ECT*, Nov 2018

Key Stellar & Nuclear Uncertainties in Stellar Evolution Modelling

Raphael HIRSCHI
Keele Uni, UK

SHEN @ Keele: L. Scott, E. Kaiser
in collaboration with:
GVA code: G. Meynet, A. Maeder, C. Georgy, S. Ekström, P. Eggenberger, A. Choplin 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) N. Nishimura
NUGRID: F. Herwig (Victoria, Canada), M. Pignatari (Hull), C. Fryer, S. Jones (LANL),
J. den Hartogh (Konkoly Obs., H), 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 (Tel Aviv,Il), T. Fischer (W.,P)
HYDRO: C. Meakin, D. Arnett (UArizona), C. Georgy (GVA), M. Viallet (MPA),
F. Roepke, L. Horst (HITS, D), P. Edelmann (Newcastle, UK), A. Cristini (Uoklahoma,US)

Keele is Not Kiel (Germany) But Where is it?

West Midlands:

Keele area

is famous for pottery: Wedgwood, ...

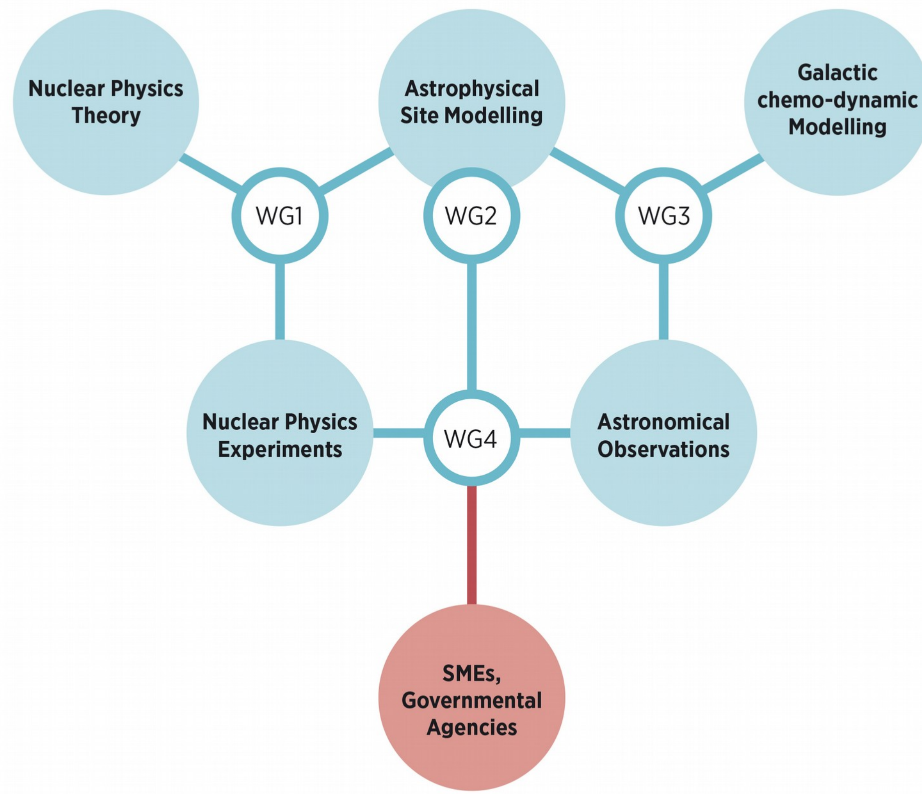
Exciting HyDeploy.co.uk / SEND projects

ChETEC COST Action (2017-2021) www.chetec.eu

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



Funding for collaboration visits: STSMs!!

Formal cooperation with JINA-CEE underway!!

30 countries joined ChETEC to coordinate research efforts in Nuclear Astrophysics:

Austria, Belgium, Bulgaria, Czech Rep., Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom

Plan

- Intro to stellar evolution and nucleosynthesis sites

- Stellar evolution modelling & physical ingredients

- Nuclear uncertainties: overview & MC studies

- Stellar uncertainties: overview & convection

- Summary & 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

Massive stars:

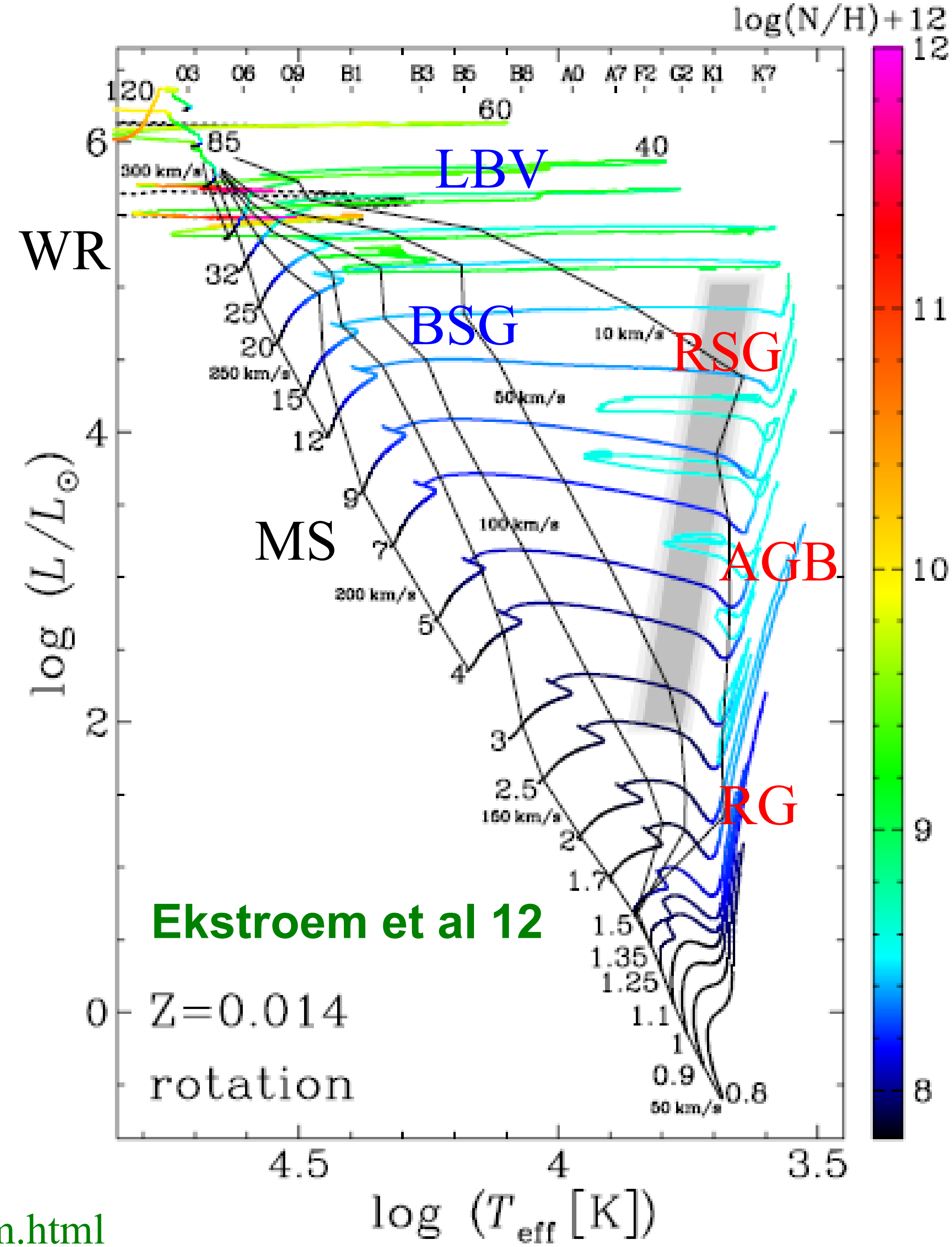
Supergiant stage (red or blue)

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

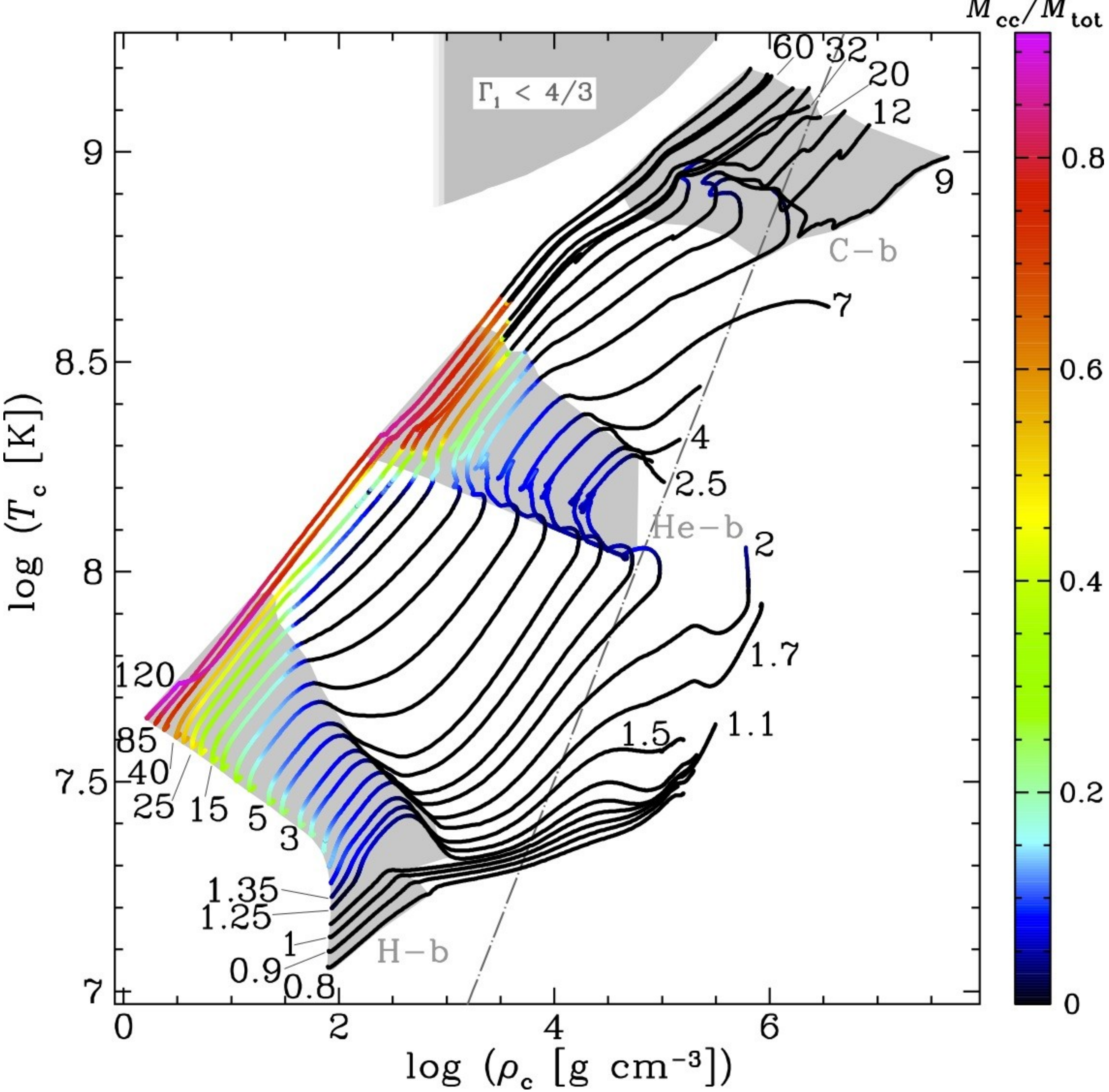


http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

Central Temperature vs Central Density Diagram

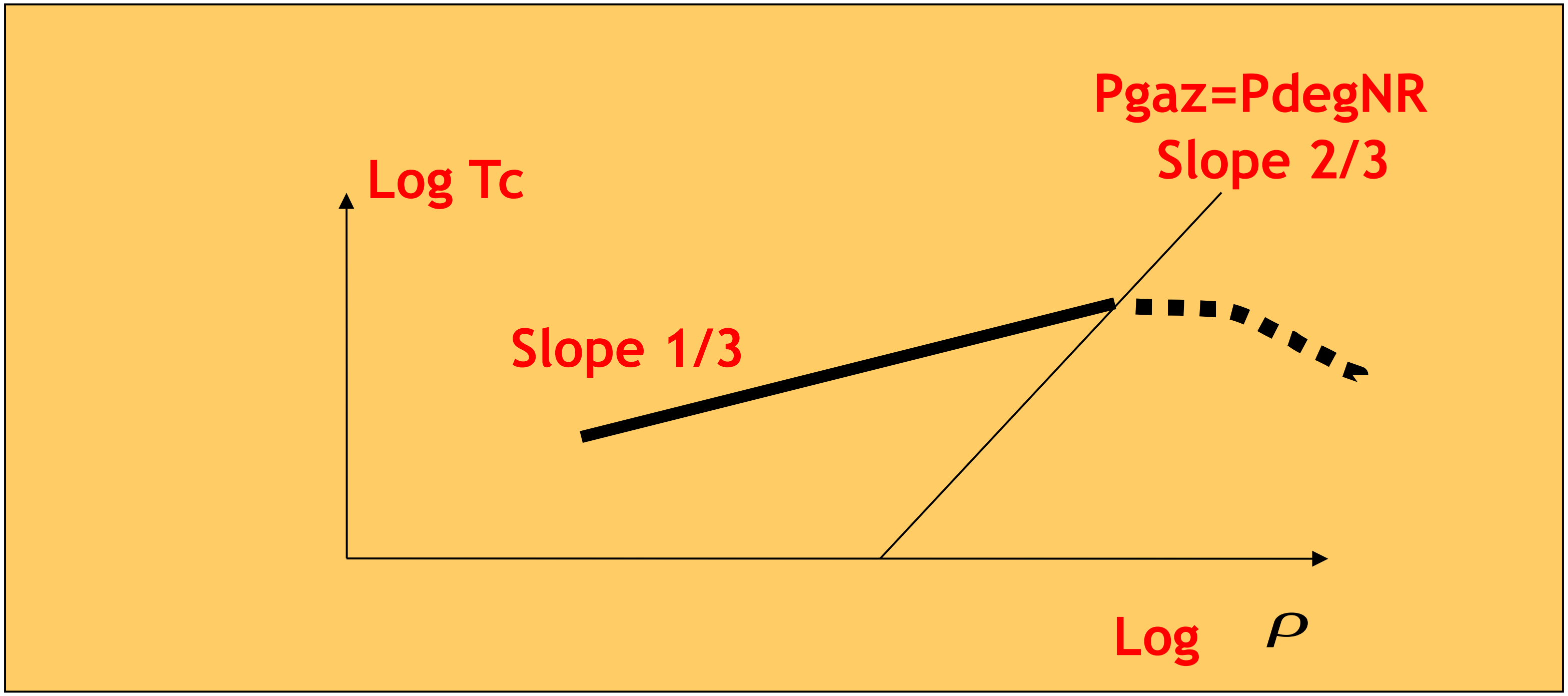
Evolution of central properties

What is the slope of the evolutionary tracks?



Ekstroem et al 12

Evolution of the temperature and density at the centre



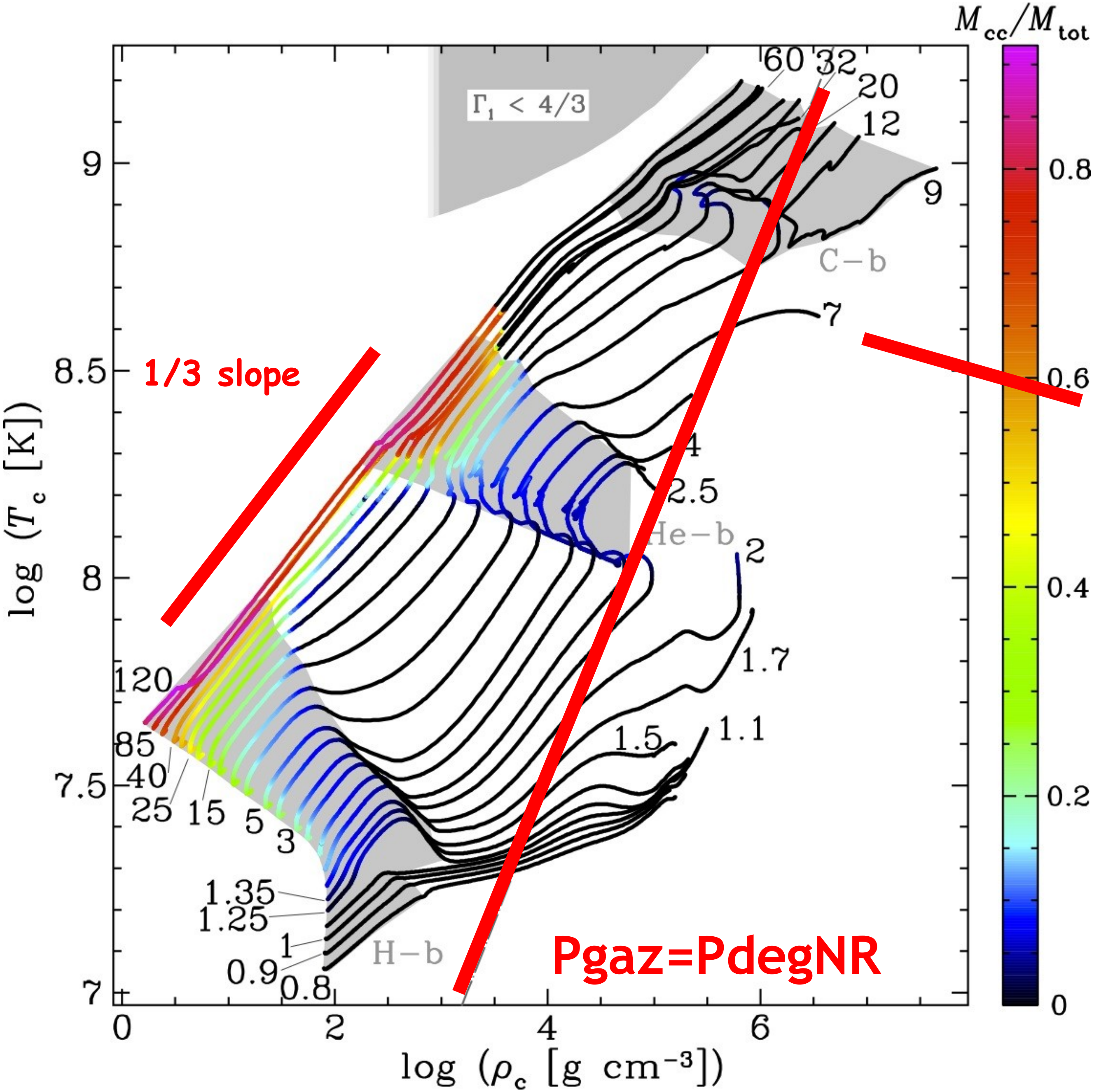
Pgaz=PdegNR

$$\frac{k}{\mu m_H}\rho T = K_1\left(\frac{\rho}{\mu e}\right)^{5/3} \quad \rightarrow T = K_1 \frac{\mu m_H}{k}\frac{1}{\mu_e^{5/3}}\rho^{2/3}$$

Non → Degenerate Conditions

Evolution of central

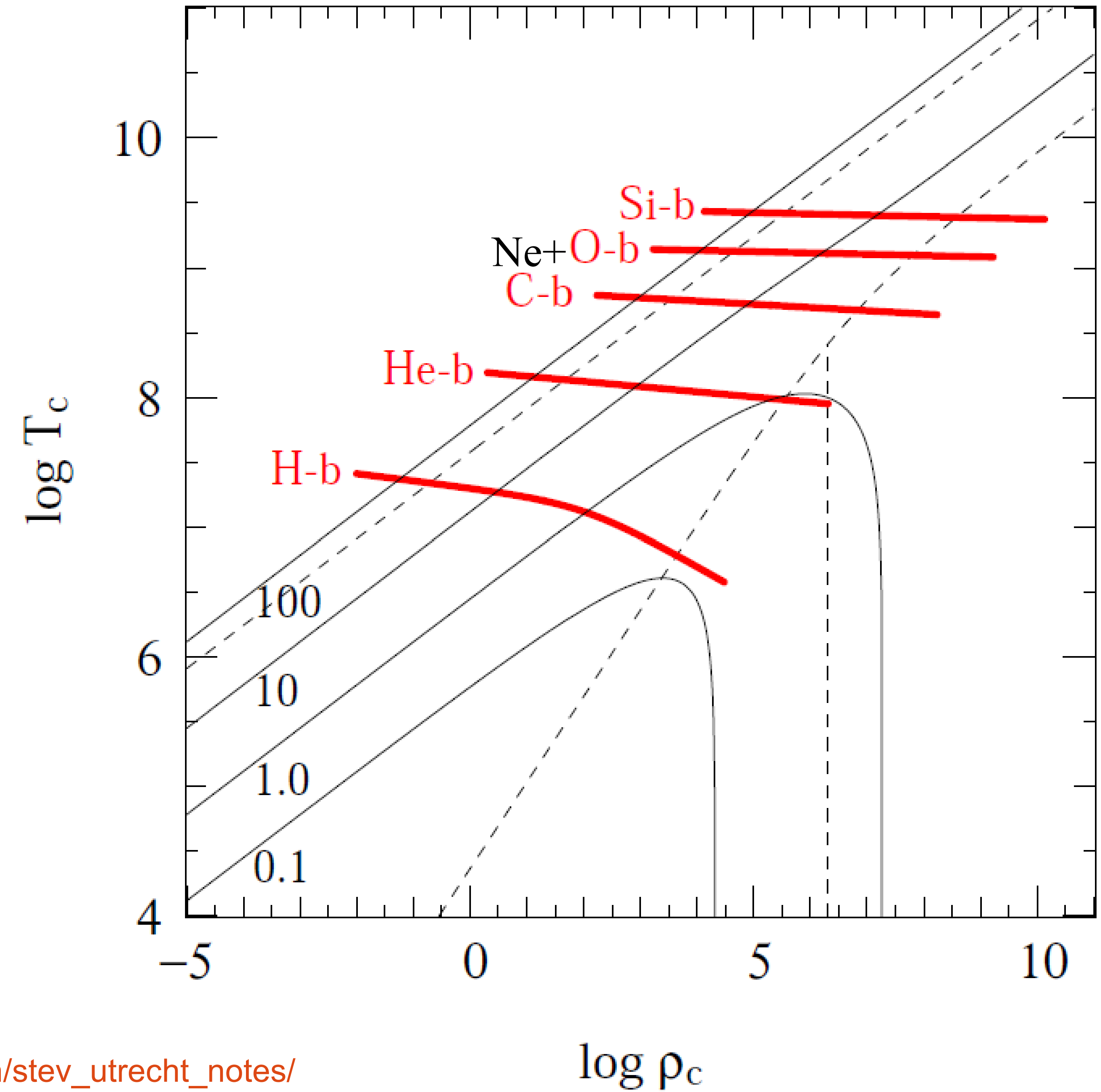
properties



Ekström et al. (2012) A&A, 537, A146)

Mass Domains

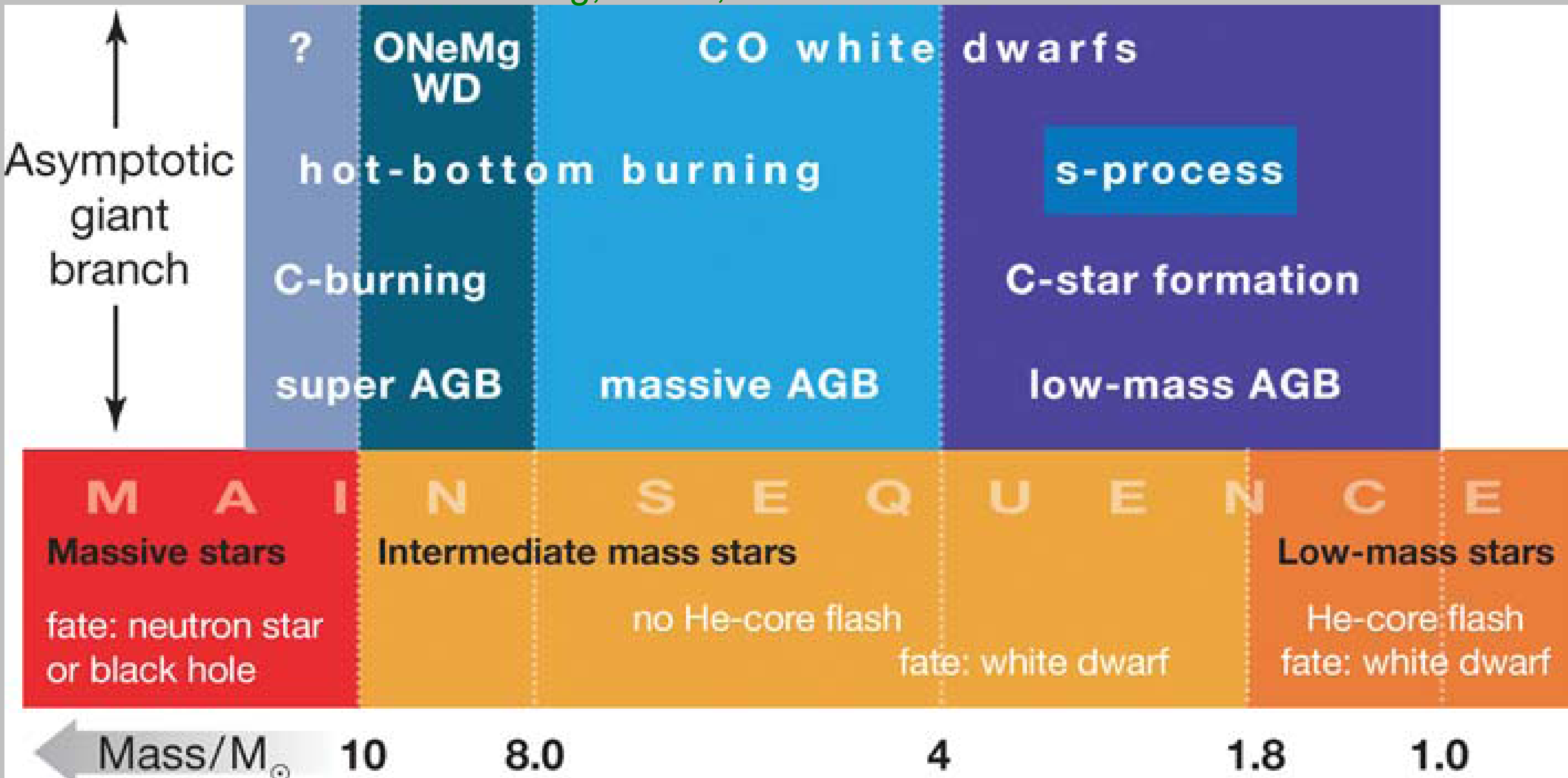
$$\epsilon_{\rm nuc} = \epsilon_0 \, \rho^\lambda \, T^\nu$$



Lecture notes from O. Pols taken from:
http://www.astro.ru.nl/~onnop/education/stev_utrecht_notes/

Mass Domains

Herwig, ARAA, 2005

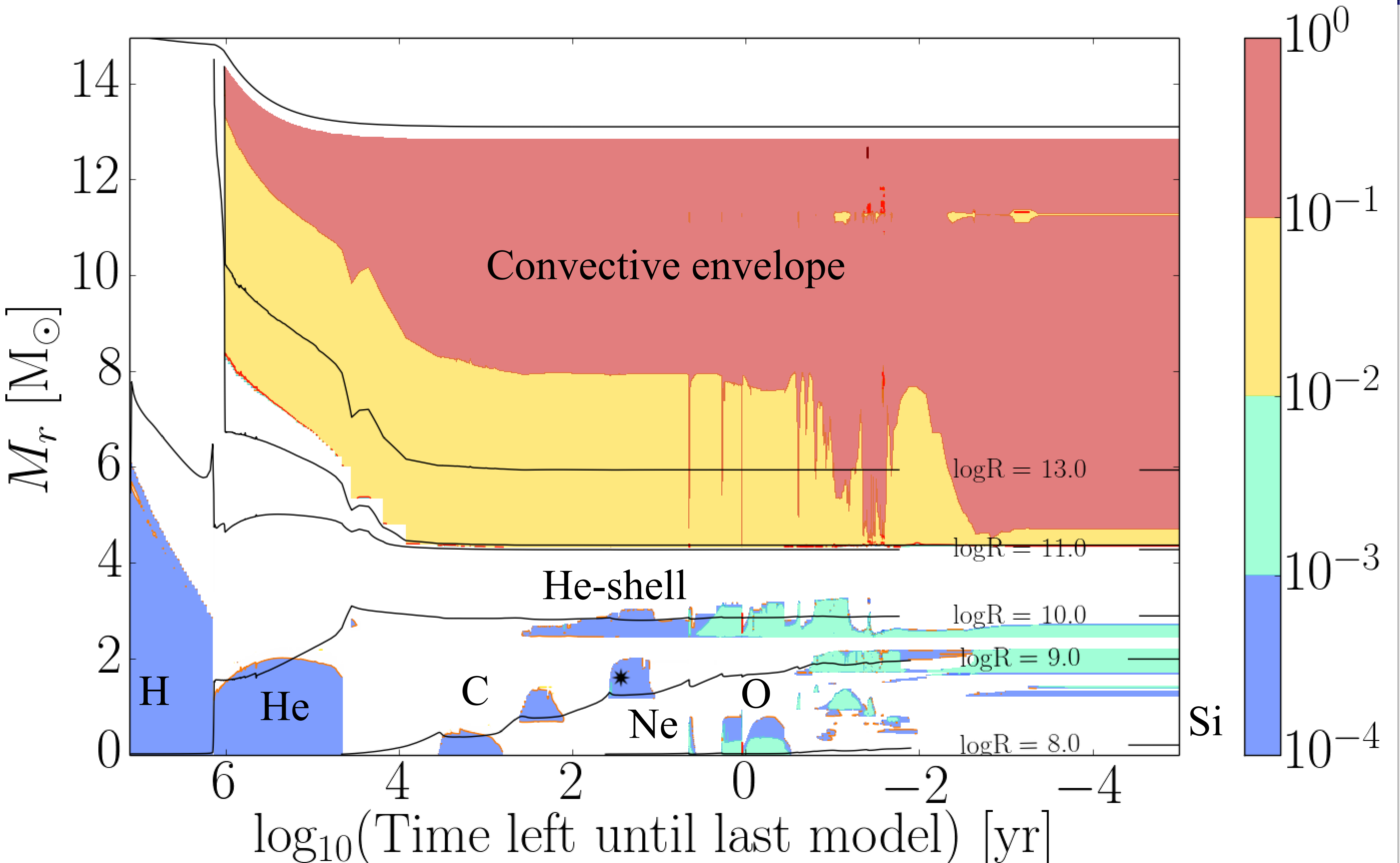


Massive stars: > 9 M_o : go through all burning stages

Intermediate-mass stars: 1.8 - 9 M_o do not ignite C-burning in centre (C-flash for SAGB stars)

Low-mass stars: <1.8M_o do not ignite He-burning in centre (He-flash)

Structure Evolution of Massive Stars



Convection takes place during most burning stages

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

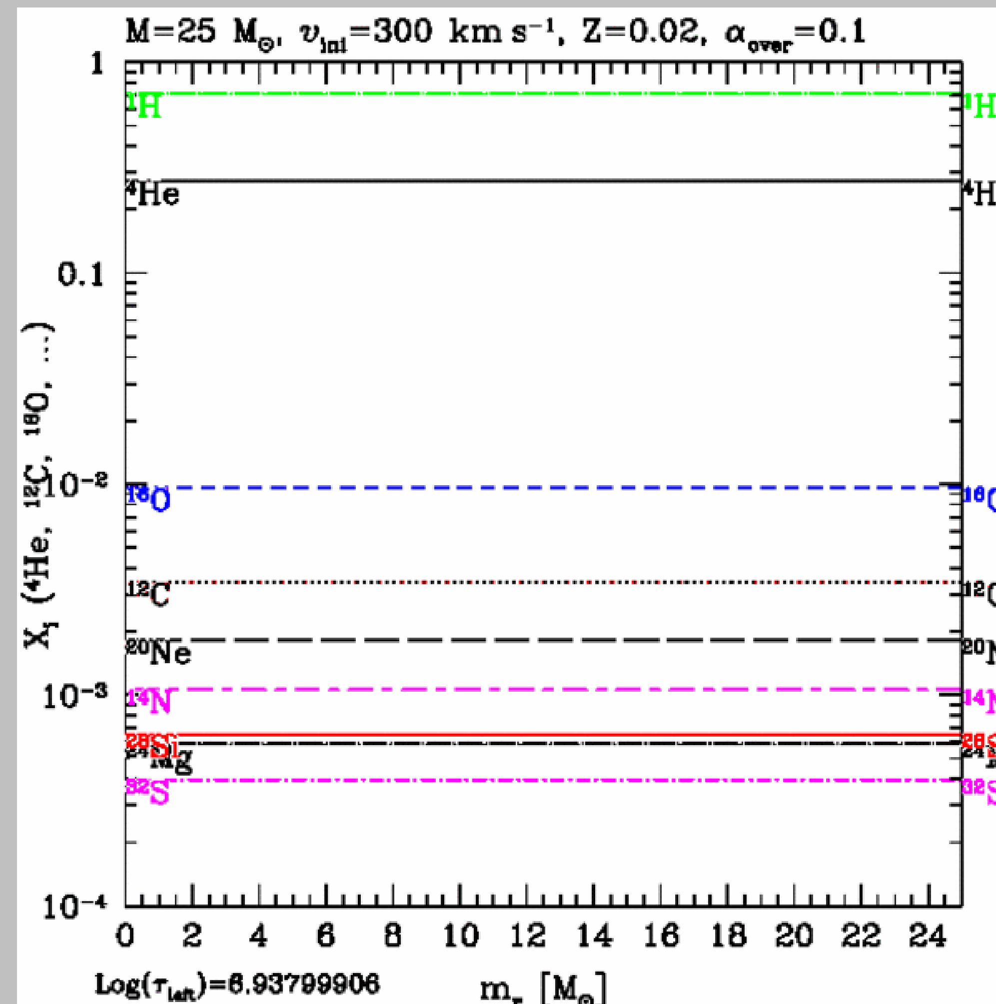
&^{14}N → ^{18}O → ^{22}Ne

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

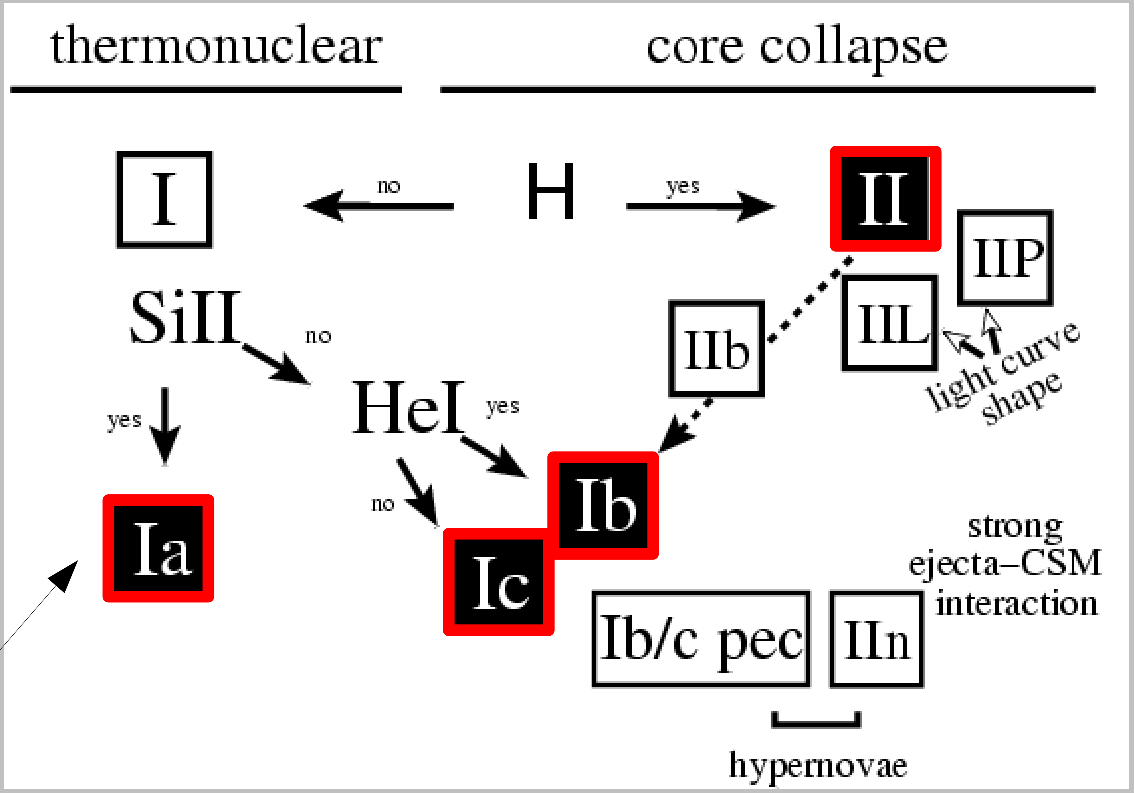
Silicon (10^{-3}): ^{28}Si, ^{32}S → ^{56}Ni



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

Supernova Explosion Types

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

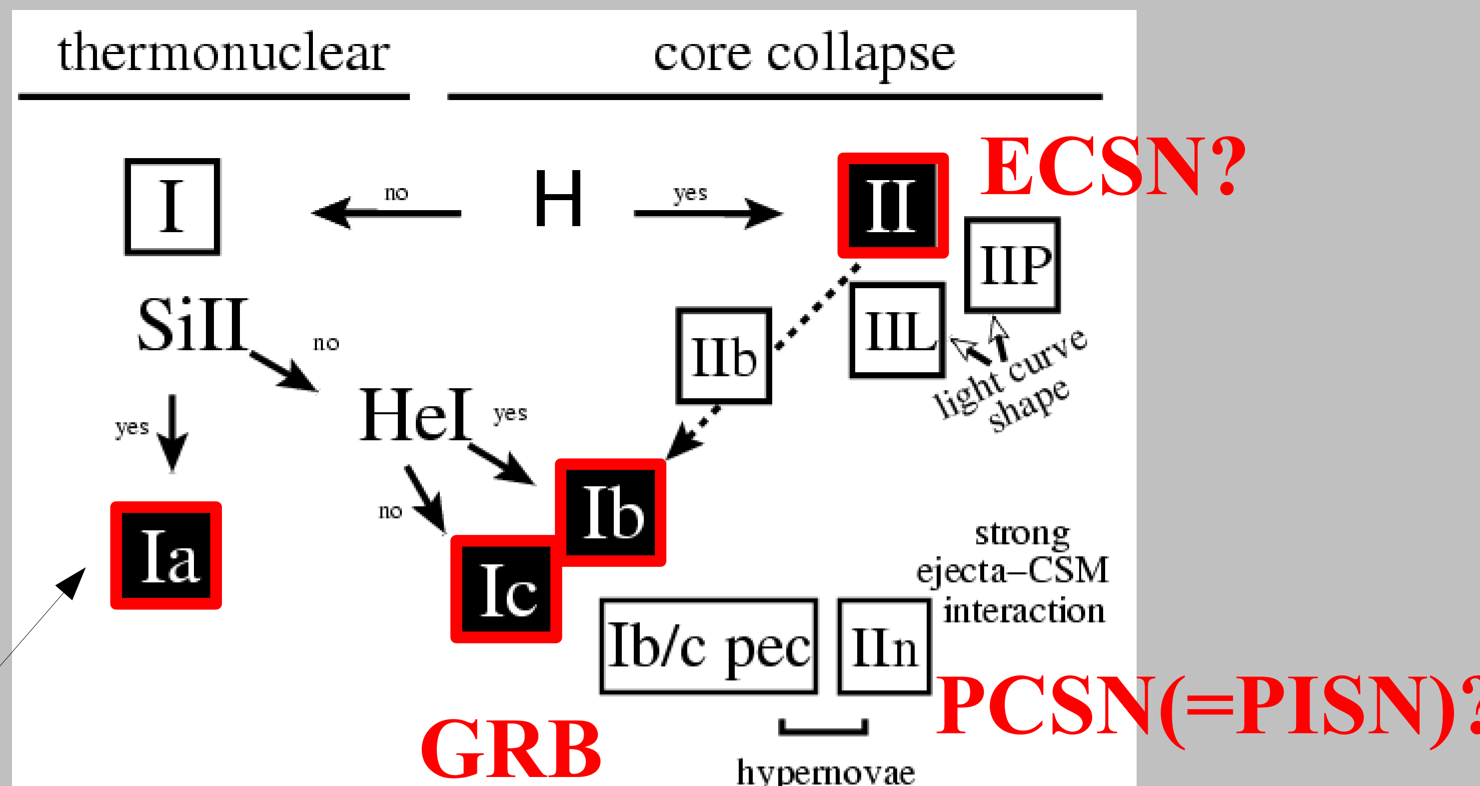


White dwarfs (WD):
in binary systems
Accretion →
Chandrasekhar
mass → SN Ia

(Turatto 03)

Supernova Explosion Types

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



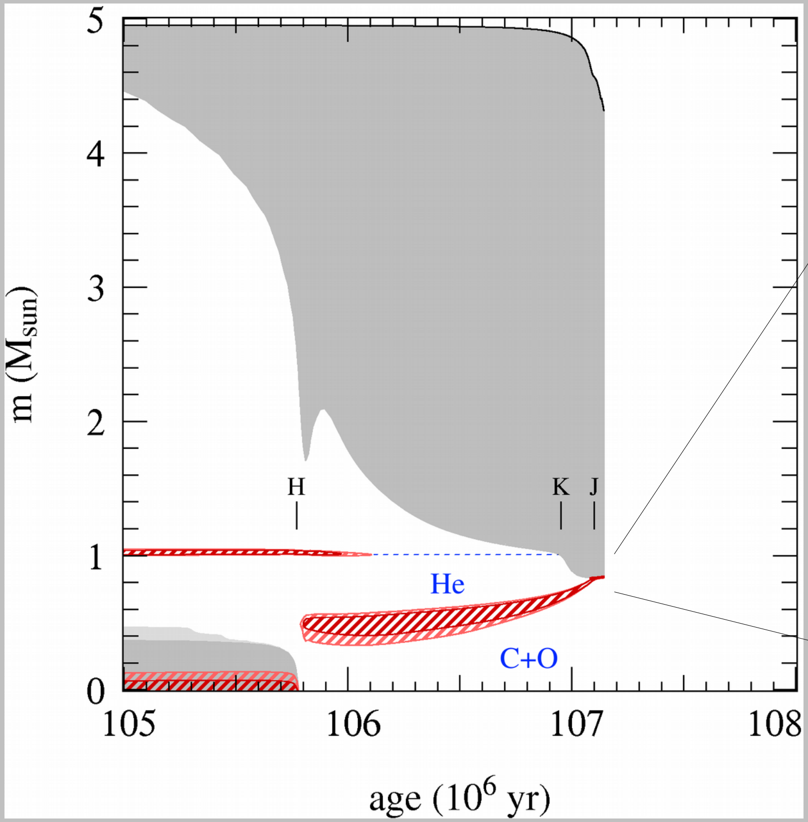
White dwarfs (WD):
in binary systems
Accretion → Chandrasekhar mass → SN Ia

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

(Turatto 03)

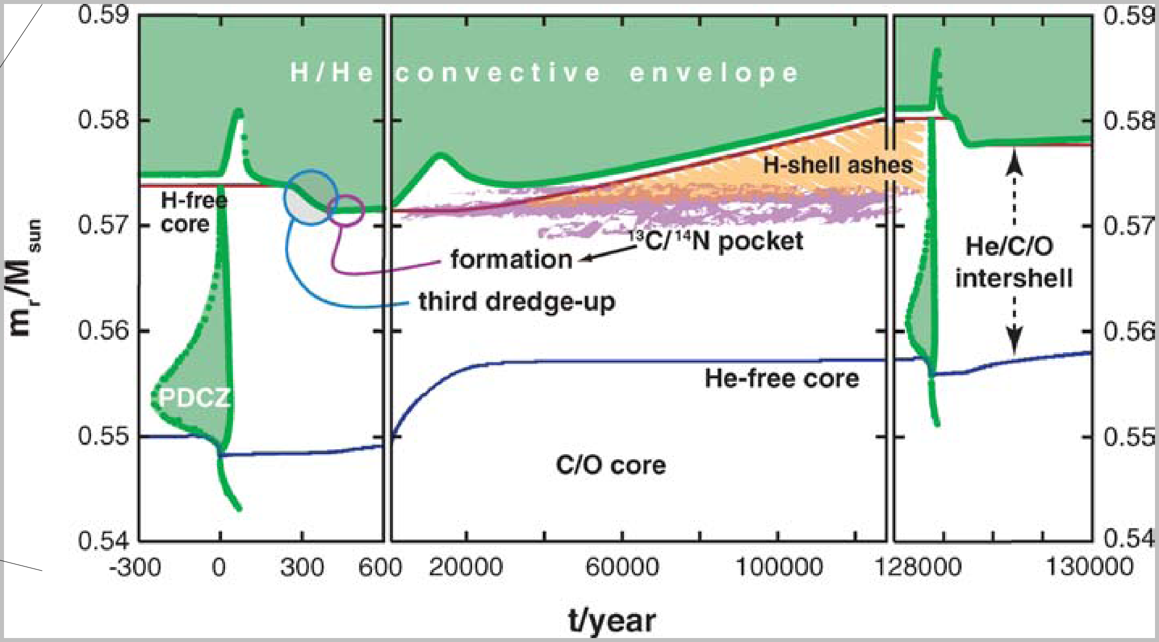
Intermediate & Low-Mass Stars

5 M$_o$ star: AGB phase



From SE notes, O. Pols (2009)

Structure in AGB phase



Herwig, ARAA, 2005

Woosley, Heger & Weaver, 2002 RvMP Vol. 74. p. 1015

See Ritter+ 2018, MNRAS For full grid of models

TABLE III. The origin of the light and intermediate-mass elements.

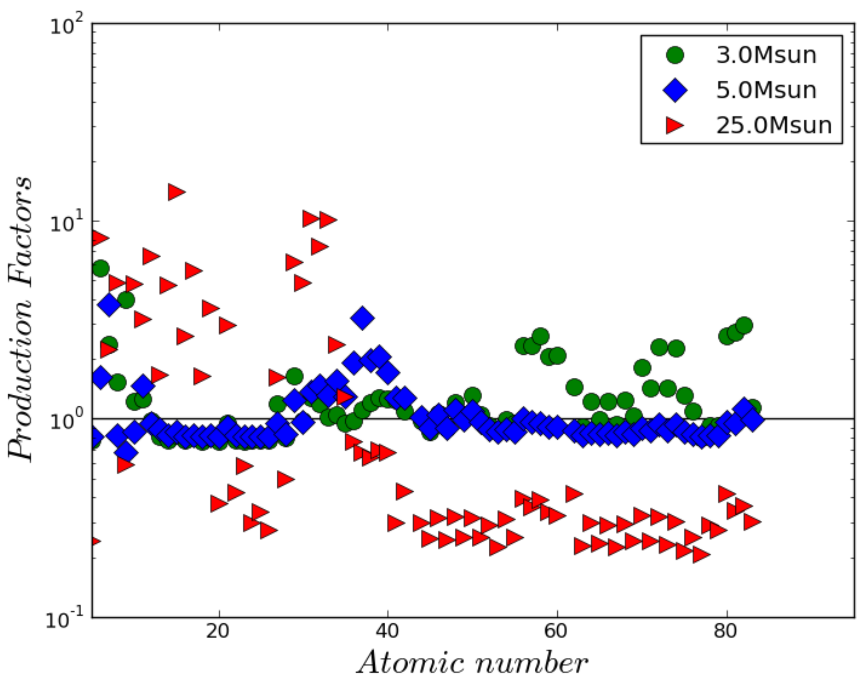
Species	Origin	Species	Origin	Species	Origin
^{1}H	BB	^{30}Si	C,Ne	^{51}V	α,Ia-det,xSi,xO,ν
^{2}H	BB	^{31}P	C,Ne	^{50}Cr	xSi,xO,α,Ia-det
^{3}He	BB,L*	^{32}S	xO,O	^{52}Cr	xSi,α,Ia-det
^{4}He	BB,L*,H	^{33}S	xO,xNe	^{53}Cr	xO,xSi
^{6}Li	CR	^{34}S	xO,O	^{54}Cr	nse-IaMCh
^{7}Li	BB,ν,L*,CR	^{36}S	He(s),C,Ne	^{55}Mn	Ia,xSi,ν
^{9}Be	CR	^{35}Cl	xO,xNe,ν	^{54}Fe	Ia,xSi
^{10}B	CR	^{37}Cl	He(s),xO,xNe	^{56}Fe	xSi,Ia
^{11}B	ν	^{36}Ar	xO,O	^{57}Fe	xSi,Ia
^{12}C	L*,He	^{38}Ar	xO,O	^{58}Fe	He(s),nse-IaMCh
^{13}C	L*,H	^{40}Ar	He(s),C,Ne	^{59}Co	He(s),α,Ia,ν
^{14}N	L*,H	^{39}K	xO,O.ν	^{58}Ni	α
^{15}N	novae,ν	^{40}K	He(s),C,Ne	^{60}Ni	α, He(s)
^{16}O	He	^{41}K	xO	^{61}Ni	He(s),α,Ia-det
^{17}O	novae, L*	^{40}Ca	xO,O	^{62}Ni	He(s),α
^{18}O	He	^{42}Ca	xO	^{64}Ni	He(s)
^{19}F	ν,He,L*	^{43}Ca	C,Ne,α	^{63}Cu	He(s),C,Ne
^{20}Ne	C	^{44}Ca	α,Ia-det	^{65}Cu	He(s)
^{21}Ne	C	^{46}Ca	C,Ne	^{64}Zn	ν-wind,α,He(s)
^{22}Ne	He	^{48}Ca	nse-IaMCh	^{66}Zn	He(s),α,nse-IaMCh
^{23}Na	C,Ne,H	^{45}Sc	α,C,Ne,ν	^{67}Zn	He(s)
^{24}Mg	C,Ne	^{46}Ti	xO,Ia-det	^{68}Zn	He(s)
^{25}Mg	C,Ne	^{47}Ti	Ia-det,xO,xSi	r	ν-wind
^{26}Mg	C,Ne	^{48}Ti	xSi,Ia-det	p	xNe,O
^{27}Al	C,Ne	^{49}Ti	xSi	$s(A<90)$	He(s)
^{28}Si	xO,O	^{50}Ti	nse-IaMCh,He(s)	$s(A>90)$	L*
^{29}Si	C,Ne	^{50}V	C,Ne,xNe,xO		

NuGrid :

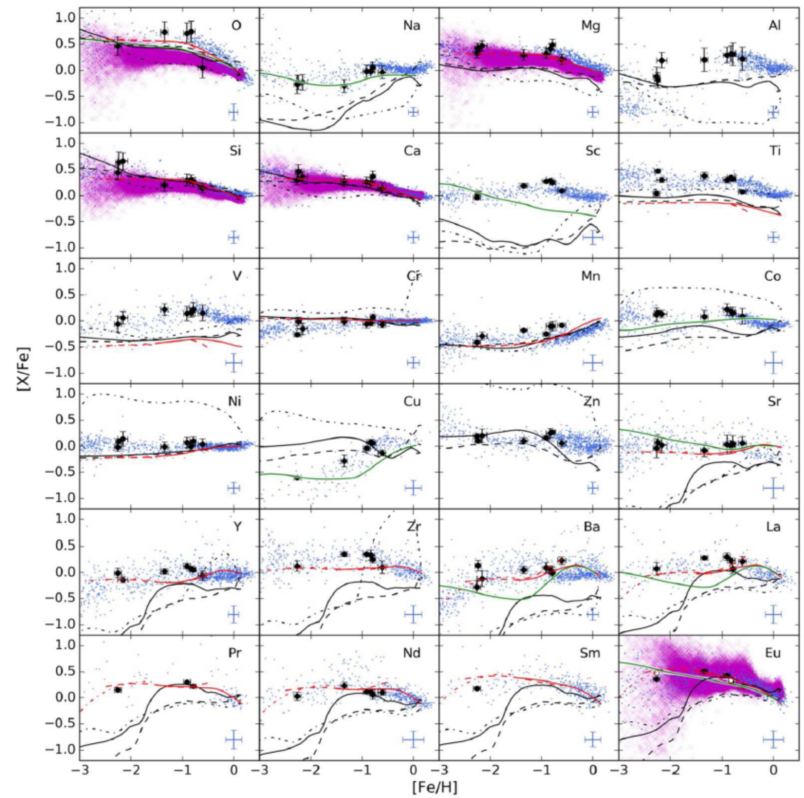
- www.nugridstars.org
- data.nugridstars.org
- wendi.nugridstars.org

The Nucleosynthesis Grid (NuGrid) project mantains and develops tools for post-processing nucleosynthesis simulations, and applies these to produce complete sets of stellar yields.

Ritter+RH+2018, MNRAS



Final elemental production factors for a low mass AGB star (3 Msun), a massive AGB star (5 Msun), and a massive star (25 Msun) (MP+2016 ApJS, CR+18, MNRAS).



GCE simulations: OMEGA vs other codes, NuGrid yields vs other yields (BC+17, ...).

Stellar Models:

Stellar structure equations + physical ingredients:

- Nuclear reactions

- Mass loss

- Rotation

- Convection

- Magnetic fields

- Binary interactions

- Equation of state, opacities & neutrino losses

including metallicity dependence

Stellar Structure Equations

The four structure equations to be solved are:

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2}$$

$$\frac{\partial L_r}{\partial m} = \epsilon_n - \epsilon_\nu - c_P\frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t}$$

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla$$

(Assuming spherical symmetry: one-dimensional model)

Lecture notes slide from Achim Weiss

Uncertain Nuclear Reactions

- Charged-particle reactions:

Key uncertain reactions dominating energy generation during secular evolution have already been identified

Explosive environments (e.g. Novae) have additional uncertain rates

- Weak interactions & neutron-captures:

Many reactions involved in e.g. s process.

How can we determine which are key?

Bottlenecks, branching points, neutron source/poison reactions

How to consider current uncertainty and importance?

Monte Carlo Sensitivity Studies

Piz Buin mountain

Monte Carlo Framework:

- PizBuin MC-wrapper

Rauscher+ 2016MNRAS.463.4153R

- Simple "brute force" approach

- Parallelised using OpenMP

Nuclear Reaction Network:

- Solver: WinNet (Winteler+ 12)

- Reaction rates ← reaclib (Rauscher & Thielemann 00)

= McWinNet

beta-decay & (n,g) uncertainties are T-dependent!

Largest simulations: ~1000 trajectories x ~1 min per run
X 10,000 MC iterations

Temp.-Dependent Uncertainties for (n,g)

For details, see T. Rauscher, ApJL, 775, 2011

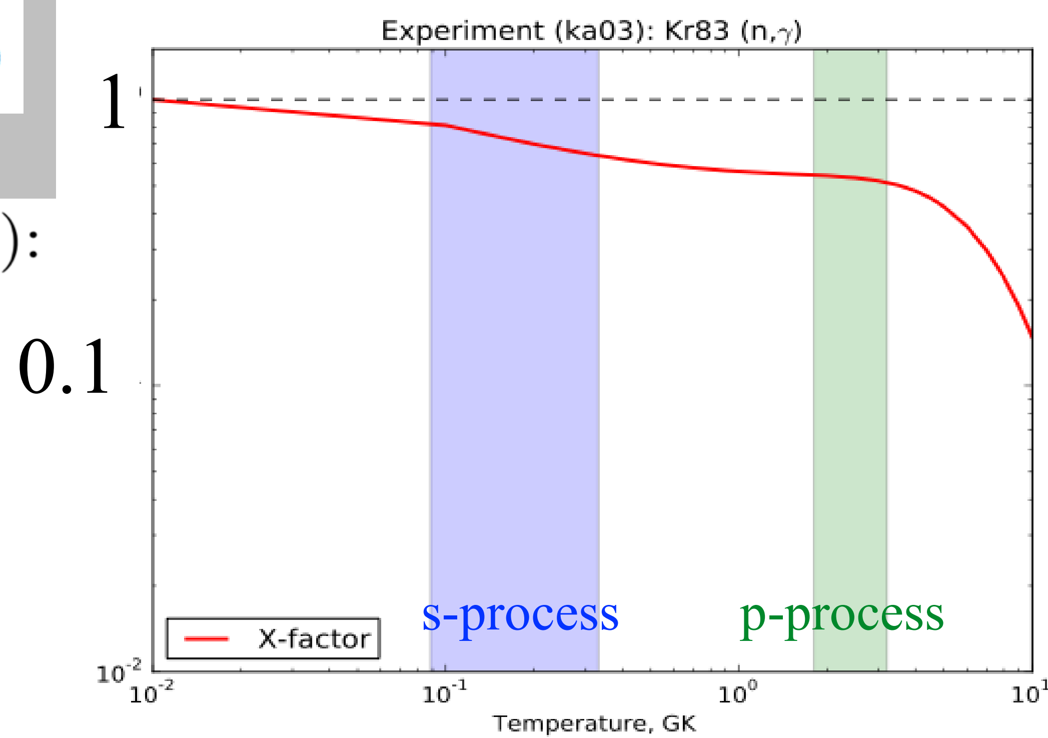
- Theoretical
  - basic rates: Reaclib (Rauscher & Thielemann 2000)
  - a constant factor 2
- Experimental
  - base rates: KADoNiS v0.3 (Dillemann el al., 2009)
  - the formula: Rauscher, ApJ, 775, 2011

X: ^{83}Kr(n,g)^{84}Kr

$$U(T) = U_{\mathrm{g.s.}} X + U_{\mathrm{e.s.}} (1 - X)$$

- ground state (experimental based): $u_{\mathrm{g.s.}} \sim 1.0 - 1.3$
- excited states (theory based): $u_{\mathrm{e.s.}} = 5$ (given constant)

$X(T)$: the fraction of particles in the ground state



Temp.-Dependent Uncertainties for beta-Decays

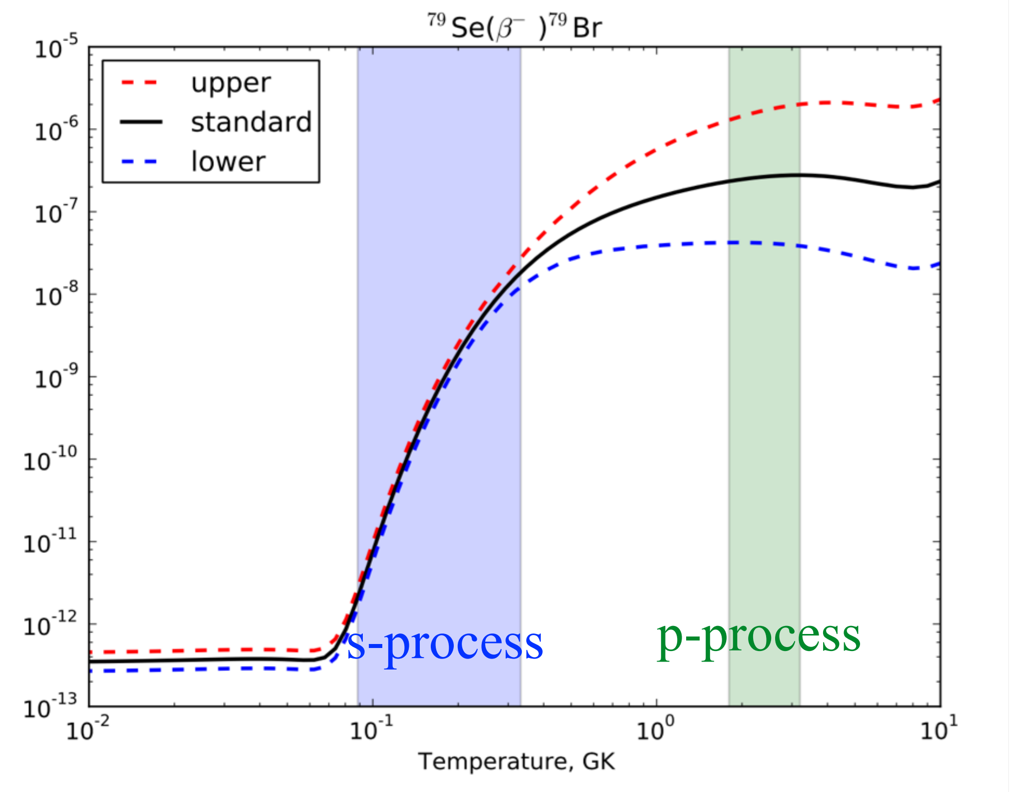
- beta-decay: only the ground state 1.3 (30%)
- beta-decay: T-dependent
  (Takahashi & Yokoi 1987, Goriely 1999)

$$U(T) = \frac{u_{\rm g.s.}}{g_0(T)} + u_{\rm e.s.}\left(1 - \frac{1}{g_0(T)}\right)$$

Beta-decay: ^{79}Se → ^{79}Br

- ground state: $u_{\rm g.s.} = 1.3$ (30 %)
- excited states: $u_{\rm e.s.} = 10$

g_0: partition function of the ground state



S Process in Massive Stars

Kaeppeler, et al, 2011, RvMP, 83, 157, ...

Weak s process: (slow neutron capture process) during core He- and shell C-burning

He: T > 0.25 GK

(~ 21.6keV)

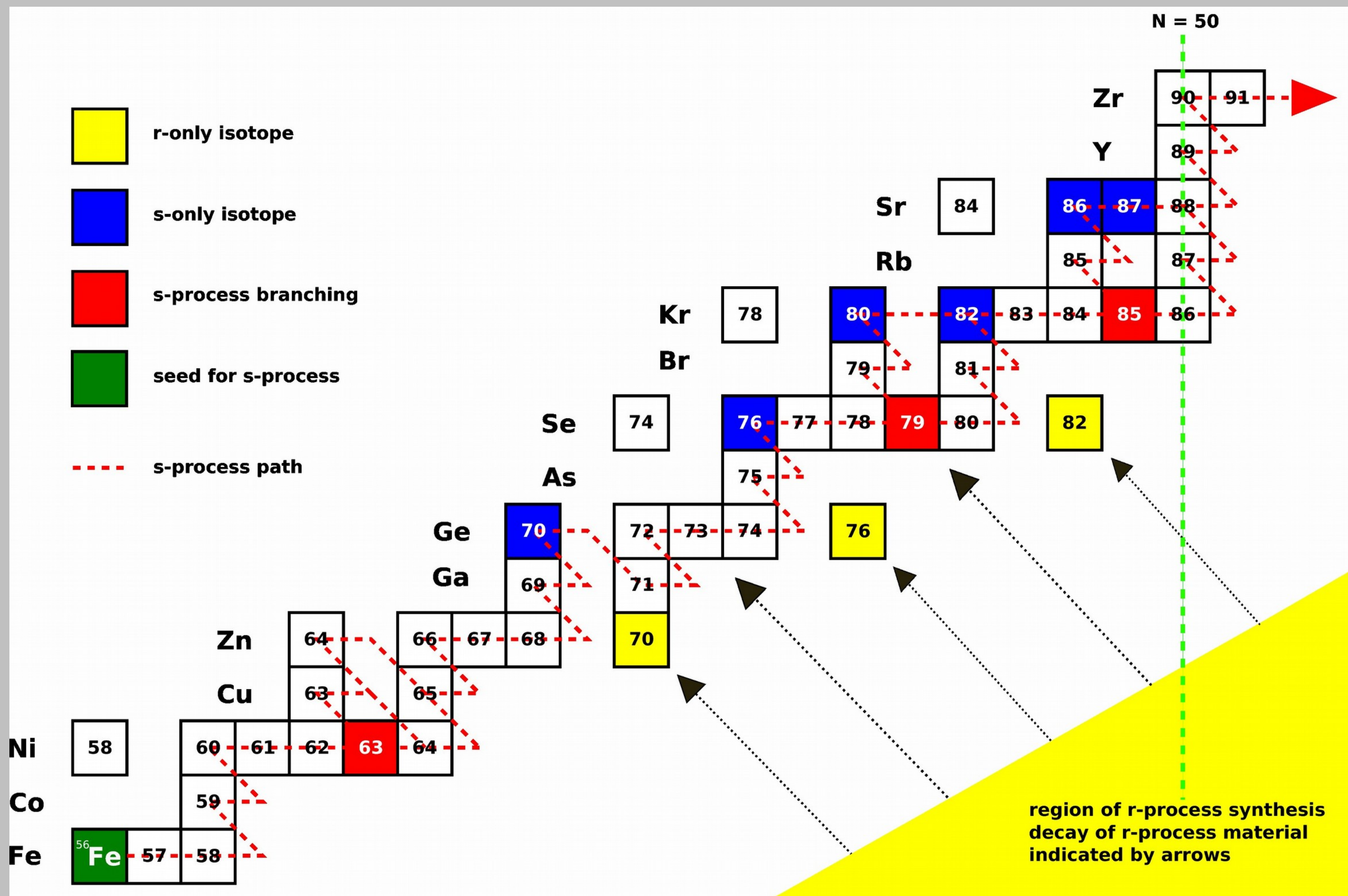
C: T ~ 1GK

N-source: $^{22}Ne(a,n)$

Seed: iron

Poisons:

- He-b.: ^{22}Ne, ^{25}Mg, ^{16}O, ^{12}C
- C-b.: ^{24}Mg, ^{25}Mg, ^{16}O, ^{20}Ne



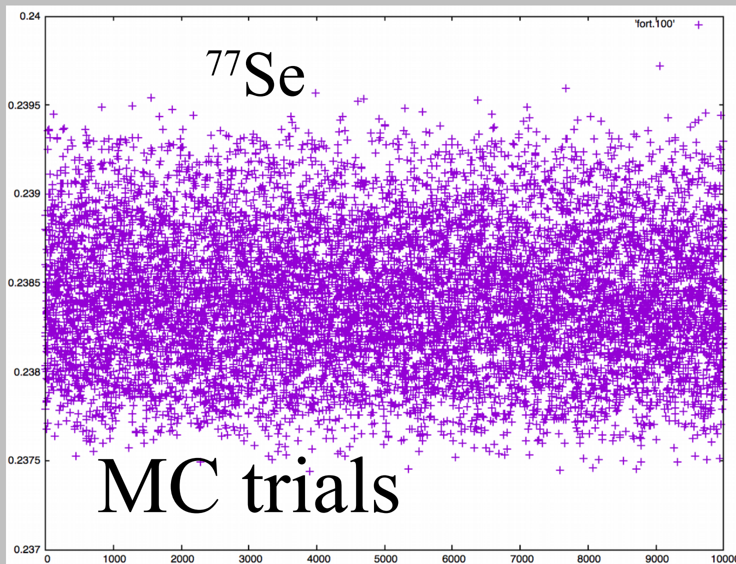
At solar Z: rotating models may produce up to 3x more s process

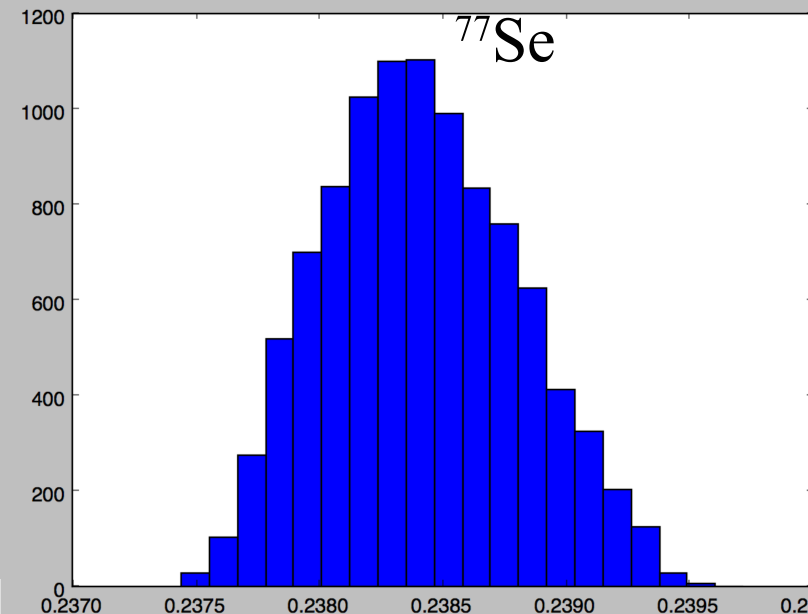
(See also Chieffi, Limongi, 2012ApJS..199...38L)

How much s process do massive rotating stars produce at low Z?

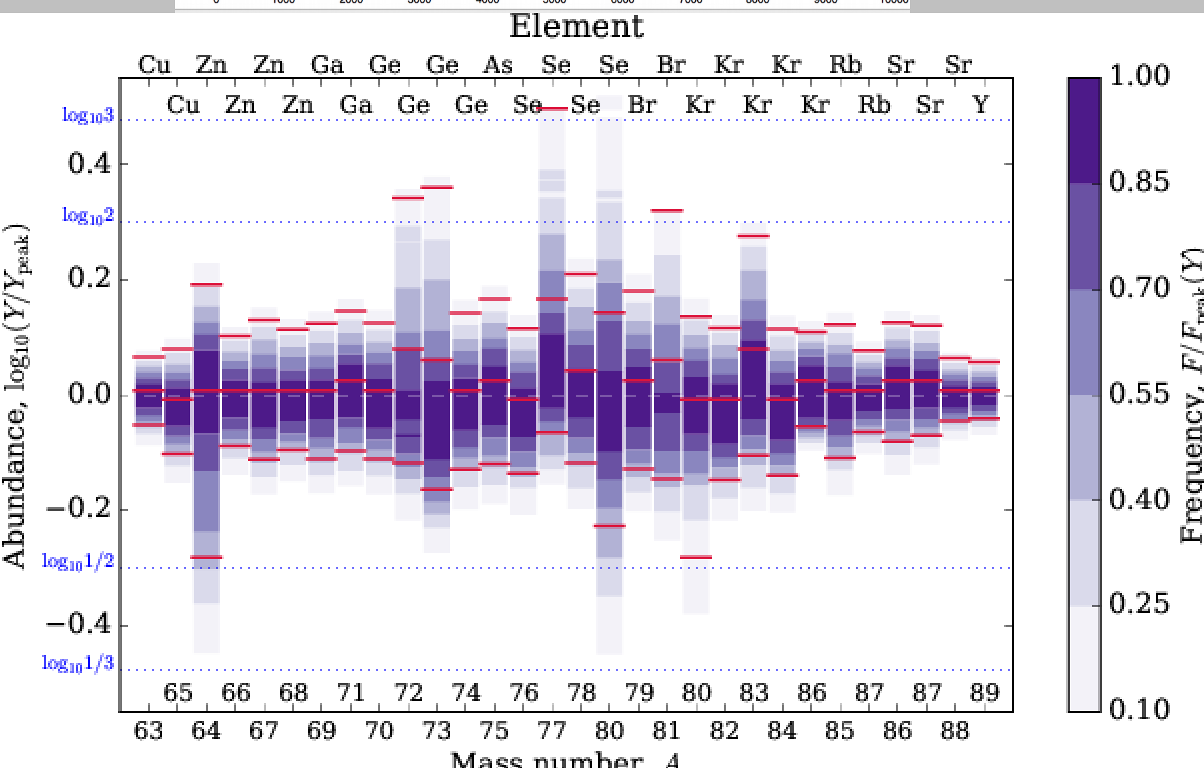
Results for Weak s Process

N. Nishimura+ 2017: http://adsabs.harvard.edu/abs/2017MNRAS.469.1752N





Abundances



← MC: varying both (n,g) & $\beta^{\pm}$

Key Reaction Lists for Weak s Process

N. Nishimura+ 2017: http://adsabs.harvard.edu/abs/2017MNRAS.469.1752N

Nuclide	$r_{\mathrm{cor},0}$	$r_{\mathrm{cor},1}$	$r_{\mathrm{cor},2}$	Key Rate Level 1	Key Rate Level 2	Key Rate Level 3	X_0 (8, 30 keV)	Weak Rate (8, 30 keV)
^{64}Zn	0.76			^{64}Cu(β^-)^{64}Zn				1.30, 1.36
	-0.46	-0.73			^{64}Cu(e$^-$, ν_e)^{64}Ni			e$^-$ capture
^{67}Zn	-0.67			^{67}Zn(n, γ)^{68}Zn			1.00, 1.00	
^{72}Ge	-0.85			^{72}Ge(n, γ)^{73}Ge			1.00, 1.00	
^{73}Ge	-0.84			^{73}Ge(n, γ)^{74}Ge			0.88, 0.81	
^{74}Ge	-0.44	-0.54	-0.67			^{74}Ge(n, γ)^{75}Ge	1.00, 1.00	
^{75}As	-0.50	-0.59	-0.70			^{75}As(n, γ)^{76}As	1.00, 1.00	
^{77}Se	-0.86			^{77}Se(n, γ)^{78}Se			1.00, 1.00	
^{78}Se	-0.71			^{78}Se(n, γ)^{79}Se			1.00, 1.00	
	0.38	0.68			^{68}Zn(n, γ)^{69}Zn		1.00, 1.00	
^{80}Se	-0.76			^{80}Br(β^-)^{80}Kr				1.31, 4.70
	0.27	0.73			^{80}Br(β^+)^{80}Se			1.31, 4.70
	0.16	0.44	0.88			^{80}Br(e$^-$, ν_e)^{80}Se		e$^-$ capture
^{79}Br	-0.64	-0.73			^{79}Br(n, γ)^{80}Br		1.00, 1.00	
^{81}Br	-0.80			^{81}Kr(n, γ)^{82}Kr			1.00, 0.98	
^{83}Kr	-0.76			^{83}Kr(n, γ)^{84}Kr			0.81, 0.74	
^{84}Kr	-0.49	-0.65	-0.76			^{84}Kr(n, γ)^{85}Kr	1.00, 1.00	
^{86}Kr	0.84			^{85}Kr(n, γ)^{86}Kr			1.00, 1.00	
	-0.30	-0.70			^{86}Kr(n, γ)^{87}Kr		1.00, 1.00	
	-0.34	-0.62	-0.90			^{85}Kr(β^-)^{85}Rb		1.30, 1.30
^{87}Rb	-0.56	-0.65	-0.95			^{87}Rb(n, γ)^{88}Rb	1.00, 1.00	

Key Reaction Levels 1-3:

N. Nishimura+ 2017

- Level 1 key rates dominate the uncertainty for a given isotope

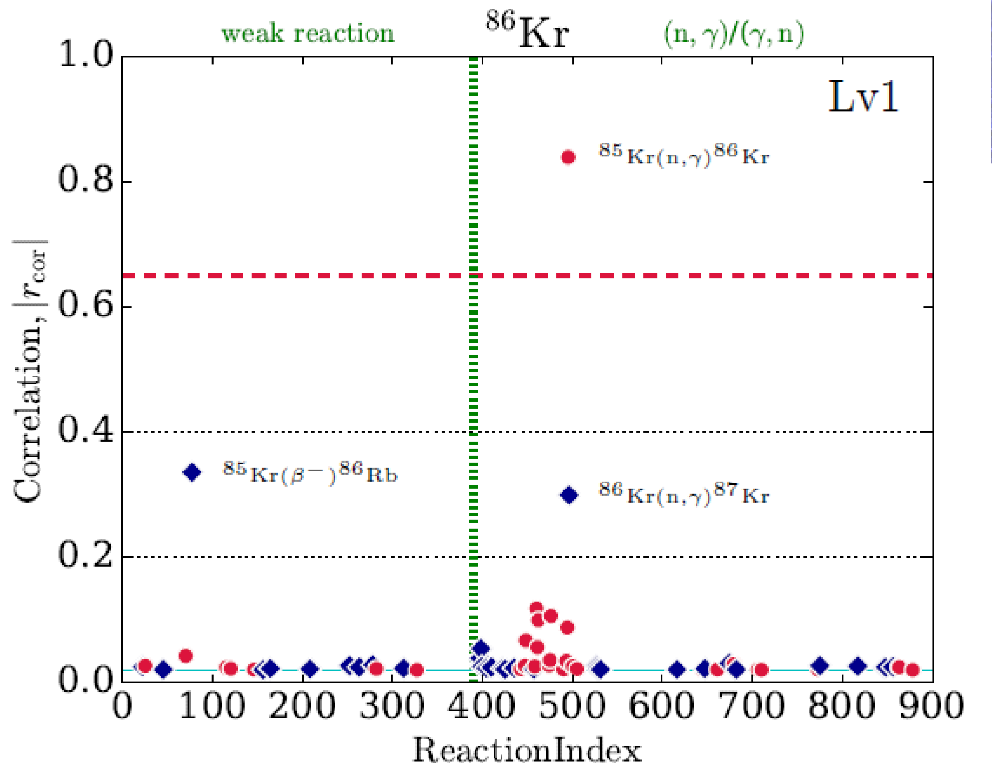
- Once level 1 rates are fixed, *then* Level 2 rates become dominant

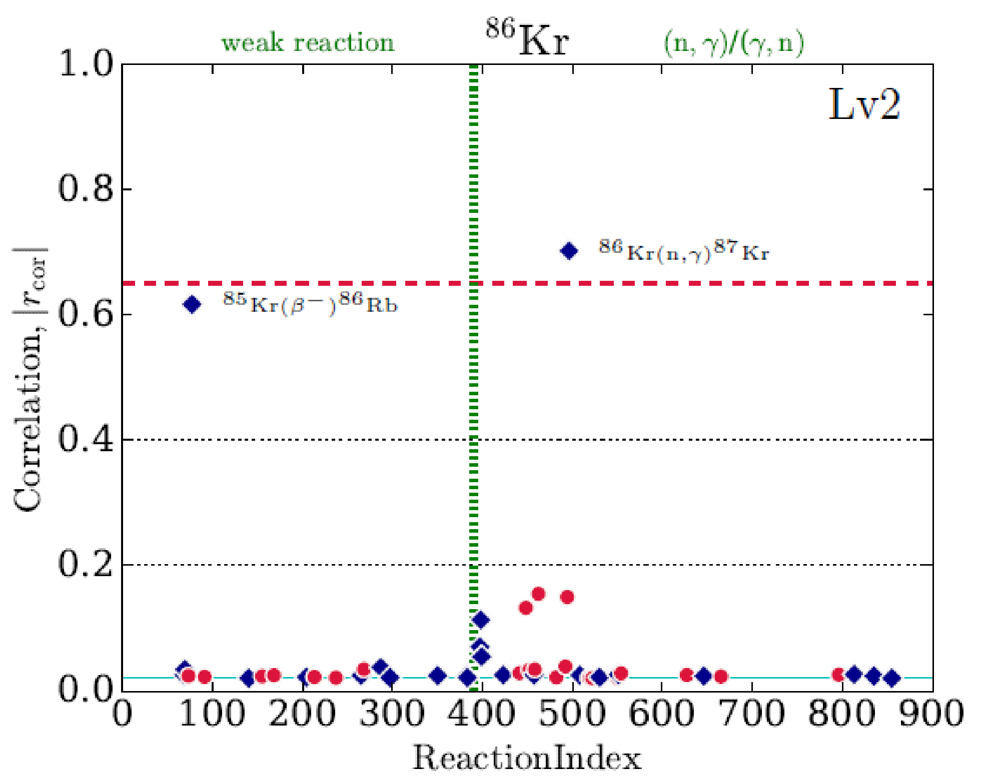
...

We adopt the Pearson product-moment correlation coefficient Pearson (1895) to quantify the correlation between rate variation and the final abundances (also used in Rauscher et al. 2016), defined by

$$r_{\rm cor} = \frac{\sum_i^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i^n (x_i - \bar{x})^2}\sqrt{\sum_i^n (y_i - \bar{y})^2} \quad (4)$$

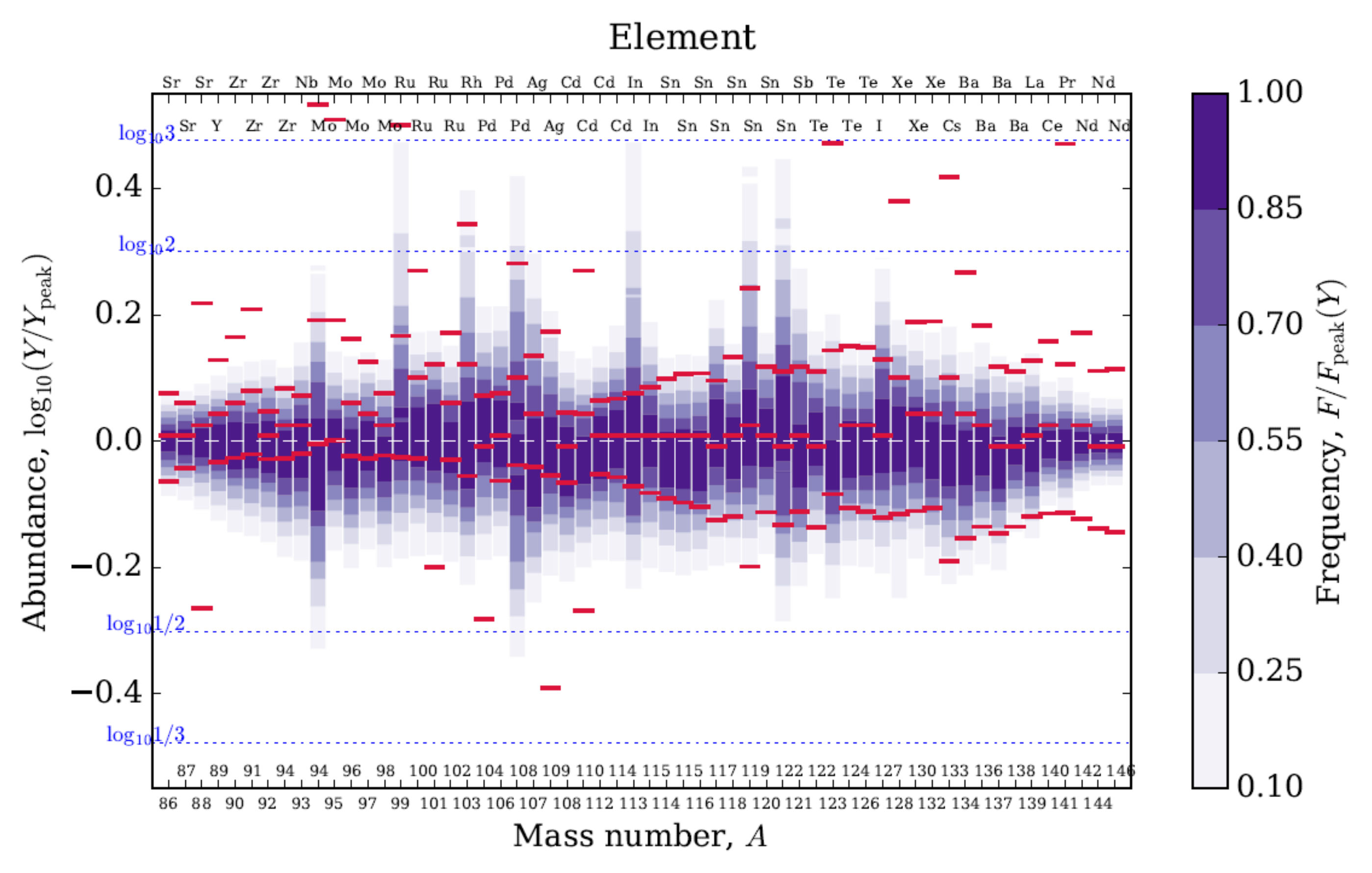
where x_i and y_i are variables with $\bar{x}$ and $\bar{y}$ being their arithmetic mean value, respectively. The summation is applied to all data for the MC runs $i = 1, 2, 3, \cdots, n$. Here, x and y in Equation 4 correspond to variation factors f and final abundances Y.





Key Reaction Lists

Priority lists established for:
- Enhanced (weak) s proc. in low-Z fast rotating stars: N. Nishimura+ 2017 MNRAS



- i process: Denissenkov+

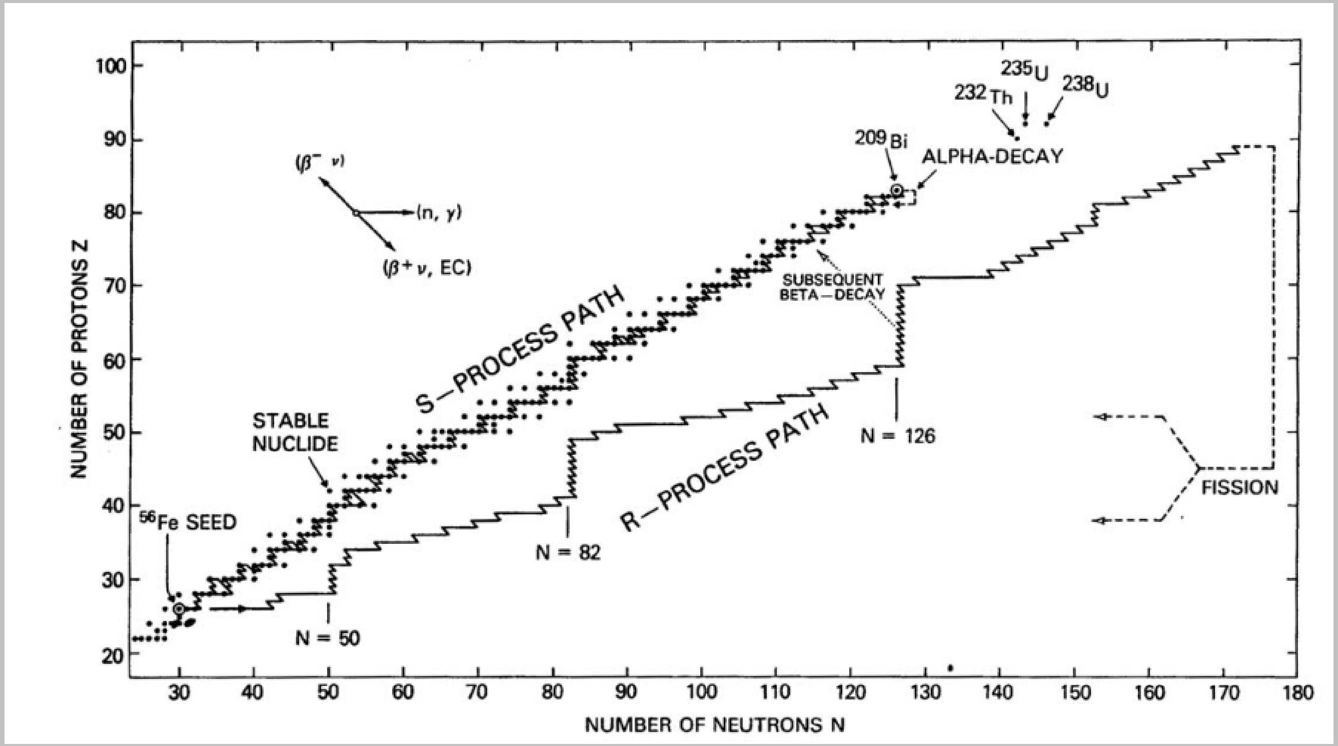
2018JPhG...45e5203D

- Gamma (aka p) process in CCSNe: T. Rauscher+ 2016 http://adsabs.harvard.edu/abs/2016MNRAS.463.4153R

- Gamma (aka p) process in Sne Ia: Nishimura+ 2018, MNRAS

- Main s process (C13-pocket & TP) Cescutti + 2018, MNRAS

Paths of neutron capture processes

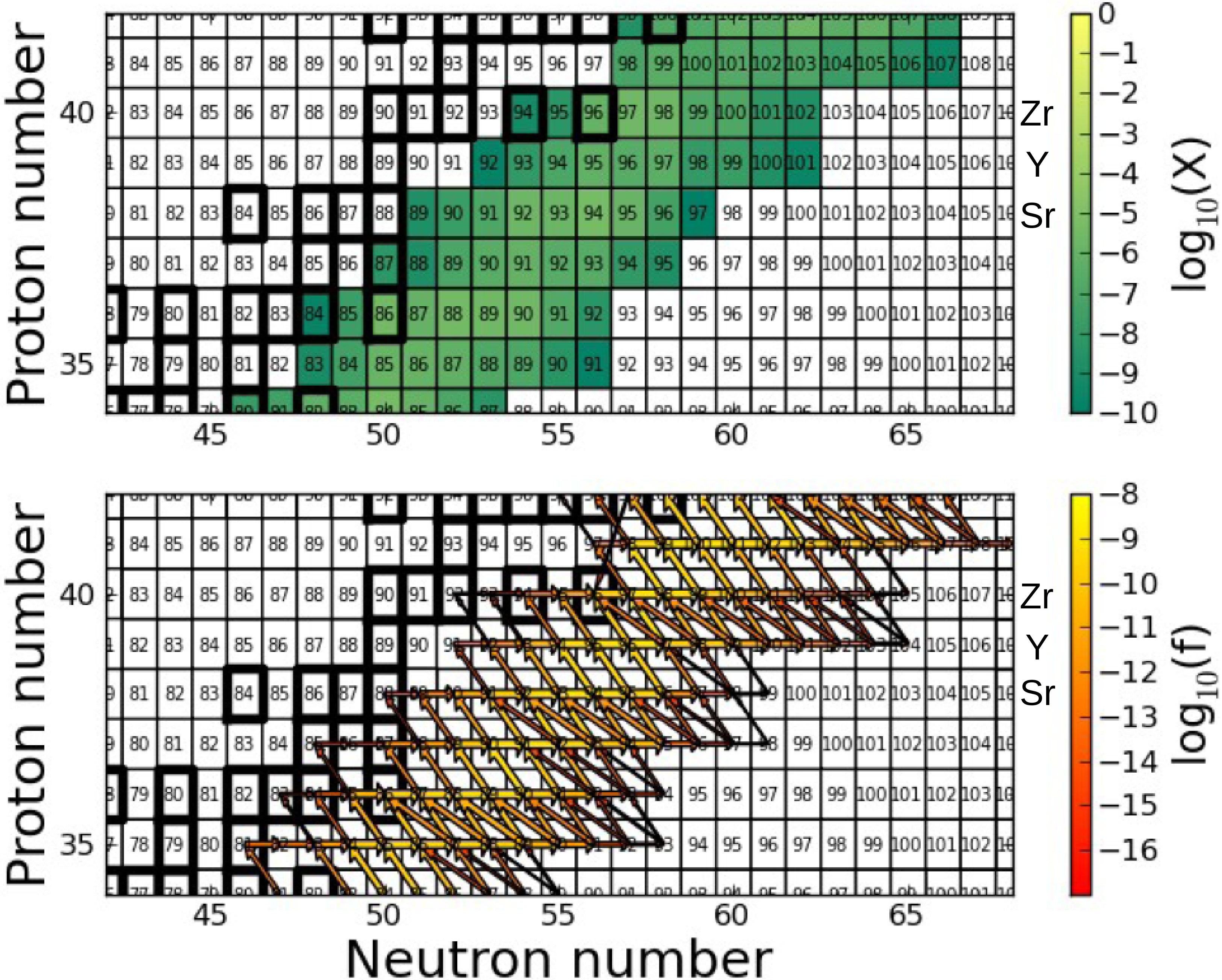


Cauldrons in the cosmos, 1988

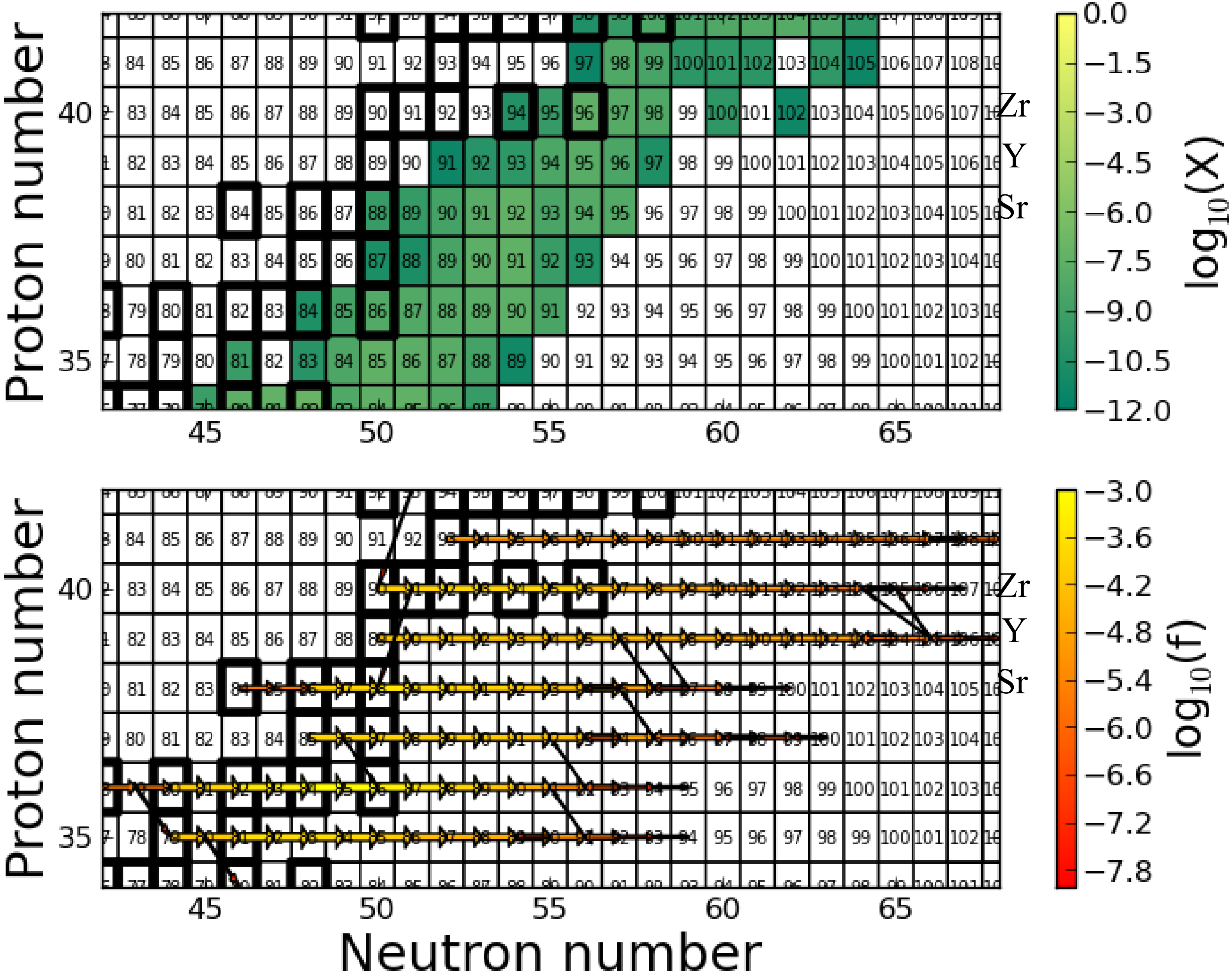
List of neutron capture processes (with products observed/measured)

- The r process (neutrino-wind, NS mergers, jet-SNe, etc) - $N_n > 10^{20}$ n cm^{-3};
- The n process (explosive He-burning in CCSN) - 10^{18} n cm$^{-3} < N_n < 10^{20}$ n cm^{-3};
- The i process - 10^{13} n cm$^{-3} < N_n < 10^{16}$ n cm^{-3};
- The s process (s process in AGB stars, s process in massive stars and fast rotators) – $N_n < 10^{13}$ n cm^{-3}.

Nucleosynthesis path of the i process: Se-Nb



Nucleosynthesis path of the n process: Se-Nb



1977

THE ASTROPHYSICAL JOURNAL, **212**:149–158, 1977 February 15

PRODUCTION OF ^{14}C AND NEUTRONS IN RED GIANTS

JOHN J. COWAN AND WILLIAM K. ROSE
Astronomy Program, University of Maryland, College Park
Received 1976 June 28

stellar/hydro

ABSTRACT

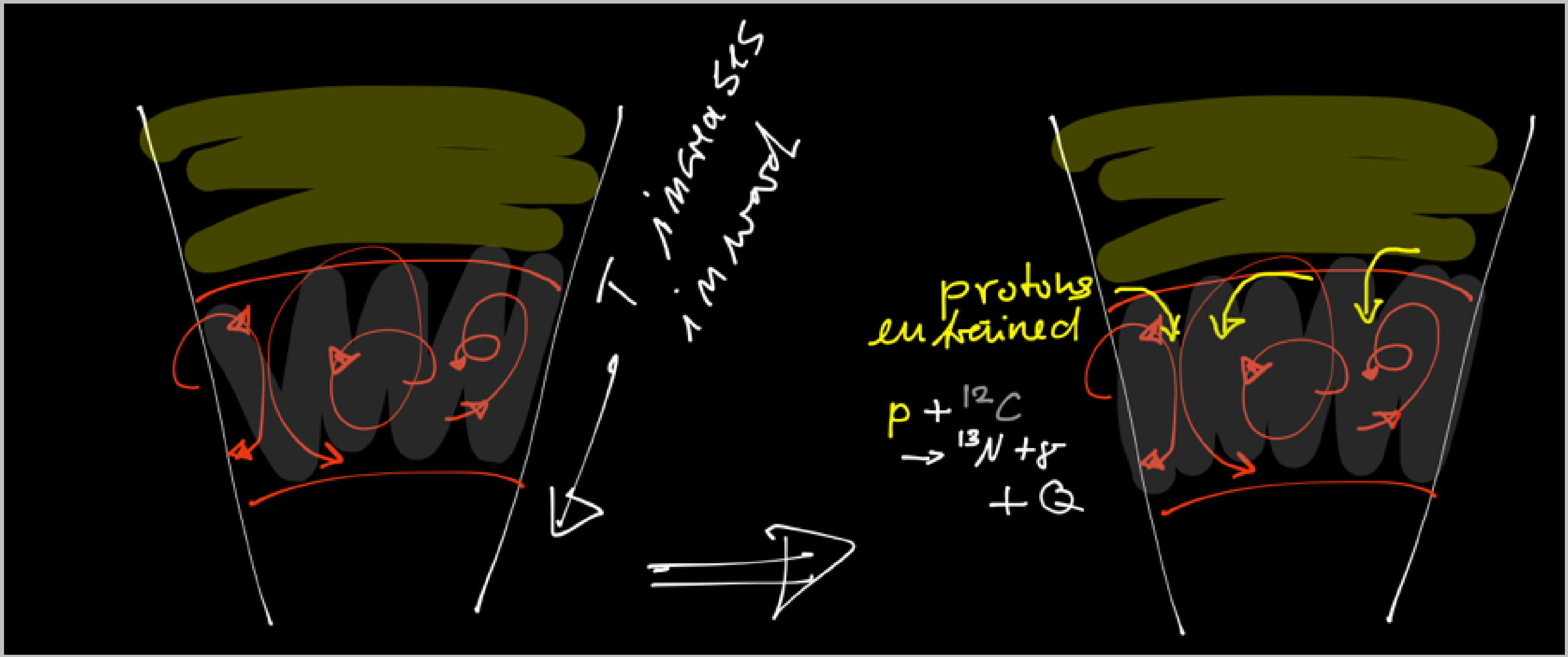
We have examined the effects of mixing various amounts of hydrogen-rich material into the intershell convective region of red giants undergoing helium shell flashes. We find that significant amounts of ^{14}C can be produced via the ^{14}N$(n, p)^{14}$C reaction. If substantial portions of this intershell region are mixed out into the envelopes of red giants, then ^{14}C may be detectable in evolved stars.

We find a neutron number density in the intershell region of $\sim 10^{15}$–10^{17} cm^{-3} and a flux of $\sim 10^{23}$–10^{25} cm^{-2} s^{-1}. This neutron flux is many orders of magnitude above the flux required for the classical *s*-process, and thus an intermediate neutron process (*i*-process) may operate in evolved red giants. The neutrons are principally produced by the ^{13}C$(\alpha, n)^{16}$O reaction.

In all cases studied we find substantial enhancements of ^{17}O. These mixing models offer a plausible explanation of the observations of enhanced ^{17}O in the carbon star IRC 10216. For certain physical conditions we find significant enhancements of ^{15}N in the intershell region.

nuclear/stellar

"Simulation" from F. Herwig



N13 and/or C13 are mixed <u>for hours</u> in regions with typical He-burning temperatures (T9 ~ 0.25-0.3 GK), <u>together with Fe-seed rich material.</u>

Main source of neutrons: C13(α,n)O16

Possible sites: low-Z LMS & MS; RAWD

Challenge: requires multi-D hydro simulations

i process in RAWD

Denissenkov + 2018: ArXiV 1809.03666

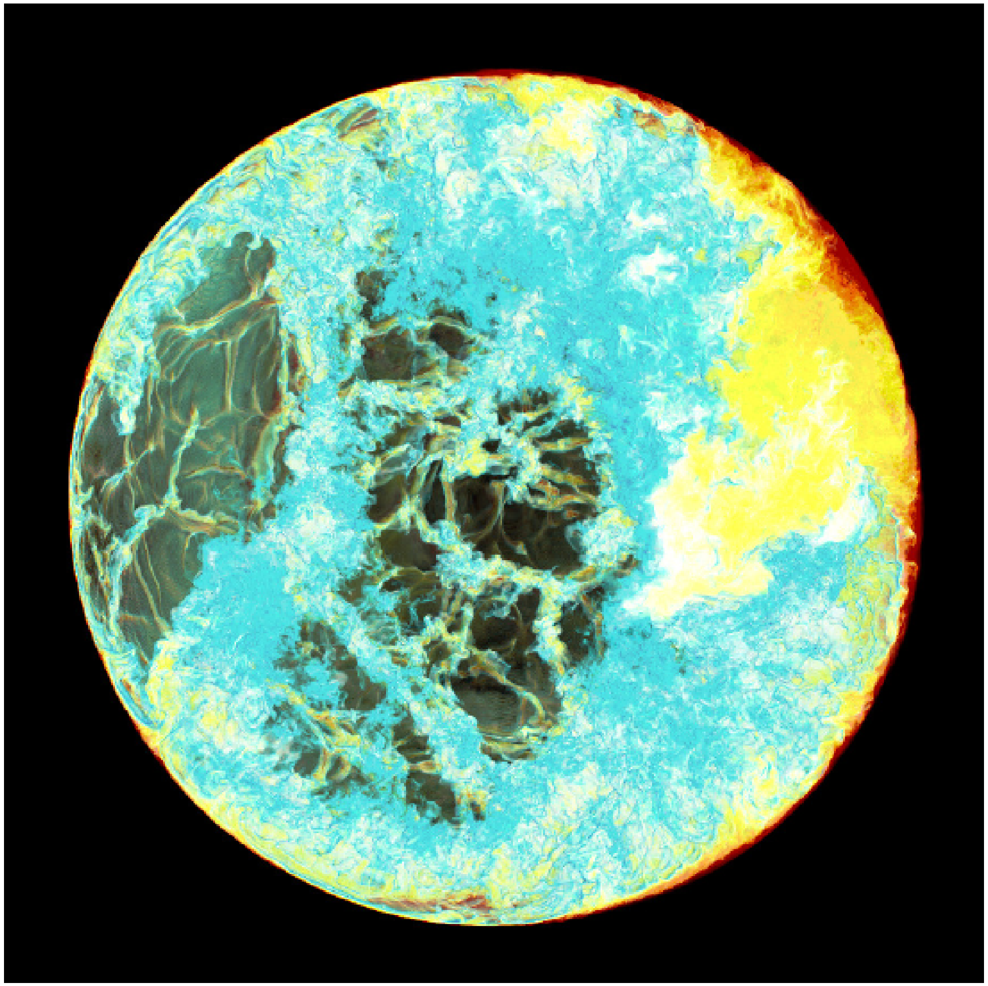


Figure 3. Fractional volume of the fluid ingested into the convection zone in run E10 at $t = 359.8$ min. The colour scale is logarithmic and very low concentrations are transparent. The front half of the sphere is not shown and the camera is looking into the back half of the sphere in this rendering.

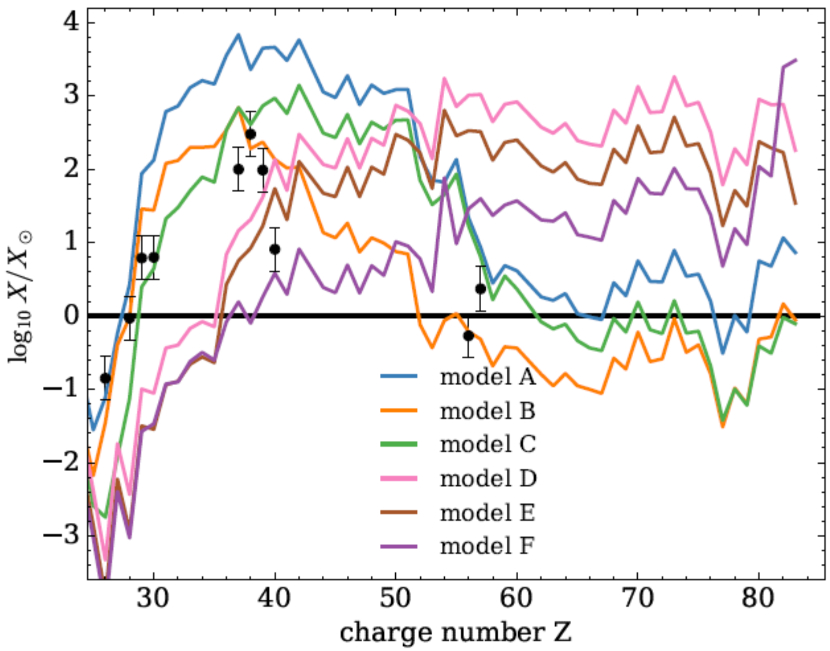


Figure 11. The elemental i-process yields (solar-scaled mass fractions) from our RAWD models. For comparison, the abundances of the first peak n-capture elements measured in Sakurai's object by Asplund et al. (1999) are shown as filled black circles with errorbars. They were interpreted by Herwig et al. (2011) as results of the i-process nucleosynthesis in the convective He shell during its very late thermal pulse in a model of Sakurai's object with a half-solar metallicity.

Stellar Explosions in Binary Systems –
Type Ia Supernovae, Classical Novae and X-Ray Bursts

Jordi José

Dept. Physics, Technical Univ. of Catalonia (UPC)
& Space Research Institut of Catalonia (IEEC)
Barcelona

Type Ia Supernovae (problems, challenges & mysteries)

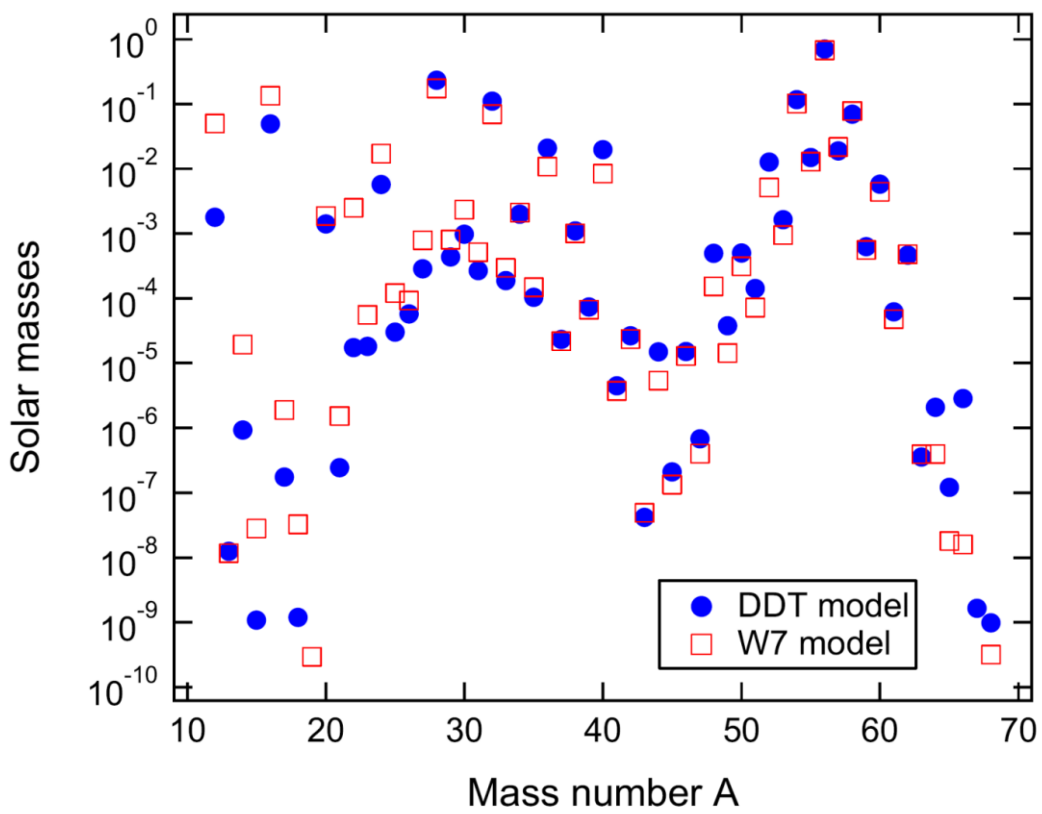
* **homogeneity:** only ~70% of all **SN Ia** have similar spectra, light curves and peak absolute magnitudes (Li et al. 2011): diversity of SNIa progenitors?

* **Scenario:** not understood ! single degenerate (WD + MS companion) vs double degenerate (WD + WD)

* **Propagation of the burning front:** subsonic vs supersonic (what causes the predicted deflagration/detonation transition?)

*** Nucleosynthesis:** five burning regimes: "normal" and "α-rich" freeze-out from nuclear statistical equilibrium (NSE) in the inner regions, and incomplete Si-, O-, and C/Ne-burning in the outermost layers (Thielemann et al. 1986; Woosley 1986)

systematic overproduction of some Fe-peak isotopes (50Ti, 54Cr)



Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

443 isotopes (H – Kr); 5267 links

W7 DDT W7+DDT

*Nuclear Uncertainties

Reaction	Importance		
	Case A	Case B	Case C
$^{12}C(\alpha,\gamma)^{16}O$	X	X	X
$^{12}C(^{12}C,\alpha)^{20}Ne$	X	X	X
$^{12}C(^{12}C,p)^{23}Na$	X	X	X
$^{16}O(n,\gamma)^{17}O$	X		
$^{16}O(\alpha,\gamma)^{20}Ne$	X		
$^{20}Ne(n,\gamma)^{21}Ne$			X
$^{20}Ne(\alpha,p)^{23}Na$	X	X	X
$^{20}Ne(\alpha,\gamma)^{24}Mg$	X	X	X
$^{22}Ne(p,\gamma)^{23}Na$	X		X
$^{22}Ne(\alpha,n)^{25}Mg$			X
$^{23}Na(n,\gamma)^{24}Na$			X
$^{23}Na(\alpha,p)^{26}Mg$		X	
$^{24}Na(p,n)^{24}Mg$			X
$^{24}Mg(\alpha,\gamma)^{28}Si$			X
$^{25}Mg(n,\gamma)^{26}Mg$		X	X
$^{25}Mg(p,\gamma)^{26}Al$			X
$^{26}Mg(p,n)^{26}Al$			X
$^{27}Al(p,\gamma)^{28}Si$			X
$^{27}Al(\alpha,p)^{30}Si$	X		X
$^{28}Si(\alpha,p)^{31}P$			X
$^{30}Si(p,\gamma)^{31}P$	X		
$^{30}Si(\alpha,\gamma)^{34}S$	X		X
$^{30}Si(\alpha,n)^{33}S$			X
$^{32}P(p,n)^{32}S$			X
$^{34}S(\alpha,p)^{37}Cl$			X
$^{36}S(p,n)^{36}Cl$			X
$^{42}Ca(\alpha,\gamma)^{46}Ti$			X
$^{45}Sc(p,\gamma)^{46}Ti$		X	
$^{45}Sc(p,n)^{45}Ti$			X

Parikh, JJ, Seitenzahl & Röpke, A&A (2013)

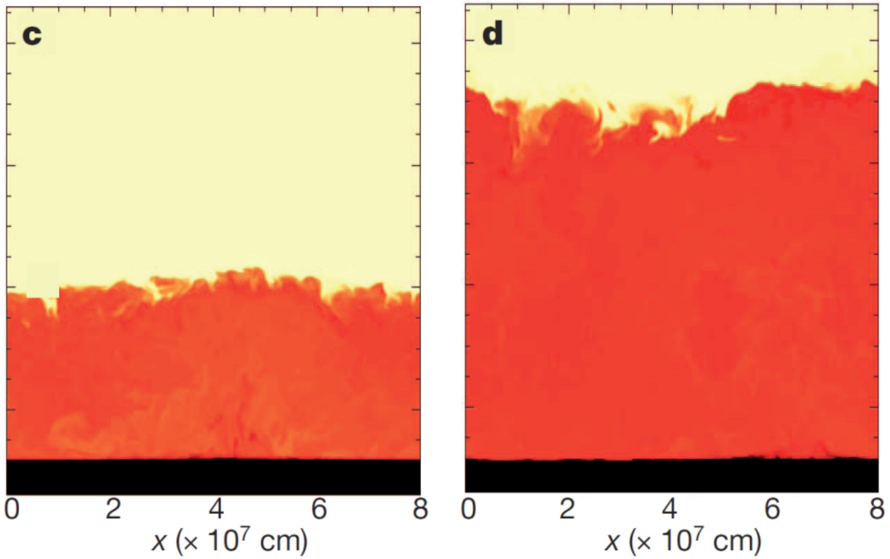
Table 2. Summary of important reactions from Table 1. Variation of each of the listed rates by a factor of 10 (up or down) modified yields of at least *three* species by at least a factor of two in the W7 model ("Case A") or the DDT model ("Case B"). If variation of the rate affected the yield of at least one species in *both* models, it is designated as "Case C".

Classical Novae (problems, challenges & mysteries)

* **Mixing** mechanism at work at the core-envelope interface during nova outbursts (3D turbulent convection?)

* The amount of **mass ejected** predicted by 1-D models is smaller than values *inferred* observationally

* Interaction between the nova ejecta, the disk and the stellar companion poorly studied: **origin of γ-ray emission at E > 100 MeV?**



Casanova, JJ, García-Berro, Shore & Calder (2011)

* Nuclear Uncertainties

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 142:105–137, 2002 September

THE EFFECTS OF THERMONUCLEAR REACTION-RATE VARIATIONS ON NOVA NUCLEOSYNTHESIS: A SENSITIVITY STUDY

CHRISTIAN ILIADIS AND ART CHAMPAGNE
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255; and Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308; iliadis@unc.edu, aec@tunl.duke.edu

JORDI JOSÉ
Departament de Física i Enginyeria Nuclear (UPC), Avinguda Víctor Balaguer, s/n, E-08800 Vilanova i la Geltrú, Barcelona, Spain; and Institut d'Estudis Espacials de Catalunya, Edifici Nexus-201, Calle Gran Capitá 2-4, E-08034 Barcelona, Spain; jjose@ieec.fcr.es

SUMNER STARRFIELD
Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504; sumner.starrfield@asu.edu

AND

PAUL TUPPER
Scientific Computing–Computational Mathematics Program, Stanford University, Stanford, CA 94305; tupper@sccm.stanford.edu
Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

Main nuclear uncertainties: [^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si, ^{30}P(p,γ)^{31}S]

Type I X-Ray Bursts (problems, challenges & mysteries)

* **Nucleosynthesis endpoint**?

* Do they **contribute to the Galactic abundances** (i.e., do they lead to mass ejection?)

* **Multidimensional effects** scarcely investigated

* Nuclear Uncertainties

The Astrophysical Journal Supplement Series, 178:110–136, 2008 September

THE EFFECTS OF VARIATIONS IN NUCLEAR PROCESSES ON TYPE I X-RAY BURST NUCLEOSYNTHESIS

Anuj Parikh[1]
Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain; xrayburst@gmail.com

Jordi José
Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, E-08036 Barcelona; and Institut d'Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain; jordi.jose@upc.edu

Fermín Moreno
Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain; moreno@ieec.fcr.es

and

Christian Iliadis
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255; and Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308; iliadis@unc.edu

~ **50,000** post-processing calculations

606 isotopes (**^{1}H** to **^{113}Xe**) and **3551** nuclear processes

* Nuclear Uncertainties

TABLE 19

Summary of the Most Influential Nuclear Processes, as Collected from Tables 1–10

Reaction	Models Affected
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$[a]	F08, K04-B2, K04-B4, K04-B5
$^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$[a]	K04-B1[b]
$^{25}\mathrm{Si}(\alpha,p)^{28}\mathrm{P}$	K04-B5
$^{26g}\mathrm{Al}(\alpha,p)^{29}\mathrm{Si}$	F08
$^{29}\mathrm{S}(\alpha,p)^{32}\mathrm{Cl}$	K04-B5
$^{30}\mathrm{P}(\alpha,p)^{33}\mathrm{S}$	K04-B4
$^{30}\mathrm{S}(\alpha,p)^{33}\mathrm{Cl}$	K04-B4,[b] K04-B5[b]
$^{31}\mathrm{Cl}(p,\gamma)^{32}\mathrm{Ar}$	K04-B1
$^{32}\mathrm{S}(\alpha,\gamma)^{36}\mathrm{Ar}$	K04-B2
$^{56}\mathrm{Ni}(\alpha,p)^{59}\mathrm{Cu}$	S01,[b] K04-B5
$^{57}\mathrm{Cu}(p,\gamma)^{58}\mathrm{Zn}$	F08
$^{59}\mathrm{Cu}(p,\gamma)^{60}\mathrm{Zn}$	S01,[b] K04-B5
$^{61}\mathrm{Ga}(p,\gamma)^{62}\mathrm{Ge}$	F08, K04-B1, K04-B2, K04-B5, K04-B6
$^{65}\mathrm{As}(p,\gamma)^{66}\mathrm{Se}$	K04,[b] K04-B1, K04-B2,[b] K04-B3,[b] K04-B4, K04-B5, K04-B6
$^{69}\mathrm{Br}(p,\gamma)^{70}\mathrm{Kr}$	K04-B7
$^{75}\mathrm{Rb}(p,\gamma)^{76}\mathrm{Sr}$	K04-B2
$^{82}\mathrm{Zr}(p,\gamma)^{83}\mathrm{Nb}$	K04-B6
$^{84}\mathrm{Zr}(p,\gamma)^{85}\mathrm{Nb}$	K04-B2
$^{84}\mathrm{Nb}(p,\gamma)^{85}\mathrm{Mo}$	K04-B6
$^{85}\mathrm{Mo}(p,\gamma)^{86}\mathrm{Tc}$	F08
$^{86}\mathrm{Mo}(p,\gamma)^{87}\mathrm{Tc}$	F08, K04-B6
$^{87}\mathrm{Mo}(p,\gamma)^{88}\mathrm{Tc}$	K04-B6
$^{92}\mathrm{Ru}(p,\gamma)^{93}\mathrm{Rh}$	K04-B2, K04-B6
$^{93}\mathrm{Rh}(p,\gamma)^{94}\mathrm{Pd}$	K04-B2
$^{96}\mathrm{Ag}(p,\gamma)^{97}\mathrm{Cd}$	K04, K04-B2, K04-B3, K04-B7
$^{102}\mathrm{In}(p,\gamma)^{103}\mathrm{Sn}$	K04, K04-B3
$^{103}\mathrm{In}(p,\gamma)^{104}\mathrm{Sn}$	K04-B3, K04-B7
$^{103}\mathrm{Sn}(\alpha,p)^{106}\mathrm{Sb}$	S01[b]

IN NUCL
NUCLEO
H[1]
a de Catalun
É
ecnica de Cat
rcelona, Spa
RENO
ica de Catalu
IADIS
hapel Hill, N
-0308; iliadis

TABLE 20

Nuclear Processes Affecting the Total Energy Output by More than 5% and at Least One Isotope

Reaction	Models Affected
$^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$[a]	K04, K04-B1, K04-B6
$^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$[a]	K04-B1, K04-B6
$^{22}\mathrm{Mg}(\alpha,p)^{25}\mathrm{Al}$	F08
$^{23}\mathrm{Al}(p,\gamma)^{24}\mathrm{Si}$	K04-B1
$^{24}\mathrm{Mg}(\alpha,p)^{27}\mathrm{Al}$[a]	K04-B2
$^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$[a]	F08
$^{28}\mathrm{Si}(\alpha,p)^{31}\mathrm{P}$[a]	K04-B4
$^{30}\mathrm{S}(\alpha,p)^{33}\mathrm{Cl}$	K04-B4, K04-B5
$^{31}\mathrm{Cl}(p,\gamma)^{32}\mathrm{Ar}$	K04-B3
$^{32}\mathrm{S}(\alpha,p)^{35}\mathrm{Cl}$	K04-B2
$^{35}\mathrm{Cl}(p,\gamma)^{36}\mathrm{Ar}$[a]	K04-B2
$^{56}\mathrm{Ni}(\alpha,p)^{59}\mathrm{Cu}$	S01
$^{59}\mathrm{Cu}(p,\gamma)^{60}\mathrm{Zn}$	S01
$^{65}\mathrm{As}(p,\gamma)^{66}\mathrm{Se}$	K04, K04-B2, K04-B3
$^{69}\mathrm{Br}(p,\gamma)^{70}\mathrm{Kr}$	S01
$^{71}\mathrm{Br}(p,\gamma)^{72}\mathrm{Kr}$	K04-B7
$^{103}\mathrm{Sn}(\alpha,p)^{106}\mathrm{Sb}$	S01

ations

606 isotopes (^{1}**H** to ^{113}**Xe**) and **3551** nuclear processes

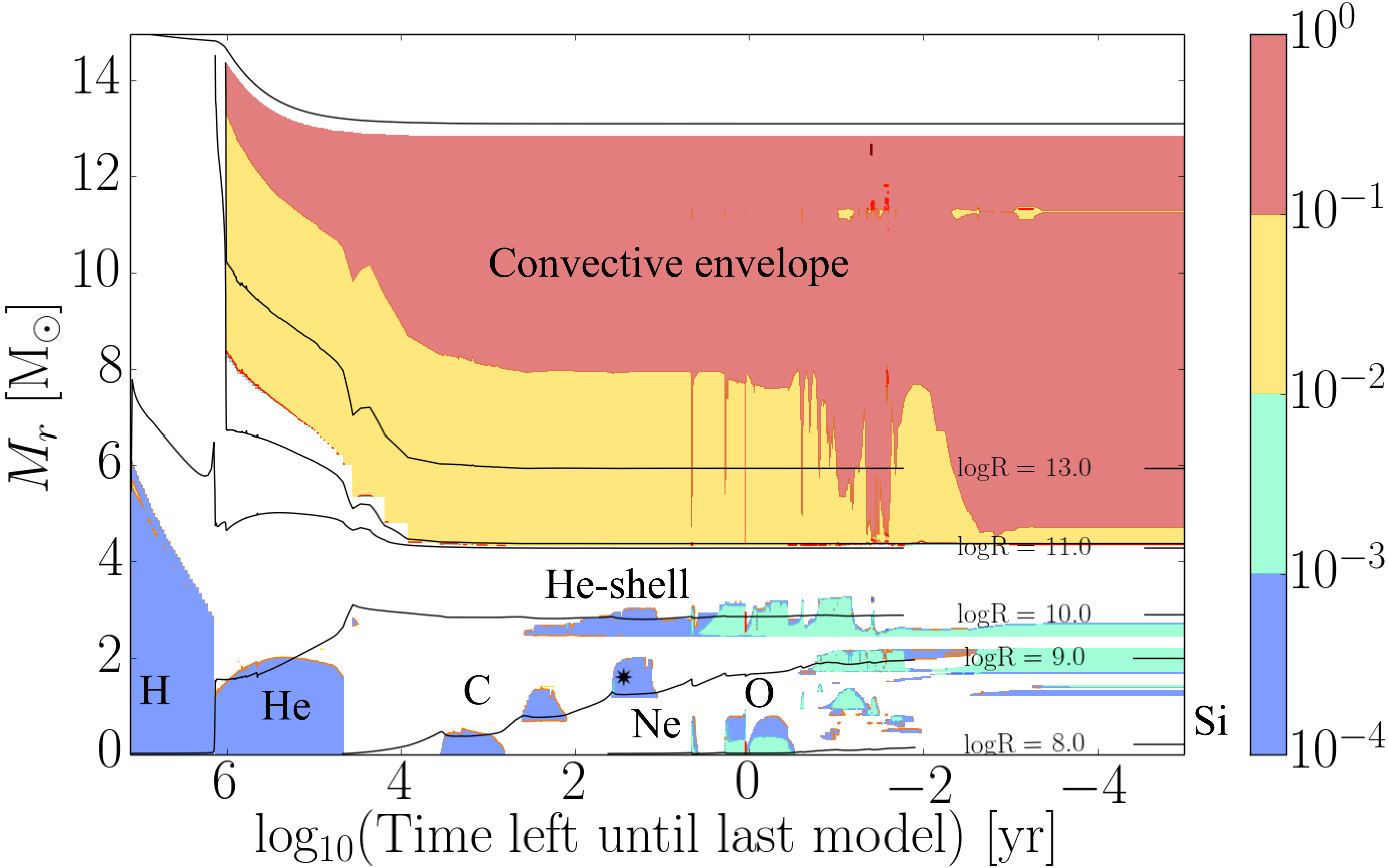
Stellar Models:

Stellar structure equations + physical ingredients:

- Nuclear reactions
- Mass loss
- Rotation
- Convection
- Magnetic fields
- Binary interactions
- Equation of state, opacities & neutrino losses

including metallicity dependence

Evolution of Massive Stars

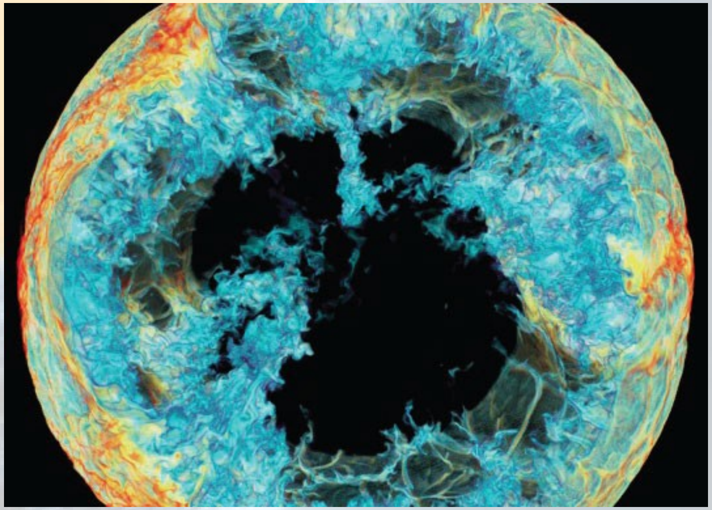


Convection takes place during most burning stages

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



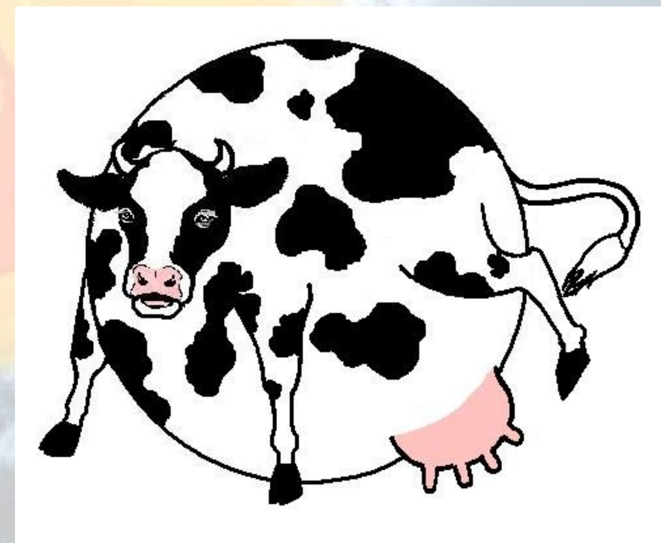
Herwig, Woodward et al 2013

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:

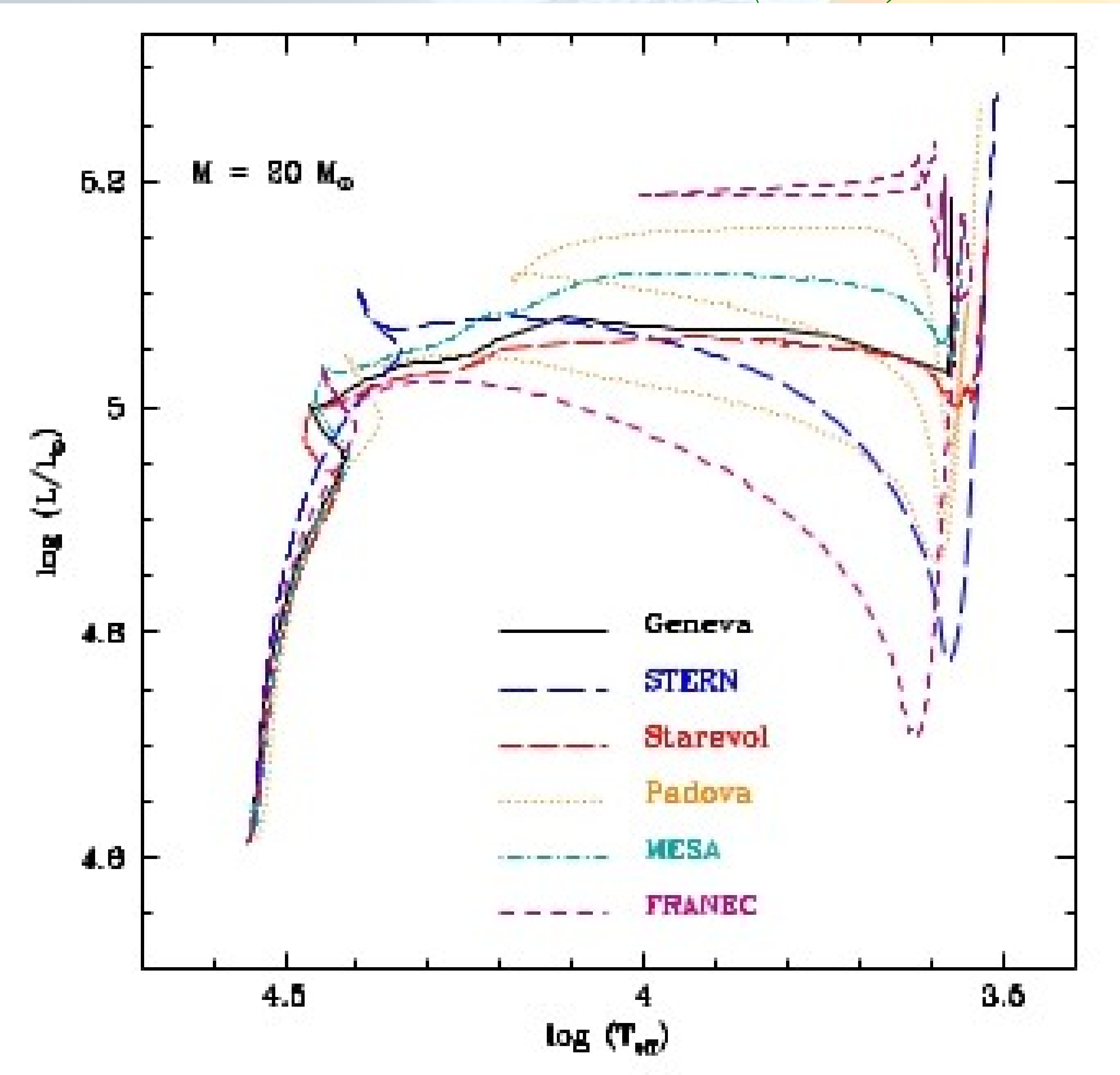
- Energy transport in convective zone: mixing length theory (MLT) *Bohm-Vitense (1957,58)*, or updates, e.g. FST: *Canuto & Mazitelli (1991)*

- 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

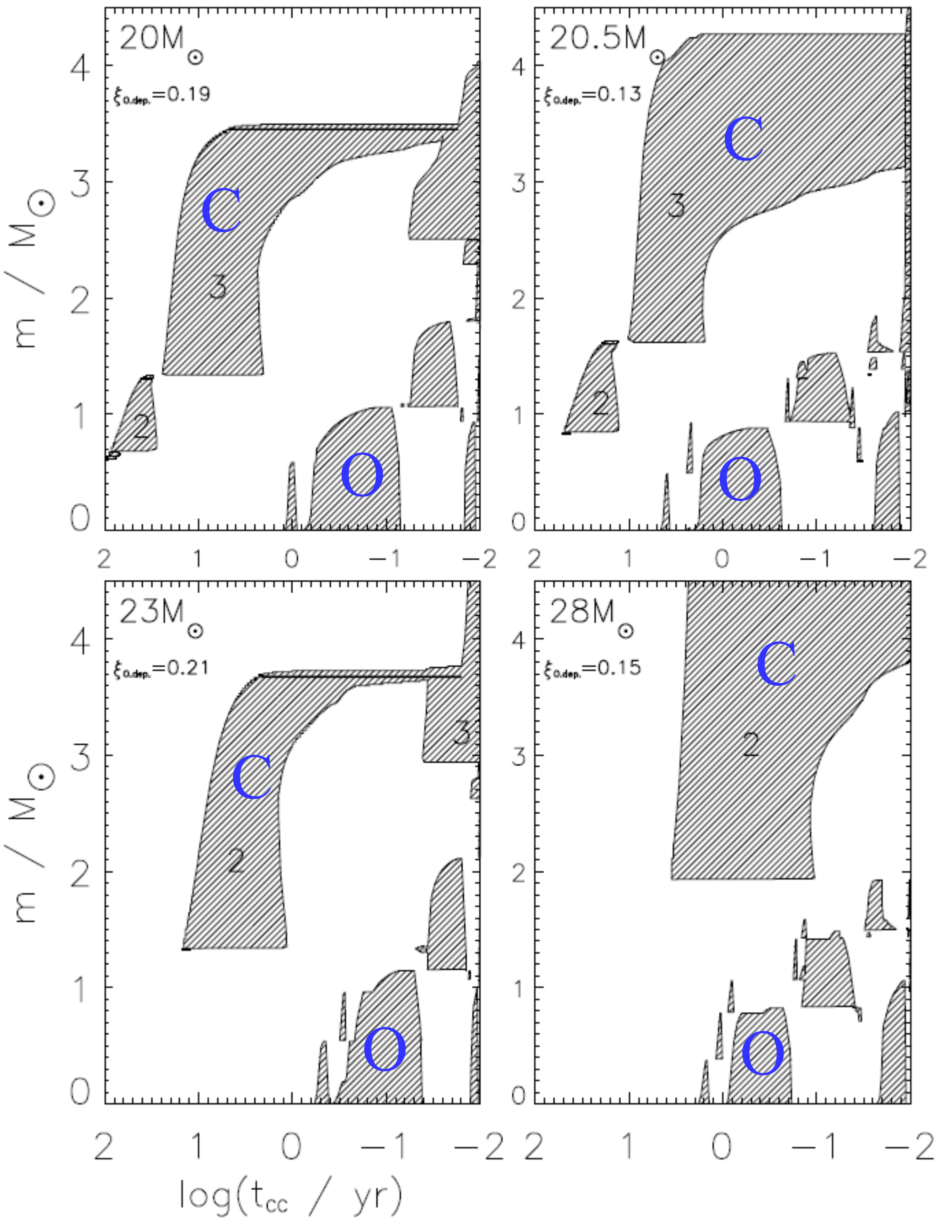


FIG. 13.— Convective history of four models showing the major

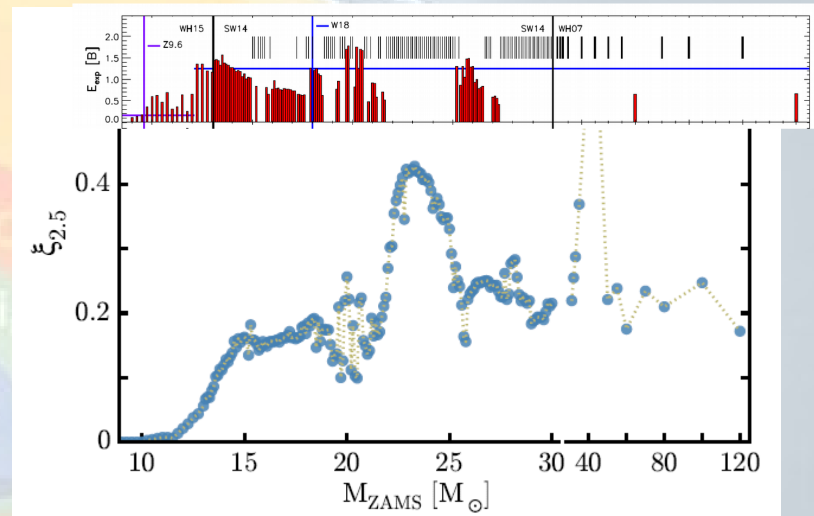


FIG. 1.— The compactness parameter, $\xi_{2.5}$, (eq. (1); O'Connor & Ott 2011) characterizing the inner 2.5 $M_\odot$ of the presupernova star is shown as a function of zero-age main sequence (ZAMS) mass for all 200 models between 9.0 and 120 $M_\odot$. The compactness

Non-monotonic behaviour!

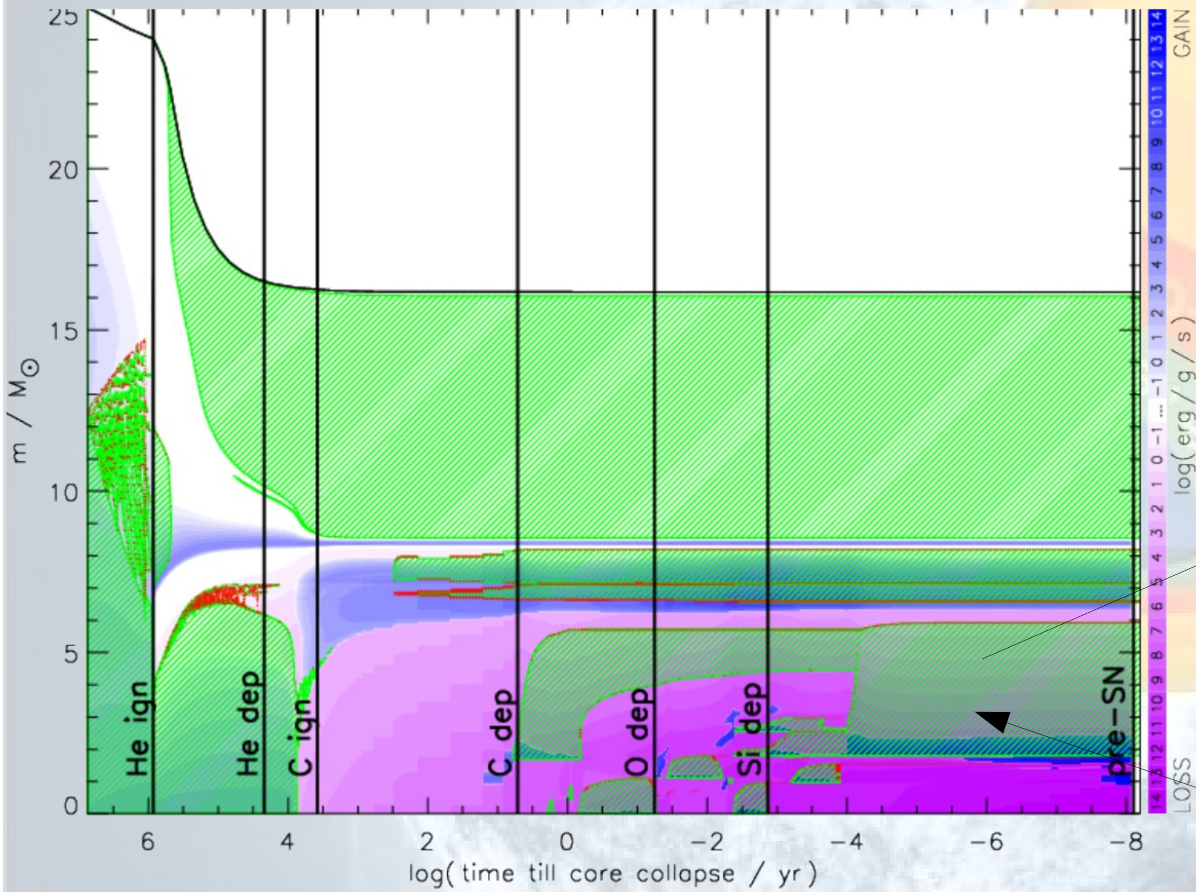
We are particularly interested in how the "explodability" of the presupernova models and their observable properties correlate with their "compactness" (Fig. 1; O'Connor & Ott 2011)

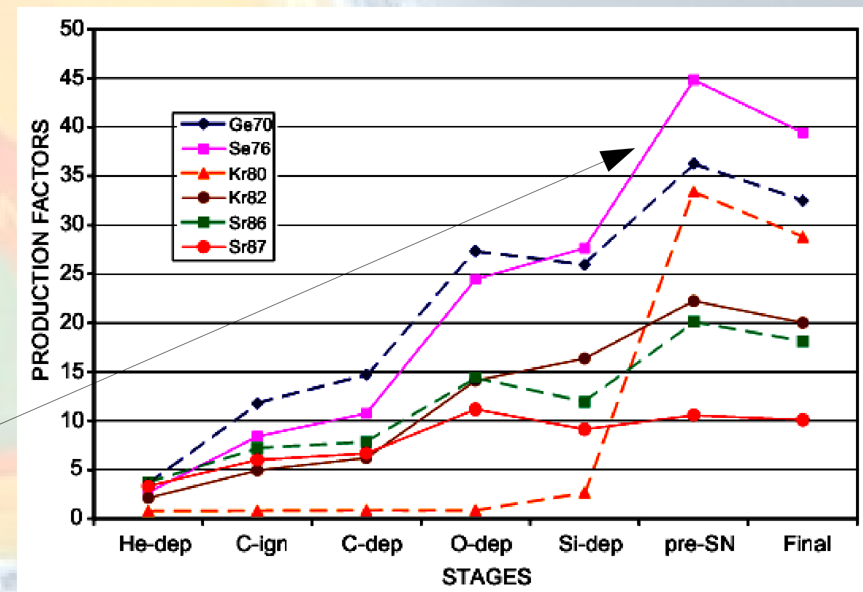
$$\xi_M = \frac{M/\mathrm{M}_\odot}{R(M)/1000\,\mathrm{km}}\bigg|_{t_{\mathrm{bounce}}}, \qquad (1)$$

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

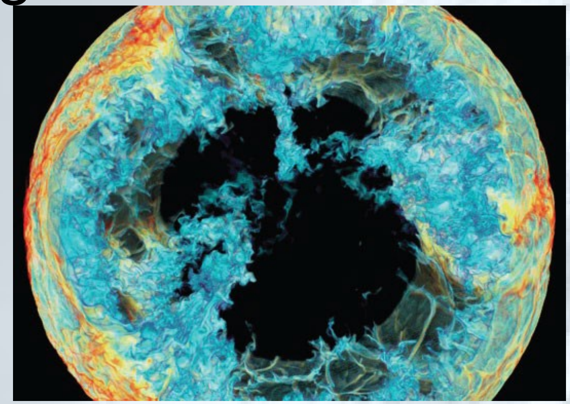
Rauscher, Heger and Woosley 2002: “Interesting and unusual nucleosynthetic results are found for one particular 20M model as a result of its special stellar structure.”

Shell mergers also affect compactness

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

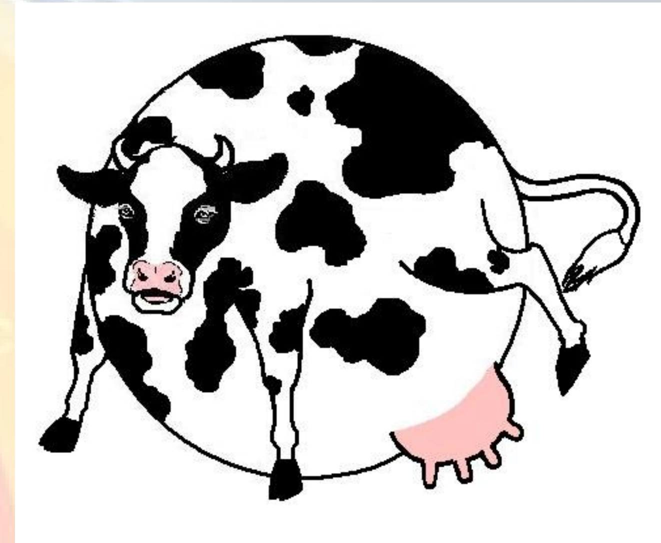
Way Forward: 1 to 3 to 1D link

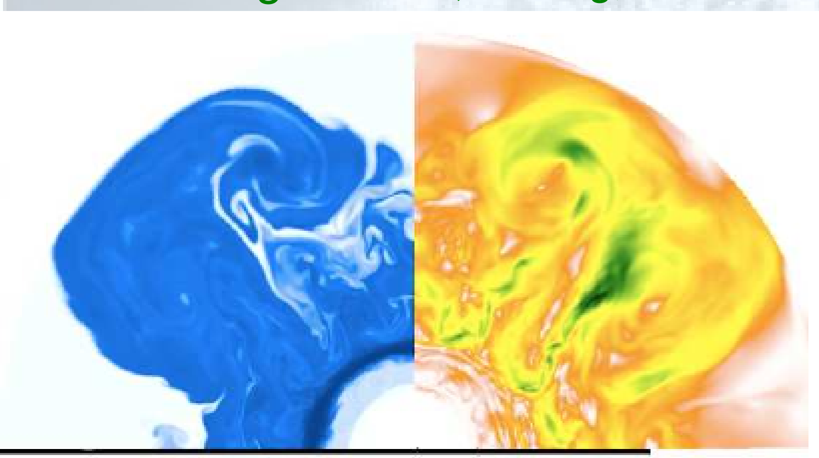
Targetted 3D simulations



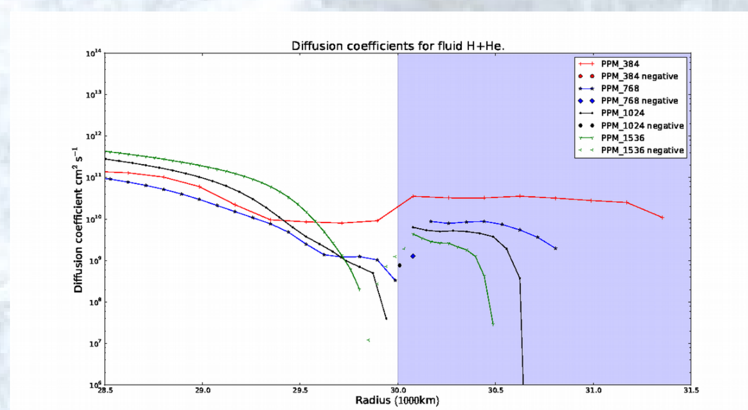
Herwig et al 06, Herwig, Woodward et al 2013

Uncertainties in 1D





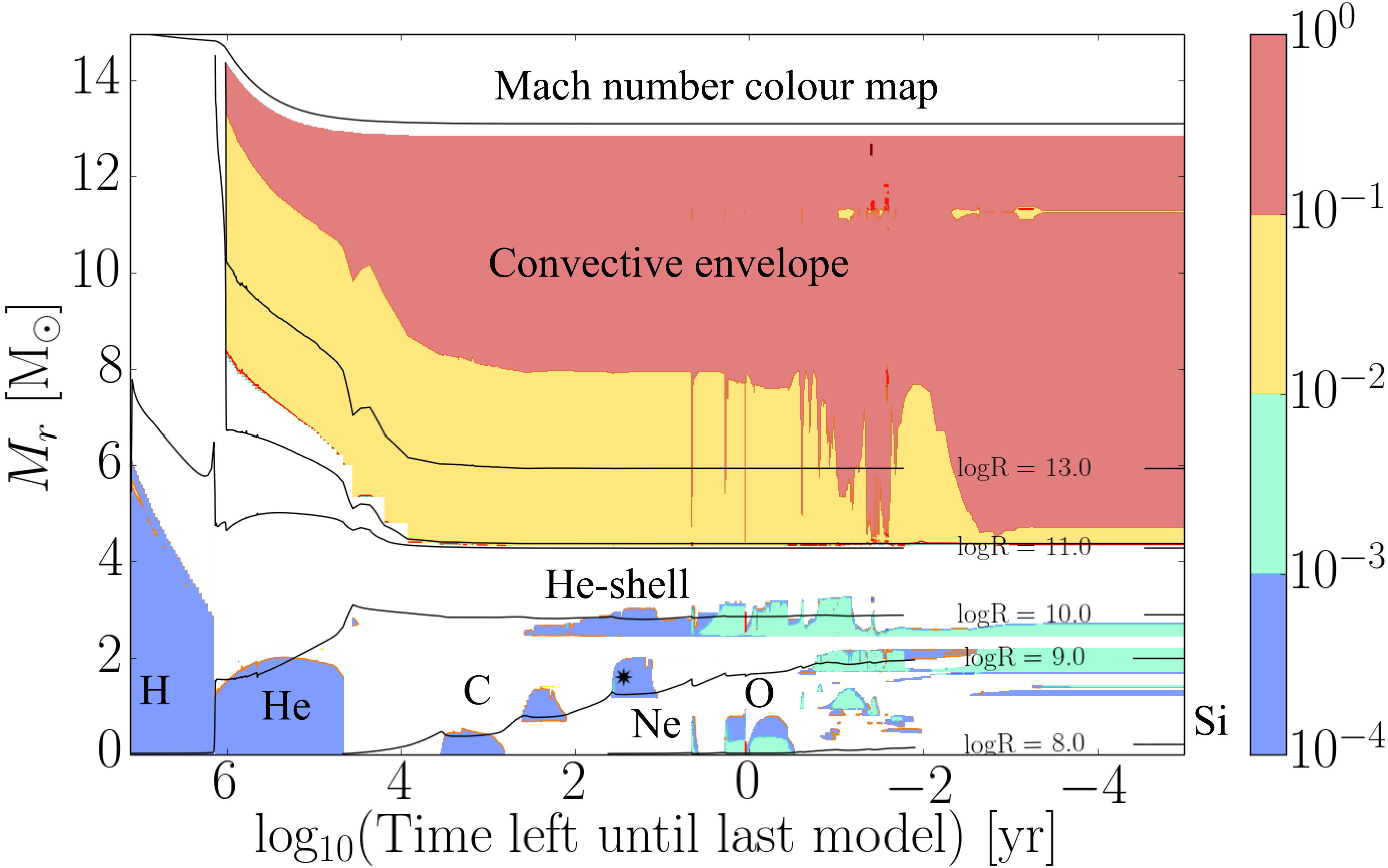
e.g. Arnett & Meakin 2011, ...
Mocak et al 2011,
Viallet et al 2013, ...



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

→ Determine effective coefficient / improve theoretical prescriptions

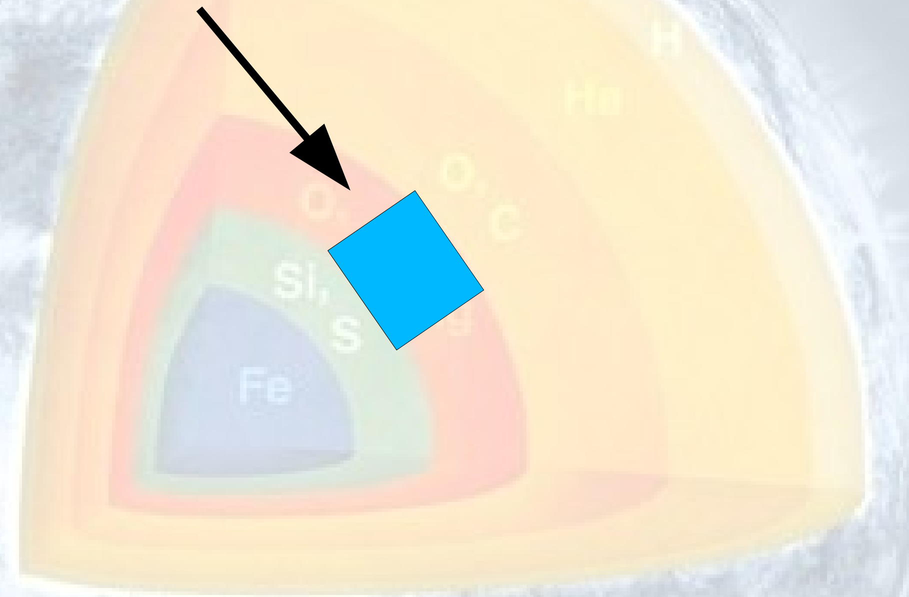
Where to Start?



Convection takes place during most burning stages

Large-Scale Hydrodynamic Simulations

- Millions up to billions of computing hours are needed to simulate fluid flows in a small part of stars

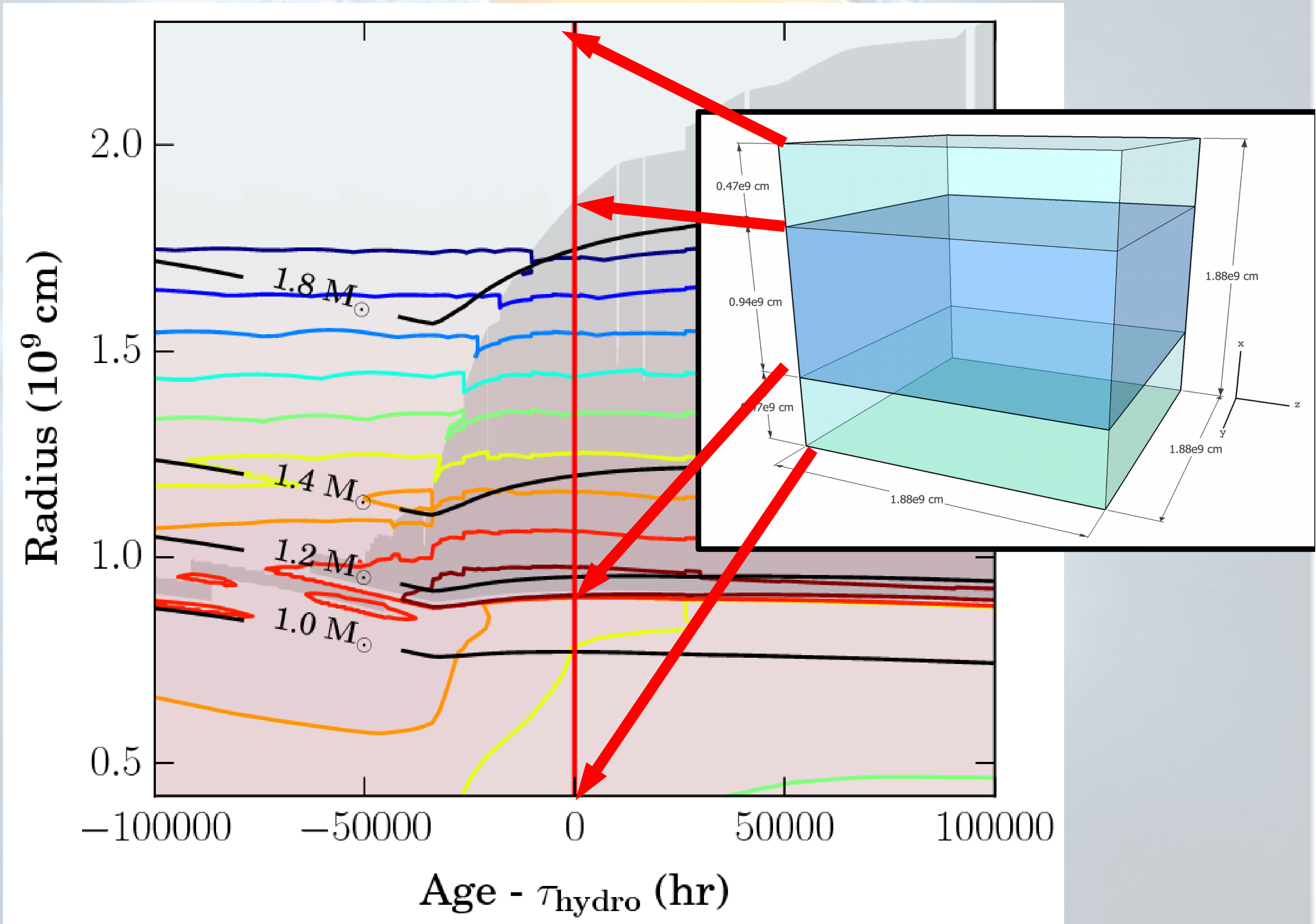


The simulation shown in this talk would have taken 85 years on this laptop!!

It only took a few months on a super-computer in Durham!

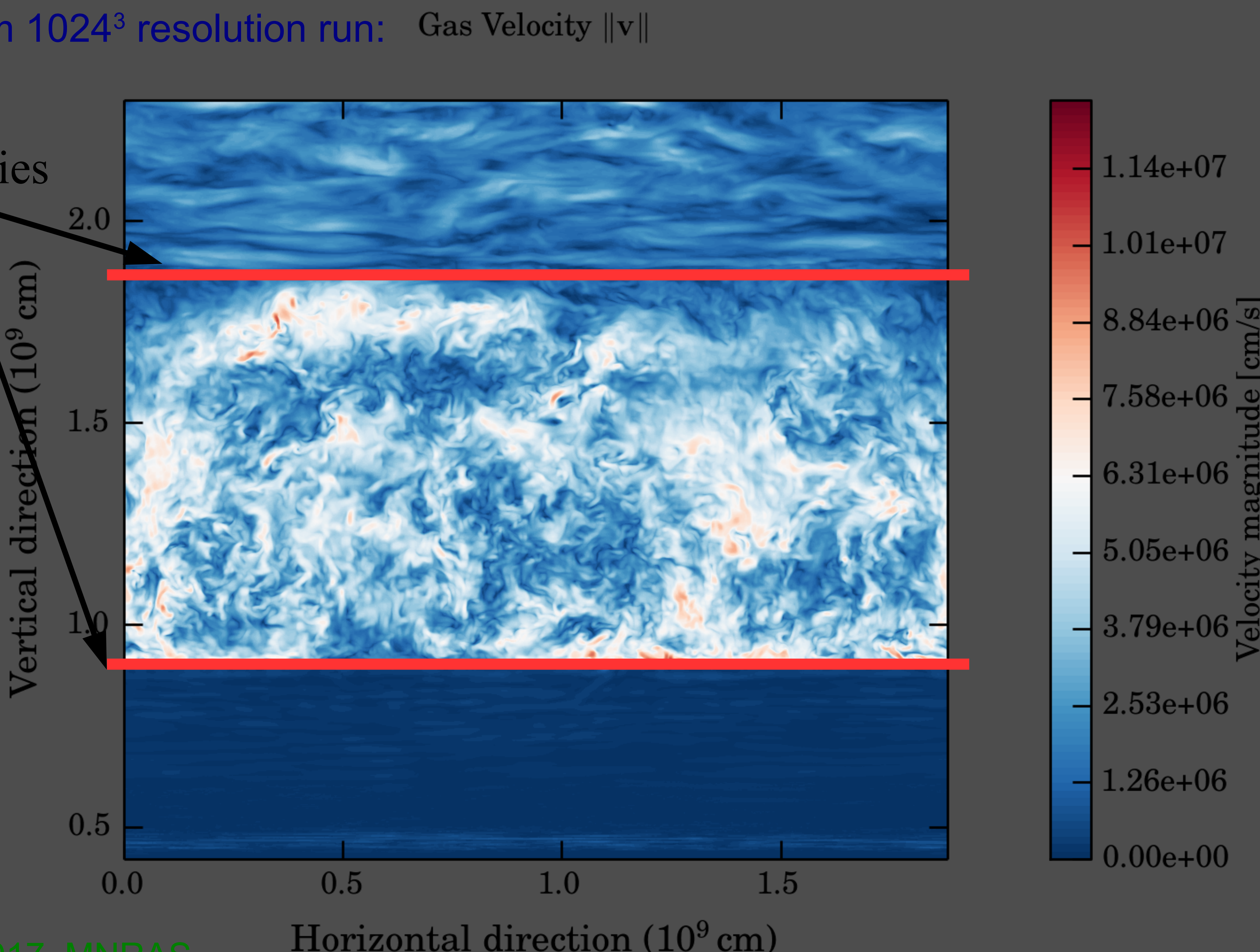
From 1D to 3D

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



3D C-shell Simulations

Snapshot from 1024^3 resolution run:

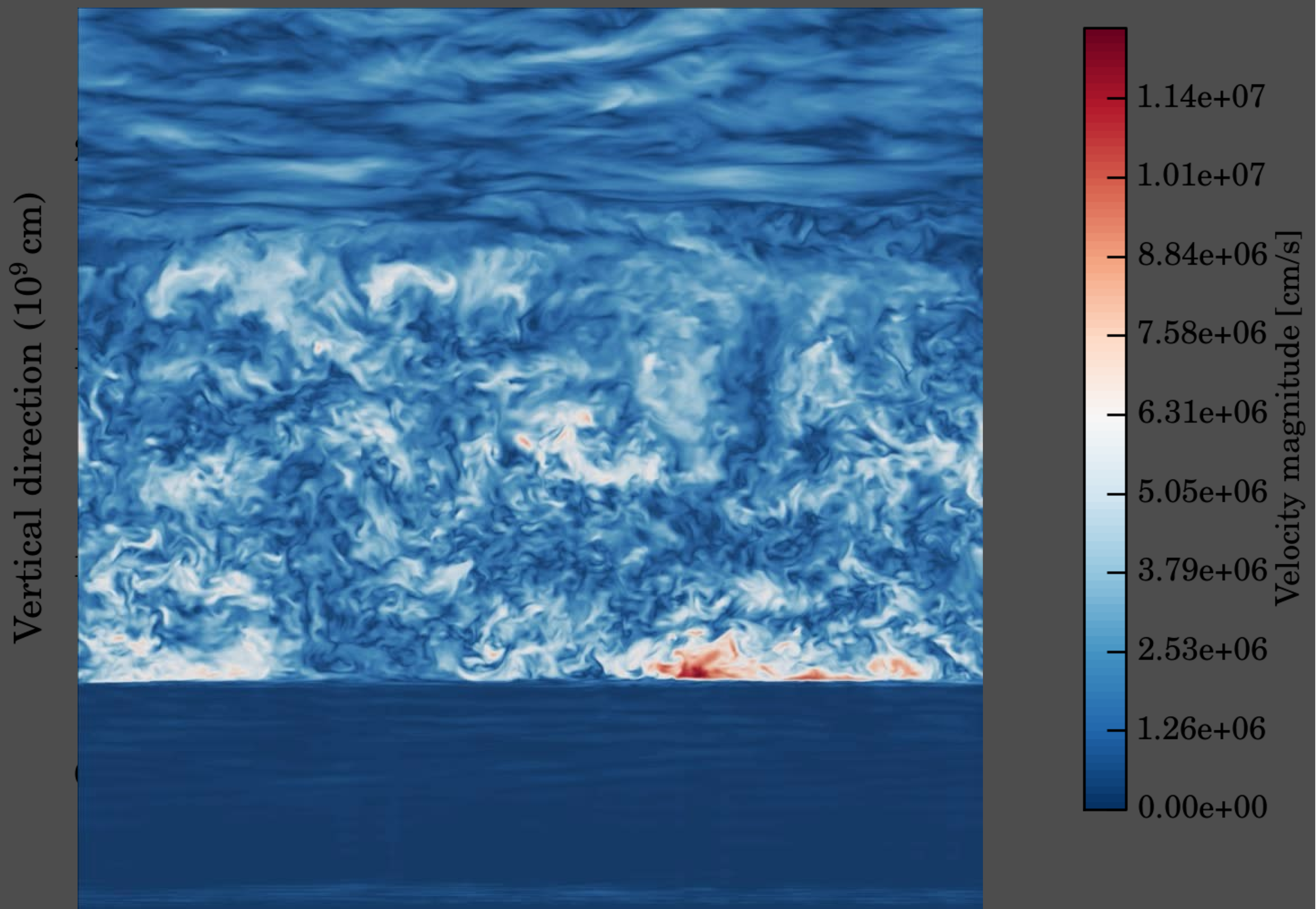


Cristini+ 2017, MNRAS

3D C-shell Simulations: |v| movie

Cristini+ 2017, MNRAS

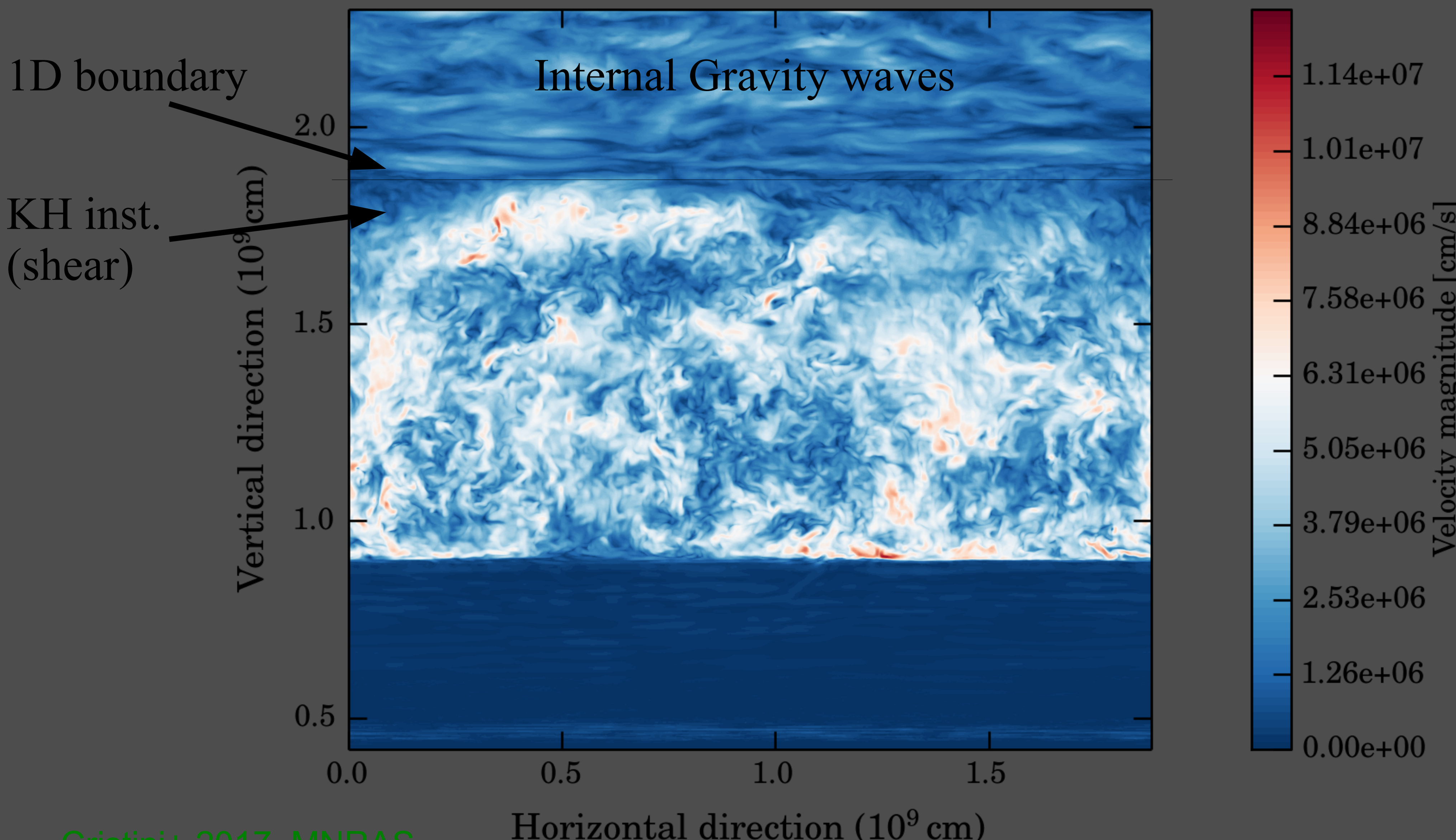
Gas Velocity ||v||



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

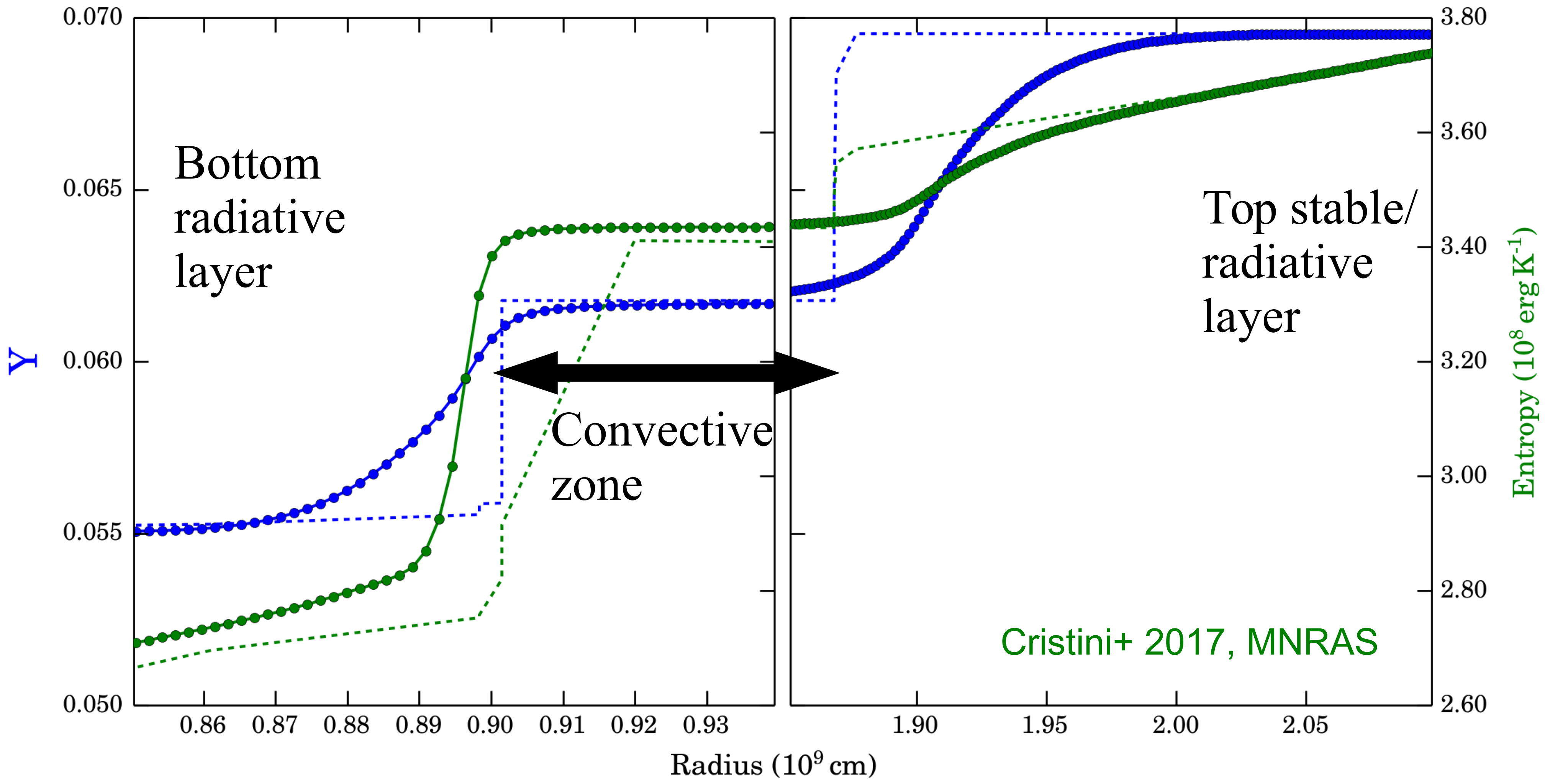
3D C-shell Simulations

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



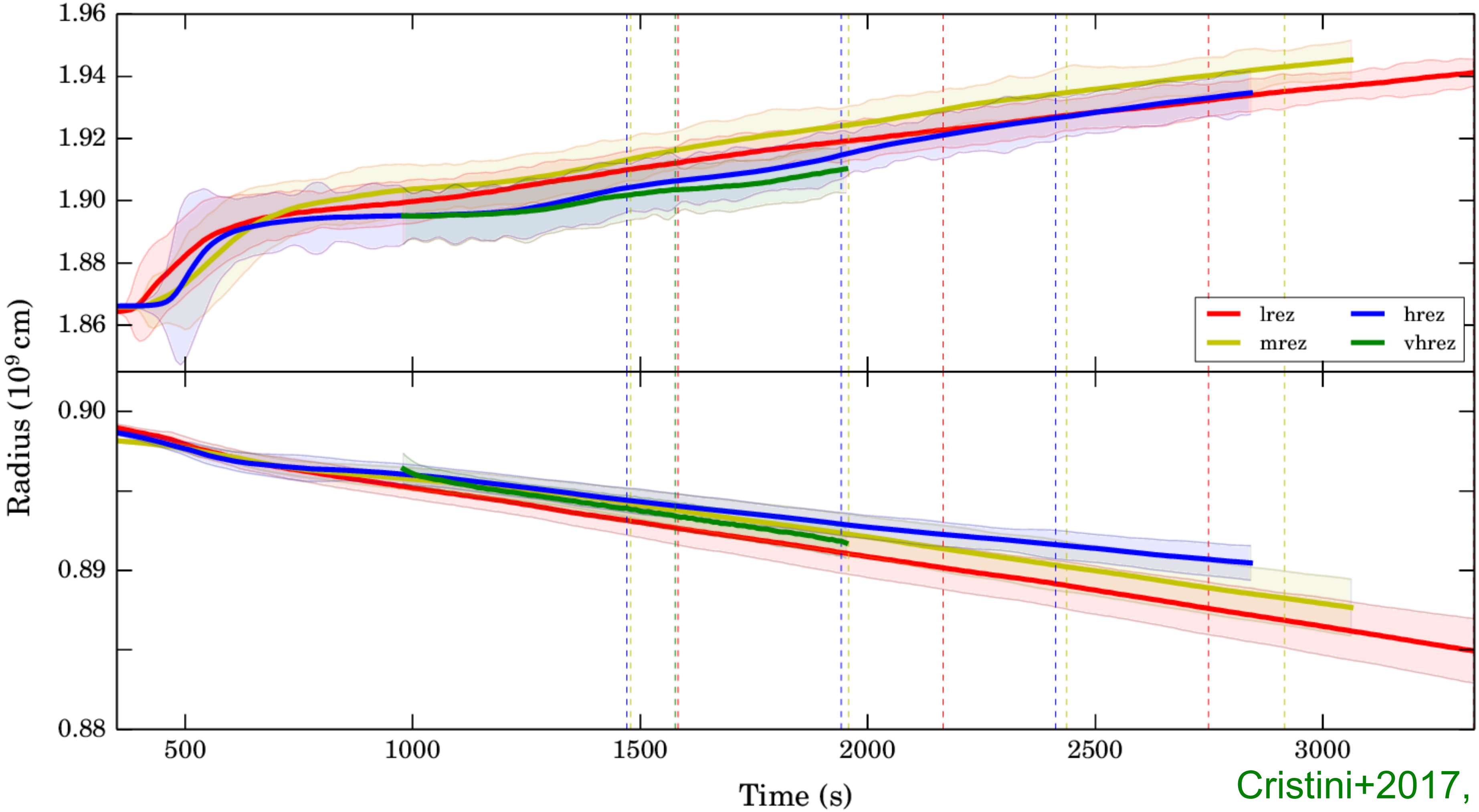
Cristini+ 2017, MNRAS

3D versus 1D



- Improved prescriptions for CBM needed!

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.

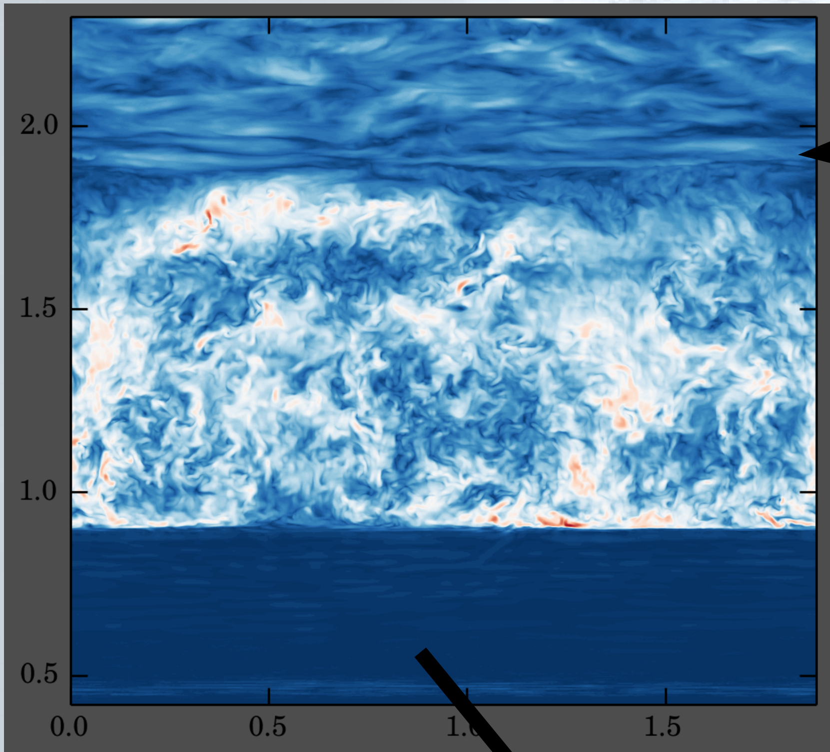
Stable Region
(IGW)
Shear Layer
Penetrative Overshoot /
Entrainment
Convective Core
(or shell)
boundary layers
∇_{rad}
∇_{ad}

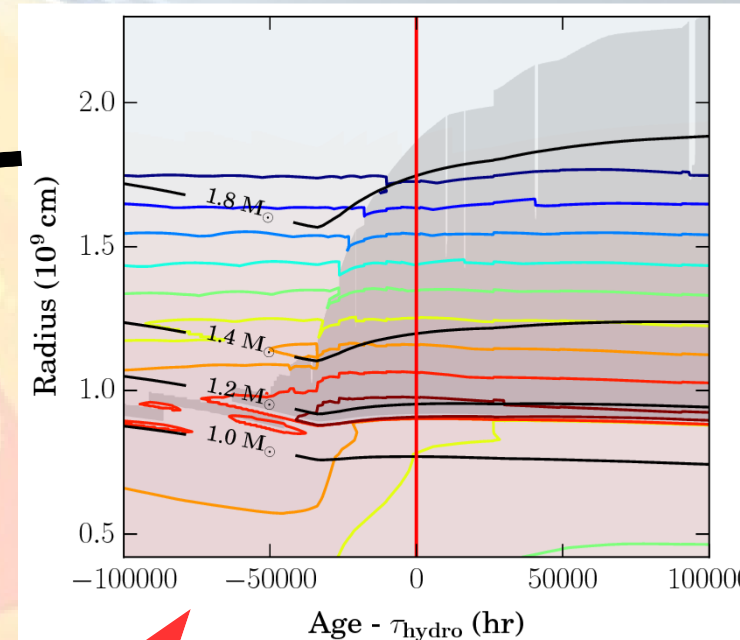
Way Forward: 1 to 3 to 1D link

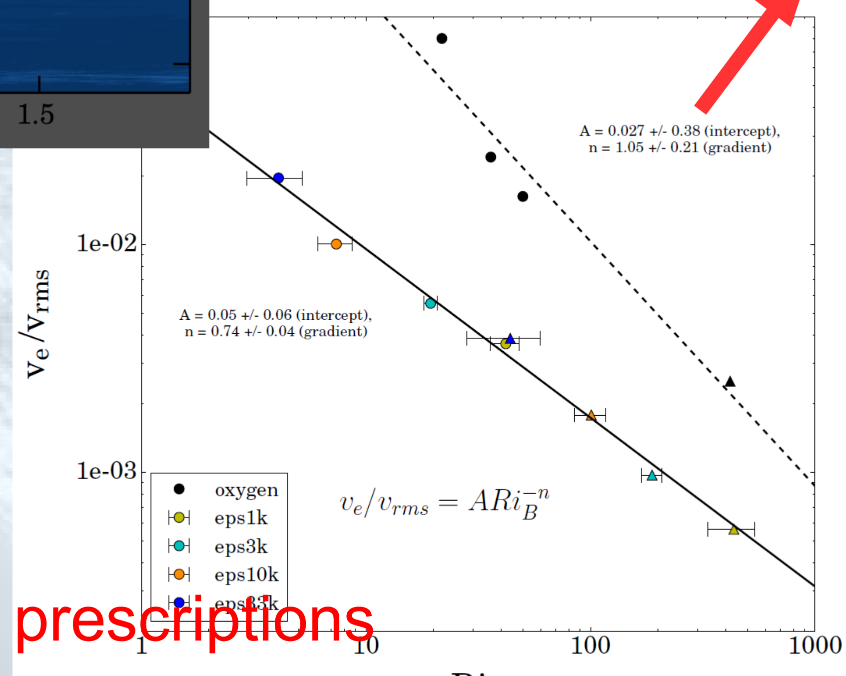
Targeted 3D simulations

Uncertainties in 1D

Cristini+2017

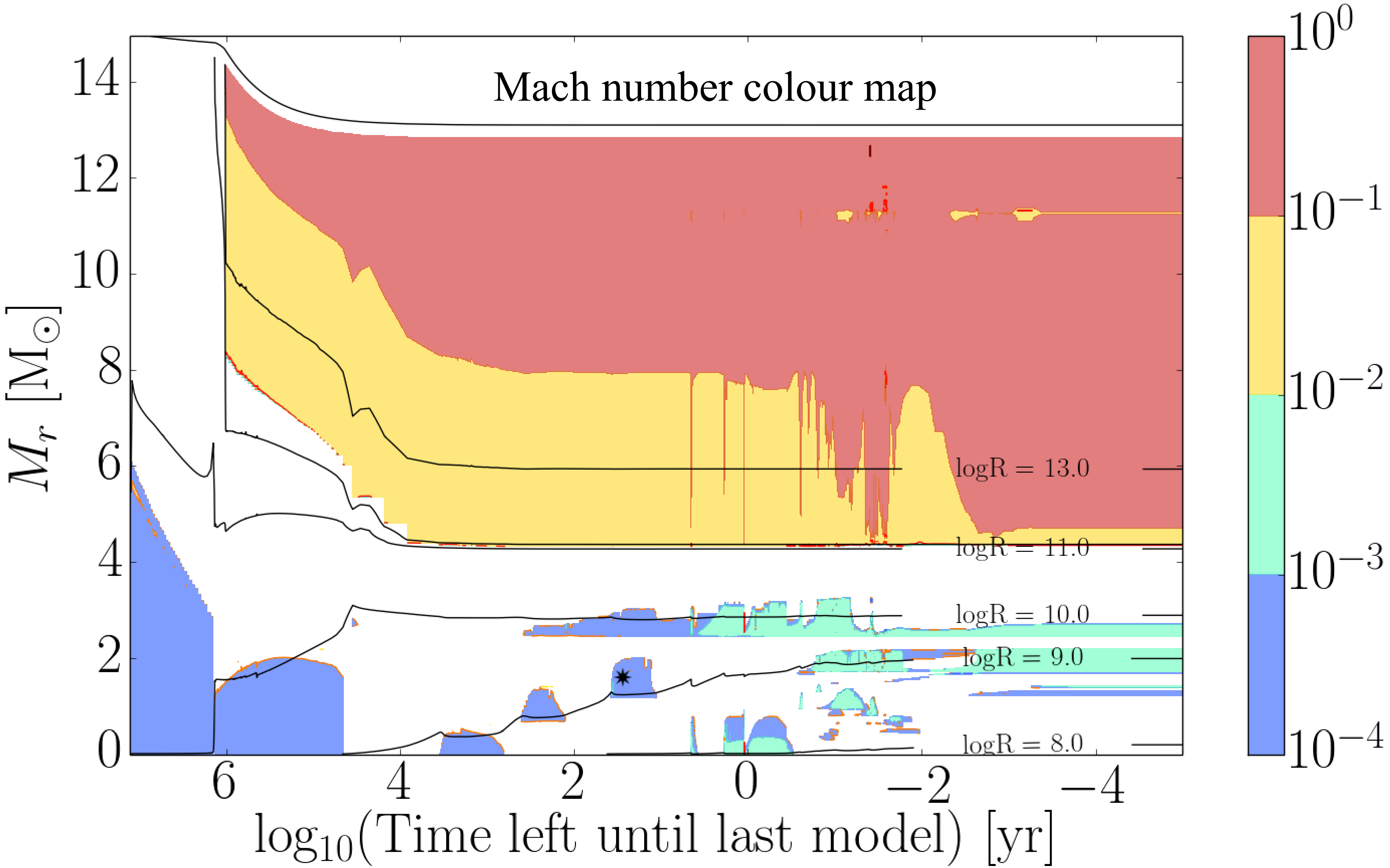






→ Improve theoretical prescriptions

Next Steps? Other Phases

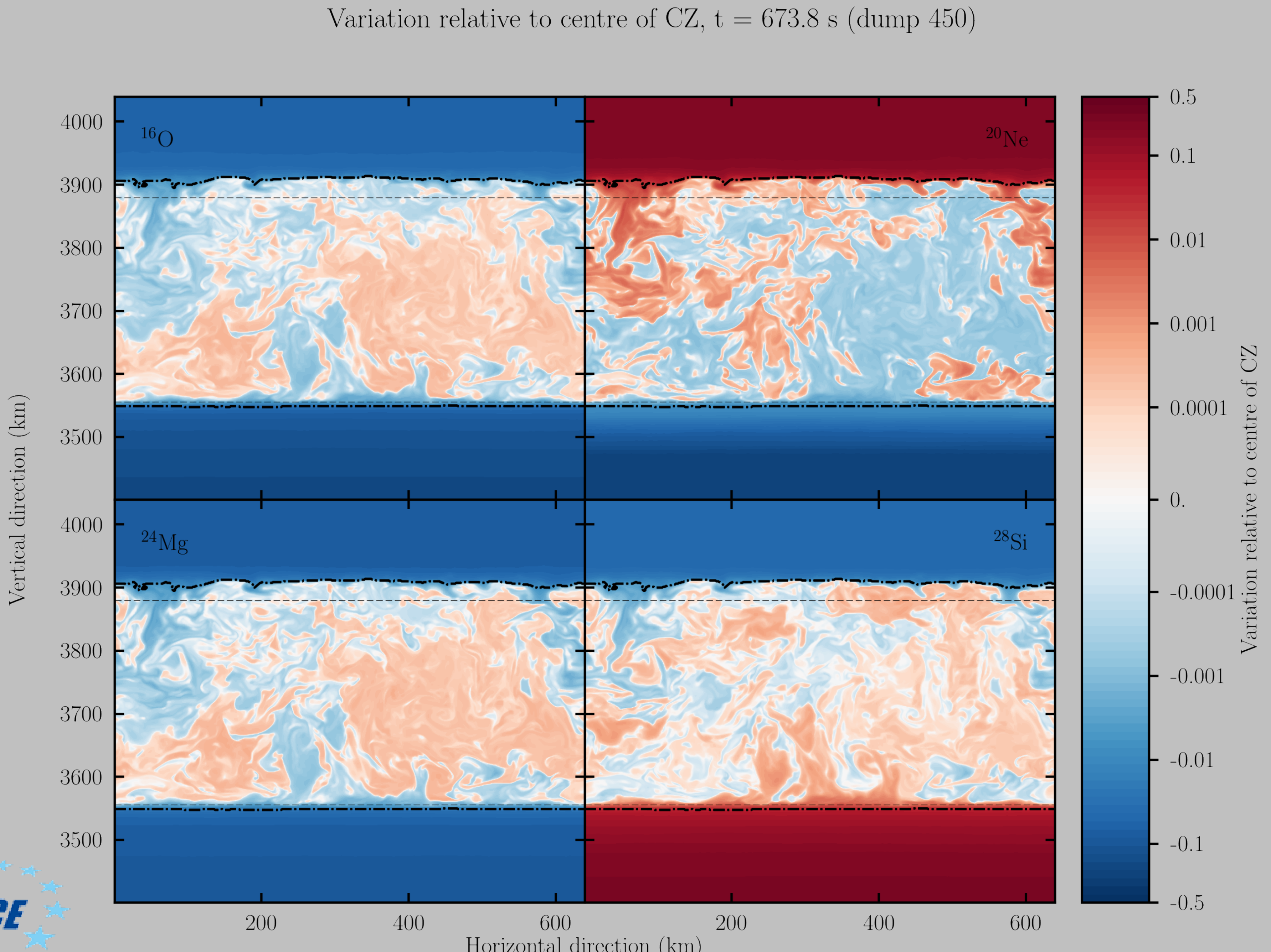


Low-Mach scheme better for for H, He phases!

3D Hydro Efforts/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, ...)
•

Ne-burning



PRACE

Mass Loss: Types, Driving & Recipes

Mass loss driving mechanism and prescriptions at 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 $Z=10^{-8}$

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

- 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

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

The fate of VMS: PCSN/BH/CCSN?

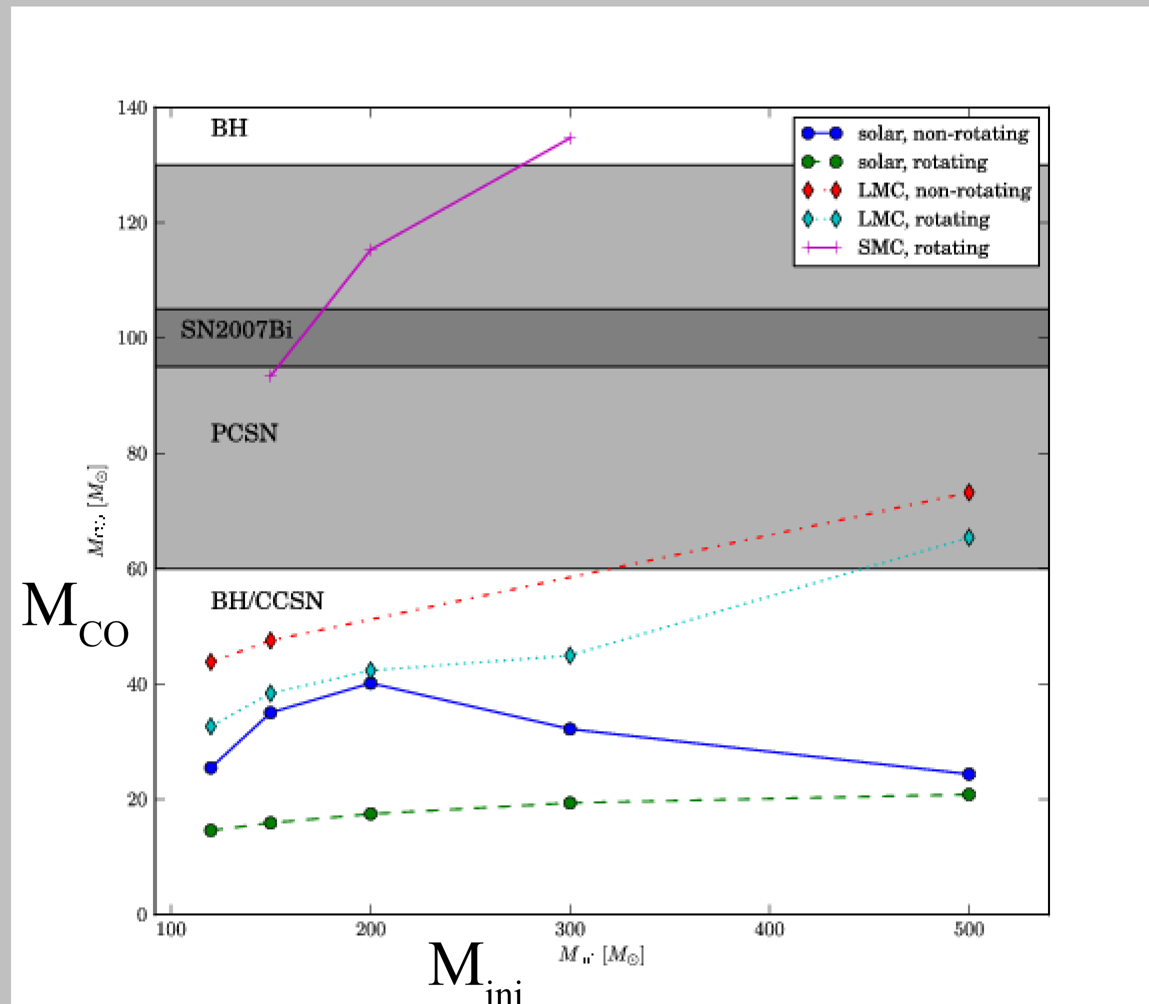
(Yusof et al 13 MNRAS, aph1305.2099)

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)

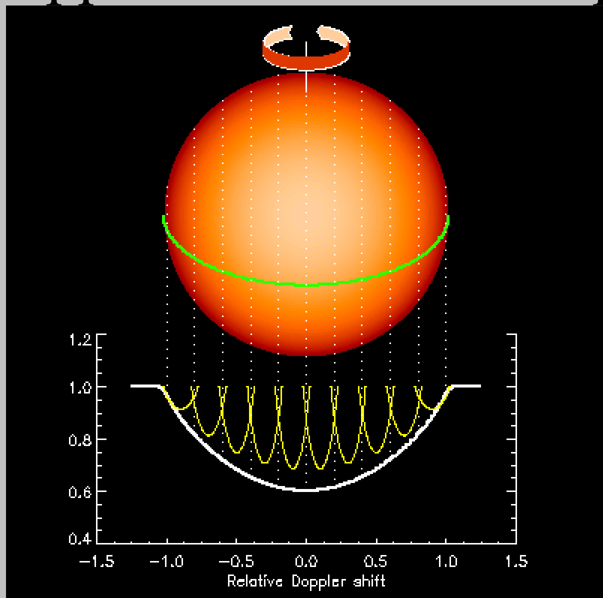
Consistent with Langer et al (2007): PCSN for $Z<Z_{\odot}/3$

Key Open Questions Concerning Mass Loss

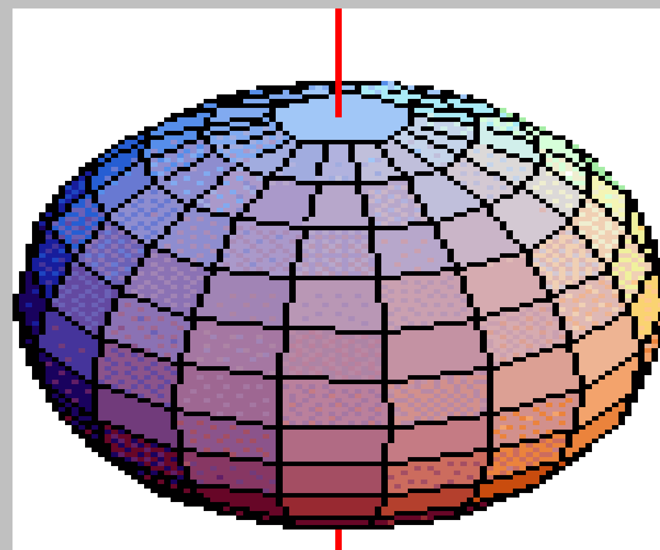
- Mass loss in cool parts of HRD: LBV & RSG, especially at low Z
- Position in & evolution across HRD: effects of rotation-induced mixing, feedback from mass loss Yusof et al 13, Langer 07, Sanyal et al 15, Kohler et al 15...
- **Mass loss near Eddington limit** Graefener & Hamann 08, Vink et al 11, ...
- 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, ...
- ...

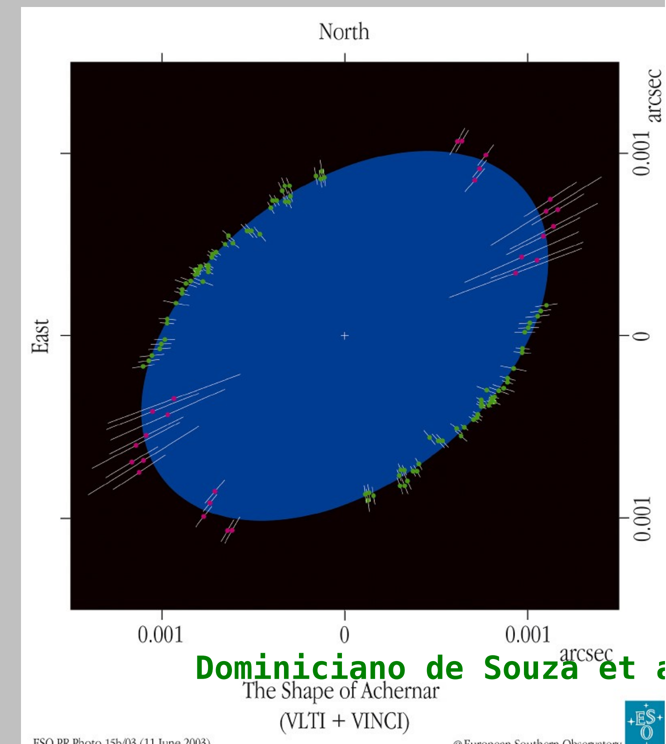
Rotational Effects on Surface

Doppler-broadened line profile



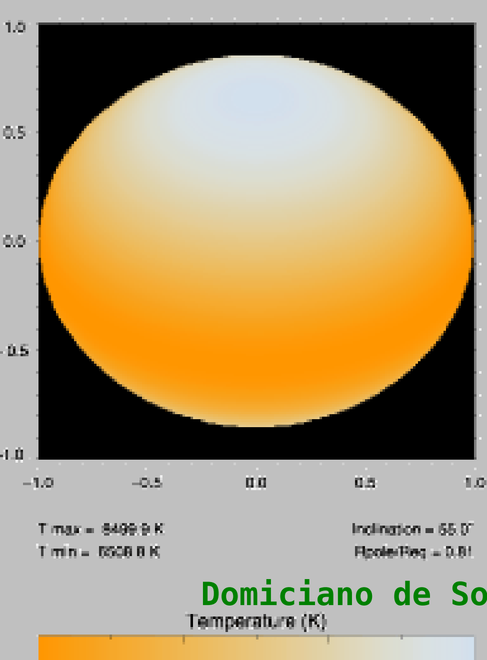
Fast rotators –> oblate shape:





Dominiciano de Souza et a

T_{eff} map (BMAD)



Domiciano de Souza et al. 2005

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

→ enhanced mass loss (+ anisotropic)

Stellar Evolution with Rotation: Geneva Code

1.5D hydrostatic code (Eggenberger et al 2008)

Rotation: (Maeder & Meynet 2008)

Centrifugal force: KEY FOR GRB prog.

$$\vec{g}_{\rm eff} = \vec{g}_{\rm eff}(\Omega, \theta) = \left(-\frac{GM}{r^2} + \Omega^2 r \sin^2\theta\right) \vec{e}_r + \Omega^2 r \sin\theta \cos\theta \, \vec{e}_\theta$$

Shellular rotation → still 1D: (Zahn 1992)

- Energy conservation:

$$\frac{\partial L_P}{\partial M_P} = \epsilon_{nucl} - \epsilon_\nu + \epsilon_{grav} = \epsilon_{nucl} - \epsilon_\nu - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} \quad (2.9)$$

- Momentum equation:

$$\frac{\partial P}{\partial M_P} = -\frac{GM_P}{4\pi r_P^4} f_P \quad (2.10)$$

- Mass conservation (or continuity equation):

$$\frac{\partial r_P}{\partial M_P} = \frac{1}{4\pi r_P^2 \overline{\rho}} \quad (2.11)$$

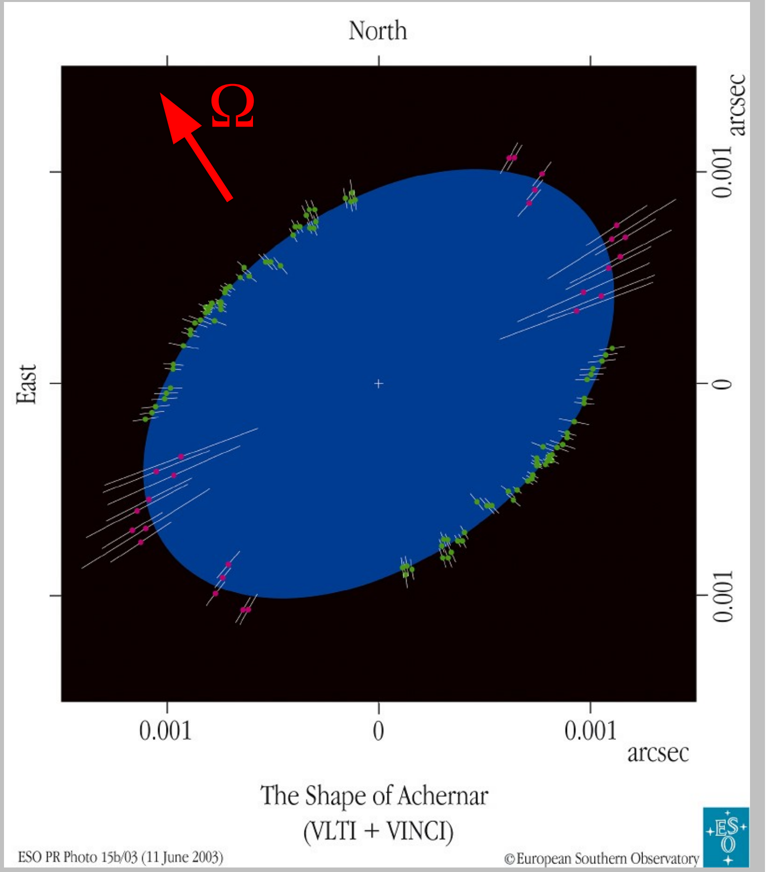
- Energy transport equation:

$$\frac{\partial \ln \overline{T}}{\partial M_P} = -\frac{GM_P}{4\pi r_P^4} f_P \min[\nabla_{\rm ad}, \nabla_{\rm rad} \frac{f_T}{f_P}] \quad (2.12)$$

where

$$\nabla_{\rm ad} = \frac{P\delta}{\overline{T}\overline{\rho} c_P} \quad \text{(convective zones)},$$

$$\nabla_{\rm rad} = \frac{3}{16\pi a c G}\frac{\kappa l P}{m \overline{T}^4} \quad \text{(radiative zones)},$$



$$f_P = \frac{4\pi r_P^4}{GM_P S_P}\frac{1}{< g^{-1} >},$$

$$f_T = \left(\frac{4\pi r_P^2}{S_P}\right)^2 \frac{1}{< g >< g^{-1} >},$$

(Meynet and Meynet 97)

Rotation Induced Transport

Zahn 1992: strong horizontal turbulence

Transport of angular momentum:

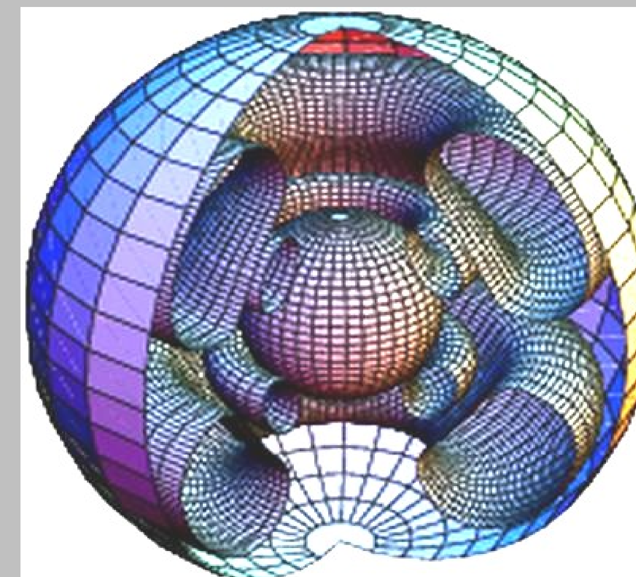
$$\rho \frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \bar{\Omega} U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4 \frac{\partial \bar{\Omega}}{\partial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

Transport of chemical elements:

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

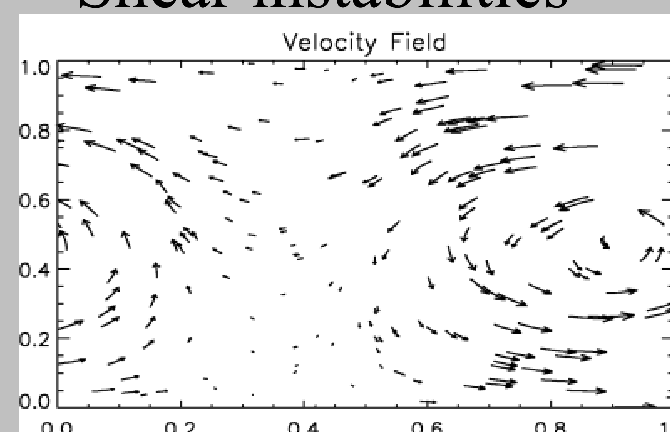
D: diffusion coeff. due to various transport mechanisms (convection, shear)

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



Meynet & Maeder 2000

Shear instabilities

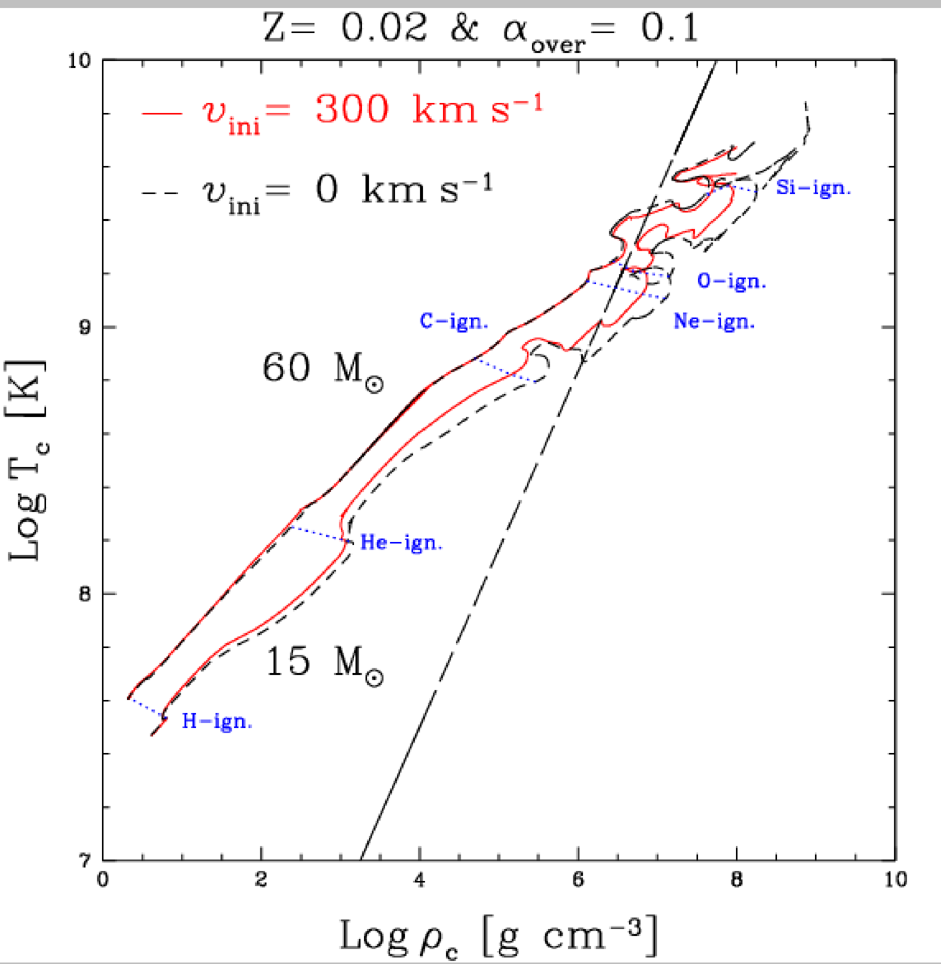


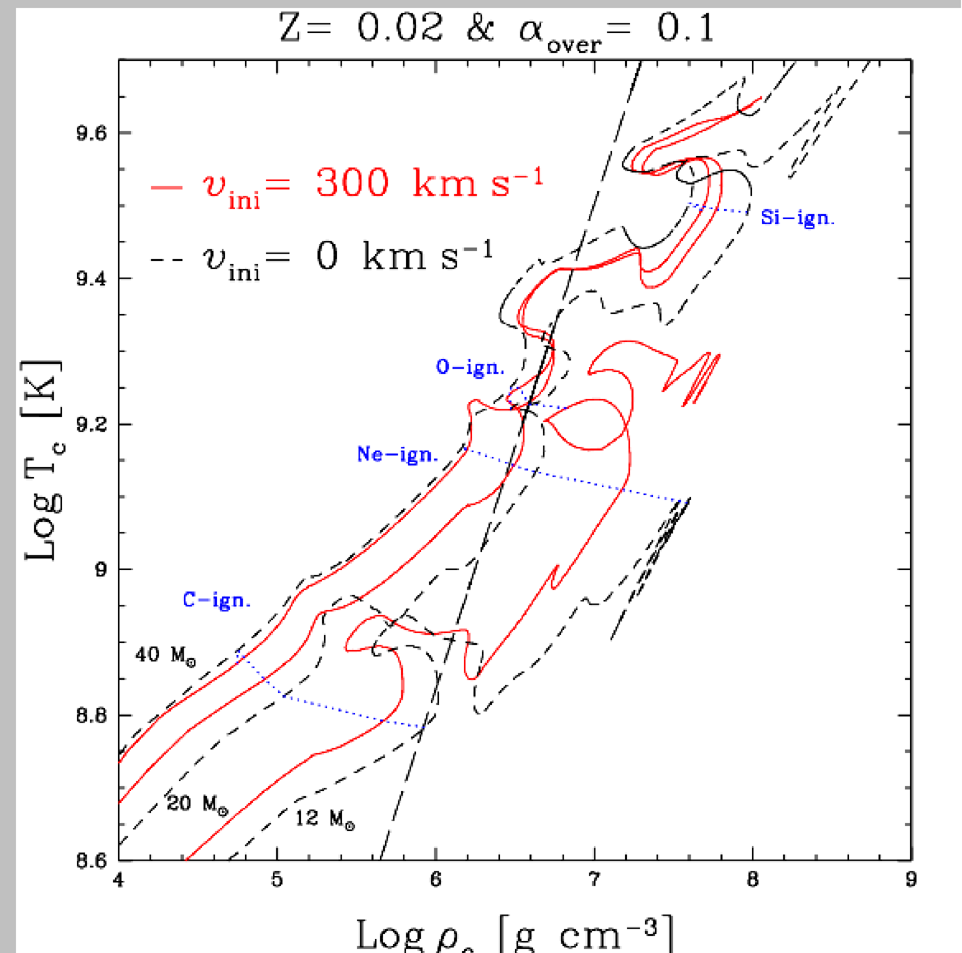
Brueggen & Hillebrandt 2000

Massive Stars

M<~30 M_o : Rotational mixing dominates → bigger cores

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





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, den Hartogh et al 2019
- …

Key Open Questions Concerning Binary Interactions

… see e.g. De Marco & Izzard 2017 review on binaries

- Distributions: mass ratios, orbital separation, fraction of single stars …
- Common envelope phase and outcome …
- Efficiency of mass transfer: how conservative? Accretion rates for Novae? …
- SN kicks and angular momentum accretion …
- Triple stars …
- …

Advert for Recent Activities

- Main & weak s processes:

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

Nugrid: set 1 (Pignatari+2016, ApJS), set1extension (Ritter+in 2018, MNRAS),

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

- Nuclear uncertainties: MC-based sensitivity studies for gamma-process (CCSNe: Rauscher+ 2016, MNRAS, SNIa: Nishimura+2018, MNRAS), weak s process (Nishimura+2017, MNRAS), main s process (Cescutti+in 2018)

- 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)

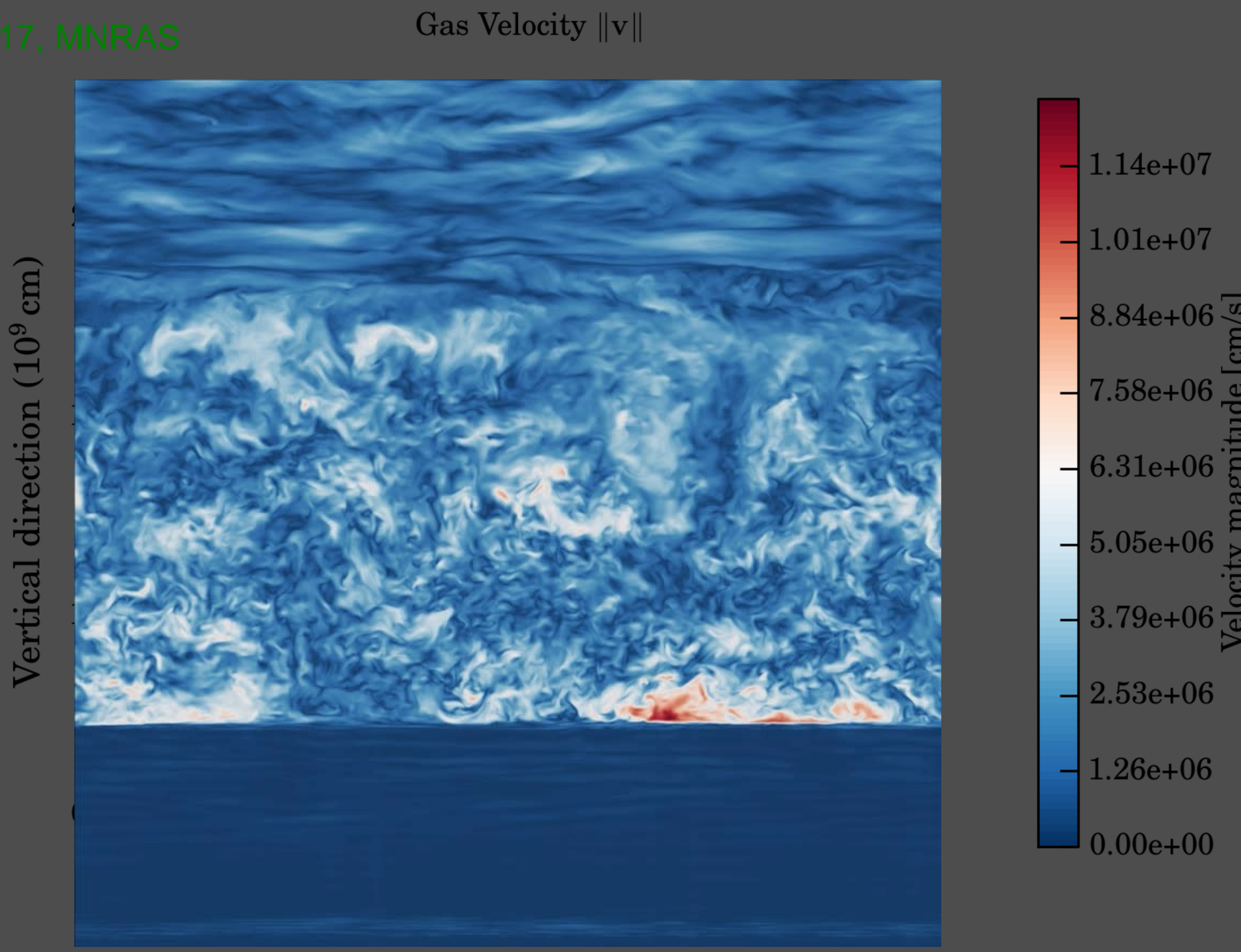
- ChETEC COST Action 2017-2021: see www.chetec.eu for details

Conclusions & Outlook

- Physical ingredients still uncertain: nuclear reactions, convection, rotation, mass loss + B-fields, binarity
- Priority lists established: large effort needed!
- 1D to 3D to 1D work underway: new CBM prescriptions under development!
- Exciting times ahead: complex physics explored & CPU-GPU supercomputers enable us to do much more in multi-D

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

Cristini+ 2017, MNRAS



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

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 subm.),

(main) 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