Neutrino flavor transformation in supernova as a probe for nonstandard neutrino-scalar interactions

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BSM Physics with neutrinos

- Neutrinos have been a great way of discovering Beyond the Standard Model physics.

- Neutrino mass and mixing are 'cracks' in the Standard Model:
  - what kind of mass, Dirac or Majorana
  - is there large CP violation in the leptons,
  - ...

- Many terrestrial experiments looking for further BSM neutrino physics are underway / under construction / being planned.

- Determining the properties of the neutrino in terrestrial experiments is hard.
  - neutrinos interact so weakly, signals must be found among significant backgrounds
- Neutrinos cannot hide in environments where Nature pushes the envelope of density, temperature, gravity, B fields, etc.
  - these environments don’t exist on Earth.

- A complimentary approach to study neutrino properties is to go to astrophysical environments.
- Given their importance to the explosions of massive stars, supernovae are the ultimate neutrino experiment.

The physics in supernova neutrinos

Neutrinos

- Neutrino mass ordering
- Number of ν flavors
- Self-interaction effects,
- MSW effects,
- Turbulence effects
- Non-standard interactions,
- Magnetic moments,
- SUSY contribution,
- ….

Nuclear / Supernova

- Progenitor and structure,
- Neutrino opacities,
- Equation of State,
- Shock position / velocity,
- Standing Accretion Shock Instability,
- Stalled shock duration,
- Nucleosynthesis conditions,
- ….

- This physics enters appears either at the neutrinosphere or via flavor transformation in the supernova mantle.

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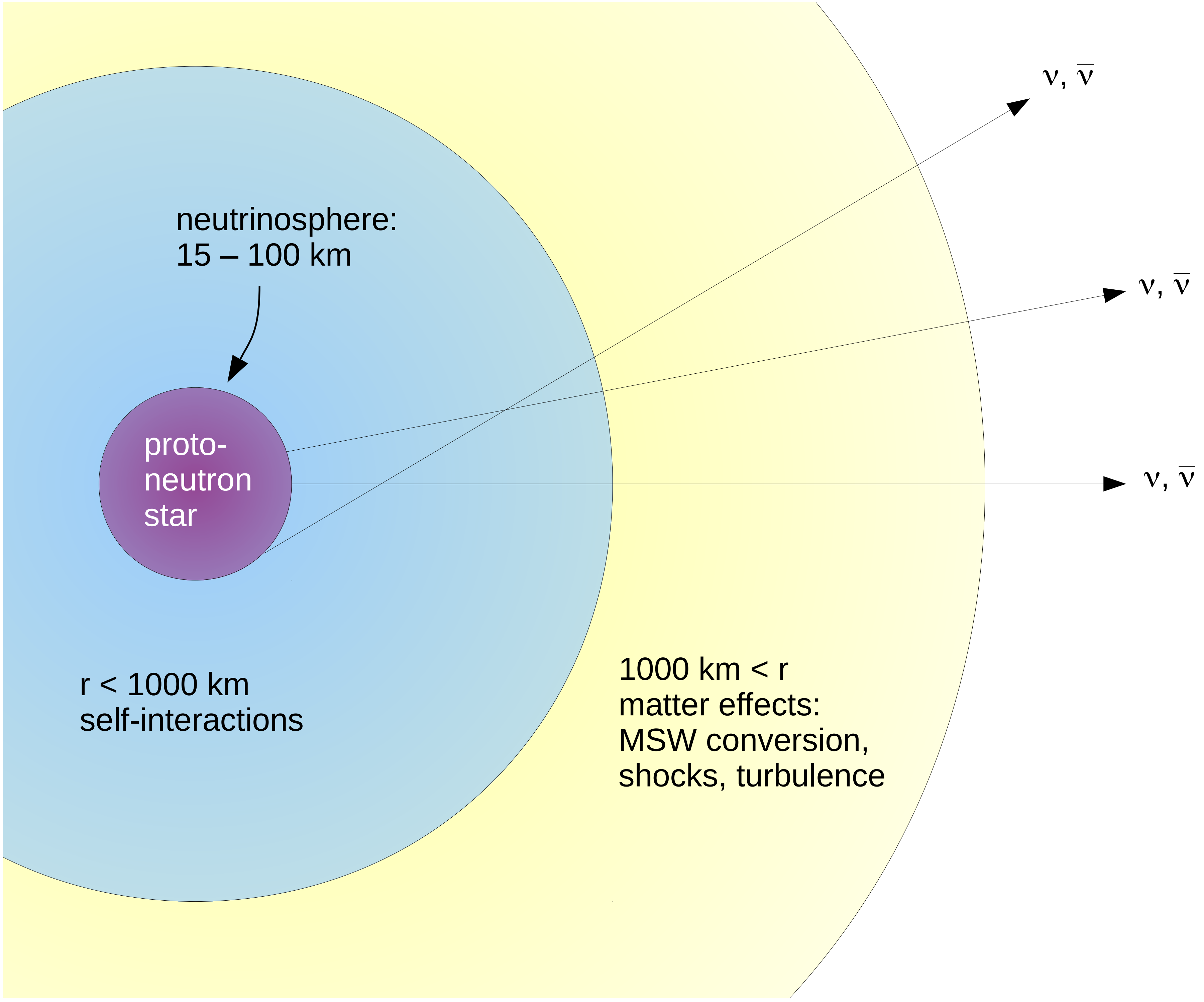


neutrinosphere:
15 – 100 km
proto-
neutron
star
r < 1000 km
self-interactions
1000 km < r
matter effects:
MSW conversion,
shocks, turbulence
$\nu, \bar{\nu}$
$\nu, \bar{\nu}$
$\nu, \bar{\nu}$

Neutrino propagation

- The ν state at r is related to the initial state through a matrix *S*.
- The probability that an initial state *j* is detected as state *i* at r is

$$P(\nu_j \rightarrow \nu_i) \equiv P_{ij} = |S_{ij}|^2$$

- *S* obeys a differential equation

$$i \frac{dS}{d\lambda} = H S$$

- *H* is the Hamiltonian, λ is an affine parameter.

- The neutrino Hamiltonian is made up of several terms:
  - the vacuum H_V term,
  - the matter potential H_M,
  - the self-interaction H_{SI},

- The vacuum term is

$$H_V = \frac{1}{2E} U_V \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U_V^\dagger$$

- E is the neutrino energy, m_1, m_2 and m_3 are the neutrino masses.
- U_V is the mixing matrix parameterized by three mixing angles θ_{12}, θ_{13} and θ_{23}.

The matter (MSW) potential

- In the presence of matter the neutrinos gain a potential energy.
- For mixing between active flavors we only need consider the Charged Current potential.

$$H_M = \pm \begin{pmatrix} V_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_{CC} = \sqrt{2}\, G_F\, n_e$$

- Not included is the small potential $V_{\mu\tau}$.
  - In the standard model $V_{\mu\tau} \approx 10^{-5}\, V_{CC}$ but in some SUSY models the $\mu\tau$ term can be $V_{\mu\tau} \approx 10^{-2}\, V_{CC}$.

The self-interaction potential

- So many neutrinos are emitted in a supernova the Hamiltonian includes a term due to neutrino self-interactions.

- At a given location and time, the self-interaction Hamiltonian due to the Standard Model V-A interaction is the same for both Dirac and Majorana neutrinos and given by

$$H_{V-A}(r,t,\boldsymbol{q}) = \sqrt{2}\,G_F \int \frac{d^3 q'}{(2\pi)^3} \left(1 - \hat{\boldsymbol{q}} \cdot \hat{\boldsymbol{q}}'\right)\left(\rho(\boldsymbol{q}') - \bar{\rho}^*(\boldsymbol{q}')\right)$$

- The evolution of a single neutrino becomes dependent upon every other neutrino emitted!

Duan et al., PRL **97** 241101 (2006)

Non-standard interactions

- Over the years many have considered new, Non-Standard Interactions (NSI), of neutrinos with matter in supernovae.
  - see Amanik, Fuller and Grinstein, Astropart. Phys. **24** 160 (2005)
  - Amanik and Fuller, PRD **75** 083008 (2007)
  - Esteban-Pretel, Tomas and Valle, PRD **76** 053001 (2007)
  - Esteban-Pretel, Tomas and Valle, PRD **81** 063003 (2010)
  - Stapleford et al, PRD **94** 093007 (2016)

  …
- We can also consider new non-standard interactions of neutrinos with other neutrinos – Non-Standard Self Interactions (NSSI).
  - see Blennow, Mirizzi, and Serpico, PRD **78** 113004 (2008)
  - Das, Dighe, and Sen, JCAP **5** 051 (2017)
  - Yang and Kneller, PRD **97** 103018 (2018)

- Consider a generic neutrino coupling via a scalar field φ and/or a pseudoscalar field χ.
- Assuming the masses of the mediators are much heavier than the energy of the neutrinos, we can use a 4-fermion interaction:

$$H_{\text{int}} = \frac{1}{8 m_{\phi}^{2}} g_{\alpha\beta} g_{\zeta\eta} (\bar{\nu}_{\alpha} \nu_{\beta})(\bar{\nu}_{\zeta} \nu_{\eta}) - \frac{1}{8 m_{\chi}^{2}} h_{\alpha\beta} h_{\zeta\eta} (\bar{\nu}_{\alpha} \gamma^{5} \nu_{\beta})(\bar{\nu}_{\zeta} \gamma^{5} \nu_{\eta})$$

- where the g's and h's coupling matrices in flavor space.
- Now use the mean field approximation and a Fierz transfromation
  - e.g. the scalar term becomes

$$(\bar{\nu}_{\alpha} \nu_{\beta})(\bar{\nu}_{\zeta} \nu_{\eta}) \approx \langle \bar{\nu}_{\alpha} \nu_{\beta} \rangle (\bar{\nu}_{\zeta} \nu_{\eta}) + (\bar{\nu}_{\alpha} \nu_{\beta}) \langle \bar{\nu}_{\zeta} \nu_{\eta} \rangle - \sum_{c,d=S,P,V,A,T} C_{SS,cd} \left[\langle \bar{\nu}_{\zeta} \Gamma^{c} \nu_{\beta} \rangle (\bar{\nu}_{\alpha} \Gamma^{d} \nu_{\eta}) + (\bar{\nu}_{\zeta} \Gamma^{c} \nu_{\beta}) \langle \bar{\nu}_{\alpha} \Gamma^{d} \nu_{\eta} \rangle \right]$$

- where the Γ's are 4x4 matrices and the C's are constants.

- In the relativistic limit only V x V and A x A terms survive.

- A distinction between Dirac and Majorana neutrinos now appears
  - e.g. for a Dirac neutrino the scalar term becomes

$$\left(\bar{\nu}_{\alpha}\nu_{\beta}\right)\left(\bar{\nu}_{\zeta}\nu_{\eta}\right)\approx-\frac{1}{2}\left[\left\langle\bar{\nu}_{\zeta L}\gamma^{\mu}\nu_{\beta L}\right\rangle\left(\bar{\nu}_{\alpha R}\gamma_{\mu}\nu_{\eta R}\right)-\left(\bar{\nu}_{\zeta L}\gamma^{\mu}\nu_{\beta L}\right)\left\langle\bar{\nu}_{\alpha R}\gamma_{\mu}\nu_{\eta R}\right\rangle\right]$$
$$+\left(\alpha\,\eta\Leftrightarrow\zeta\,\beta\right)$$

  - but for a Majorana neutrino the scalar term becomes

$$\left(\bar{\nu}_{\alpha}\nu_{\beta}\right)\left(\bar{\nu}_{\zeta}\nu_{\eta}\right)\approx-\frac{1}{2}\left[\left\langle\bar{\nu}_{\zeta L}\gamma^{\mu}\nu_{\beta L}\right\rangle\left(\bar{\nu}^{C}_{\alpha L}\gamma_{\mu}\nu^{C}_{\eta L}\right)+\left(\bar{\nu}_{\zeta L}\gamma^{\mu}\nu_{\beta L}\right)\left\langle\bar{\nu}^{C}_{\alpha L}\gamma_{\mu}\nu^{C}_{\eta L}\right\rangle\right]$$
$$+\left(\alpha\,\eta\Leftrightarrow\zeta\,\beta\right)$$

- A similar distinction occurs for a pseudoscalar interaction.
- In the ultra relativistic limit, the right-hand component of the neutrino fields vanish.
  - for Dirac neutrinos there is no effect from the new interactions

- Evaluating the averages we find the NSSI for Majorana neutrinos due to a scalar and/or pseudoscalar interaction is given by

$$H_{NSSI}(r,t,\boldsymbol{q})=4\int\frac{d^3q'}{(2\pi)^3}\left(1-\hat{\boldsymbol{q}}\cdot\hat{\boldsymbol{q}}'\right)G\left(\rho^*(\boldsymbol{q}')-\bar{\rho}(\boldsymbol{q}')\right)G^\dagger$$

- The elements of the G matrices are

$$G_{\alpha\beta}=\frac{1}{4m_\phi}g_{\alpha\beta}+\frac{1}{4m_\chi}h_{\alpha\beta}$$

- Compare that with the effective Hamiltonian derived from the Standard Model V-A interaction.

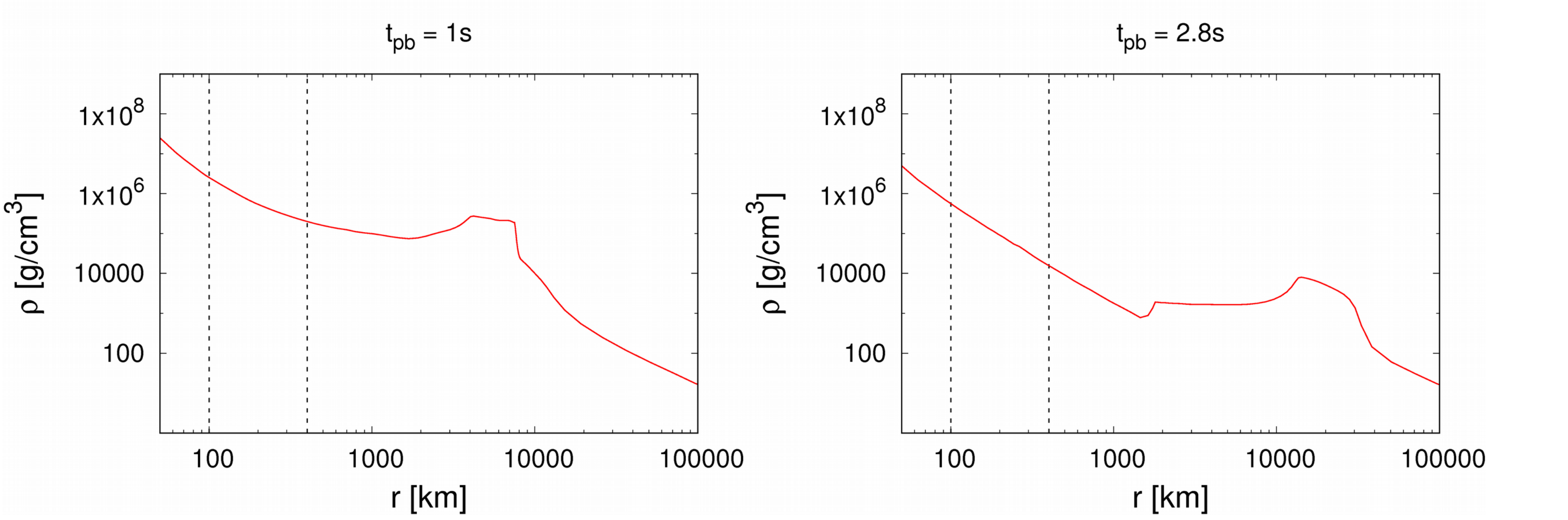
$$H_{V-A}(r,t,\boldsymbol{q})=\sqrt{2}G_F\int\frac{d^3q'}{(2\pi)^3}\left(1-\hat{\boldsymbol{q}}\cdot\hat{\boldsymbol{q}}'\right)\left(\rho(\boldsymbol{q}')-\bar{\rho}^*(\boldsymbol{q}')\right)$$

- Aside from the coupling matrix G, the difference is the very subtle change of using ρ^* compared to ρ.

NSSI with supernova neutrinos

- Using a multi-angle code, we compute the neutrino evolution at two epochs during a core-collapse supernova:
  - an early time t_{pb} = 1.0 s after the core rebounds,
  - a later time t_{pb} = 2.8 s after the bounce.
- The electron density profiles and the neutrino spectra at the neutrinosphere are taken from a simulation by Fischer et al.

Fischer *et al.*, A&A **517** A80 (2010)



- The neutrino mixing parameters are from the PDG.

Flavor preserving NSSI

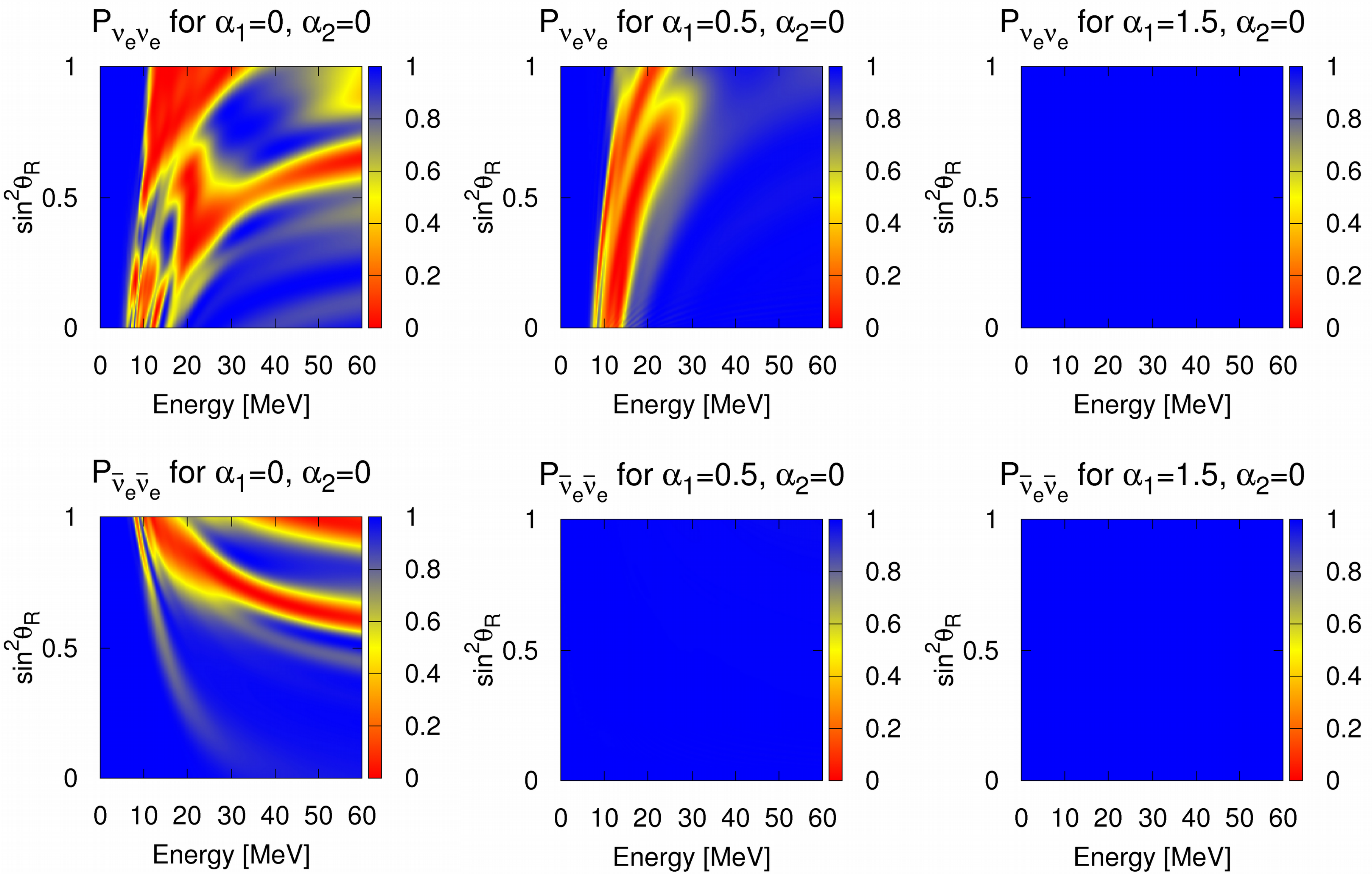
- We shall consider only the case where the G matrix is flavor symmetric and of the form

$$G=\left[\frac{\sqrt{2}\,G_F}{4}\right]^{1/2}\begin{pmatrix}\alpha_1 & \alpha_2 & \alpha_2\\ \alpha_2 & \alpha_1 & \alpha_2\\ \alpha_2 & \alpha_2 & \alpha_1\end{pmatrix}$$

- When α_1 or $\alpha_2 = 1$, the NSSI has the same strength as the V-A.

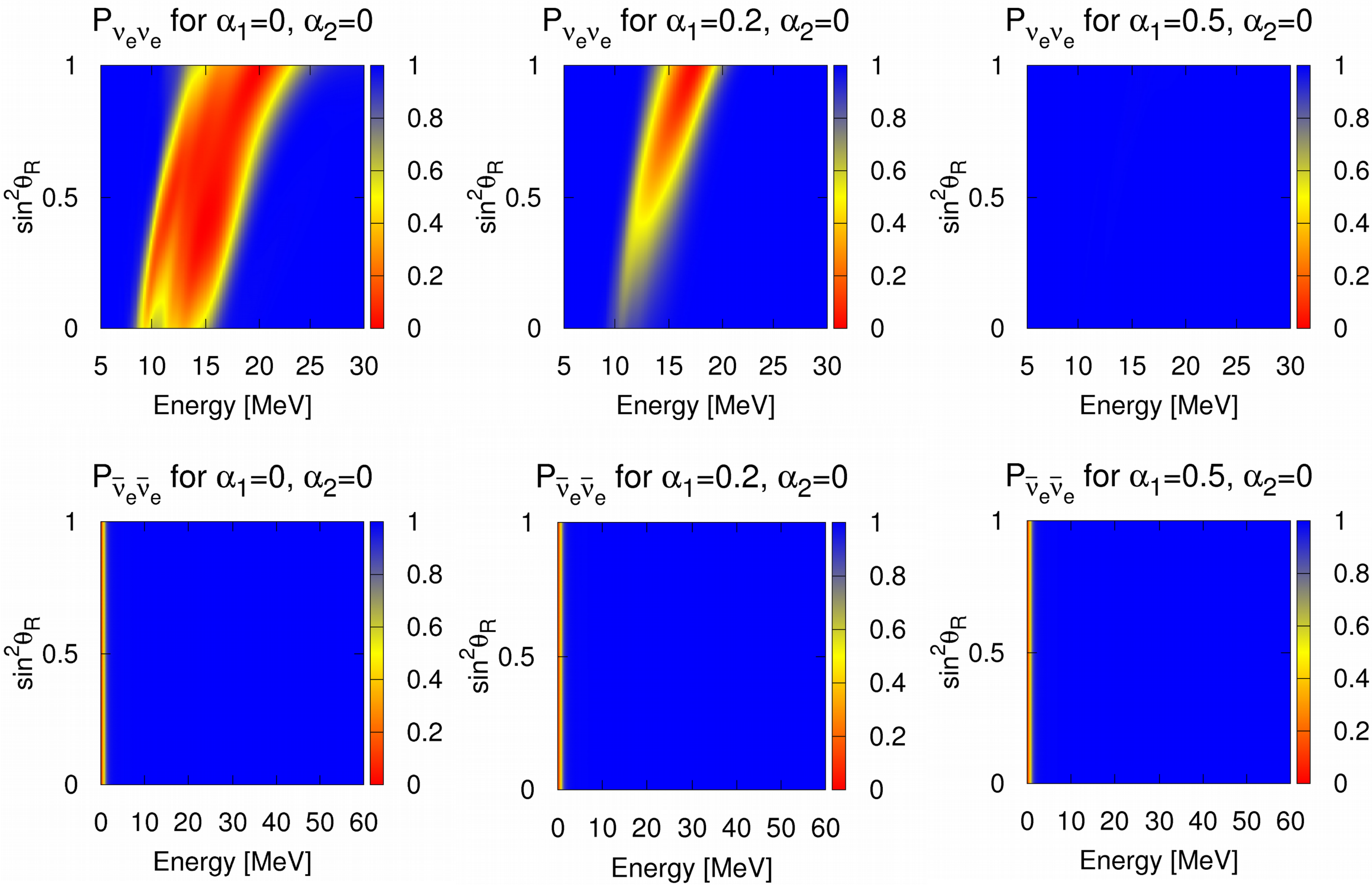
- First consider the $t = 1.0$ s case, an Inverted Mass Ordering and only flavor preserving (FP) NSSI: $\alpha_1 \neq 0$, $\alpha_2 = 0$.

- The survival probability 'heatmaps' at r = 400 km



- As we increase α_1 the self-interaction effects disappear.

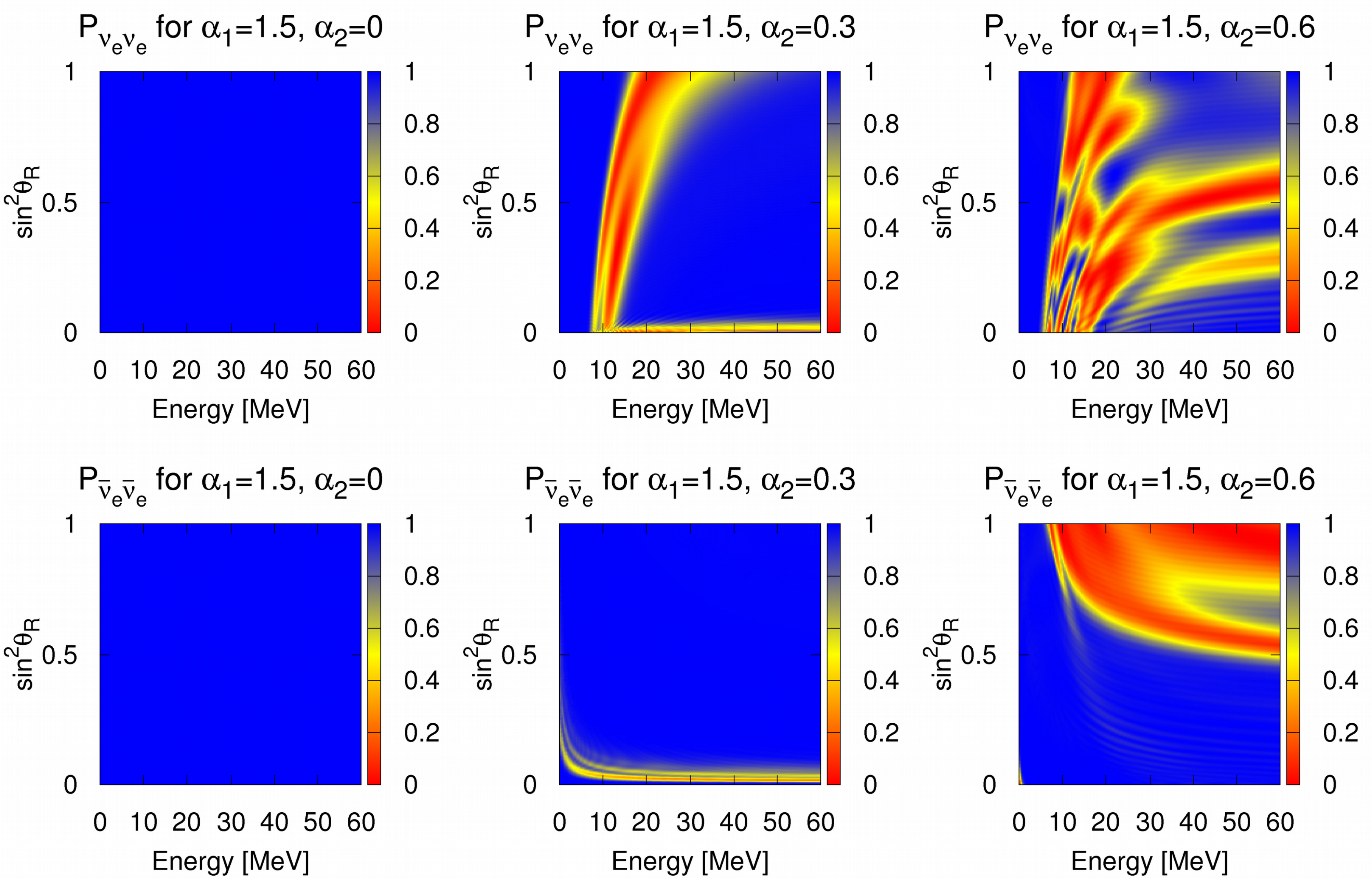
- Now we consider the $t = 2.8$ s epoch.



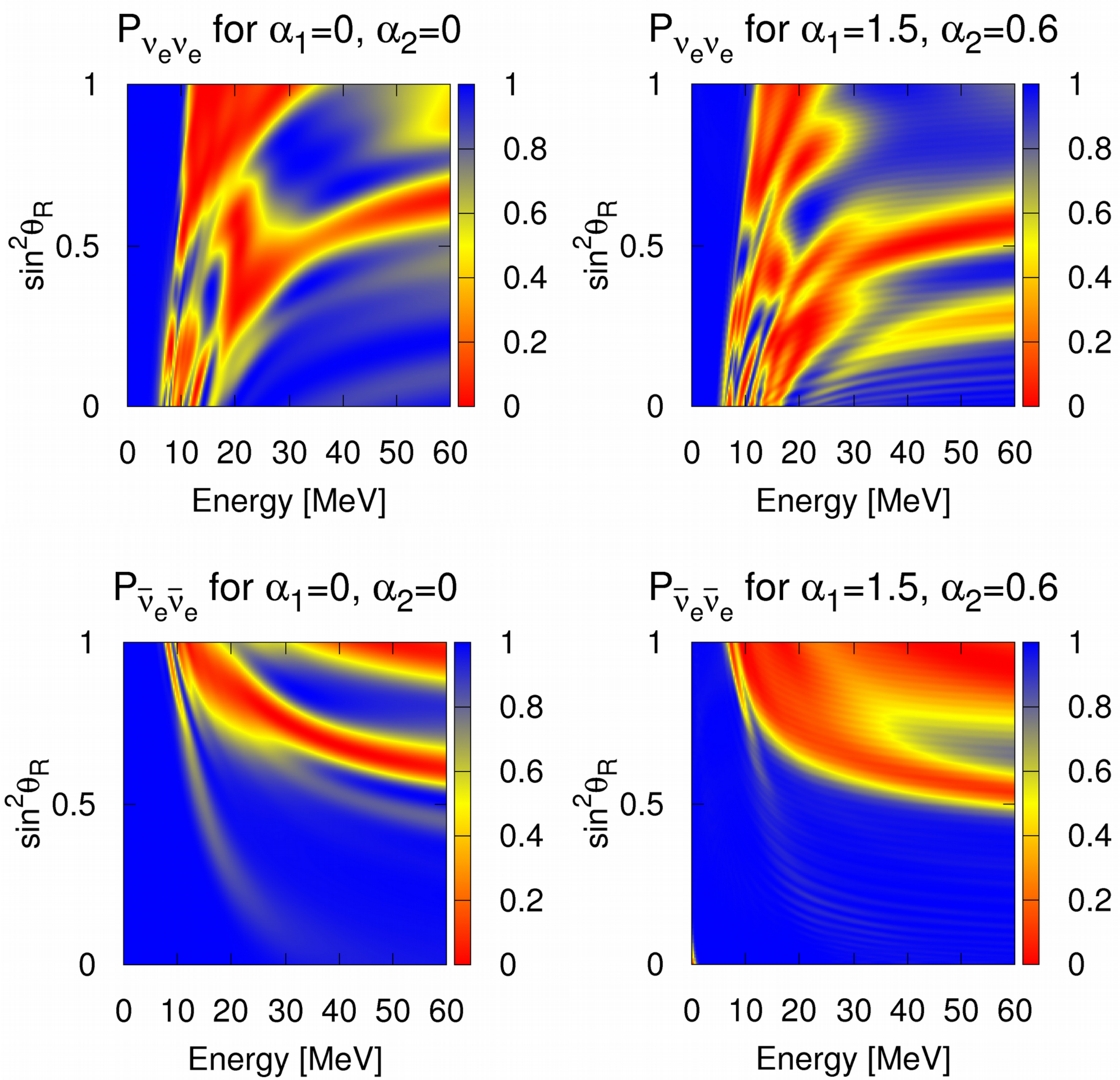
- Again, as we increase α_1 the self-interaction effects disappear

Flavor violating NSSI

- Now consider flavor violating cases: $\alpha_1 \neq 0$, $\alpha_2 \neq 0$ at $t = 1.0$ s

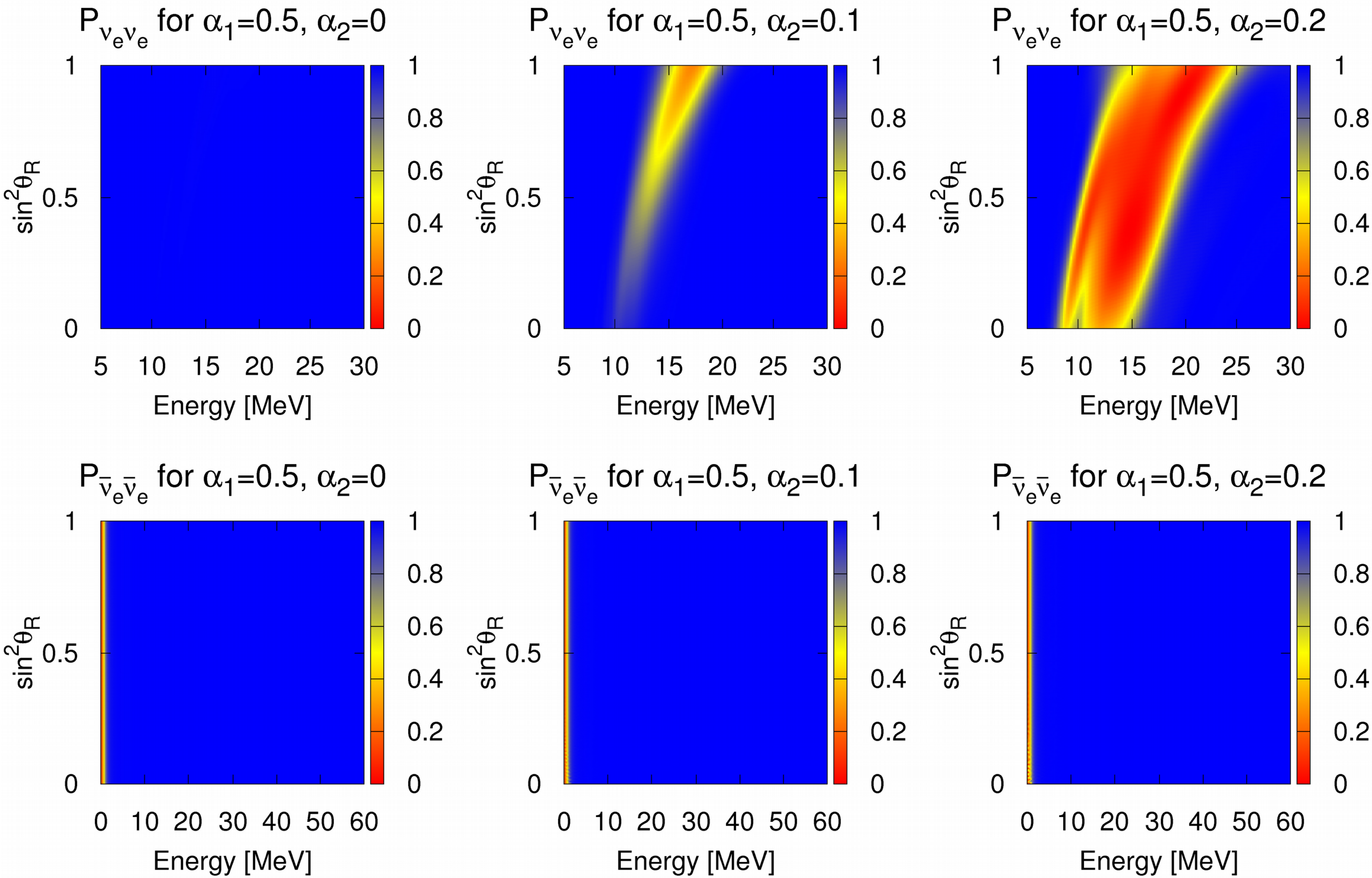


- Flavor violating NSSI restores the self-interaction effects.



- The final result can look very similar to the SM.

- And at $t = 2.8$ s

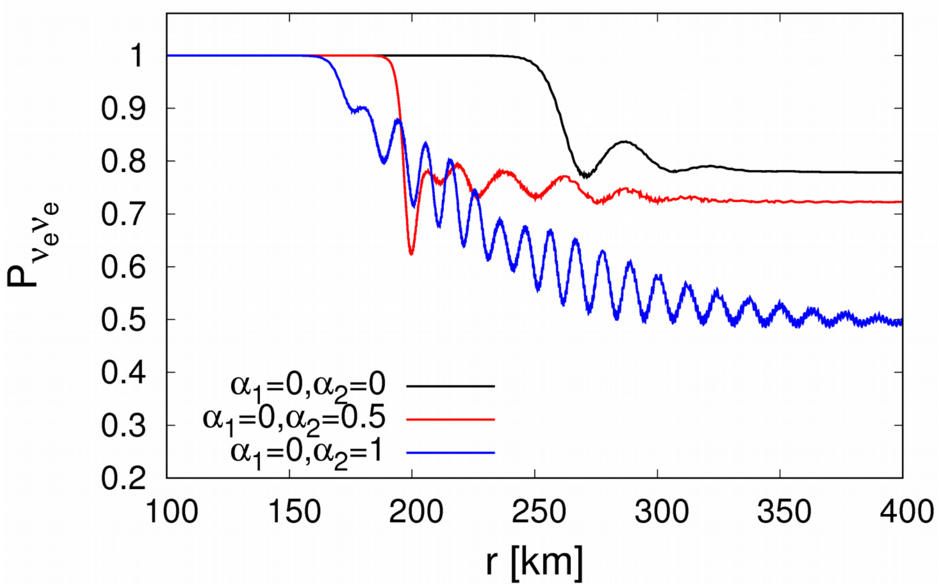


- Again, flavor violating NSSI restores the self-interaction effects and can give results which are almost identical with the SM.

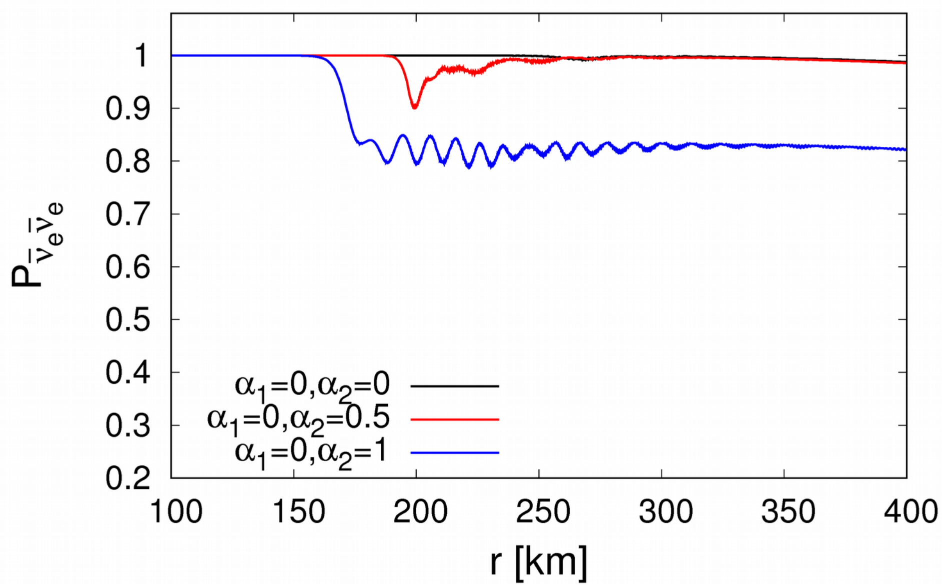
Pure flavor violating NSSI

- Finally we consider pure flavor violating cases, $\alpha_1 = 0$, $\alpha_2 \neq 0$, at $t = 2.8$ s.

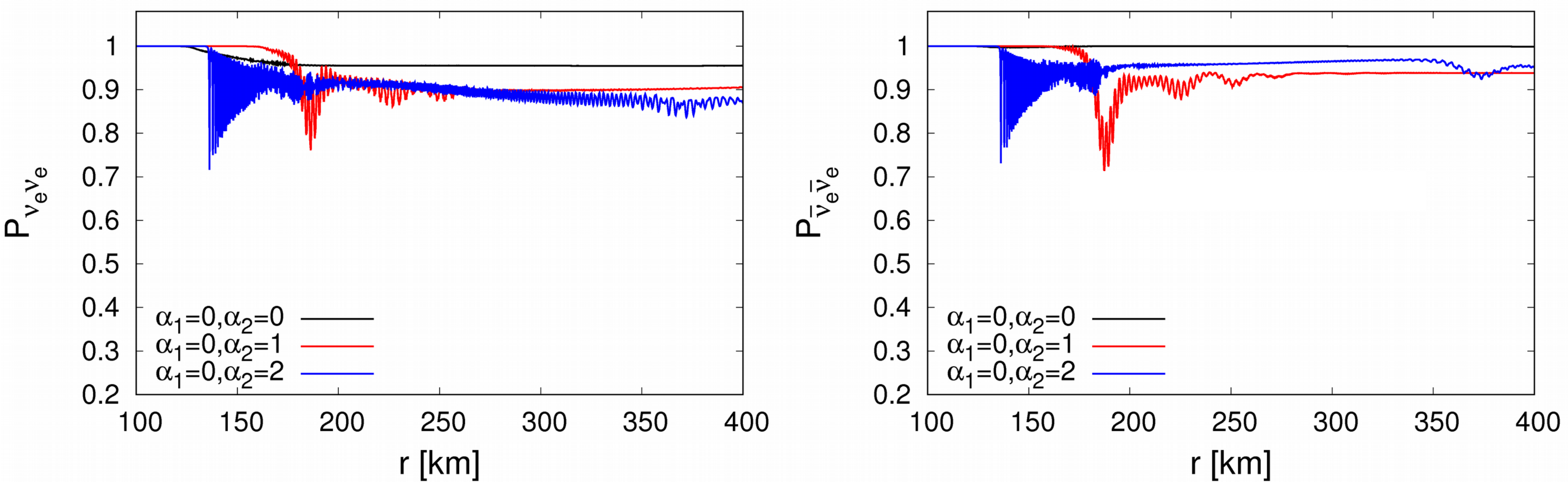
Angle integrated, flux-weighted survival probability



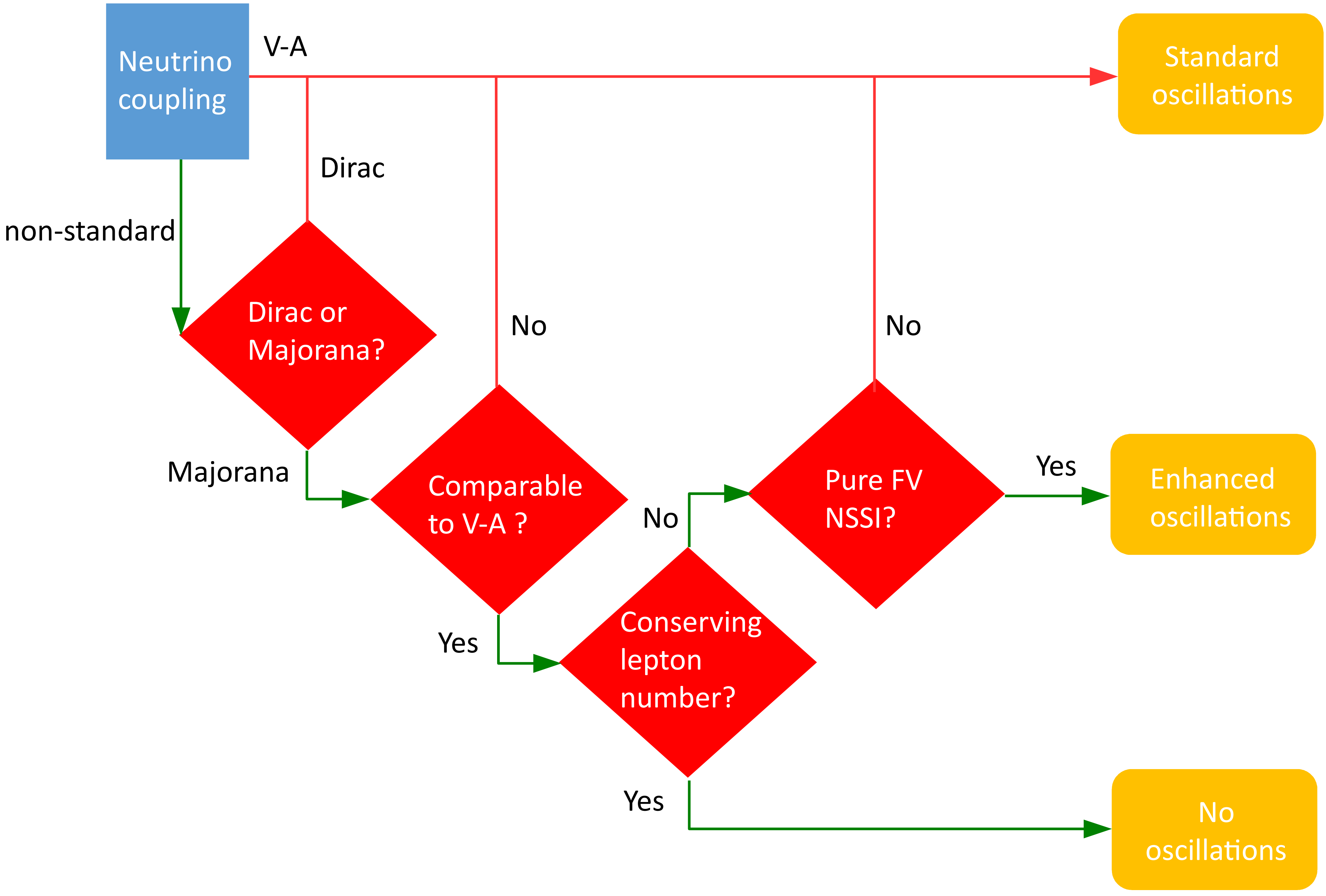
Angle integrated, flux-weighted survival probability



- Pure flavor violating NSSI in the IMO leads to earlier/larger self-interaction effects in the neutrinos and self-interction effects in the antineutrinos where none were before.



- Pure flavor violating NSSI leads to self-interaction effects in the NMO where they were very small without NSSI.



Neutrino coupling
V-A
Standard oscillations
Dirac
non-standard
Dirac or Majorana?
No
No
Majorana
Comparable to V-A ?
Pure FV NSSI?
Yes
Enhanced oscillations
No
Yes
Conserving lepton number?
Yes
No oscillations

Summary

- Supernova neutrinos are sensitive to non-standard scalar / pseudoscalar interactions with other neutrinos if they are Majorana particles.

- Flavor preserving NSSI damp / remove Standard Model neutrino self-interactions effects
- Flavor violating NSSI restores neutrino self-interactions
- Pure flavor violating NSSI promotes neutrino self-interactions

- Future work:
  - the signatures of NSSI in detectors need to be computed.
  - we need an understanding of why NSSI has the effects it does.