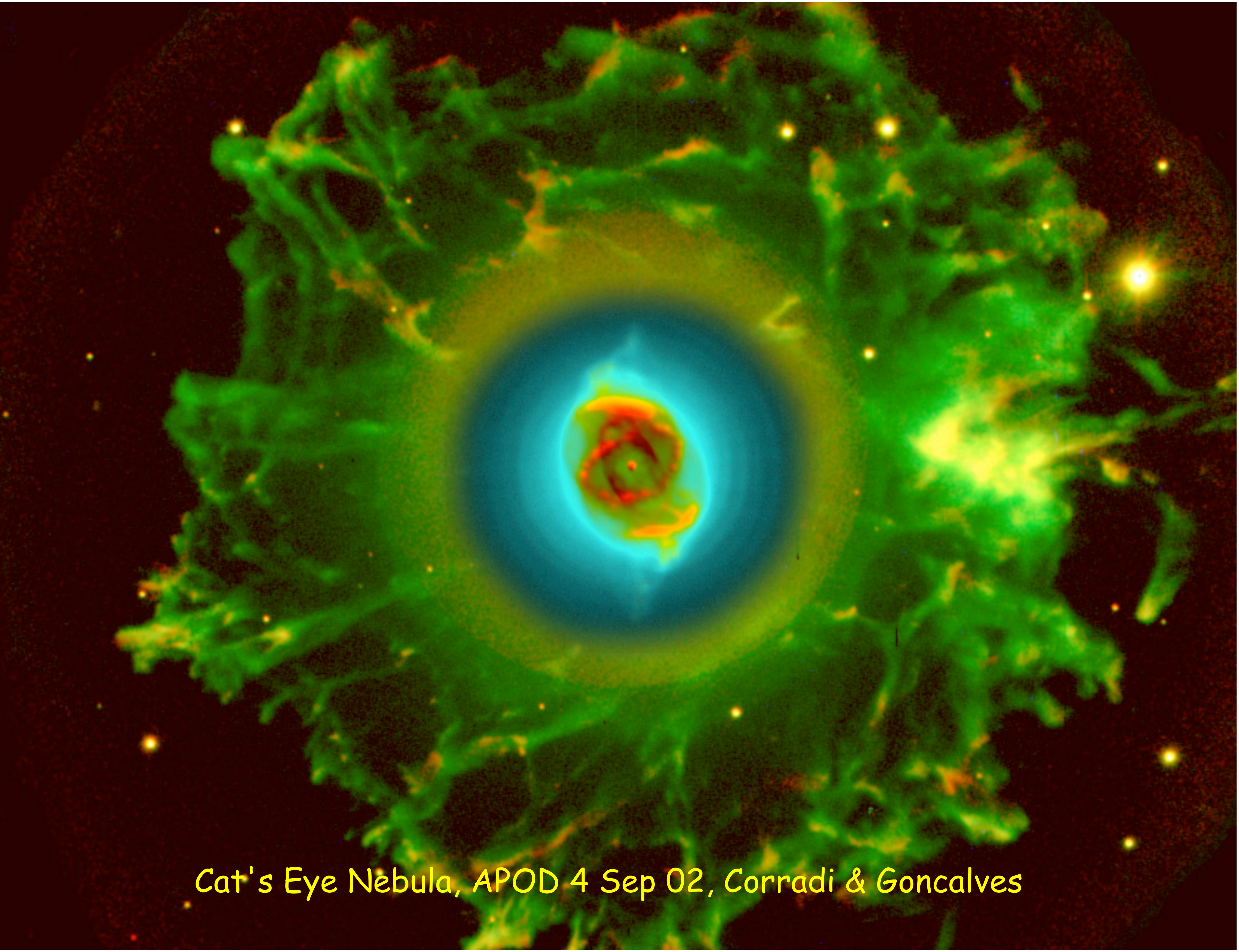
Cat's Eye Nebula, APOD 4 Sep 02, Corradi & Goncalves

Nuclear astrophysics in the early universe

Falk Herwig

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

LA-UR 05-2041

Three fundamental (nuclear?) astrophysical questions:

1. How did the first stars and their cosmological environment in the early universe form and evolve?
2. How do galaxies like our Milky Way form and evolve?
3. What is the origin of the elements, in particular the trans-iron elements made in the r-process?

Improve stellar nucleosynthesis models:

1. Nuclear Astrophysics with Neutron Facilities: s-process as a diagnostic tool for fundamental processes in stars
2. Nuclear reaction rate input physics
3. Mixing in the stellar interior:
    1. Rotation, magnetic fields, convection - in 1D
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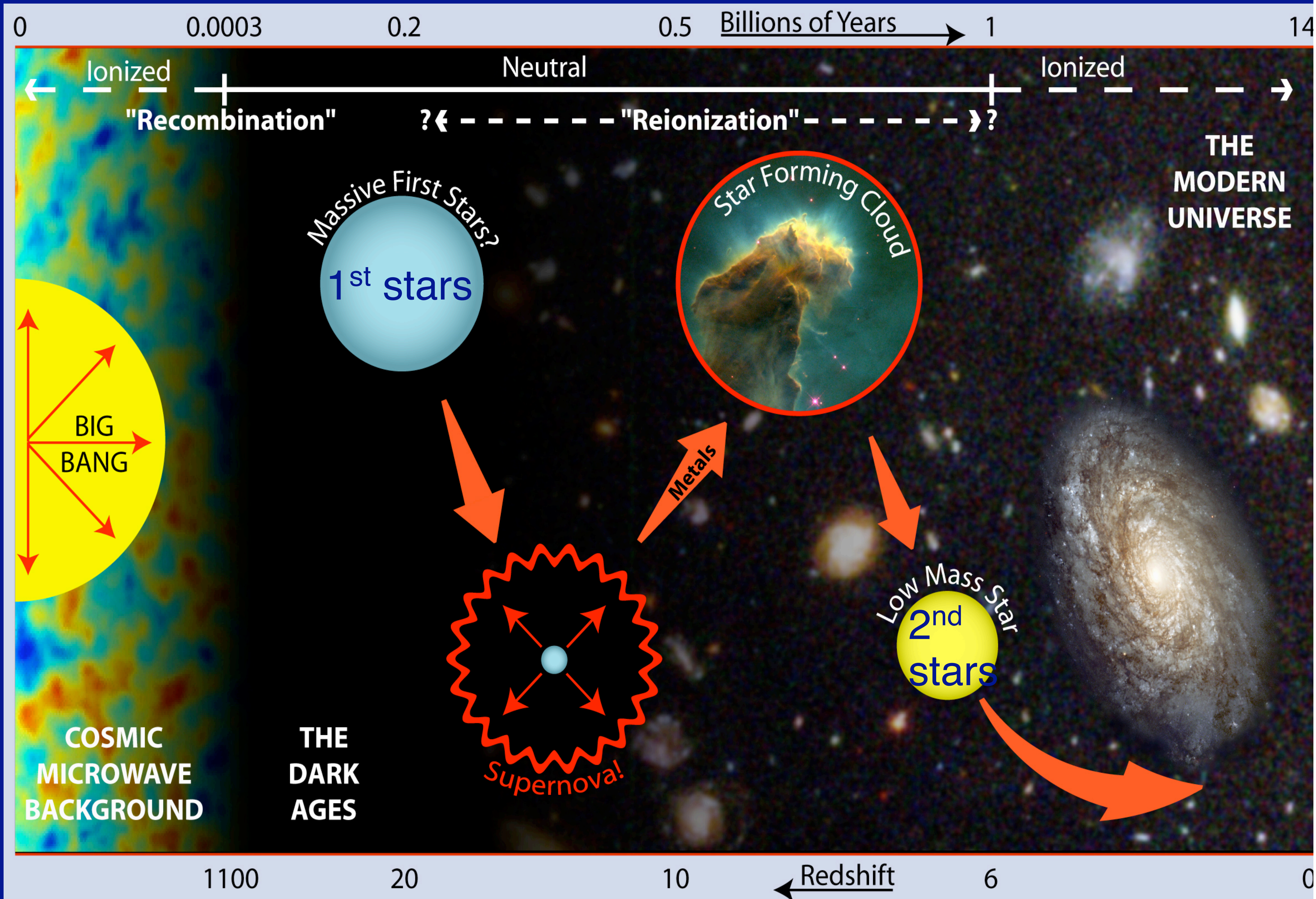
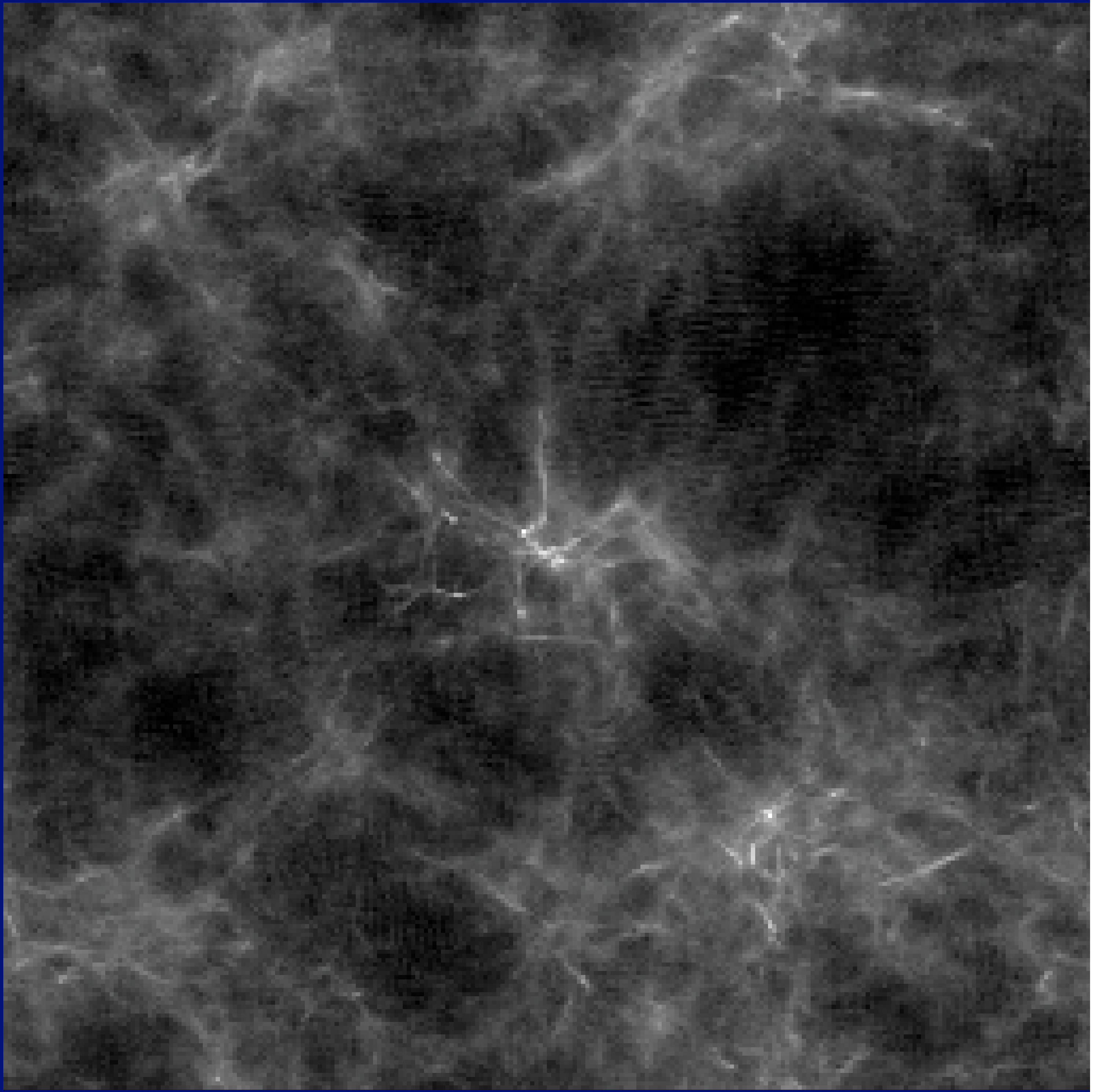

0
0.0003
0.2
0.5
Billions of Years
1
14
Ionized
Neutral
Ionized
"Recombination"
?
"Reionization"
?
THE
MODERN
UNIVERSE
Massive First Stars?
1st stars
Star Forming Cloud
BIG
BANG
Metals
Low Mass Star
2nd stars
Supernova!
COSMIC
MICROWAVE
BACKGROUND
THE
DARK
AGES
1100
20
10
Redshift
6
0

Dark matter Evolution: the formation of the nurseries of the first stars

B W O'Shea, UCSD, 2003, 300kpc 3D box projection



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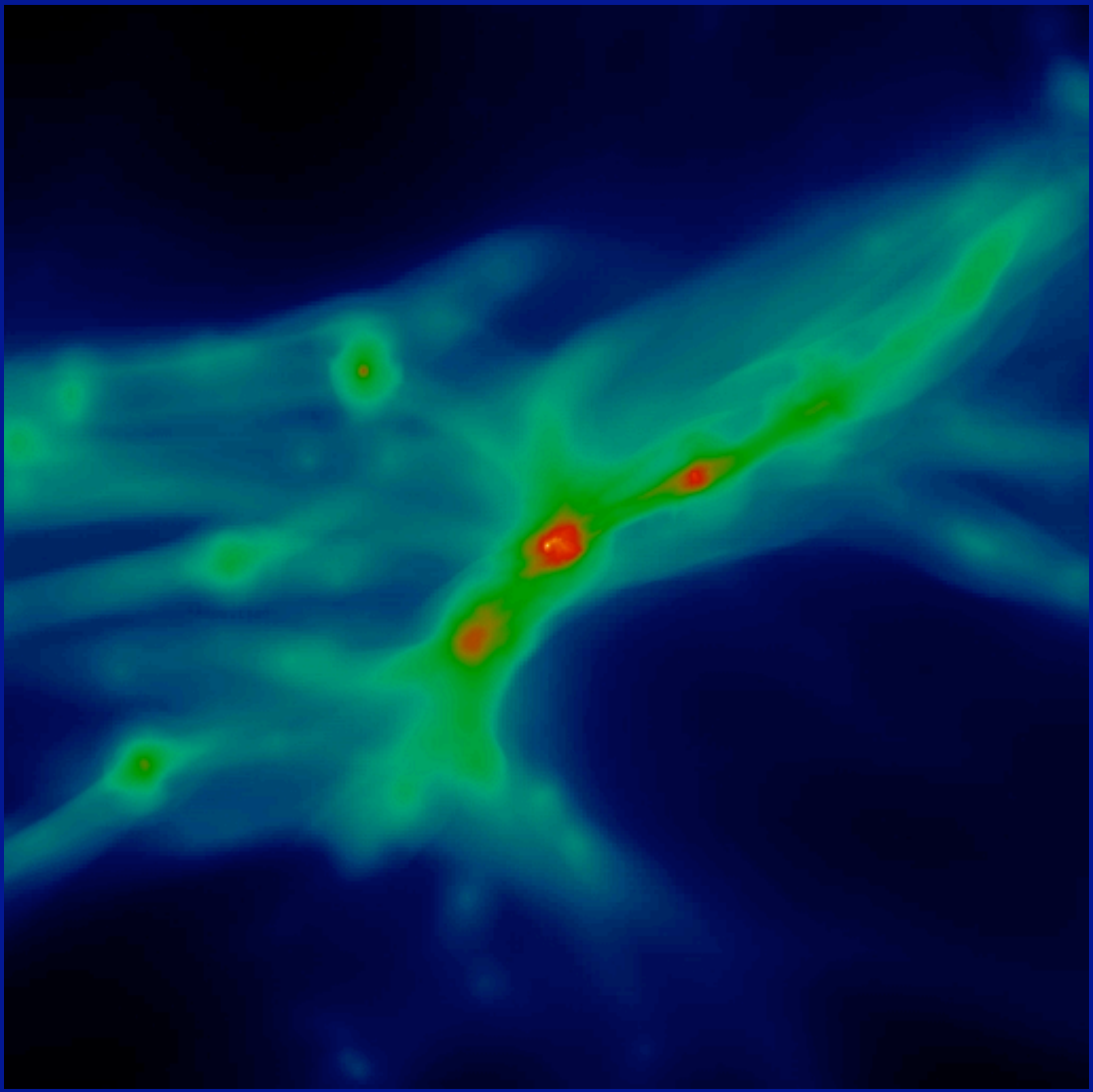
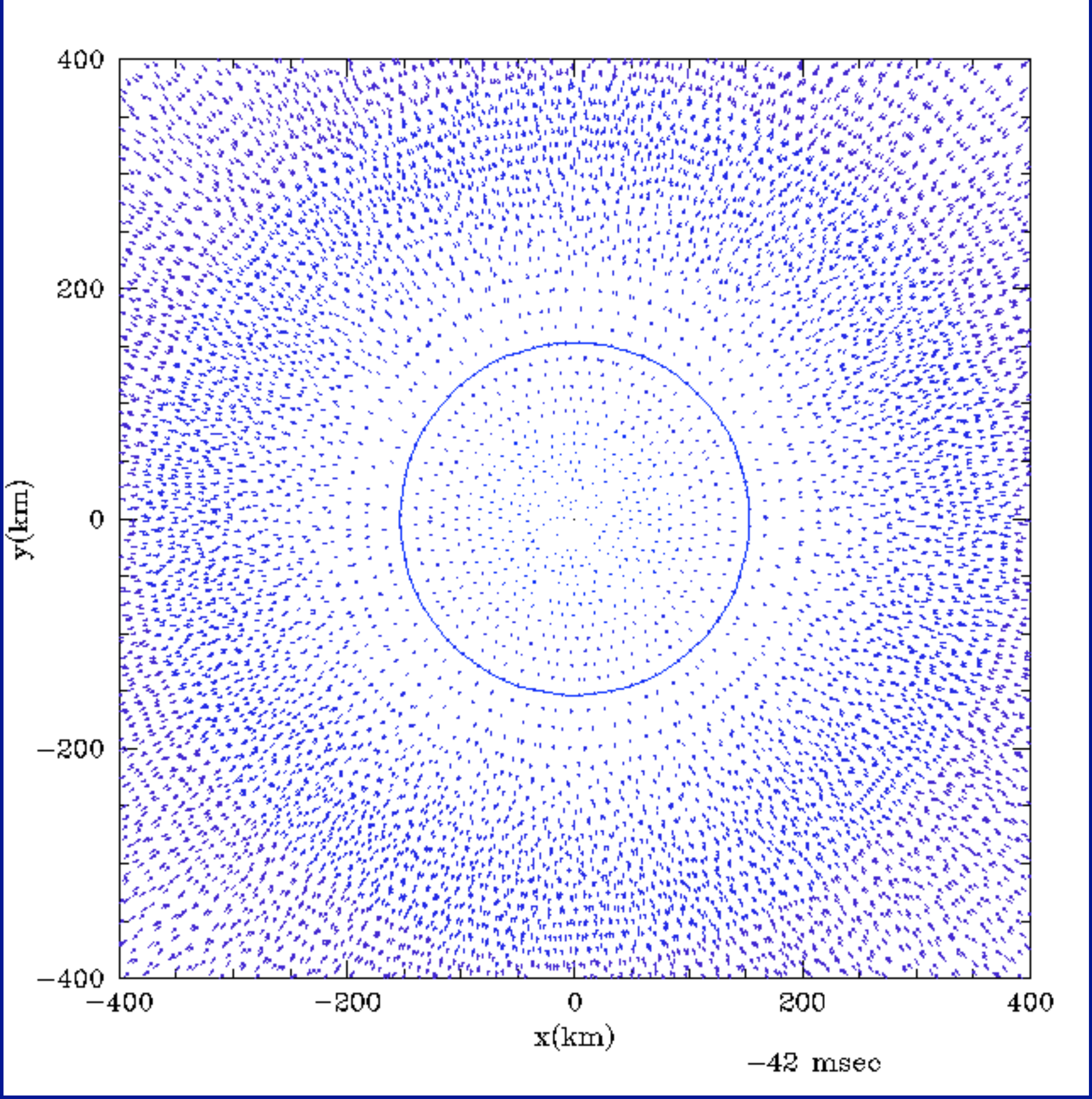


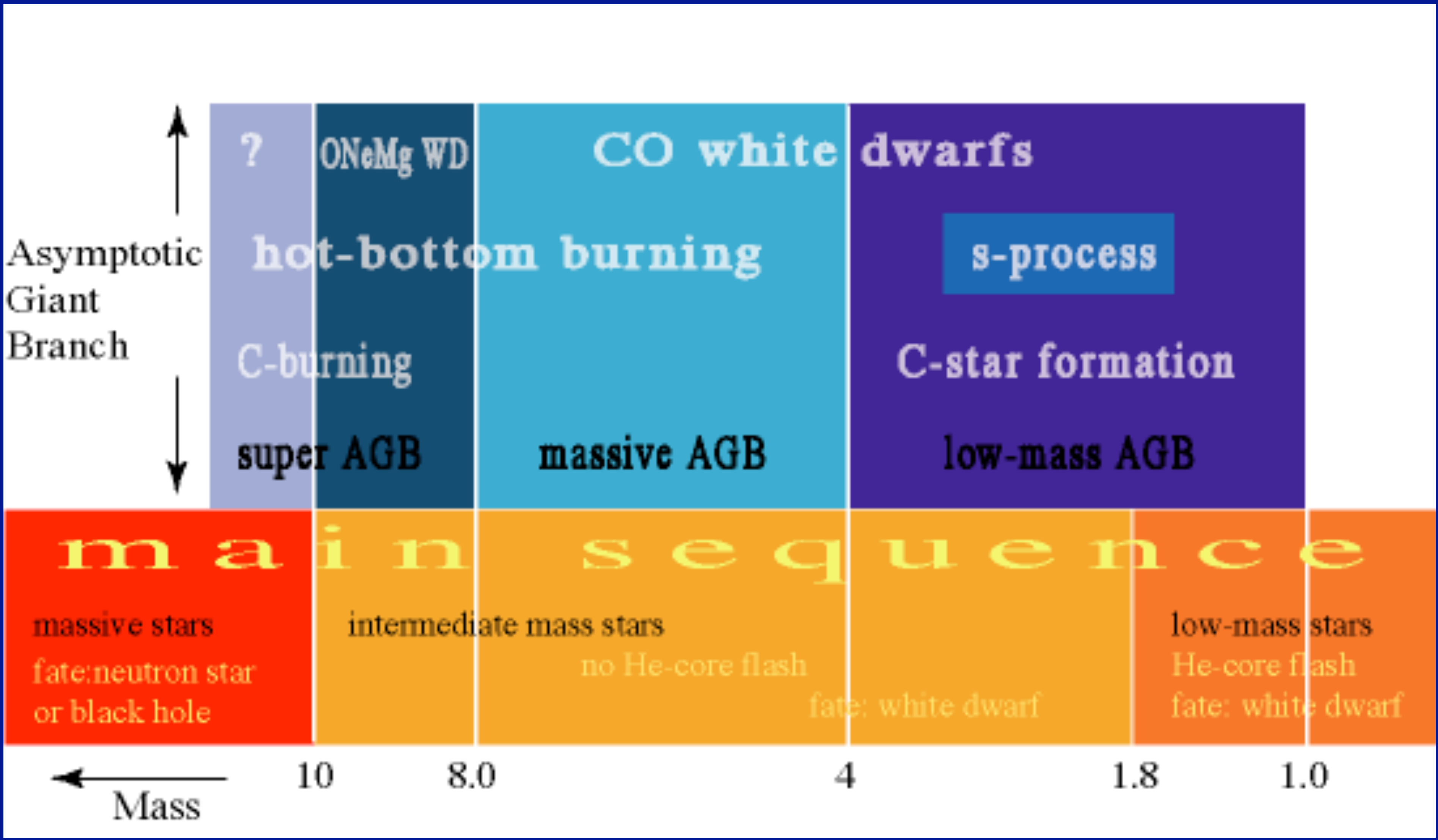
Distribution of baryonic matter clustering around the dark matter halo in a hydrodynamics and N-body simulation at redshift z~17 (O'Shea etal. 2005).

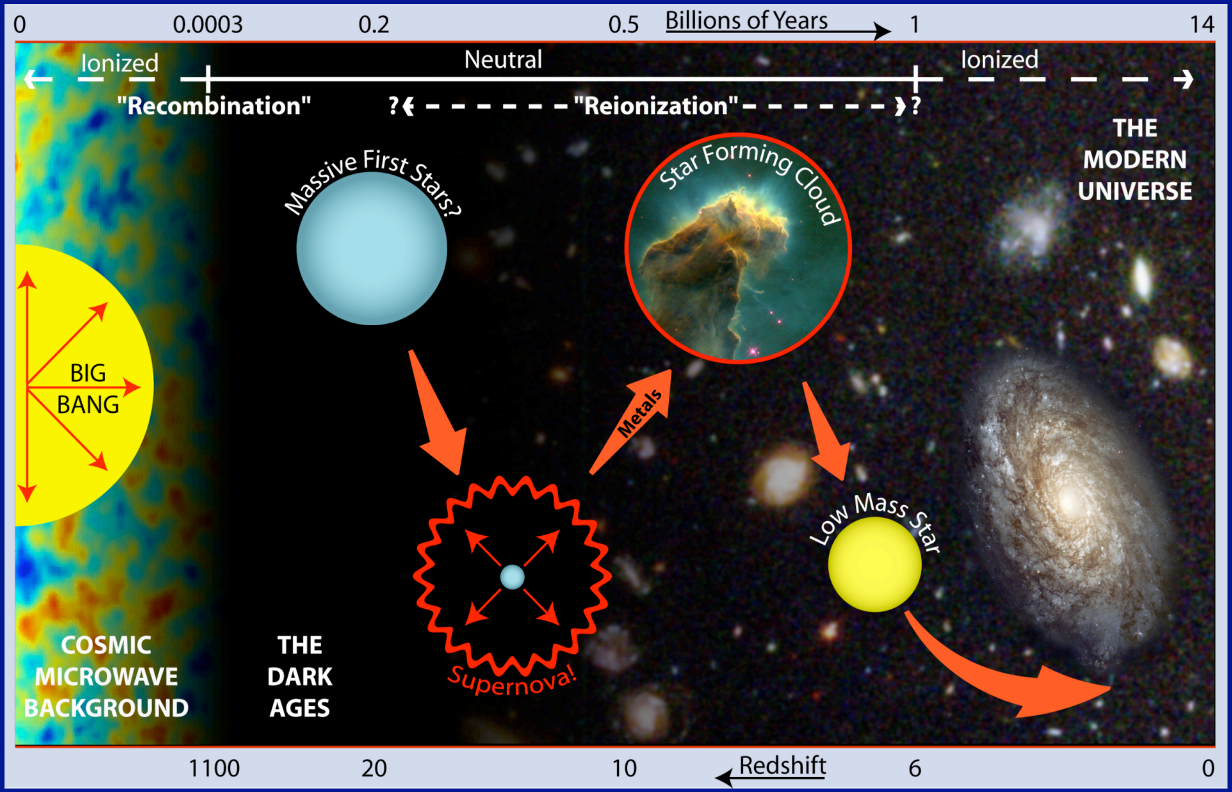
Supernova Explosions



3D SPH core collapse simlulation, Chris Fryer, LANL, 2002.

Add a primordial intermediate mass star





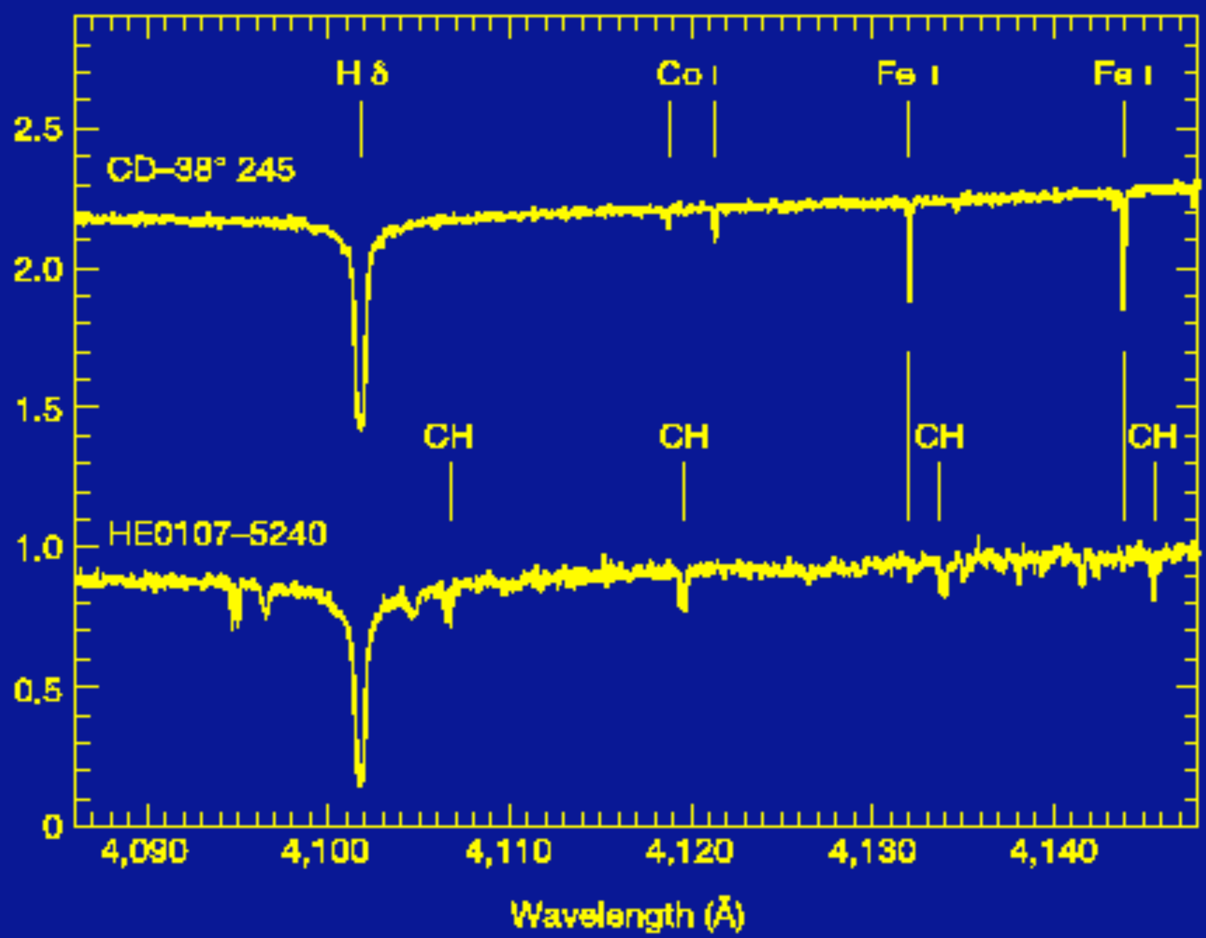
(mix of?) 1^{st} stars

\+

self or external pollution

= observations of 2^{nd} stars

The second star HE 0107-5240



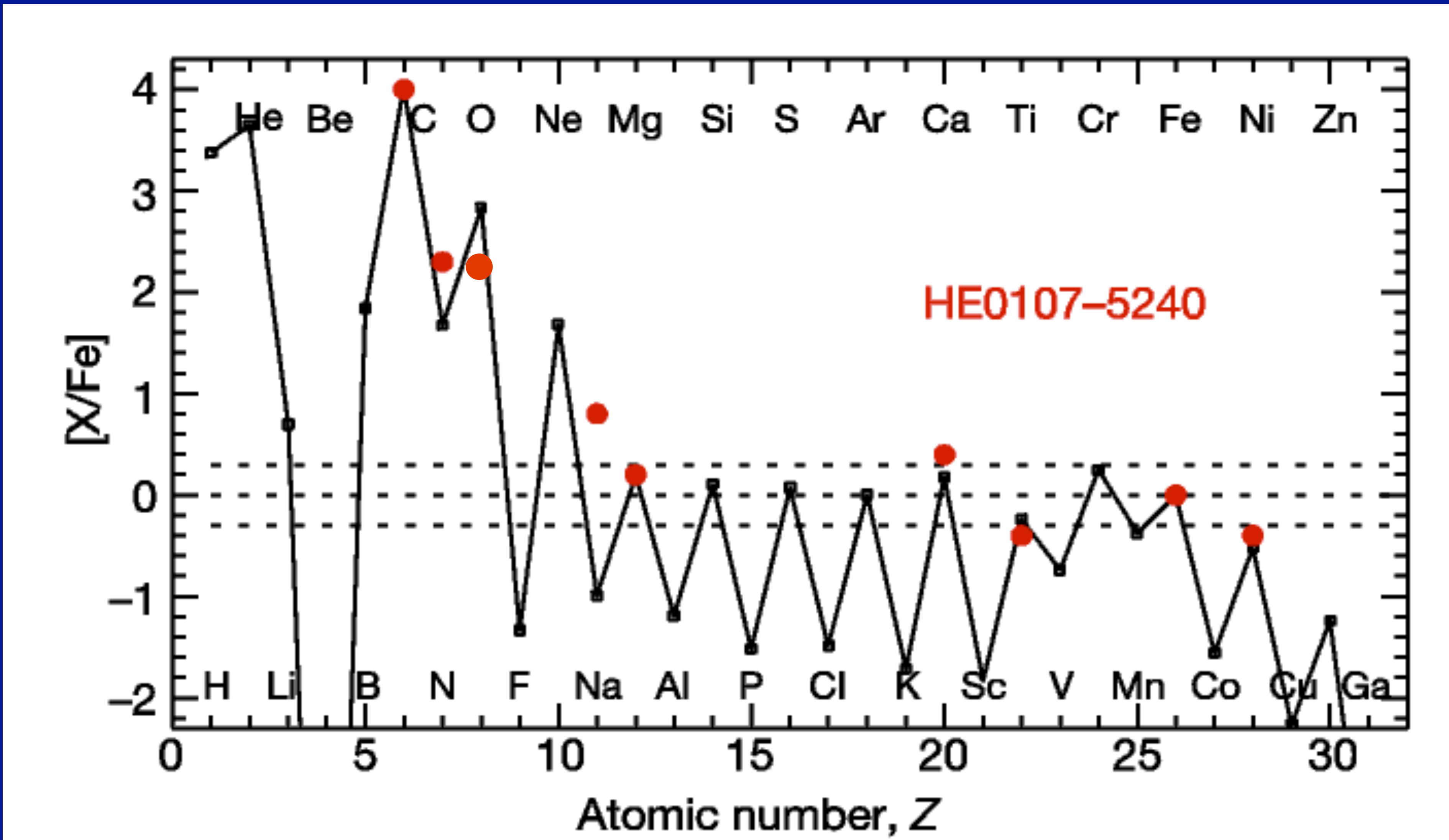
Christlieb etal 2002

Low mass star -> long lifetime, [Fe/H] = -5.3

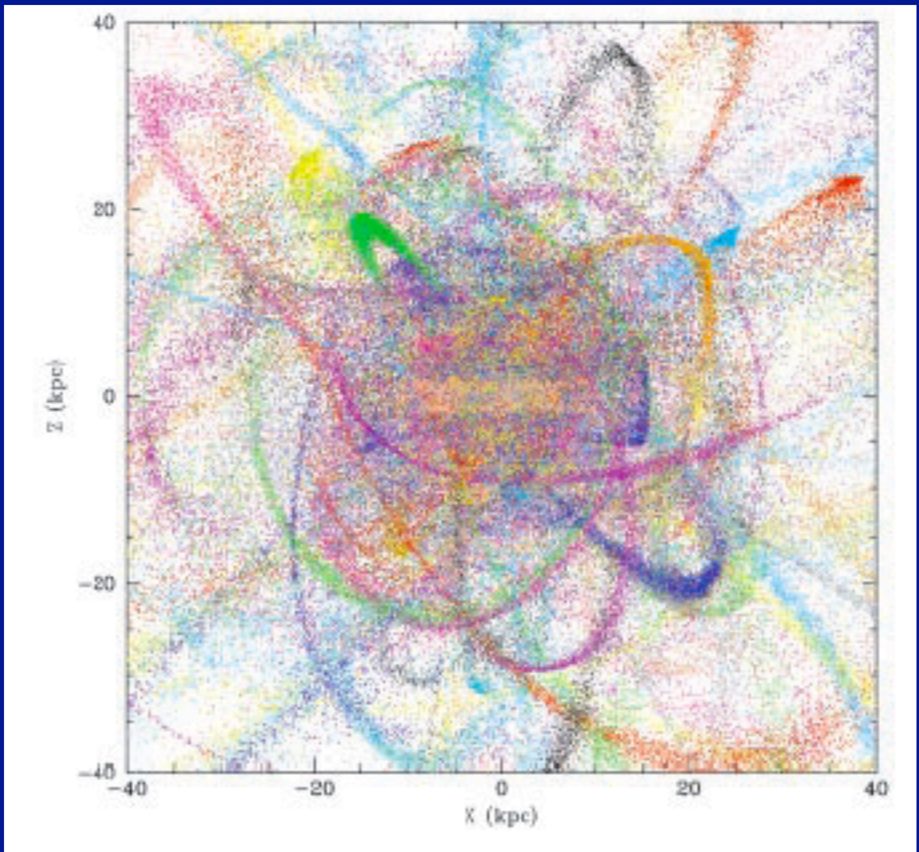
Three possible sites of origin for the observed abundance pattern:

1. one or multiple first SN *and /or intermediate mass stars*
2. self-pollution
3. external pollution by binary AGB companion

Umeda & Nomoto 2003: $25M_{sun}$ "mixing and fallback" SN



2. How do galaxies like our Milky Way form and evolve?



Framework: merging history within a ΛCDM universe.

Fig: A simulation of the baryon halo built up through accretion of 100 satellite galaxies.

(Bland-Hawthorn & Freeman, Science 287, 2000)

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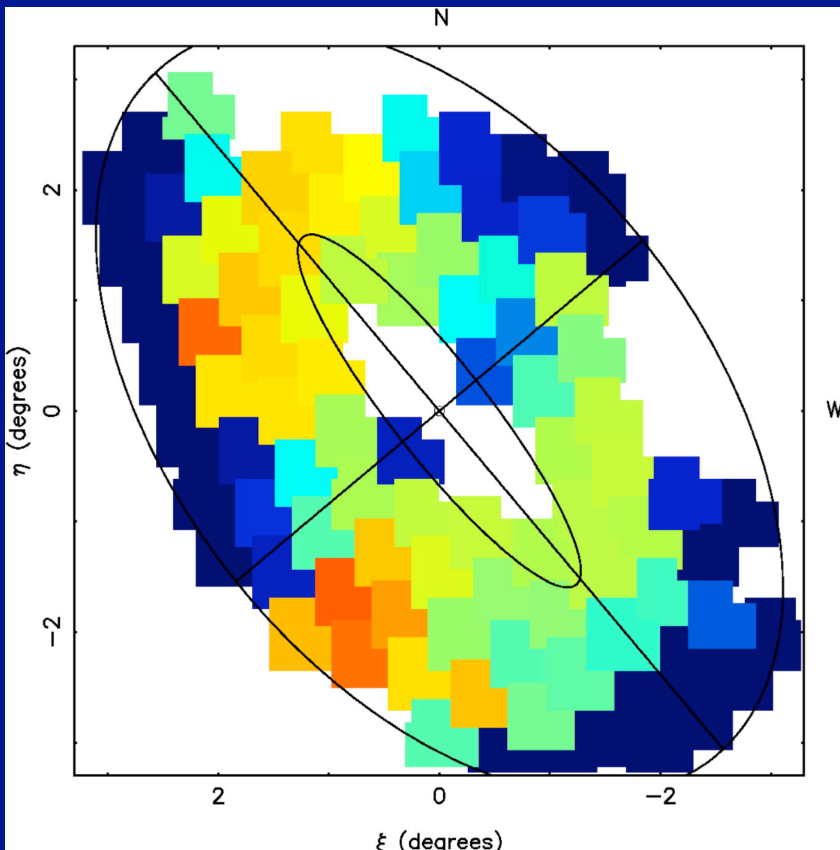


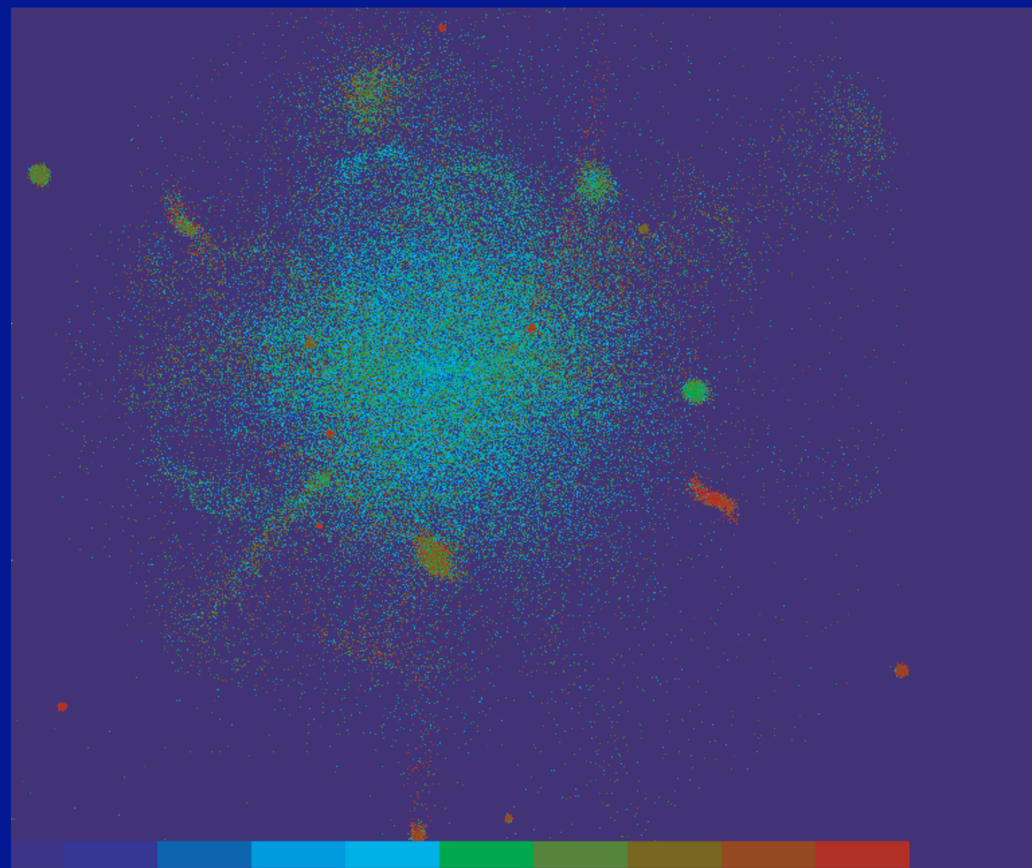
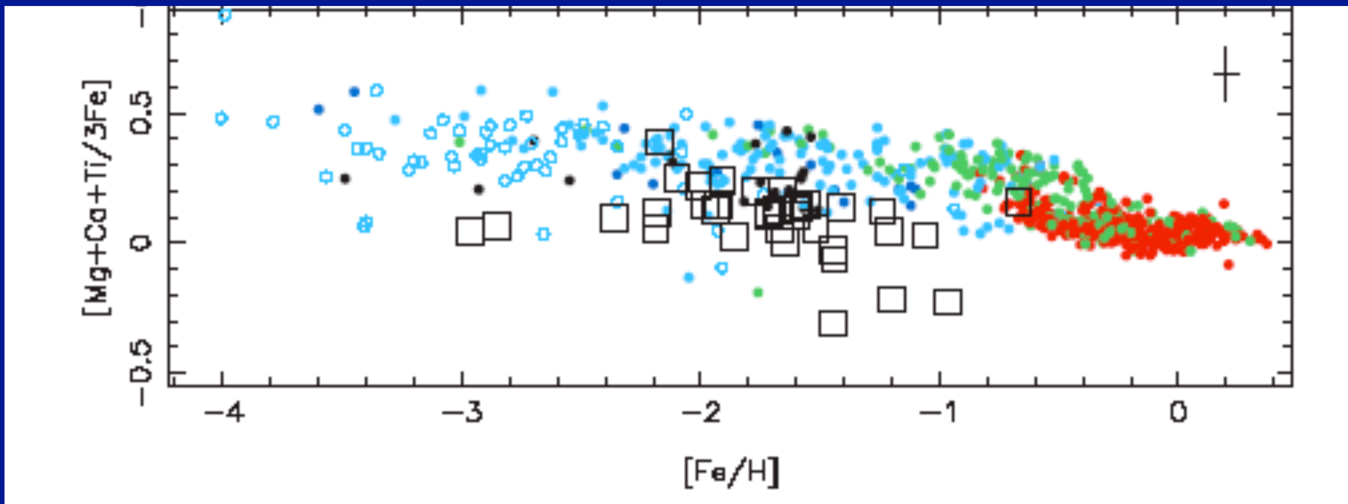


Figure 1 Observed metallicity distribution In M 31, based on photometry, color codes metallicity **(Ferguson etal 2002).**

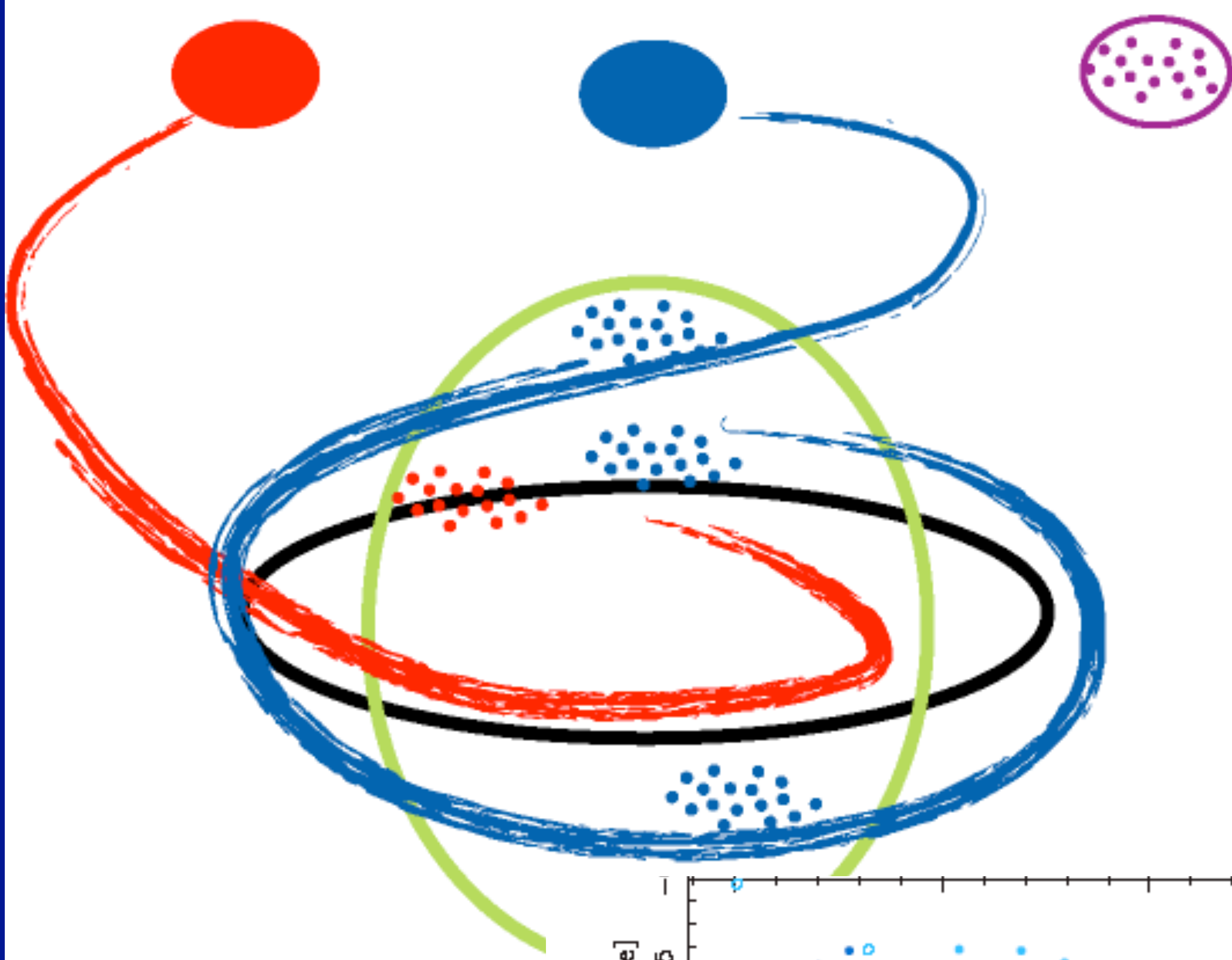
Figure 2 Galactic chemical evolution model, color codes metallicity **(Font etal 2004).**

Stellar abundances to reconstruct the merger history of galaxies



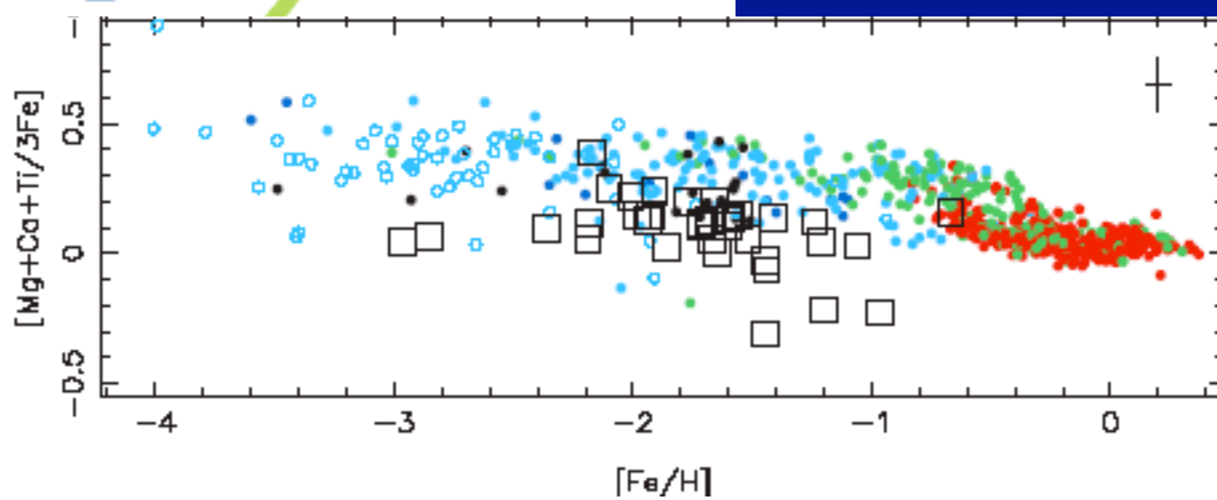
Abundances of stars in the galaxy halo and in satellite dwarf galaxies

Venn etal 2004



Abundances of stars in the galaxy halo and in satellite dwarf galaxies

Venn etal 2004
Robertson etal 2005
astroph/0501398



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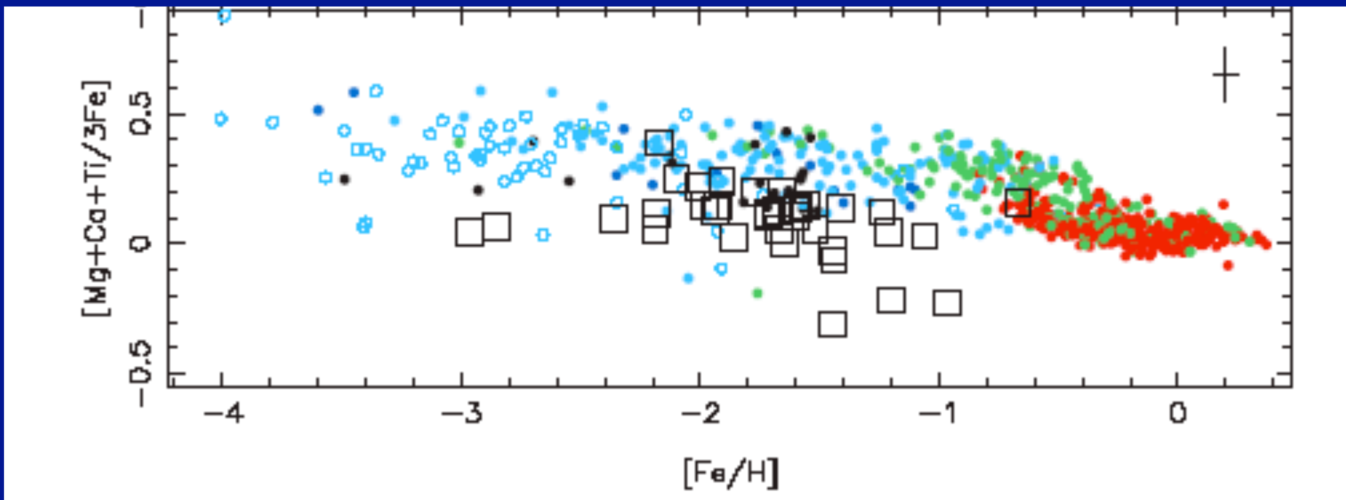

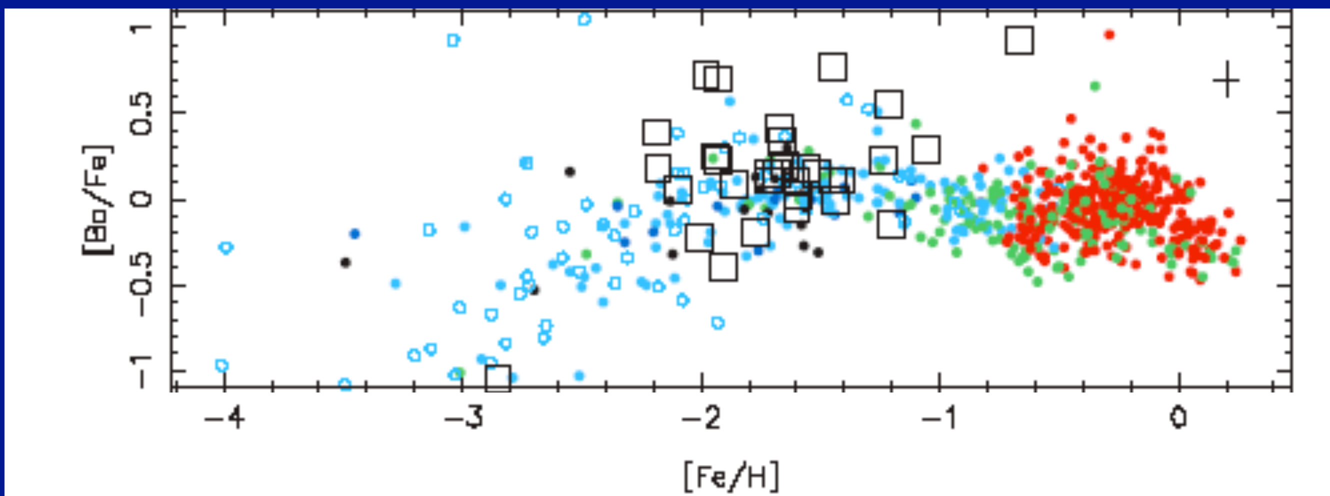

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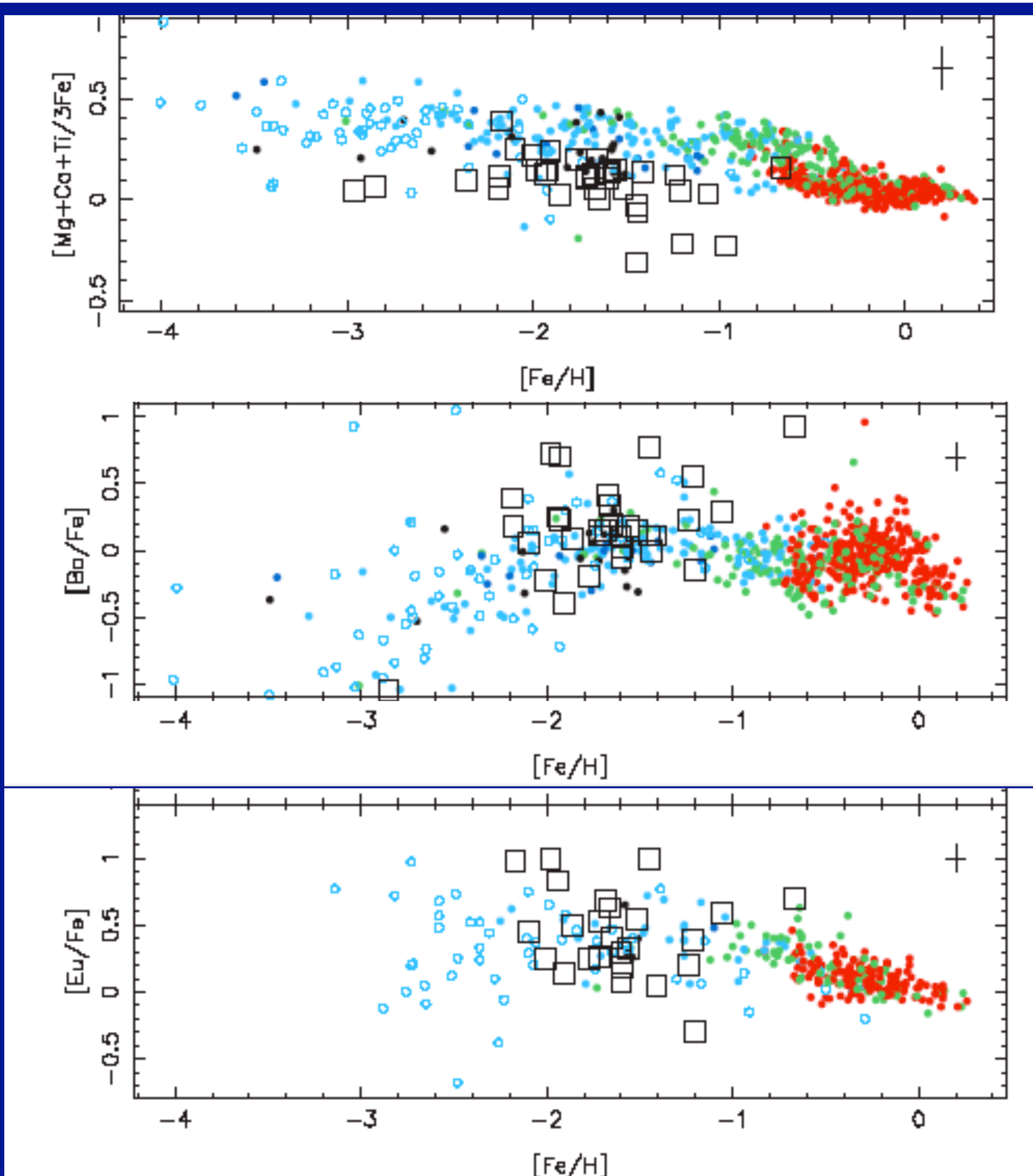


3. What is the origin of the elements, in particular the trans-iron elements made in the r-process?

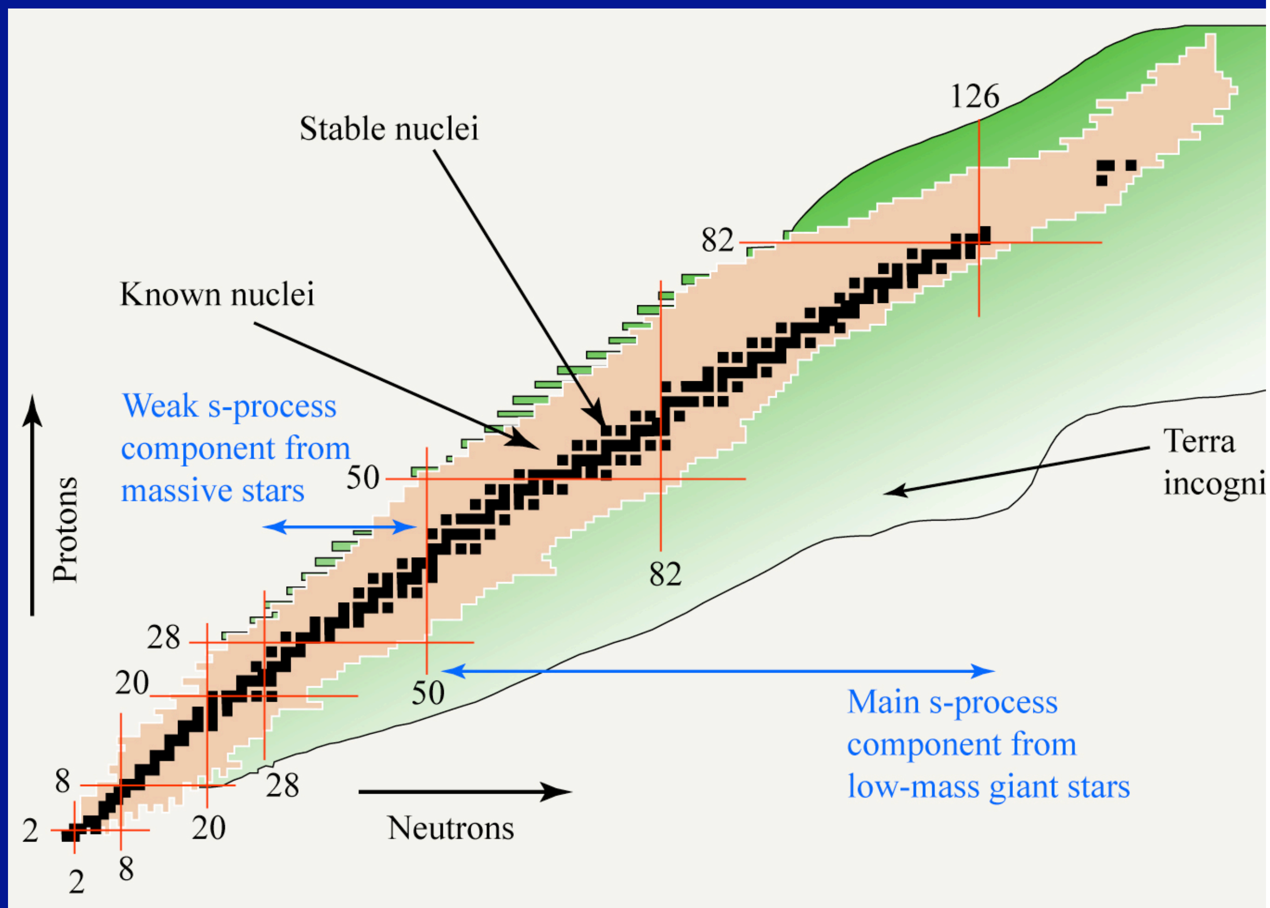
What is the s-process?

The elements are made by a number of distinct nuclear processes with distinct signatures:

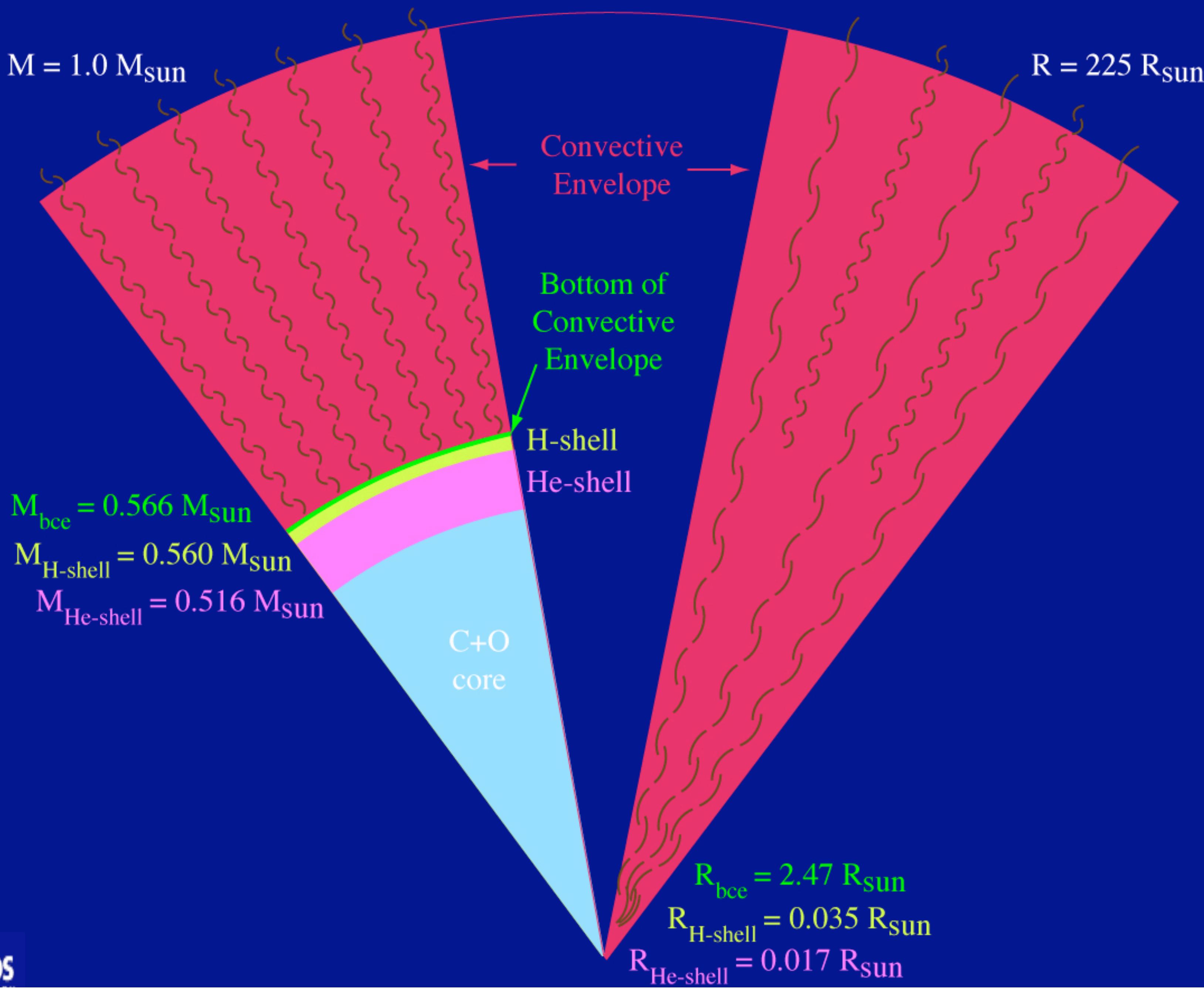
- some involve the capture of a charged particle like protons or α-particles
- some are induced by neutron-capture

In the s-process the n-captures are slower than subsequent β-decays.

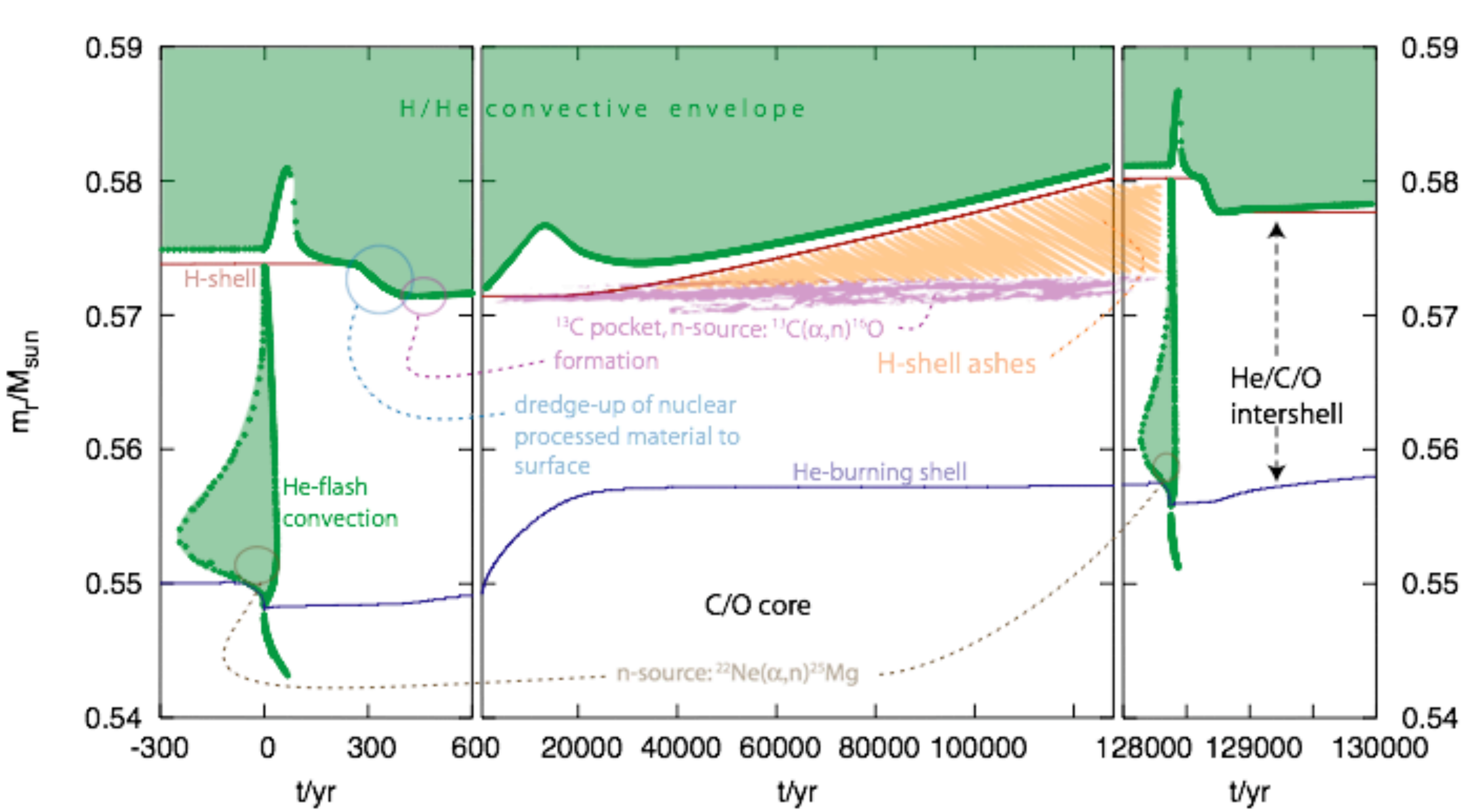
Typical neutron densities are $7 < \log N_n < 10$.



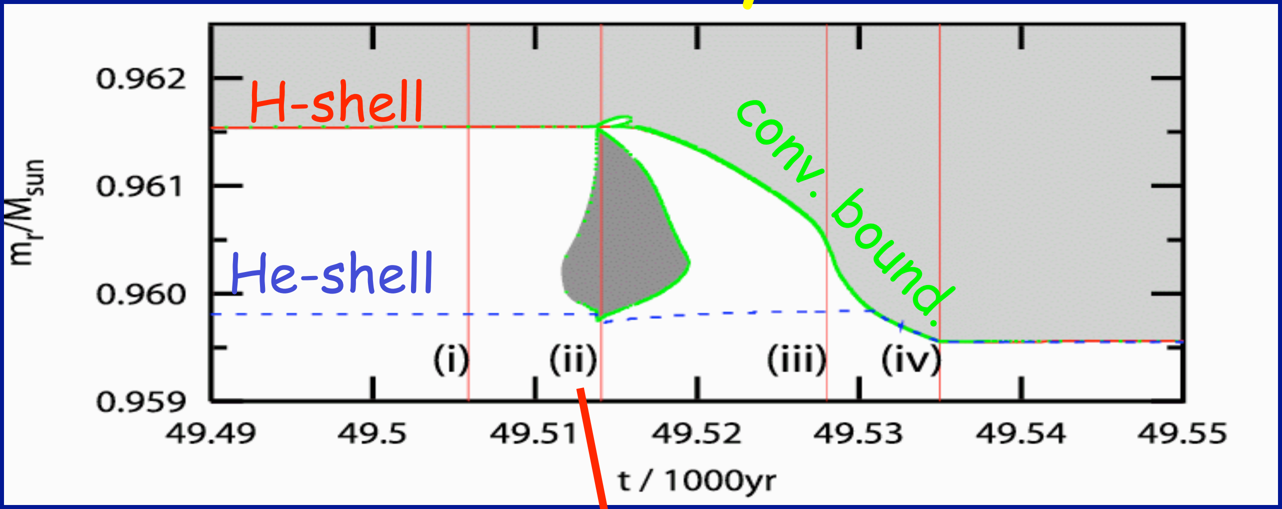
Global Structure of an AGB star



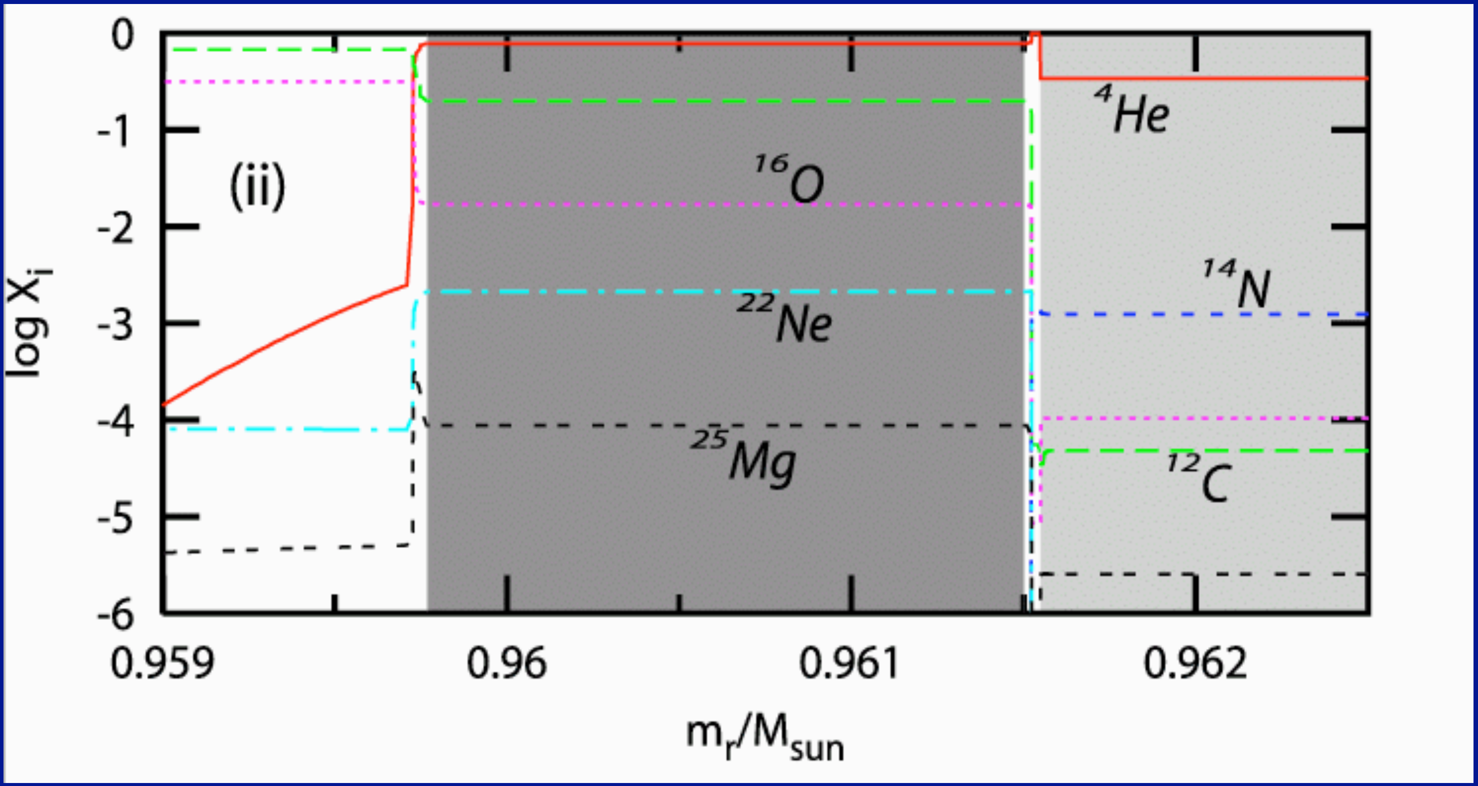
Internal evolution of AGB stars



Nucleosynthesis and Mixing

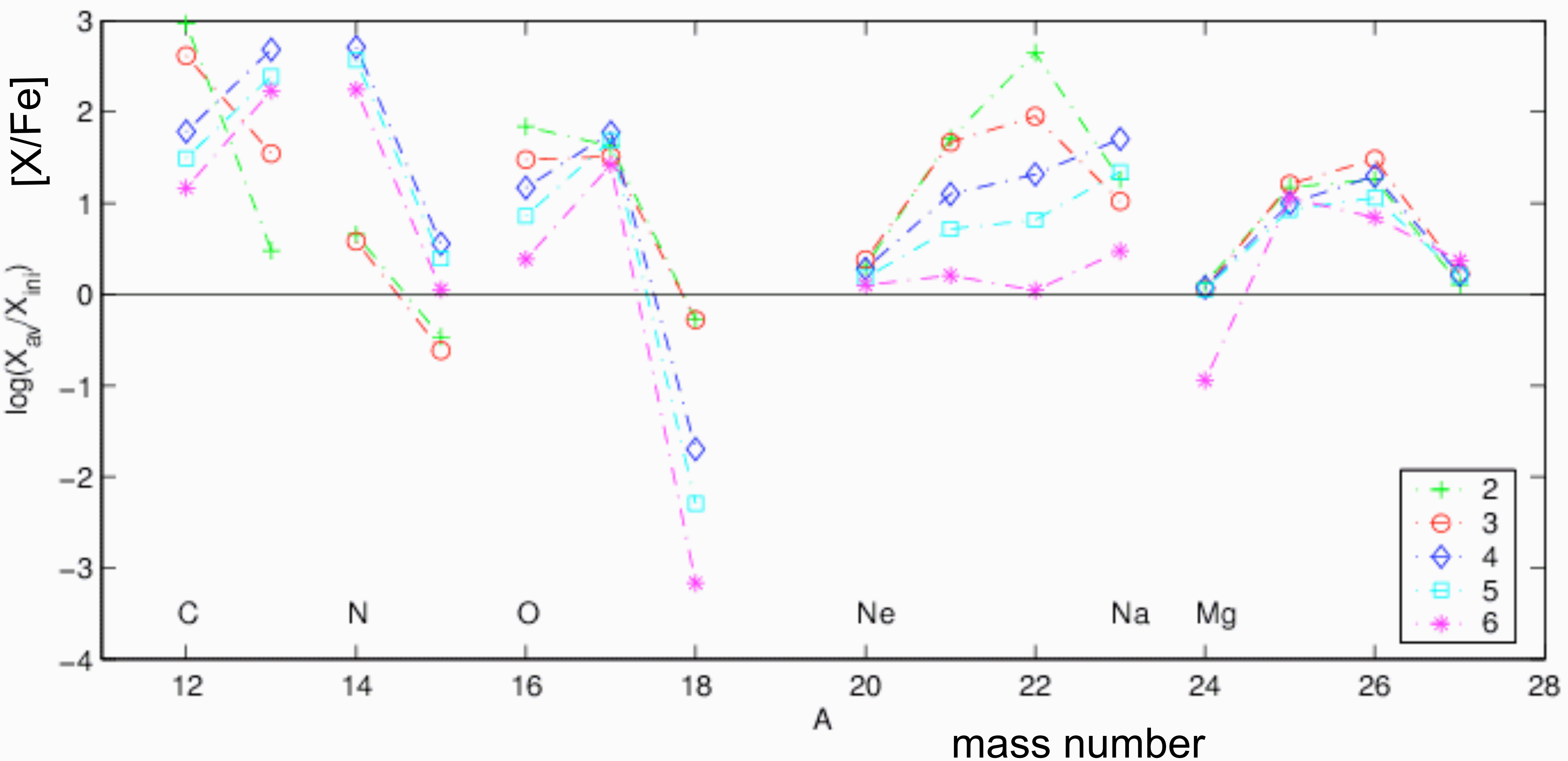


Herwig 2004, ApJ 605



Neutron source reaction $^{22}Ne(\alpha,n)^{25}Mg$

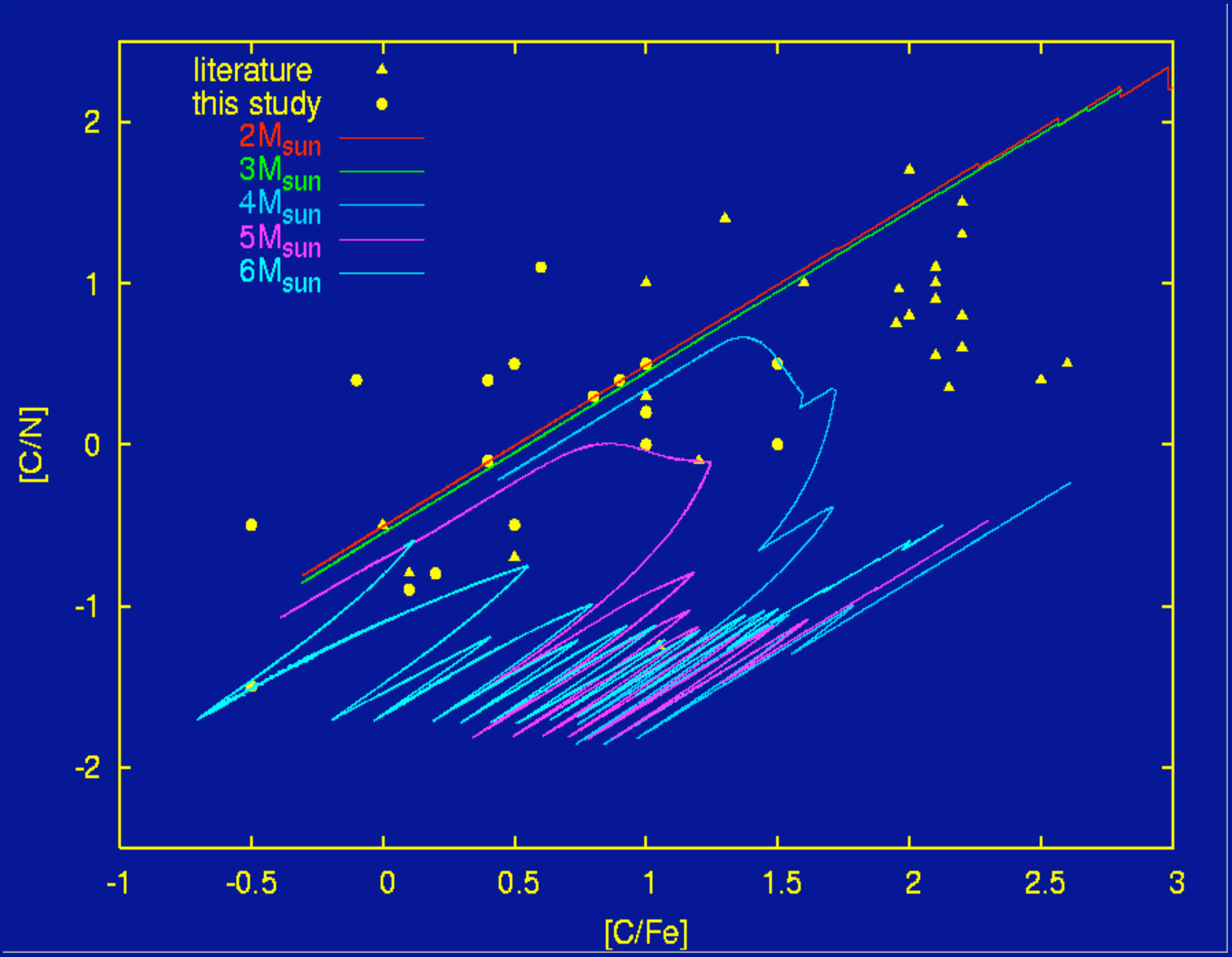
New stellar evolution yields: Overproduction of EMP AGB stars



$Z = 10^{-4}$, Herwig 2004, ApJS 155

Origin of Nitrogen in the early universe

(with Johnson, Beers & Christlieb)



1. Where does the N in the C-rich stars come from?

2. Where are the EMP stars poluted by the N rich IMS?

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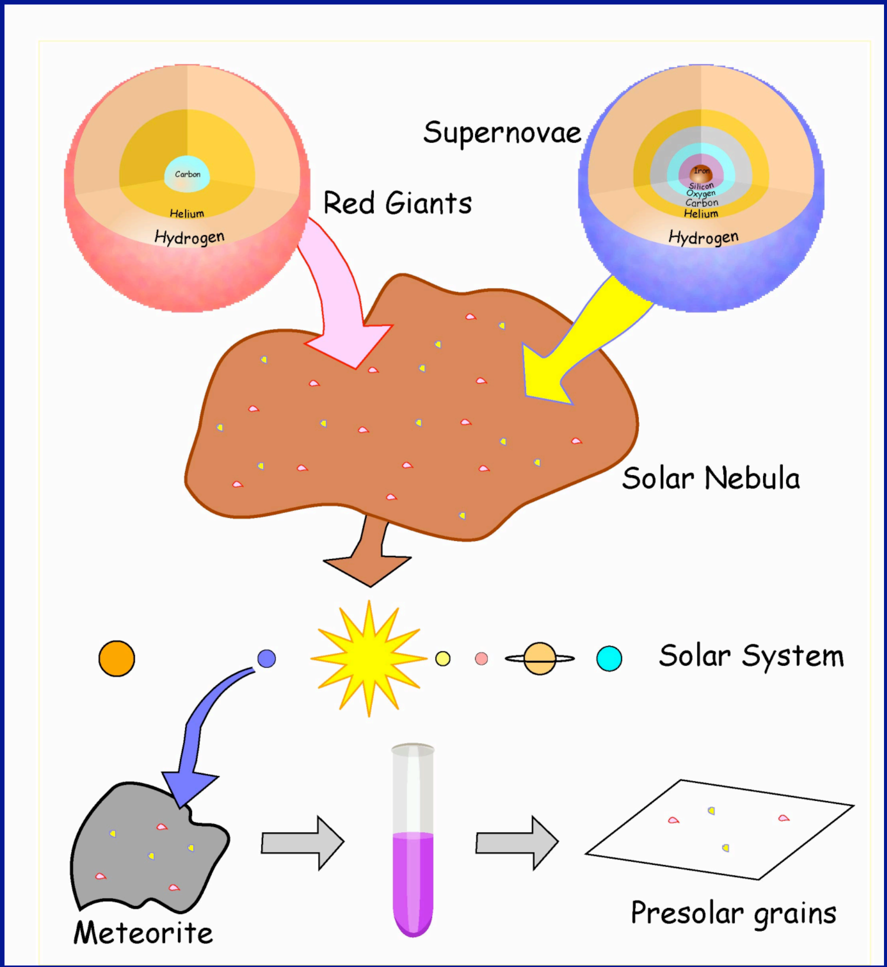
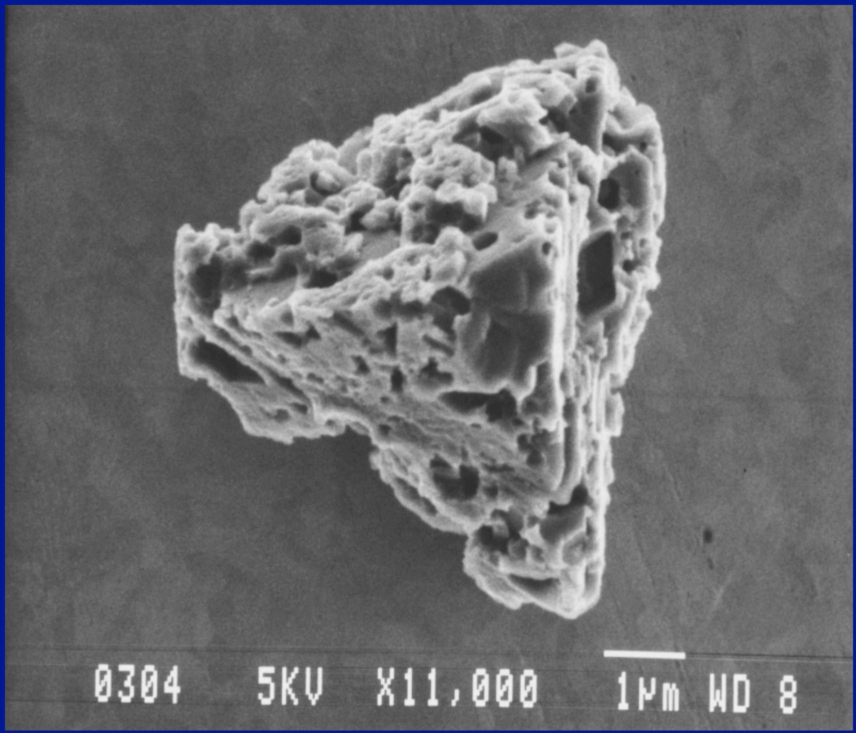
s-process as a diagnostic tool: The Observable

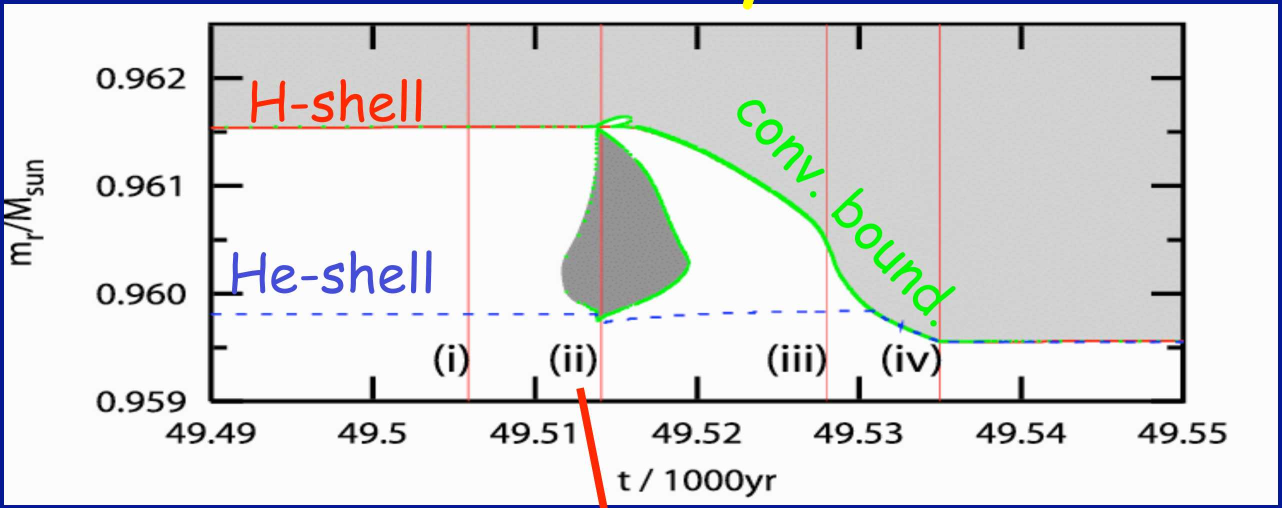
Dust forms in the cool mass-loss outflows of s-process generating stars (low-mass giants)



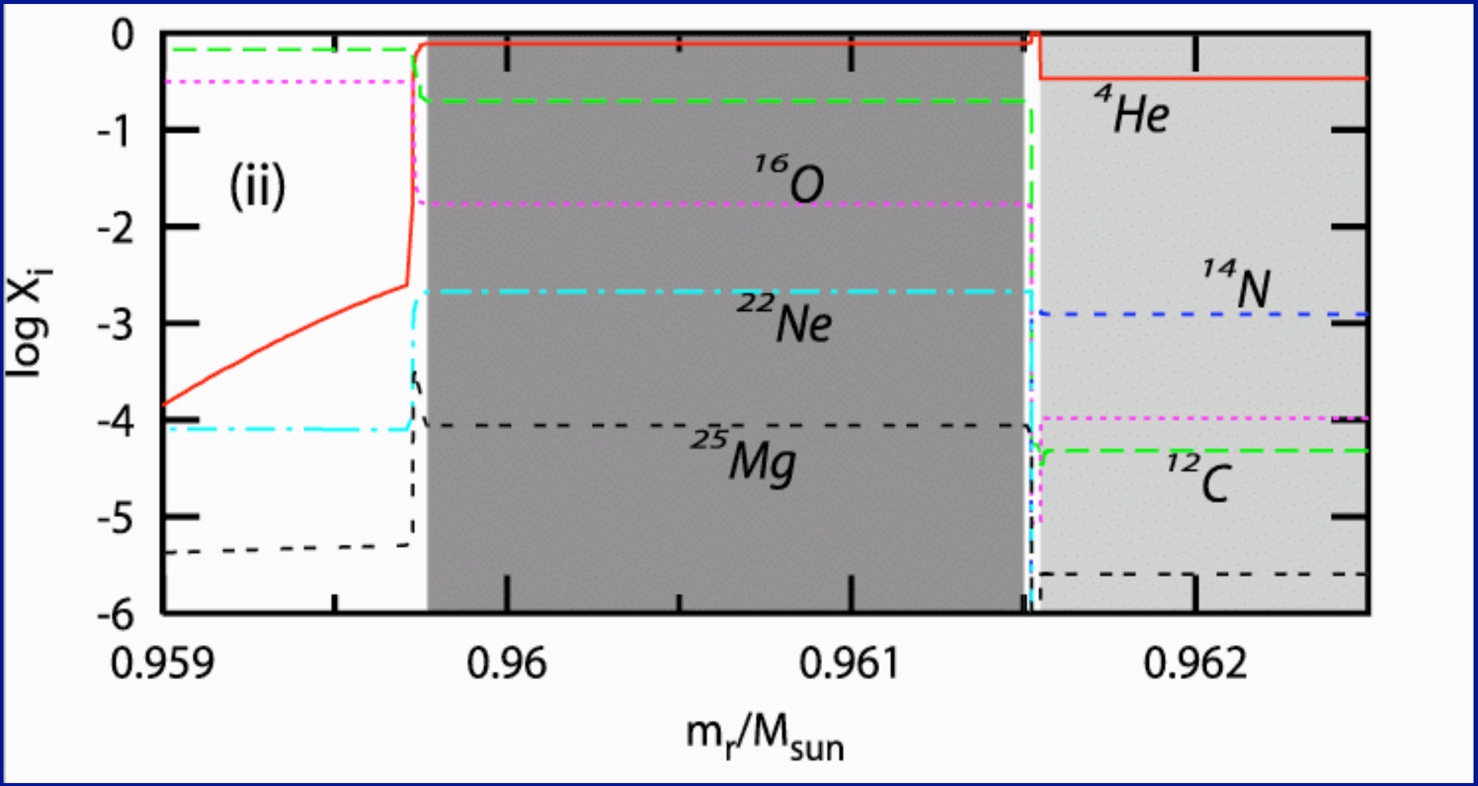
Individual dust grains extracted from primitive meteorites can be associated with their individual site of origin around one star ... tracing that star's individual isotopic signatur



Nucleosynthesis and Mixing



Herwig 2004, ApJ 605



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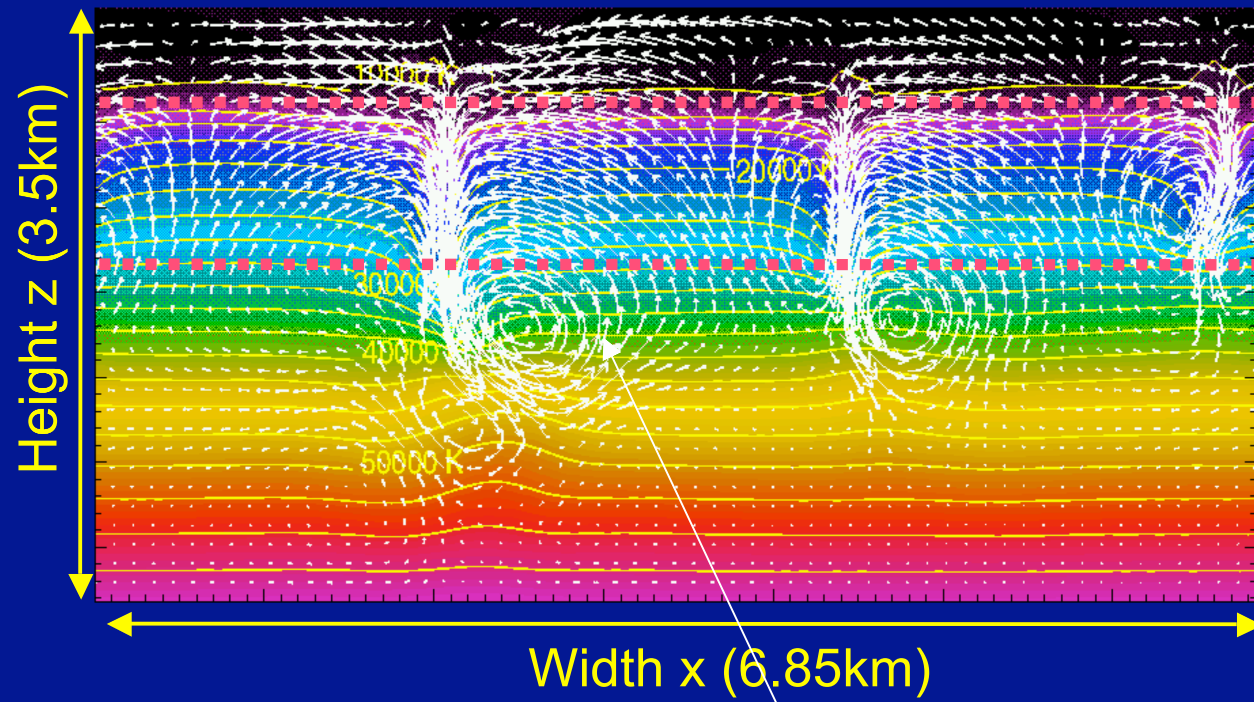
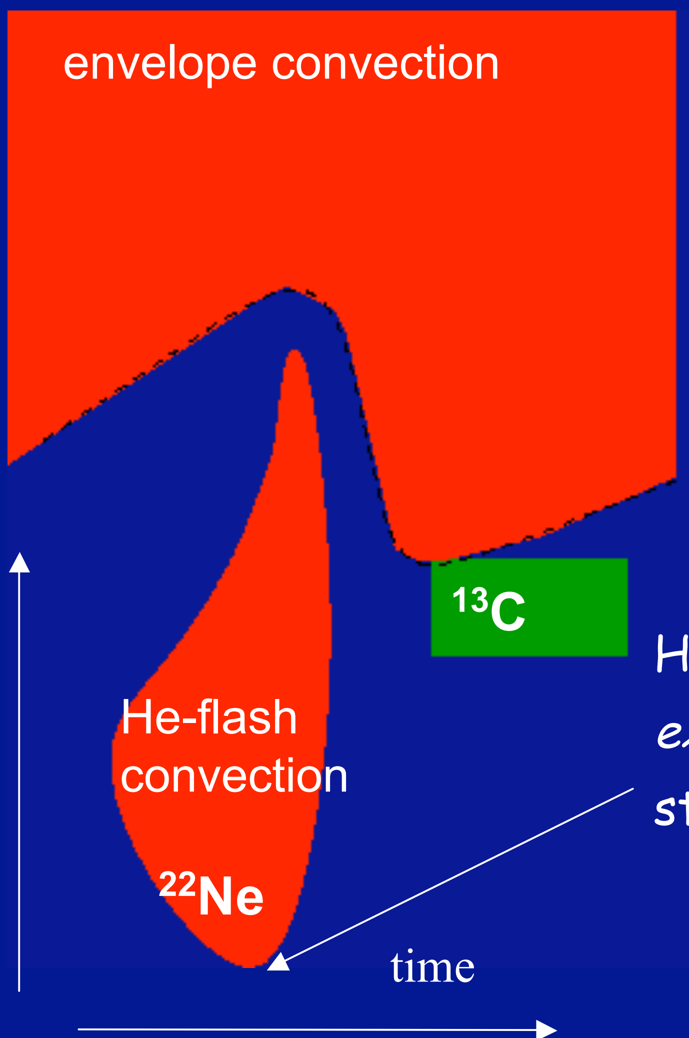
Test Convection

2D-simulation of White Dwarf convection zon



Schematic of He-shell flash

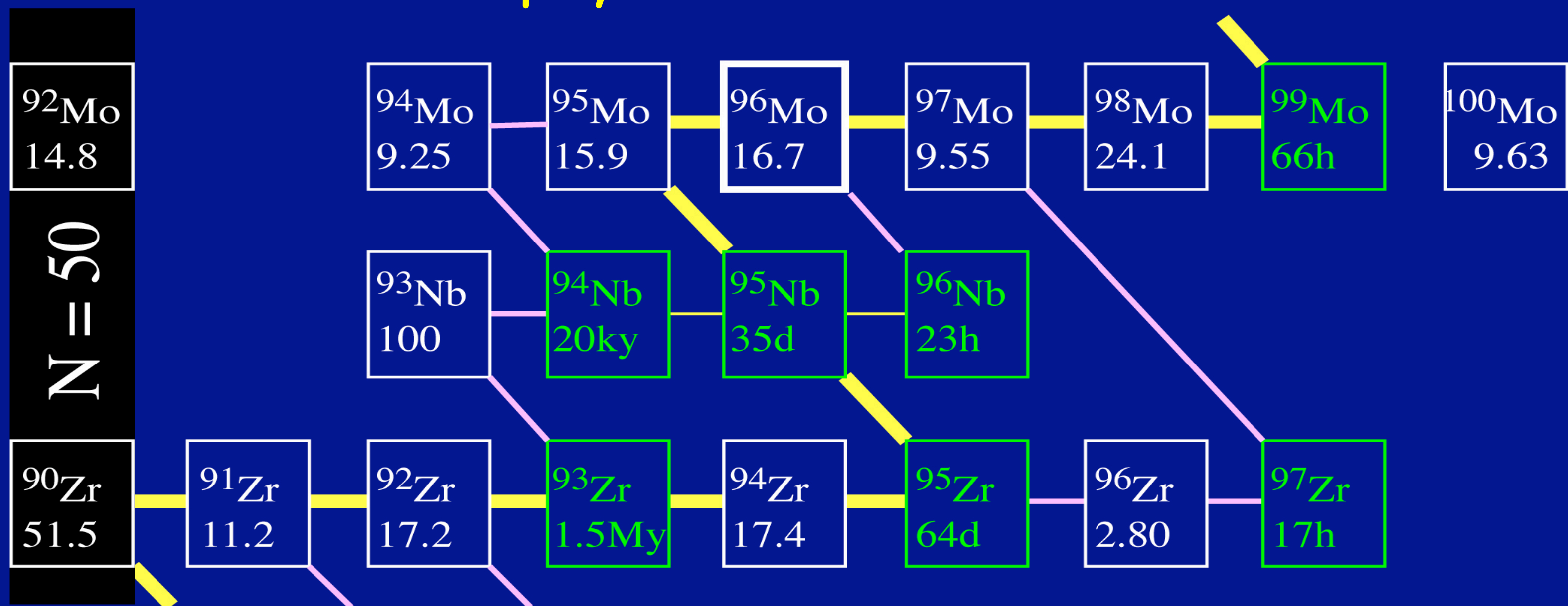


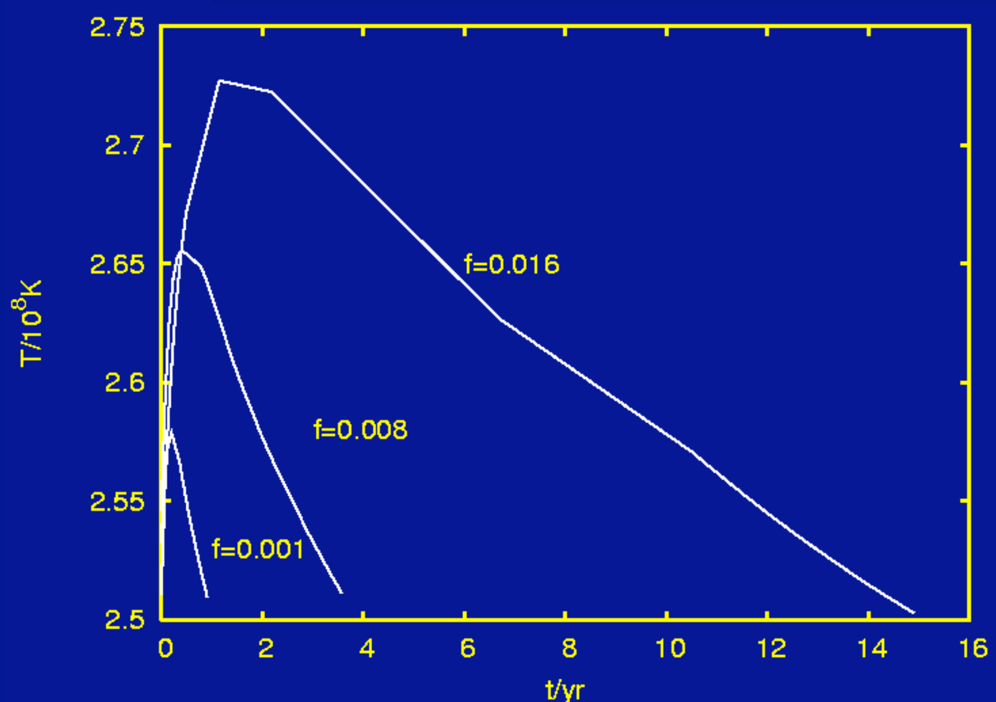
How efficient is *extra mixing* in deep stellar interior?

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

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

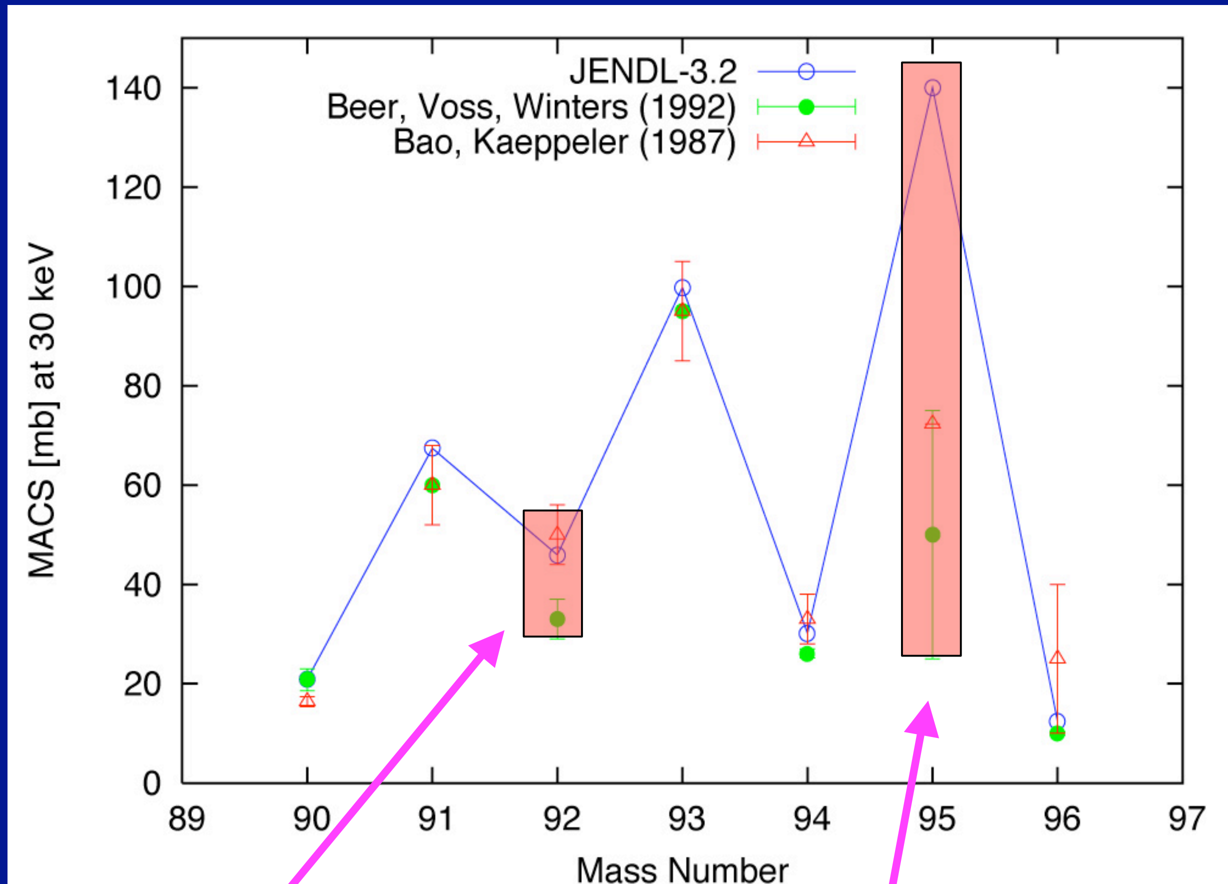
Nuclear Astrophysics with Neutron Facilities





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

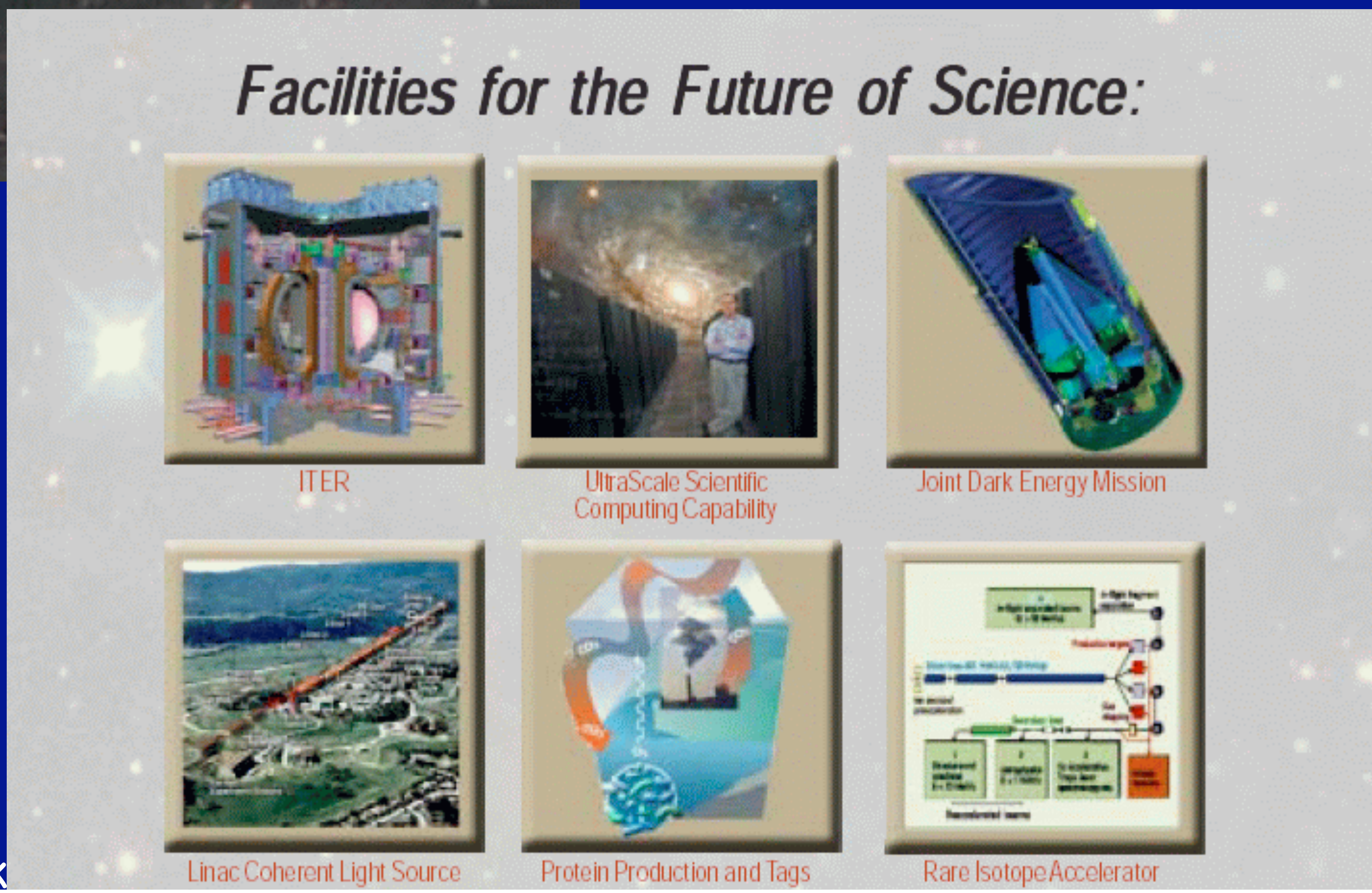
Cross Sections of Radioactive Isotopes?



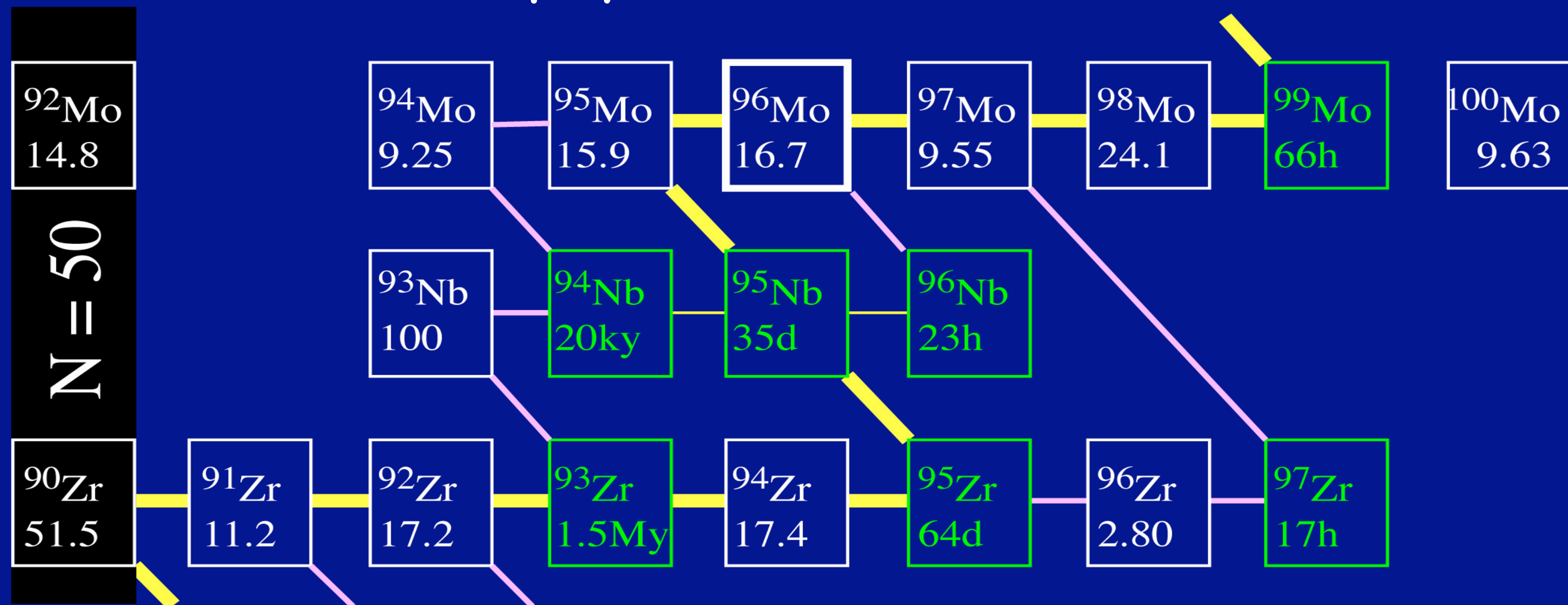
will be measured with DANCE at LANSCE and at FKZ

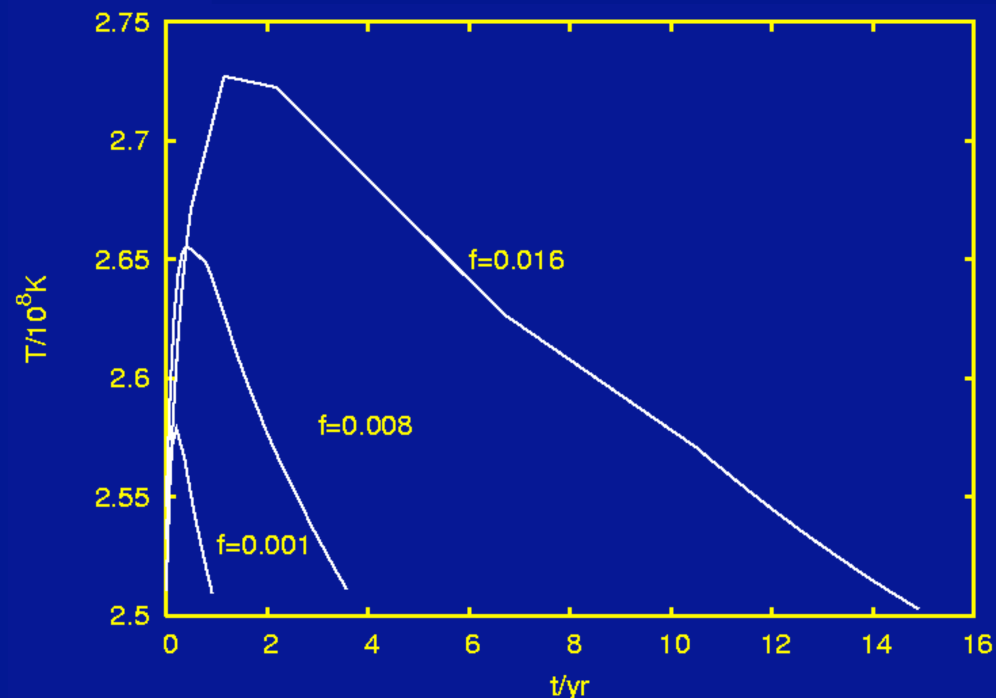
too short-lived for any existing facility

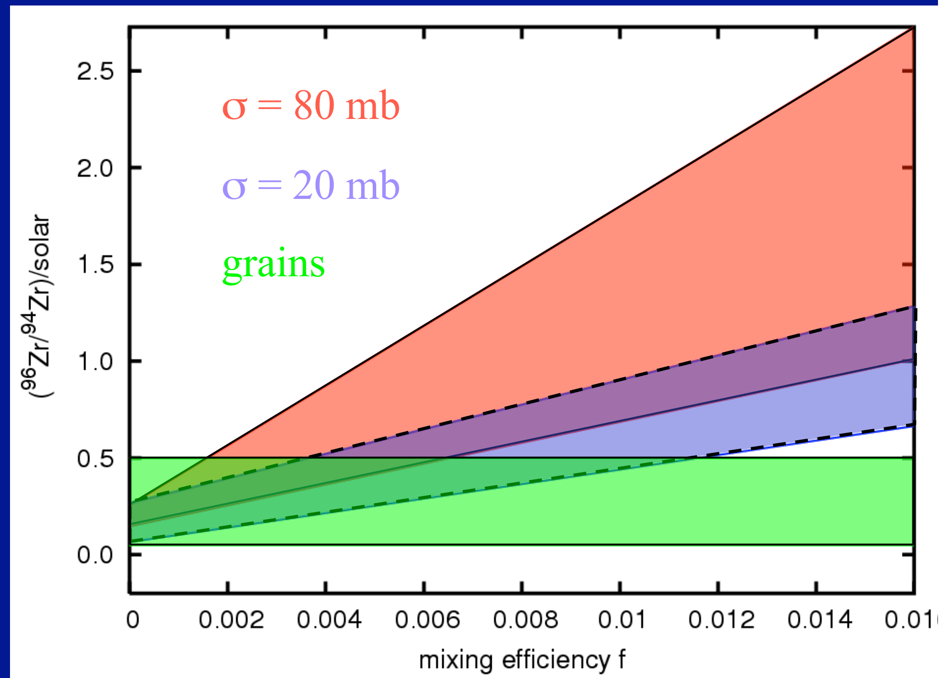
Office of Science
U.S. DEPARTMENT OF ENERGY



Nuclear Astrophysics with Neutron Facilities







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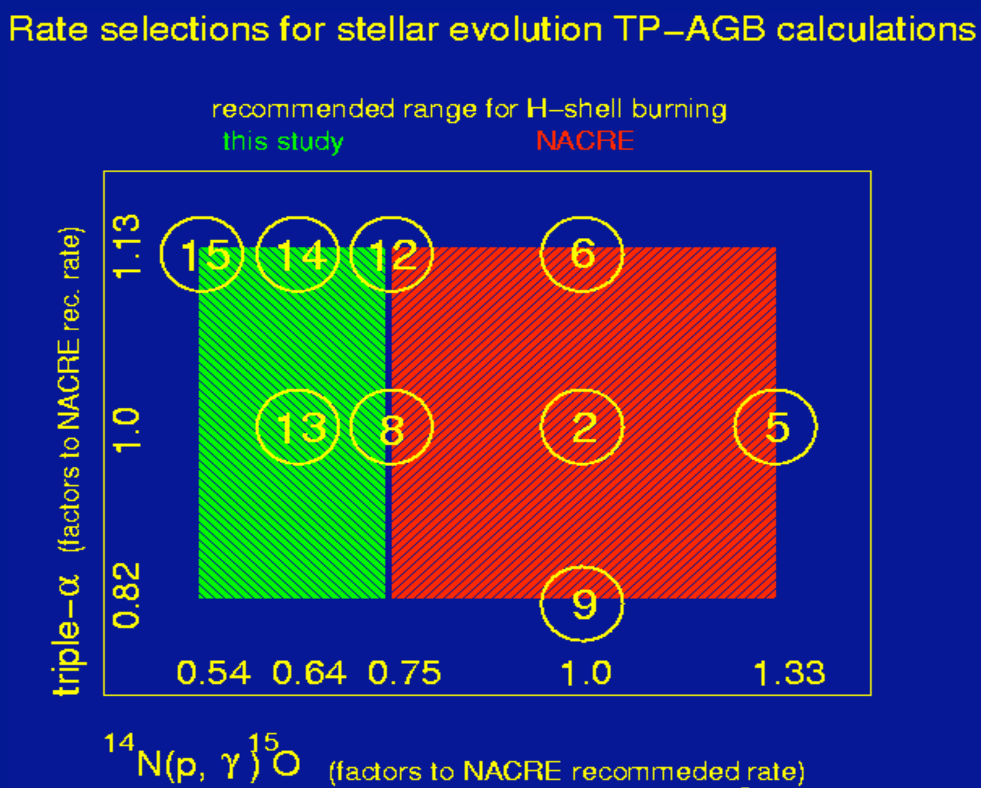
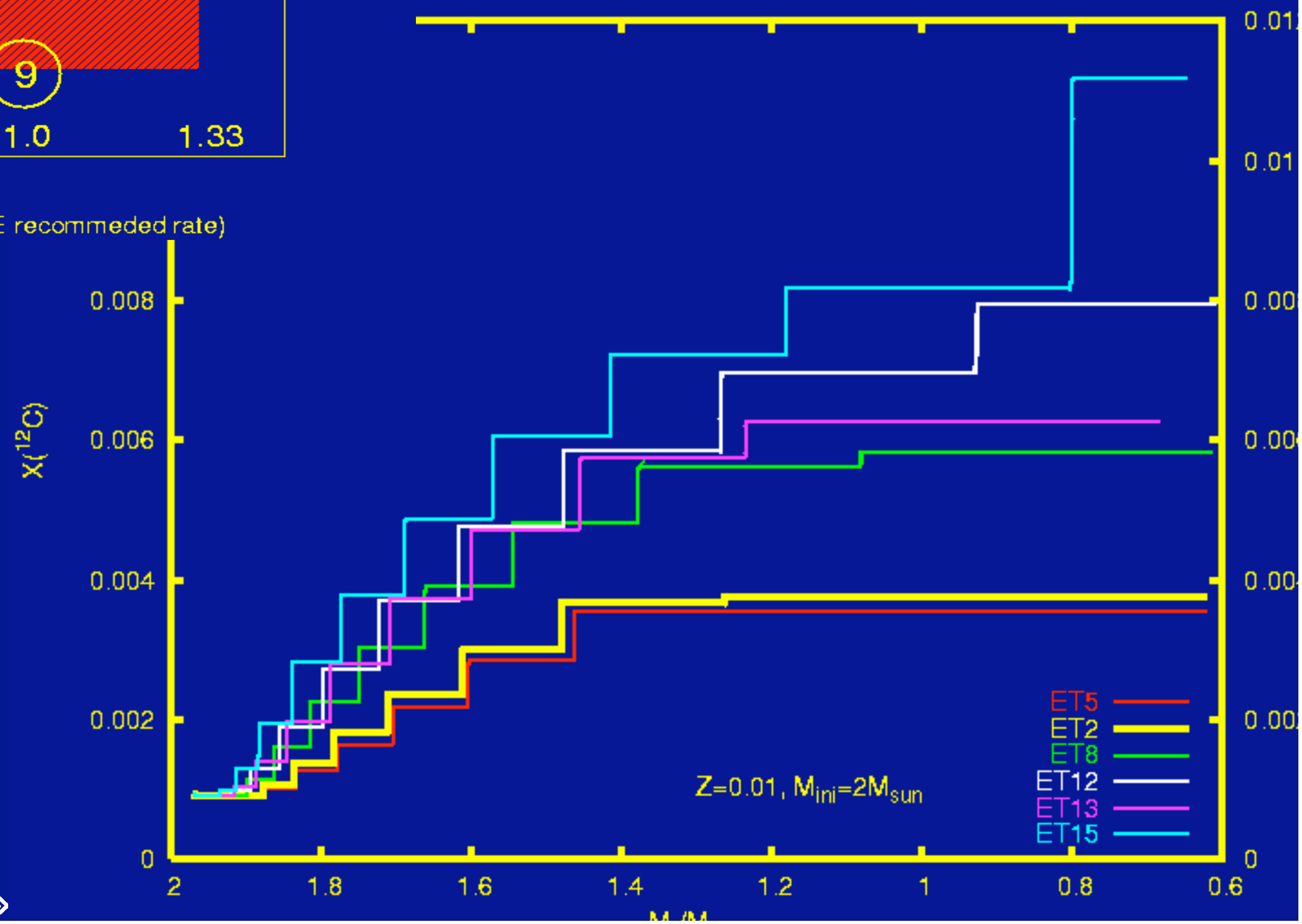
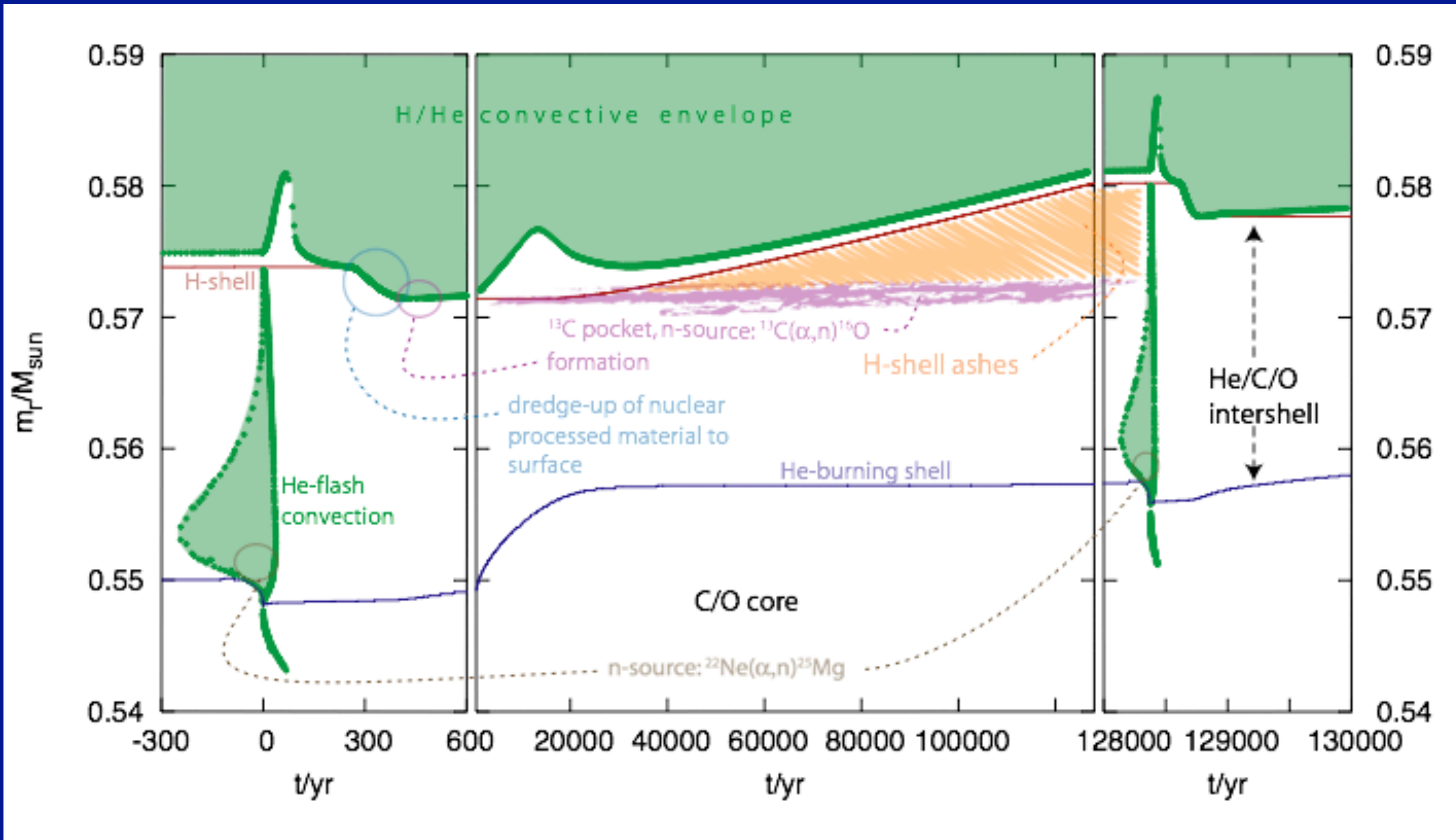


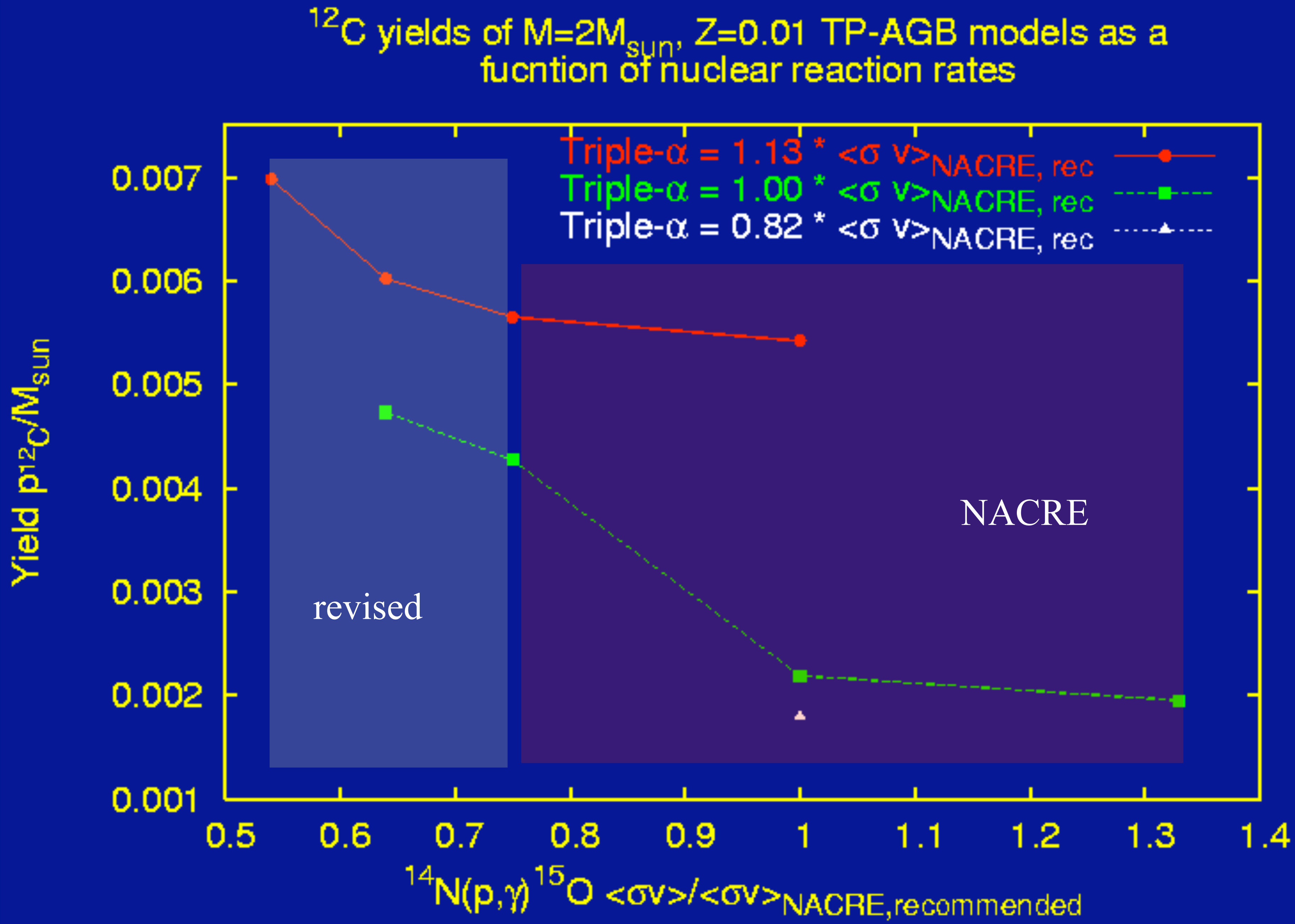
C-surface abundance
evolution of
complete $M=2M_{sun}$, $Z=0.01$
for a range
of rate selections



Internal evolution of AGB stars

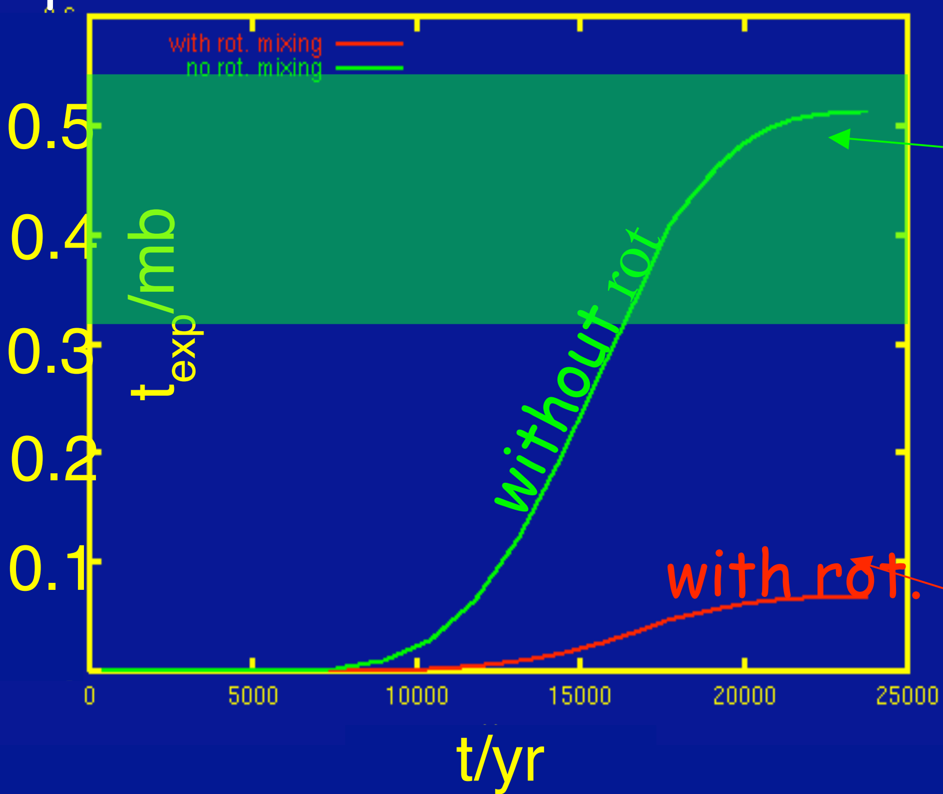


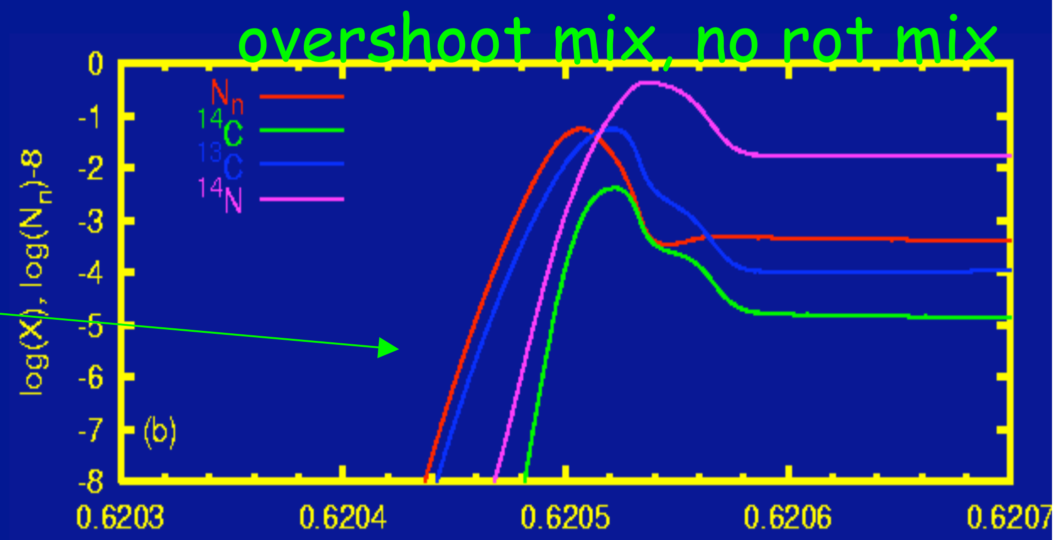
Nuclear reaction rate input: (Herwig & Austin 2004, ApJL)

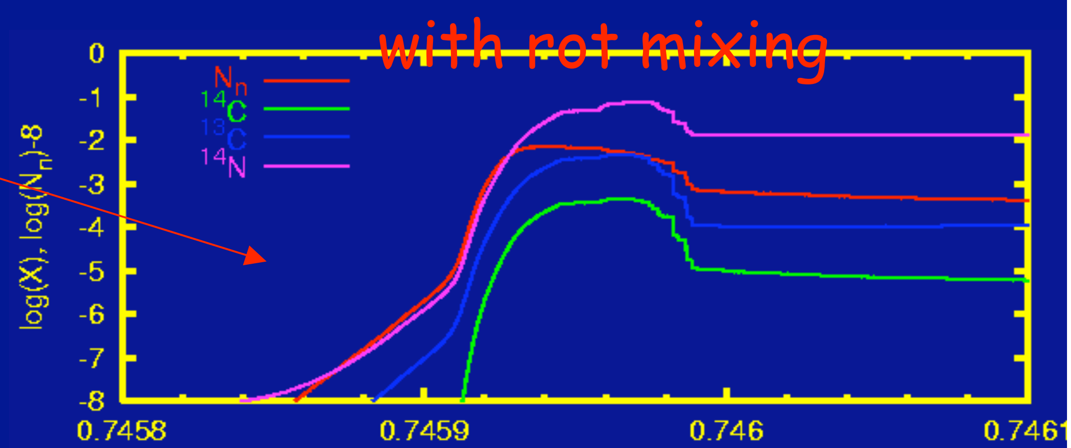


s-process in Rotating AGB Stars

Neutron exposure in s-process production site:



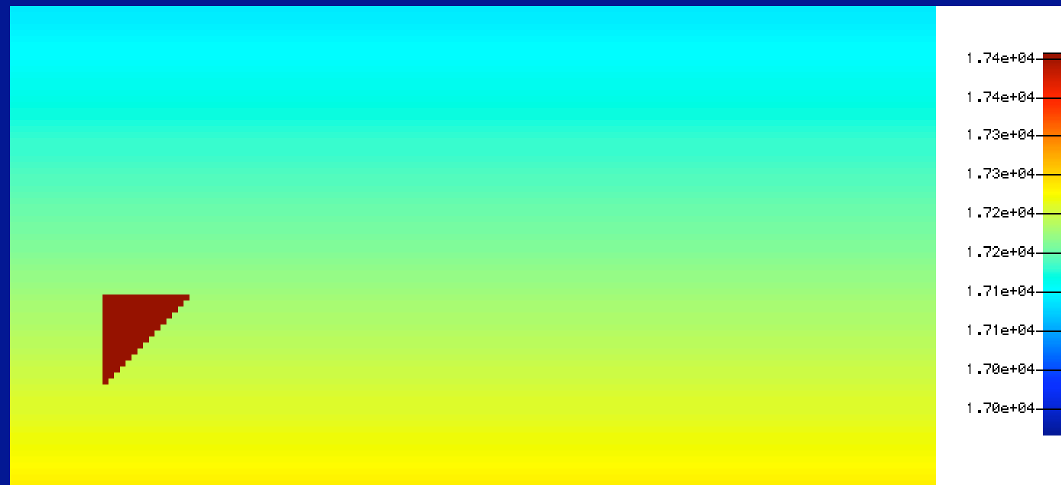




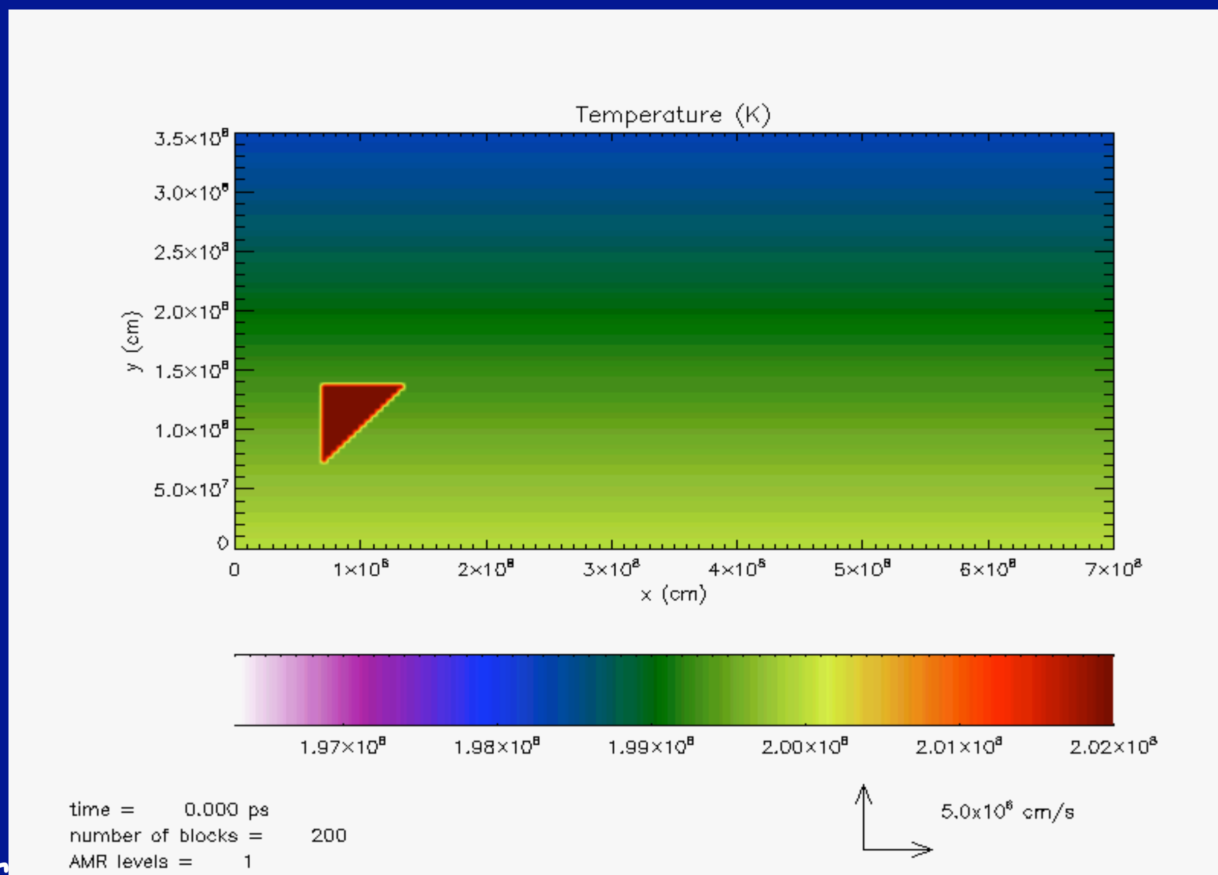
Langer etal (1999), Herwig etal (2003)

Comparison of incompressible (1% entropy contrast) convection

LANL code

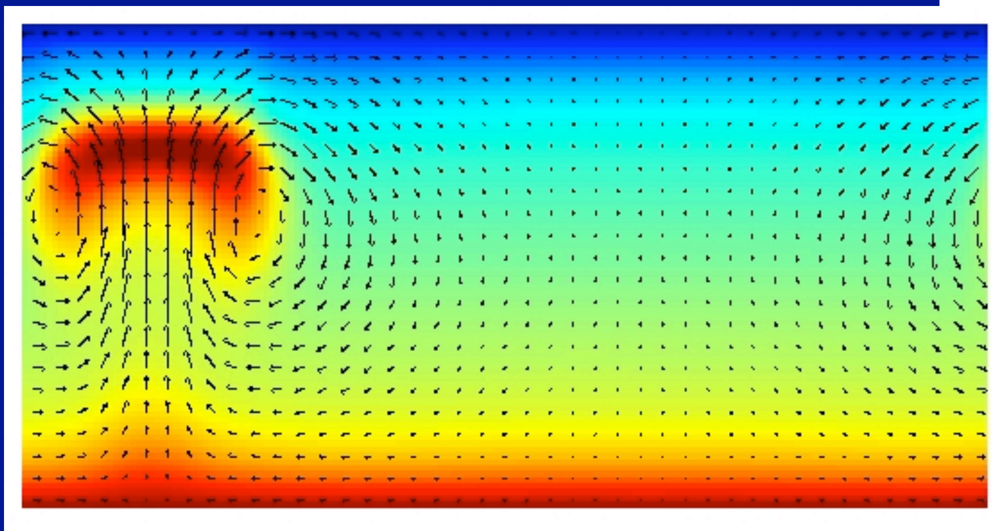


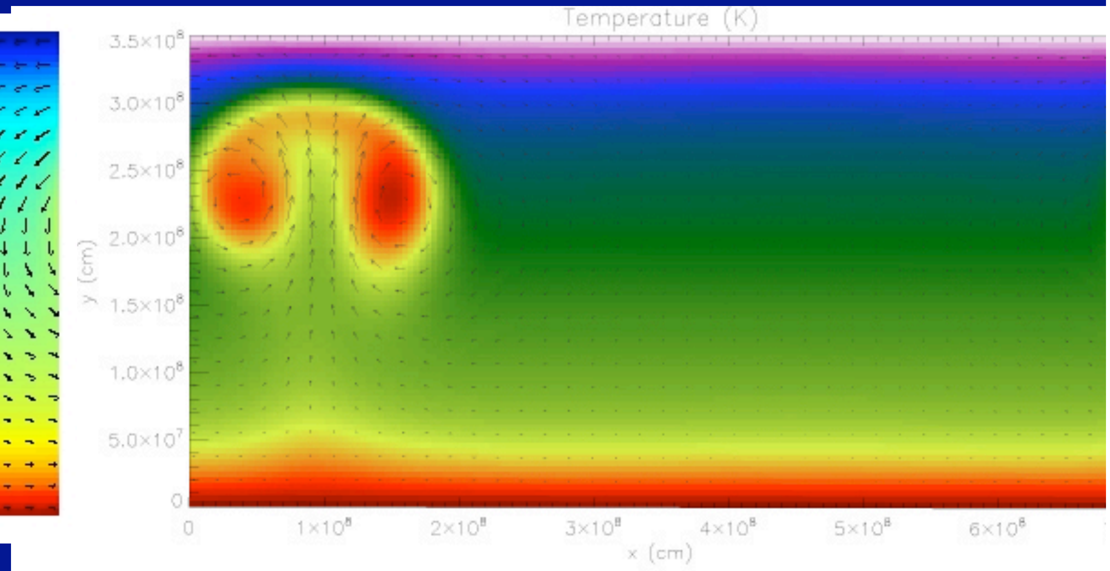
FLASH

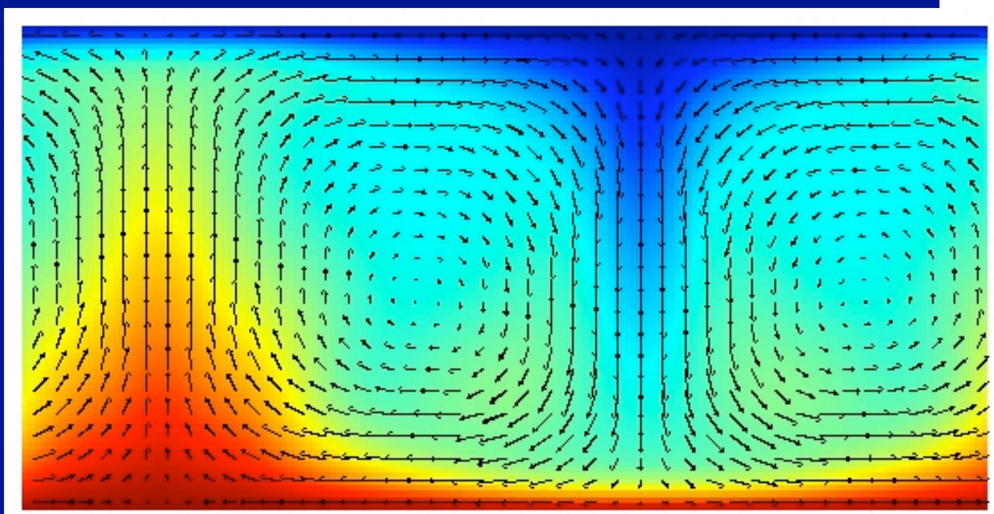


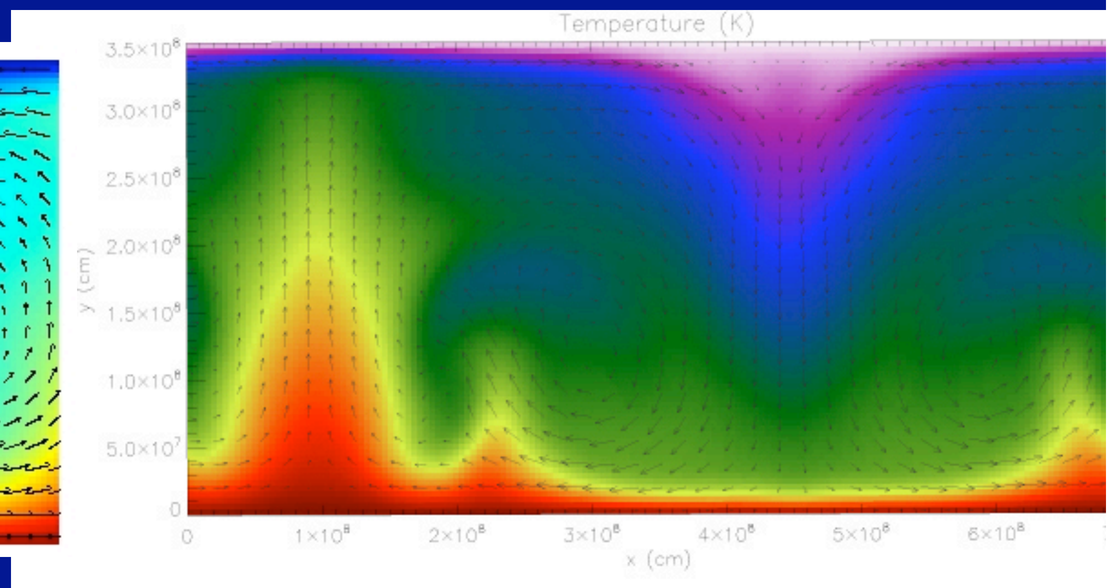
Snapshots at 200s and 1000s

LANL code	FLASH









Concluding Remarks

I. Nuclear Astrophysics can in the future help to answer fundamental questions of astronomy - enter astrophysics mainstream?!

II. Full and detailed grids of stellar yield calculations are needed!

III. Nuclear astrophysics with neutron facilities and radioactive targets can improve fundamental stellar physics!

IV. The Age of Spectroscopic Surveys has arrived: HK, HES, SEGUE, AAOmega, LAMOST, RAVE, VLT/FLAMES, GAIA, LSST

   a. Example SEGUE: 35.000 candidates for [Fe/H] < -3

   b. Science case: What happened after the Big Bang? Origin of the elements? How did Galaxies form and evolve?