Neutrino Flavor Transformation in Compact Object Mergers and Collapsars

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- Introduction
- Explanation of "Matter-Neutrino" resonance
- Implications

Black Hole Accretion Disks

Two types of disks

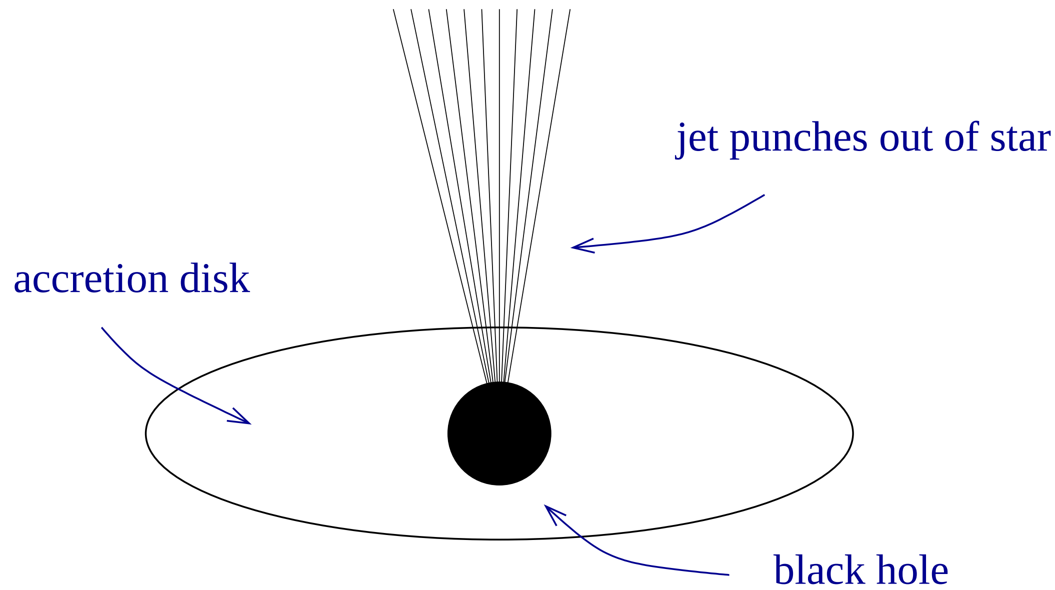
- compact objects mergers
- collapsars - collapse of a rotating massive star

Neutrinos have implications for

- dynamics
- nucleosynthesis

Stellar Collapse Disks: Collapsars

- Failed Supernova
- Too much rotation for real collapse & bounce



Accretion disks form in rare types of core collapse supernovae. Neutrinos from the disk may provide some of the energy required to power a jet.

Compact Object Merger Disks

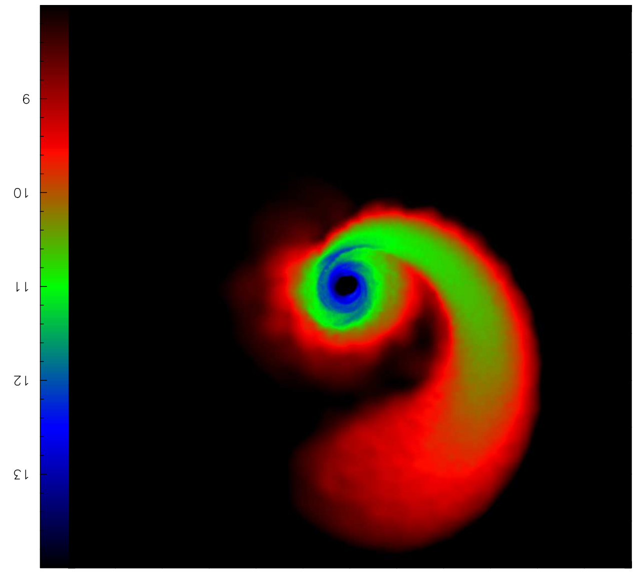


figure from Karobkin 2012

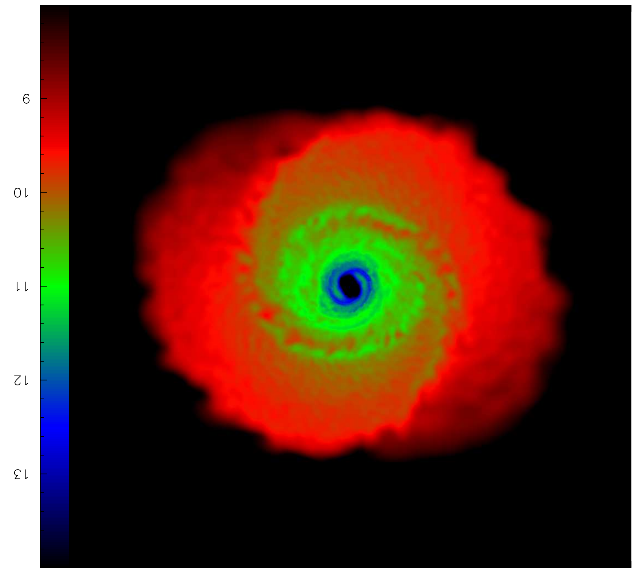


figure from Karobkin 2012

Compact Object Merger Hypermassive Neutron Star and Disk

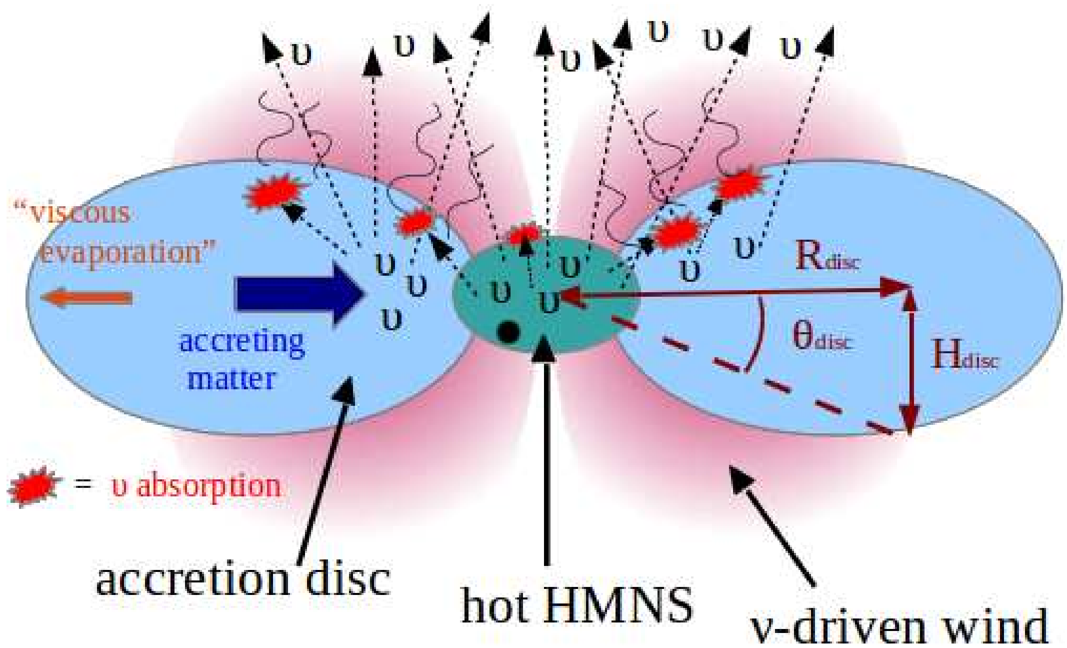
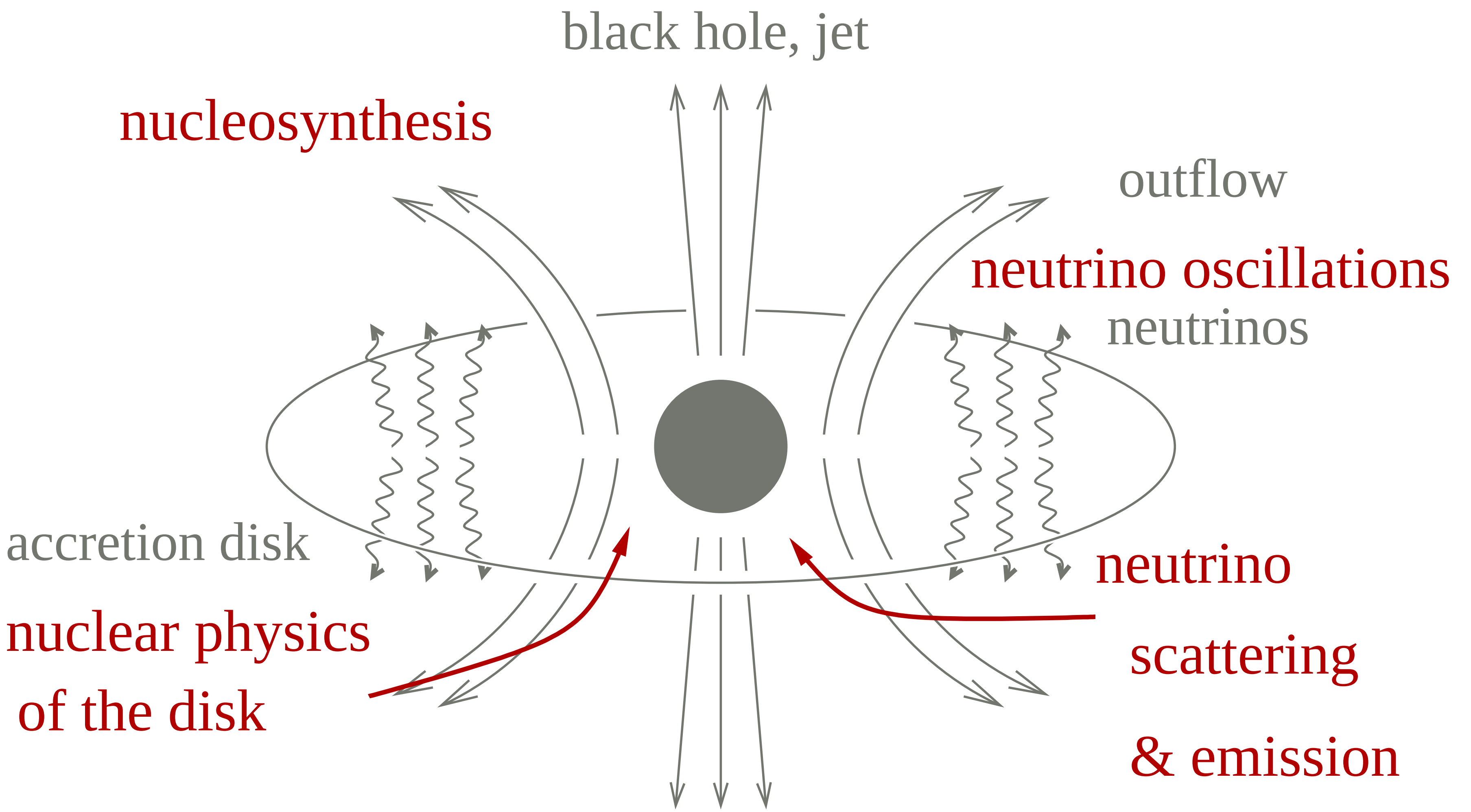


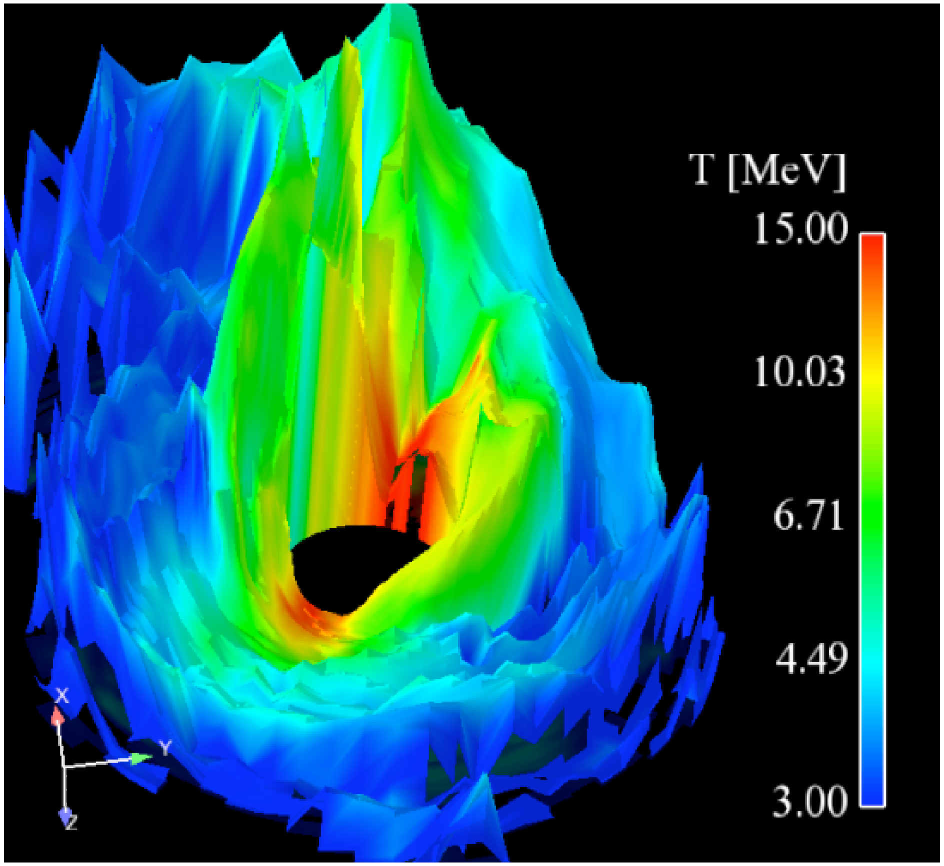
Fig. from Perego et al 2014

Neutrino and Nuclear Physics in Disks

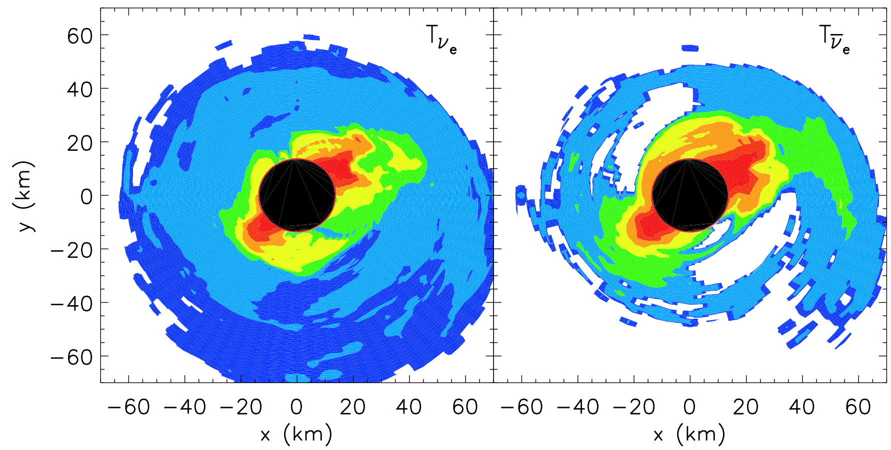


Accretion Disk ν_e temperatures

from postprocessing of a Ruffert and Janka disk



Caballero et al 2012



Surman et al 2008

Neutrinos from ν_e and $\bar{\nu}_e$ emitting disks

Characteristics

- primarily ν_e and $\bar{\nu}_e$ for collapsars, dominated by ν_e, $\bar{\nu}_e$ for compact object mergers
- similar spectra to supernovae
- emitted from a fairly different geometry
- emission surface for neutrinos is larger than for antineutrinos
- antineutrinos have higher temperature than neutrinos
- merger disks emit more antineutrinos than neutrinos

Neutrino Oscillations above disks

Oscillation Equation

Modified wave equation

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

- $\psi = (\psi_e, \psi_\mu)$
- $\frac{\delta m^2}{4E}$ vacuum contribution
- V_e matter potential
- V_ν^a,V_ν^b neutrino self interaction potential
- Survival Probability: $P_{\nu_e} = |\psi_e|^2$, if $\psi = (1,0)$ initially

Common Types of Oscillations

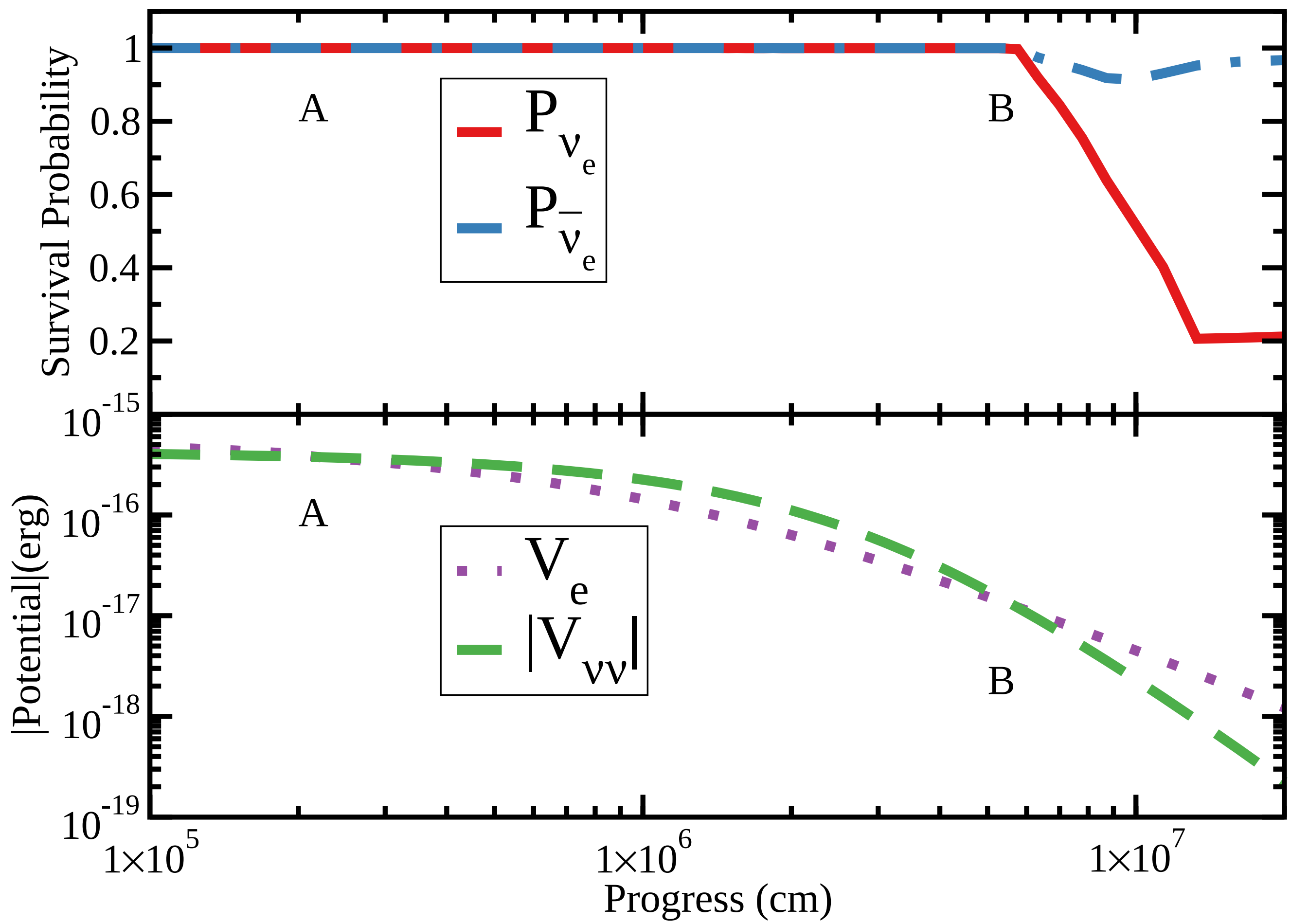
Modified wave equation

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

- $\frac{\delta m^2}{4E} >> V_e, V_\nu^a$: vacuum, terrestrial
- $V_e \sim \frac{\delta m^2}{4E}$: MSW, solar
- $V_\nu^a \gtrsim \frac{\delta m^2}{4E}$: collective, supernovae

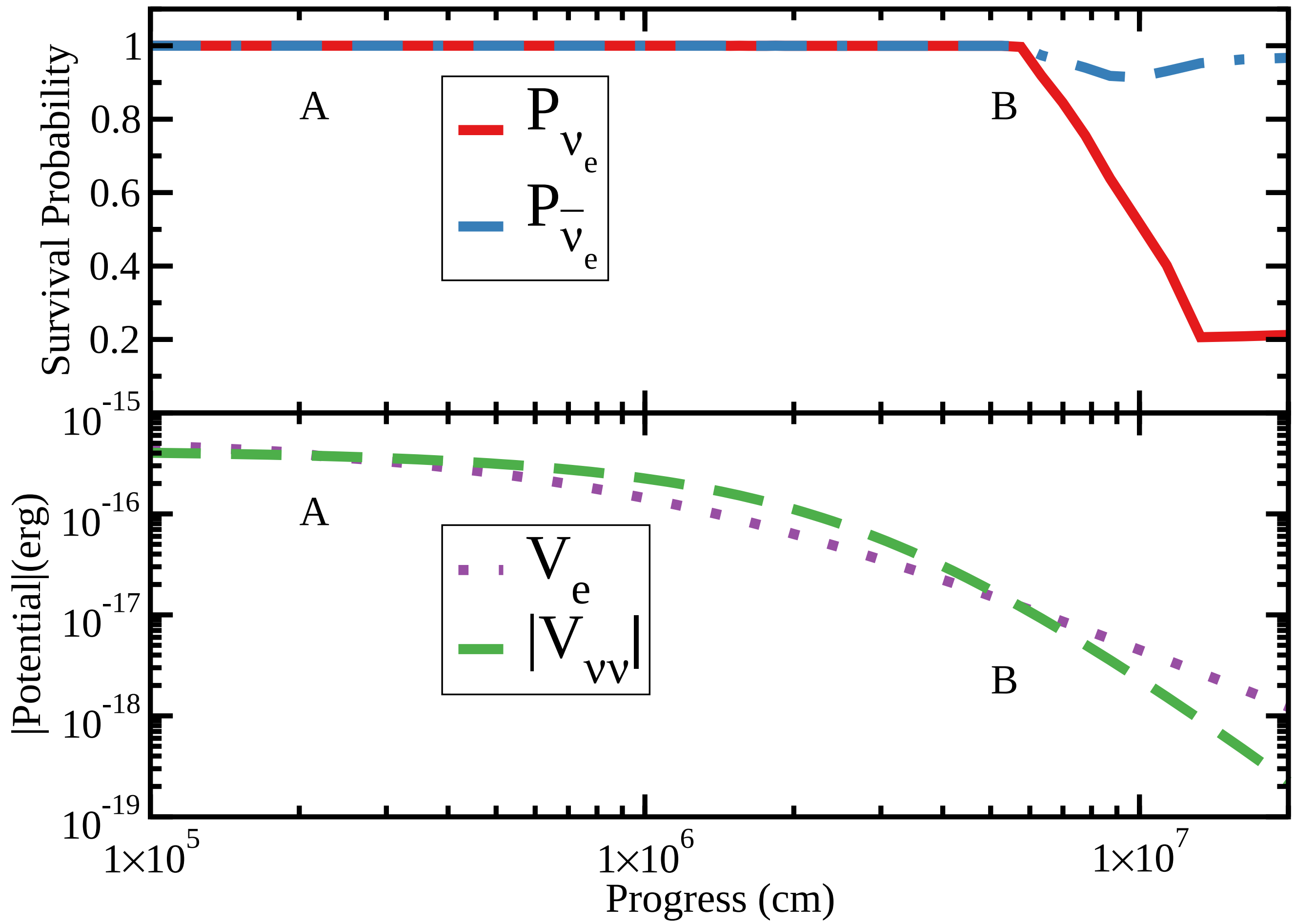
Matter Neutrino Resonance above a Merger Disk

neutrino and antineutrino emitting surfaces are the same



Top panel shows survival probabilities. Looks like no known supernova, solar, or terrestrial type oscillation Fig. from Malkus et al 2014

Resonance transition occurs close to disk



In the region of the transition expect free nucleons, so

$\nu_e + n \to p + e^-$ and $\bar{\nu}_e + p \to n + e^+$ will be affected. Fig. from Malkus et al 2014

Neutrino Oscillations: scales

Modified wave equation

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

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. At short distance V_ν term is roughly constant, at large distance it declines roughly as $1/r^4$

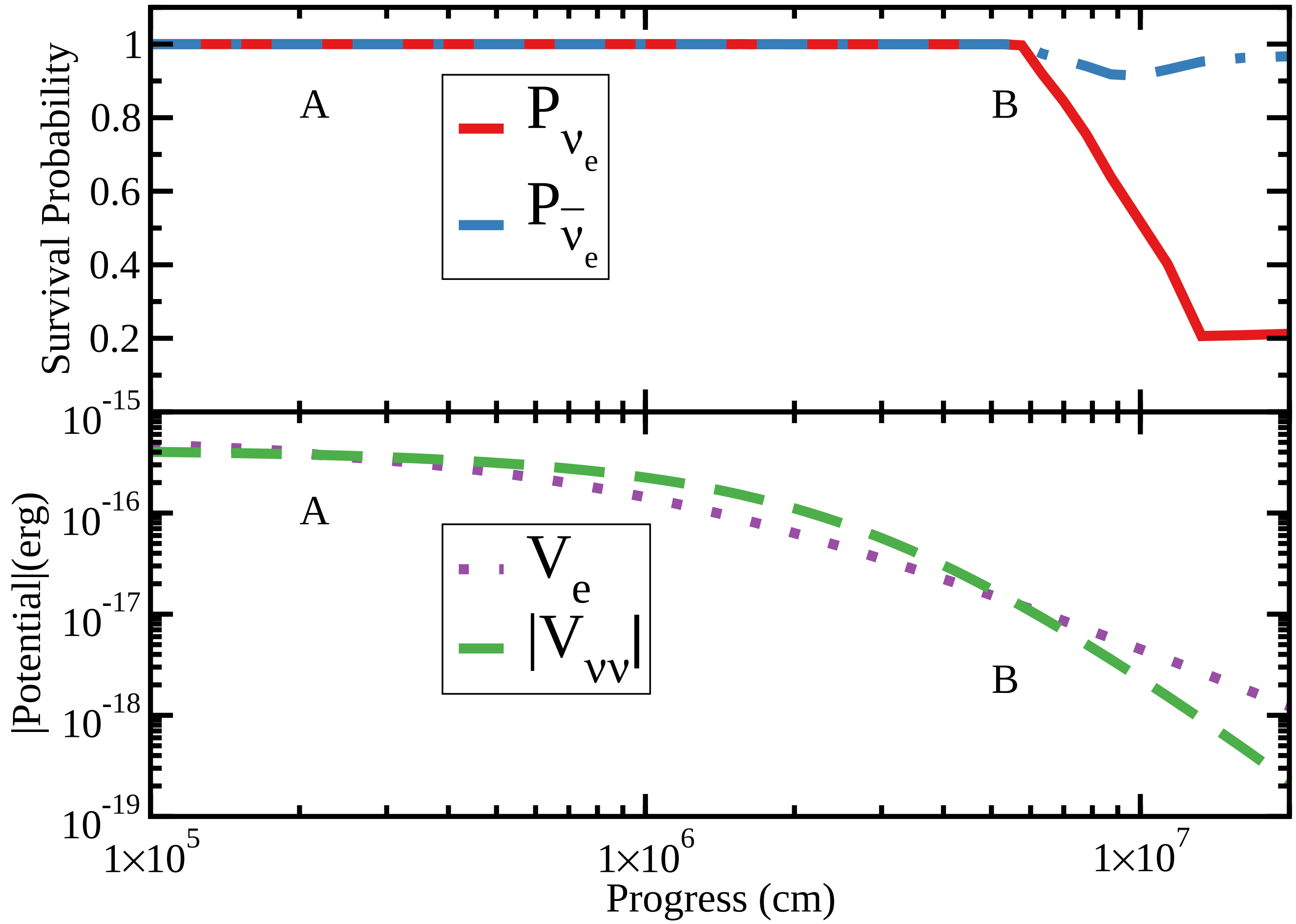
What's different about neutrinos from compact object mergers?

Antineutrinos outnumber neutrinos, so the unoscillated neutrino self interaction potential $V_\nu^a = N_{\nu,eff} - N_{\bar{\nu},eff}$ is negative.

Note: $N_{\nu,eff} = N_{\nu_e,eff} - N_{\nu_\mu,eff}$, so

$$V_\nu^a = (N_{\nu_e,eff} - N_{\nu_\mu,eff}) - (N_{\bar{\nu}_e,eff} - N_{\bar{\nu}_\mu,eff})$$

Neutrino-Matter Resonance Transition



Bottom panel shows potentials. Dotted green line indicates *negative potential*. Oscillation occurs at crossing of V_e and V_ν^a. Fig. from Malkus et al 2014

Analytic Description: "Matter Neutrino Resonance"

- System finds a resonance where $V_\nu^a + V_e \sim 0$ and then tries to maintain a position there
- In order to maintain the resonance the neutrinos change flavor $V_\nu^a \propto N_{\nu,eff,unosc}(2P_{\nu_e} - 1) - N_{\bar{\nu},eff,unosc}(2P_{\bar{\nu}_e} - 1)$ where P is survival probability
- Adiabaticity - time to complete transition must be greater than time needed to change flavor: limit on $\frac{\delta m^2}{4E} \sin 2\theta$
- The sum of flavor isospin vectors is restricted (approximately) to $\hat{z}$ direction.

Phenomenological Prediction: "Matter Neutrino Resonance"

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

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

$\alpha \sim N_{\nu_e,eff,unosc}/N_{\bar{\nu}_e,eff,unosc}$ is the asymmetry and

$\mu_\nu \sim N_{\nu_e,eff,unosc}$ is the scale of the neutrino self interaction potential

Now compare analytic prediction with numerical calculation

Neutrino-Matter Transition: Predictable Behavior

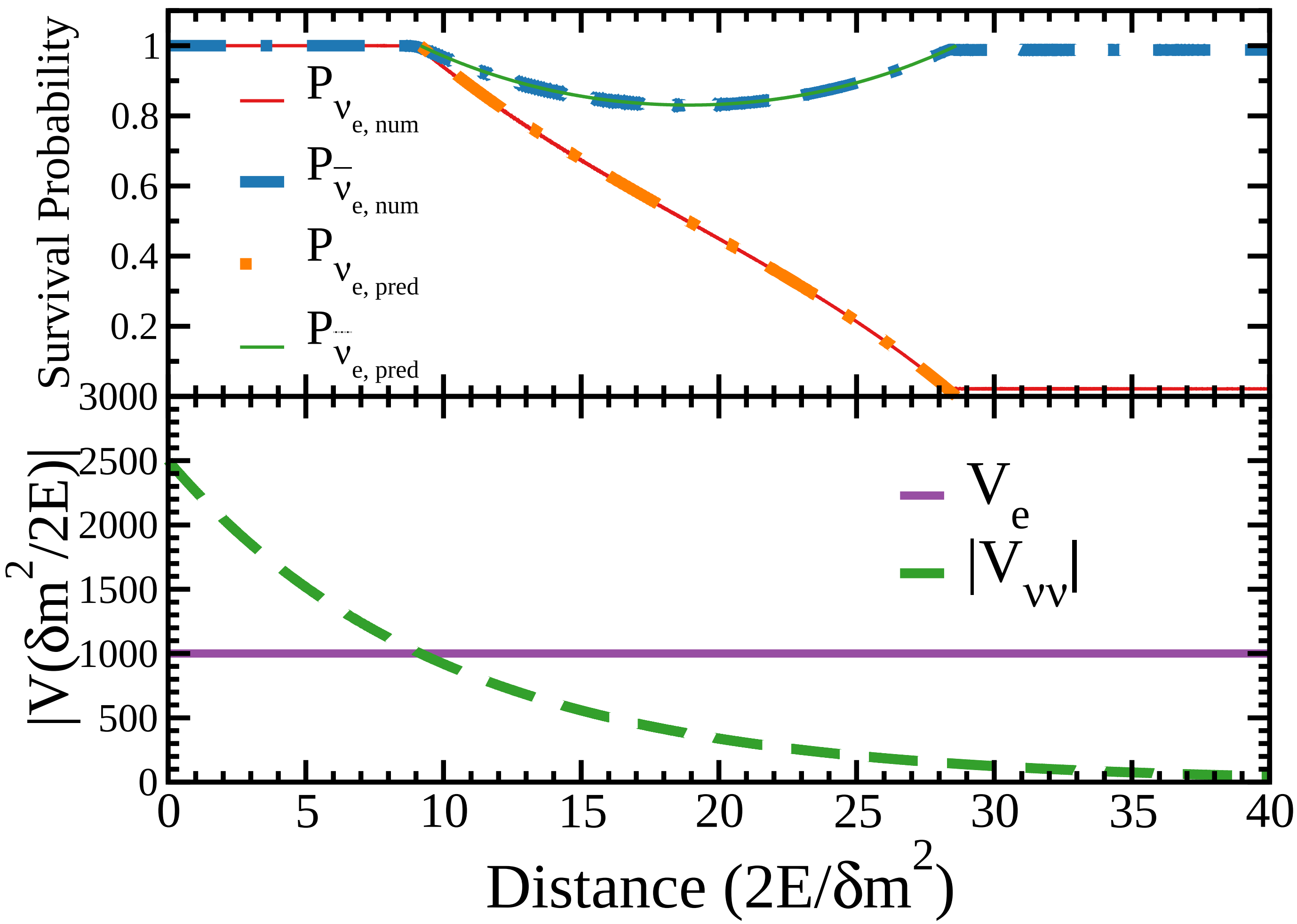
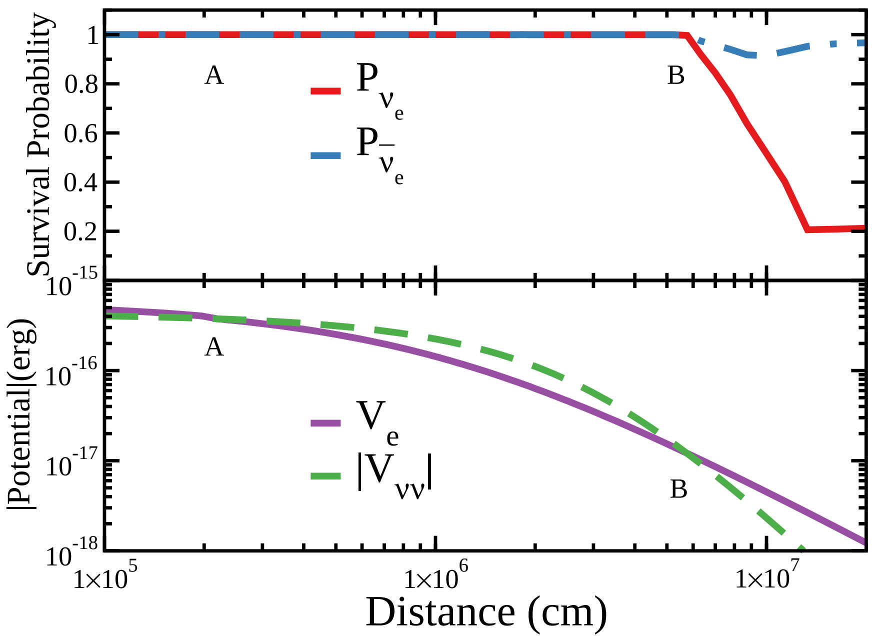
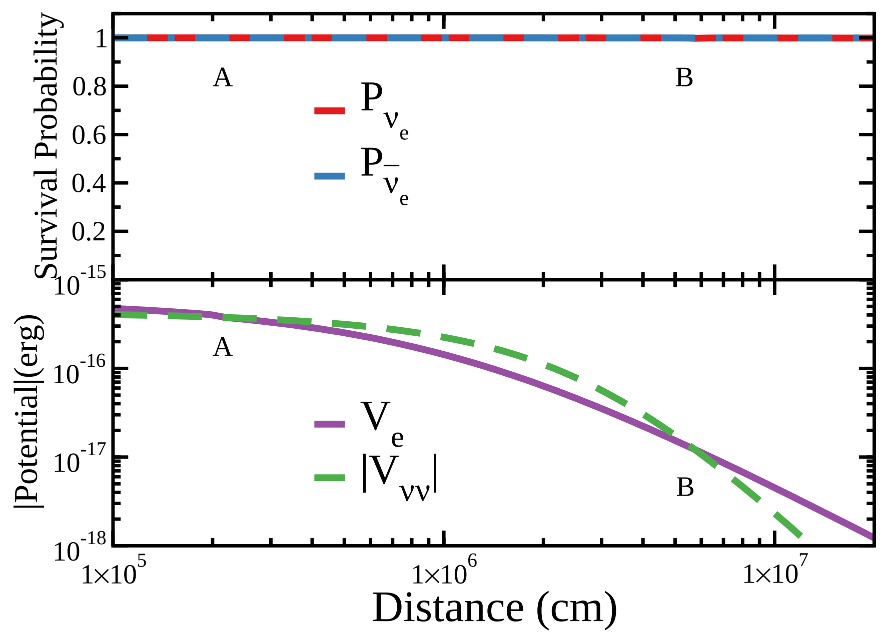


Fig. from Malkus et al 2014

Prediction suggests that sufficient ν_μ, ν_τ flux will shut off the resonance transition



ν_x scaled to 35%

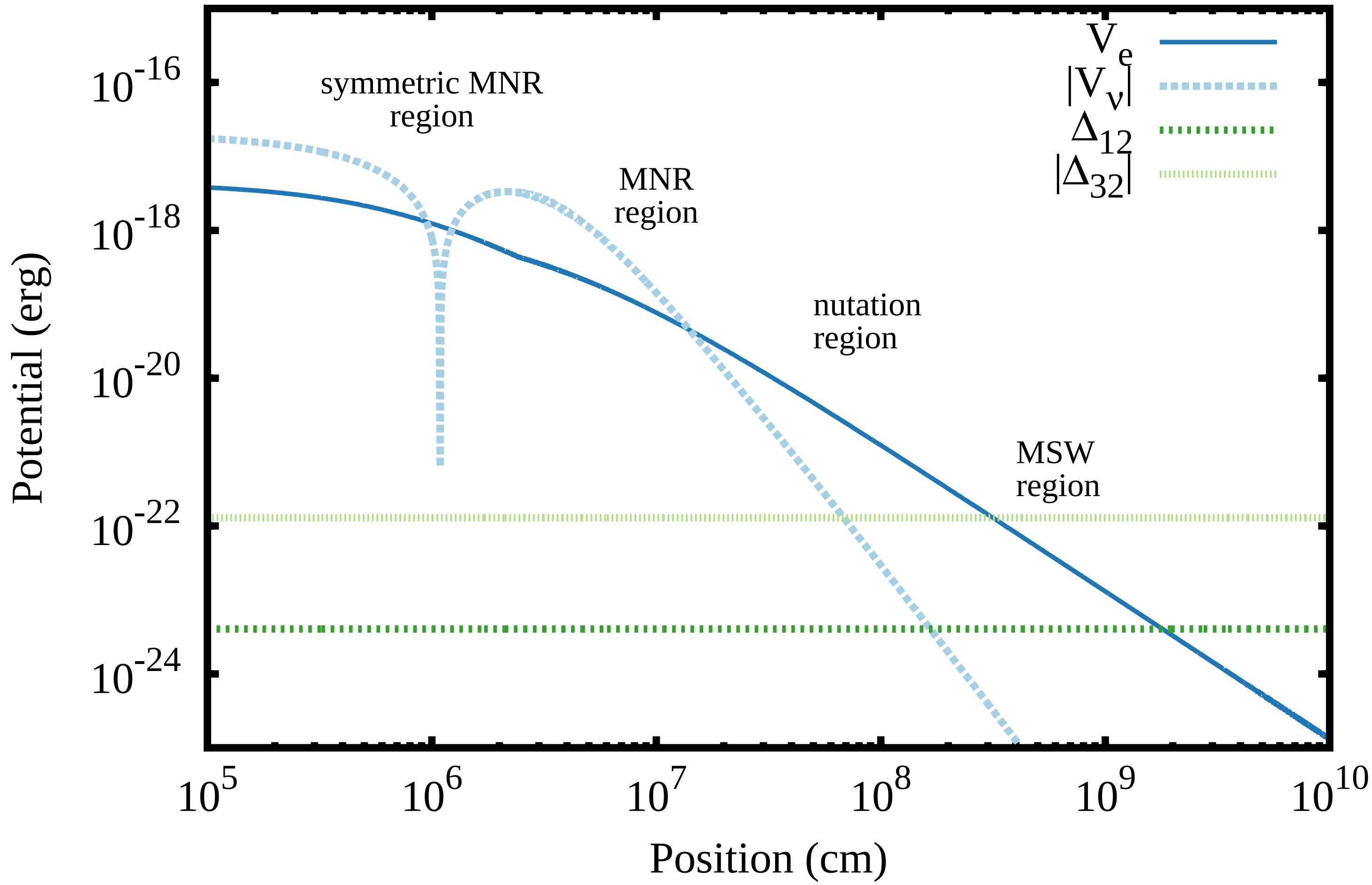


ν_x scaled to 40%

Numerical calculation confirms this. Fig. from Malkus et al 2014

Symmetric vs. Standard Matter Neutrino Resonance Potentials

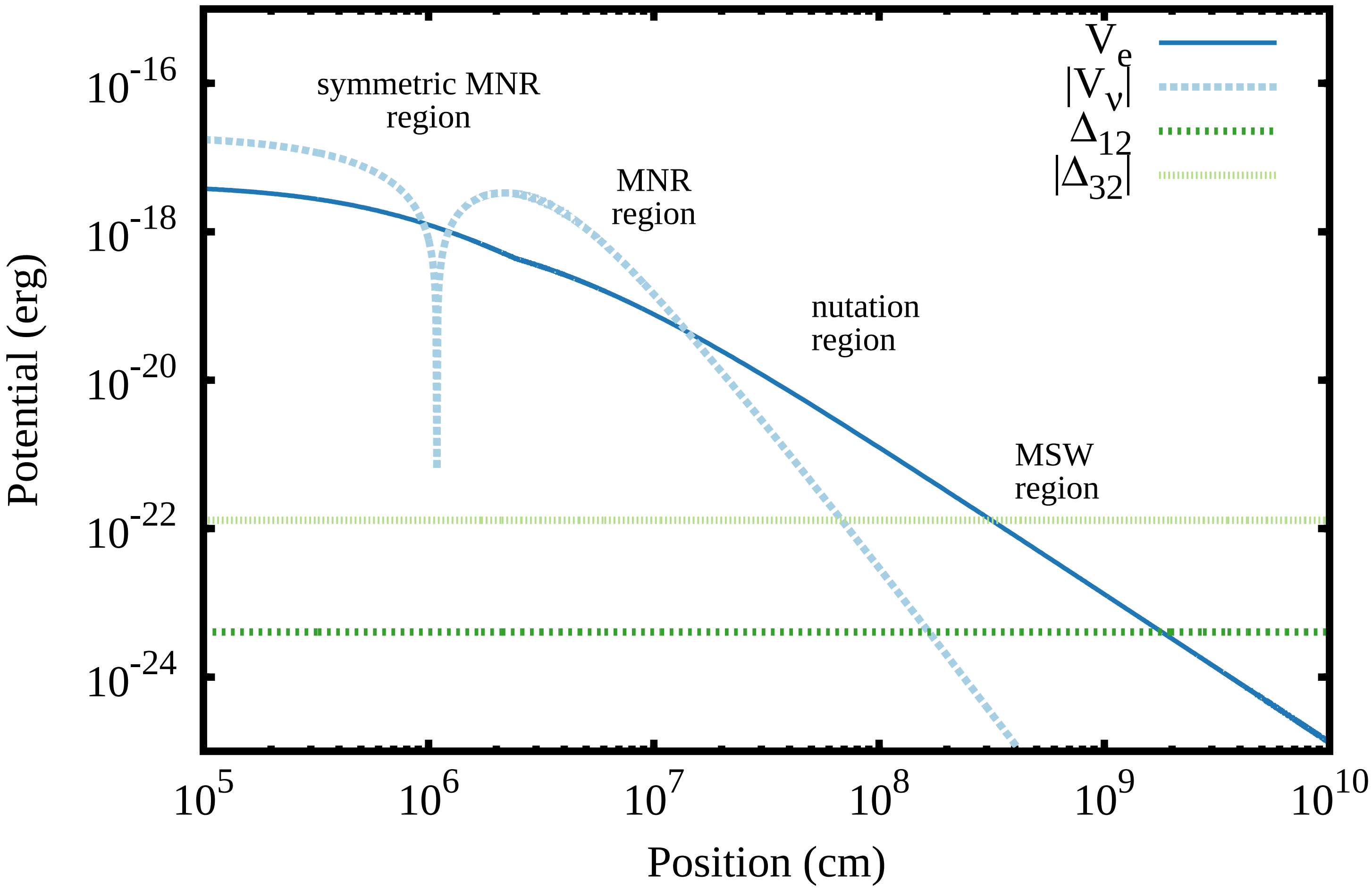
Neutrino emitting surface is larger than the antineutrino emitting surface



Symmetric Matter Neutrino Resonances come from geometric effects

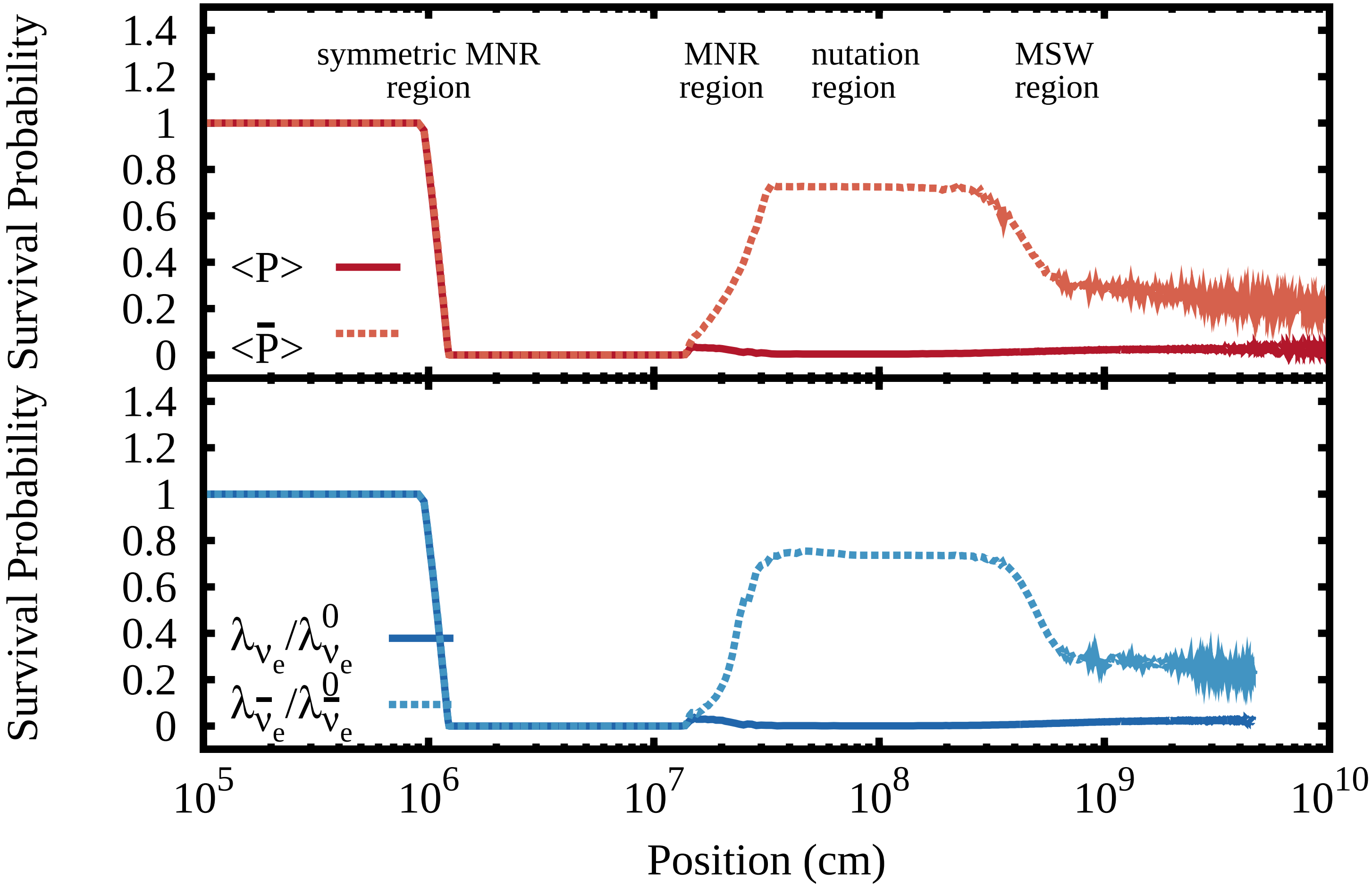
- Recall $V_\nu^a \propto N_{\nu,eff,unosc}(2P_{\nu_e} - 1) - N_{\bar{\nu},eff,unsoc}(2P_{\bar{\nu}_e} - 1)$
- $N_{eff} \sim$ flux * $\langle 1 - \cos\theta \rangle$
- $\langle 1 - \cos\theta \rangle$ evolves differently for ν_e and $\bar{\nu}_e$ if the emission surfaces are different sizes
- potential can switch from negative to positive due to this geometric effect

Symmetric MNR: occurs when ν_e and $\bar{\nu}_e$ surfaces are different sizes



Symmetric MNR flavor transformation

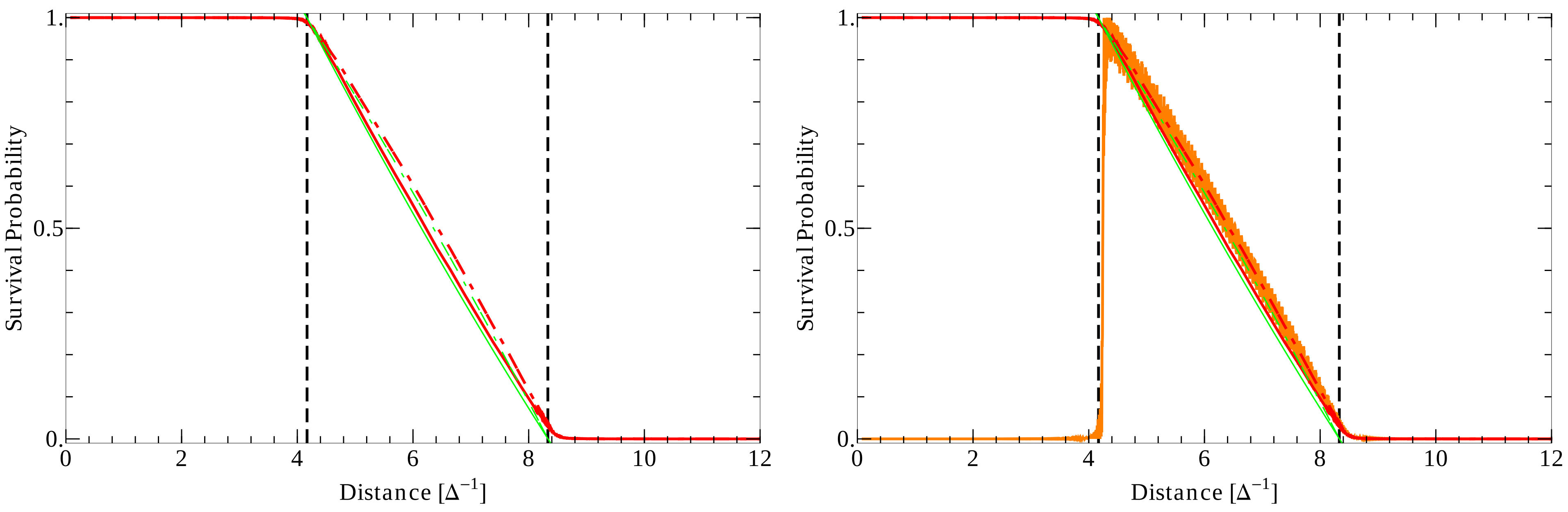
Malkus et al in prep



First oscillation is symmetric, second is standard.

Symmetric MNR transitions are adiabatic: neutrinos follow instantaneous eigenstates

Figure from Daavid Vaananen



Collapsar type disks have both types of MNR

Collapsar type disks are globally deleptonizing, i.e. neutrinos outnumber antineutrinos when you are far from the disk:

$$V_\nu^a = N_{v,eff} - N_{\bar{\nu},eff} > 0$$

But, they can be locally leptonizing, i.e. near the disk surface antineutrinos can outnumber neutrinos:

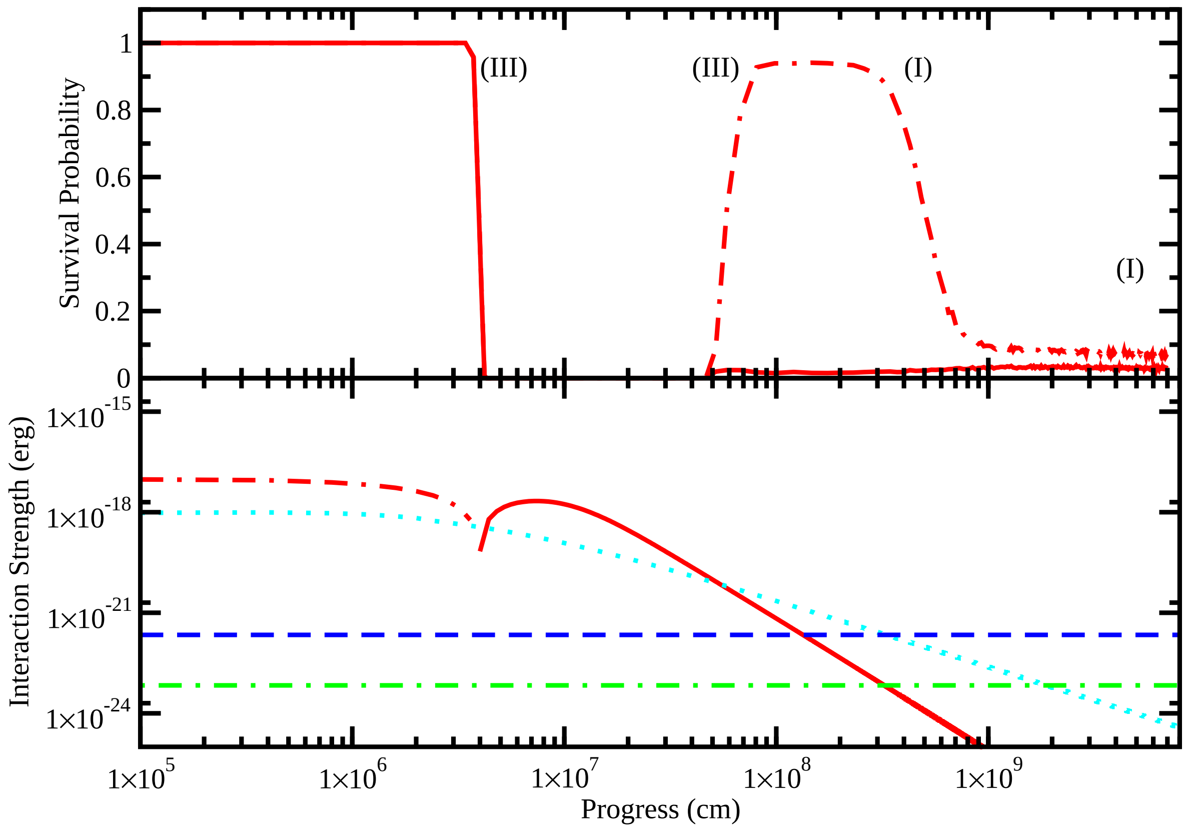
$$V_\nu^a = N_{v,eff,unosc} - N_{\bar{\nu},eff,unosc} < 0$$

Again the geometric effect: along a neutrino trajectory, the potential starts negative and then switches sign.

Neutrino-matter resonance point occurs near switch-over point

Flavor transformation above a collapsar disk

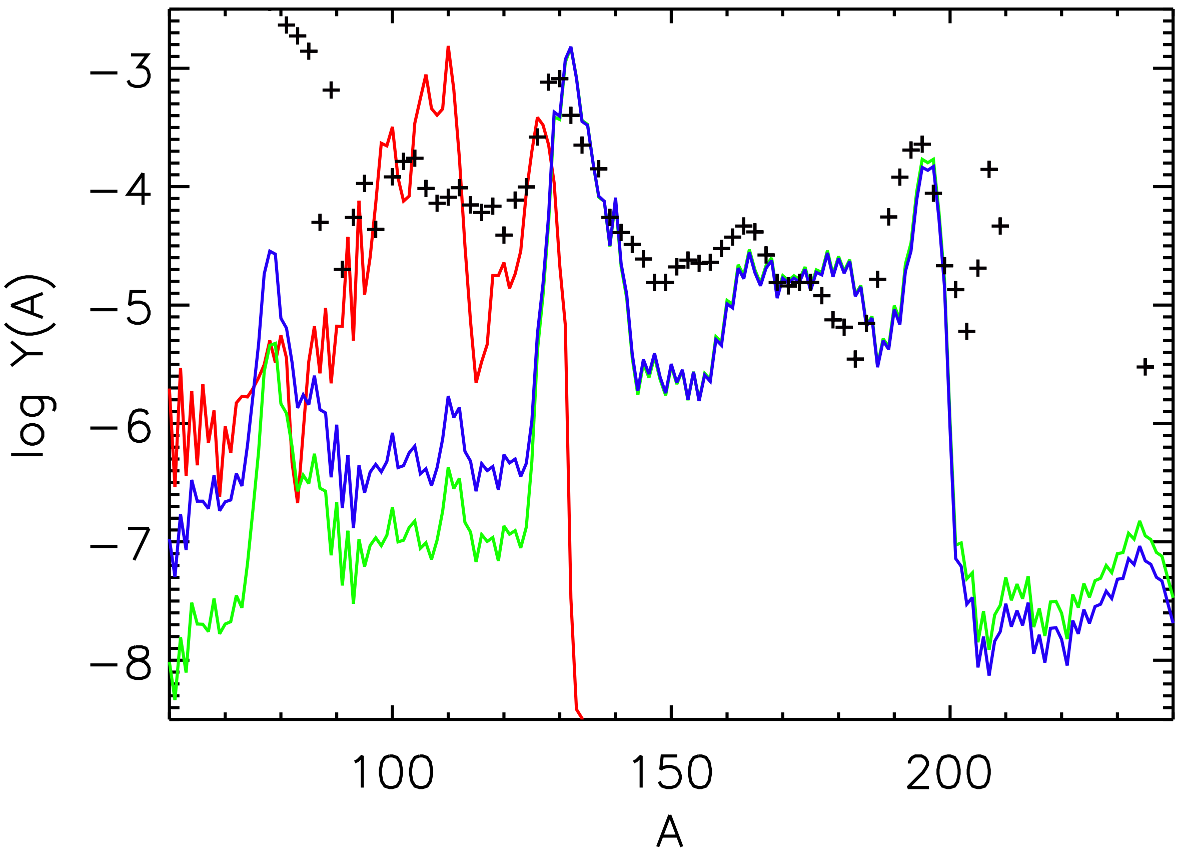
figure from Malkus et al 2012



Upper panel: solid red - electron neutrino survival probability

Upper panel: dashed red - electron antineutrino survival probability

Accretion Disk Nucleosynthesis



red - no oscillations, blue - oscillations

Malkus et al 2012

Preliminary: Calculation with 3-D Geometry

Uses neutrinos from Perego's hypermassive neutron star and disk

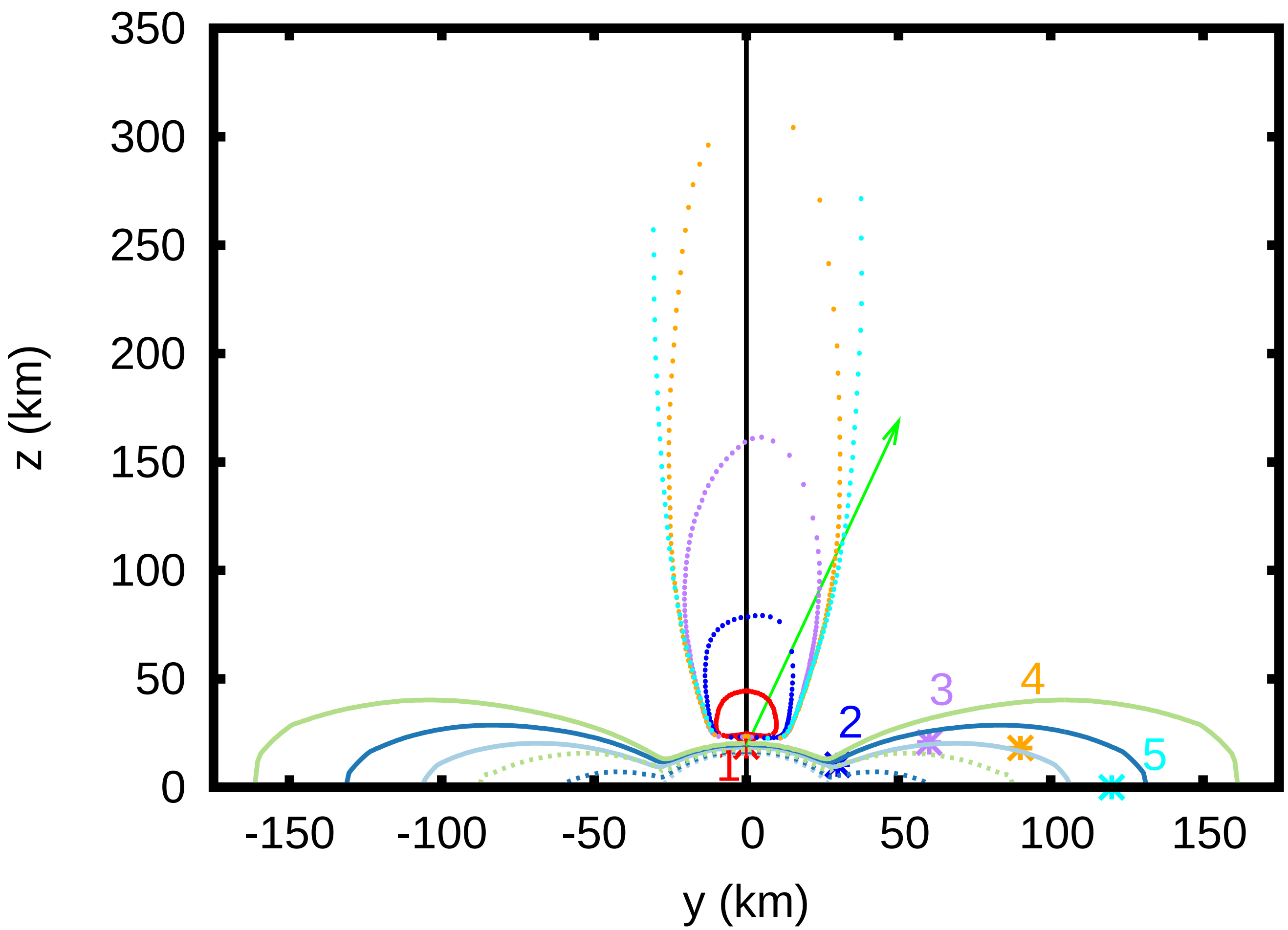


Figure by Yonglin Zhu

Prelimary: Oscillation Probability

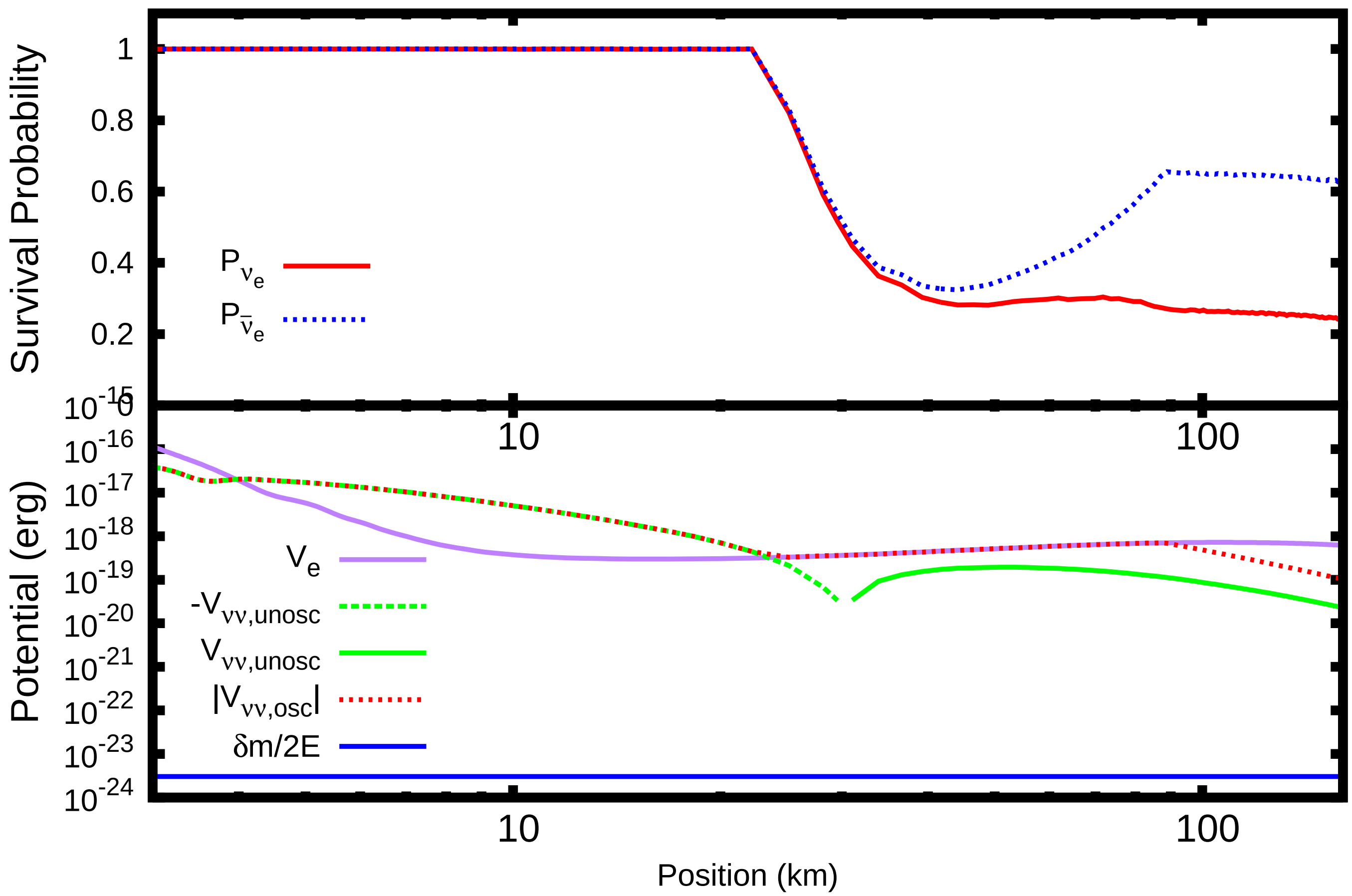


Figure by Yonglin Zhu

Conclusions

- Disk neutrinos exhibit a unique flavor transformation phenomenon
- We call this a matter-neutrino resonance transition
- We've found two types, symmetric and standard
- This transition can change the result of wind nucleosynthesis dramatically
- More to be considered, e.g. multi-angle effects