Neutrino flavor transformation in supernova nucleosynthesis

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Neutrinos from proto-neutron stars

Characteristics

- All flavors of neutrinos and antineutrinos
- ν_e has lowest temperature, followed by $\bar{\nu}_e$, then ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$
- emission surface for all types of νs is very similar
- neutrino flux slightly larger than antineutrino flux (deleptonizing)

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

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

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

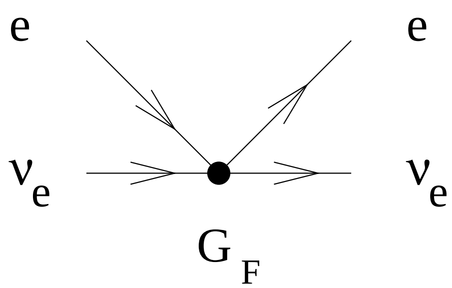
Oscillations change the spectra of ν_es and $\bar{\nu}_e$s

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

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

Neutrino oscillations

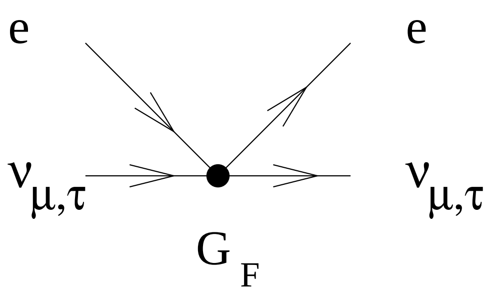
Neutrino propagation in matter: forward scattering on electrons, neutrinos leads to an effective potential



CC+NC

$$V_e = \frac{V_{\nu_e,e} - V_{\nu_x,e}}{2} = 2\sqrt{2} G_F N_e(r)$$

electron density $N_e(r)$



NC

$$V_\nu = V_{\nu,\nu} - V_{\nu,\bar{\nu}}$$

similar idea for ν - νs

Modified wave equation

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

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 $V_e \propto G_F N_e(r)$
- self interaction scale is
  $V_\nu \propto G_F(N_{\nu_e} * \text{angle} - N_{\nu_\mu} * \text{angle}) - G_F(N_{\bar{\nu}_e} * \text{angle} - N_{\bar{\nu}_\mu} * \text{angle})$

Far from proto-neutron star neutrinos V_ν term declines roughly as $1/r^4$

Supernova neutrino transition regions

MSW

- Traditional MSW region
- vacuum interaction strength is the same size as matter potential
- neutrino self interaction strength is small
- i.e $\delta m_{ij}^2/E_\nu \sim \sqrt{2}G_F N_e \gg V_{\nu\nu}$

collective

- "Traditional" nutation in NFIS picture (also called bipolar)
- $\delta m_{ij}^2/E_\nu \sim V_{\nu\nu}$
- occurs closer to proto-neutron star than MSW
- occurs when matter potential is both large and small

Supernova neutrino transition regions

MSW

- Occurs in outer layers of the star (He layer or a somewhat before)
- Straightforward to calculate (same thing that happens in the sun)
- (recall: neutrino self interaction strength is small)
- does not influence most nucleosynthesis

collective

- occurs closer to PNS than MSW regions $\sim 100\,\mathrm{km}$
- neutrinos in this region can moderately influence some nucleosynthesis

Consequences for wind nucleosynthesis

The earlier the oscillation starts, the more important the consequences

Electron fraction, i.e neutron to proton ratio, is set by the weak interactions: $\nu_e + n \leftrightarrow p + e^-$, $\bar{\nu}_e + p \leftrightarrow n + e^+$

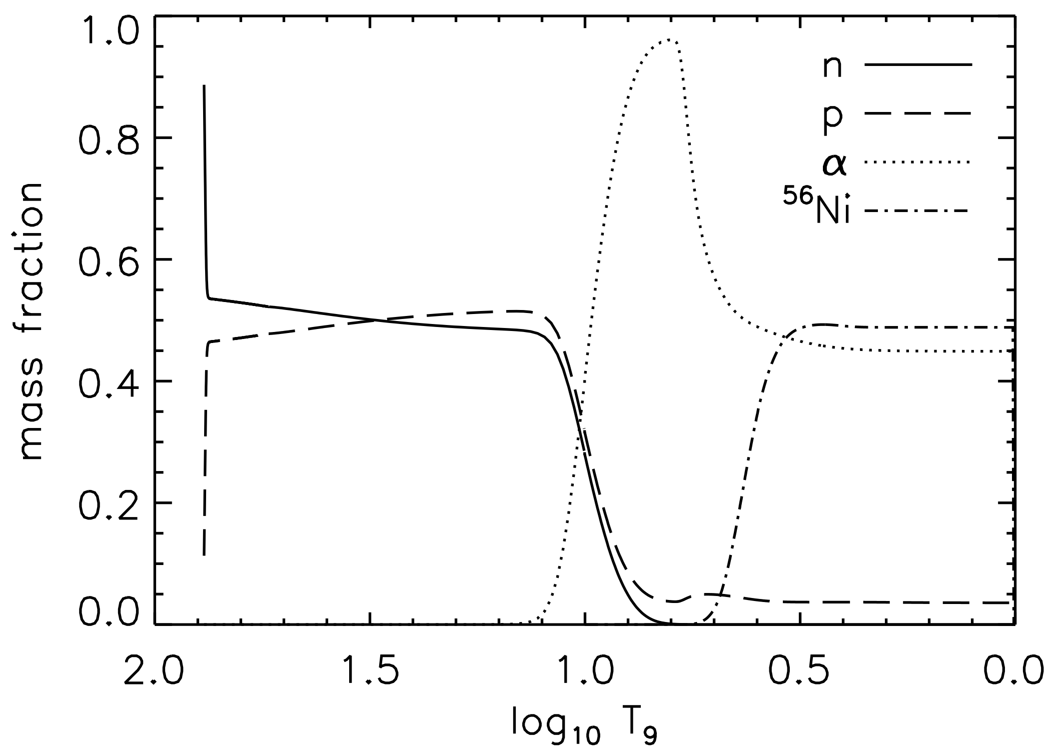
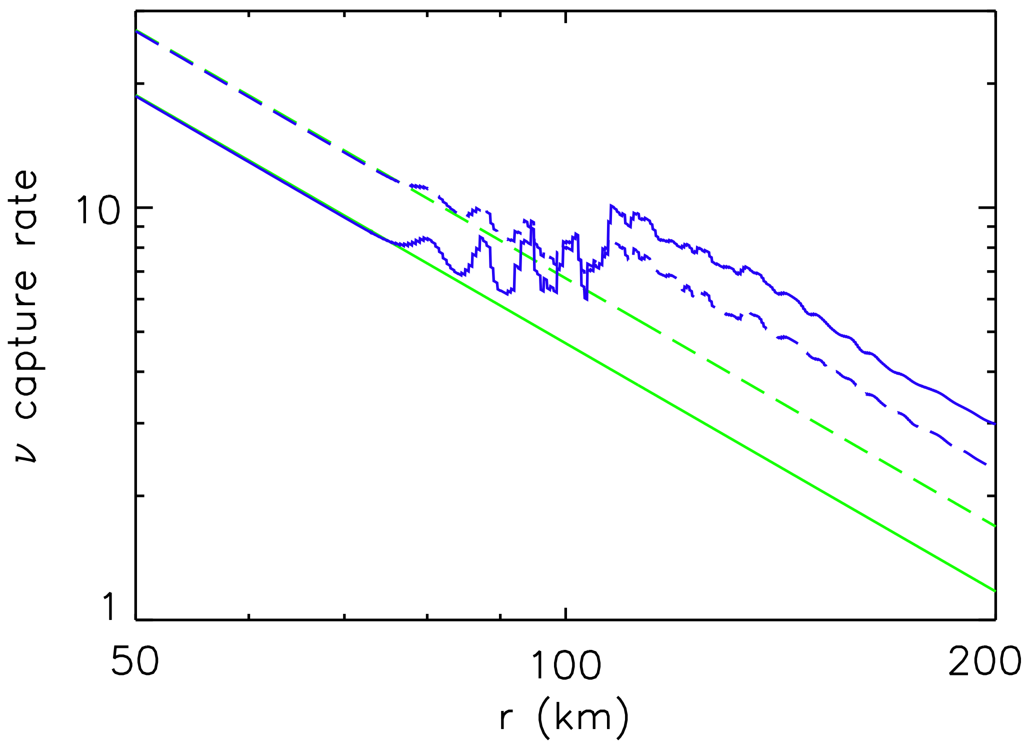


Figure from Surman, GCM and Sabbatino 2011

Electron neutrino and antineutrino capture rates



- ν_e solid line
- $\bar{\nu}_e$ dashed line
- green no oscillation
- blue oscillation

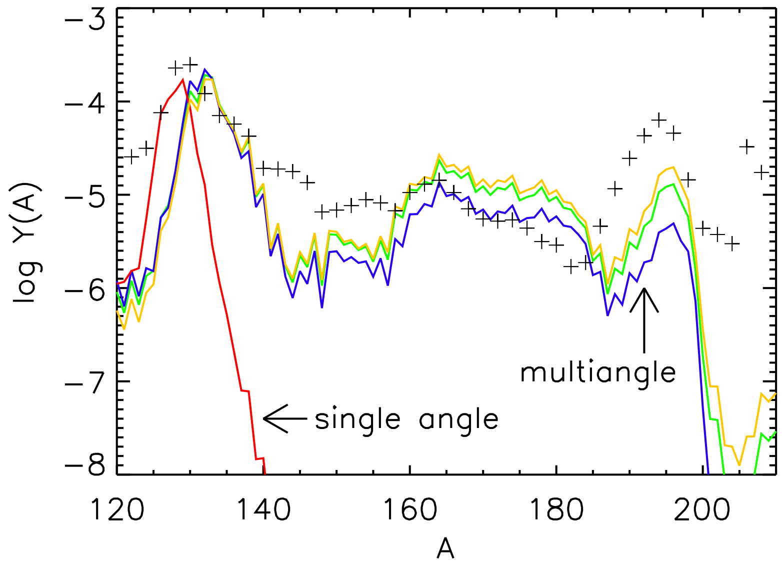
figure from Duan, Friedland, GCM and Surman 2011

Shows the influence of collective oscillations

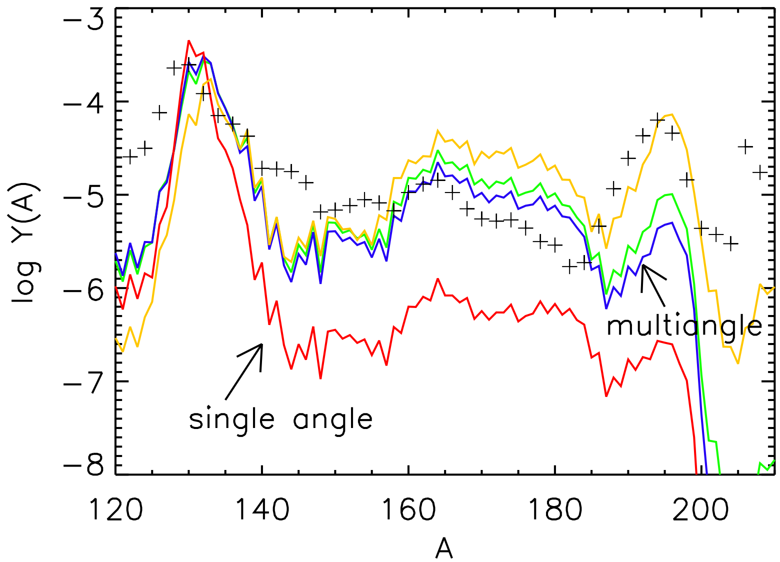
ν_es are exchanging with ν_μs, ν_τs $\bar{\nu}_e$s are exchanging with $\bar{\nu}_\mu$s, $\bar{\nu}_\tau$s

Nucleosynthesis with collective oscillations

In SN winds, the oscillation often starts after nuclei begin to form



Early time density profile, $s/k = 200$, $\tau = 15\mathrm{ms}$



Late time density profile, $s/k = 200$, $\tau = 18\mathrm{ms}$

wind conditions tweaked to create r-process favorable conditions

Could the oscillations start earlier?

- instabilities - talks by Duan, Raffelt
- sterile neutrinos - Balantekin, Tamborra and others
- NSIs

Non standard interactions in supernovae

Non standard interactions effectively change the matter potential, $V_e \to V_e + V_{NSI}$, and produce off-diagonal contributions to V_e. They can also change V_ν but we won't consider this.

$$V_{NSI} = \sqrt{2} G_F n_N \left(\begin{array}{cc} \sim \delta\epsilon^n & \sim \epsilon_0 \\ \sim \epsilon_0^* & 0 \end{array} \right) . \tag{1}$$

ϵs are remarkable poorly contrained by experiment - Lunardini, Friedland, Wright

Total matter potential in SN conditions when the NSI contribution is negative

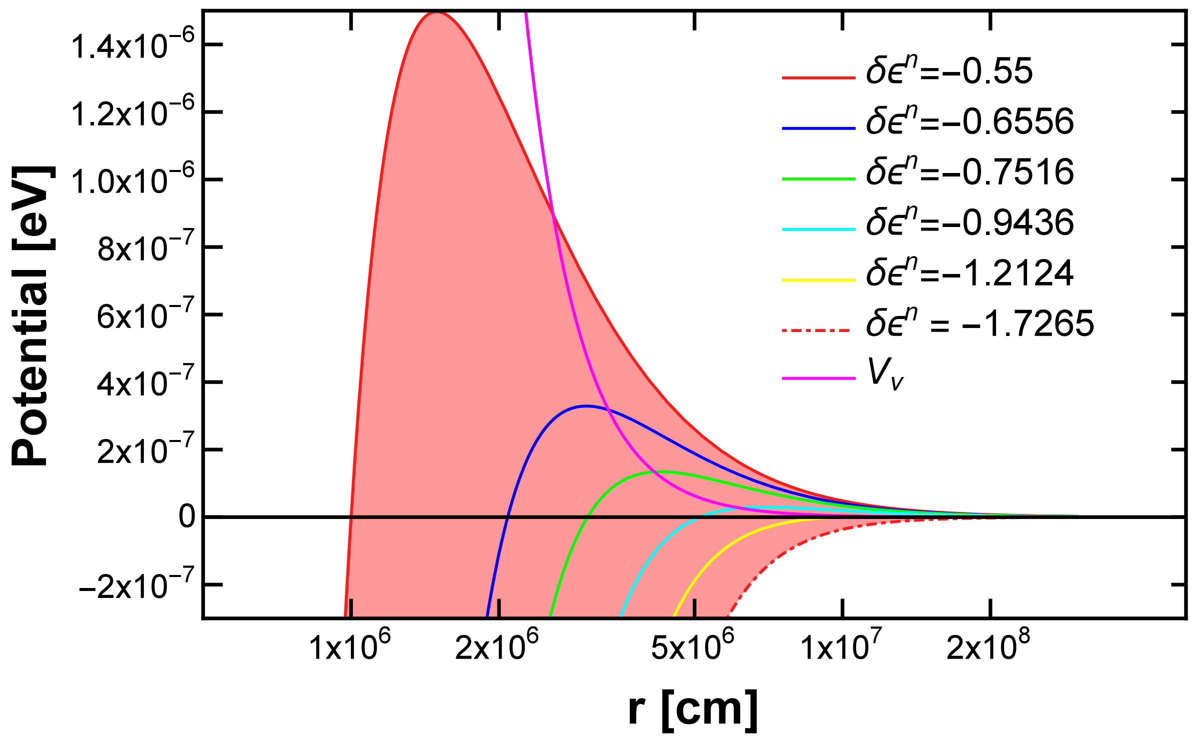


Fig. from Stapleford et al 2016, density, Y_e fitted to accretion phase of Fischer et al

Non standard interactions in SN

Survival Probabilities

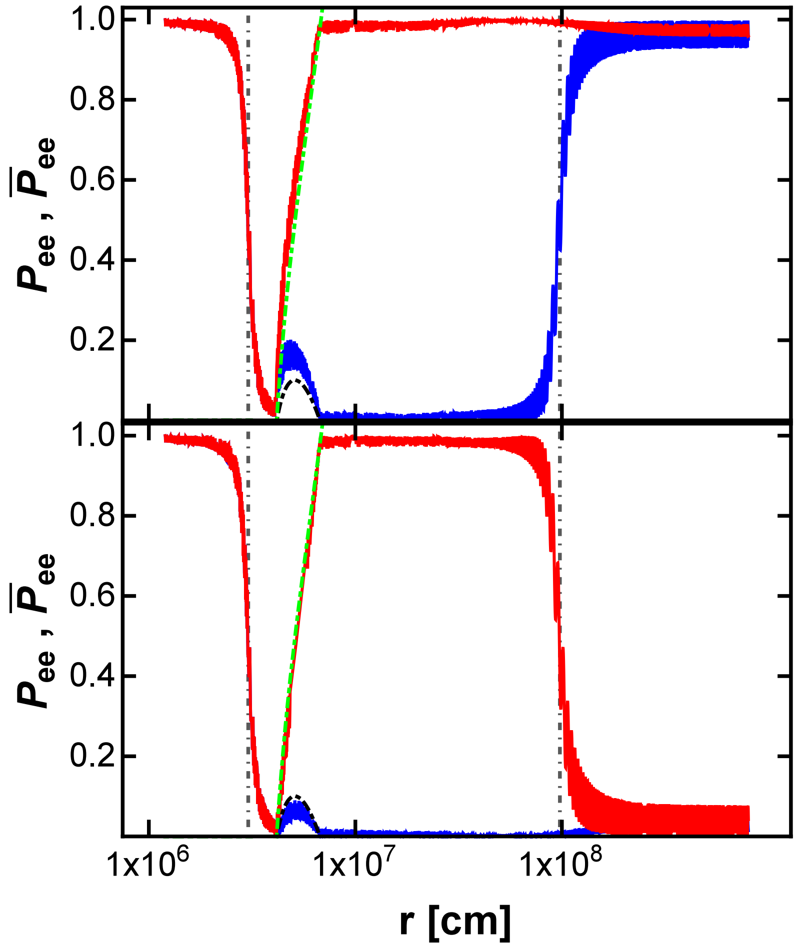


Fig. from Stapleford et al 2016, $\delta\epsilon_n = -0.75$, $\epsilon_0 = 0.002$, density, Y_e from accretion phase of Fischer et al

NSI in SN-like conditions

1st transition is an I-resonance

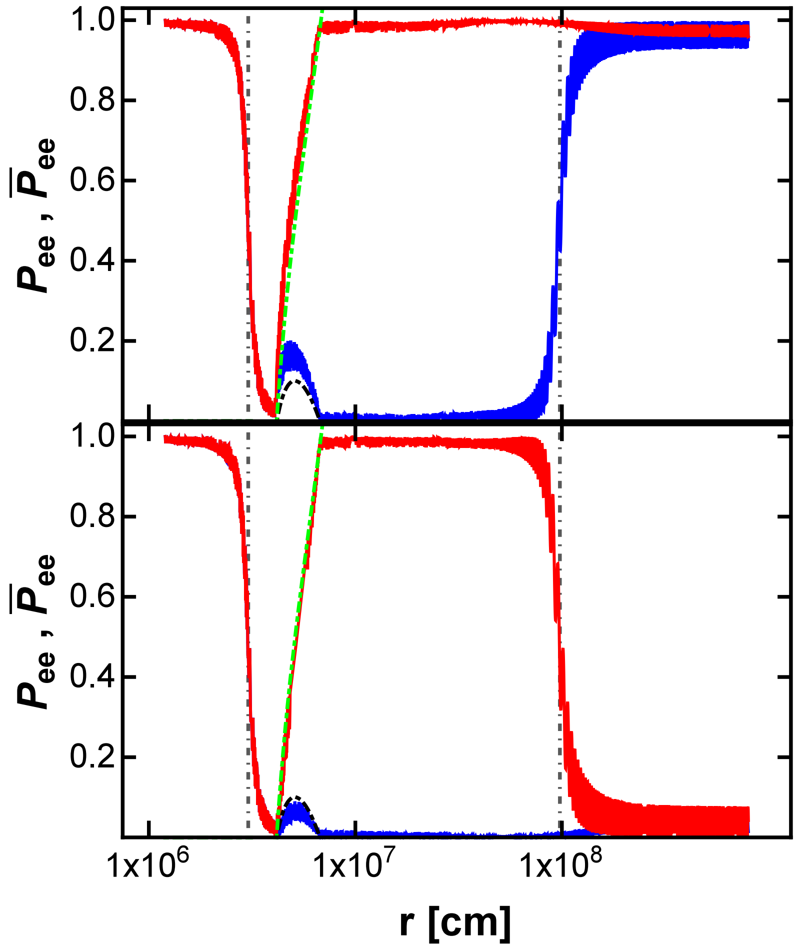


Fig. from Stapleford et al 2016, $\delta\epsilon_n = -0.75$, $\epsilon_0 = 0.002$, density, Y_e from accretion phase of Fischer et al

I-resonance known since Esteban-Pretel et al 2007

NSI in SN-like conditions

1st transition is an I-resonance

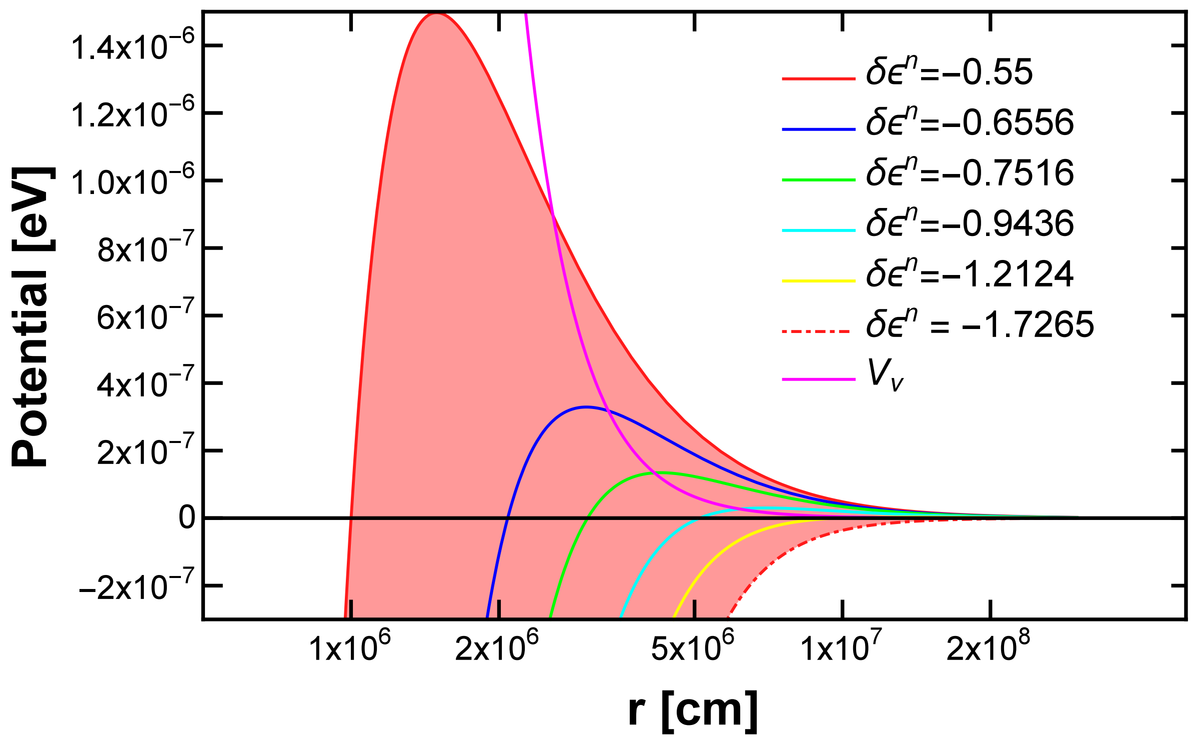


Fig. from Stapleford et al 2016, density, Y_e fitted to accretion phase of Fischer et al

NSI in SN-like conditions

2nd transition is a matter neutrino resonance

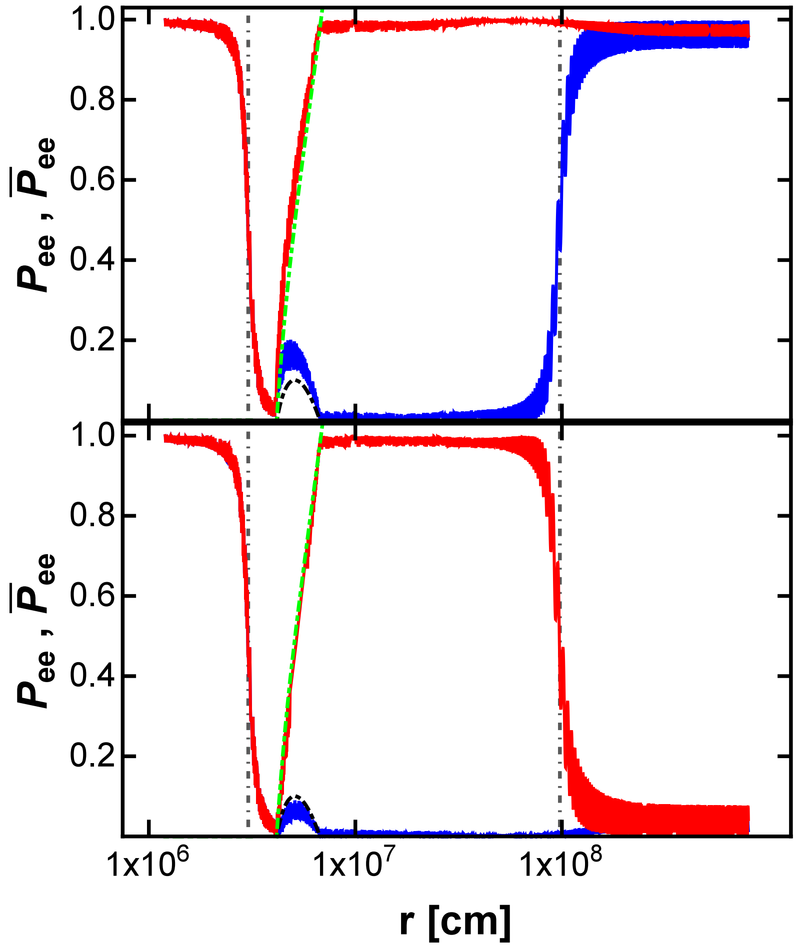


Fig. from Stapleford et al 2016, $\delta\epsilon_n = -0.75$, $\epsilon_0 = 0.002$, density, Y_e from accretion phase of Fischer et al

What are the characteristics of a matter neutrino resonance?

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

Happens here because the I-resonance converted both neutrinos and antineutrinos and this flips the sign of V_ν.

recall self interaction scale is

$$V_\nu \propto G_F(N_{\nu_e} * \mathrm{angle} - N_{\nu_\mu} * \mathrm{angle}) - G_F(N_{\bar{\nu}_e} * \mathrm{angle} - N_{\bar{\nu}_\mu} * \mathrm{angle})$$

Work on Matter Neutrino Resonance in various contexts: Duan, Friedland, Kneller, Malkus, GCM, Qian, Surman, Stapleford, Väänänen, Volpe, Wu, Zhu

NSI in SN-like conditions

crossing of V_e and V_ν is an MNR

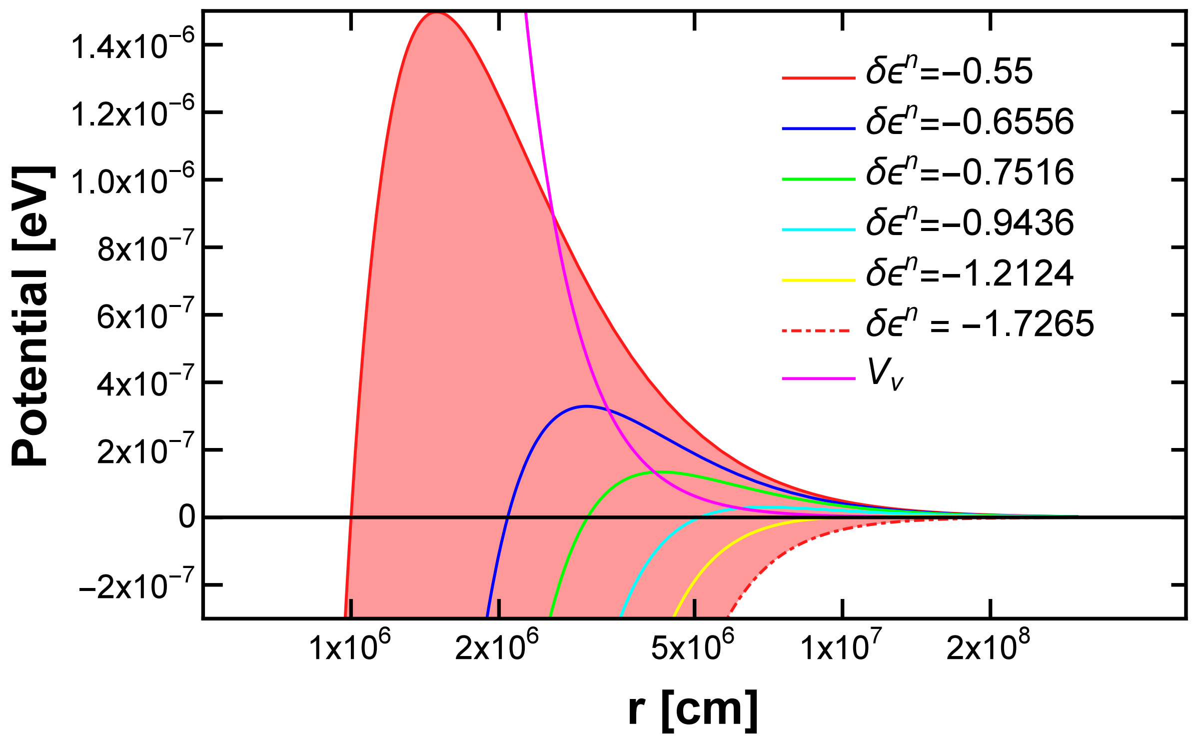


Fig. from Stapleford et al 2016, density, Y_e fitted to accretion phase of Fischer et al

What are the characteristics of a matter neutrino resonance?

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

Happens here because the I-resonance converted both neutrinos and antineutrinos and this flips the sign of V_ν.

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

Neutrino-matter transition: single energy model

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

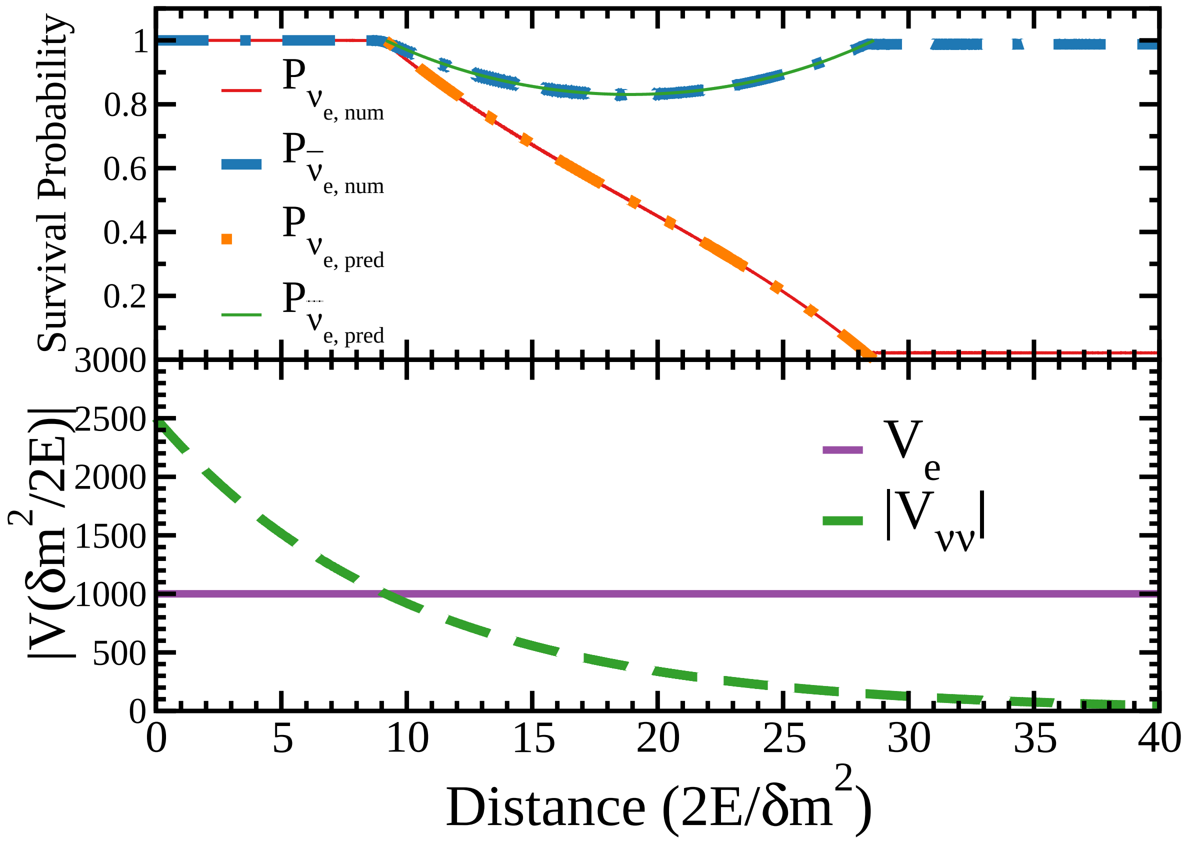


Fig. from Malkus et al 2014

Matter neutrino resonance transitions

What is happening?

Descriptions: 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

Neutrino-Matter Transition: single energy model

Compare numerics to prediction

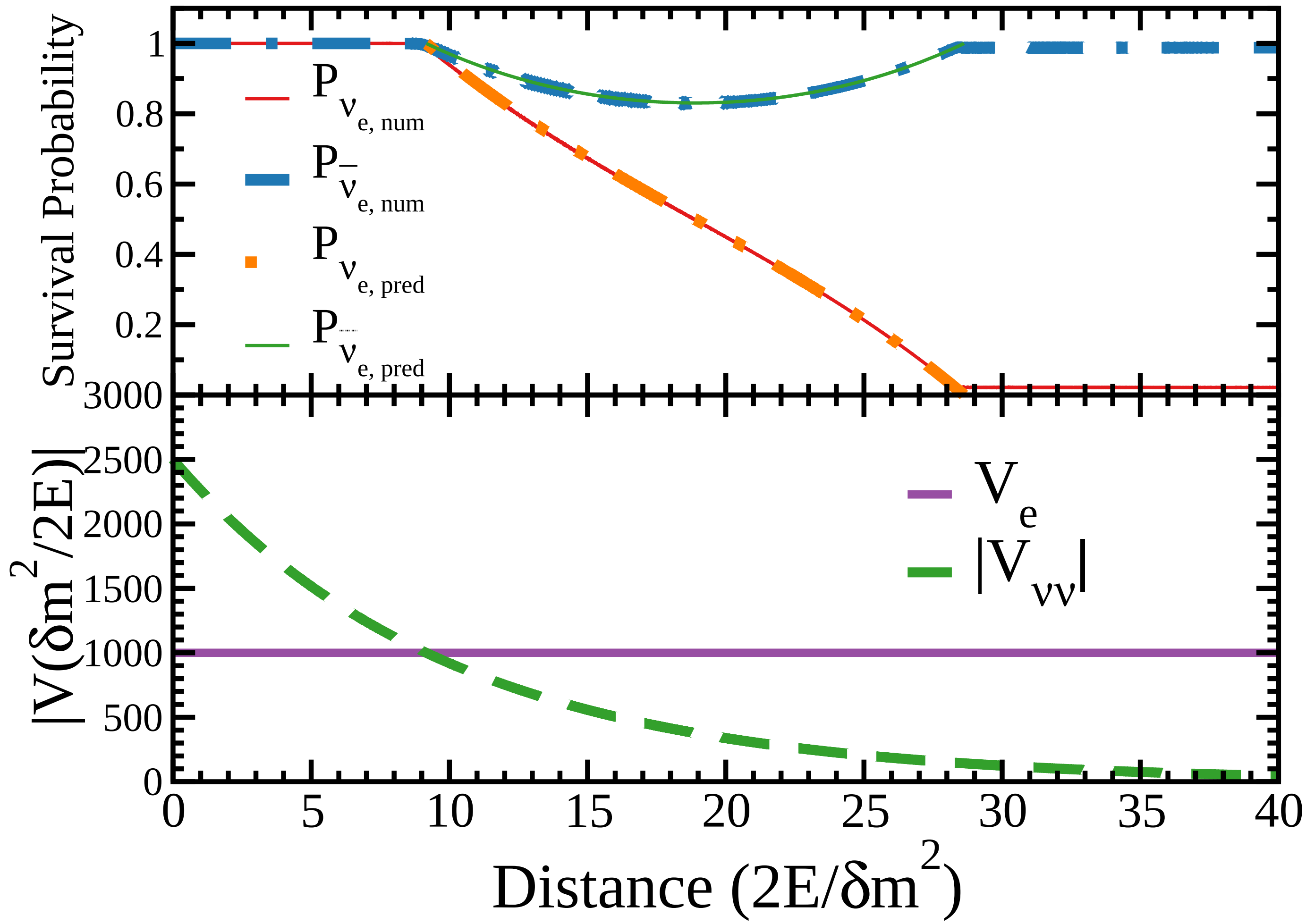
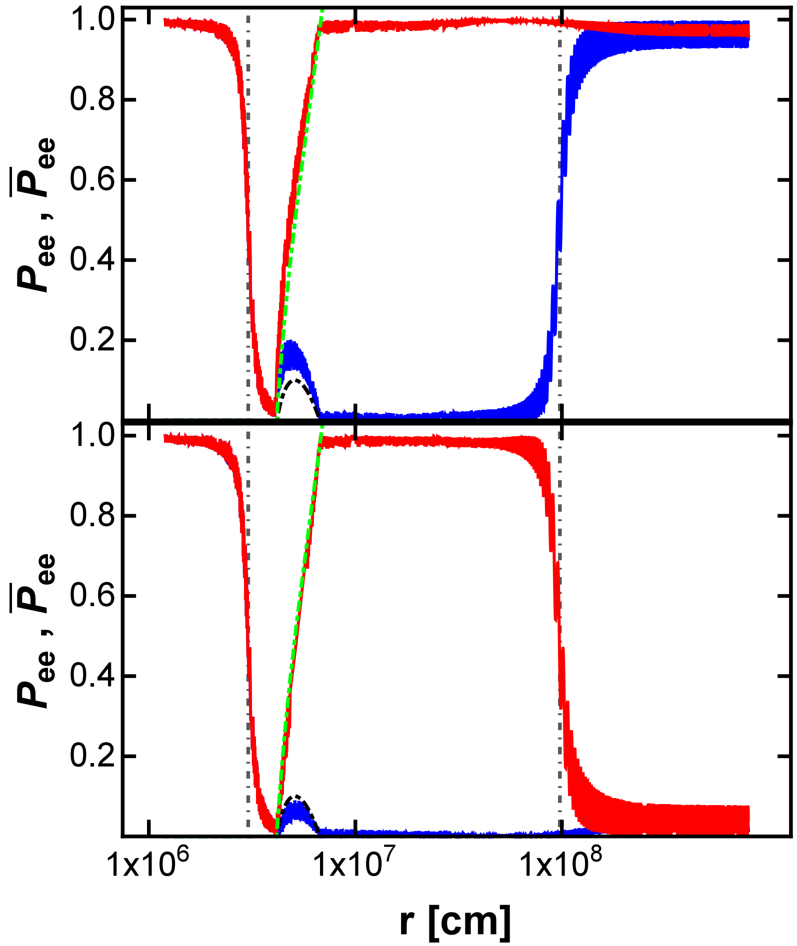


Fig. from Malkus et al 2014

NSI in SN-like conditions

3rd transition is an MSW transition



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NSI transition parameter space

shows regions that could affect nucleoysnthesis

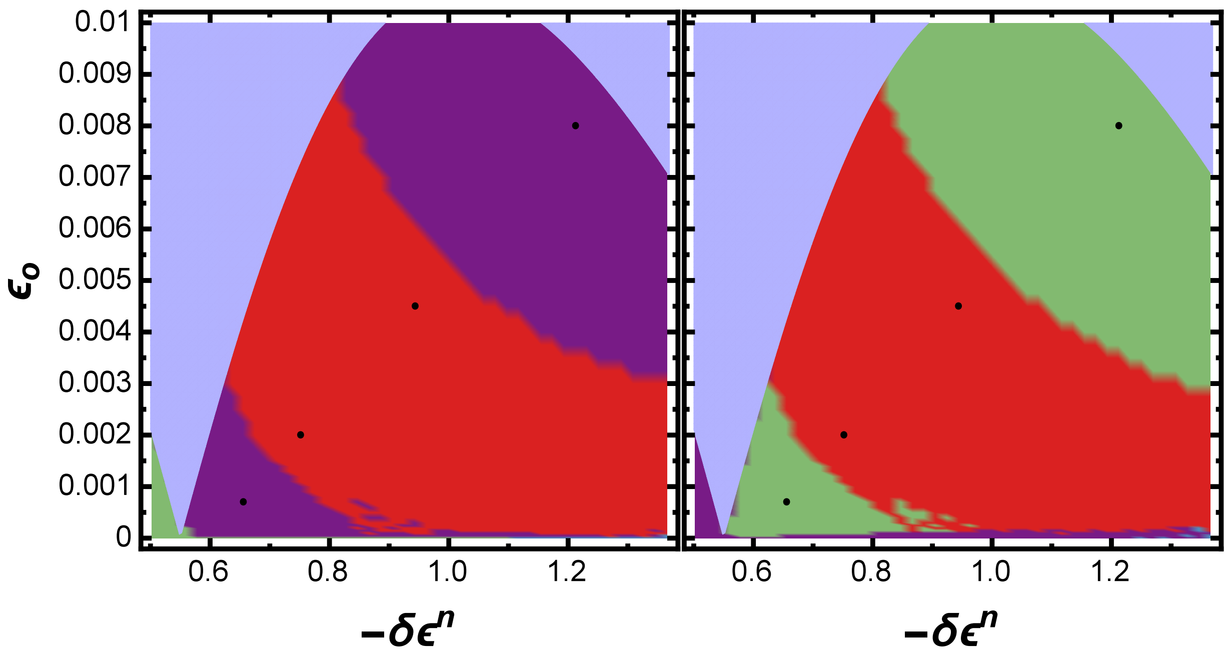


Fig. from Stapleford et al 2016, red region is MNR region, purple is collective

What about neutrinos from SN accretion disks?

How can oscillations effect nucleosynthesis?

Neutrinos from SN accretion disks

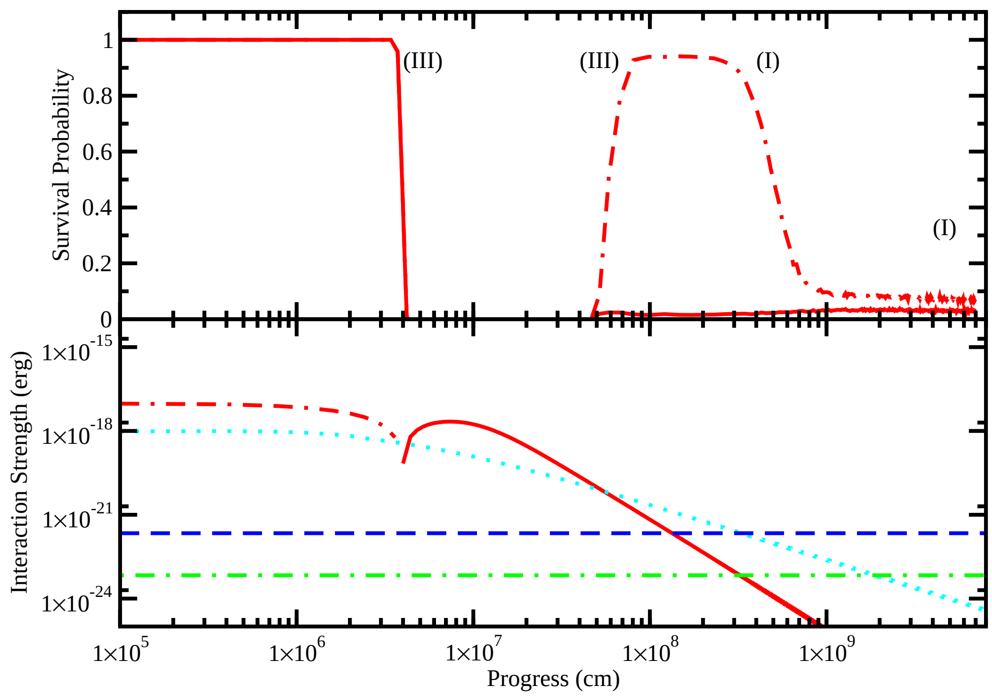
- more ν_e and $\bar{\nu}_e$ than ν_μ and $\bar{\nu}_\mu$
- more ν_e than $\bar{\nu}_e$ (deleptonizing)
- similar spectra in PNS
- emitted from a fairly different geometry
- emission surface for neutrinos is larger than for antineutrinos
- emission surface difference creates conditions for a matter neutrino resonance

see papers by Caballero et al for estimates of neutrino detection rates from black hole accretion disks

Are accretion disk oscillations different than PNS?

yes, matter neutrino resonance transitions (MNR)

Geometry can cause $V_{\nu\nu}$ to switch sign

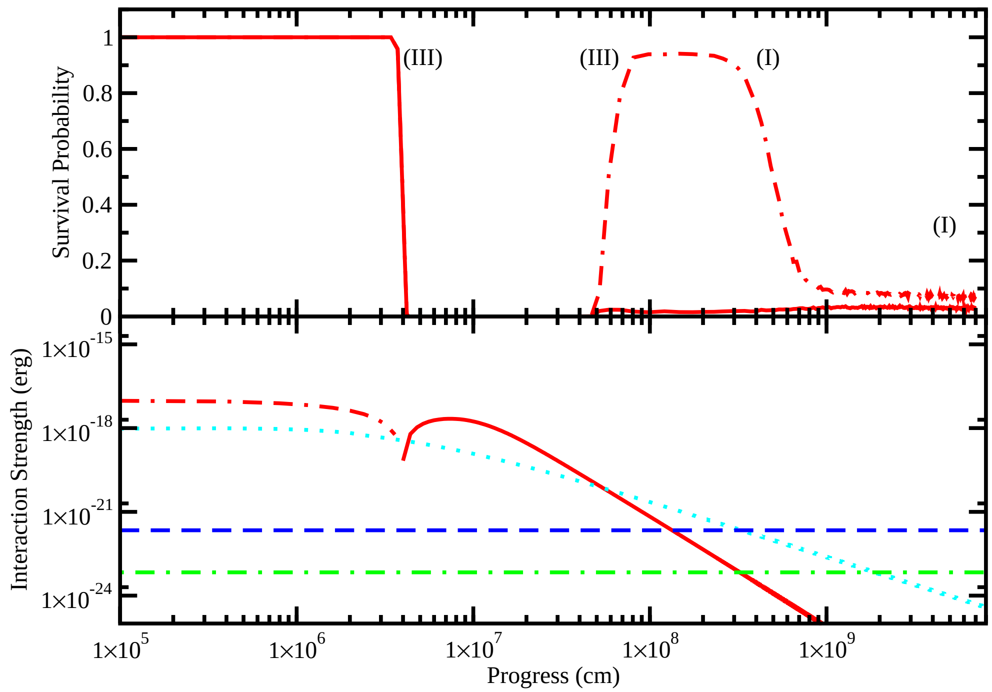


Lower Panel, dotted light blue line - V_e, dashed and solid red - V_ν Different size disks for ν_e and $\bar{\nu}_e$ Malkus et al '12

Are accretion disk oscillations different than PNS?

yes, matter neutrino resonance transitions (MNR)

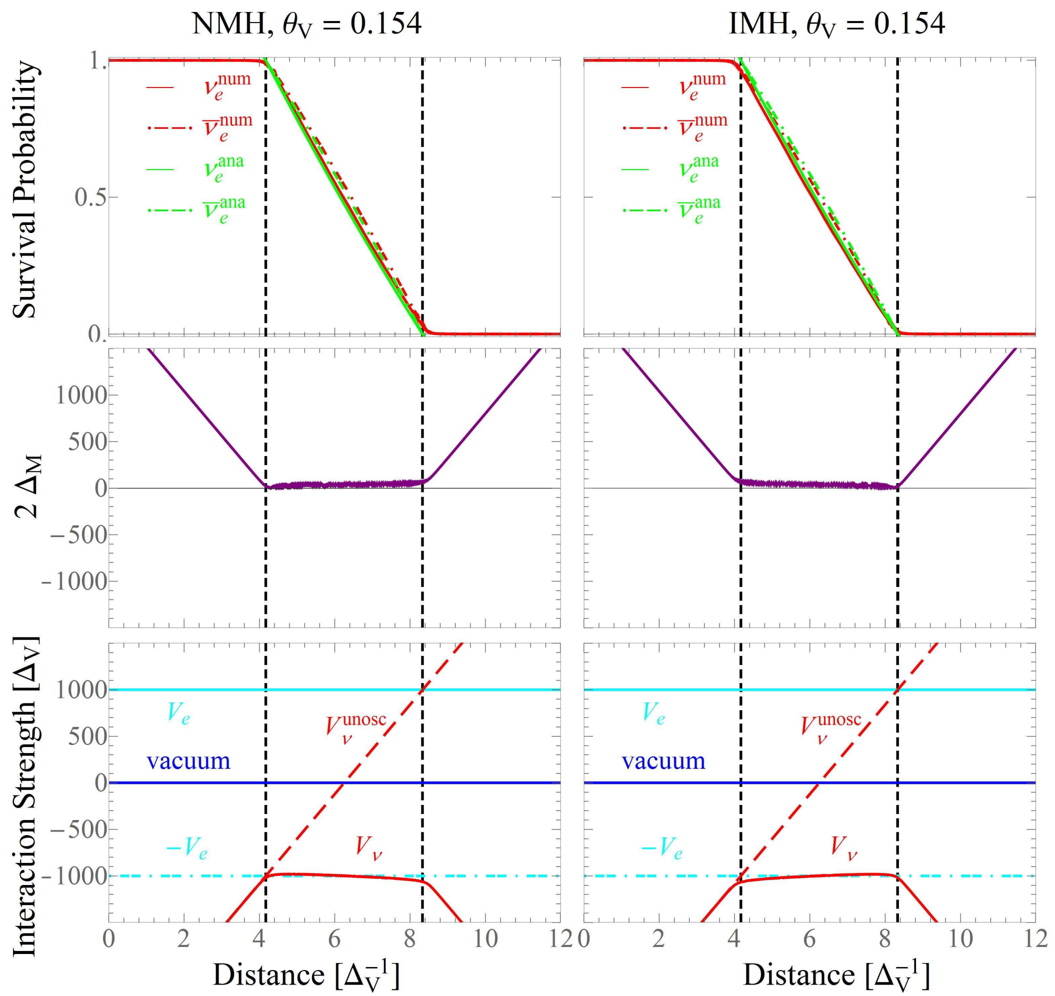
Geometry can cause $V_{\nu\nu}$ to switch sign



self interaction scale is

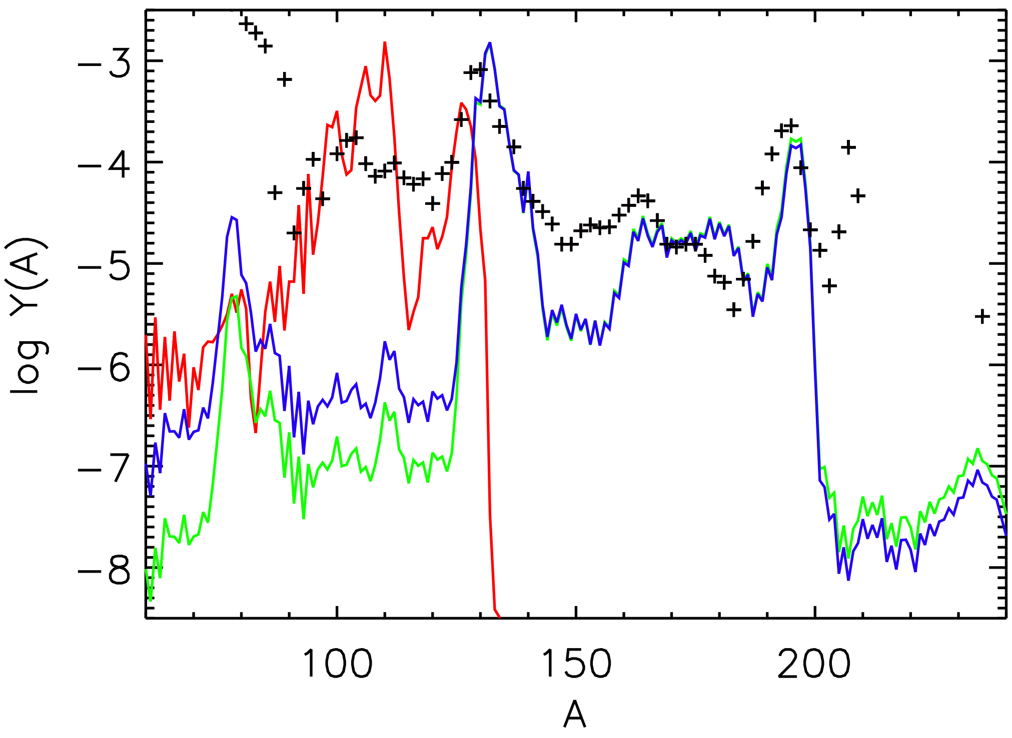
$$V_{\nu} \propto G_F(N_{\nu_e} * \text{angle} - N_{\nu_\mu} * \text{angle}) - G_F(N_{\bar{\nu}_e} * \text{angle} - N_{\bar{\nu}_\mu} * \text{angle})$$

Survival Probabilities for a Symmetric MNR



Vänäänanen et al '16

Accretion disk wind nucleosynthesis



red - no oscillations, blue - oscillations

$s/k = 50$, figure from Malkus et al 2012

Conclusions

proto-neutron star supernovae neutrinos

- In the SN, oscillations increase ν_e, $\bar{\nu}_e$ capture rates
- In the SN, "standard" multiangle collective oscillations tend to occur after the most important point for wind nucleosynthesis
- but there is some re-arrangement of the abundance pattern
- other instabilities may cause oscillations to occur earlier
- NSI effects could cause the oscillations to occur earlier - MNR!

accretion disk supernova neutrinos

- matter-neutrino enhanced transitions may cause an eary oscillation
- results in a reduction of both ν_e and $\bar{\nu}_e$
- one expects significant changes the abundance pattern in this case