Neutrino physics (II+III)

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Neutrino parameters: what do we know?

Physical mass and mixing parameters in the lepton sector

$$\frac{m_{\nu_i}}{2}\nu_{iL}\nu_{iL} + m_{e_i}\overline{e_{iR}}e_{iL} \qquad j^{\mu}_{\mathrm{c,lep}} = U^{\dagger}_{ij}\overline{\nu}_{iL}\gamma^{\mu}e_{jL}$$

$$m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3},\ \theta_{23},\ \theta_{12},\ \theta_{13},\ \delta,\ \alpha,\ \beta$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$$0 \le \theta_{23}, \theta_{12}, \theta_{13} \le \frac{\pi}{2}, \quad 0 \le \delta < 2\pi, \quad 0 \le \alpha, \beta < \pi$$

Accessible to oscillations

Charged sector

Not accessible to oscillations

$m_{e,\mu,\tau}$

Δm_{12}^2

$|\Delta m_{23}^2|$

$\text{sign}(\Delta m_{23}^2)$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

m_{lightest}

α

β

$$(\Delta m_{ij}^2 \equiv m_{\nu_j}^2 - m_{\nu_i}^2)$$

$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

$$\Delta m_{\text{SUN}}^2 \equiv \Delta m_{12}^2 \ll |\Delta m_{23}^2| \Rightarrow \Delta m_{23}^2 \approx \Delta m_{13}^2 \equiv \Delta m_{\text{ATM}}^2$$

Charged sector

$m_{e,\mu,\tau}$

Well known

Accessible to oscillations

Δm^2_{12}

$|\Delta m^2_{23}|$

$\text{sign}(\Delta m^2_{23})$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

Known

Not accessible to oscillations

m_{lightest}

α

β

Bounds

$\Delta m^2_{\mathrm{ATM}} \sim 2.4 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45^\circ$ (ATM, K2K, Minos)

$\Delta m^2_{\mathrm{SUN}} \sim 0.76 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 35^\circ$ (SUN, KamLAND)

$\theta_{13} < 7^\circ \quad (2\sigma)$ (CHOOZ, Minos + ATM, SUN)

$|m_{ee}| = |U^2_{ei} m_{\nu_i}| < \mathcal{O}(1) \times 0.4\,\mathrm{eV}$ (Heidelberg-Moscow)

$(m^\dagger m)_{ee} = |U_{ei}|^2 m^2_{\nu_i} < (2.2\,\mathrm{eV})^2$ (Mainz, Troitsk)

$\sum_i m_{\nu_i} < \mathcal{O}(1)$ eV (priors) (Cosmology)

Guidelines for theory:

$$m_{\nu_i} \ll 174\,\mathrm{GeV}$$
$$\theta_{23} \sim 45^\circ (= 45^\circ ?)$$
$$\theta_{12} \sim 30^\circ\text{–}35^\circ \neq 45^\circ$$
$$\theta_{13} < 7^\circ$$
$$|\Delta m^2_{12} / \Delta m^2_{23}| \approx 0.035 \ll 1$$

Neutrino parameters: how do we know?

- Neutrino oscillations
  - Beta decay
    - Double beta decay
      - Astrophysics, cosmology

Neutrino oscillations

Flavor and mass eigenstates (again)

ν_e, ν_μ, ν_τ

"flavour" eigenstates
paired to charged leptons
in charged current

$j^\mu_{\mathrm{c,lep}} = \bar{e}_{iL} \gamma^\mu \nu_{e_i L}$
diagonal

ν_1, ν_2, ν_3

"mass" eigenstates

m^ν_{ij} diagonal
(and positive)

$$\boxed{\nu_{e_i} = U_{ih} \nu_h}$$

$$(\overline{\nu}_{e_i} = U^*_{ih} \overline{\nu}_h)$$

Oscillations (in vacuum)

$$|\nu_{e_i}\rangle = U^*_{ih}|\nu_h\rangle \Rightarrow e^{-iHt}|\nu_{e_i}\rangle = U^*_{ih}e^{-iE_ht}|\nu_h\rangle \qquad E_h \approx p + \frac{m_h^2}{2E}$$

$$P(\nu_{e_i} \to \nu_{e_j}) = \left|\langle \nu_{e_j}|e^{-iHt}|\nu_{e_i}\rangle\right|^2, \ \langle \nu_{e_j}|e^{-iHt}|\nu_{e_i}\rangle = U_{jh}e^{-iE_ht}U^\dagger_{hi}$$

Spin irrelevant (E » m_ν)
Majorana phases irrelevant

$$P(\nu_{e_i} \to \nu_{e_j}) = P(\overline{\nu}_{e_j} \to \overline{\nu}_{e_i}) \quad \text{CPT}$$
$$P(\nu_{e_i} \to \nu_{e_j}) = P(\overline{\nu}_{e_i} \to \overline{\nu}_{e_j}) \quad \text{CP}\ , \qquad P_{\text{tot}} = 1$$
$$P(\nu_{e_i} \to \nu_{e_j}) = P(\nu_{e_j} \to \nu_{e_i}) \quad \text{T}$$

In the simplest 2ν case:

$$\begin{aligned} \nu_e &= \nu_1 \cos\theta + \nu_2 \sin\theta \\ \nu_\mu &= -\nu_1 \sin\theta + \nu_2 \cos\theta \end{aligned} \Rightarrow P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

(to be integrated over energy, position and convoluted with cross section, resolution, efficiency...)

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

- Oscillation amplitude: $A = \sin^2 2\theta$ (does not tell θ from π/2 -θ)
- Oscillation length: $\lambda = \frac{4\pi E}{\Delta m^2} \approx 2.48\text{km}\frac{E(\text{ GeV})}{\Delta m^2(\text{eV}^2)}$
- Oscillation phase: $\phi = \frac{\Delta m^2 L}{4E} \approx 1.27\frac{\Delta m^2(\text{eV}^2)L(\text{km})}{E(\text{ GeV})}$
- L « λ $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \left(\frac{\Delta m^2 L}{4E}\right)^2$

  Perturbation theory limit

  Oscillations have no time to occur

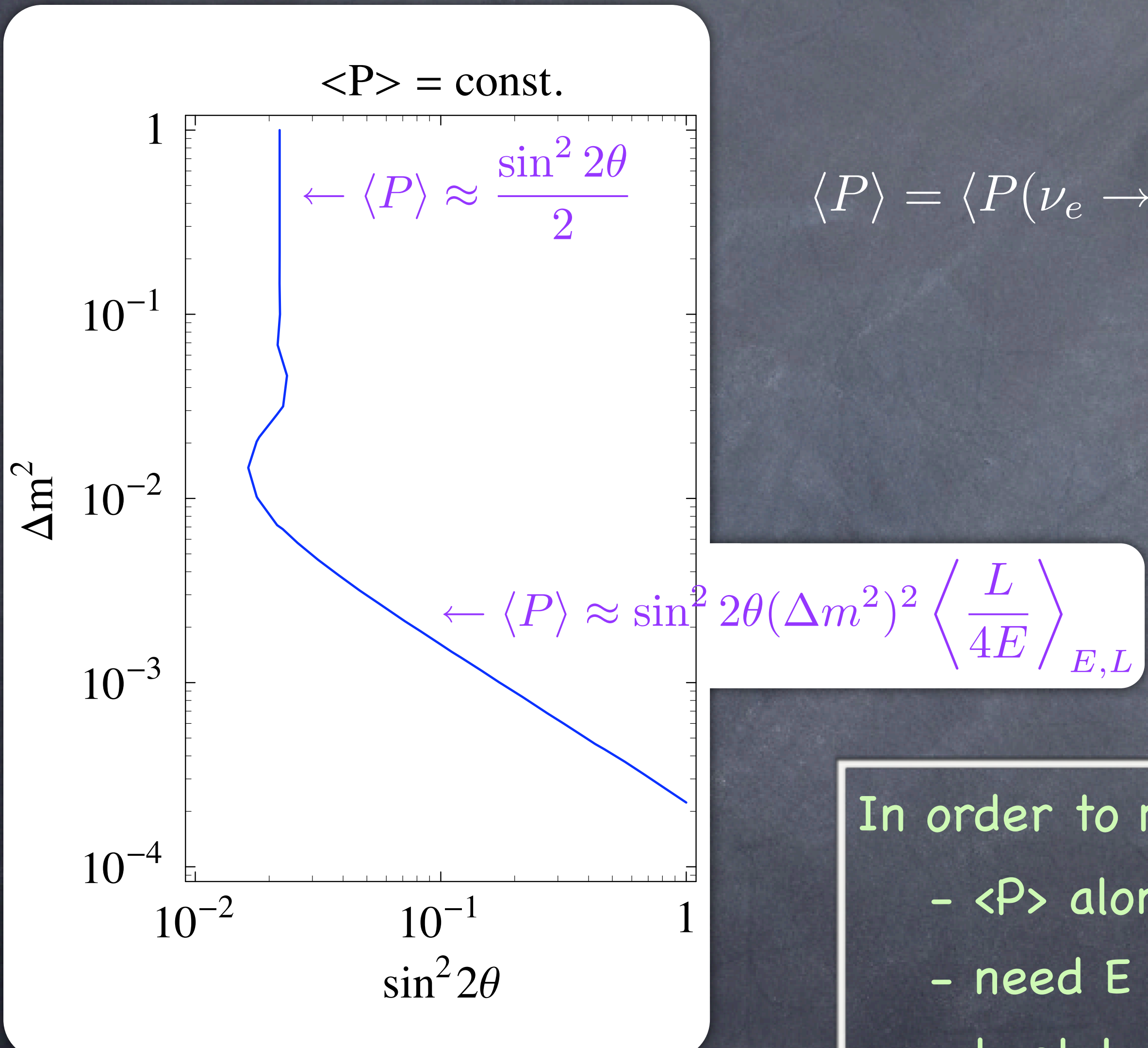
  P ∝ $(L/E)^2$, Flux ∝ $1/L^2$
- L » λ $P(\nu_e \to \nu_\mu) = \frac{\sin^2 2\theta}{2} = \sin^2\theta\cos^2\theta + \cos^2\theta\sin^2\theta$

  Classical limit

  Fast oscillations average out

  P independent of L,E, Flux ∝ $1/L^2$
- L ≈ λ oscillation phenomena show up

A typical sensitivity plot



$$\langle P \rangle = \langle P(\nu_e \to \nu_\mu) \rangle_{E,L} = \left\langle \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E} \right\rangle_{E,L}$$

In order to measure both $\sin^2 2\vartheta$ and Δm^2:

- <P> alone is not sufficient
- need E or L
- best to be in the $\frac{\Delta m^2 L}{4E} \sim 1$ regime

Caveats

- In vacuum only
- Coherence can be lost because
  - of averaging over the oscillation phase
  - the wave packets corresponding to different mass eigenstates travel at different velocities
  - of reduction to the neutrino subsystem
- Simplified derivation: E constant more appropriate? It does not really matter (change of variable in the wave packet integral)
  - e.g., if coherence is not lost

$$
\begin{aligned}
\langle \nu_{e_j}, x | e^{-iHt} | \psi_0 \rangle &= \int \frac{dp}{2\pi} U_{e_j k} e^{i(px - E_k(p)t)} U^\dagger_{k e_i} f(p) \\
&= \int \frac{dp}{2\pi} \left[U_{e_j k} e^{-i \frac{m_k^2 t}{2p}} U^\dagger_{k e_i} \right] e^{ip(x-t)} f(p) \\
&= U_{e_j k} e^{-i \frac{m_k^2 t}{2p}} U^\dagger_{k e_i} \psi_0(x - t)
\end{aligned}
$$

3 ν

Exact 3ν formulae:

$$P(\nu_{e_i} \to \nu_{e_j}) = P(\overline{\nu}_{e_j} \to \overline{\nu}_{e_i}) = P_{\rm CP} + P_{\not{\rm CP}}$$
$$P(\overline{\nu}_{e_i} \to \overline{\nu}_{e_j}) = P(\nu_{e_j} \to \nu_{e_i}) = P_{\rm CP} - P_{\not{\rm CP}}$$

$$P_{\rm CP} = \delta_{ij} - 4\,{\rm Re}(J^{ji}_{12}) S^2_{12} - 4\,{\rm Re}(J^{ji}_{23}) S^2_{23} - 4\,{\rm Re}(J^{ji}_{31}) S^2_{31}$$
$$P_{\not{\rm CP}} = 8 \sigma_{ij} J_{\rm CP} S_{12} S_{23} S_{31}$$

$$S_{hk} = \sin \frac{\Delta m^2_{hk} L}{4E}$$

$$J^{ji}_{12} = U_{jh} U^\dagger_{hi} U_{ik} U^\dagger_{kj}, \quad {\rm Im}(J^{ji}_{hk}) = \sigma_{ji} \sigma_{hk} J_{\rm CP}, \quad \sigma_{ij} = \sum_k \epsilon_{ijk} = \pm 1, 0$$

$3\,\nu \Rightarrow 2\,\nu$

CHOOZ: $S_{12}^2 \ll 1,\ S_{23}^2 \approx S_{13}^2:$ $P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{23}^2 L}{4E}$

ATM: $S_{12}^2 \ll 1,\ S_{23}^2 \approx S_{13}^2,\ \theta_{13} \ll 1:$ $P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E}$

$P(\nu_e \to \nu_{\mu,\tau}) \ll 1$

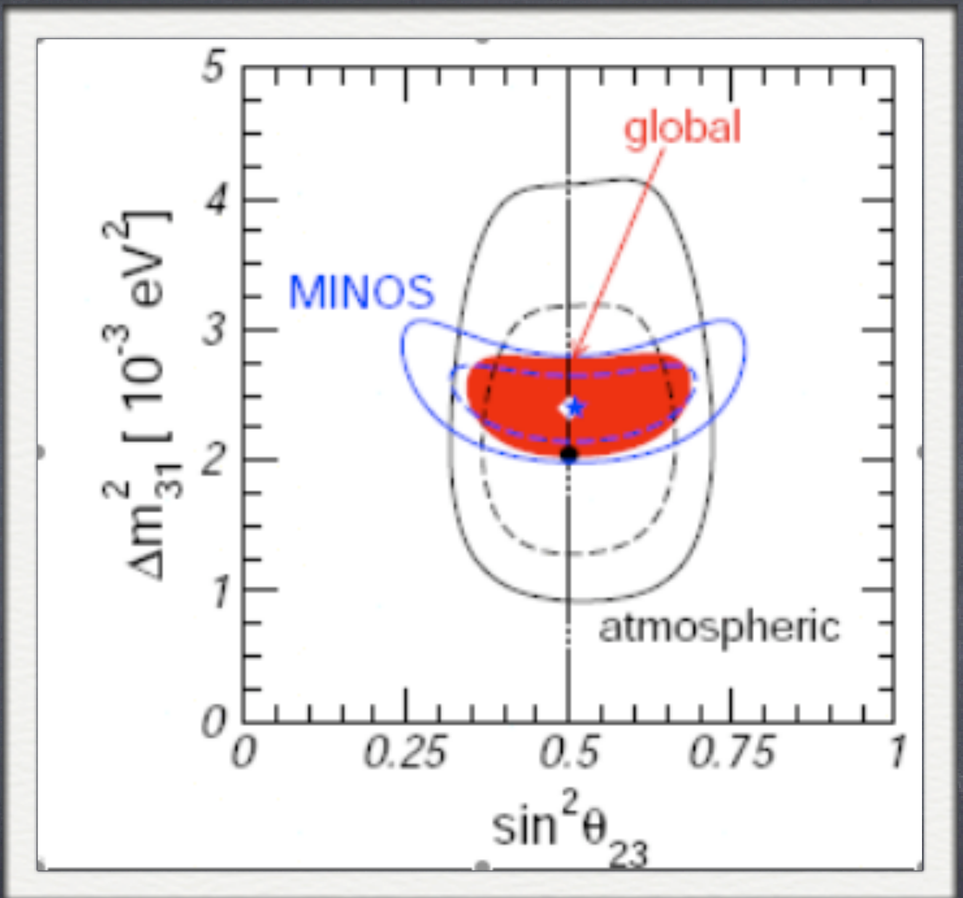
SUN: S_{23}^2, S_{13}^2 terms suppressed by $\theta_{13}:$ $P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E}$

Neutrino oscillation experiments

Δm^2_{23} and θ_{23}

(mainly) SK, K2K, Minos, Opera

Global fit

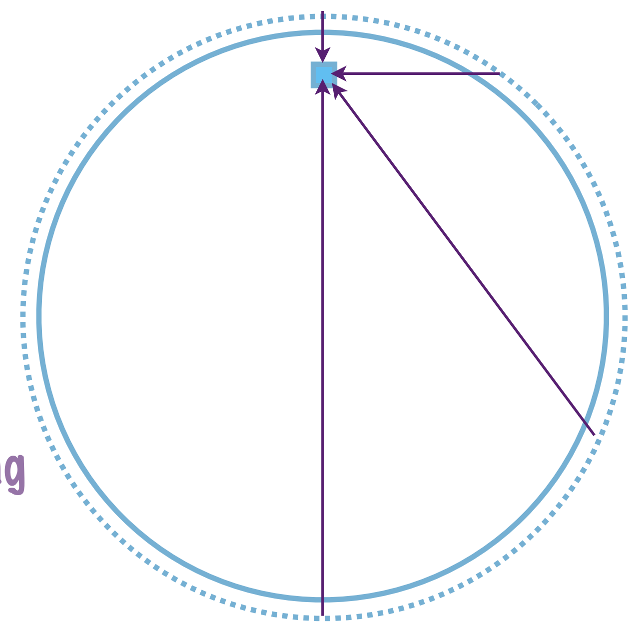


Schwetz et al, Neutrino 2010 update of NJP 10 (2008) 113011

Atmospheric neutrinos

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$

$2\ \nu_\mu$ for each ν_e

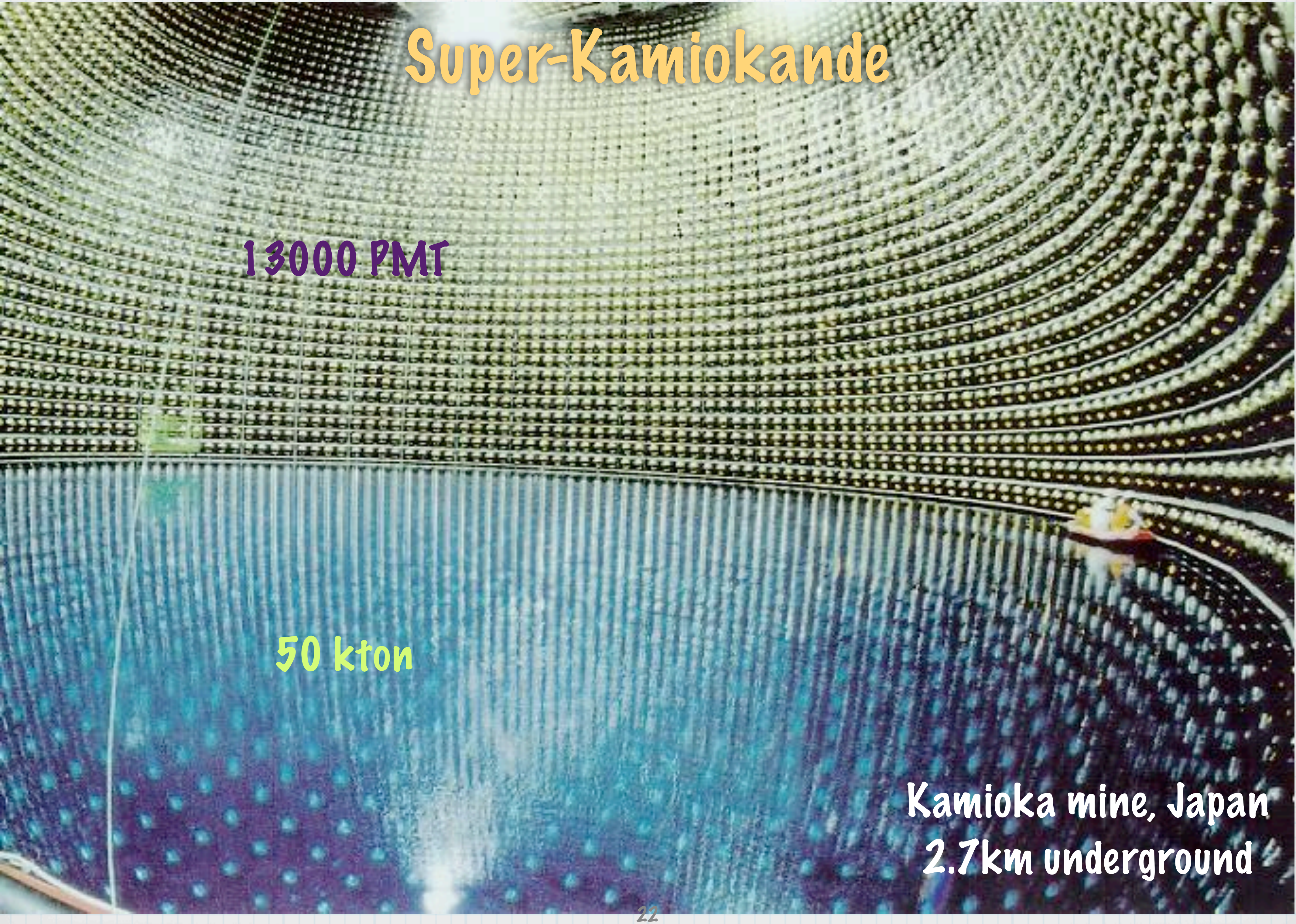


Disappearance as function of L independent of uncertainties on flux

Actually:
- Energetic μ long-lived, interacting
- Kaons are also produced so that the ratio is > 2

Need to measure:
- neutrino flavor
- neutrino direction
- possibly energy range

$$L = 10^{2\div4}\,\mathrm{km}$$
$$E = (0.1 \div 10)\,\mathrm{GeV} \quad \rightarrow \frac{\Delta m^2_{23} L}{4E} = 10^{-2\div2}$$
$$\Delta m^2_{23} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$$


Super-Kamiokande
13000 PMT
50 kton
Kamioka mine, Japan
2.7km underground

Super-Kamiokande: detection

* CC-interactions on nuclei: $\nu + N \rightarrow l + N'$
* Neutrino type:
  - $\nu_\mu \rightarrow \mu \rightarrow$ clean Cherenkov ring
  - $\nu_e \rightarrow e \rightarrow$ fuzzy Cherenkov ring
* ν direction: correlated with the direction of the lepton if $E \gg$ GeV
* ν energy: classify the events in sample with different E distribution:
  - Fully Contained sub-GeV neutrino direction (L) not determined
  - Fully Contained multi-GeV lepton and neutrino directions correlated
  - Partially Contained μ ($E \sim$ few GeV) E_ν not known
  - Upgoing stopping μ ($E \sim 10$ GeV)
  - Up & through going μ ($E > 10$ GeV)

Takeuchi, Neutrino 2010

Zenith angle & lepton momentum distributions

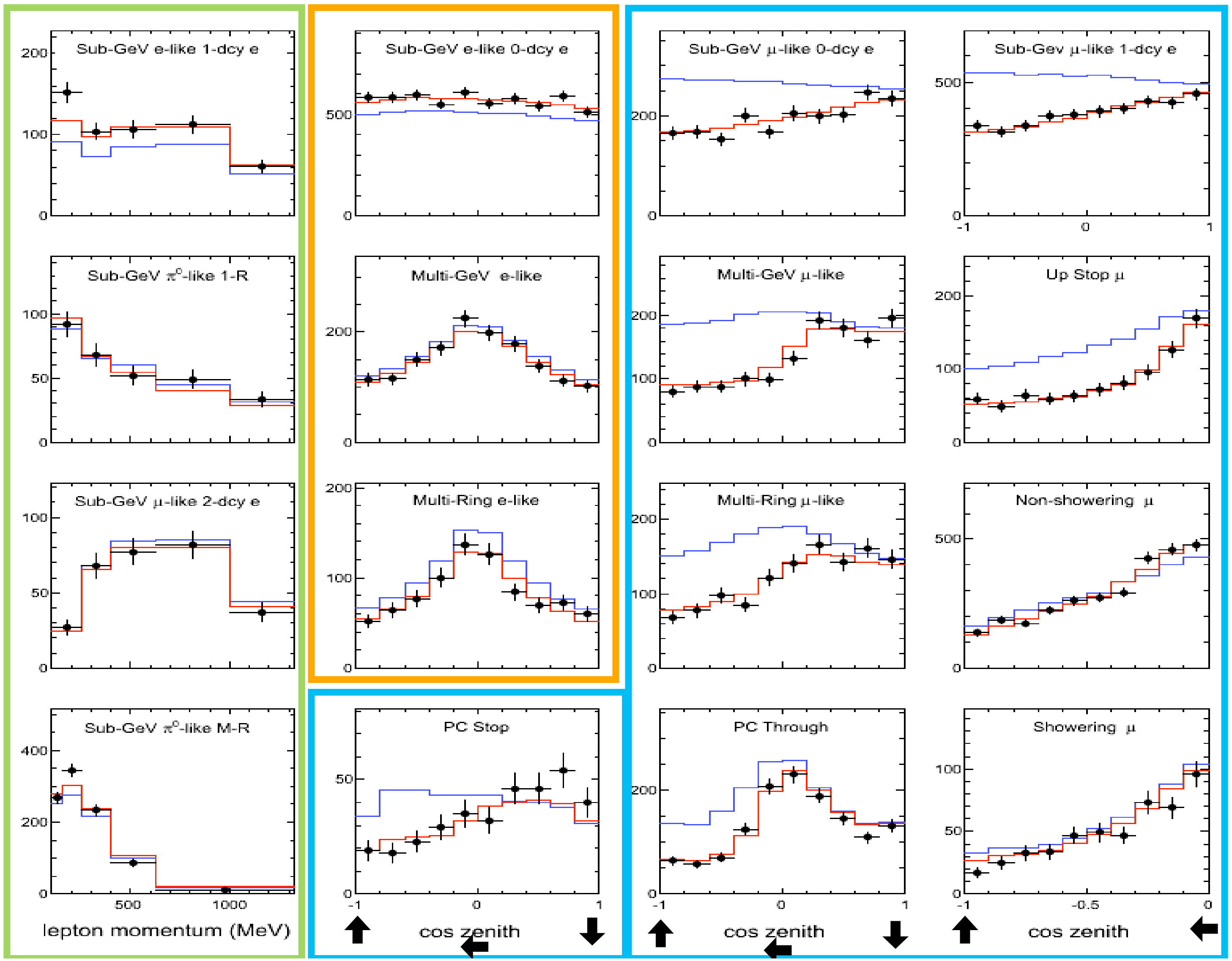
$\nu_\mu - \nu_\tau$ oscillation (best fit)

null oscillation

momentum | **e-like** | **μ-like**

SK-I+II+III

Preliminary



Live time:
SK-I
1489d (FCPC)
1646d (Upmu)
SK-II
799d (FCPC)
827d (Upmu)
SK-III
518d (FCPC)
636d (Upmu)

Sub-GeV samples are divided to improve sensitivity to low-energy oscillation effects

Jun 2009

Muons neutrinos disappear

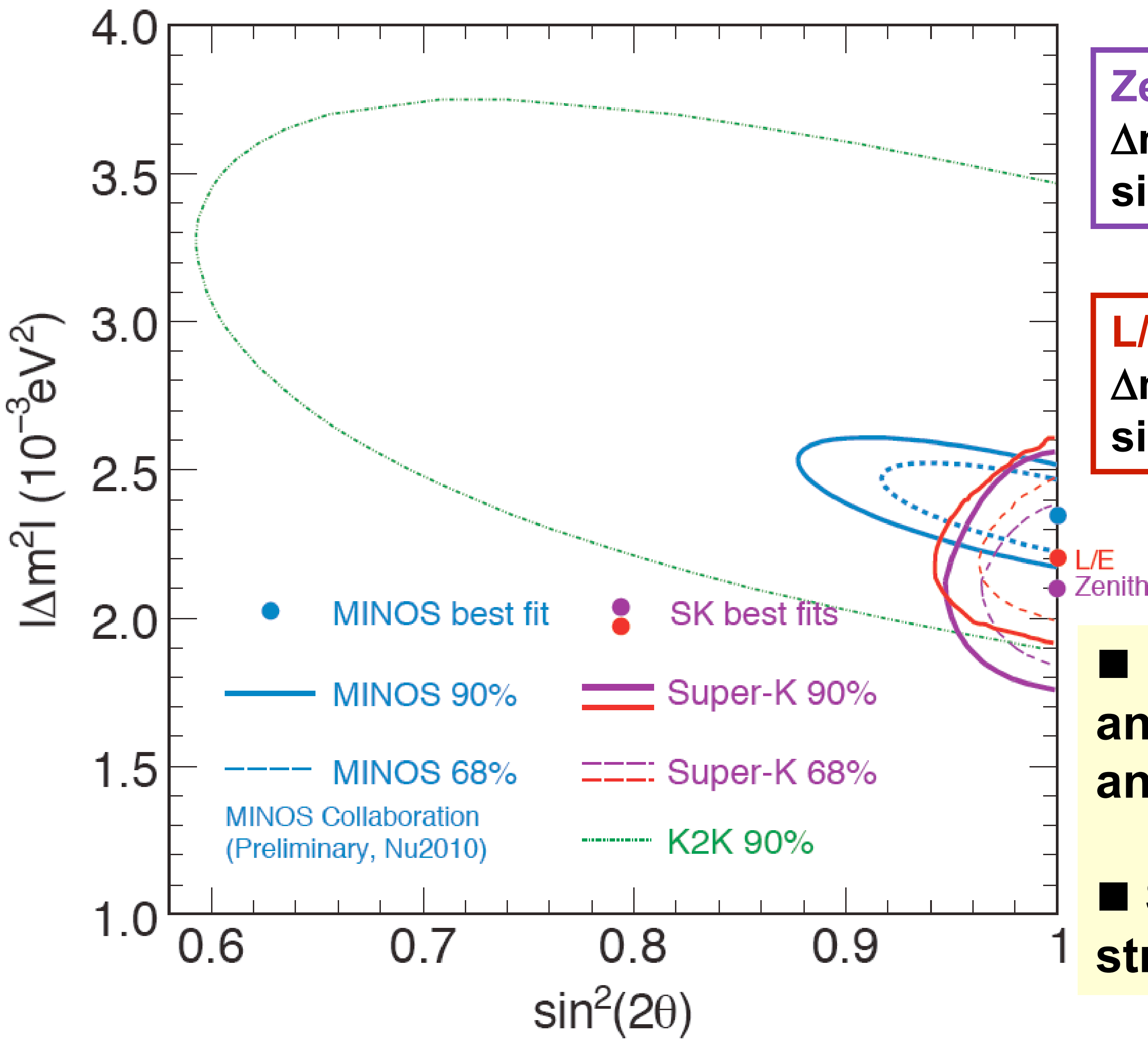
Electron neutrinos do not

Takeuchi, Neutrino 2010

2-flavor oscillation analysis results

SK-I+II+III *Preliminary*

Jun 2009



Zenith Physical Region (1σ)
Δm_{23}^2=2.11+0.11/-0.19 x10^{-3}
$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

L/E Physical Region (1σ)
Δm_{23}^2=2.19+0.14/-0.13 x10^{-3}
$\sin^2 2\theta_{23}$>0.96 (90%C.L.)

- **Both results of zenith angle analysis and L/E analysis are consistent.**
- **SK provides the most stringent limit for $\sin^2(2\theta_{23})$.**

Also

- Oscillation pattern smeared out. Still different, exotic disappearance mechanisms (decay, Lorentz, CPT-violation) are ruled out (marginal)

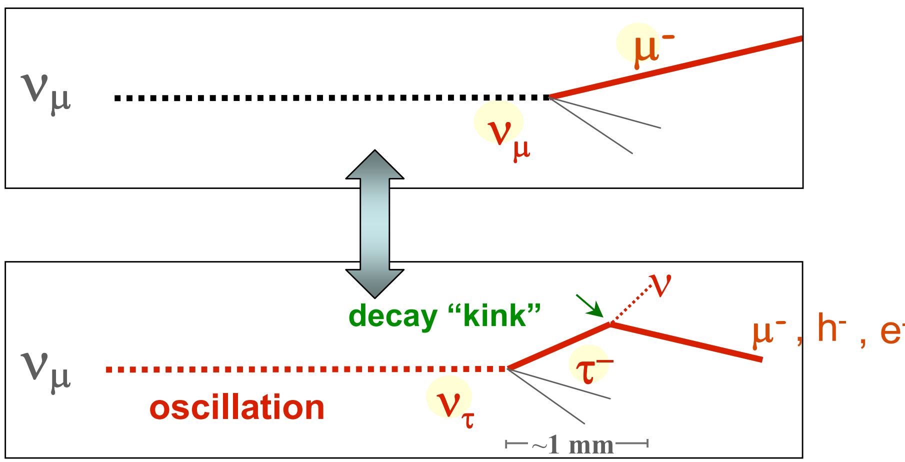
- Sterile neutrino analysis:
  - matter effects (relevant for sterile at high energy: resonance and then suppression)
  - neutral current multiring events (only affected by sterile)
  - τ appearance sample

- No electron neutrino transition, compatible with CHOOZ bound

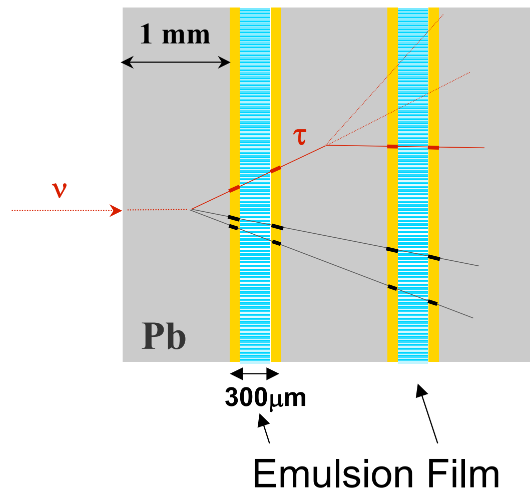
Atmospheric anomaly: $\nu_\mu \rightarrow \nu_\tau$ oscillations

Opera: explicit detection of ν_τ appearance

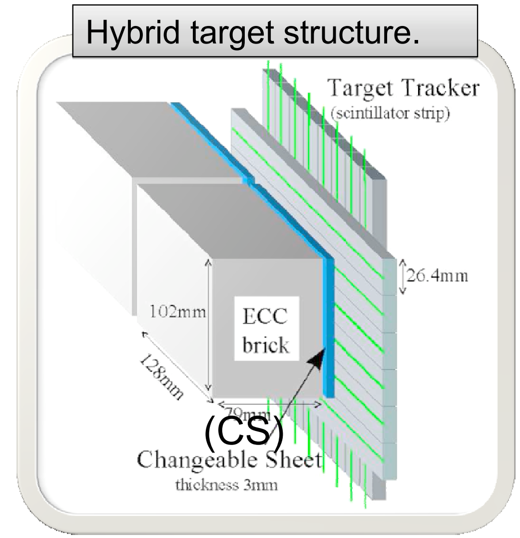
CERN → LNGS beam



The heart of the experiment:
THE ECC TARGET BRICKS



Stack of
57 OPERA films,
56 lead plates (10 X_0)



ECC is the detector
first observation of ν_τ **events**

DONUT **experiment at FERMILAB:**
(K. Niwa and collaborators):
9 τ events, 1.5BG.
K. Kodama et al. (DONuT Collaboration), Phys. Lett. B 504, 218 (2001).

• One muonless event showing a τ ➔ 1-prong hadron decay topology has been detected and studied in detail. It passes all kinematical cuts required to reduce the physics background. It is the first ν_τ candidate event in OPERA.

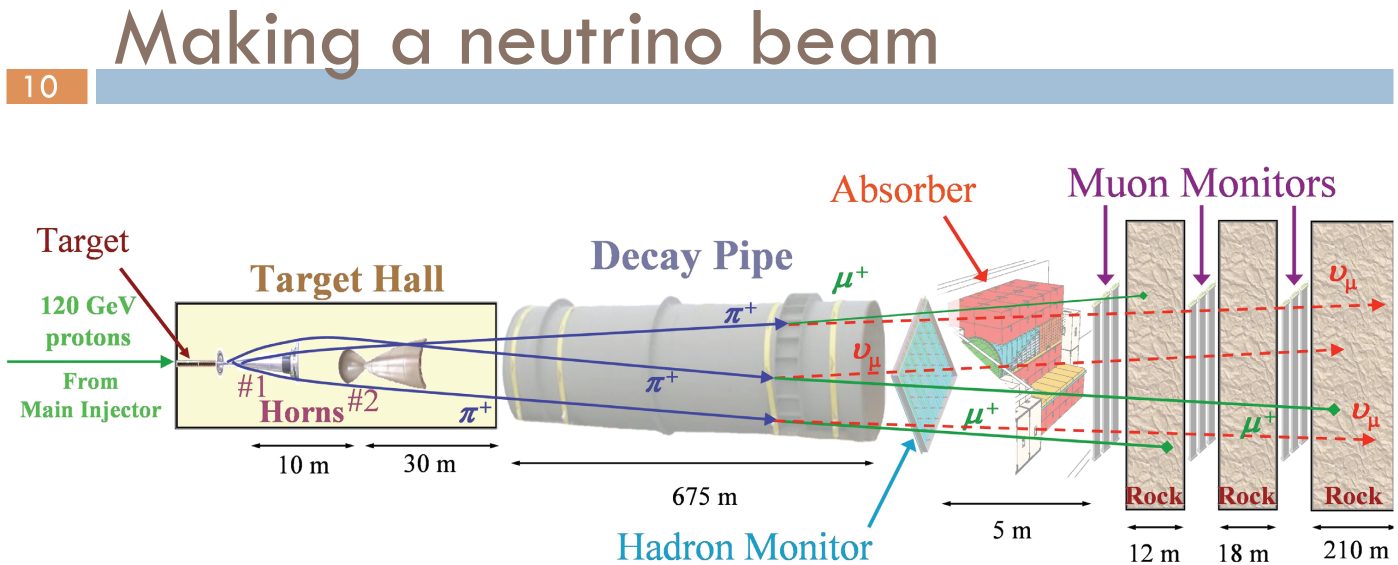
Sato, Neutrino 2010

K2K and NuMi

- KEK → SK pulsed conventional ν_μ beam
- $L \approx 250$ km, $E \approx 1.3$ GeV, osc phase ≈ 1
- Measure $\Delta\vartheta$, E_μ → reconstruct E_ν
- Near detector to measure flux

- FNAL → Minos pulsed conventional ν_μ beam
- $L \approx 735$ km, E ≈ few GeV, osc phase ≈ 1
- Minos = magnetized tracking calorimeter
- Near detector to measure flux

More on Minos



- Minos can
  - see ν_μ CC (penetrating muons) → confirms SK ATM (see previous plot)
  - see ν_x NC (diffuse hadron shower) → confirms no oscillations into sterile
  - see ν_e CC (compact em shower) → bound on θ_{13}
  - tell μ^+ from μ^-
- The beam can be switched between ν_μ and $\overline{\nu}_\mu$ → test CPT

ν_e Appearance Results

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

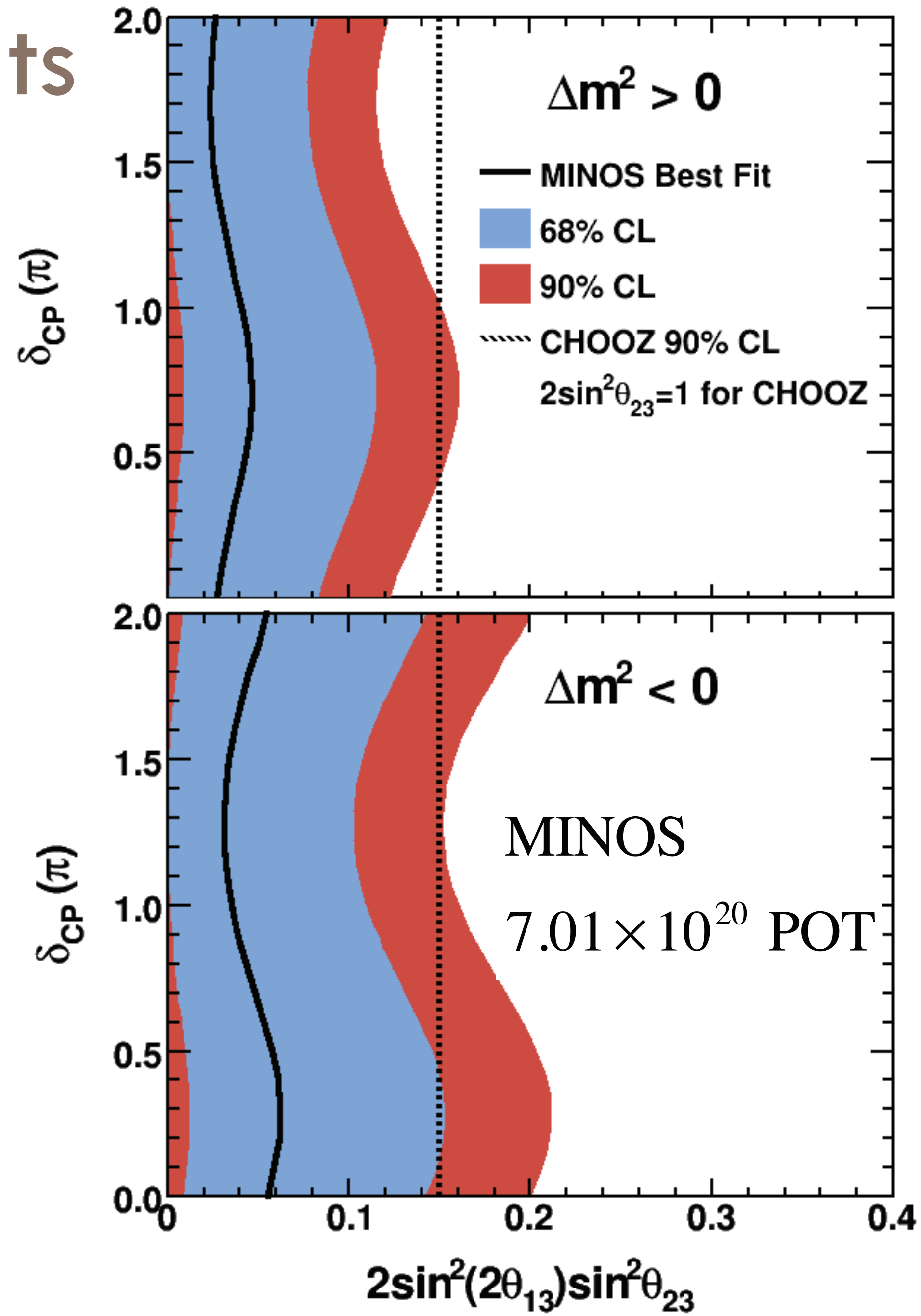
$\left|\Delta m^2_{32}\right| = 2.43 \times 10^{-3}\ \text{eV}^2$

$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

$\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

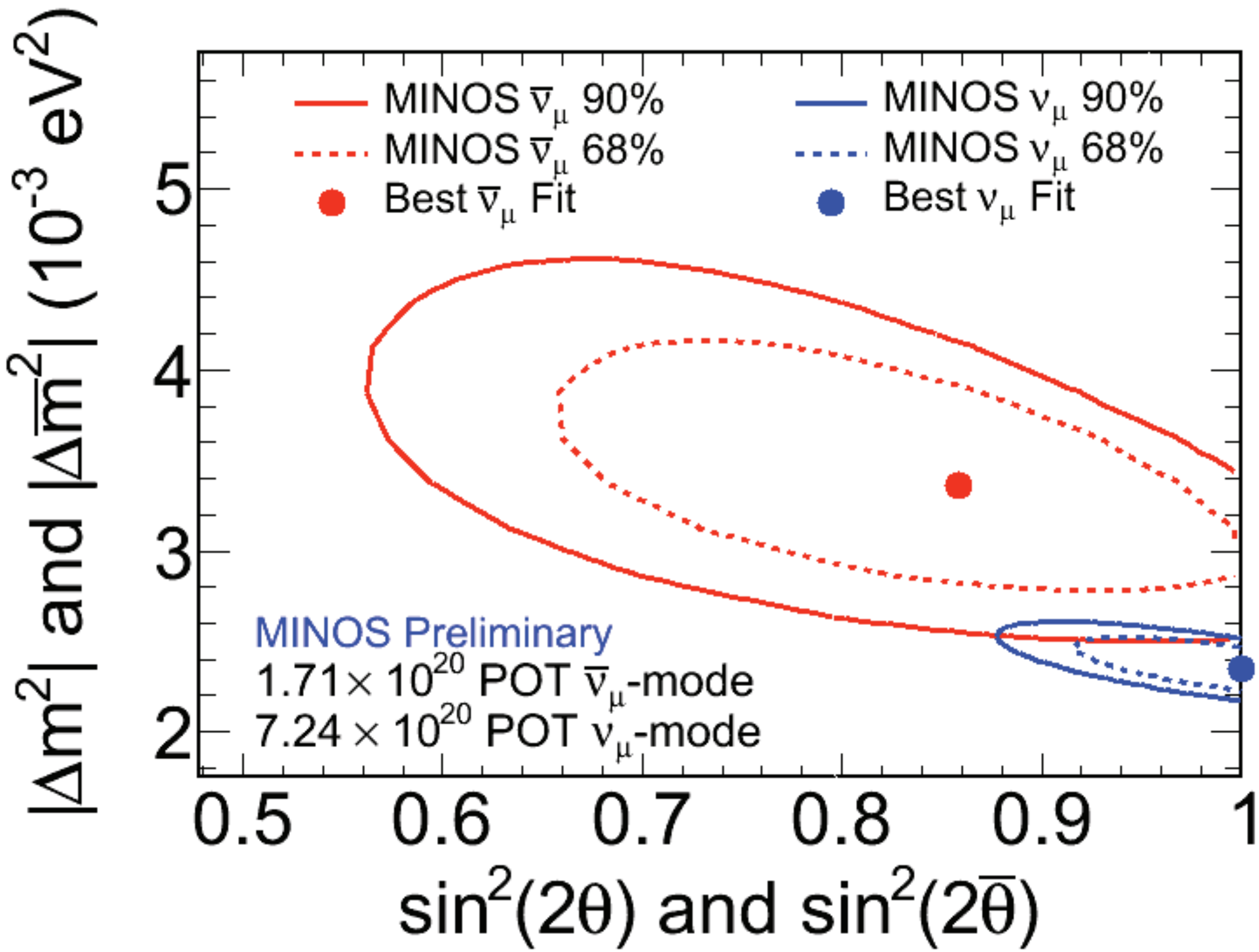
at 90% C.L.

arXiv:1006.0996v1 [hep-ex]



P. Vahle, Neutrino 2010

Comparisons to Neutrinos

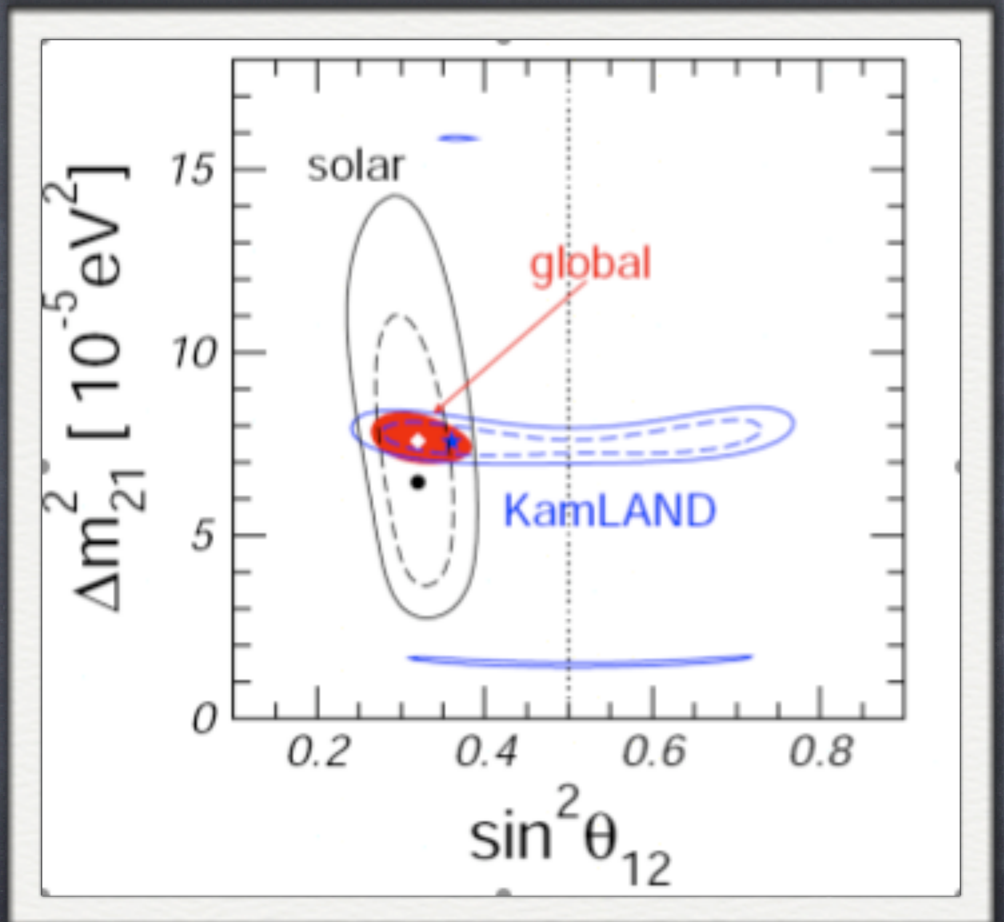


P. Vahle, Neutrino 2010

Δm^2_{12} and θ_{12}

(mainly) SK, SNO, Borexino, KamLAND

Global fit



Schwetz et al, Neutrino 2010 update of NJP 10 (2008) 113011

Matter effects

Incoherent scattering – typical mean free paths

(depend on flavor, "simplified" energy dependence):

λ (E) ~ 10 cm (100 MeV/E)^2 **in proto-neutron star cores**

λ (E) ~ 10^{10} km (10 MeV/E)^2 **in the Sun**

λ (E) ~ 10^9 km (GeV/E)^2 **in the Earth's mantle**

Coherent forward scattering is enhanced by $1/(G_F E^2)$

$$\begin{array}{ll} \text{incoherent:} & dP_{\rm sc}/dx \sim G_{\rm F}^2 E^2 n \\ \text{coherent:} & d\phi_{\rm co}/dx \sim G_{\rm F} n \end{array} \rightarrow \frac{dP_{\rm sc}}{d\phi_{\rm co}} \sim G_{\rm F} E^2 \sim 10^{-5} \left(\frac{E}{\rm GeV}\right)^2$$

It affects the neutrino phases in a flavor dependent way

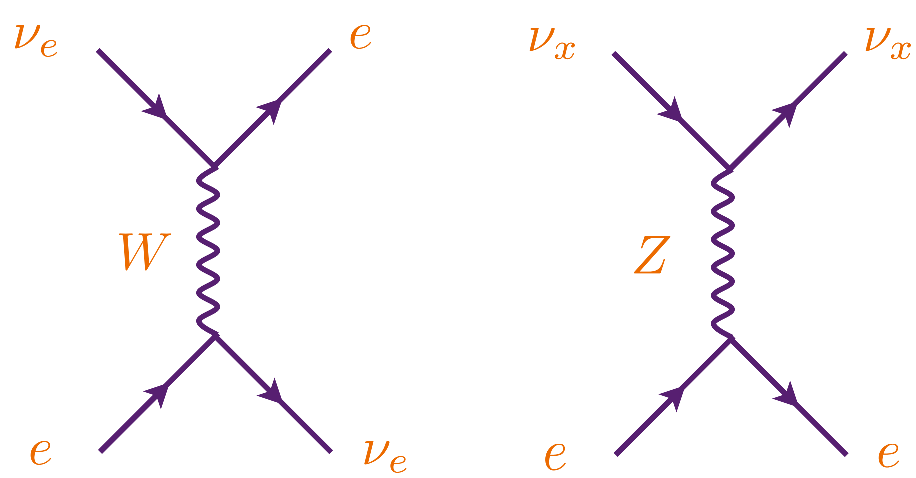
In matter:

$$H = \frac{1}{2E} U \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V & & \\ & 0 & \\ & & 0 \end{pmatrix} + \text{univ. terms}$$

Free Hamiltonian (first term) — **MSW potential** (second term)

$$V = V_e - V_\mu = \sqrt{2} G_F n_e \quad (\text{neutral matter, } n_\nu \ll n_e)$$

$$V_\mu = V_\tau \quad (\text{tree level, neutral matter, } L_\mu = L_\tau)$$



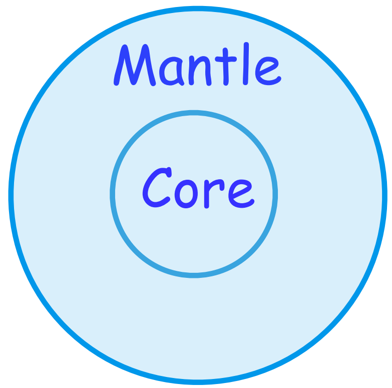
+ u, d,...

for $\overline{\nu}$: $\begin{cases} U \to U^* \\ V \to -V \end{cases}$

Propagation in constant density

Oscillation formulae still hold with $\vartheta \to \vartheta_m$, $\Delta m^2 \to (\Delta m^2)_m$,
where ϑ_m , $(\Delta m^2)_m$ depend on the neutrino energy

The Earth:



$\rho_m \sim$ 3-5 g/cm^3
$\rho_c \sim$ 10-15 g/cm^3

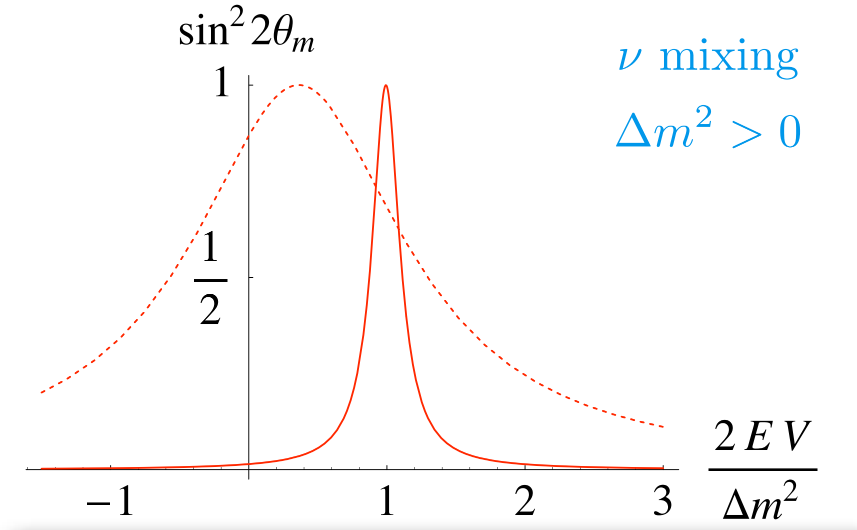
Propagation in the Earth affects

- Atmospheric ν's (only through the subdominant $\nu_e \leftrightarrow \nu_{\mu,\tau}$)
- Solar, SN ν's (D/N effect)
- Terrestrial experiments (Long Baseline)

Resonance (2ν)

$$H = \begin{pmatrix} \sin^2\theta + \dfrac{2EV}{\Delta m^2} & \sin\theta\cos\theta \\ \sin\theta\cos\theta & \cos^2\theta \end{pmatrix} \frac{\Delta m^2}{2E} + \text{universal terms}$$

Resonant enhancement of the mixing angle: $\dfrac{2EV}{\Delta m^2} = \cos 2\theta \Rightarrow \begin{cases} (\sin 2\theta)_m = 1, \\ (\Delta m^2)_m = \Delta m^2 \sin 2\theta \end{cases}$



Also: $(\Delta m^2)_m = \Delta m^2 \dfrac{\sin 2\theta}{(\sin 2\theta)_m}$

- Resonance width = $\tan 2\vartheta$ ($\vartheta < 45°$)
- $\vartheta < 45°$ ⇒ resonance only if $V \times \Delta m^2 > 0$
- SUN: $V > 0$, $(\Delta m^2)_{12} > 0$ ⇒ resonance only if $\vartheta < 45°$
- Note also: $(2EV)/(\Delta m^2)_{12} \gg 1 \Rightarrow \nu_e \approx (\nu_2)_m$

Resonance: formulae

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{1 + \left(\frac{2EV}{\Delta m^2}\right)^2 - 2\cos 2\theta \frac{2EV}{\Delta m^2}} \qquad (\Delta m^2)_m = \Delta m^2 \left[1 + \left(\frac{2EV}{\Delta m^2}\right)^2 - 2\cos 2\theta \frac{2EV}{\Delta m^2}\right]^{1/2}$$

$$\frac{2EV}{\Delta m^2} = \frac{E}{E_{\rm res}} \cos 2\theta \qquad E_{\rm res} = \frac{\Delta m^2}{2V} \cos 2\theta \approx 8\,{\rm GeV} \left(\frac{\Delta m^2}{2 \cdot 10^{-3}\,{\rm eV}^2} \frac{n_e}{1.65\,{\rm gr/cm}^3}\right)$$

$$\frac{(\sin^2 2\theta)_m}{\sin^2 2\theta} = \left[\frac{\Delta m^2}{(\Delta m^2)_m}\right]^2$$

* Matter effects are negligible:
  - when $E \ll E_{res}$
  - when $L \ll \lambda_m$ ($\sin x \approx x$)

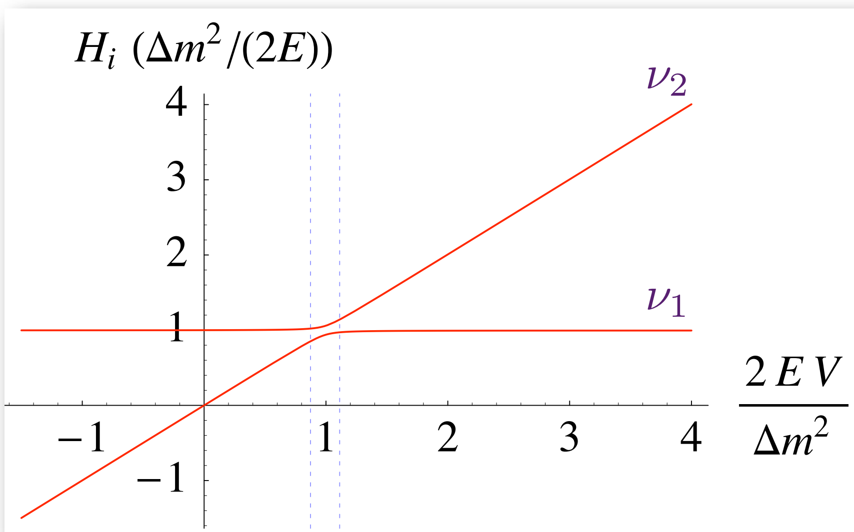
Propagation in varying density (2 ν)

$H(t) = H_{free} + V_{MSW}(t)$ time-dependent hamiltonian

Adiabatic evolution: no $\nu_1 \leftrightarrow \nu_2$ transitions

Adiabaticity condition: $\frac{d\theta_m}{dx} \ll \frac{(\Delta m^2)_m}{2E}$

Adiabatic resonance crossing → large flavor swap even for small ϑ



$$E \gg E_{\rm res} \rightarrow V = 0$$

$$\nu_e \approx (\nu_2)_m \rightarrow \nu_2 = \nu_e \sin\theta + \nu_\mu \cos\theta$$

$$P(\nu_e \rightarrow \nu_\mu) \approx \cos^2\theta$$

The adiabatic approximation must break at small ϑ

Level crossing

* The adiabatic approximation is worst at the resonance $$\frac{d\theta_m}{dx} \ll \frac{(\Delta m^2)_m}{2E}$$

* Adiabatic condition at the resonance: $$\gamma \equiv \frac{\Delta m^2}{2E(V'/V)_{\rm res}} \frac{\sin^2 2\theta}{\cos 2\theta} \gg 1$$

* If $\gamma \lesssim 1$ but $\gamma \gg 1$ at production and detection $$P(\nu_1 \to \nu_2) \equiv P_c \approx e^{-\gamma/2}$$

Landau-Zener

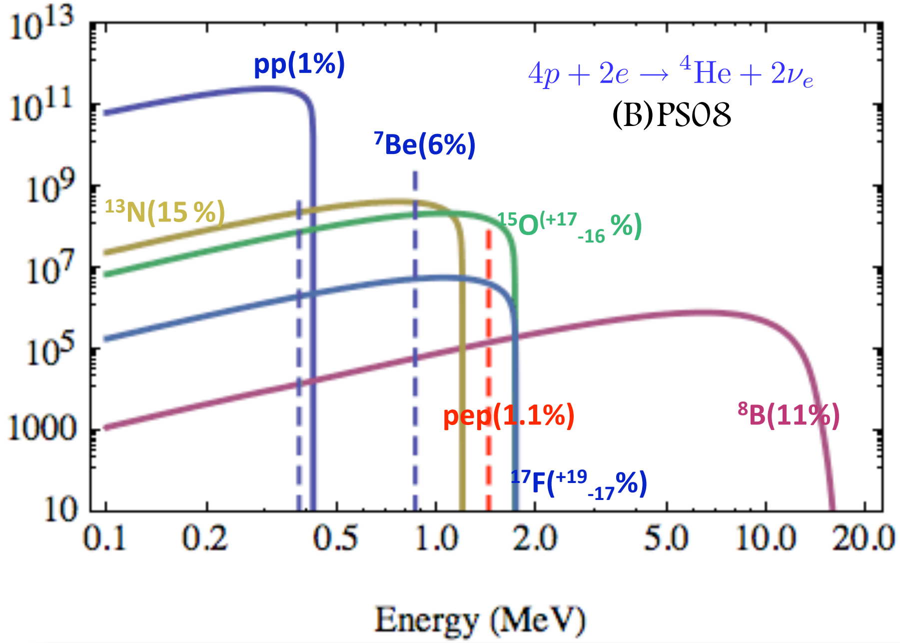
* Example: SN neutrinos ($\Delta m^2 > 0$) or antineutrinos ($\Delta m^2 > 0$) for $\vartheta_{13} < 10^{-3}$

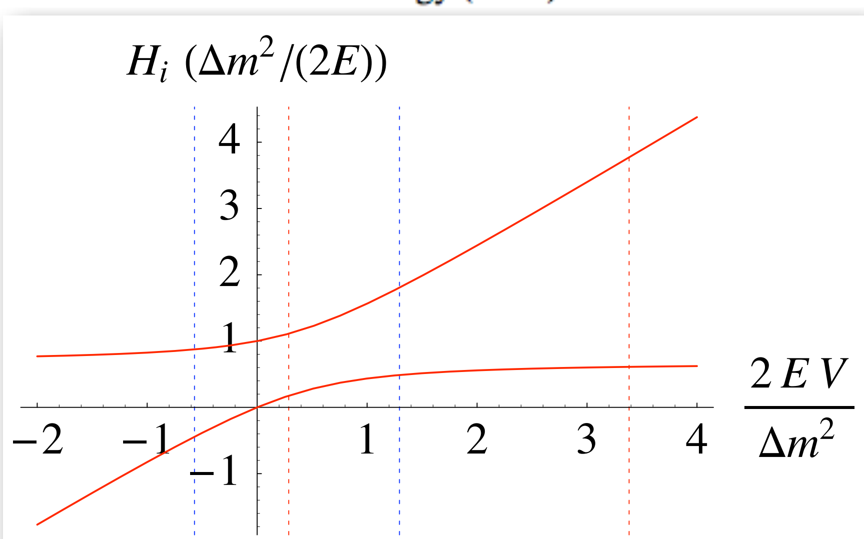
Solar neutrinos (ν_e)

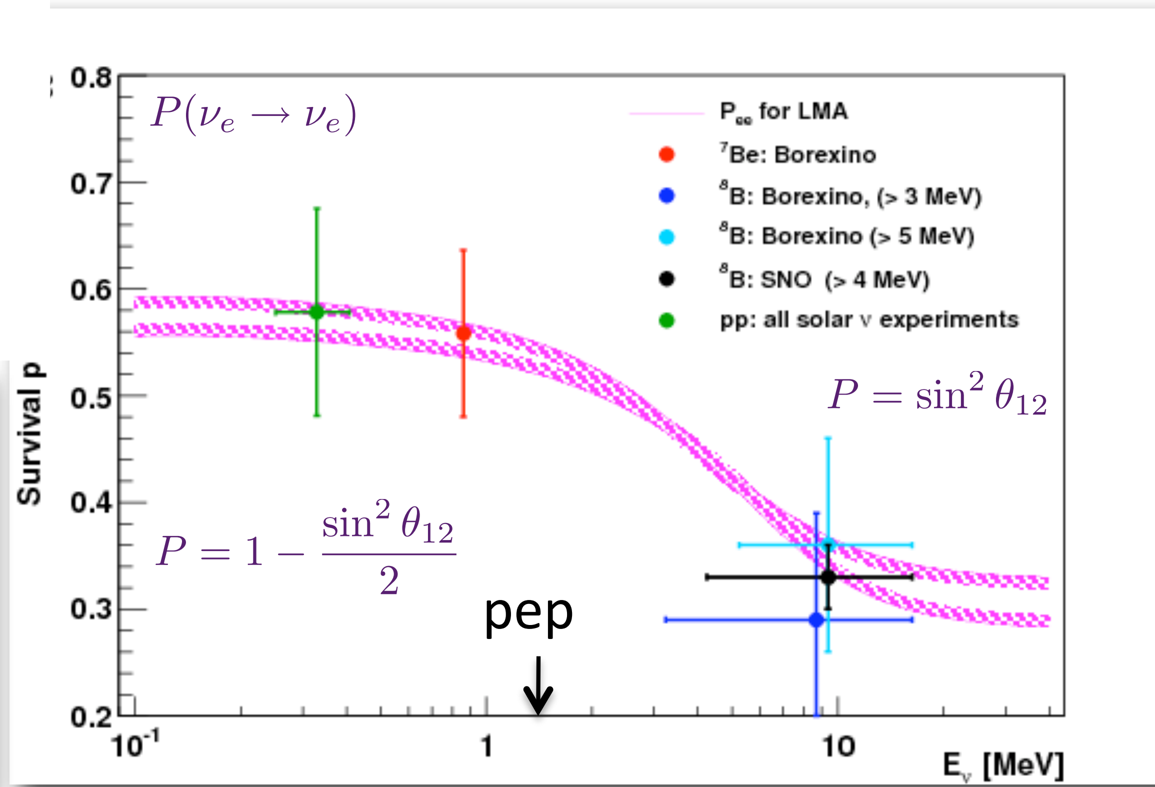
$$0\,\mathrm{MeV} < E_\nu < 14\,\mathrm{MeV}$$

$$E_{\mathrm{res}}(\mathrm{core}) \sim 3\,\mathrm{MeV}$$

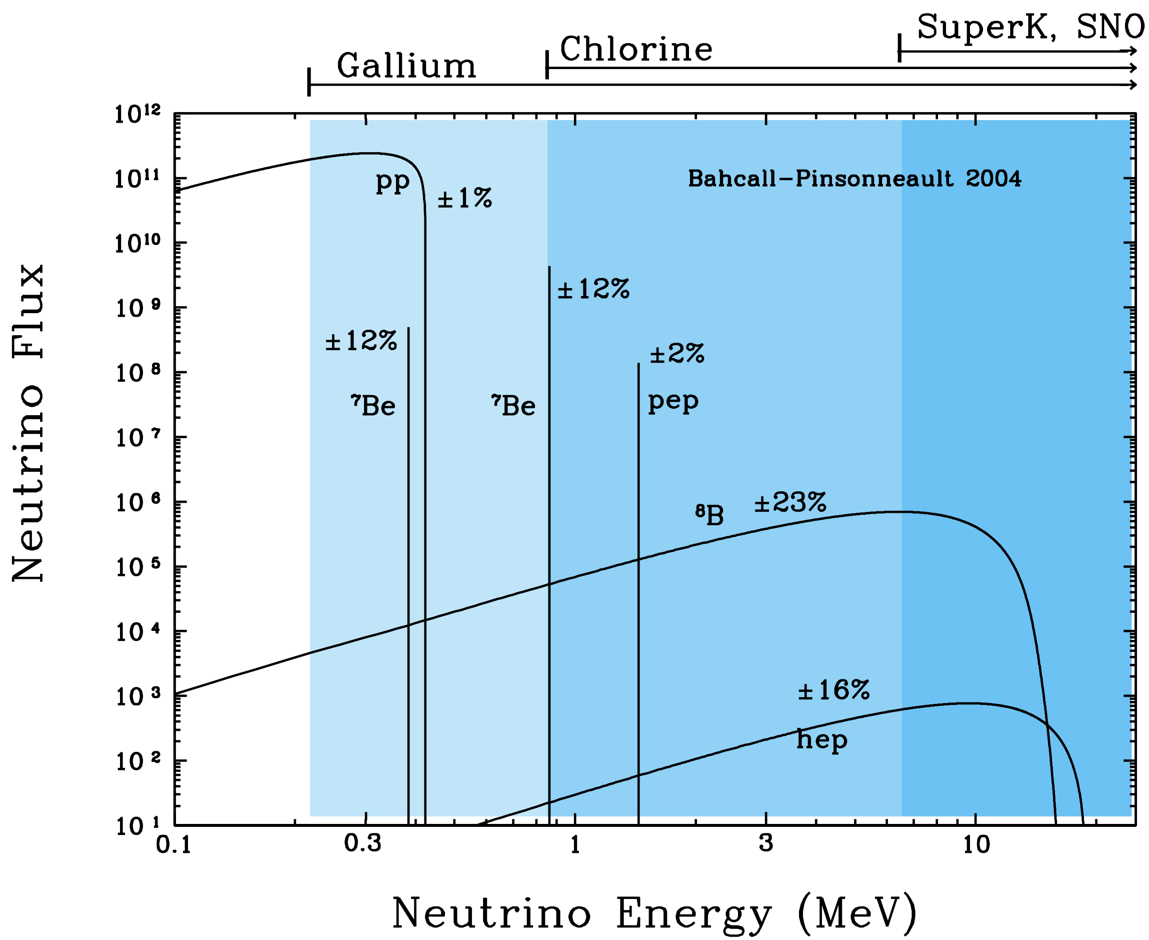
$$(\Delta m^2_{12} = 0.8 \times 10^{-4}\,\mathrm{eV}^2)$$







Solar neutrino experiments



Chlorine: Homestake (68)

$\nu_e\,^{37}\mathrm{Cl} \to e\,^{37}\mathrm{Ar}$

$E_\nu > 0.814\,\mathrm{MeV}$

Gallium: SAGE, Gallex/GNO

$\nu_e\,^{71}\mathrm{Ga} \to e\,^{71}\mathrm{Ge}$

$E_\nu > 0.233\,\mathrm{MeV}$

H_2O: K, SK

$\nu_{e,x} e \to \nu_{e,x} e$

$E_\nu > 5.5\,\mathrm{MeV}$

D_2O: SNO

$\nu_{e,x} e \to \nu_{e,x} e$ (ES)

$\nu_e D \to ppe$ (CC)

$\nu_x D \to \nu_x pn$ (NC)

Borexino (ES)

Sudbury neutrino observatory (SNO)

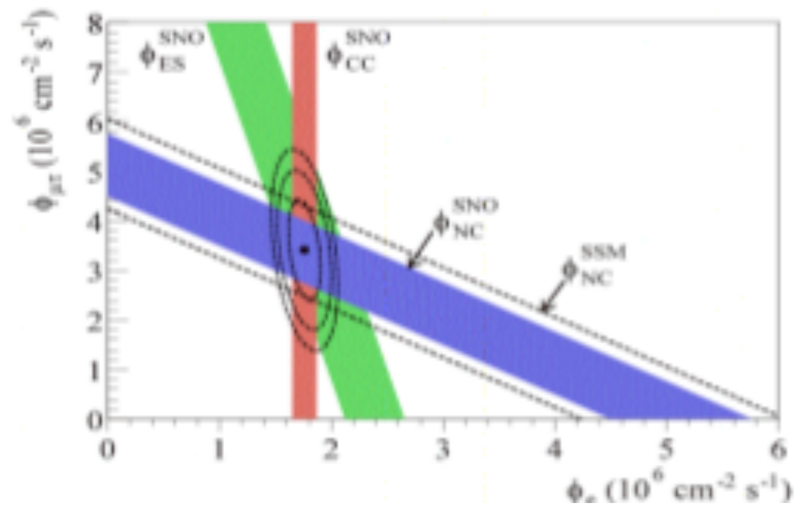
* Heavy water (D_2O) in phase I
  + salt (Cl) in phase II
  + ^{3}He prop counter in phase III

* ES: $\nu_x e \to \nu_x e \Rightarrow \Phi(\nu_e) + 0.155\,\Phi(\nu_{\mu,\tau})$
  θ_e
  Point at sun

* CC : $\nu_e D \to ppe \Rightarrow \Phi(\nu_e)$
  θ_e E_e
  Energy spectrum

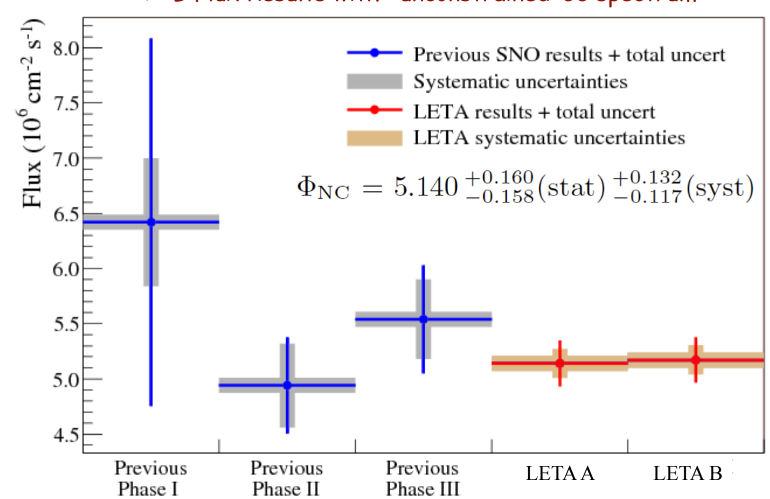
* NC: $\nu_x D \to \nu_x pn \Rightarrow \Phi(\nu_e) + \Phi(\nu_{\mu,\tau})$
  γ from n capture in D (15%) or Cl (45%)
  Ring shape, n ^{3}He → p ^{3}H seen in PC (ph III)

Test of SSM



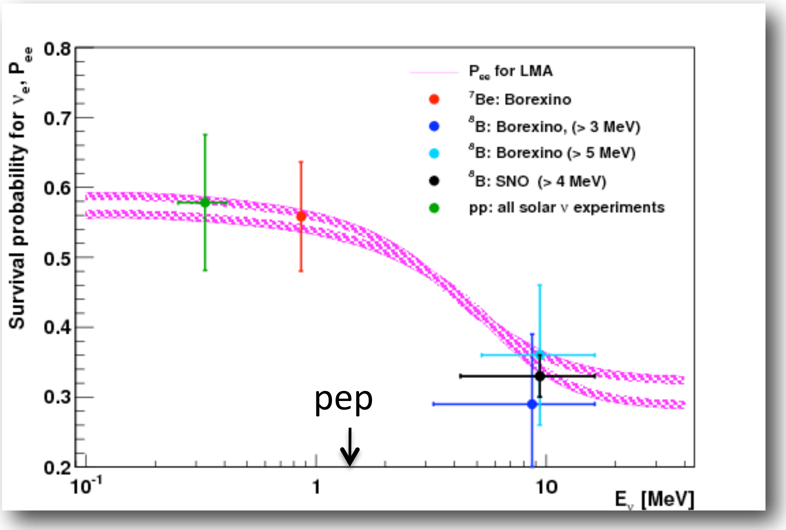
Low Energy Threshold Analysis

➢^{8}B Flux Results with `unconstrained' CC spectrum



Borexino

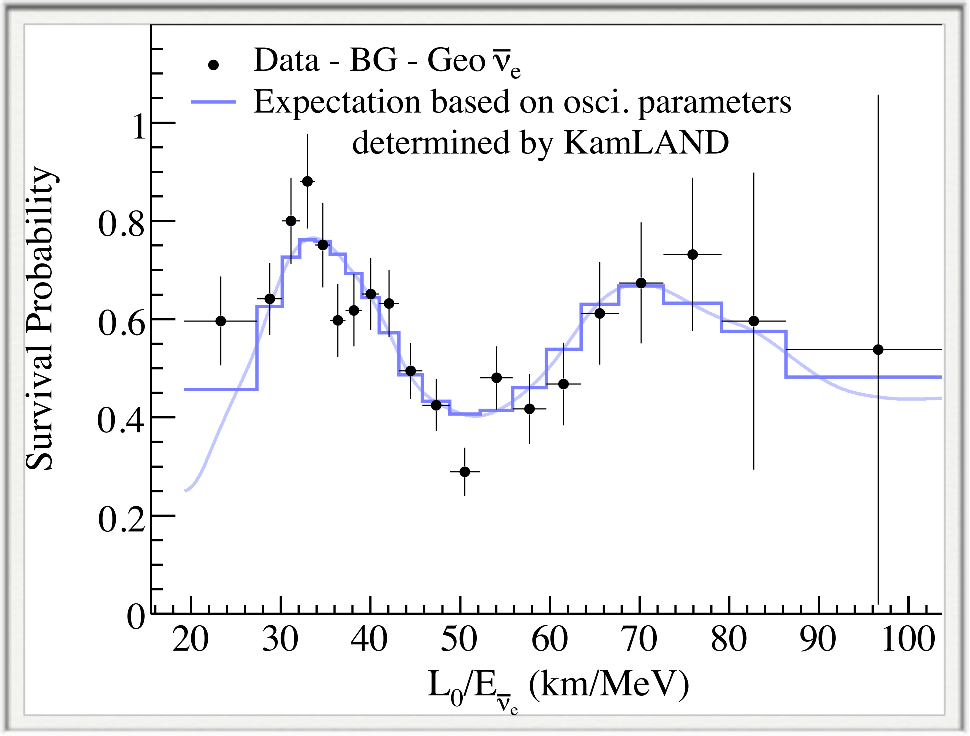
- Low E scintillator detector
- Solar neutrino ES
  - e with $dE_e \sim 5\%$ at 1MeV down to < 0.3 MeV
  - ^{7}Be neutrino rate
  - Constrains the survival probability in the vacuum oscillation region



- Geoneutrinos (antinu from radioactivity, $E < 3$ MeV) inverse beta
  - e^+ and delayed coincidence with $E = 2.2$ MeV photon from neutron capture
  - ~ 10 events

KamLAND

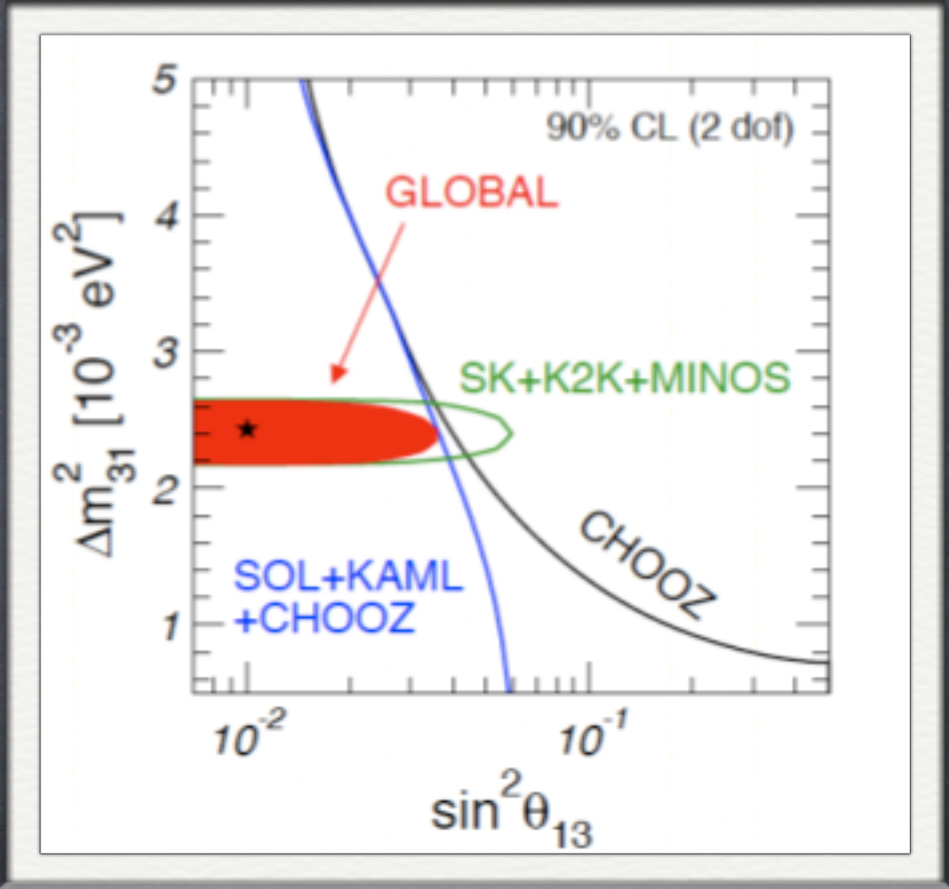
- $\overline{\nu}_e$ from several reactors (E ~ few MeV) at L ~ 200 km: $\frac{\Delta m^2_{12} L}{4E} = \mathcal{O}(1)$
  (initial flux well known)
- $\overline{\nu}_e p \to e^+ n$ in scintillator
  (delayed coincidence and E_{th} > E_{radio}: background suppression)
- $E_{\nu_e} = E_{e^+} + m_n - m_p \to$ good spectrum, Δm^2_{12} determination
- Observation of oscillation dip!



θ_{13}

CHOOZ, Minos and ATM, SUN subleading

Global fit



Schwetz et al, Neutrino 2010 update of NJP 10 (2008) 113011

The unknown parameters

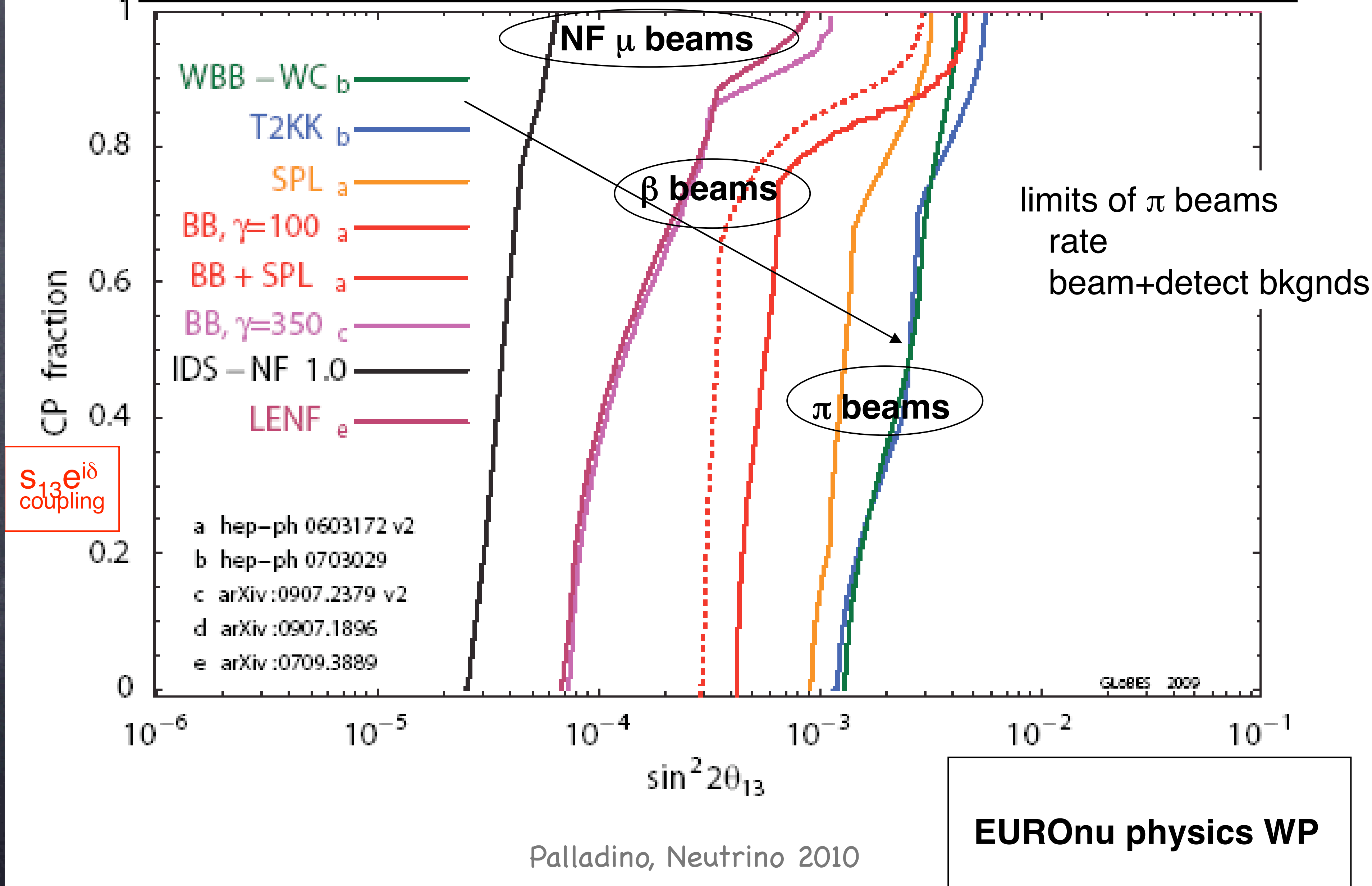
ϑ_{13}

* Origin of masses and mixing
  - Discriminate models
  - Origin of solar and atmospheric angles
  - Neutrino mass pattern
* Phenomenology
  - Leptonic CP-violation
  - Supernova signals
  - Subleading effects
* Experiments
  - Rich experimental program available

    (subleading effect in SUN and ATM)

$$\left.\begin{aligned} P(\nu_\mu \leftrightarrow \nu_\tau) &\approx \sin^2\theta_{23}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\mu) &\approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\tau) &\approx \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \end{aligned}\right\} + \Delta m^2_{SUN}$$

$\sin^2 2\theta_{13}$ discovery at 3σ CL

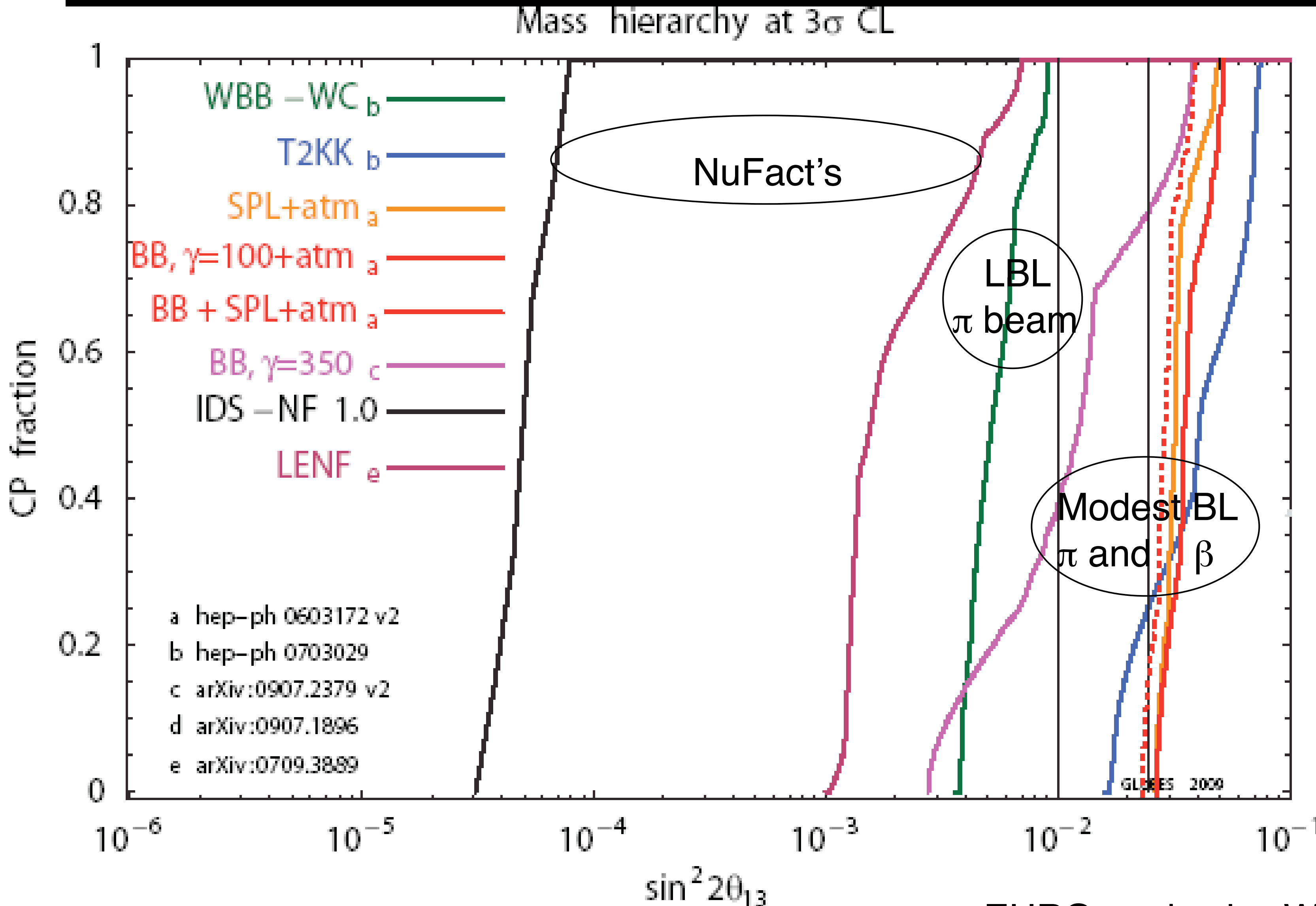


sign(Δ m^2) and matter effects

$$\Delta m^2_{12} = 0: \; H_{\text{eff}} = \frac{1}{2E}\left[U\begin{pmatrix}0 & & \\ & 0 & \\ & & \Delta m^2_{23}\end{pmatrix}U^\dagger \pm \begin{pmatrix}2EV & & \\ & 0 & \\ & & 0\end{pmatrix}\right]$$

* Enhancement/suppression in neutrino/antineutrino channel depending on sign(Δm^2)
* A measurement of sign(Δm^2) needs
  - E ~ 10 GeV (resonance)
  - long baseline ($\sin(x) \neq x$)
  - $\nu_e \leftrightarrow \nu_{\mu,\tau}$
* sign(Δm^2) determines the pattern of neutrino masses and affects the
  - SN neutrino signal
  - terrestrial experiments
  - $0\nu2\beta$ decay

sign Δm^2_{atm} discovery at 3σ CL



Palladino, Neutrino 2010

EUROnu physics WP

CP-violation

* Is there CP-violation in the lepton sector?

* Is it at the origin of the Baryon asymmetry in the universe?

* Can we observe it in neutrino experiments?
  - Dirac (CKM-like) CP-violation
  - Majorana CP-violation

CKM-like CP-violation

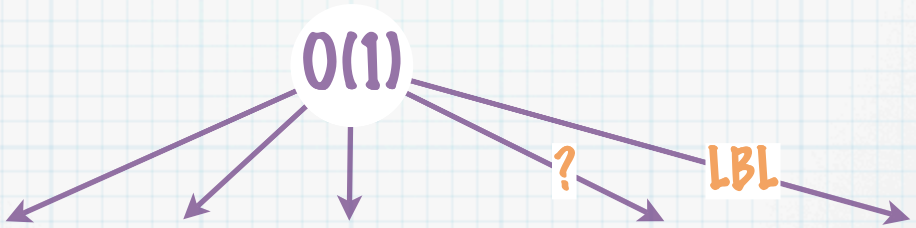
$$P(\nu_{e_i} \to \nu_{e_j}) = P(\overline{\nu}_{e_j} \to \overline{\nu}_{e_i}) = P_{\rm CP} + P_{\not{\rm CP}}$$
$$P(\overline{\nu}_{e_i} \to \overline{\nu}_{e_j}) = P(\nu_{e_j} \to \nu_{e_i}) = P_{\rm CP} - P_{\not{\rm CP}}$$

At accelerators, due to the smallness of $(\Delta m^2)_{12}/(\Delta m^2)_{23}$ and ϑ_{13} :

$$\left.\begin{aligned} P(\nu_\mu \leftrightarrow \nu_\tau)_{\rm CP} &\approx \sin^2\theta_{23}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\mu)_{\rm CP} &\approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\tau)_{\rm CP} &\approx \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \end{aligned}\right\} + \Delta m^2_{\rm SUN}\ \text{corr.}$$

CKM-like CP-violation

Large angles (unlike in quark sector) enhance CP-violation



$$P_{\rm CP} = \pm \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta \, S_{\rm SUN} S^2_{\rm ATM}$$

A small ϑ_{13} enhances the $\nu_e \leftrightarrow \nu_{\mu,\tau}$ CP-asymmetry

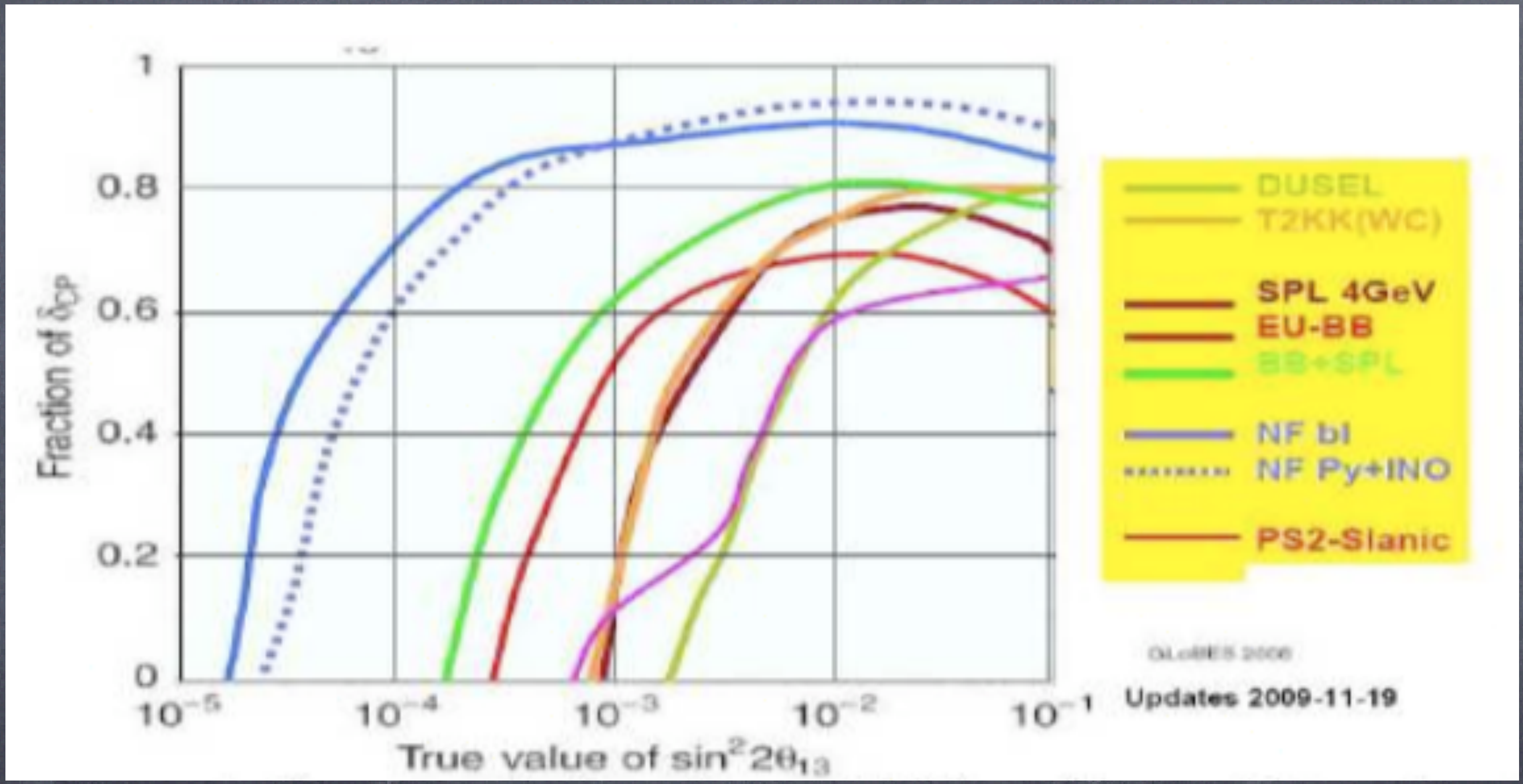
$$a_{\rm CP} = \frac{P(\nu_e \to \nu_\mu) - P(\overline{\nu}_e \to \overline{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\overline{\nu}_e \to \overline{\nu}_\mu)} \propto \frac{1}{\sin 2\theta_{13} + \ \text{corr.}}$$

The statistical sensitivity is independent of ϑ_{13} (on a wide range)

$$\delta a \sim \frac{1}{\sqrt{N}} \propto \frac{1}{\sin 2\theta_{13}} \to \text{stat. error} \sim \delta a / a \sim \text{constant with } \theta_{13}$$

Fake CP-violation

* In practice one has to take into account the contribution to the measured asymmetry from the CP-asymmetry of
    - the source
    - the matter along the path of neutrinos
    - the target
* That requires a good knowledge of
    - the initial fluxes
    - the Earth (electron) density profile
    - the neutrino cross sections
* Also useful are
    - the measurement of the energy spectrum
    - 2 baselines
    - additional channels

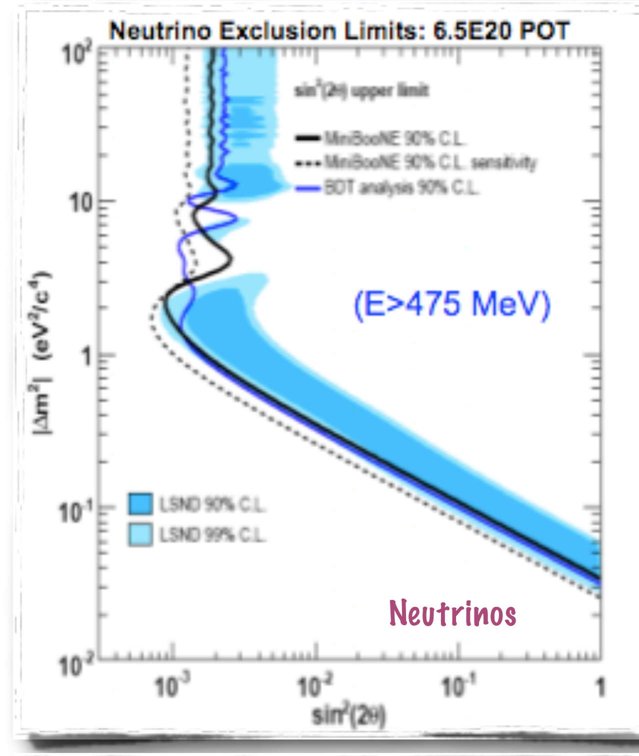


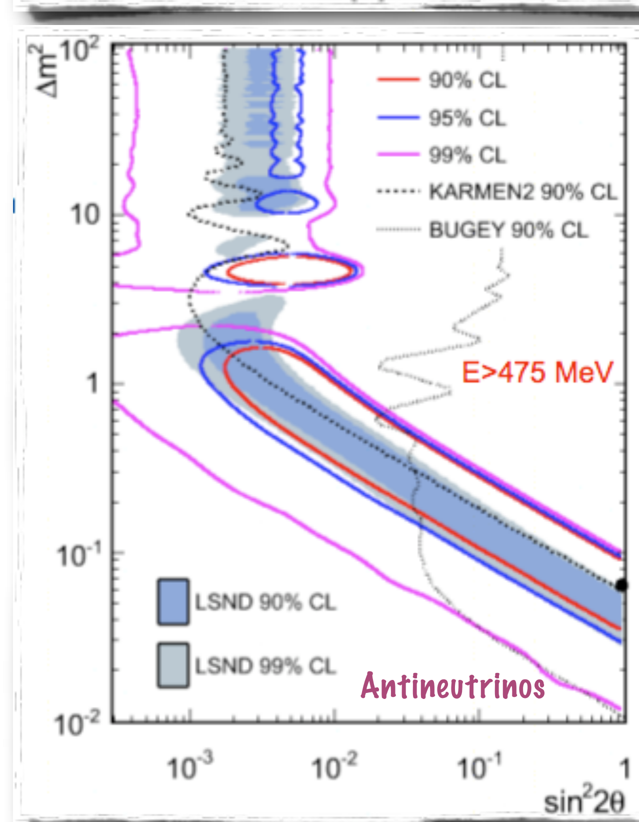
Palladino, Neutrino 2010

Anomalous anomalies

LSND & MiniBooNE

- The LSND evidence (antineutrino mu → e transitions)
  - does not fit in the 3 neutrino oscillation framework
  - does not nicely fit in a 4 neutrino oscillation framework
- Tested by MiniBOONE
  - same L/E, O(10) larger L, E
  - Neutrino run excludes LSND at more than 90% CL (anomaly at wrong L/E, low E and large background)
  - Antineutrino run finds an excess compatible with LSND (neutrino 2010)





Beyond oscillations

Charged sector

$m_{e,\mu,\tau}$

Accessible to oscillations

Δm^2_{12}

$|\Delta m^2_{23}|$

$\text{sign}(\Delta m^2_{23})$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

$(\Delta m^2_{ij} \equiv m^2_{\nu_j} - m^2_{\nu_i})$

Not accessible to oscillations

m_{lightest}

α

β

$m_{lightest}$

- Probed by
  - beta decay
  - double beta decay
  - cosmology

β decay endpoint

$$(A,Z) \to (A,Z+1) + e^- + \overline{\nu}_e; \quad \text{e.g.: } {}^3\text{H} \to {}^3\text{He} + e^- + \overline{\nu}_e$$

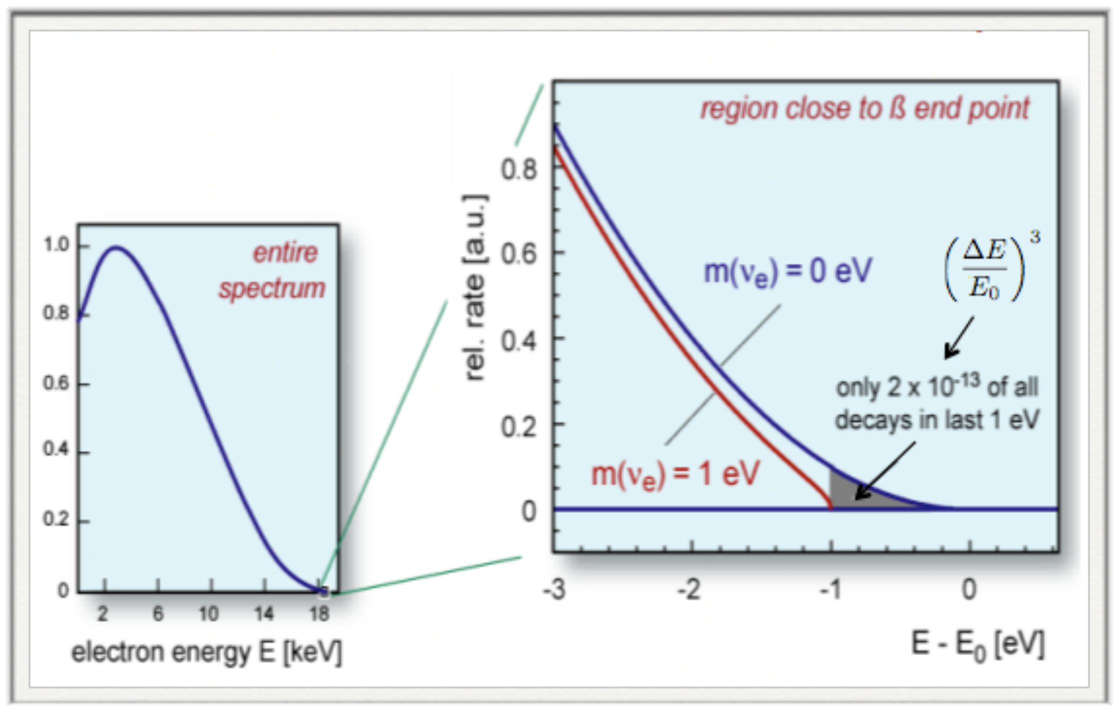
$$\frac{dN}{dE} \propto \sum |U_{eh}|^2 \Gamma(m_h^2, E) \approx \Gamma((m^\dagger m)_{ee}, E)$$

$$(m^\dagger m)_{ee} = |U_{eh}|^2 m_h^2 = c_{13}^2 (m_1^2 c_{12}^2 + m_2^2 s_{12}^2) + m_3^2 s_{13}^2$$

$\approx m^2$ (degenerate neutrinos)

Independent of
- Phases
- Nuclear matrix elements
- Dirac vs Majorana
- Cosmological models

$m < 2.3$ eV (Mainz, Troitsk)
$\to 0.2$ eV (Katrin)



$0\nu 2\beta$ decay

* Signals L-violation
* Probes the Majorana nature of neutrinos
* Allows to access parameters not accessible to oscillations:
  * Absolute mass scale
  * Majorana phases

Dirac vs Majorana (particle content)

* A Dirac fermion (e + e^c) corresponds to

  4 degrees of freedom = 2 x particle + 2 x antiparticle

* A Majorana fermion (ν) corresponds to

  2 degrees of freedom = 2 x particle = 2 x antiparticle

* The difference shows up only in the m ≠ 0 case:
  - Dirac (m = 0)

    $\overline{\nu}_L|0\rangle = |\nu -\rangle$ $\qquad$ $\nu_L|0\rangle = |\overline{\nu} +\rangle$

  - Majorana (m = 0)

    $\overline{\nu}_L|0\rangle = |\nu -\rangle$ $\qquad$ $\nu_L|0\rangle = |\nu +\rangle$

* In oscillations, once the O(m/E) terms have been neglected:
  - the elicity does not play a role
  - there is no L-violation
  - oscillation formulae are identical for Dirac and Majorana ν's

Dirac vs Majorana (particle content)

* A Dirac fermion ($e + e^c$) corresponds to

  4 degrees of freedom = 2 x particle + 2 x antiparticle

* A Majorana fermion (ν) corresponds to

  2 degrees of freedom = 2 x particle = 2 x antiparticle

* The difference shows up only in the $m \neq 0$ case:
  - Dirac ($m \neq 0$)

    $$\overline{\nu}_L|0\rangle = |\nu -\rangle + \mathcal{O}\left(m/E\right)|\nu +\rangle \qquad \nu_L|0\rangle = |\overline{\nu} +\rangle + \mathcal{O}\left(m/E\right)|\overline{\nu} -\rangle$$

  - Majorana ($m \neq 0$)

    $$\overline{\nu}_L|0\rangle = |\nu -\rangle + \mathcal{O}\left(m/E\right)|\nu +\rangle \qquad \nu_L|0\rangle = |\nu +\rangle + \mathcal{O}\left(m/E\right)|\nu -\rangle$$

* In oscillations, once the O(m/E) terms have been neglected:
  - the elicity does not play a role
  - there is no L-violation
  - oscillation formulae are identical for Dirac and Majorana ν's

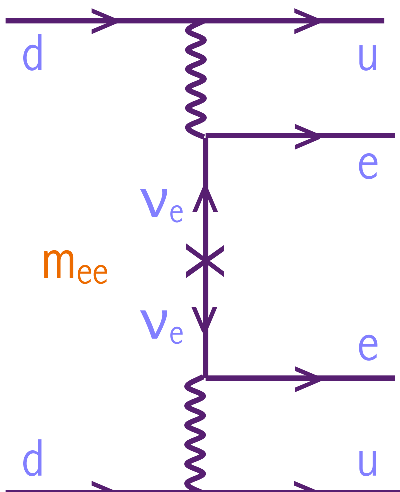
0ν2β decay

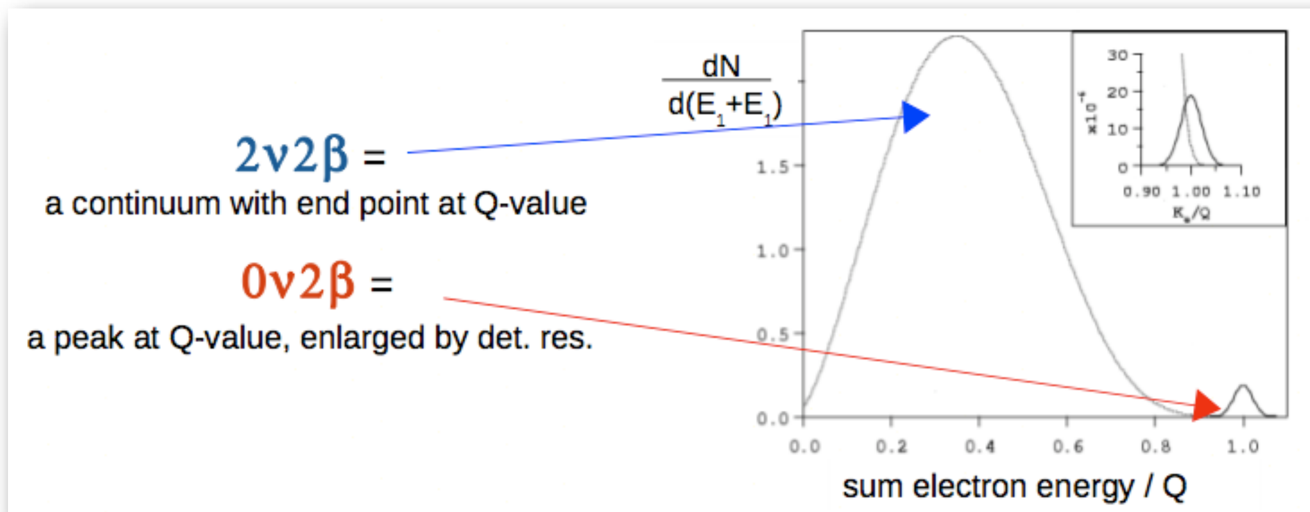
$$(A,Z) \to (A,Z+2) + 2e^-; \quad \text{e.g.: } {}^{76}\text{Ge} \to {}^{76}\text{Se} + 2e^-$$

Depends on
- Phases
- Nuclear matrix elements
- Dirac vs Majorana

$$\Gamma \propto |m_{ee}|^2 \langle Q \rangle^2$$

$$m_{ee} = U_{eh}^2 m_h = c_{13}^2(m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\alpha}) + m_3 s_{13}^2 e^{2i\beta'}$$





$$|m_{ee}| < \mathcal{O}(1) \times 0.4\,\text{eV (Heidelberg-Moscow)} \to \mathcal{O}(1) \times 0.01\,\text{eV (Genius)}$$

Cosmology

* Neutrino physics affects
  - Cosmic Microwave Backgrouns (CMB)
    Anisotropies in the photon radiation at decoupling ($T \sim 0.3$ eV) are sensitive to the total radiation density through the energy fraction in neutrinos $\propto m_{cosmo} = m_1 + m_2 + m_3$
  - Large Scale Structures (LSS)
    Free streaming of relativistic non-interacting particles smoothes density fluctuation leading to the structures observed today. The length scale of the effect depends on the neutrino masses

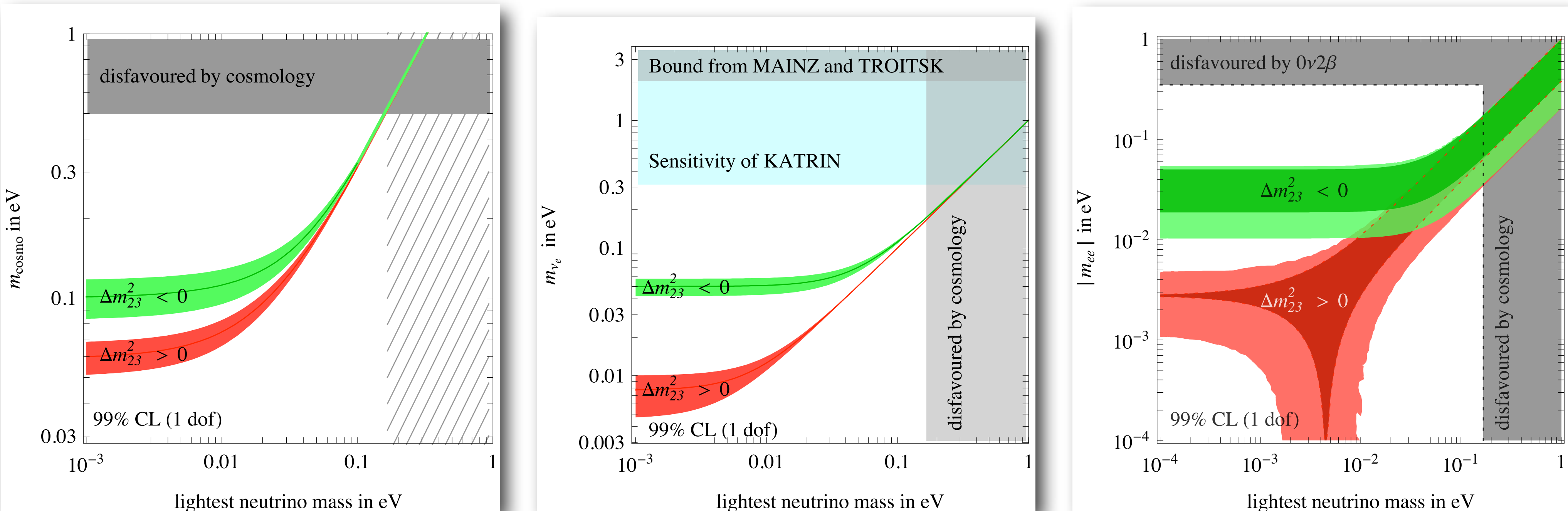
  Under assumptions on the cosmological model (plausible, consistent): structures generated by gaussian adiabatic fluctuations, constant spectral index n, SM spectrum + cold dark matter + CC

* @99% CL CMB: $m_{cosmo} < 2.6$ eV (Planck: 0.2 eV)
  with LSS: $m_{cosmo} < 0.5$ eV

Cosmology

(LSS constraint more powerful but less reliable: effect larger at small scales where computations are not easy)

* Neutrinos also affect
  - Big Bang nucleosynthesis (BBN)
    The present relative abundance of p, n, light elements is determined by standard inverse beta reactions involving neutrinos at their decoupling temperature $T \sim$ MeV
  - possibly Baryogenesis (through leptogenesis)
    $n_B/n_\gamma \approx 6\ 10^{-10}$ might be associated to a lepton asymmetry formed by the CP asymmetric decay out of equilibrium of heavy right-handed neutrinos (transformed into a Baryon asymmetry by sphalerons).
    An economical and successful Baryogenesis mechanism

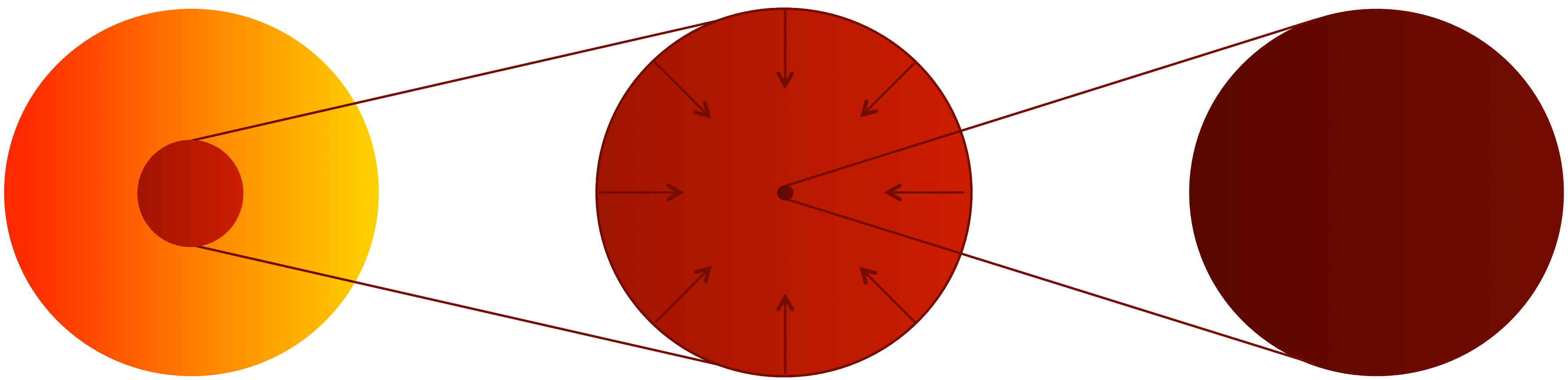


Strumia Vissani review

Astrophysics: supernovae

Supernova neutrinos

- Probe of core-collapse supernova physics
- Some sensitivity to neutrino parameters (uncertainties on the source)
- Constraint on exotic (neutrino) physics

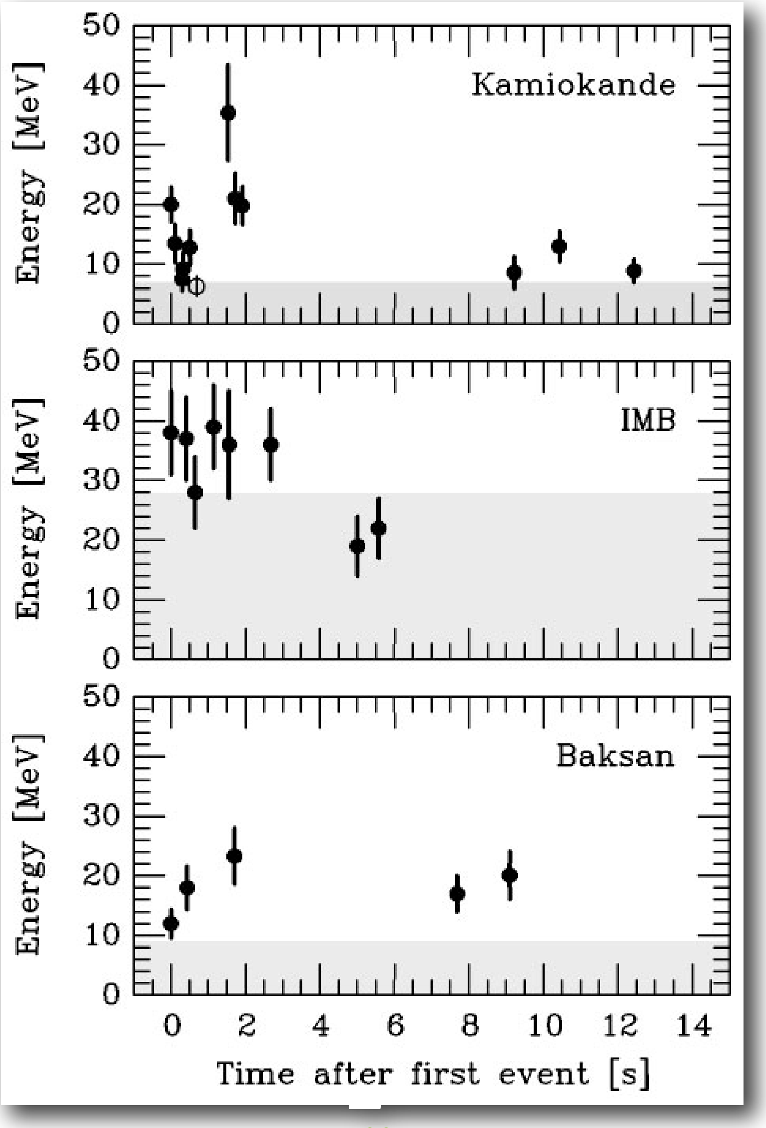


$M \sim 1.5 M_{\rm SUN}$
$R \sim 8000\,{\rm km}$
$\rho \sim 10^9\,{\rm g/cm}^3$
$T \sim 0.7\,{\rm MeV}$

$$E_{\rm out} \sim E_{\rm b} \sim 3 \times 10^{53}\,{\rm erg}$$
$$= \begin{cases} 0.01\% \text{ photons} \\ 1\% \text{ kinetic energy} \\ 99\% \text{ neutrinos} \end{cases}$$
$$\lambda \sim 10\,{\rm cm} \Rightarrow t_{\rm diff} \sim \frac{3R^2}{\lambda} \sim 10\,{\rm sec}$$

$R \sim 30\,{\rm km}$
$\rho \sim 3 \times 10^{14}\,{\rm g/cm}^3$
$T \sim 30\,{\rm MeV}$

SN 1987A



Raffelt

Constraints on exotic scenarios

* Energy loss argument: $\frac{d\epsilon}{dt} < 10^{19}\,\mathrm{erg/s/g}$

* Constrains invisible escape channels
    - axions
    - KK gravitons
    - sterile neutrinos

* E.g.: $\sin^2 2\vartheta_S < 10^{-8}$ for large Δm^2

Future SN

Future SN (1/30yr?)				
Detector	SK	SNO	LVD	KamLAND
ν events (from 10kpc)	~ 8000	~ 800	~ 400	~ 330

@ neutrinosphere: $\langle E_{\nu_e} \rangle \sim 11\,\text{MeV} < \langle E_{\overline{\nu}_e} \rangle \sim 16\,\text{MeV} < \langle E_{\overline{\nu}_x} \rangle \sim 25\,\text{MeV}$

@ Earth: the energy spectra depend on ϑ_{13} and

sign$(\Delta m^2)_{23}$

e.g.: NH & $\vartheta_{13} > 0.05 \Rightarrow \Phi(\nu_e) = \Phi_0(\nu_{\mu,\tau})$

$(\Delta m^2)_{23}$ resonance crossed by neutrinos (antineutrinos) if NH (IH)

$P_C = 0$ ($P_C = 1$) if $\vartheta_{13} > 0.05$ ($\vartheta_{13} < 0.001$)

($(\Delta m^2)_{12}$ is always adiabatic)

($(\Delta m^2)_{23} = 2\,E\,(V_\mu - V_\tau)$ resonance plays a role if $\Phi(\nu_\mu) \neq \Phi(\nu_\tau)$)

Neutrino physics (III)

Andrea Romanino
SISSA/ISAS

Theoretical impact

$\Delta m^2_{\mathrm{ATM}} \sim 2.4 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45^\circ$ (ATM, K2K, Minos)

$\Delta m^2_{\mathrm{SUN}} \sim 0.76 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 35^\circ$ (SUN, KamLAND)

$\theta_{13} < 7^\circ \quad (2\sigma)$ (CHOOZ, Minos + ATM, SUN)

$|m_{ee}| = |U^2_{ei} m_{\nu_i}| < \mathcal{O}(1) \times 0.4\,\mathrm{eV}$ (Heidelberg-Moscow)

$(m^\dagger m)_{ee} = |U_{ei}|^2 m^2_{\nu_i} < (2.2\,\mathrm{eV})^2$ (Mainz, Troitsk)

$\sum_i m_{\nu_i} < \mathcal{O}(1)$ eV (priors) (Cosmology)

Guidelines for theory:

$m_{\nu_i} \ll 174\,\mathrm{GeV}$

$\theta_{23} \sim 45^\circ (= 45^\circ ?)$

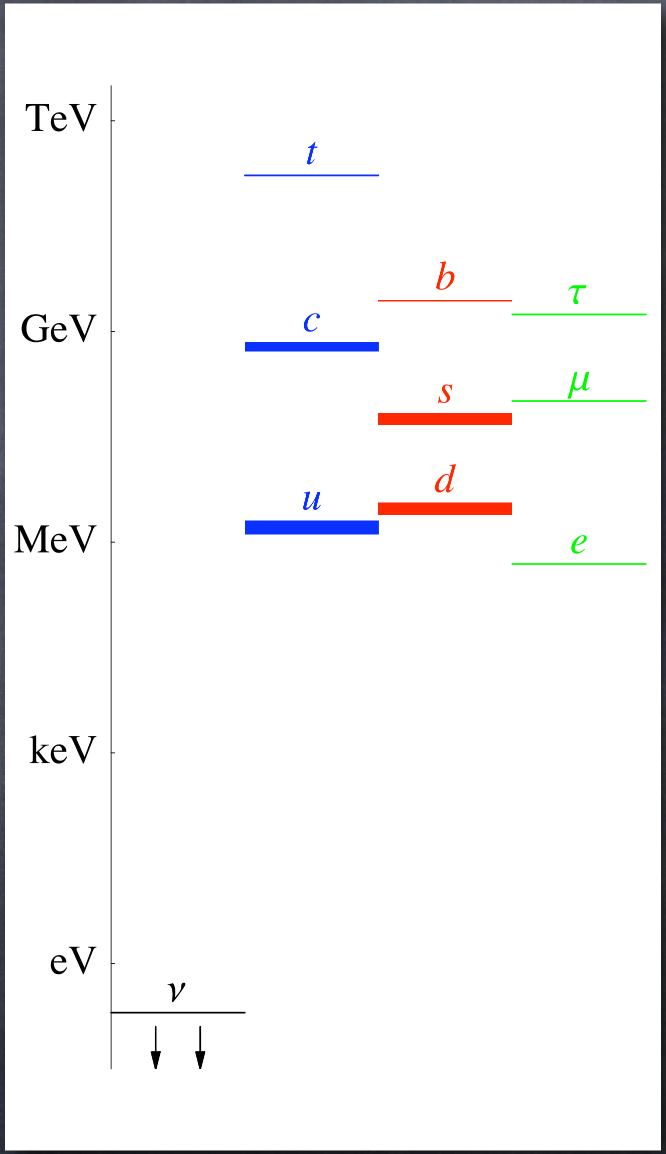
$\theta_{12} \sim 30^\circ\text{–}35^\circ \neq 45^\circ$

$\theta_{13} < 7^\circ$

$|\Delta m^2_{12} / \Delta m^2_{23}| \approx 0.035 \ll 1$

Origin of neutrino masses

Smallness of neutrino masses



- Natural scale of fermion masses: <H> = 174 GeV
- Why m_ν / <H> < 10^{-12} ?
- Must have a different origin than m_e / <H> = 0.3 x 10^{-5}
  - larger hierarchy
  - family independent
  - well understood

Neutrino (and fermion) masses in the SM

Taking only $U(1)_{em}$ and $SU(3)_c$ into account

- L fields:

	u_L	d_L	ν_L	e_L	$\overline{u_R}$	$\overline{d_R}$	$\overline{e_R}$
Q	⅔	−⅓	0	−1	−⅔	⅓	1
$SU(3)_c$	3	3	1	1	$\bar{3}$	$\bar{3}$	1

- Gauge invariant LL terms:

$$m_u \overline{u_R} u_L + m_d \overline{d_R} d_L + m_e \overline{e_R} e_L + \frac{m_\nu}{2} \nu_L \nu_L$$

(smallness of neutrino masses not understood at this level)

Taking into account (exact) $SU(2)_L \times U(1)_Y$

- L fields:

	$(u_L\ d_L)$	$(\nu_L\ e_L)$	$\overline{u_R}$	$\overline{d_R}$	$\overline{e_R}$
$SU(2)_L$	2	2	1	1	1
$U(1)_Y$	1/6	-1/2	-⅔	⅓	1
$SU(3)_c$	3	1	$\bar{3}$	$\bar{3}$	1

- Gauge invariant LL terms:

None!

- No fermion mass term is allowed in the limit of exact EW symmetry (the SM is a "chiral" theory)

Fermion masses from EWSB (at the ren. level)

- Fermion masses arise because <H> breaks the EW symmetry
  H = (h^+,h^0) ≈ (1, 2, ½) → <h^0> = v = 174 GeV

- Example: electron mass term (L = (ν_L e_L), Q = (u_L d_L))

$$\lambda_E \overline{e_R} L\, H^\dagger = \lambda_E \overline{e_R}(e_L h^0 + \nu_L h^+) \to m_E \overline{e_R} L e_L, \quad m_E = \lambda_E v$$

- In general

$$\begin{aligned}\mathcal{L}_{\rm SM}^{\rm flavor} &= \lambda^E_{ij}\overline{e_{iR}}L_j H^\dagger + \lambda^D_{ij}\overline{d_{iR}}Q_j H^\dagger + \lambda^U_{ij}\overline{u_{iR}}Q_j H + \text{h.c.} \\ &= m^E_{ij} e^c_i e_j \quad + m^D_{ij} d^c_i d_j \quad + m^U_{ij} u^c_i u_j \quad + \text{h.c.} + \ldots\end{aligned}$$

with $m^E_{ij} = \lambda^E_{ij} v \quad m^D_{ij} = \lambda^D_{ij} v \quad m^U_{ij} = \lambda^U_{ij} v$

$m^\nu_{ij} = 0$

What do we learn?

- $m_\nu = 0$: nice starting point
- $m_\nu \neq 0$: need something on top of the SM
- several possibilities

2 main options

1. the new ingredients live at $M \gg M_Z$ (example: see-saw)
2. the new ingredients live at $M \lesssim M_Z$ (example: Dirac neutrinos)

Option 1: $M \gg M_Z$

Theorem

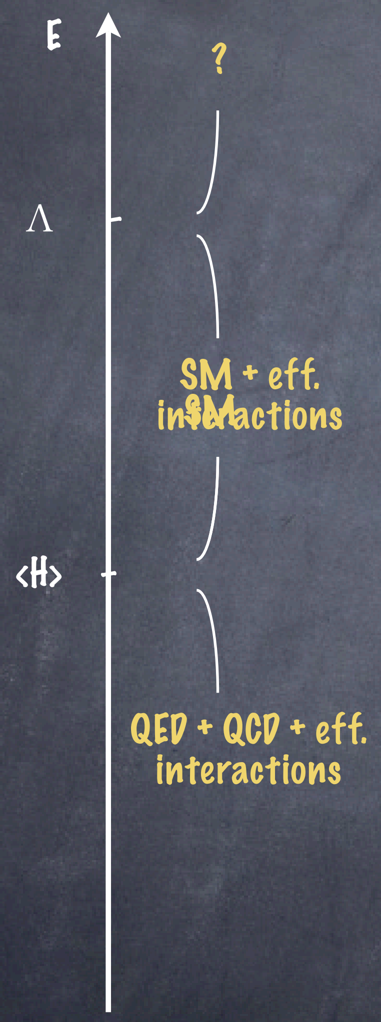
Theorem

* The effect of any high scale [$M \gg M_Z$] physics [responsible for neutrino masses] can be described at low E by effective interactions involving only light dofs and symmetries (no need to know the microscopic theory and dofs). The effective interactions are suppressed by M

Theorem

- The effect of any high scale [$M \gg M_Z$] physics [responsible for neutrino masses] can be described at low E by effective interactions involving only light dofs and symmetries (no need to know the microscopic theory and dofs). The effective interactions are suppressed by M
- Example: SM interactions can be described at $E \ll M_Z$ by effective Fermi interaction involving only light fermions

The SM as an effective theory

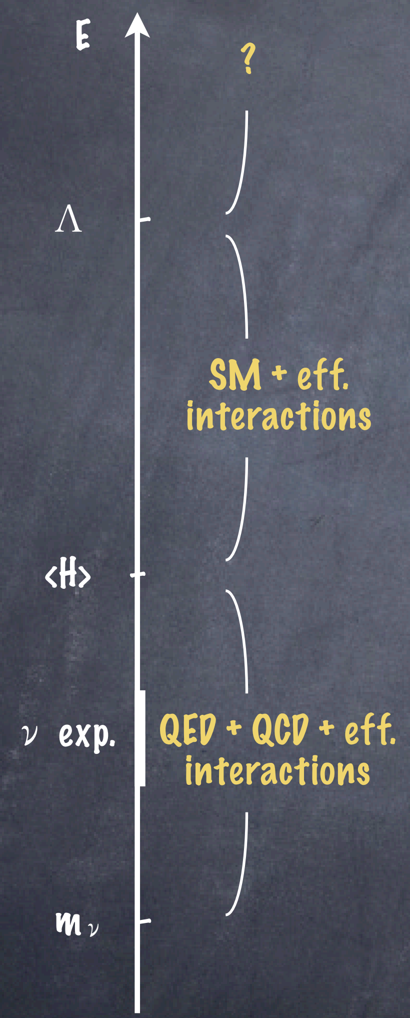


- Analogously...

$$\mathcal{L}^{\rm eff}_{E\ll\Lambda} = \mathcal{L}^{\rm ren}_{\rm SM} + \mathcal{L}^{\rm NR}_{\rm SM}$$

- No hint of NR interactions from TeV scale
- Only evidence of NR interactions: neutrino masses

The SM as an effective theory



- $$\mathcal{L}^{\text{eff}}_{E \ll \Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \mathcal{L}^{\text{NR}}_{\text{SM}}$$
  $$= \mathcal{L}^{\text{ren}}_{\text{SM}} + \frac{h_{ij}}{2\Lambda}(HL_i)(HL_j) + \ldots$$
- $m^{E,D,U}_{ij} = \lambda^{E,D,U}_{ij} v \quad m^{\nu}_{ij} = h_{ij} v \times \frac{v}{\Lambda}$ (Majorana)
  $$\Lambda \sim 0.5 \times 10^{15}\,\text{GeV} h \left(\frac{0.05\,\text{eV}}{m_\nu} \right)$$
- $M_{GUT} \approx 2 \times 10^{16}$ GeV
- Room for leptogenesis
- L^{eff} is sensitive to the GUT scale only through L- and B-violating operators

- Nice
  - The smallness of neutrino masses is well and economically understood in a model-independent way in terms of the heavyness of the scale at which L is violated
- What makes neutrinos special?
  - They are the only fermions in the SMfor which a mass does not arise (after EWSB) from a renormalizable interaction with the Higgs fields (and neutrinos turn out to be Majorana
- But
  - Could not ν have a light ν_R partner as all other SM fermions?

Right-handed neutrinos ($f^c \equiv \overline{f_R}$)

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{matrix} u^c \\ d^c \end{matrix} \quad \begin{pmatrix} \nu \\ e \end{pmatrix} \quad \begin{matrix} \nu^c \\ e^c \end{matrix}$$

$SU(3)_C \times SU(2)_W \times U(1)_Y$

$$\lambda_\nu \nu_c L H \rightarrow m_\nu = \lambda_\nu v$$

(like the other fermions)

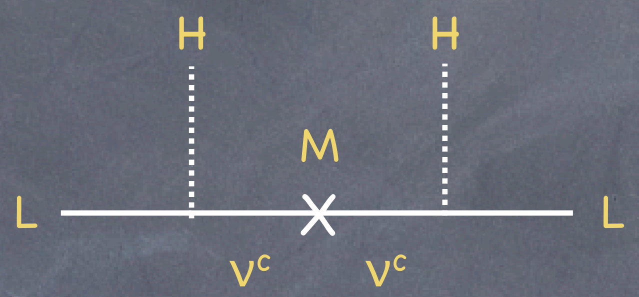
ν_c is a SM singlet and can therefore be heavy

$$\mathcal{L}_{\mathrm{HE}} \supset -\frac{M}{2}\nu^c\nu^c$$

(unlike the other fermions)

See-saw

Integrate out ν^c:



$$\frac{h}{\Lambda}(HL)(HL)$$

$$\frac{h}{\Lambda} \to -\lambda^T \frac{1}{M} \lambda$$

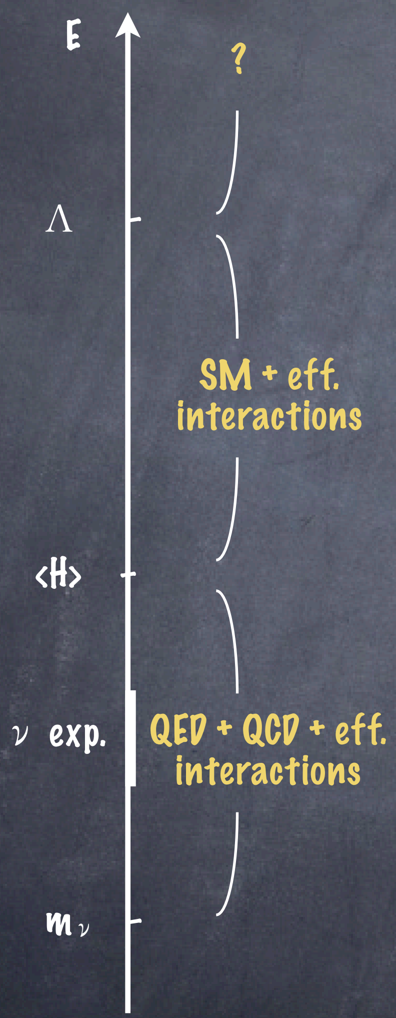
$$m_\nu = -m_\mathrm{D}^T \frac{1}{M} m_\mathrm{D}$$

Majorana

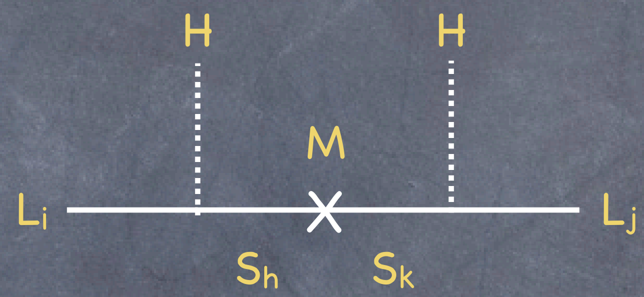
Origin of (LH) (LH)
(at M » M_Z)

Renormalizable origin of LLHH

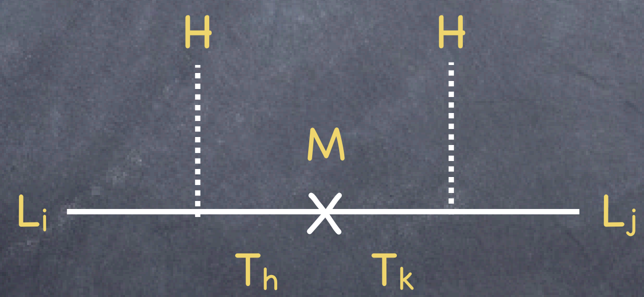
$$\mathcal{L}^{\text{eff}}_{E \ll \Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \frac{h_{ij}}{\Lambda}(HL_i)(HL_j) + \ldots$$



$L_i H \approx (1,2,-½) \otimes (1,2,½) = (1,1,0) \oplus (1,3,0)$

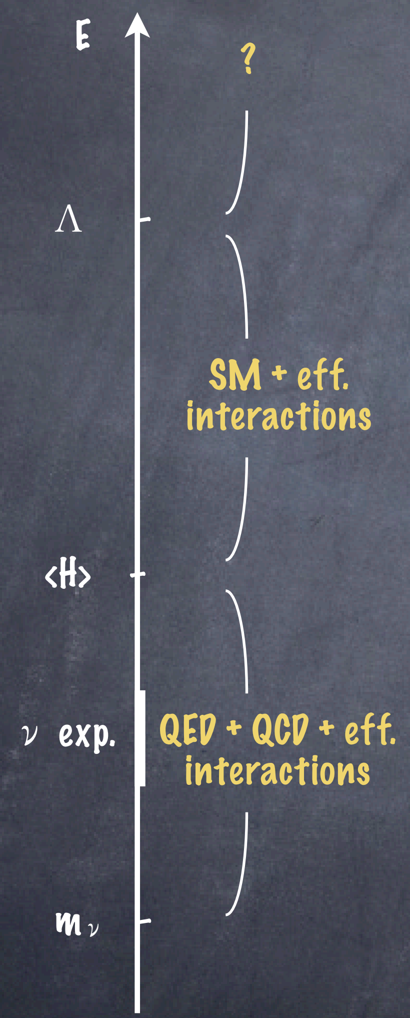


See-saw type I



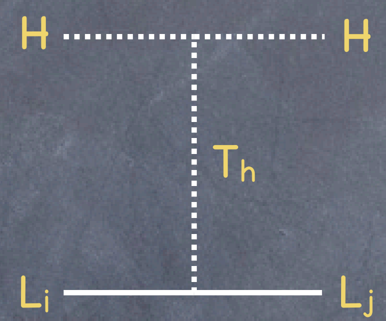
See-saw type III

Renormalizable origin of LLHH



$$\mathcal{L}^{\rm eff}_{E\ll\Lambda} = \mathcal{L}^{\rm ren}_{\rm SM} + \frac{h_{ij}}{\Lambda}(HL_i)(HL_j) + \dots$$

$HH \approx (1,2,-\tfrac{1}{2}) \otimes (1,2,-\tfrac{1}{2}) = (1,\cancel{1},-1)_a \oplus (1,3,-1)_s$



See-saw type II

- Any number of S_h, T_h
- No loops if low energy supersymmetry

Option 2: $M \lesssim M$

- Standard paradigm:

$$\mathcal{L}^{\text{eff}}_{E\ll\Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \frac{h_{ij}}{\Lambda}(HL_i)(HL_j) + \dots$$

$$\Lambda \sim 0.5 \times 10^{15}\,\text{GeV}\,h\left(\frac{0.05\,\text{eV}}{m_\nu}\right) \gg \text{TeV}$$

- Alternative: the SM extension accounting for neutrino masses arises at a scale Λ < TeV (the EFT description does not hold)

Example: Dirac neutrinos

- Lepton number is "exactly" conserved: $h_{ij} = 0$
- Neutrino masses then need an L = -1 neutrino ν^c

$$m_{ij}^N \nu_i^c \nu_j + m_{ij}^E e_i^c e_j + m_{ij}^D d_i^c d_j + m_{ij}^U u_i^c u_j + \text{h.c.}$$

- In the SM:

$$\begin{aligned}\mathcal{L}_{\text{SM}}^{\text{flavor}} &= \lambda_{ij}^N \nu_i^c L_j H + \lambda_{ij}^E e_i^c L_j H^\dagger + \lambda_{ij}^U u_i^c Q_j H + \lambda_{ij}^D d_i^c Q_j H^\dagger + \text{h.c.} \\ &= m_{ij}^N \nu_i^c \nu_j \quad + m_{ij}^E e_i^c e_j \quad + m_{ij}^U u_i^c u_j \quad + m_{ij}^D d_i^c d_j \quad + \text{h.c.} + \ldots\end{aligned}$$

$$m_{ij}^N = \lambda_{ij}^N v \quad m_{ij}^E = \lambda_{ij}^E v \quad m_{ij}^D = \lambda_{ij}^D v \quad m_{ij}^U = \lambda_{ij}^U v$$

- Needs L and $\lambda^N < 10^{-11}$: why?

$\lambda^N < 10^{-11}$ (1)

- L is conserved + $\lambda \nu^c LH$ forbidden by a symmetry, e.g. because it is charged under a U(1) symmetry:

$$\lambda \nu^c LH \to \lambda \left(\frac{\phi}{M}\right)^n \nu^c LH, \quad \lambda_{\text{eff}} = \lambda \left(\frac{\langle\phi\rangle}{M}\right)^n$$

[Chacko Hall Okui Oliver ph/0312267 Chacko, Hall Oliver Perelstein ph/0405067 Davoudiasl Kitano Kribs Murayama ph/0502176]

- interesting (model dependent) consequences for cosmology (was also motivated by LSND), no consequences for LHC:

$$\frac{\langle H\rangle}{M} \sim \frac{m_\nu}{\langle\phi\rangle} \sim g_{\phi\nu\nu^c} \lesssim 10^{-5} \quad \text{(BBN)}$$

$\lambda^N < 10^{-11}$ (2)

- L is conserved + λ^N originates in extra-dimensions
  - ν^c lives in the flat bulk of large extra dimensions:

$$\lambda_{\rm eff} = \frac{\lambda}{(2\pi R M_*)^{\delta/2}} = \lambda \frac{M_*}{M_{\rm Pl}}$$

[Arkani-Hamed et al. ph/9811448
Dienes Dudas Gherghetta ph/9811428]

    - 5D $\nu^c \leftrightarrow$ 4D $(\nu^c)_n$ $\qquad$ $M_n \approx n/R$ (large n)
    - Brane-bulk mixing: $m \approx \lambda_{\rm eff} \langle H \rangle$

$$\nu_i = U_{ik}\hat{\nu}_k + \frac{m_i}{M_n} N_n$$

In the presence
of bulk mass terms

[Lukas Ramond R Ross
ph/0008049, ph/0011295]

Standard
3 (mainly) active
neutrino mixing

Small
(mainly) sterile
component

  - ν^c and L are localized in distant points of a (warped) extra dimension:

$$\lambda \propto e^{-(\text{superposition of the wave functions})}$$

Low scale lepton number violation

$$\mathcal{L}^{\rm eff}_{E\ll\Lambda} = \mathcal{L}^{\rm ren}_{\rm SM} + \frac{h_{ij}}{\Lambda}(HL_i)(HL_j) + \ldots$$

- $h \approx 10^{-13}$–10^{-11} allows Λ < TeV
- Why? E.g. $h\dfrac{LLHH}{\Lambda} \to h\left(\dfrac{\phi}{M}\right)^n \dfrac{LLHH}{\Lambda}$, $h_{\rm eff} = h\left(\dfrac{\langle\phi\rangle}{M}\right)^n$ (as before)
- How is (HLHL) generated? Origin of L-violation?

The origin of the neutrino flavour structure

(ATM, K2K)

(SUN,KamLAND)

(CHOOZ, Palo Verde + ATM)

$$\Delta m^2_{\mathrm{ATM}} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45^\circ$$

$$\Delta m^2_{\mathrm{SUN}} \sim 0.8 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 30^\circ\text{–}35^\circ$$

(Heidelberg-Moscow)

$$\theta_{13} < 10^\circ$$

(Mainz, Troitsk)

(Cosmology)

Guidelines for theory:

$$|m_{ee}| = |U_{ei}^2 m_{\nu_i}| < \mathcal{O}(1) \times 0.4\,\mathrm{eV}$$

$$(m^\dagger m)_{ee} = |U_{ei}|^2 m^2_{\nu_i} < (2.2\,\mathrm{eV})^2$$

$$\sum_i m_{\nu_i} < 0.6\,\mathrm{eV} \ \ (\mathrm{priors})$$

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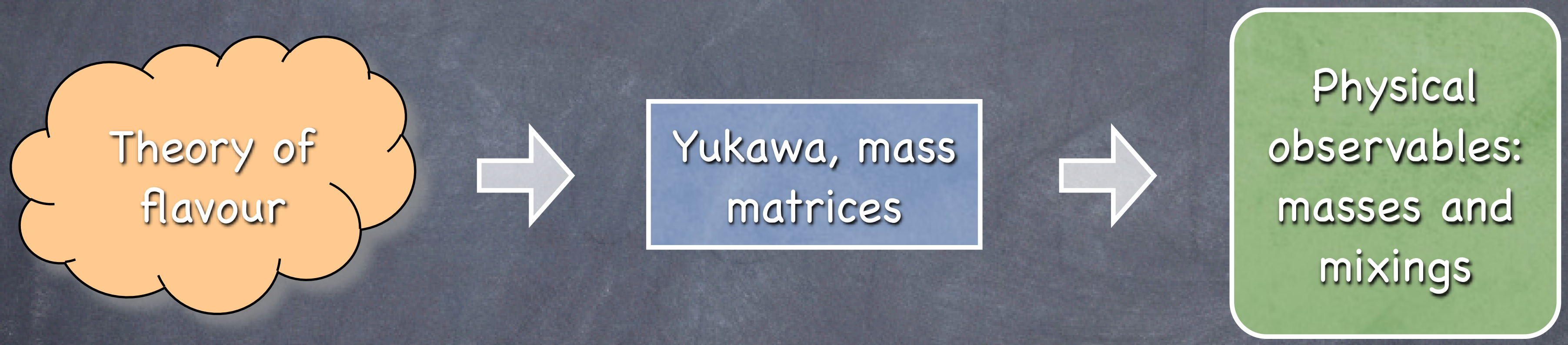
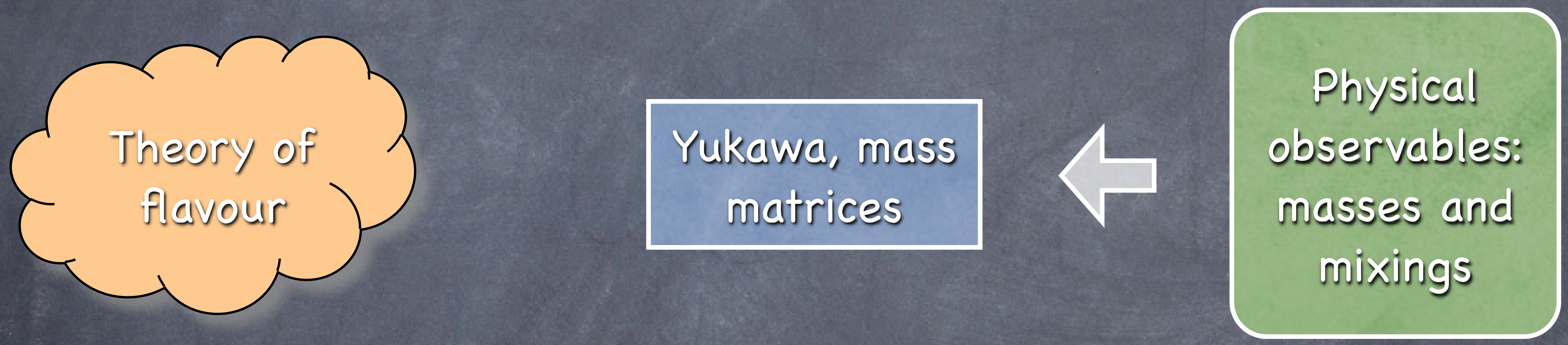

Theory of flavour
Yukawa, mass matrices
Physical observables: masses and mixings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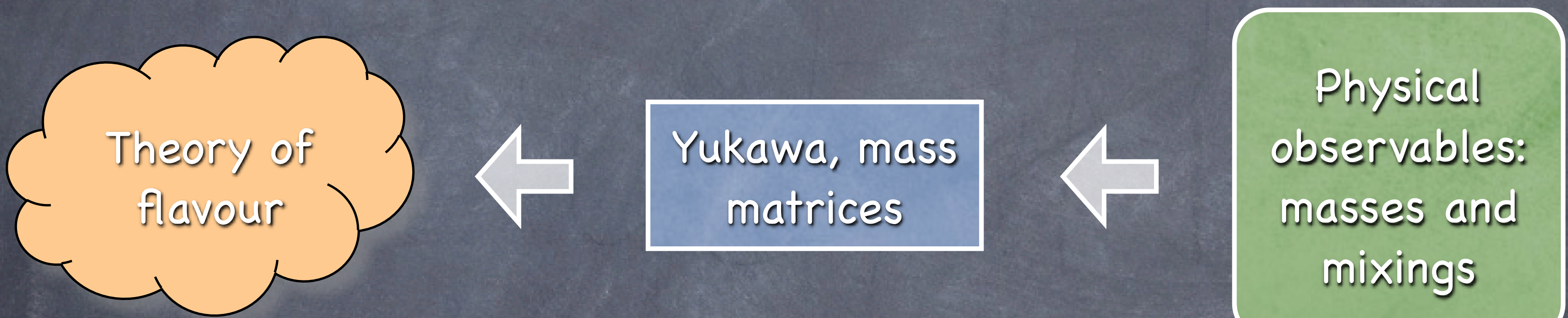
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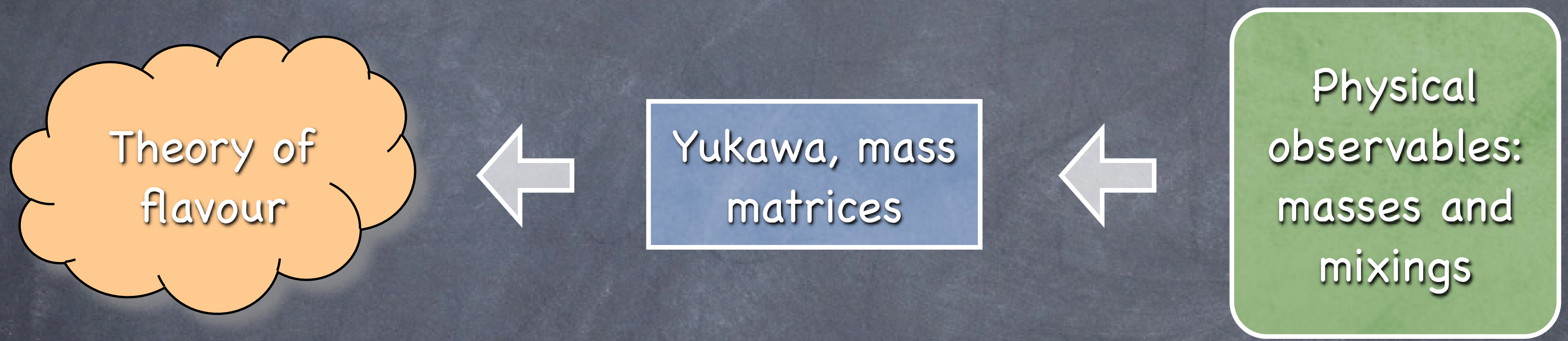
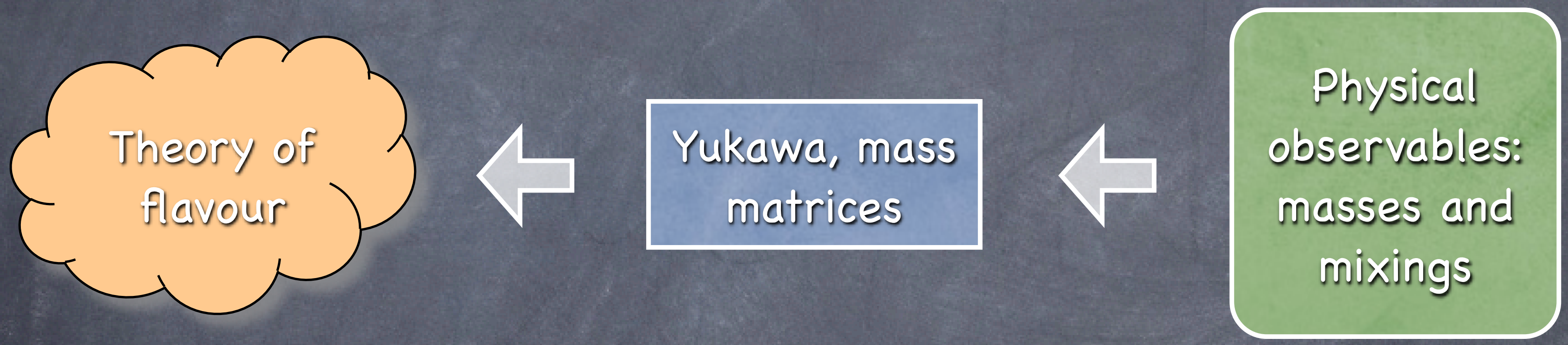


Quarks:
10 parameters



Quarks:
36 parameters

Quarks:
10 parameters