Neutrino flavor transformation from 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 (NC State), Yonglin Zhu (NC State)

Why examine neutrino flavor transformation for mergers?

- Recent hints from astronomy that a rare event may be responsible for the main r-process Frebel, Roderer. mergers?
- Current and upcoming radioactive beam experiments will reduce uncertainties in nuclear masses, reactions for nucleosynthesis.
- Many new merger simulations currently being performed.
- Flavor transformation may affect not only nucleosynthesis but also dynamics, jet formation in mergers.

Nucleosynthesis from neutron star mergers

- tidal ejecta
- collisional ejecta

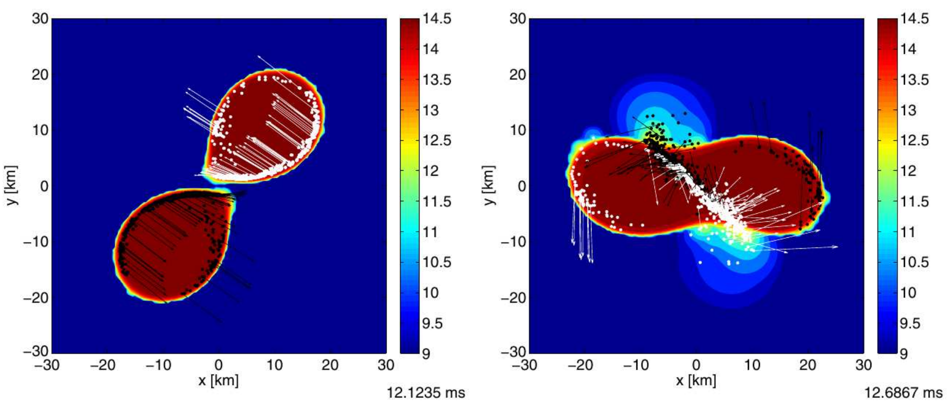


fig. from Bauswein et al 2013

- disk/hypermassive NS outflow
- outflow from viscous heating

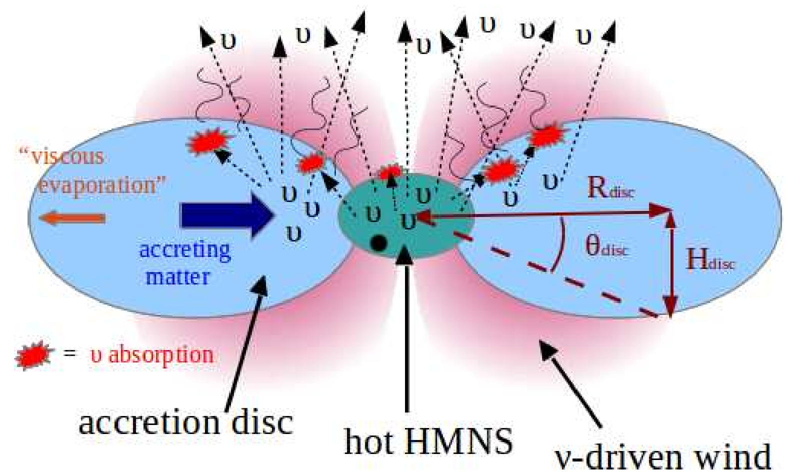


fig. from Perego et al 2014

Nucleosynthetic outflow influenced by neutrinos

- tidal ejecta
- collisional ejecta

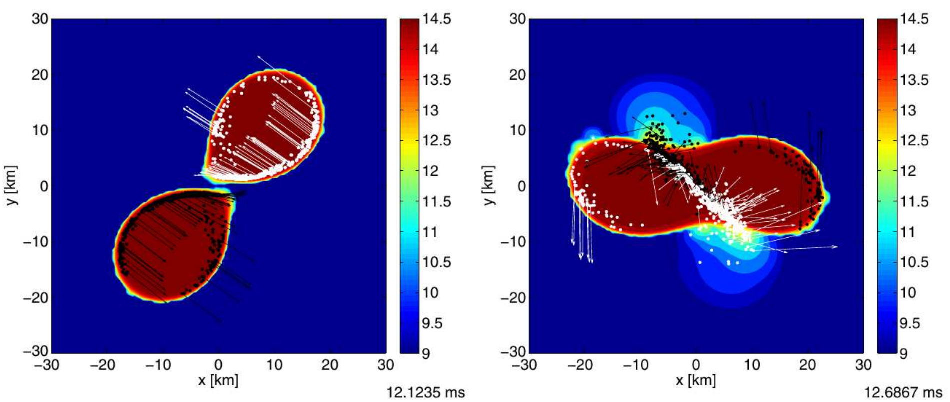


fig. from Bauswein et al '13

- disk/hypermassive NS outflow
- outflow from viscous heating

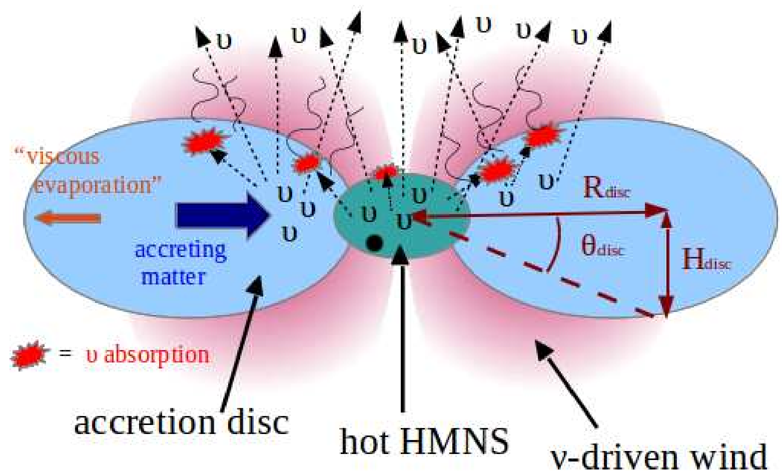


fig. from Perego et al '14

The influence of neutrinos on tidal, collisional outflow

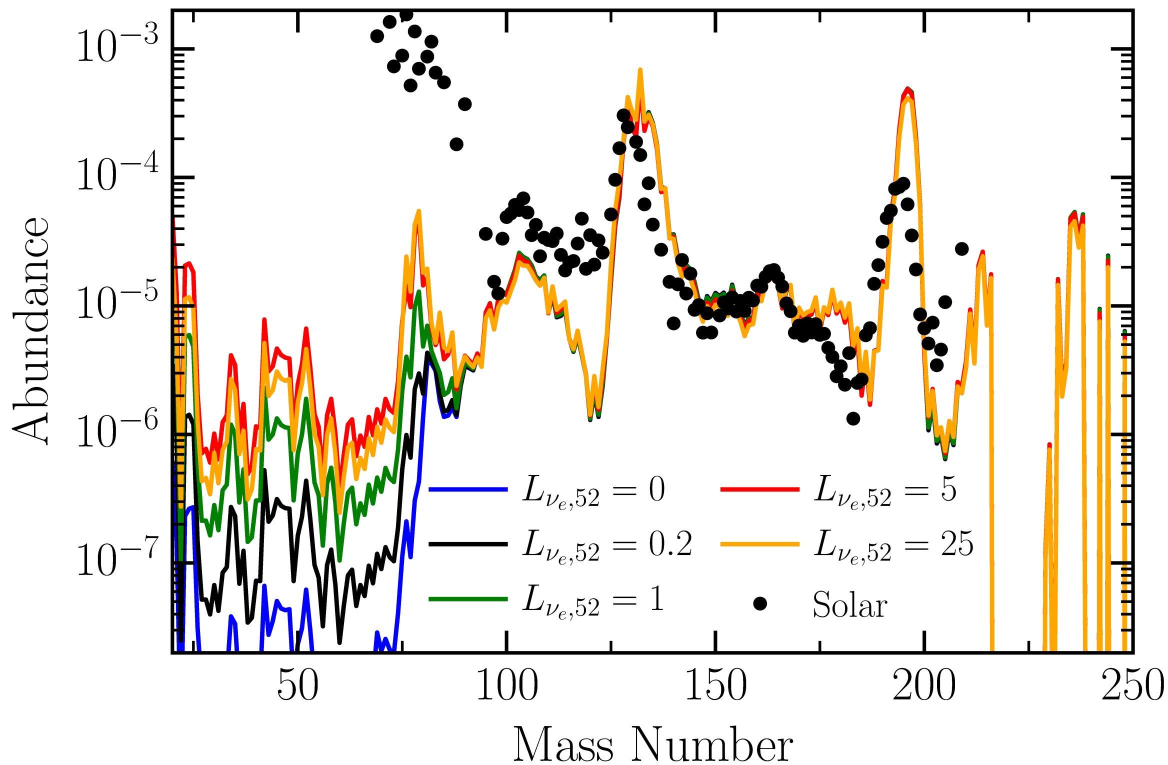
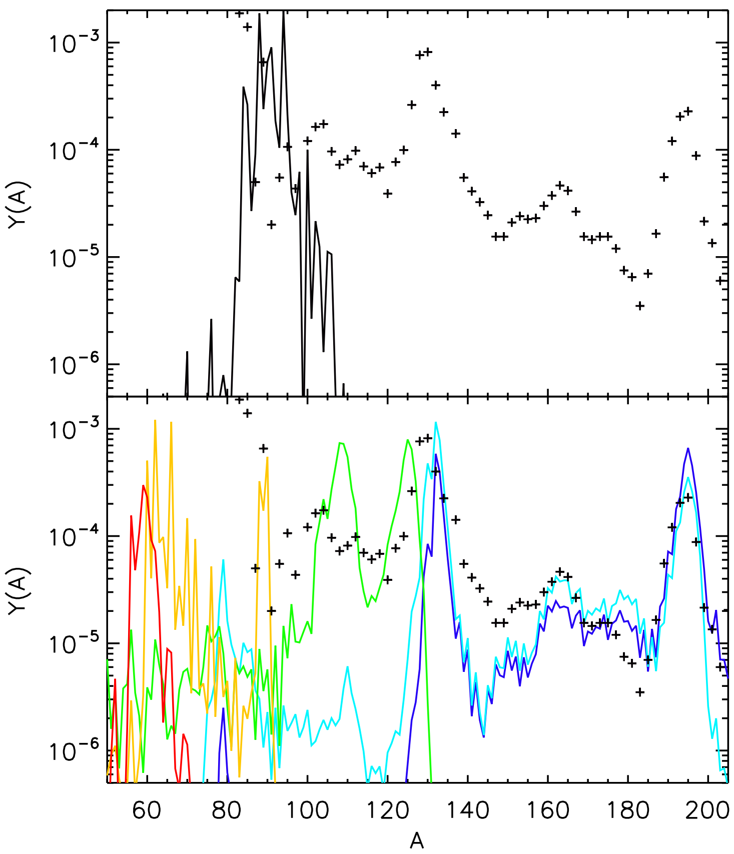


Fig. from Roberts et al 2016, for more collisional/tidal ejecta with neutrinos see also Wanajo et al '14, Sekiguichi et al '15, '16, Just '15, Radice et al '16, Lehner et al '16

The influence of neutrinos on wind outflow



Malkus et al '16 For wind neutrino influence on nucleosynthesis/Y_e see also Surman et al '08, Wanajo et al '12, Caballero et al '14, Metzgeret al '14, Perego et al '14, Foucart et al '15, Martin et al '16, Wu et al '16

Neutrinos influence nucleosynthesis

Neutrinos change the ratio of neutrons to protons

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

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

Oscillations change the neutrinos

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 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

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

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: vacuum

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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$\frac{\delta m^2}{4E} >> V_e, V_{\nu\nu} \rightarrow$ vacuum oscillations

e.g. atmospheric neutrinos, most terrestrial oscillation experiments

Oscillations: MSW

Modified wave equation

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

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$\frac{\delta m^2}{4E} \sim V_e >> V_{\nu\nu} \rightarrow$ MSW oscillations

e.g. sun, outer layers of supernova, outer layers of compact object merger

Oscillations: nutation/bipolar

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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- ν self-interaction scale $V_{\nu\nu} \propto G_F N_\nu * \mathrm{angle} - G_F N_{\bar{\nu}} * \mathrm{angle}$

$\frac{\delta m^2}{4E} \sim V_{\nu\nu} \rightarrow$ nutation/bipolar oscillations

e.g. supernova (100s of km), see e.g. Balantekin, Dighe, Duan, Carlson, Fuller, Kneller, Mirrizi, Pehlivan, Raffelt, Qian, Volpe, Yoshida, Yuksel, black hole accretion disks Dasgupta et al

Oscillations: matter neutrino resonance

Modified wave equation

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

Scales in the problem:

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

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

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

Oscillations: nonlinear

Modified wave equation

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

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.

Why are merger oscillations different than supernova?

Potentials $V_{\nu\nu}$ and V_e can have opposite sign

Capture some basic behavior with a toy model: single energy gas of neutrinos and antineutrinos. More antineutrinos than neutrinos. Let density of neutrinos and antineutrinos decline. Matter stays fixed.

Calculate survival probabilities: $P_{\nu_e} = |\psi_{\nu_e}|^2$, $P_{\bar{\nu}_e} = |\psi_{\bar{\nu}_e}|^2$

MNR transition: single energy model

Potentials $V_{\nu\nu}$ and V_e can have opposite sign

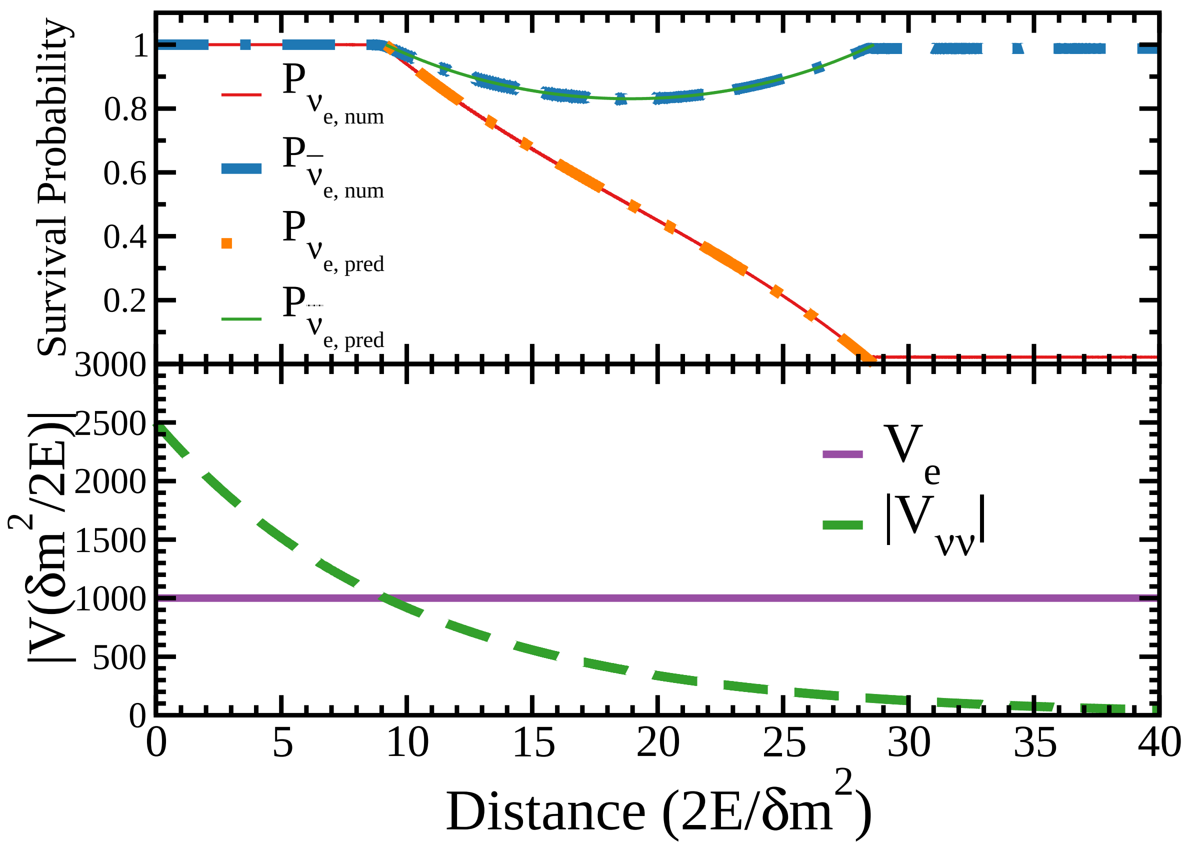


Fig. from Malkus et al 2014

Matter neutrino resonance transitions

What is happening?

Explanations: Neutrinos stay "on resonance" Malkus et al '14, instantaneous mass splitting stays "small" Väänännen et al '16, neutrinos are "adiabatic" Wu et al '16, Väänännen et al '16 all lead to same formula at zero order

$$P_{\nu_e} \approx \frac{\left(\alpha^2-1\right)\mu_\nu(r)^2-V_e(r)^2}{4V_e(r)\mu_\nu(r)} - 1/2$$

$$P_{\bar{\nu}_e} \approx \frac{\left(\alpha^2-1\right)\mu_\nu(r)^2+V_e(r)^2}{4\alpha V_e(r)\mu_\nu(r)} + 1/2$$

α is the asymmetry between antineutrinos and neutrinos and μ_ν is the scale of the neutrino self interaction potential

MNR transition: single energy model

Compare numerics to prediction

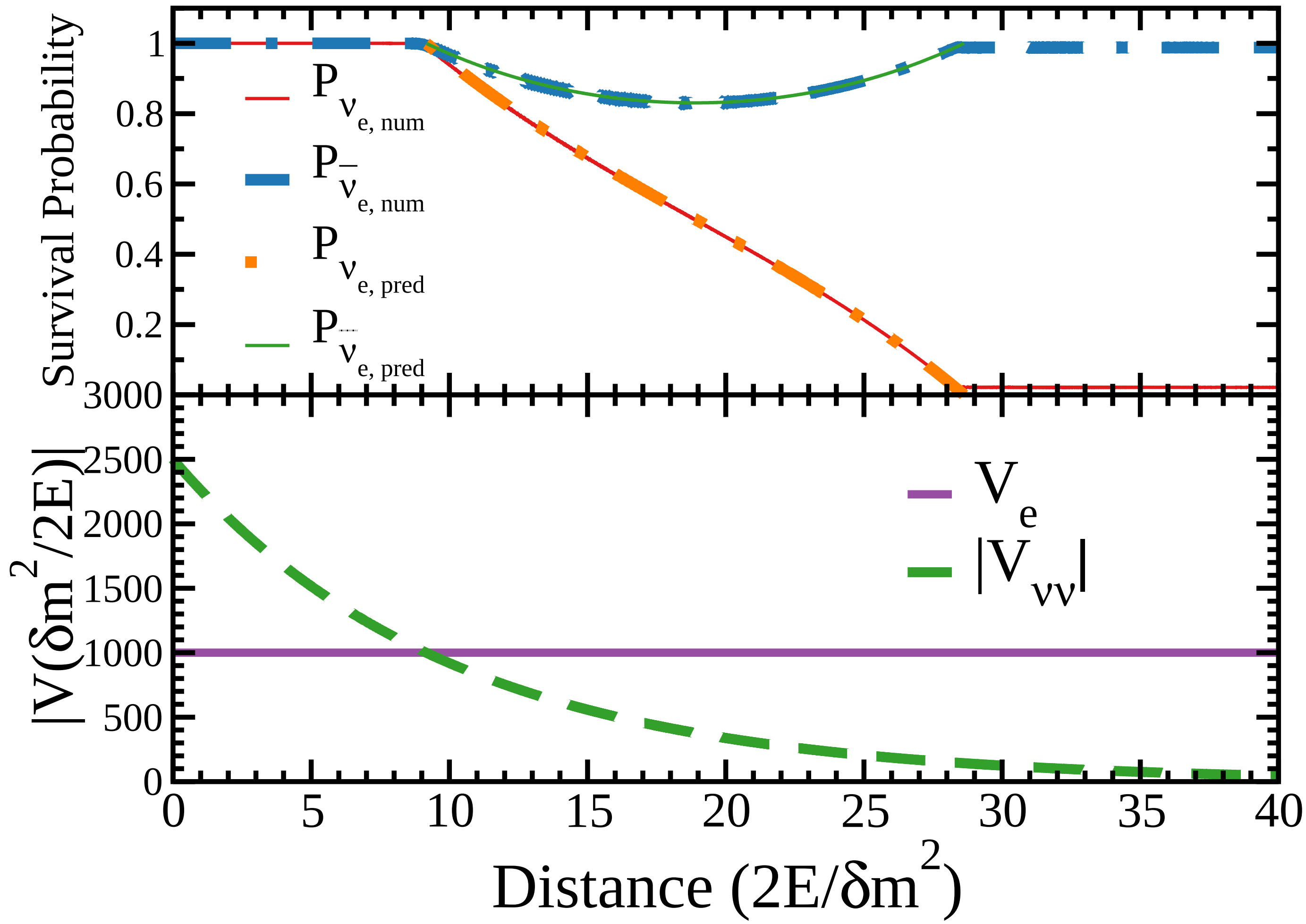


Fig. from Malkus et al 2014

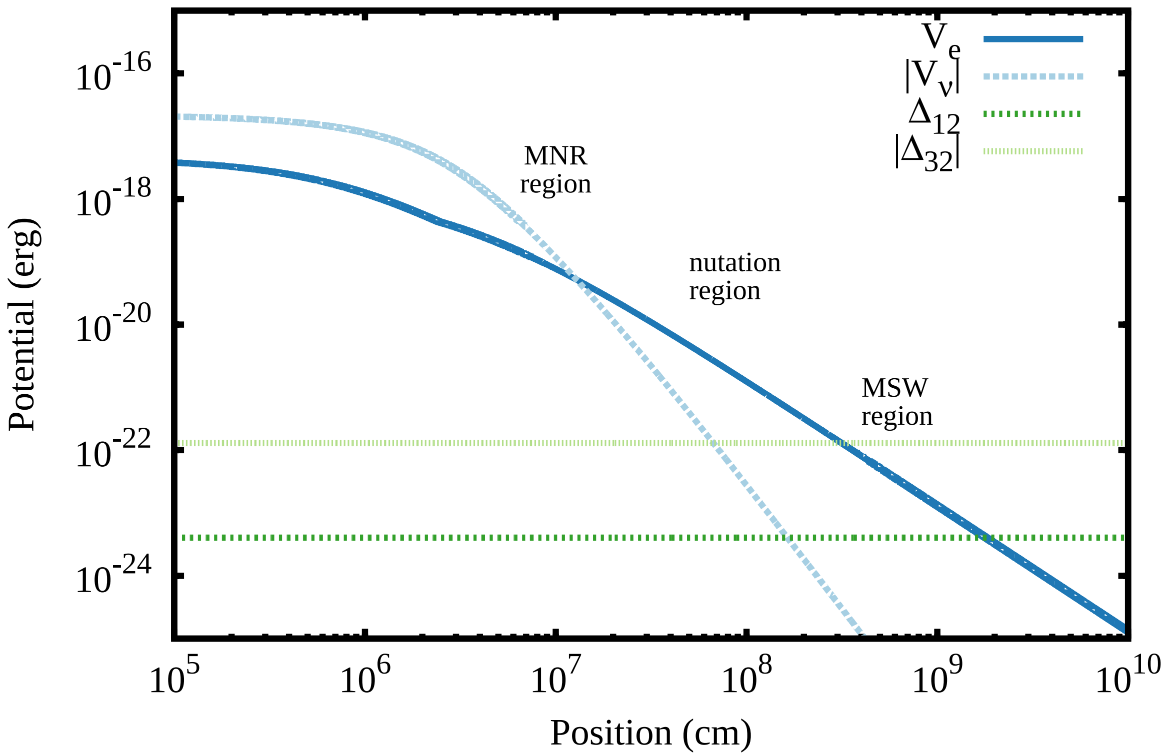
Now switch to a disk geometry and a multi-energy calculation

Neutrino disk is 45 km, neutrinos have temperature 6.4 MeV

Antineutrino disk is 45 km, antineutrinos have temperature of 7.1 MeV

Launch a neutrino at 45 degrees to the disk.

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



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

multi-energy, single angle calculations

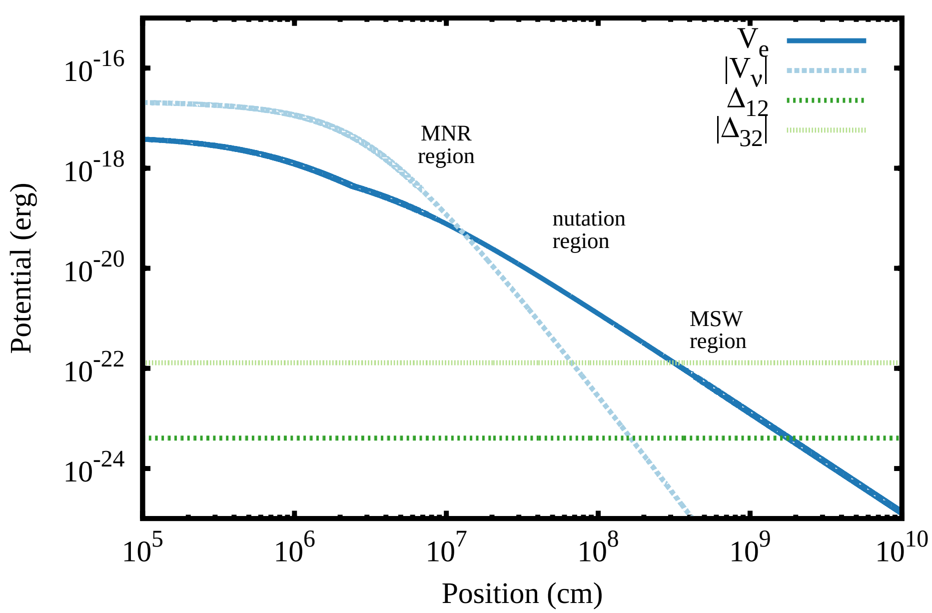


fig. from Malkus et al 2016

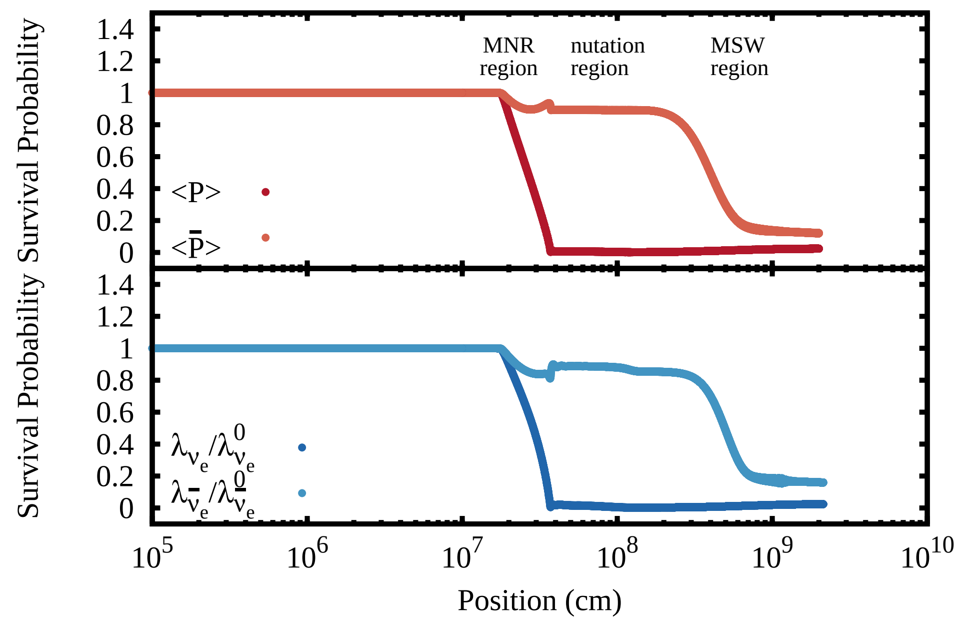
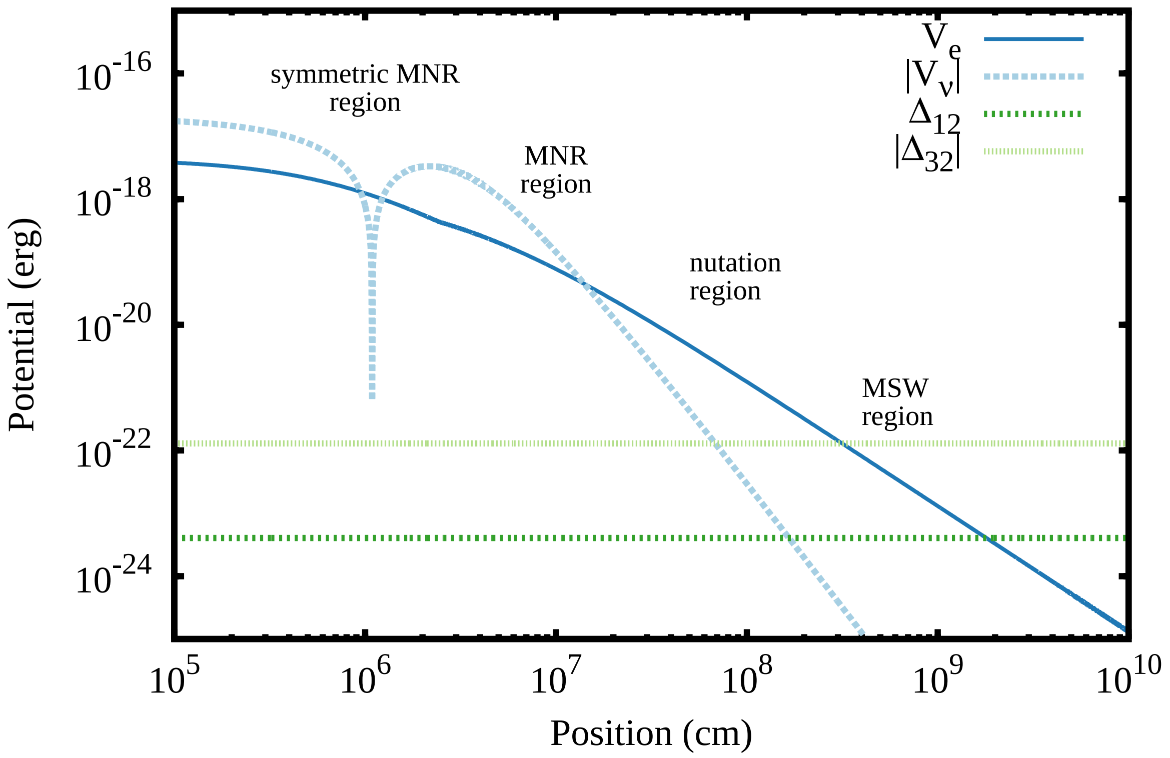


fig. from Malkus et al 2016, see also Frensel et al 2016

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



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

multi-energy, single angle calculations

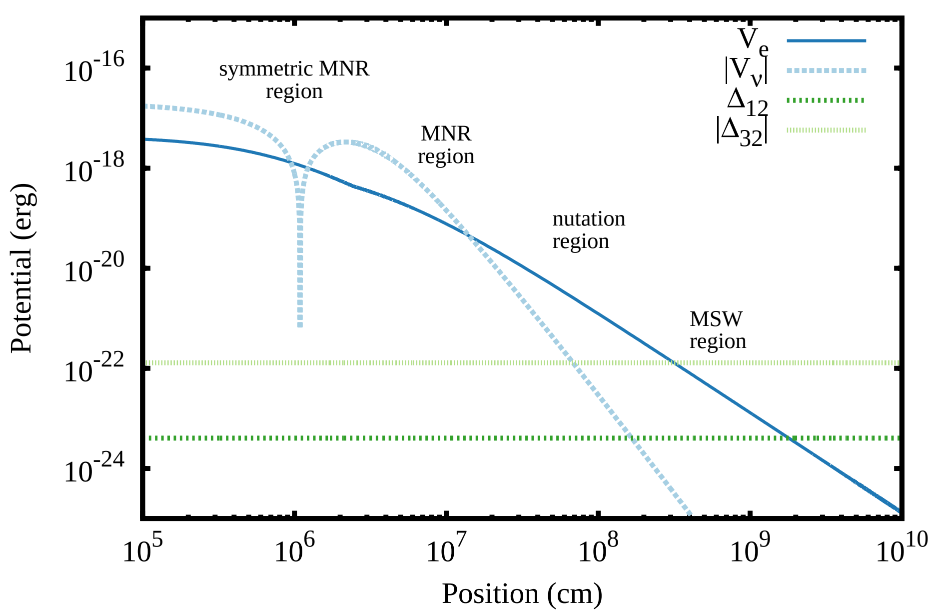


fig. from Malkus et al 2016

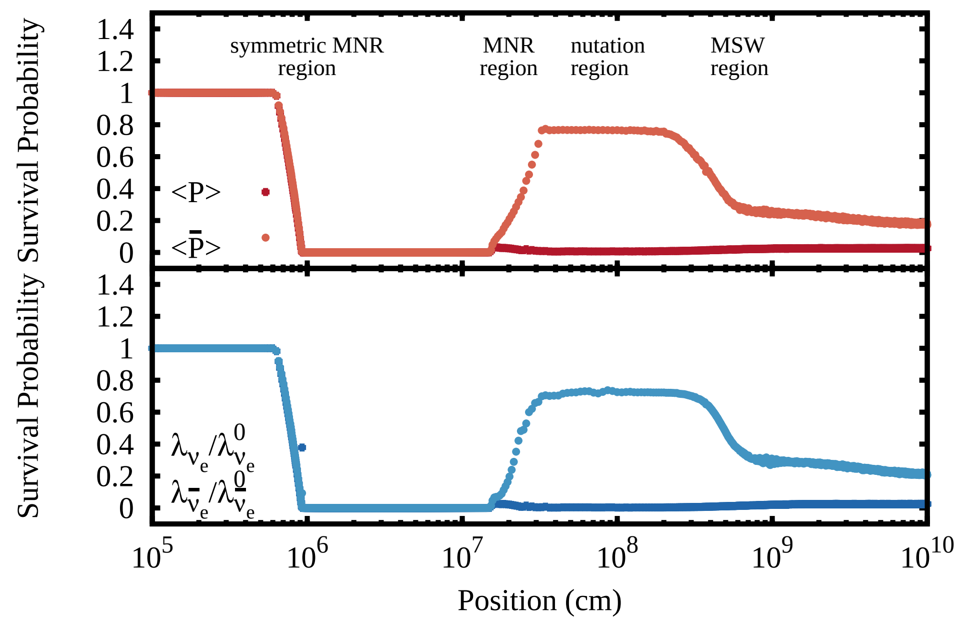
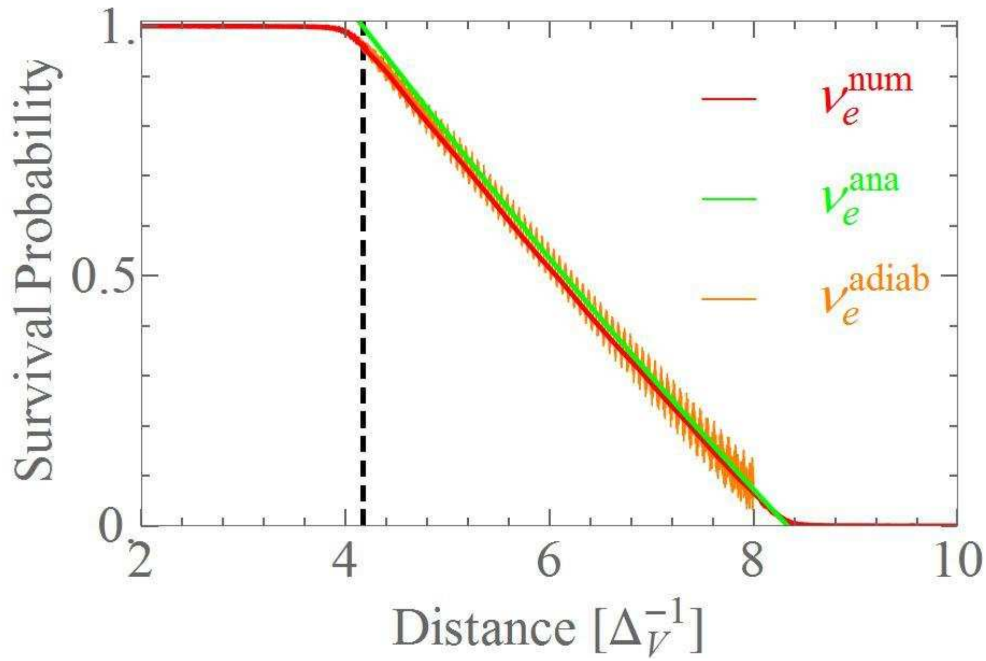


fig. from Malkus et al 2016

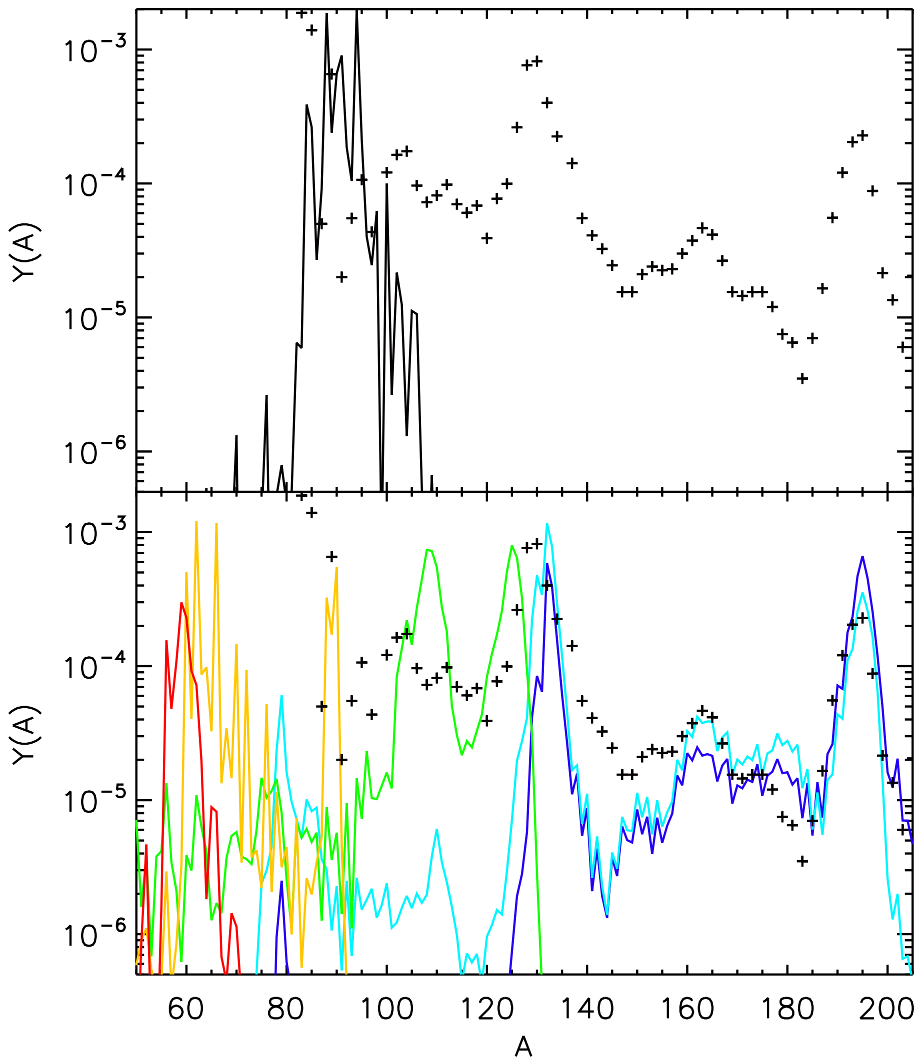
Analytic survival probability prediction also works for symmetric MNR transitions

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



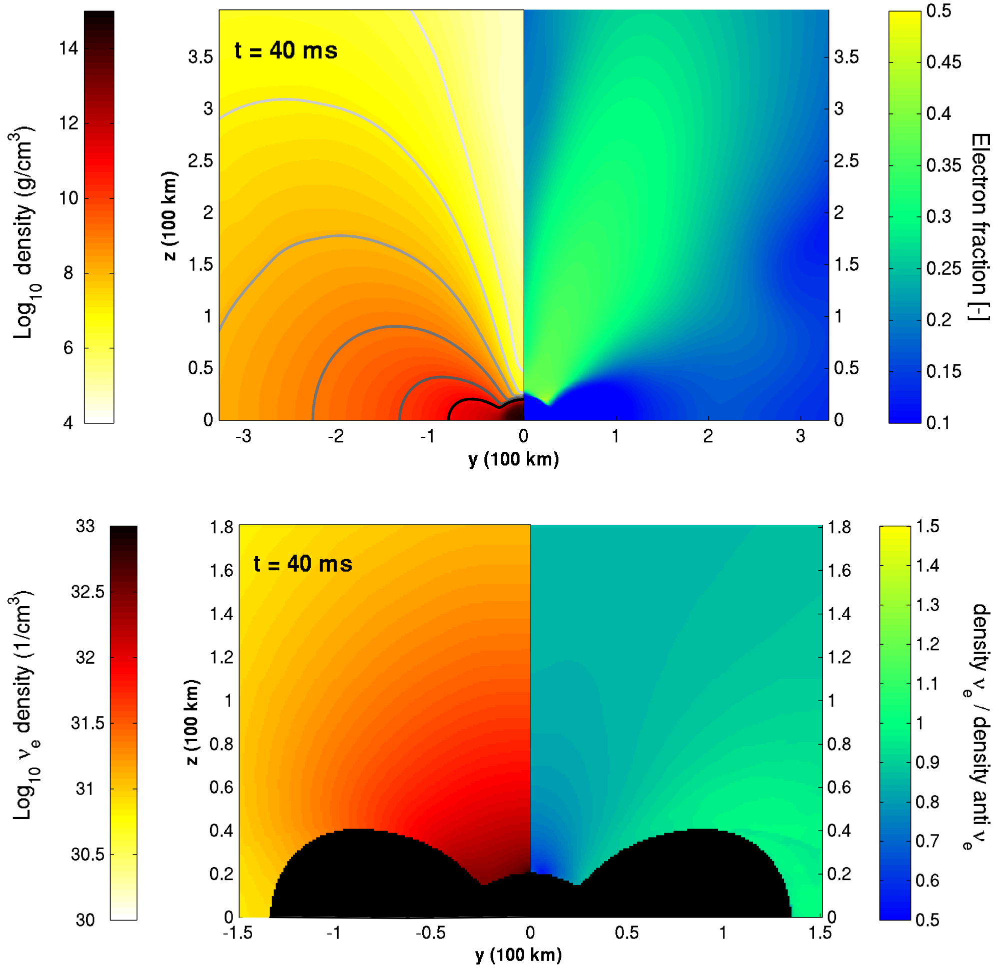
Symmetric MNR Fig. from Väänänen '16

How oscillations effect nucleosynthesis



Malkus et al '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

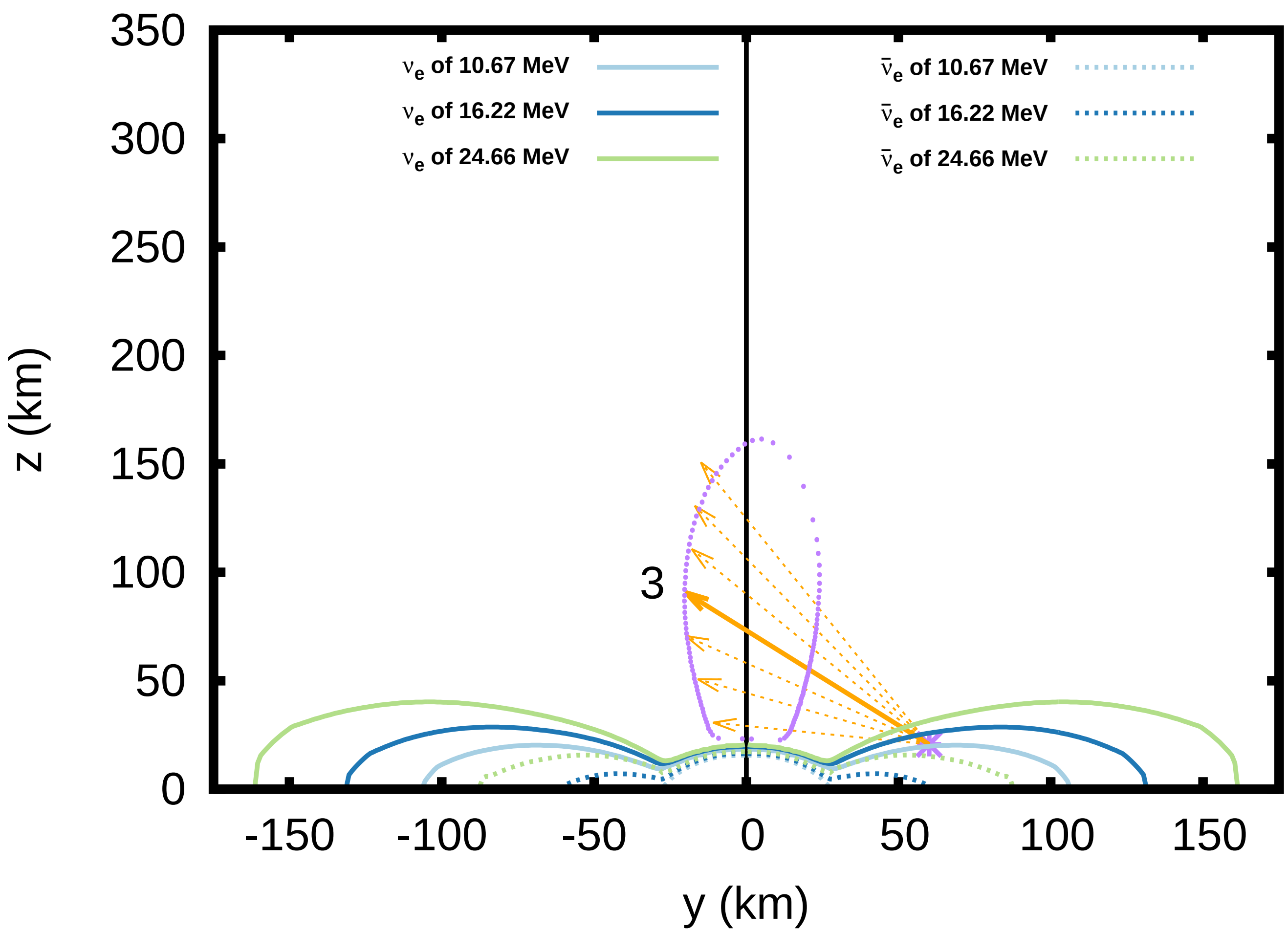


Fig. from Zhu et al 2016

Potentials and survival probabilities along a sample trajectory

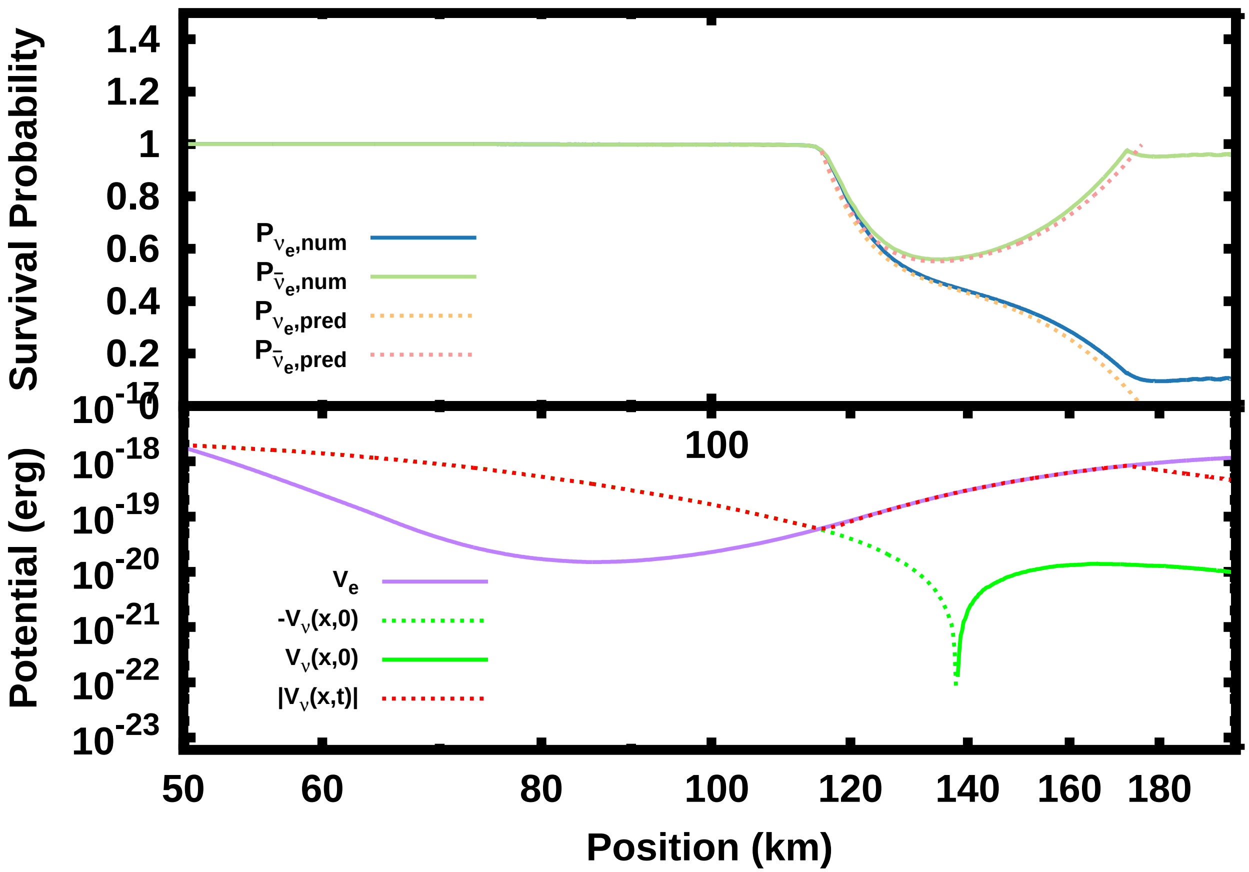


Fig. from Zhu et al 2016

Neutrino densities in a dynamical merger remnant

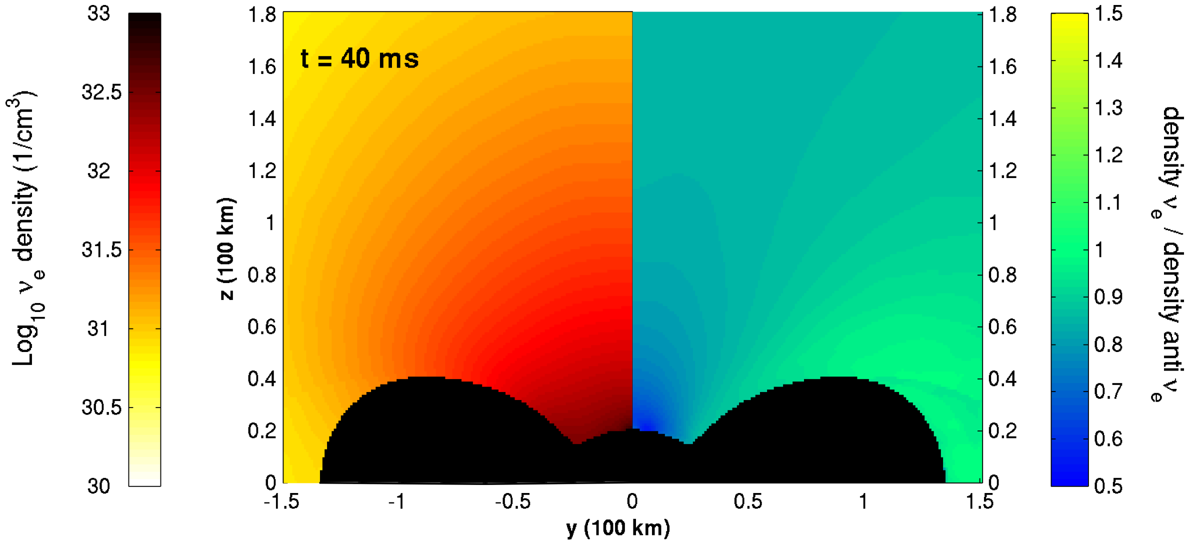


Fig. from Zhu et al '16

Conclusions

Rapid progress in last couple years:

- Predictions of matter neutrino resonance transition behavior
- Likely exists in mergers, caveat: multi-angle
- Likely a significant impact on nucleosynthesis

What to do next?

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

Long term

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