Neutrinos on the Earth and from the Sky

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7th NeXT Workshop
Abingdon, UK

Plan of lectures

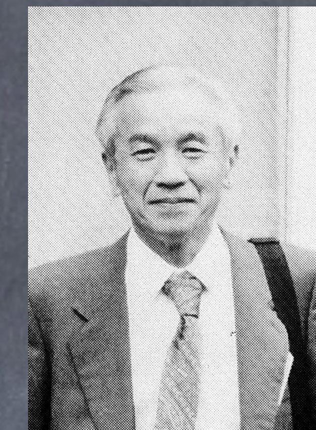
I From the beginning...

II Neutrino oscillations

III High-energy neutrinos

IV New physics with neutrino telescopes

First ideas

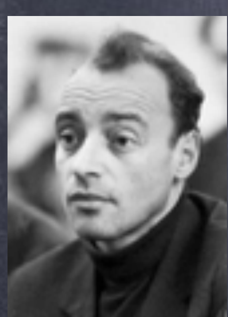


1957: B. Pontecorvo
Suggested the idea of neutrino oscillations
(neutrino-antineutrino oscillations)

1962: Z. Maki, M. Nakagawa, S. Sakata
Proposed the concept of flavor mixing and oscillations

1967: B. Pontecorvo
Study of flavor oscillations of two neutrinos
Introduced the concept of sterile neutrinos
Considered for the first time solar neutrino oscillations

PMNS mixing matrix



1969: V. Gribov and B. Pontecorvo
Computed the oscillation probability in vacuum
(for Majorana neutrinos) without steriles

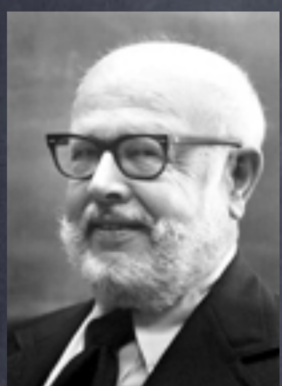
1969: J. N. Bahcall and S. Frautschi
Detailed study of solar neutrino oscillations in vacuum

1974: S. Eliezer and D. A. Ross
1976: S. M. Bilenky and B. Pontecorvo
Quark-lepton analogy

1976: H. Fritzsch and P. Minkowski
1976: S. Eliezer and A. R. Swift
Oscillations and decays in neutrino beams

The search of solar neutrinos

After (unsuccessfully) trying to detect reactor antineutrinos, also at Savannah River, with a neutrino reaction in 1955… there was a remaining powerful source: the SUN



1958: H. D. Holmgren, R. L. Johnston, A. G. W. Cameron and W. A. Fowler
Developed the solar neutrino model: ^{7}Be and ^{8}B neutrinos

1983: S. Chandrasekhar and W. A. Fowler

1964: J. N. Bahcall and R. Davis
Back-to-back papers that laid out the theory and experimental approaches for the detection of solar neutrinos

Solar neutrino problem: less neutrinos than expected

1968: R. Davis Jr, D. S. Harmer and K. C. Hoffman
First detection of solar neutrinos (deficit)

2002: R. Davis Jr, M. Koshiba and R. Giacconi

MASS & MIXING ⇒ OSCILLATIONS

flavor eigenstates $\qquad\qquad$ mass eigenstates

$\nu_e \quad \nu_\mu \quad \nu_\tau \quad \neq \quad \nu_1 \quad \nu_2 \quad \nu_3$

produced in CC processes $\qquad\qquad$ free propagation eigenstates

connected via the (non-diagonal) PMNS mixing matrix

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W^+_\mu \sum_\alpha \left(\overline{\ell}_{L\alpha} \, \gamma^\mu \nu_{L\alpha} \right) + h.c.$$

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W^+_\mu \sum_{\alpha j} \left(\overline{\ell}_{L\alpha} \, \gamma^\mu \left(U_{PMNS} \right)_{\alpha j} \nu_{Lj} \right) + h.c.$$

$$\left(i\gamma_\mu \partial^\mu - m \right) \nu = 0$$

$$i\left(\partial^0 - \vec{\sigma} \, \vec{\nabla} \right) \nu_L = m \nu_R$$

$$i\left(\partial^0 + \vec{\sigma} \, \vec{\nabla} \right) \nu_R = m \nu_L$$

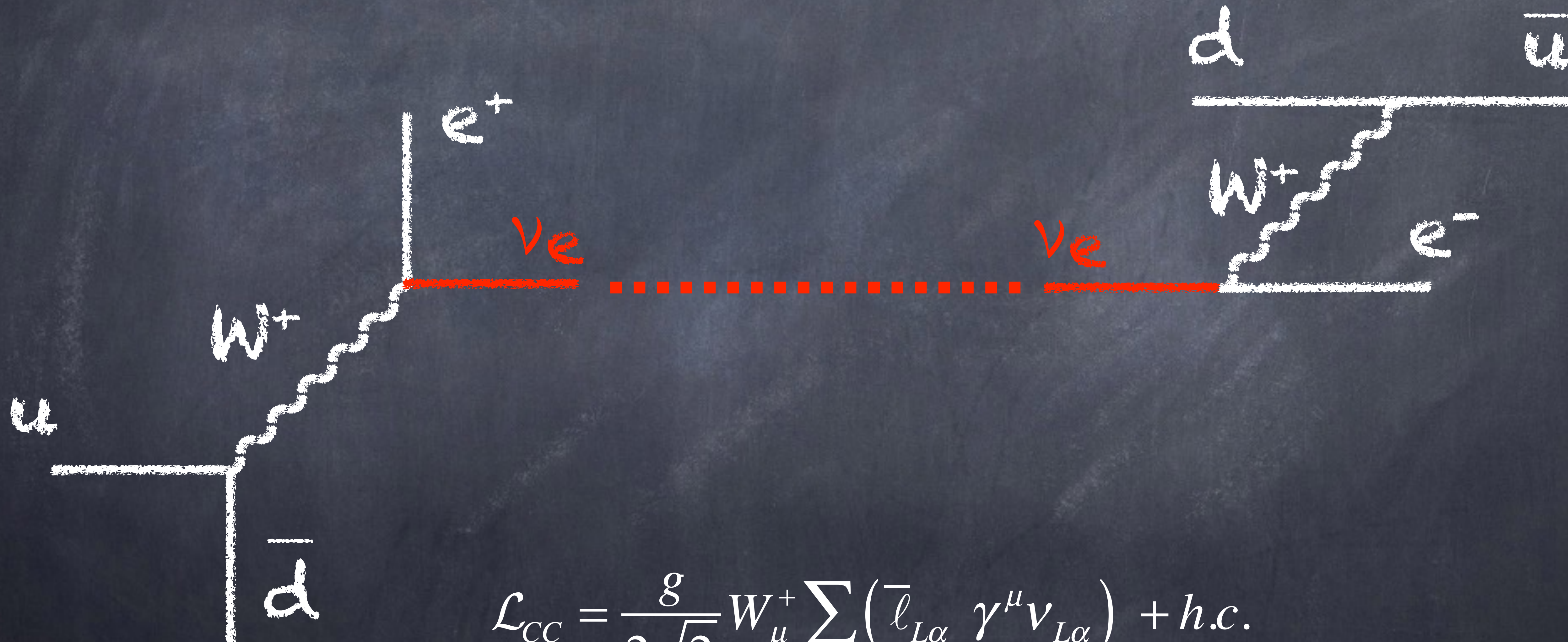
$$i \, \partial_t \left(\nu^{\mp}_{L,R} \right)_i = H_i \, \left(\nu^{\mp}_{L,R} \right)_i$$

MASS & MIXING ⇒ OSCILLATIONS

at short distances

Production

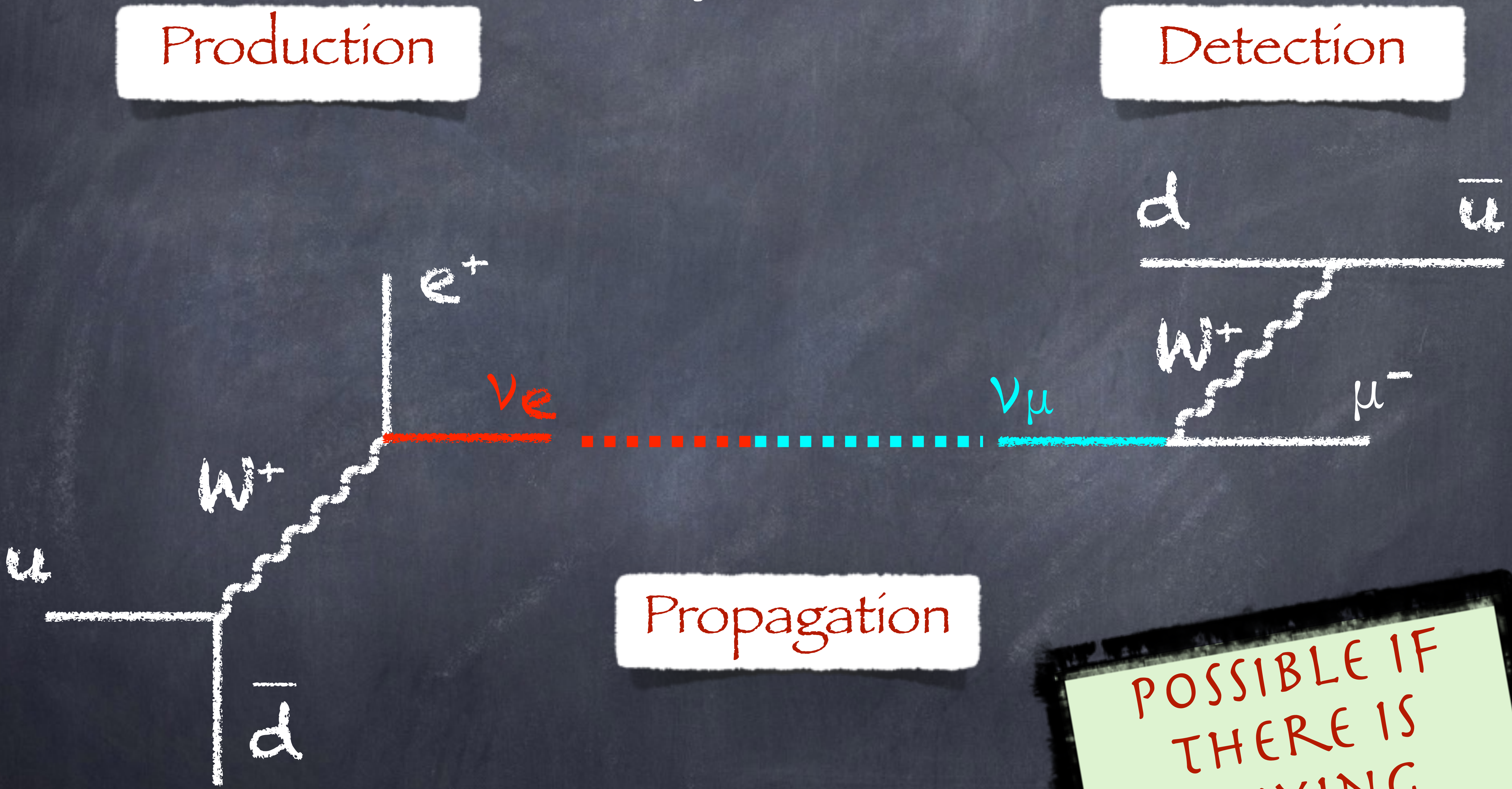
Detection



$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W_\mu^+ \sum_\alpha \left(\bar{\ell}_{L\alpha} \, \gamma^\mu \nu_{L\alpha} \right) + h.c.$$

MASS & MIXING ⇒ OSCILLATIONS

at longer distances



POSSIBLE IF THERE IS MIXING

Basics: oscillations in vacuum

In principle, one should use wave packets, but using plane waves provides the correct result

$$i\frac{\partial \nu_i}{\partial t} = E_i \ \nu_i$$

Each mass eigenstate evolves as a plane wave:

$$\left|\nu_i(t)\right\rangle = e^{-iE_i t}\left|\nu_i(t=0)\right\rangle$$

and acquires a different phase $E_i t$

but flavor eigenstates are a combination of mass eigenstates

$$\left|\nu_\alpha(t)\right\rangle = \sum_i U^*_{\alpha i}\left|\nu_i(t)\right\rangle = \sum_i U^*_{\alpha i}\ e^{-iE_i t}\left|\nu_i(t=0)\right\rangle$$

Basics: oscillations in vacuum

Probability of detecting ν_β at a time t after having produced ν_α

$$P_{\alpha\beta} = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2 = \left| \sum_{ij} U^*_{\alpha i} U_{\beta j} \langle \nu_j | \nu_i(t) \rangle \right|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} \; e^{-iE_i t} \right|^2$$

but neutrino masses are very small, so they are (almost) always very relativistic

$$E_i \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E}$$

$$P_{\alpha\beta} = \left| \sum_i U^*_{\alpha i} U_{\beta i} \; e^{-i\frac{\Delta m_i^2}{2E}t} \right|^2$$

if non-degenerate states and if sufficient time of travel

mass and mixing ⇒ oscillations ($P_{\alpha\beta} \neq 0$)

Basics: oscillations in vacuum

- Pure quantum mechanical effect: interference of different components with different phases and amplitudes

  - Relative phases depend on distance, mass square differences and energy

  - Amplitudes depend on mixing

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{j\neq i} \mathrm{Im}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

The mixing matrix U

(nxn) unitary matrix $\Rightarrow$ n^2 real parameters

$n(n-1)/2$ mixing angles

$n(n+1)/2$ phases

Dirac

$n + (n-1) = 2n-1$ phases can be absorbed in redefinitions of lepton fields

$n(n+1)/2 - (2n-1) = (n-1)(n-2)/2$ physical phases

Majorana

n phases can be absorbed in redefinitions of lepton fields

$n(n+1)/2 - n = n(n-1)/2$ physical phases

but $(n-1)$ phases do not enter oscillations

Basics: oscillations in vacuum

For two neutrinos: $$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Appearance $\nu_\alpha \to \nu_\beta$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E}\right)$$

Disappearance $\nu_\alpha \to \nu_\alpha$ $$P_{\alpha\alpha} = 1 - P_{\alpha\beta}$$

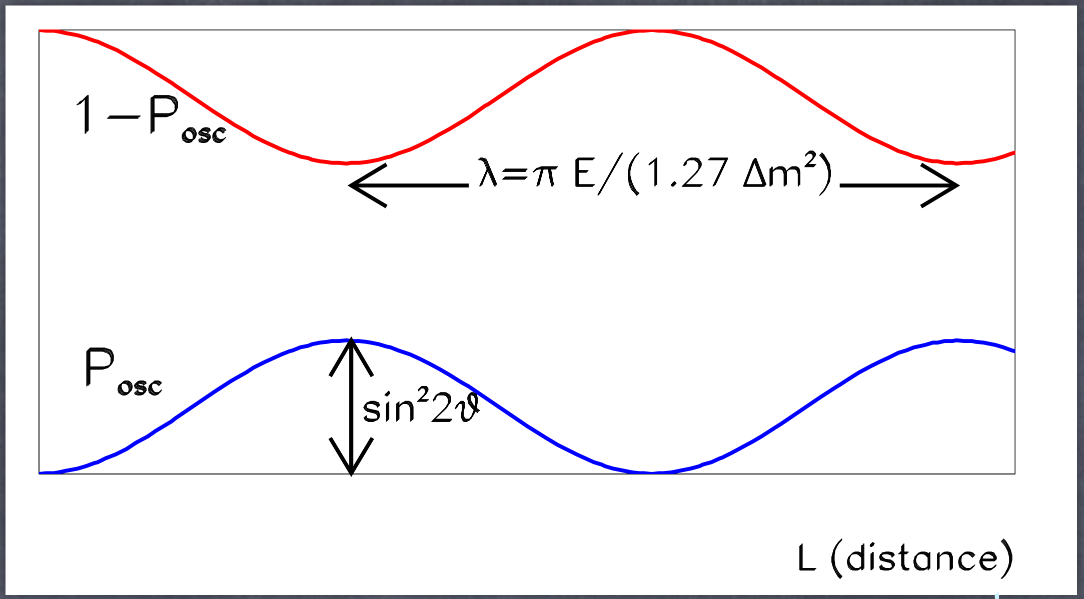
Maximal effect for $L \sim E/\Delta m^2$

If $L \ll E/\Delta m^2$: No time to oscillate $P_{\alpha\beta} \approx 0$

If $L \gg E/\Delta m^2$: oscillations are averaged $\langle P_{\alpha\beta}\rangle = \frac{1}{2}\sin^2(2\theta)$

Basics: oscillations in vacuum

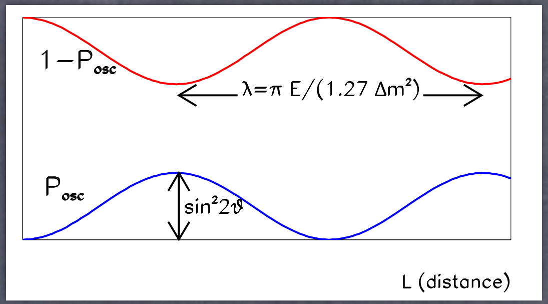
Maximal effect for $L \sim E/\Delta m^2$



From M. Maltoni

Basics: oscillations in vacuum

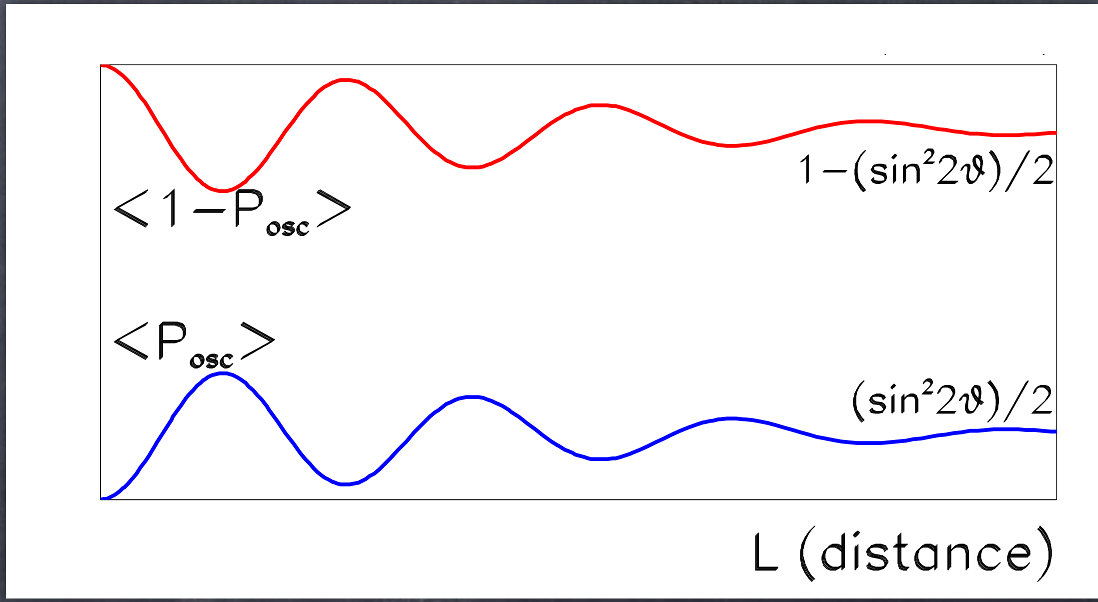
Maximal effect for L ~ E/ Δm^2



From M. Maltoni

Very long distances

L >> E/ Δm^2



Basics: oscillations in vacuum

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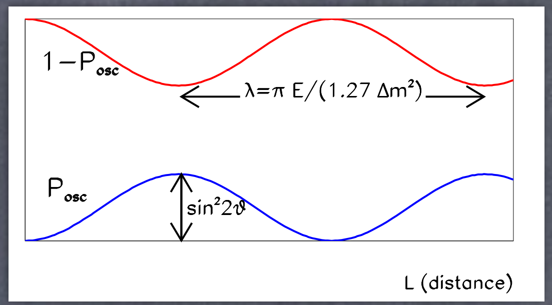

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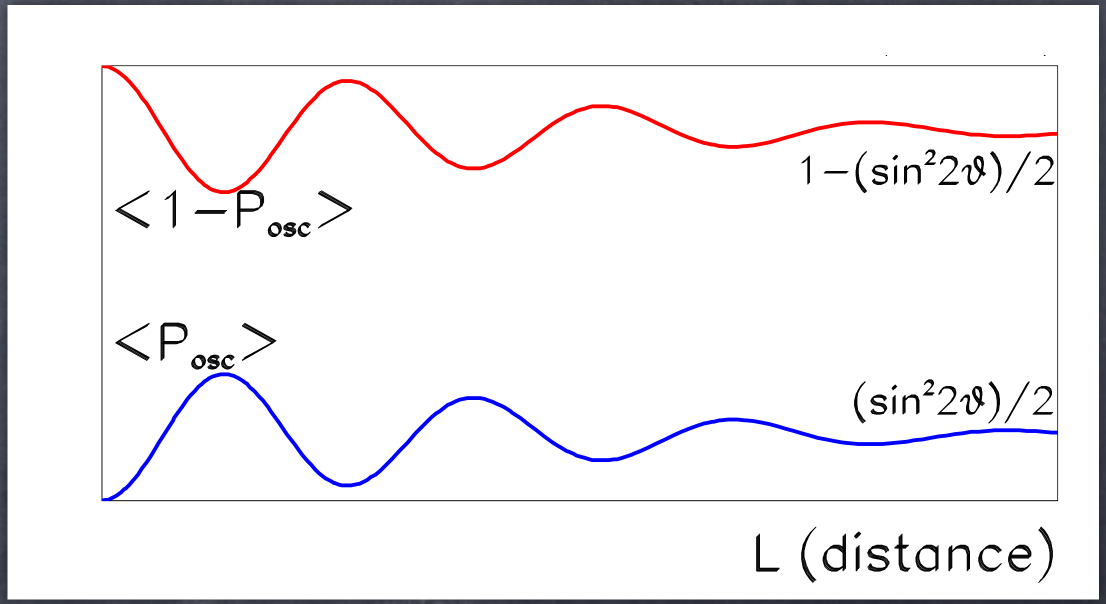
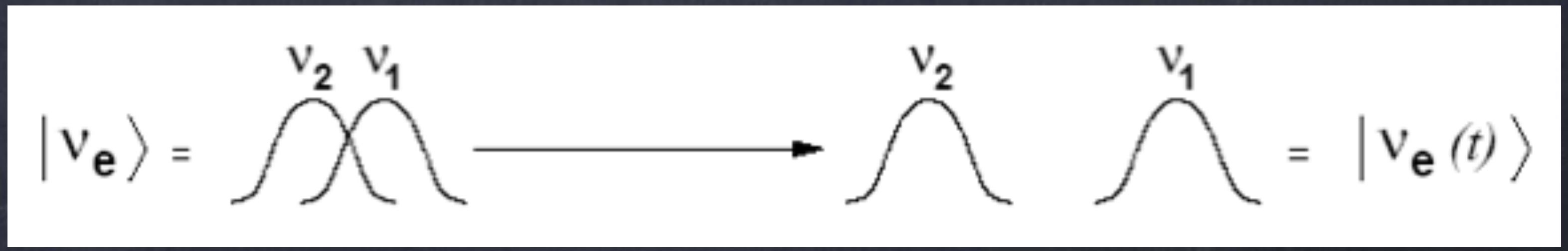
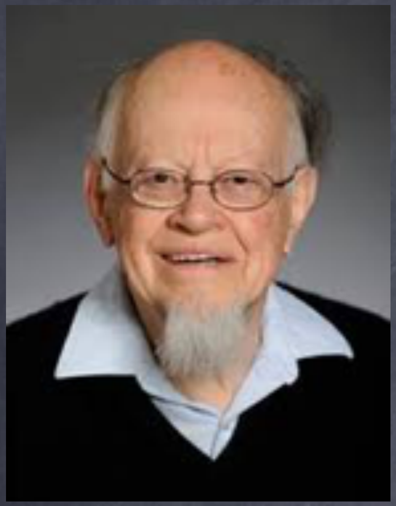


wave packets separate so that they cannot be differentiated in the detector

$$\left\langle P_{\alpha\beta}\right\rangle = \sum_i \left|U_{\alpha i}\right|^2 \left|U_{\beta i}\right|^2$$



Matter effects



1978: L. Wolfenstein
Pointed out the effect of forward scattering in neutrino oscillations in matter

index of refraction

$$\text{Amplitude} = e^{iEnL}$$

$$n = 1 + 2\pi N f(0)/E^2 = 1 + V/E$$

incoherent process

coherent forward scattering

optical theorem [$4\pi \, \text{Im}\, f(0) / E = \sigma$]

Absorption: $E \, \text{Im}(\Delta n) \propto N \sigma$

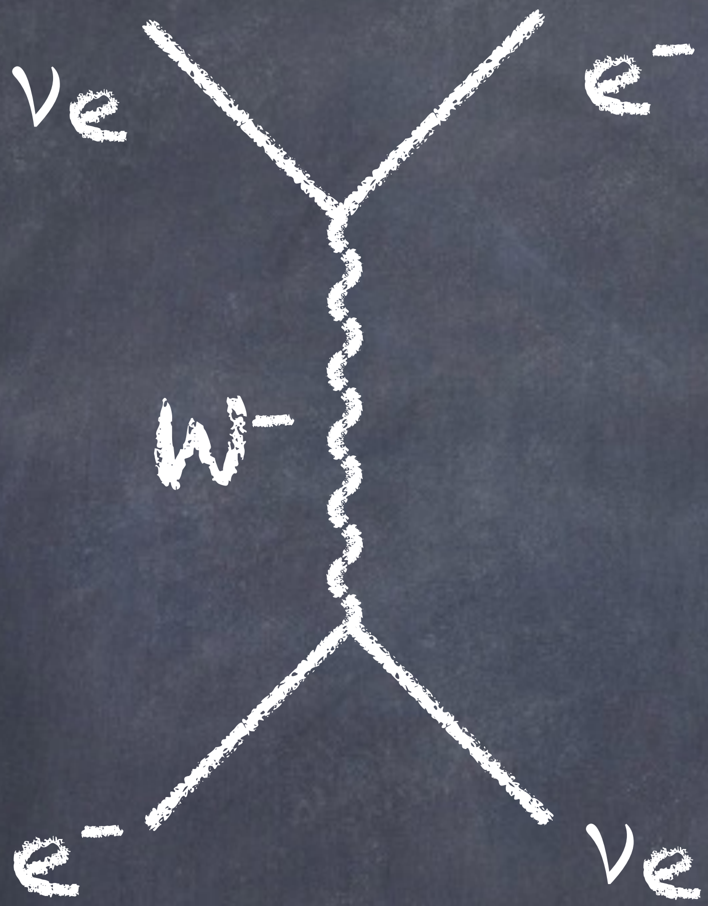
$E \, \text{Re}(\Delta n) \propto N \, \text{Re}\, f(0) / E$

$\sigma \propto G_F^2$

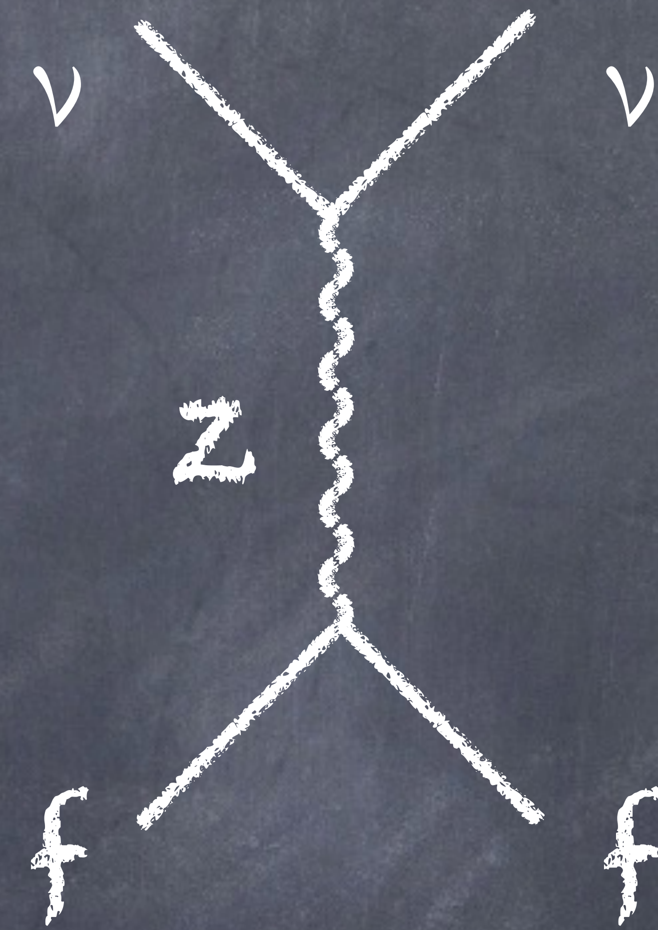
$\text{Re}\, f(0) \propto G_F$

Matter effects

Charged Currents



Neutral Currents



$$\bar{V} = -V$$

$$V_{CC} = \sqrt{2}\, G_F\, N_e$$

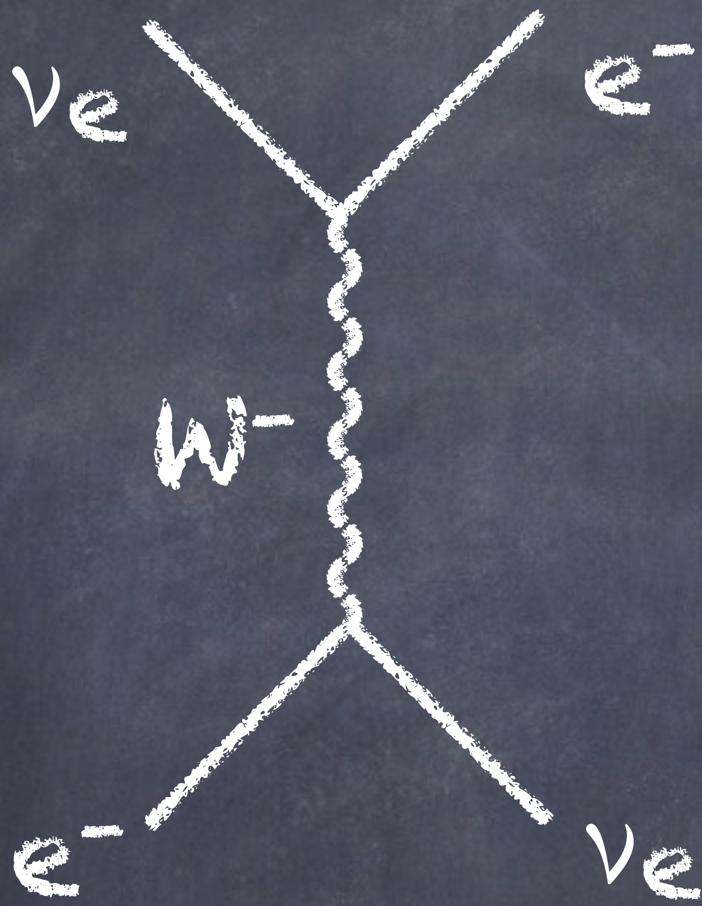
$$V_{NC} = -1/\sqrt{2}\, G_F\, N_n$$

$$V_e = V_{CC} + V_{NC}$$

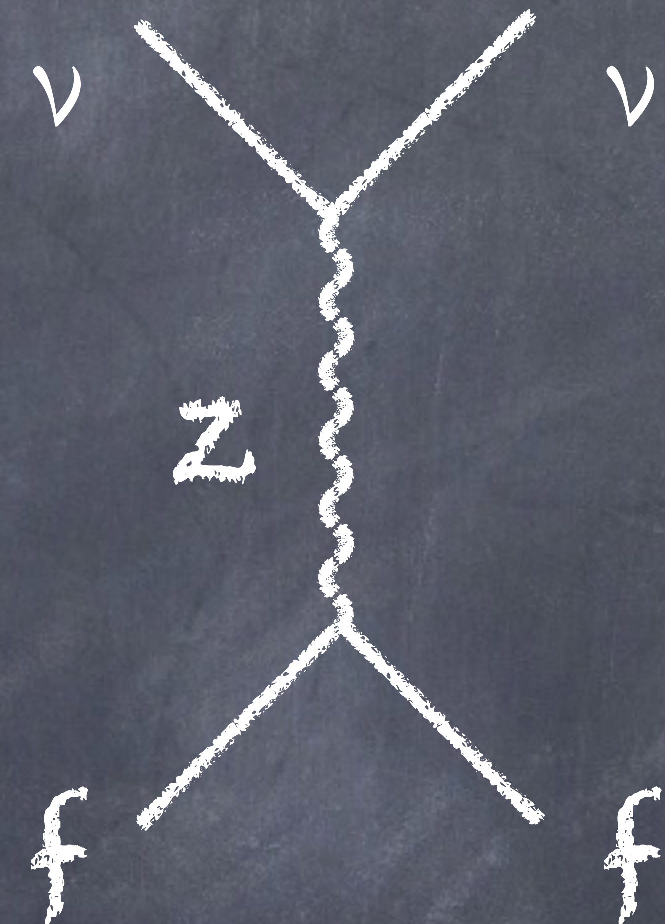
$$V_\mu = V_\tau = V_{NC}$$

Matter effects

Charged Currents



Neutral Currents



$$\overline{V} = -V$$

$$V_{CC} = \sqrt{2}\, G_F N_e \qquad V_{NC} = -1/\sqrt{2}\, G_F N_n$$

$$V_e = V_{CC} + V_{NC} \qquad V_\mu = V_\tau = V_{NC}$$

only relative terms matter!

Matter effects

tiny Δn: a matter of scales

solar core

$V_\odot \sim 10^{-12}$ eV

Earth core

$V_\oplus \sim 10^{-13}$ eV

coherent scattering
(for GeV energies)

$$\frac{\Delta m^2_{31}}{2E} \sim V_\oplus \sim R_\oplus^{-1}$$

absorption

$$\sigma \sim \frac{G_F^2 s}{\pi} \sim 10^{-38} \left(\frac{E}{\text{GeV}}\right) \text{cm}^2$$

$$n\sigma \sim \left(\frac{E}{10\ \text{TeV}}\right) R_\oplus^{-1}$$

Basics: oscillations in matter

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[U\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}U^\dagger + \begin{pmatrix}V_e & 0\\ 0 & V_\mu\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

getting rid of terms proportional to the identity:

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}-\frac{\Delta m^2}{4E}\cos(2\theta)+\sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin(2\theta)\\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta)\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

diagonalizing (at a given point):

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta_m & \sin\theta_m\\ -\sin\theta_m & \cos\theta_m\end{pmatrix}\begin{pmatrix}\nu_1^m\\ \nu_2^m\end{pmatrix}$$

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m_m^2}$$

$$\Delta m_m^2 = \sqrt{\left(\Delta m^2\cos(2\theta)-2EV_{CC}\right)^2+\left(\Delta m^2\sin(2\theta)\right)^2}$$

Basics: oscillations in matter

resonance enhancement

$$\tan(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m^2 \cos(2\theta) - 2EV_{CC}}$$


1985-1986: S. Mikheyev and A. Yu Smirnov
Pointed out the possibility of neutrino resonant enhancement and adiabatic conversion in matter

In a medium with varying density θ_m is a dynamical quantity

$$i\frac{d}{dx}\begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m_m^2}{4E} & -i\frac{d\theta_m}{dx} \\ i\frac{d\theta_m}{dx} & \frac{\Delta m_m^2}{4E} \end{pmatrix}\begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix}$$

adiabatic conversion
(MSW effect)

slowly varying density: $\frac{\Delta m_m^2}{4E} >> \frac{d\theta_m}{dx}$

$$P_{ee}^{adiabatic} = \sin^2\theta \sin^2\theta_m + \cos^2\theta \cos^2\theta_m$$

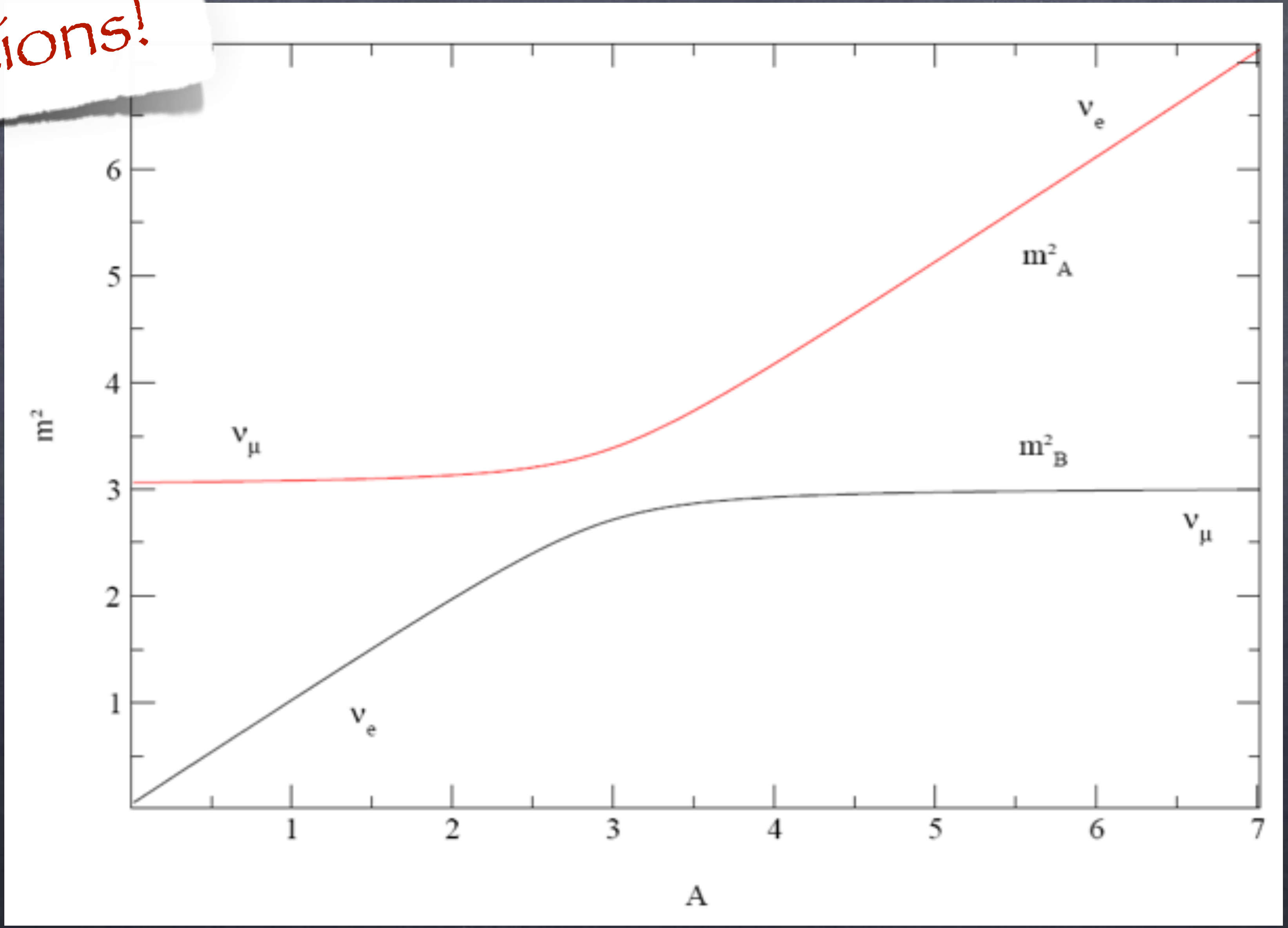
for solar neutrinos, oscillations are averaged

BASICS: OSCILLATIONS IN MATTER

At high solar densities, ν_e is mostly the most massive state ν_2

For adiabatic propagation, it exits the Sun as purely ν_2, which, for small mixing, is mostly ν_μ

No oscillations!



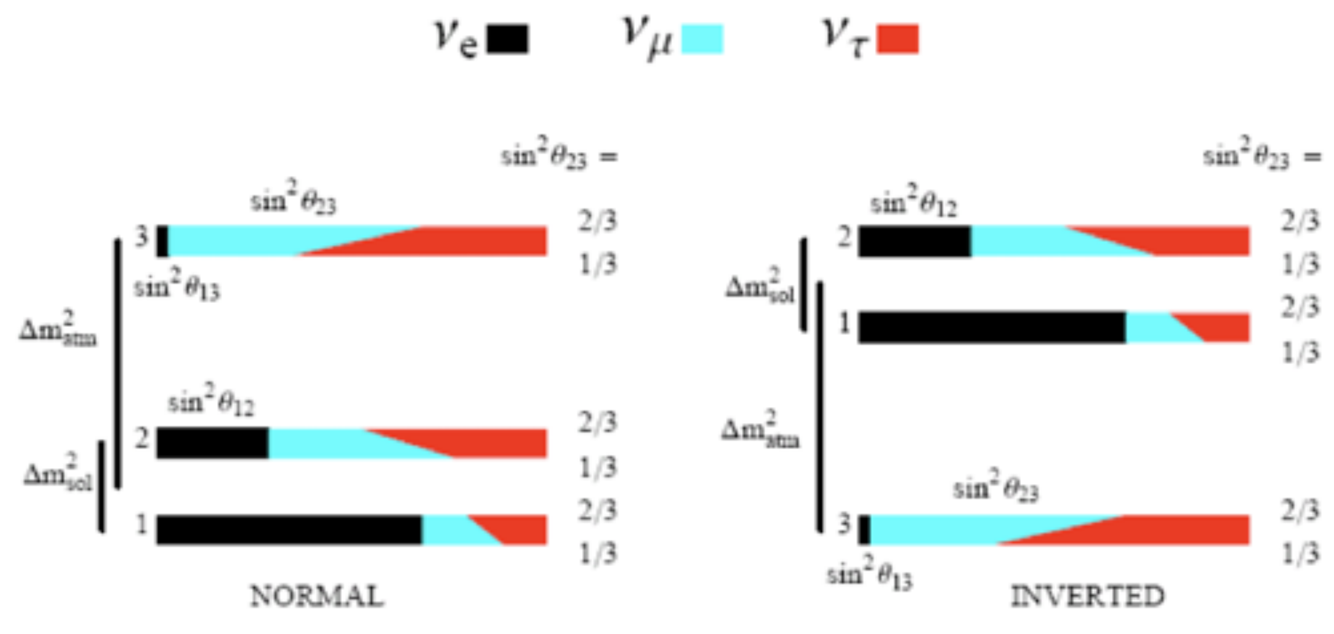
What do we want to know?

3 mixing angles + 1 Dirac phase + 2 Majorana phases

$$U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

solar angle | reactor angle | atmospheric angle | Majorana phases

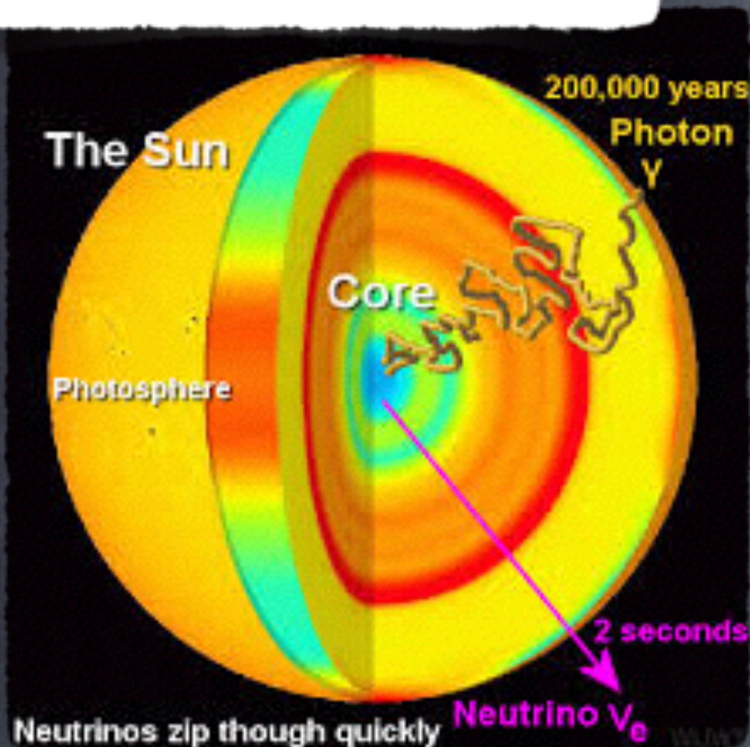
2 possible mass orderings



O. Mena and S. J. Parke, *Phys. Rev. D69:117301, 2004*

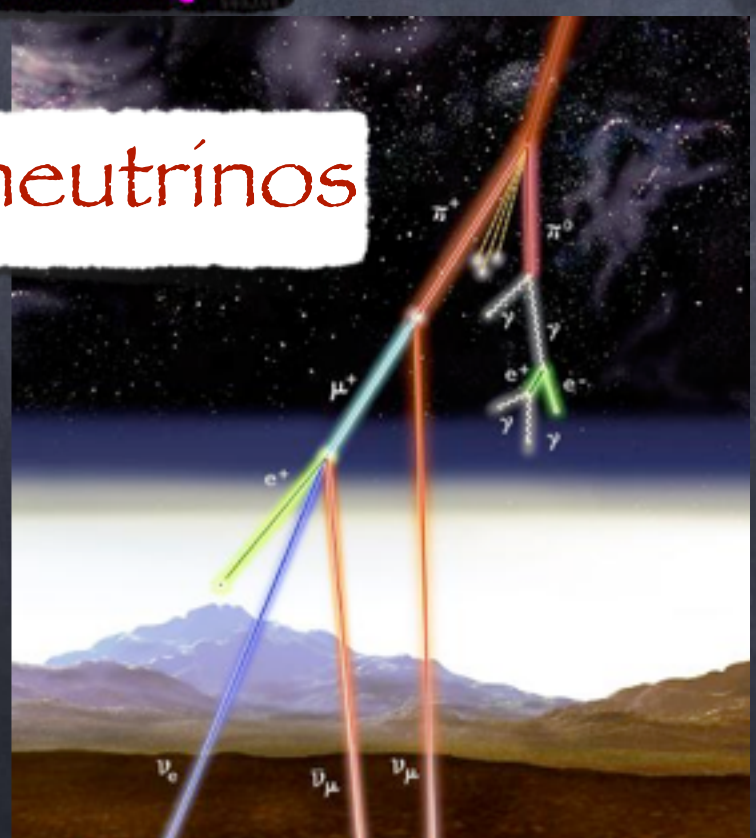
How do we know?

solar neutrinos

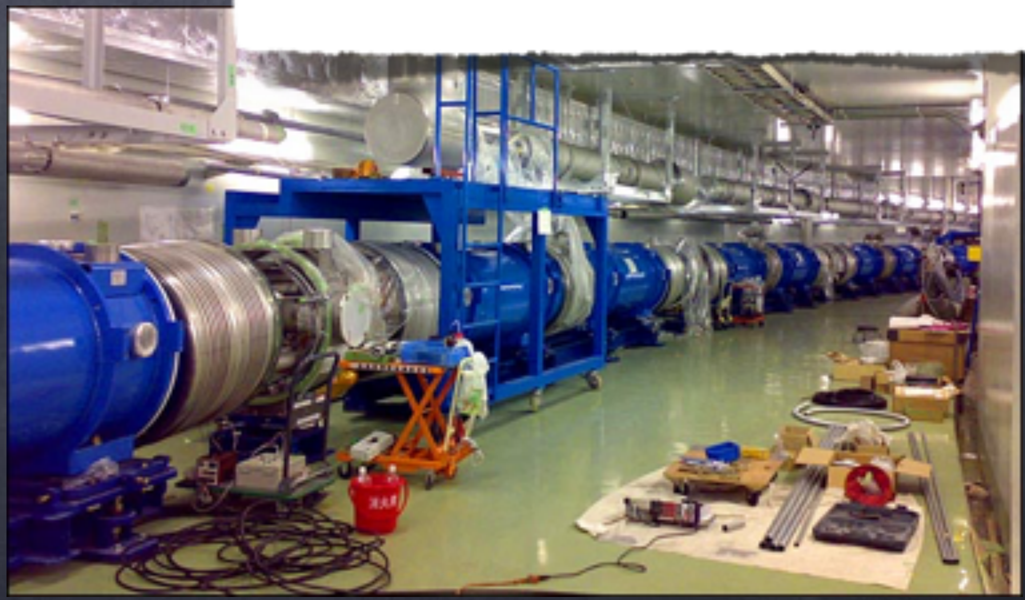


reactor neutrinos

atmospheric neutrinos



accelerator neutrinos



Connection theory/experiment

baseline

neutrino energy

$$N_\beta(L) = T \times N_T \times \int \Phi(E_\nu)\sigma(E_\nu)\, P\left(\nu_\alpha \to \nu_\beta; E_\nu, L\right)\varepsilon(E_\nu)\, dE_\nu$$

time

detector efficiency

number of targets

cross section

oscillation probability

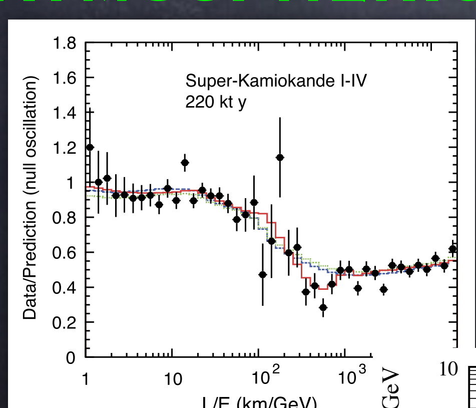
number of detected events

neutrino flux

What have we observed?

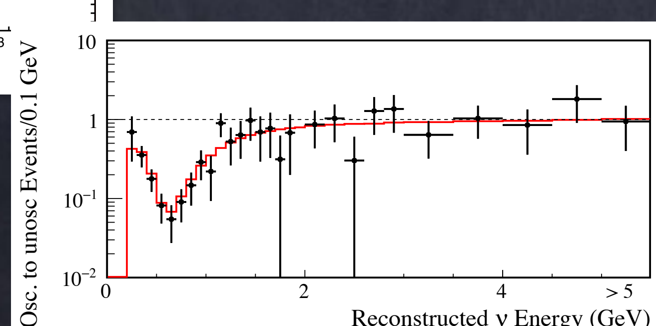
- atmospheric ν_μ and $\bar{\nu}_\mu$ disappear (mostly to $\nu_\tau/\bar{\nu}_\tau$) — SK, MINOS, ICECUBE
- accelerator ν_μ and $\bar{\nu}_\mu$ disappear — K2K, T2K, MINOS, NOvA
- accelerator ν_μ appear as ν_e — T2K, MINOS, NOvA
- solar ν_e disappear — Cl, Ga, SK, SNO, Borexino
- reactor $\bar{\nu}_e$ disappear at ~200 km — KamLAND
- reactor $\bar{\nu}_e$ disappear at ~1 km — D-Chooz, Daya Bay, Reno

ATMOSPHERIC

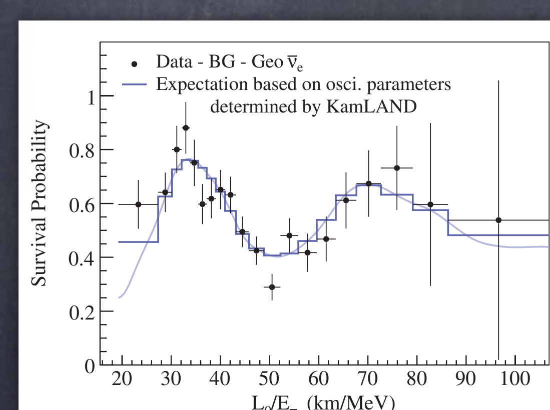


L/E

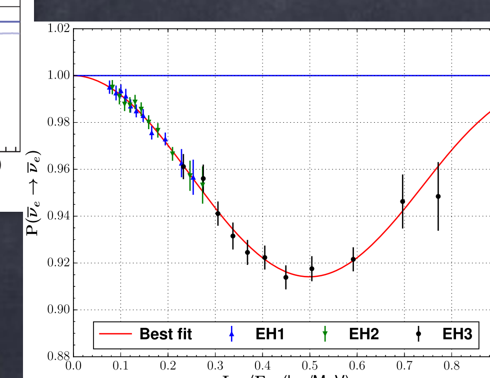
ACCELERATOR



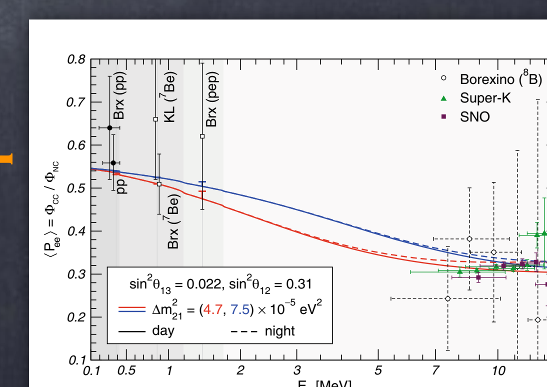
REACTOR LBL



REACTOR MBL



SOLAR



What do we know?

3σ ranges

$\Delta m^2_{21} = (7.03 - 8.09) \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2\theta_{12} = 0.271 - 0.345$

solar sector

$\sin^2\theta_{13} = 0.01934 - 0.02397$

reactor sector

$|\Delta m^2_{31}| = (2.407 - 2.643) \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.385 - 0.638$

atmospheric and acc. sector

I. Esteban et al., JHEP 1701:087, 2017

What don't we know?

θ_{23} octant: $\theta_{23} > 45^\circ$ or $\theta_{23} < 45^\circ$

CP violation (but... $\delta_{bf} \approx \frac{3\pi}{2}$)

Mass hierarchy: sign of Δm^2_{31}

What do we know?

3σ ranges

$\Delta m^2_{21} = (7.03 - 8.09) \times 10^{-5}\ \mathrm{eV}^2$ $\sin^2\theta_{12} = 0.271 - 0.345$ solar sector	$\sin^2\theta_{13} = 0.01934 - 0.02397$ reactor sector	$\lvert\Delta m^2_{31}\rvert = (2.407 - 2.643) \times 10^{-3}\ \mathrm{eV}^2$ $\sin^2\theta_{23} = 0.385 - 0.638$ atmospheric and acc. sector

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Mass hierarchy: sign of Δm^2_{31}

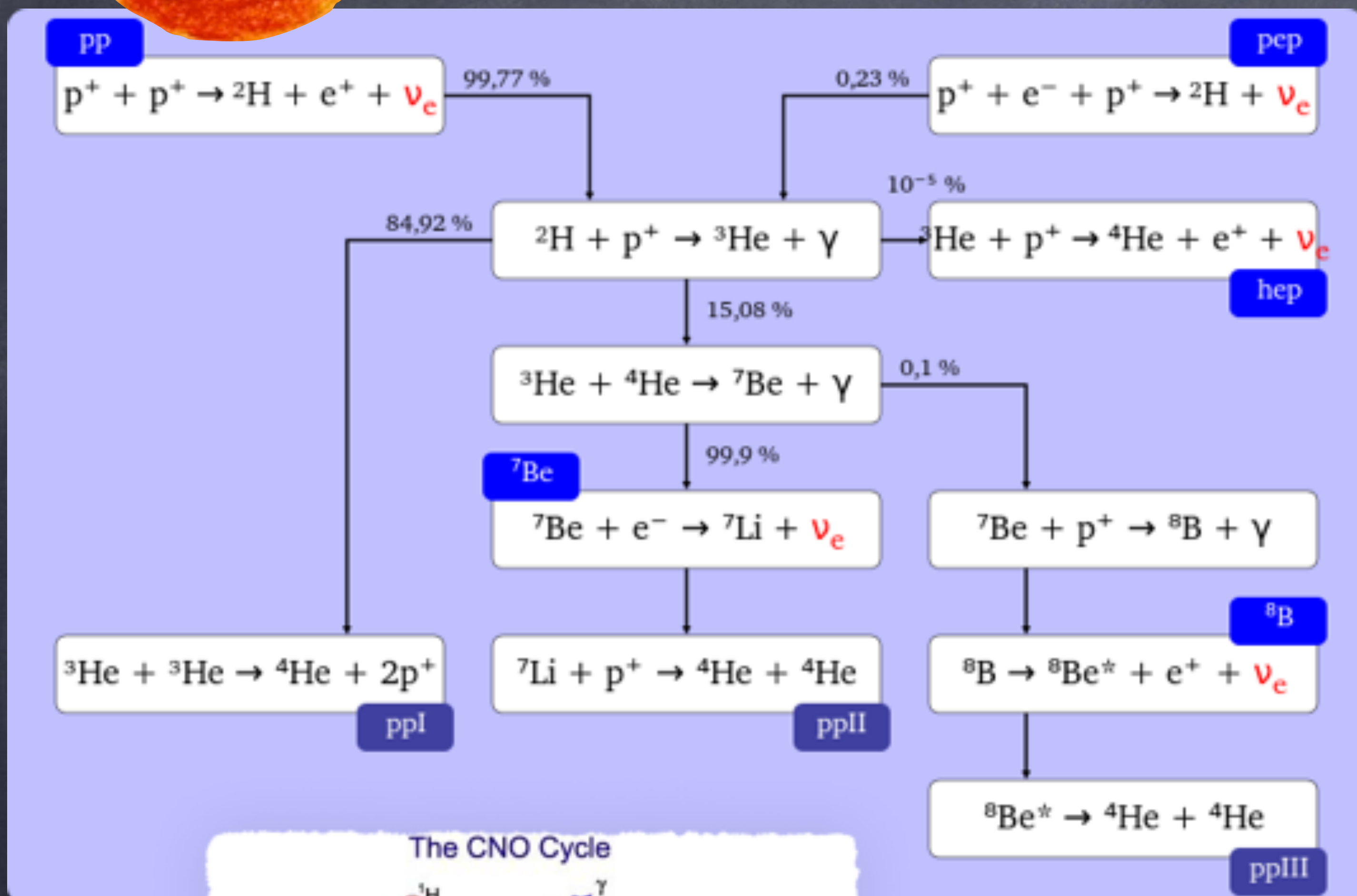
Extra (sterile) neutrinos?

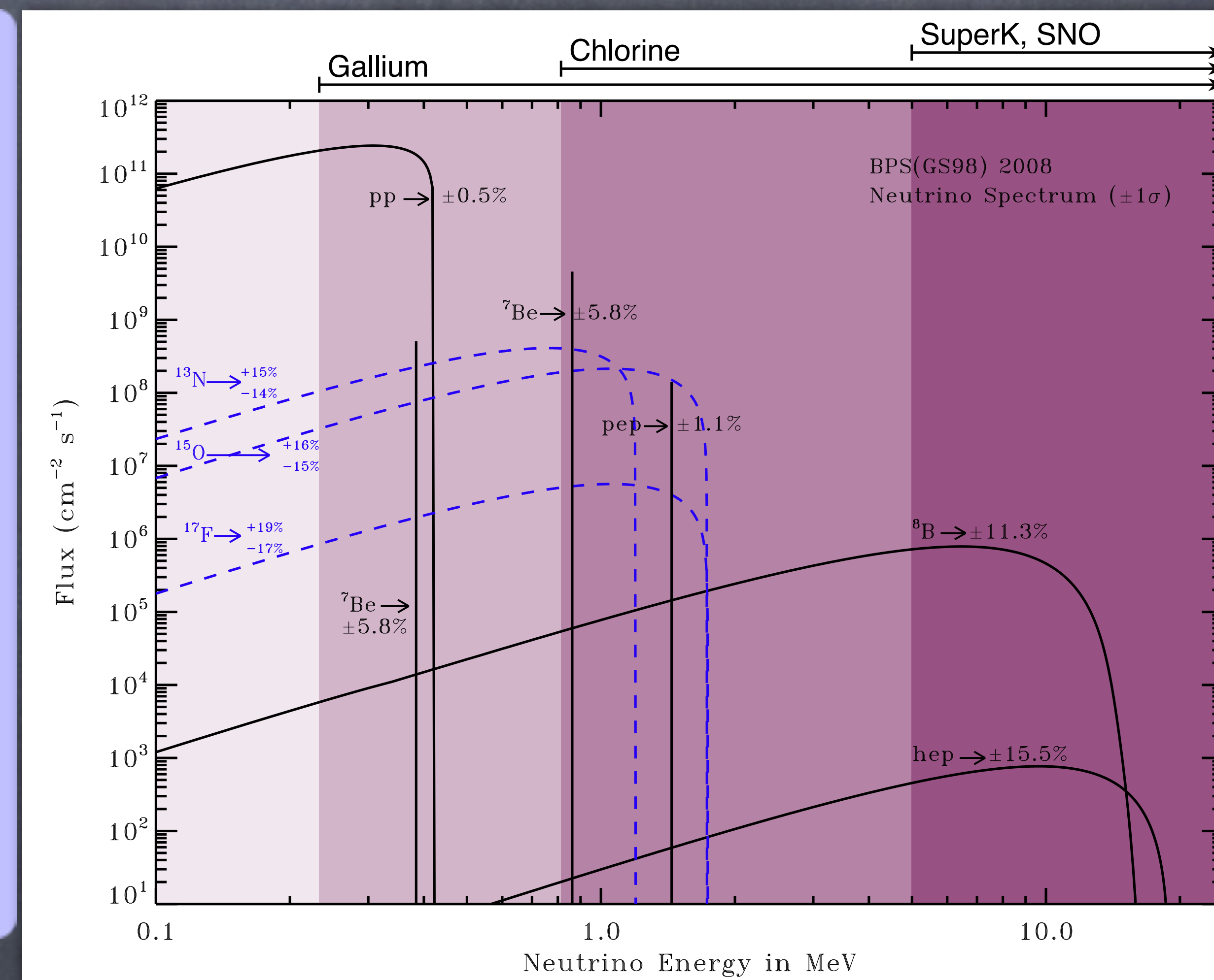
New Physics (NSI, neutrino decay, etc)?

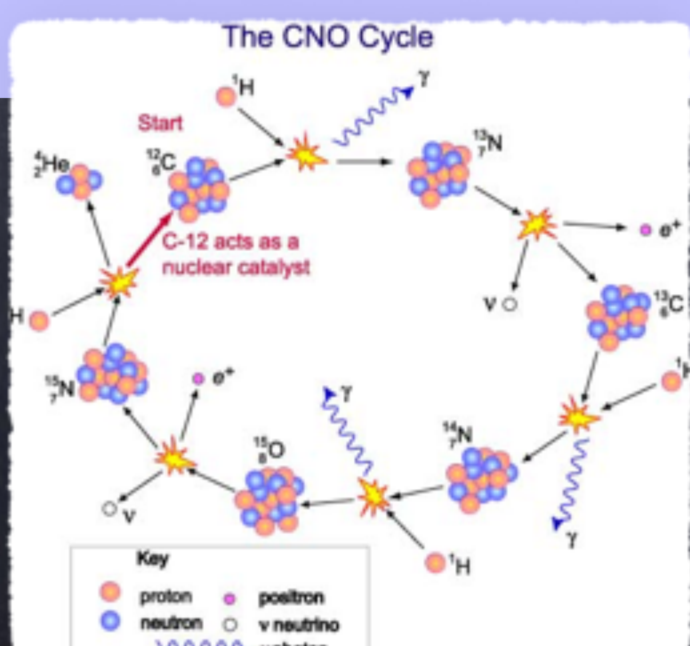
	DOMINANT DEPENDENCE	IMPORTANT DEPENDENCES
solar experiments	θ_{12}	$\Delta m^2_{21}, \theta_{13}$
reactor LBL experiments	Δm^2_{21}	θ_{12}, θ_{13}
reactor MBL experiments	θ_{13}	Δm^2_{31}
atmospheric experiments	$\Delta m^2_{31}, \theta_{23}$	θ_{13}, δ
accelerator LBL disappearance experiments	Δm^2_{31}	θ_{23}
accelerator LBL appearance experiments	θ_{13}	$\Delta m^2_{31}, \theta_{23}, \delta$

SOLAR NEUTRINOS

a nuclear fusion reactor ν_e







two mechanisms:

pp chain and CNO cycle

SOLAR NEUTRINOS

real-time experiments

radiochemical detectors

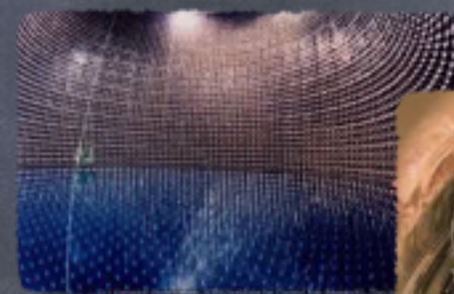
Homestake: E>0.81 MeV

SAGE: E>0.233 MeV

GALLEX/GNO: E>0.233 MeV

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

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$



Cherenkov detectors

KamiokaNDE: E>7.5 MeV

Super-Kamiokande: E>5 MeV

SNO: E>5 MeV

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

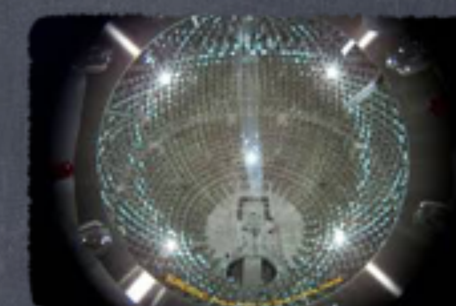
CC: $\nu_e + d \rightarrow p + p + e^-$

NC: $\nu_x + d \rightarrow n + p + \nu_x$

Scintillator detectors

Borexino: E>0.2 MeV

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



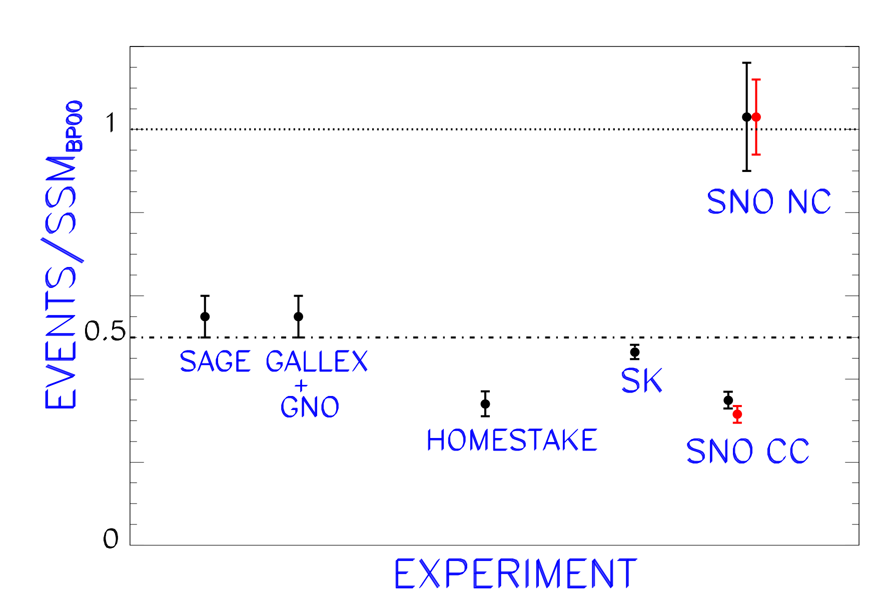
M. Koshiba

1987: Kamiokande
First real-time measurement of the solar neutrino flux (SN1987A, atmospheric anomaly)

2002: R. Davis Jr, M. Koshiba and R. Giacconi

SOLAR NEUTRINOS

From M. Maltoni

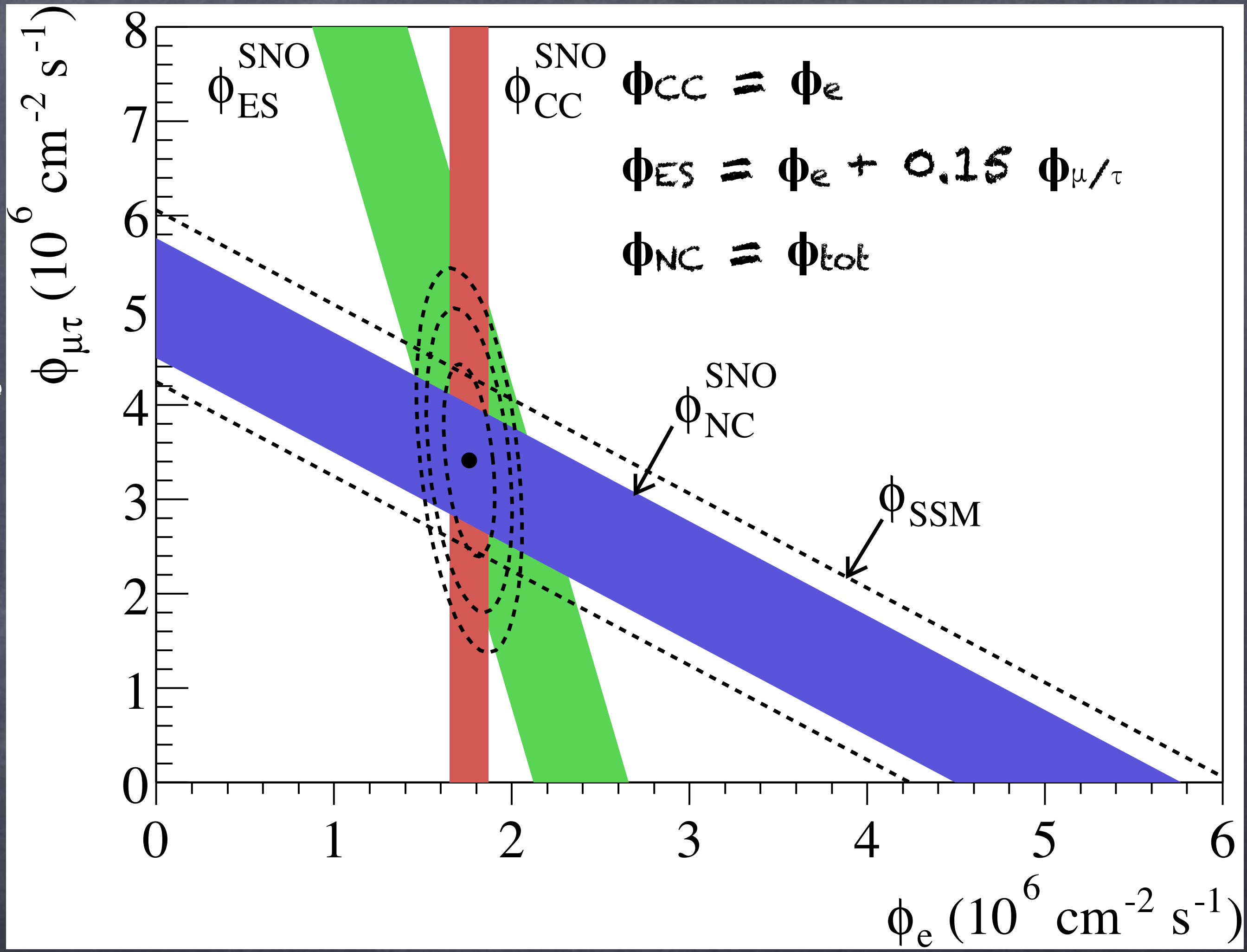


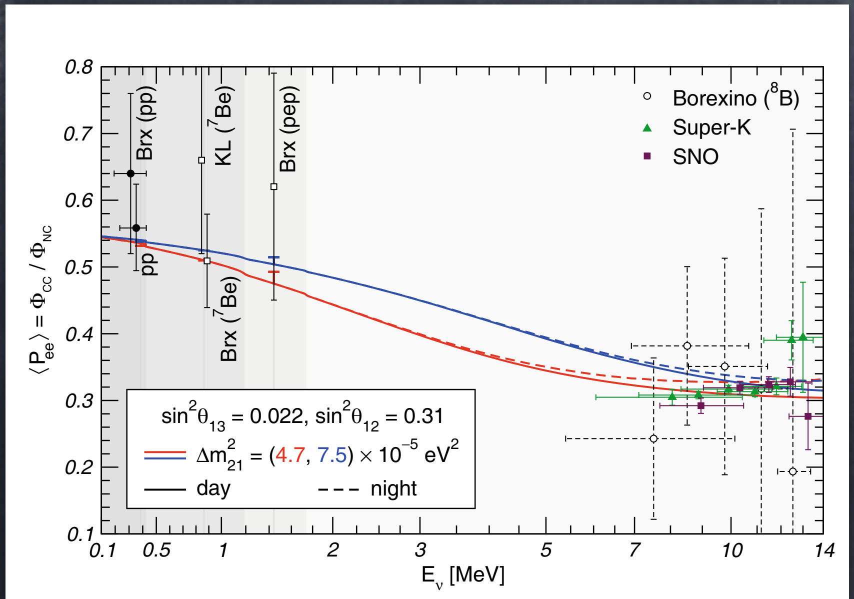
Energy-dependent suppression of the flux:

$\phi_{measured} \sim 0.3-0.6$

Survival probability (P_{ee}) reduces to a two-neutrino problem in matter

$\phi_e = \phi_{tot} P_{ee}$





M. Maltoni and A. Yu Smirnov, Eur. Phys. J. A 52:87, 2016

2002: A. B. McDonald

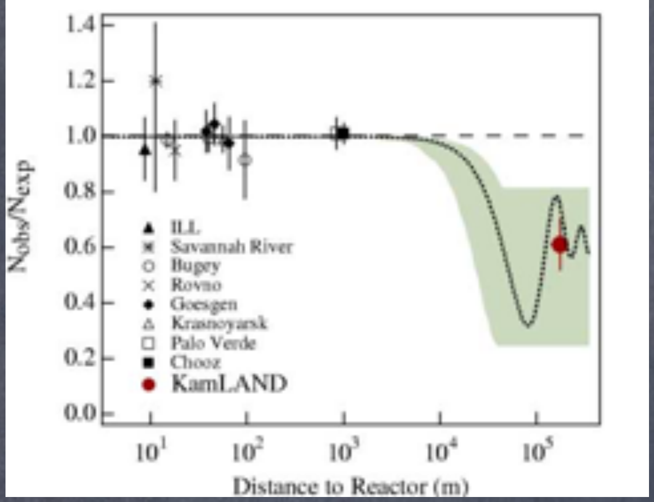
Discovery of neutrino conversion by SNO

2015: T. Kajita and A. B. McDonald

REACTOR ANTINEUTRINOS

$$P_{ee} \approx 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

$\bar{\nu}_e$



nuclear fission reactors

~6 antineutrinos per fission or

2×10^{20} ν/s GW

Four main isotopes:

^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu

$$\bar{\nu}_e + p \rightarrow n + e^+ \qquad E_{th} = 1.8\ \text{MeV}$$

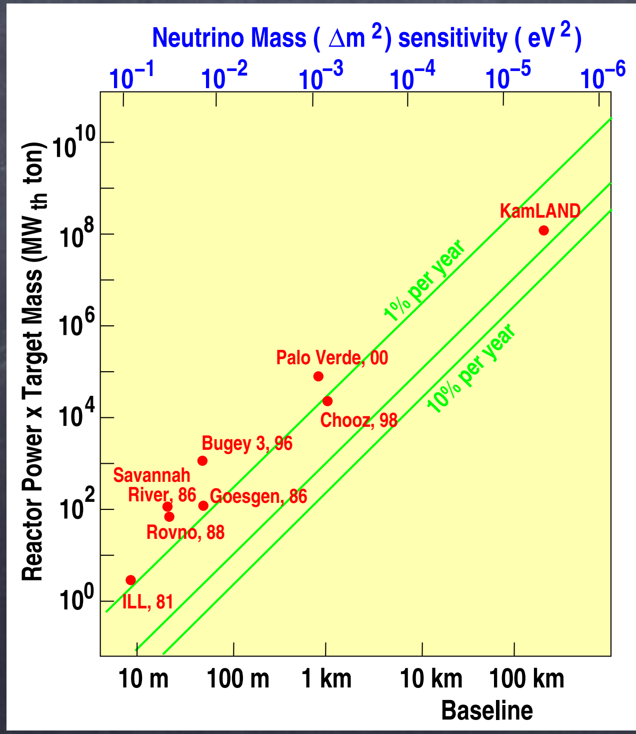
1956-1959: Savannah River
First neutrino detection

1980's: ILL, Gösgen, Rovno
1990's: Krasnoyarsk, Savannah River, Bugey
Short baselines

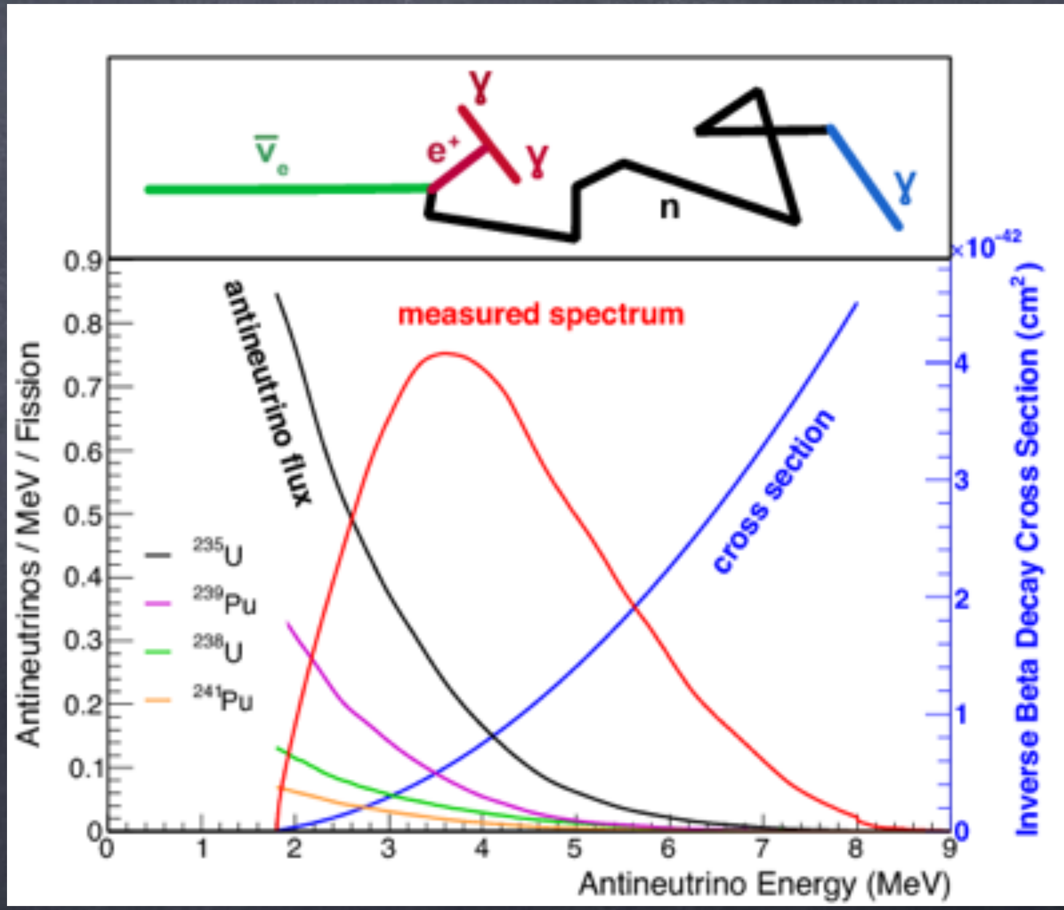
1999: CHOOZ
2000: Palo Verde
First limits on θ_{13}

2002: KamLAND
Discovery of antineutrino oscillations

2011-2012: Daya Bay, RENO, D-CHOOZ
Measurement of θ_{13}



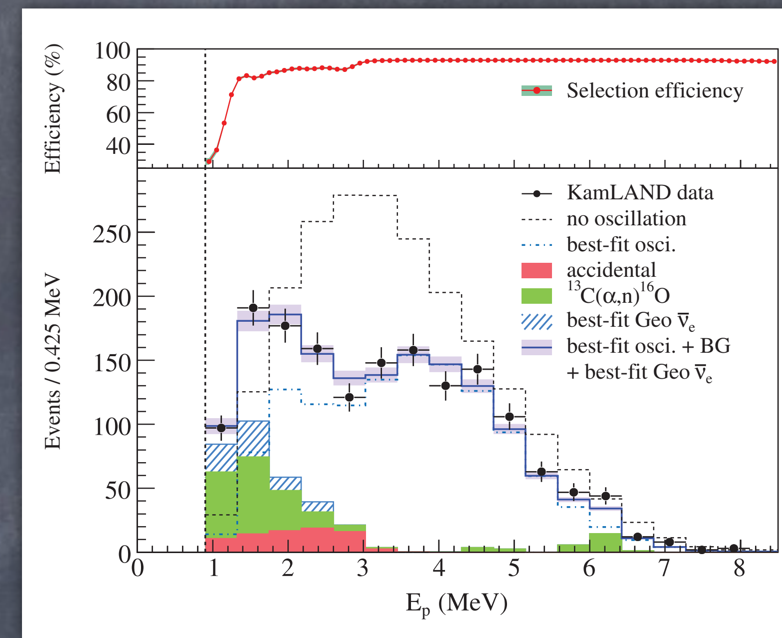
C. Bemporad, G. Gratta and P. Vogel, Rev. Mod. Phys. 74:297, 2002



P. Vogel, L. Wen and C. Zhang, Nature Commun. 6:6935, 2015

LBL reactor antineutrinos $\bar{\nu}_e$

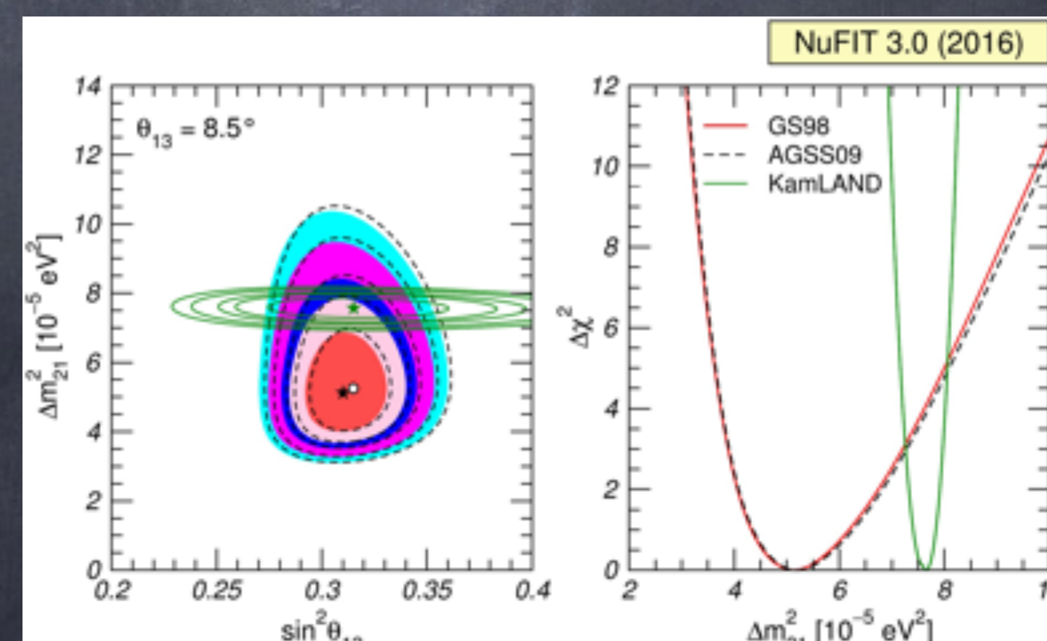
multiple nuclear fission reactors
at an average baseline of ~180 km



S. Abe et al. [KamLAND Collaboration], Phys. Rev. Lett. 100:221803, 2008

Survival probability (P_{ee}) reduces to a two-neutrino problem in vacuum for $\Delta m^2_{31} \gg E/L$

$$P_{ee} \approx 1 - \frac{1}{2}\sin^2(2\theta_{13}) - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



I. Esteban et al., JHEP 1701:087, 2017

2σ tension on Δm^2_{21}
between solar and KamLAND data

MBL reactor antineutrinos

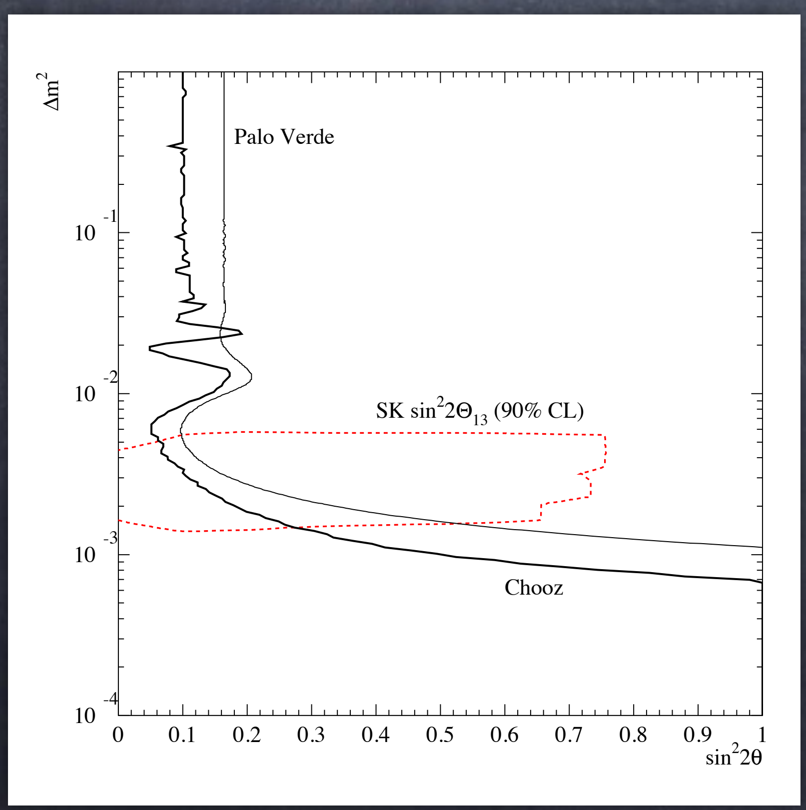
nuclear fission reactors at a average baselines of ~1 km

Survival probability (P_{ee}) reduces to a two-neutrino problem in vacuum for $\Delta m^2_{21} \ll E/L$

$$P_{ee} \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

until 2011

only limits

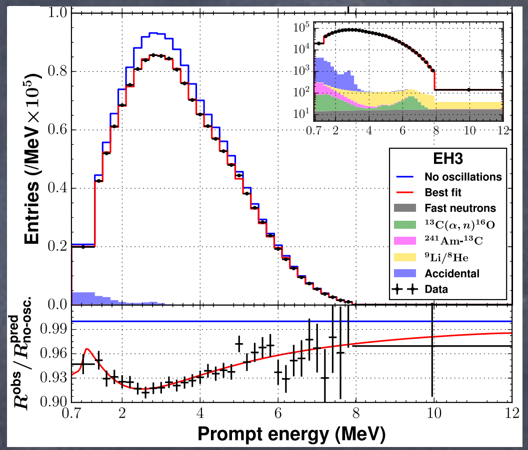


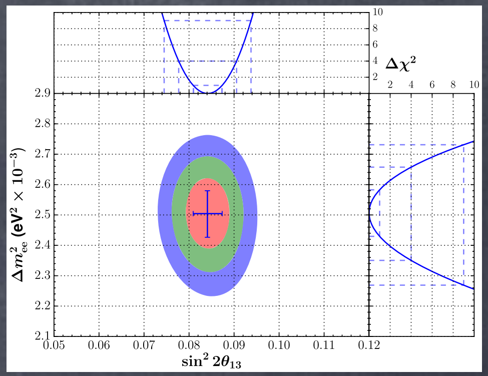
C. Bemporad, G. Gratta and P. Vogel, Rev. Mod. Phys. 74:297, 2002

since 2012

determination of θ_{13}

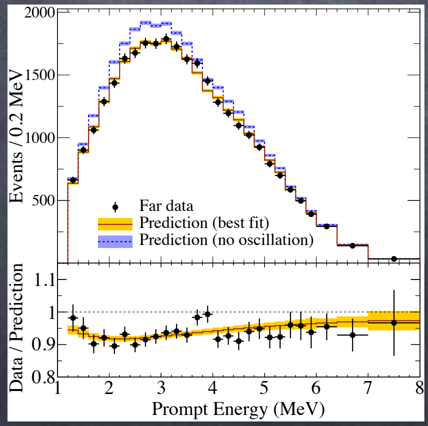
Daya Bay





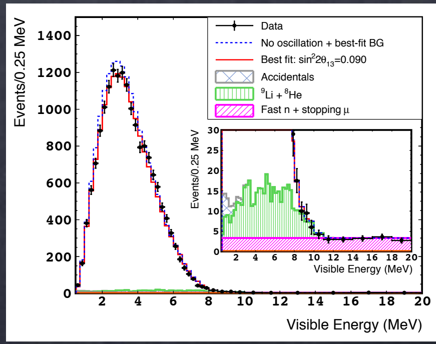
F. P. An et al. [Daya Bay Col.], Phys. Rev. D95:072006, 2016

RENO



S. H Seo et al. [RENO Col.], arXiv:1610.04326

D-Chooz



Y. Abe et al. [Double Chooz Col.], JHEP 1410:086, 2014

Accelerator neutrinos

Two types of experiments: disappearance and appearance

- produced from π decay
- baselines > 100 km
- energies ~ GeV
- $\nu_\mu \rightarrow \nu_\mu$
- $\nu_\mu \rightarrow \nu_e$

$$\nu_\mu / \bar{\nu}_\mu$$

$$\nu_l + N \rightarrow l + X$$

Disappearance probability ($P_{\mu\mu}$) reduces to a two-neutrino problem in vacuum for $\Delta m^2_{21} \ll E/L$

$$P_{\mu\mu} \approx 1 - \left(\cos^4\theta_{13}\sin^2(2\theta_{23}) + \sin^2\theta_{13}\sin^2\theta_{23}\right)\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

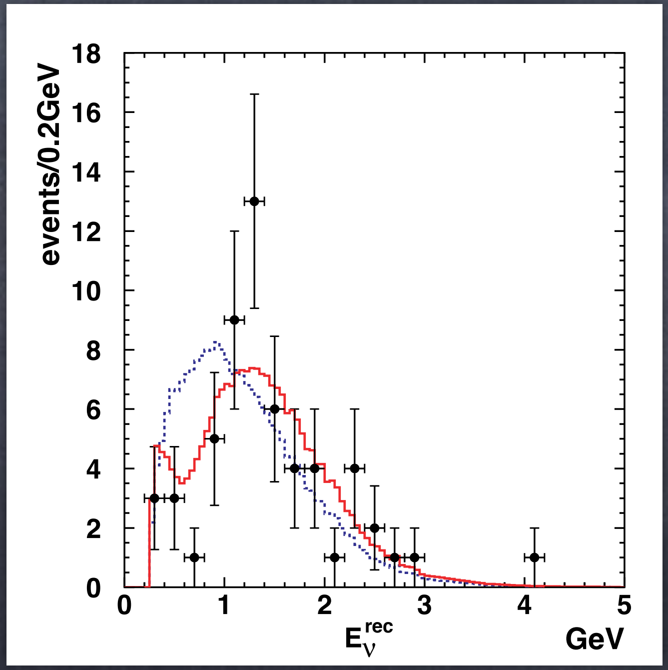
Appearance probability ($P_{\mu e}$) incorporates genuine three-neutrino effects

Accelerator neutrinos: disappearance

K2K

L ~ 250 km
E ~ 1 GeV
only neutrinos

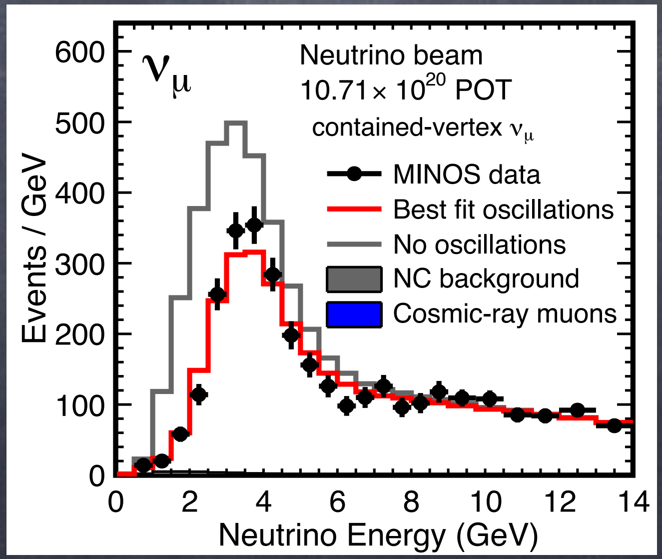
2000: K2K
First positive measurement of neutrino oscillations in which both the source and detector were under control

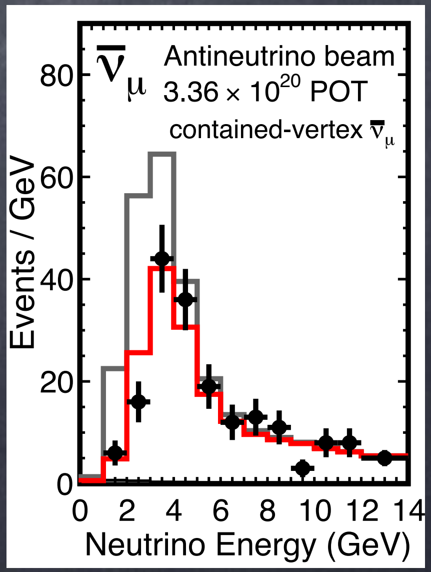


M. H. Ahn et al. [K2K Col.], Phys. Rev. D74:072003, 2006

MINOS

L ~ 735 km
E ~ few GeV
two iron detectors:
Near (1 ton) and
Far (5.4 kton)





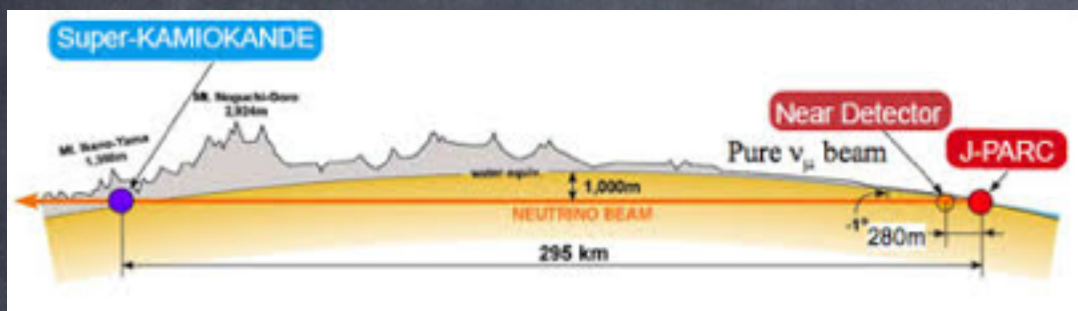
J. Evans [MINOS Col.], Adv. High Energy Phys. 2013:182537, 2013

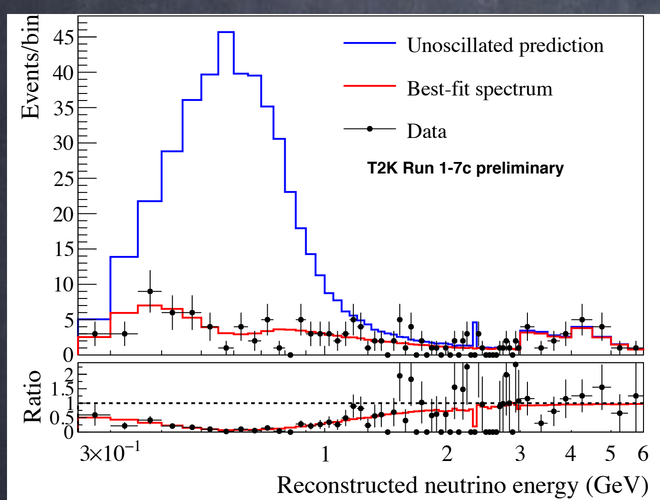
Accelerator neutrinos: disappearance

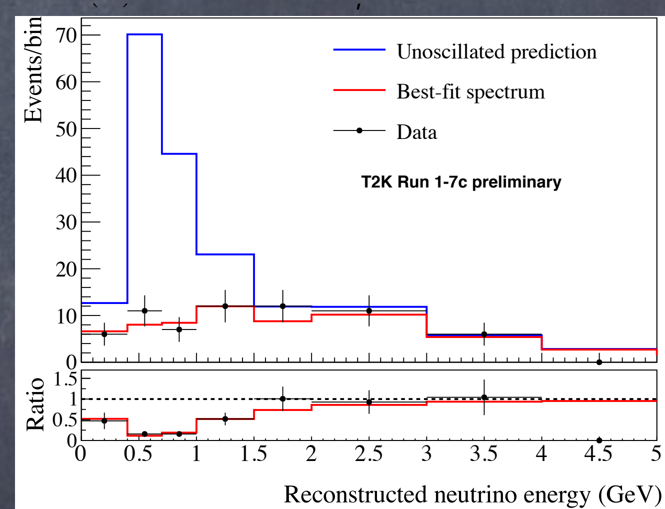
T2K

L ~ 295 km

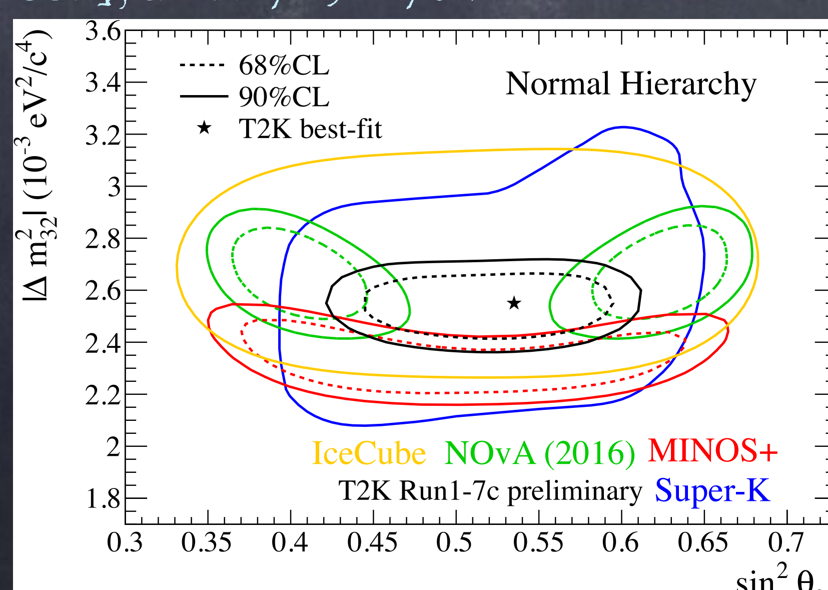
E ~ 0.6 GeV







K. Duffy [T2K Col.], arXiv:1705.01764

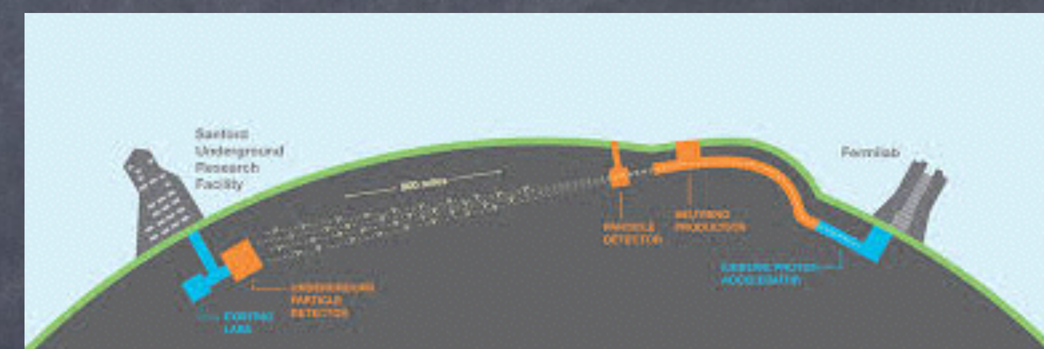


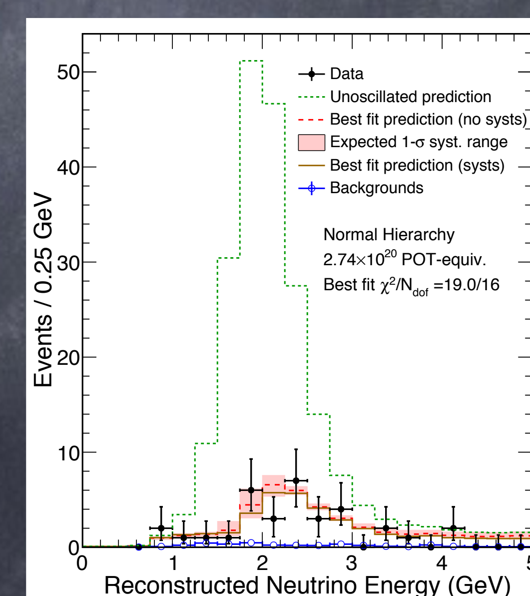
NOvA

L ~ 735 km

E ~ few GeV

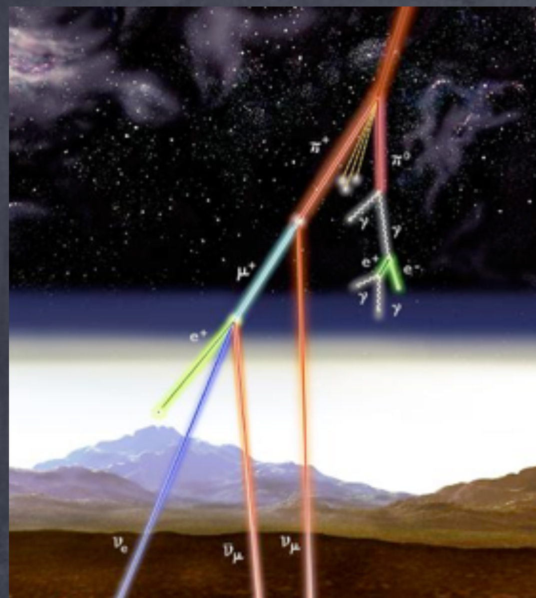
two scintillator detectors: Near (0.2 ton) and Far (14 kton)





P. Adamson et al. [NOvA Col.], Phys. Rev. D93:051104, 2016

ATMOSPHERIC NEUTRINOS

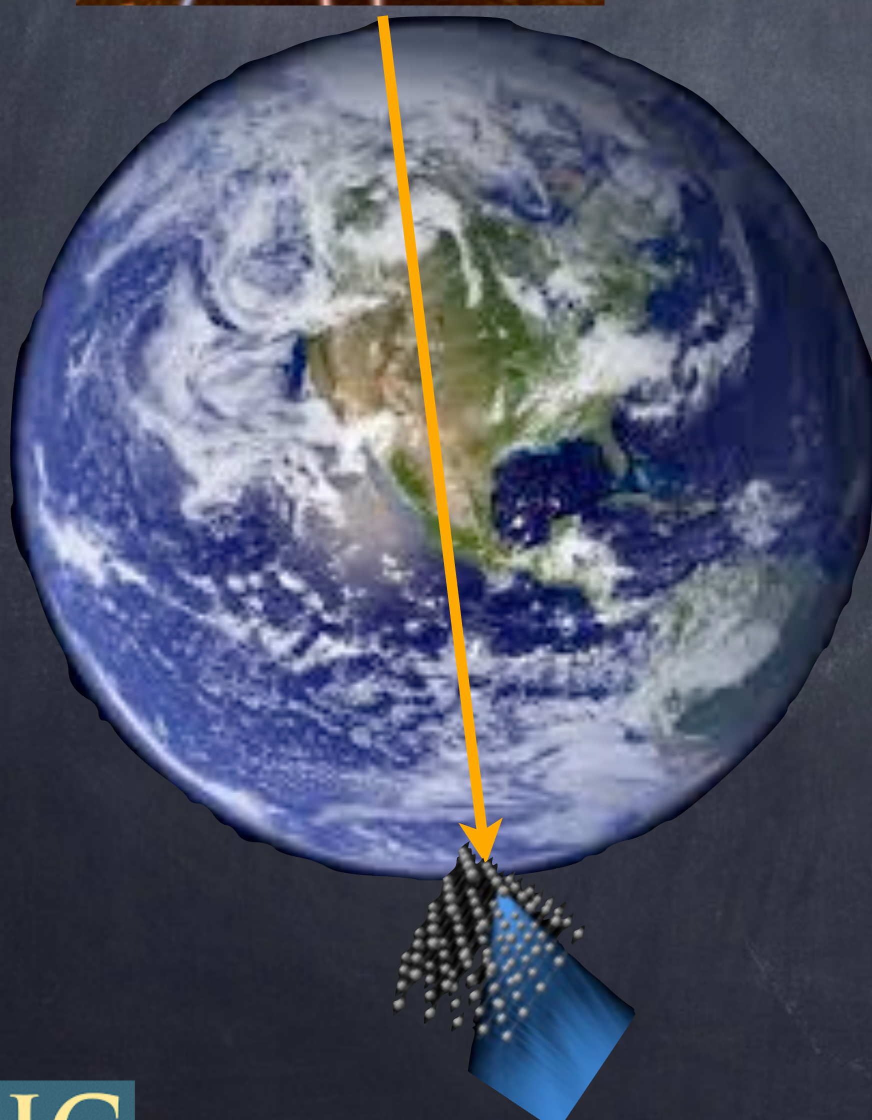


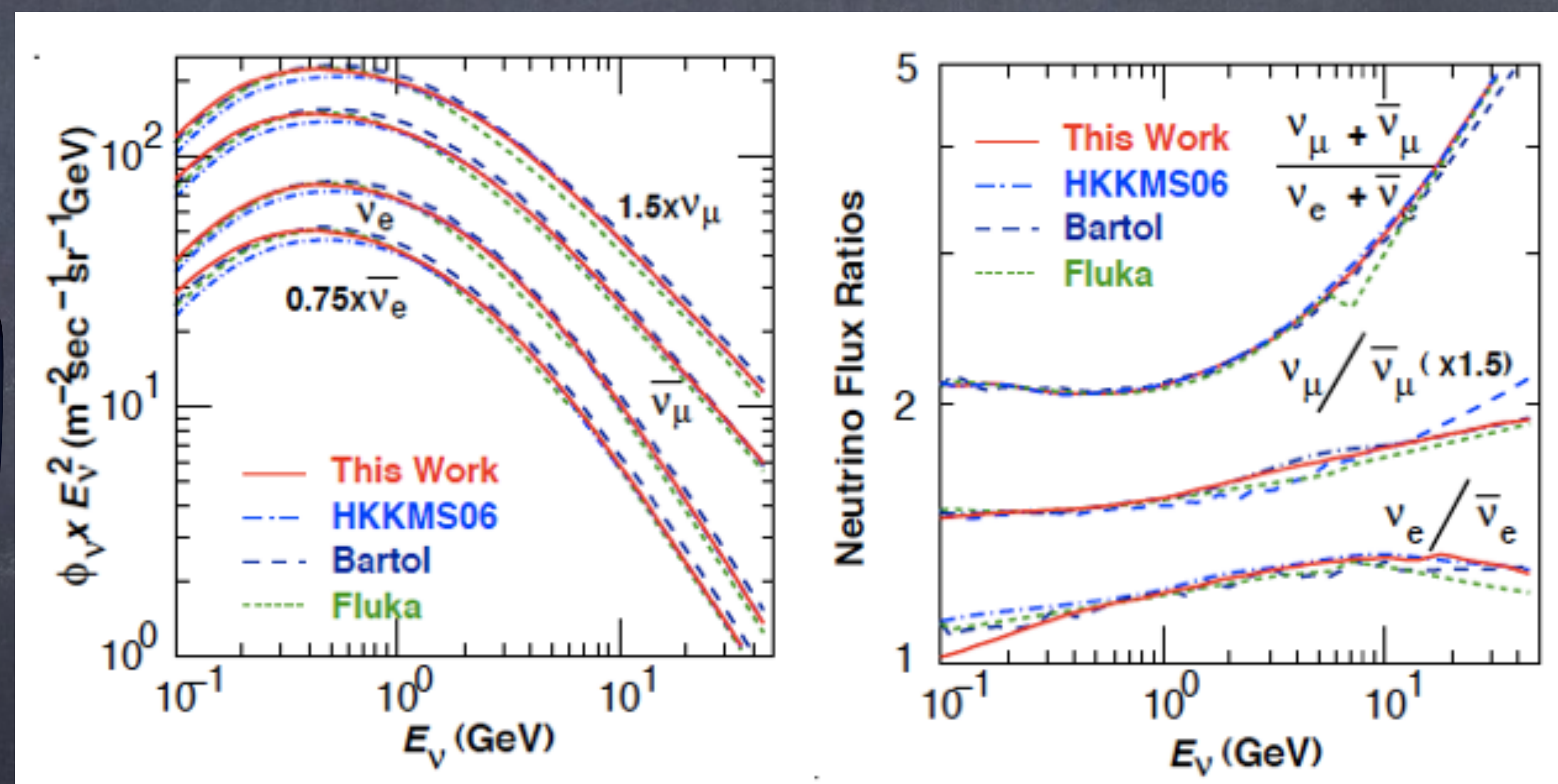
$$p + X \rightarrow \pi^{\pm} / K^{\pm} + Y$$

$$\mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Huge range of energies and baselines





M. Honda, T. Kajita, K. Kasahara and S. Midorikawa, Phys. Rev. D83:123001, 2011

G. D. Barr, T. K. Gaisser, P. Lipari, S. Robbins and T. Stanev, Phys. Rev. D70:023006, 2004
G. Battistoni, A. Ferrari, T. Montarulli and P. R. Sala, Astropart. Phys. 19:269, 2003

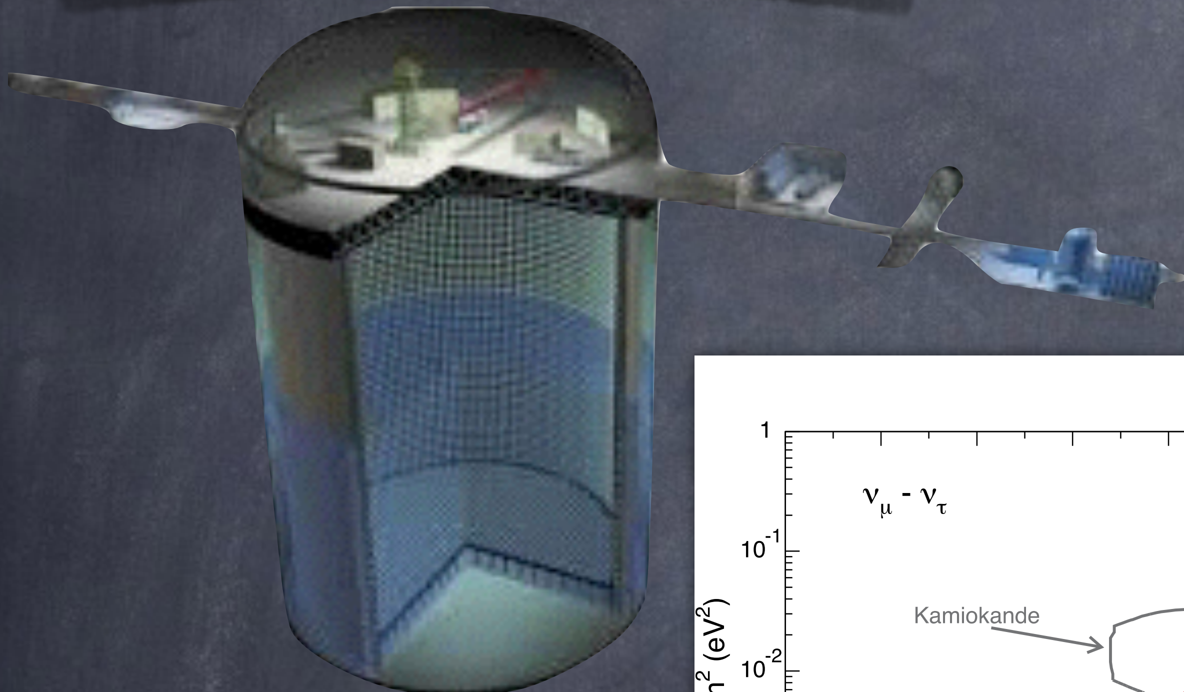
ATMOSPHERIC NEUTRINOS ν_μ / ν_e

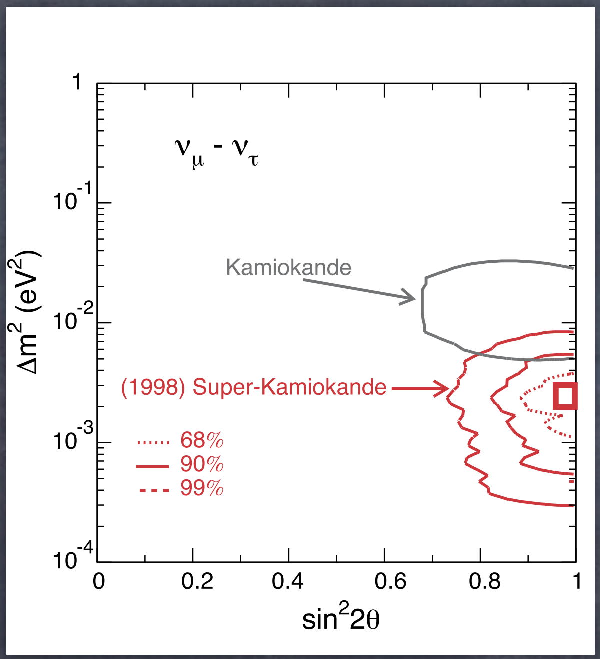
Super-Kamiokande

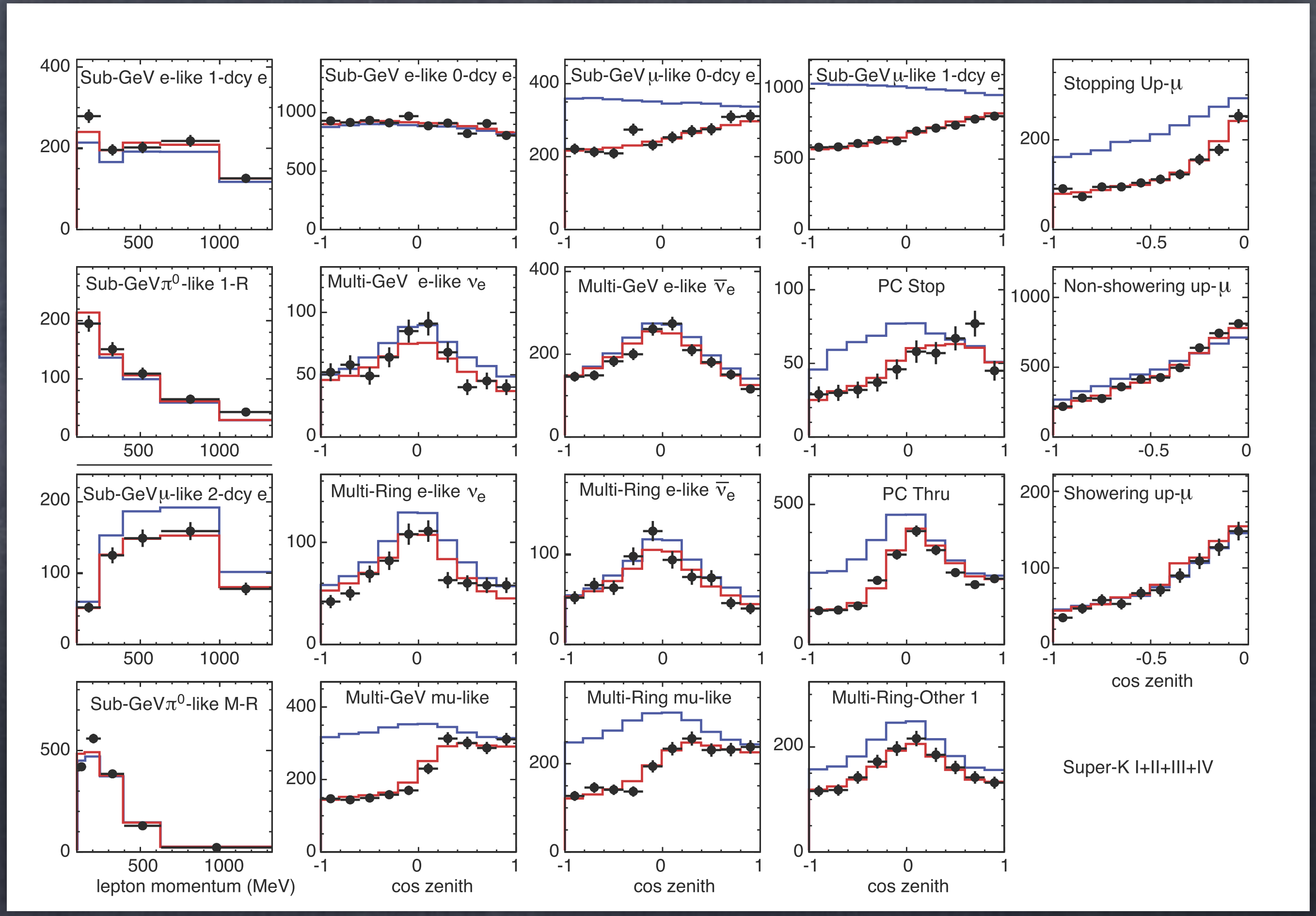
leading experiment during the last 20 years

50 kton water-Cherenkov detector

$\nu_l + N \rightarrow l + X$







1998: T. Kajita
Discovery of neutrino oscillations by SK

2015: T. Kajita and A. B. McDonald

T. Kajita et al. [Super-Kamiokande Collaboration], Nucl. Phys. B908:14, 2016

Beyond the two-neutrino picture

- determination of the θ_{23} octant
- determination of the mass hierarchy
- determination of CP violation
- improvement of two-neutrino analyses

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad A \equiv \frac{V\,L}{2\Delta} \qquad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

upper sign: neutrinos
lower sign: antineutrinos

appearance probability in accelerator experiments

ATMOSPHERIC TERM

$$P_{\mu e} \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \frac{\sin^2\left((1 \mp A)\Delta\right)}{(1 \mp A)^2}$$

INTERFERENCE TERM

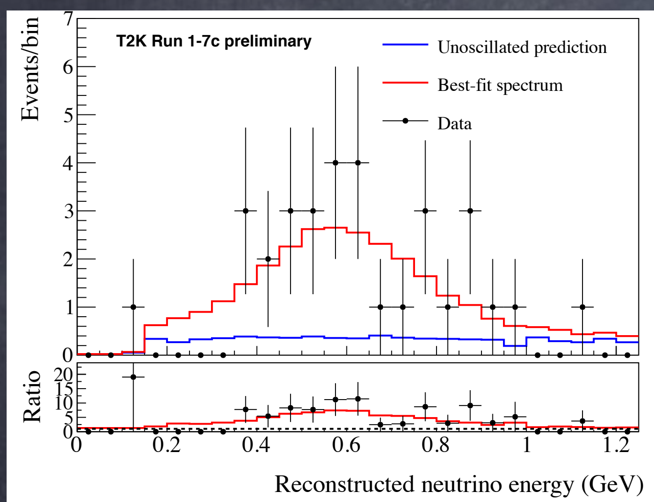
$$+ \alpha \sin(2\theta_{13}) \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23}) \frac{\sin(A\Delta)}{A} \frac{\sin\left((1 \mp A)\Delta\right)}{(1 \mp A)} \cos(\Delta \pm \delta)$$

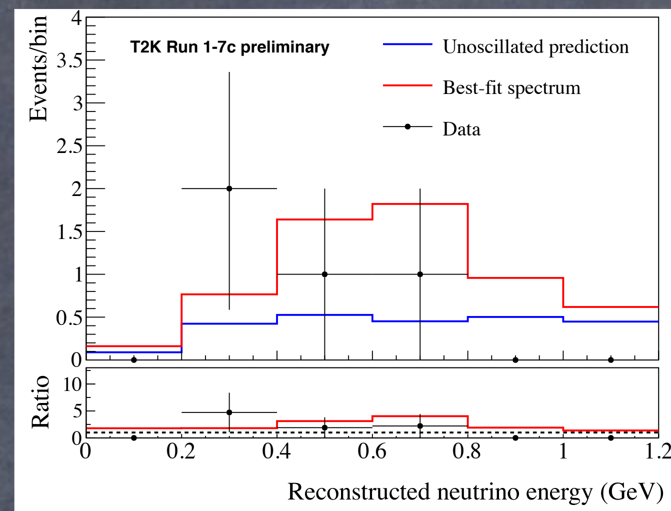
$$+ \alpha^2 \cos^2\theta_{23} \sin^2(2\theta_{12}) \frac{\sin^2(A\Delta)}{A^2}$$

SOLAR TERM

Accelerator neutrinos: appearance

T2K

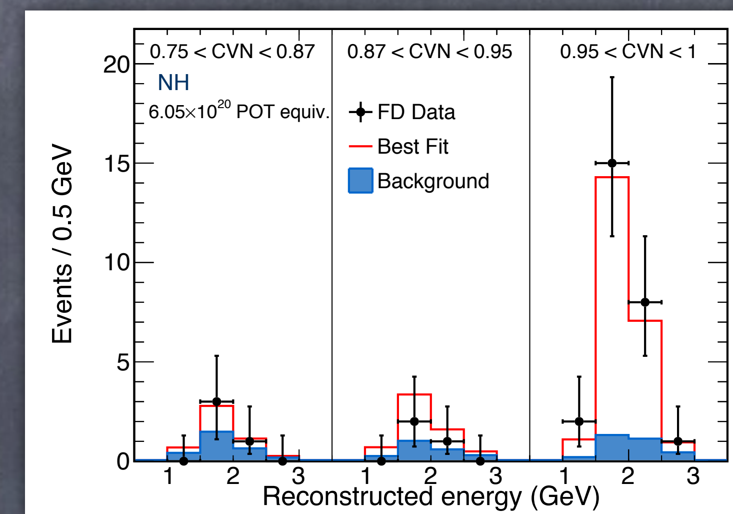




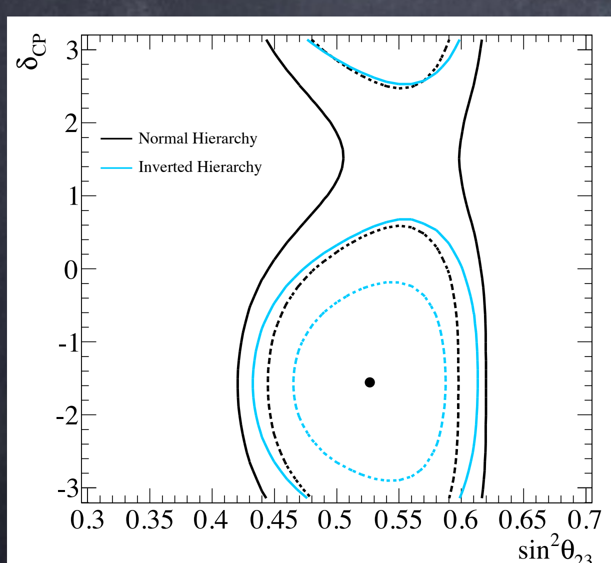
K. Duffy [T2K Col.], arXiv:1705.01764

NOvA

33 ν_e candidates and 8 expected from background



P. Adamson et al. [NOvA Col.], Phys. Rev. Lett. 118:231801, 2017



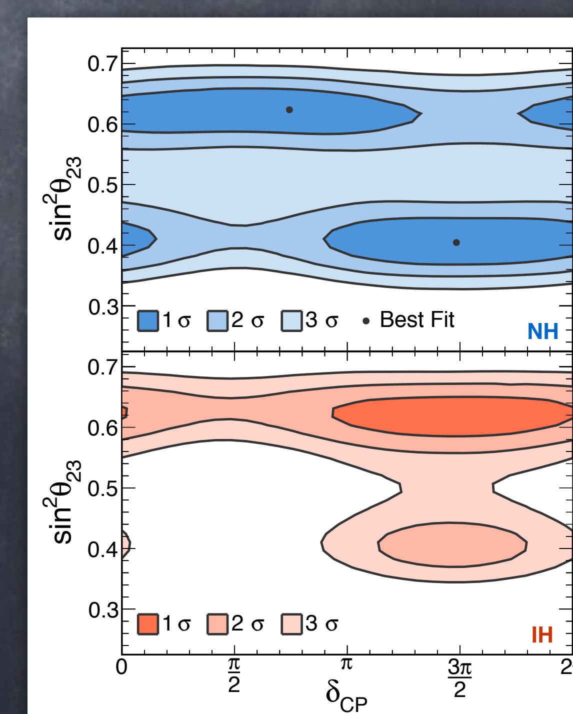
K. Abe et al. [T2K Col.], Phys. Rev. D91:072010, 2015

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

more ν_e than expected

less $\bar{\nu}_e$ than expected $\Rightarrow$

significance of $\delta=3\pi/2$ and NH larger than expected



ATMOSPHERIC NEUTRINOS: MASS HIERARCHY

θ_{13} drives subdominant $\nu_\mu \to \nu_e$ transitions in atmospheric neutrinos traversing the Earth with energies between 1-10 GeV

$$\frac{F_e}{F_e^0} - 1 \approx \left(r \sin^2\theta_{23} - 1\right) P_{2\nu}\left(\Delta m^2_{31}, \theta_{13}\right)$$

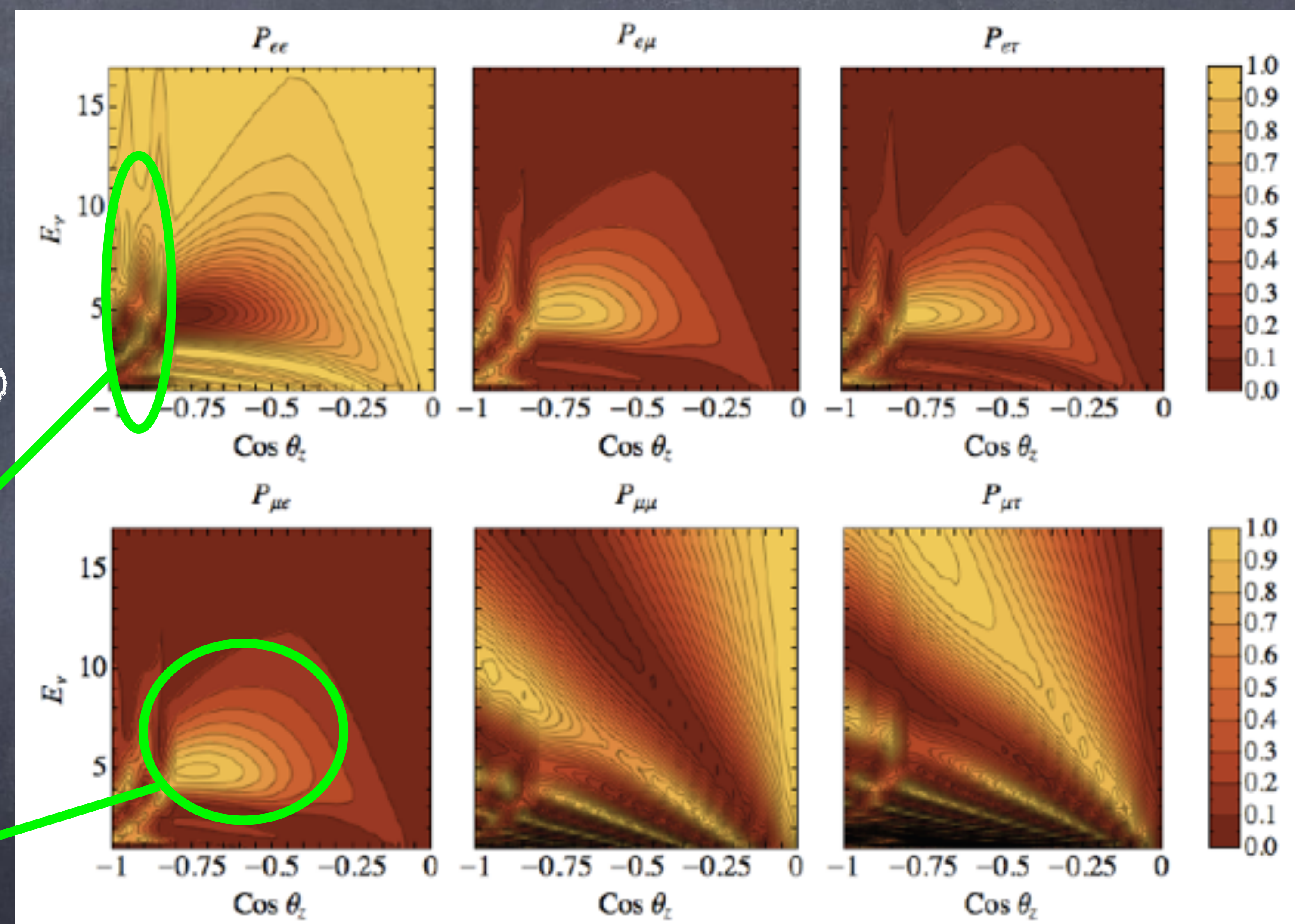
$$+ \left(r \cos^2\theta_{23} - 1\right) P_{2\nu}\left(\Delta m^2_{21}, \theta_{12}\right)$$

$$+ \left(\delta - \text{dependent term}\right)$$

$$r = \frac{F_\mu^0}{F_e^0} \approx 2 \text{ (sub-GeV); } 2.6-4.5 \text{ (multi-GeV)}$$

mantle-core effect

mantle effect



E. Kh. Akhmedov, S. Razzaque and A. Yu. Smirnov, JHEP 1302:082, 2013

only present for neutrinos if NH and for antineutrinos if IH

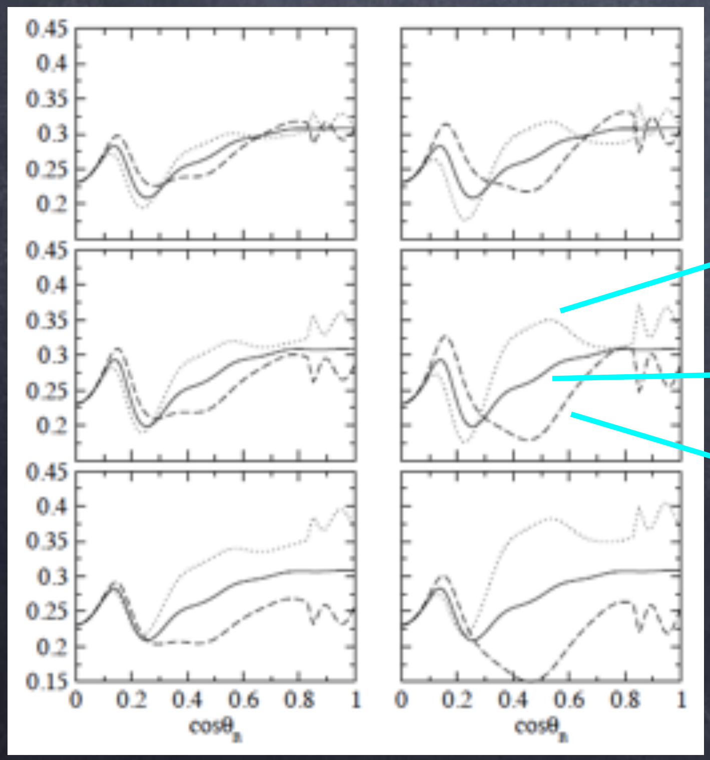
ATMOSPHERIC NEUTRINOS: MASS HIERARCHY

Two types of detectors

with charge discrimination

magnetized detectors

$$A_{\mu^-\mu^+} = \frac{N_{\mu^-} - N_{\mu^+}}{N_{\mu^-} + N_{\mu^+}}$$



SPR and S. T. Petcov, Nucl. Phys. B712:392, 2005

without charge discrimination

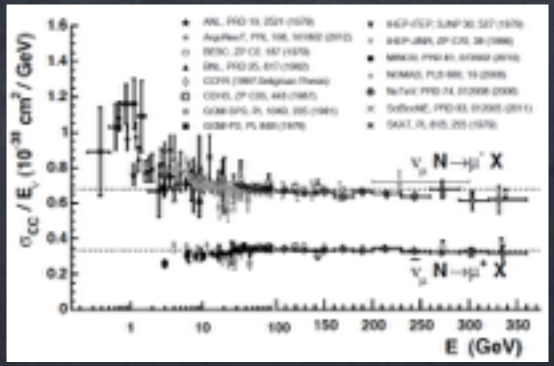
neutrinos are not distinguished from antineutrinos

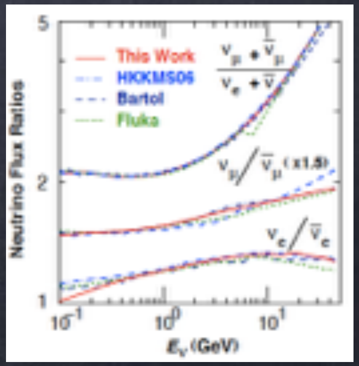
But at first order...

$$P^{NH} = \bar{P}^{IH}$$

how can we determine the hierarchy?

cross sections and fluxes are different





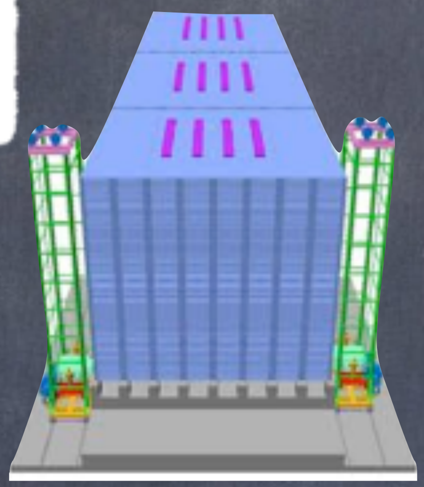
ATMOSPHERIC NEUTRINOS: MASS HIERARCHY

Future detectors

with charge discrimination

without charge discrimination

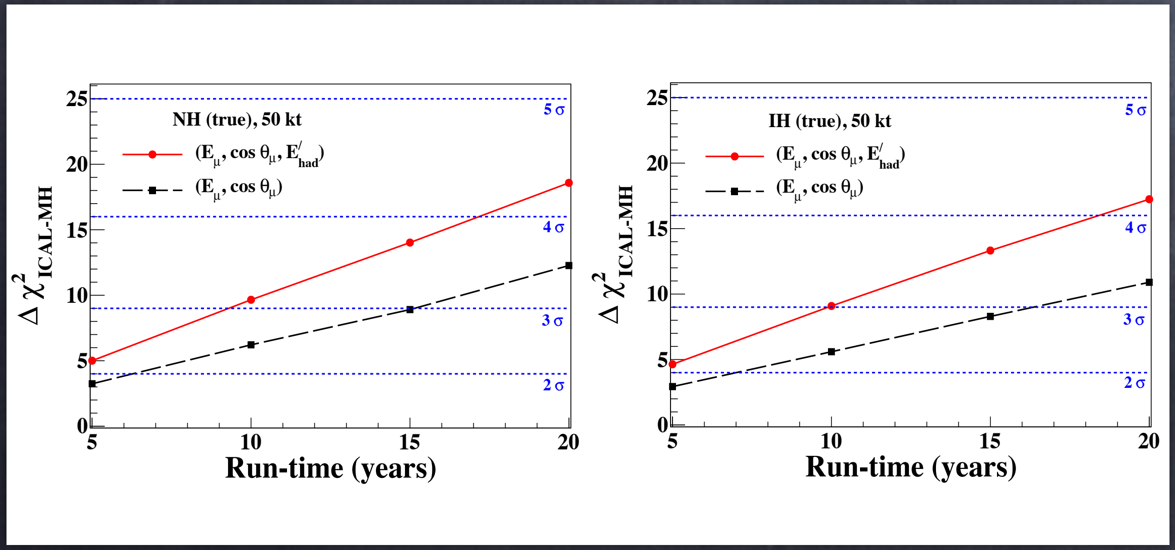
ICAL@INO: 50 kton



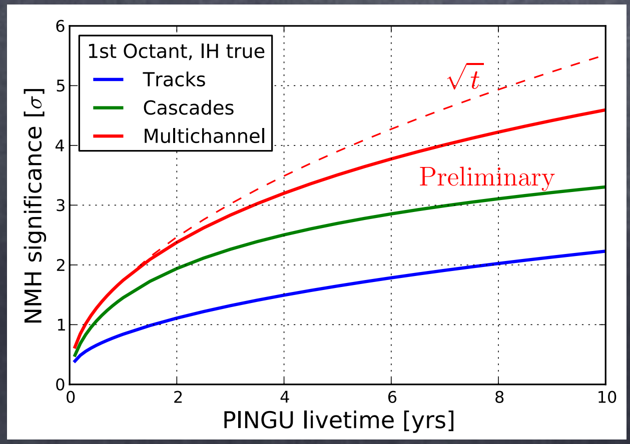
PINGU

ORCA

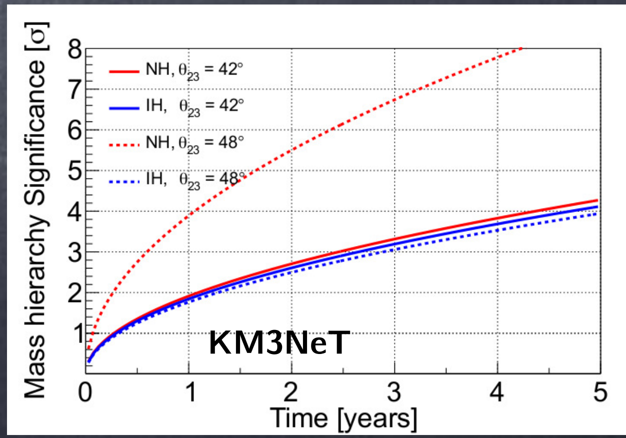
few Mton



S. Ahmed et al. [ICAL Col.], Pramana 88:79, 2017



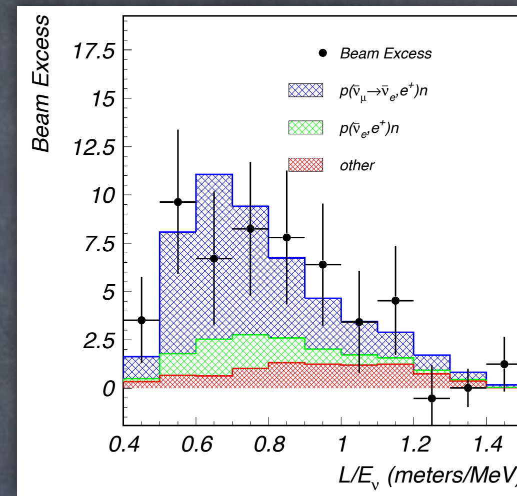
M. G. Aartsen et al. [PINGU Col.], arXiv:1401.2046



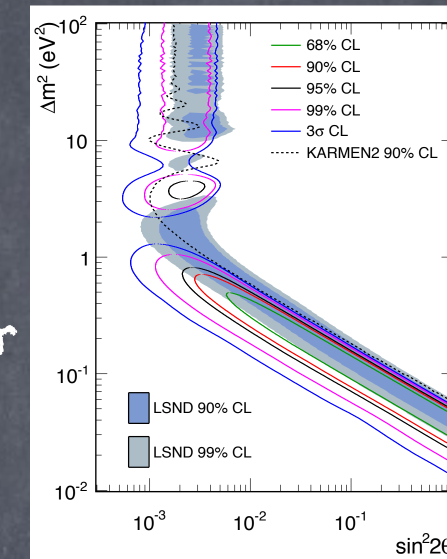
S. Adrian-Martinez et al. [KM3NeT Col.], J. Phys. G43:084001, 2016

STERILE NEUTRINOS?

The LSND experiment observed ν_e appearance at short distance



MiniBooNE is compatible with LSND...
but not with other short-baseline experiments

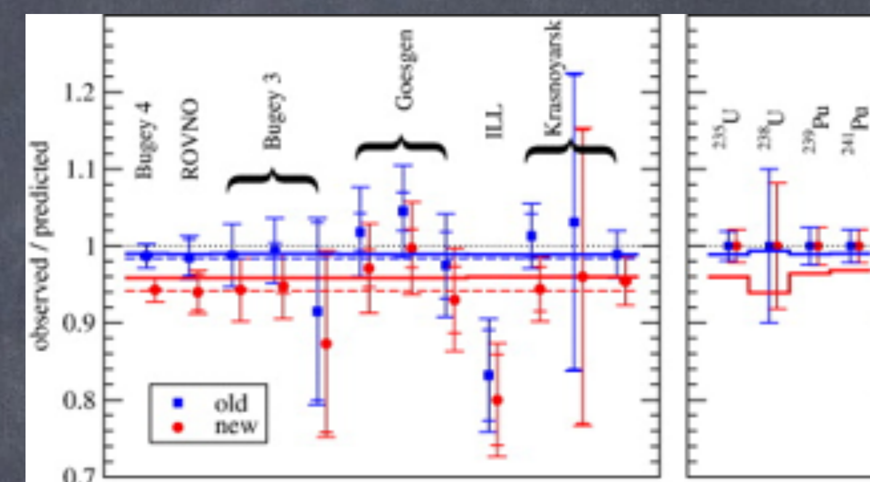


$$P_{LSND} \propto |U_{e4}|^2 |U_{\mu 4}|^2 \qquad P_{SB} \propto |U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right)$$

After reevaluating the reactor neutrino fluxes, predictions were lower by about 3.5%

Th. A. Mueller, Phys. Rev. C83:054615, 2011

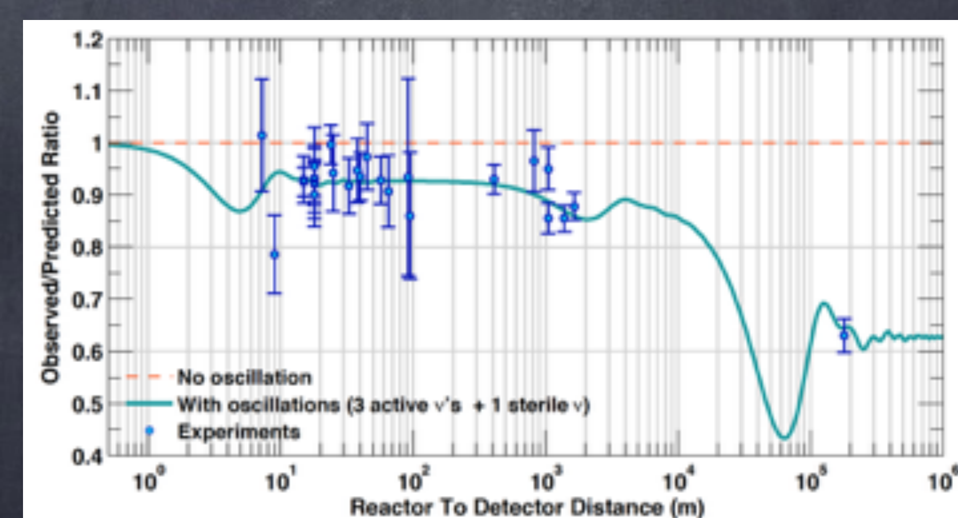
P. Huber, Phys. Rev. C84:024617, 2011



An sterile neutrino at the eV scale?

Incompatible with short-baseline and atmospheric neutrinos

Problems in cosmology



NON-Standard Interactions?

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$H_\nu = H_{vac} + H_{mat}$$

$$H_{\bar{\nu}} = \left(H_{vac} - H_{mat}\right)^*$$

$$-\mathcal{L}_{NSI} = \sqrt{2}G_F\varepsilon^{fP}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu\nu_{L\beta}\right)\left(\bar{f}\gamma^\mu f_P\right)$$

$$\varepsilon^{f}_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$$

The most general matter potential

(after subtraction of a term proportional to identity)

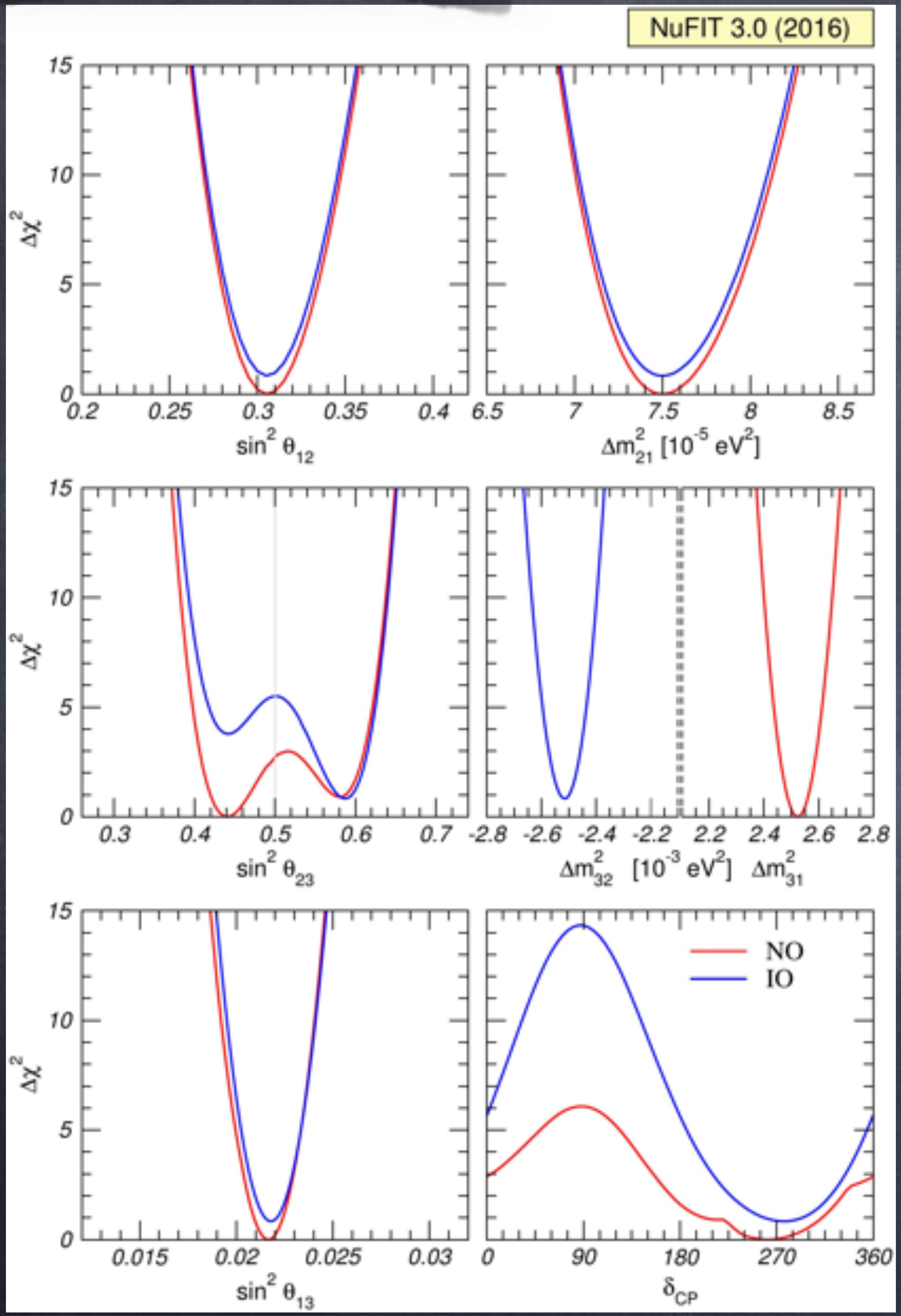
$$H_{mat} = \sqrt{2}\ G_F N_e(x)\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} + \sqrt{2}\ G_F\sum_{f=e,u,d}N_f(x)\begin{pmatrix}\varepsilon^f_{ee}&\varepsilon^f_{e\mu}&\varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu}&\varepsilon^f_{\mu\mu}&\varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau}&\varepsilon^{f*}_{\mu\tau}&\varepsilon^f_{\tau\tau}\end{pmatrix}$$

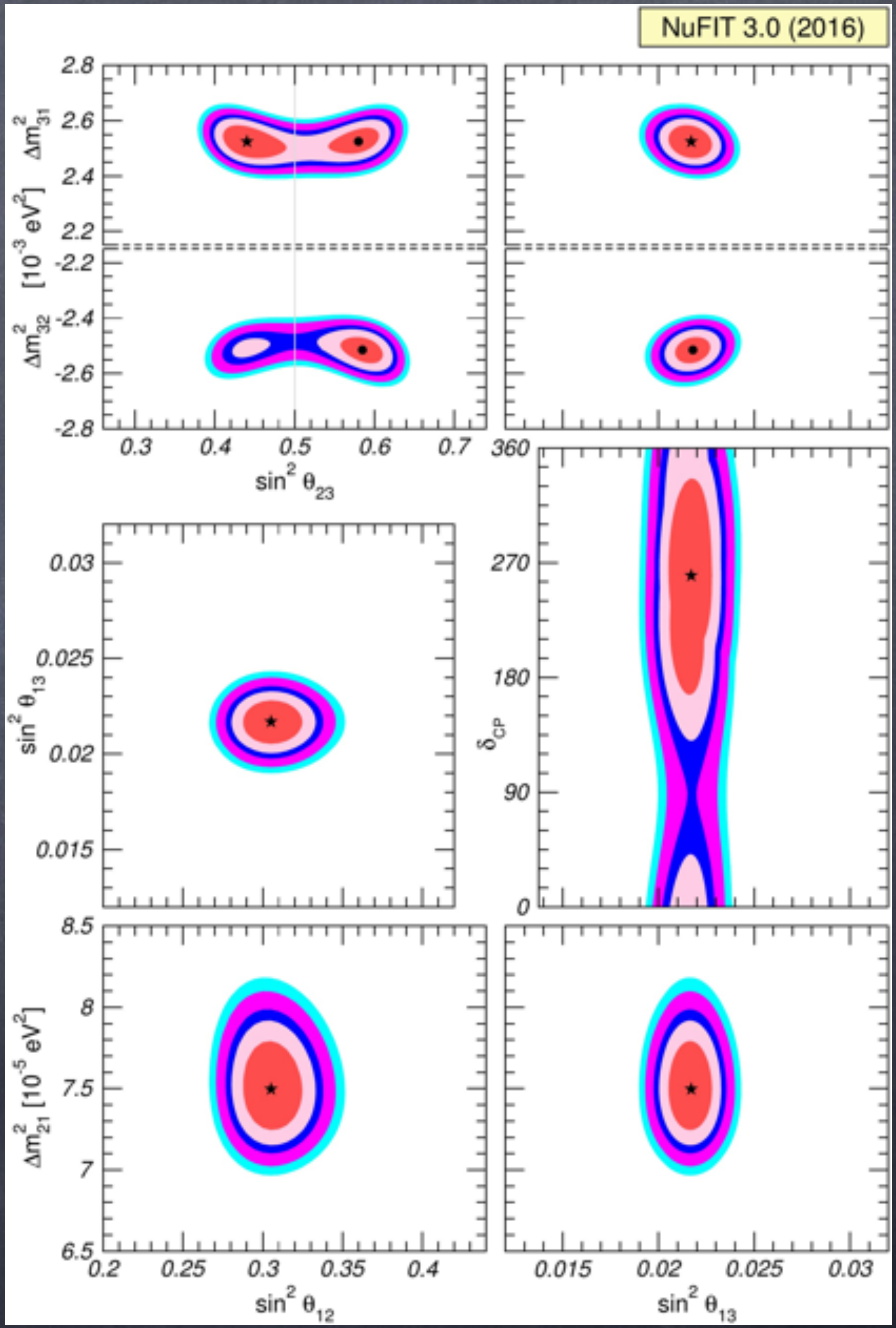
Potential effects in all experiments

Parameter degeneracies

Few percent errors

CURRENT STATUS





I. Esteban et al., JHEP 1701:087, 2017