SLAC NATIONAL ACCELERATOR LABORATORY

Neutrino Flavor Conversion in Dense Astrophysical Environments

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Presentation outline

The presentation is organized as follows:

- **Part I:** Introduction
- **Part II:** Matter-neutrino resonances*
    - Basic questions: What are they? Where do they occur? Consequences?
    - Interesting scenarios (numerical examples)
- **Part III:** Conclusions

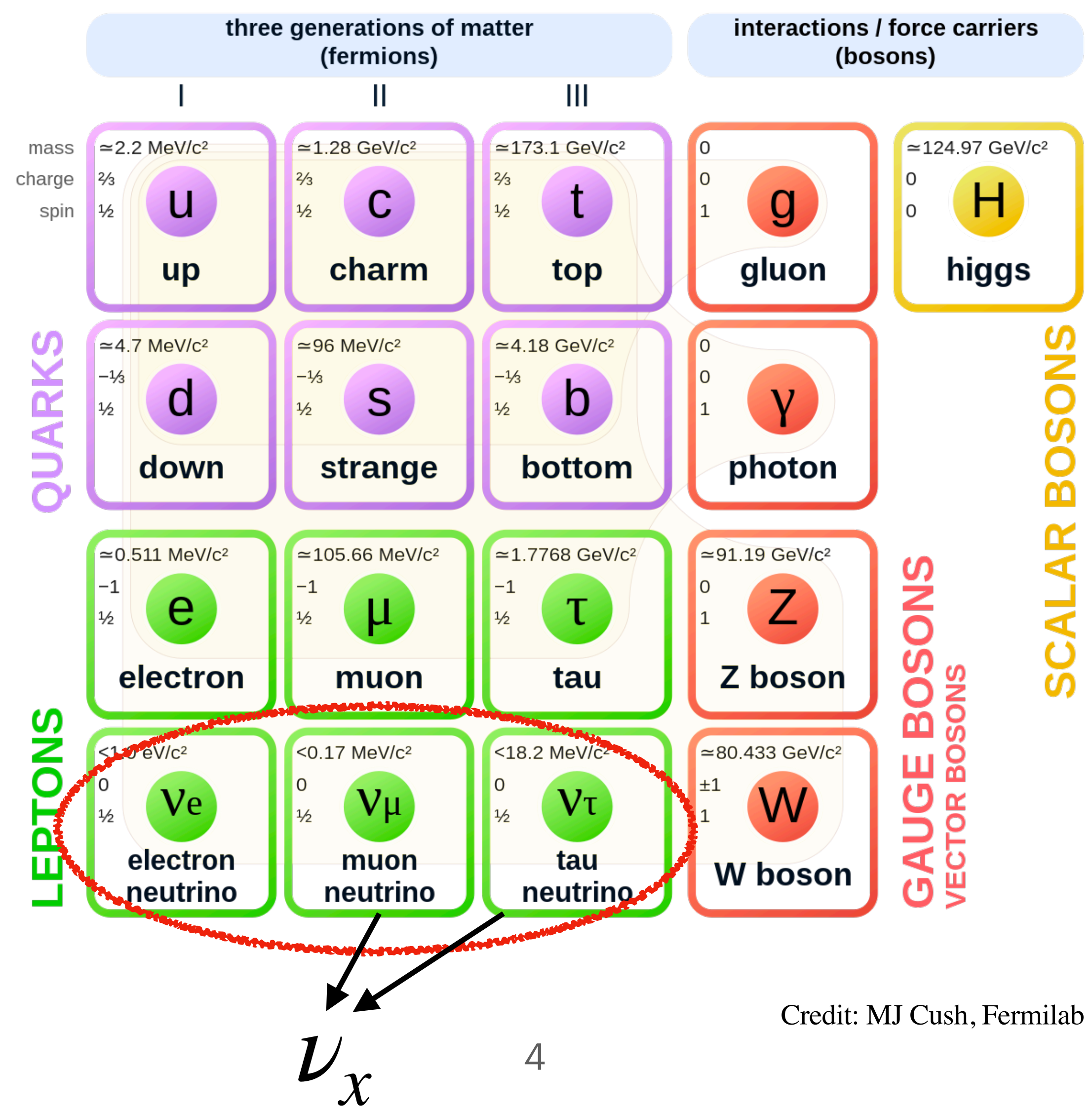
*Not to be confused with the MSW resonant effect

Part I

Introduction

Neutrinos are fun

- Neutrinos are neutral fermions (spin 1/2)
- Tiny masses and weak coupling to matter
- Three families of neutrinos



Credit: MJ Cush, Fermilab

Neutrino oscillations in vacuum

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha j} |\nu_j\rangle$$

Mass eigenstate

Flavor eigenstate

Lepton mixing matrix (PMNS)

Mass eigenstates evolve with different phases → neutrino oscillations

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Mass eigenstate

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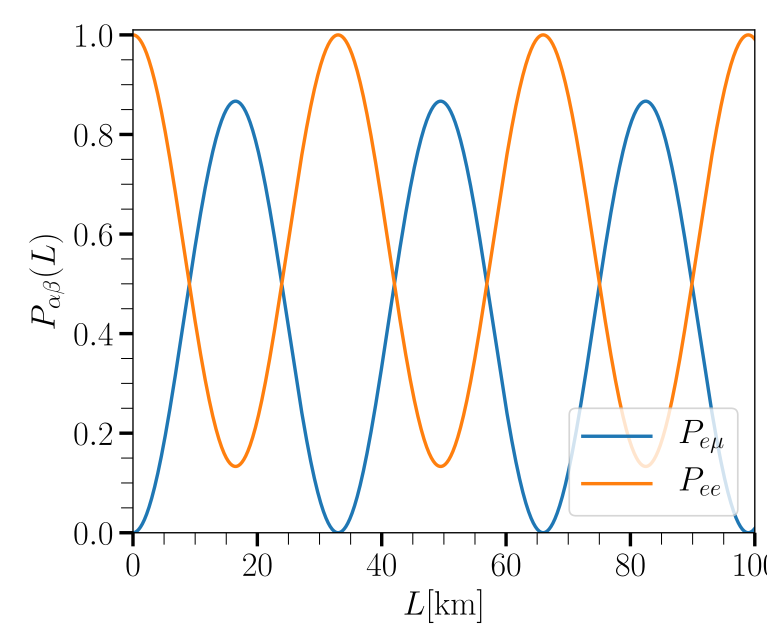
Transition probability
(two-flavor)

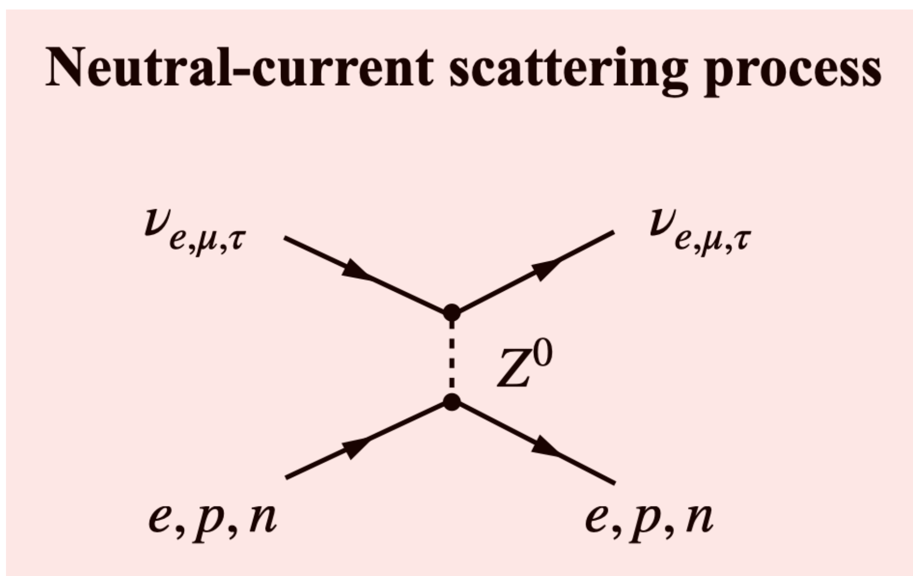
amplitude **frequency**

$$P_{e\mu}(L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

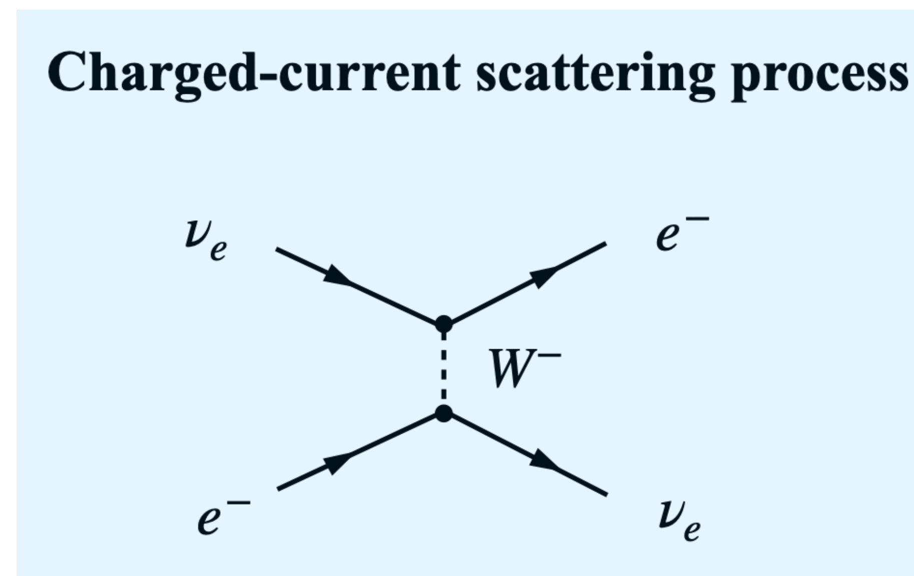


Neutrino oscillations in matter

- Matter background (e, p, n) modify how neutrinos oscillate inside the astrophysical source



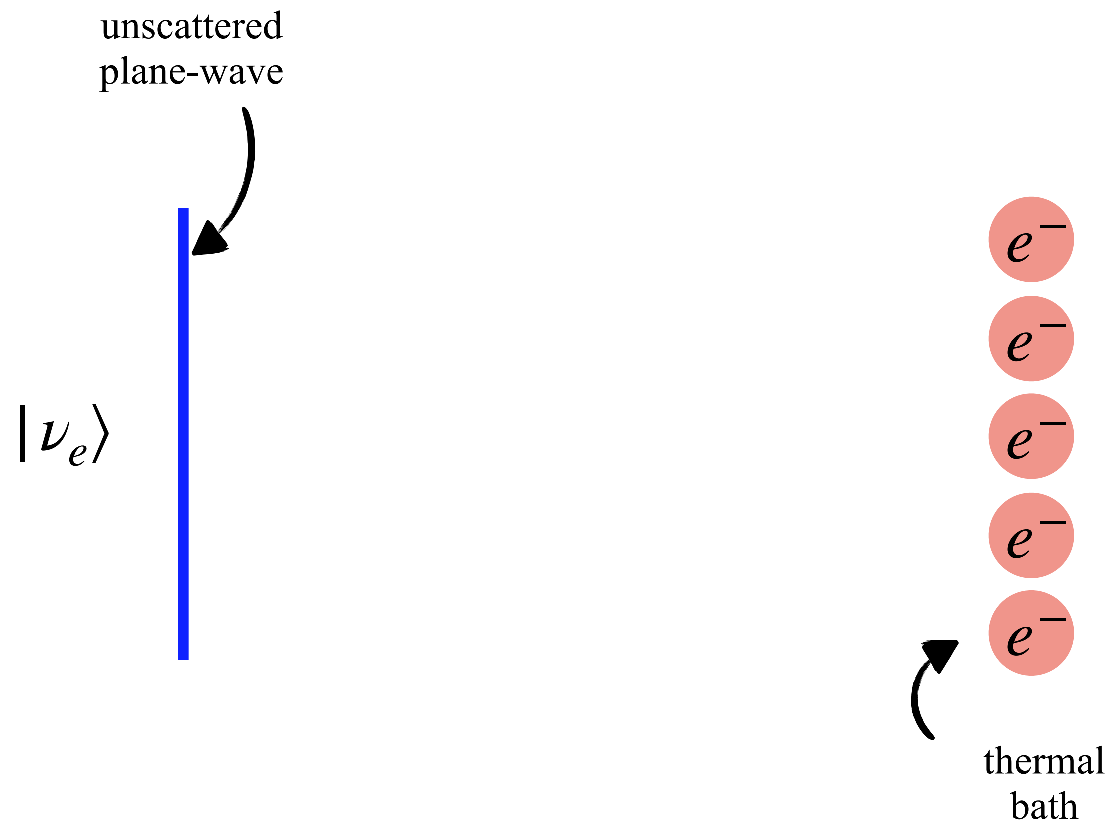
(Not observable, overall phase)



(Observable)

- Neutrinos undergo *coherent forward scattering* with particles in the background

Neutrino oscillations in matter



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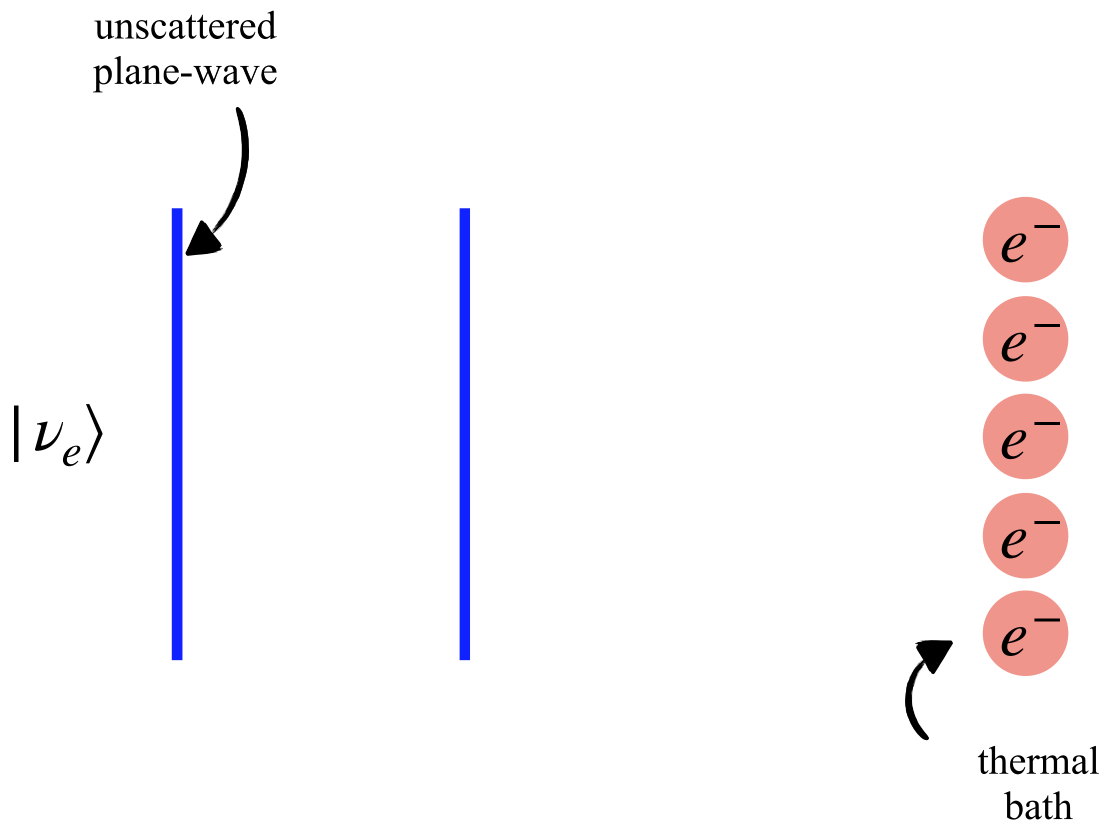

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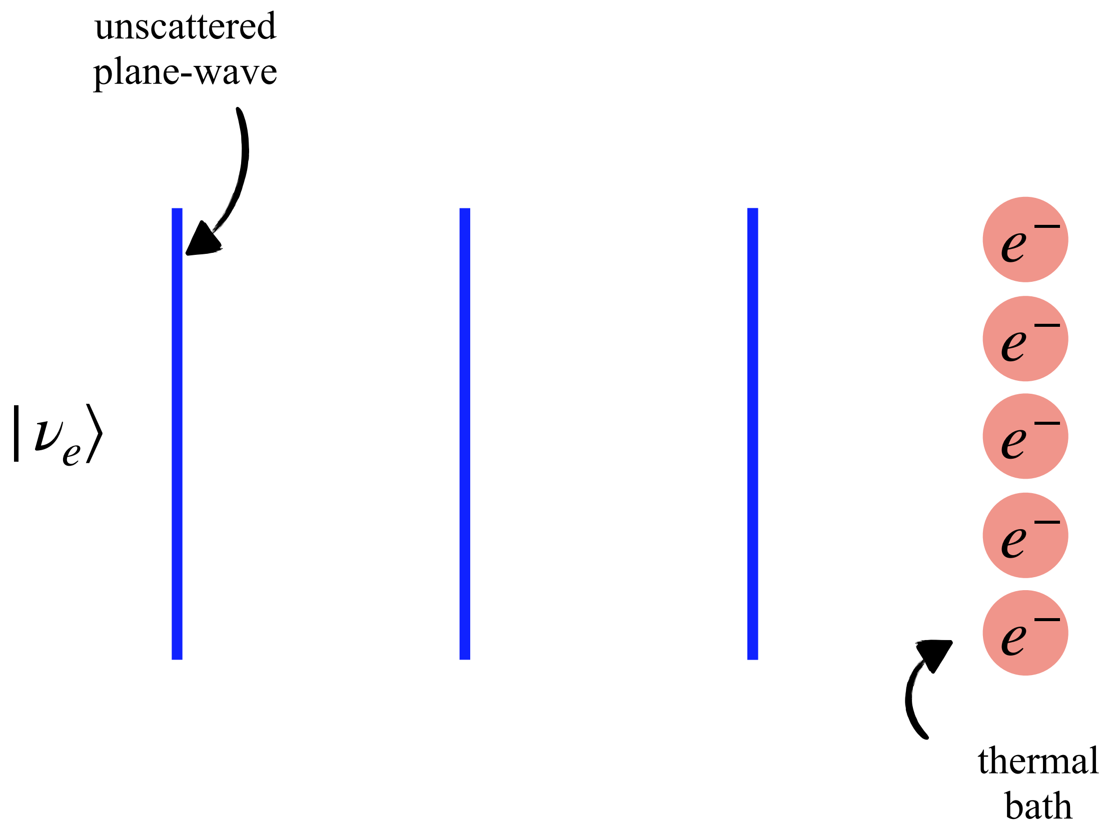

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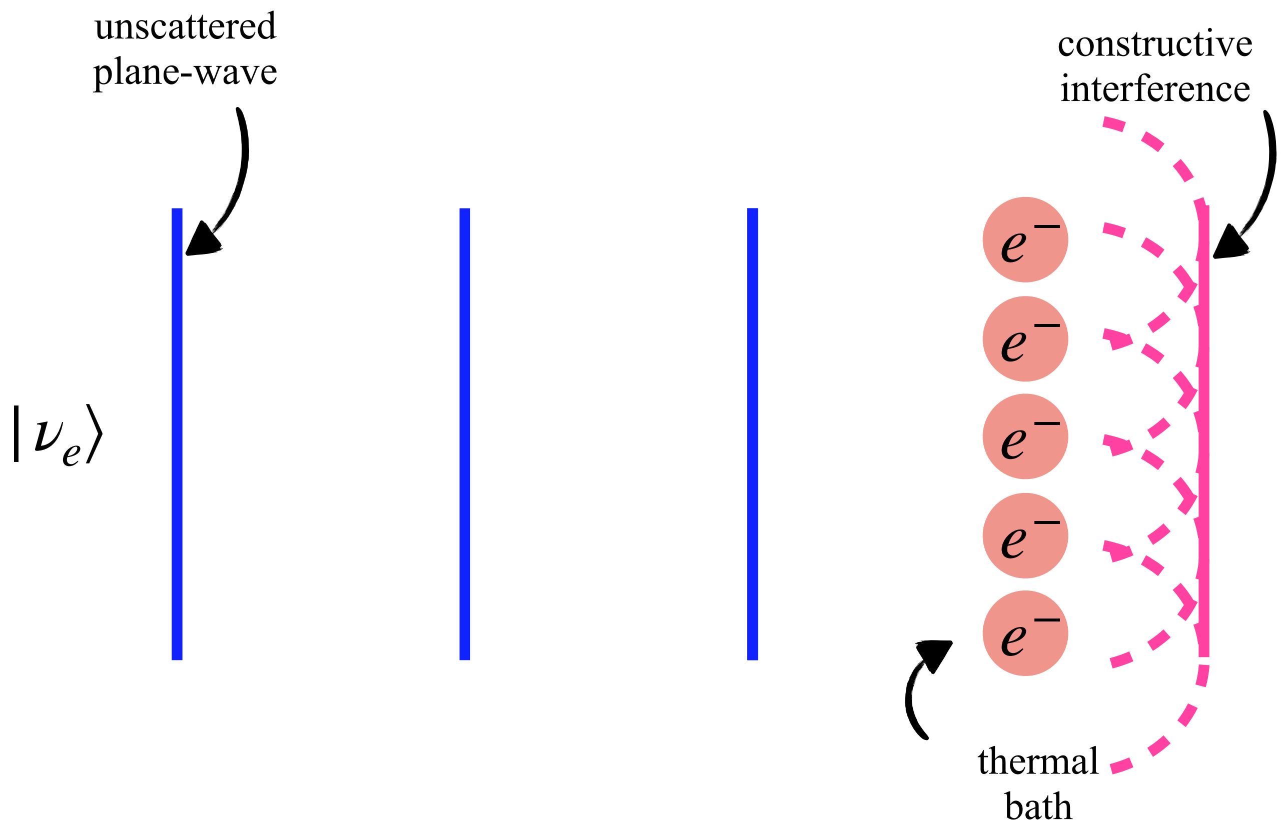
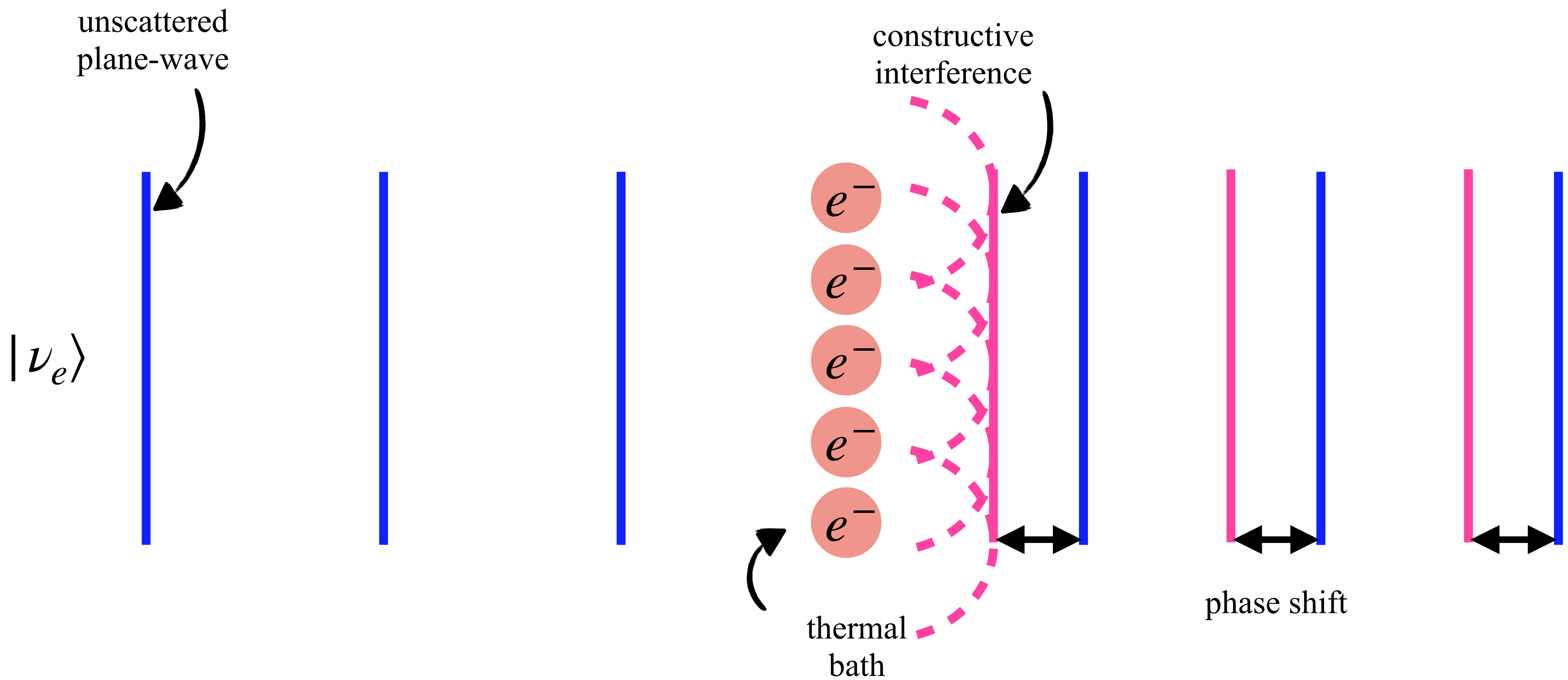


Neutrino oscillations in matter



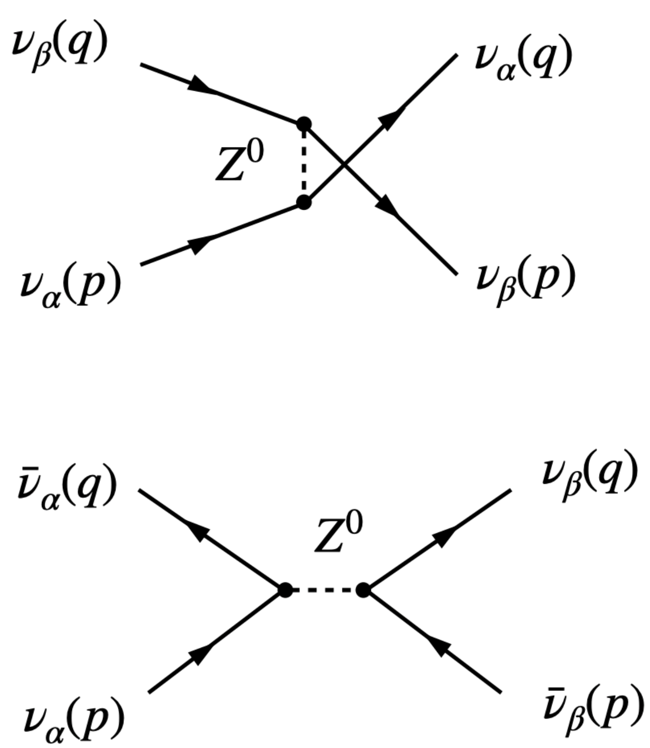
- Phase shift → Mikheyev-Smirnov-Wolfenstein (MSW) resonant effect[1,2]
- Neutrinos experience a potential $V_{CC} = \sqrt{2}G_F n_e$ (refraction)

[1]Neutrino Oscillations in Matter, Wolfenstein, Phys. Rev. D 17, 2369 (1978)

[2]Resonant amplification of neutrino oscillations in matter and solar neutrino spectroscopy, Mikheev & Smirnov, Nuovo Cim.C 9 (1986) 17-26

Neutrino-neutrino interaction

- Neutrinos also constitute a background for other neutrinos
- Neutrino-neutrino interaction induces *collective oscillations*[1-5]



[1]Neutrino oscillations at high densities, Pantaleone, Physics Letters B 287 (1992) 128-132

[2]Collective Neutrino Oscillations, Duan et al, Ann. Rev. Nucl. Part. Sci. 60:569 (2010)

[3]Supernova Neutrinos: Production, Oscillations and Detection, Mirizzi et al, Rivista del Nuovo Cimento Vol. 39, N. 1-2 (2016)

[4]Collective neutrino flavor conversion: Recent developments, Chakraborty et al, 1602.02766

[5]New Developments in Flavor Evolution of a Dense Neutrino Gas, Tamborra et al, Ann. Rev. Nucl. Part. Sci. 71 (2021) 165-188

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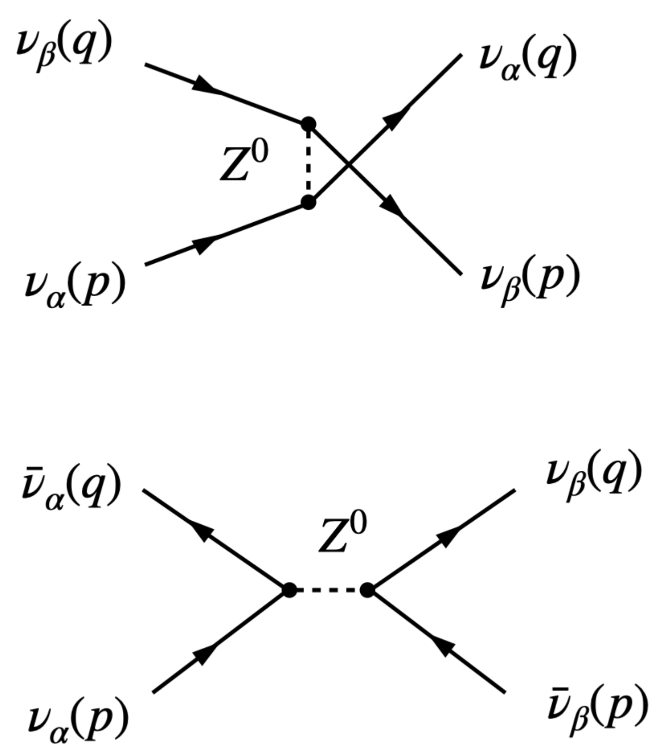
Momentum of test neutrino

$$H_{\nu\nu}(\vec{p}) = \sqrt{2} G_F n_\nu \int d\vec{q} \left[\rho(\vec{q}) - \bar{\rho}(\vec{q})\right]\left(1 - \frac{\vec{p}\cdot\vec{q}}{|\vec{p}||\vec{q}|}\right)$$

Neutrino interaction strength (“μ”)

Momentum of background neutrino

Density matrices for ν and $\bar{\nu}$



- *Non-linear* behavior of flavor evolution and *collective* conversion

[1] Neutrino oscillations at high densities, Pantaleone, Physics Letters B 287 (1992) 128-132

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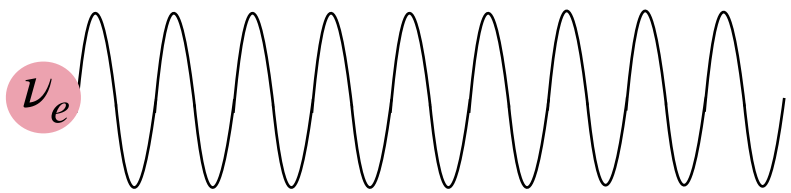
Neutrino flavor conversion

$\omega \sim \mathcal{O}(10)\ \mathrm{km}^{-1}$

- **Vacuum oscillations -** driven by Δm^2



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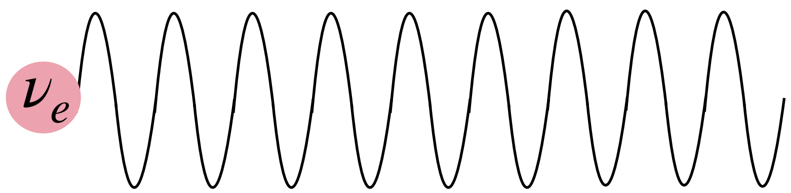
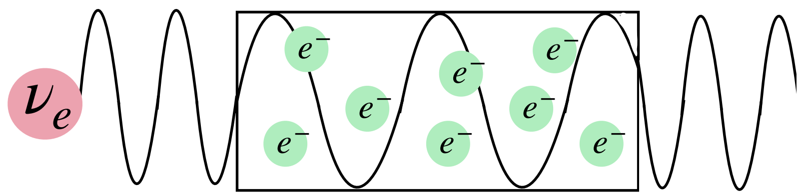


- **Neutrino-matter interaction -** coherent forward scattering with electrons (i.e. MSW effect)

$\lambda \sim \mathcal{O}(10^4)\ \mathrm{km}^{-1}$



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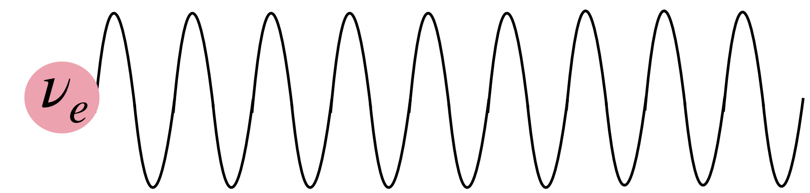

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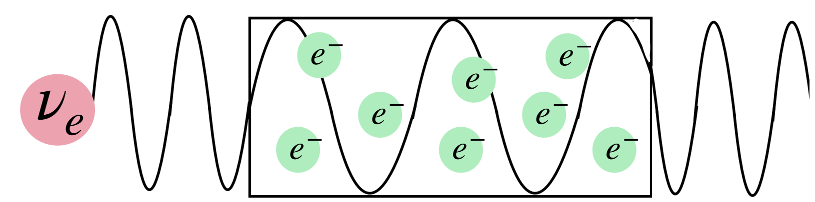
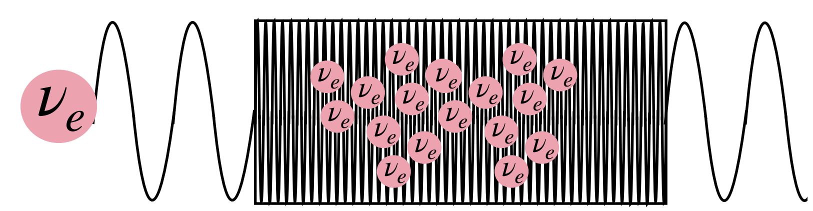
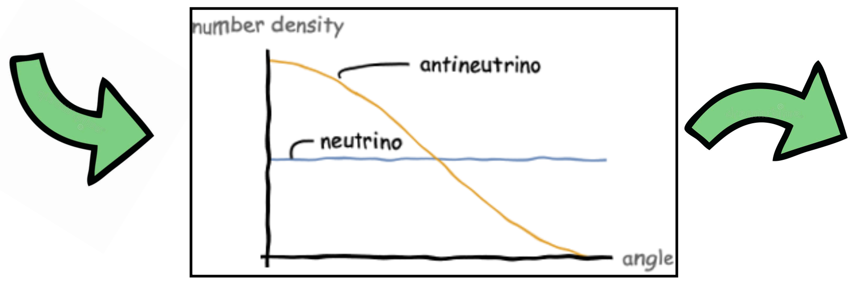


- **Neutrino-neutrino interaction —** coherent forward scattering with background neutrinos → *Collective flavor conversion*

$\mu \sim \mathcal{O}(10^5)\ \mathrm{km}^{-1}$



Key inputs: **angular distributions of ν_e and $\bar{\nu}_e$**



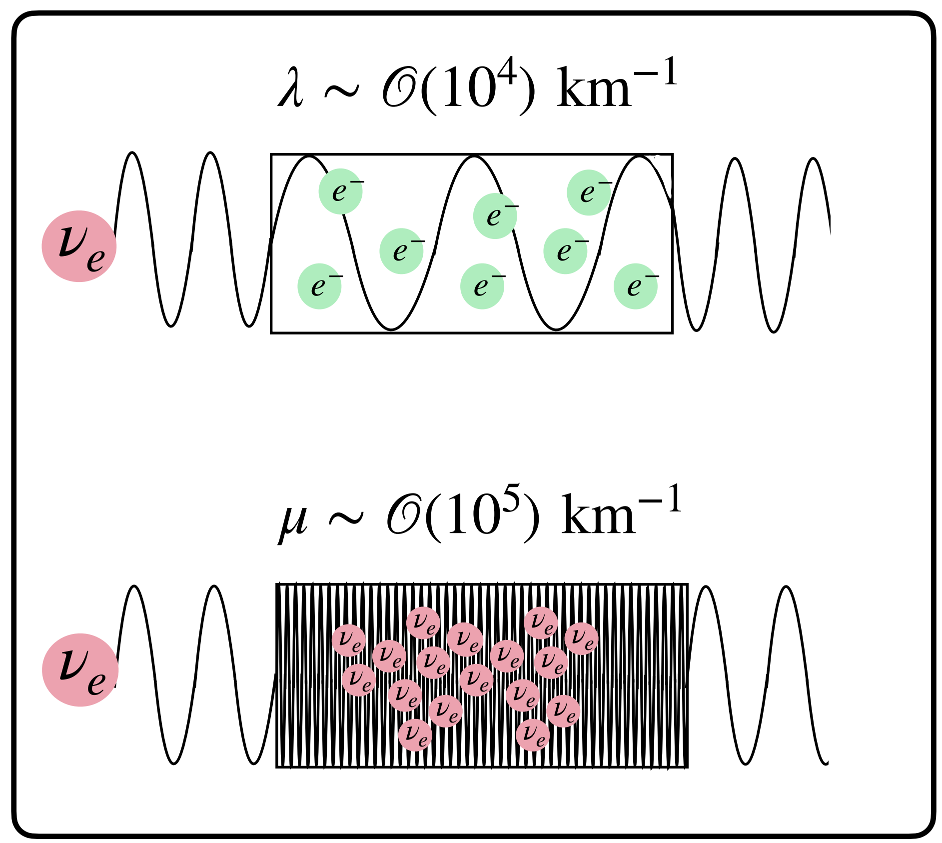
Determines the flavor dynamics

Neutrino flavor conversion

These two can interfere roughly when $\mu \sim \lambda$

Neutrino-matter interaction

Neutrino-neutrino interaction



(second part of the talk)

Collective neutrino conversion

- Neutrinos with different momenta evolve collectively
- The (mean-field) equations of motion describing neutrino flavor conversion are:

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \overrightarrow{\nabla}_x\right)\rho(\vec{x}, \vec{p}, t) =$$

$$\left(\frac{\partial}{\partial t} + \underbrace{\vec{v} \cdot \overrightarrow{\nabla}_x}_{\text{advection}}\right)\bar{\rho}(\vec{x}, \vec{p}, t) =$$

Spatial variations[1]

[1]Neutrino propagation hinders fast pairwise flavor conversions, Shalgar, **Padilla-Gay** & Tamborra, *JCAP* 06 (2020) 048

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$$\left(\frac{\partial}{\partial t} + \vec{v}\cdot\vec{\nabla}_x\right)\rho(\vec{x},\vec{p},t) = -\,i\left[H(\vec{x},\vec{p},t),\rho(\vec{x},\vec{p},t)\right]$$

$$\left(\frac{\partial}{\partial t} + \underbrace{\vec{v}\cdot\vec{\nabla}_x}_{\text{advection}}\right)\bar{\rho}(\vec{x},\vec{p},t) = -\,i\,\underbrace{\left[\bar{H}(\vec{x},\vec{p},t),\bar{\rho}(\vec{x},\vec{p},t)\right]}_{\text{refraction}}$$

Spatial variations[1] Coherent forward scattering[2]

[1]Neutrino propagation hinders fast pairwise flavor conversions, Shalgar, **Padilla-Gay** & Tamborra, *JCAP* 06 (2020) 048

[2]Neutrino Flavor Pendulum Reloaded: The Case of Fast Pairwise Conversion, **Padilla-Gay**, Tamborra & Raffelt, Phys.Rev.Lett. 128 (2022)

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Spatial variations[1] — Coherent forward scattering[2] — Non-forward scattering[3,4]

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[2]Neutrino Flavor Pendulum Reloaded: The Case of Fast Pairwise Conversion, **Padilla-Gay**, Tamborra & Raffelt, Phys.Rev.Lett. 128 (2022)

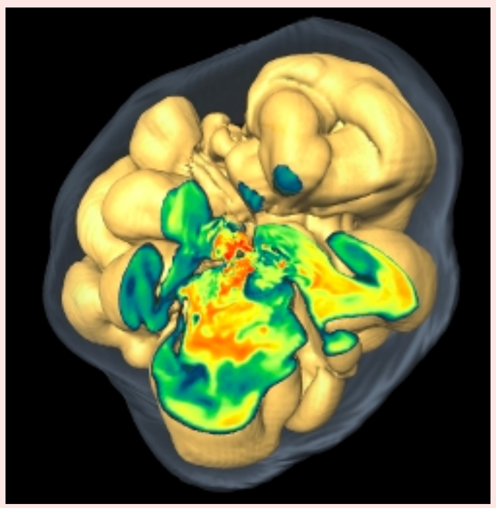
[3]Neutrino fast flavor pendulum. II. Collisional damping, **Padilla-Gay**, Tamborra & Raffelt, *Phys.Rev.D* 106 (2022) 10, 103031

[4]Collisions and collective flavor conversion: Integrating out the fast dynamics, Fiorillo, **Padilla-Gay** & Raffelt, 2312.07612

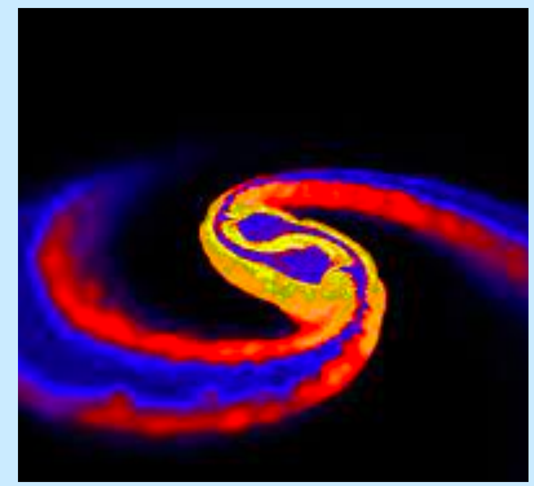
Neutrinos in dense astrophysical environments

Copiously produced ~10^{58} neutrinos (MeV)

In core-collapse supernovae:



In compact binary mergers:

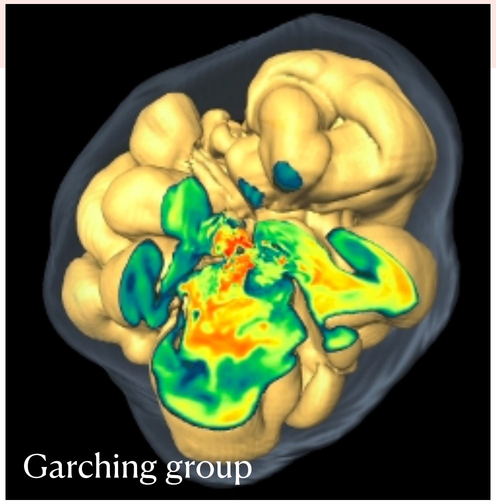


Neutrinos in dense astrophysical environments

Copiously produced $\sim 10^{58}$ neutrinos (MeV)

In core-collapse supernovae:

- Neutrinos carry 99% of the grav. energy
- Neutrinos can revive the stalled shock[1]
- More ν_e than $\bar{\nu}_e$ (neutronization burst)[2]



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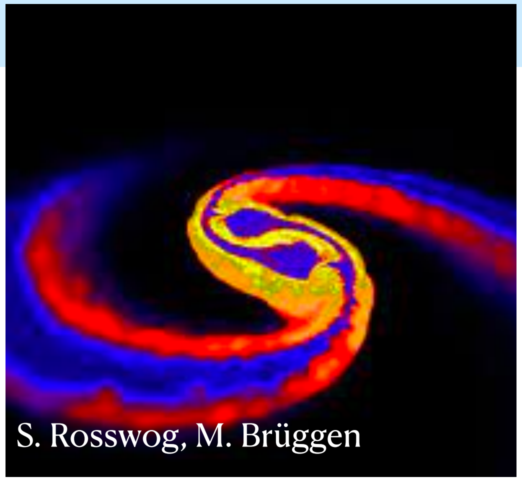

[1] Revival of a stalled supernova shock by neutrino heating, Bethe & Wilson, Astrophysical Journal, 1985, p. 14-23.
[2] Theory of Core-Collapse Supernovae, Janka et al, Phys.Rept.442:38-74, 2007

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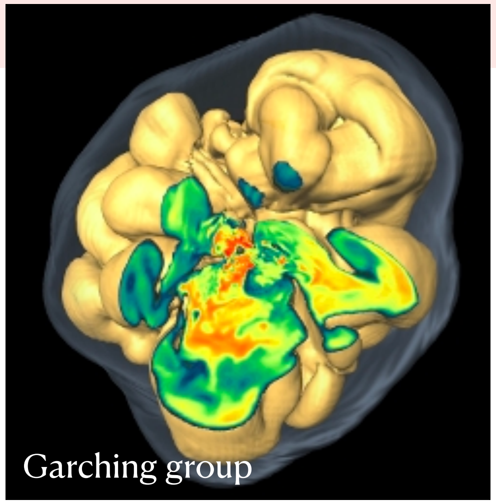
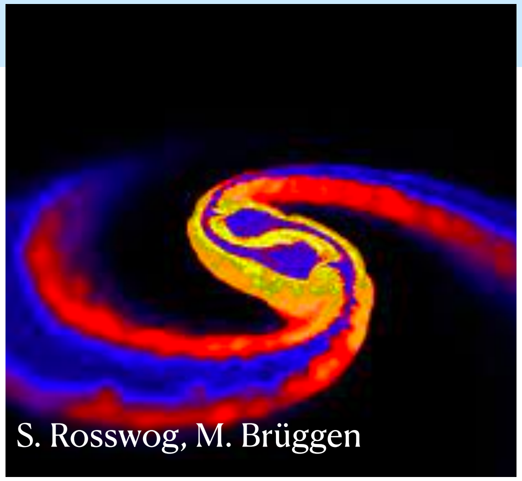
- Neutrinos cool the disk
- Neutrinos dominate the ejecta in polar region
- More $\bar{\nu}_e$ than ν_e (n-rich, merger protonizes)[3]





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[3]Coalescing neutron stars, Ruffert, Janka & Takahashi, Astronomy and Astrophysics, v.319, p.122-153

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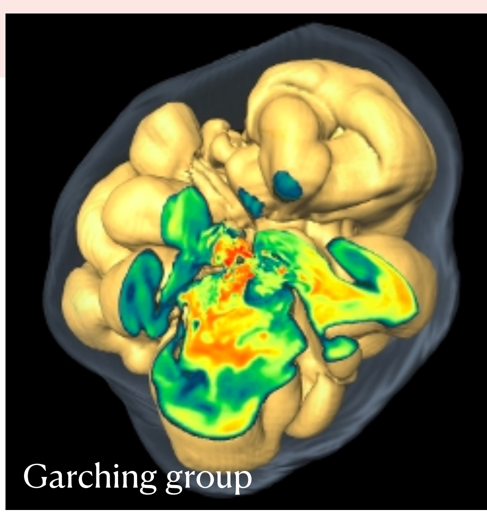
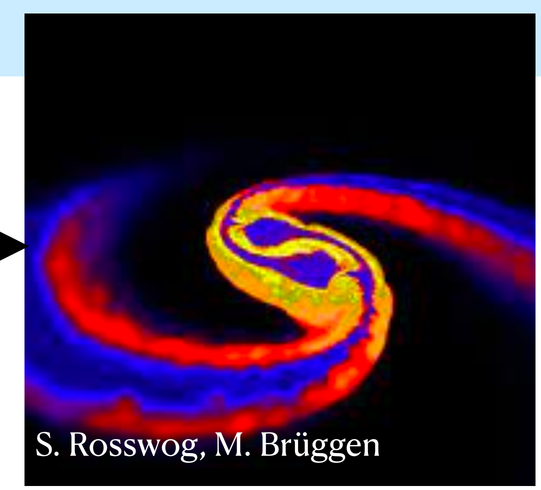
- ν's affect nucleosynthesis[4-7] (set Y_e)



Flavor dependent processes



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[4]Nucleosynthesis in Supernovae, Hoyle & Fowler (1960), Astrophysical Journal, vol. 132, p.565
[5]r-Process in Neutron Star Mergers, Freiburghaus, Rosswog & Thielemann, C. Freiburghaus *et al* 1999 *ApJ* **525** L121
[6]Enhanced triple-α reaction reduces proton-rich nucleosynthesis in supernovae, Jin, Roberts, Austin & Schatz, Nature volume 588, (2020)
[7]Successful νp-process in neutrino-driven outflows in core-collapse supernovae, A. Friedland, P. Mukhopadhyay, A. Patwardhan, 2312.03208

What are we missing?

- Full solution of quantum neutrino transport
- Implementation of neutrino conversion in hydrodynamical simulations
- Self-consistent treatment of neutrino conversion within nucleosynthesis networks

🤔

Part II

Matter-neutrino Resonances (MNR)

Ian Padilla-Gay, Shashank Shalgar, Irene Tamborra, *Symmetry breaking due to multi-angle matter-neutrino resonance in neutron star merger remnants*, arXiv:24XX.XXXXX

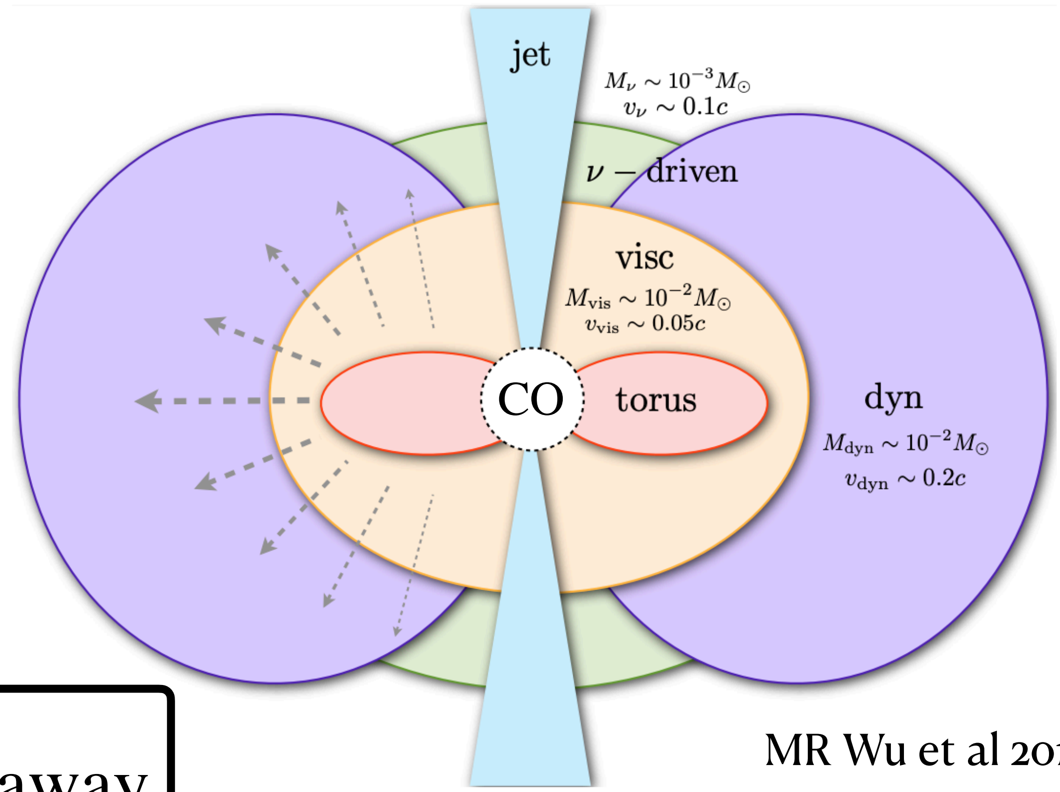
✅ Matter-neutrino resonances in a multi-angle framework

Are matter-neutrino resonances still relevant?

Neutrino conversion in compact binary mergers

Mergers can host:

- MSW resonant conversion, ~km away
- Fast flavor conversion in the proximity of decoupling regions[1], ~m away
- Matter-neutrino resonances (MNR), ~m-km away



MR Wu et al 2017

[1]Multi-Dimensional Solution of Fast Neutrino Conversions in Binary Neutron Star Merger Remnants, **Padilla-Gay**, Shalgar & Tamborra, JCAP 01 (2021) 017

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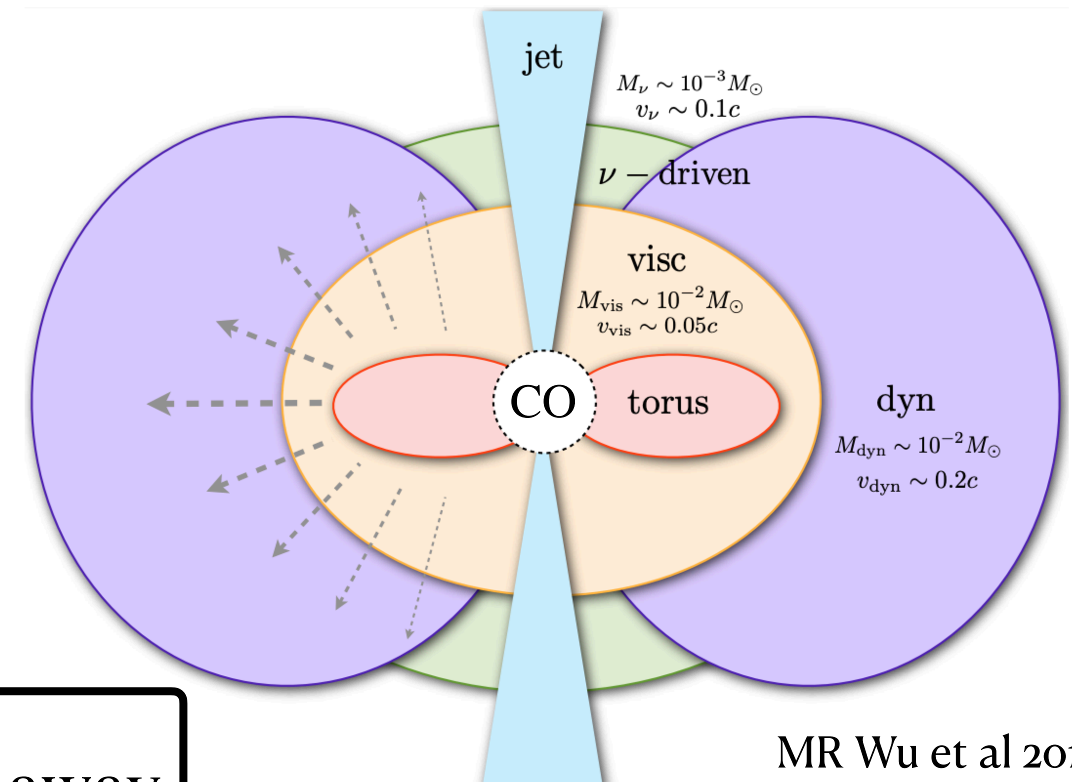


MR Wu et al 2017

Key ingredient: overall excess $\bar{\nu}_e > \nu_e$ in the neutrino emission[2,3,4]

[1]Multi-Dimensional Solution of Fast Neutrino Conversions in Binary Neutron Star Merger Remnants, **Padilla-Gay**, Shalgar & Tamborra, JCAP 01 (2021) 017

[2]Coalescing neutron stars, Ruffert, Janka & Takahashi, Astronomy and Astrophysics, v.319, p.122-153

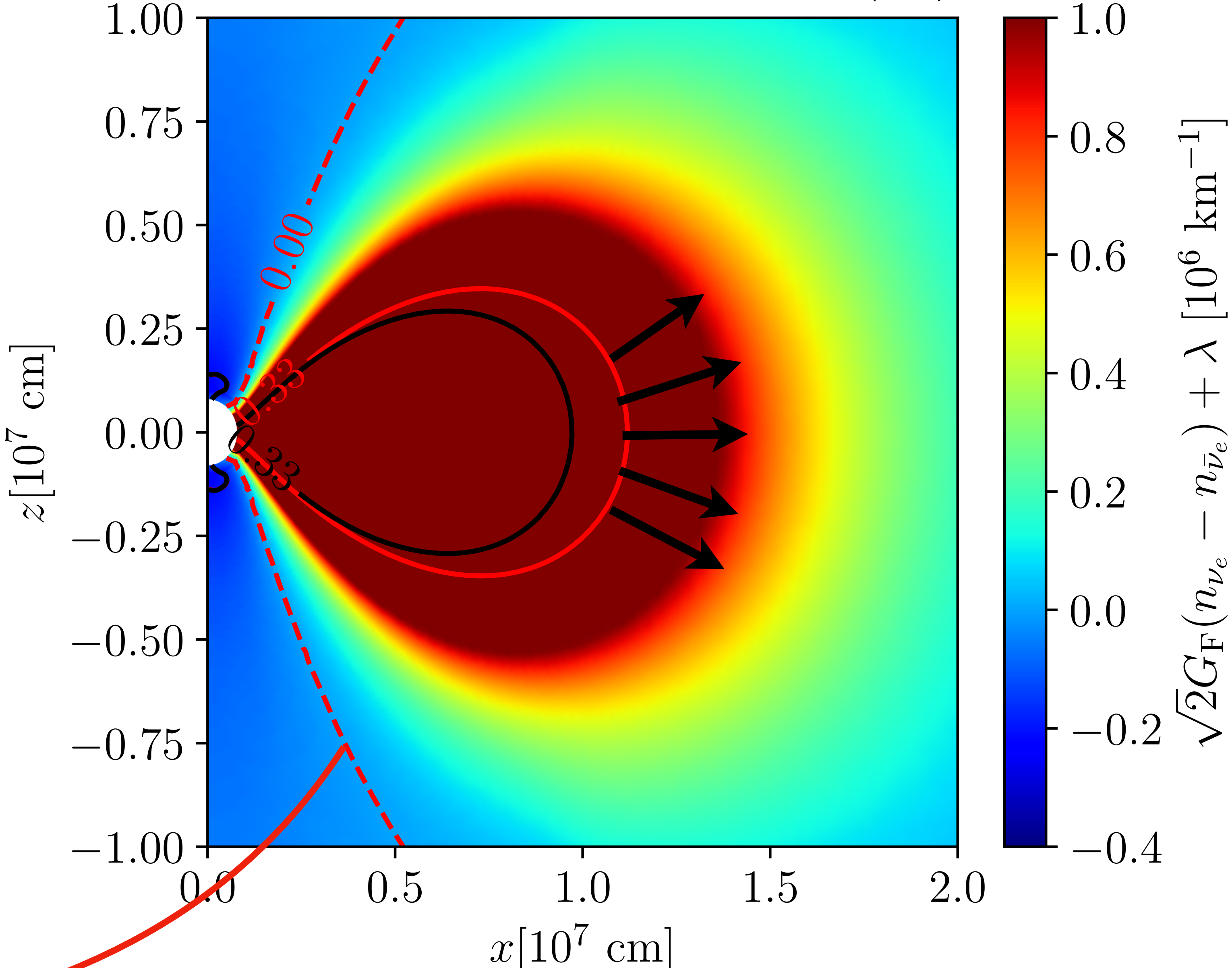
[3]Post-merger evolution of a neutron star-black hole binary with neutrino transport, Foucart et al, Phys. Rev. D 91, 124021 (2015)

[4]Neutrino-driven winds from neutron star merger remnants, A. Perego et al, *MNRAS*, Volume 443, Issue 4, 2014

MNRs, what are they?

- The MNR is the ***enhancement*** of flavor conversion due to the ***cancellation*** of neutrino and matter Hamiltonians[1]
- Conditions for MNR have been recognized in the past

Data from model "M3A8m3a5" of Just et al, MNRAS (2015)

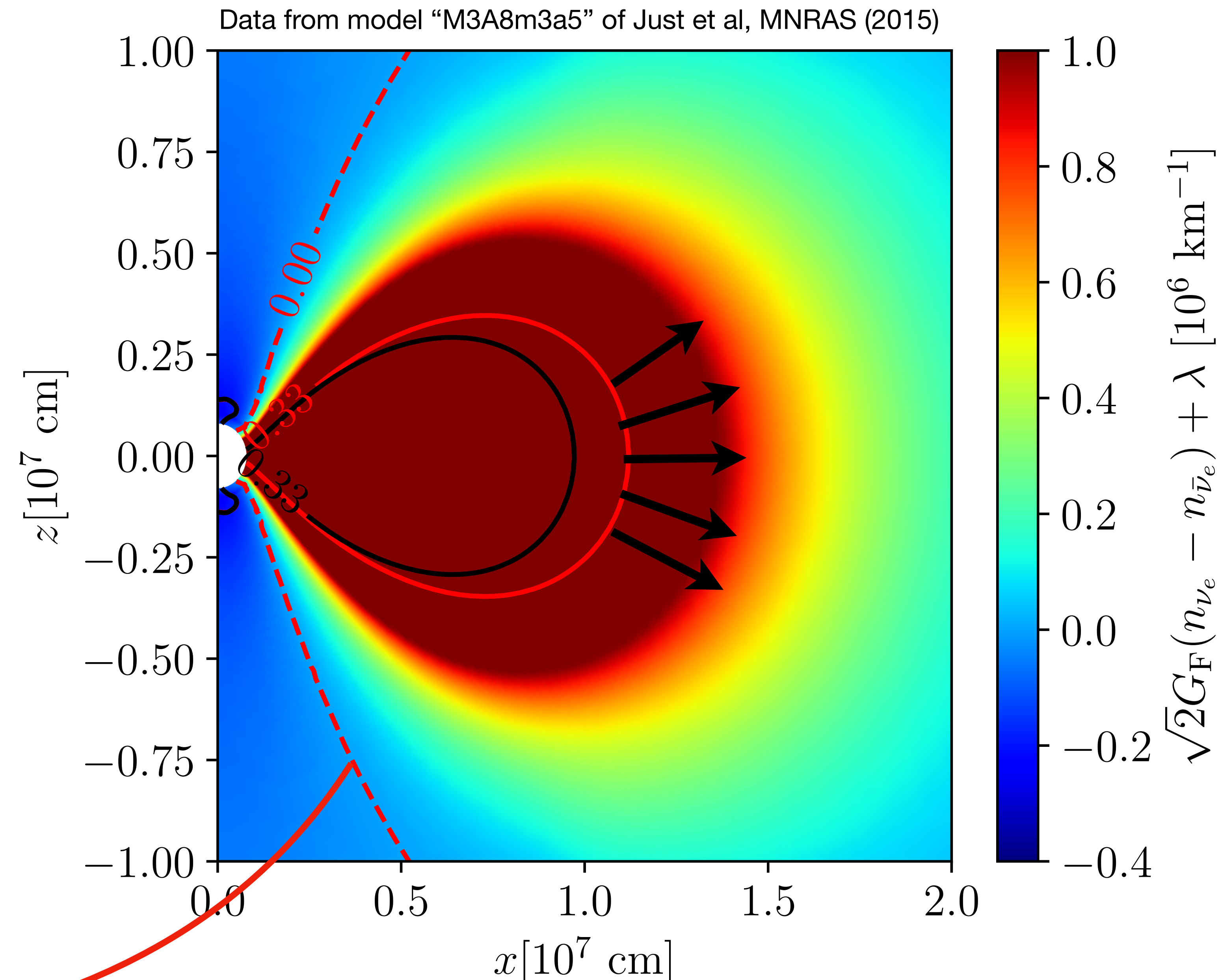


Interesting regions for MNR (near & far)

[1]Matter-Neutrino Resonance Above Merging Compact Objects, Malkus, Friedland & McLaughlin, 1403.5797

MNRs, what are they?

- The MNR is the ***enhancement*** of flavor conversion due to the ***cancellation*** of neutrino and matter Hamiltonians[1]
- Conditions for MNR have been recognized in the past
- However, most studies assume there is no dependence on the emission angle[1-5]…
- …other papers assume there is[6,7] (kind of)



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[1]Matter-Neutrino Resonance Above Merging Compact Objects, Malkus, Friedland & McLaughlin, 1403.5797

[2]Uncovering the Matter-Neutrino Resonance, Vaananen & McLaughlin, Phys.Rev.D 93 (2016) 10, 105044

[3]Symmetric and Standard Matter-Neutrino Resonances Above Merging Compact Objects, Malkus, McLaughlin & Surman, *Phys.Rev.D* 93 (2016) 4, 045021

[4]Matter Neutrino Resonance Transitions above a Neutron Star Merger Remnant, Zhu, Perego & McLaughlin, Phys. Rev. D 94, 105006 (2016)

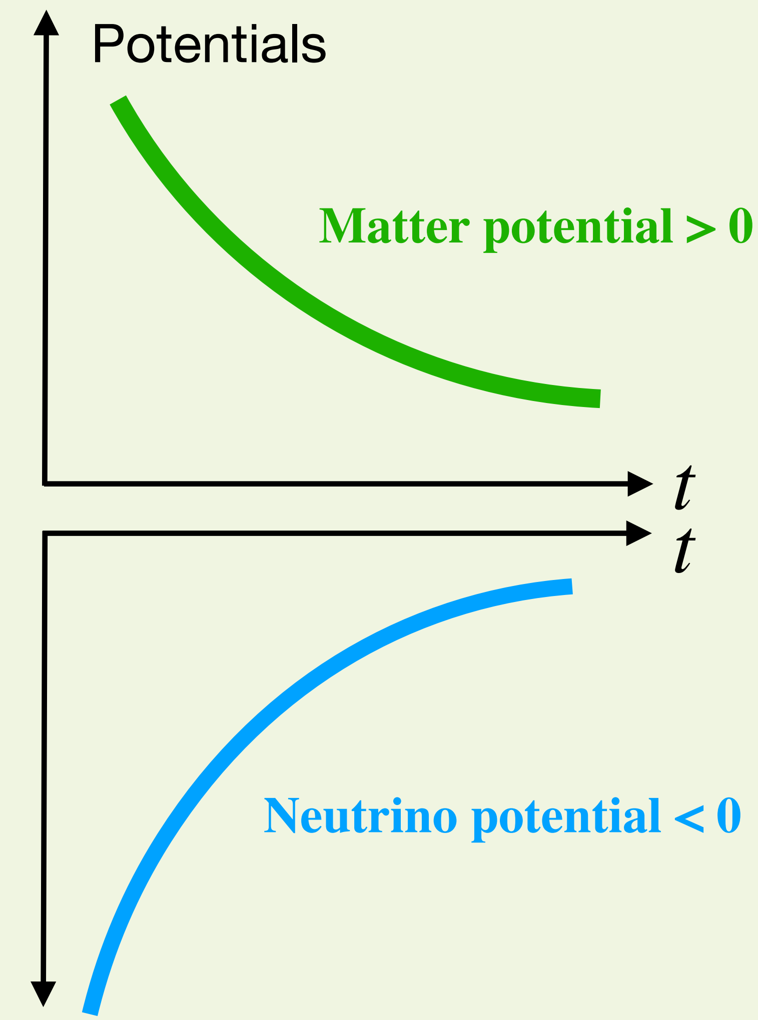
[5]Physics of neutrino flavor transformation through matter-neutrino resonances, Wu, Duan & Qian, Physics Letters B (2016), pp. 89-94

[6]Matter-neutrino resonance in a multiangle neutrino bulb model, Vlasenko, A. and McLaughlin, Phys. Rev. D 97, 083011 (2018)

[7]Multi-angle calculation of the matter-neutrino resonance near an accretion disk, Shahank Shalgar, JCAP02(2018)010

Matter-neutrino resonance: basic example

$$H_{\text{mat}} = \begin{pmatrix} \lambda & 0 \\ 0 & 0 \end{pmatrix}, \text{ where } \lambda = \frac{\sqrt{2} G_F \rho_B}{m_N} Y_e$$ is ***positive***



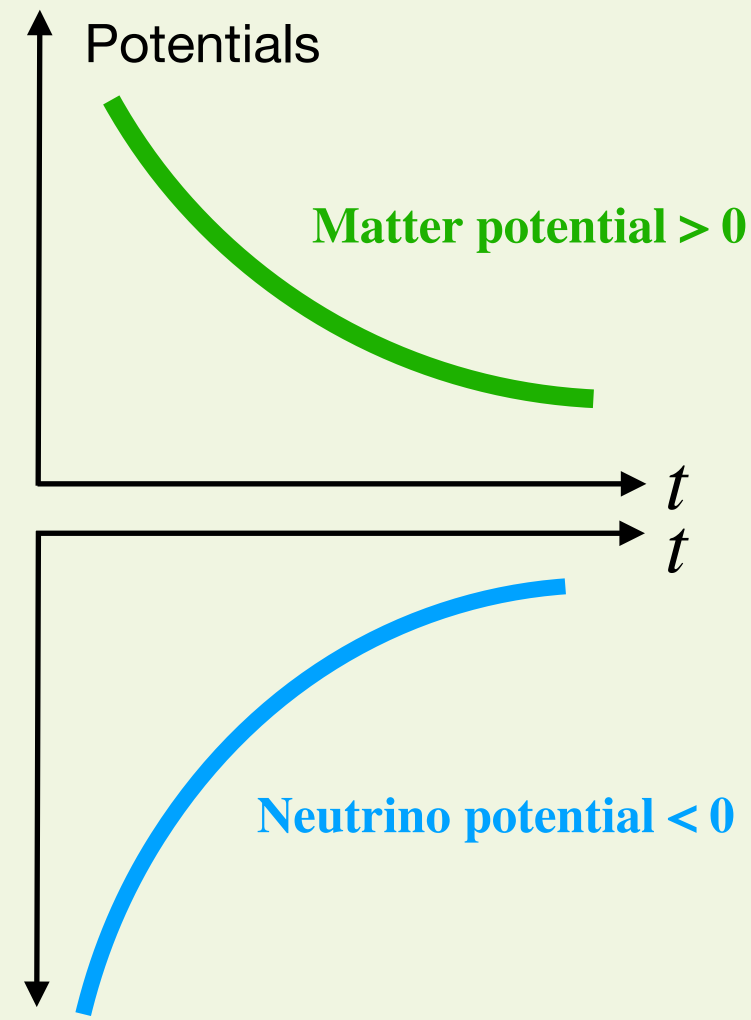
$$H^{\nu\nu}_{ee}(v) = \sqrt{2} G_F (n_{\nu_e} - n_{\bar{\nu}_e})^*$$ ***negative*** (NS mergers)

*No angular dependence → single angle approx.

Matter-neutrino resonance: basic example

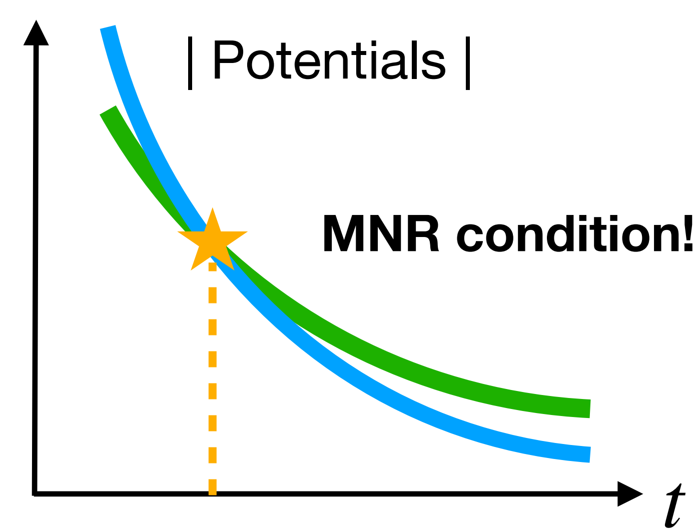
$$H_{\text{mat}} = \begin{pmatrix} \lambda & 0 \\ 0 & 0 \end{pmatrix}, \text{ where } \lambda = \frac{\sqrt{2} G_F \rho_B}{m_N} Y_e \quad \text{is } \textbf{\textit{positive}}$$

$$H_{ee}^{\nu\nu}(v) = \sqrt{2} G_F (n_{\nu_e} - n_{\bar{\nu}_e})^* \; \textbf{\textit{negative}} \text{ (NS mergers)}$$

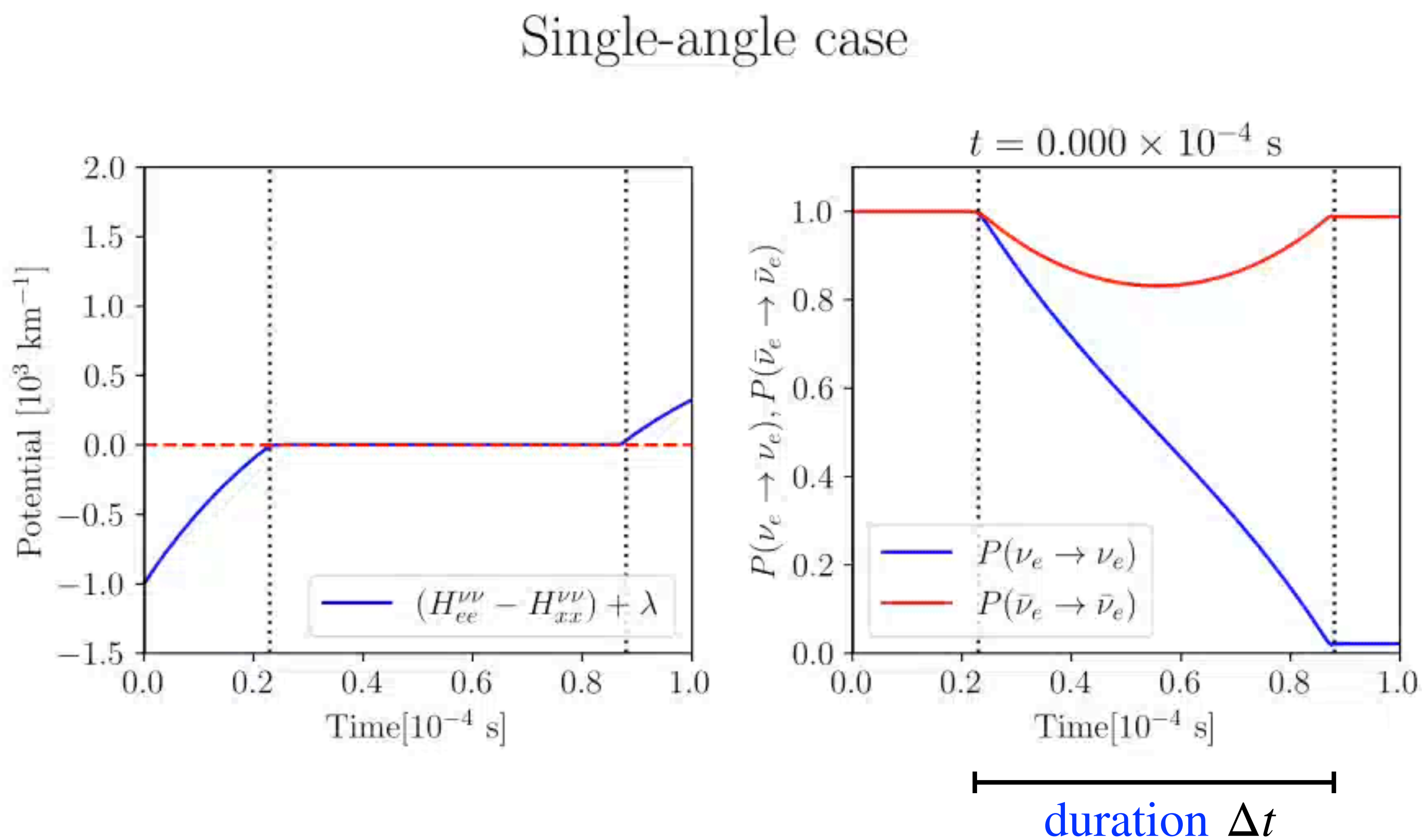


$$H_{ee}^{\nu\nu} - H_{xx}^{\nu\nu} + \lambda \approx 0$$

*No angular dependence → single angle approx.

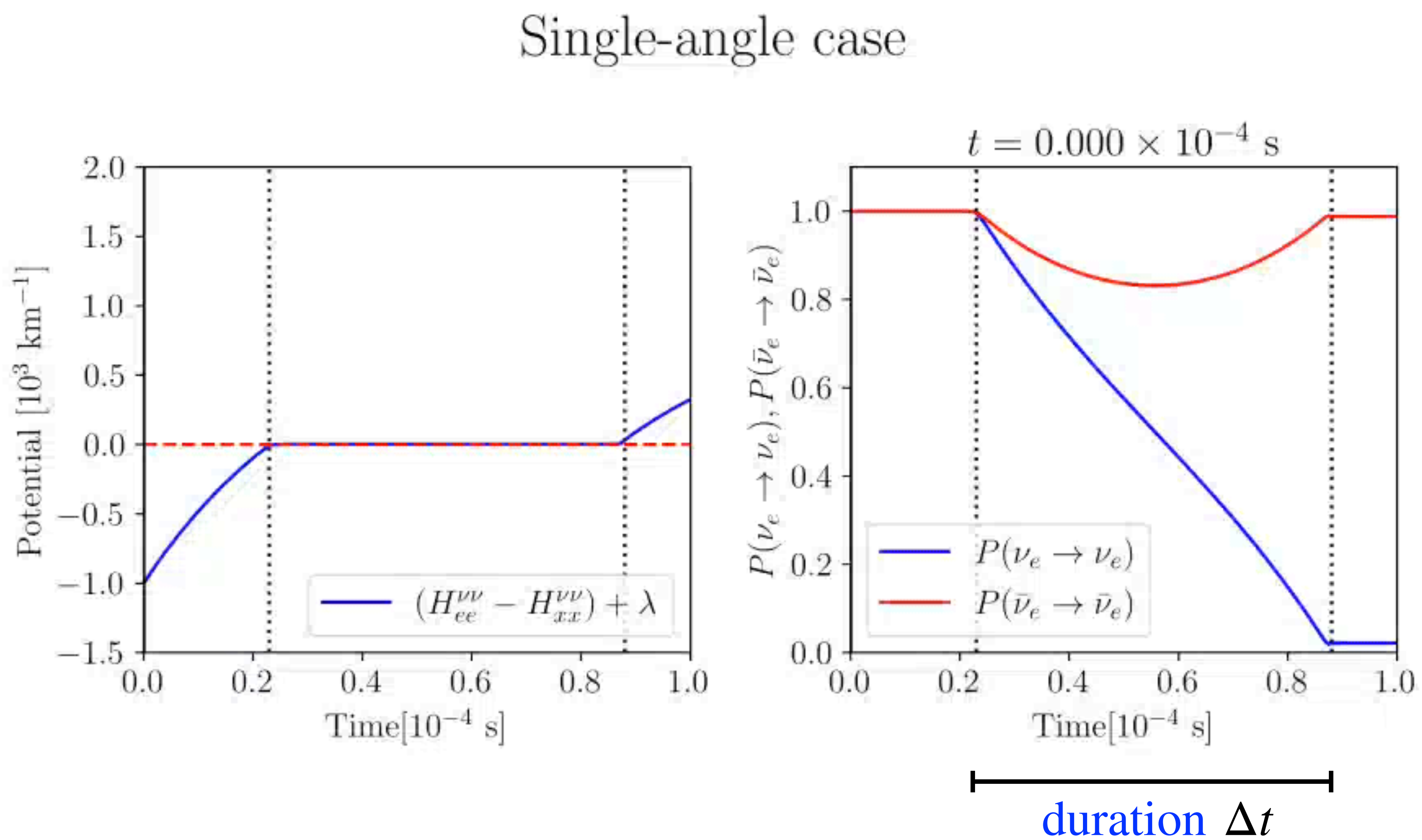


Matter-neutrino resonance: basic example



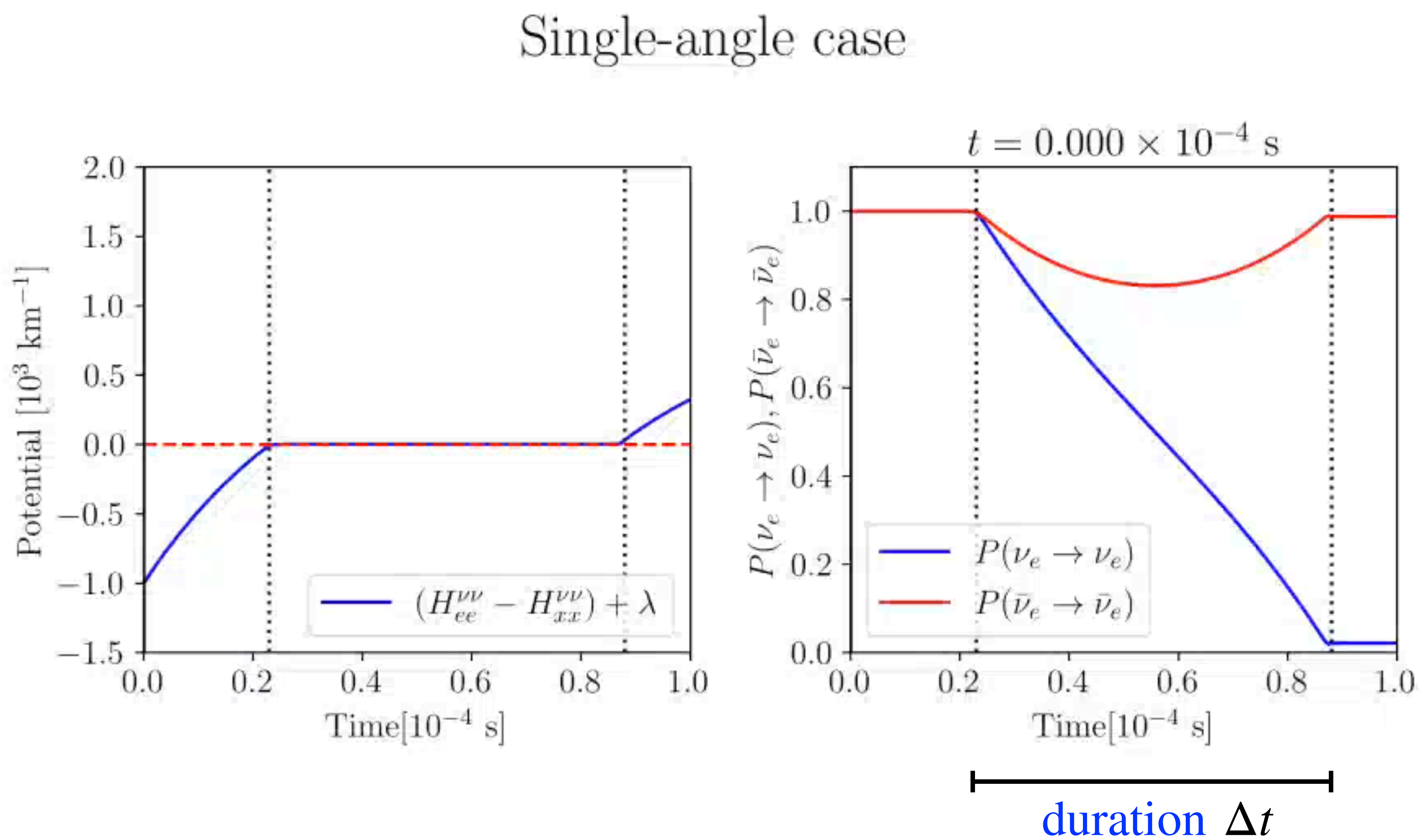
- When the neutrino and matter potential cancel each other: neutrinos completely change flavor

Matter-neutrino resonance: basic example



- When the neutrino and matter potential cancel each other: neutrinos completely change flavor
- Occurs for both mass hierarchies (unlike the MSW effect)

Matter-neutrino resonance: basic example



- When the neutrino and matter potential cancel each other: neutrinos completely change flavor
- Occurs for both mass hierarchies (unlike the MSW effect)
- System stays on resonance for a period of time: duration $\Delta t \approx \tau_{\lambda/\mu} \log\big((1+\alpha)/(\alpha-1)\big)$ where $\tau_{\lambda/\mu} = \left| \frac{d \log[\lambda(t)/\mu(t)]}{dt} \right|^{-1}$ is the **effective timescale** and $\alpha = n_{\bar{\nu}_e}/n_{\nu_e}$ the neutrino/antineutrino **asymmetry**

Matter-neutrino resonance: advanced example

$$H_{\rm mat} = \begin{pmatrix} \lambda & 0 \\ 0 & 0 \end{pmatrix}, \text{ where } \lambda = \frac{\sqrt{2} G_F \rho_B}{m_N} Y_e \quad \text{is } \textbf{\textit{positive}}$$

$$H_{\nu\nu}(v) = \sqrt{2} G_F n_{\nu_e} \int dv' [\rho(v') - \frac{n_{\bar{\nu}_e}}{n_{\nu_e}} \bar{\rho}(v')](1 - v v') \; \textbf{\textit{negative}} \text{ (NS mergers)}$$

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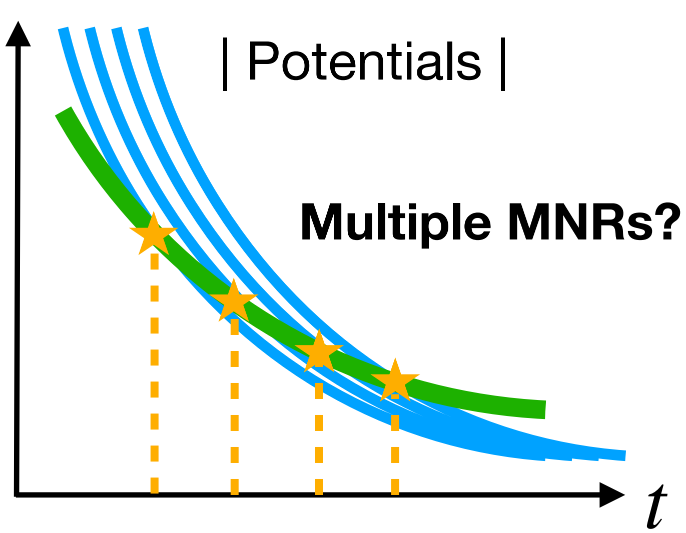
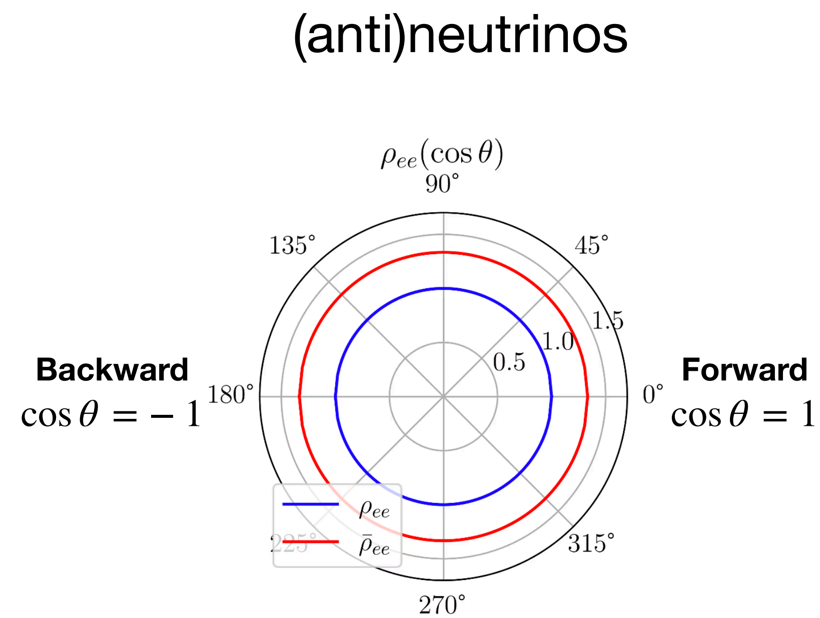
$$H^{\nu\nu}_{ee}(v) - H^{\nu\nu}_{xx}(v) + \lambda \approx 0$$

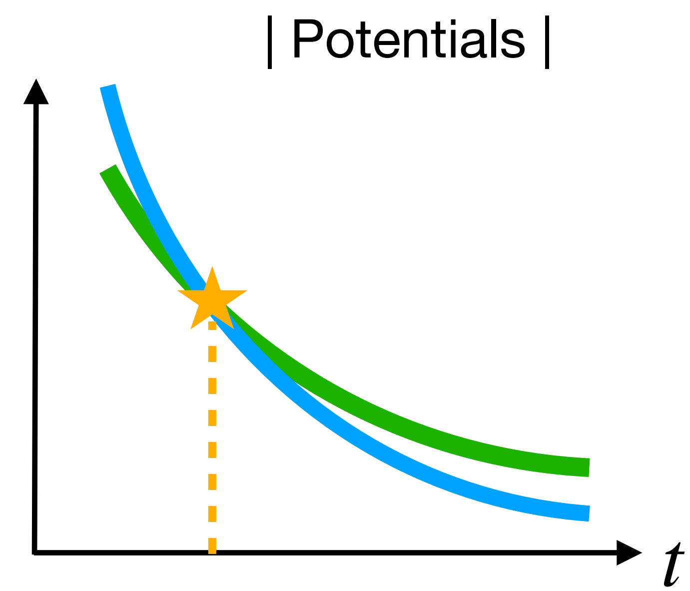
Cancellation does not occur at the same location for different emission angles!



Three interesting cases

1) **Isotropic** neutrino distributions
(recovers the single-angle approx.)

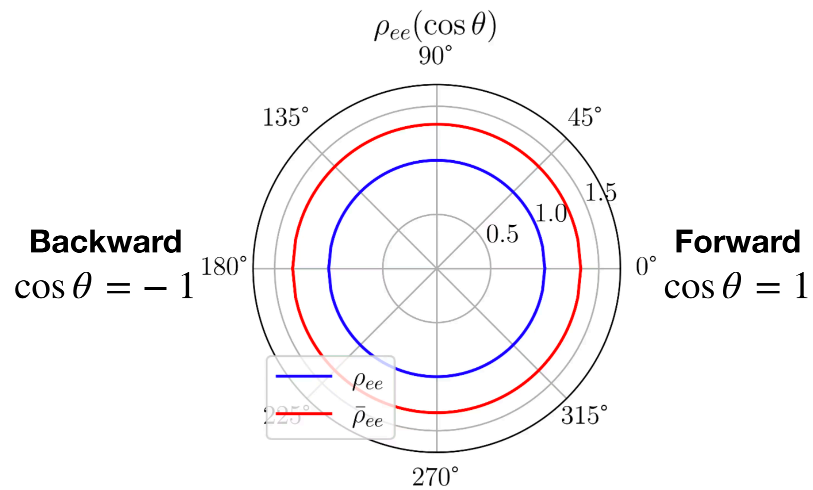


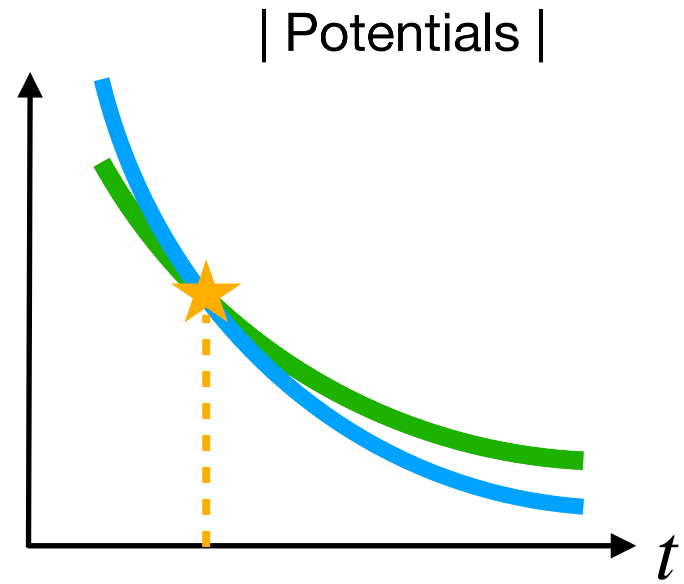


Three interesting cases

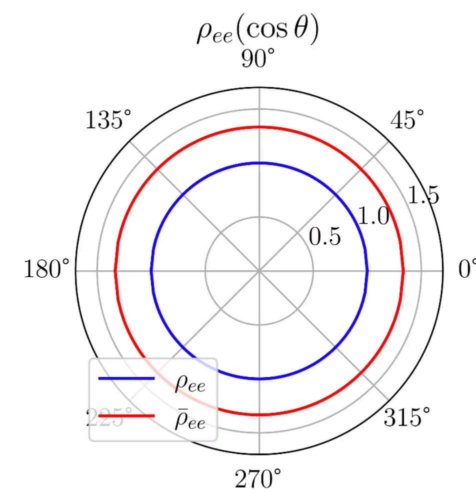
(anti)neutrinos

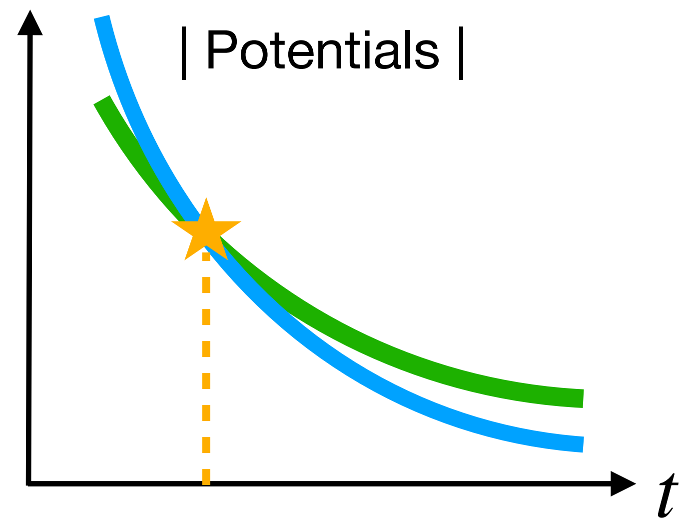
1) **Isotropic** neutrino distributions (recovers the single-angle approx.)





2) **Isotropic,** but with a very tiny (10^{-22}) anisotropy. Much larger perturbations arise naturally in the medium

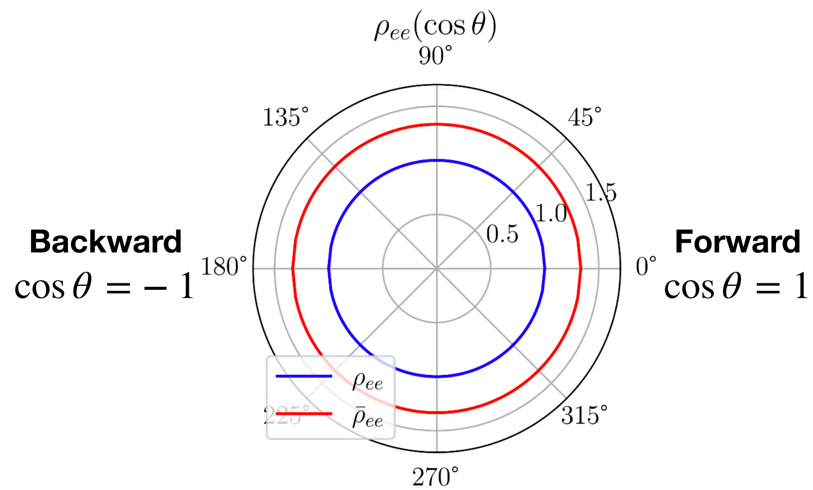


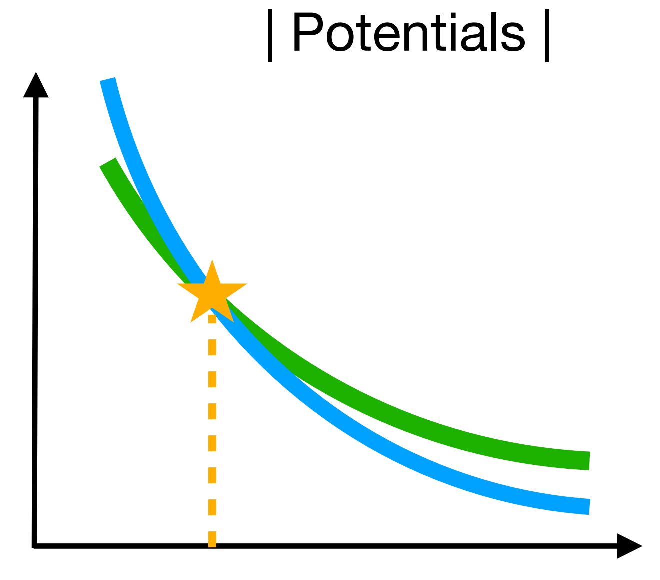


Three interesting cases

(anti)neutrinos

1) **Isotropic** neutrino distributions (recovers the single-angle approx.)





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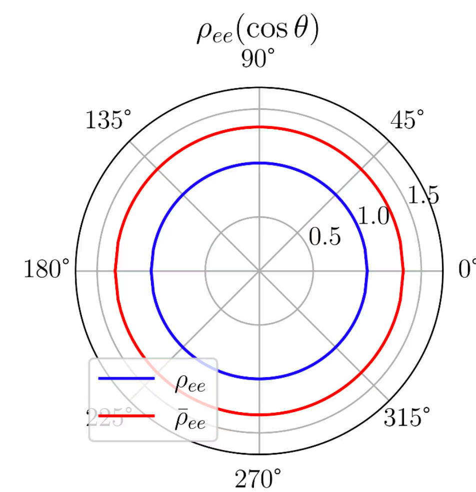
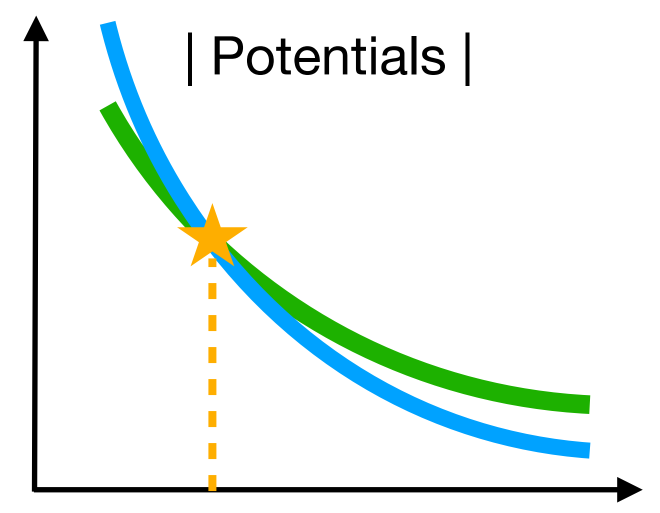
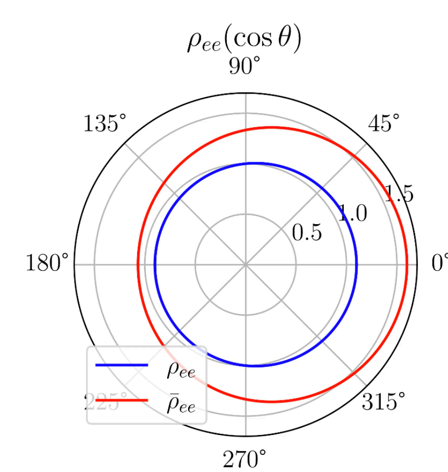
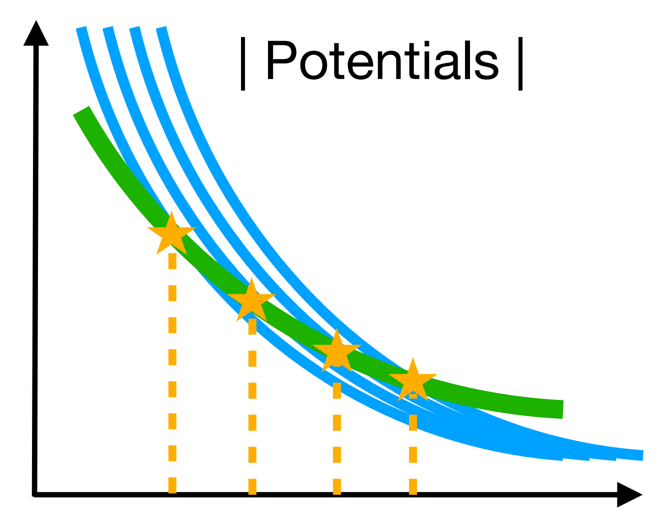


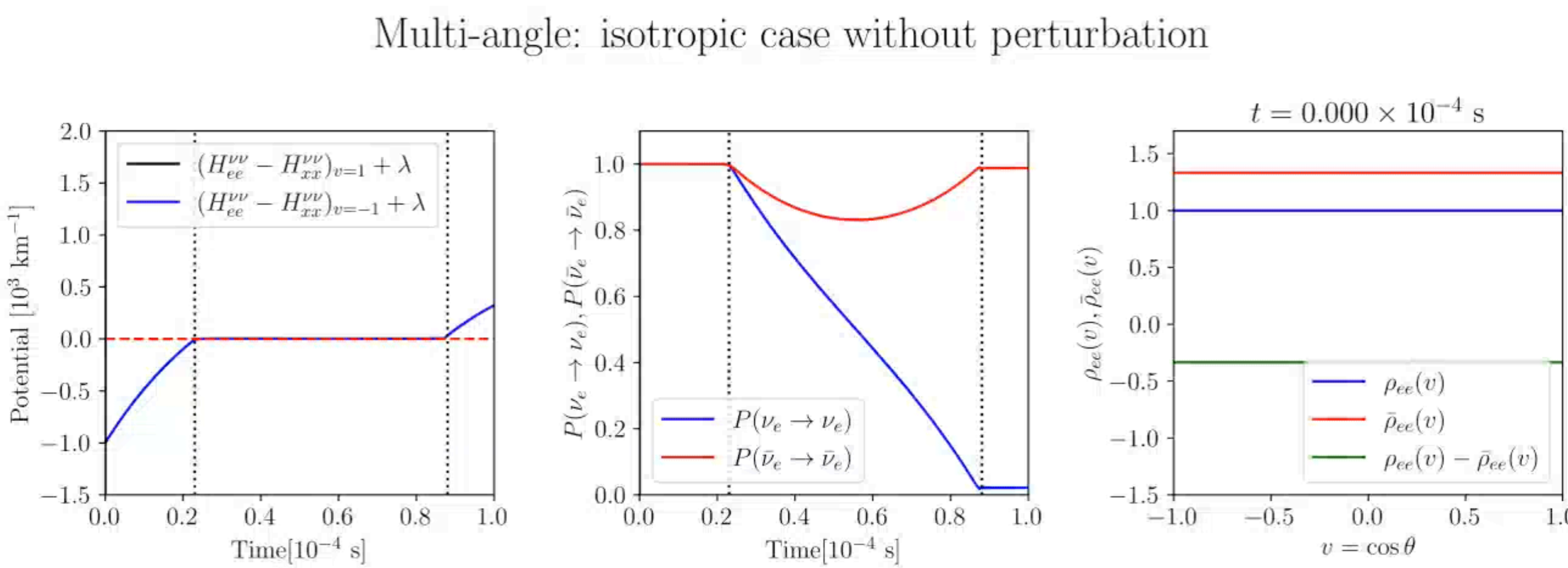


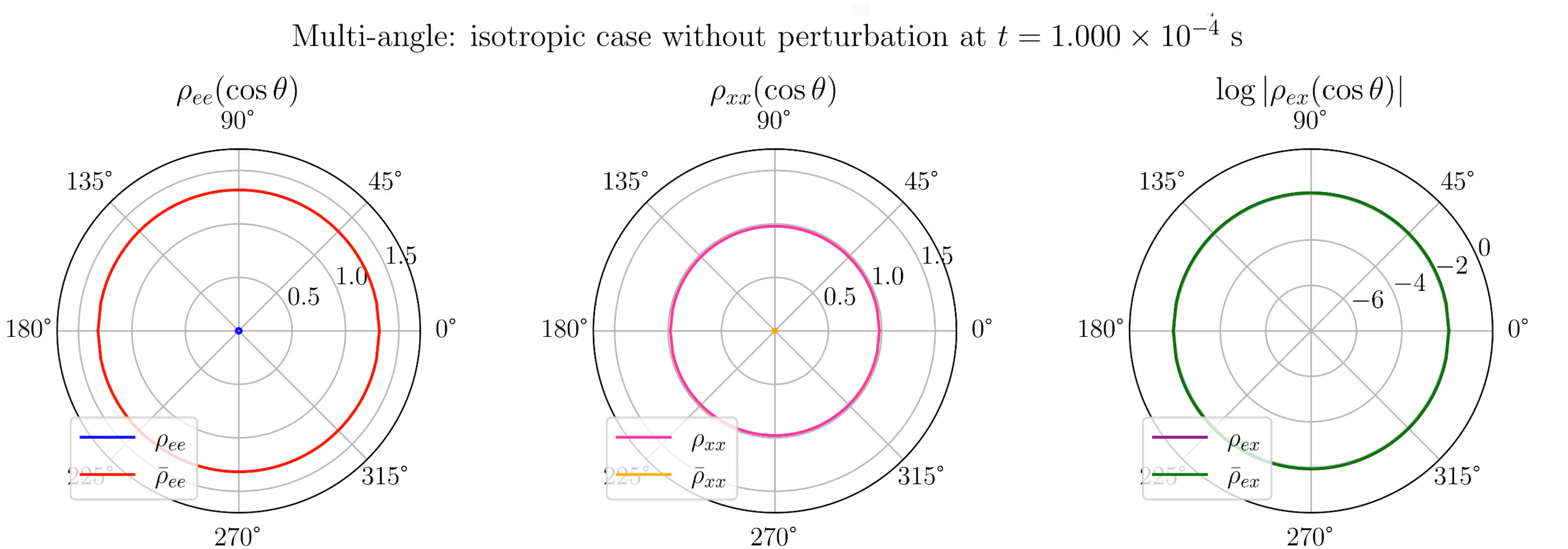
3) **Non-isotropic** neutrino distributions. To be expected in realistic astrophysical environments





1) Perfectly isotropic distribution. Single-angle approximation recovered



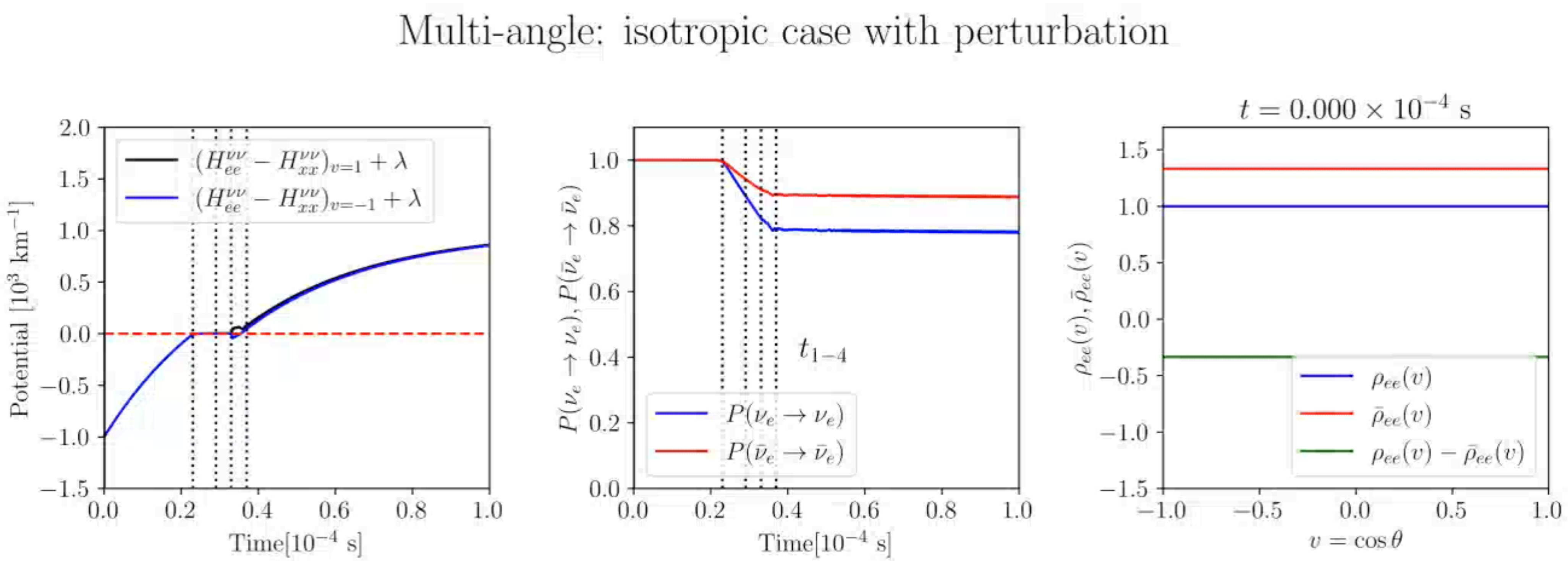


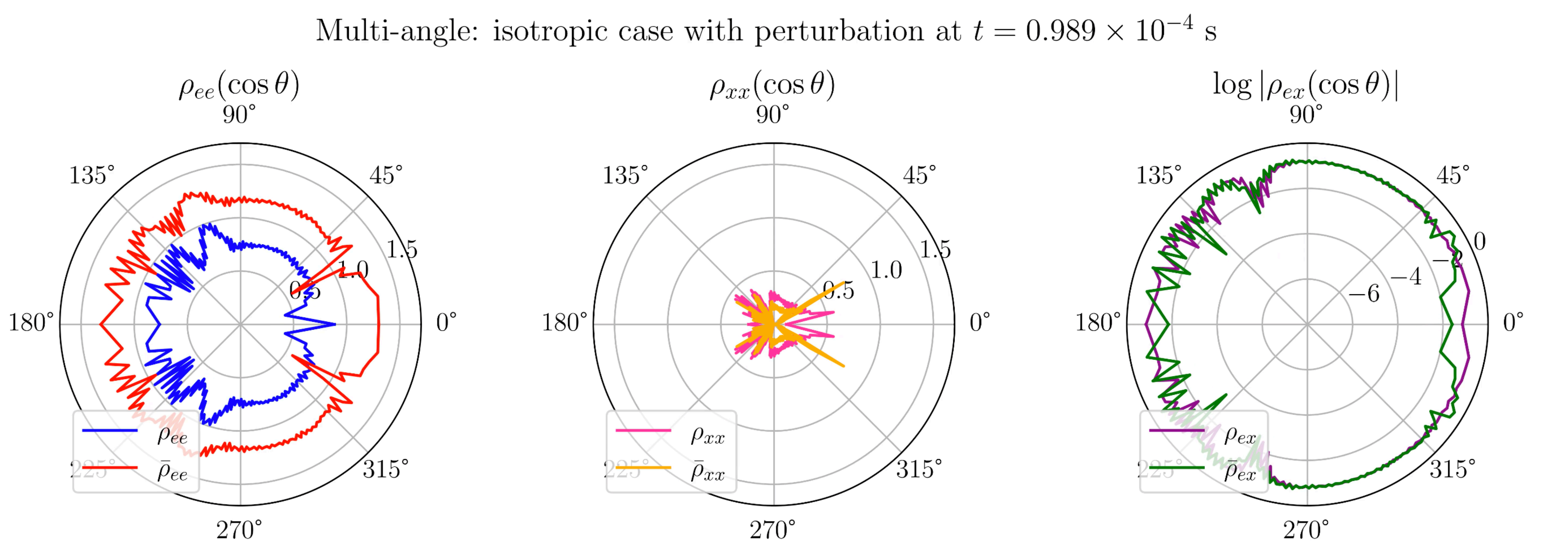
$\nu_e, \bar{\nu}_e$ abundances

$\nu_x, \bar{\nu}_x$ abundances

ν_e-ν_x coherence
$\bar{\nu}_e$-$\bar{\nu}_x$ coherence

2) Isotropic distribution with a $\sim 10^{-22}$ perturbation. Dipole mode grows exponentially. Isotropy is dynamically broken



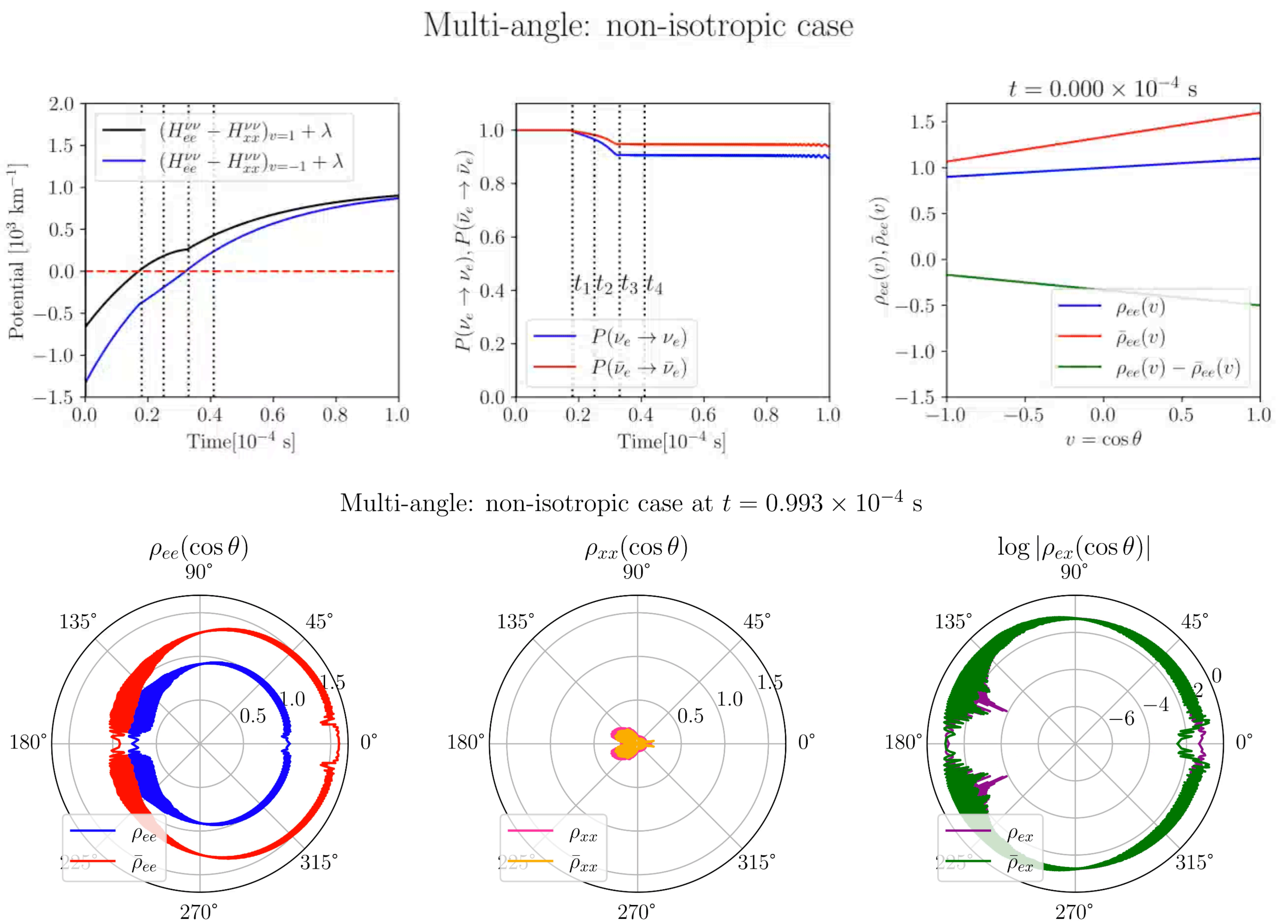


$\nu_e, \bar{\nu}_e$ abundances

$\nu_x, \bar{\nu}_x$ abundances

ν_e-ν_x coherence
$\bar{\nu}_e$-$\bar{\nu}_x$ coherence

3) Non-isotropic distribution relevant for astrophysical systems. MNR not sustained, different directions interfere



$\nu_e, \bar{\nu}_e$ abundances

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ν_e-ν_x coherence
$\bar{\nu}_e$-$\bar{\nu}_x$ coherence

Part III

Conclusions

Conclusions

- Neutrino flavor evolution in dense astrophysical environments is **very complex** (sensitive to very small variations)
- Non-trivial role of neutrino-neutrino interaction in the equations of motion; **angle-dependence** is hard
- If MNR's occur in NS remnants, they will most likely be **interrupted** by emerging anisotropies
- Implications for **realistic** astrophysical sources remain to be understood