesis), Jones et al 16

→ Determine effective coefficient / improve theoretical prescriptions

321D – MLT Replacement + New CBM Prescriptions

Long term: MLT-replacement theory (Arnett et al 2015), RANS implementation (Mocak et al 2015), Arnett et al 2016

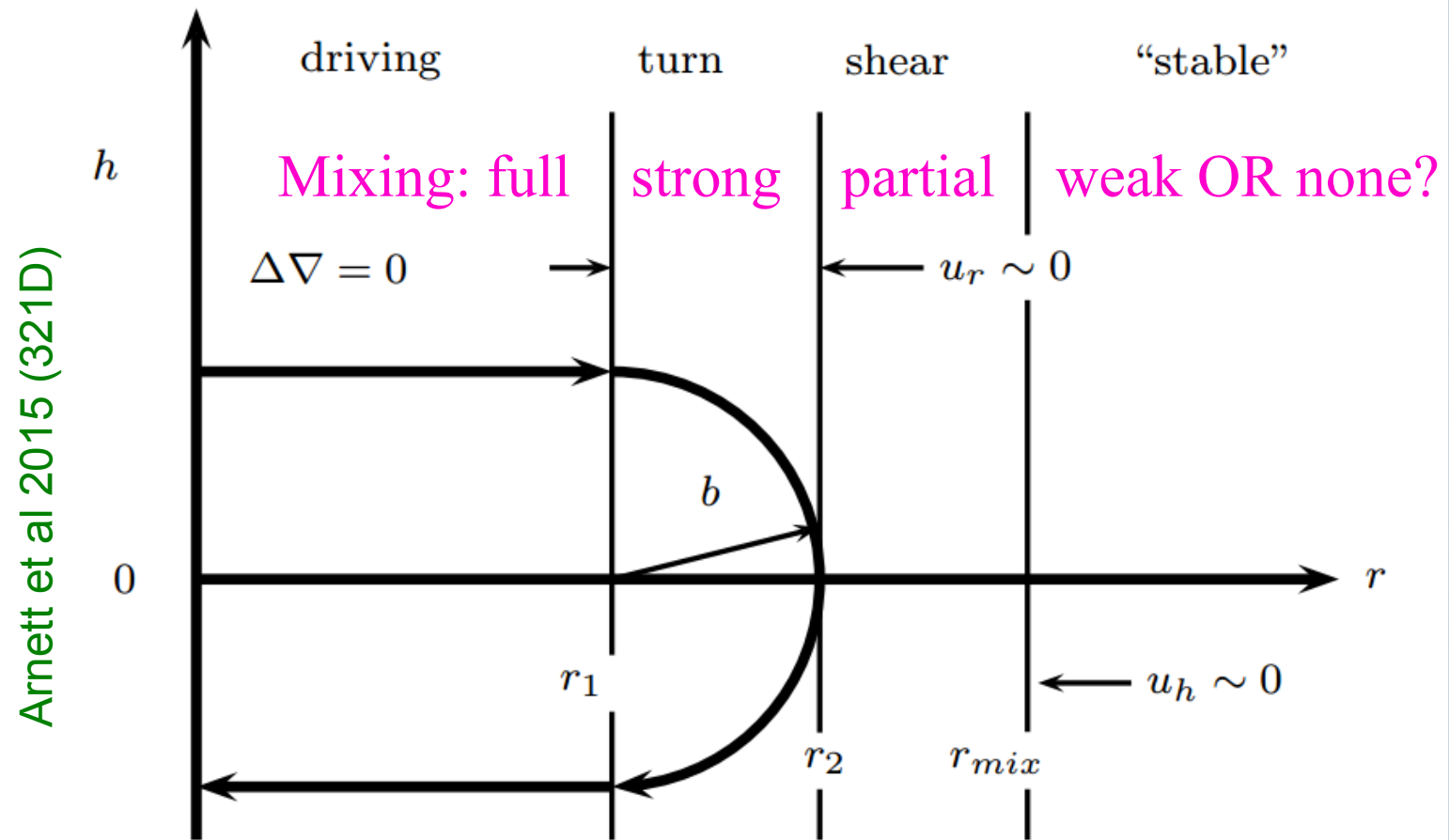
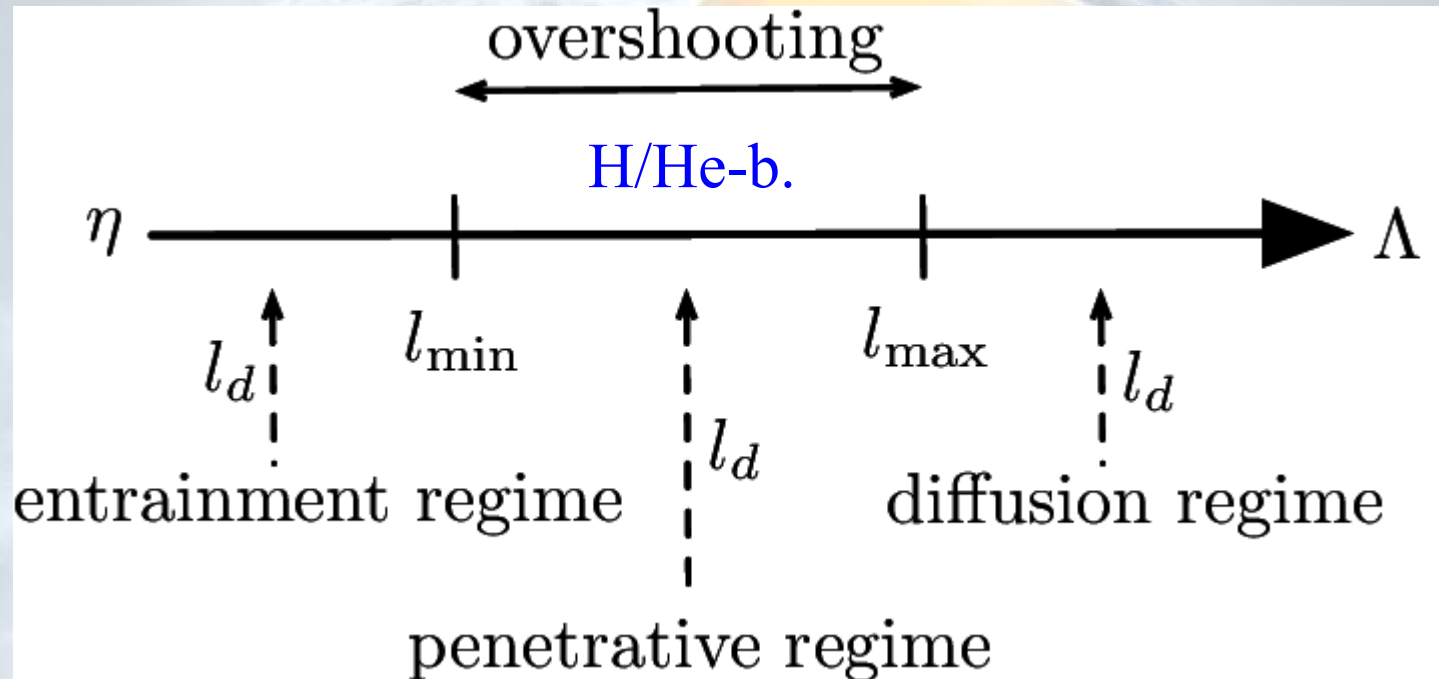


Figure 5. Simplified schematic of a convective boundary. The length b corresponds to the radius of curvature needed to reverse (contain) the flow ($u_r \rightarrow -u_r$). The centrifugal acceleration is provided by pressure fluctuations (see text). The boundaries oscillate due to surface waves. The radial direction is denoted by r and the transverse by h . Orientation is for the top of a convection zone; the bottom may be described by appropriate reversals.

Importance of Thermal Effects

Viallet et al 2015



Advanced phases:
O/Si-b.

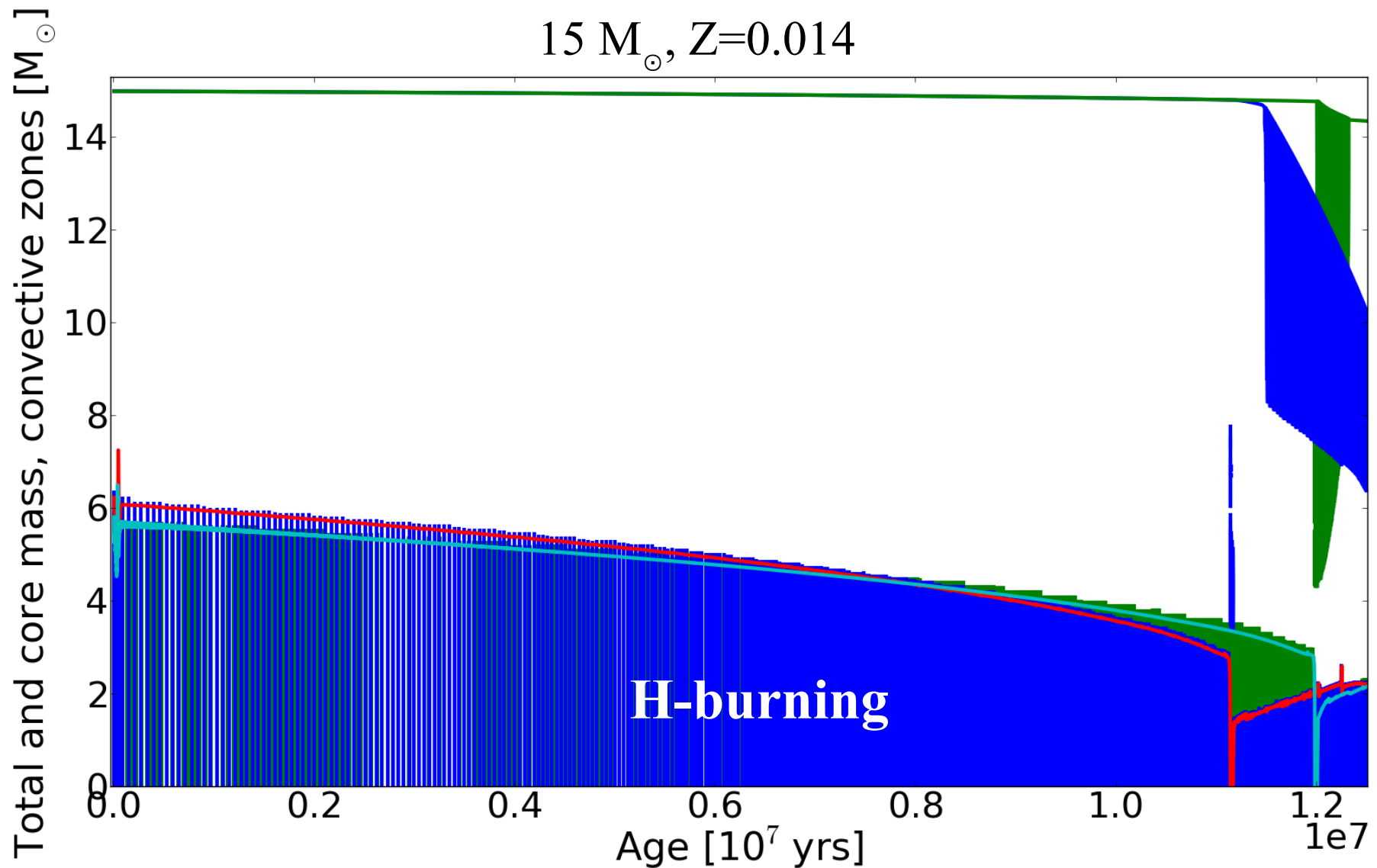
Stellar surface

Thermal effects determine which prescription/implementation to adopt:

Penetrative vs exp-D vs Entrainment CBM?

Back to 1D

Penetrative vs *exp-D* CBM: prescription choice affects results

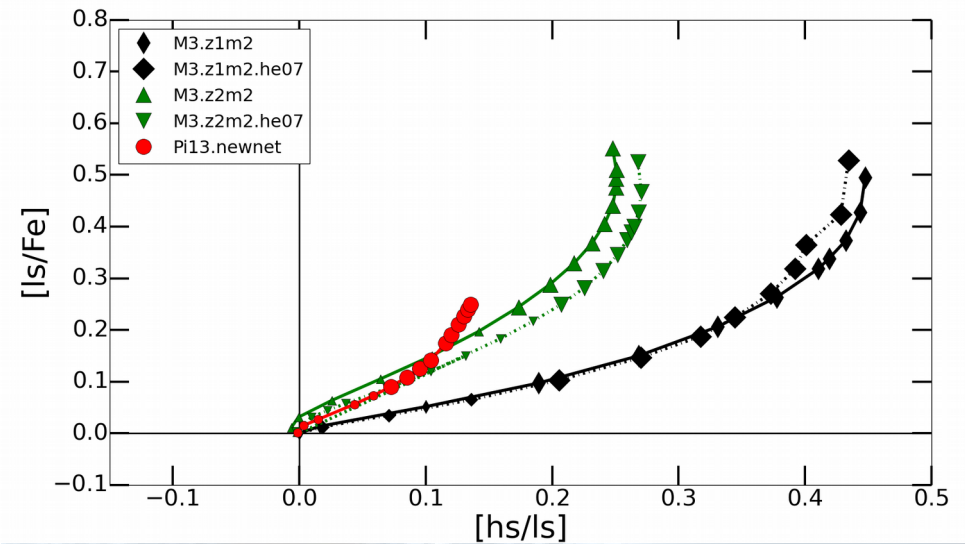
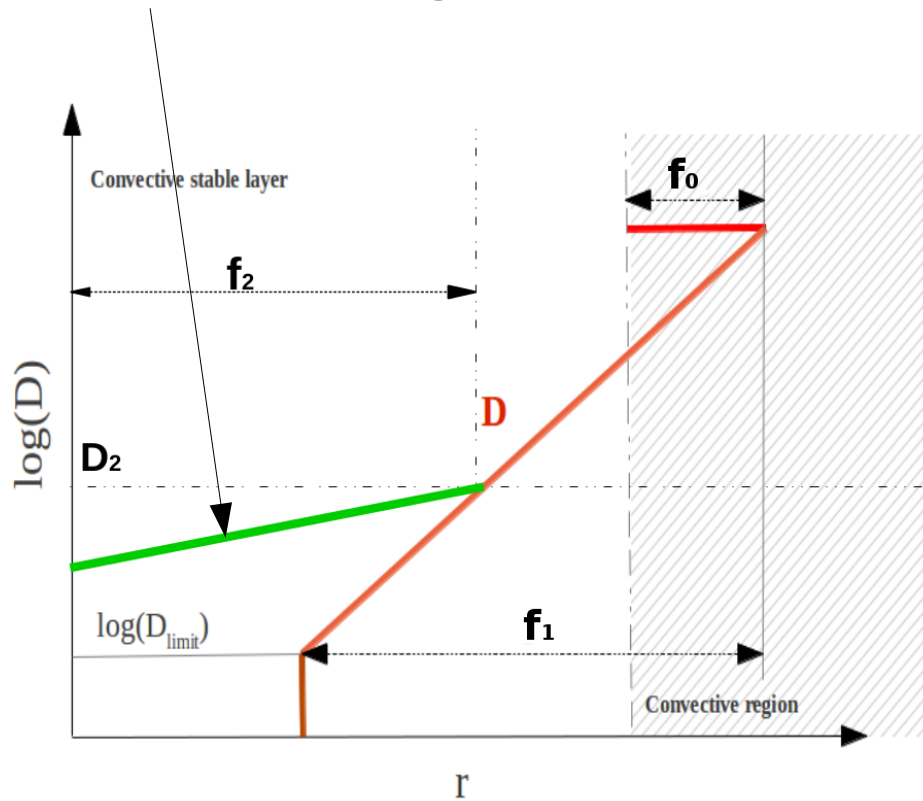


Back to 1D: CBM in AGB Stars (NuGrid project)

Internal gravity wave (IGW) driven mixing

Battino, ..., Hirschi et al ApJ 2016

2-3 M_{\odot} , $Z=0.01-0.02$



1) CBM (first f) plays a key role both for the C13 pocket via CBM below CE (needed for TDU) and for the c12 & o16 abundances in the intershell via CBM below TPs

2) IGW (second f) plays a key role for the C13 pocket (not so much for mixing below the Tps)

Study of the effects of rotation and B-field underway (den Hartogh, Hirschi, Herwig et al in prep)

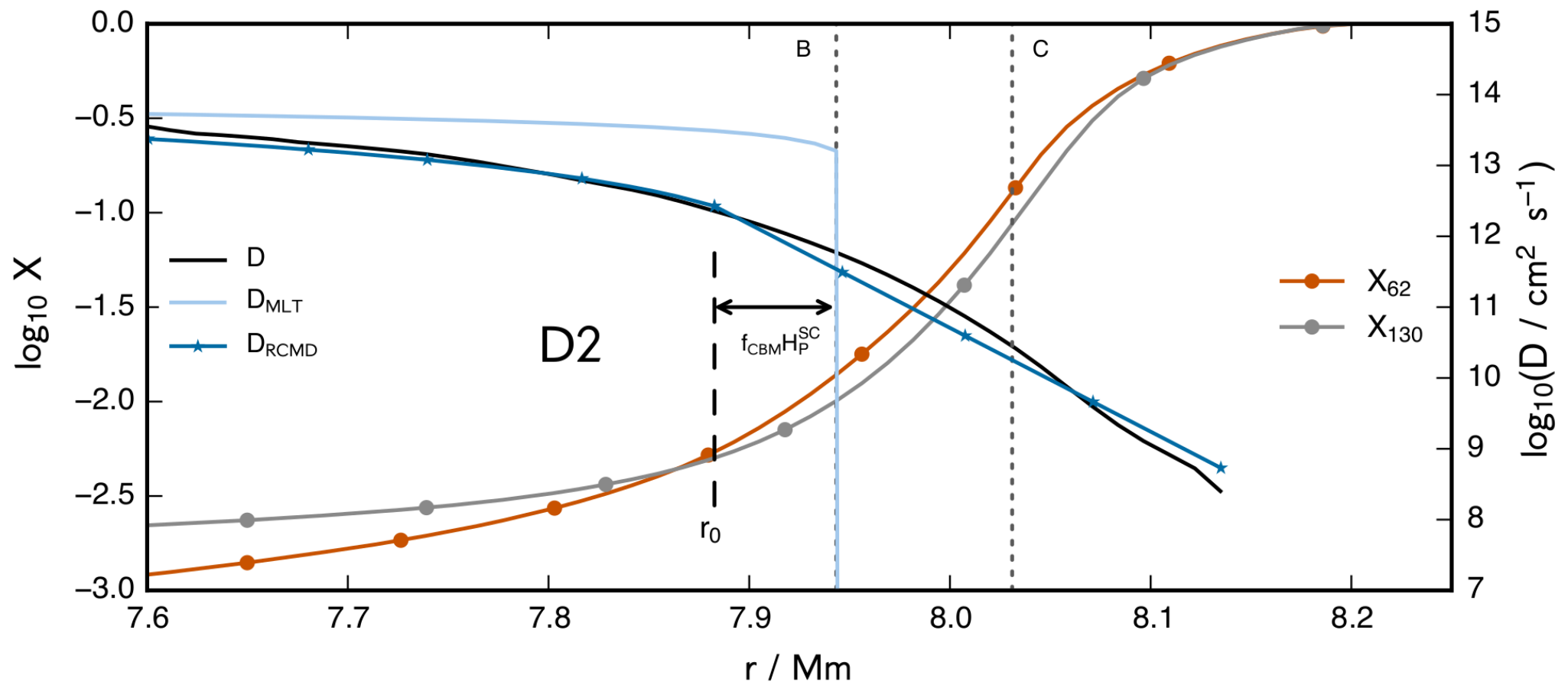
MIXING IN STARS

1D MIXING MODEL

$$\frac{1}{3} v_{\text{MLT}} \times \min(\ell, r_0 - r)$$

$$f_{\text{CBM}} = 0.03$$

$$D(r) = D(r_0) \times \exp \left\{ -\frac{2(r - r_0)}{f_{\text{CBM}} H_P(r_0)} \right\}$$



S. Jones, RA, SS, AD, PW, FH (2016, ArXiv e-prints, arXiv:1605.03766)

SLH (Seven-League Hydro) Code

F. Miczek, F. K. Röpke, P. V. F. Edelmann

- ▶ solves the compressible Euler equations in 1-, 2-, 3-D
- ▶ explicit and implicit time integration
- ▶ flux preconditioning to ensure correct behavior at low Mach numbers
- ▶ other low Mach number schemes (e.g. AUSM⁺-up)
- ▶ works for low and high Mach numbers on the same grid
- ▶ hybrid (MPI, OpenMP) parallelization (scaling up to 100 000 cores)
- ▶ several solvers for the linear system:
BiCGSTAB, GMRES, Multigrid, (direct)
- ▶ arbitrary curvilinear meshes
- ▶ radiation in the diffusion limit
- ▶ general equation of state
- ▶ general nuclear reaction network



Seven-League Hydro

Conclusions & Outlook

- General link between MS and SN type understood

BUT

- Physical ingredients still uncertain: convection, rotation, mass loss, B-fields, binarity

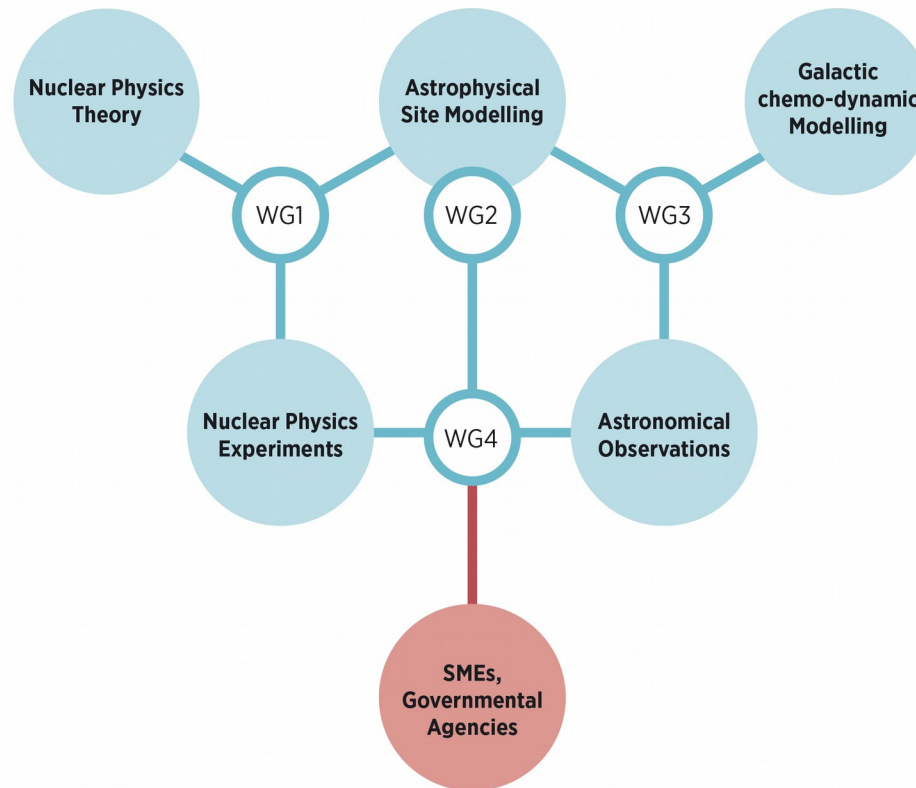
- 1D to 3D to 1D work underway for convection and rotation

- Priority list established: **large effort needed!**

ChETEC COST Action (2017-2021)

Chemical Elements as Tracers of the Evolution of the Cosmos

A network to bring European research, science and business together to further our understanding of the early universe



~100 scientists across 25-30 European countries to coordinate research efforts in Nuclear Astrophysics

http://www.cost.eu/COST_Actions/ca/CA16117