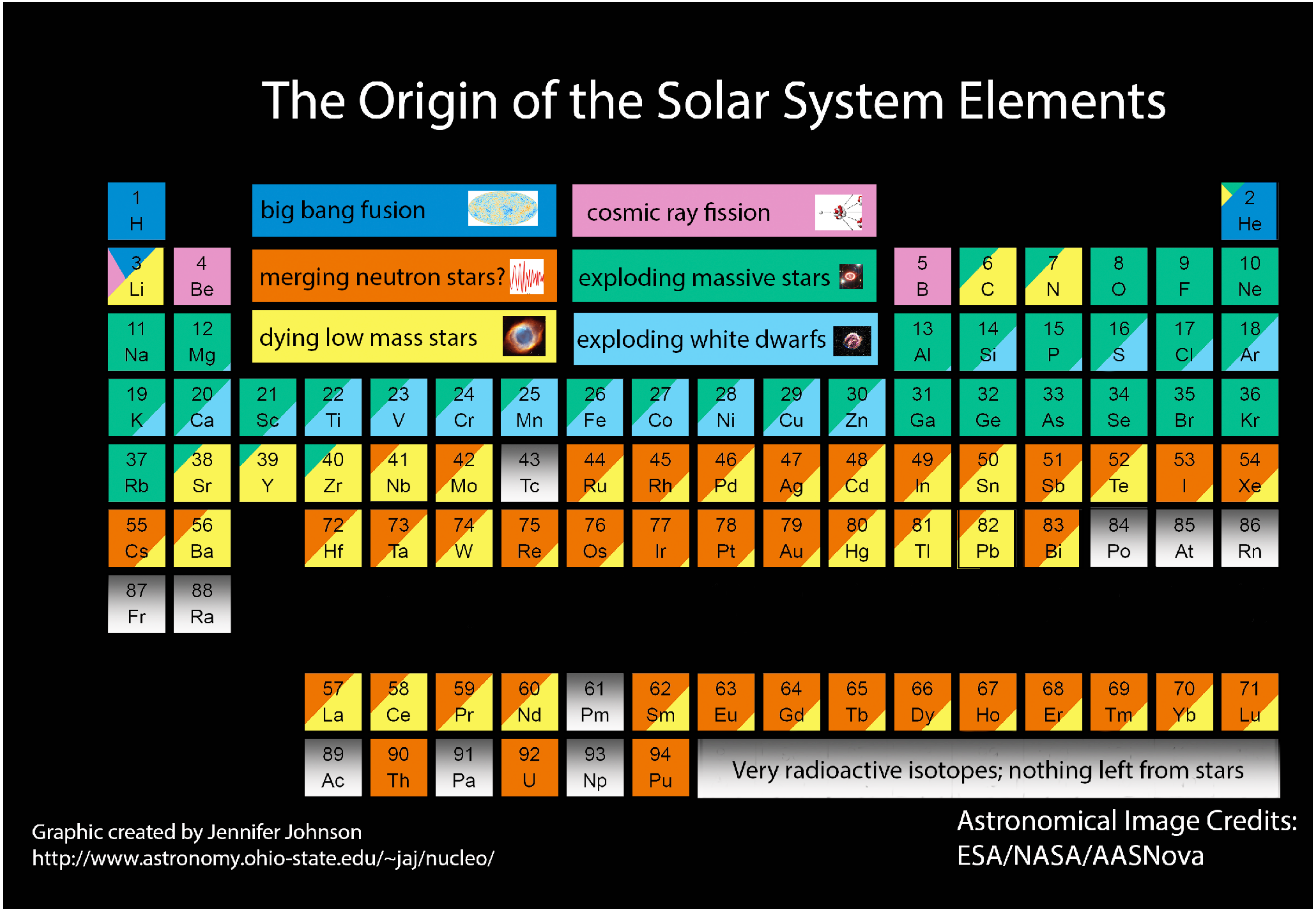
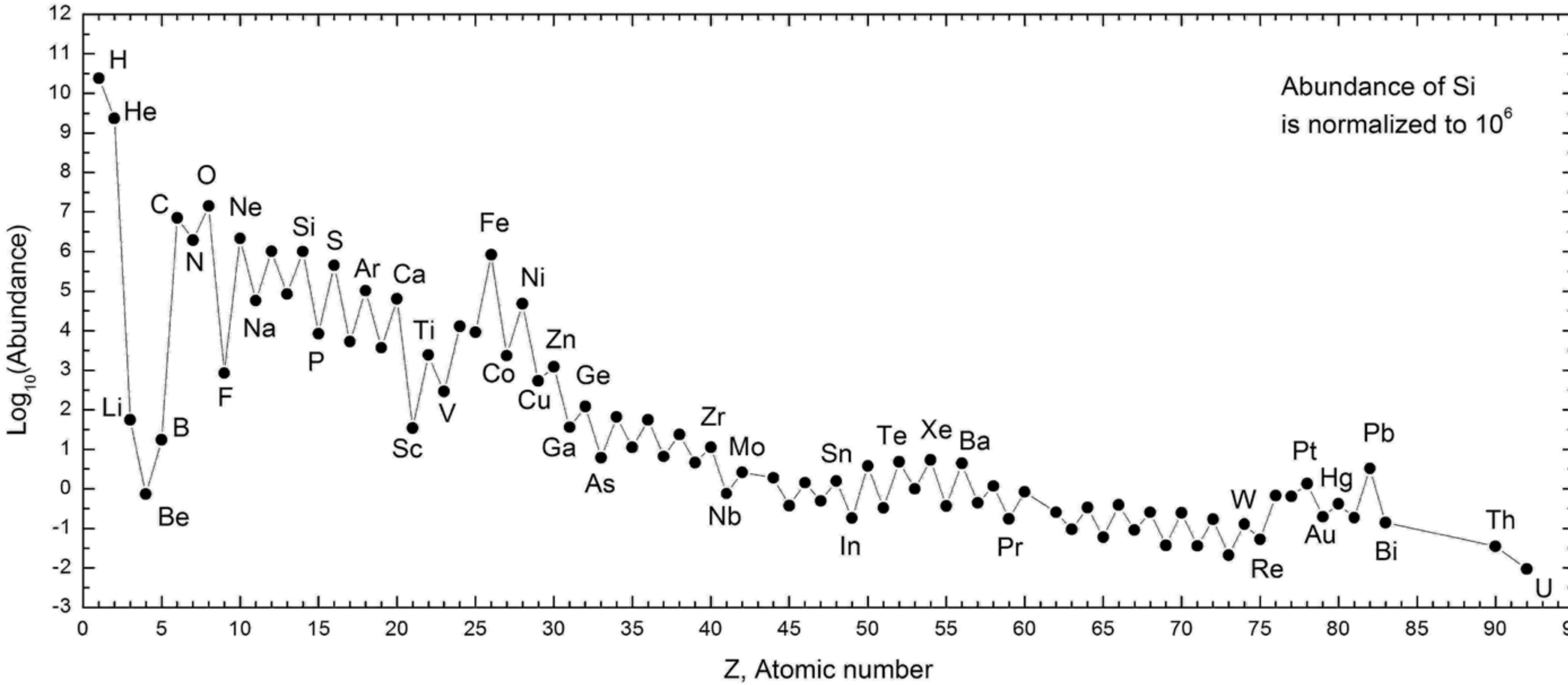
Lecture 20: Stellar Nucleosynthesis

Lamers & Levesque Ch. 30



Solar system abundances



– note large dip between He and C
– alpha reactions C, O, Ne, Mg, Si, S, Ar, Ca, … → odd-even effect
– iron peak

from http://www2.mpia-hd.mpg.de/homes/semenov/Lectures/Lectures.html

Chemical Yields

The yields of a star depend on its nuclear evolution and mass loss. Consider the evolution of single stars at different mass ranges:

$0.01 \lesssim M_i \lesssim 0.8M_\odot$: lifetime is longer than the age of the universe; these stars are still in their MS phase and have not yet contributed to ISM enrichment.

$0.8 \lesssim M_i \lesssim 8M_\odot$: stars progress through core H, shell H, and core He + shell H fusion. They lose a small fraction of their mass in the red giant phase, then go through dredge-ups during the AGB phase that bring CNO cycle, He fusion, and s-process products to the surface. Severe mixing and high mass loss during the AGB phase produces large chemical yields.

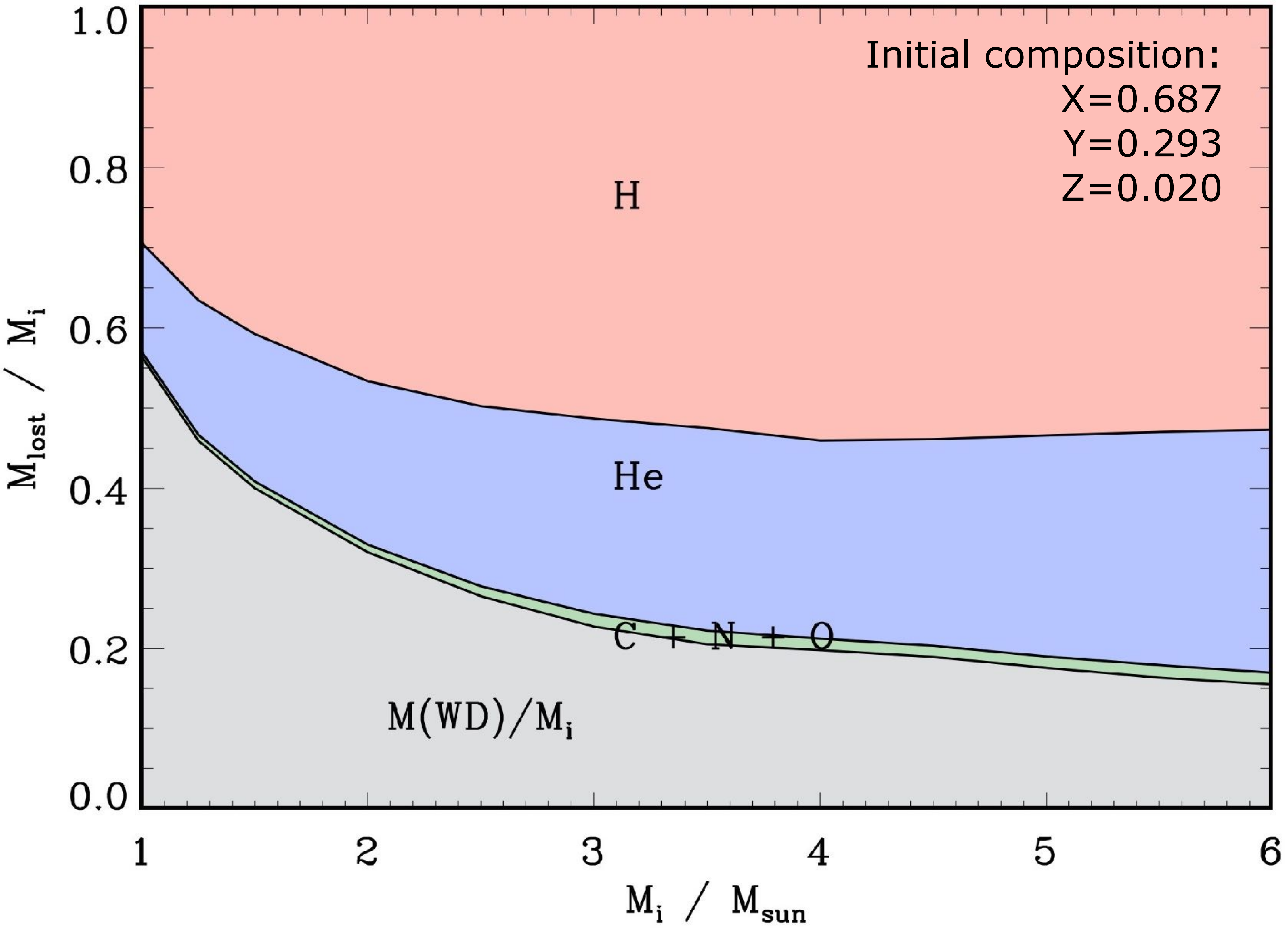
$8 \lesssim M_i \lesssim 25M_\odot$: stars go through all fusion phases and explode as RSGs. Deep convective envelopes and strong mass loss during RSG phase combined with SN explosion produces large chemical yields.

$25 \lesssim M_i \lesssim 50M_\odot$: stars go through all fusion phases and explode as WRs. They experience high mass loss as RSGs and WNs (ejecting products of the CNO cycle) and as WCs (ejecting products of He fusion)

$50 \lesssim M_i \lesssim 120M_\odot$: stars go through all fusion phases and explode as WRs. They experience high mass loss during LBV eruptions (ejecting products of the CNO cycle) and as WN and WC stars.

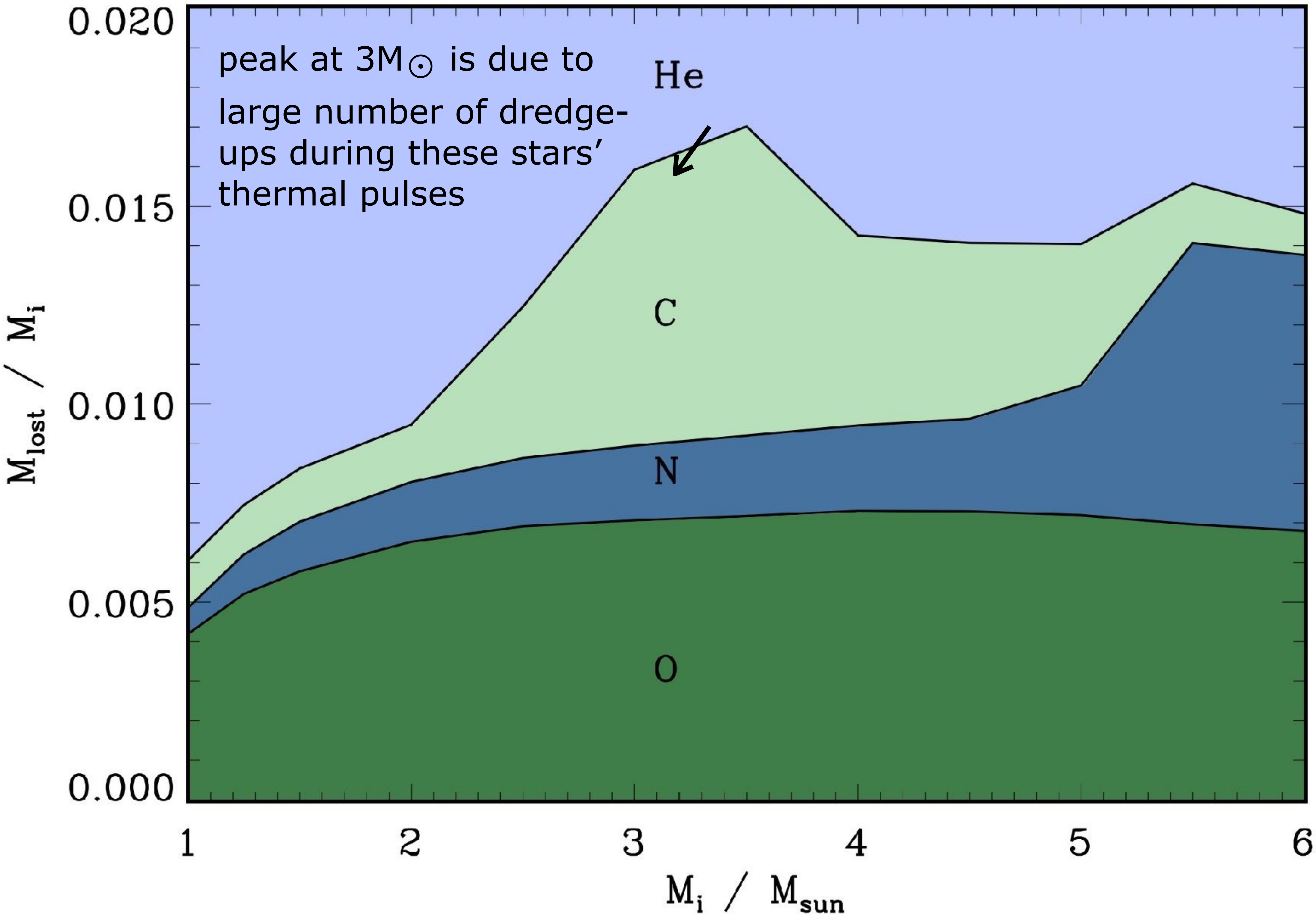
Chemical Yields

Low-mass stars



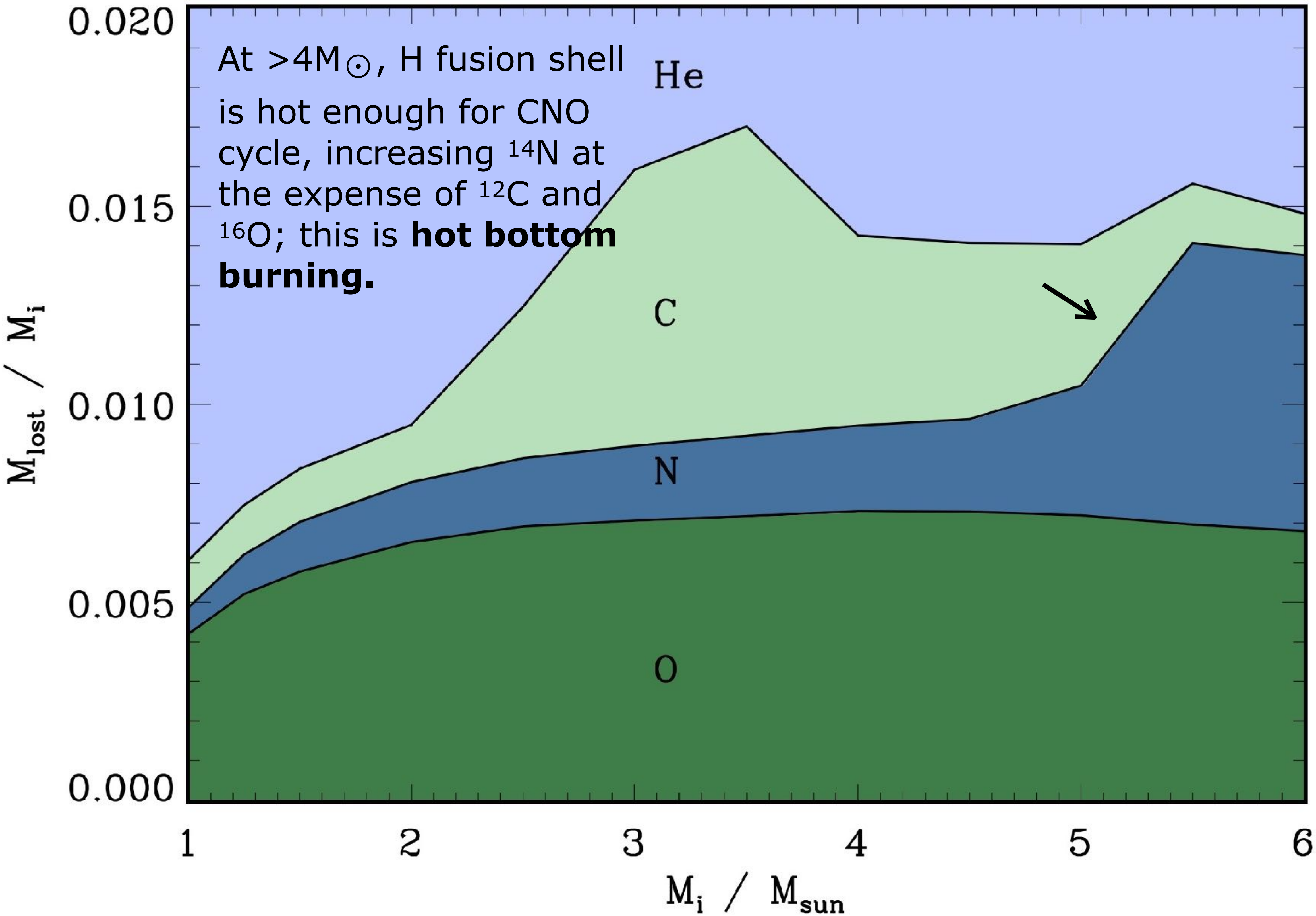
Chemical Yields

Low-mass stars



Chemical Yields

Low-mass stars

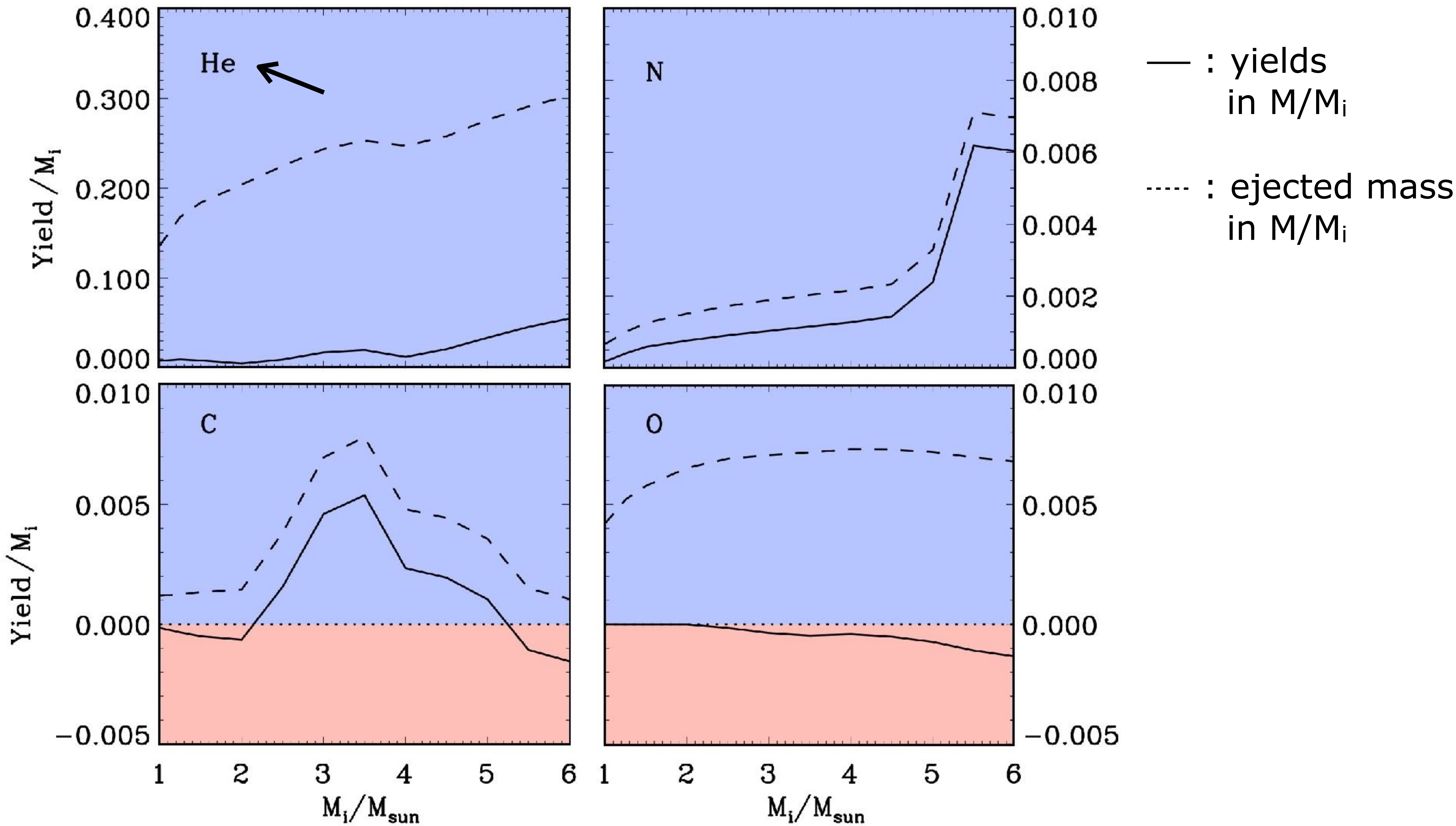


At >4M$_\odot$, H fusion shell is hot enough for CNO cycle, increasing ^{14}N at the expense of ^{12}C and ^{16}O; this is **hot bottom burning.**

Chemical Yields

Low-mass stars

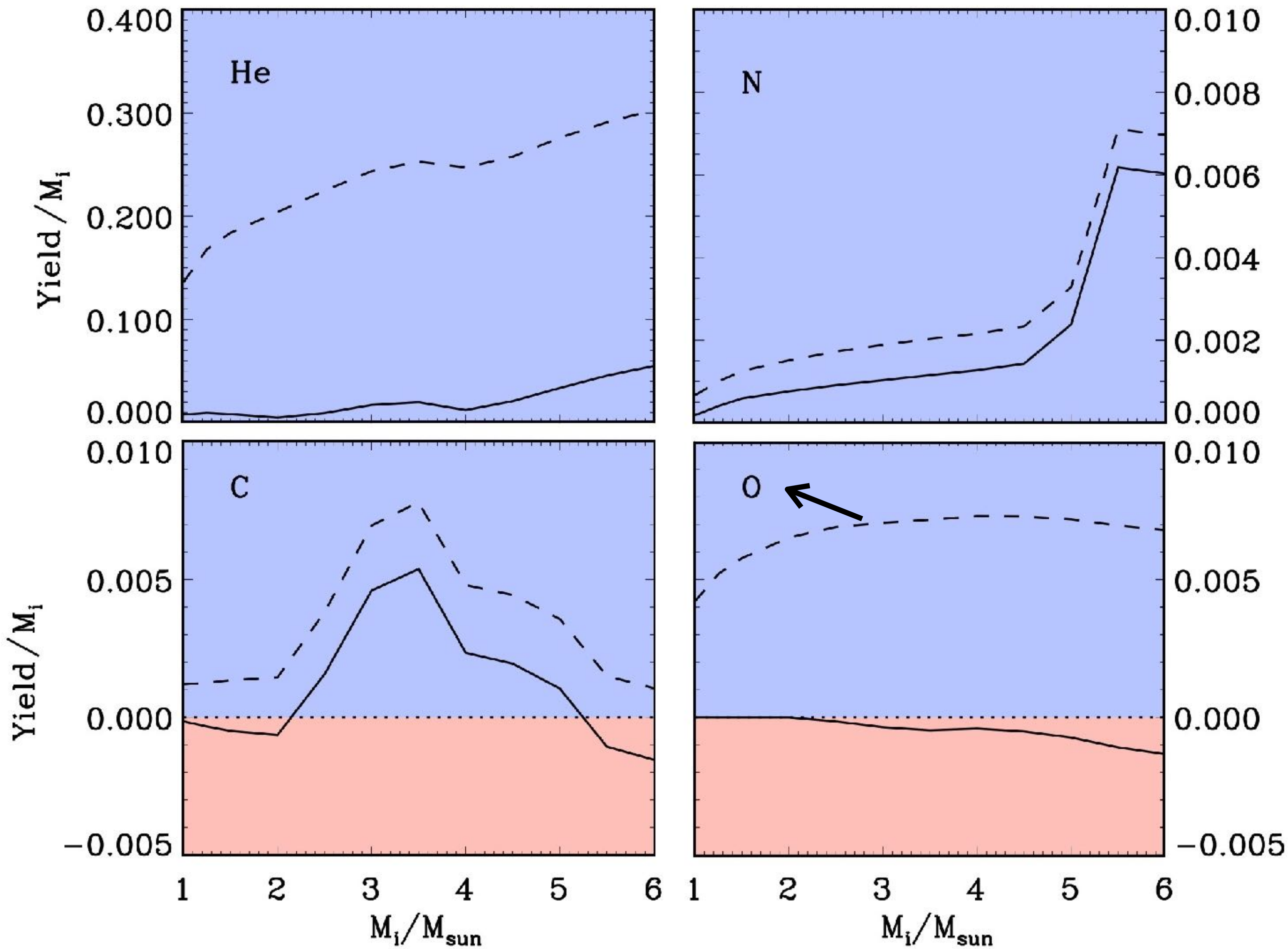
He yield is small; 25% of the stellar mass is ejected in He, but initial composition was 29.3%.



Chemical Yields

Low-mass stars

Same is true for O; the yield is even negative. This is a consequence of O being converted into C and N in the CNO cycle of low-mass stars.



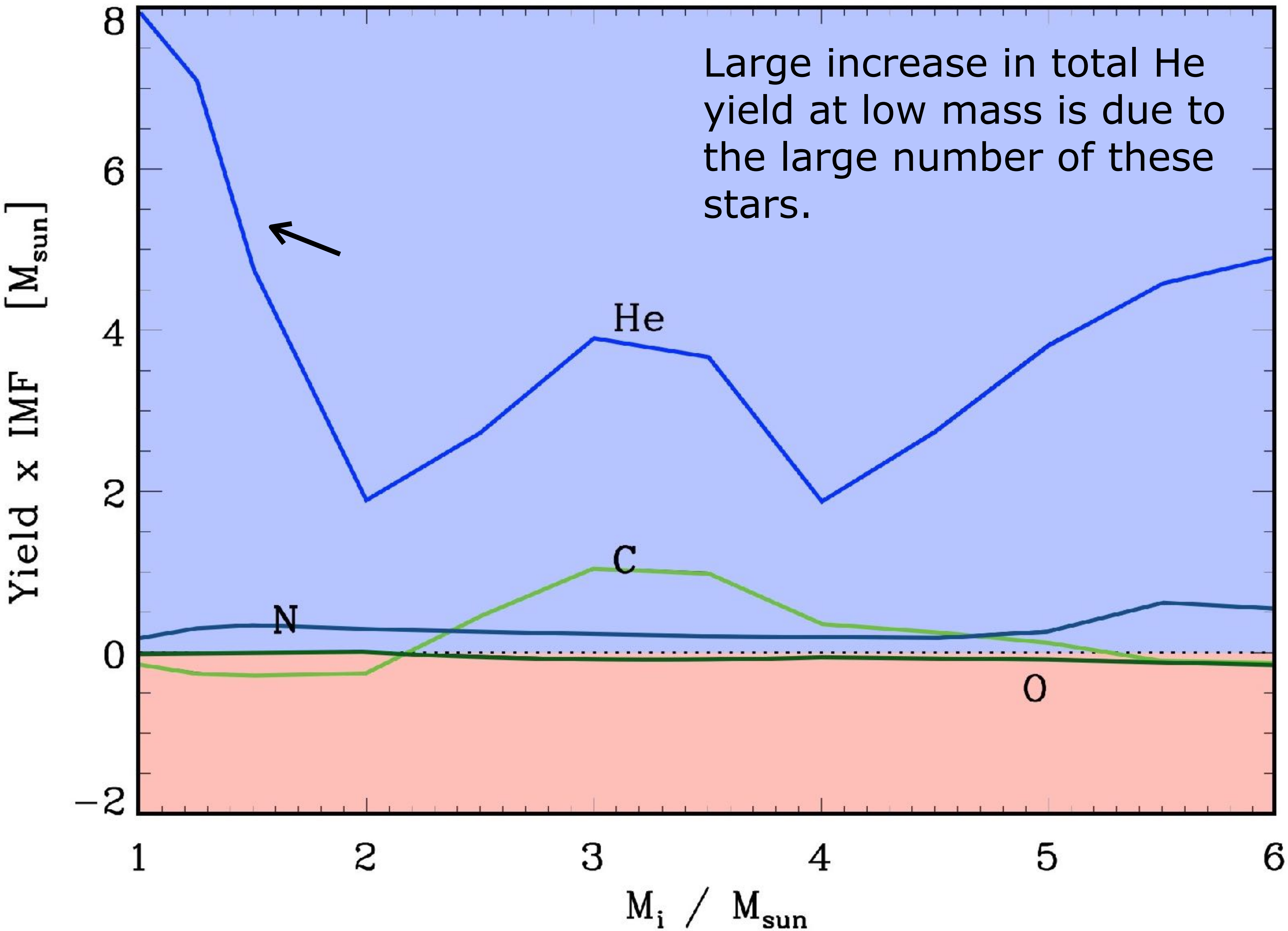
—— : yields in M/M_i

······ : ejected mass in M/M_i

Chemical Yields

Low-mass stars

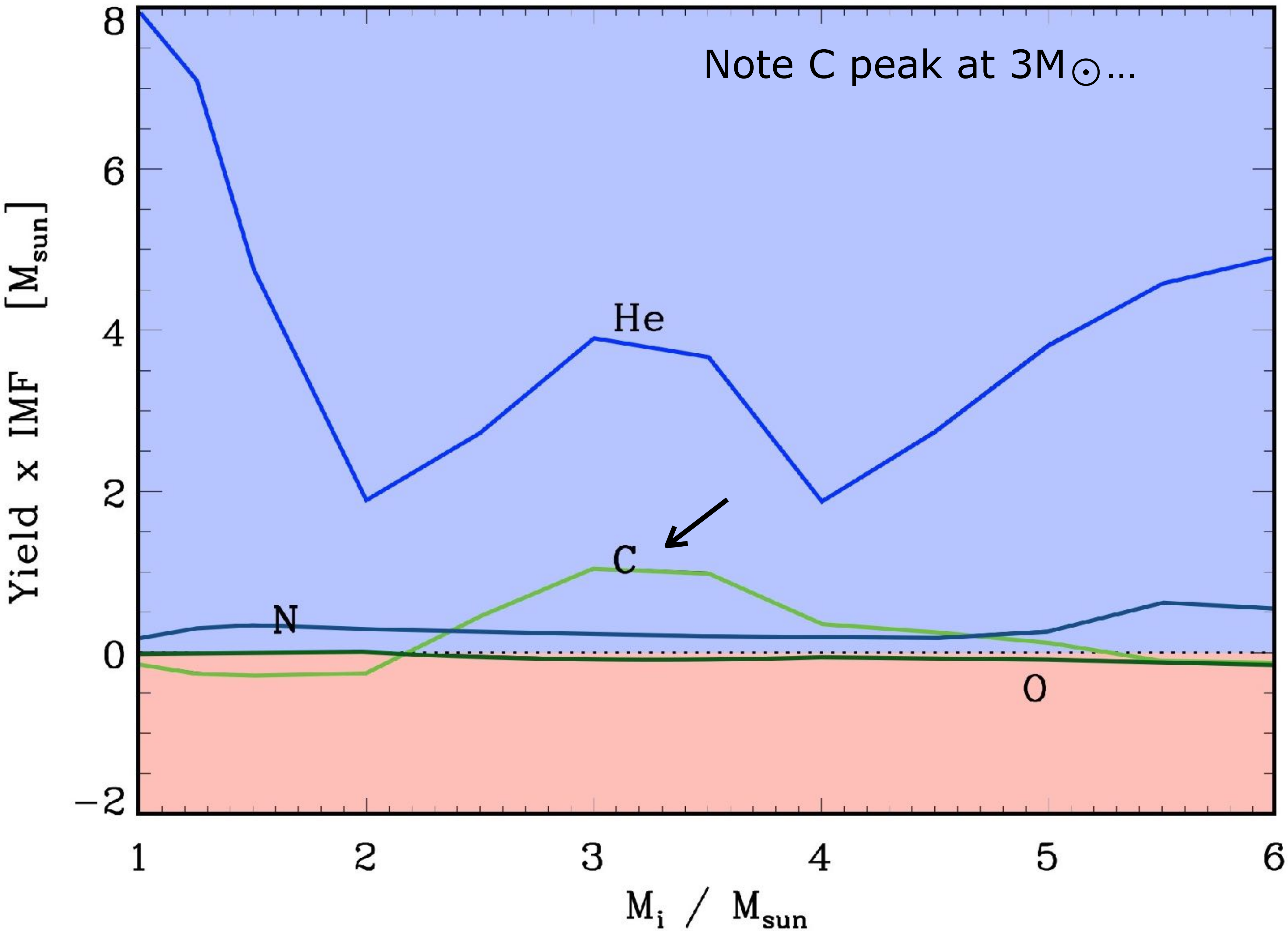
Total yields for an assumed Saltpeter stellar mass function: $N(M_i)=1000 \times M_i^{-2.35}$



Chemical Yields

Low-mass stars

Total yields for an assumed Saltpeter stellar mass function: $N(M_i) = 1000 \times M_i^{-2.35}$



Chemical Yields

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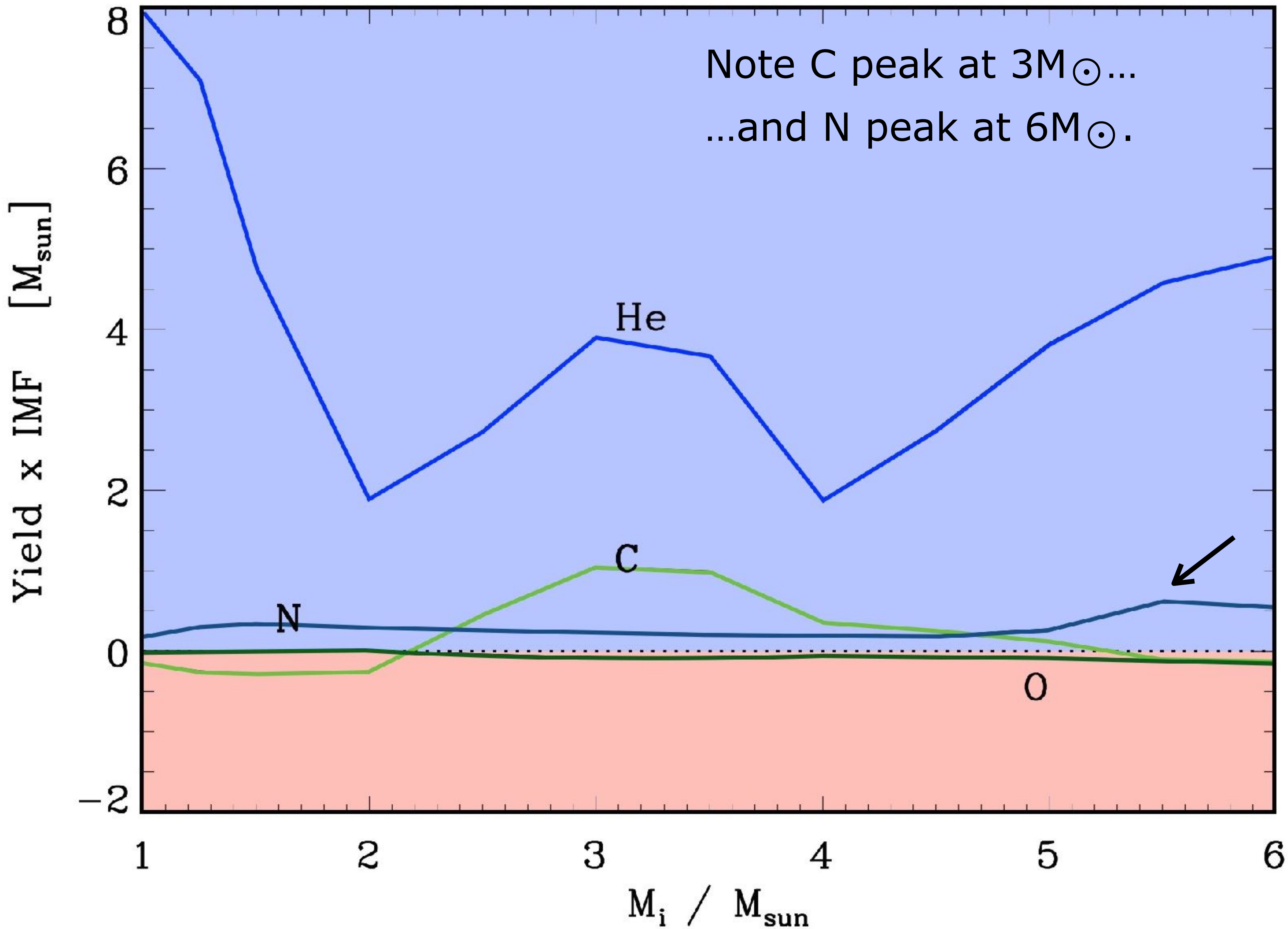
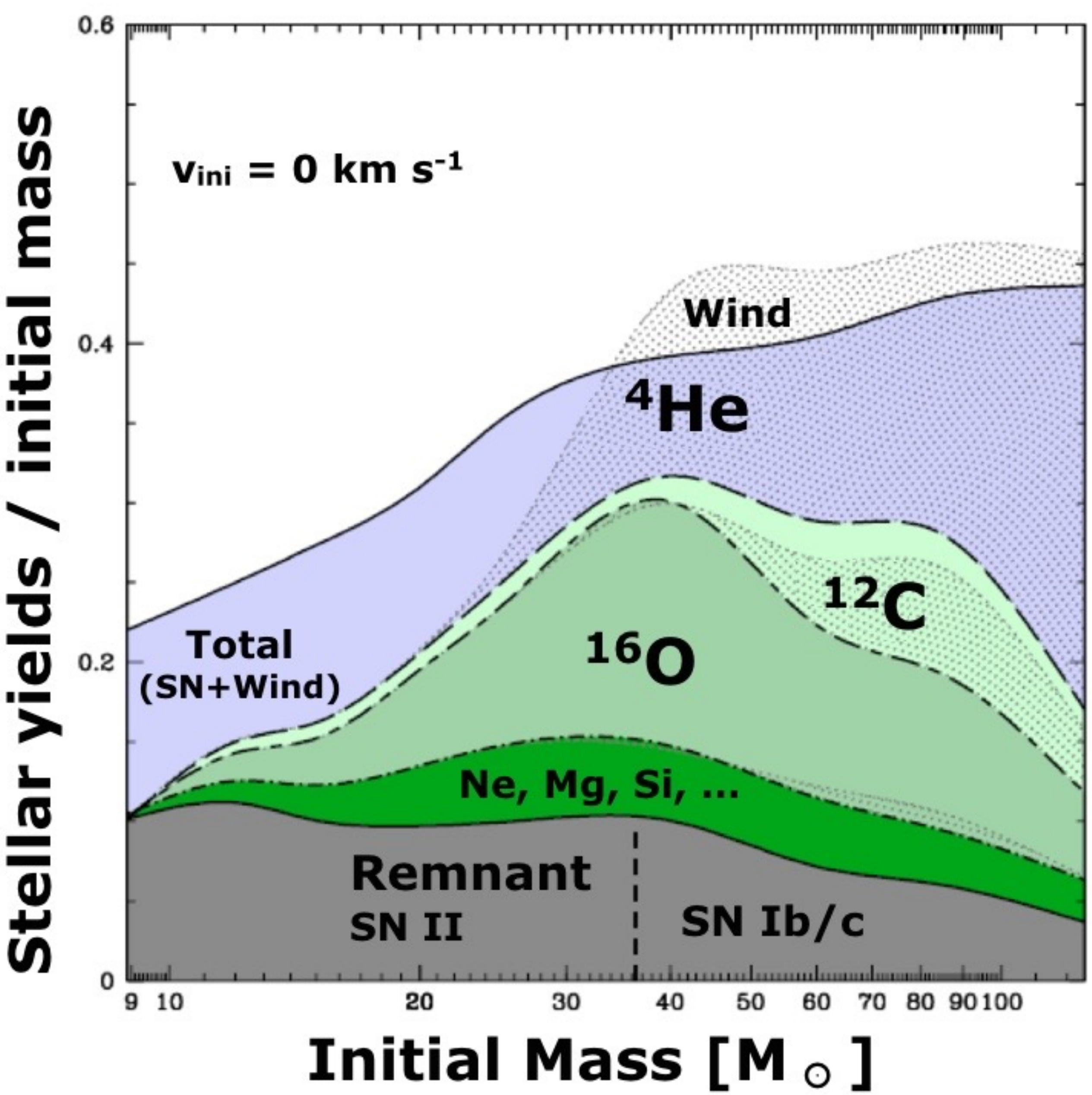


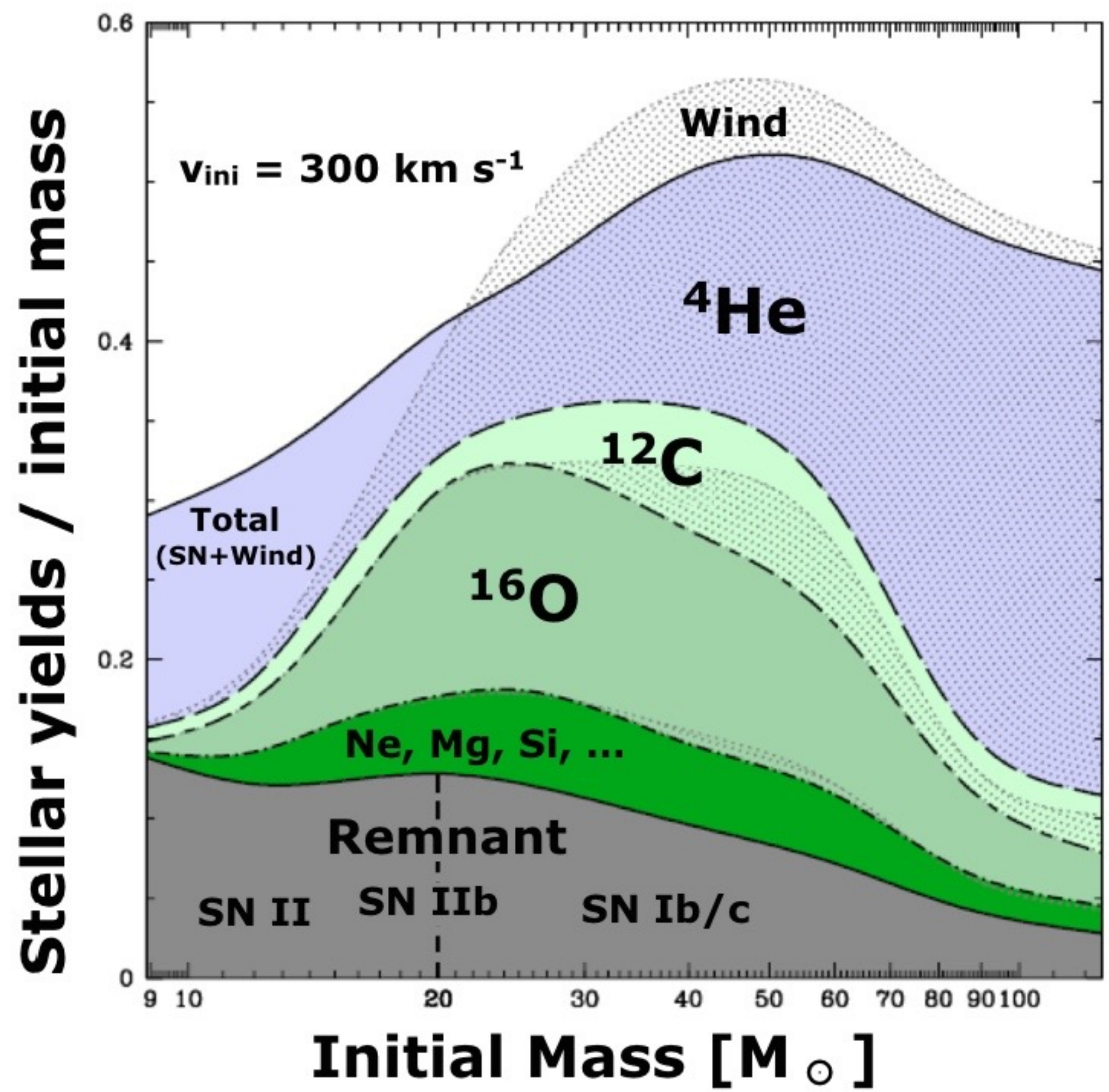
Chemical Yields

Massive stars

Compare the yields of different chemical elements for solar-metallicity non-rotating (left) and rapidly-rotating (right) massive stars.

- yield of He is constant at ~10% of M_i up until $>60M_\odot$, which eject more He
- stars at $M_i > 15M_\odot$ contribute C, O, and α-elements to ISM enrichment



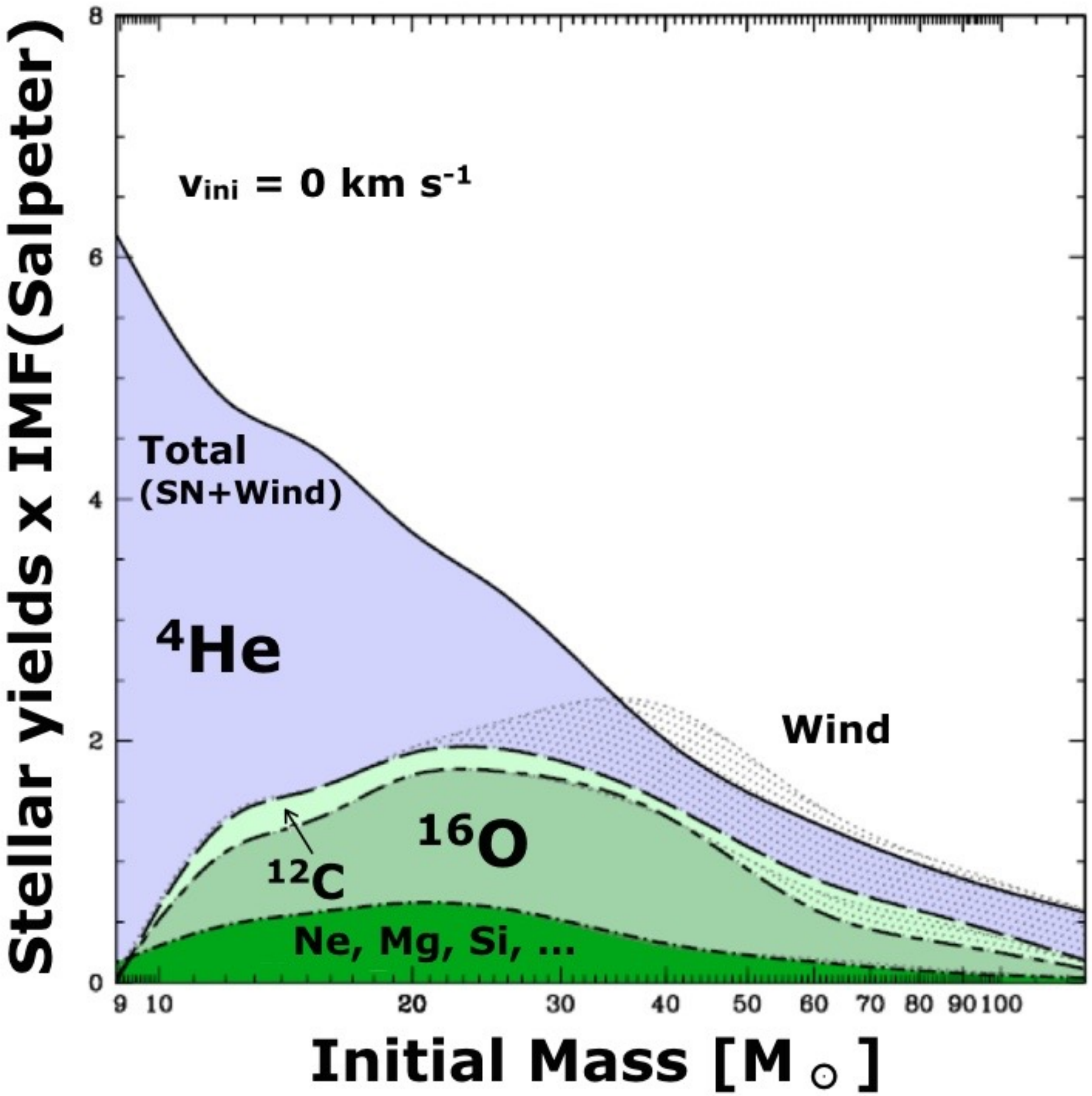


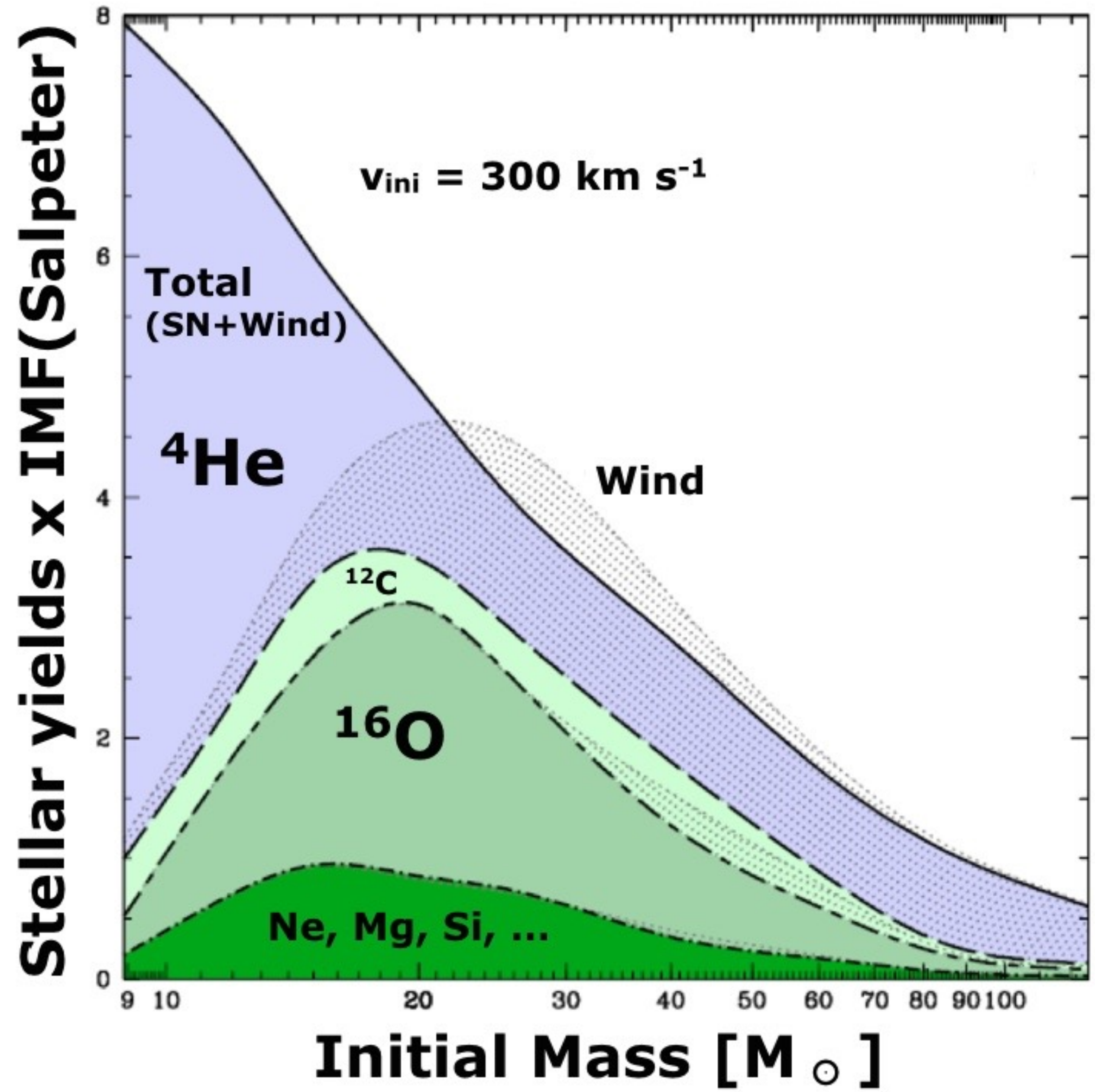
Chemical Yields

Massive stars

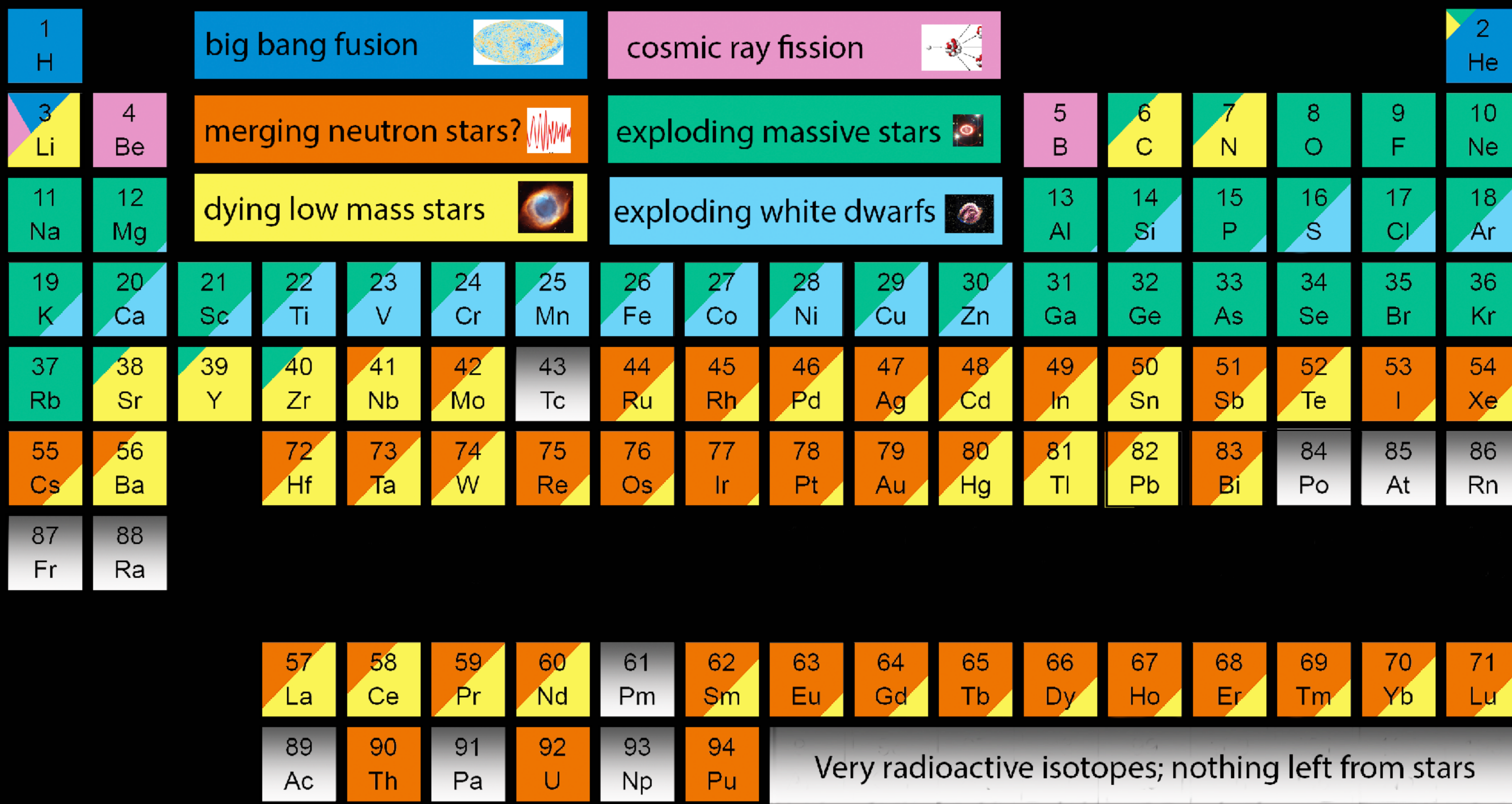
Total yields for an assumed Saltpeter stellar mass function: $N(M_i)=1000 \times M_i^{-2.35}$

- He increases strongly for lower-mass stars
- C is roughly constant for all massive stars
- α-elements mainly due to $20 < M_i < 40 M_\odot$
- larger yield of O vs. C explains why cosmic C abundance is 3x lower than O
- rotating stars contribute more He, C, and O





The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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Chemical Yields

Main producers of various elements

He:

—most was formed in the Big Bang

—the most massive (20-120$M_\odot$) and least massive (M_i <10$M_\odot$) stars eject He by their winds

—10 < M_i < 20$M_\odot$ eject most of their He in SNe

—although M_i <10$M_\odot$ stars eject a smaller fraction of their mass as He, the larger number of them implies that even stars with M_i <20$M_\odot$ contribute significantly to He enrichment

—most of the enrichment of He comes from stars with 1< M_i <30$M_\odot$

Chemical Yields

Main producers of various elements

O:

—most O enrichment is by SNe of $M_i > 10 M_\odot$ stars, with a peak contribution at $20 < M_i < 60 M_\odot$

—$M_i > 10 M_\odot$ stars also lose O in the form of WC and WO star winds

—low-mass stars contribute very little to the enrichment of O

α-elements, Ne-Si:

—enrichment of these elements is due to SNe from massive stars of $M_i > 8 M_\odot$

Fe-peak elements and beyond:

—these elements are created and ejected in SN explosions, due to core collapse SNe of massive stars or white dwarfs exceeding the Chandrasekhar limit.

neutron-rich s-process elements:

—low-mass s-process elements (Sr, Y, Zr) are formed in massive stars and ejected in SN explosions

—more massive s-process elements (Ba, Ce) are formed in low-mass AGB stars from neutrons formed during He fusion by the process $^{13}C(\alpha,n)^{16}O$

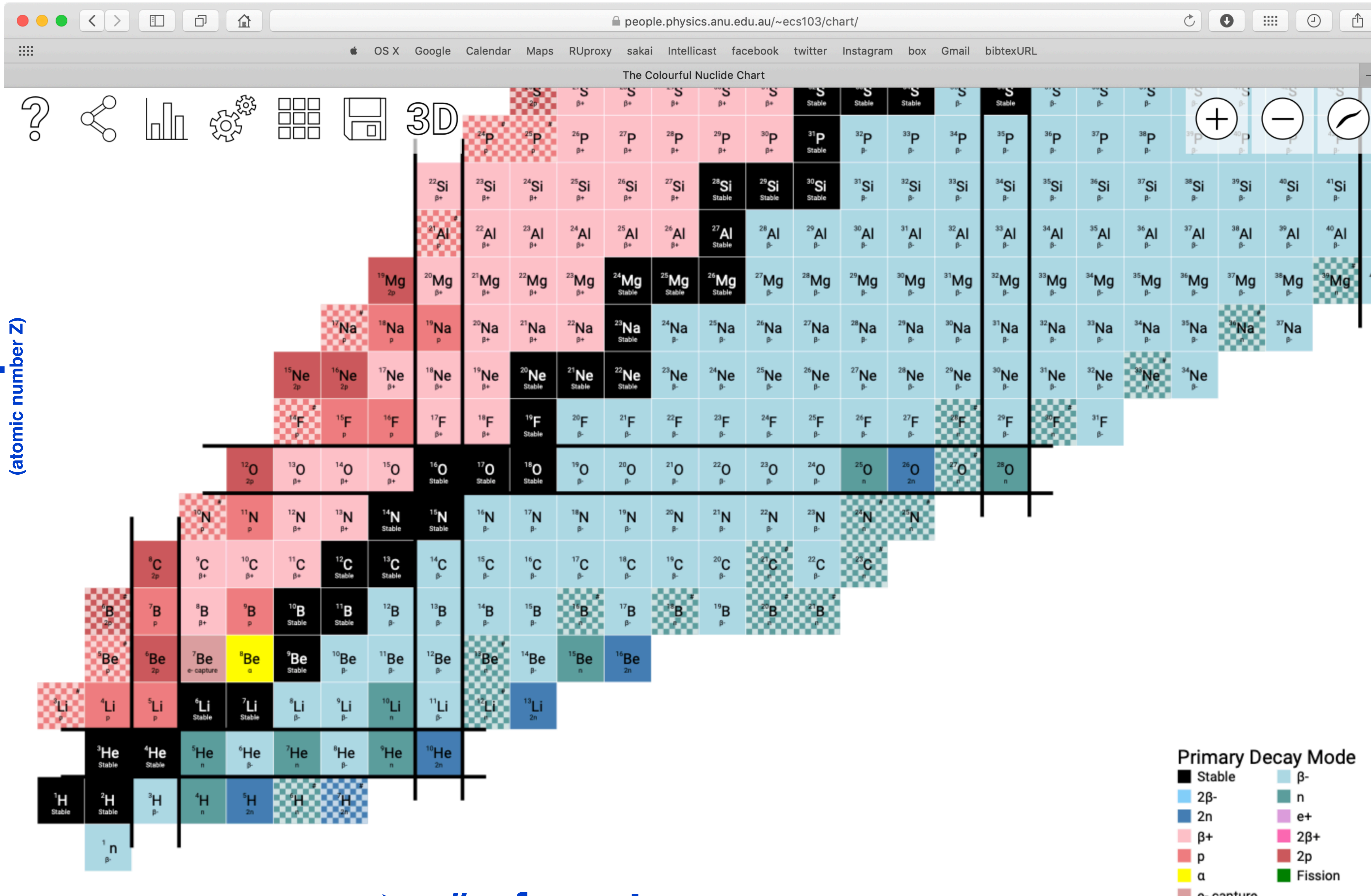
neutron-rich r-process elements:

—these are formed during the gravitational collapse of massive stars and ejected in SN explosions

—merging neutron stars could also provide a source of n-rich r-process elements

Chart of the nuclides

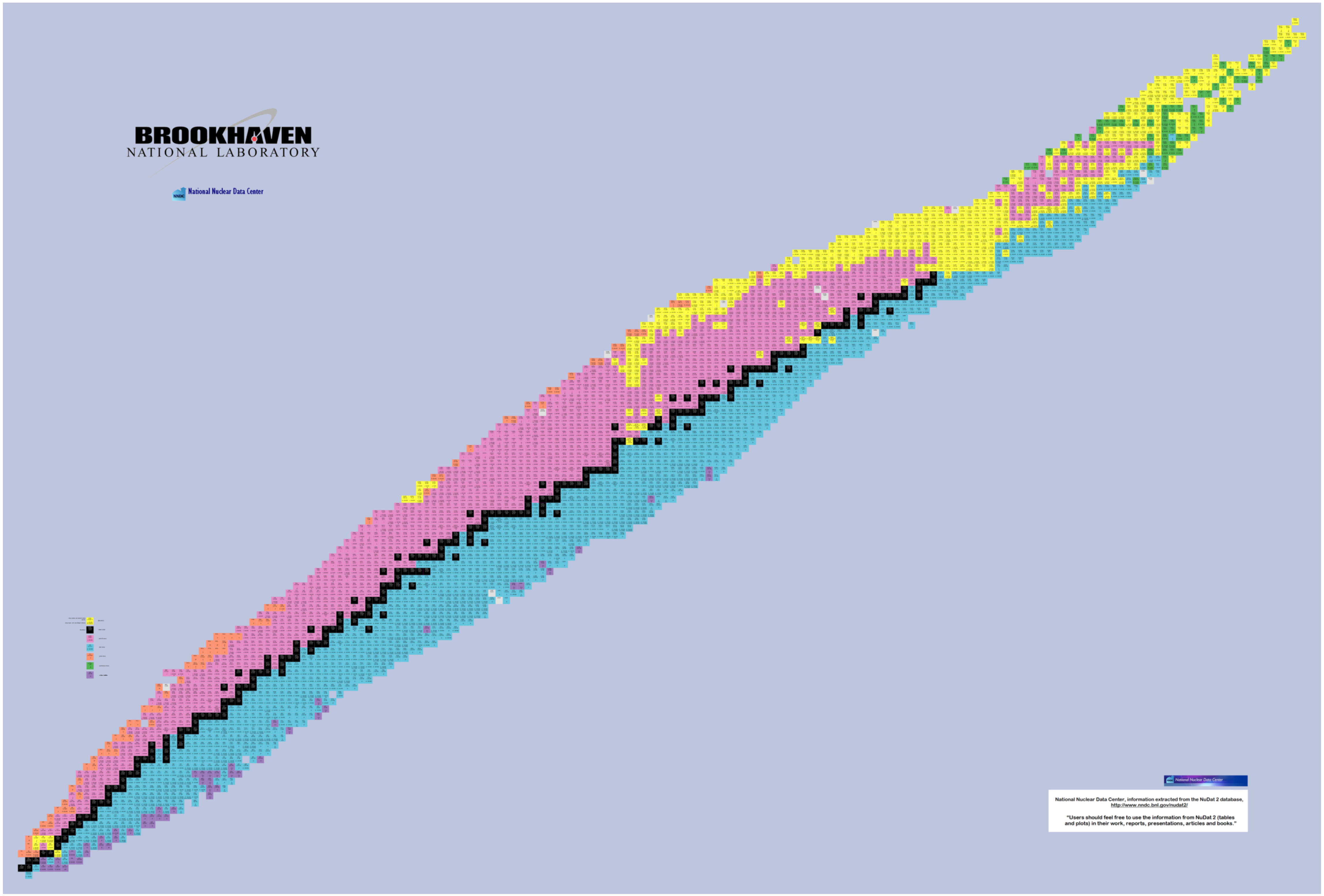
of protons
(atomic number Z)



# of neutrons
(mass number – atomic number, A – Z)

from https://people.physics.anu.edu.au/~ecs103/chart/

Chart of the nuclides



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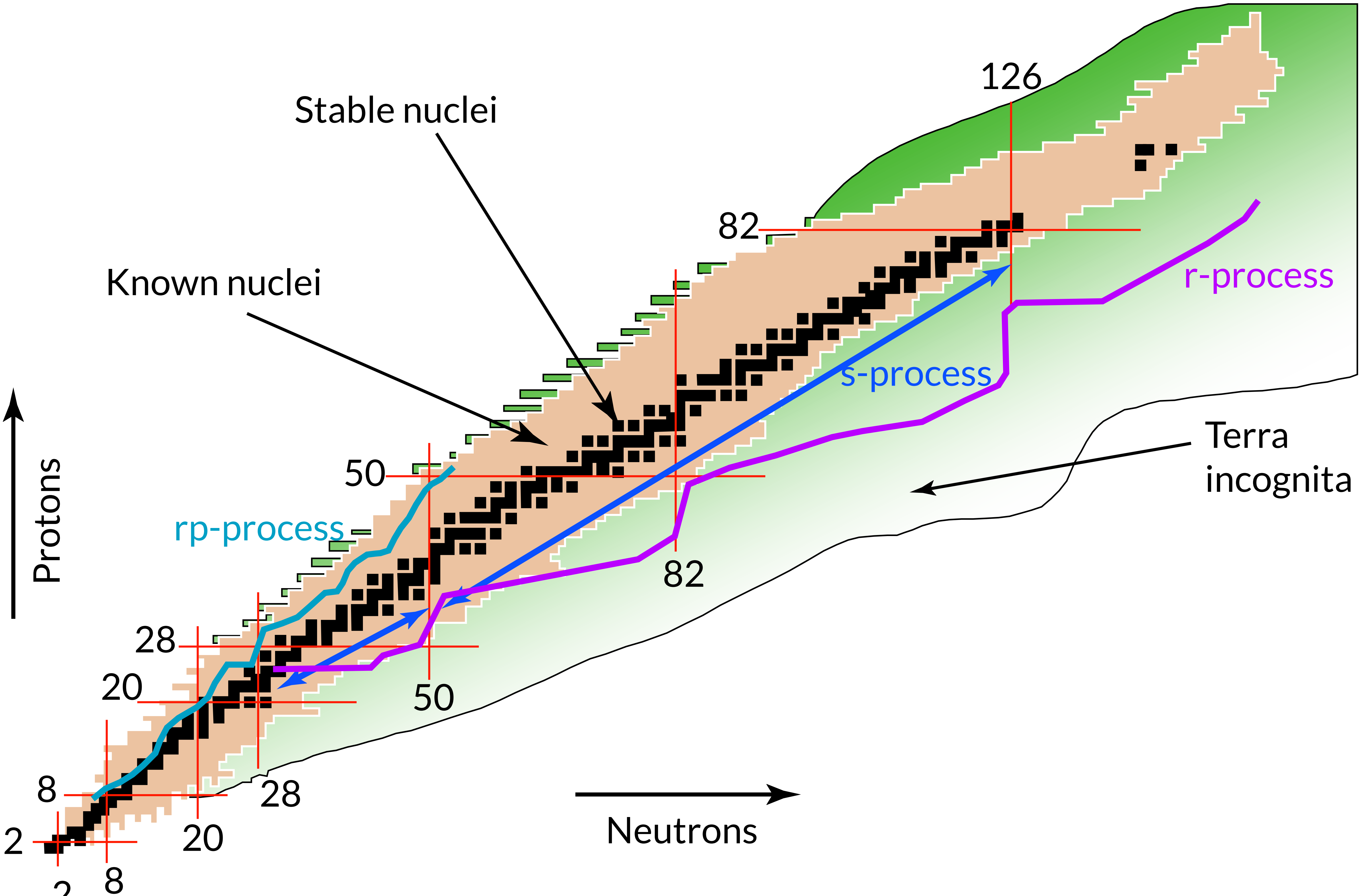
from https://en.wikipedia.org/wiki/Table_of_nuclides

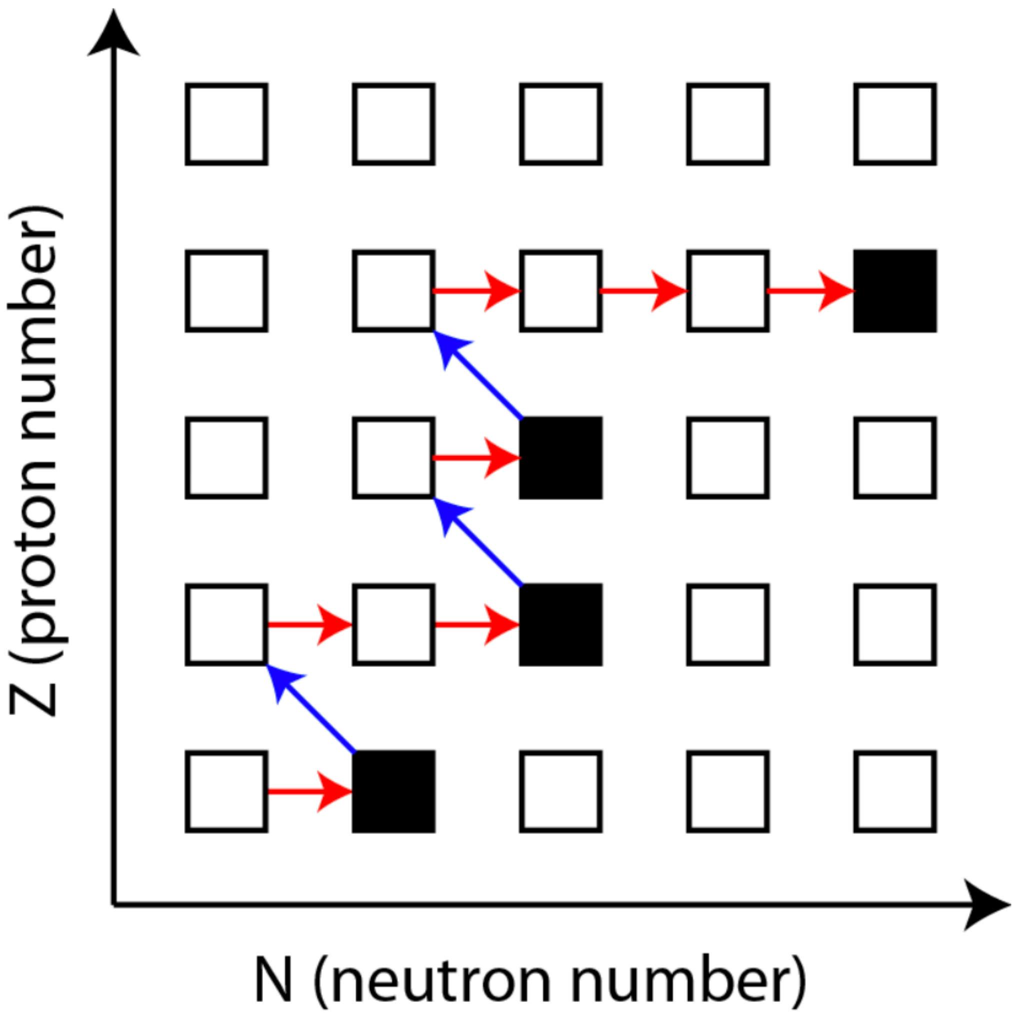


from http://cococubed.asu.edu/pix_pages/nuclide_chart.shtml

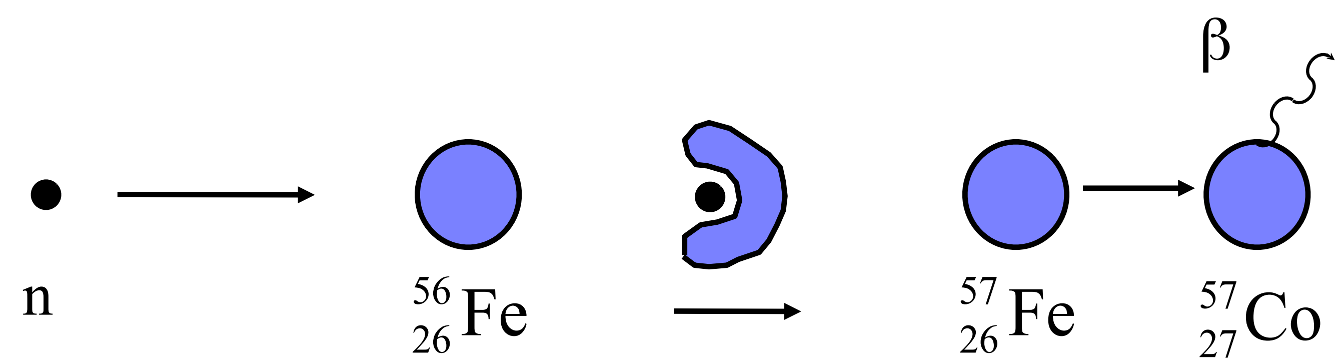
s-process (“slow” neutron capture)

THE SLOW NEUTRON CAPTURE PROCESS

s-process: neutron capture rates are slow relative to β-decay; $\tau_n \gg \tau_\beta$



s-process: Slow neutron capture:



Absorb n^0, then … later … emit e^- (β-particle)

Progress up the valley of stability.

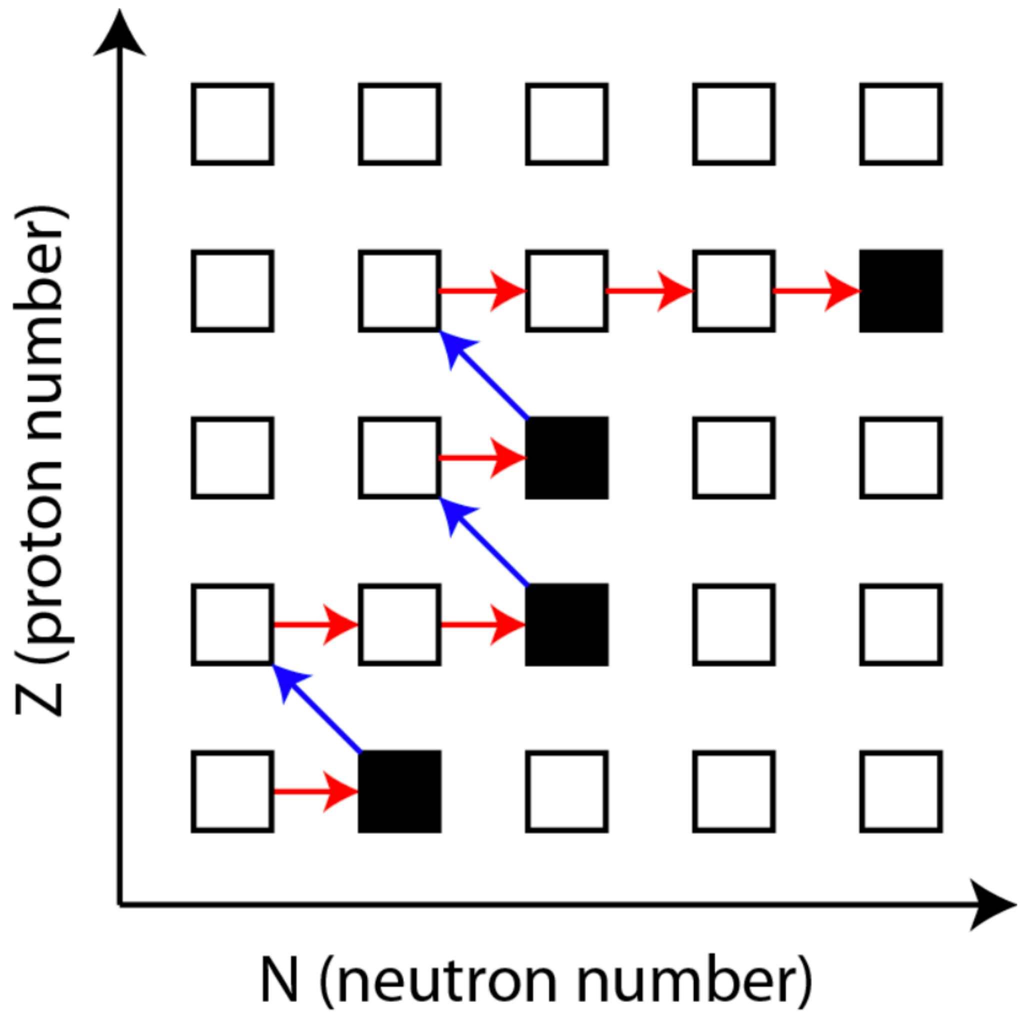
$$(Z, N) + n \leftrightarrow (Z, N+1) + \gamma$$

$$(Z, N) \rightarrow (Z+1, N-1) + e^- + \bar{\nu}_e$$

from https://www.matthewmumpower.com/static/presentations/Frontiers2019Lecture/index.html#/the-s-process
and http://www2.mpia-hd.mpg.de/homes/semenov/Lectures/Lectures.html

r-process ("rapid" neutron capture)

WHAT HAPPENS WHEN $\tau_n \ll \tau_\beta$?



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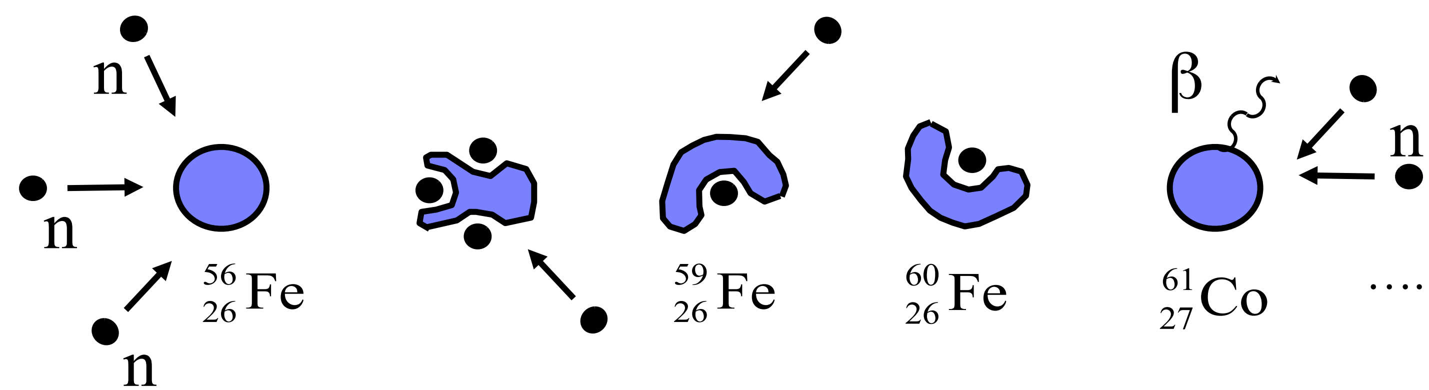

High n^0 flux: absorb many n^0s before β emission

We're going to go far from the stable isotopes (further to the right)!

This is known as the rapid neutron capture process (r-process)

from https://www.matthewmumpower.com/static/presentations/Frontiers2019Lecture/index.html#/the-rprocess-1
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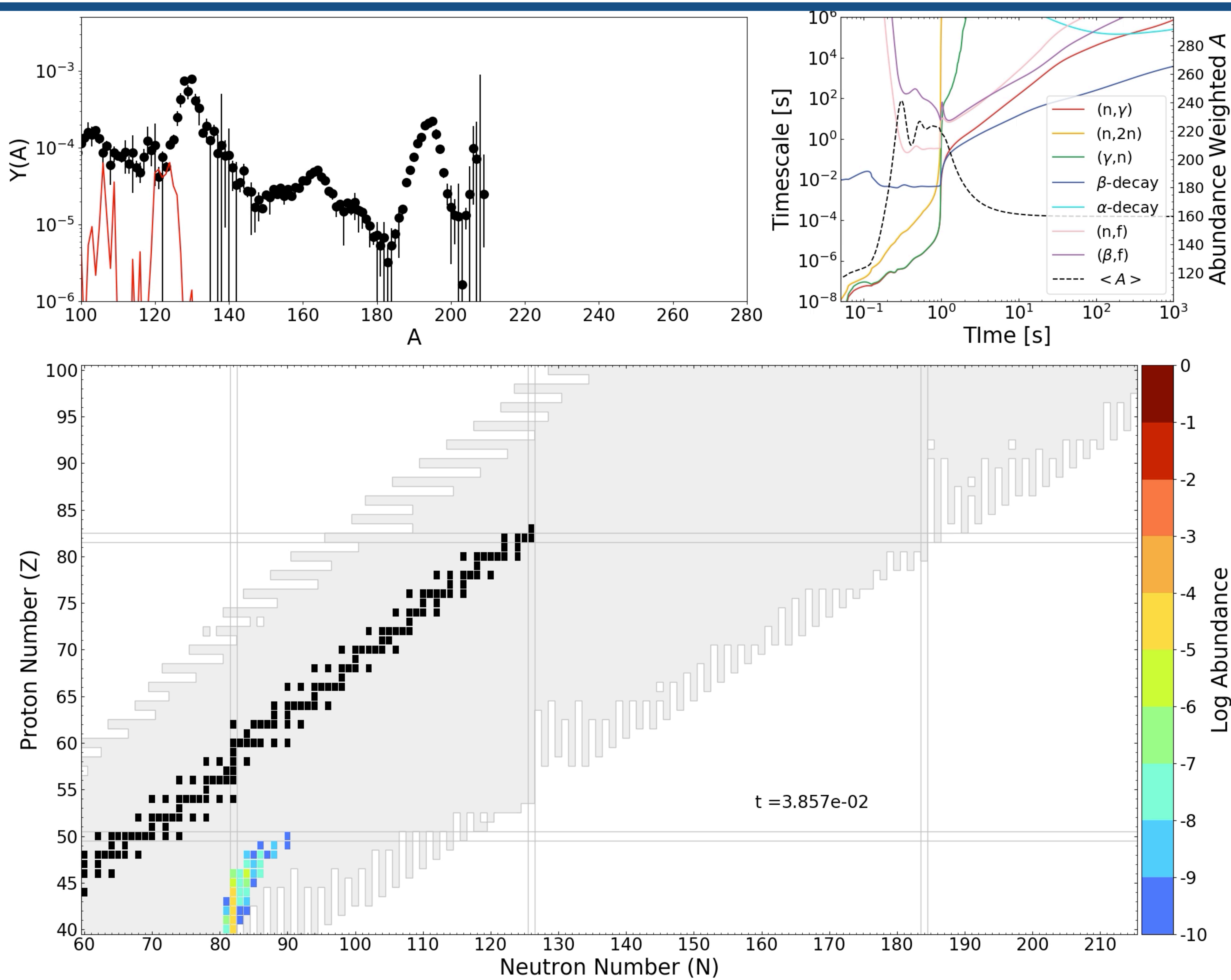
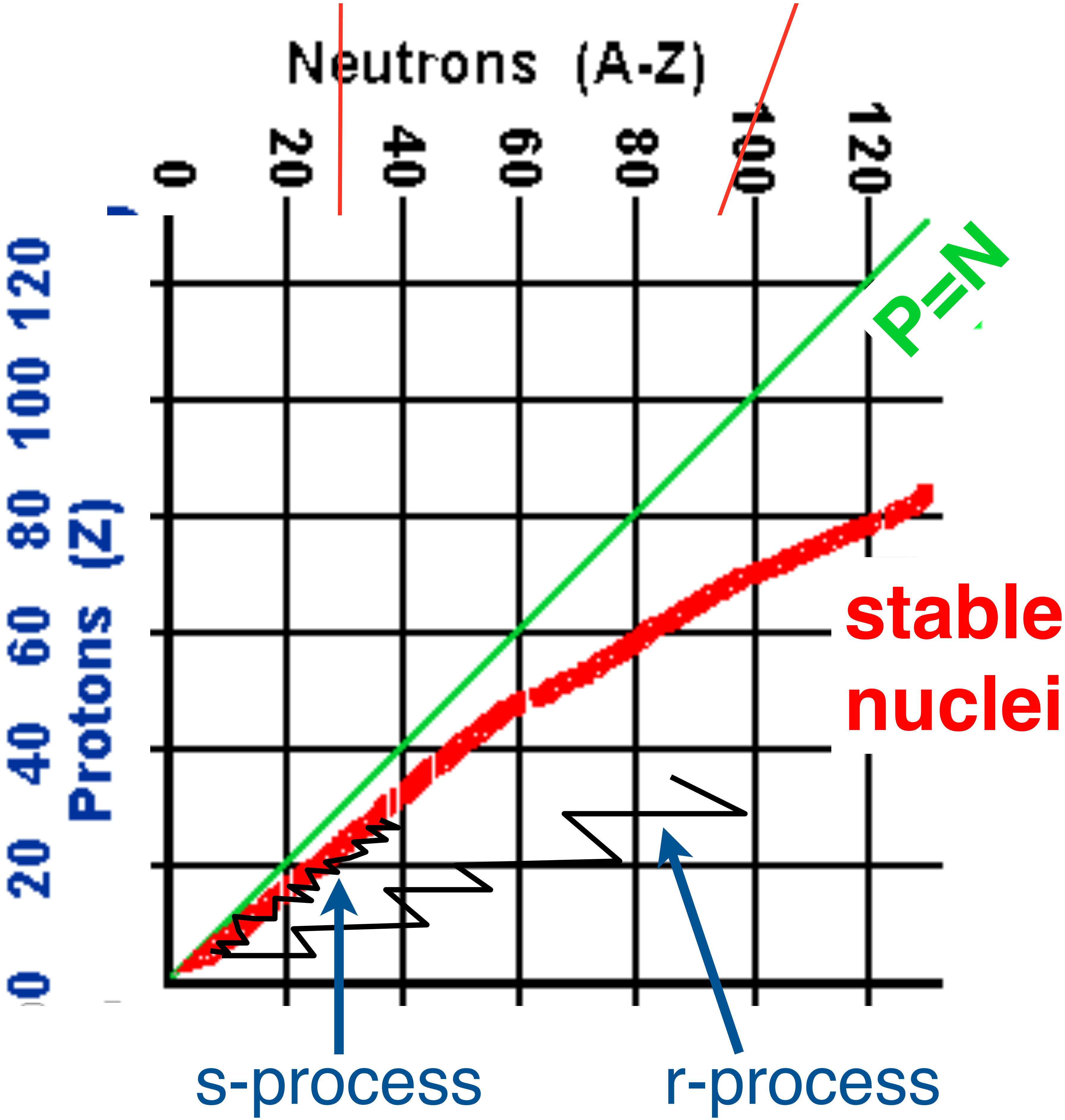


from https://matthewmumpower.com/static/prism_nsm_rprocess.mp4



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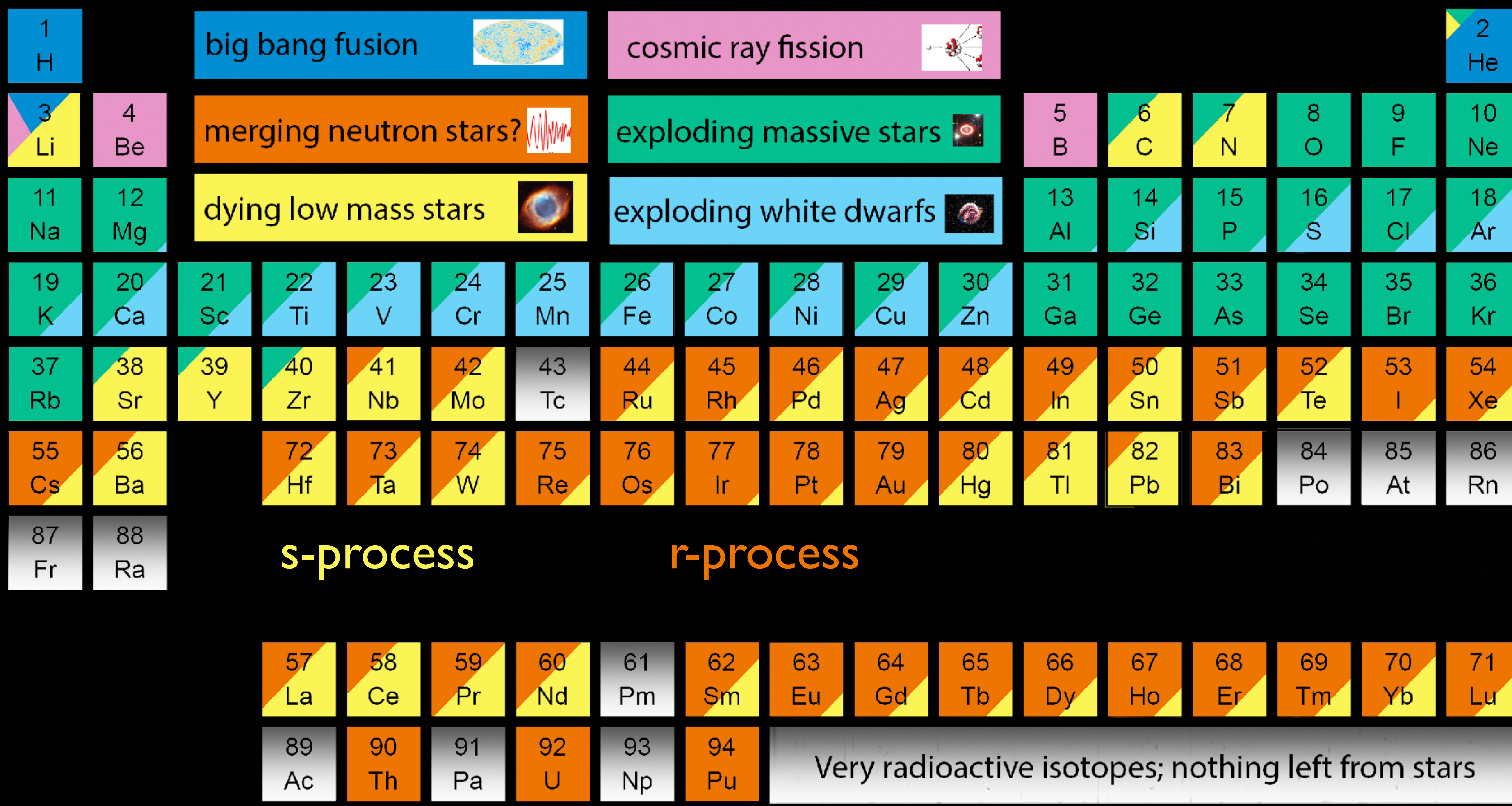

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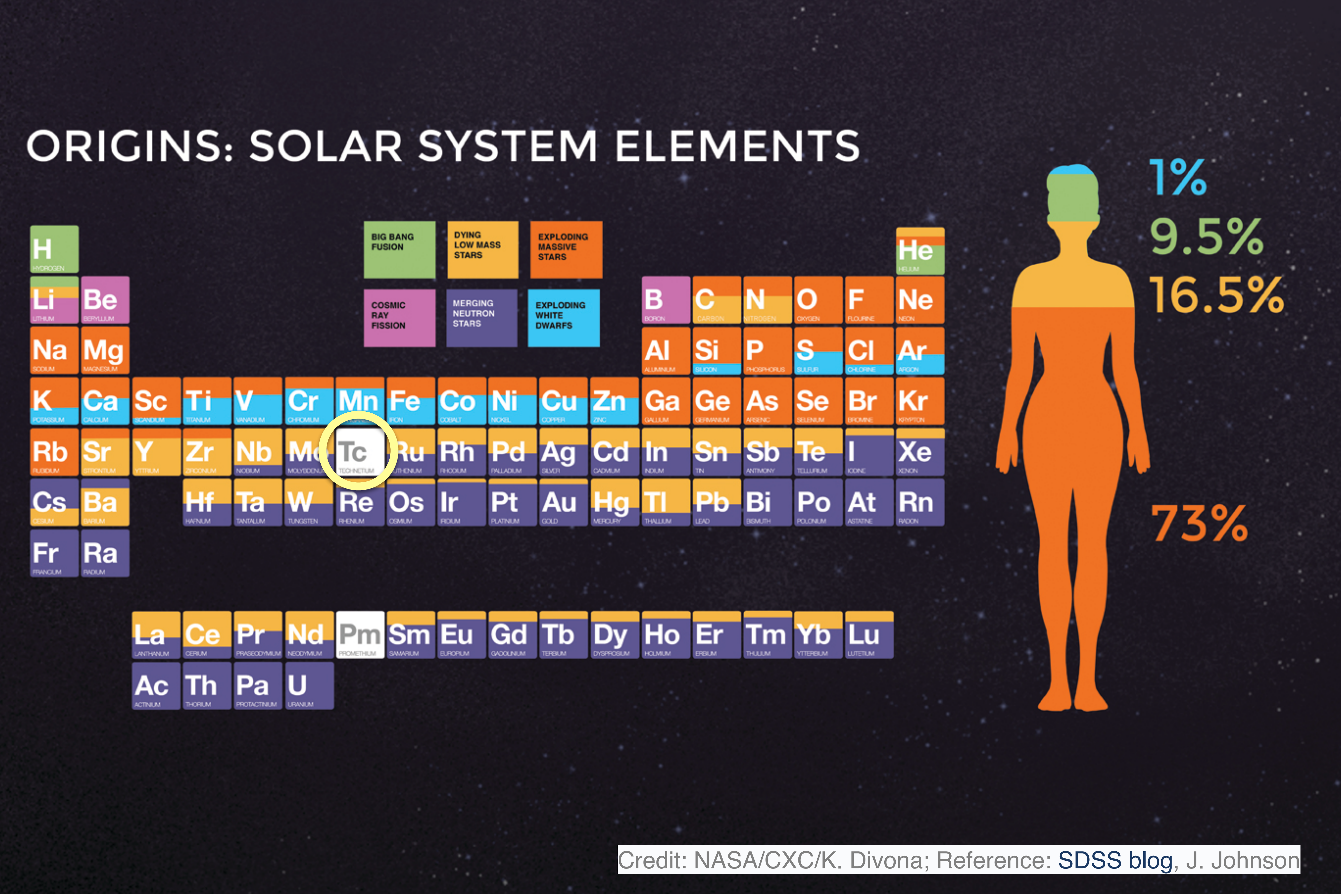

from https://chandra.harvard.edu/photo/2017/casa_life/
adapted from http://blog.sdss.org/2017/01/09/origin-of-the-elements-in-the-solar-system/

Chemical Yields

Two final comments...

1. The evolution of stars described above is far from certain
— meridional circulation in rapidly-rotating stars increases mixing
— rapid rotation produces higher mass loss rates by stellar winds
— RSG and LBV mass loss rates are both poorly quantified
All matter because yields depend on the timing of mixing and mass loss by winds.

2. Binary evolution will significantly impact predictions of yields
— mass transfer in binaries can change stellar evolution considerably
— non-conservative mass transfer could allow stars to lose a significant fraction of their mass before they are chemically enriched by nuclear fusion