Neutrino physics
(theory)

Mariam Tórtola

AHEP group. IFIC, Valencia

International Meeting on Fundamental Physics 2012
Benasque, May 29th 2012

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VNIVERSITAT DE VALÈNCIA

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Outline

1.- What we know from neutrino experiments:

* neutrino masses
* neutrino mixing matrix

2.-Explaining the information we have:

* neutrino mass models
* the flavor problem
* neutrino anomalies: sterile neutrino, NSI

3.- Open questions in neutrino physics.

PART 1

What we know from neutrino experiments: neutrino masses and mixings

If neutrinos are massive ...

In general, the flavor eigenstates are an admixture of the mass eigenstates:

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i} \nu_{iL}$$

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

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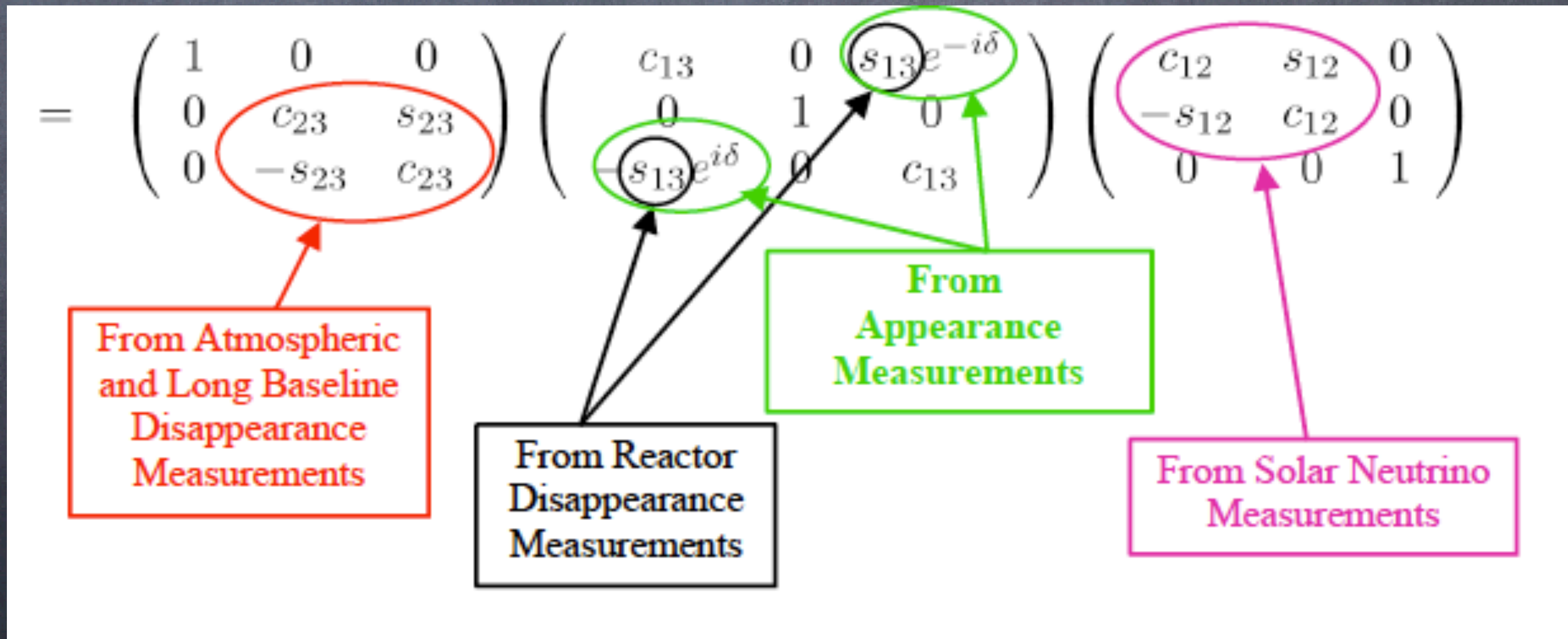
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



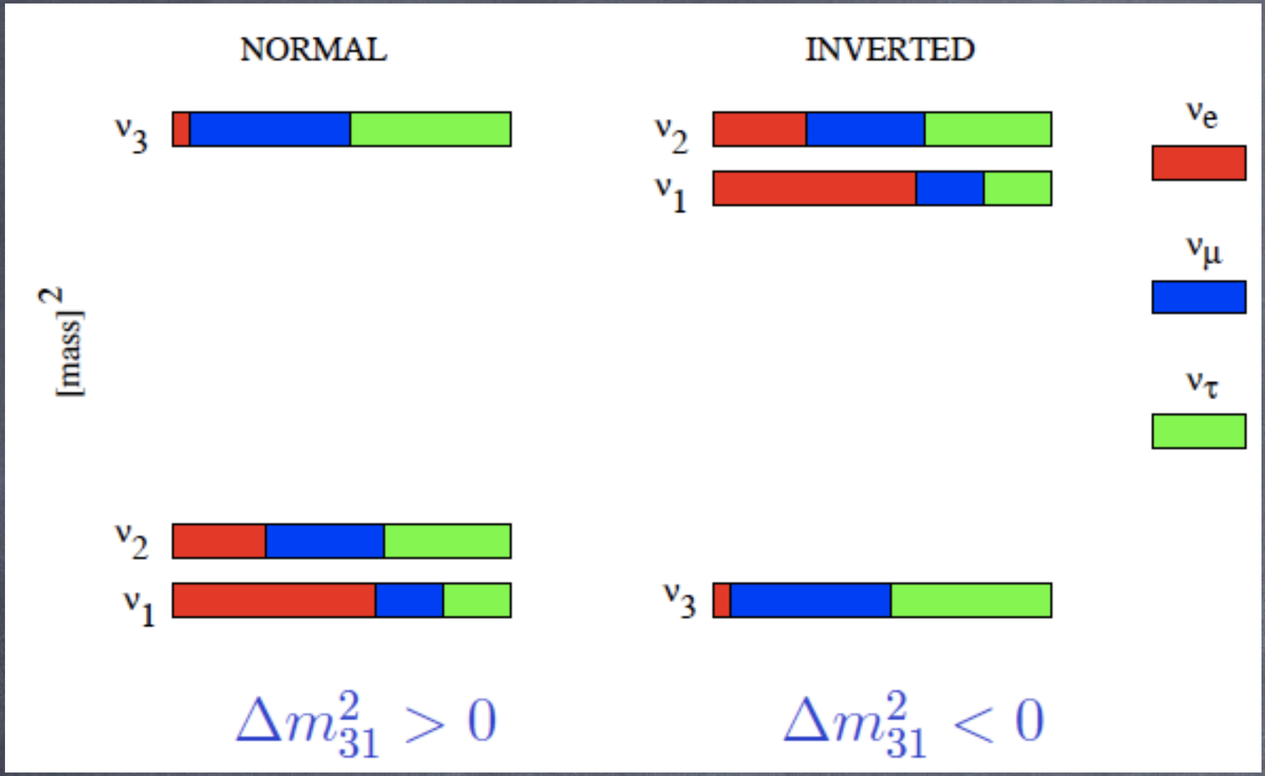
θ_{23}

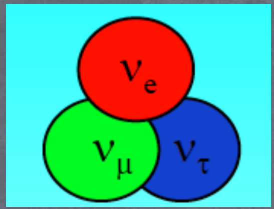
θ_{13}

θ_{12}

δ

There are two possible mass orderings:





- Neutrino oscillations are sensitive only to Δm^2_{ij}
  - Δm^2_{31} : atmospheric + long-baseline
  - Δm^2_{21} : solar + KamLAND
- absolute scale m_ν: laboratory measurements + cosmology

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Solar neutrinos

* produced in nuclear reactions in the core of the Sun:

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

pp cycle

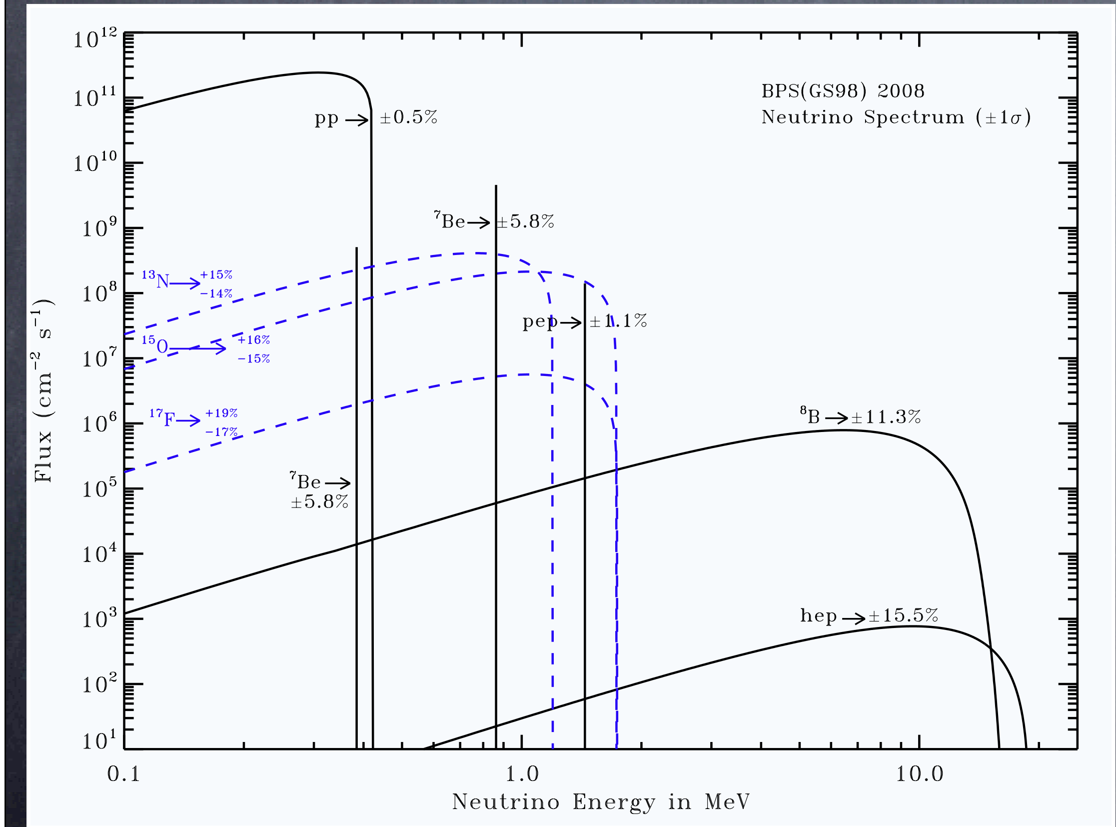
CNO

Reaction	source	Flux ($cm^{-2}s^{-1}$)
$p\,p \rightarrow d\,e^+\,\nu$	pp	$5.97(1 \pm 0.006)\times10^{10}$
$p\,e^-\,p \rightarrow d\,\nu$	pep	$1.41(1 \pm 0.011)\times10^{8}$
${}^3He\,p \rightarrow {}^4He\,e^+\,\nu$	hep	$7.90(1\pm 0.15)\times10^{3}$
${}^7Be\,e^- \rightarrow {}^7Li\,\nu\,\gamma$	${}^7Be$	$5.07(1 \pm 0.06)\times10^{9}$
${}^8B \rightarrow {}^8Be^*\,e^+\,\nu$	${}^8B$	$5.94(1 \pm 0.11)\times10^{6}$
${}^{13}N \rightarrow {}^{13}C\,e^+\,\nu$	${}^{13}N$	$2.88(1 \pm 0.15)\times10^{8}$
${}^{15}O \rightarrow {}^{15}N\,e^+\,\nu$	${}^{15}O$	$2.15(1 \pm {}^{0.17}_{0.16})\times 10^{8}$
${}^{17}F \rightarrow {}^{17}O\,e^+\,\nu$	${}^{17}F$	$5.82(1 \pm {}^{0.19}_{0.17})\times10^{6}$

ν fluxes

SSM predictions

ν energy spectra



Peña-Garay & Serenelli,arXiv:0811.2424

First solar ν detectors: the radiochemical experiments

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- Chlorine experiment:
  - gold mine in Homestake (South Dakota)
  - 615 tons of perchloro-ethylene (C_2Cl_4)
  - detection process: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
  - only 1/3 of SSM prediction detected:

$$R_{Cl}^{SSM} = 8.12 \pm 1.25 \text{ SNU}$$

$$R_{Cl} = 2.56 \pm 0.16 \text{ (stat.)} \pm 0.16 \text{ (syst.) SNU}$$

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- Gallium experiments (GALLEX/GNO, SAGE):

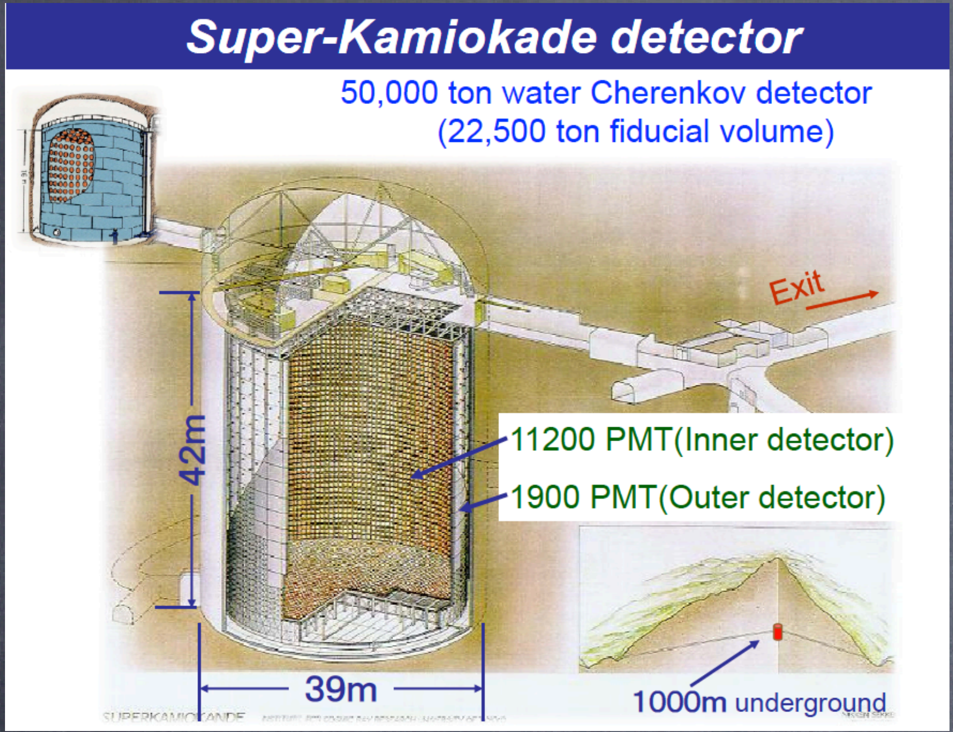
$$R_{GALLEX/GNO} = 69.3 \pm 4.1 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

$$R_{SAGE} = 66.9 \pm 3.9 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

$$R_{Ga}^{SSM} = 126.2 \pm 8.5 \text{ SNU}$$

→ 50% deficit

Solar neutrinos in Cherenkov detectors



- sensitive to all neutrino flavors:

$$\nu_x \, e^- \rightarrow \nu_x \, e^-$$

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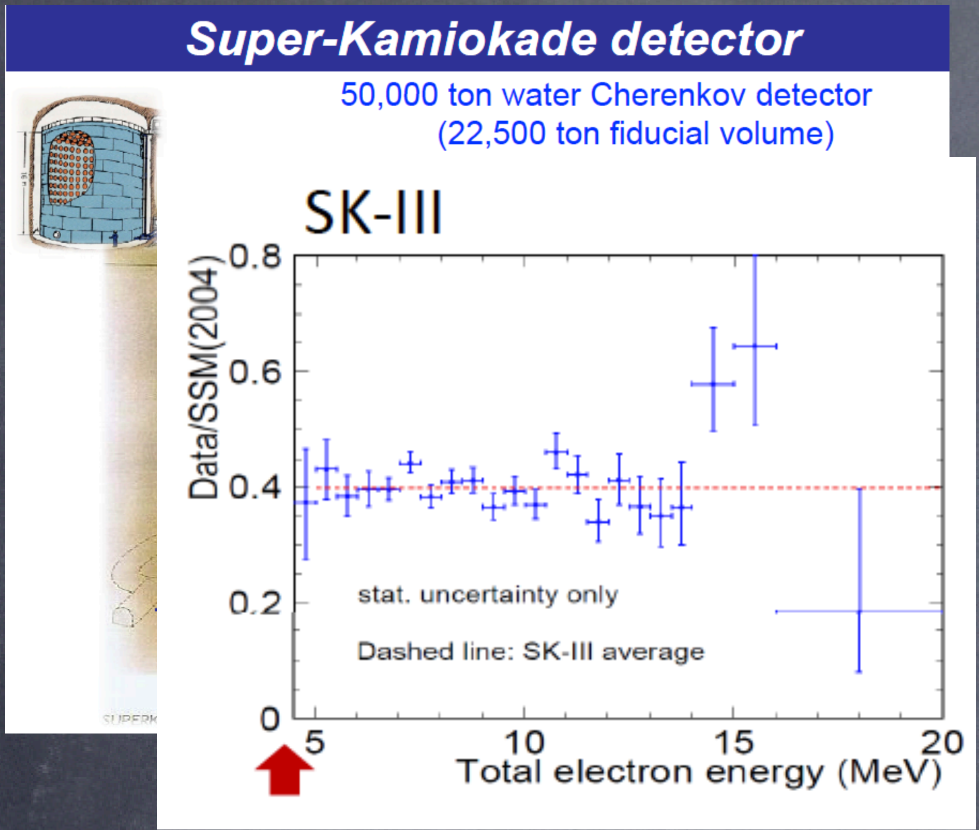

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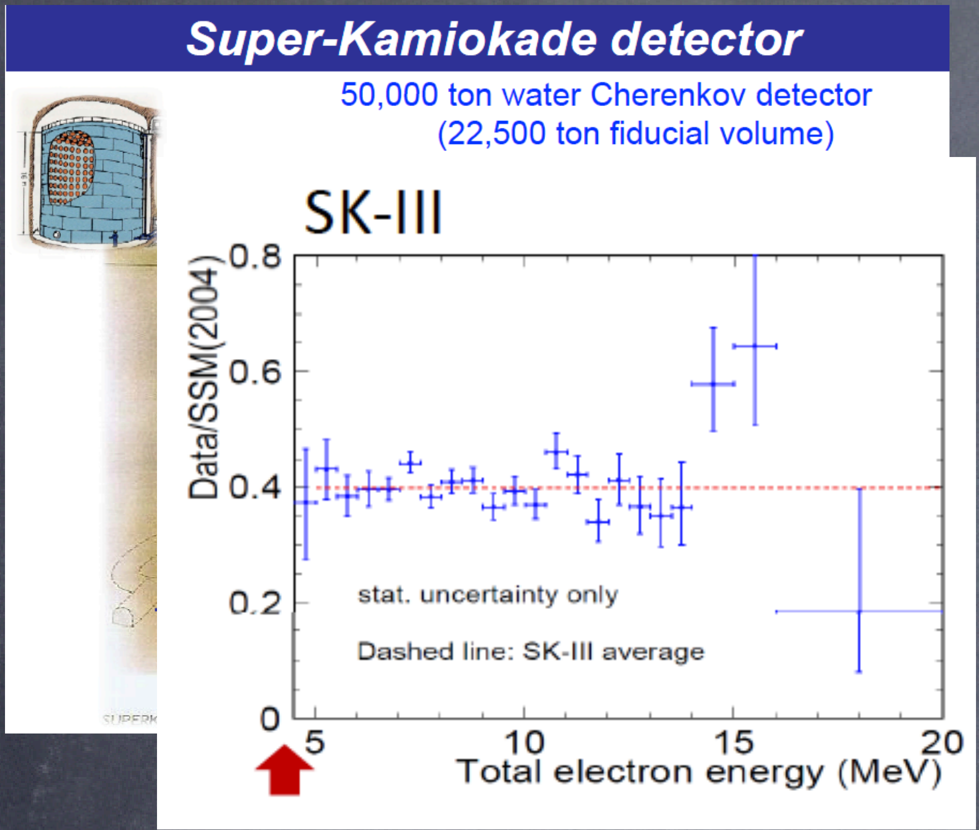

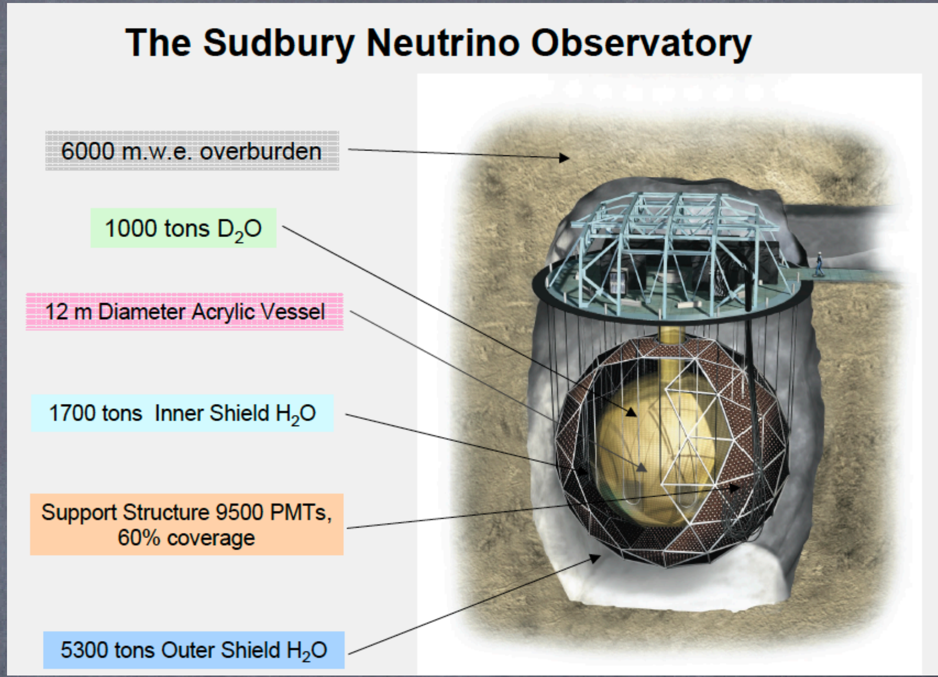

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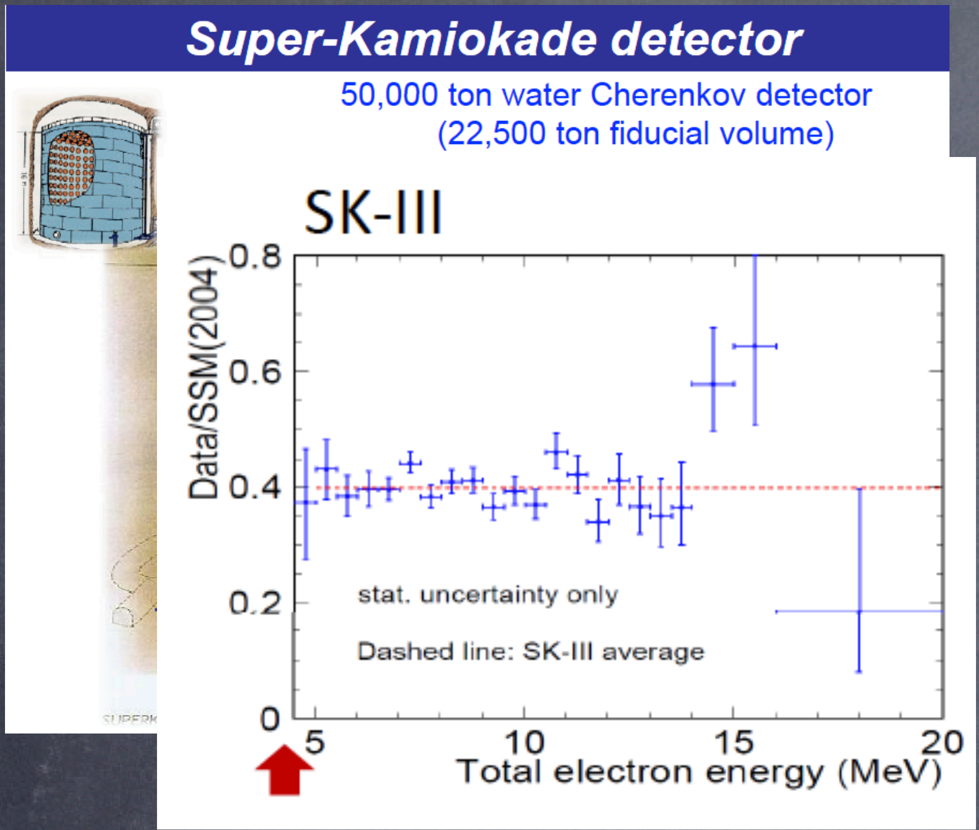

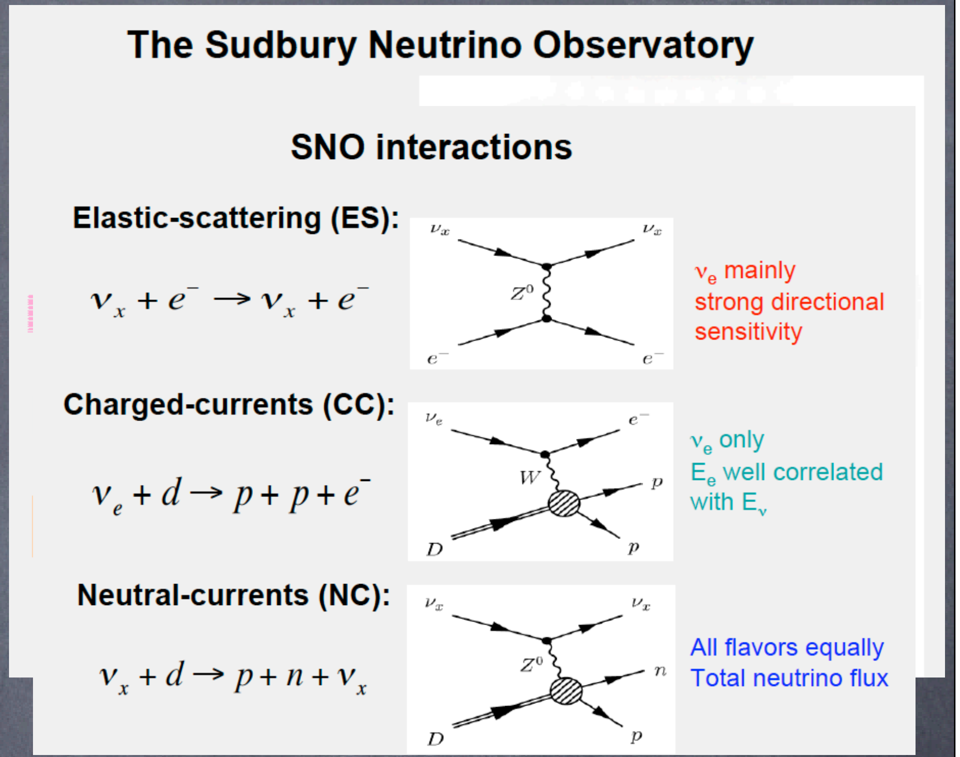

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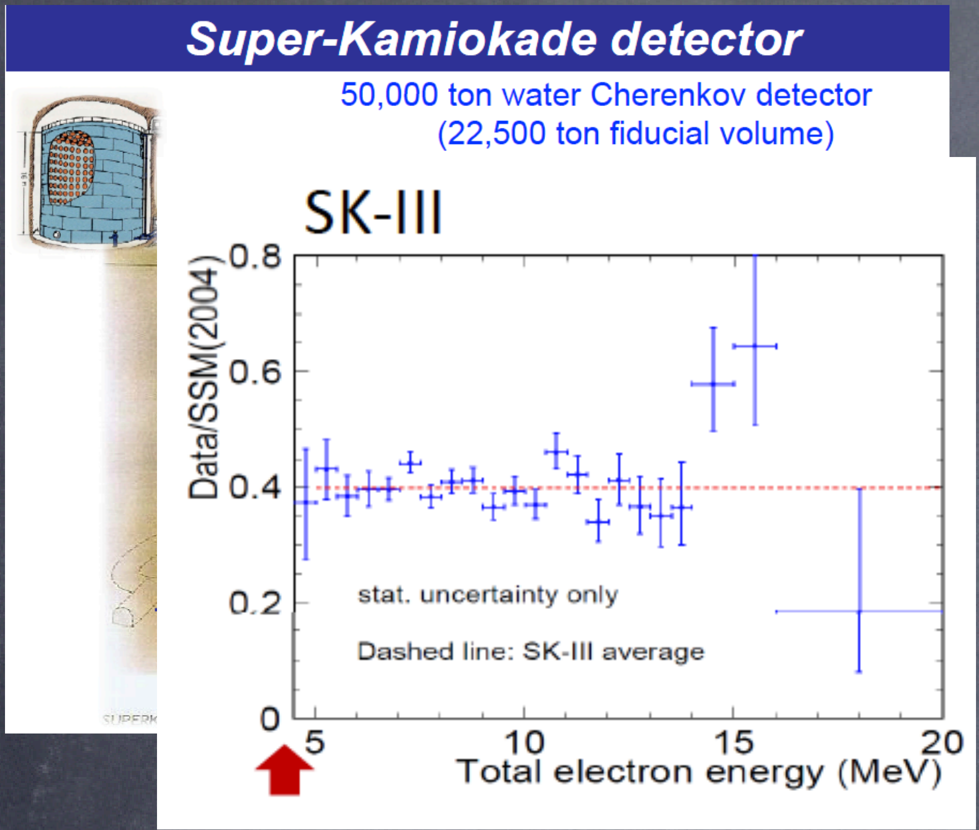

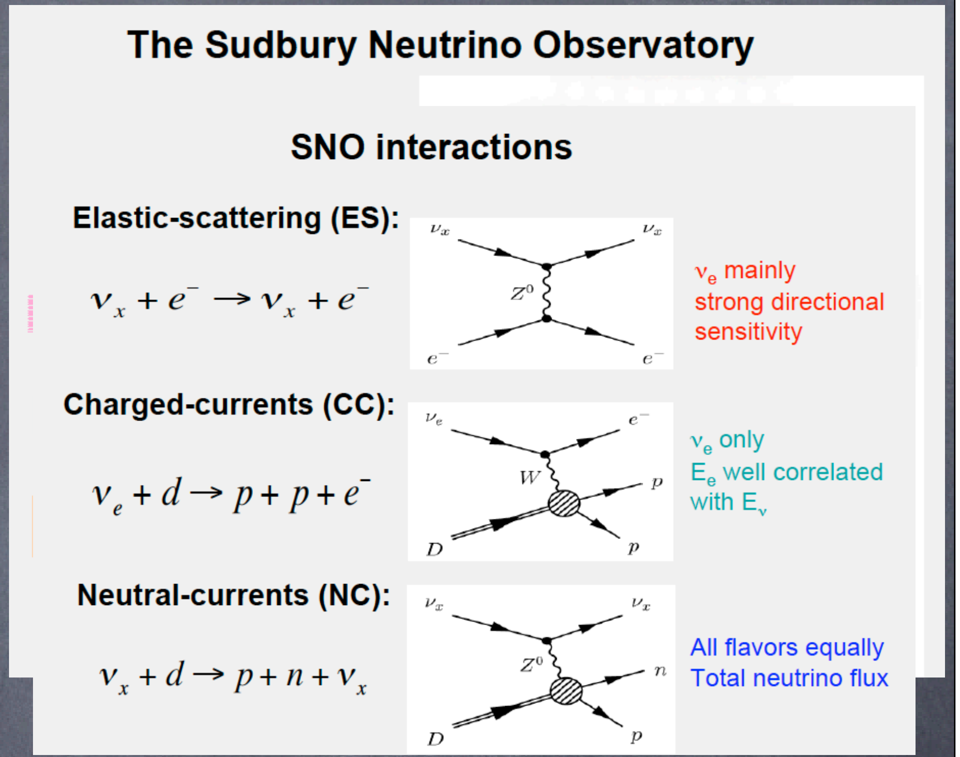

ν_e flux (CC):

30%

$$\frac{\phi^{SNO}_{CC}}{\phi^{SNO}_{NC}} = 0.301 \pm 0.033\ldots$$

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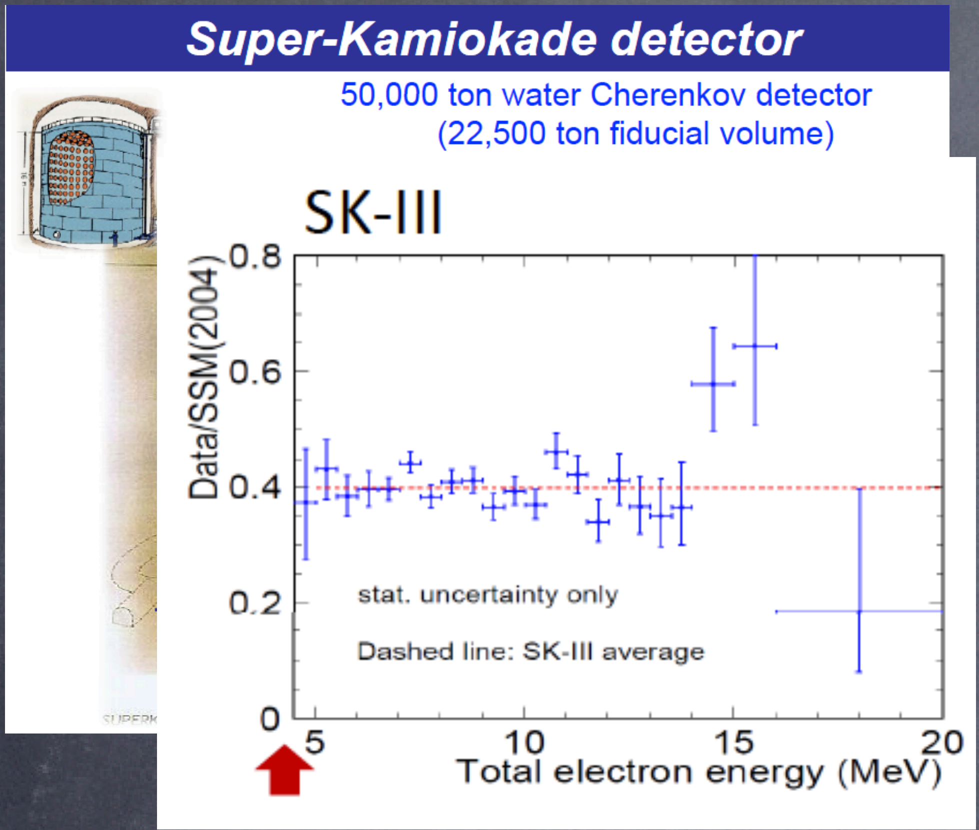

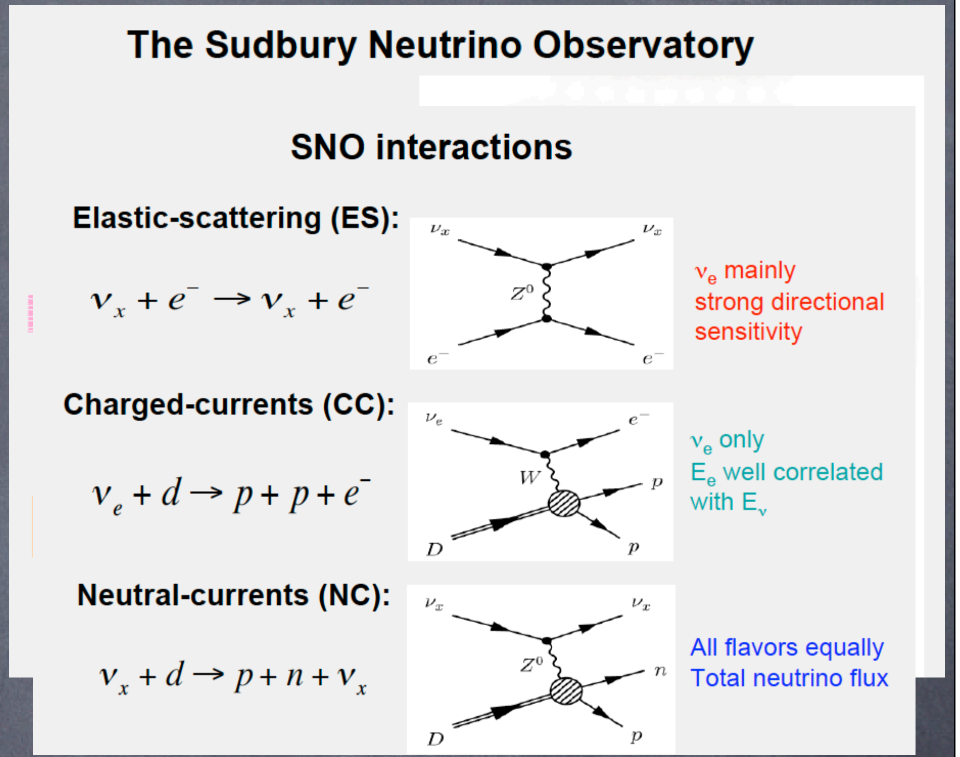

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ν_e flux (CC): 30%

$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$$

total ν flux (NC):

$$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst})$$

100%

Solar ν oscillation parameters

Homestake (E_ν > 0.814 MeV)

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

SAGE/GALLEX-GNO (E_ν >0.233 MeV)

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

Super-Kamiokande ($E_e \gtrsim 5$ MeV)

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

SNO ($E_e \gtrsim 5$ MeV)

[CC] $\nu_e + d \rightarrow p + p + e^-$

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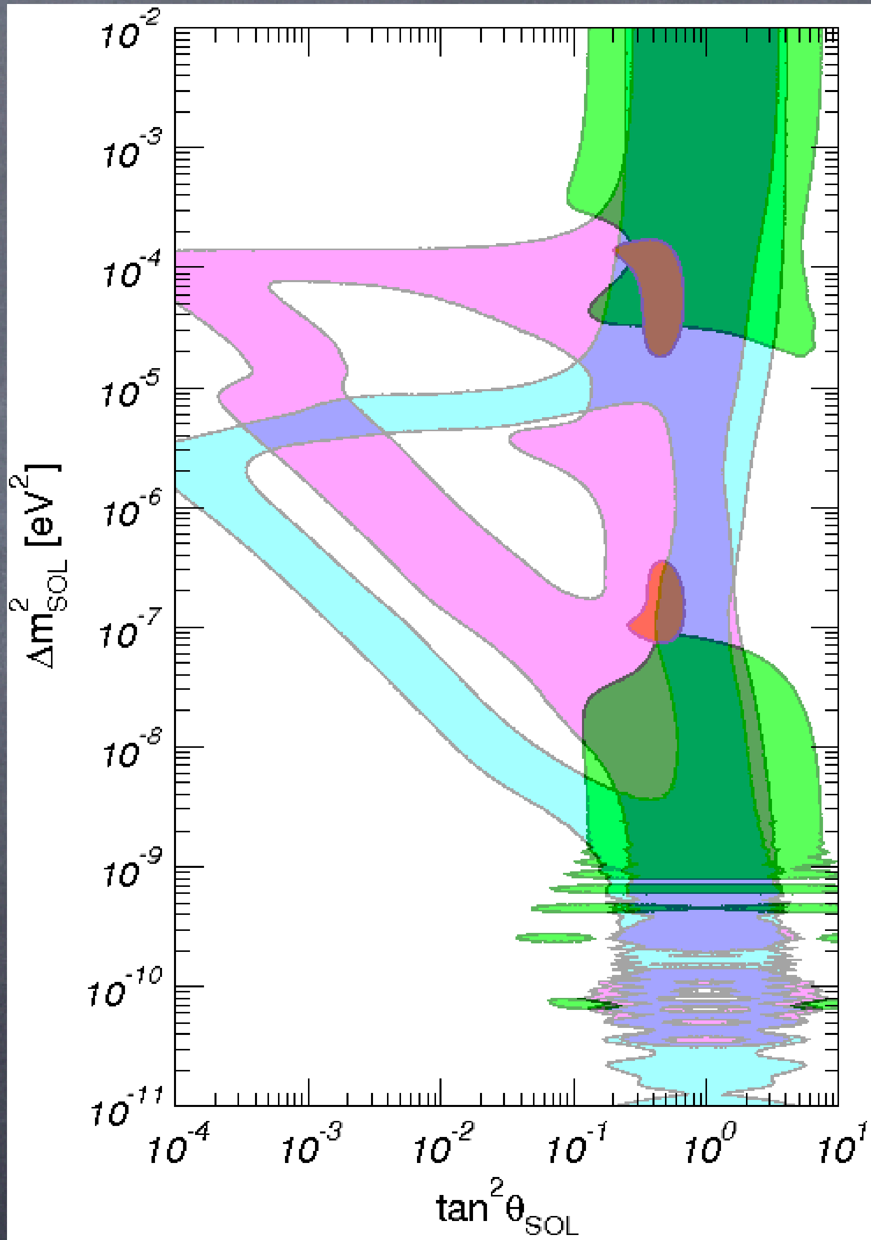

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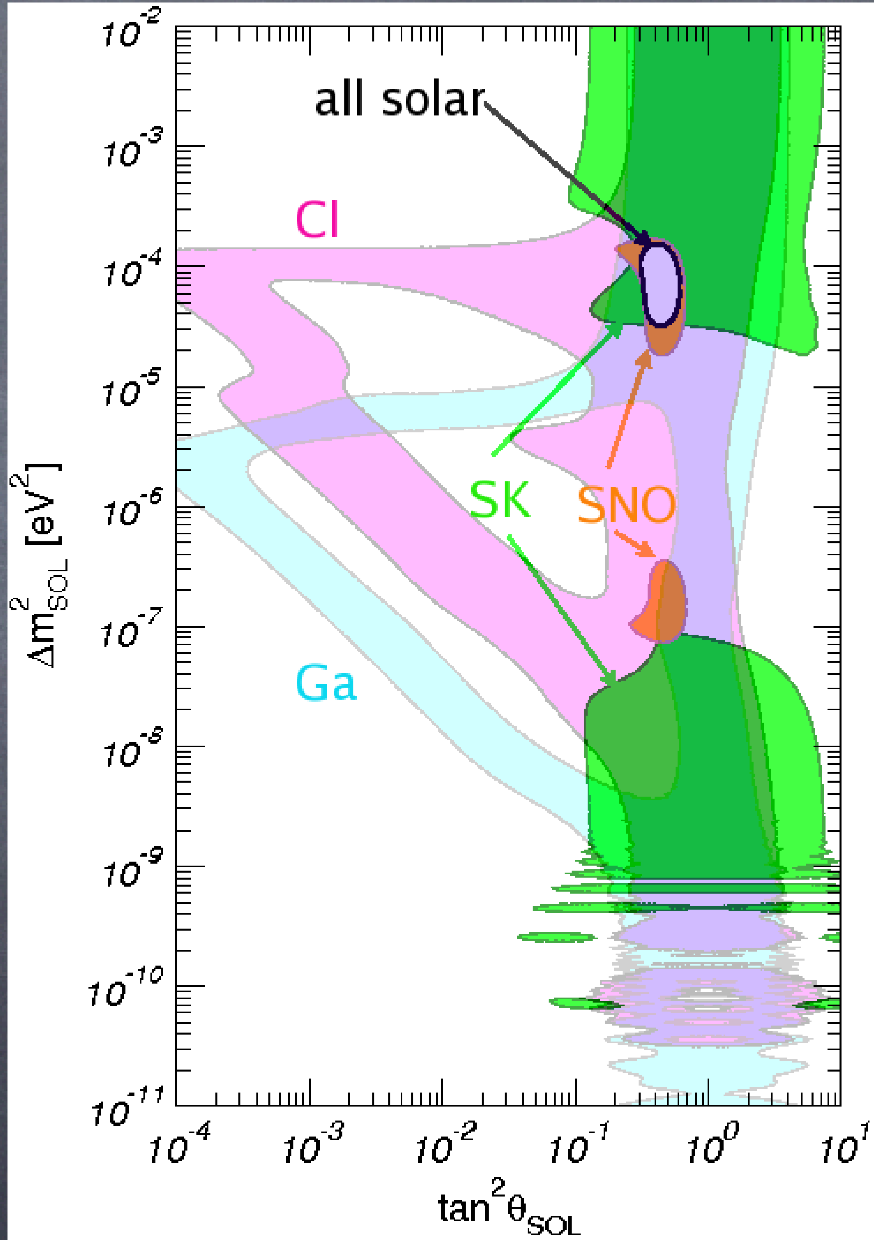
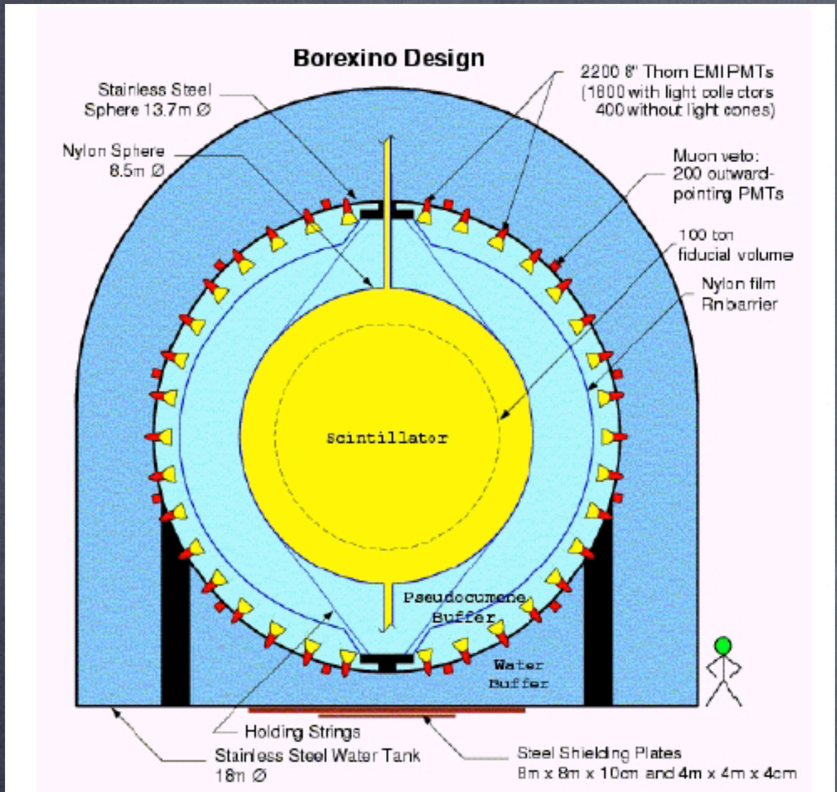
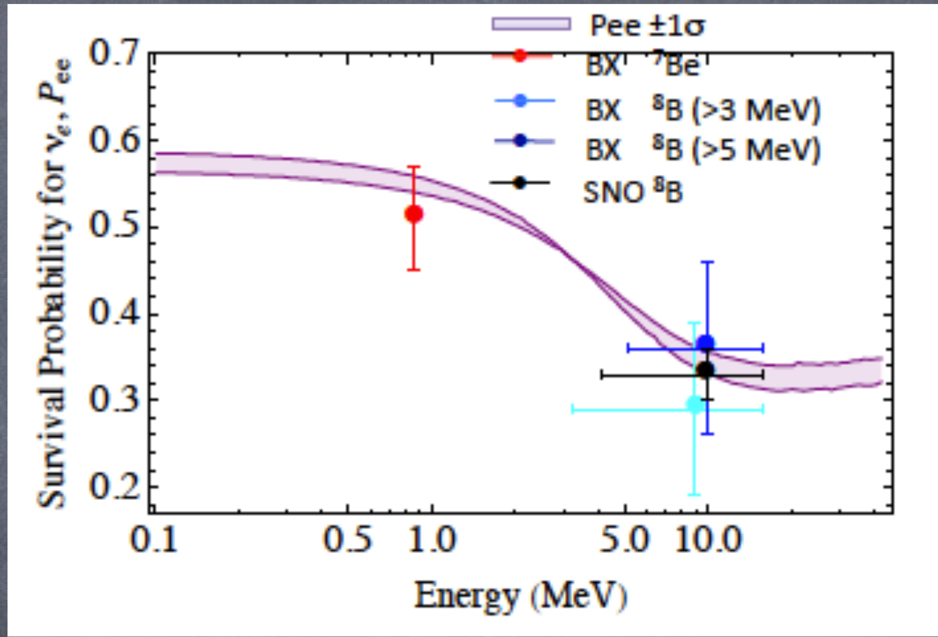


→ only LMA allowed at 3σ

→ max. mixing excluded at 5σ

Borexino: detection of low energy solar neutrinos





- 300 ton. liquid scintillator
- first real-time measurement of 7Be neutrinos (< 5% error)
- first real-time measurement of 8B flux below 4 MeV

→ consistent with LMA parameters

The KamLAND reactor experiment

- reactor experiment: $\bar{\nu}_e + p \to e^+ + n$
- CPT invariance: $(\Delta m^2_{21}\,,\ \theta_{12})$
- average distance ~ 180 km

→ sensitive to $\Delta m^2_{21} \sim 10^{-5}$ eV^2 (Δm^2_{LMA})

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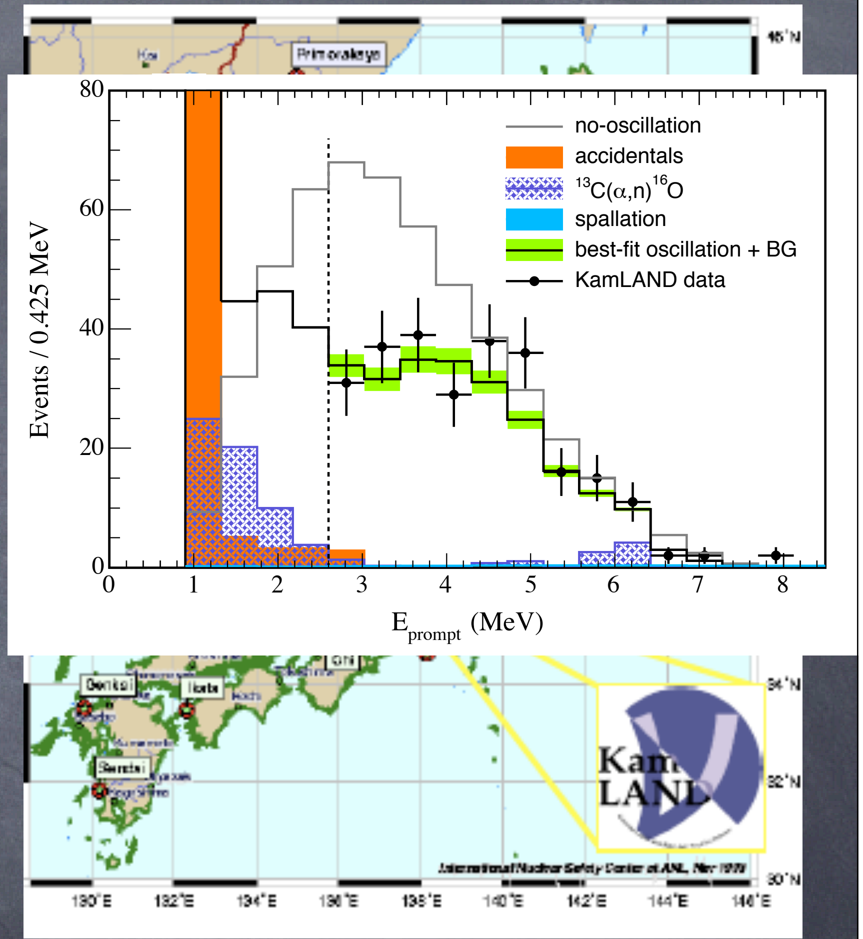
2002: First evidence $\bar{\nu}_e$ disappearance

→ confirmation of solar LMA ν oscillations

KamLAND Coll, PRL 90 (2003) 021802



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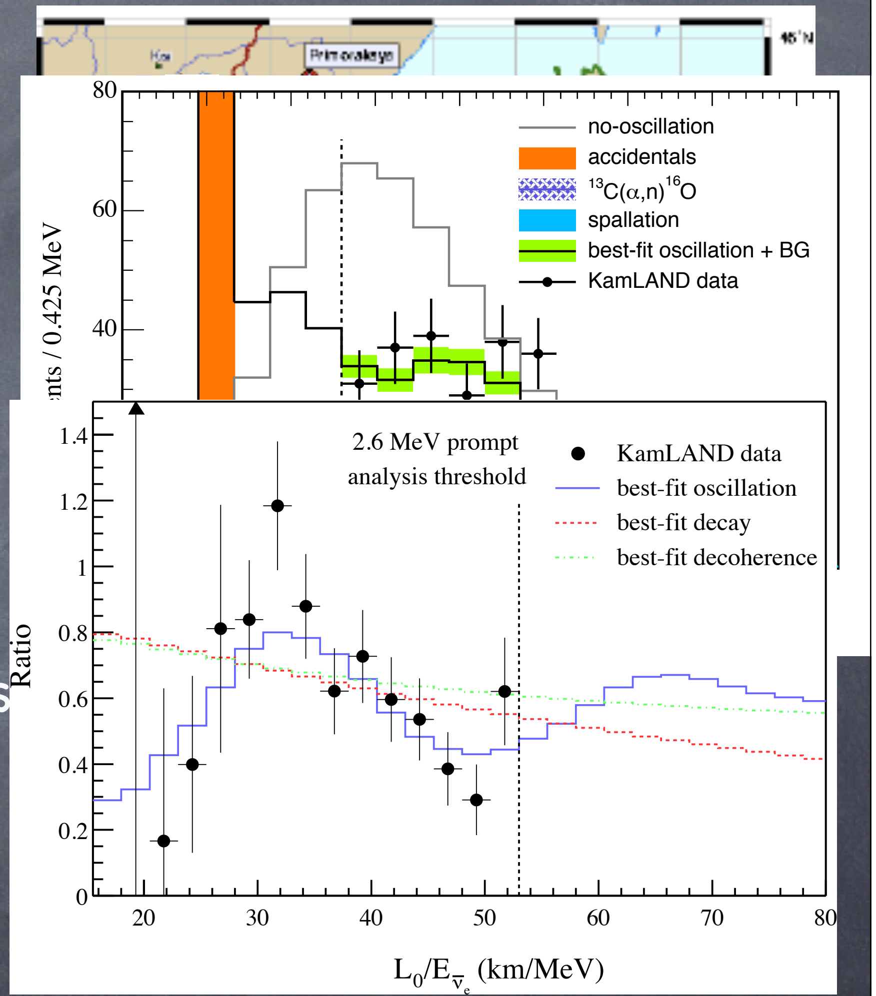
KamLAND Coll, PRL 90 (2003) 021802

2004: spectral distortions (L/E)

KamLAND Coll, PRL 94 (2005) 081801



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KamLAND Coll, PRL 90 (2003) 021802

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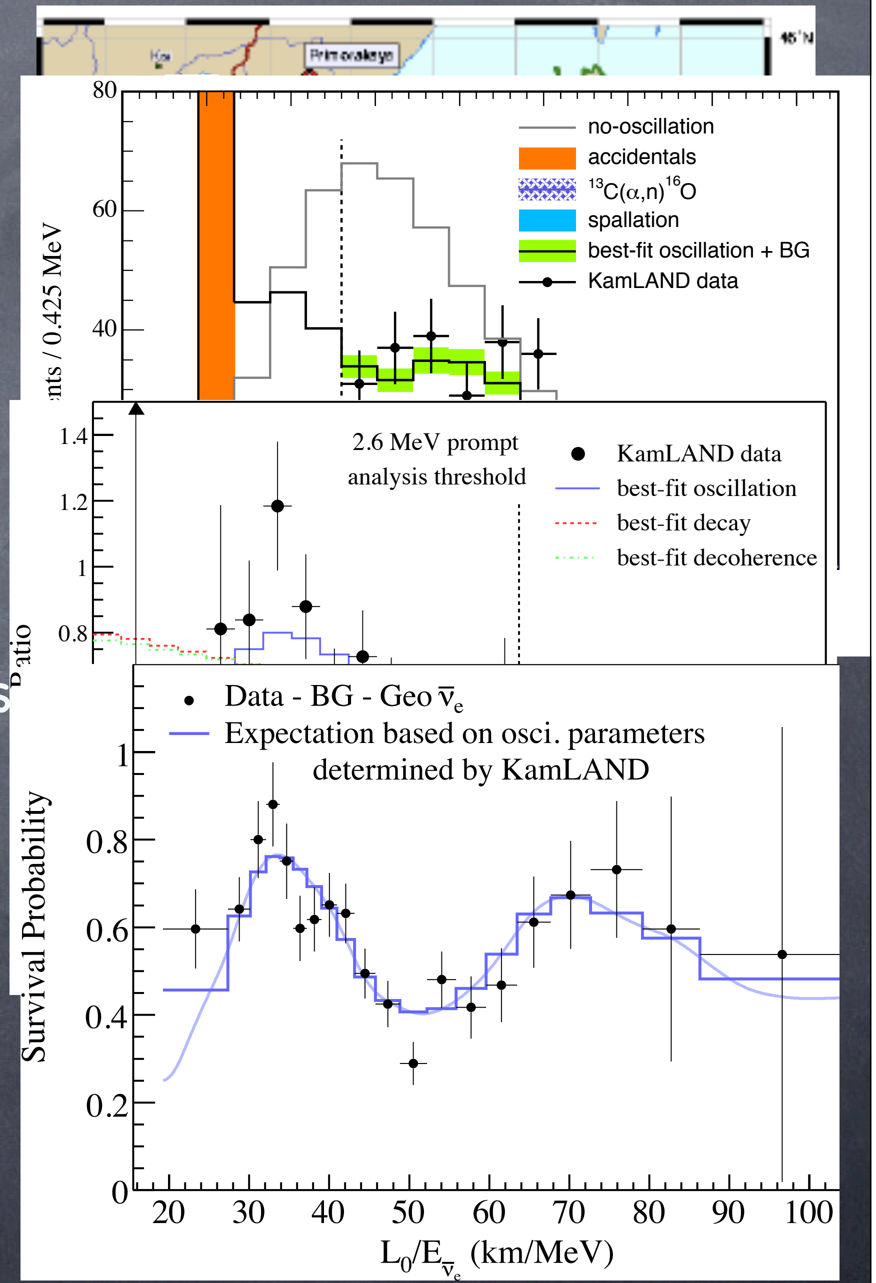
KamLAND Coll, PRL 94 (2005) 081801

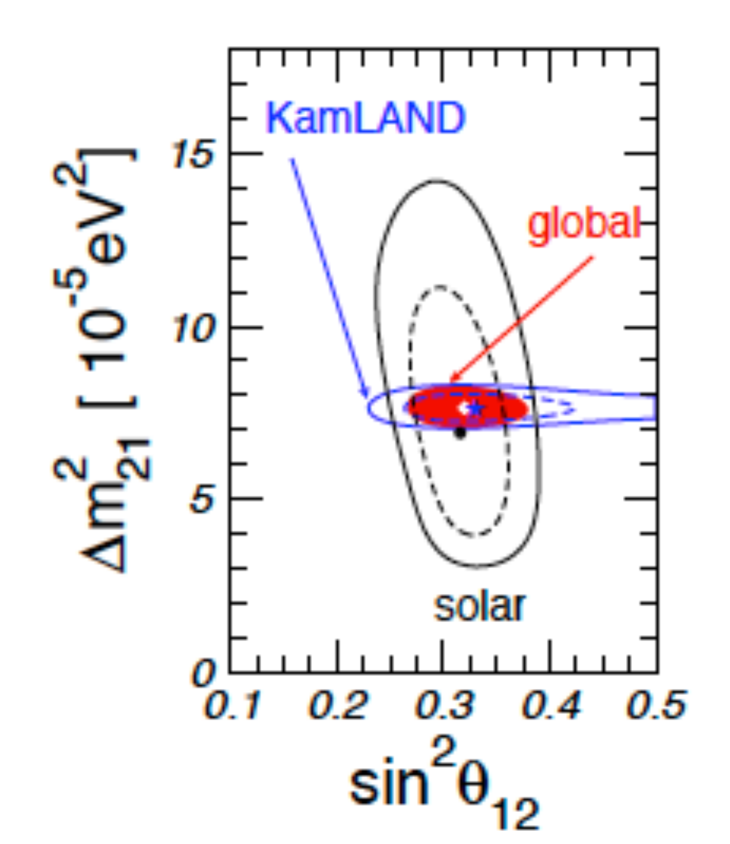
2008: 1-period oscillations observed

→ high precision determination Δm^2_{21}

KamLAND Coll, PRL 100 (2008) 221803



Combined analysis solar + KamLAND data



- KamLAND confirms LMA
- Best fit point:
  $\sin^2\theta_{12} = 0.320^{+0.015}_{-0.017}$
  $\Delta m^2_{21} = 7.62 \pm 0.19 \times 10^{-5}$ eV^2
- max. mixing excluded at more than 7σ

Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

➡ Bound on θ_{12} dominated by solar data.

➡ Bound on Δm^2_{21} dominated by KamLAND.

Determination of oscillation parameters from global ν data

- The solar sector: $(\Delta m^2_{21}, \sin^2\theta_{12})$
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Atmospheric neutrinos

Cosmic rays interacting with the Earth atmosphere producing pions and kaons, that decay generating neutrinos:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
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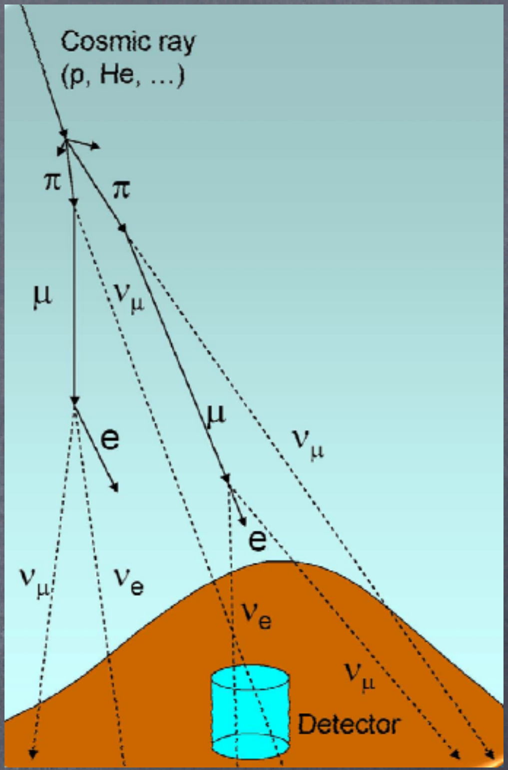

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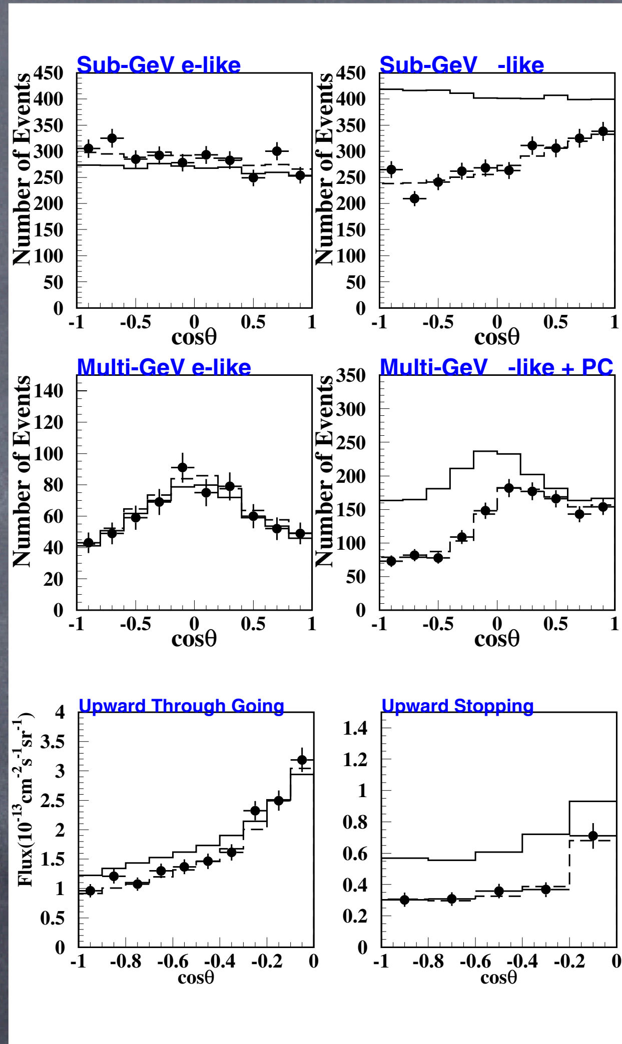
1998: Evidence ν_μ oscillations at Super-K: $\nu_\mu \to \nu_\tau$



Super-K Coll., PRL 8 (1998) 1562.

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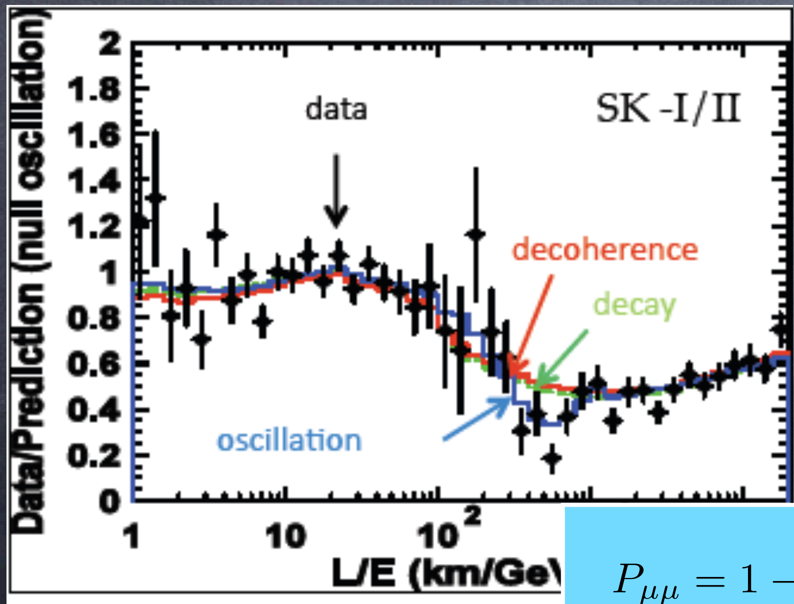
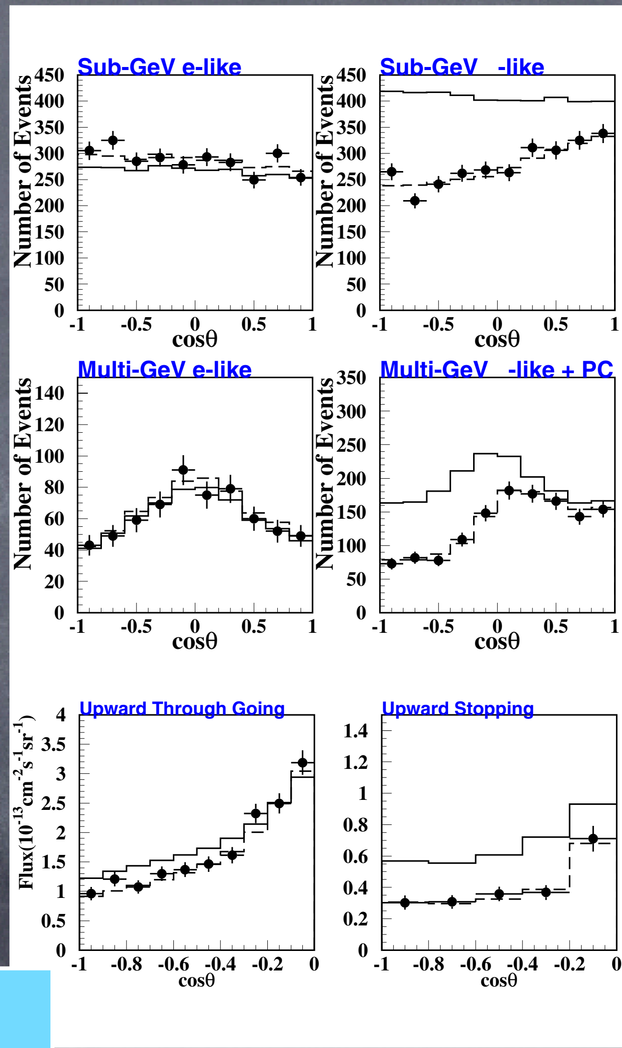
2004: oscillatory L/E pattern





$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4}\frac{L}{E_\nu}\right)$$

Super-K Coll, PRL93, 101801 (2004)

Super-K Coll., PRL 8 (1998) 1562.

Long-baseline accelerator experiments

Neutrino beam production:

$$p + X \to \pi^{\pm} + Y$$

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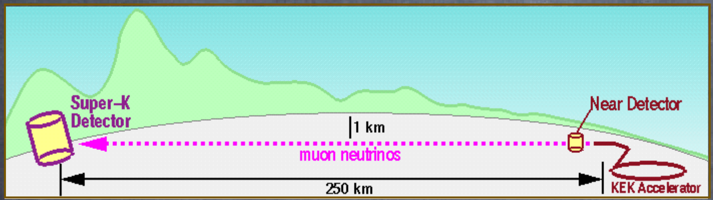
K2K: KEK →Kamioka



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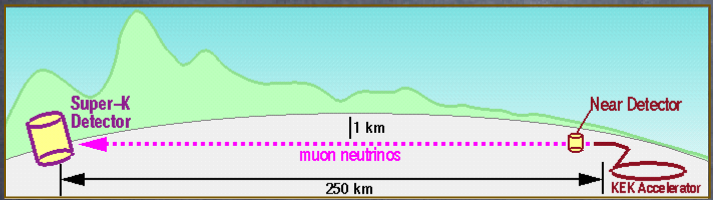
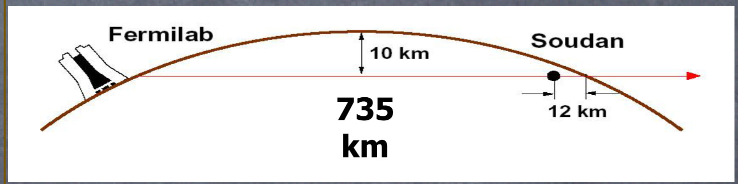


MINOS: Fermilab → Soudan



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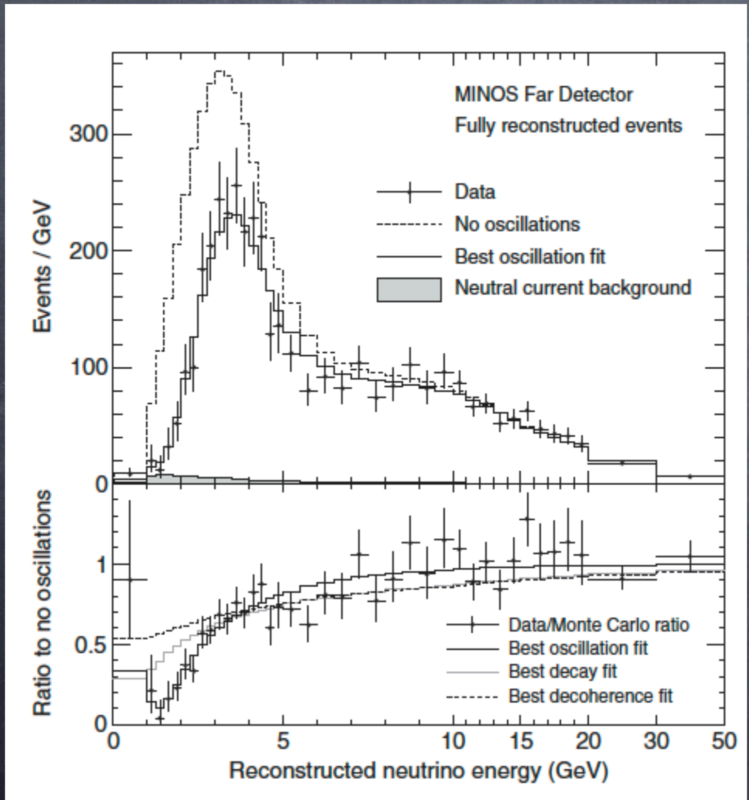

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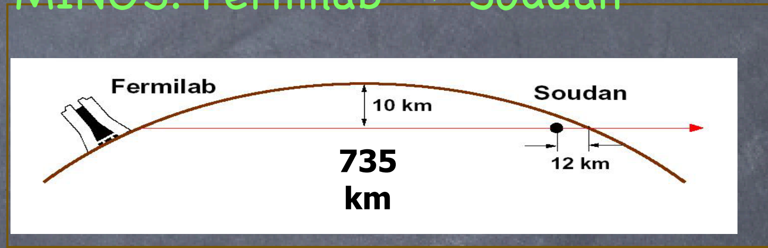


* ν_μ disappearance
* spectral distortions

[MINOS Collaboration], PRL106, 181801 (2011)

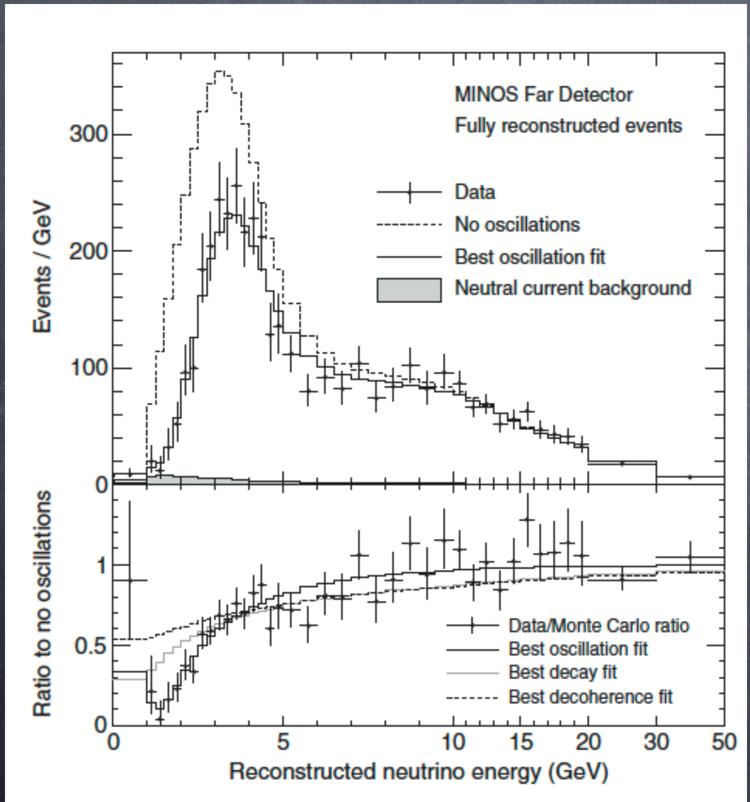
Long-baseline accelerator experiments

Neutrino beam production: $p + X \rightarrow \pi^{\pm} + Y$

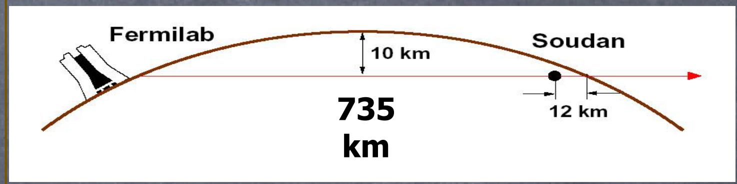
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

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

Goal: test atmospheric oscillations and improve parameter determination.
-> the experimental setup must be adjusted to be sensitive to $\Delta m^2 \sim 10^{-3}$ eV^2.



MINOS: Fermilab → Soudan



- ν_μ disappearance
- spectral distortions

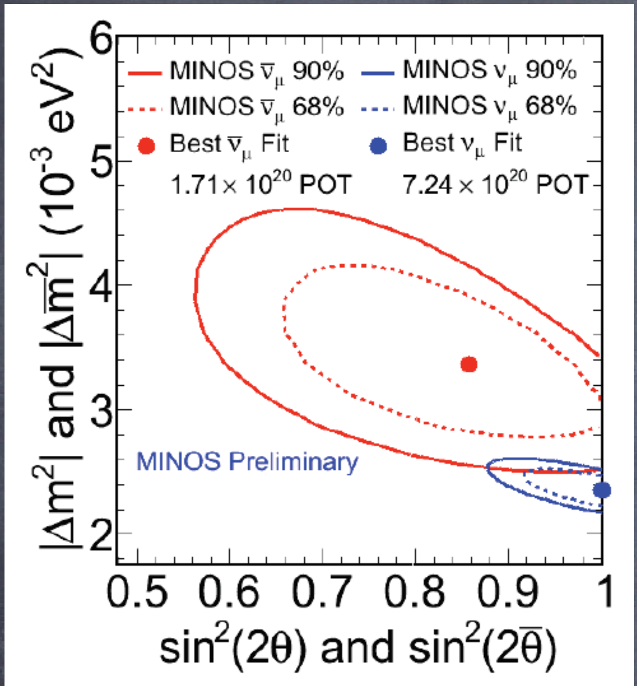
→ consistent with atmospheric data

→ atm oscillations confirmed by lab. exps.

[MINOS Collaboration], PRL106, 181801 (2011)

MINOS neutrino and neutrino results

[MINOS Collaboration], PRL107, 021801 (2011)



$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

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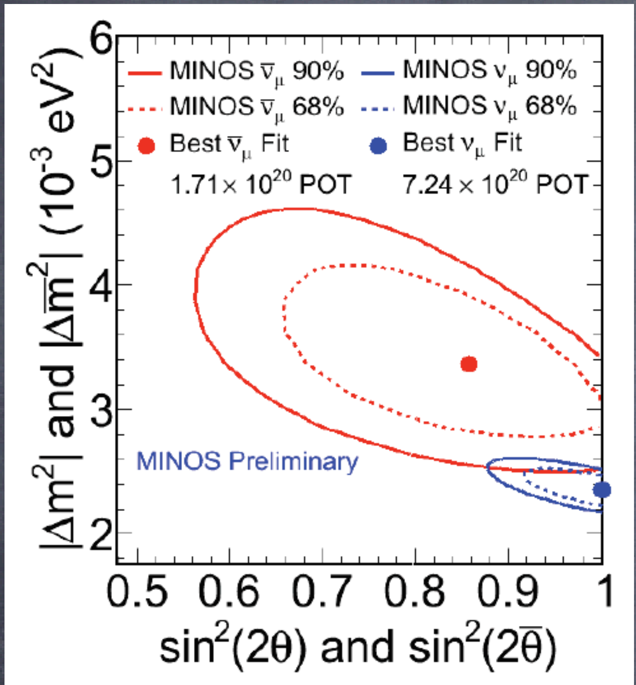
[MINOS Collaboration], PRL107, 021801 (2011)



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2σ inconsistency

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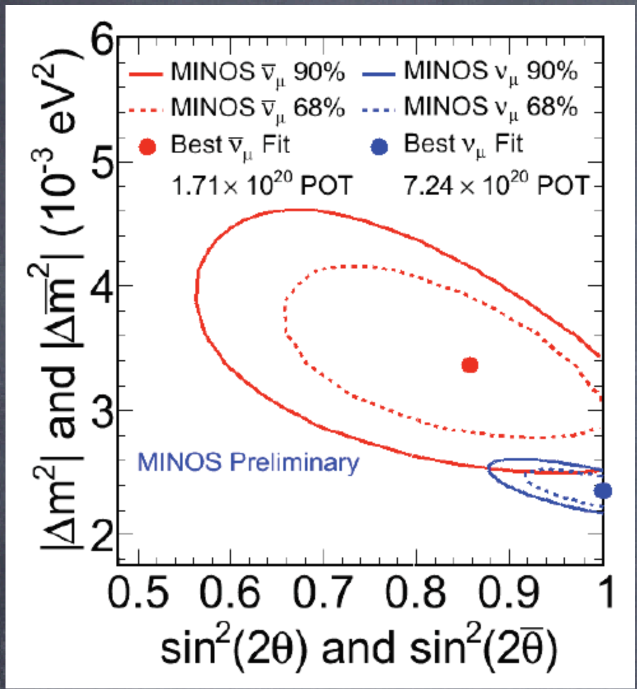

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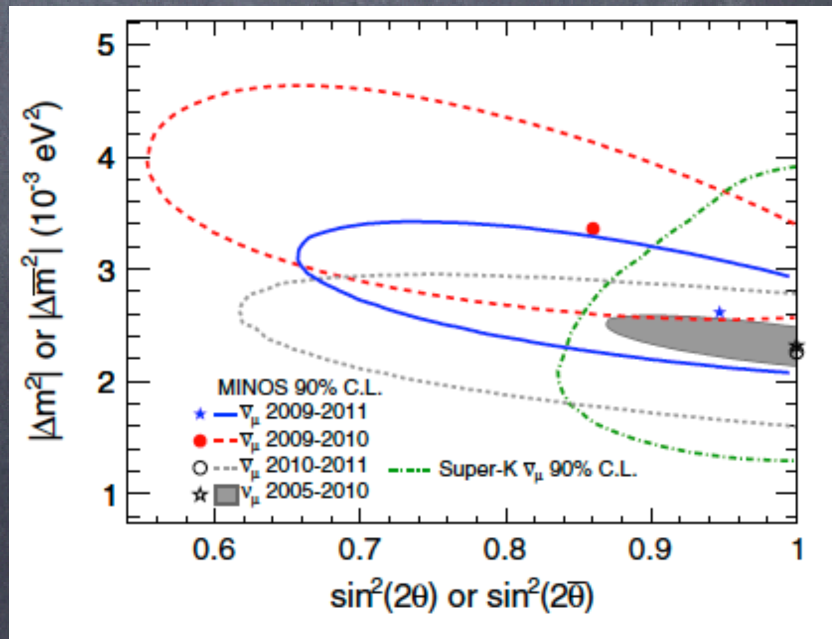
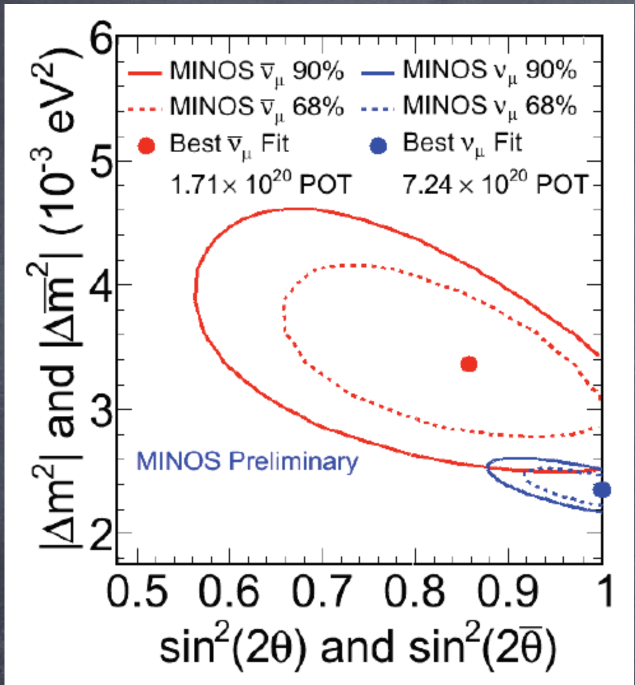
[MINOS Collaboration], PRL108, 191801 (2012)



MINOS neutrino and neutrino results

[MINOS Collaboration], PRL107, 021801 (2011)



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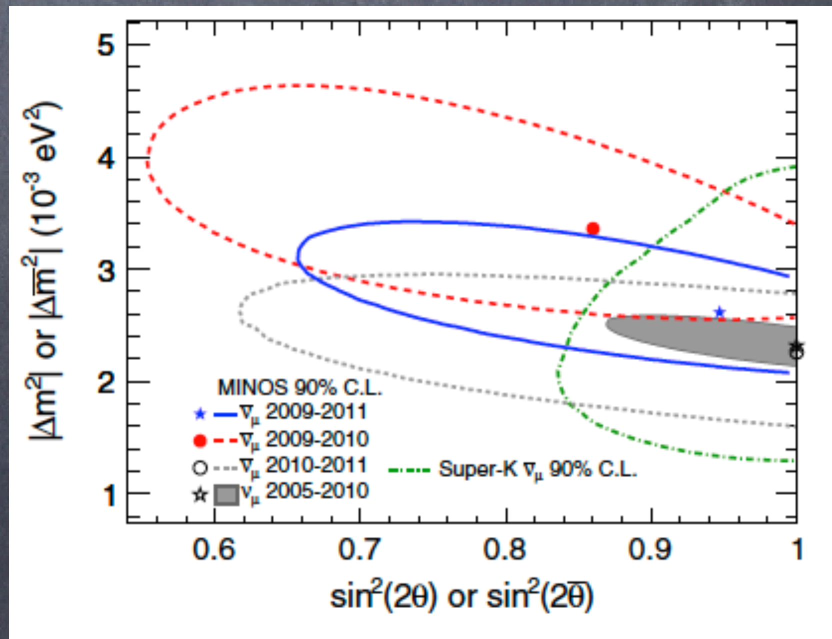
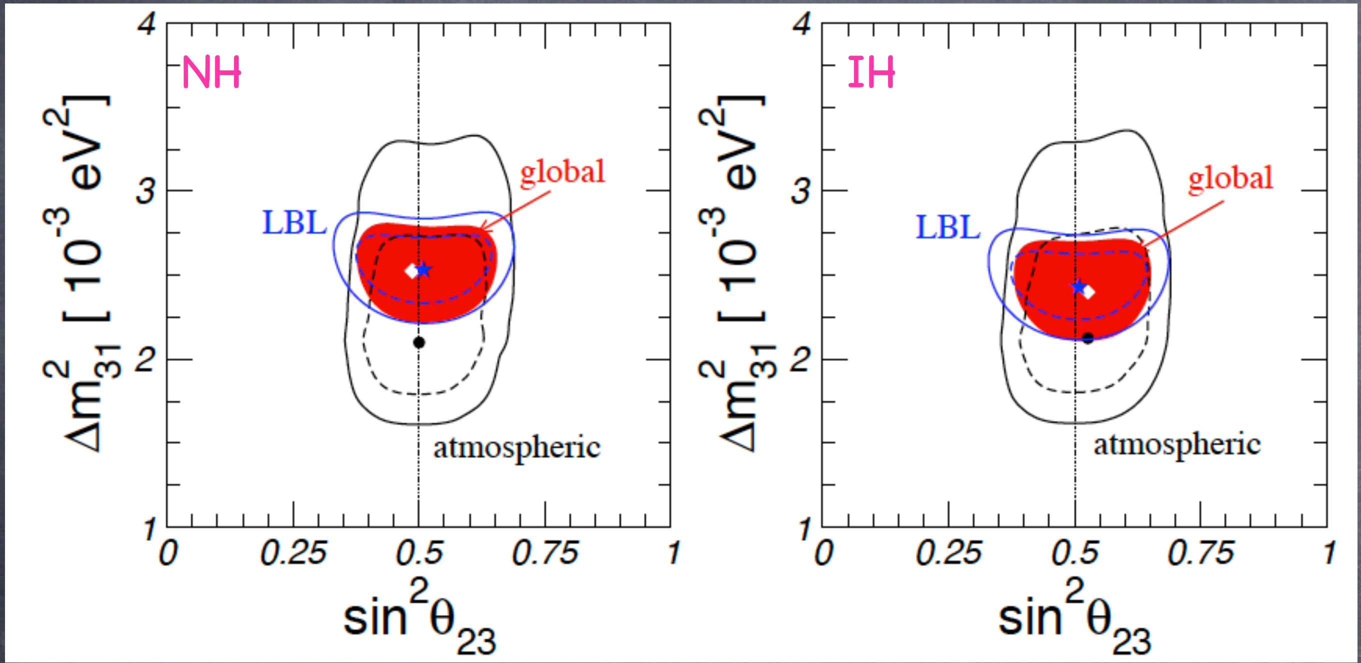


$$\Delta \bar{m}^2 = [2.62^{+0.31}_{-0.28}(\mathrm{stat}) \pm 0.09(\mathrm{syst})] \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\bar{\theta}) = 0.95^{+0.10}_{-0.11}(\mathrm{stat}) \pm 0.01(\mathrm{syst}),$$
$$\sin^2(2\bar{\theta}) > 0.75 (90\%\mathrm{C.L.}),$$

Combined analysis atmospheric + LBL data

➡ Super-Kamiokande (I + II + III) + K2K and MINOS long-baseline data



➡ Determination of θ_{23} and Δm^2_{31} is now dominated by LBL data

Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

* Best fit point:

$\sin^2\theta_{23} = 0.49^{+0.08}_{-0.05}$

$\Delta m^2_{31} = 2.53^{+0.08}_{-0.10} \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{23} = 0.53^{+0.05}_{-0.07}$

$\Delta m^2_{31} = -(2.40^{+0.10}_{-0.07} \times 10^{-3}\ )\ \mathrm{eV}^2$

Determination of oscillation parameters from global ν data

- The solar sector: $(\Delta m^2_{21}, \sin^2\theta_{12})$
- The atmospheric sector: $(\Delta m^2_{31}, \sin^2\theta_{23})$
- The reactor mixing angle θ_{13}

Searches for ν_e appearance

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E) + \ldots$$

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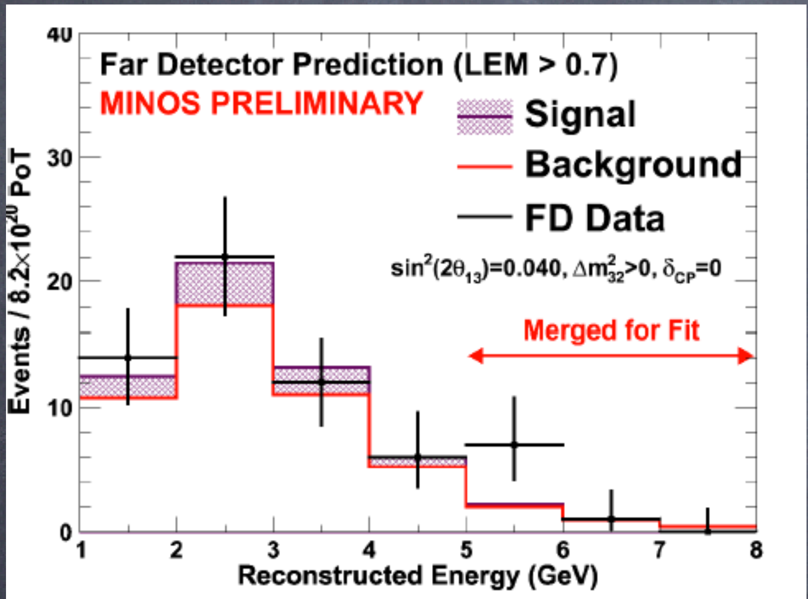
MINOS (8.2x10^{20} p.o.t.)



* 62 electron events observed
* 49.5 ± 7.0 (stat) ± 2.8 (syst) expected
  ➡ 1.7σ excess

[MINOS Collaboration], PRL107, 181802 (2011)

Searches for ν_e appearance

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E) + \ldots$$

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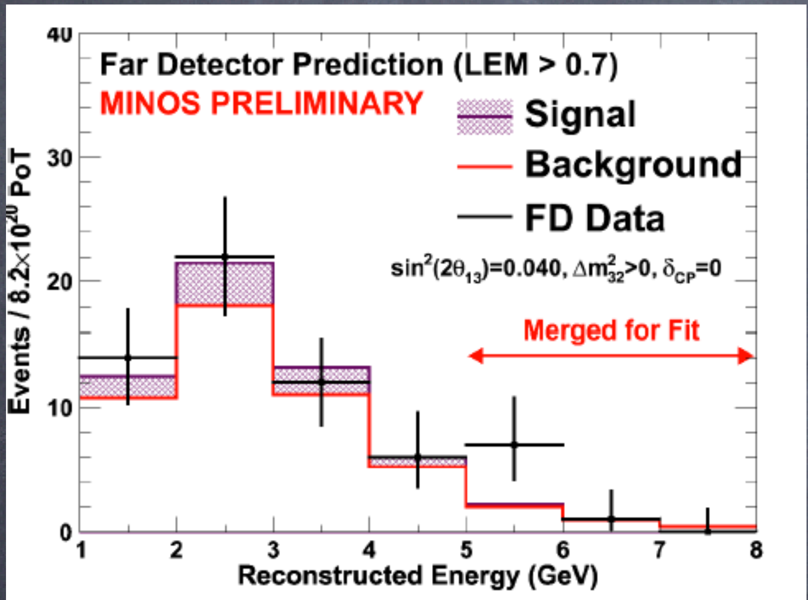
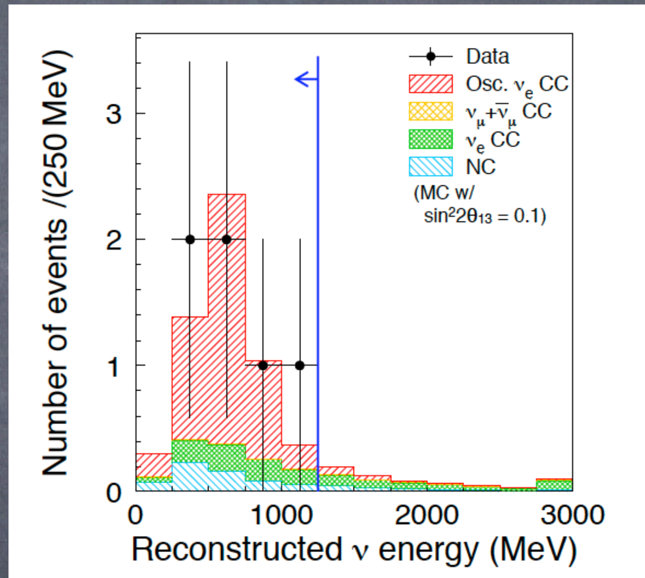


- 62 electron events observed
- 49.5 ± 7.0 (stat) ± 2.8 (syst) expected

  ➡ 1.7σ excess

T2K $(1.43\times10^{20}$ p.o.t.)



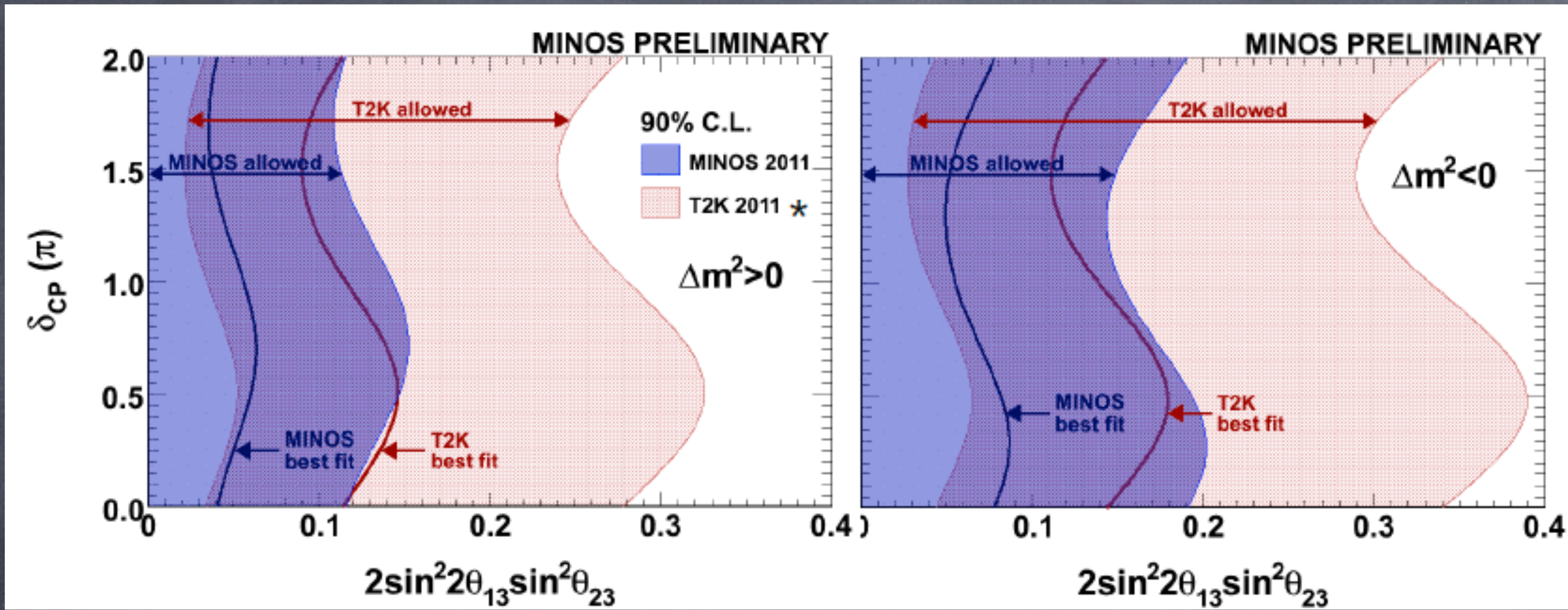
- 1.5 events expected
- 6 candidate events

  ➡ 2.5σ significance

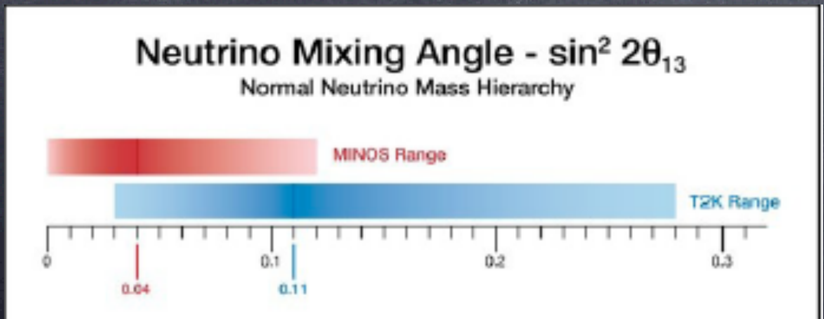
[MINOS Collaboration], PRL107, 181802 (2011)

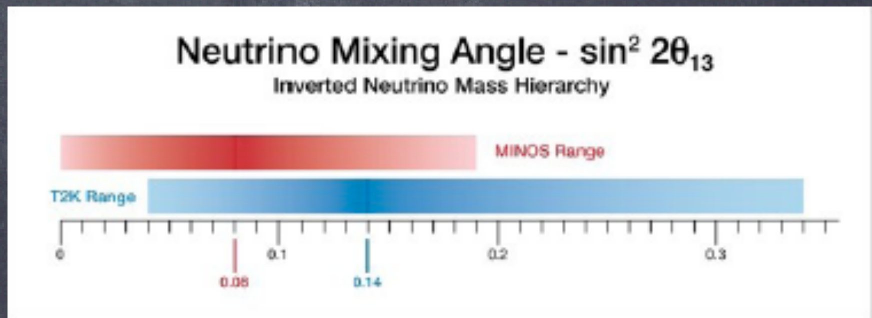
[T2K Collaboration], PRL107, 041801 (2011).

Comparison of MINOS and T2K results



Overlay of the two 90% CL allowed regions (δ=0, θ_{23}=π/4)

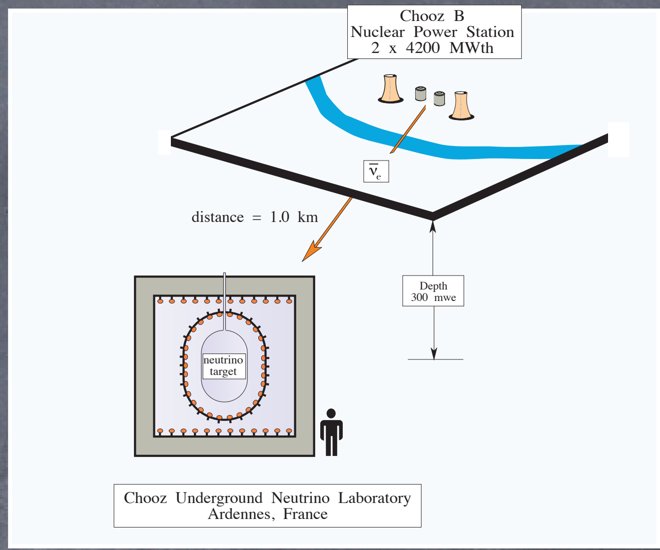




The CHOOZ reactor experiment

- disappearance reactor ν_e
- L = 1 km, E~MeV
- 2ν approx: Δm^2_{31} , θ_{13}

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



- non-observation of ν_e disappearance:

R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

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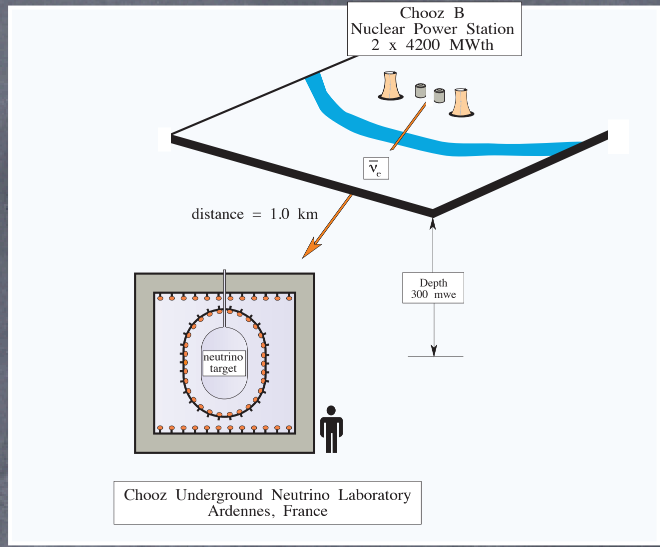
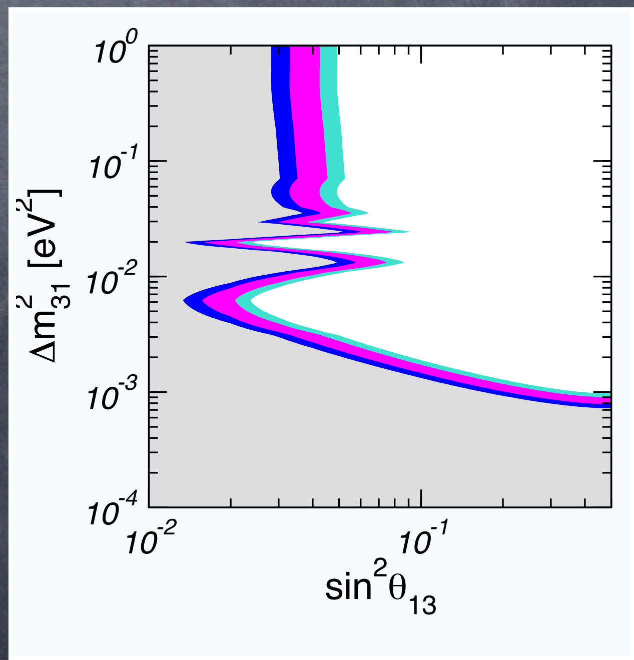
→ Exclusion plot (Δm^2_{31} , θ_{13}) plane

For $\Delta m^2_{31} = 2.5 \cdot 10^{-3}$ eV^2

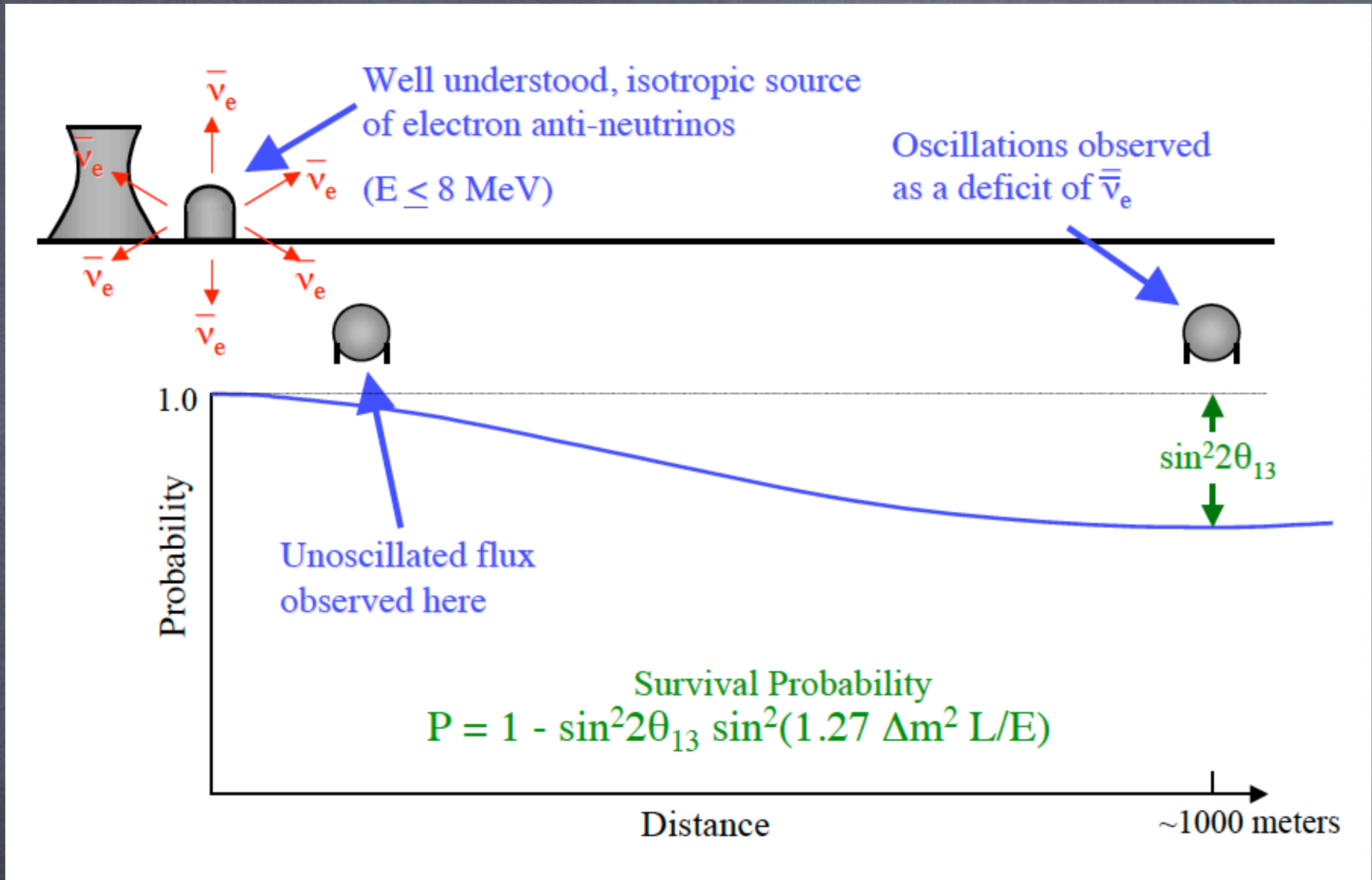
-> $\sin^2\theta_{13} < 0.039$ (90%CL)

CHOOZ Collaboration, EPJ C27 (2003) 331.





New generation reactor experiments



- more powerful reactors (multi-core)
- larger detector volume
- 2-3 detectors at 100 m - 1 km.
- sensitivity after 3 years (90% C.L.): $\sin^2\theta_{13}$~0.0025 – 0.008

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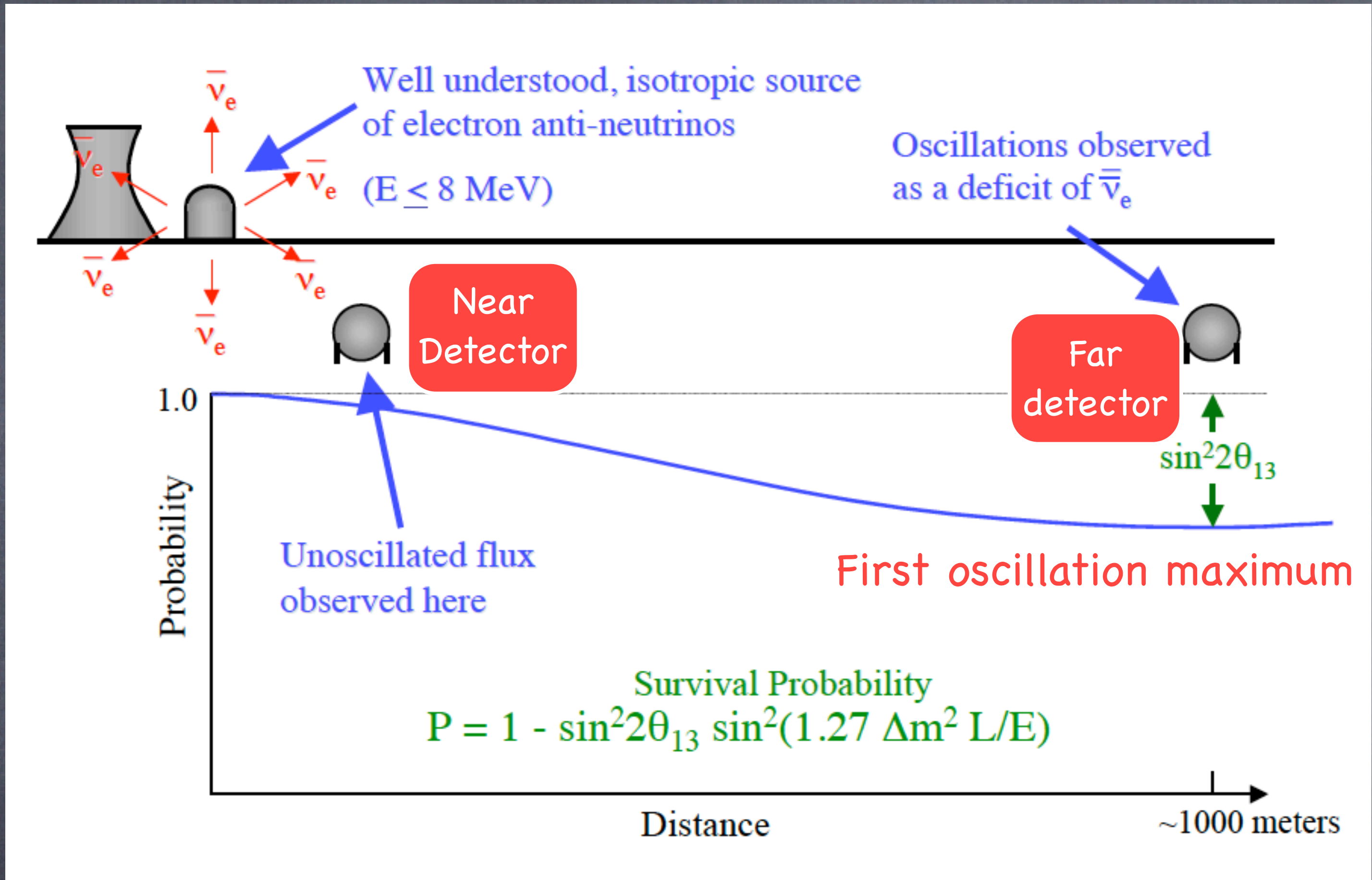

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The race for θ_{13}

The race for θ_{13}

29/12/2011

2 reactor cores + 1 FD (ND 2013)

livetime: 101 days

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041\ (\text{stat}) \pm 0.030\ (\text{syst})$

Double CHOOZ Coll, PRL 108 (2012) 131801

→ $\theta_{13}=0$ excluded at 2σ

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Double CHOOZ Coll, PRL 108 (2012) 131801

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08/03/2012

6 reactor cores + 6 neutrino detectors (3ND,3FD)

livetime: 55 days

$\text{Sin}^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

Daya Bay Coll., PRL 108 (2012) 171803

→ $\theta_{13}=0$ excluded at 5.2σ

The race for θ_{13}

29/12/2011

2 reactor cores + 1 FD (ND 2013)

livetime: 101 days

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041\ (\text{stat}) \pm 0.030\ (\text{syst})$

Double CHOOZ Coll, PRL 108 (2012) 131801

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$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

Daya Bay Coll., PRL 108 (2012) 171803

→ $\theta_{13}=0$ excluded at 5.2σ

03/04/2012

6 reactor cores + 2 neutrino detectors (3ND,3FD)

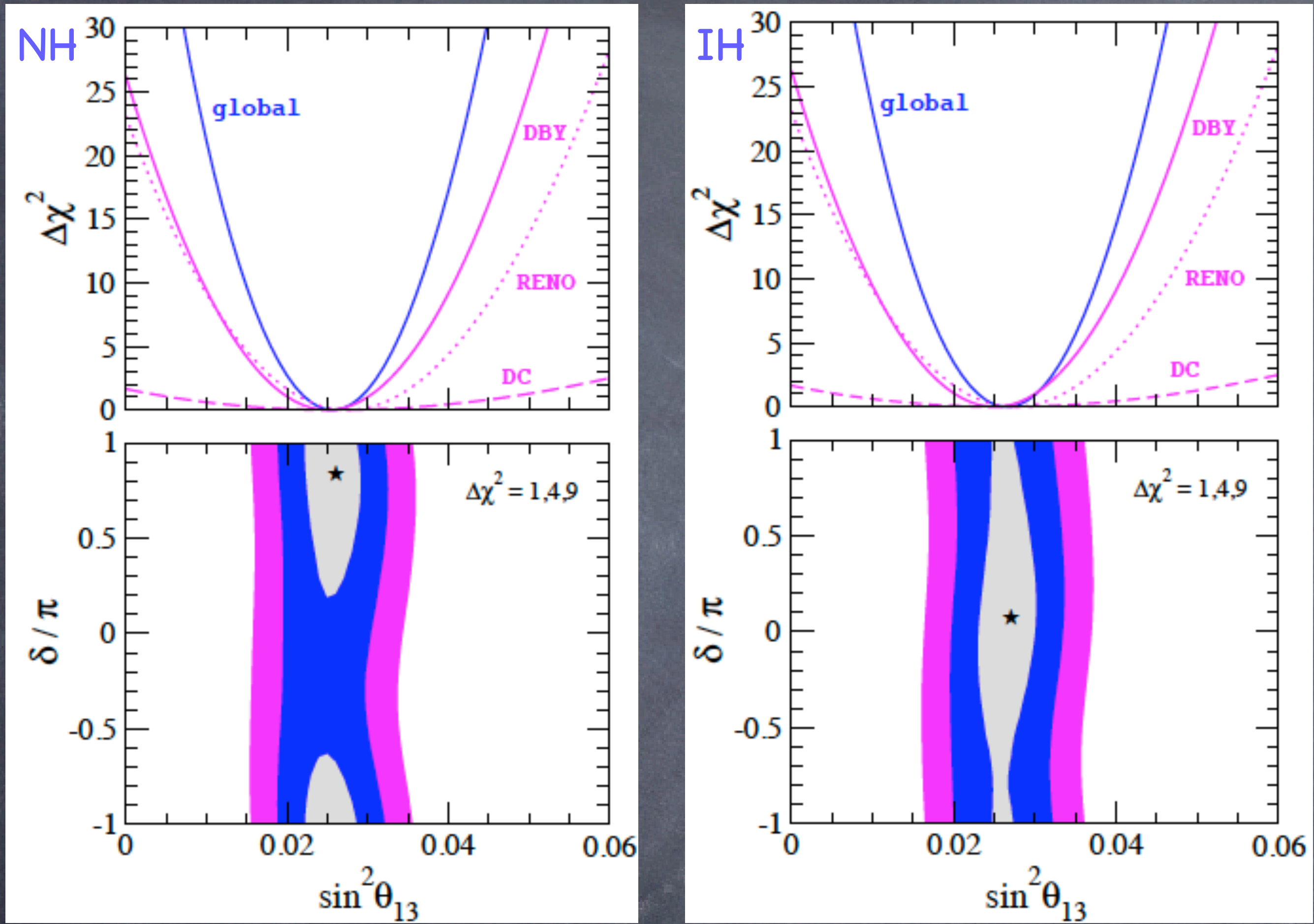
livetime: 229 days

$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$

RENO Coll., PRL 108 (2012) 191802

→ $\theta_{13}=0$ excluded at 4.9σ

θ_{13} determination from global analysis



NH

$$\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004}$$

IH

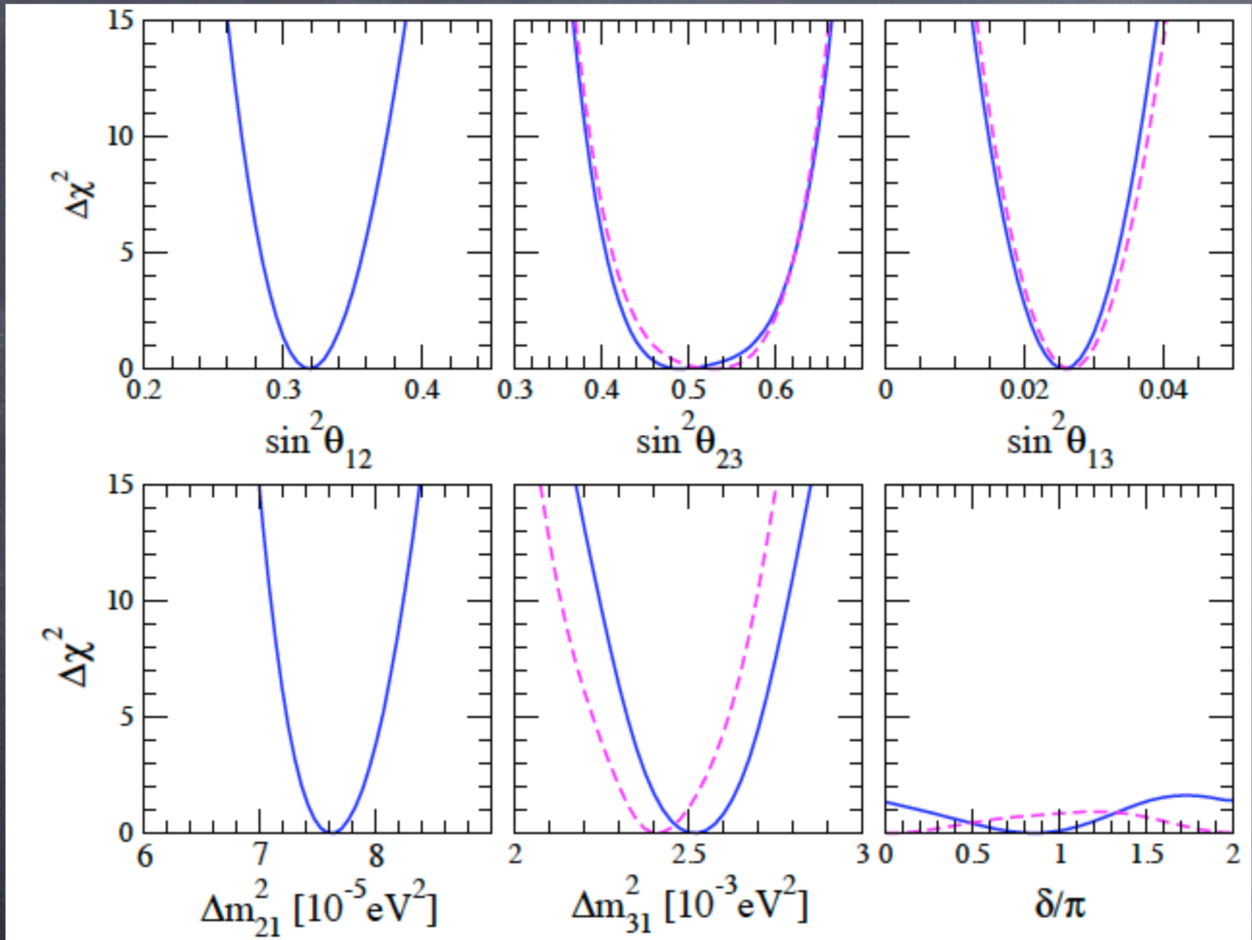
$$\sin^2\theta_{13} = 0.027^{+0.003}_{-0.004}$$

$\theta_{13} = 0$ excluded at 8σ for both hierarchies

Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

- Bound on θ_{13} dominated by Daya Bay and RENO
- weak sensitivity to CP phase δ

3-flavour oscillation parameters



parameter	best fit $\pm 1\sigma$	
Δm^2_{21} [10^{-5}eV^2]	7.62 ± 0.19	3%
Δm^2_{31} [10^{-3}eV^2]	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	4%
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	5%
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	10%
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	15%
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]	

Forero, M.T., Valle, arXiv:1205.4018 [hep-ph]

Absolute scale of neutrino mass

* Tritium β-decay experiments:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

→ m_β < 2.3 (2.1) eV at 95%CL Mainz (Troitsk)

Kraus et al, EPJ C40 (2005) 447

Troitsk Collaboration PRD 84 (2011) 112003

→ KATRIN sensitivity m_β~0.2 eV

* Neutrinoless double β-decay:

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

→ 90%CL upper limit from Heidelberg-Moscow < 0.35 eV

Klapdor-Kleingrothaus et al, EPJ A12 (2001) 147.

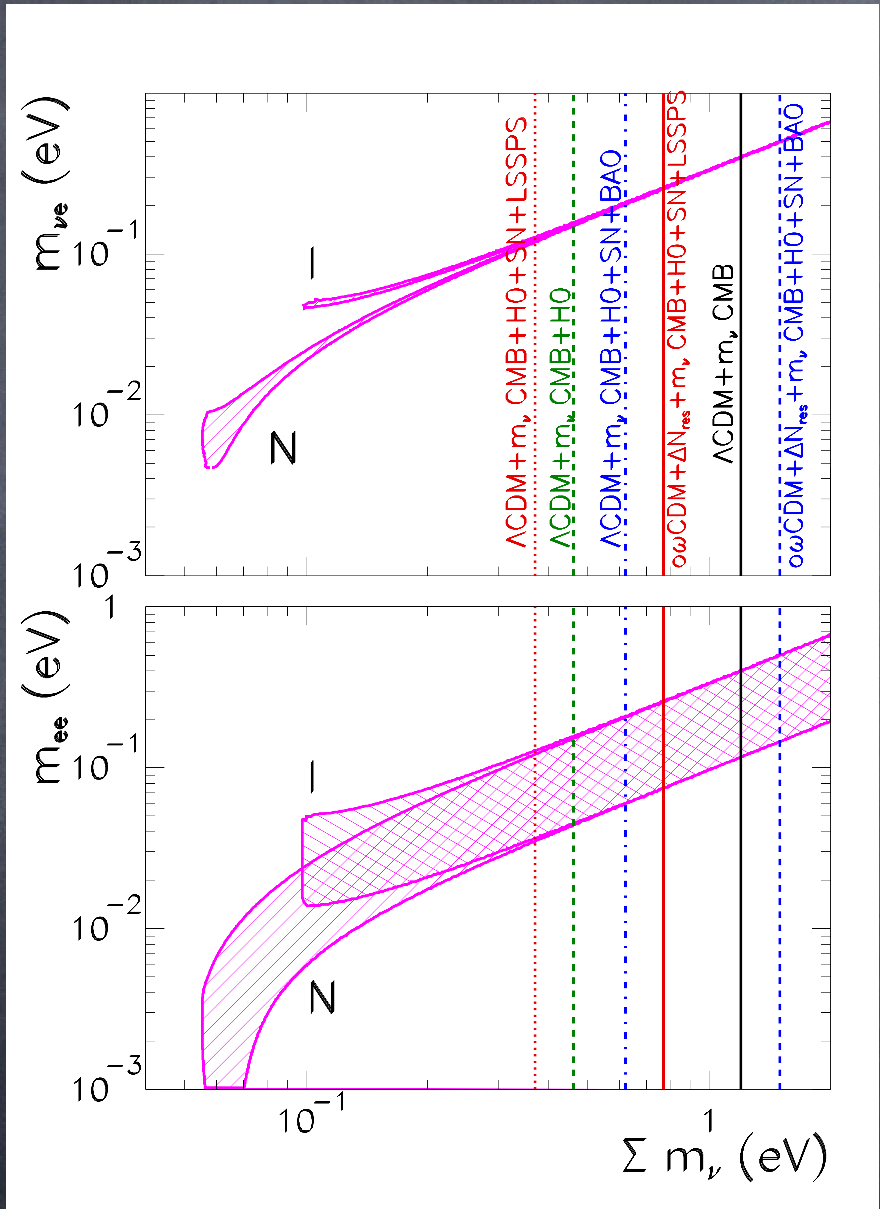
* Cosmology:

$\Sigma\, m_i = m_1 + m_2 + m_3$

Model	Observables	Σm_ν (eV) 95% Bound
$o\omega$CDM $+ \Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+BAO	≤ 1.5
$o\omega$CDM $+ \Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+LSSPS	≤ 0.76
ΛCDM $+ m_\nu$	CMB+H0+SN+BAO	≤ 0.61
ΛCDM $+ m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
ΛCDM $+ m_\nu$	CMB (+SN)	≤ 1.2
ΛCDM $+ m_\nu$	CMB+BAO	≤ 0.75
ΛCDM $+ m_\nu$	CMB+LSSPS	≤ 0.55
ΛCDM $+ m_\nu$	CMB+H0	≤ 0.45

González-García et al, JHEP 1008 (2010) 117.

Constraints on m_ν from neutrino oscillations



95% CL regions

González-García et al, JHEP 1008 (2010) 117.

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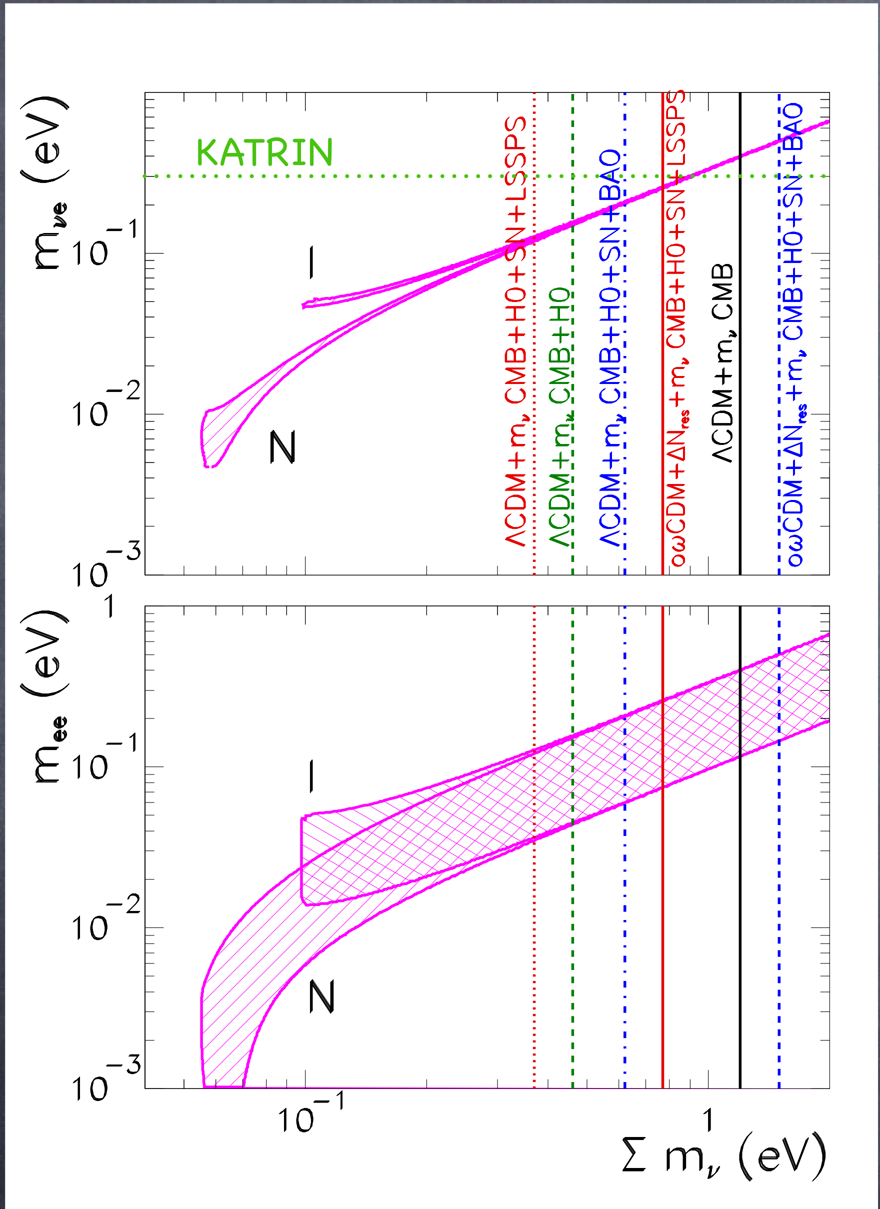

95% CL regions

⇒ most of the bounds out of reach for KATRIN

González-García et al, JHEP 1008 (2010) 117.

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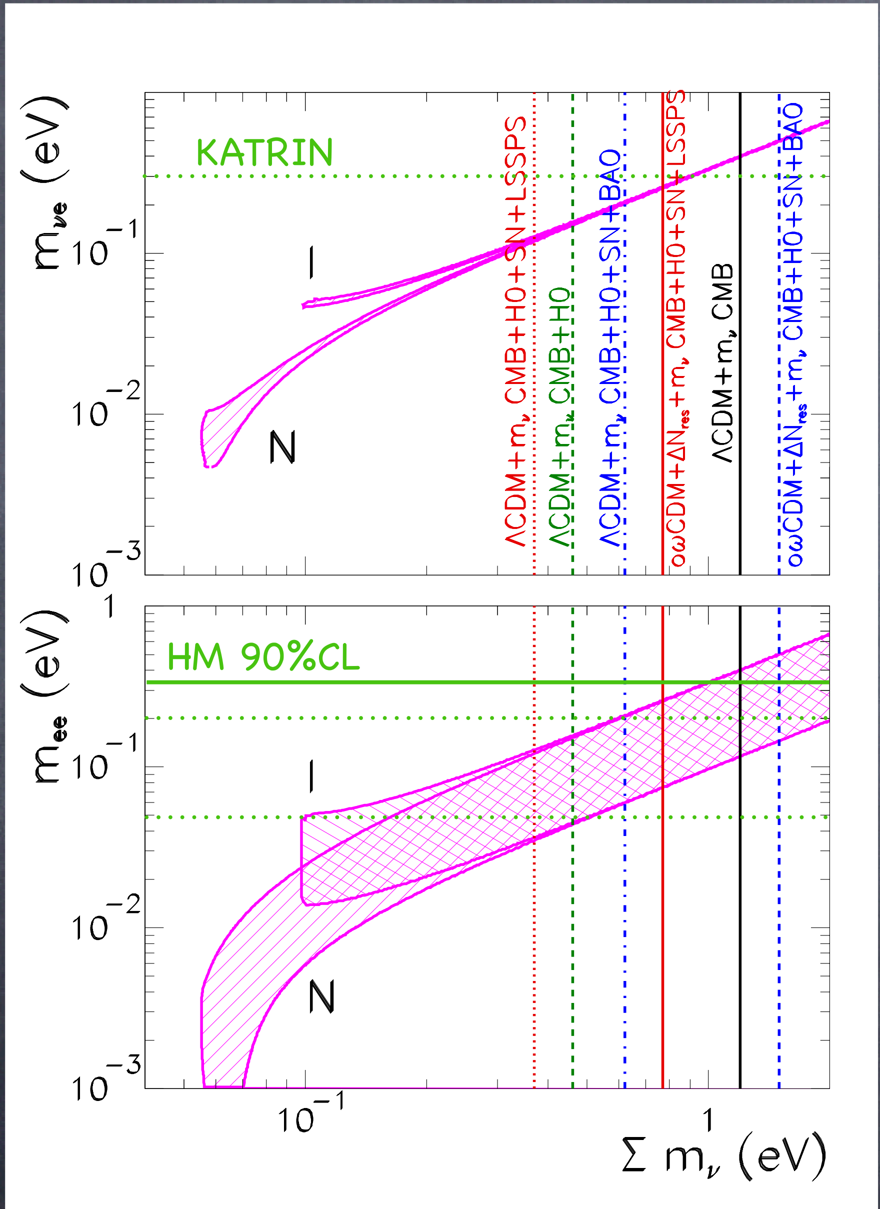

95% CL regions

⇒ most of the bounds out of reach for KATRIN

⇒ next generation of $2\beta 0\nu$ exp. will test allowed ranges

González-García et al, JHEP 1008 (2010) 117.

PART 2

Trying to explain what we know....

Explaining what we know....

- neutrinos are massive: how do they get its mass?
- neutrino masses and mixings: why so different from the quark sector?
- neutrino anomalies beyond 3ν mixing: are there sterile neutrinos? non-standard neutrino interactions?

Models of neutrino mass

* In the SM neutrinos are massless:

  1) the absence of ν_R prevents Dirac mass term

  2) conservation of L forbids Majorana mass term

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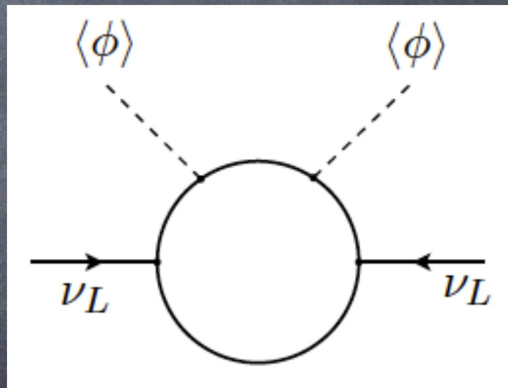
* dim-5 operator can induce neutrino masses:

$$Y^2 \frac{(L^T \tilde{\phi}^*)(\tilde{\phi}^\dagger L)}{\Lambda} \longrightarrow m_\nu \sim Y^2 \frac{v^2}{\Lambda}$$



Weinberg, PRL43 (1979) 1566

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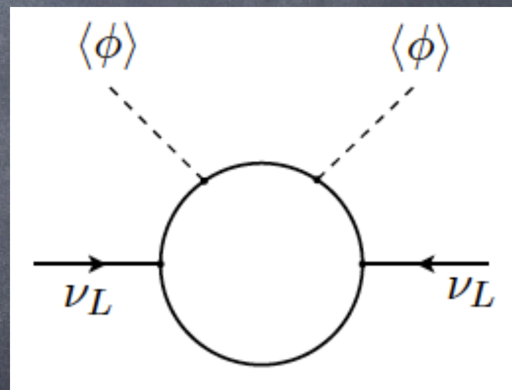


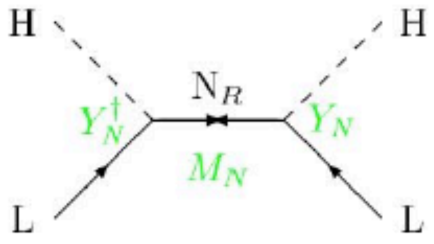
Weinberg, PRL43 (1979) 1566

For very large Λ, m_ν is supressed -> seesaw mechanism

Seesaw mass models

⇒ neutrino masses are generated through their mixing with heavy particles

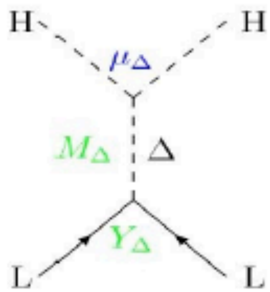
Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic

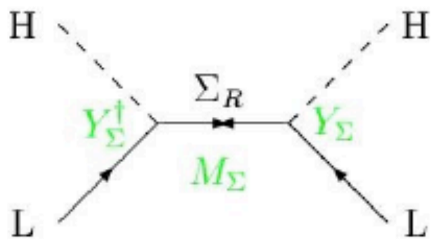
Scalar triplet: (type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet: (type-III seesaw)

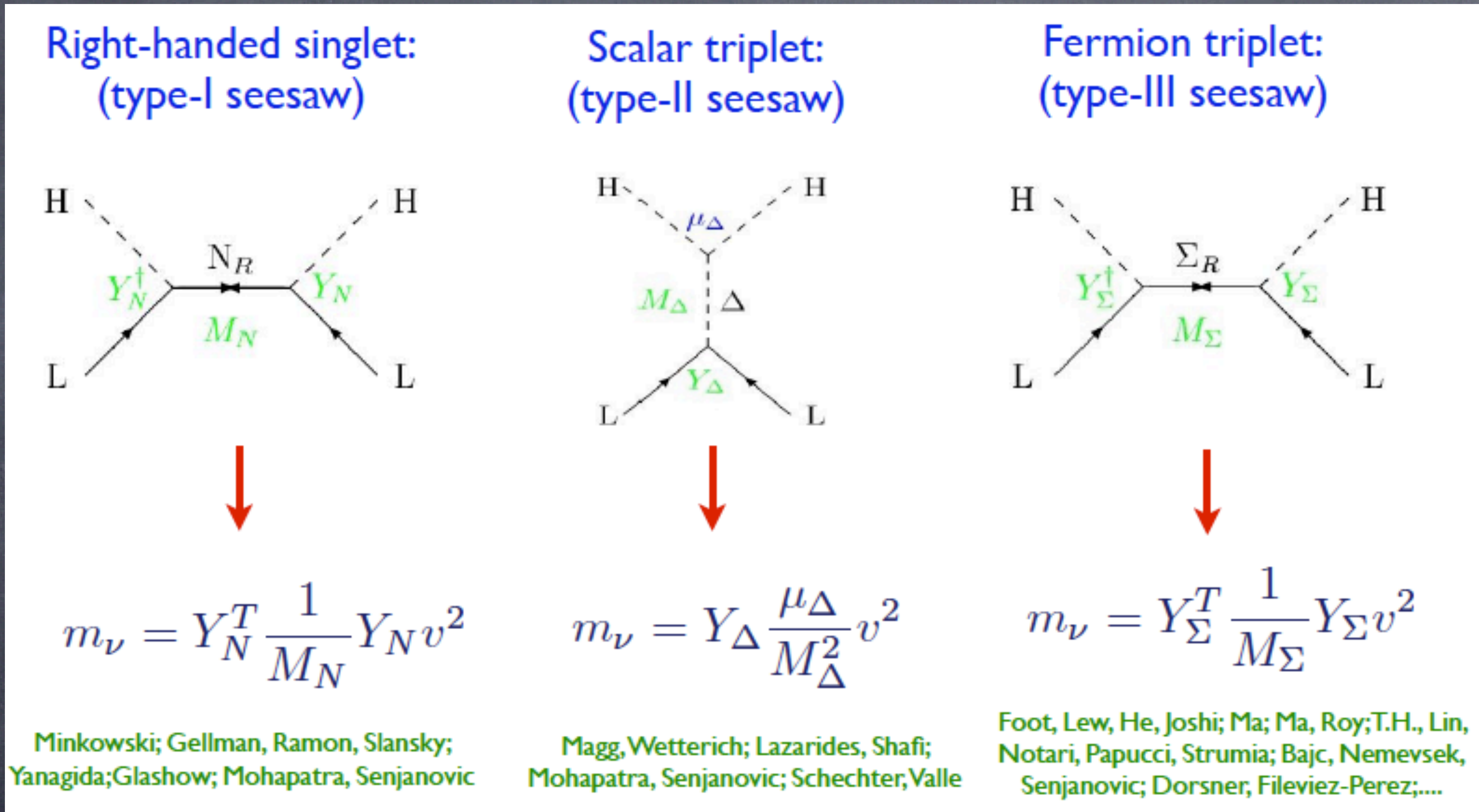


$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

Seesaw mass models

⇒ neutrino masses are generated through their mixing with heavy particles



Low-energy seesaw models:

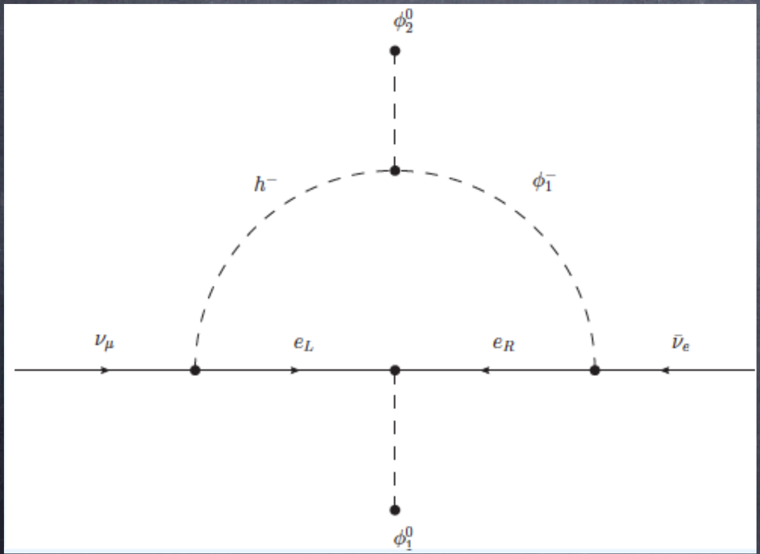
- inverse seesaw — Mohapatra and Valle, PRD 34 (1986) 1642
- linear seesaw — Akhmedov et al, NPB 368 (1996) 270

Radiative models of neutrino masses

- extension of scalar sector of the SM -> generate L violation
- neutrino masses can be generated through loops
  - ⇒ loop suppression accounts for the smallness of m_ν

Zee model

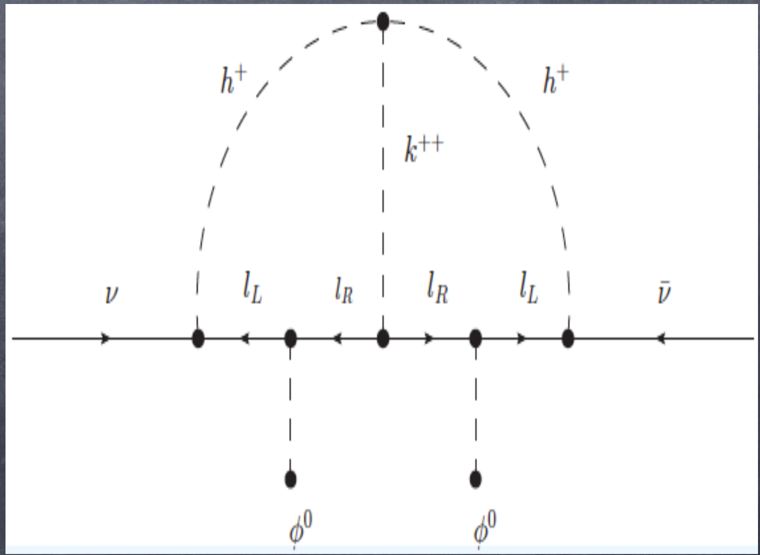
+ singlet scalar h^+
+ extra Higgs doublet H



Zee, PLB 93 (1980) 389

Zee-Babu model

+ singlet scalar h^+
+ singlet scalar k^{++}



Zee, NPB 264 (1986) 99; Babu, PLB 203 (1988) 132

Mixing and mass hierarchies: neutrinos vs quarks

mixing matrix:

$$U_\nu = \begin{pmatrix} 0.80-0.83 & 0.36-0.45 & 0.15-0.18 \\ 0.46-0.54 & 0.47-0.59 & 0.63-0.75 \\ 0.24-0.36 & 0.59-0.69 & 0.65-0.76 \end{pmatrix}$$

$$U_{\mathrm{CKM}} = \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.008 & 0.040 & 0.999 \end{pmatrix}$$

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$$U_{\mathrm{HPS}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & \cancel{0} \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

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$$U_{\mathrm{CKM}} = \begin{pmatrix} 1 & \varepsilon & \varepsilon \\ \varepsilon & 1 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix}$$

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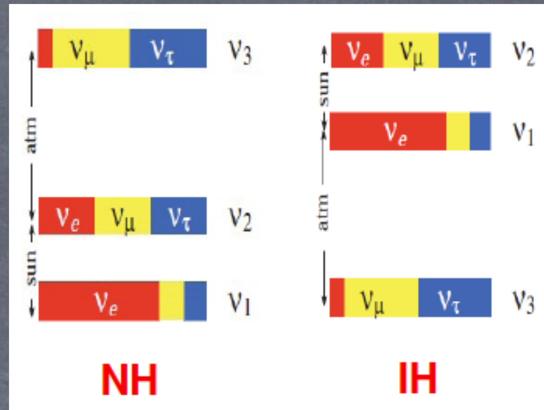
masses:



$$\lambda_C < \frac{m_2^\nu}{m_3^\nu} < 1 \qquad 0 < \frac{m_1^\nu}{m_2^\nu} < 1$$

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$$U_{\rm CKM} = \begin{pmatrix} 1 & \varepsilon & \varepsilon \\ \varepsilon & 1 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix}$$

$$\frac{m_2^u}{m_3^u} \approx \lambda_C^4 \qquad \frac{m_1^u}{m_2^u} \approx \lambda_C^3$$

$$\frac{m_2^{d,l}}{m_3^{d,l}} \approx \lambda_C^2 \qquad \frac{m_1^{d,l}}{m_2^{d,l}} \approx \lambda_C^2$$

$$\lambda_C \sim 0.22$$

The flavour problem

* Why do fermion masses show these hierarchical relations?
* Why do quarks and leptons mix?
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* Why do quarks and leptons mix?
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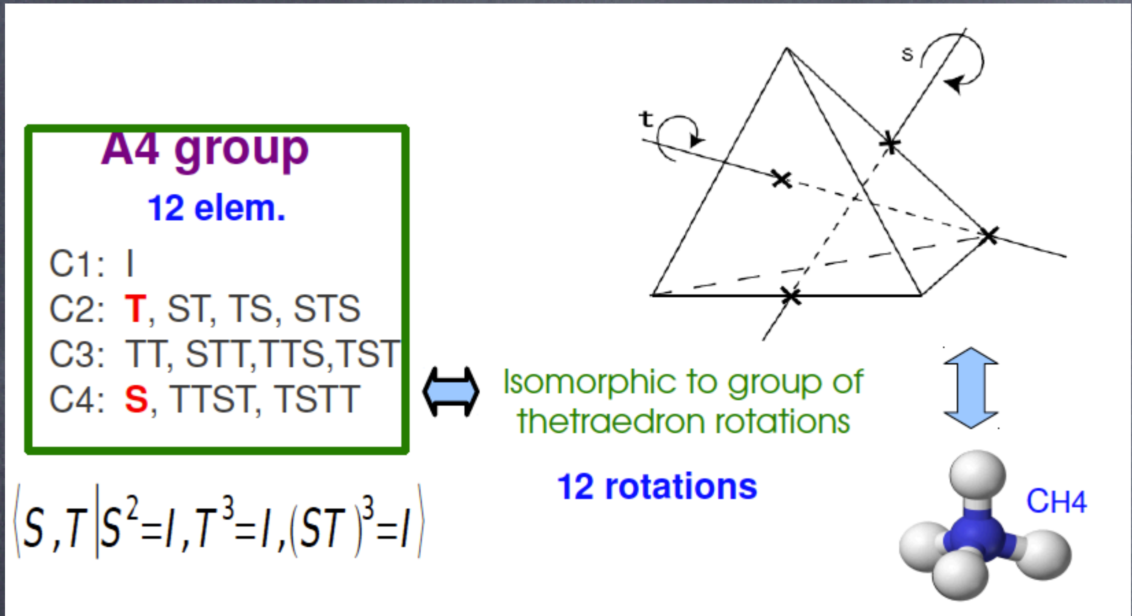
$\Rightarrow$ adding a flavor symmetry to the SM: $SU_c(3) \times SU_L(2) \times U_Y(1) \times G_f$

Group	d	Irr. Repr.'s	Presentation
$D_3 \sim S_3$	6	$1,\ 1',\ 2$	$A^3 = B^2 = (AB)^2 = 1$
D_4	8	$1_1, ...1_4, 2$	$A^4 = B^2 = (AB)^2 = 1$
D_7	14	$1,\ 1',\ 2,\ 2',\ 2''$	$A^7 = B^2 = (AB)^2 = 1$
A_4	12	$1,\ 1',\ 1'',\ 3$	$A^3 = B^2 = (AB)^3 = 1$
$A_5 \sim PSL_2(5)$	60	$1,\ 3,\ 3',\ 4,\ 5$	$A^3 = B^2 = (BA)^5 = 1$
T'	24	$1,\ 1',\ 1'',\ 2,\ 2',\ 2'',\ 3$	$A^3 = (AB)^3 = R^2 = 1,\ B^2 = R$
S_4	24	$1,\ 1',\ 2,\ 3,\ 3'$	$BM : A^4 = B^2 = (AB)^3 = 1$ $TB : A^3 = B^4 = (BA^2)^2 = 1$
$\Delta(27) \sim Z_3 \rtimes Z_3$	27	$1_1, ...1_9, 3, \overline{3}$	
$PSL_2(7)$	168	$1, 3, \overline{3}, 6, 7, 8$	$A^3 = B^2 = (BA)^7 = (B^{-1}A^{-1}BA)^4 = 1$
$T_7 \sim Z_7 \rtimes Z_3$	21	$1, 1', \overline{1'}, 3, \overline{3}$	$A^7 = B^3 = 1,\ AB = BA^4$

Altarelli & Feruglio, arXiv: 1002.0211

A_4 flavor symmetry



One of the most popular choices:

⇒ smallest group with 3 irrep

⇒ has three 1-dim irreps 1, 1′, 1″ and 1 3-dim irrep.

A_4 predicts tribimaximal mixing:

$\sin^2\theta_{12} = 1/3 \qquad \sin^2\theta_{23} = 1/2$

$\sin^2\theta_{13} = 0$

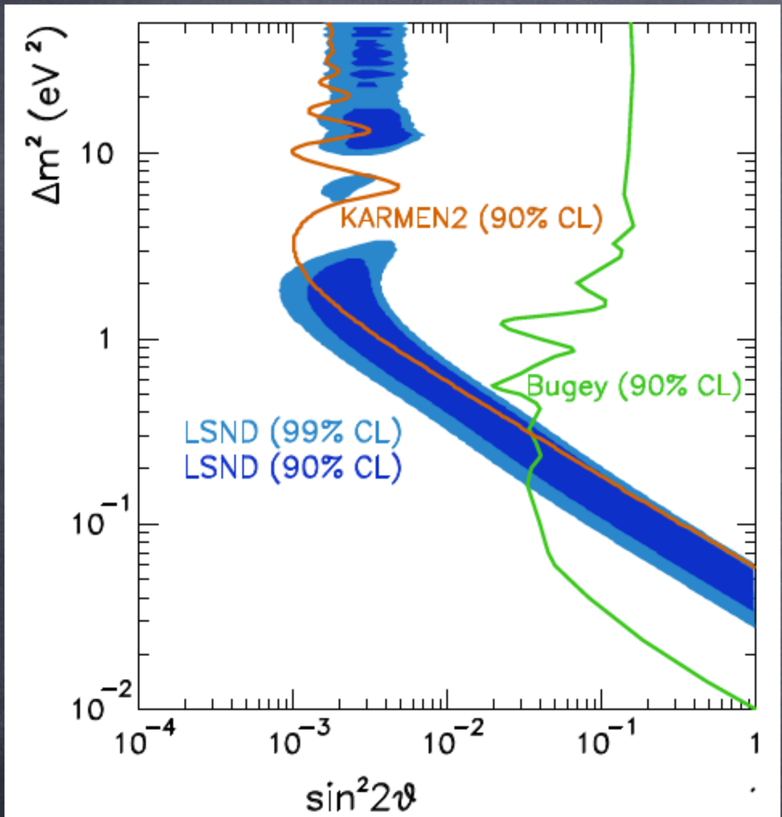
⇒ After reactor measurements: TBM predictions need large corrections on θ_{13}

* perturbations of TBM do not work because all angles get corrections of the same order — Altarelli and Feruglio, 1002.0211
* modifications of TBM models with extra scalar singlet fields can solve the problem — Morisi et al, PRD 84 (2011) 053002

Anomalies beyond 3ν mixing (I)

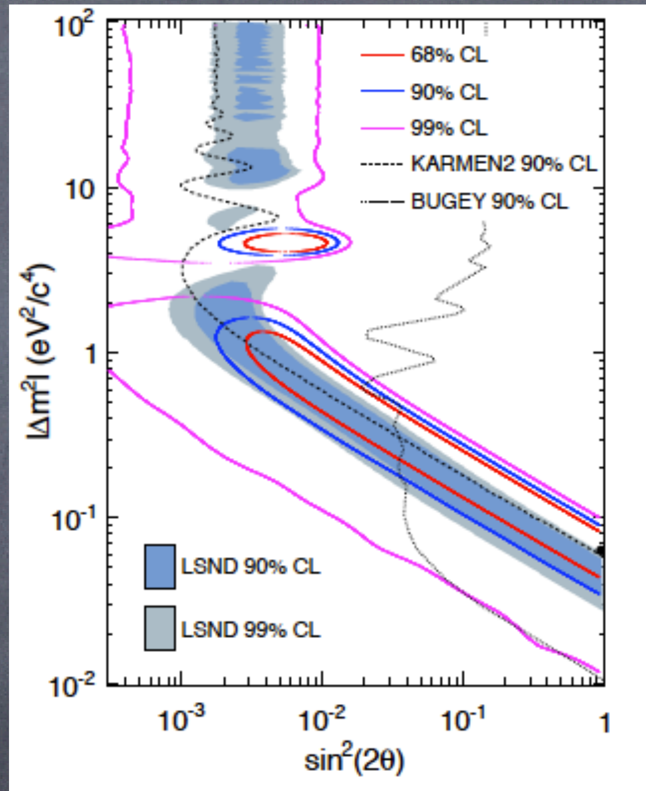
LSND

LSND Collab., PRD 64 (2001) 112007



MiniBooNE $\bar{\nu}$

MiniBooNE Collab., PRL 105 (2010) 181801

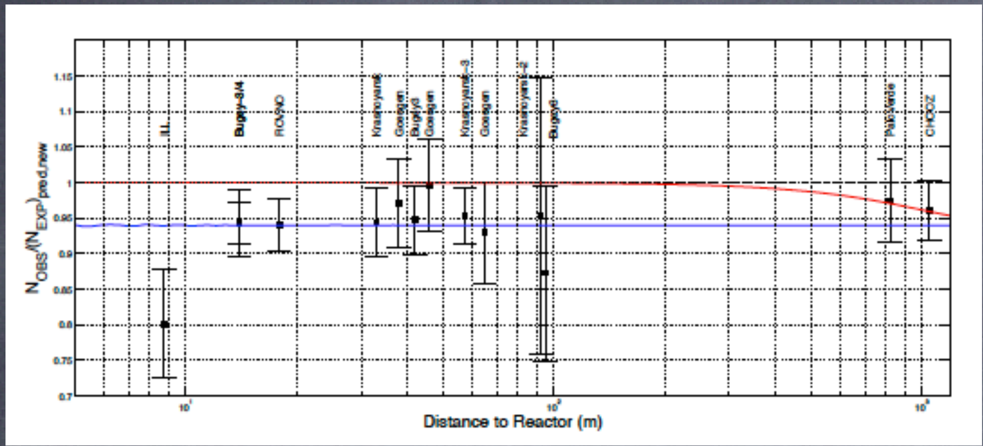


positive signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance with similar L/E

→ neutrino oscillations with $\Delta m^2 \sim 0.2$–10 eV^2 → 4th light sterile neutrino required !!!

Anomalies beyond 3ν mixing (II)

reactor anomaly

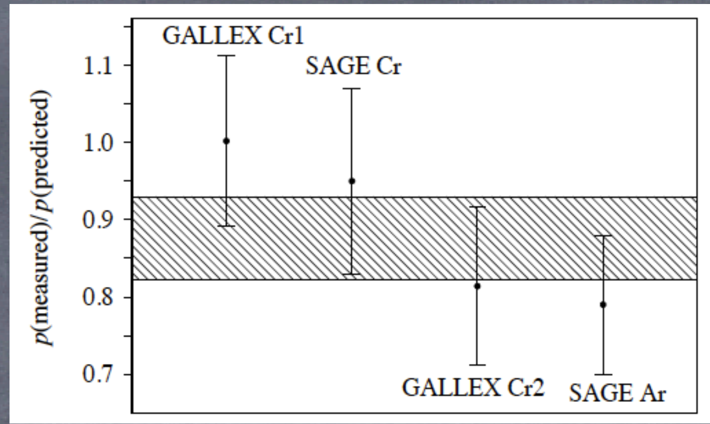


Mention et al, PRD 83 (2011) 073006

* increase of 3.5% in the calculated reactor fluxes ⇒ deficit in number of detected over expected neutrinos:

R = 0.927 ± 0.023

Gallium anomaly



SAGE Coll, PRC 73 (2006) 045805

Giunti and Laveder, PRC 83 (2011) 065504

* averaged deficit of ν_e:

R = 0.86 ± 0.06

⇒ comparable deficits, similar L/E

Gallium + SBL reactor combined fit:

$\Delta m^2 > 1.5\ eV^2$, $\sin^2 2\theta = 0.17 \pm 0.04$ (1σ)

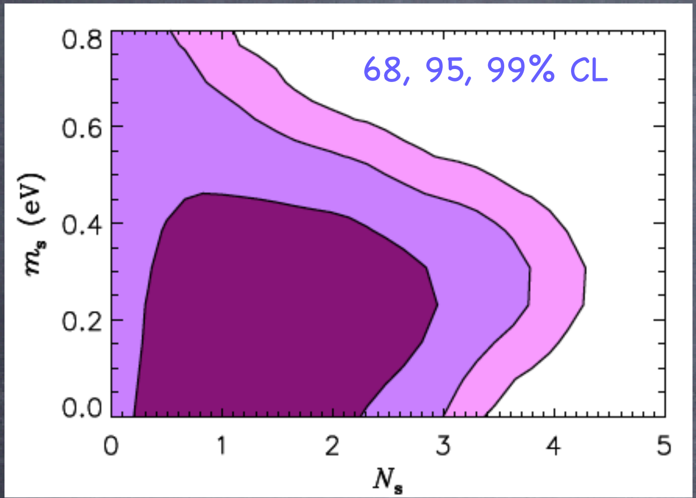
Abazajian et al, arXiv:1204.5379 [hep-ph]

Cosmological bounds on sterile ν

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]$$

$N_s = \Delta N_{eff} \approx N_{eff} - 3$

CMB + LSS:



$N_s = 1.3 \pm 0.9$; $m_s < 0.66$ eV (95% CL)

Hamann et al, PRL 105(2010) 181301

$N_s = 1.61 \pm 0.92$; $m_s < 0.70$ eV (95% CL)

Giusarma et al, PRD 83 (2011) 115023

BBN: $N_s < 1$ at 95% CL

Mangano and Serpico, PLB 701 (2011) 296

CMB + LSS + BBN

$N_s = 0.85^{+0.39}_{-0.56}$ at 95% CL

Hamann et al, JCAP 1109 (2011) 034

Planck sensitivity: $\Delta N_{eff} \approx \pm 0.26$

Status of sterile neutrino hypothesis

Global analysis SBL $\bar{\nu}_e$ and ν_μ disappearance + $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ appearance searches + Gallium data

+ 1 sterile neutrino: (3+1) scheme

Abazajian et al, arXiv:1204.5379 [hep-ph]

- only one extra mass scale.
- no CP violation: fails in reconciling neutrino (MiniBooNE) with antineutrino data (LSND + MiniBooNE).

$\Rightarrow$ strongly disfavoured due to incompatibility of LSND and MiniBooNE antineutrino signal with the rest of data.

+ 2 sterile neutrinos: (3+2) scheme

- 2 new mass scales + CP violation-> reconciles neutrino and antineutrino results.
- in better agreement with data after new reactor fluxes determination.
- strong tension between appearance and disappearance data sets.
- disfavoured by cosmological data.

Alternatives: (3+1+CPT), (3+1+NSI)

Giunti and Laveder, PRD 83 (2011) 053006

Akhmedov and Schwetz, JHEP 1010 (2010) 115

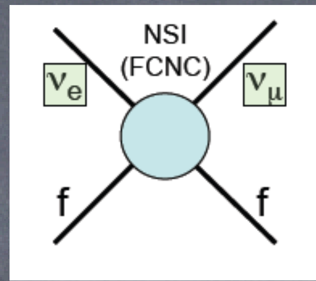
New high precision SBL exp are needed to solve this problem

Non-standard neutrino interactions

- NC interactions predicted in extensions of the SM:
  flavour-changing: $\nu_\alpha\, f \rightarrow \nu_\beta\, f$ non-universal: $\nu_\alpha\, f \rightarrow \nu_\alpha\, f$

- effective 4-fermion operator:

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



- the presence of NSI may affect neutrino propagation and detection:

Wolfenstein 78, Valle 87, Roulet 91, Guzzo et al, 91

$$\mathcal{H}_F = \frac{1}{2E}\left\{ U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger + a_{\rm CC} \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ (\epsilon^m_{e\mu})^* & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ (\epsilon^m_{e\tau})^* & (\epsilon^m_{\mu\tau})^* & \epsilon^m_{\tau\tau} \end{pmatrix} \right\}$$

- bounds on NSI come mainly from:

  - ν scattering: LSND, CHARM, reactor exp. — Barranco et al., 2005, 2007
  - $e^- e^+ \rightarrow \nu\, \nu\, \gamma$ at LEP — Berezhiani & Rossi, 2002
  - atmospheric data — Fornengo et al., 2002; Friedland et al., 2004, Maltoni 2008

Current bounds on neutrino NSI

NSI on electrons	NSI on d quark	NSI on u quark
$-0.14 < \varepsilon_{ee}^{eL} < 0.06$	$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	$-1 < \varepsilon_{ee}^{uL} < 0.3$
$-0.03 < \varepsilon_{ee}^{eR} < 0.18$	$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	$-0.4 < \varepsilon_{ee}^{uR} < 0.7$
$-0.033 < \varepsilon_{\mu\mu}^{eL} < 0.055$	$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$
$-0.040 < \varepsilon_{\mu\mu}^{eR} < 0.053$	$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$
$-0.6 < \varepsilon_{\tau\tau}^{eL} < 0.16$	$\lvert\varepsilon_{\tau\tau}^{dL}\rvert < 1.1$	$\lvert\varepsilon_{\tau\tau}^{uL}\rvert < 1.4$
$-0.4 < \varepsilon_{\tau\tau}^{eR} < 0.6$	$\lvert\varepsilon_{\tau\tau}^{dR}\rvert < 6$	$\lvert\varepsilon_{\tau\tau}^{uR}\rvert < 3$
$\lvert\varepsilon_{\tau\tau}^{eV}\rvert < 0.12$	$\lvert\varepsilon_{\tau\tau}^{dV}\rvert < 0.038$	$\lvert\varepsilon_{\tau\tau}^{uV}\rvert < 0.039$
$\lvert\varepsilon_{e\mu}^{eL}\rvert < 0.13$	$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$
$\lvert\varepsilon_{e\mu}^{eR}\rvert < 0.13$	"	"
$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.33$	$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$
$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.28$	"	"
$\lvert\varepsilon_{\mu\tau}^{eL}\rvert < 0.1$	$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$
$\lvert\varepsilon_{\mu\tau}^{eR}\rvert < 0.1$	"	"

90% CL

$\Rightarrow$ model independent bounds

$\Rightarrow$ ν_μ-NSI strongly constrained, weaker bounds in the e-τ sector

Davidson et al, 2003
Barranco et al, 2007,
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Low energy seesaw schemes:

- sizeable rates for LFV processes
- NSI in ν propagation associated to the non-unitarity of mixing matrix. $\eta \sim \varepsilon^2/2 \Rightarrow \varepsilon < 10^{-2}$

Process	$\mu \to e\gamma$	90% CL
Hierarchy	NH	IH
$\lvert\eta_{12}^{I}\rvert <$	1.4×10^{-3}	1.4×10^{-3}
$\lvert\eta_{13}^{I}\rvert <$	2.0×10^{-2}	$2.1(1.6) \times 10^{-2}$
$\lvert\eta_{23}^{I}\rvert <$	$2.7(2.1) \times 10^{-2}$	$2.5(1.9) \times 10^{-2}$
$\lvert\eta_{12}^{L}\rvert <$	$11.0(9.6) \times 10^{-4}$	$1.5(1.1) \times 10^{-3}$
$\lvert\eta_{13}^{L}\rvert <$	$3.1(2.7) \times 10^{-2}$	3.3×10^{-2}
$\lvert\eta_{23}^{L}\rvert <$	$2.8(2.2) \times 10^{-2}$	3.0×10^{-2}

Forero et al, JHEP 1109 (2011) 142

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* similar slightly stronger bounds in
Antusch et al, NPB 810 (2009) 369.

Forero et al, JHEP 1109 (2011) 142

PART 3

Open questions in neutrino physics

Open questions in ν physics

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- θ_{23} octant: is ν_μ-ν_τ mixing maximal?

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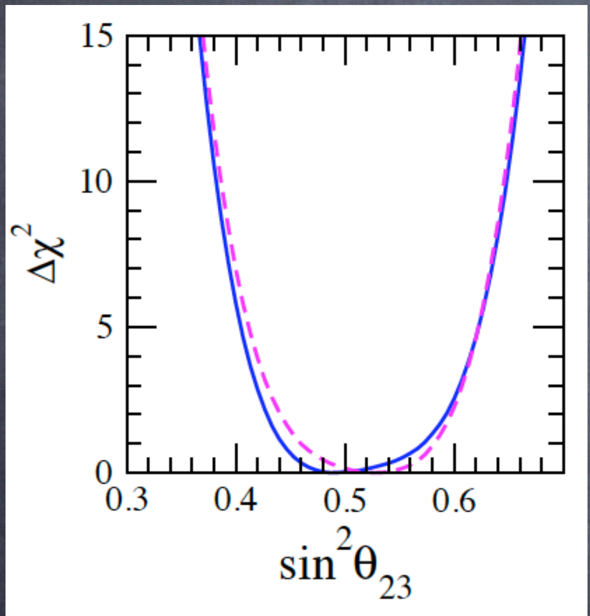
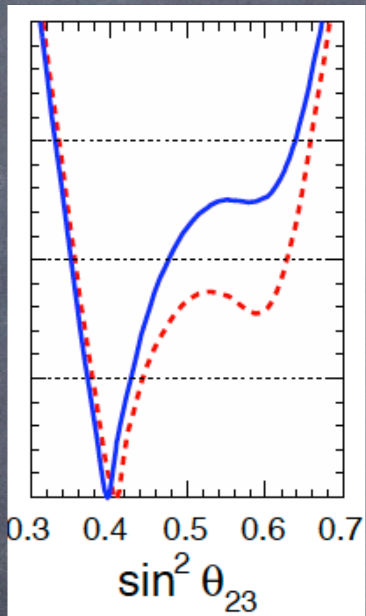
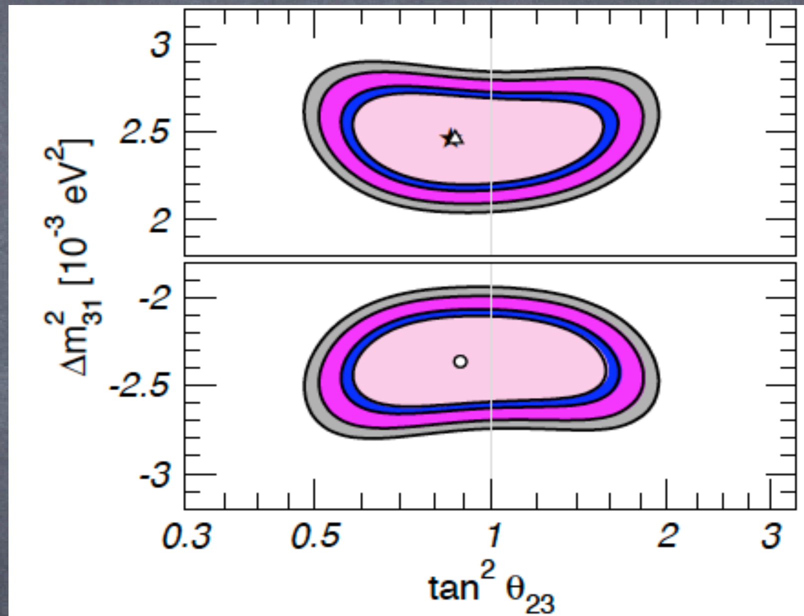


Forero, MT, Valle, 2012



Fogli et al, 2012



González-García et al, 2010

nearly maximal:
$\sin^2\theta_{23} = 0.49(0.53)$
no siginificative
preference

first octant
$\sin^2\theta_{23} \approx 0.40$
max. mixing at 2σ
(NH)

first octant
$\sin^2\theta_{23} \approx 0.46$
max mixing
allowed 90% CL

Open questions in ν physics

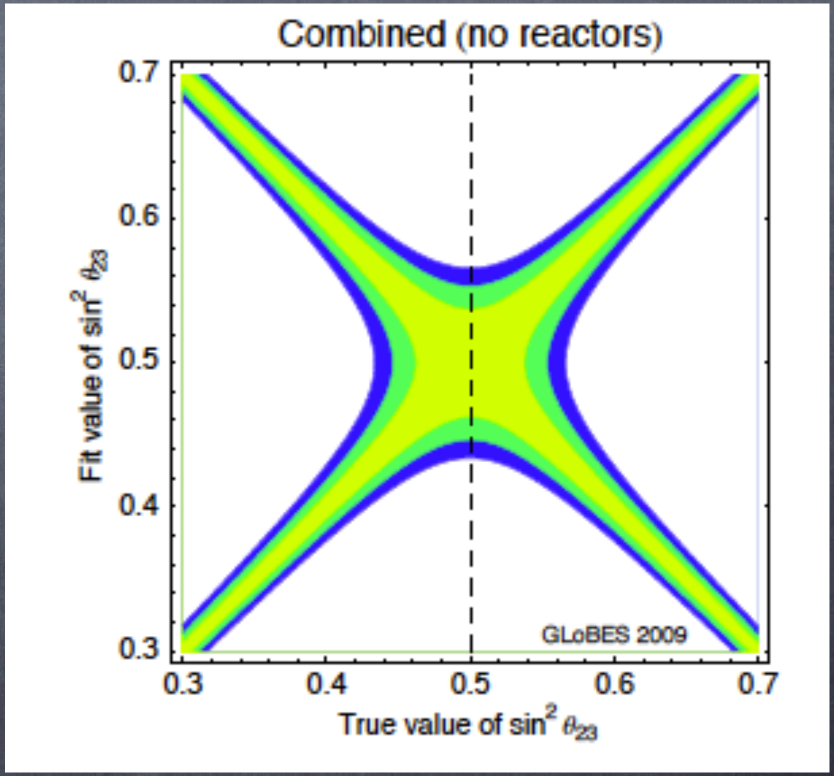
- θ_{23} octant: is ν_μ-ν_τ mixing maximal?

  ⇒ combination LBL accelerator + SBL reactor

appearance at LBL:

$$P_{\mu e} = \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \text{correc}$$

⇒ anticorrelation θ_{23}-θ_{13}



Huber et al, JHEP 0911 (2009) 044.

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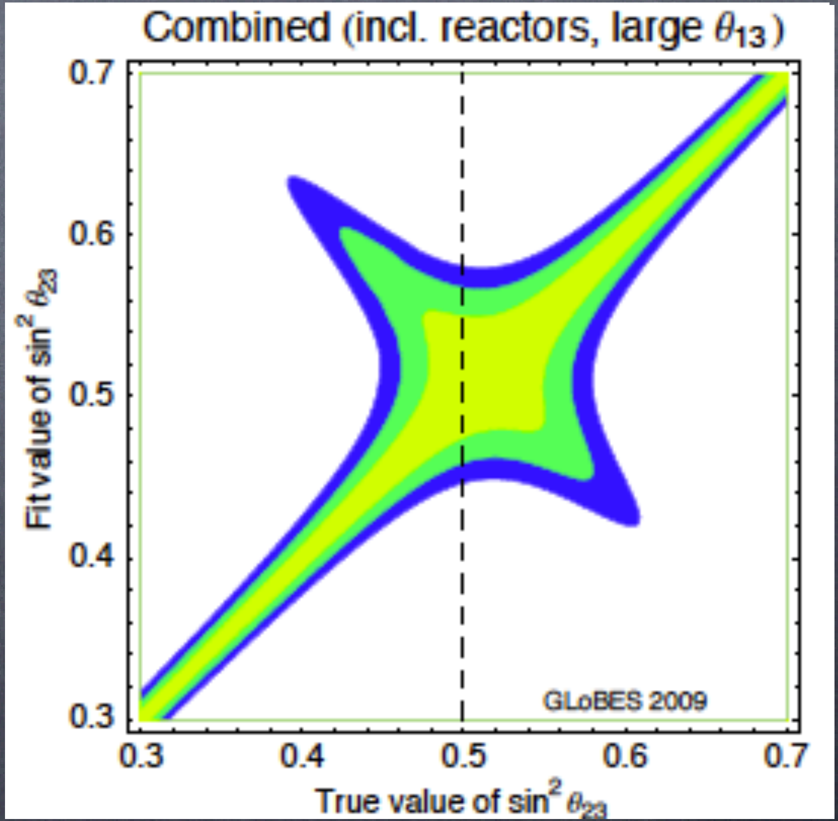
⇒ anticorrelation θ_{23}-θ_{13}

disappearance at SBL reactor:

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

⇒ indep. measurement of θ_{13}



Huber et al, JHEP 0911 (2009) 044.

Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH

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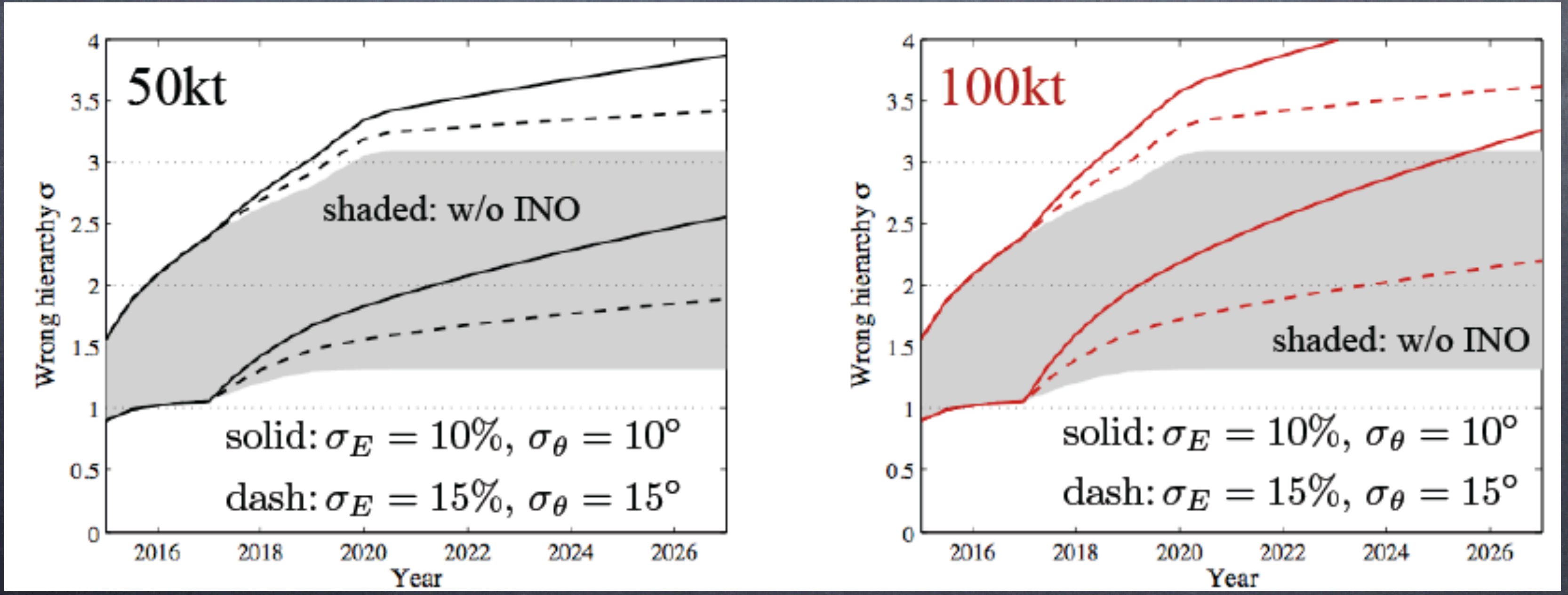

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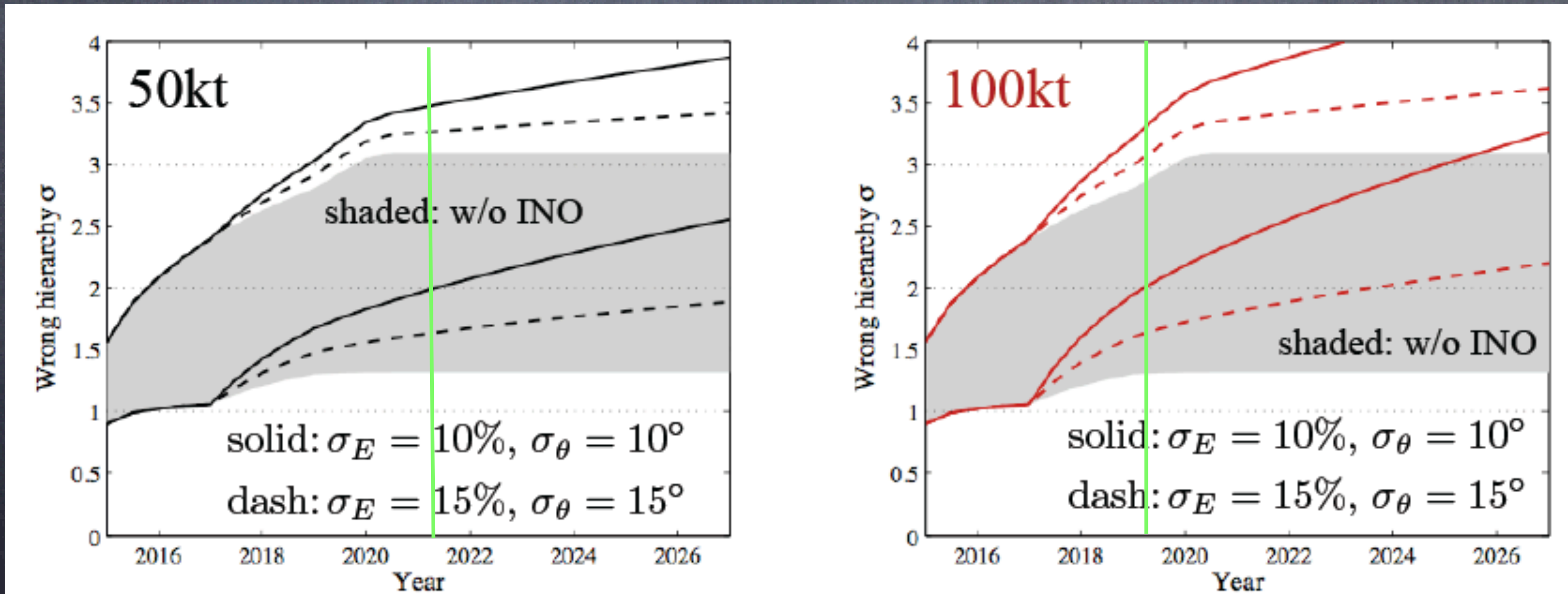

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2σ rejection ~ 2020

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⇒ reactor experiment with intermediate baseline (~60 km)

$$P^{NH(IH)}(\bar{\nu}_e \rightarrow \bar{\nu}_e)\Big|_{\frac{\Delta m^2_\odot L}{2\pi E_\nu}=1} = 1 - 2\sin^2\theta\cos^2\theta - \cos^4\theta\sin^2 2\theta_\odot \stackrel{(+)}{-} \cos 2\theta_\odot\, 2\sin^2\theta\cos^2\theta\cos\pi\frac{\Delta m^2_{31}}{\Delta m^2_\odot}$$

maximum of Δm_{12} osc

Petcov and Piai, PLB 533 (2002) 94 (2002)

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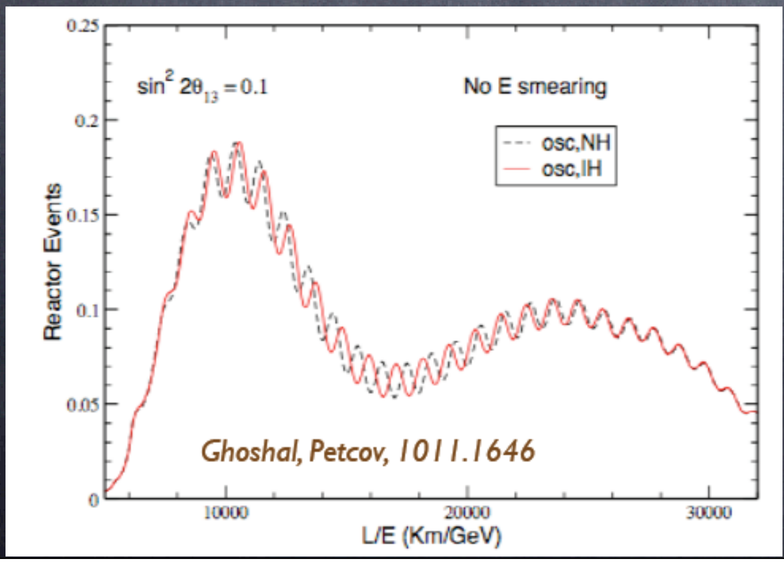

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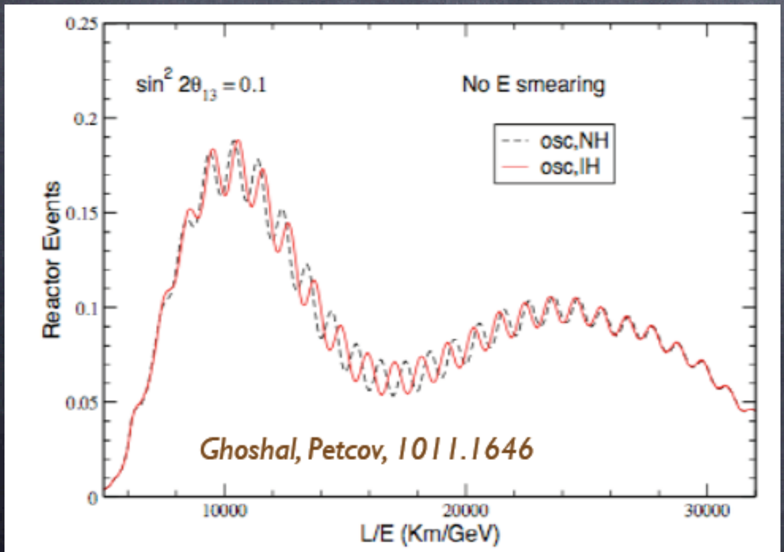

10 kton detector with very good energy resolution -> MH at 90%CL in 5 years.

Zhan et al, PRD 79 (2009) 073007.

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- CP violation in the neutrino sector

T2K and NOvA have poor discovery potential for δ_{CP}

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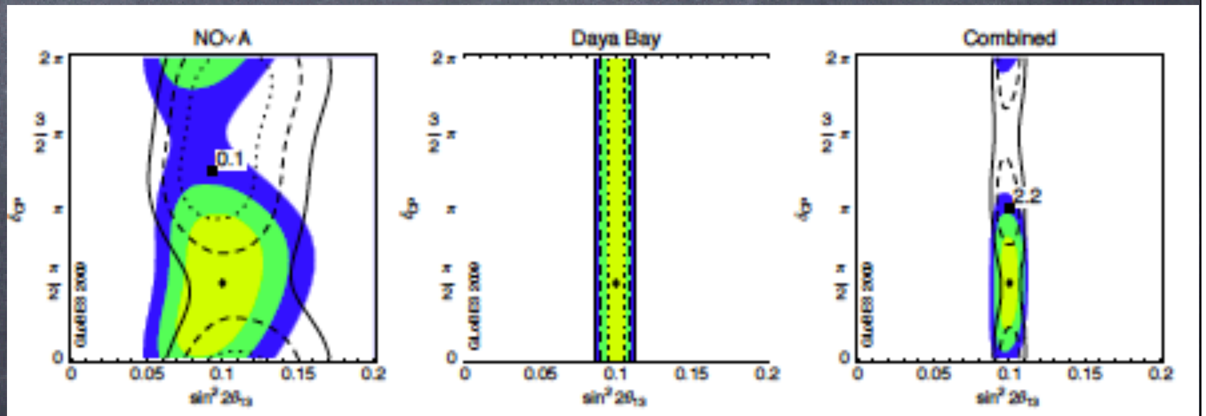

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T2K and NOvA have poor discovery potential for δ_{CP}

$\Rightarrow$ combination with reactors

$\Rightarrow$ new generation of experiments (superbeam/β-beam with Mton det) will perform a more solid determination of δ_{CP}

Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH
- CP violation in the neutrino sector
- absolute neutrino mass

$\Rightarrow$ slight improvement on Σm_ν expected from Planck.

(weak lensing of galaxies + Planck ~ 0.05 eV)

Hannestad et al, JCAP 0606 (2006) 025

$\Rightarrow$ direct mass searches: β, 2β decay.

Open questions in ν physics

- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH
- CP violation in the neutrino sector
- absolute neutrino mass
- Dirac or Majorana?

$\Rightarrow$ positive signal in $2\beta0\nu$ decay experiment

Open questions in ν physics

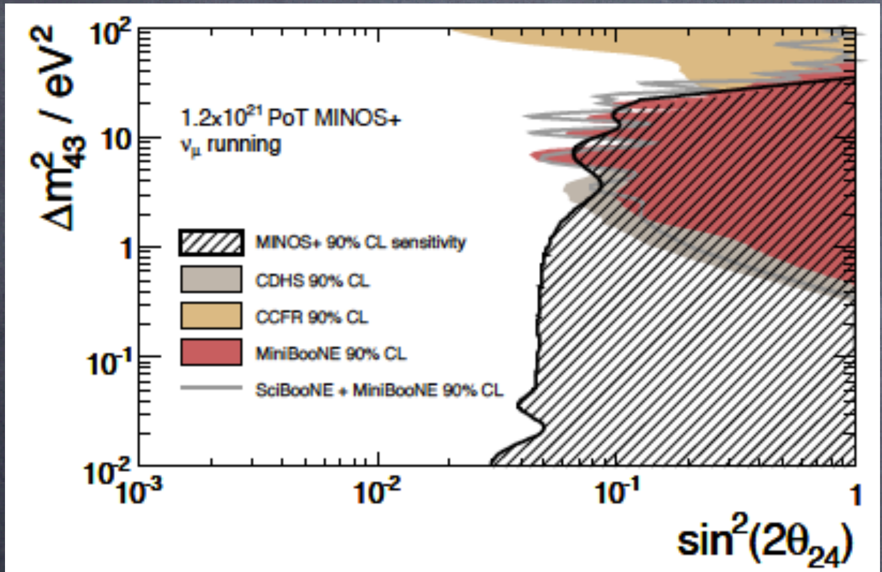
- θ_{23} octant: is ν_μ-ν_τ mixing maximal?
- neutrino mass hierarchy: NH or IH
- CP violation in the neutrino sector
- absolute neutrino mass
- Dirac or Majorana?
- are there sterile neutrinos, NSI?

  $\Rightarrow$ new SBL experiments, cosmological data, MINOS+

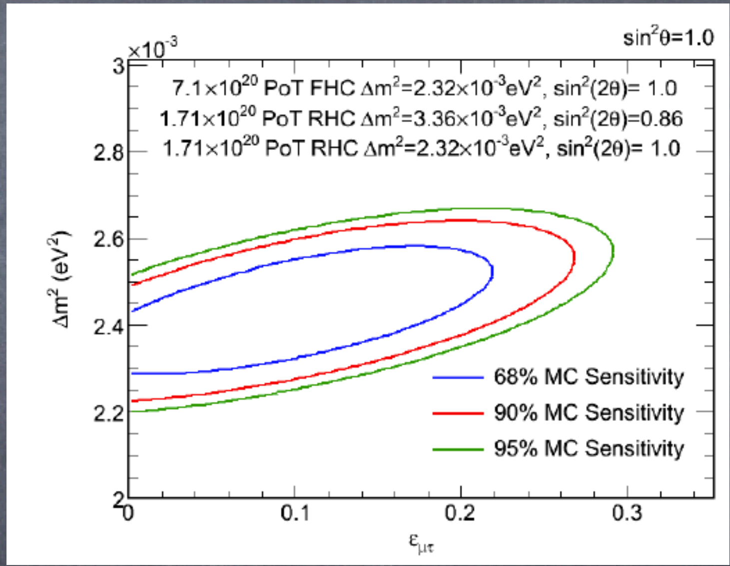
MINOS+ searches for new physics

MINOS+: running of MINOS during NovA era

⇒ high statistics neutrino data collected in MINOS FD will test the existence of NSI and sterile neutrinos



MINOS+ sensitivity to θ_{24}



MINOS+ sensitivity to NSI coupling $\varepsilon_{\mu\tau}$

MINOS+ proposal, Tzanankos et al, FERMILAB-PROPOSAL-1016.

Summary

* Neutrino oscillations are well stablished with observations in several experiments, with natural and artificial sources.

* Oscillation parameters are measured accurately ($\lesssim$ 10%) by the combination of different experiments.

* The mixing angle θ_{13} has been measured at 3 reactor experiments with good level of statistical significance.

* Theoretical efforts should be made to accommodate the neutrino masses and mixings in a consistent theory.

* There are open issues in neutrino physics, like the existence of sterile neutrinos or non-standard interactions.

* Questions to be answered by the next generation of neutrino experiments: δ_{CP}, mass hierarchy, new physics...