# Convective mixing and nucleosynthesis in super-AGB stars

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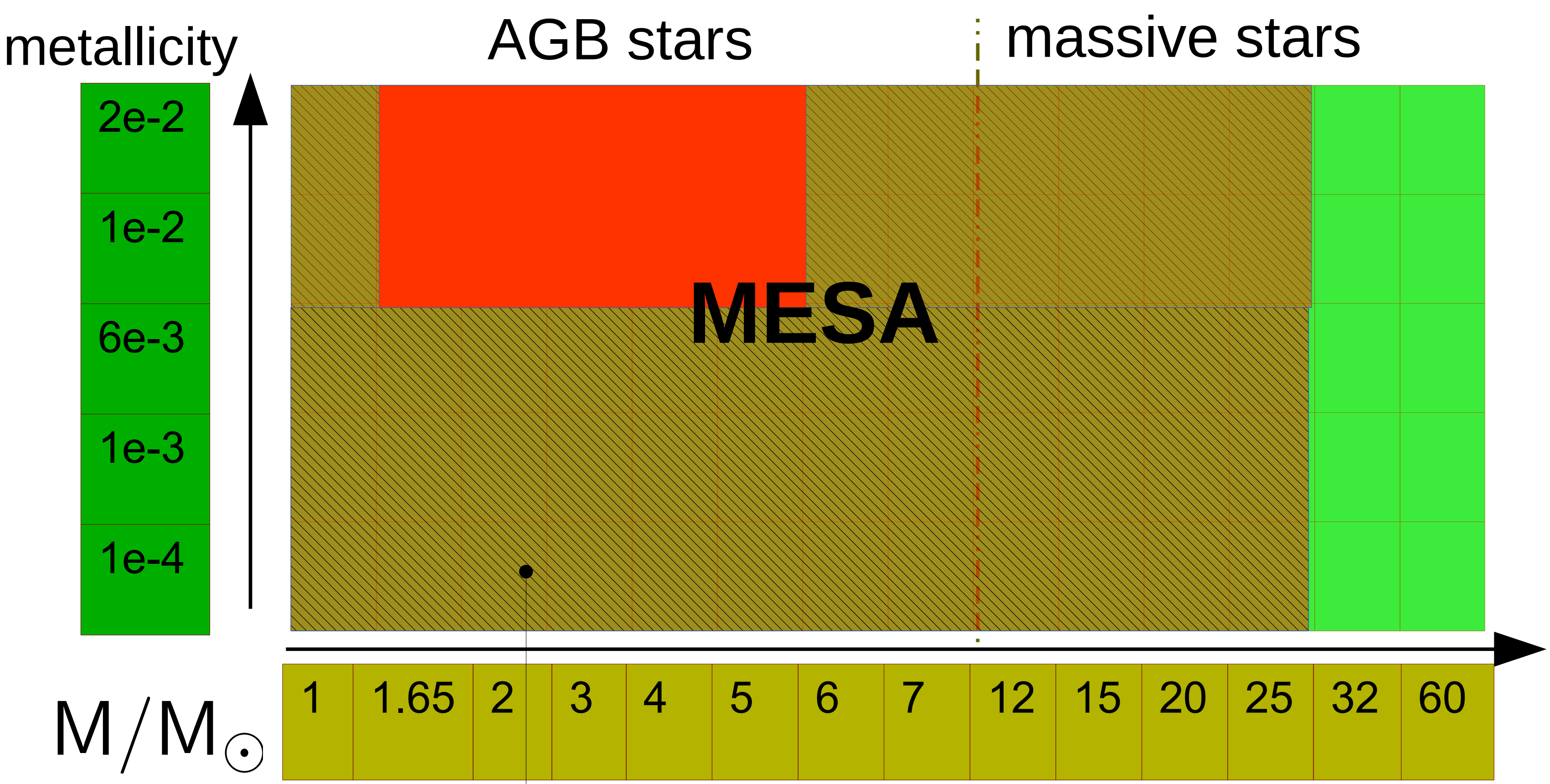
# Outline

- Features of SAGB stars in NuGrid yield set
  - Hot dredge-up
  - Hot bottom burning
- i process & H ingestion in SAGB stars
- Rapidly accreting white dwarfs
  - Low or negative retention rate
  - H ingestion & I process
- Hybrid white dwarfs
  - Unusual SN Ia progenitors
  - Urca process

**Set 1: astro-ph Pignatari13+, arxiv: 1307.6961**

**Set 1 extension**

C. Ritter, S. Jones, M. Pignatari, F. Herwig, R. Hirschi, C. Fryer, N. Nishimura, P. A. Denissenkov & the NuGrid collaboration

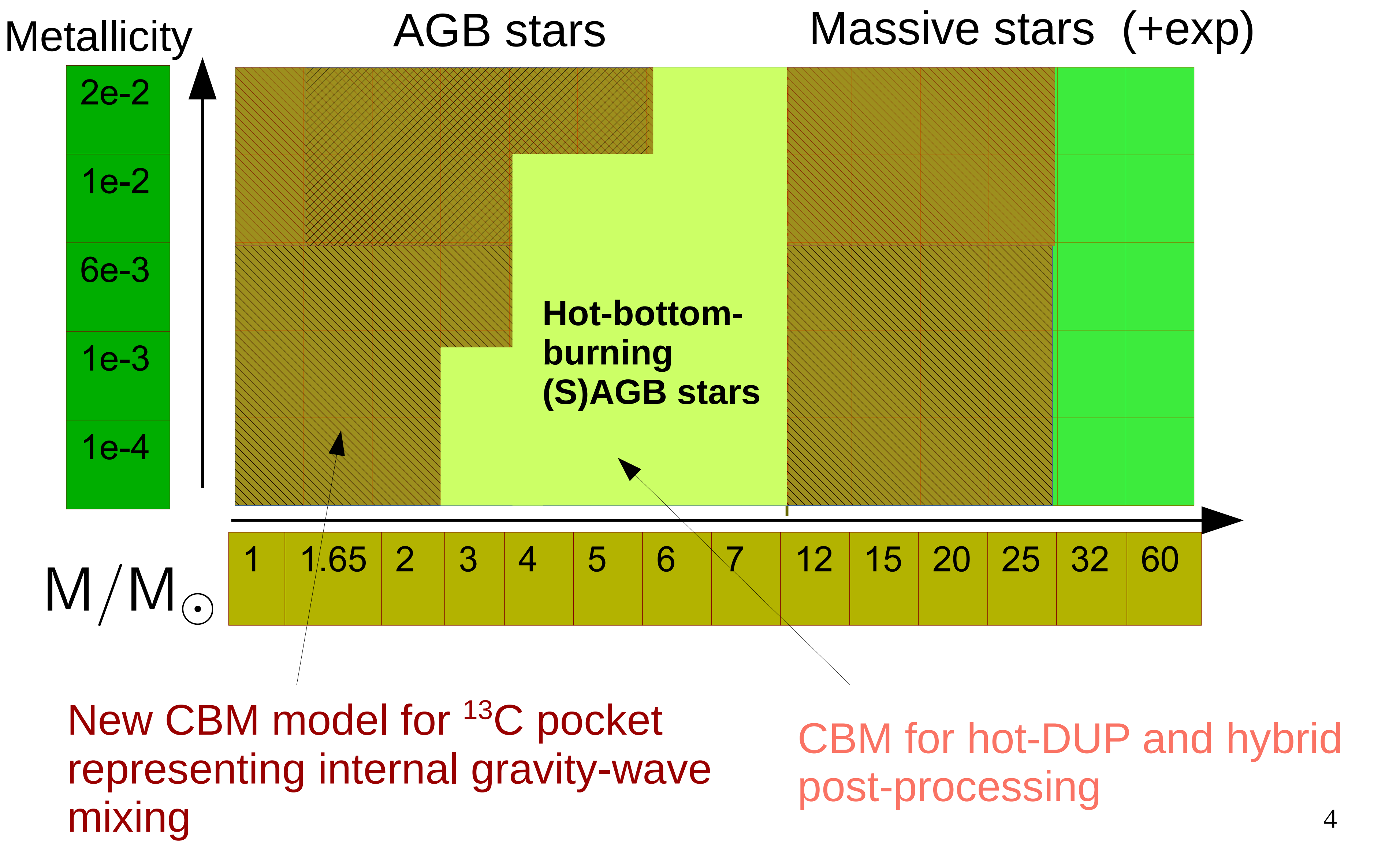



- http://data.nugridstars.org
- Python tools to analyze and explore data
- Experimental: http://wendi.nugridstars.org

- up to 1000 isotopes
- 2000 grid zones
- $10^5$ models

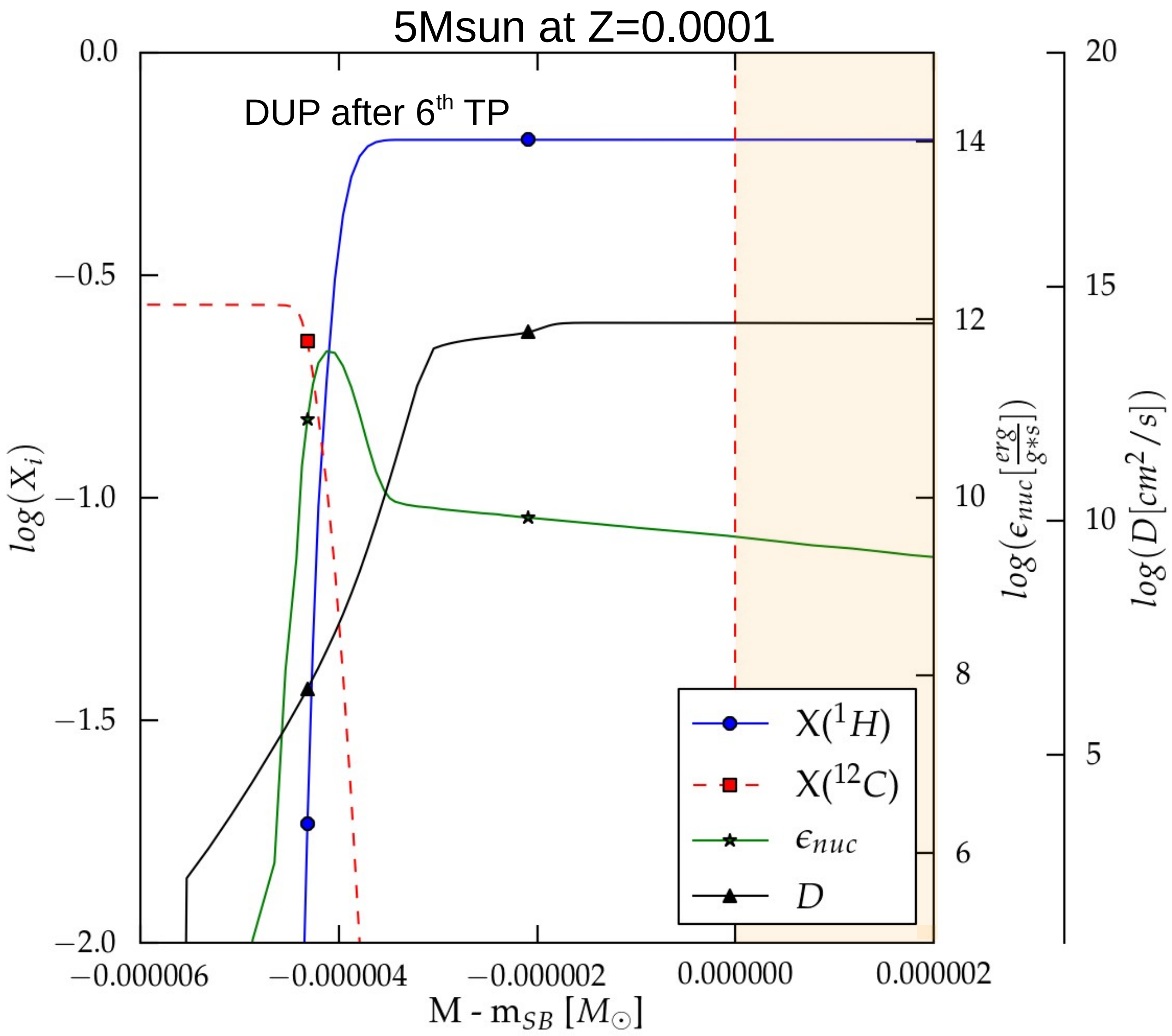
+ stellar evolution data for each time step and mass zone

# Hot-bottom burning (S)AGB stars



# Hot dredge-up

- Hot dredge-up in massive and SAGB stars (Herwig 04, Goriely+ 04)
- Corrosive H-shell flame-like burning
- log $L_H$~ 5 ... 7 or more
- For M > 3 ... 4$M_{sun}$ and Z < 0.006
- H-burn and hot DUP increases with convective boundary mixing (CBM)

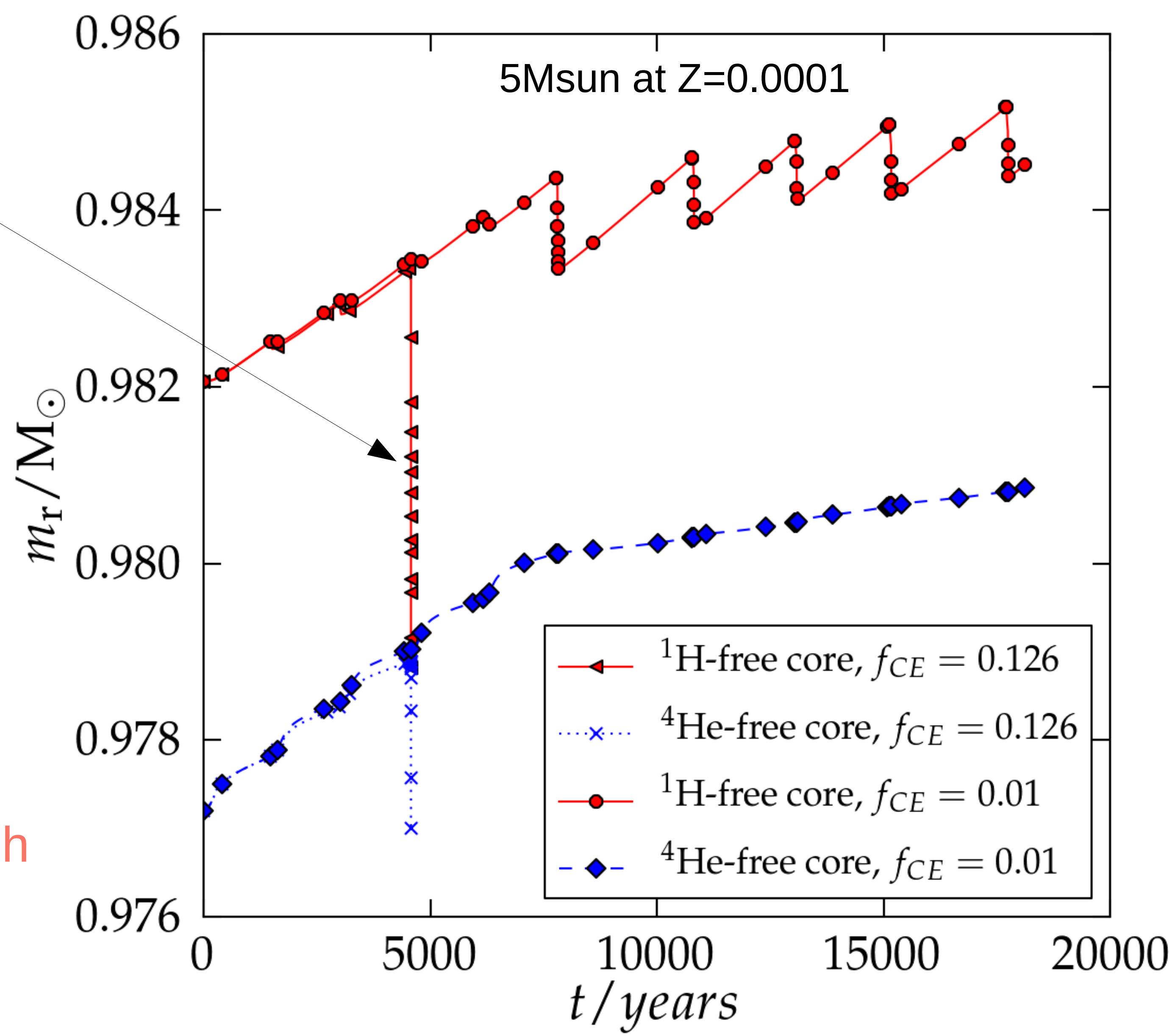


# Hot dredge-up

- CBM efficiency similar to what is needed for $^{13}C$ pocket formation in low-mass AGB stars will lead to enelope ejections and termination of AGB determines core growth
- Expect reduced CBM due to buoyancy feedback of hot-DUP burn

We reduce CBM at high mass and low Z!

Fate as ECSN or WD uncertain!



# Challenge of HBB yields

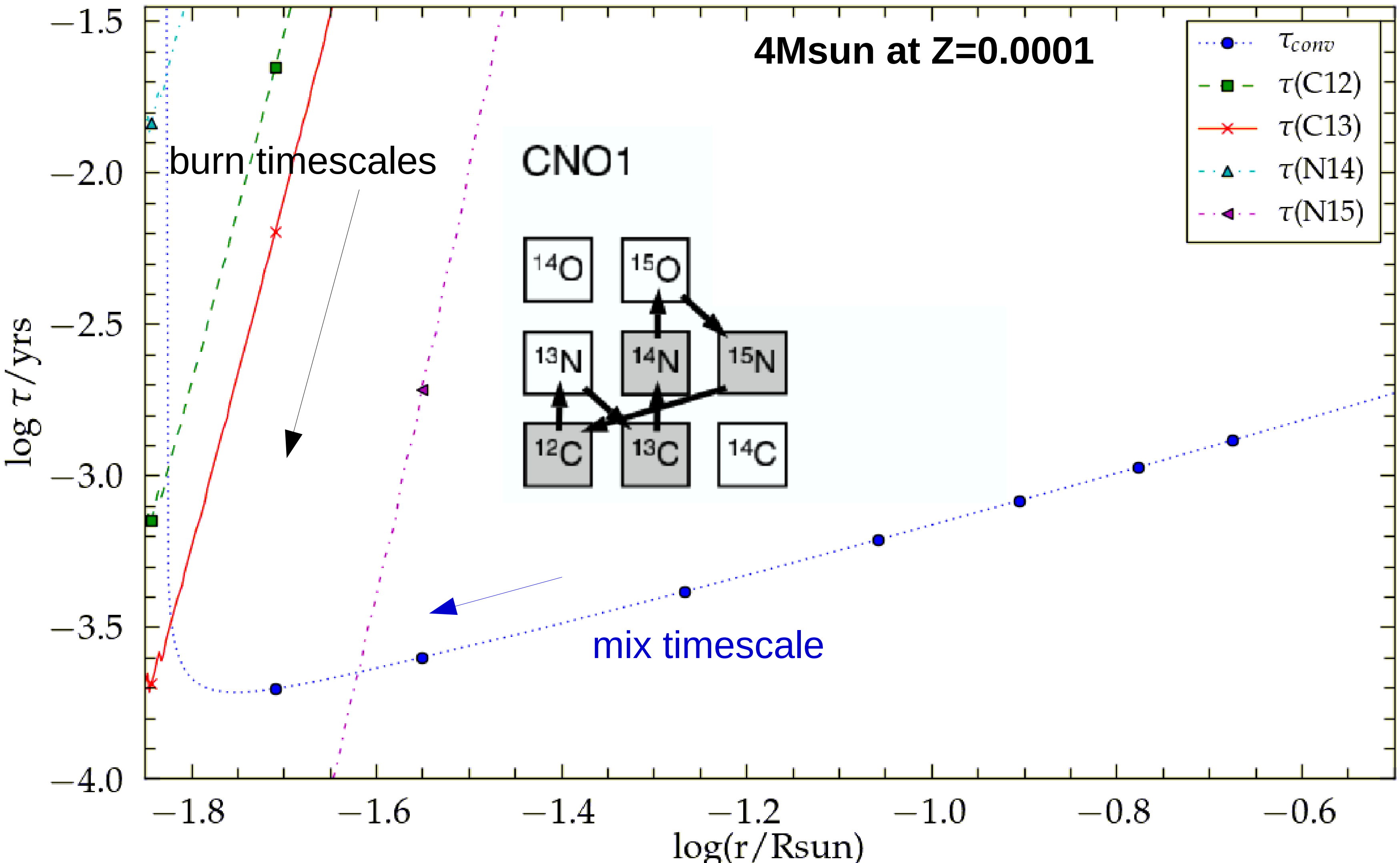
Yields/Msun 5Msun at Z=0.0001

| | specie | This work | H04 | K10 | C15 |
|---|---|---|---|---|---|
| CNO | C-12 | 6.948E-04 | 4.587E-04 | 2.787E-03 | 1.274E-02 |
| | C-13 | 9.086E-05 | 4.372E-05 | 4.059E-04 | 1.856E-04 |
| | N-14 | 4.691E-03 | 1.680E-03 | 2.405E-02 | 3.405E-04 |
| | O-16 | 1.824E-04 | 3.008E-04 | 6.094E-04 | 9.350E-04 |
| s process | Sr-88 | 8.969E-10 | | | 2.238E-08 |
| | Zr-90 | 1.520E-10 | | | 4.399E-09 |
| | Ba-136 | 2.236E-11 | | | 1.029E-09 |
| | Pb-208 | 1.465E-10 | | | 1.284E-08 |
| | C-12/C-13 | 7.65 | 10.49 | 6.87 | 68.64 |
| | C-12/O-16 | 3.81 | 1.52 | 4.5 | 13.63 |

H04: Herwig 04
K10: Karakas 10
C15: Cristallo+ 15

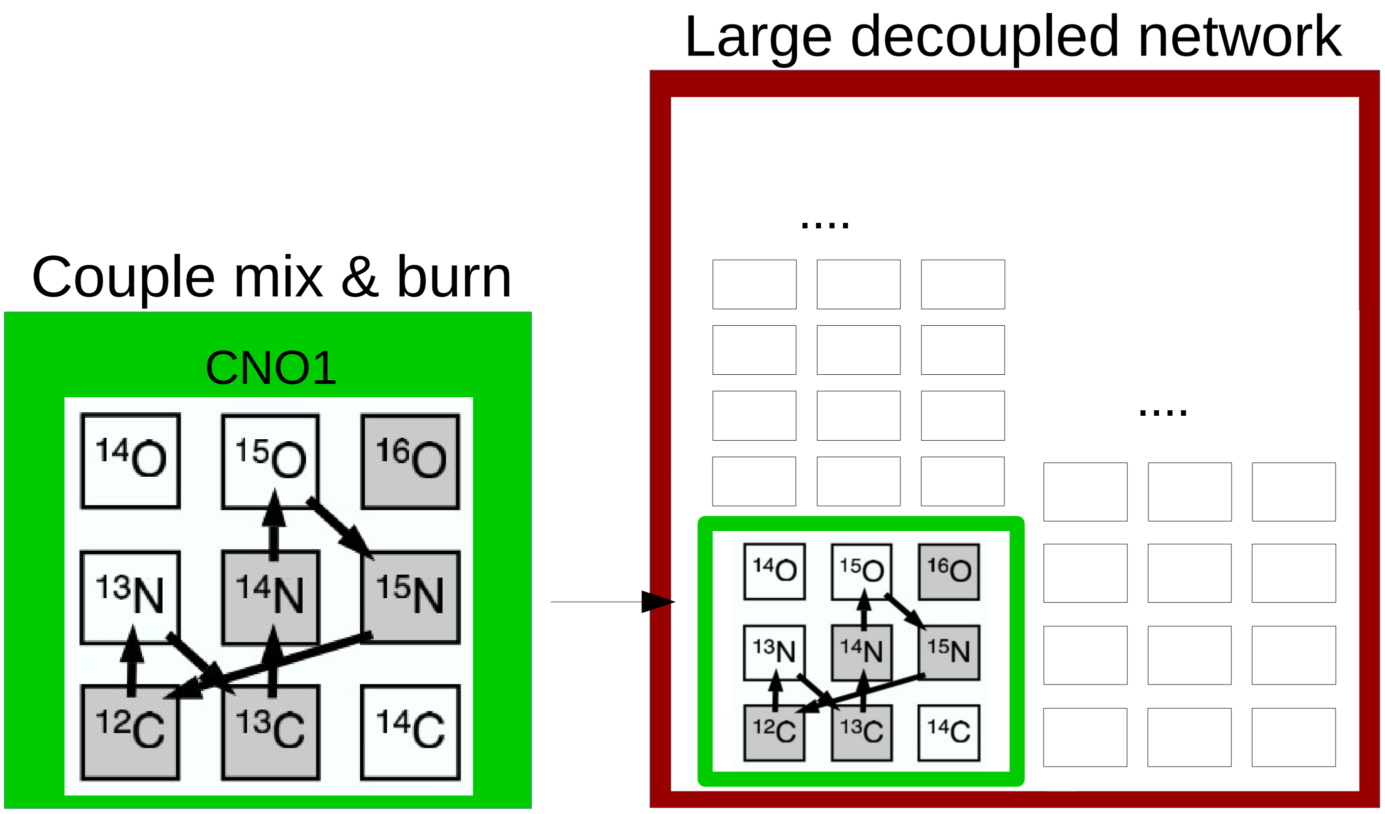
**Difference in CNO element predictions!**

# Time scales involved in HBB




**Mixing and burning on same time scale!**
**Need coupling of mixing and burning contrary to post-processing codes.**

# Post-processing of light and heavy species simultaneously: A hybrid approach




**Resolve production of light elements!**

# Challenge of HBB yields

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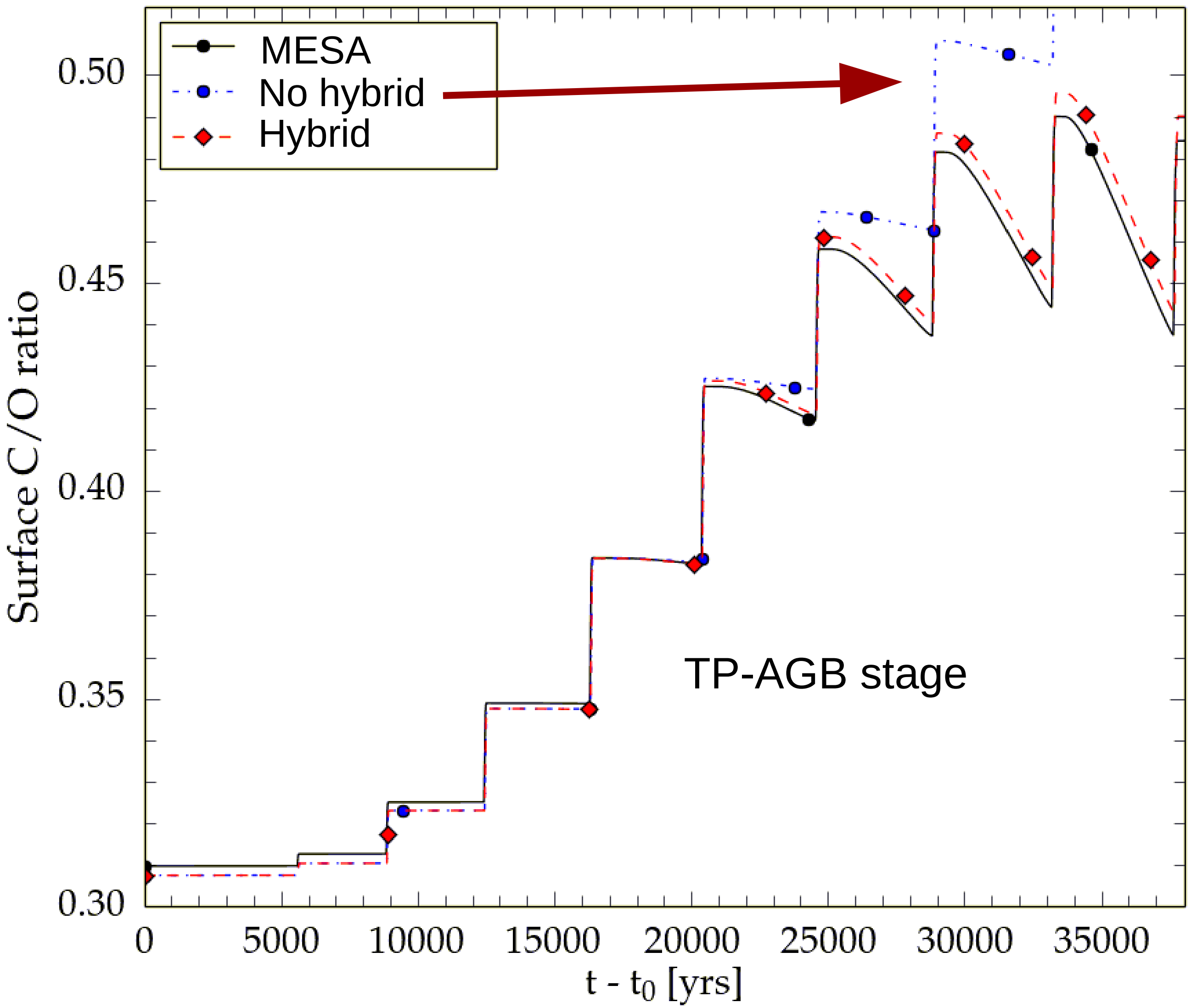
H04: Herwig 04
K10: Karakas 10
C15: Cristallo +15

**Prediction of light & heavy elements!**

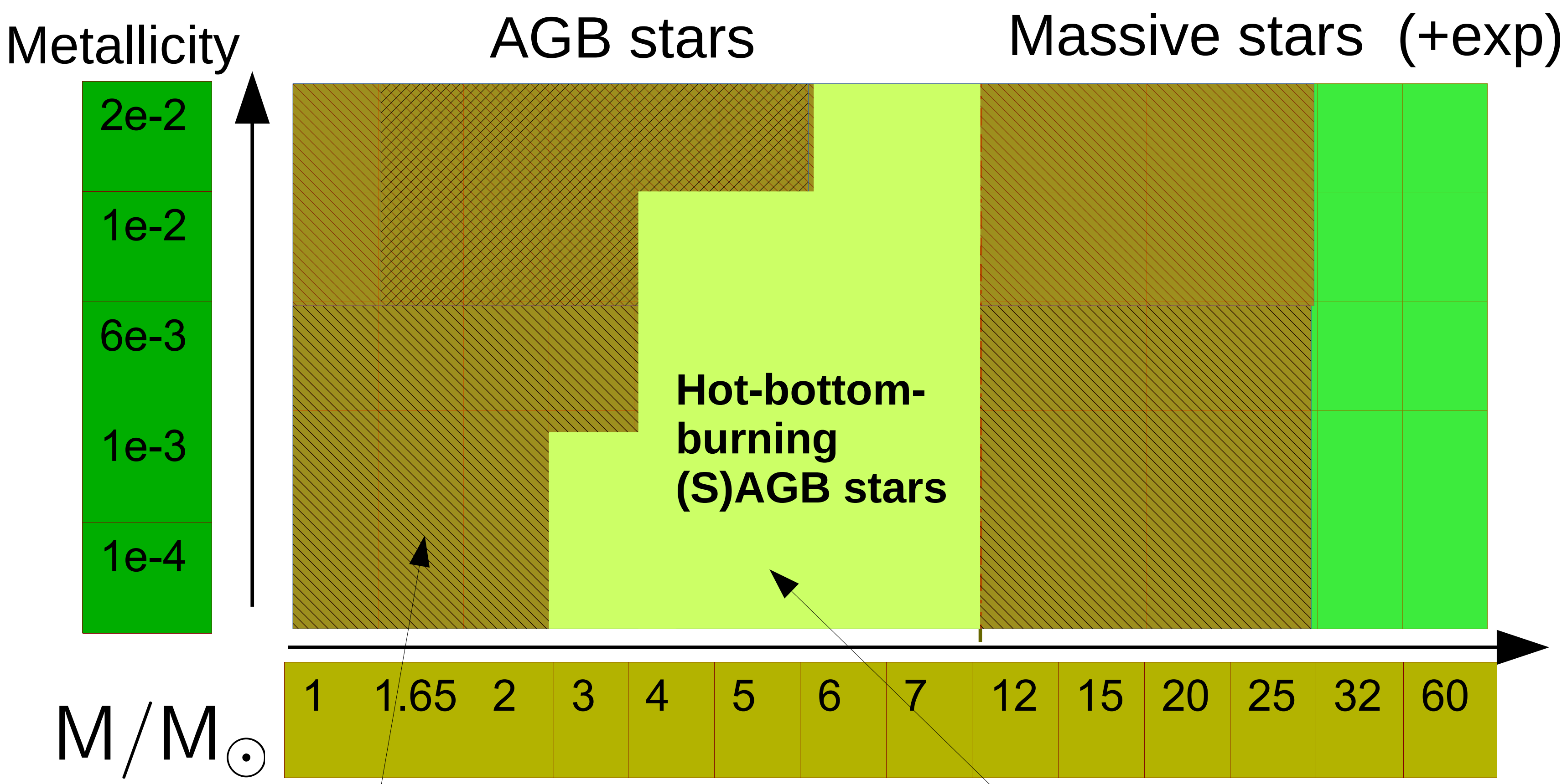
# C/O surface ratio with hybrid post-processing

- Hybrid mode gives C/O surface ratio evolution of stars at low Z in agreement with MESA predictions
- But: When hybrid mode is turned off qualitative and quantitative different C/O evolution

**5Msun at Z=0.01**



# Hot-bottom burning (S)AGB stars

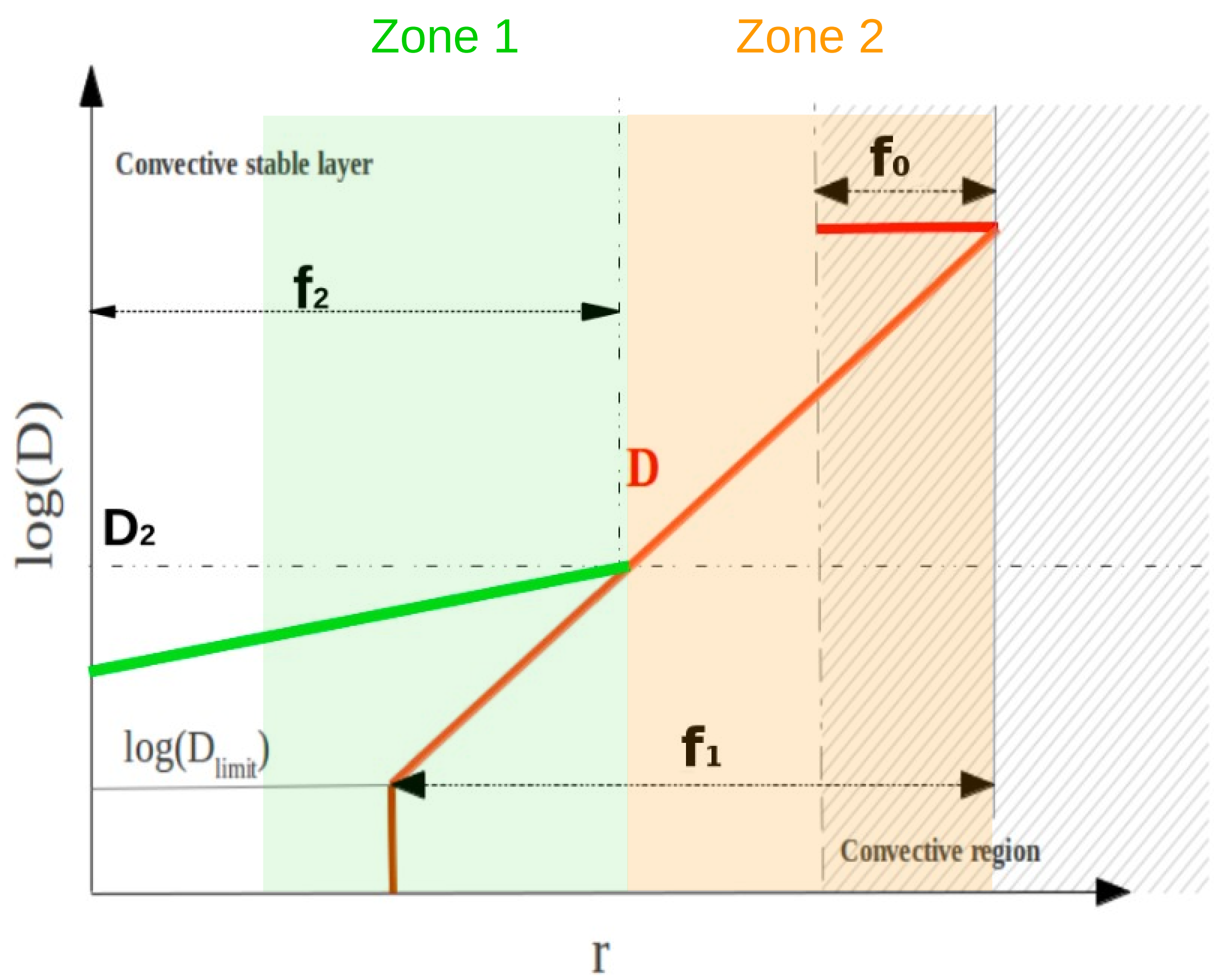



New CBM model for $^{13}C$ pocket representing internal gravity-wave mixing

CBM for hot-DUP and hybrid post-processing

# New 2-zone exponential mixing model for the $^{13}$C pocket

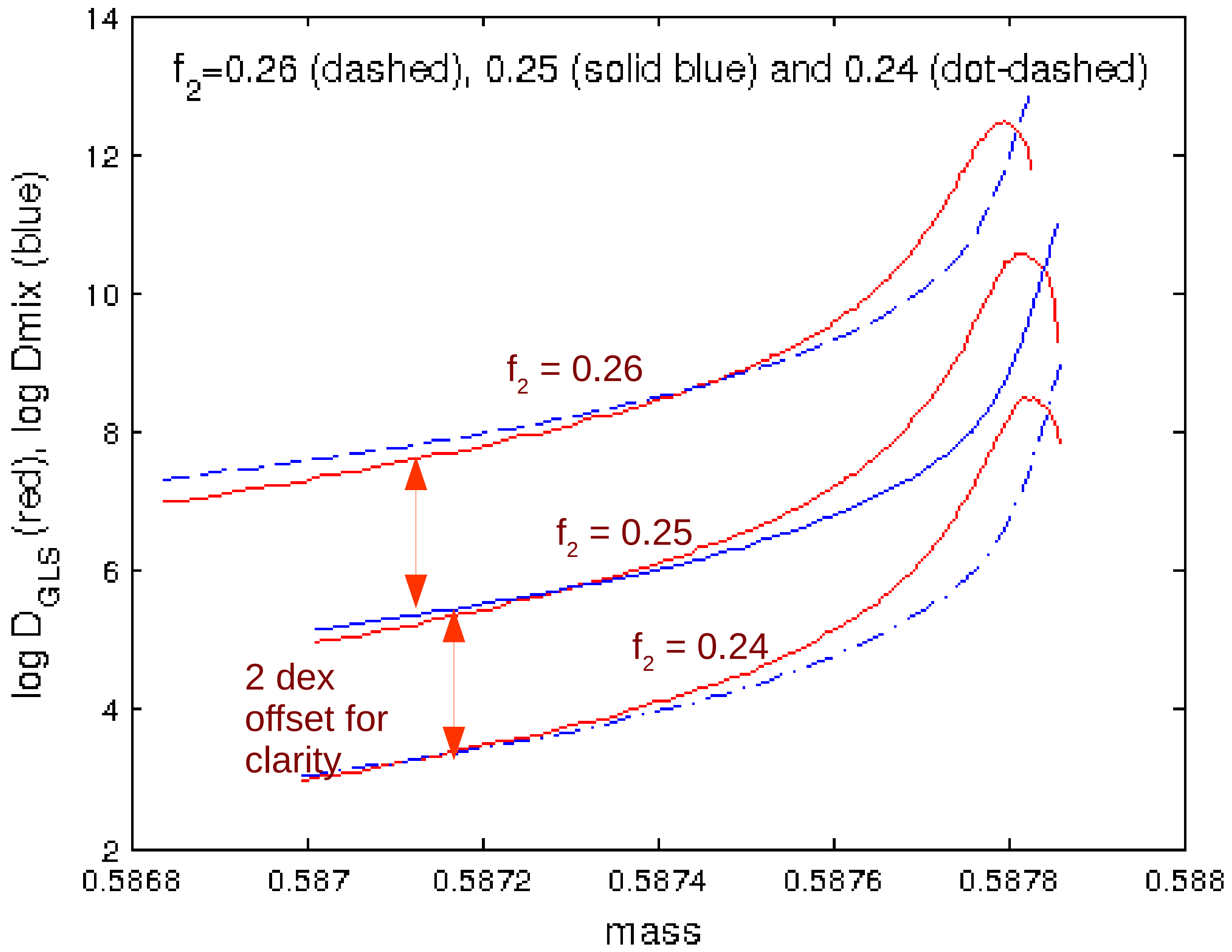
- MESA implementation of 2-zone convective boundary mixing (CBM)
  - zone 1: **motivated by hydrodynamic simulations** (e.g. Herwig+ 06,07, Woodward+ 15) rapid decline of convective mixing efficiency across formal Schwarzschild boundary
  - zone 2: **motivated by theory of mixing due to internal gravity waves** (Denissenkov & Tout 2003) shallow decline starting from low level in formally radiative layer




*Battino, Pignatari, Ritter+ (2016, ApJ rev. requested)*

# New 2-zone exponential mixing model for the $^{13}C$ pocket

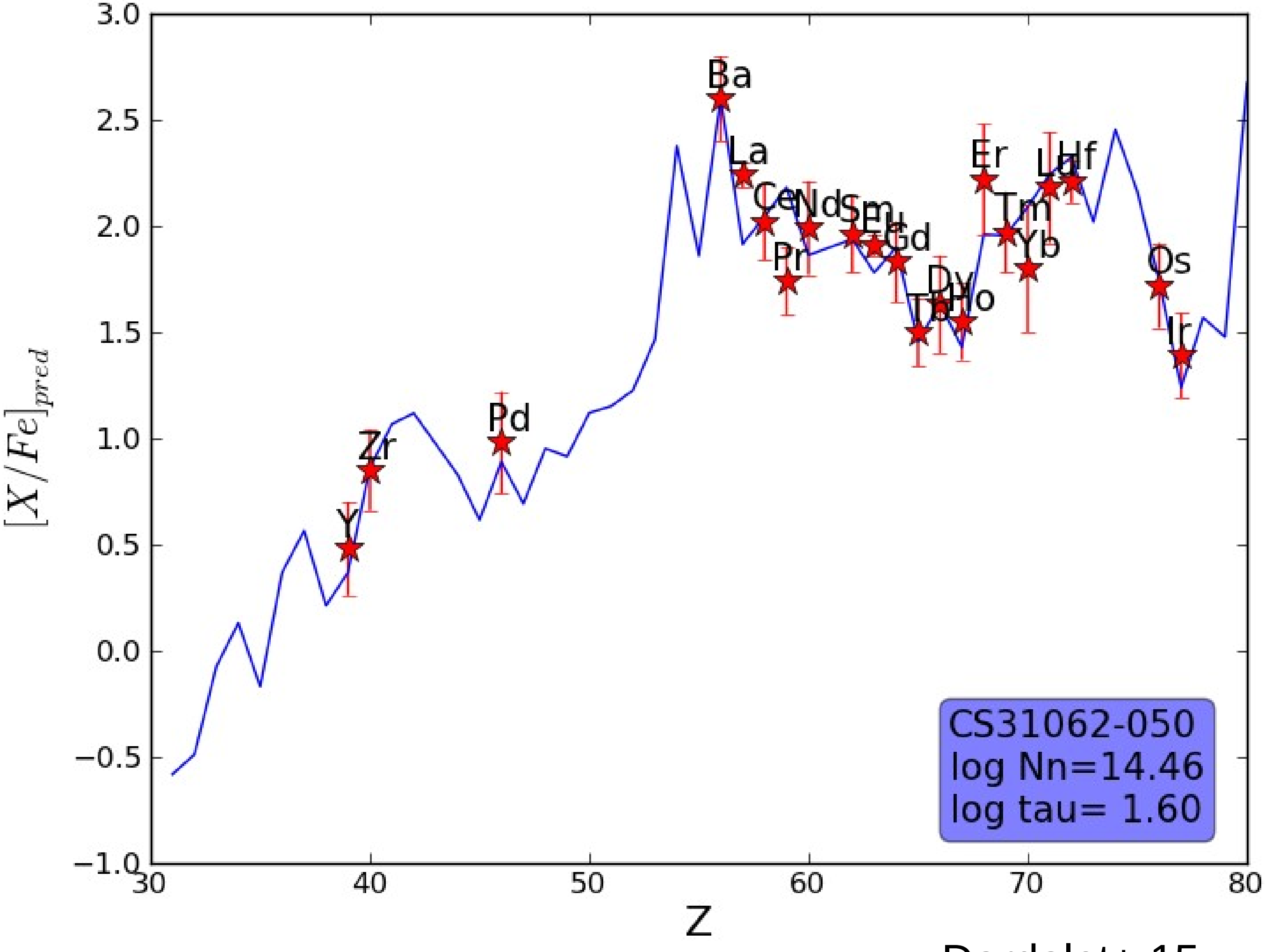
- MESA implementation of 2-zone convective boundary mixing (CBM)
  - Comparison with internal gravity wave mixing profile from Denissenkov & Tout (2003)
  - 2-zone exponential model parameters have been calibrated with stellar and pre-solar grain observables




*Battino, Pignatari, Ritter+ (2016, ApJ rev. requested)*

# Observational hints of i process: CEMP-r/s stars

- I-process 1-zone model in good agreement with observed heavy-element signature
- Similar results for a good fraction of CEMP-r/s stars
- [hs/ls] ~ +1

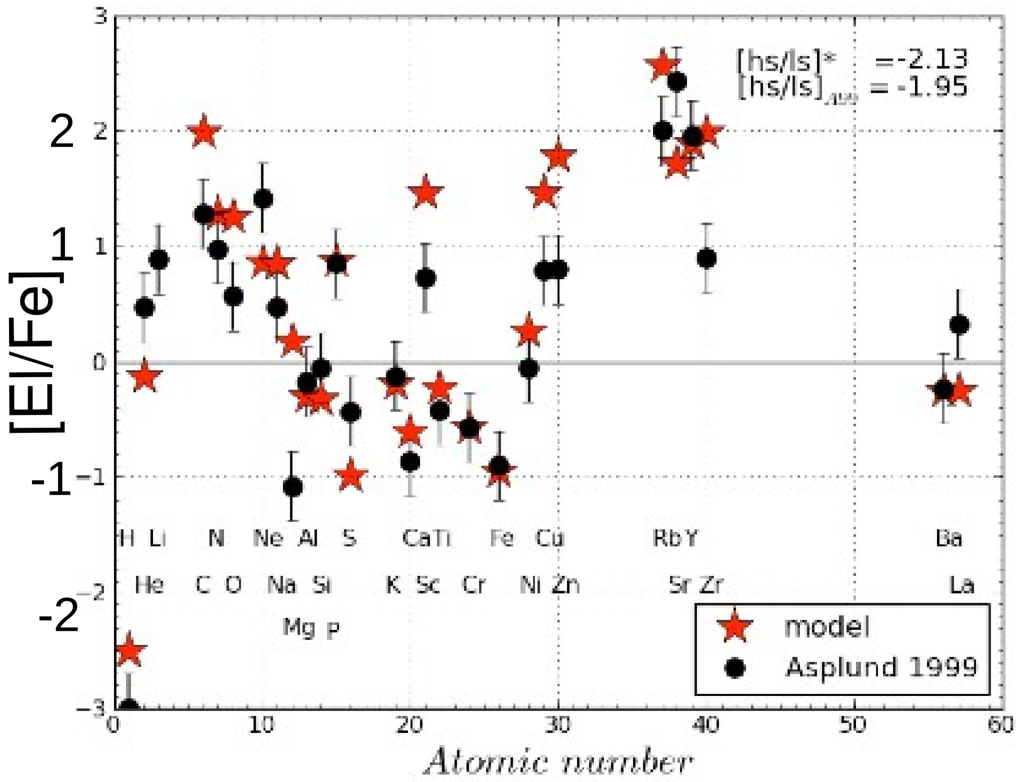



Dardalet+ 15

# More observational hints of i process

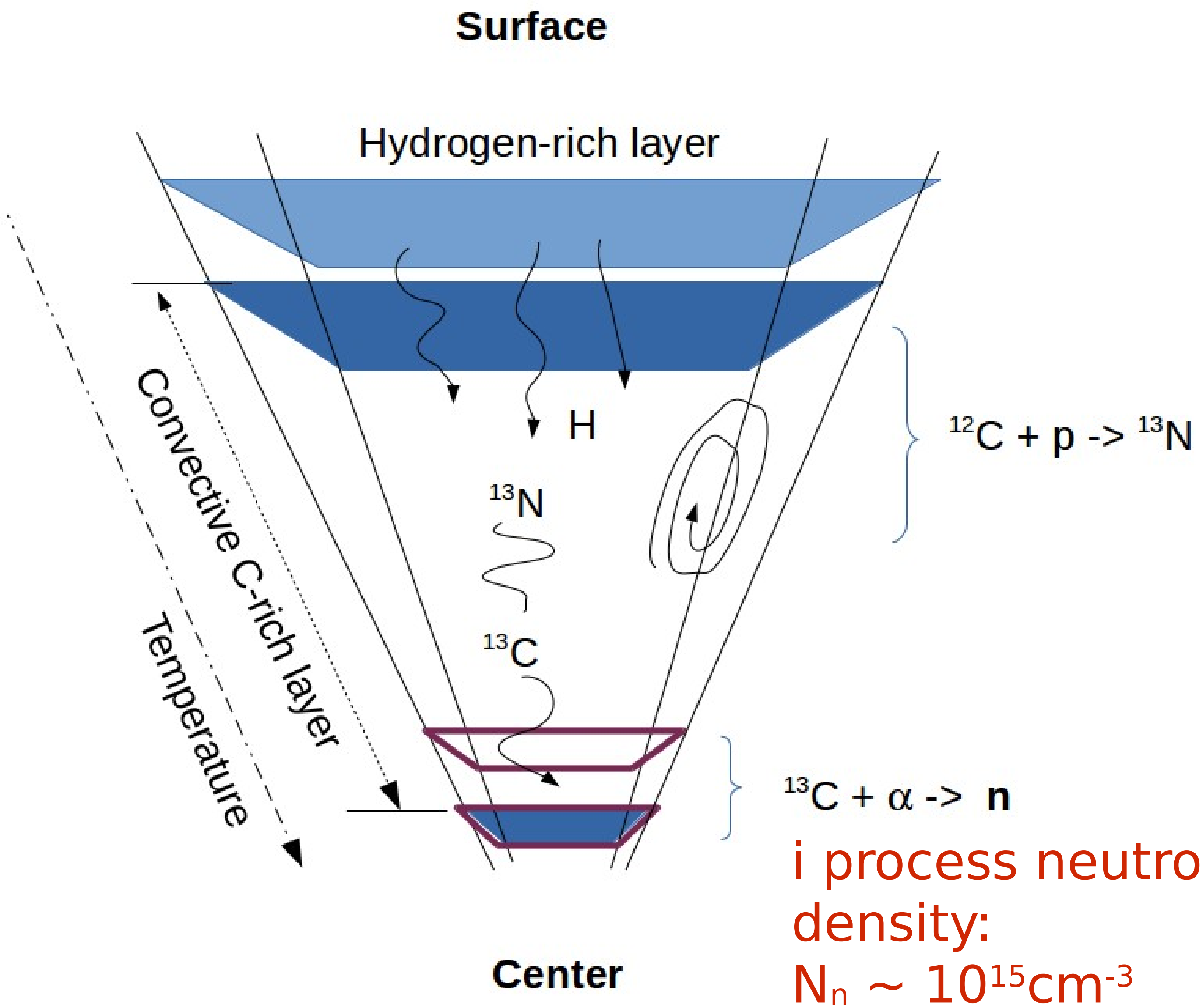
- Ba and La and their ratios observed in Open clusters (Mishenina+ 15)
- Low-Z Post-AGB stars in small and large Megallanic cloud, I process possibly common occurance at low-Z (Lugaro+ 15)
- Anomalous abundance in pre-solar grains (Jadhav+ 13, Fujya+ 13)
- Sakurai's object: Constraining i-process simulations with observations: elemental, isotopic abundances, light-curve and more

Observed abundance confronted with model




Herwig+ 11

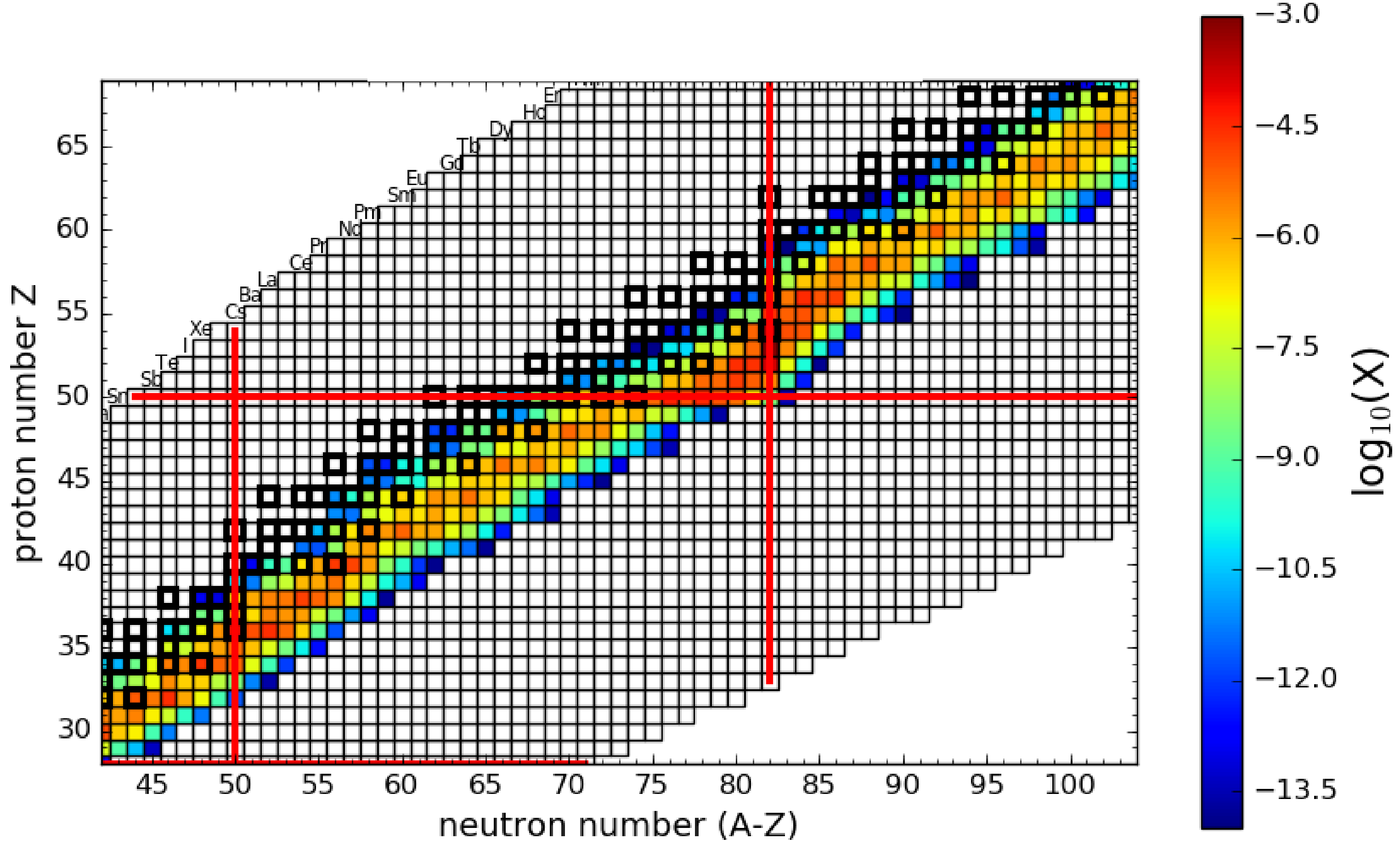
# The neutron source of the i process




i process neutron density:
$N_n \sim 10^{15} cm^{-3}$

# i process nucleosynthesis path in the isotopic chart

- I-process 1-zone model can explain some CEMP-r/s stars (Dardalet+15)
- T, rho, C12 typical for He-burning plus 1 to 5% H
- Nuclear physics challenge: involves many nuclear cross sections of unstable species




*Bertolli+ 13, Denissenkov+, Herwig+ in prep.*

# What are the possible sites of i process?

**Known sites:**

- He-core flashes (e.g. Fujimoto 2000, Campbell+ 10)
- He-shell flashes (e.g Campbell+ 08, Iwamoto+ 04, Suda+ 10)
- VLTPs (Herwig+ 11)

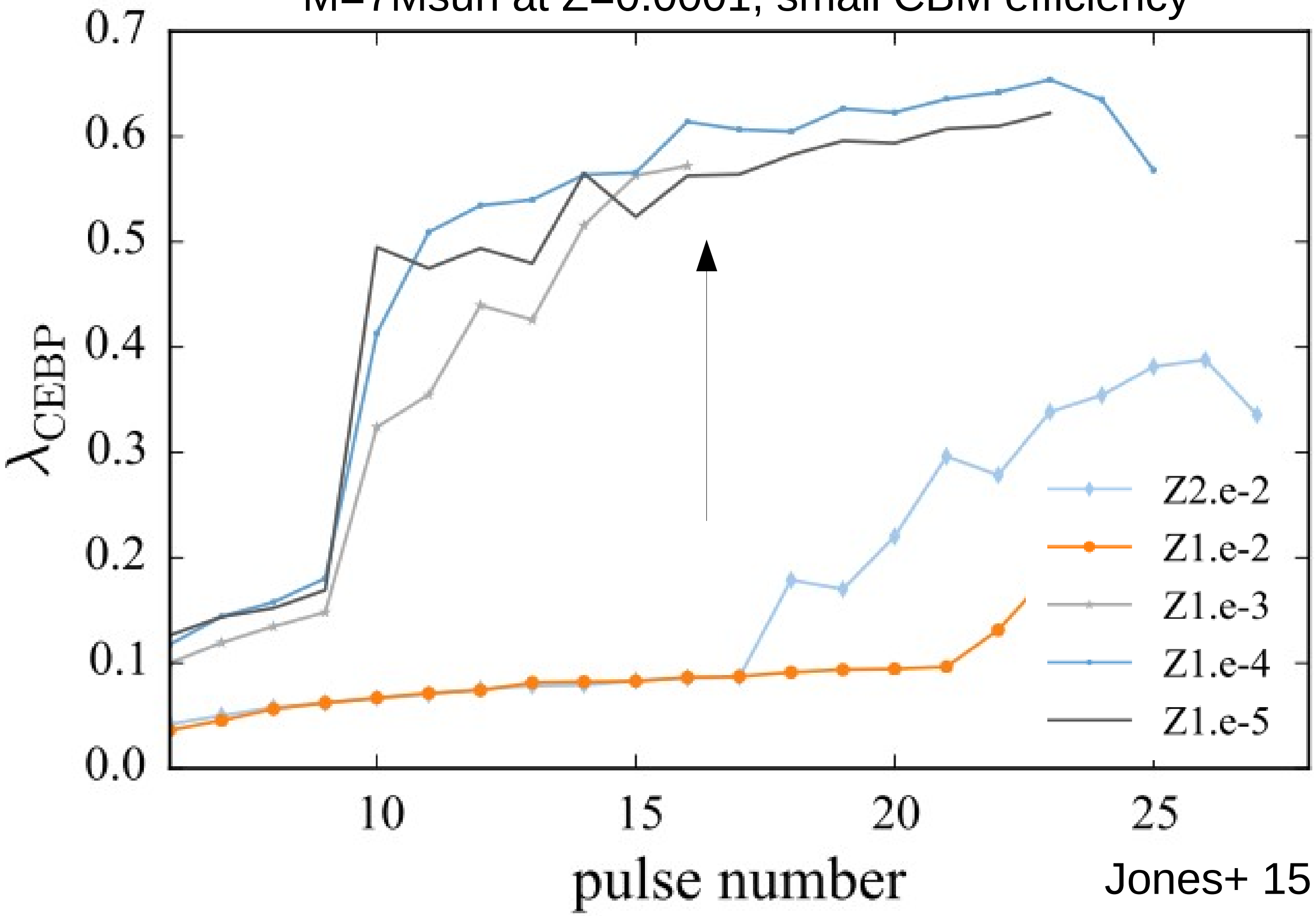
**New sites:**

- SAGB stars (Jones+ 15)
- Rapidly accreting white dwarfs (Denissenkov+ in prep)

# Super-AGB stars: evolution towards ECSN (?)

- Super-AGB stellar evolution models with CBM
- Generally: DUP efficiency increases for low Z
- This makes it more difficult to reach Chandrasekhar mass!

M=7Msun at Z=0.0001, small CBM efficiency



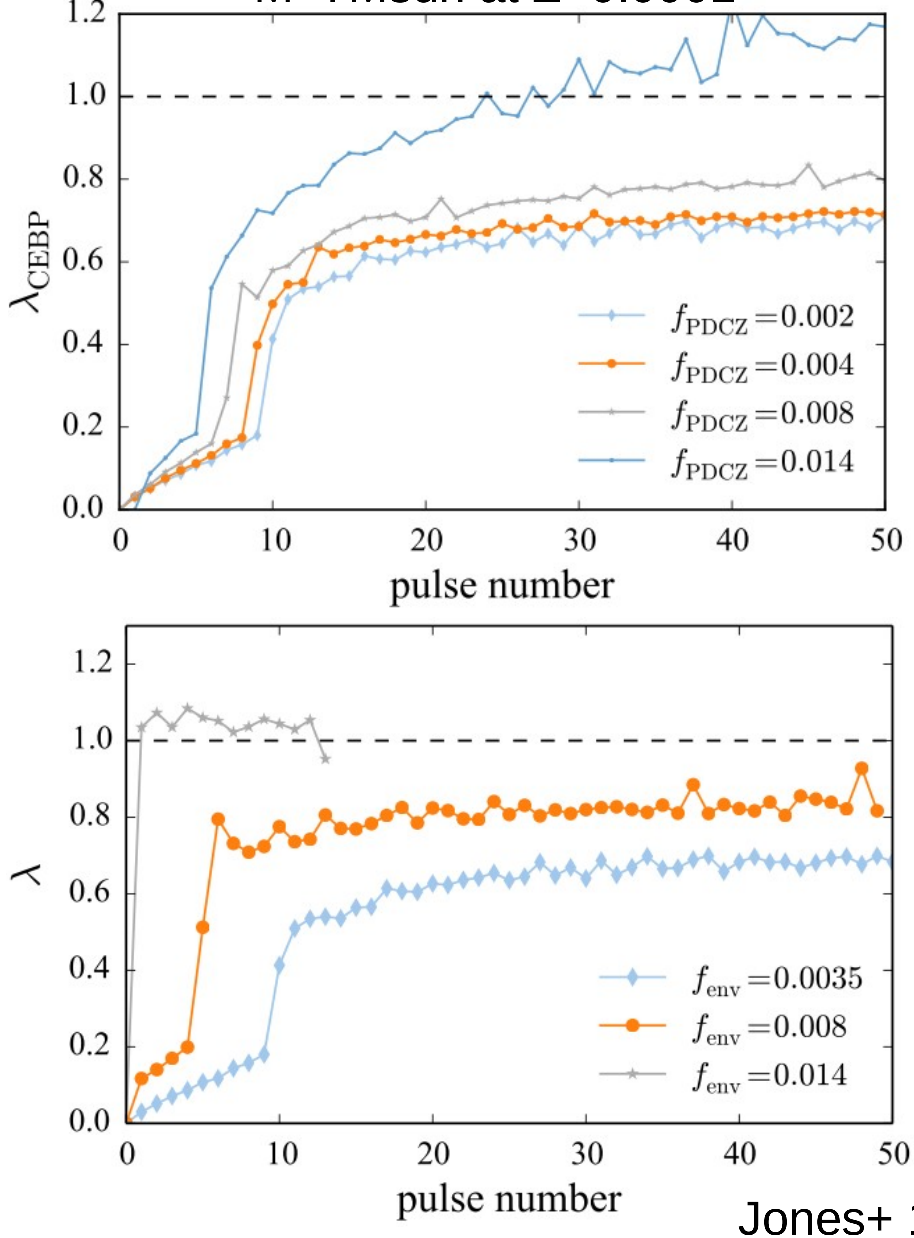

Jones+ 15

# Evolution towards ECSN

- Strong dependents of lambda on mixing efficiency below the PDCZ
- Strong CBM at the bottom of the conv. envelope also leads to stronger TDUP.

If DUP lambda close to 1 or larger then there is no path to ECSN!

M=7Msun at Z=0.0001

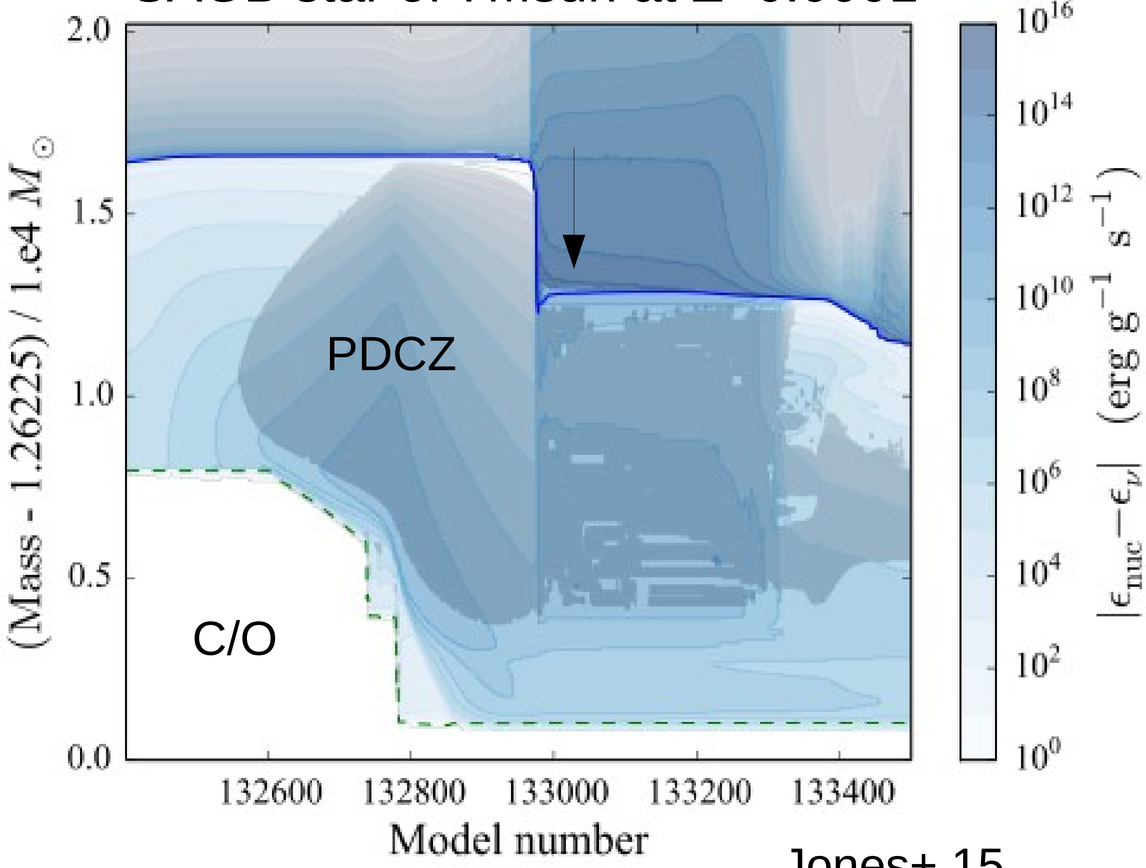



Jones+ 15

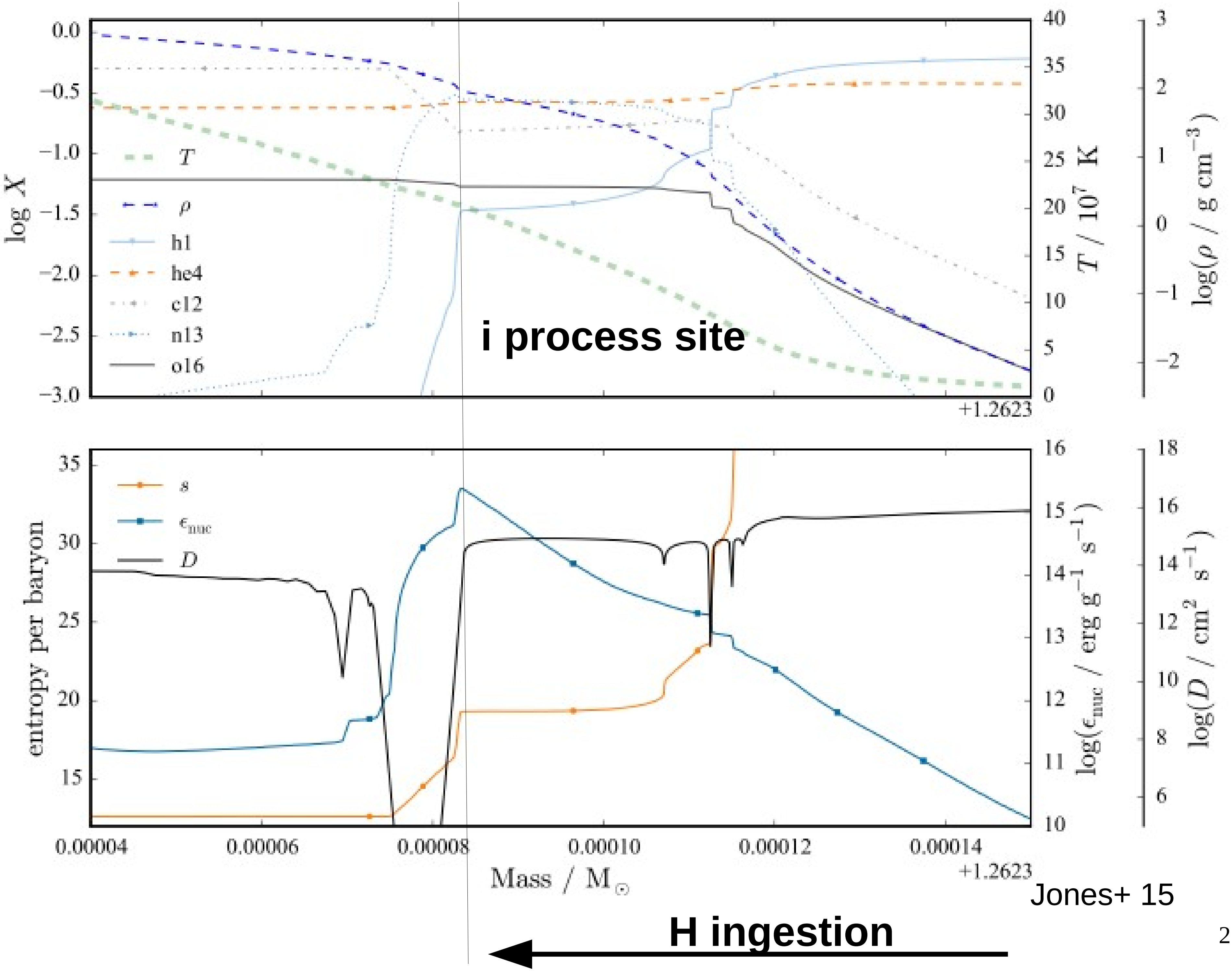
# New site: I process in SAGB stars

- I process during dredge-out & TP-AGB phase of SAGB stars
- SAGB stars with 1e-5<Z<0.02 evolve torward exchange of material

SAGB star of 7Msun at Z=0.0001




Jones+ 15


log X
T
ρ
h1
he4
c12
n13
o16
i process site
T / 10^7 K
log(ρ / g cm^-3)
+1.2623
entropy per baryon
s
ε_nuc
D
log(ε_nuc / erg g^-1 s^-1)
log(D / cm^2 s^-1)
Mass / M_⊙
+1.2623
H ingestion

Jones+ 15

# 1D fails to describe the HIF

Energy release violates hydrostatic equilibrium assumption.

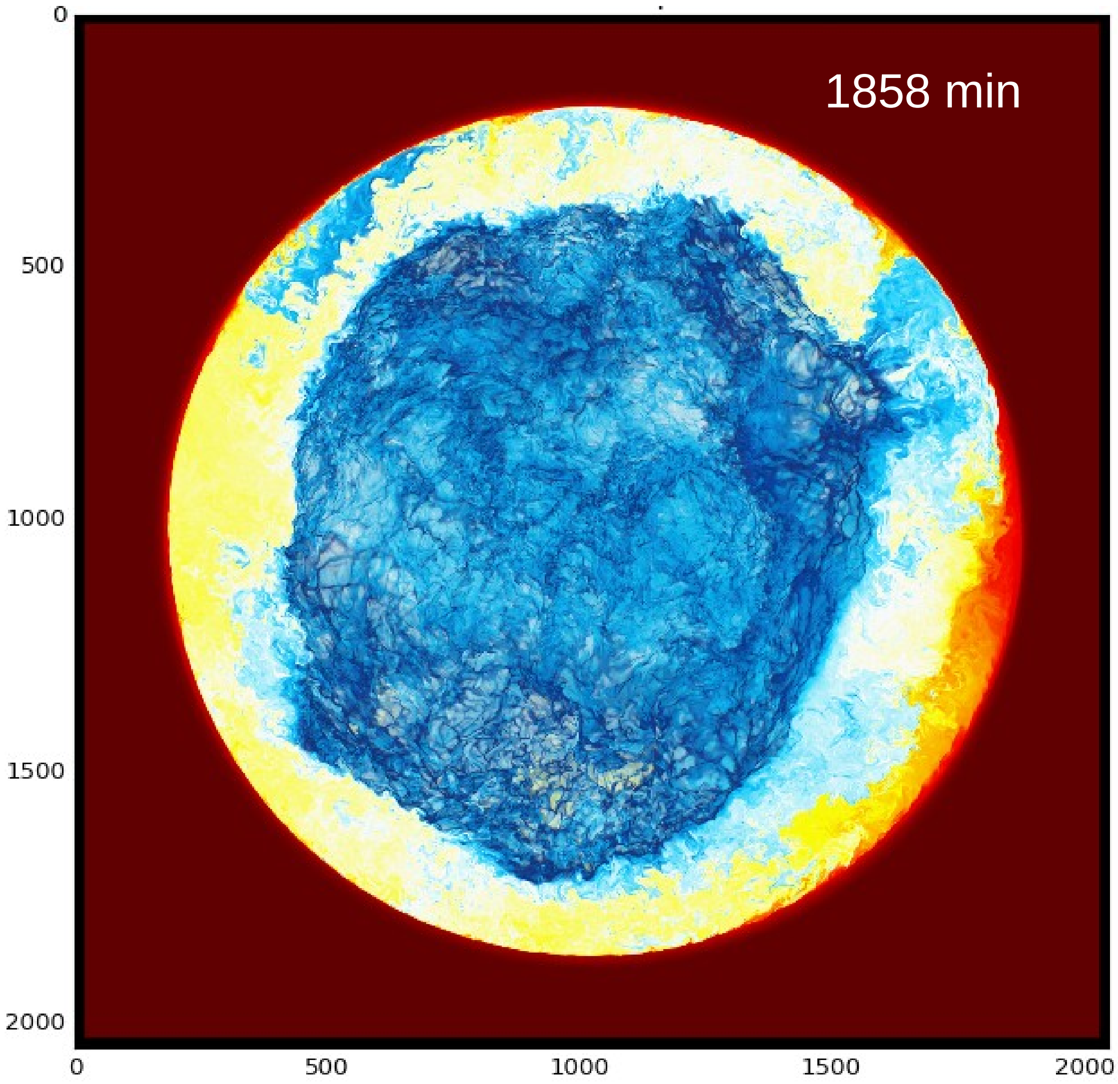
Energy feedback not included in mixing length theory.

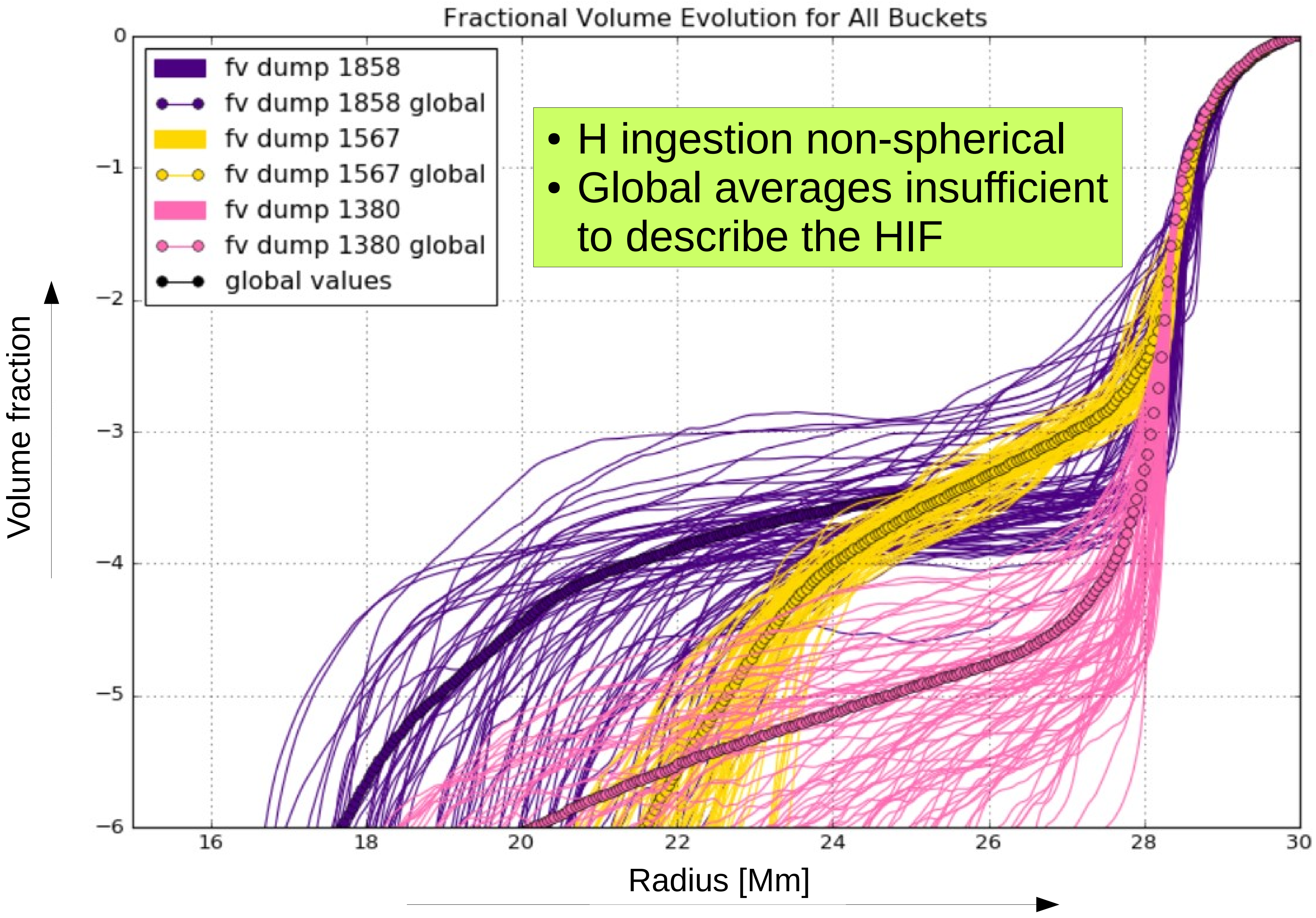
Need for 3D hydrodynamics!

Jones+ 15

# Low-Z AGB star with 3D hydro

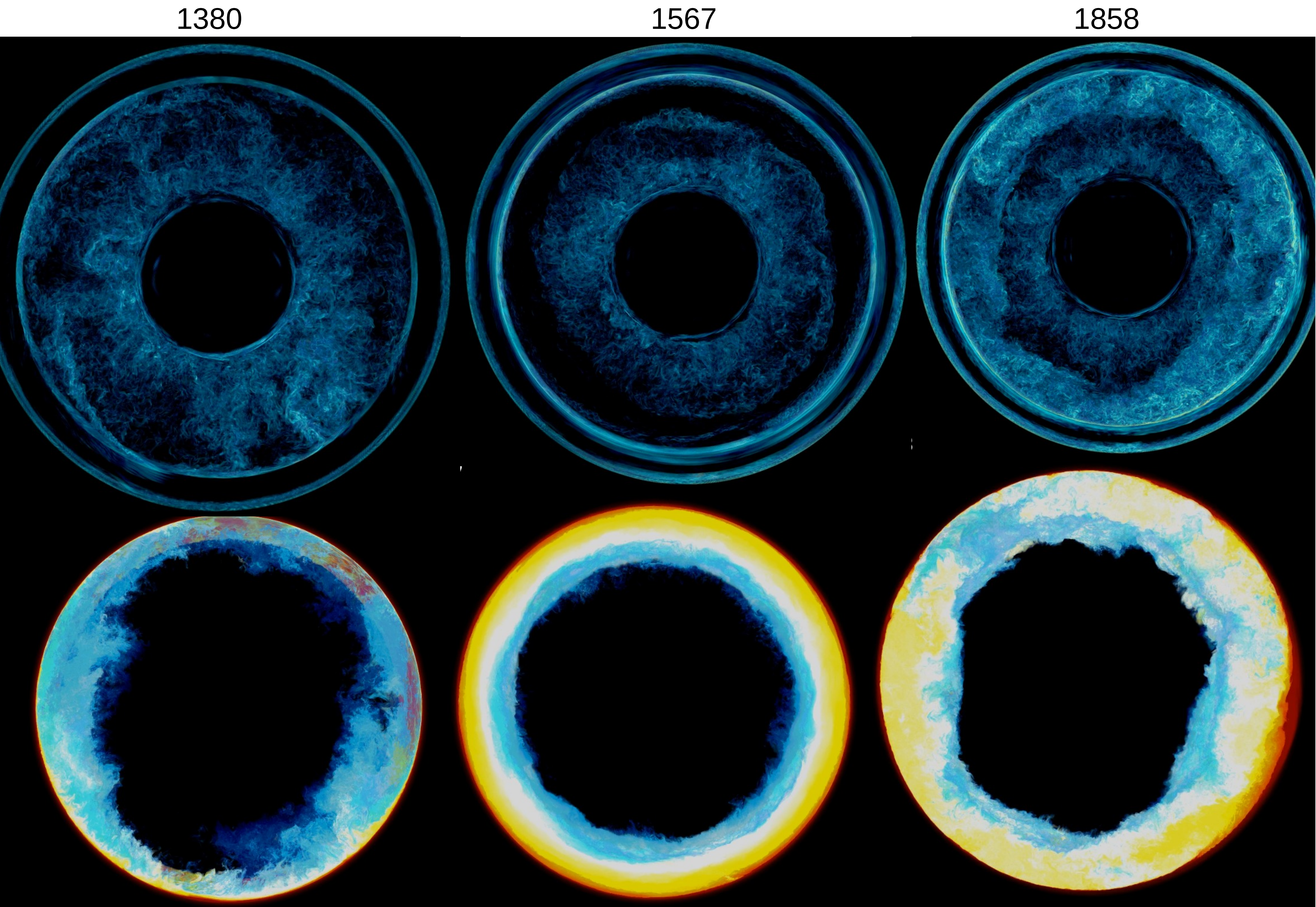
- 2Msun at Z=1e-5 in $1536^3$ resolution (Blue Waters)
- One hemisphere showing entrained H-rich gas
- Violent H burning: GOSH (Herwig+ 14, Woodward+ 15)






Sandalski+ 16, in prep.

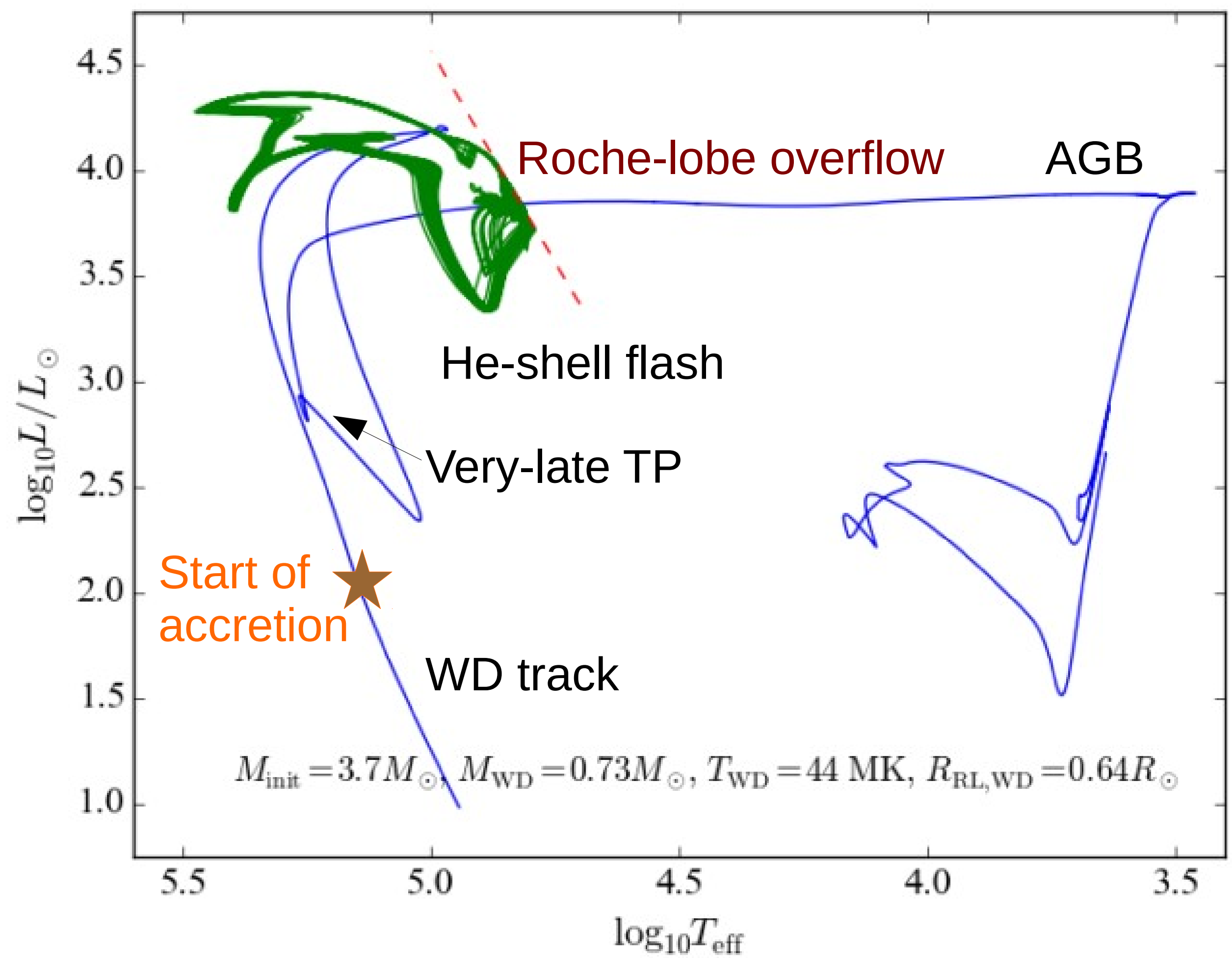
# Entrained H-rich material and vorticity for low-Z AGB



# Rapidly accreting white dwarfs (RAWD): A new i-process site

Single degenerate channel for SNIa

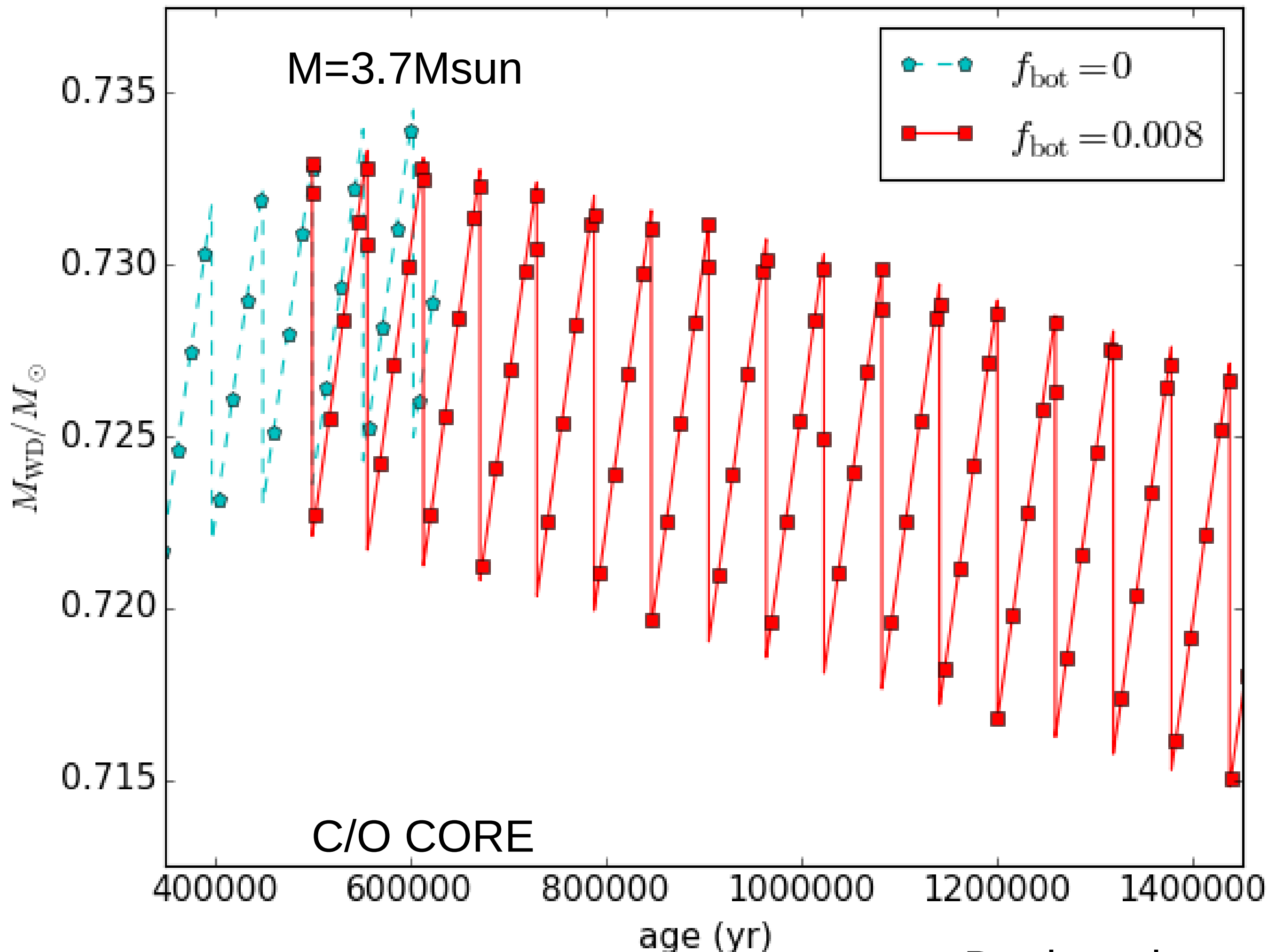
- Stable H-shell burning but He-shell flashes! (Cassisi+98)
- First multi-He-flash RAWD simulations (Denissenkov+16,in prep.)




Denissenkov+ 16 in prep

# SD channel as a candidate for SNIa?

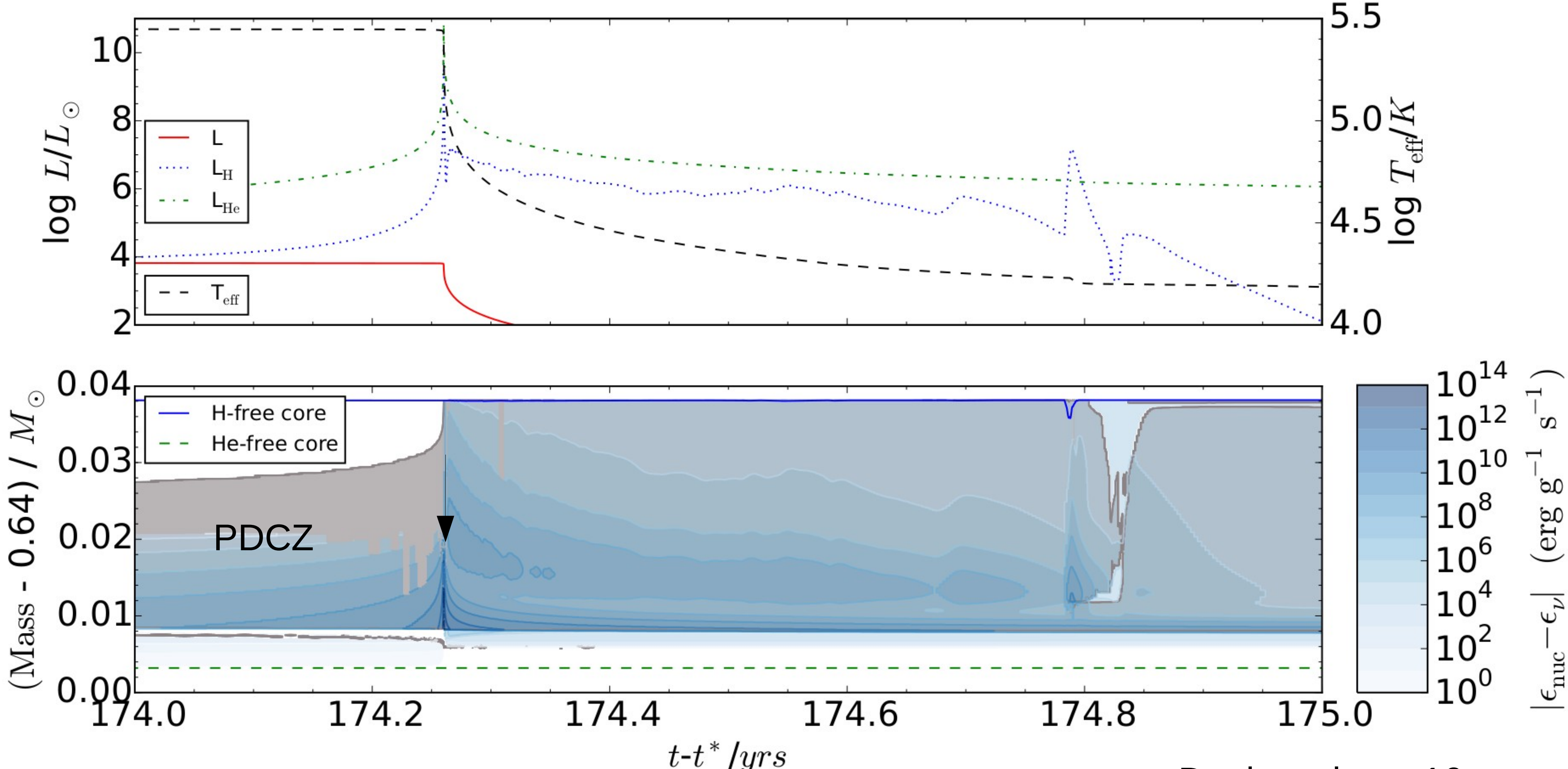
- 10% or less retention efficiency
- In some cases even negative retention rates




Denissenkov+ 16 in prep

WD cannot explode as SNIa!

# H-Ingestion flashes




Denissenkov+ 16
in prep

Found in **ALL** He-shell flashes

Normal HIF Like in Sakurai & low-Z AGB stars

(Herwig+11, Suda+10)

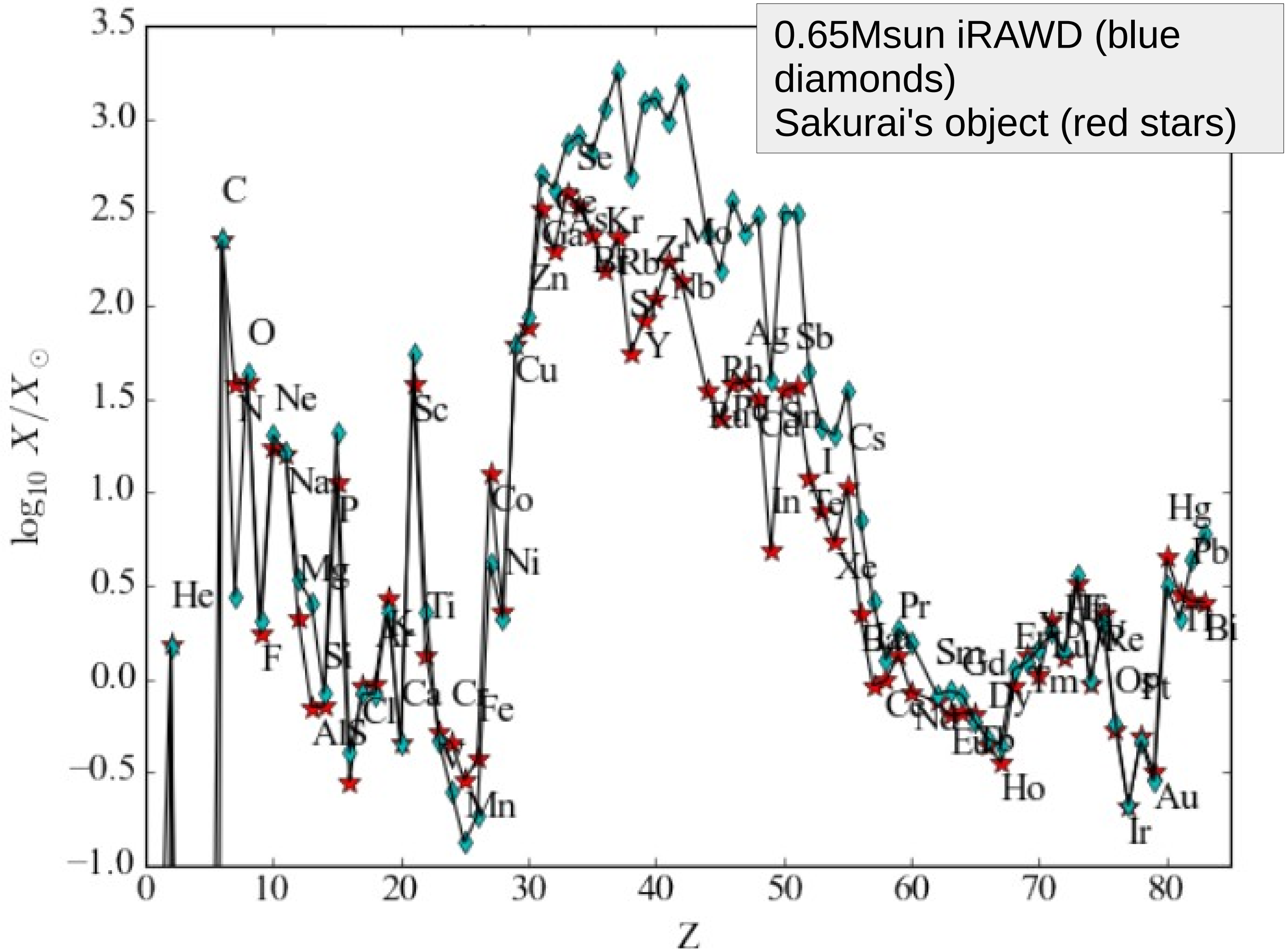
# Multi-zone simulation of i process in RAWDs

- Rapidly accreting white dwarfs with i process:

  **iRAWDs**

- Most i-process material is ejected into ISM due to low retention rate

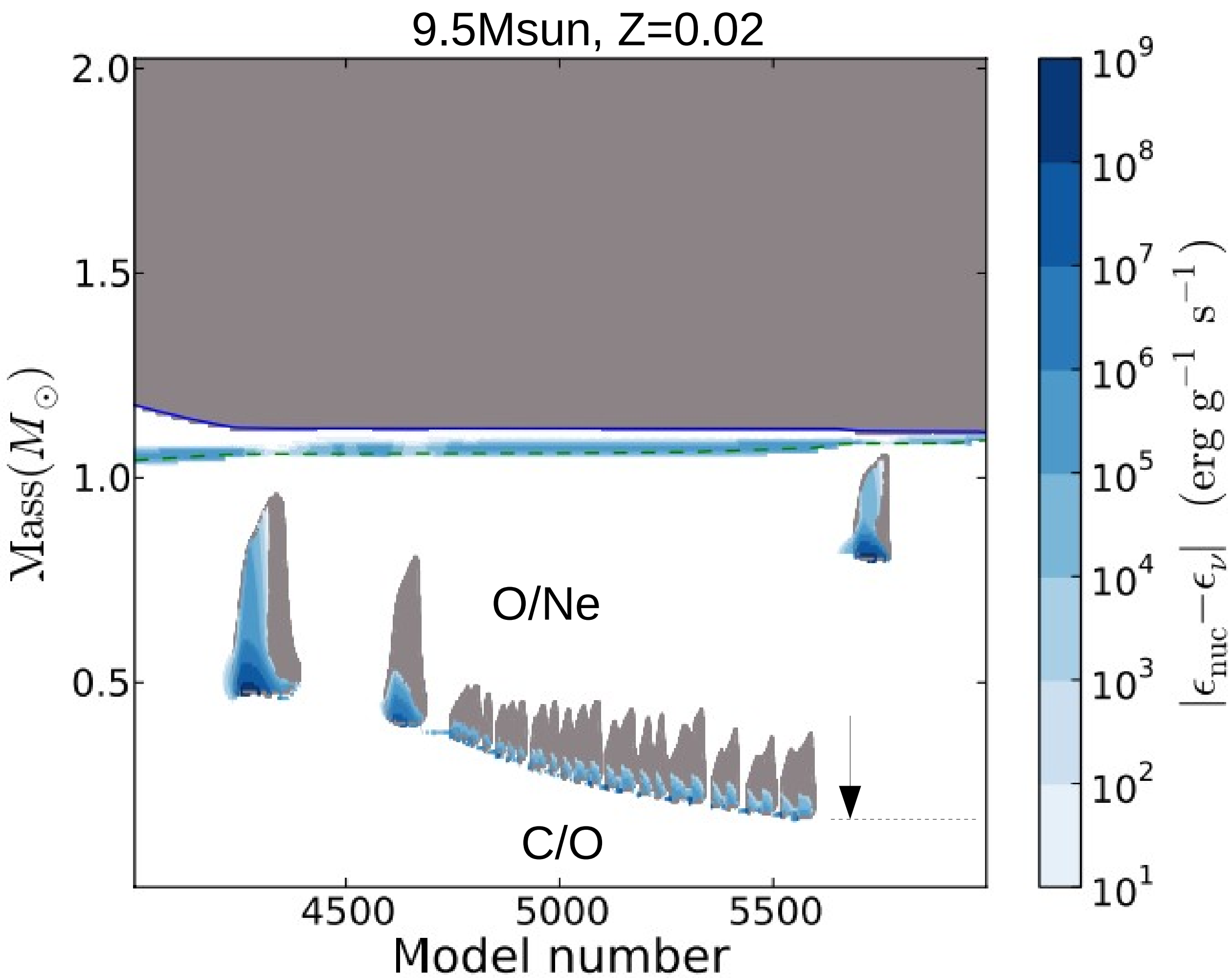
- Estimates indicate first-peak iRAWD production to GCE similar to AGB contribution




Denissenkov+ 16 in prep

# What are Hybrid WD's?

- In SAGB stars with CBM the C-flame torwards center extinguishes
- C/O core left in center
- CONe "Hybrid" WD (Denissenkov+13, Chen+14)
- Study of hybrid WDs in wider parameter space by Farmer+15




Denissenkov+ 13

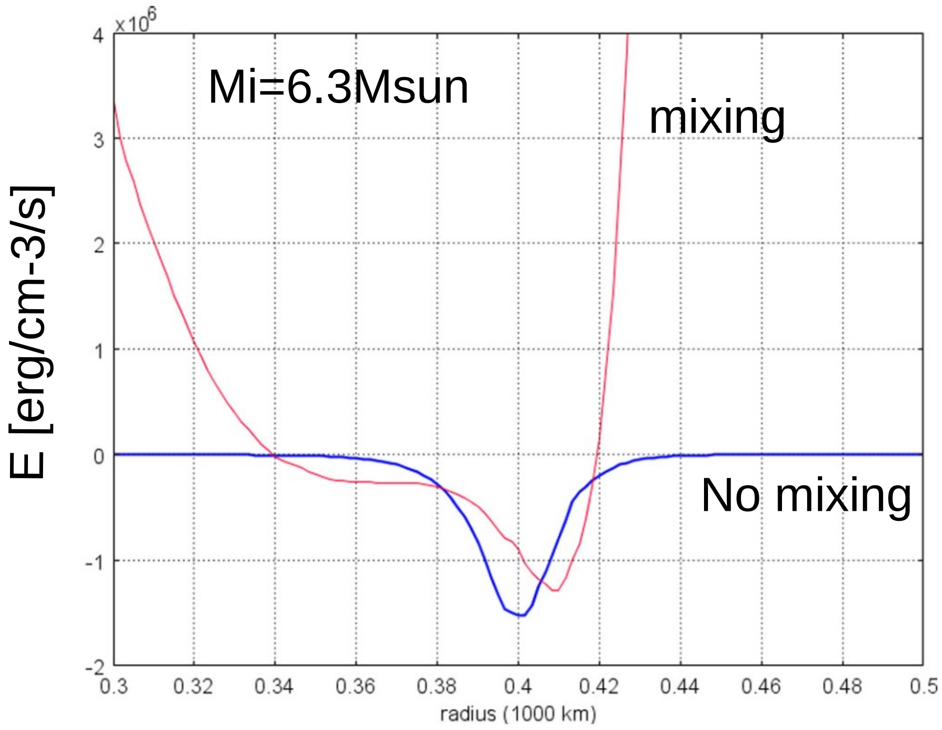
# Observable implications

- 1% to serveral % of SNIA might be a hybrid WD (Meng+ 14, Kromer+ 15)
- Youngest predicted SNIa of 30Myrs due to hybrid progenitor (Wang+ 14)
- Off-center SNIa explosion simulations with hybrid WD progenitors (Kromer+ 15, Willcox+ in prep) favoring faint SNIax

# Structure of acccreting Hybrid WD's

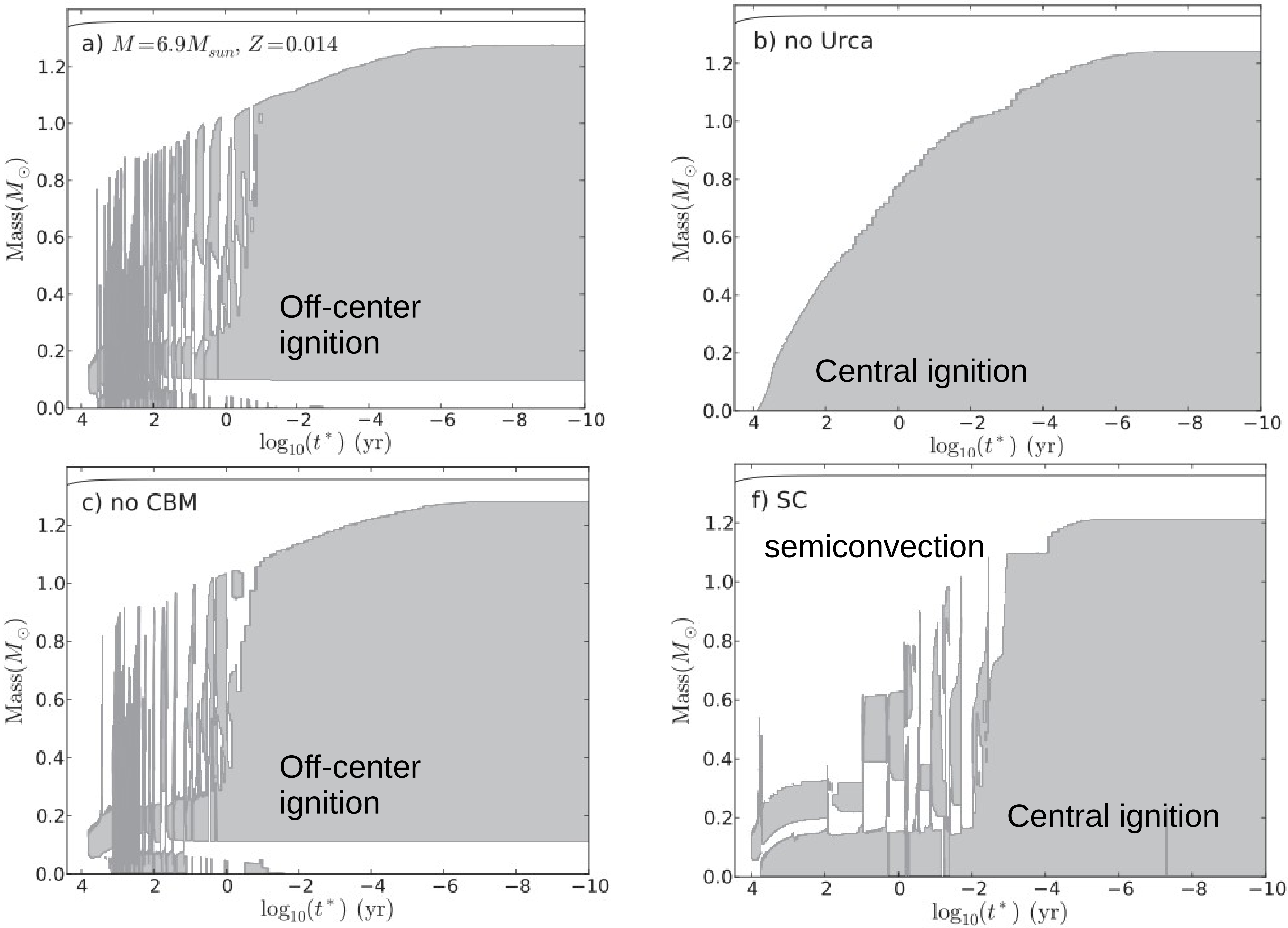
- Urca processes important for internal structure
- MLT not sufficient to describe Urca – convection interactions
- Need for reactive-convective 3D hydrodynamics

**Energy release due to Urca process**




Denissenkov+ 15

→ Can we estimate the impact of different outcomes of the Urca-process?

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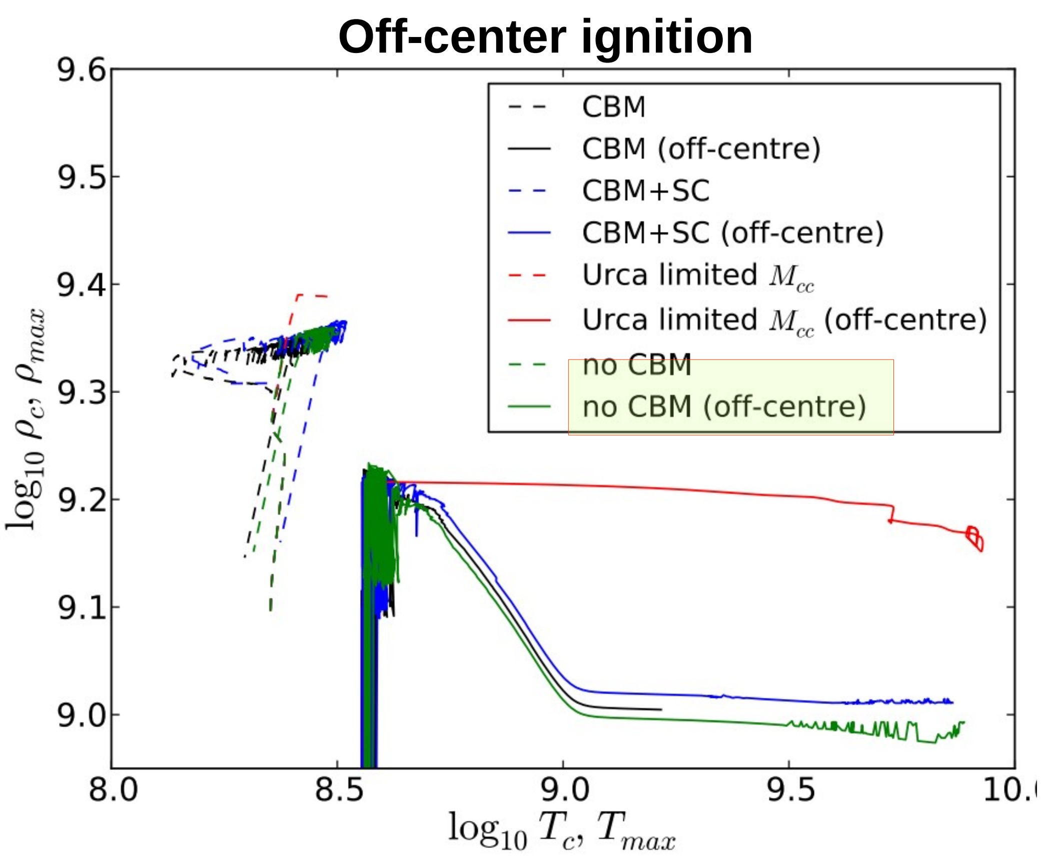
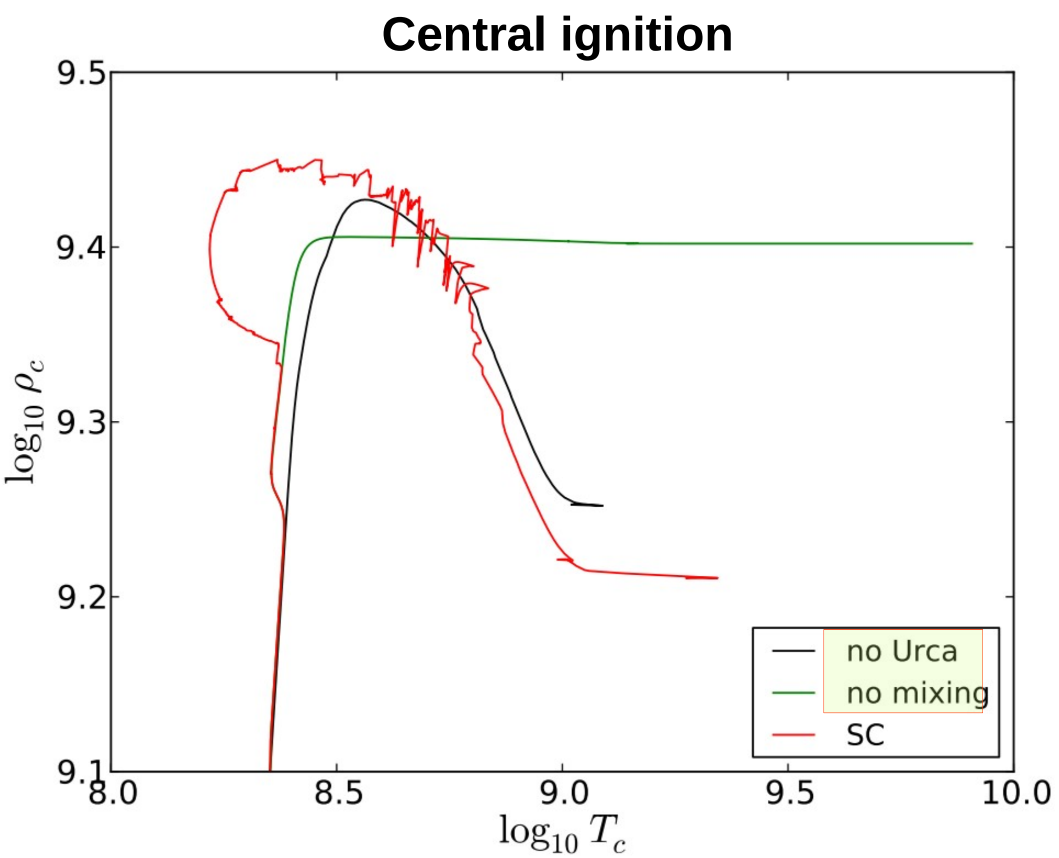
# A wide variaty of possible SNIa progenitor structures




Denissenkov+ 15

→ Large uncertainty affecting the progenitor model of SNIa!