Nuclear and neutrino physics in the r-process

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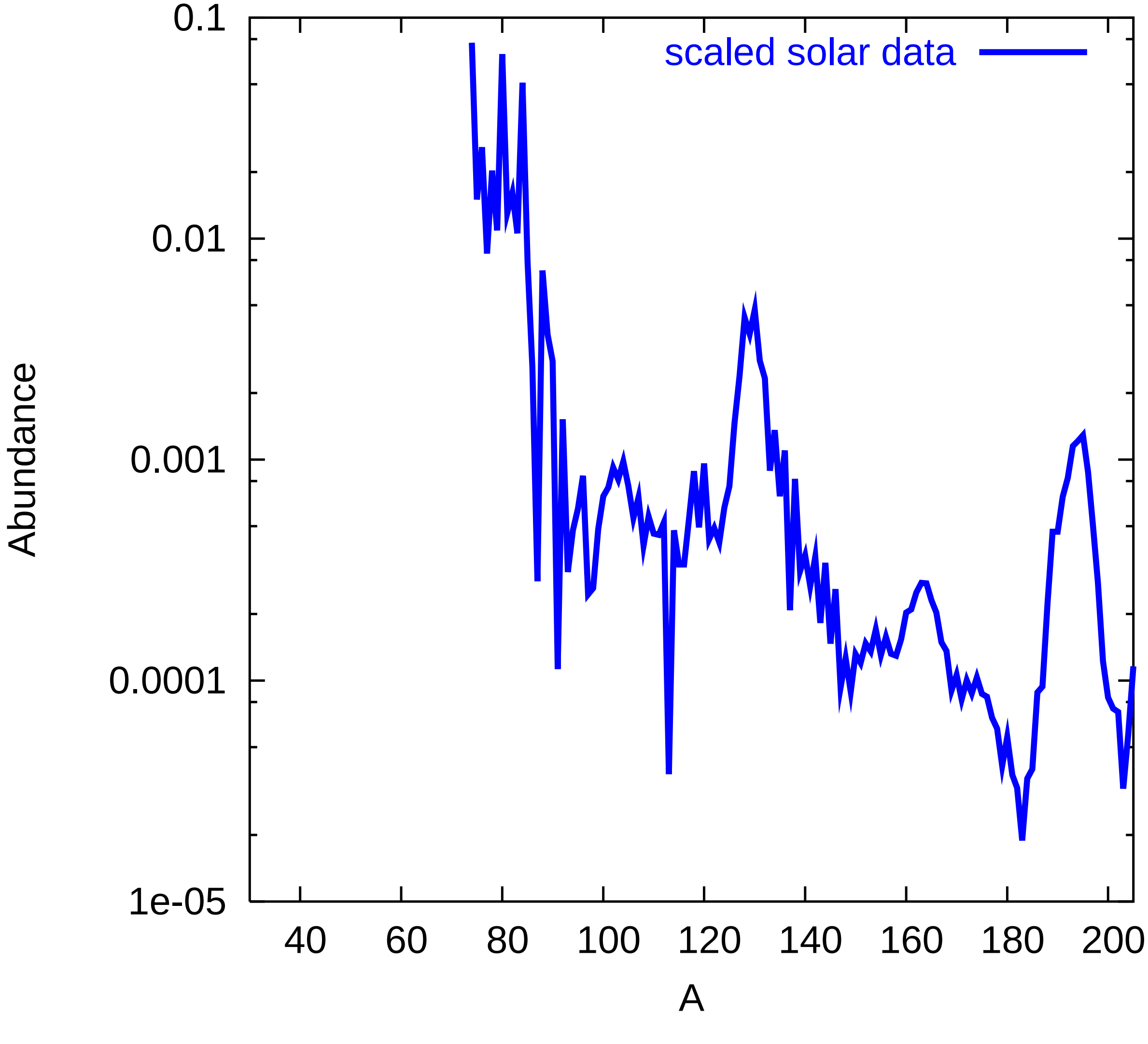
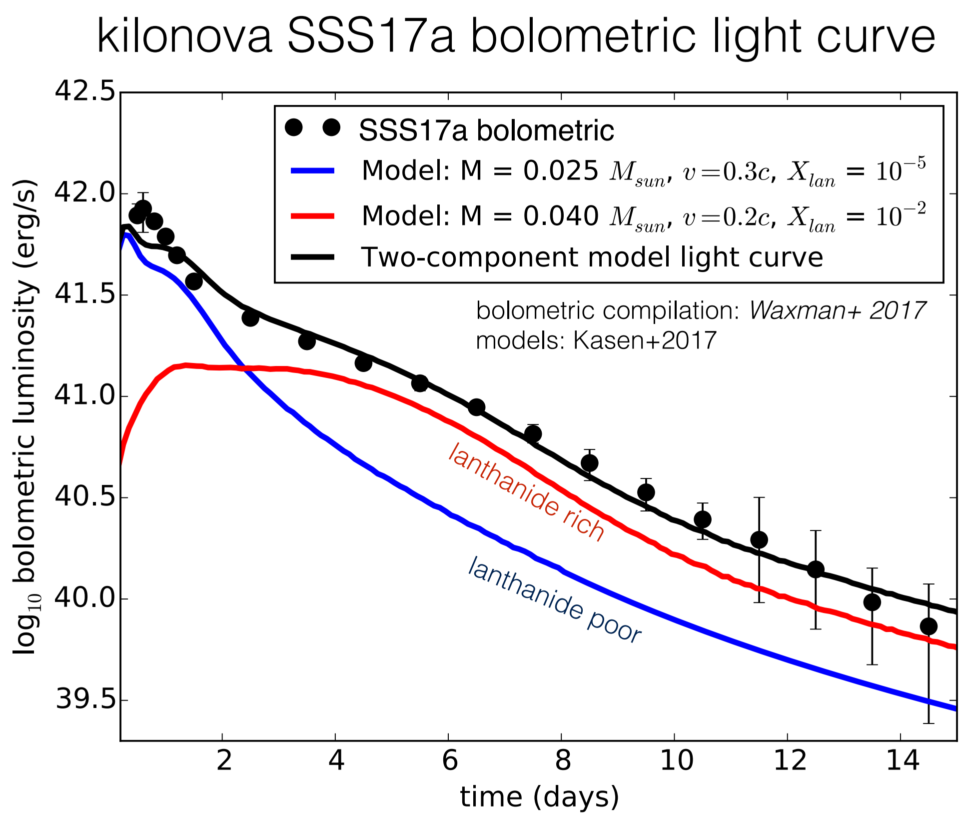
The r-process

- Elements beyond the iron peak in three main categories
  - r-process
  - s-process
  - p-process
- examples of r-process elements
  - Europium
  - Platinum
  - Uranium
  - Thorium

Solar Abundances

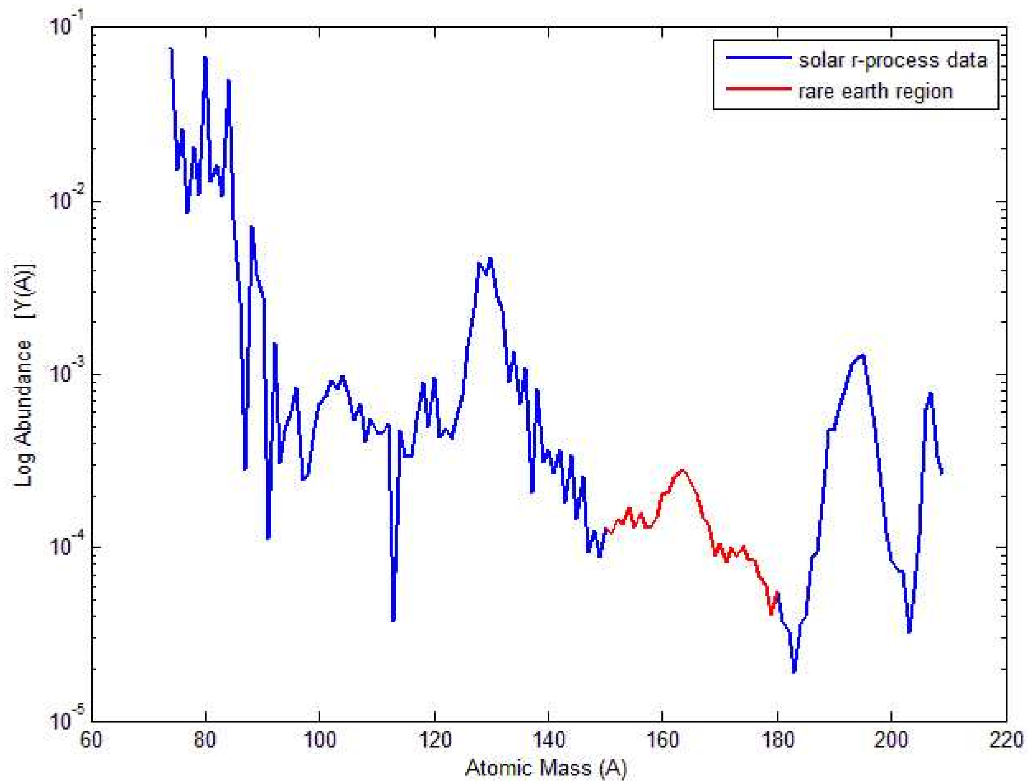


Electromagnetic counterpart to the neutron star merger GW signal

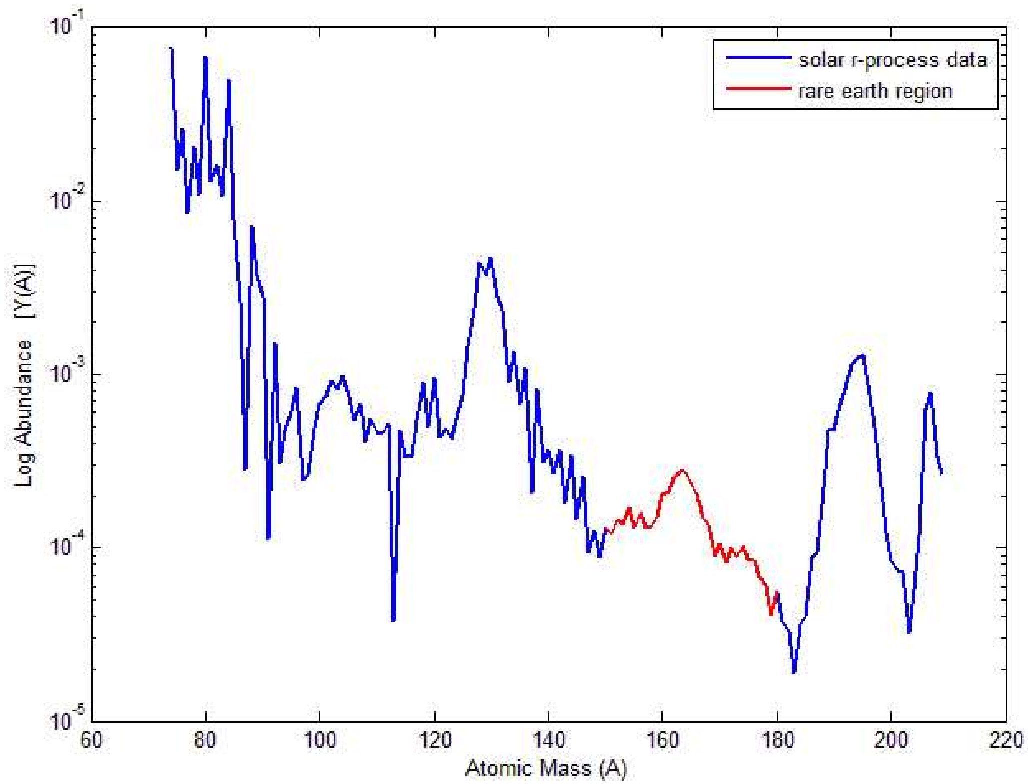


Material with significant opacity is the best fit to the data Slide credit: Dan Kasan

Where are the lanthanides?

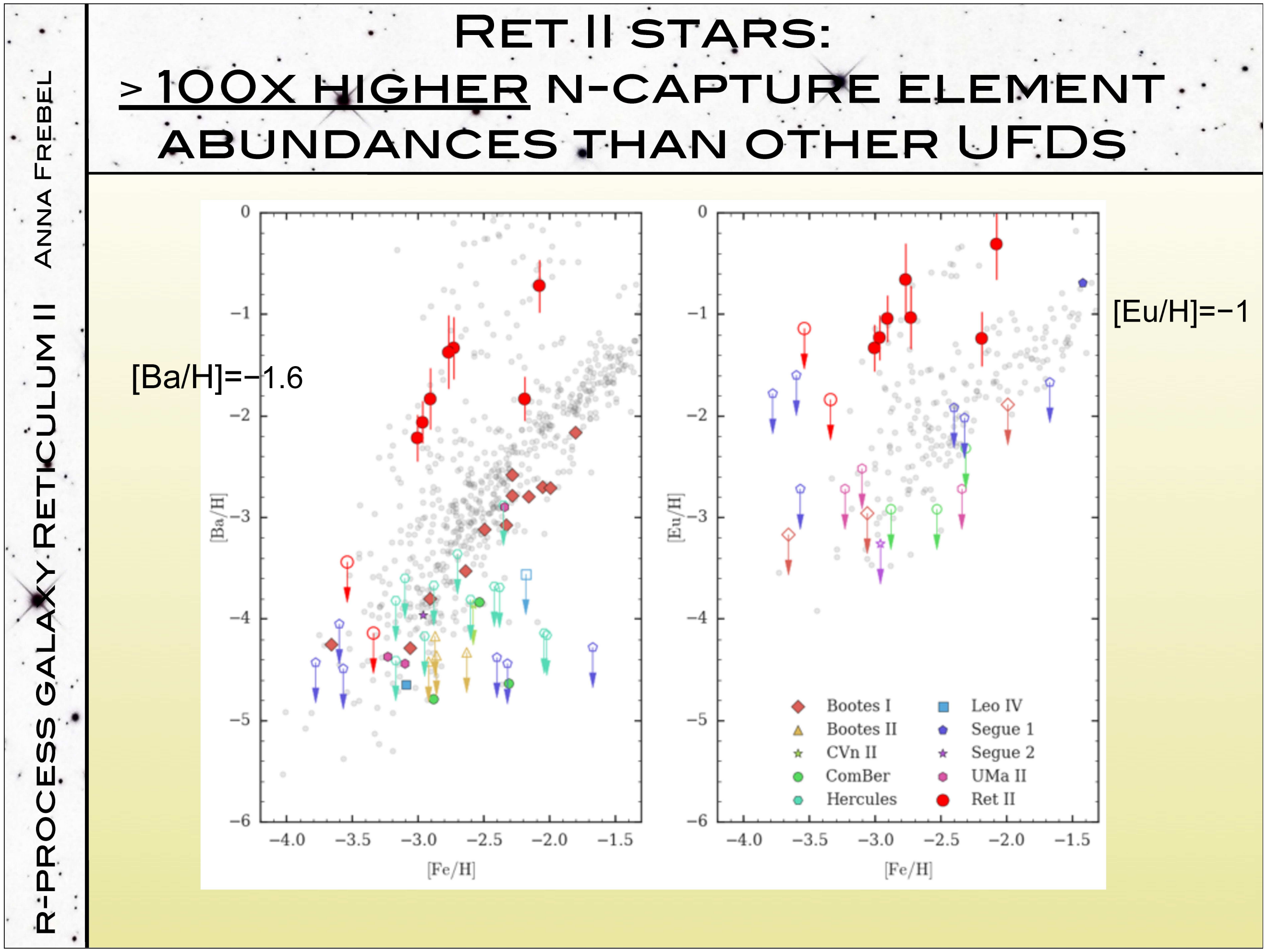


This gives a hint about the r-process



If lanthanides are required to fit the electromagnetic counterpart, then at least some r-process was synthesized in this merger.

Ultra faint dwarf galaxies



One galaxy of ten has r-process elements Slide credit: Anna Frebel

This gives another hint

These observations (Ji et al 2016) suggest a “rare and prolific” event. The rare event could be

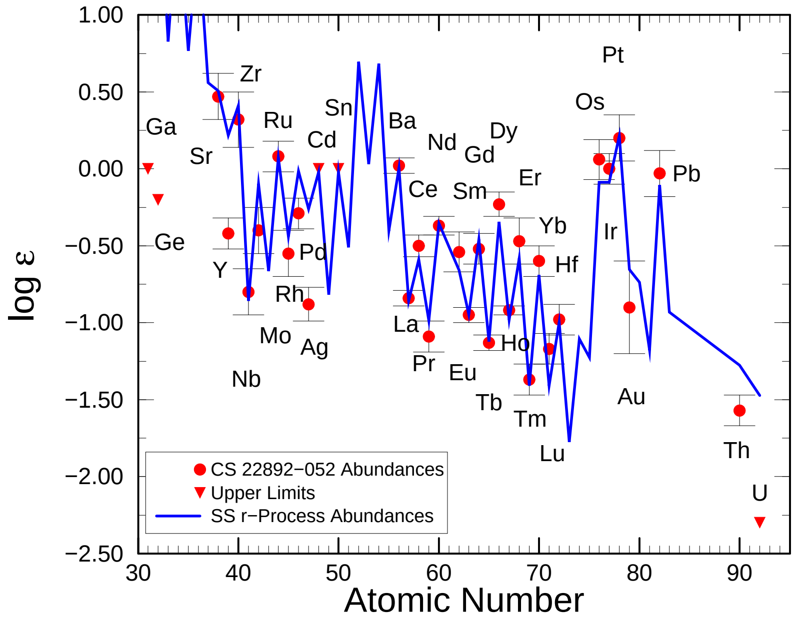
- neutron star merger
- black hole neutron star merger
- jets from core collapse
- black hole accretion disk supernovae
- other unusual core collapse supernovae

But “regular” core collapse supernovae are disfavored.

r-process in Halo Stars:

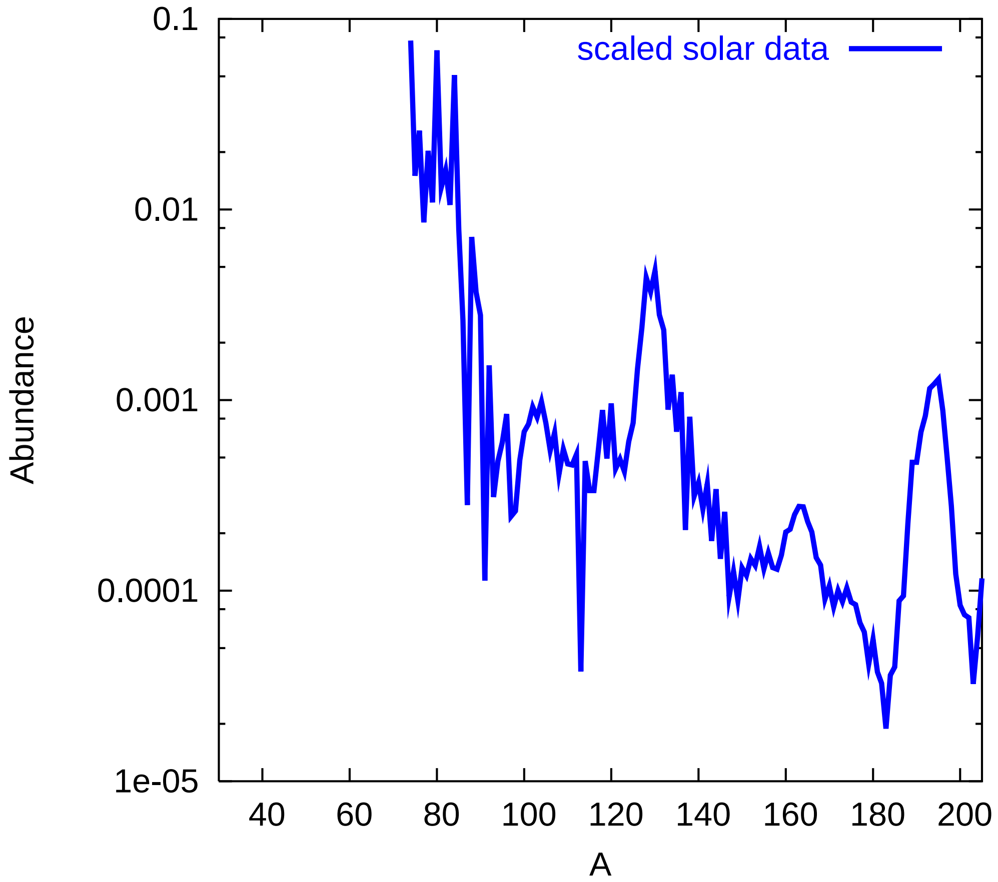
Halo Stars:

- two r-process sites
  - Figure from Cowan and Sneden (2004)
- robust "main" r-process



A third hint

At least in some old stars, the lanthandides are produced together with the 3rd peak.



A couple open questions regarding the r-process

- Are neutron star mergers the only site of the r-process?
- Where in the merger are the r-process elements made?

Nucleosynthesis from neutron star mergers

- tidal ejecta
- collisional ejecta

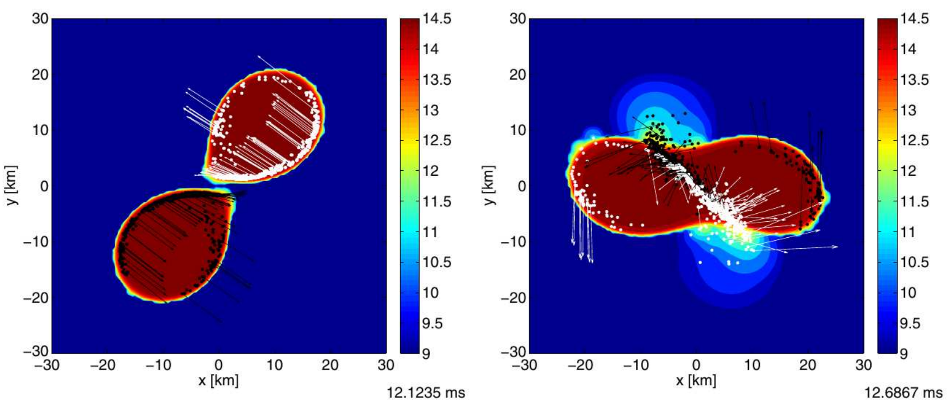


fig. from Bauswein et al 2013

- disk/hypermassive NS outflow
- outflow from viscous heating

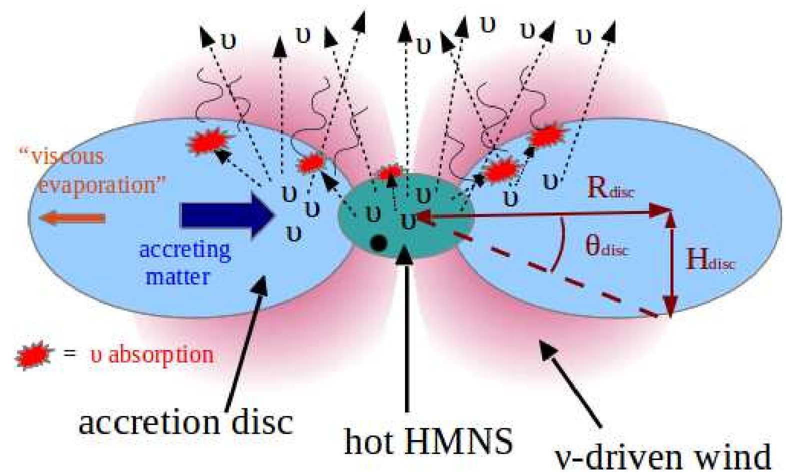
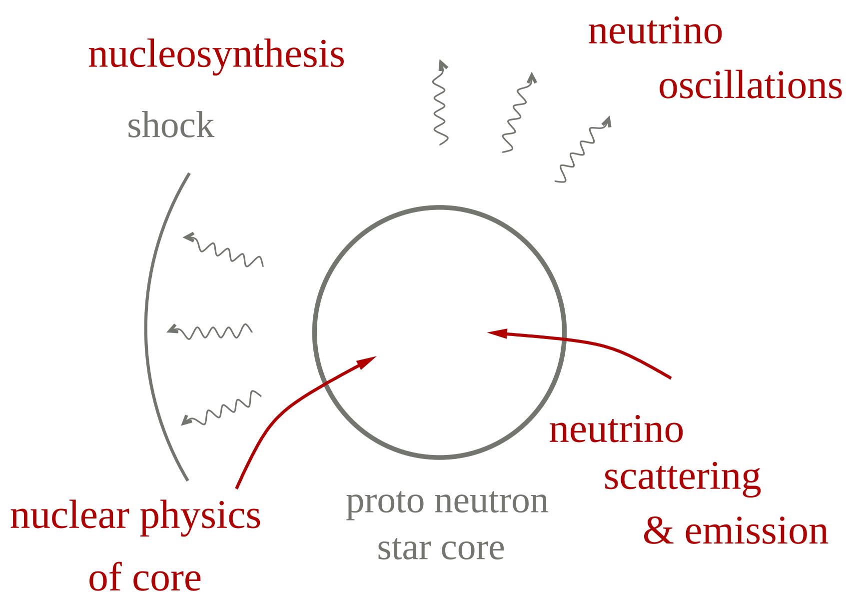
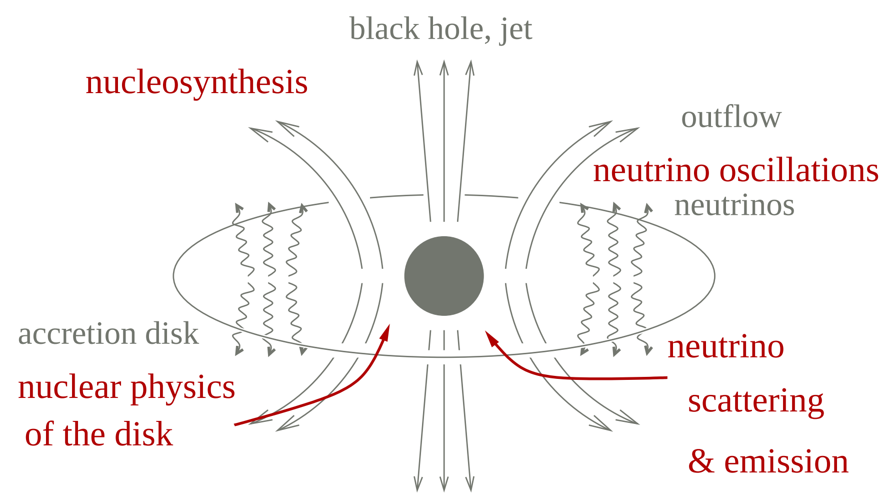


fig. from Perego et al 2014

Explosions of Massive Stars:
Where is the nuclear-neutrino physics?





proto-neutron star

accretion disk aound central object

Some roles that nuclear/neutrino physics plays

- decays of particular nuclei drive the light curve
- nuclear structure/reactions determine the abundance pattern for a given set of astrophysical conditions
- most of the relevant nuclei are unmeasured/off stability
- interactions involving neutrinos determine relative numbers of neutrons and protons near central object
- neutrinos flavor transform

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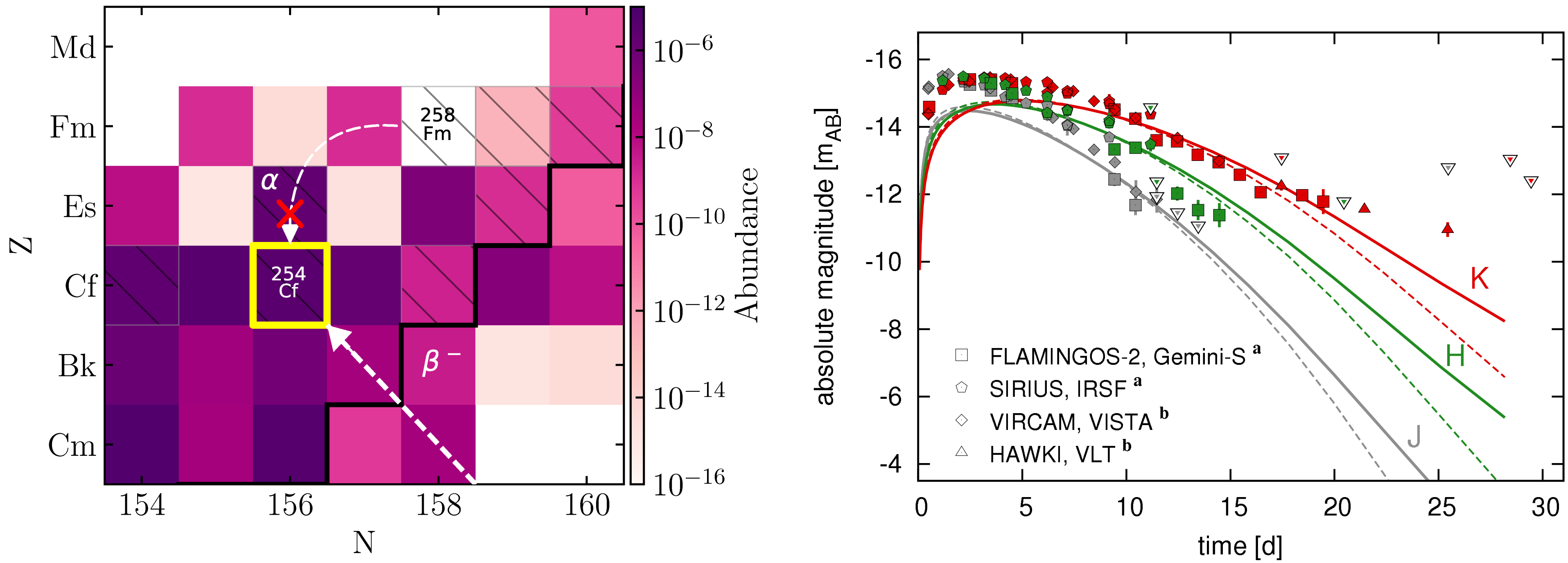
Fission of 254Cf changes the light curve



Late time beta decay feeds 254Cf which is very long lived

figs. from Zhu et al 2018

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Abundance pattern with different mass models

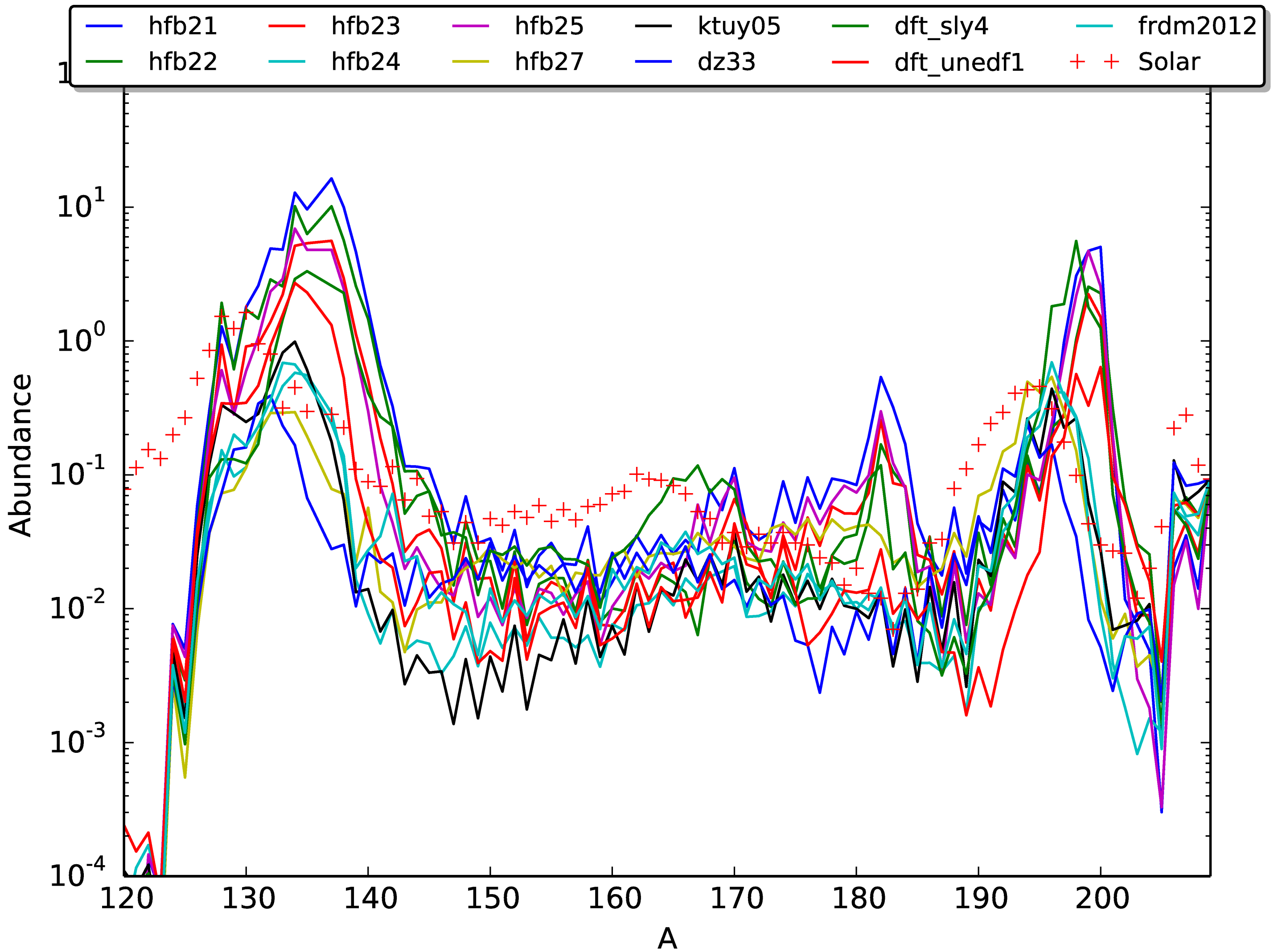

Figure credit: FIRE collaboration

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Experimental reach

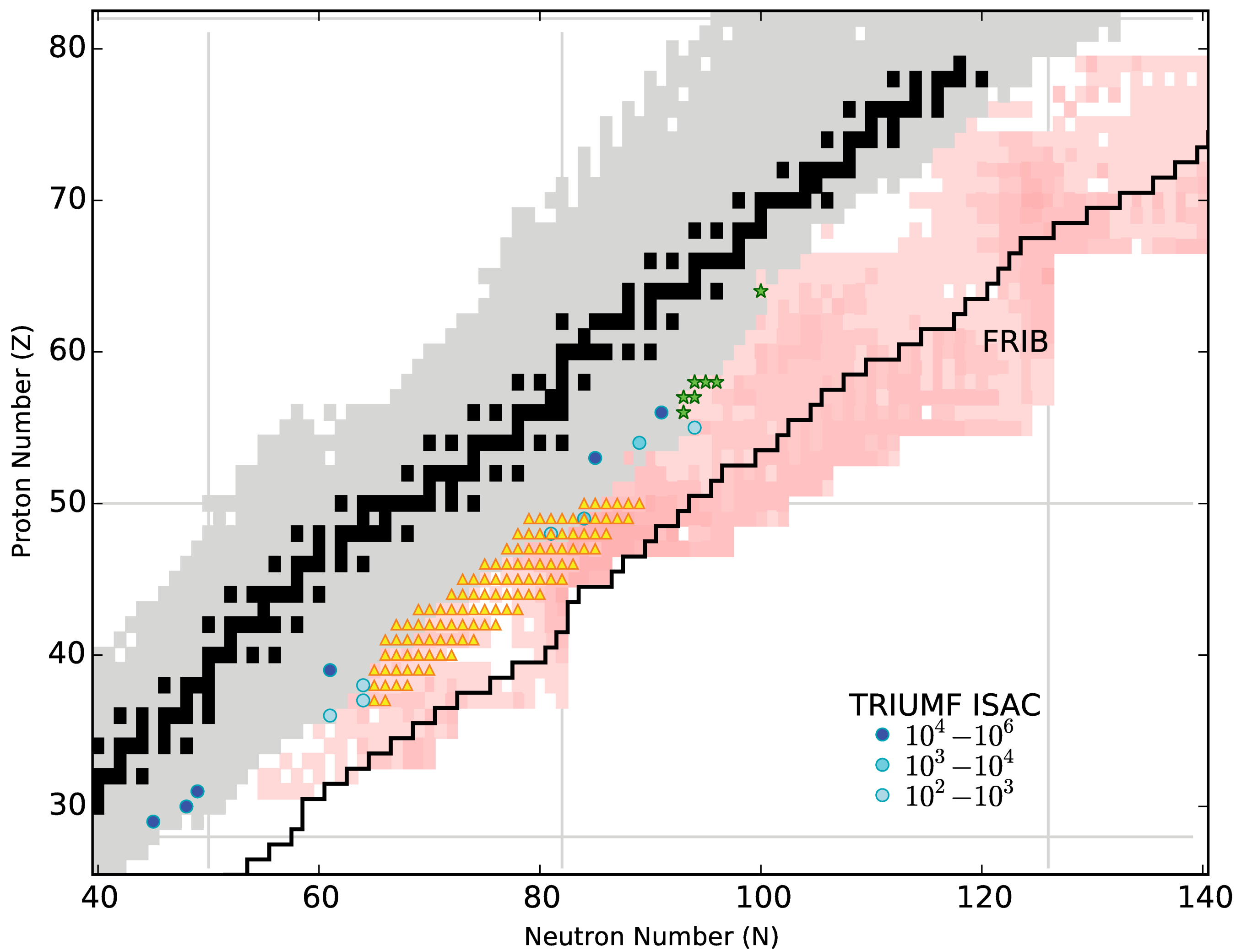


Fig. from Mumpower et al 2016

What can nuclear measurements contribute to our understanding of the site of the r-process?

And which nuclei are most useful to measure?

Answer this question with a theory technique: reverse engineering

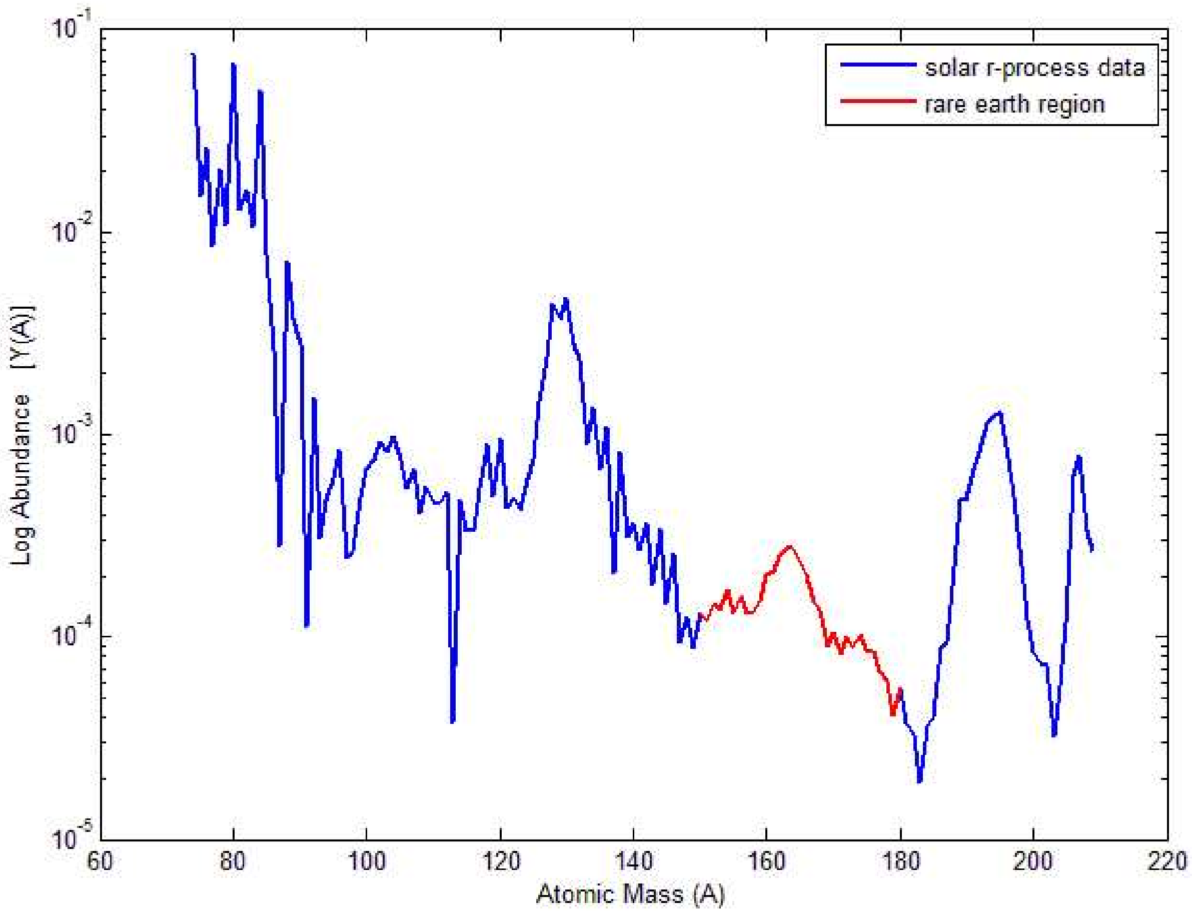
Reverse Engineering

Predicts trends in the nuclear masses

- using the measured r-process abundance pattern
- and Markov Chain Monte Carlo (MCMC)

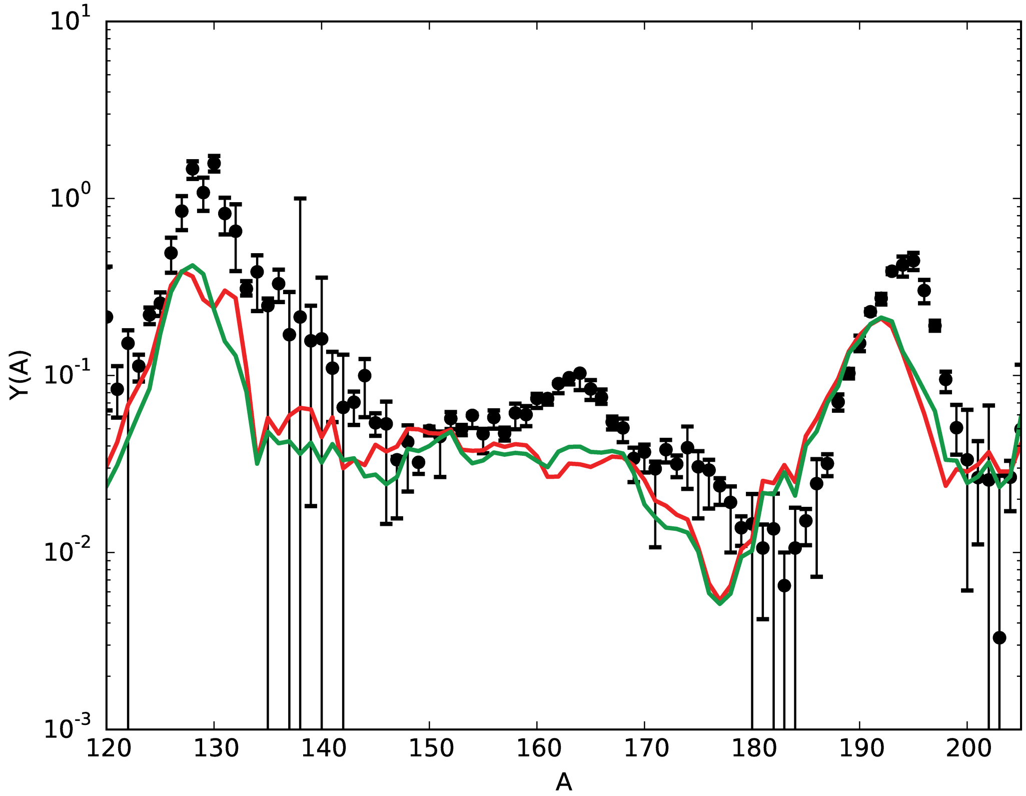
Not intended as a replacement for a mass model, as it uses different data.

Example: the rare earth peak



Solar abundance data with the rare earth peak in red

Step one: Identify a "base" mass model



Choose the Duflo-Zuker mass model since it doesn't produce a rare earth peak, green line is "very neutron rich cold conditions", red line is "hot conditions" Fig. from Mumpower et al 2016

Step two: Add a term to the base model

$$M(Z, N) = M_{DZ}(Z, N) + a_N e^{-(Z-C_Z)^2/(2f)} \quad (1)$$

Decision: let each isotone be independent (a_Ns). Why? Measured data shows similar isotone structure for nearby elements. Require an exponential fall off in element number (Z) to avoid altering measured masses and also to keep the fit to a local region.

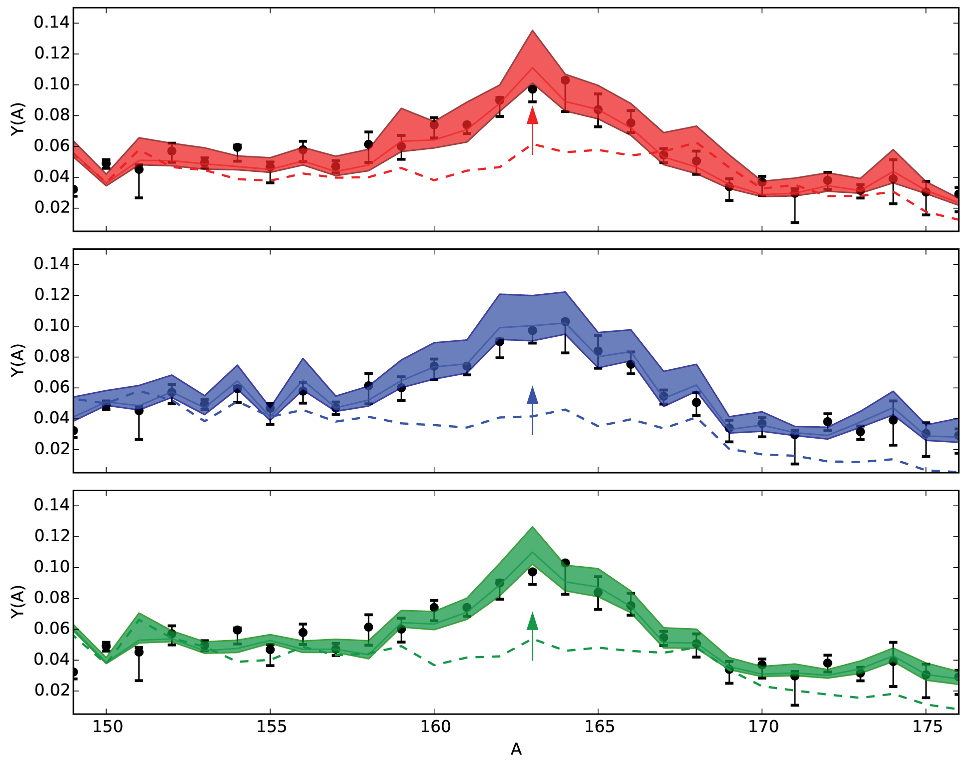
Step two: Add a term to the base model

$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C_Z)^2/(2f)} \tag{2}$$

Now use MCMC to determine the a_N and the C_Z

Details: Metropolis algorithm, start with all $a_N = 0$, for each choice of a_N, C_Z consistent separation energies, beta decay Q values and neutron capture rates are calculated, algorithm converges in about 10,000 steps.

Example calculations: success in matching the abundance pattern



Mumpower et al 2017

Mass surface for "hot" conditions

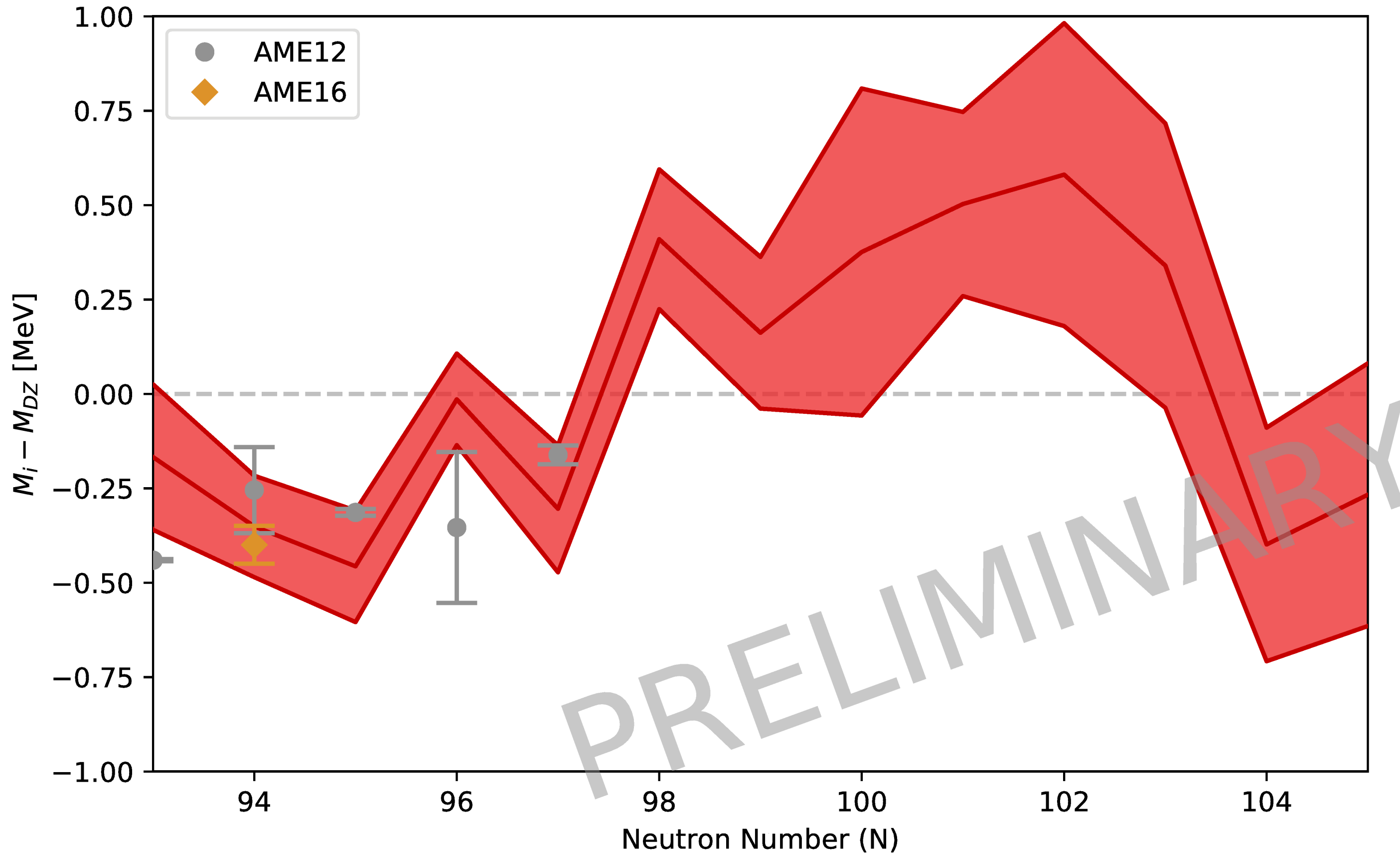
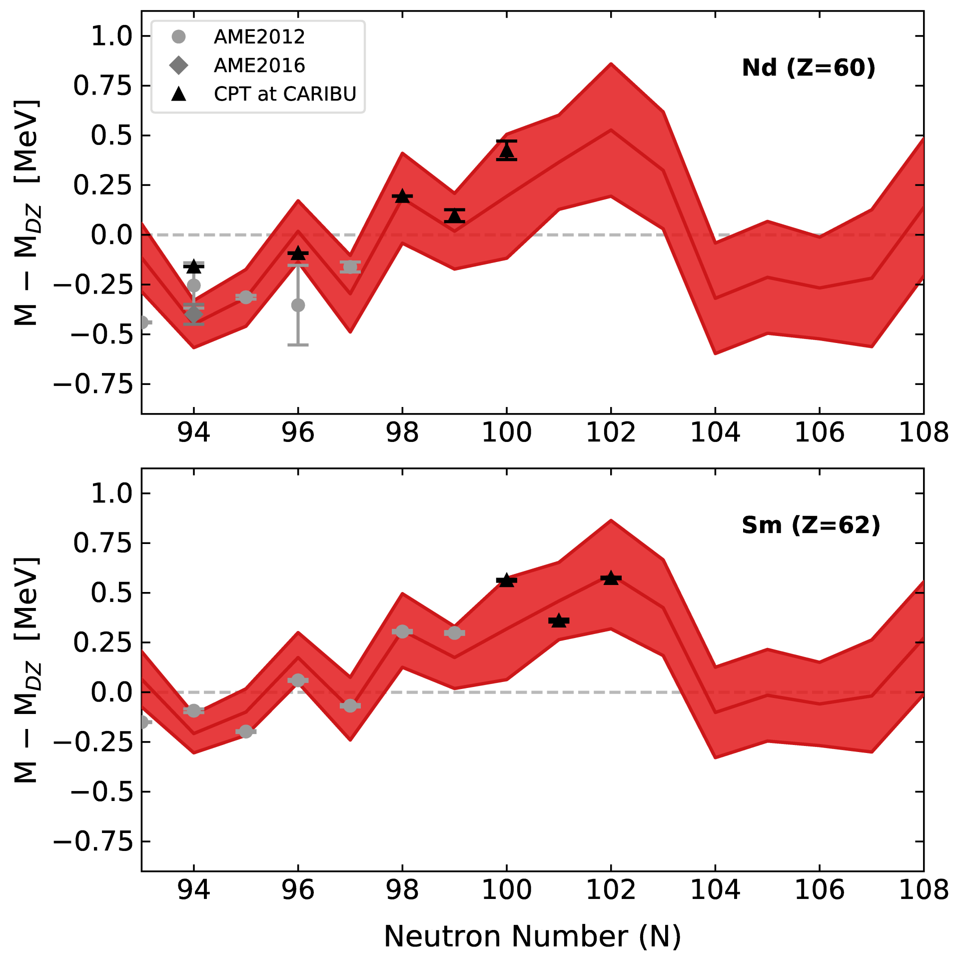


Figure of Neodynium mass surface from Nicole Vassh

Mass surface for “hot” conditions



Orford, Vaash, et al PRL 2018

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- neutrinos transform

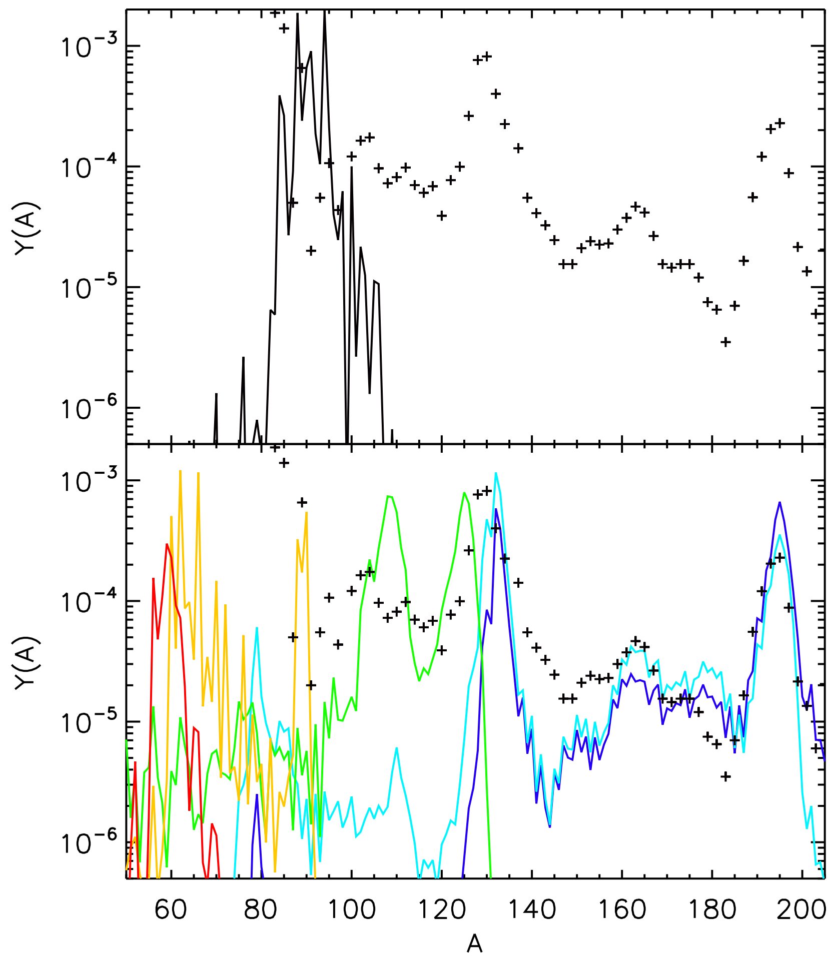
How neutrinos influence nucleosynthesis

Neutrinos change the ratio of neutrons to protons

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

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

So different neutrino spectra affects the elements produced



Accretion disk wind nucleosynthesis, Malkus et al '16, see also Surman et al '06, Wu et al '17

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Neutrino flavor transformation

alters the numbers of neutrons and protons

Neutrinos change the ratio of neutrons to protons

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

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

Oscillations change the spectra of ν_es and $\bar{\nu}_e$s

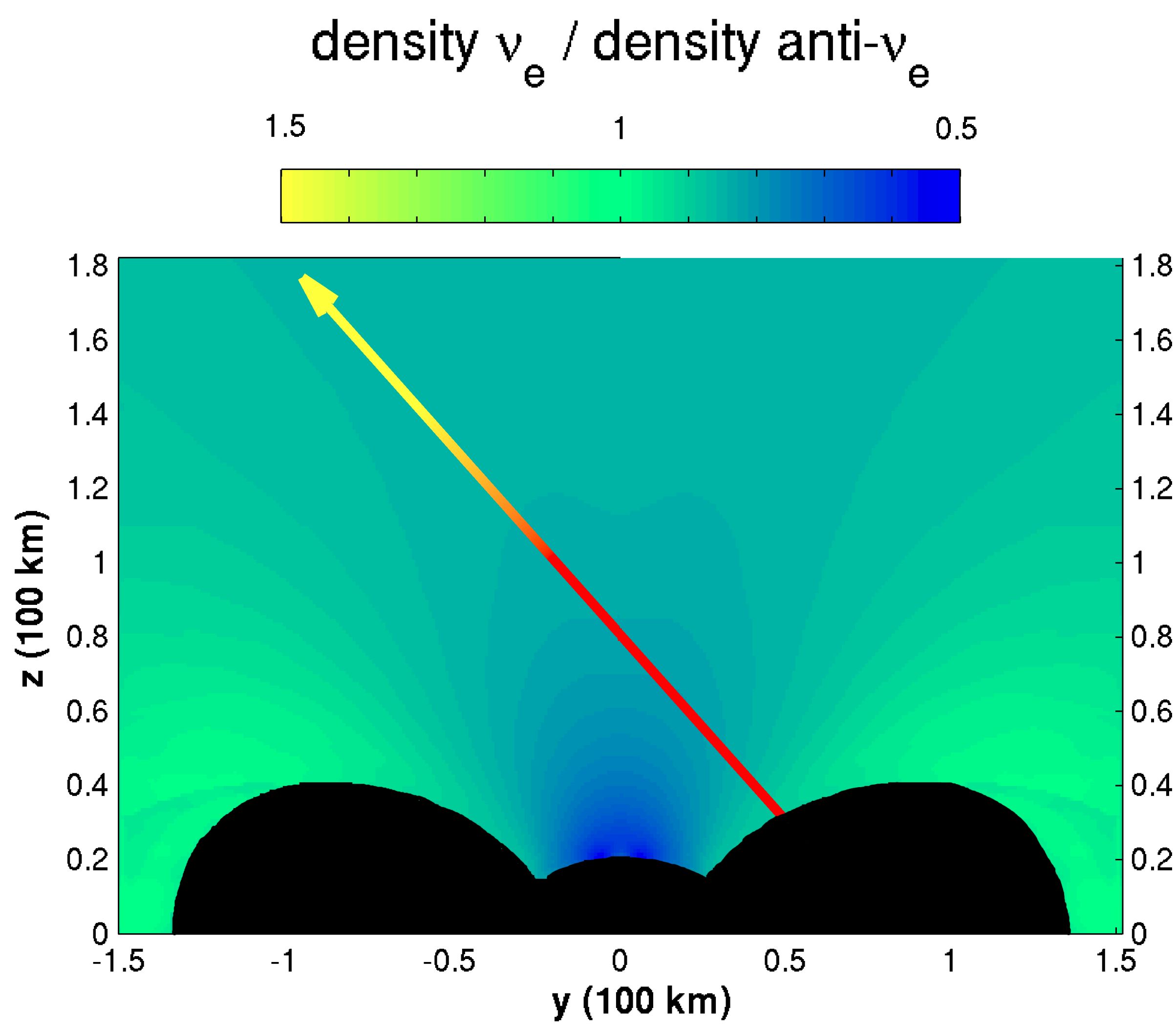
$$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$$

$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

Mergers have less ν_μ, ν_τ than ν_e and $\bar{\nu}_e$

$\rightarrow$ oscillation reduces numbers of ν_e, $\bar{\nu}_e$

Neutrino flavor transformation in mergers



Oscillation calculations by Zhu et al, see also Frensel et al, merger remnant simulation by Perego

Survival Probabilites

We plot results as survival probabilities.

P_{ν_e} is the probability that a neutrino that starts as electron type will still be electron type when it is measured later.

Potentials and survival probabilities along a sample trajectory

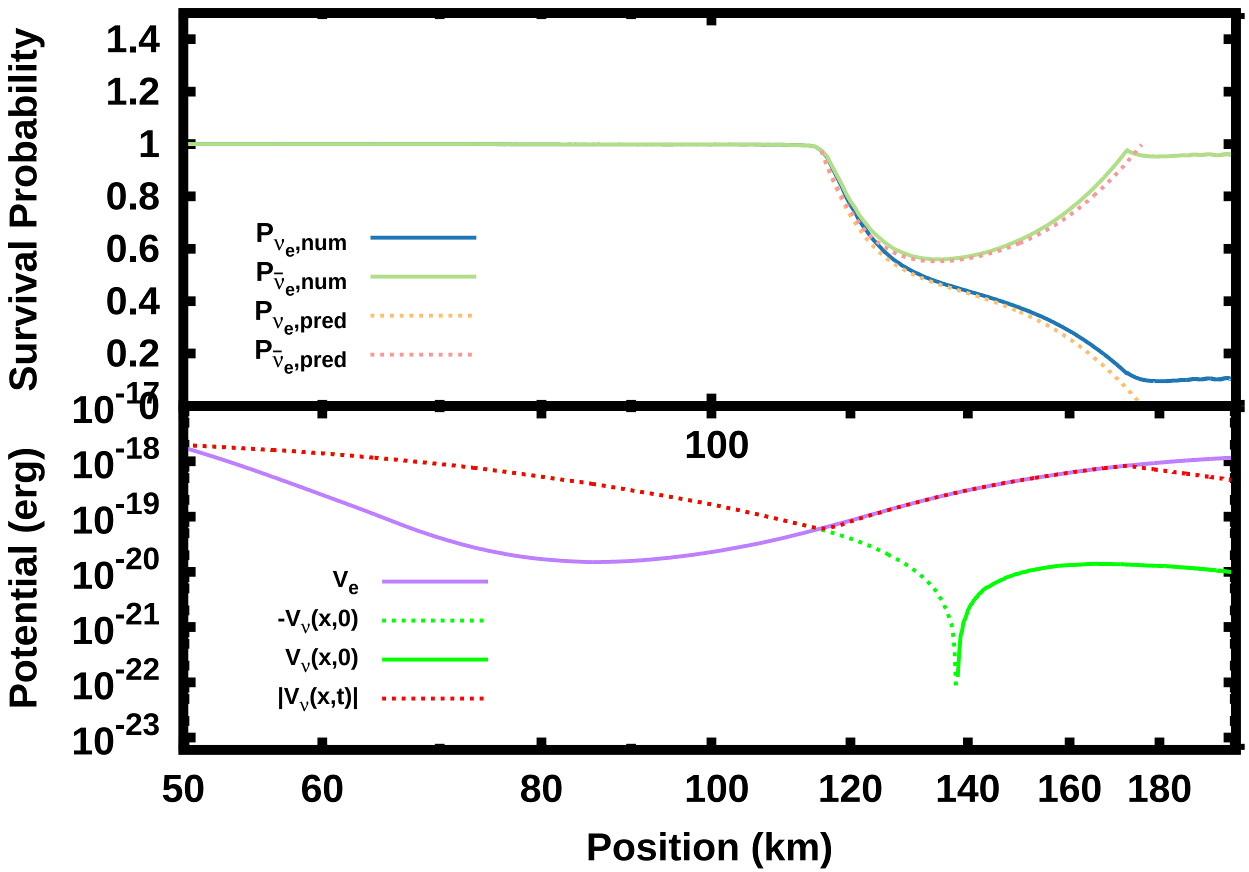


Fig. from Zhu et al 2016

Flavor transformation: Hamiltonian

Hamiltonian:

$$\begin{pmatrix} V_e + V_{\nu\nu}^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_{\nu\nu}^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_{\nu\nu}^b + \frac{\delta m^2}{4E}\sin(2\theta) & -V_e + -V_{\nu\nu}^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}$$

Scales in the problem:

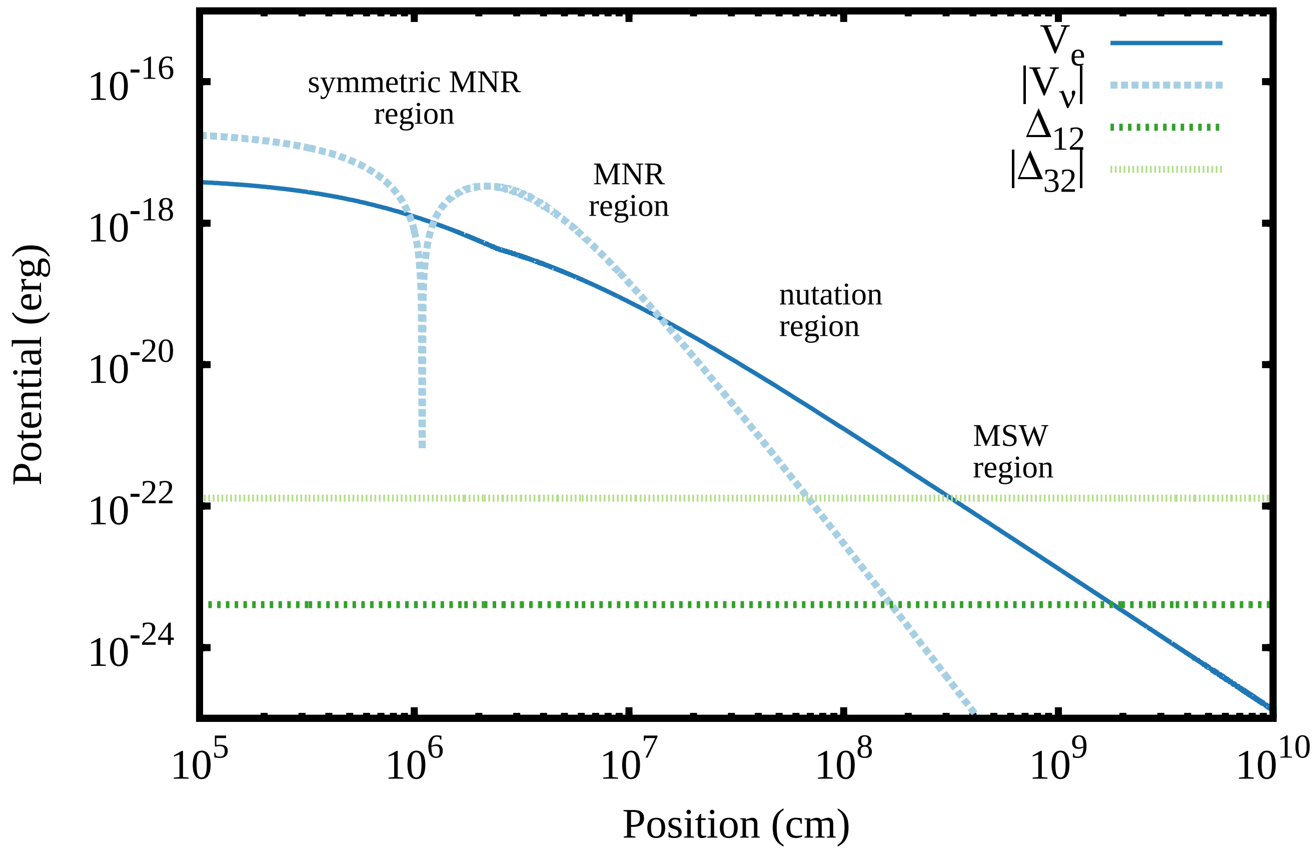
- vacuum scale $\frac{\delta m^2}{4E}$
- matter scale $V_e \propto G_F N_e(r)$
- neutrino self-interaction scale
  $V_{\nu\nu} \propto G_F N_\nu * \mathrm{angle} - G_F N_{\bar{\nu}} * \mathrm{angle}$

We need thousands of these coupled equations: $i\frac{d}{dt}S = HS$

Types of merger oscillations: jargon

- $\frac{\delta m^2}{4E} \sim V_e$ MSW
- $\frac{\delta m^2}{4E} \sim V_{\nu\nu} \propto G_F N_\nu * \text{angle} - G_F N_{\bar{\nu}} * \text{angle}$ collective nutation
- $V_e \sim V_{\nu\nu}$ matter neutrino resonance Malkus et al 2012, Malkus et al 2014, see also Wu '16, Vaananen '16, Tian '17, Chatelain '17
- $V_{\nu\nu} \sim$ perturbation wave number fast e.g. Abbar and collaborators

What the potentials look like



Acceretion disk, Malkus '16, Vaananen '16

Merger oscillations: survival probabilities

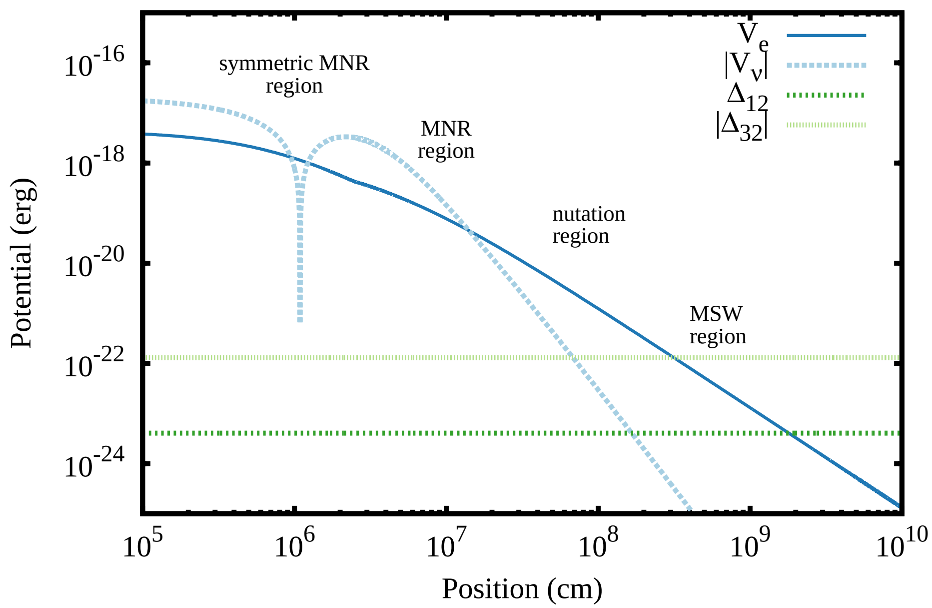


fig. from Malkus et al 2016

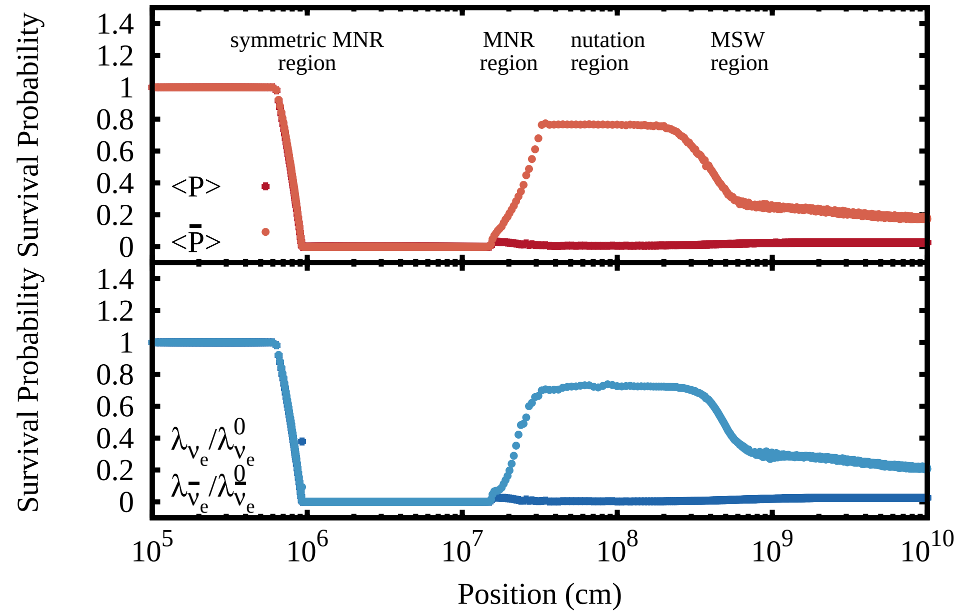
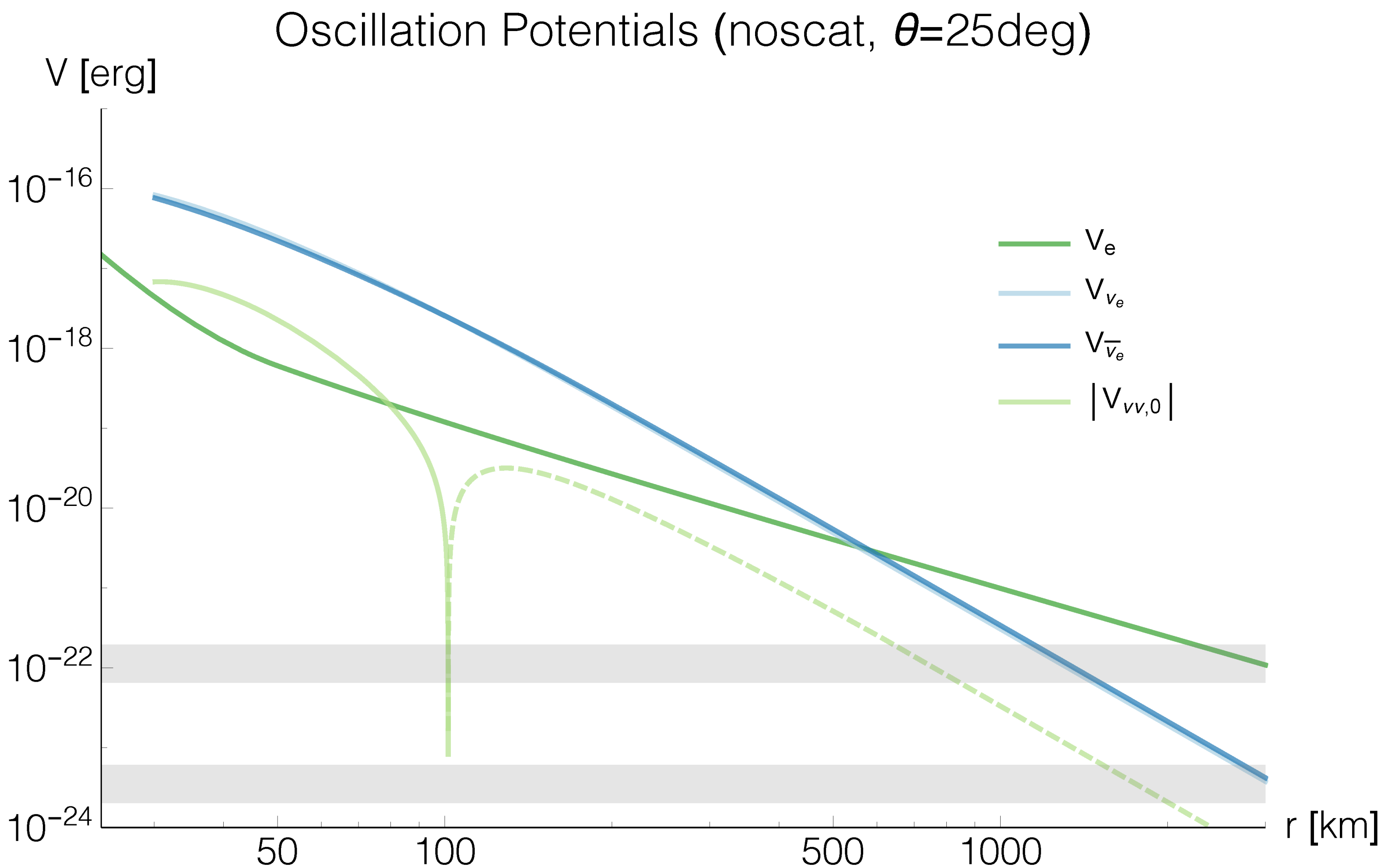


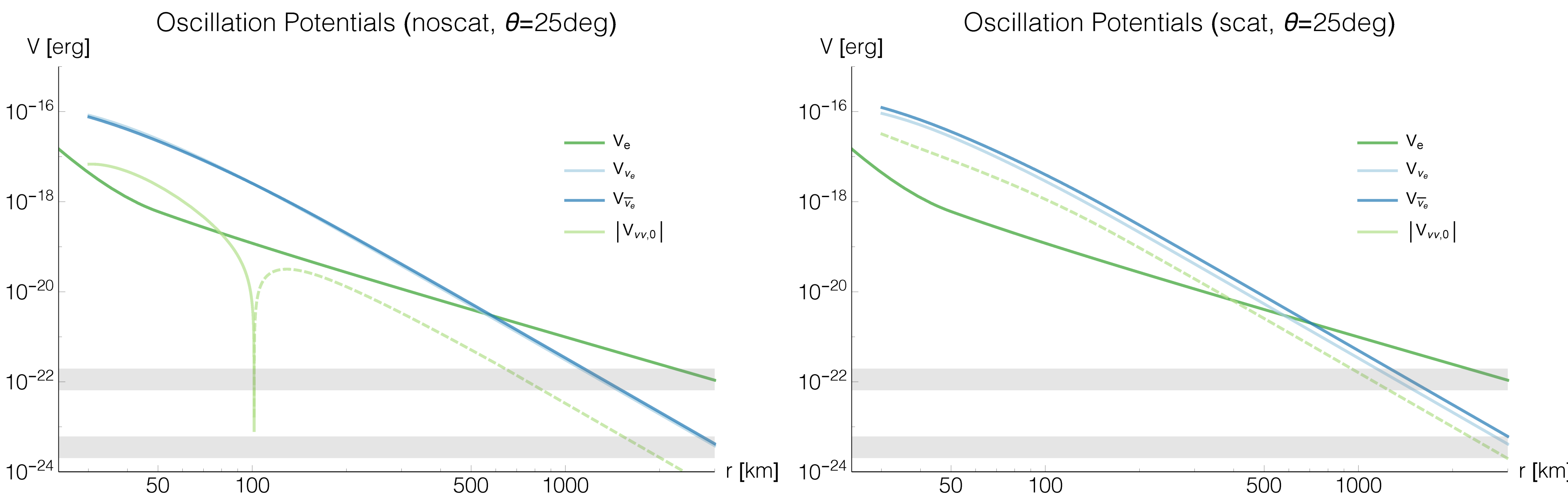
fig. from Malkus et al 2016

A calculation of the potentials and oscillations using GR ray tracing



ray tracing by B. Deaton, neutron star merger model by F. Foucart

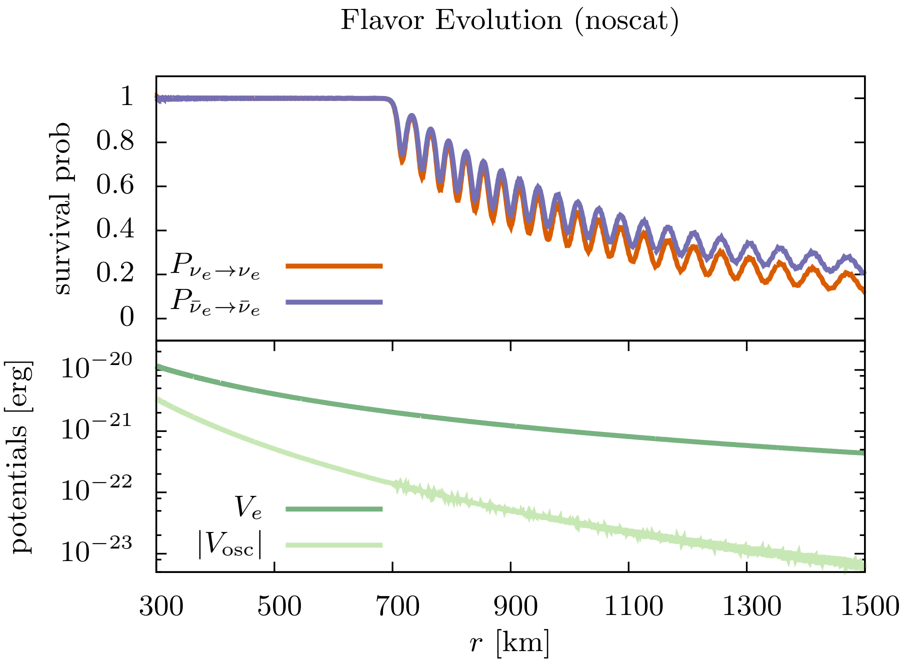
The importance of elastic scattering in the potentials

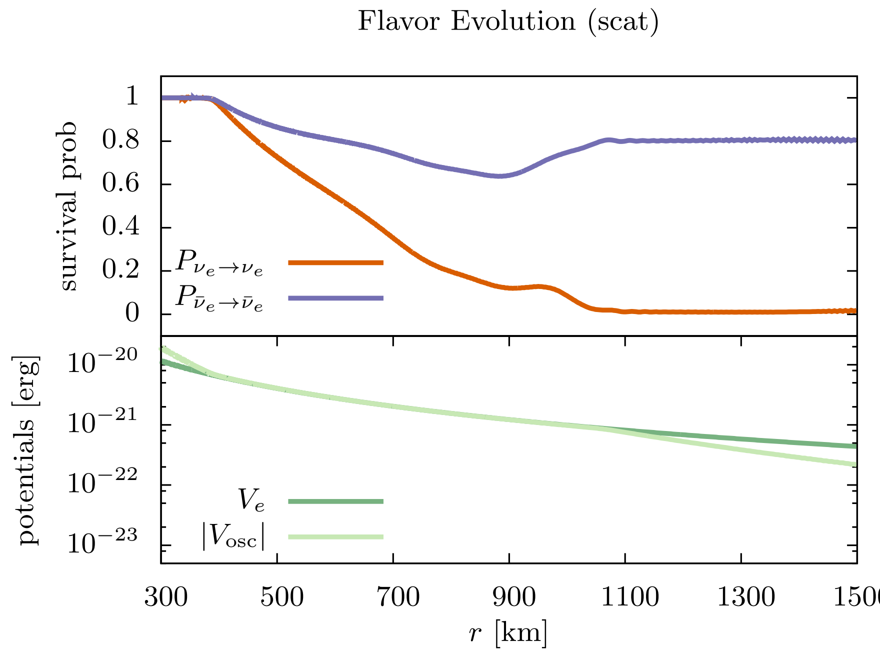


Not including scattering (left) and including scattering (right).

Deaton et al '18

Survival Probabilities



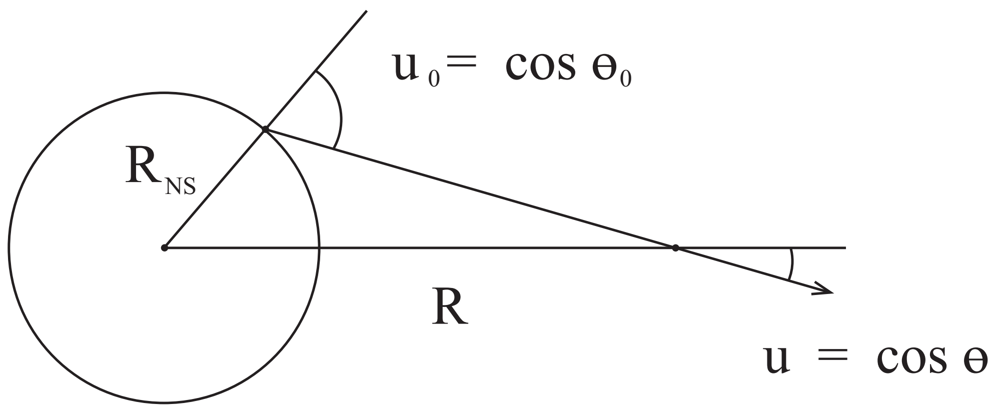


Not including scattering (left) and including scattering (right)

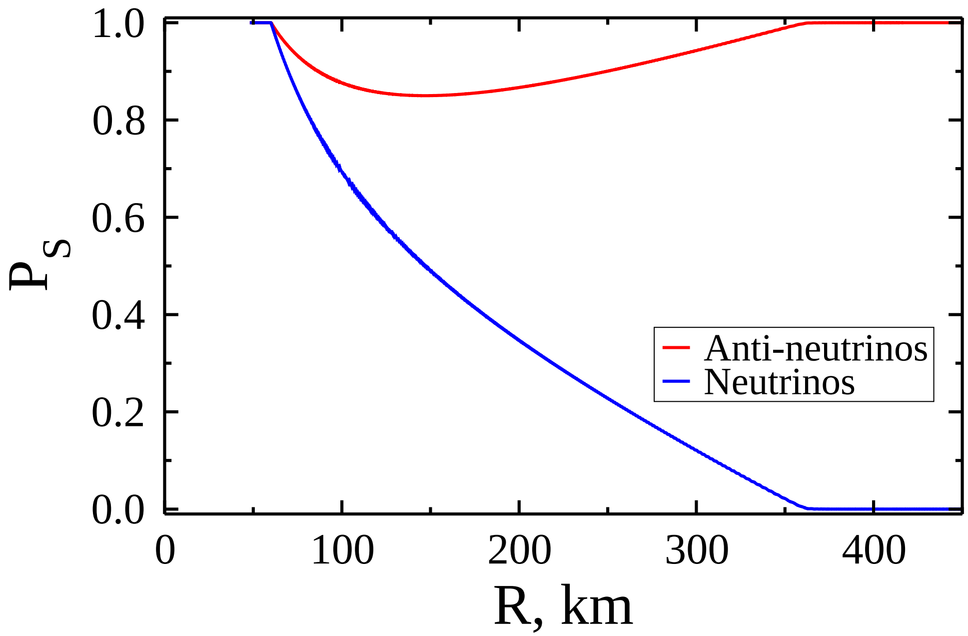
First attempt at multi-angle calculations

To perform such a calculation, it helps to have some spatial symmetry.

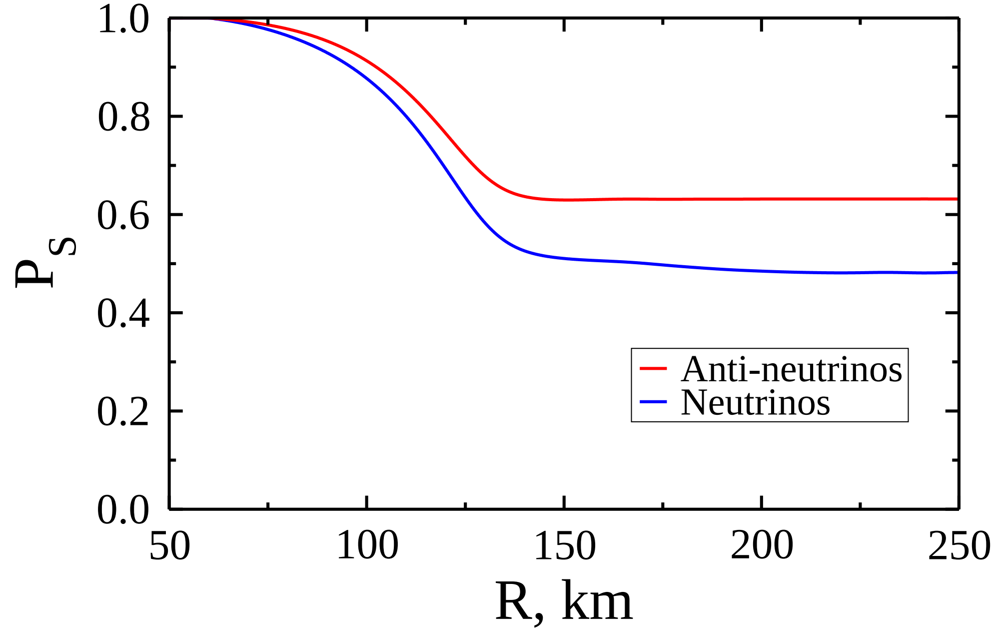
Our choice: spherical symmetry



Multi-angle in spherical geometry



single angle



multi-angle

Qualitative effect is robust the changes in parameters, such as size, density scale. Also robust to extended emission surface. Vlasenko et al 2018

Conclusions

Successes in last couple years:

- nuclear masses: reverse engineering successfully implemented
- neutrinos: matter-neutrino resonance discovered

Looking to the future:

- nuclear masses: use reverse engineering to explore more masses
- neutrinos: explore collisions

Long term:

- nuclear masses: look forward to measurements at FRIB
- neutrinos: multi-angle in a dynamical merger simulation