Neutrino Oscillations in Matter

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Outline

- Historical overview – solar neutrino problem
- Quick review of vacuum oscillations
- What changes in matter?
  - Matter of constant density
  - Matter with varying density (MSW effect)
- Effects on neutrinos from the Sun

Motivation & MSW origin

- 1968
  - Ray Davis and co. see about a third as many neutrinos from they expect based on the Solar Standard Model (SSM)
- 1978
  - L. Wolfenstein. Neutrino oscillations in matter. PRD 17 (2369)
- 1984
  - S.P. Mikheyev and A. Yu. Smirnov. Resonance enhancement of oscillations in matter and solar neutrino spectroscopy.

Vacuum oscillations

Assume 2 mass/flavor states:

$$\begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If an electron neutrino is created, some time (~distance) later probability of seeing non-electron neutrino:

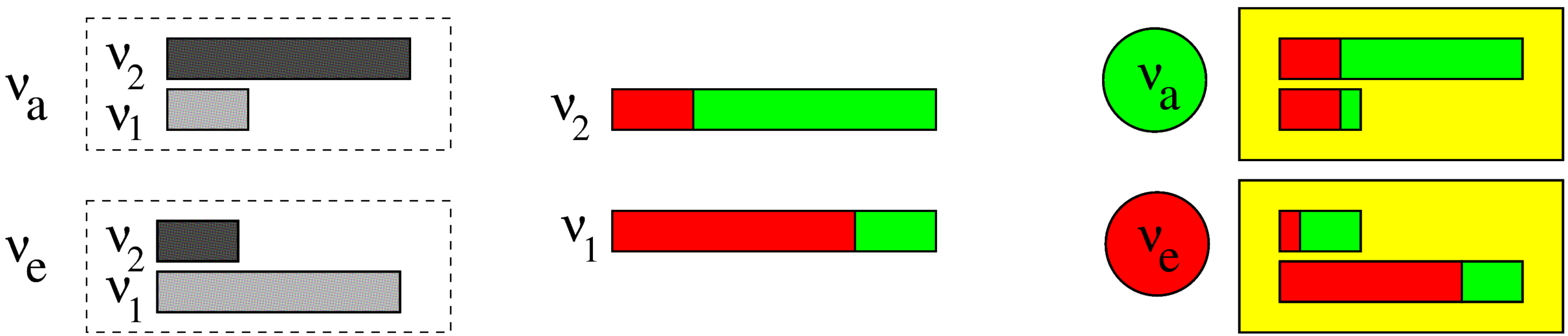
$$|\nu(t)\rangle = \cos\theta\, e^{-iE_1 t} |\nu_1\rangle + \sin\theta\, e^{-iE_2 t} |\nu_2\rangle$$

$$P(\nu_e \rightarrow \nu_a) = |\langle \nu_a | \nu(t) \rangle|^2$$

$$= \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

Important concepts: Relative phase difference, oscillation length.

Neutrino composition



a). b). c).

Amount of each mass state in given flavor state.

\+

Amount of flavor state in given mass state

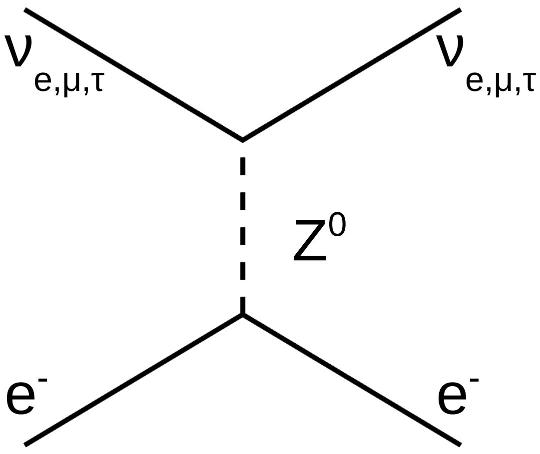
=

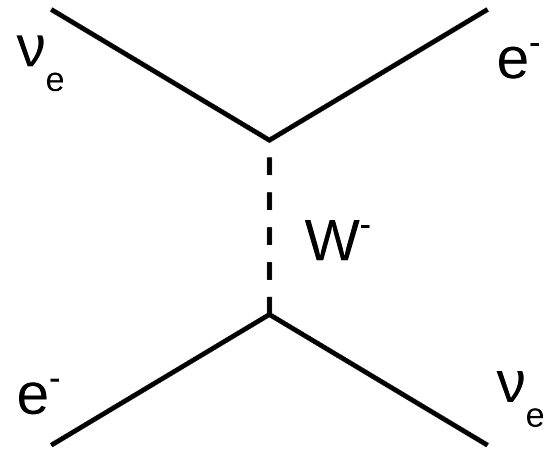
Total composition of each flavor state.

Yes, there is non-electron flavor in the electron neutrino. This is ok, because when produced the phases of the nu1 nua part and the nu2 nua part interfere destructively... The different phase velocities are what cause constructive interference later.

Illustration from Smirnov arxiv:hep-ph/0305106

Oscillations in matter





All flavors of neutrino are affected by NC interactions.
Electron neutrinos have additional CC interaction

H -> H+V

$V = V_e – V_a = \text{sqrt}(2)*G_F n_e$

Extra phase difference: $(V_e – V_a)t$

Refraction length: phase -> $2\pi = \text{sqrt}(2)\pi/(G_F n_e)$

Matter with constant density

The mixing angle changes (rel. to vacuum): θ_m

Composition changes: ν_{1m} ν_{2m}

Oscillation length changes.

The values of these change, but new values are constant.

Depth is maximal = Resonance.

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\sqrt{2} G_F n_e \frac{2E_\nu}{\Delta m^2} - \cos 2\theta\right)^2}$$

$$\sqrt{2} G_F n_e \frac{2E_\nu}{\Delta m^2} = cos2\theta$$

Resonance condition

Matter with varying density

Example – neutrinos traveling from center to edge of Sun

Additional time dependence in n_e.

Adiabatic condition: $d(\theta_m)/dt << |H_{2m}-H_{1m}|$
(ν_{1m} doesn't go to ν_{2m})
Amount of ν_{1m}, ν_{2m} in given flavor is determined by $n_e(0)$.

Depending on where n_{Res} is relative to creation point, different things can happen.

Conversion

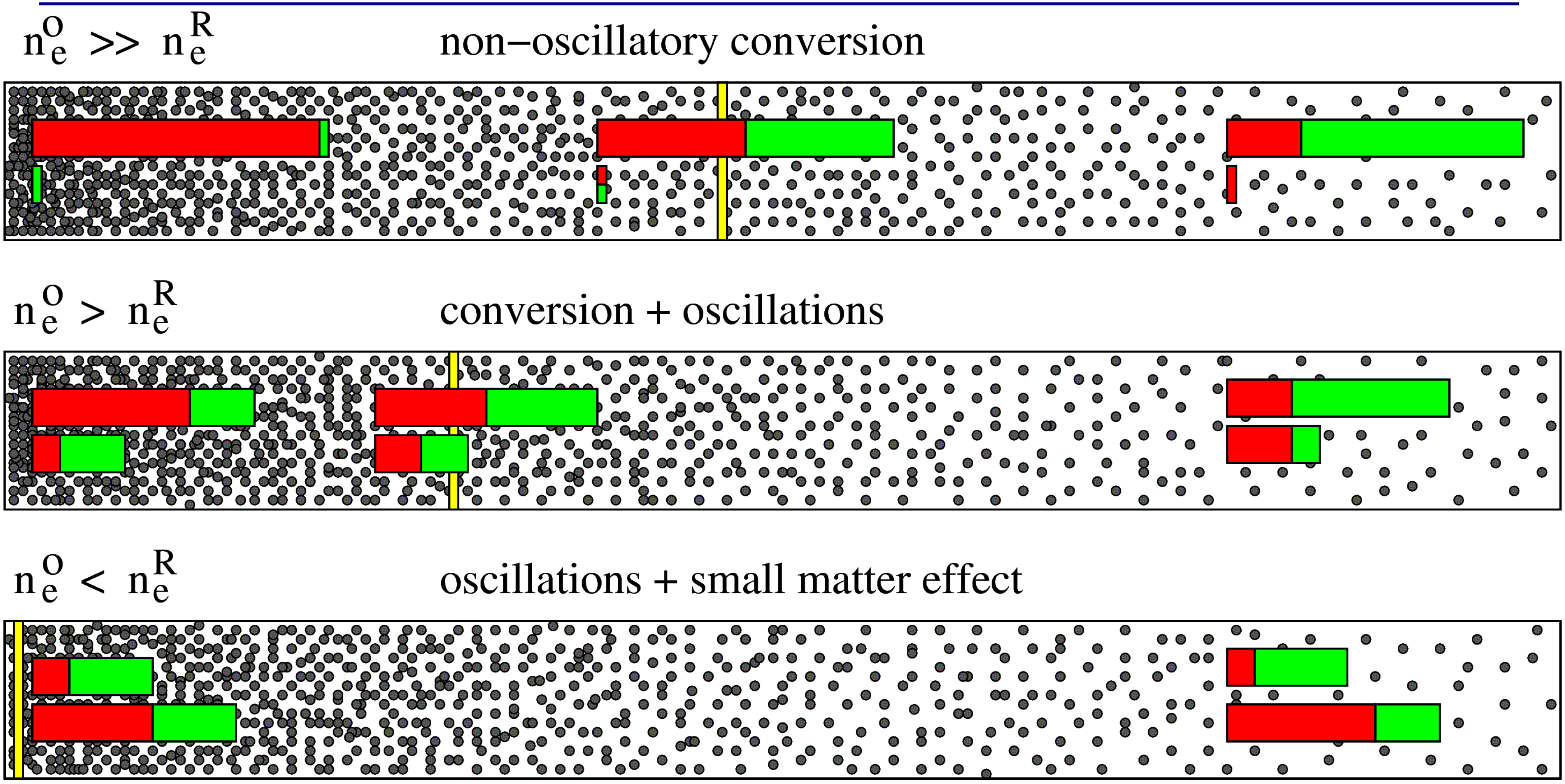


Illustration from Smirnov arxiv:hep-ph/0305106

What happens to solar neutrinos

- Exact story depends on neutrino energy.
  - See previous slide (E>10MeV, 2<E<10MeV, E<2MeV).
  - Basically, density of Sun means when neutrinos are produced they have a larger nu2 component than they would if produced in a vacuum.
- Problem solved 1998-2002
  - SN1987a (=>neutrinos have mass?)
  - Super-K (atmospheric neutrino oscillation, day-night asymmetry)
  - SNO (correct total number of neutrinos..)

Conclusion

- Matter effects are important when considering neutrino oscillations
- There are two* types of effects
  - Resonance
  - Adiabatic conversion (MSW)
- Solar neutrino problem solved

* In systems where the density doesn't change too fast.

References

- L. Wolfenstein, *Neutrino oscillations in matter*, Phys. Rev. D **17**, 2369 (1978).
- S.P. Mikheev and A. Yu. Smirnov, *Resonance enhancement of oscillations in matter and solar neutrino spectroscopy*, Sov. J. Nucl. Phys. **42**, 1441 (1985).
- H.A. Bethe, *Possible Explanation of the Solar-Neutrino Puzzle*, Phys. Rev. Lett. **56**, 1305 (1986).
- A. Yu. Smirnov, *The MSW effect and Solar Neutrinos*, arxiv:hep-ph/0305106