AGB stars as laboratories for nuclear physics

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with

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Mommy...

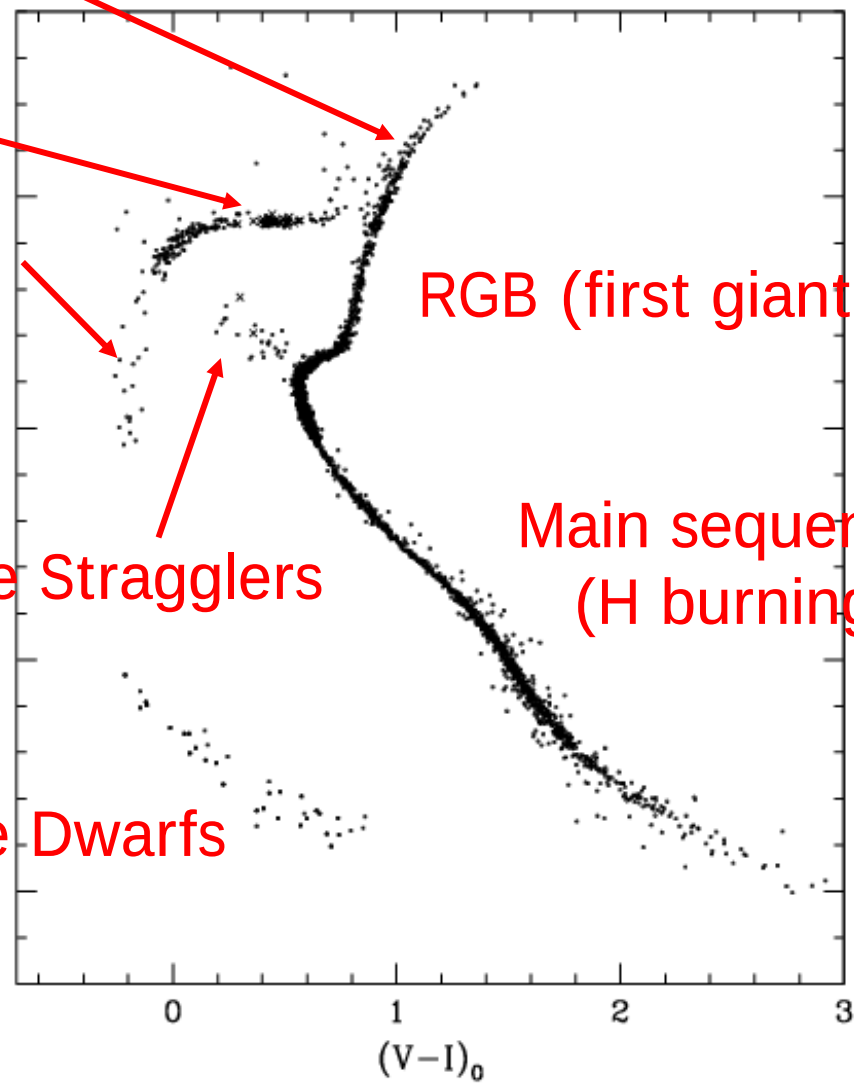
where did all the Praesodymium come from?

AGB Nucleosynthesis

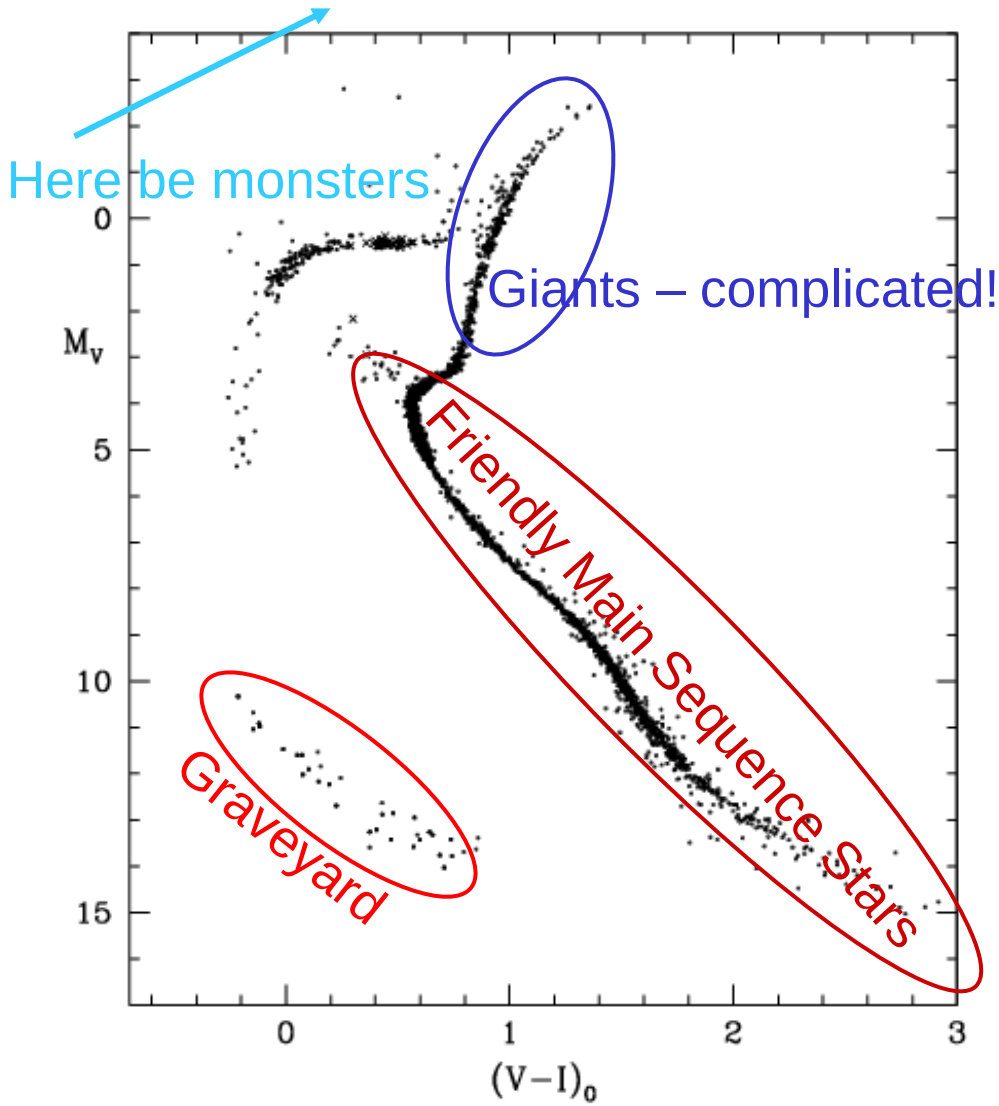
1. He Flashes and hot bottoms etc
2. C stars
3. S-process elements
4. ^{19}F
5. ^{25}Mg and ^{26}Mg (and Al isotopes)
6. ^{23}Na
7. ^{7}Li
8. ^{14}N
9. etc...

HR Diagram (Globular Cluster)

AGB (Second giant branch)



HR Diagram (Globular Cluster)



Nucleosynthesis

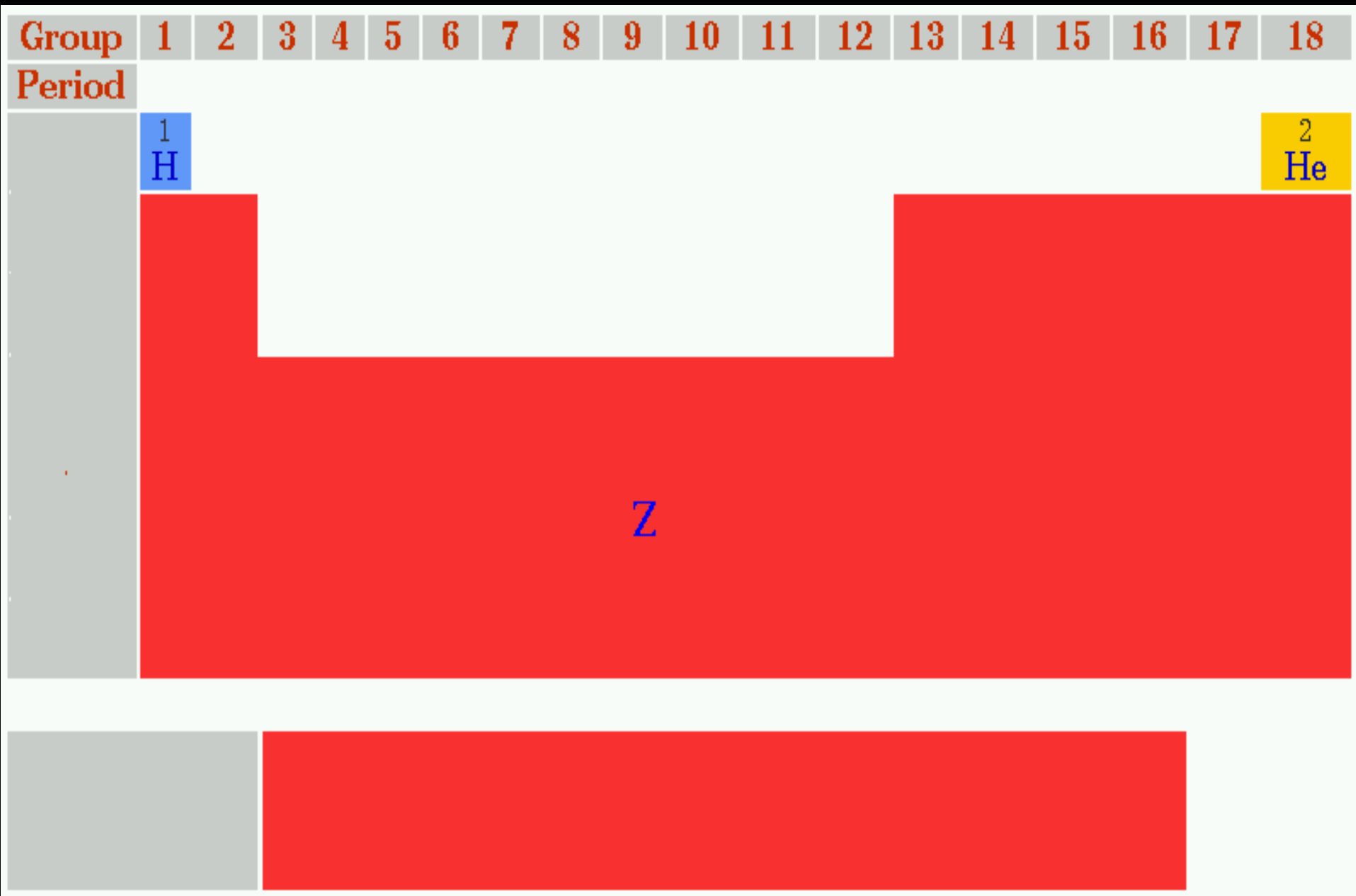
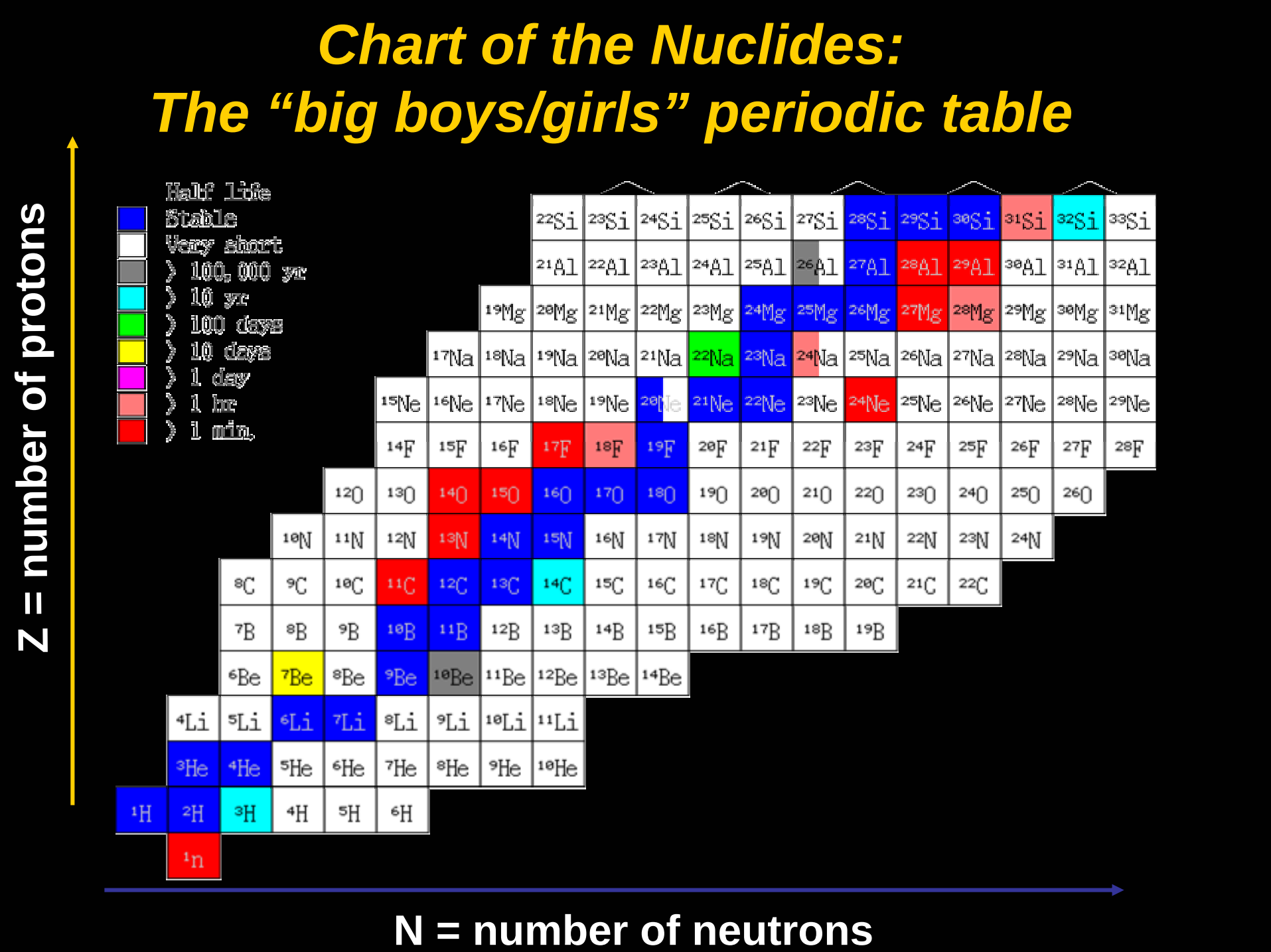


Chart of the Nuclides: The "big boys/girls" periodic table



Why was it OK to have H, He and "Z"?

- For the structure we need the energy generation
- Burning H to He or He to C covers most of HRD!
- So we can make accurate models with only H and He burning
- Very few species needed
- Me: H, He^3, He^4, C^{12}, N^{14} and O^{16}

H burning

- PP chains or CNO cycle(s)

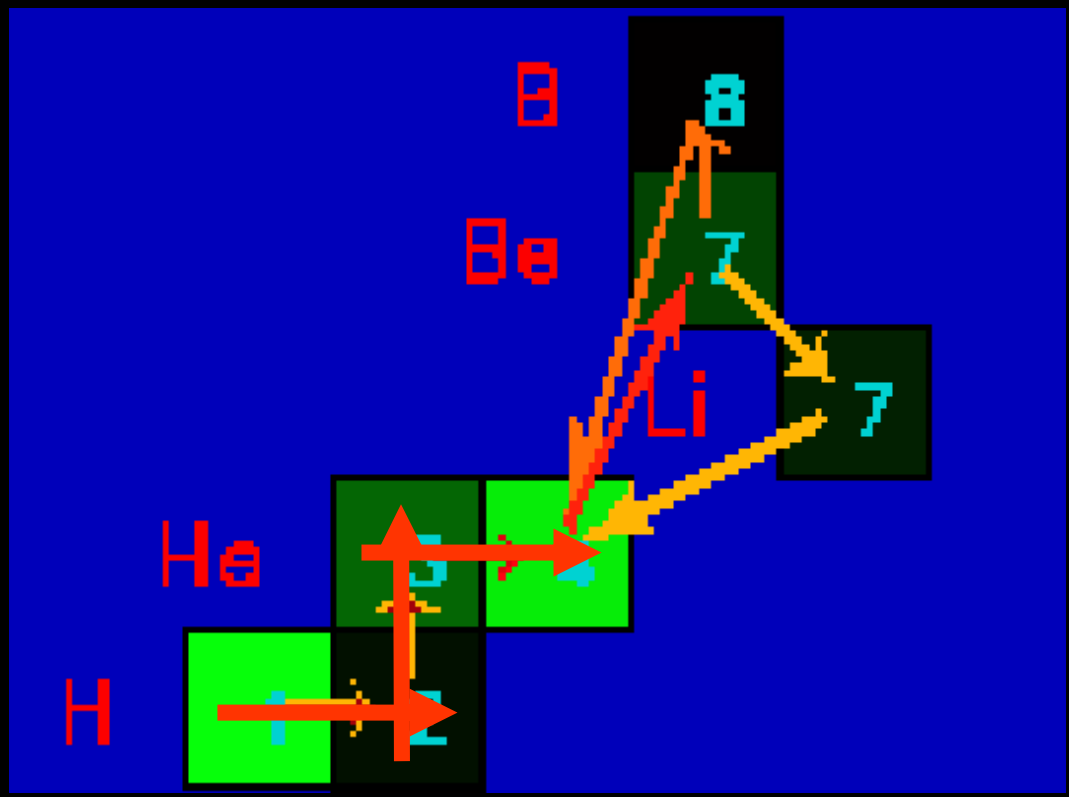
- PP chains: pure H gas is all that's needed
- CNO cycles require CNO as *catalysts*

PP Chains

First reaction: $p + p \rightarrow D^2 + \gamma$

$D^2 + p \rightarrow He^3 + \gamma$

$He^3 + He^3 \rightarrow He^4 + 2p$



This is PPI Chain

PP Chains

Branching reaction: $He^3 + He^4 \rightarrow Be^7 + \gamma$

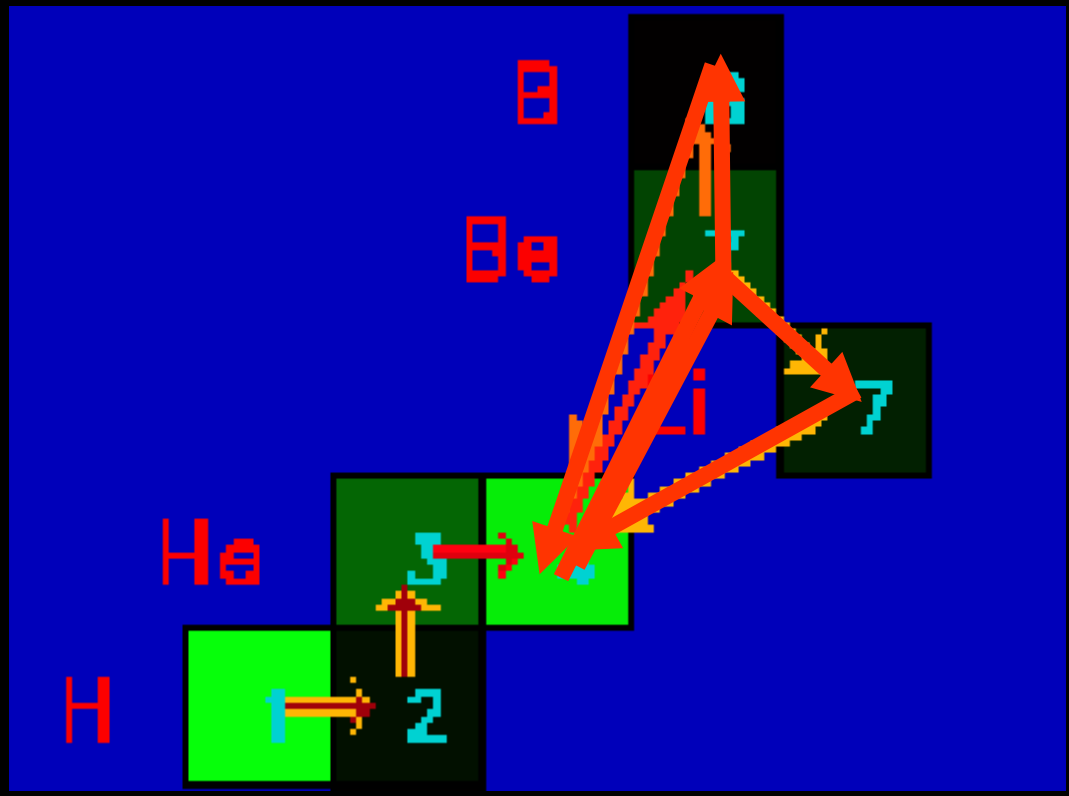
$Be^7 + p \rightarrow B^8 \rightarrow He^4 + He^4$

$Be^7 + e \rightarrow Li^7$

$Li^7 + p \rightarrow He^4 + He^4$

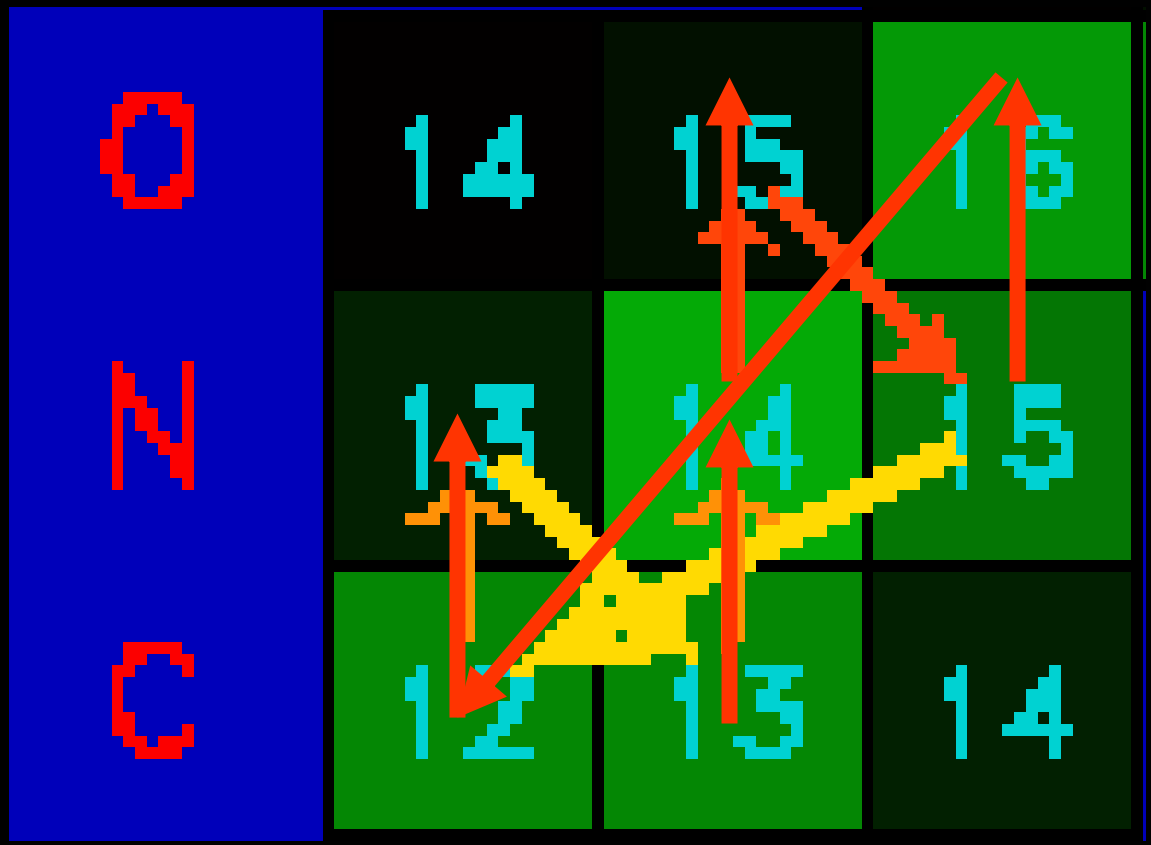
This is PPII Chain

This is PPIII Chain

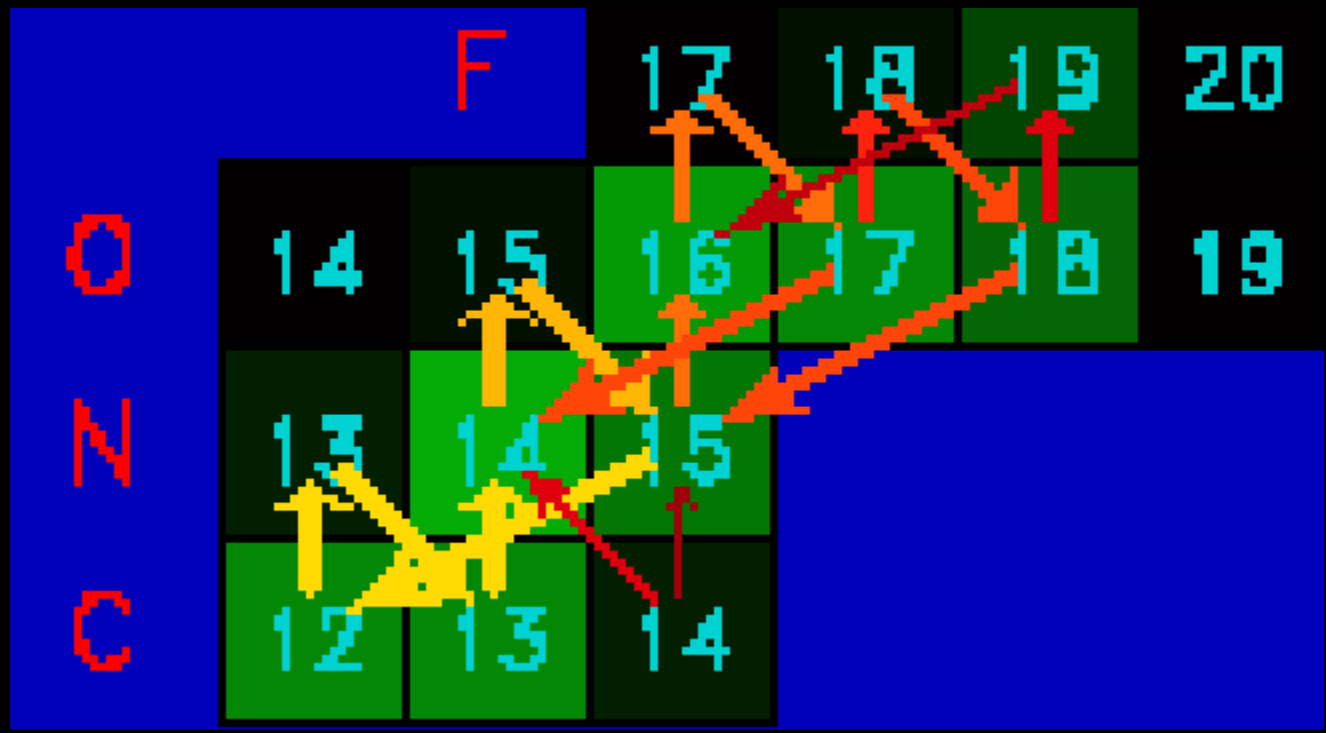


CNO Cycles: First step is CN cycle

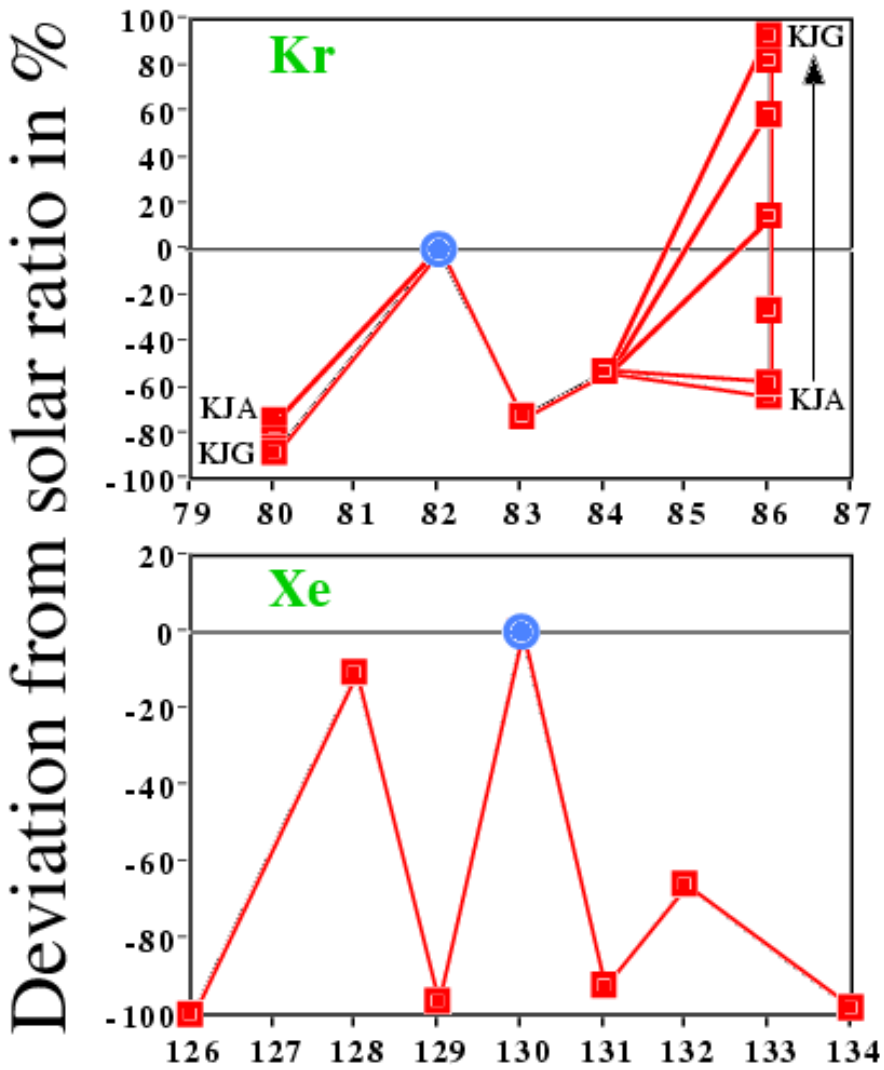
$C^{12} + 4p \rightarrow C^{12} + He^{4}$



CNO Cycles

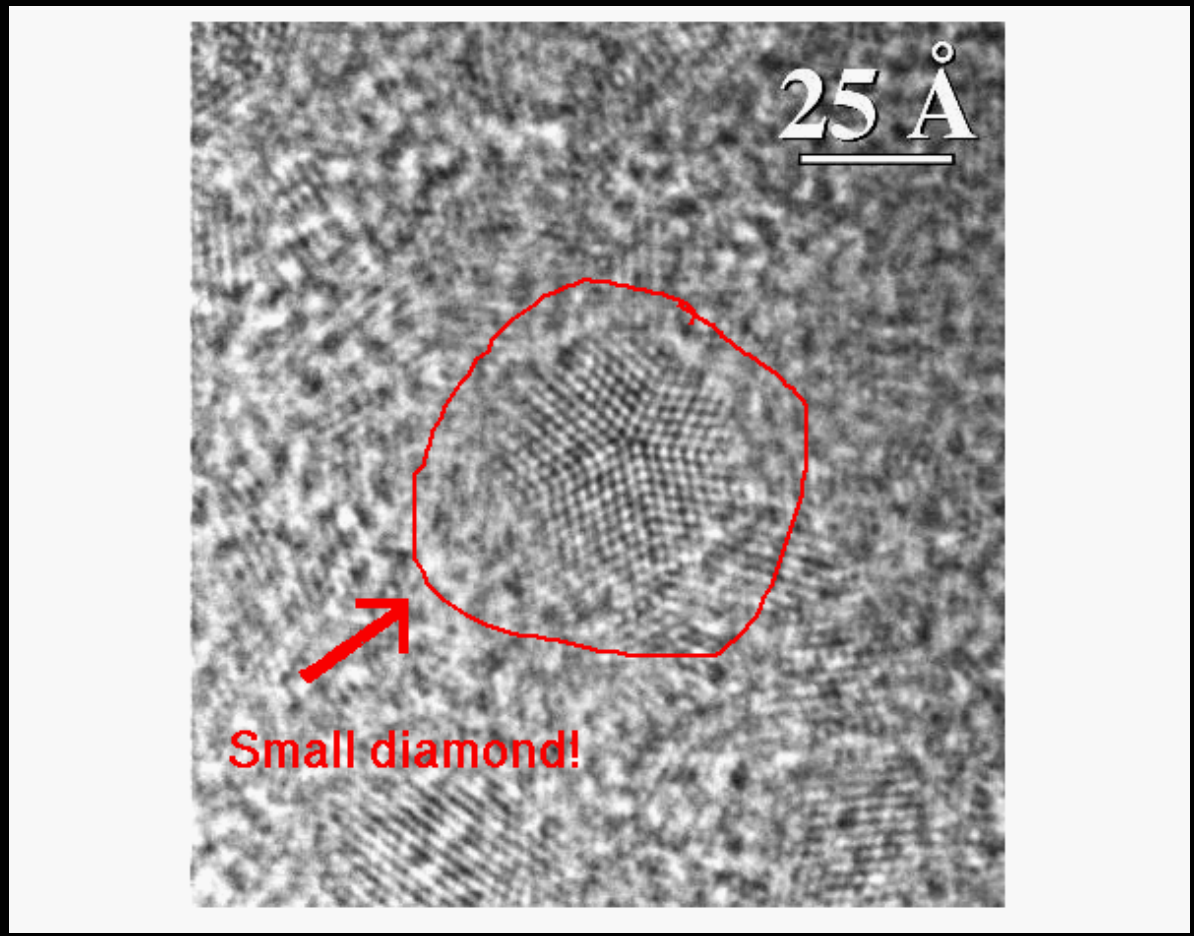


And then things went CRAZY!



Who were the trouble makers?

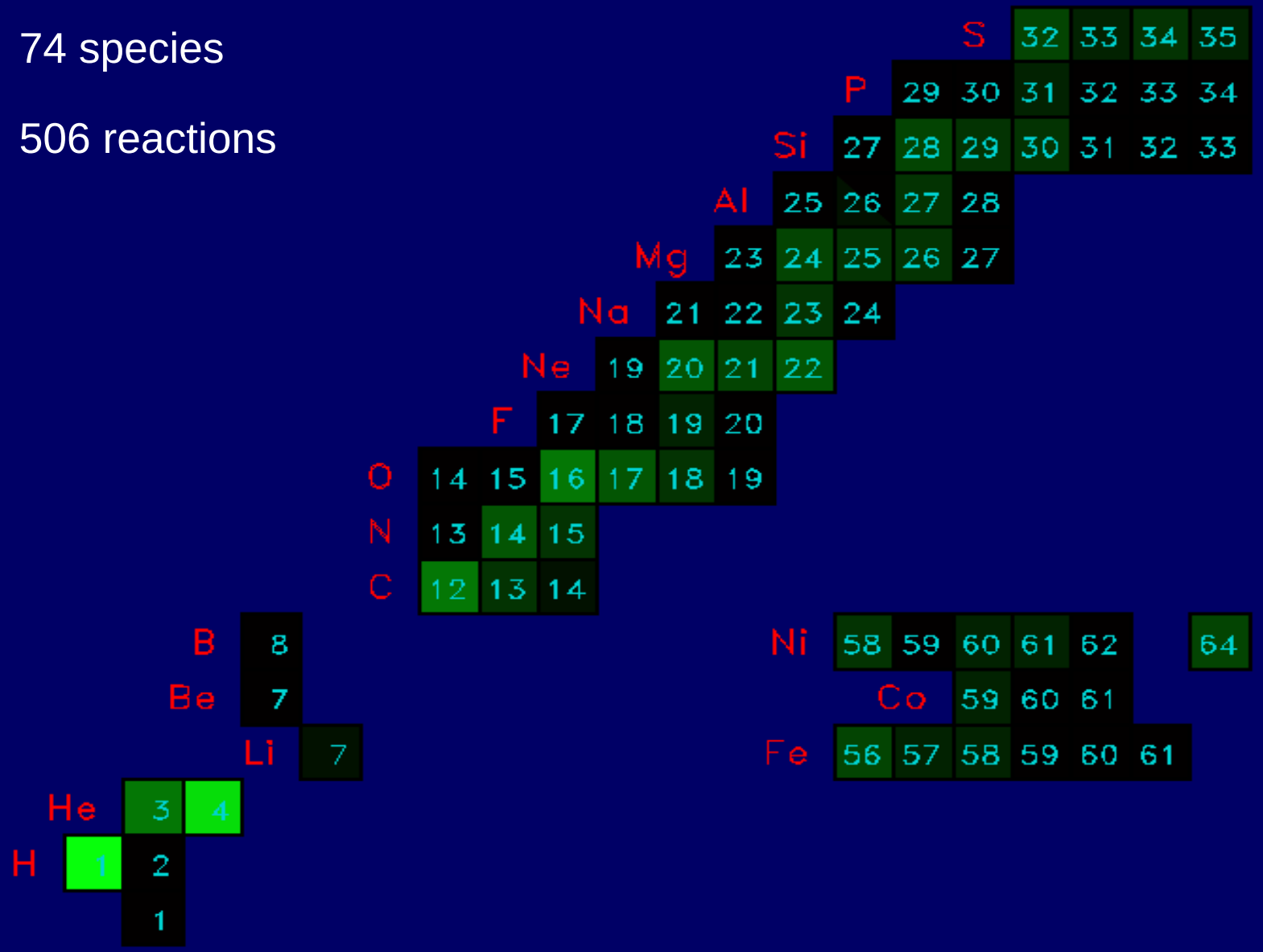
- **Pre-solar meteorite grains…**
- **Pieces of stars! In the lab!**



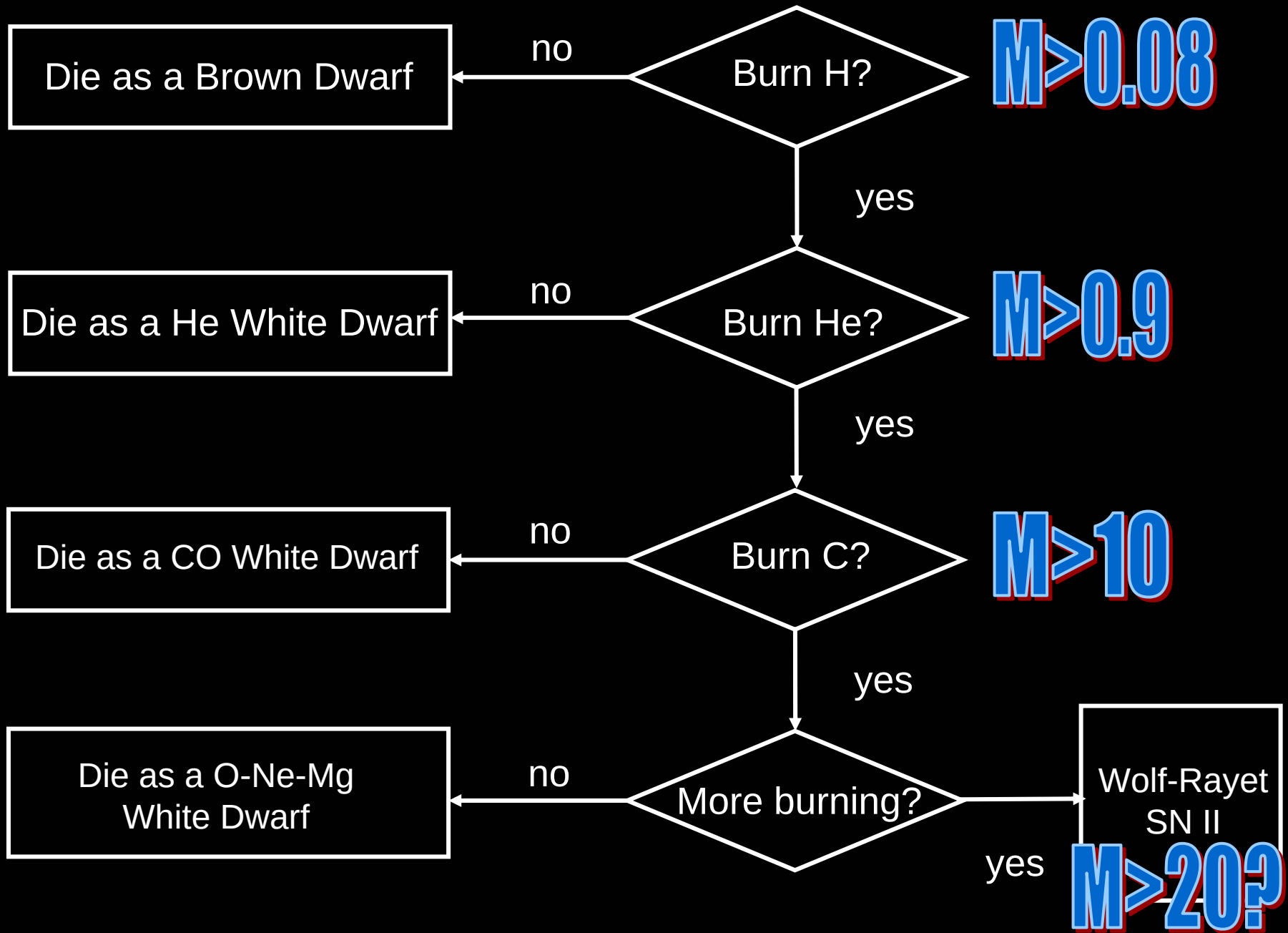
The Nuclear Network we now use

74 species

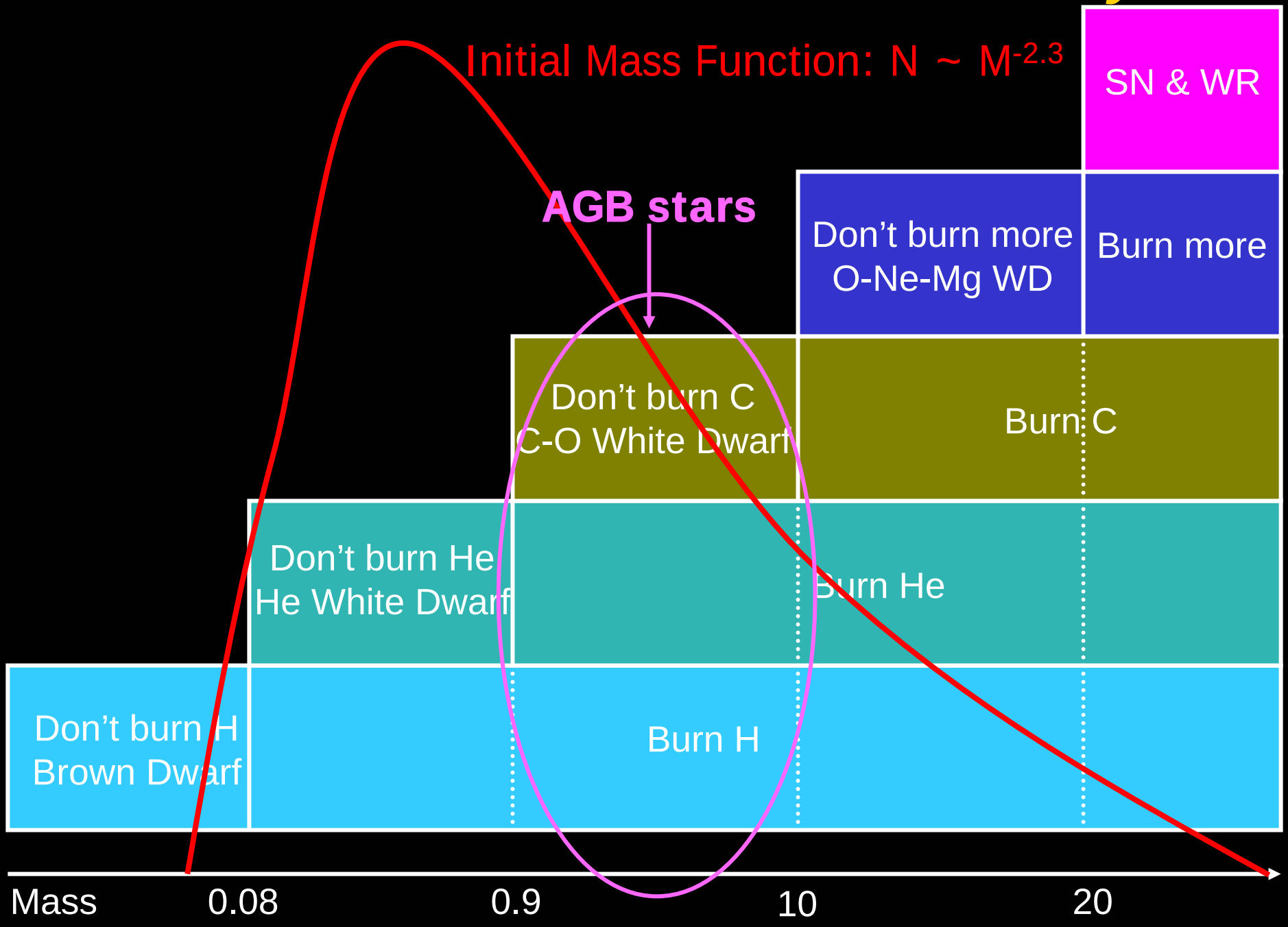
506 reactions



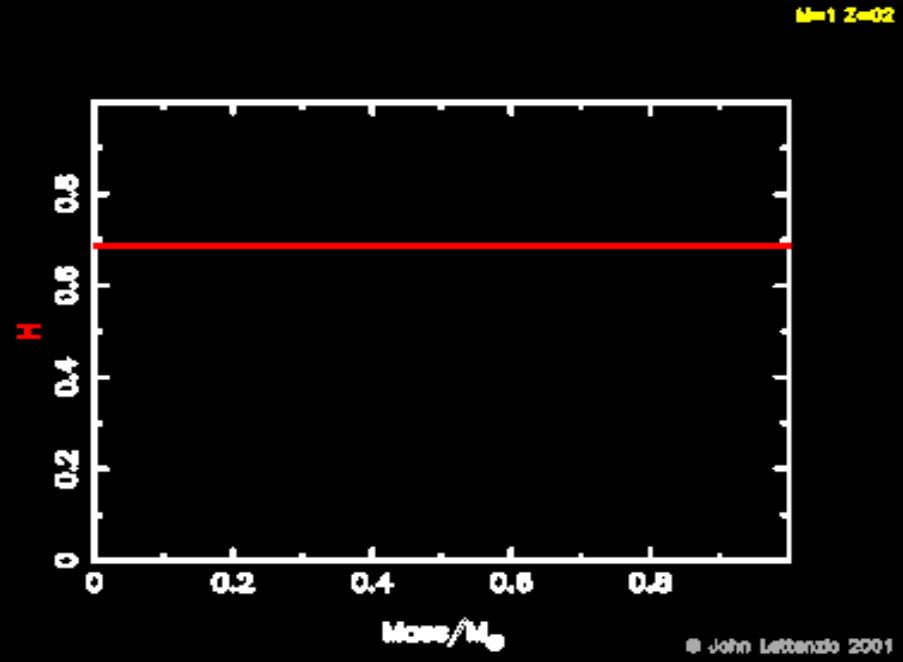
Basic Stellar Evolution: Mass is the key!

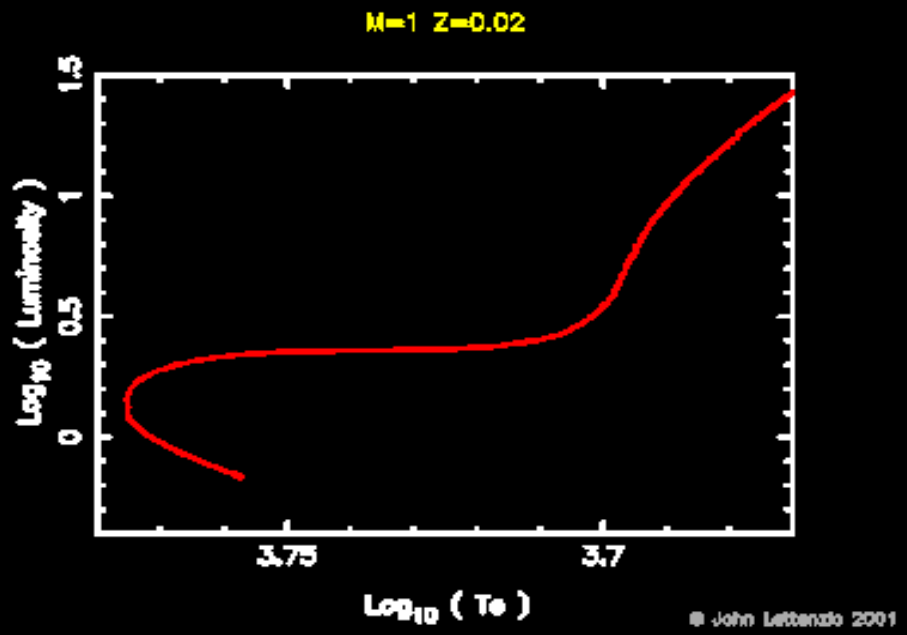


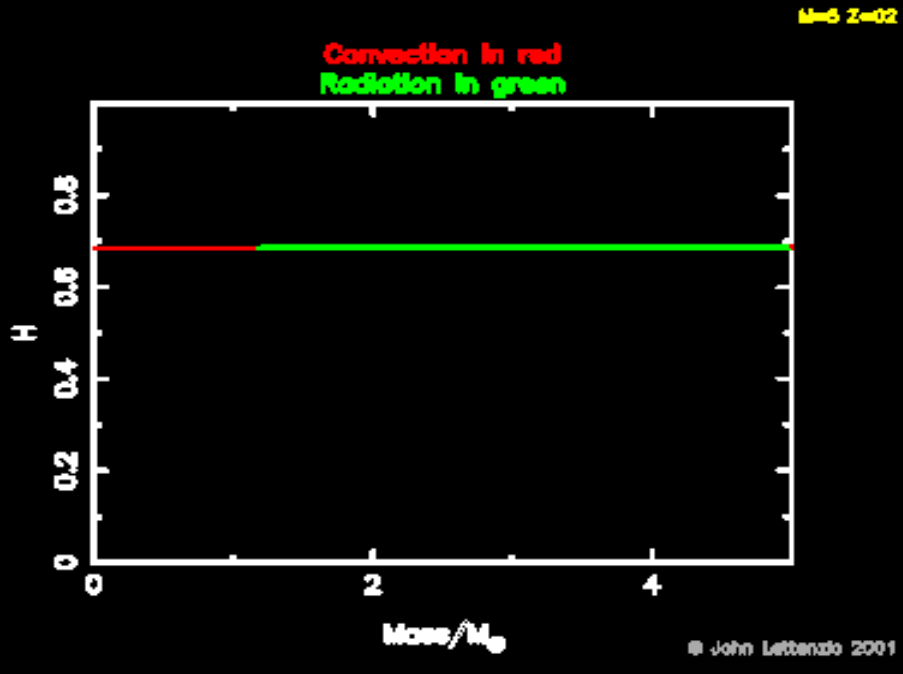
Basic Stellar Evolution: Mass is the key!

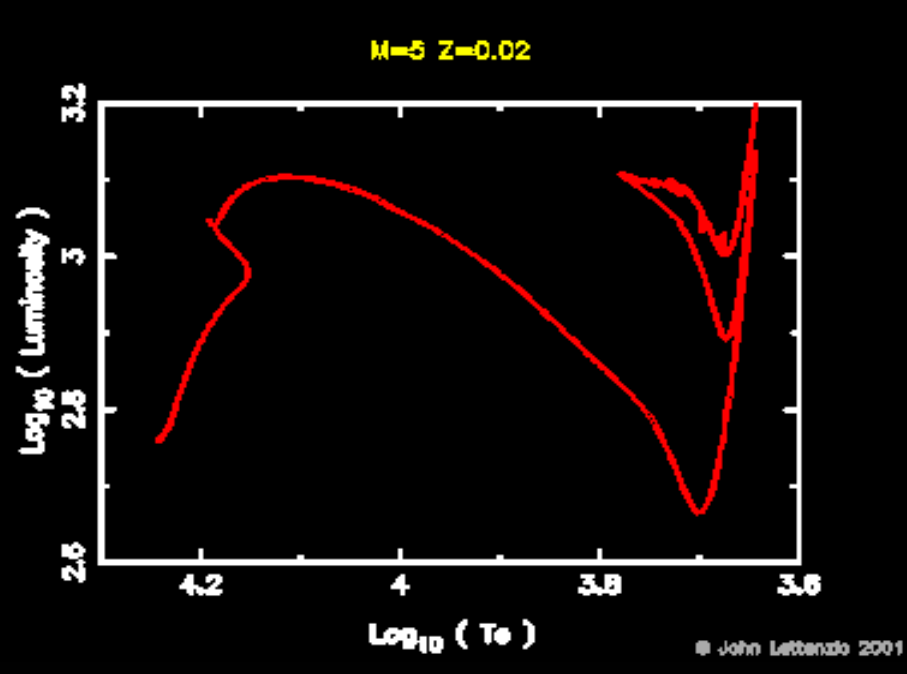


Basic Stellar Evolution at M=1 and 5

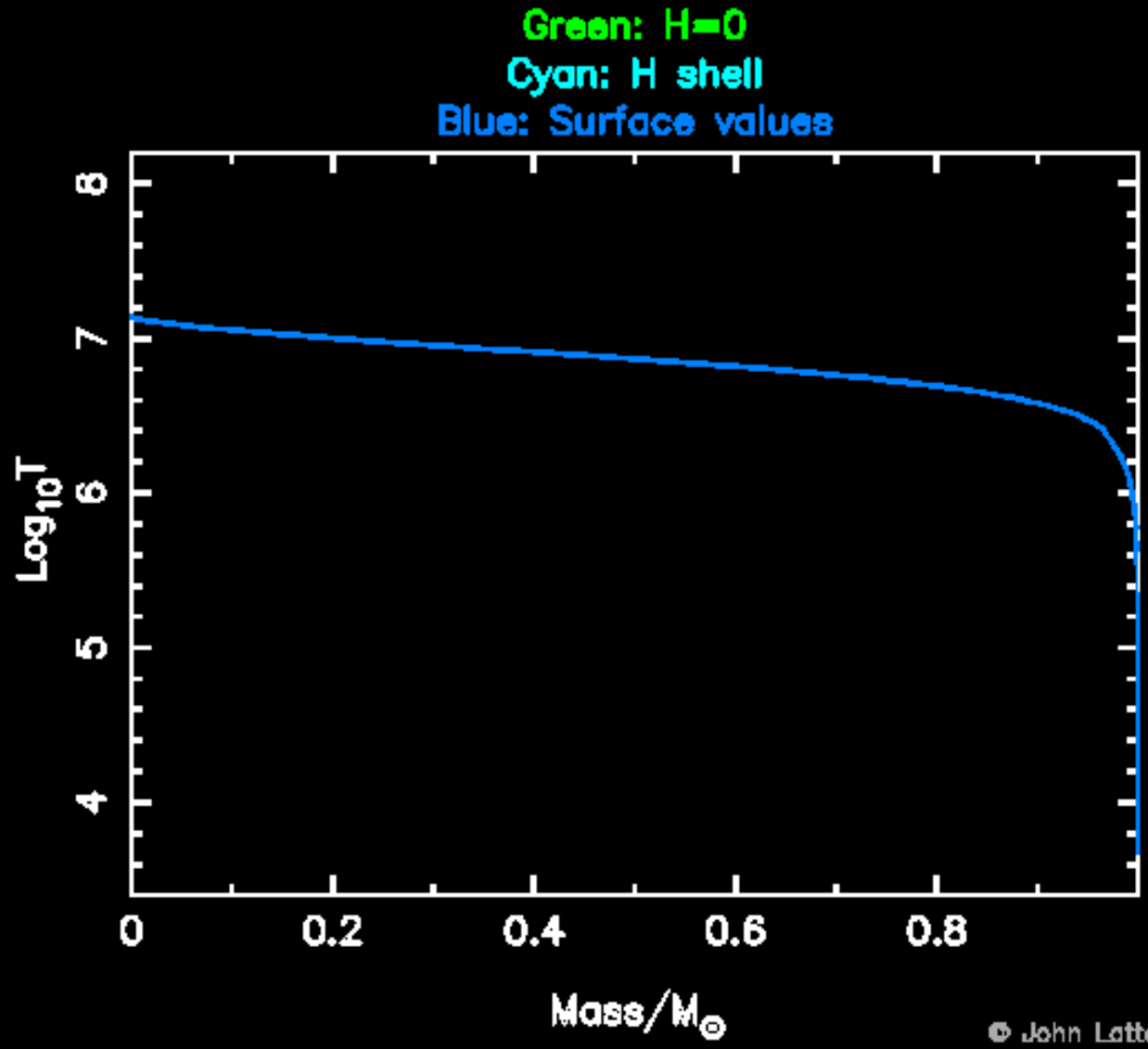




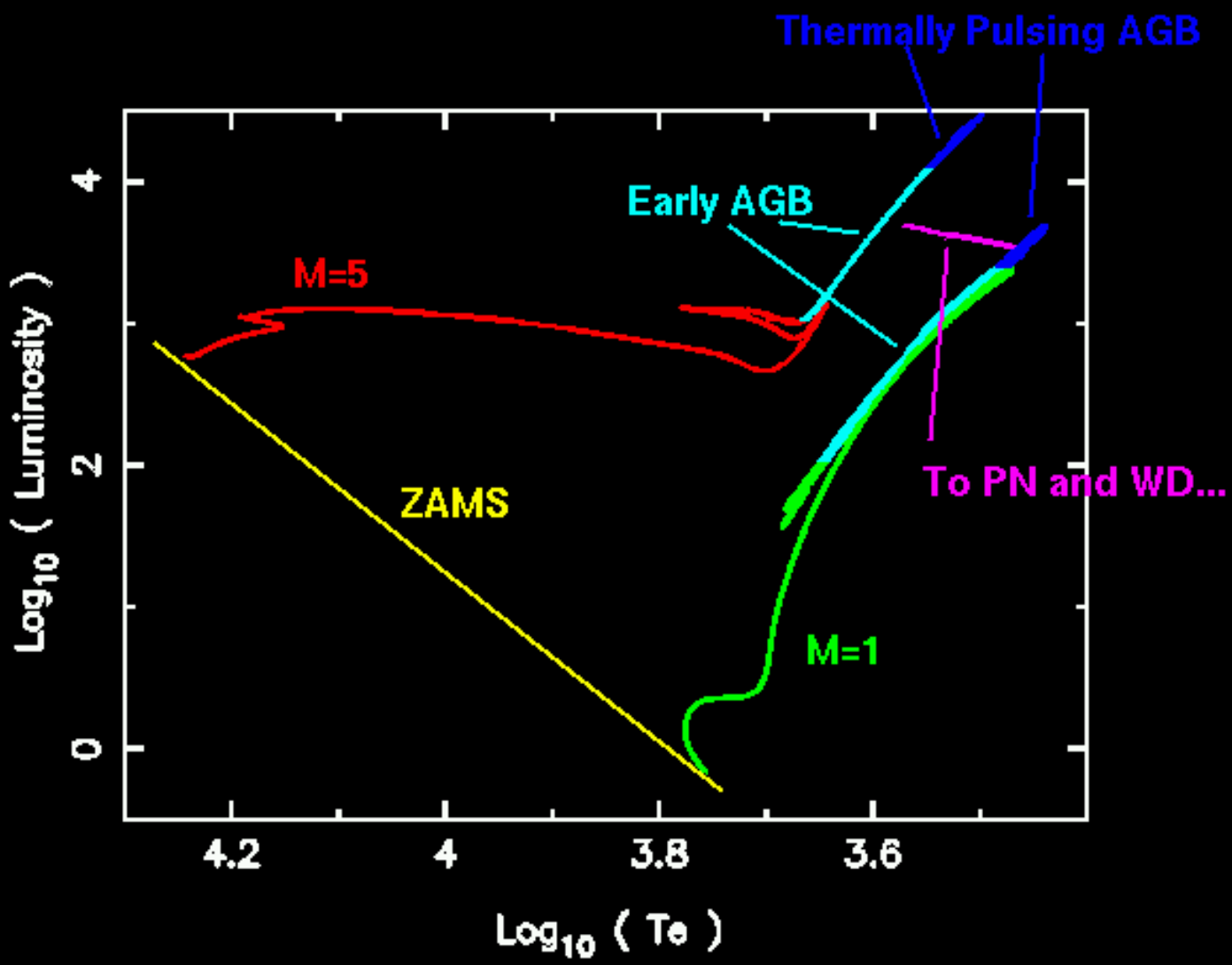




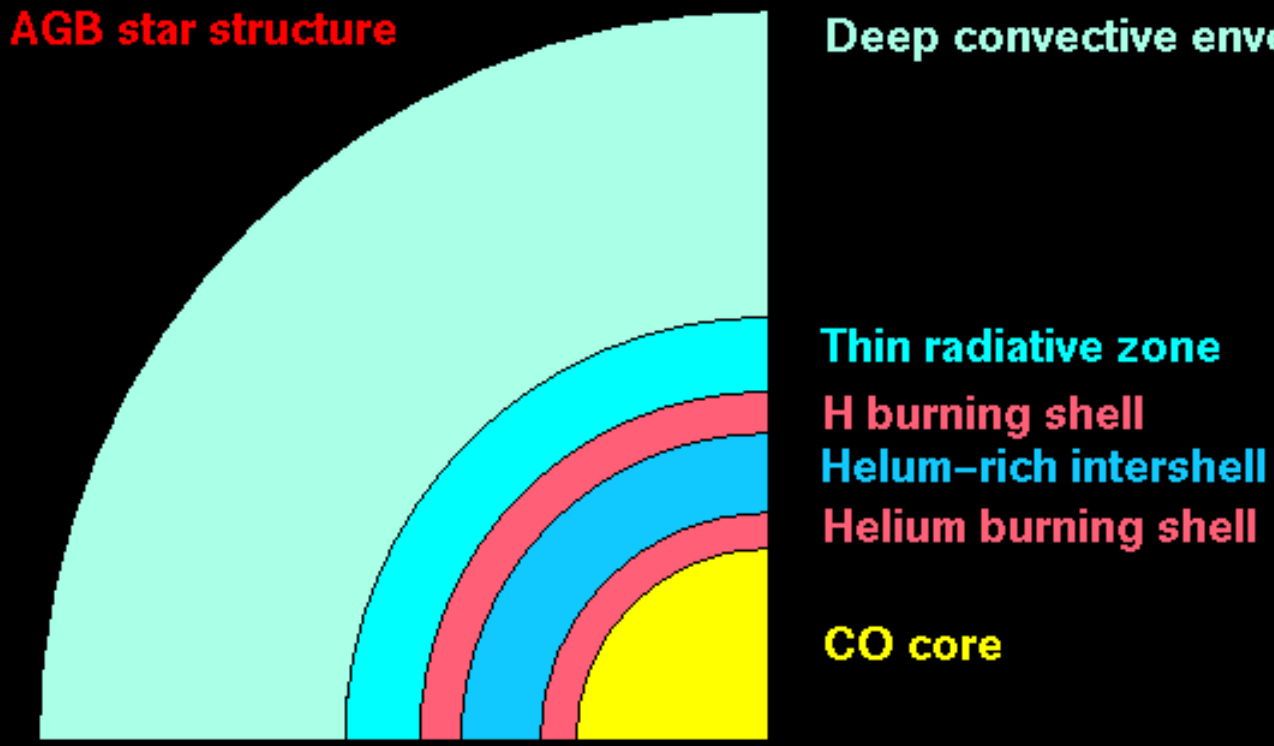
H burning summary at M=1



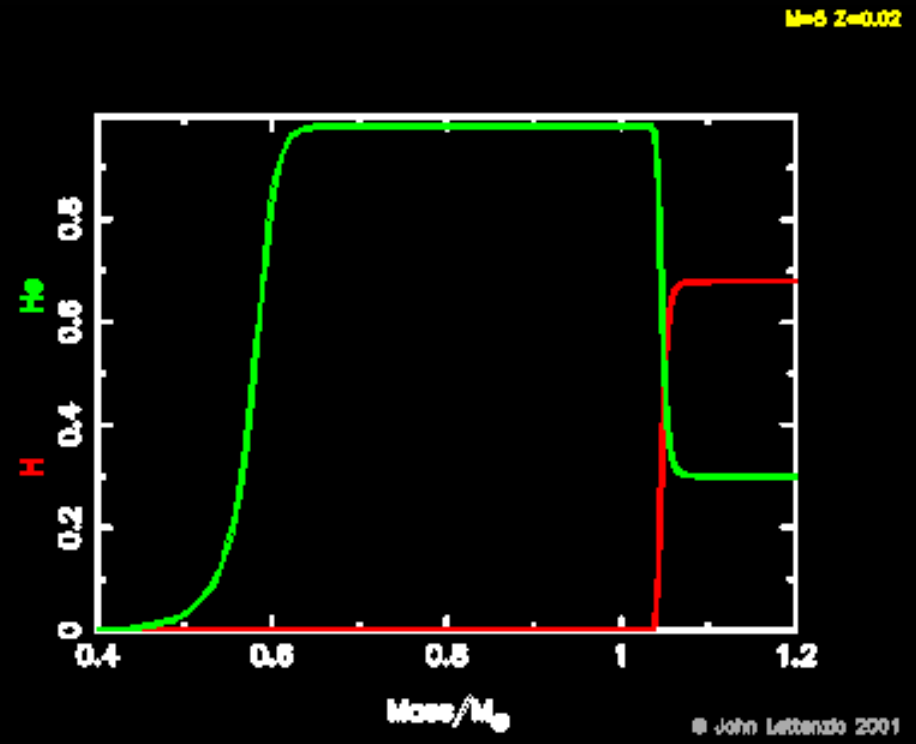
End of H burning: He ignition

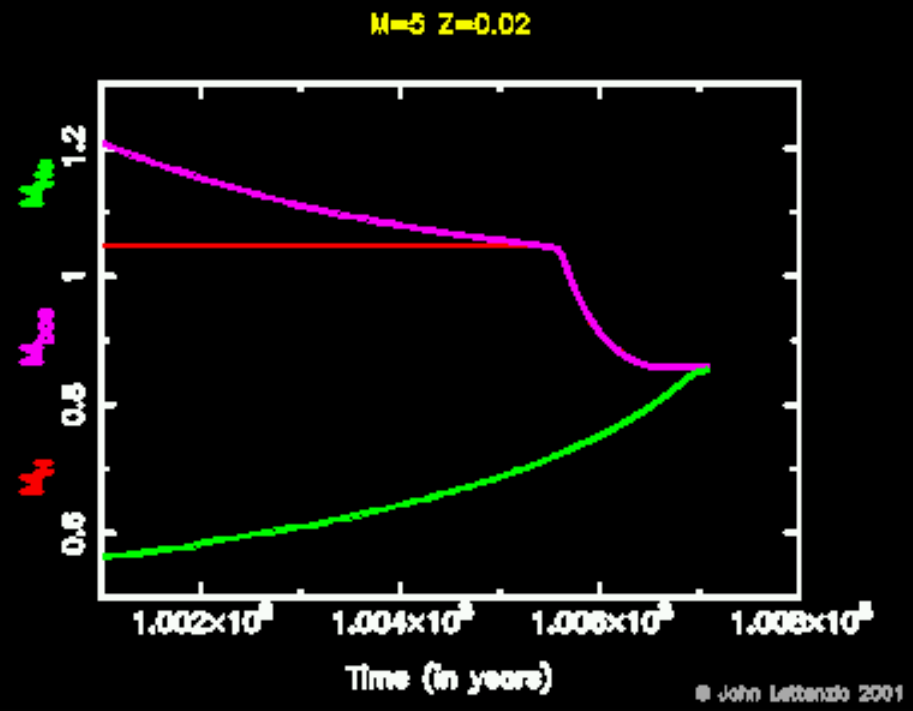


Following He exhaustion: AGB Evolution



Early AGB Evolution: Second Dredge-Up





Thermally pulsing AGB phase

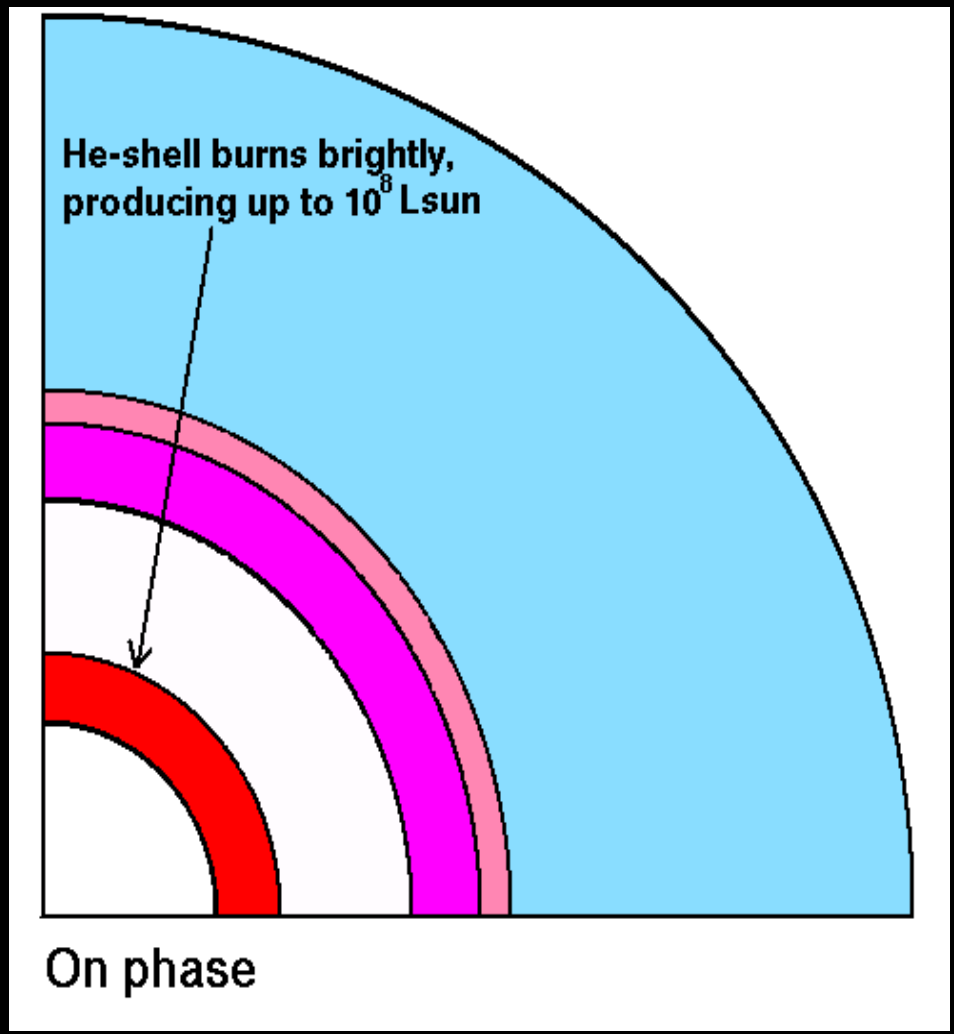
Deep convective Envelope

Thin radiative zone
H-burning shell

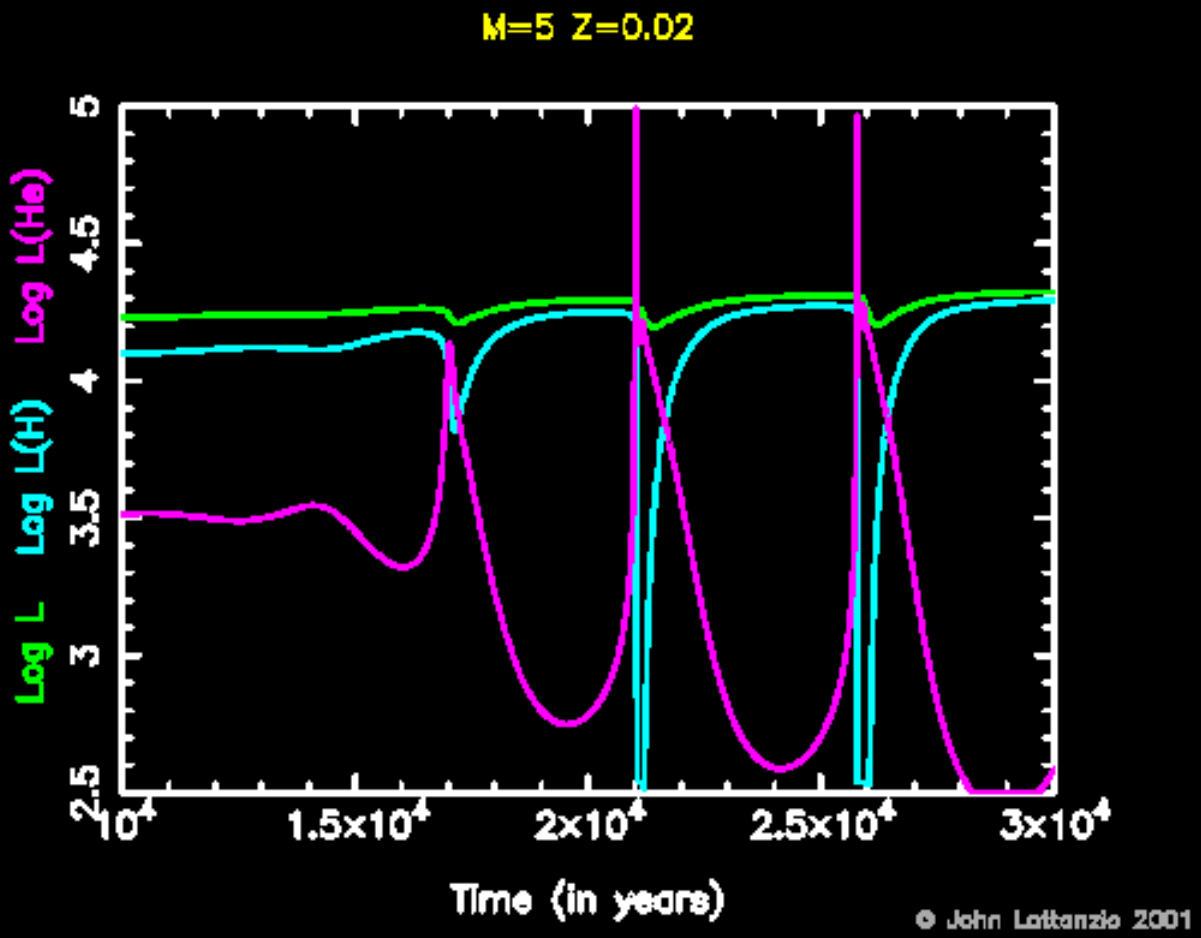
He-rich intershell

He-burning shell

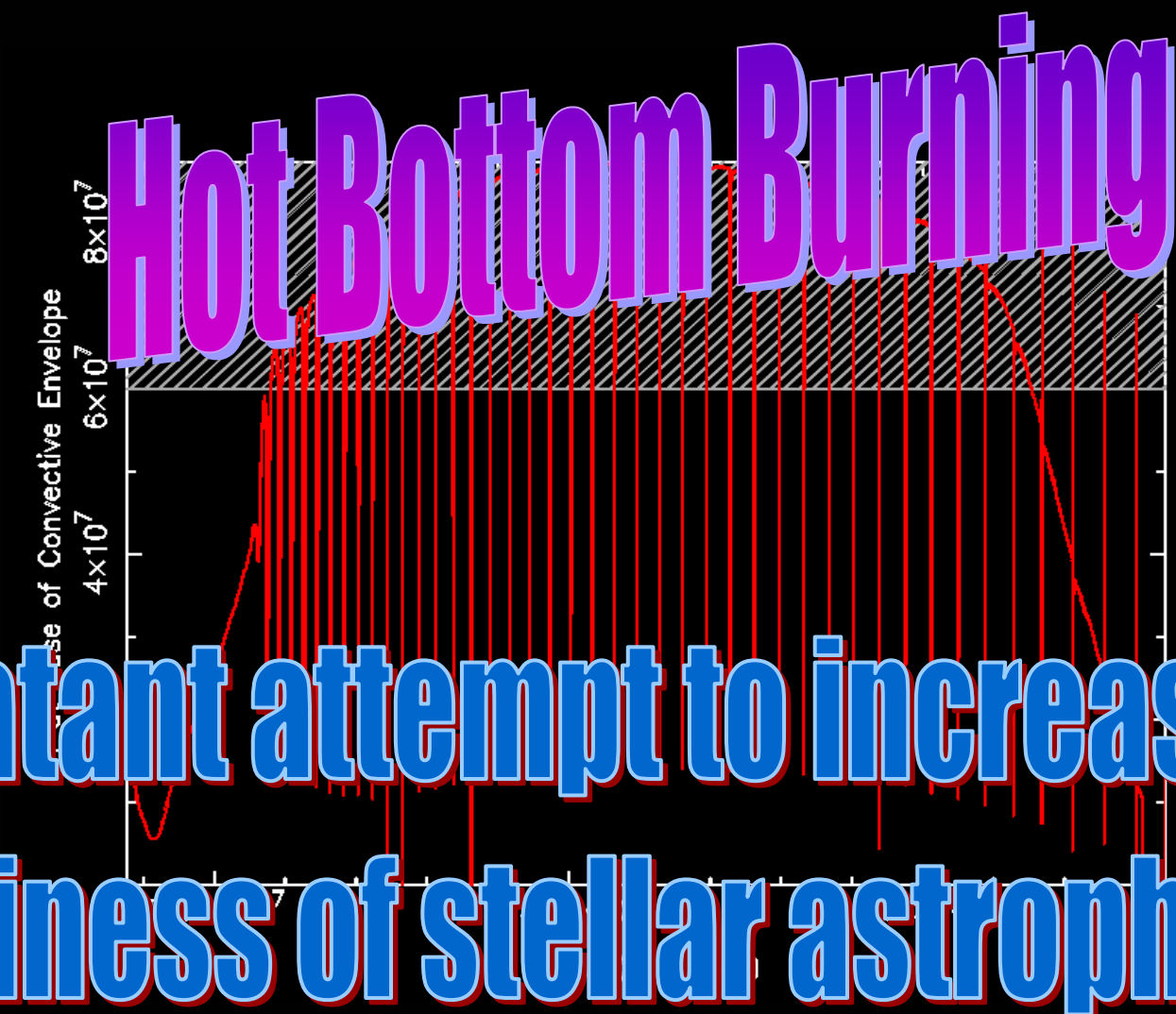
CO core



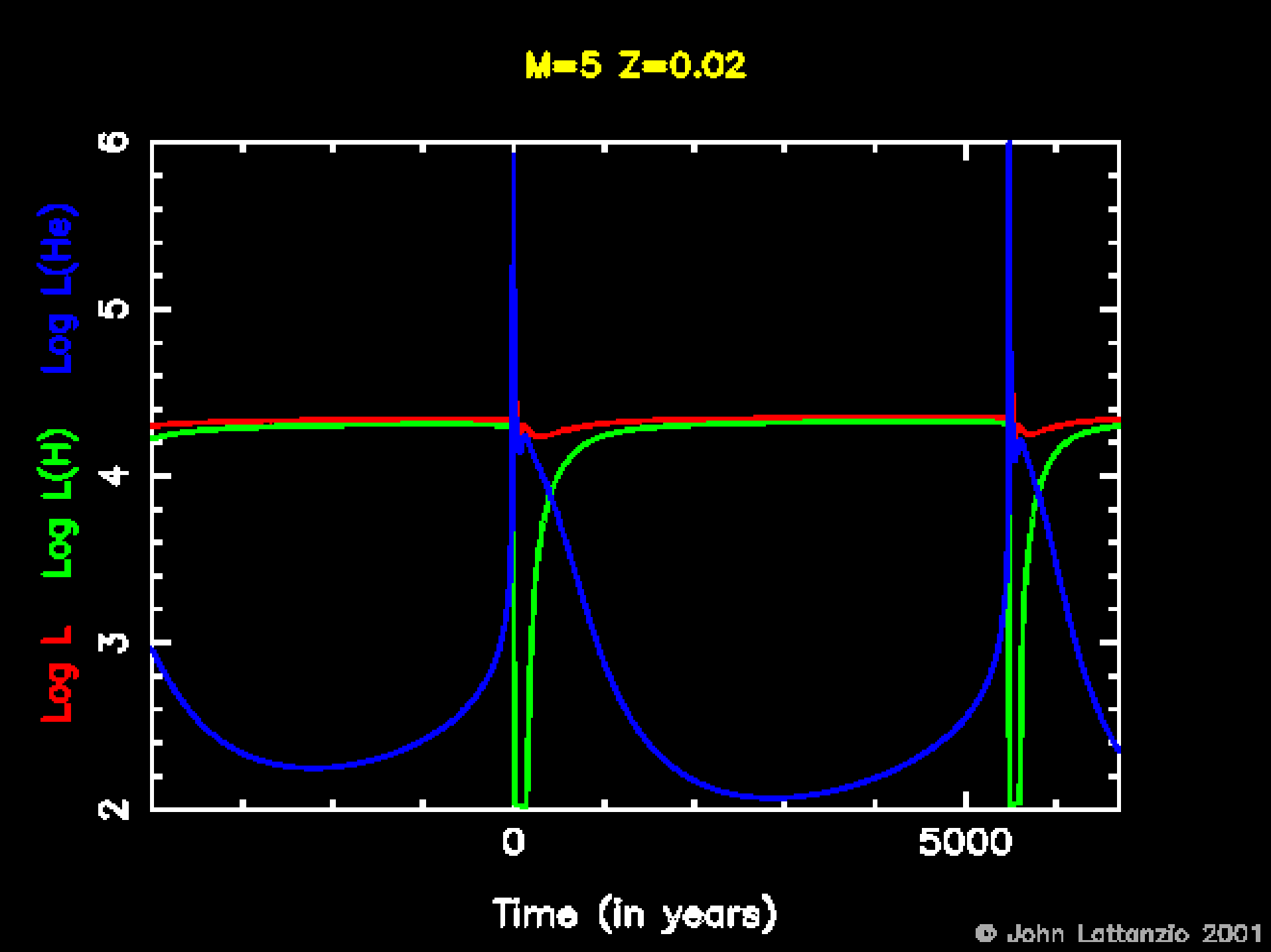
AGB Evolution

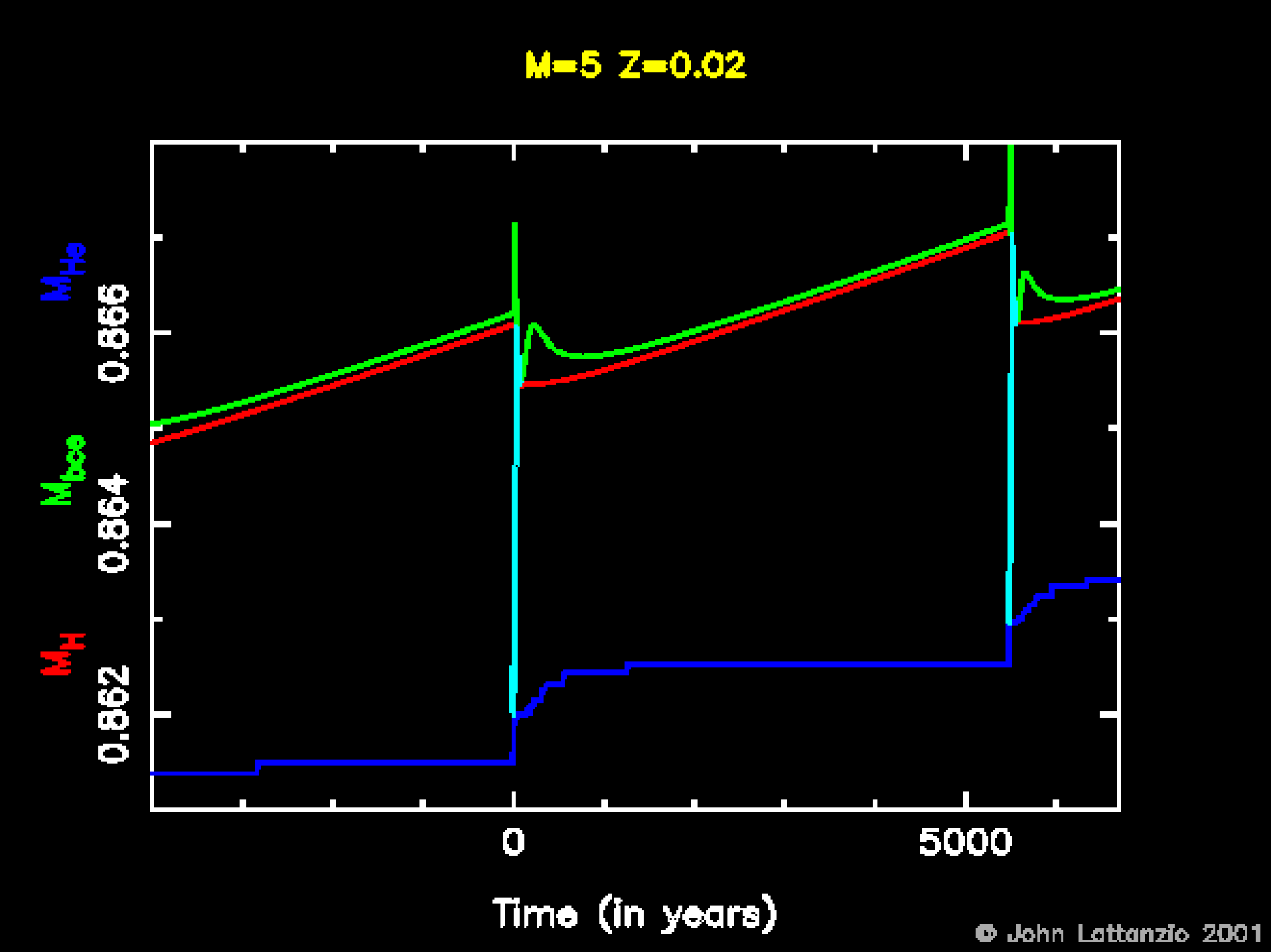


AGB evolution: M = 6.5, Z=0.02

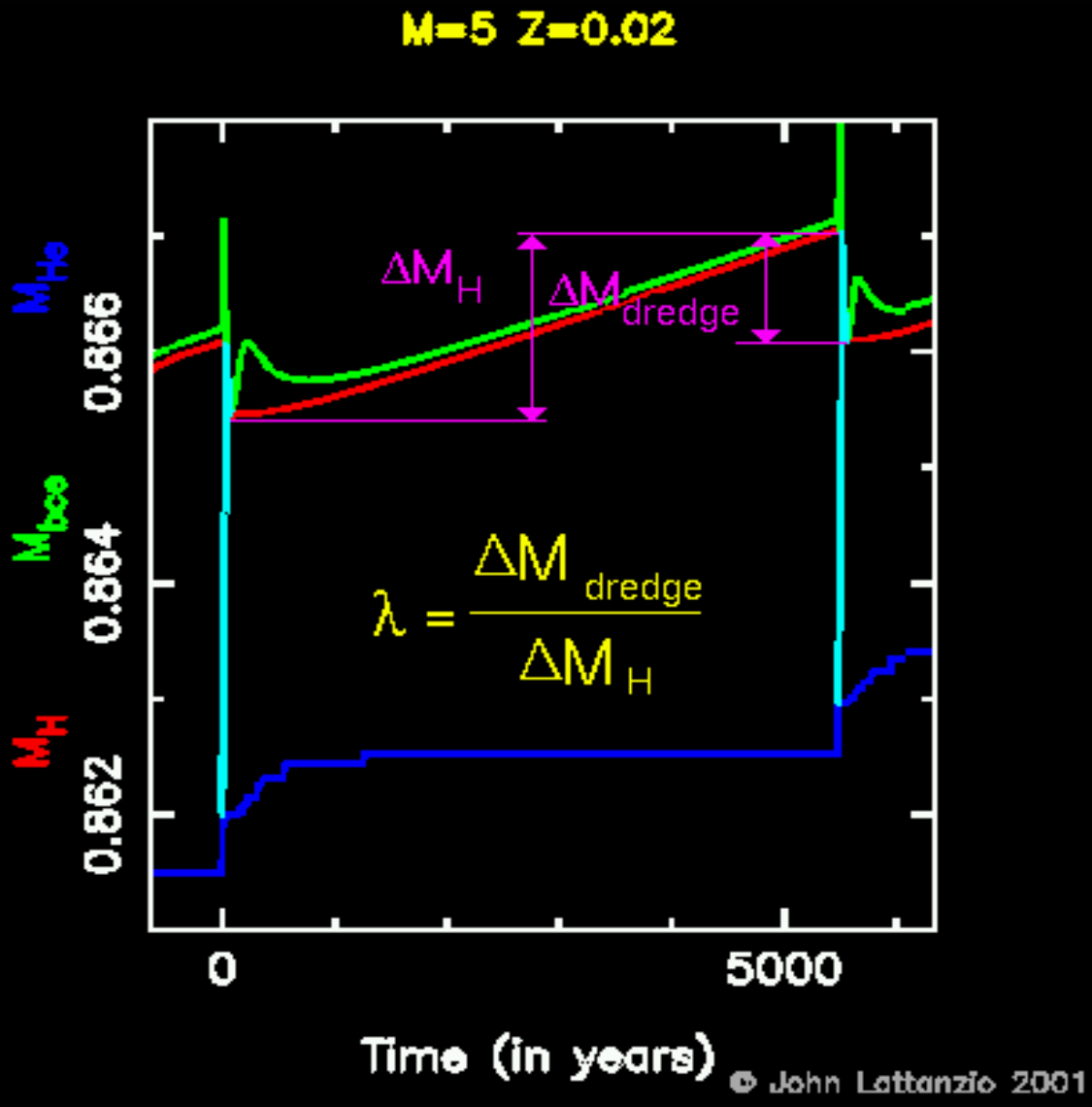


Blatant attempt to increase the sexiness of stellar astrophysics...


M=5 Z=0.02
Log L
Log L(H)
Log L(He)
6
5
4
3
2
0
5000
Time (in years)
© John Lattanzio 2001


M=5 Z=0.02
M_{He}
M_{bce}
M_H
0.866
0.864
0.862
0
5000
Time (in years)
© John Lattanzio 2001

Dredge-Up Parameter: λ



AGB Evolution

Mixing Zones →

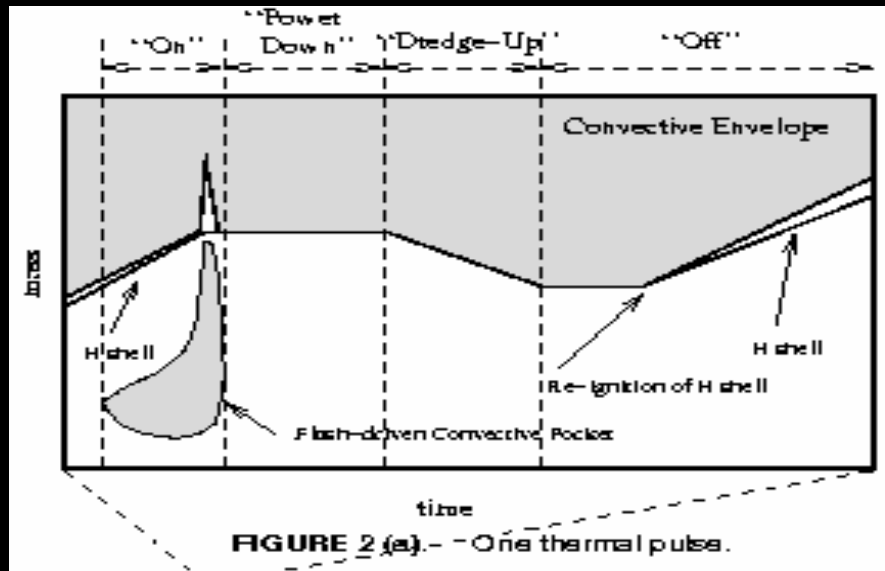


FIGURE 2 (a).– One thermal pulse.

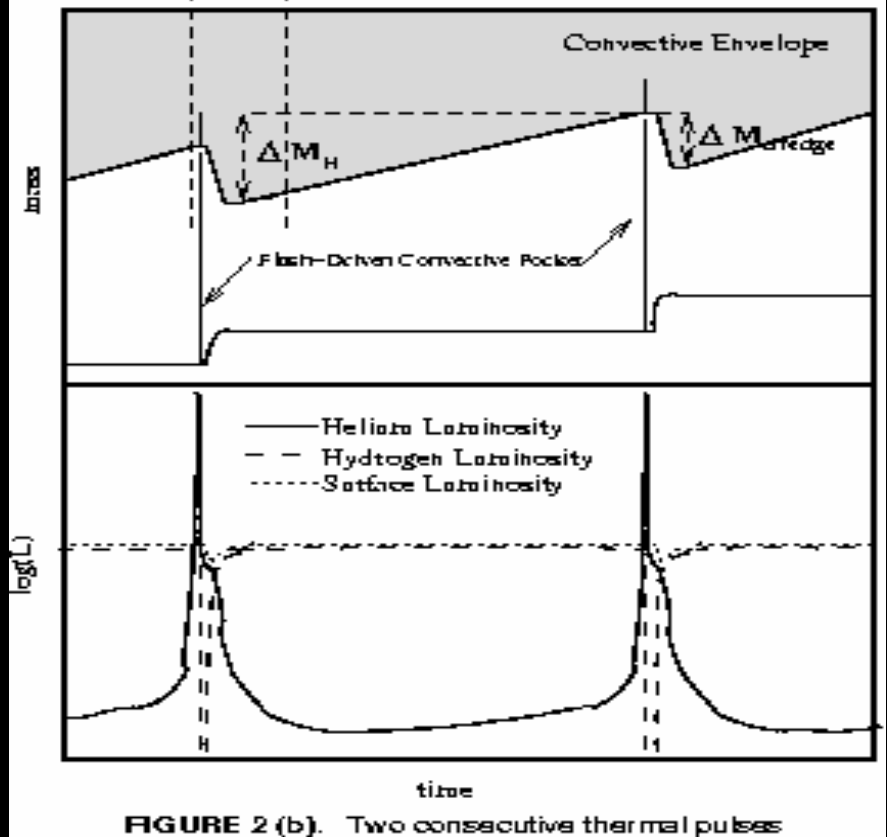
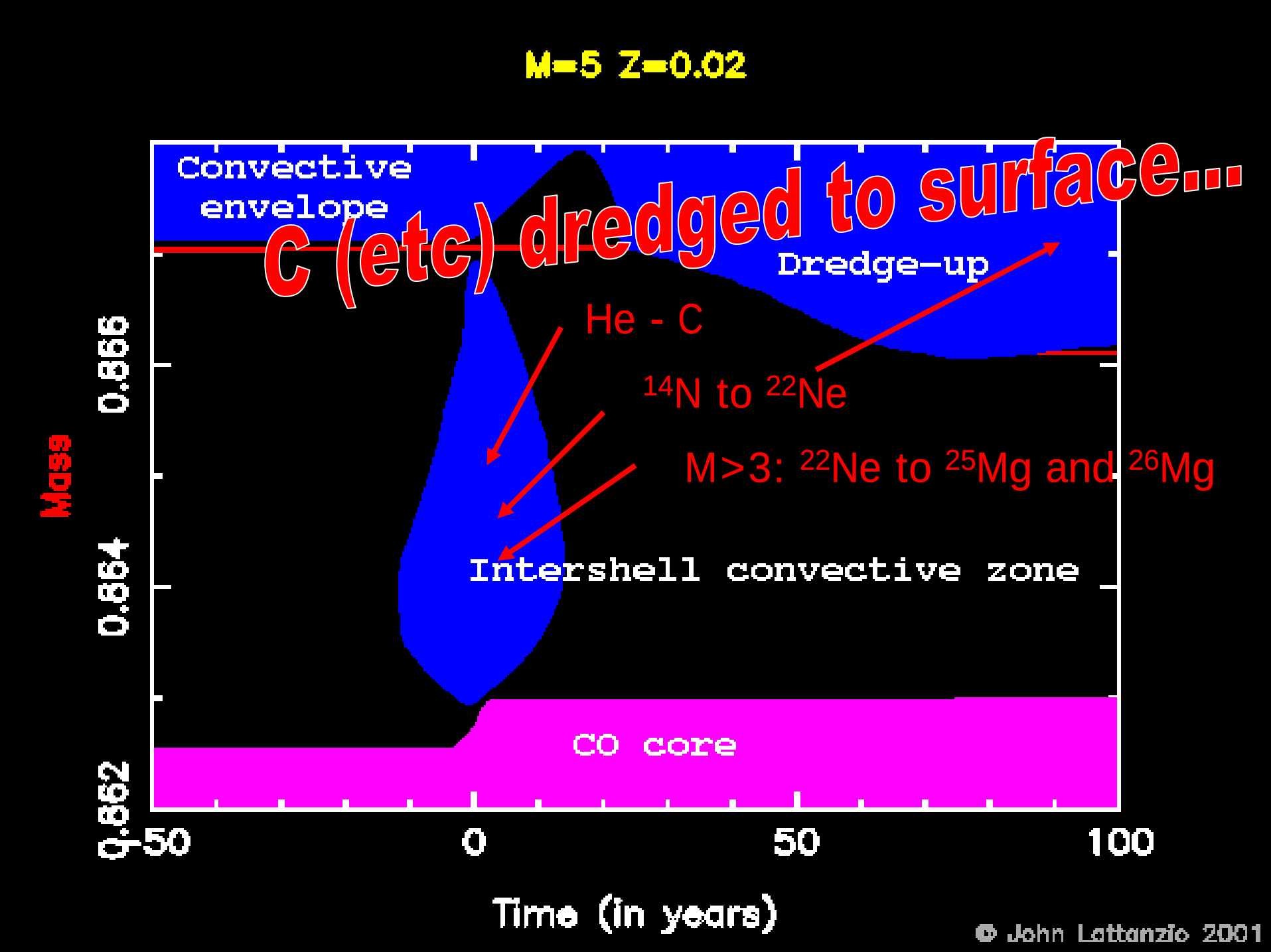
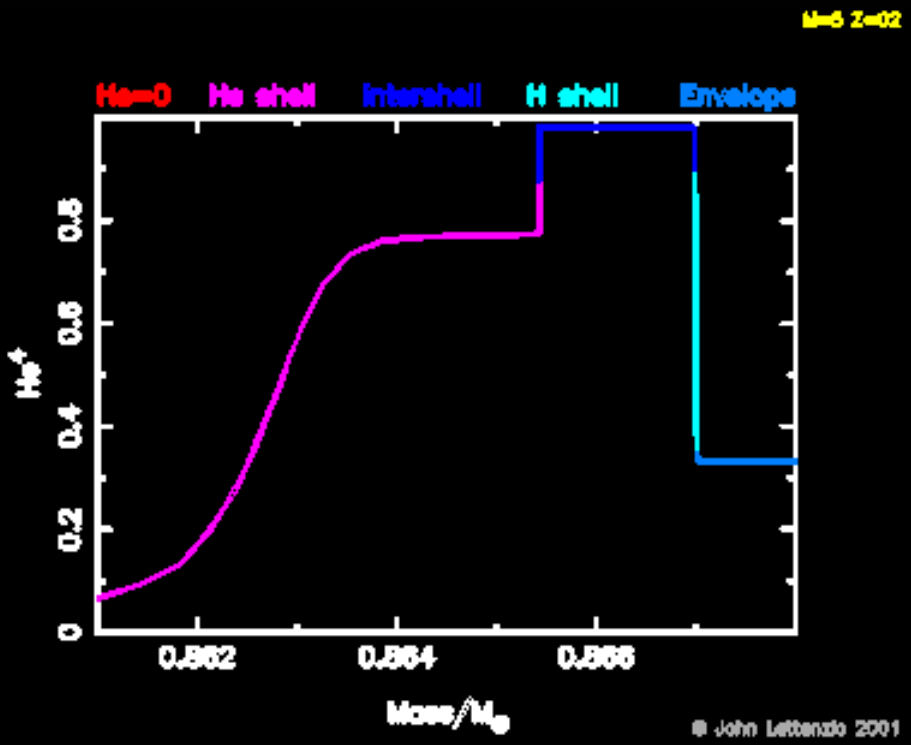
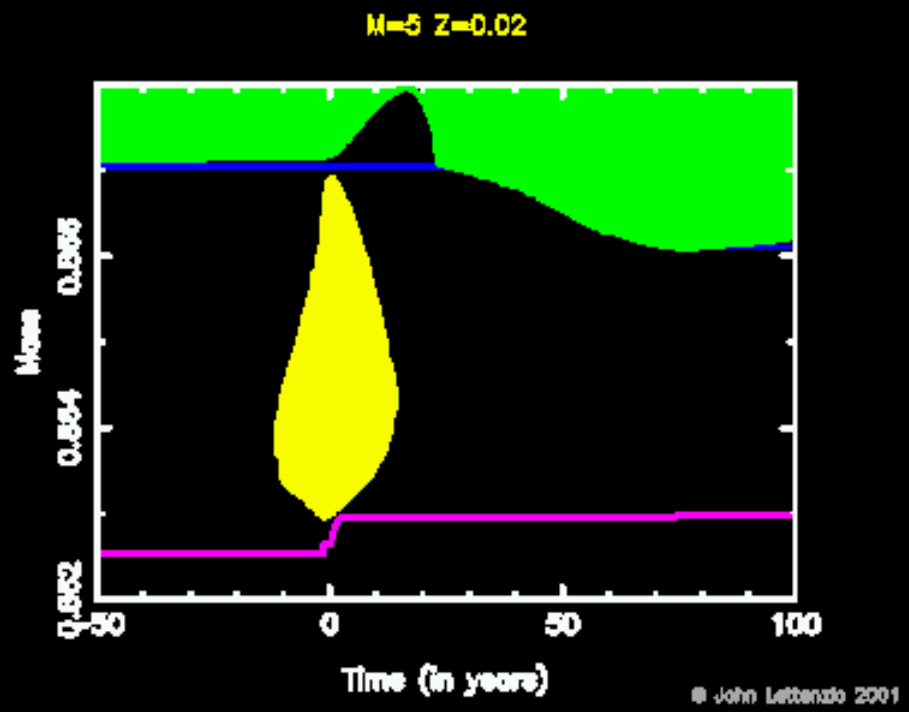


FIGURE 2 (b). Two consecutive thermal pulses


M=5 Z=0.02
Convective envelope
C (etc) dredged to surface...
Dredge-up
He - C
14N to 22Ne
M>3: 22Ne to 25Mg and 26Mg
Intershell convective zone
CO core
Mass
0.862
0.864
0.866
-50
0
50
100
Time (in years)
© John Lattanzio 2001

AGB movies

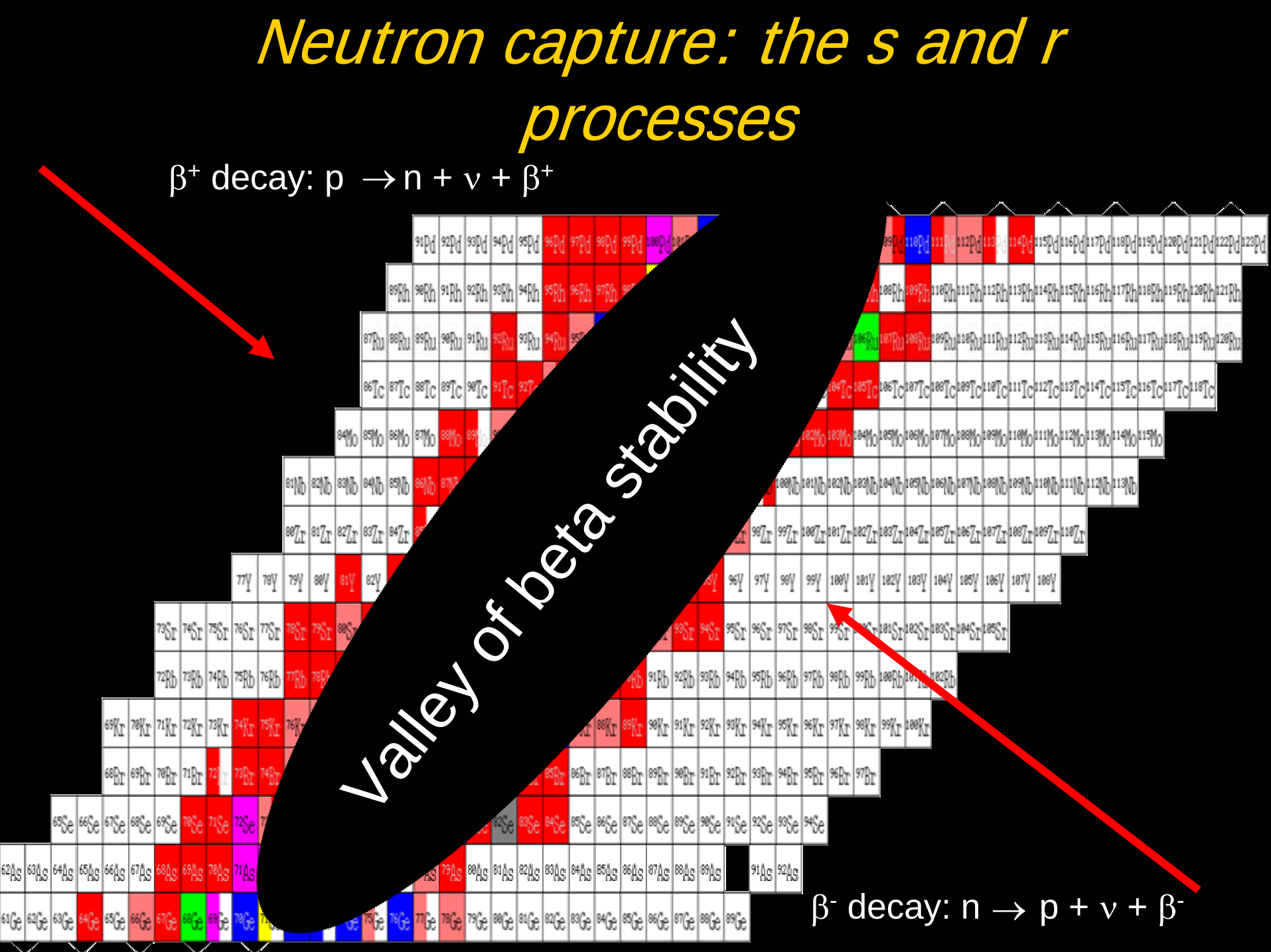

M=5 Z=02
He=0
He shell
Intershell
H shell
Envelope
0
0.2
0.4
0.6
0.8
0.862
0.864
0.866
Mass/M⊙
© John Lattanzio 2001


M=5 Z=0.02
0.862
0.864
0.866
Mass
-50
0
50
100
Time (in years)
© John Lattanzio 2001

M – MS – S – C(N)

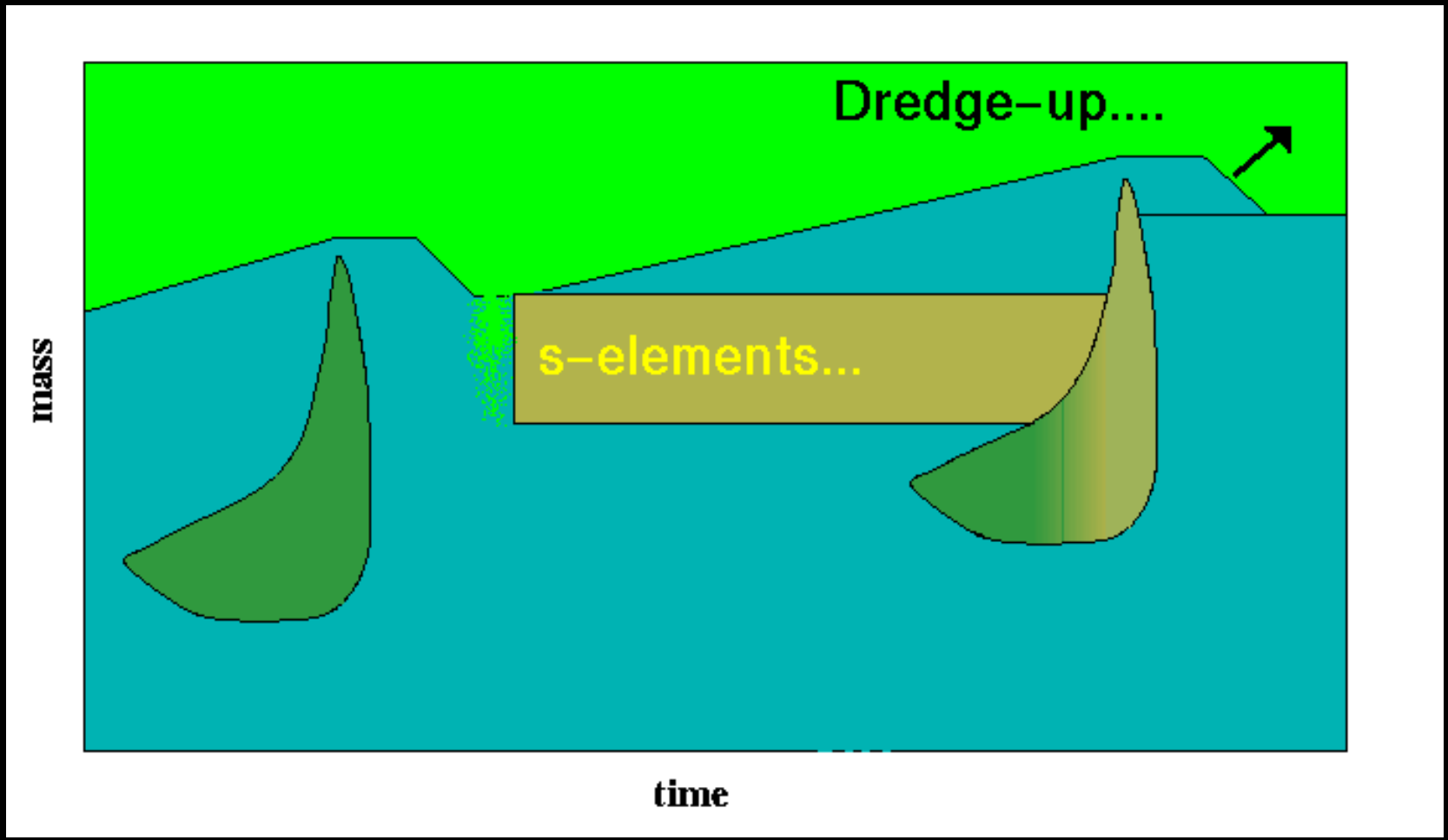
- Add C at each drede-up episode
- Eventually C/O > 1
- M star turns into a C star
- Fits observations (pretty much...)

Neutron capture: the s and r processes



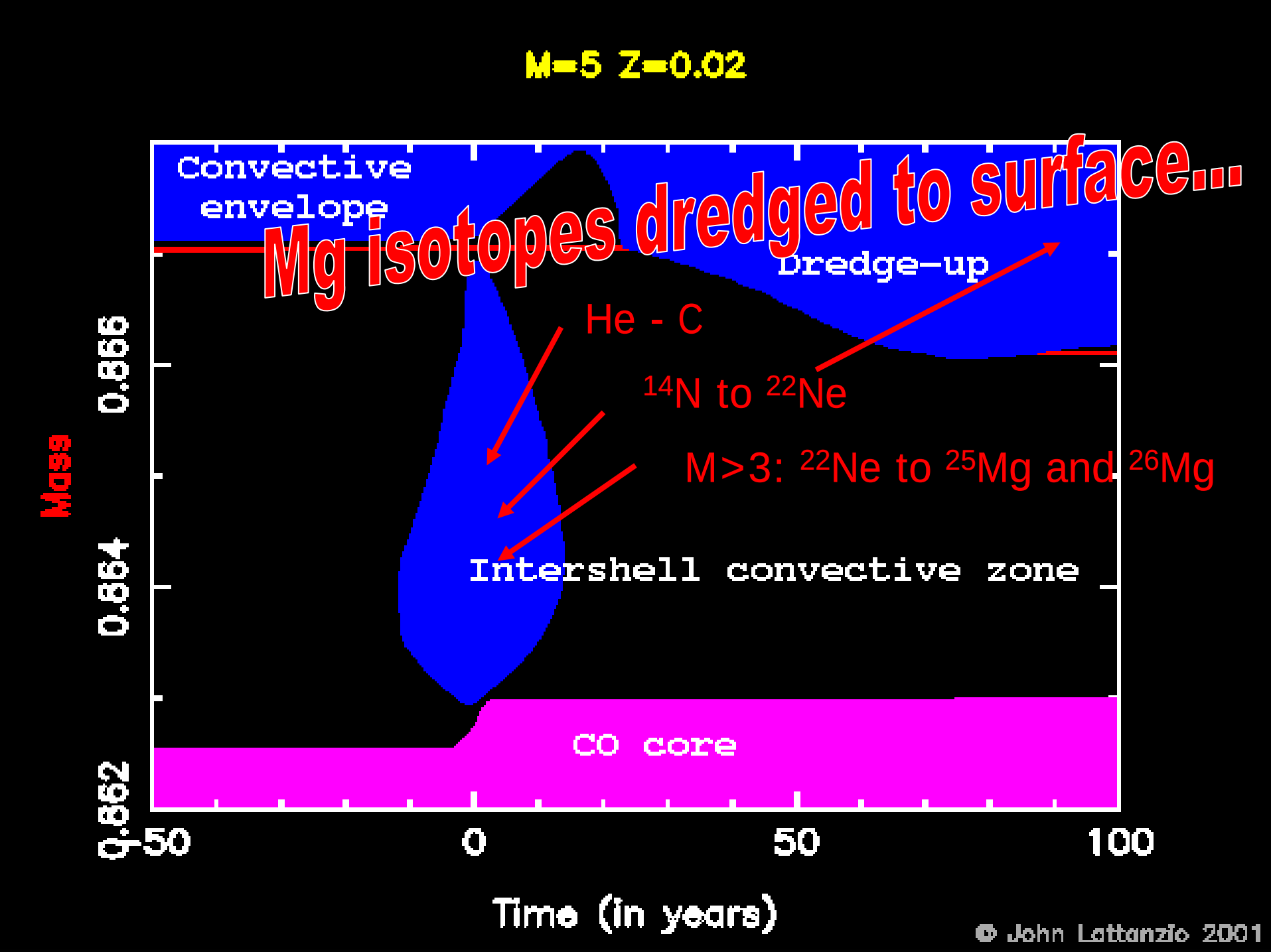
S-process elements in AGB stars

Neutron capture on Fe: Sr, Y, Zr, Ba, Kr etc…

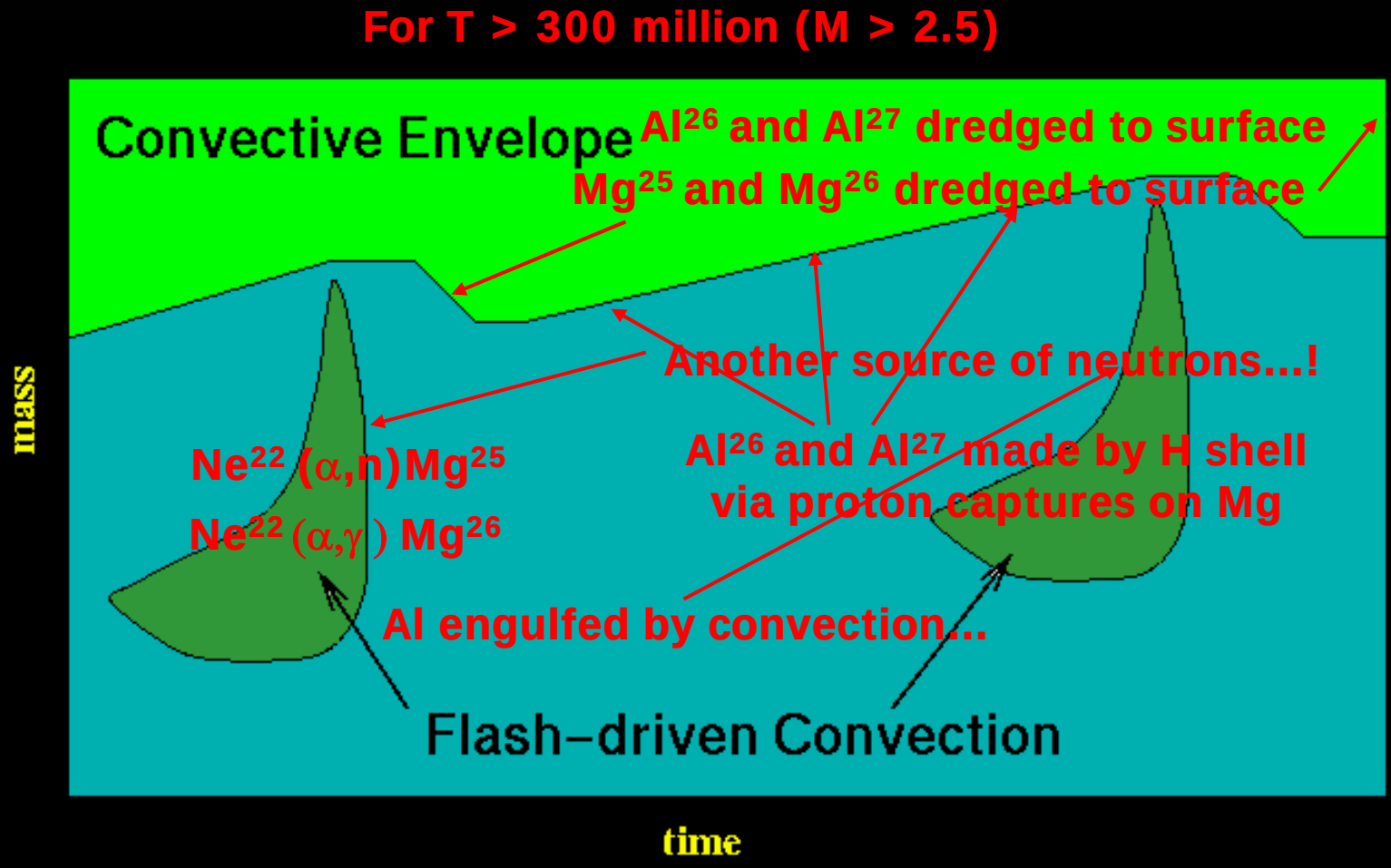


Mg isotopes in field stars

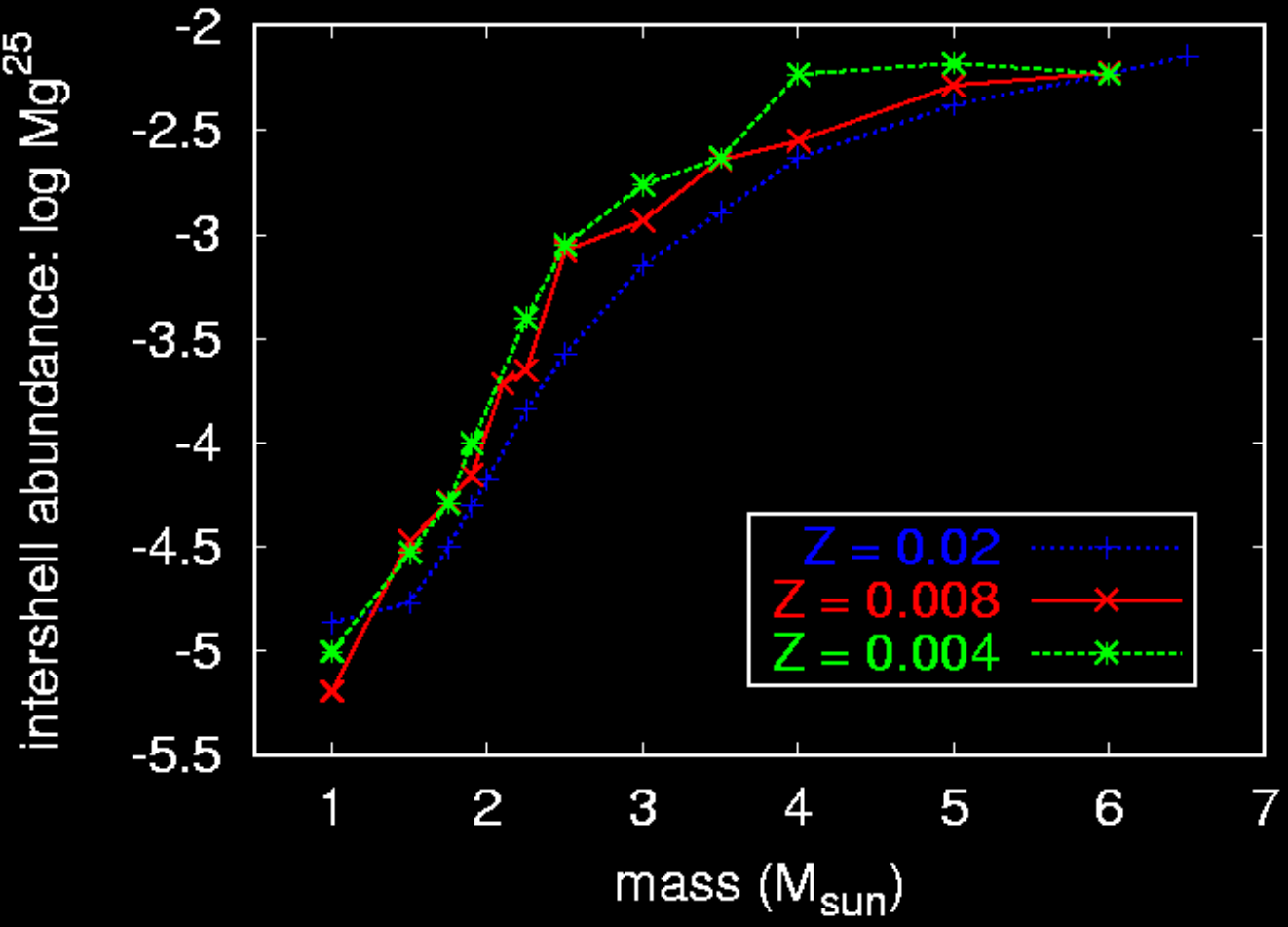
- Gay and Lambert found some enhancements in heavy isotopes
- Does not fit SN models...

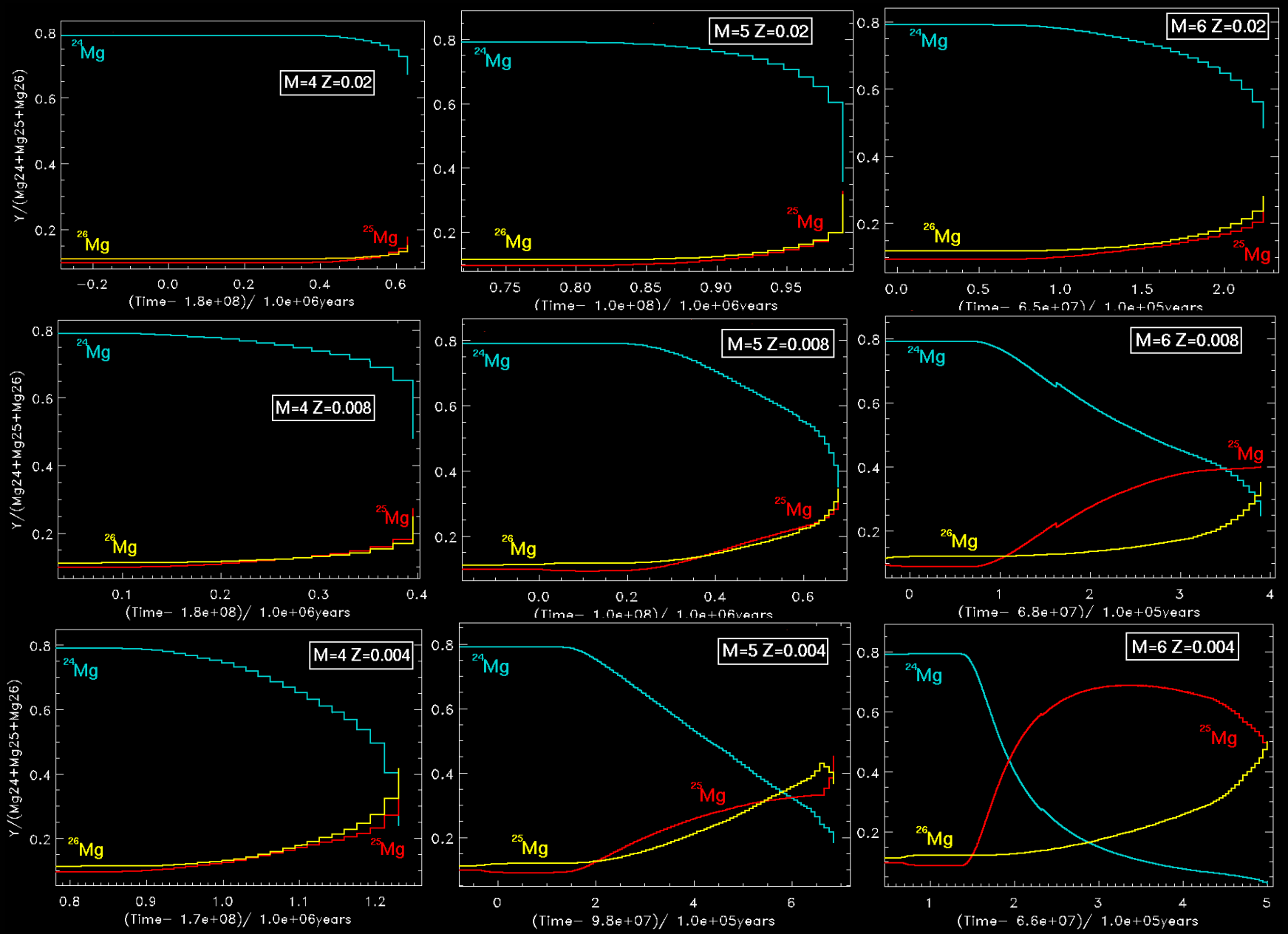

M=5 Z=0.02
Convective envelope
Mg isotopes dredged to surface...
Dredge-up
He - C
14N to 22Ne
M>3: 22Ne to 25Mg and 26Mg
Intershell convective zone
CO core
Mass
0.862
0.864
0.866
-50
0
50
100
Time (in years)
© John Lattanzio 2001

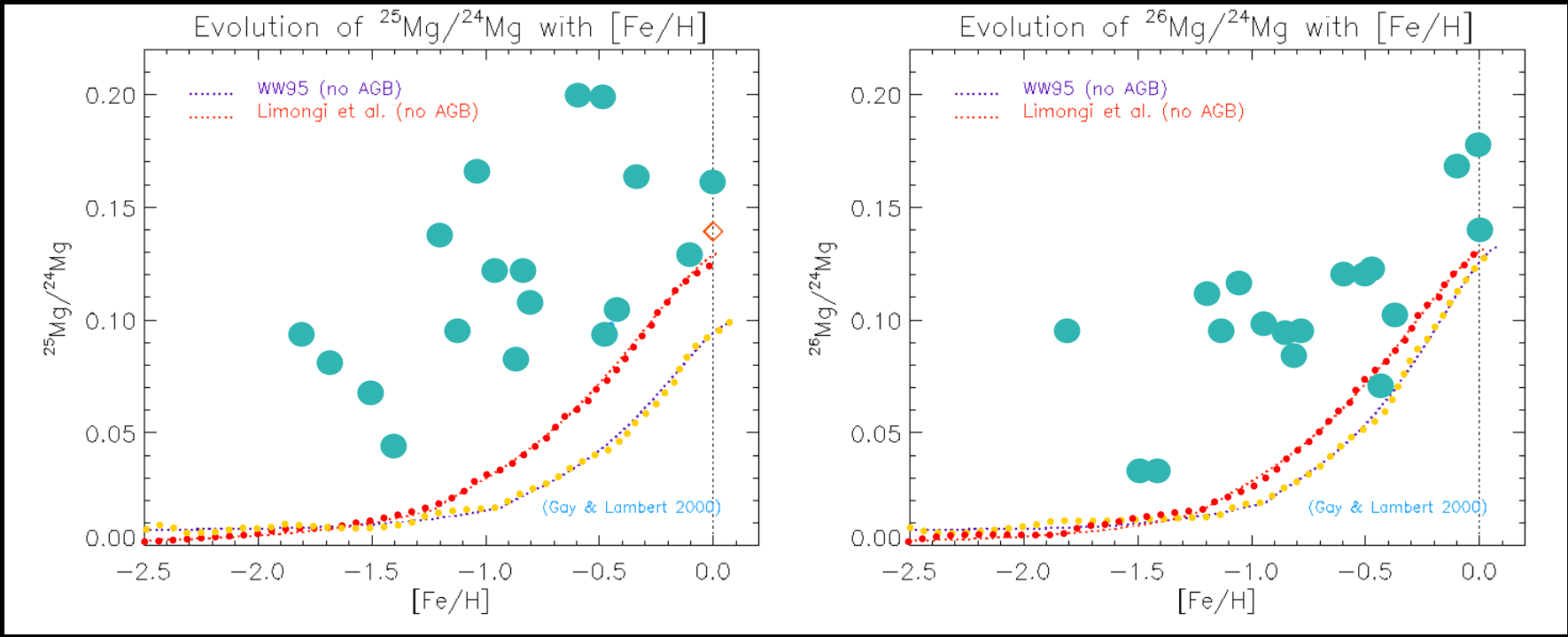
$Mg^{25,26}$ (and maybe $Al^{26,27}$)



Intershell abundances: as a function of mass & Z



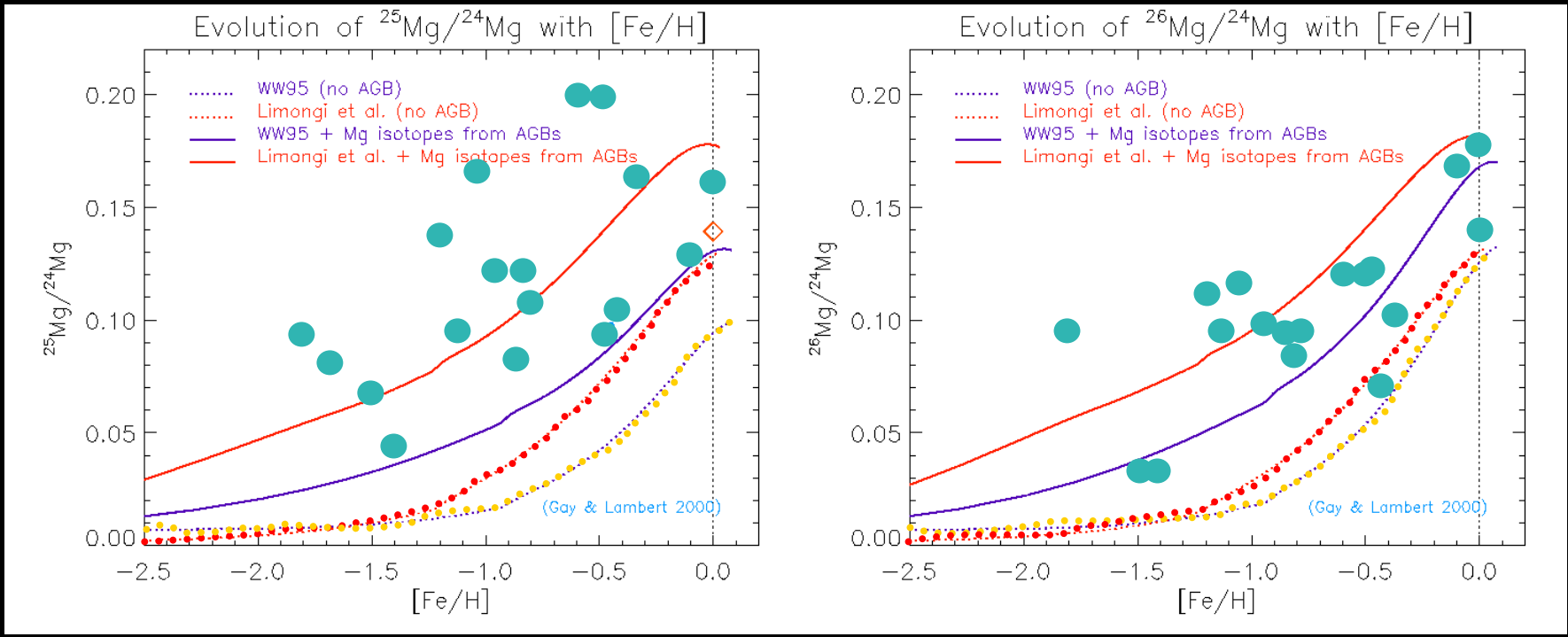

M=4 Z=0.02
M=5 Z=0.02
M=6 Z=0.02
M=4 Z=0.008
M=5 Z=0.008
M=6 Z=0.008
M=4 Z=0.004
M=5 Z=0.004
M=6 Z=0.004
24Mg
25Mg
26Mg
Y/(Mg24+Mg25+Mg26)
(Time− 1.8e+08)/ 1.0e+06years
(Time− 1.0e+08)/ 1.0e+06years
(Time− 6.8e+07)/ 1.0e+05years
(Time− 1.7e+08)/ 1.0e+06years
(Time− 9.8e+07)/ 1.0e+05years
(Time− 6.6e+07)/ 1.0e+05years



Massive stars produce most of the galactic magnesium, which is primarily ^{24}Mg at low Z

But 3 - 6 M_{sun} AGB stars can produce large amounts of the heavy magnesium isotopes

(Y. Fenner, A. Karakas, B. Gibson, J. Lattanzio)



AGB stars are needed to recover the observed $^{25,26}M/^{24}Mg$ ratios at low metallicity

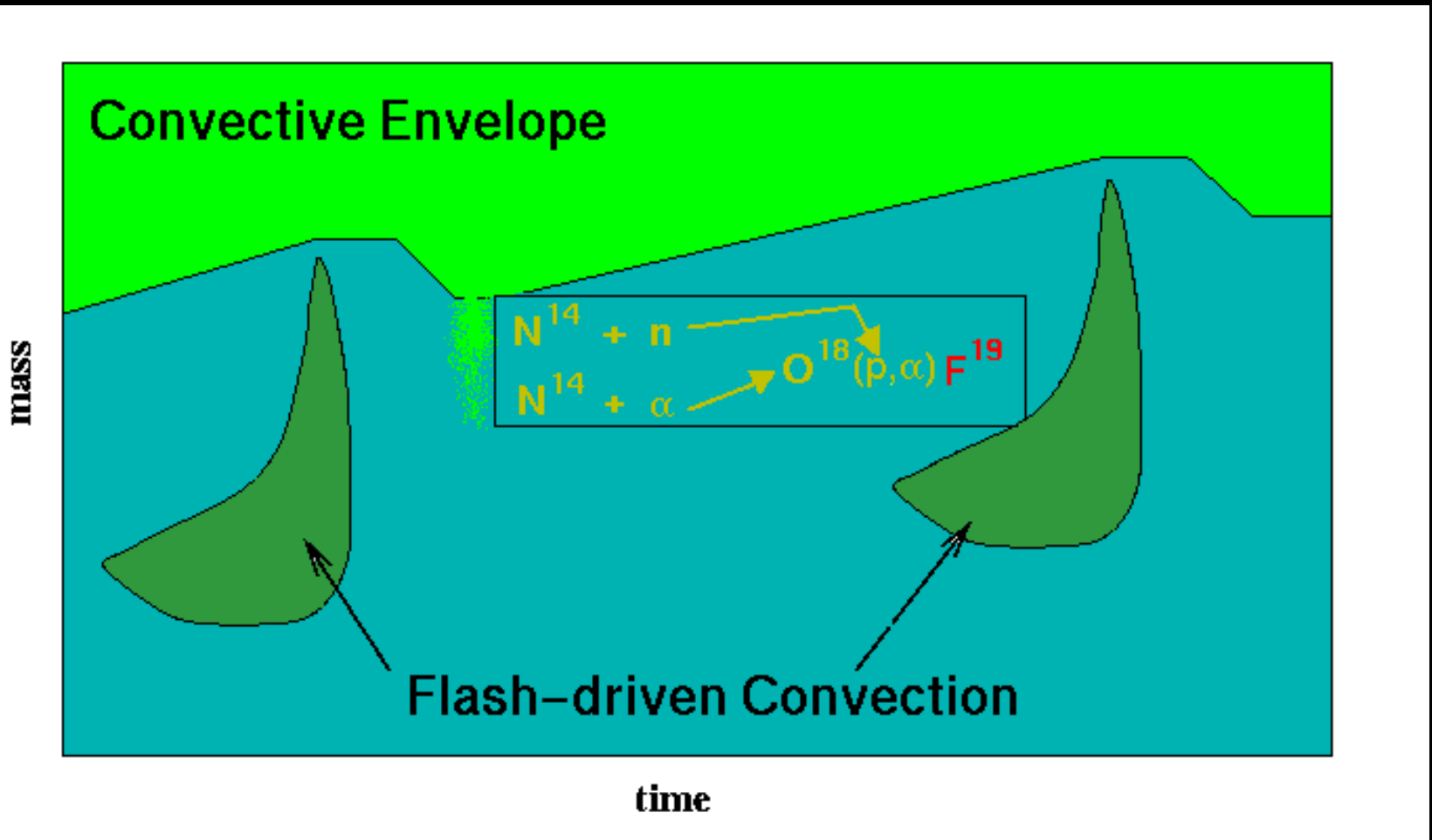
Limongi et al. (2002) calculations generate more $^{25,26}Mg$ than Woosley & Weaver (1995)

(Y. Fenner, A. Karakas, B. Gibson, J. Lattanzio, PASA, 2003)

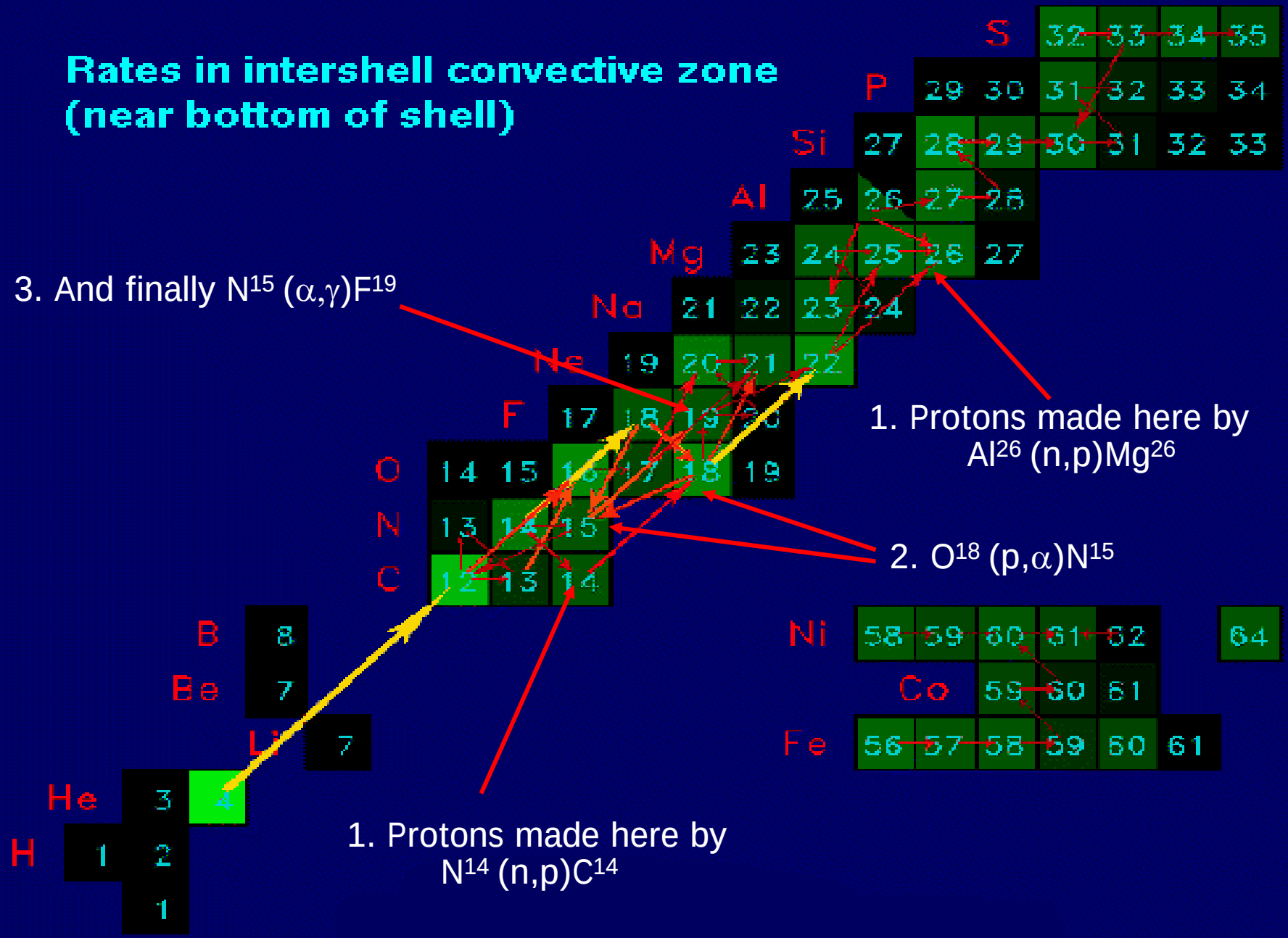
Fluorine

- Observations show [F/O] correlates with C/O
- This implicates thermal pulses
- Complicated - different reaction paths
  - depends on mass
  - depends on composition
  - depends on pulse number

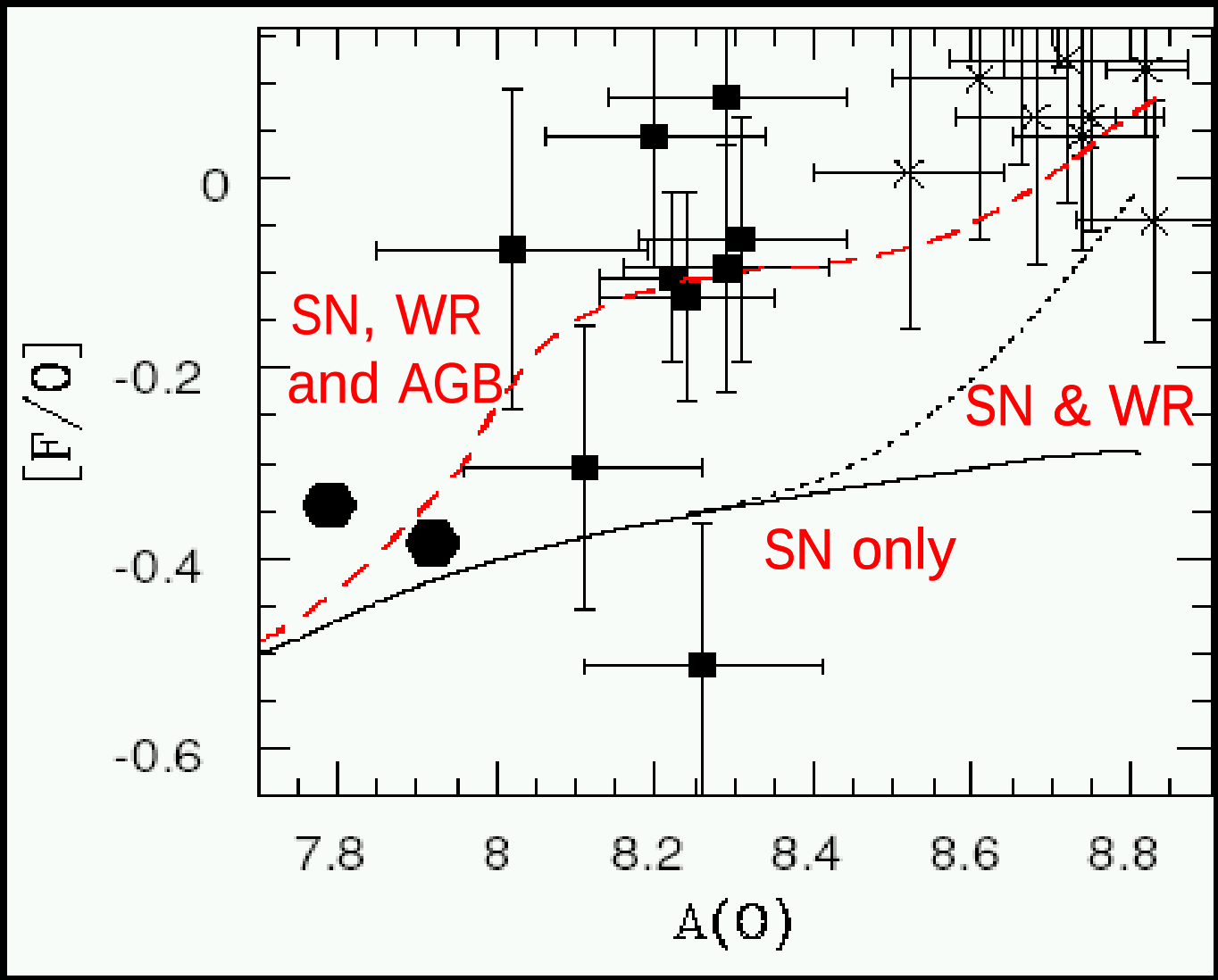
Fluorine


Convective Envelope
$N^{14} + n$
$N^{14} + \alpha$
$O^{18}(p,\alpha)F^{19}$
Flash–driven Convection
mass
time

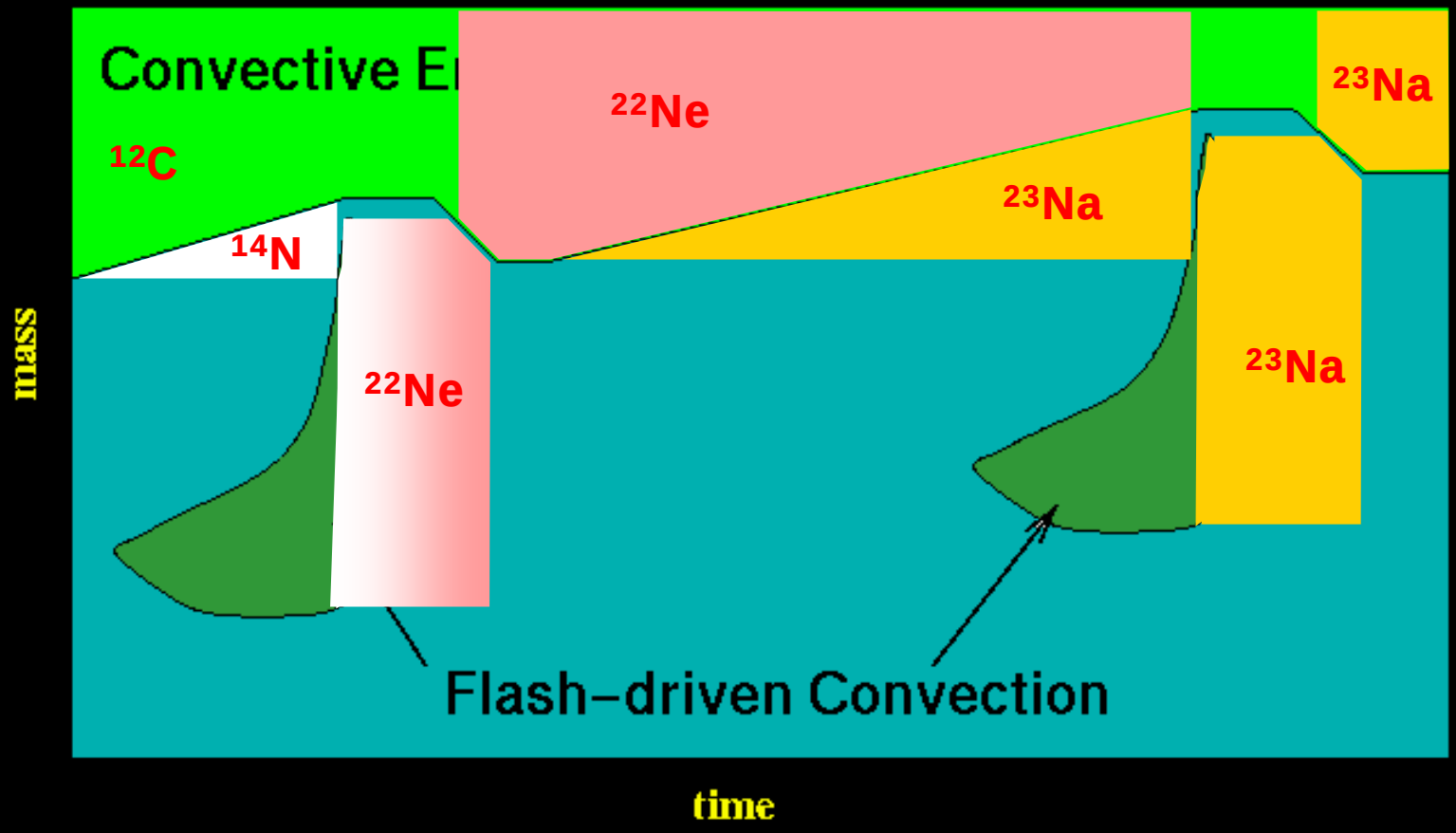
Rates in intershell convective zone (near bottom of shell)



GCE of ^{19}F – Renda et al (submitted)



Sodium



Note: some ^{23}Na is primary and some is secondary!

Making Li

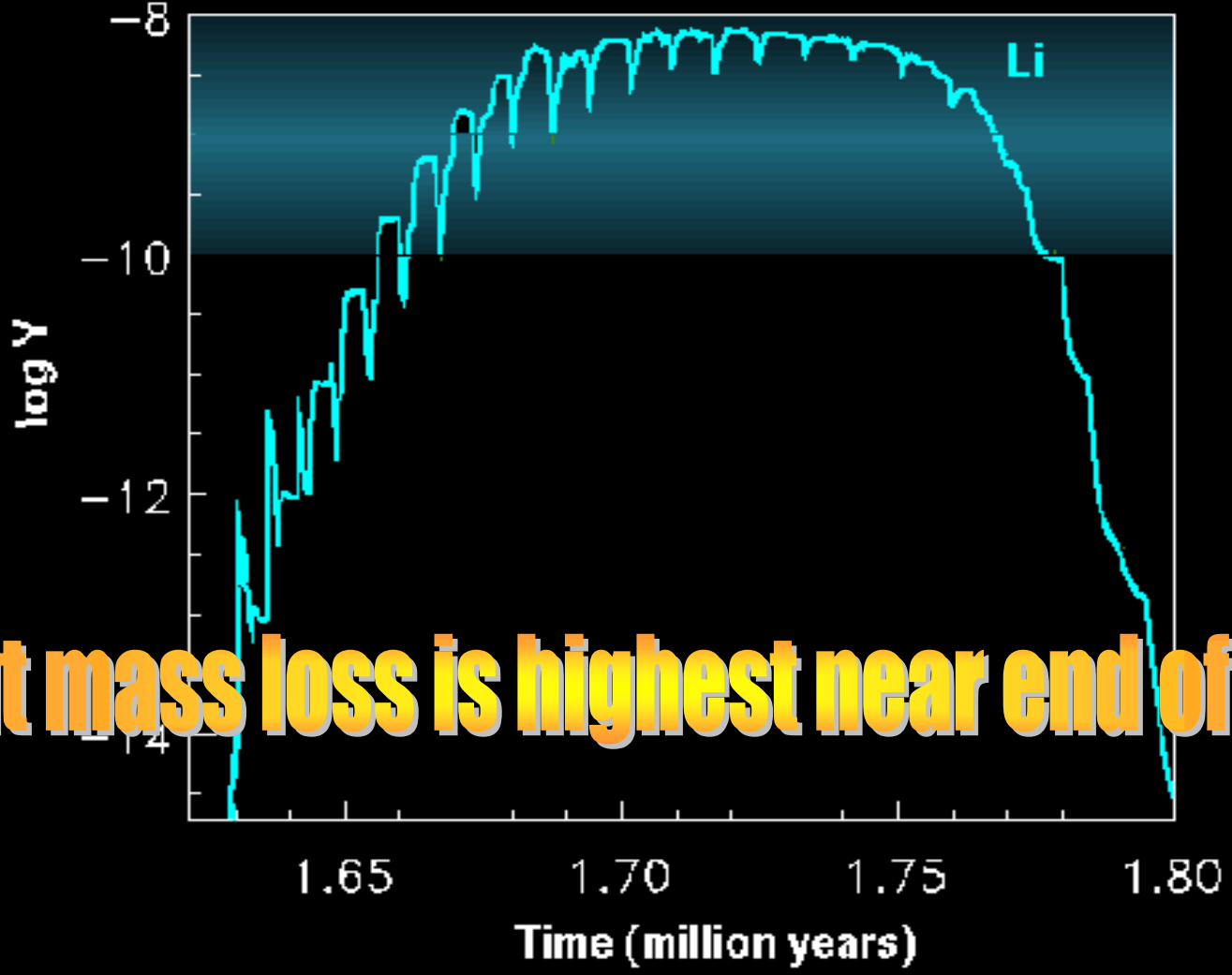
Li is sexy...ask any cosmologist...

Cameron-Fowler Beryllium Transport Mechanism

$^{3}He\ (\alpha,\gamma)\ ^{7}Be\ (\beta^{-},\nu)\ ^{7}Li \rightarrow\ ^{7}Li(\ p,\alpha)\ ^{4}He\ = PPII$ (bad)

$^{3}He\ (\alpha,\gamma)\ ^{7}Be \rightarrow\ ^{7}Be\ (\ p,\gamma)\ ^{8}B\ (\beta^{+}\nu)\ ^{8}Be\ (\alpha)\ ^{4}He\ = PPIII$ (bad)

Making Li



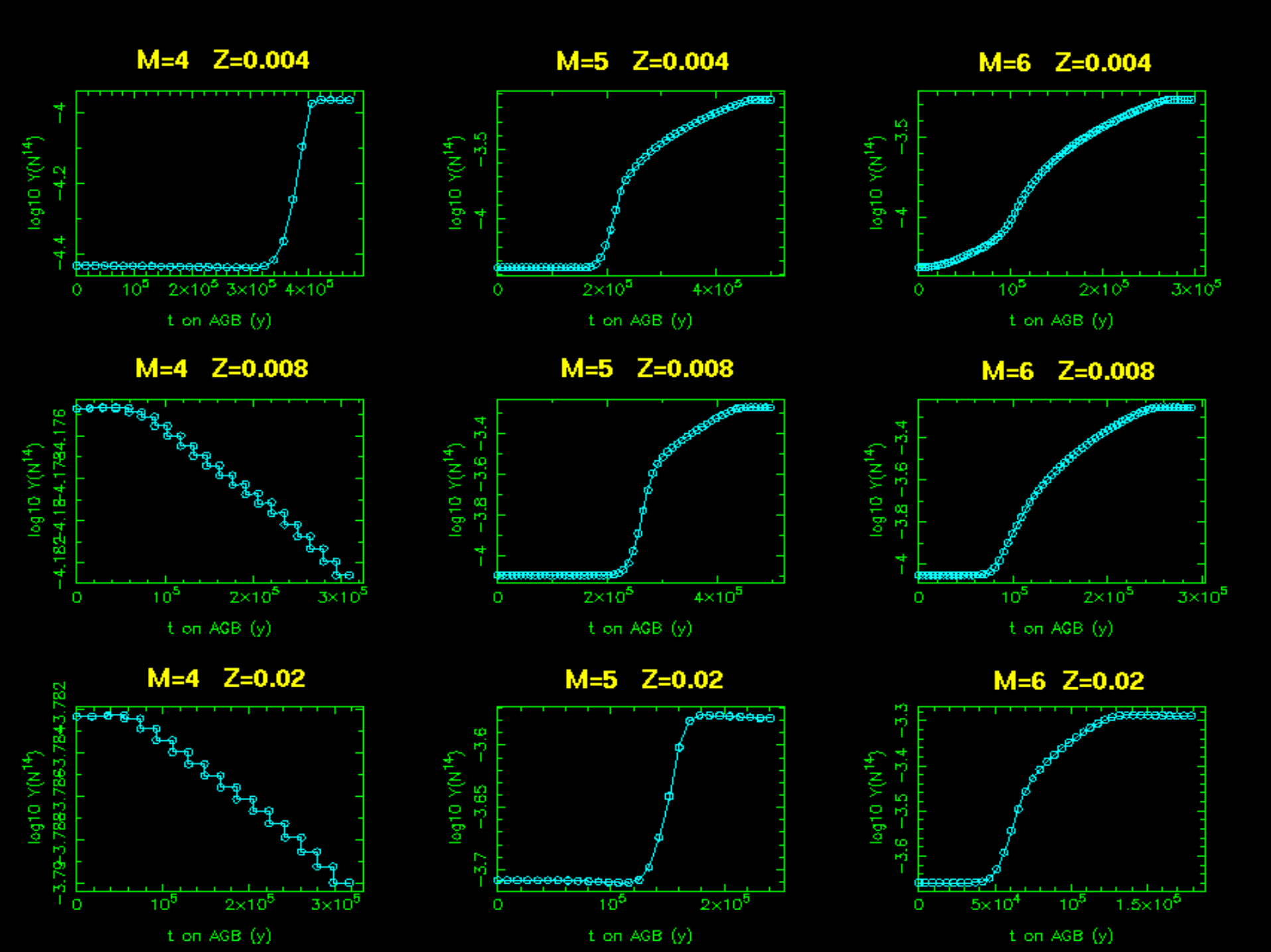
But mass loss is highest near end of AGB

...when the Li has all been destroyed....

Primary Nitrogen in the early Universe

- Various observations 9eg Lyman alpha clouds) show a primary source of N in the early Universe...

- AGB stars again?
- Primary C is produced by dredge-up (H $\rightarrow$ He $\rightarrow$ C)
- CNO cycles make N^{14} from C and O
- Thus HBB makes Primary N^{14}


M=4 Z=0.004
M=5 Z=0.004
M=6 Z=0.004
M=4 Z=0.008
M=5 Z=0.008
M=6 Z=0.008
M=4 Z=0.02
M=5 Z=0.02
M=6 Z=0.02
log10 Y(N14)
t on AGB (y)

Summary of Nucleosynthesis in AGB stars

- Dredge-up increases: C, Ne^{22}, Mg^{25}, Mg^{26}
- H shell and HBB (M>4) burns:
  1) C and O into N: O down and N up
  2) Ne22 into Na23: Na up
  3) Mg25 and Mg26 made: $Mg^{25,26}$ increased
- More massive stars (M > 6?):
  1) Mg24 burned into Al27: Mg^{24} down Al^{27} up

- Overall
  1) Increases in N, Na, heavy Mg, Al
  2) Decreases in O, Mg^{24}

The End?

"This is not the end...

...it is not even the beginning of the end...

...but it may be the end of the beginning."

More appropriate for a theorist

Man will occasionally stumble over the truth, but most times he will pick himself up and carry on...

Play Tom Lehrer Song