Keele University

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Progenitors of Core Collapse SNe

Raphael HIRSCHI

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NUGRID: F. Herwig (Victoria, Canada), M. Pignatari (Hull), C. Fryer (LANL), Laird (York), UChicago, UFrankfurt, …
MESA: B. Paxton (KITP), F. X. Timmes, (UArizona, US)
SNe: K. Nomoto (IPMU, J), C. Frohlich, M. Gilmer (NCSU), A. Kozyreva (), T. Fischer (W.,P)
HYDRO: C. Meakin, D. Arnett (UArizona), C. Georgy (GVA), M. Viallet (MPA), F. Roepke, P. Edelmann, S. Jones (HITS, D)

SN87A 30 Years Anniversary!


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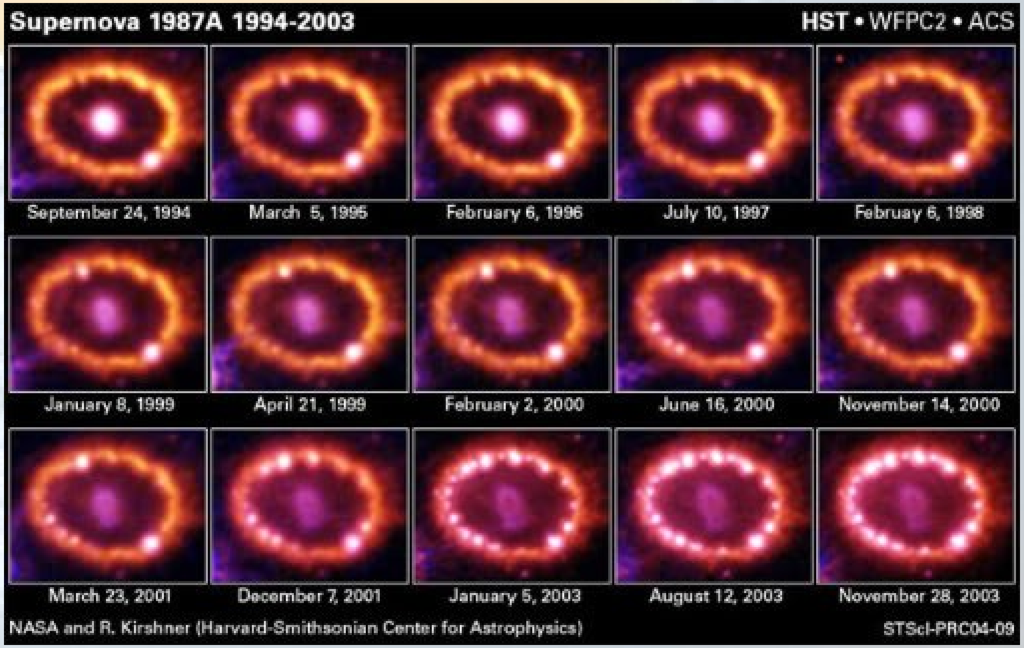
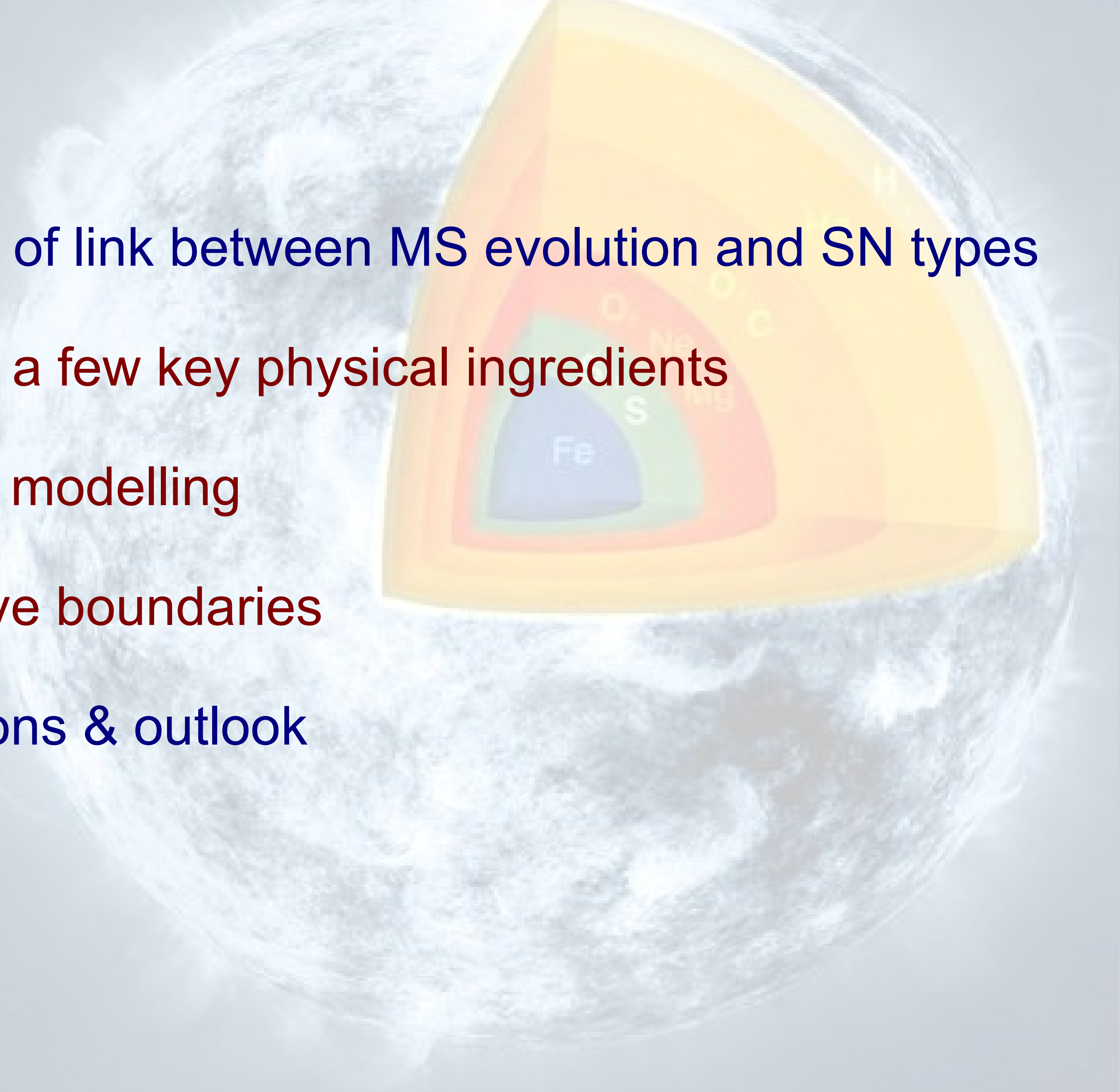
23/02/1987



- Exquisite Observations!
- Great memories!

Plan



- Overview of link between MS evolution and SN types
- Effects of a few key physical ingredients
- 1D vs 3D modelling
- Convective boundaries
- 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:

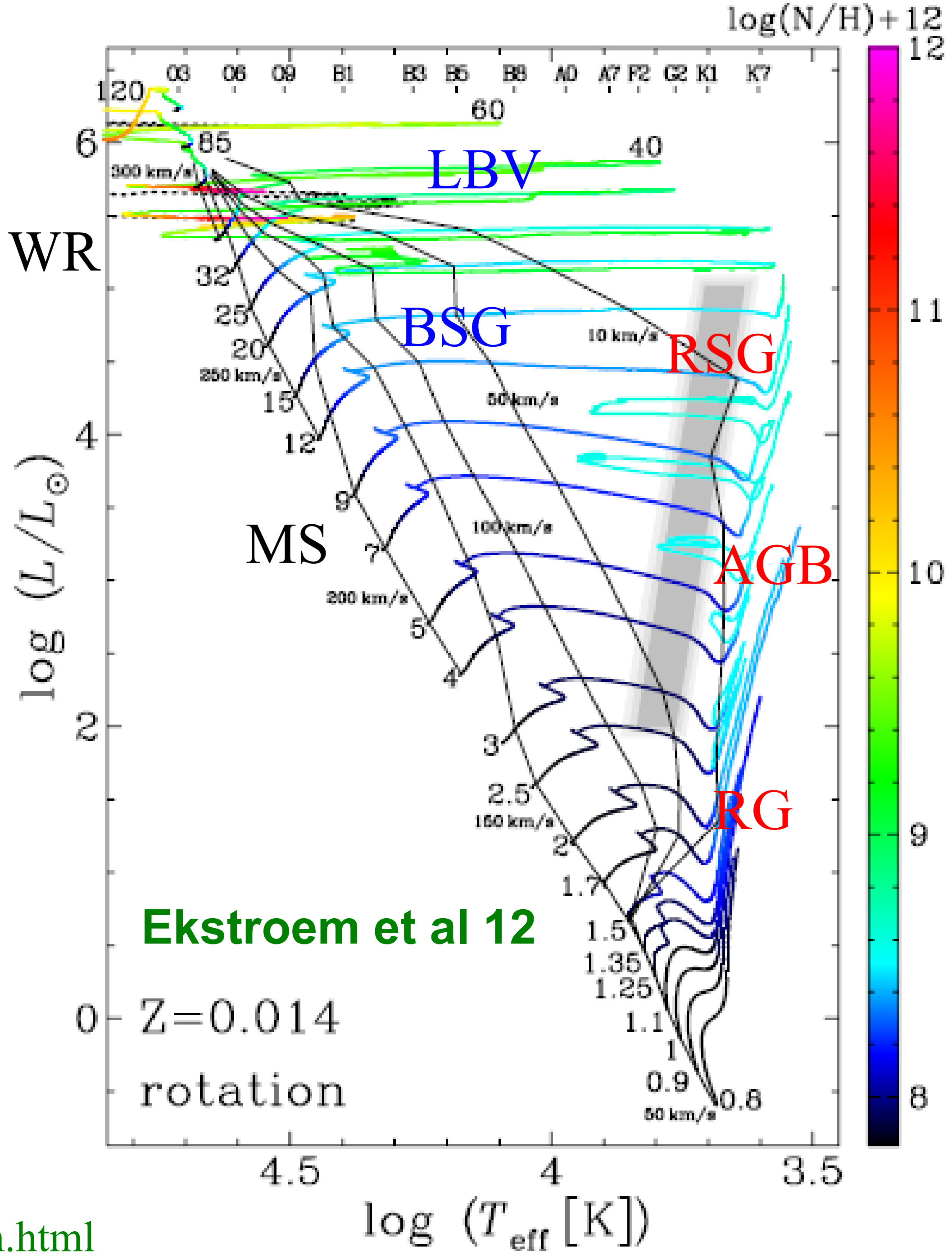
Supergiant stage (red or blue)

Wolf-Rayet (WR): M > 20-25 M_o

WR without RSG: M > 40 M_o

Advanced stages: C,Ne,O,Si

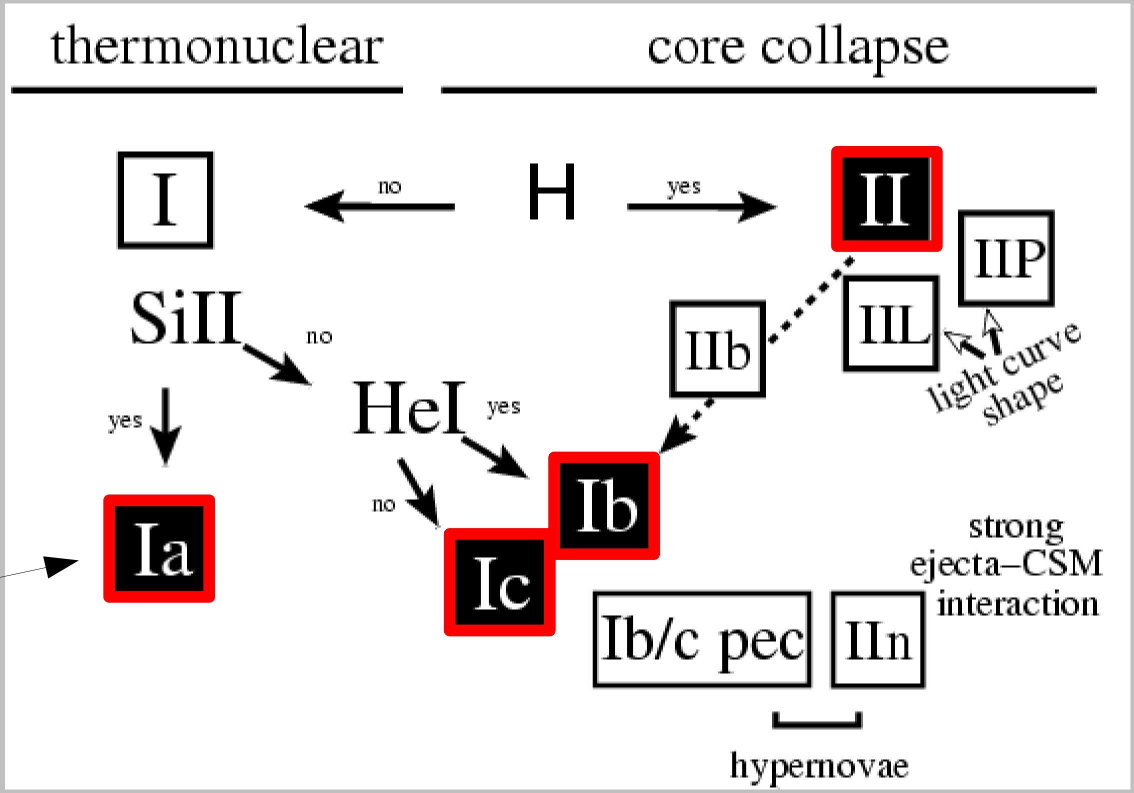
→ iron core → SN/NS/BH



http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

Supernova Explosion Types

Massive stars: → SN II (H envelope),
Ib (no H), Ic (no H & He) ← WR



White dwarfs (WD):
in binary systems
Accretion →
Chandrasekhar
mass → SN Ia

(Turatto 03)

Binary interactions: → SN II: RSG → BSG (SN87A, e.g. Podsiadlowski+ 91)
Ib (no H), Ic (no H & He) via mass transfer: smaller mass

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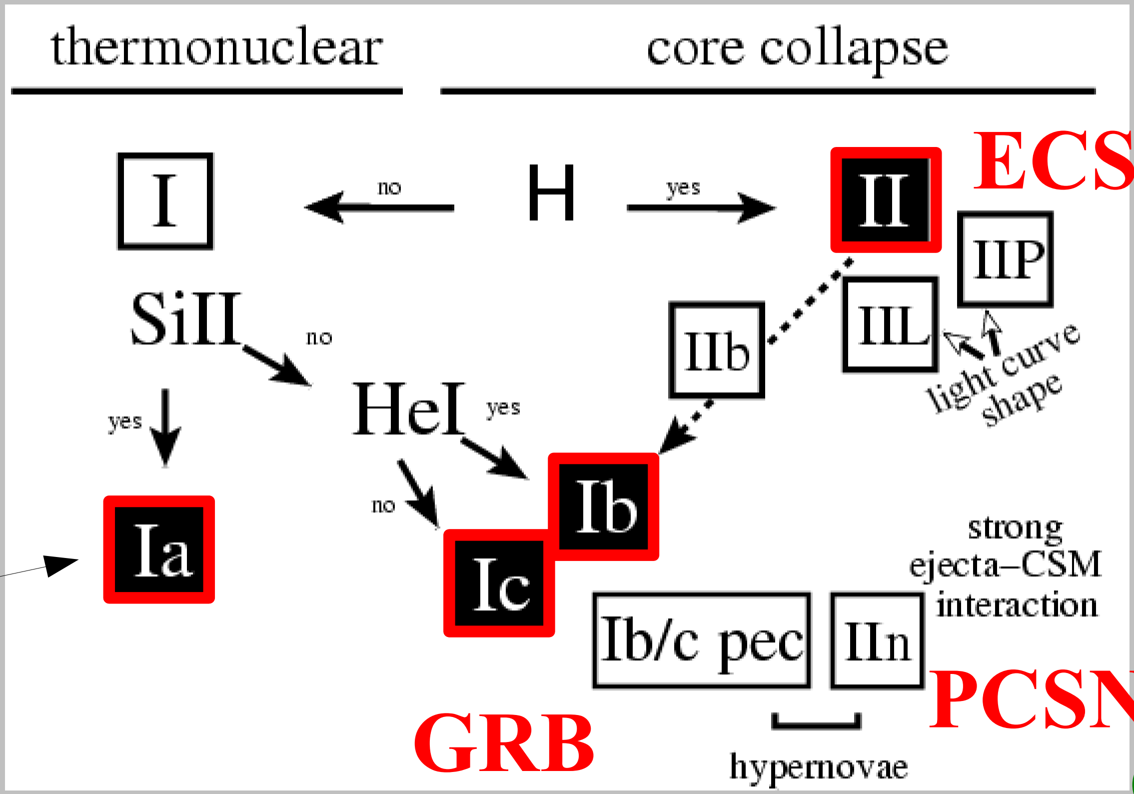


ECSN?

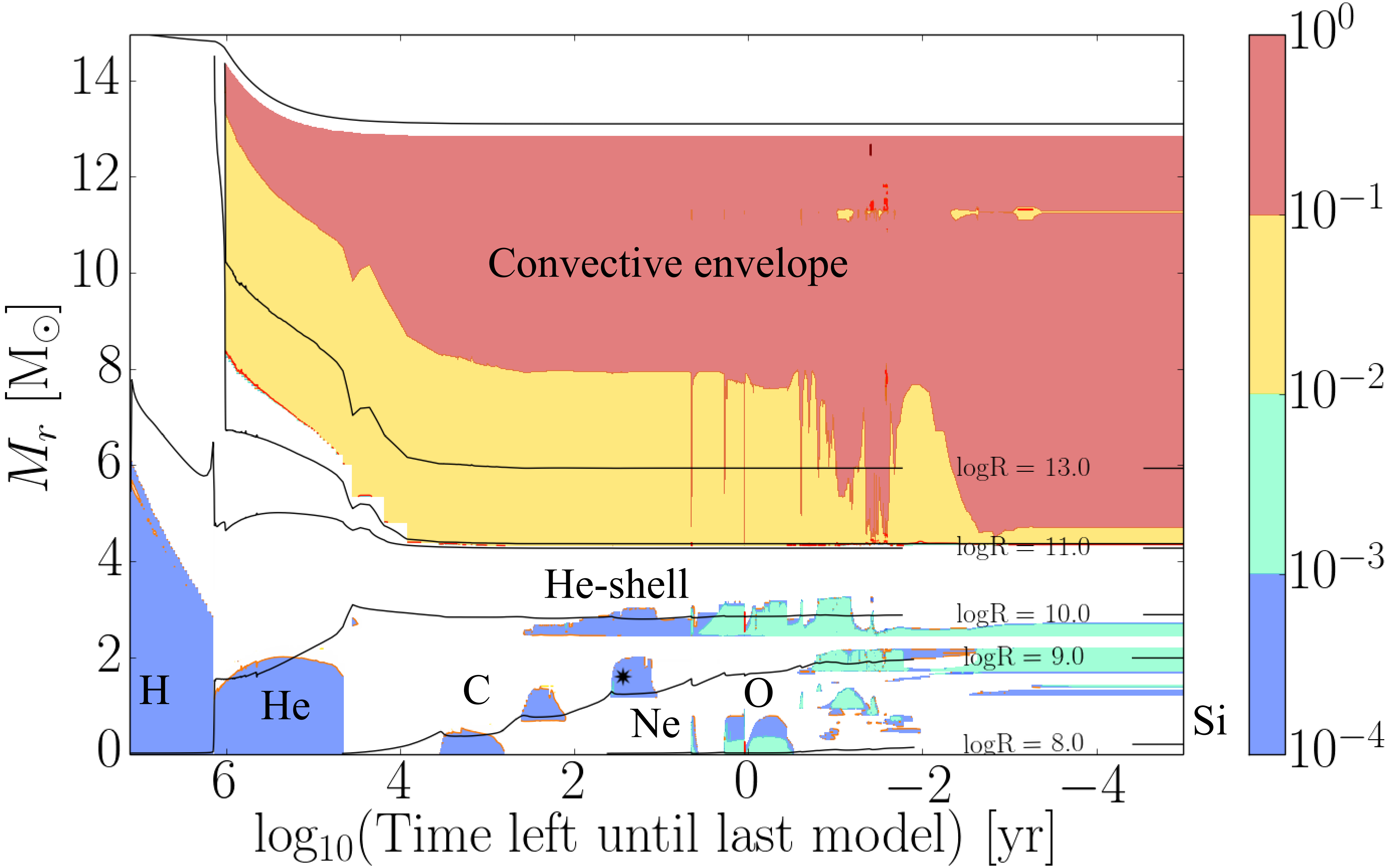
GRB

PCSN (=PISN)?
(Kozyreva+ 16)

White dwarfs (WD):
in binary systems
Accretion →
Chandrasekhar
mass → SN Ia

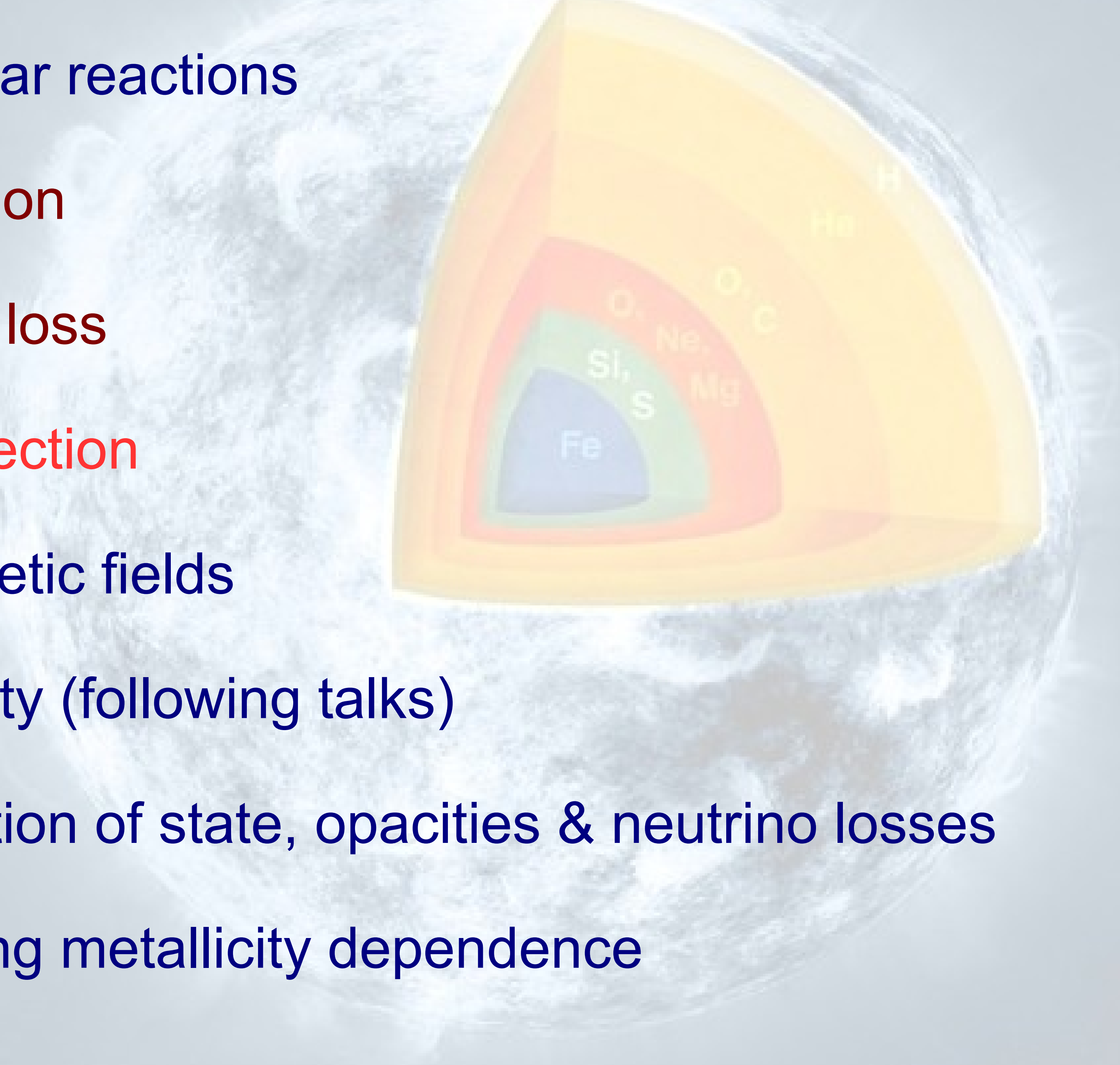
Binary interactions: → SN II: RSG → BSG (SN87A, e.g. Podsiadlowski+ 91)
Ib (no H), Ic (no H & He) via mass transfer: smaller mass

Evolution of Massive Stars



Convection takes place during most burning stages

Physical Ingredients

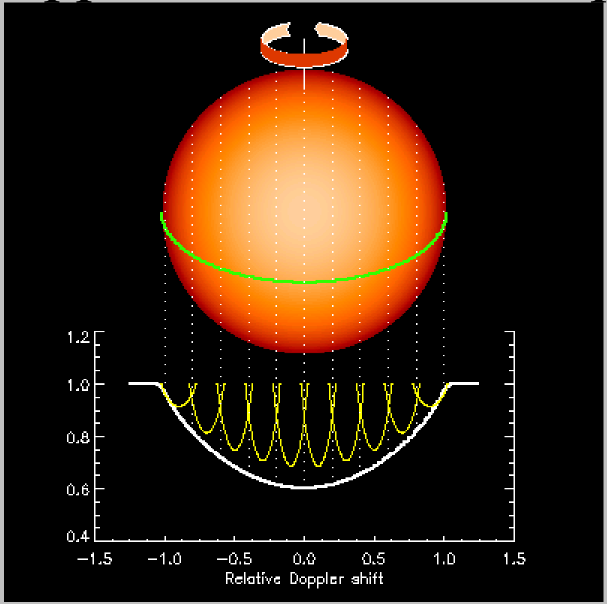


- Nuclear reactions
- Rotation
- Mass loss
- Convection
- Magnetic fields
- Binarity (following talks)
- Equation of state, opacities & neutrino losses

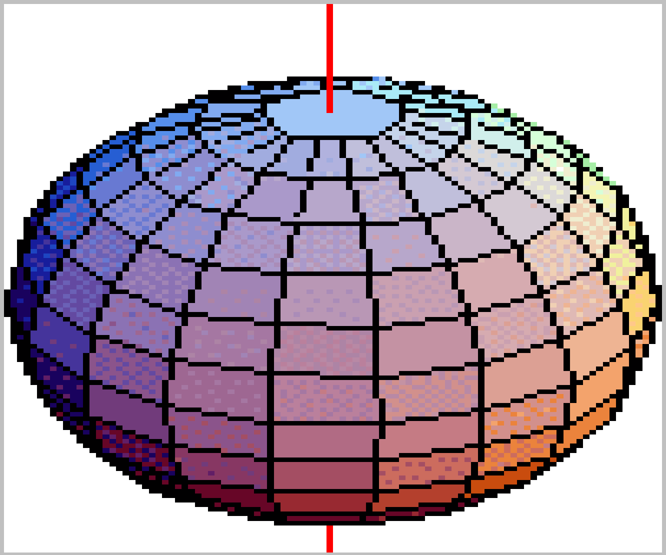
including metallicity dependence

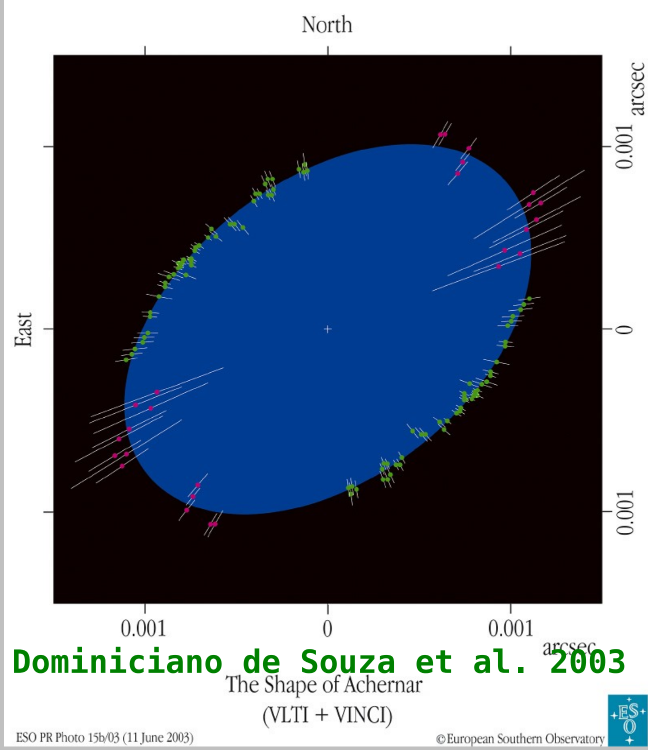
Rotational Effects on Surface

Doppler-broadened line profile

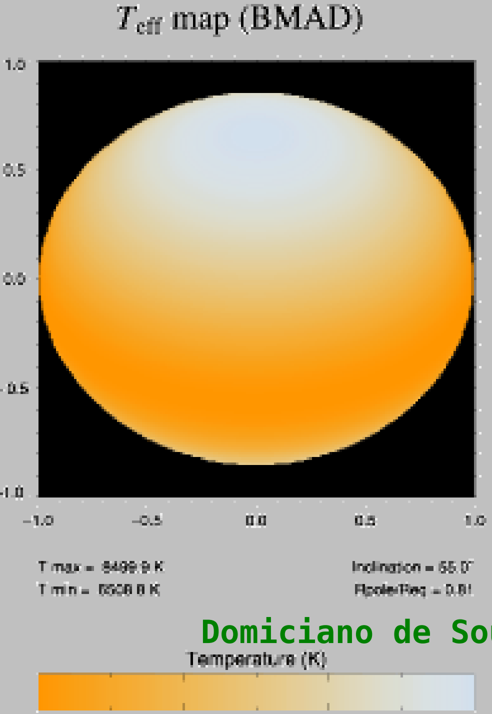


Fast rotators –> oblate shape:





Dominiciano de Souza et al. 2003

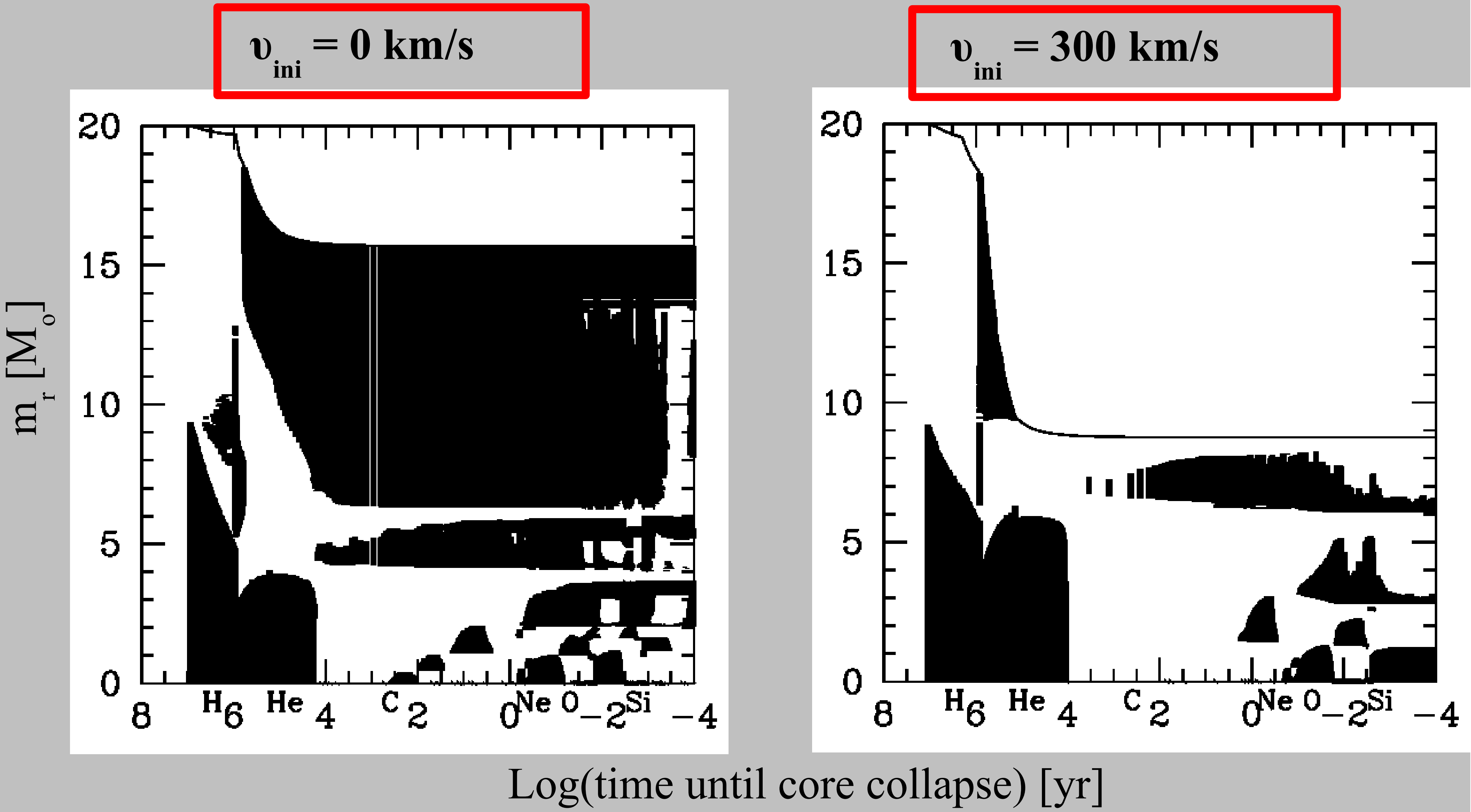


Domiciano de Souza et al. 2005

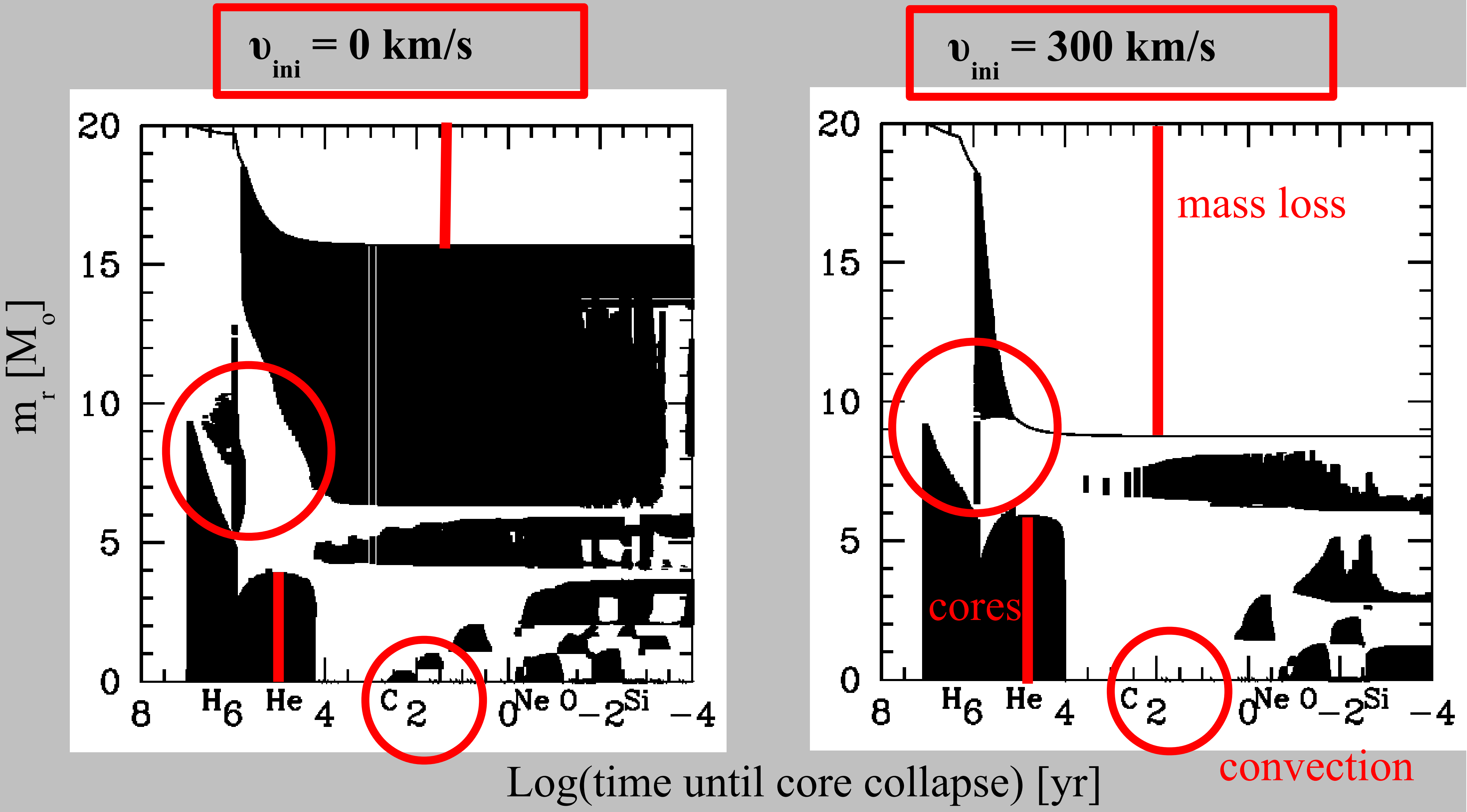
← Altair: pole brighter than equator: Effect compatible with von-Zeipel theorem (1924)

→ enhanced mass loss (+ anisotropic)

Kippenhahn Diagrams, $M_{ini} = 20\ M_o$



Kippenhahn Diagrams, $M_{ini} = 20\ M_o$



υ_{ini} = 0 km/s

υ_{ini} = 300 km/s

mass loss

cores

convection

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 η=~0.5
- AGB: Super winds? Dust Bloecker et al 1995, with η=~0.05
- LBV eruptions: continuous driven winds? Owocki et al
- …

What changes at low Z?

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

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

- α = 0.5-0.6 (Kudritzki & Puls 00, Ku02)

(Nugis & Lamers, Evans et al 05)

- α = 0.7-0.86 (Vink et al 00,01,05)

$Z(LMC) \sim Z_o/2.3$ => Mdot/1.5 – Mdot/2

$Z(SMC) \sim Z_o/7$ => Mdot/2.6 - Mdot/5

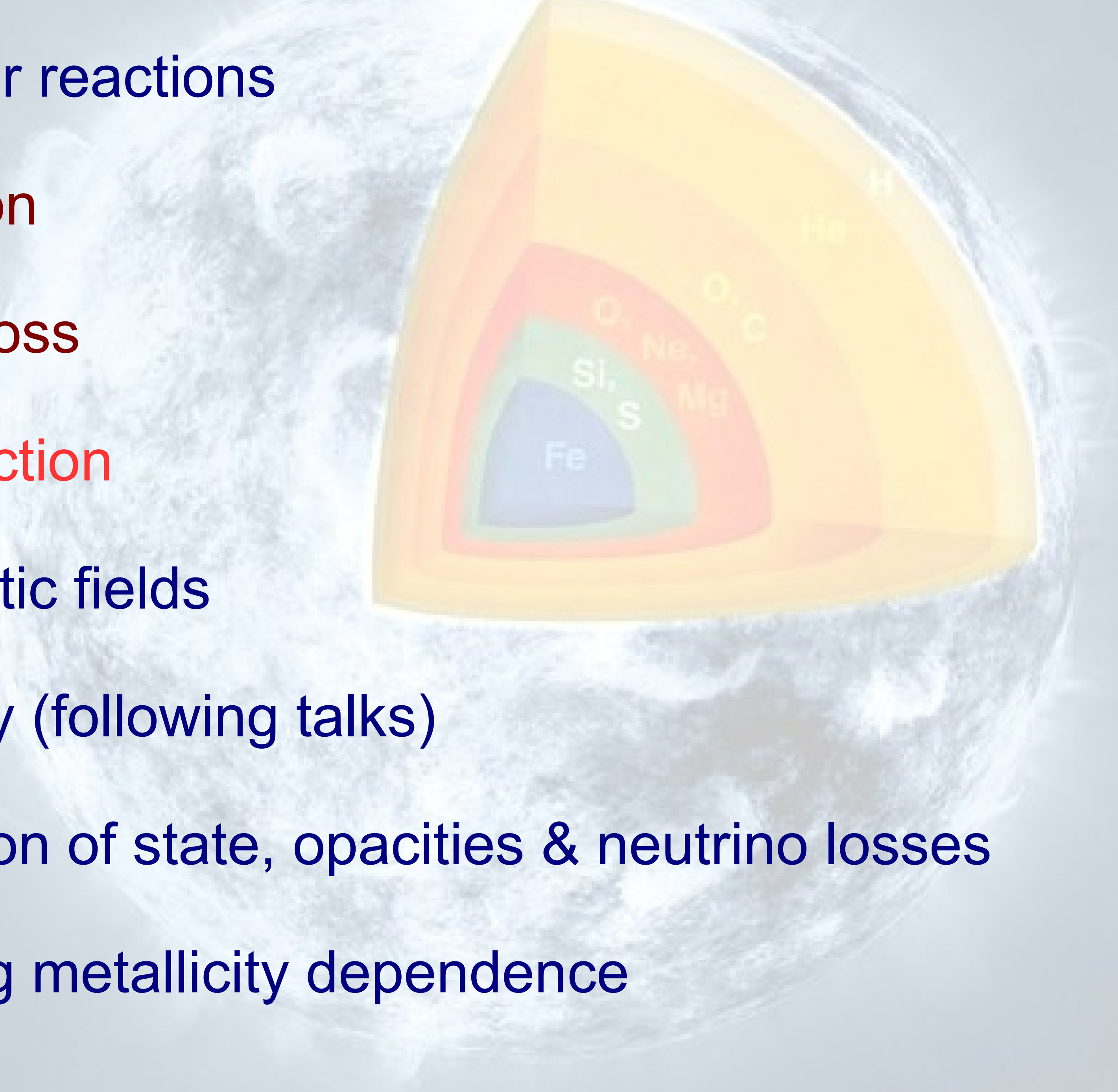
Mass loss at low Z still possible?

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

Mechanical mass loss ← critical rotation/ Eddington limit

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

Physical Ingredients



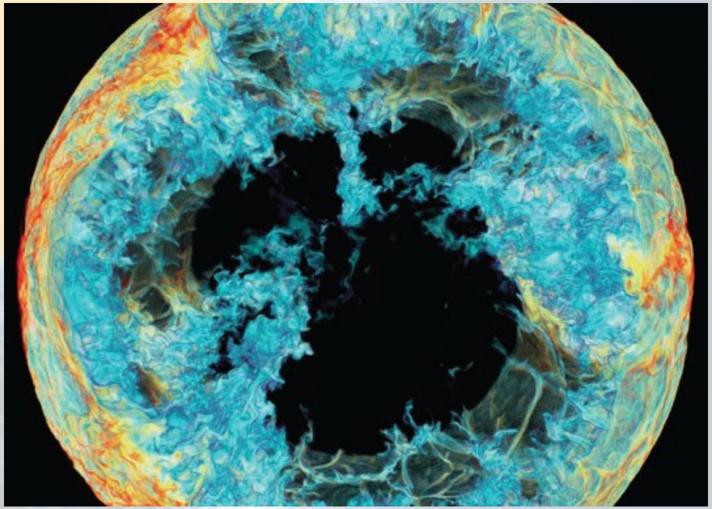
- Nuclear reactions
- Rotation
- Mass loss
- Convection
- Magnetic fields
- Binarity (following talks)
- Equation of state, opacities & neutrino losses

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 ($t_{conv} \sim$ 1s - 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

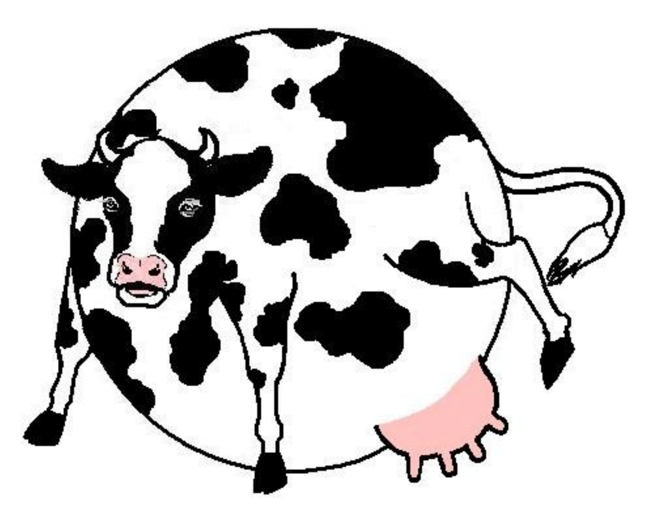
Advantages:

- 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

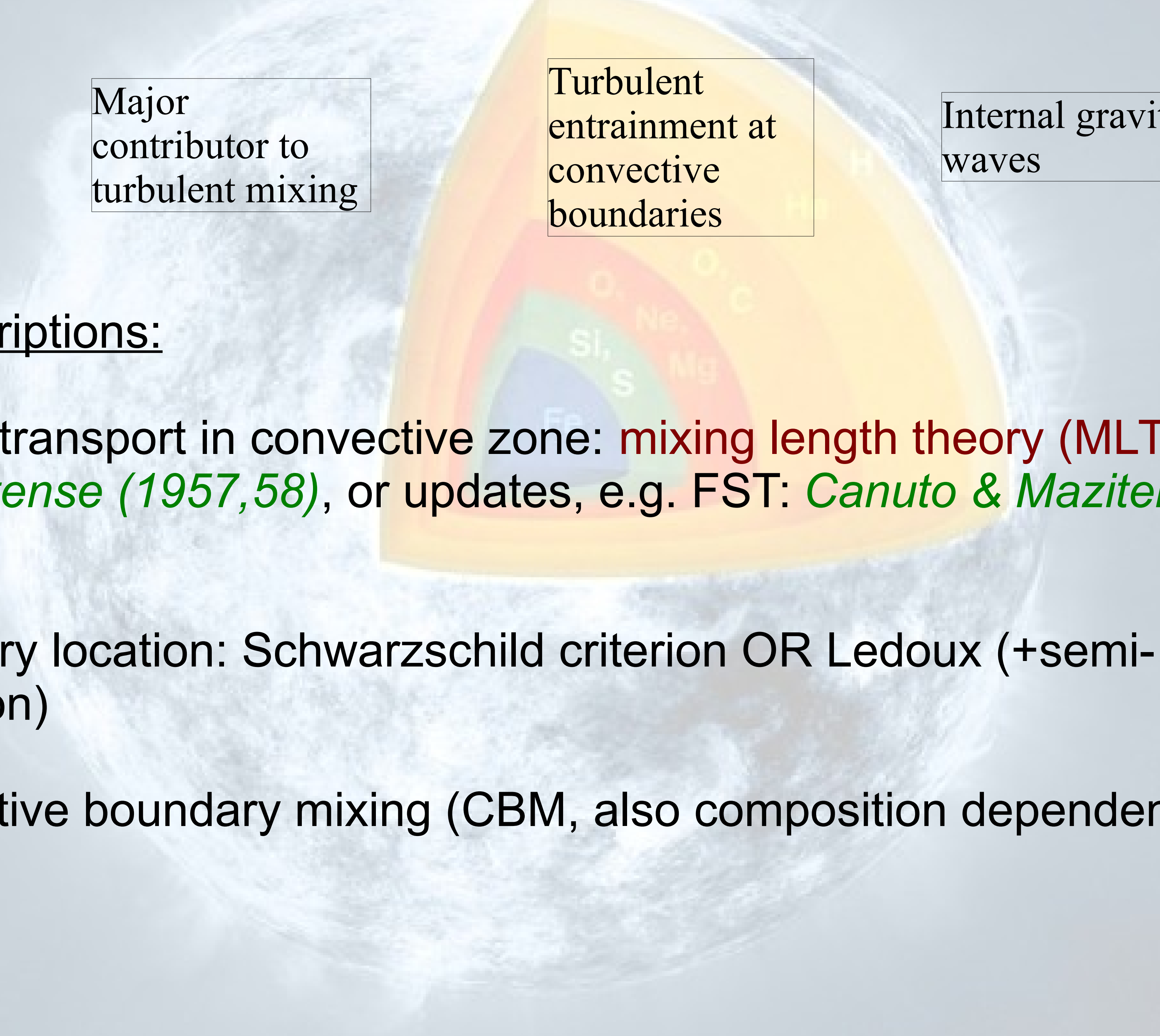
1D stellar models



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:

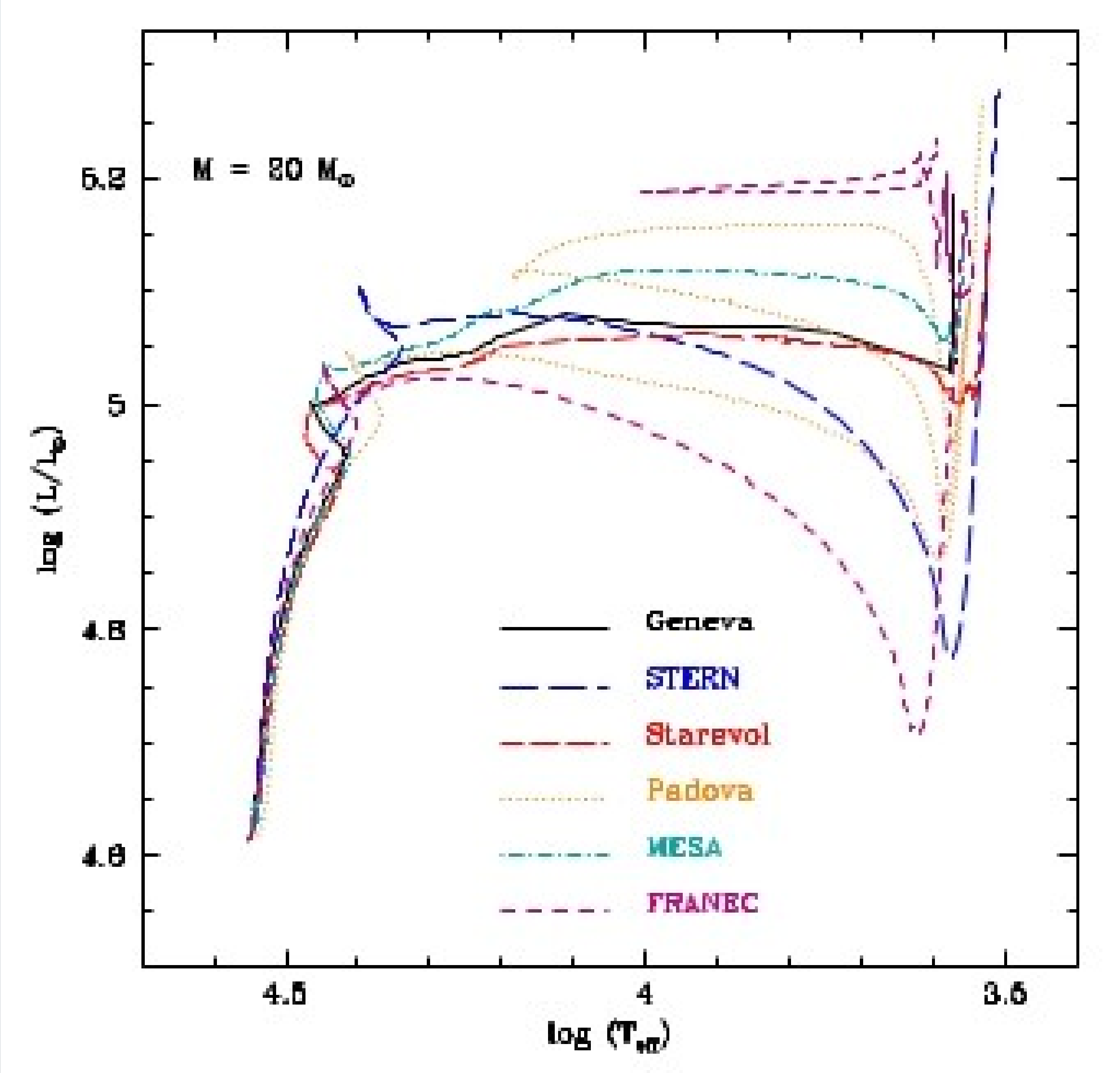
- Energy transport in convective zone: mixing length theory (MLT) *Bohm-Vitense (1957,58)*, or updates, e.g. FST: *Canuto & Mazitelli (1991)*

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

- Convective boundary mixing (CBM, also composition dependent)

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

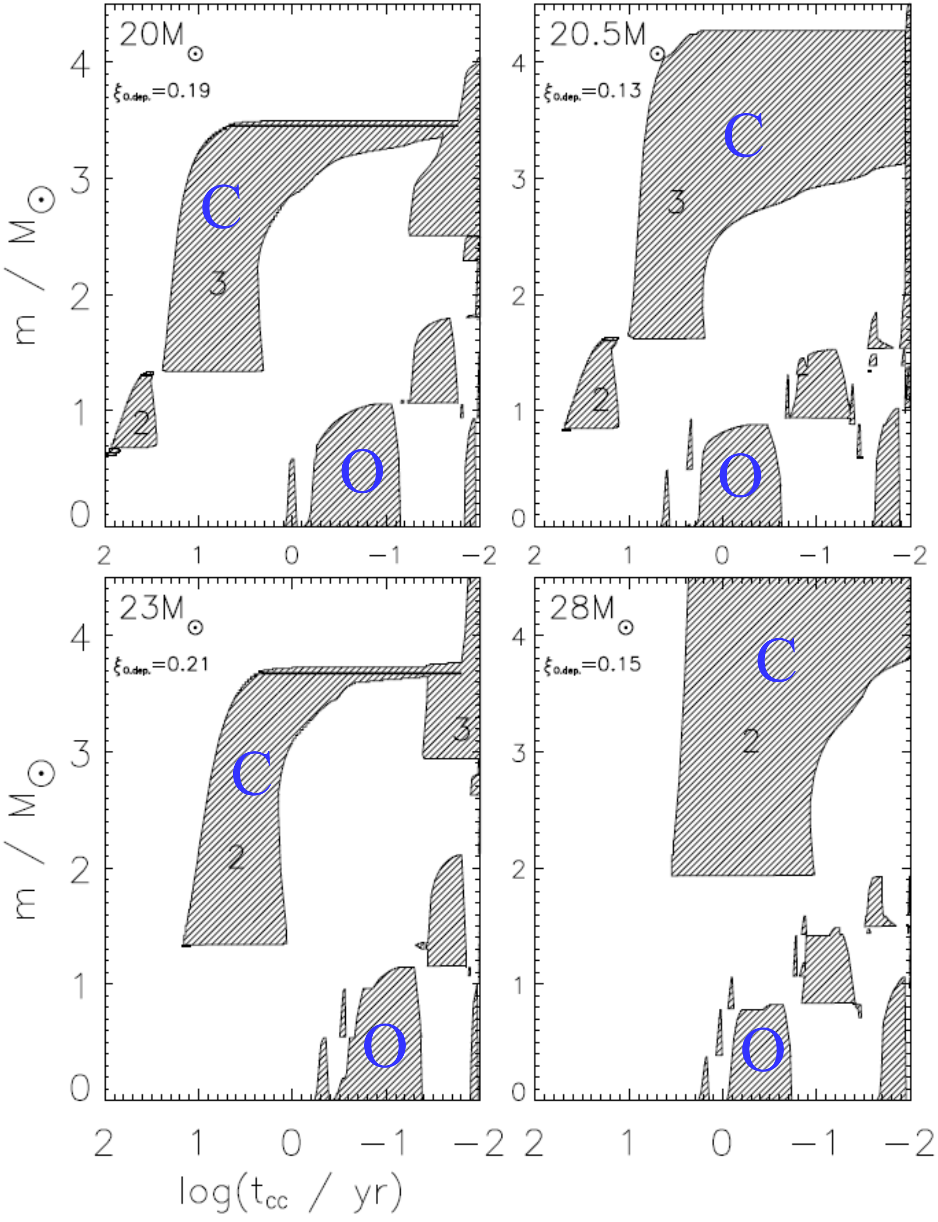


FIG. 13.— Convective history of four models showing the major

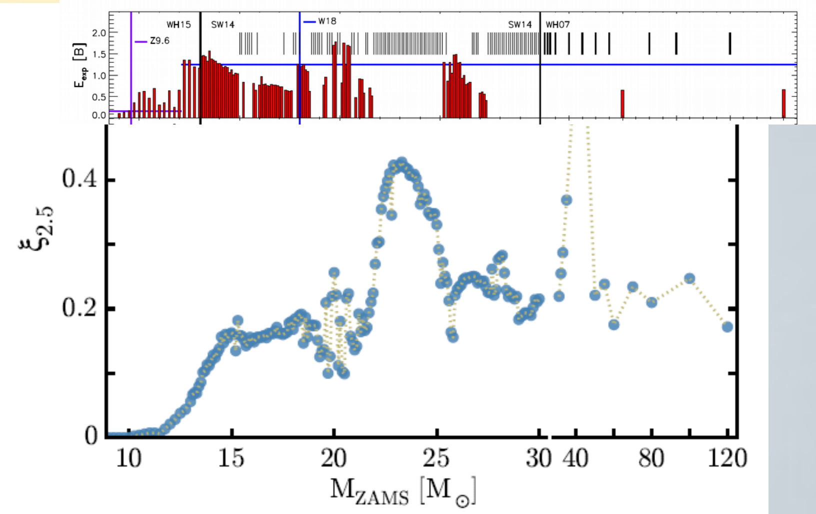
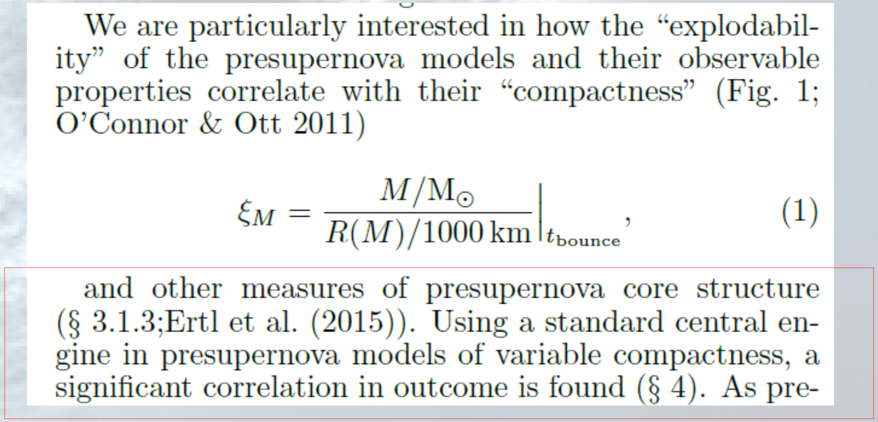


FIG. 1.— The compactness parameter, $\xi_{2.5}$, (eq. (1); O'Connor & Ott 2011) characterizing the inner 2.5 $M_\odot$ of the presupernova star is shown as a function of zero-age main sequence (ZAMS) mass for all 200 models between 9.0 and 120 $M_\odot$. The compactness

Non-monotonic behaviour!



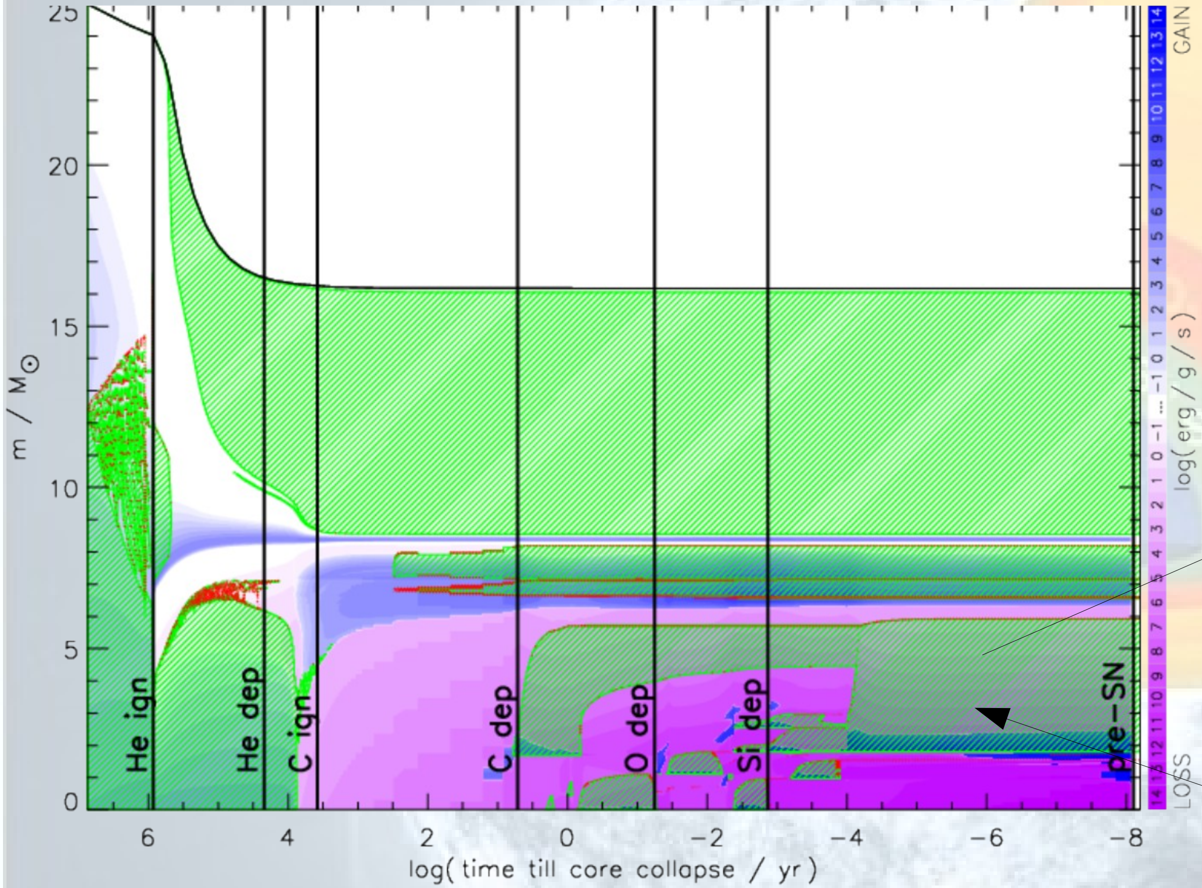
We are particularly interested in how the "explodability" of the presupernova models and their observable properties correlate with their "compactness" (Fig. 1; O'Connor & Ott 2011)

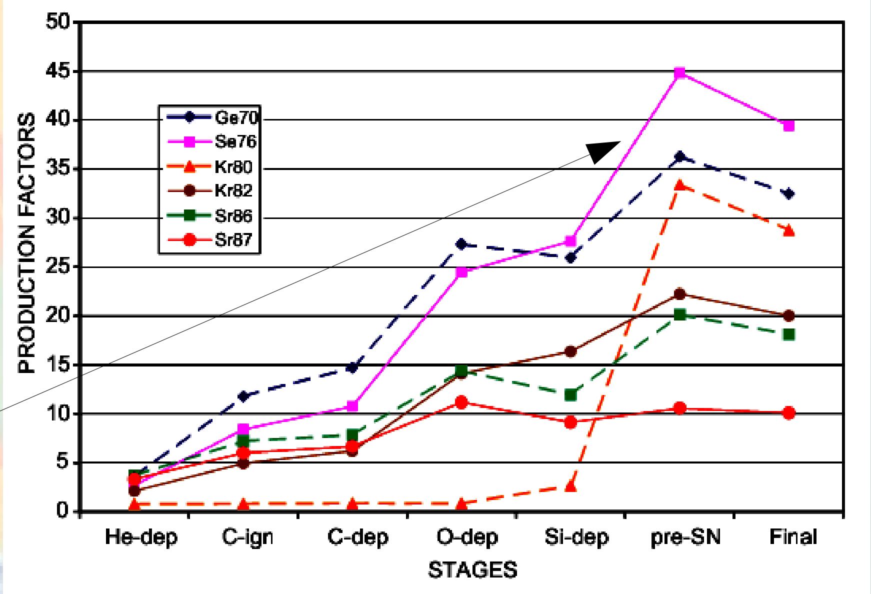
$$\xi_M = \left.\frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}\right|_{t_\mathrm{bounce}}, \qquad (1)$$

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

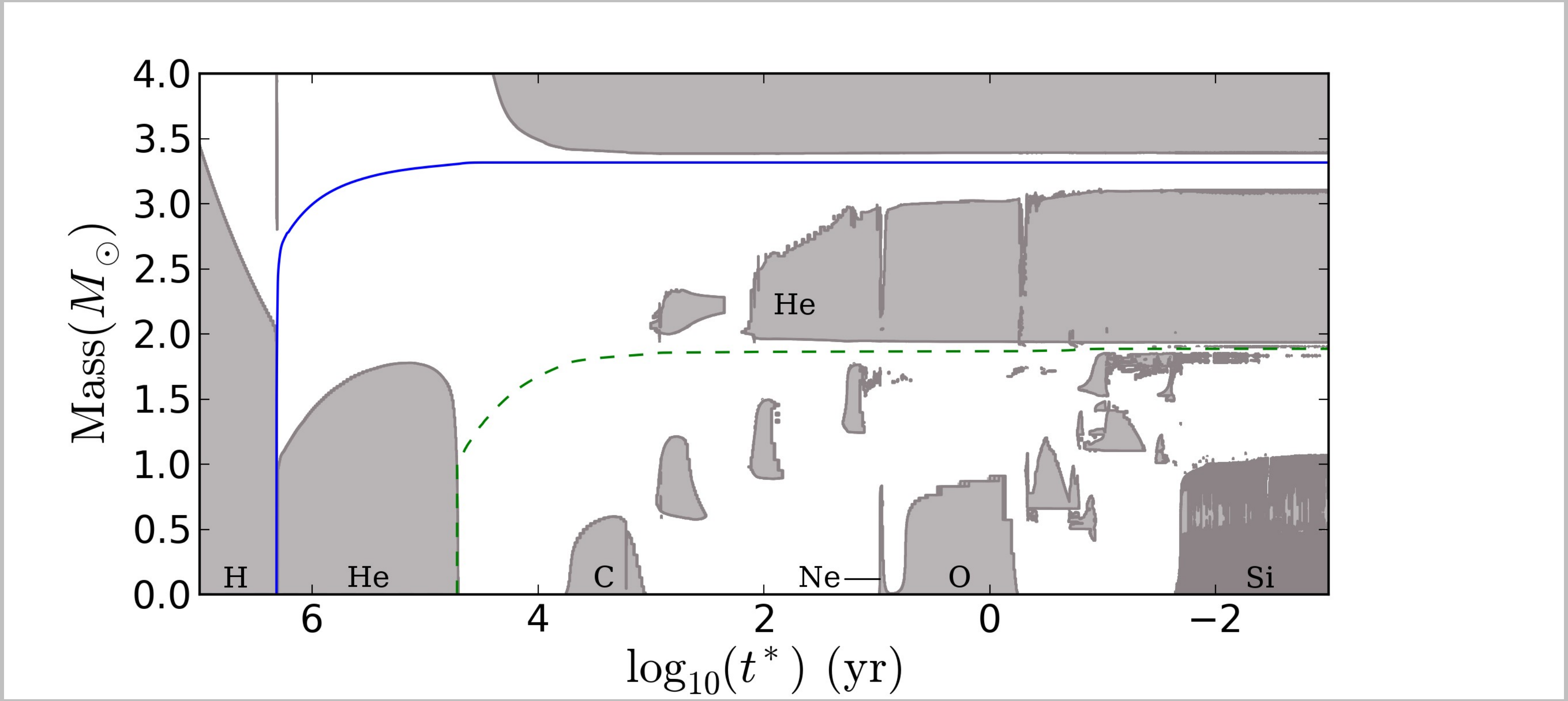
Convection physics uncertainties affect fate of models: strong/weak/failed explosions!!!

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

7-15 M_o models ← MESA stellar evolution code: http://mesa.sourceforge.net/

Paxton et al 10,12

12 M_o is a typical massive star:

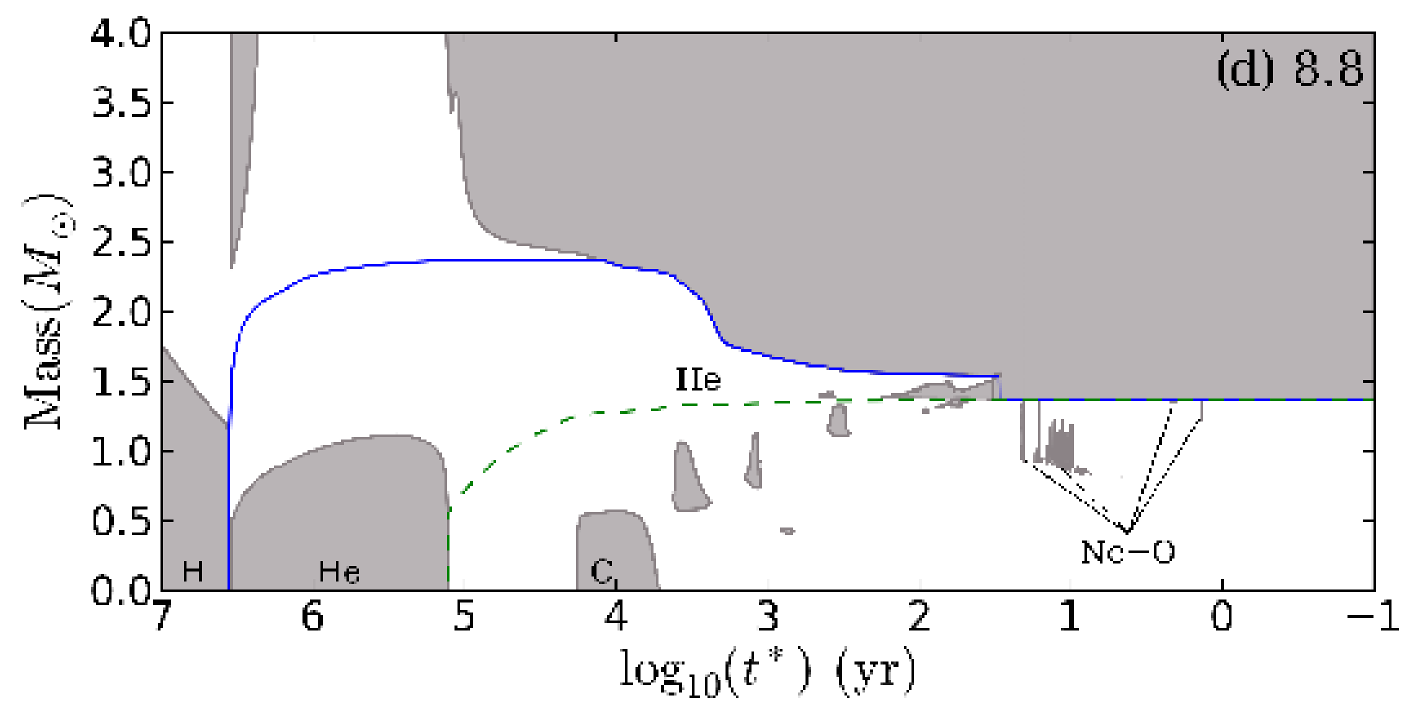


All burning stages ignited centrally. Fate: Fe-CCSN

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_o failed massive star:



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 ...

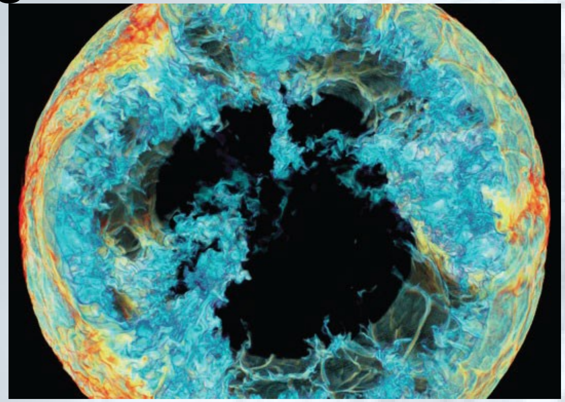
Ne-b. starts off-centre but does not reach the centre.
MESA → Oxygen deflagration

Fate: ECSN!

Key uncertainties: convective boundary mixing, mass loss

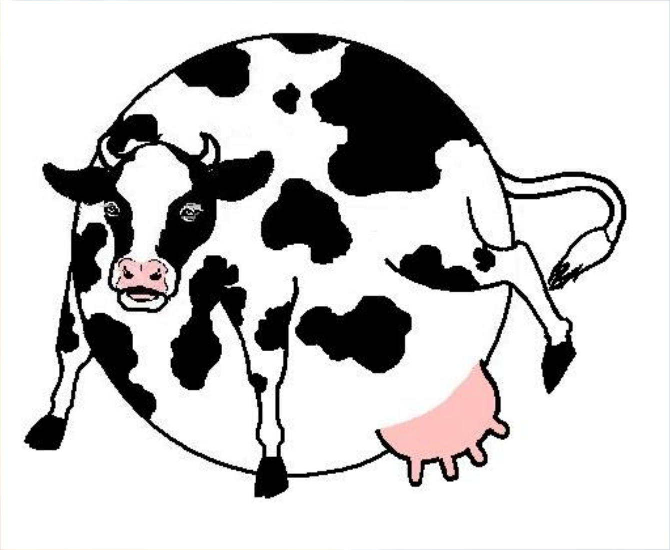
Way Forward: 1 to 3 to 1D link

Targetted 3D simulations

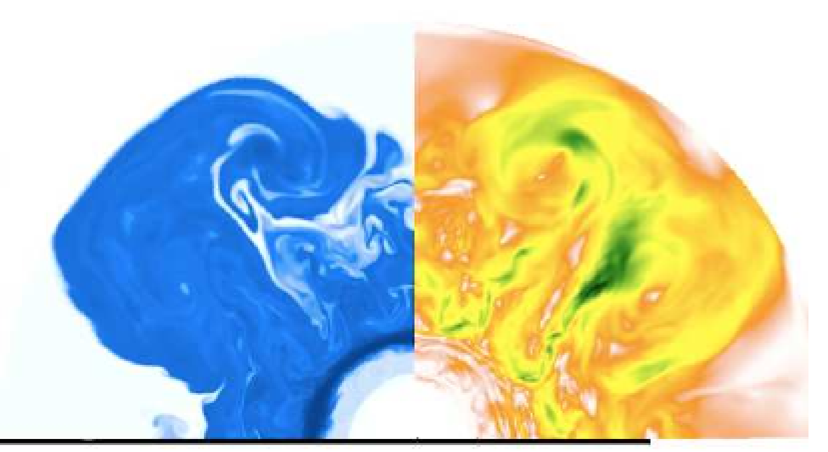


Herwig et al 06, Herwig, Woodward et al 2013

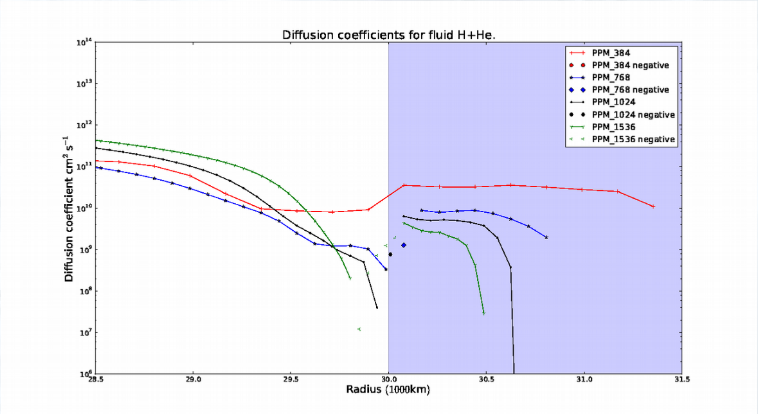
Uncertainties in 1D



+asteroseismology



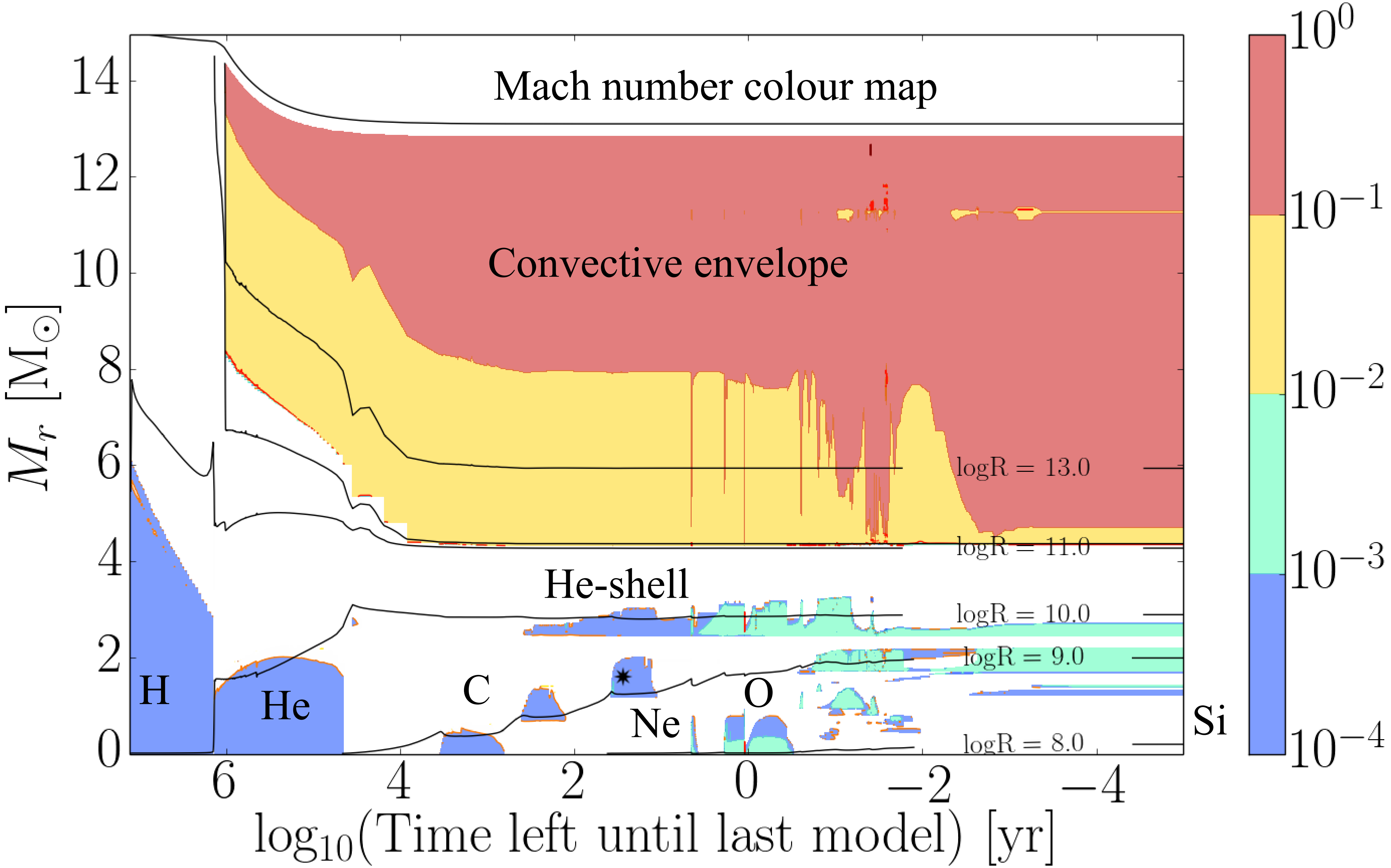
e.g. Arnett & Meakin 2011, ...
Mocak et al 2011,
Viallet et al 2013, ...



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

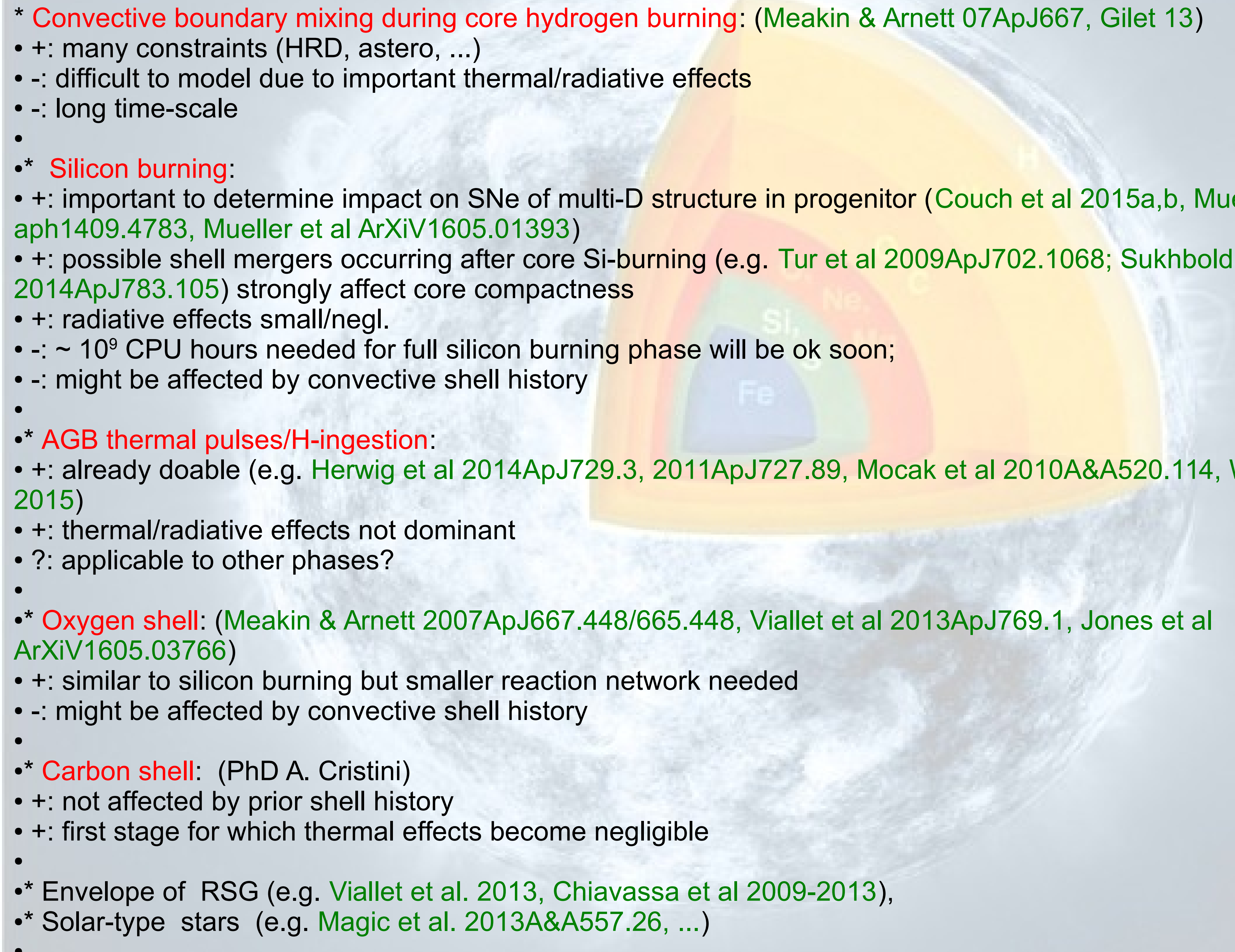
→ Determine effective coefficient / improve theoretical prescriptions

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.
- -: ~ 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, ...)
-

Where to Start? Carbon burning shell

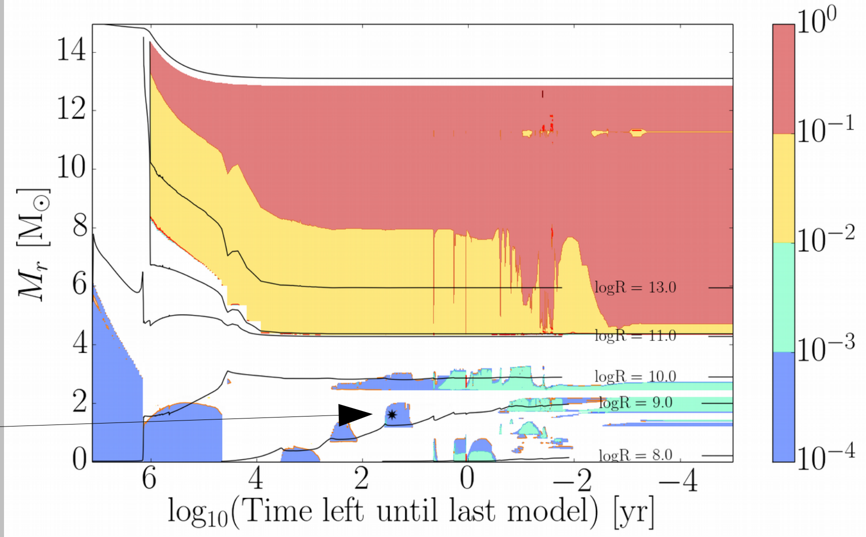
- “Simple” convective history before C-shell

- 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

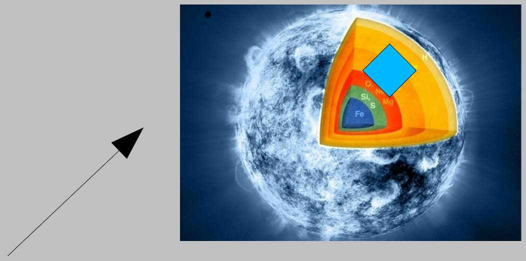


C-shell

C-shell Setup & Approximations

- PROMPI code Meakin, Arnett et al 2007-...

- Initial conditions provided by stellar model from GENEC:



$15M_\odot$, non-rotating at solar metallicity (see previous slide)

- “Box in a star” (plane-parallel) simulation using Cartesian co-ordinates

- Parameterised gravitational acceleration and ^{12}C+^{12}C 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

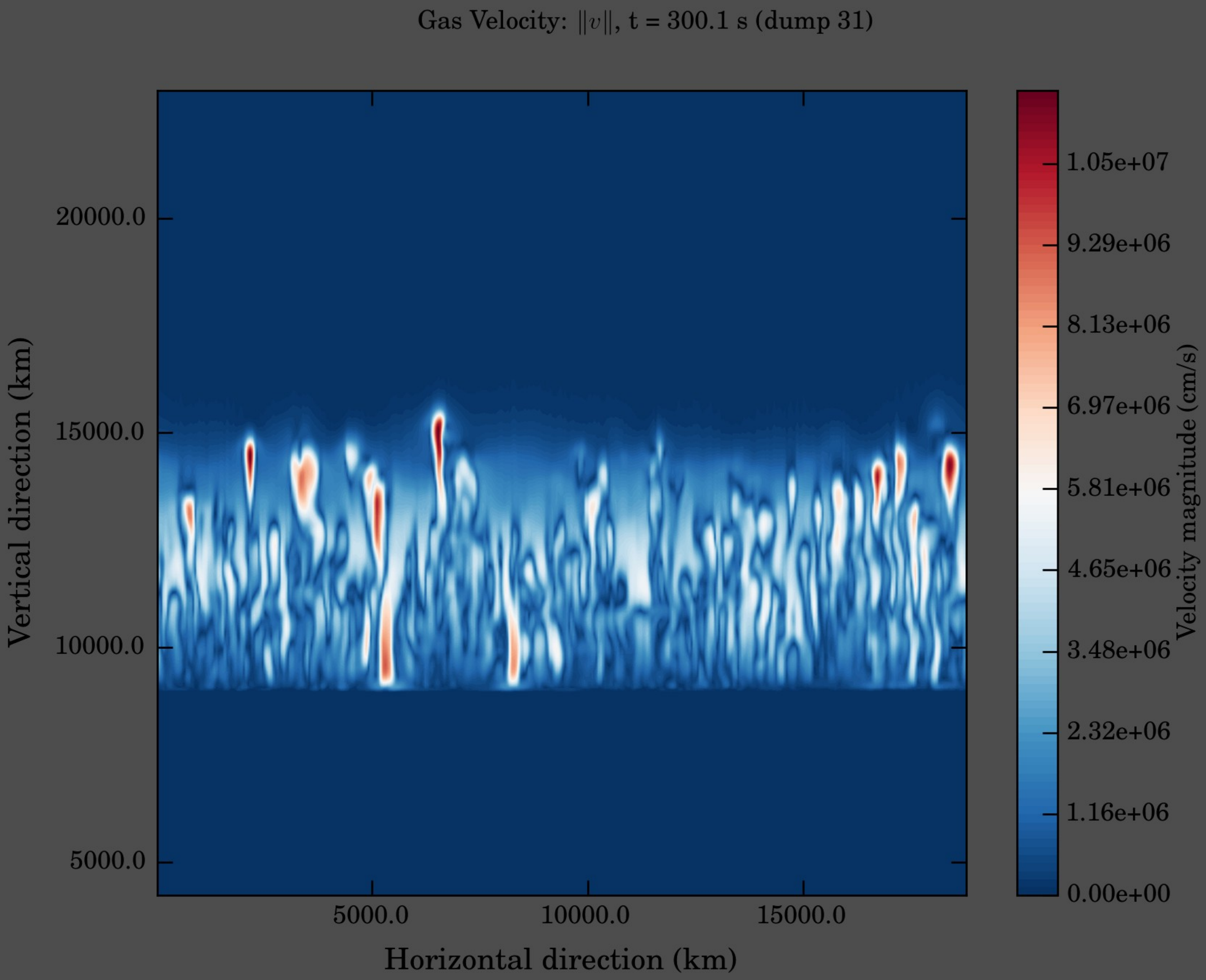
- Constant abundance of ^{12}C fuel over simulation time

- 4 resolutions: lrez: 128^3, mrez: 256^3, hrez: 512^3, vhrez: 1024^3

C-shell Simulations

384^3 res.

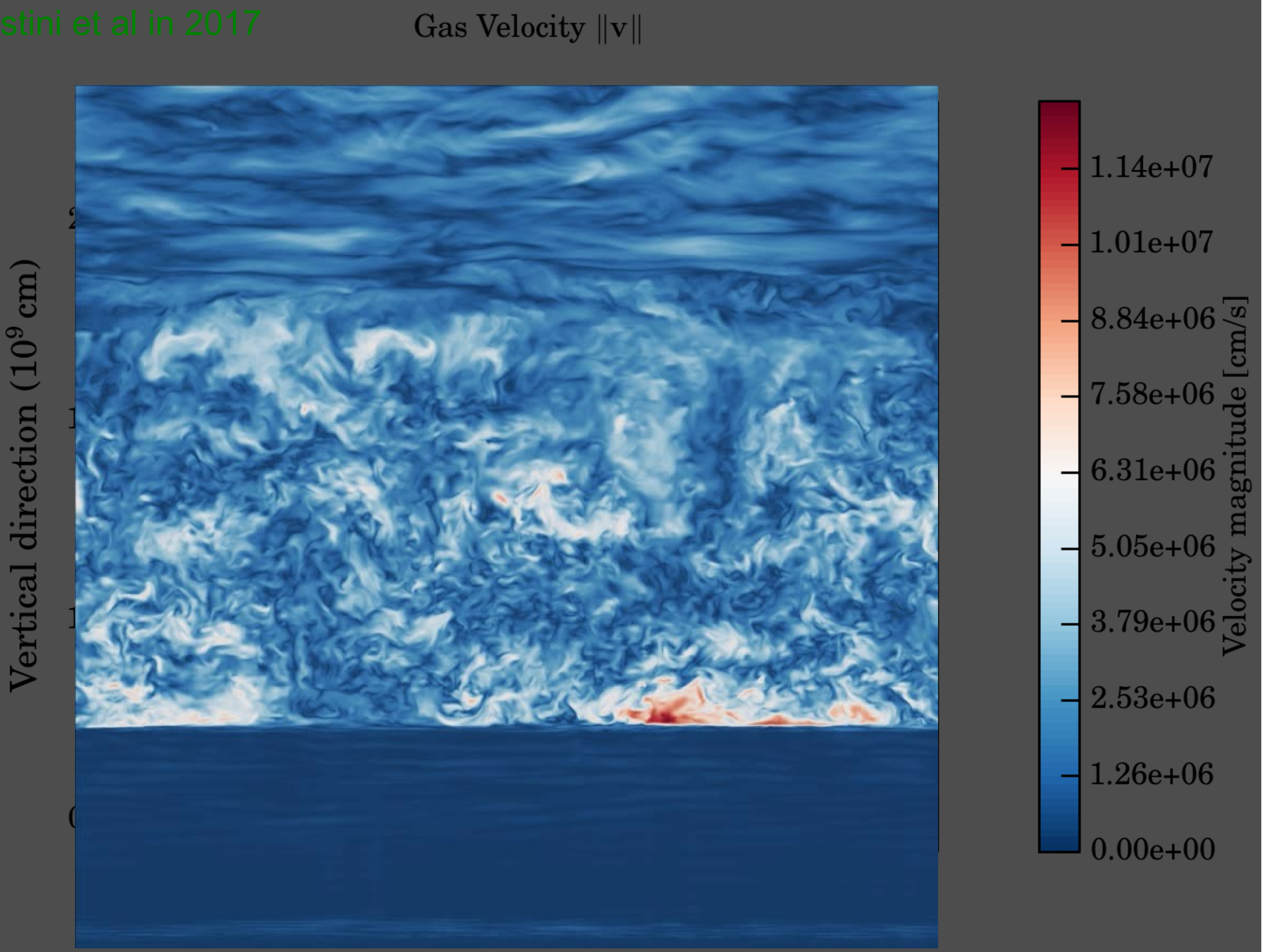
run



Cristini et al in 2017

C-shell Simulations: $|v|$ movie

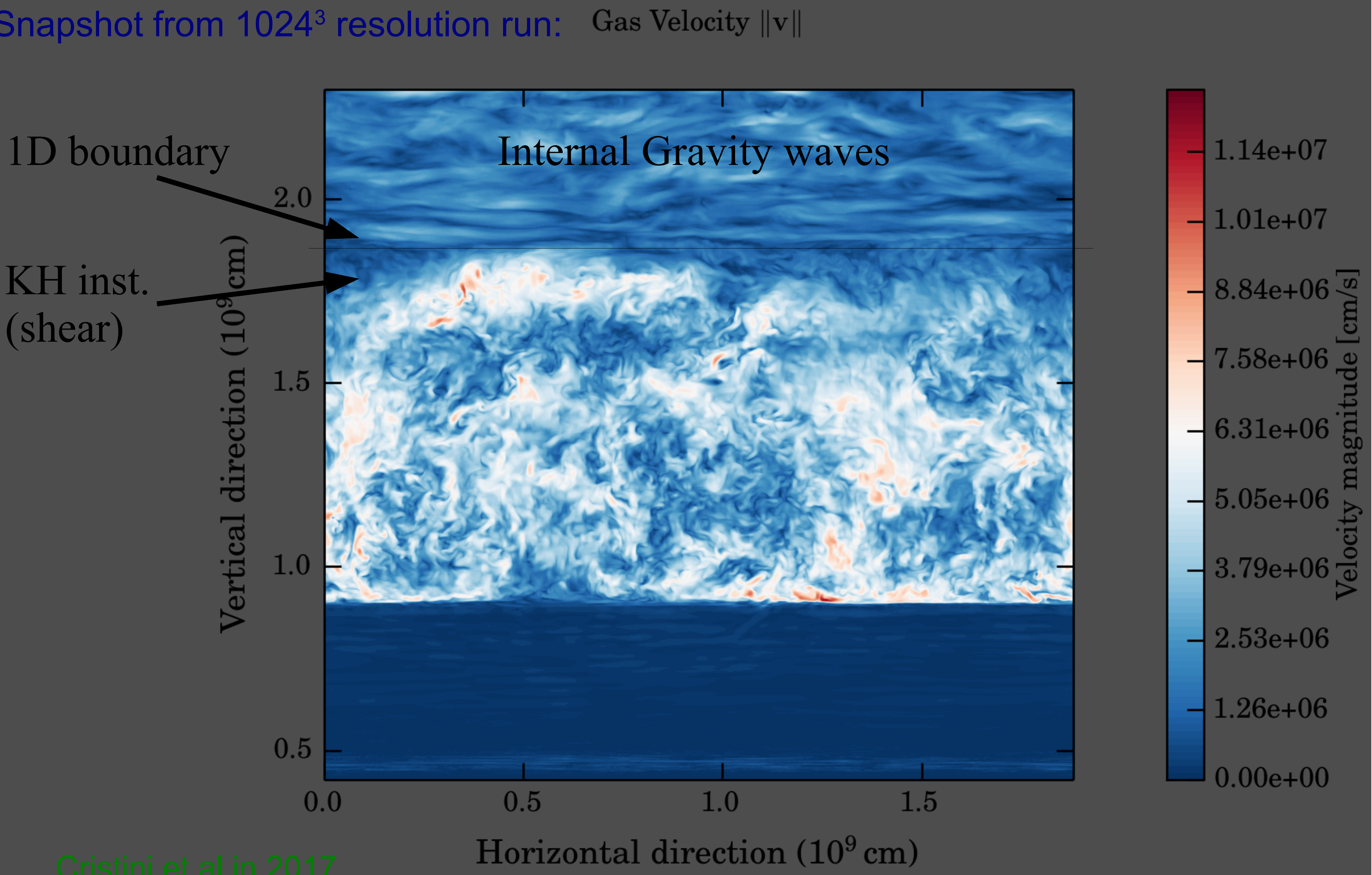
Cristini et al in 2017



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

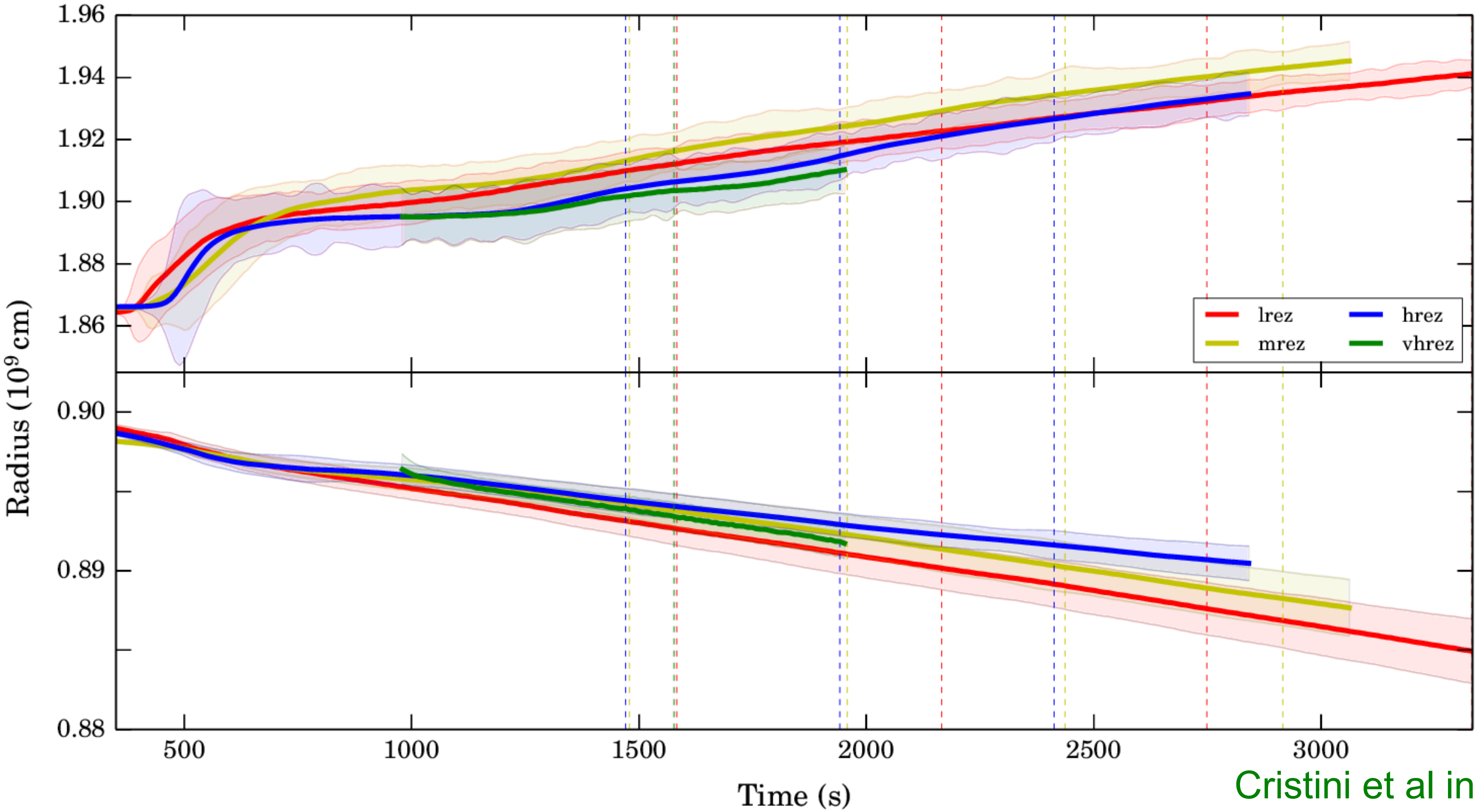
C-shell Simulations

Snapshot from 1024^3 resolution run:



Cristini et al in 2017

Boundary Entrainment

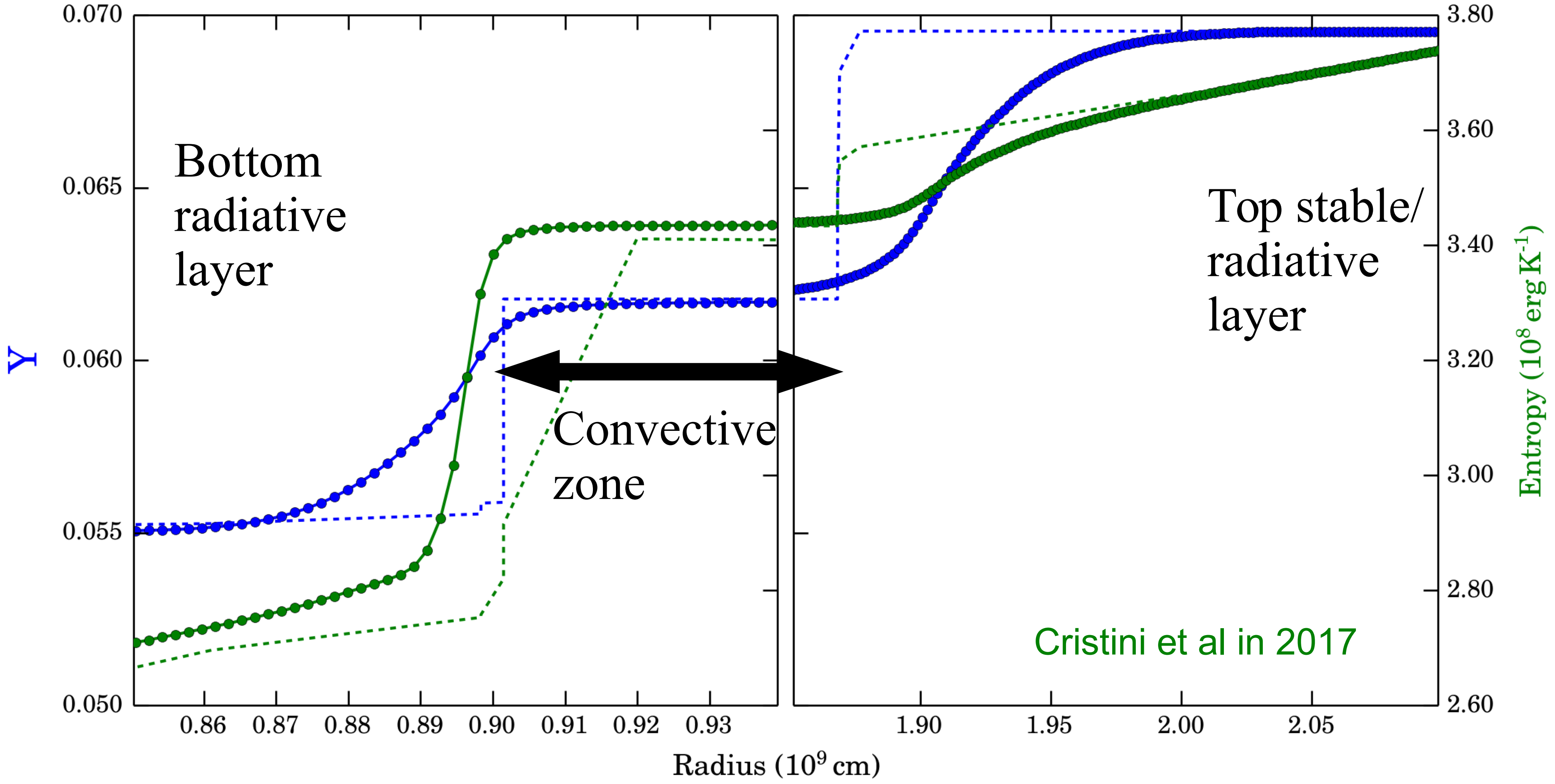


Cristini et al in prep

Top: u_e ~ 20,000 cm/s; Bottom: u_e ~ 3,000 cm/s. *Rescaled for eps_{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.

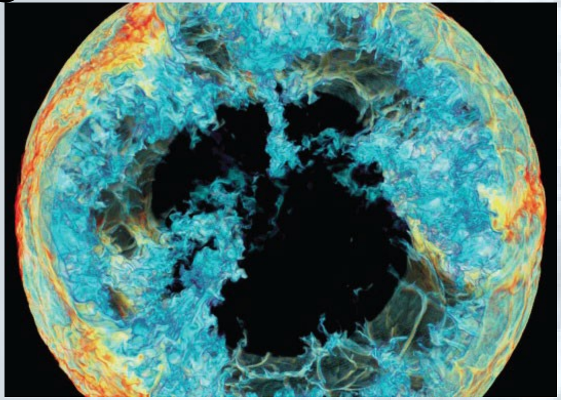
3D versus 1D



- Improved prescriptions for CBM needed!

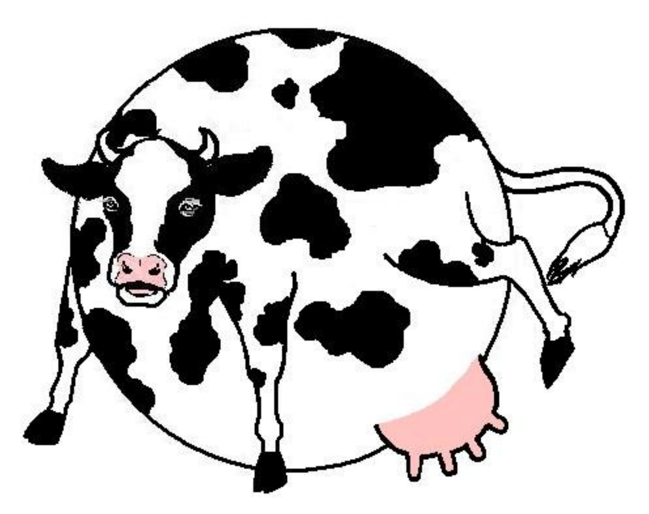
Way Forward: 1 to 3 to 1D link

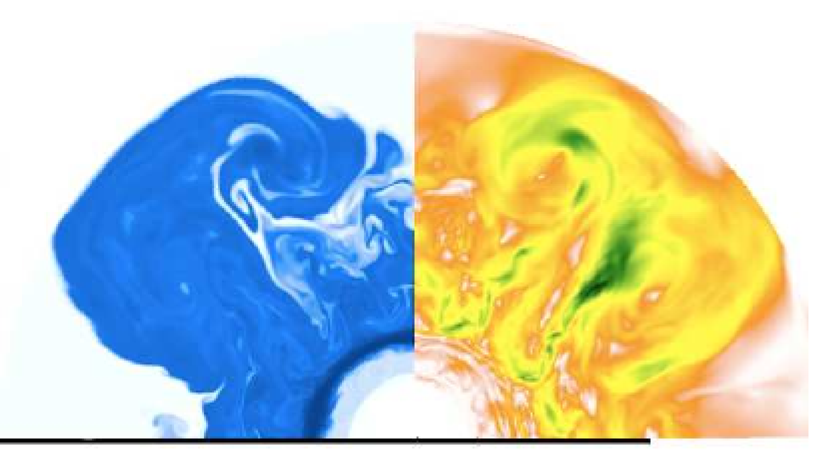
Targetted 3D simulations



Herwig et al 06, Herwig, Woodward et al 2013

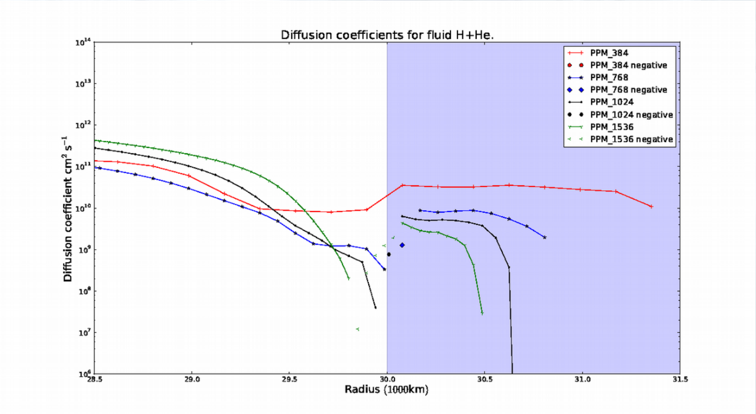
Uncertainties in 1D





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

+asteroseismology



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

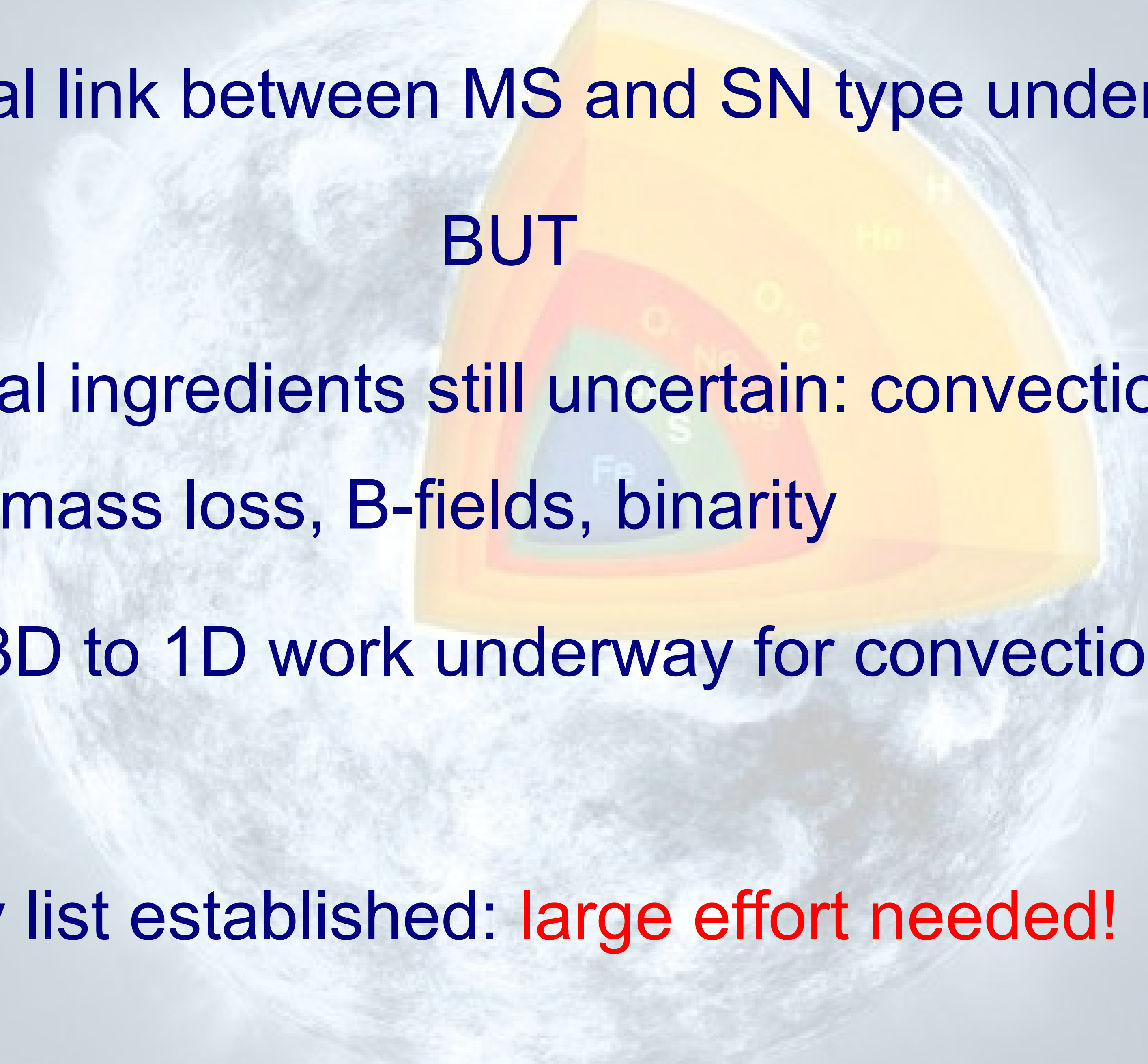
→ Determine effective coefficient / improve theoretical prescriptions

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

Conclusions & Outlook



- General link between MS and SN type understood

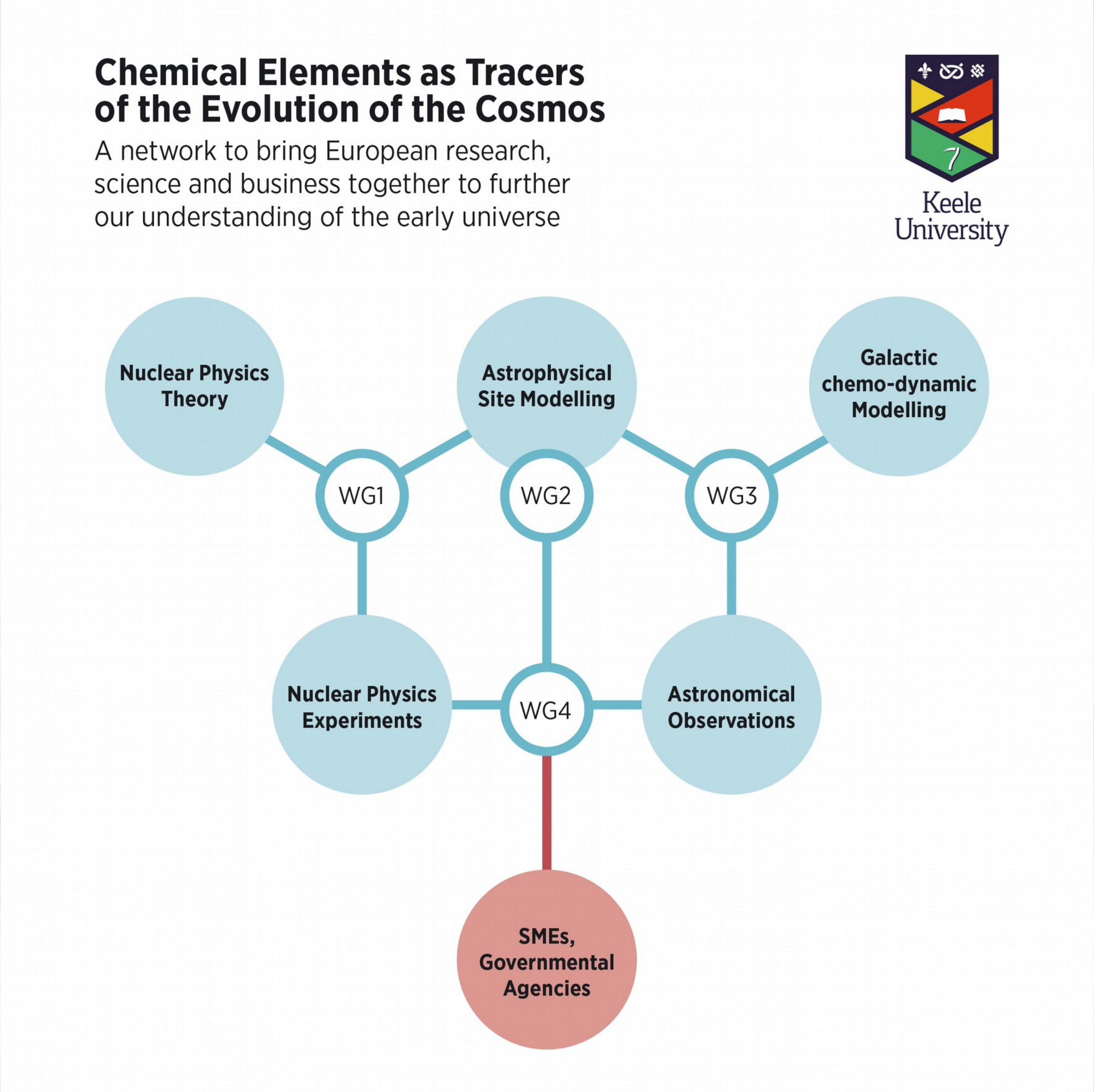
BUT

- 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

Keele University

Nuclear Physics Theory

Astrophysical Site Modelling

Galactic chemo-dynamic Modelling

WG1

WG2

WG3

Nuclear Physics Experiments

WG4

Astronomical Observations

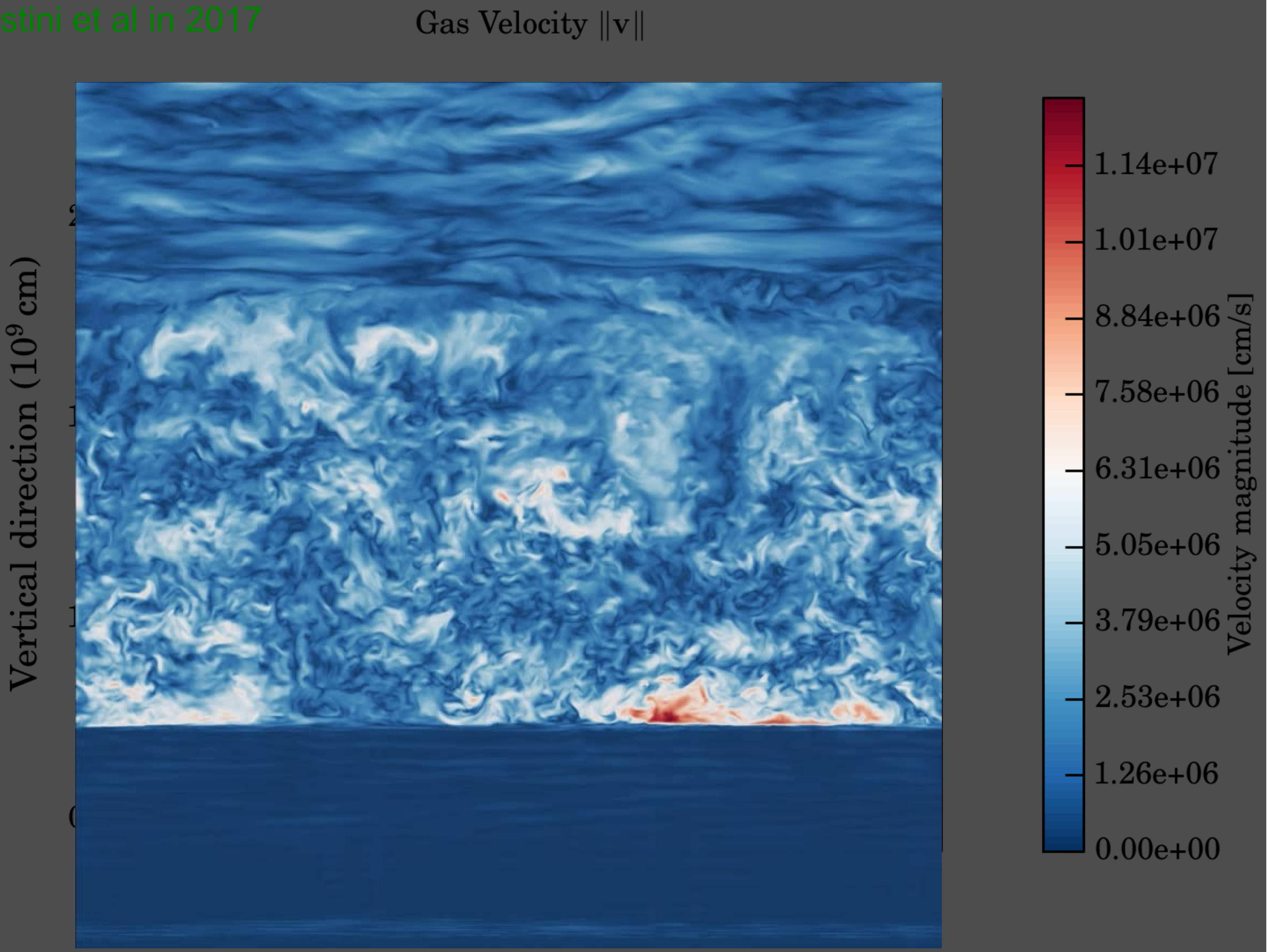
SMEs, Governmental Agencies

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

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

C-shell Simulations: $|v|$ movie

Cristini et al in 2017



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

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

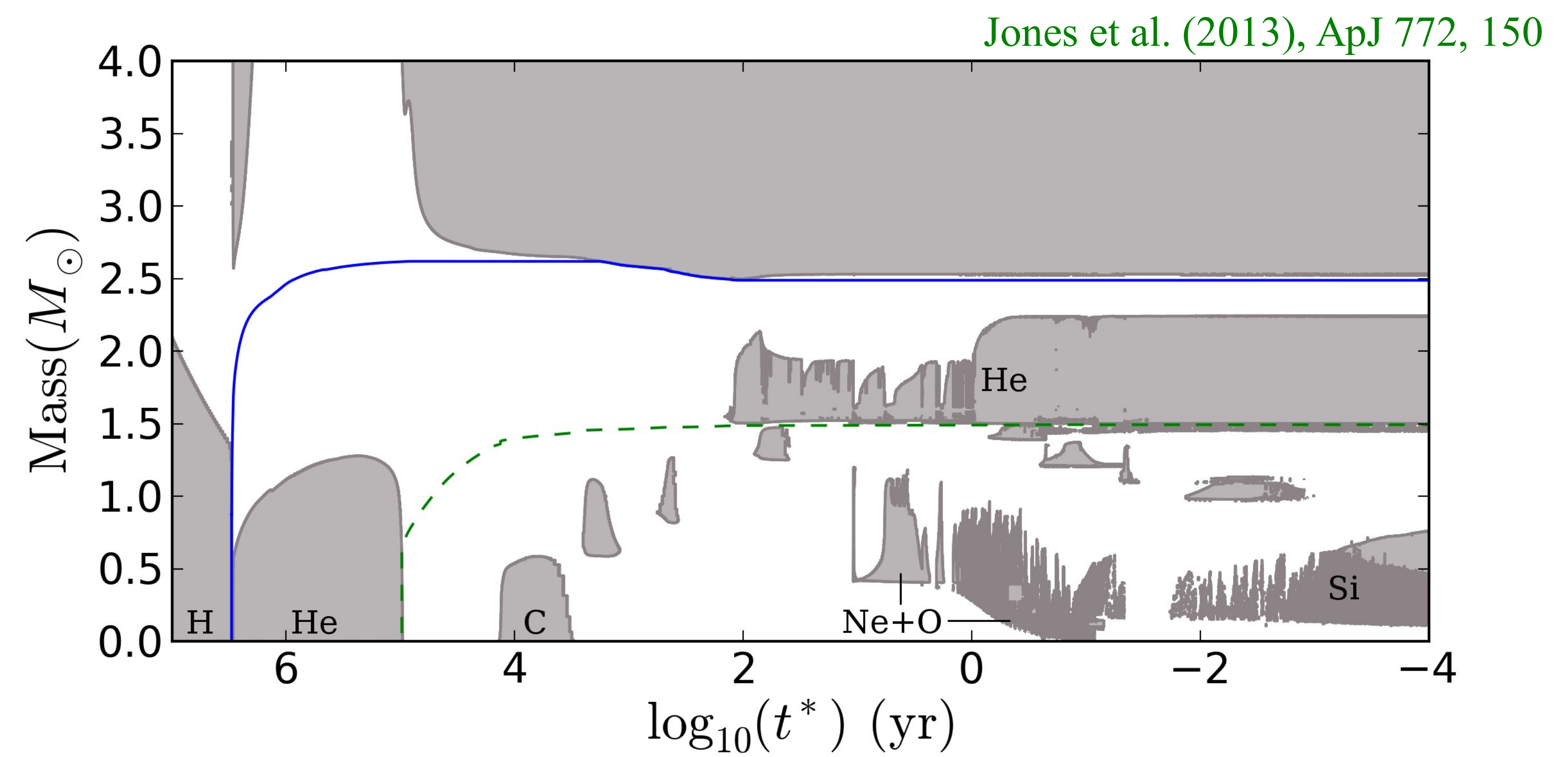
Textbooks:

- 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

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

9.5 M_o still a massive star:



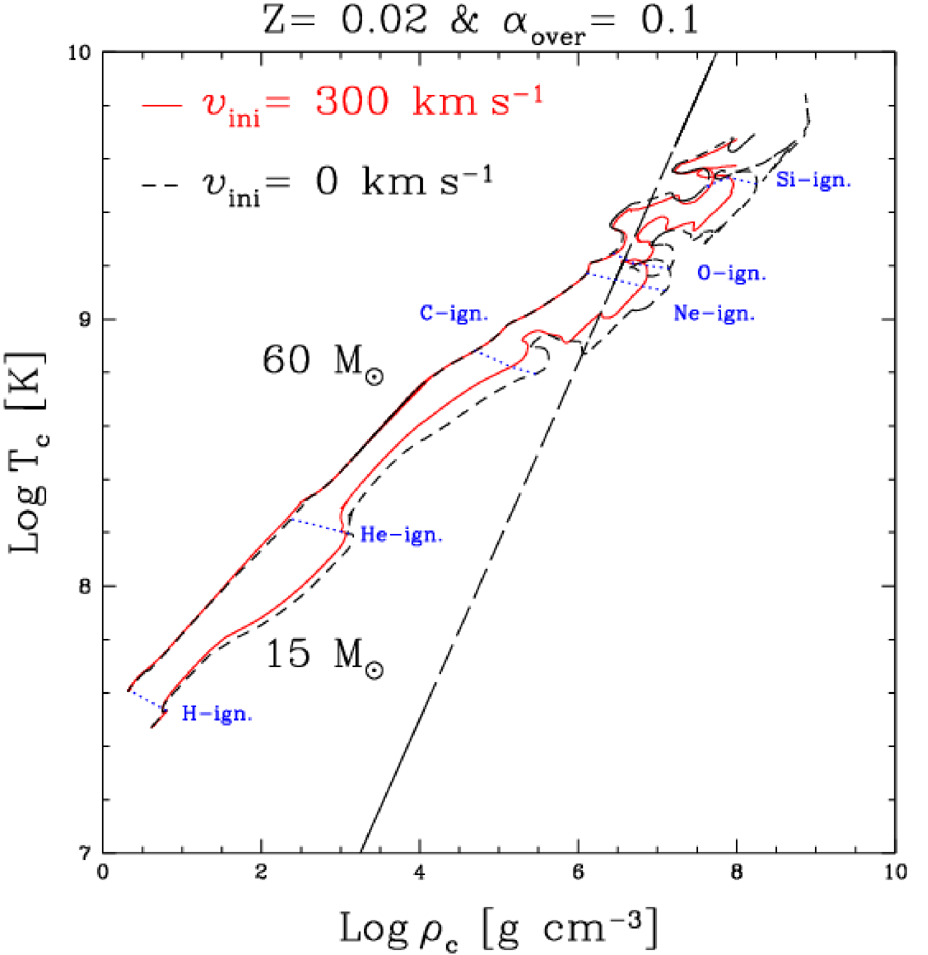
Ne-Si burning stages ignited off-centre. Fate: still Fe-CCSN

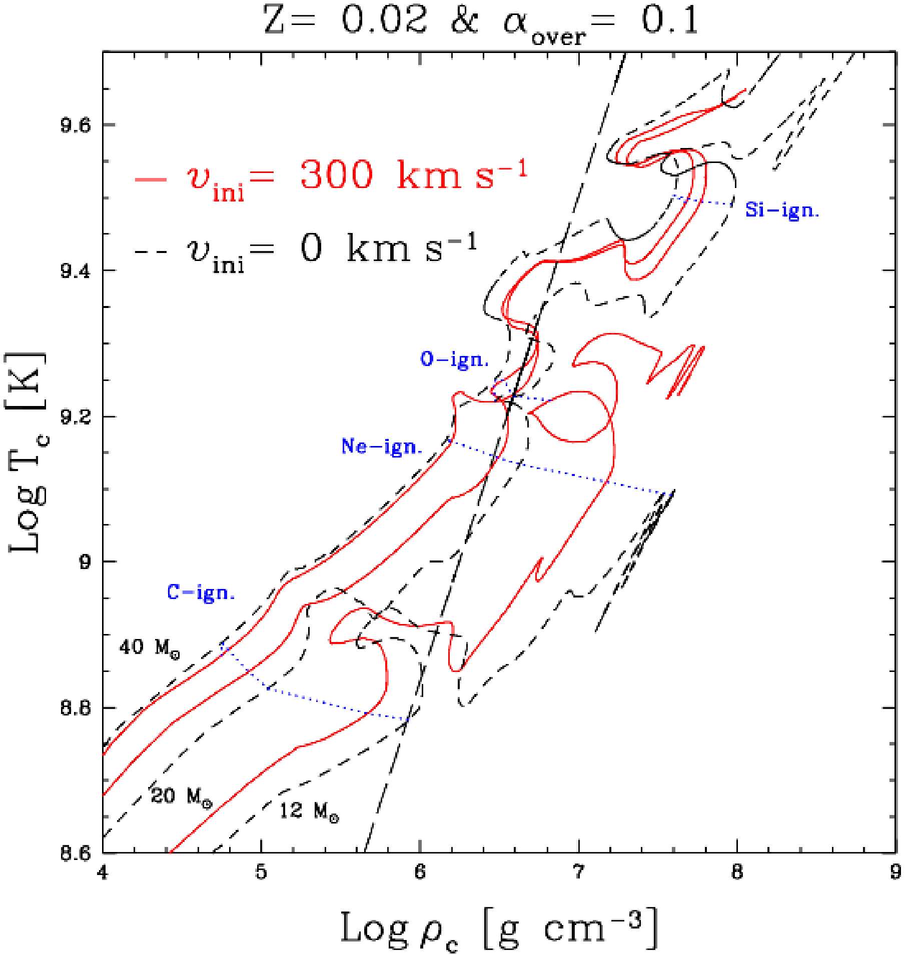
Simulations include 114-isotope network!

Massive Stars

M<~20 M_o : Rotational mixing dominates → bigger cores

M>~30 M_o : mass loss dominates → ~ or smaller cores



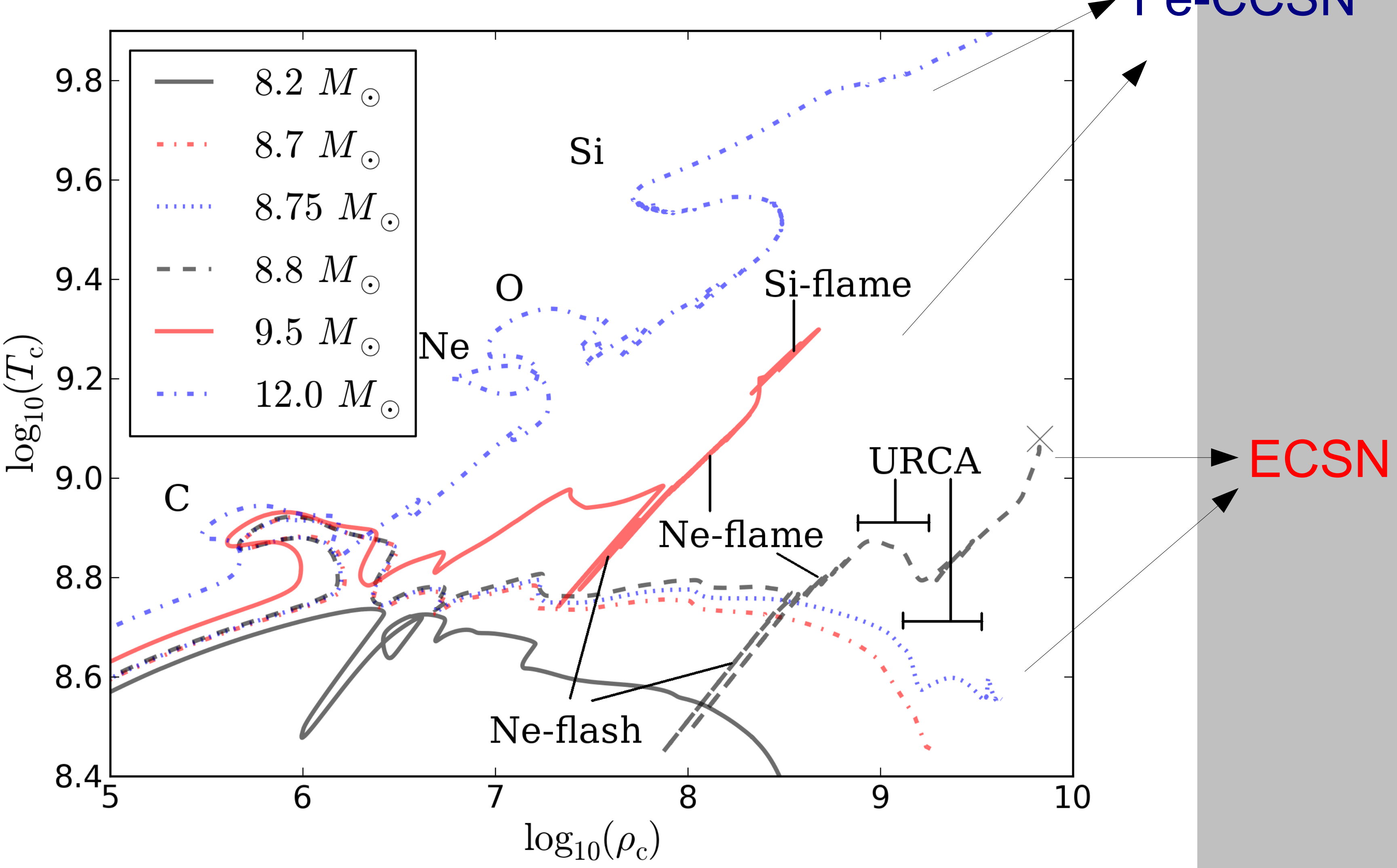


CO-core mass & C/O ratio: key parameters that determine evolution during late stages but things are complicated

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

7-15 M_o models ← MESA stellar evolution code:

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



Fe-CCSN

ECSN

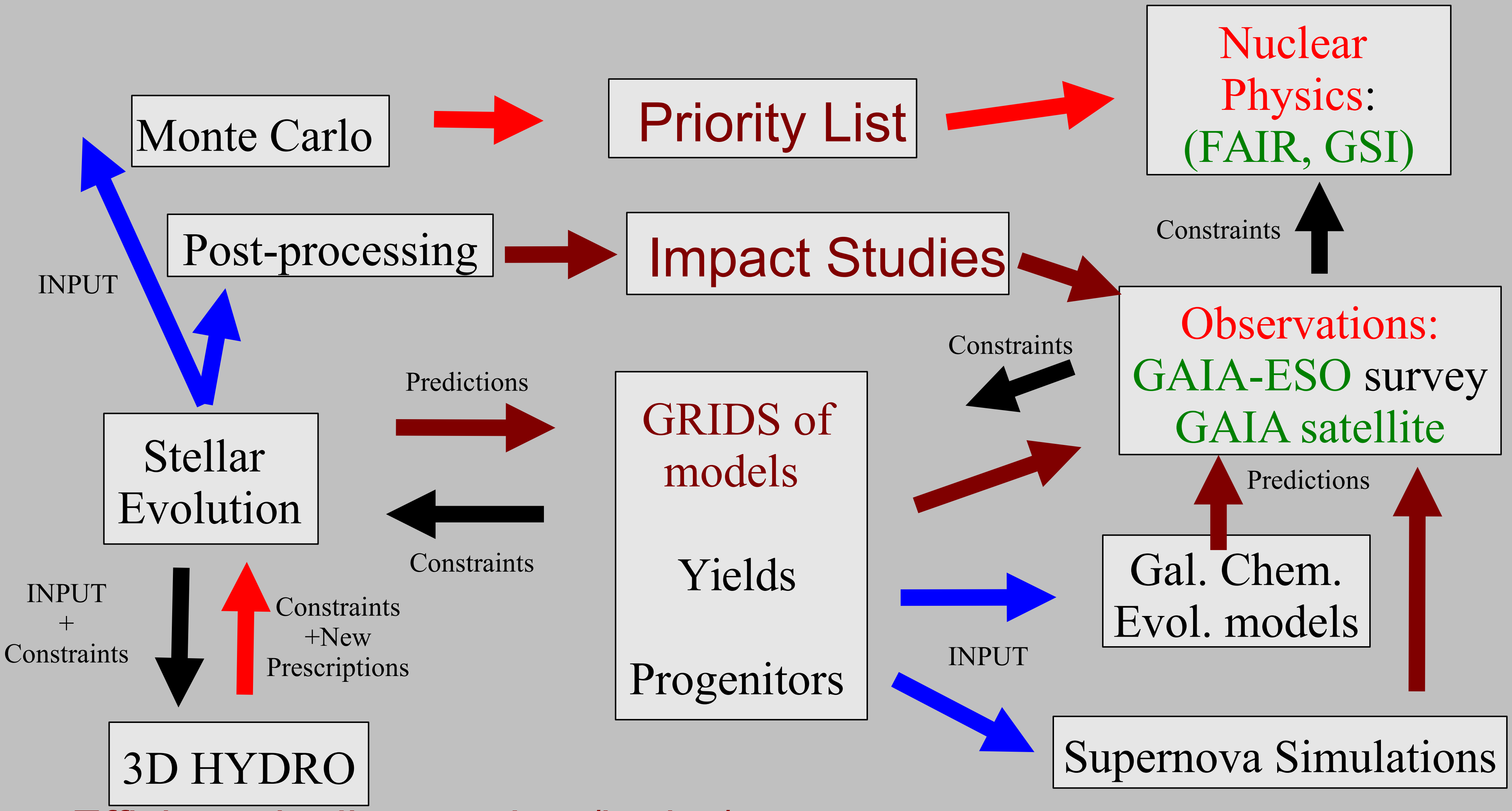
Both SAGB and failed massive stars may produce ECSN

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

Stellar HYdrodynamics Nucleosynthesis & Evolution (SHYNE) Project

ERC Starting grant: 2012-2017

TOOL SUITE → DATASETS → IMPACT



Monte Carlo

Post-processing

INPUT

Stellar Evolution

INPUT + Constraints

Constraints +New Prescriptions

3D HYDRO

Predictions

Constraints

Priority List

Impact Studies

GRIDS of models

Yields

Progenitors

Nuclear Physics: (FAIR, GSI)

Constraints

Observations: GAIA-ESO survey GAIA satellite

Constraints

Predictions

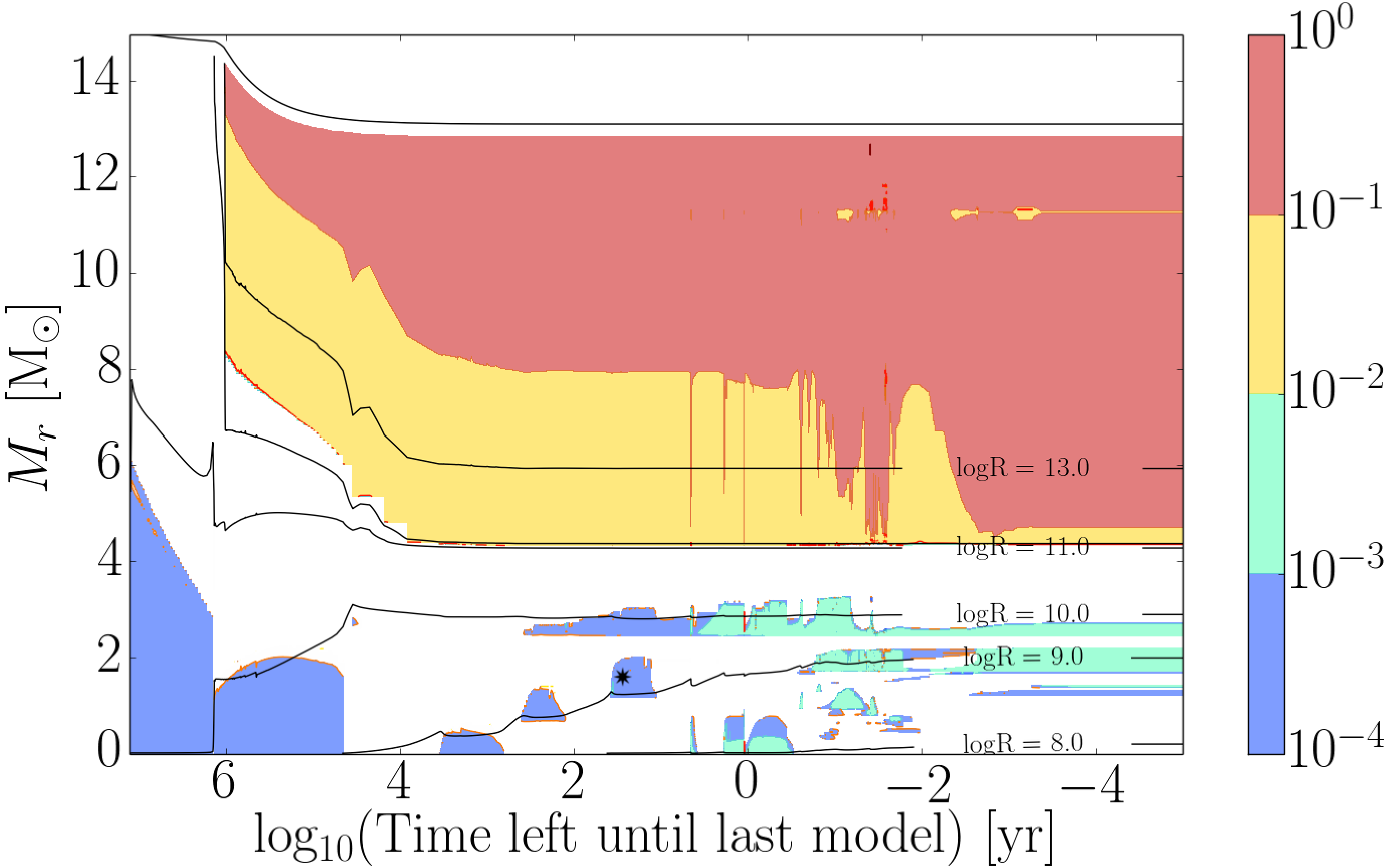
Gal. Chem. Evol. models

INPUT

Supernova Simulations

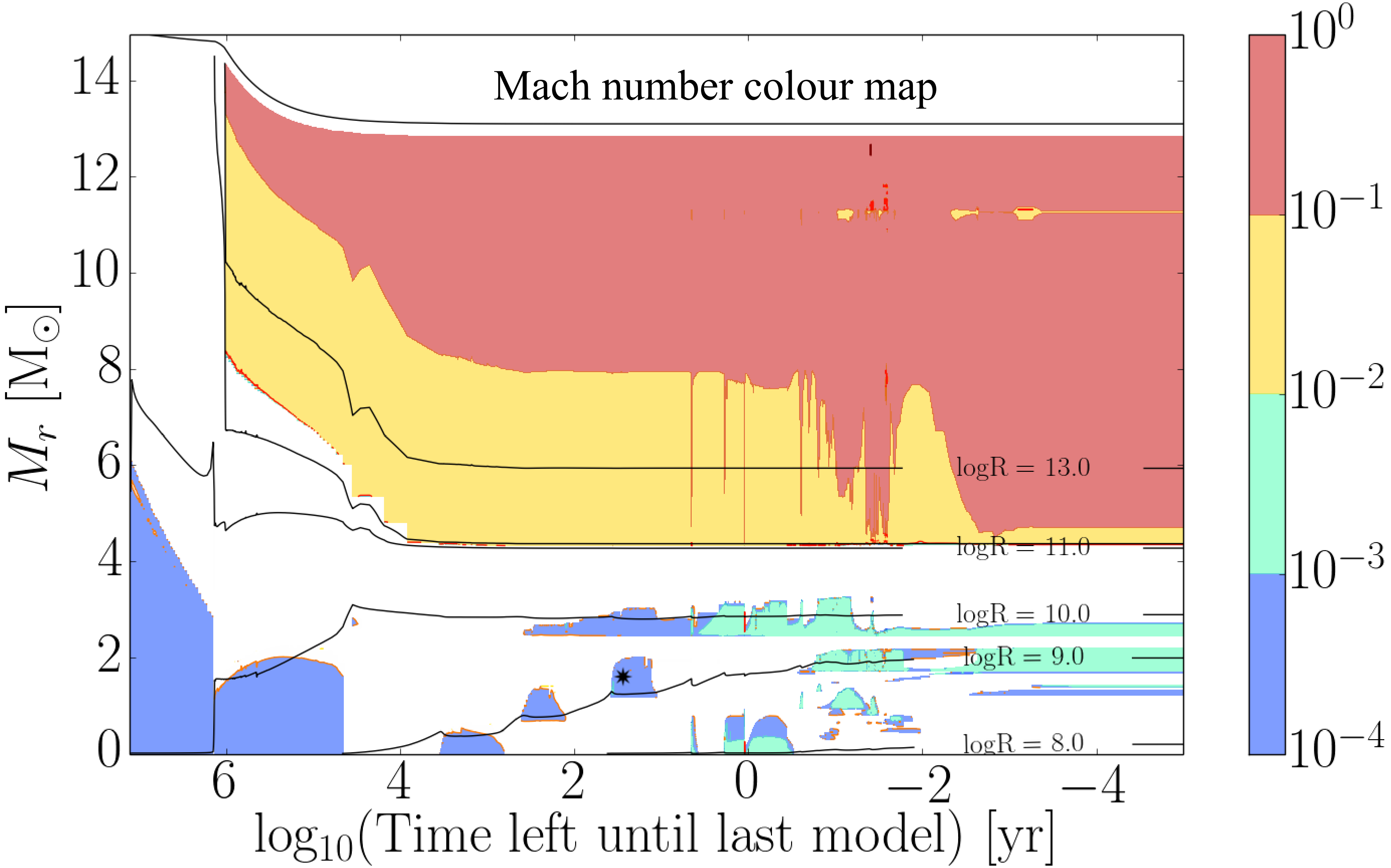
- Efficient pipeline: nuclear/hydro/astro

Next Steps? Carbon Burning



Run simulation at later point during C-burning shell + vary Lum

Next Steps? Other Phases



Low-Mach scheme better for for H, He phases!

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

Arnett et al 2015 (321D)

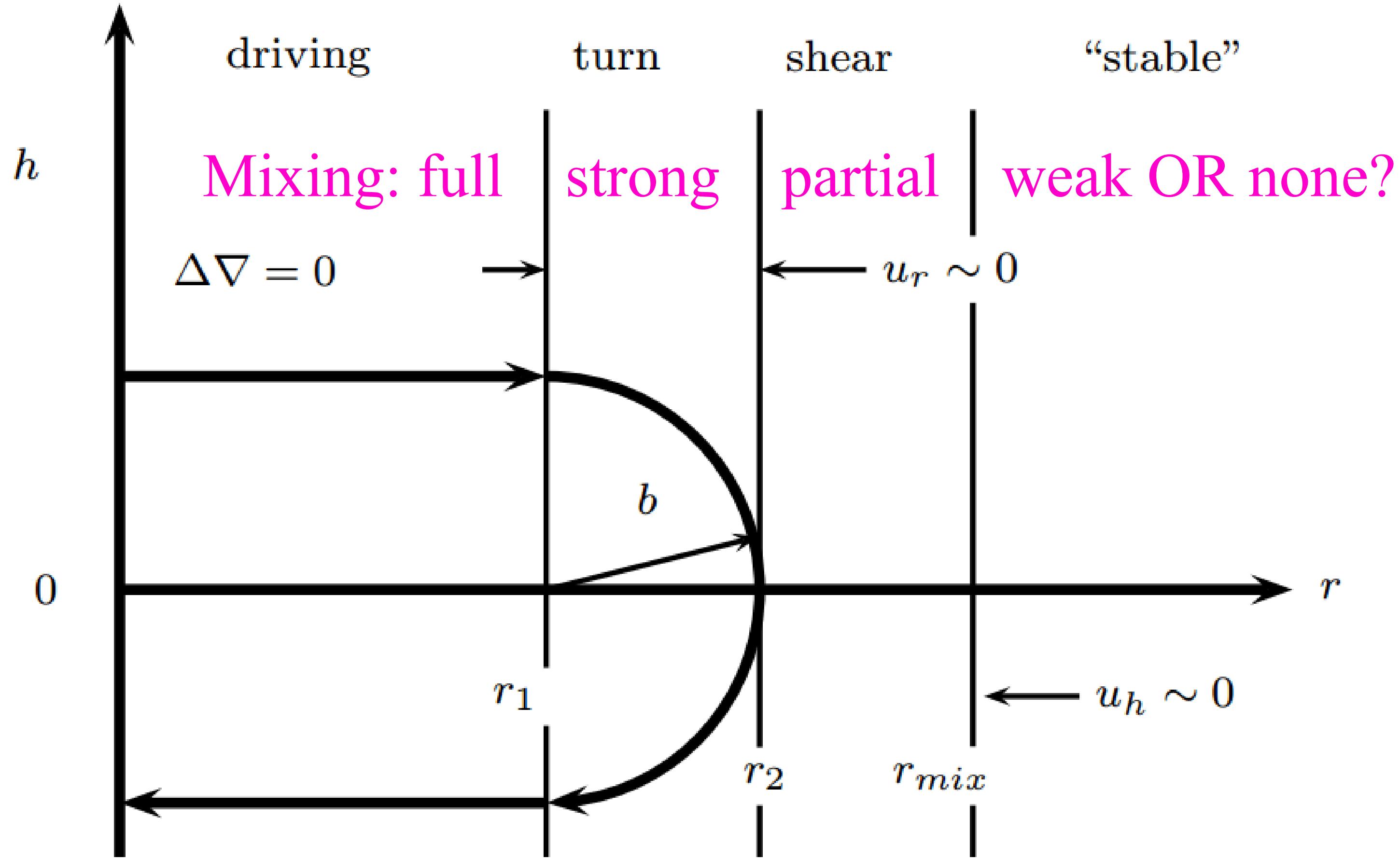
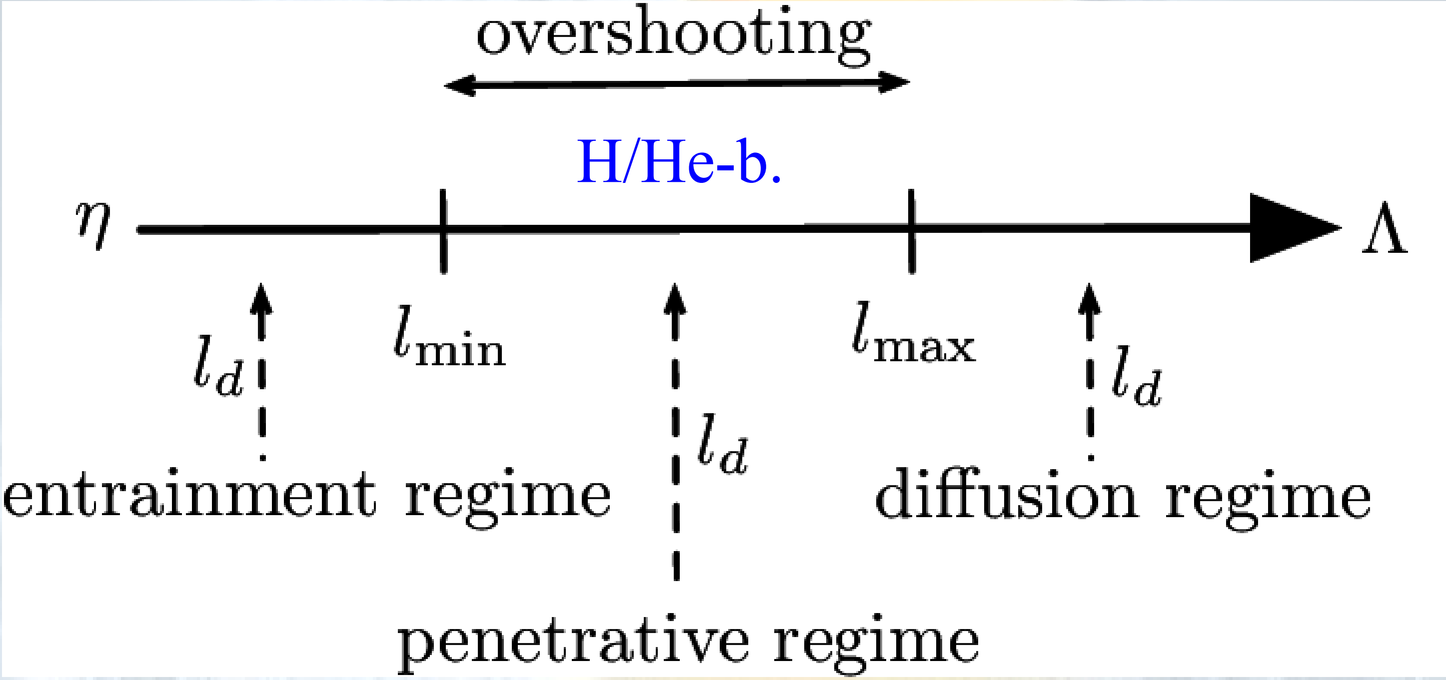


Figure 5. Simplified schematic of a convective boundary. The length b corresponds to the radius of curvature needed to reverse (contain) the flow ($u_r \rightarrow -u_r$). The centrifugal acceleration is provided by pressure fluctuations (see text). The boundaries oscillate due to surface waves. The 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.



H/He-b.

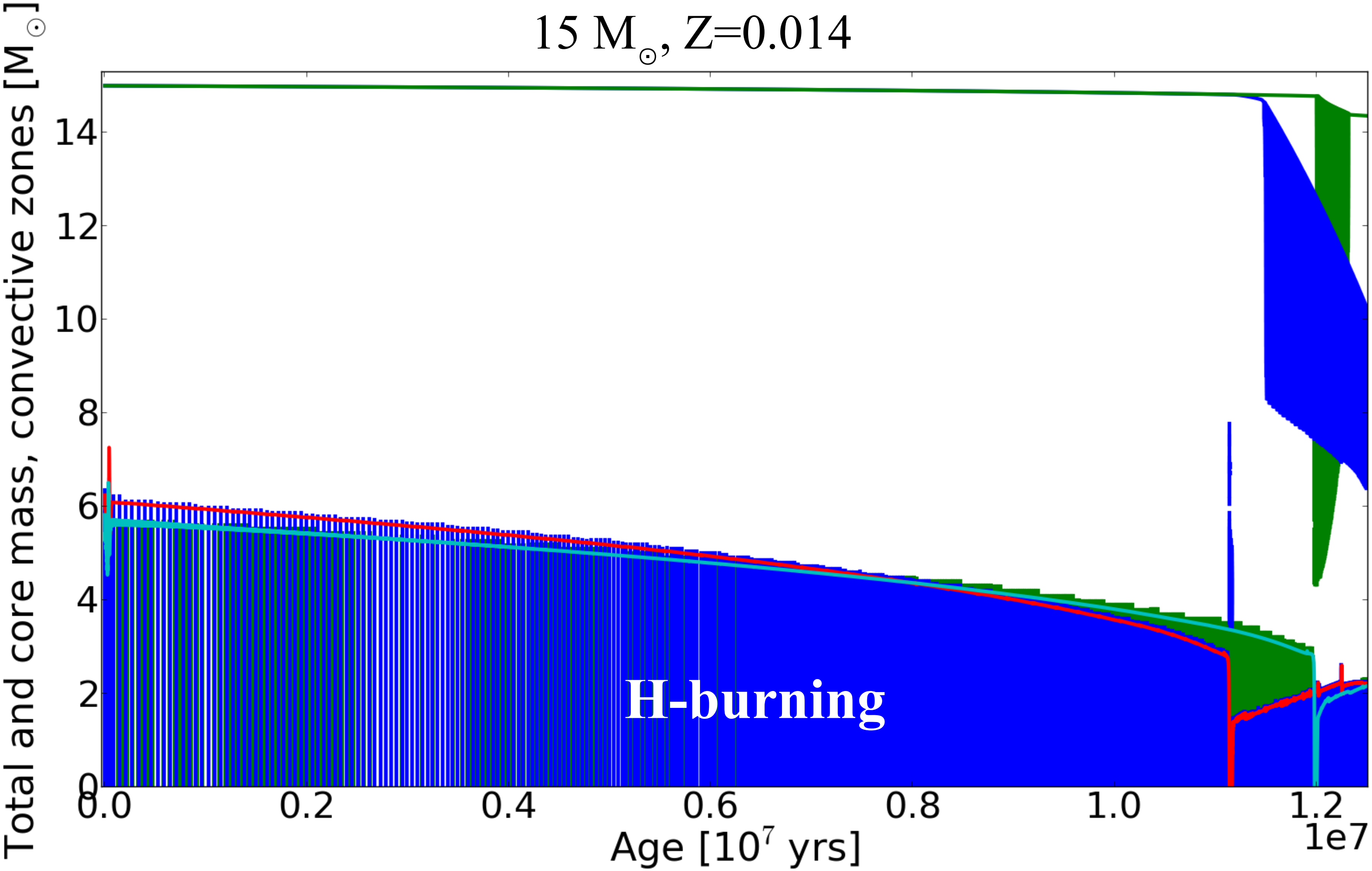
Stellar
surface

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

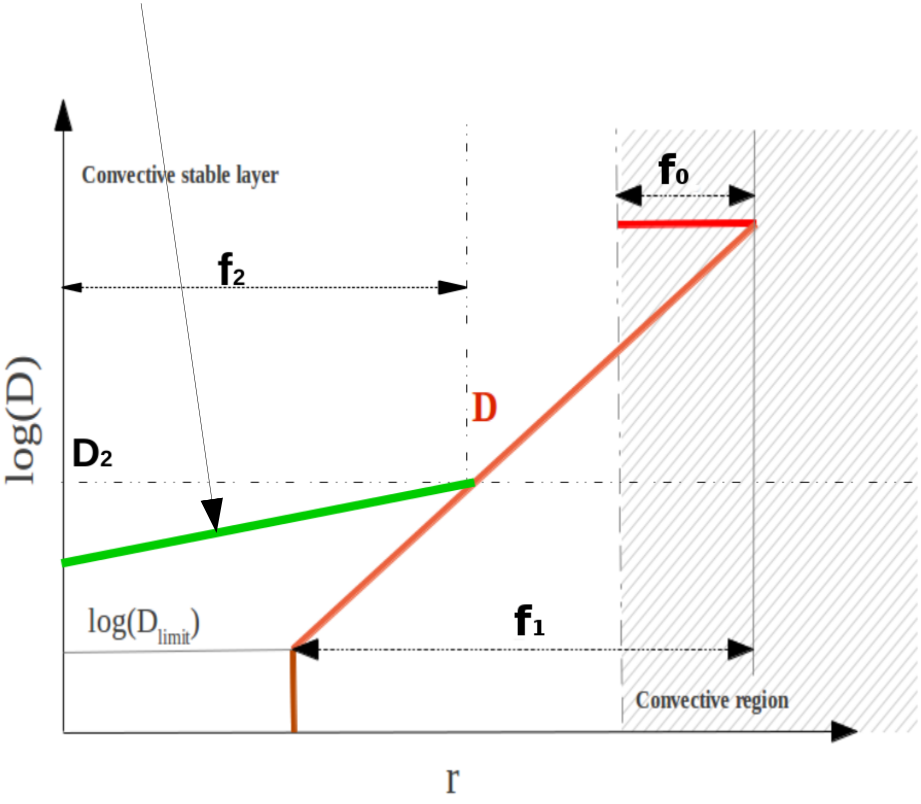


Cristini et al in prep

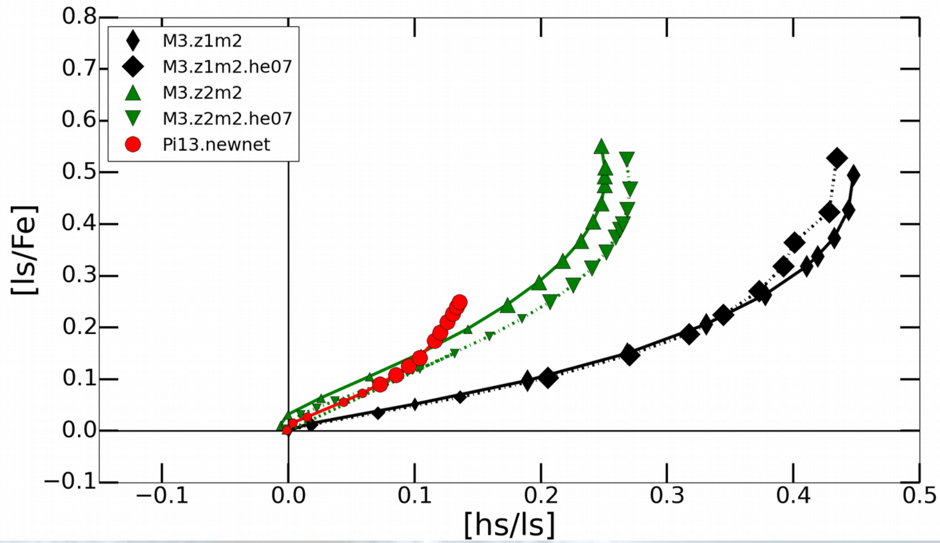
Back to 1D: CBM in AGB Stars (NuGrid project)

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)

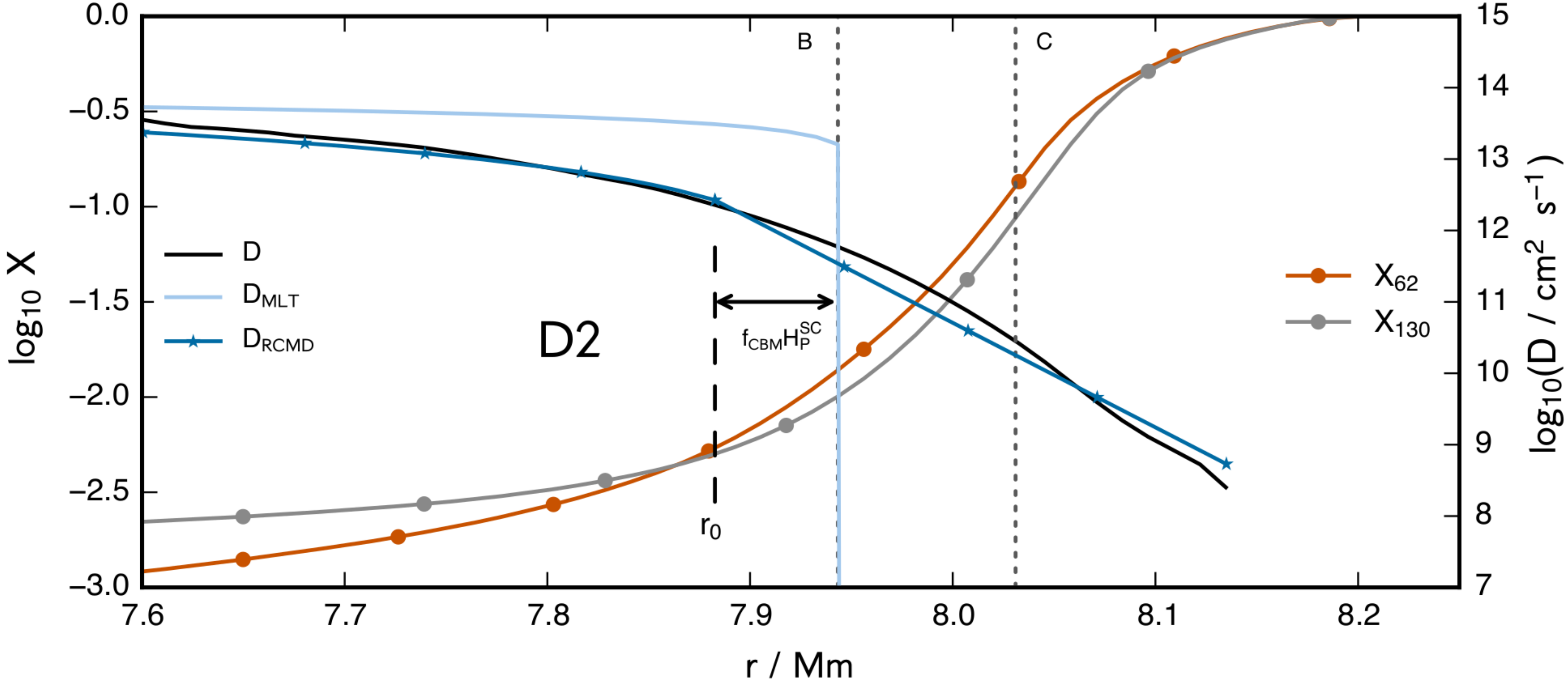
MIXING IN STARS

1D MIXING MODEL

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

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

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



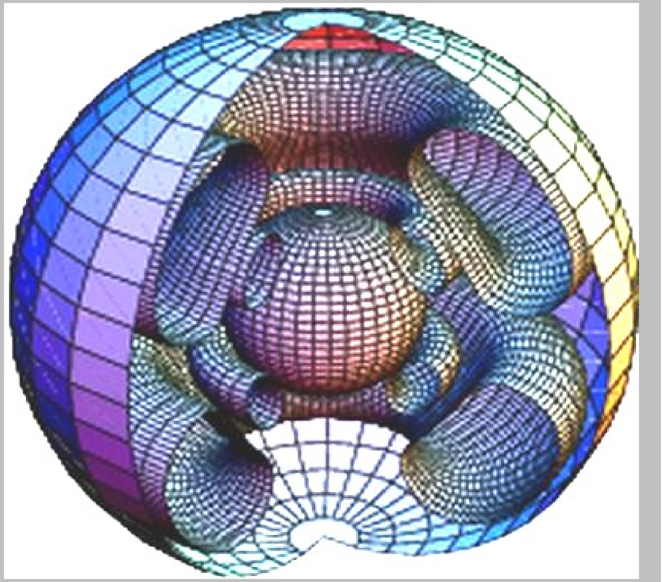
S. Jones, RA, SS, AD, PW, FH (2016, ArXiv e-prints, arXiv:1605.03766)

Rotation-Induced Transport

Zahn 1992: strong horizontal turbulence

Transport of angular momentum:

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \bar{\Omega} U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial\bar{\Omega}}{\partial r}\right)}_{\text{diffusion term}}$$

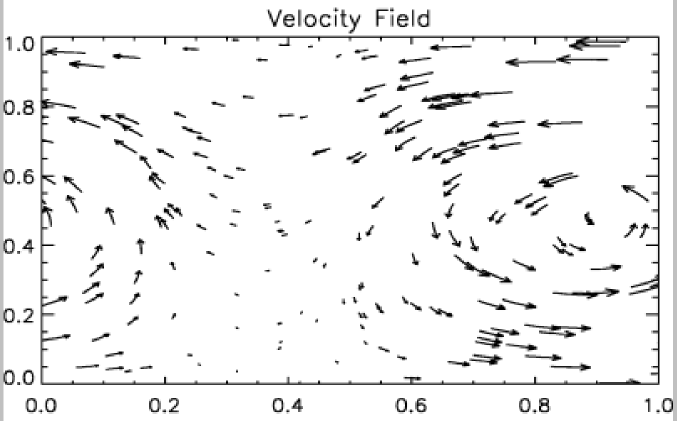


Meynet & Maeder 2000

Transport of chemical elements:

$$\rho\frac{\mathrm{d}X_i}{\mathrm{d}t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^2 \left[D + D_{eff}\right]\frac{\partial X_i}{\partial r}\right) + \left(\frac{\mathrm{d}X_i}{\mathrm{d}t}\right)_{\mathrm{nucl}}$$

Shear instabilities



Brueggen & Hillebrandt 2000

D: diffusion coeff. due to various transport mechanisms (convection, shear)

D_{eff}: diffusion coeff. due to meridional circulation + horizontal turbulence

2.3. Dynamical shear

The criterion for stability against dynamical shear instability is the Richardson criterion:

$$\boxed{Ri = \frac{N^2}{(\partial U/\partial z)^2} > \frac{1}{4} = Ri_c,} \tag{1}$$

where U is the horizontal velocity, z the vertical coordinate and N^2 the Brunt-Väisälä frequency:

$$N^2 = \frac{g\delta}{H_P}[\nabla_{ad} - \nabla + \frac{\varphi}{\delta}\nabla_\mu] \tag{2}$$

Hirschi et al 2004

2.3.1. The recipe

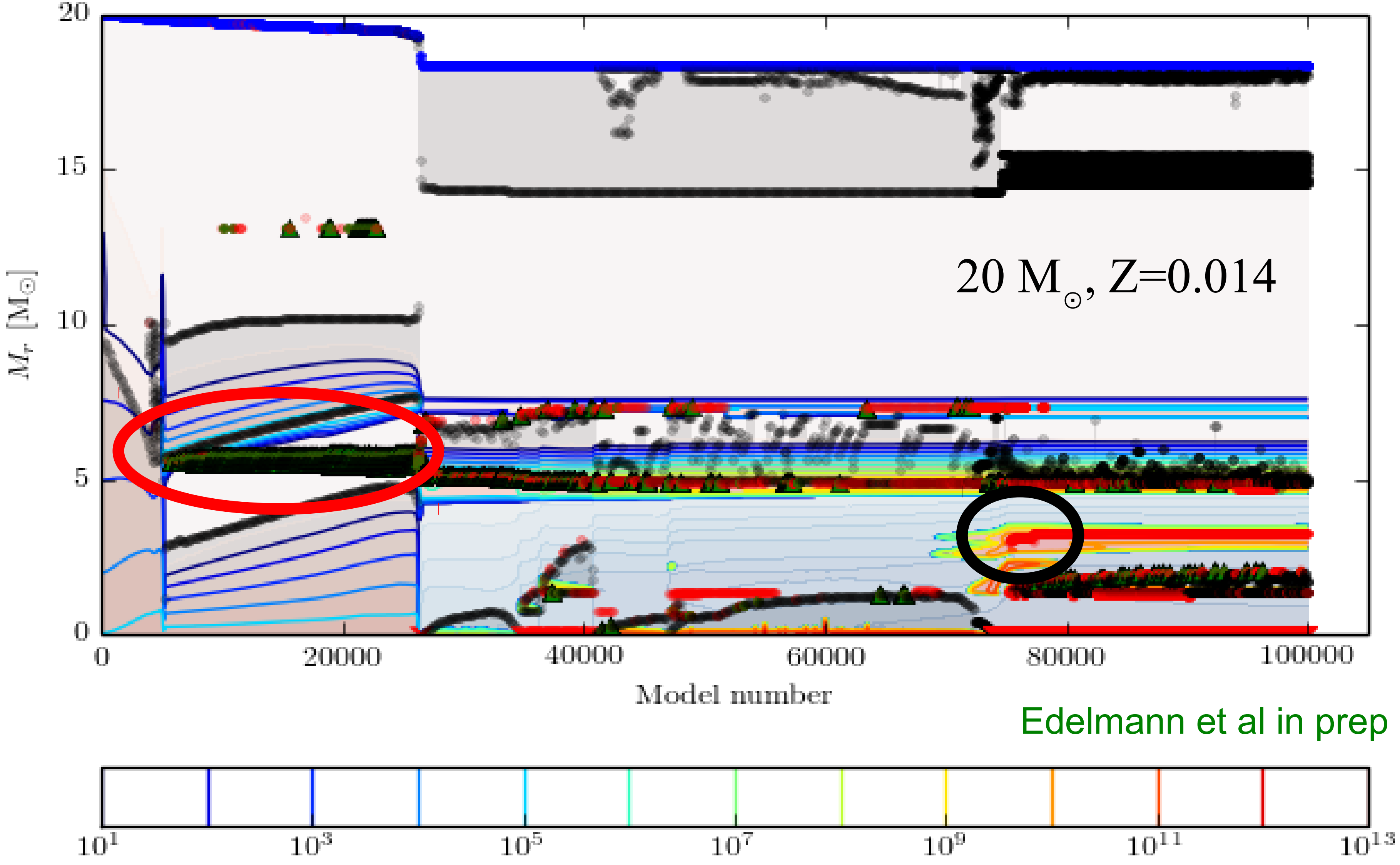
The following dynamical shear coefficient is used, as suggested by J.–P. Zahn (priv. comm.):

$$\boxed{D = \frac{1}{3}vl = \frac{1}{3}\ \frac{v}{l}\ l^2 = \frac{1}{3}\ r\frac{\mathrm{d}\,\Omega}{\mathrm{d}\,r}\ \Delta r^2 = \frac{1}{3}\ r\Delta\Omega\ \Delta r} \tag{5}$$

where r is the mean radius of the zone where the instability occurs, $\Delta\Omega$ is the variation of Ω over this zone and Δr is the extent of the zone. The zone is the reunion of

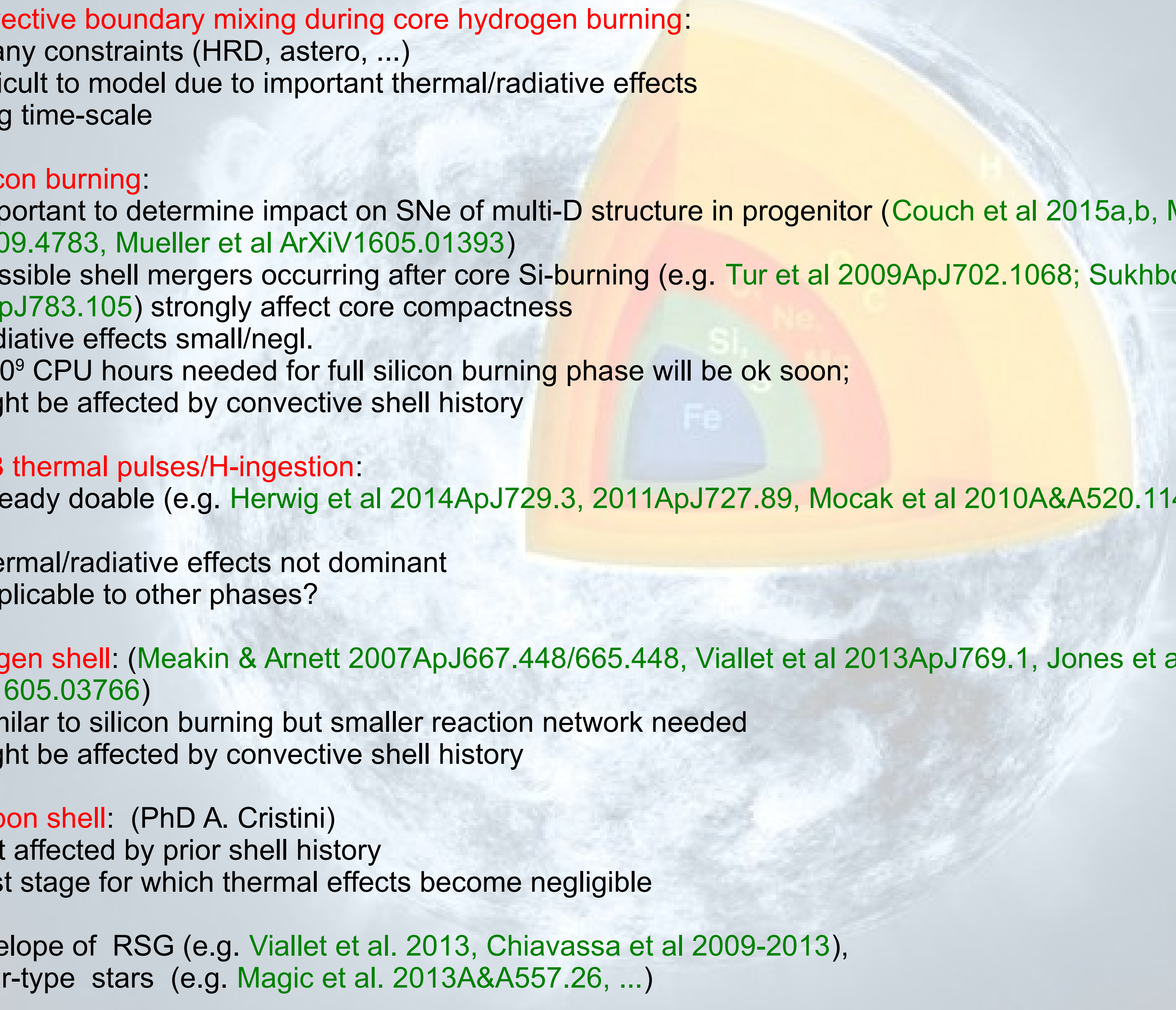
Dynamical Shear

Energy generation contours (red/color: heating, blue: cooling, grey: convection)



Edelmann et al in prep

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 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, ...)
-