The MonKey Project

An Update on Stellar Yields

Current State of the Art Yields

- The most boring part of stellar evolution?
- Or is it isochrone construction?

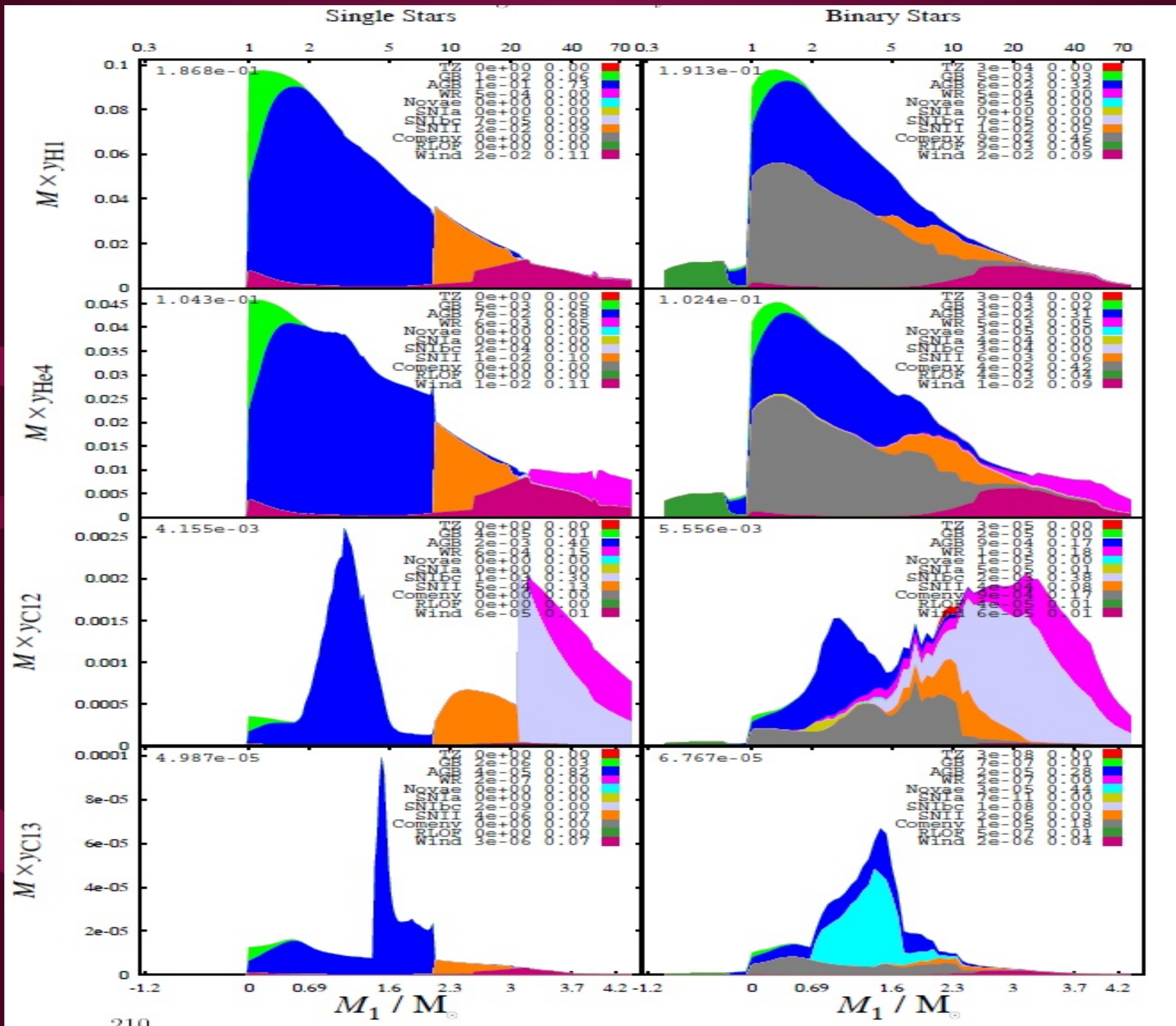
- Run lots of models and collect numbers…

- Well – its not that easy
- But its not exciting by itself
- Although the implications/results are fascinating
- Hence the need for more and better yields

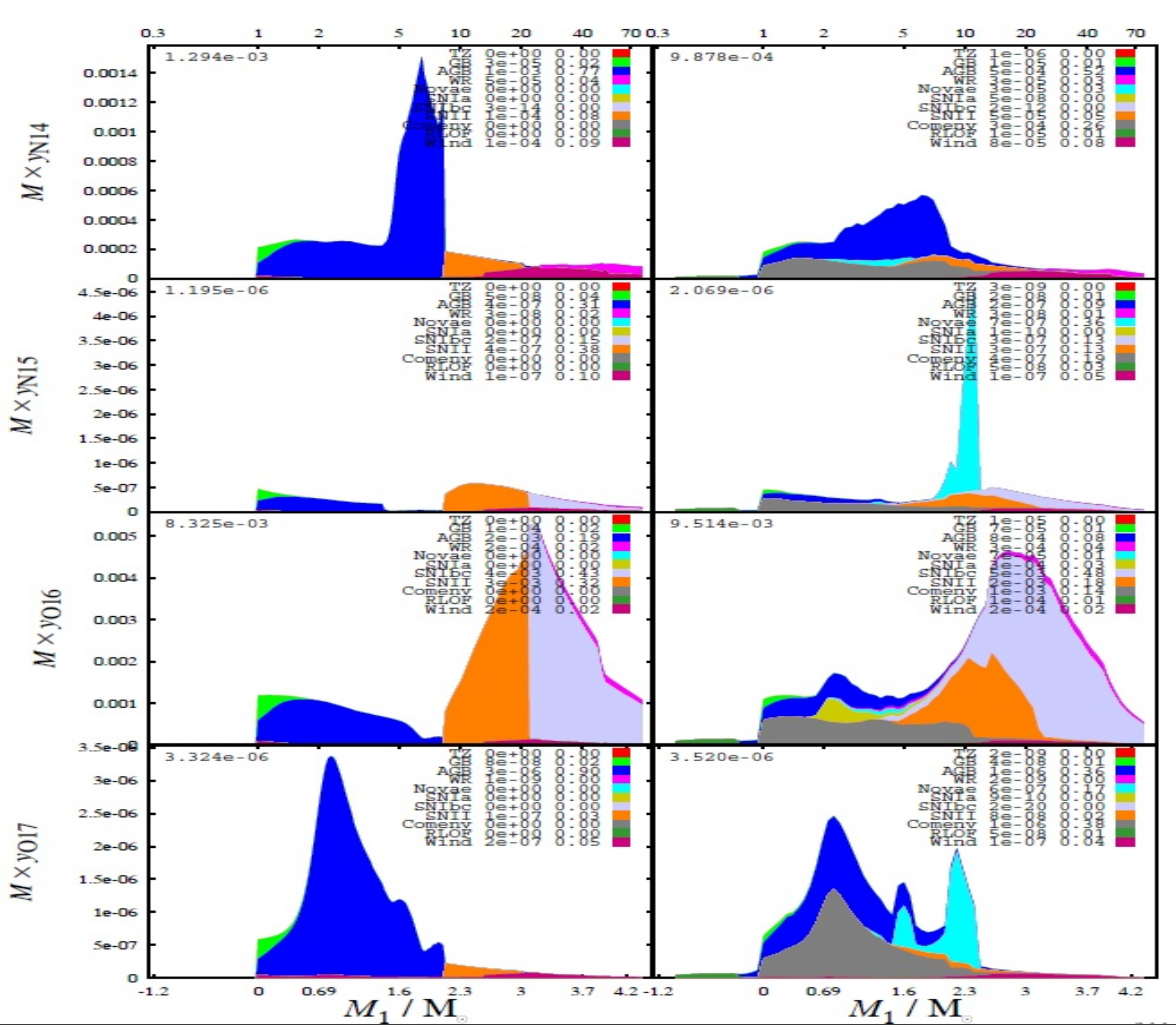
What is needed?

- Reliable models for all masses and compositions…
- Very demanding: from low mass to hypernovae
- Novae?
  - Small role…^{13}C and some other things…
- Binaries?
  - Usually ignored (except for SNI!)
  - Very good at ending evolution early…
  - eg see Rob Izzard’s thesis

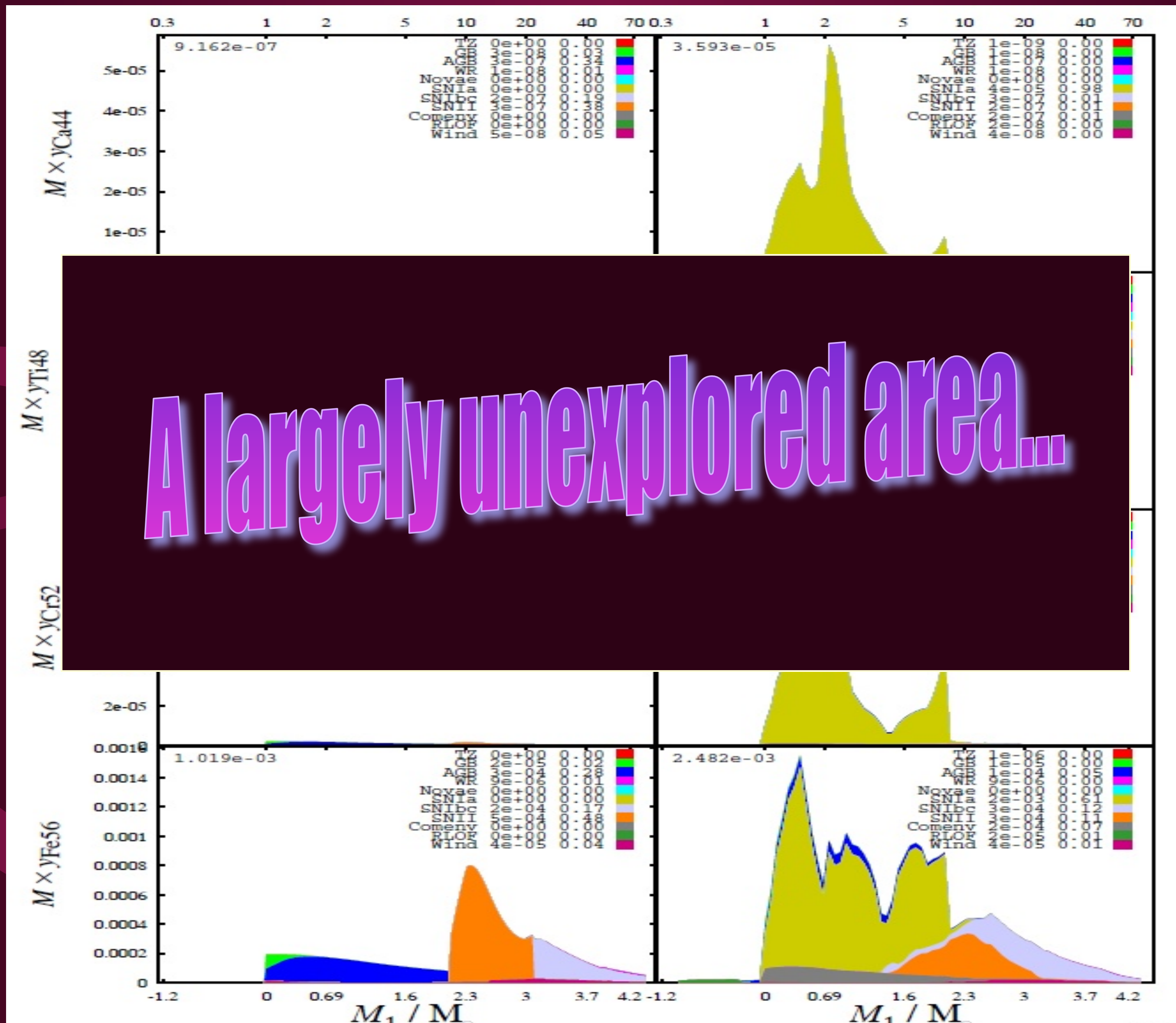
Binaries: Rob Izzard's thesis



Binaries: Rob Izzard's thesis



Binaries: Rob Izzard's thesis



A largely unexplored area...

But- back to reality

- We provide yields for AGB models
- ie masses between 1 and 8 $M_\odot$
- We assume others provide massive star yields

- Super-AGB I will discuss separately

Usual Inputs

- Stellar model inputs as usual
- Detailed reaction rates now important…
  - May not affect structure
  - But definitely affect yields
  - Models more reliable than yields!
- Mass-loss ends the AGB – crucial input!

- Some other caveats discussed later…

Current State of the Art

- Karakas and Lattanzio (2007, PASA)

CSIRO PUBLISHING
www.publish.csiro.au/journals/ … 2007, **24**, 103–117

Stellar Model

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Table 1. Grids of stellar masses for each Z, noting if the models experience the core He-flash (CHe), the third dredge-up (TDU), and hot bottom burning (HBB)

Mass	$Z = 0.02$	$Z = 0.008$	$Z = 0.004$	$Z = 10^{-4}$
1.0	CHe	CHe	CHe	–
1.25	CHe	CHe	CHe	CHe,TDU
1.5	CHe	CHe	CHe,TDU	–
1.75	CHe	CHe,TDU	CHe,TDU	CHe,TDU
1.9	CHe	CHe,TDU	CHe,TDU	–
2.0	CHe	–	–	TDU
2.1	–	CHe,TDU	–	–
2.25	CHe,TDU	TDU	TDU	TDU
2.5	TDU	TDU	TDU	TDU
3.0	TDU	TDU	TDU	TDU,HBB
3.5	TDU	TDU	TDU	TDU,HBB
4.0	TDU	TDU,HBB	TDU,HBB	TDU,HBB
5.0	TDU,HBB	TDUHBB	TDU,HBB	TDU,HBB
6.0	TDU,HBB	TDU,HBB	TDU,HBB	TDU,HBB
6.5	TDU,HBB	–	–	–
7.0	–	–	–	TDU,HBB[a]

Current State of the Art

- Updated by Karakas (2010, MNRAS)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **403,** 1413–1425 (2010) doi:10.1111/j.1365-2966.2009.16198.x

Updated stellar yields from asymptotic giant branch models

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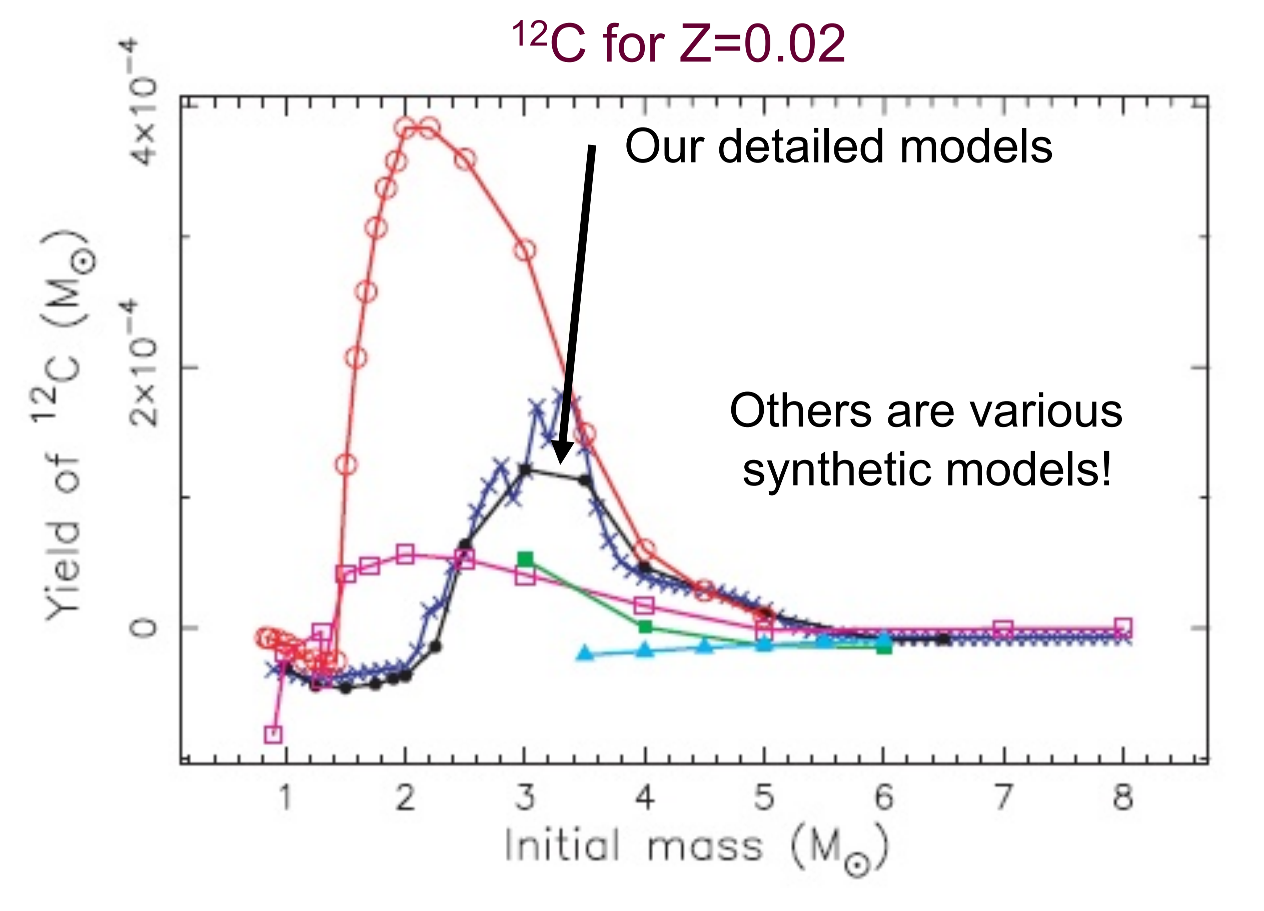
The yields are computed using an updated reaction rate network that includes the latest NeNa and MgAl proton capture rates, with the main result that between ∼6 and 30 times less Na is produced by intermediate-mass models with hot bottom burning. In low-

$3\,M_\odot$) $Z = 0.0001$ AGB models are also presented, along with a finer mass grid than used in previous studies. The yields are computed using an updated reaction rate network that includes the latest NeNa and MgAl proton capture rates, with the main result that between ∼6 and 30 times less Na is produced by intermediate-mass models with hot bottom burning. In low-mass AGB models, we investigate the effect, on the production of light elements, of including some partial mixing of protons into the intershell region during the deepest extent of each third dredge-up episode. The protons are captured by the abundant ^{12}C to form a ^{13}C pocket. The ^{13}C pocket increases the yields of ^{19}F, ^{23}Na, the neutron-rich Mg and Si isotopes, ^{60}Fe and ^{31}P. The increase in ^{31}P is by factors of ∼4 to 20, depending on the metallicity. Any structural changes caused by the addition of the ^{13}C pocket into the He intershell are ignored. However, the models considered are of low mass and any such feedback is likely to be small. Further study is required to test the accuracy of the yields from the partial-mixing models. For each mass and metallicity, the yields are presented in a tabular form suitable for use in galactic chemical evolution studies or for comparison to the composition of planetary nebulae.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: AGB and post-AGB – stars: Population II – ISM: abundances.

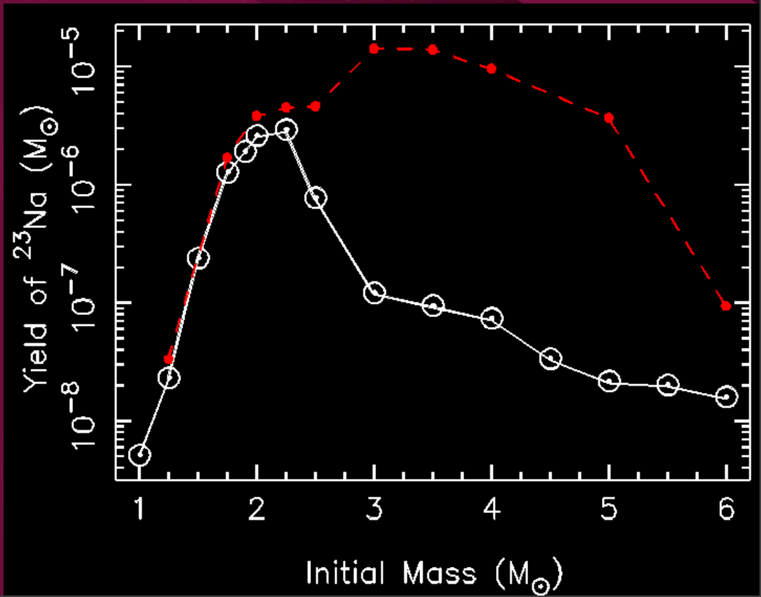
Typical Results

$$M_i = \int_0^{\tau} [X(i) - X_0(k)] \frac{dM}{dt} dt,$$



Current Problems
Warning: Personal Bias to GCs!

- Mg isotopes!
  - Many obs show ^{25}Mg ~ constant 5% of total Mg
  - Theory shows it varies from 0-100%
  - But ^{26}Mg is roughly constant!
- Depleting enough O for globular clusters remains difficult
- Making enough ^{23}Na is hard
  - It leaks into ^{24}Mg at high T
- Many others…



Warnings

- No ^{13}C pocket formed in these models!
- Small effect on light elements
  - See Karakas (2010)
- We need to include the post-Fe elements
  - AGB stars are big s-processors….so include it!
- What about deep-mixing?
  - It happens…
  - But its been ignored!

THE MONASH CHEMICAL YIELDS PROJECT

MonXey

Everybody's got something to hide…

"…except for me and my MonKey"

The Beatles

MonKey – a new Set of Yields

- Latest rates at time of calculation
- Fine grid in mass and composition
- Includes ^{13}C pocket (std form)
- Includes all species up to Pb and Bi
- Includes thermohaline mixing
- Includes effect of enhanced C (from dredge-up) on envelope opacity
- Includes effect of enhanced N (from HBB) 0n envelope opacity

MonKey – a new Set of Yields

- Includes Super-AGB models for "second" time
  - Siess did the first!
  - Siess models use some mixing approximations we do not like much…
  - Siess models use large amount of synthetic evolution to get through lots of pulses (see instability talk!)
- Consistent initial compositions at low Z
  - For very low [Fe/H] we take our mix from Z=0 yields
  - Mix this with Big Bang material to get required [Fe/H]
  - Use this as initial composition (not a scaled solar abundance)

People involved

- John Lattanzio (Monash U)
- Simon Campbell (Monash U)
- Amanda Karakas (Mt Stromlo/ANU)
- Ross Church (Lund Observatory)
- Herbert Lau (Bonn)
- George Cool Angelou (Monash U)
- Richard Stancliffe (Mt Stromlo/ANU)
- Sergio Cristallo (Teramo Observatory)
- Carolyn Doherty (Monash U)
- Pilar Gil Pons (Barcelona)
- Stuart Heap (Monash U)
- Maria Lugaro (Monash U)

Super-AGB stars

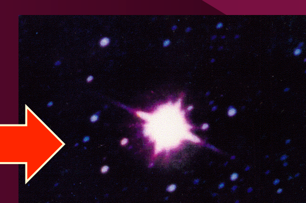
- **Carolyn Doherty's thesis**
- Co-supervisors
  - Pilar Gil Pons
  - Lionel Siess
- Detailed evolution and nucleosynthesis
  - See earlier for new work on instability ending SAGB lifetime?

Super AGBs

- Intermediate mass ~ 6.5 -11.5 $M_{\odot}$ stars
  - Depends critically on mixing during core He burning phase
- Undergo core H & He Burning
- Off centre degenerate carbon ignition
- 2nd Dredge Up (or dredge out!) reduces the core mass below $M_{Chandreskhar.}$
- Thermally pulsing Super AGB Phase
- Final fate determined by the competition between the growth of the core and the rate of mass lost from the envelope

ONe
White Dwarf

OR

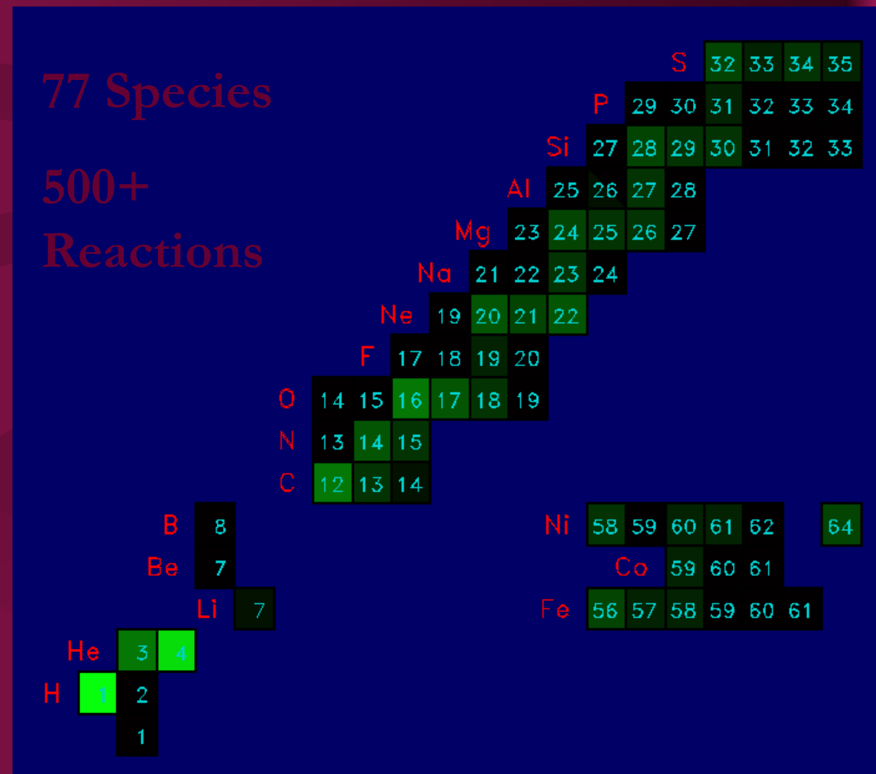


Stellar Models

Evolution

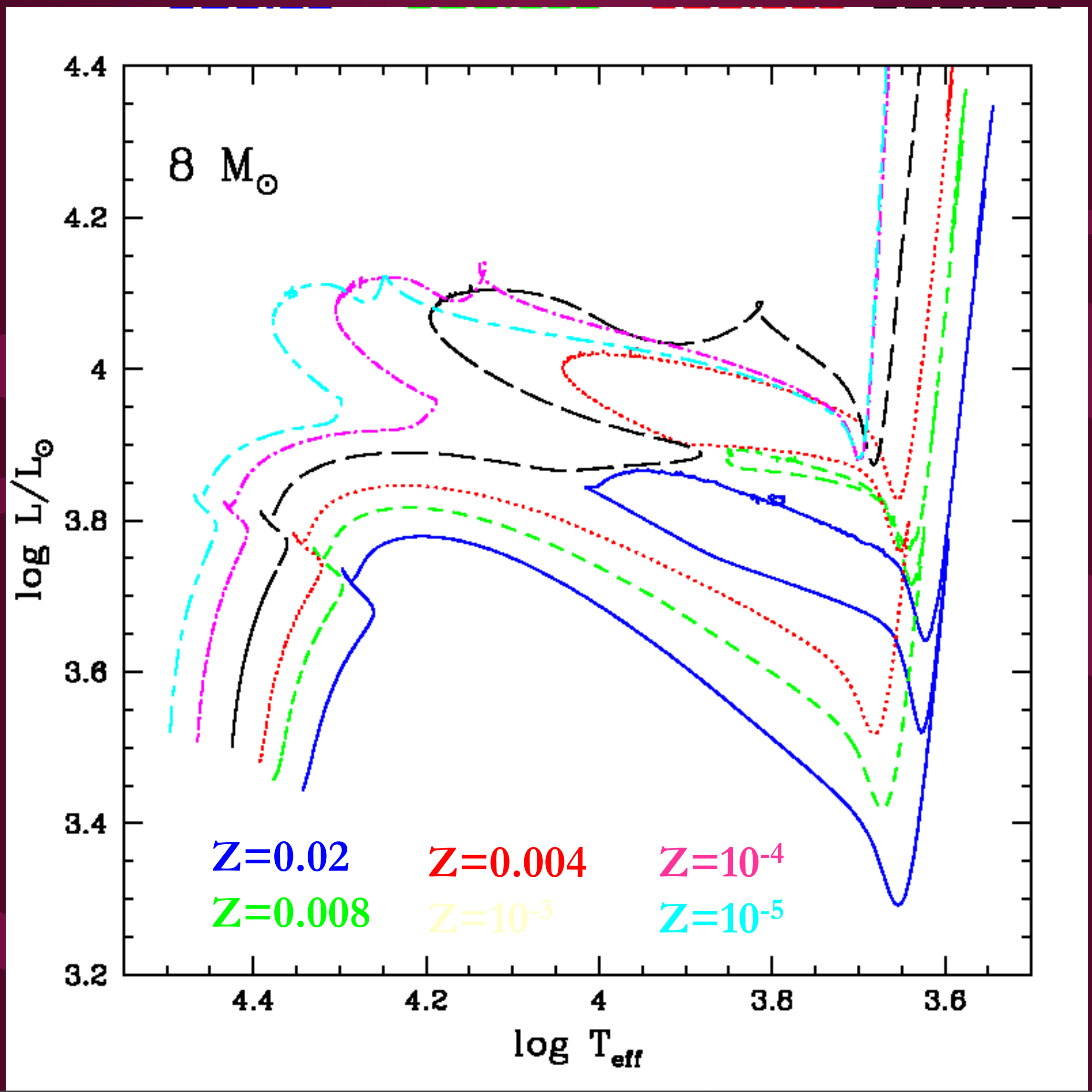
- Z=0.02, 0.004, 0.008, 0.001, 10^{-4} ($<10^{-5}$)
- $M = 6.5 - 9.4\ M_{\odot}$
  - Approx $0.5 M_{\odot}$ steps
- ZAMS – End* of TP-(S)AGB
- Effects of different Mass loss rates and different mixing length parameter.

Nucleosynthesis

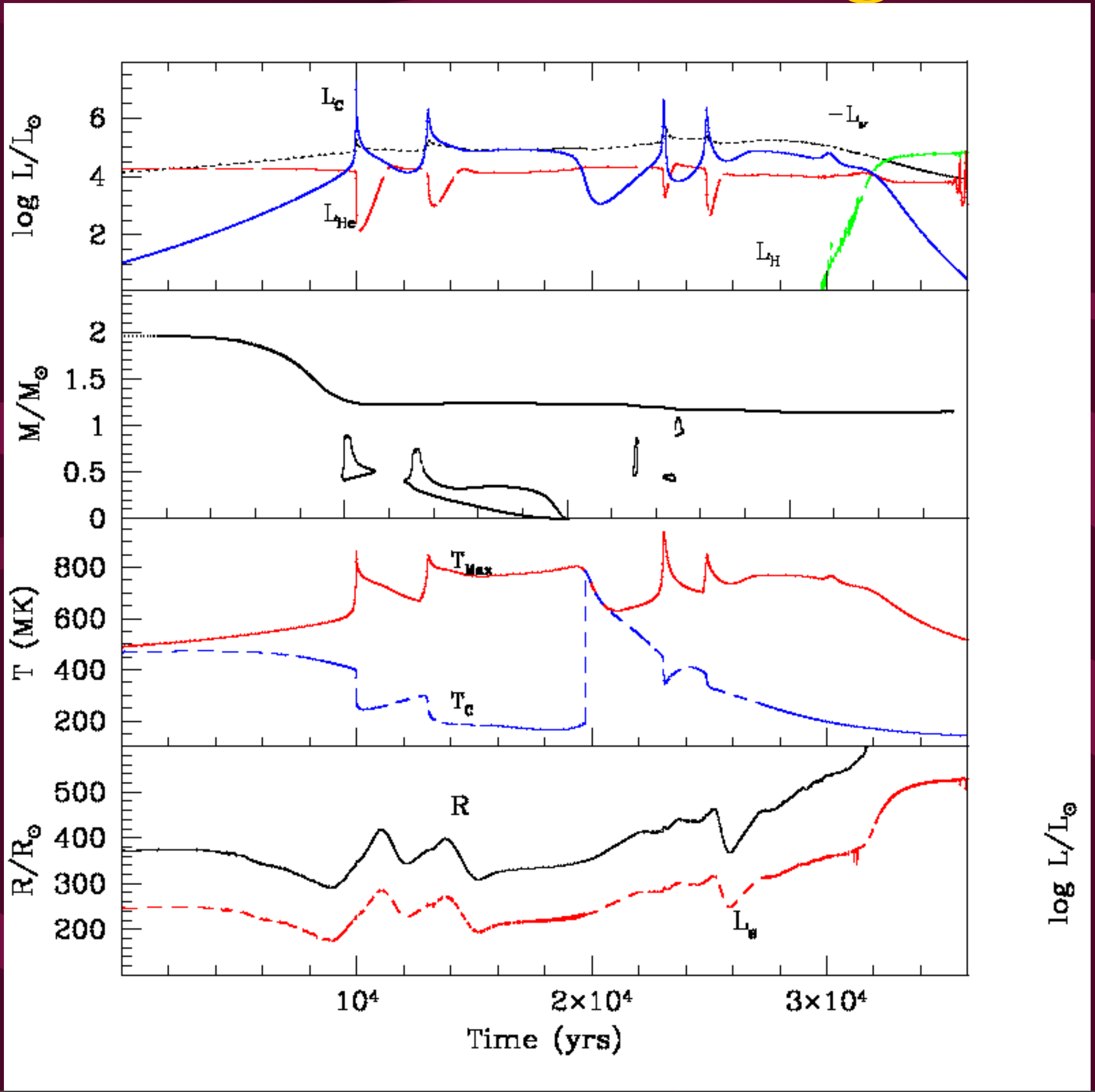


- Post Processing code MONSOON
- Reaction rates from JINA

Lives of intermediate mass stars prior to carbon ignition

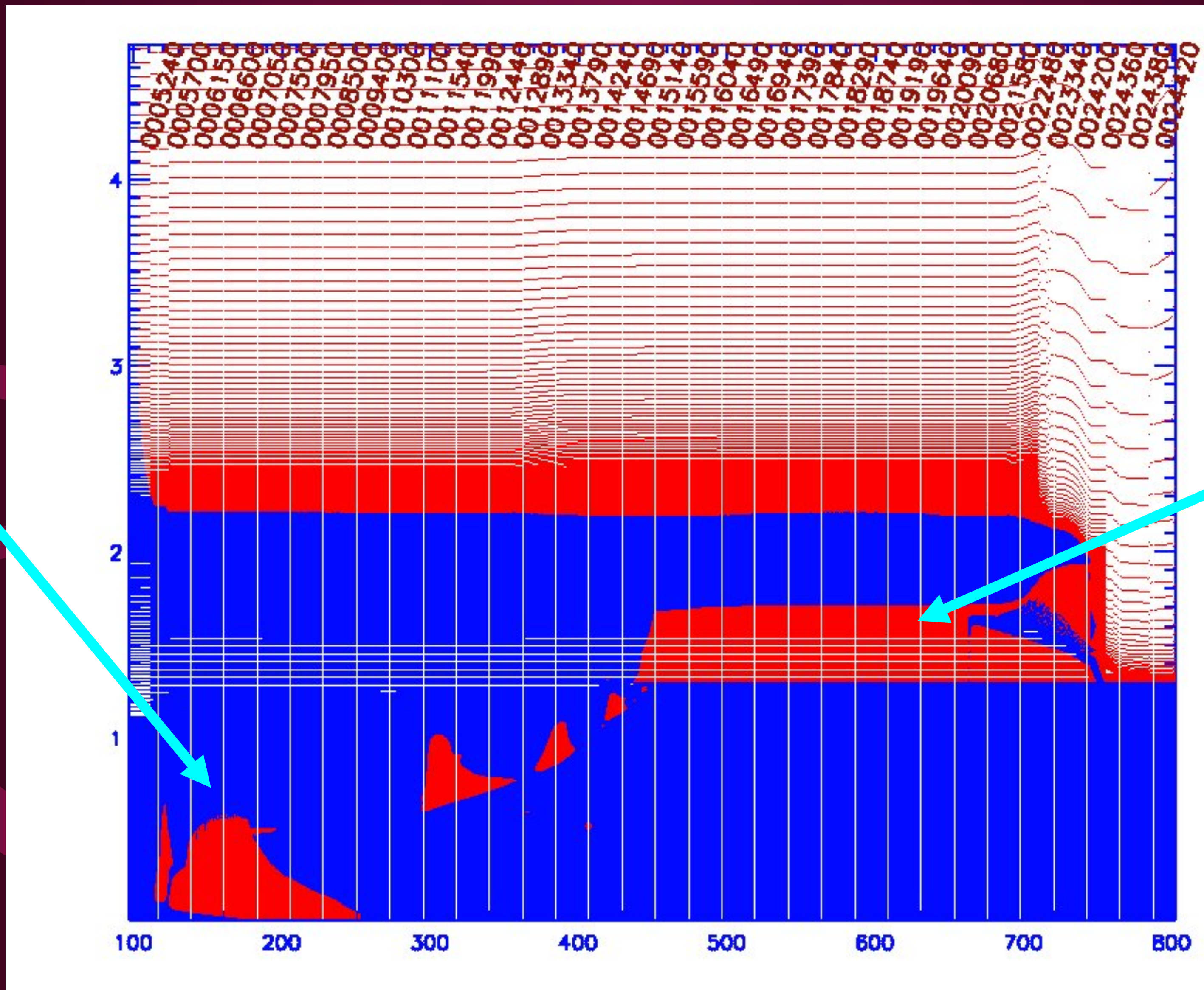


Carbon burning



Dredge Out

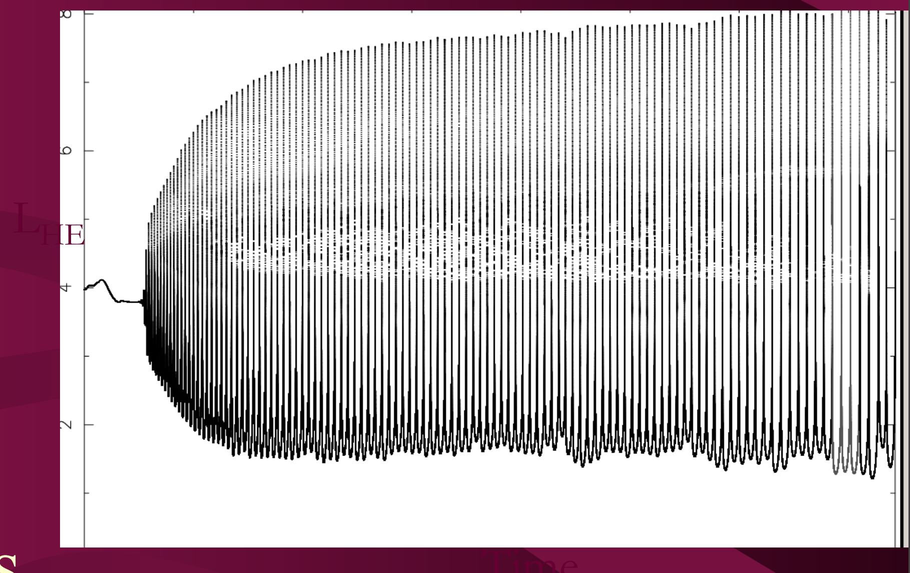
Carbon burning



Helium burning

Overview of TP-SAGB Phase

- ONeMg Core
- Many TPs (50 - 500+)
- $M_{dot} > 10^{-5}$ M ☼ per year (VW93)
- 1.06 M ☼ < M_C < 1.37 M ☼
- Between 3-4 Million time steps



THERMAL PULSE

$T_{HeShell}$ > 350MK

THIRD DREDGE UP

Efficient Dredge up
0.6 < λ < 0.9

HOT BOTTOM BURNING

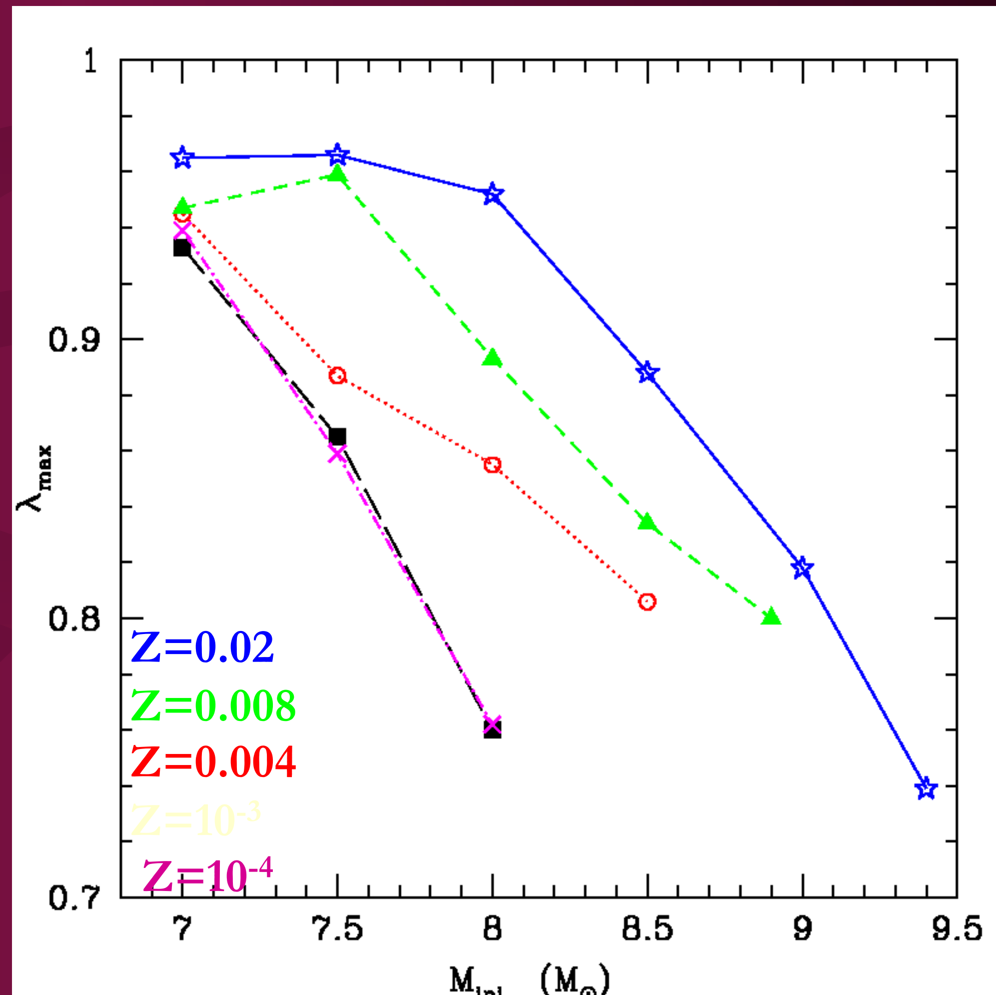
•Very hot T_{BCE} > 100 MK

Third Dredge Up

- Studies by
  - Siess (2010)
  - Ventura & D'Antona (2011)
  - Poelerands (2008)

find NO 3DU.

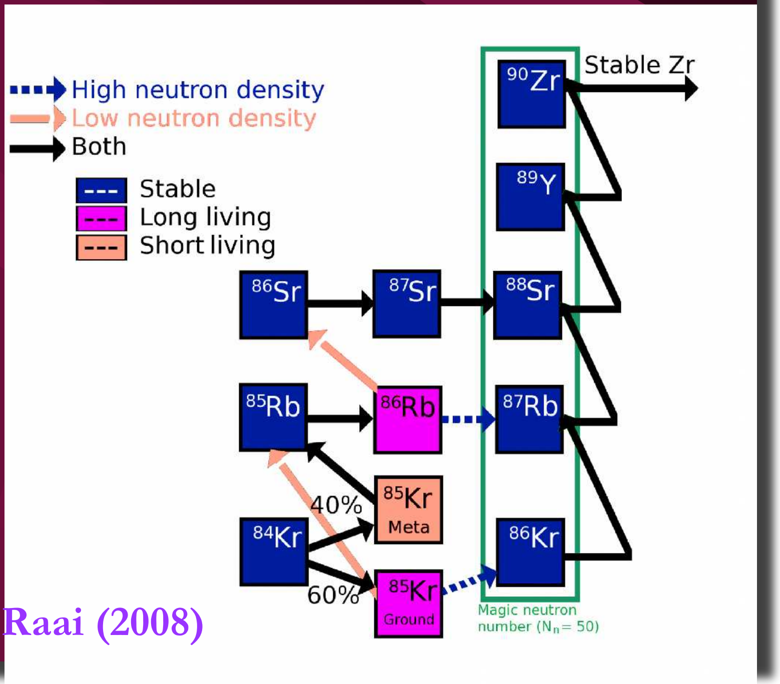
But we have efficient 3DU (albeit of small mass)



Rubidium Rich SAGBs?

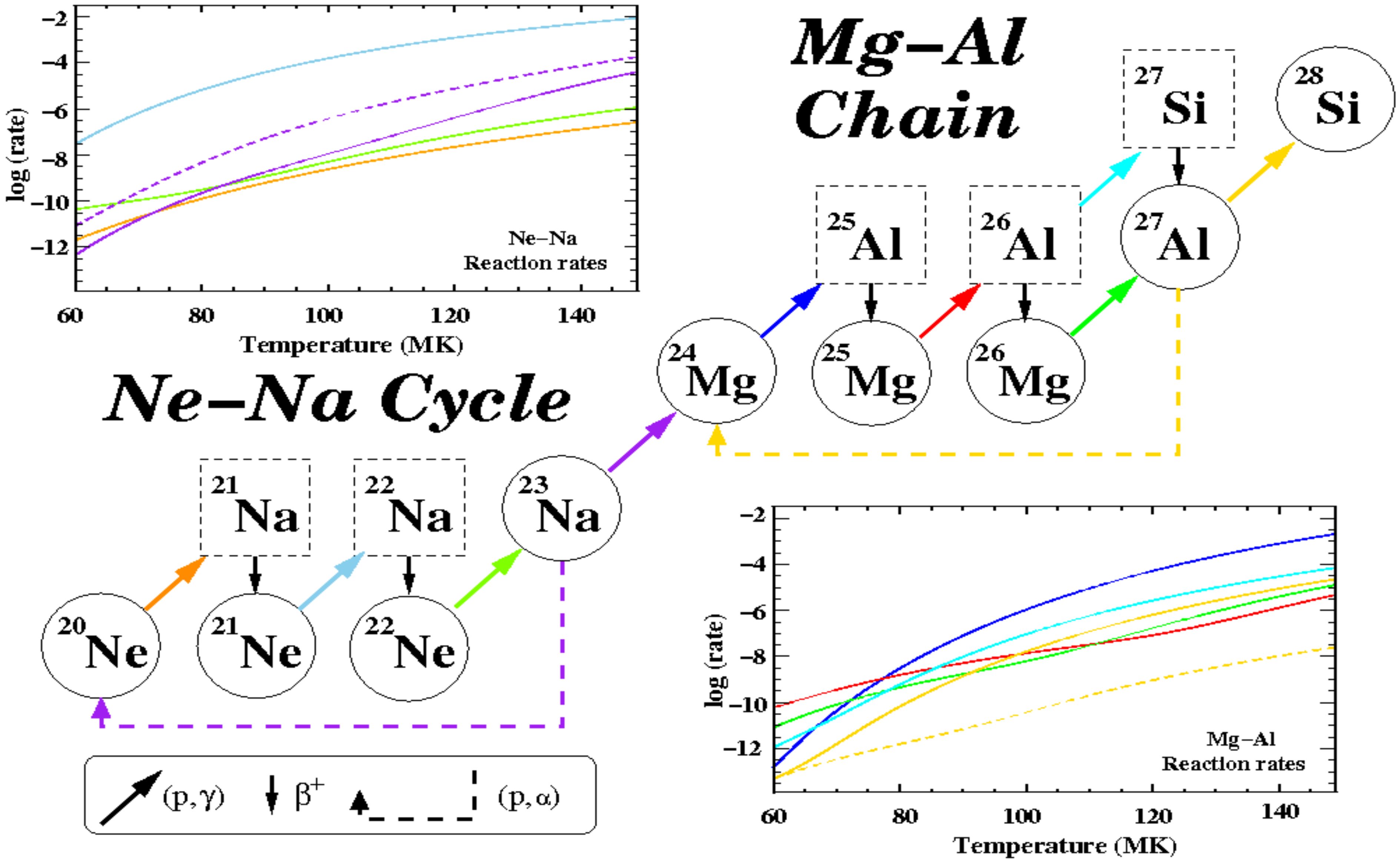
- Galactic, LMC and SMC massive O rich AGB stars show overabundance of Rb
- Larger overabundances of Rb correlate with larger V_{exp} and larger M_{bol}
- V_{exp} and Mbol both correlate with mass
- This suggests most massive AGB (Super AGB)

Rb primarily an r process element but some s process production via large n flux via $^{22}Ne(a,n)^{25}Mg$

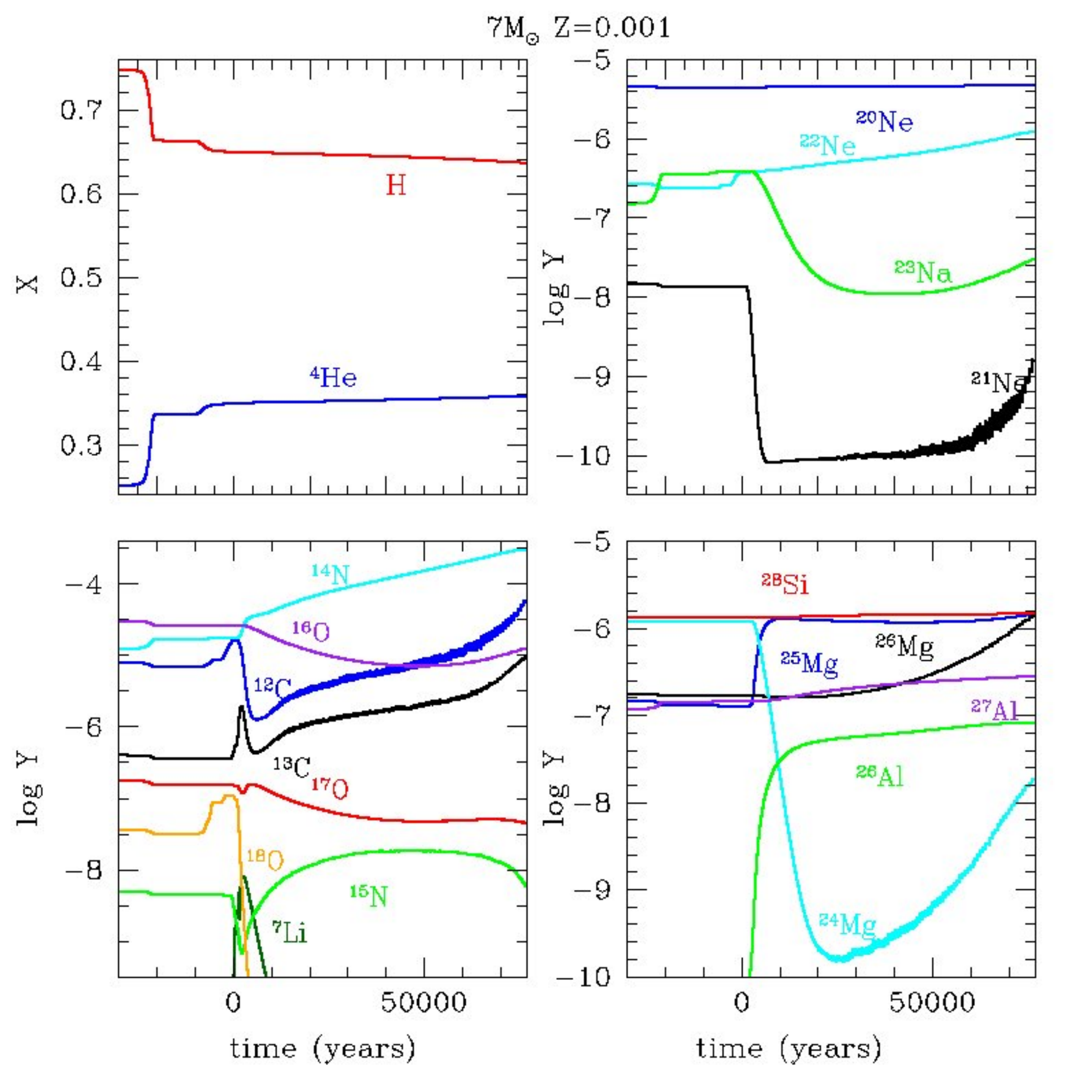


Van Raai (2008)

Very Hot HBB: T ~ 150 MK!



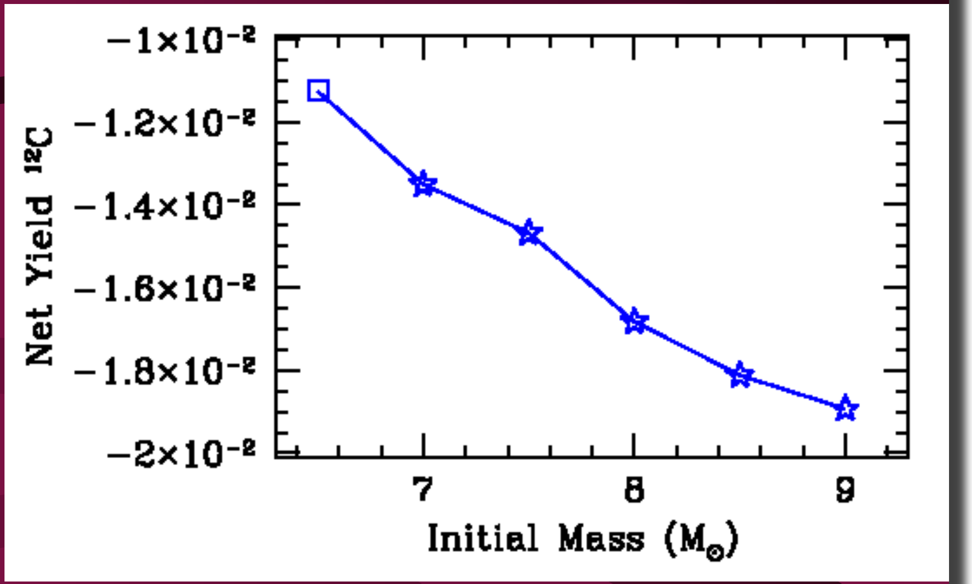
Globular Cluster Abundance Anomalies

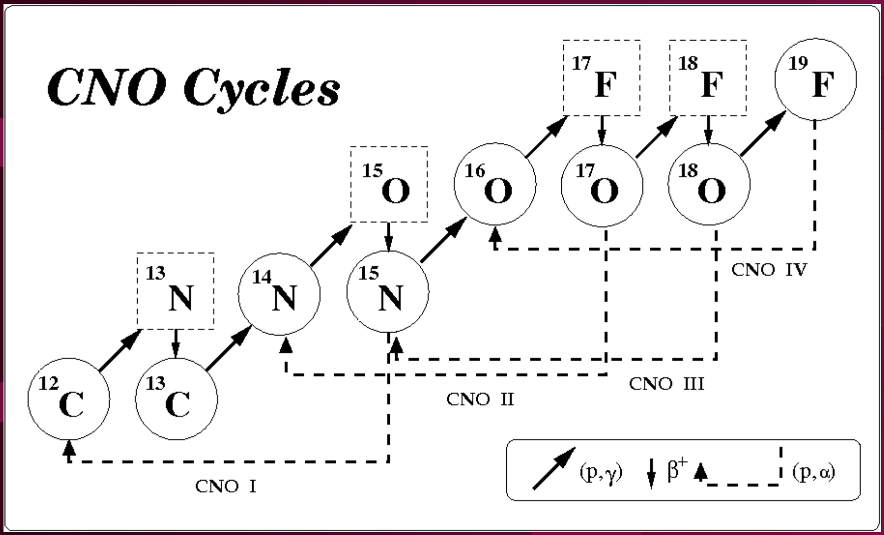


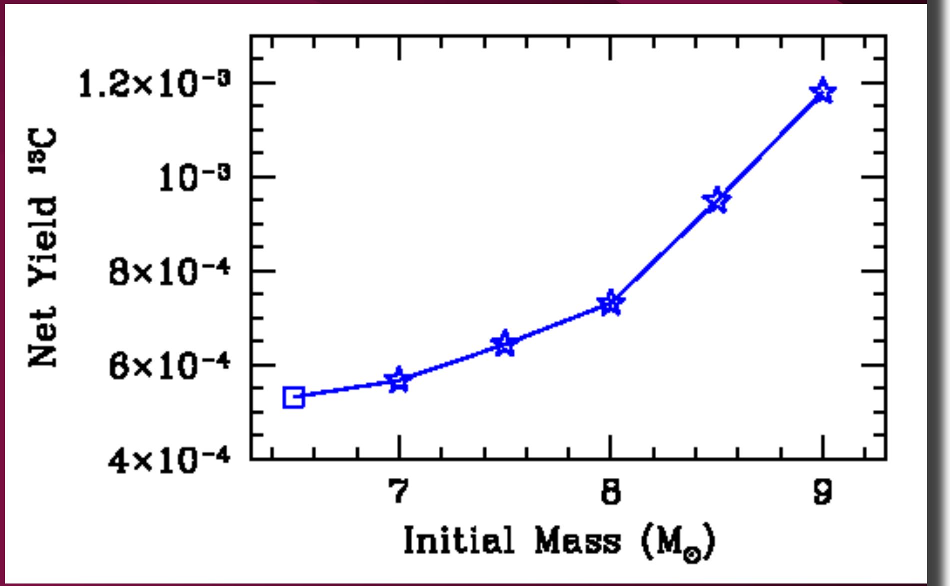
1. C+N+O constant ???
2. O –Na anti-correlation?
3. Mg –Al anti-correlation
4. Mg isotopes?
5. C-N anti correlation

CNO Yields:

^{12}C & ^{13}C



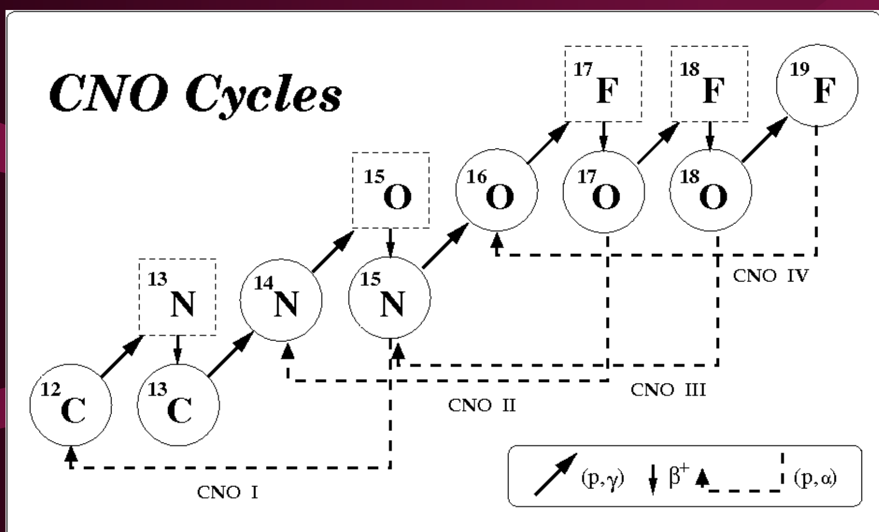


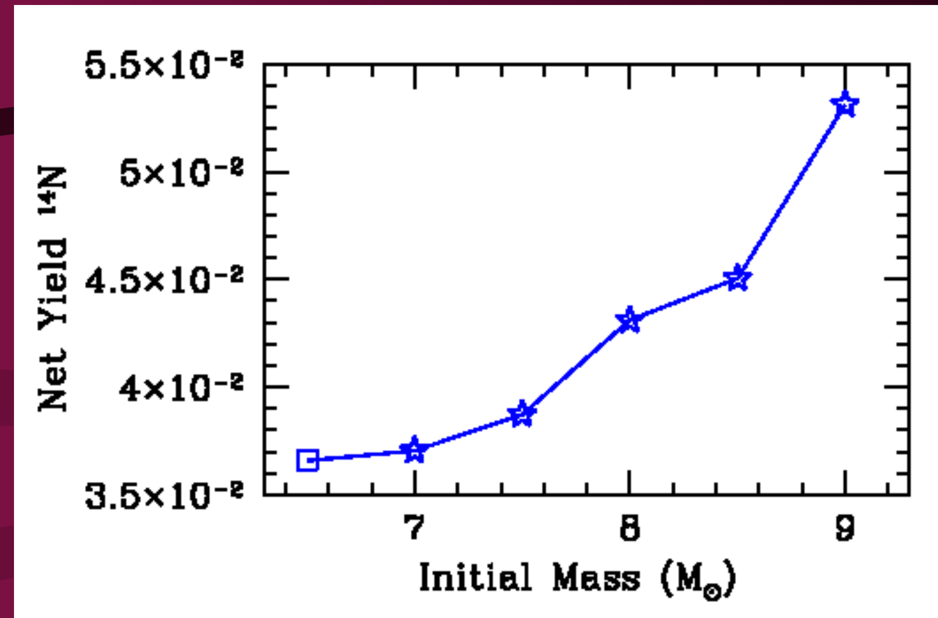


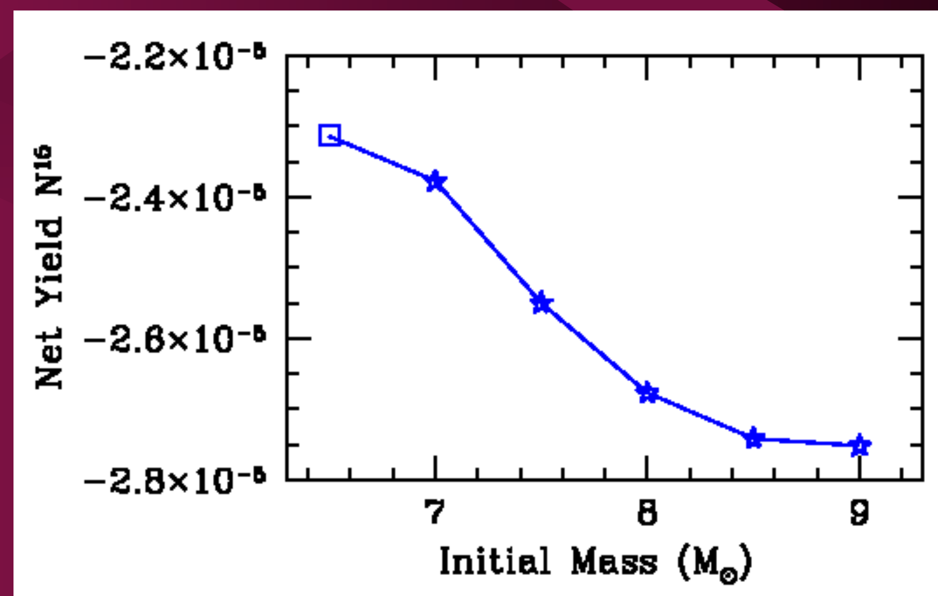
Z=0.02

CNO Yields:

^{14}N & ^{15}N



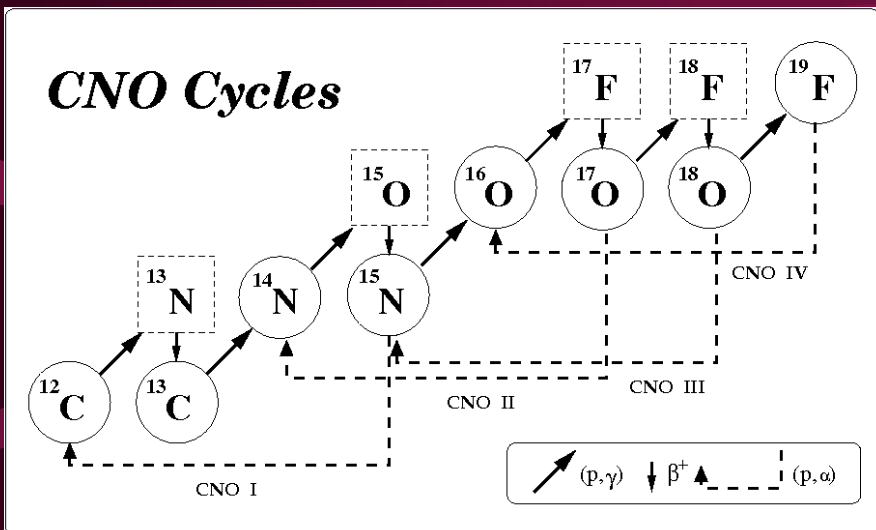




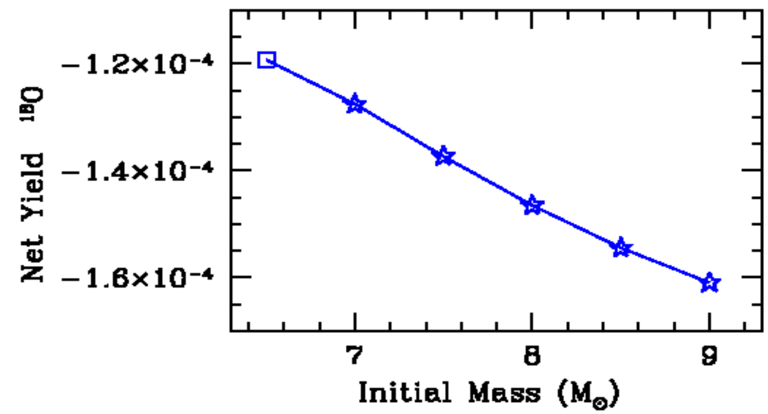
Z=0.02

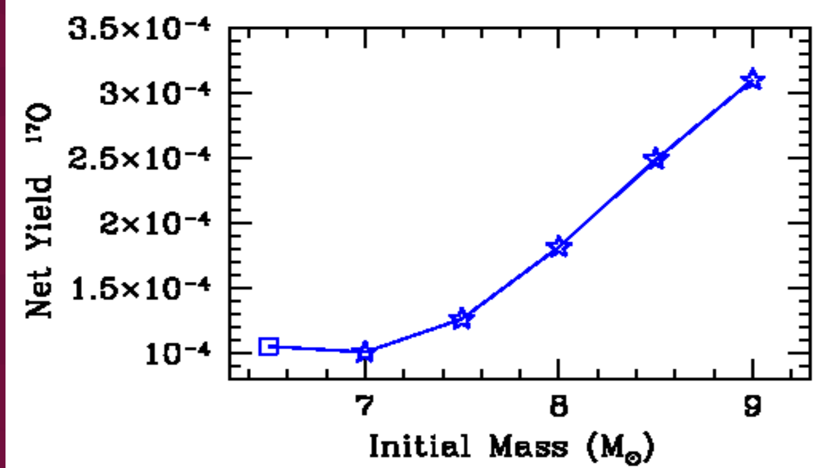
CNO Yields:

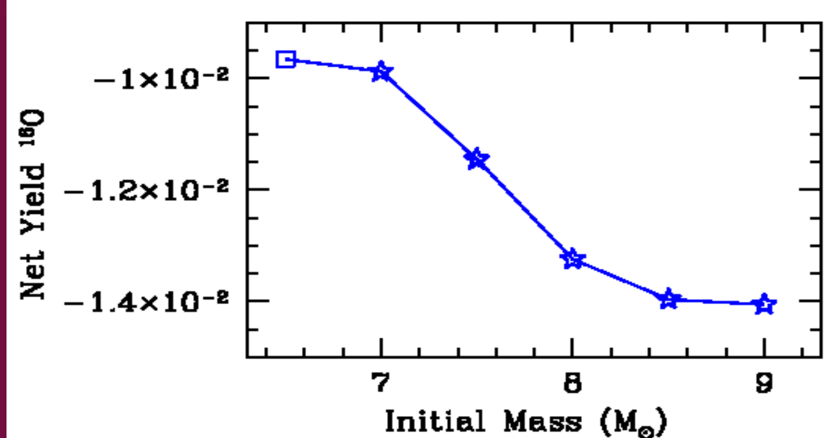
^{16}O, ^{17}O, & ^{18}O



Z=0.02

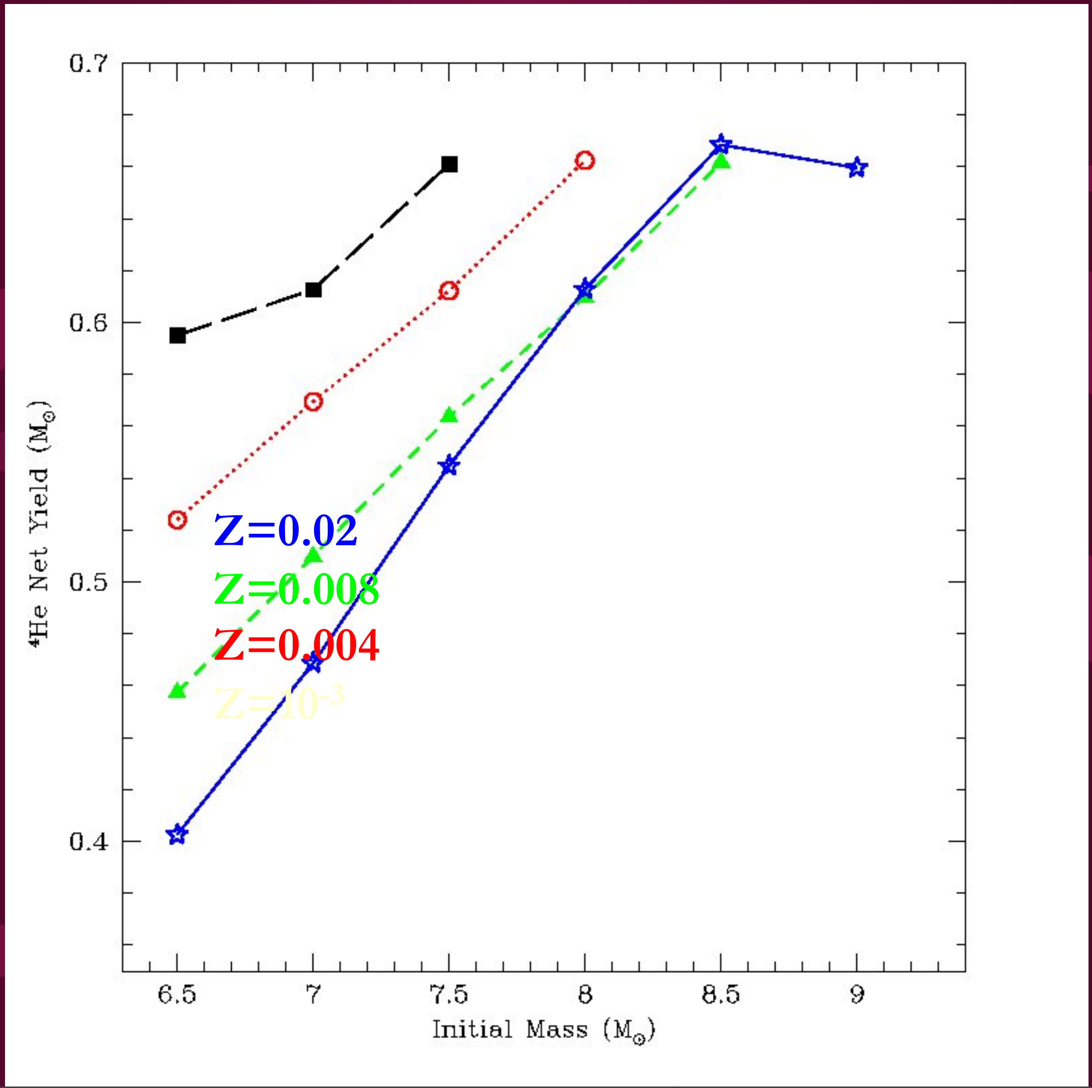




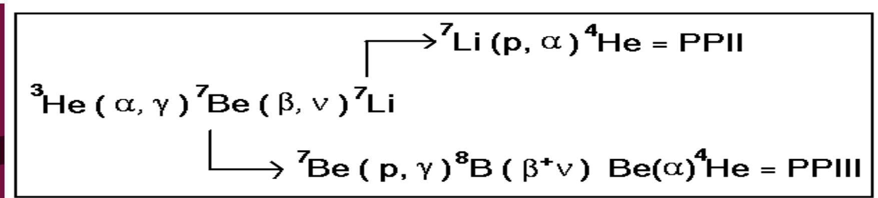


^{4}He

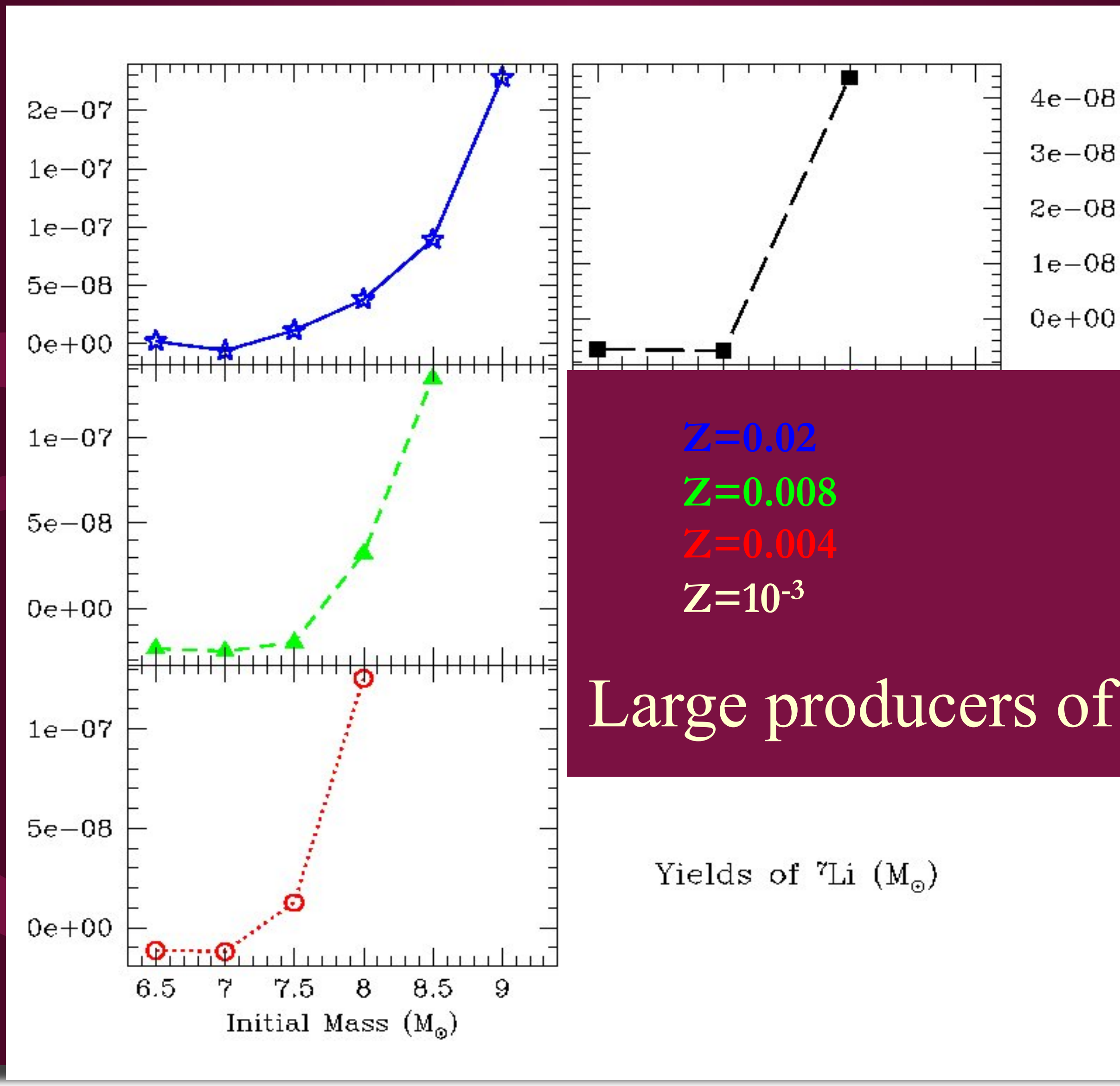
Super AGBs very large producers of ^{4}He, primarily due to deep 2nd Dredge up.



^{7}Li



Cameron-Fowler mechanism



Z=0.02

Z=0.008

Z=0.004

Z=10^{-3}

Large producers of ^{7}Li

Summary

- We have explored a large range of masses and metallicities for these Super AGB stars
- They undergo third dredge up! ☺
- Super AGBs are more complex than AGB stars!
- With current recommended reaction rates these models do not match the observed globular cluster abundance anomalies
- Need to resolve end of AGB and the convergence problems
- Need to run complete s-process network through hundreds of pulses per star…

Preminінary to MonKey!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Nuclear Astrophysics
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- Nuclear properties for astrophysics
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- Novae and X-ray bursts
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