Darmstadt, March 18

L9: Massive Stars:

Tackling Key Modelling Uncertainties with Large-Scale Simulations

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Recent work

- Massive stars and the (not always) weak s process:

Large grid of massive star models + weak s proc (Frischknecht+2016, MNRAS):

Nugrid: set 1 (Pignatari+2016, ApJ), set1extension (Ritter+in prep),

s process with new convective boundary mixing (CBM): (Battino+ ApJ 2016)

- Nuclear uncertainties: MC-based sensitivity studies for gamma-process (Rauscher+2016, MNRAS), weak s process (Nishimura+2017, MNRAS), main s process (Cescutti+in prep)

- Stellar uncertainties:

Multi-D tests of convection (Cristini+ 2017, MNRAS) and rotation (Edelmann+2017, A&A)

- Reviews/book chapters: Springer Handbook of Supernovae

“Pre-supernova Evolution and Nucleosynthesis in Massive Stars and Their Stellar Wind Contribution” (doi:10.1007/978-3-319-20794-0_82-1)

“Very Massive and Supermassive Stars: Evolution and Fate” (doi:10.1007/978-3-319-20794-0_120-1)

- ChETEC COST Action started in April 2017: see www.chetec.eu for details

Plan

- Late evolution and fate of massive stars

- Convection/rotation in 1D and multi-D

- Very Massive Stars

- Conclusions and future work

Evolution of Surface Properties

Main sequence:

hydrogen burning

After Main Sequence:

Helium burning

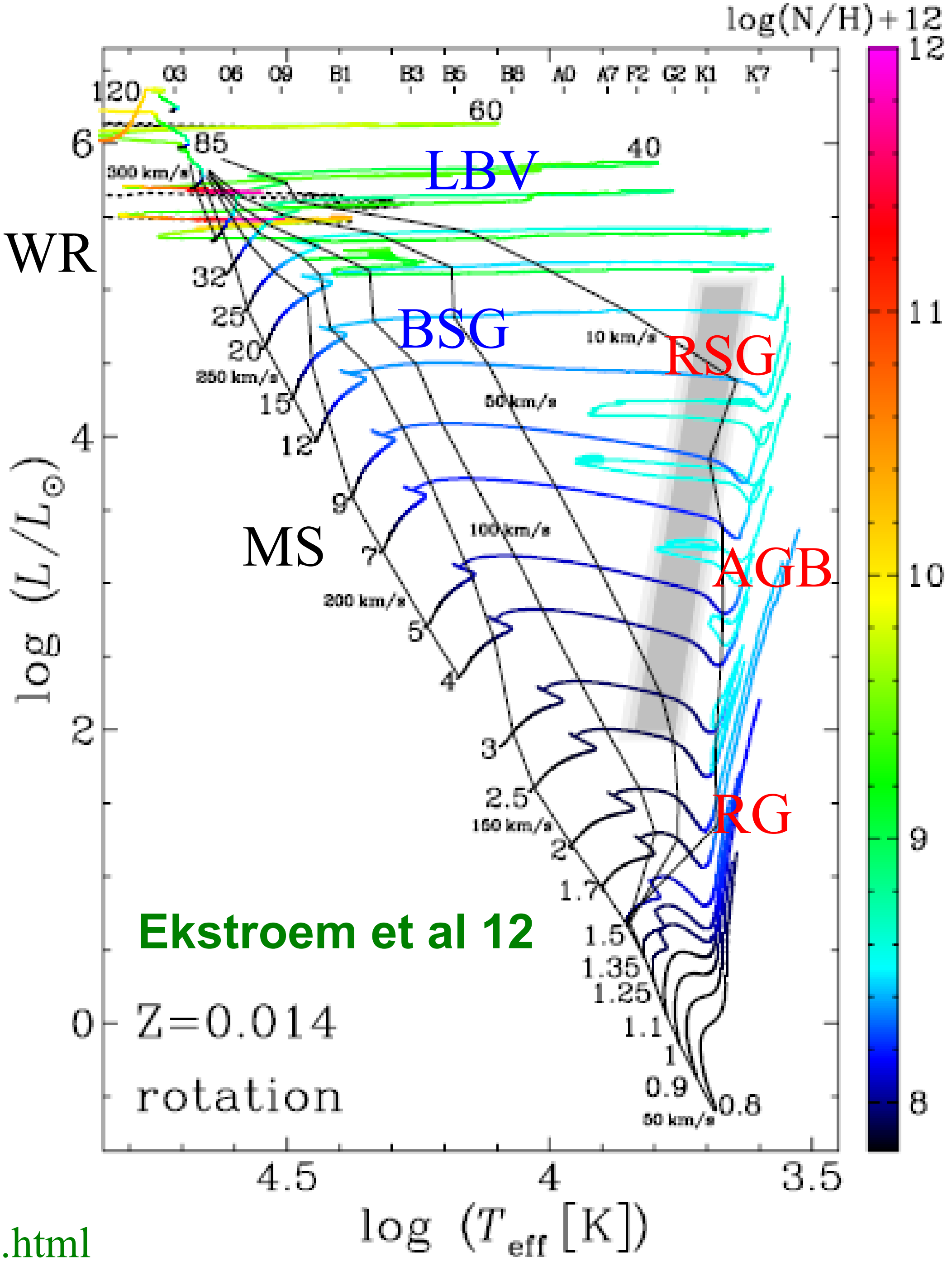
Supergiant stage (red or blue)

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

WR without RSG: M > 40 M_o

Advanced stages: C,Ne,O,Si

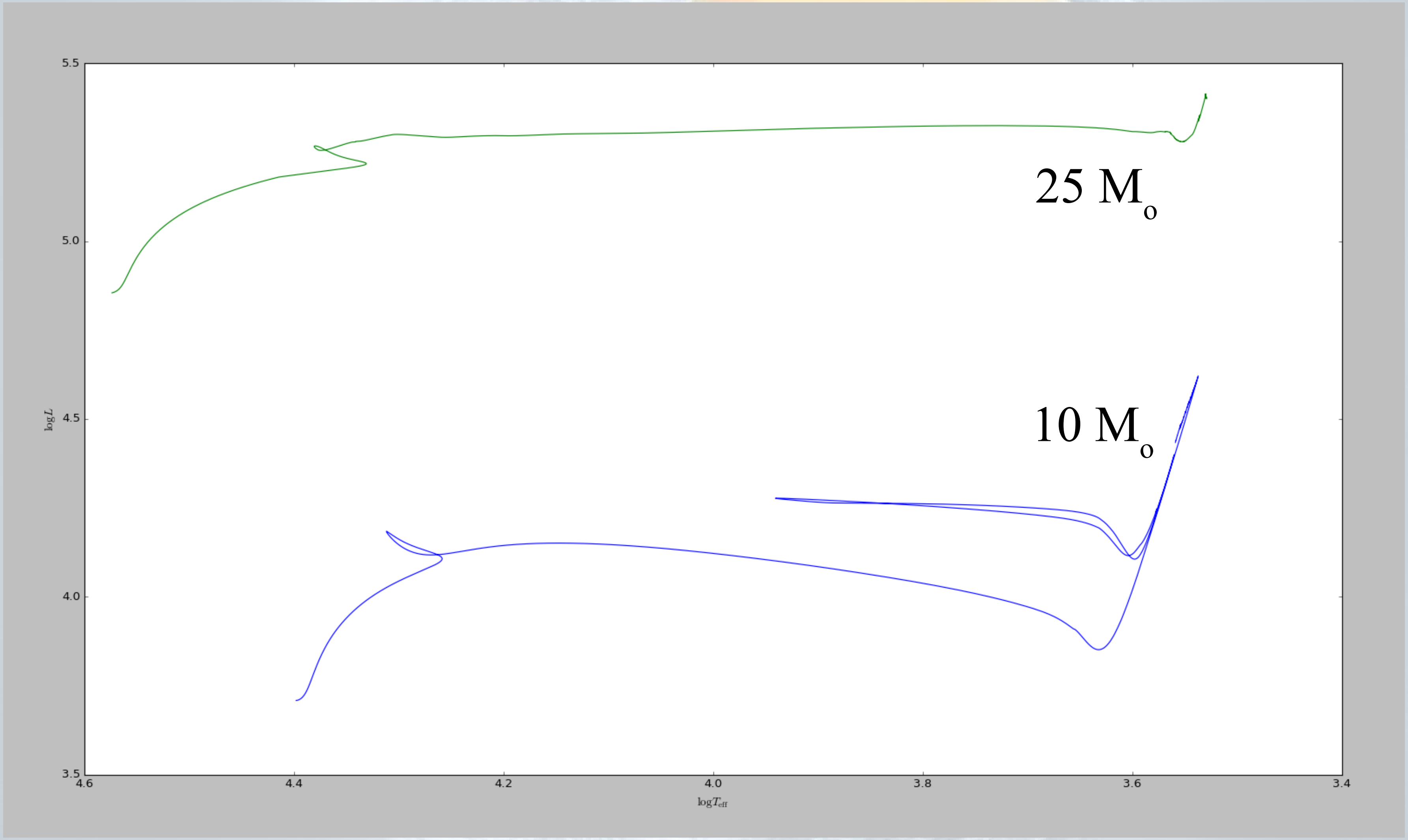
→ iron core → SN/NS/BH



Ekstroem et al 12

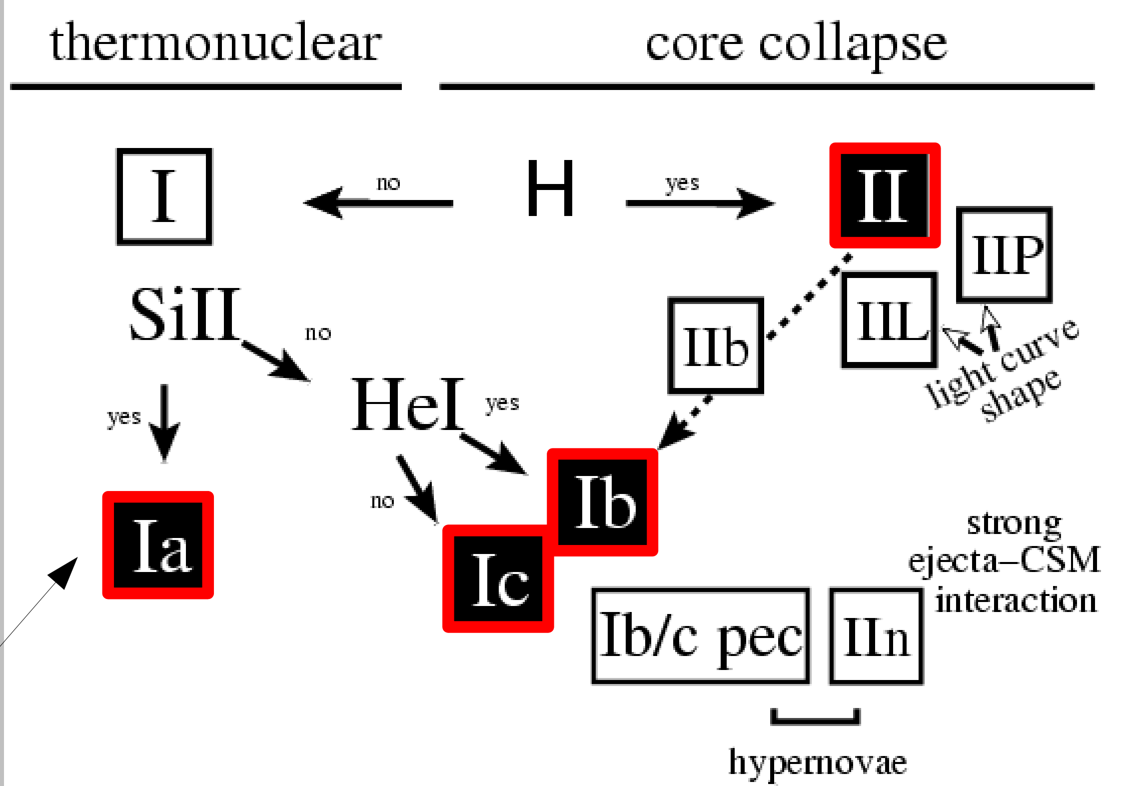
http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

Evolution Surface Properties: Darmstadt Team!



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)

Supernova Explosion Types

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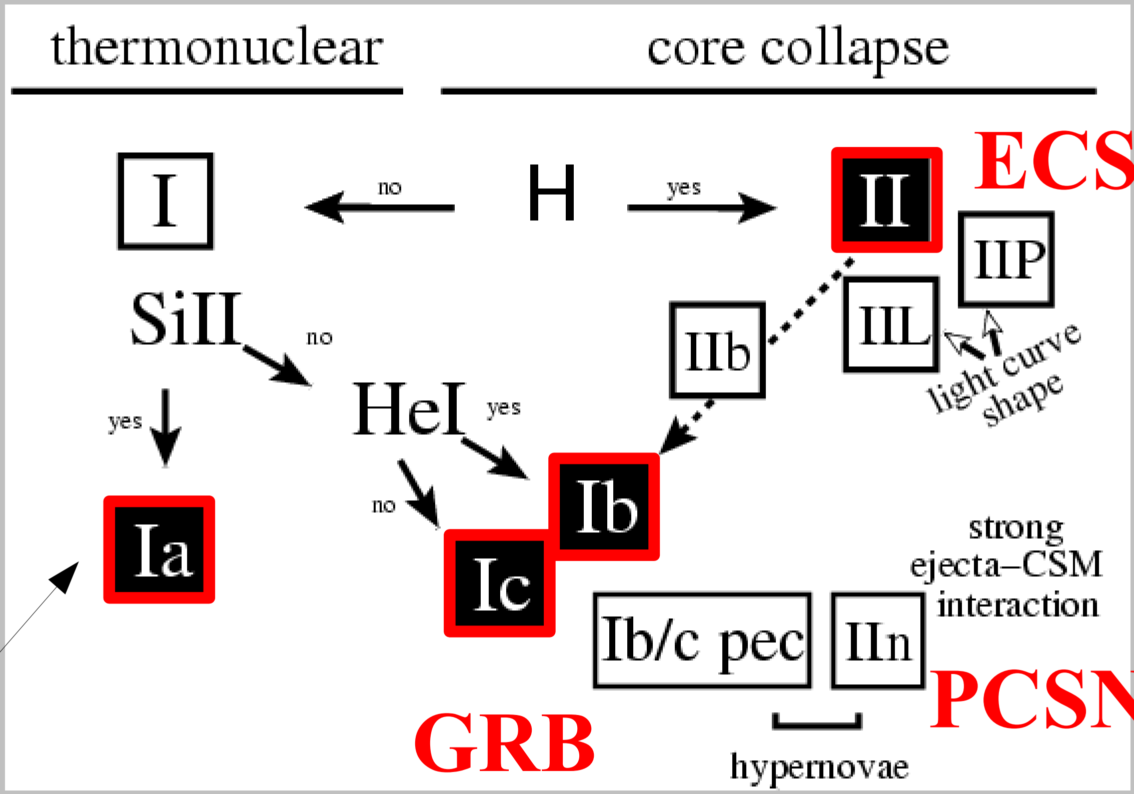


ECSN?

GRB

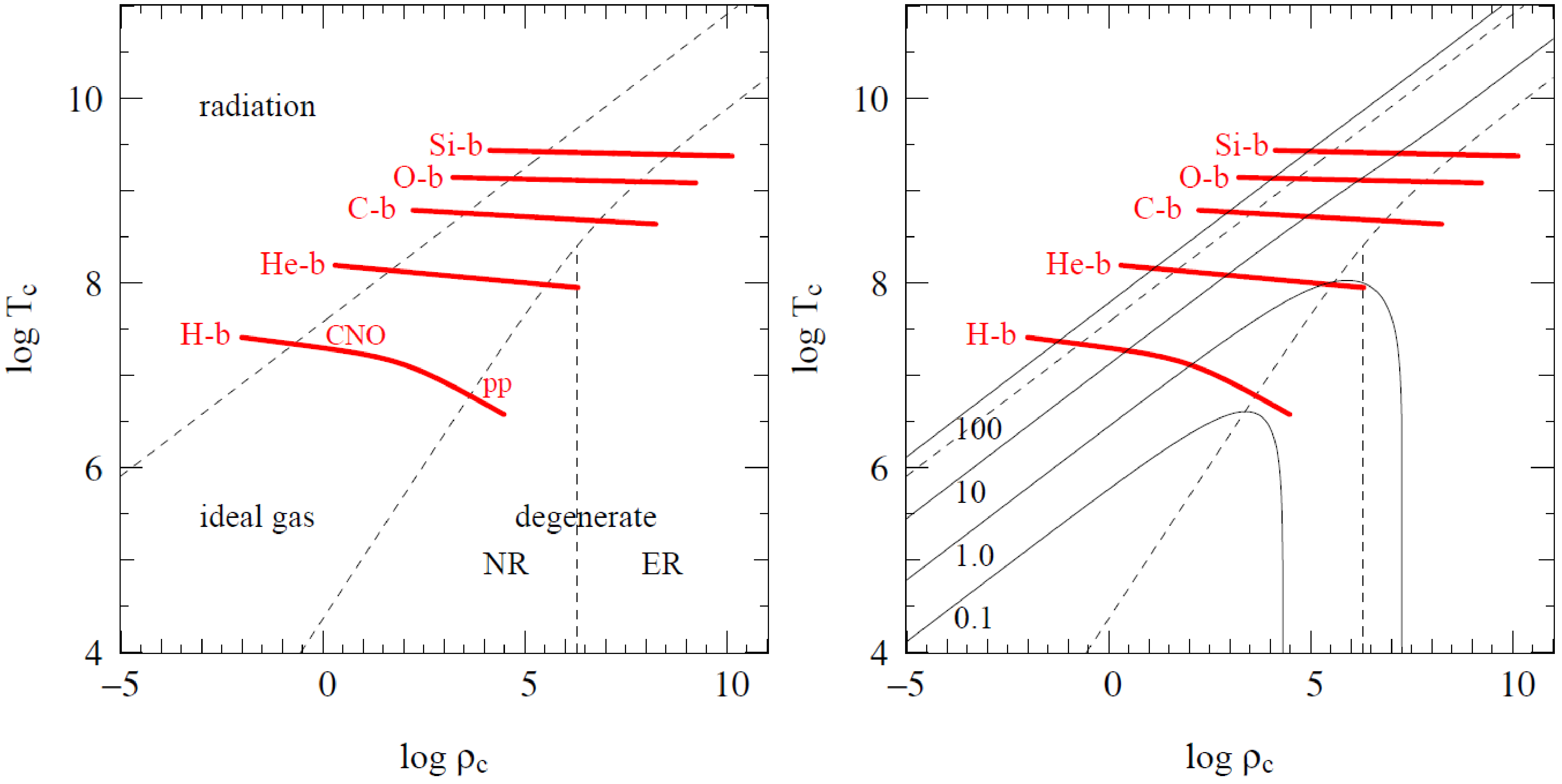
PCSN(=PISN)?

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

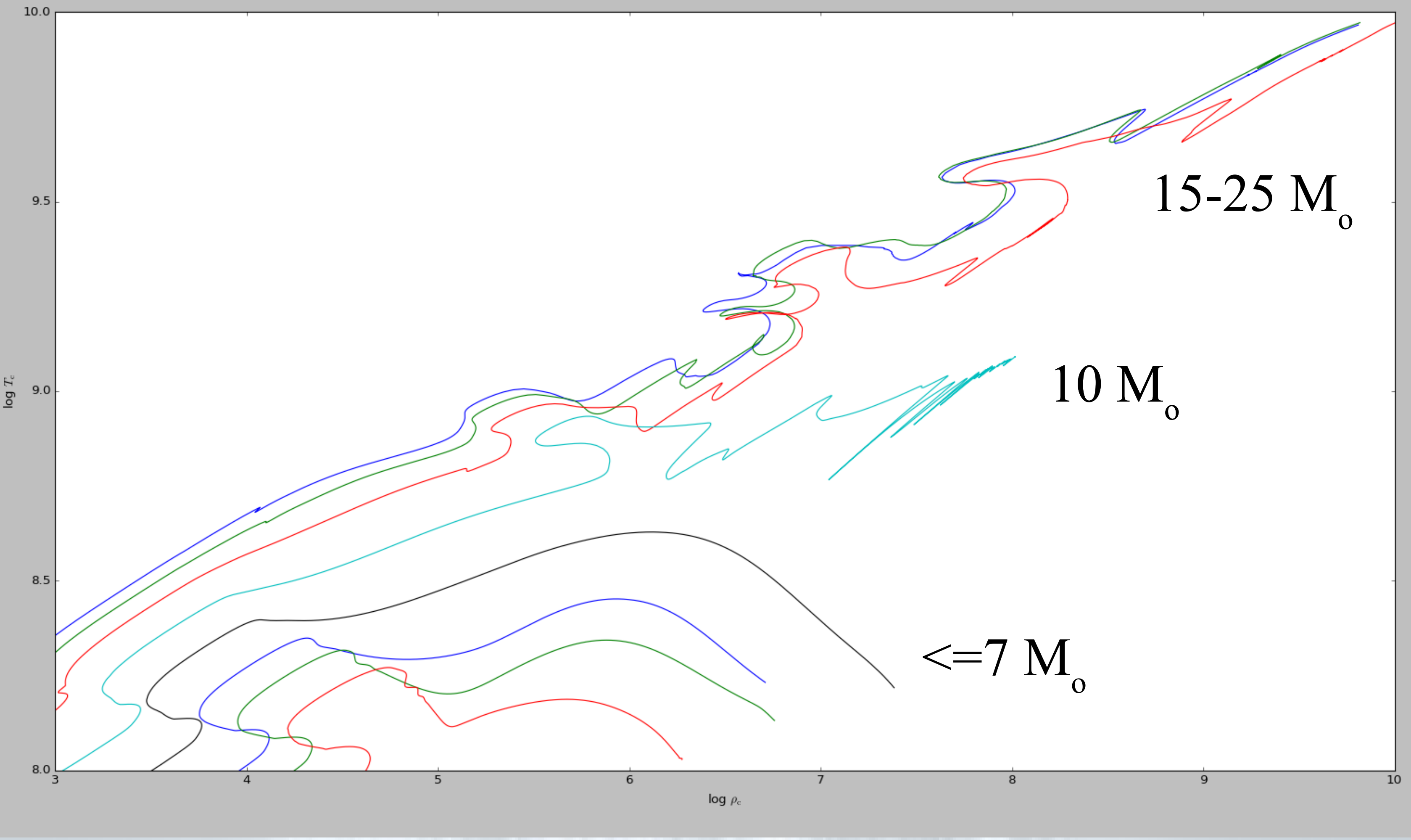
(Hirschi+05
Woosley+06
Yoon+06, ...)

(Turatto 03)

Schematic Evolution in $T_c - Rho_c$



Evolution in T_c – Rho_c : Darmstadt Team!



15-25 M_o

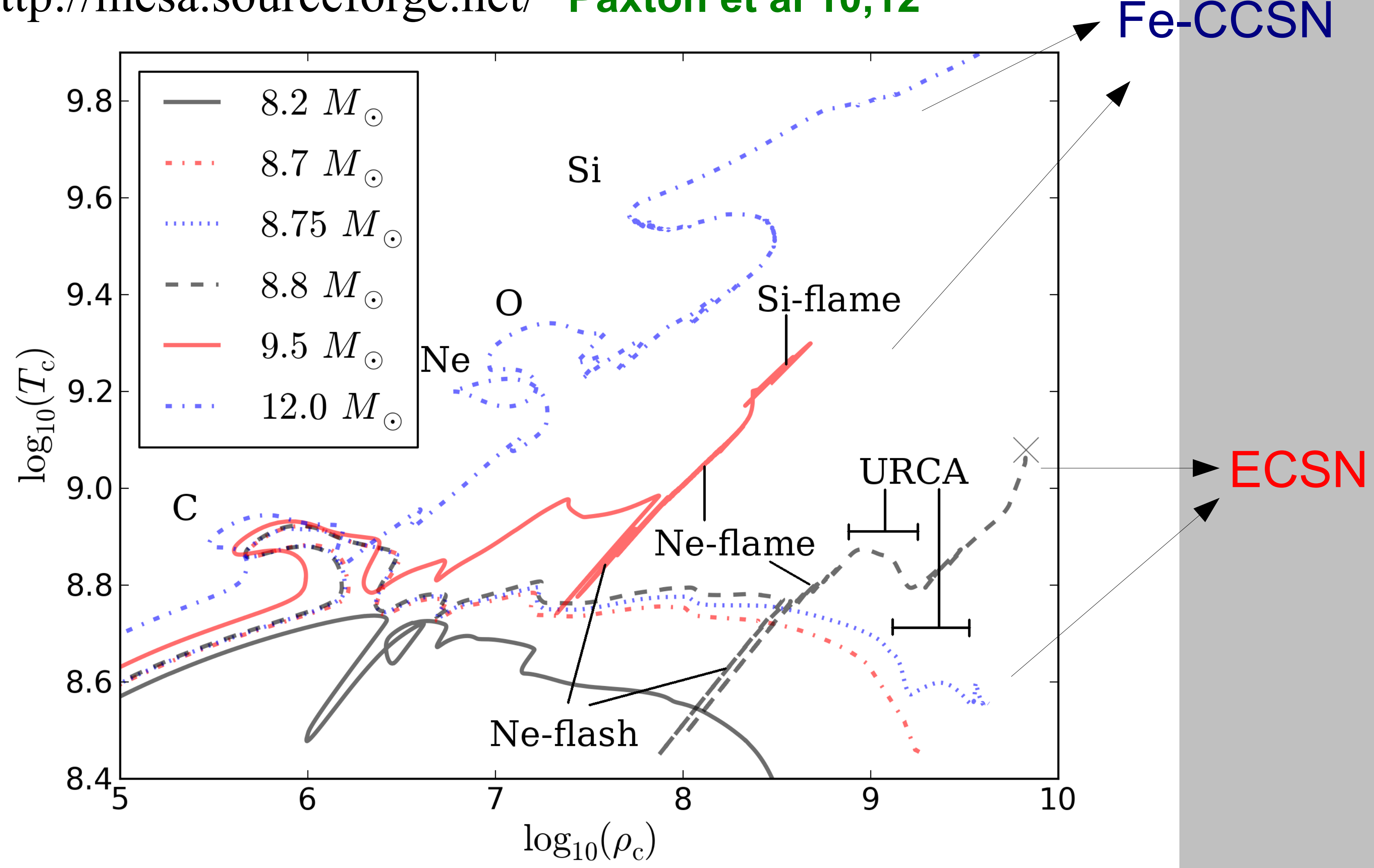
10 M_o

<=7 M_o

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**



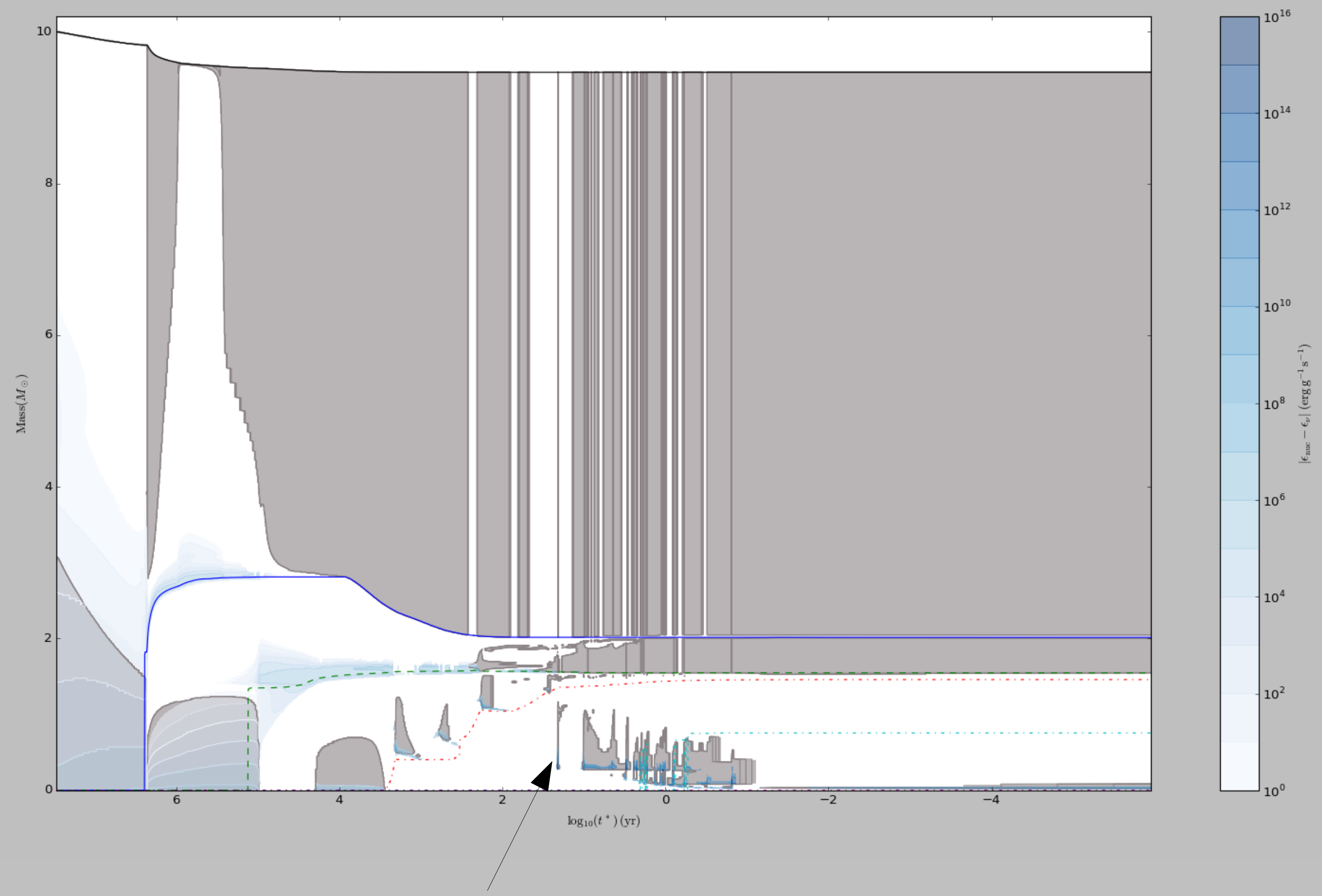
Fe-CCSN

ECSN

Both SAGB and failed massive stars may produce ECSN

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

Convection in 10 M_o model from Darmstadt Team



Ne-O flame has almost reached the centre

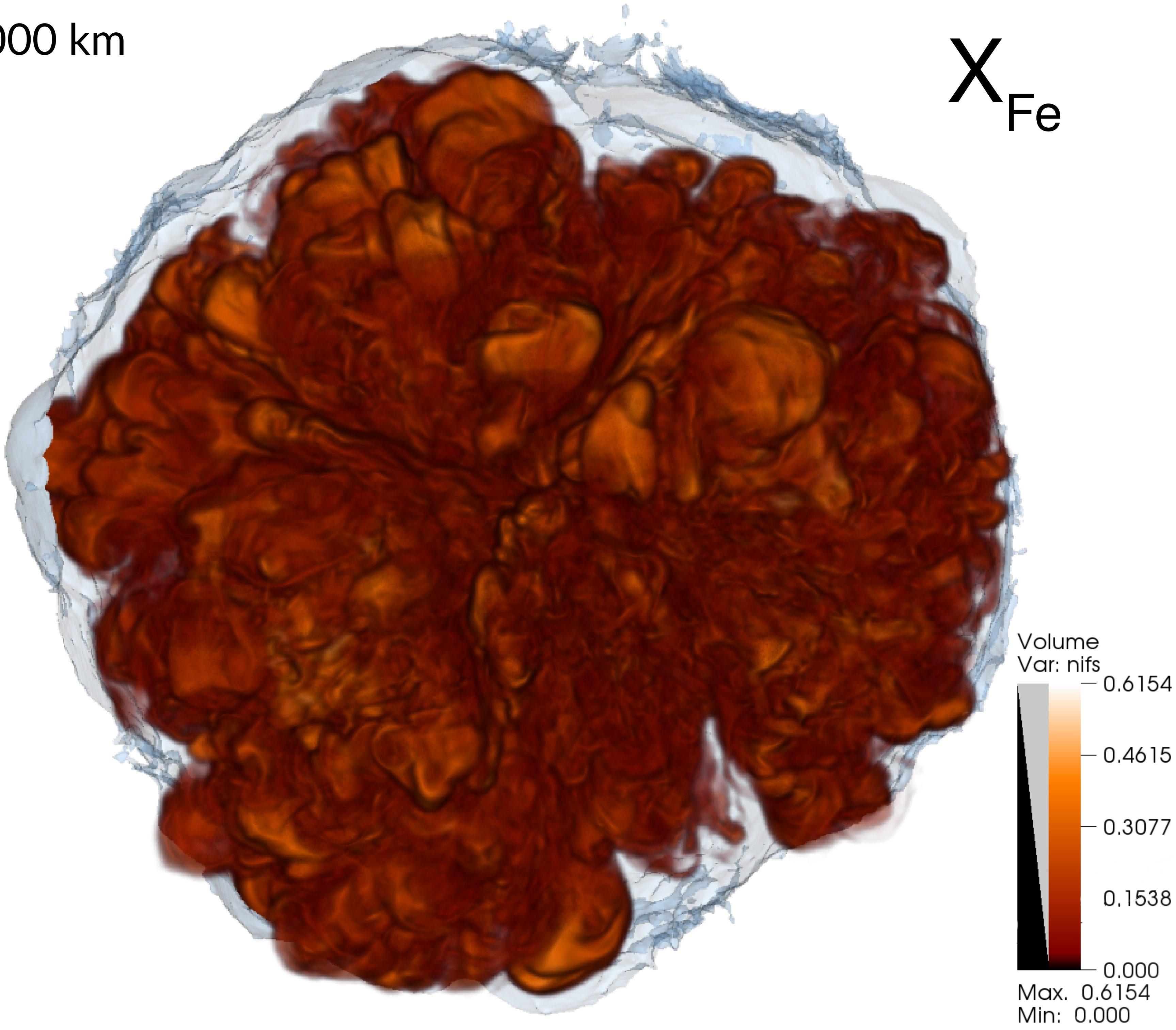
Scale: 400,000 km
Time: 60 s

O DEFLAGRATION

3D 4π: 512^3

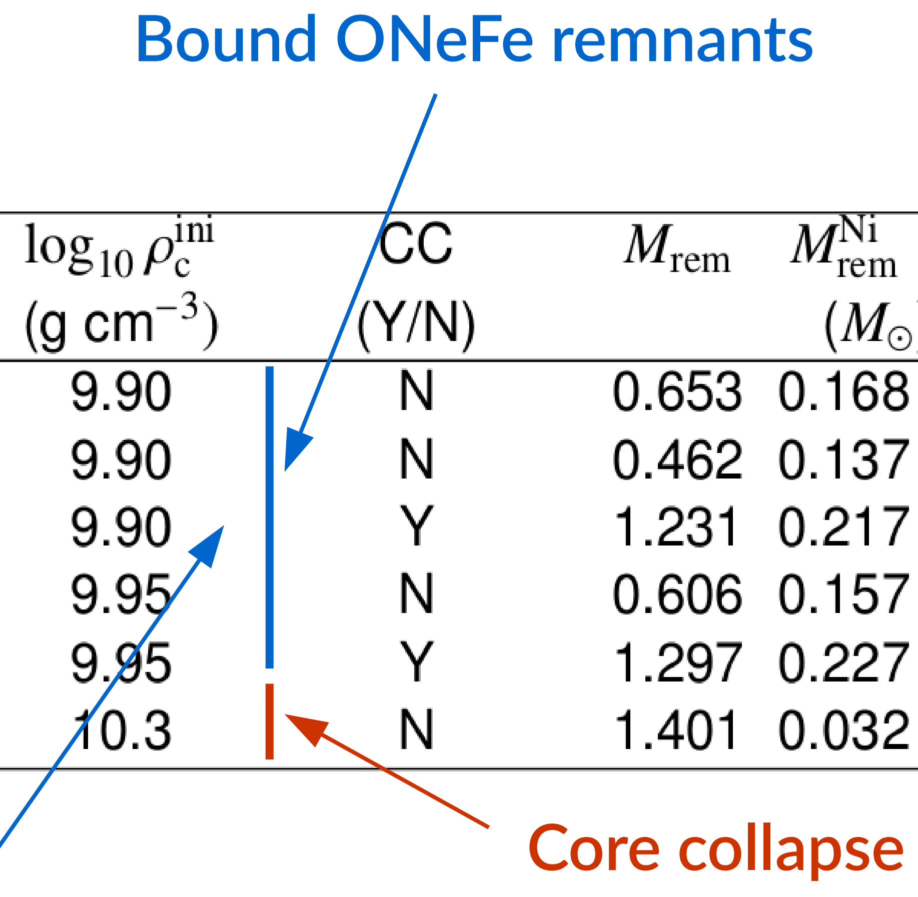
THERMONUCLEAR EXPLOSION?

X_{Fe}



DIAGNOSTICS

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



Bound ONeFe remnants

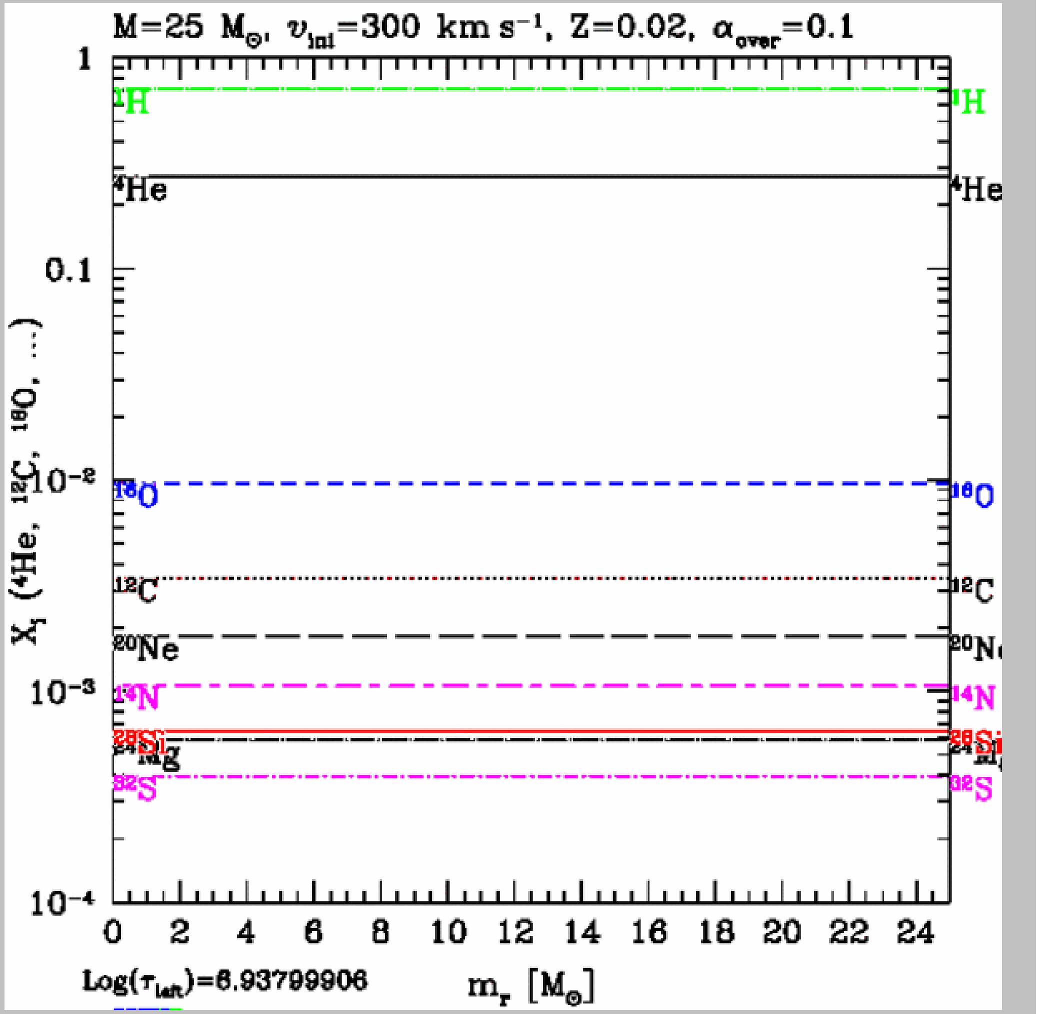
id.	res.	$\log_{10}\rho_c^{\mathrm{ini}}$	CC	M_{rem}	$M_{\mathrm{rem}}^{\mathrm{Ni}}$	M_{ej}	$M_{\mathrm{ej}}^{\mathrm{Ni}}$	$\langle Y_{\mathrm{e,re}}$
		(g cm^{-3})	(Y/N)		($M_{\odot}$)			
G13	256^3	9.90	N	0.653	0.168	0.735	0.236	0.49
G14	512^3	9.90	N	0.462	0.137	0.929	0.349	0.49
G15	256^3	9.90	Y	1.231	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**

Massive Stars: Evolution of the chemical composition

Burning stages (lifetime [yr]):



Hydrogen (10^{6-7}): ^{1}H → ^{4}He

& ^{12}C, ^{16}O → ^{14}N

Helium (10^{5-6}): ^{4}He → ^{12}C, ^{16}O

&^{14}N → ^{18}O → ^{22}Ne

Carbon (10^{2-3}):^{12}C → ^{20}Ne, ^{24}Mg

Neon (0.1-1): ^{20}Ne → ^{16}O, ^{24}Mg

Oxygen (0.1-1): ^{16}O → ^{28}Si, ^{32}S

Silicon (10^{-3}): ^{28}Si, ^{32}S → ^{56}Ni

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

Physical Ingredients

- Nuclear reactions

- Mass loss

- Convection

- Rotation

- Magnetic fields

- Binarity

- Equation of state, opacities & neutrino losses

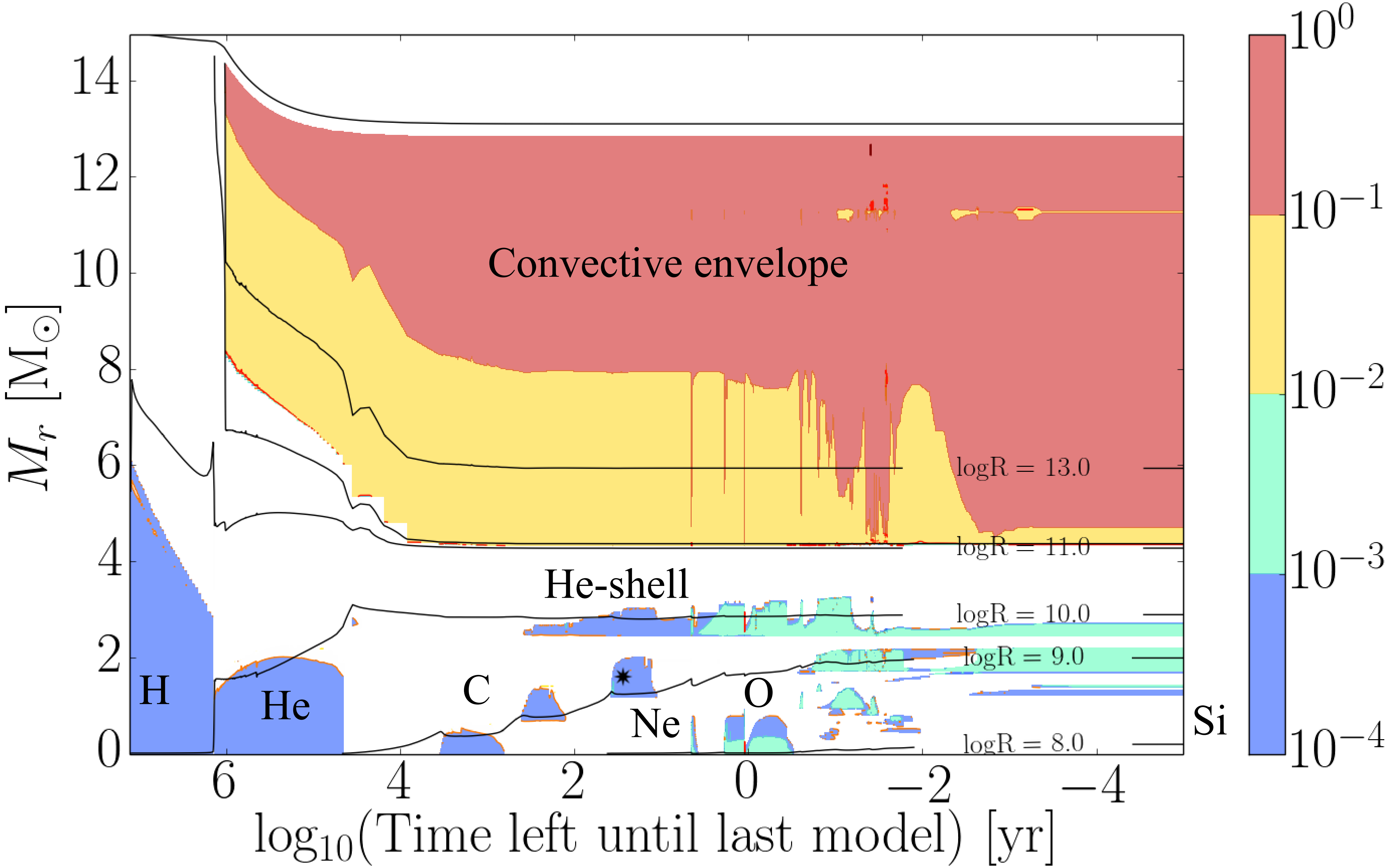
including metallicity dependence

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, ...

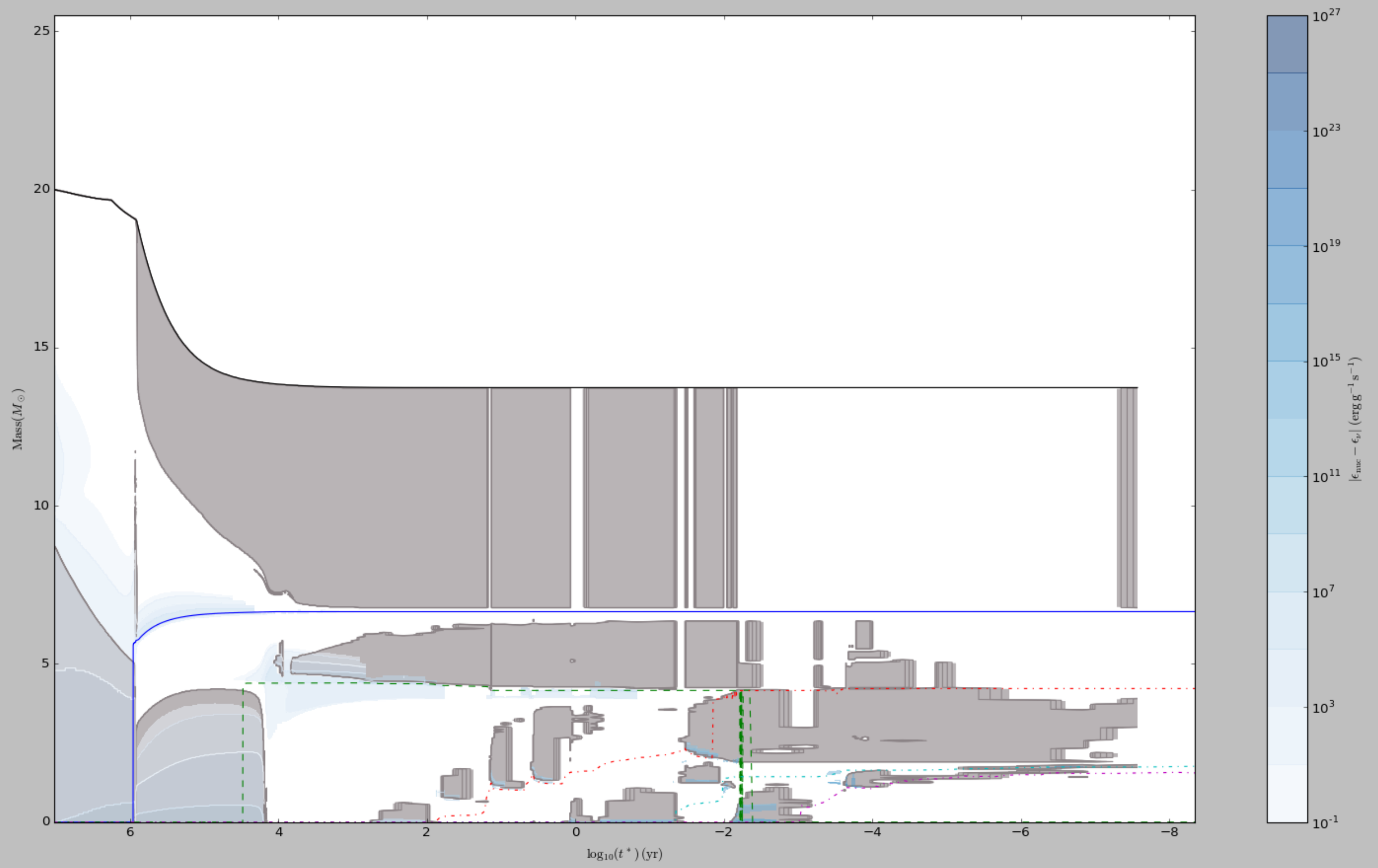
- …

Evolution of Massive Stars



Convection takes place during most burning stages

Convection in 20 M_o model from Darmstadt Team

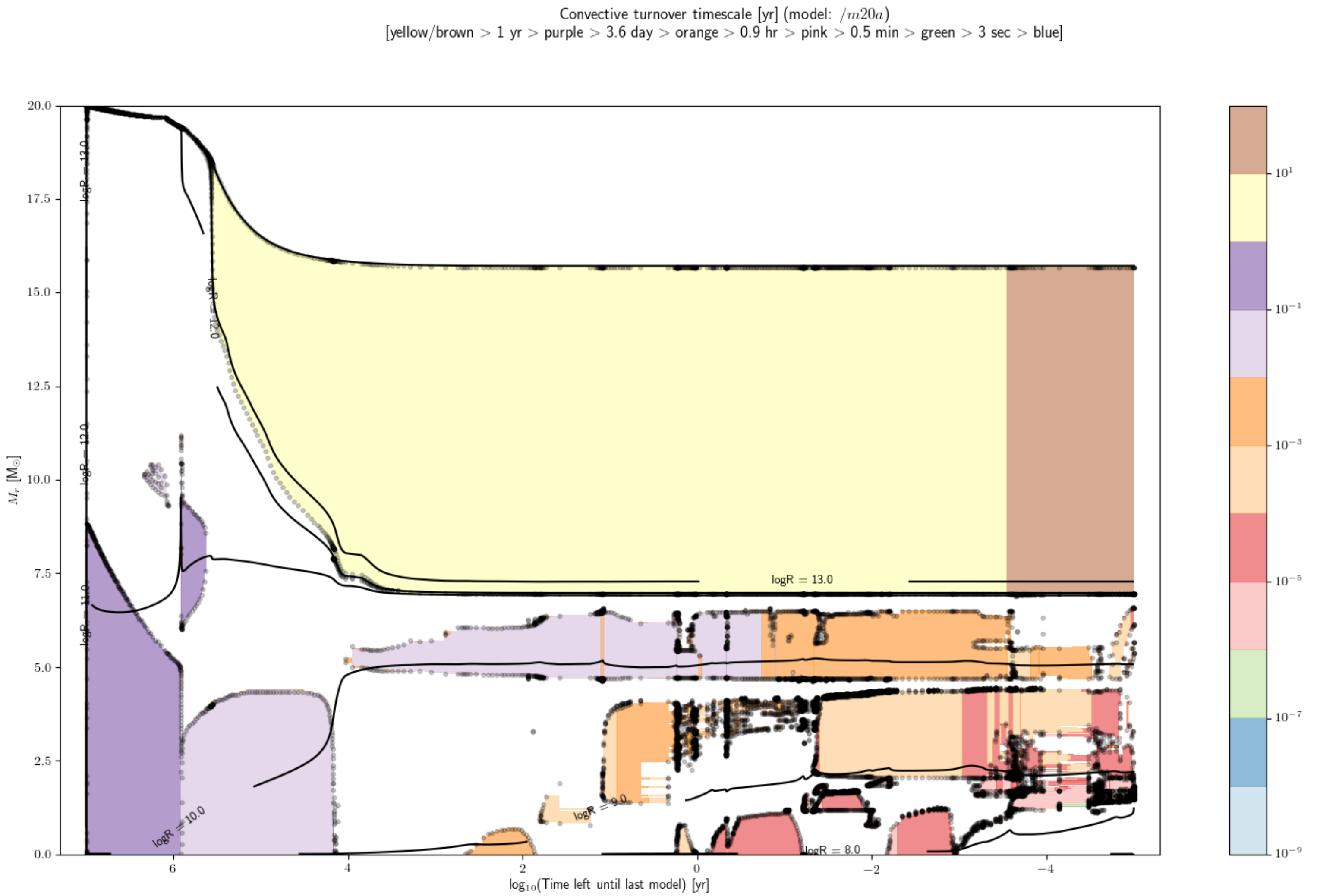


Convection in stars

- highly turbulent (Reynolds number $\mathrm{Re} := \frac{v \rho l_m}{\eta} \approx 10^{10}$; η viscosity; $l_m = 10^9$ cm; lab.: turbulence for $\mathrm{Re} > 100$);)
- 3-dimensional and non-local
- motion in compressible medium on dynamical timescales (v speed of blobs $\approx 10^3$ cm/s $= 10^{-5} v_{\mathrm{sound}}$)
- 3-d hydro simulations limited to illustrative cases
- 2-d hydro: larger stellar parameter range; shallow convective layers
- dynamical models: averages, simplifications, too complicated for stellar evolution

$\Rightarrow \nabla$ from simple approaches with additional extensions

Timescale of Convective Flows



Convection timescale: $t_{dyn} << t_{KH},t_{nuc}$

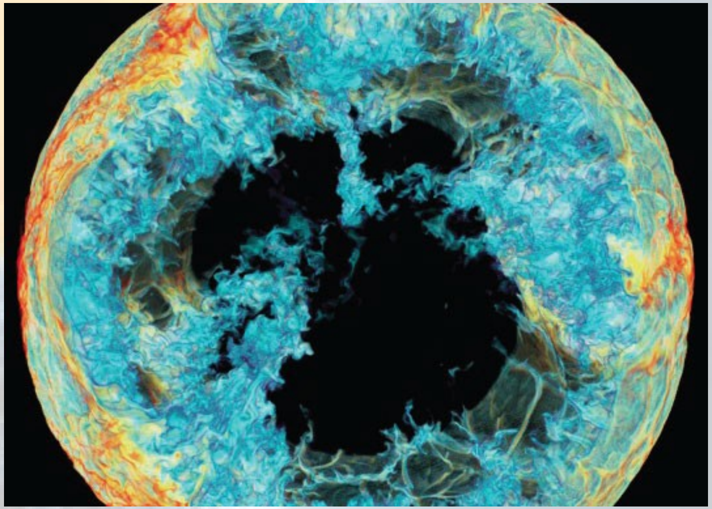
3D stellar models

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)



Herwig, Woodward et al 2013

What's missing?

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

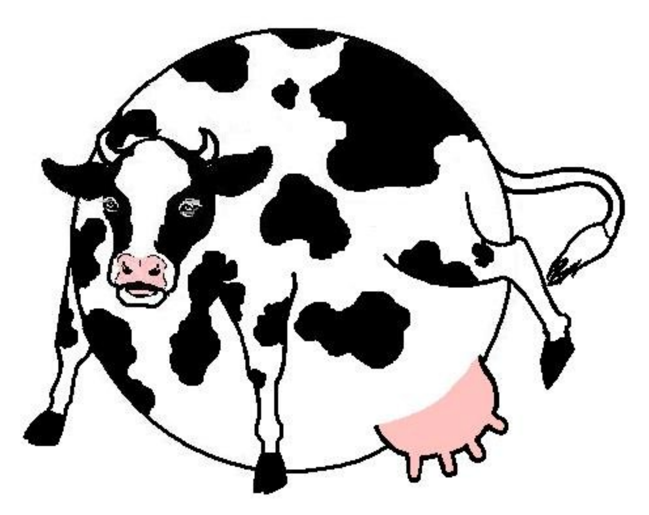
Advantages:

- 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

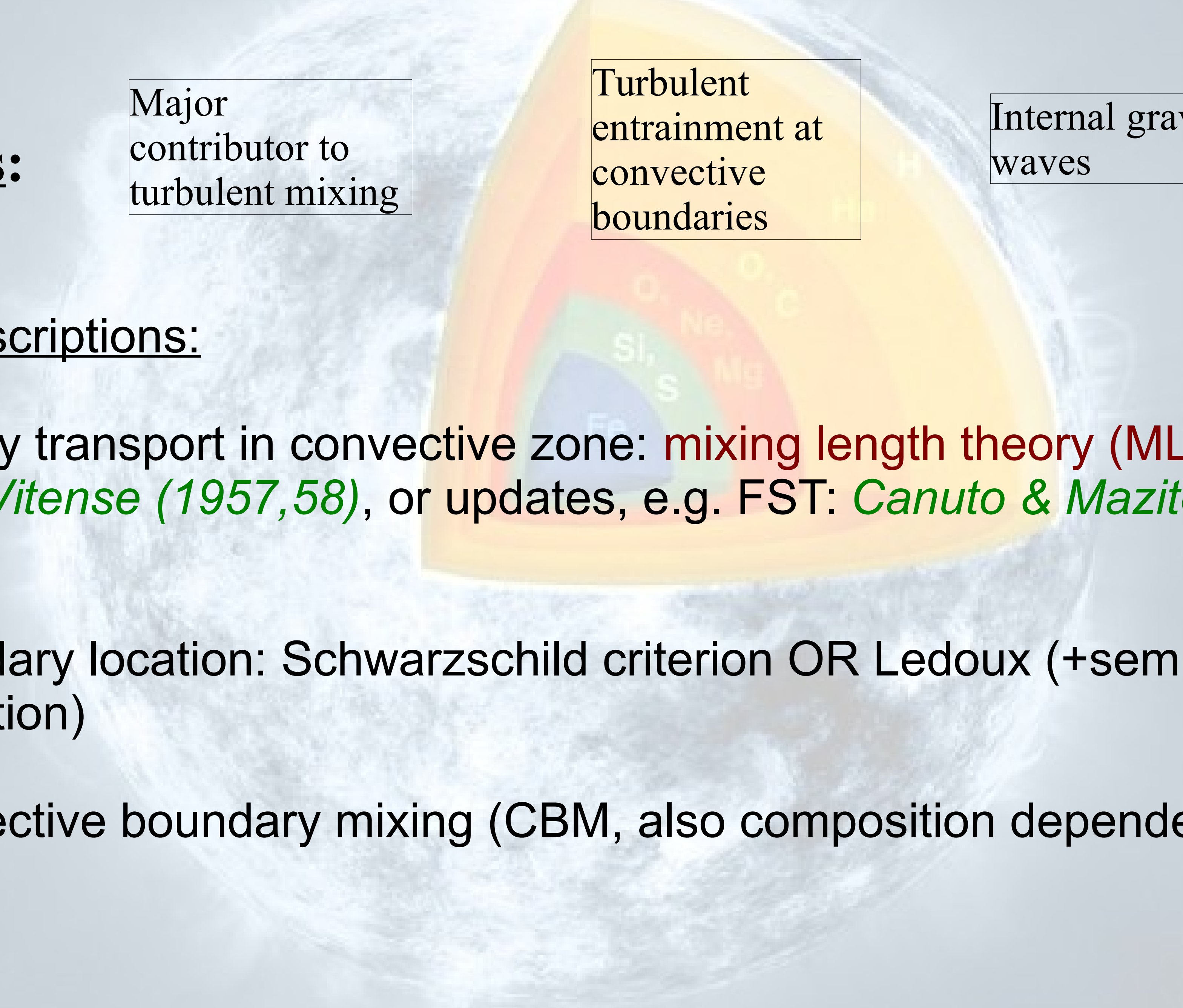
1D stellar models



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)

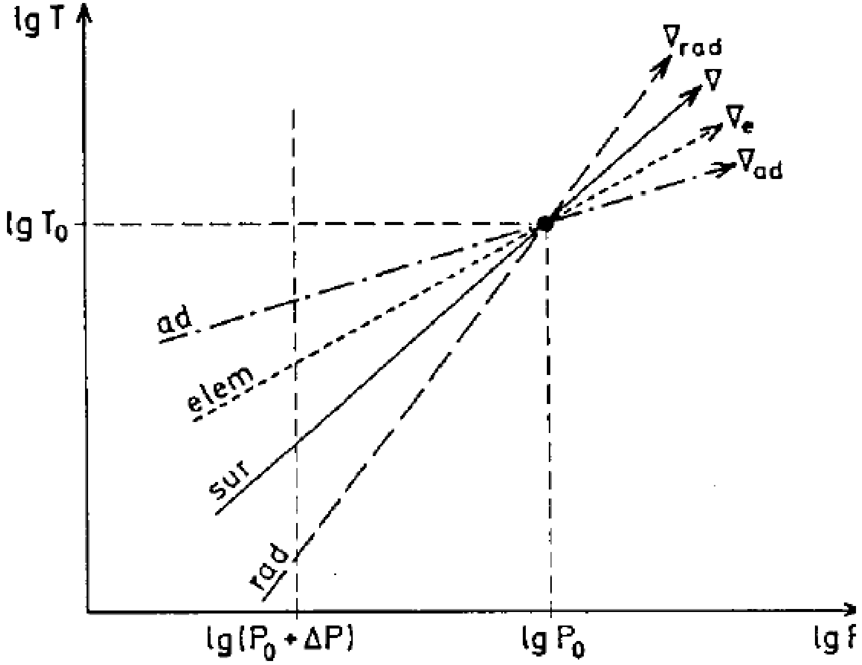
- Convective boundary mixing (CBM, also composition dependent)

Stability condition . . .

$$\begin{aligned}
\left(\frac{\mathrm{d}\ln T}{\mathrm{d}\ln P}\right)_s &< \left(\frac{\mathrm{d}\ln T}{\mathrm{d}\ln P}\right)_e + \frac{\varphi}{\delta}\left(\frac{\mathrm{d}\ln \mu}{\mathrm{d}\ln P}\right)_s \\
\nabla_s &< \nabla_{\mathrm{ad}} + \frac{\varphi}{\delta}\nabla_\mu \\
\nabla_{\mathrm{rad}} &< \nabla_{\mathrm{ad}} + \frac{\varphi}{\delta}\nabla_\mu
\end{aligned}$$

The last equation holds in general cases and is called the Ledoux-criterion for dynamical stability. If $\nabla_\mu = 0$, the Schwarzschild-criterion holds. Note: $\nabla_\mu > 0$ and will stabilize.

The four ∇



In an unstable layer, the following relations hold:

$$\nabla_{\rm rad} > \nabla > \nabla_e > \nabla_{\rm ad}$$

The task of convection theory is to calculate ∇!

The Mixing Length Theory

$$\begin{aligned} F &= \frac{L_r}{4\pi r^2} = F_{\rm conv} + F_{\rm rad} \\ F &=: \frac{4acG}{3}\frac{T^4 m}{\kappa P r^2}\nabla_{\rm rad} \\ F_{\rm rad} &= \frac{4acG}{3}\frac{T^4 m}{\kappa P r^2}\nabla \\ F_{\rm conv} &= \rho v c_P (DT) \end{aligned}$$

A blob starts somewhere with $DT > 0$ and loses identity after a typical mixing length distance l_m. On average

$$\frac{DT}{T} = \frac{1}{T}\frac{\partial(DT)}{\partial r}\frac{l_m}{2} = (\nabla - \nabla_e)\frac{l_m}{2}\frac{1}{H_P}$$

The mixing length parameter

- mixing length $l_m = \alpha_{\mathrm{MLT}} H_P$; α_{MLT}: mixing-length parameter
- α_{MLT} of order 1
- determined usually by solar models, $\alpha_{\mathrm{MLT}} \approx 1.6 \cdots 1.9$
- or other comparisons with observations (giant stars with CE)
- NO calibration or meaning!

Examples for ∇: Sun: $r = R_\odot/2$, $m = M_\odot/2$, $T = 10^7$, $\rho = 1$, $\delta = \mu = 1$

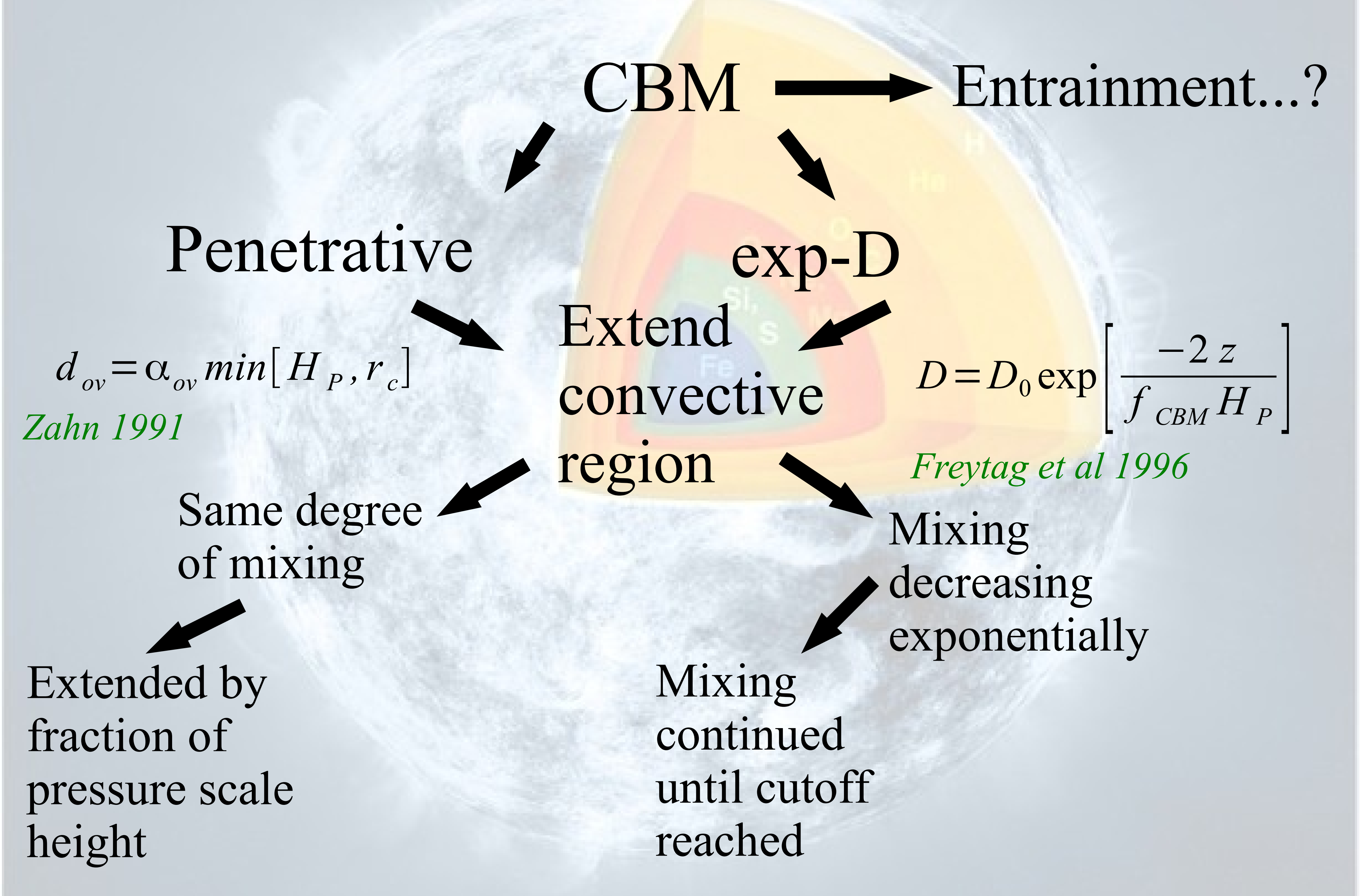
$$\rightarrow U = 10^{-8} \rightarrow \nabla = \nabla_{\mathrm{ad}} + 10^{-5} = 0.4$$

(as long as $\nabla_{\mathrm{rad}} < 100 \cdot \nabla_{\mathrm{ad}}$); at center, $\nabla = \nabla_{\mathrm{ad}} + 10^{-7}$.

Deficits of MLT

- local theory → no overshooting from convective boundaries due to inertia of convective elements
- time-independent → instantaneous adjustment; critical if other short timescales (pulsations, nuclear burning) present
- only one length scale, but spectrum of turbulent eddies → improvements by Canuto & Mazzitelli
- presence of chemical gradients ignored (semiconvection) → treatment of such layers unclear; probably slow mixing on diffusive timescale due to secular g-modes; T-gradient radiative?

Convective Boundary Mixing (CBM)



CBM → Entrainment...?

Penetrative

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

Zahn 1991

exp-D

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

Freytag et al 1996

Extend convective region

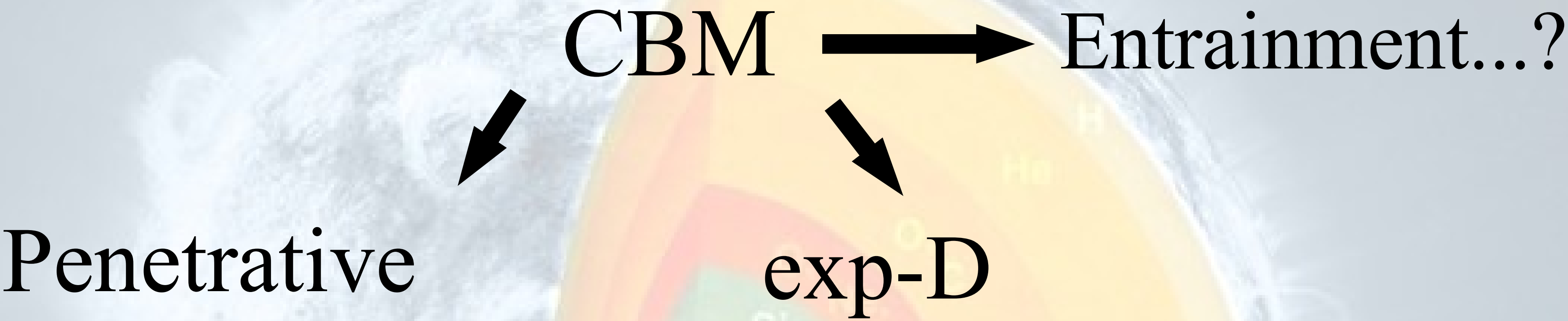
Same degree of mixing

Extended by fraction of pressure scale height

Mixing decreasing exponentially

Mixing continued until cutoff reached

Convective Boundary Mixing (CBM)


CBM → Entrainment...?

Penetrative

exp-D

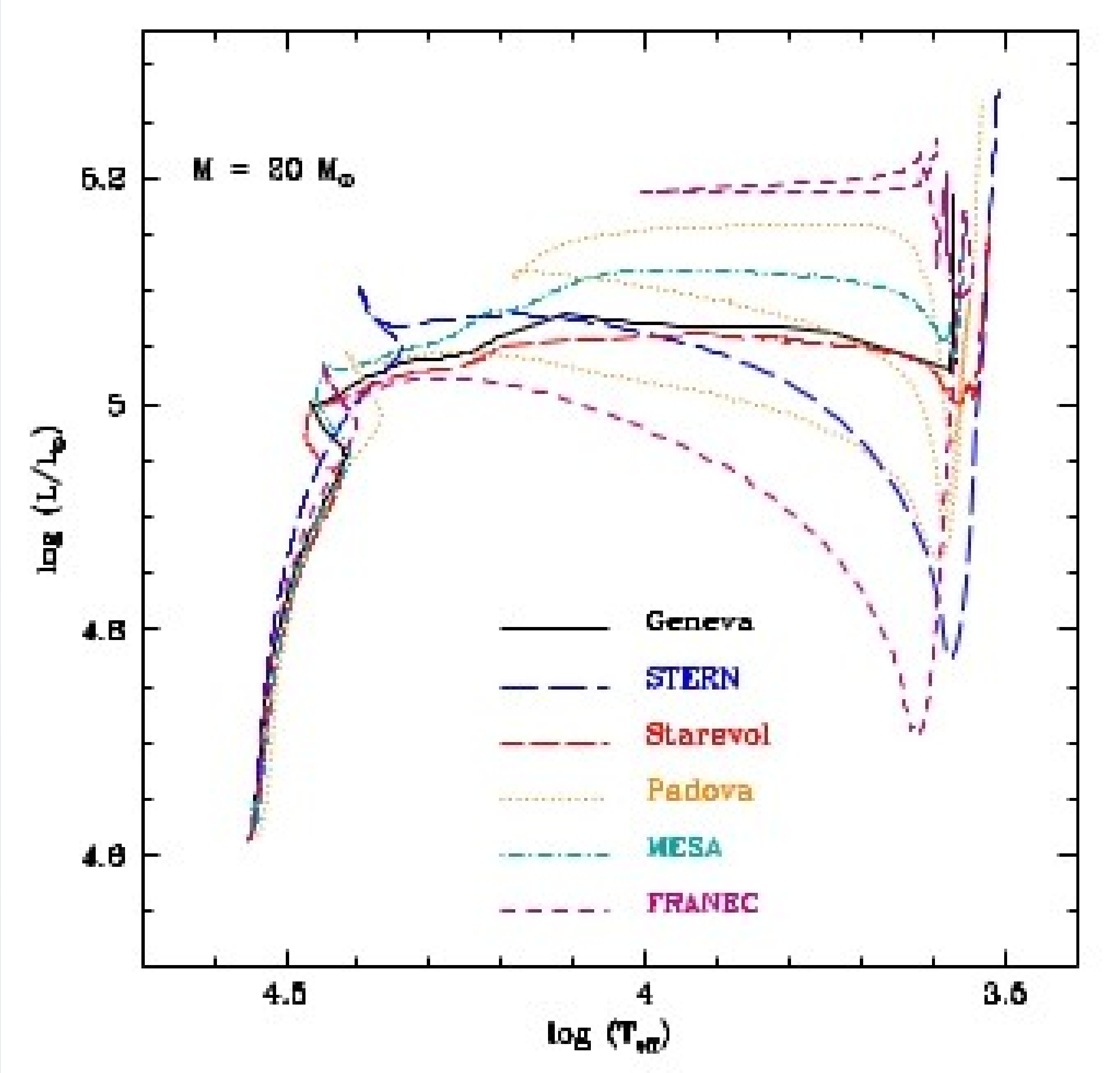
- Inspired by multi-D hydro simulations

- 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

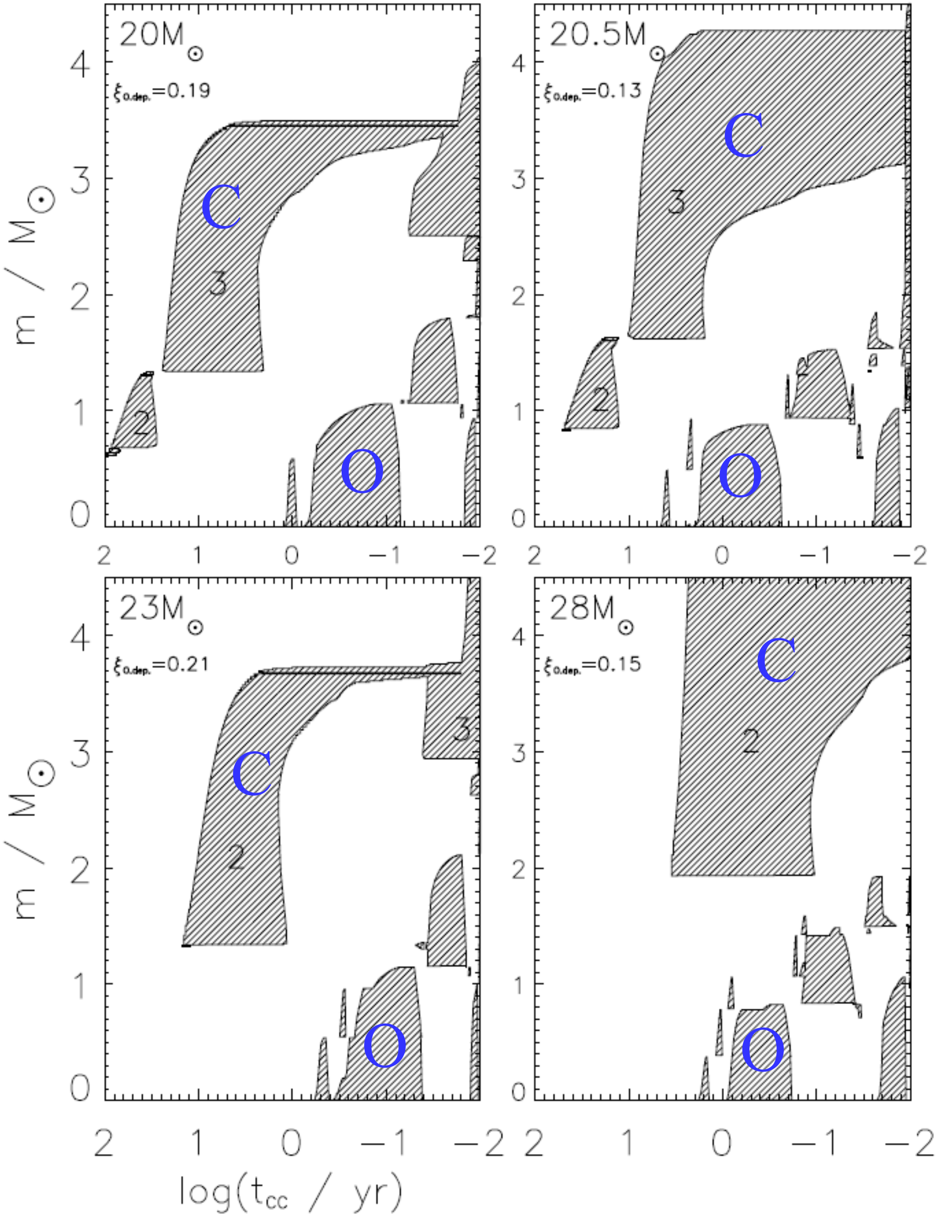


FIG. 13.— Convective history of four models showing the major

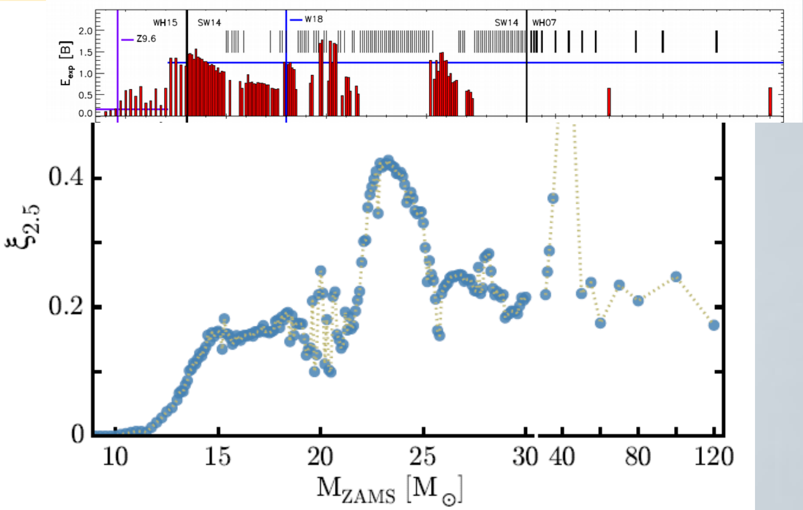
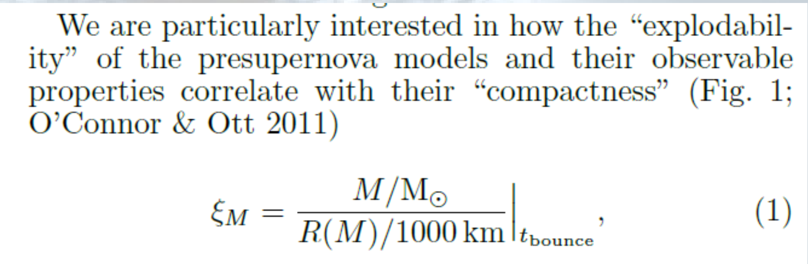


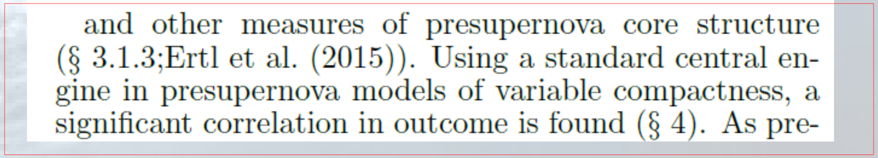
FIG. 1.— The compactness parameter, $\xi_{2.5}$, (eq. (1); O'Connor & Ott 2011) characterizing the inner 2.5 $M_\odot$ of the presupernova star is shown as a function of zero-age main sequence (ZAMS) mass for all 200 models between 9.0 and 120 $M_\odot$. The compactness

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)

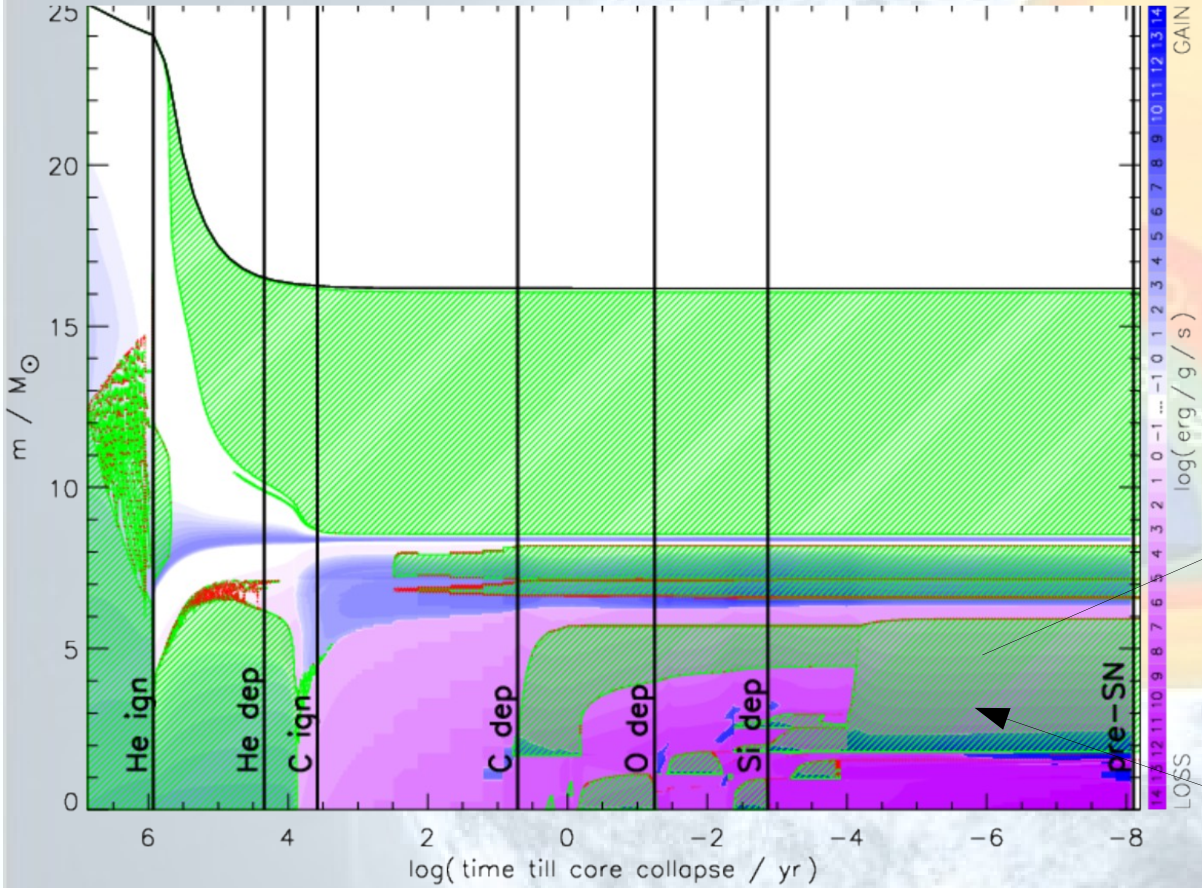
$$\xi_M = \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}\Big|_{t_\mathrm{bounce}}, \qquad (1)$$

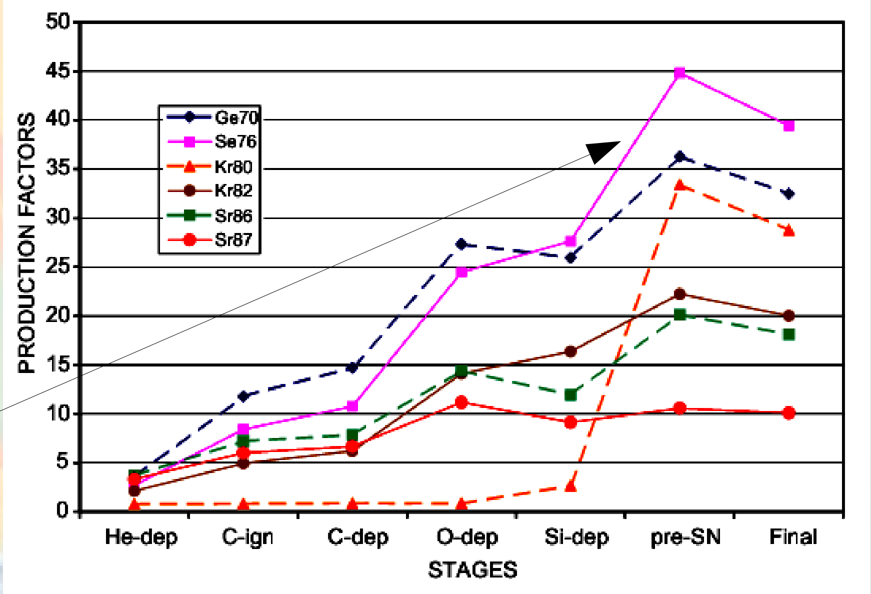


and other measures of presupernova core structure (§ 3.1.3;Ertl et al. (2015)). Using a standard central engine in presupernova models of variable compactness, a significant correlation in outcome is found (§ 4). As pre-

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.”

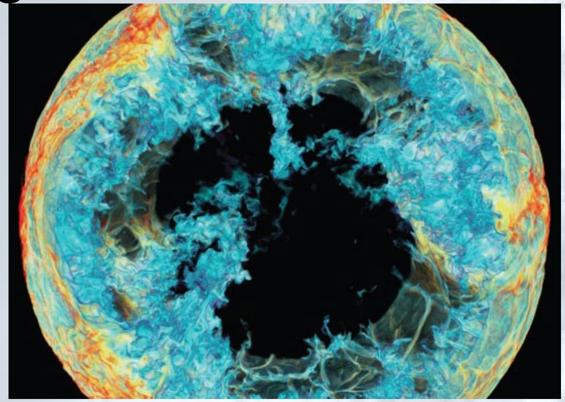
Shell mergers also affect compactness

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

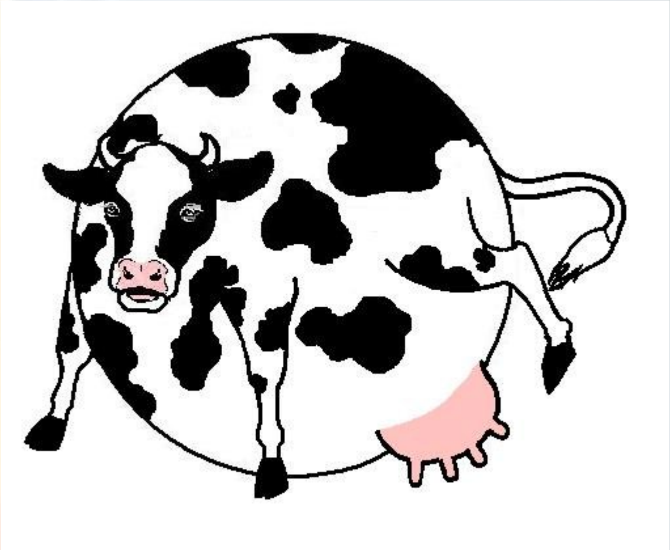
Way Forward: 1 to 3 to 1D link

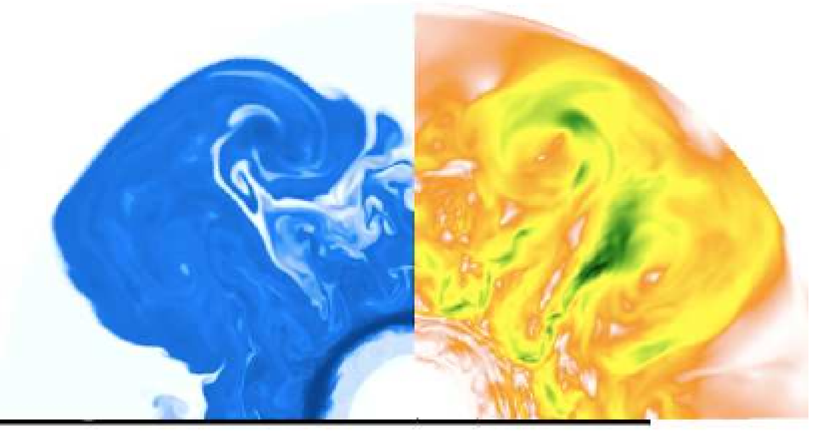
Targetted 3D simulations

Uncertainties in 1D

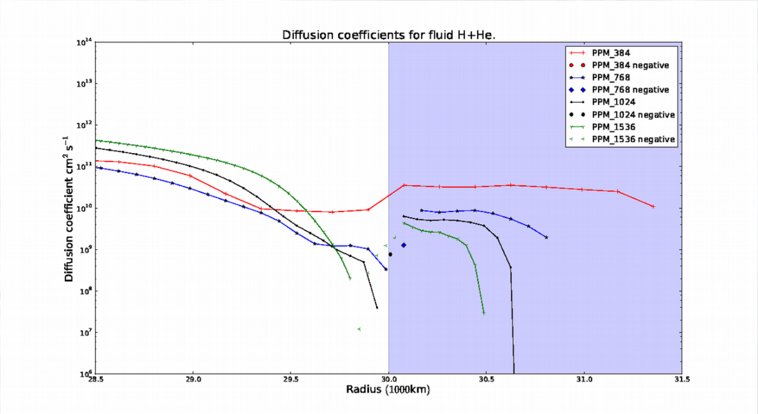


Herwig et al 06, Herwig, Woodward et al 2013





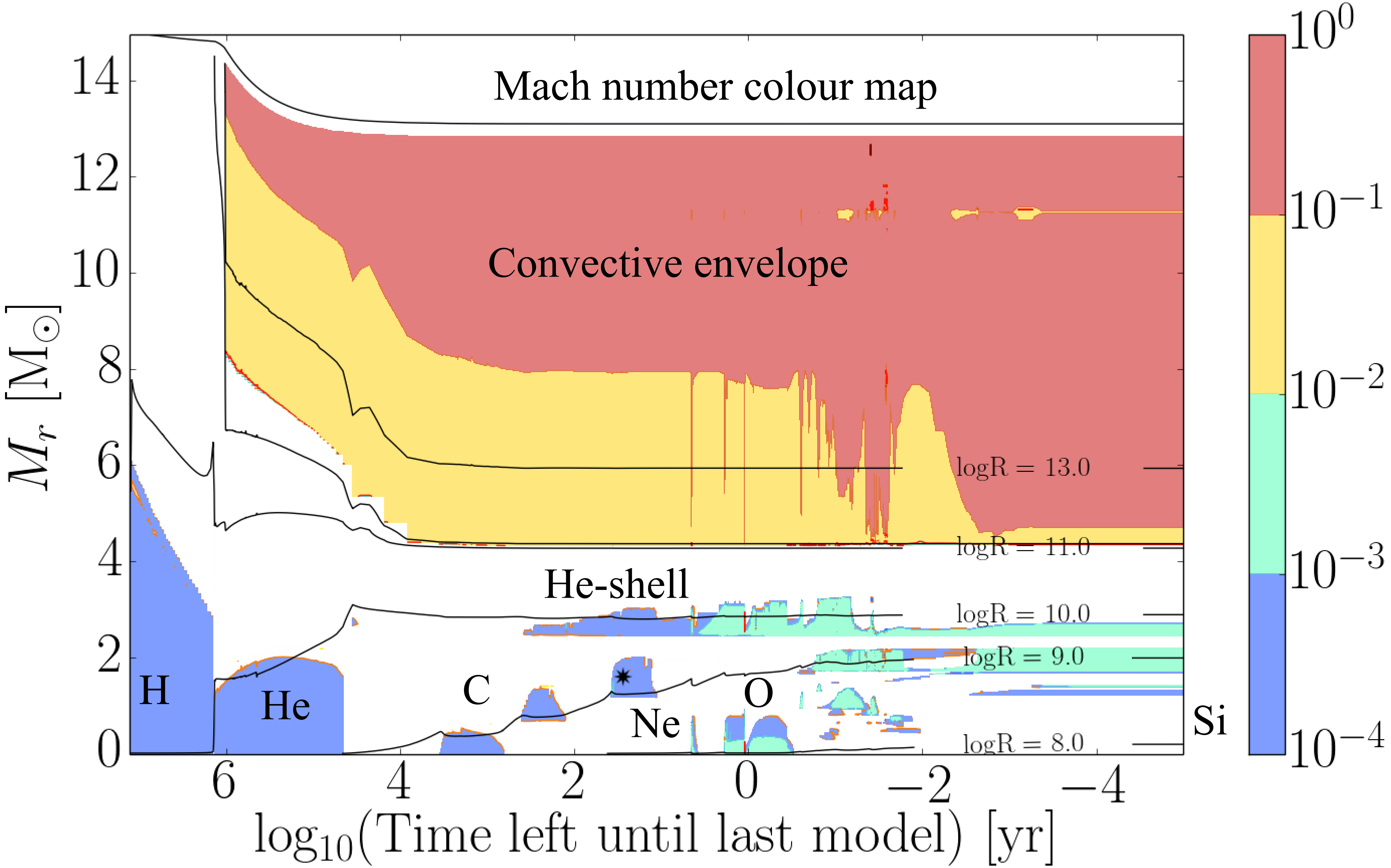
e.g. Arnett & Meakin 2011, ...
Mocak et al 2011,
Viallet et al 2013, ...



Meakin et al 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

Where to Start? Carbon burning shell

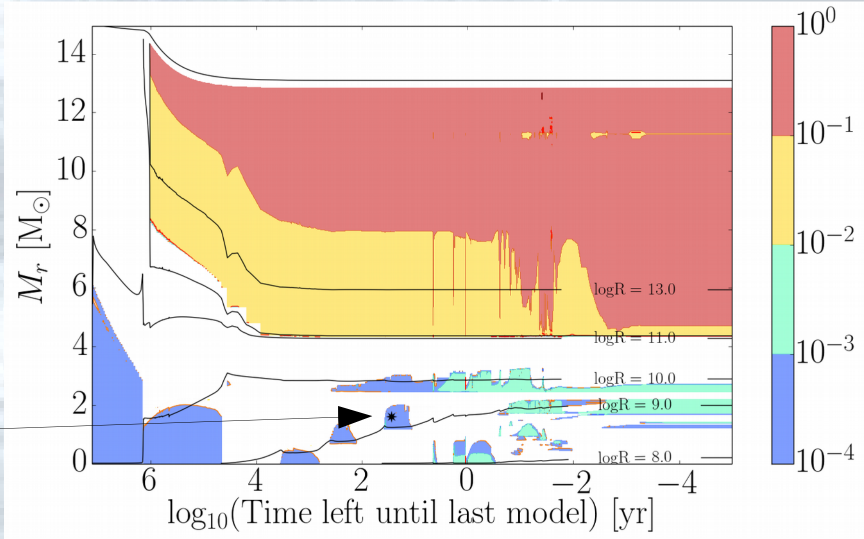
- "Simple" convective history before C-shell

- 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

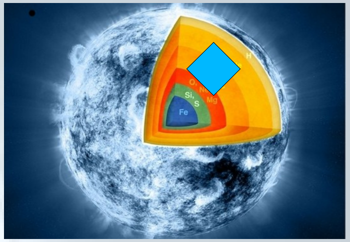


C-shell

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

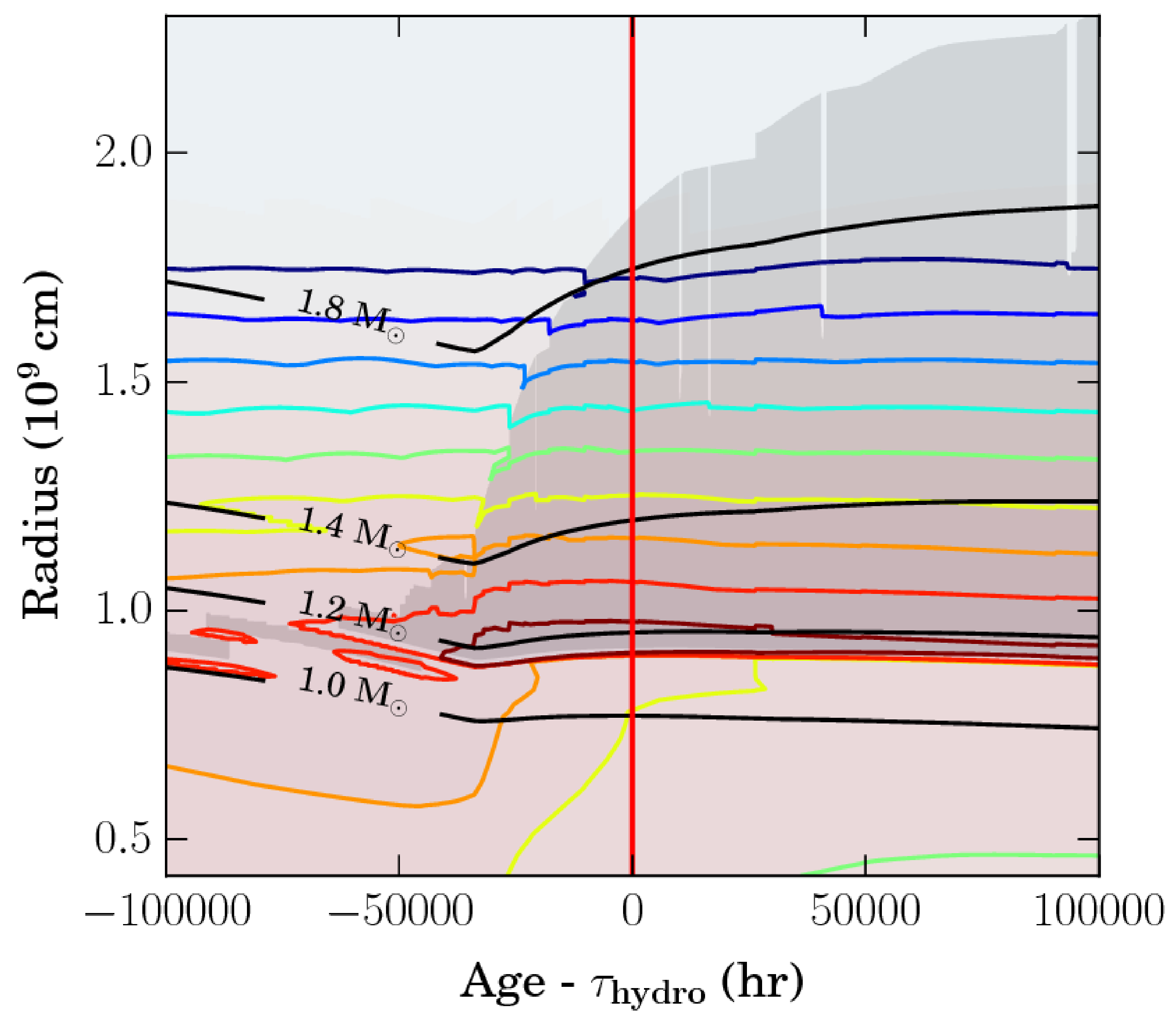
- Turbulence initiated through random low-amplitude perturbations in temperature and density

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

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

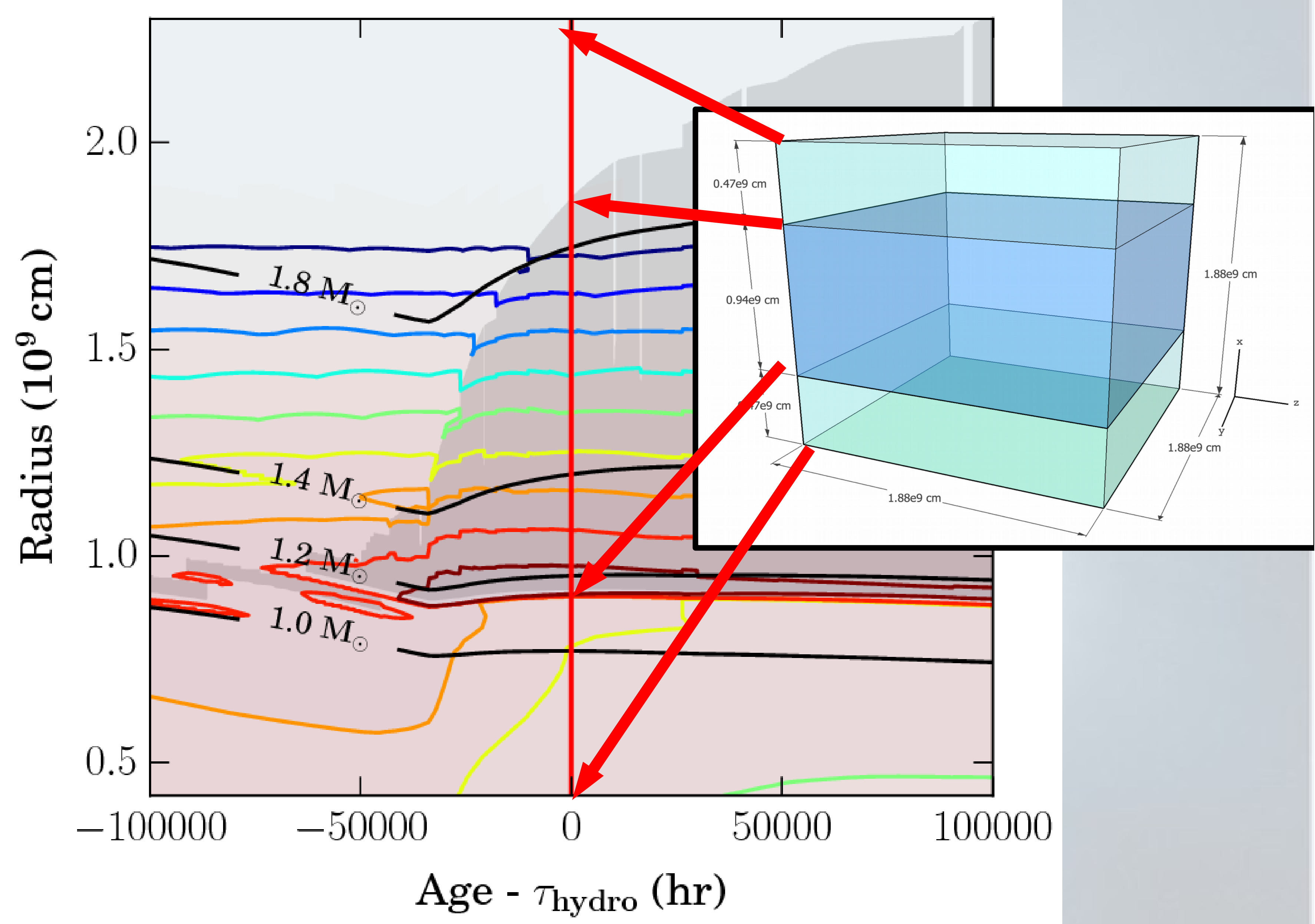
From 1D to 3D

C-shell in 15 $M_\odot$, Z=0.014 1D stellar evolution model



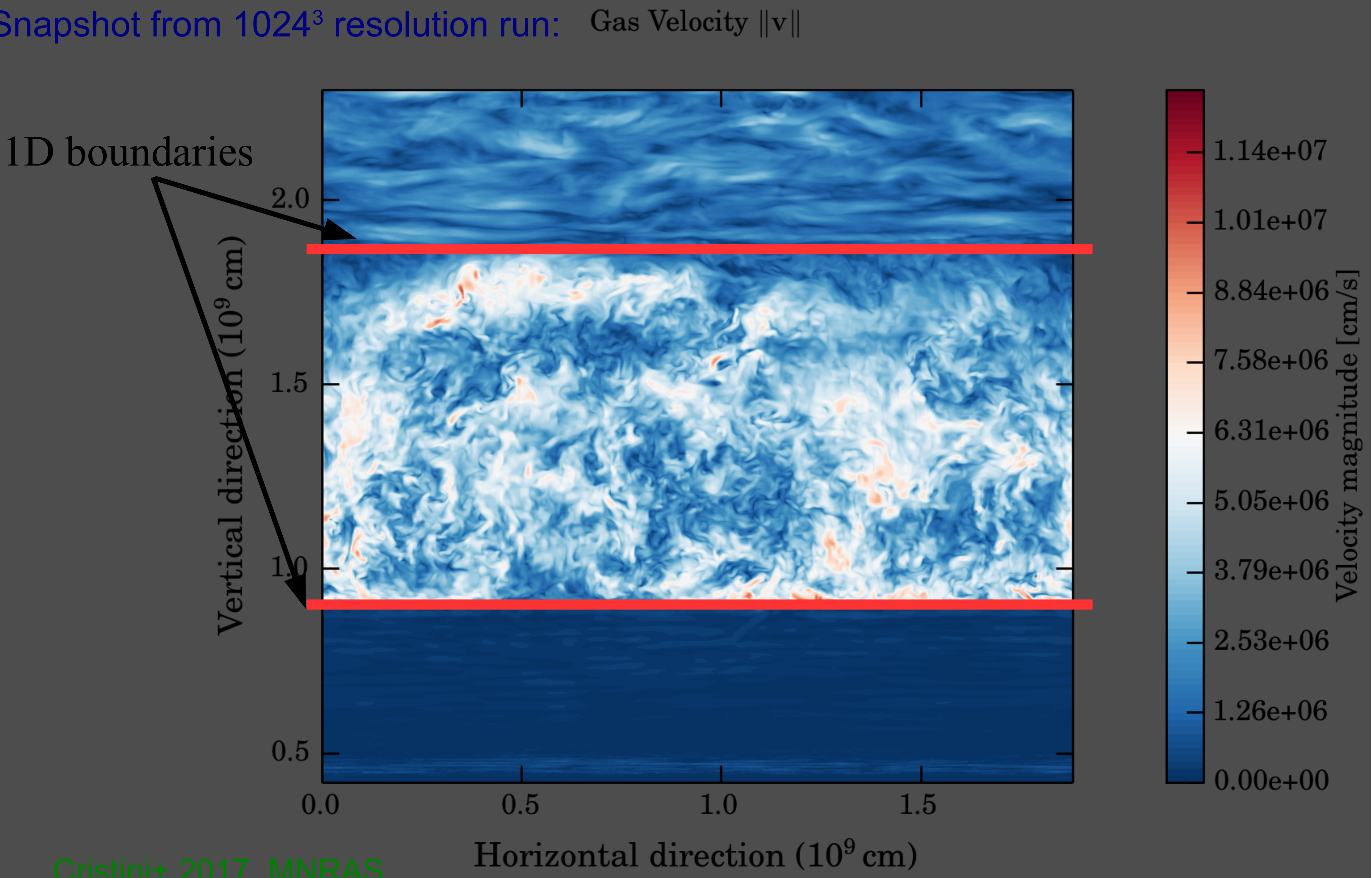
From 1D to 3D

C-shell in 15 $M_\odot$, Z=0.014 1D stellar evolution model



3D C-shell Simulations

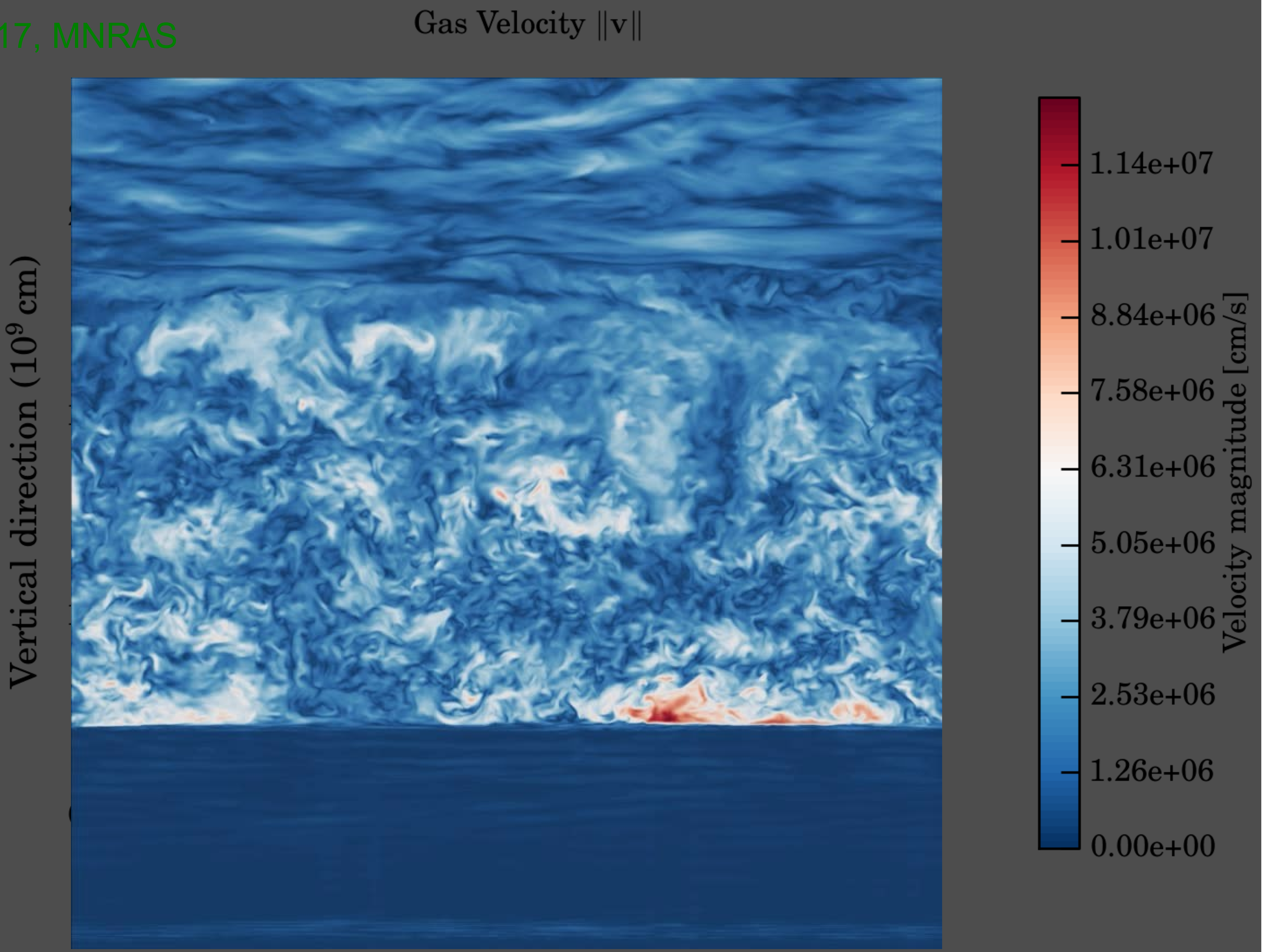
Snapshot from 1024^3 resolution run:



Cristini+ 2017, MNRAS

3D C-shell Simulations: $|v|$ movie

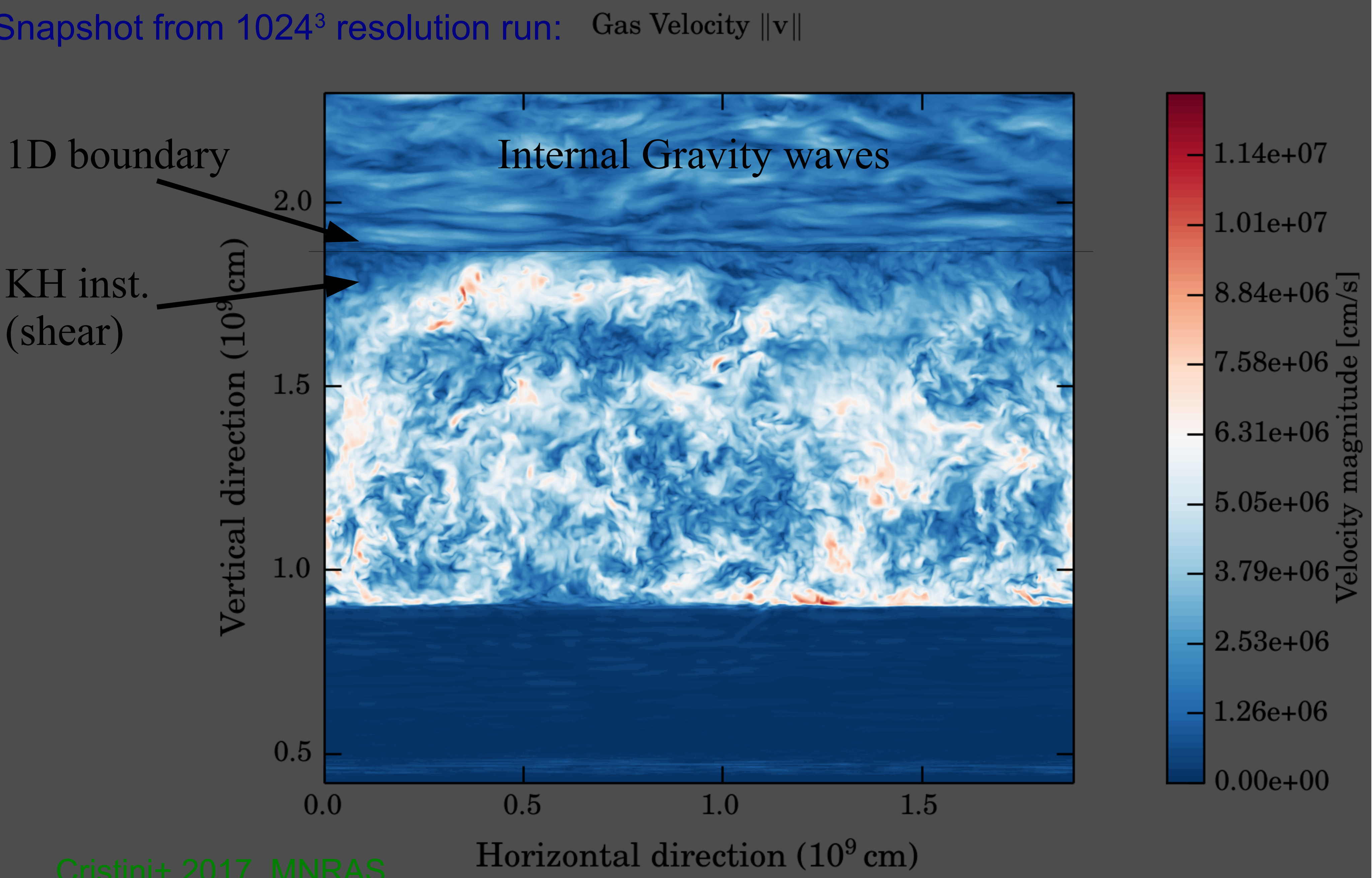
Cristini+ 2017, MNRAS



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

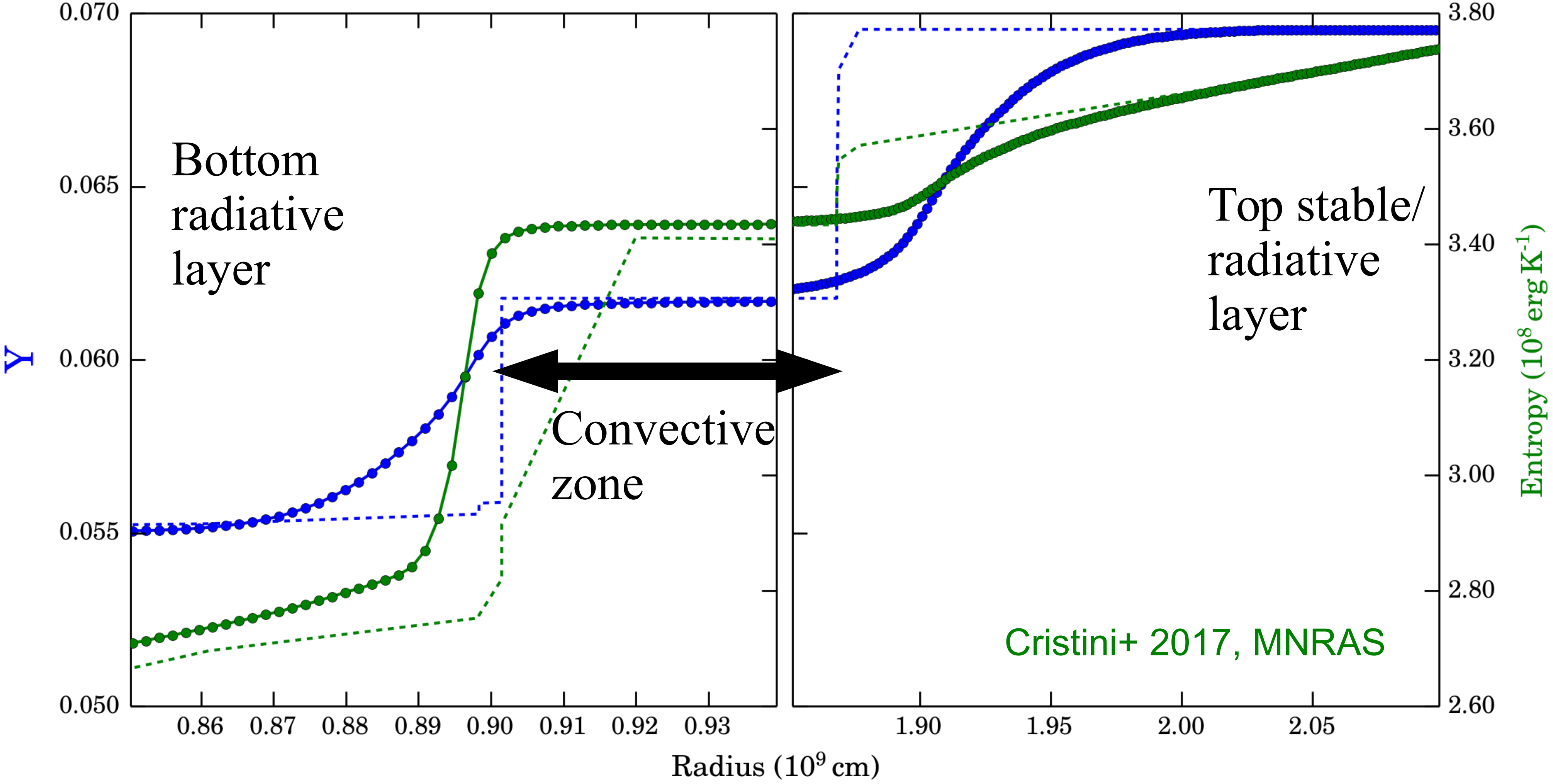
3D C-shell Simulations

Snapshot from 1024^3 resolution run:



Cristini+ 2017, MNRAS

3D versus 1D



Bottom radiative layer

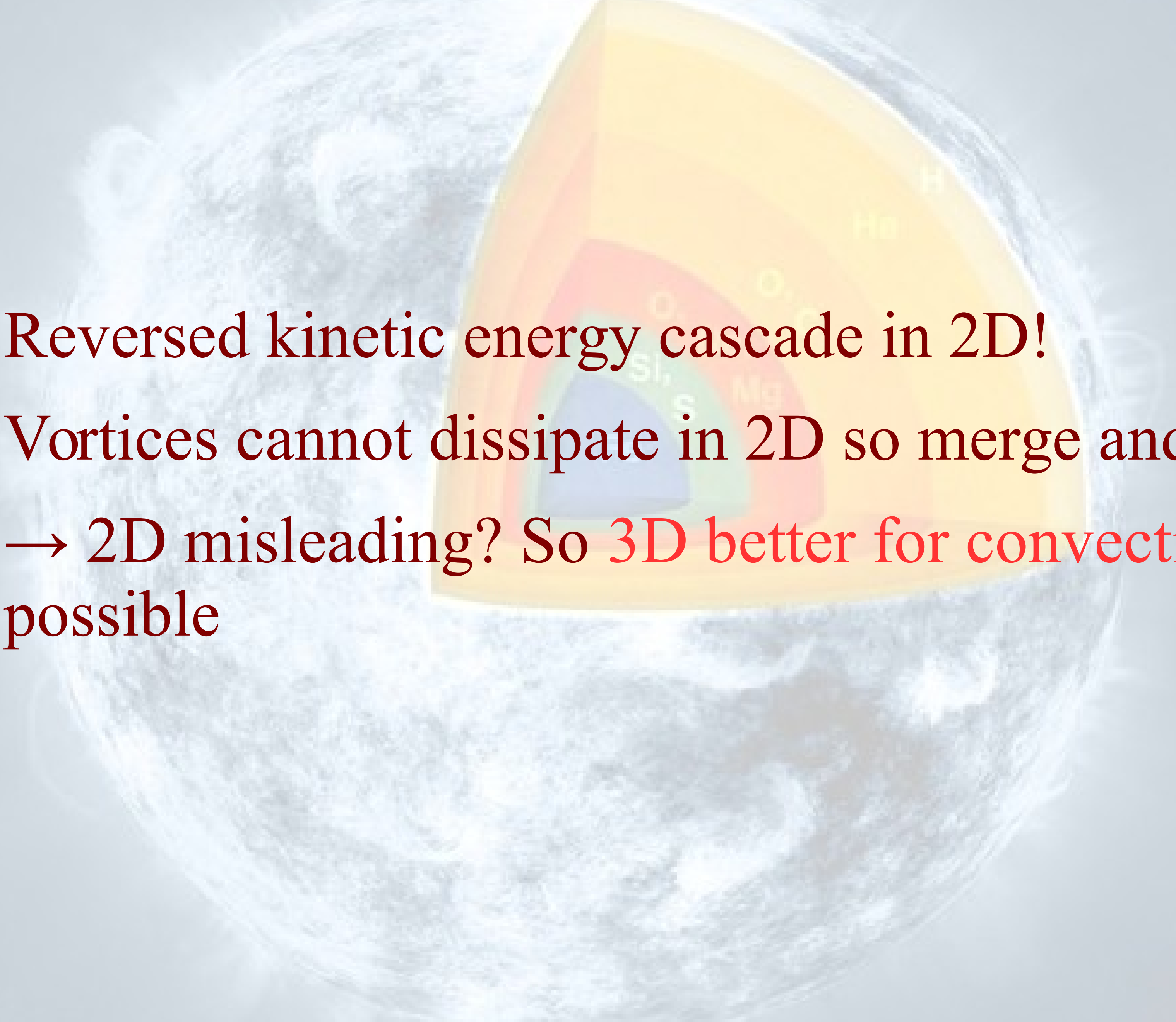
Convective zone

Top stable/ radiative layer

Cristini+ 2017, MNRAS

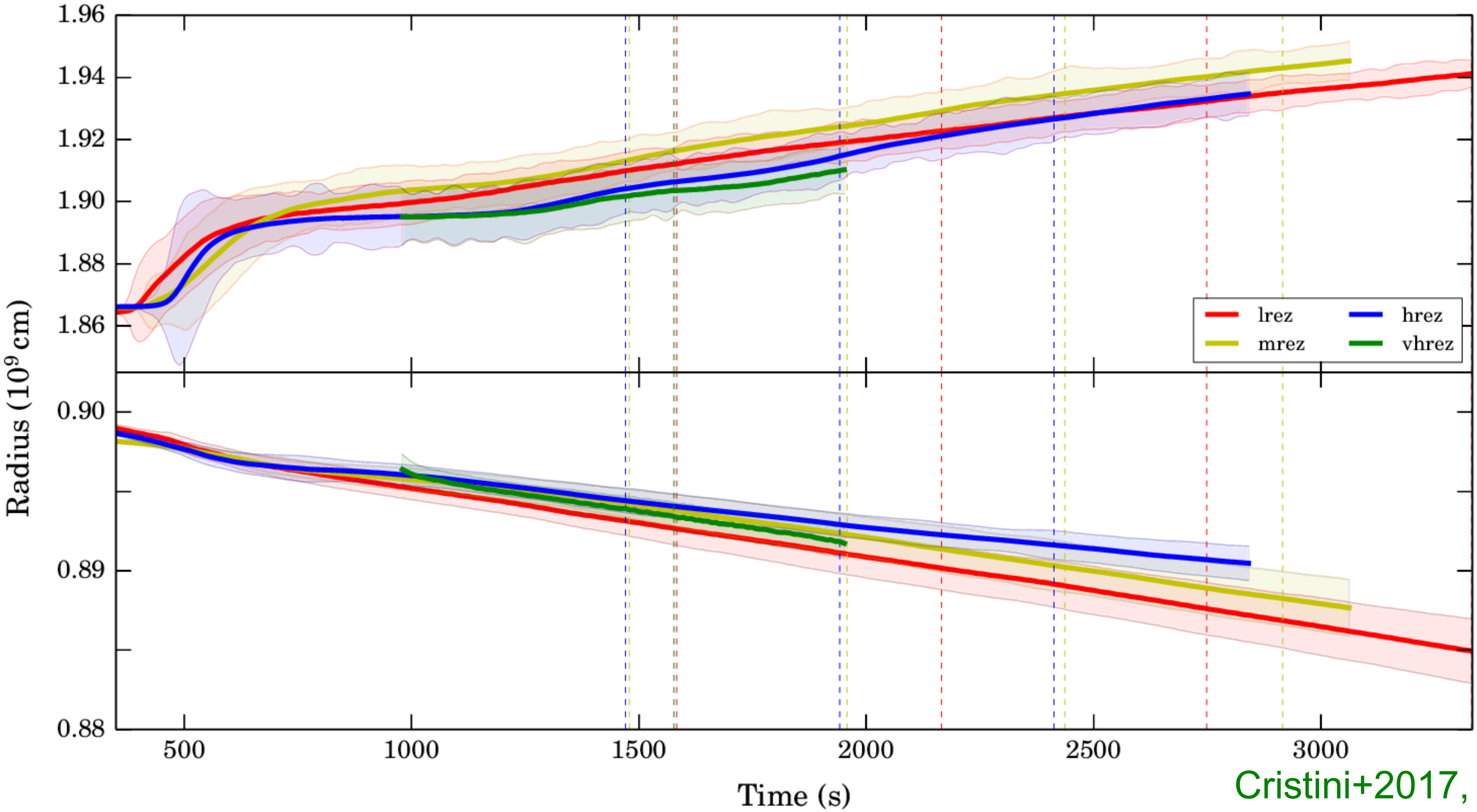
- Improved prescriptions for CBM needed!

What About 2D?



- Reversed kinetic energy cascade in 2D!
- Vortices cannot dissipate in 2D so merge and grow
- → 2D misleading? So 3D better for convection if possible

Boundary Entrainment

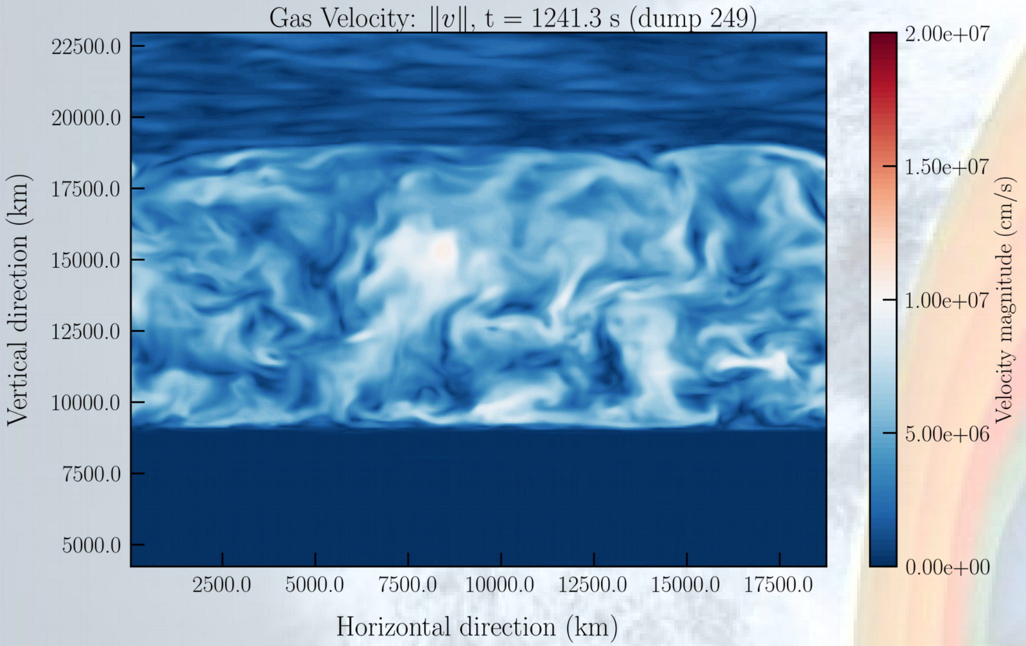


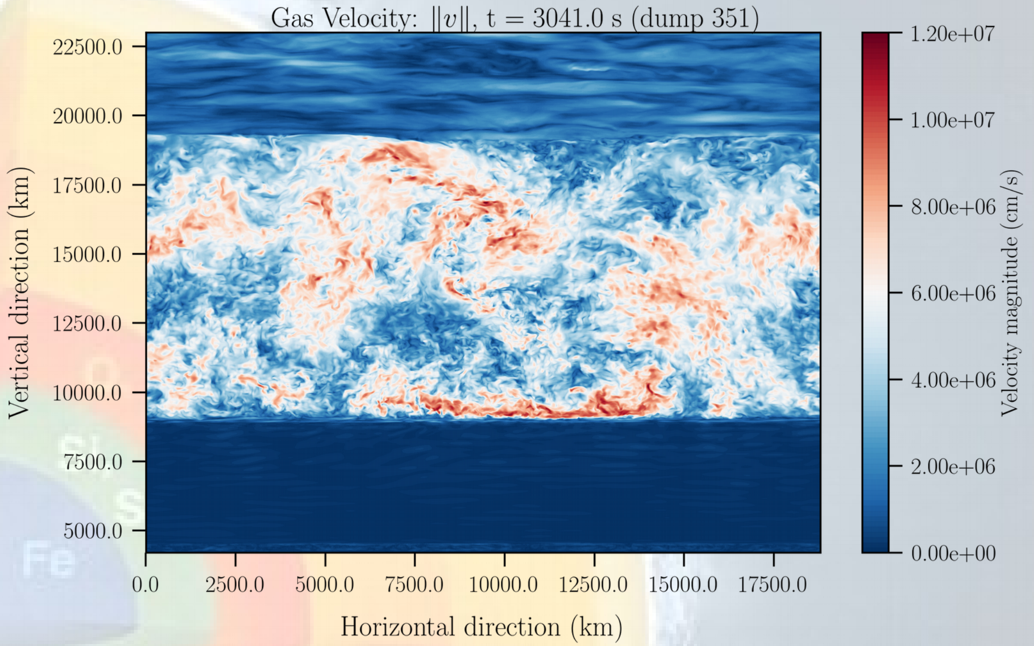
Cristini+2017, MNRAS

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: ΔR ~ 6x10^8 cm, bottom: ΔR ~ 10^8 cm: large but reasonable

Consistent with oxygen-shell results and entrainment law.

Resolution & Luminosity Study





Luminosity Resolution	128	256	512	1024
1			eps1	
33			eps33	
100			eps100	
333			eps333	
1000	lrez	mrez	hrez/eps1k	vhrez
3333			eps3k	
10000			eps10k	
33333			eps33k	

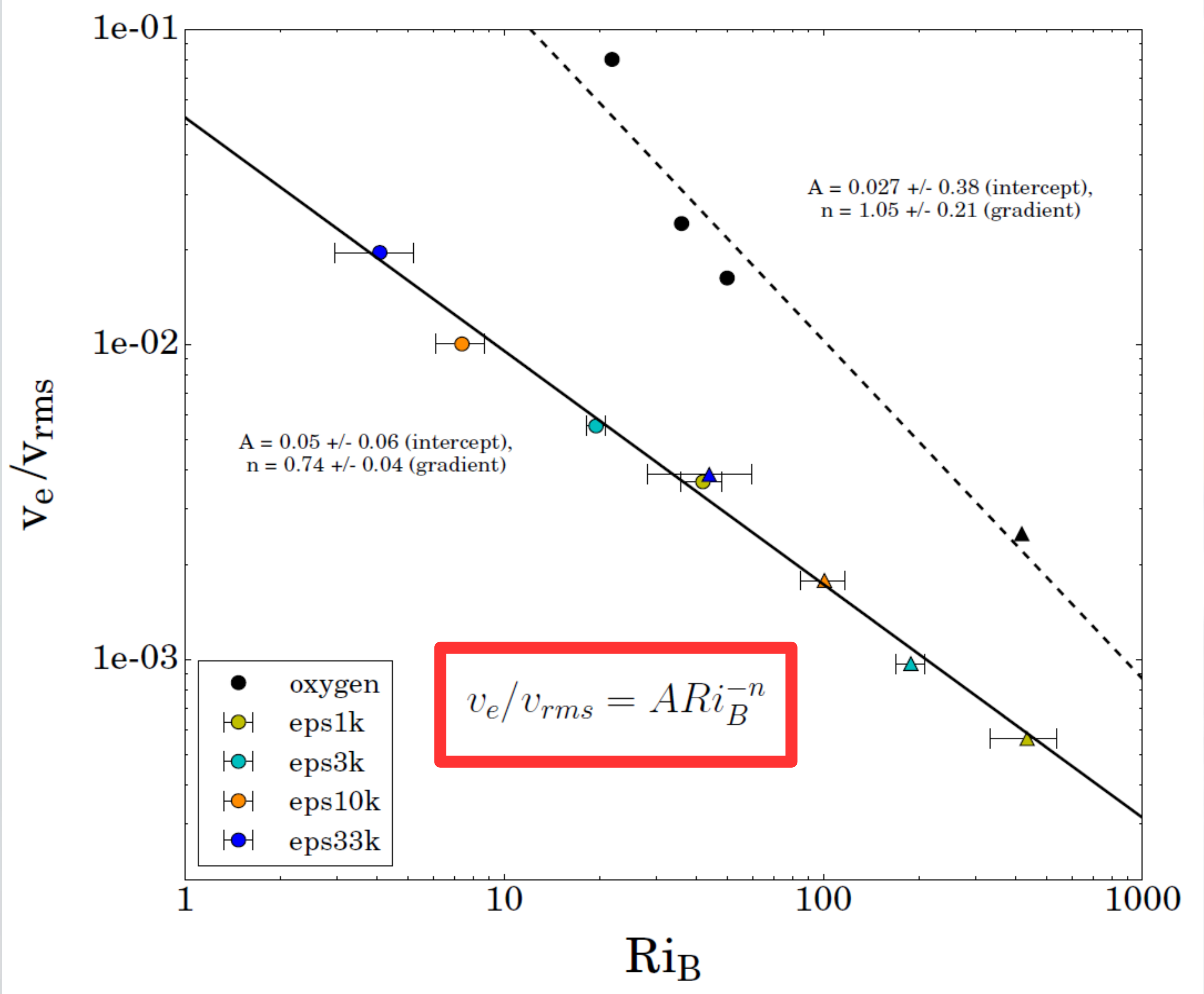
Resolution study

Luminosity study

Cristini+2017, MNRAS

Entrainment Law

Cristini et al in prep (see also Garcia & Mellado, 2014, Deardor 1980, Chemel, Staquet and Chollet 2010, Fernando, 1991, Stevens and Lenschow, 2001, Jonker+ 2013)



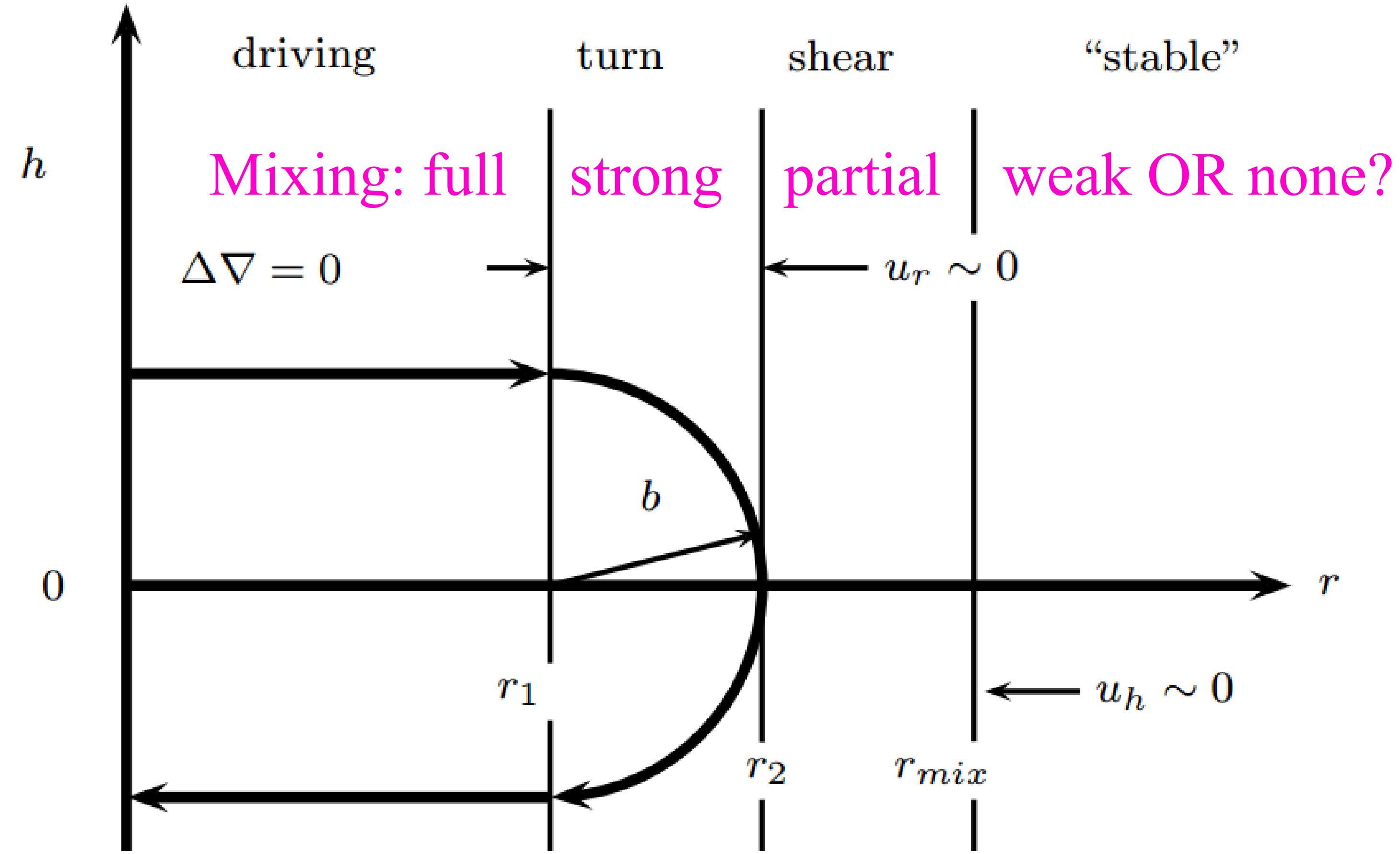
$$v_e / v_{rms} = A Ri_B^{-n}$$

$$Ri_B = \frac{\Delta B \times l}{v_{rms}^2}$$

$$Ri_B = \frac{\text{stabilising potential}}{\text{turbulent kinetic energy}}$$

321D – MLT Replacement + New CBM Prescriptions

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



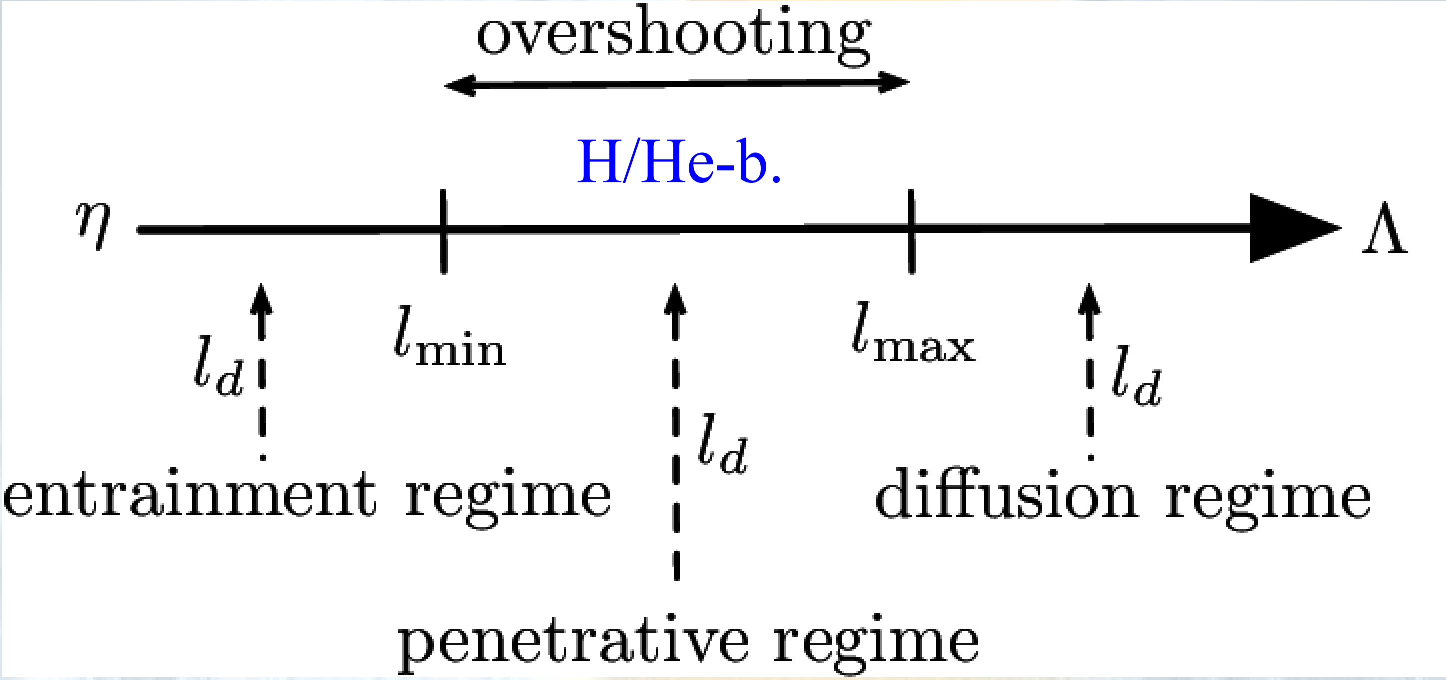
Arnett et al 2015 (321D)

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.



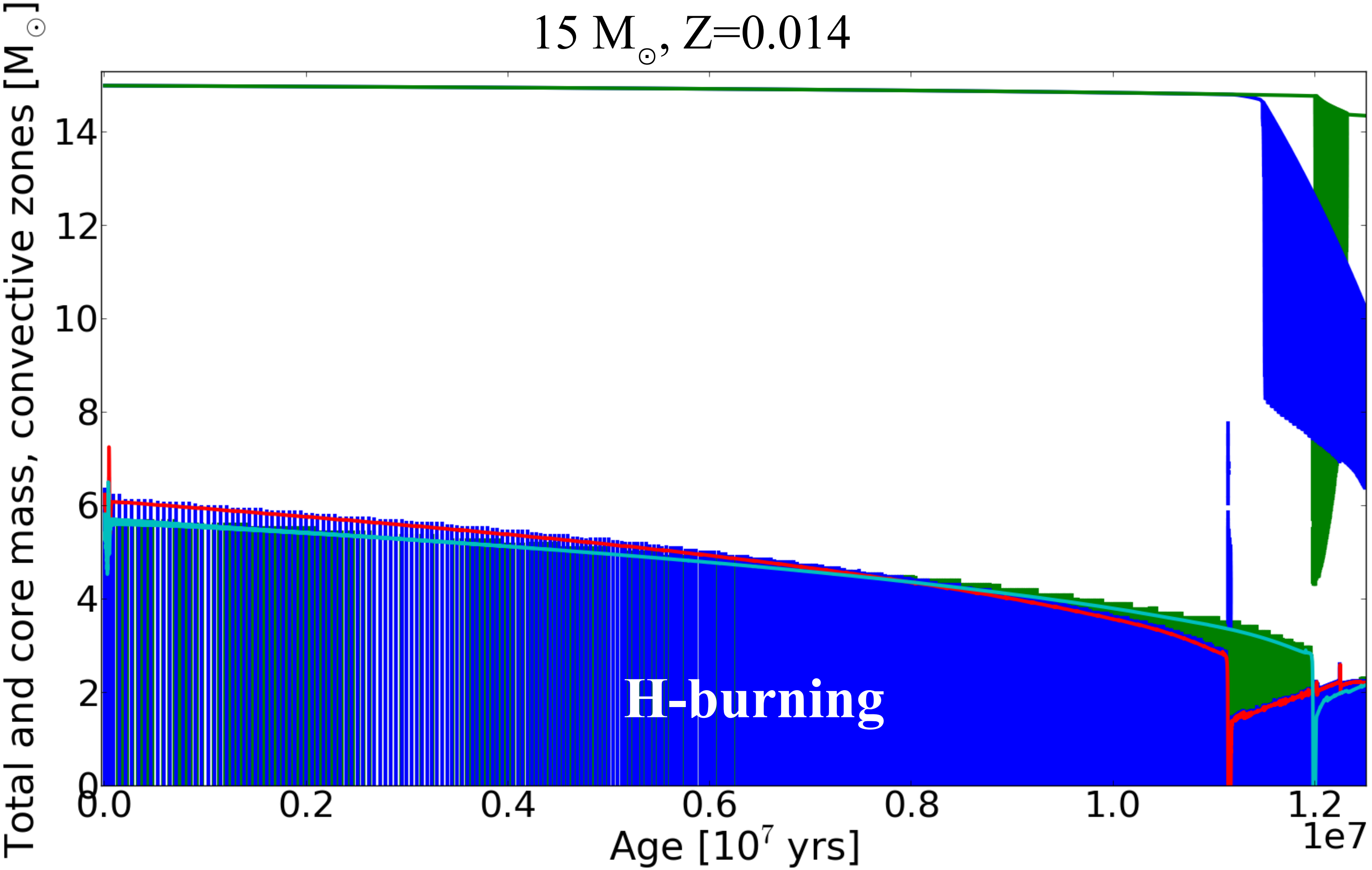
Stellar
surface

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+ 2017, MNRAS

GENEC - CBM

- Applied on H- and He-burning cores
- Penetrative overshoot – extension of convective zone by $\alpha_{ov} H_P$
  - Instantaneous mixing, nabla = nabla_ad
- Default values for alpha_ov are:
  - 0 for M < 1.25 Msun
  - 0.05 for 1.25 Msun < M < 1.7 Msun
  - 0.1 for M > 1.7 Msun

New CBM Prescriptions for GENEC

Convective Shear Mixing

$$D = D_0 \exp \frac{-2z}{f H_P}$$

- Modelled as diffusion
- Diffusive heat transport

$\rightarrow \quad \nabla_{rad}$

Herwig (2000)

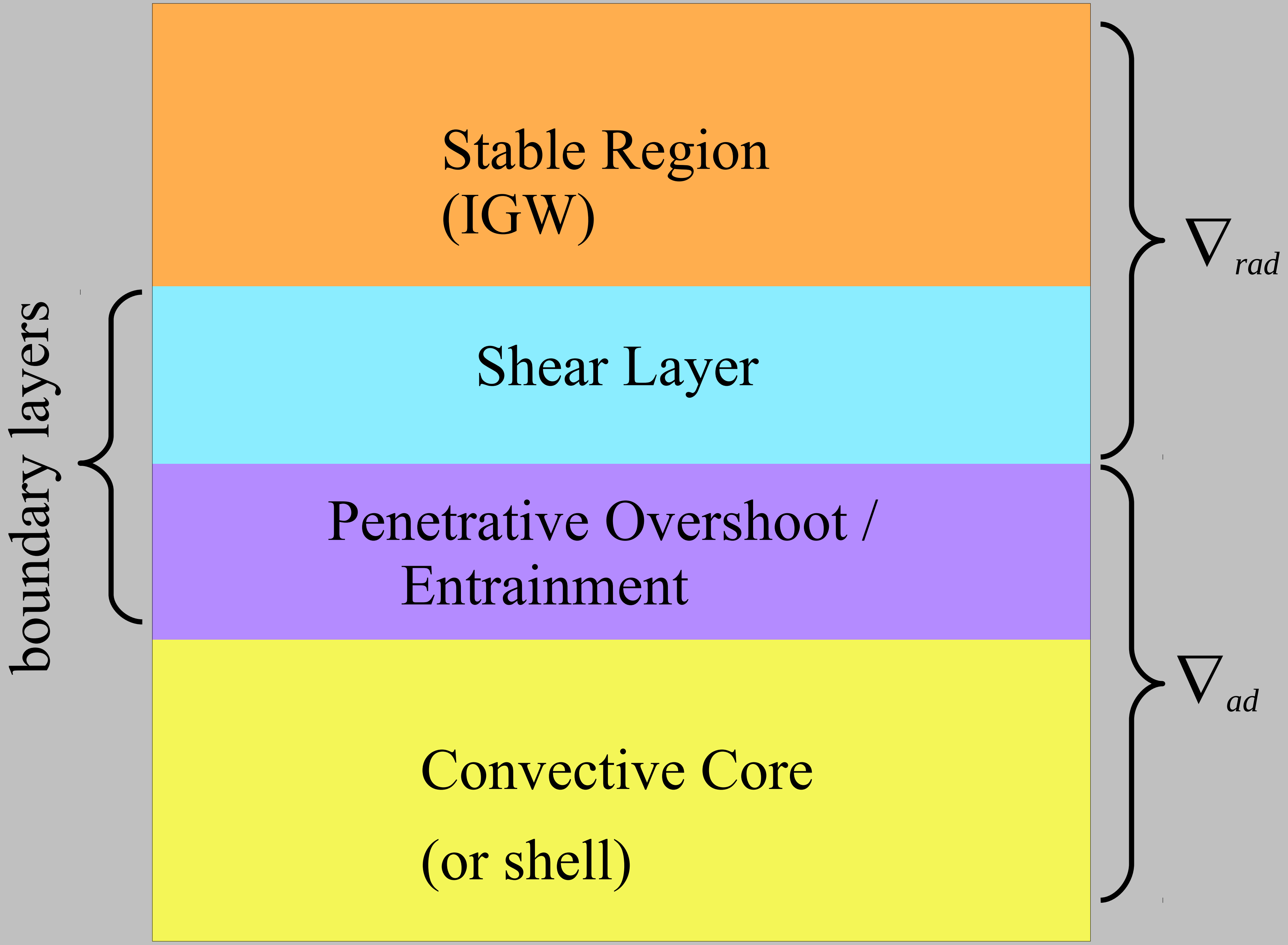
Entrainment

$$\dot{M} = 4\pi r^2 \rho v_c A Ri_b^{-n}$$

- Growth of convective zone
- Instantaneous mixing
- Convective heat transport

$\rightarrow \nabla_{ad}$

Meakin & Arnett (2007)



Stable Region
(IGW)

Shear Layer

Penetrative Overshoot /
Entrainment

Convective Core

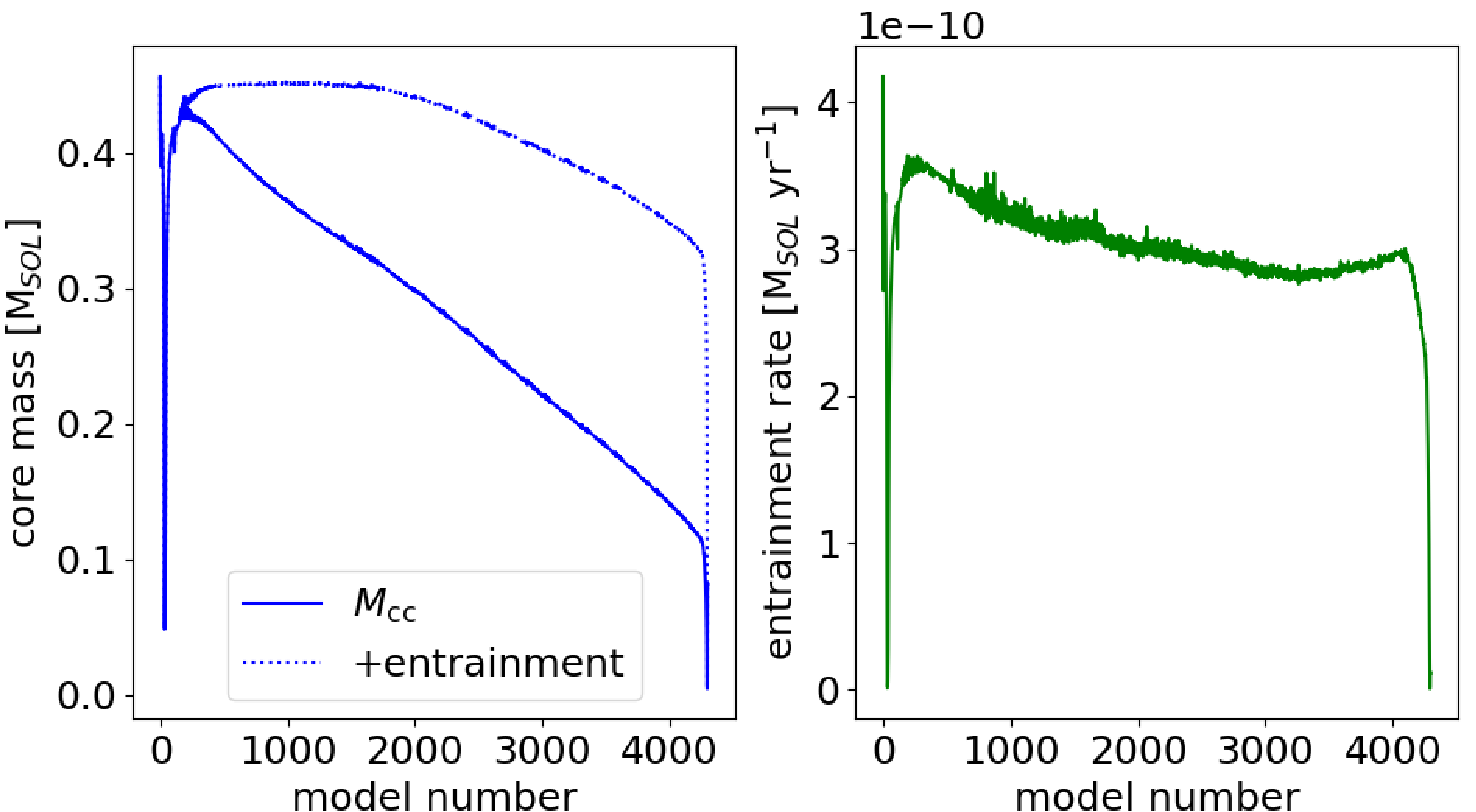
(or shell)

boundary layers

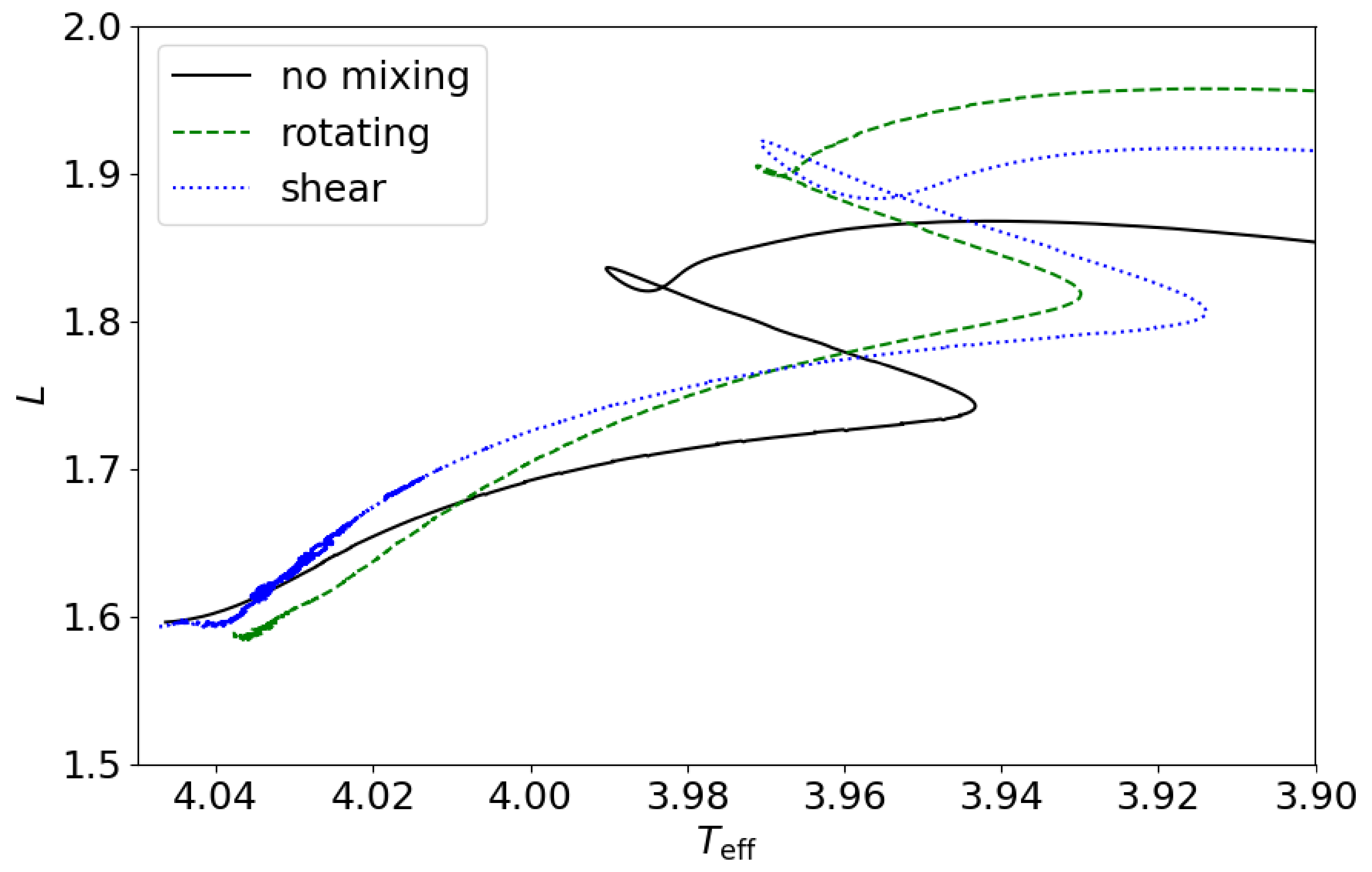
∇_{rad}

∇_{ad}

Initial Results



Initial Results



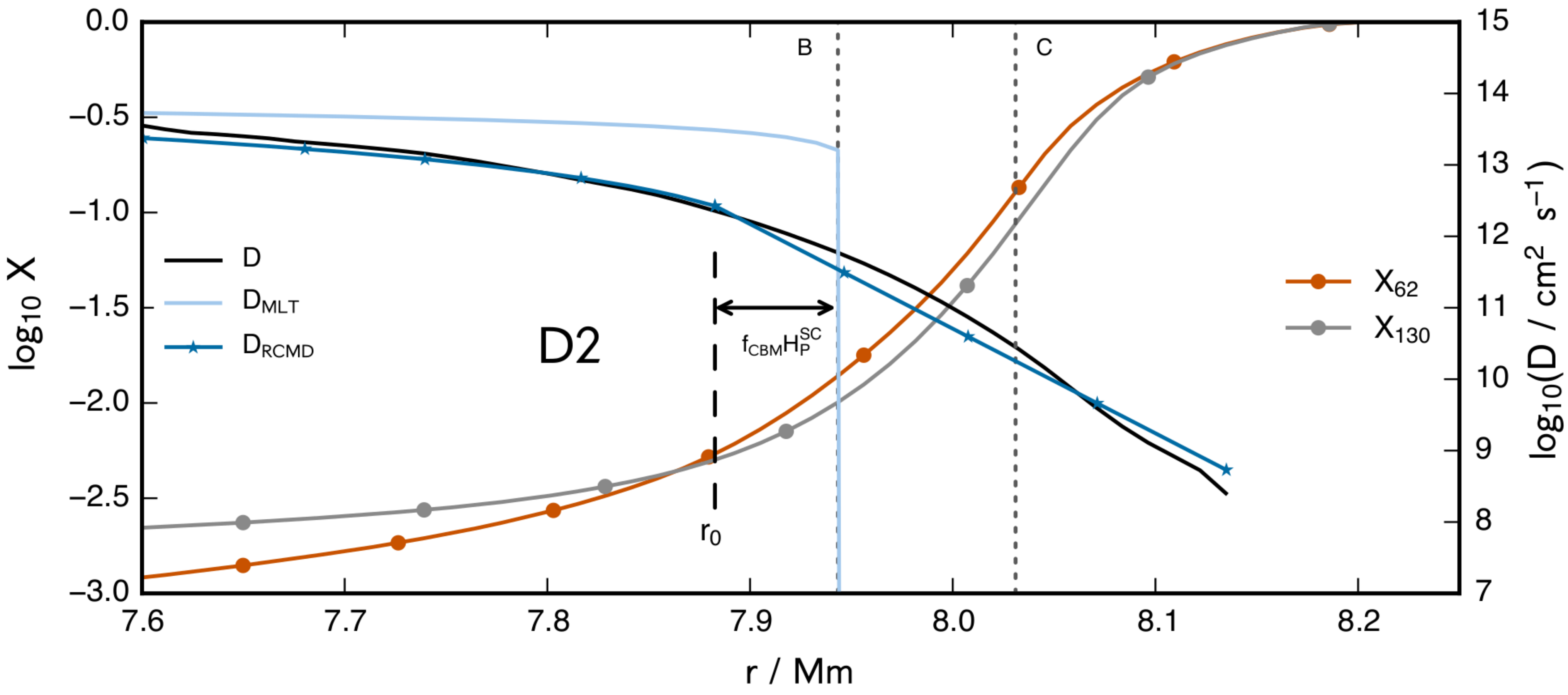
MIXING IN STARS

1D MIXING MODEL

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

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

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

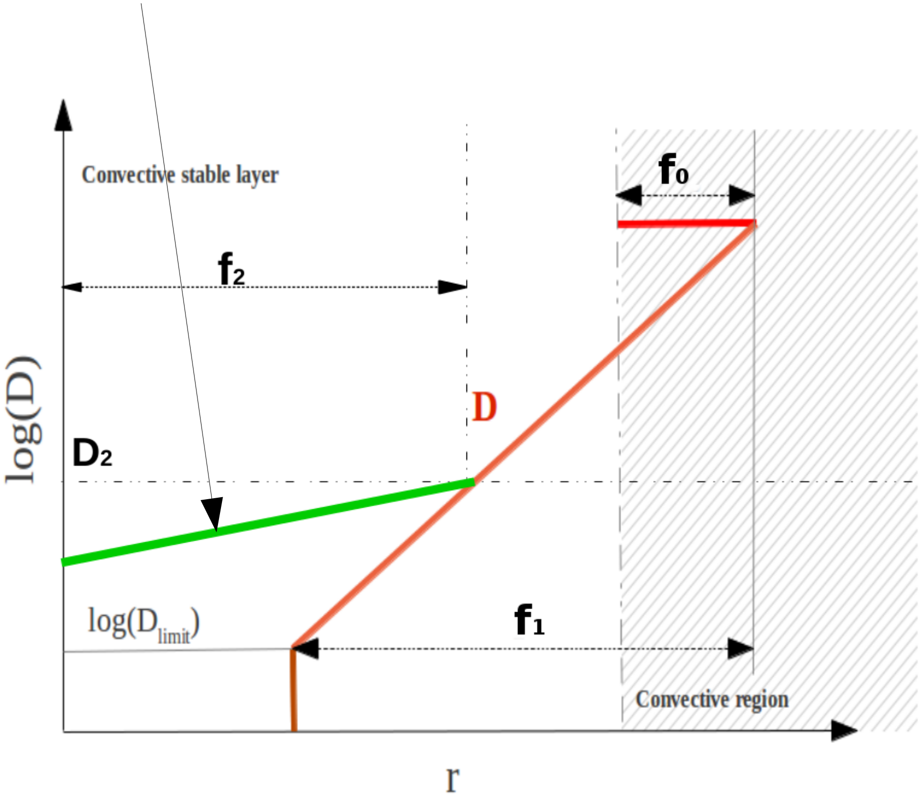


S. Jones, RA, SS, AD, PW, FH (2016, ArXiv e-prints, arXiv:1605.03766)

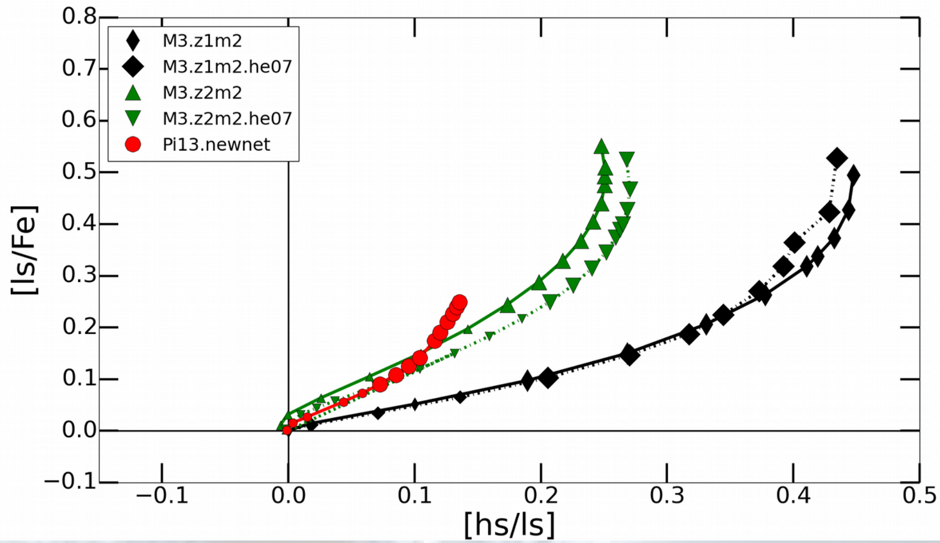
Back to 1D: CBM in AGB Stars (NuGrid project)

Internal gravity wave (IGW) driven mixing

Battino,…,Hirschi et al ApJ 2016



$2\text{-}3\ M_\odot$, 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

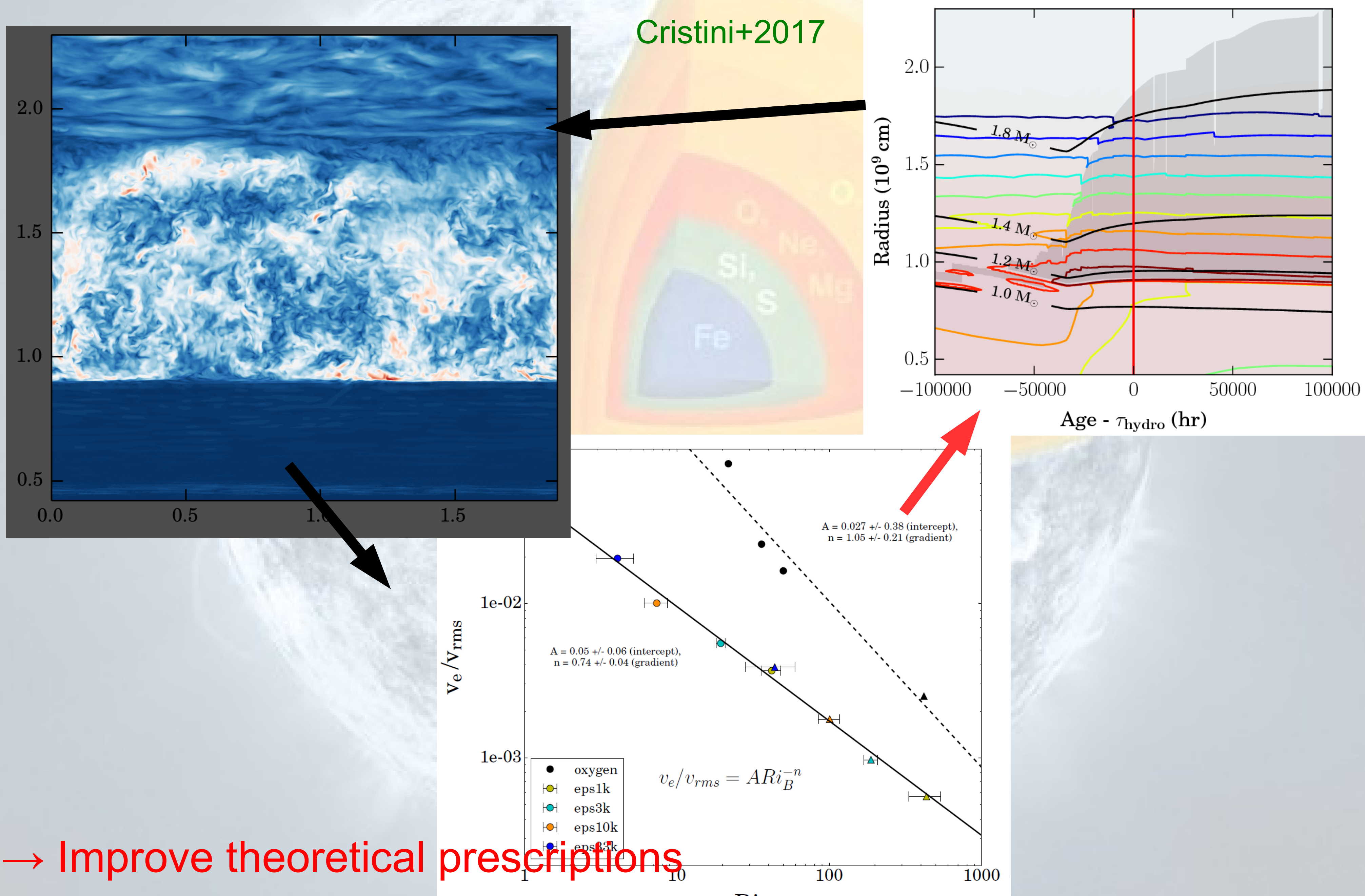
2) IGW (second f) plays a key role for the C13 pocket (not so much for mixing below the Tps)

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

Way Forward: 1 to 3 to 1D link

Targeted 3D simulations

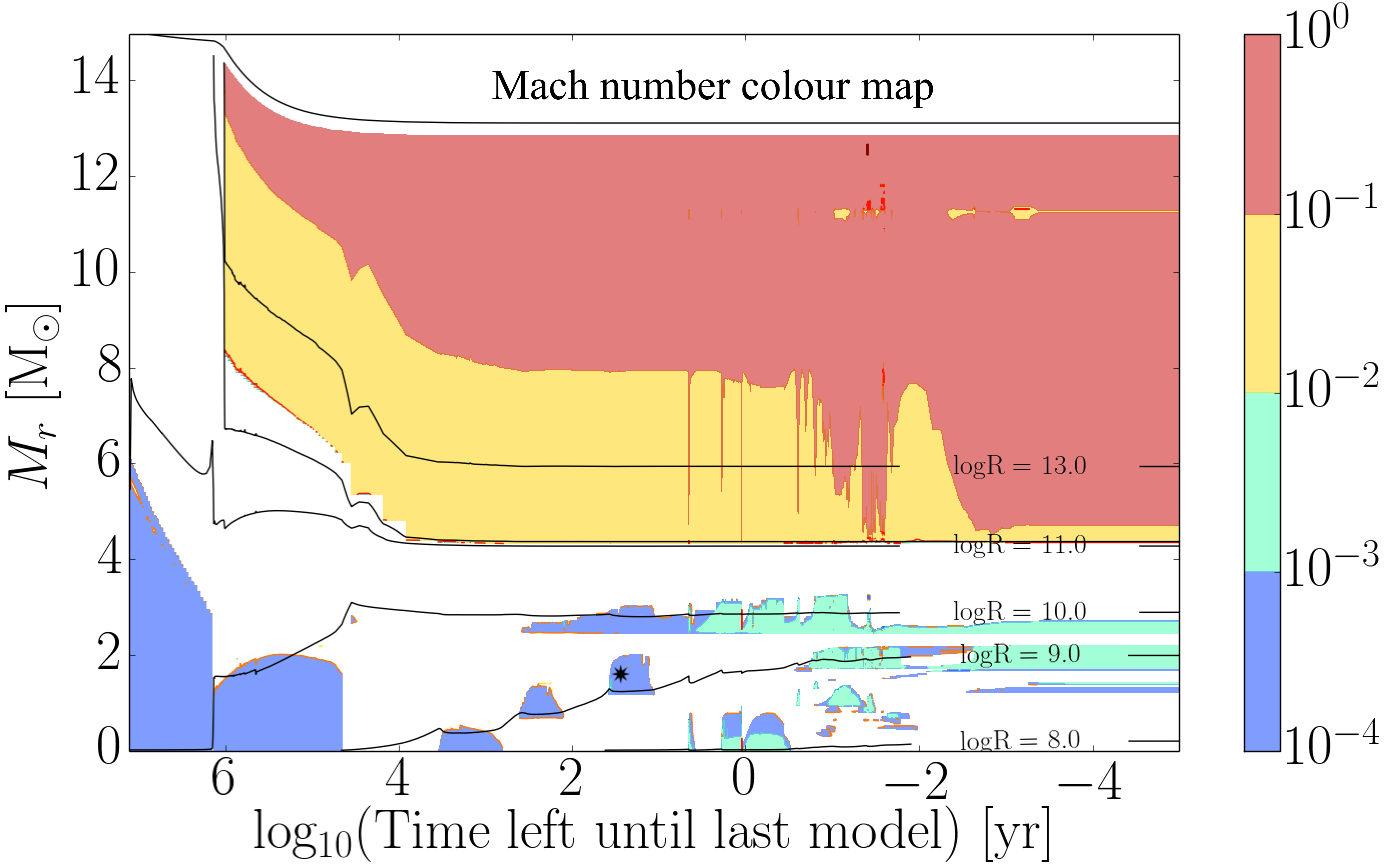
Uncertainties in 1D



Cristini+2017

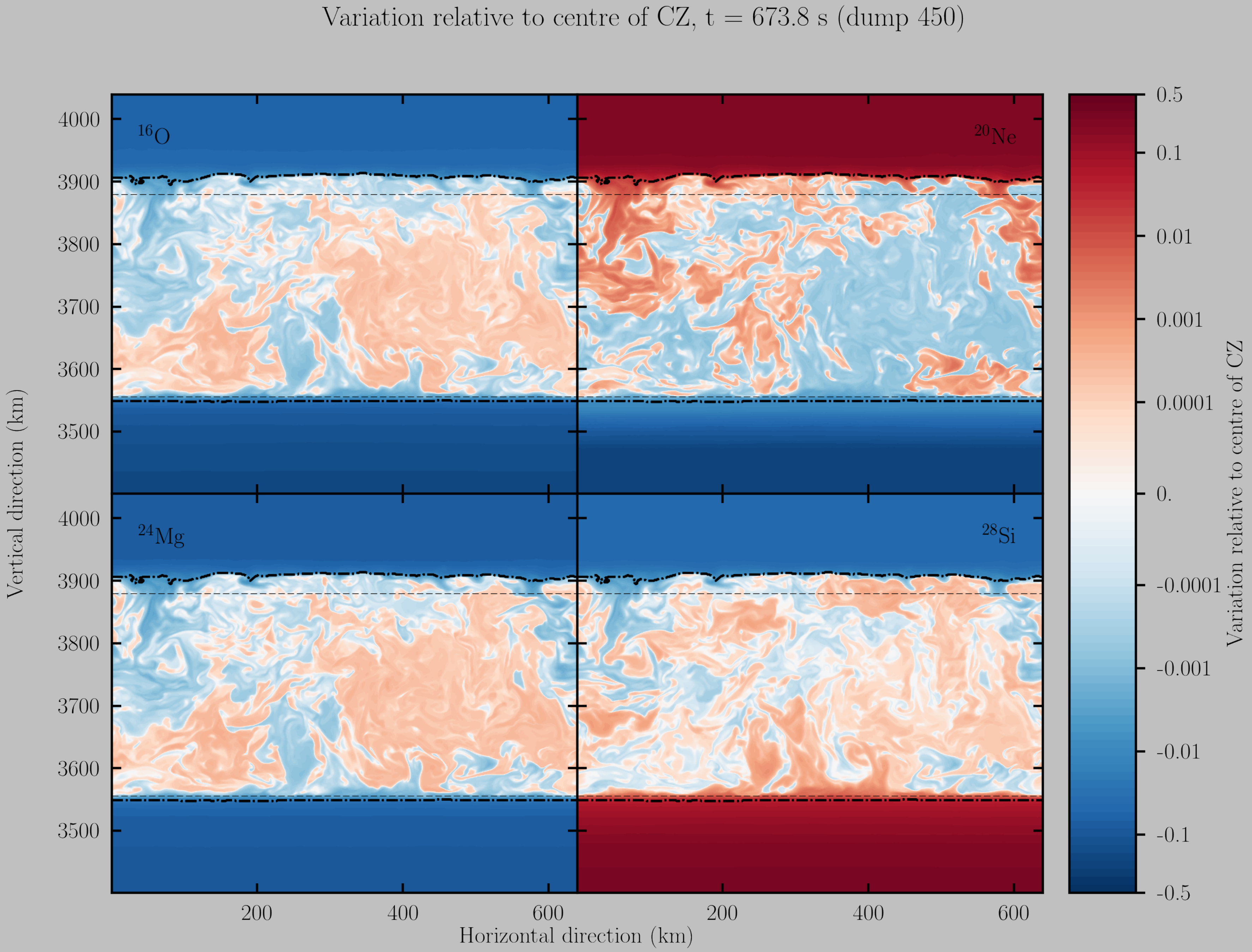
→ Improve theoretical prescriptions

Next Steps? Other Phases



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

Ne-burning


Variation relative to centre of CZ, t = 673.8 s (dump 450)
^{16}O
^{20}Ne
^{24}Mg
^{28}Si
4000
3900
3800
3700
3600
3500
Vertical direction (km)
200
400
600
Horizontal direction (km)
0.5
0.1
0.01
0.001
0.0001
0.
-0.0001
-0.001
-0.01
-0.1
-0.5
Variation relative to centre of CZ

Key Open Questions Concerning Rotation

- Uncertainties in strength of rotation-induced mixing Hunter et al 07/08, Maeder et al 07, …
- Importance/impact of diff. prescriptions & their implementations (advective vs diffusive) Meynet et al LNP, 13, Meynet/Maeder et al ..., Chieffi & Limongi et al 13, Heger et al 2000, Paxton et al 13 (MESA), Martins & Palacios, 13
- Interaction between magnetic fields and rotation: Solid body rotation? More or less mixing? Spruit 02, Heger et al 05-..., Yoon et al 06-... Maeder et al 2005-..., Potter et al 12, ...
- Impact of binary interactions on distribution of rotation velocities
  Langer et al 2012, de Mink et al 2013, ...
- Additional transport mechanism for Ω needed ←asteroseismology
  Cantiello et al. 14, Eggenberger 15; Spada et al. 16, Eggenberger et al 16 in prep
- …

Rotation-Induced Transport

Zahn 1992: strong horizontal turbulence

Transport of angular momentum:

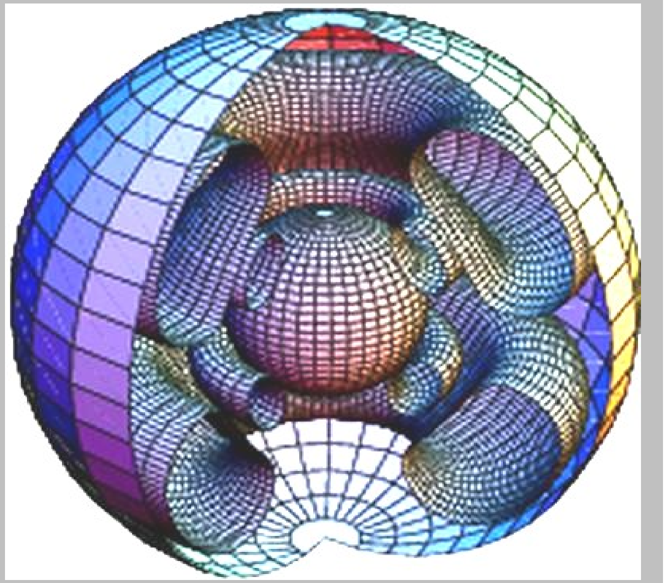
$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \bar{\Omega} U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial \bar{\Omega}}{\partial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

Transport of chemical elements:

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

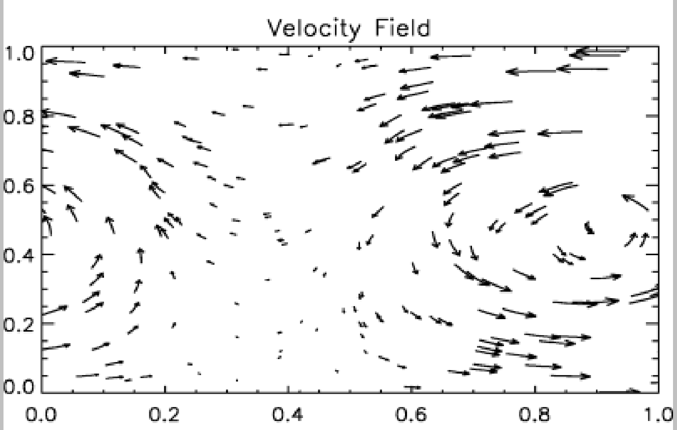
D: diffusion coeff. due to various transport mechanisms (convection, shear)

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



Meynet & Maeder 2000

Shear instabilities



Brueggen & Hillebrandt 2000

2.3. *Dynamical shear*

Hirschi et al 2004

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

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

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

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

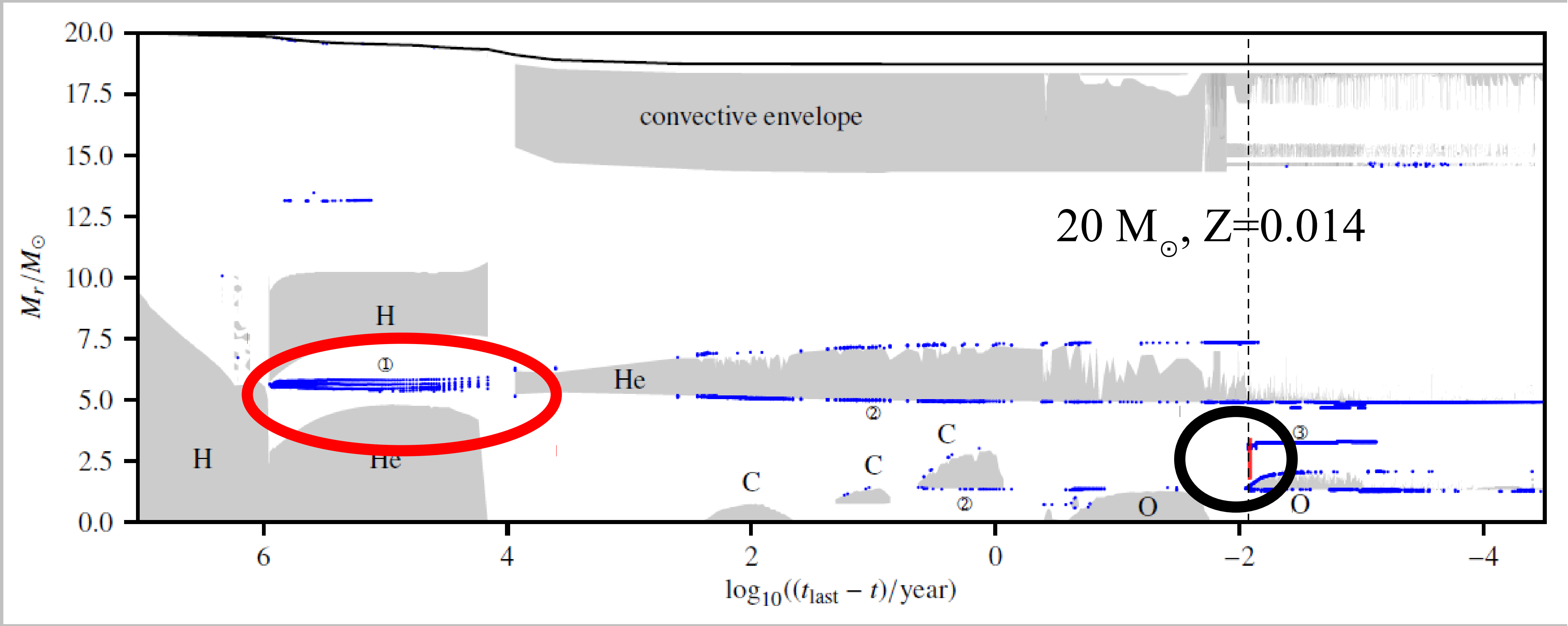
2.3.1. The recipe

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

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

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



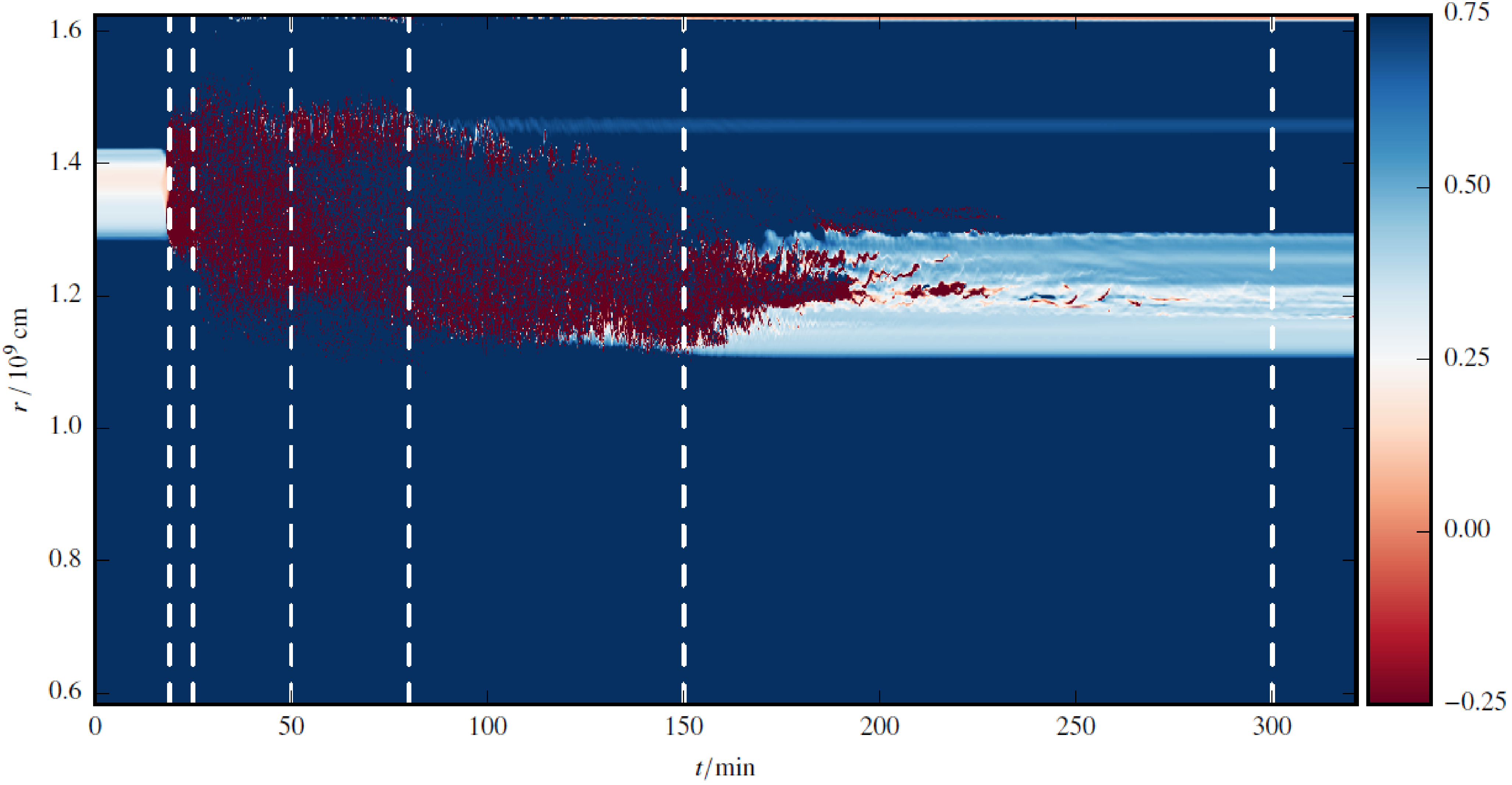
Edelmann et al 2016, A&A

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

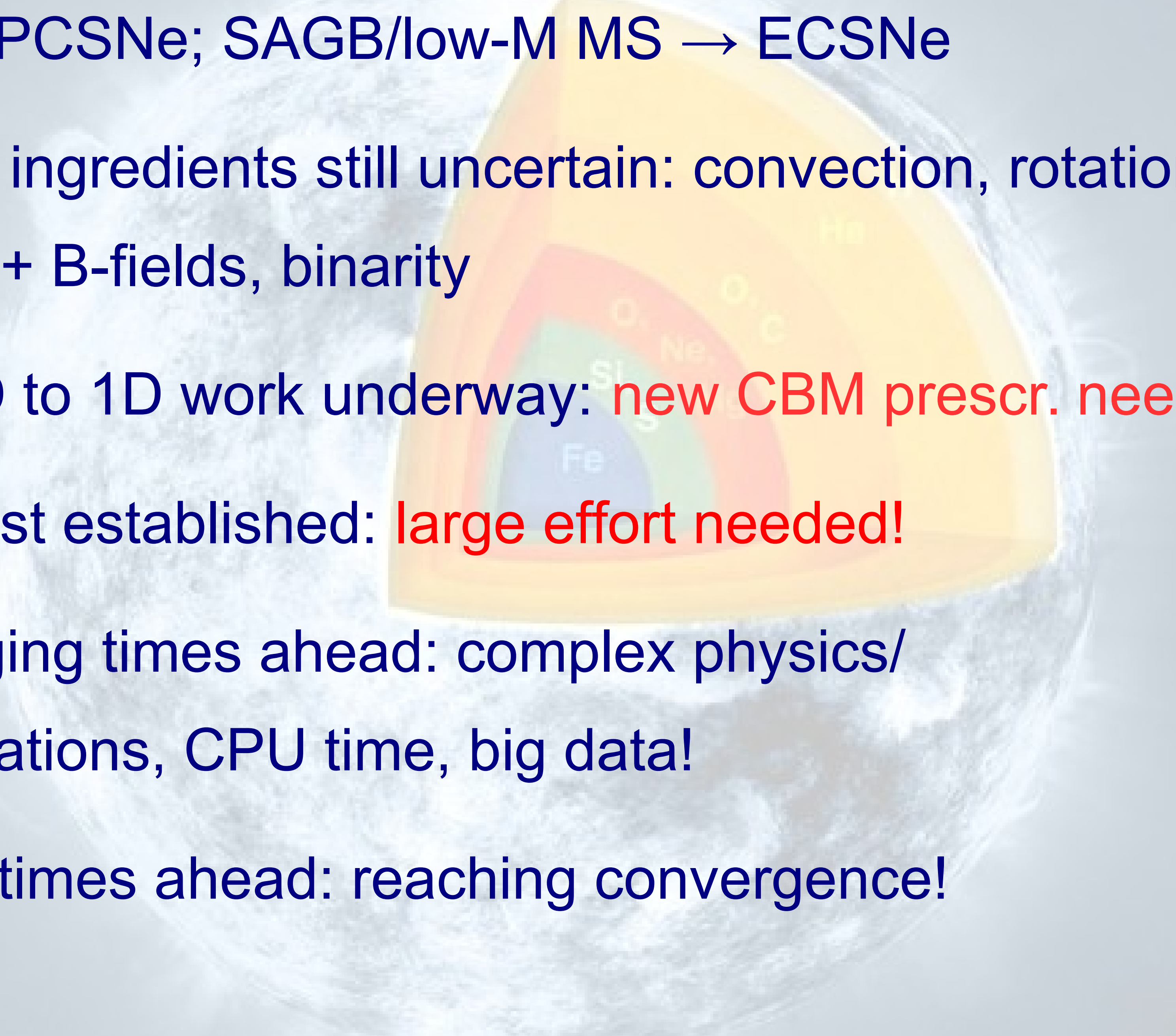
Dynamical Shear: Ri Time Evolution in 2D



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, ...)
-

Conclusions & Outlook



- VMS → PCSNe; 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!

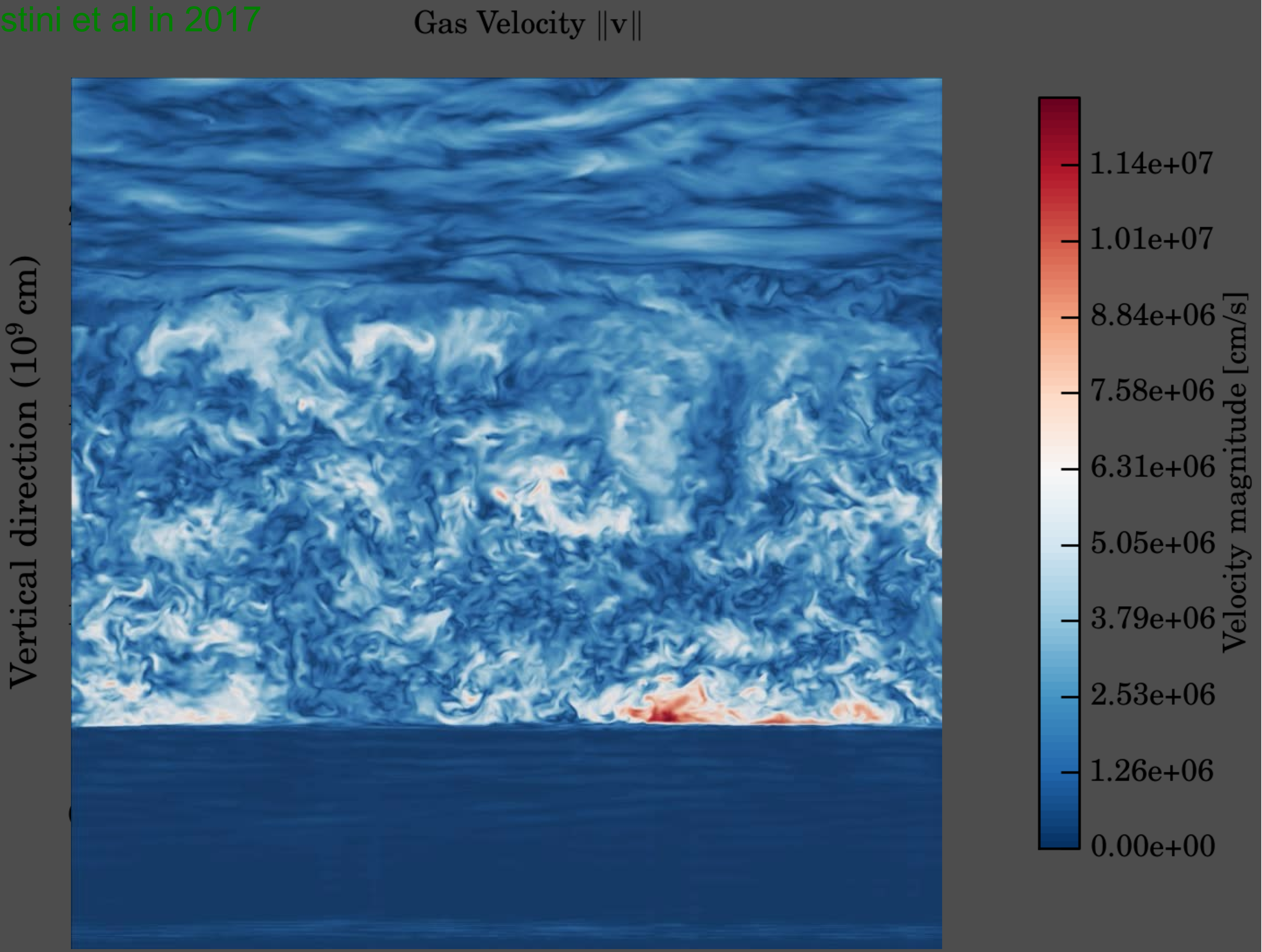
- Priority list established: large effort needed!

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

- Exciting times ahead: reaching convergence!

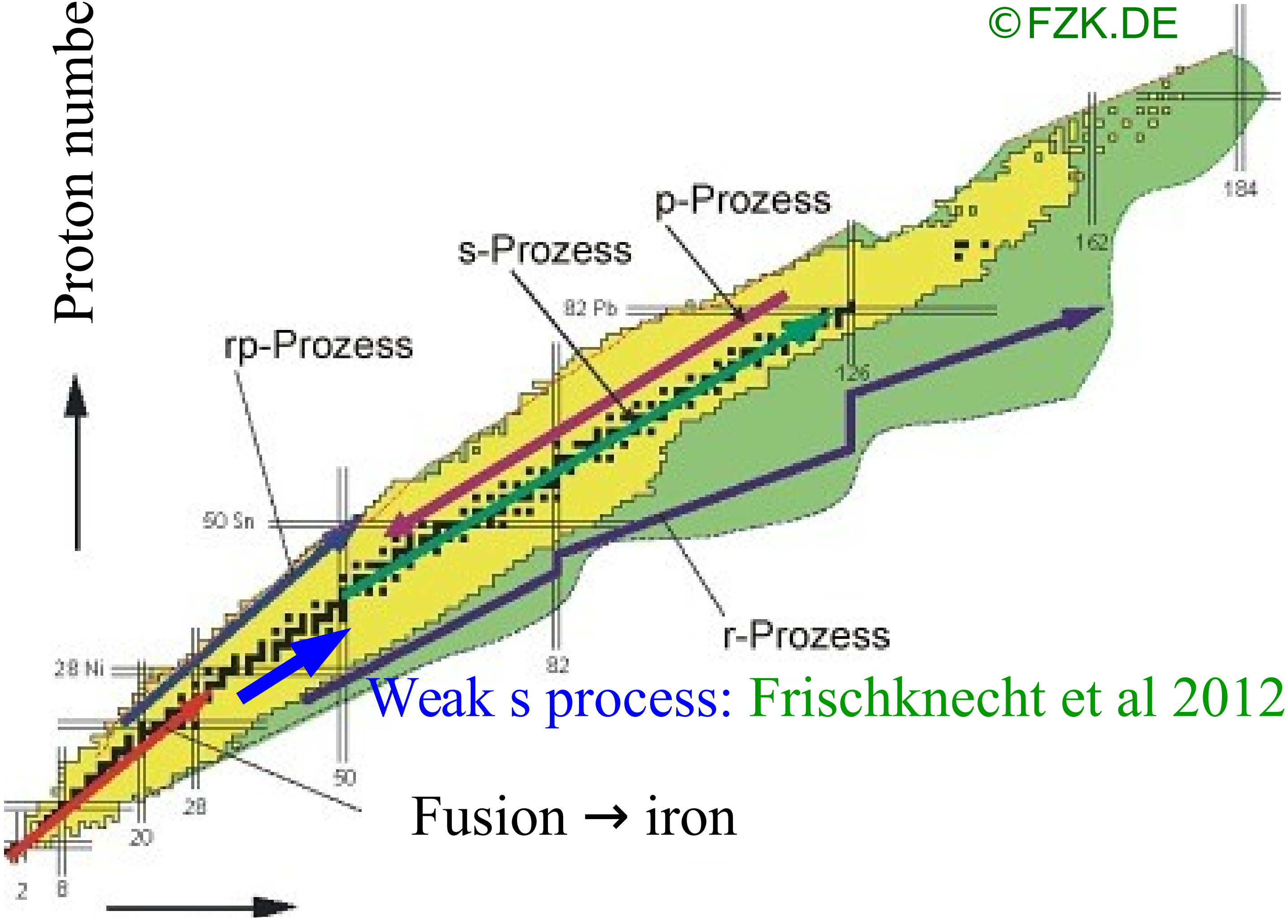
C-shell Simulations: $|v|$ movie

Cristini et al in 2017



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

Stars: Importance for Nucleosynthesis



©FZK.DE

Proton number

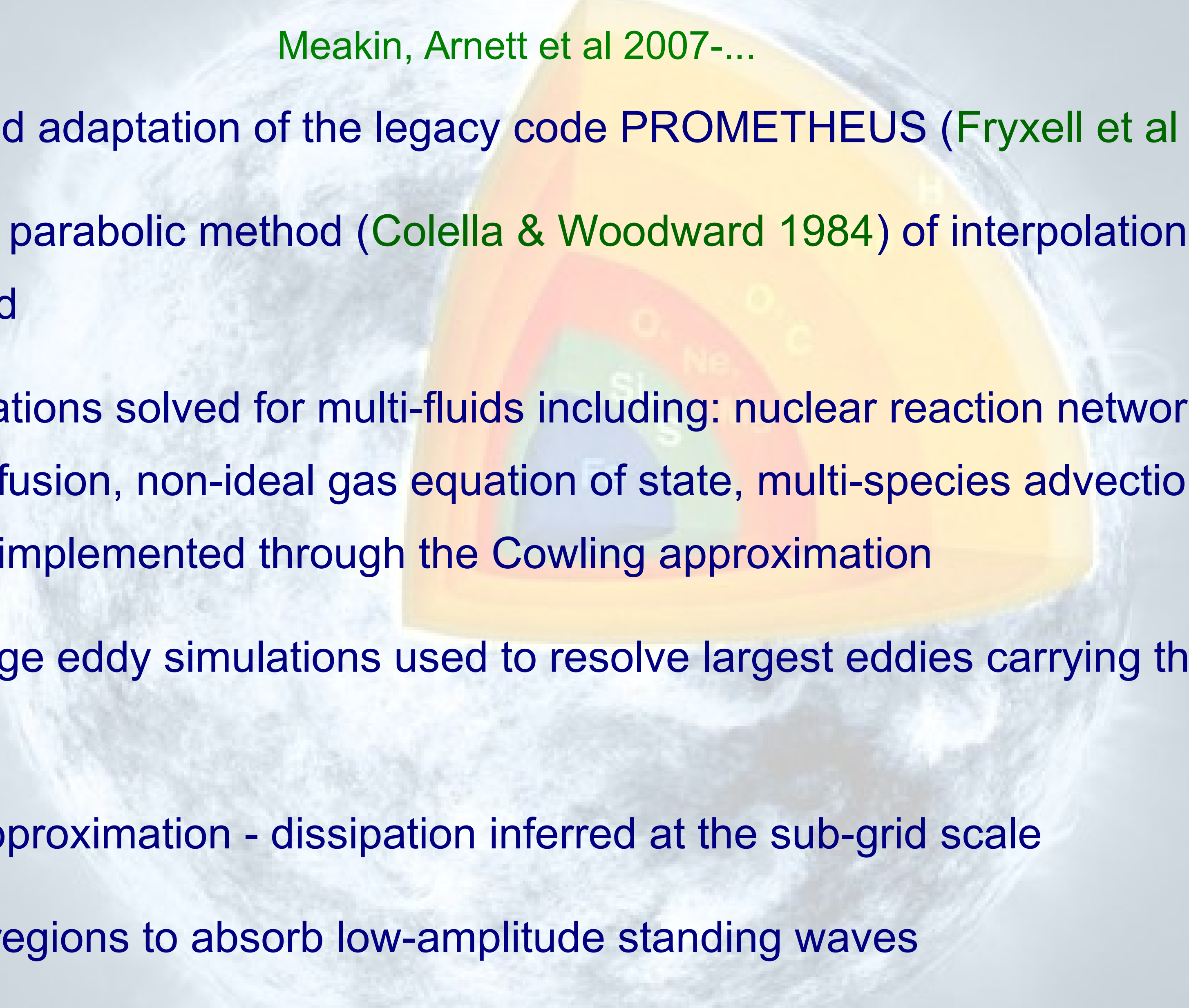
Neutron number

Weak s process: Frischknecht et al 2012, 2016

Fusion → iron

PROmetheus MPI (PROMPI) code

Meakin, Arnett et al 2007-...



- Parallelised adaptation of the legacy code PROMETHEUS (Fryxell et al 1989)

- Piecewise parabolic method (Colella & Woodward 1984) of interpolation onto a Eulerian grid

- Euler equations solved for multi-fluids including: nuclear reaction network, radiative diffusion, non-ideal gas equation of state, multi-species advection, self-gravity implemented through the Cowling approximation

- Implicit large eddy simulations used to resolve largest eddies carrying the majority of energy

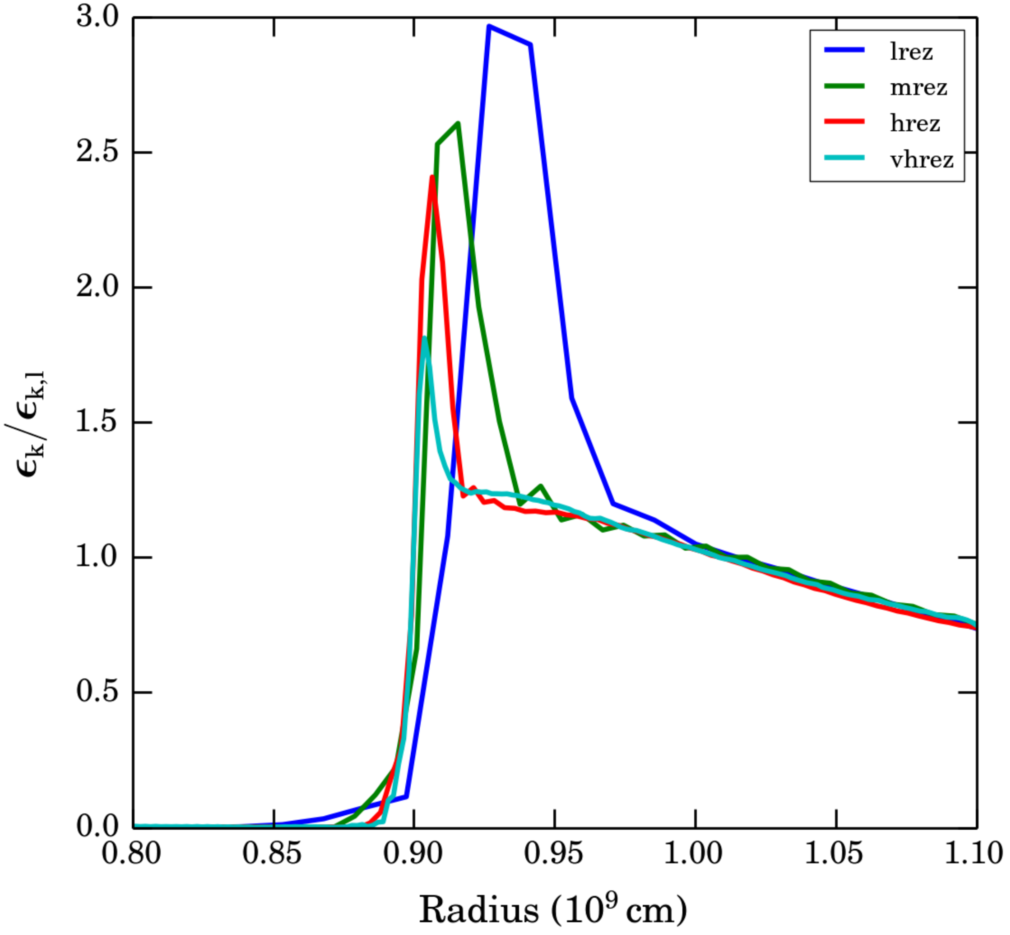
- Inviscid approximation - dissipation inferred at the sub-grid scale

- Damping regions to absorb low-amplitude standing waves

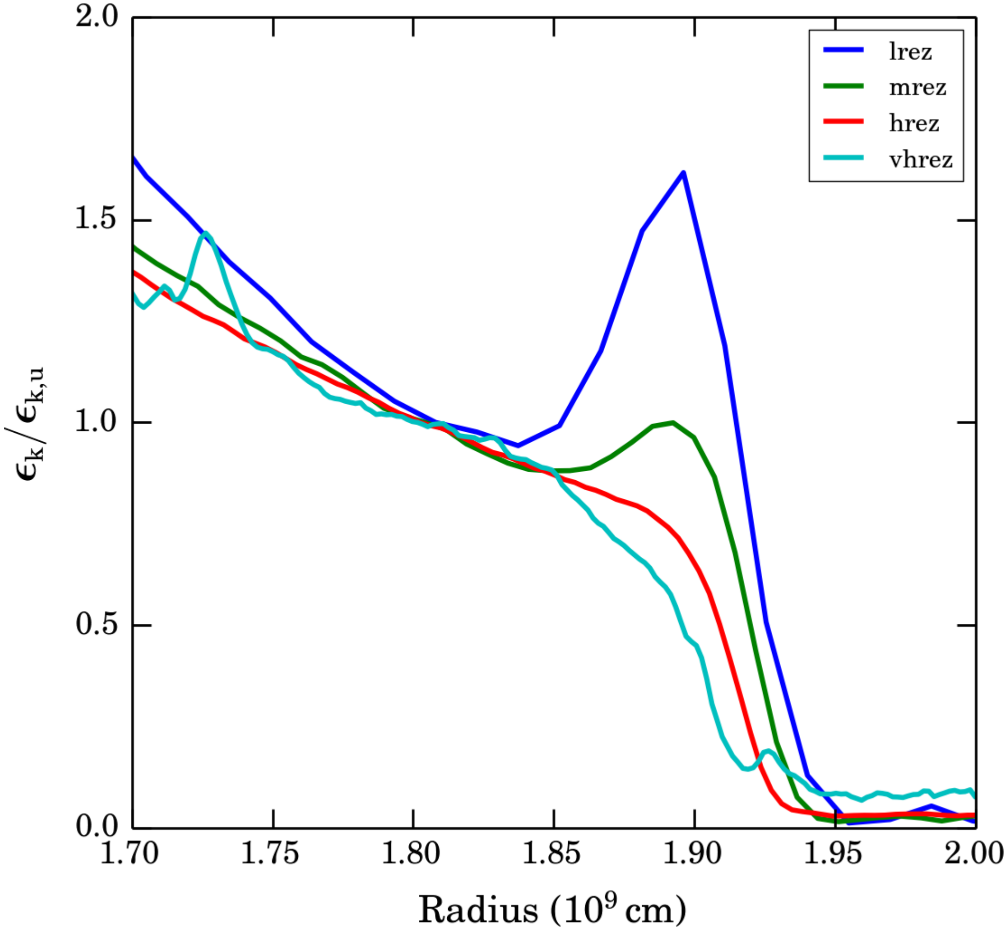
RANS Analysis: Reaching Convergence?

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!

How massive can stars be?

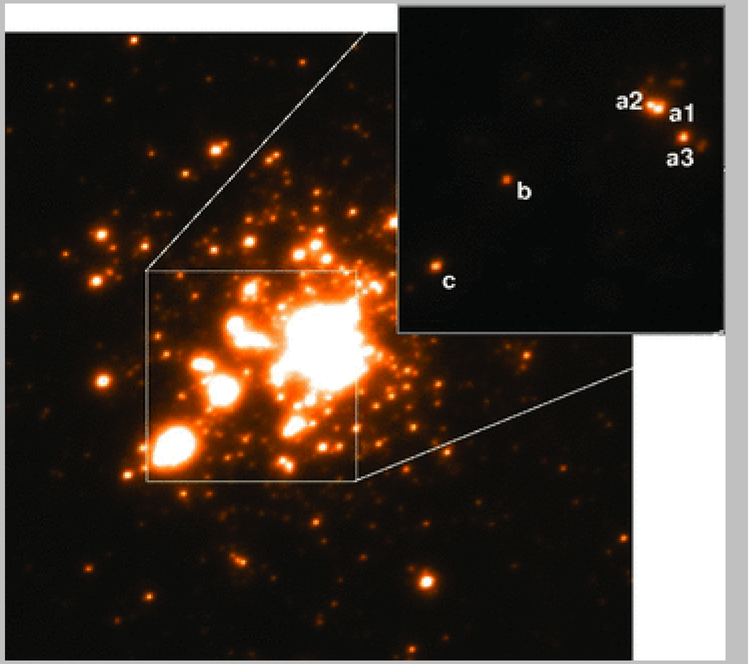
Do very massive stars (VMS: $M>100M_o$) exist?

Very Massive Stars in the Local Universe, 2014, Springer, Ed. Jorick S. Vink

- Star formation: already difficulties with 30 M_o stars but 2/3D simulations are promising (Kuiper et al 11, Krumholz 2014)
- Stellar evolution: possible up to ~ 1,000 M_o (BUT mass loss/rad.) (Baraffe et al 01)

Can we see them?

- Rare and short-lived
- Need to look at youngest and most massive clusters:
  - Arches: M<~150 Mo (Figer 05, Martins et al 08)
  - NGC 3603 & R136: new $\mathbf{M_{max}=320M_o}$**!** **(Crowther et al 10, MNRAS)**



R136 cluster

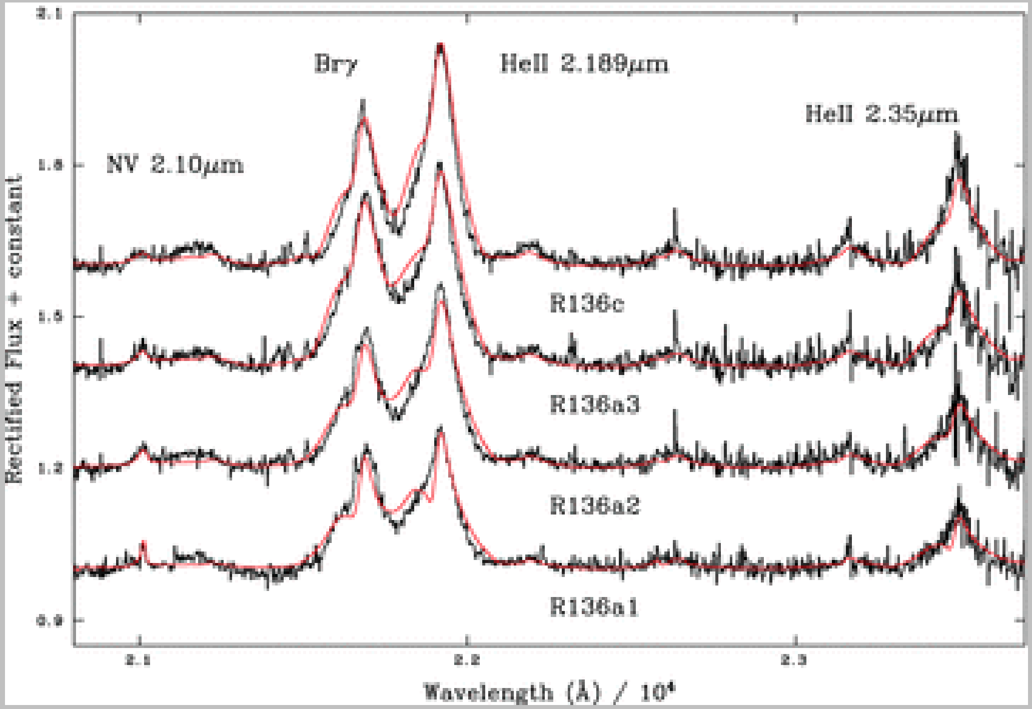
Mass Determination

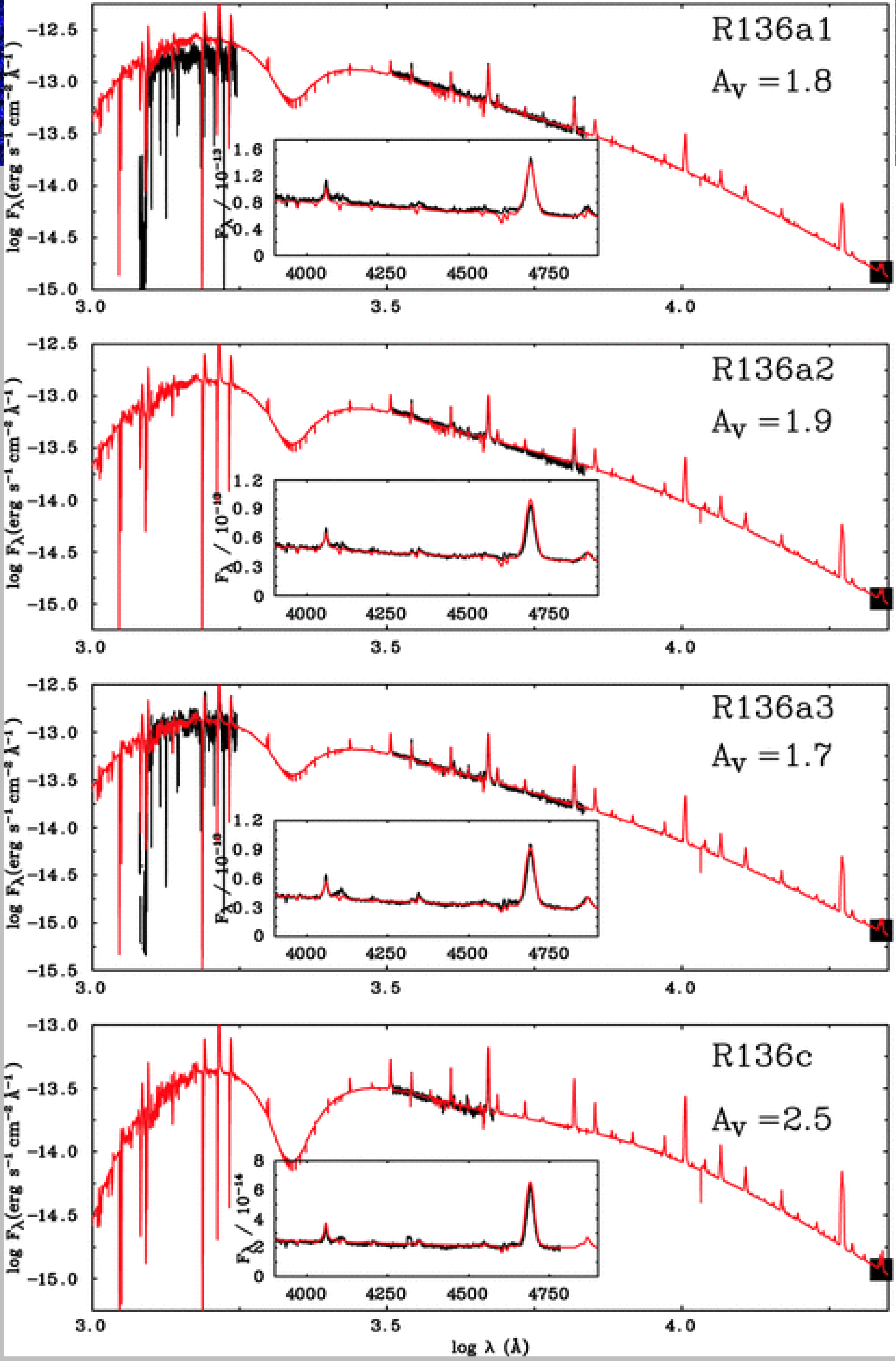
Best with binary system

but often not available

Using model atmosphere and

compare them to observations:



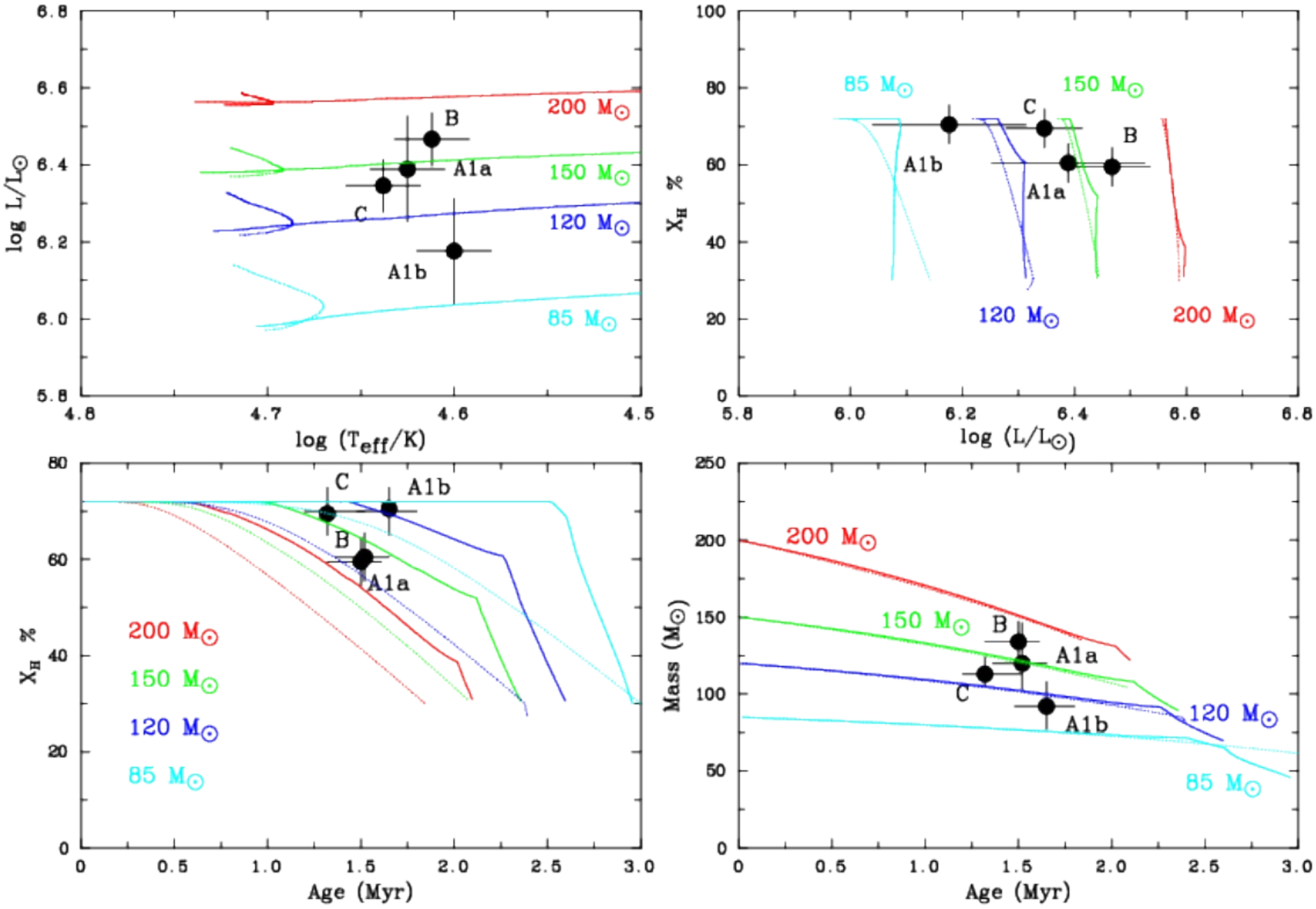


Crowther et al 10, MNRAS

NGC 3603

Cluster in our galaxy with about 10^4 M_o so we can expect 1-2 stars more massive than 150 M_o.

Crowther et al 10, MNRAS



Results:
age: 1.5+/-0.1 Myr

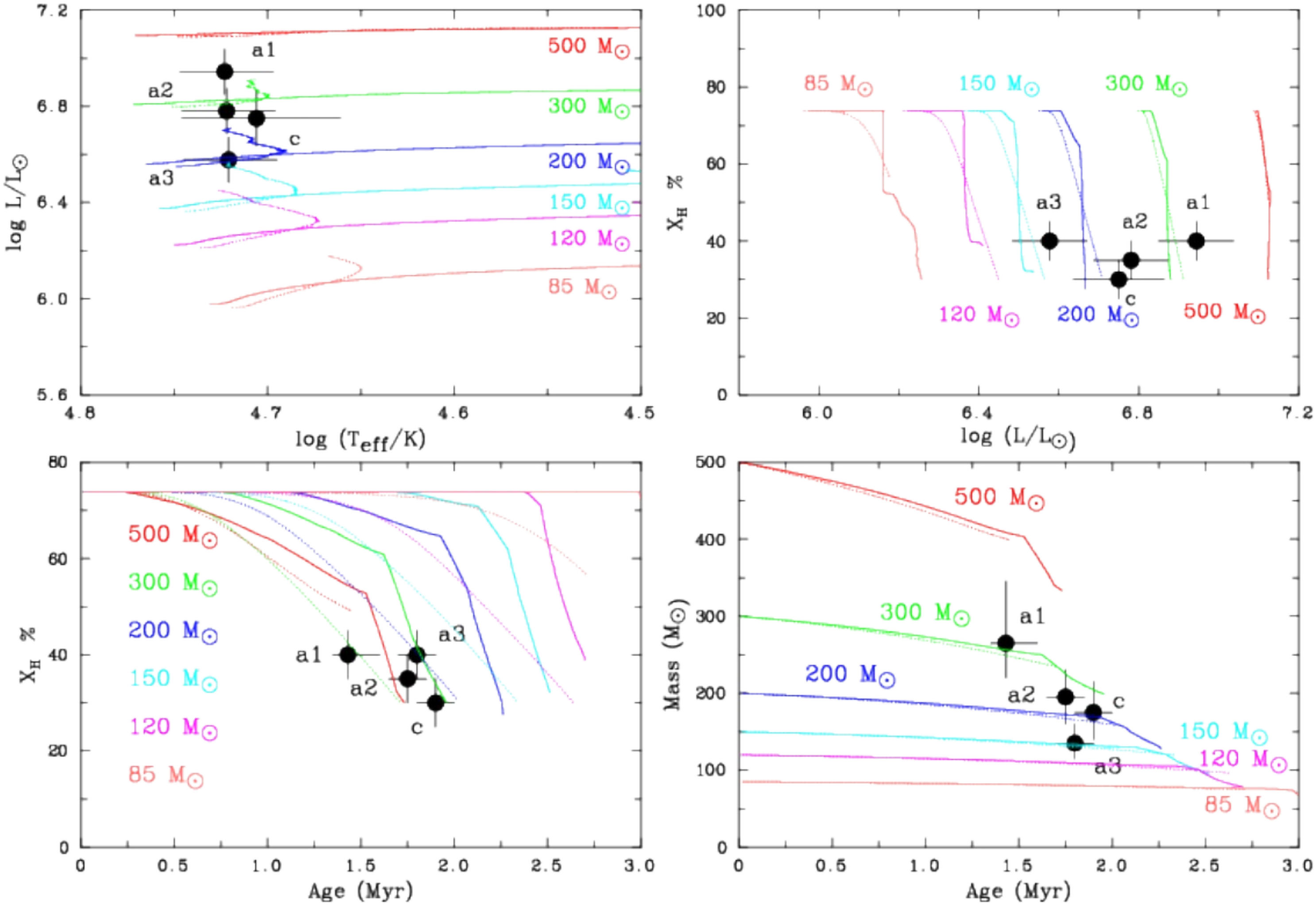
Initial masses:
B: 160 +/-20 M_o
A1a: 148 +40-27 M_o
C: 137 +/-17 M_o
A1b: 106 +/-23 M_o

Checks: masses of A1a & A1b consistent with dyn. masses; X-ray data for bin.

R136

Cluster in the LMC with about $5x10^4$ M_o so we expect a few stars more massive than 150 M_o.

Crowther et al 10, MNRAS



Results:
age: 1.7+/-0.2 Myr

Initial masses:
a1: 320 +100-40 M_o
a2: 240 +/-45 M_o
c: 220 +55-45 M_o
a3: 165 +/-30 M_o

Checks: clumped mass loss rates derived: $2\text{-}5x10^{-5}$ M_o/yr match Vink et al predictions

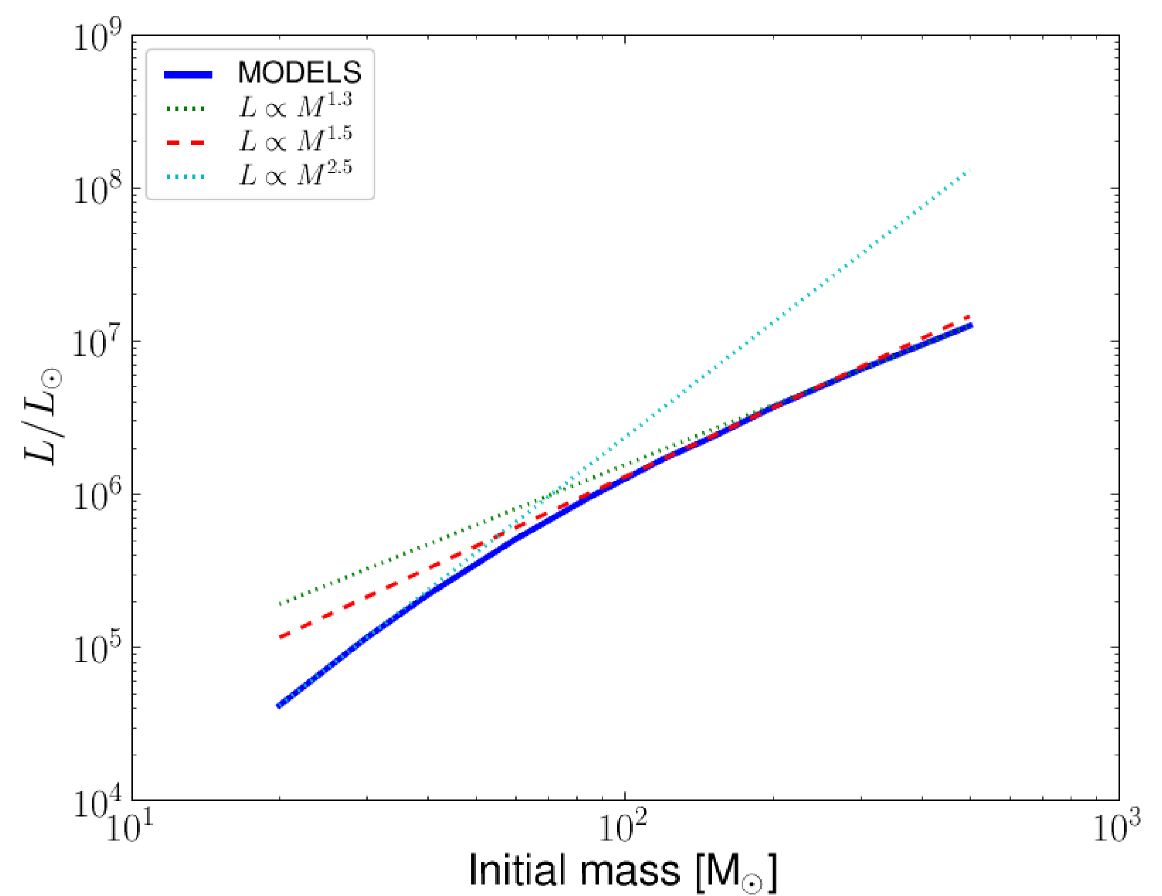
Very Massive Stars are Very Luminous (~10^7 $L_\odot$)

R136a1 ($10^7 L_\odot$) alone supplies 7% of the ionizing flux of the entire 30 Doradus region!

What is the shape of the luminosity vs mass relation in this mass range?

Textbooks: L ~ M^3 for stars in the solar mass range

Above 100 M_o: L~$M^{1.5}$

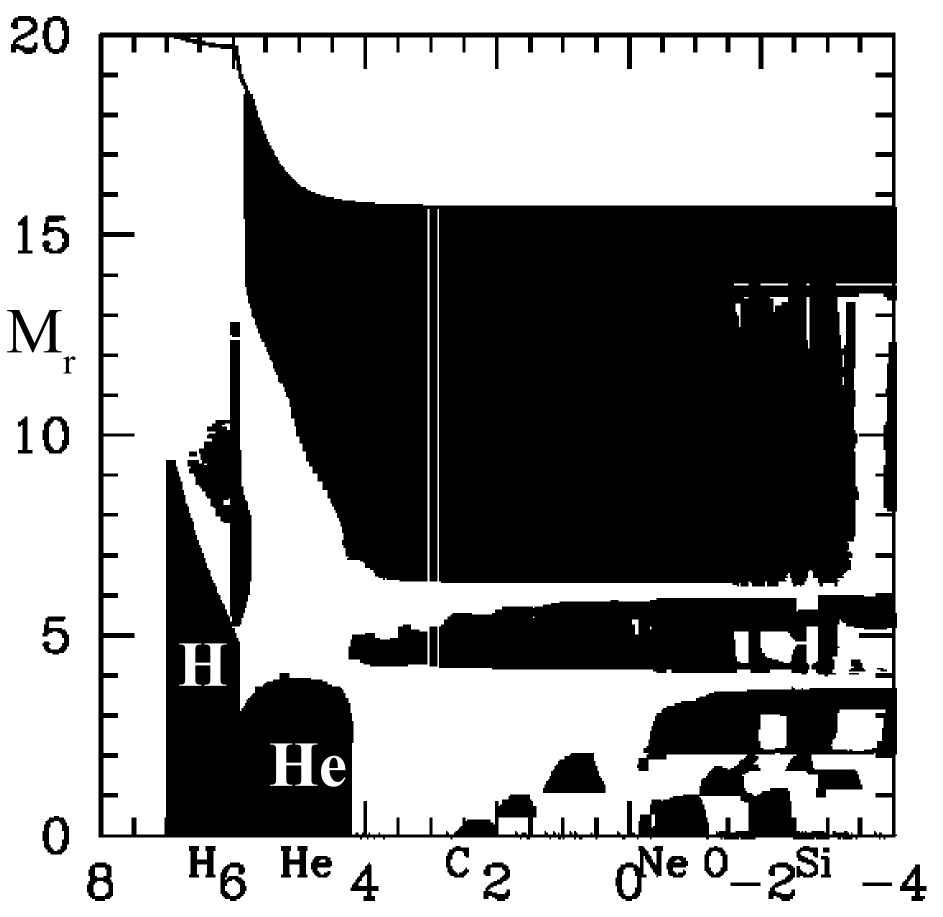


Yusof et al 13 MNRAS, aph1305.2099

The Evolution of VMS

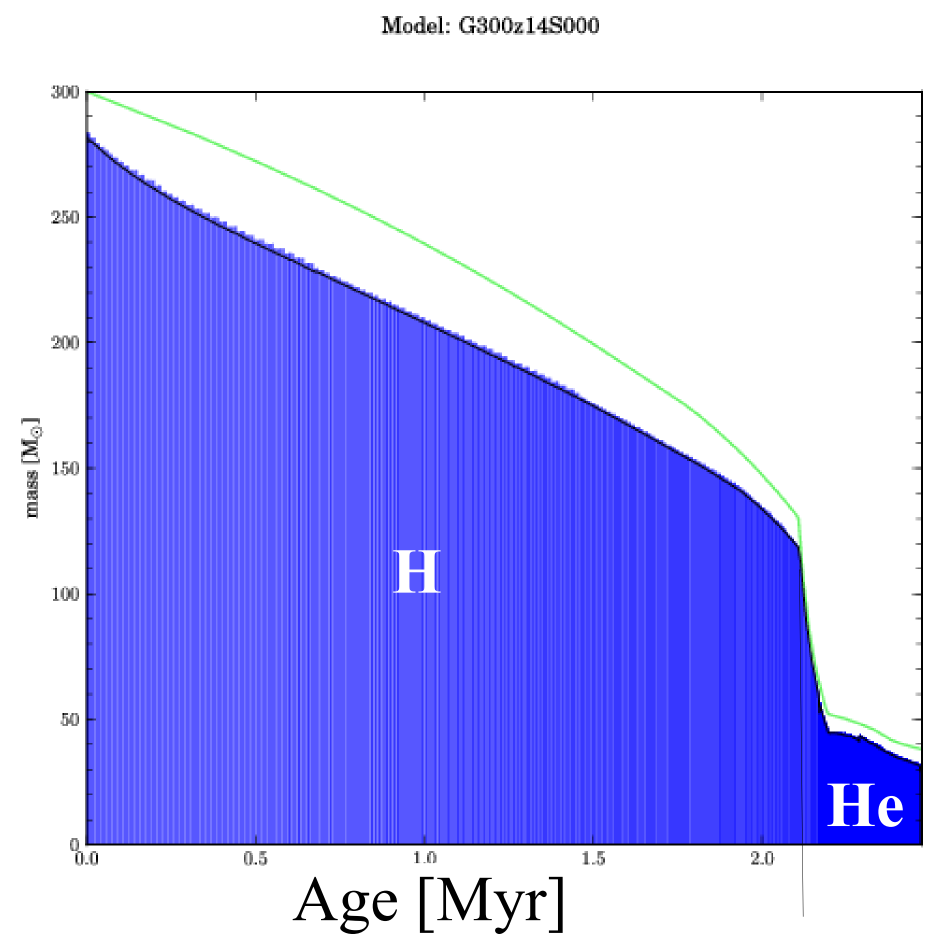
VMS = Very Massive Stars for M > 100 $M_\odot$

20 $M_\odot$



Log10(Time left until collapse)

300 $M_\odot$

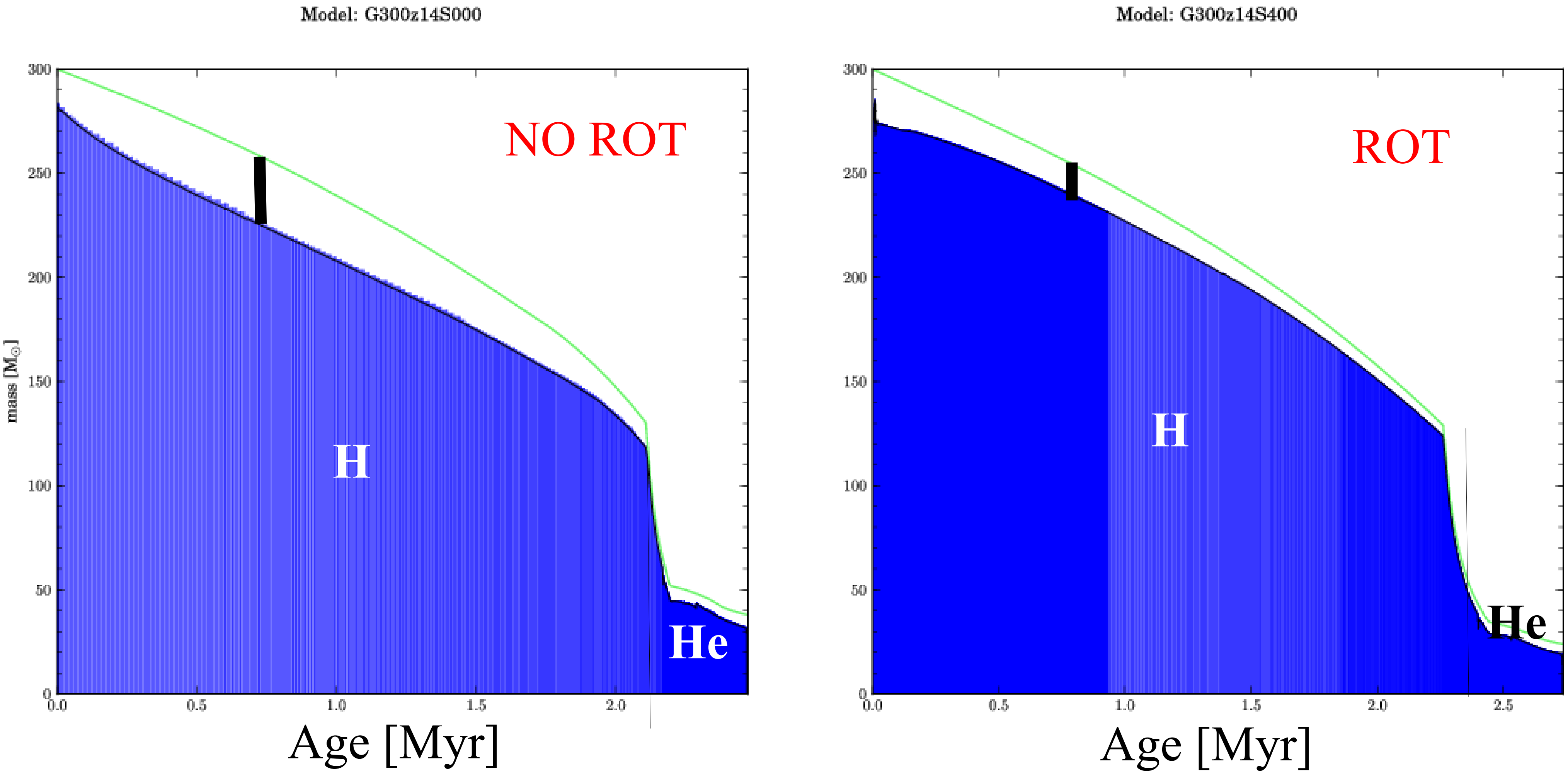


(Yusof et al 13 MNRAS, aph1305.2099)

VMS: much larger convective core & mass loss!

The Evolution of VMS

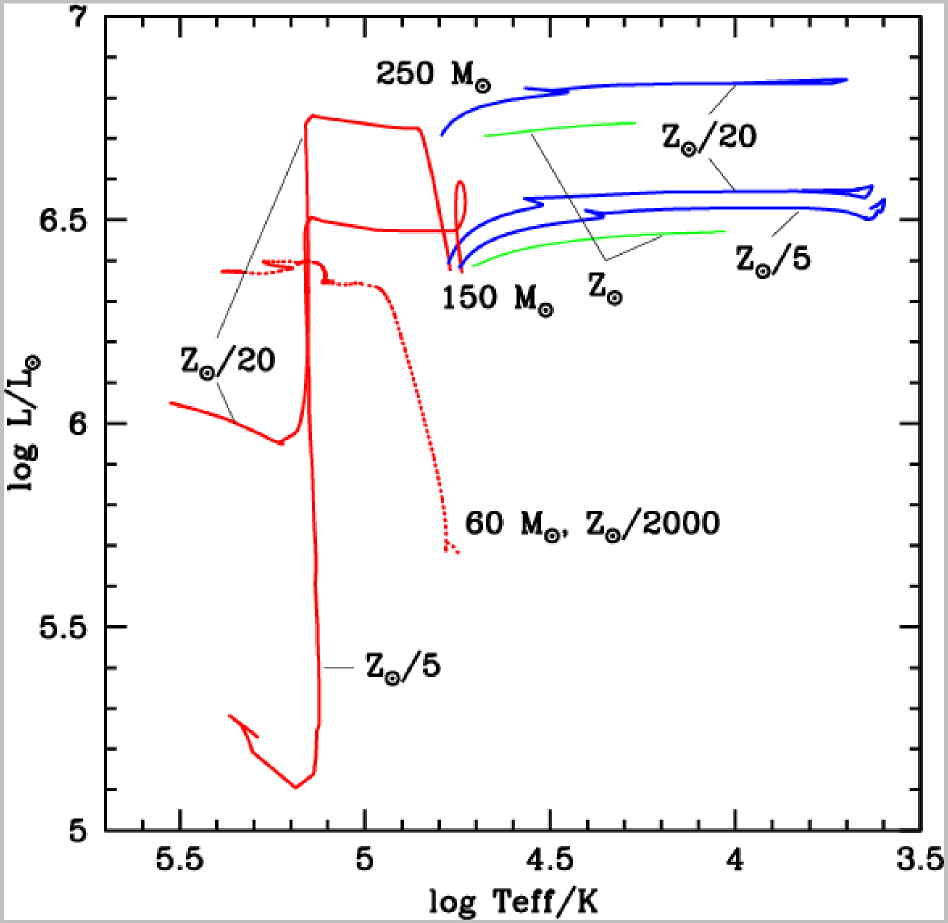
Rotating VMS have even larger convective core and (usually) mass loss



(Yusof et al MNRAS 2013)

Evolution of VMS across HRD: role of rotation/Mdot

Langer et al 07 (see also Yusof et al 2013)



Fast rotation → stars stay hot. Slow rotation → stars become cool. Different mass loss driving, Z dep.?

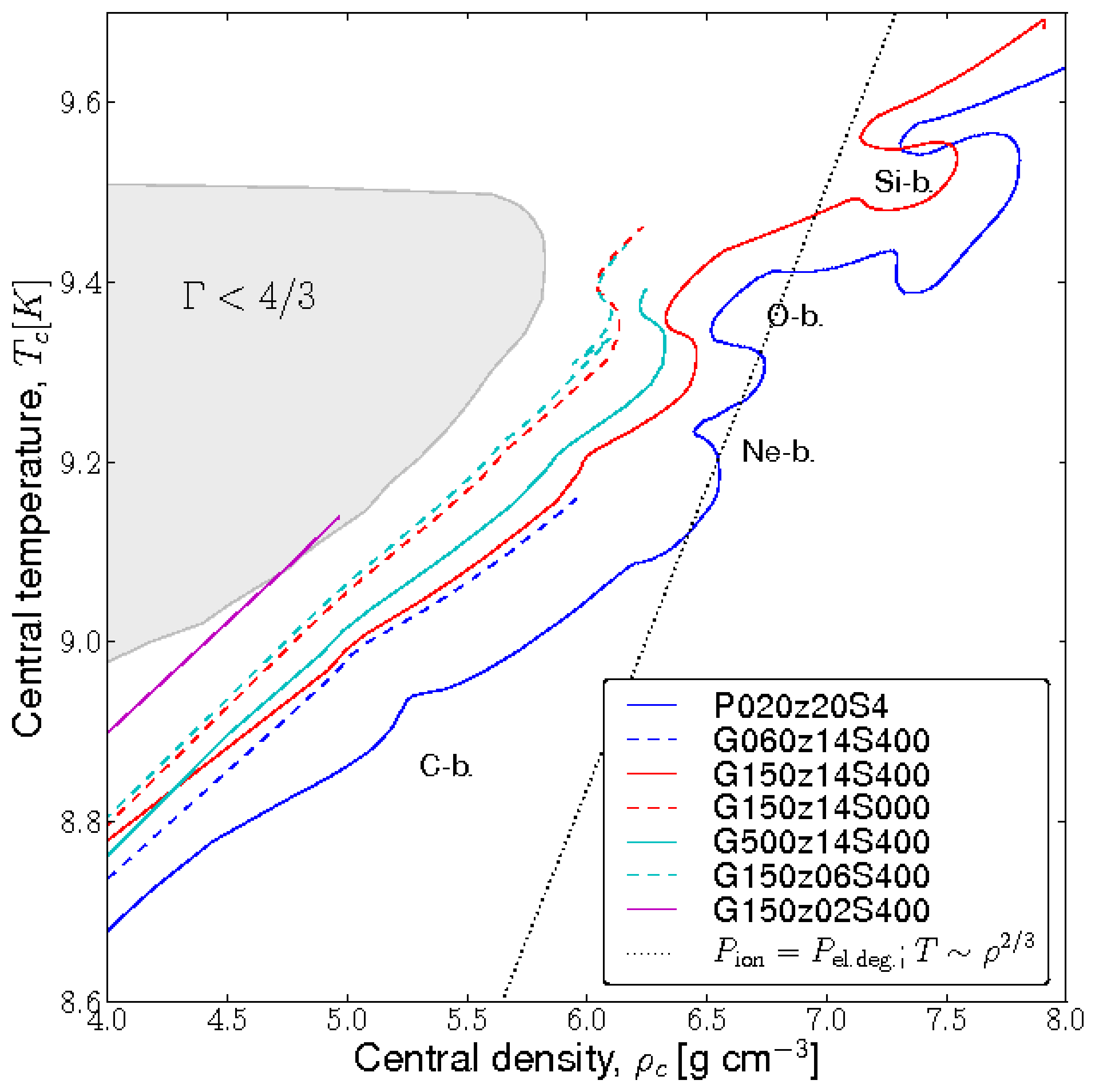
The fate of VMS: PCSN/BH/CCSN?

Pair-Creations

→ Runaway

expl. O-burning

→ Bright SN



Pair Creation SN (M:140-260 Mo) (Heger and Woosley 02, Scannapieco et al 05)

The fate of VMS: PCSN/BH/CCSN?

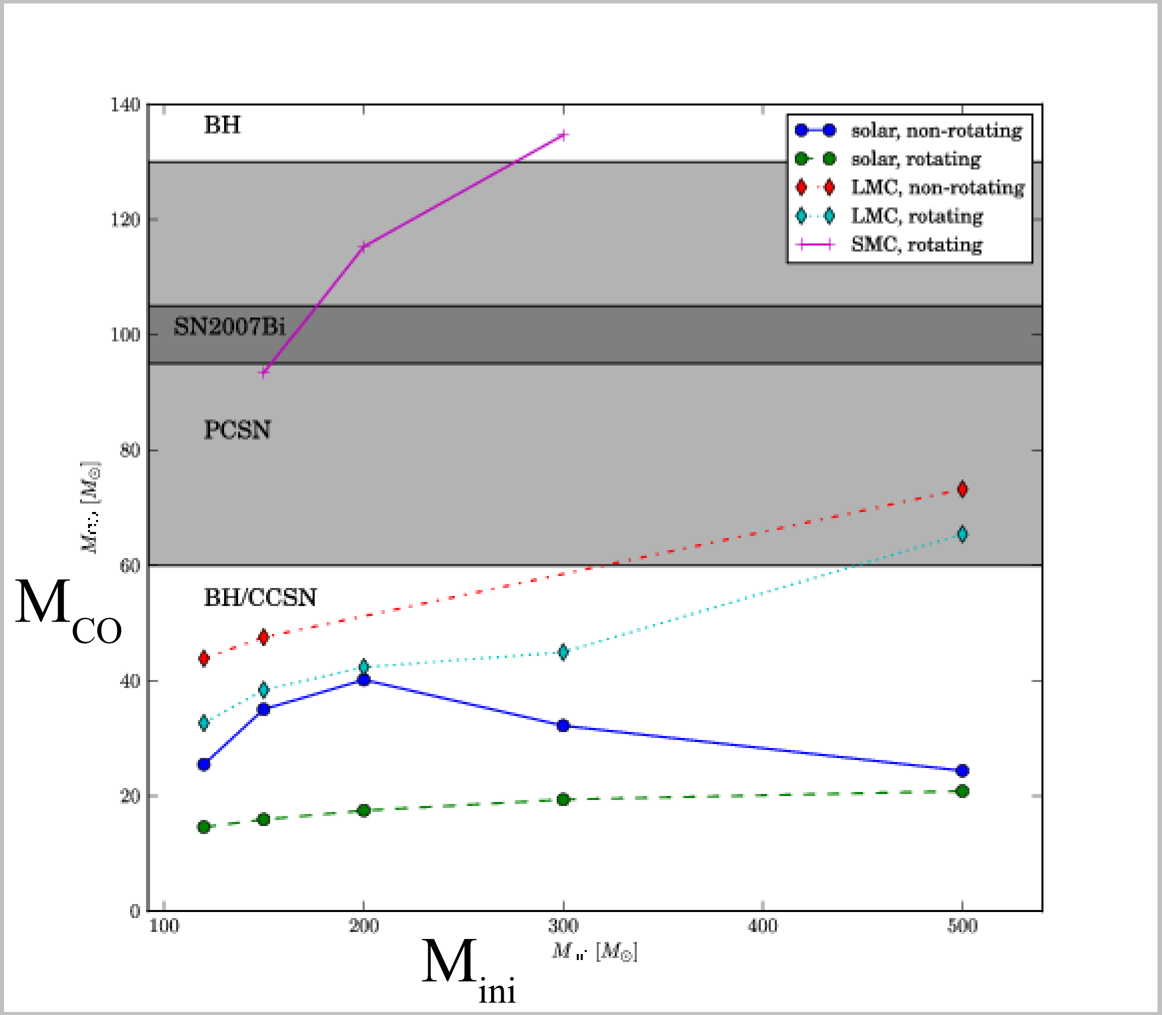
(Yusof et al 13 MNRAS, aph1305.2099)

Z_{solar}: no PCSN

(Rotating) models with Z<Z(LMC) lose less mass,

and enter the PCSN instability region!

BUT mass loss uncertain!



PCSN range from Heger & Woosley (2002)

Consistent with Langer et al (2007): PCSN for $Z<Z_\odot/3$

The fate of VMS: SNII/SNIb-c?

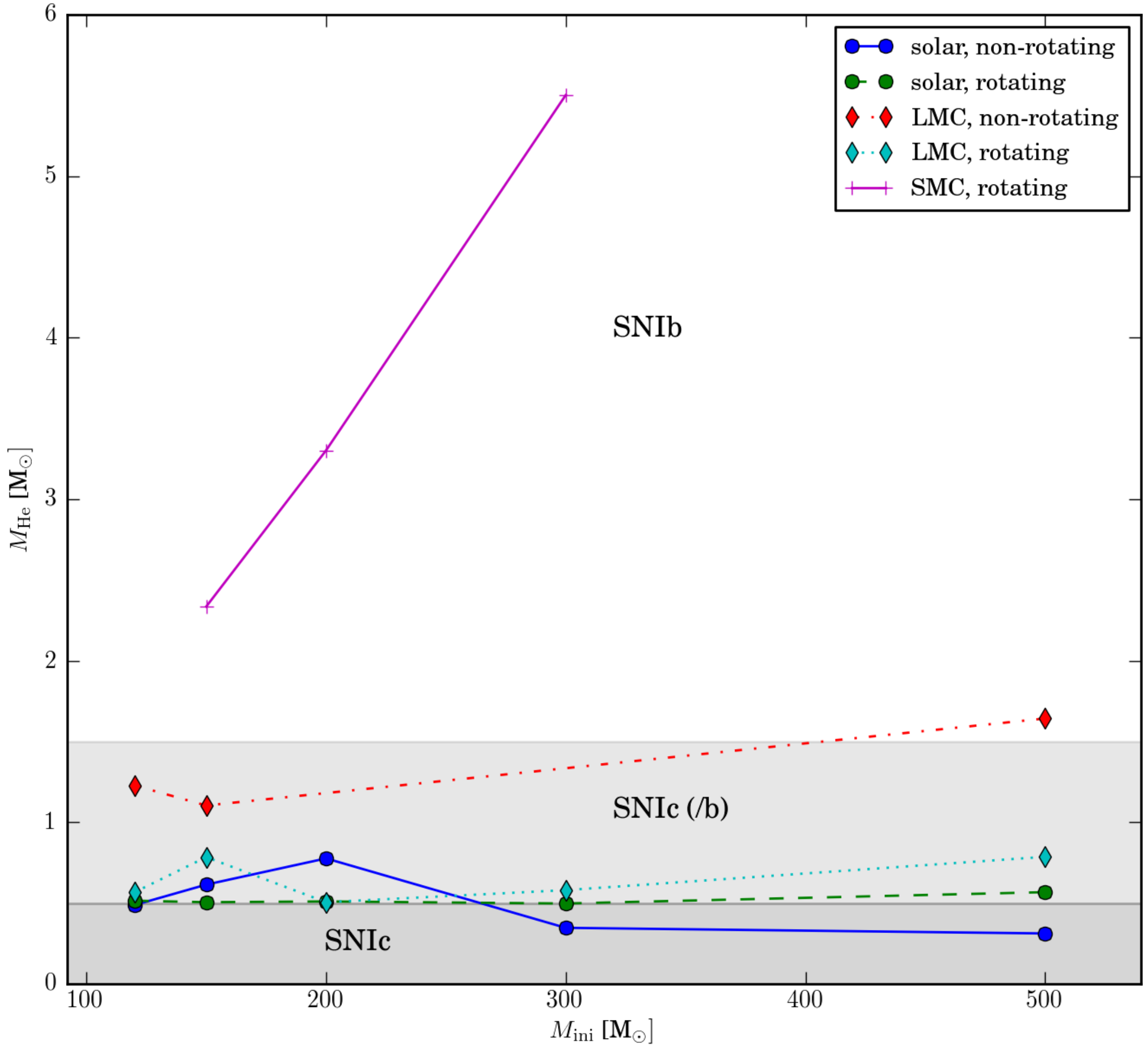
SN type:

- NO SNIIn predicted!
~ NOT ok for SN2006gy
(e.g. Woosley et al 2007)

- SNIc at solar Z,

- SNIb/c at Z(SMC)
~ ok for SN2007bi
(Gal-Yam 2009)
BUT see Dessart et al 12,13+ Panstarrs results
Jerkstrand et al 16

(Yusof et al 13 MNRAS, aph1305.2099)

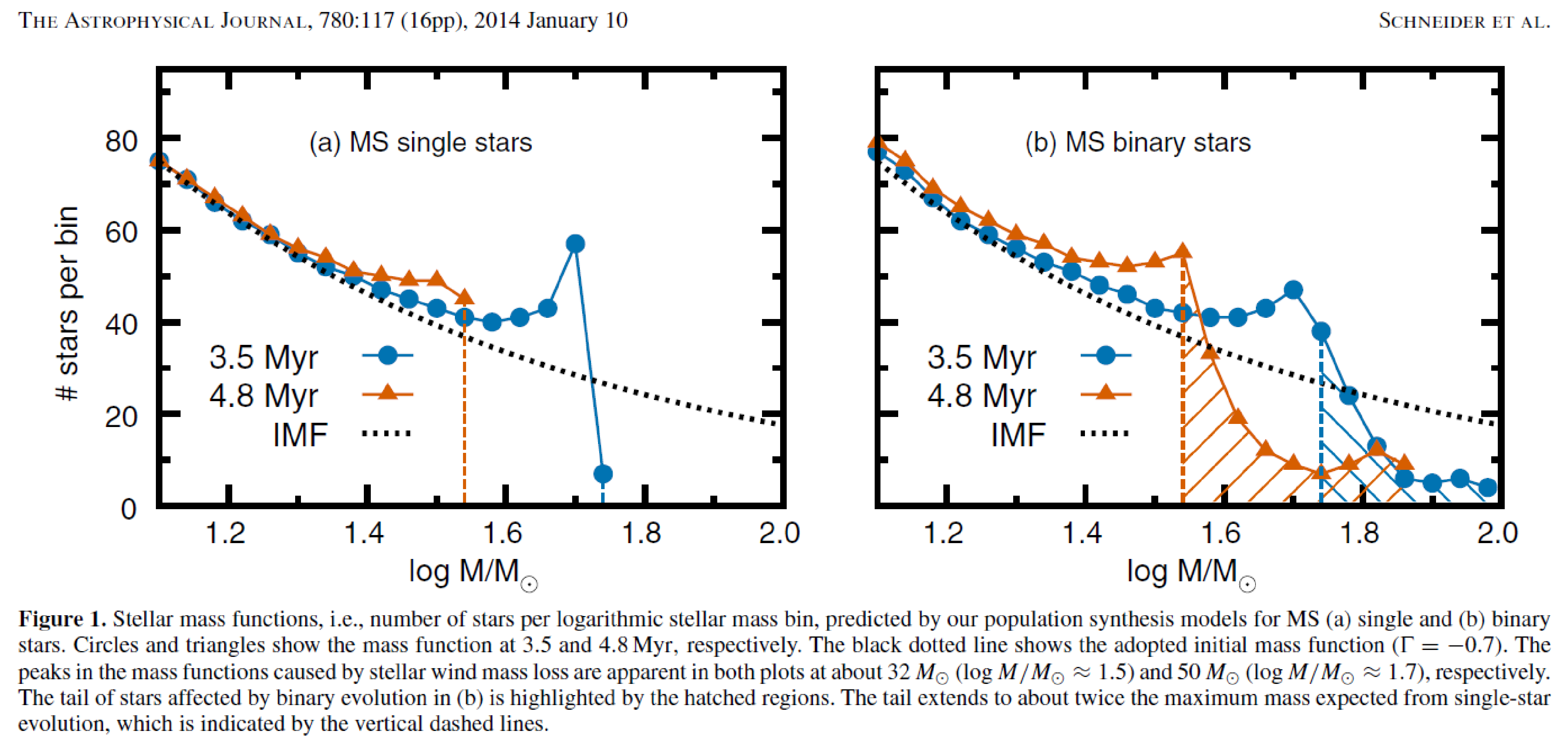


NEW FLASH PCSN SIMULATIONS OF GENEC MODELS UNDERWAY!!
Kozyreva et al 2017, Gilmer et al 2017, talk by Kozyreva

Binarity

Population synthesis for VMS

Schneider et al 2014ApJ...780..117S

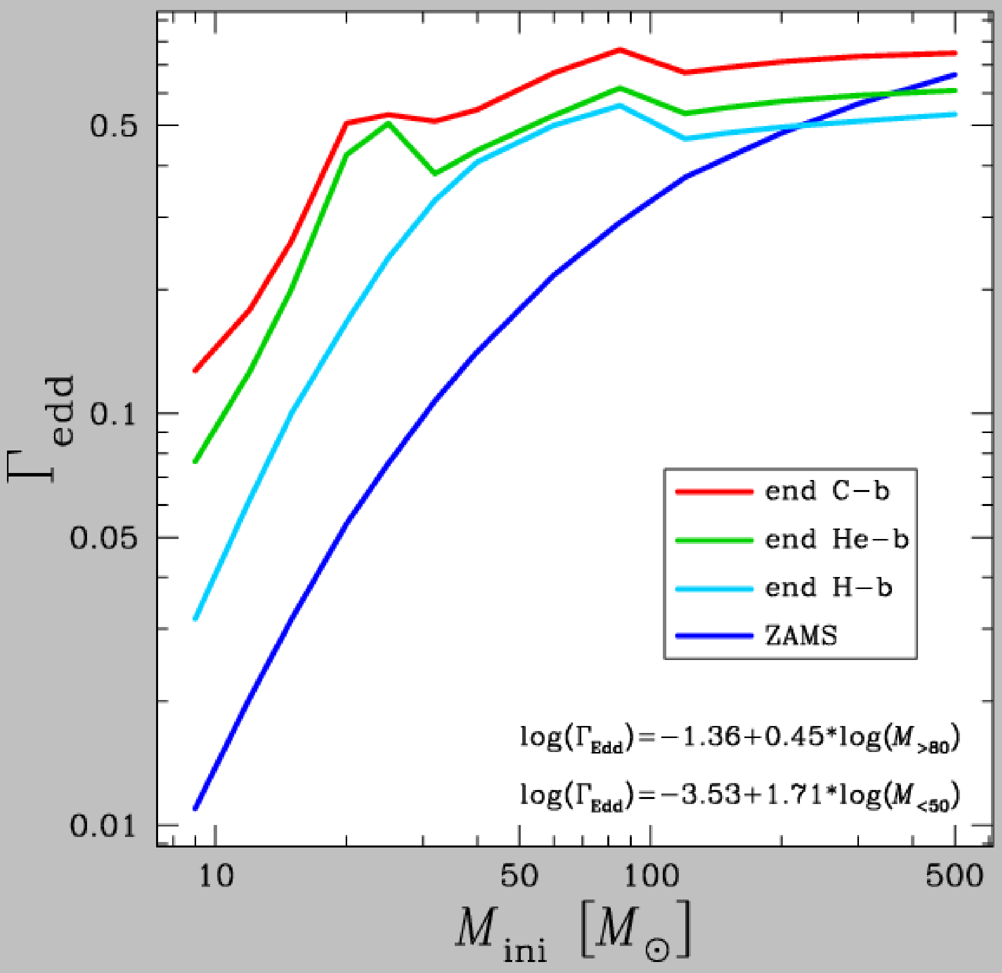


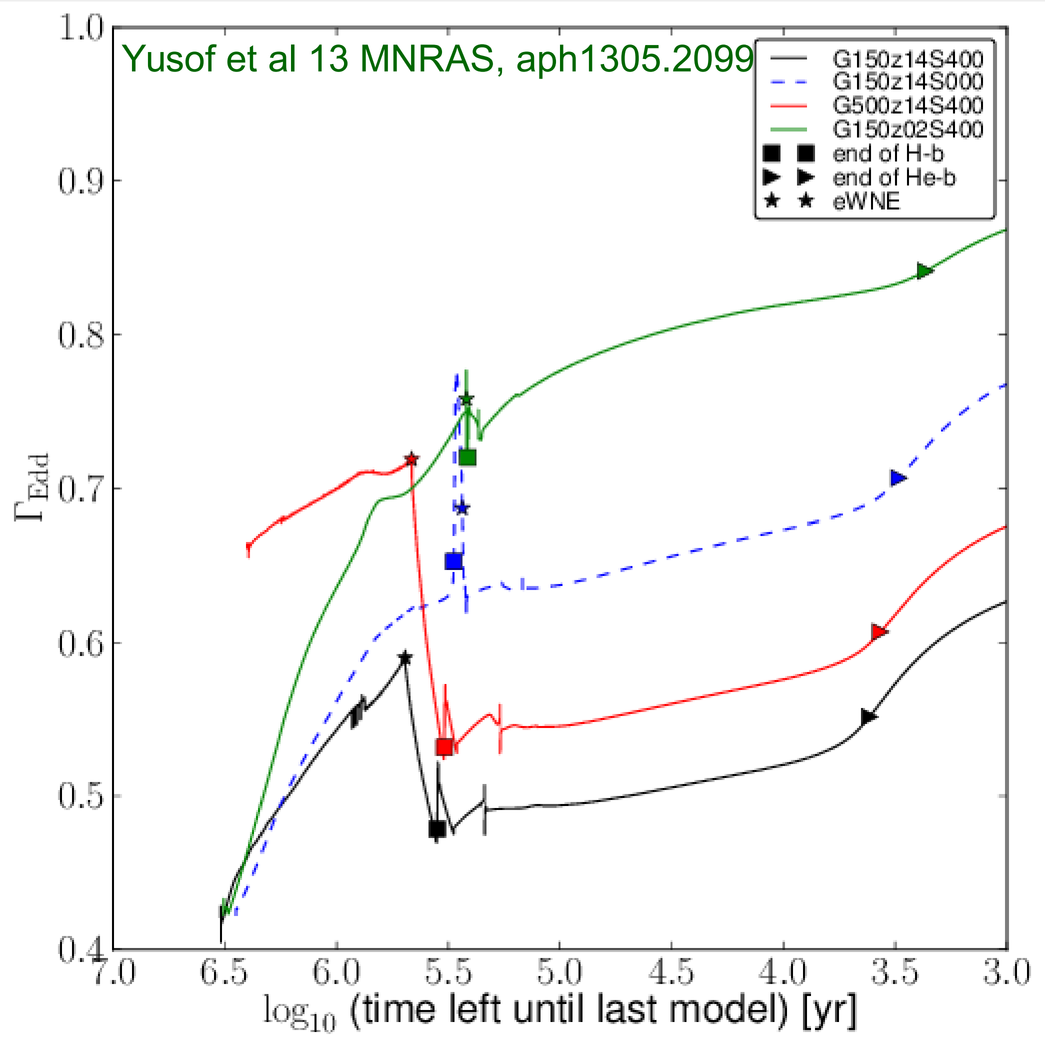
THE ASTROPHYSICAL JOURNAL, 780:117 (16pp), 2014 January 10 SCHNEIDER ET AL.

Figure 1. Stellar mass functions, i.e., number of stars per logarithmic stellar mass bin, predicted by our population synthesis models for MS (a) single and (b) binary stars. Circles and triangles show the mass function at 3.5 and 4.8 Myr, respectively. The black dotted line shows the adopted initial mass function ($\Gamma = -0.7$). The peaks in the mass functions caused by stellar wind mass loss are apparent in both plots at about 32 $M_\odot$ ($\log M/M_\odot \approx 1.5$) and 50 $M_\odot$ ($\log M/M_\odot \approx 1.7$), respectively. The tail of stars affected by binary evolution in (b) is highlighted by the hatched regions. The tail extends to about twice the maximum mass expected from single-star evolution, which is indicated by the vertical dashed lines.

Evolution of Eddington Factor

$\Gamma_{\mathrm{Edd}} < 1$ but Γ_{Edd} close to 1 if mass loss is low




Yusof et al 13 MNRAS, aph1305.2099

Γ_{Edd} may be larger than one below surface, see Sanyal et al. (2015).

Mass Loss near the Eddington Limit

Vink et al A&A 531, A132 (2011)

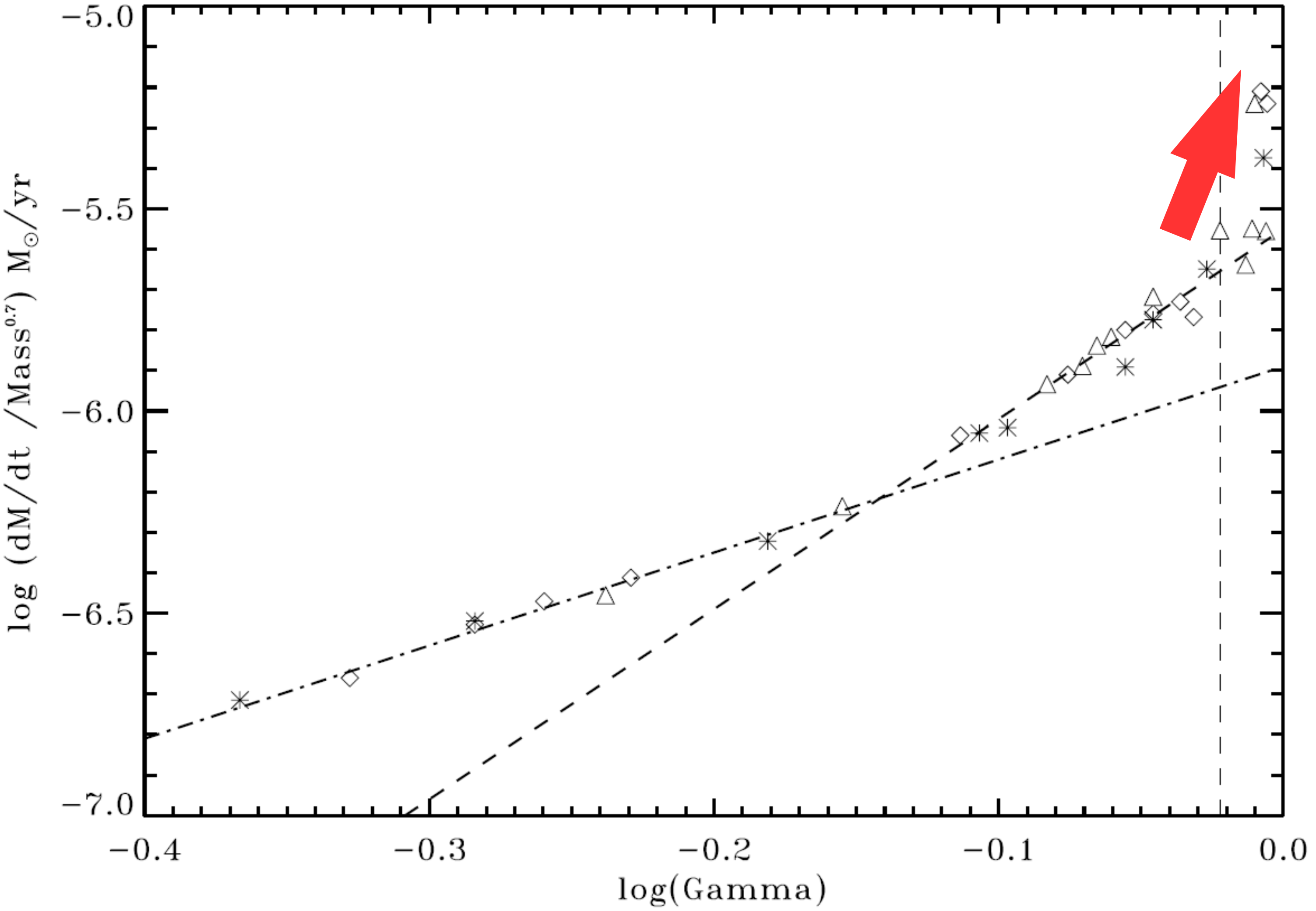
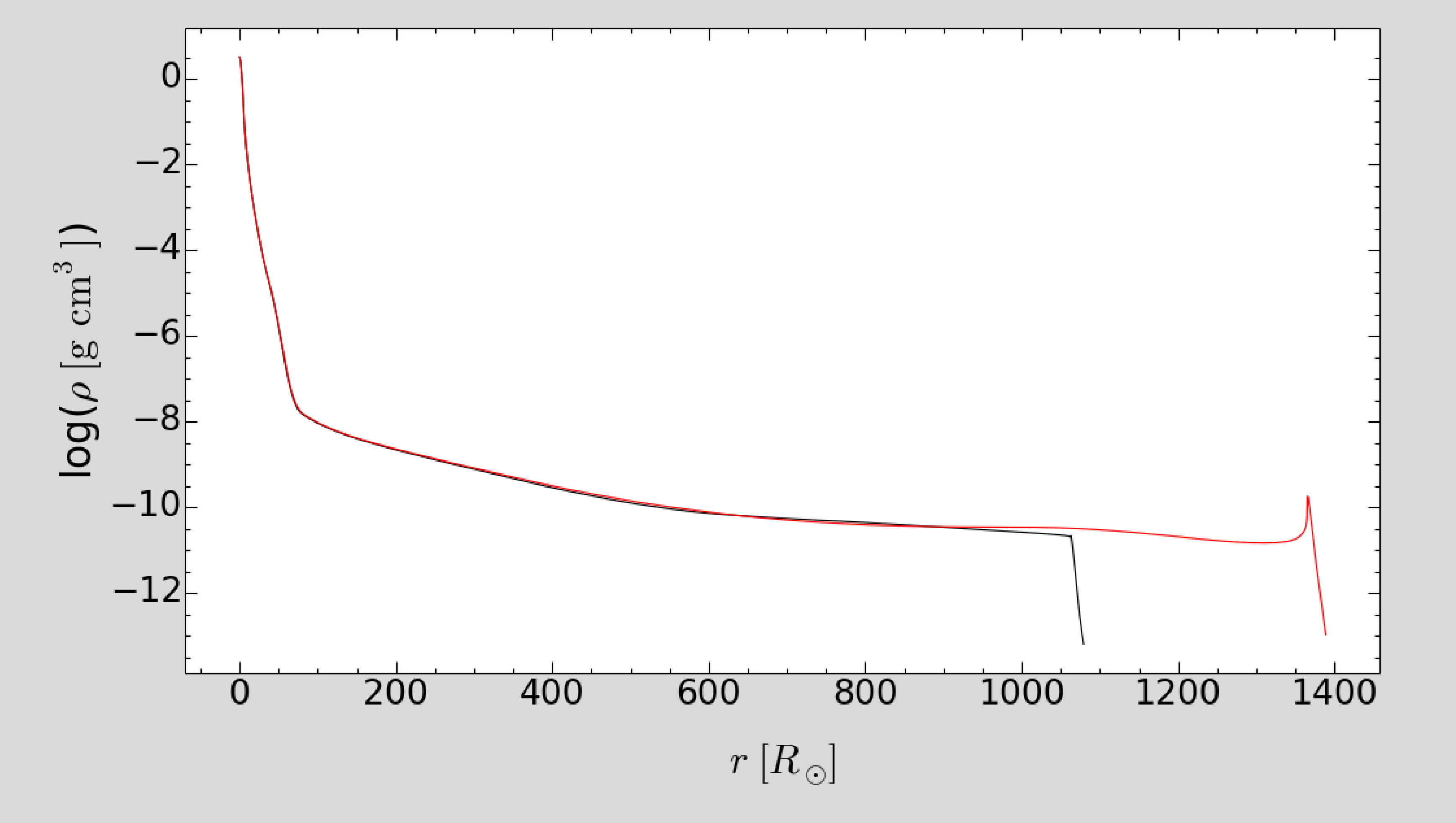


Fig. 5. The predicted mass-loss rates divided by $M^{0.7}$ versus Γ_e for models approaching the Eddington limit. The dashed-dotted line represents the best linear fit for the range $0.4 < \Gamma_e < 0.7$. The dashed line represents the higher $0.7 < \Gamma_e < 0.95$ range. Symbols are the same as in Fig. 1.

Envelope Inflation

- VMS may be very extended after MS. This sometimes leads to a density inversion in outer layer:

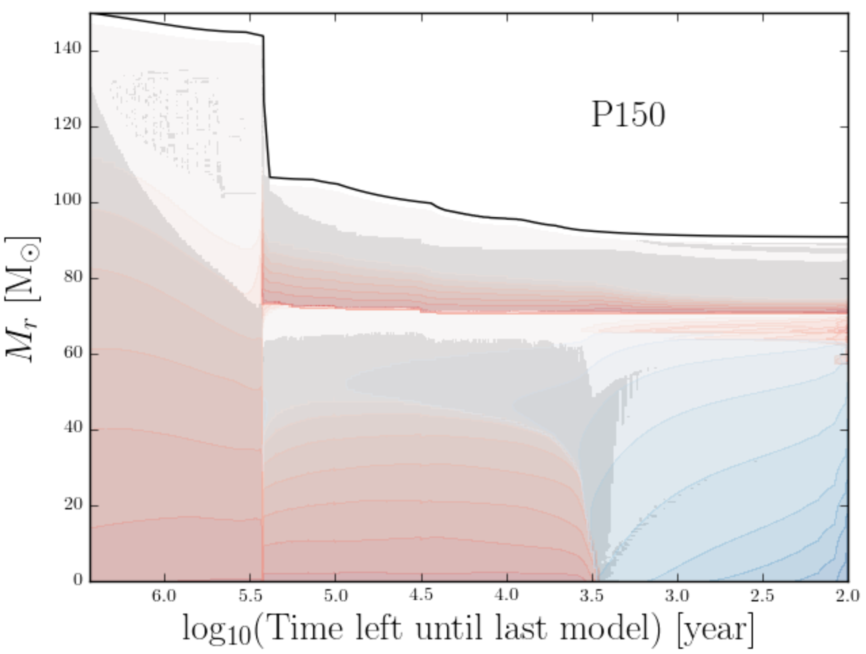


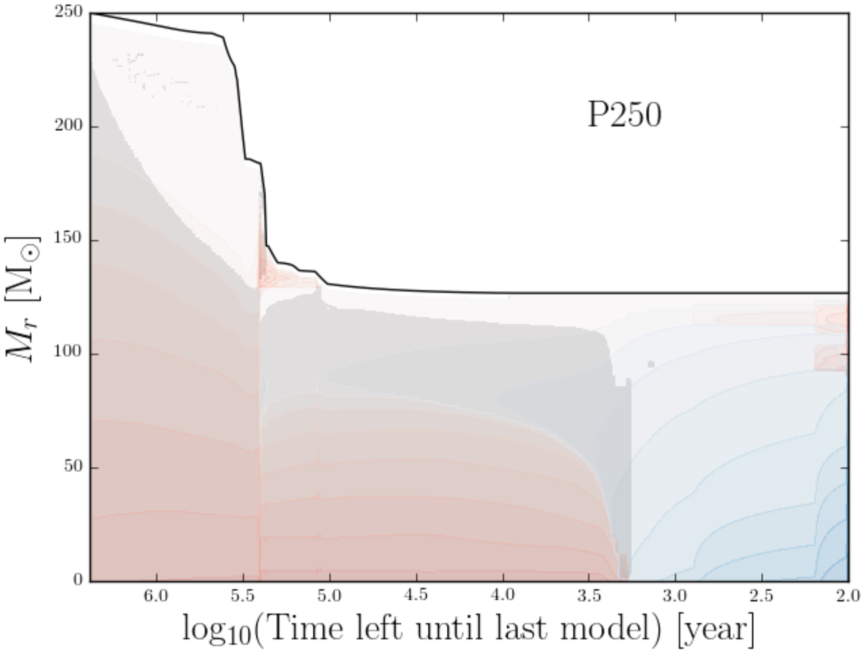
Unstable numerically → use of density scale height (black curve) stabilizes models with modest impact on radius

PCSN Model Grid at Z=0.001

(Kozyreva+RH+ 2017MNRAS.464.2854K, Gilmer+RH+ ApJ accepted, ArXiV170607454G)

- New GENEC progenitor models at Z=0.001 (non-rotating):
- M_{ini}=150,175, 200, 250 $M_\odot$
- Exploded with FLASH in 1D, 2D and 3D + Light curves with STELLA





Pre-SN: H-rich, extended envelope (1267$R_\odot$) H-poor, compact env. (2.4$R_\odot$)

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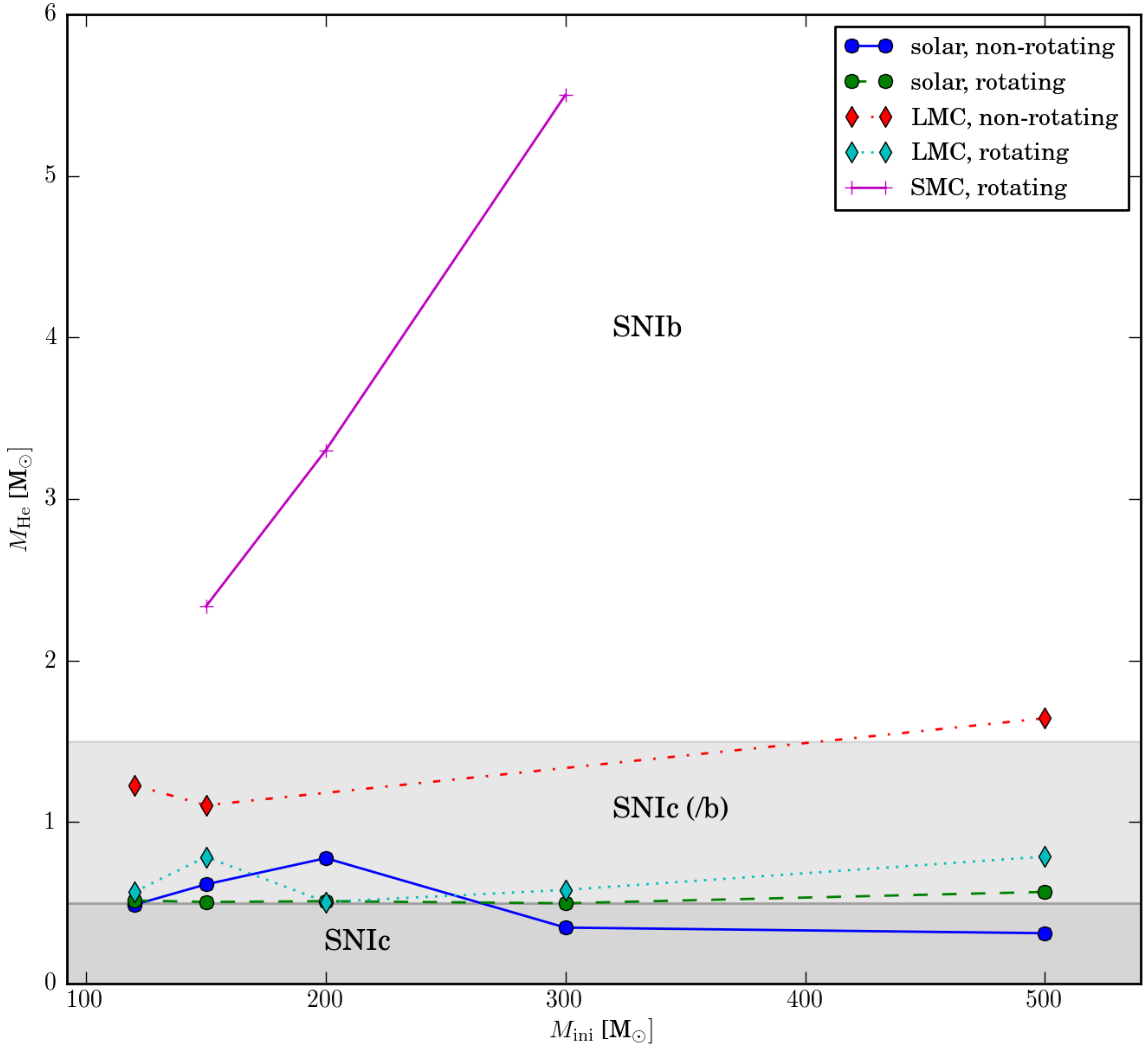

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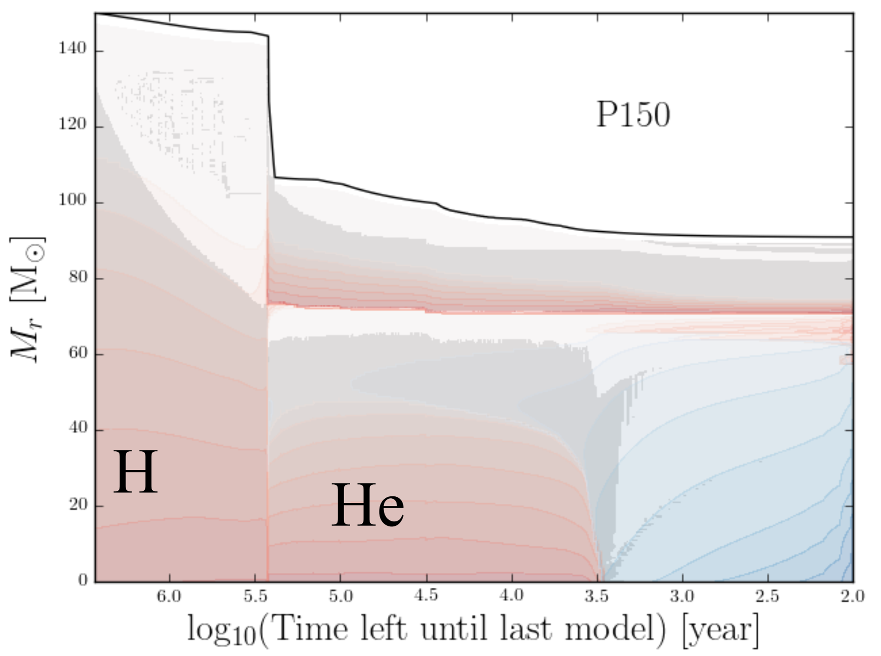
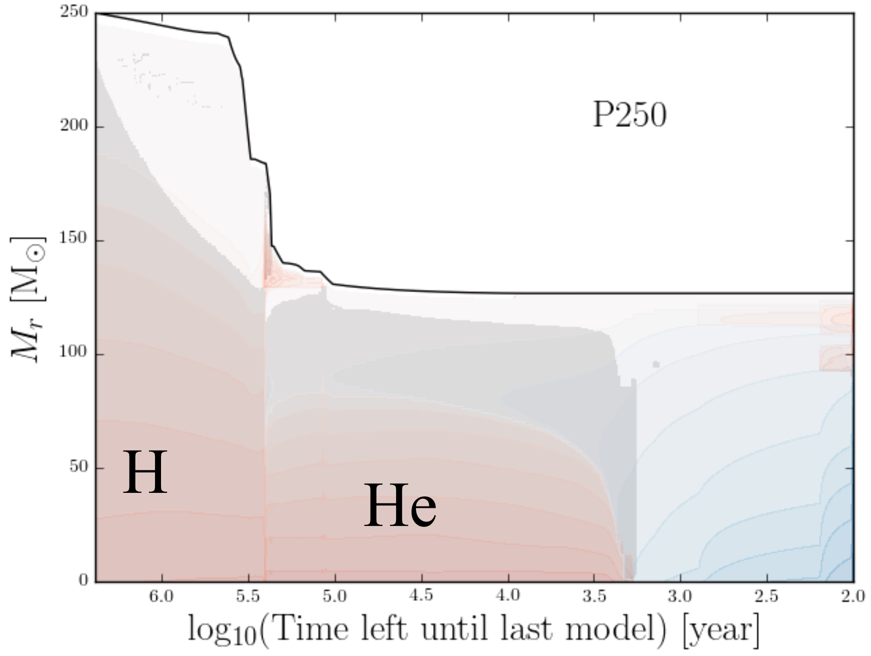


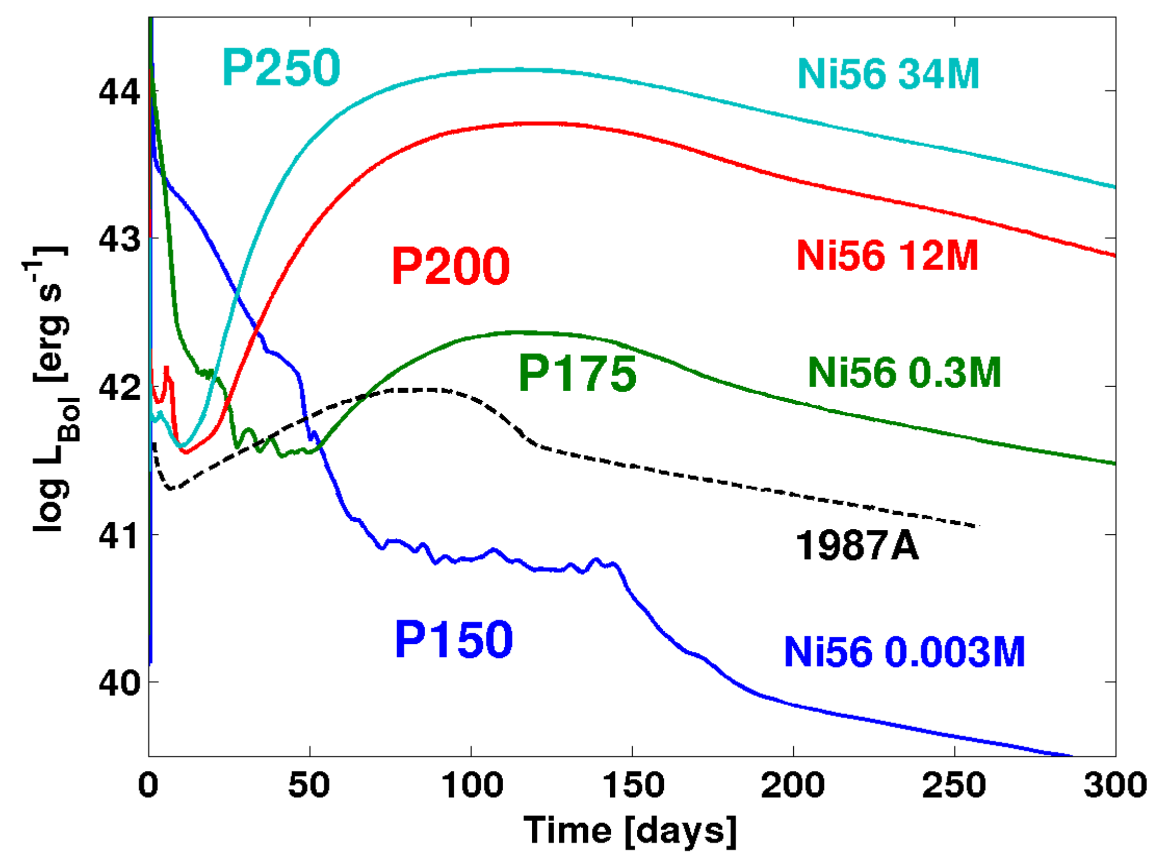


Pre-SN: H-rich, extended envelope (1267$R_{\odot}$) H-poor, compact env. (2.4$R_{\odot}$)

Light Curves of PISNe at Z=0.001

(Kozyreva+RH+ 2017MNRAS.464.2854K, Gilmer+RH+ 2017ApJ.846.100, ArXiV170607454G)

- Exploded with FLASH in 1D, 2D and 3D + Light curves with STELLA

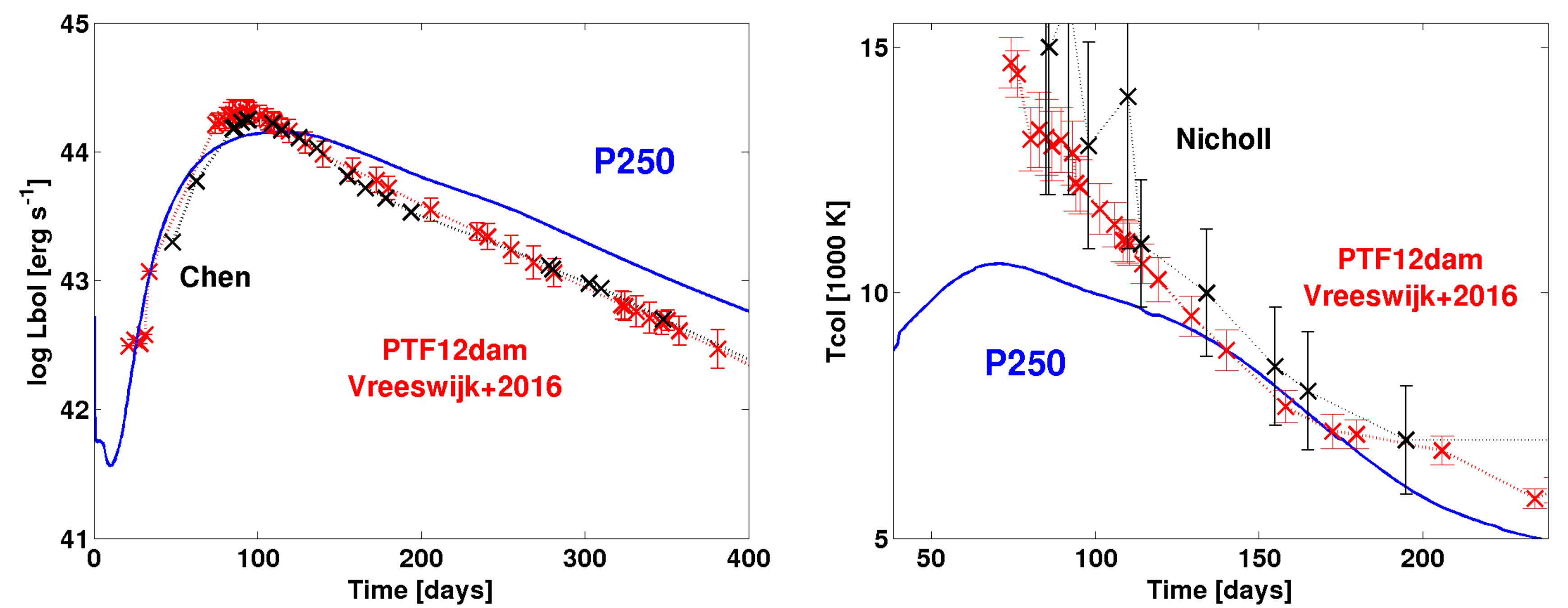


Comparison to PTF12dam

(Kozyreva+RH+ 2017MNRAS.464.2854K, Gilmer+RH+ 2017ApJ.846.100, ArXiV170607454G)

- Exploded with FLASH in 1D, 2D and 3D + Light curves with STELLA

Bolometric — Colour temperature



GENEC high-mass PISNe look as *relatively* fast SLSNe!
250 M$_\odot$ GENEC PISN – might be a candidate for PTF12dam!?

Mixing found in 3D models might change the spectrum!

First Generations: Fate of Non-Rotating Stars

Z~0:

M<25 Mo: SNII

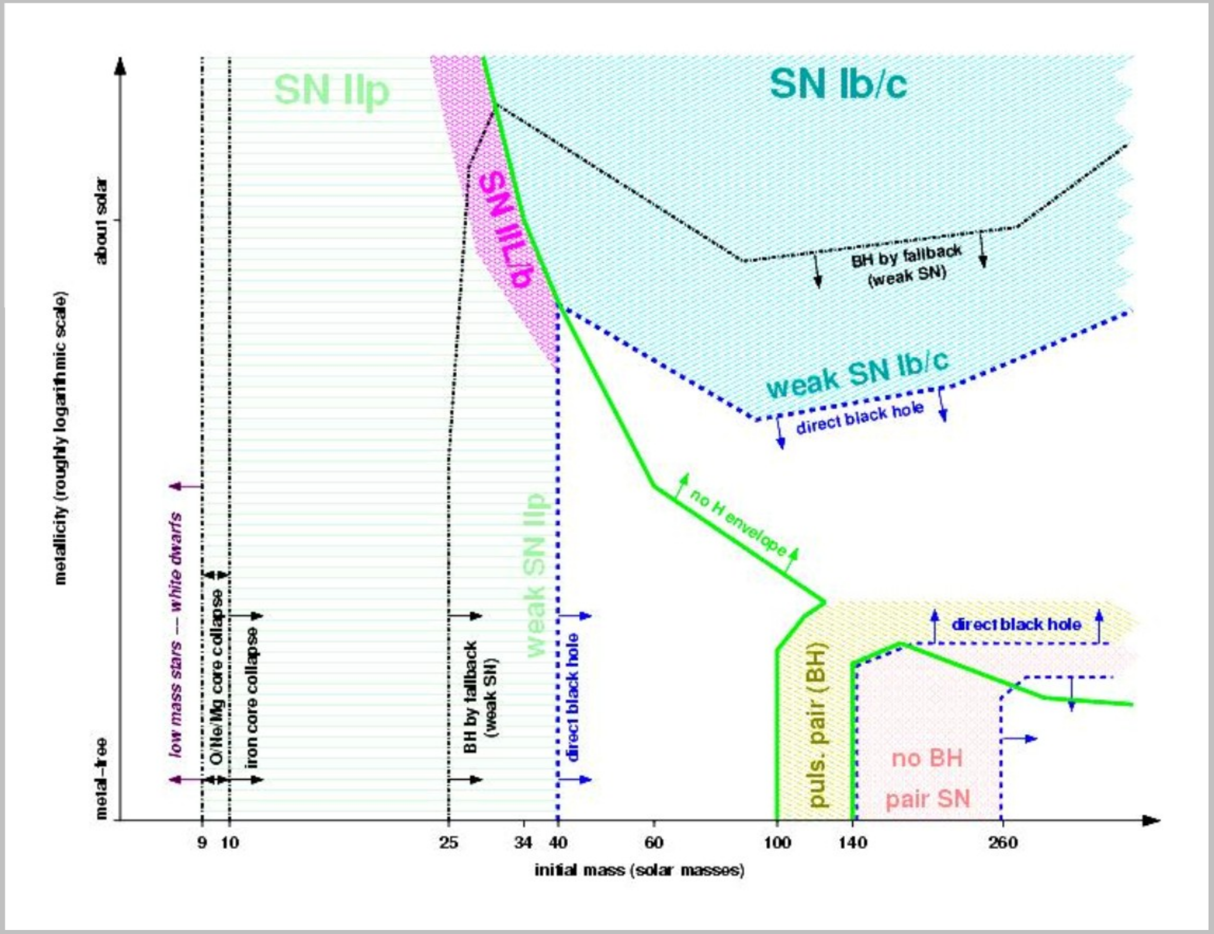
25-40: weak SNII

40-140:BH, no SN

140-260: PCSN (=PISN)

260-?: BH, no SN

Heger, Fryer et al 2003



Pair Creation SN (M:140-260 Mo) (Heger and Woosley 02, Scannapieco et al 05):

- Chemical signature of PCSN not observed in EMP stars
  (Umeda and Nomoto 02,03,05, Chieffi and Limongi 00,02,04)
- Due to strong mass loss? Hirschi 2007, Ekström et al 2008
- 2006gy might be a PCSN (Smith et al 07, Langer et al 07, Heger et al 07)

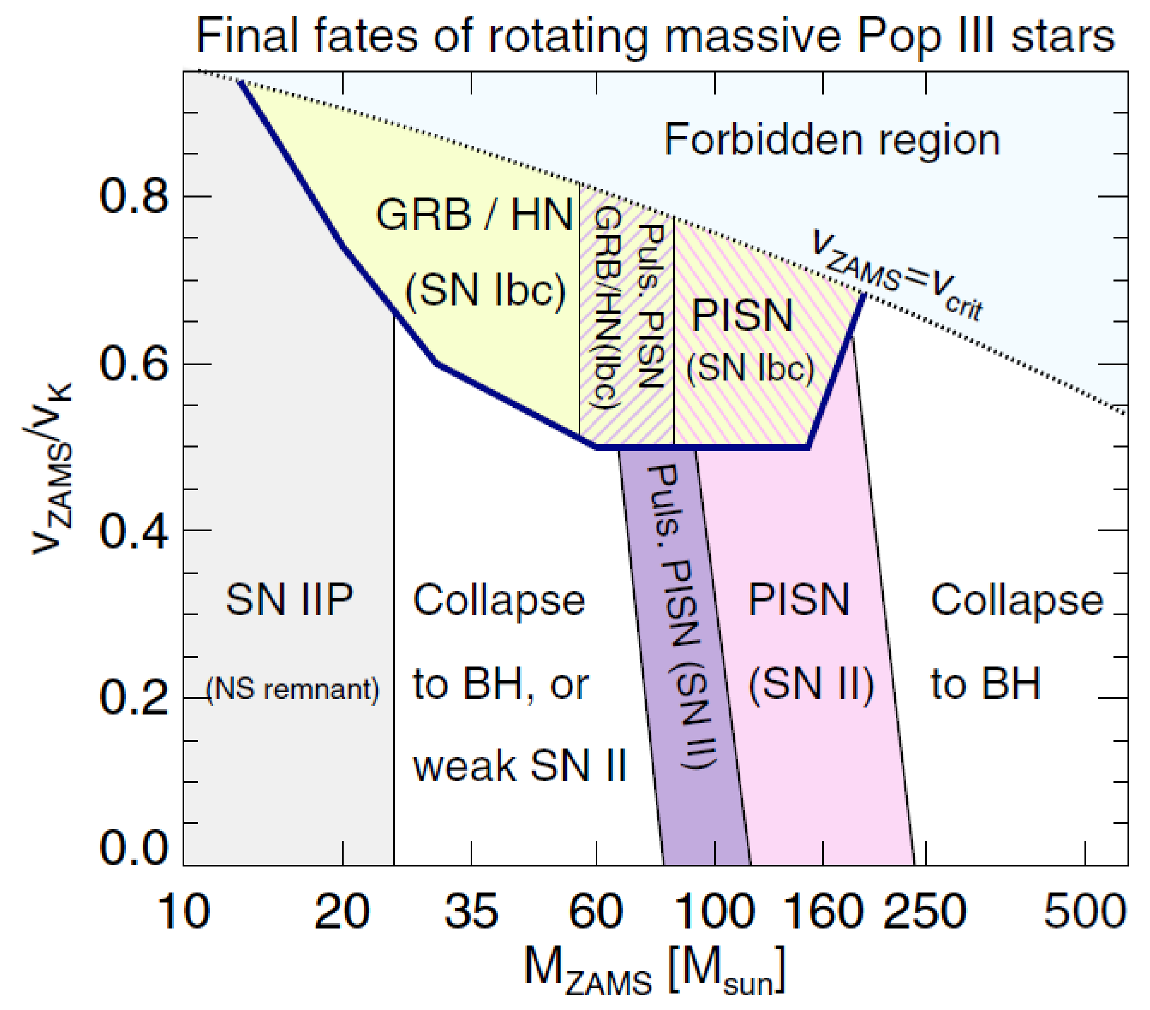
The fate of VMS @ Z=0

Yoon et al 2012 (see also Chatzopoulos, & Wheeler 2012 and Heger & Woosley 2012, Heger & Woosley 2002)

Z= 0:
Models including Mdot, rotation & B-fields

Rotation lowers mass range for PISN

Mechanical Mdot important



Papers/Reviews

- West, Heger, Austin, “The Impact of Helium-burning Reaction Rates on Massive Star Evolution and Nucleosynthesis”, 2013ApJ...769....2W (see also Tur et al 2010ApJ...718..357T, 2009ApJ...702.1068T)

- Chieffi, Limongi, “Pre-supernova Evolution of Rotating Solar Metallicity Stars in the Mass Range 13-120 $M_{\odot}$ and their Explosive Yields”, 2012ApJS..199...38L

- Yusof, N. et al , “Evolution and fate of very massive stars”, 2013MNRAS.433.1114Y: M_{max} ~ 320 M_{o}!!!

- Takahashi, Umeda, Yoshida, “Evolution of progenitors for electron capture supernovae”, 2013ApJ...771...28T

Viallet, M.; Meakin, C.; Arnett, D.; Mocák, M., “Turbulent Convection in Stellar Interiors. III. Mean-field Analysis and Stratification Effects”, 2013ApJ...769....1V

- Gilet, C.; et al, “Low Mach Number Modeling of Core Convection in Massive Stars”, 2013ApJ...773..137G

- Paxton, Bill et al,”MESA: Planets, Oscillations, Rotation, and Massive Stars”, 2013ApJS..208....4P

- Sukhbold, Tuguldur; Woosley, S. E.: “The Compactness of Pre-supernova Stellar Cores”, 2014ApJ...783...10S

- Jones, S.; et al, “Advanced Burning Stages and Fate of 8-10 M_{o} Stars”,2013ApJ...772..150J

Denissenkov, P. A.; et al, “The C-flame Quenching by Convective Boundary Mixing in Super-AGB Stars and the Formation of Hybrid C/O/Ne White Dwarfs and SN Progenitors”, 2013ApJ...772...37D

Keller, S. C et al, “A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3”, 2014Natur.506..463K : [Fe/H]<-7!!

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

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, ...)