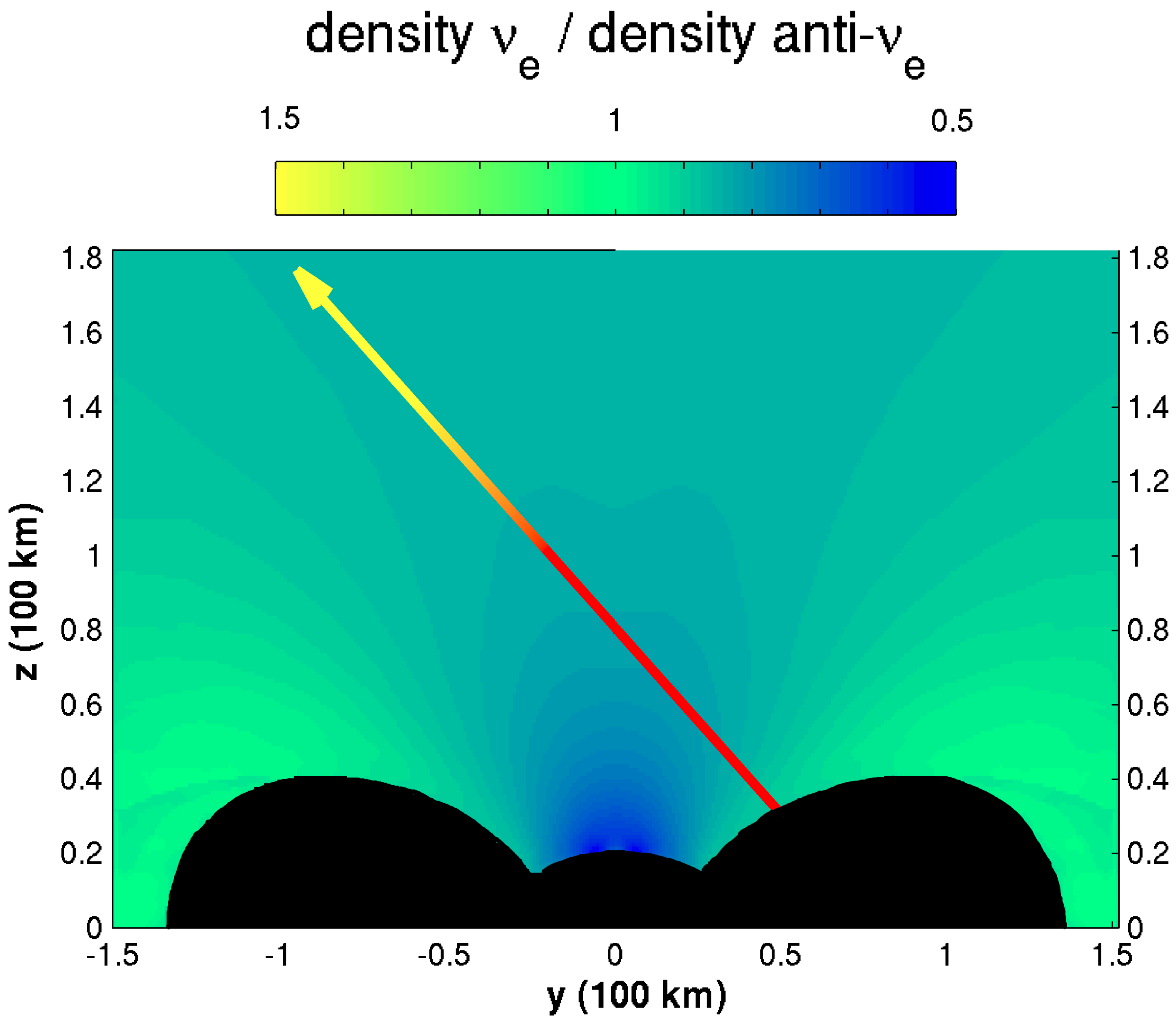
Neutrino flavor transformation in compact object mergers

Gail McLaughlin

North Carolina State University

Collaborators: Jim Kneller (NC State), Alex Friedland (SLAC), Annie Malkus (University of Wisconsin), Albino Perego (Darmstadt), Rebecca Surman (Notre Dame), Daavid Väänänen (UBC), Alexey Vlasenko (NC State), Yonglin Zhu (NC State)

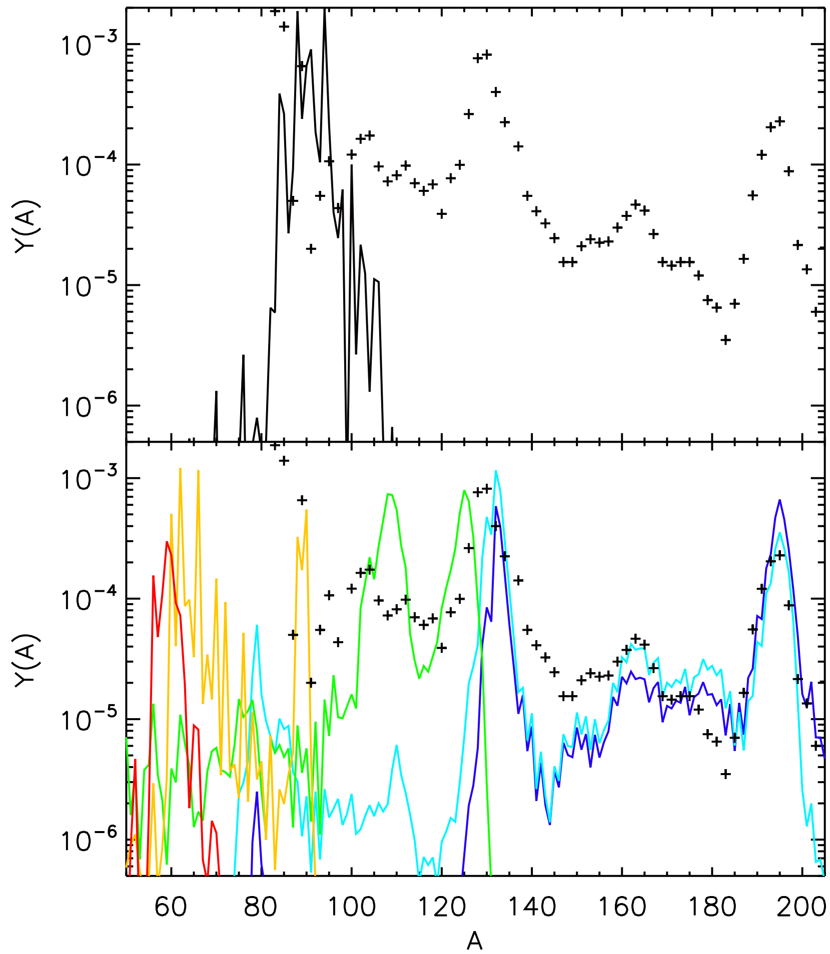
Neutrino flavor transformation in mergers



Why examine neutrino flavor transformation for mergers?

- neutrinos influence nucleosynthesis
- neutrinos can contribute to jet production
- neutrinos could be detected see work by Caballero
- and any other time you want to know the flavor content of the neutrino field.

How flavor transformation can change nucleosynthesis



Accretion disk wind nucleosynthesis, Malkus et al '16

How neutrinos influence nucleosynthesis

Neutrinos change the ratio of neutrons to protons

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

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

Neutrino flavor transformation changes neutrons and protons

Neutrinos change the ratio of neutrons to protons

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

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

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 $\bar{\nu}_e$

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

Neutrino flavor transformation: calculations

We keep track of quantum mechanical phases of the neutrinos.

These phases are not the same for different types of neutrinos $\rightarrow$ flavor transformation.

$$i\frac{d}{dt}S = HS$$

S is the evolution matrix (phase information), H is the Hamiltonian

Evolution matrix formulation, Kneller, GCM 2006

Flavor transformation: Hamiltonian

Hamiltonian:

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

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

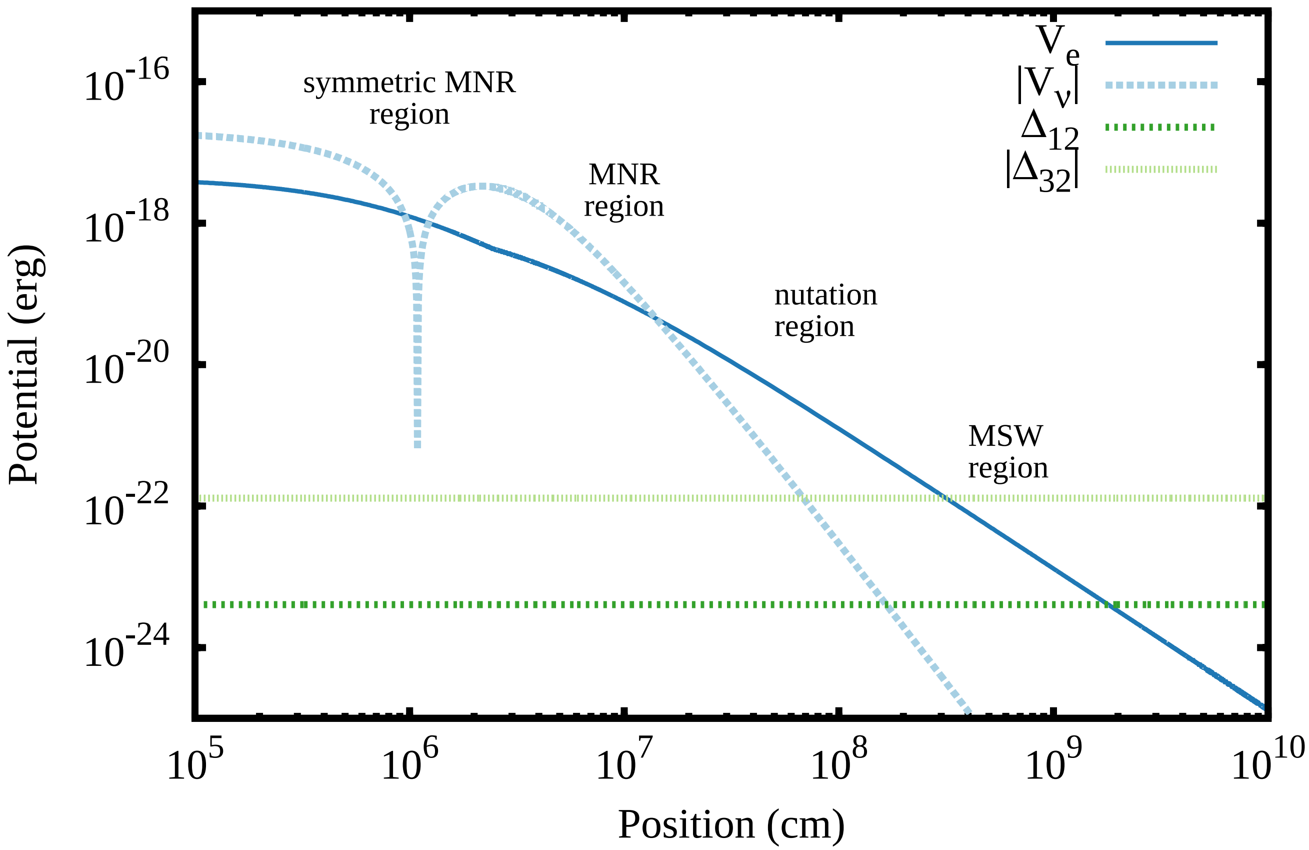
Types of merger oscillations:scales

- $\frac{\delta m^2}{4E} \sim V_e \propto G_F N_e(r)$
- $\frac{\delta m^2}{4E} \sim V_{\nu\nu} \propto G_F N_\nu * \mathrm{angle} - G_F N_{\bar{\nu}} * \mathrm{angle}$
- $V_e \sim V_{\nu\nu}$
- $V_{\nu\nu} \sim$ perturbation wave number

Types of merger oscillations: jargon

- $\frac{\delta m^2}{4E} \sim V_e$ MSW
- $\frac{\delta m^2}{4E} \sim V_{\nu\nu} \propto G_F N_\nu * \mathrm{angle} - G_F N_{\bar{\nu}} * \mathrm{angle}$ collective nutation
- $V_e \sim V_{\nu\nu}$ matter neutrino resonance
- $V_{\nu\nu} \sim$ perturbation wave number fast

What the potentials look like



Acceretion disk, Malkus '16, Vaananen '16

Oscillations: nonlinear

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

Merger oscillations: survival probabilities

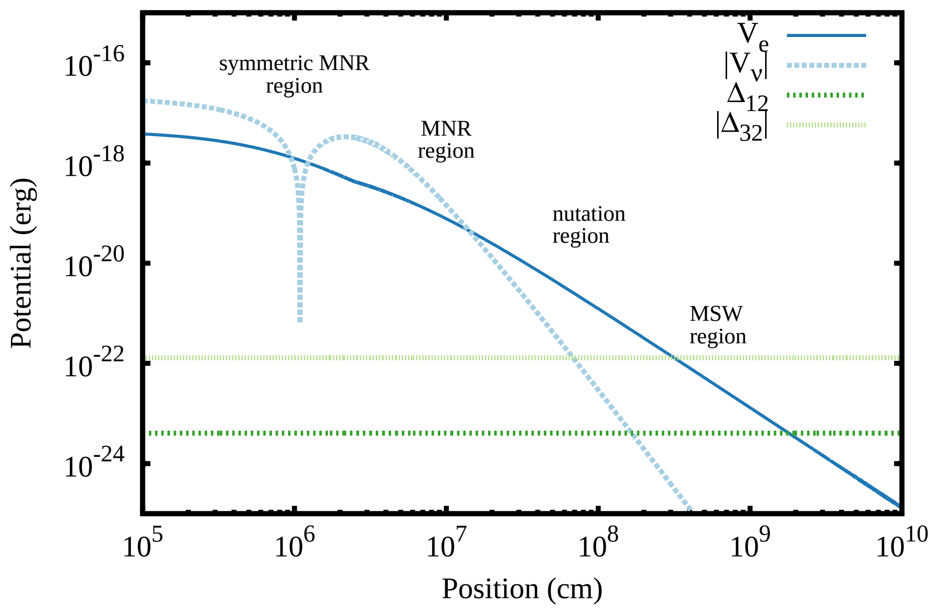


fig. from Malkus et al 2016

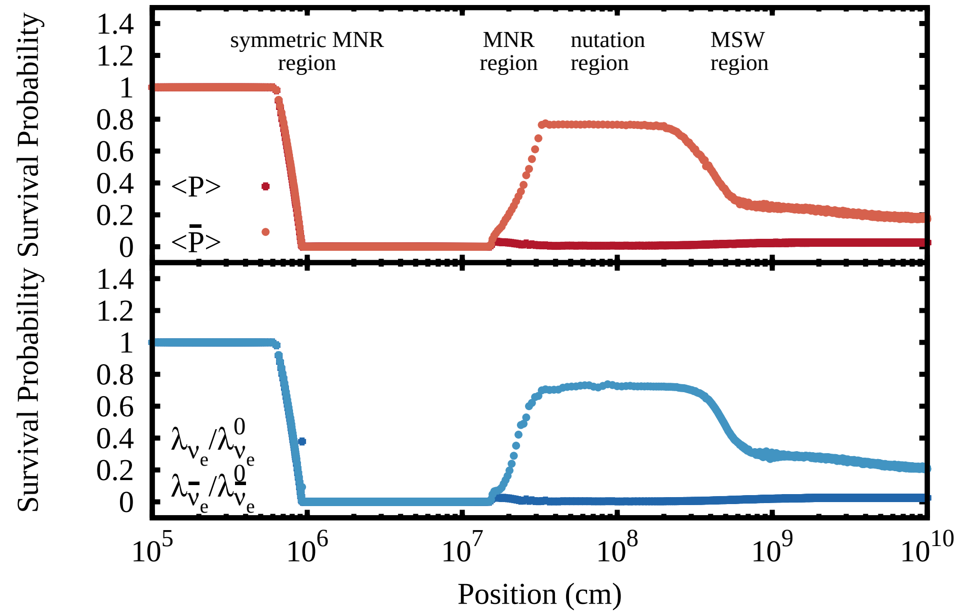
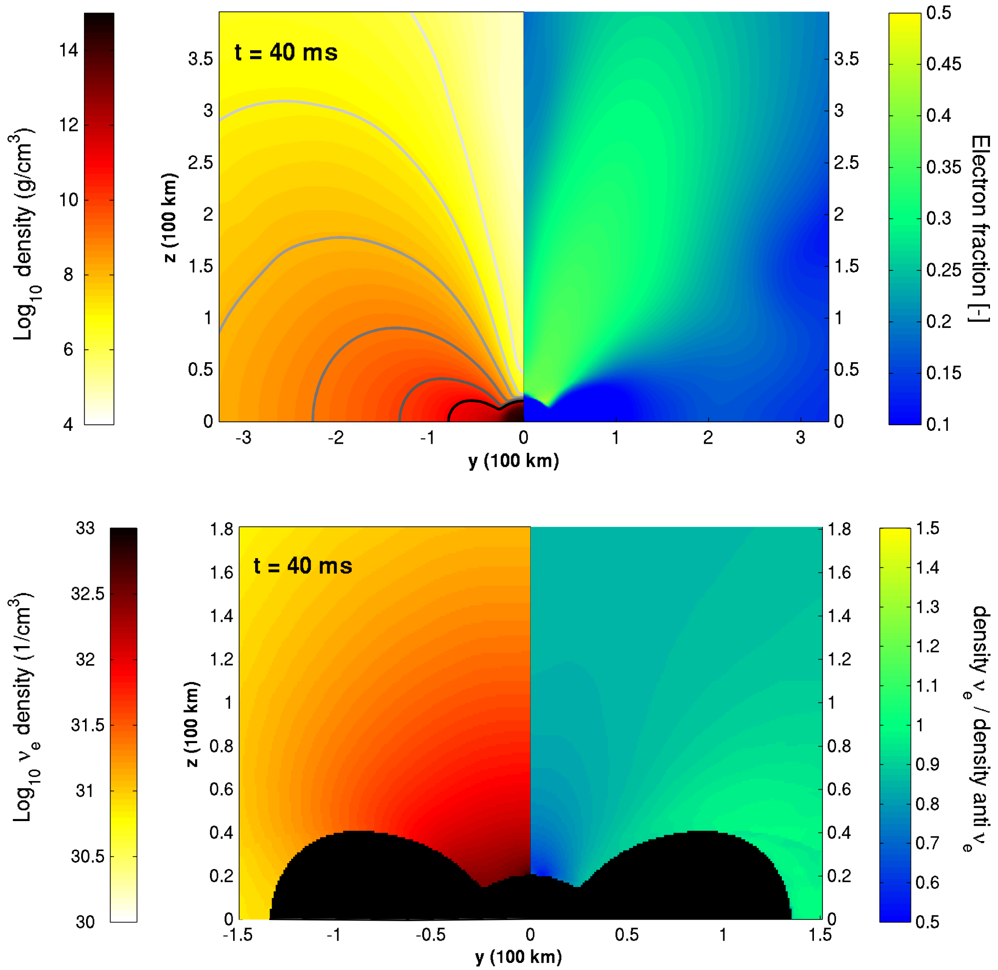


fig. from Malkus et al 2016

Nicely explained by theory predictions… Malkus et al, Wu, et al, Vaananen et al

Turning to a dynamical merger calculation



Zhu et al '16

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

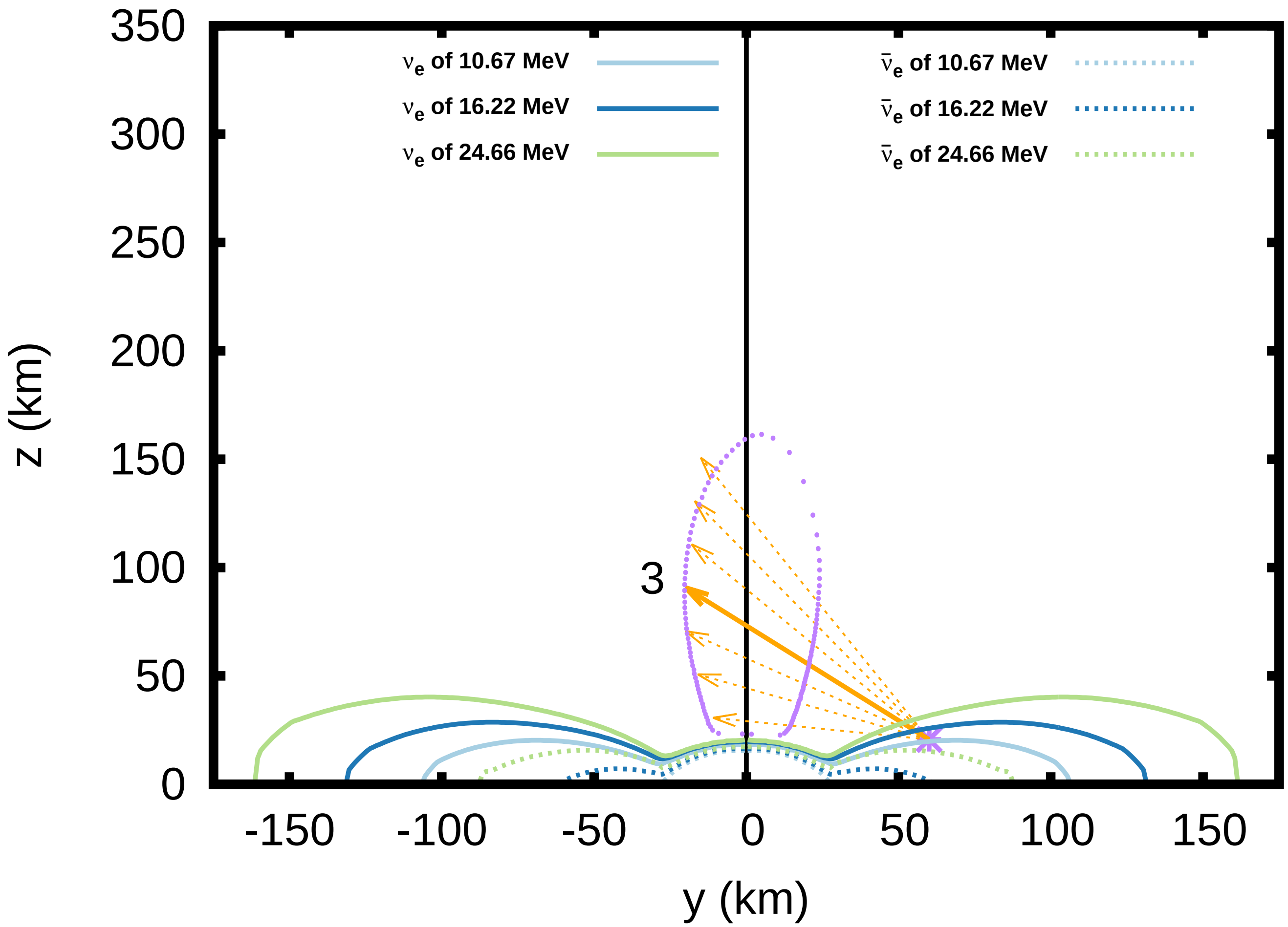


Fig. from Zhu et al 2016

Potentials and survival probabilities along a sample trajectory

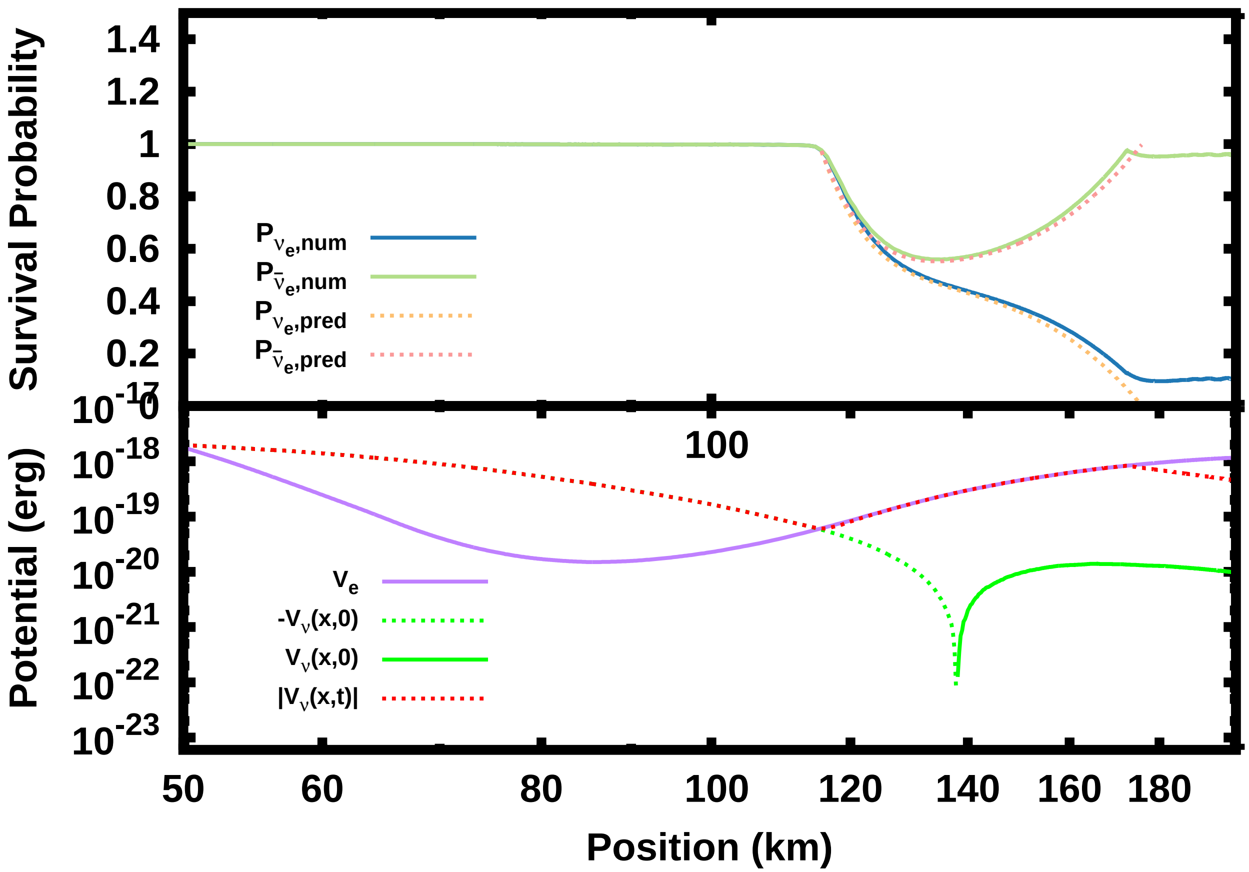
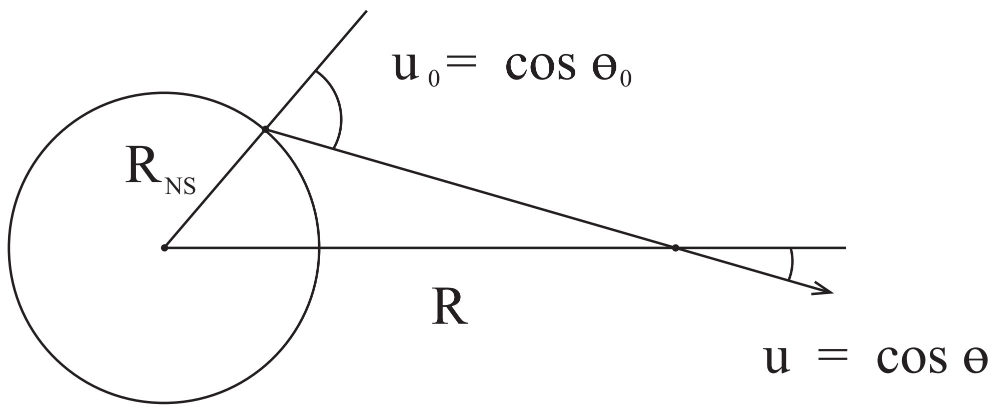


Fig. from Zhu et al 2016

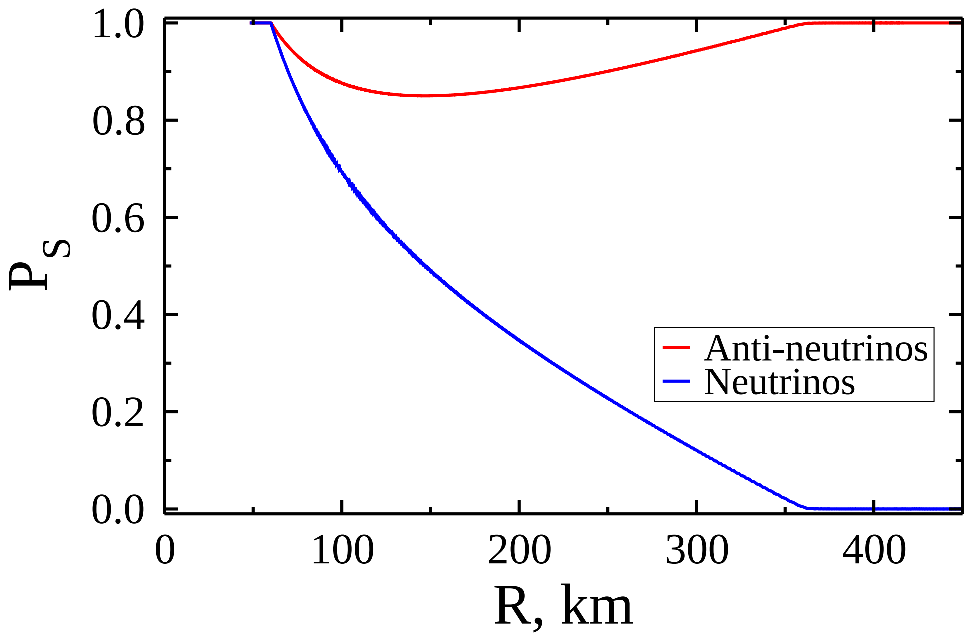
Relaxing the single-angle approximation

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

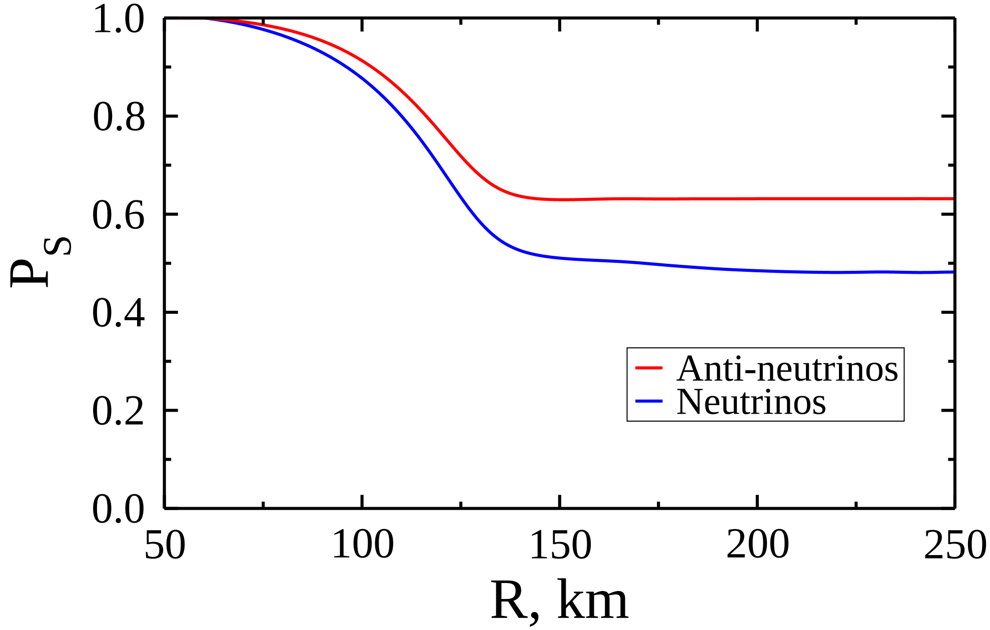
Our choice: spherical symmetry



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:

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

Looking to the future:

- 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