Oscillations of SN neutrinos:

a few more observations

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LANL

INFO 11

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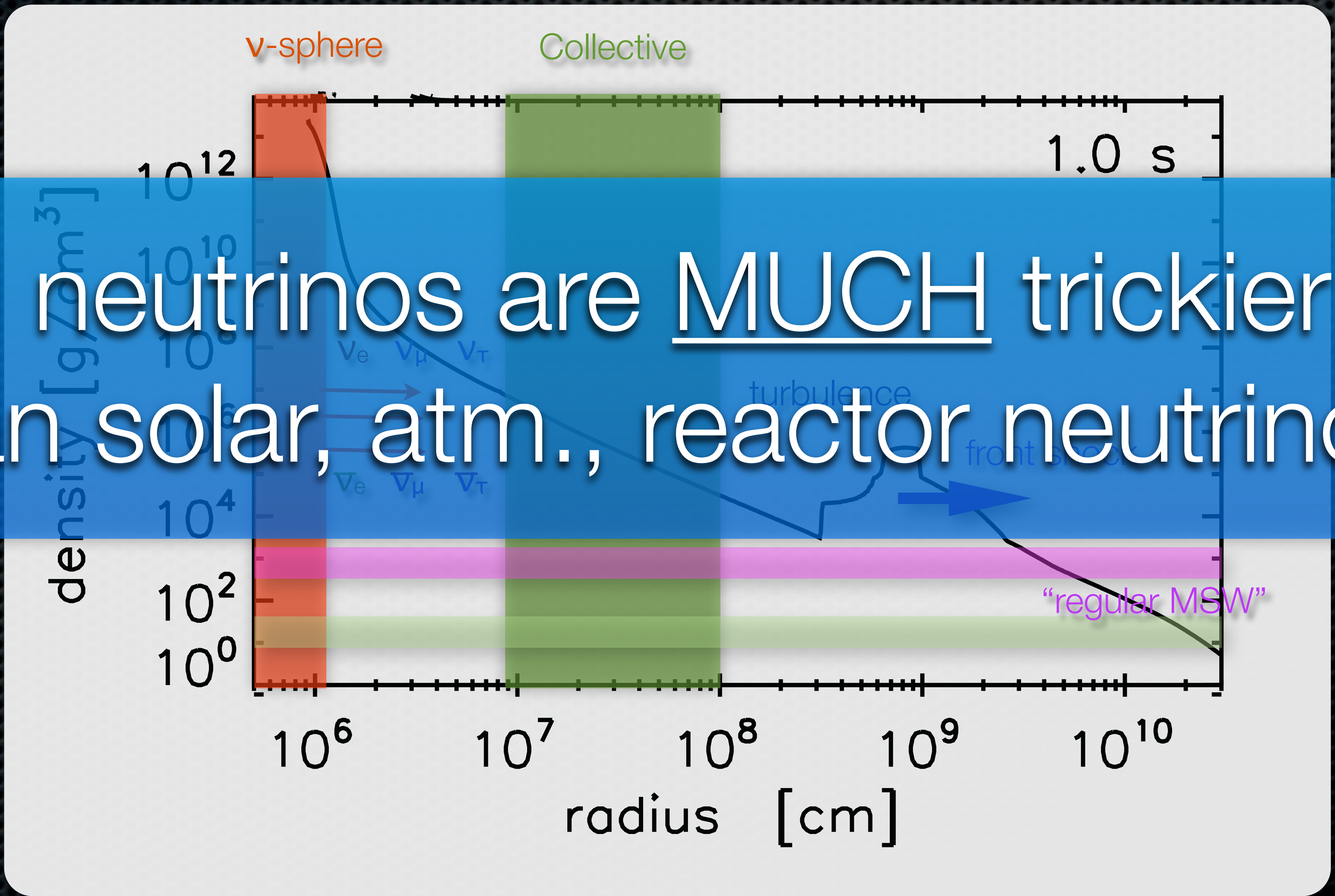
Back to supernova neutrino oscillations: a few FAQs

- What kind of physics is involved?
  - Do you really need theorists for this?
- Why should I worry about this now if the SN 2027 is more than a decade away?
- Why should this be part of the science case for LBNE?
- Turbulence is messy. Can it be treated robustly?
- Do you really need 3 flavor multi-angle calculations?
  - Why should I trust your codes?

What kind of physics is involved?

- Relevant physical processes (a cartoon)

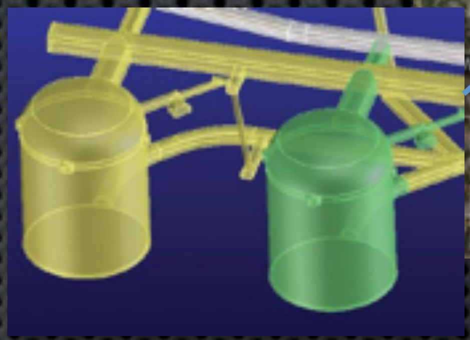


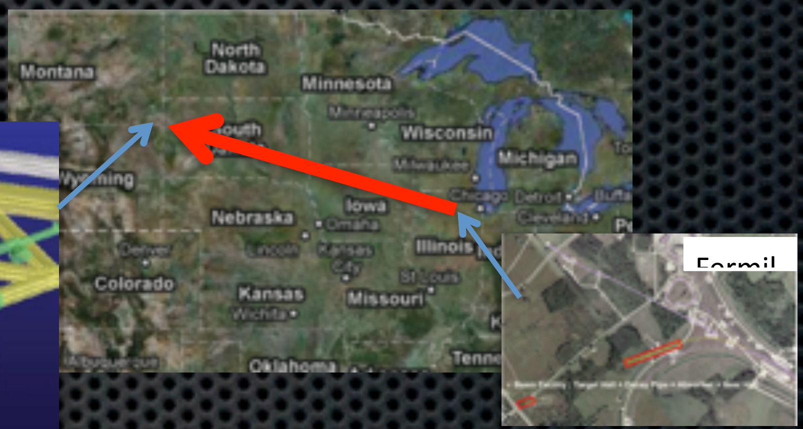
SN neutrinos are <u>MUCH</u> trickier than solar, atm., reactor neutrinos

This is where many branches of physics converge

- Astrophysics, broadly defined
- Plasma physics, turbulence, etc
- Many-body physics
- Particle physics
- Nuclear physics
  - E.g., nucleosynthesis
- Numerical modeling

Why now?

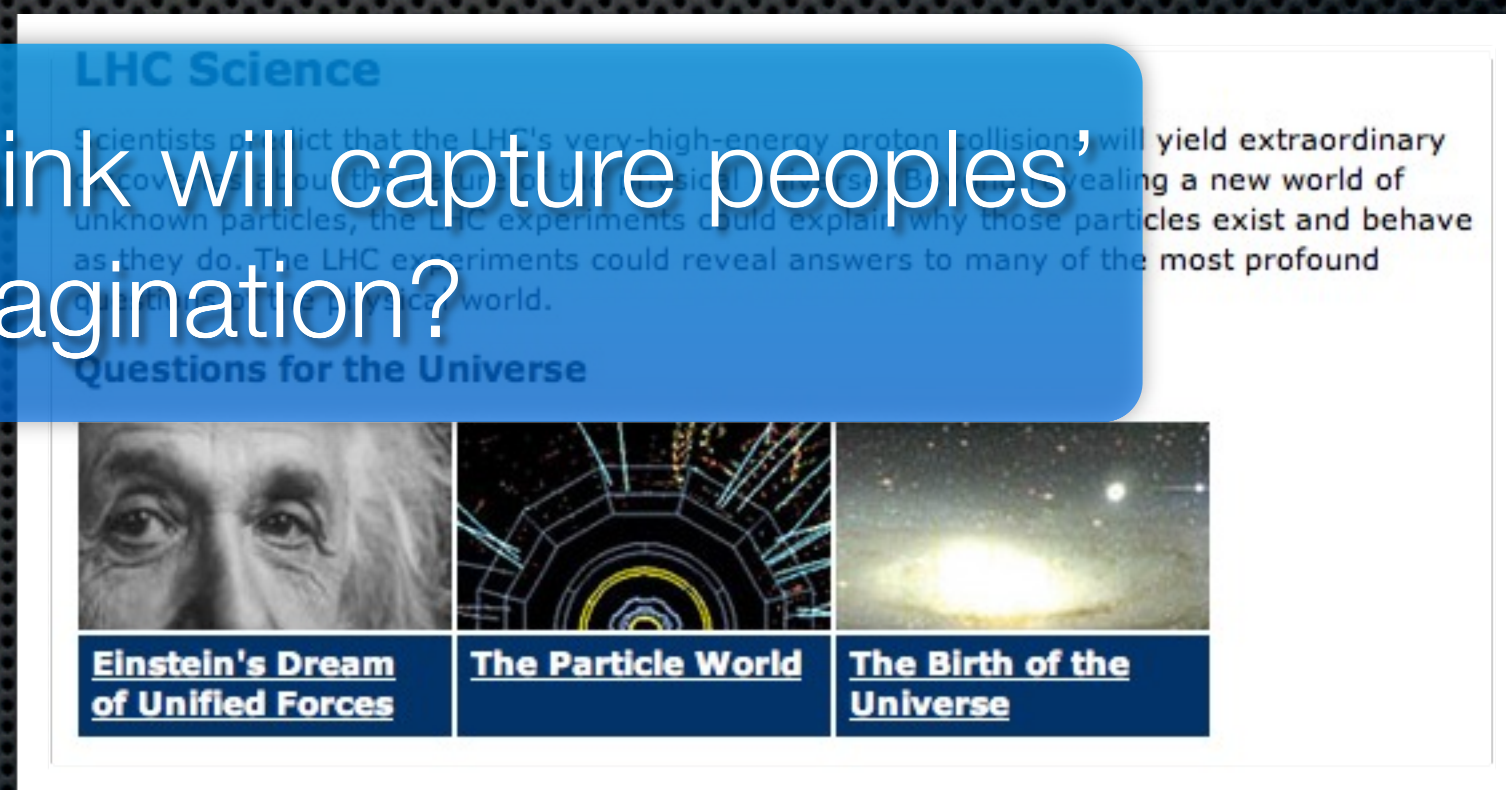




- *A priori*, oscillations can impact
  - Nucleosynthesis
  - Explosion (?)
  - Signal observed in terrestrial detectors
- Our understanding of the expected signal may inform detector design
  - People are used to thinking about supernova neutrinos as something that can always wait.
  - Prime example: LBNE. Characteristics of the LBNE detectors are will be decided very soon.

Shouldn’t LBNE have a simple science case?

- LBNE
  - Measure the delta angle (CP violation)
- LHC:



Which do you think will capture peoples’ imagination?

Snapshot taken this morning from http://www.uslhc.us/LHC_Science

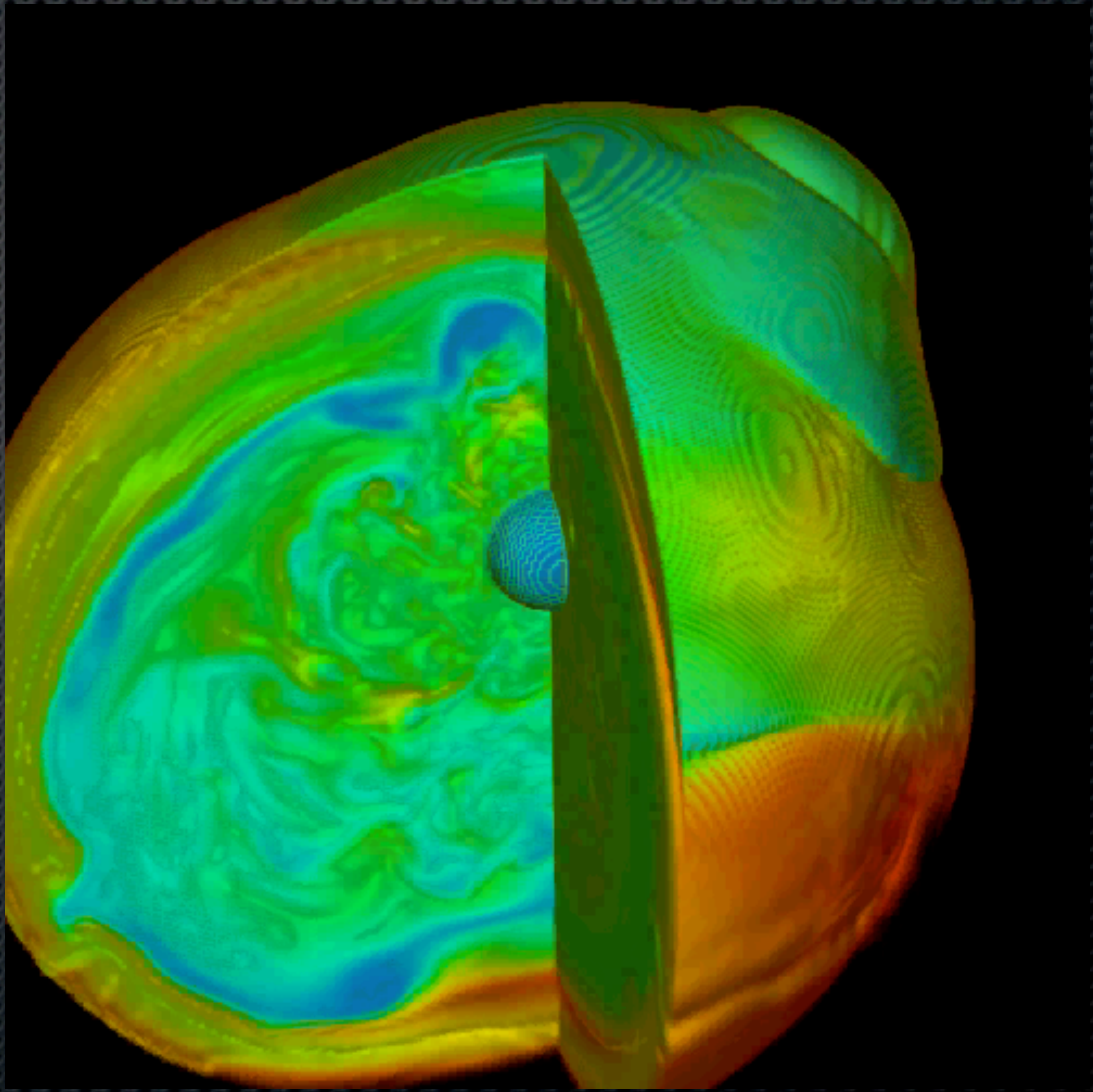
Let’s try again

- LBNE:
  - CP violation
  - Precision tests of neutrino-matter interactions
    - TeV-scale BSM physics
  - New weakly interacting particles
  - Peering inside an exploding star
  - Origin of heavy elements in the Universe
  - Neutrino oscillations in the regime inaccessible on Earth
  - Ma
  - ....

Sounds more interesting to me, even without “Einstein’s dream”, etc

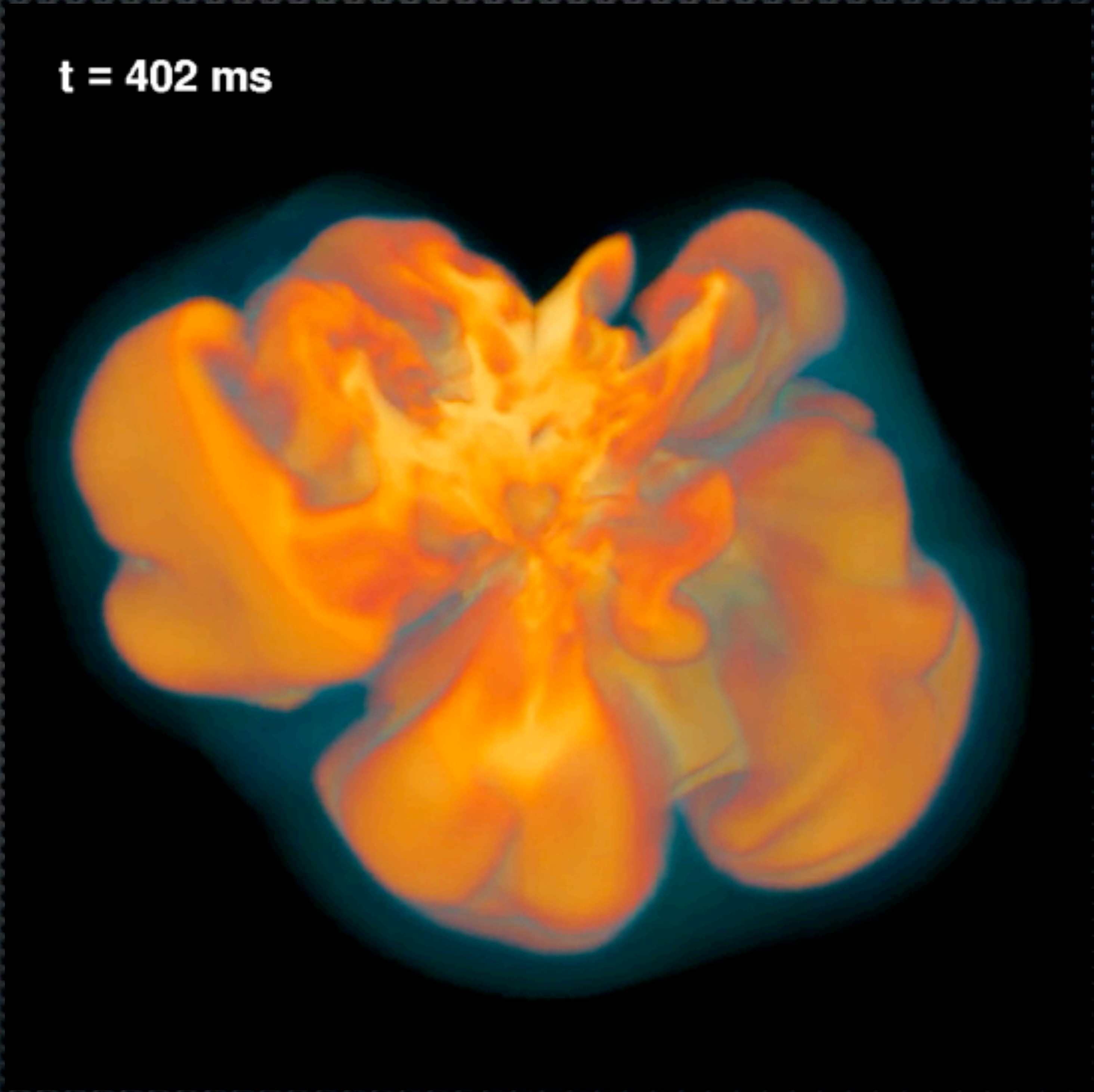
More complications: 3D simulations show turbulence

- 3d simulations of the accretion shock instability Blondin, Mezzacappa, & DeMarino (2002)
- See http://www.phy.ornl.gov/tsi/pages/simulations.html
- No central heating. Still,
  - extensive, well-developed turbulence behind the shock



More 3D simulations

- beautiful simulation from the web page of K.Kifonidis http://www.mpa-garching.mpg.de/~kok/
- Neutrino flavor transformations happen in the dynamically changing profile of the expanding shock and turbulence



Turbulence and MSW

- The level-jumping probability now depends on fluctuations
  - relevant scales are small, O(10 km)
  - take large-scale fluctuations from simulations, scale down with a Kolmogorov-like power law
  - contributions of different scales to the level-jumping probability are given by the following spectral integral

$$P \simeq \frac{G_F}{\sqrt{2} n_0'} \int dk C(k) G\left(\frac{k}{2\Delta \sin 2\theta}\right), \qquad G(p) \simeq \frac{\Theta(p-1)}{p\sqrt{p^2-1}}.$$

for details, see Friedland & Gruzinov, astro-ph/0607244

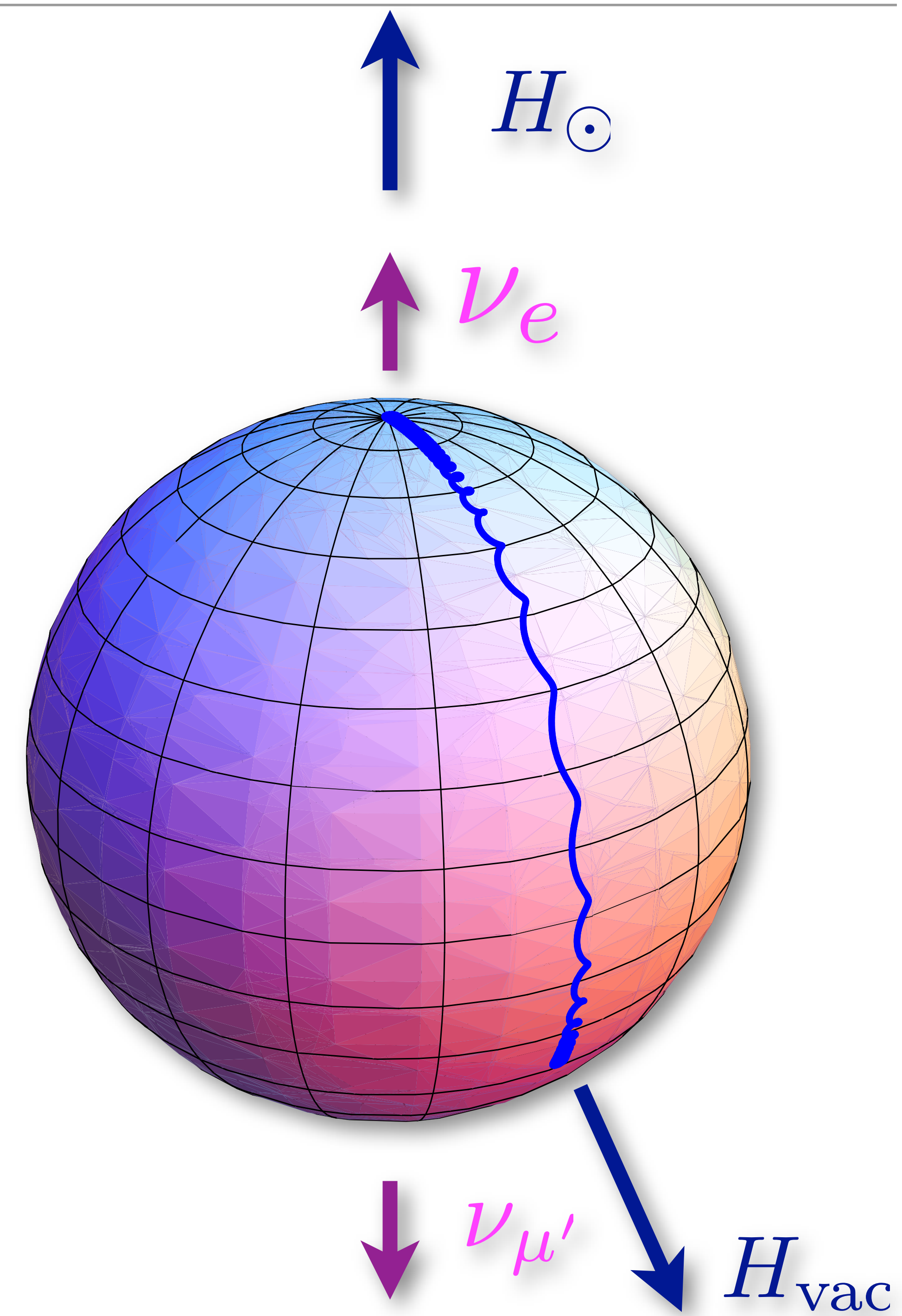
To gain some intuition, consider spin representation

- Like any two-state QM system, the neutrino flavor state can be thought of as a spin. We can depict its evolution by showing the trajectory of the expectation value of the spin, $\langle \nu | \vec{\sigma} | \nu \rangle$, on a sphere

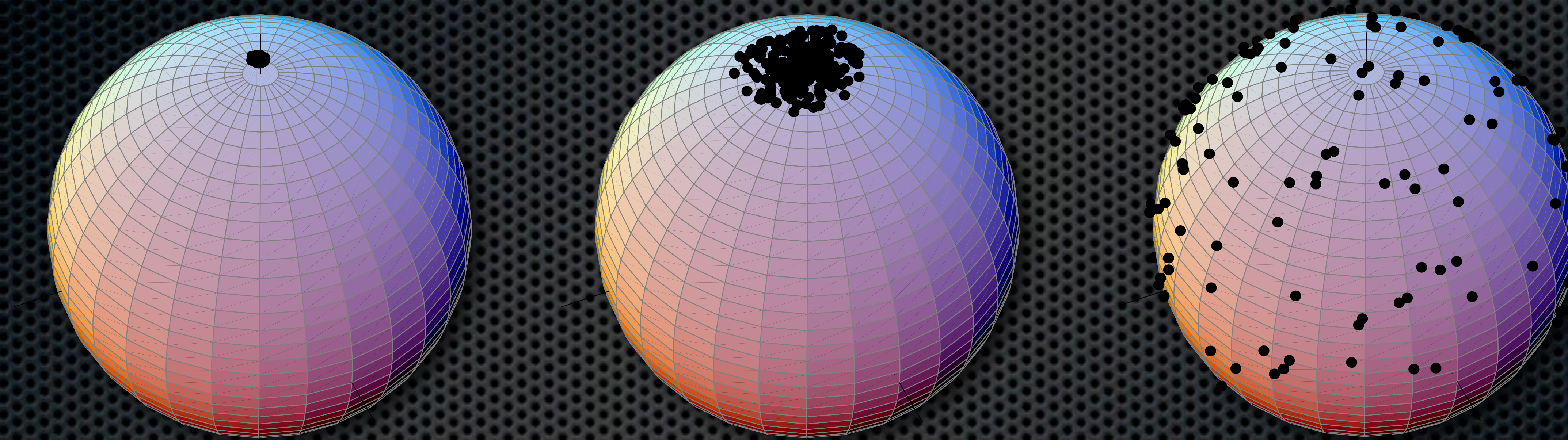
- The oscillation Hamiltonian acts as an external magnetic field. The matter potential changes the z-component of the field.

$$H(r) = \frac{\Delta m^2_{\rm mat}}{2E_\nu} \begin{pmatrix} -\cos 2\theta_{\rm mat} & \sin 2\theta_{\rm mat} \\ \sin 2\theta_{\rm mat} & \cos 2\theta_{\rm mat} \end{pmatrix} = \vec{H}(r) \cdot \vec{\sigma}$$

- In the adiabatic case, the spin follows the changing "magnetic field".



Turbulence makes neutrinos diffuse in the flavor space



- Need to estimate the rate of diffusion
  - Given large-scale fluctuations in published simulations (order 1), completely depolarized regime

$$\rho_{final} \to \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix}$$

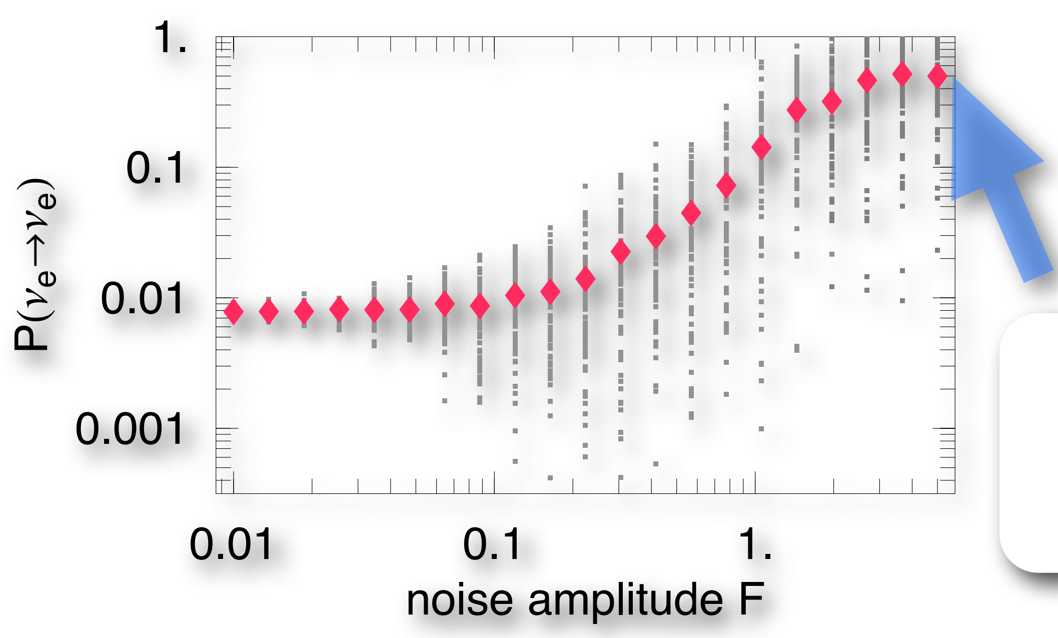
Observable effect

- To achieve complete depolarization, density fluctuations on large scales need to satisfy

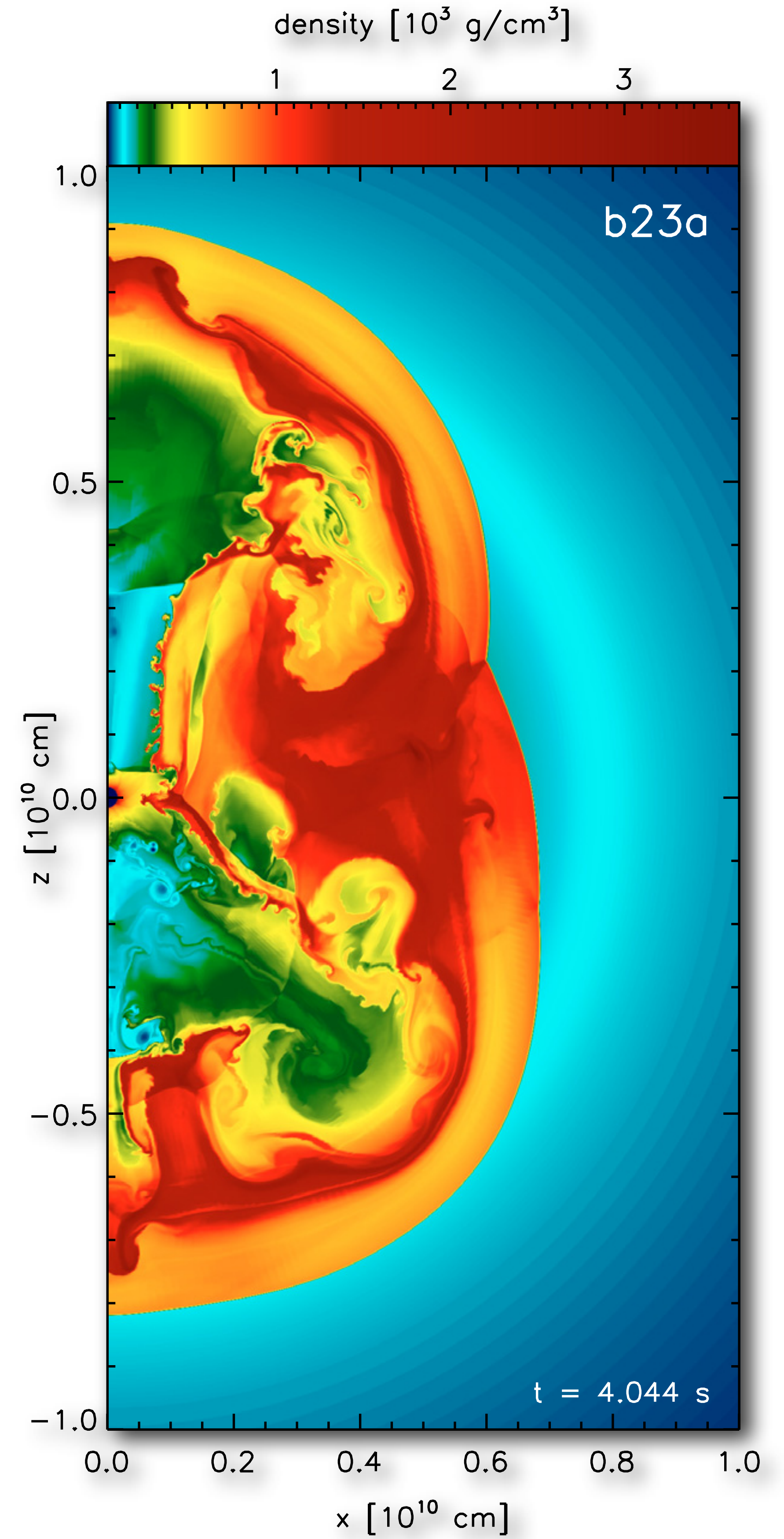
$$\frac{\delta\rho_r}{\rho_r} \gtrsim 0.1\theta_{13}^{1/3}$$

- Simulations show order one fluctuations → criterion satisfied and by a large margin

Details in A.F., A. Gruzinov, astro-ph/0607244

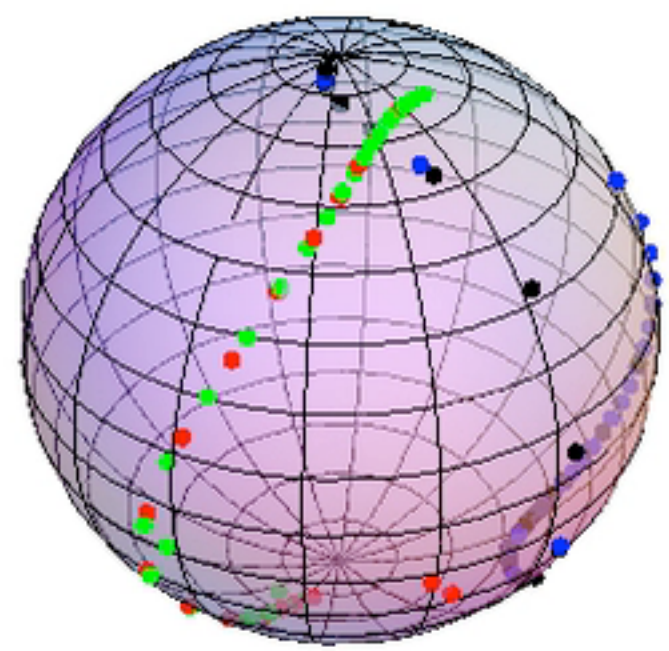


We are here



Collective motions in action

- Here is the evolution of the collective mode as a function of radius in one of our 2-flavor (single-angle) calculations



r=200.10 km

Different regimes

- For some initial spectra, multiple spectral splits
- For other conditions, only low-energy split features
  - This can be potentially very significant: high energy features easily observable
- If we understand the phase diagram, we can read a lot about the fluxes in all flavors from the signal

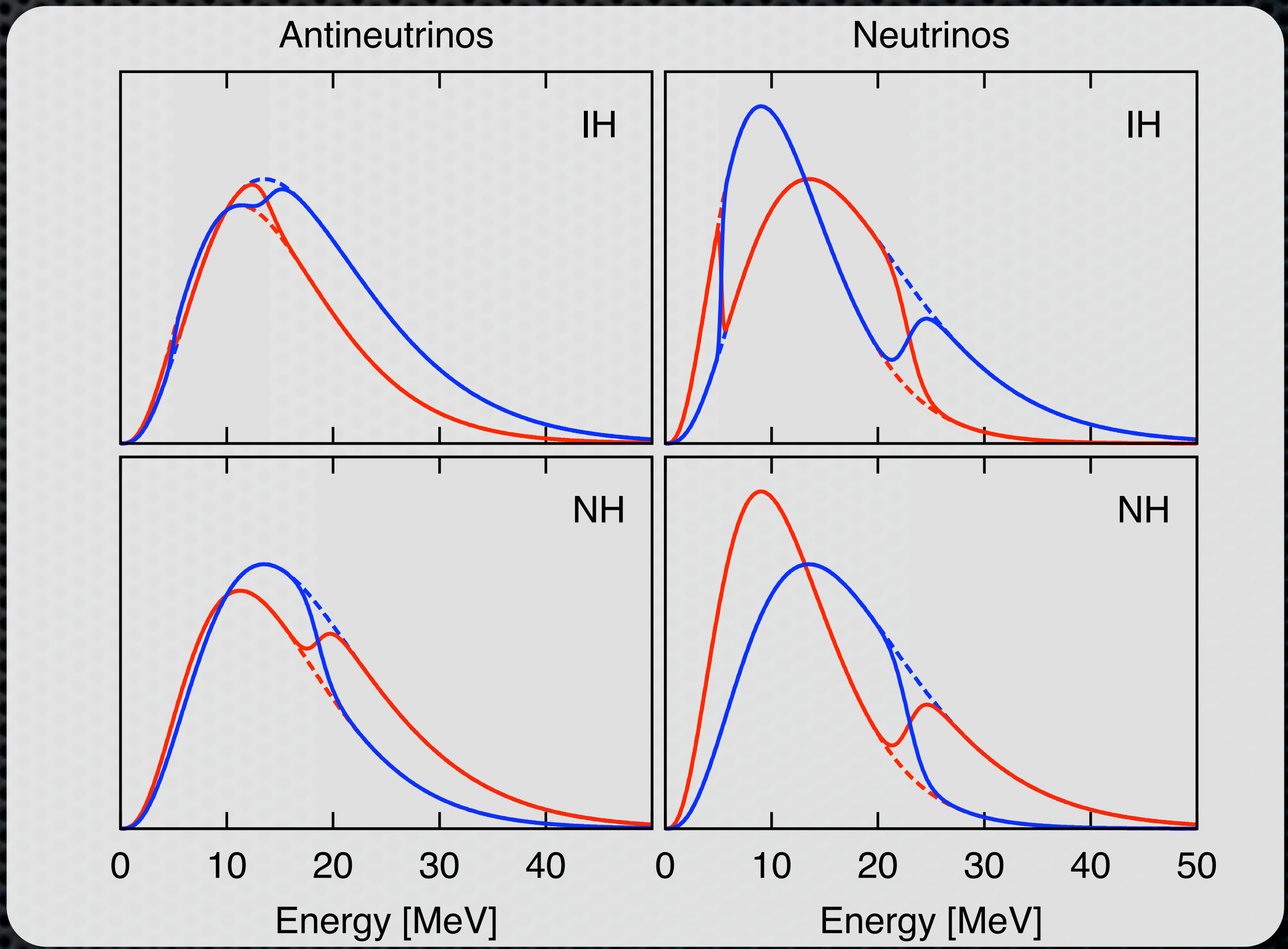
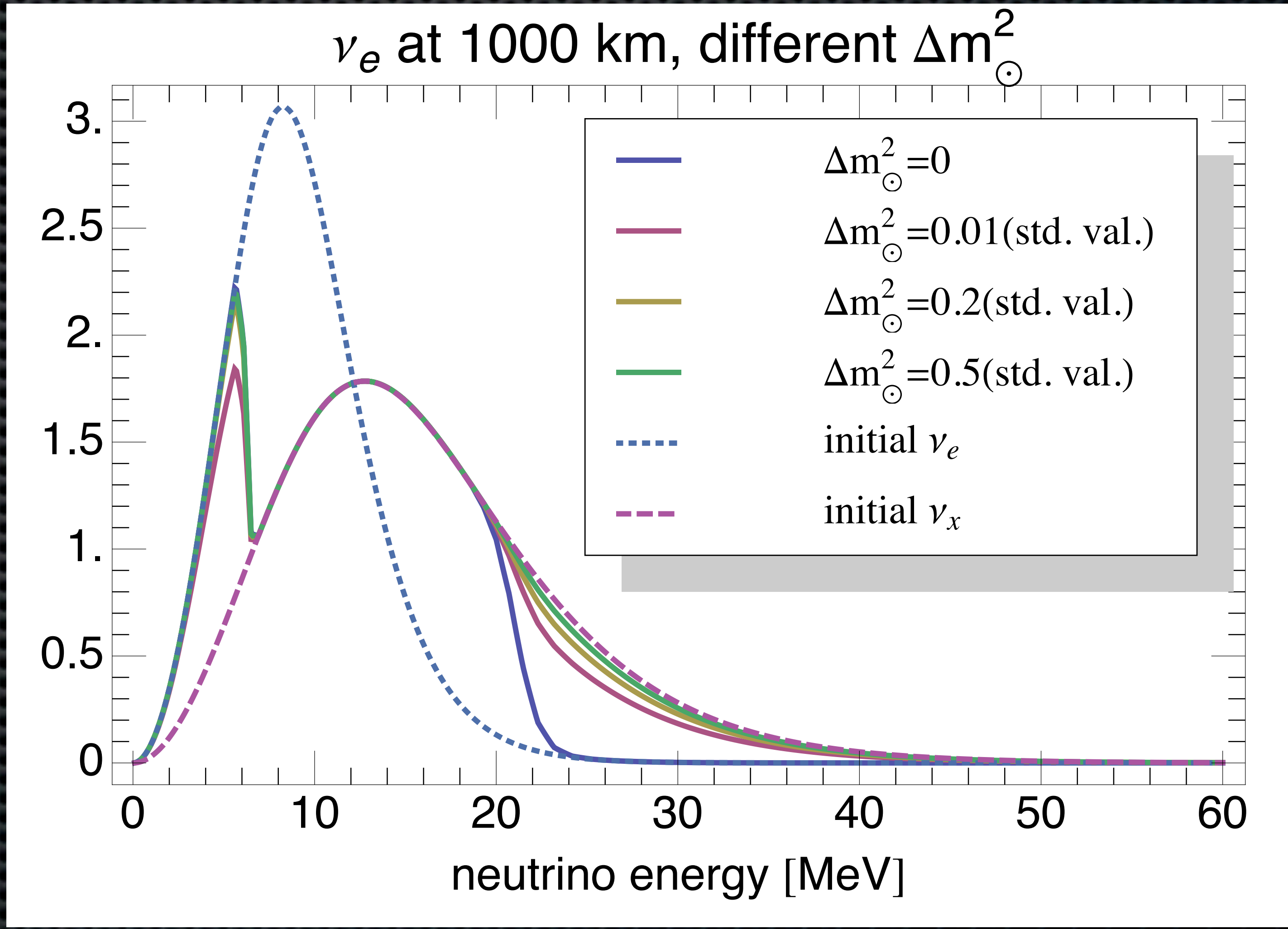


Fig. from Dasgupta, Dighe, Raffelt, Smirnov, arXiv:0904.3542 [hep-ph] -> PRL (2009)

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 $\Delta m_\odot^2\neq0$, the answer is closer to the realistic $\Delta m_\odot^2$ than to $\Delta m_\odot^2=0$

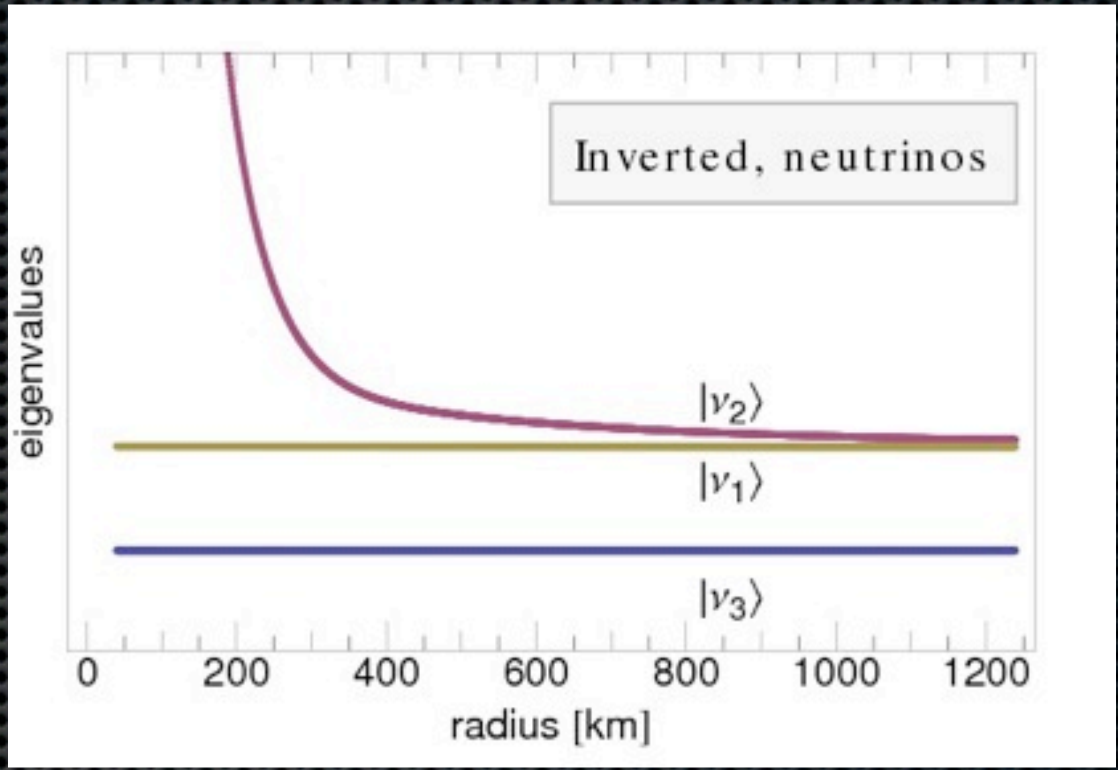


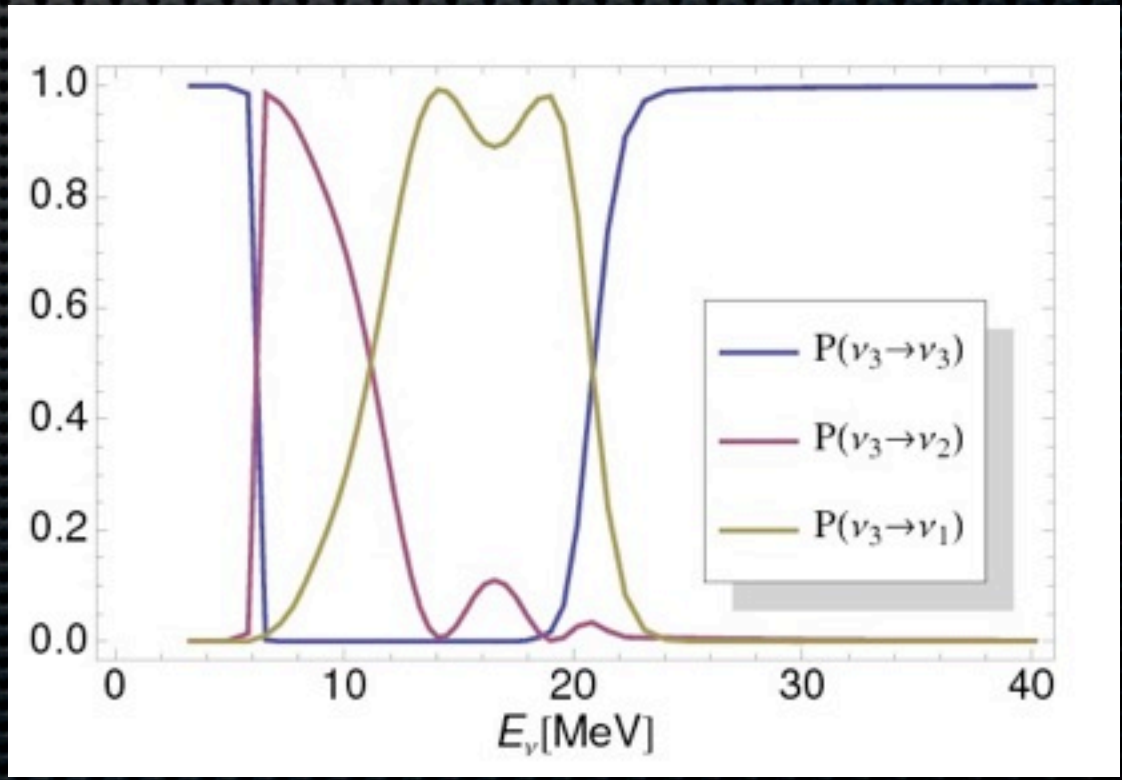
For details, see A. Friedland, Phys. Rev. Lett.104, 191102 (2010)

3-flavor pattern of transitions

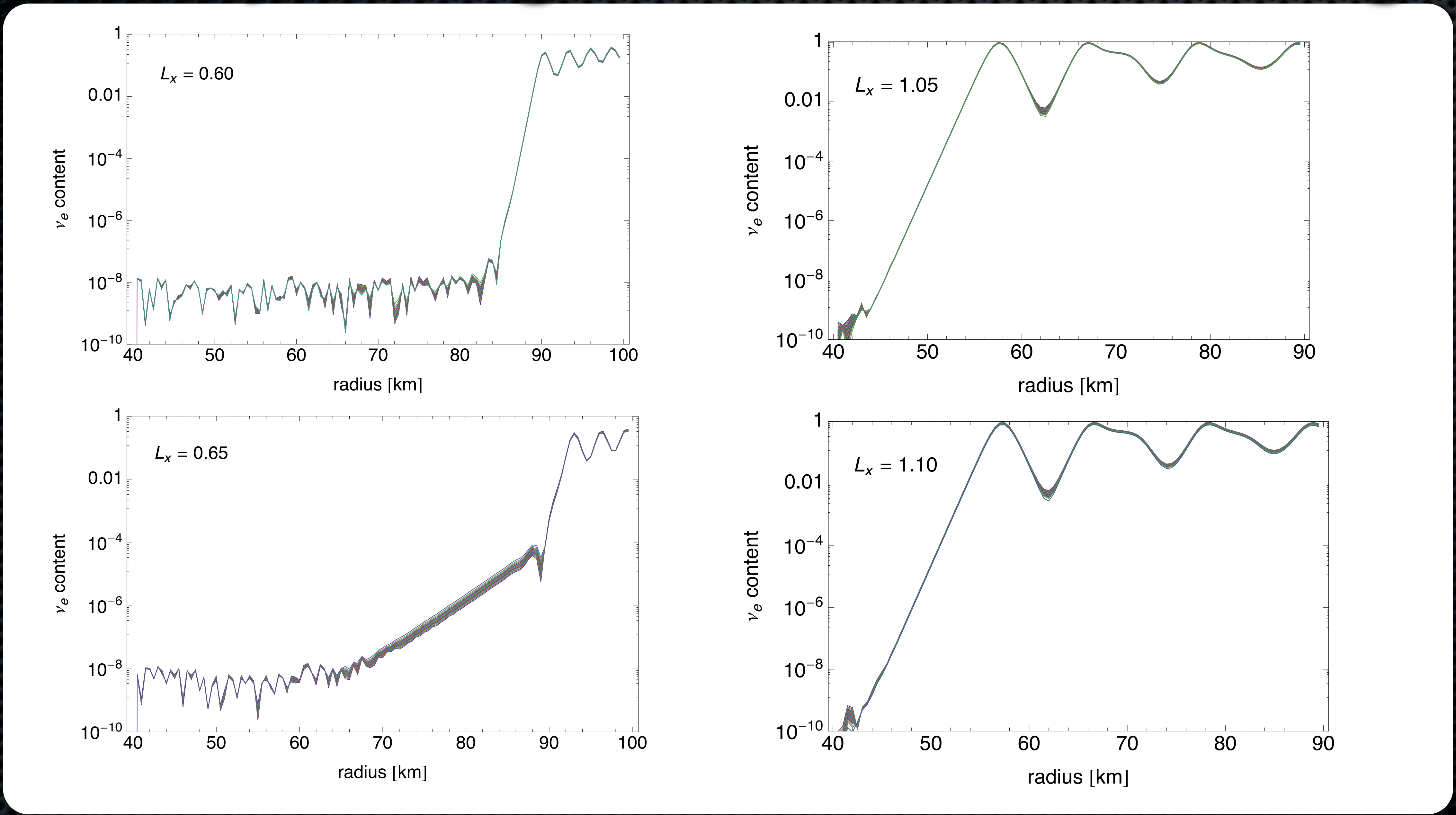
- E_ν < 6 MeV:
  - no permulations
- 6 MeV < E_ν < 10 MeV
  - $\nu_1 \rightarrow \nu_1$, $\nu_2 \leftrightarrows \nu_3$,
- 10 MeV < E_ν < 20 MeV
  - $\nu_2 \rightarrow \nu_3$, $\nu_3 \rightarrow \nu_1$, $\nu_1 \rightarrow \nu_2$
- E_ν > 20 MeV
  - $\nu_1 \leftrightarrows \nu_2$, $\nu_3 \rightarrow \nu_3$

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





Lastly, single- vs. multi-angle

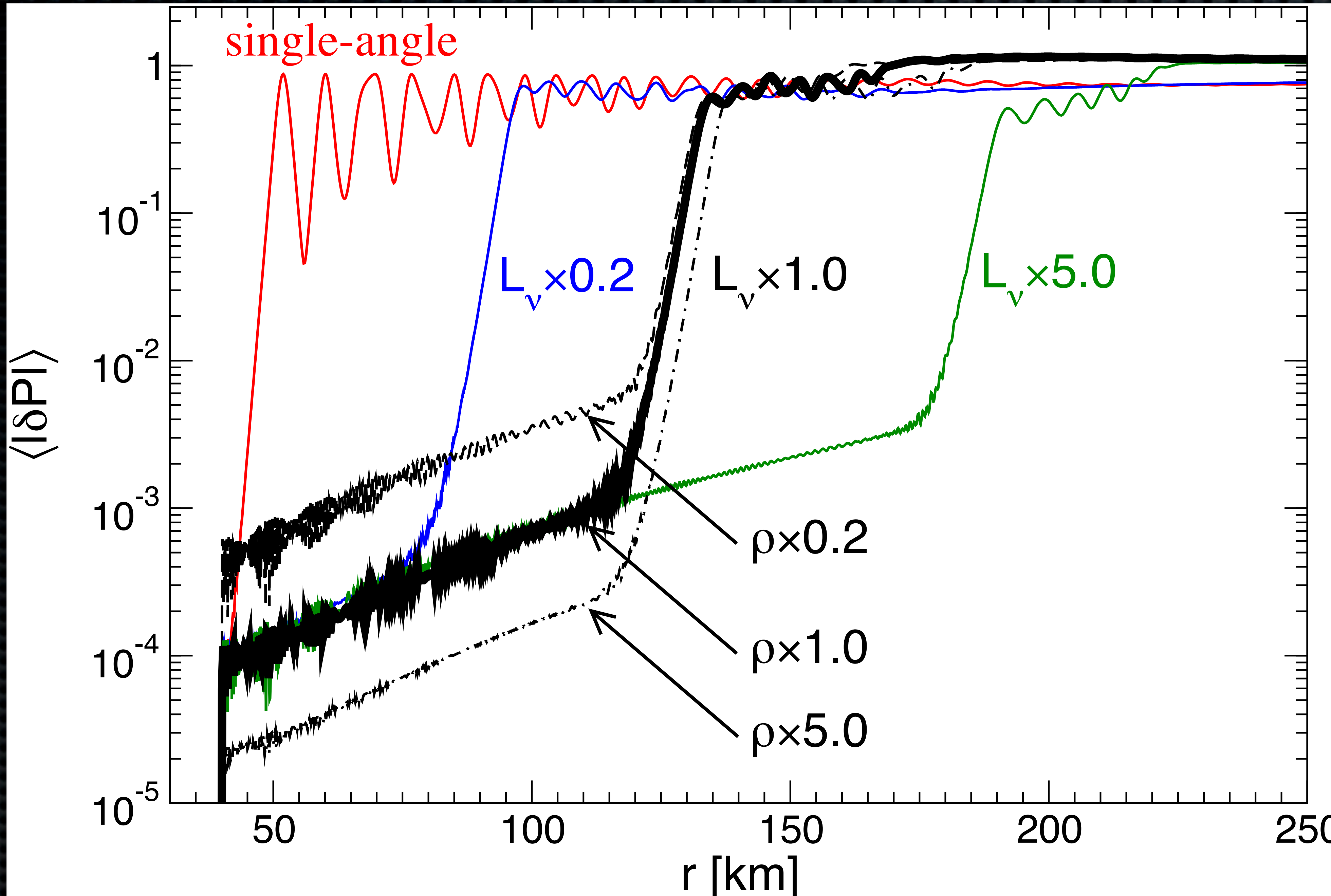


Varying luminosity of the ***nonelectron*** flavors

Single-angle calculations

This is 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?

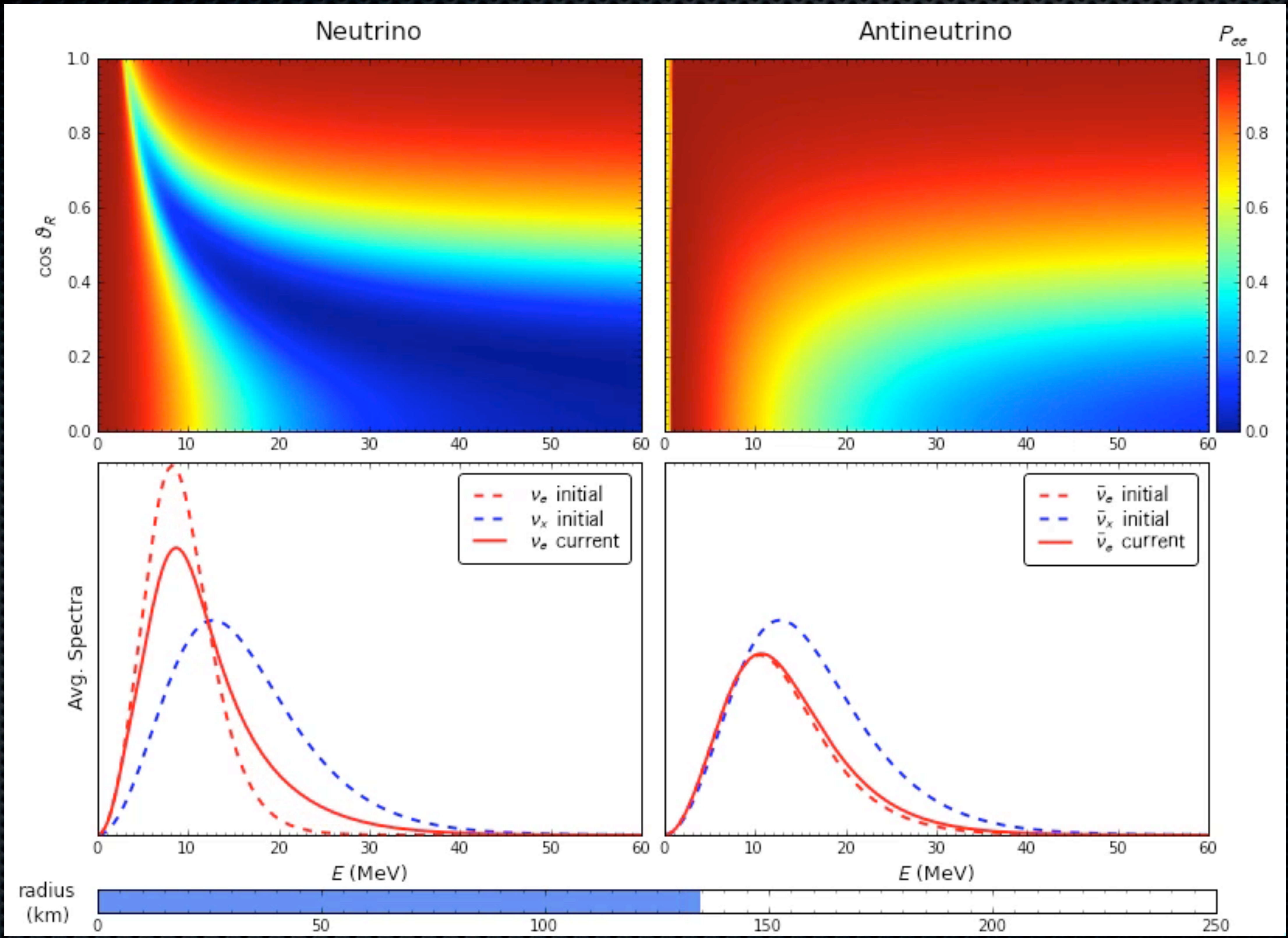


Multiangle suppression

Supernova models saved

From Duan & Friedland, Phys. Rev. Lett. 106, 091101 (2011)

Complicated pattern in energy-emission angle space



see Duan & Friedland, PRL (2011)

Multiangle problem

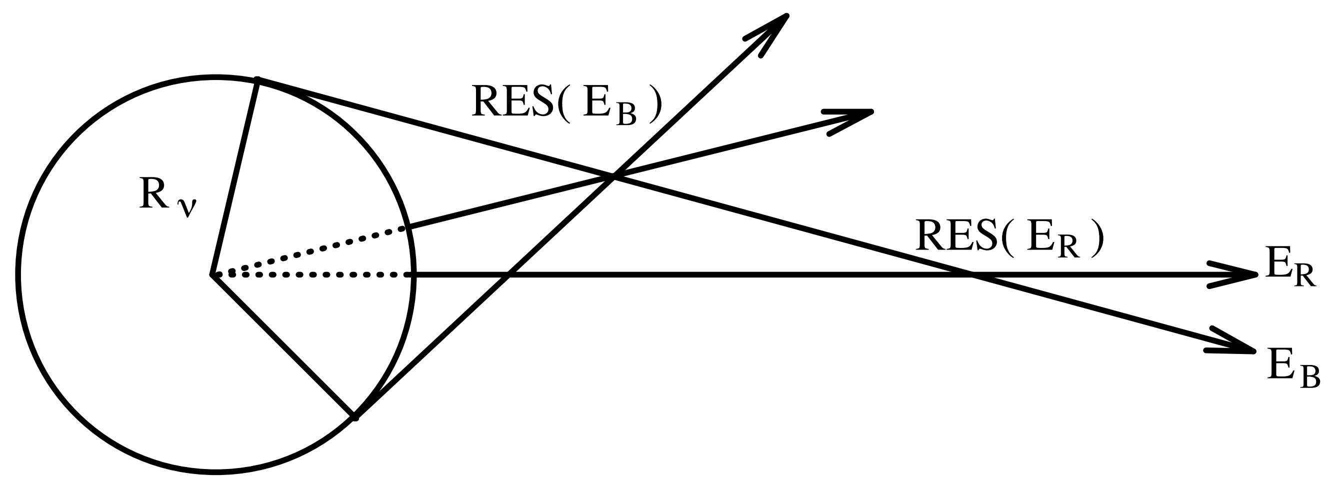


Figure from Qian & Fuller, astro-ph/9406073

- Multiangle calculations: 10^3 energy bins and 10^4 angle bins: some computing required!

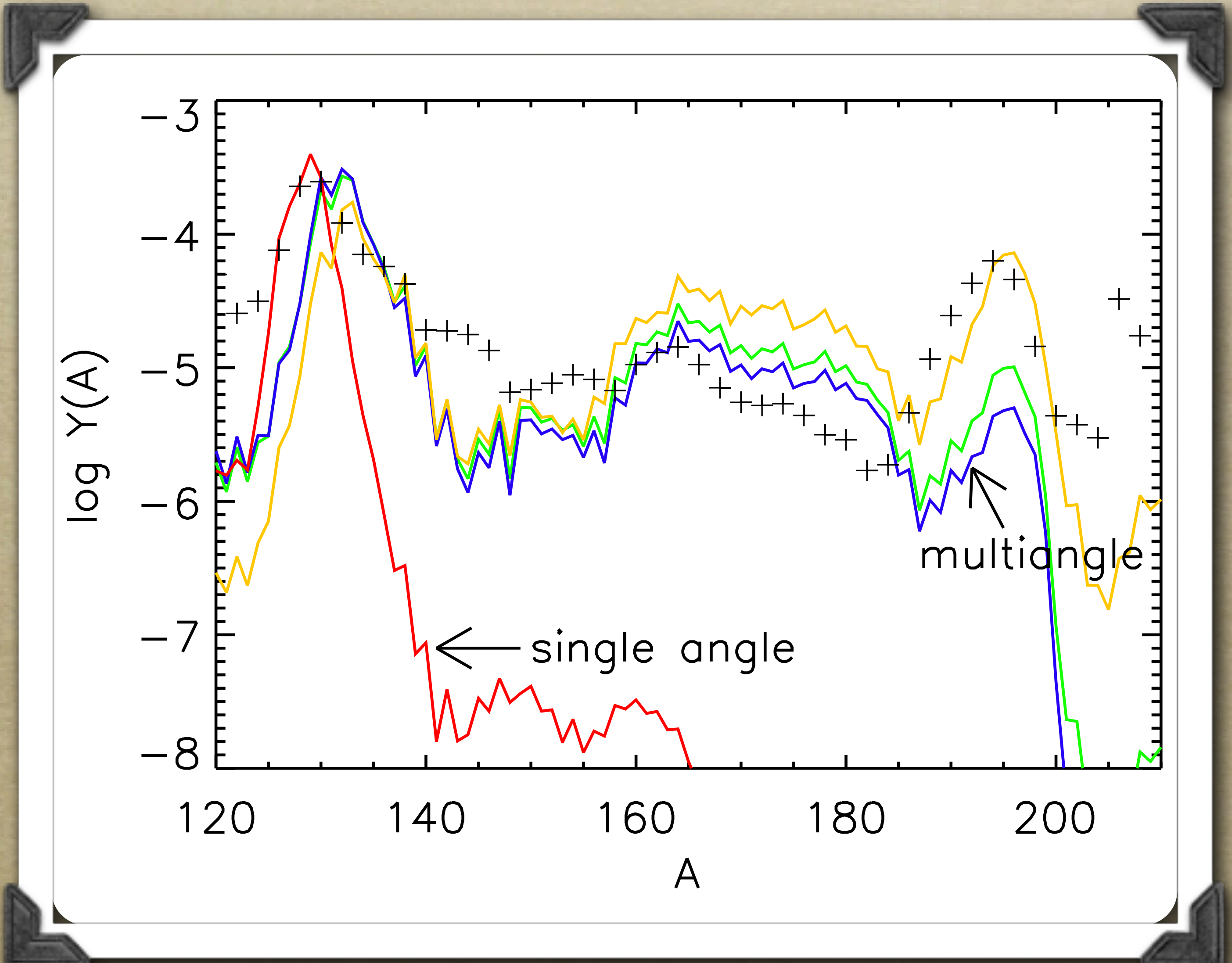
Impact on the r-process

Duan, Friedland, McLaughlin, Surman, arXiv:1012.0532,
J.Phys.G38:035201,2011.

- *Strategy:*
  - *Take the "usual" setup by the r-process people -- no special tunings or modifications*
  - *Compute collective oscillations starting with the "usual" late-time spectra [Keil, Janka, Raffelt (2003)]*
  - *See what happens*
  - *"Ridiculously simplistic model"*

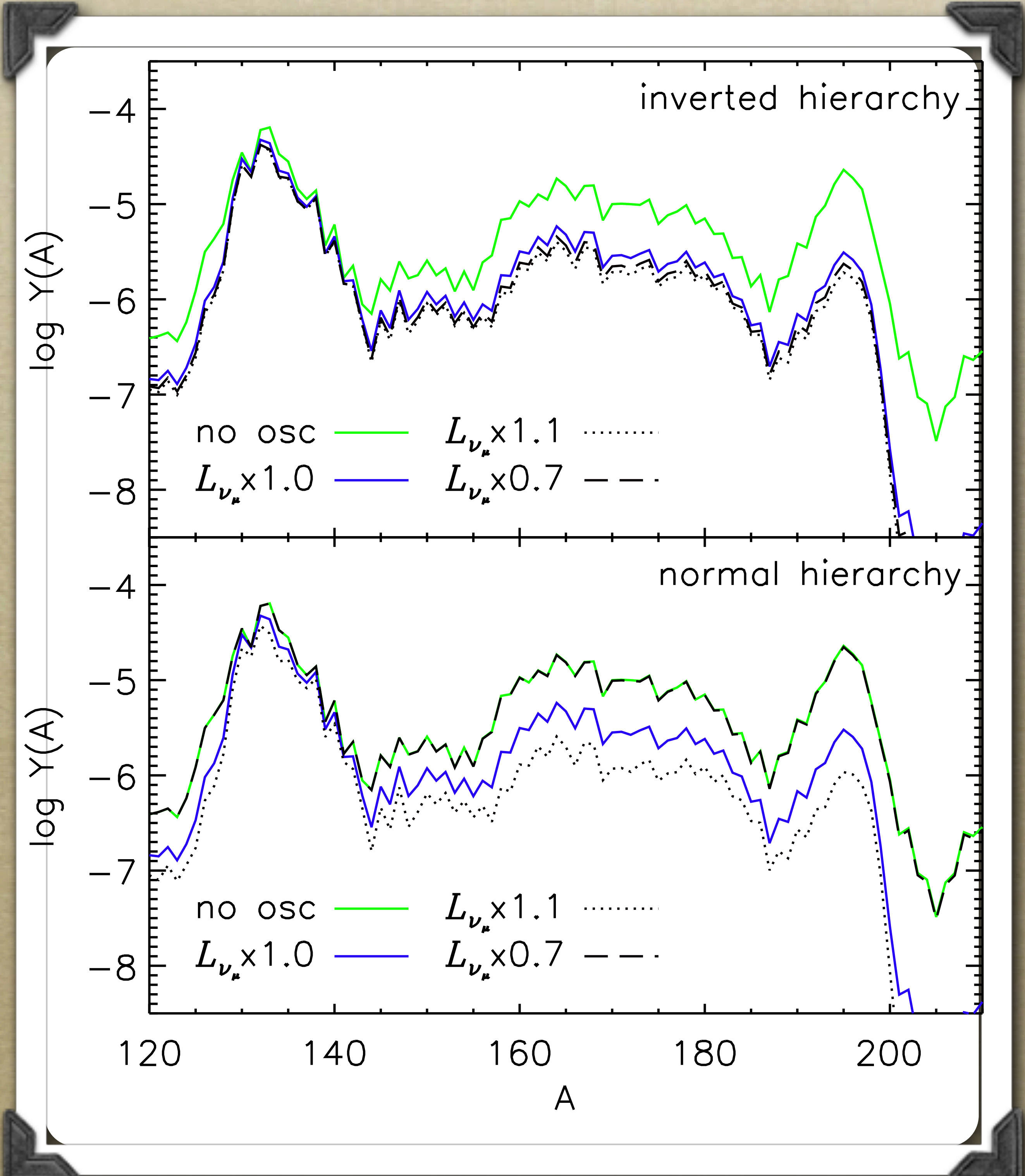
Need to be computed well

- *Where exactly the oscillations start and how they develop during the first 100 km is crucial for the r-process nucleosynthesis*



Sensitive to emitted spectra

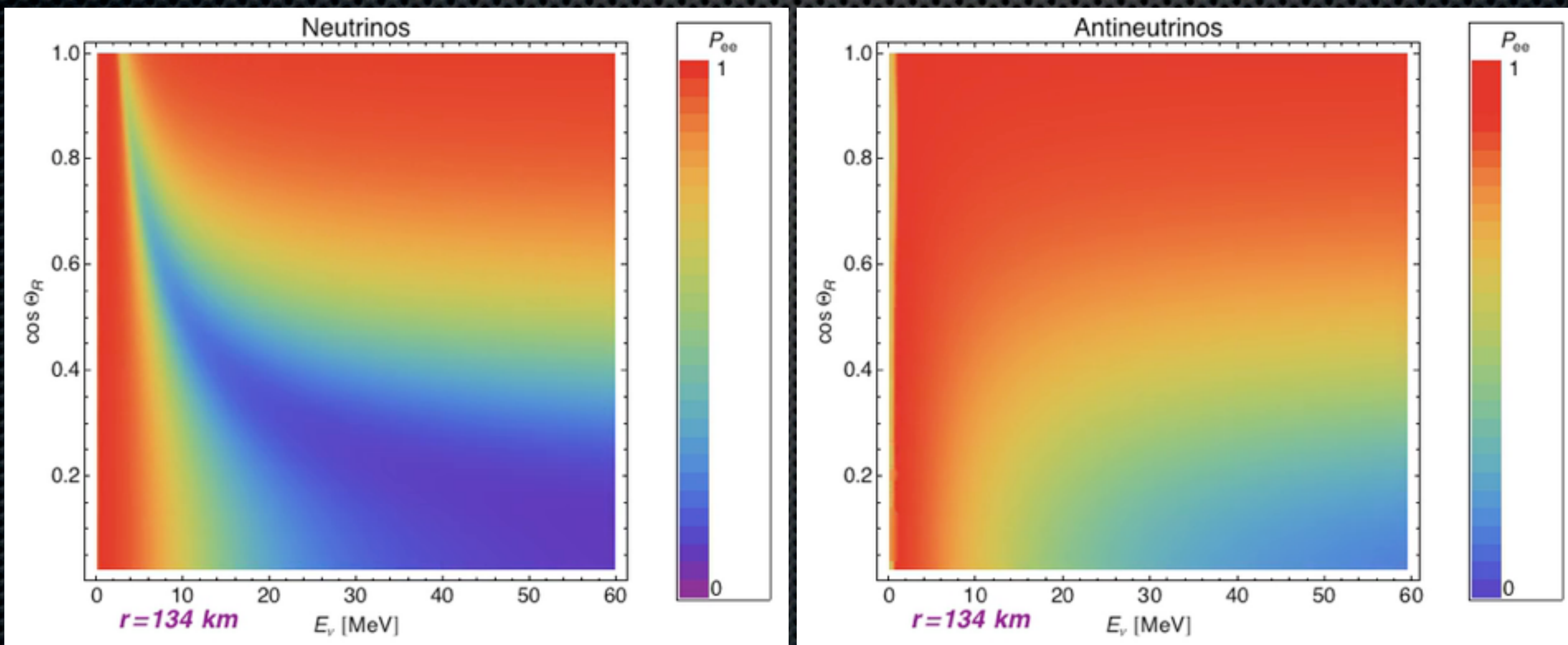
- *Details of the emitted spectra matter*
- *As the collective oscillations go into different regimes, so do the yields*



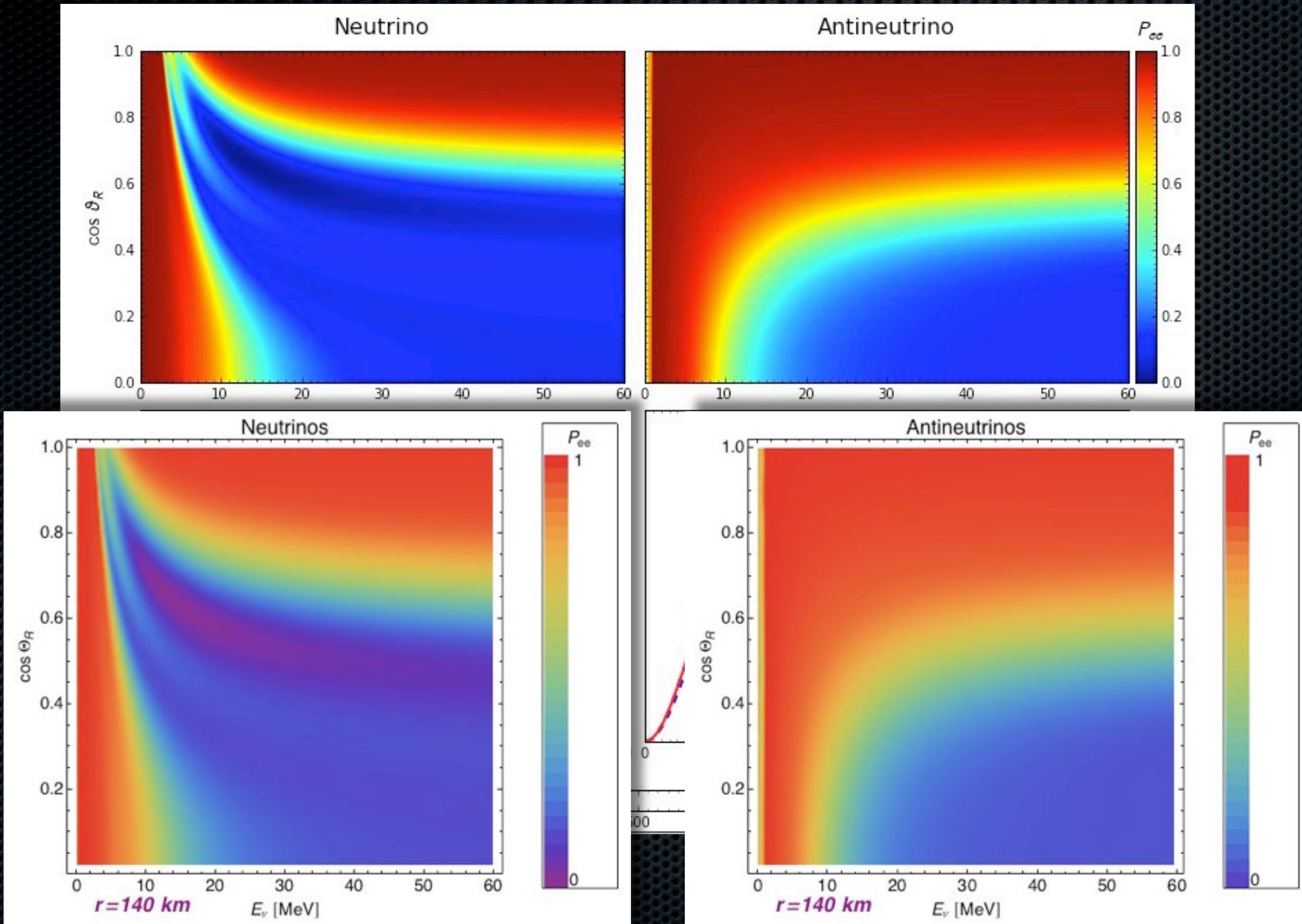
Code validation?

- Since the field crucially relies on the supercomputer codes, how do we validate the codes?
  - E.g., in cosmology people did N-body code comparison projects
- Take codes by different people
  - who haven’t seen each other’s codes
- Run the same test problem
- Compare results without tweaking

- As I understand, this was how the original results were computed
  - Comparison between Huaiyu's and Joe's codes
  - Also, the Bari group wrote a multiangle code, and seemed to agree with Duan et al
- I did some comparisons between my and Huaiyu's code
  - Take codes by different people ✔
    - who haven't seen each other's codes ✔
  - Run the same test problem ✔
  - Compare results without tweaking ✔

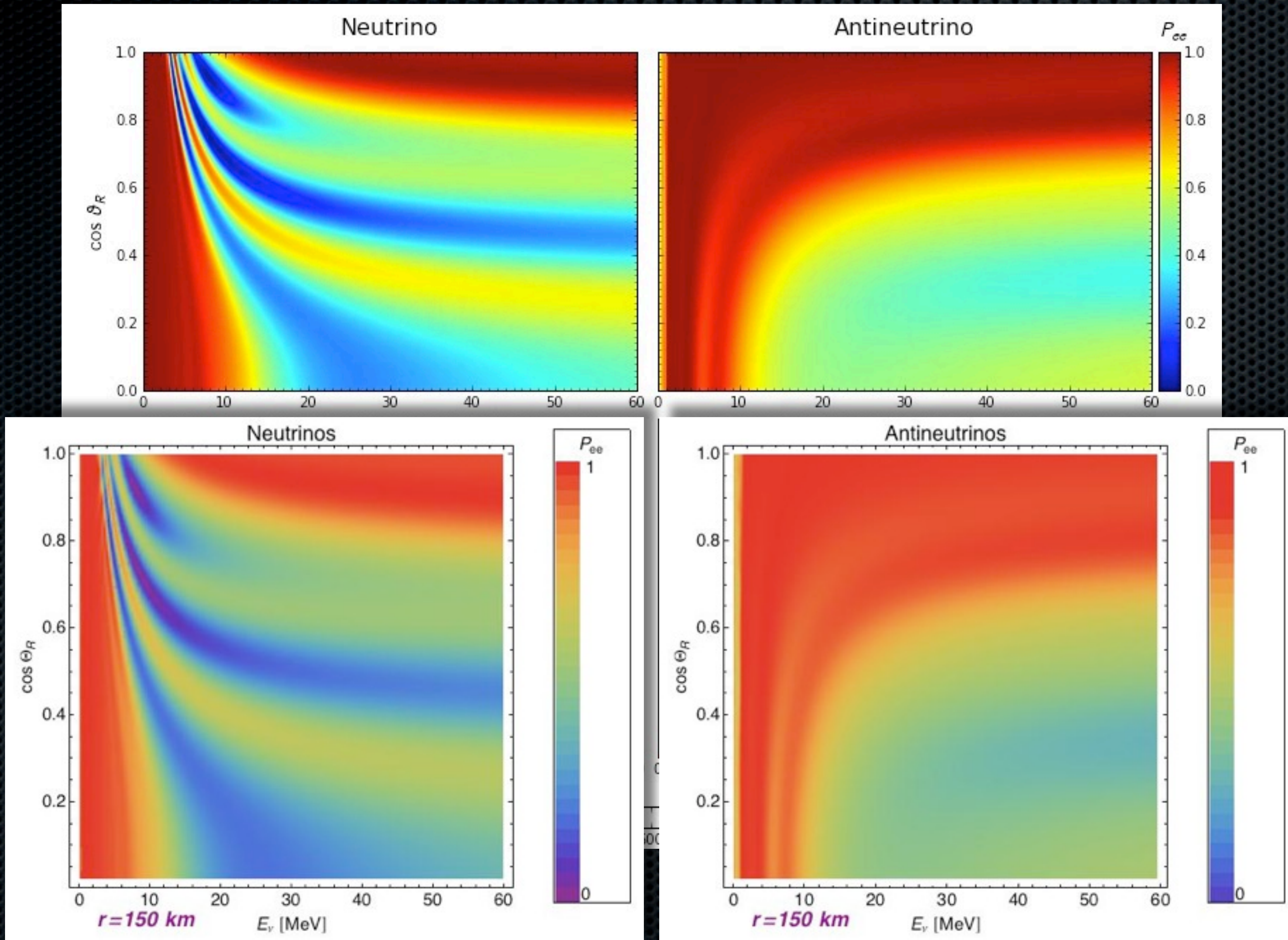

Neutrinos
Antineutrinos
P_{ee}
1
0
$\cos\Theta_R$
1.0
0.8
0.6
0.4
0.2
0
10
20
30
40
50
60
E_ν [MeV]
r=134 km

r = 140 km

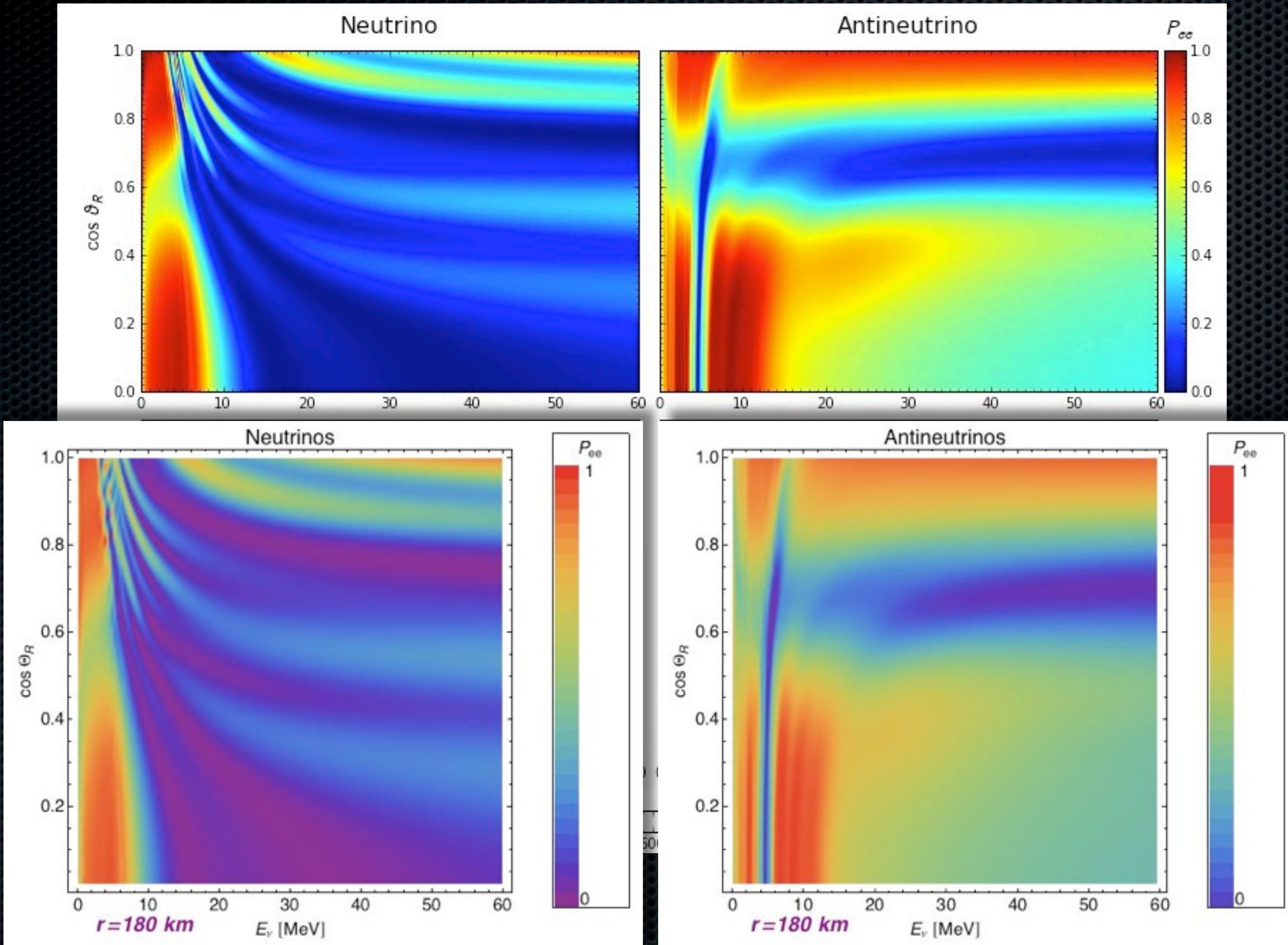


Neutrino
Antineutrino
P_{ee}
$\cos\vartheta_R$
Neutrinos
Antineutrinos
P_{ee}
$\cos\Theta_R$
r=140 km
E_ν [MeV]
r=140 km
E_ν [MeV]

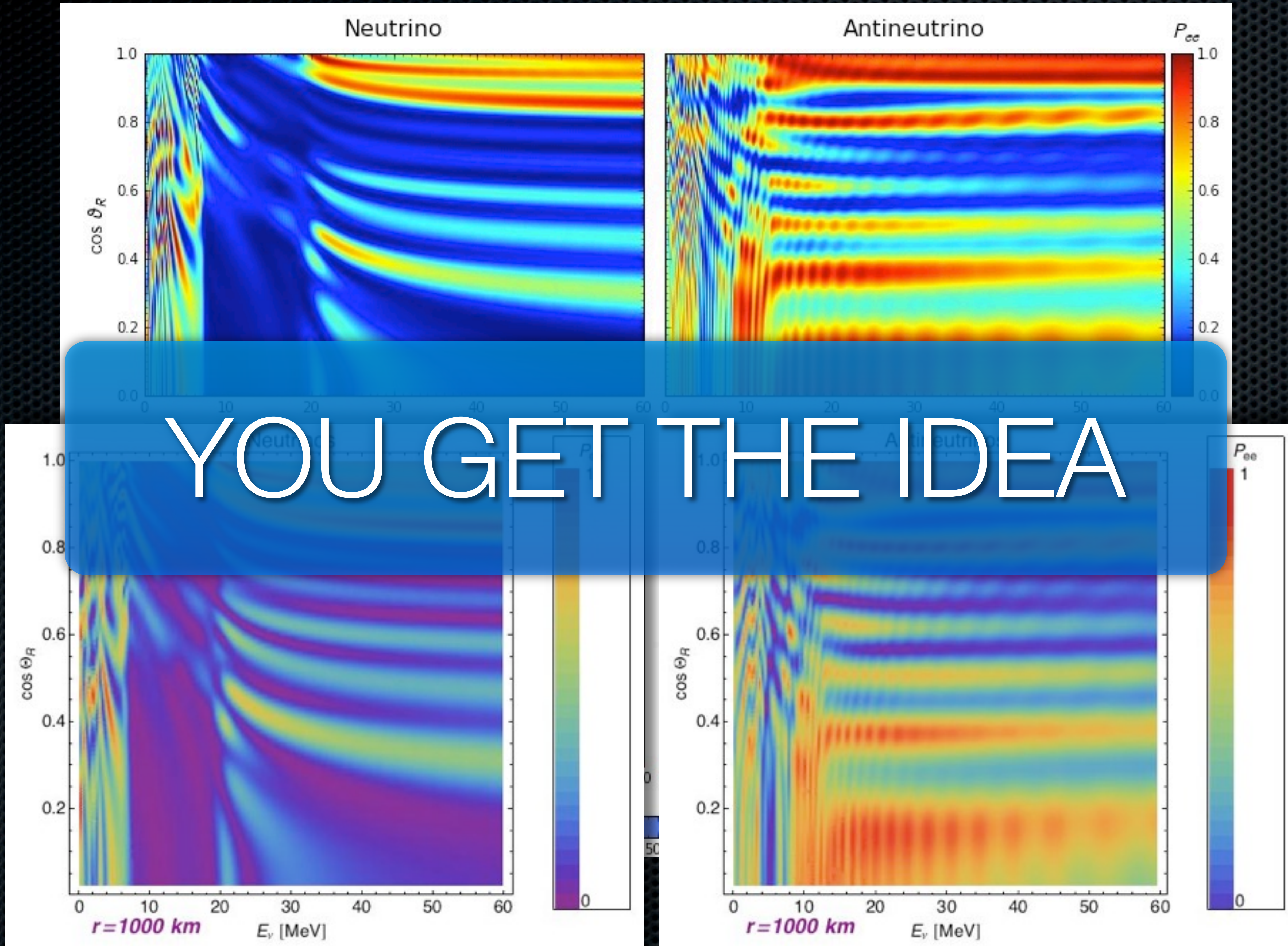
r = 150 km


Neutrino
Antineutrino
P_{ee}
$\cos\vartheta_R$
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
Neutrinos
Antineutrinos
P_{ee}
1
0
$\cos\Theta_R$
$r = 150$ km
E_ν [MeV]

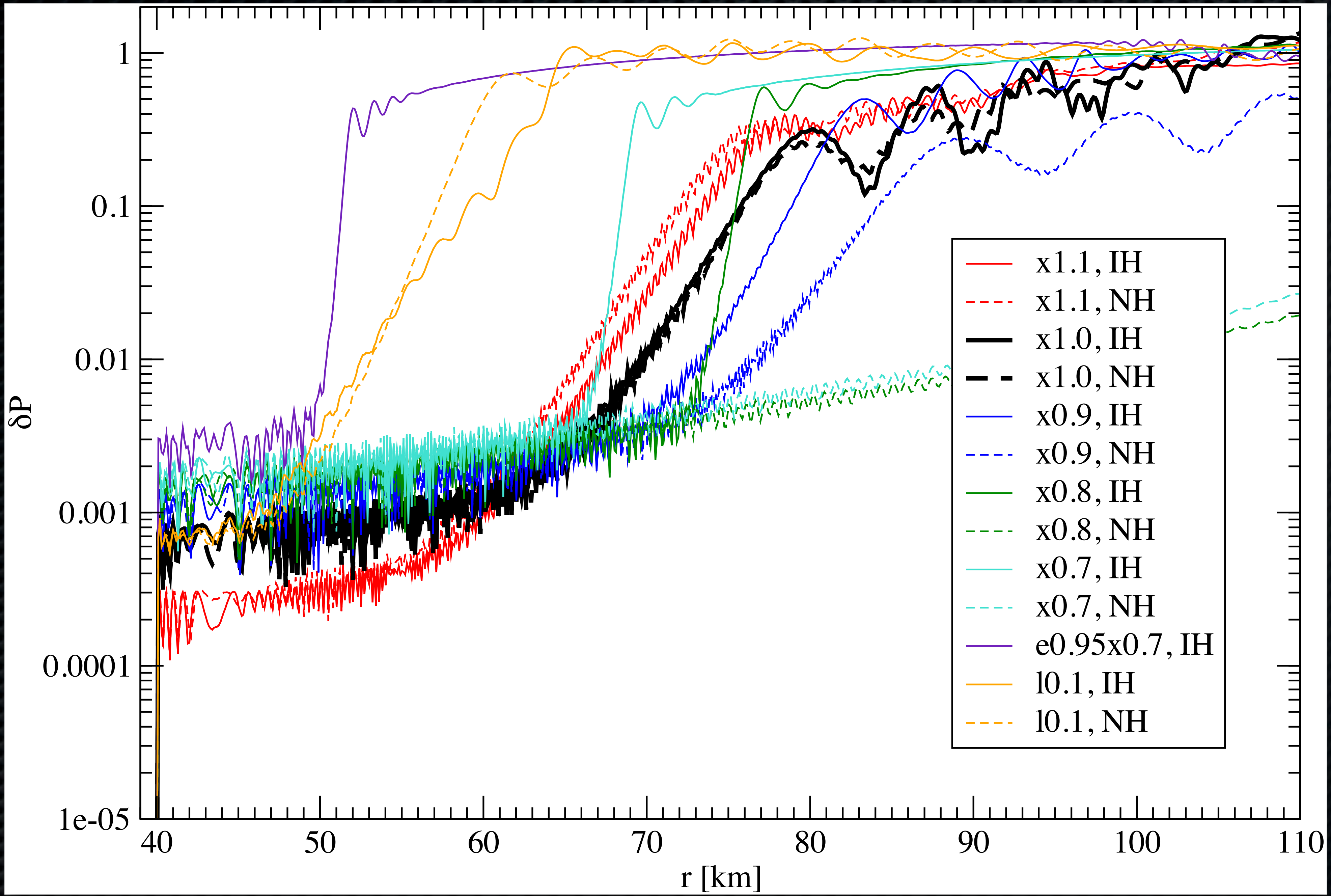
r = 180 km


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

r = 1000 km



YOU GET THE IDEA



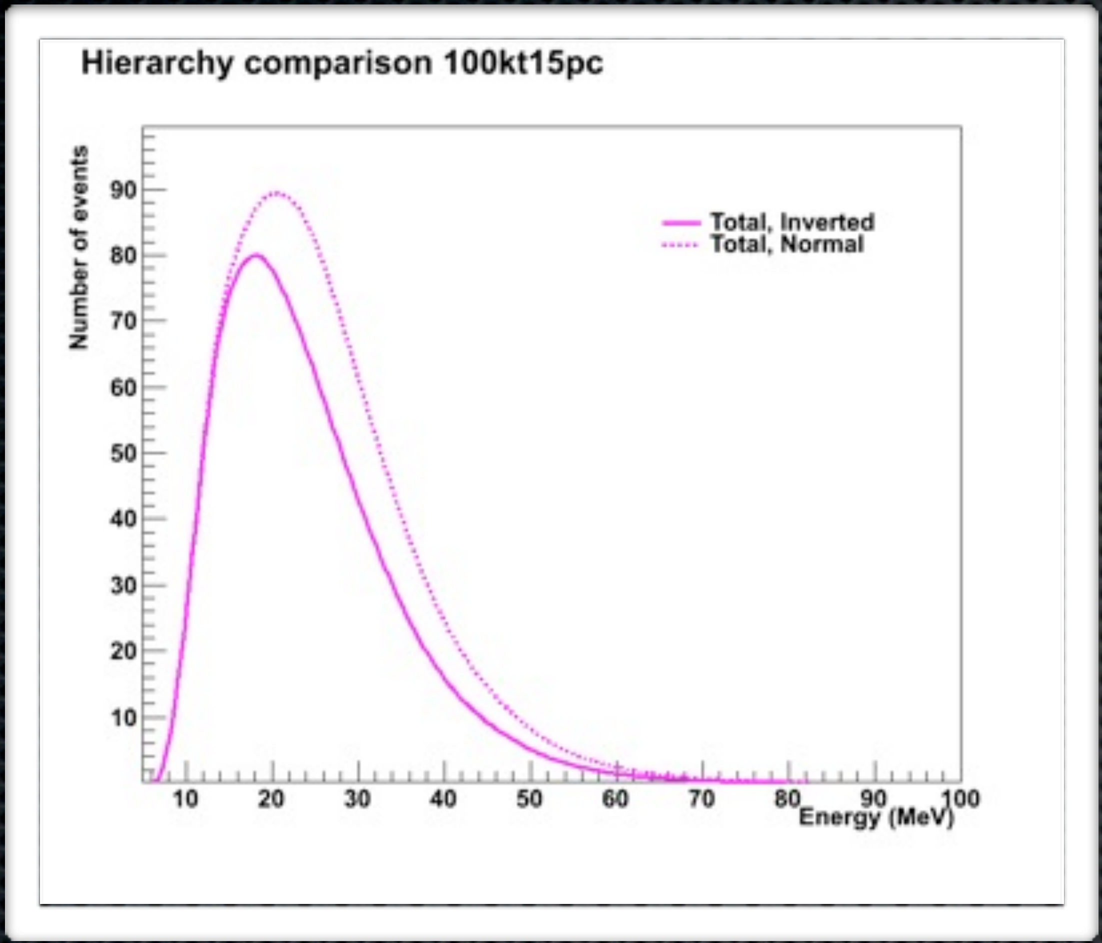
Onset depends on L_x, L_e fluxes

implications for nucleosynthesis (see Huaiyu's and Gail's talks)

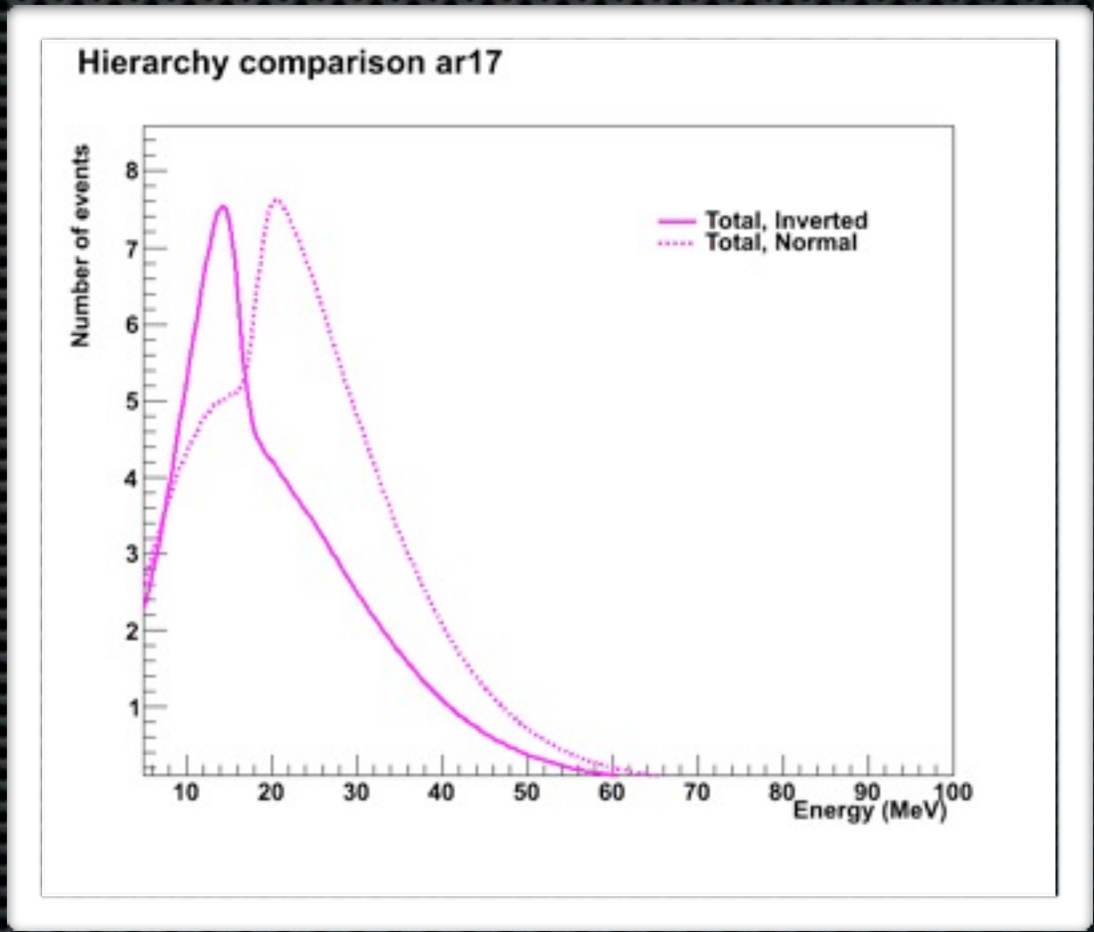
always suppressed at small r

Detector simulations

WC



LAr



- Calculations by the SN burst working group
  - Kate Scholberg et al

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
- "Neutrino-vision": observing the explosion in real time
- Neutrino parameters: hierarchy, theta_13
- Matter at nuclear densities. r-process. Testing physics beyond SM
- We are handing a gift to the LBNE community, they should embrace it, not be afraid of it ;-)