The Influence of Neutrino Flavor Transformation on Nucleosynthesis from Black Hole Accretion Disks

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- Introduction
- Explanation of “Matter-Neutrino” resonance
- Implications

Black Hole Accretion Disks

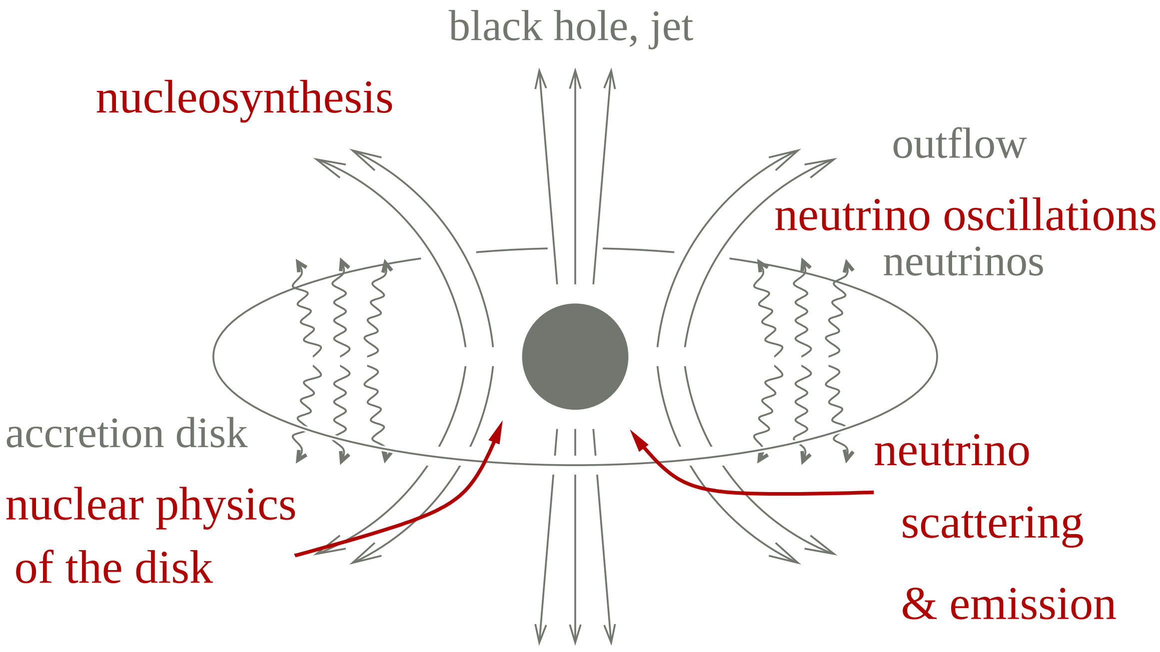
Two types of disks

- compact object mergers
- collapsars

Some interesting types of nucleosynthesis

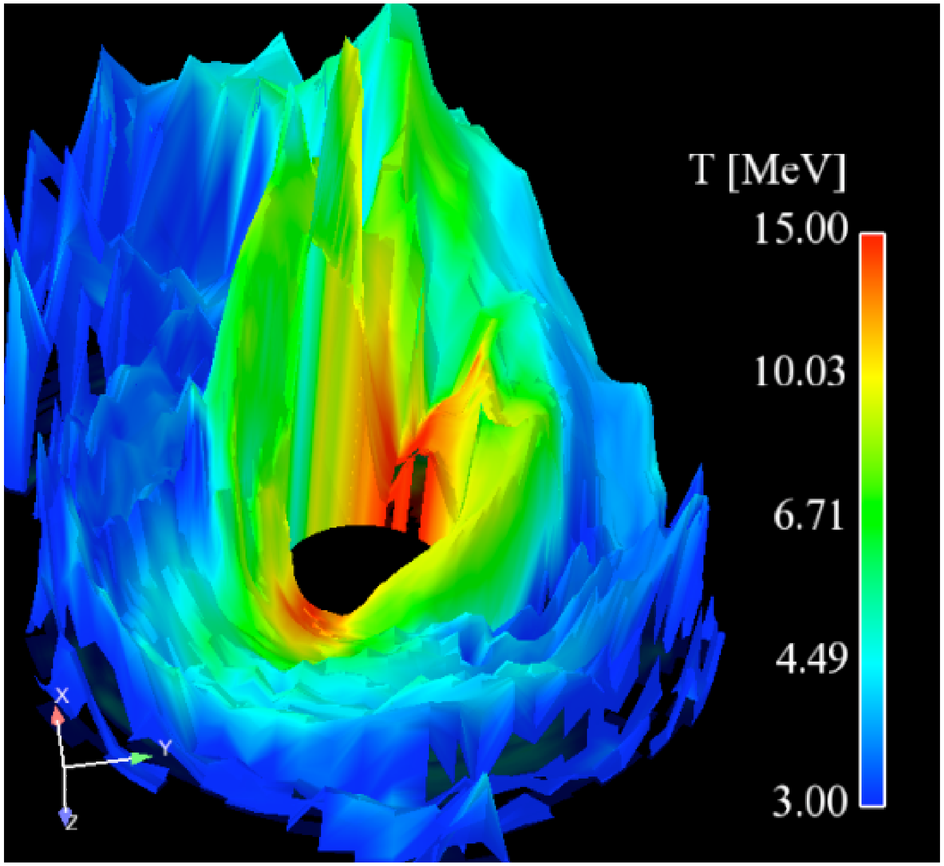
- r-process
- $^{56}\mathrm{Ni}$ and other iron group nuclei
- p-process

Nucleosynthesis in Winds

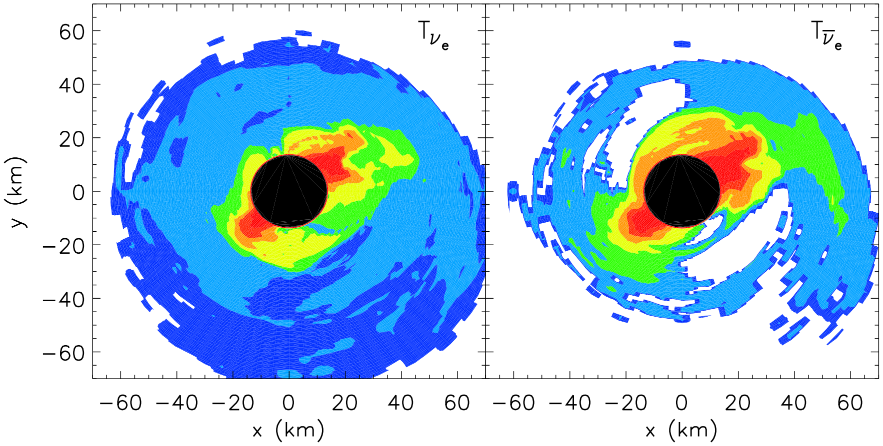


- r-process
- p-process
- ^{56}Ni -light curves!
- ν-process

Accretion Disk ν_e temperatures



Caballero et al 2012



Surman et al 2008

The weak interaction

Converting neutrons to protons occurs primarily through

- electron (neutrino) capture $n + \nu_e \leftrightarrow e^- + p$
- positron (anti-neutrino) capture $p + \bar{\nu}_e \leftrightarrow e^+ + n$

A few words about neutrinos...

They are emitted from complicated neutrino surfaces.

General relativistic effects determine their paths and energies.

They oscillate! e.g. As a ν_e travels it may turn into a combination of ν_e, ν_μ and ν_τ. talks by Wu, Pllumbi

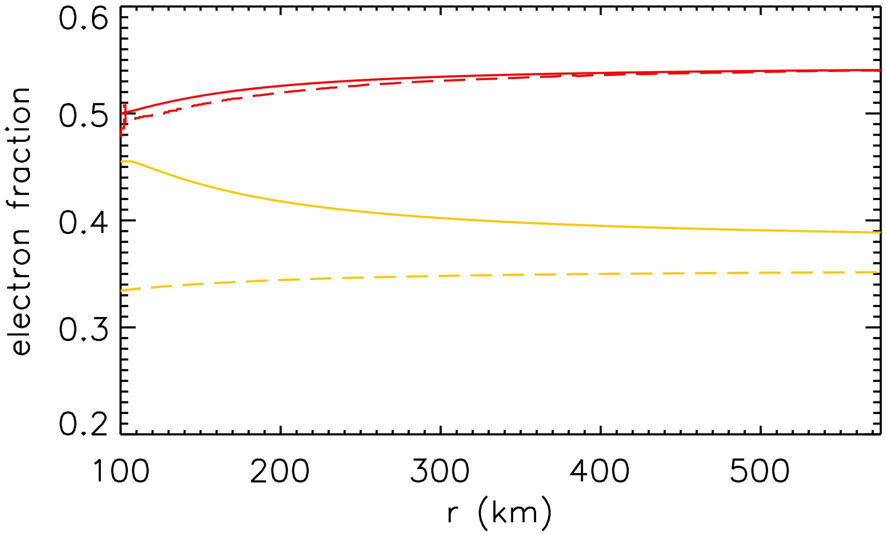
ν general relativistic effects - high entropy trajectory

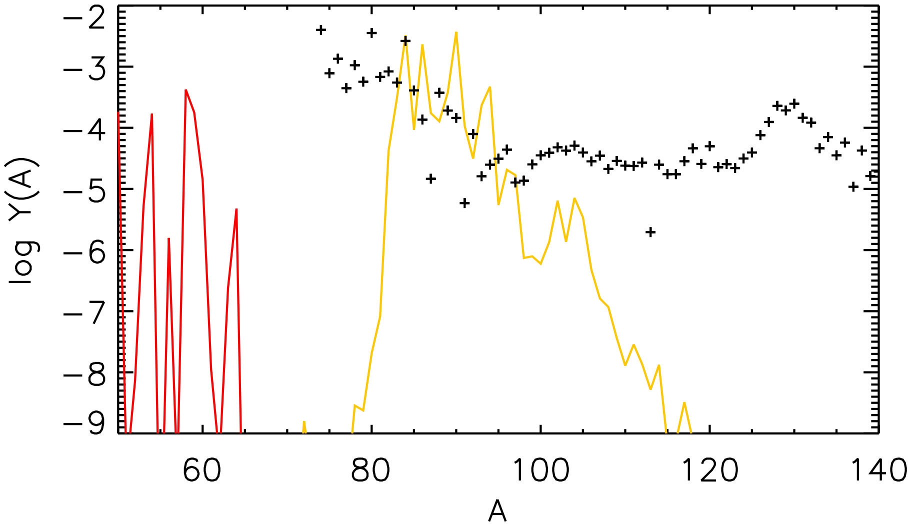
Iron group elements

- yellow - No GR
- red - ν GR, no rot., a $= 0$

with s/k $= 40$, $\beta = 2$

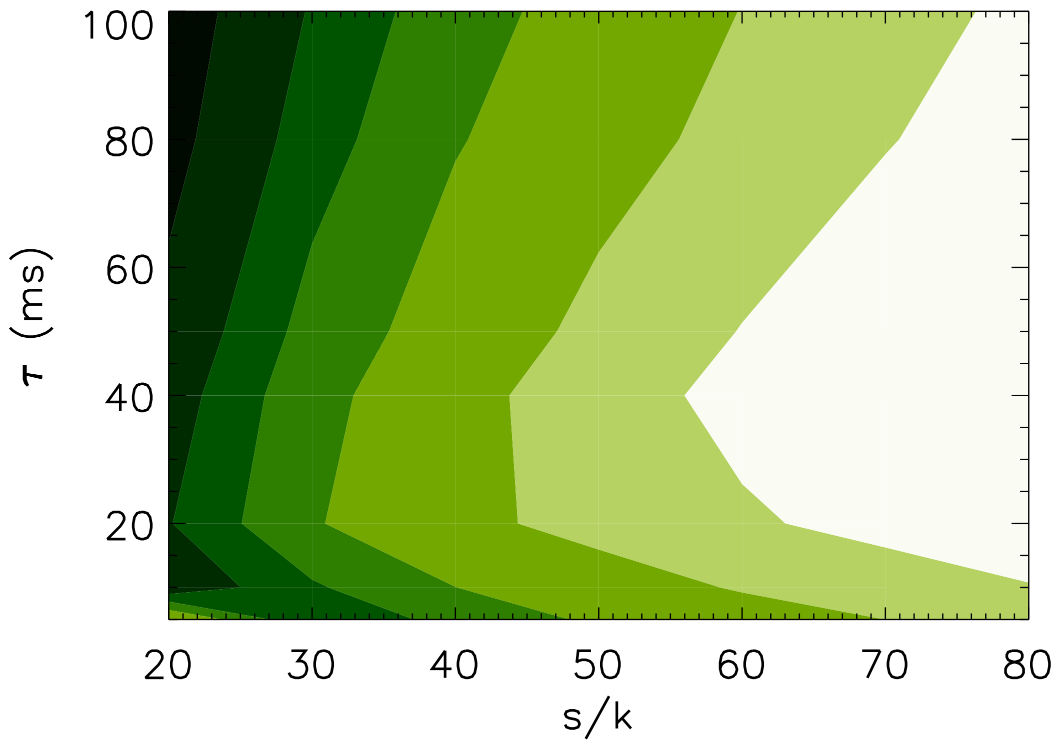
Caballero et al 2012





Compact Object Merger Disk Winds: Nickel - 56

n,p $\rightarrow^{4}\mathrm{He} \rightarrow$ iron peak nuclei $\rightarrow$ heavier nuclei

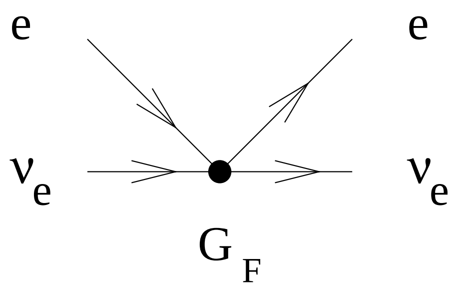


Surman et al 2014

Neutrino Oscillations (no GR)

Neutrino Oscillations

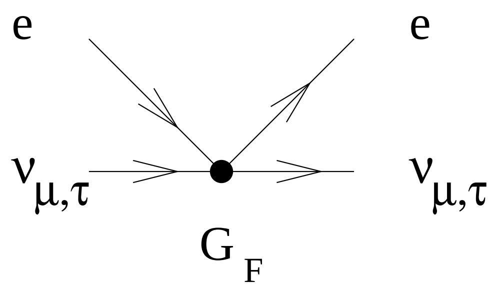
Neutrino propagation in matter: forward scattering on electrons, neutrinos leads to effective potential



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

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

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

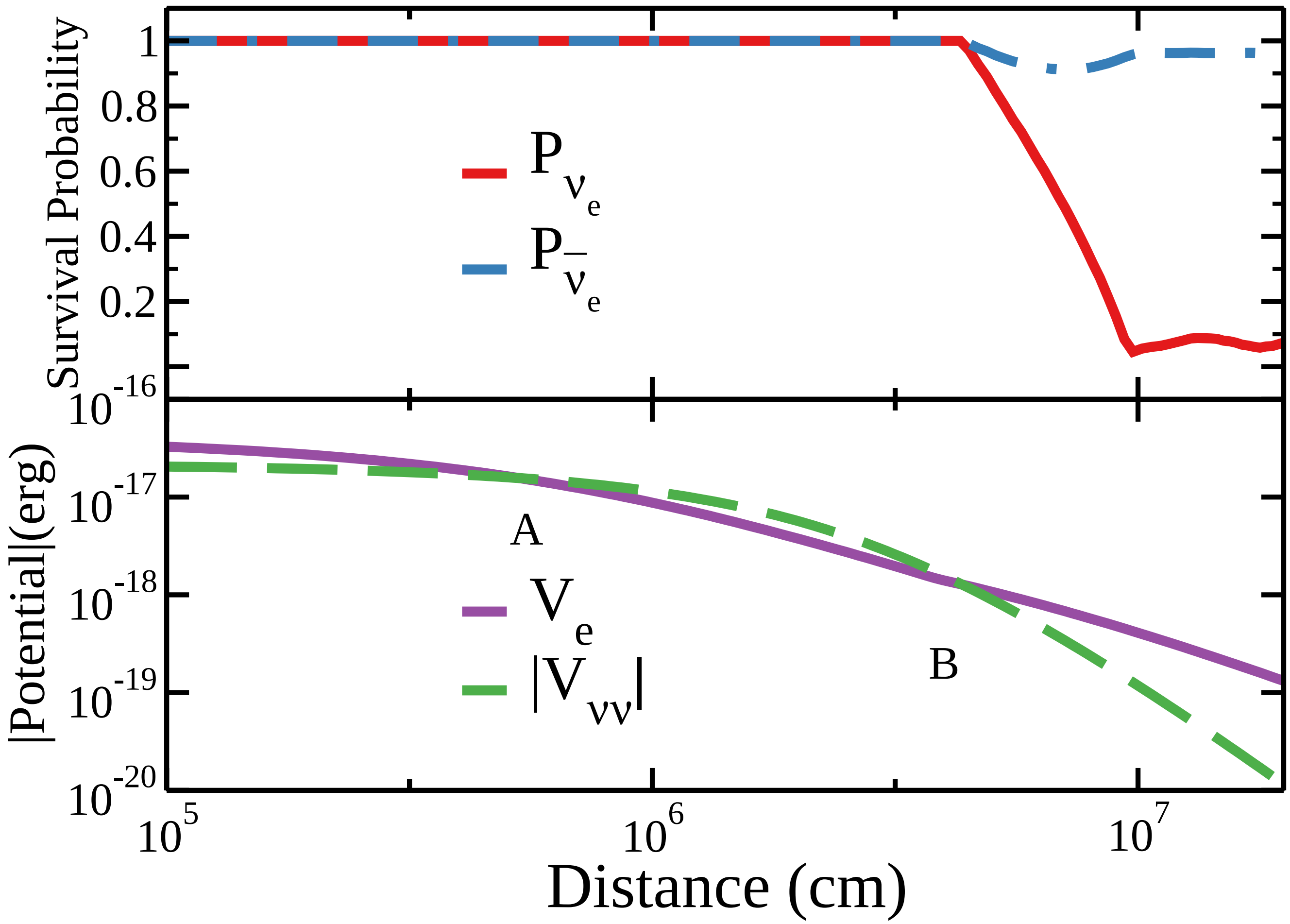
Modified wave equation

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

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

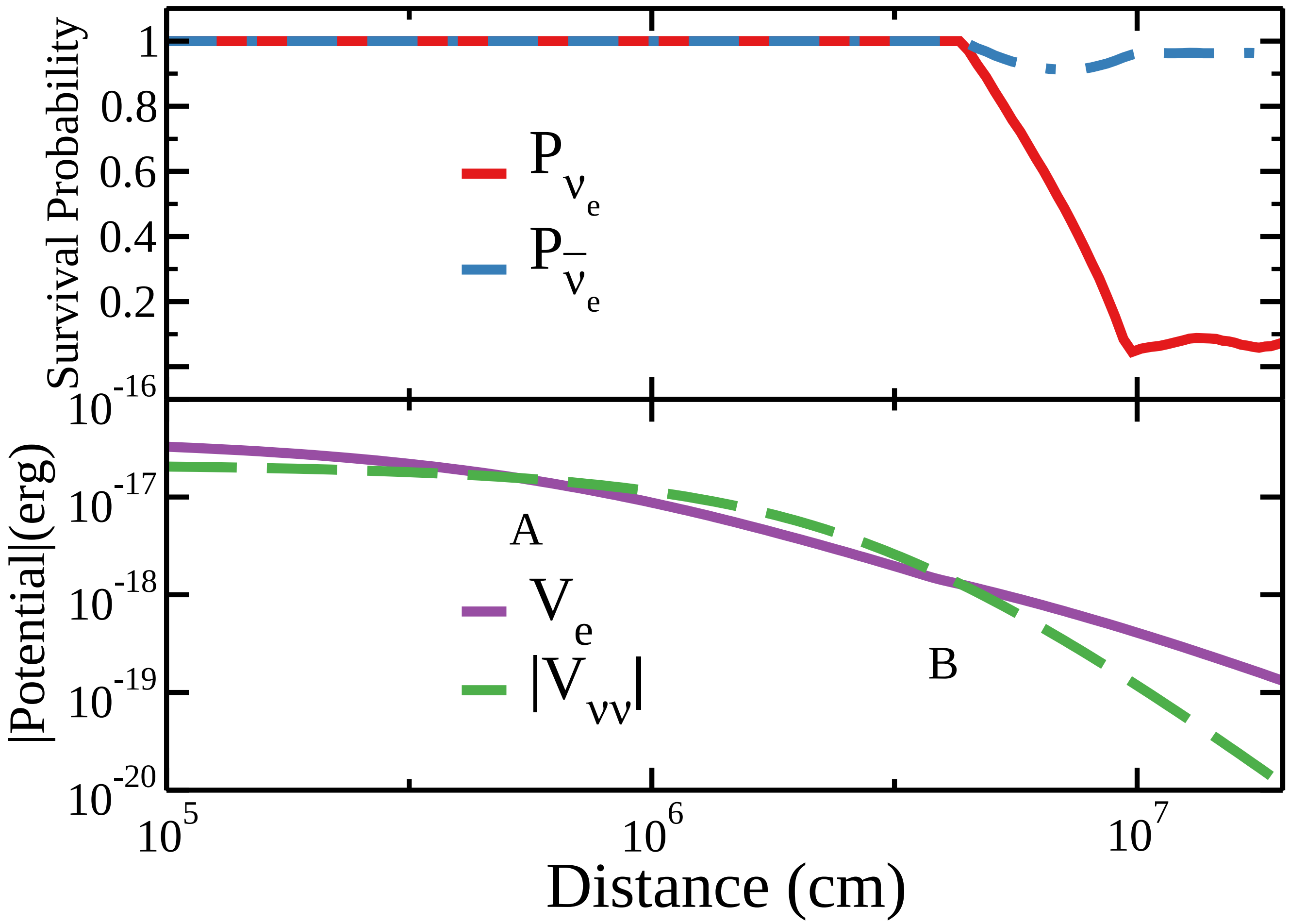
Lets oscillate neutrinos above a merger-type disk

Matter Neutrino Resonance above a Merger Disk



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

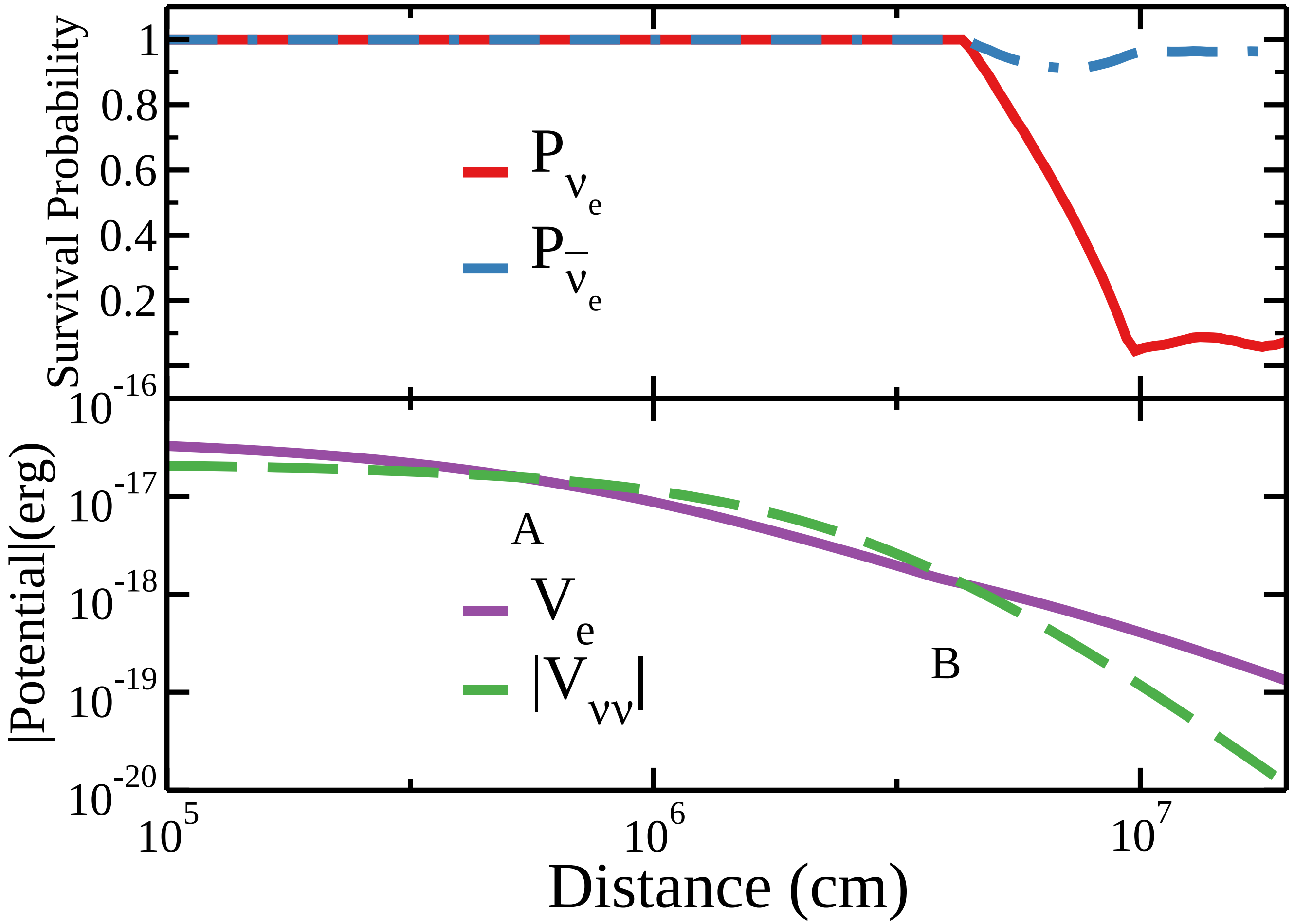
What's different about neutrinos from black hole accretion disks?

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

Phenomenological Prediction: “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 $V_\nu^a \propto N_{\nu,eff}(2P_{\nu_e} - 1) - N_{\bar{\nu},eff}(2P_{\bar{\nu}_e} - 1)$ 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 doesn’t precess, instead sum vector is restricted to $\hat{z}$ direction.

Phenomenological Prediction: “Matter Neutrino Resonance”

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

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

α is asymmetry and μ_ν is the scale of the neutrion self interaction protential

Now compare analytic prediction with numerical calculation

Neutrino-Matter Transition: Predictable Behavior

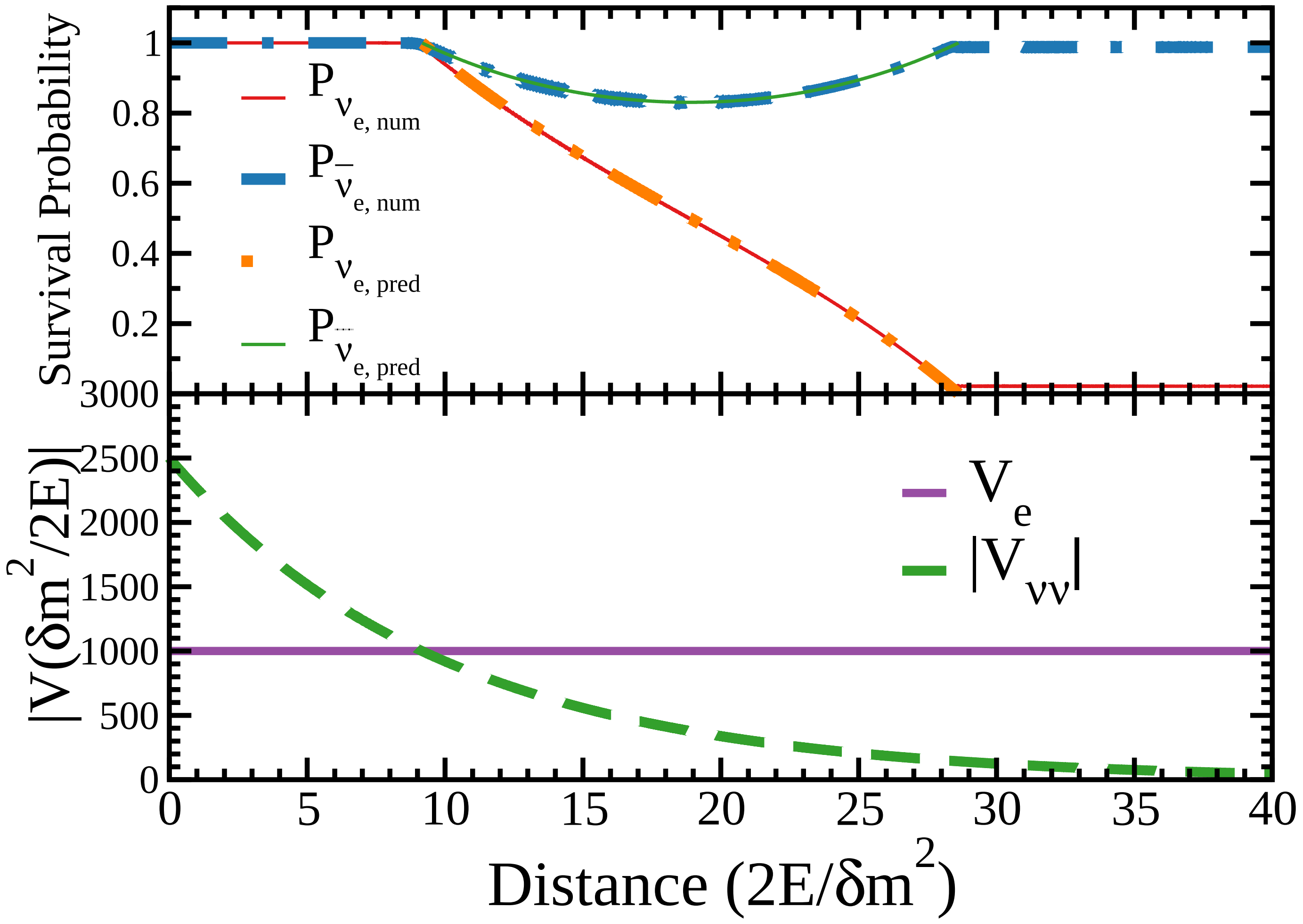
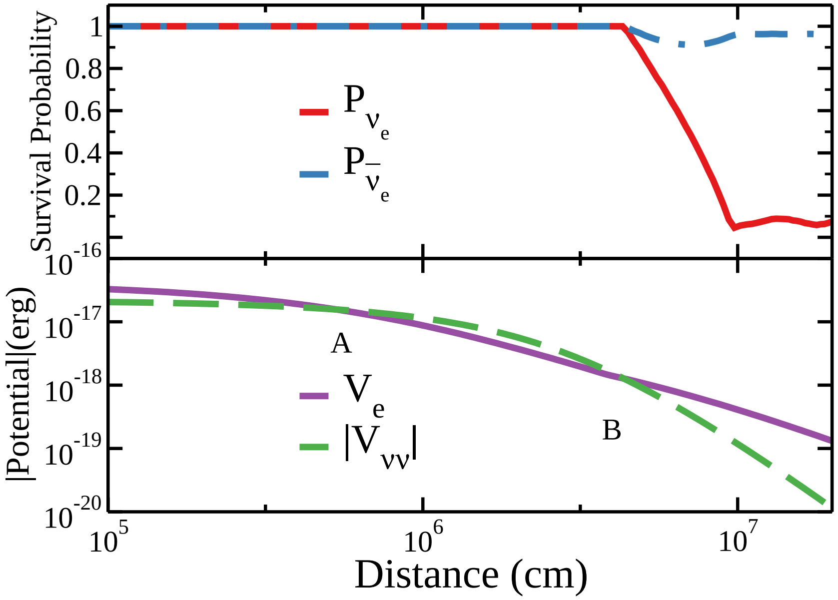
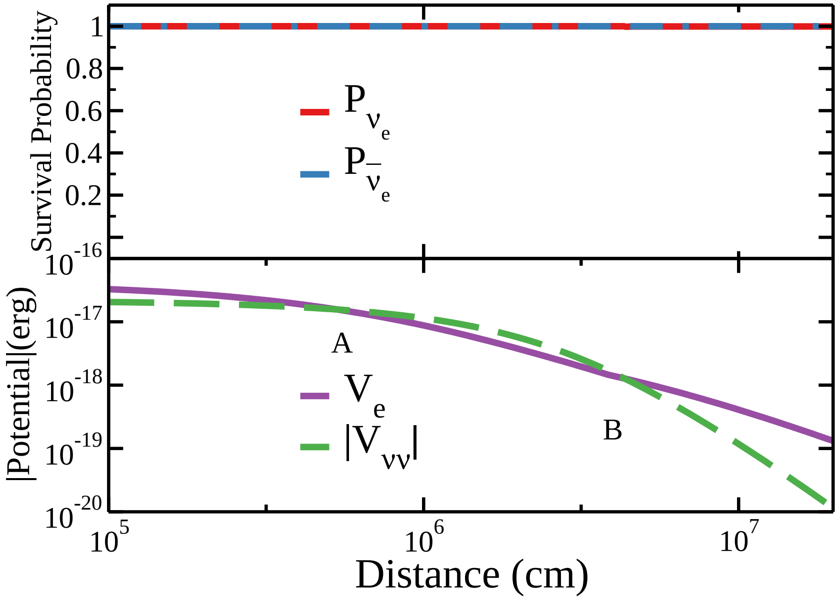


Fig. from Malkus et al 2014

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



ν_x scaled to 35%



ν_x scaled to 60%

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

Sufficient μ, τ neutrino flux will shut off the resonance transition: What does this mean?

- ν_μ, ν_τ flux which is of order the ν_e flux turns off the transition
- typical prediction is that ν_μ, ν_τ about 20% of ν_e
- this means transition occurs
- significantly larger flux would turn off transition
- this creates a major change in the nucleosynthesis
- e.g. nickel or the r-process

To understand the nucleosynthesis, we need to know to ν_μ, ν_τ flux well

Matter-Neutrino Resonance: Collapsar type disks

Matter-Neutrino Resonance: Collapsar type disks

Collapsar type disks are globally deleptonizing, i.e. neutrinos outnumber antineutrinos when you are far from the disk: $V_\nu^a = N_{\upsilon,eff} - N_{\bar{\nu},eff} > 0$

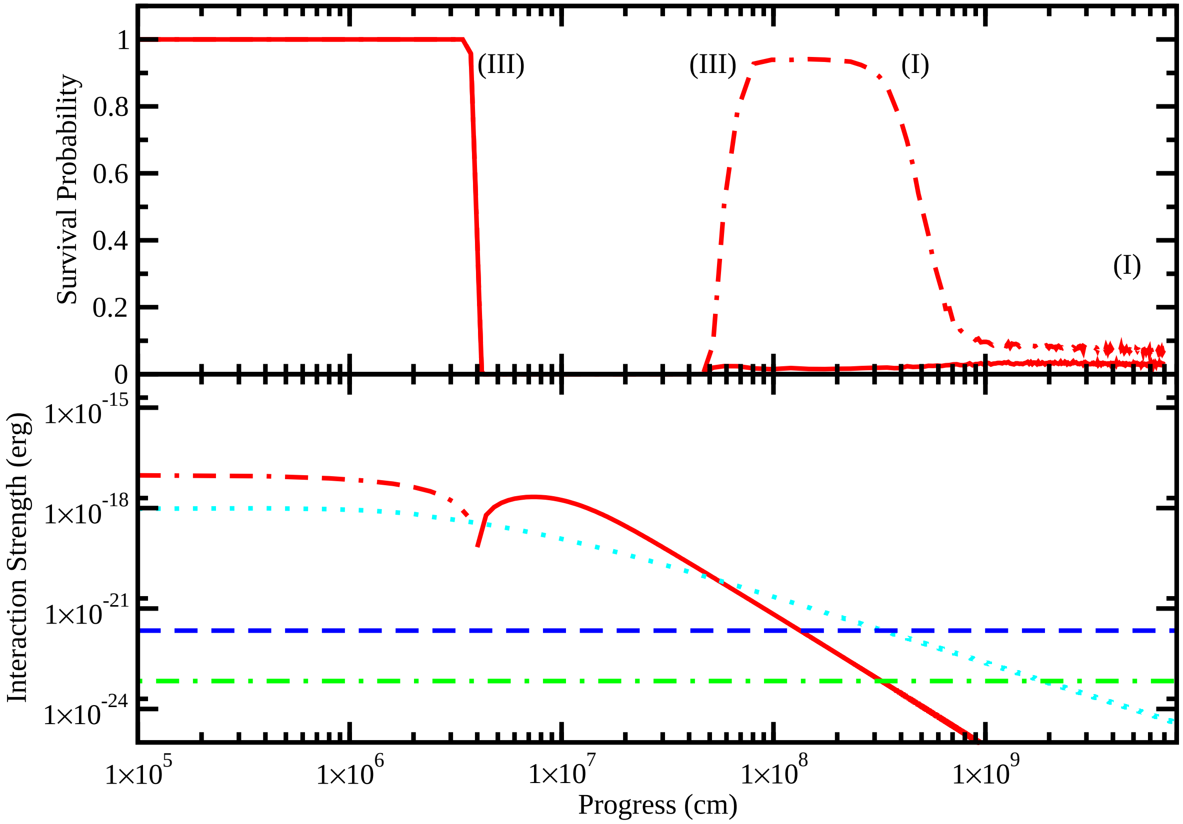
But, they can be locally leptonizing, i.e. near the disk surface antineutrinos can outnumber neutrinos: $V_\nu^a = N_{\upsilon,eff} - N_{\bar{\nu},eff} < 0$

Implications: along a neutrino trajectory, the potential starts negative and then switches sign.

Neutrino-matter resonance point occurs near switch-over point

Inverted hierarchy, $\bar{\nu}$ dominated first, ν later

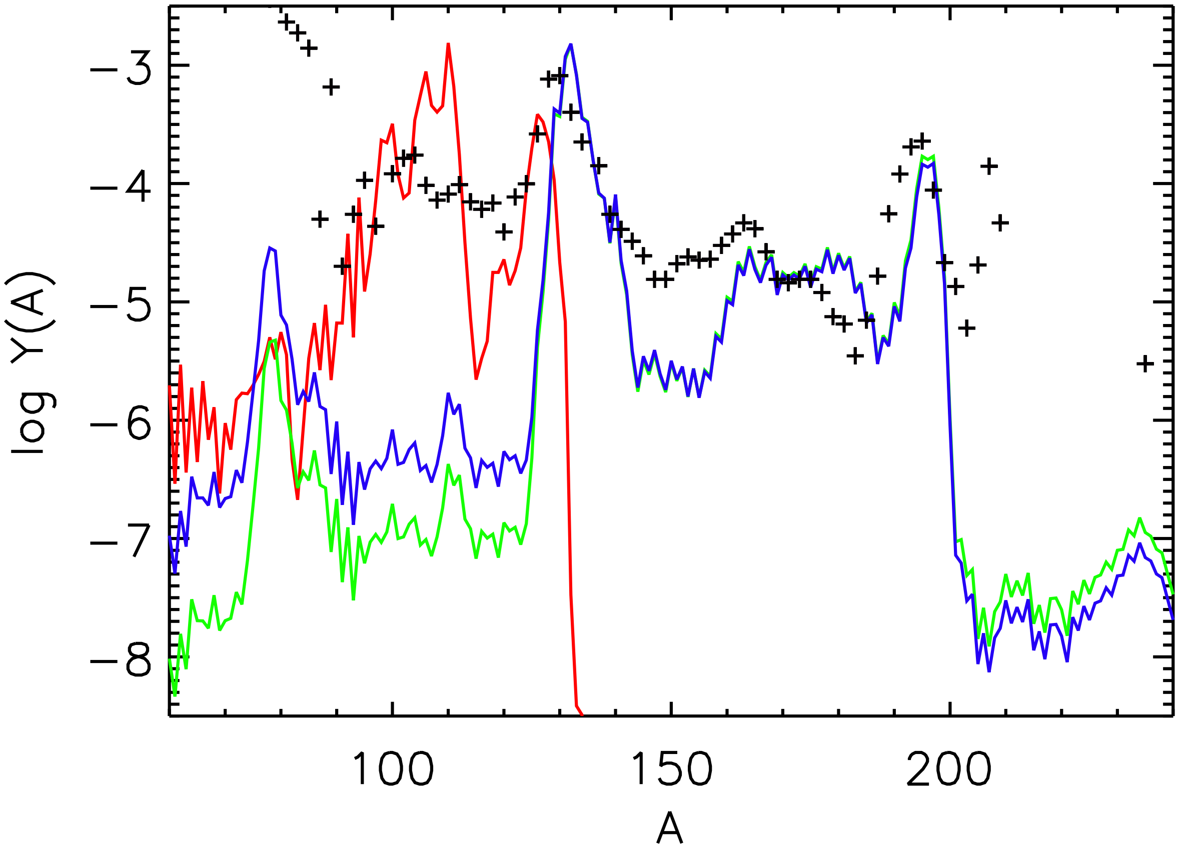
figure from Malkus et al 2012



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

Conclusions

- When anti-neutrinos outnumber neutrinos (e.g. disks) a new flavor transformation phenomenon can occur
- We call this a matter-neutrino resonance transition
- This transition can change the result of wind nucleosynthesis dramatically or perhaps neutrino heating from the wind
- More to be considered, e.g. multi-angle effects together with 3-D disk emission surfaces