Two topics:

neutrino flavor transformation from compact object mergers

and

reverse engineering the rare earth peak

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Topic one: neutrino flavor transformation

Why examine neutrino flavor transformation for mergers?

- neutrinos influence nucleosynthesis
- neutrinos can contribute to jet production
- neutrinos could be detected (if lucky!)
- and any other time you want to know the flavor content of the neutrino field.

Example: neutrinos influence nucleosynthesis

Neutrinos change the ratio of neutrons to protons

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

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

Oscillations change the neutrinos

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 oscillations usually studied in free streaming limit

Usually calculated in a regime with few collisions, so above trapping surfaces $\rightarrow$ free streaming approximation

Interesting flavor transformation behavior stems from the potentials neutrinos experience. These potentials come from coherent forward scattering from neutrons, protons, electrons, positrons, neutrinos.

Oscillations: scales

Modified wave equation

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

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
  $V_{\nu\nu} \propto G_F N_\nu * \text{angle} - G_F N_{\bar{\nu}} * \text{angle}$

Oscillations: matter neutrino resonance

Modified wave equation

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

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$V_e \sim V_{\nu\nu} \rightarrow$ MNR oscillations

e.g. Mergers, black hole accretion disks, Malkus et al '12, '14, Duan, Frensel, Fuller, Kneller, Malkus, GCM, Qian, Patwardhan, Perego, Shalgar, Surman, Tian, Wu, Väänänen, Volpe, Zhu

Oscillations: nonlinear

Modified wave equation

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

Whenever $V_{\nu\nu}$ is important, the problem is very nonlinear. $V_{\nu\nu}$ depends on the number density of each flavor of neutrino, which depends how the neutrinos have oscillated.

multi-energy : each energy neutrino and antineutrino has its own equation, solved simultaneously with the others
multi-angle : each emitted neutrino and antineutrino has its own equation, solved simultaneously with the others

This means thousands of these coupled equations.

Survival Probabilites

We plot results as survival probabilities.

$P_{\nu_e} = |\psi_{\nu_e}|^2$, $P_{\bar{\nu}_e} = |\psi_{\bar{\nu}_e}|^2$

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

Start in flavor states (assume fast oscillations saturate)

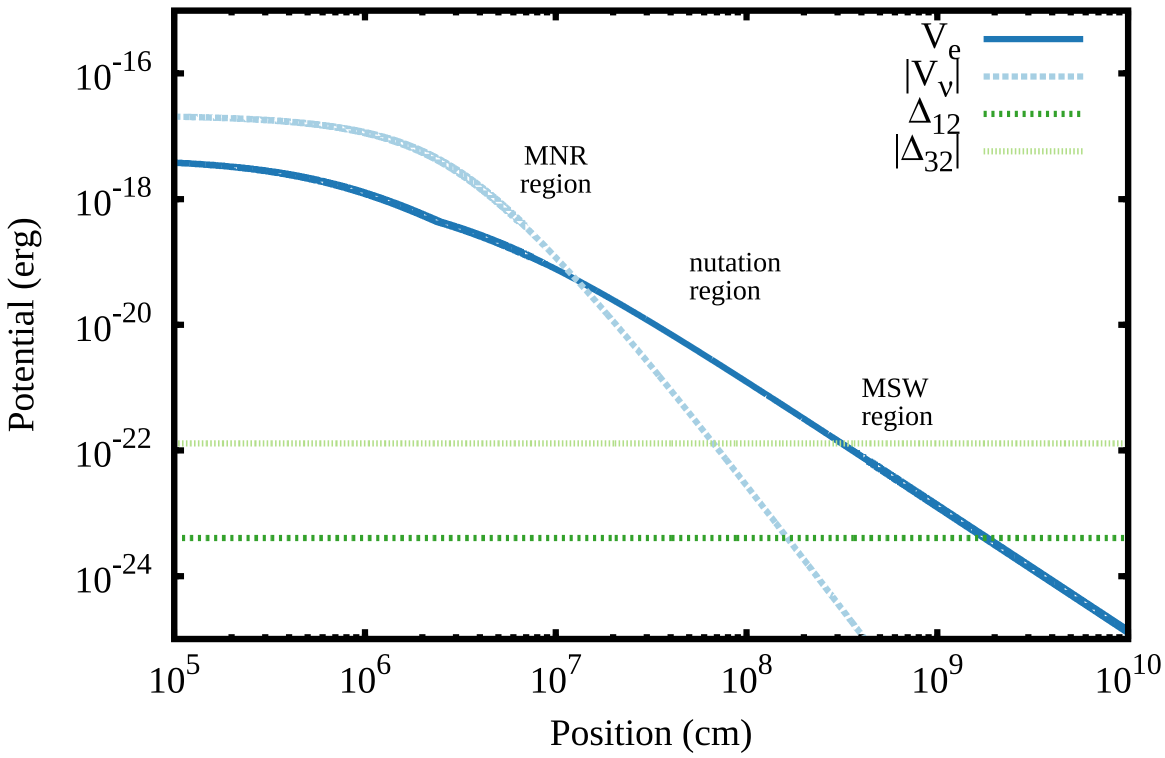
Multi-energy, single angle calculation

Neutrino emitting surface is 45 km, T = 6.4 MeV

Antineutrino emitting surface is 45 km, T = 7.1 MeV

Launch a neutrino at 45 degrees.

Merger oscillations: potentials for same size ν_e and $\bar{\nu}_e$ surfaces



Merger oscillations: survival probabilities for same size ν_e and $\bar{\nu}_e$ surfaces

multi-energy, single angle calculations

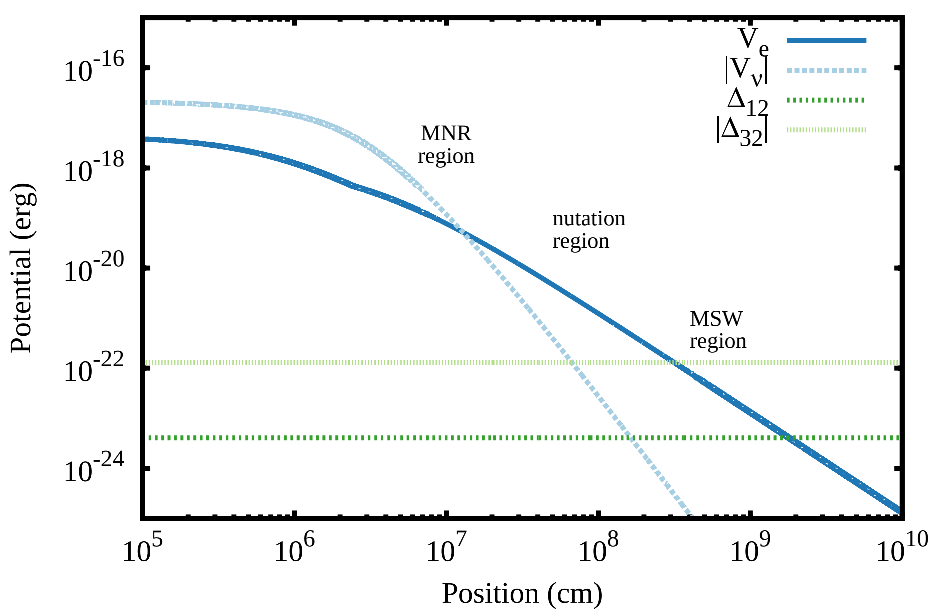


fig. from Malkus et al 2016

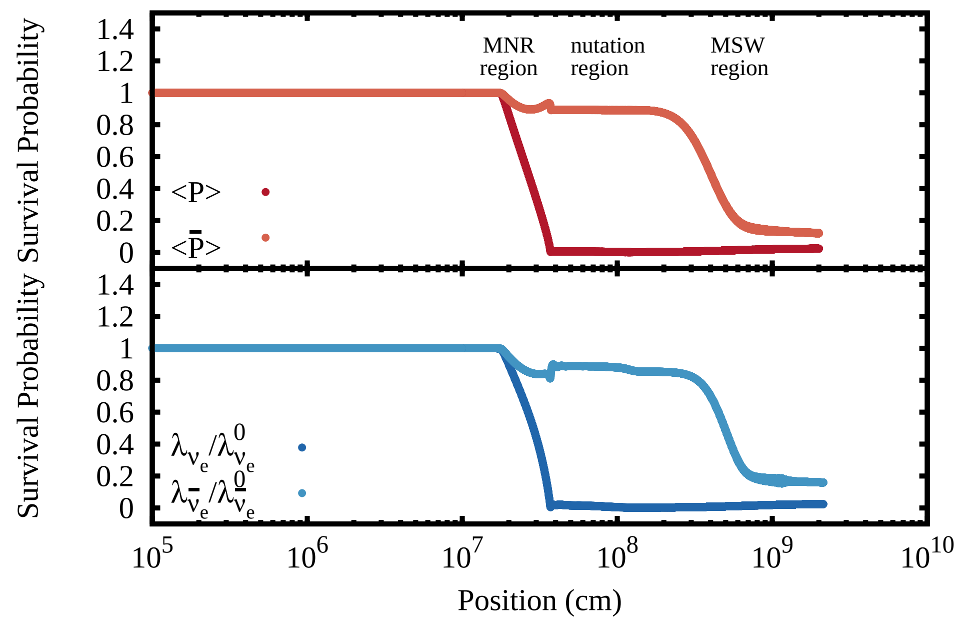


fig. from Malkus et al 2016, see also Frensel et al 2016

MNR transition: explained by single-energy single-angle model

Compare numerics to prediction Malkus et al, Wu, et al, Vaananen et al

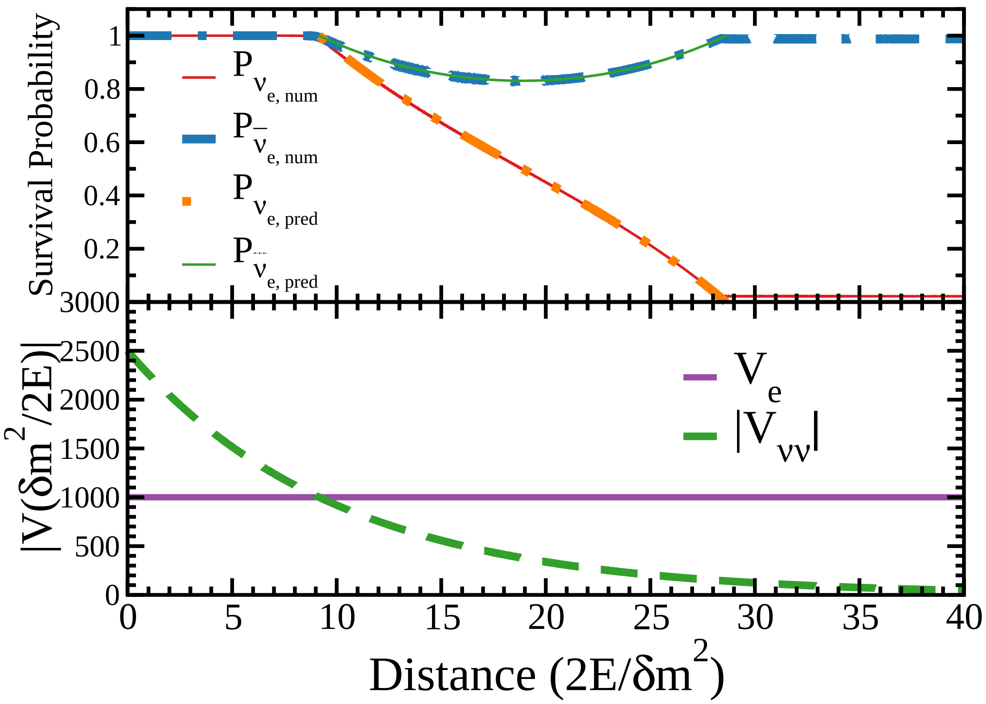
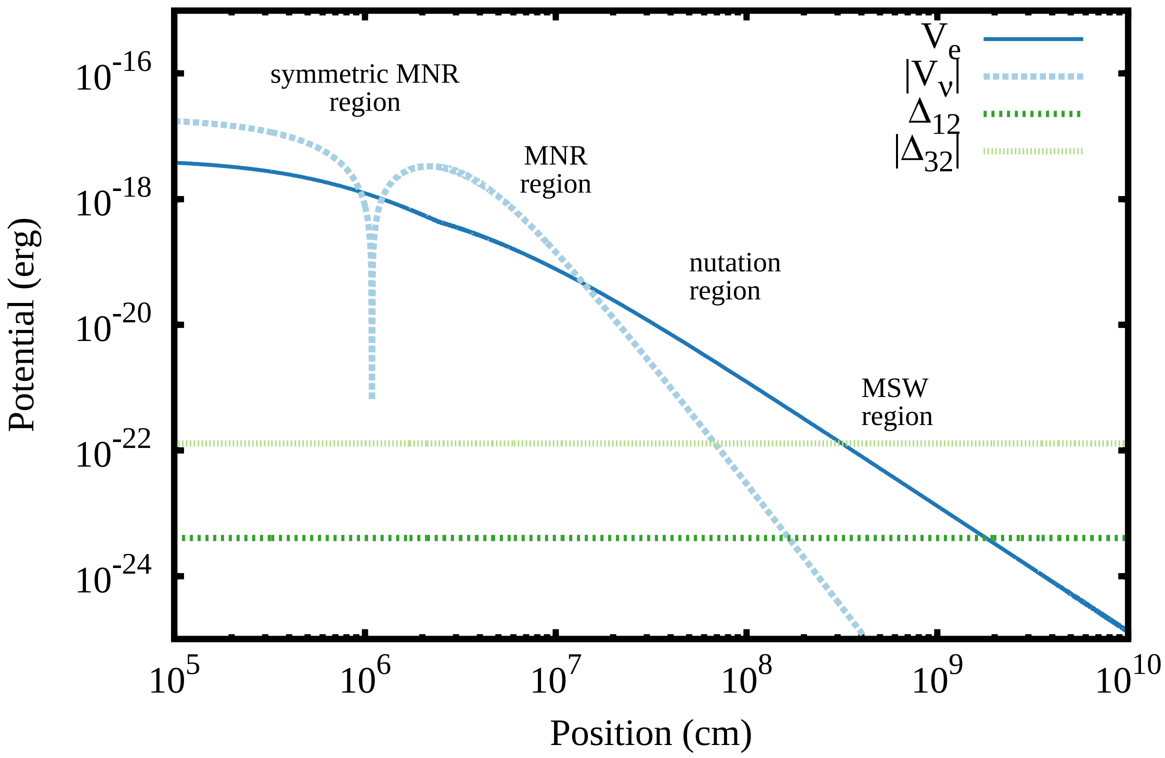


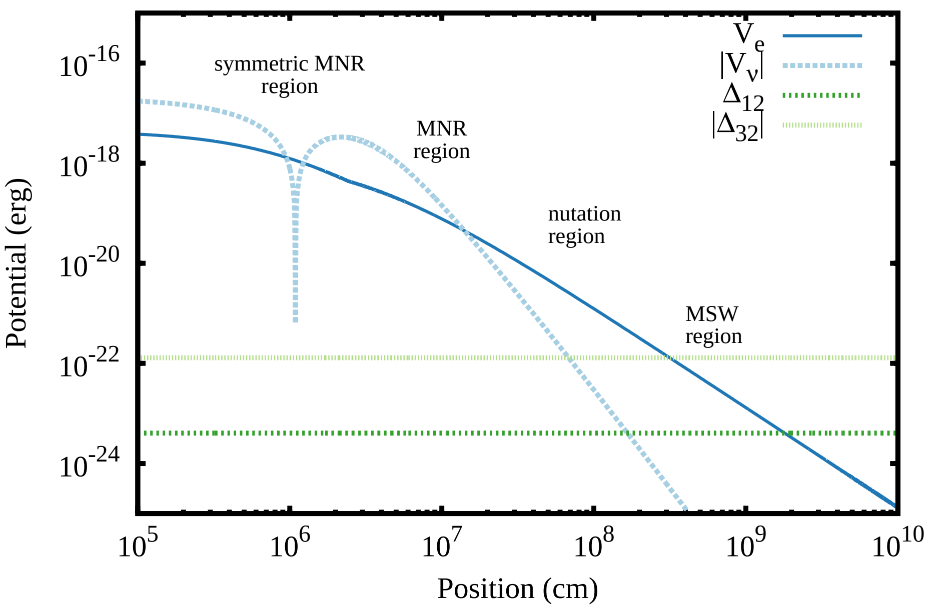
Fig. from Malkus et al 2014

Merger oscillations: potentials for different size ν_e and $\bar{\nu}_e$ surfaces



Merger oscillations: survival probabilities for different size ν_e and $\bar{\nu}_e$ surfaces

multi-energy, single angle calculations



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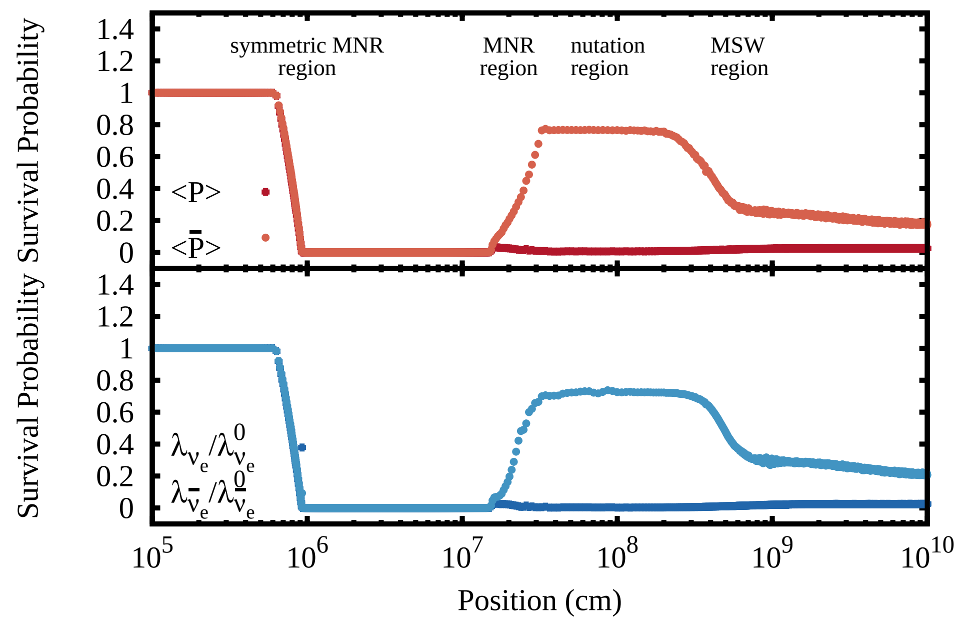
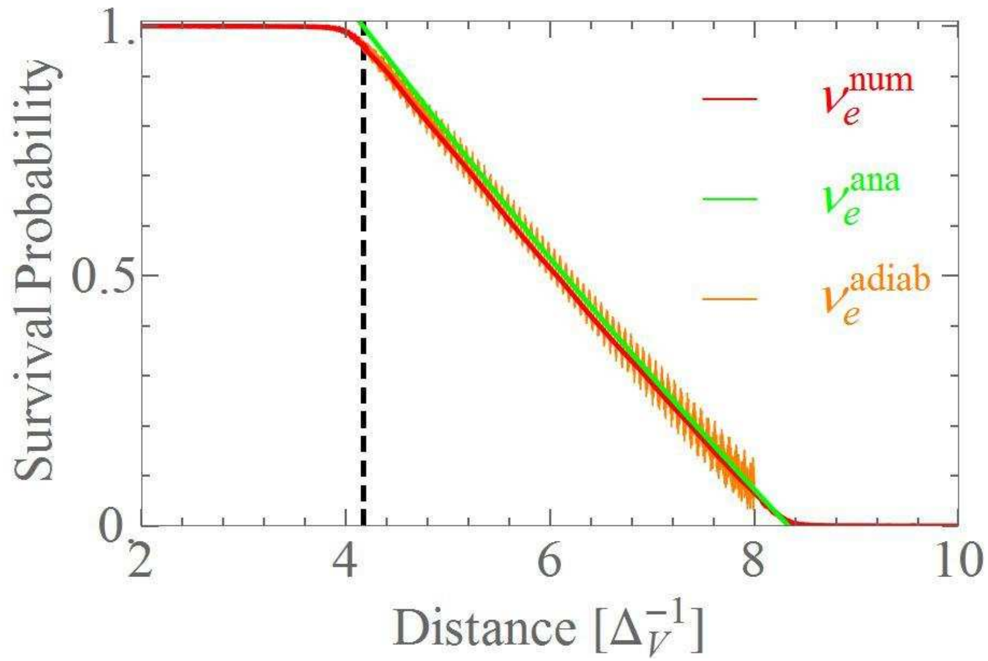


fig. from Malkus et al 2016

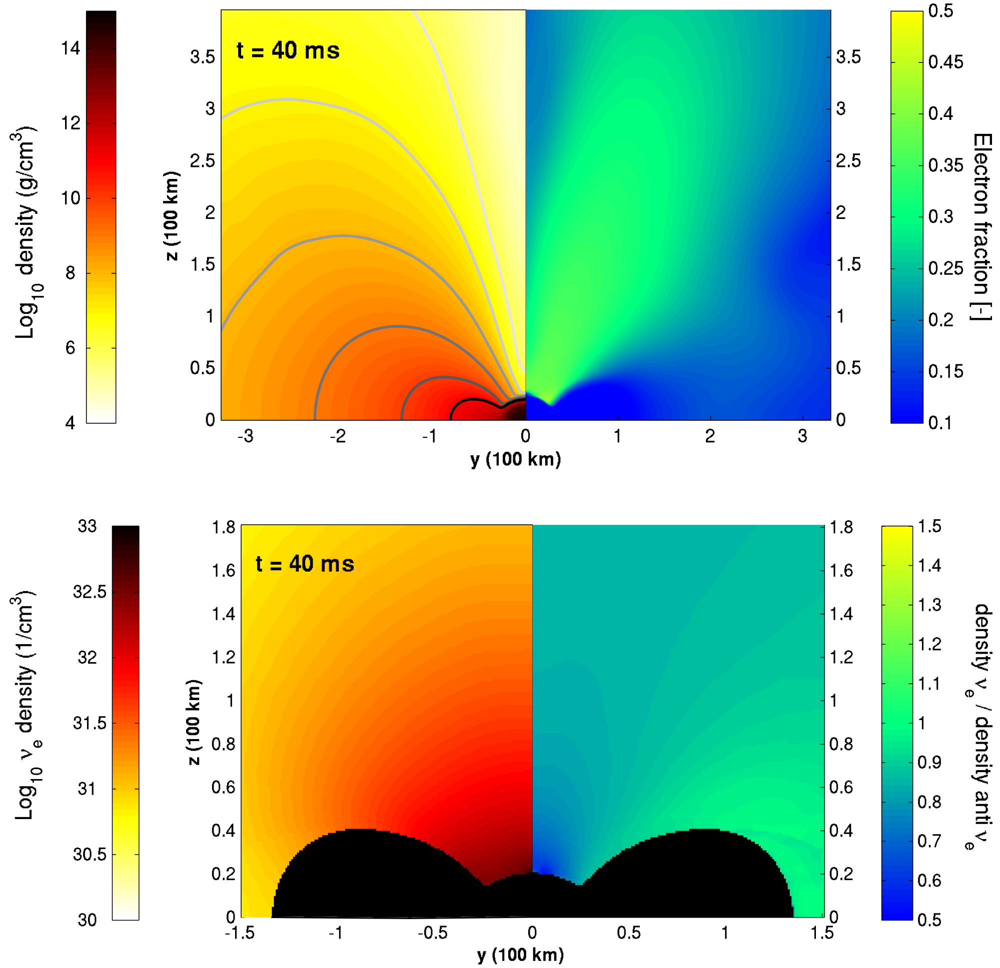
Analytic survival probability prediction also works for symmetric MNR transitions

Geometry causes $V_{\nu\nu}$ to switch sign



Symmetric MNR Fig. from Väänänen '16

Matter densities in a dynamical merger calculation



Zhu et al '16

Resonance locations, $V_e \sim V_{\nu\nu}$, in the dynamical merger remnant

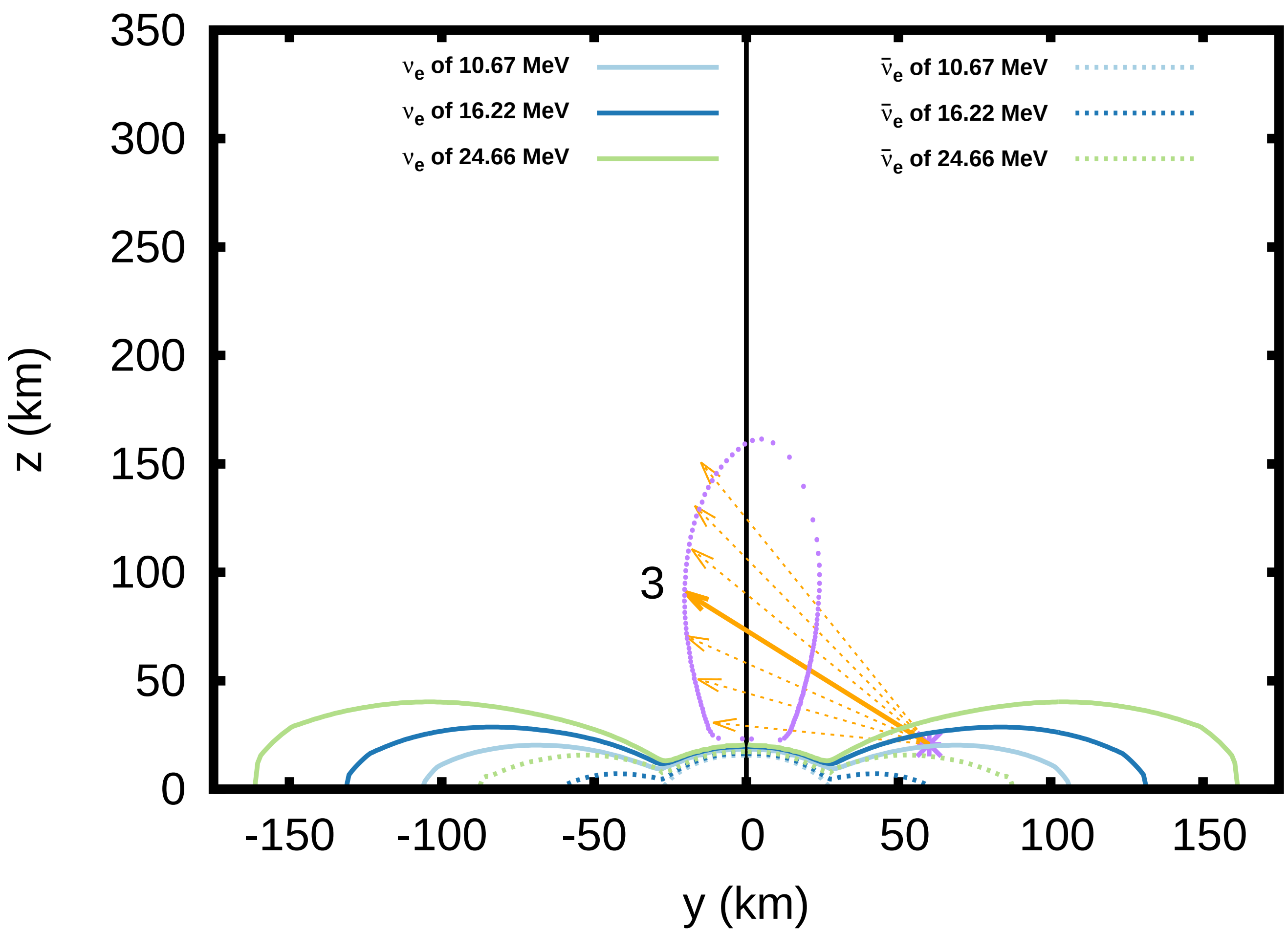


Fig. from Zhu et al 2016

Potentials and survival probabilities along a sample trajectory

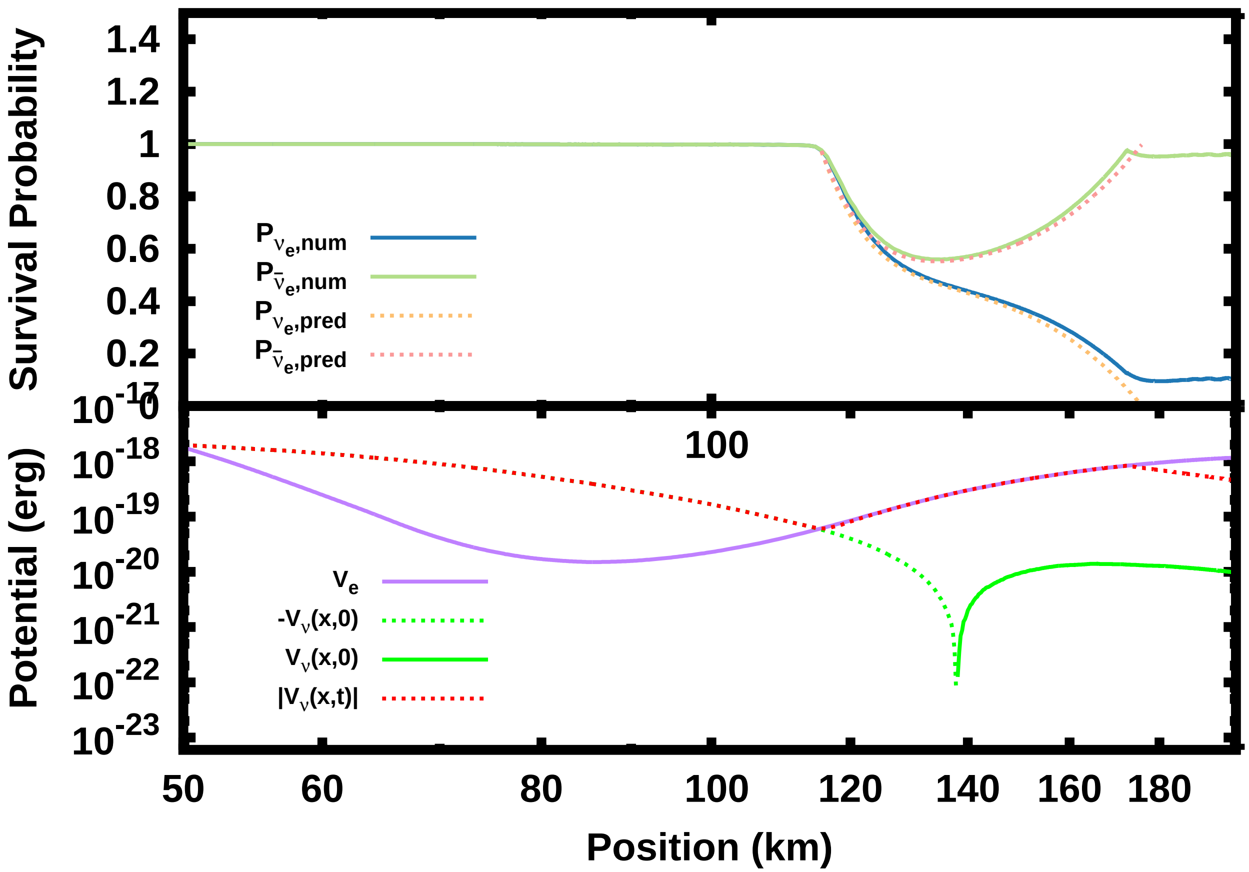


Fig. from Zhu et al 2016

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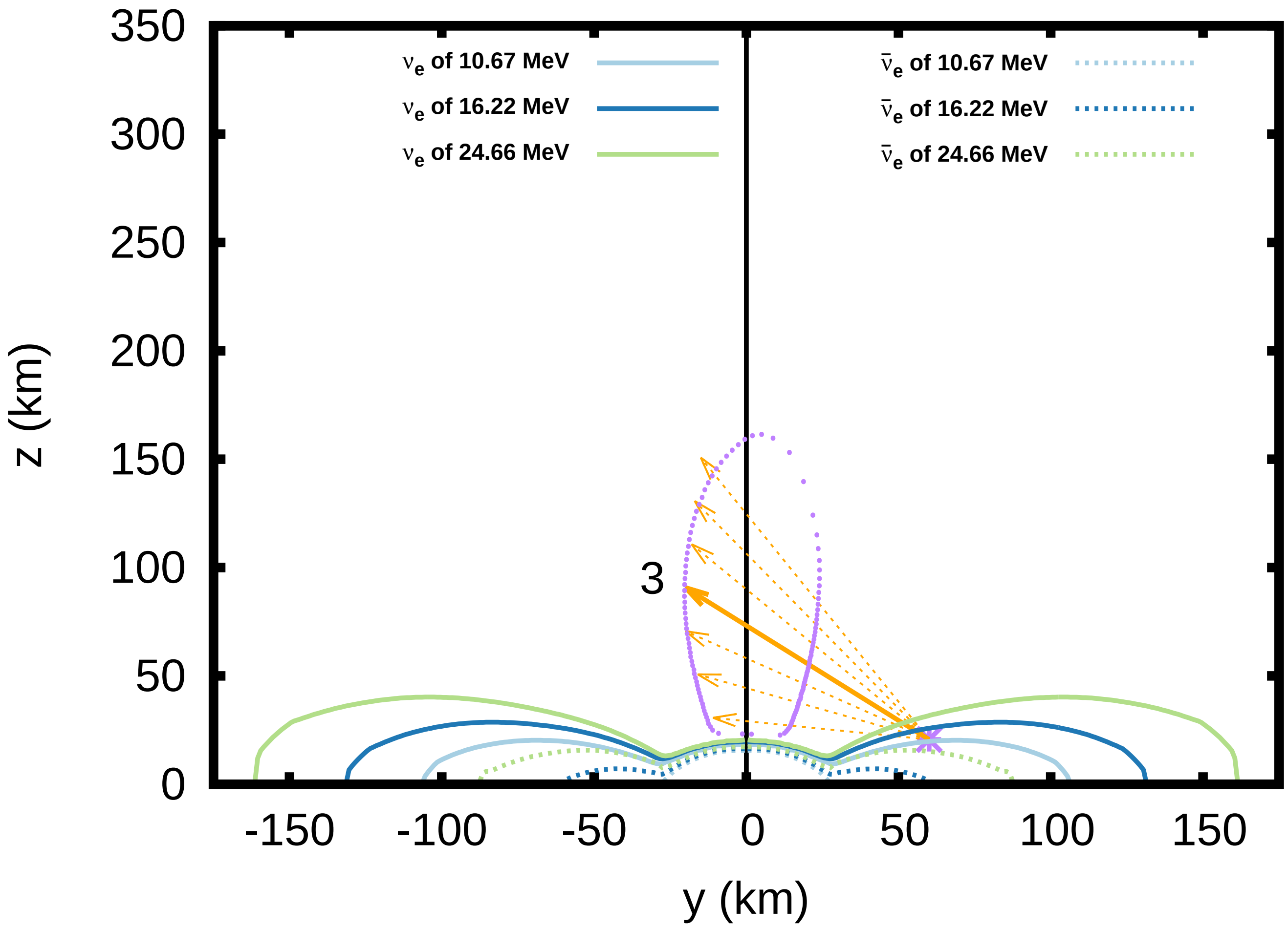


Fig. from Zhu et al 2016

Resonance locations, $V_e \sim V_{\nu\nu}$, in the dynamical merger remnant

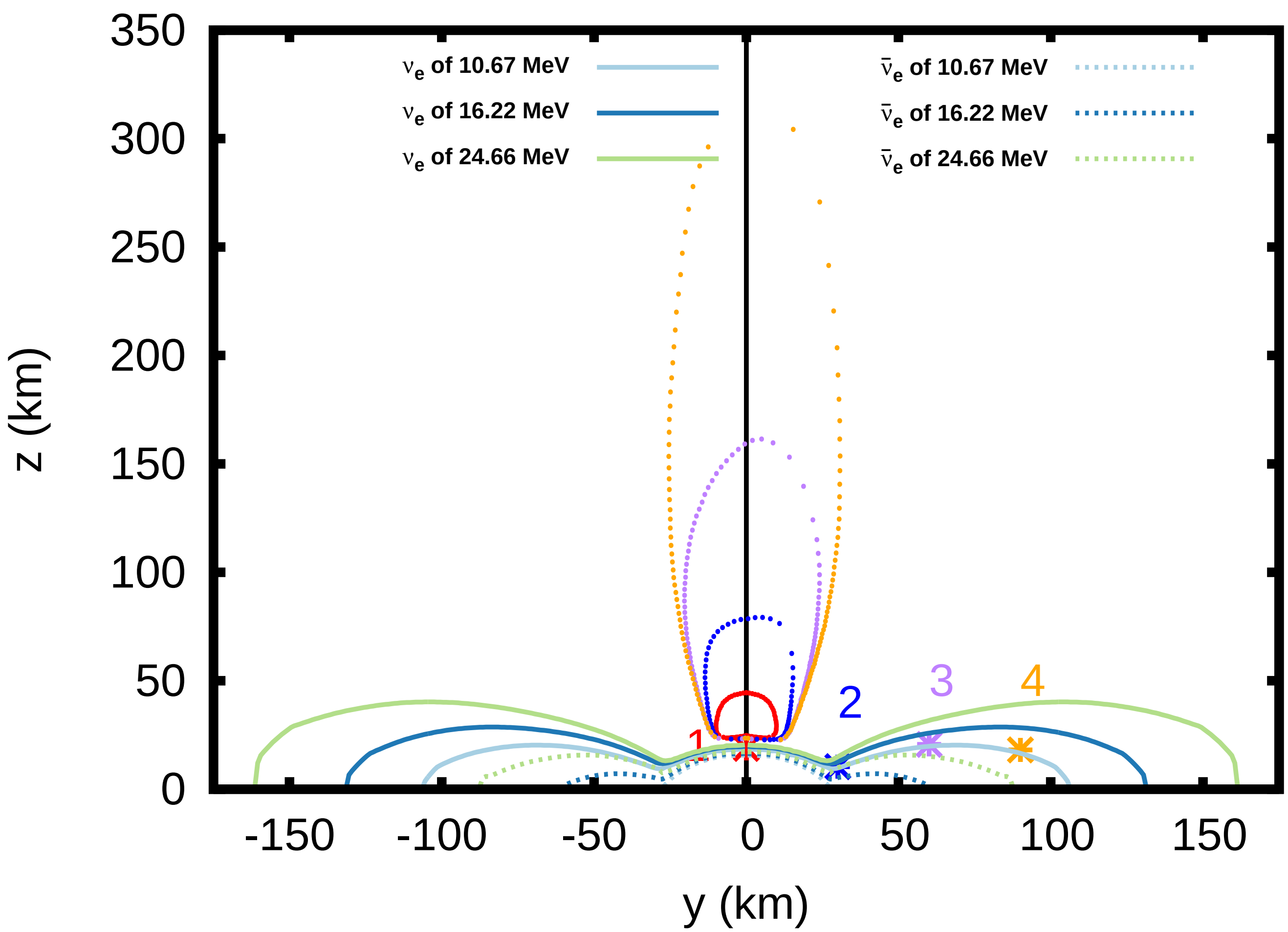


Fig. from Zhu et al 2016

Conclusions

Rapid progress in last couple years:

- Predictions of matter neutrino resonance transition behavior
- Likely exists in mergers
- Likely affects nucleosynthesis

What to do next?

- a little more theory work
- keep up with dynamical models as they advance transport
- more physical effects, e.g. general relativity

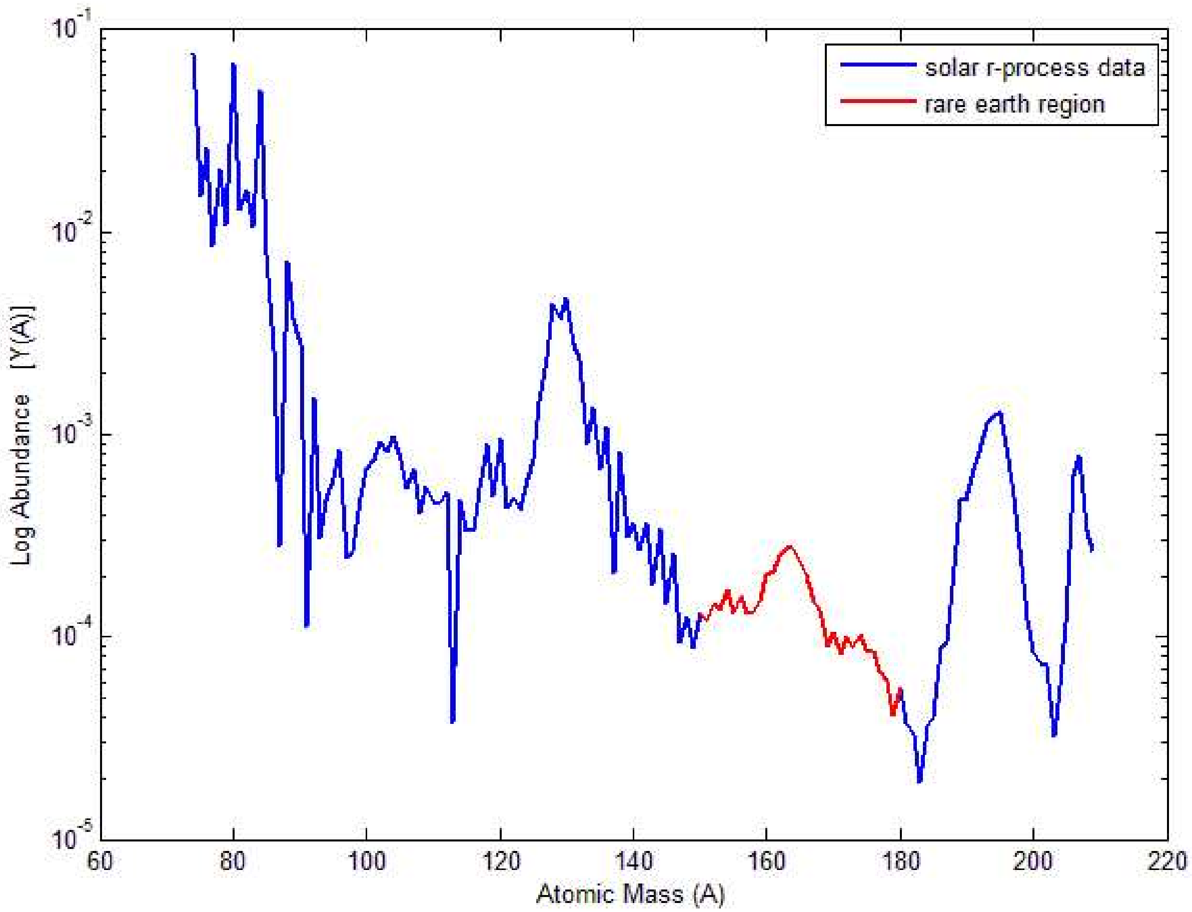
Long term

- multi-angle effects in full geometry
- decoupling regime, feedback into dynamical calculation

Topic 2:

reverse engineering the rare earth peak

The solar rare earth peak



Solar abundance data with the rare earth peak in red

Approaches to studying the rare earth peak

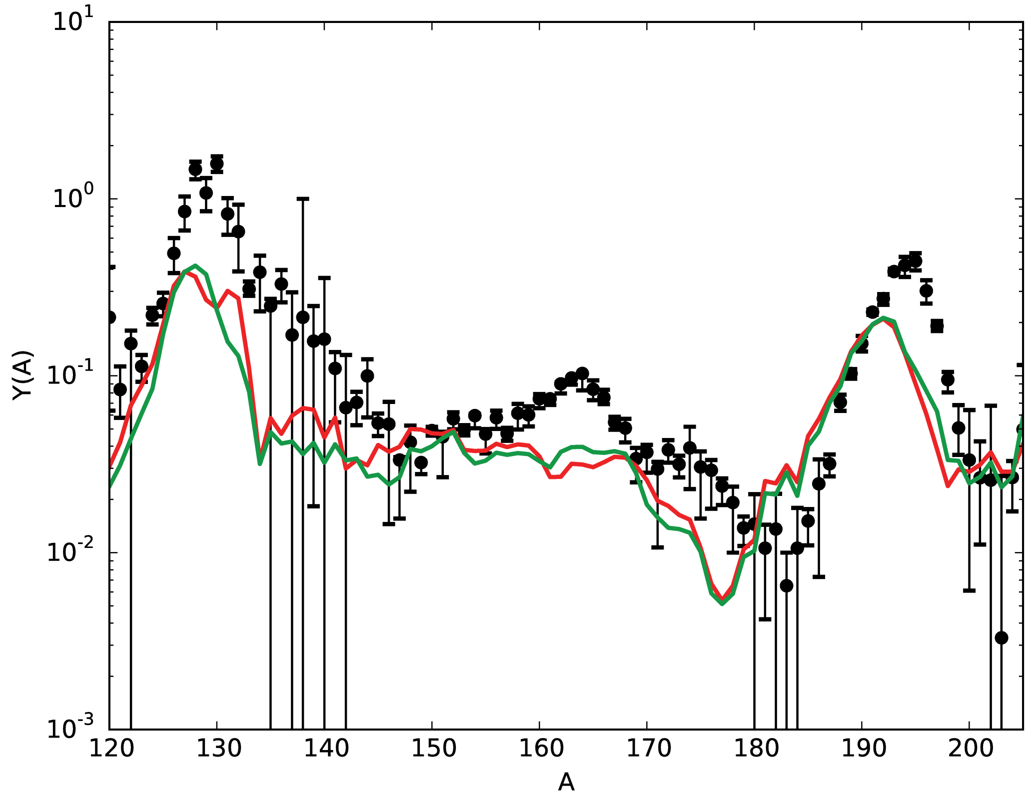
Usual procedure:

- Continue to improve hydrodynamics, neutrino transport and general relativistic treatments in astrophysical simulations
- Calculate abundance pattern with a nuclear model and thermodynamic conditions as input

Alternative approach:

- Assume a set of thermodynamic conditions
- Back out properties of the nuclear model, for this set of conditions

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

What term though?

Step two: Add a term to the base model

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

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.

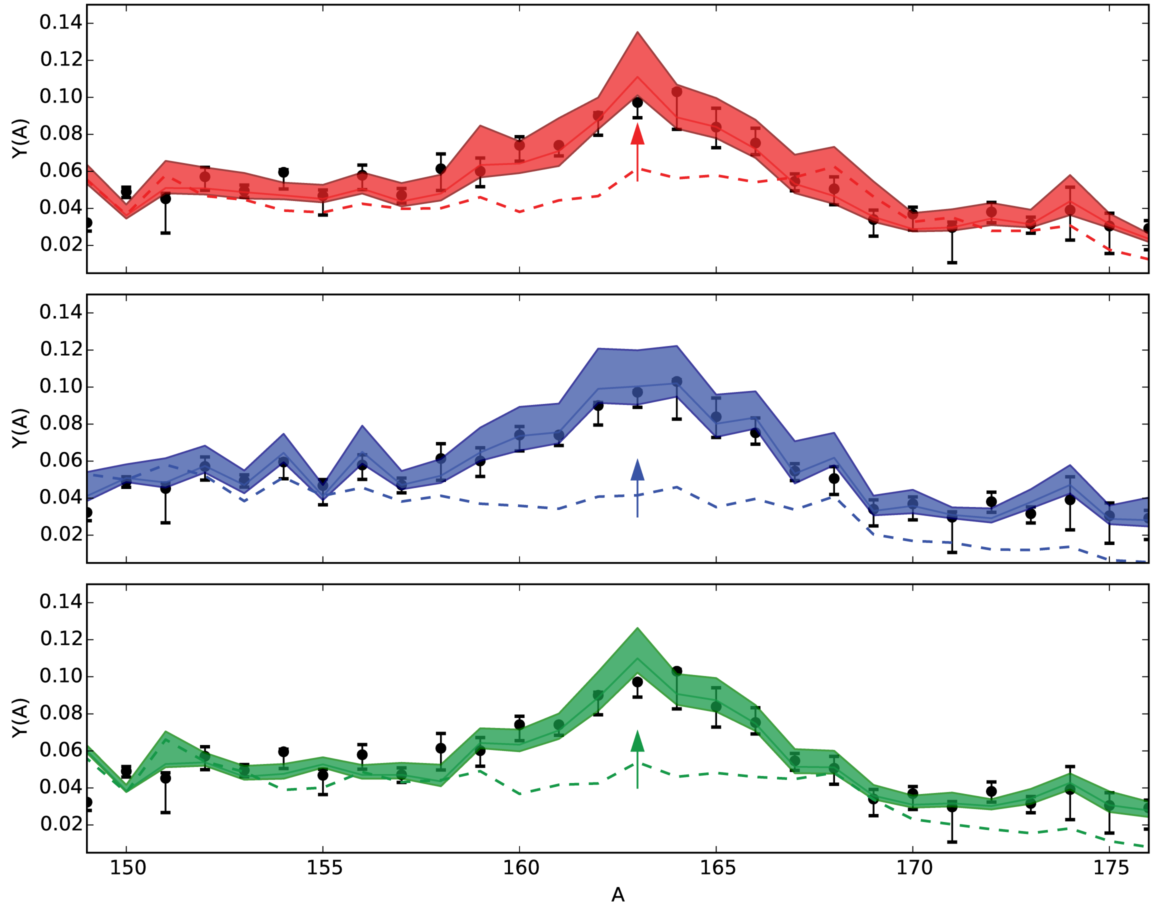
Step two: Add a term to the base model

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

Now use MCMC to determine the a_N and the C_Z

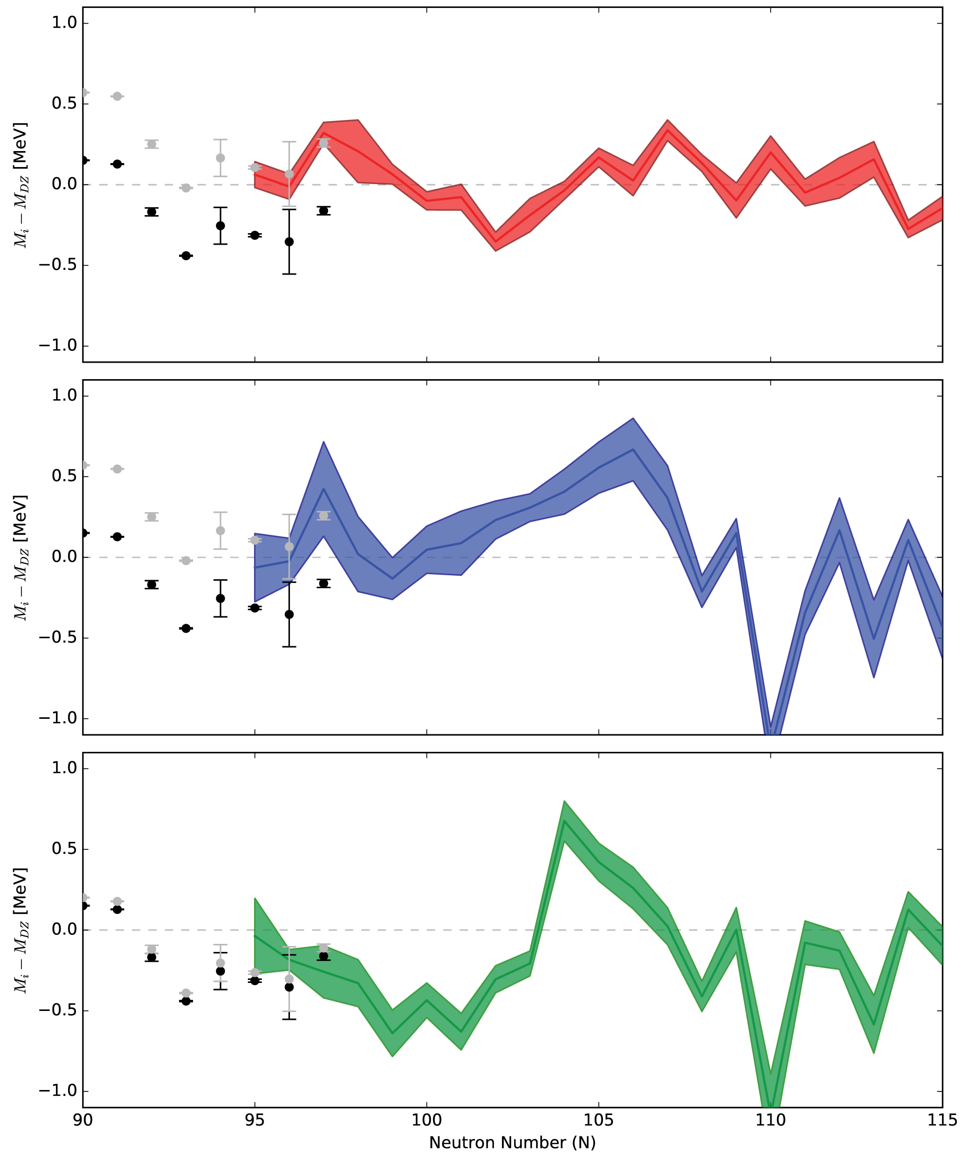
Details: Metropolis algorithm, start with all $a_N = 0$, for each choice of a_N, C_Z consistent separation energies, beta decay Q values and neutron capture rates are calculated, algorithm converges in about 10,000 steps.

Step three: use MCMC to find a better fit to the rare earth peak



Mumpower et al 2017

Example calculations



Mumpower et al 2017, Nd isotopic chain

Including measured beta decay rates

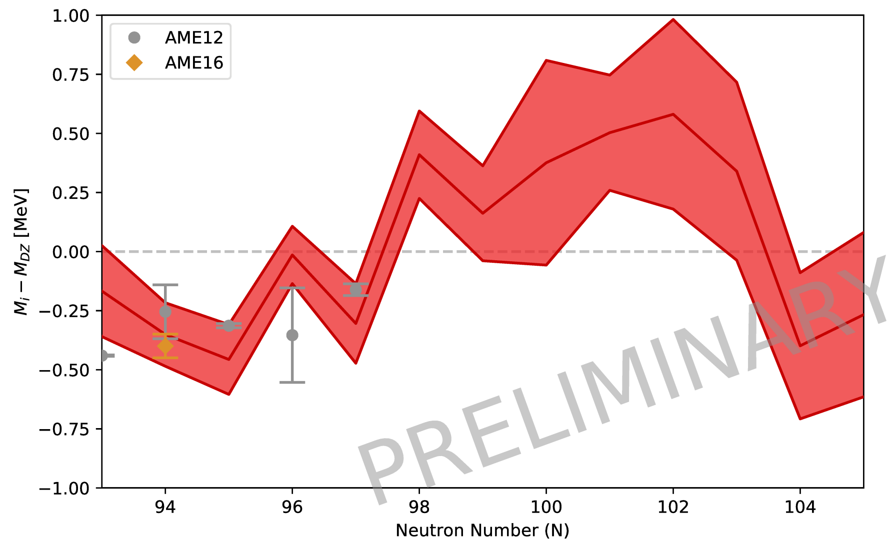


Fig. from Nicole Vassh

Comparing with recently measured masses

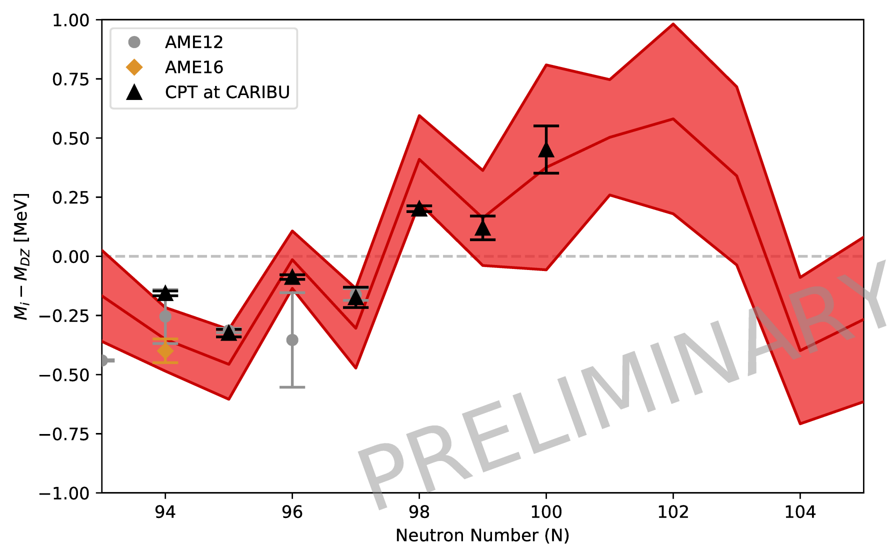


Fig. from Nicole Vassh

Conclusions

Reverse engineering of nuclear masses looks promising

- use MCMC for nuclear masses, coordinated with neutron capture, beta decay
- different classes of thermodynamic conditions predict different mass patterns

Where to go from here

- continue to improve MCMC
- continue compare with (and include) measured data as it becomes available
- examine additional uncertainties

Conclusions, cont.

Goal

- test the dynamical formation mechansim of the rare earth peak (as opposed to the fission formation mechanism)
- eventually infer astrophysical conditions, this is complementary to approach taken by observations, simulations