Oscillations of supernova neutrinos

Alexander Friedland

Los Alamos

CERN

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Flavor transformations

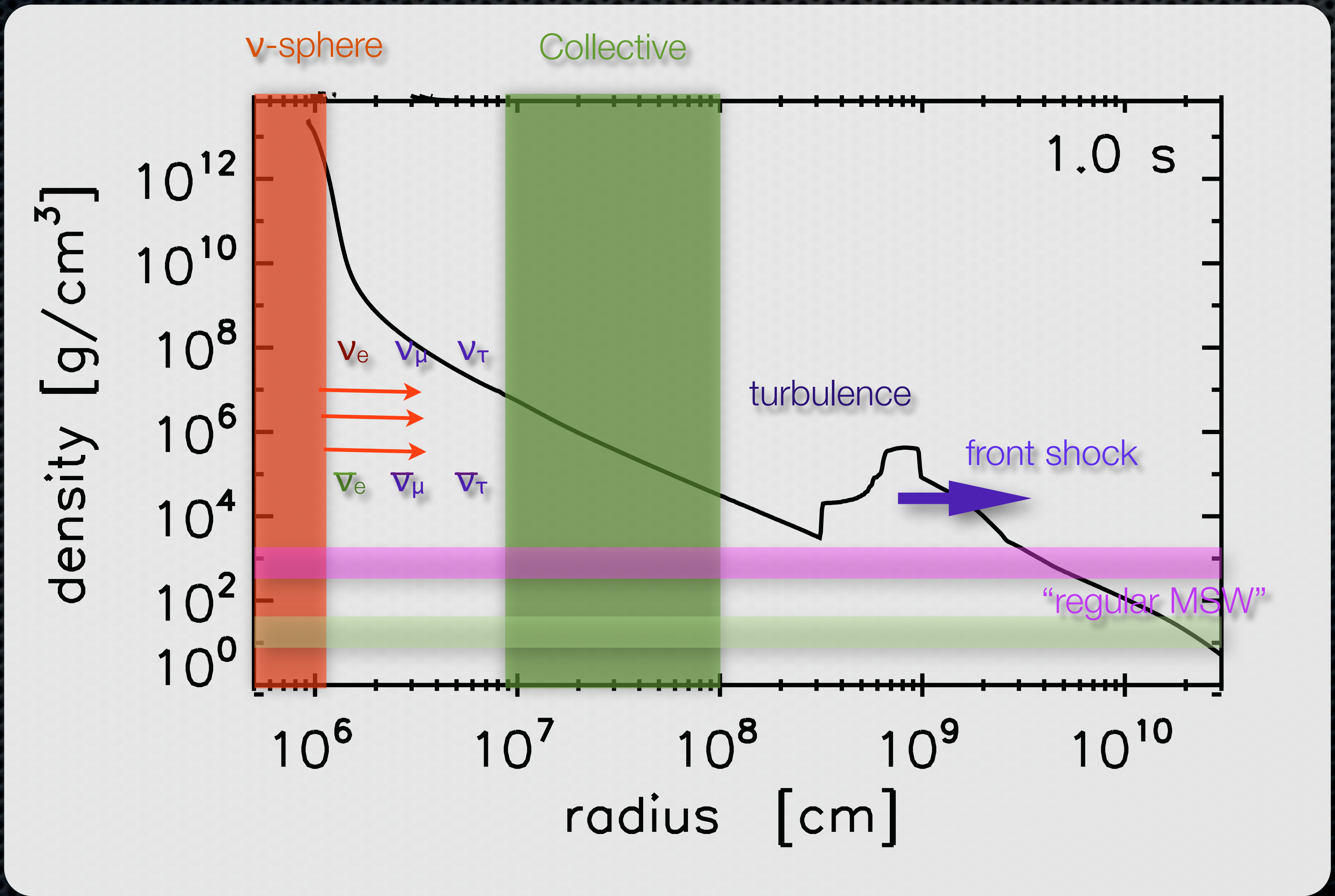
- By now, we know that neutrinos oscillate between flavors
  - Oscillations are seen at solar, atmospheric, reactor, and beam neutrino experiments
- Supernova neutrinos must also transform flavors
  - *no longer optional!*
- Initial spectra of ν_e, anti-ν_e, and $\nu_{\mu\tau}$ are permuted by oscillations in a nontrivial way
  - What's observed on Earth as ν_e, anti-ν_e, is not the original ν_e, anti-ν_e spectra
- To extract physics from the supernova signal, these transformations must be understood!

Why now?

- People are used to thinking about supernova neutrinos as a problem that can always be postponed to next year
  - After all, we are talking about SN2027!
- It turns out we need answers very soon
  - Example: a large detector for the LBNE in the US. People would like to make design decisions over the next several years. What characteristics would be optimal for supernova neutrino detection?
- But why should this be difficult?

The supernova case is MUCH trickier!

- Relevant physical processes (a cartoon)



- Let’s review these physics ingredients
  - As of now, these ingredients haven’t yet been put together in a satisfactory manner

Collective neutrino effects

- Close to the protoneutron star, the neutrino background itself becomes important in the oscillation Hamiltonian

$$\begin{aligned} n_\nu(r) &\sim \frac{L_\nu}{4\pi r^2 c \langle E_\nu \rangle} \\ &\sim \frac{10^{52}\ \mathrm{erg/s}}{4\pi (10^7\ \mathrm{cm}\ )^2 \times 3 * 10^{10}\ \mathrm{cm/s}\ 10^7\ \mathrm{eV}} \\ &\sim 10^{31}\ \mathrm{cm}^{-3} \end{aligned}$$

Fuller et al, 1987; Notzold & Raffelt, 1988; ....

- The neutrino induced contribution is proportional to the density matrix of the background neutrinos

$$\sqrt{2} G_F \sum_{\hat{p}, E_\nu} n_{\hat{p}, E_\nu} (1 - \cos \Theta_{\hat{k}, \hat{p}}) |\psi_{\hat{p}, E_\nu}\rangle \langle \psi_{\hat{p}, E_\nu}|$$

Pantaleone, 1992; Sigl & Raffelt, 1993; ...

Properties of the Neutrino Hamiltonian

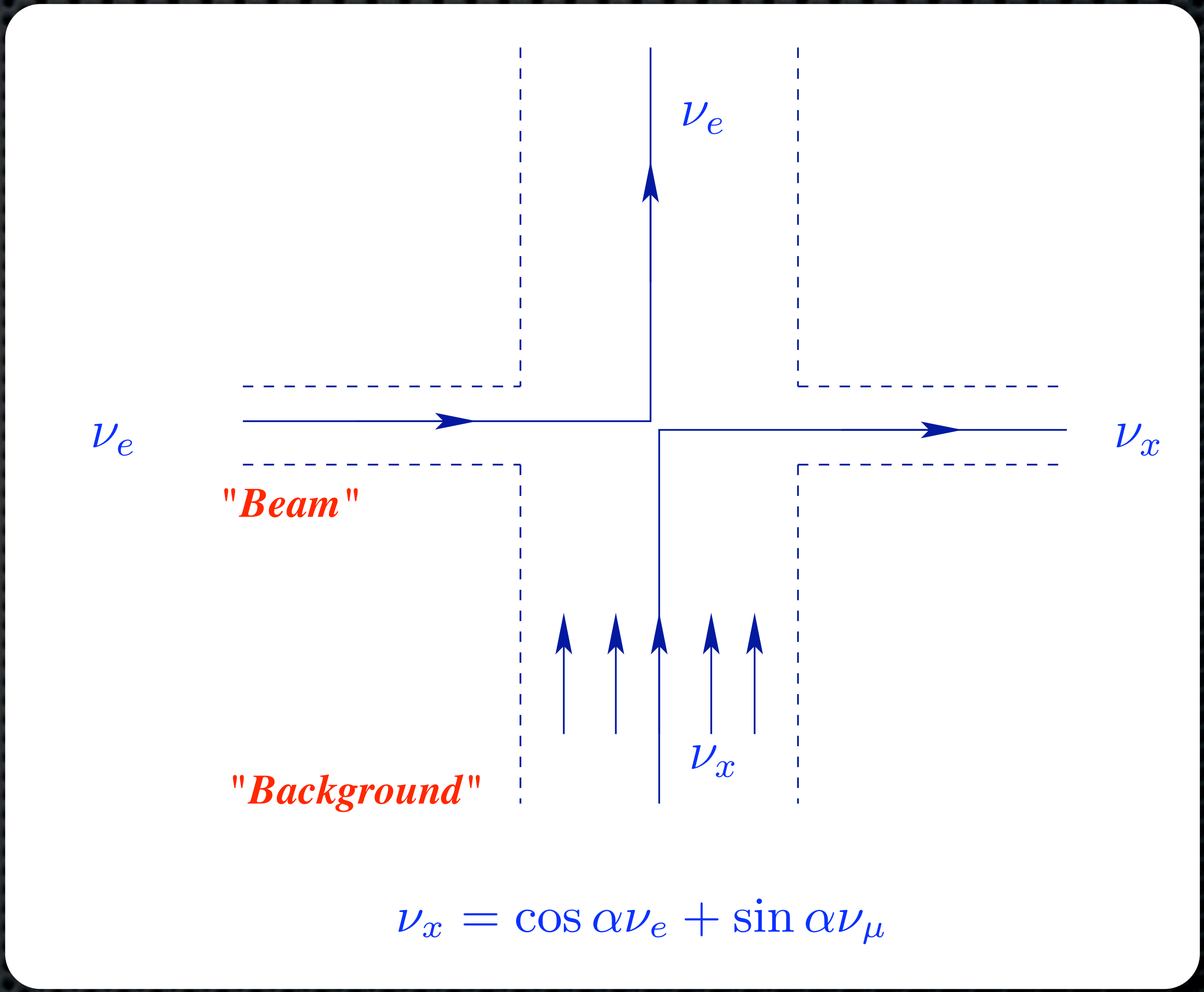
- Neutrinos of different energies and directions are now coupled
- The evolving states of neutrinos are feeding back into the Hamiltonian
- If the background is in a flavor superposition state, the Hamiltonian has nonzero off-diagonal terms -> further flavor conversion

$$|\psi\rangle\langle\psi| \equiv \begin{pmatrix} |\psi_e|^2 & \psi_e\psi_\mu^\dagger \\ \psi_e^\dagger\psi_\mu & |\psi_\mu|^2 \end{pmatrix}$$

- Even if initially neutrinos are almost in flavor states, since the evolution is nonlinear, the off-diagonal terms could, in principle, grow

Neutrino "self-refraction"

- Seemingly bizarre behavior
- Example: Neutrino in the "beam" scatters on an ensemble of the "background" neutrinos
- Maximum flavor conversion not when the beam is made of ν_μ but when it's made of
  - $(\nu_e + \nu_\mu)/\mathrm{sqrt}(2)$
- A oscillation Hamiltonian emerges as the <u>coherent</u> part of the scattering.



From Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

“Multiangle” evolution

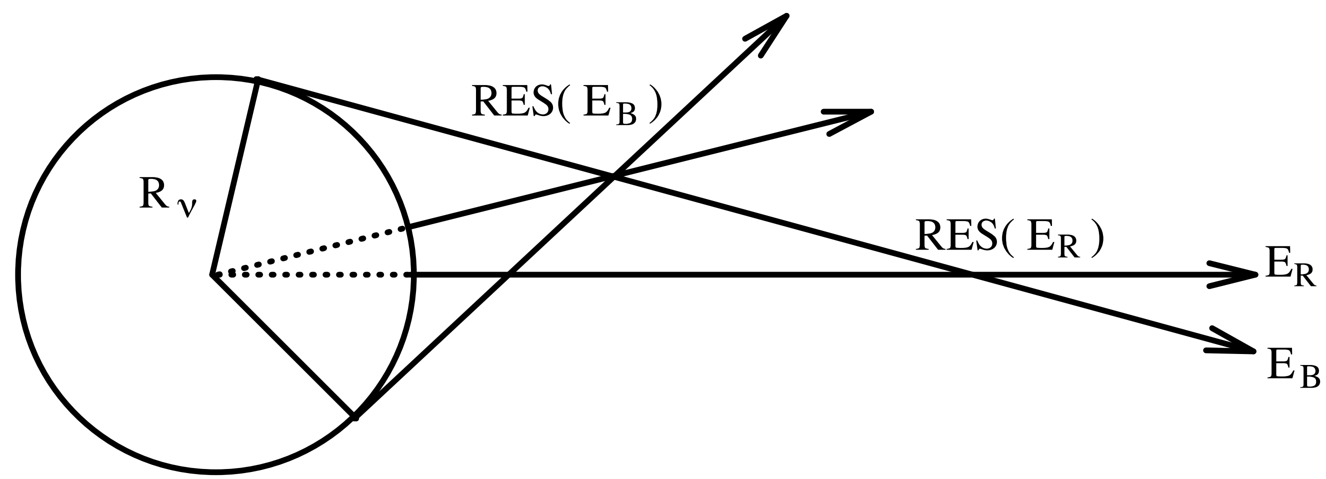


Figure from Qian & Fuller, astro-ph/9406073

- In principle, a complicated numerical problem: coupled neutrinos with different energies and emission angles
- Not enough computing power in 1994

- First supercomputer modeling by Duan, Fuller, Carlson, Qian, 2005, 2006, *major breakthrough*!
  - Convergence achieved when 10^5 - 10^6 angle * energy bins, each of which is quickly oscillating: supercomputing required!
- In the calculations found large flavor transformations at ~ 100-300 km from the collapsed core

Remarkable early work

- Early universe, no anisotropy (no angular bins). Simple, (but fruitful!) modeling
- "However, the nonlinearity of the system creates an instability ... The situation is analogous to a rigid pendulum positioned [...] suddenly inverted."

Kostelecky & Samuel, *Neutrino oscillations in the early universe with an inverted neutrino mass hierarchy*, PLB 318, 127 (1993).

Neutrino oscillations in the early universe with nonequilibrium neutrino distributions, PRD 3184 (1995)

- In fact, a simple neutrino-antineutrino (spin-up, spin-down) system is not just "like" an inverted pendulum, it is exactly it!

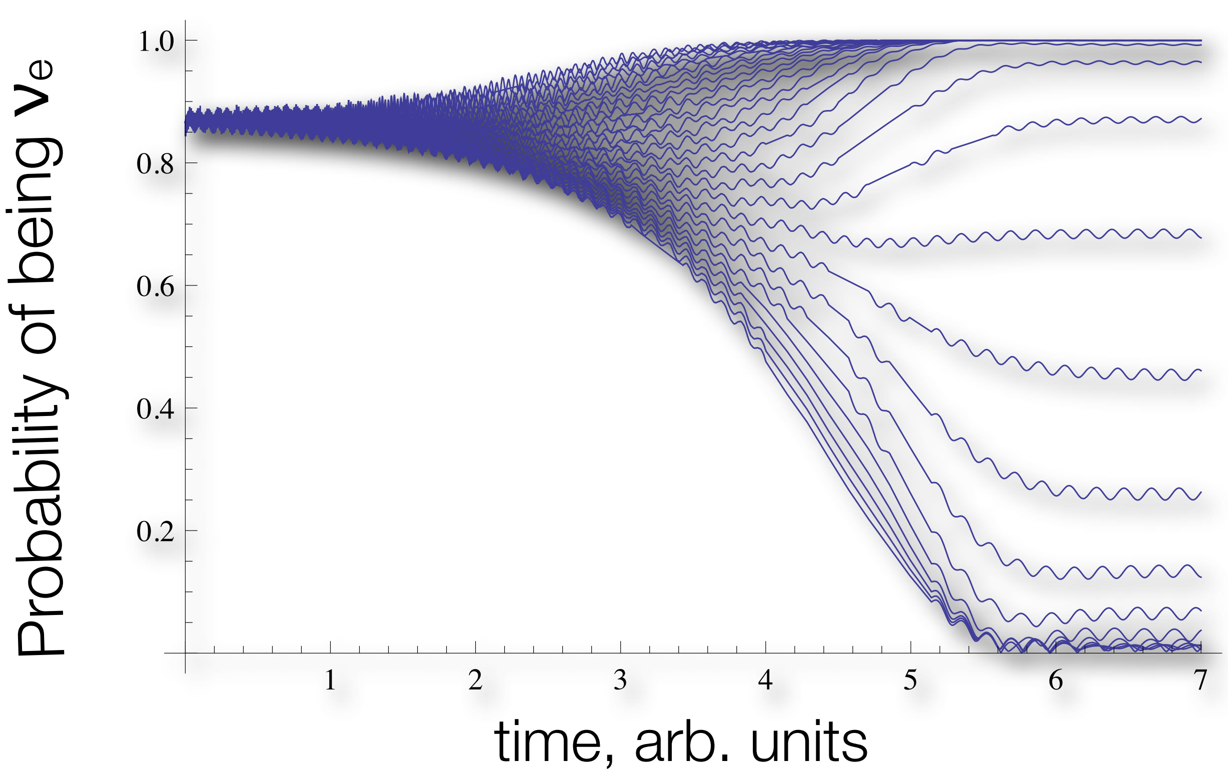
Hannestad, Raffelt, Sigl, Wong, *Self-induced conversion in dense neutrino gases: Pendulum in flavour space*, PRD74, 105010 (2006)

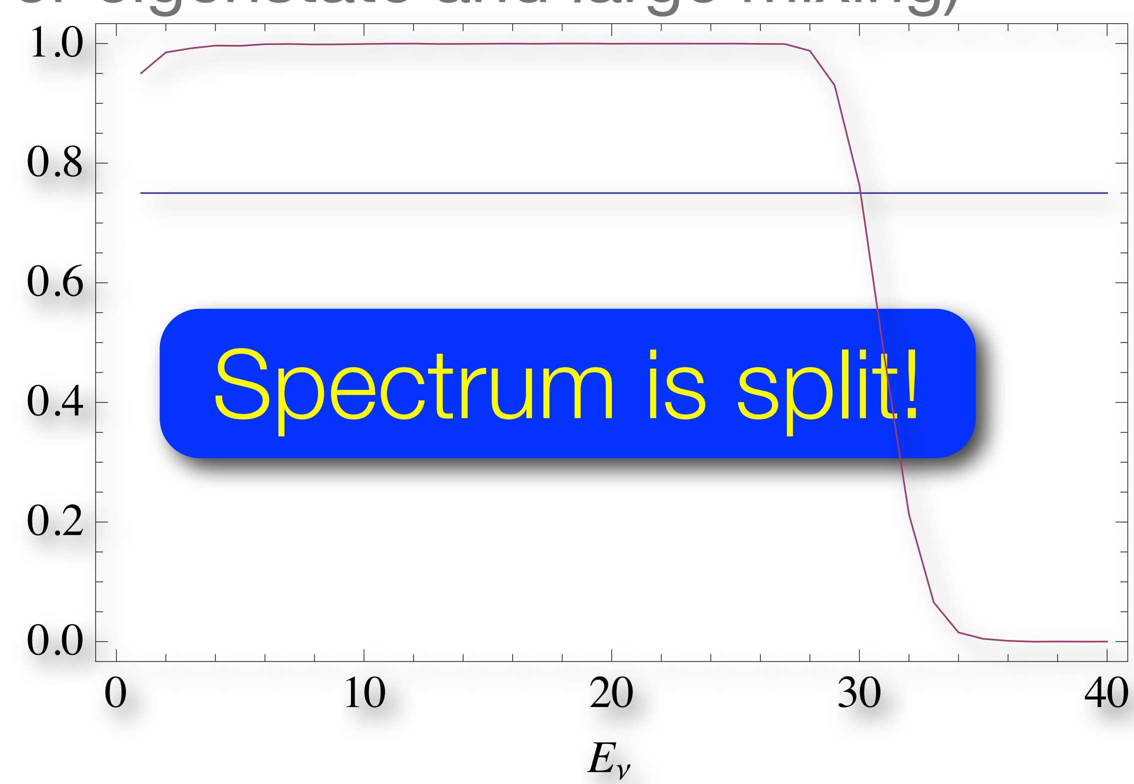
Spectral splits: simplest toy problem (after Raffelt & Smirnov, 2007)

- Start with 40 neutrinos of different energies, all initially in the same flavor superposition state $\cos\theta_0\,|\nu_e\rangle + \sin\theta_0\,|\nu_\mu\rangle$. Take small vacuum mixing.

- Let the self-coupling be large initially (much larger than the vacuum oscillation terms for these neutrinos).

- Relax the self-coupling gradually to zero. What is the final state of this system? (This can also describe initial flavor eigenstate and large mixing)

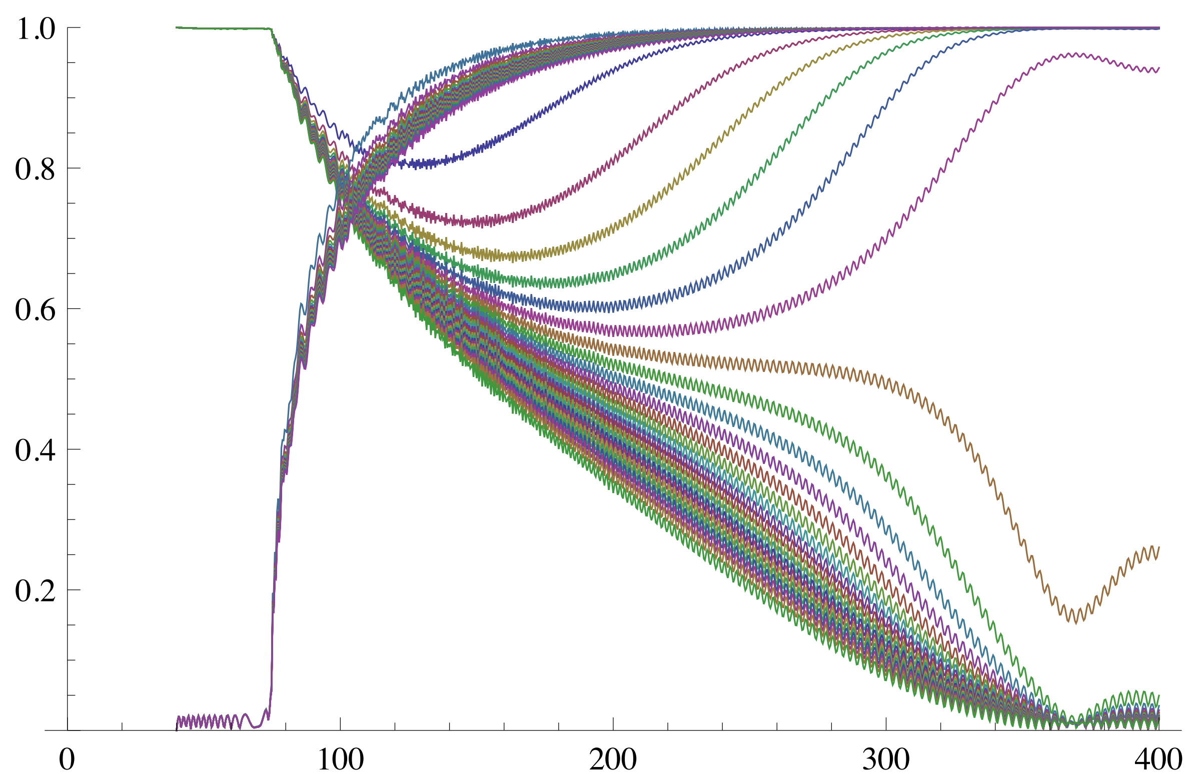


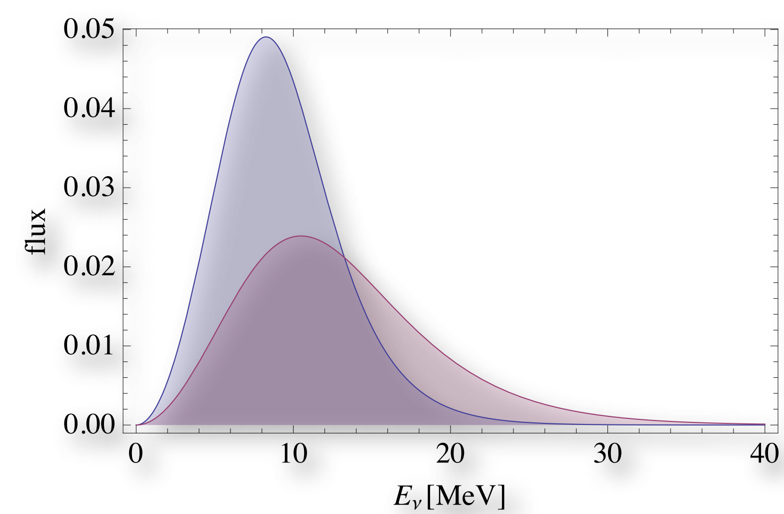


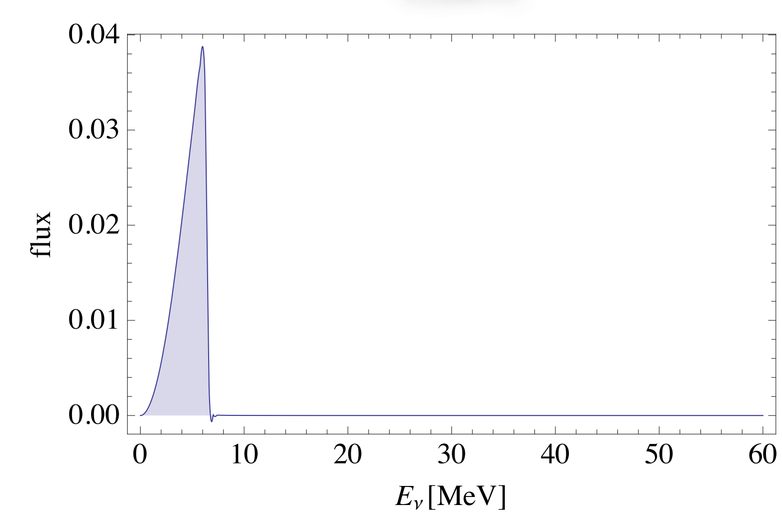
Electron neutrinos and antineutrinos

- Electron and anti-electron neutrinos in the initial state, but no mu, tau neutrinos (rough toy model of the accretion regime)

- Electron anti-neutrinos are entirely converted into anti-mu; neutrinos are split: low-energy part of the spectrum remains nu_e

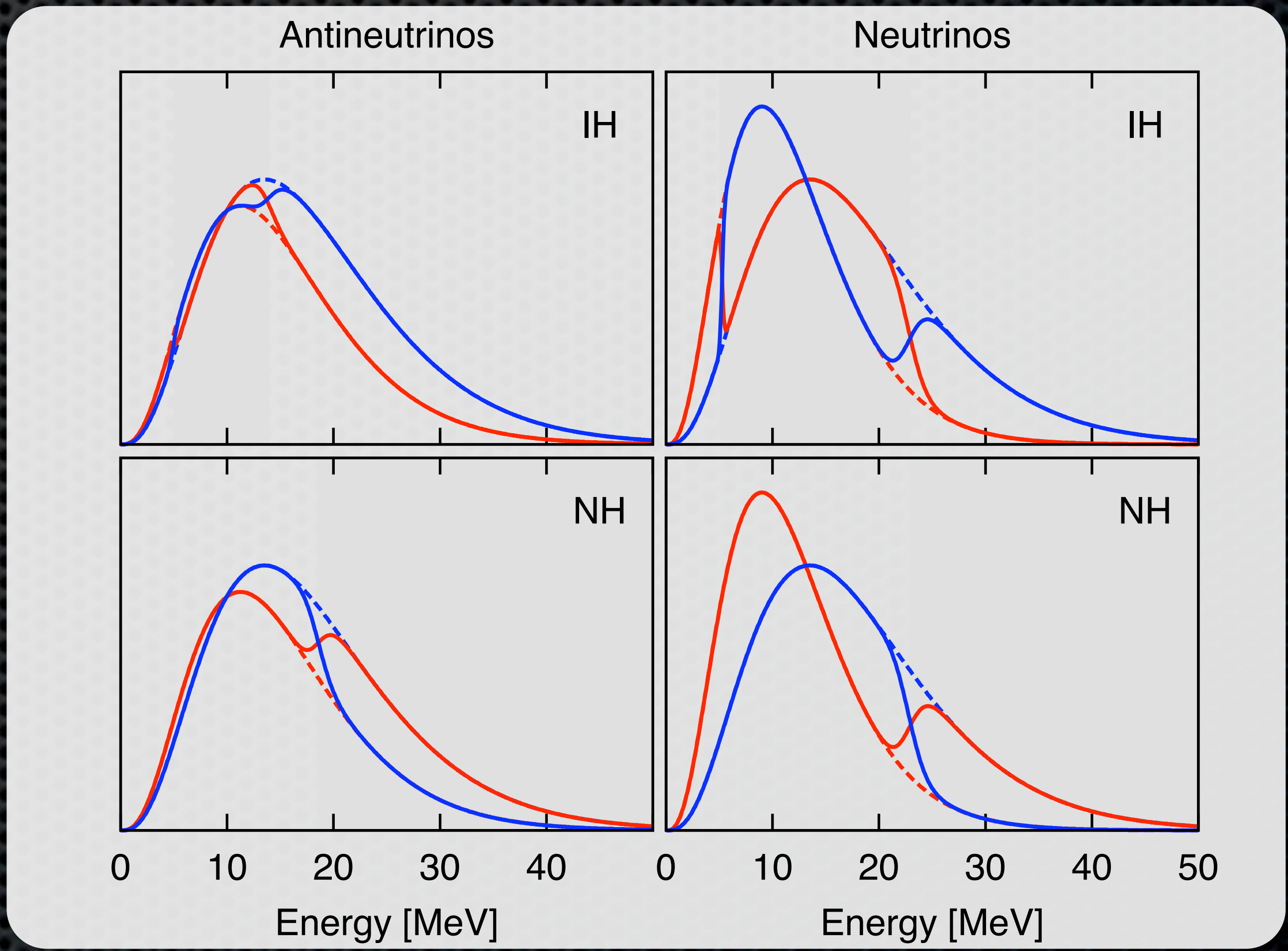






Multiple spectral splits

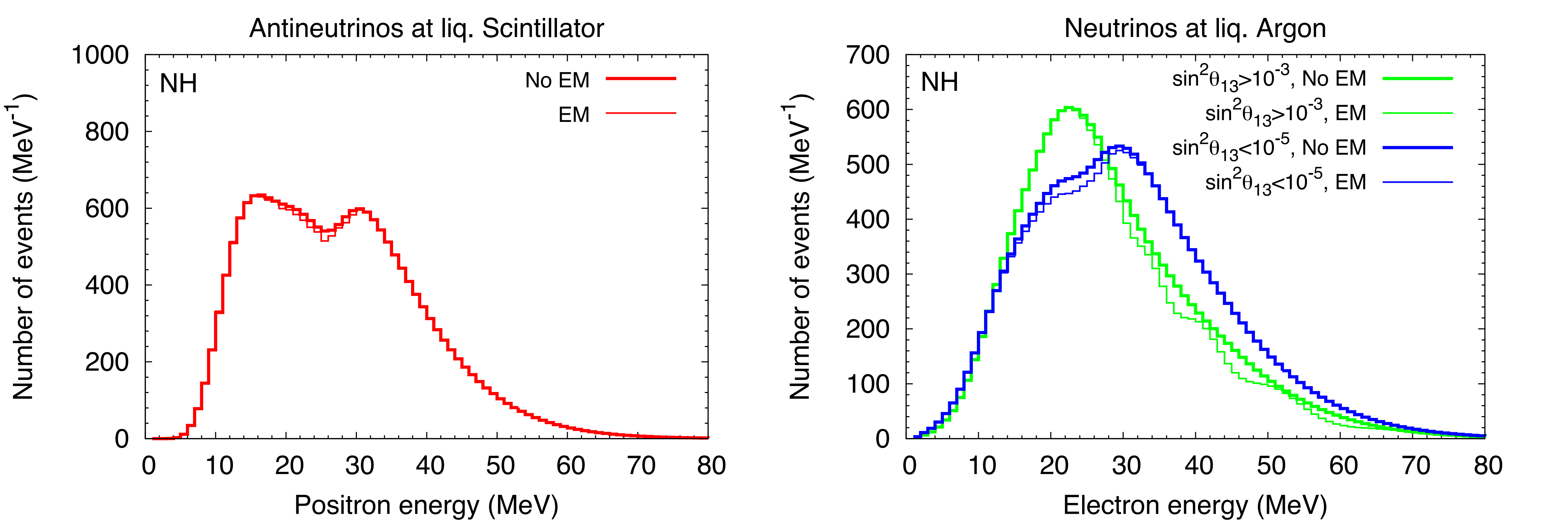
- Calculations with the late-time spectra of the type we are interested in seem to give very curious results, including multiple spectral splits
  - This can be potentially very significant: high energy features are easier to observe



Dasgupta, Dighe, Raffelt, Smirnov, arXiv:0904.3542 [hep-ph] -> PRL (2009)

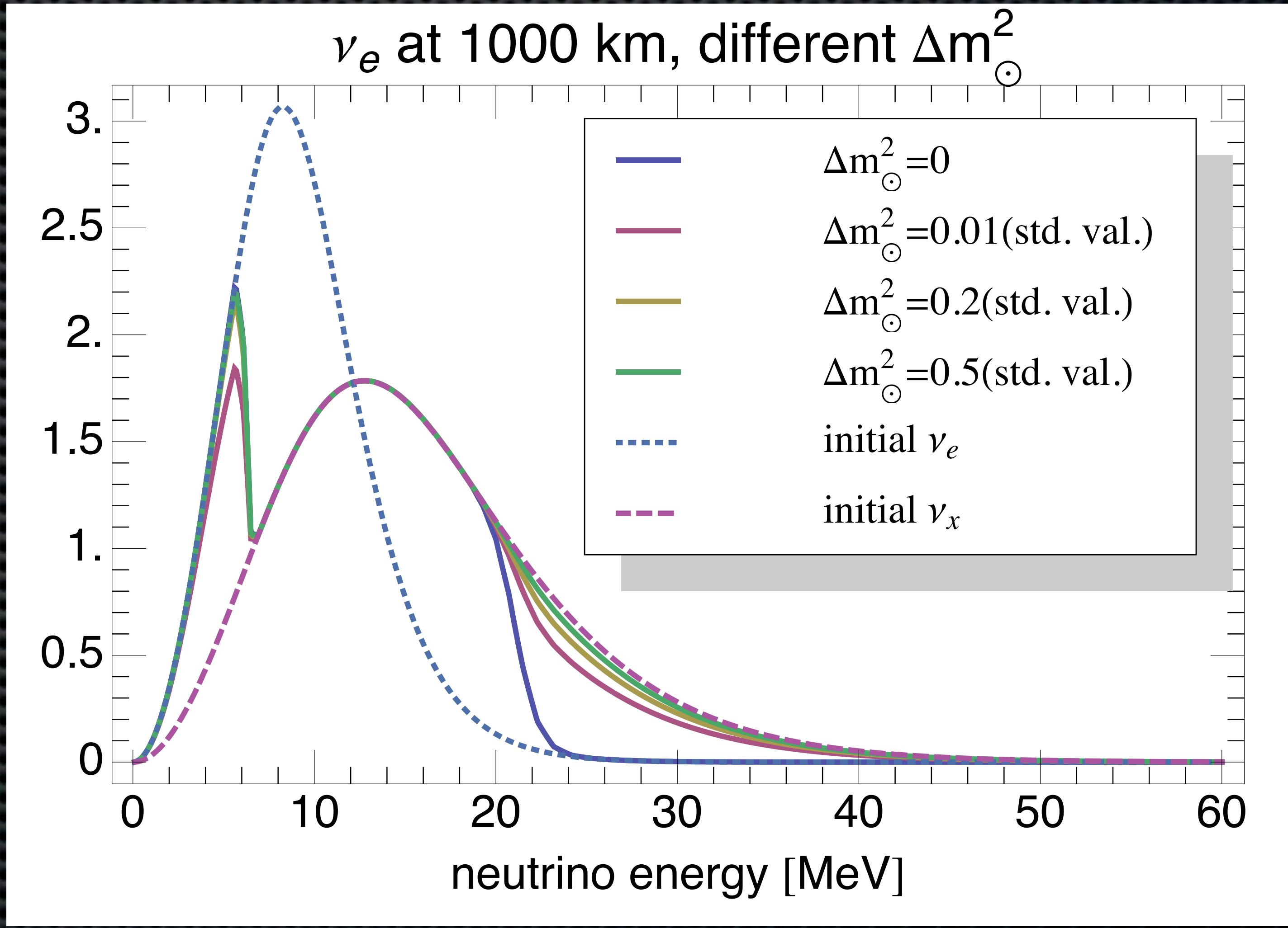
High energy splits are much easier to see!

- Example: from Choubey, Dasgupta, Dighe, Mirizzi, arXiv:1008.0308



More fun: 3-flavor effects

- adding solar $\Delta m_\odot^2$ can drastically change the evolutions
- At first glance, this result is extremely weird:
  - At $\Delta m_\odot^2=0$, 2-flavor result is reproduced
  - As soon as $\Delta m_\odot^2\neq 0$, the answer is closer to the realistic $\Delta m_\odot^2$ than to $\Delta m_\odot^2=0$

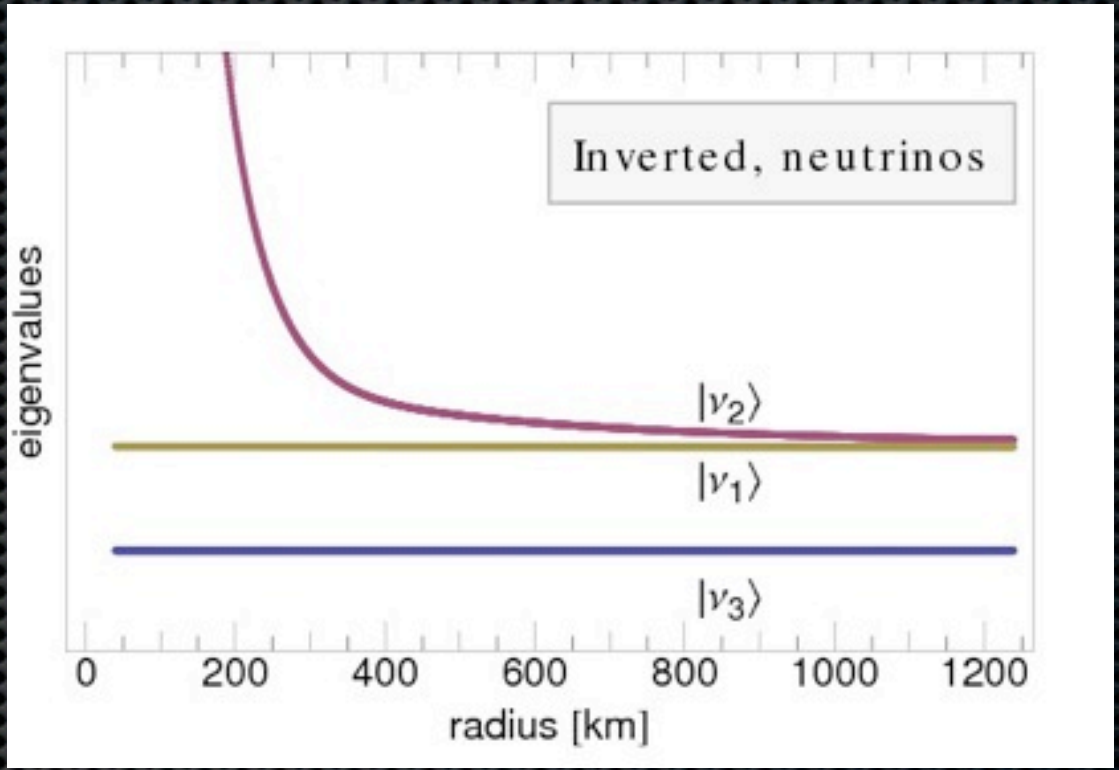


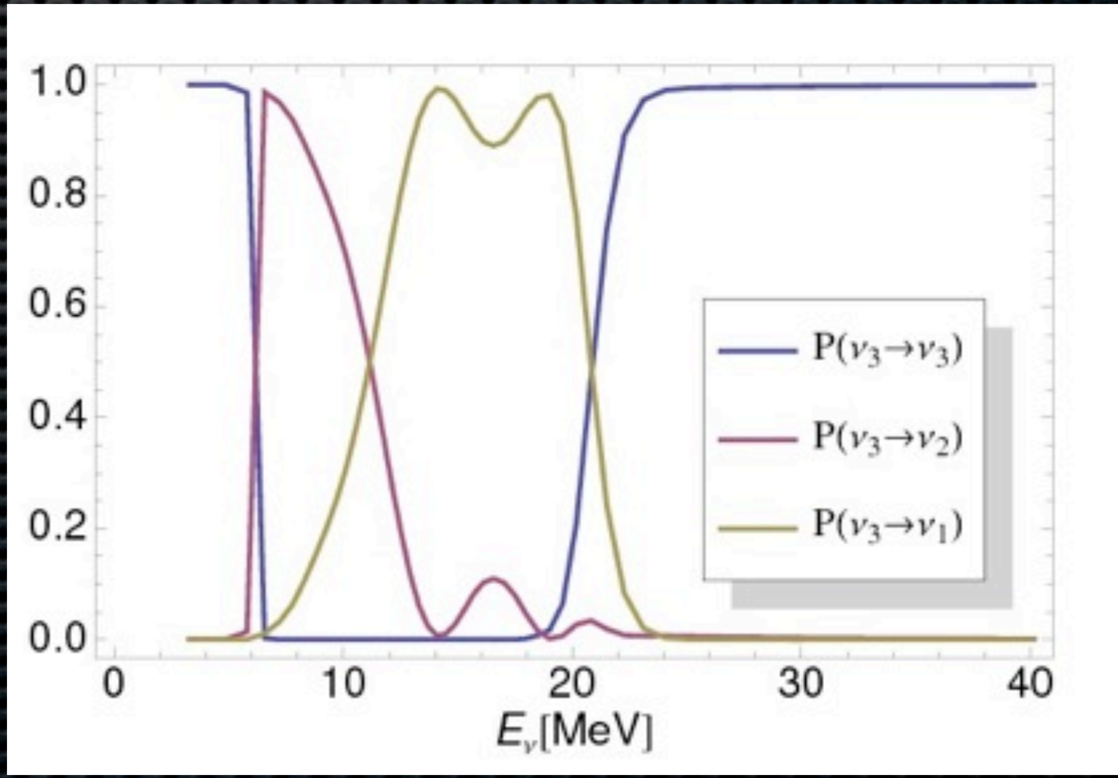
For details, see A. Friedland, Phys. Rev. Lett.104, 191102 (2010)

3-flavor pattern of transitions

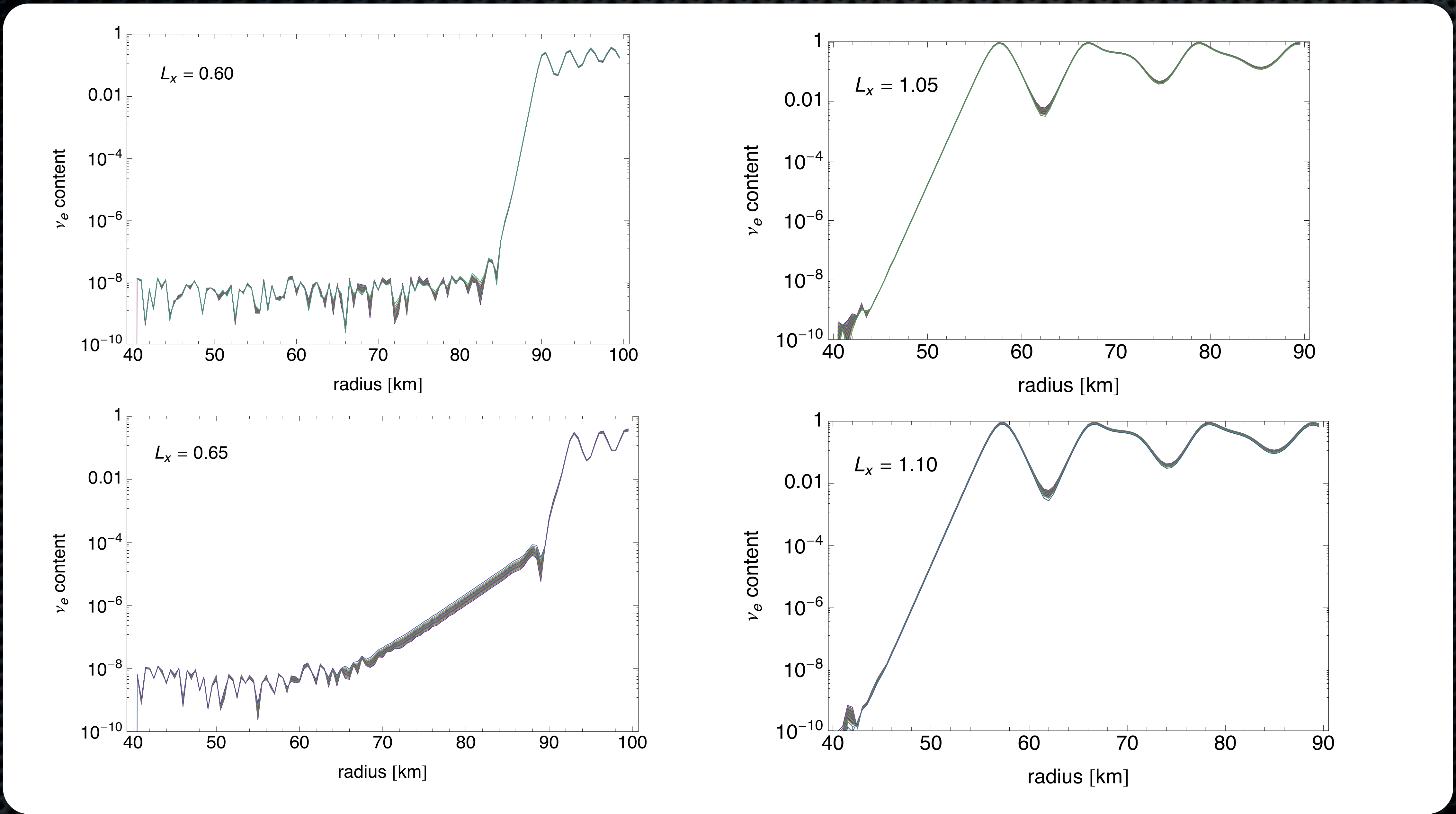
- $E_\nu < 6$ MeV:
  - no permulations
- 6 MeV $< E_\nu <$ 10 MeV
  - $\nu_1 \rightarrow \nu_1$, $\nu_2 \leftrightarrows \nu_3$,
- 10 MeV $< E_\nu <$ 20 MeV
  - $\nu_2 \rightarrow \nu_3$, $\nu_3 \rightarrow \nu_1$, $\nu_1 \rightarrow \nu_2$
- $E_\nu >$ 20 MeV
  - $\nu_1 \leftrightarrows \nu_2$, $\nu_3 \rightarrow \nu_3$

For details, see A. Friedland, Phys. Rev. Lett.104, 191102 (2010)





Look where oscillations start

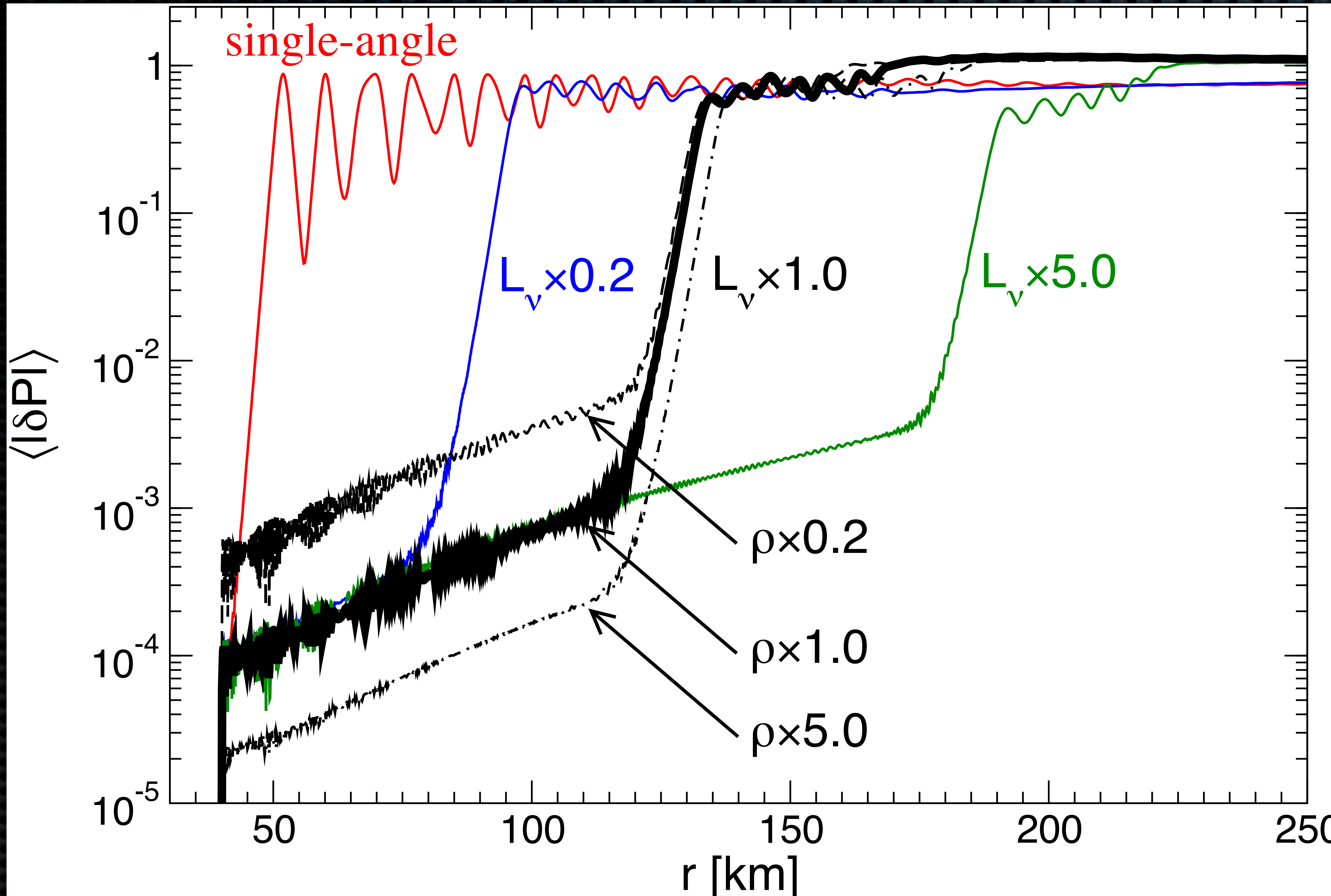


Varying luminosity of the *nonelectron* flavors

Single-angle calculations

This is potentially dangerous

- Calculations of collective transformations assume the free-streaming regime
  - i.e., oscillations and collisions are separated
  - at the very least, results have to pass a consistency check
- If oscillations start close to the neutrino-sphere, they could affect transport/decoupling
  - Implications for the SN transport paragidm?



Multiangle suppression

Independent of density, dependent on luminosity

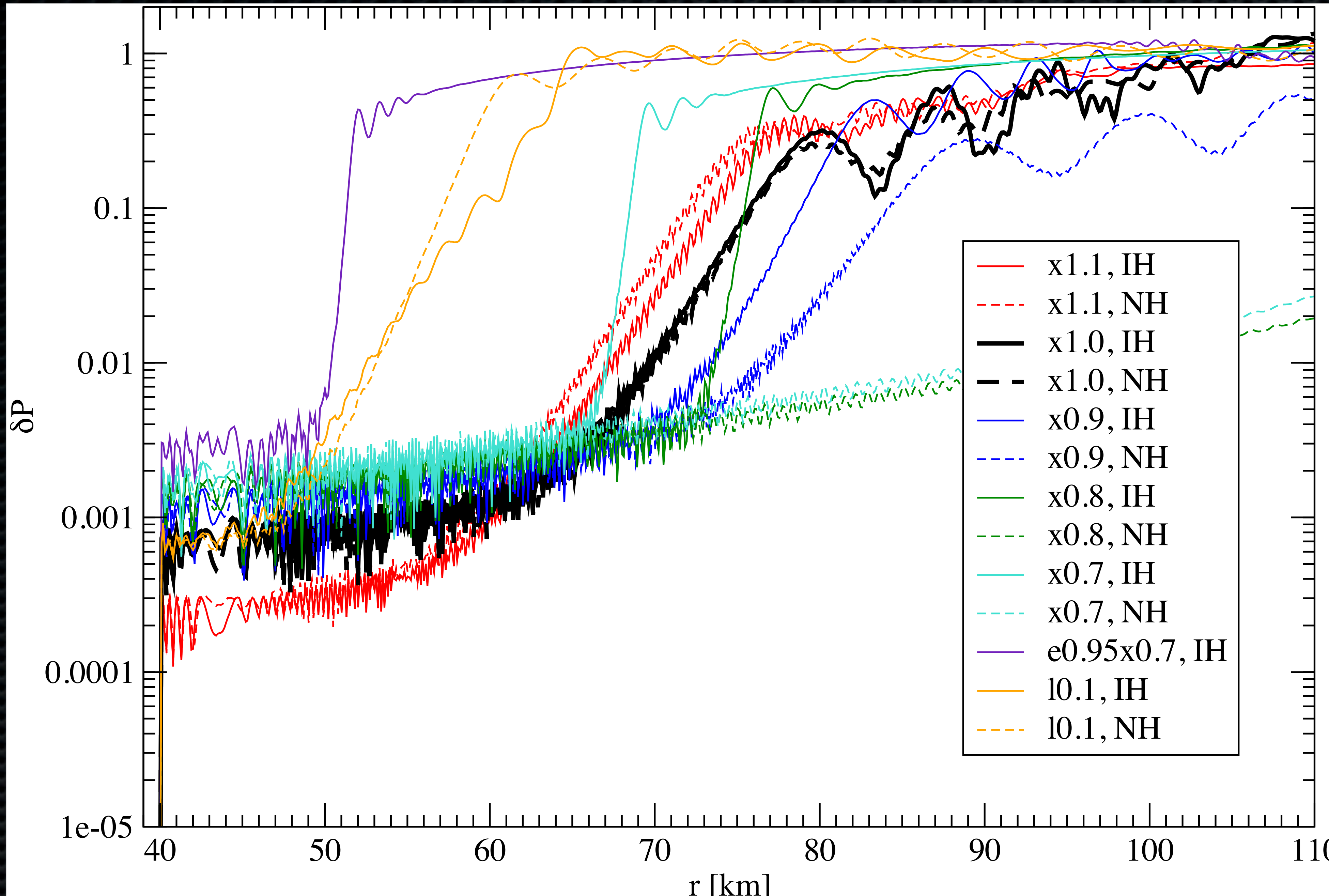
From Duan & Friedland, PRL (2011)

- The collective regime: neutrino-neutrino coupling stronger than the vacuum term

$$G_F|N_\nu - N_{\bar{\nu}}|\langle 1 - \cos\Theta(r_{\nu\nu})\rangle \gtrsim \Delta m^2/E_\nu.$$

- Yet, flavor conversion is only observed when they become comparable

$$|N_\nu - N_{\bar{\nu}}|\langle 1 - \cos\Theta(r_{\nu\nu})\rangle \sim \Delta m^2/(G_F E_\nu),$$



Onset depends on L_x, L_e fluxes

implications for nucleosynthesis

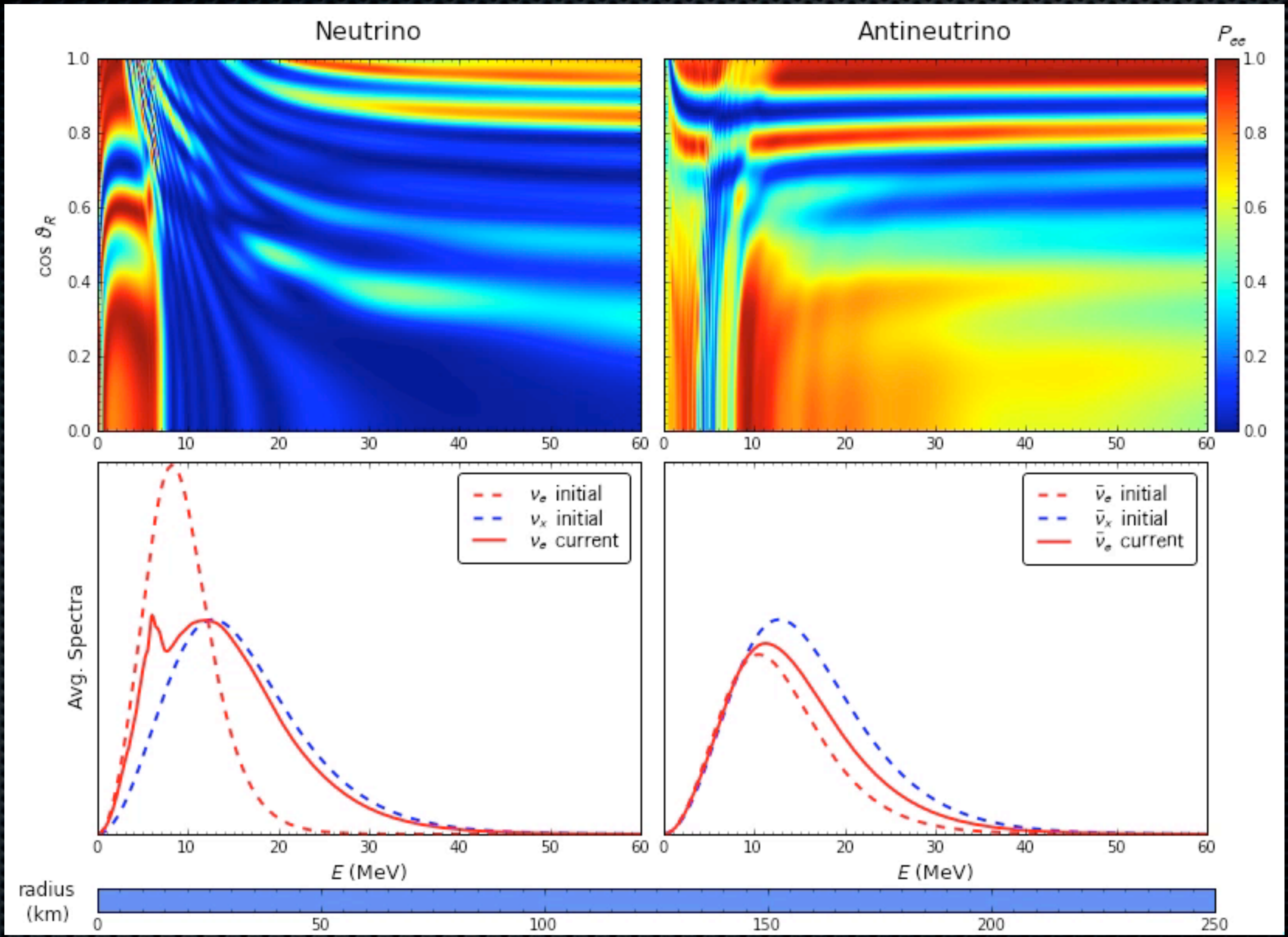
see, e.g., Duan, Friedland, McLaughlin, Surman, The influence of collective neutrino oscillations on a supernova r-process, J. Phys. G G38, 035201 (2011)

always suppressed at small r

Code validation?

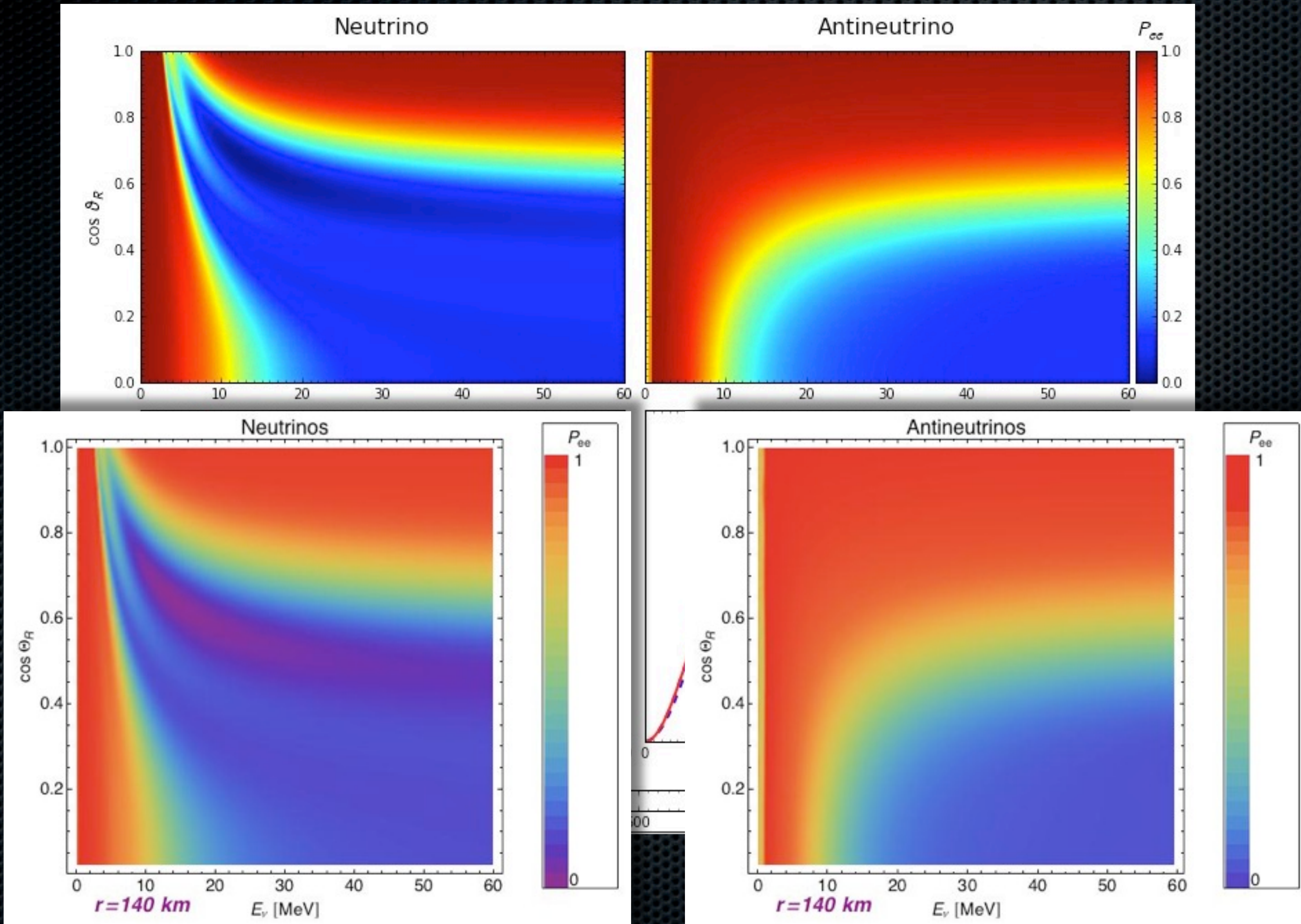
- The original results by Duan, Carlson, Fuller, Qian (2006) were computed with two different codes
- Also, the Bari group (Fogli at al) presented a multiangle calculation in 2007, which agreed with Duan et al and was a major step toward the acceptance of the results
- More examples: Recent work by Mirizzi &Tomas, arXiv:1012.1339, is in agreement with Duan & Friedland, arXiv:1006.2359
- I did some comparisons between my and Duan's code
  - Codes by different people who haven't seen each other's codes ✔
  - Run the same test problem ✔
  - Compare results without tweaking ✔

Duan & Friedland, PRL (2011)

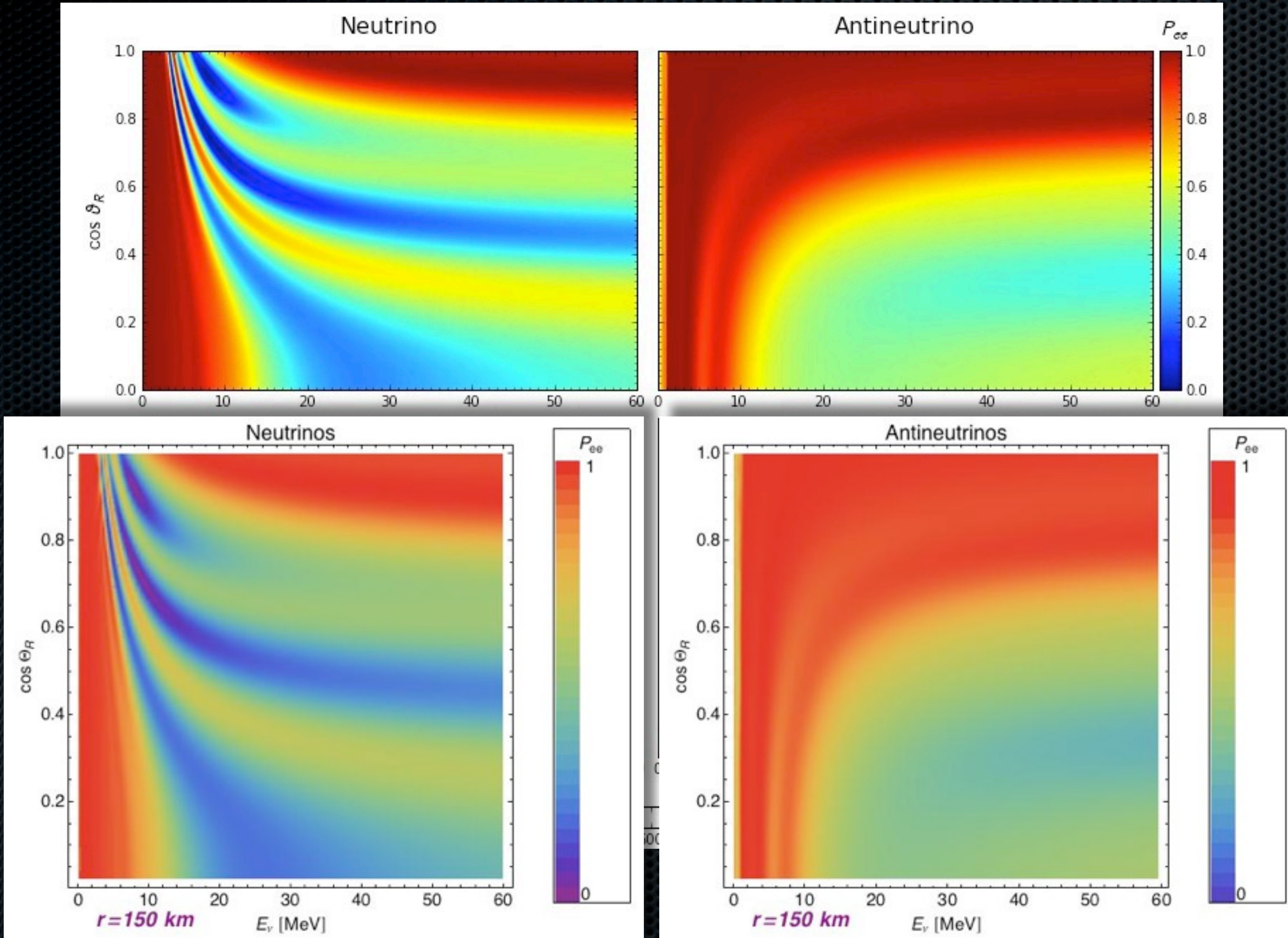


Complicated multiangle evolution!

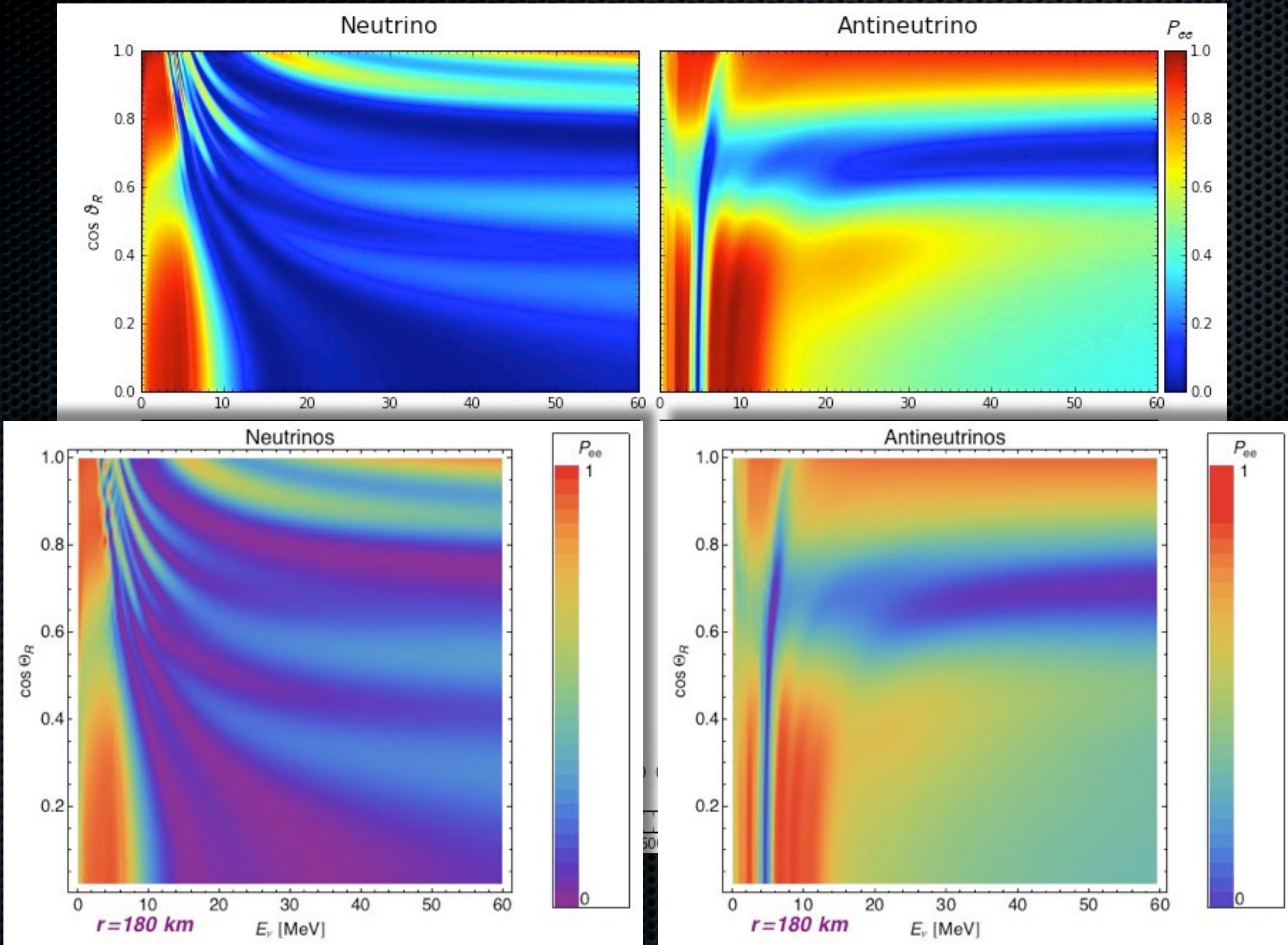
r = 140 km


Neutrino
Antineutrino
P_{ee}
$\cos \vartheta_R$
Neutrinos
Antineutrinos
$\cos \Theta_R$
r=140 km
E_ν [MeV]
r=140 km
E_ν [MeV]

r = 150 km

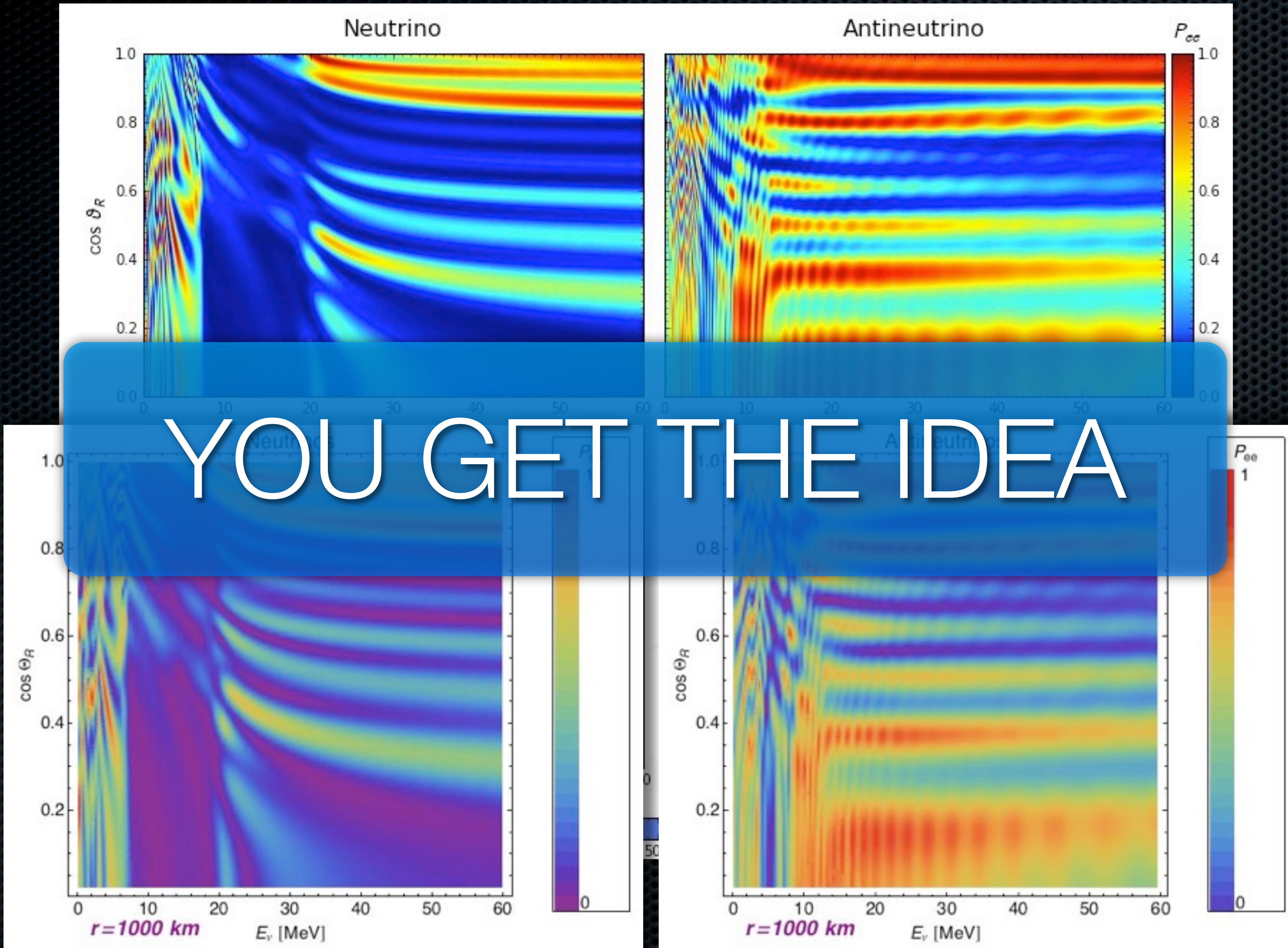

Neutrino
Antineutrino
P_{ee}
$\cos\vartheta_R$
Neutrinos
Antineutrinos
$\cos\Theta_R$
r=150 km
E_ν [MeV]

r = 180 km

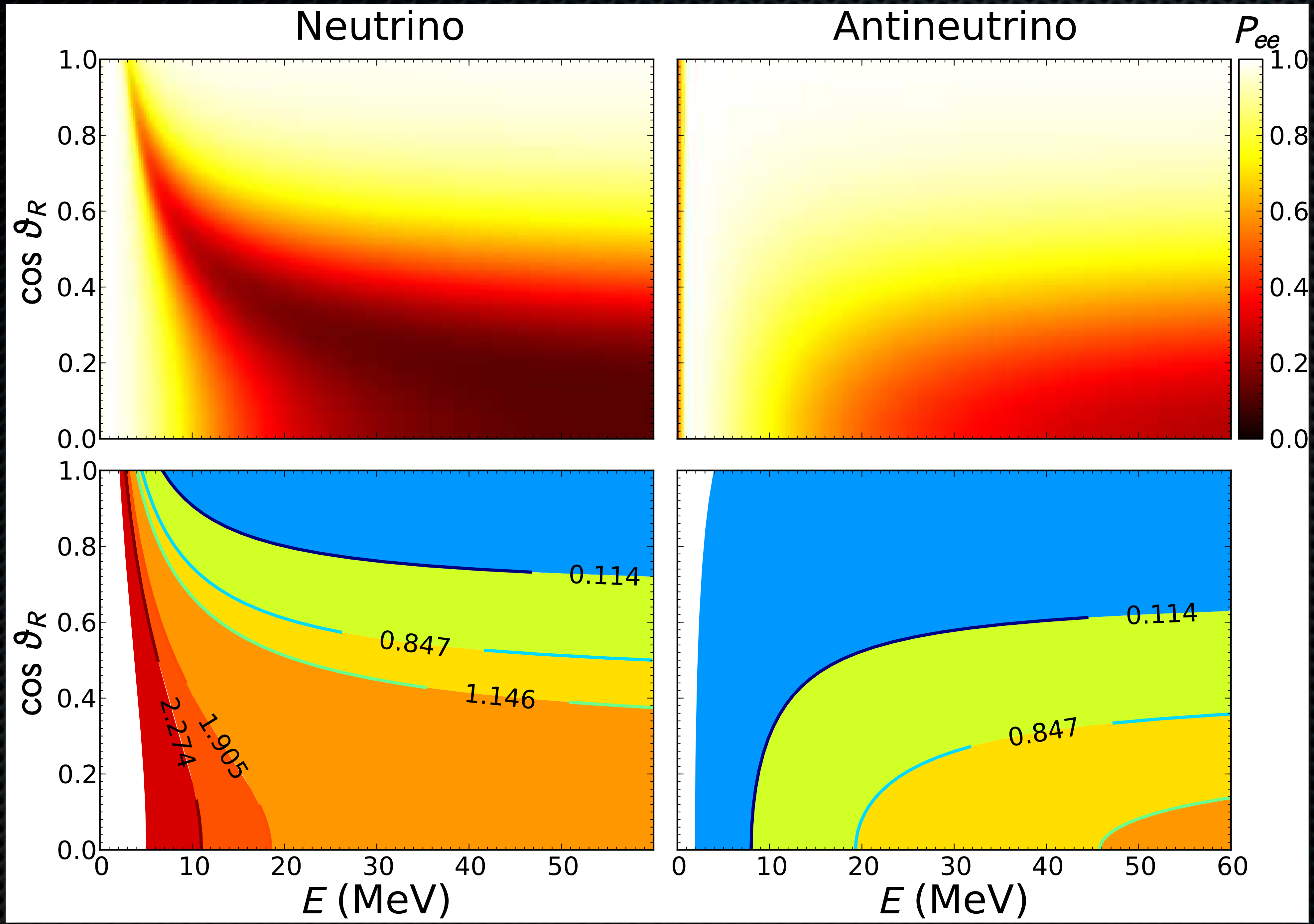


Neutrino
Antineutrino
P_{ee}
$\cos\vartheta_R$
Neutrinos
Antineutrinos
$\cos\Theta_R$
$r = 180$ km
E_ν [MeV]

r = 1000 km



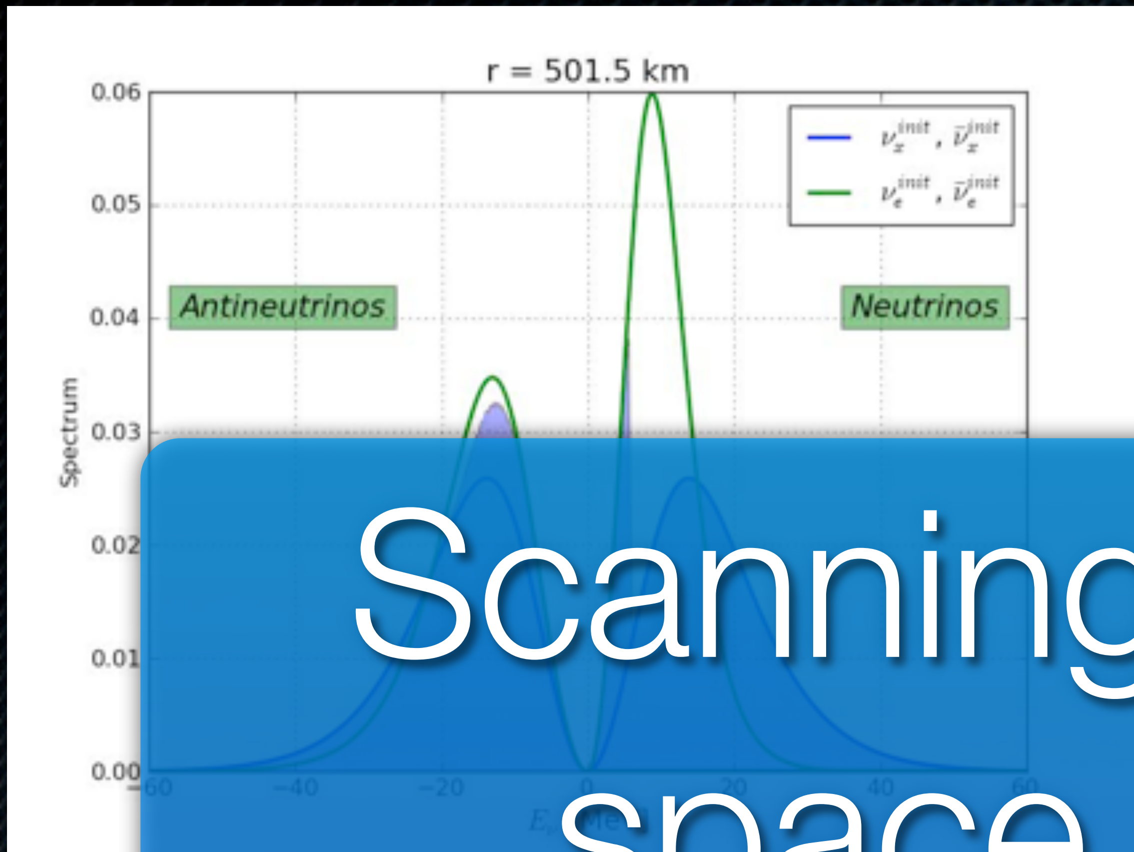
YOU GET THE IDEA



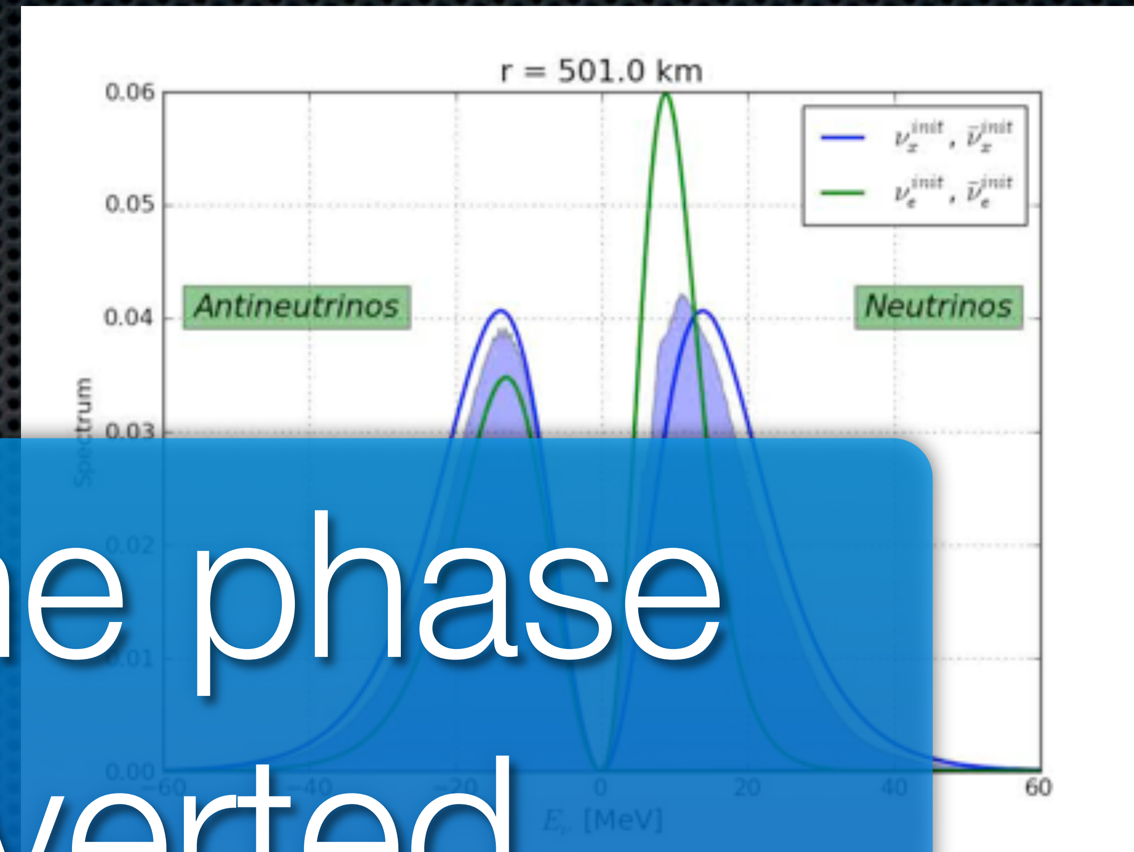
Osc. pattern at the start

the correlation between energy and angle can be explained analytically

Scanning the phase space, inverted hierarchy

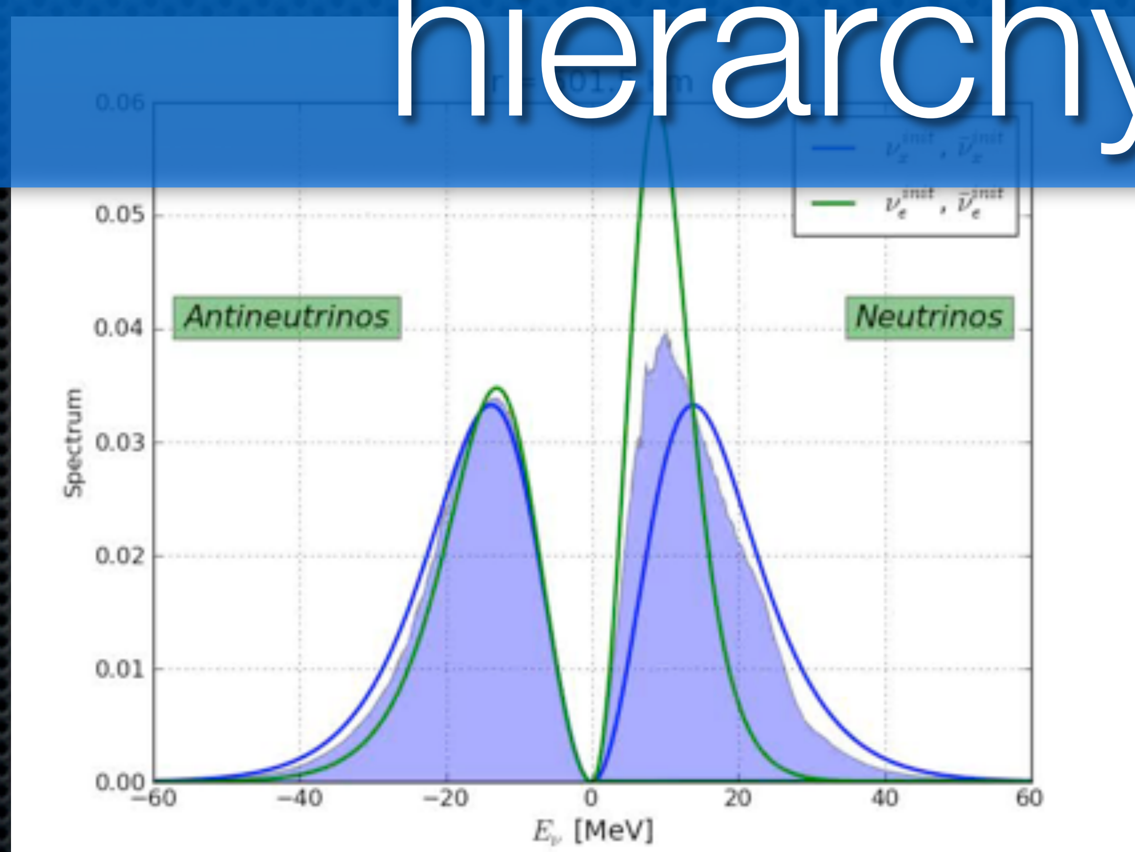


Lx=0.7



Lx=1.1

Lx=0.9



Keil, Janka, Raffelt q=3.0 spectra, vary Lx

Value of theta13 suggested by T2K this week

Incomplete roadmap

- At this point, many directions to pursue:
  - Physics of coupled spin systems with long-ranged forces. Connections to other physical systems
    - Very similar phenomena in superconductor physics (Pehlivan, Balantekin, Kajino, Yoshida, arXiv:1105.1182). Thanks to Georg Raffelt for discussions!
  - Physics of the multiangle transformations in the supernova setup (not yet fully understood)
  - Connection to neutrino experiments: modeling various conditions to predict what can be seen on Earth and how to optimize detectors
  - Studying particle physics implications: Adding physics beyond the Standard Model -- potential for powerful constraints
  - Implications for the nucleosynthesis and other astrophysics?

Summary

- The physics of supernova neutrino oscillations is extremely rich, much more interesting than thought 10 years ago!
- Collective modes, changing density profile, stochastic fluctuations ...
- The ingredients are all known physics → not optional
- Needed: more manpower (brainpower!) -- both numerics and analytics
- Needed: combine large-scale SN simulations (*with good spectra*) and neutrino oscillations to predict time-dependent signals for various models
- Needed: good detectors for both nue and nue-bar.
  - The supernova has been very kind to us, patiently waiting for the right detectors to be built