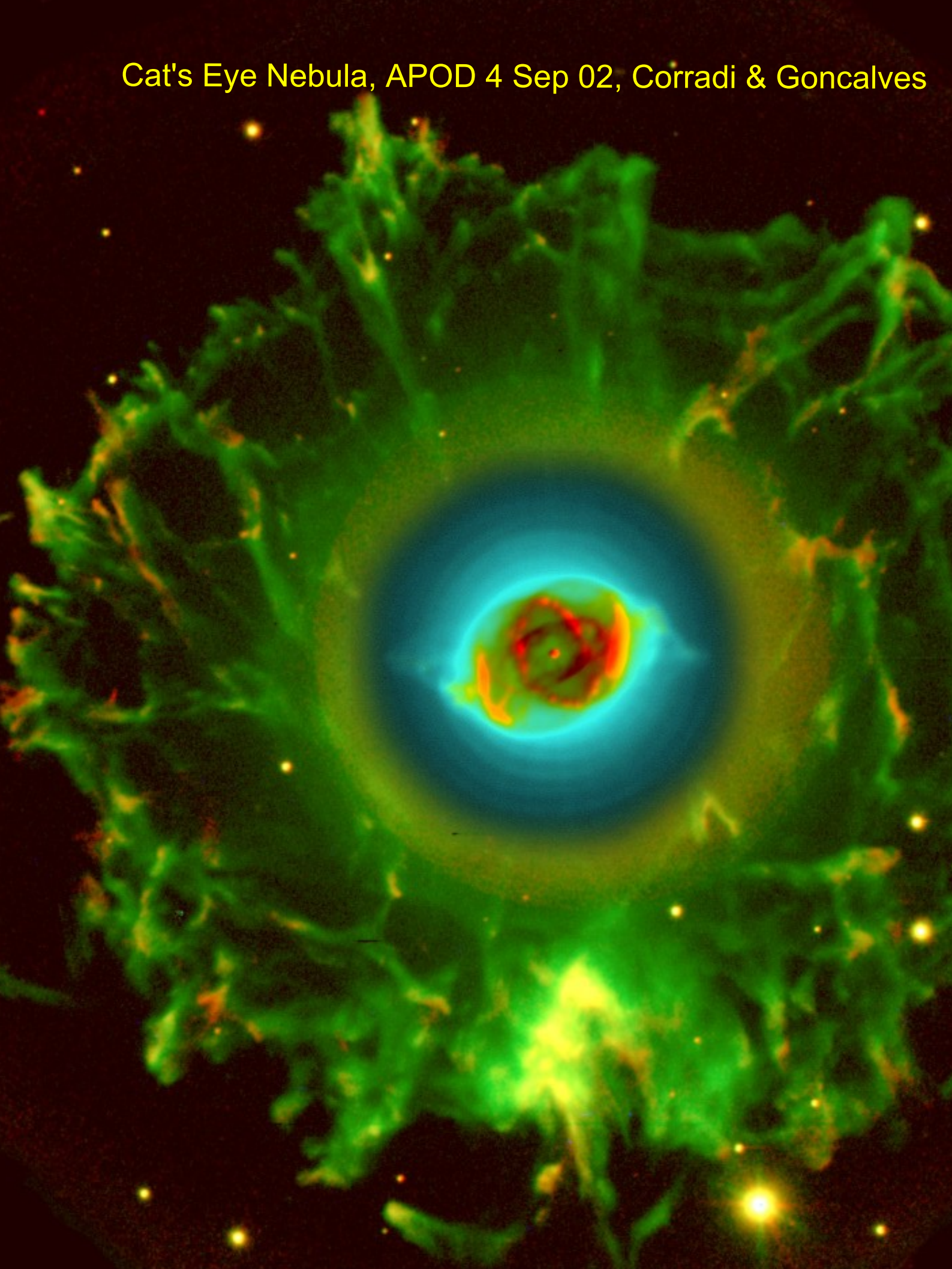
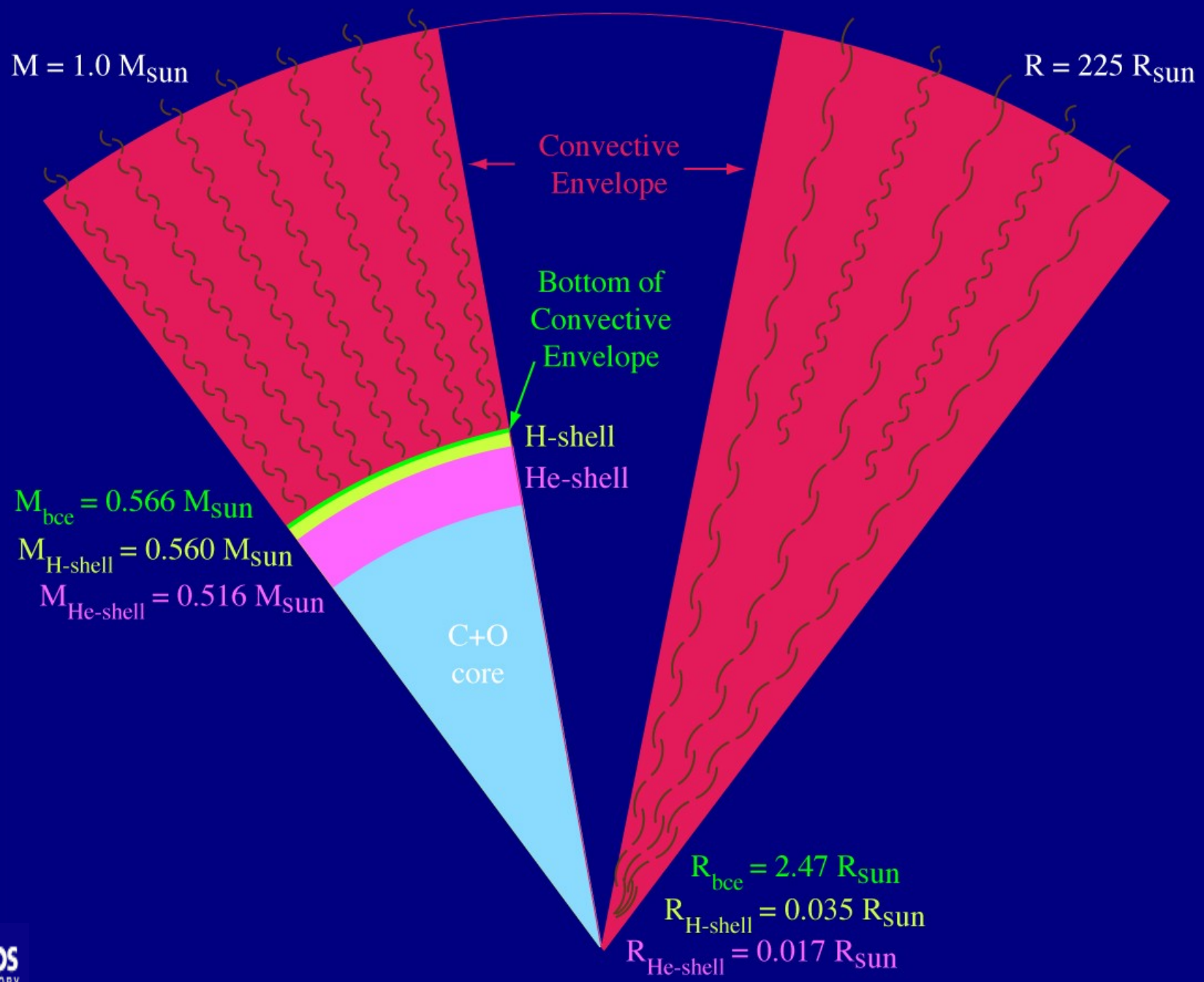

Cat's Eye Nebula, APOD 4 Sep 02, Corradi & Goncalves

Mixing, Nucleosynthesis, and Stellar Yields in Intermediate Mass AGB stars

Falk Herwig

Los Alamos National Laboratory, New Mexico, USA
Theoretical Astrophysics Group and
Los Alamos Neutron Science Center

Global Structure of an AGB star



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Why are we interested in AGB stars?

- Probes of (extra-galactic) stellar populations
- Main nuclear production site of the s-process: half of all trans-iron elements.
- Progenitors of (Central Stars of) Planetary Nebulae and White Dwarfs.
- Study Nucleosynthesis and Mixing processes in AGB stars: e.g. interplay of overshooting, rotation and magnetic fields.
- The Role of AGB stars at extremely- or ultra-low metallicity.
- Contribution of AGB stars to Chemical Evolution of Galaxies.

Stellar evolution in

Predictor vs Corrector Mode

Application vs Validation & Verification Mode

Each topic (s-process, EMP stars, mixing processes, progeny etc) can be addressed in both modes:

Can lead to new problems to work on or to work on the same problem and ask different questions ► progress?!?!??!?!

Synthetic vs Evolution Models

Synthetic Models:

- set of fitting formulae to properties of evolution models
- parameterization of properties of AGB star
- can be quantitatively better than evolution models
- can not include anything that has no been previously studied in evolution models
- relies strongly on calibrations

Evolution Models:

- solution of the full set of stellar structure and evolution equations.
- parameterization of physical processes in AGB stars
- still quantitatively in disagreement with observations
- still computationally messy

Synthetic vs Evolution Models

Synthetic Models:

- very usefull for the V&V approach: break down large observational body into easy to apply constraints for evolution models
- very usefull in stellar population models
- currently synthetic models can not be constructed for EMP/UMP

Evolution Models:

- include thermodynamic feedback of new or updated input physics
- investigate mixing and nucleosynthesis in EMP/UMP stars

Synthetic vs Evolution Models

Synthetic Models:

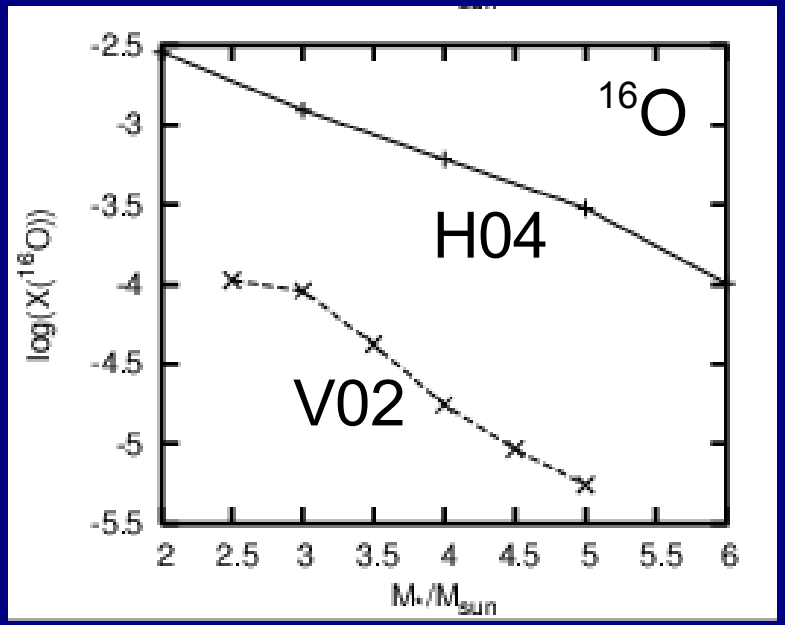
- Renzini & Voli (1981)
- van den Hoek & Groenewegen
- Marigo: most advanced, many observational tests, well calibrated (hybrid model)
- Izzard etal: specifically for application in rapid (=synthetic) binary code

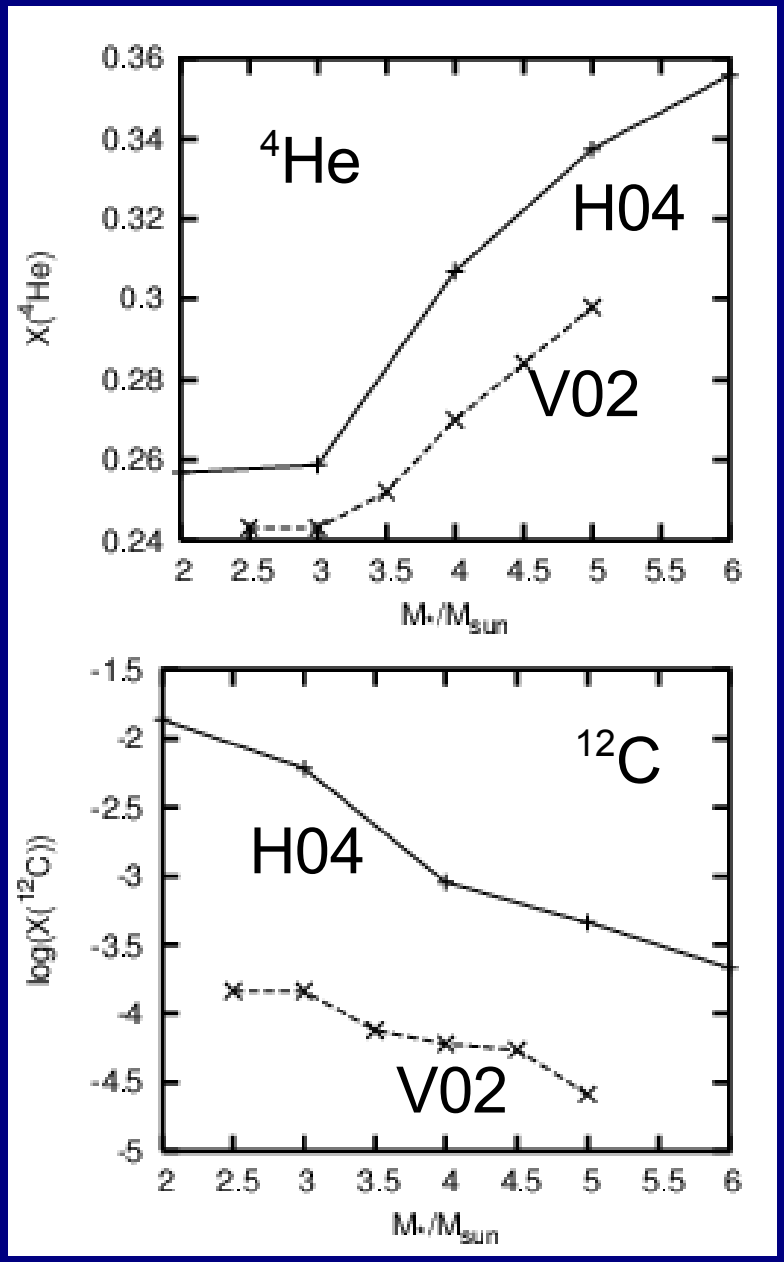
Evolution Models:
(only work specifically with yields in mind)

- Forestini & Charbonel (1997) calculated first TPs and then made synthetic ext. (hybrid)
- Lattanzio (not published)
- Karakas & Lattanzio(partly published, 2003, PASA)
- Ventura etal (2002) A&A, 393
- Herwig (2004), ApJS,155,

Ventura etal 2002 vs Herwig 2004

average X in ejecta

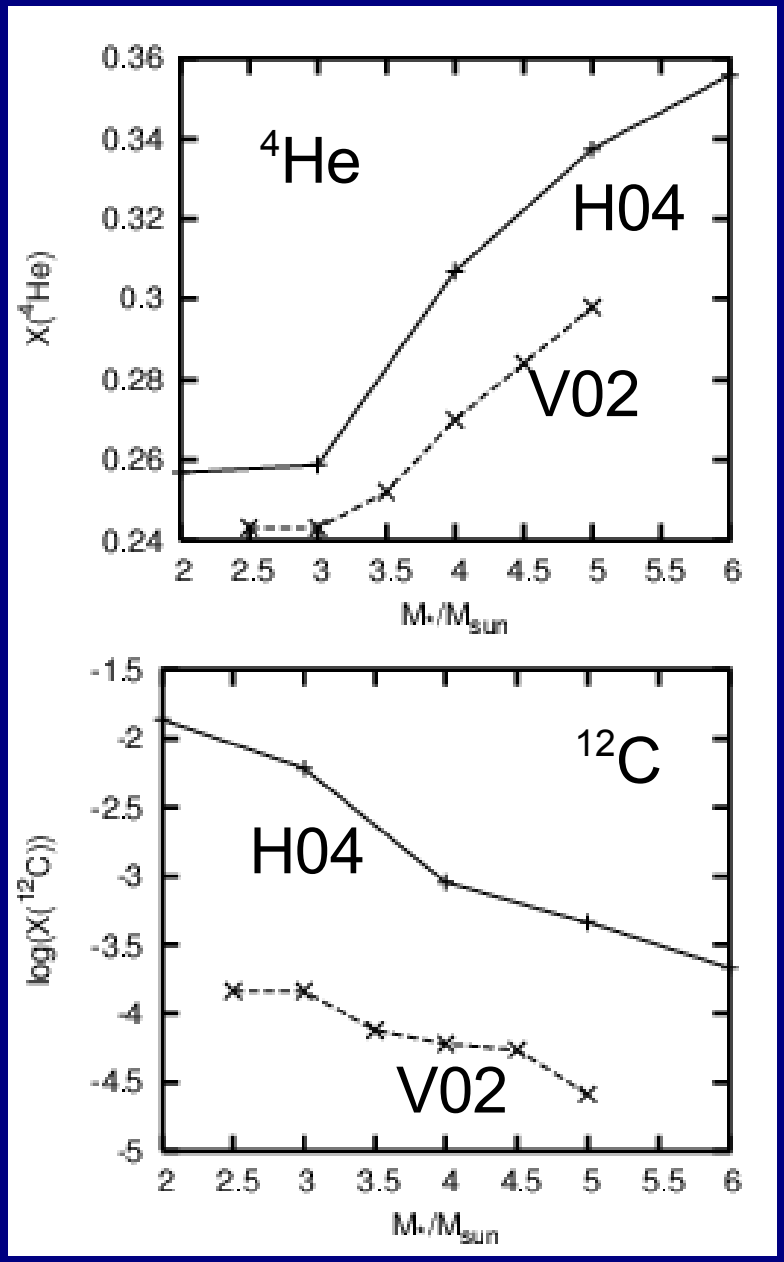




V02: Ventura etal 2002
H04: Herwig 2004

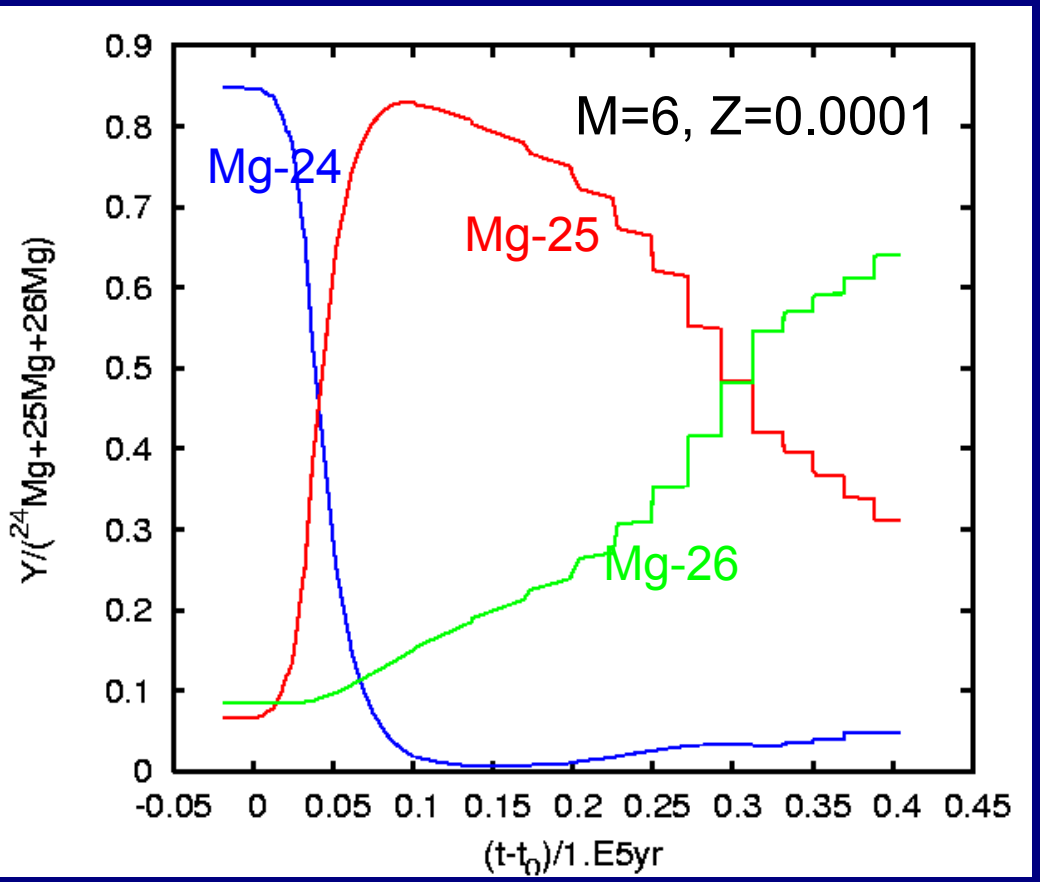
Ventura etal 2002 vs Herwig 2004

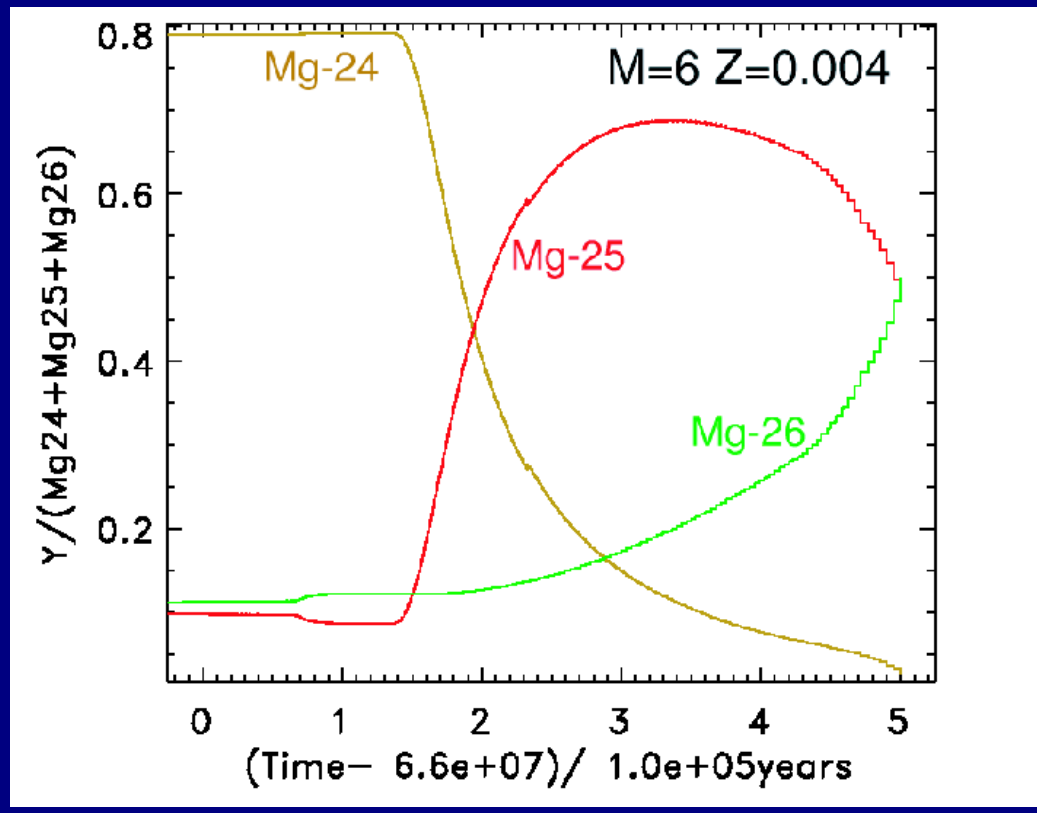
	V02	H04
dredge-up λ	0.2-0.4	~1.0
convection	FST	MLT
[C/Fe] @[Fe/H]=-2.3 (non-HBB)	0.9	2.6-3.0
species	He, Li, C, N, O	He, C-Si
s-process	no	approx.
Z	0.0002-0.01	0.0001



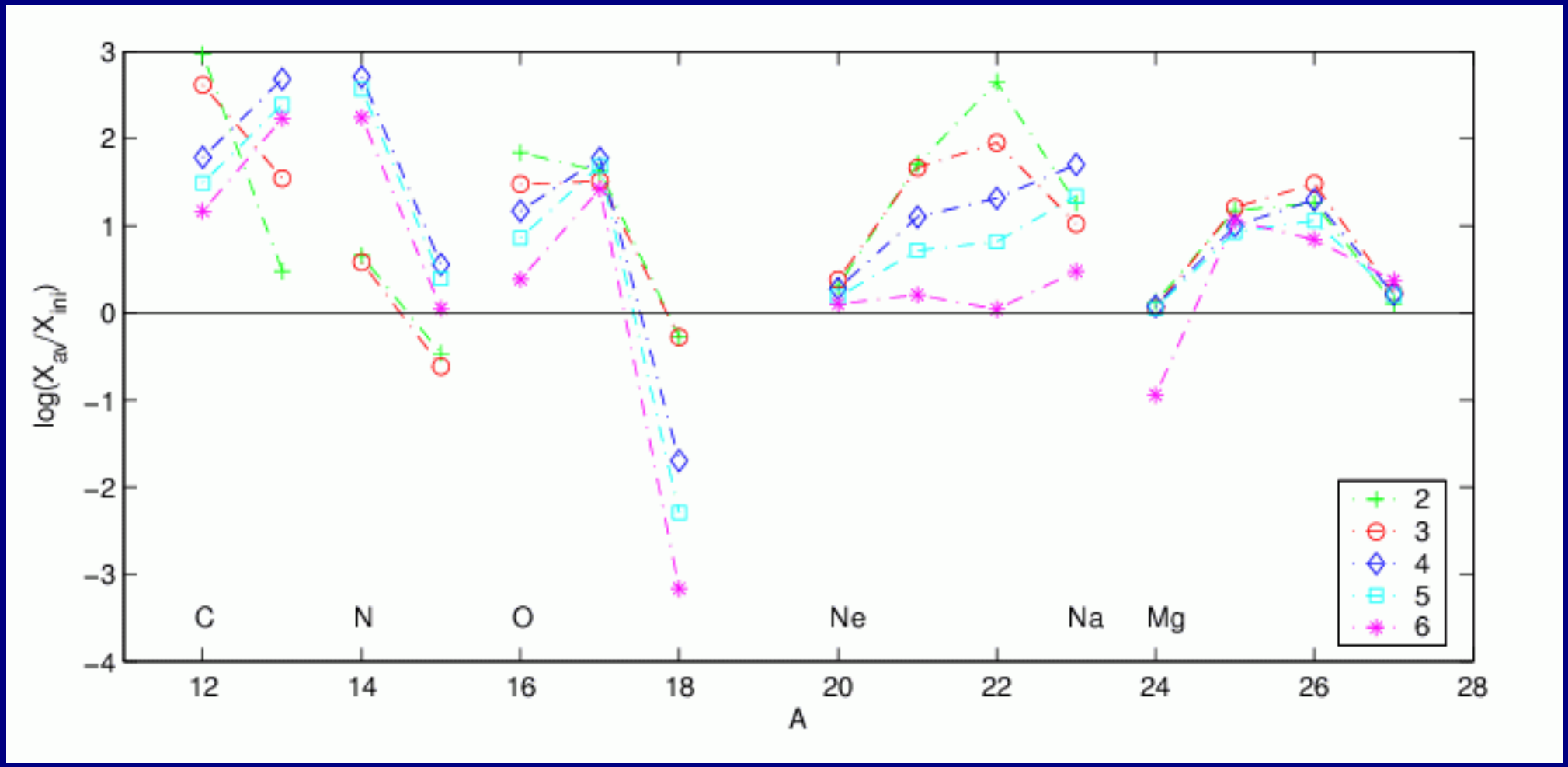
Karakas & Lattanzio 2003 vs Herwig 2004

	dredge-up λ	species	s-process	Z
K03	0.9	Na, Mg, Al	approx.	0.004-0.02
H04	~1.0	He, C-Si	approx.	0.0001





Intermediate Mass Star Nuclear Production @ Z=0.0001 ([Fe/H]=-2.3)



Herwig 2004, ApJS 155

Nitrogen: Where does in come from in (single) CEMP(-s) stars?

Remember Jennifer's talk!

- **Multiple Sources:** bubbles of IMS stars, no need to modify stellar models

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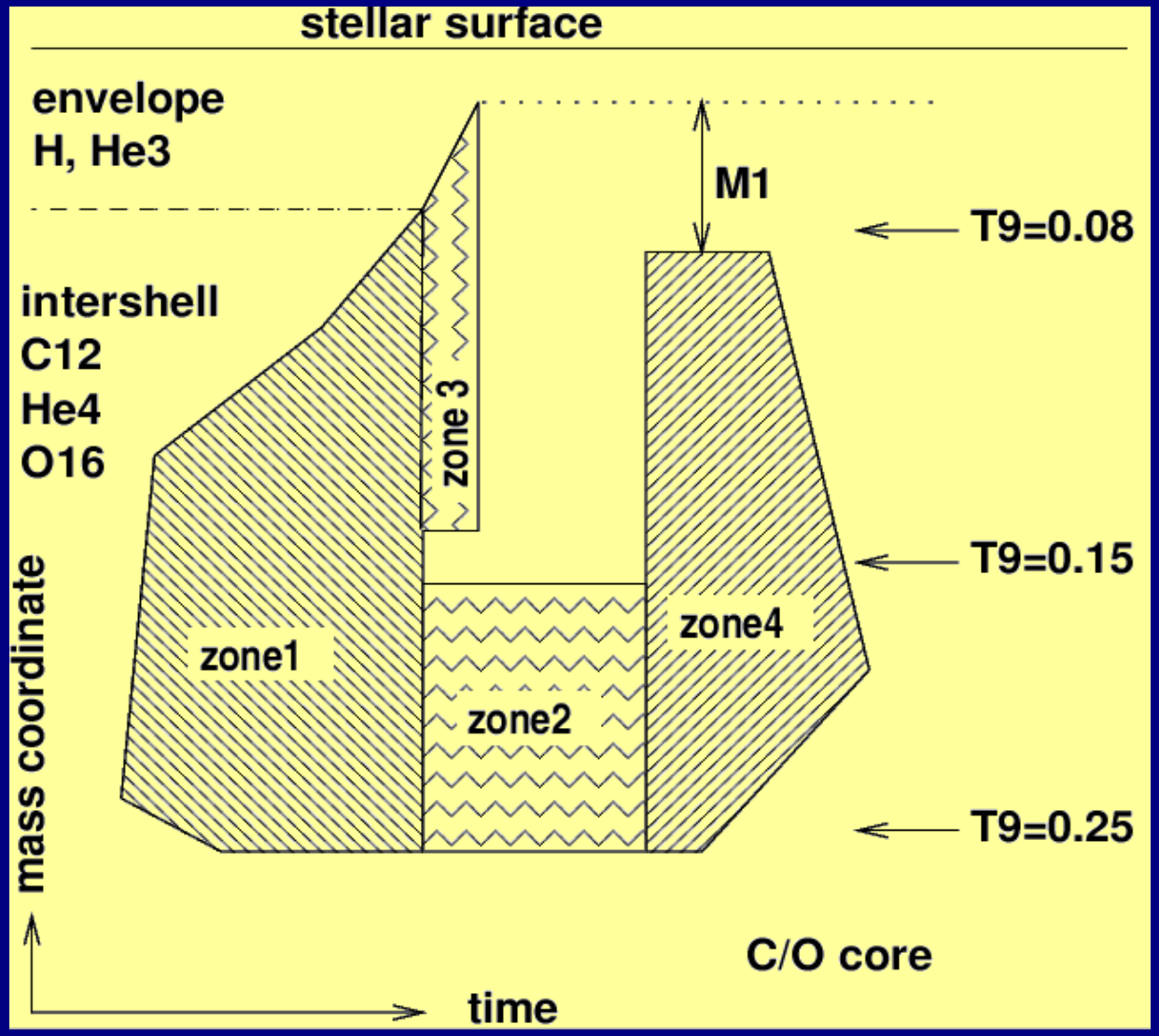
  - pre-AGB rotation (Meynet)
  - HIF: H-ingestion flash (Straniero etal)

Ultra-metal poor or Z=0 evolution:

- no CNO for CNO cycle
- H-shell very hot
- may show HIF (Hydrogen-ingestion flash)

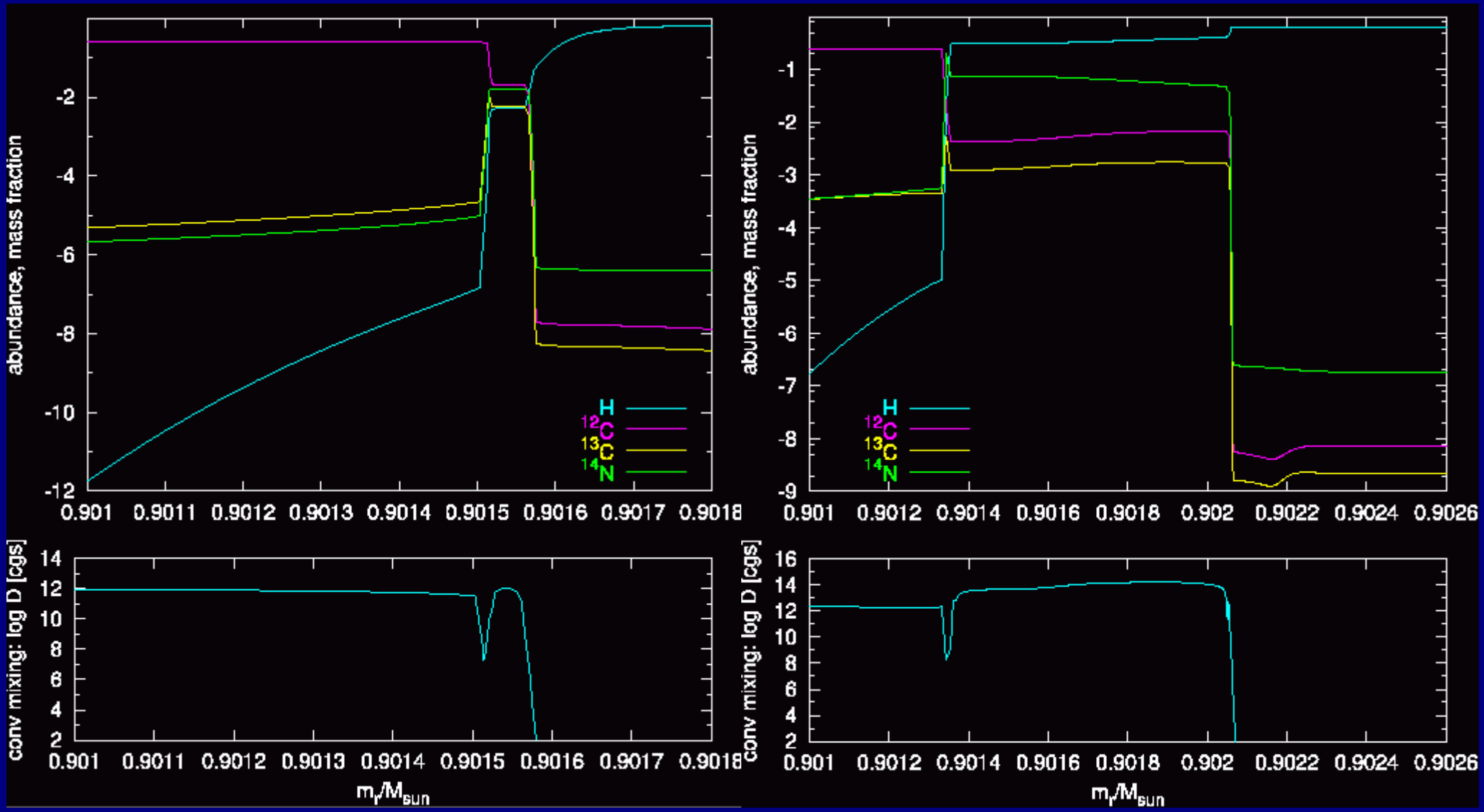


- Ingestion of H into He-flash convection (Fujimoto etal 2000, Herwig 2002, Iwamoto etal 2004)
- Known or suspected to happen in several other situations, e.g. young WDs (born again AGB stars)

Herwig etal 1999, Herwig 2001

- whether or not HIF occurs depends on excact interplay of convection, rotation and likely also magnetic fields
- and so does the exact morphology of the different zone
- this determines the nuclear evolution

$M=5M_{sun}$, Z=0.0, time sequence of profiles in H-flash region (on top of He-shell flash convection zone)



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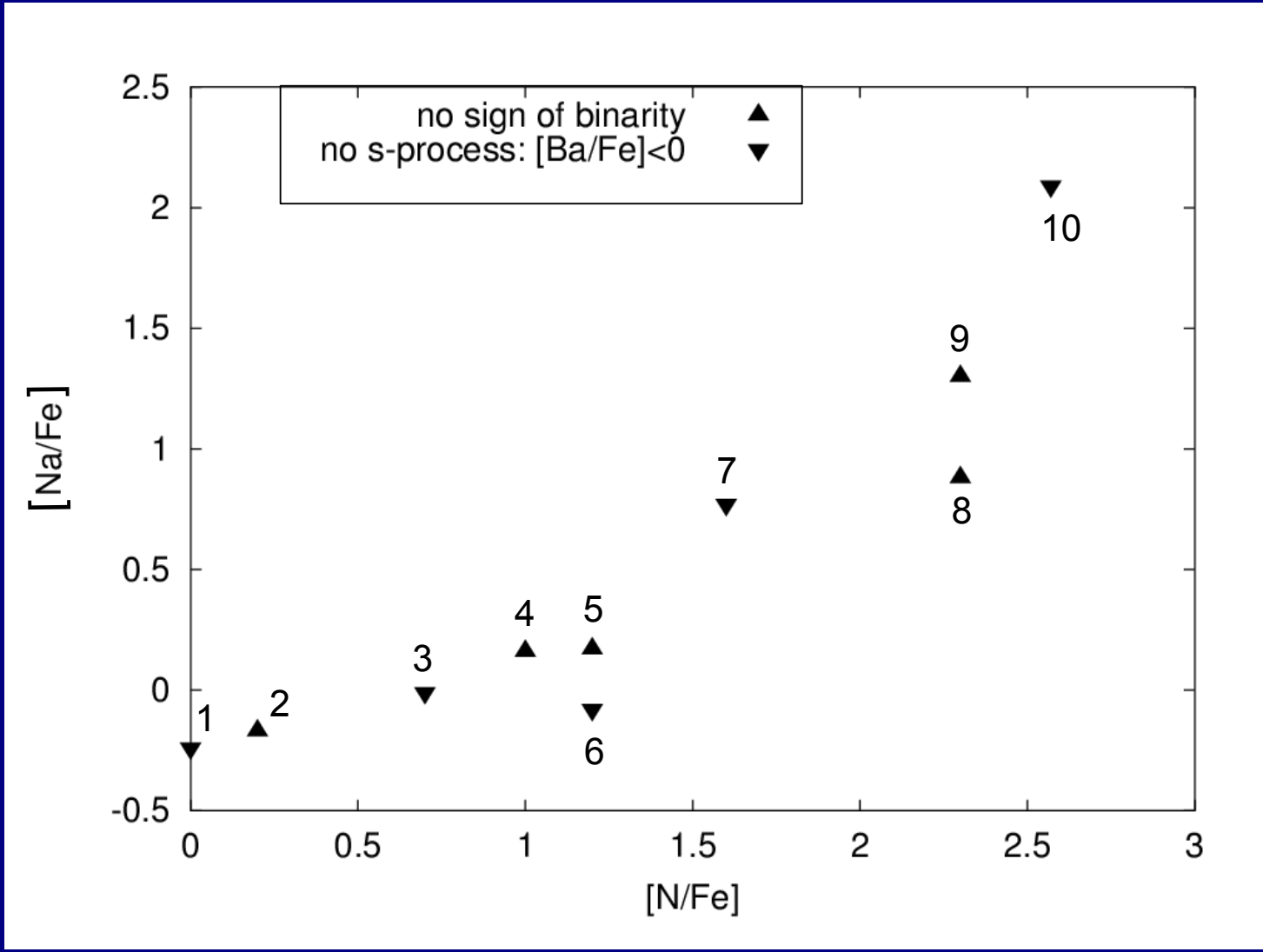
- **Single Source:**
  - pre-AGB rotation (Meynet)
  - HIF: H-ingestion flash (Straniero etal)
  - AGB extra-mixing (Nollet etal)

N-Na correlation of C-rich non-binaries or non-s-process EMP stars



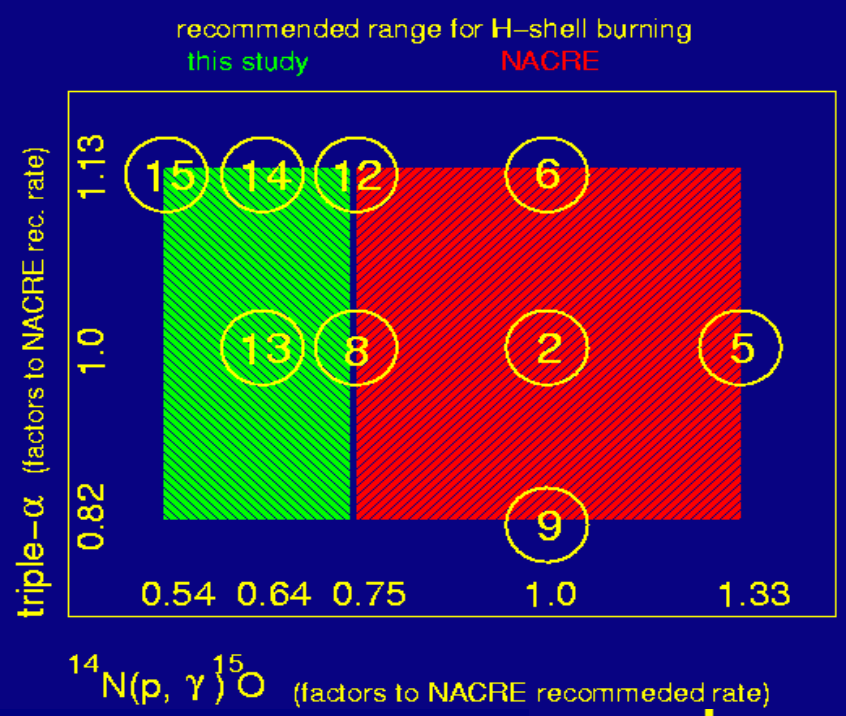
poster outside Herwig etal

Now return to higher Z ...
.... and how we can improve models ...

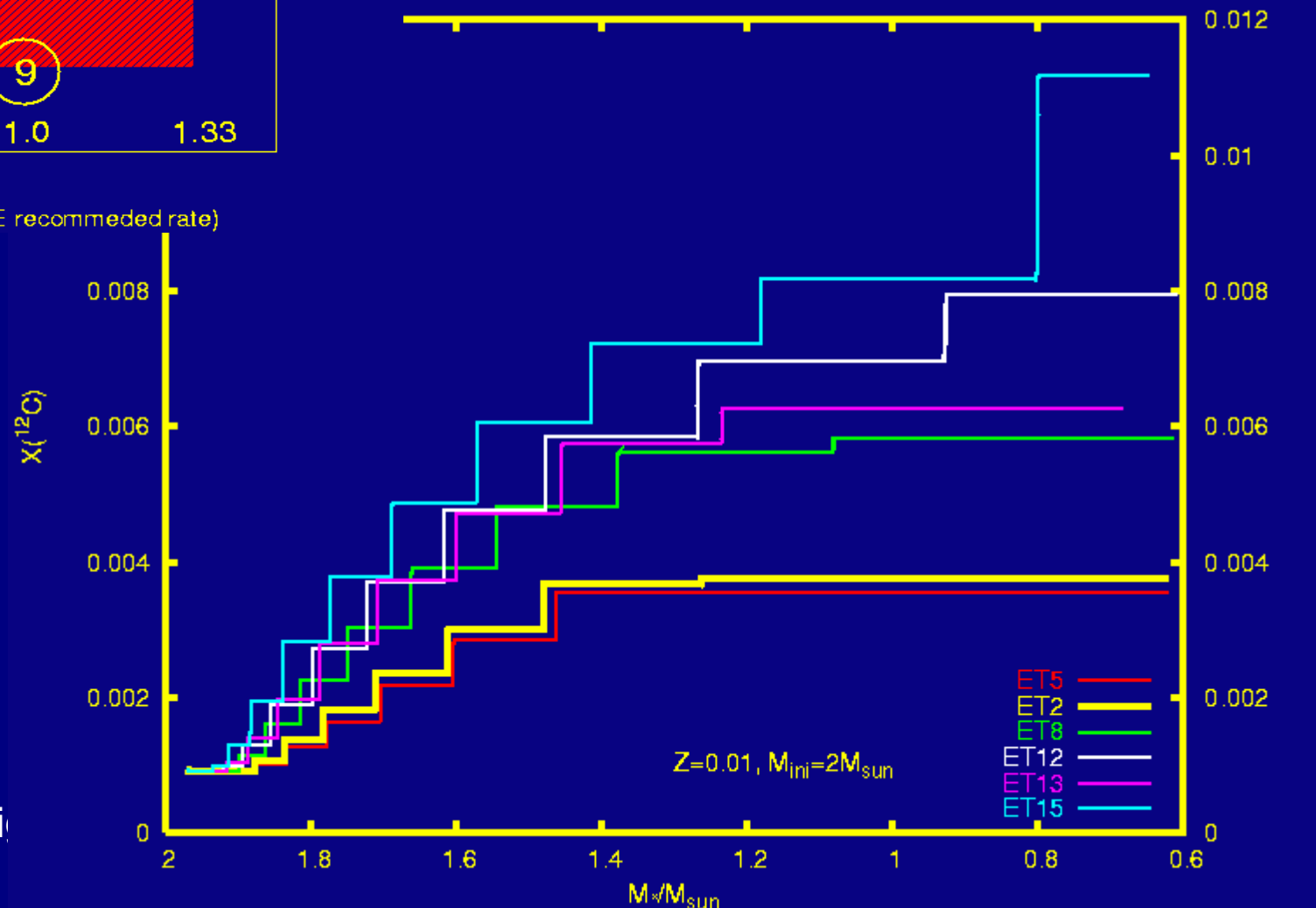
Nuclear Physics input

✔ C-star formation very sensitive to nuclear physics input. Revised reaction rate for $^{14}N(p,\gamma)^{15}O$ leads to more efficient dredge-up (Herwig & Austin 2004, ApJ Let, in press)

Rate selections for stellar evolution TP–AGB calculations



C-surface abundance evolution of complete $M=2M_{sun}$, $Z=0.01$ for a range of rate selections



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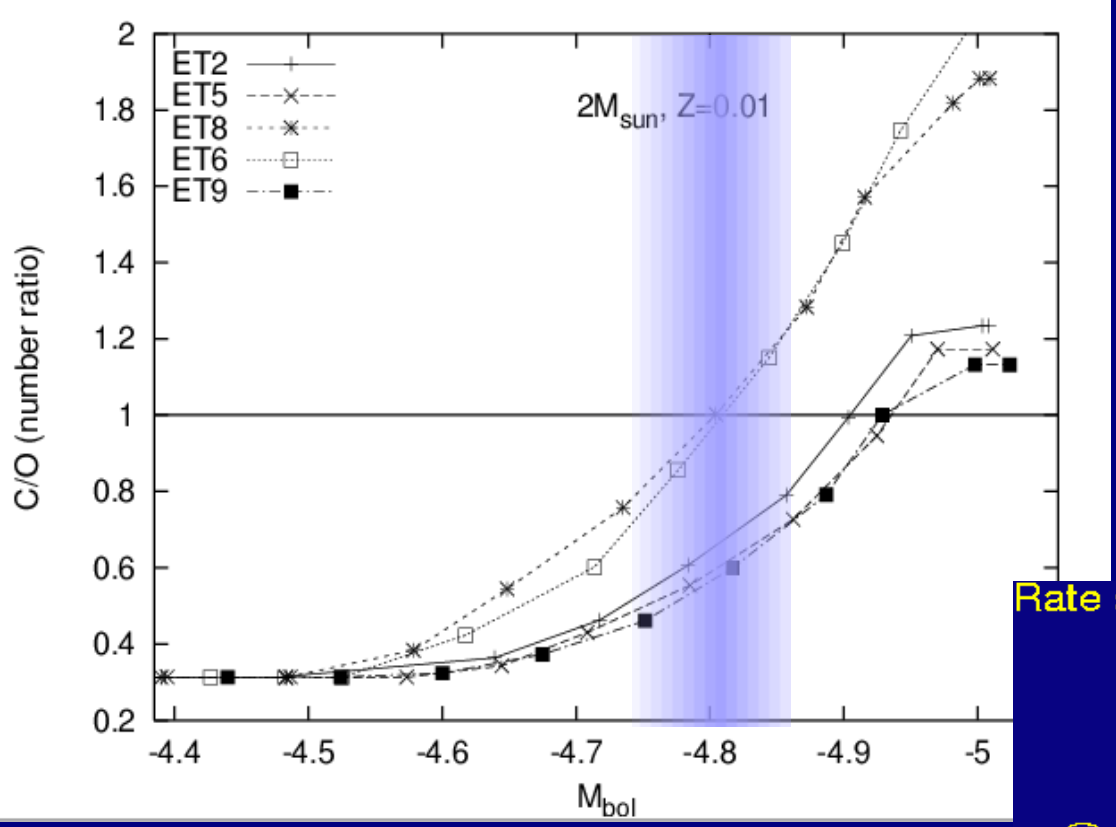
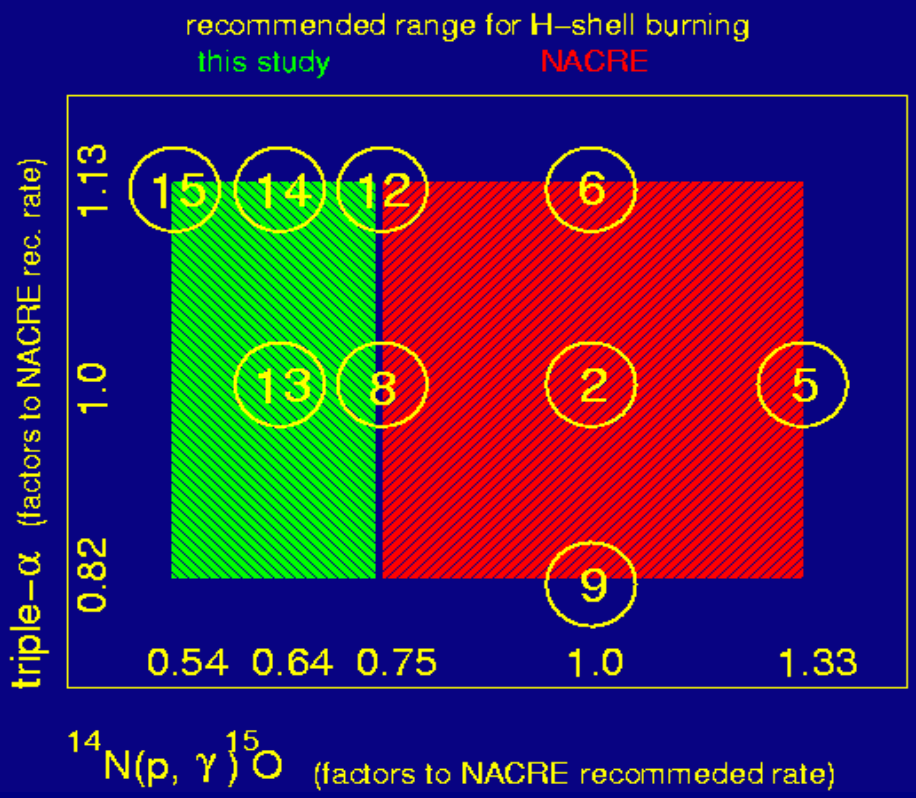
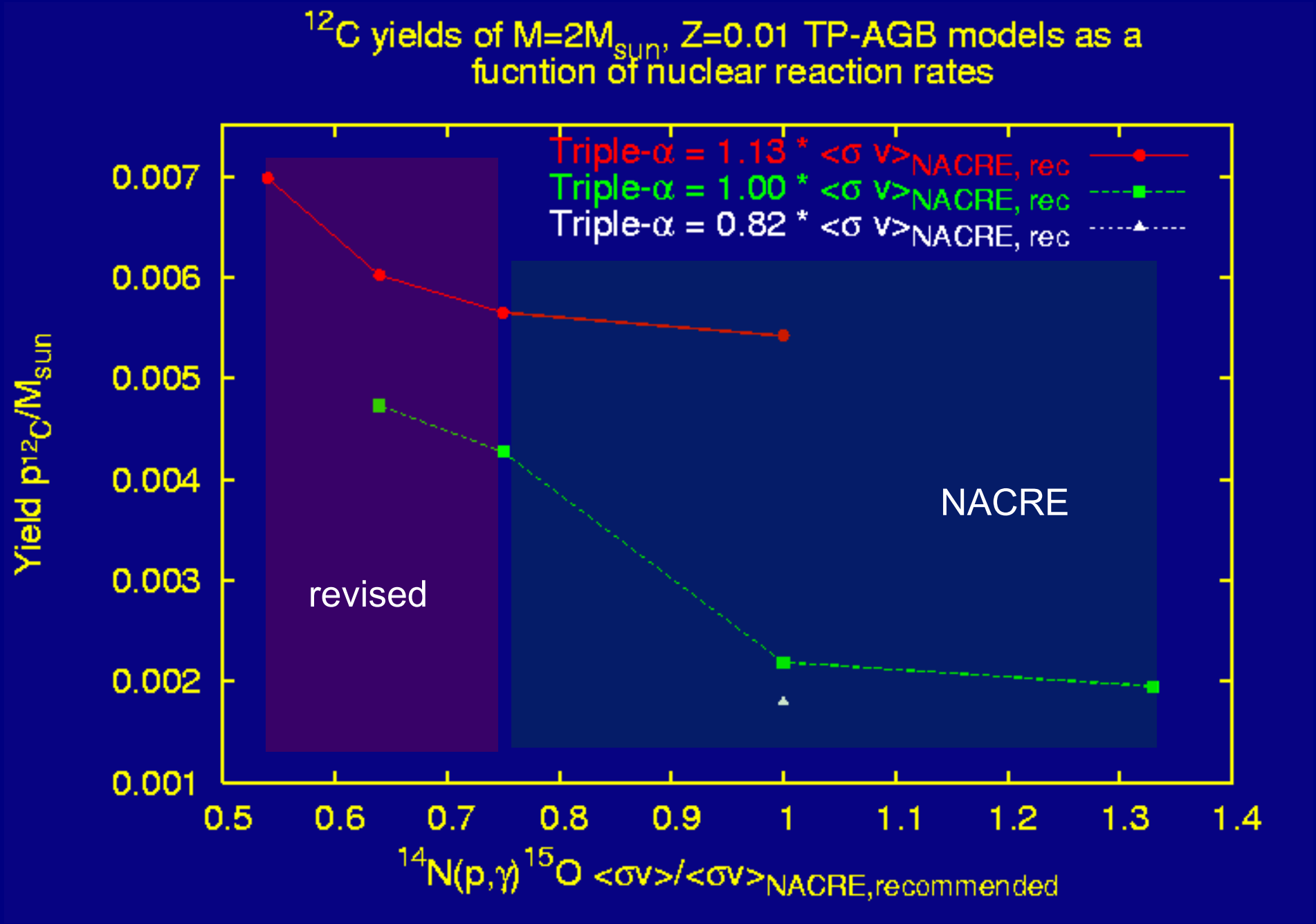


Rate selections for stellar evolution TP–AGB calculations




^{12}C yields of M=2M$_{sun}$, Z=0.01 TP-AGB models as a fucntion of nuclear reaction rates
Triple-α = 1.13 * <σ v>$_{NACRE, rec}$
Triple-α = 1.00 * <σ v>$_{NACRE, rec}$
Triple-α = 0.82 * <σ v>$_{NACRE, rec}$
revised
NACRE
Yield p^{12}C/M$_{sun}$
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
^{14}N(p,γ)^{15}O <σv>/<σv>$_{NACRE,recommended}$

Other means for the corrector approach:

- ➔Direct hydrodynamic simulations of mixing and burning in stellar interior nuclear production site, new program with ASC codes at LANL

- ➔Progenitors and progeny of AGB stars: RGB and White Dwarfs

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- Consistency between RGB and AGB mixing models

Other means for the corrector approach:

➔Direct hydrodynamic simulations of mixing and burning in stellar interior nuclear production site, new program with ASC codes at LANL

➔Progenitors and progeny of AGB stars: White Dwarfs and RGB

- Consistency between RGB and AGB mixing models
- Werner etal (2004a,b) observations of H-deficient CSPN, show on their surface the progenitor AGB intershell, based on FUSE data:

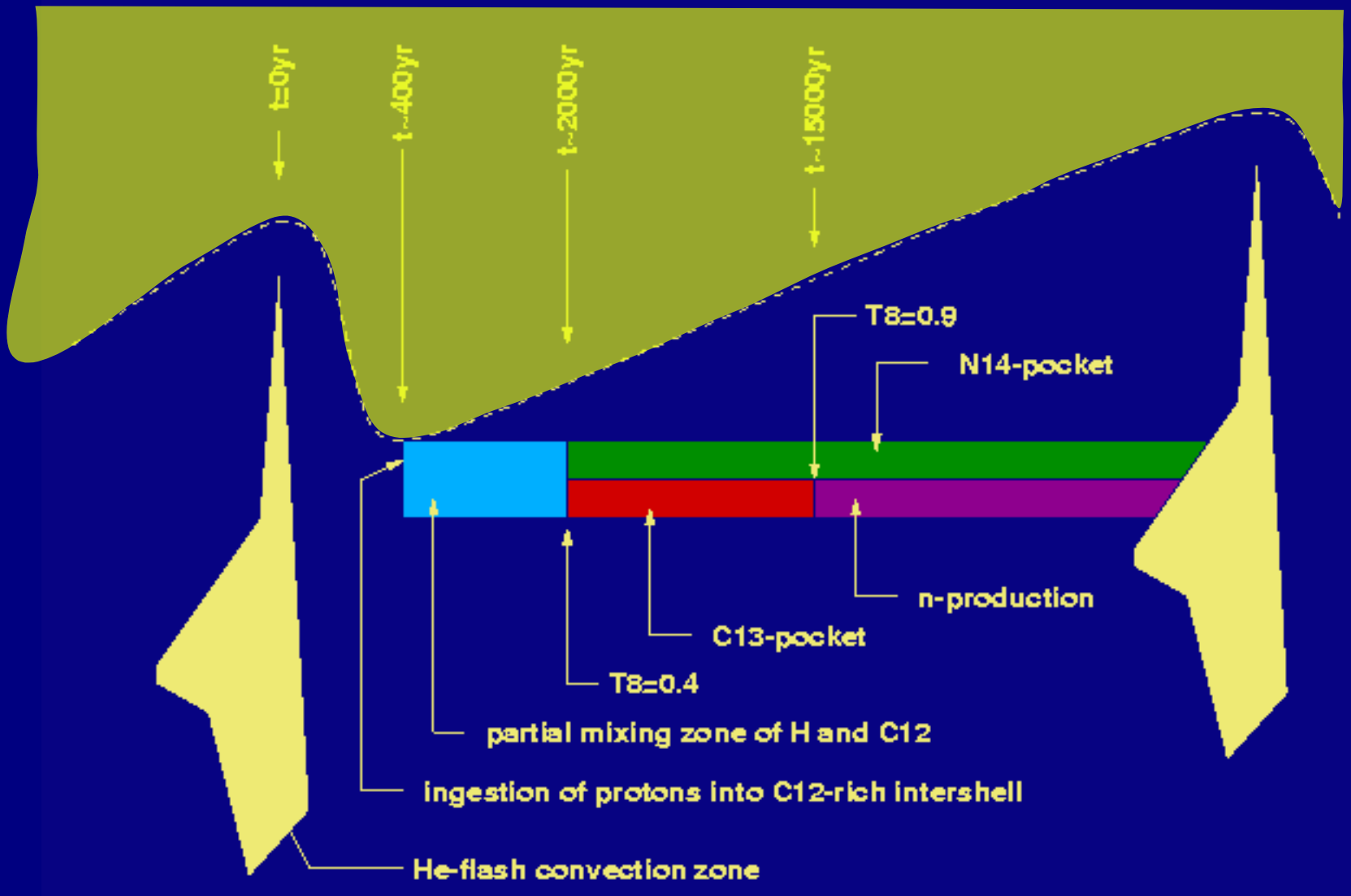
$$X(Ne)=0.02,\ X(Fe)=0.01X(Fe)_{sol},\ \log X(F)\sim-4$$

Other means for the corrector approach:

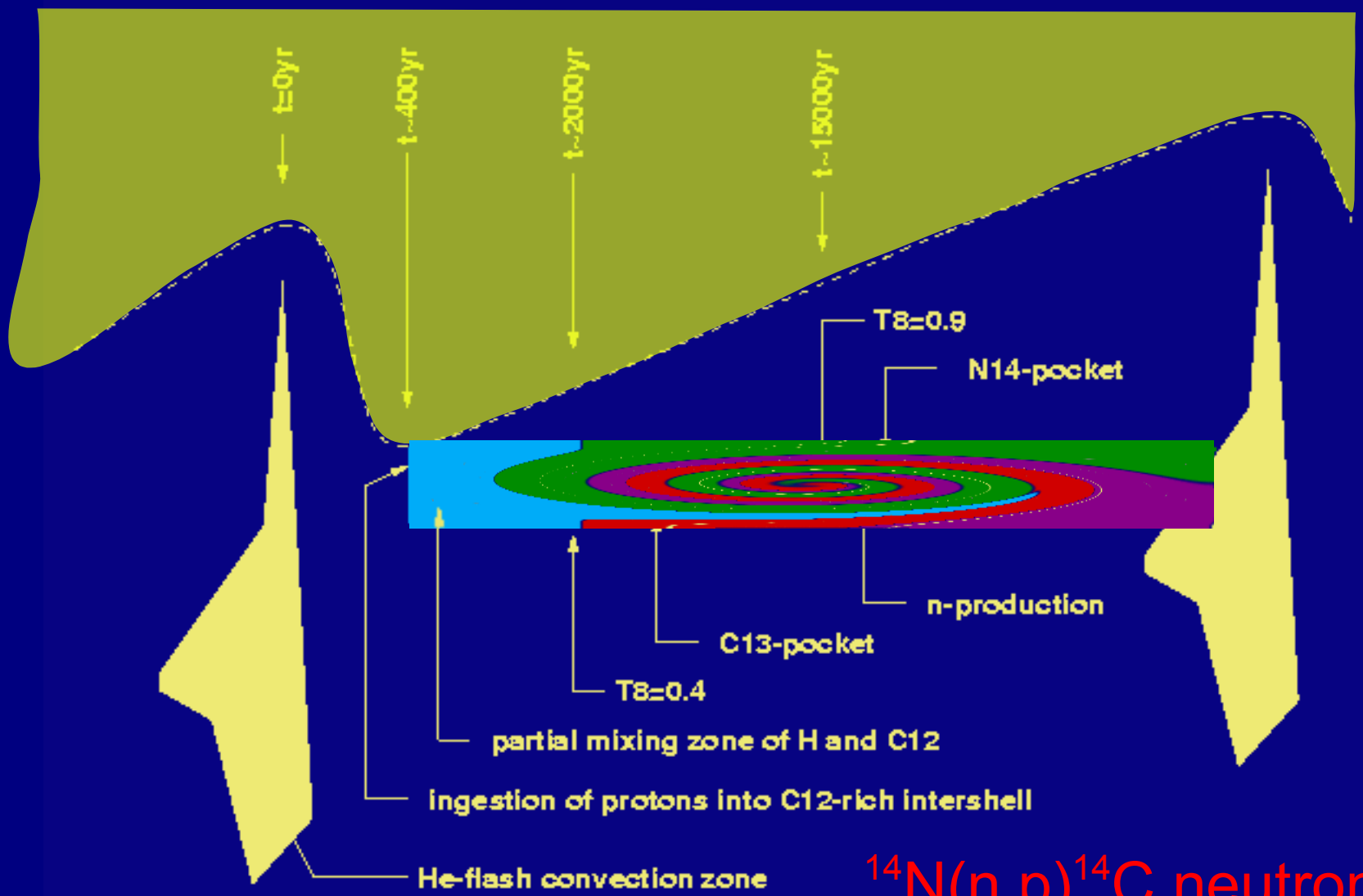
➔s-process as a diagnostic tool:

- Rotation in Stellar Evolution Herwig etal 2003, ApJ
- Nuclear Astrophysics with Neutron Facilities

Probing Rotation with the s-process



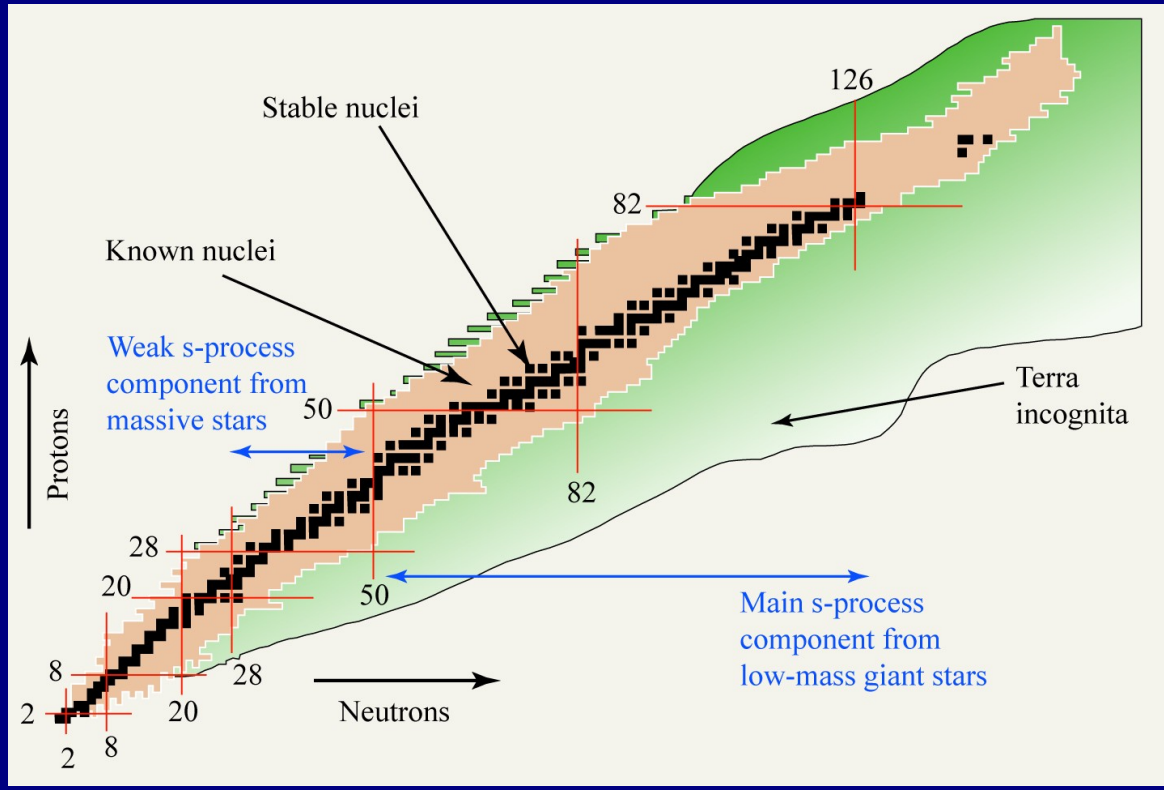
Probing Rotation with the s-process

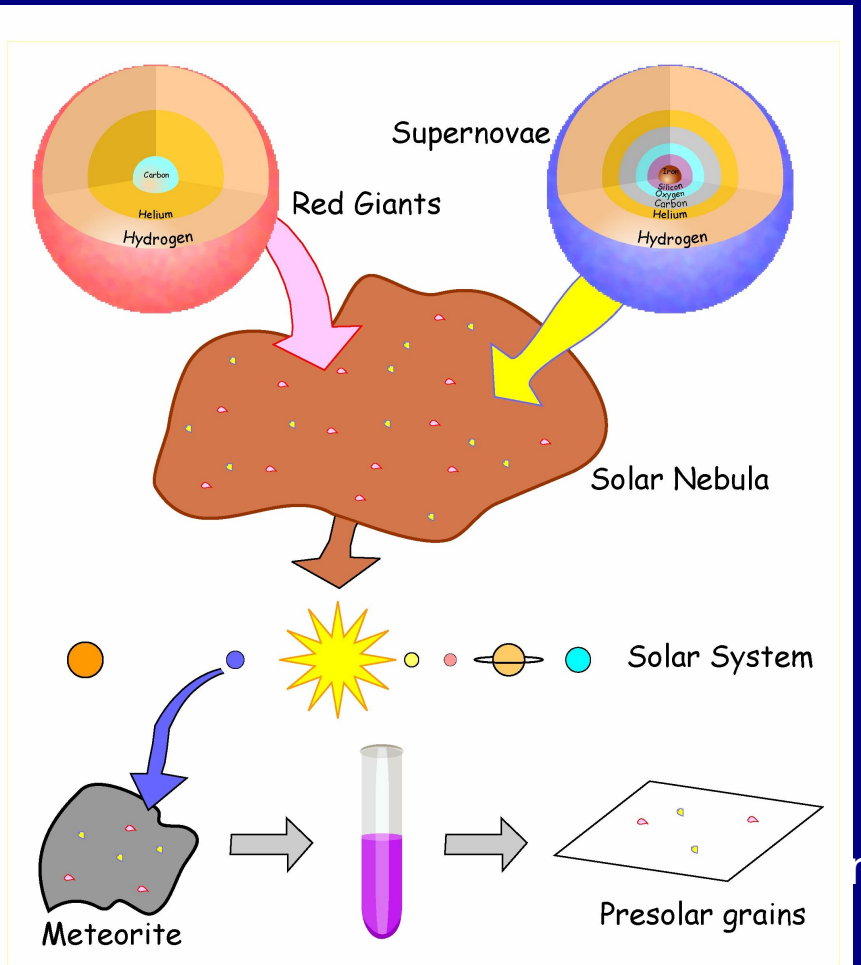


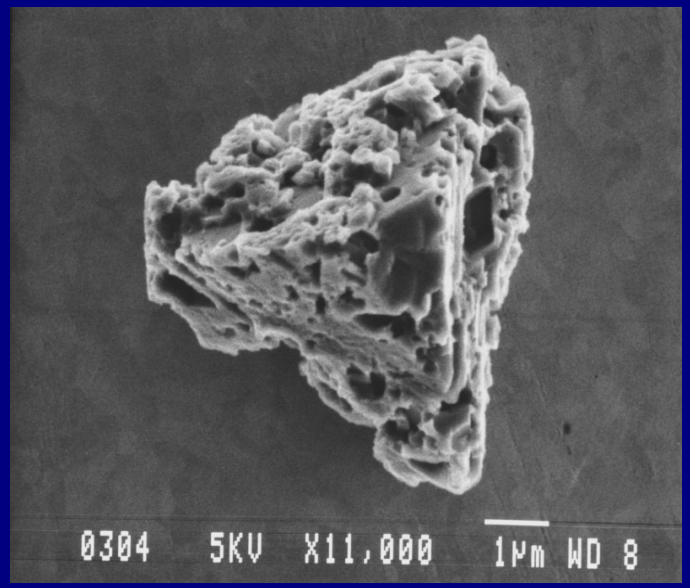
$^{14}N(n,p)^{14}C$ neutron poison

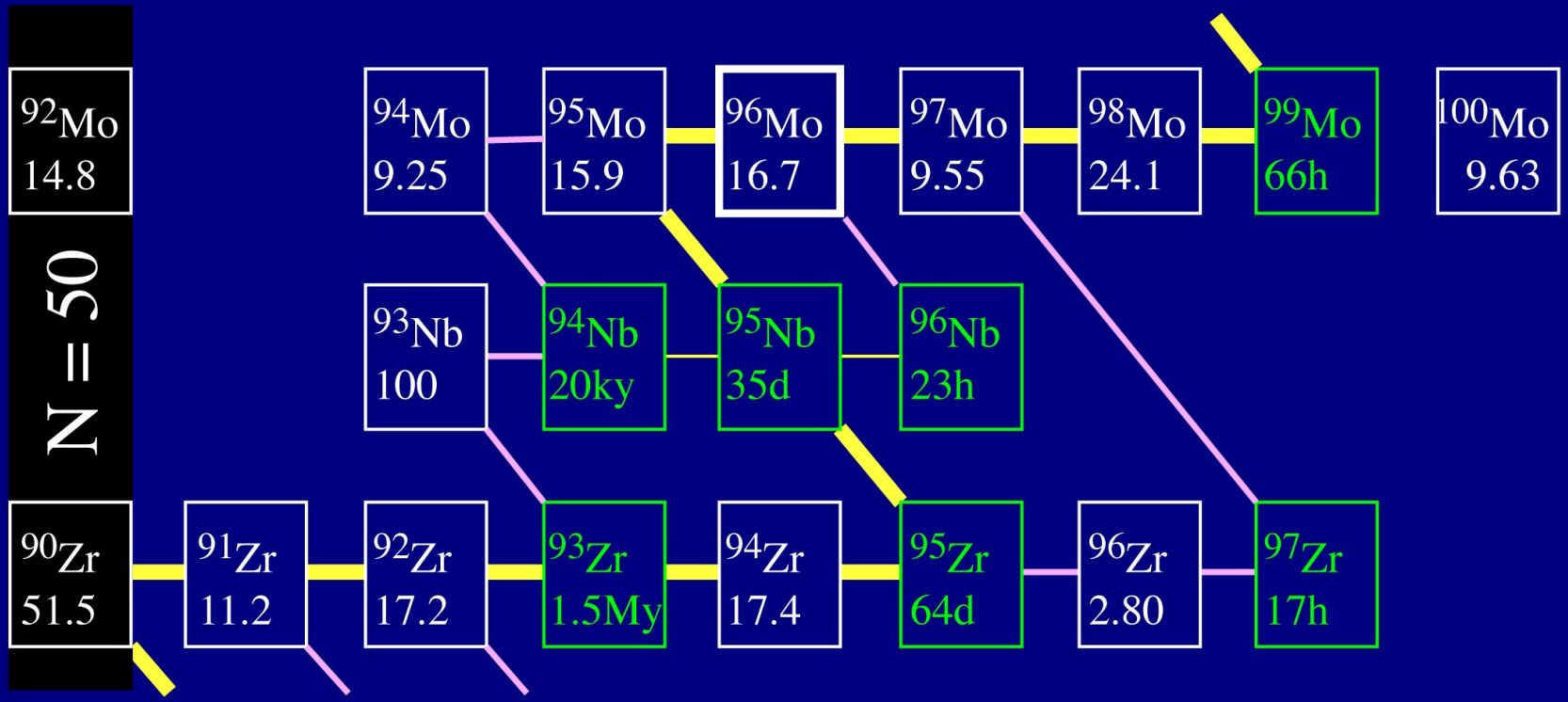
Herwig etal 2003, ApJ

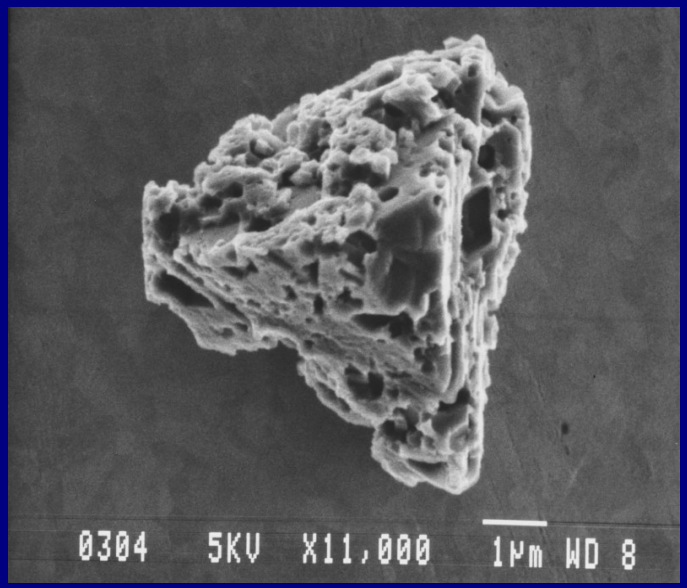
s-process branchings as a diagnostic tool to probe stellar interior physics





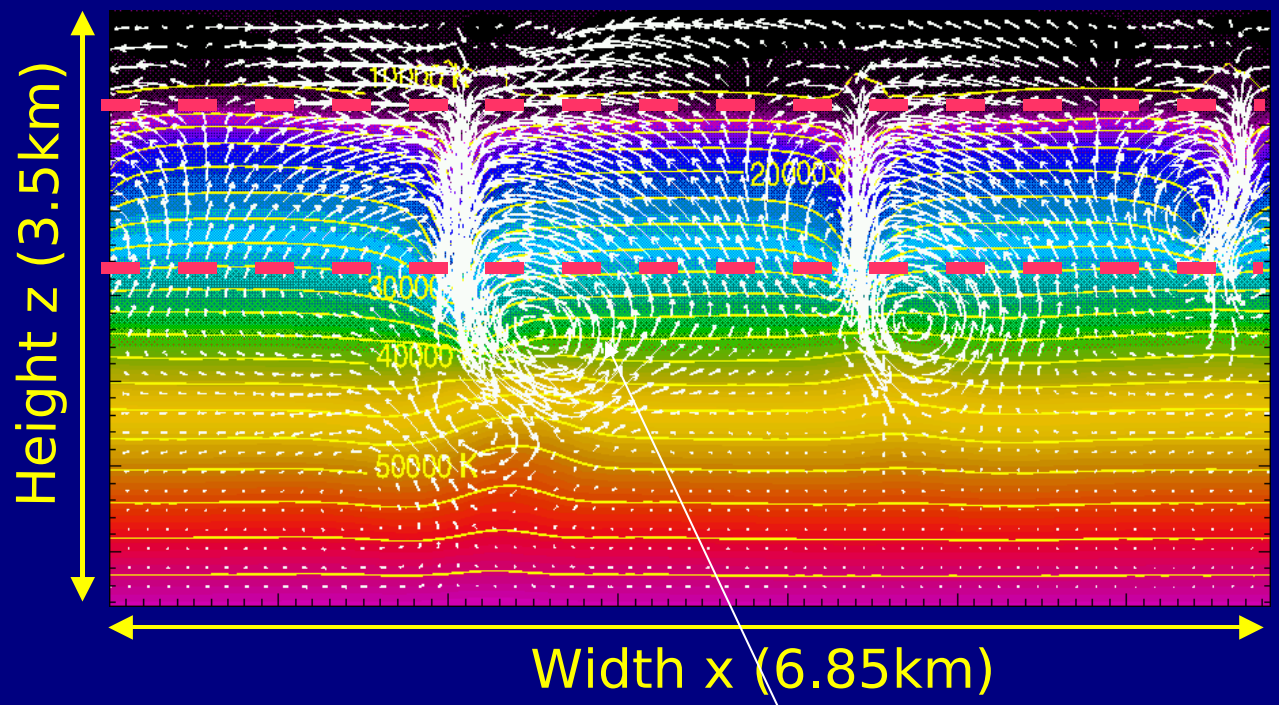



N = 50
92Mo 14.8
94Mo 9.25
95Mo 15.9
96Mo 16.7
97Mo 9.55
98Mo 24.1
99Mo 66h
100Mo 9.63
93Nb 100
94Nb 20ky
95Nb 35d
96Nb 23h
90Zr 51.5
91Zr 11.2
92Zr 17.2
93Zr 1.5My
94Zr 17.4
95Zr 64d
96Zr 2.80
97Zr 17h

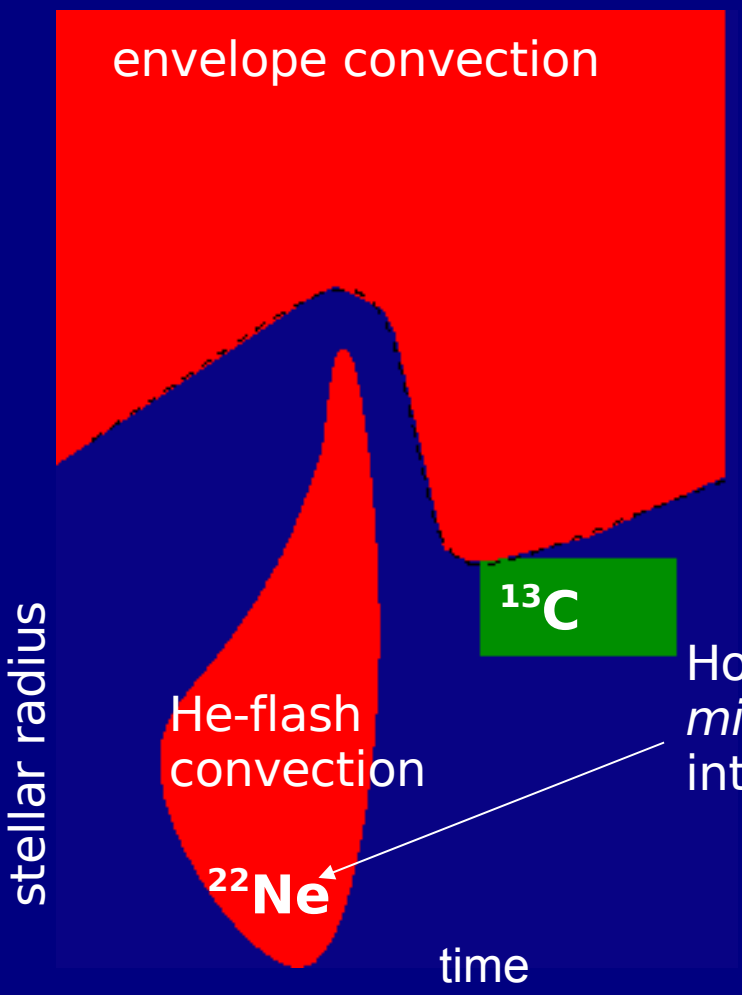

0304 5KV X11,000 1μm WD 8

Convection

2D-simulation of White Dwarf convection zone



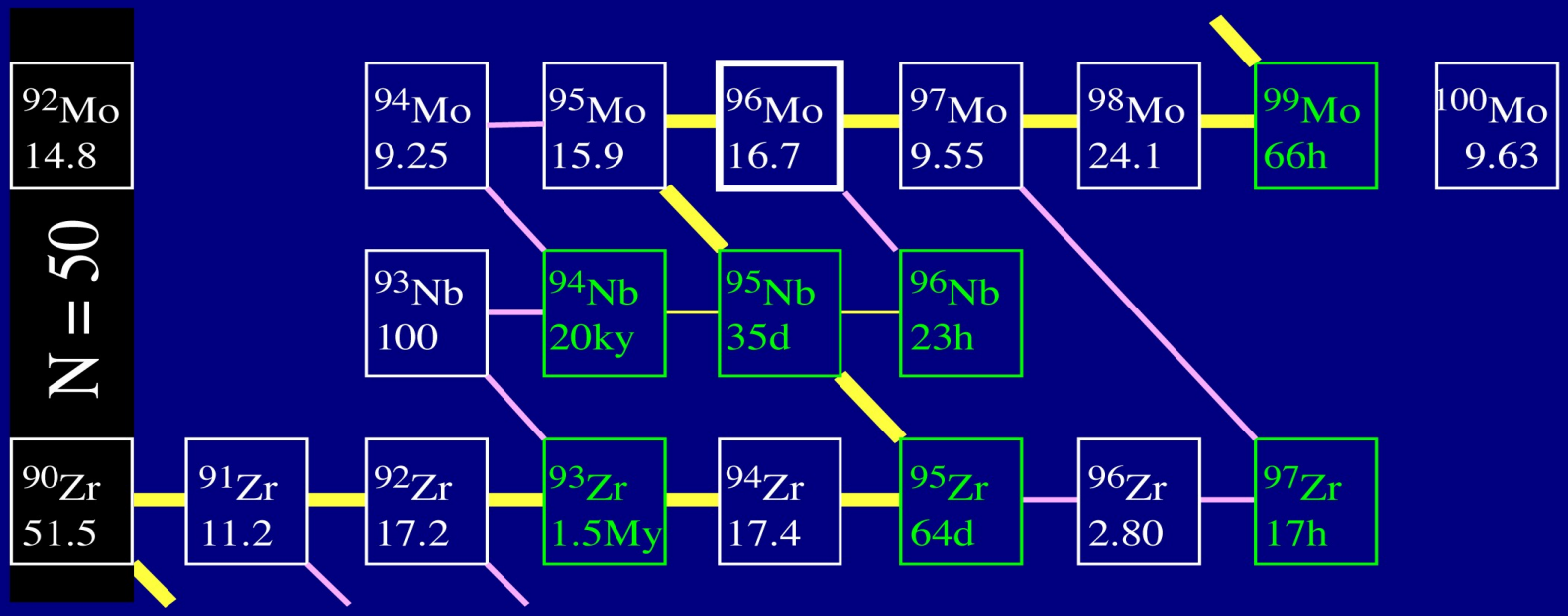
Schematic of He-shell flash

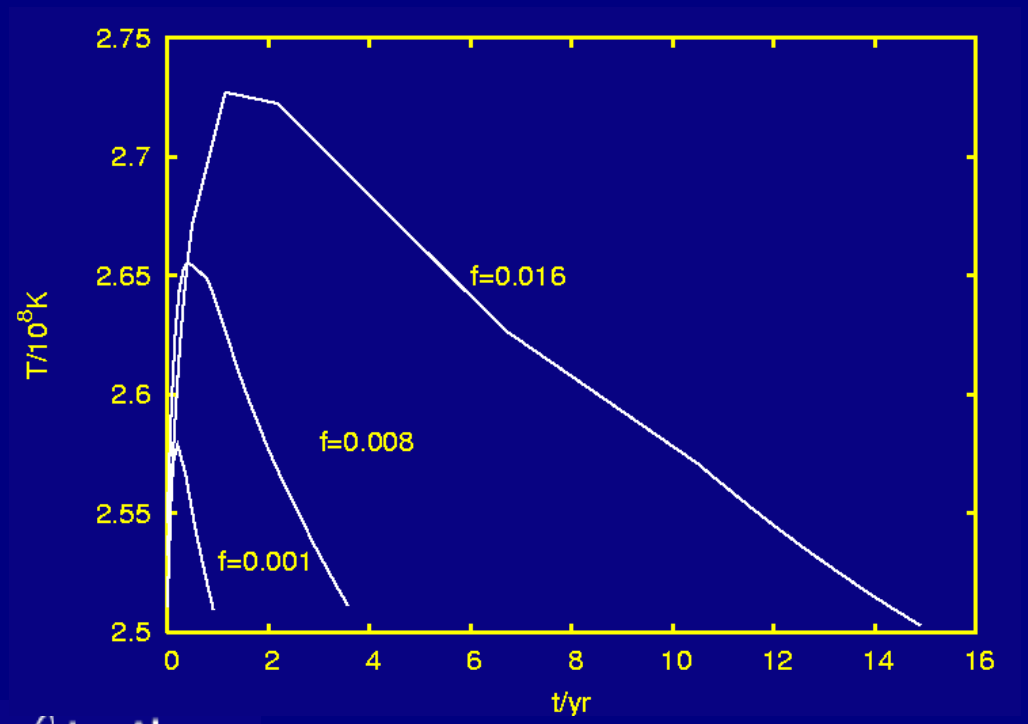


How efficient is *extra mixing* in deep stellar interior?

Mixing extends into stable layers -> *extra mixing*.

Test with 1D exponential diffusion approximcation, efficiency parameter f.

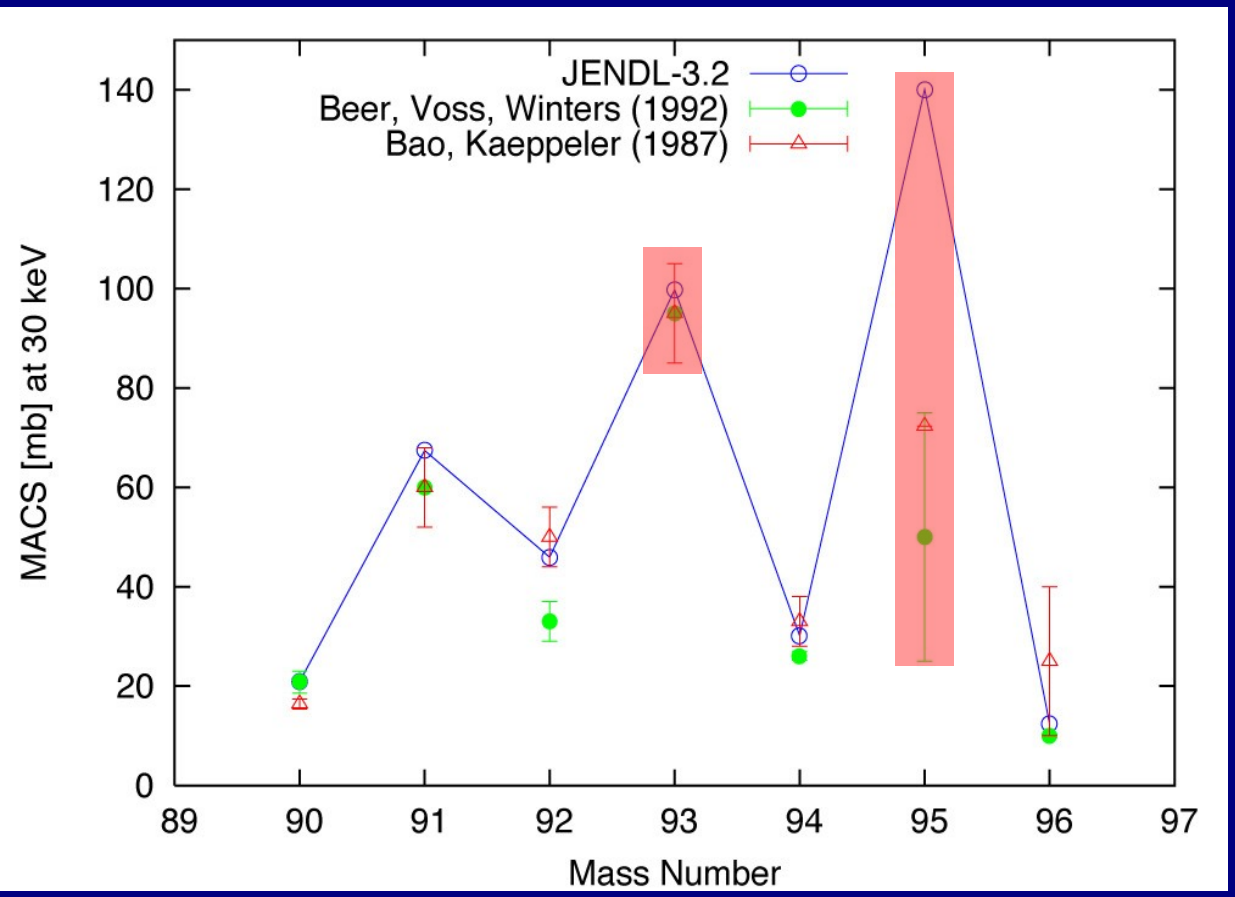




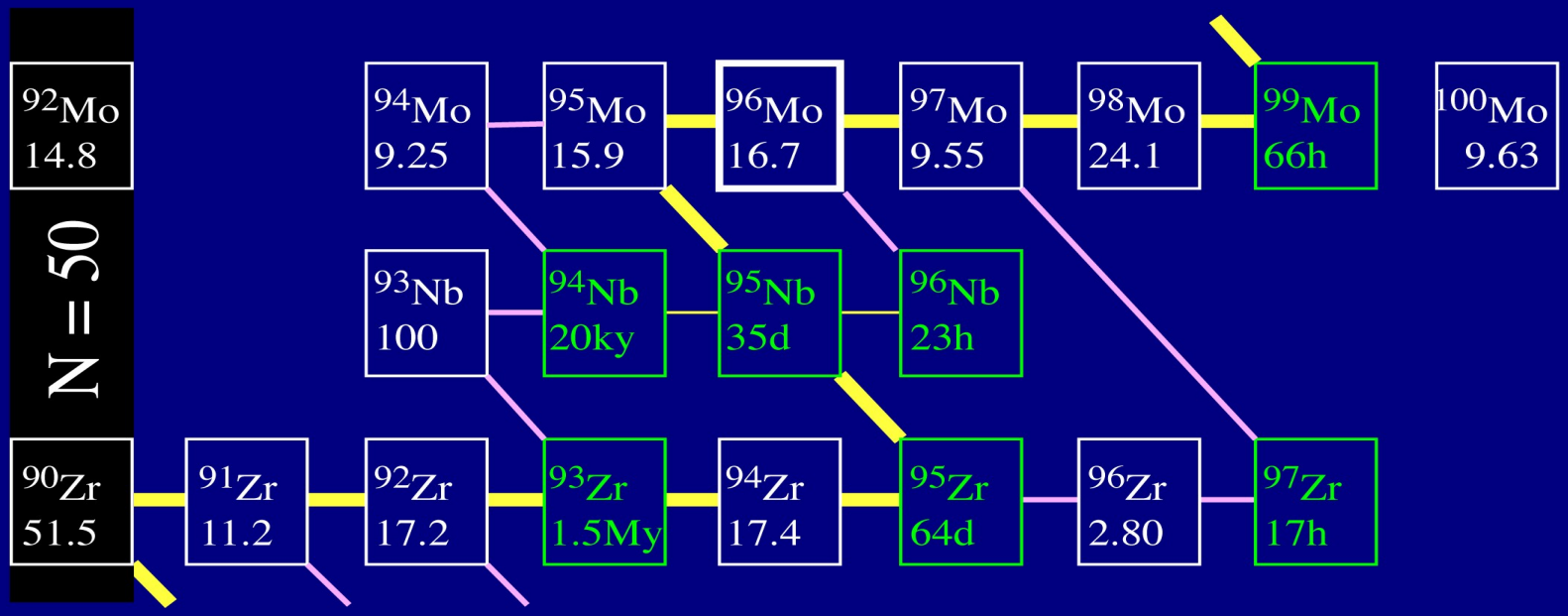
Temperature at the bottom of the He-shell flash convection zone determined by mixing parameter f ⇒ determines $^{96}Zr/^{94}Zr$ ratio in grains!

Cross Sections of Radioactive Isotopes?

Nuclear data and theory modeling (LANL Nuclear Theory Group,T. Kawano)



- Existing remarkable discrepancy of Maxwell-averaged neutron capture cross sections for ^{95}Zr should be resolved.
- New experimental data on ^{93}Zr will help estimate the odd/even effect of the cross sections.
- Cross section calculations with Hauser-Feshbach theory and the Direct/semidirect model can then be improved.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93Nb 100
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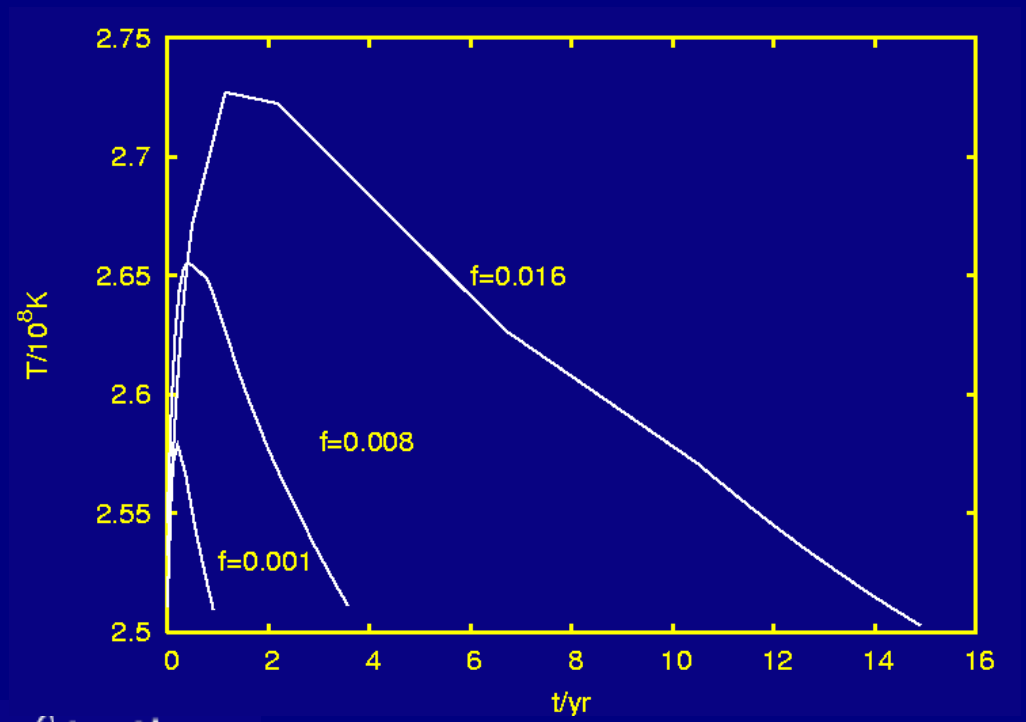
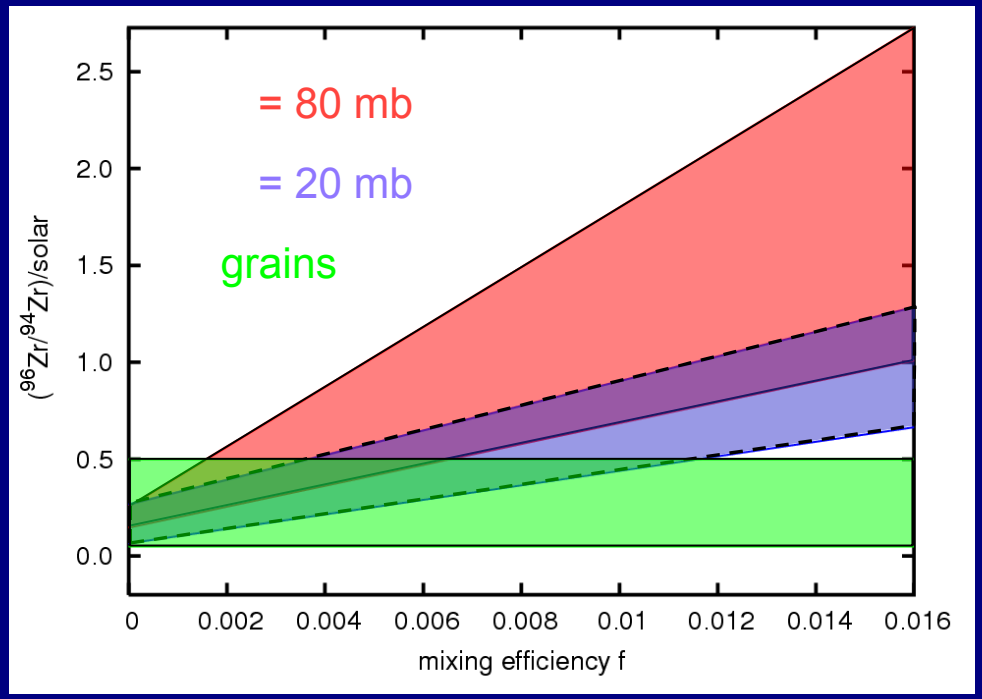
95Nb 35d
96Nb 23h
90Zr 51.5
91Zr 11.2
92Zr 17.2
93Zr 1.5My
94Zr 17.4
95Zr 64d
96Zr 2.80
97Zr 17h


T/10^8K
t/yr
f=0.016
f=0.008
f=0.001
2.75
2.7
2.65
2.6
2.55
2.5
0
2
4
6
8
10
12
14
16

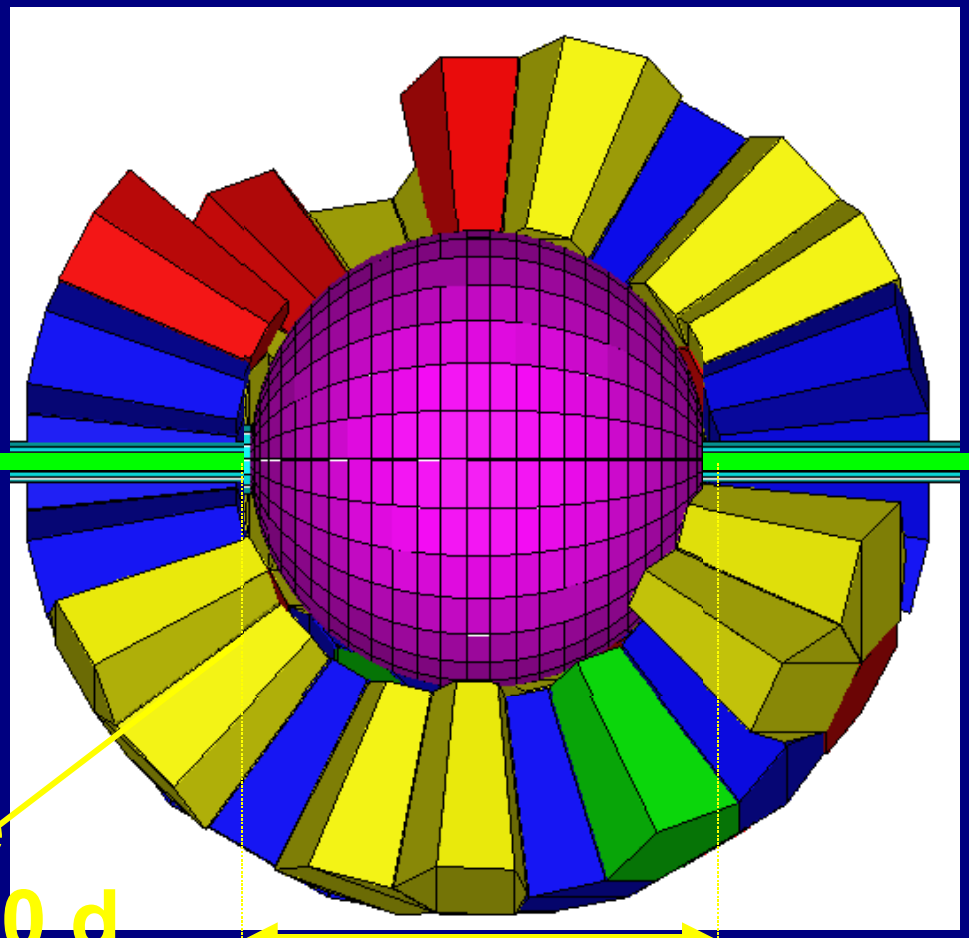

= 80 mb
= 20 mb
grains
(96Zr/94Zr)/solar
mixing efficiency f
2.5
2.0
1.5
1.0
0.5
0.0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016

Neutron capture experiments with unstable isotopes and fundamental stellar physics evaluations

Isotope	Half-Life	Facility	Observable	Stellar Physics	Comment
^{151}Sm	93 yr	DANCE: experiment finished	^{152}Gd in solar distribution ^{151}Eu/^{153}Eu ratio hyperfine line split	Timescale of hot Helium-shell flash	Pre-DANCE uncertainty: ± 30%
^{134}Cs	2 yr	DANCE: planned	Ba isotope ratios from presolar grains	Sets ^{12}C abundance of He-shell flash	Pre-DANCE uncertainty: ± 30%
^{135}Cs	2 x 10^6 yr			Amount of rotation	± 10%
^{95}Zr	64 d	RIA	^{96}/Zr/^{94}Zr ratio presolar grains	Temperature at bottom of He-shell flash region	Current uncertainty: 20 - 80 mb

*D*etector for *A*dvanced *N*eutron *C*apture *E*xperiments

collimated neutrons beam



34 cm

sample
$t_{1/2}$ > 100 d
m ~ 1 mg

neutrons:

- spallation source
- thermal .. 500 keV
- 20 m flight path
- 3 10^5 n/s/cm^2/decade

-Detector:

- 160 BaF_2 crystals
- 4 different shapes
- R_i=17 cm, R_a=32 cm
- 90 %

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Facilities for the Future of Science

A Twenty-Year Outlook

Office of Science
U.S. DEPARTMENT OF ENERGY

Facilities for the Future of Science:

ITER

UltraScale Scientific Computing Capability

Joint Dark Energy Mission

Linac Coherent Light Source

Protein Production and Tags

Rare Isotope Accelerator

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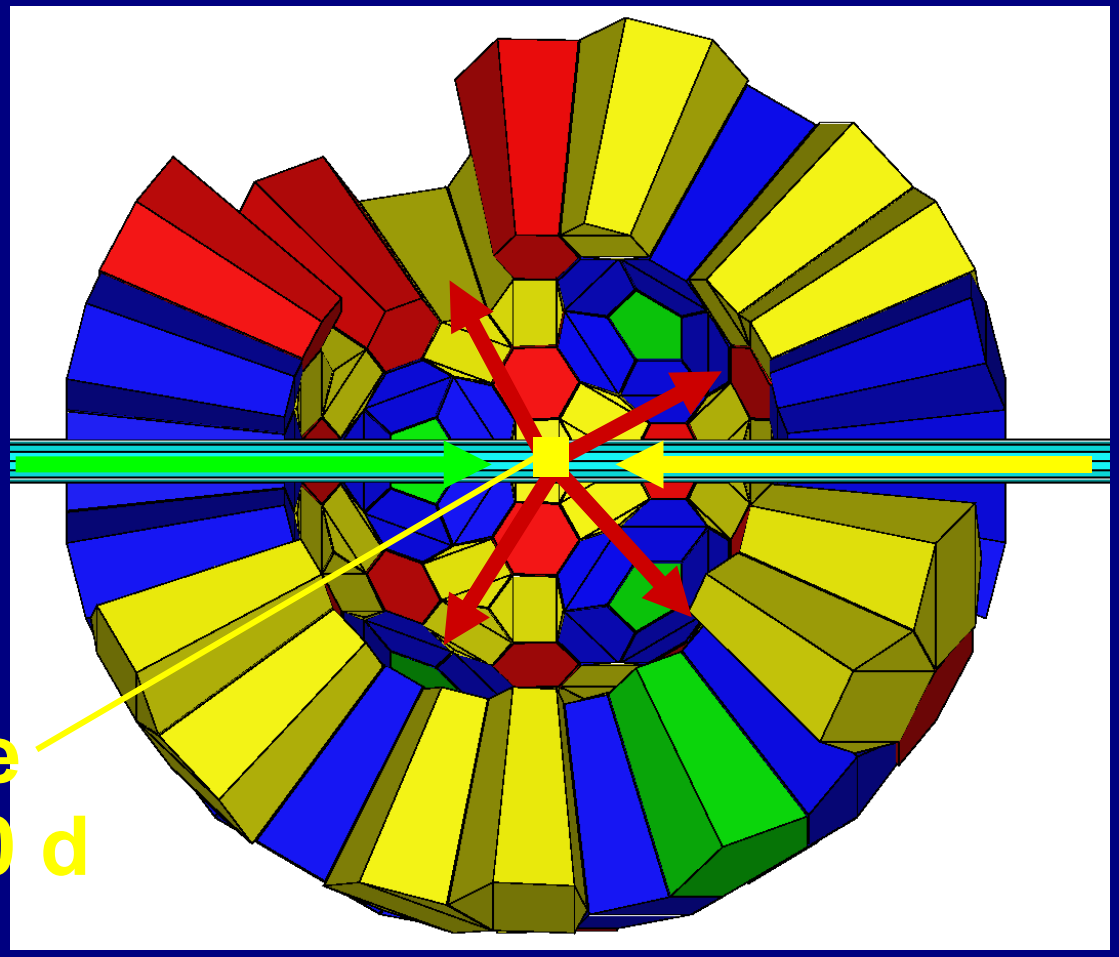
RIA – parasitic mode



sample
$t_{1/2}$ ~ 10 d
m ~ 10 µg

RIA:
- **spallation source**
- **> 10^{10} particles / s**
- **10 d**

neutrons:

- **VdG**
- **1 .. 500 keV**
- **20 d**

-Detector:

- **4**
- **100 %**
-

Conclusions

- Predictor vs Corrector mode
- Synthetic vs Evolution models
- Comparison of recent yields from evolution models
- Ultra-metal poor models, HIF
- Where the nitrogen comes from
- How to improve models