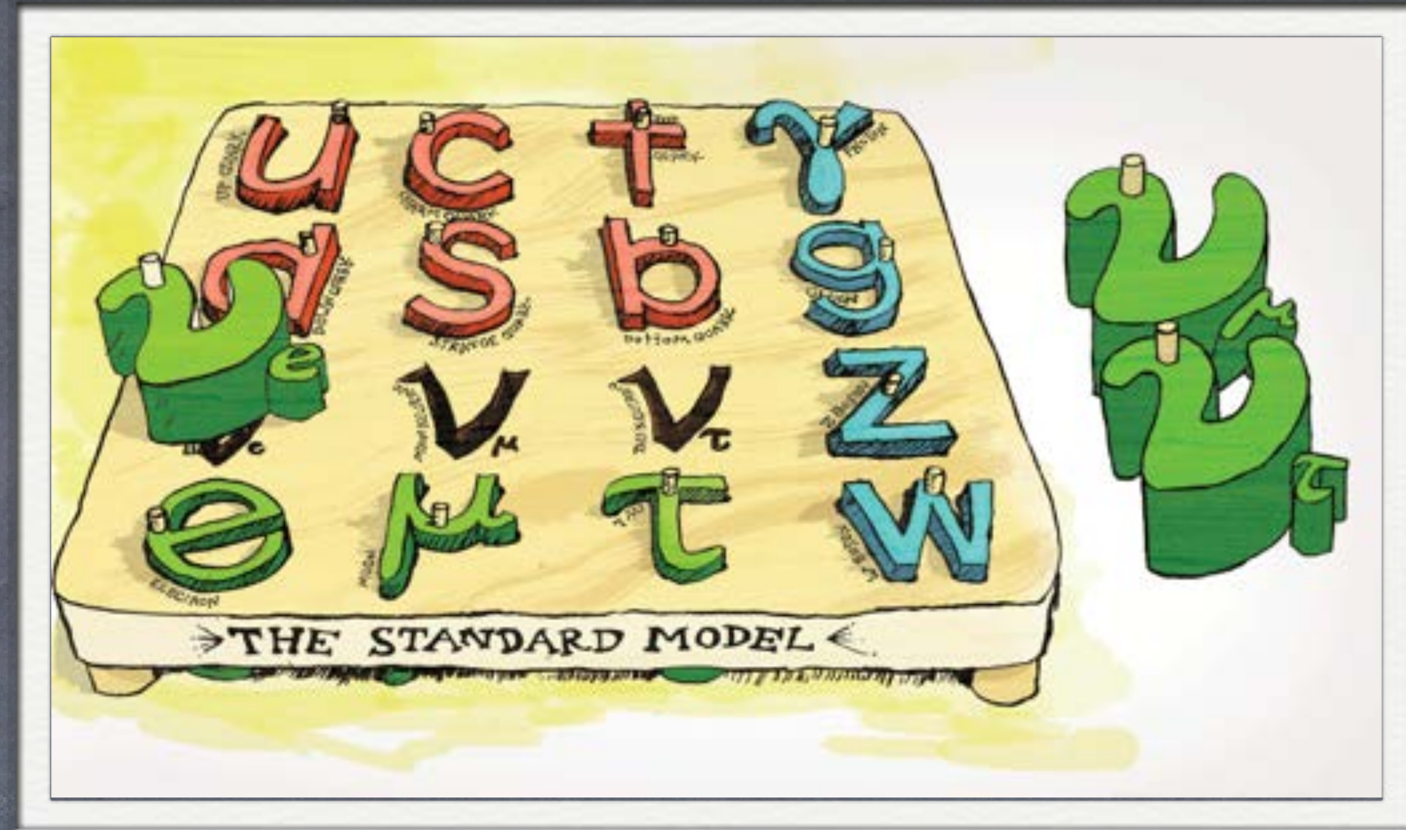


Coherent Neutrino Flavor Transitions in Supernovae

Alex Friedland, Los Alamos

July 21, 2014

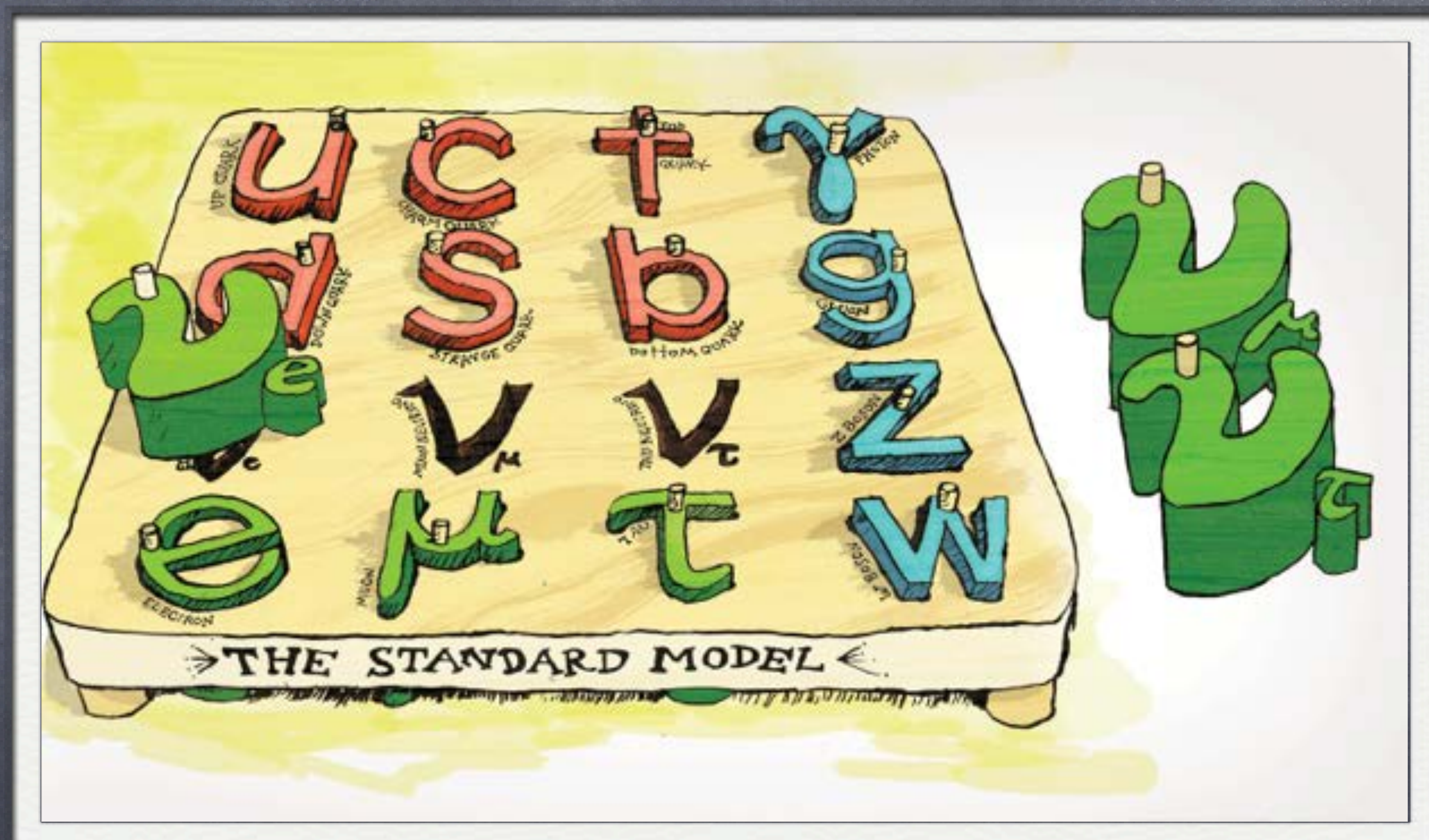
2014 International Summer School on AstroComputing

Outline

- Neutrino oscillations: a historical introduction
- Oscillation physics 101
- Neutrino oscillations in SN-like environments
  - Rich physics: known knowns
  - Rich physics: known unknowns
- Some applications: Galactic SN in a terrestrial detector, nucleosynthesis, explosion?

Source: Symmetry magazine feature

http://www.symmetrymagazine.org/article/february-2013/neutrinos-the-standard-model-misfits



Q: find an inaccuracy in this illustration

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$

$\Delta(m^2) < 0.0075$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 0.02$, CL = 90% (if $\Delta(m^2)$ is large)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)

$\Delta(m^2) < 0.09$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 2.5 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

PDG 1996

http://pdg.lbl.gov/1996/www_2ltab.ps

While no direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained, suggestive evidence has come from solar neutrino observations, from anomalies in the relative fractions of ν_e and ν_μ observed in energetic cosmic-ray air showers, and possibly from a $\overline{\nu}_e$ appearance experiment at Los Alamos. Sample limits are:

Solar Neutrinos

Detectors using gallium ($E_\nu \gtrsim 0.2$ MeV), chlorine ($E_\nu \gtrsim 0.8$ MeV), and Ĉerenkov effect in water ($E_\nu \gtrsim 7$ MeV) measure significantly lower neutrino rates than are predicted from solar models. The deficit in the solar neutrino flux compared with solar model calculations could be explained by oscillations with $\Delta m^2 \leq 10^{-5}$ eV^2 causing the disappearance of ν_e.

Atmospheric Neutrinos

Underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a ν_μ/ν_e ratio much less than expected and also a deficiency of upward going ν_μ compared to downward. This could be explained by oscillations leading to the disappearance of ν_μ with $\Delta m^2 \approx 10^{-3}$ to 10^{-2} eV^2.

PDG 1998

http://pdg.lbl.gov/1998/sumtab/02lw.pdf

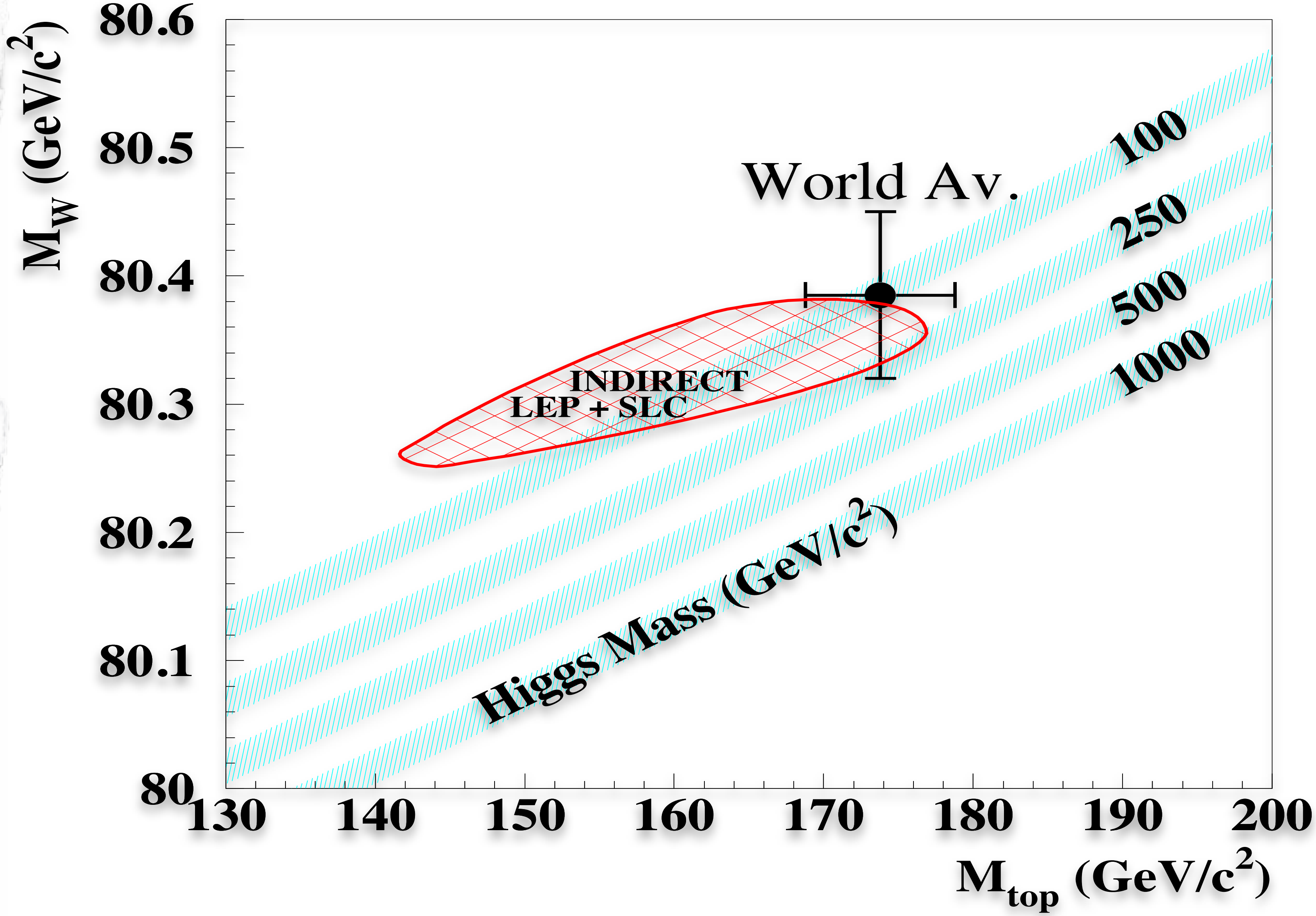
There is now rather convincing evidence that neutrinos have nonzero mass from the apparent observation of neutrino oscillations, where the neutrinos come from π (or K) $\rightarrow\ \mu \rightarrow\ e$ decays in the atmosphere; the mesons are produced in cosmic-ray cascades.

PDG 2000

http://pdg.lbl.gov/2000/lxxx_index.pdf

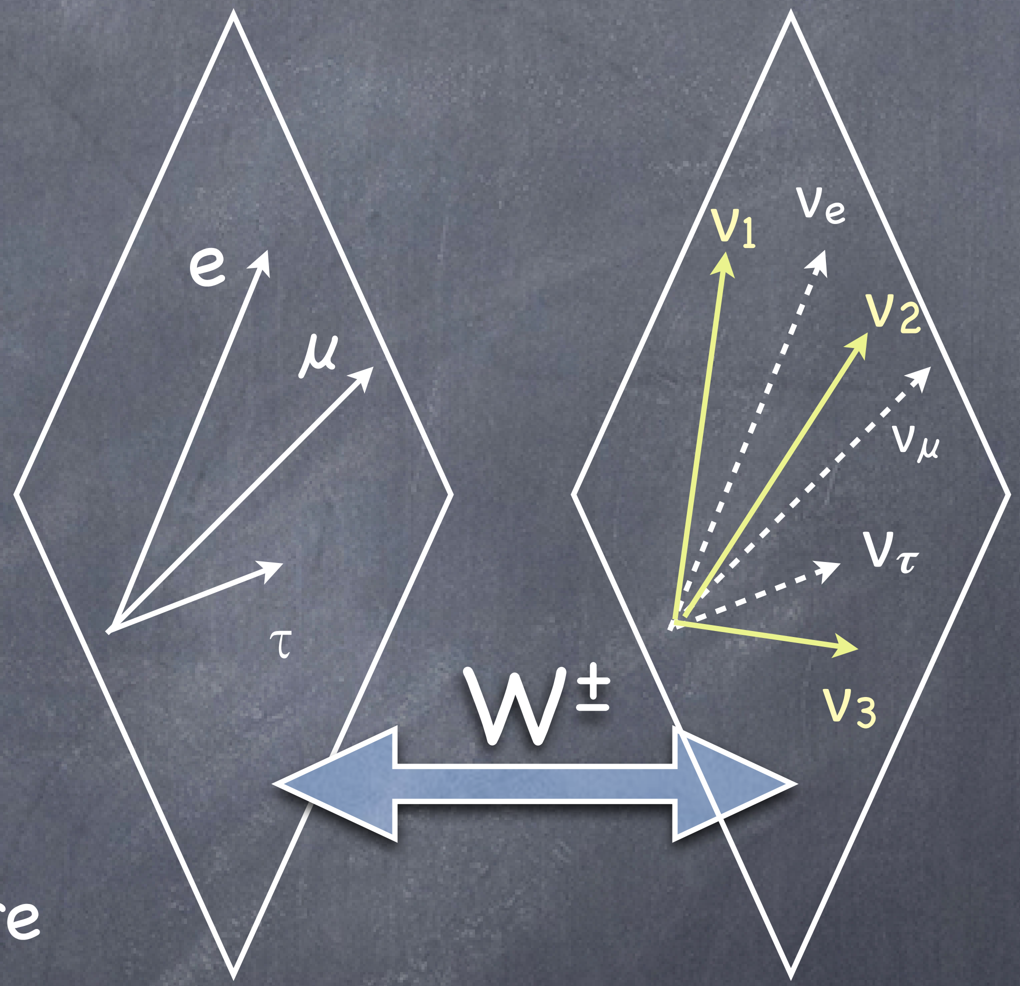
For comparison

hep-ph/
9810316;
Fig. 18



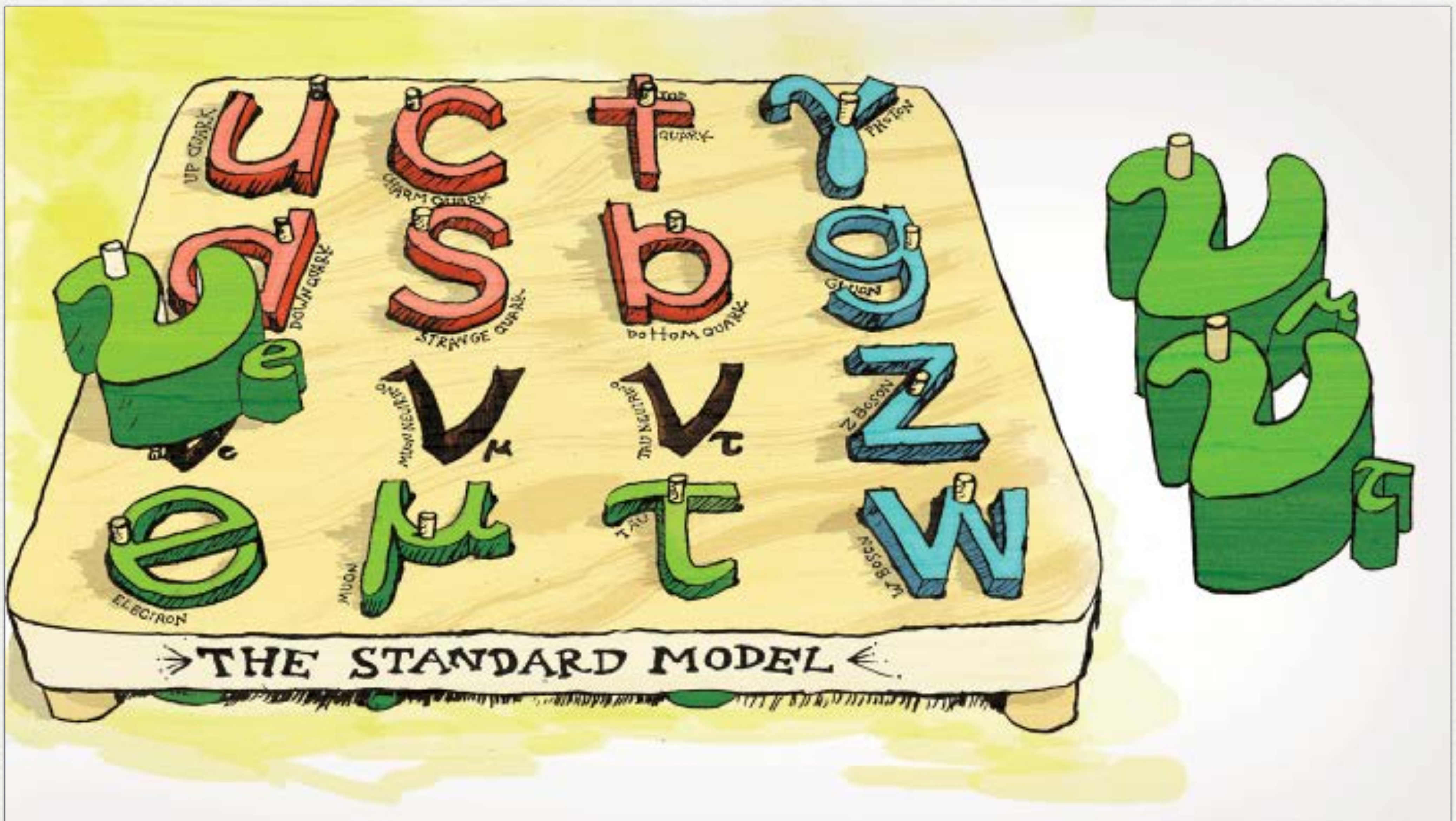
What do we call a particle?

- A mass eigenstate
  - think, e.g., e vs μ vs τ
- Before the discovery of oscillations, neutrinos were the only particles defined as flavor eigenstates (by their interactions with the W boson)
- We now know what neutrino particles are
  - They have been given imaginative names
    - ν_1, ν_2, ν_3



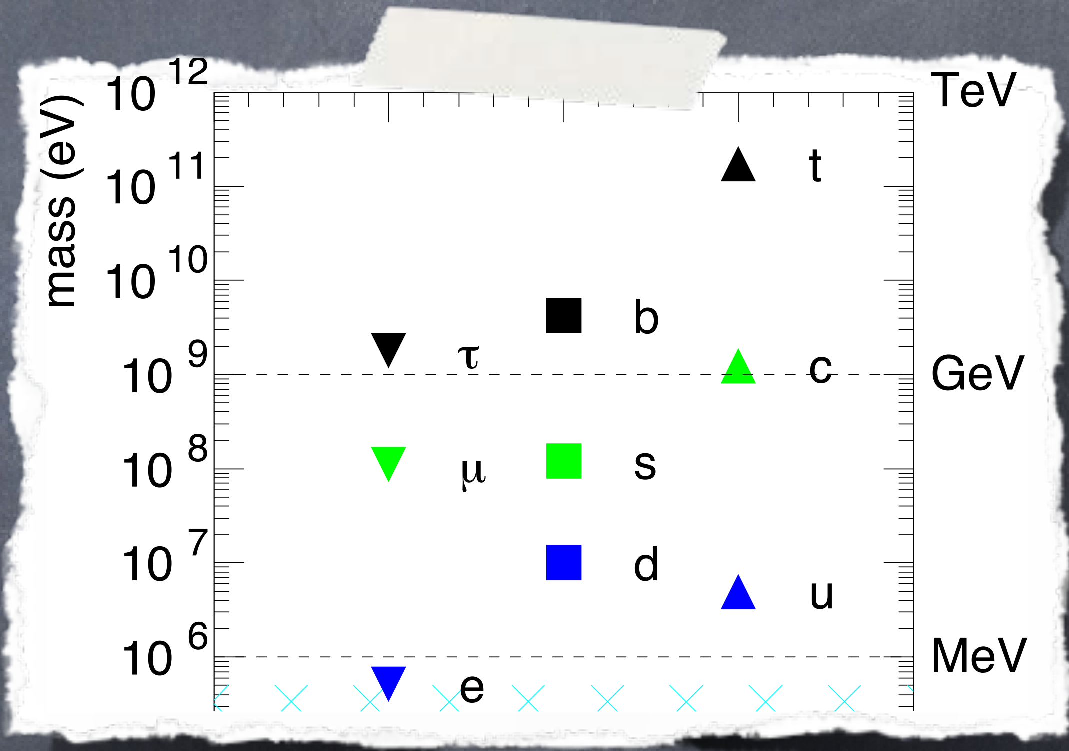
Note large misalignment between the two neutrino bases

Let's see what Symmetry magazine calls a particle



How do we measure neutrino masses?

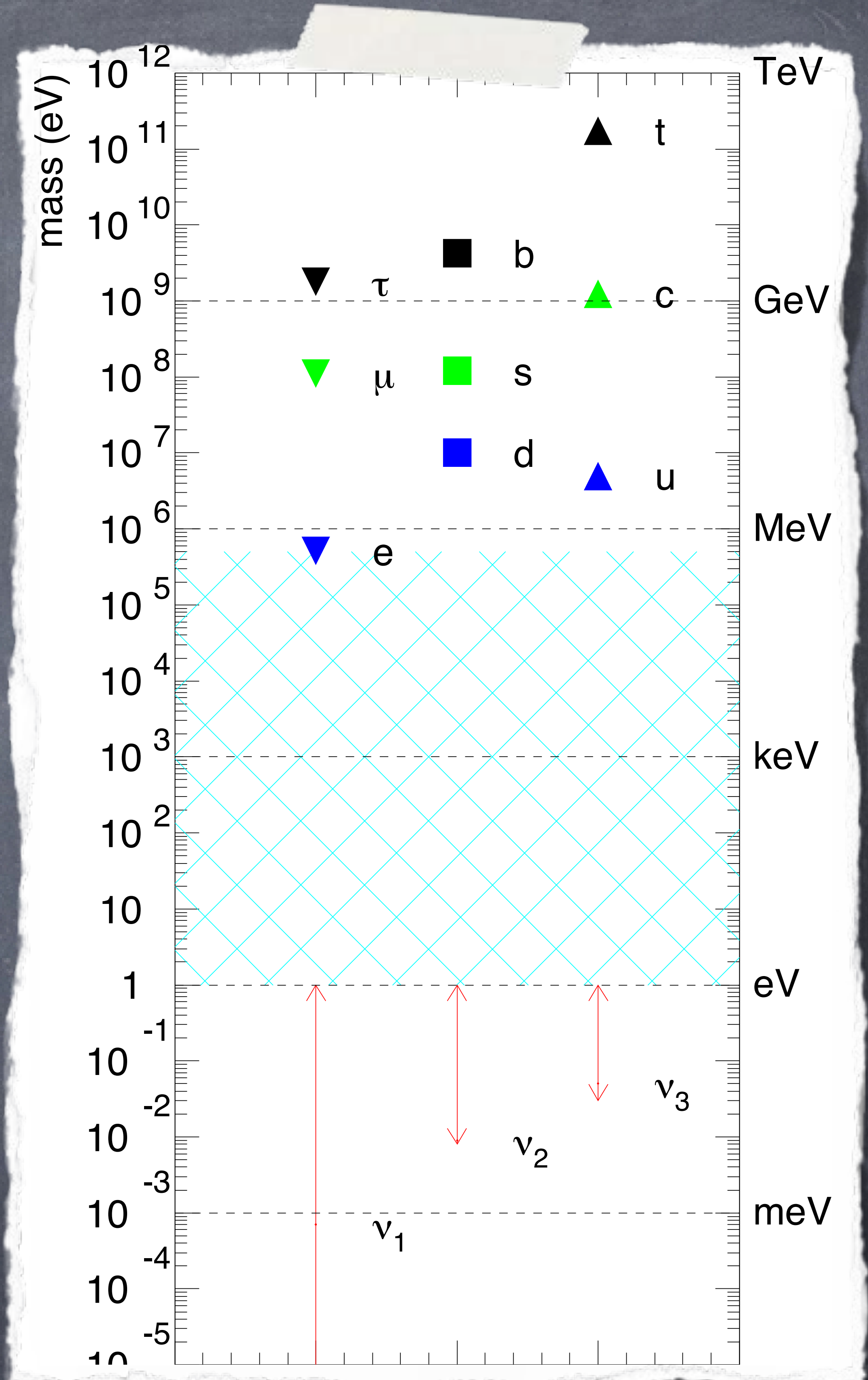
- Neutrino have a mass
- Other particles have masses ...



But neutrino masses are unusual

and neutrinos interact weakly, decouple at low energy (non-renormalizable operator!)

We can't slow them down to weigh at our leisure



Need extraordinary measures

- Endpoint spectra of a decay process EXTREMELY accurately
  - beta-decay of tritium; Katrin
- Majorana mass term is an operator that violates something
  - Neutrinoless double-beta decay; EXO, Majorana, GERDA
- Slow neutrinos down by redshift; use gravity for detection
  - cosmology; CMB, LSS, lensing
- Use interferometry
  - oscillation experiments

Interferometry 101

- Usual argument: start with the ultra-relativistic expansion

$$E = \sqrt{m^2 + p^2} \simeq p^2 + m^2/2p$$

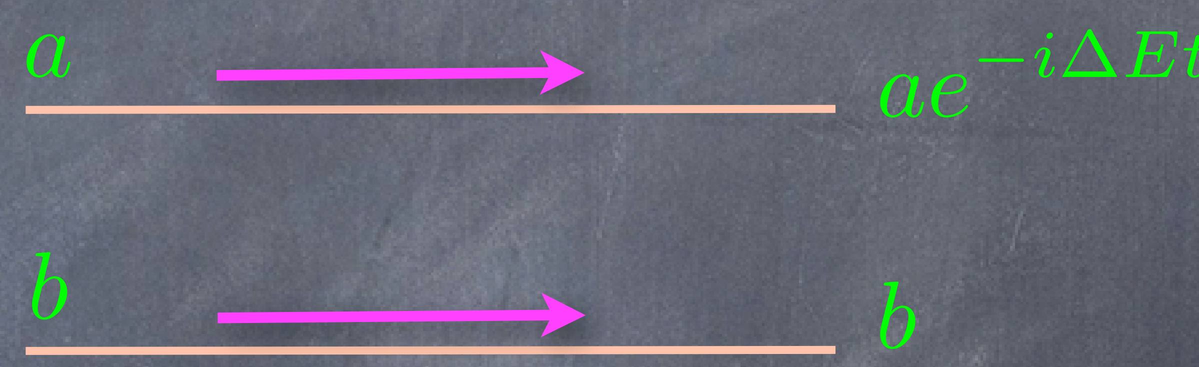
- assume the two states have the same momentum, then

$$\Delta E \simeq \Delta m^2/2p$$

- Or, assume they have the same energy

- Or, assume they have the same velocity

- In fact, it's neither



Interferometry 101

- In fact, it's neither
- For example, for the ^{8}B decay reaction in the Sun there are amplitudes to go into three final states with different particles

$$^8B \to {}^8Be + e^+ + \nu_1$$
$$\to {}^8Be + e^+ + \nu_2$$
$$\to {}^8Be + e^+ + \nu_3$$

- Q: show that the standard expression for ΔE is valid

$$\Delta E \simeq \Delta m^2/2p$$

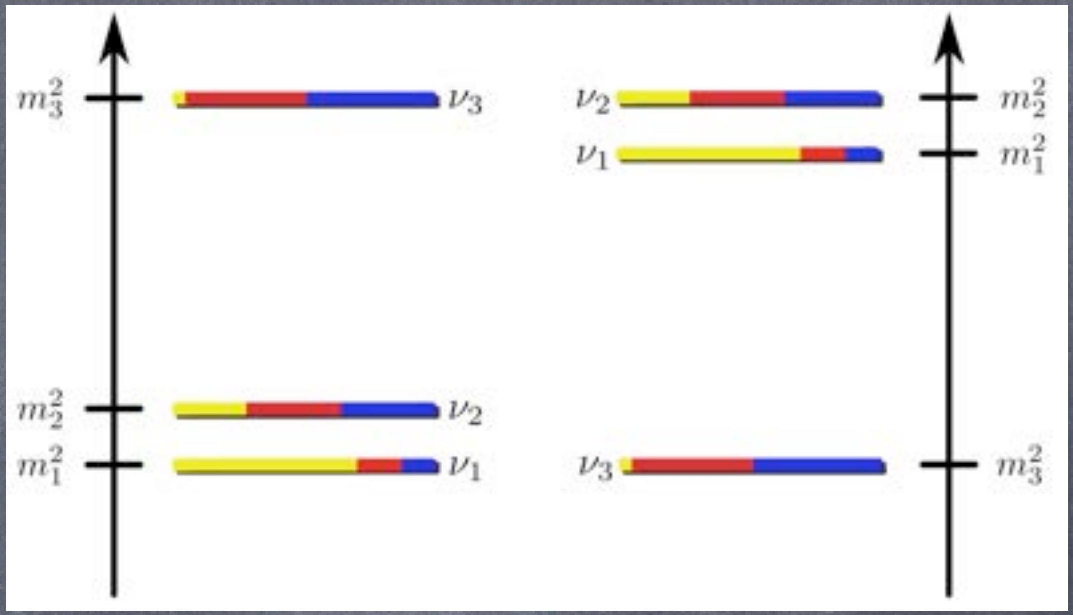
- Q: It may seem that we can just measure the energy of the neutrino accurately enough to decide which final state it went into.
  - How's this consistent with oscillations?

Hint: think uncertainty principle

Accurate energy measurement entails loss of position measurement

What we presently know about neutrinos

- Two mass splittings,
  - Δm^2_{atm} ~2.3 x10^{-3} eV,
  - Δm^2_{sol} ~7.1 x10^{-5} eV
- Three mixing angles,
  - θ_{23}~ 45°±8°,
  - θ_{12}~ 34°±1°,
  - θ_{13}~ 8.7°±0.3°
    - θ_{13}: from unknown to best measured in a blink of an eye



<u>Known unknowns:</u>

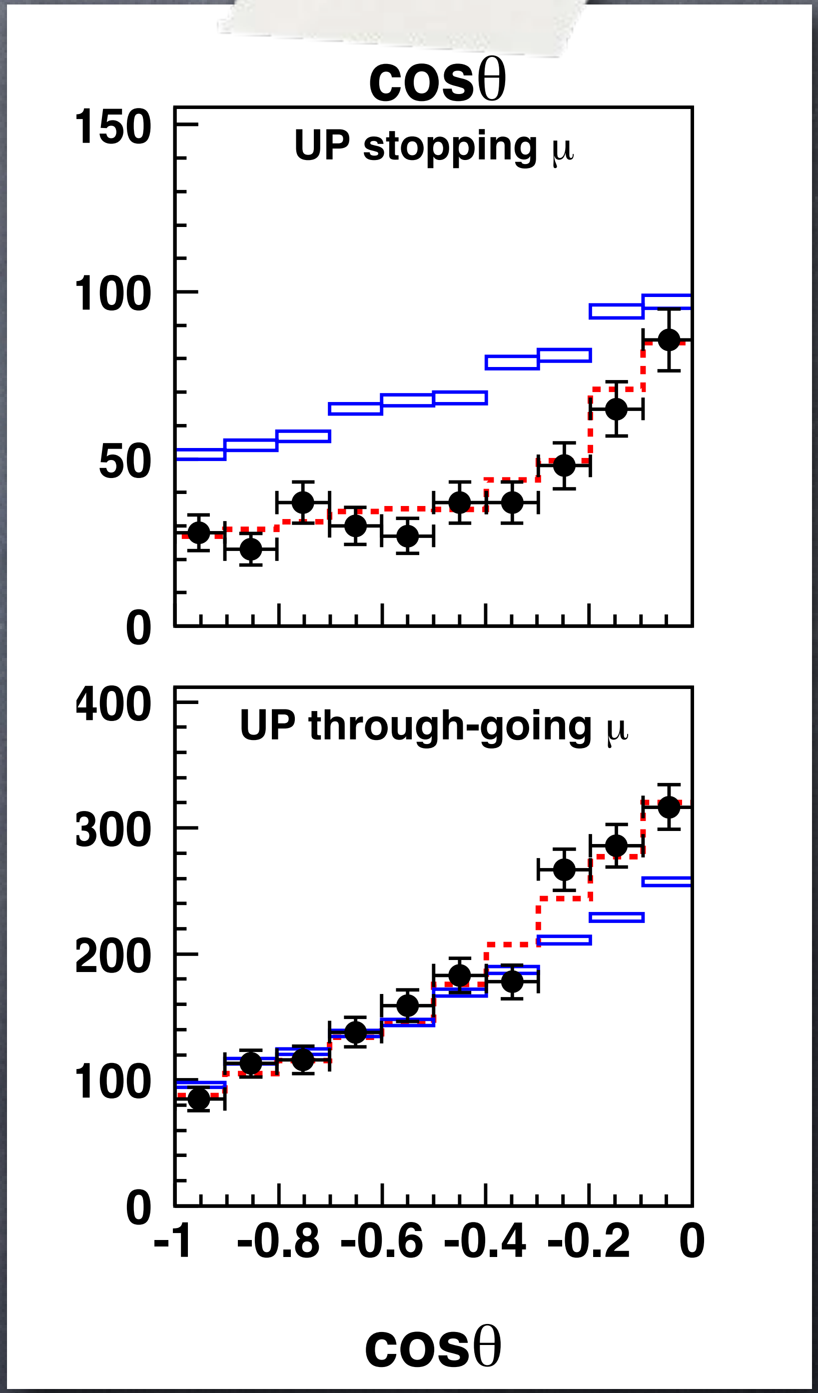
mass hierarchy

CP phase δ,

Dirac or Majorana

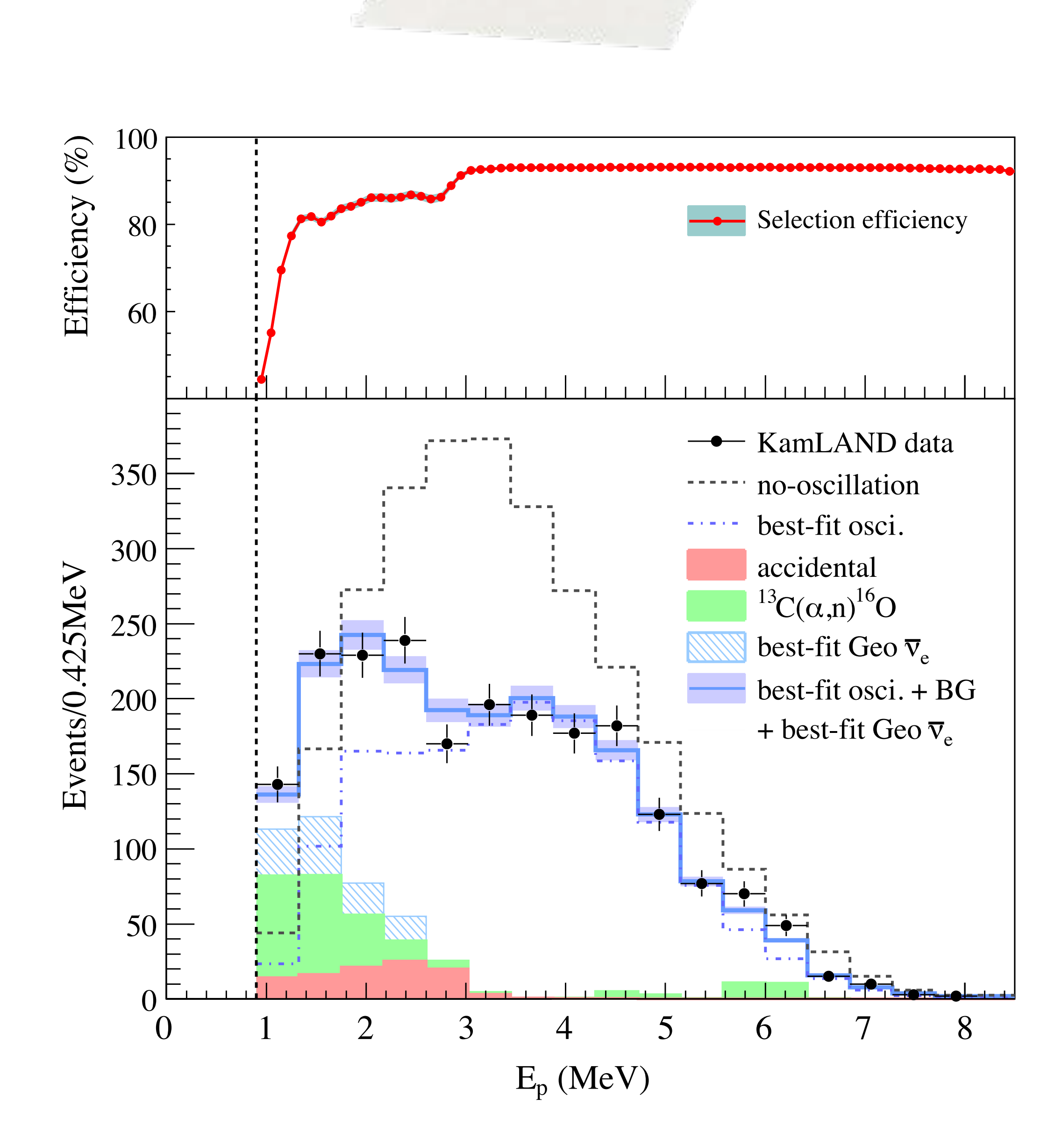
Atmospheric neutrinos

- For atmospheric neutrinos with a few GeV energies
- $l_{osc} \sim E/\Delta m^2_{atm} \sim 10^3$km, good distance scale to probe on the scales of the earth
- Super-Kamiokande!
- $\nu_\mu \rightarrow \nu_\tau$ oscillation favored



Reactor neutrinos, KamLAND

- For reactor antineutrinos with a few MeV energies
- $l_{osc} \sim E/\Delta m^2_{sol} \sim 10^2$km, good distance scale to probe on the scales of Japan
- The most precise measurement of Δm^2_{sol}



Reactor neutrinos, Daya Bay

- For reactor antineutrinos with a few MeV energies
- $l_{osc} \sim E/\Delta m^2_{atm} \sim 1$ km, good distance scale to probe next to a power station

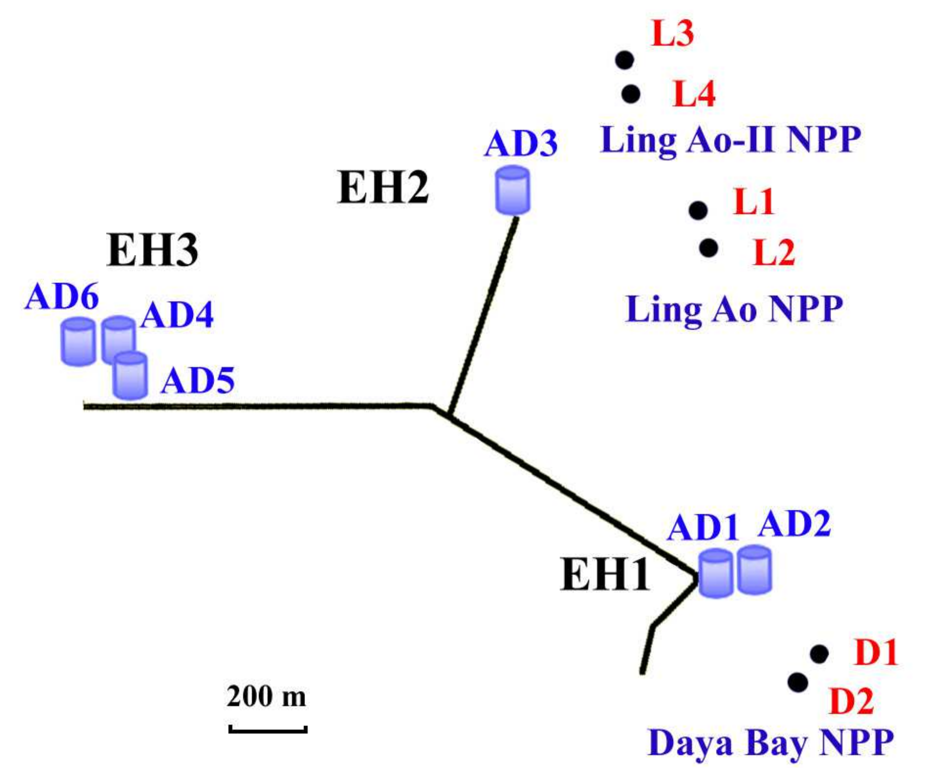


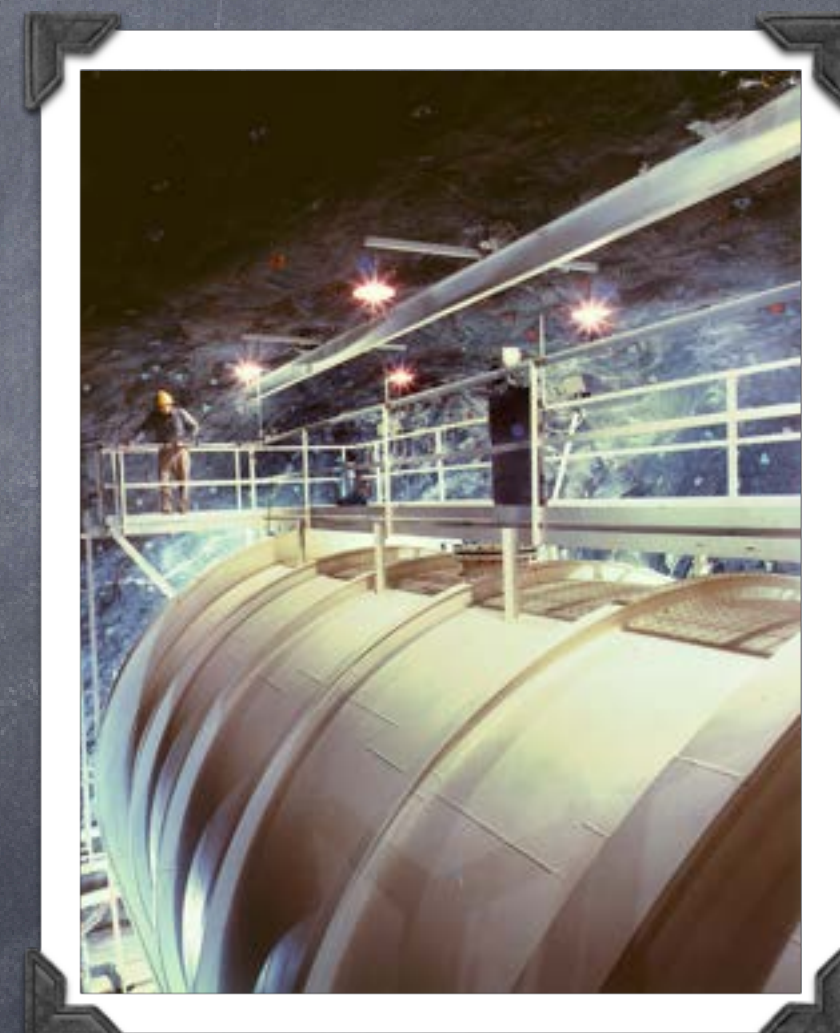
Fig. 1. Layout of the Daya Bay experiment. The dots represent reactor cores, labeled as D1, D2, L1, L2, L3 and L4. Six antineutrino detectors (ADs) were installed in three experimental halls (EHs).

Solar neutrino oscillations

- The first neutrino oscillation effect was observed in 1968, by the Homestake experiment in the US
  - 100,000 gallons of dry-cleaning fluid (tetrachloroethylene) 4,850 feet underground. Every few weeks, extracted Ar, formed by

$$\nu_e +^{37} Cl \rightarrow e^- +^{37} Ar$$

  - Expected ~ 51 atoms of Ar, but saw only ~ 17



BULLETIN BOARD

Volume 21, Number 36 | Published by the BNL Public Relations Office | September 14, 1967

9-1307-66

Solar Neutrinos Are Counted At Brookhaven

- http://www.bnl.gov/bnlweb/raydavis/BB_sept1967.pdf
- No mention of oscillations

The theoretical forecast had led scientists to believe that the neutrino emission from the sun would allow from 1.5 to 5 neutrino captures per day. In the single experiment performed to date, Dr. Davis reports that the capture rate in the underground tank was less than 2 neutrinos per day. Knowing this plus the efficiency of neutrino capture allowed Dr. Davis and his group to calculate the flux from the Boron-8 decay to be approximately 60 million solar neutrinos per square inch per second at the earth's surface. Previous calculations had predicted the flux could be anywhere from 40 million to 150 million solar neutrinos per square inch per second at the earth's surface.

Matter matters

- Wolfenstein 1978: matter effect, by analogy with the Kaon regeneration in matter
  - Coherent forward scattering (index of refraction) is different for ν_e and ν_μ, ν_τ (birefringence)
  - Correct equations (up to the sign and $\sqrt{2}$)
  - But, the evolution equations in the falling solar density profile are not actually solved
    - Similar scenario later plays out for collective oscillations in supernovae
  - a large part of Wolfenstein's paper is on new physics FCNC

MSW, 1985-86

- Mikheev and Smirnov solved the evolution equation in the solar density profile
- Found large conversion possible for small vacuum mixing
- Their paper was rejected
- They attempted repackaging in the supernova neutrino context, bury the word “resonance”
  - see arxiv:0706.0454

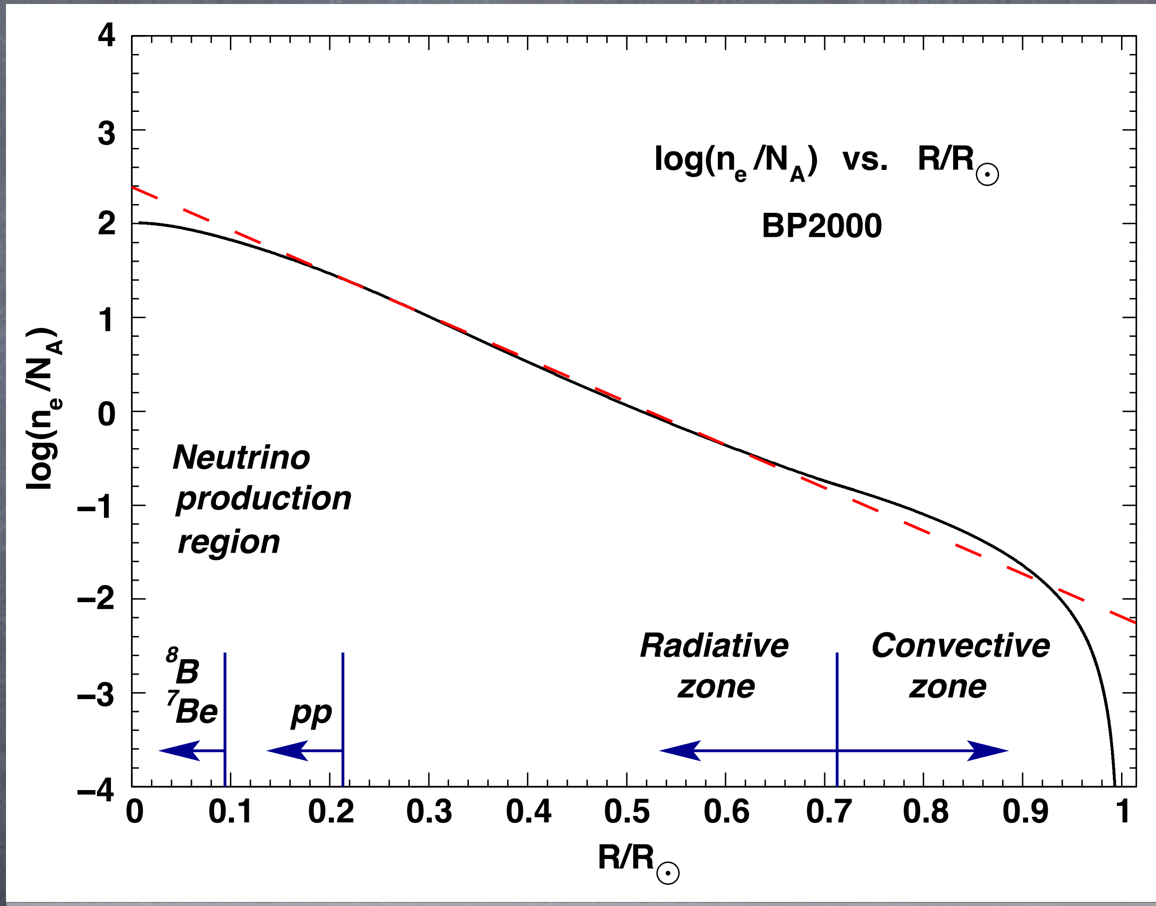
Comments (June 2007)

1. This paper presents, in particular, our first analytic results on the adiabatic conversion of neutrinos in matter. It has been written in summer-fall 1985. In attempt to avoid problems with publication (we had before), we tried to hide the term “resonance”, and did not discussed applications to the solar neutrinos; also we have not included references to our previous papers on the resonance enhancement of neutrino oscillations.

This short paper has been submitted to JETP Letters in the fall 1985 and successfully ... rejected. It was resubmitted to JETP in December of 1985. The results of the paper have been reported at the 6th Moriond workshop in January 1986 and included in several later reviews. The paper was reprinted in “Solar Neutrinos: The first Thirty Years”, Ed. J. N. Bahcall, et al., Addison-Wesley 1995.

MSW then is accepted by the neutrino practitioners

- Large conversion for small mixing angles
  - And people know that mixing angles are naturally small
- “Generic” mechanism, since the solar density profile spans orders of magnitude



Meanwhile, the HEP community remains largely skeptical

- Georgi & Luke, Nucl Phys B347, 1-11 (1990)

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly

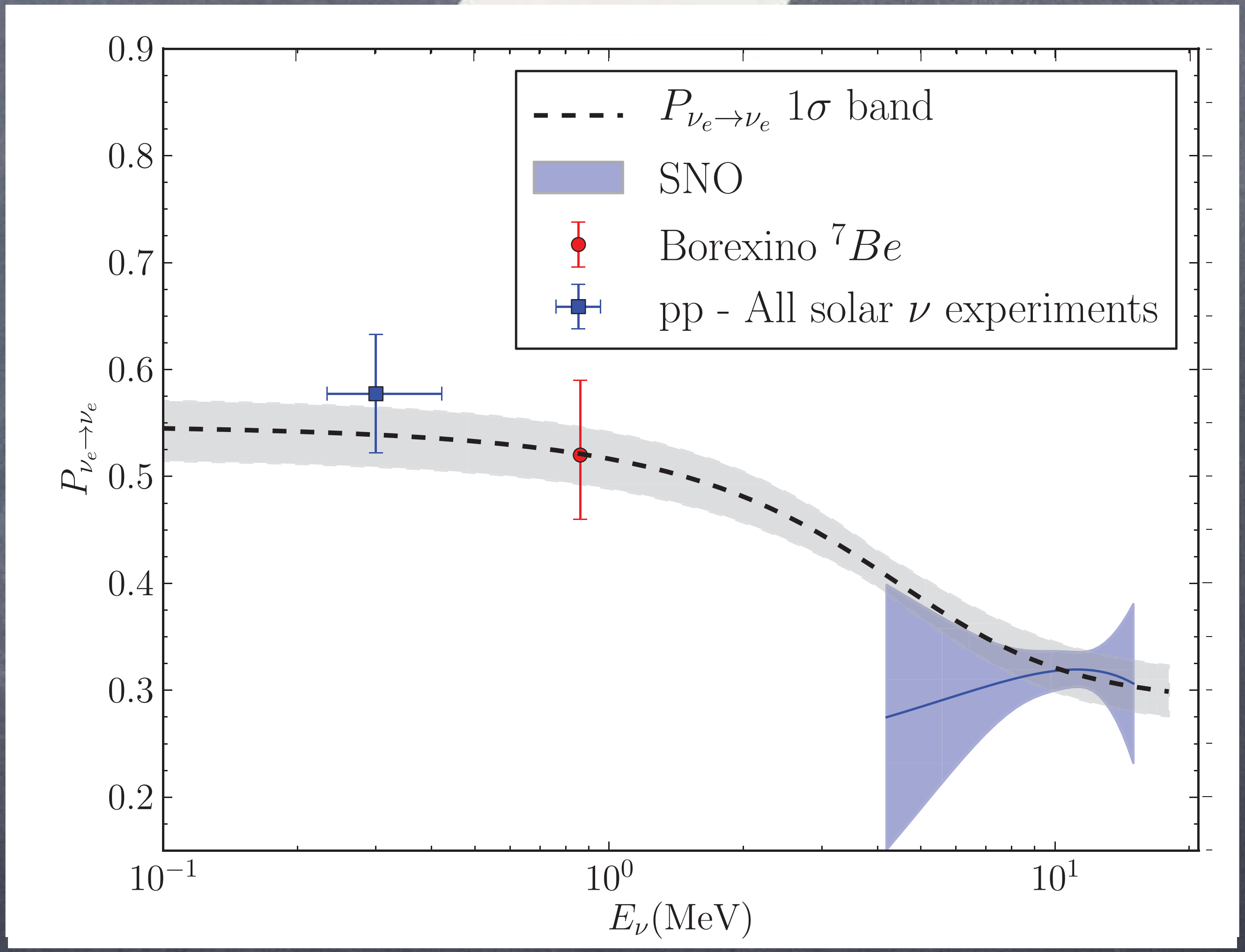
- Other quotes in Bahcall, physics/0406040

In hindsight

- The θ_{12} mixing angle eventually turns out to be large
  - The hierarchy of small mixings is not present in the lepton sector
- The mass-squared splitting turns out to be fine-tuned to the matter density in the center of the Sun

Solar neutrinos: data

- Data shows that electron neutrino survival probability is energy-dependent
- Nontrivial, requires a coincidence of something
- The matter density in the Sun, the solar mass splitting and the neutrino energy ~ 1 MeV conspire



$$\sqrt{2}G_F n_\odot \sim \Delta m^2_{sol}/2E_\nu$$

Solar neutrino flavor oscillations 101

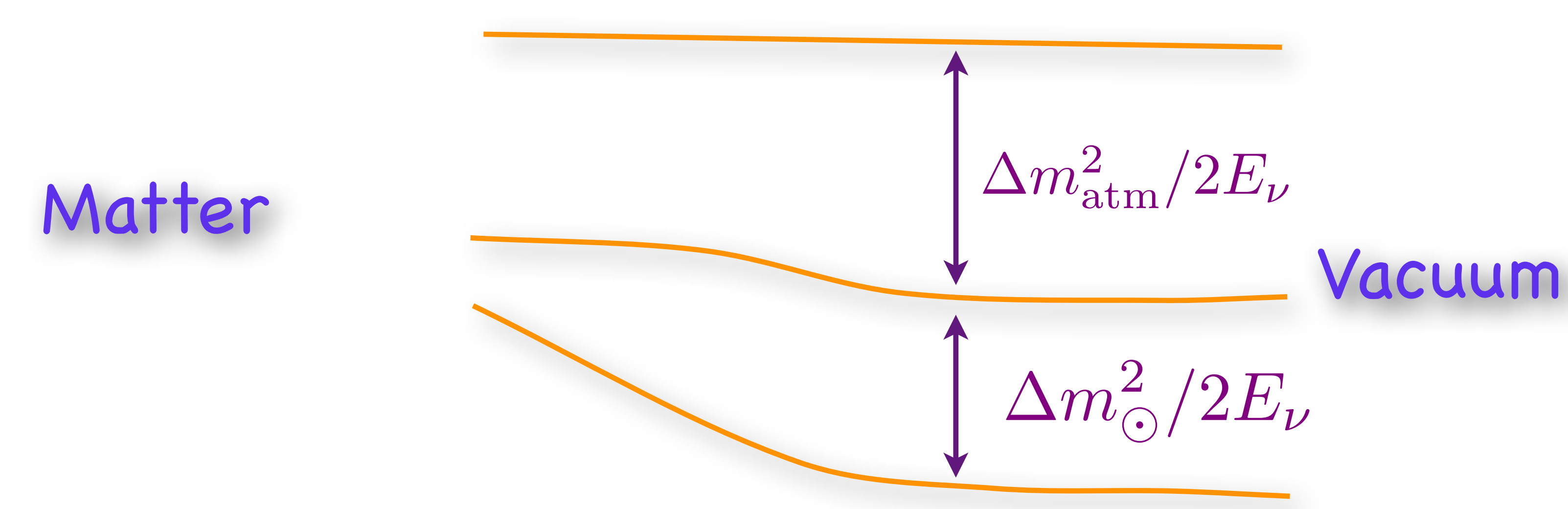
- Solar neutrinos: simple quantum mechanics problem

$$i\partial_t|\psi_i\rangle = H_{\rm osc}|\psi_i\rangle$$

$$H_{\rm osc} = H_{\rm vac} + H_{\rm matter} \rightarrow H_{\rm ee} = \sqrt{2}G_F N_e$$

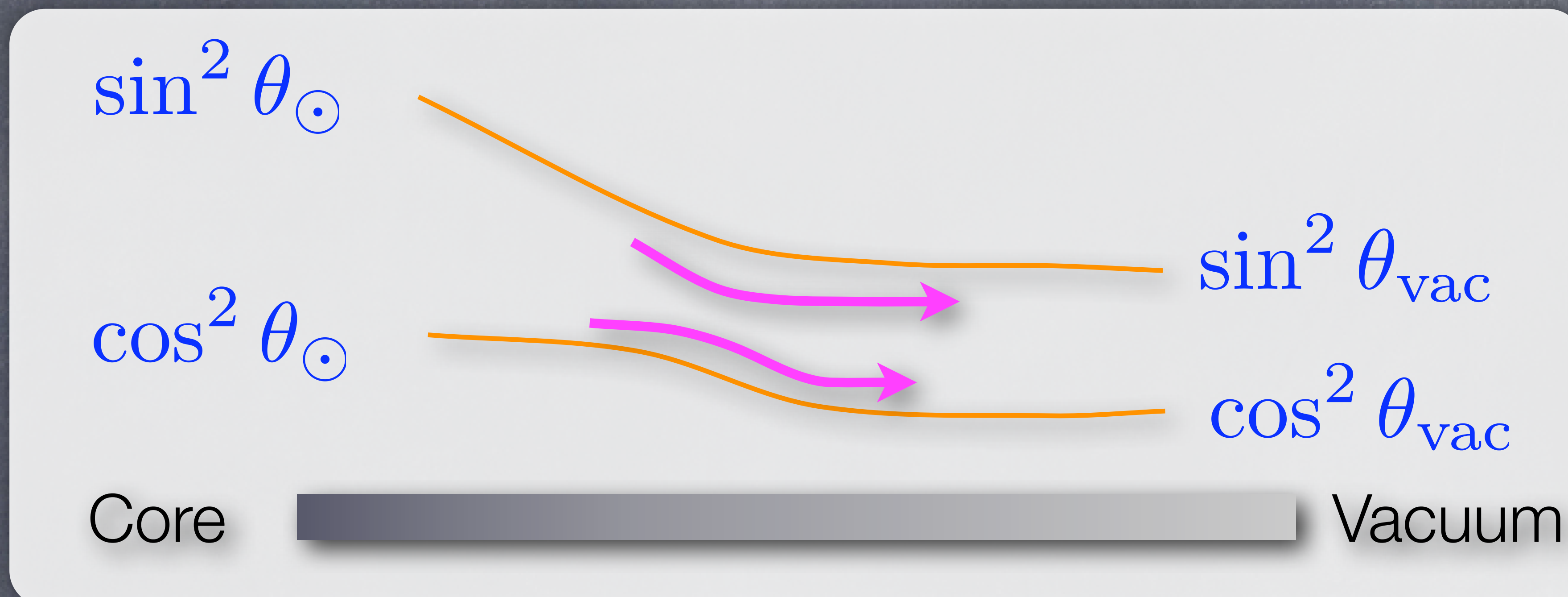
Hamiltonian eigenvalues (for normal hierarchy)

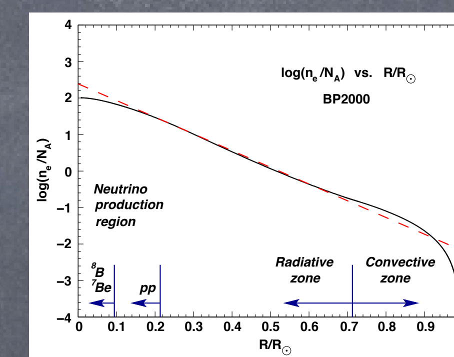
Not to scale!



2-state oscillations

$$P_2(\nu_e \to \nu_e) \quad = \quad \sin^2\theta \sin^2\theta_\odot + \cos^2\theta \cos^2\theta_\odot$$

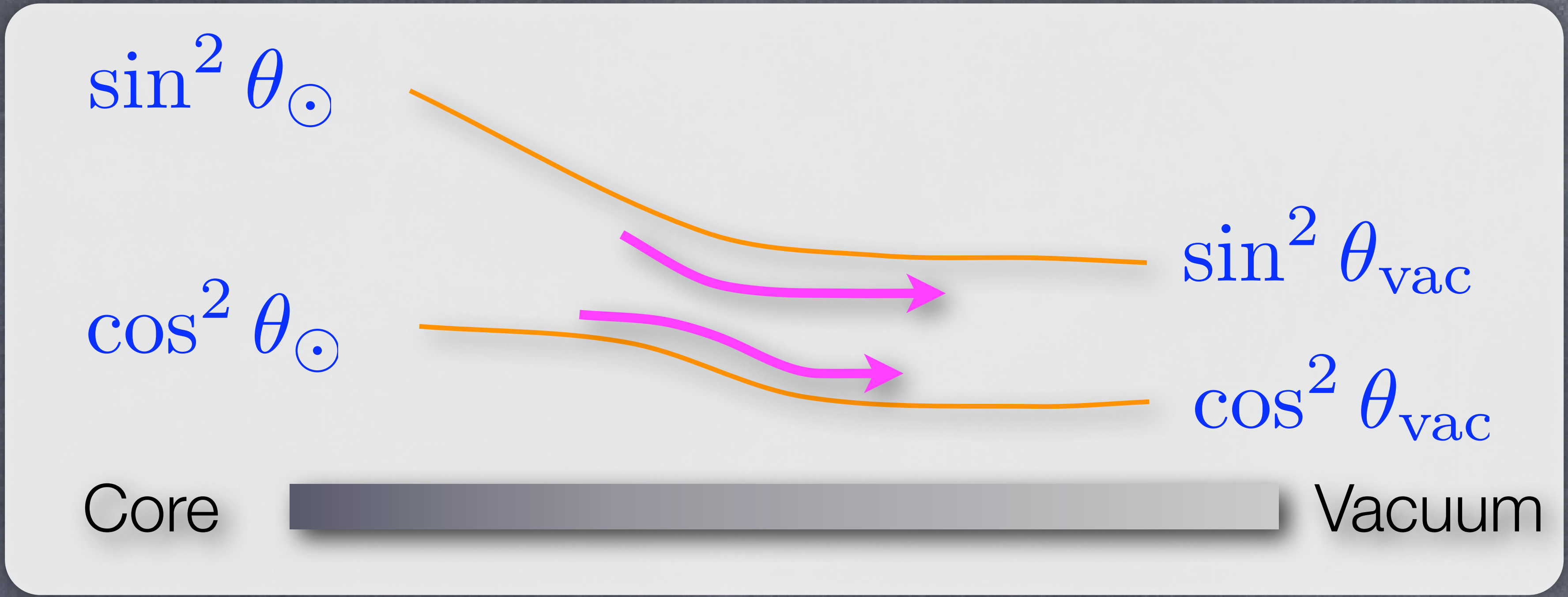




- The evolution is adiabatic (no level jumping), since l_{osc} << density scale height ($|d \ln\rho/dr|^{-1}$)
- Q: convince yourself of that
    - Hint: for most of the Sun, the density scale height is $R_{sun}/10$, while l_{osc} is comparable to the width of Japan (why? KamLAND)

2-state oscillations

$$P_2(\nu_e \to \nu_e) \quad = \quad \sin^2\theta \sin^2\theta_\odot + \cos^2\theta \cos^2\theta_\odot$$

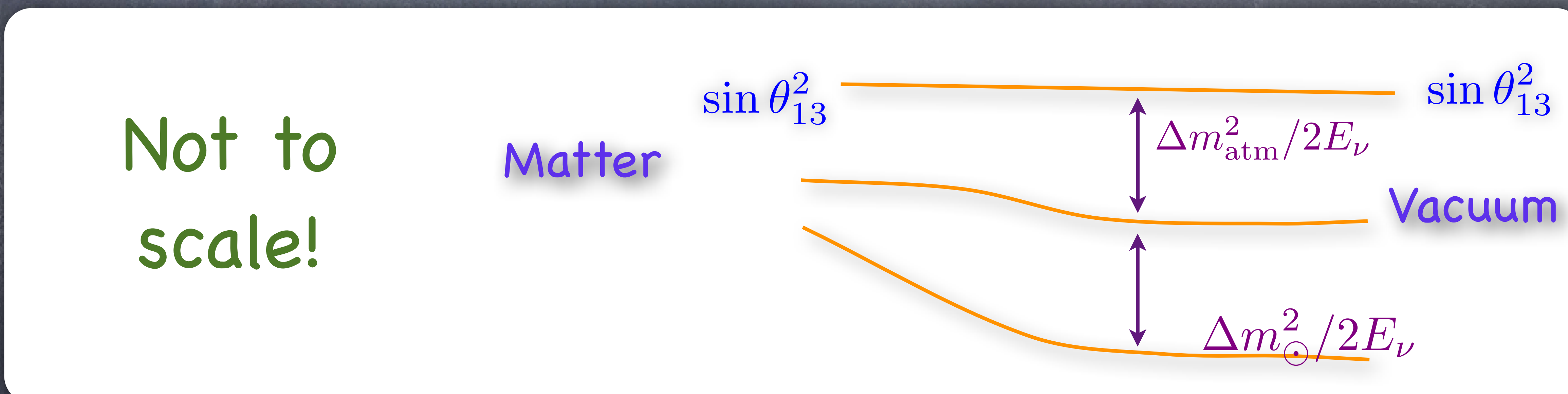


- Also, coherence between the mass eigenstates is lost
- Q: convince yourself of that
    - Hint: How does the oscillation length compare to the size of the production region?

3-state oscillations

- The third state provides a ~ 4.5% correction

$$
\begin{aligned}
P_3(\nu_i \to \nu_i) &= \sin\theta_{13}^4 + \cos\theta_{13}^4 P_2(\nu_i \to \nu_i) \\
&\simeq 0.955 P_2(\nu_i \to \nu_i)
\end{aligned}
$$

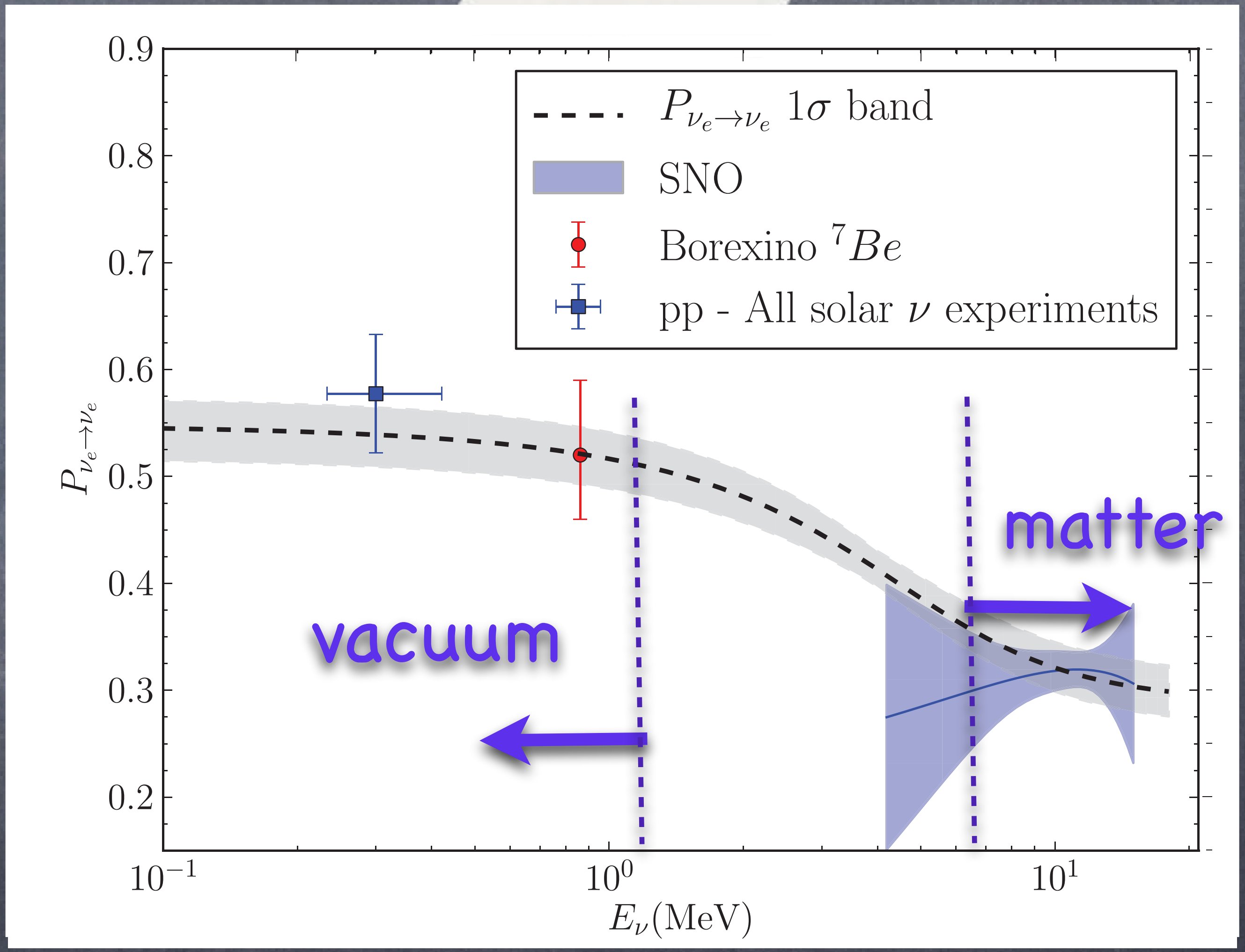


- Notice that the projection of the electron neutrino on the third state is $\sin\theta_{13}^2$, unaffected by matter

Now, back to the data

- The low-energy neutrinos (< 1 MeV) are in the vacuum oscillation regime (matter doesn't matter)

$$P_3(\nu_e \to \nu_e) \quad \to \quad \cos^4\theta_{13}(\sin^4\theta_{12} + \cos^4\theta_{12})$$

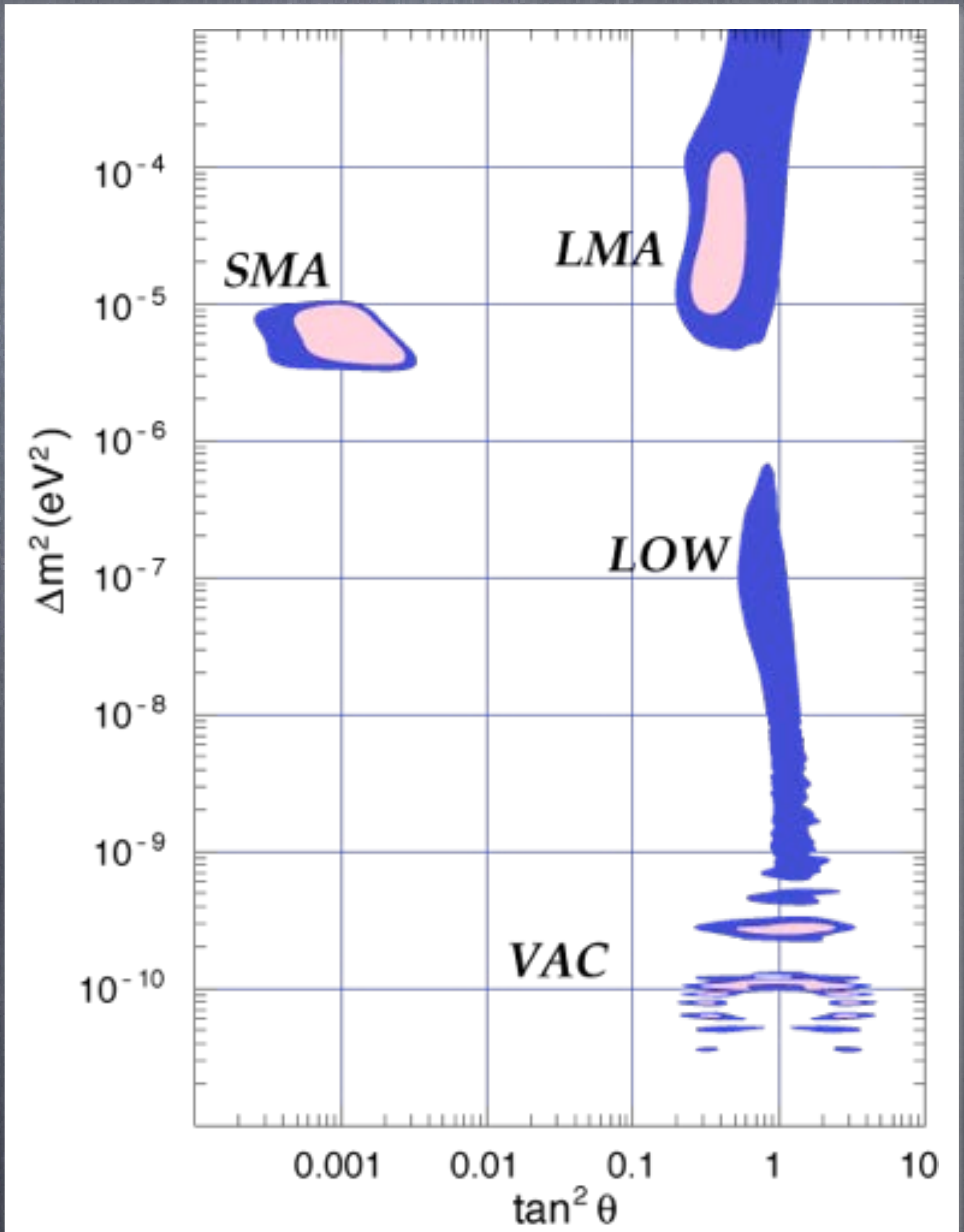


- while the high energy ^{8}B neutrinos are in the matter dominated regime (produced as ν_2)

$$P_3(\nu_e \to \nu_e) \quad \to \quad \cos^4\theta_{13}\sin^2\theta_{12}$$

Comment on fine-tuning

- All solutions possible in 2000 had to be tuned in some way
- VAC: osc length to 1 A.U.
- LOW: resonance in the Earth
- SMA: on the boundary of adiabatic and non-adiabatic + tuned to the central solar density
- **LMA: tuned to the central solar density**



A. de Gouvea, A.F., H. Murayama, PLB 490, 125 (2000)
A.F., PRL 85, 936 (2000)

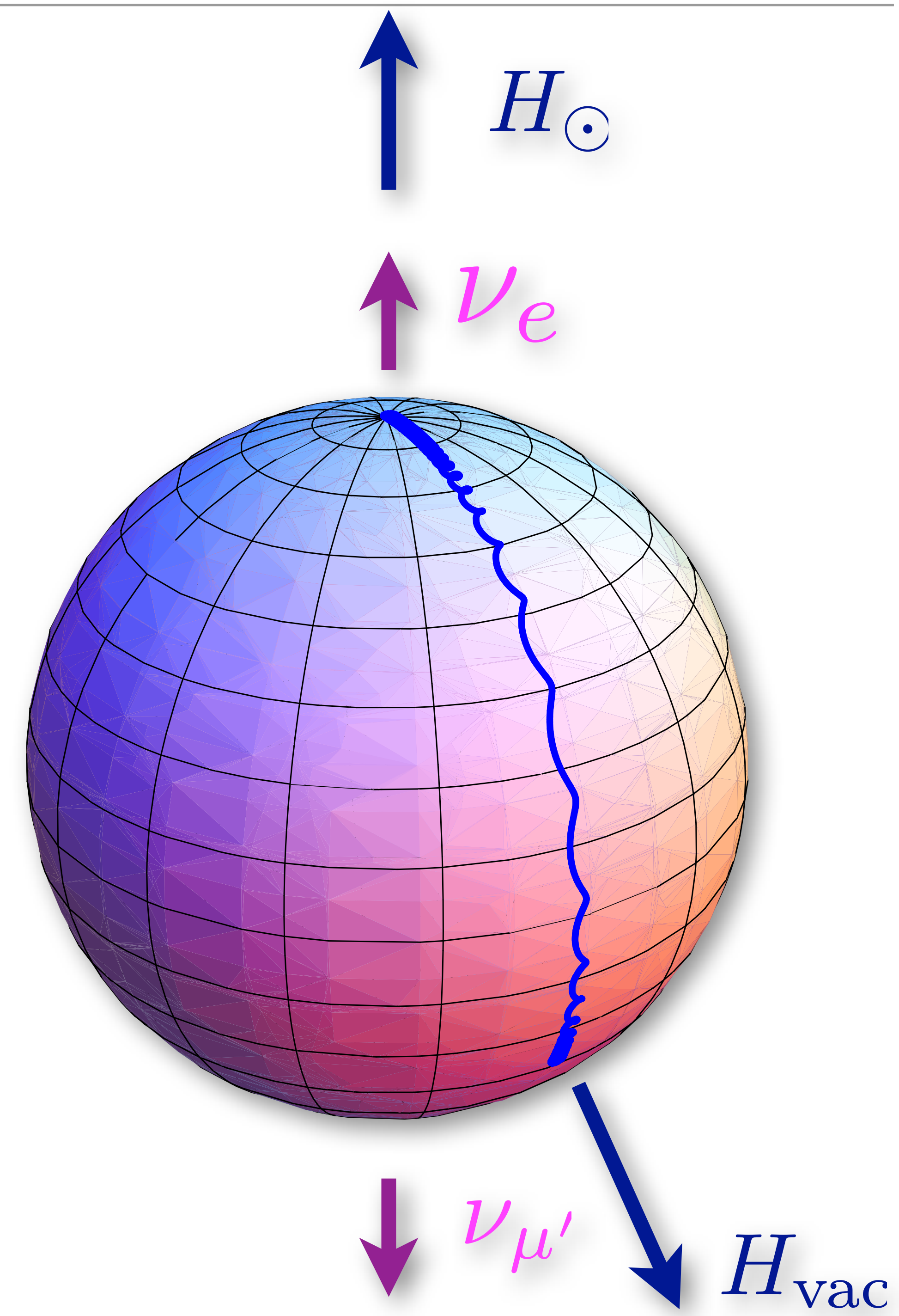
Ordinary MSW in the spin representation

- 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.

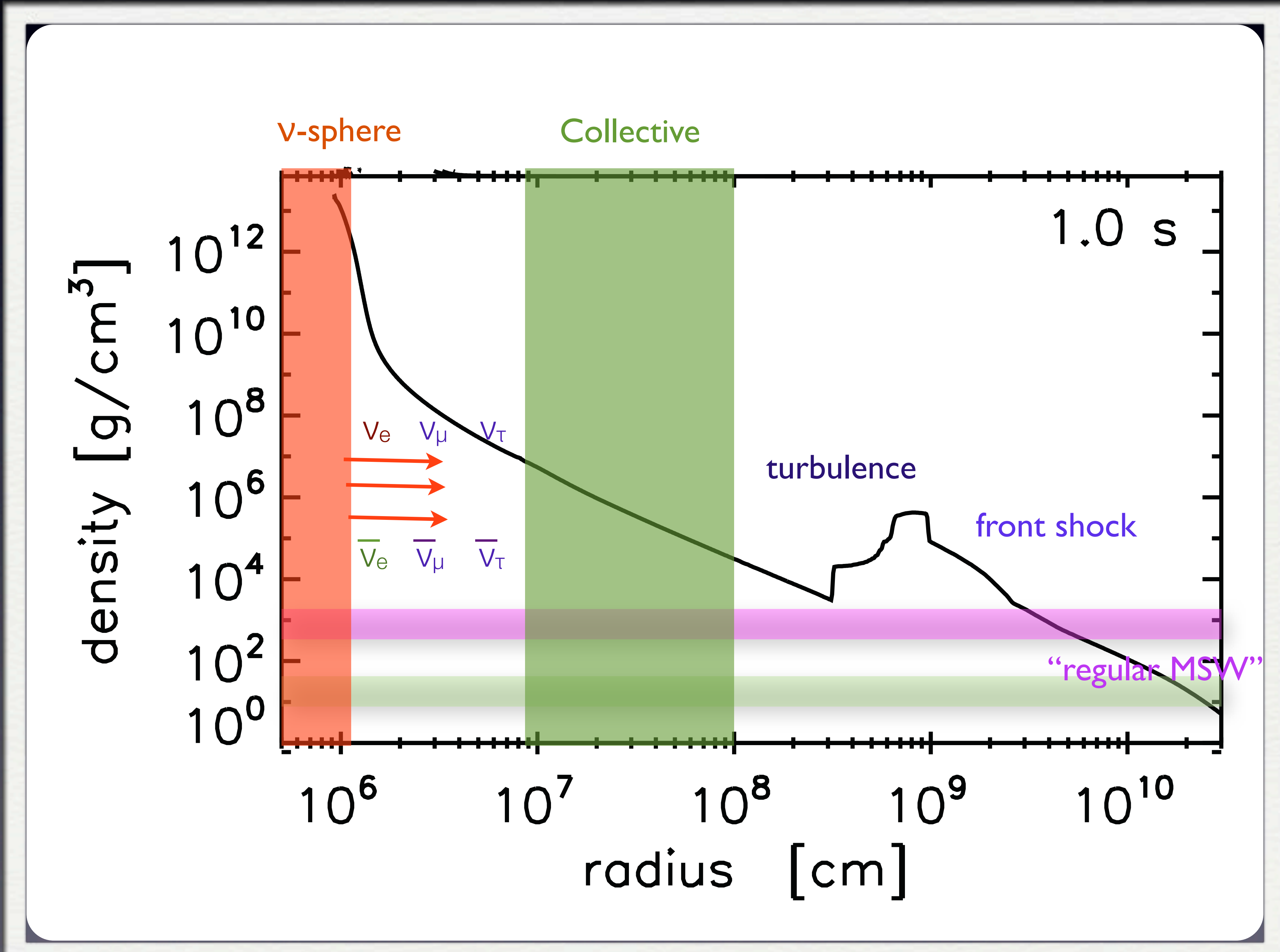
$$H(r) = \frac{\Delta m^2_{\rm mat}}{2E_\nu} \begin{pmatrix} -\cos 2\theta_{\rm mat} & \sin 2\theta_{\rm mat} \\ \sin 2\theta_{\rm mat} & \cos 2\theta_{\rm mat} \end{pmatrix} = \vec{H}(r) \cdot \vec{\sigma}$$

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

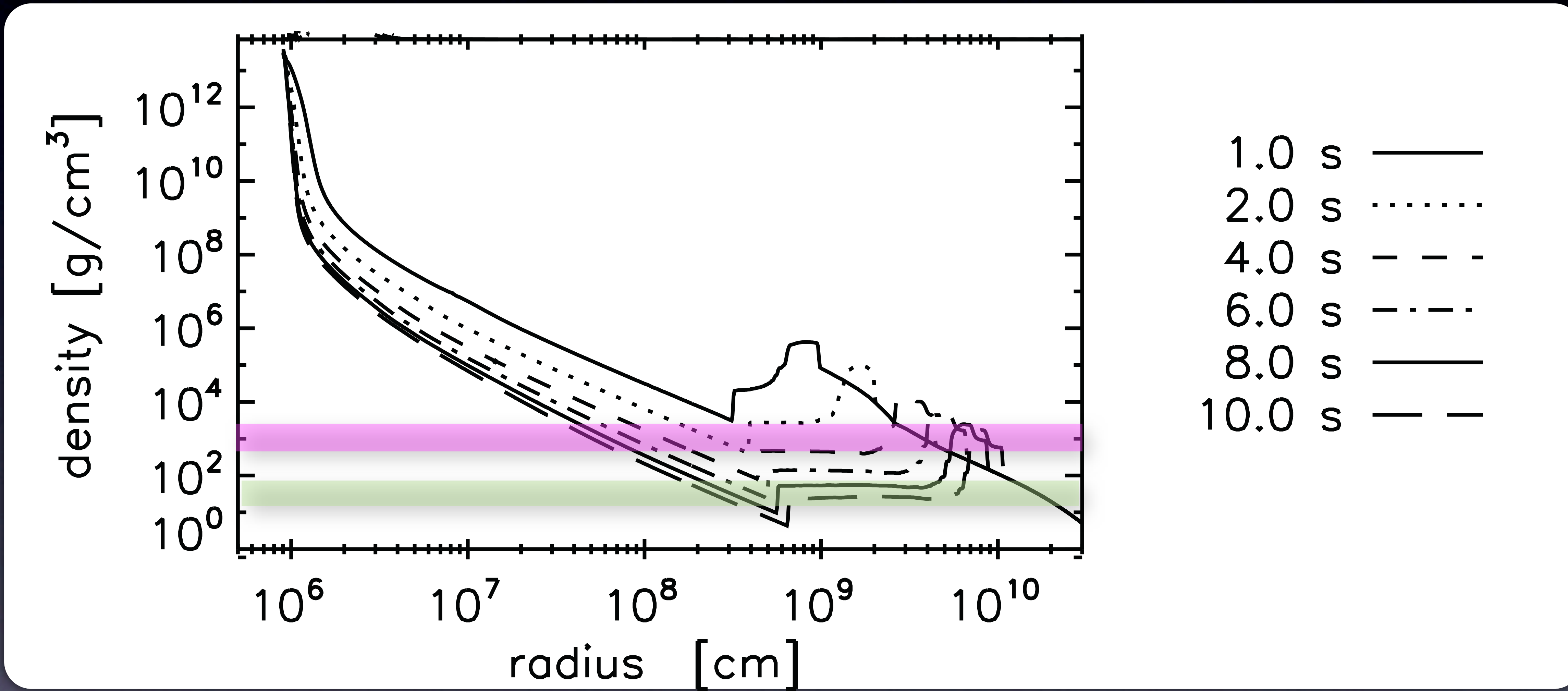


Supernova neutrinos: the richest neutrino oscillation problem known

SN ν oscillations: physics cartoon



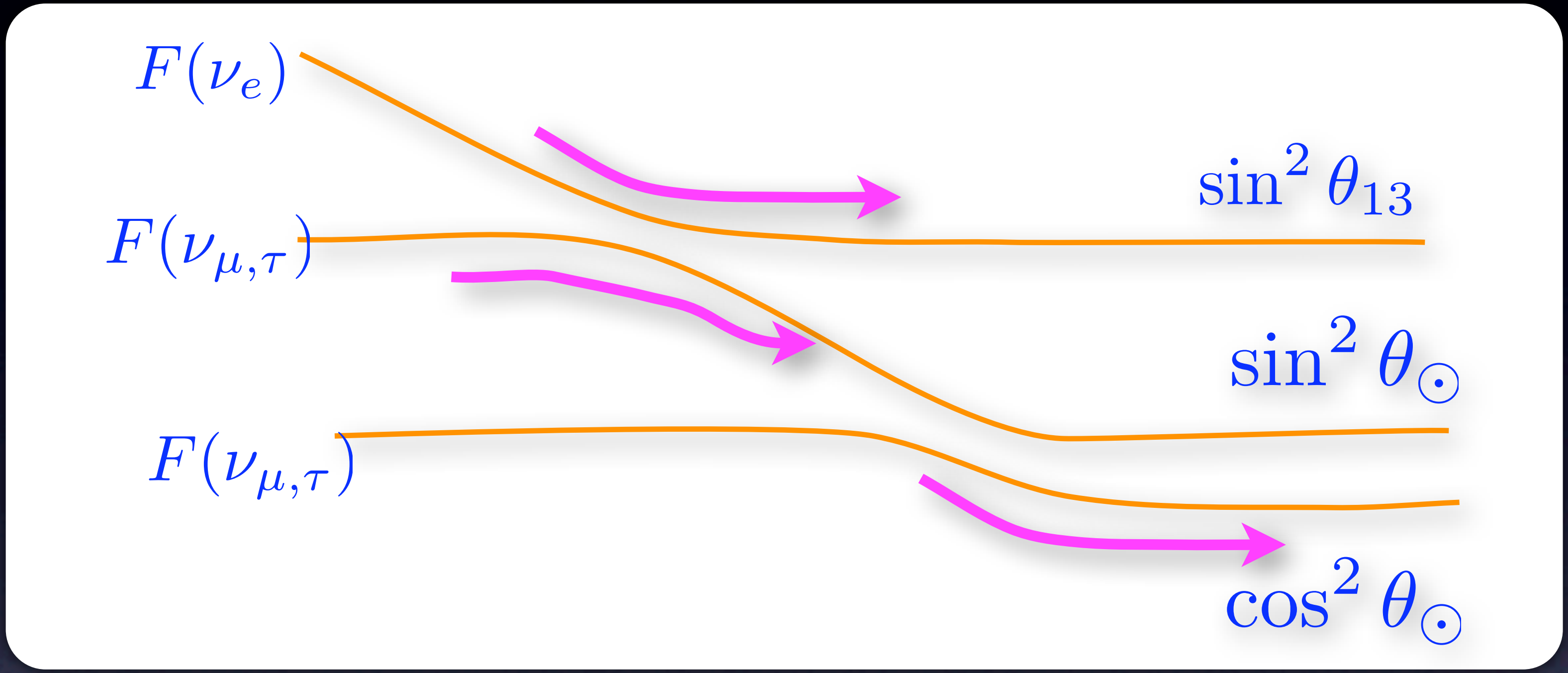
Dynamical density profile

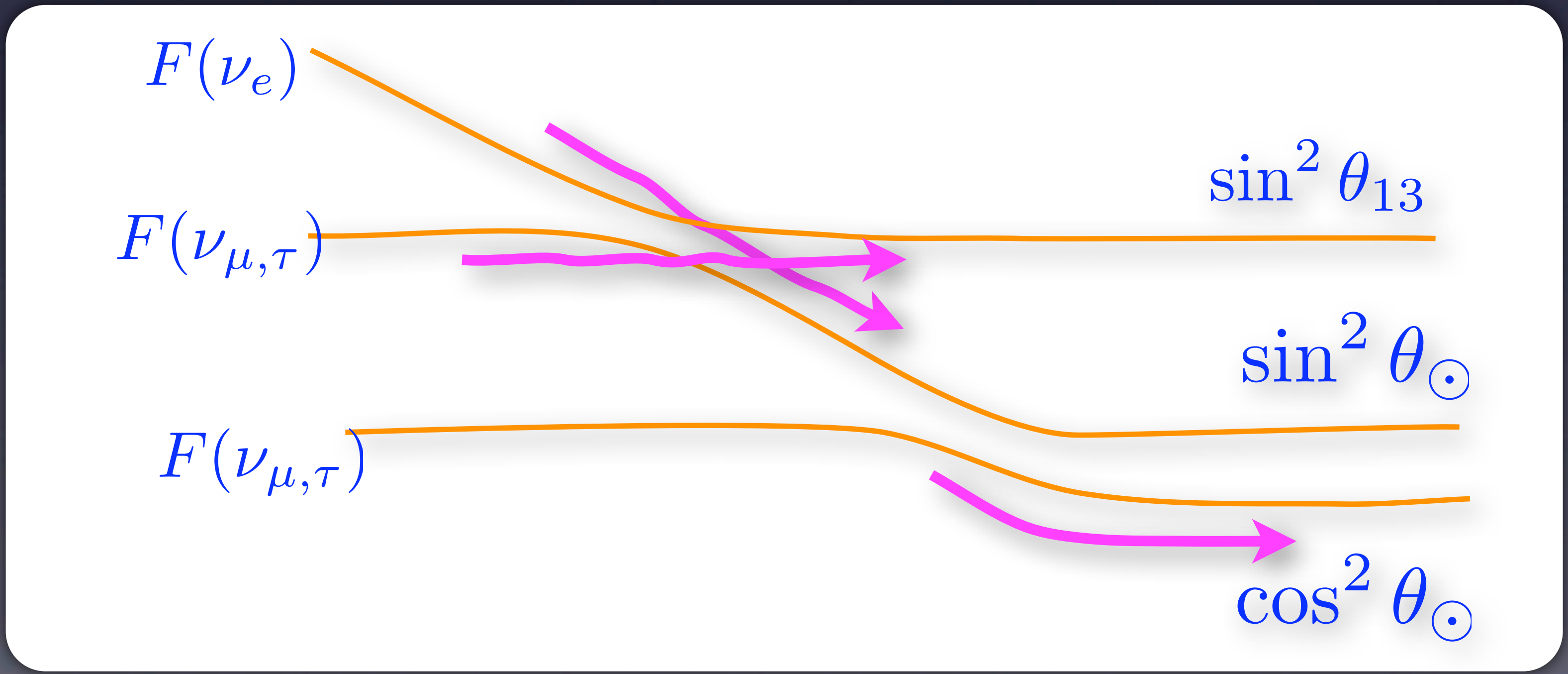


- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are being emitted
  - See Schirato & Fuller (2002) astro-ph/0205390

Moving shock and MSW transformations

- The shock is infinitely sharp from the neutrinos' point of view (photon mean free path).
- When it arrives at the resonance, the evolution becomes non-adiabatic.

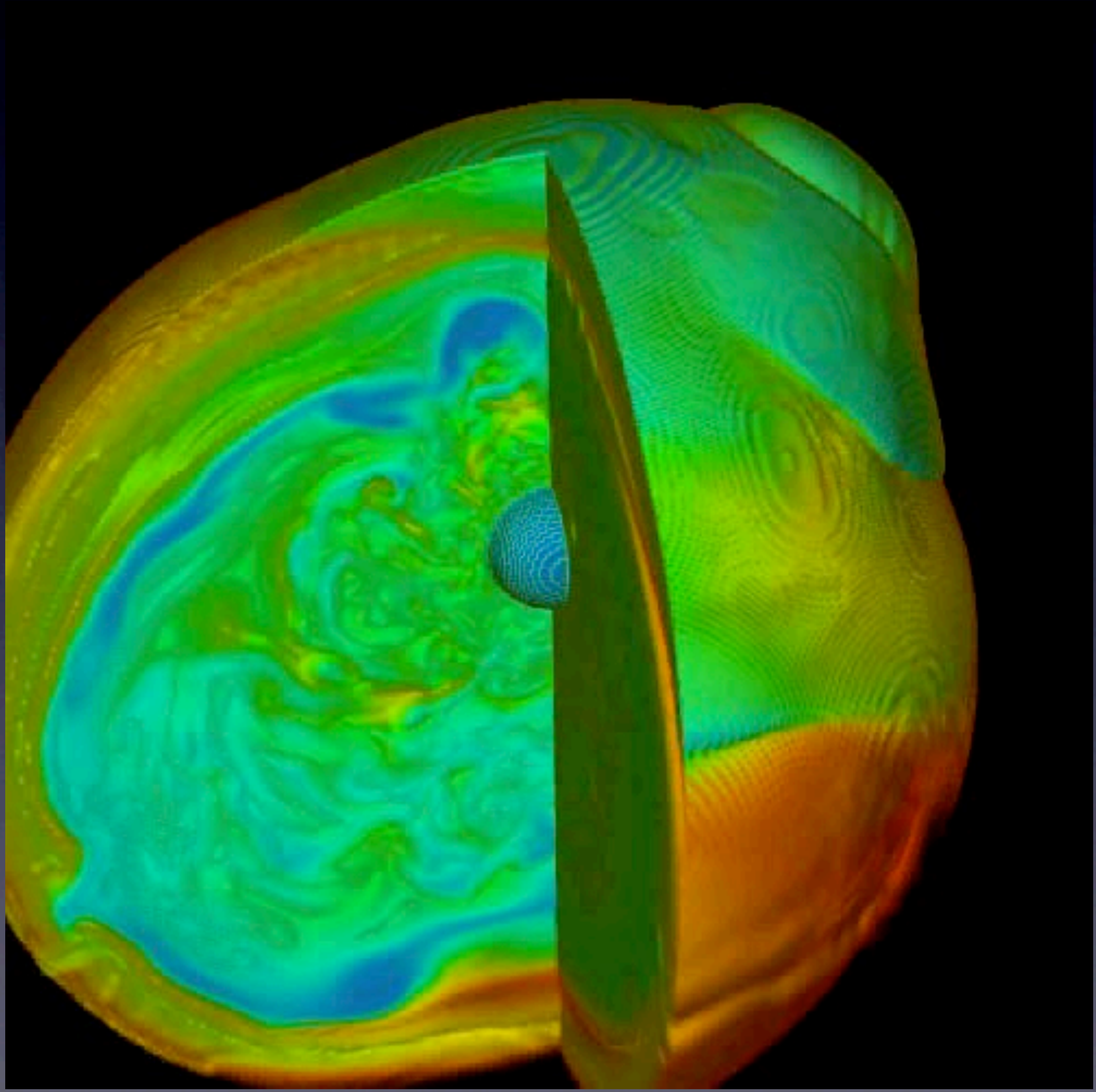




For inverted hierarchy, the same happens in antineutrinos.

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



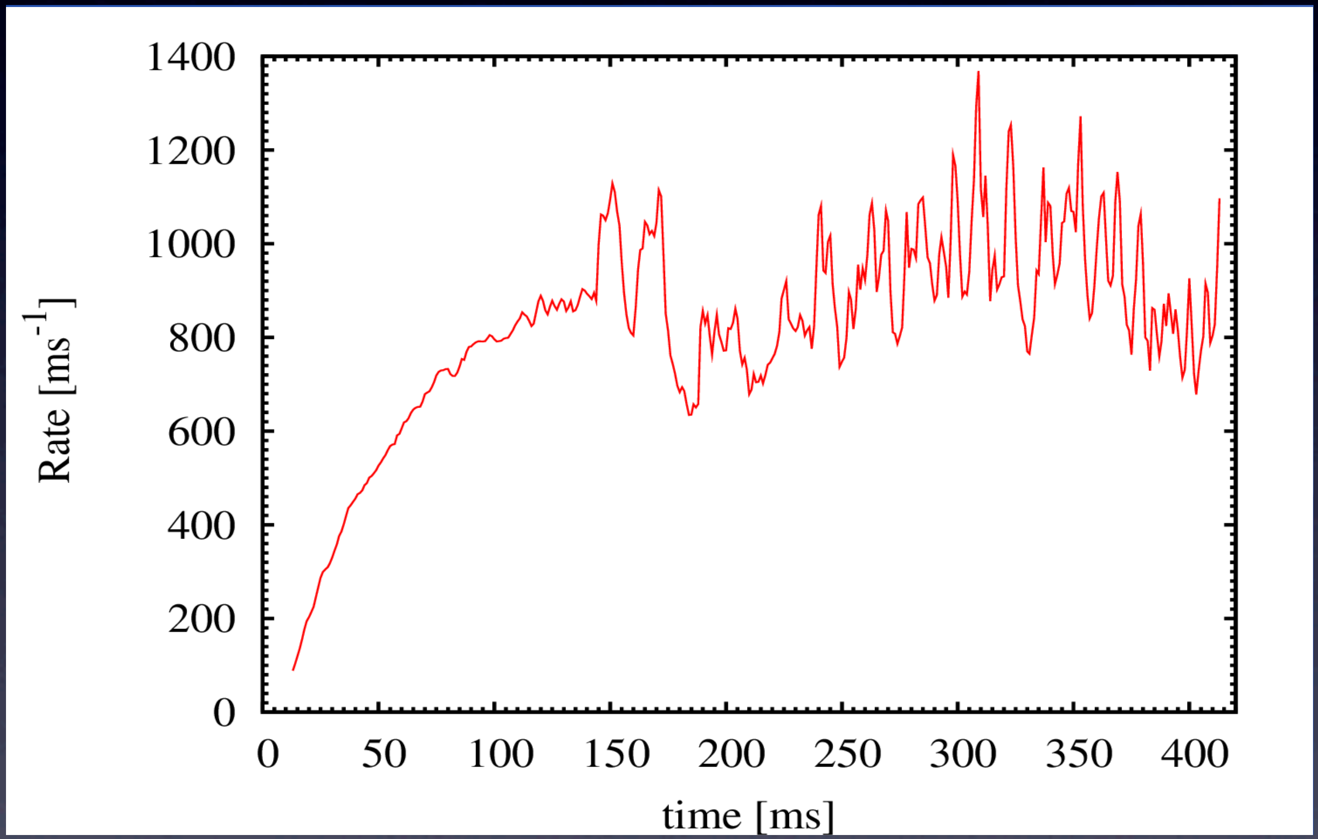
Reproduced in a backyard water experiment

- Foglizzo, Masset, Guilet, Durand, Phys. Rev. Lett. 108, 051103 (2012)
- Made PRL cover and APS Viewpoint highlight

Neutrino signature of SASI

- The large sloshing motion could result in rapid variation of the neutrino event rate during the accretion phase

- It was suggested to look for this with IceCube

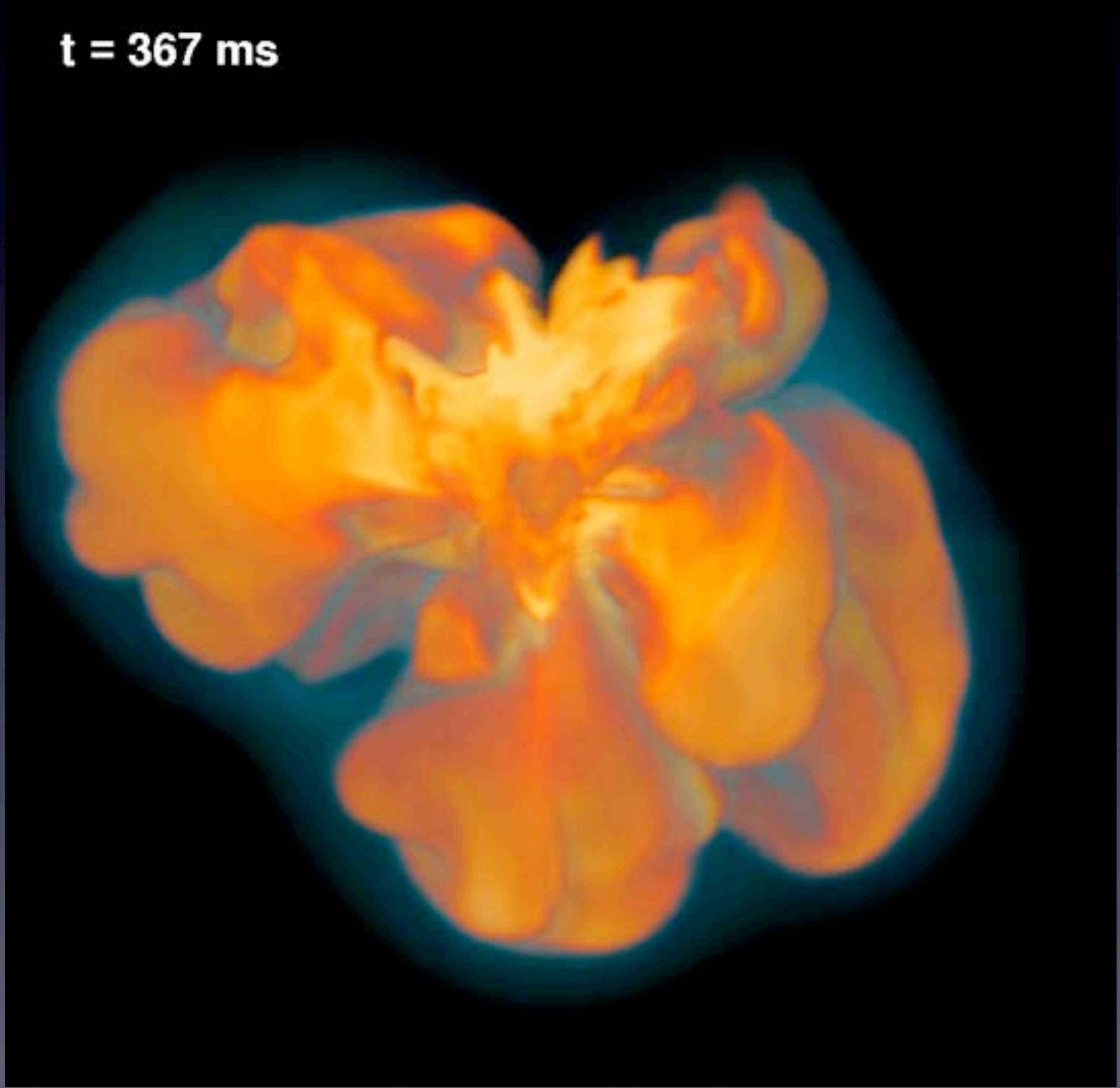


Lund, Marek, Lunardini, Janka, Raffelt, arXiv:1006.1889

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



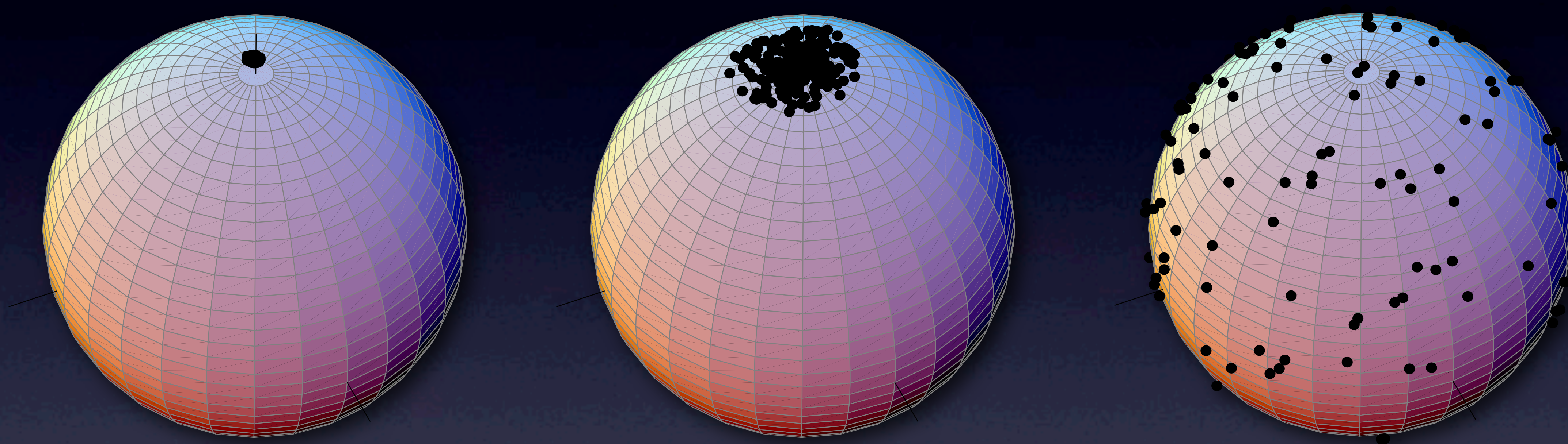
Turbulence and MSW

- The level-jumping probability 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

Turbulence makes neutrinos diffuse in the flavor space



- Need to estimate the rate of diffusion
  - Needed: high-resolution simulations from the beginning through the first several seconds
  - Given large-scale fluctuations in published simulations (order 1), completely depolarized regime expected

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

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

Neutrino "self-refraction"

- Neutrinos undergo flavor conversion in the background of other neutrinos

- The neutrino induced contribution depends on the flavor states of the background neutrinos

$$\sqrt{2}G_F \sum_{\vec{p}} n_i (1 - \cos\Theta_{\vec{p}\vec{q}}) |\psi_{\vec{p}}\rangle\langle\psi_{\vec{p}}|$$

- One has to evolve the neutrino ensemble as a whole

- Rich many-body physics, with many regimes

Fuller et al, Notzold & Raffelt 1988; Pantaleone 1992; ... Duan, Fuller, Qian, Carlson, 2006; + hundreds more

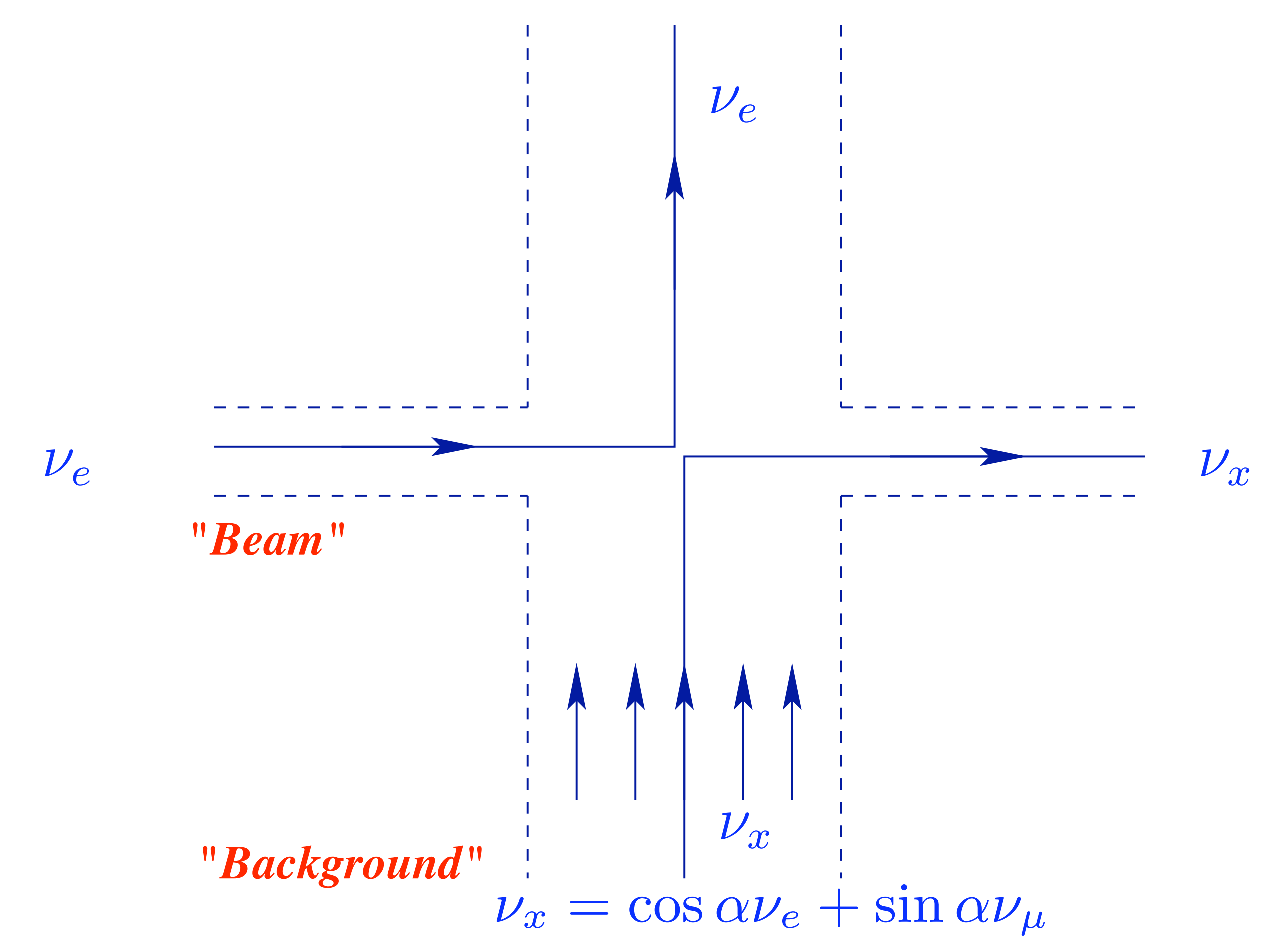
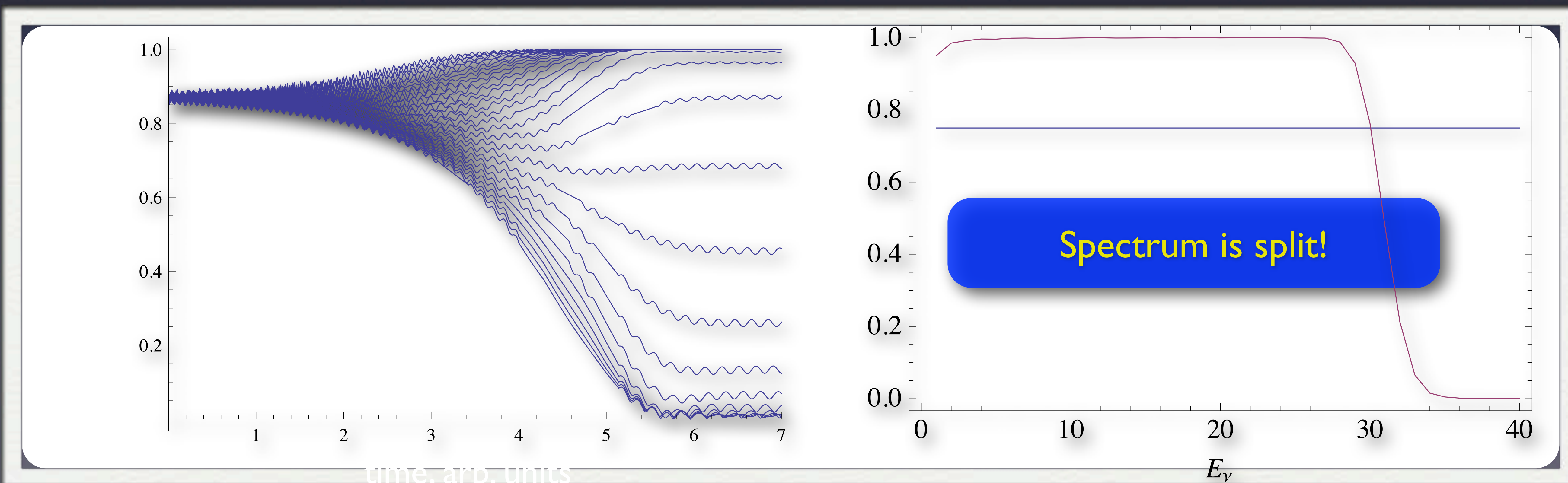


Figure from Friedland & Lunardini, Phys. Rev. D 68, 013007 (2003)

Simplest toy problem

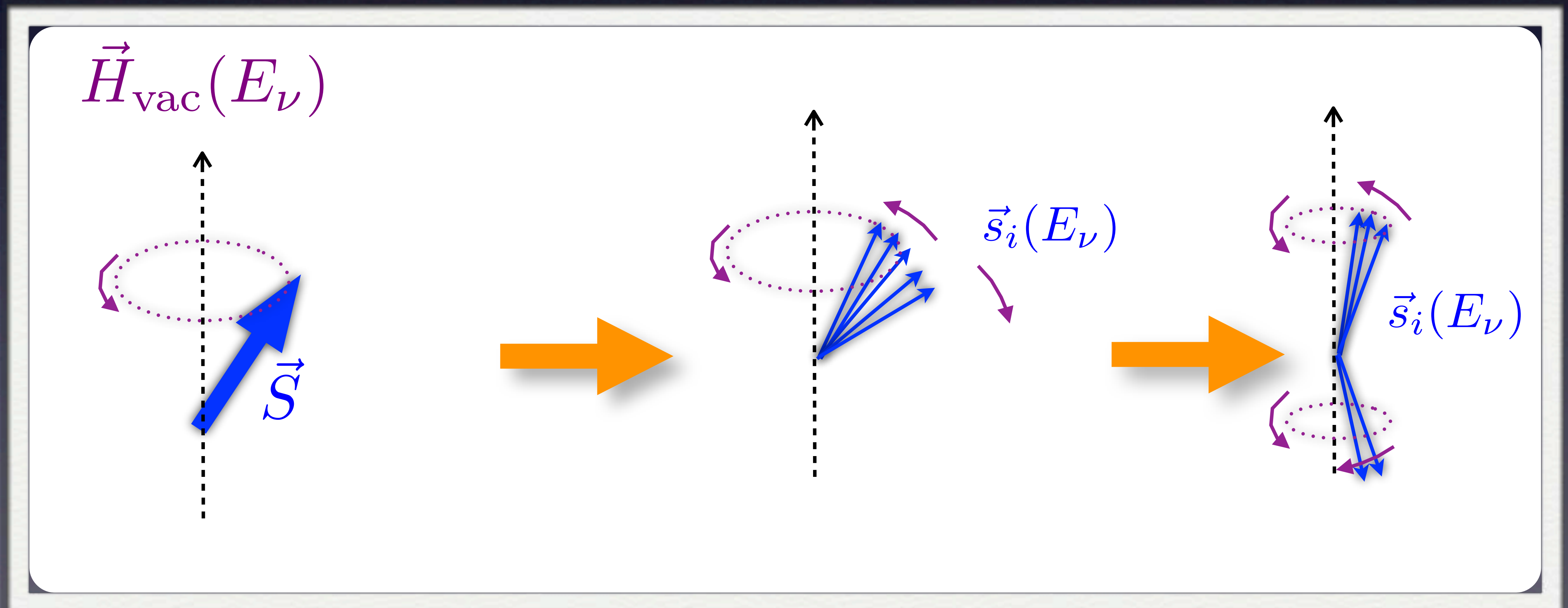
(after Raffelt & Smirnov, 2007)

- Start with 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 the self-coupling to be large initially (much larger than the vacuum oscillation terms for these neutrinos).
- Gradually relax the self-coupling to zero. What is the final state of this system?



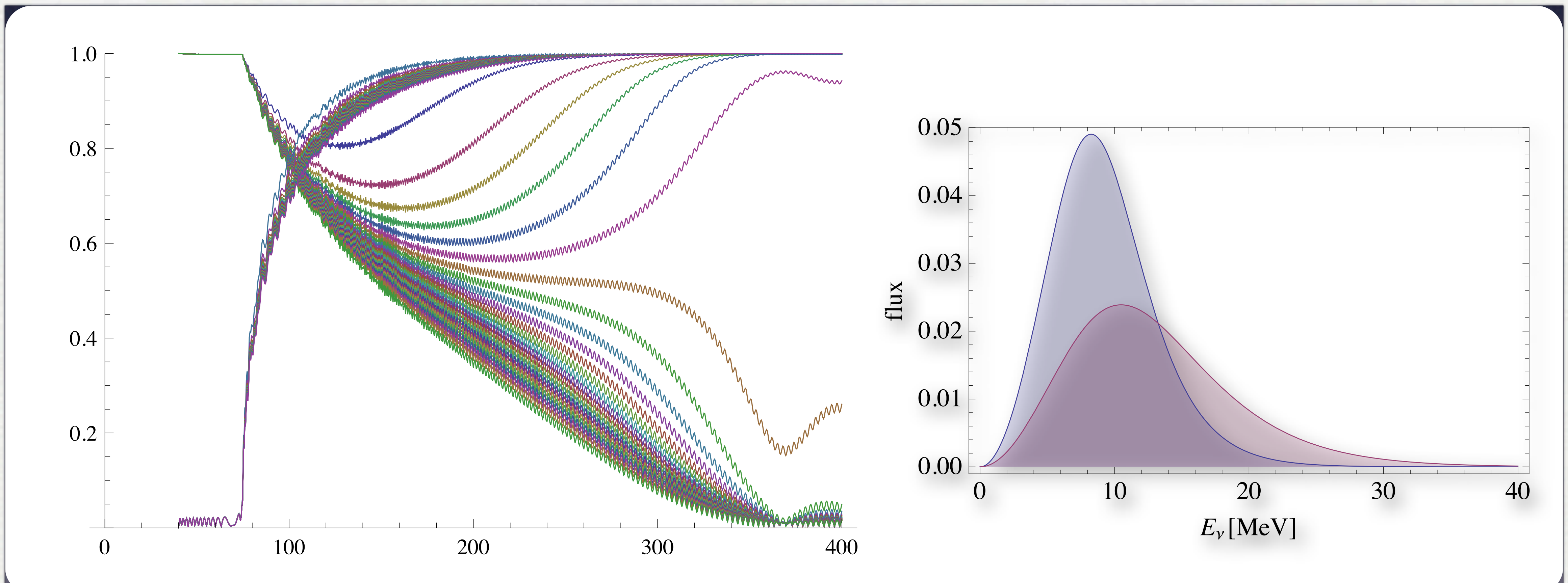
Simplest toy problem: spin picture

- as the self-coupling is gradually taken to zero, spins align or anti-align along the external field



Toy problem

- ν_e and anti-ν_e in the initial state, no ν_x
  - 2-flavors, single-angle (averaged coupling approximation)
    - Anti-ν_e are entirely converted into anti-mu;
    - ν_e's are *split*: low-energy part of the spectrum remains ν_e



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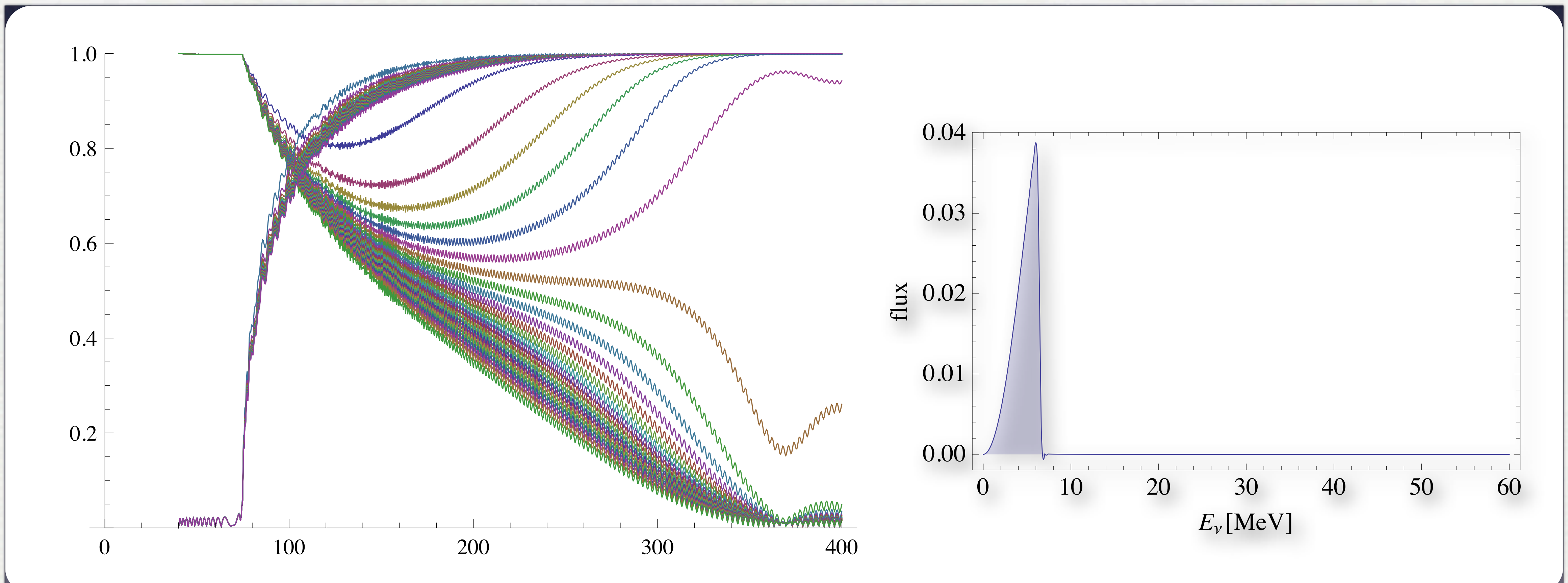
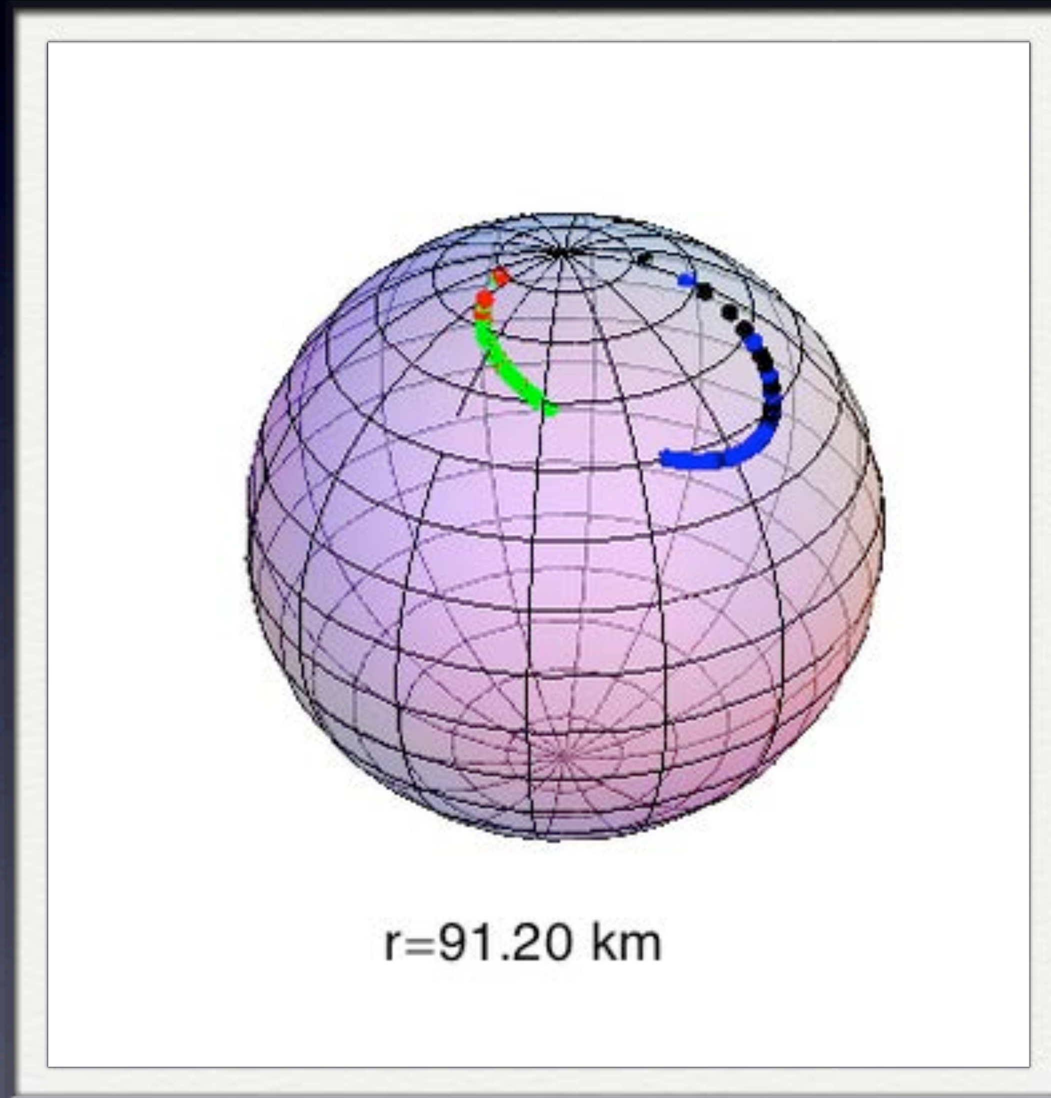


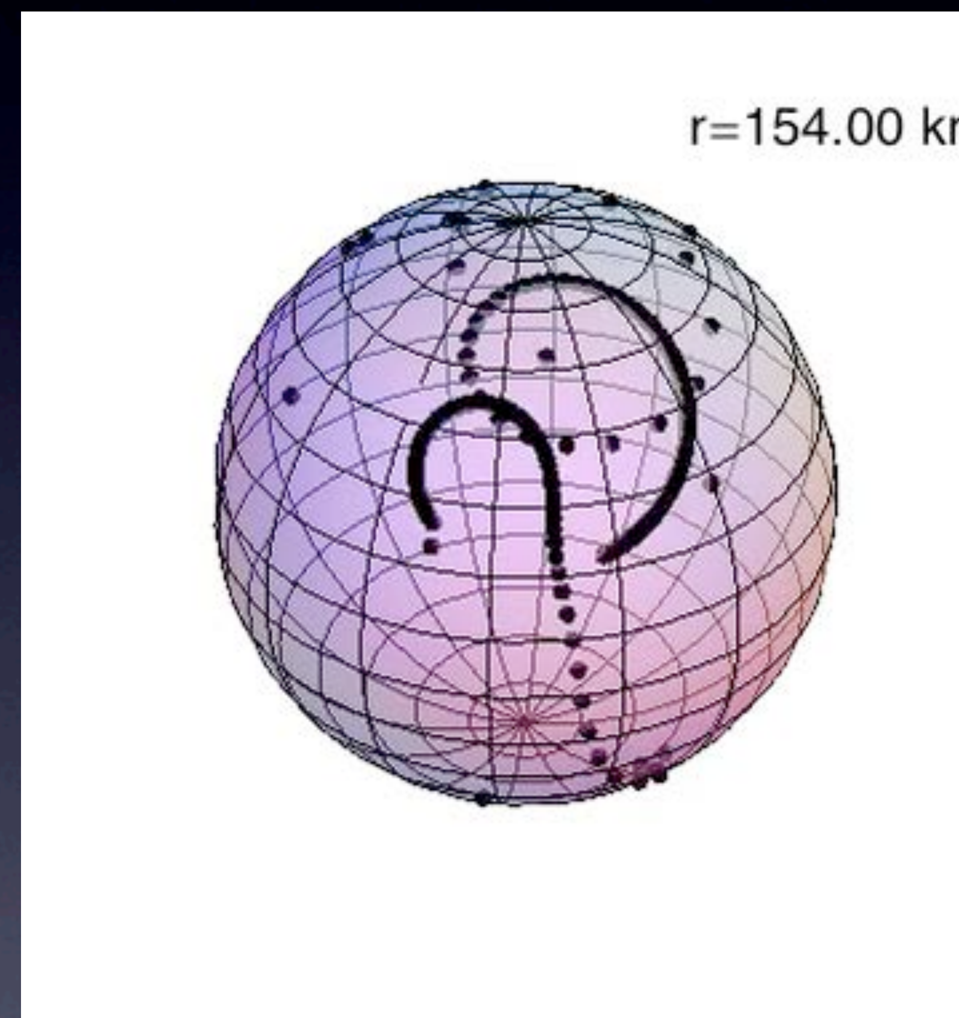
Collective motions in action

- Here is an example of collective evolution as a function of radius in one of our simplified calculations
    - 2-flavor, single-angle



Another example

- Note that the evolution is completely different



Order-of-magnitude estimates

- "Standard" MSW: transition from matter- to vacuum domination

$$\Delta m^2/2E_\nu \sim \sqrt{2} G_F N_e.$$

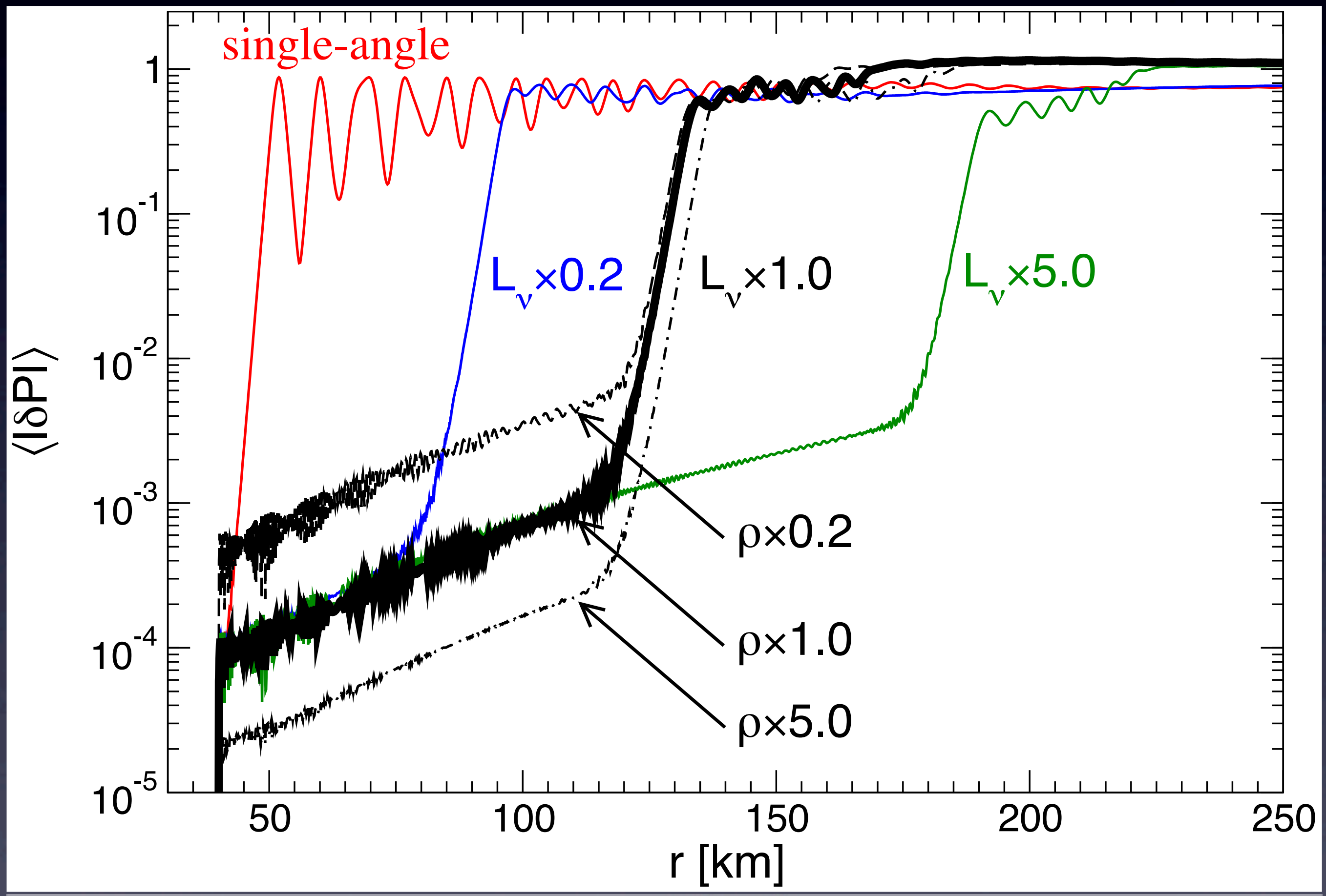
- Turbulence: relevant density fluctuations on the scale of the neutrino osc. length on resonance

- Collective effects: transition from synchronized regime (strong self-coupling) to vacuum

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

This picture is very neat, perhaps too much so

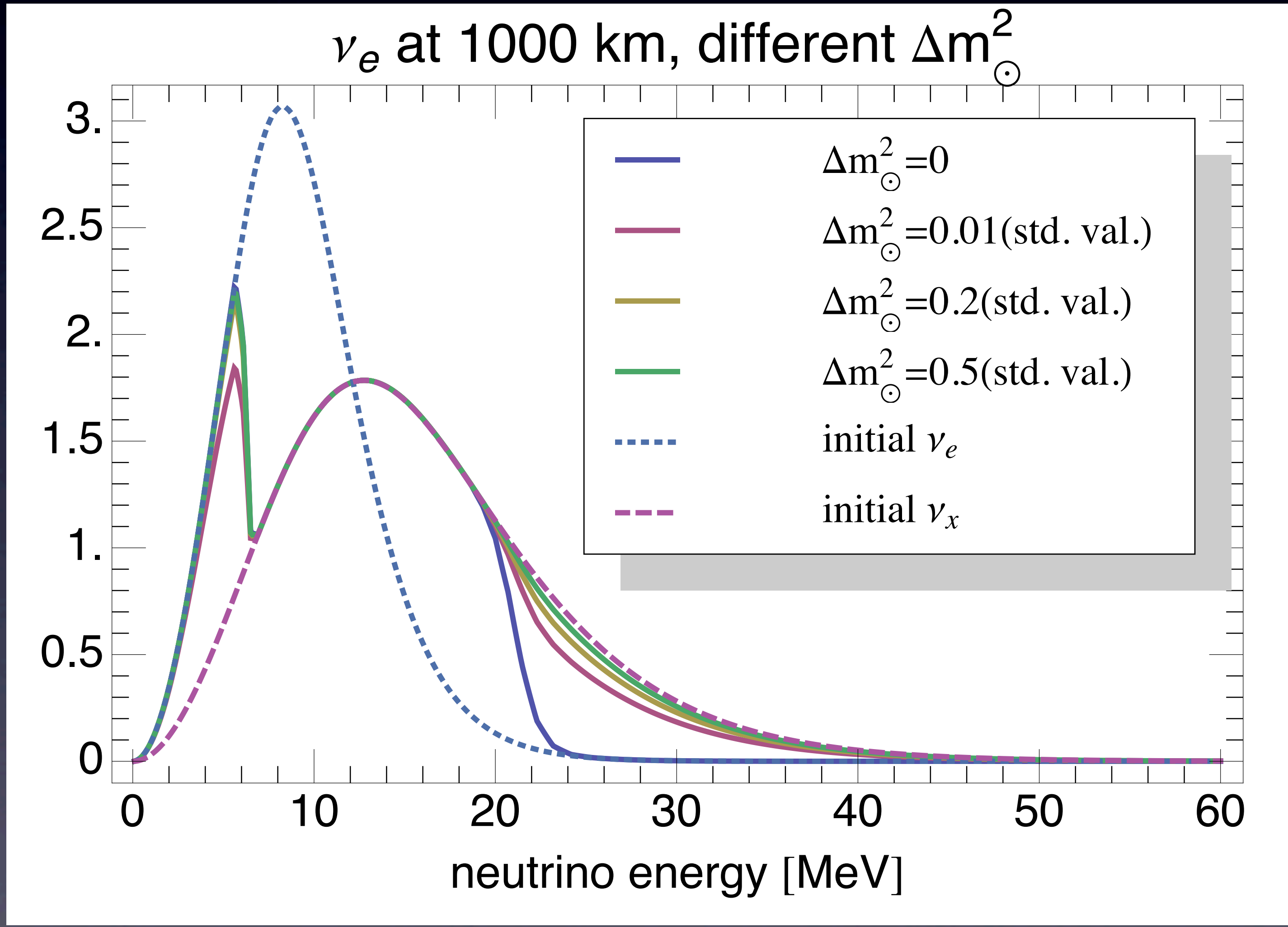
- Do collective oscillations happen close to, or even inside the neutrino-sphere?
- Crucial for the validity of the supernova models!



H. Duan & A.F., Phys. Rev. Lett. 106, 091101 (2011)

Can adding a tiny parameter (additional d.o.f.) have a large effect?

- Example where the solar mass splitting is turned on gradually
  - 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 $\Delta m_\odot^2=0$
- 2-flavor trajectory can be unstable in the 3-flavor space

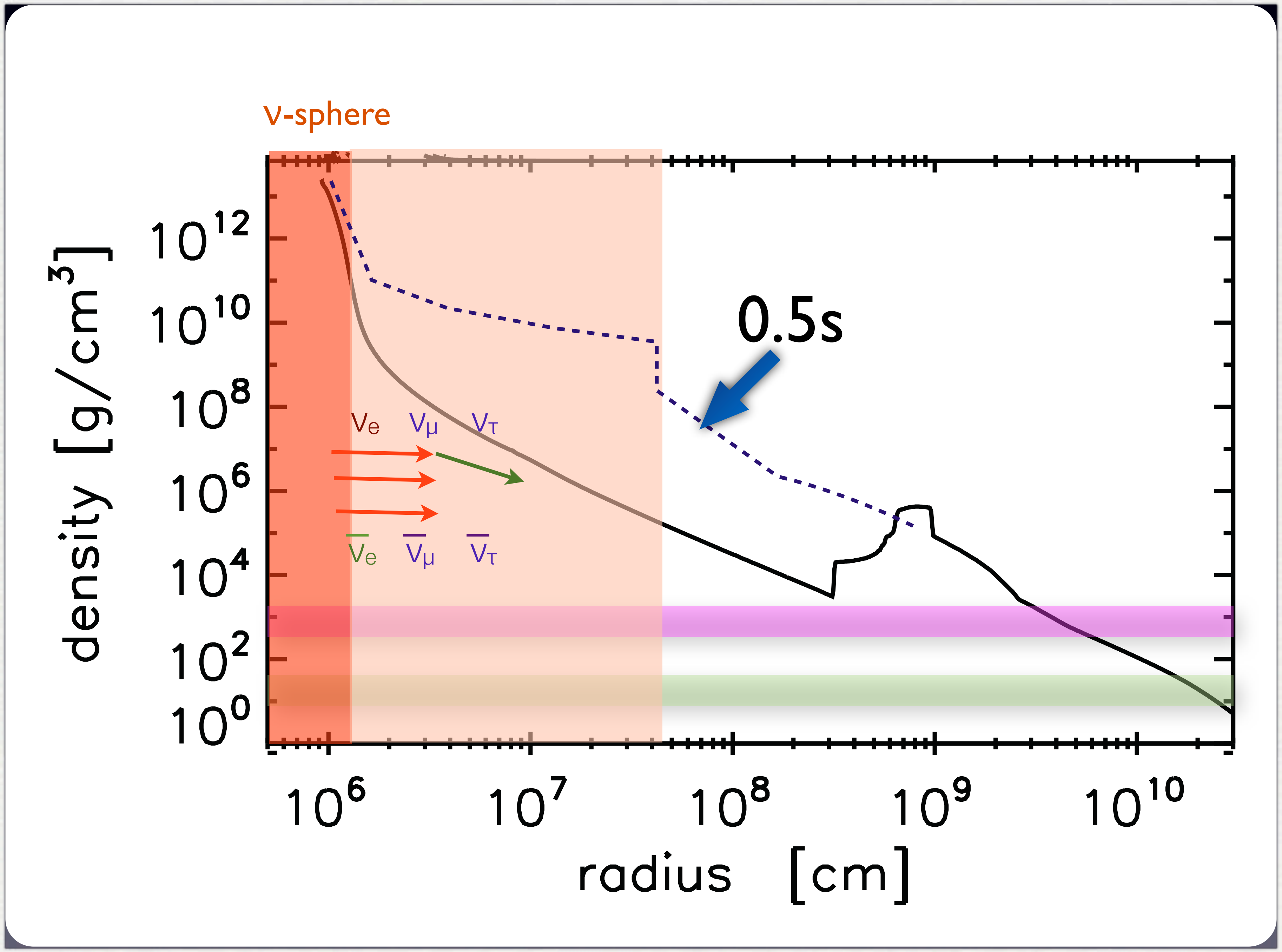


For details, see A. F., Phys. Rev. Lett.104, 191102 (2010);
also Dasgupta, Dighe, Raffelt, Smirnov, PRL (2009)

Breaking of spherical symmetry

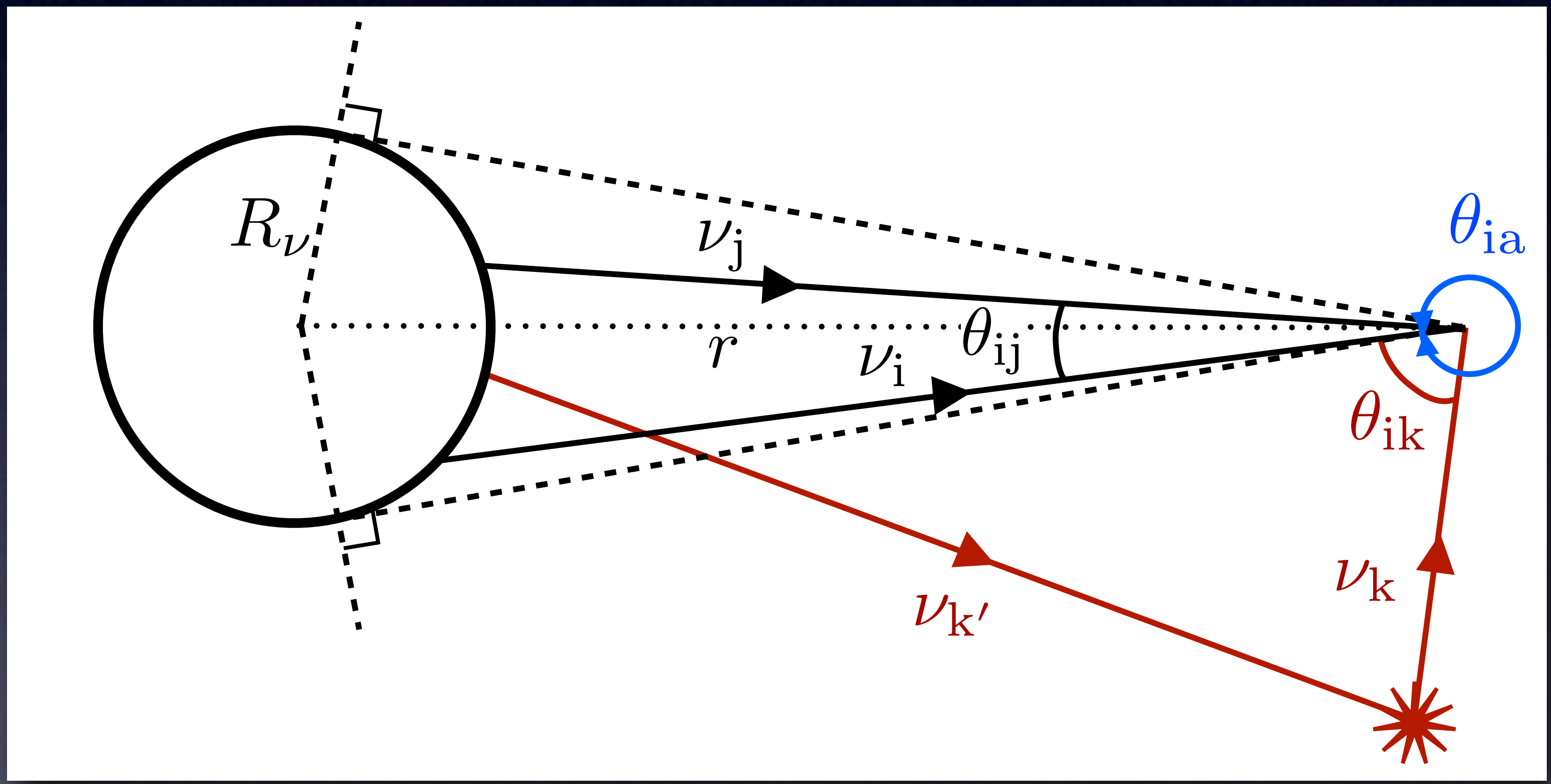
- The system could be unstable to axial symmetry breaking
  - Raffelt, Sarikas de Sousa Seixas, PRL 111, 091101 (2013)
  - Mirizzi, PRD 88, 073004 (2013); arXiv: 1308.5255

What about neutrinos scattering above ν-sphere?



What happens during the accretion stage?

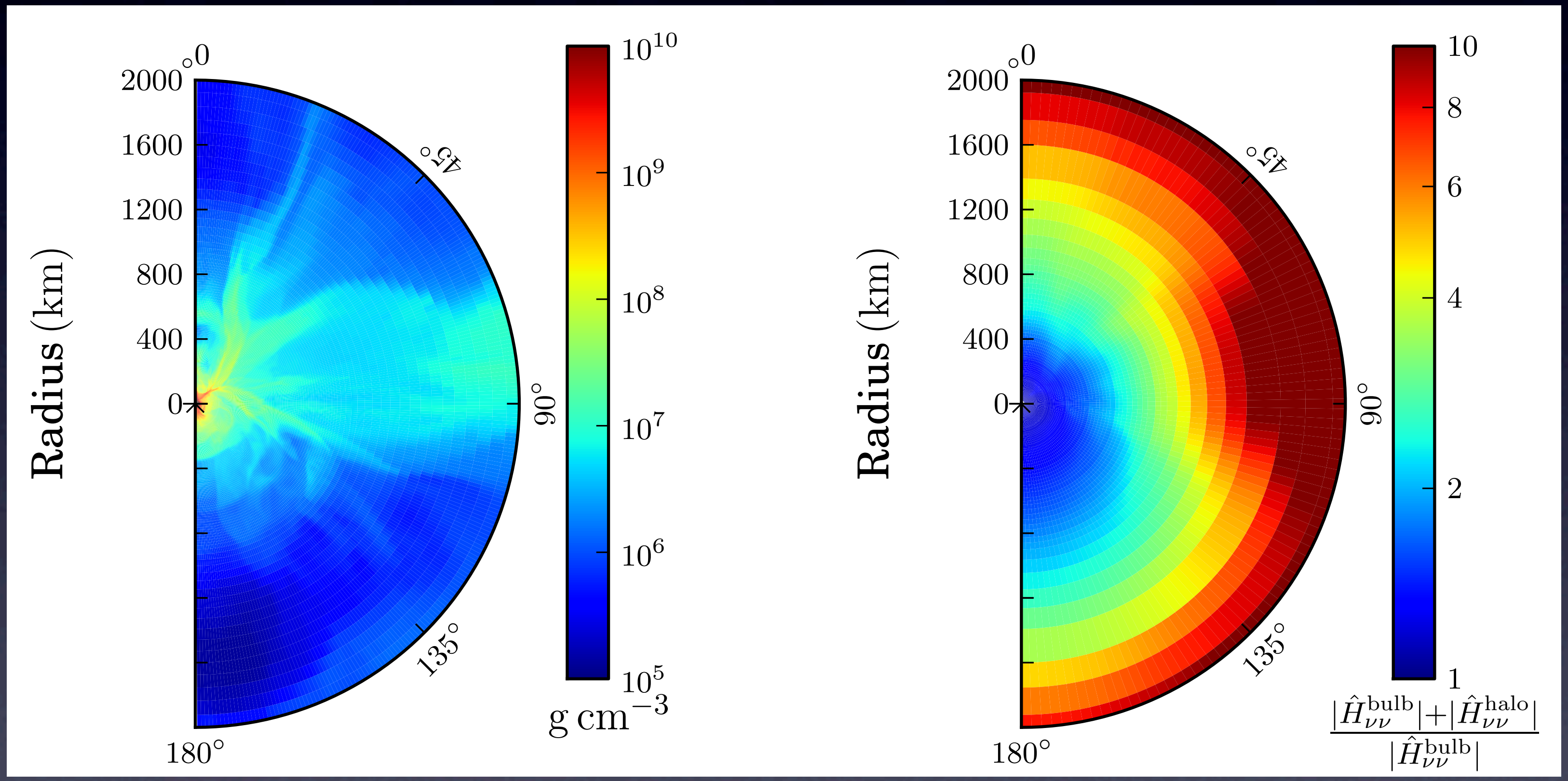
Cherry, Carlson, A.F., Fuller, Vlasenko, PRL (2012)



- "Halo" neutrinos dominate oscillation Hamiltonian

Why is this a problem?

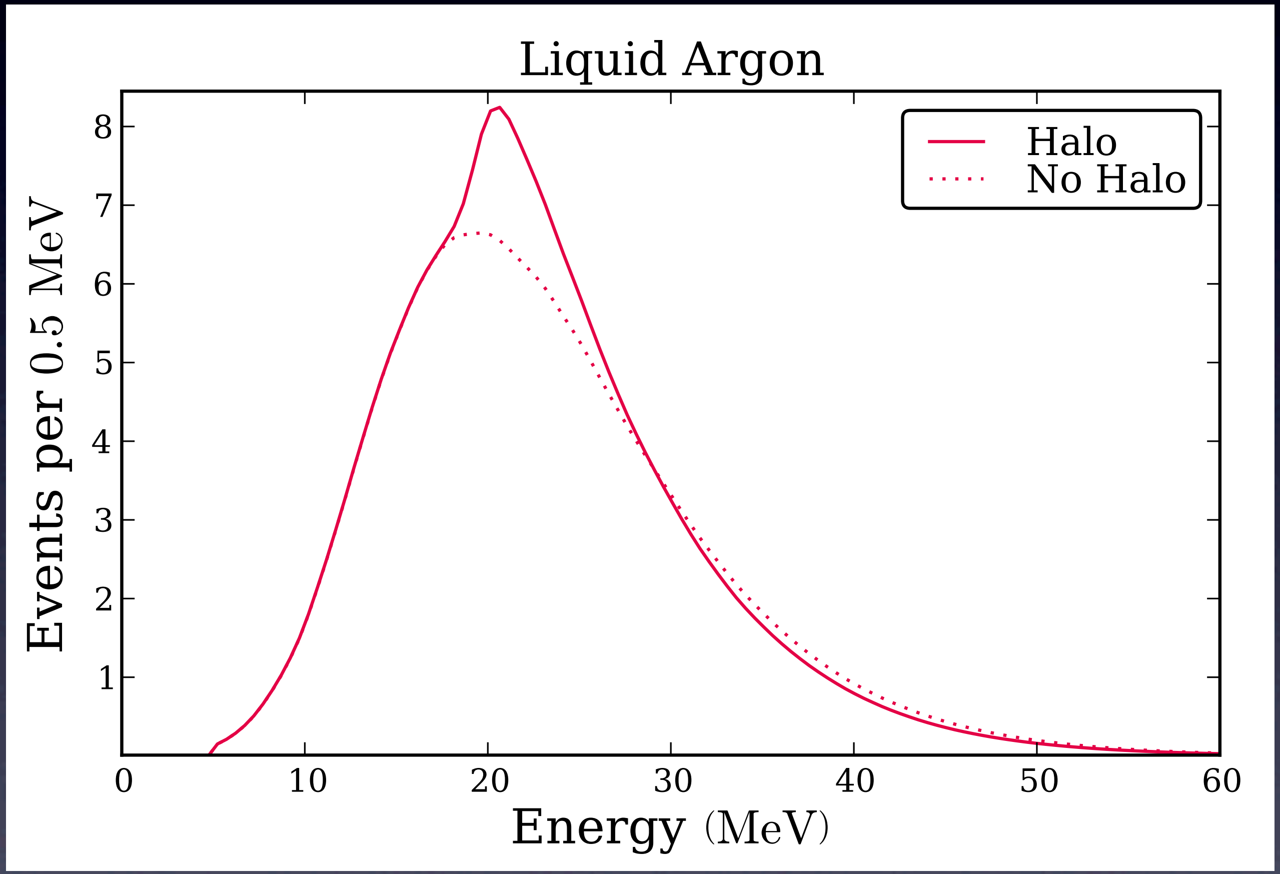
- Scattering matter is highly inhomogeneous
  - in both density and chemical composition
- worse, some scattering is backwards
- Nobody knows how to do the general problem at the moment: need "super-supercomputing"?



Cherry, Carlson, A.F., Fuller, Vlasenko, PRL (2012)

Early in the explosion, computable

- Early in the explosion, large-scale density fluctuations haven't developed yet
- The problem can be modeled numerically and the halo can be shown to have an effect



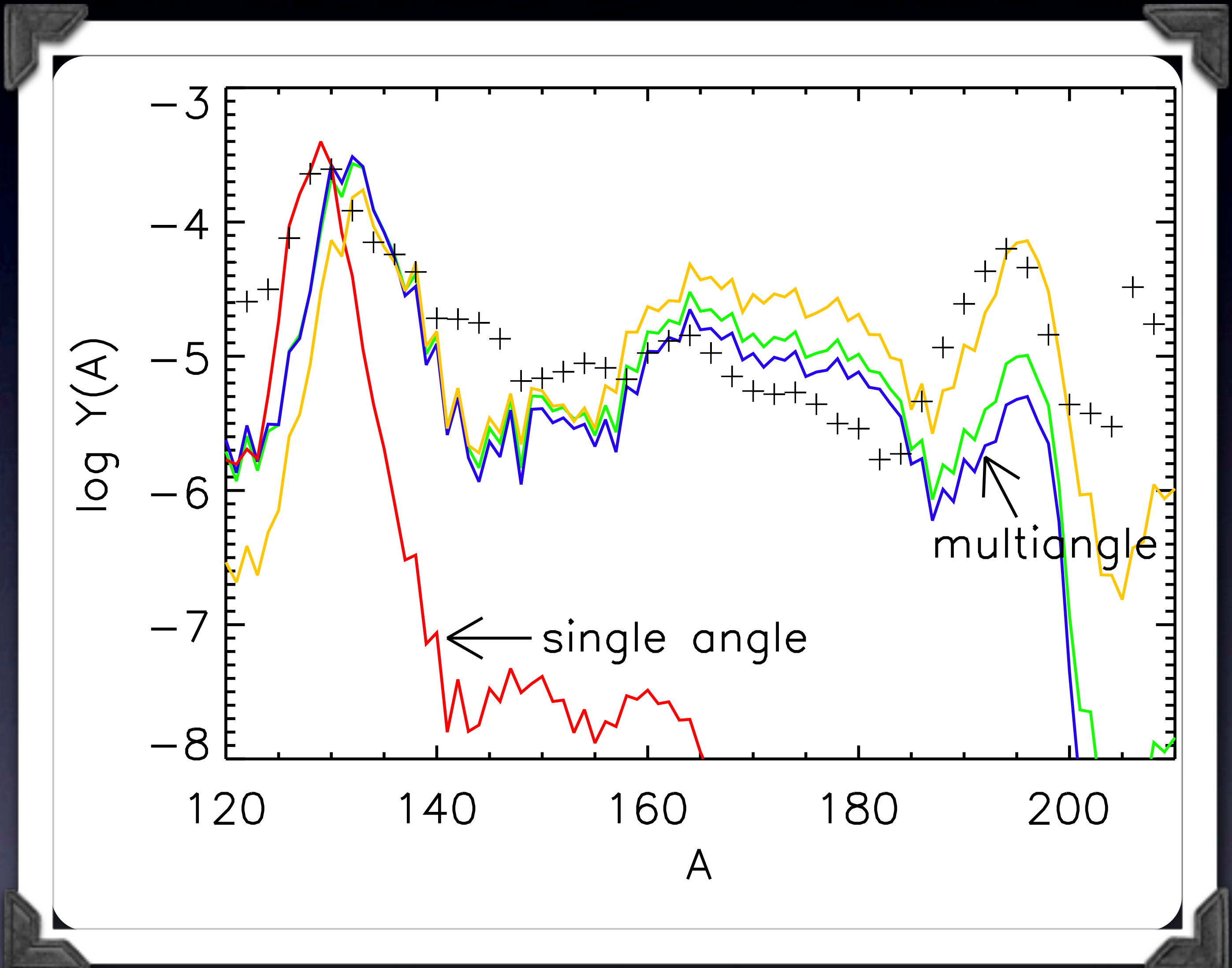
Cherry, Carlson, A.F., Fuller, Vlasenko, PRD (2013)

What’s next?

- Establish what is important experimentally
  - Galactic SNB in terrestrial detectors
  - Astrophysical impact: nucleosynthesis
- On the theoretical side:
  - Given the large spectrum of possibilities, definitive end-to-end treatment does not appear feasible (or useful at this point)
  - What is needed most urgently is to obtain a list of effects that can qualitatively (and sizably!) affect the evolution of neutrinos
  - Qualitative understanding when something might matter is very important

Direct impact on the r-process

- Where exactly the oscillations start and how they develop early on is crucial for the r-process

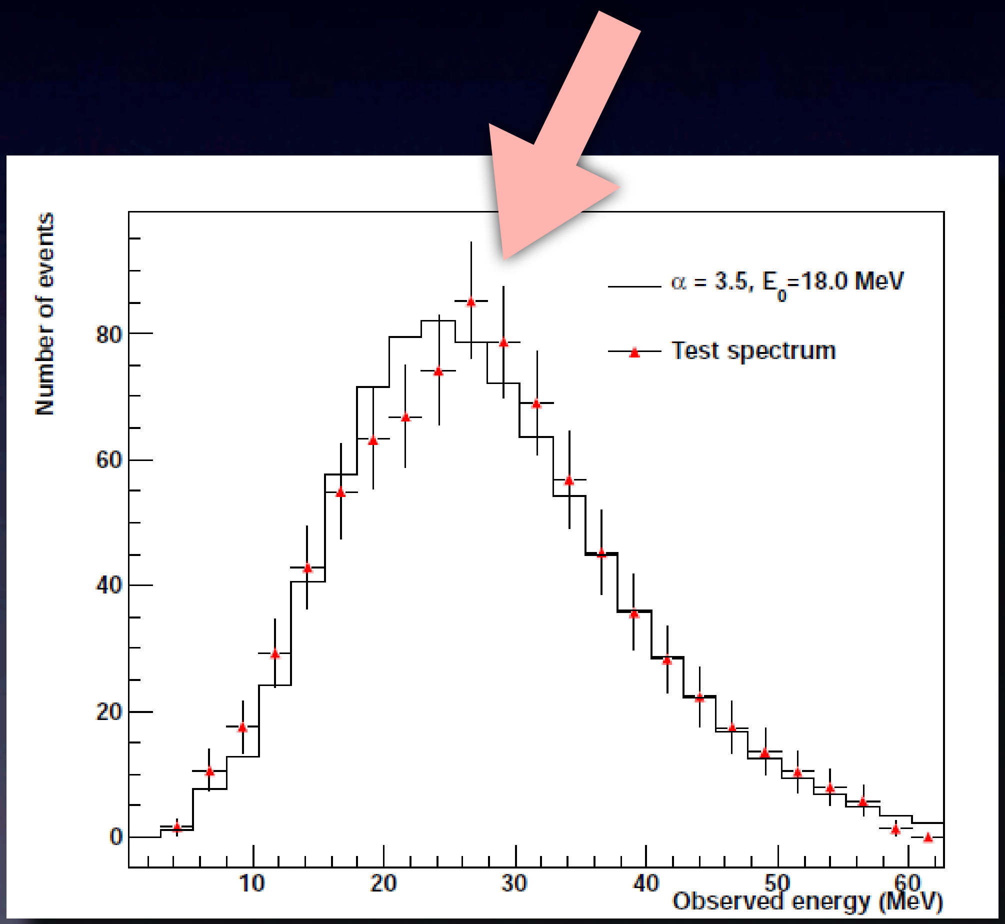


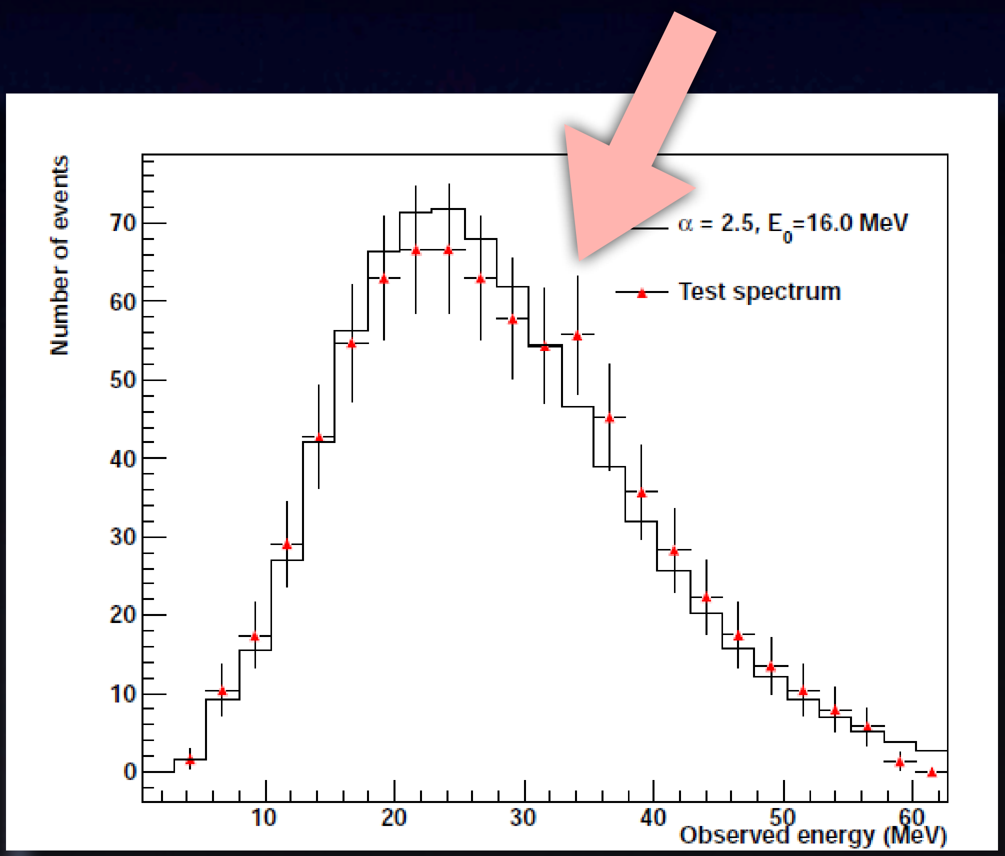
Duan, A.F., McLaughlin & Surman,
The influence of collective neutrino oscillations on a supernova r-process,
J. Phys. G 38, 035201 (2011)

What are we looking for?

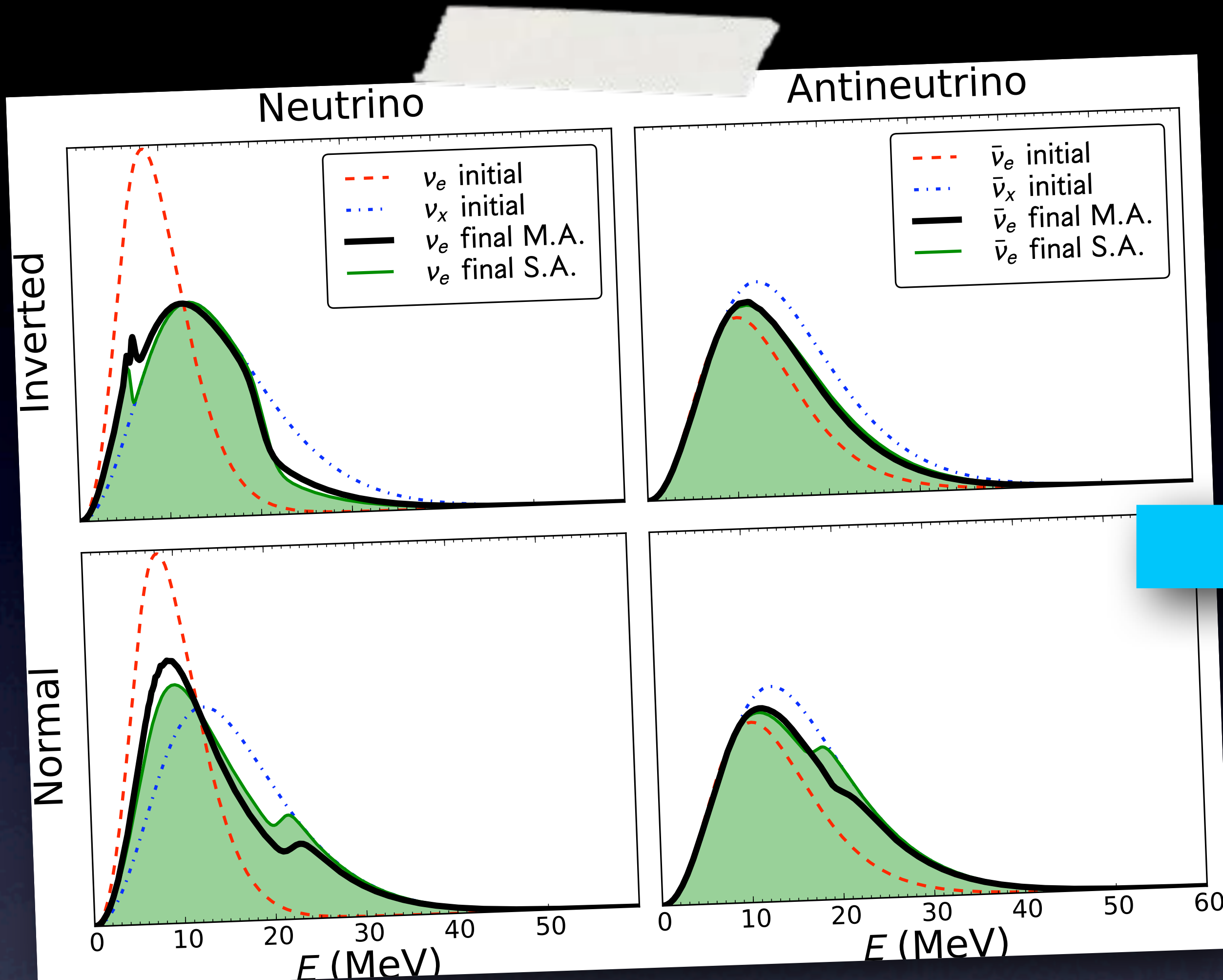
Modeling multiangle collective + moving shock by A. F.

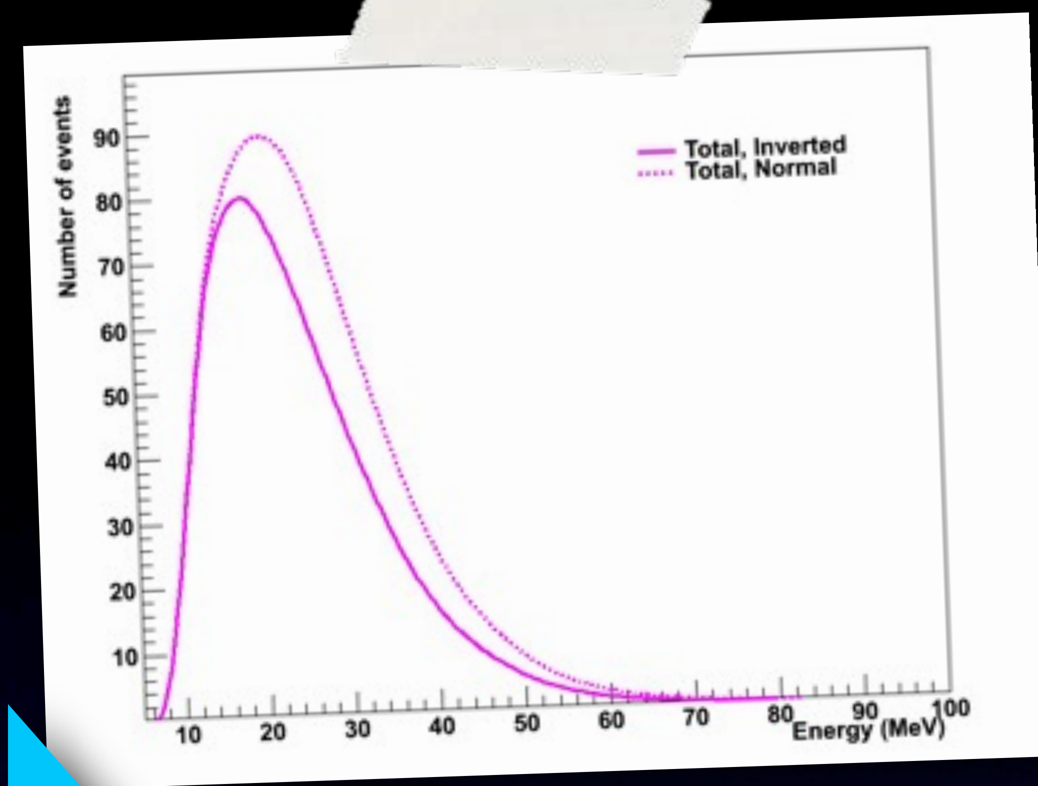
Detector model by K. Scholberg



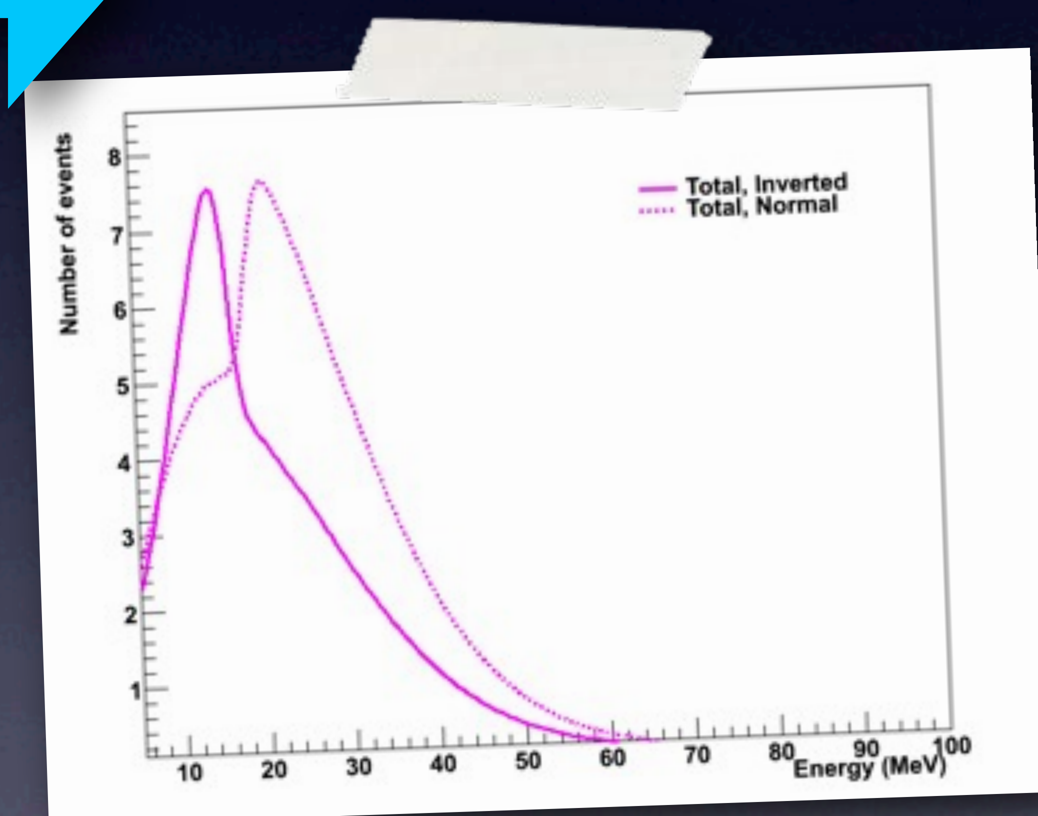


- Experimentally, of special values are phenomena that can give nonthermal features in the spectrum



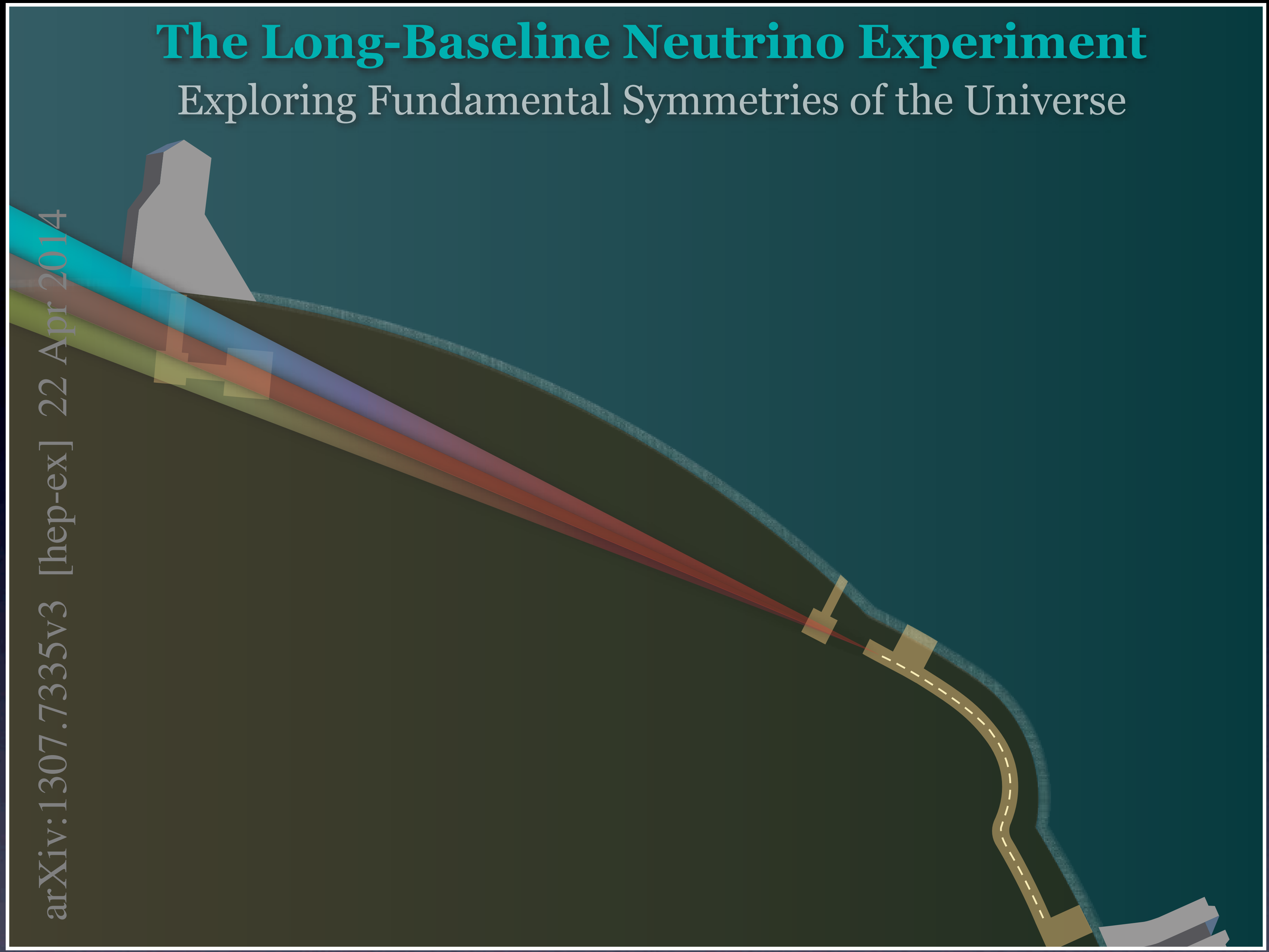


WC



LAr

* spectra by Duan & Friedland
* detector modeling by Kate Scholberg & co



LBNE Science document, arXiv: 1307.7335v3 (April 22, 2014)

The role of matter in collective oscillations

- Naively, one might have expected collective oscillations to be suppressed whenever the matter potential exceeds the neutrino self-interaction
- This, however, does not happen.
  - Duan, Fuller, Carlson, Qian, PRD 2006
  - Fogli, Lisi, Marrone, Mirizzi, JCAP 2007
- One can understand this by going to the rotating basic, in which matter seems to disappear

Multiangle effect of matter

- In multiangle calculations, different trajectories accumulate different phases due to the matter potential
- This suppresses collective oscillations in very dense matter
- Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico, Sigl, PRD 78, 085012 (2008)

Neutron star ccretion disks

- The matter in the disk starts out neutron-rich
- Unlike the "standard SN" case, there are more electron antineutrinos than neutrinos
  - otherwise, "normal"
- In this case, a novel "Matter-Neutrino Resonance" is possible

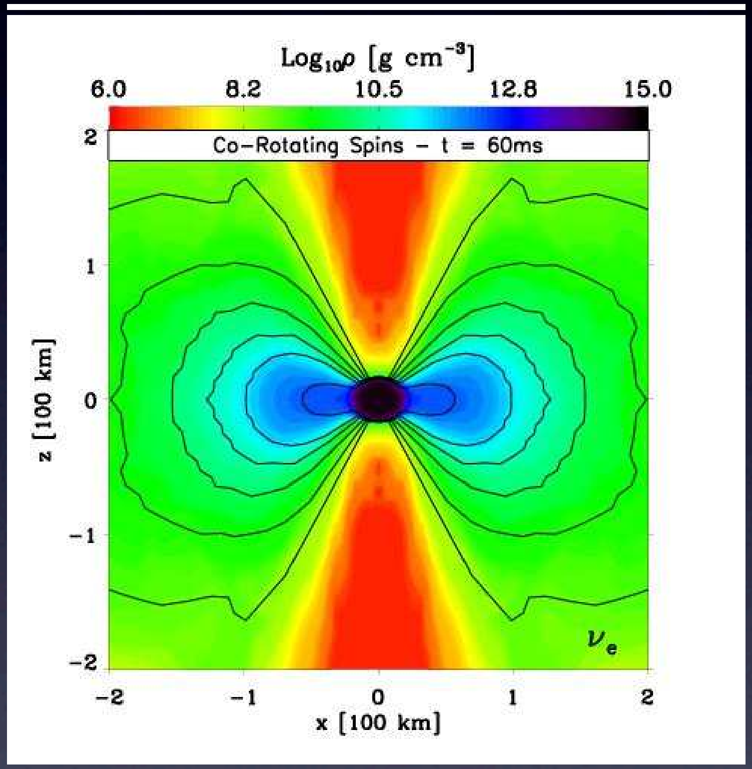
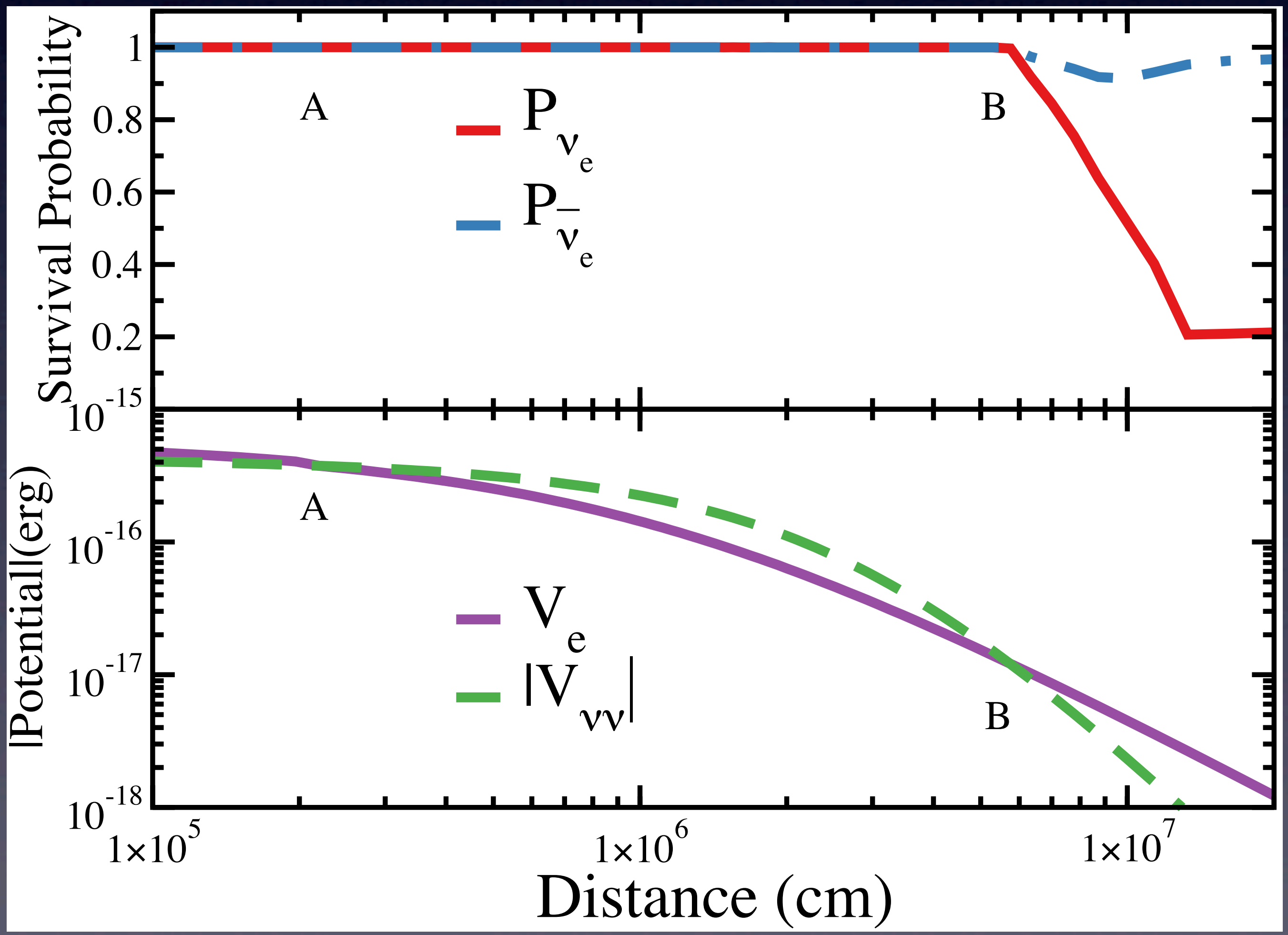


Fig from
Dessart, Ott, Burrows, Rosswog, Livne,
Neutrino signatures and the neutrino-driven wind in Binary Neutron Star Mergers,
arXiv:0806.4380

Matter-neutrino resonance

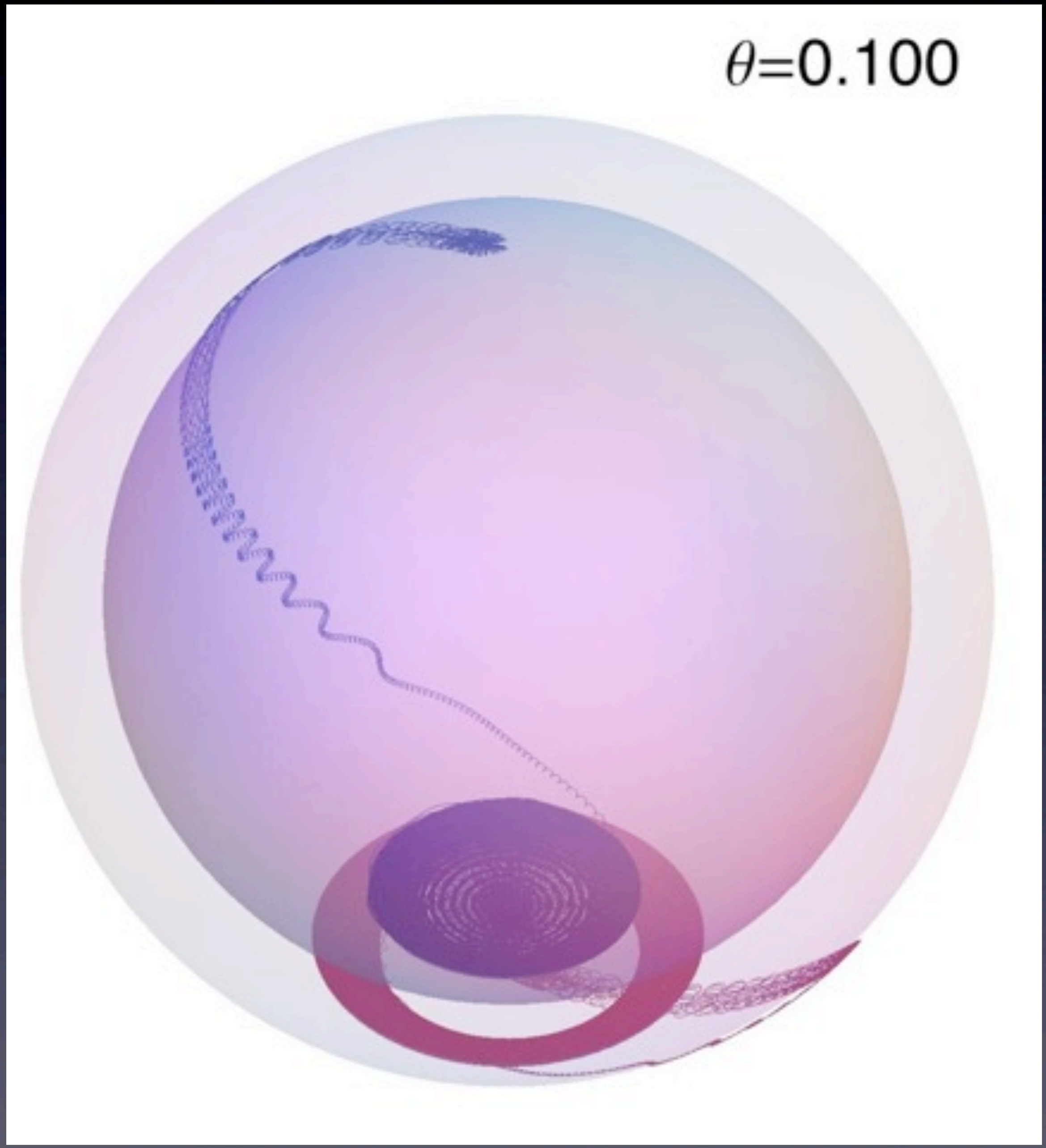
Malkus, Friedland, McLaughlin, 1403.5797

- At point B, where neutrino self-potential is equal and opposite to the matter term, an unusual transformation takes place
  - Complete conversion of electron neutrinos
  - while antineutrinos return to their original states



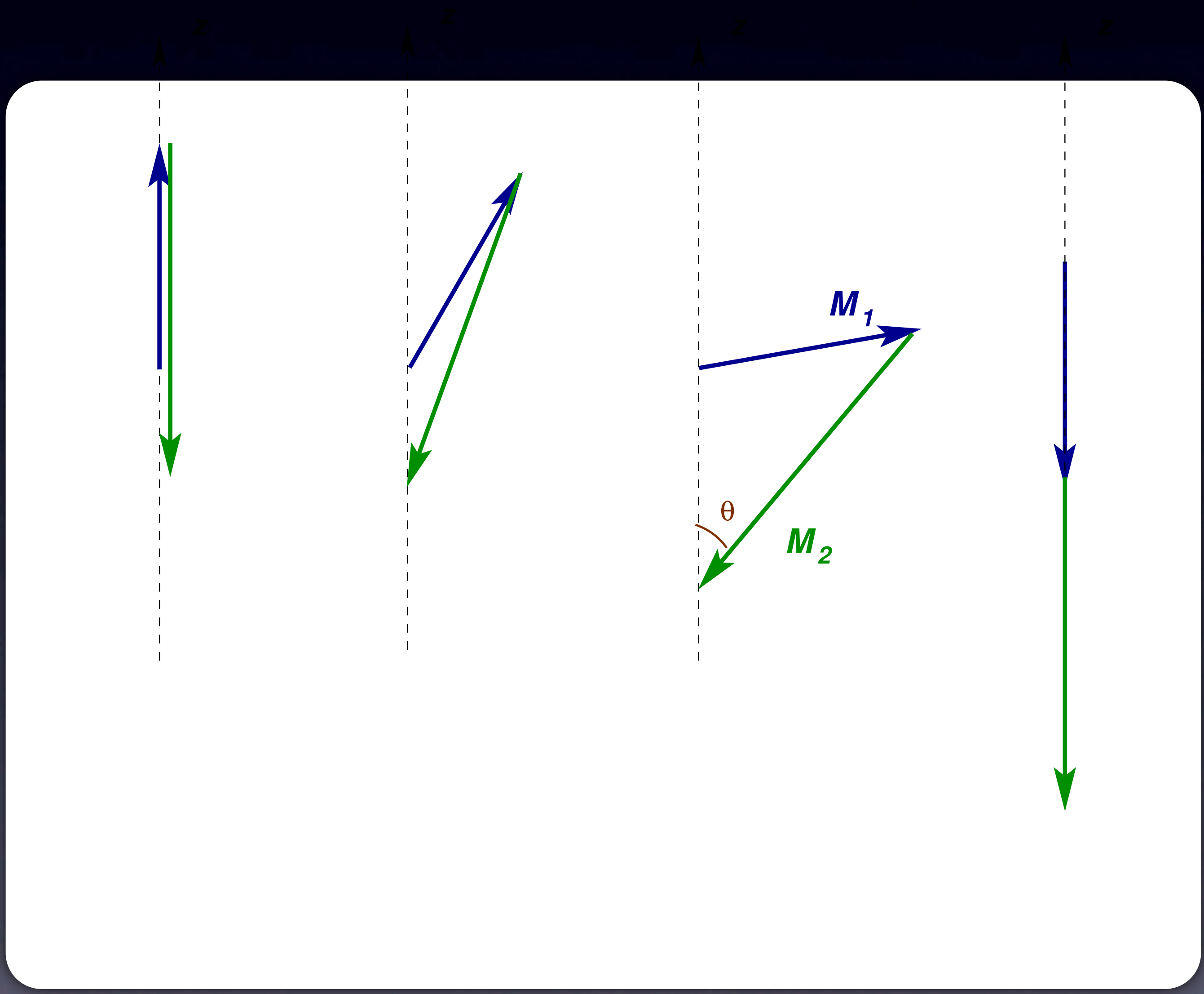
Two-energy model

- The basic mechanism behind this behavior can be most easily understood in a two-spin model



The basic mechanism

- As the matter and neutrino self-potentials cancel, the neutrino spins go from anti-aligned to aligned, while the sum remains along the direction of matter
  - Notice that this happens when the vacuum potential is much smaller than matter or neutrino self-interactions!



Basic analytics

- A bit of technical details: summing up the equations of motion, we see that the total momentum must remain aligned along the matter direction (to avoid fast precession)

- From the difference, we see that the motion indeed requires the cancellation between large potentials

$$\frac{d\boldsymbol{M}_1}{dt} = \boldsymbol{M}_1 \times (\boldsymbol{V} + \boldsymbol{V}_{matt}) + \mu(t)\boldsymbol{M}_1 \times \boldsymbol{M}_2,$$

$$\frac{d\boldsymbol{M}_2}{dt} = \boldsymbol{M}_2 \times (-\boldsymbol{V} + \boldsymbol{V}_{matt}) + \mu(t)\boldsymbol{M}_2 \times \boldsymbol{M}_1.$$

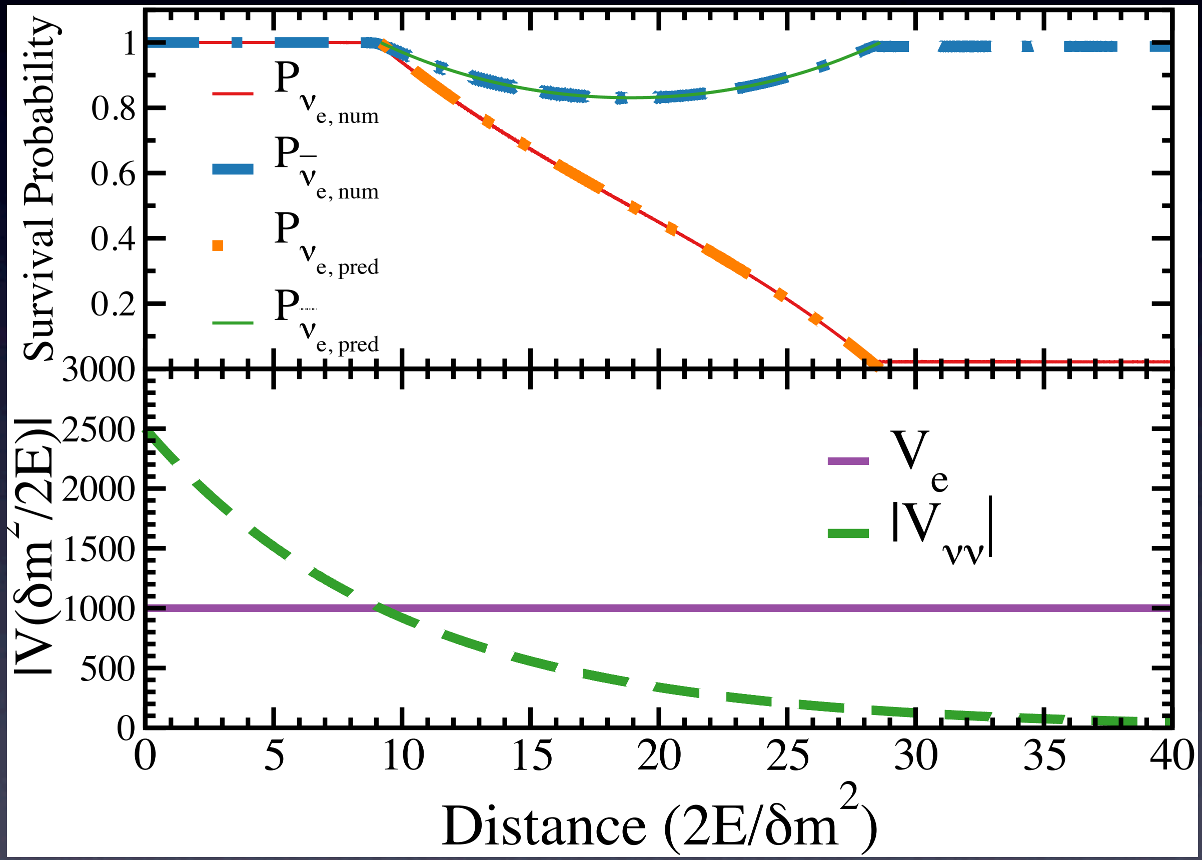
$$\frac{d(\boldsymbol{M}_1 + \boldsymbol{M}_2)}{dt} = (\boldsymbol{M}_1 + \boldsymbol{M}_2) \times \boldsymbol{V}_{matt} + (\boldsymbol{M}_1 - \boldsymbol{M}_2) \times \boldsymbol{V}.$$

$$\frac{d(\boldsymbol{M}_1 - \boldsymbol{M}_2)}{dt} = (\boldsymbol{M}_1 - \boldsymbol{M}_2) \times \boldsymbol{V}_{matt} + \mu(t)(\boldsymbol{M}_1 - \boldsymbol{M}_2) \times (\boldsymbol{M}_1 + \boldsymbol{M}_2) + (\boldsymbol{M}_1 + \boldsymbol{M}_2) \times \boldsymbol{V}$$

$$\boldsymbol{V}_{matt} + \mu(t)(\boldsymbol{M}_1 + \boldsymbol{M}_2) \simeq 0.$$

Good agreement

- The resulting analytics described the system extremely well



(a)Antineutrinos initially dominate.

A few quantitate observations

- Notice that the relevant quantity here is the absolute value of the matter potential, not dispersion
  - Matter matters!
- Notice also that the total electron number changes
  - This cannot be due to only neutrino self-interactions, cf the standard split phenomenon, which obeys flavor conservation
  - The effect is caused by the off-diagonal vacuum term
    - This requires theta13 to be sufficiently large
    - Measured value by Daya Bay turns out to be sufficient for realistic physical conditions!

Impact on nucleosynthesis?

- This type of transformation is in principle very relevant for nucleosynthesis
  - sweeps away electron neutrinos, while keeping the antineutrinos, all with no sterile
  - Happens close to the disk, where neutron-to-proton ratio is still formed
  - Needs investigation

Summary

- The physics of SN neutrino oscillations is extremely rich, much more interesting than thought 10 years ago!
- Collective oscillations: qualitatively new phenomenon, inaccessible in the lab
  - Known physics → not optional
- Need to explore and understand different physical regimes of oscillations
- *High-quality, high resolution SN simulations are urgently needed*