Astro 596/496 NPA
Lecture 28
April 8, 2019

Announcements:

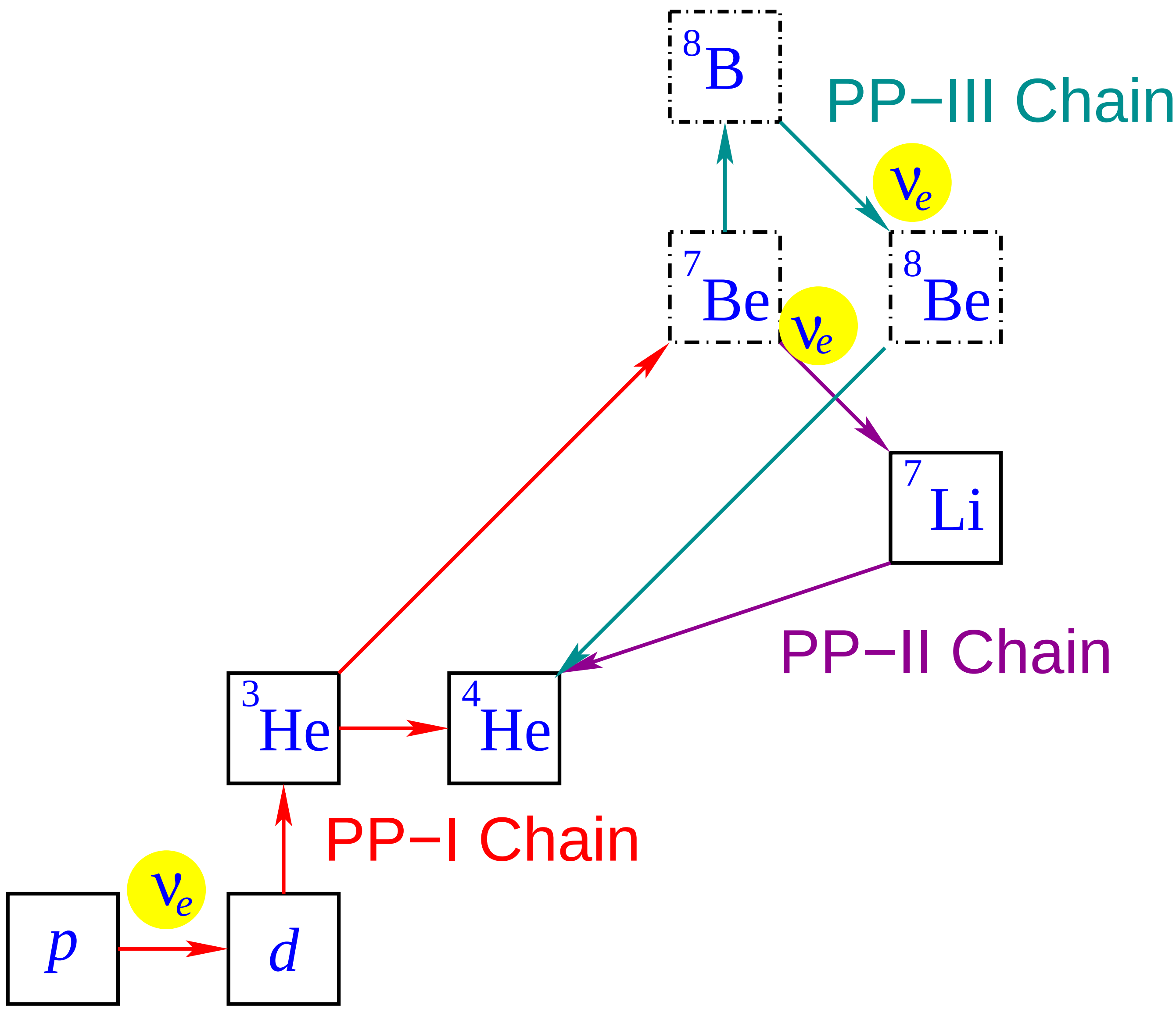
- **Problem Set 5 due Friday**
- **Event Horizon Telescope announcement Wed 8:00am**
  live streaming: Astro Atlas Room, Physics Interaction Room

Last Time:

- solar hydrogen burning reactions and neutrino production
  Q: how are most solar neutrinos created?
  Q: what is important about the ^{8}B *neutrinos?*

`www: Standard Solar Model neutrino spectra`

- solar neutrino radiochemical experiments
  Q: challenges? how are these addressed?
  Ray Davis: Chlorine (Homestake Mine) *Q: result?*
  Gallium experiments (GALLEX, SAGE) *Q: result?*


8B
PP–III Chain
νe
7Be
8Be
νe
7Li
PP–II Chain
3He
4He
PP–I Chain
νe
p
d

Radiochemical Experiments

Homestake Mine Ray Davis Jr. et al 1967-1995
Chlorine target: $^{37}\text{Cl} + \nu_e \rightarrow {}^{37}\text{Ar} + e$
threshold $E_\nu > |Q| = 0.814$ MeV: only measure ^{7}Be, ^{8}B νs

$$\frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SSM}}} = 0.33 \pm 0.03 \pm 0.05 \ll 1! \qquad (1)$$

original *Solar neutrino problem*

Gallium target: $^{71}\text{Ga} + \nu \rightarrow {}^{71}\text{Ge} + e$
GALLEX: Gran Sasso, Italy; SAGE: Baksan, Russia
threshold $E_\nu > |Q| = 0.233$ MeV: some pp νs contribute!

$$\frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SSM}}} = 0.59 \pm 0.06 \pm 0.04 \qquad (2)$$

Significant deficit! *Solar neutrino problem #2*

Q: what additional info would we like? how to measure?

Water Čerenkov Experiments

target: water
process: electron scattering $\boxed{\nu e \to \nu e}$
for $E_\nu \gtrsim 0.5$ MeV, recoil electron $v_e \sim c$

but in water, refractive index $n = 1.34 \Rightarrow v_e > c/n$
emit "sonic boom" photons: Čerenkov radiation
"optical shock wave," cone of light
cone opening angle depends on $v_e \to E_e$

`www: Super-K events`

 Q: advantages of water Čerenkov vs radiochemical?

In praise of Water Čerenkov

- *detect neutrinos in "real time"*
- $E_e \to \nu$ energy $\to$ spectrum
- cone orientation $\to \nu$ direction info!

Super-Kamiokande. Kamioka Mine, Japan: 1996-

`www: Super-K image`

direction: νs point back to Sun (check)

`www: Neutrino image of the Sun`

$e\nu$ elastic scattering in pure water

Energy threshold: 5 MeV $\Rightarrow$ see only ^{8}B νs

spectrum: shape matches SSM!

...but $\Phi(^8\text{B})_{\text{SK}}/\Phi(^8\text{B})_{\text{SSM}} \sim 50\%$!

Solar neutrino problem #3

Neutrinos and the Weak Interaction

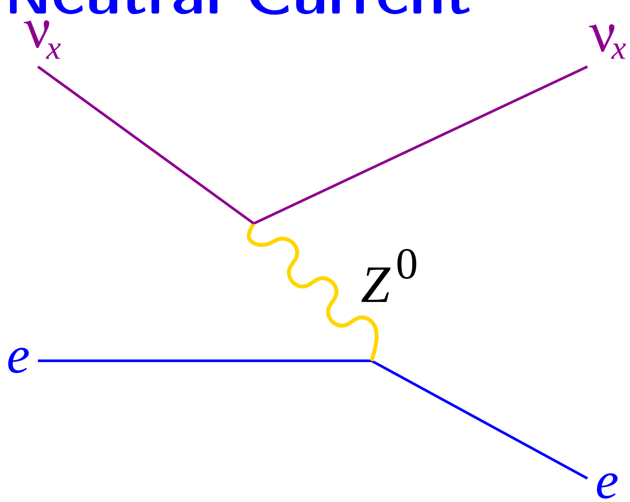
neutrinos interact via the Weak interaction only (and gravity)

couple via exchange of Weak bosons

Example: $\nu e \rightarrow \nu e$ elastic scattering

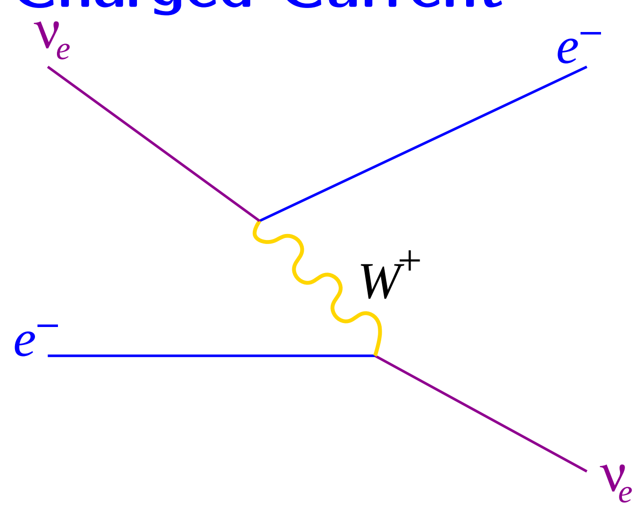
exchange Z^0:

Neutral Current



exchange $W^{\pm}$:

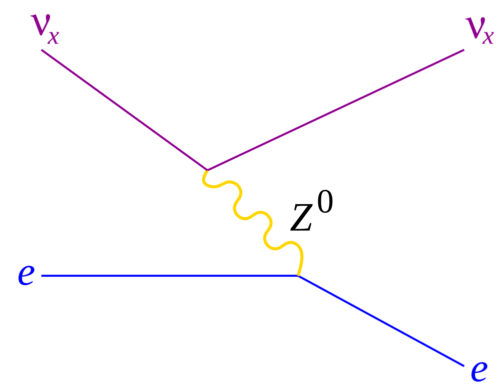
Charged Current



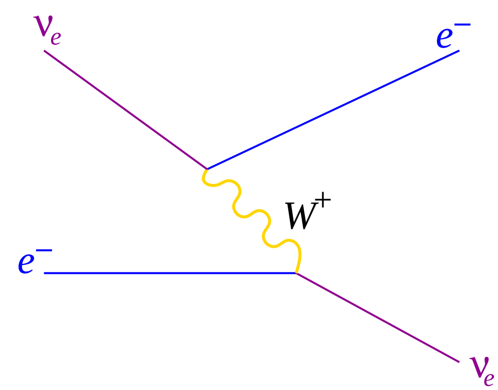
Q: what is the crucial difference here?

Neutral vs Charged Current

neutral current events
occur for all ν (and $\bar{\nu}$) flavors
with equal probability



charged current events
only have e^- targets (no ambient μ or τ!)
occur for only for ν_e!



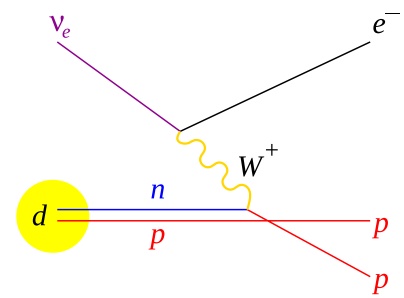
Q: so what would be a good experiment to do?

Sudbury Neutrino Observatory (SNO)

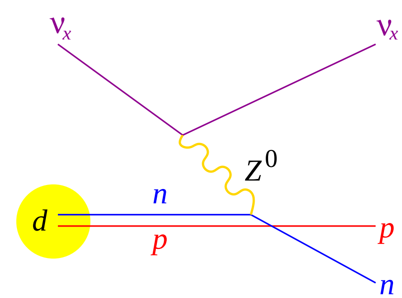
SNO **Art McDonald et al**: 1999-present
site: mine in Sudbury, Ontario, Canada
ultrapure heavy water: D_2O

Reactions:

$\nu_e + d \rightarrow e^- + p + p$ **Charged current**: *ν_e only*
Threshold: 1.4 MeV $\rightarrow$ ^{8}B only



$\nu_x + d \rightarrow \nu'_x + p + n$ ν' flavor $= \nu$ flavor
Neutral current: *all flavors*
Threshold: 2.2 MeV $\rightarrow$ ^{8}B only



∞

also: Salt phase – dissolve NaCl in SNO tank
big σ for ^{35}Cl$(n,\gamma)^{36}$Cl $\rightarrow$ improved NC

SNO Results

Charged-current flux: ν_e only

$$\Phi_{\text{CC}}^{\text{SNO}} = \left[1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{sys})\right] \times 10^6\ \nu\ \text{cm}^{-2}\ \text{s}^{-1} \tag{3}$$

Neutral-current flux: all ν species

$$\Phi_{\text{NC}}^{\text{SNO}} = [5.21 \pm 0.27(\text{stat}) \pm 0.38(\text{sys})] \times 10^6\ \nu\ \text{cm}^{-2}\ \text{s}^{-1} \tag{4}$$

Thus we have

$$\frac{\Phi_{\text{CC}}^{\text{SNO}}}{\Phi_{\text{NC}}^{\text{SNO}}} = \frac{\nu_e\ \text{flux}}{\text{all}\ \nu\ \text{flux}} = 0.306 \pm 0.026(\text{stat}) \pm 0.024(\text{sys}) \tag{5}$$

Which means...

Solar Neutrino Problem(s) Pre-SNO

observed ν fluxes *less than* *Standard Solar Model* predictions

- Radiochemical: Chlorine, Gallium
- Water Čerenkov: Super-Kamiokande

  but $\nu_{\mathrm{super-k}}$ point back to Sun, have expected energy spectrum

Possible Solutions

- Standard Solar Model wrong–ν flux overpredicted (but pp?)
- Standard Model of particle physics wrong

Experimentum Crucis: SNO

- independently measure ^{8}B ν_e flux, all-flavor flux
- $\Phi_{\nu_\mathrm{e}}/\Phi_{\mathrm{tot}} = 0.31$

$\Rightarrow$ large non-ν_e flux arriving in detectors!

Implications: New Neutrino Physics!

The Sun makes only ν_e

Q: why? e.g., why not ν_μ?

$\longrightarrow$ if no new ν physics, only ν_e at Earth

$\longrightarrow$ predict $\Phi_{\mathrm{CC}}(\nu_e) = \Phi_{\mathrm{NC}}(\nu_x)$

SNO measures $\Phi_{\mathrm{NC}}(\nu_x) > \Phi_{\mathrm{CC}}(\nu_e)$!

with *very* high confidence!

non-ν_e flux arriving in detector!

A big deal:

- demands **new neutrino physics**
- independent of detailed solar model

Triumph of the Standard Solar Model

SNO bonus: can infer total ^{8}B ν flux
compare Bahcall SSM (Bahcall & Pinsonneault 2004):

$$\begin{aligned}\Phi_{\rm SSM}(^8{\rm B}) &= 5.79(1 \pm 0.23) \times 10^6 \ \nu \ {\rm cm}^{-2} \ {\rm s}^{-1} \\ &= [1.10 \pm 0.04({\rm exp}) \pm 0.23({\rm thy})] \, \Phi_{\rm NC}^{\rm SNO}\end{aligned}$$

consistent! *Standard Solar Model working extremely well!*
$\Rightarrow$ *major triumph for stellar evolution and nuclear astrophysics!*
woo hoo!

2002 Nobel Prize in Physics: Ray Davis

2015 Nobel Prize in Physics: Art McDonald

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed–you call
It wonderful; I call it crass.

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963 + 2019 Update!

Neutrinos, they are very small.
They have no charge and ~~have no~~ tiny mass
And ~~do not~~ hardly interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

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Solar Neutrino Schizophrenia

total $\nu_e + \nu_\mu + \nu_\tau$ flux *in detectors*
agrees with SSM flux *out of solar core*

but solar νs must *start as ν_e*
$\rightarrow$ neutrinos must **transmute** on the way!
i.e., $\nu_e \rightarrow \nu_{\mu,\tau}$!

there's more:

ν_e Experiment	$E_{\nu,\mathrm{min}}$ Threshold	Obs/SSM
Gallium	> 0.233 MeV	$0.59 \pm 0.06 \pm 0.04$
Chlorine	> 0.814 MeV	$0.33 \pm 0.03 \pm 0.05$
Super-K	> 5 MeV	~ 0.4

$\Rightarrow$ transmutations must be energy-dependent:
Q: what should dependence be like?
`www: solar nu spectrum`

Solar Neutrino Transformation Properties

Need:

- small ν_e suppression at low energies (pp: $\lesssim$ 0.4 MeV)
- large ν_e suppression ($>$ 50%) at higher energies

Non-trivial neutrino physics required!

Neutrino Oscillations in Vacuum: The Quantum Neutrino

If *neutrinos have nonzero mass*
- family status (e, μ, τ "**flavor**"), and
- **mass**

can be **distinct**!

ν family $\rightarrow$ lepton number conservation in Weak interactions
formally, νs couple to Weak interaction as
flavor eigenstates
flavor basis vectors $|\nu_\alpha\rangle$, $\alpha = e, \mu, \tau$

free (vacuum) neutrino $\rightarrow$ *propagates* as
mass eigenstate
mass basis vectors $|j\rangle$, $j = 1, 2, 3$

Basis Transformation: Flavor/Weak $\leftrightarrow$ Mass/Vacuum

Key idea: **mass eigenstate $\neq$ flavor eigenstate**

analogous to spin-$\frac{1}{2}$: S_z eigenstates $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ vs S_x eigenstates $\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$, $\frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}$

basis vector in one scheme is linear combo of *both* basis vectors in other

either basis a valid description of ν state

physical situation selects most natural choice:

- ν production/detection: Weak interaction $\rightarrow$ *flavor* basis
- ν propagation in vacuum $\rightarrow$ *mass* basis

basis vectors related by linear transformation

(P)MNS=Pontecorvo, Maki, Nakagawa, Sakata matrix

$$|\nu_{\text{flavor}}\rangle_{i\in e,\mu,\tau} = \sum_{j=1,2,3} U_{ij} |\nu_{\text{mass}}\rangle_j \quad (6)$$

$$|\nu_{\text{mass}}\rangle_{i\in 1,2,3} = \sum_{j=e,\mu,\tau} U^\dagger_{ij} |\nu_{\text{flavor}}\rangle_j \quad (7)$$

U is time-indep, unitary: $U^{-1} = U^\dagger$; $U^\dagger U = UU^\dagger = 1$

Neutrino Flavor Change

Key idea:

- neutrinos *born* in Weak interactions
  $\rightarrow$ *created* as *Weak* eigenstates
- *propagate* as *vacuum* eigenstates
- then *detected* in *Weak* interactions

Evolution of wavefunction during propagation
changes probability of remaining a ν_e state

If mass eigenstates have definite p and thus $E_j = \sqrt{p^2 + m_j^2}$
(as in vacuum), then Schrödinger:

$$i\hbar \frac{d}{dt} |\nu_{\text{mass}}\rangle_j = H_{\text{vacuum}} |\nu_{\text{mass}}\rangle_j = E_j |\nu_{\text{mass}}\rangle_j \tag{8}$$

and so

$$|\nu_{\text{mass}}(t)\rangle_j = e^{-iE_j t/\hbar} \, |\nu_{\text{mass}}(0)\rangle_j \tag{9}$$

Two flavors: allow 2 flavors (e and x) to mix
write $|f\rangle = U_{\text{vac}}|m\rangle$, where

$$U_{\text{V}} = \begin{pmatrix} \cos\theta_{\text{V}} & \sin\theta_{\text{V}} \\ -\sin\theta_{\text{V}} & \cos\theta_{\text{V}} \end{pmatrix} \quad (10)$$

with vacuum mixing angle $\theta_{\text{V}} \in (0, \pi/4)$ ("ν_e mostly ν_1")

$$|\nu_e(t)\rangle = e^{-iE_1 t/\hbar}\cos\theta_{\text{V}}|1\rangle + e^{-iE_2 t/\hbar}\sin\theta_{\text{V}}|2\rangle \quad (11)$$

where E_1, E_2 have same momentum p

Solar neutrinos start ($t = 0$) as pure ν_e
QM **amplitude** at t to *remain* ν_e:

$$\langle\nu_e(0)|\nu_e(t)\rangle = e^{-iE_1 t/\hbar}\cos\theta_{\text{V}}^2 + e^{-iE_2 t/\hbar}\sin\theta_{\text{V}}^2 \quad (12)$$

$\Rightarrow$ probability to remain ν_e:

$$|\langle\nu_e(0)|\nu_e(t)\rangle|^2 = 1 - \sin^2 2\theta_{\text{V}}\ \sin^2\left[1/2\ \frac{(E_2 - E_1)t}{\hbar}\right]$$

Since $m(\nu_i) \ll p$, $E_j = \sqrt{p^2 + m_j^2} \simeq p^2 + m_j^2/2p$, and

$$E_2 - E_1 \simeq \frac{m_2^2 - m_1^2}{2E} = \frac{\pm\Delta m^2}{2E} \qquad (13)$$

$\Delta m^2 = |m_2^2 - m_1^2| > 0$

E = avg energy.

In time t go distance $L \simeq ct$

$$\begin{aligned} P(\nu_e^{\text{birth}} \rightarrow \nu_e^{\text{detect}}) &= |\langle \nu_e(0)|\nu_e(t)\rangle|^2 \\ &= 1 - \sin^2 2\theta_V \, \sin^2\left(\pi \frac{L}{L_V}\right) \qquad (14) \\ &= 1 - \sin^2 2\theta_V \, \sin^2\left[1.27 \frac{\Delta m^2(\text{eV}^2) L(\text{km})}{E(\text{GeV})}\right] \end{aligned}$$

where $L_V = 4\pi\hbar E/\Delta m^2$ "vacuum osc. length"

$$P(\nu_e^{\text{birth}} \rightarrow \nu_e^{\text{detect}}) = |\langle \nu_e(0) | \nu_e(t) \rangle|^2 = 1 - \sin^2 2\theta_{\text{V}} \, \sin^2 \left(\frac{\pi L}{L_{\text{V}}} \right)$$

Minimum mass sensitivity: $\pi L / L_{\text{V}} = \pi/2$
If $L_{\text{V}} \ll 1$ AU: wash out differences among species
If $L_{\text{V}} \simeq 1$ AU: solve solar ν problem!

$$\Delta m^2 \sim 10^{-12} \text{ eV}^2 \left(\frac{E}{10 \text{ MeV}} \right) \tag{15}$$

solves solar ν problem, but dubious
Q: why?
$\Rightarrow$ "just-so" solution

also note: if Δm^2 larger, $L_V \ll 1 AU$

$$\Rightarrow \quad |\langle \nu_e(0) | \nu_e(t) \rangle|^2 \simeq 1 - \frac{1}{2} \sin^2 2\theta \geq \frac{1}{2} \tag{16}$$

but we need suppression $> 50\%$!
can't do this with vaccuum oscillations!