Neutrinos from supernovae and compact object mergers

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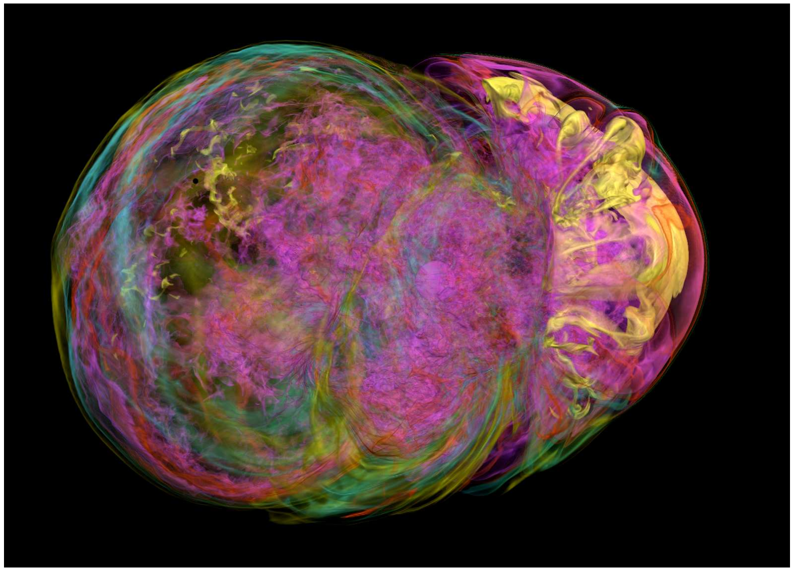
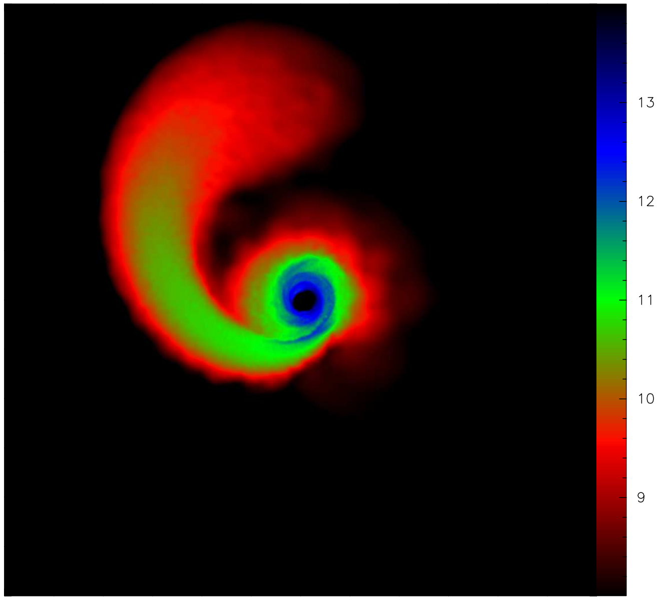
Explosions of core collapse supernovae and mergers:



Core collapse supernova

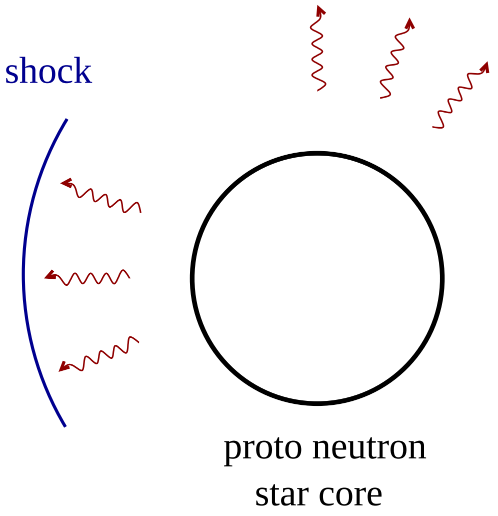
from Blondin et al.



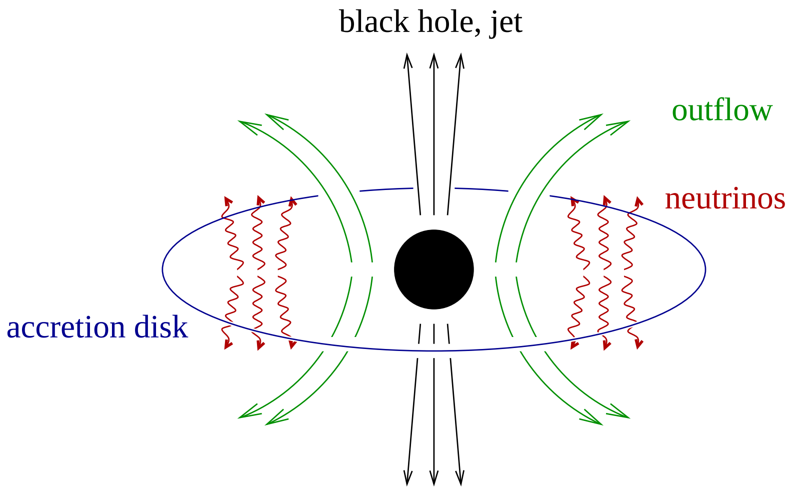
Compact object merger

from Rosswog et al.

Explosions of core collapse supernovae and mergers: What's happening at the center?

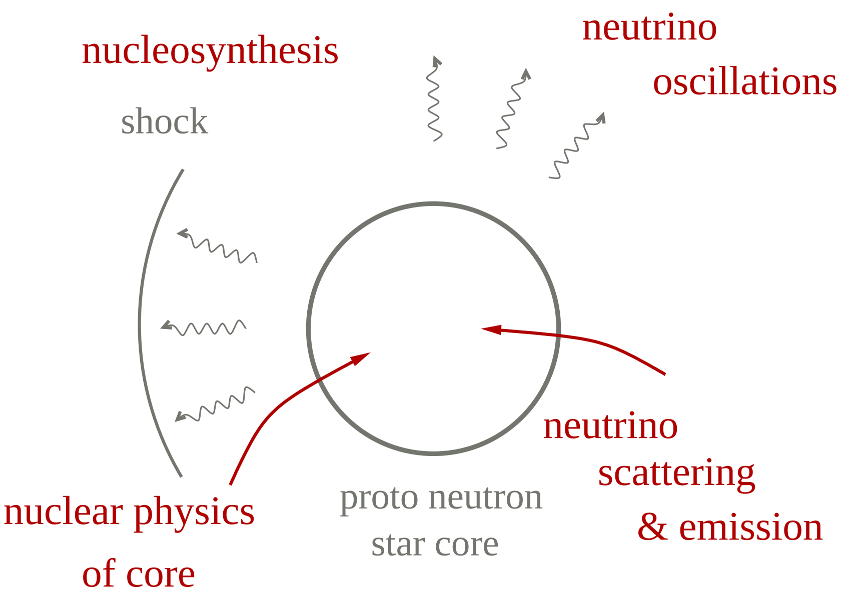


Standard core core collapse SN

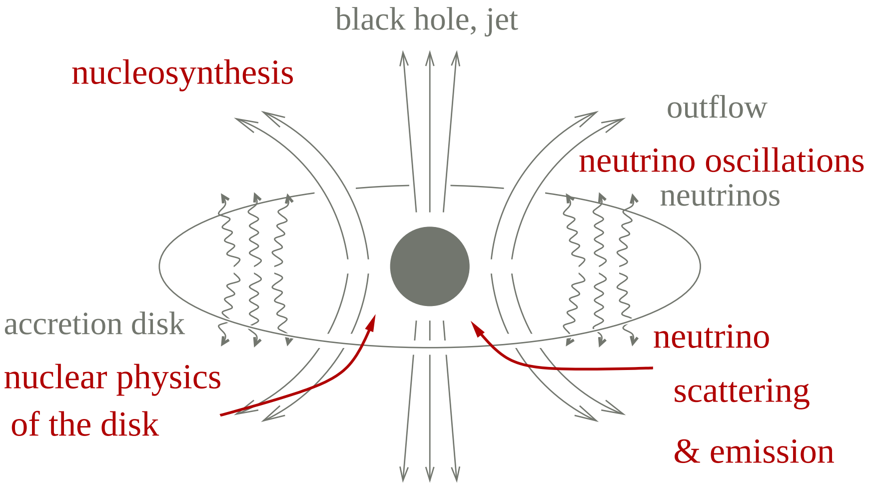


black hole - neutron star merger

Explosions of core collapse supernovae and mergers: Where is the microphysics?



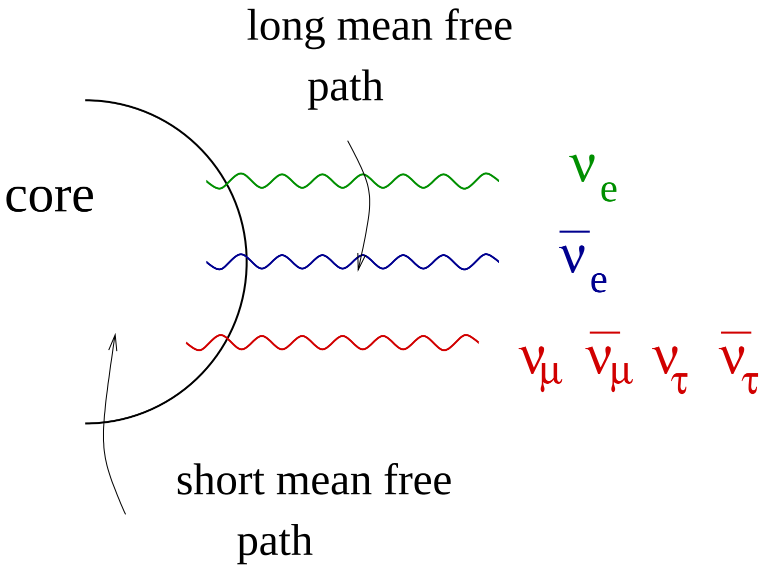
Standard core core collapse SN



black hole neutron star merger

Core collapse supernova neutrinos

All types of neutrinos emanate from the proto-neutron star core. They travel through the outer layers of the SN, then to earth.



SN neutrinos:

- may be detected
- oscillate
- nucleosynthesis
- explosion dynamics

Neutrinos from proto-neutron stars

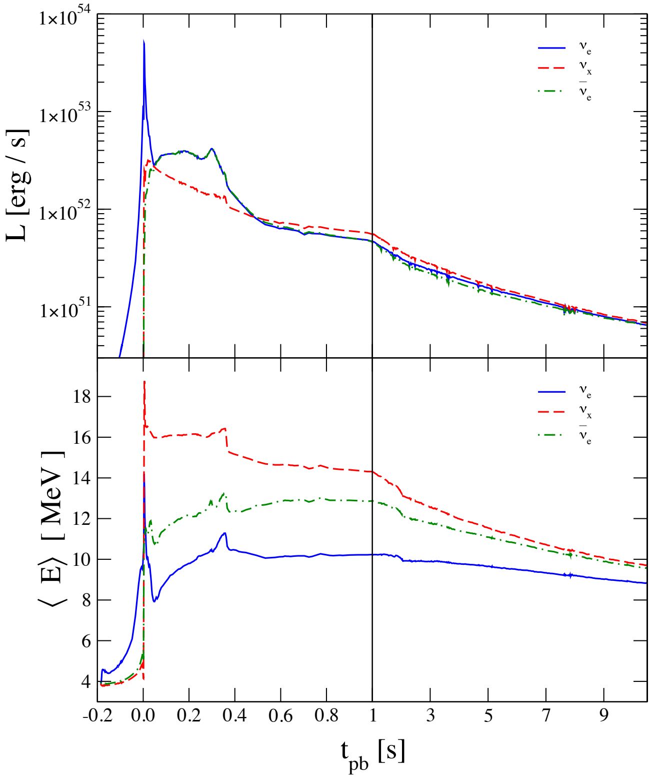
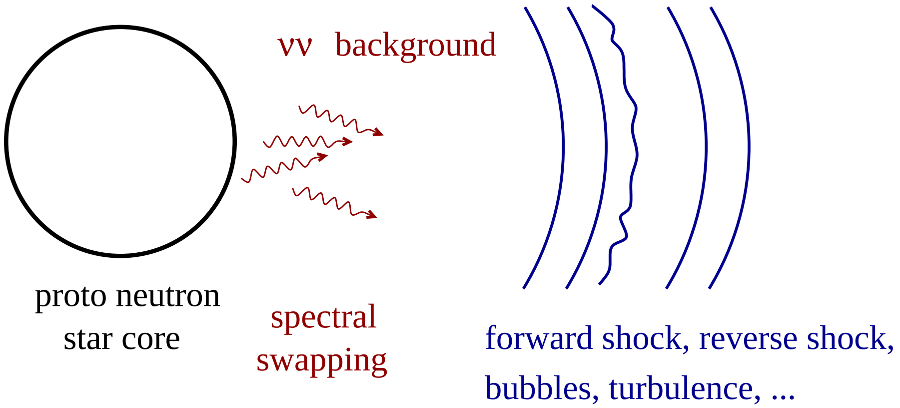


Fig. from review by Kneller and Horiuchi '17

- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$
- ν_e flux slightly larger than $\bar{\nu}_e$ flux (deleptonizing)

Once a supernova neutrino signal is measured

Want to work backwards to extract as much physics as possible



SN neutrinos:

- emission spectra
- hydrodynamic effects
- oscillations of neutrinos

Neutrino flavor transformation

Typically calculated by evolving density matrix, S-matrix or wave function. Example, S-matrix

$$i\hbar\frac{dS}{d\lambda} = HS(\lambda, \lambda_0)$$

Use this to determine density matrix or read off survival probabilities, e.g.

$$P_{\nu_e \to \nu_e} = |S_{ee}|^2$$

Note: many terms from the full quantum kinetic equations are neglected. For example, scattering (i.e. scattering that is typically included in Boltzman equation), spin coherence terms (coupling of neutrinos to antineutrinos).

The Hamiltonian

Consider only two flavors of neutrinos:

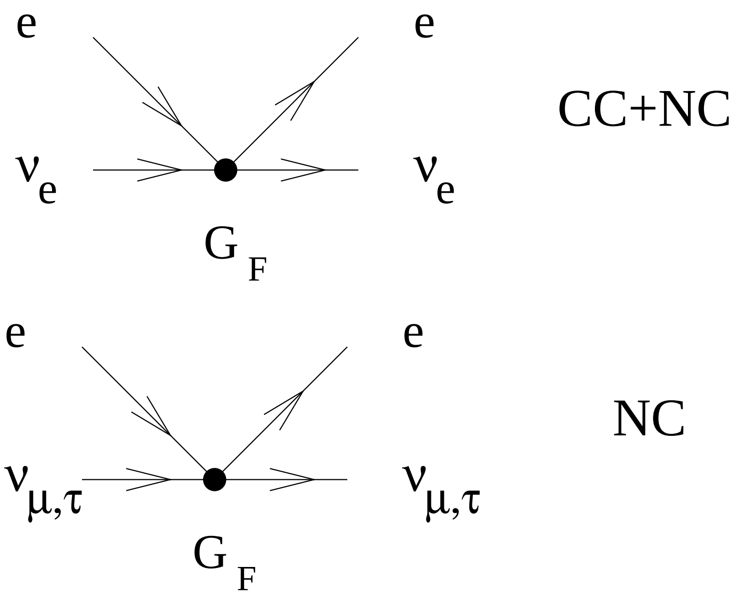
$$H = \begin{pmatrix} V_e + V_\nu^a - \frac{\delta m^2}{4E}\cos(2\theta) & V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) \\ V_\nu^b + \frac{\delta m^2}{4E}\sin(2\theta) & -V_e + -V_\nu^a + \frac{\delta m^2}{4E}\cos(2\theta) \end{pmatrix}$$

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

Matter: electrons, protons, neutrons

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



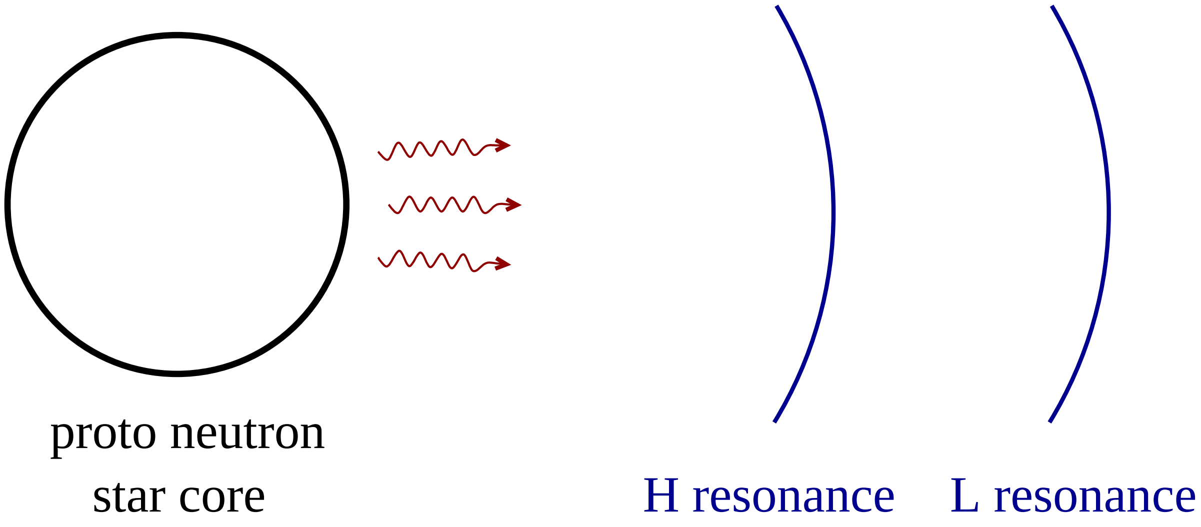
$$V_e = \frac{V_{\nu_e,e} - V_{\nu_x,e}}{2} = 2\sqrt{2} G_F N_e(r)$$

electron density $N_e(r)$

assumes an isotropic distribution of matter!

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

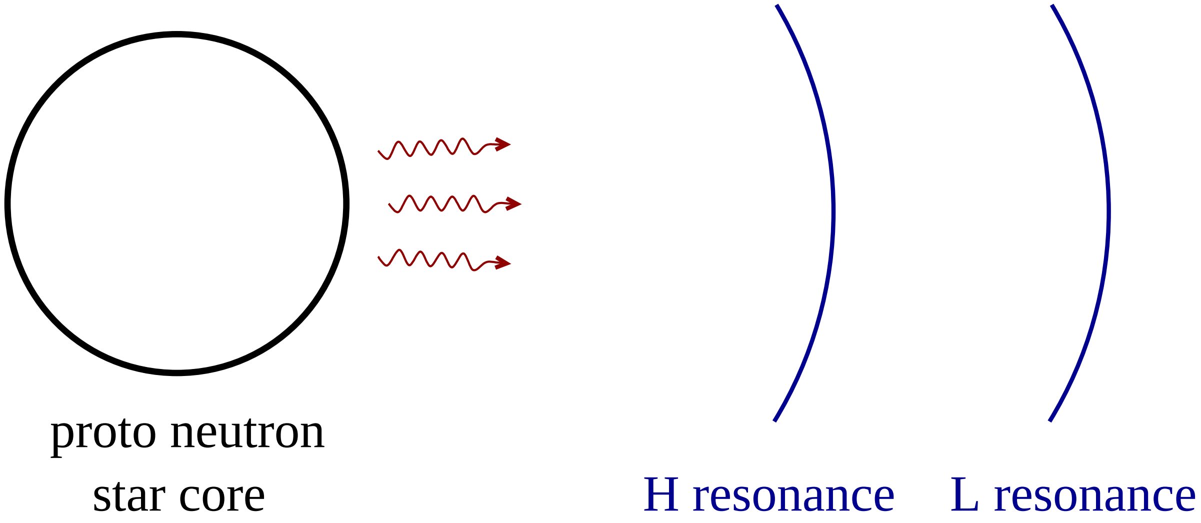
MSW: matter potential ∼ vacuum strength



Matter enhanced region

- Traditional MSW region, similar to sun
- i.e. $\delta m^2_{ij}/E_\nu \sim \sqrt{2}G_F N_e \gg V_{\nu\nu}$

MSW in core collapse supernovae



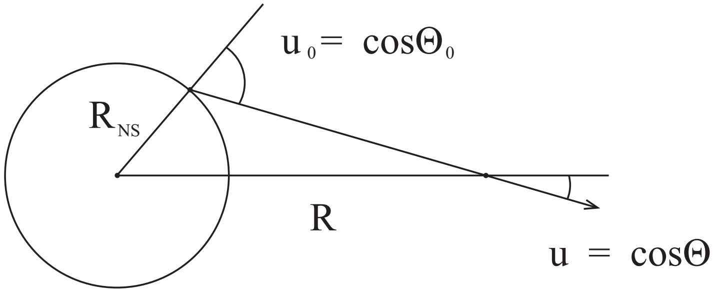
Matter enhanced region

- occurs in outer layers of the star (He layer or a somewhat before)
- straightforward to calculate (same thing that happens in the sun)
- and neutrino self interaction strength is small

Neutrino potential in the Hamiltonian

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

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



not isotropic, but there is symmetry!

To calculate this term, we need to know how all the other neutrinos are transforming!

Neutrino flavor transformation: nonlinearity

Neutrino oscillations with a substantial neutrino potential: numerically demanding

1. Non-linear effects $V_\nu \sim |\psi_\nu|^2$
2. Requires multi-group treatment: Background involves sum over neutrino momentum and angle.

Depending on the problem, one may require 1000s of bins in energy and angle, calculated simultaneously.

Sometimes use approximations such as “single energy” or “single angle”, “bulb model”, ...

The neutrino potential leads to “collective” effects

This occurs at roughly when the scales of the vacuum potential and the neutrino potential match.

collective oscillations

- “Traditional” nutation in NFIS picture (also called bipolar)
- $\delta m^2_{ij}/E_\nu \sim V_{\nu\nu}$
- occurs closer to proto-neutron star than MSW regions $\sim$ 100 km
- occurs when matter potential is both large and small

Oscillations change the neutrinos

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

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

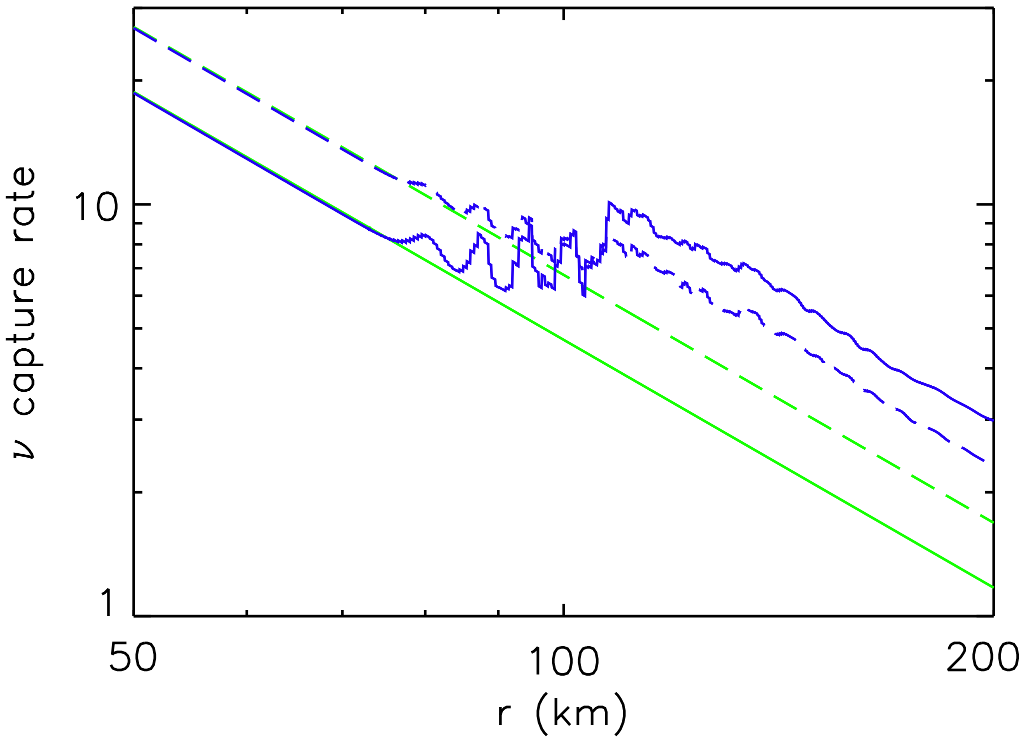
$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

So the rates of these reactions are changed:

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

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

ν_e and $\bar{\nu}_e$ capture rates on nucleons



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

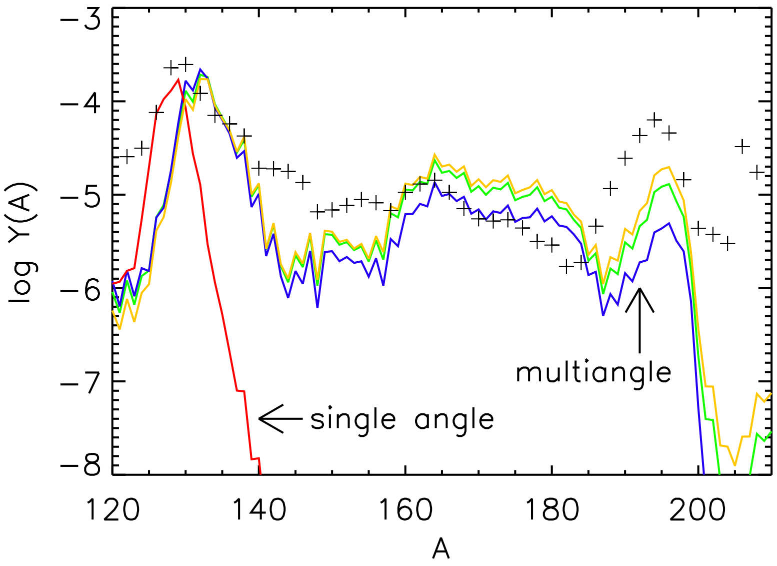
figure from Duan et al 2011

Shows the influence of collective oscillations, inverted hierarchey

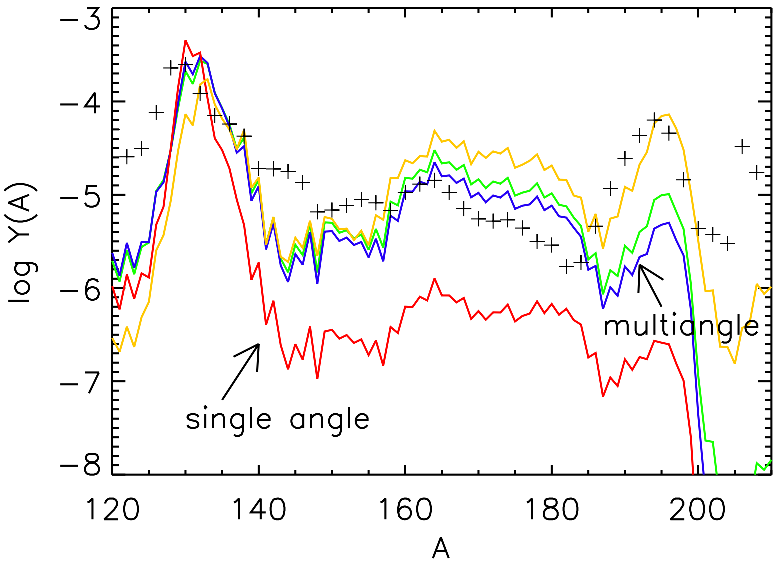
ν_es are exchanging with ν_μs, ν_τs $\bar{\nu}_e$s are exchanging with $\bar{\nu}_\mu$s, $\bar{\nu}_\tau$s

Neutrino Flavor Transformation

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

Supernova neutrino detection

Neutral current (unchanged by oscillations!)

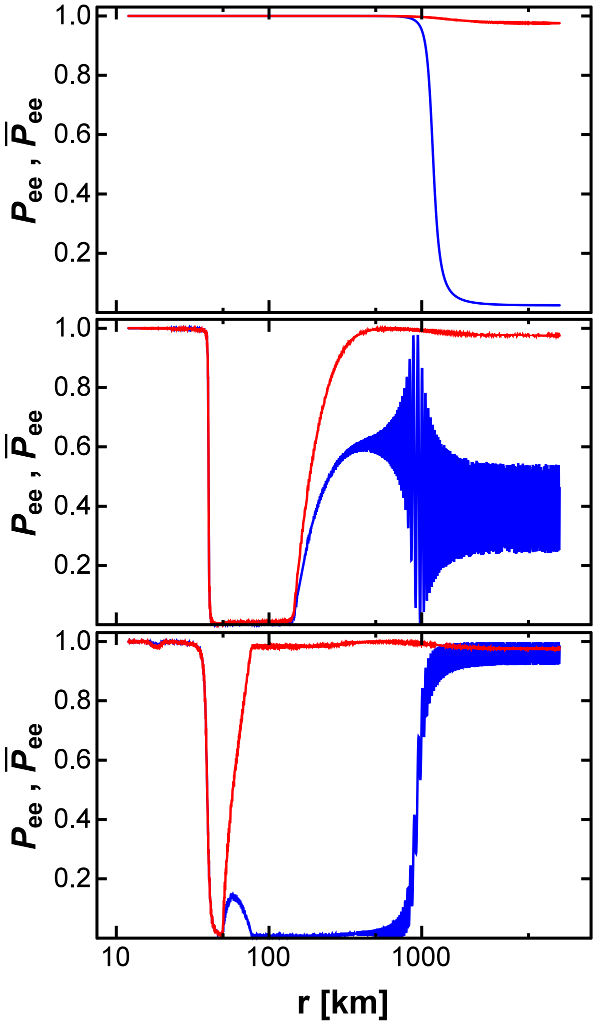
- neutrino emission timescale
- average energies of neutrinos at emission

Charged current νs mixed by oscillations.

- collective
- MSW
- turbulence(?)
- "fast" oscillations(?)

There will be degeneracies, so both ν_e and $\bar{\nu}_e$ detection is needed.

NSI effects would muddy the waters



Stapleford et al 2016, top panel: normal heirarchy, no NSI, middle and bottom values, different NSI parameter choices

$(\delta\epsilon_n = -0.84, \epsilon_0 = 0.00025$ and $\delta\epsilon_n = -0.84, \epsilon_0 = 0.001$

Mergers

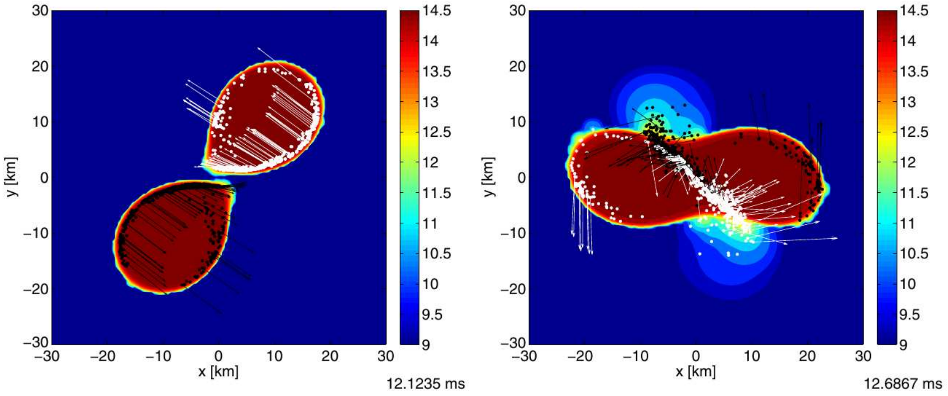


fig. from Bauswein et al 2013

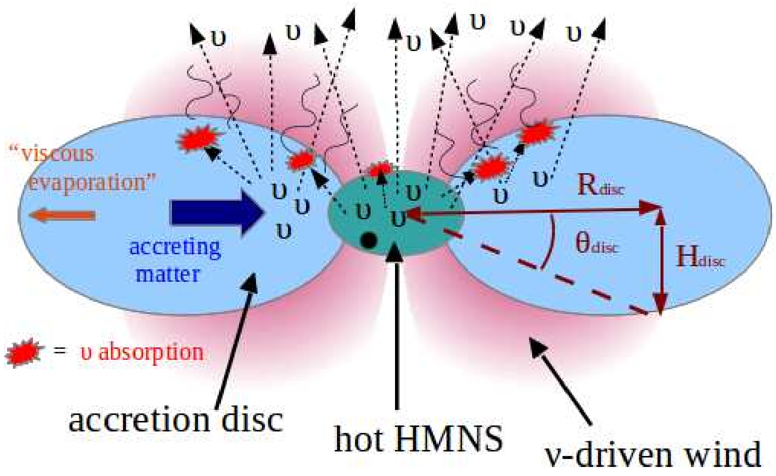
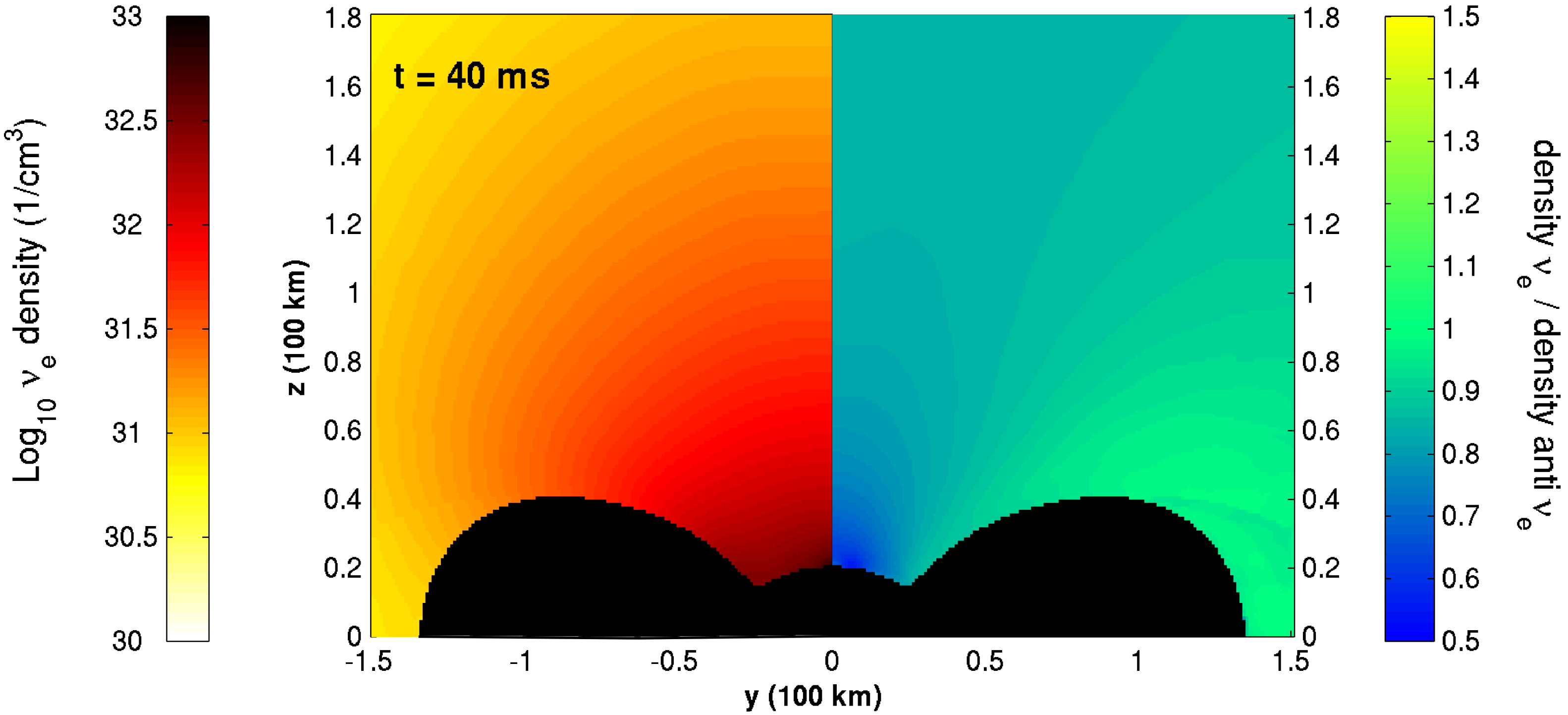


fig. from Perego et al 2014

Neutrinos from Mergers

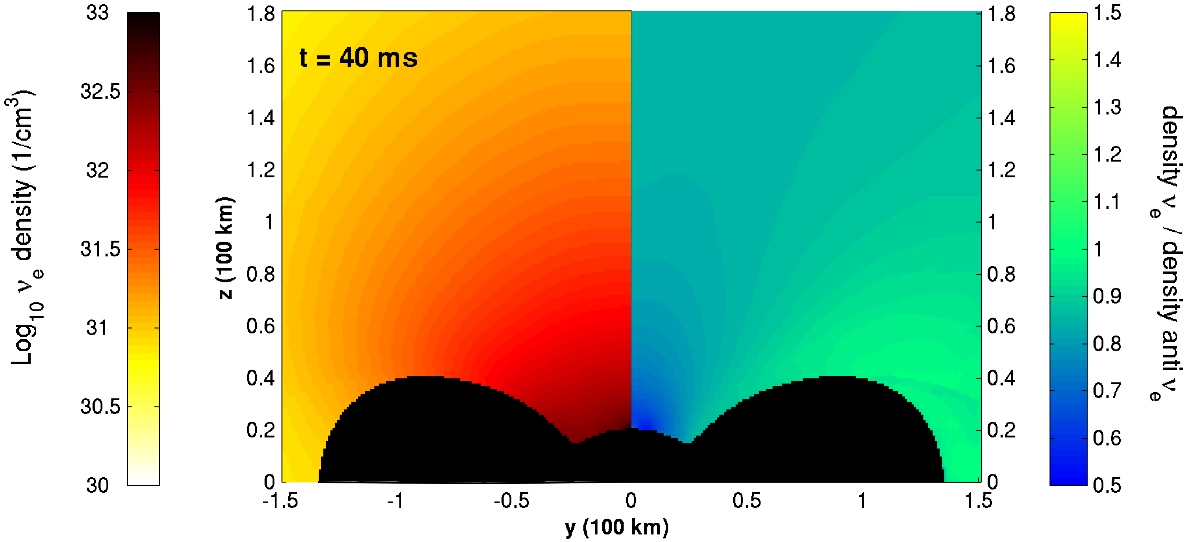


Simulation by Perego

Density of neutrinos is above a merger is similar to that of a supernova, but unlike in supernova, the neutrinos and outnumber the antineutrinos.

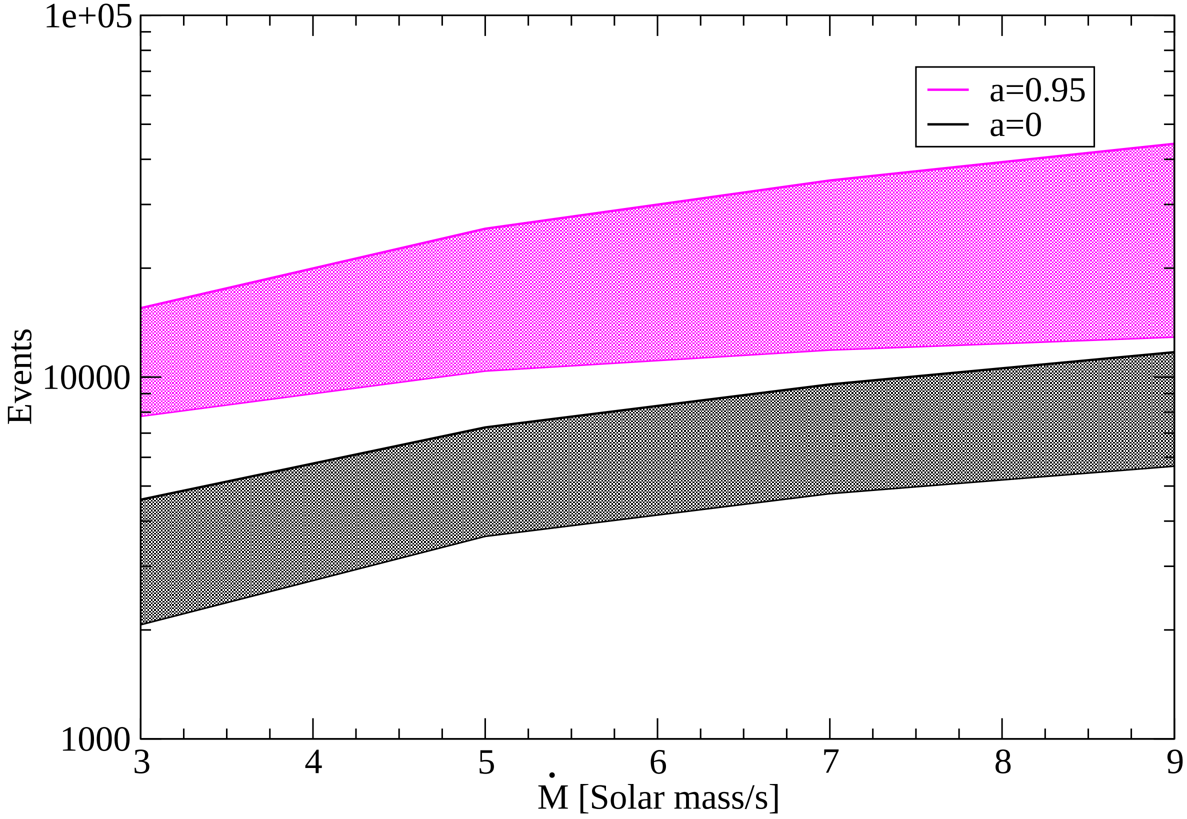
We lost some symmetry (as compared to the core collapse supernova).

Neutrinos from Mergers



- more ν_e and $\bar{\nu}_e$ than ν_μ and $\bar{\nu}_\mu$
- more $\bar{\nu}_e$ than ν_e (leptonizing)
- similar spectra as to protoneutron star
- emission surface for neutrinos is larger than for antineutrinos

Galactic mergers are detectable with νs



Shows events in SuperK from an accretion torus around black hole, from Caballero et al 2016. Similar numbers to supernovae, timescale different (tenths of seconds vs. ten seconds)

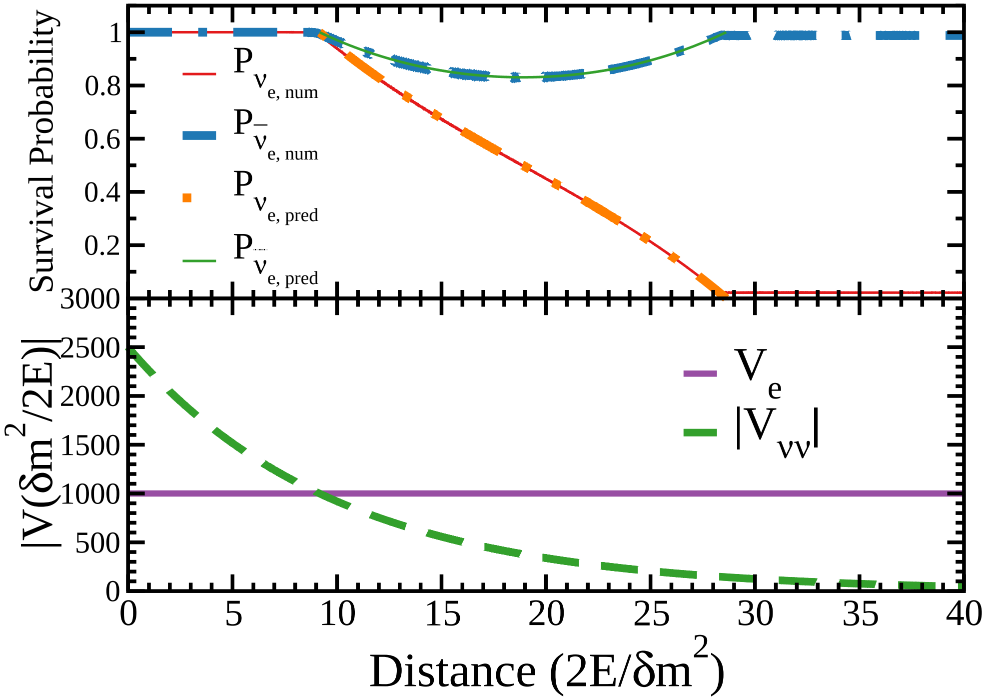
Flavor transformation in mergers

Possibilities:

- MSW: $\delta m^2/2E \sim V_e$, like sun, supernova
- Collective: $\delta m^2/2E \sim V_\nu$, like superonvae
- Matter neutrino resonance: $V_\nu \sim V_e$, unlike sun, supernovae

Matter neutrino resonance transition

Happens when potentials V_ν and V_e are similar magnitude and opposite sign

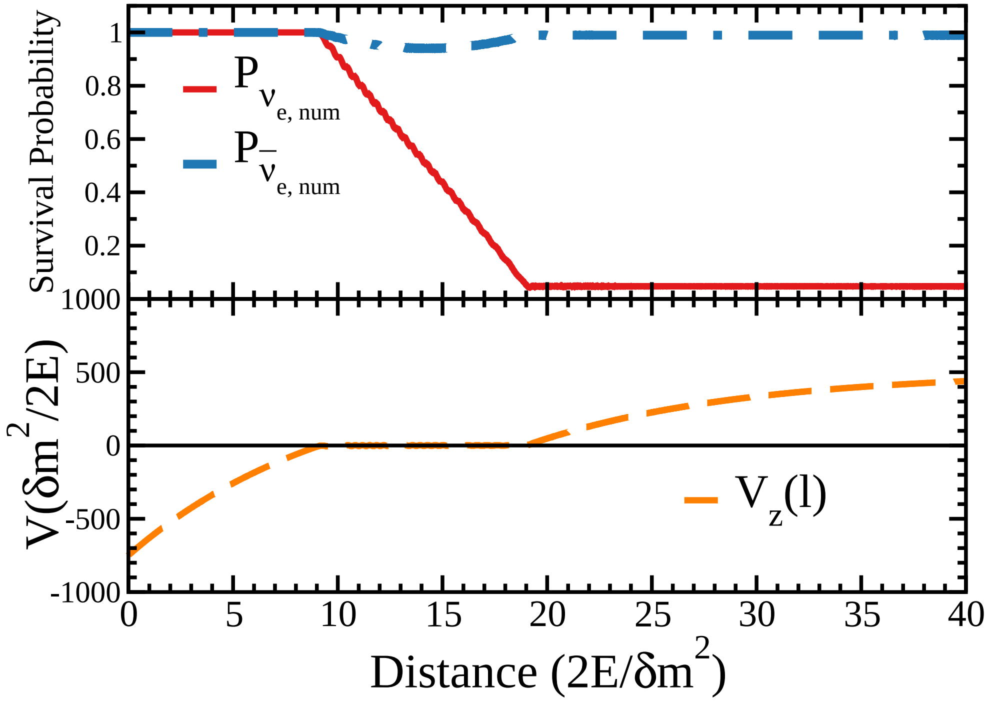


Standard MNR Malkus et al ’14, see also Malkus et al ’12, Wu et al ’16, Vaanenan et al ’16

This is a single energy, “single angle” calculation

MNR transition is like MSW "on steriods"

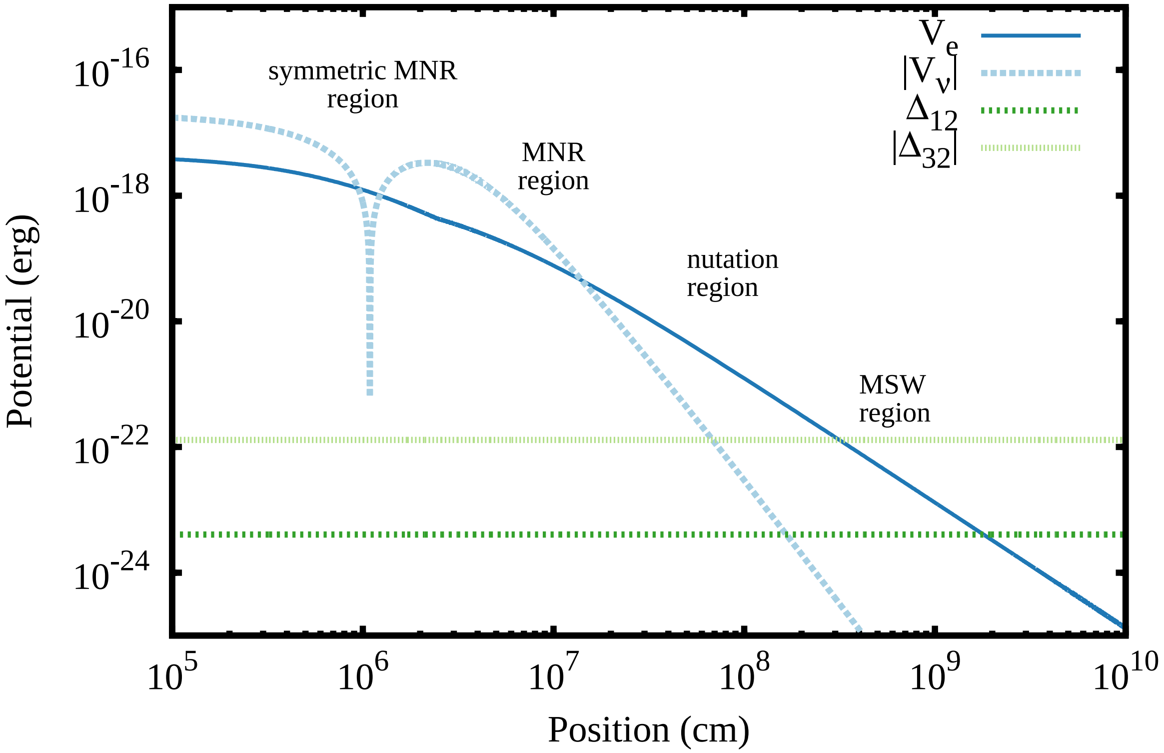
Sum of potentials V_ν and V_e tracks near zero



Standard MNR Malkus et al '14, see also Malkus et al '12, Wu et al '16, Vaanenan et al '16

Geometric effects on the neutrino potential

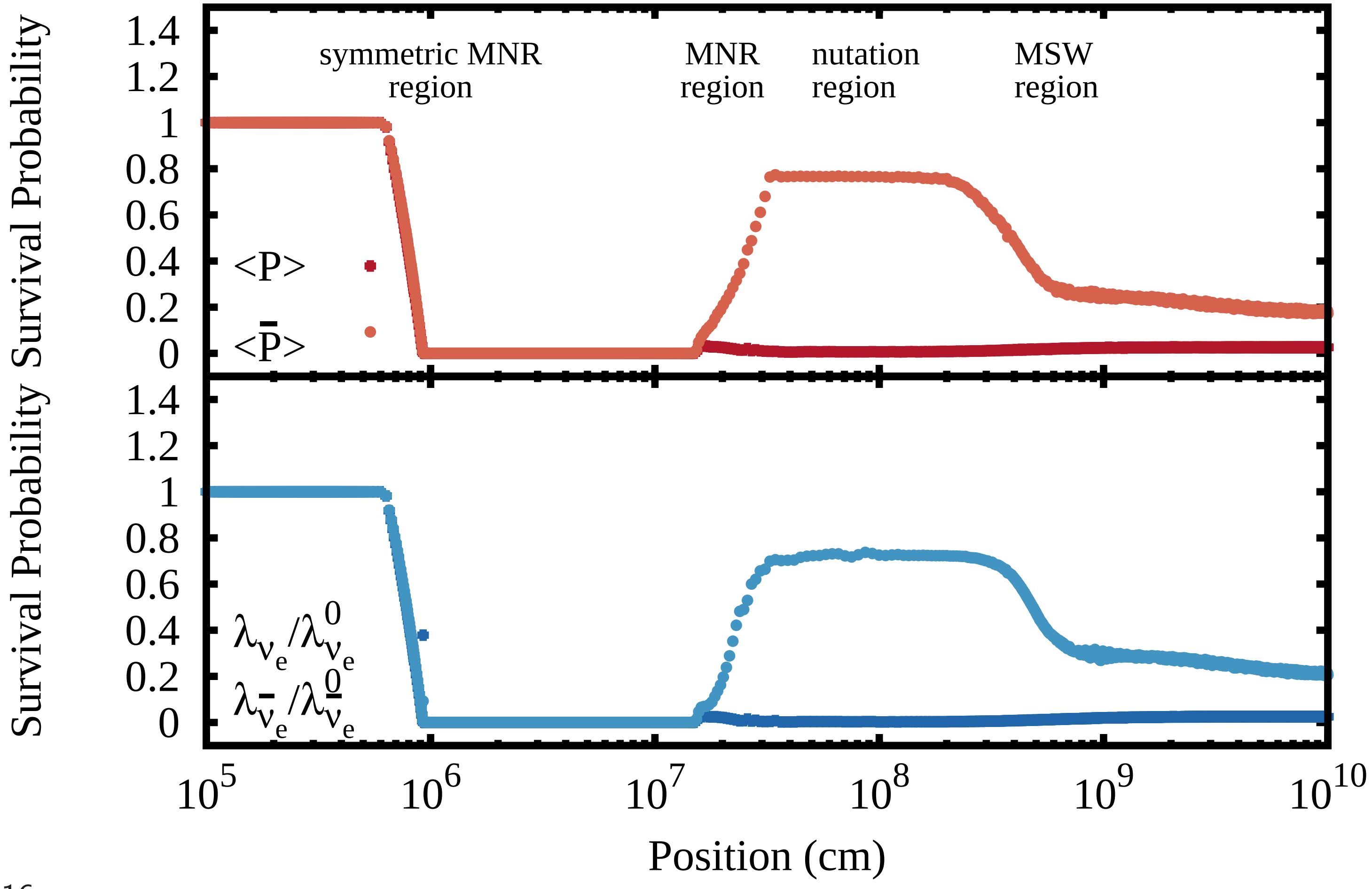
Geometry can cause V_ν to switch sign



A larger ν_e emission surface leads to an additional type of MNR.

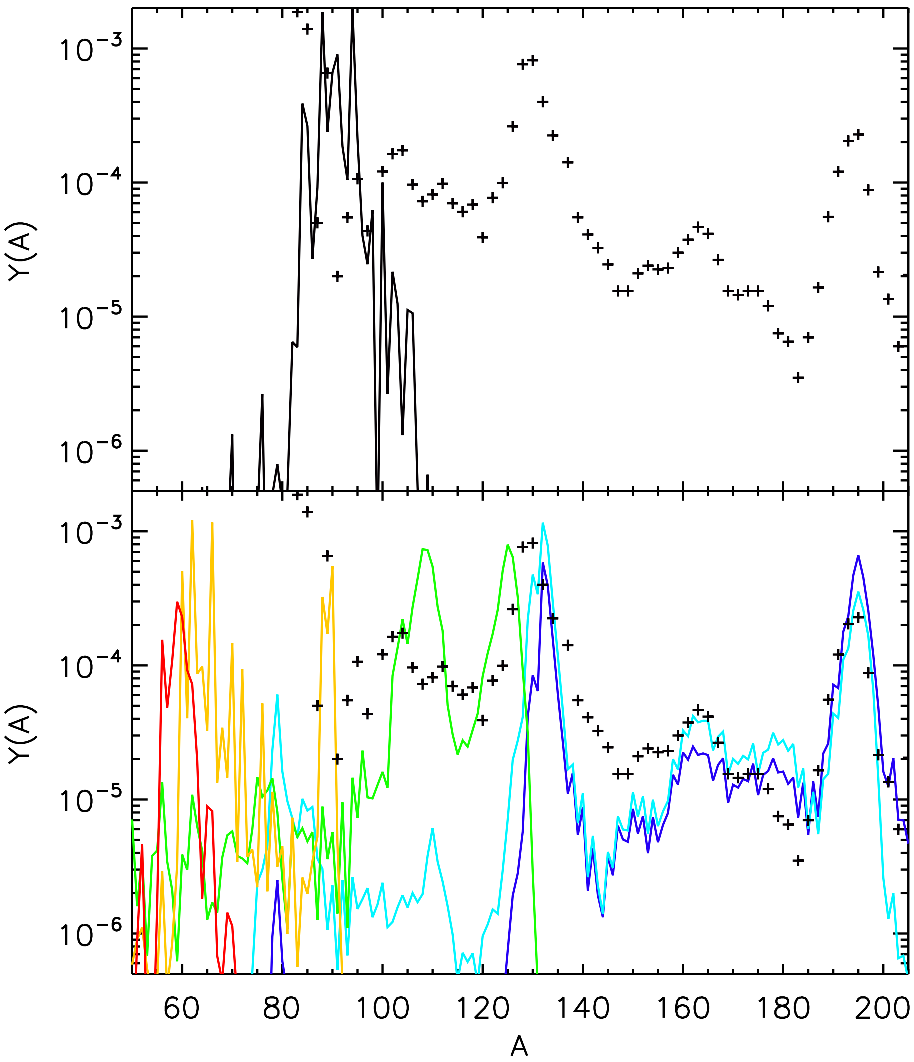
Potential for different size disks for ν_e and $\bar{\nu}_e$ Malkus '16

Some neutrino trajectories in mergers will see both standard and symmetric transitions



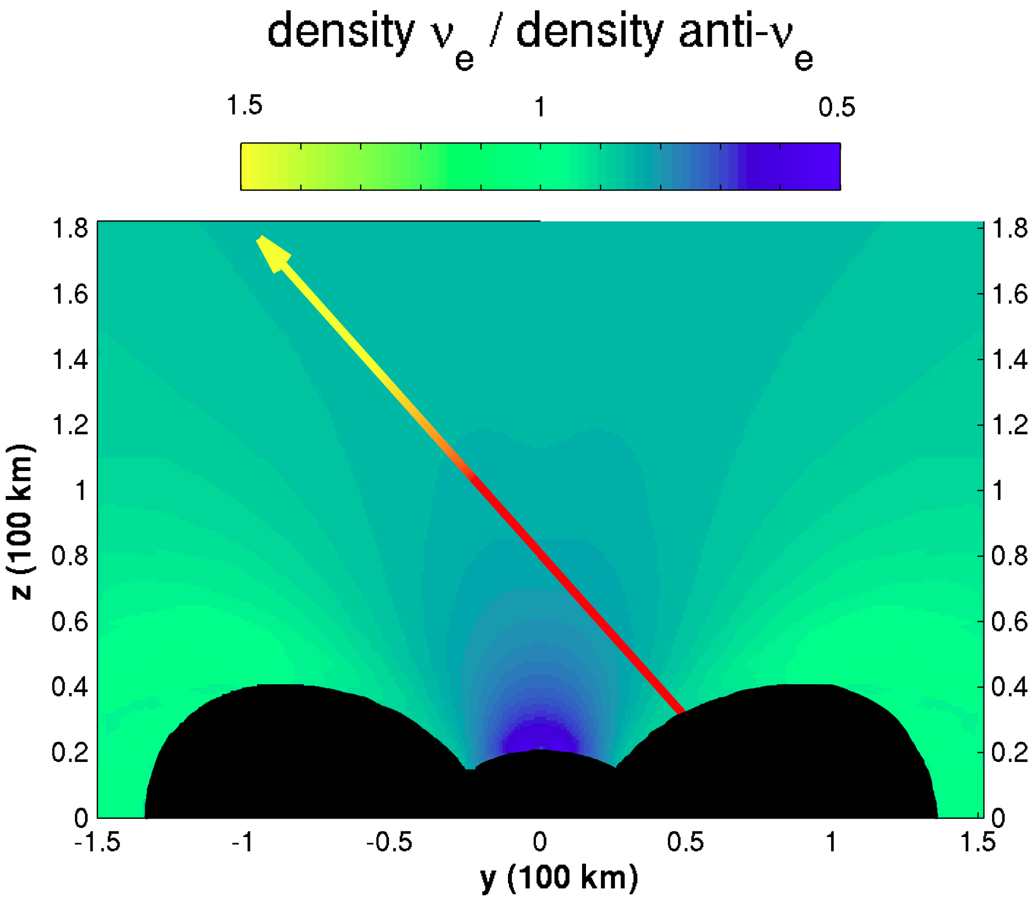
Malkus et al '16

How oscillations affect nucleosynthesis



Malkus et al '16

Return to the dynamical merger remnant



How do these neutrinos flavor transform?

Neutrino oscillations from a dynamical merger calculation

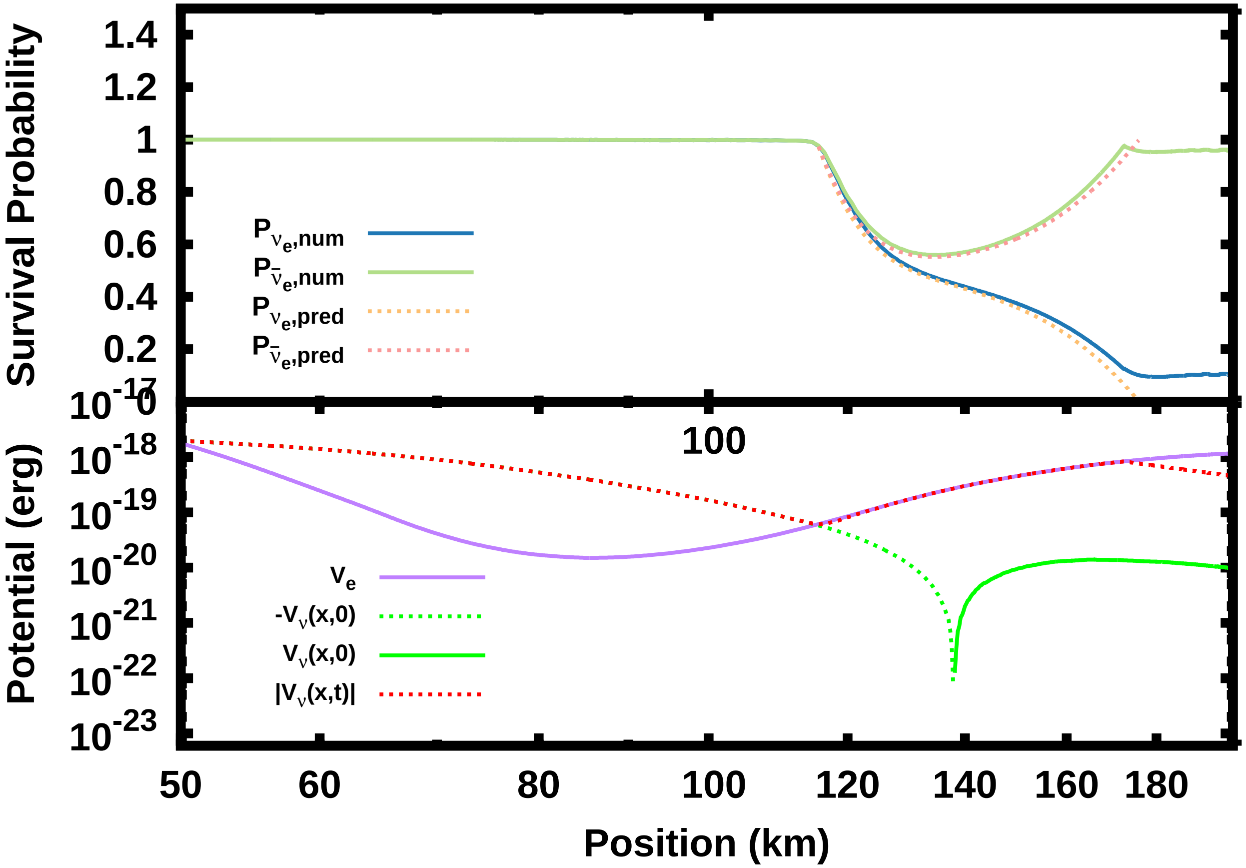


Fig. from Zhu et al '16

Neutrinos flavor transform over the center

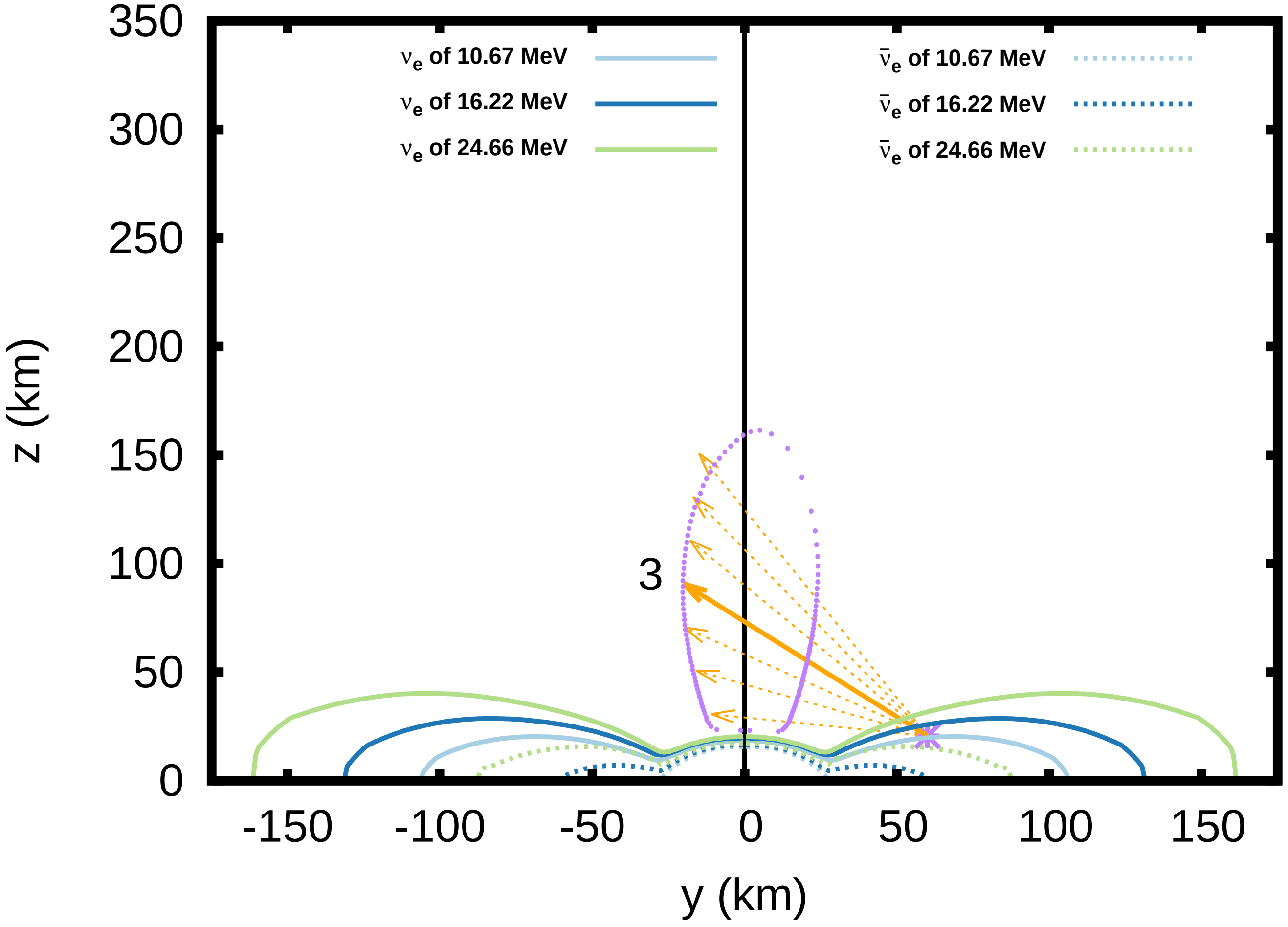
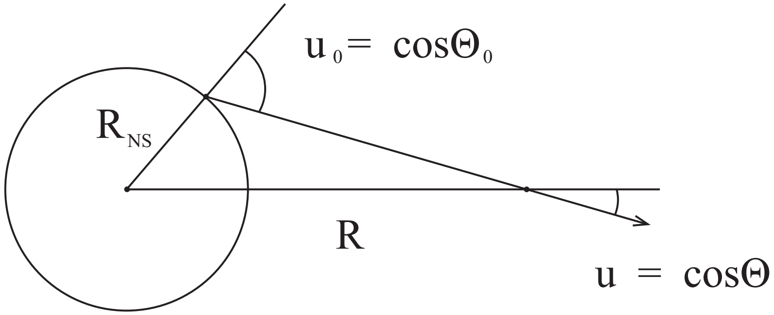
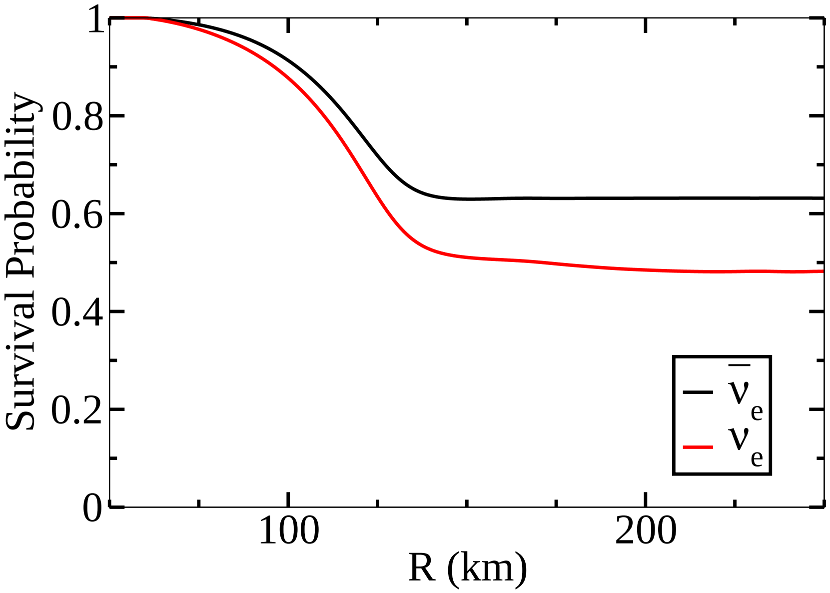


Fig. from Zhu et al '16

Hypermassive neutron star: multi-angle





Vlasenko et al, in prep.

Conclusions

supernova neutrinos

- essential part of SN dynamics, nucleosynthesis
- we'd like to use their detection to learn about the center of the explosion
- neutrinos can flavor transform collectively, by MSW, other ways as well

merger neutrinos

- essential part of merger dynamics, nucleosynthesis
- if close enough, neutrinos are detectable
- oscillations: matter neutrino resonance transitions occur!

Lots more to study!