Fission and the r-process

Nikolaj Thomas Zinner

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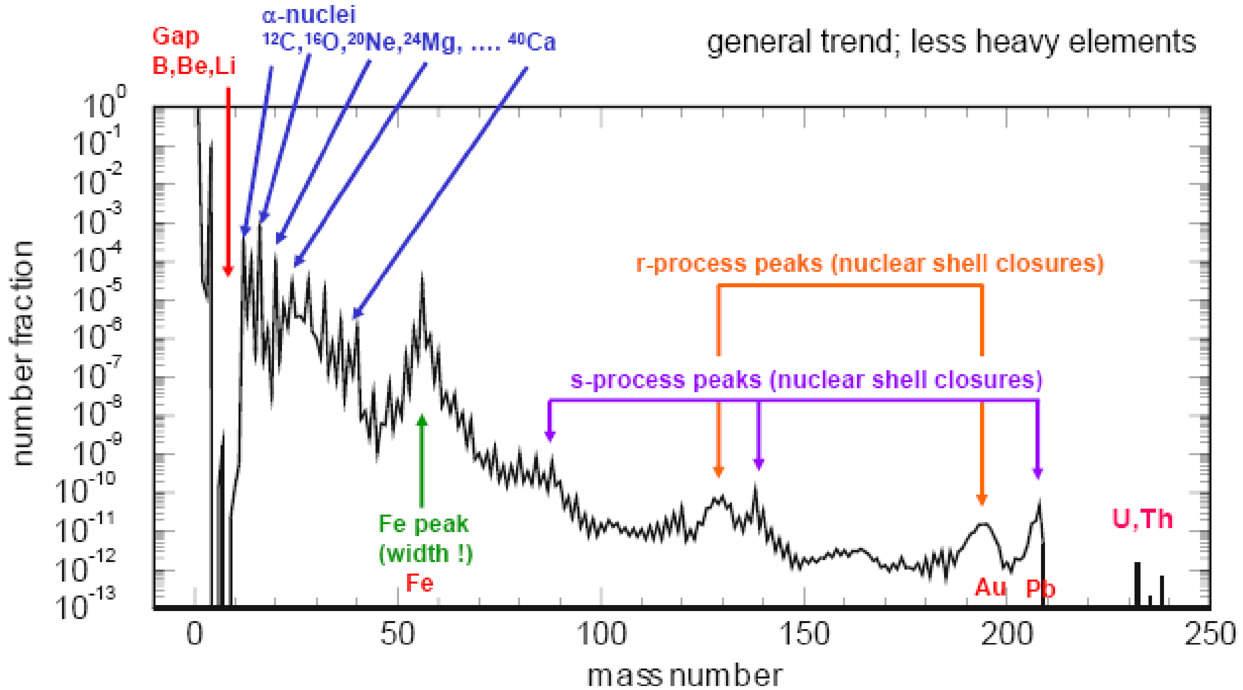
Element Abundances

Hydrogen mass fraction	X = 0.71
Helium mass fraction	Y = 0.28
Metallicity (mass fraction of everything else)	Z = 0.019
Heavy Elements (beyond Nickel) mass fraction	4E-6



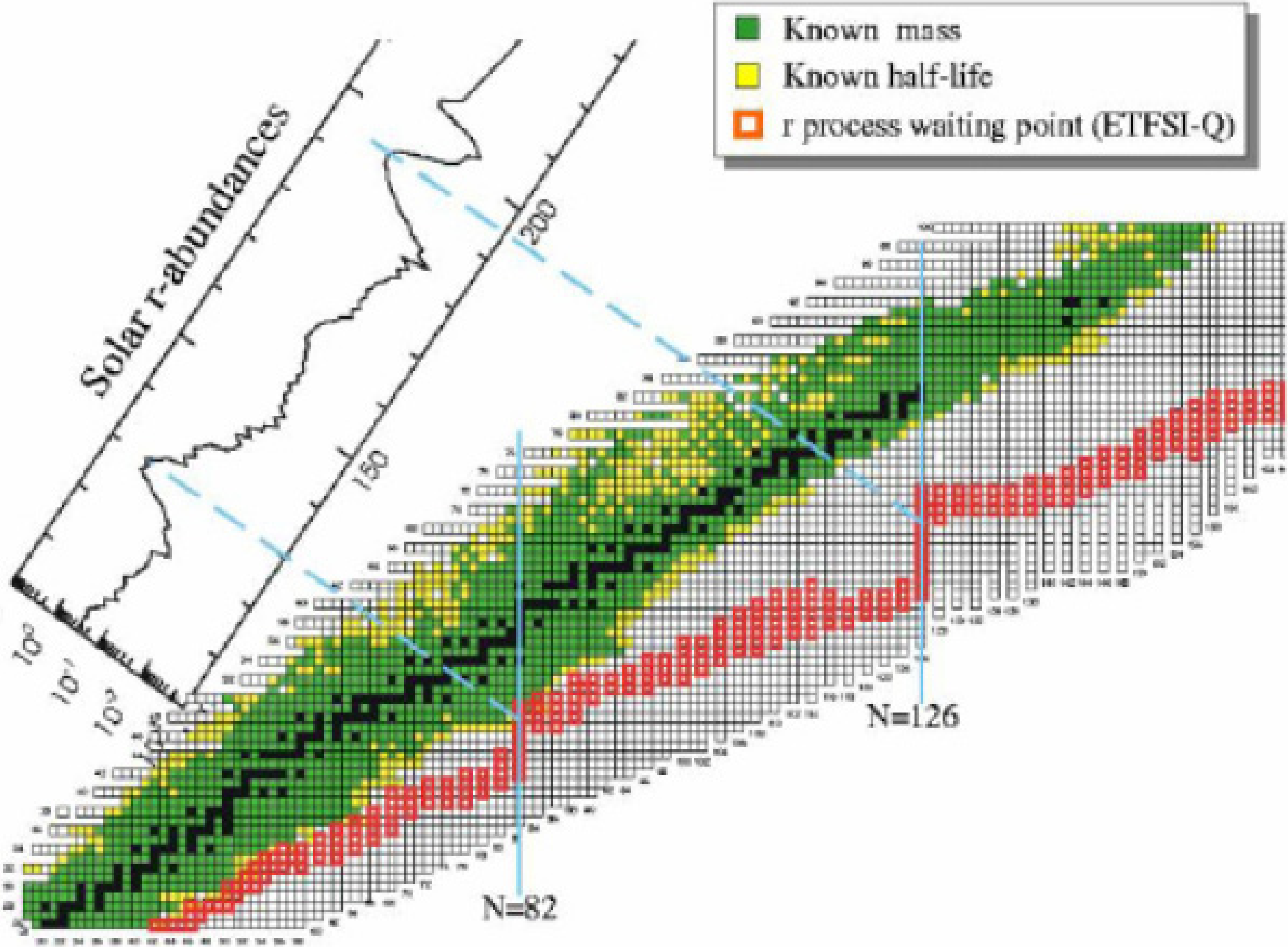
Heavy Element Formation

- Stellar Burning cannot produce nuclei beyond the iron group.
- Going above this point requires capture of light particles on heavier nuclei.
- The most common process is that of neutron capture.
- Density of neutrons in environment determines capture flow in nuclear chart.

r-process Nucleosynthesis

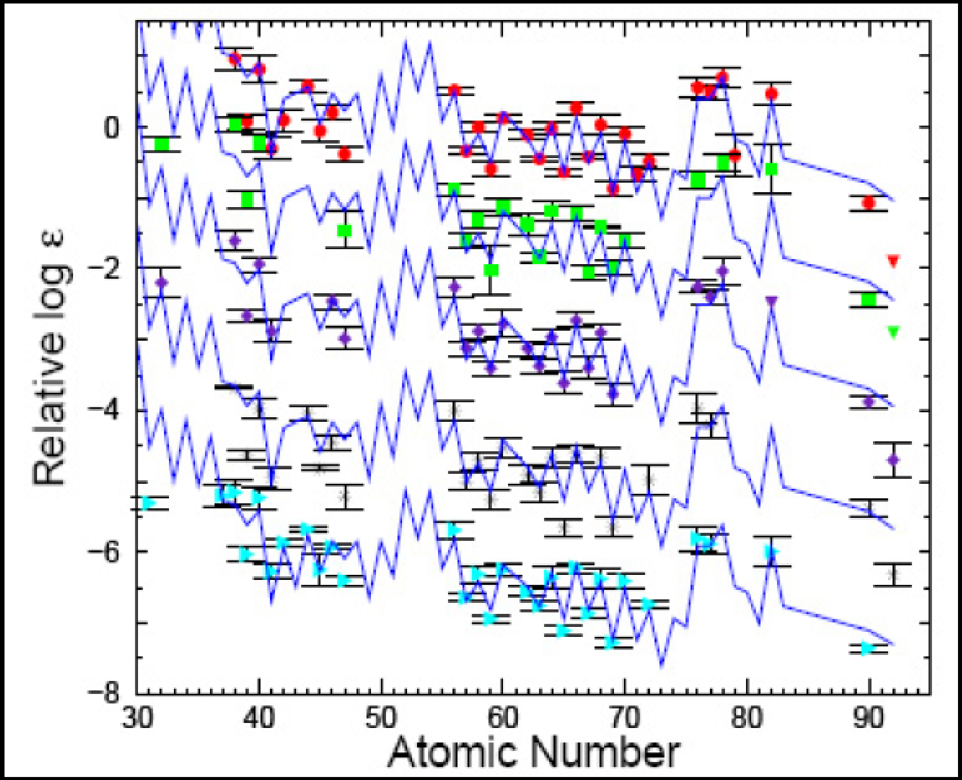
- Where does it take place?
- Are there multiple components?
- What is the production rate?
- Halo Stars tell us a lot about the abundances to expect from r-process nucleosynthesis.
- They are old and metal-poor, indicating sole contamination from a nearby core-collapse Supernova.

The r process "path"



UMP Star Observations

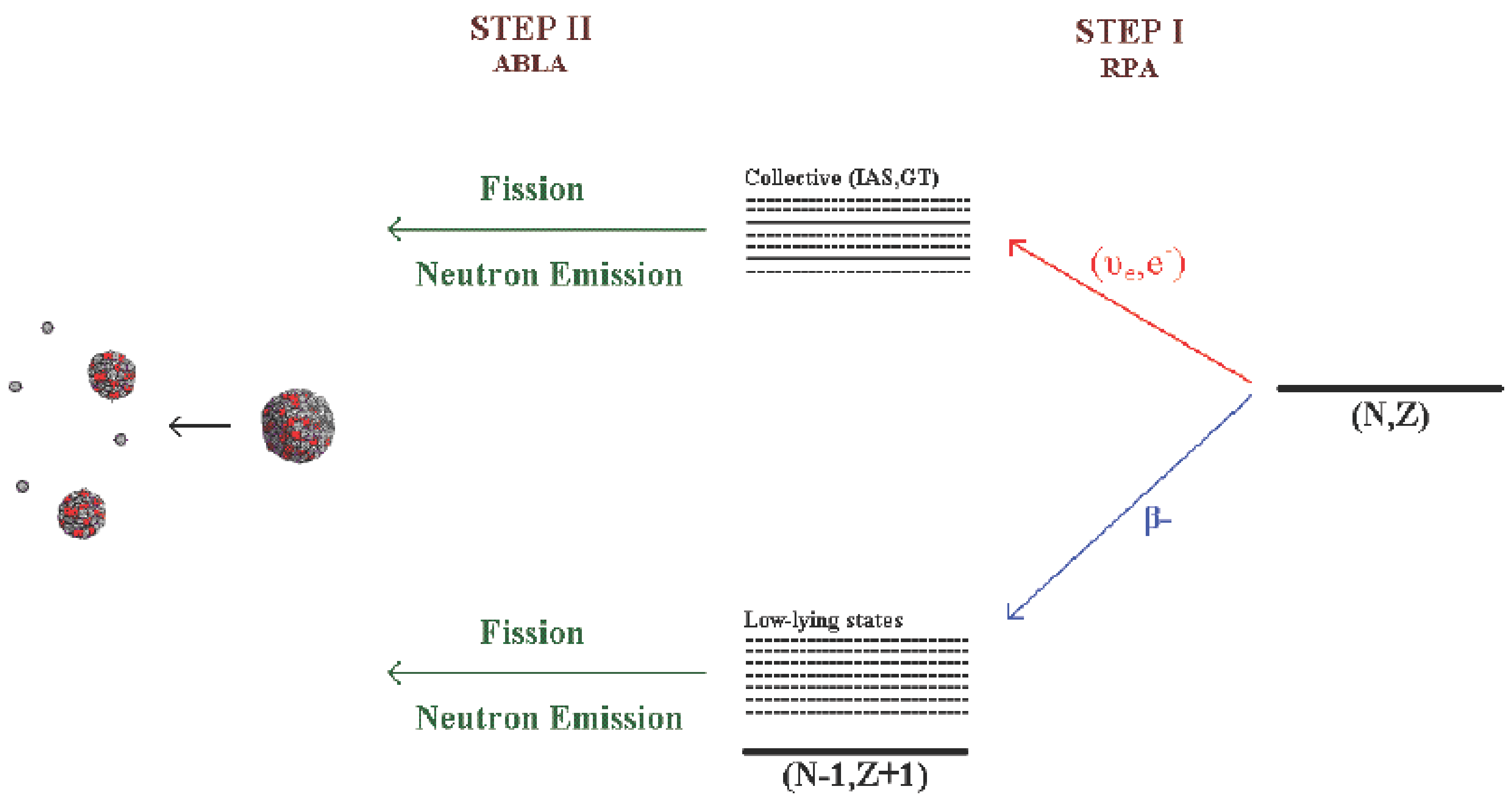
- Pattern robust for A>130. Deviations below.
- Fits solar values.
- Indicates universal mechanism!
- Fission cycling has been suggested.
- We wanted to explore fission in the r-process for dynamical simulations.



Nuclear Physics Input

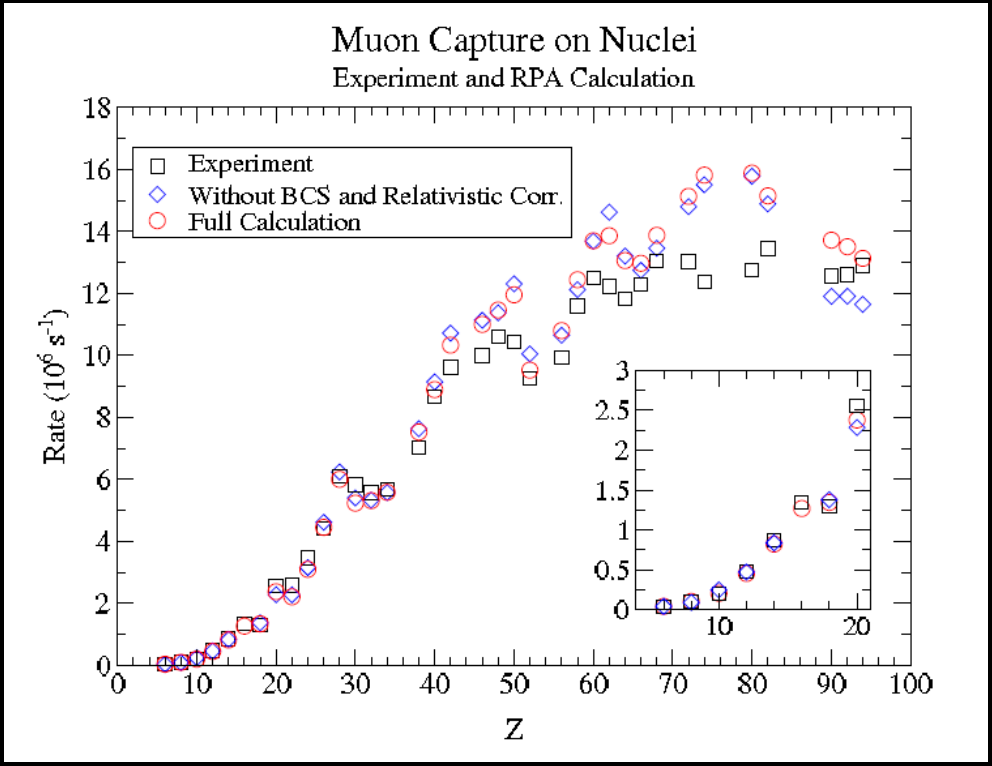
- We are concerned with weak interactions.
- Want to consider neutrinos with high average energies.
- Beta decay in nuclei with large Q-values.
- Particle spallation and fission are channels that need to be considered.
- Need a good model for both nuclear structure and decay of excited states.

TWO-STEP MODEL



Validating the Nuclear Model

- Use Muon Capture on nuclei.
- Measured in many nuclei across the chart.
- Energetics is similar to Supernova neutrinos.
- Excellent benchmark
- We improved the theoretical model for heavy nuclei.
- Agreement with data to within 15%.

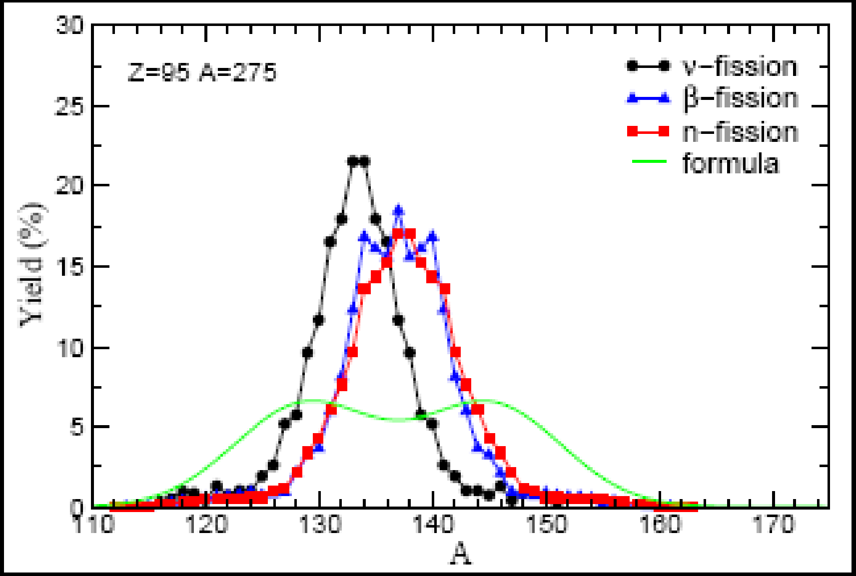


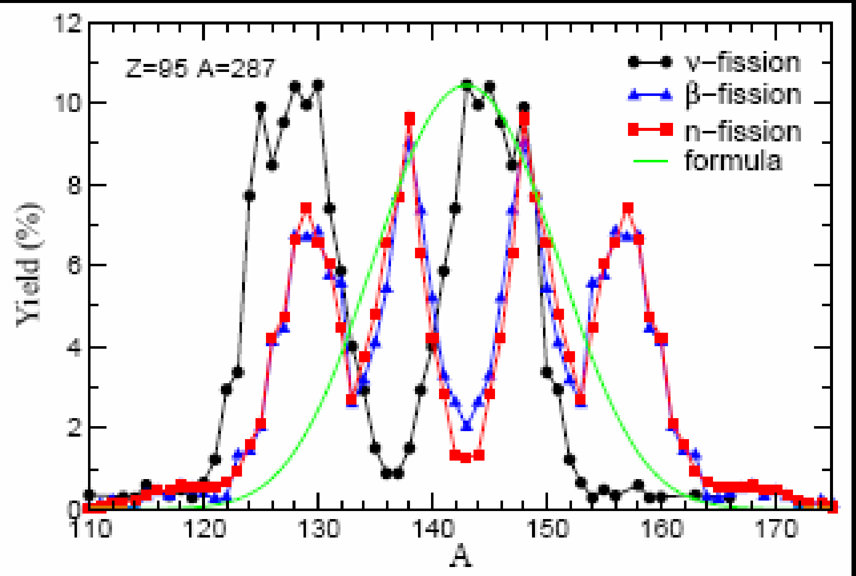
Nuclear Fission Model

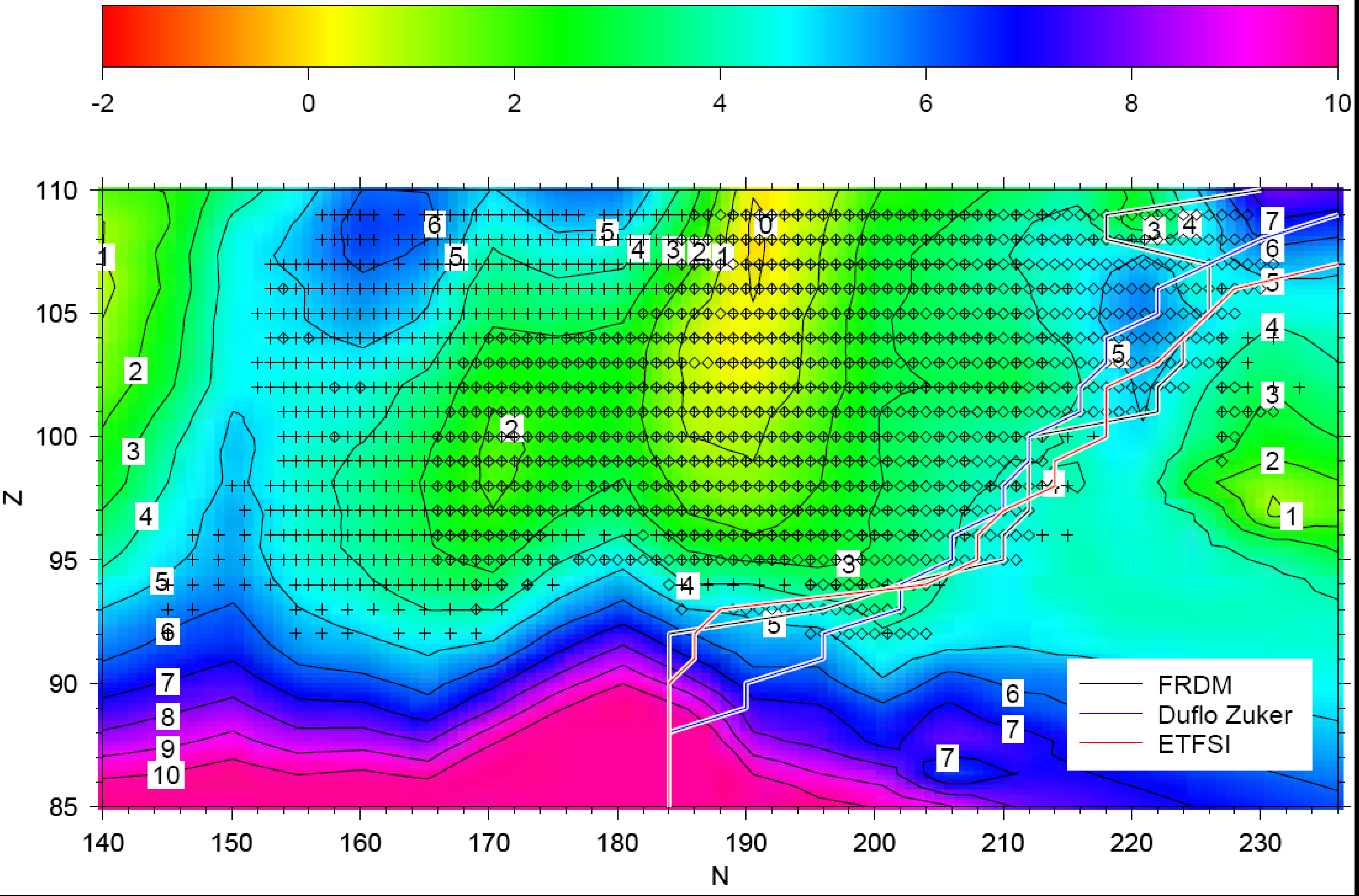
- ABLA gives probabilities of fission and neutron evaporation.
- Fission fragment distributions are calculated.
- Method is tested against experimental data on fission fragments in reactions with similar energetics.
- Need all channels in the network!

Fission Fragment Distributions

- Profiles change drastically with A!
- Contradicts previous estimates (formula).
- Region of fission is very important for fragments and redistribution of matter.



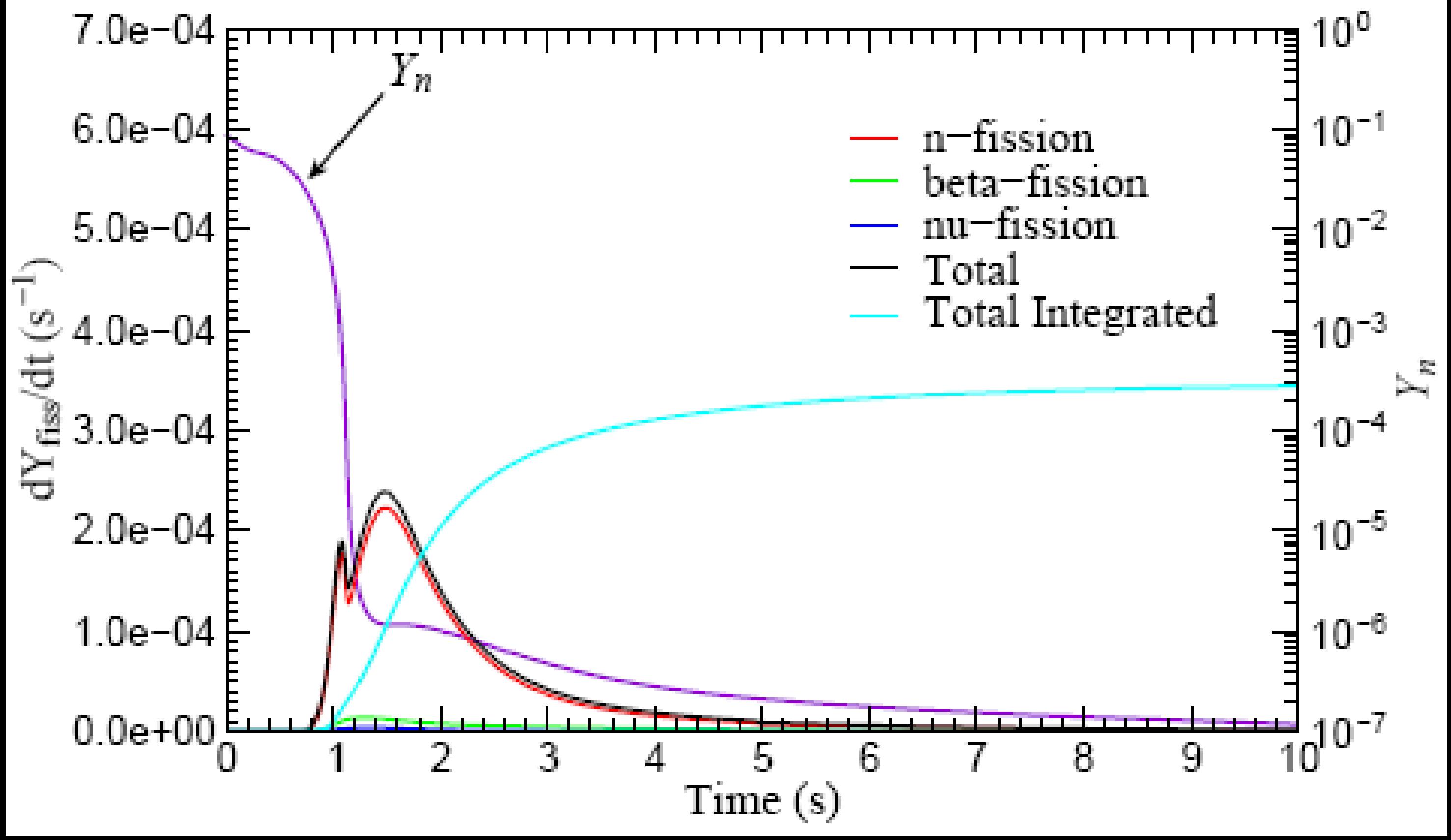




r-process fission region with TF fission barriers contours and neutron drip lines. Crosses indicate that n-fission dominates n-gamma. Diamonds indicate that spontaneous or beta-delayed fission operate on timescales of less than 1 s.

The amount of fission depends on the ability to breach the barrier at N=184.

r-process Movie



Fission timescales.

Initial Phase where fission takes place at N=184. Then neutron density drops but beta-delayed fission during decay back to stability induce further fission and neutron release. Dominance of n-fission due to short timescale of few ms. Beta-delayed is order of magnitude higher.

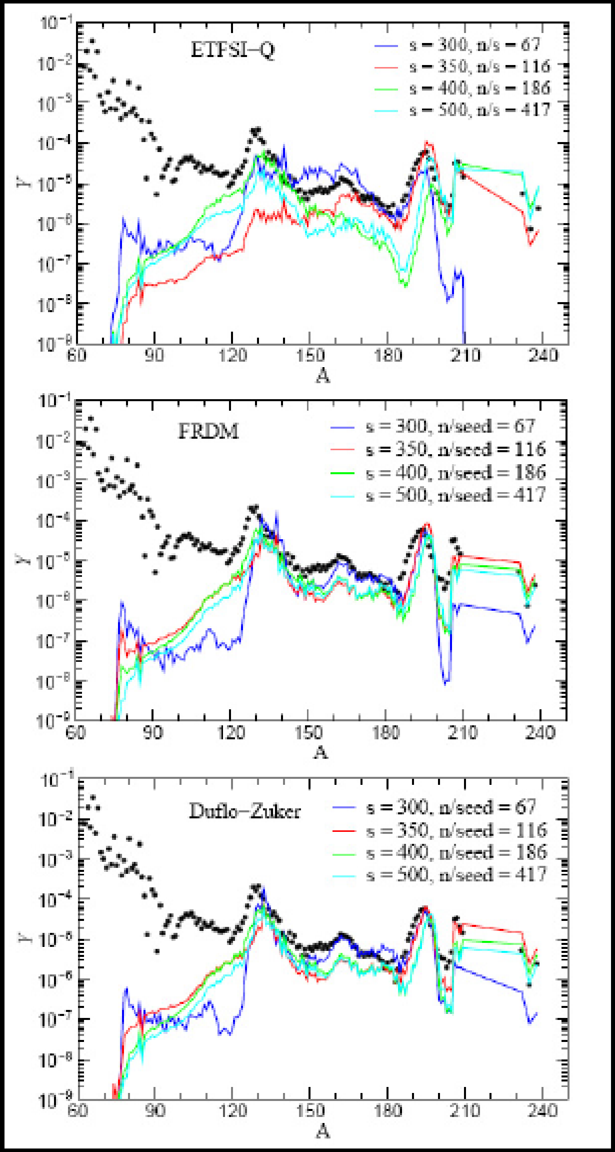
Beta is small. Neutrino is zero!

Fission Percentages

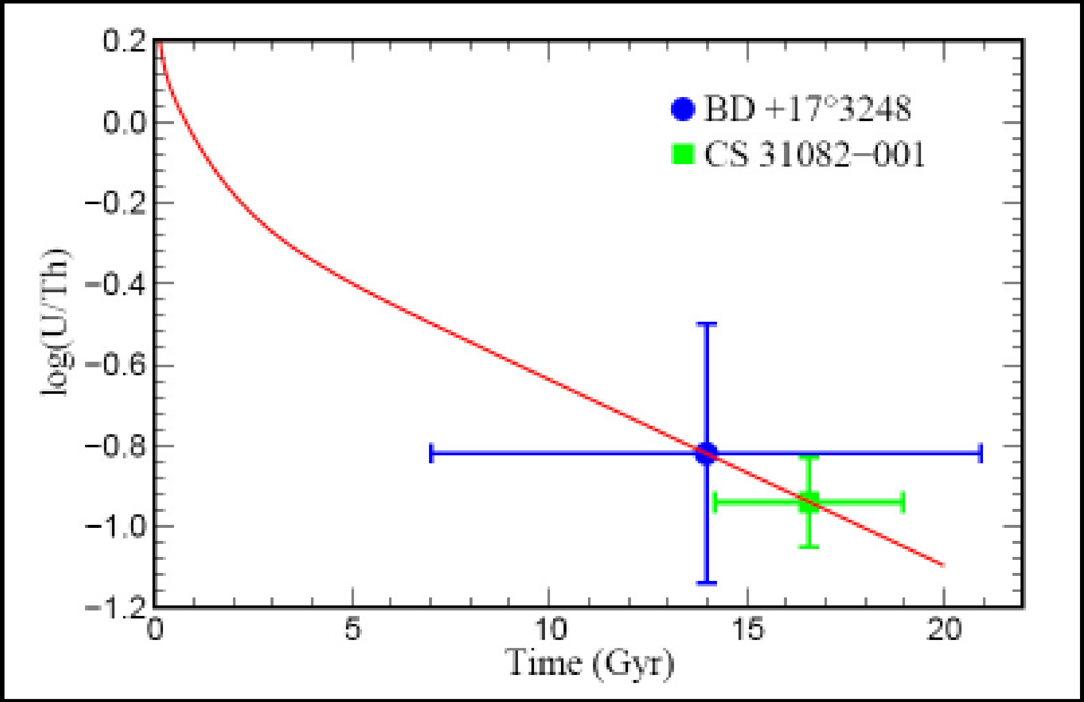
$S = 350$ ($Y_n/Y_{seed} = 116$)	(n,fission)	β-induced	ν-induced	Total
ETFSI-Q	0	0	0	0
FRDM	10	1	0	11
Duflo-Zuker	10	1	0	11
$S = 400$ ($Y_n/Y_{seed} = 186$)	(n,fission)	β-induced	ν-induced	Total
ETFSI-Q	33	5	0	38
FRDM	36	3	0	39
Duflo-Zuker	36	3	0	39
$S = 500$ ($Y_n/Y_{seed} = 417$)	(n,fission)	β-induced	ν-induced	Total
ETFSI-Q	56	4	0	60
FRDM	58	5	0	63
Duflo-Zuker	58	5	0	63

Mass Model Dependencies

- Mass models with strong shell gaps at N=82 and 126 show similar features.
- Not too dependent on initial conditions once fission is reached.
- Produce many fragments in the A=130-190 range.
- Robust pattern as in UMP stars.



Cosmochronometry



Good agreement between the fission model and the data on UMP stars.

Summary

- Need accurate experimental info and theoretical modeling for rates and cross sections.
- Fission in the r-process needs accurate fragment yields. Very dependent on mass!
- Robust production of A>130 elements depends on strength of shell closures in mass models.
- Need for experimental information on masses!

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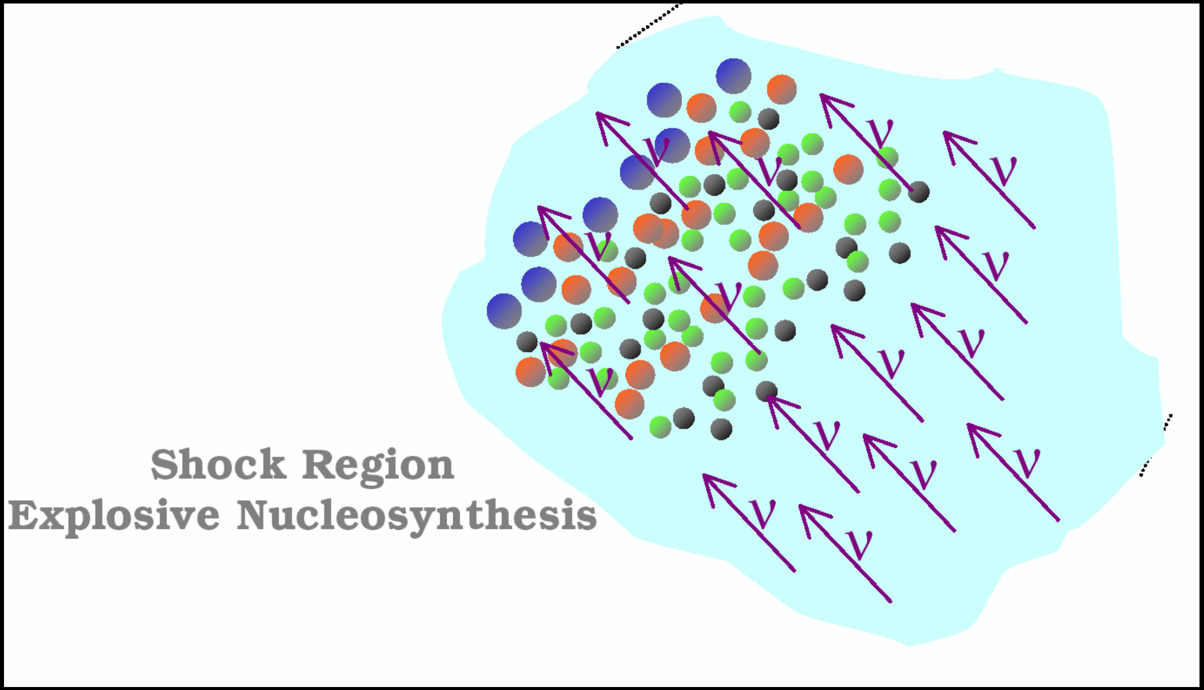
- Petr Vogel

Thank you for your attention!

Innermost Supernova Ejecta



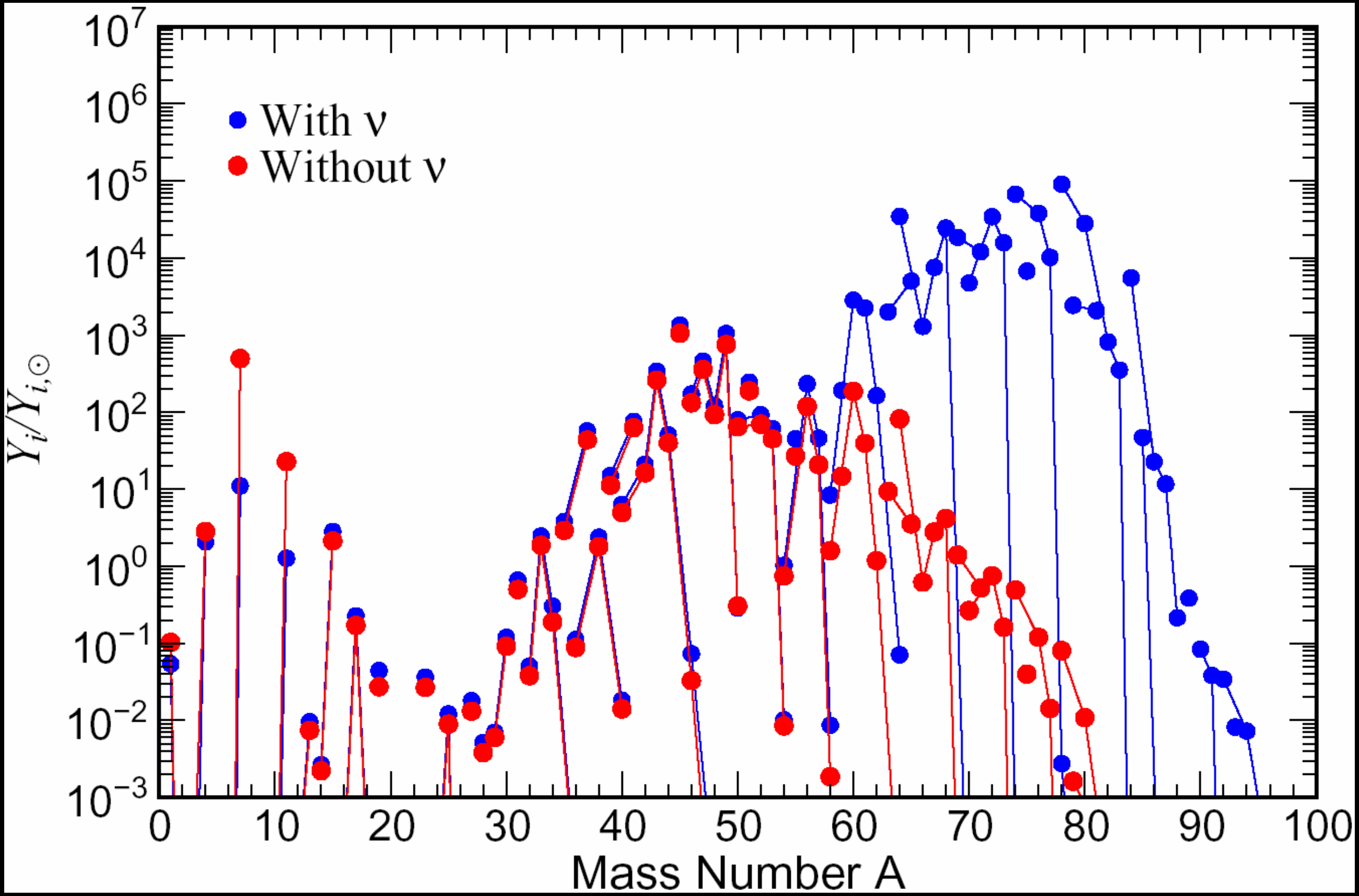
$$\nu_e + n \rightleftarrows p + e^-$$

$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Neutrino reactions determine the composition.

Close to the mass cut where will be more proton than neutrons!

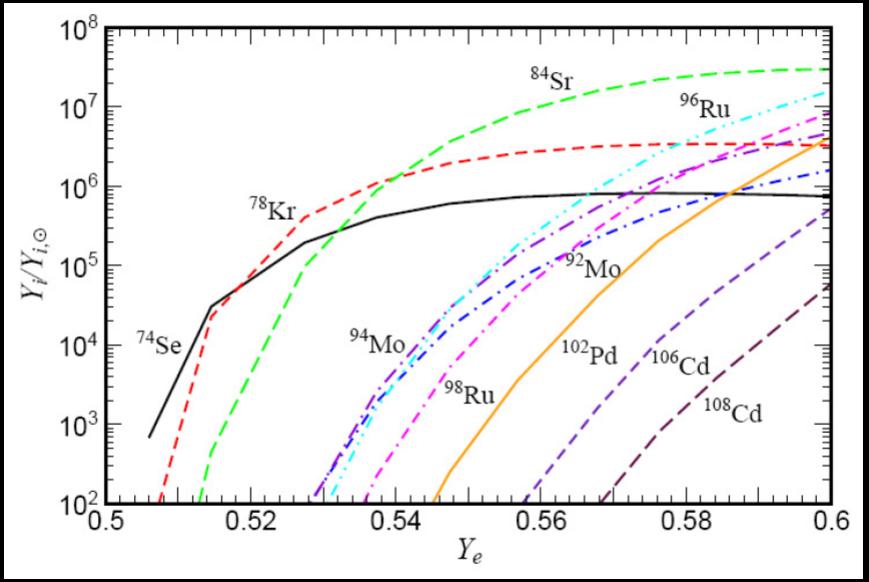
Matter Flow Beyond A=64



Obvious effect of neutrinos on mass flow to heavier nuclei

νp-process Nucleosynthesis

- Antineutrinos are key!
- Turn protons into neutrons.
- Neutrons can be captured on nuclei that are proton-rich.
- Bridge waiting-points where proton capture is slow.
- Produce rare proton-rich nuclei!



$$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\text{Ge} \rightarrow {}^{64}\text{Ga} + p; \quad {}^{64}\text{Ga} + p \rightarrow {}^{65}\text{Ge}; \ldots$$

UMP Stars Comparison