Multi-Angle Calculations of Matter-Neutrino Resonance

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Neutrino Flavor in Astrophysics

- Astrophysical environments (early Universe, supernovae, compact object mergers) are strongly affected by neutrinos.
- Neutrinos can undergo flavor transformation.
- Electron neutrinos interact with matter differently than other flavors, so neutrino flavor matters.
- Flavor physics can therefore affect observables:
  - Elemental abundances
  - Neutrino spectra
  - Dynamics of mergers and supernovae

Flavor Transformation in Dense Environments

- Flavor can be described by N_F x N_F density matrices *f*
- For each neutrino momentum, there are two matrices: one for neutrinos and one for anti-neutrinos.
- *f* evolve according to a Schrödinger equation:

$$i\dot{f} = [N + M - V, f]$$

$$i\dot{\bar{f}} = \left[N + M + V, \bar{f}\right]$$

- *N*, *M* and *V* are the neutrino, matter and vacuum potentials, respectively.

Regimes of Flavor Transformation

Flavor transformation can occur when combinations of scales in the Hamiltonian become comparable to the vacuum term:

$M \approx V$	MSW Effect
$N \approx V$	Collective Oscillations
$M + N \approx V$	Matter-Neutrino Resonance

Turbulence & Fast Oscillations can also lead to flavor transformation, outside of these regimes.

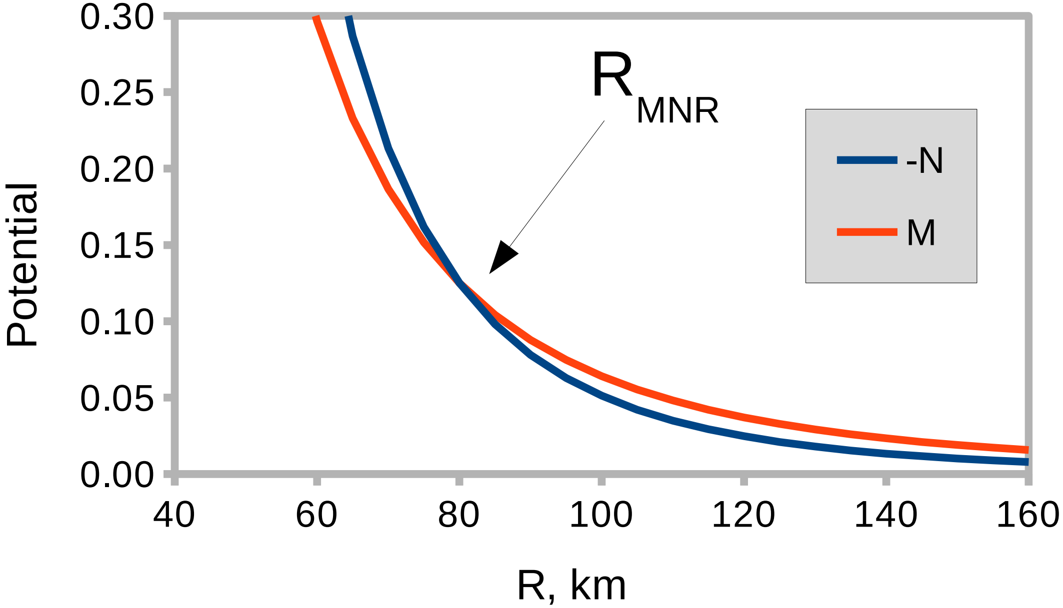
Matter-Neutrino Resonance in Compact Object Mergers

- In mergers, the anti-neutrino contribution to *H* can be larger than the neutrino contribution.
- In this case, the neutrino potential has the opposite sign to the matter potential.
- A cancellation between matter and neutrino potentials can occur. This is known as a matter-neutrino resonance (MNR).
- MNRs can lead to flavor transformation even when matter & neutrino potentials are individually >> *V*.

Previous Work: Single-Angle MNR

Malkus, Friedland, McLaughlin (2014)

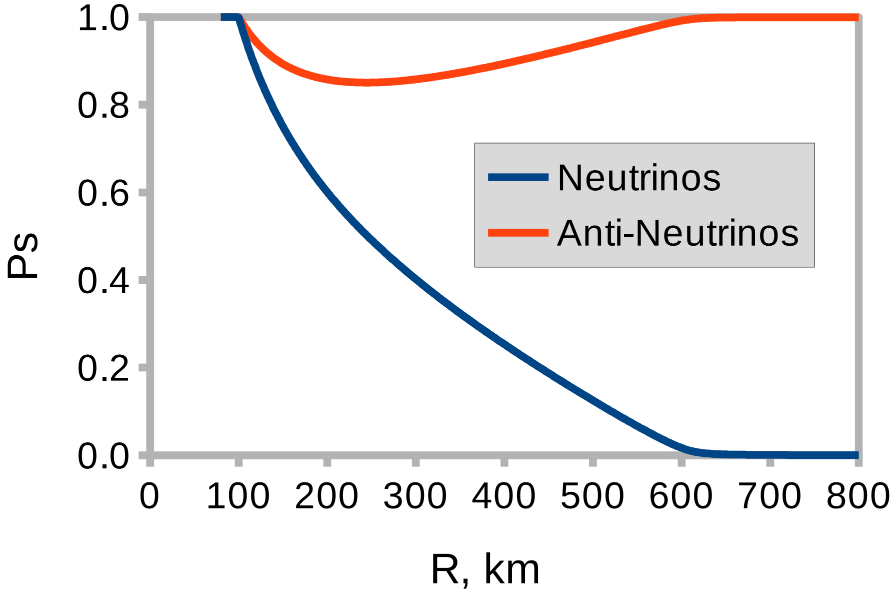
- Single-angle approximations set the flavor to be the same for all neutrino trajectories, and follow one trajectory.
- In many models of mergers and supernovae, $M \sim R^{-3}$ and $N \sim R^{-4}$ for sufficiently large R.
- For $|N|$ initially > $|M|$, with opposite sign, there is a cancellation at some value of $R = R_{MNR}$, where $N = -M$.



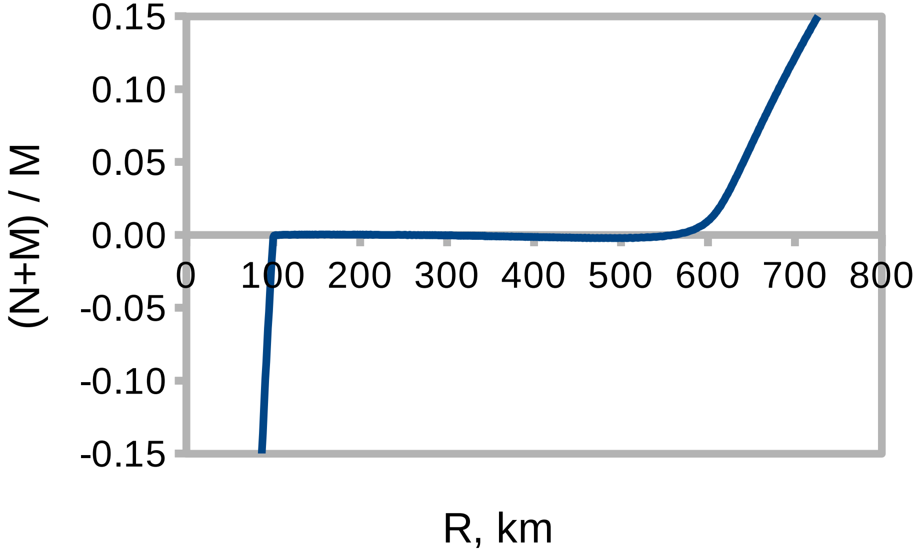
Single-Angle MNR

- In single-angle MNR, neutrinos can transform fully while anti-neutrinos return to original state
- Matter + neutrino potential remains near zero until transformation is complete

Survival Probabilities

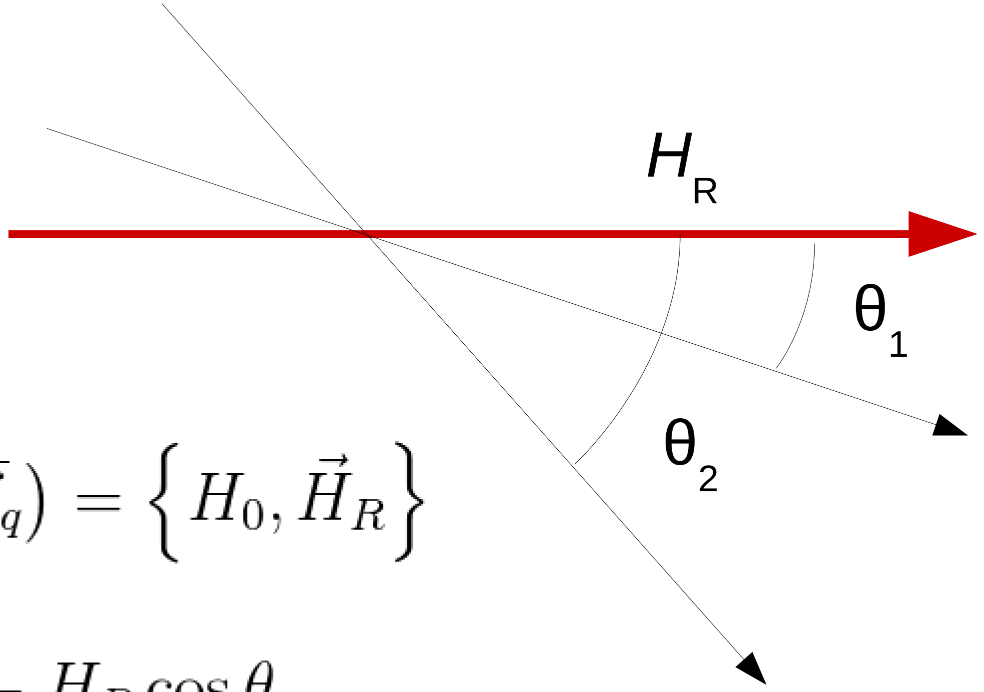


Total / Matter Potential



Multi-Angle MNR

- In a non-isotropic system, neutrino potential depends on the propagation angle.



$$H_\mu \propto \int \tilde{d}q\, q_\mu \left(f_q - \bar{f}_q\right) = \left\{H_0, \vec{H}_R\right\}$$

$$N = k^\mu H_\mu / E = H_0 - H_R \cos\theta$$

In this illustration, $N_1 < N_2$

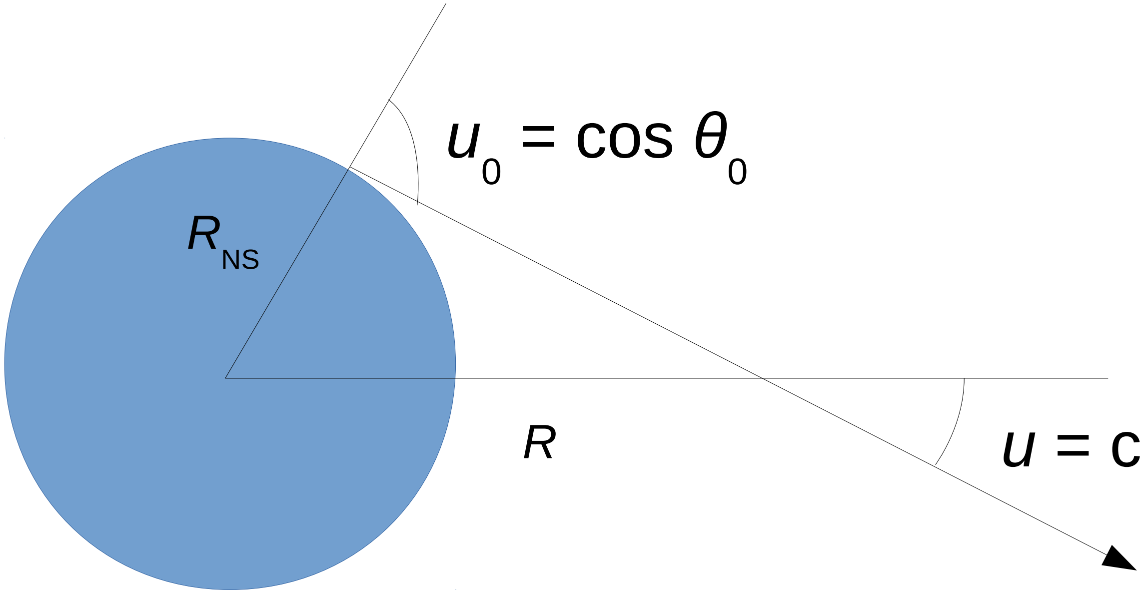
Multi-Angle MNR

- The location of the MNR depends on the value of *N*.
- **Neutrinos on different trajectories cross the MNR at different locations.**
- Because the MNR is spread out over a wide region, multi-angle models with MNR can be expected to behave very differently than single-angle models.
- Example of multi-angle models:
  - Beam of neutrinos with a nonzero opening angle (Shalgar 2017)
  - Spherical bulb model (Vlasenko, McLaughlin)
  - “Realistic” merger geometry, with cylindrical or no symmetry (very computationally expensive).

The Spherical Bulb Model

- We use the simplest self-consistent model: single-energy spherical bulb with two flavors.
- This model captures the key feature of multi-angle MNR: the position of the resonance varies for different trajectories.
- We begin with a neutrino driven wind-like model: compact central source, high entropy, relatively low matter density proportional to R^{-3}.
- Some of these assumptions are relaxed later.

Spherical Bulb Geometry

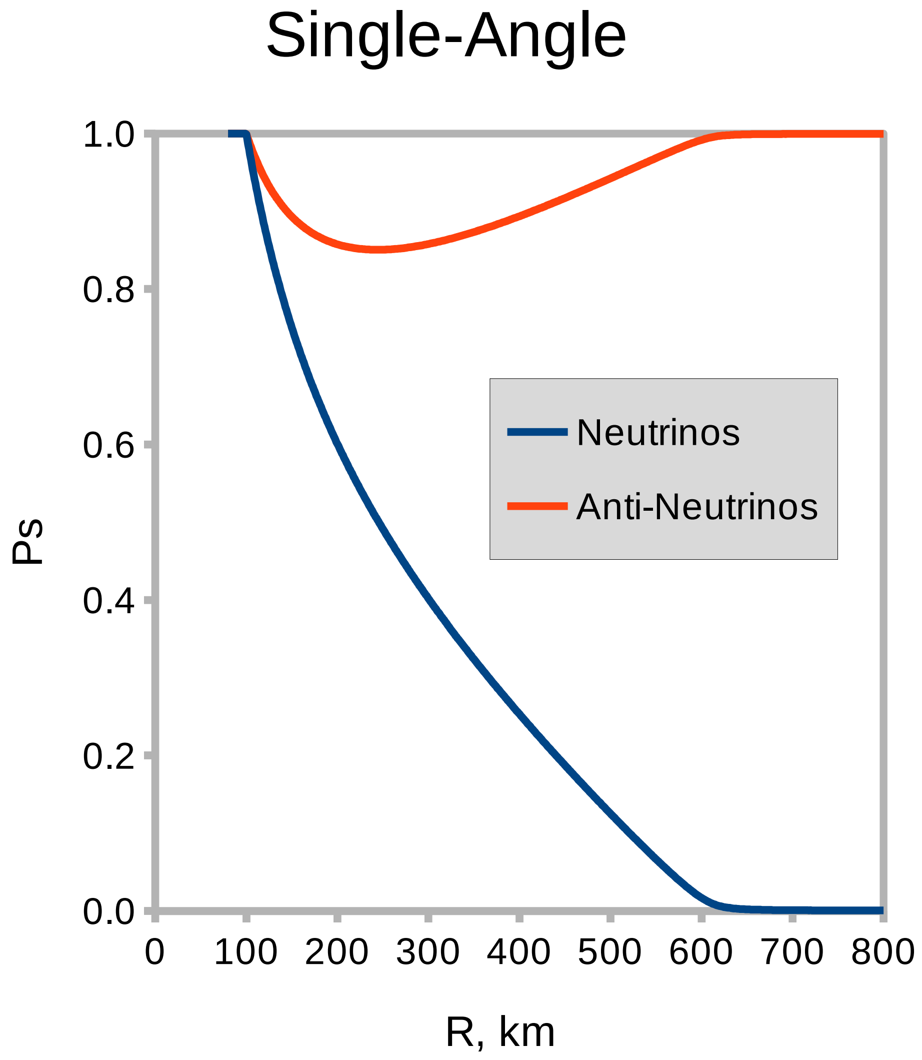


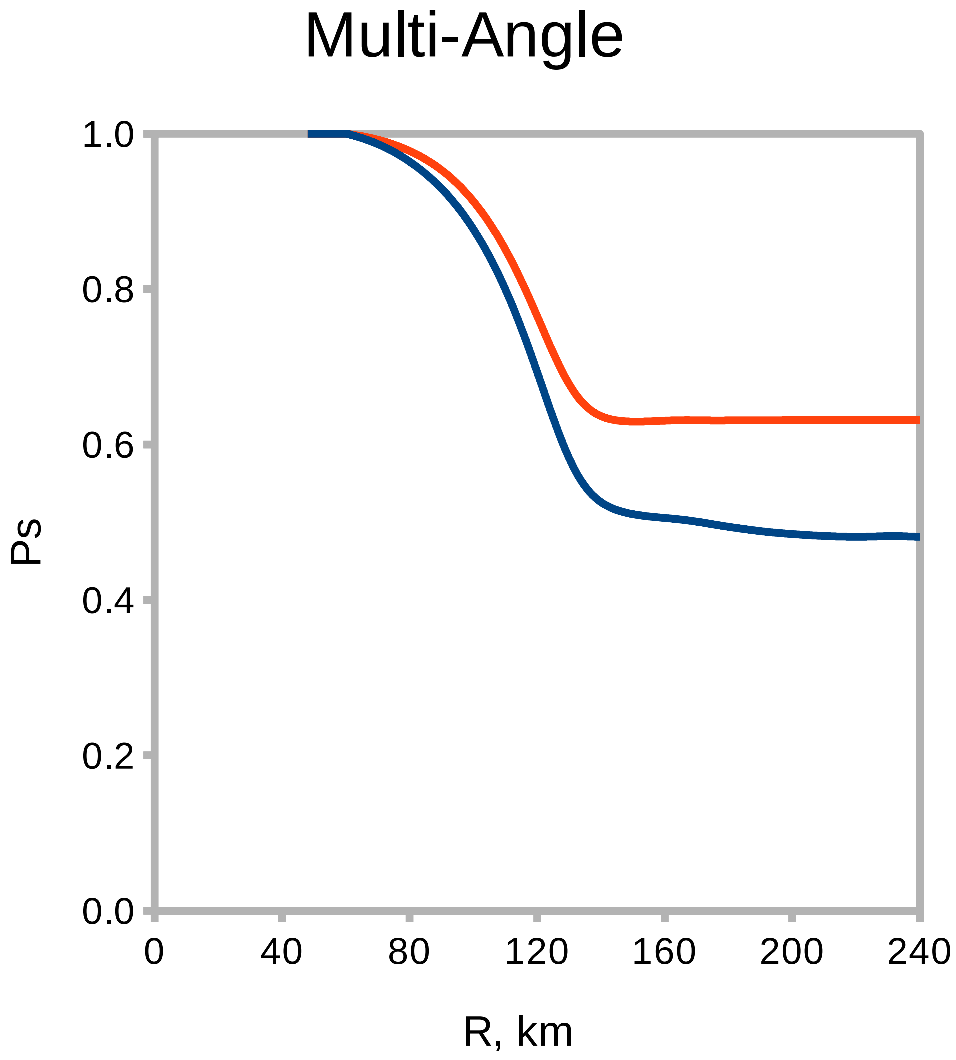
$$M = \sqrt{2} G_F Y_e n_B \propto Y_e R^{-3}$$
$$N = \sqrt{2} G_F \left[(n_\nu - n_{\bar{\nu}}) - u \left(\Phi_\nu - \Phi_{\bar{\nu}} \right) \right] \propto R^{-4}$$

Model Parameters

- Neutrinosphere radius R_{NS}. Neutrino flux is proportional to R^2_{NS} .
- MNR radius R_{MNR} . Here, defined as R at which $M = N$ for radially emitted neutrinos ($u_0 = 1$).
- Ratio of anti-neutrino to neutrino contribution to potential, α. For MNR models, $\alpha > 1$.
- Vacuum mixing angle, mass hierarchy, etc.
- For benchmark model, choose $R_{NS} = 15$ km, $R_{MNR} = 60$ km, $\alpha = 1.4$, normal hierarchy, θ_{13}

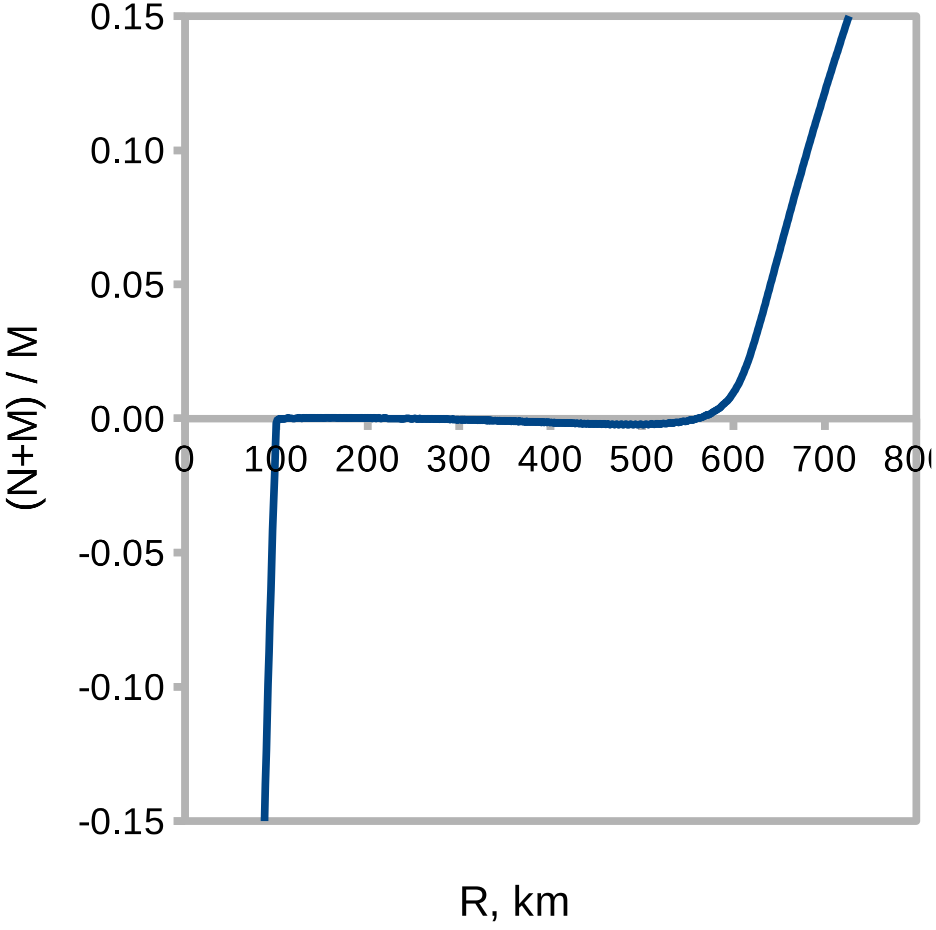
Single-Angle vs. Spherical Bulb: Survival Probabilities


Single-Angle

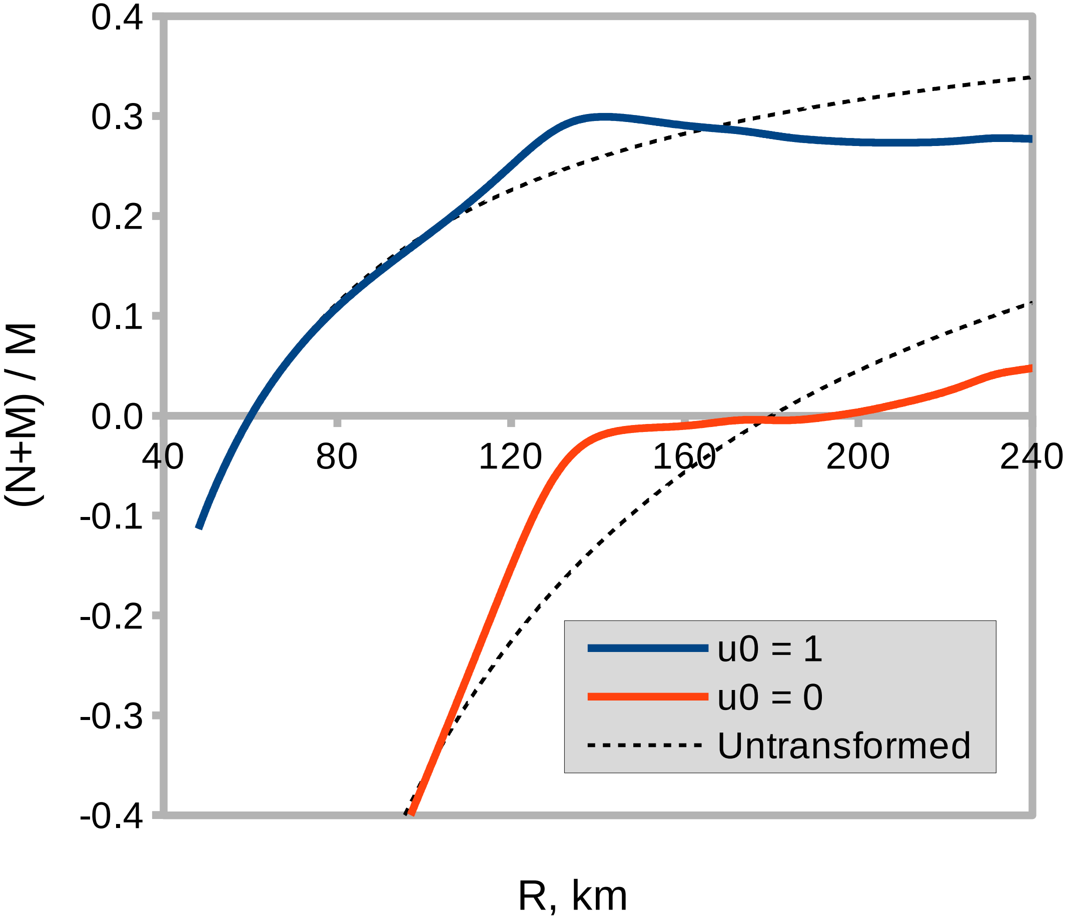

Multi-Angle

Single-Angle vs. Spherical Bulb: Total Potential

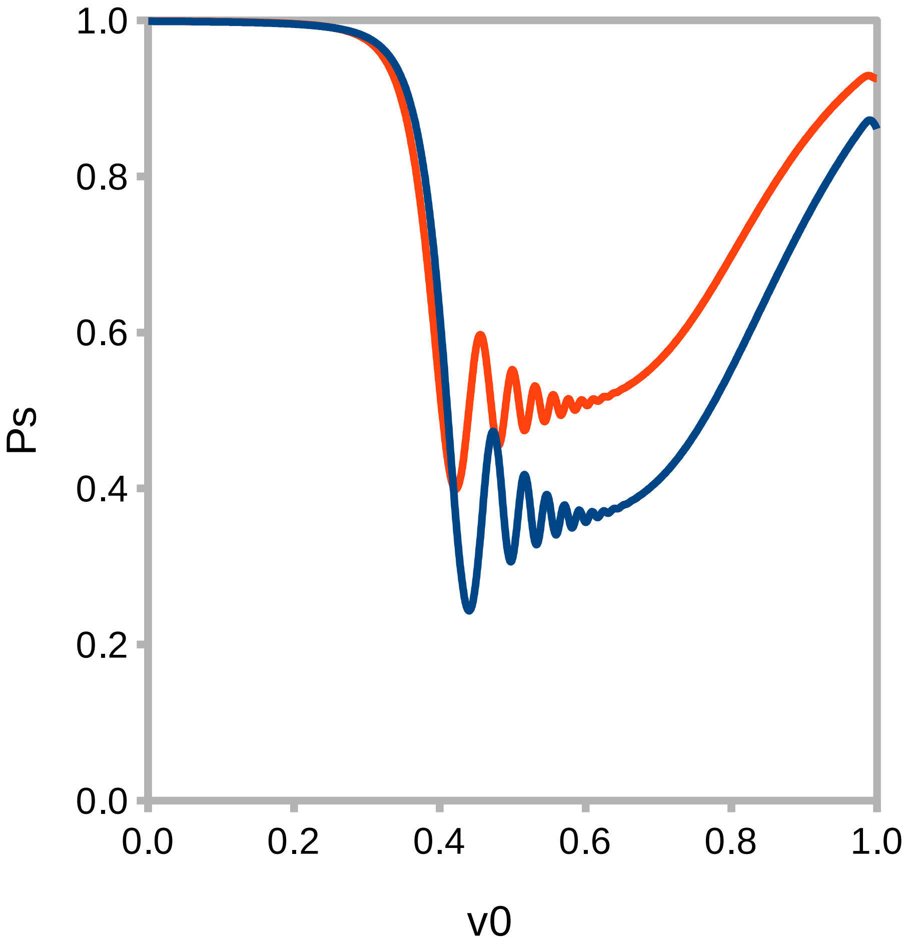
Single-Angle

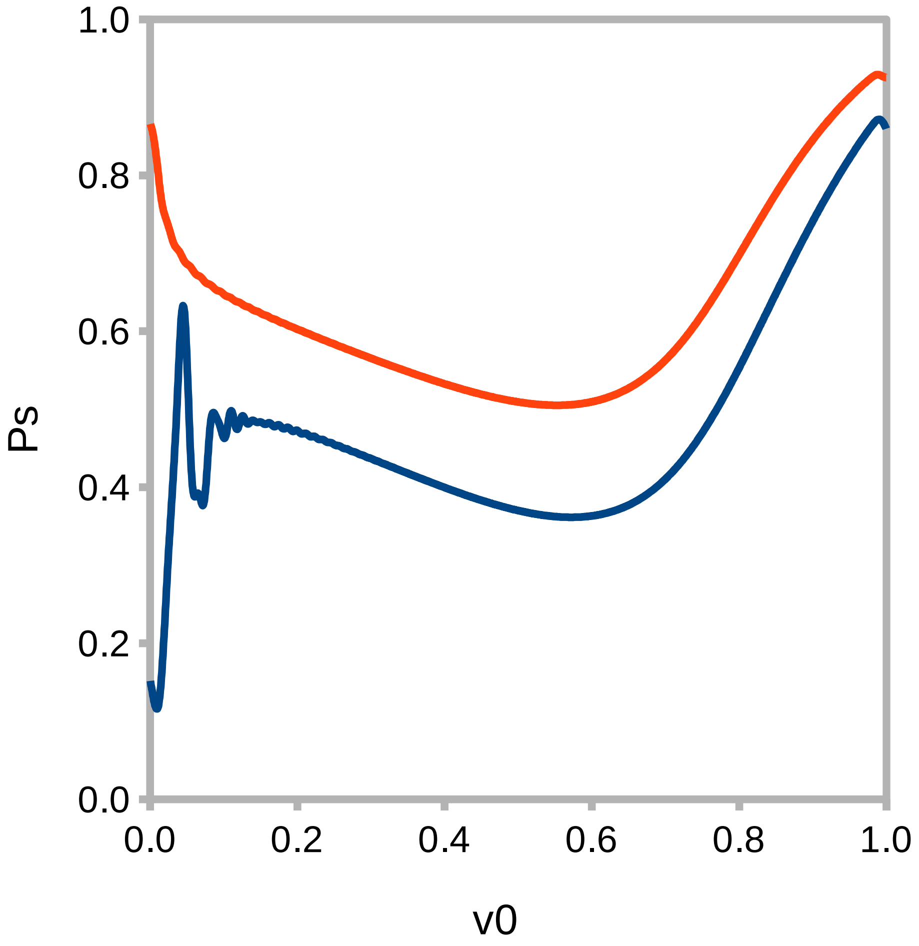


Multi-Angle



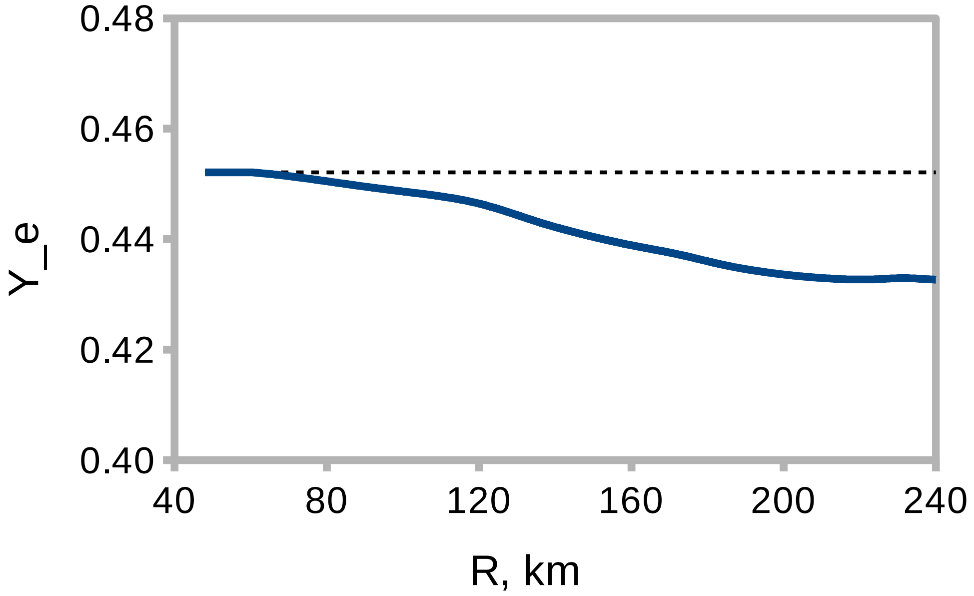
Survival Probabilities as Function of Emission Angle


Survival Probabilities, R = 120 km


Survival Probabilities, R = 240 km

Effect on Matter Composition

Assumptions: neutrons & protons in equilibrium with neutrinos, neglect electron capture

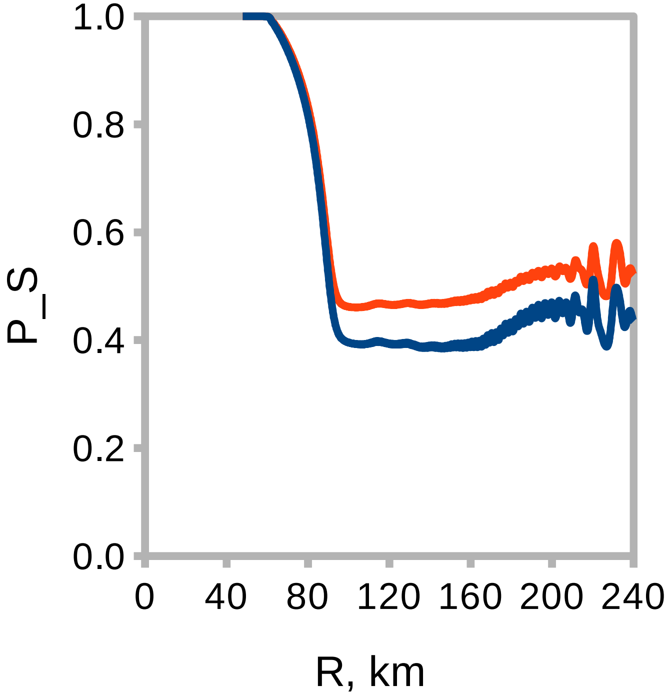


- MNR results in a modest Y_e decrease (~ few percent).
- Not as much of an effect as in single-angle calculations.
- However, even a modest decrease of Y_e can have large effects on nucleosynthesis, particularly near Y_e ~ 0.4 and high entropy.

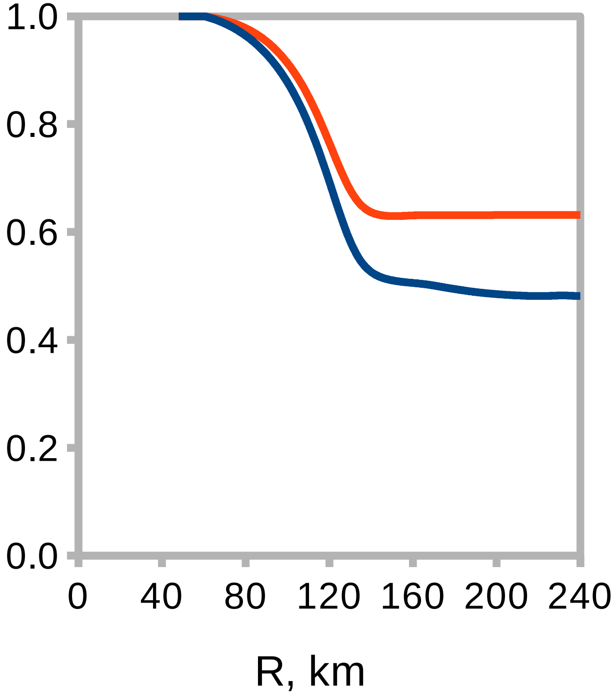
Sensitivity to Model Parameters

Anti-neutrino to neutrino ratio (α)

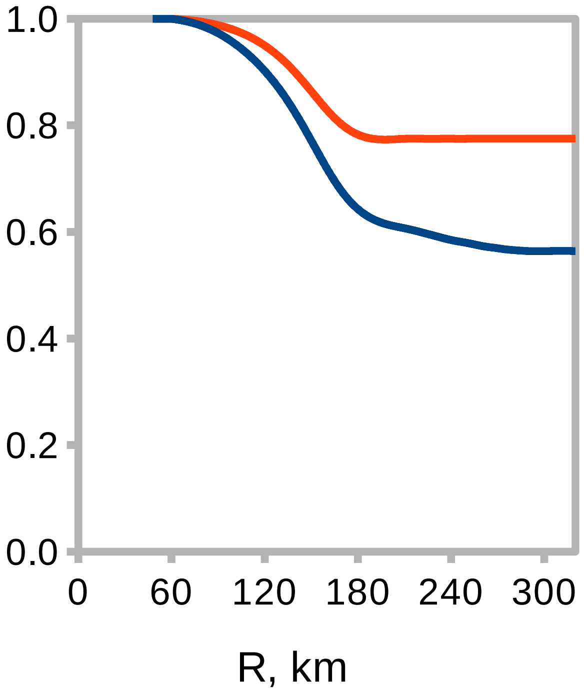
R_{NS} = 15 km, R_{MNR} = 60 km



α = 1.2



α = 1.4



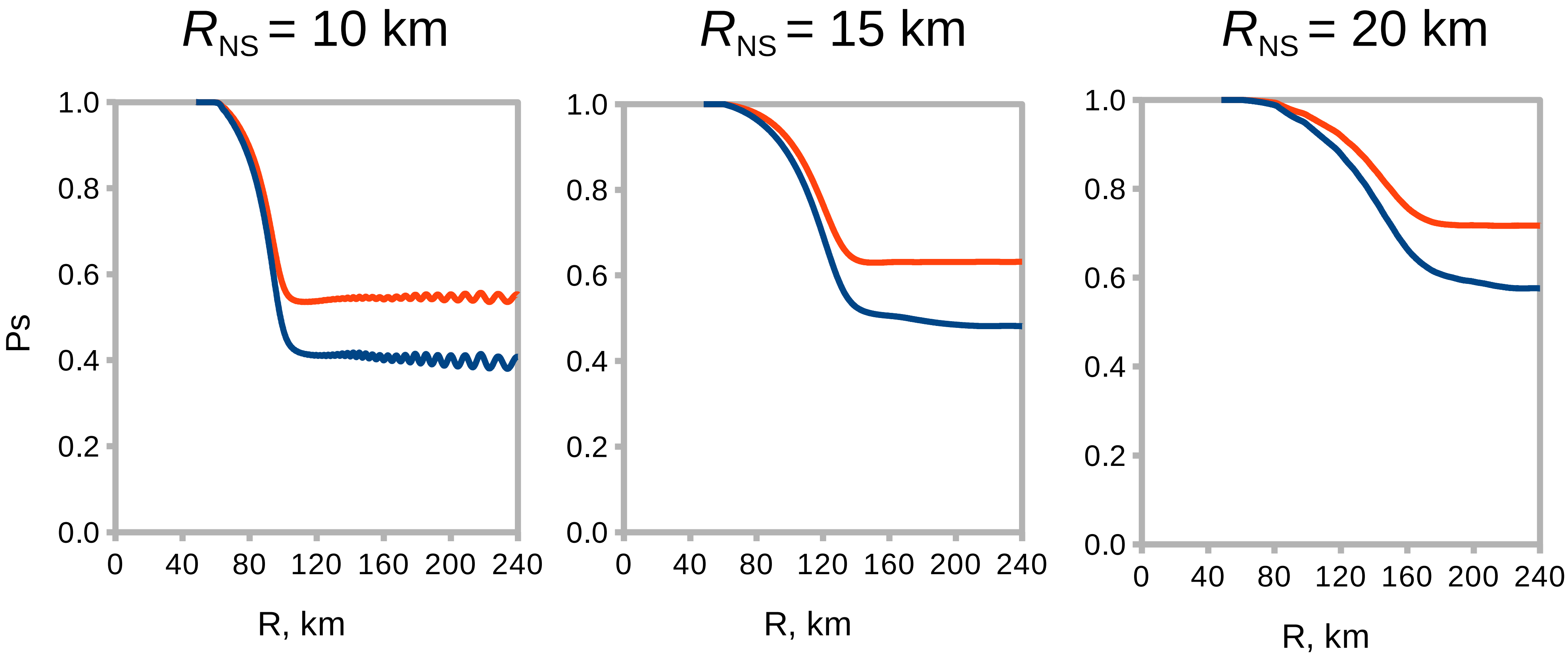
α = 1.6

Larger values of α lead to greater difference between neutrino and anti-neutrino flavor transformation.

Sensitivity to Model Parameters

Neutrinosphere radius

$\alpha = 1.4$, $R_{MNR} = 60$ km



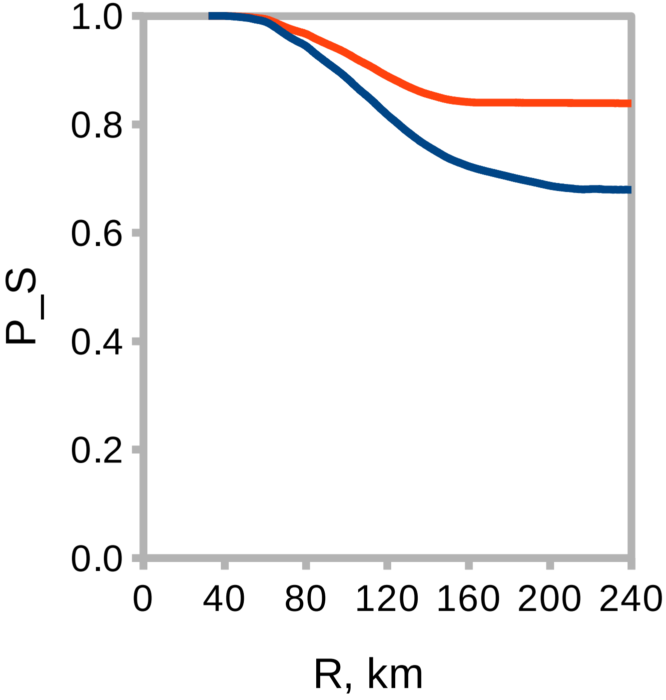
Large neutrinosphere radius (and large neutrino flux) slightly suppresses flavor transformation

Sensitivity to Model Parameters

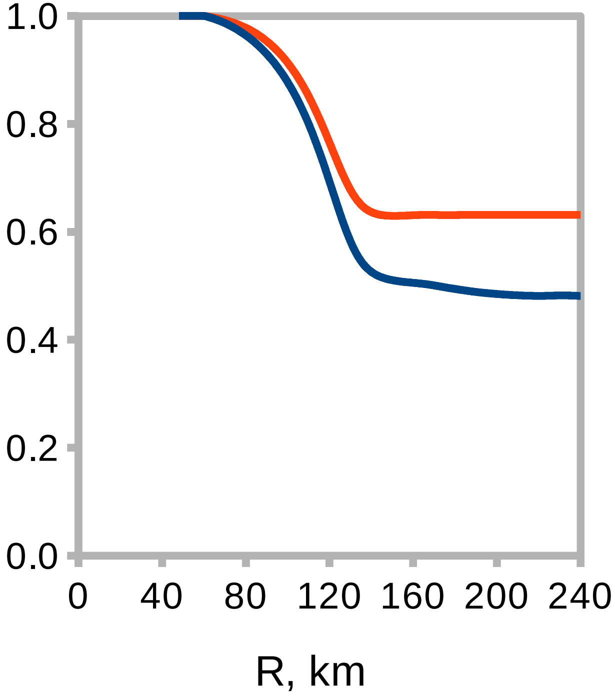
MNR radius

$\alpha = 1.4$, $R_{NS} = 15$ km

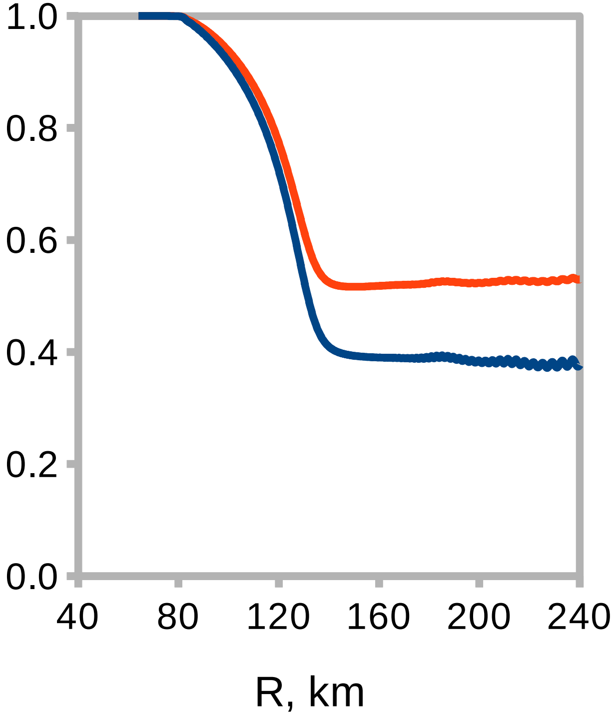
$R_{MNR} = 40$ km



$R_{MNR} = 60$ km



$R_{MNR} = 80$ km

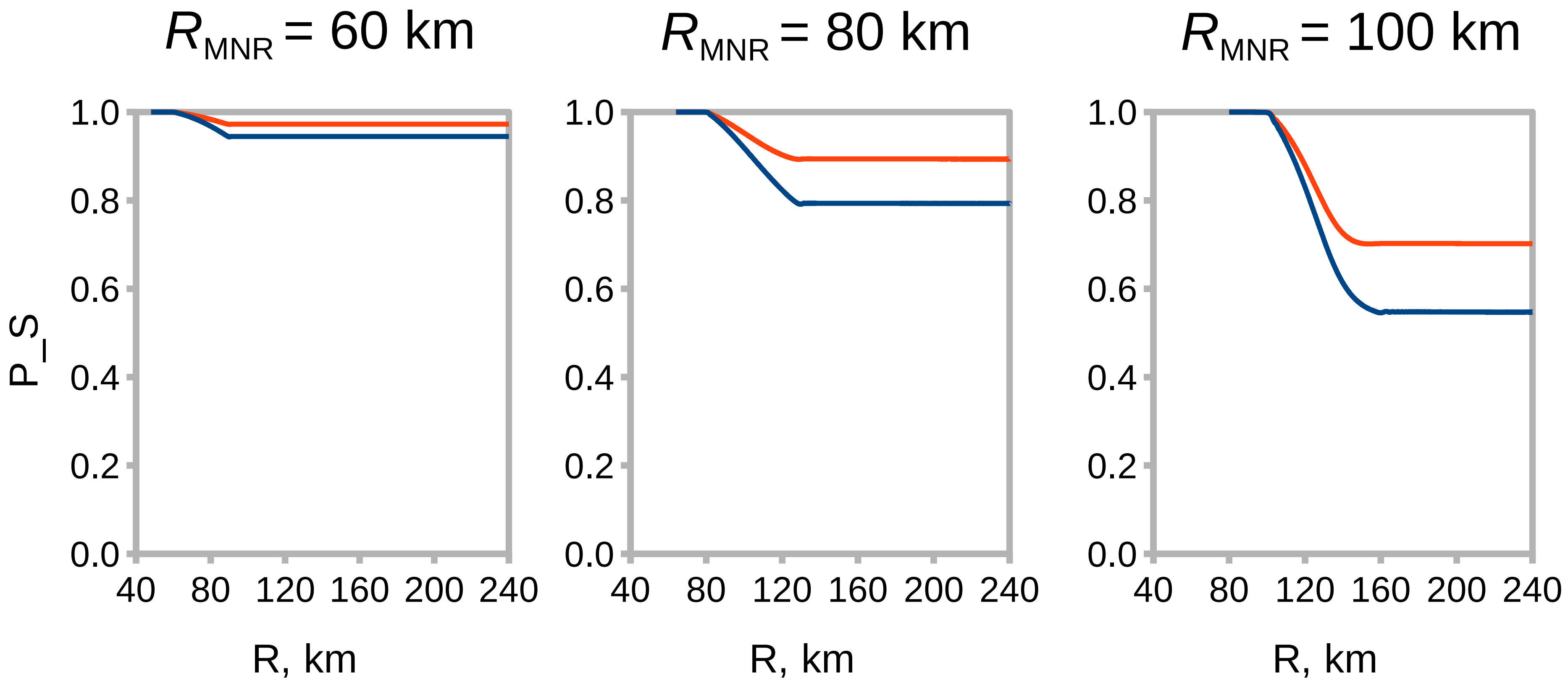


Larger MNR radius enhances flavor transformation

Sensitivity to Model Parameters

Shallow Density Profile ($M \sim R^{-1}$ instead of R^{-3})

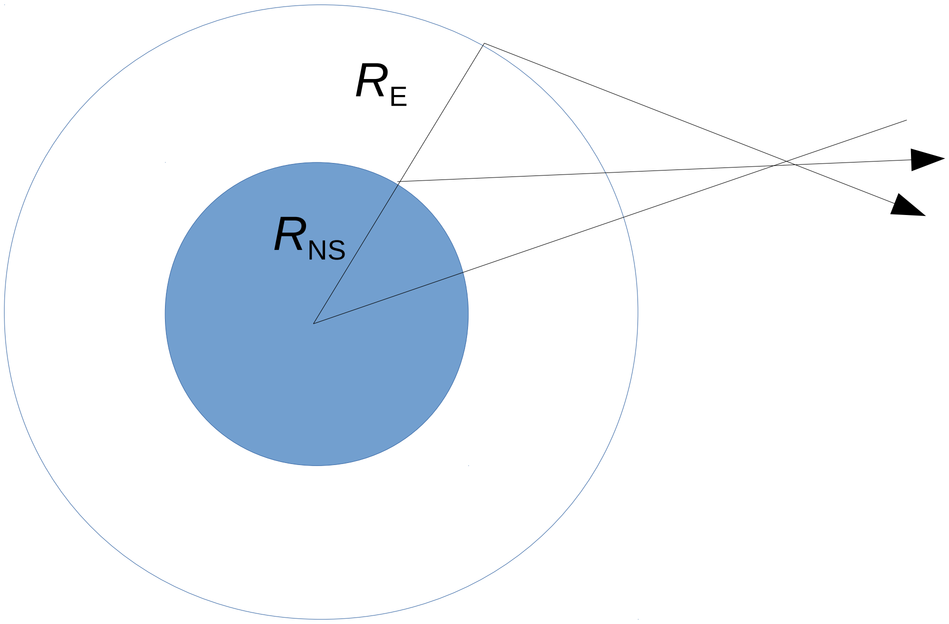
$\alpha = 1.4$, $R_{NS} = 15$ km

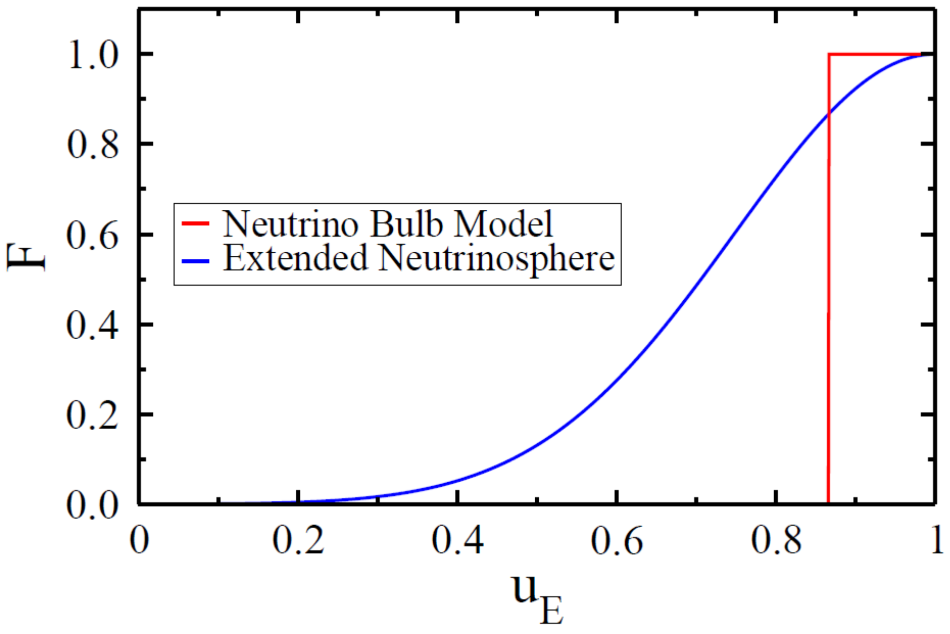


Shallow matter density profile suppresses MNR, but flavor transformation is restored for larger R_{MNR}.

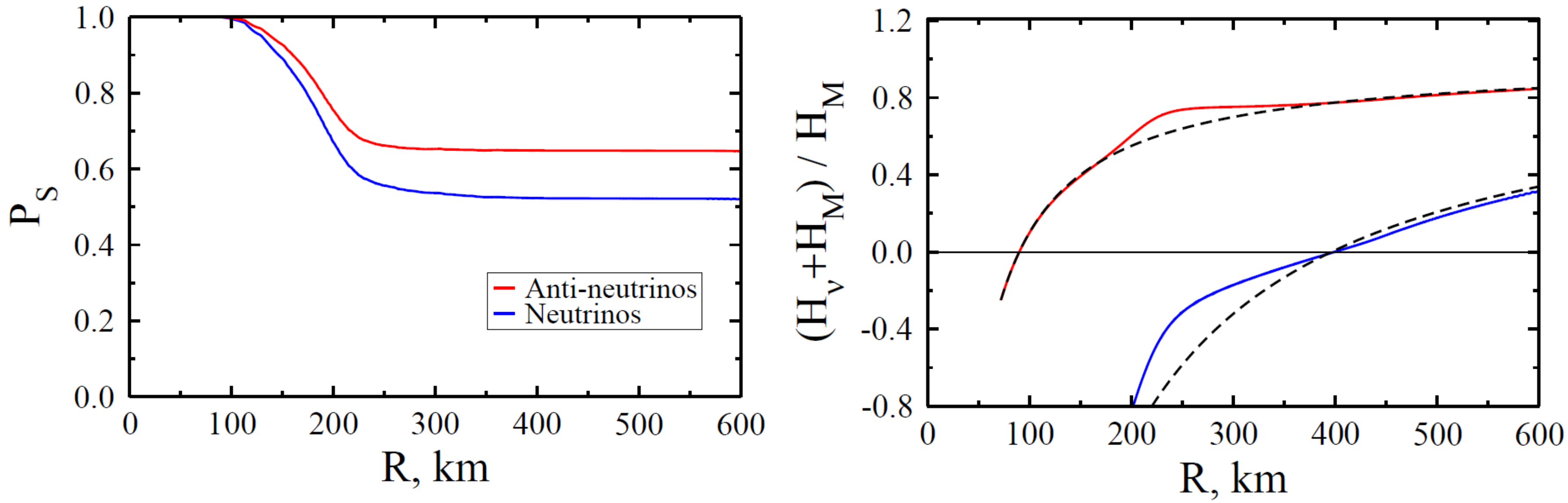
Extended Neutrinosphere Model

- In a compact object merger, a significant fraction of neutrinos (~50%) come from sources outside the neutrinosphere (the accretion disk and the scattered halo).
- These extra neutrinos contribute disproportionately to *N*.
- We can model this by extending the initial radius from R_{NS} to $R_E > R_{NS}$, and adding neutrinos on shallower trajectories:





Extended Neutrinosphere Model



- Pattern of flavor transformation very similar to bulb model, but MNR takes longer (note the horizontal scale).
- This is because the “tail” of the neutrino distribution at large emission angles takes a long time to pass through resonance.

Conclusion

We examined multi-angle MNR in a spherical bulb model and found that:

- A new type of neutrino flavor transformation occurs with MNR in multi-flavor calculations.
- This type of flavor transformation is qualitatively different from that seen in single-angle calculations.
- Neutrinos and anti-neutrinos transform differently, altering proton-neutron ratio and possibly affecting nucleosynthesis.
- The results are robust, remaining qualitatively similar under a wide variety of physical conditions.
- Therefore, neutrino flavor transformation due to MNR is likely to be important in compact object mergers.