Keele University

Basel, September 16

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Massive Star Evolution: Key Uncertainties

Raphael HIRSCHI

SHYNE @ Keele: N. Nishimura, A. Kozyreva, J. den Hartogh, A. Cristini

in collaboration with: C. Georgy (GVA)

GVA code: G. Meynet, A. Maeder, S. Ekström, P. Eggenberger and C. Chiappini (IAP, D)

VMS: N. Yusof, H. Kassim (UM, KL, Malaysia), P. Crowther (Sheffield), O. Schnurr (IAP)

Nucleo: F.-K. Thielemann, U. Frischknecht, T. Rauscher (Basel, CH/Herts, UK)

NUGRID: F. Herwig (Victoria, Canada), M. Pignatari (Hull), C. Fryer (LANL), Laird (York), UChicago, UFrankfurt, …

MESA: B. Paxton (KITP), F. X. Timmes, Arizona (US)

SNe: K. Nomoto (IPMU, J), T. Fischer (TUD, D)

HYDRO: C. Meakin, D. Arnett (Arizona), M. Viallet (MPA), F. Roepke, P. Edelmann, S. Jones (HITS, D)

Plan

- Late evolution of massive stars: brief overview

- Key uncertainties: convection and convective boundary mixing

- Conclusions & outlook

Recent Papers/Reviews

Reviews:

- Umeda, Yoshida and Takahashi, “Massive Star Evolution and Nucleosynthesis -Lower End of Fe-Core Collapse Supernova Progenitors and Remnant Neutron Star Mass Distribution”, 2012arXiv1207.5297U, Accepted for publication in Progress of Theoretical and Experimental Physics

- Langer, “Pre-Supernova Evolution of Massive Single and Binary Stars”, ARAA, 2012, astroph-1206.5443

- Maeder and Meynet, “Rotating massive stars: From first stars to gamma ray bursts”, 2012RvMP...84...25M

- Woosley, Heger and Weaver,”The evolution and explosion of massive stars”, 2002RvMP...74.1015W

Textbooks:

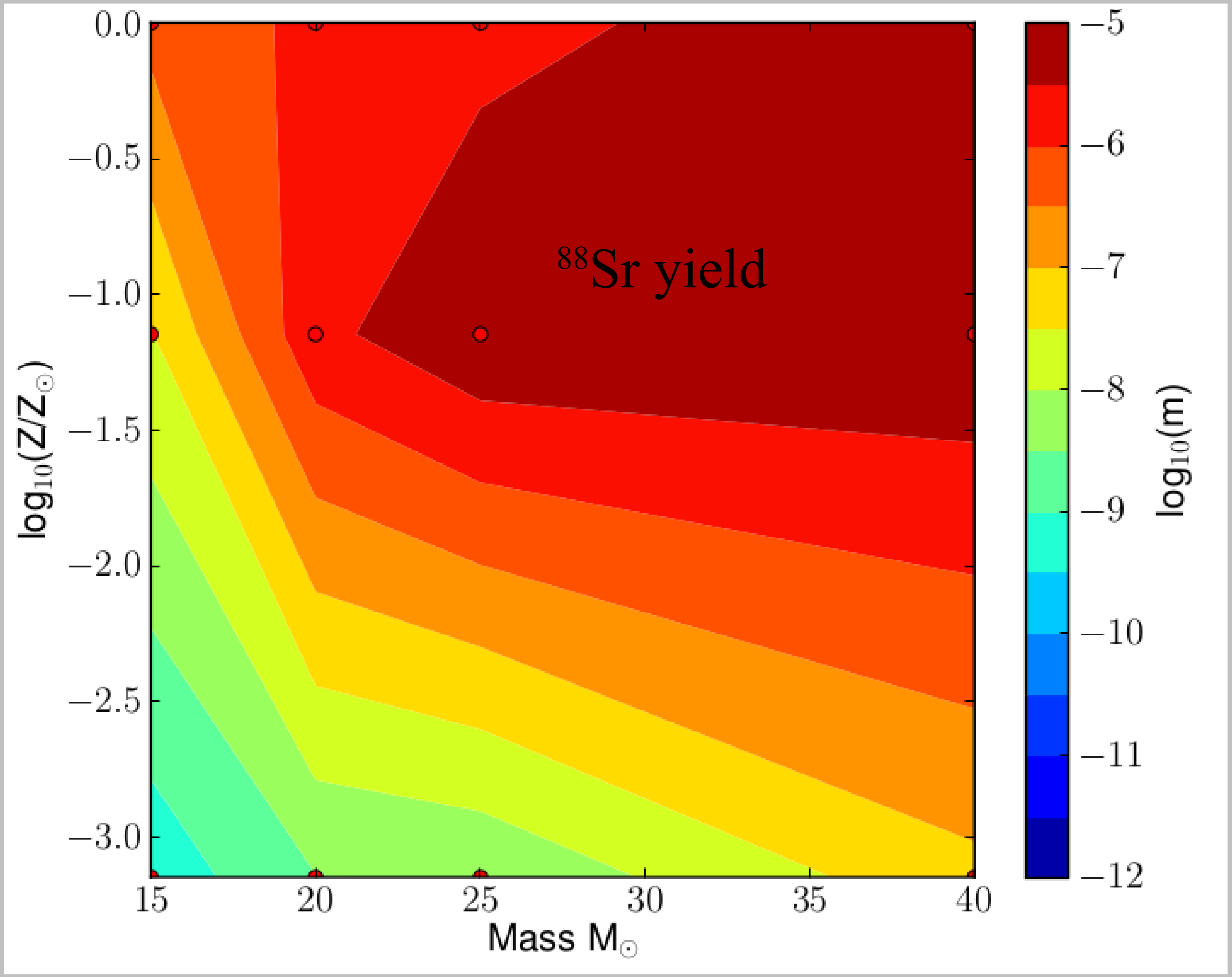
- R. Kippenhahn & A. Weigert, Stellar Structure and Evolution, 1990, Springer-Verlag, ISBN 3-540-50211-4

- A. Maeder, Physics, Formation and Evolution of Rotating Stars, 2009, Springer-Verlag, ISBN 978-3-540-76948-4

S-Process Models of Massive Rotating Stars

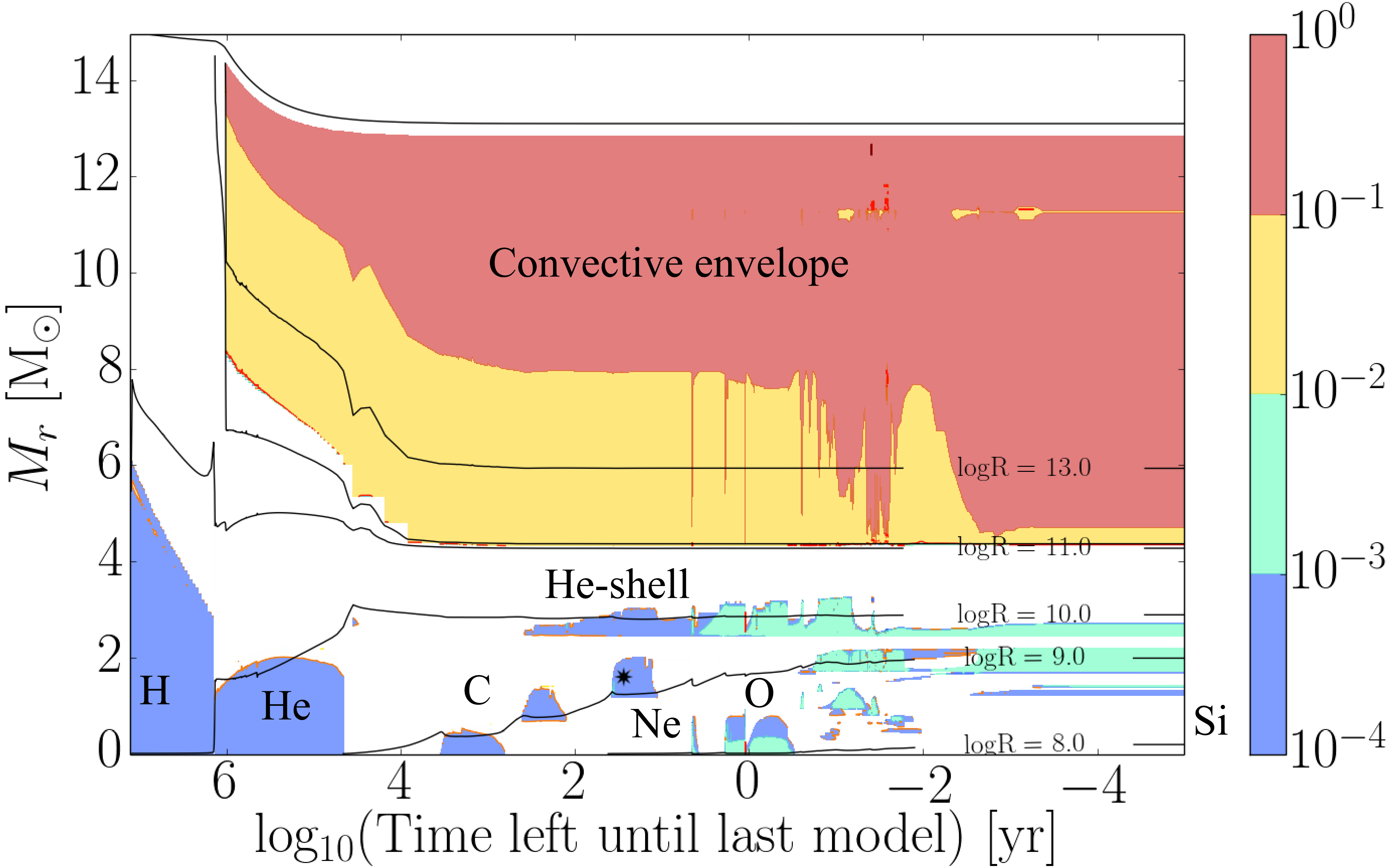
- FULL GRID NOW PUBLISHED!

Frischknecht, Hirschi et al, MNRAS, 2016, 456, 1803



Nuclear uncertainties, Nishimura, Hirschi, Rauscher & Murphy, in prep

Evolution of Massive Stars: Structure Evolution Diagr.



Convection takes place during most burning stages

Physical Ingredients & their Uncertainties

- Nuclear reactions: Talk by Thomas Rauscher, ...
- Mass loss: Jorick Vink & Nathan Smith
- Convection: This talk
- Rotation: Talk by Cyril Georgy
- Magnetic fields
- Binarity: Talk by Norbert Langer
- Equation of state, opacities & neutrino losses

including metallicity dependence

Convection: Current Implementation in 1D Codes

Multi-D processes:

Major contributor to turbulent mixing

Turbulent entrainment at convective boundaries

Internal gravity waves

1D prescriptions:

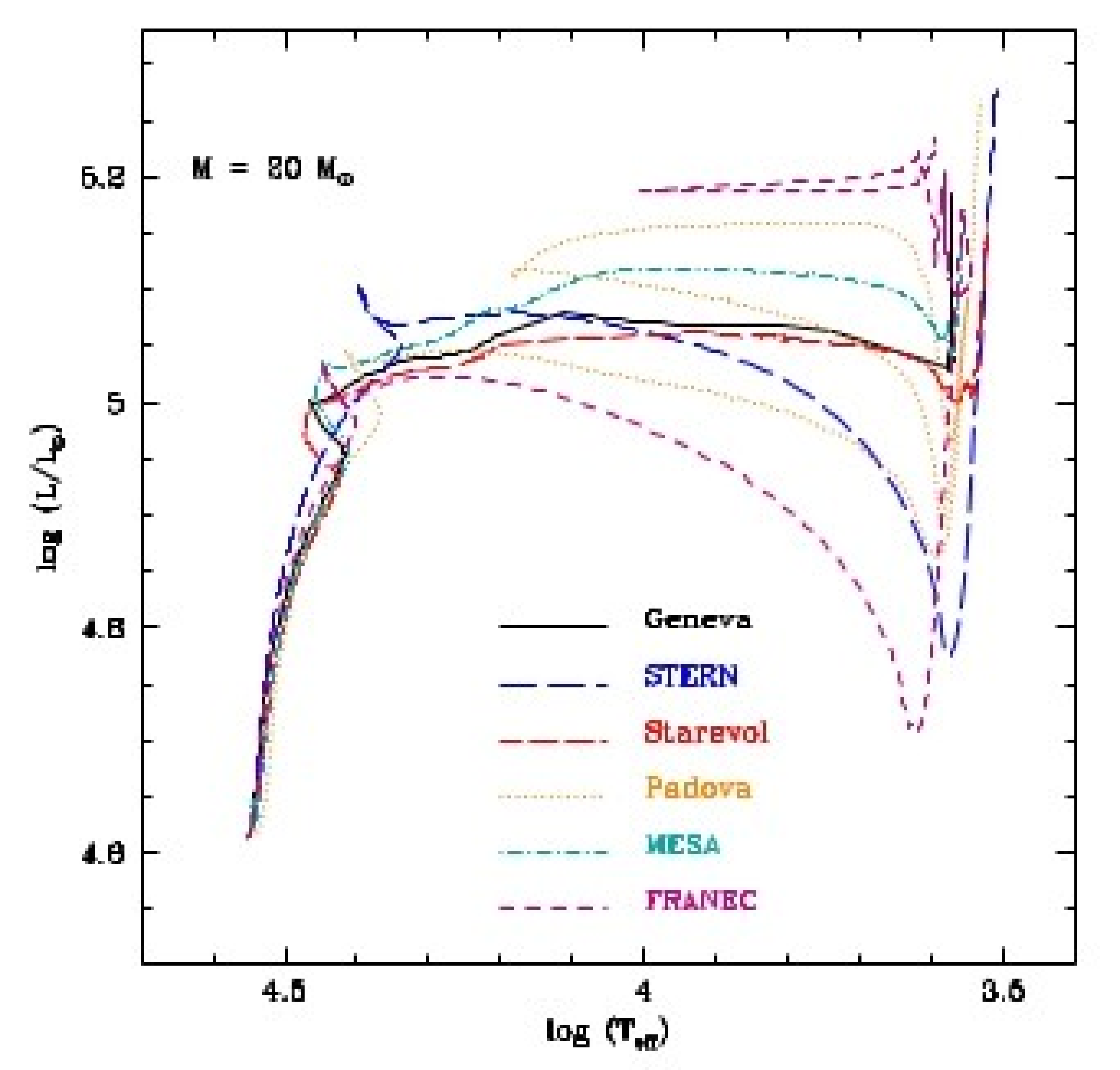
- Energy transport in convective zone: mixing length theory (MLT) *Bohm-Vitense (1957,58)*, or updates, e.g. FST: *Canuto & Mazitelli (1991)*

- Boundary location: Schwarzschild criterion OR Ledoux (+semi-convection)

- Convective boundary mixing (CBM, also composition dependent)

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

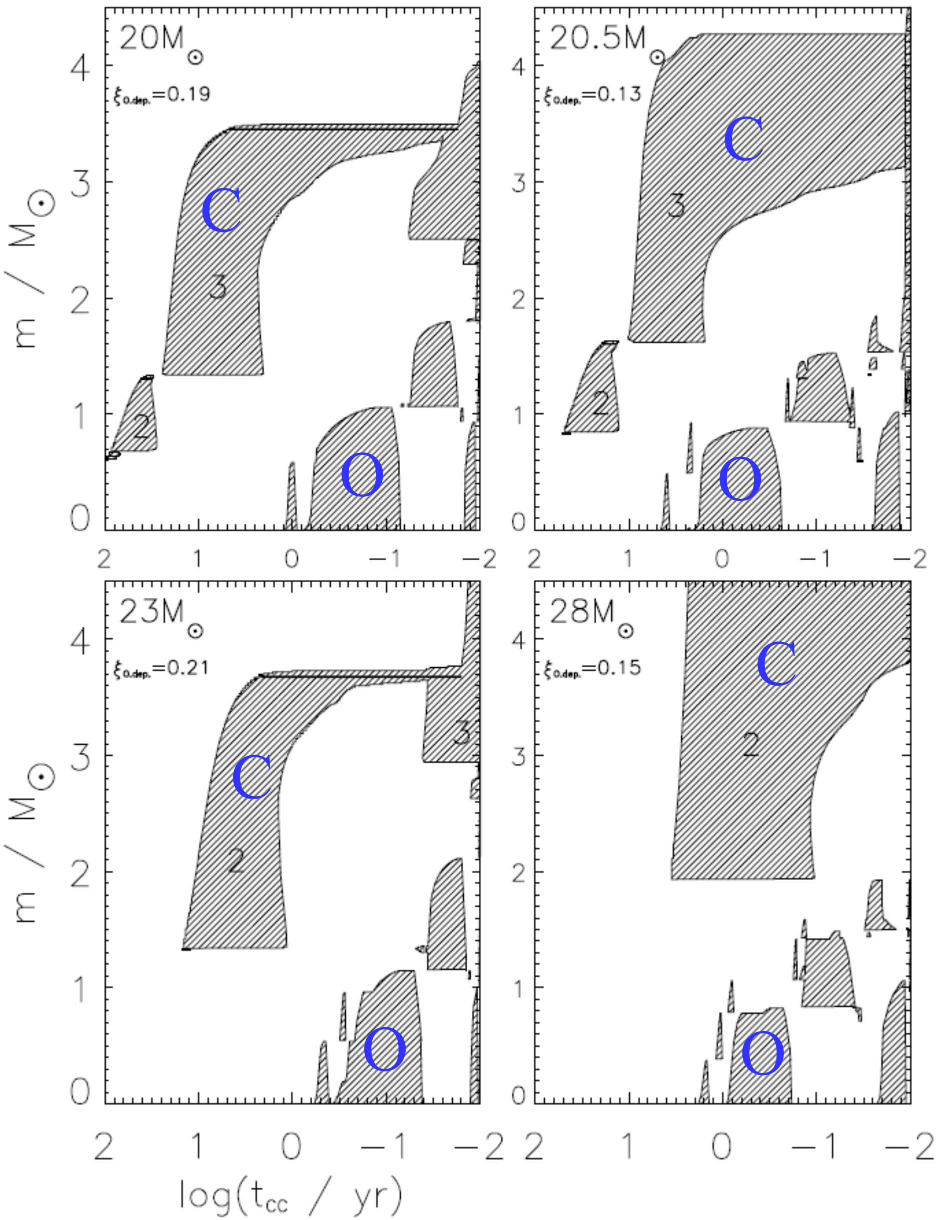


FIG. 13.— Convective history of four models showing the major

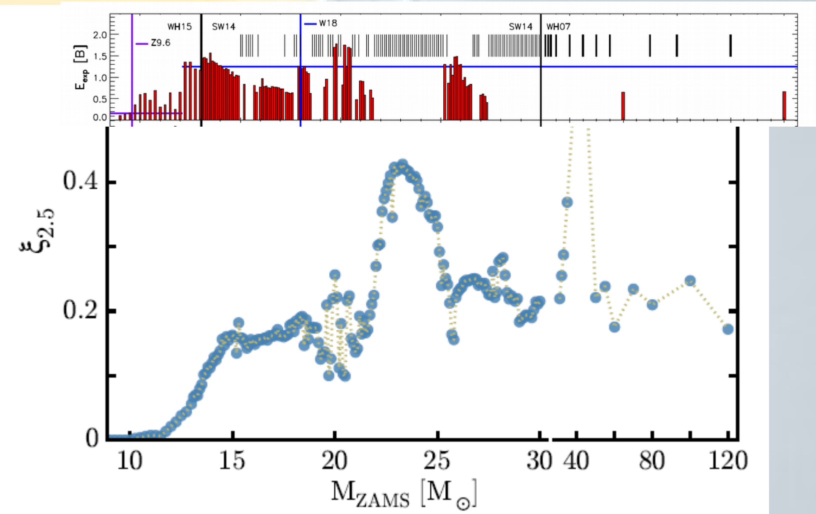


FIG. 1.— The compactness parameter, $\xi_{2.5}$, (eq. (1); O'Connor & Ott 2011) characterizing the inner 2.5 $M_\odot$ of the presupernova star is shown as a function of zero-age main sequence (ZAMS) mass for all 200 models between 9.0 and 120 $M_\odot$. The compactness

Non-monotonic behaviour!

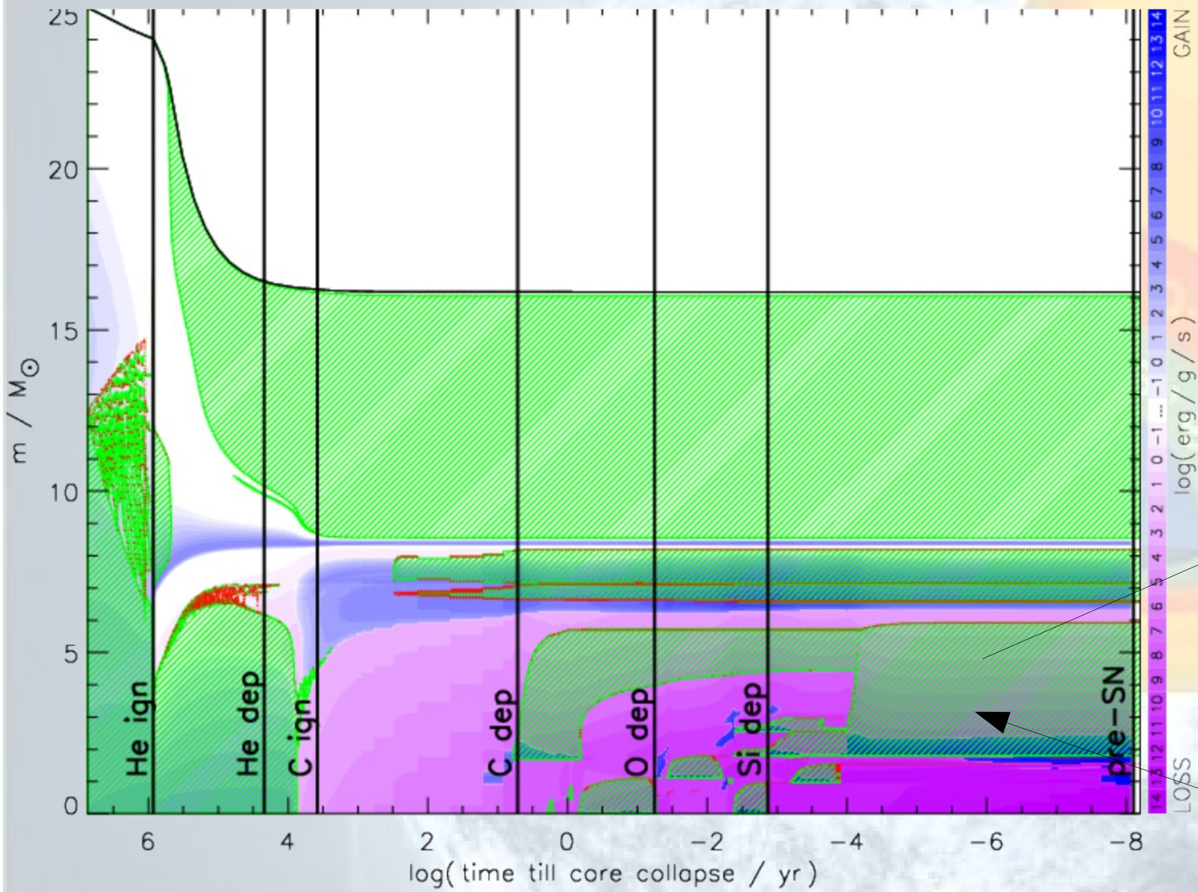
We are particularly interested in how the "explodability" of the presupernova models and their observable properties correlate with their "compactness" (Fig. 1; O'Connor & Ott 2011)

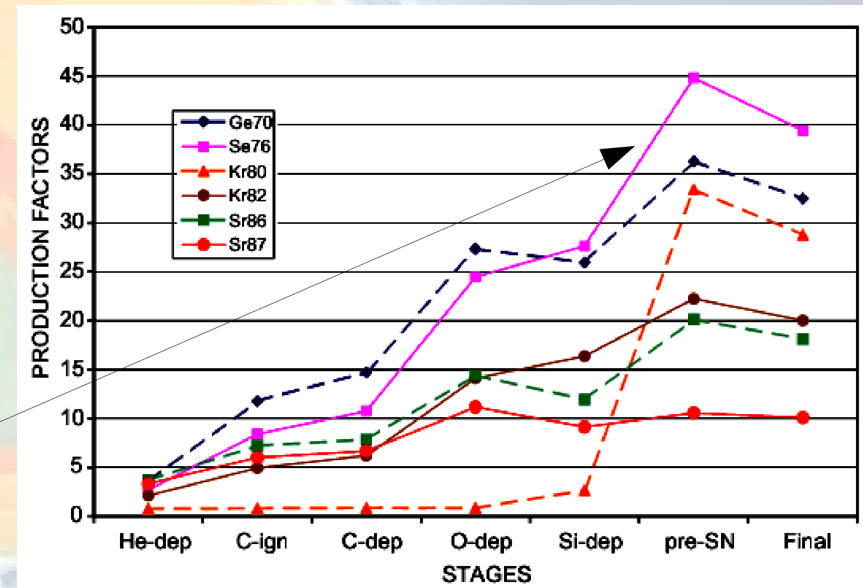
$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M)/1000\,\mathrm{km}}\Big|_{t_{\mathrm{bounce}}}, \quad (1)$$

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

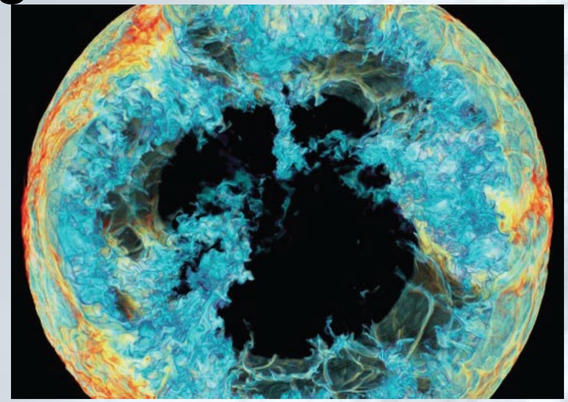
Rauscher, Heger and Woosley 2002: “Interesting and unusual nucleosynthetic results are found for one particular 20M model as a result of its special stellar structure.”

Shell mergers also affect compactness

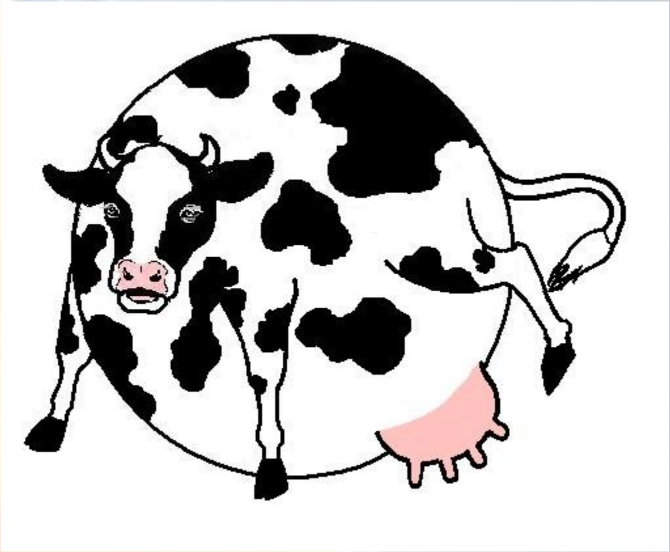
Convection physics uncertainties affect fate of models: strong/weak/failed explosions!!!

Way Forward: 1 to 3 to 1D link

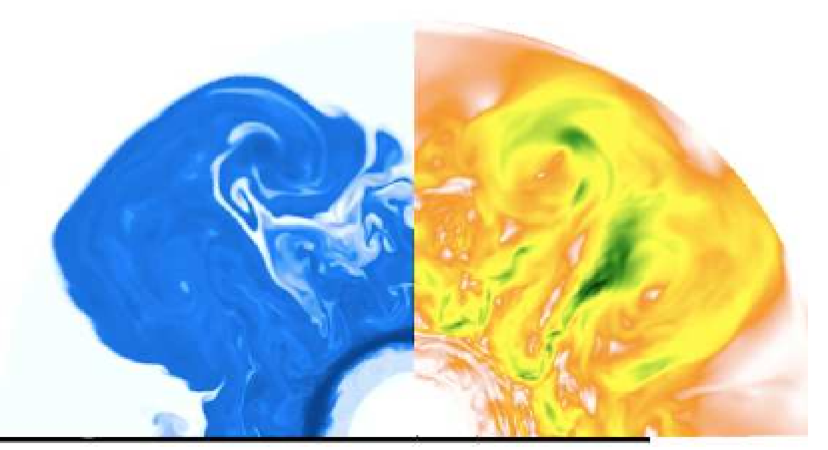
Targetted 3D simulations



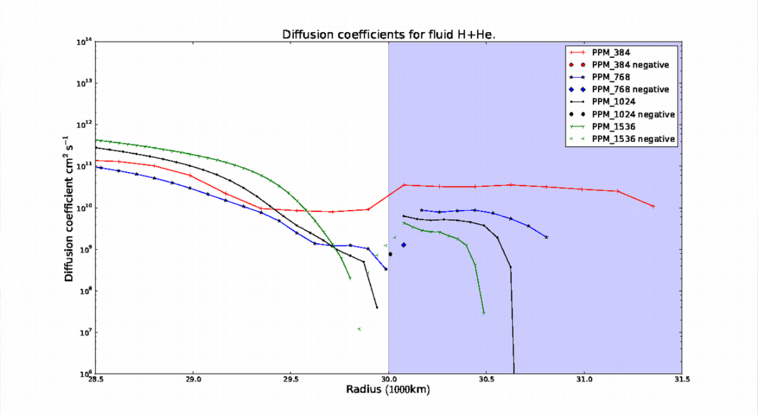
Uncertainties in 1D



Herwig et al 06, Herwig, Woodward et al 2013



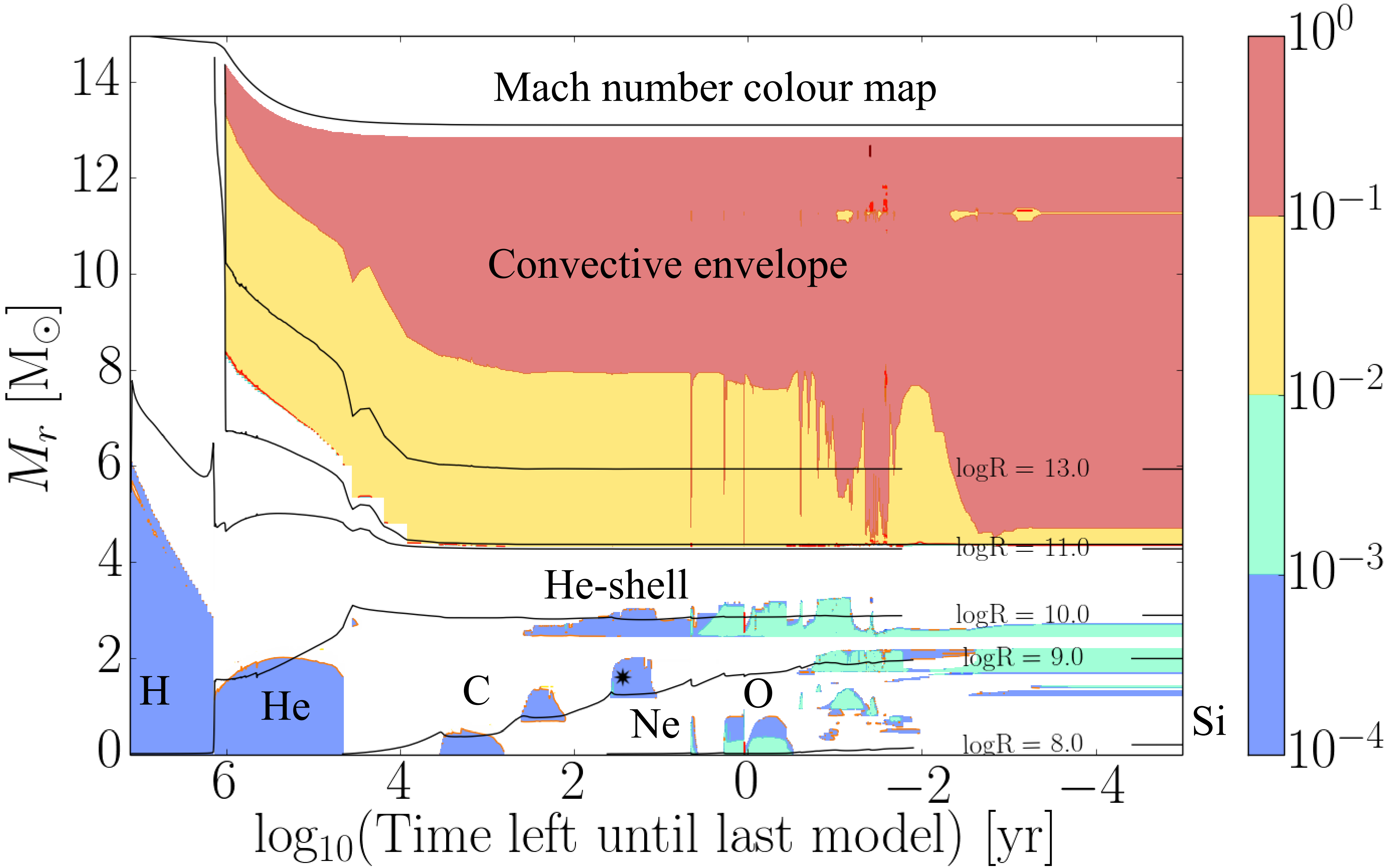
e.g. Arnett & Meakin 2011, ...
Mocak et al 2011,
Viallet et al 2013, ...



Meakin et al 2009 ; Bennett et al (thesis)

→ Determine effective coefficient / improve theoretical prescriptions

Where to Start?

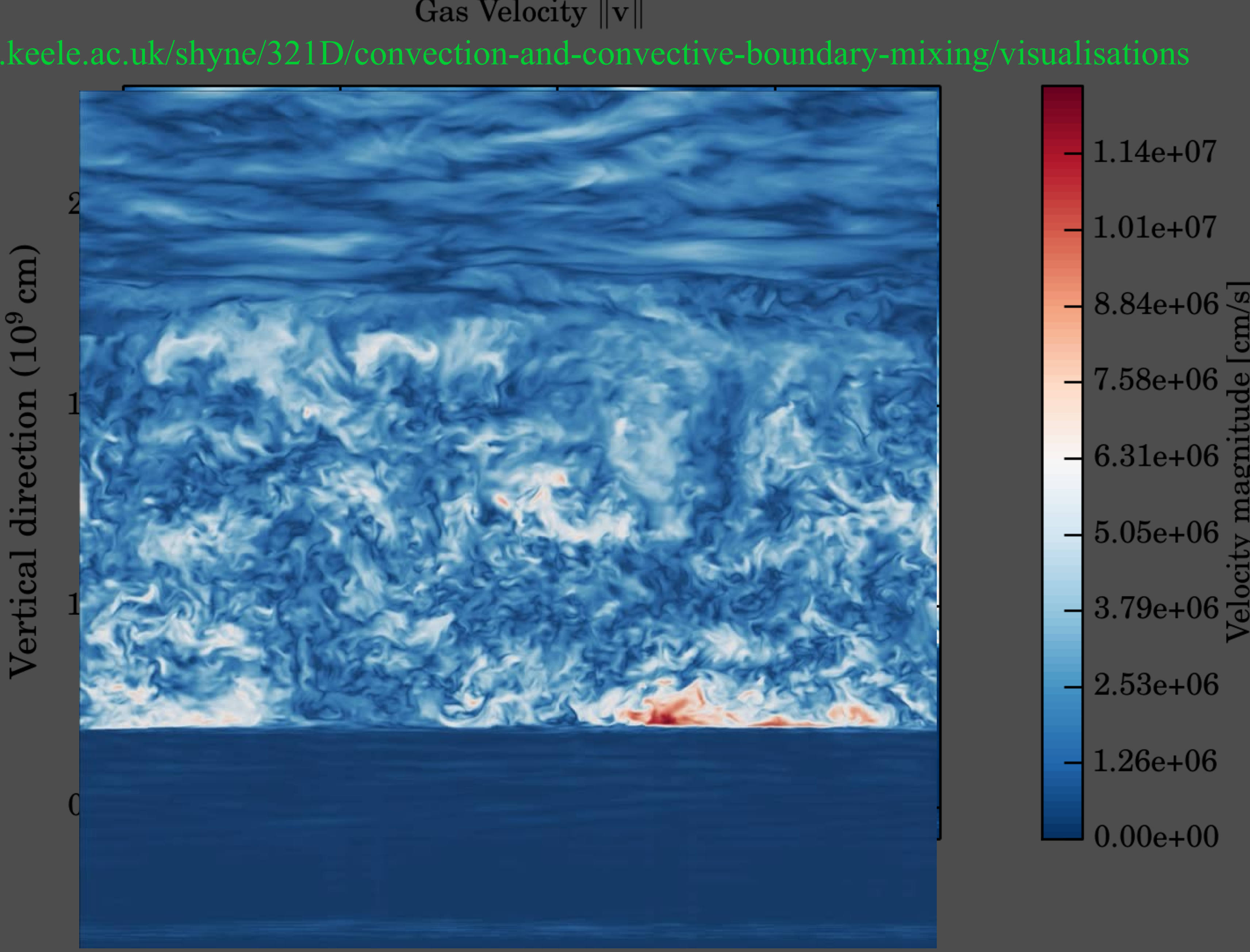


Convection takes place during most burning stages

Priority List (Hirschi et al 2014, NICXIII)

* 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 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.
• -: ~ 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, ...)
•

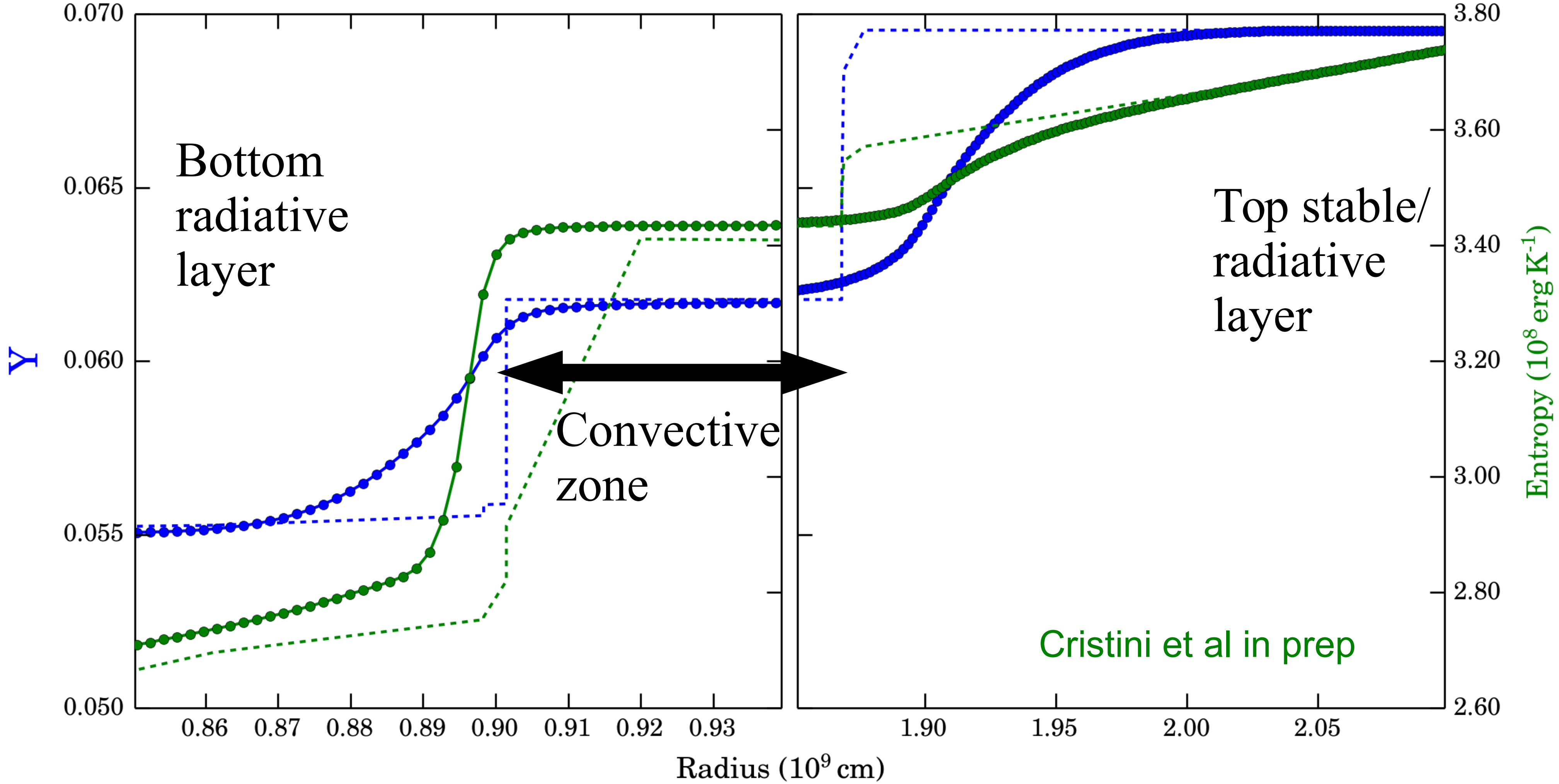
C-shell Simulations: $|v|$ movie



http://www.astro.keele.ac.uk/shyne/321D/convection-and-convective-boundary-mixing/visualisations

Cristini et al in prep

3D versus 1D



- Improved prescriptions for CBM needed!

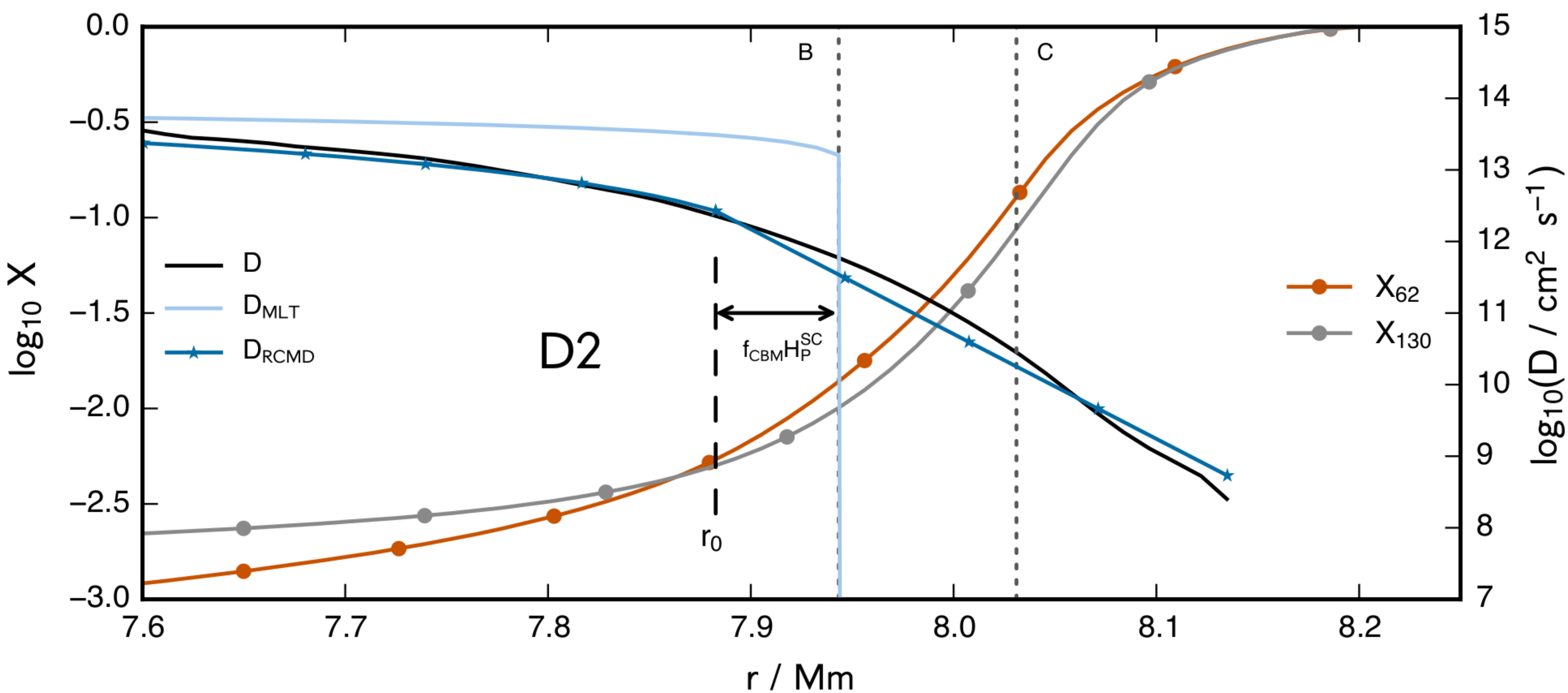
MIXING IN STARS

1D MIXING MODEL

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

$f_{CBM} = 0.03$

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

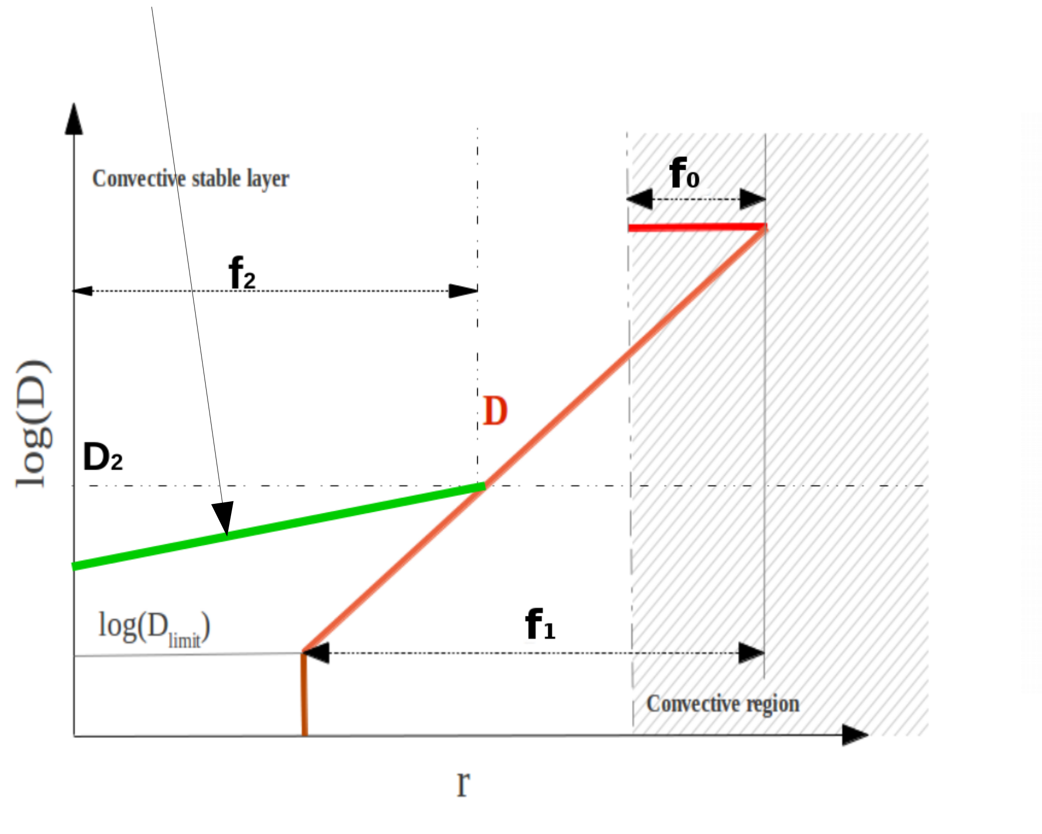


S. Jones, RA, SS, AD, PW, FH (2016, ArXiv e-prints, arXiv:1605.03766)

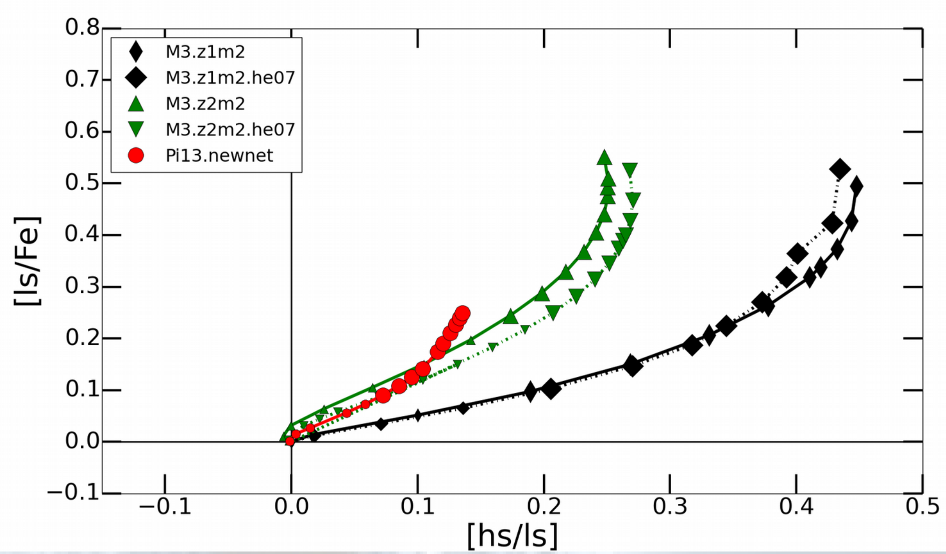
Back to 1D: CBM in AGB Stars (NuGrid project)

Internal gravity wave (IGW) driven mixing

Battino,…,Hirschi et al ApJ 2016 accepted



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)

Conclusions & Outlook

- Late stages very lively!

- MS → CCSNe; SAGB/low-M MS → ECSNe

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

- 1D to 3D to 1D work underway: new CBM prescr. needed!

- Priority list established: large effort needed!

- Challenging times ahead: complex physics/ implementations, CPU time, big data!

- Exciting times ahead: reaching convergence!

Priority List (Hirschi et al 2014, NICXIII)

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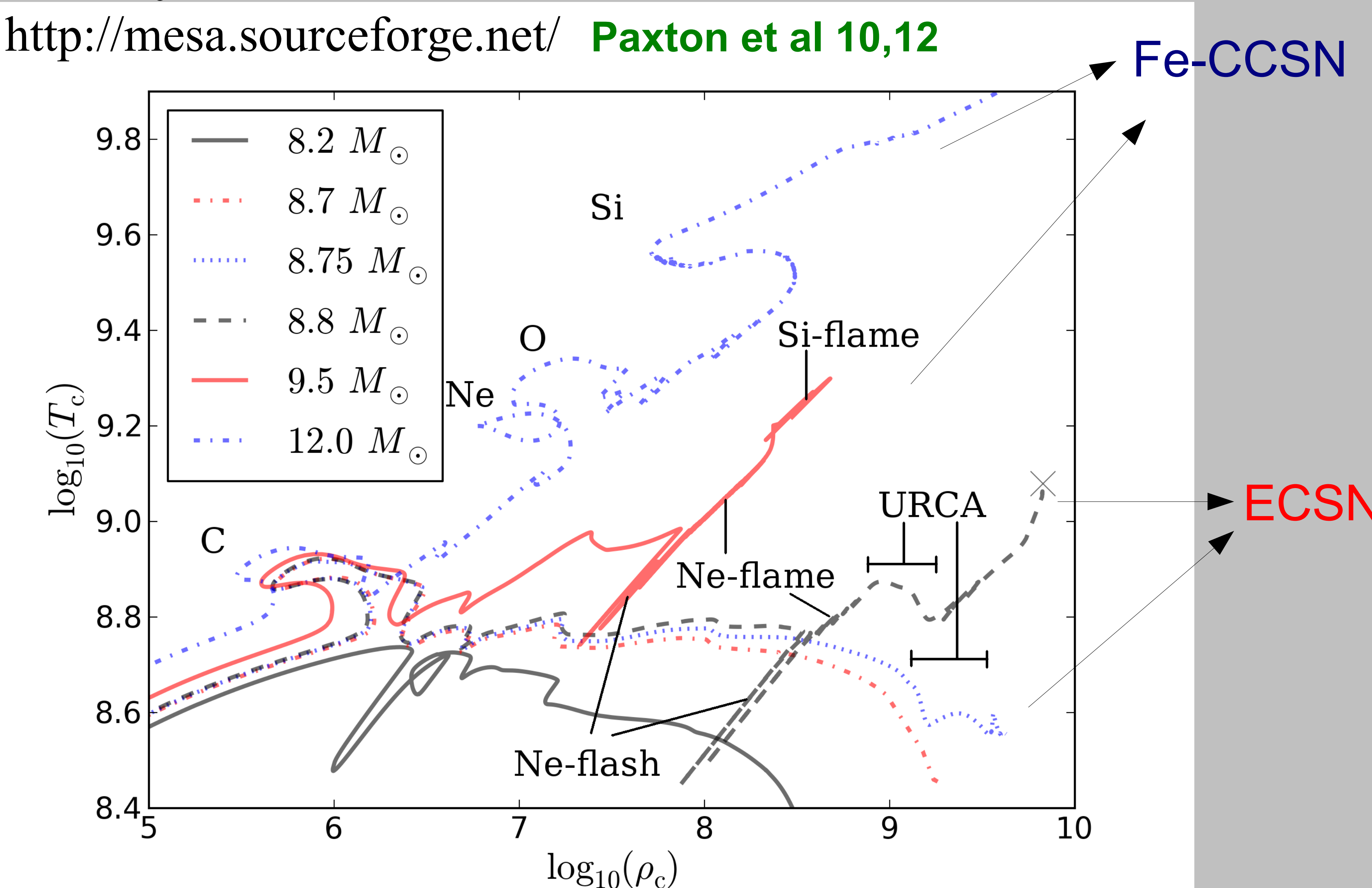
Fate of Least-Massive MS: ECSN/Fe-CCSN?

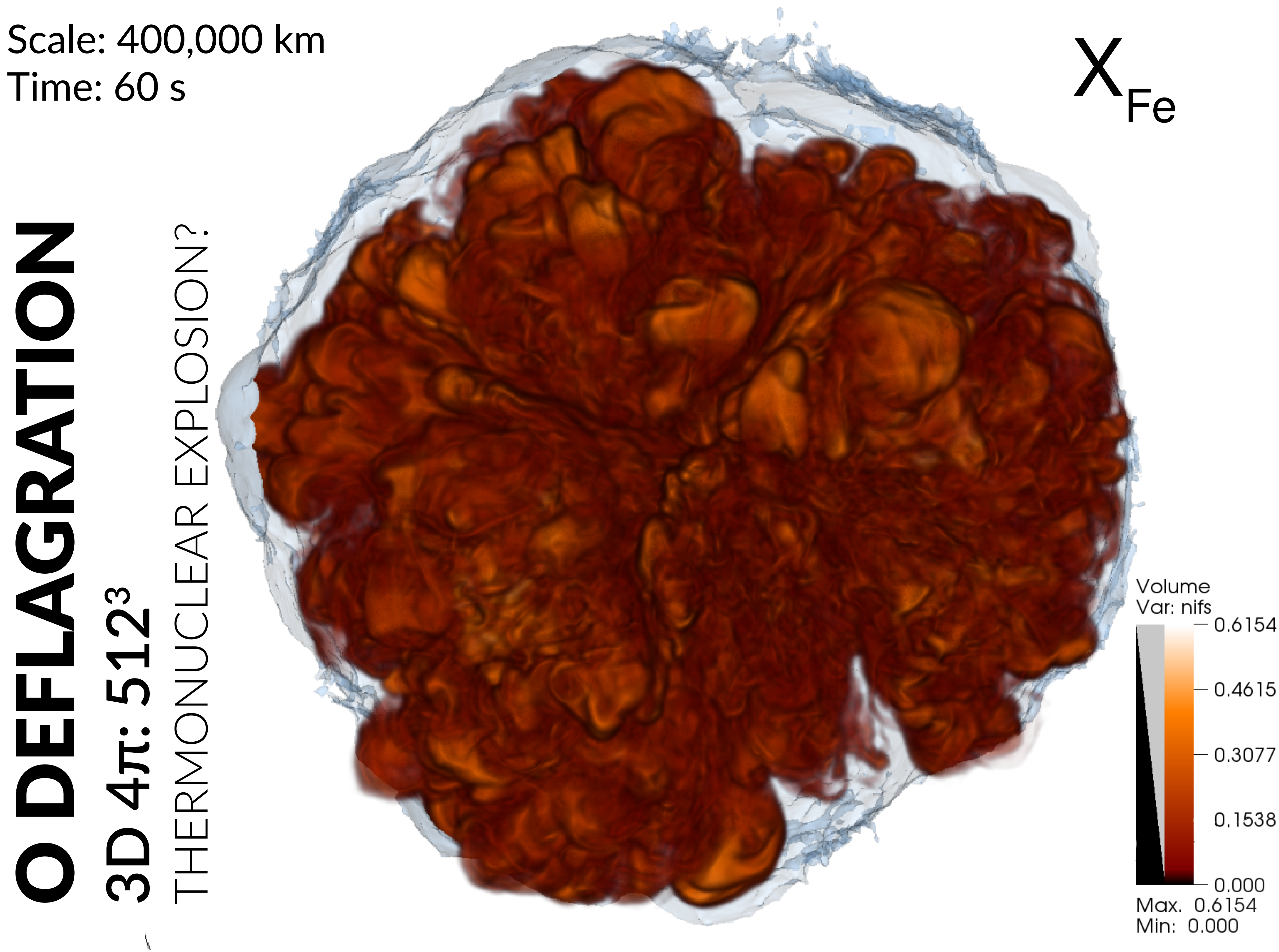
7-15 $M_\odot$ models ← MESA stellar evolution code:

http://mesa.sourceforge.net/ **Paxton et al 10,12**



Both SAGB and failed massive stars may produce ECSN

Jones et al. (2013), ApJ 772, 150


Scale: 400,000 km
Time: 60 s
X Fe
O DEFLAGRATION
3D 4π: 512³
THERMONUCLEAR EXPLOSION?
Volume
Var: nifs
0.6154
0.4615
0.3077
0.1538
0.000
Max. 0.6154
Min: 0.000

DIAGNOSTICS

S. Jones, FKR, RP, IRS, STO, PVFE
arXiv:1602.05771

Bound ONeFe remnants

id.	res.	$\log_{10} \rho_c^{ini}$ (g cm^{-3})	CC (Y/N)	M_{rem}	M_{rem}^{Ni} ($M_\odot$)	M_{ej}	M_{ej}^{Ni}	$\langle Y_{e,re}$
G13	256^3	9.90	N	0.653	0.168	0.735	0.236	0.49
G14	512^3	9.90	N	0.462	0.137	0.929	0.349	0.49
G15	256^3	9.90	Y	1.231	0.217	0.158	0.044	0.49
J01	256^3	9.95	N	0.606	0.157	0.798	0.254	0.49
J02	256^3	9.95	Y	1.297	0.227	0.100	0.021	0.49
H01*	256^3	10.3	N	1.401	0.032	0.000	0.000	0.47

Core collapse

What would these things actually **look like**? Faint SN1a? Have we seen them? → **Radiative transfer calculations required**