NEUTRINO PHYSICS

Atmospheric and Solar Evidence

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

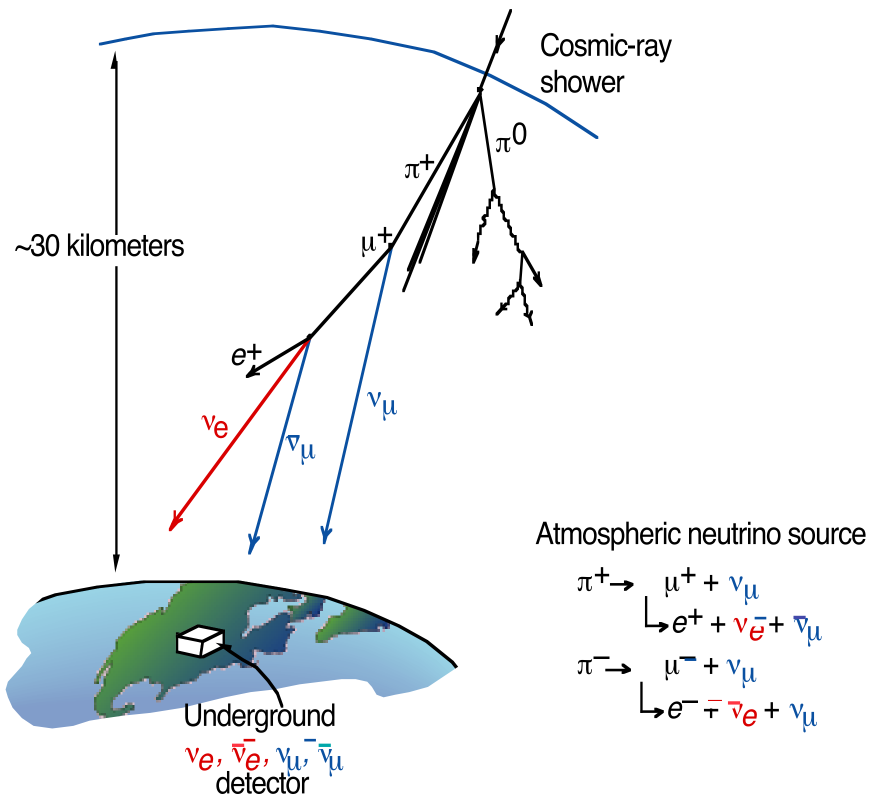
Fisica delle Particelle Elementari, Anno Accademico 2015-16

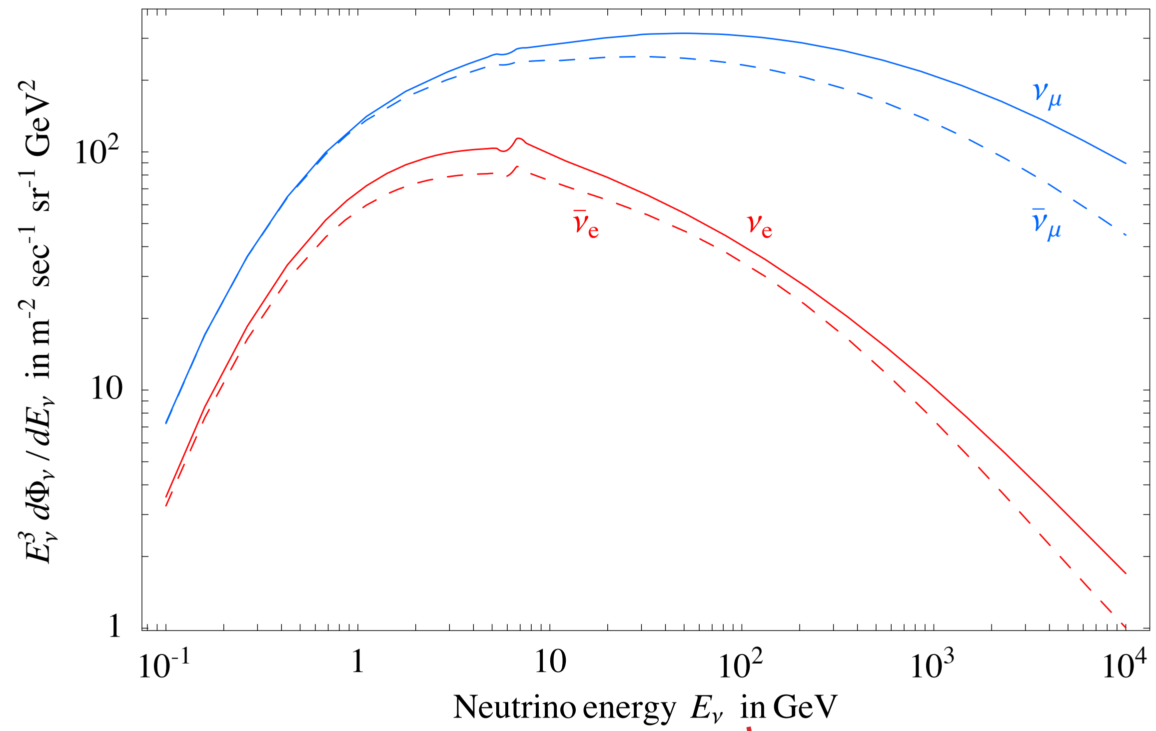
`http://www.roma1.infn.it/people/rahatlou/particelle`

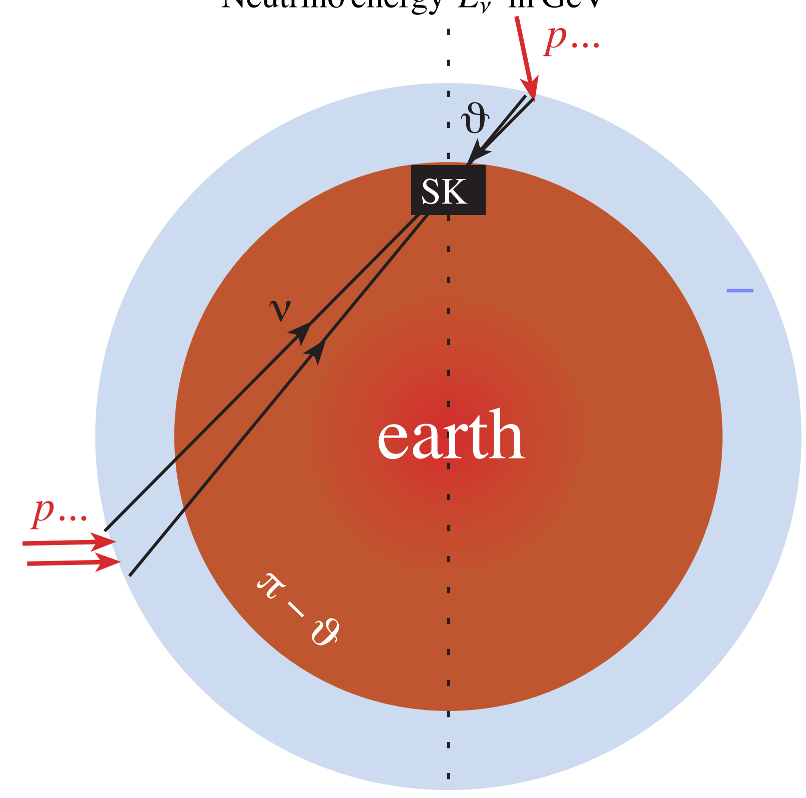
ATMOSPHERIC EVIDENCE

THE ATMOSPHERIC NEUTRINOS

- Primary cosmics produce π in upper atmosphere: $\pi \Rightarrow \mu\nu_\mu$, $\mu \Rightarrow e\nu_\mu\nu_e$ $\varphi(\nu_\mu)=2\varphi(\nu_e)$ at few % level



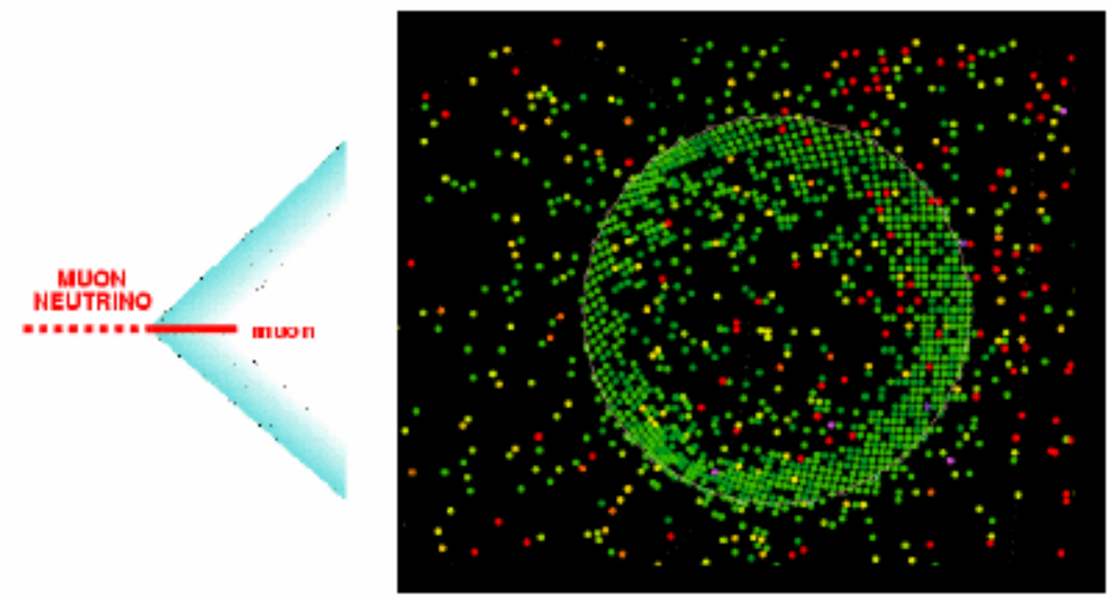


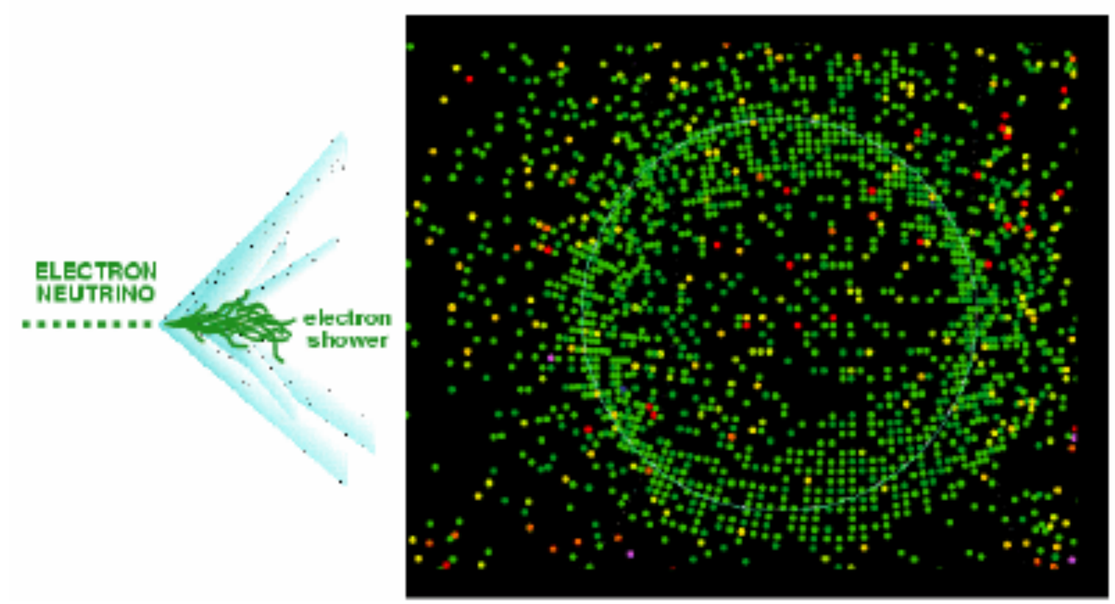


- Isotropy of the >2GeV cosmic rays flux +Gauss' law :
- ν rate up/down symmetric
- no need knowledge flux

SUPERKAMIOKANDE

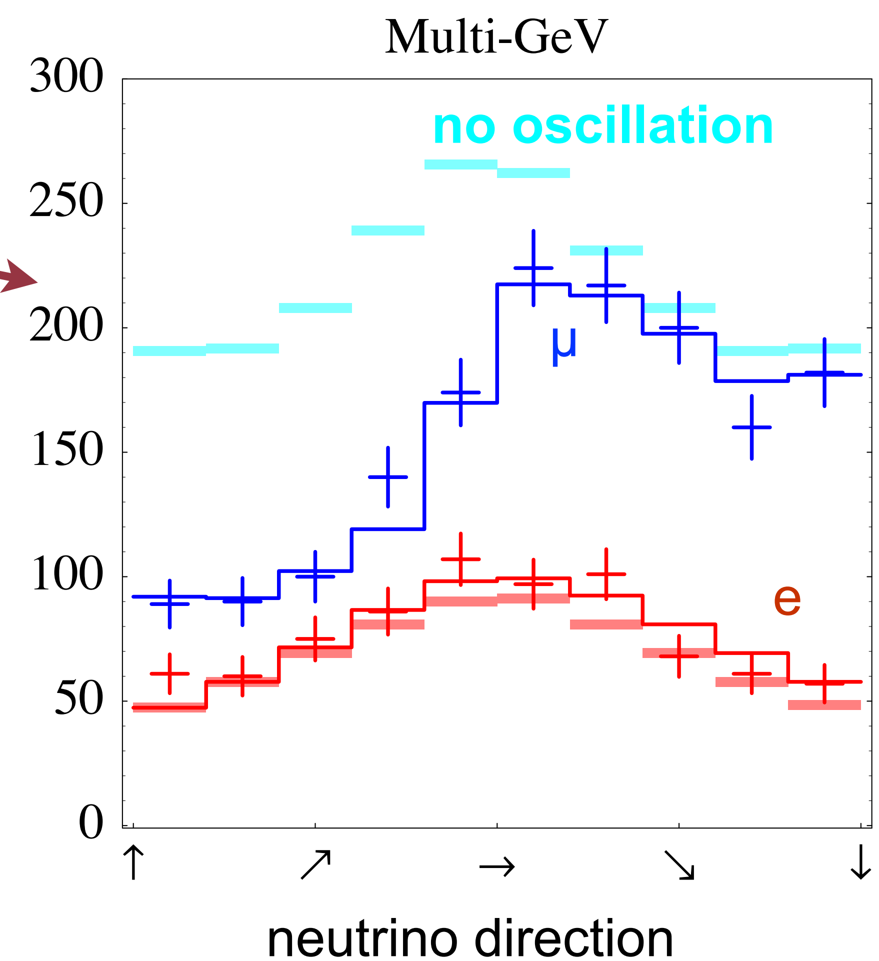
- Water Cherenkov H_2O + PMT
  - Unsegmented⇒ requires low rate and low multiplicity⇒underground $\Phi=2/cm^2s \Rightarrow\approx$1kevents/year
  - CC interaction on nucleons: $\nu_l N \rightarrow l N'$, $\sigma(\nu)\approx 3\sigma(\bar{\nu})$
  - e/μ separation not $e(\mu)^+$, $e(\mu)^-$
  - ν from everywhere: no E_ν reconstruction
  - wide energy range: GeV-TeV
  - $E_l \geq 1.5$GeV $\Rightarrow \theta_{\nu l} \approx 15°$⇒direction⇒ measure L

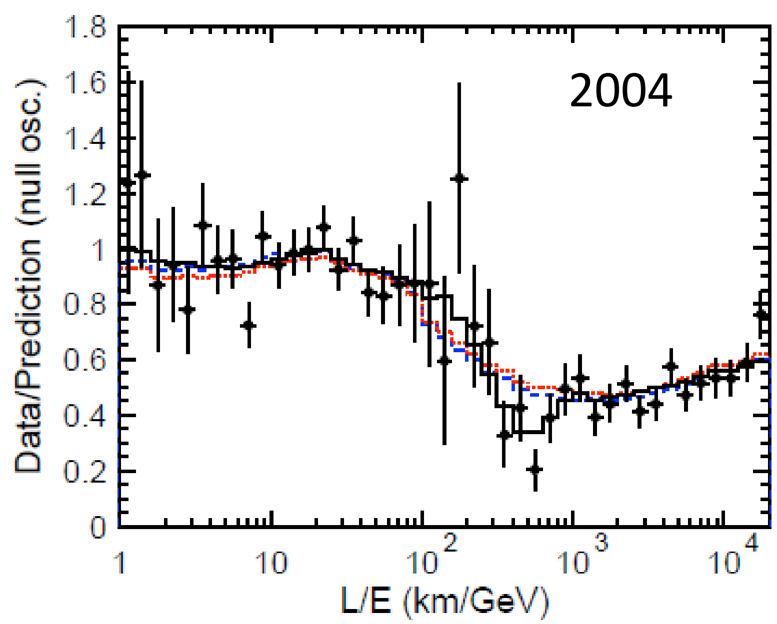


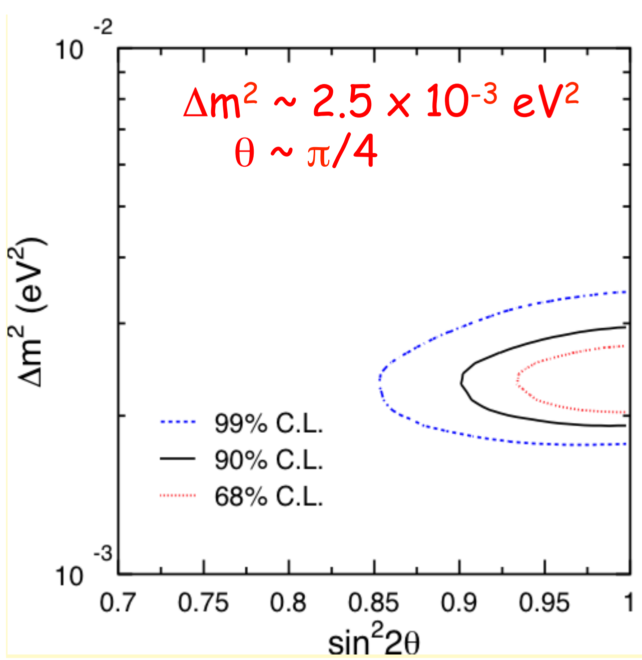


Atmospheric Anomaly

- $[\varphi(\nu_\mu)/\varphi(\nu_e)]/[\varphi(\nu_\mu)/\varphi(\nu_e)]_{MC} \sim 0.65$
- Anomaly without relying on knowledge of neutrino fluxes
  - ν_e as expected, ν_μ deficit from below
  - $\nu_\mu \Longrightarrow \nu_e$? not at leading order
  - $\nu_\mu \Longrightarrow \nu_\tau$? yes
- $P_{\mu\mu} = 1 - \sin^2(2\vartheta_{23})\sin^2(\Delta m^2 L/4E_\nu)$
  - Zenith no oscillation, Nadir average oscillation
    - $\Rightarrow P_{\mu\mu} = 1 - 0.5 \cdot \sin^2(2\vartheta_{23}) = N^{\uparrow}/N^{\downarrow} \Rightarrow \boldsymbol{\vartheta = 45°}$
  - Oscillations start horizontal:
    - $E_\nu \sim$ GeV, $L \sim 1000$ km, $\Rightarrow \boldsymbol{\Delta m^2 \sim E_\nu/L \sim 3 \cdot 10^{-3}\ eV^2}$
- Restricting to cleanest events

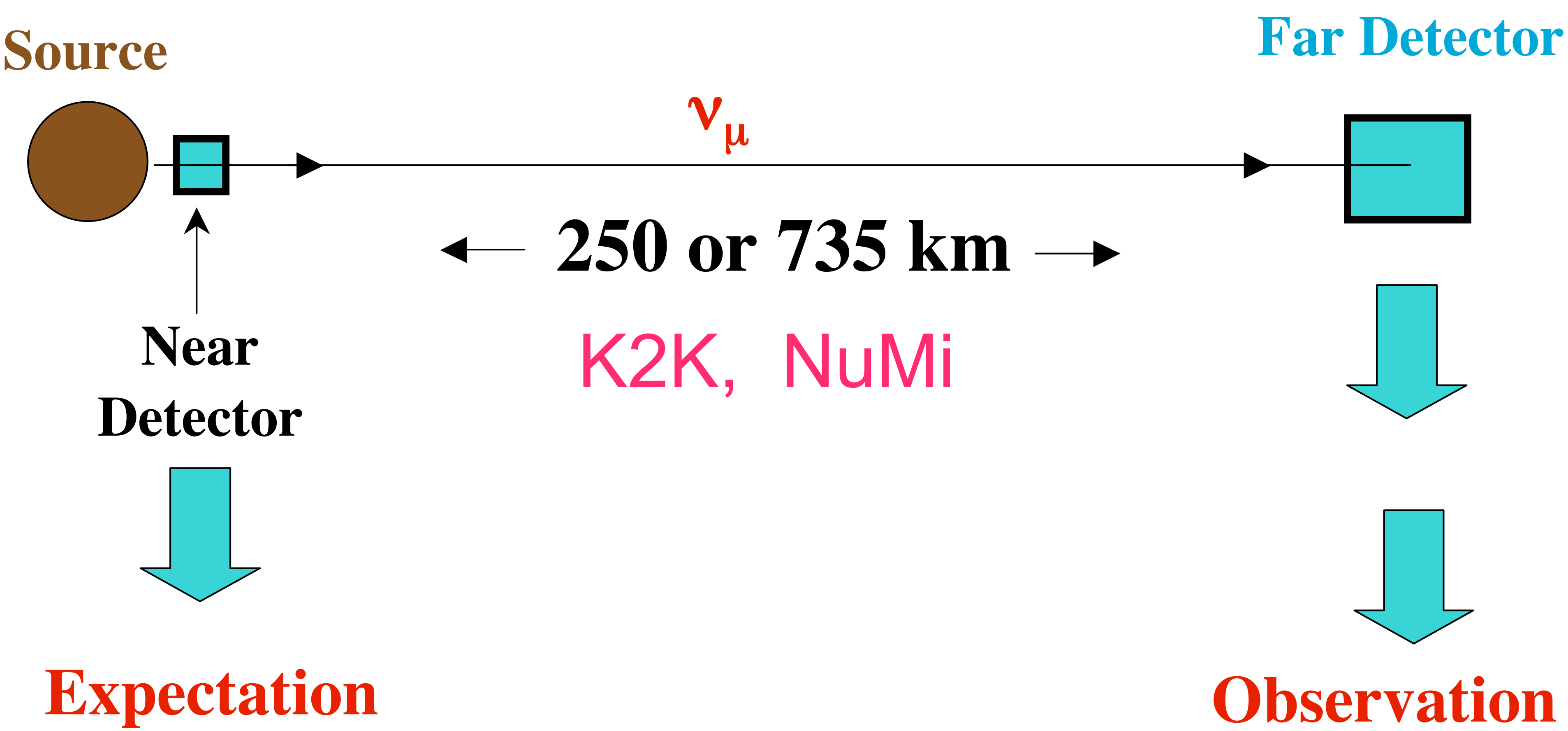






TEST OF $P_{\mu\mu}$ ANOMALY

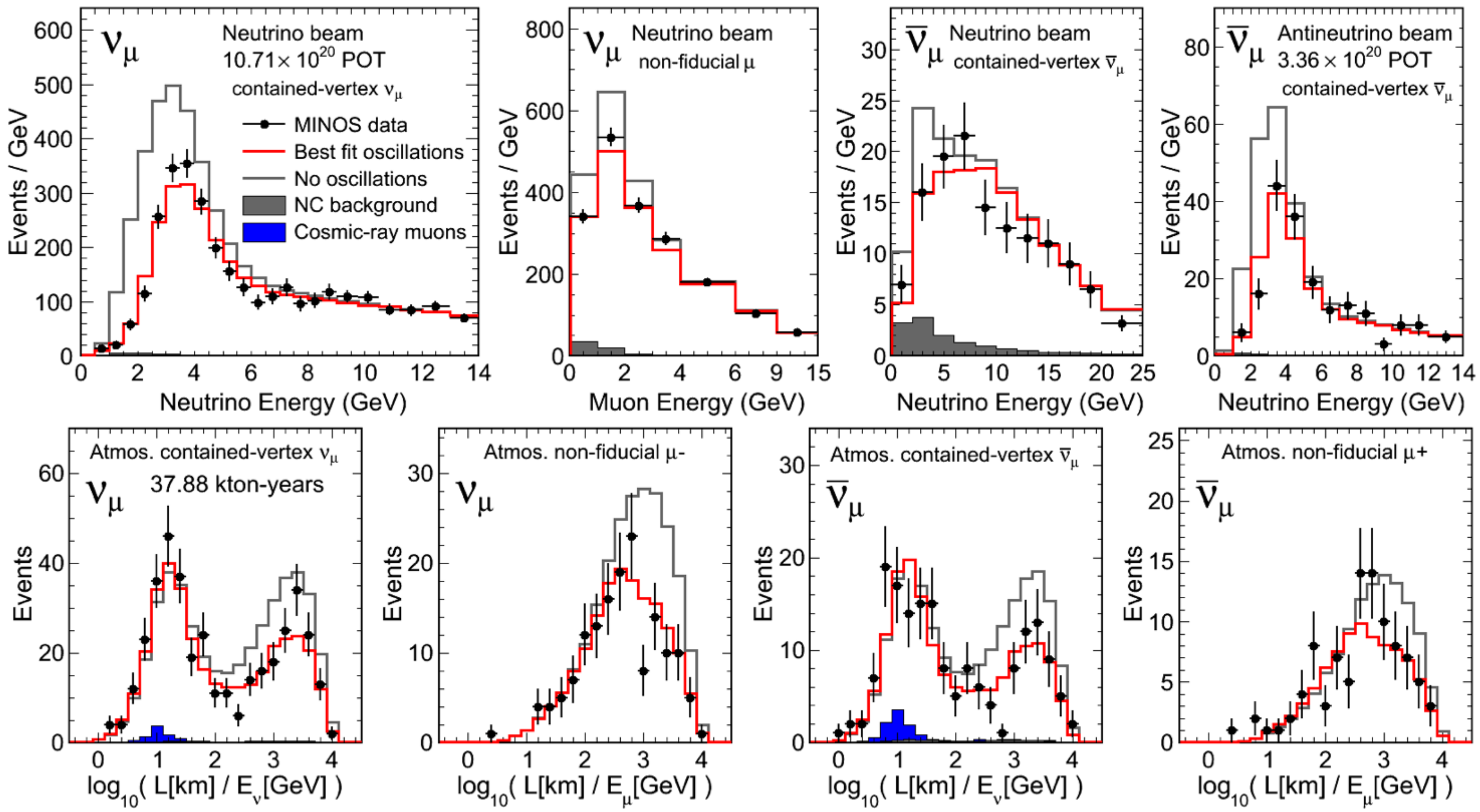
- $\Delta m^2_{Atm} \sim E_\nu/L \sim 3 \cdot 10^{-3}\ eV^2$
- Build an experiment and ν_μ beam with $\Delta m^2_{Atm} L/E_\nu \sim 1$,
  - $E_\nu \approx$ few GeV $\approx m_p$, $L \approx O(100\ km)$, $\theta_{\mu\nu} \approx 1$(if $\nu_\mu\, n \Rightarrow \mu^- p$ dominant reaction)



Neutrino beam: p on target →Kπ(μ) focus and decay →shielding→ $90\%\nu_\mu$, $8\%\nu_\mu$, $1\%\nu_e$, $1\%\nu$

$\pi^+ \rightarrow \mu^+\nu_\mu$ (99.99%), $\pi^+ \rightarrow e^+\nu_e(10^{-2}\%)$, $K^+ \rightarrow \mu^+\nu_\mu$(63%), $K^+ \rightarrow \pi^0\, e^\pm(\mu^\pm)\, \overset{(-)}{\nu}$(4%), $K^0 \rightarrow \pi^\pm\, e^\pm(\mu^\pm)\overset{(-)}{\nu}$(≈30%)

TEST OF $P_{\mu\mu}$ ANOMALY AND $|\Delta m_{ATM}|$



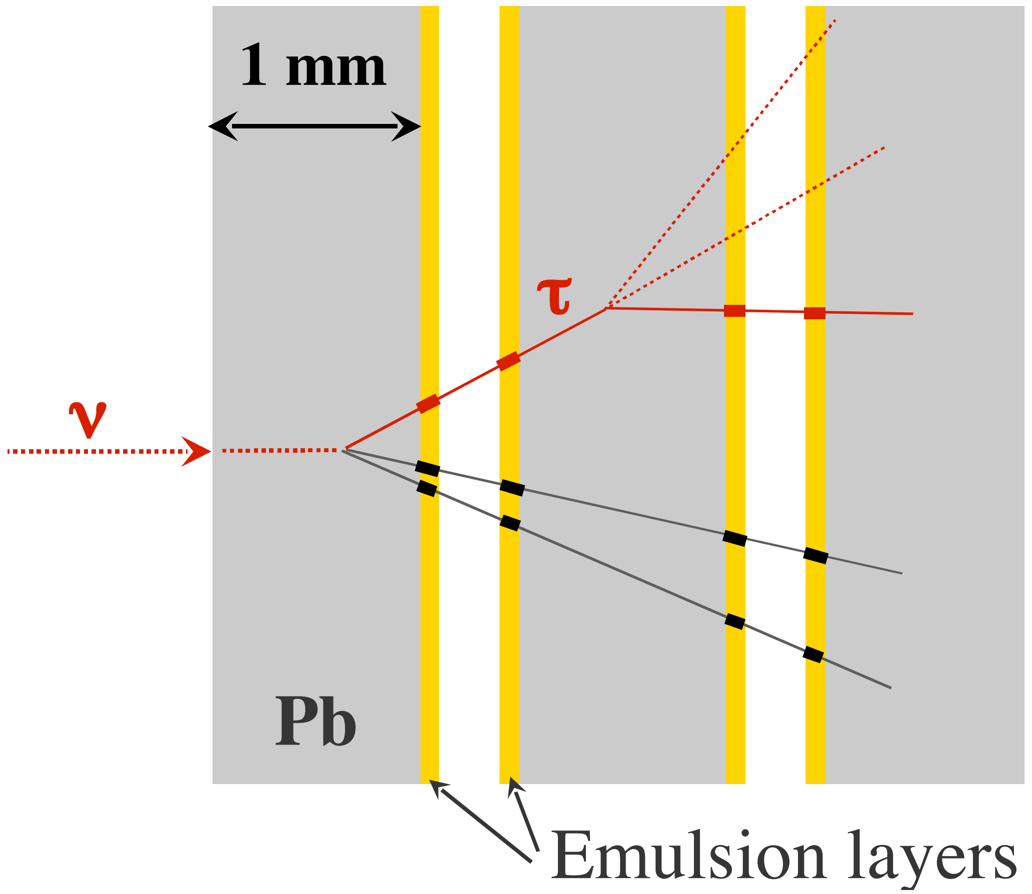
exp:3564
seen 2894

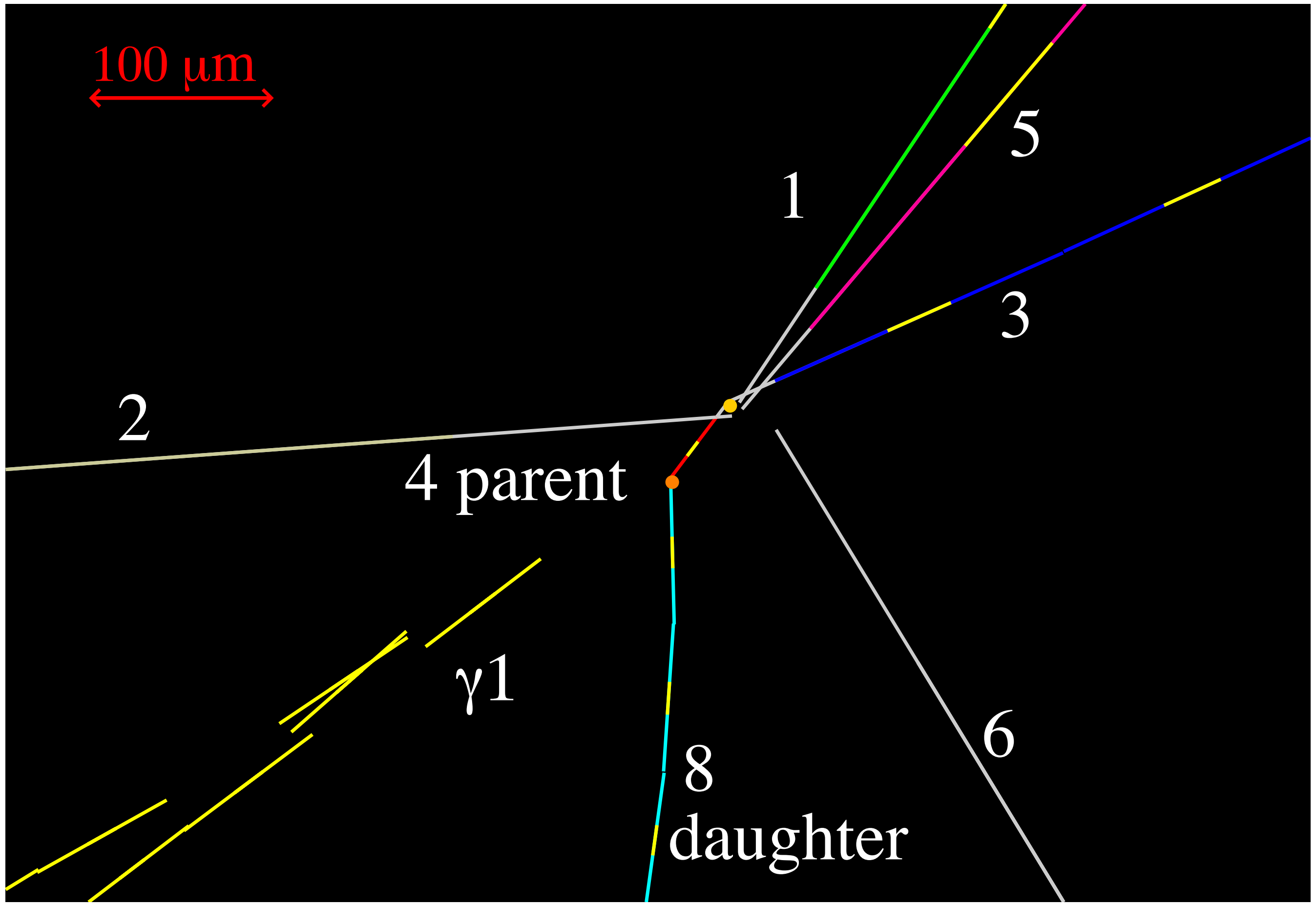
- Pulsed ν_μ beam
  - Kamiokande: WC, pulsed beam used to discriminate against atmospheric ν
  - MINOS: magnetized calorimeter
- $\nu_\mu\, n \Rightarrow \mu^- p$ dominant reaction
  - E_ν reconstructed from E_μ and $\theta_{\mu\nu} \approx 1$ since ν source known
  - observe energy-dependent ν_μ deficit $|\Delta m^2_{atm}| \approx (2.38 \pm 0.15) 10^{-3}\ eV^2$

$\theta_{atm} \approx \theta_{23} \approx 45°$,
$|\Delta m^2_{13}| \approx |\Delta m^2_{23}| \approx |\Delta m^2_{atm}| \approx (2.38 \pm 0.15) \cdot 10^{-3}\ eV^2$

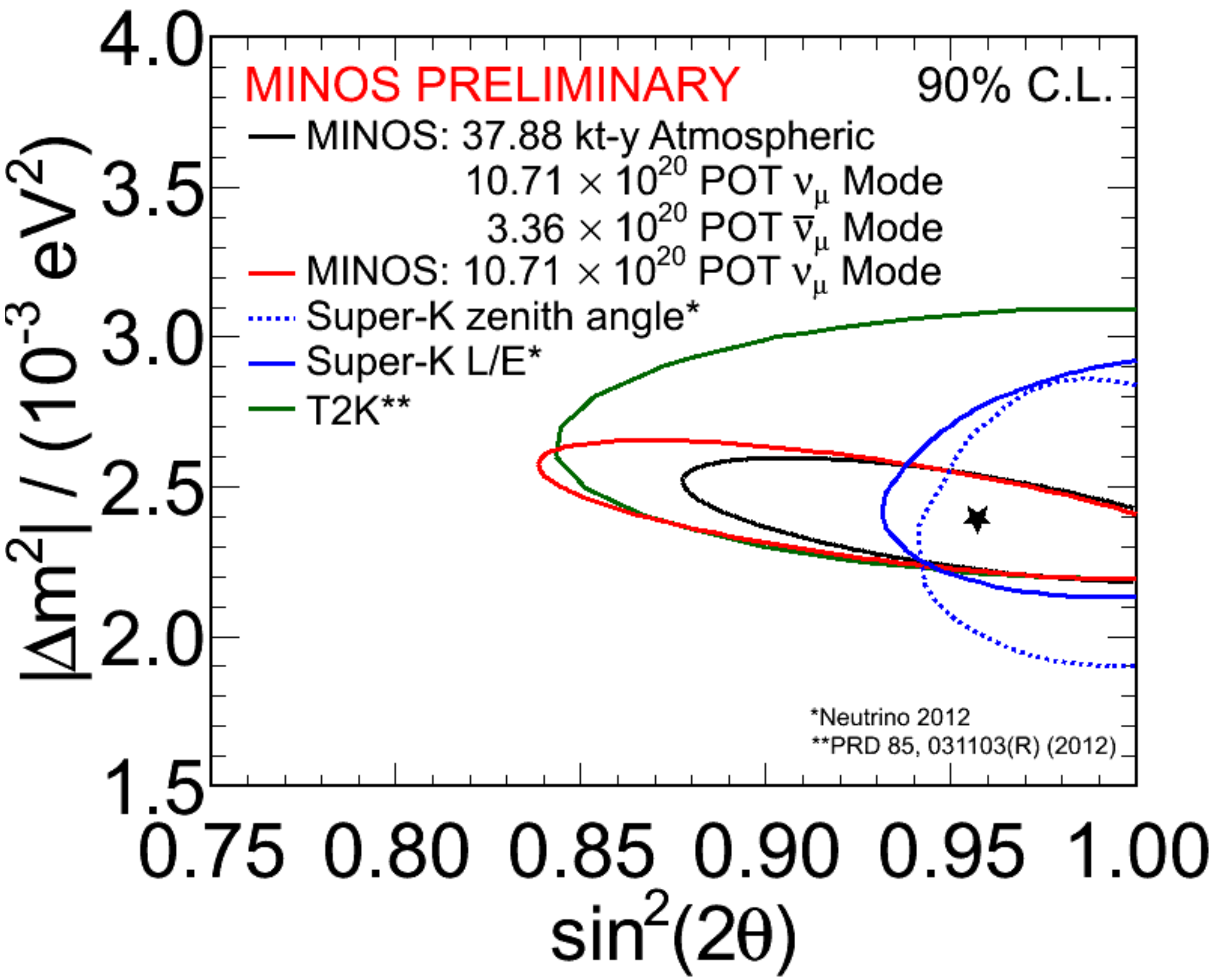
OPERA: $\nu_\mu \rightarrow \nu_\tau$

- Appearance of ν_τ $\nu_\tau N \rightarrow \tau^- N'$
  - Need O(kTon) target mass + high granularity detector (σ~μm) for τ detection ($c\tau$~87 μm) and bkgd rejection (mainly $\nu_\mu N \rightarrow c\mu X$)
  - Lead-nuclear emulsion
- ν_μ beam: CERN-LNGS: L≈750 km, $\langle E_\nu \rangle \approx$17GeV





Atmospheric Neutrino Summary



- Large Δm and large mixing angle observed

Oscillation searches sensitive to δm^2

EXPERIMENTS SENSITIVE TO δM^2 IN $\Delta M^2 \to \infty$

Previously we have considered experiments with sensitivity to Δm^2 in the limit $\delta m^2 \to 0$. At the other end of the spectrum, there are expts. with leading sensitivity to δm^2, for which one can take $\Delta m^2 \to \infty$:

$$\frac{\delta m^2 x}{4E} \sim \mathcal{O}(1) \quad \text{and} \quad \frac{\Delta m^2 x}{4E} \gg 1$$

This is the case, for instance, of long-baseline reactor experiments (KamLAND) with large x and relatively low E. At low $E \sim$ few MeV, the main observable is the disappearance probability P_{ee}. Prove that:

$$\boxed{P_{ee} \simeq \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\delta m^2 x}{4E}\right)\right] + \sin^4\theta_{13}}$$

(which does not depend on hierarchy, $\nu/\bar{\nu}$, $\cancel{CP}$)

Namely, the 3ν probability (for $\theta_{13} \neq 0$) is related to the 2ν probability (at $\theta_{13} = 0$) by the relation:

$$\boxed{P^{3\nu}_{ee} = \cos^4\theta_{13}\, P^{2\nu}_{ee} + \sin^4\theta_{13}}$$

from E.Lisi "Neutrinos: theory and phenomenology"

EXPERIMENTS SENSITIVE TO δM^2 IN $\Delta M^2 \to \infty$

Important note: The Δm^2-averaged form for P_{ee},

$$P_{ee}^{3\nu} = c_{13}^4 \, P_{ee}^{2\nu}(\delta m^2, \theta_{12}) + s_{13}^4$$

holds not only for KamLAND, but also for solar neutrinos (proof omitted) where, however, $P_{ee}^{2\nu}$ takes a very different form due to matter effects in the Sun.

Therefore, via $P_{ee}^{3\nu}$, solar + KamLAND experiments allow to set constraints on δm^2 and on the 1st-row elements of the PMNS matrix (in absolute value):

$$|U| = \begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \leftarrow \text{functions of } \theta_{12}, \theta_{13}$$

Recap of leading sensitivity:

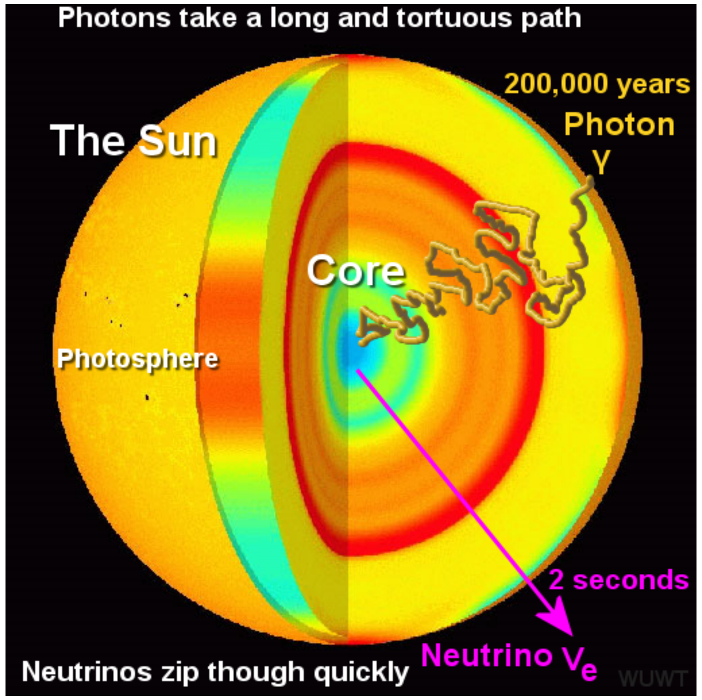
Solar + KamLAND	→	θ_{12}	θ_{13}	δm^2
ATM + LBL accel.	→	θ_{23}	θ_{13}	$\lvert\Delta m^2\rvert$
SBL reactors	→		θ_{13}	$\lvert\Delta m^2\rvert$

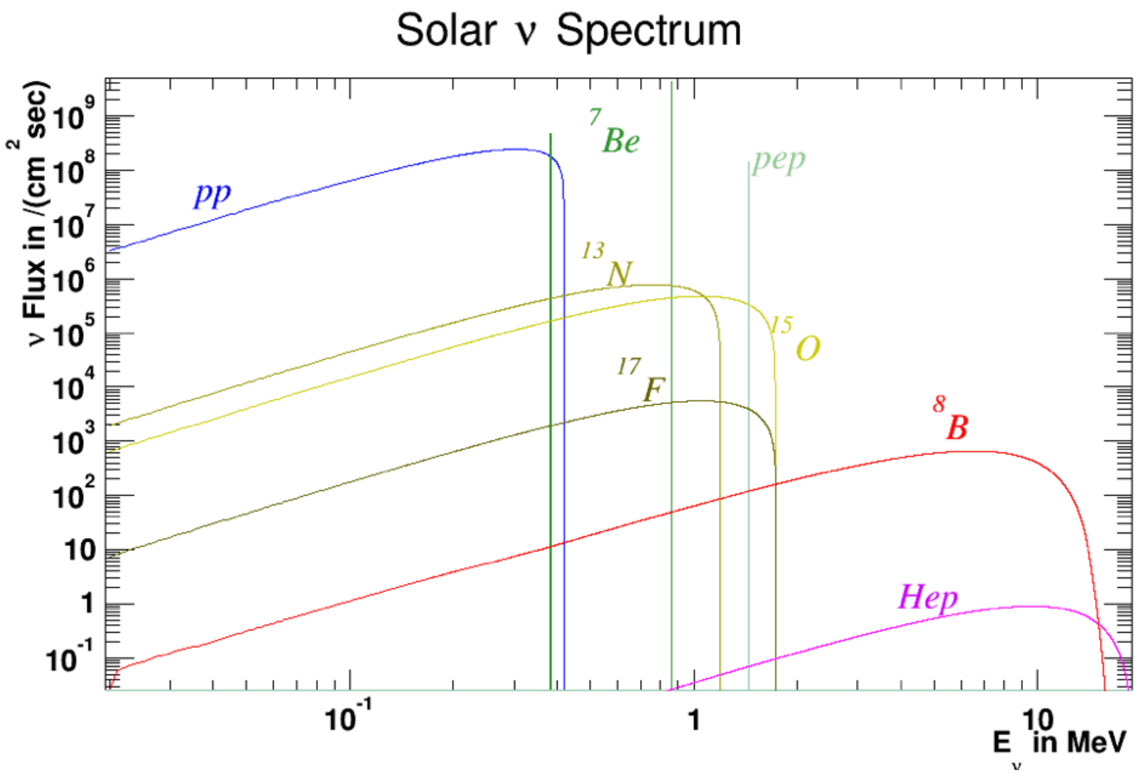
from E.Lisi "Neutrinos: theory and phenomenology"

SOLAR EVIDENCE

Solar Neutrinos

- Must account for neutrino propagation through matter
  - neutrinos produced in Sun core
  - electron neutrinos interact with matter
    - charged current t channel
- Mikheyev-Smirnov-Wolfenstein (MSW) effects
  - account for interaction with atoms in the Sun
  - electron neutrino continuously regenerated
  - neutrino cross section increases with neutrino energy in t-channel
    - energy << M_W in the propagator
  - matter effects increase with neutrino energy
- Matter effects small or negligible for very low energy neutrinos
- Matter effects significant for higher energy neutrinos from Sun
- Direct impact on observed oscillation amplitude and frequency





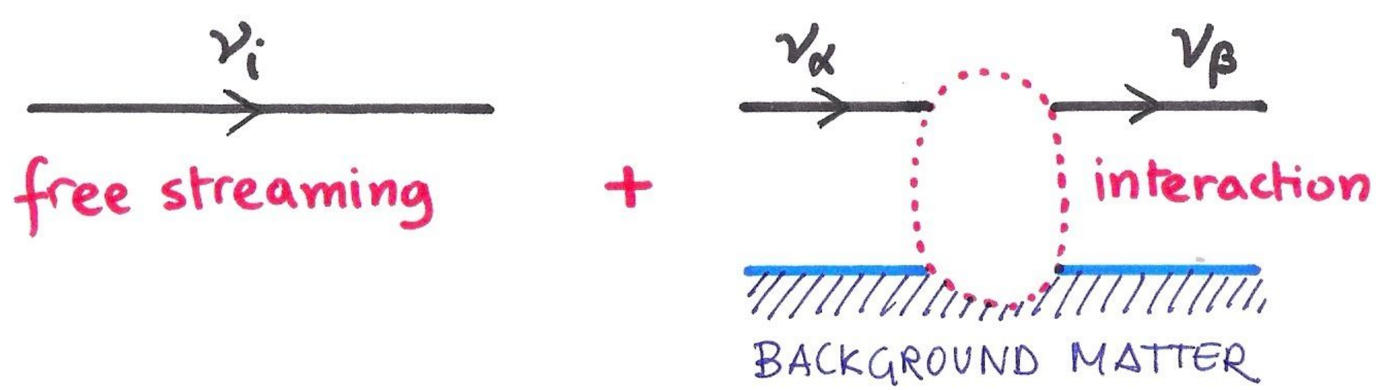
Neutrino oscillation in matter

- Matter effect analogous to light in medium (air, water): even if absorption negligible, matter effect can reduce v=c/n. In some materials (birefringence) n changed in a polarized dependent way

- Coherent forward scattering ⇒ flavour dependent refraction index $n=1+V/E_\nu$

- Flavour basis: $H=H_{VAC} + V$
  - $H_{VAC} = U H_{Mass} U^\dagger$
  - V = dynamical contribution to the forward scattering

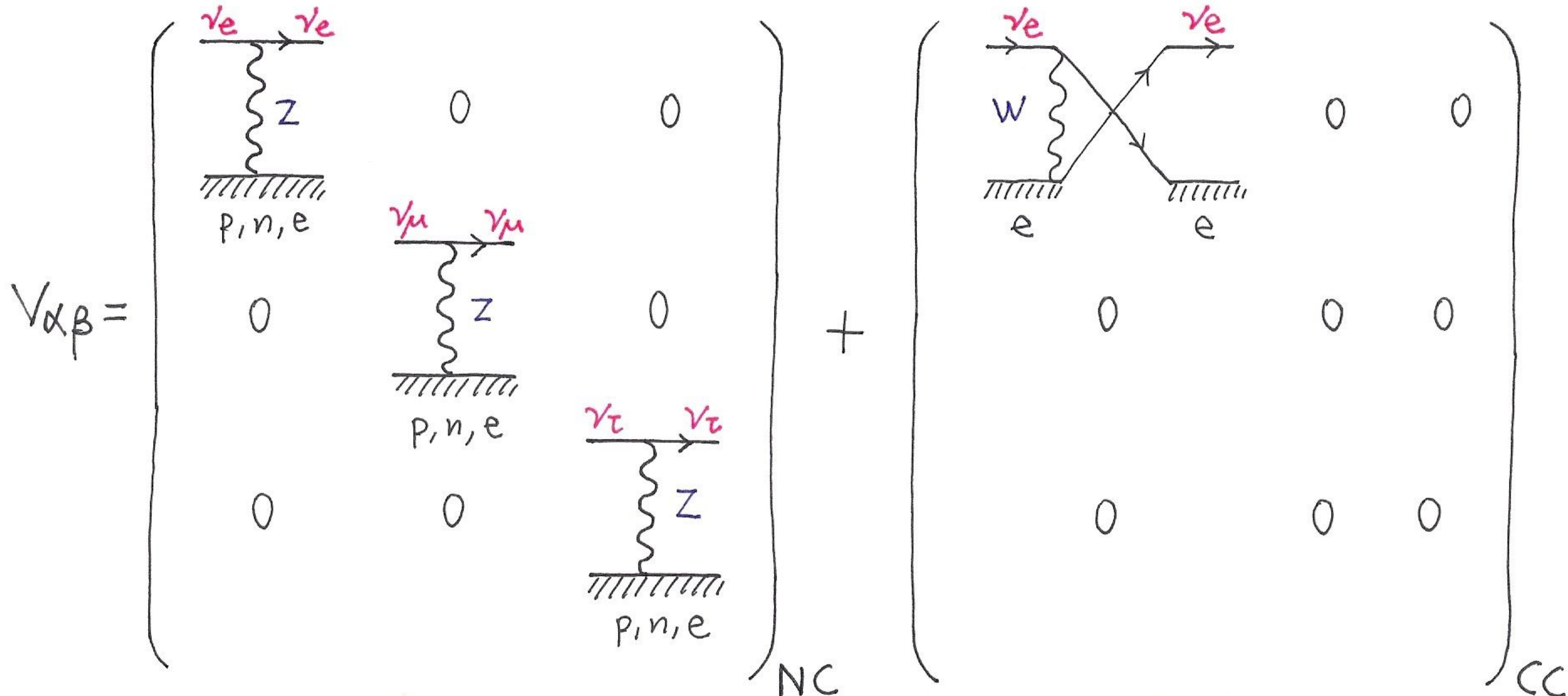
$$H_{flavor} = \underbrace{\frac{1}{2E} U \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U^\dagger}_{\text{VACUUM (KINEMATICS)}} + \underbrace{\begin{pmatrix} V_{ee} & V_{e\mu} & V_{e\tau} \\ V_{\mu e} & V_{\mu\mu} & V_{\mu\tau} \\ V_{\tau e} & V_{\tau\mu} & V_{\tau\tau} \end{pmatrix}}_{\text{MATTER (DYNAMICS)}}$$



from E.Lisi "Physics of Massive neutrinos"

NEUTRINO OSCILLATION IN MATTER

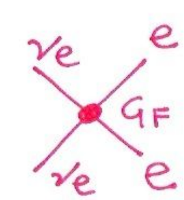
Within the Standard Model, and in ordinary matter:



proportional to unity and unobservable

observable in ν_e oscillations

Relevant term is the $\nu_e - \nu_{\mu,\tau}$ energy difference: $V_{CC} \simeq$



(No analogous for μ, τ, which are absent in ordinary matter)

from E.Lisi "Physics of Massive neutrinos"

NEUTRINO OSCILLATION IN MATTER

- It turns out that the V_{CC}^{ee} interaction energy is (see next page):

$$V = \sqrt{2}\, G_F N_e$$

where N_e = electron number density, and $V \to -V$ for $\nu \to \bar{\nu}$

- Then, the Hamiltonian of ν propagation in matter reads:

$$\boxed{H_{flavor} = \frac{1}{2E} U \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U^+ + \frac{1}{2E} \begin{pmatrix} A & & \\ & 0 & \\ & & 0 \end{pmatrix}}$$

where $A = 2\sqrt{2}\, G_F N_e E$

- The relative size of matter/vacuum terms is given by $A/\Delta m_{ij}^2$. Roughly speaking, one may expect sizable effects for $A/\Delta m_{ij}^2 \sim \mathcal{O}(1)$.

- The dependence $A = A(x)$ makes the evolution nontrivial in many cases.

$$\frac{A}{\Delta m_{ij}^2} = 1.526 \times 10^{-7} \left(\frac{N_e}{\mathrm{mol/cm^3}}\right)\left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{\mathrm{eV}^2}{\Delta m_{ij}^2}\right)$$

from E.Lisi "Neutrinos: theory and phenomenology"

2 ν OSCILLATION IN CONSTANT MATTER

$$P_{e\mu} = \sin^2 2\tilde{\theta}\,\sin^2\left(\frac{\Delta\tilde{m}^2 L}{4E}\right)$$ (tutorial)

$$\sin 2\tilde{\theta} = \frac{\sin 2\theta}{\sqrt{\left(\cos 2\theta - \frac{A}{\Delta m^2}\right)^2 + \sin^2 2\theta}}$$

"Breit-Wigner" resonance form

$$\frac{\Delta\tilde{m}^2}{\Delta m^2} = \frac{\sin 2\theta}{\sin 2\tilde{\theta}}$$

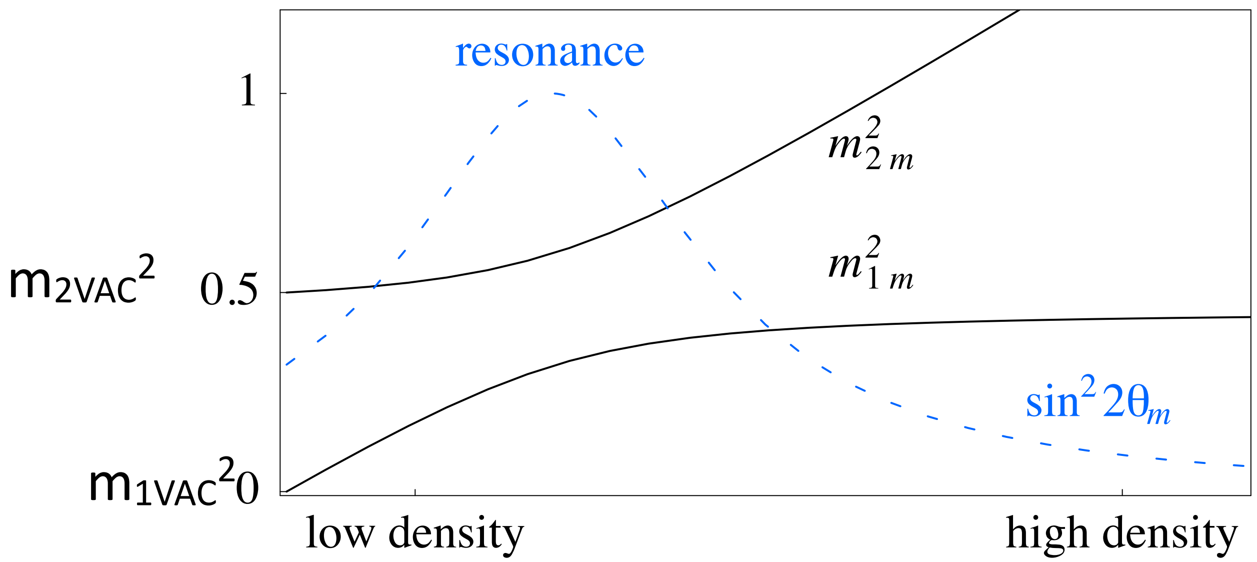
Can get a MSW resonant behavior for $c_{2\theta} \sim A/\Delta m^2$

$\rightarrow \Delta m^2 c_{2\theta} = 2\sqrt{2} G_F N_e E$

$\rightarrow \sin^2 2\tilde{\theta} \sim 1$ (enhanc.)

$\rightarrow \Delta\tilde{m}^2$ minimized

Can get suppression for $A \gg \Delta m^2 \rightarrow \sin^2 2\tilde{\theta} \sim 0$



Limiting cases:

$A/\delta m^2 \ll 1$: $(\delta\tilde{m}^2, \tilde{\theta}) \simeq (\delta m^2, \theta)$ ← vacuum-like

$A/\delta m^2 \simeq \cos 2\theta$: $(\delta\tilde{m}^2, \tilde{\theta}) \simeq (\delta m^2 \sin 2\theta, \pi/4)$ ← reson.

$A/\delta m^2 \gg 1$: $(\delta\tilde{m}^2, \tilde{\theta}) \simeq (A, \pi/2)$ ← matter dominance

- A(ν) = -A ($\bar{\nu}$) ⇒ asymmetry between neutrinos and antineutrinos: no resonance
- Matter effect distinguishes between θ ⇔ π/2-θ, Δm^2 ⇔ $-\Delta m^2$ and change energy dependence
- Oscillation suppressed when matter dominates: independent $\lambda_{MAT} = \pi/\sqrt{2}(G_F N_e) \approx 3000$ km in the earth mantle
- Matter effect important when $\lambda_{MAT} \approx \lambda_{VAC}$

from E.Lisi "Physics of Massive neutrinos"

MATTER EFFECT IN SLOW VARYING DENSITY

It turns out that, for the $(\delta m^2, \theta_{12})$ values chosen by nature, the adiabatic approximation can be applied to solar ν_e. In this case, $\tilde{\theta}_{12}(x_f) = \theta_{12}$ (vacuum value at the exit from the Sun), while $\tilde{\theta}_{12}(x_i)$ must be evaluated at the production point x_i. Limiting cases:

E $\lesssim$ few MeV (vacuum dominance): $A/\delta m^2 \lesssim 1$ and $\tilde{\theta}_{12}(x_i) \simeq \theta_{12}$

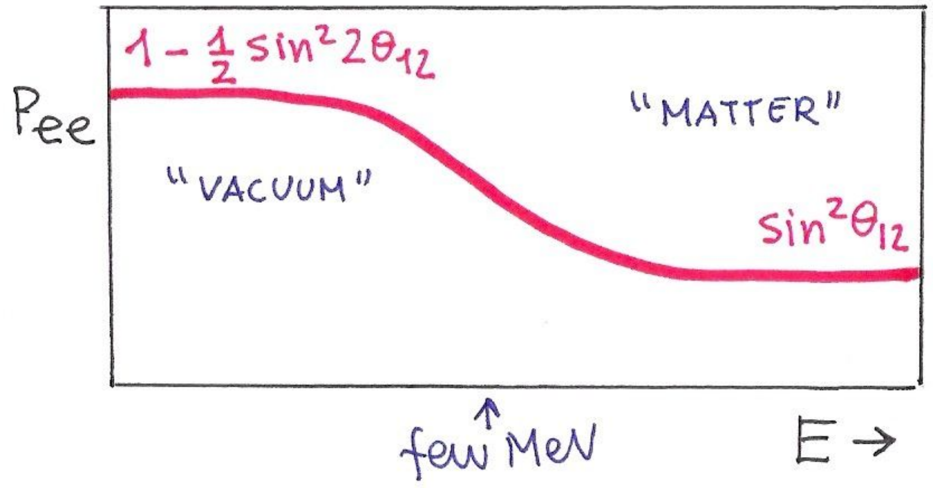
$P_{ee} \simeq c_{12}^4 + s_{12}^4 = 1 - \frac{1}{2}\sin^2 2\theta_{12}$

This is the averaged vacuum probability, octant symmetric.

E $\gtrsim$ few MeV (matter dominance): $A/\delta m^2 \gtrsim 1$ and $\tilde{\theta}_{12}(x_i) \sim \pi/2$

$P_{ee} \simeq \sin^2\theta_{12}$

This is the matter-dominated probability, octant-asymmetric



The Pee transition from "low" to "high" E is a signature of matter effects in the Sun.

Thanks to matter effects we can determine the octant of the mixing angle θ_{12}.

from E.Lisi "Neutrinos: theory and phenomenology"

NEUTRINOS FROM THE SUN

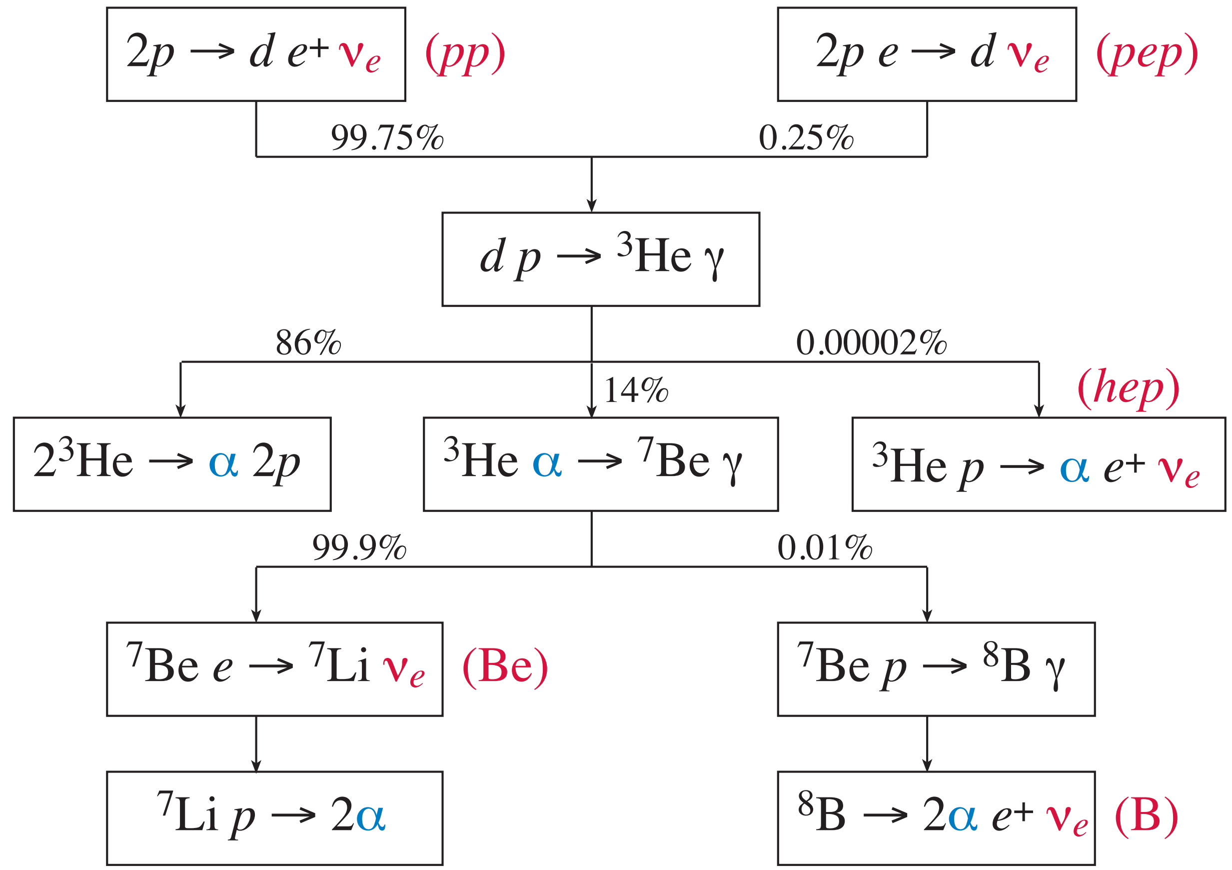
In the center of the sun

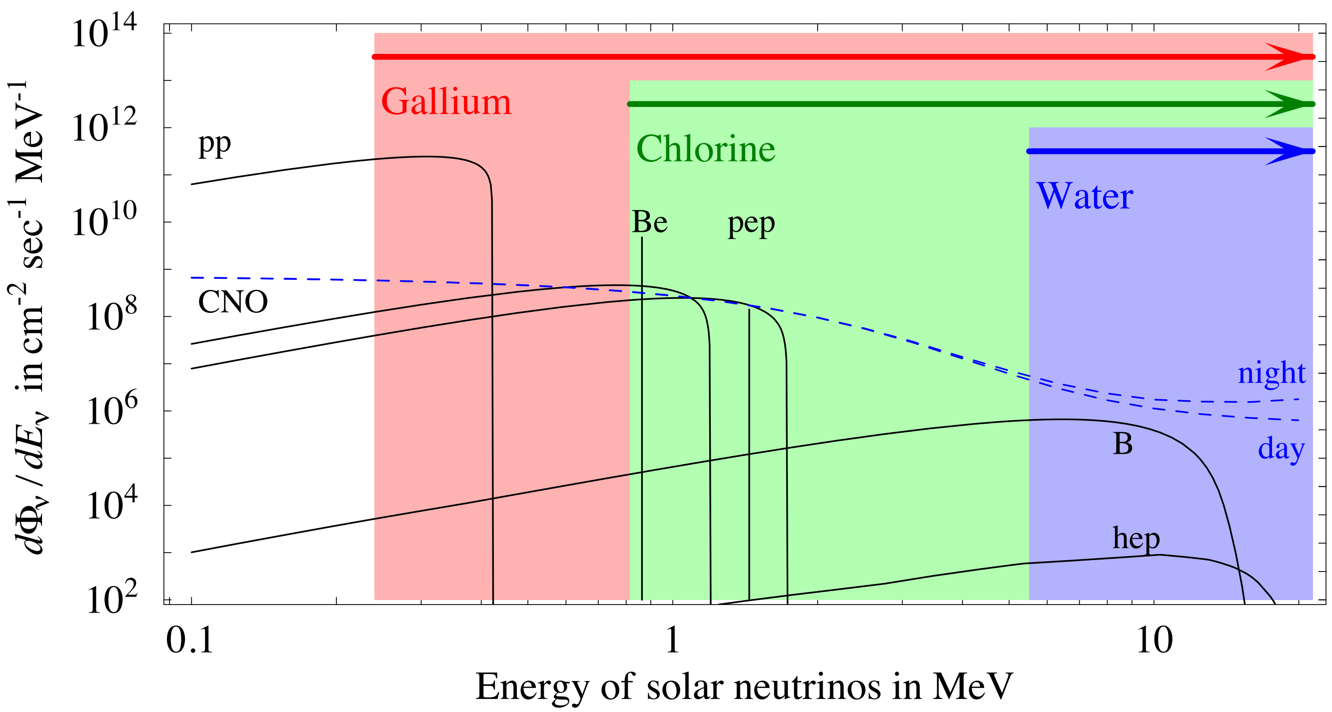
$4p + 2e^{-} \rightarrow {}^{4}He + 2\nu_e$

Q=26.73 MeV

$<E_\nu> \approx 0.3$MeV

Solar $\Phi(\nu) \approx 6 \cdot 10^{10}\ \nu/cm^2s$





Radio Chemical exp:

-Homestake: $\nu\, {}^{71}Ga \rightarrow e^{-}\, {}^{71}Ge$

-Gallex: $\nu\, {}^{37}CL \rightarrow e^{-}\, {}^{37}Ar$

Real Time Water Čerenkov exp:

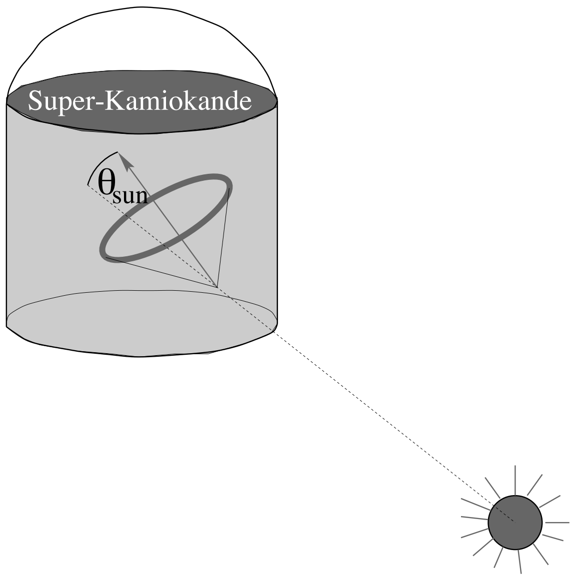
-SuperKamiokande: ES $\nu_{e,\mu,\tau} e \rightarrow \nu_{e,\mu,\tau} e$

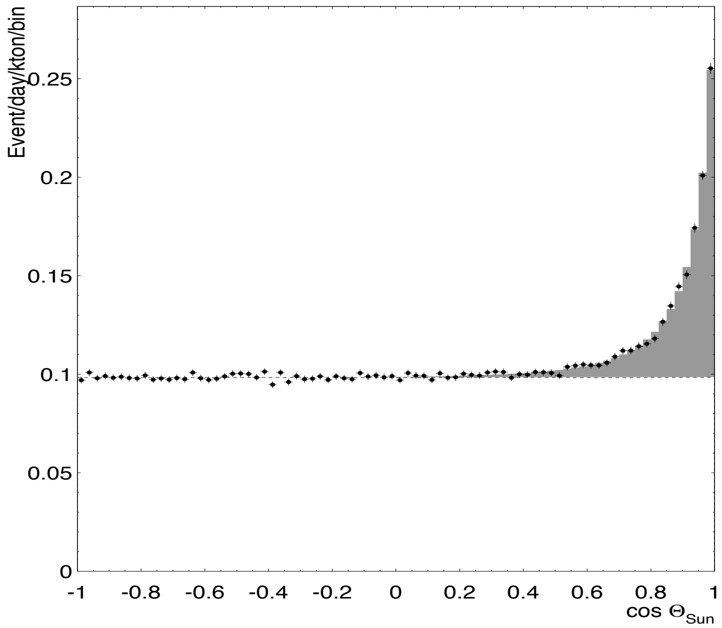
-SNO:ES+CC+NC

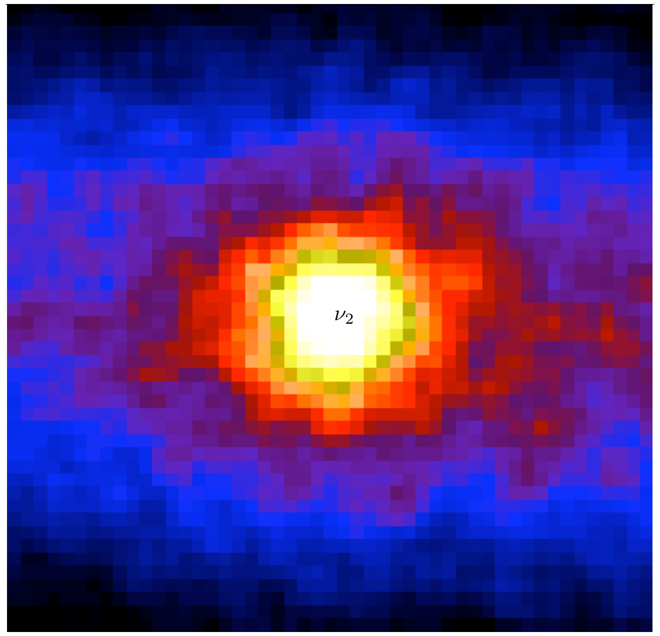
Real Time scintillator exp:

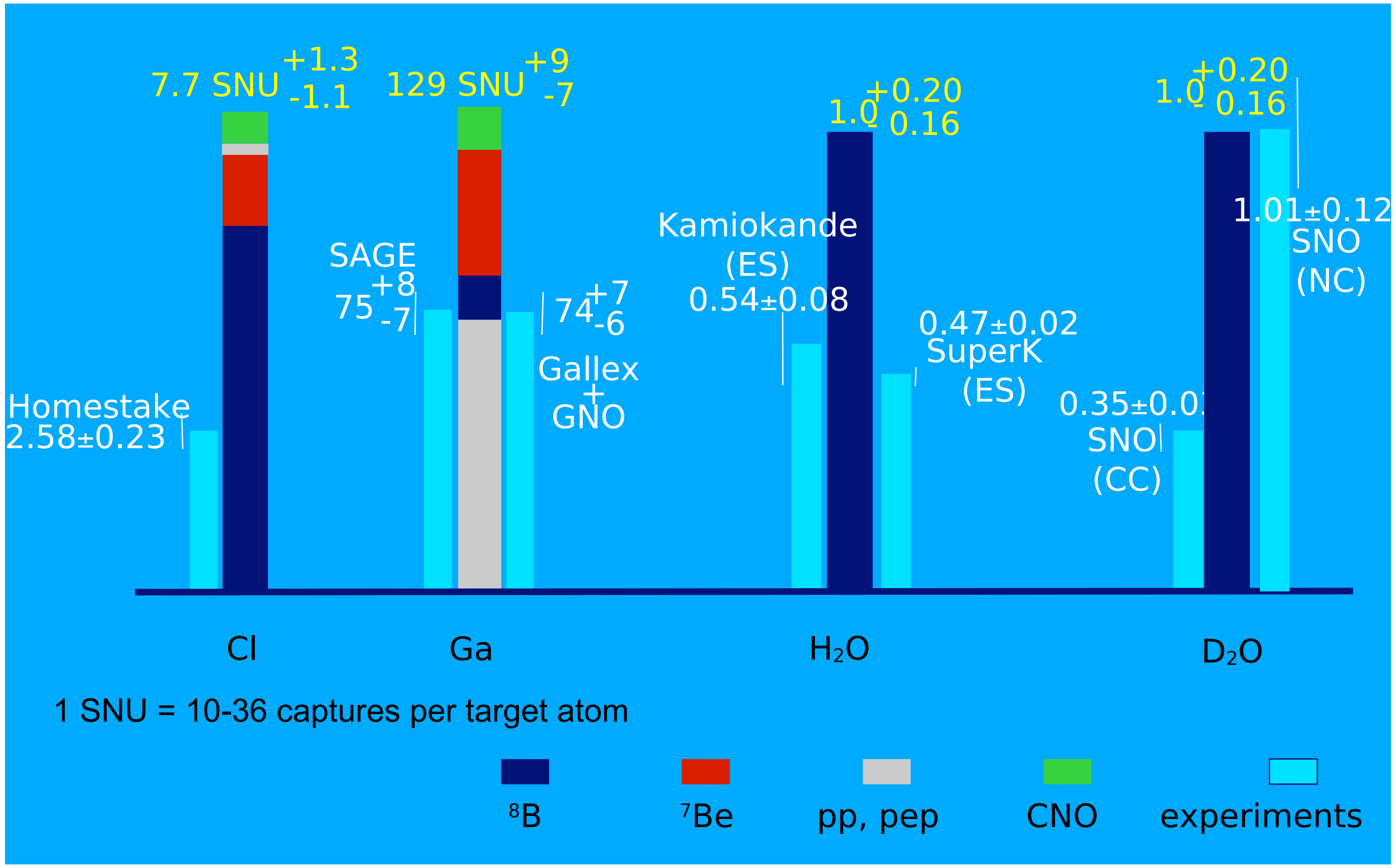
Borexino: ES $\nu_{e,\mu,\tau} e \rightarrow \nu_{e,\mu,\tau} e$

MEASURED NEUTRINO FLUX





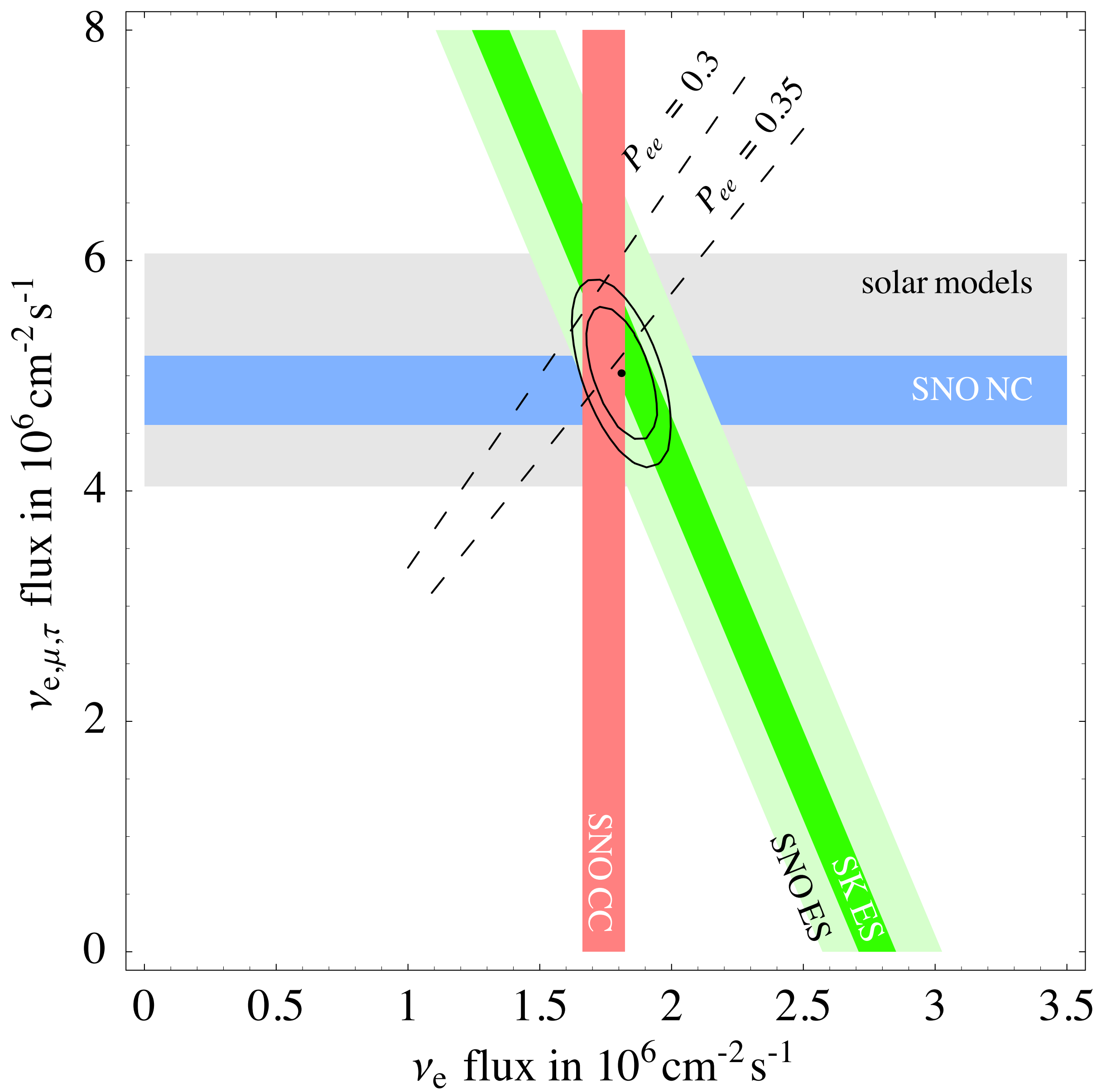




SNO: TOTAL FLUX MEASUREMENT

- D_2O Čerenkov detector:
  - ES: $\nu_{e,\mu,\tau} + e \longrightarrow \nu_{e,\mu,\tau} + e$ $\Rightarrow \Phi(\nu_e) + 0.155\,\Phi(\nu_{\mu,\tau})$
  - CC: $\nu_e + D \longrightarrow e^- + p + p$ $\Rightarrow \Phi(\nu_e)$
  - NC: $\nu + D \longrightarrow \nu + p + n$ $\Rightarrow \Phi(\nu_{e,\mu,\tau})$
- NC rate as expected from Solar Model
- ES rate consistent with SK
- CC rate:

$$\frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_{\mu,\tau})} = 0.357 \pm 0.030$$

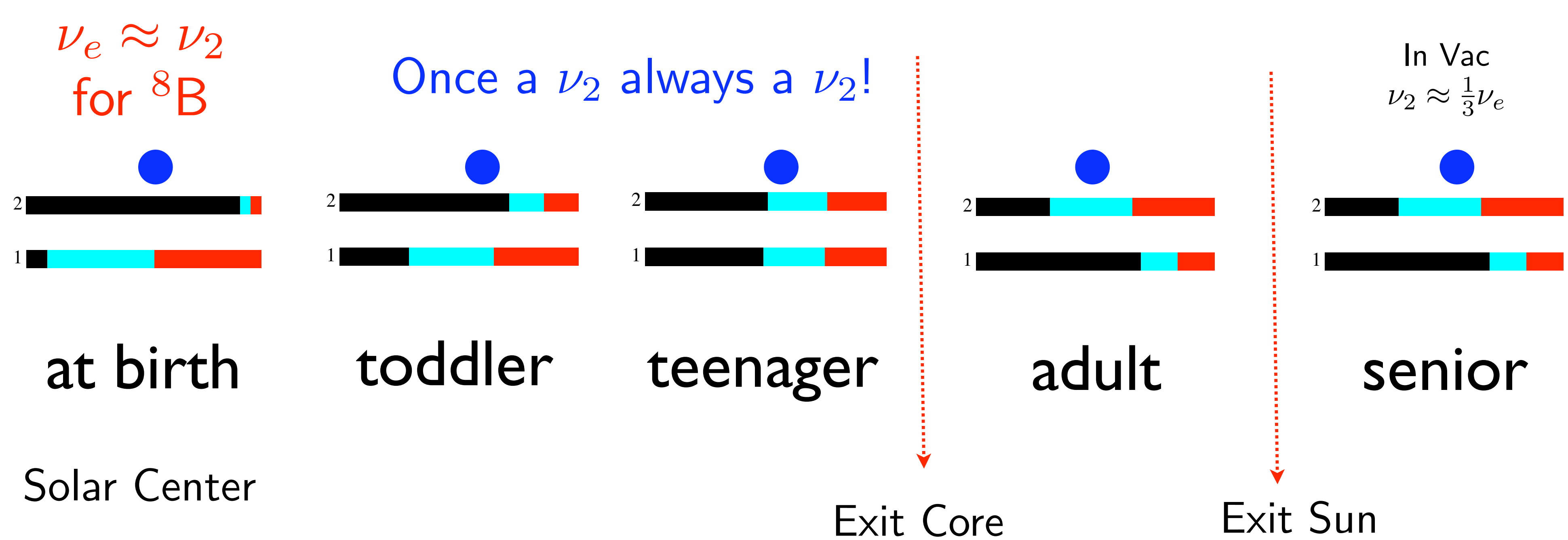


- $P_{ee}<0.5$ can't be vacuum oscillation!
  - Averaged oscillations $|\Delta m^2_{12}| \approx 7.58 \cdot 10^{-5}\ eV^2$, $L \approx 150 \cdot 10^6$ km
    - $P_{ee} = 1 - 0.5 \cdot \sin^2(2\theta_{sun}) > 0.5$

MATTER EFFECT

- At the center of the sun $V_W=0.75 \cdot 10^{-5} eV^2/MeV$ $\Rightarrow A/\Delta m^2=E/3MeV$
  - For pp ν_e's (E≈0.2 MeV) H_{Vac} dominates ⇒Average osc. $P_{ee}= 1-0.5 \cdot \sin^2(2\theta_{sun})$ ⇒ *no Δm sensitivity*
  - For ^8B ν_e's (E≈8 MeV) H_M dominates⇒ H_{Tot} diagonal⇒ ν_e heavier mass eigenstate $\nu_{2(}V>0)$
    - ^8B ν_e's propagate outward adiabatically

- At the exit of the core: $\nu_2 = \nu_e \sin(\theta_{sun}) + \nu_X \cos(\theta_{sun})$ ⇒ $P_{ee}= \sin^2(\theta_{sun})$

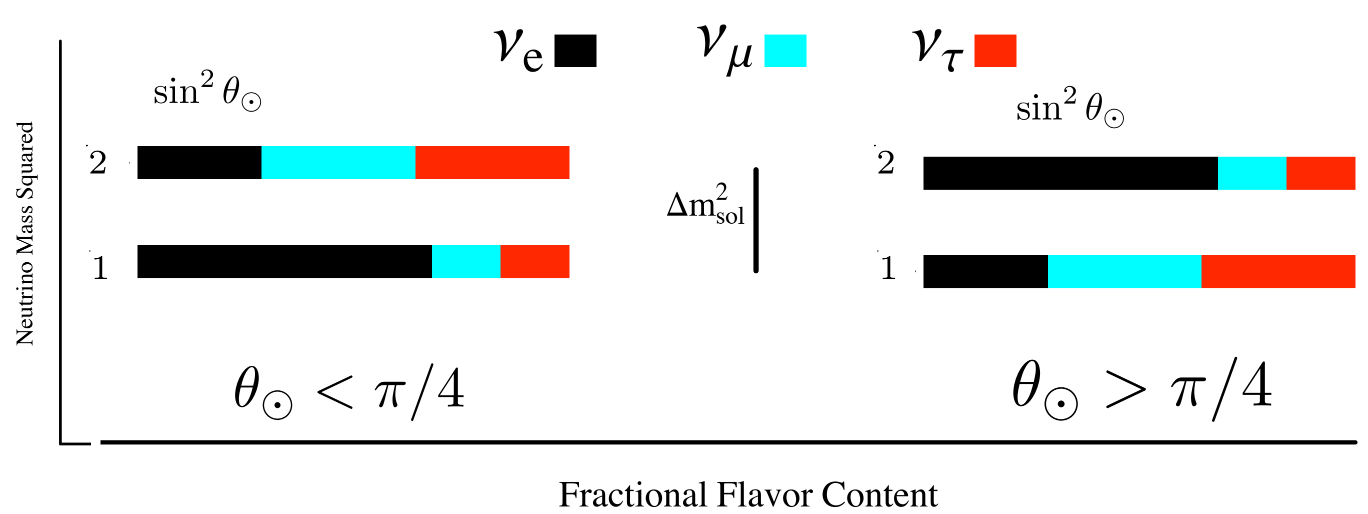


Large Mixing Angle + MSW

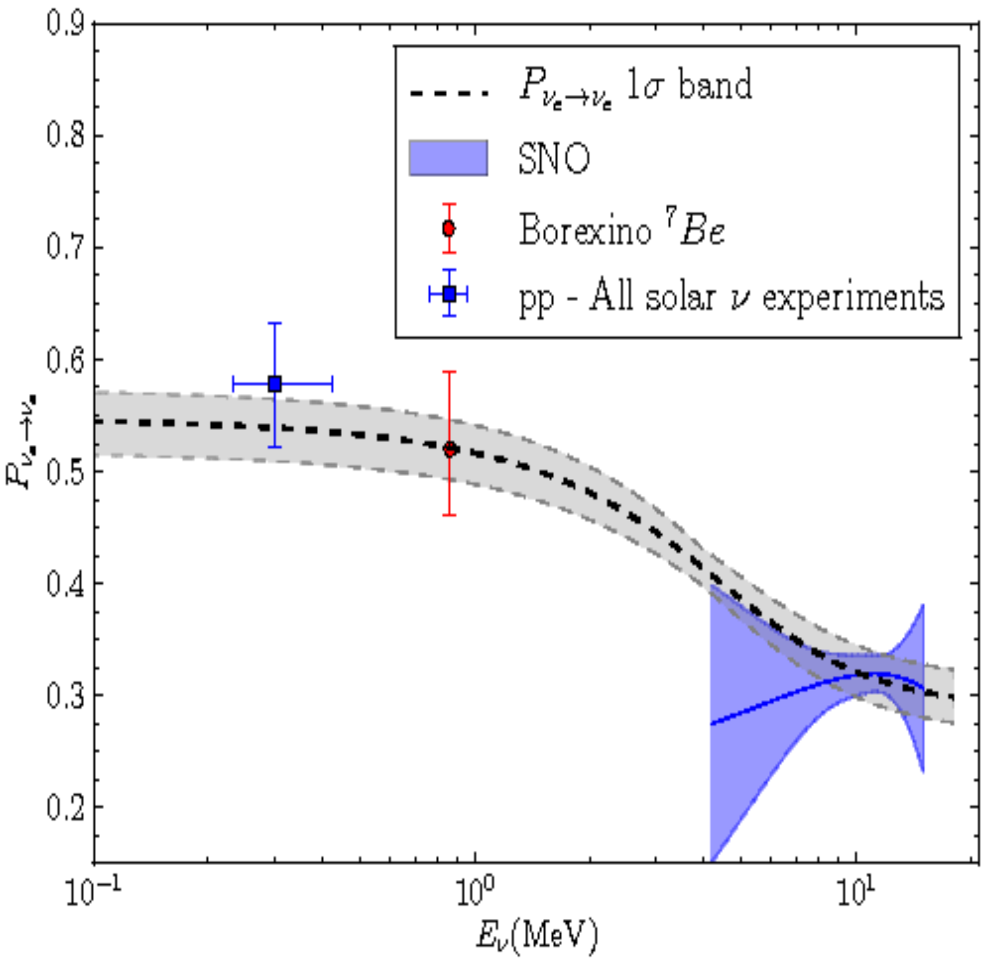
- Theory: $P_{ee}= 1.15 \cdot \sin^2(\theta_{sun})$
- Result: $P_{ee}=0.357\pm0.030$

  $\Rightarrow \tan^2(\theta_{sun})=0.45\pm0.05$, $\theta_{sun}\approx30°$

- Octant and mass hierarchy resolved



The overall picture

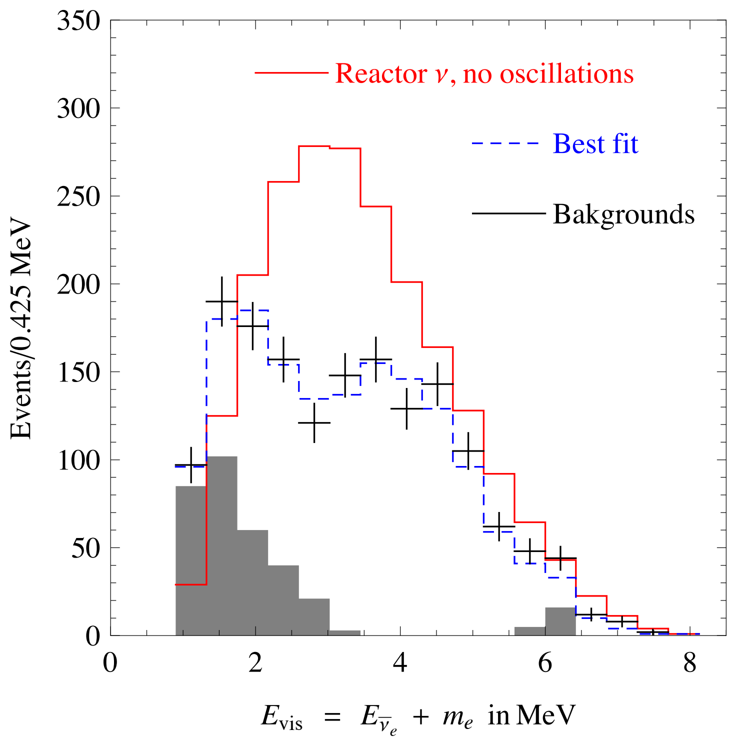


REACTOR EVIDENCE

- Solar ν_e disappearance: first signal of neutrino anomaly
  - $\vartheta_{13} \sim 9°$ ⇒ ν_3 couples feebly to electrons: solar neutrino born ν_e, they are a mixture of ν_1 and ν_2
  - Solar neutrino flavour change is $\nu_e \Rightarrow \nu_X$ where ν_X combination of ν_μ and ν_τ (look same below CC E^{th})
  - 2 neutrino system: $\theta_{sun} \approx \theta_{12}$, $\Delta m_{sun}^2 \approx \Delta m_{12}^2$

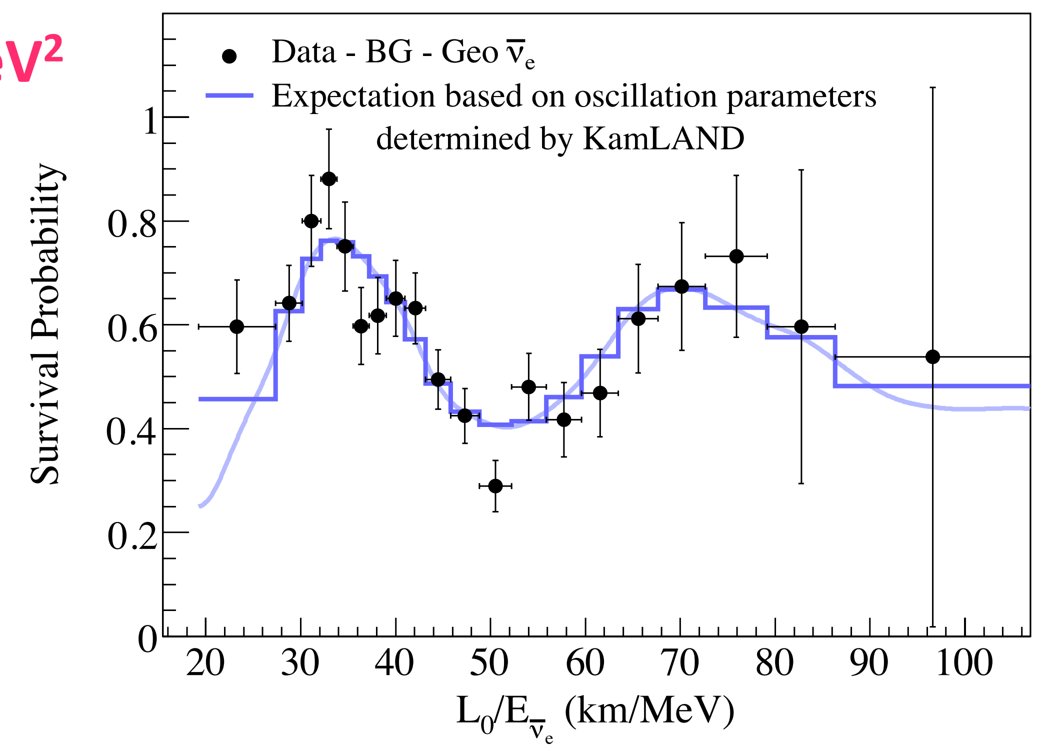
- Reactors: $E_\nu \approx$MeV, L≈180km
  - Atmospheric and matter effect negligible ($|x| \sim E/10GeV$)

$$P[\bar{\nu}_e \to \bar{\nu}_e] = cos^4(\theta_{13})(1 - sin^2(2\theta_{12})sin^2(\Delta m_{12}^2 L/4E))$$



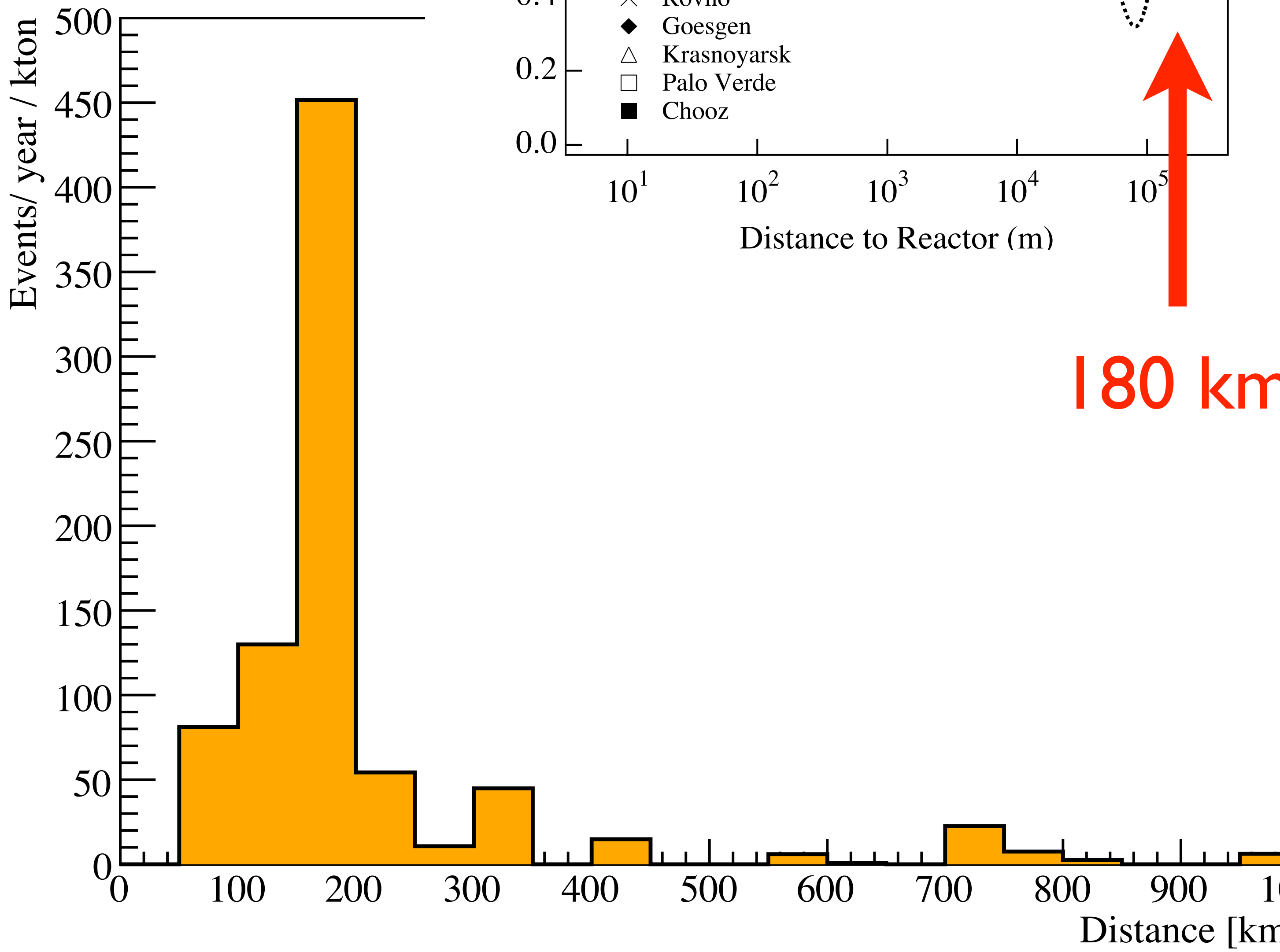
$|\Delta m^2_{12}| \approx (7.58 \pm 0.21) \cdot 10^{-5}$ eV^2

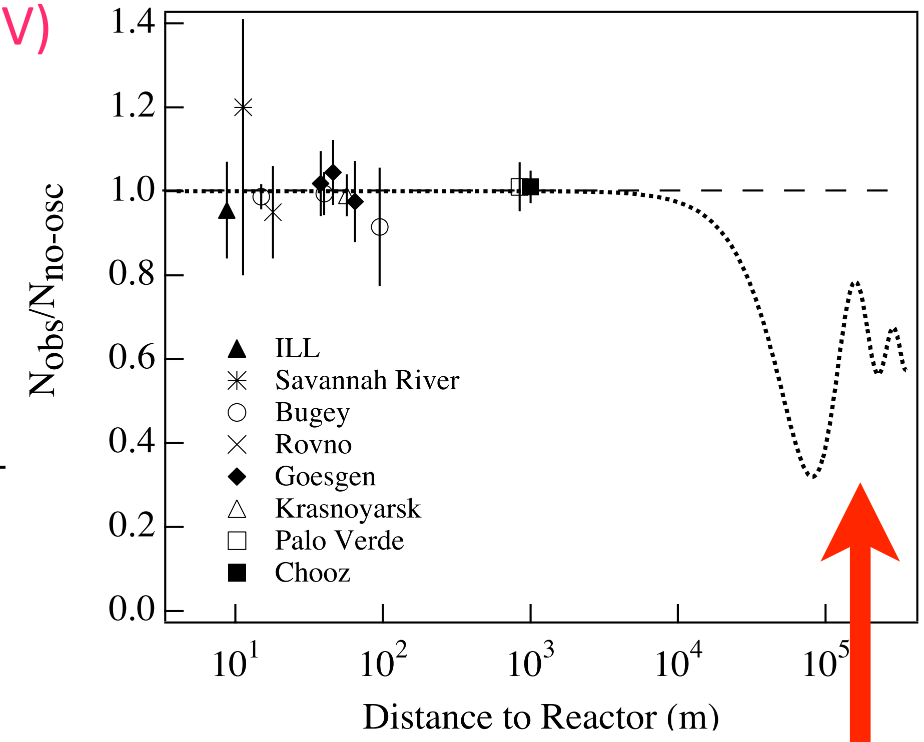
No distinction between
$\theta \Leftrightarrow \pi/2-\theta$, $\Delta m^2 \Leftrightarrow -\Delta m^2$



REACTOR CONFIRMATION: KAMLAND

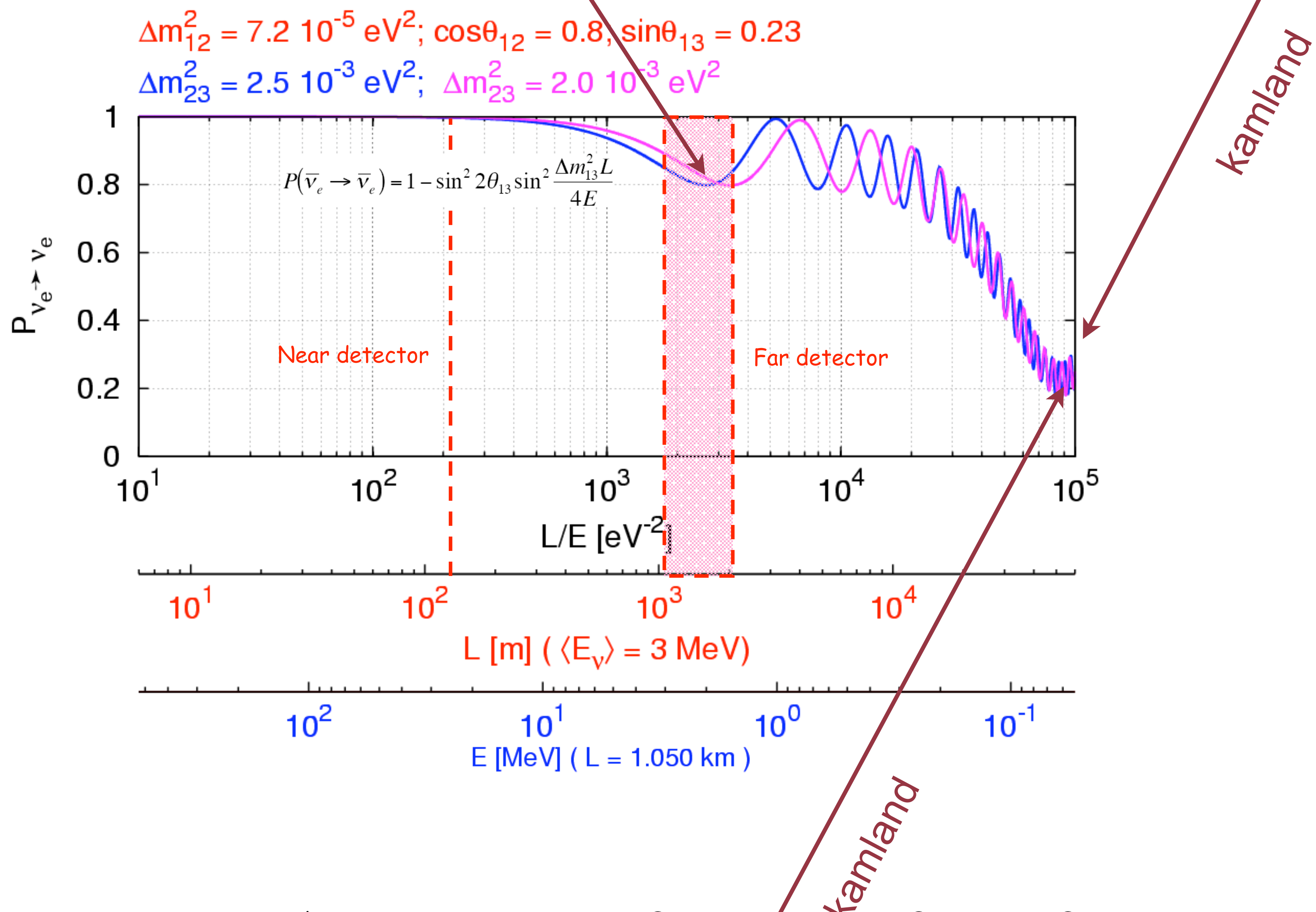
- Reactors: $E_\nu \approx$ MeV, $L \approx 180$ km
  - Atmospheric and matter effect negligible ($A/\Delta m^2 = E/10$ GeV)





REMINDER

$$P[\nu_e \rightarrow \nu_e] = 1 - sin^2(2\theta_{13})sin^2\Delta_{atm} - cos^4(\theta_{13})sin^2(2\theta_{sun})sin^2\Delta_{sun}$$



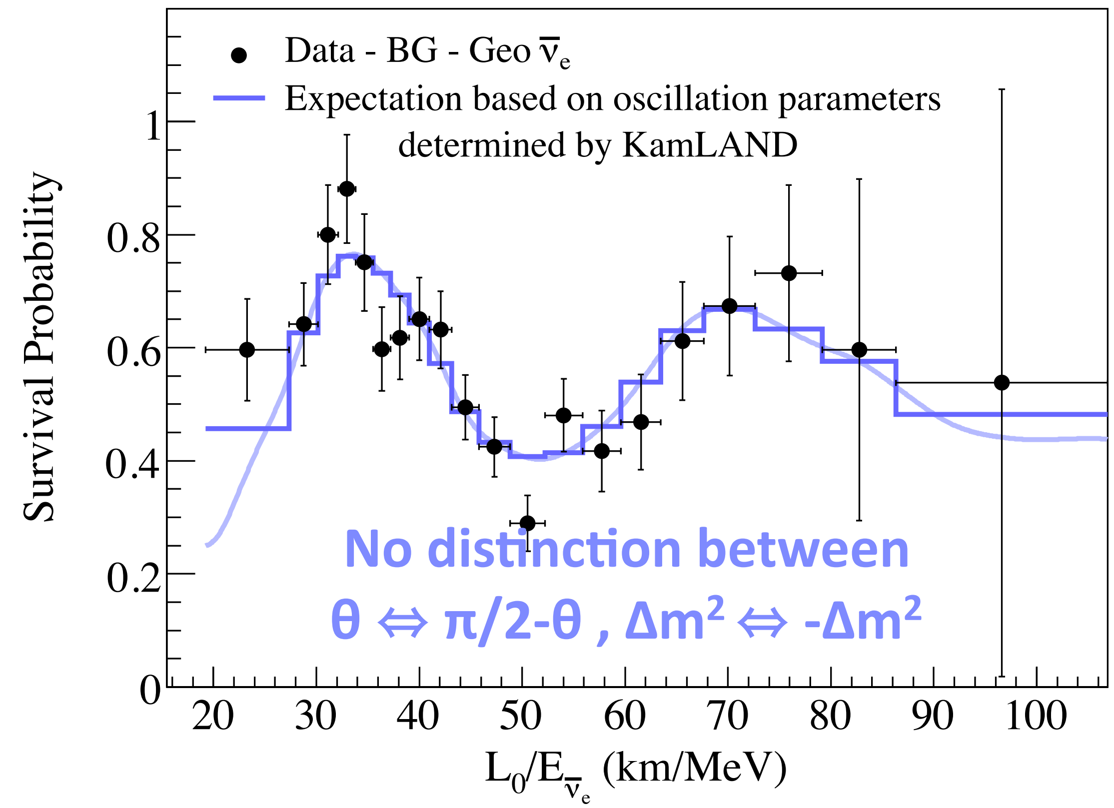
$$P[\bar{\nu}_e \rightarrow \bar{\nu}_e] = cos^4(\theta_{13})(1 - sin^2(2\theta_{12})sin^2(\Delta m^2_{12}L/4E))$$

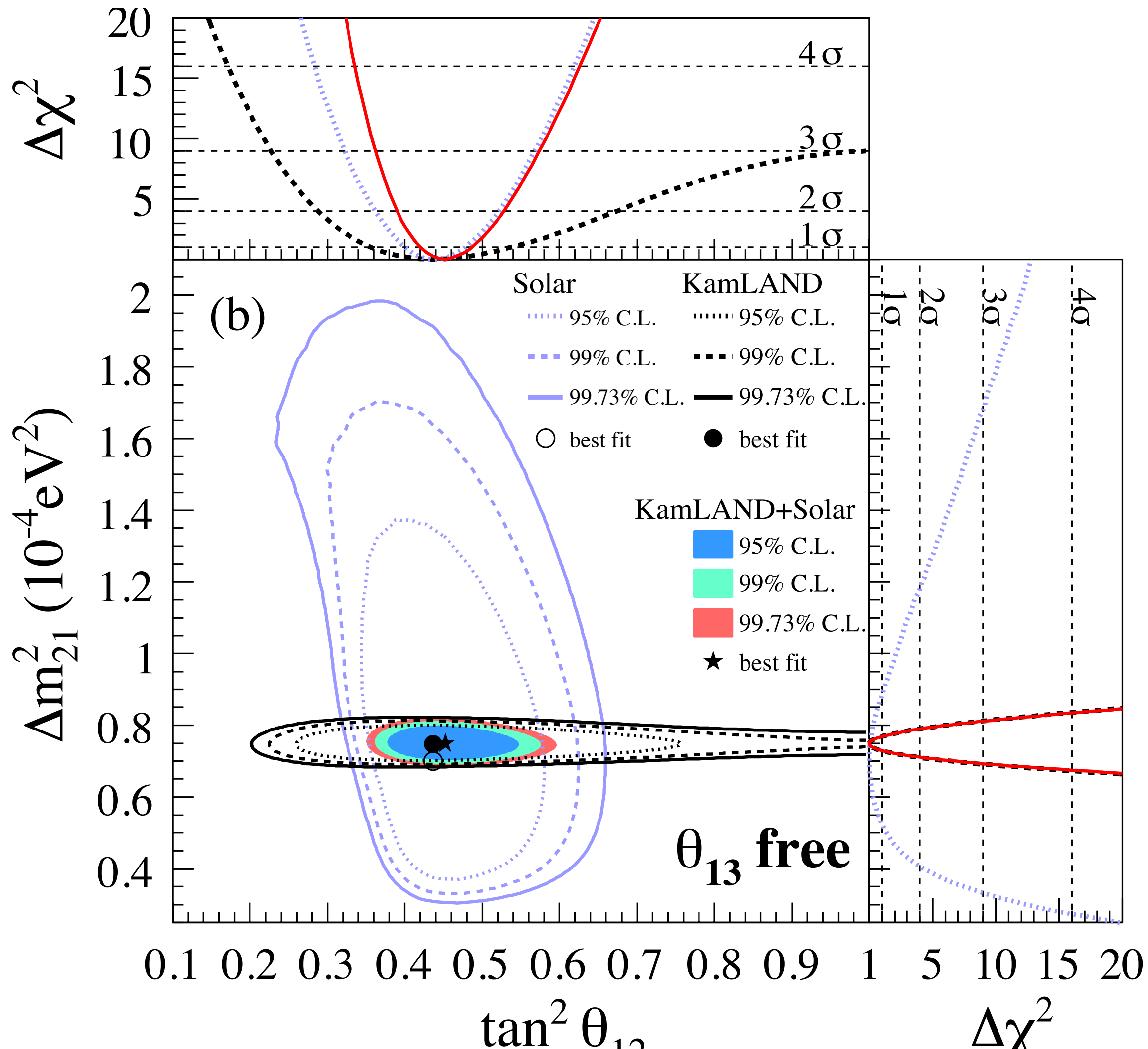
Big effect: ν source knowledge not critical

RESULTS

One period of oscillation observed

$$P[\bar{\nu}_e \rightarrow \bar{\nu}_e] = cos^4(\theta_{13})(1 - sin^2(2\theta_{12})sin^2(\Delta m^2_{12}L/4E))$$





In the two neutrino framework

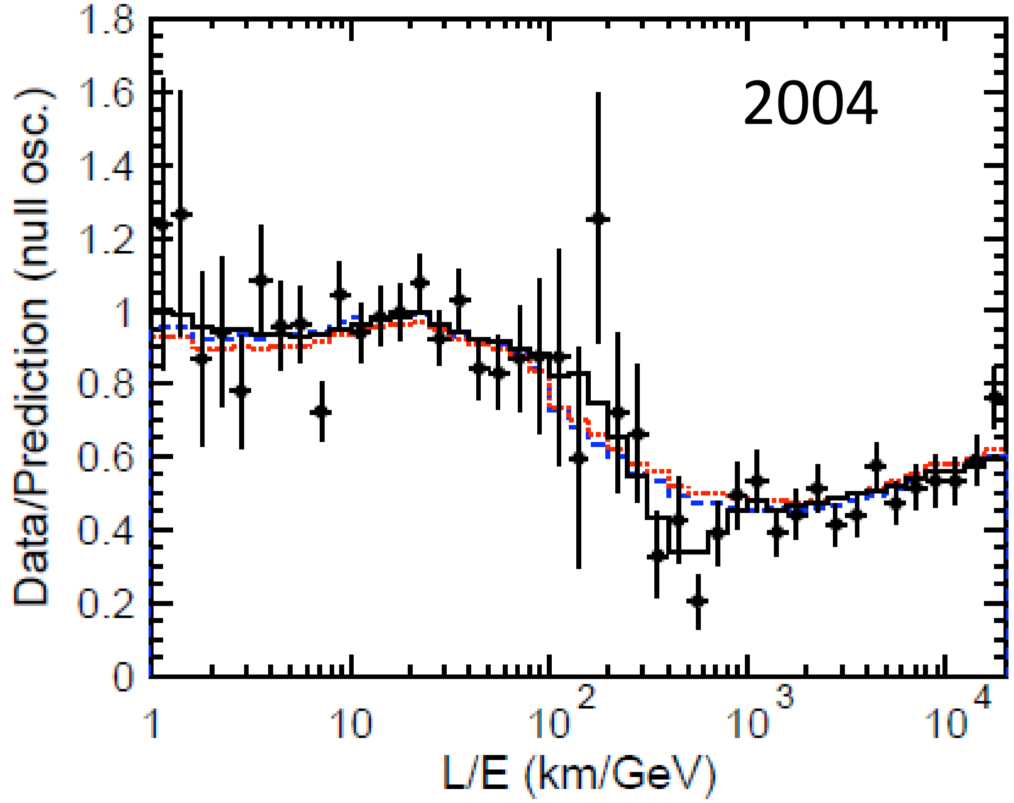
complementary of solar/reactor exp.

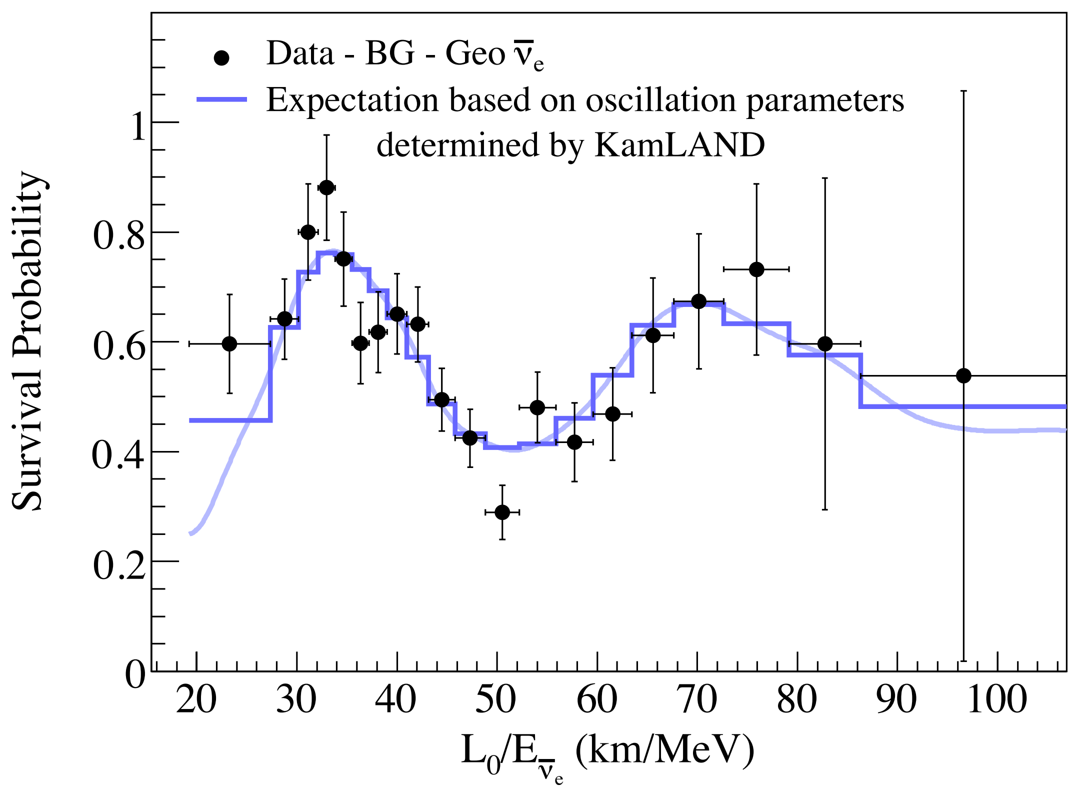
$|\Delta m^2_{12}| \approx (7.58 \pm 0.21) \cdot 10^{-5}\ eV^2$

SUMMARY: THE TURNING POINT

Atmospheric: $\Delta m^2 \sim 2.4\ 10^{-3}\ eV^2$

Solar: $\delta m^2 \sim 7.6\ 10^{-5}\ eV^2$





- One Mass scale dominance:
  - Only 3 parameters: $\Delta m^2, \vartheta_{23}, \vartheta_{13}$, $|U_{e3}| = \sin(\vartheta_{13})$, $|U_{\mu 3}| = \cos(\vartheta_{13}) \sin(\vartheta_{23})$
  - Experiment with $\Delta m^2 L/E = O(1)$ sensitive $|U_{e3}|$ (flavour content of ν_3)

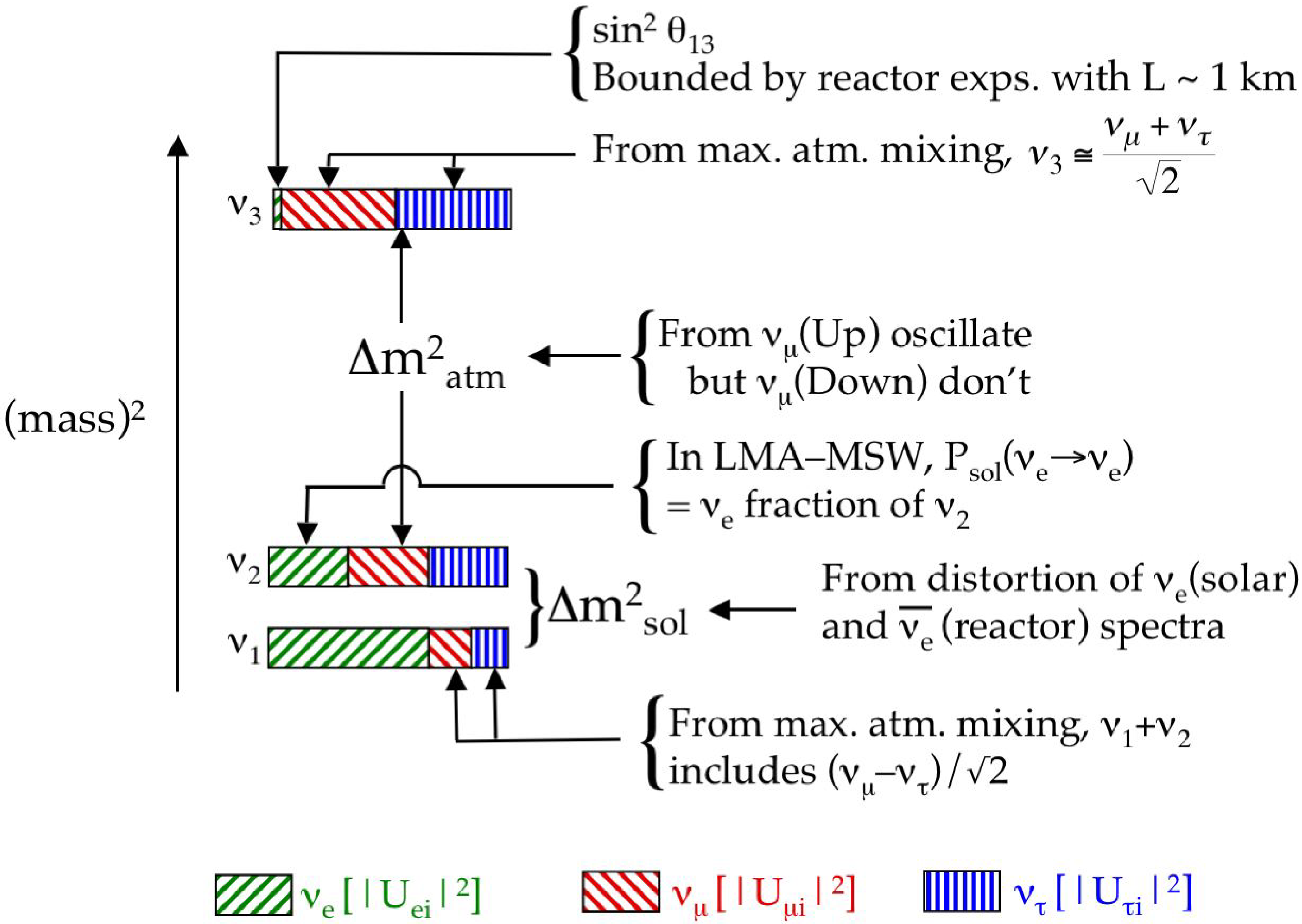
$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

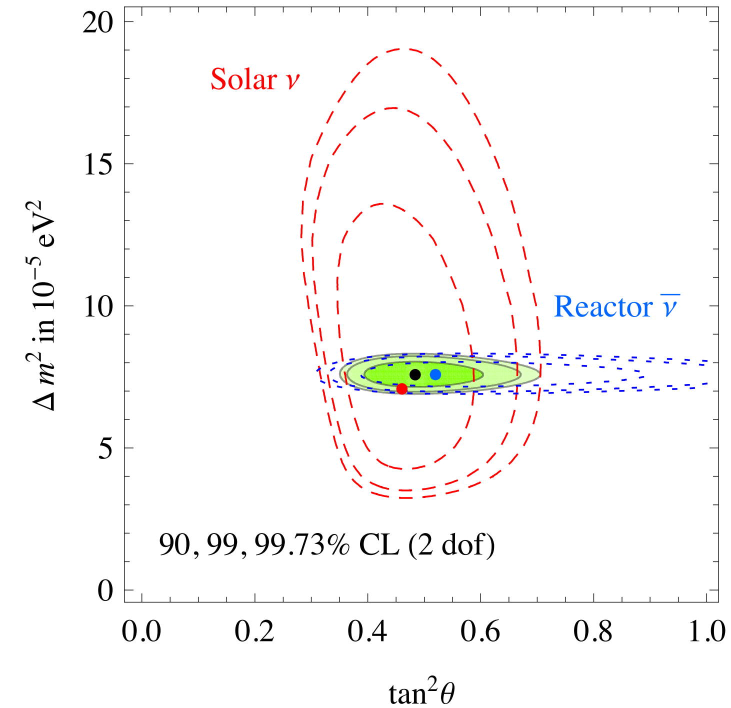
- At solar energies(MeV) μ,τ under production threshold:
  - mixing depends only on first raw: $\delta m^2, \vartheta_{13}, \vartheta_{12}$, $|U_{e3}| = \sin(\vartheta_{13})$, $|U_{e2}| = \cos(\vartheta_{13}) \sin(\vartheta_{12})$
- ϑ_{13} only link between oscillations: $\vartheta_{13} \sim 9° \Rightarrow$ decoupled

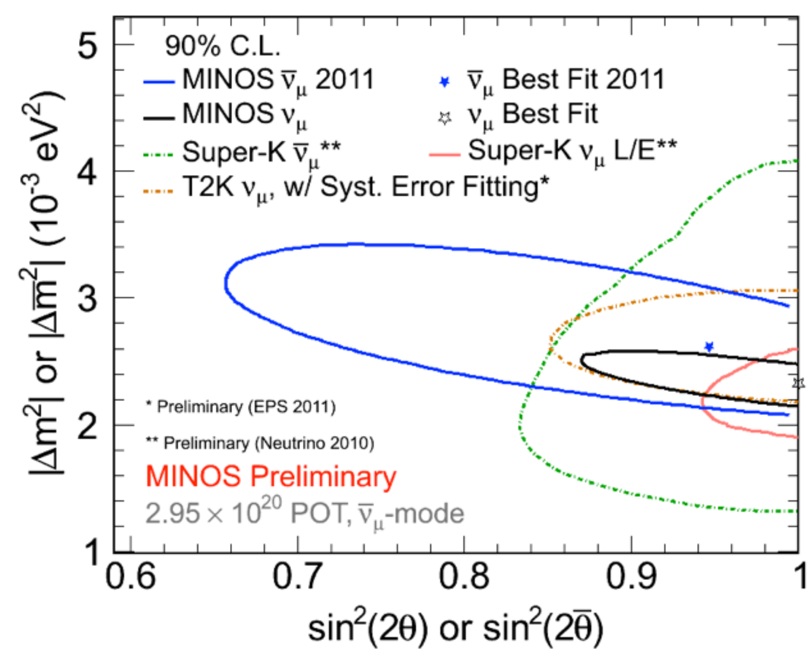
Mass Hierarchy

$\theta_{atm} \approx \theta_{23} \approx 45°$, $\theta_{sun} \approx \theta_{12} \approx 30°$, $\theta_{13} \approx 9°$

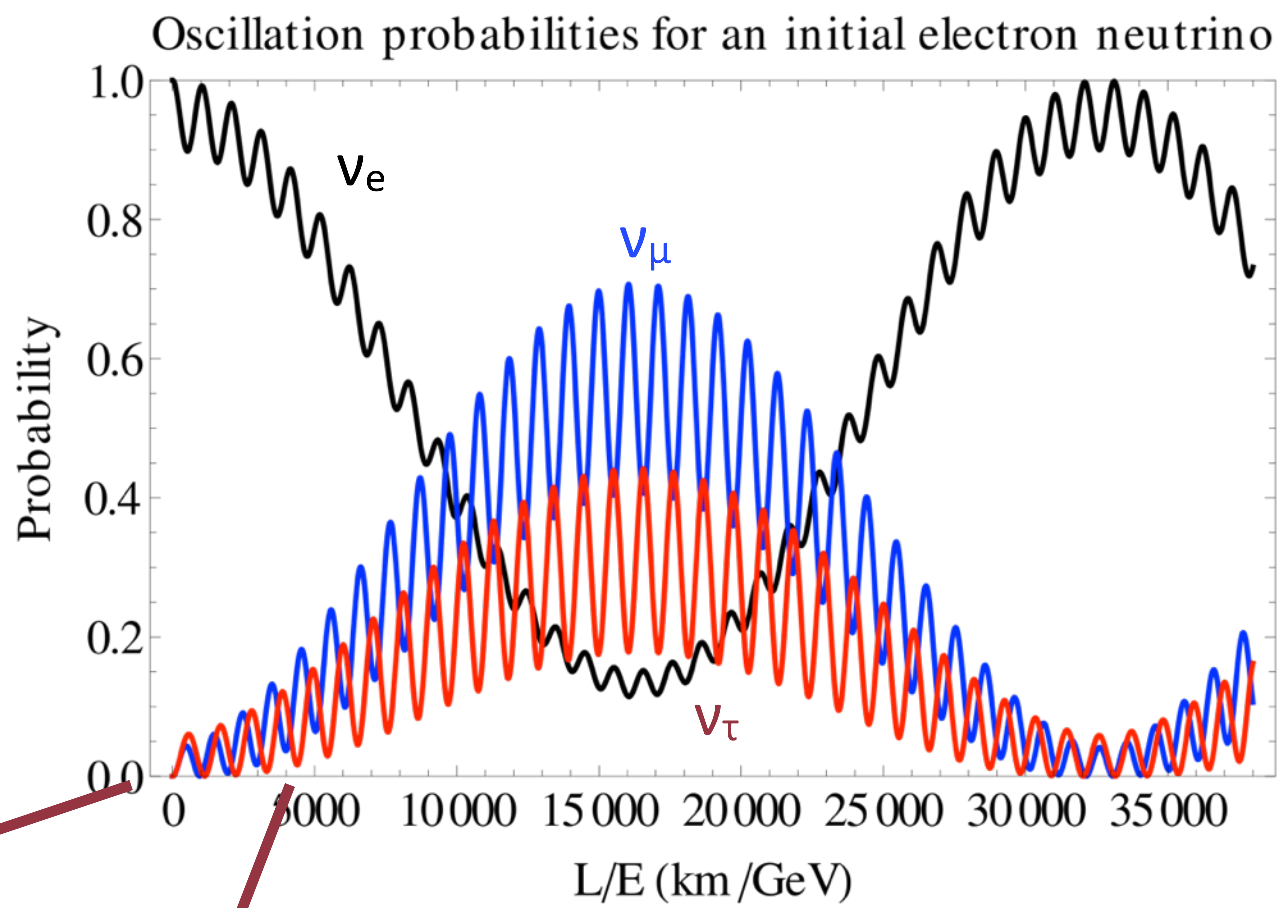
$|\Delta m^2_{13}| \approx |\Delta m^2_{23}| \approx |\Delta m^2_{atm}| \approx (2.40 \pm 0.15) \cdot 10^{-3}\ eV^2$ $\Delta m^2_{12} \approx \Delta m^2_{sol} \approx (7.58 \pm 0.21) \cdot 10^{-5}\ eV^2$



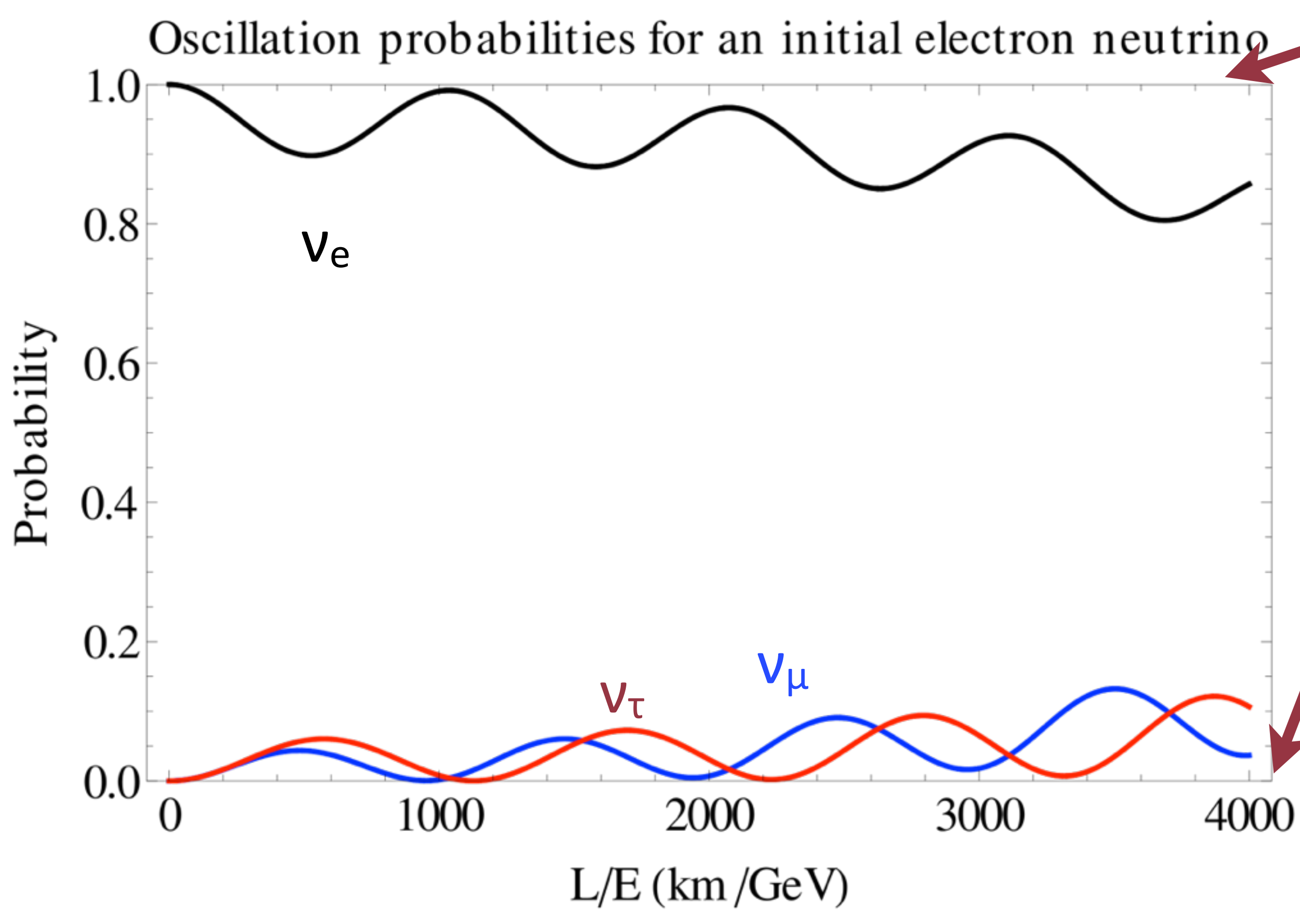




ν_e OSCILLATION

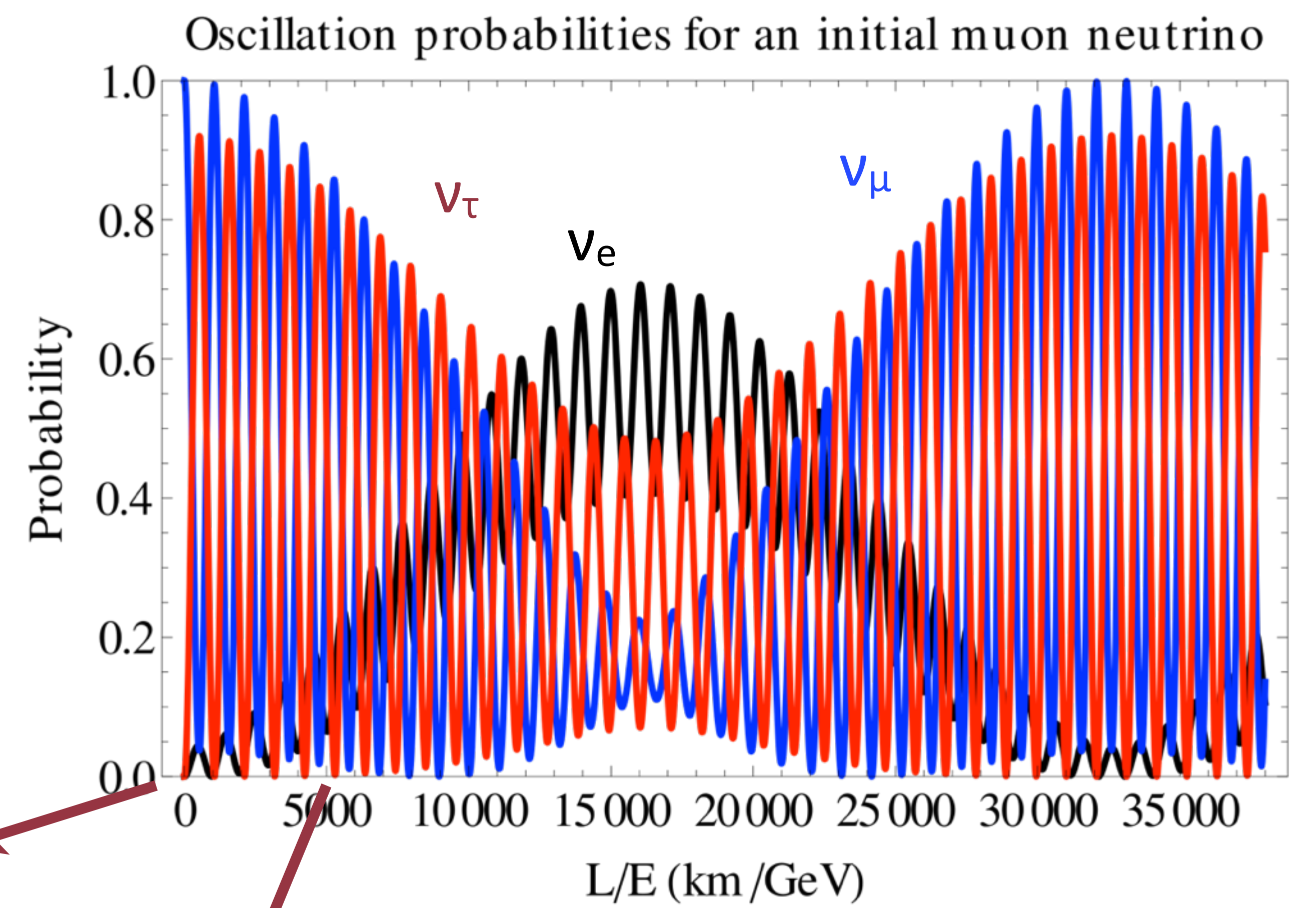


Short Baseline

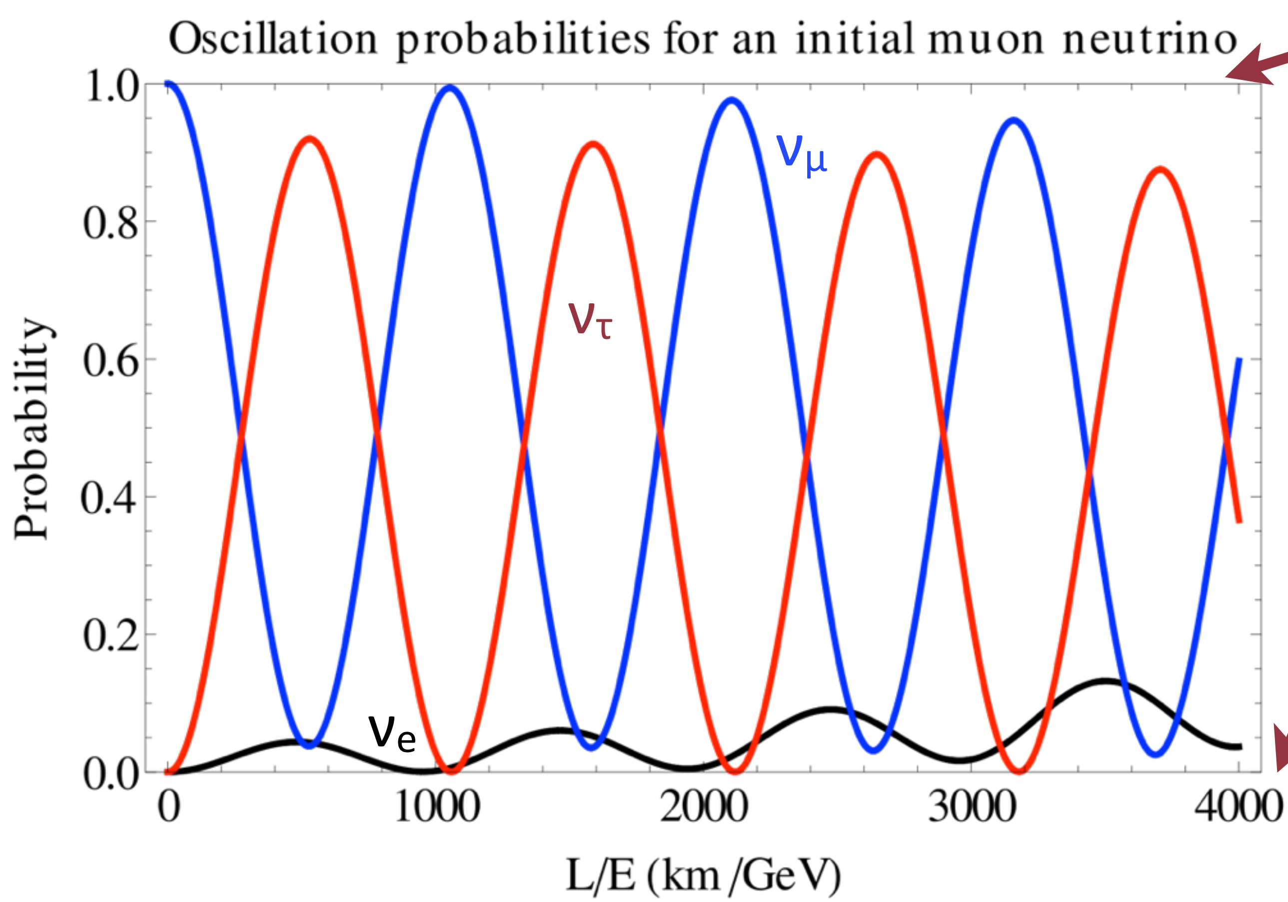


Long Baseline

ν_μ OSCILLATION

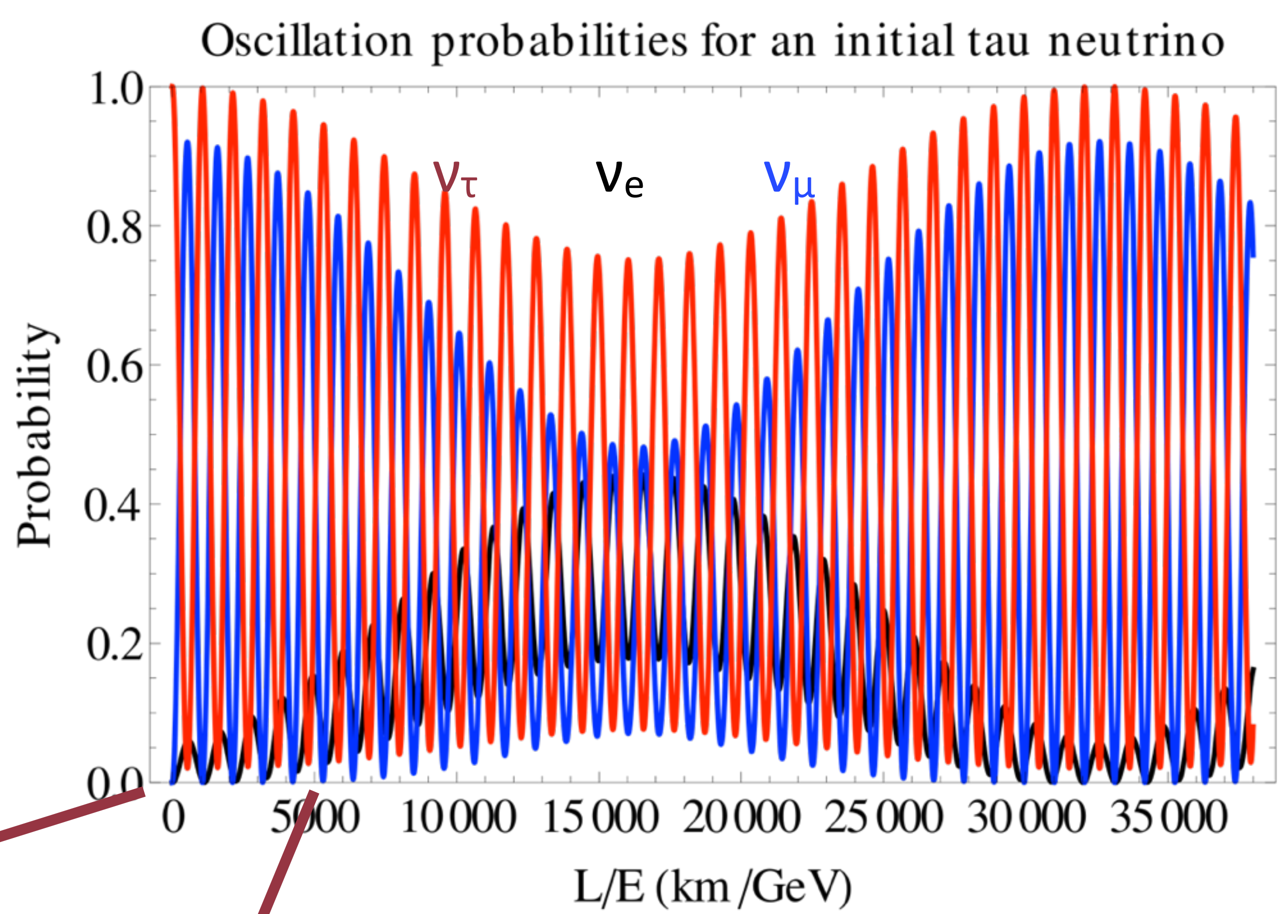


Short Baseline

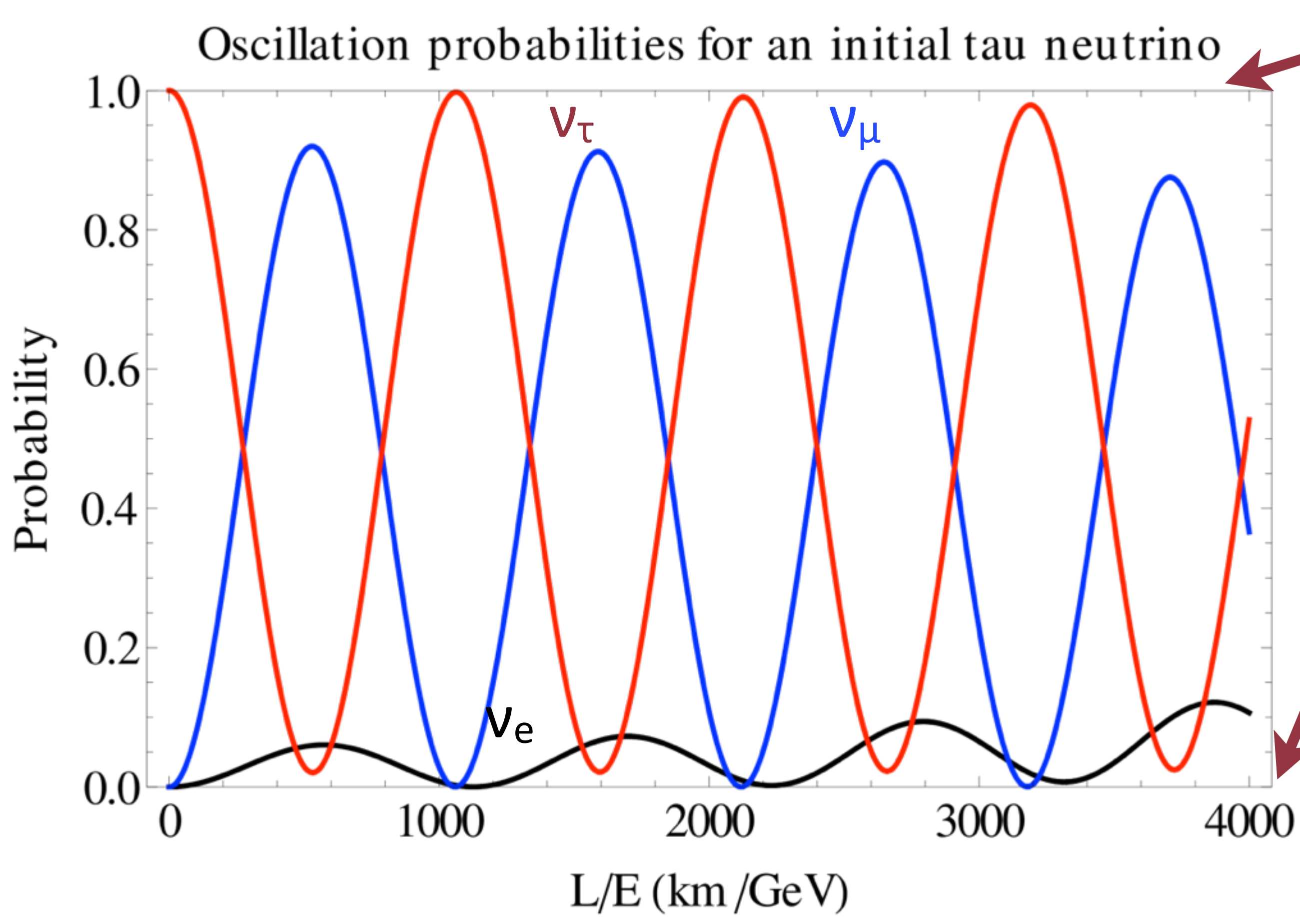


Long Baseline

ν_τ OSCILLATION



Short Baseline



Long Baseline