Supernova Nucleosynthesis and Neutrinos

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Some Locations for Nucleosynthesis

Proto-neutron star supernovae

- Explosive Burning yesterday's talk by Heger
- Neutrino winds originally discussed by Woosley et al, Meyer et al, Takahashi et al

Other core collapse supernovae, e.g. collapsars, hypernovae or similar

- Explosive Burning e.g. Maeda & Nomoto, Nomoto & Tominga
- Disk outflow, neutrino driven or otherwise Surman et al, Metzger et al.
- Jets e.g. Winteler et al. 2012, Nakamura et al. 2012,Papish et al. 2013

Compact Object Mergers

- tidal tail ejection
- Disk wind
- Disk disintegration

Types of Nucleosynthesis

Four types of interesting nucleosynthesis

- r-process
- p-process
- $^{56}\mathrm{Ni}$ and other iron group nuclei
- $^{44}\mathrm{Ti}$ see talk by Grebenev next

Necessary Physics

- hydrodynamics
- EOS, neutrino opacities
- nuclear properties, reactions
- neutrino flavor transformation

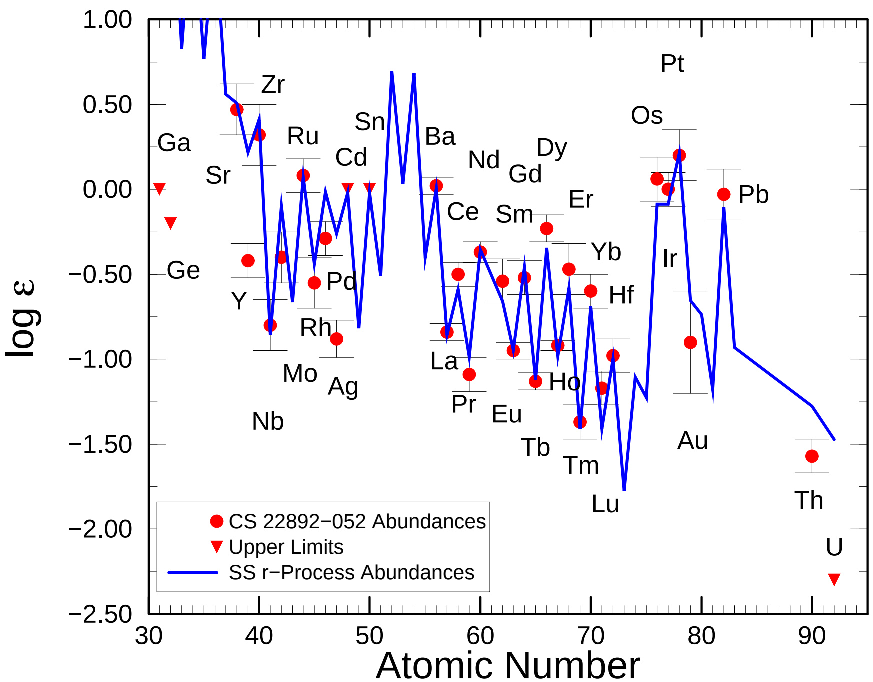
Interesting Questions

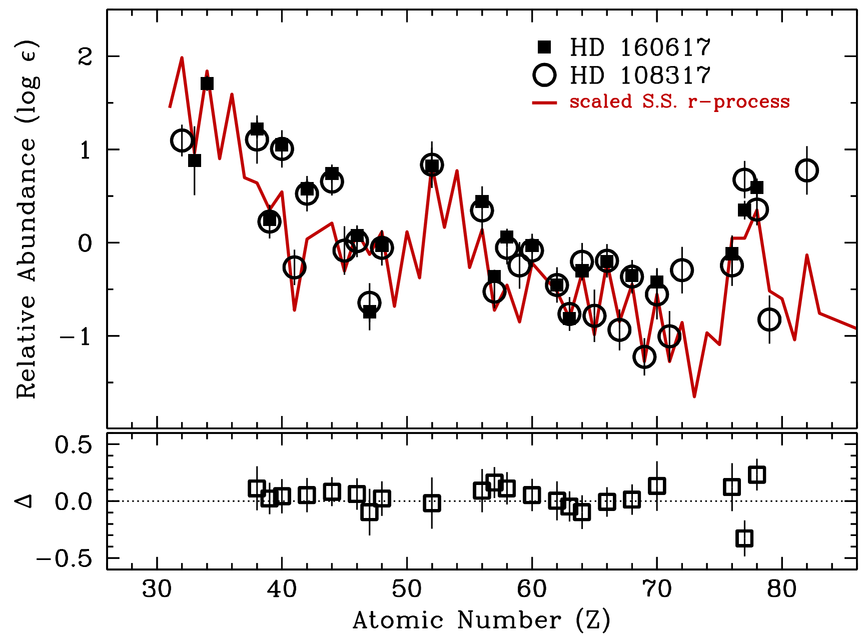
- What is the site of the r-process?
- What the is the site of the p-process elements? LEPP?
- What nuclei do core collapse supernovae make?
- What nuclei do compact object mergers make?
- What nuclei do hypernovae make?
- What nuclei do disks (collapsar, mergers) make?

Avenues for exploration

- What can be learned from astronomical observation?
- What can be learned from neutrino physics?
- What can be learned from supernova/neutron star models?
- What can be learned from a detailed analysis of the abundance pattern?

Astronomical observation: r-process





Roederer et al

Cowan and Sneden

Halo (old) stars show a pattern above the second peak that is robust and matches solar. e.g. Sneden et al, Honda et al., Frebel et al Second peak may be robust as well. Roederer et al.

Inferences:

Inference 1: There is a different mechanism for the main r-process, for Ag, Pd (weak r-process?), and for N=50 nuclei (Sr, Y, Zr)

Inference 2: For the main r-process site, we want something that happens early enough to allow for the population of a few halo stars, and that is robust (produces the same pattern over and over again)

Traditional speculation: Core collapse supernovae are favored over neutron star mergers for the main r-process e.g. Argast et al, Wanajo et al

Most obvious site, supernova neutrino winds, do not appear to make r-process

Need neutron rich material and the Y_e in the wind is too high.

But could potentially get other things, like p-process

Suggested mechanisms for p-process:

- $Y_e \sim 0.485$ and some neutrino capture on nuclei Fuller and Meyer 1995
- νp -process - Y_e slightly proton rich and antineutrino capture on protons Frohlich et al

Back to r-process: basic inferences inconsistent without fixes - either change the interpretation of the data or find a way to make SN work

Some possible fixes

- maybe supernovae form jets Winteler et al, Nakamura et al, Papish et al
- maybe there are lots of "collapsars" around that make r-process from disk nucleosynthesis Surman et al
- maybe lumps of material in 2D O-Ne-Mg supernovae make r-process Wanajo et al
- maybe mergers evolve on a different timescale Korobkin et al
- maybe halo stars come from dwarf galaxies without a lot of gas around, i.e. maybe the stars are older than we think Frebel
- maybe a sterile neutrino will help the neutrino wind nucleosynthesis GCM et al, Tamborra et al.

What is required to make the r-process in mergers or supernova

Two options:

- eject material far from neutrinos and/or fast, and with little heating
- let the neutrinos set a low Y_e $(E_{\bar{\nu}_e} > E_{\nu_e})$

Why are the neutrinos important? They are in charge changing interactions

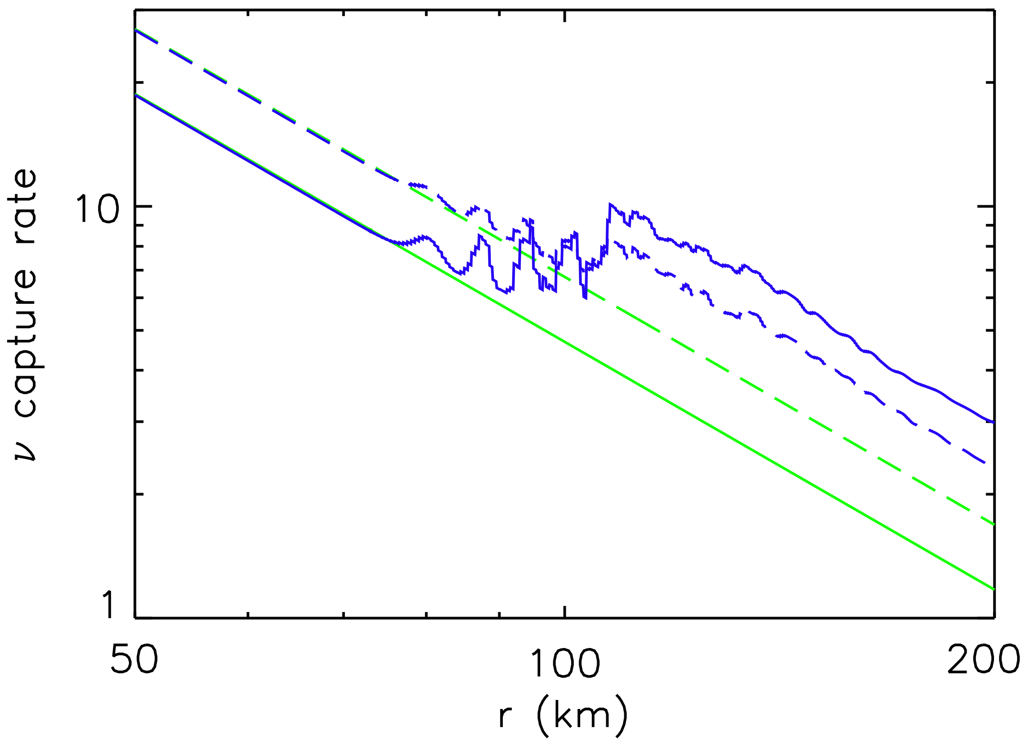
- $\bar{\nu}_e + p \leftrightarrow n + e^+$
- $\nu_e + n \leftrightarrow p + e^-$

Why don't (active) neutrino oscillations help the r-process in supernovae?

- oscillation increases the ν_e energy, makes $\nu_e + n \rightarrow p + e^-$ go faster
- oscillation tends to start late

Neutrino Flavor Transformation

Bipolar/nutation oscillations begin when the scale of the neutrino self interaction potential, $V_{\nu\nu} \sim G_F(n_{\nu,eff} - n_{\bar{\nu},eff})$ approaches the scale of the vacuum term $\delta m^2/E$.

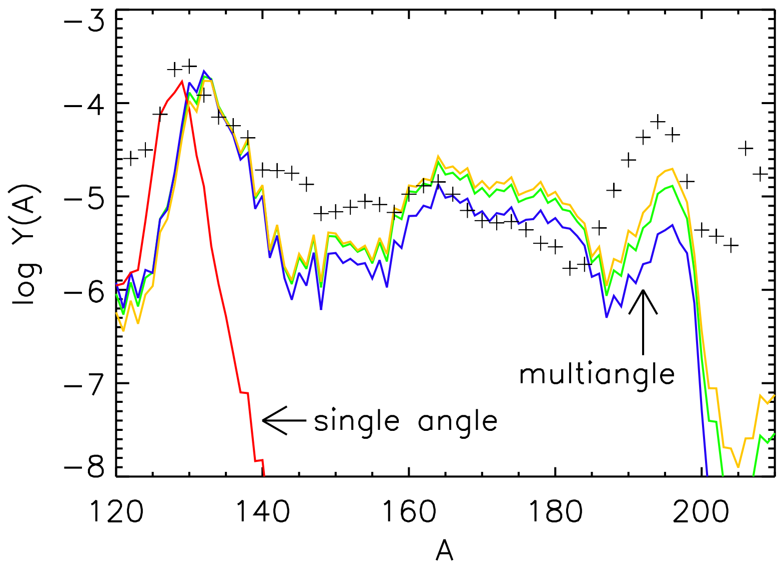


- ν_e solid line
- $\bar{\nu}_e$ dashed line
- green no oscillation
- blue oscillation

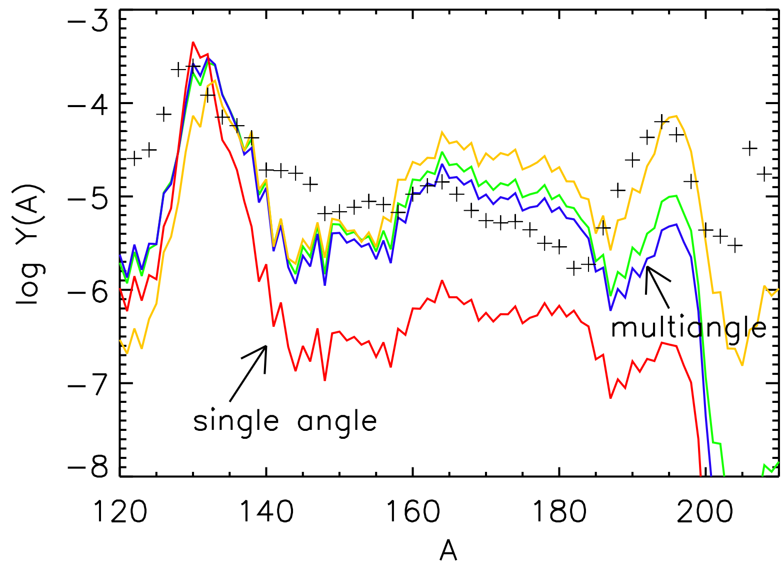
Fig. from Duan et al. 2011

Small but non-negligible impact on nucleosynthesis

In SN winds, the oscillation often starts after nuclei begin to form



Early time density profile, $s/k = 200$, $\tau = 15\mathrm{ms}$



Late time density profile, $s/k = 200$, $\tau = 18\mathrm{ms}$

wind conditions tweaked to create r-process favorable conditions

For recent discussion of PNS winds, see Arcones and Thielemann 2012

Neutrino Flavor Transformation and p-process in supernovae

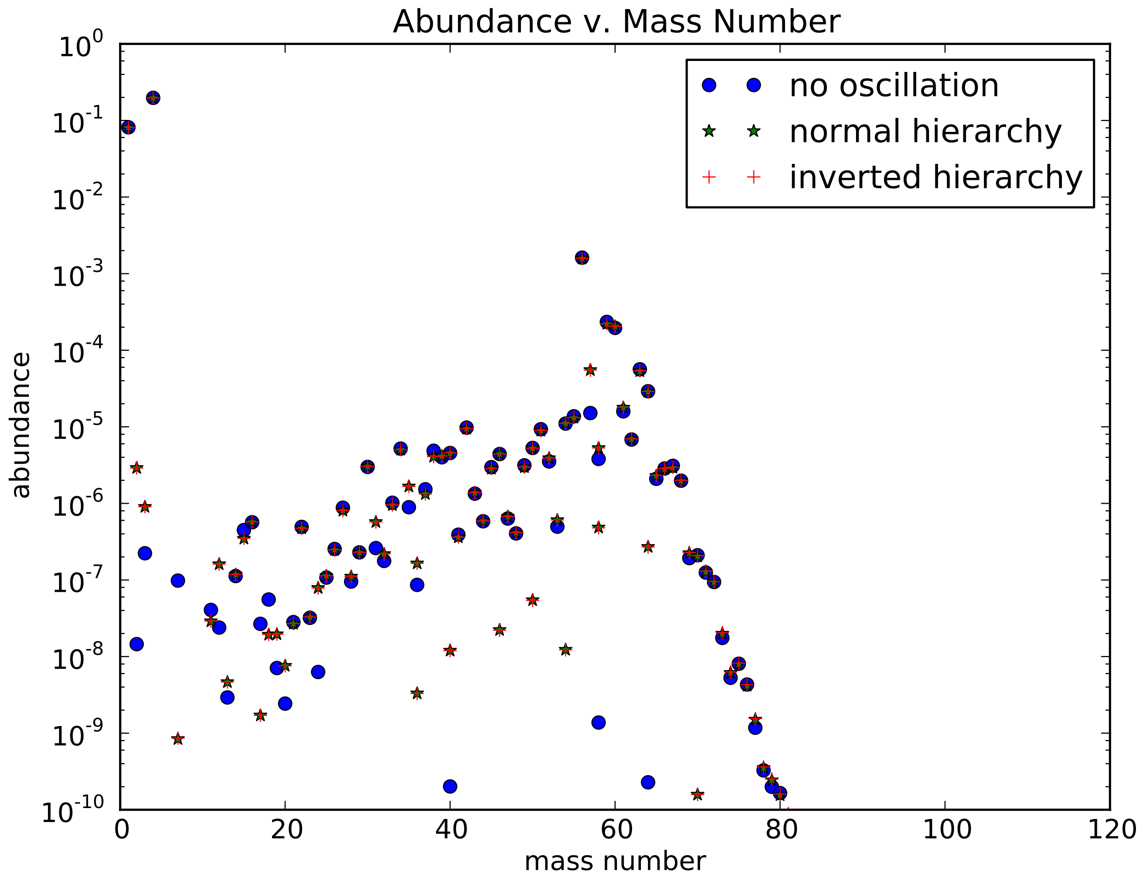


Fig. from C. Frohlich

Again, a small but non-negligible effect

Jets from Supernovae

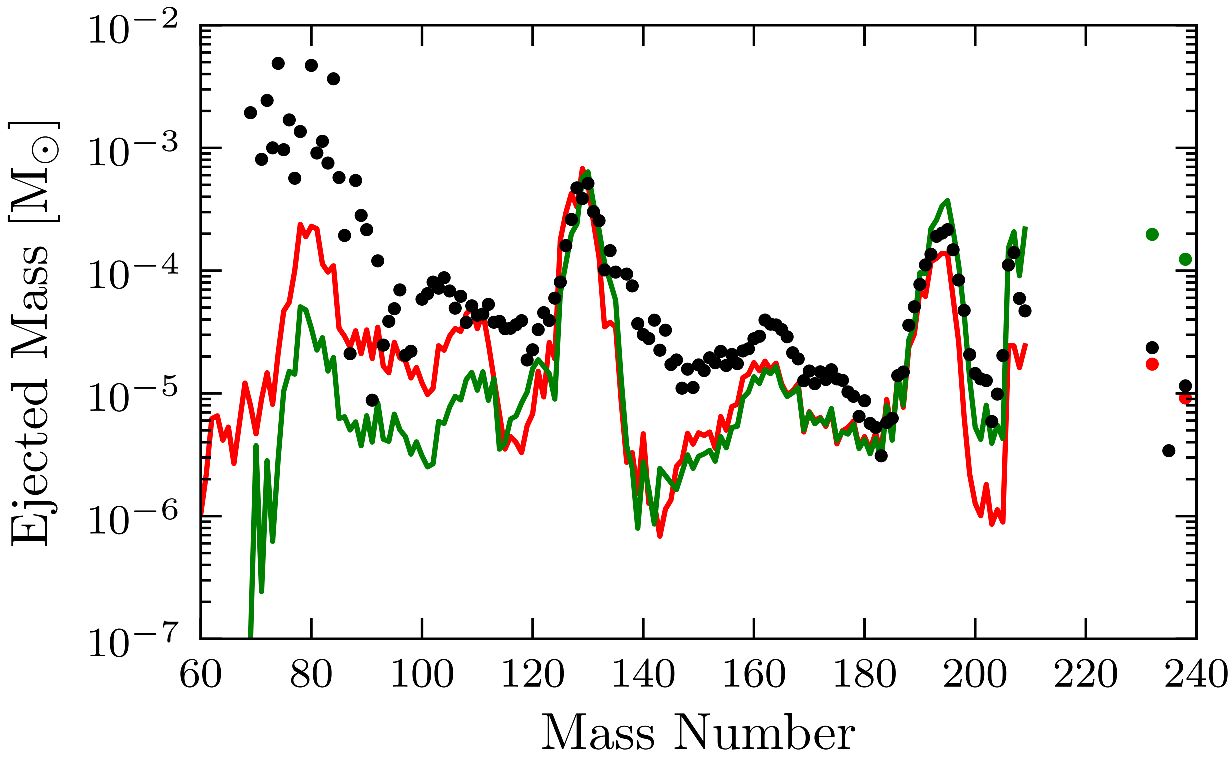
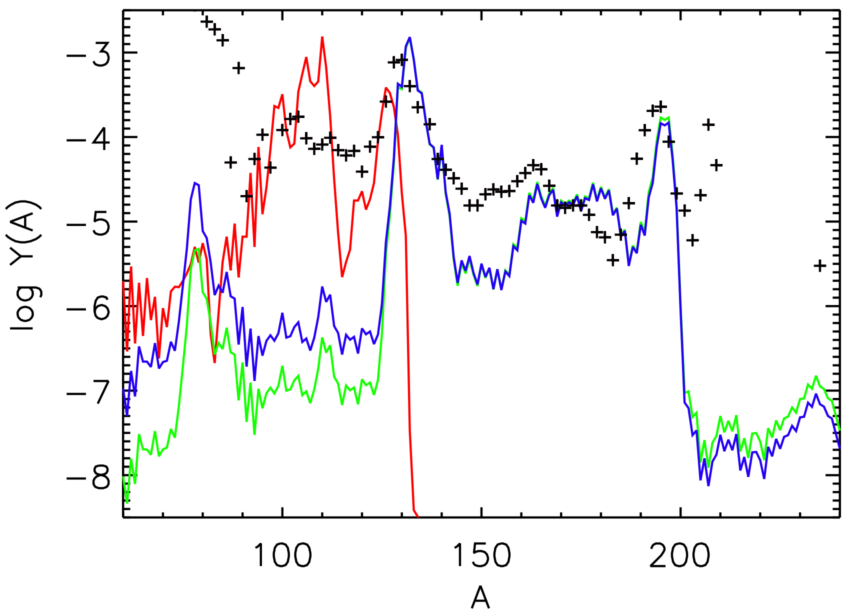


Fig. from C. Winteler et al. 2012

If you have a magnetorotationally driven jet, it is possible to eject material with little heating and little influence of the neutrinos. e.g. Winteler et al. 2012, Nakamura et al. 2012,Papish et al. 2013

Accretion Disk (Collapsar-type) Nucleosynthesis



- in disks neutrino potential can be negative
- matter potential is positive
- cancellation causes a new type of neutrino transformation

red - no oscillations, blue - oscillations

s/k $= 50$, $\beta = 1.4$ (moderate acceleration) figure from Malkus et al 2013

Neutrino Oscillations: scales

Modified wave equation

$$i\hbar c \frac{d}{dr}\psi_\nu = \begin{pmatrix} V_e + V_\nu^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & -V_e + -V_\nu^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix} \psi$$

Scales in the problem:

- vacuum scale $\frac{\delta m^2}{4E}$
- matter scale $V_e \propto G_F N_e(r)$
- neutrino self-interaction scale $V_\nu \propto G_F N_\nu * \mathrm{angle} - G_F N_{\bar{\nu}} * \mathrm{angle}$

V_ν has some subtleties. For proto-neutron star neutrinos V_ν term declines roughly as $1/r^4$

Neutrino Oscillations with Self-Interaction

Neutrino oscillations are with the self-interaction are numerically more demanding than standard matter enhanced neutrino effects. Calculations see Balantekin, Dighe, Duan, Fuller, Kajino, Kneller, Raffelt, Volpe, Yoshida and more

1. Non-linear effects $V_\nu \sim |\psi_\nu|^2$
2. Requires multi-group treatment: Background involves sum over neutrino momentum and angle.

We rewrite the problem as an S-matrix problem

$$i\hbar \frac{dS}{dx} = HS$$

and solve in an adiabatic basis. Kneller and McLaughlin

Accretion disk neutrino transition regions

Type I - Matter enhanced region

- Traditional MSW region
- vacuum interaction strength is the same size as matter potential
- neutrino self interaction strength is small
- i.e $\delta m_{ij}^2/E_\nu \sim \sqrt{2} G_F N_e \gg V_{\nu\nu}$

Type II - nutation/bipolar

- "Traditional" nutation in NFIS picture (also called bipolar)
- $\delta m_{ij}^2/E_\nu \sim V_{\nu\nu}$
- occurs closer to PNS than Type I regions
- occurs when matter potential is both large and small

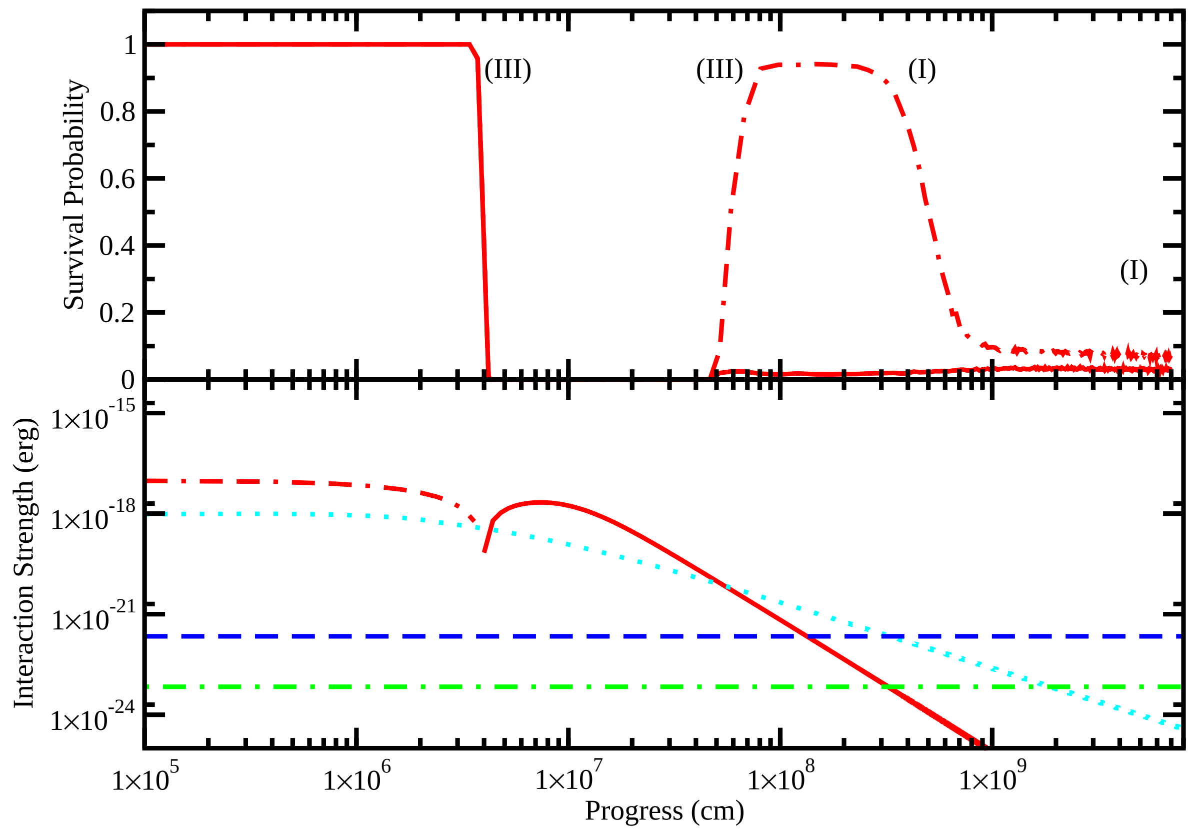
Accretion disk transition regions

Type III "Neutrino - Matter enhanced" New!

- Self-interaction potential $\sim$ matter potential
- vacuum interaction strength is small
- i.e. $\delta m_{ij}^2 / E_\nu << \sqrt{2} G_F N_e \sim V_{\nu\nu}$
- potentials have opposite signs! cancellation!
- occurs in both hierarchies
- not a usual situation in supernovae

Massive star accretion disks:
$\bar{\nu}$ dominated first, ν later

Malkus et al. 2012



Upper panel: solid red - electron neutrino survival probability

Upper panel: dashed red - electron antineutrino survival probability

Flavor Transformation: PNS vs. Disks

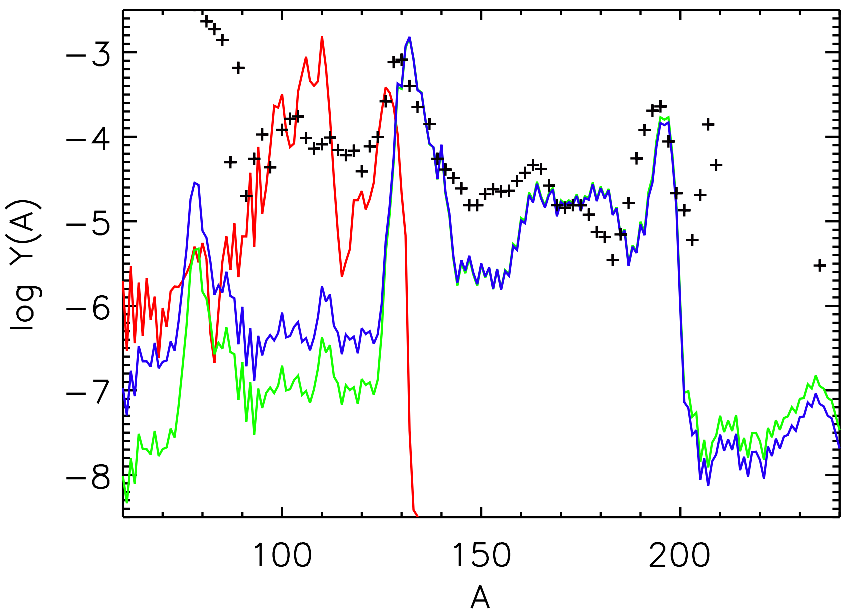
Supernovae Neutrinos

- In the SN, oscillations tend to occur after the most important point for wind nucleosynthesis
- In the SN, oscillations increase ν_e, $\bar{\nu}_e$ capture rates
- There is some re-arrangement of the abundance pattern

Accretion disk neutrinos

- In the accretion disk, they occur earlier, because of the "matter-neutrino enhanced" transition Malkus et al 2012
- In the "collapsar-type" accretion disk, oscillations decrease ν_e, $\bar{\nu}_e$ capture rates
- One expects significant changes the abundance pattern

Accretion Disk (Collapsar-type) Nucleosynthesis



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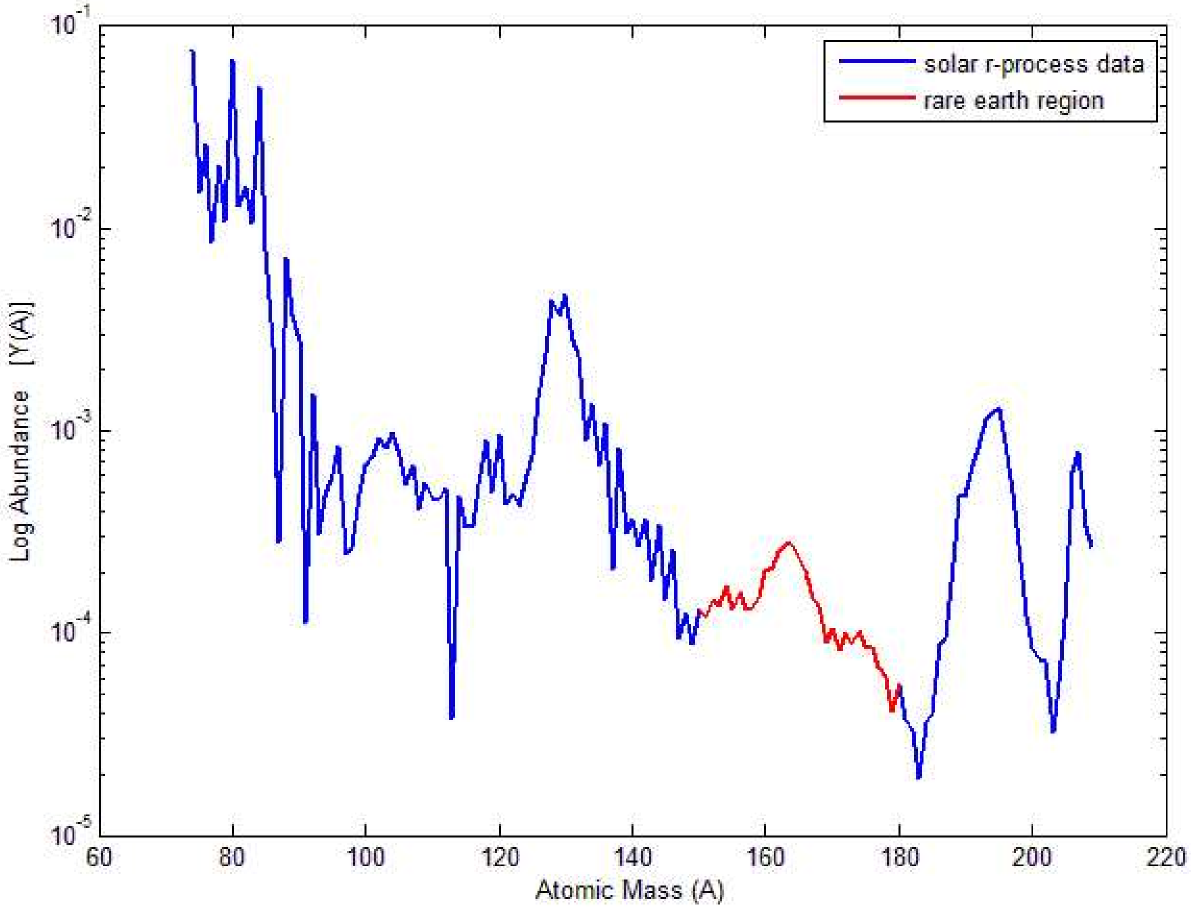
Back to ideas for the r-process:
jets, disks, compact object mergers

They all claim to have enough neutrons...

How can we decide? Can radioactive beams help?

The rare earth peak

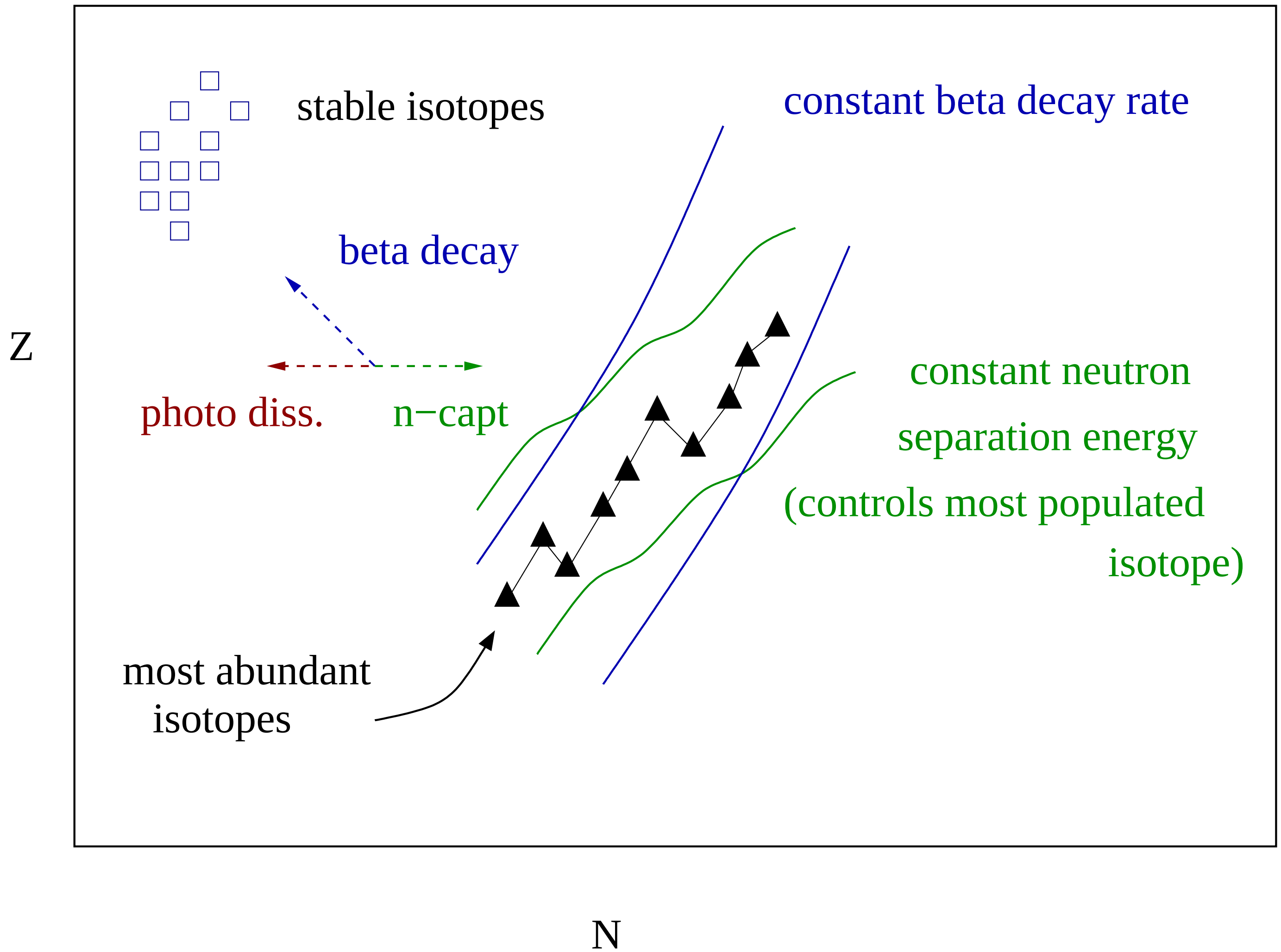


Solar abundance data with the rare earth peak in red

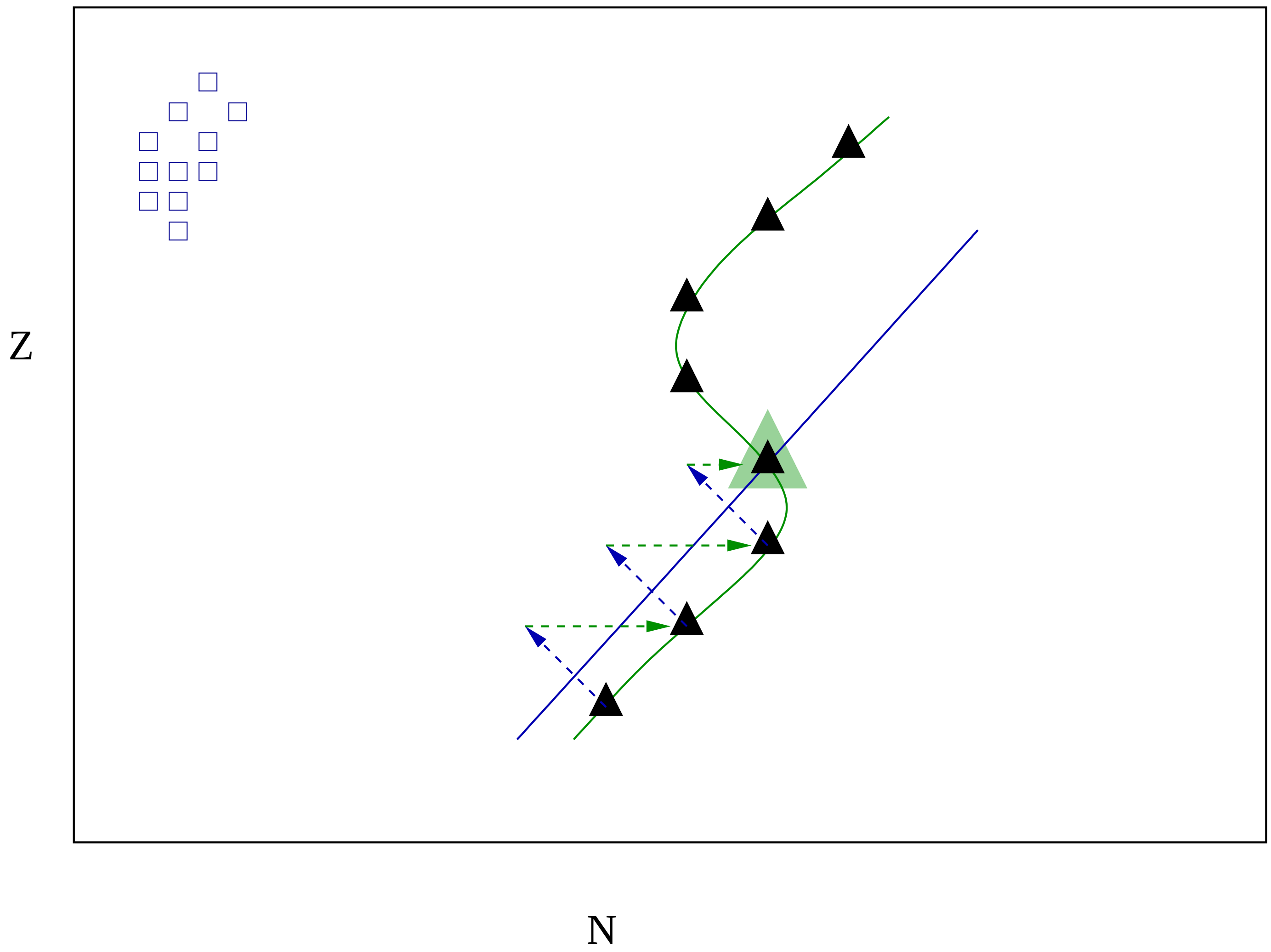
Constaining conditions using abundance patterns
e.g. rare earth peak

- Determine how the rare earth peak forms
- Consider the nuclear physics uncertainties
- Determine the range of thermodynamic conditions that are successful

How to read r-process flow plots

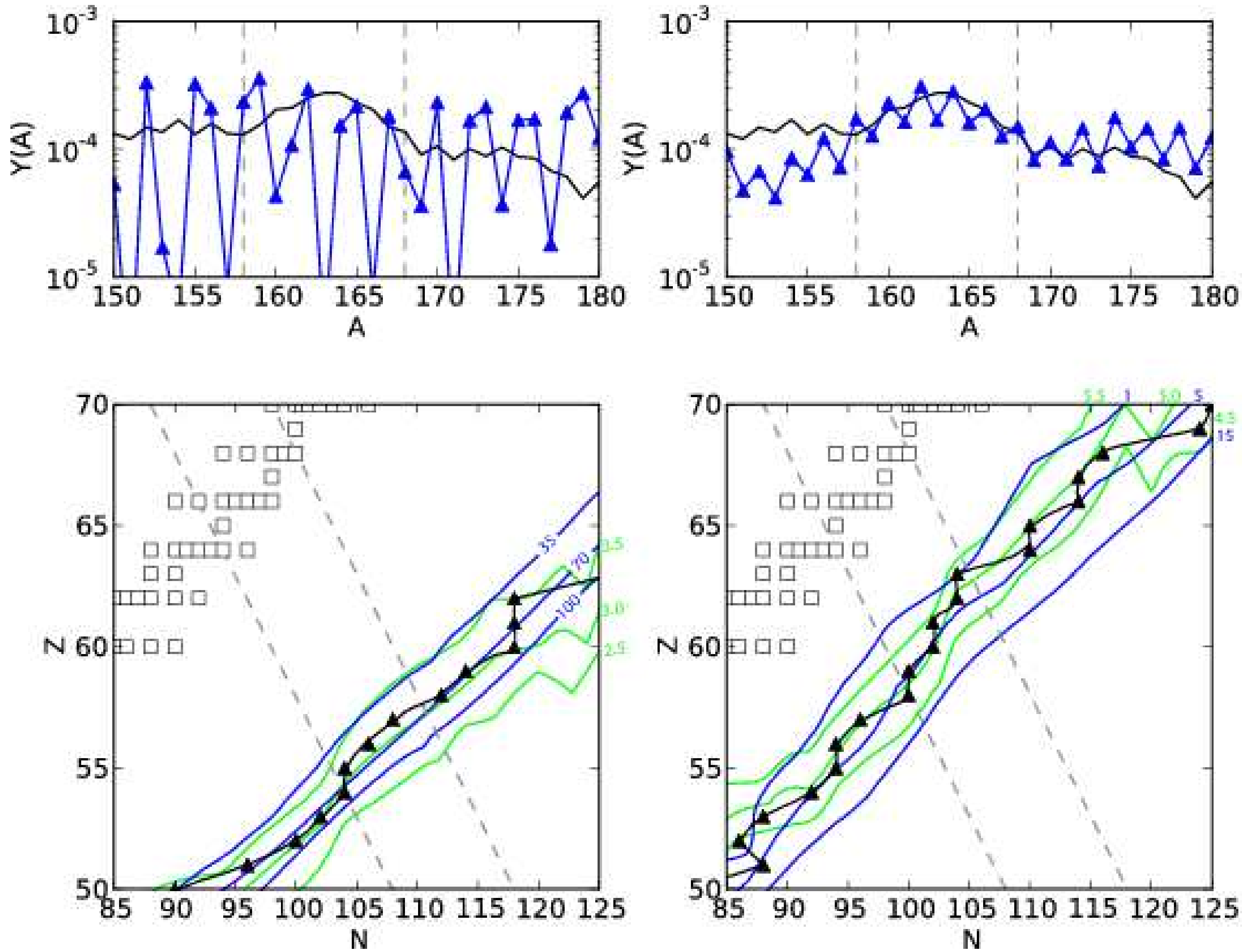


How to form structures



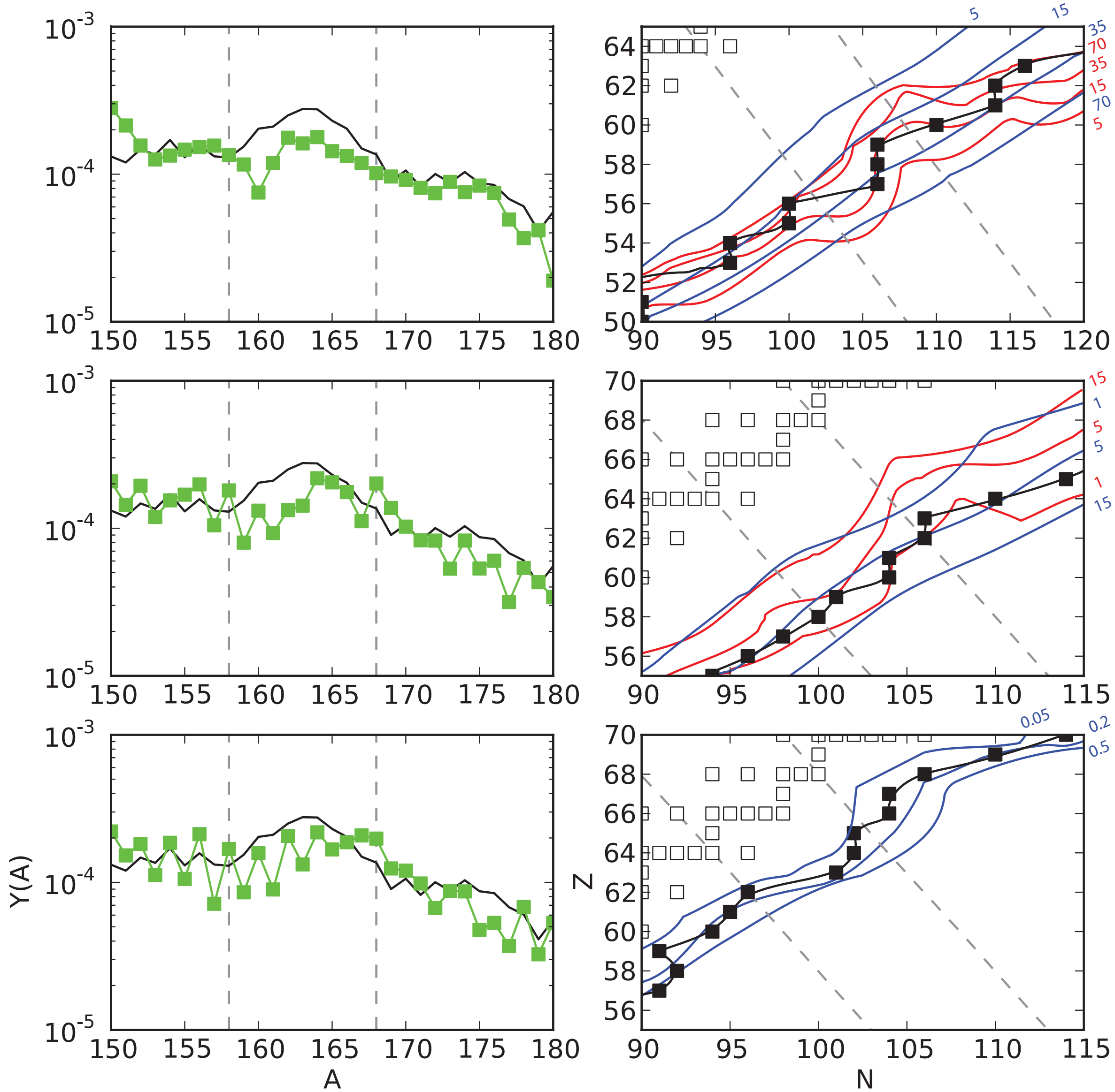
Hot rare earth peak formation

Mumpower, GCM, Surman 2012, see also Surman and Engel 1997



Neutron capture just below the peak and photo-dissociation above FRDM

Correct structure must persist until neutrons are exhausted

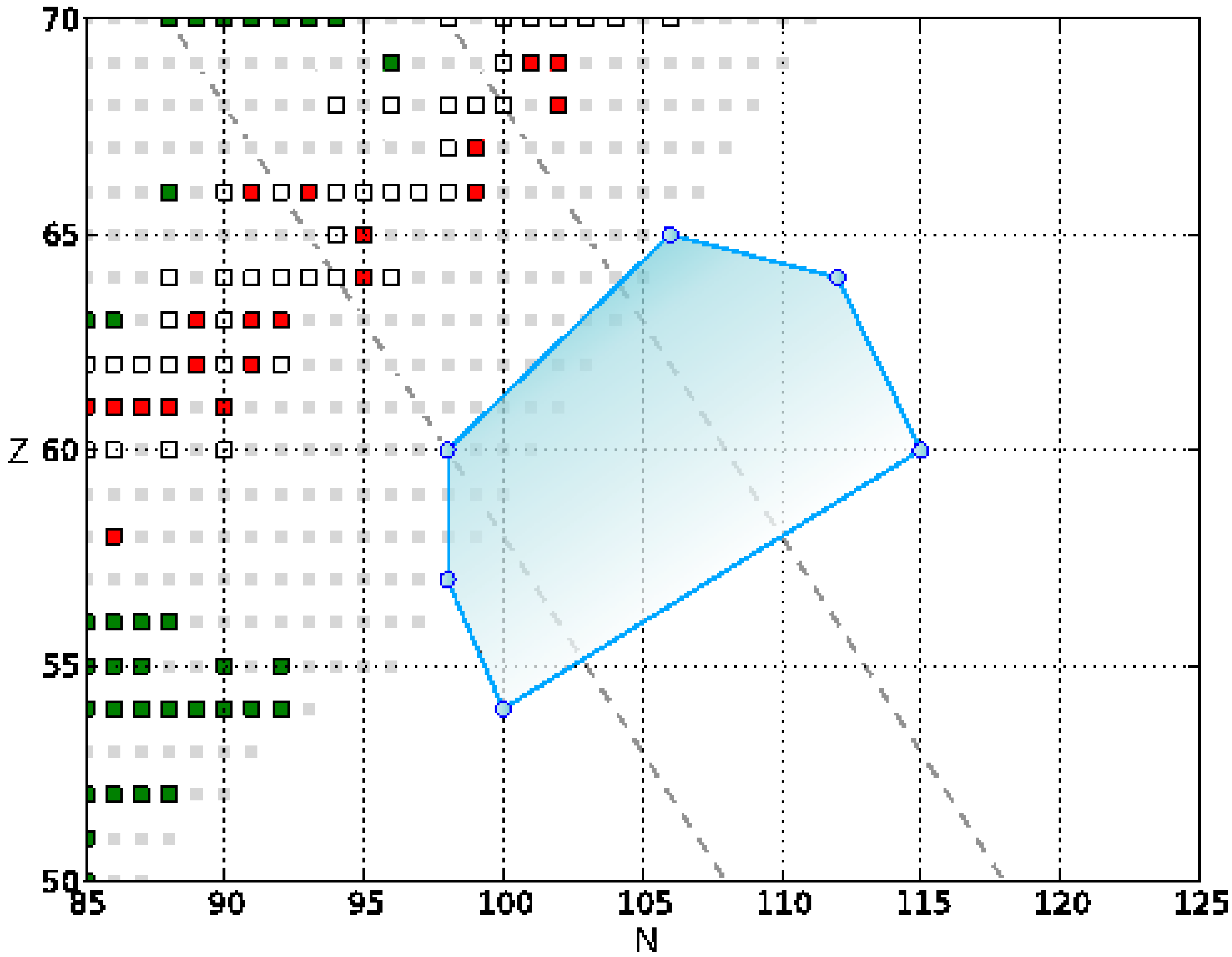


Calculation with different mass model ETFSI

Reduce nuclear physics uncertainties:

Most important nuclei for the formation of the rare earth peak

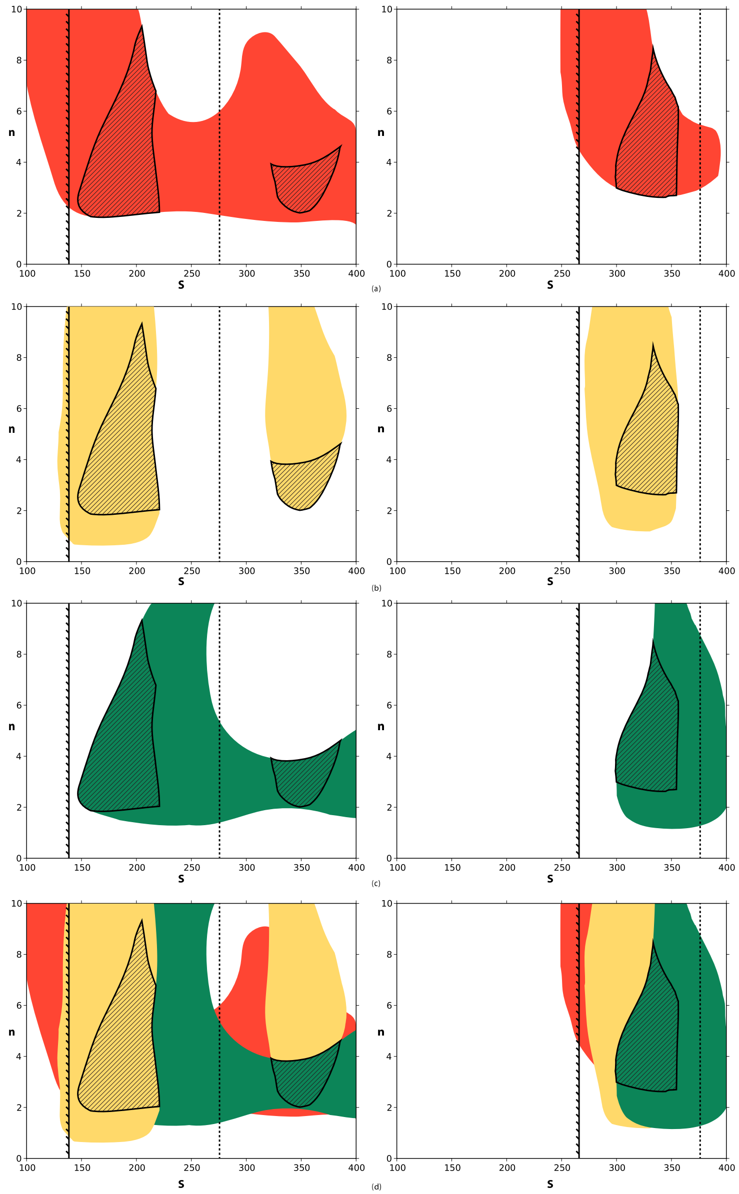
Mumpower, GCM, Surman 2012



Conclusions

- Exciting era in supernova nucleosynthesis
- Calculations are improving as are observations
- r-process not yet settled: compact object mergers, SN jets, accretion disks
- Neutrino oscillations are a significant factor in accretion disk nucleoesynthesis
- Nailing down nuclear properties will give us additional clues to astrophysical conditions for example, that make the rare earth peak

Constraints on the rare earth peak from solar data



Red: comparison to data with $G^{REP} < 0.15$

Yellow: rare earth to A=195 ratio to within a factor of 2

Green: measures late time neutron capture on the sides of the peak $\Delta G^{A=150-180}_{final/min} < 1$ see also Arcones and Martinez-Pinedo 2011

Constrain cooling time scale $T \sim t^{-n}$ and entropy/baryon s

Calculation with the FRDM (finite range droplet model) using $Y_e = 0.3$, $Y_e = 0.4$