Neutrino Course
(Part II)

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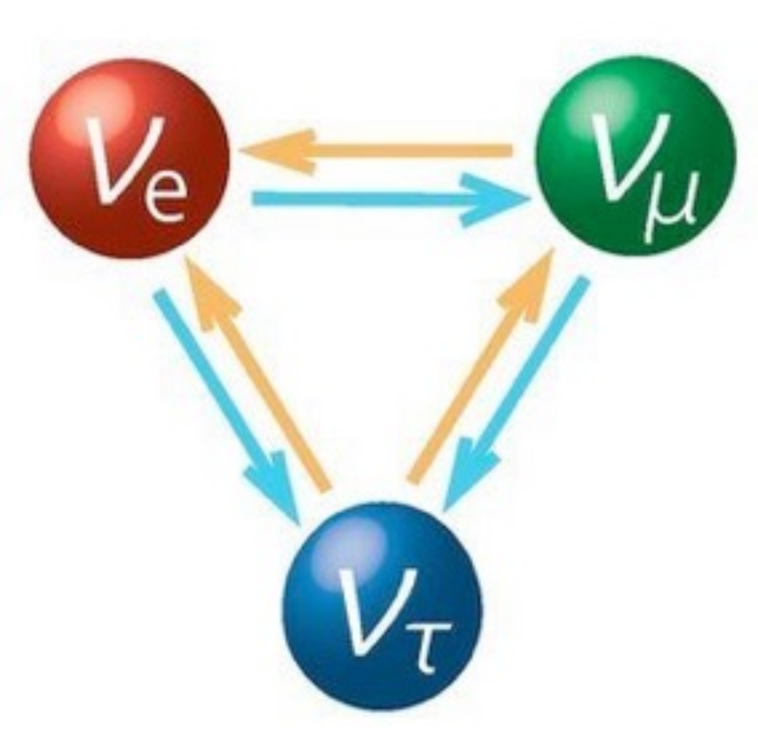
Outline

- Introduction to neutrino physics
- Neutrinos in the Standard Model
- Neutrino masses beyond the Standard Model
- Neutrino oscillations in vacuum and matter
- Three-flavour neutrino oscillations
- Neutrino oscillations beyond 3 flavours: sterile neutrinos
- The absolute scale of neutrino mass
- Neutrino physics beyond the Standard Model

Three-flavour neutrino oscillations



two-neutrino approximation:

$\boxed{\Delta m^2_{21} \ll \Delta m^2_{31}}$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\theta_{12}, \Delta m^2_{21}$

solar + KamLAND

$\theta_{13}, \Delta m^2_{31}$

SBL reactor

$\theta_{23}, \Delta m^2_{31}$

atmospheric + LBL

Precision measurements of parameters require full 3-nu analysis

three-neutrino analysis:

$\theta_{12}, \Delta m^2_{21}, \theta_{13}$

$\theta_{13}, \Delta m^2_{31}, \theta_{12}$

$\theta_{23}, \Delta m^2_{31}, \theta_{13},$
$\Delta m^2_{21}, \delta$

all data samples are connected → a global 3ν analysis is required.

The solar neutrino sector

Solar neutrinos

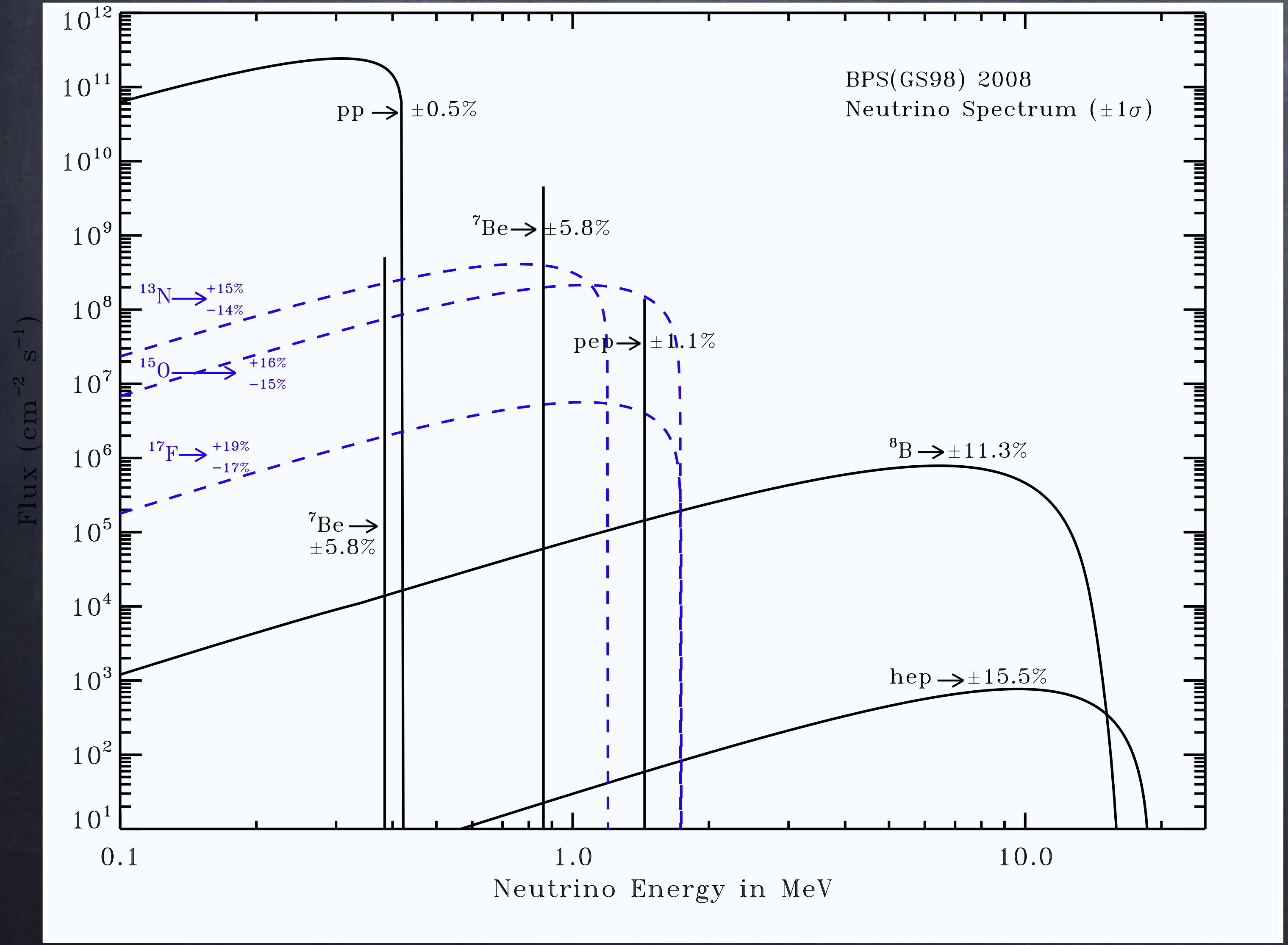
- produced in nuclear reactions in the core of the Sun:

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

pp cycle

CNO

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

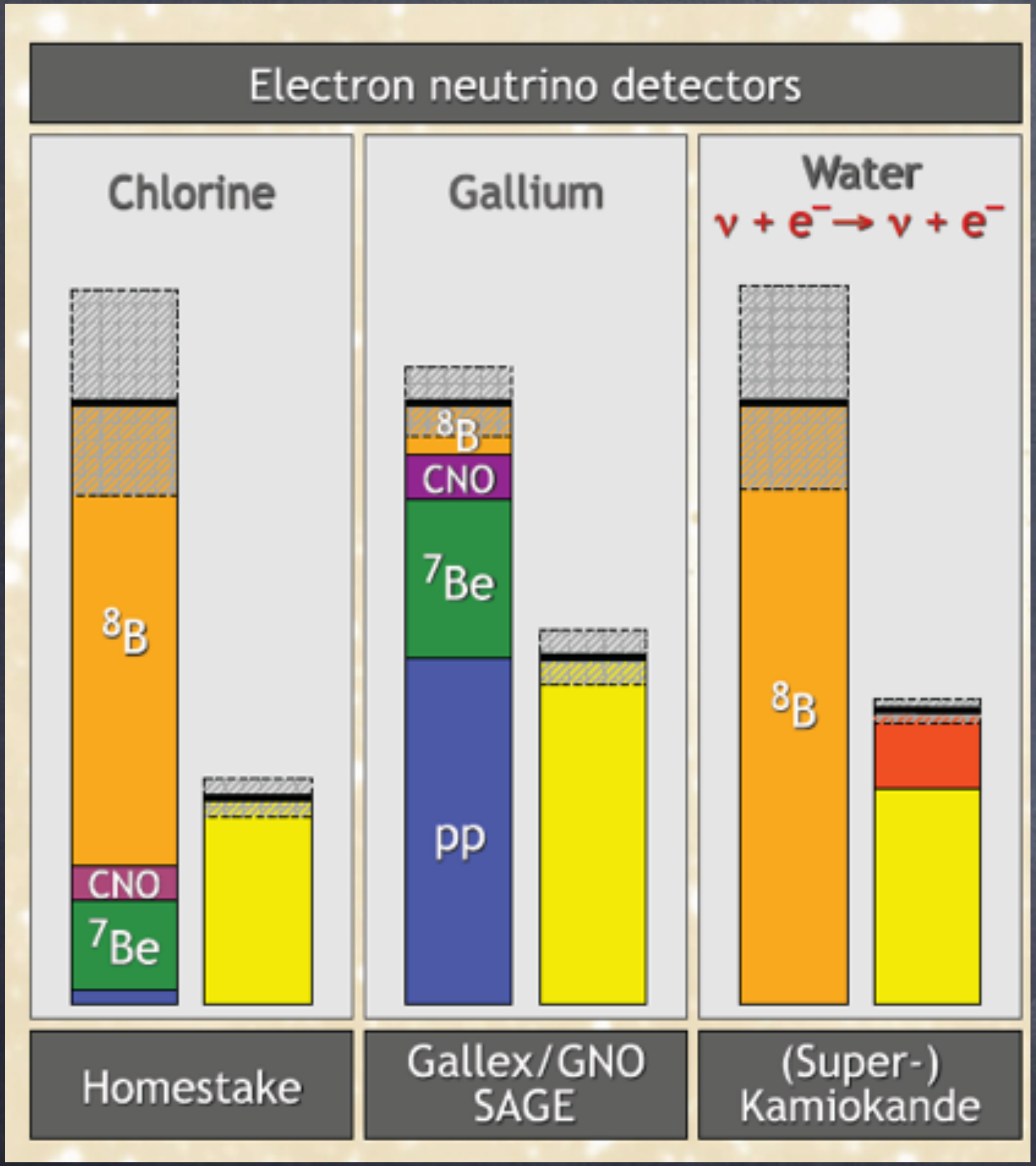


ν fluxes

SSM predictions

ν energy spectra

The solar neutrino problem



↓ ~30% ↓ ~50% ↓ ~40%

➡ All the experiments detect less neutrinos than expected (30-50%)

Why the deficit observed is different?

- different type of neutrinos observed

→ radiochemical: ν_e while Super-K: ν_α

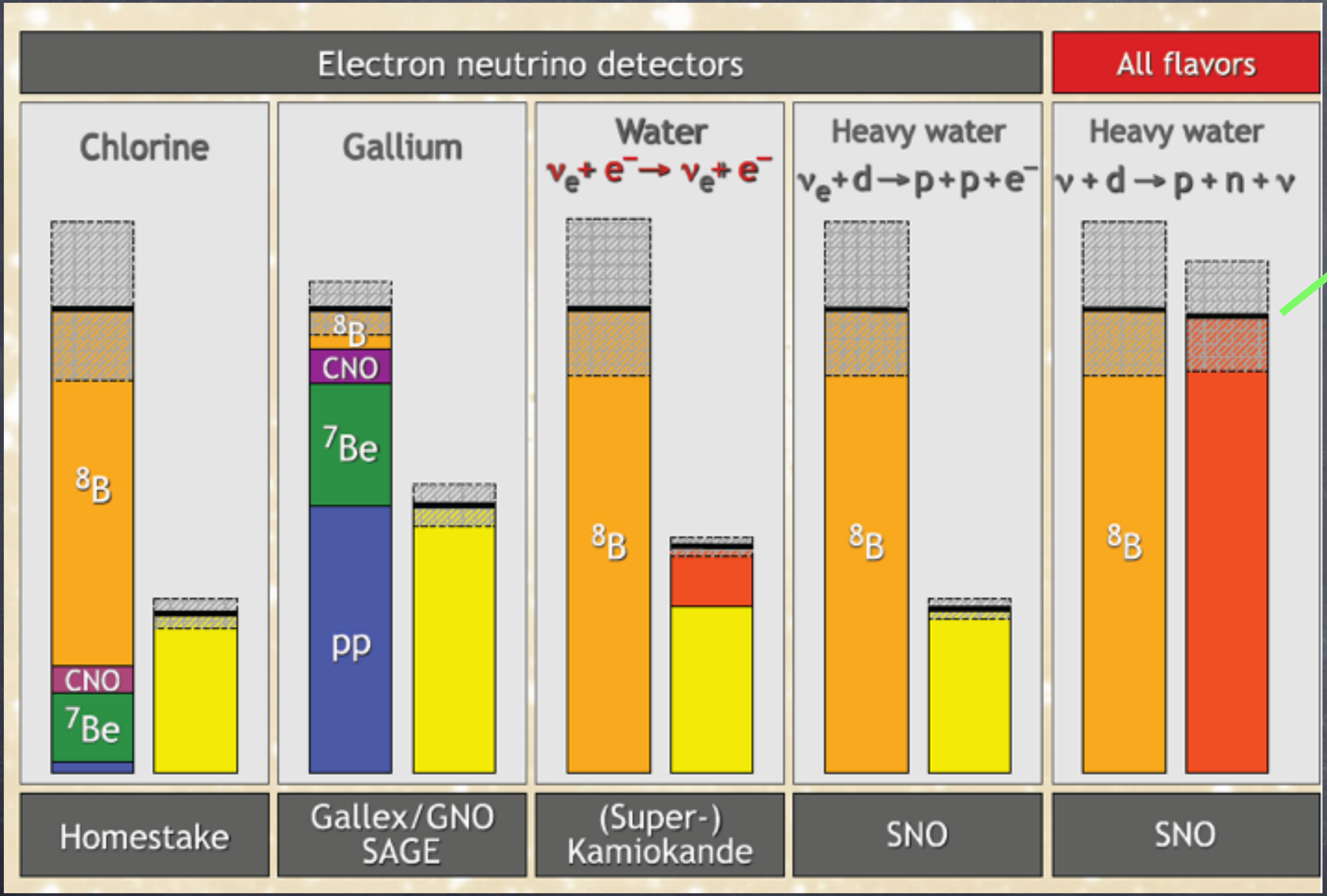
- different E-range sensitivity:

→ Cl: E > 0.814 MeV

→ Ga: E > 0.233 MeV

→ Super-K: E > 5 MeV

The solar neutrino ~~problem~~



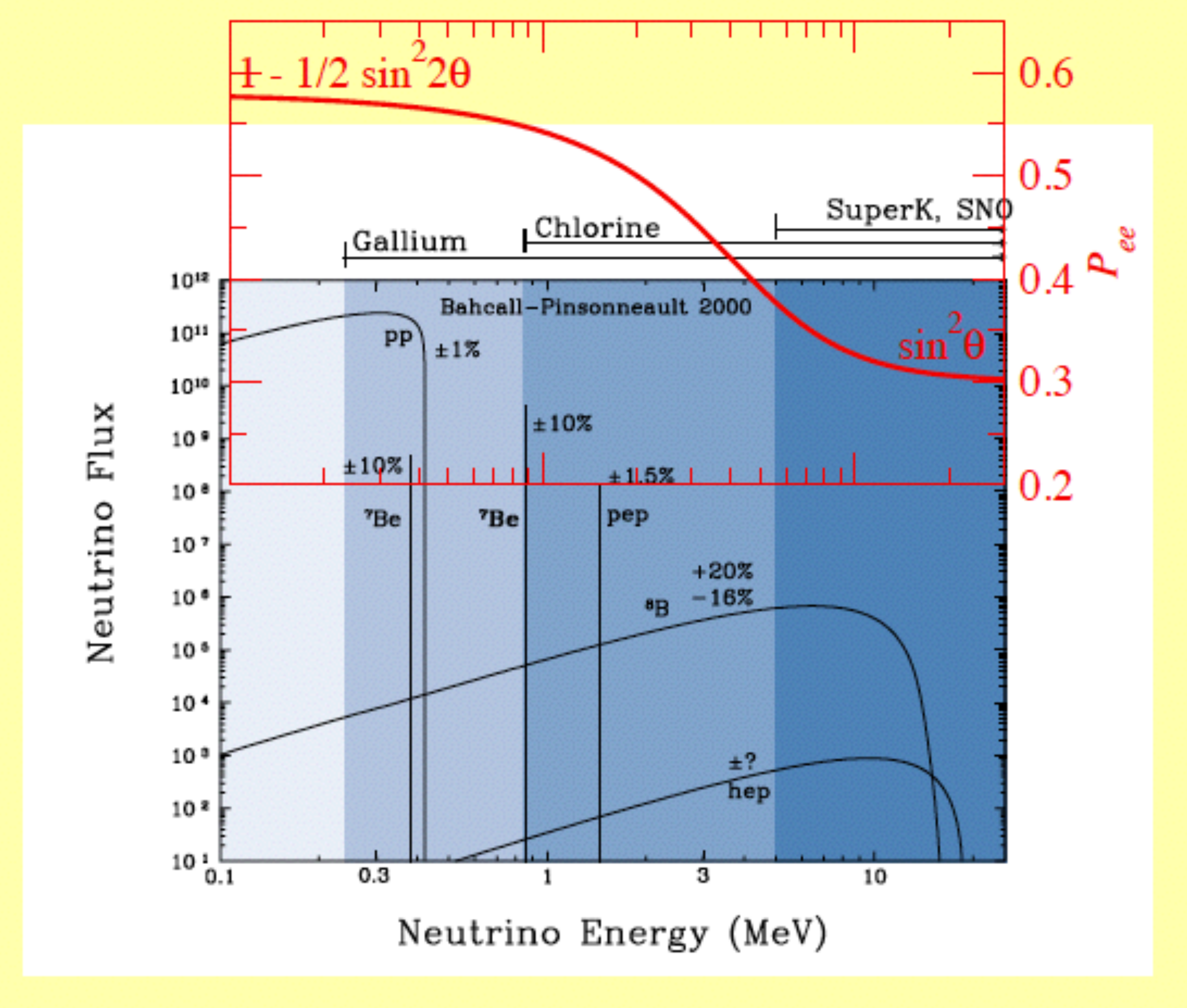
All neutrinos are there!!

The Sun produces ν_e that arrive to the Earth as 1/3 ν_e + 1/3 ν_μ + 1/3 ν_τ

➡ flavor conversion: $\nu_e \rightarrow \nu_x$

Conversion mechanism ?
Neutrino oscillations ??

Different energy suppression of solar fluxes



- Ga experiments: pp neutrinos

$$\boxed{P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta}$$

with $\sin^2 2\theta \simeq 0.84$ Pee > 0.5

- Cl + Super-K: ^{8}B neutrinos

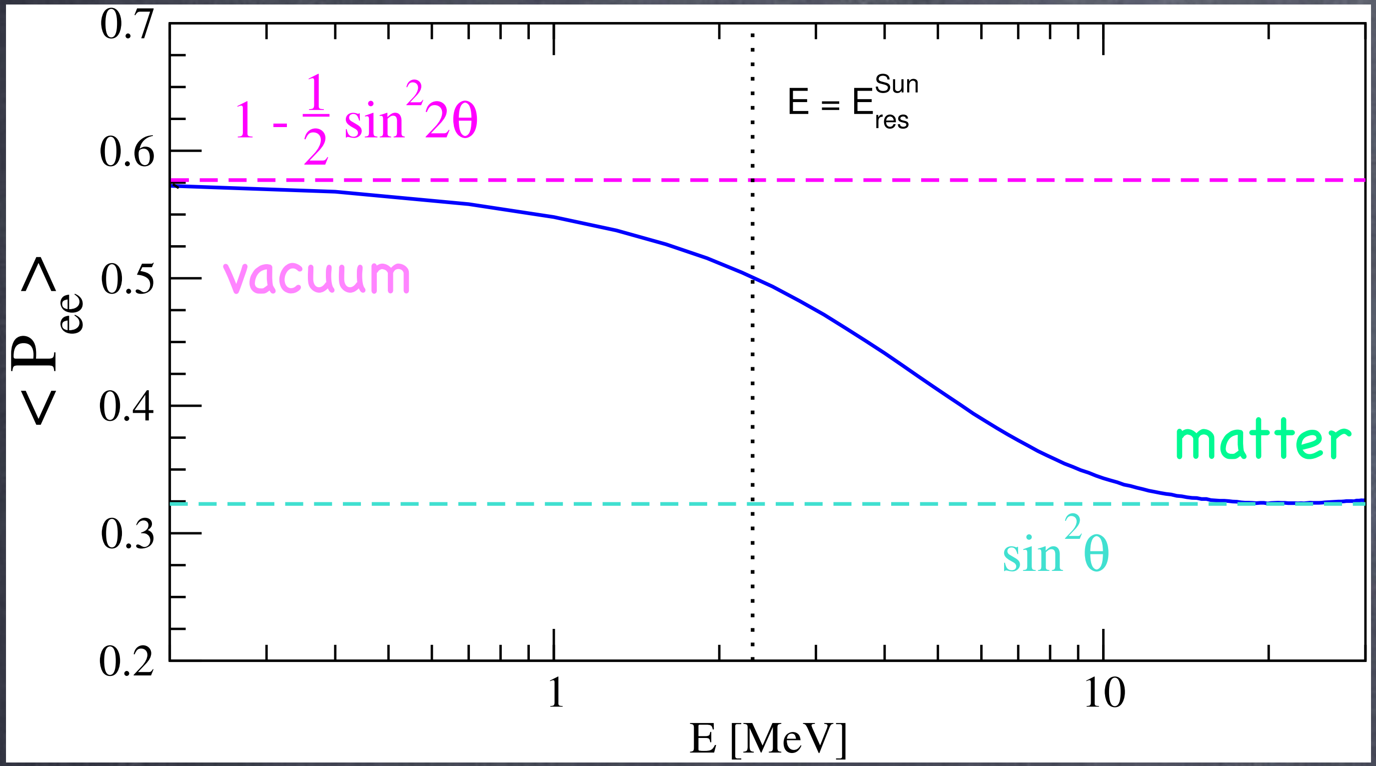
$$\boxed{P_{ee} = \sin^2\theta}$$

→ Pee ~ 0.3

→ stronger neutrino deficit is expected

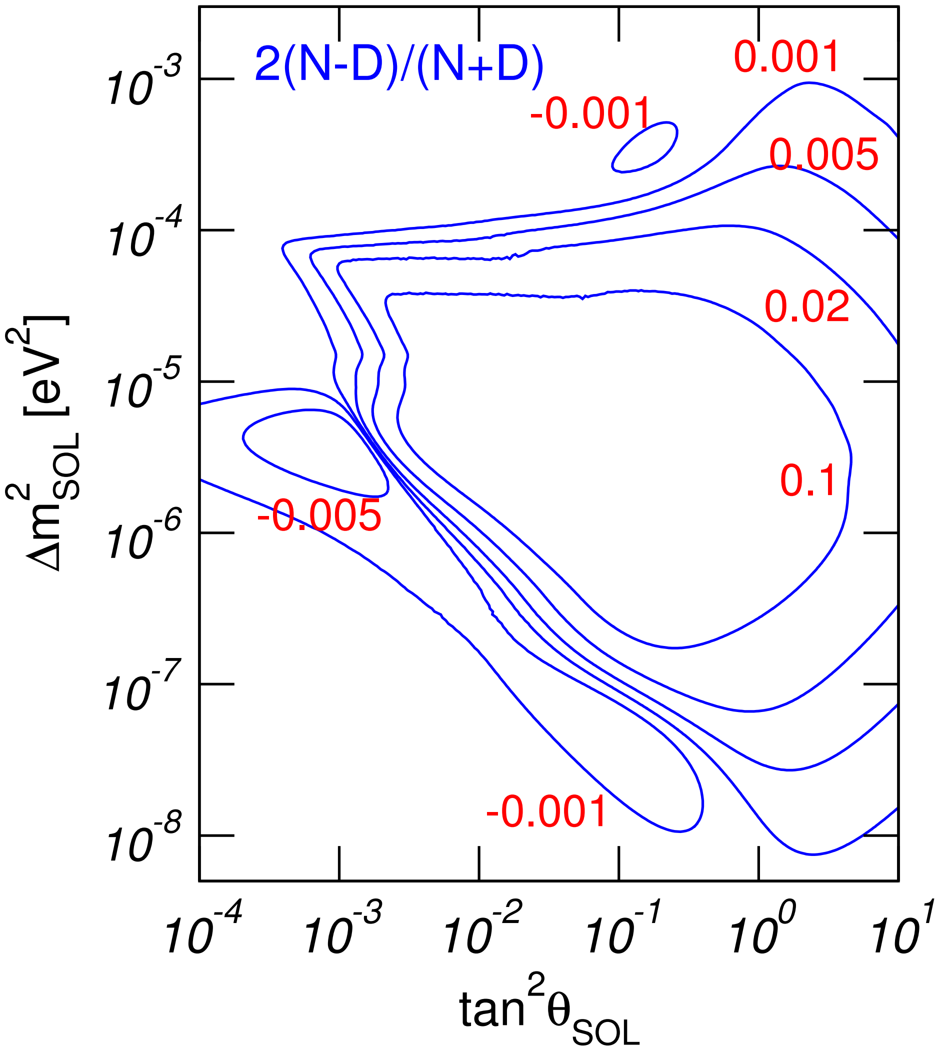
Solar neutrino oscillations: observables

ν survival probability



- observation of low and high energy solar neutrinos (vacuum vs strong matter effect regimes)
- direct test of MSW effect through observation of upturn in intermediate region

day-night asymmetry



- indication of Earth matter effects
- expected to be very small

Analysis of solar neutrino data

Homestake ($E_\nu > 0.814$ MeV)

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

SAGE/GALLEX-GNO ($E_\nu > 0.233$ MeV)

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

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

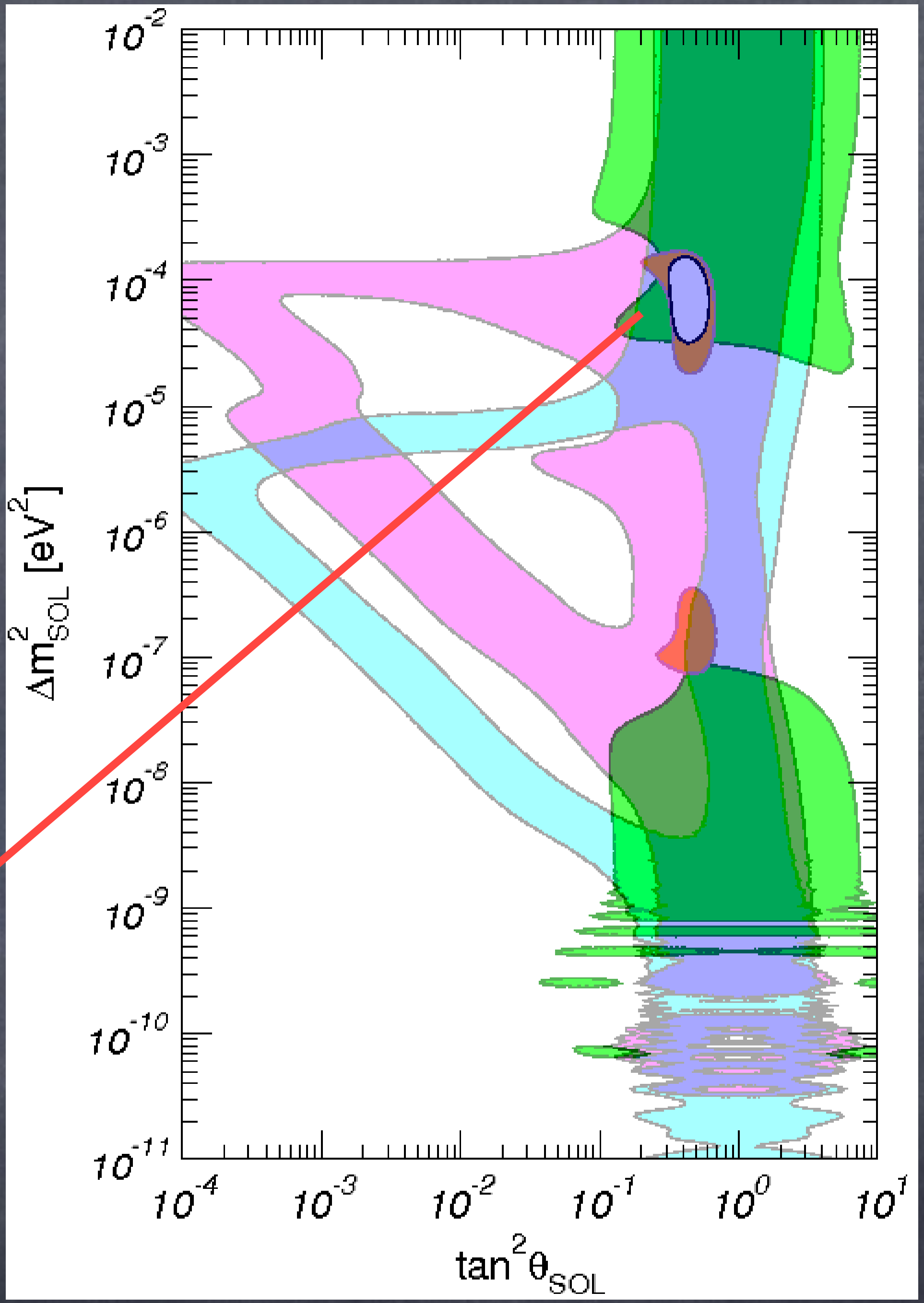
$\nu_x + e^- \rightarrow \nu_x + e^-$

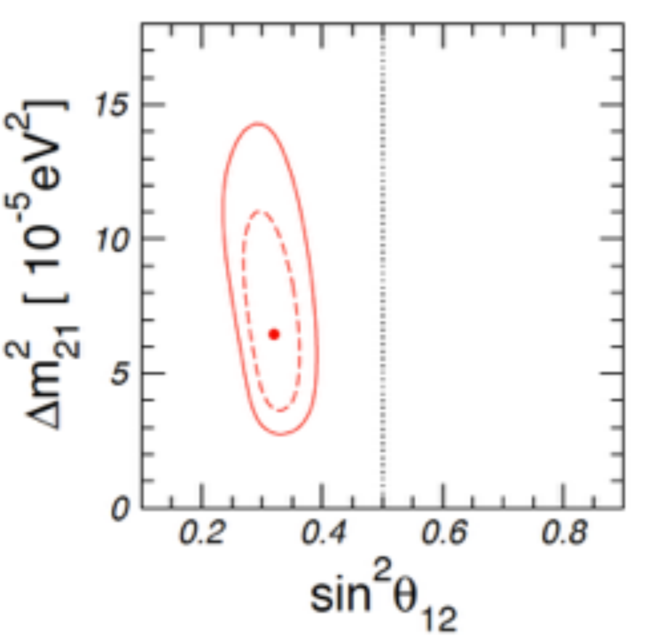
SNO ($E_e \gtrsim 5$ MeV)

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

[NC] $\nu_x + d \rightarrow \nu_x + n + p$

[ES] $\nu_x + e^- \rightarrow \nu_x + e^-$





- LMA solution:
  $\Delta m^2 \sim 10^{-5}$ eV^2 $\sin^2\theta \sim 0.30$

The KamLAND reactor experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector

- reactor experiment:

$$\overline{\nu}_e + p \rightarrow n + e^+$$

- CPT invariance: same oscillation channel as solar ν_e (Δm^2_{21}, θ_{12})

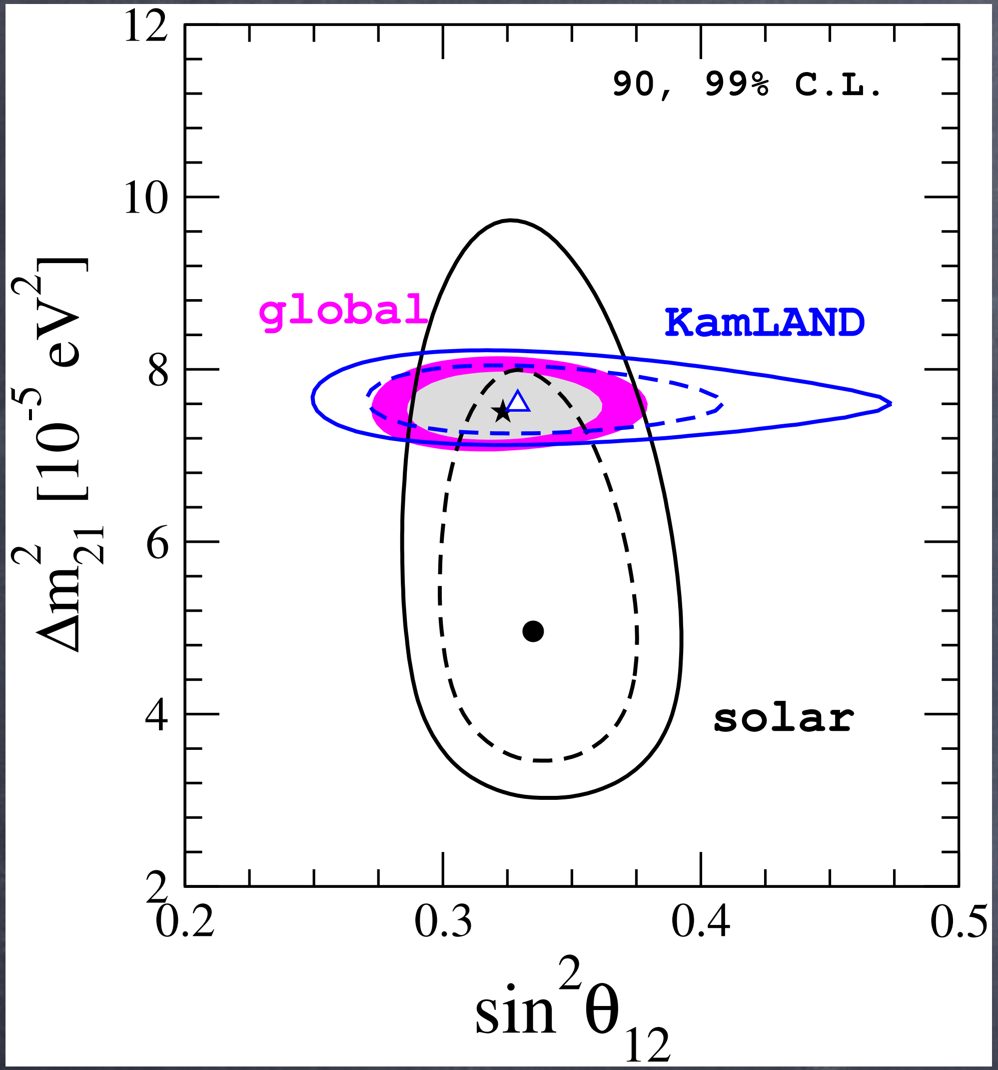
- ~50 commercial power reactors

- average distance ~ 180 km

→ E_ν/L sensitivity range: $\Delta m^2 \sim 10^{-5}$ eV^2

→correct order of magnitude to test solar neutrino oscillations in LMA region

Combined analysis solar + KamLAND



- KamLAND confirms solar neutrino oscillations.
- Best fit point:

  $\sin^2\theta_{12} = 0.321^{+0.018}_{-0.016}$

  $\Delta m^2_{21} = 7.56 \pm 0.19 \times 10^{-5}$ eV^2
- max. mixing excluded at more than 7σ

de Salas et al, arXiv:1708.01186

(to be uploaded)

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

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

➡ mismatch between Δm^2_{21} from solar and KamLAND

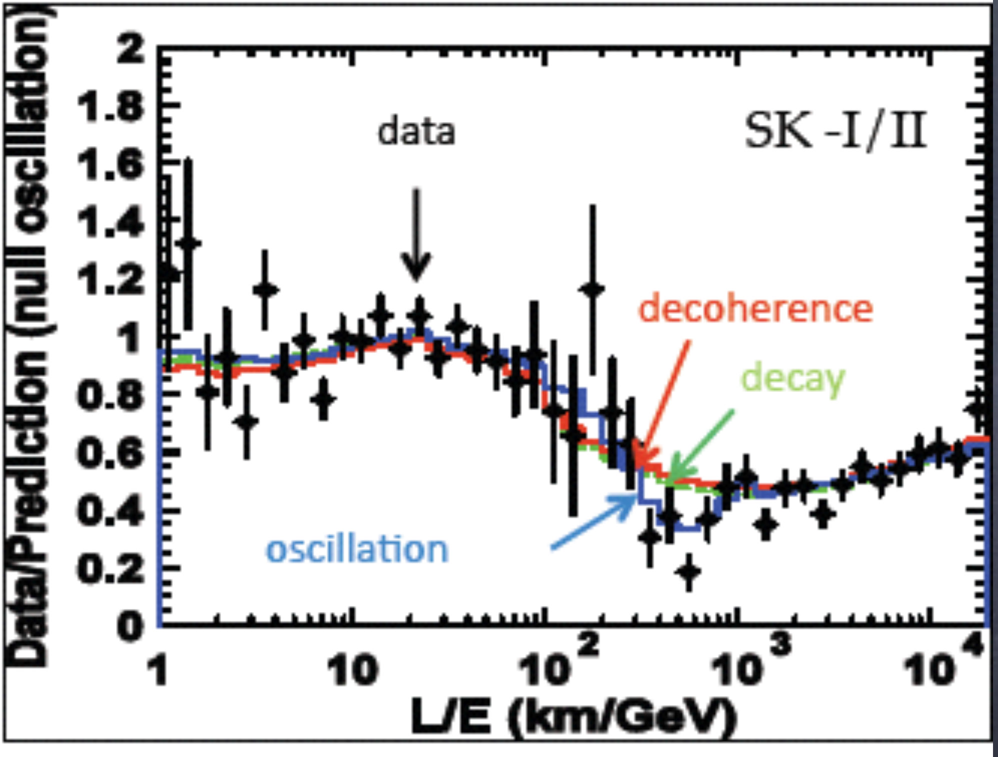
The atmospheric neutrino sector

Atmospheric neutrinos

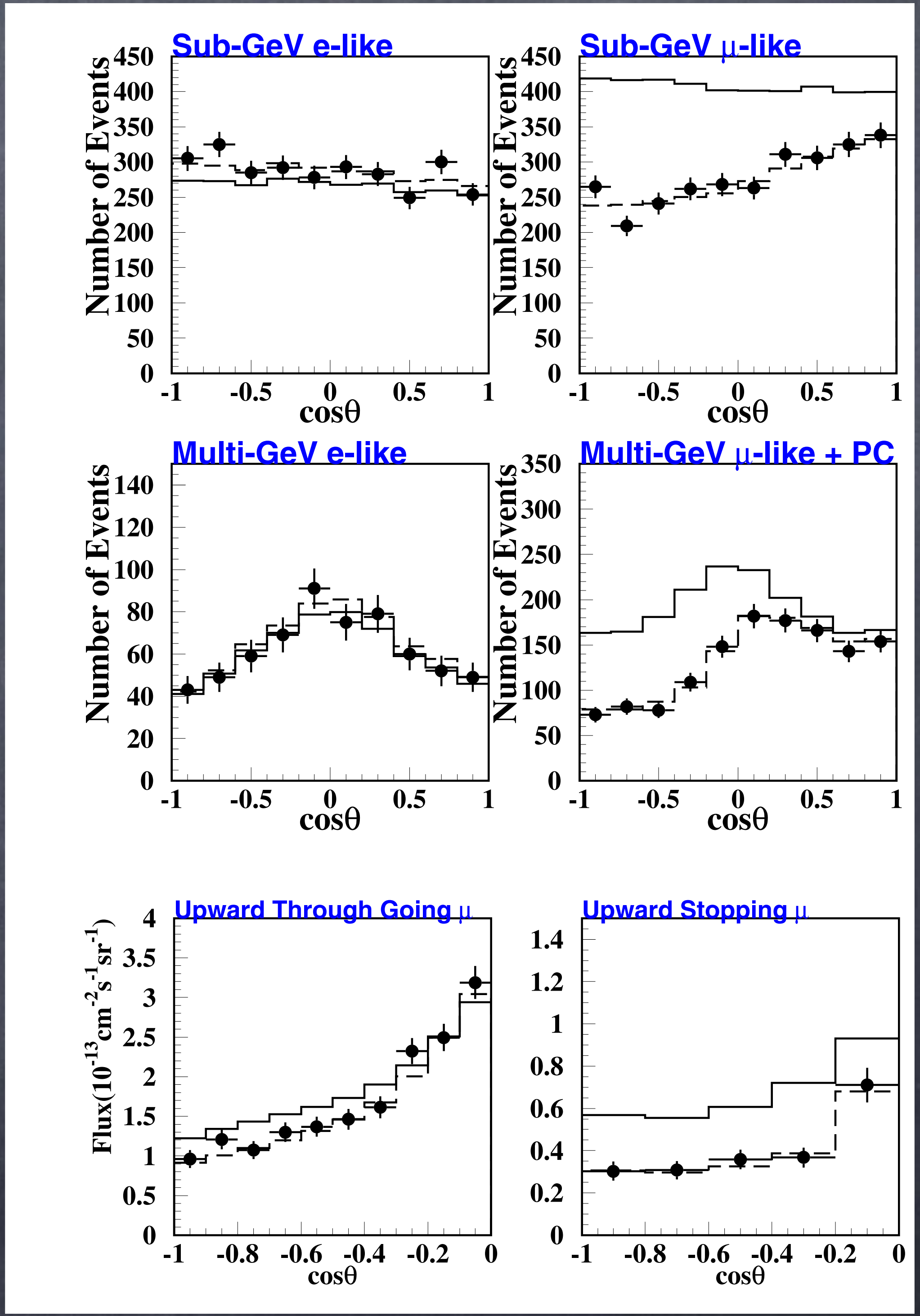
1998: Evidence ν_μ oscillations at Super-K

oscillation channel $\nu_\mu \rightarrow \nu_\tau$

2004: oscillatory L/E pattern



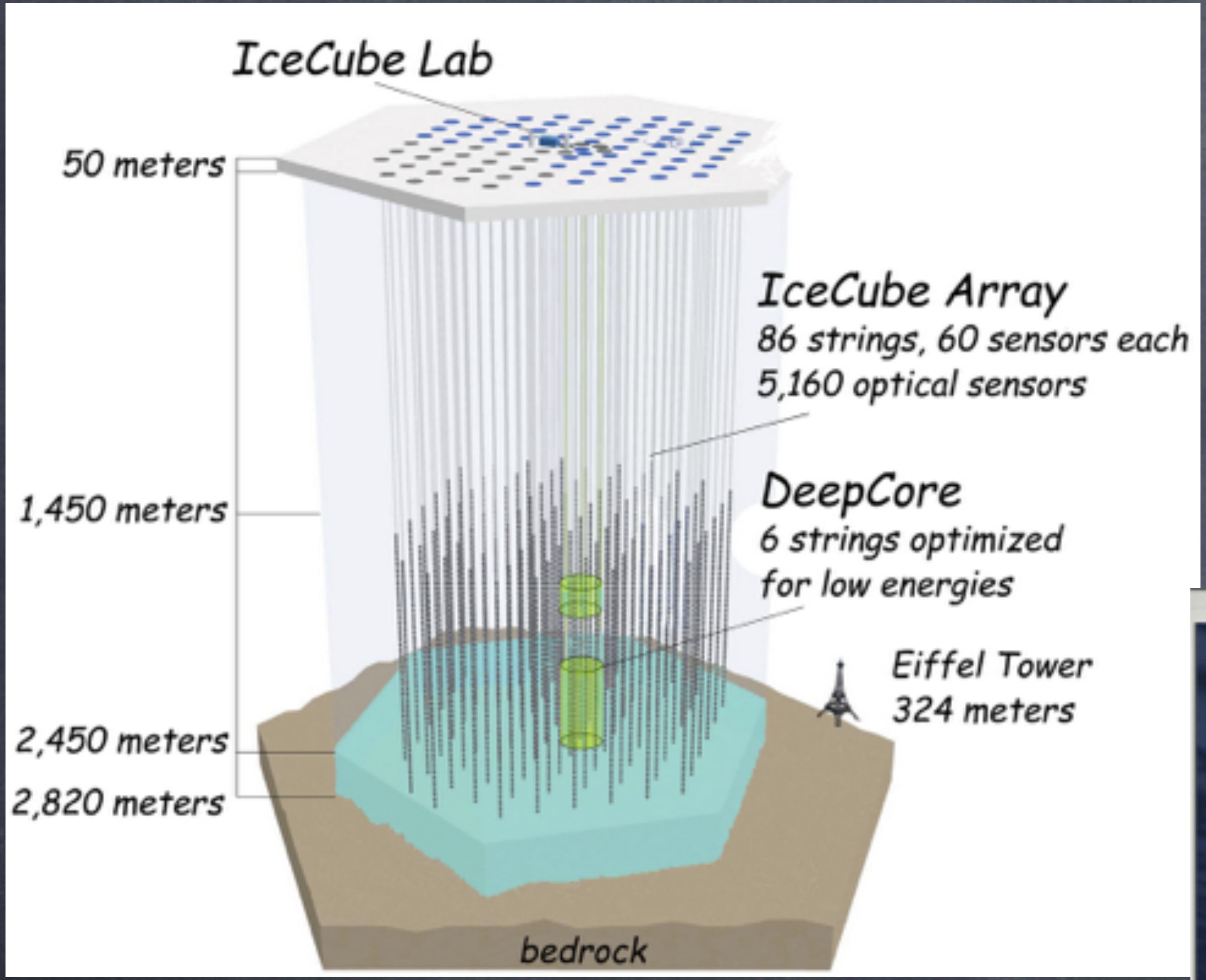
Super-K Coll, PRL93, 101801 (2004)



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

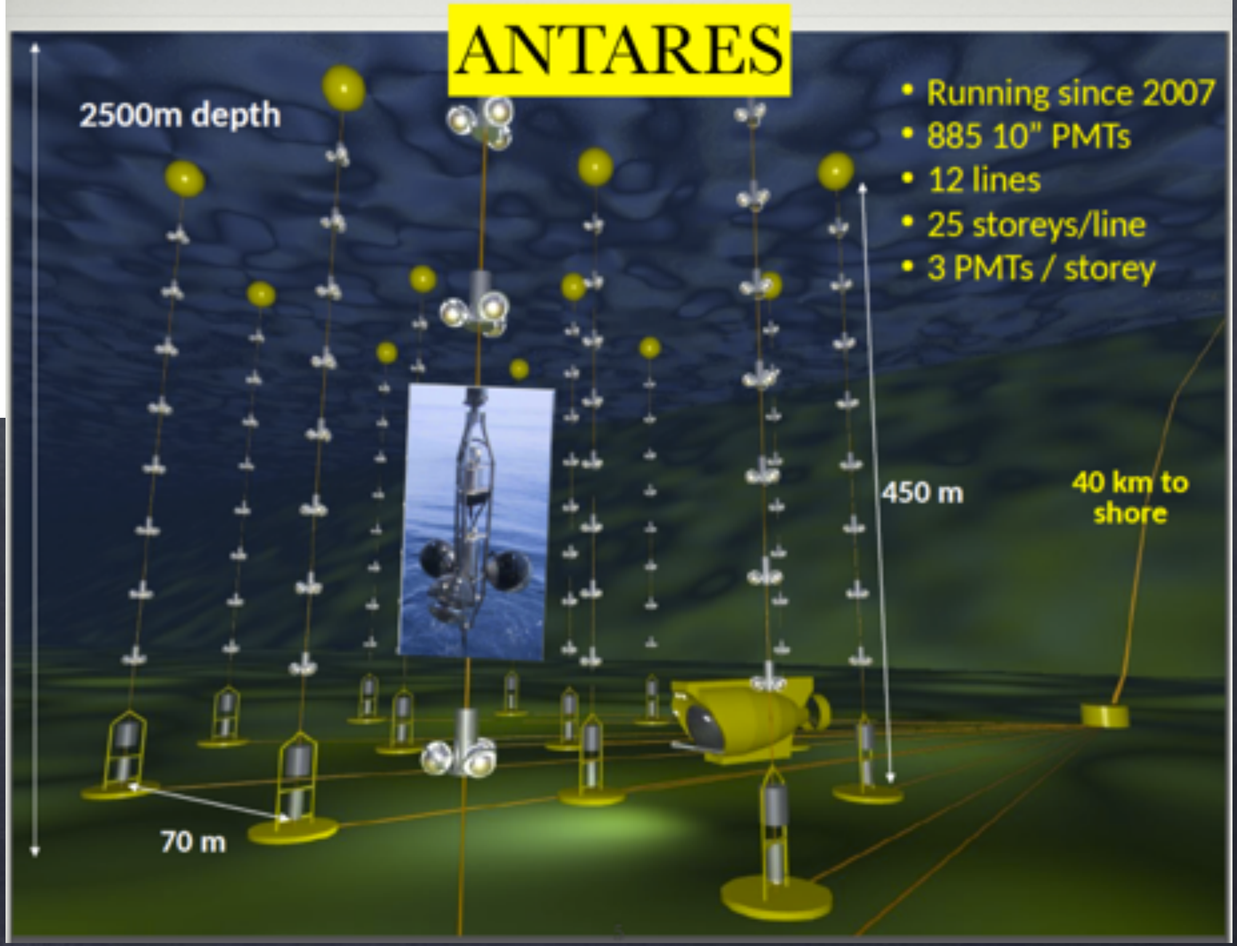
Super-K Coll., PRL 8 (1998) 1562.

Neutrino telescopes



IceCube-DeepCore,

$E_\nu \in [6\text{–}56\ \mathrm{GeV}]$



ANTARES

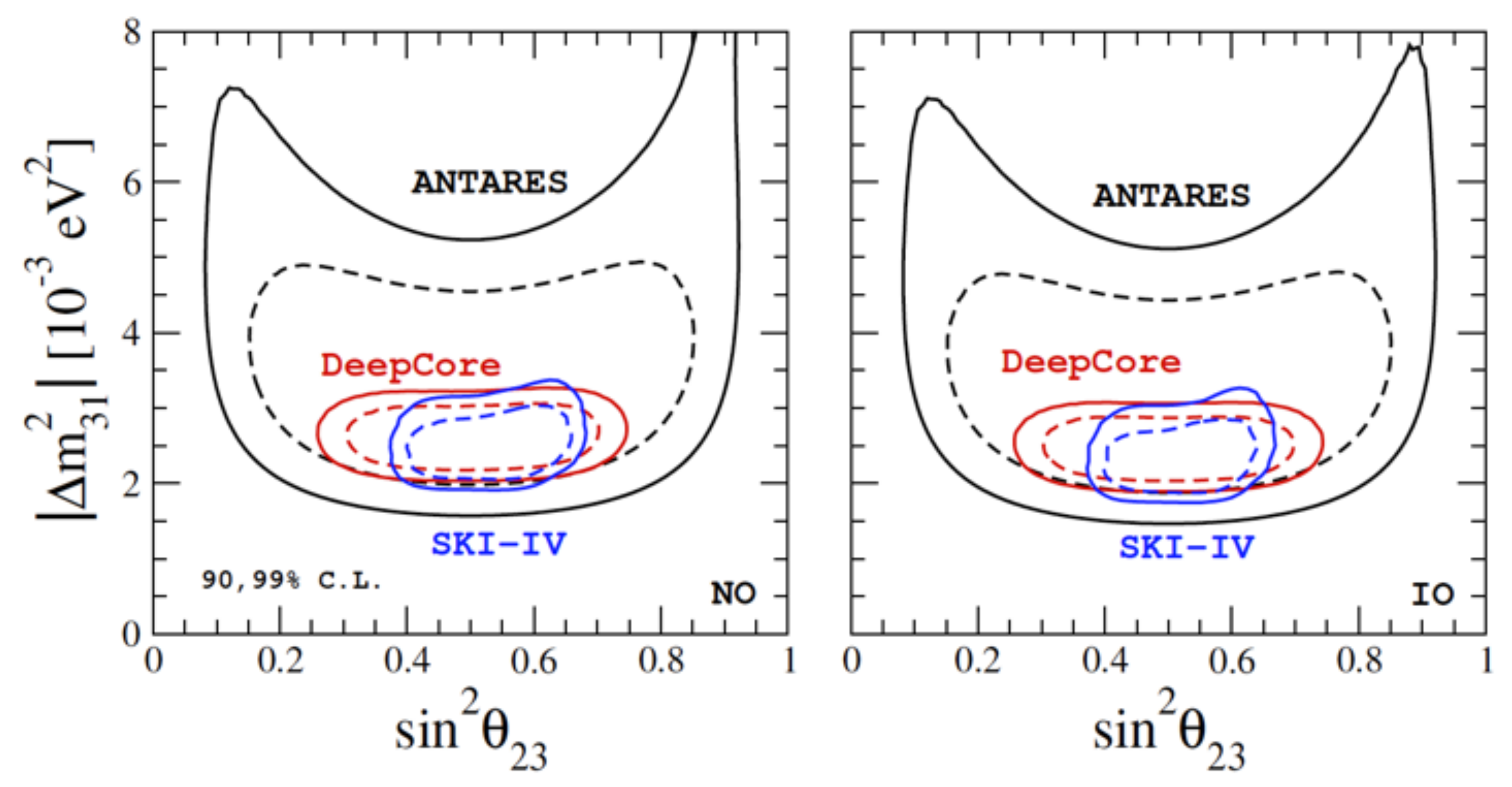
$E_\nu > 20\ \mathrm{GeV}$

Atmospheric neutrino experiments

Super-Kamiokande (phases I to IV) Wendell et al, PRD81 (2010)

IceCube-DeepCore (3 years of data) Aartsen et al, arXiv:1410.7227

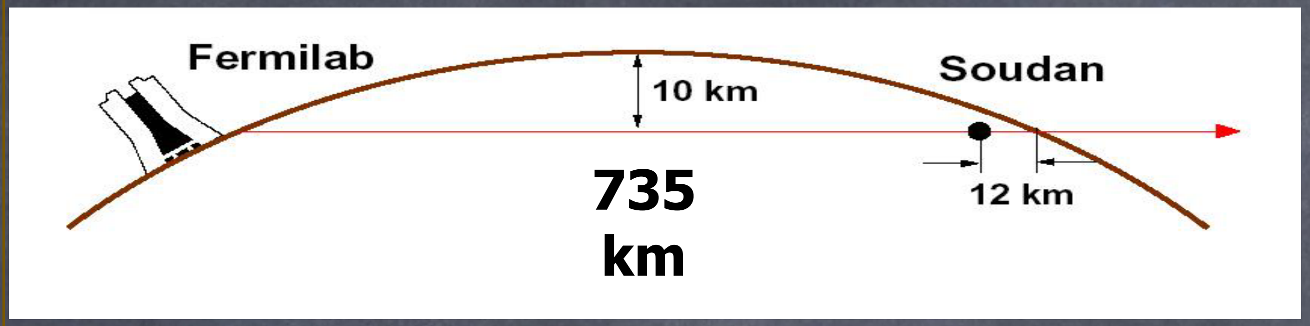
ANTARES (863 days of data) Adrián-Martínez et al, PLB 2012



de Salas et al, arXiv:1708.01186

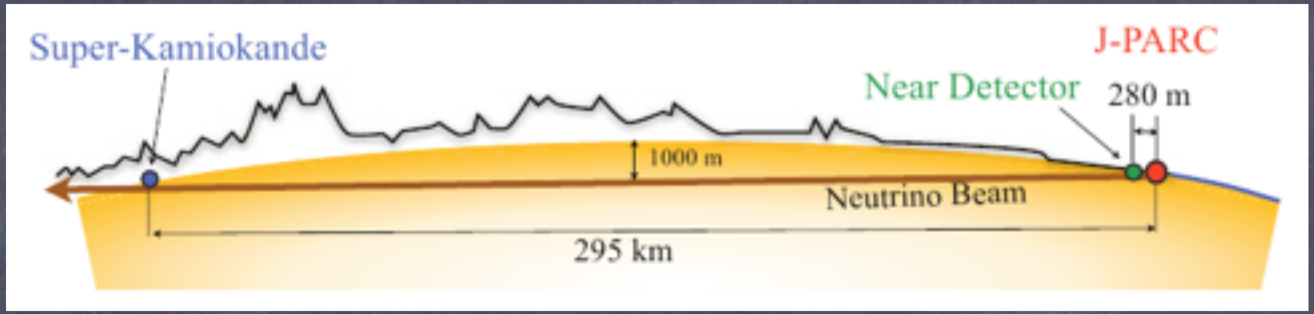
LBL accelerator neutrino experiments

MINOS



Feb2005 - Jun2016

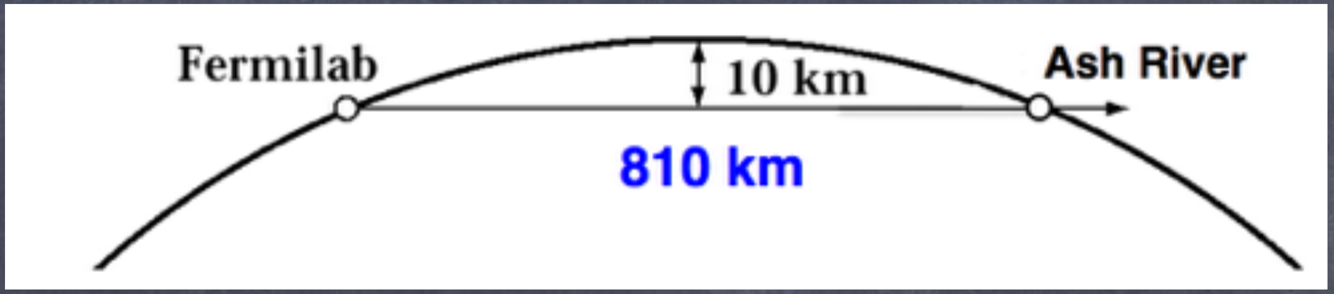
T2K



From Jan2010

running in antineutrino channel

NovA



From Oct2014

running in antineutrino channel

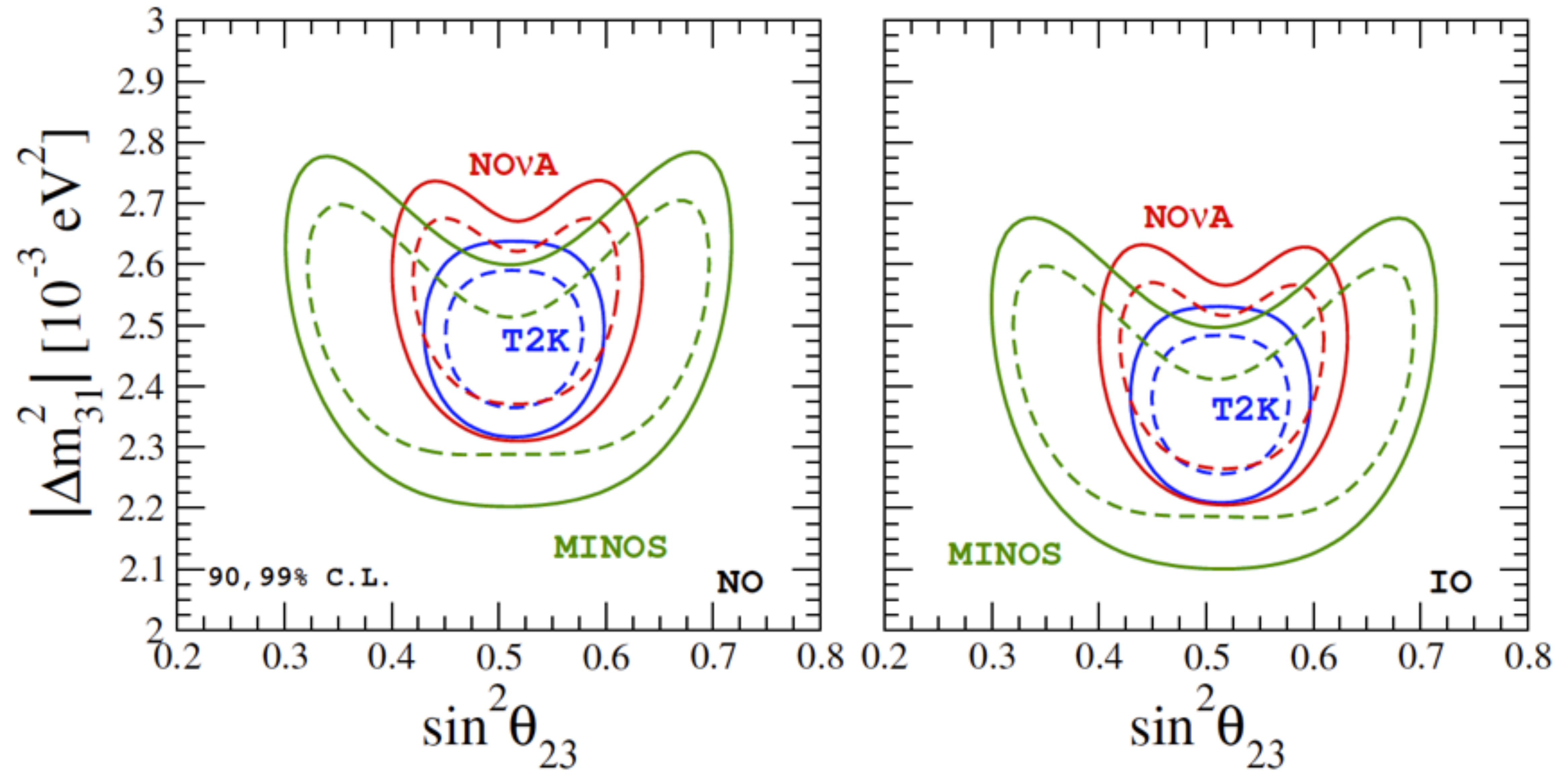
GOAL: observation of ν_μ disappearance, ν_e appearance and spectral distortions expected in the case of neutrino oscillations

→ consistent with atmospheric data

→ atm ν oscillations confirmed by laboratory exps

Accelerator LBL experiments

MINOS + T2K (neutrino + antineutrino)
NOvA (only neutrino data)

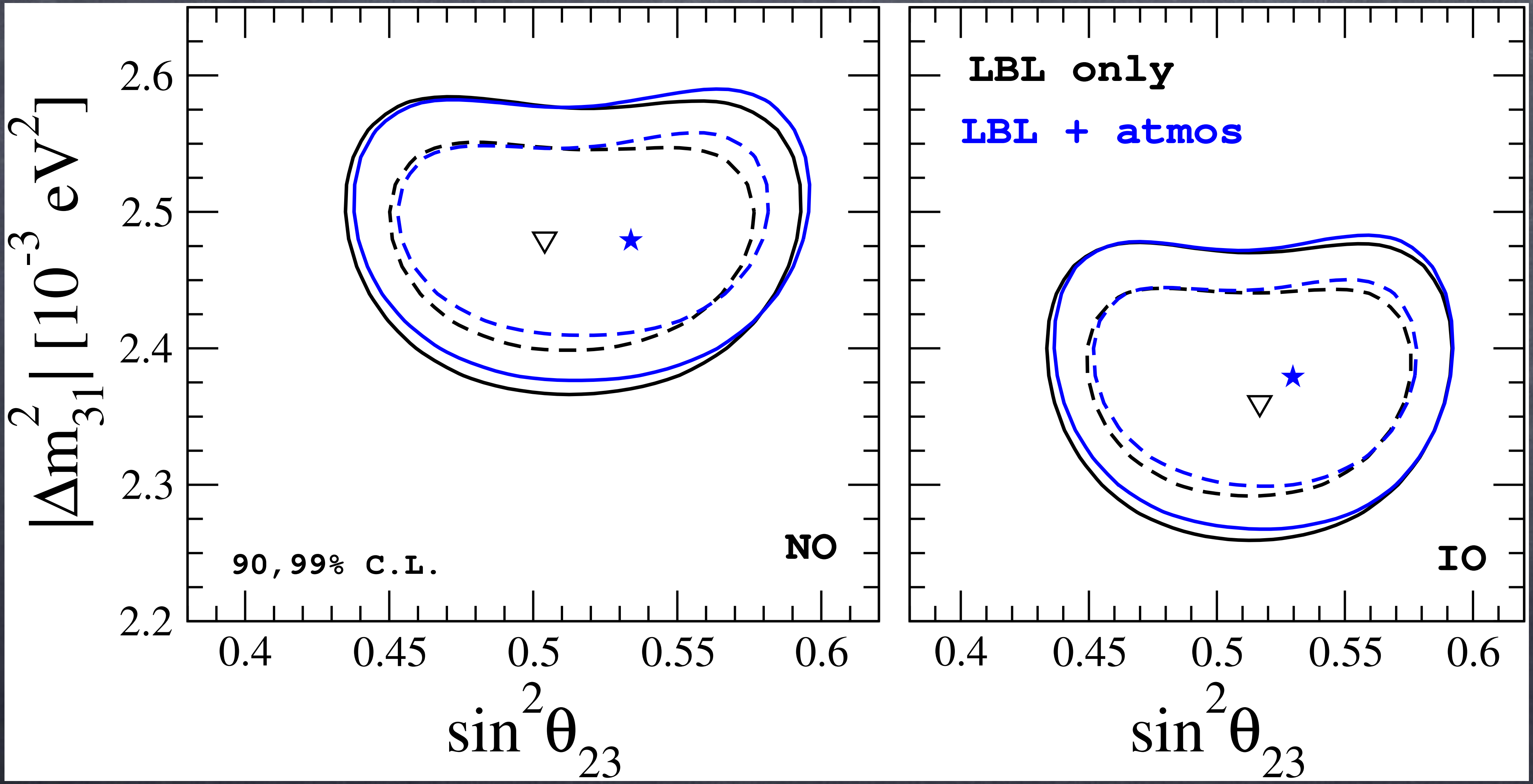


all experiments prefers mixing close to maximal

de Salas et al, arXiv: 1708.01186

Atmospheric parameters

Combined analysis atmospheric + LBL data



atmospheric parameters are mostly constrained by LBL data

de Salas et al, arXiv:1708.01186

The reactor mixing angle θ_{13}

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:

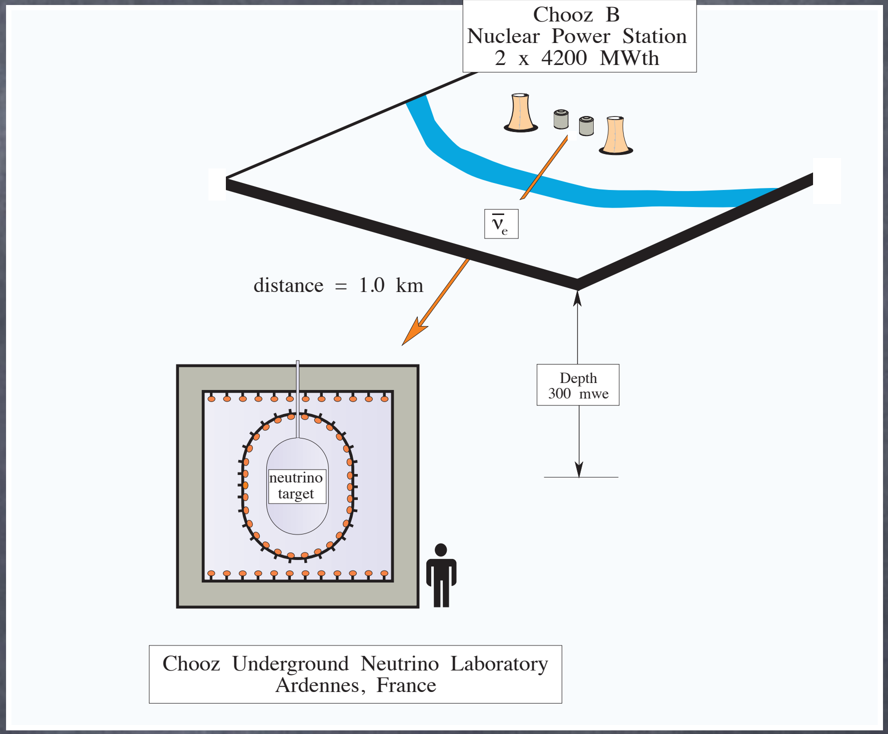
R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

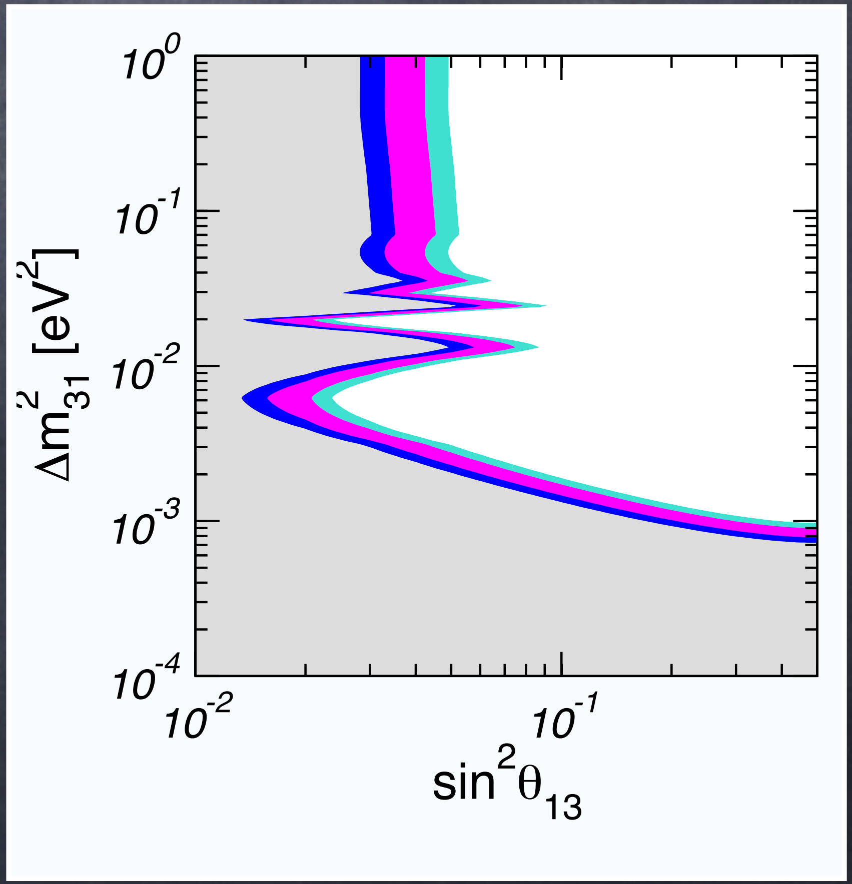
→ Exclusion plot
(Δm^2_{31}, θ_{13}) plane

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

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

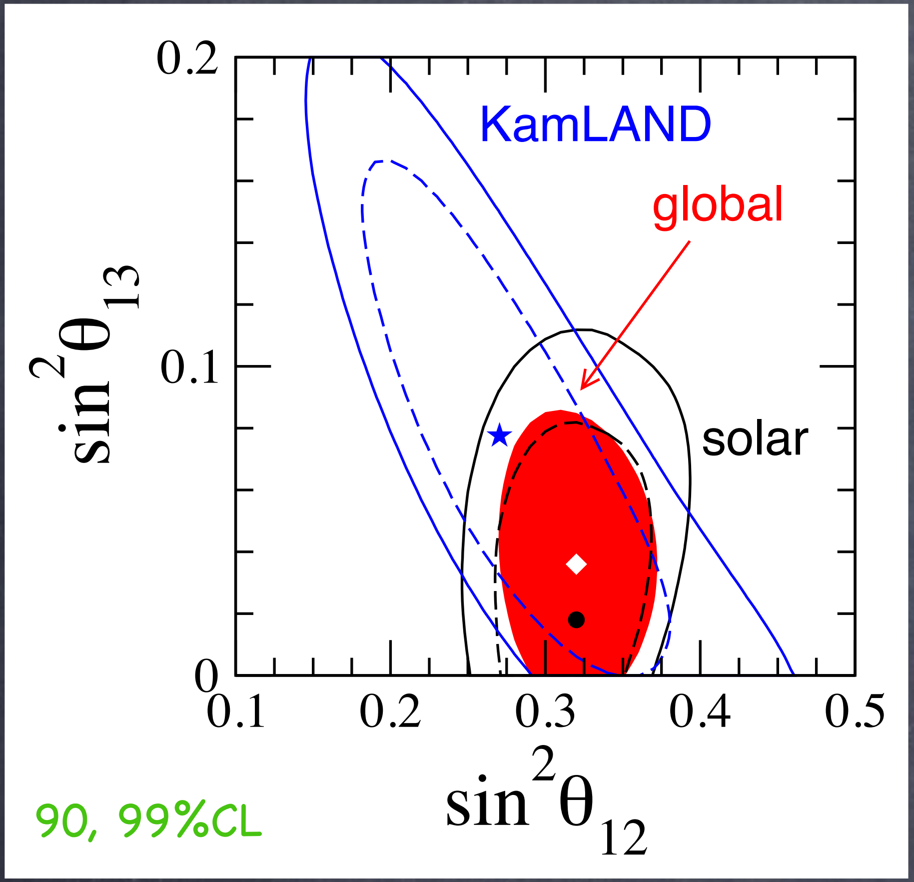
CHOOZ Collaboration, EPJ C27 (2003) 331.





Hints on $\theta_{13} \neq 0$ from combined analysis

solar + KamLAND



90, 99%CL

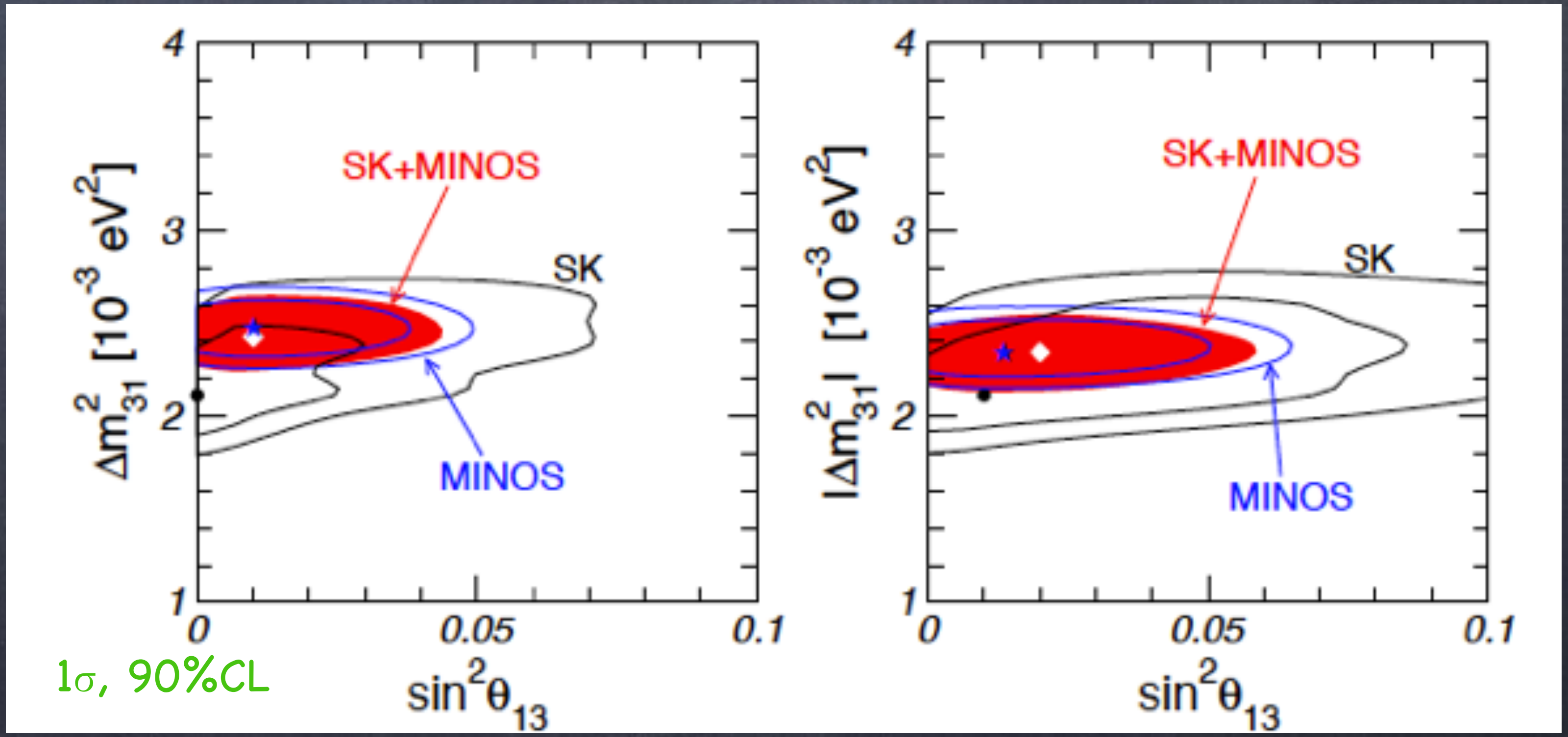
Forero, MT, Valle, 2012

→ the interplay between solar and KamLAND data leads to a non-trivial constraint on θ_{13}:

$$\sin^2\theta_{13} = 0.035 \pm^{0.016}_{0.015} \qquad (1\sigma)$$

atmospheric + LBL

→ a mismatch between BFP for Δm^2 from atm and LBL data results in a prefered non-zero value for θ_{13}



1σ, 90%CL

For IH, $\sin^2\theta_{13} = 0.023 \pm^{0.015}_{0.012} \qquad (1\sigma)$

Schwetz, MT, Valle, NJP 13 (2011) 063004

Searches for ν_e appearance at LBL

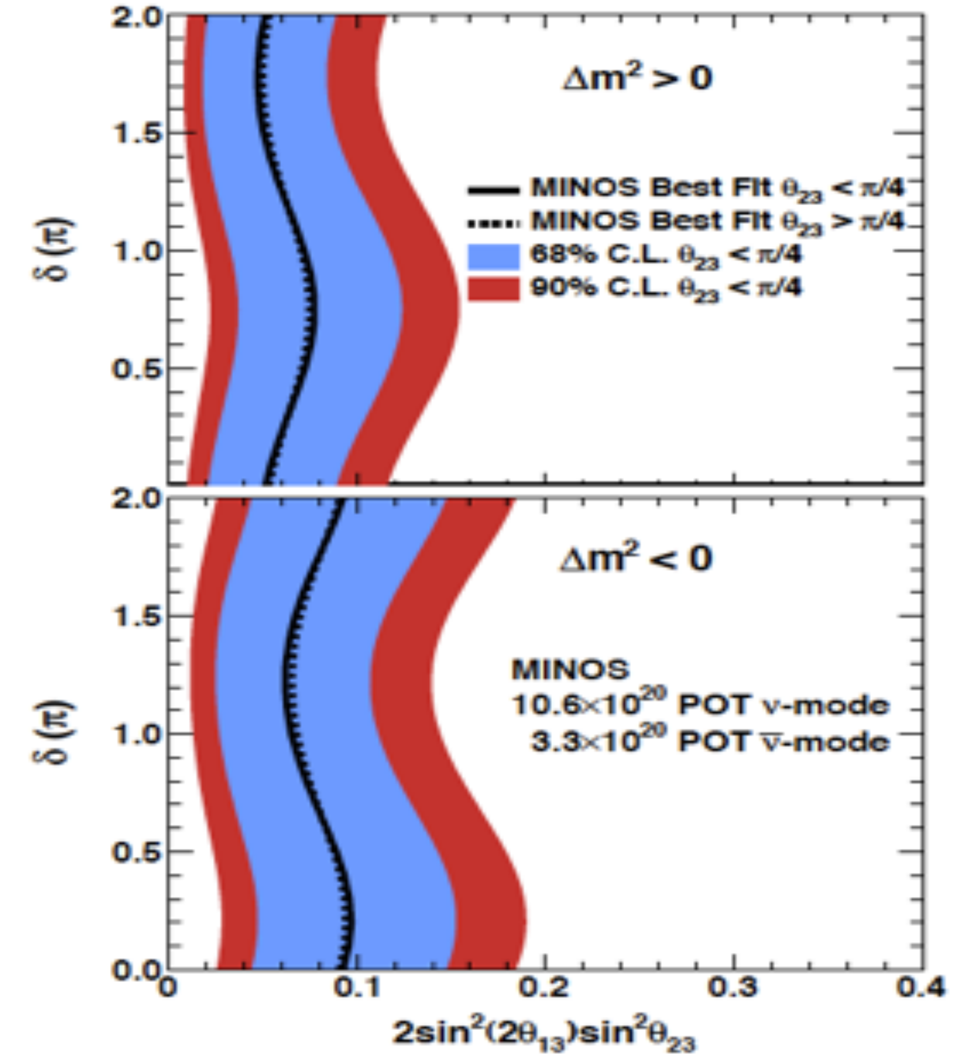
$$P(\nu_\mu \to \nu_e) \cong \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\boxed{\sin\delta_{CP}}$$

MINOS

MINOS Coll., PRL 110 (2013)

ν beam: 152 events observed vs 128.6±32.5

$\bar{\nu}$ beam: 20 events observed vs 17.5±33.7

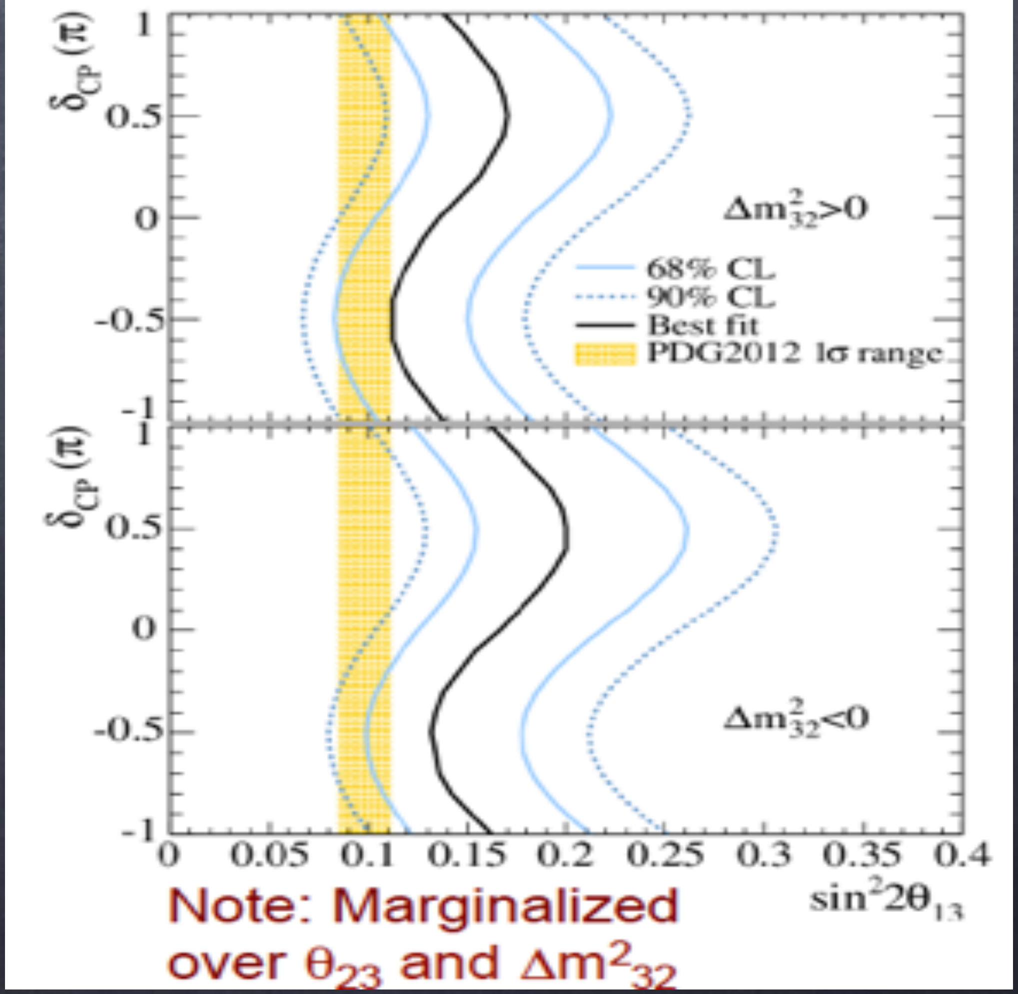


T2K

T2K Coll., PRL 112 (2014)

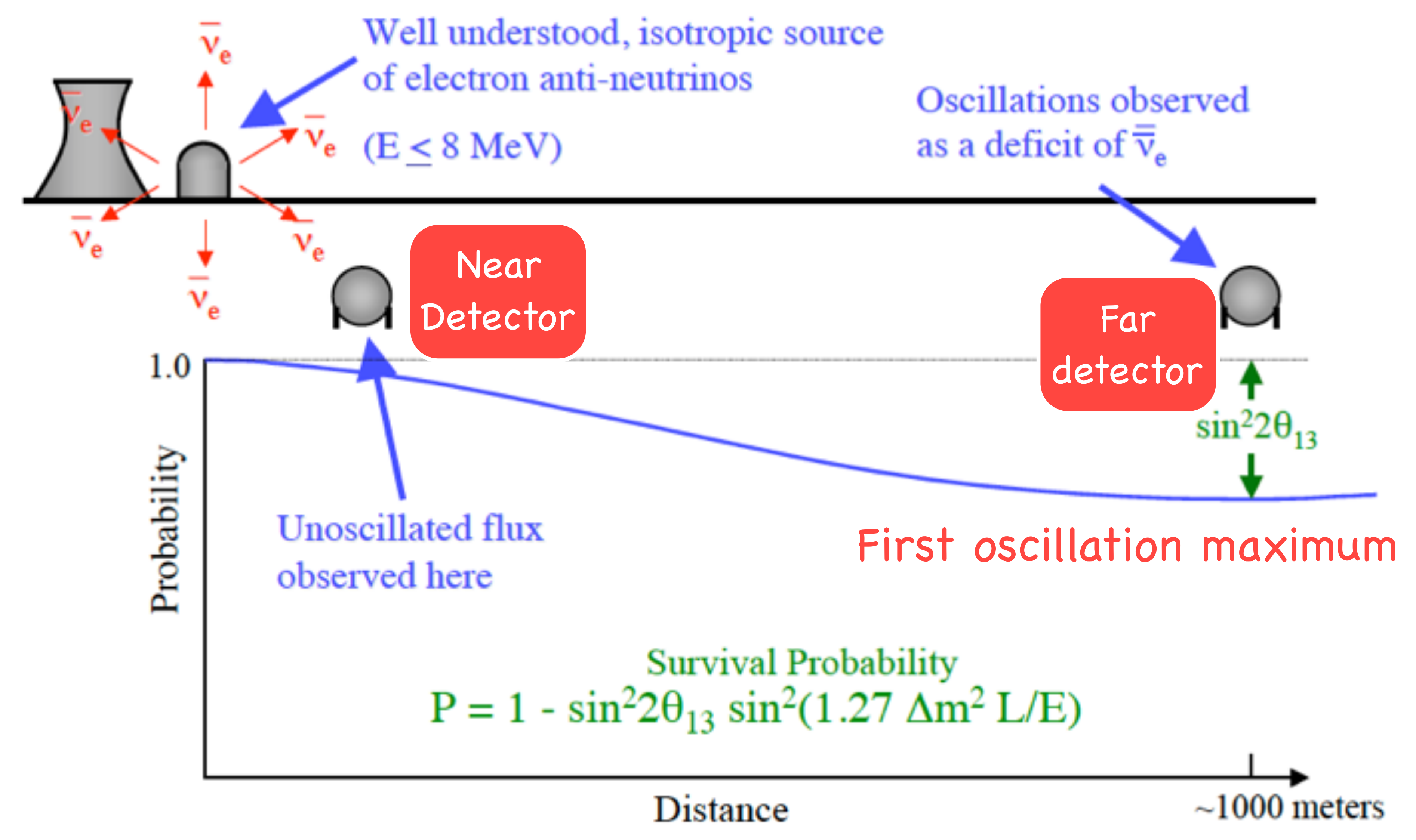
- 28 ν_e events observed
- 4.92±0.55 expected w/o oscillations

→ ν_e appearance confirmed at 7.3σ



Note: Marginalized over θ_{23} and Δm^2_{32}

New generation of reactor experiments



- more powerful reactors (multi-core)
- larger detector volume
- 2-6 detectors at 100 m - 1 km.

Three on-going reactor experiments

Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Designed Sensitivity (90%CL)
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~ 0.008
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~ 0.03
Reno	16.5	409/1444	16/16	120/450	~ 0.02

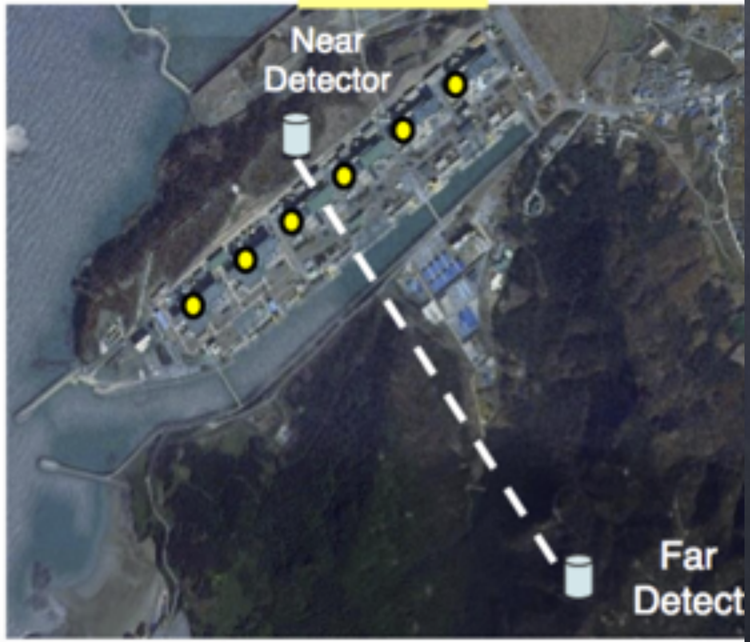
Daya Bay

6 cores + 4 ND + 4FD

Double Chooz

2 cores + 1 ND + 1 FD

Reno

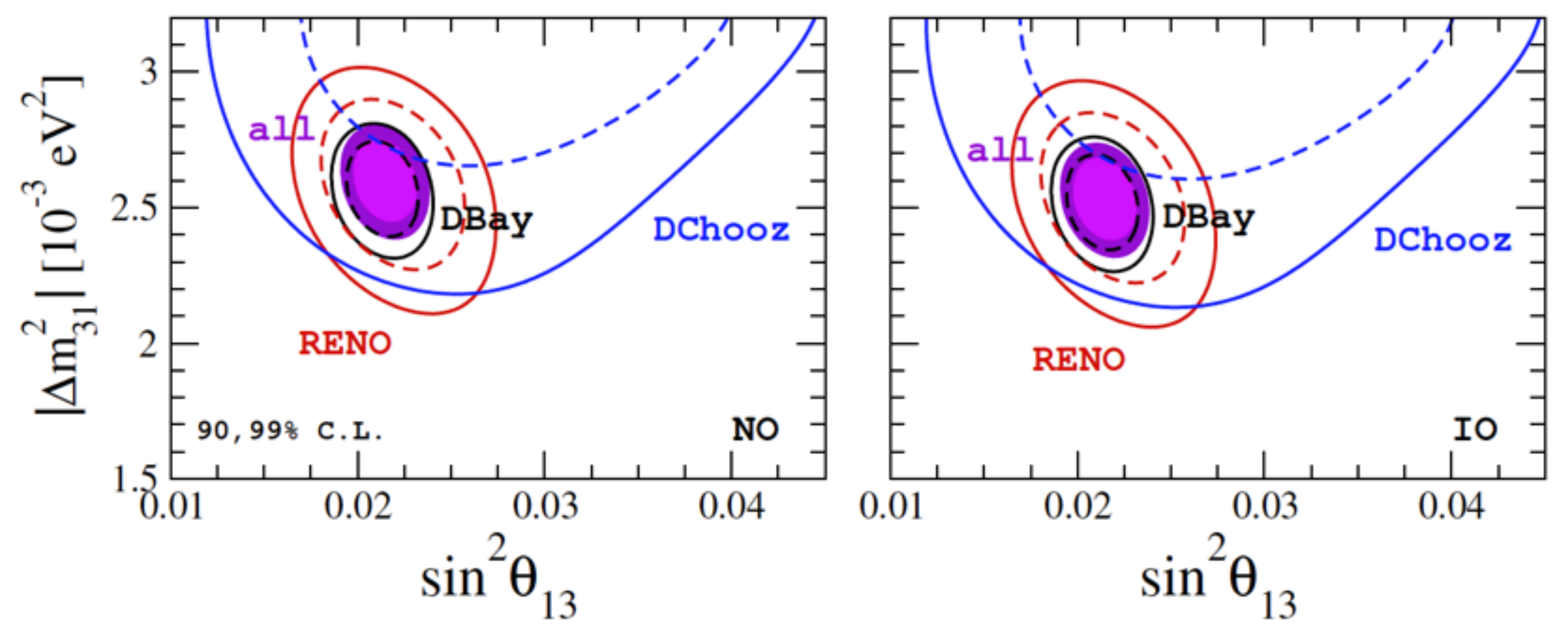


6 cores + 1 ND + 1 FD

Reactor sector

Daya Bay + RENO + Double Chooz

de Salas et al, arXiv:1708.01186

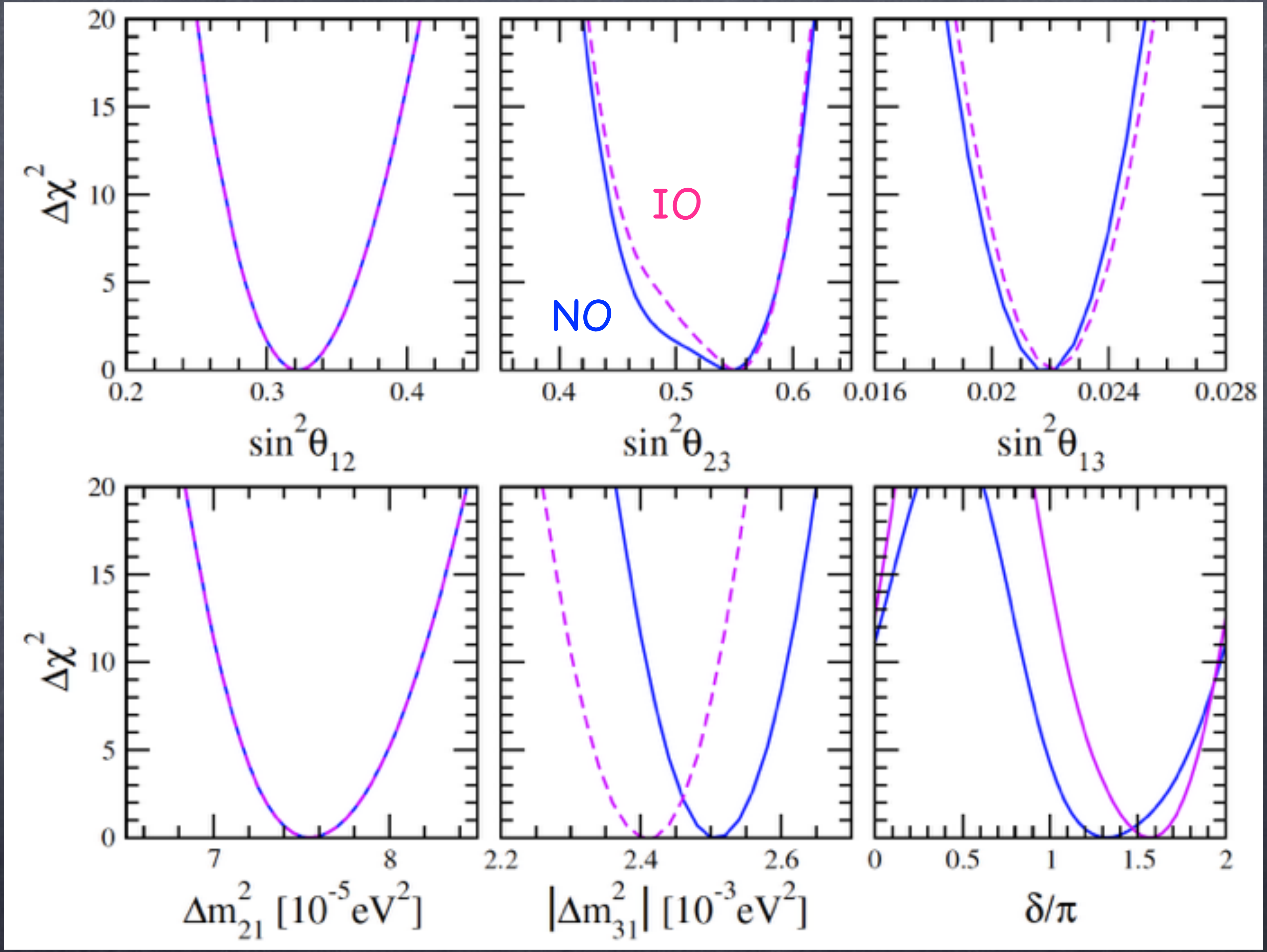


Precision dominated by Daya Bay

Updated global fit summary

de Salas et al, arXiv:1708.01186

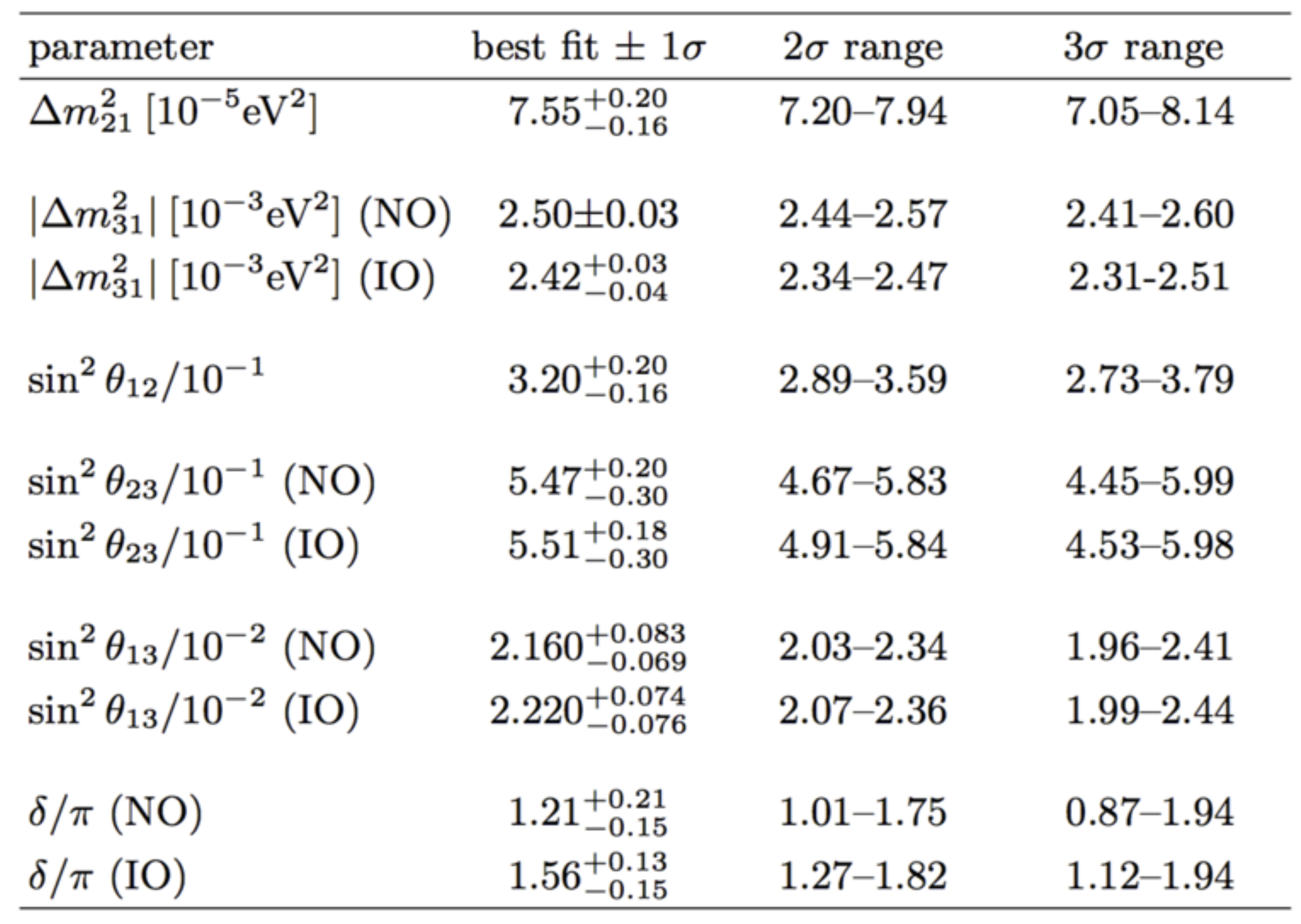
(to be uploaded)



- preference for Normal Ordering with $\Delta\chi^2$ (IO-NO) ≈ 11.7 (7.7 wo SK)

➡ Inverted Ordering disfavoured at 3.4σ (2.8σ wo SK)

Updated global fit summary



parameter	best fit ± 1σ	2σ range	3σ range	relative 1σ
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50±0.03	2.44–2.57	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44	
δ/π (NO)	$1.21^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94	15%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94	8.7%

!!!

**IO ranges: calculated wrt local minimum

de Salas et al, arXiv: 1708.01186

Neutrino oscillations beyond 3 flavours: sterile neutrinos

How many neutrinos?

- according to LEP measurements of invisible Z decay width:

→ $N_\nu = 2.984 \pm 0.008$ (light, active neutrinos)

Experimental hints for a 4th sterile neutrino:

- LSND signal for $\overline{\nu}_\mu \to \overline{\nu_e}$ oscillations with E/L ~ 1 eV^2
- MiniBooNE searches for $\overline{\nu}_\mu \to \overline{\nu_e}$ and $\nu_\mu \to \nu_e$ at similar E/L
- Reactor antineutrino anomaly: very short baseline $\overline{\nu_e}$ disappearance indicated by the reevaluated reactor neutrino fluxes
- Gallium anomaly: ν_e disappearance during calibration of Gallium solar experiments with radioactive sources (L ~ 1 m)

What is a sterile neutrino?

- sterile neutrino = singlet fermion of the Standard Model

→ it has no interactions (exceptions: Higgs, mixing and physics BSM)

Motivations: sterile neutrinos can explain...

- neutrino oscillation anomalies ($m \sim$ eV)
- small neutrino masses (seesaw mechanism, $m >$ TeV-M_{Pl})
- baryon asymmetry of the universe (leptogenesis, $m \gg 1$ GeV)
- (part of) the dark matter of the universe ($m \sim$ keV)

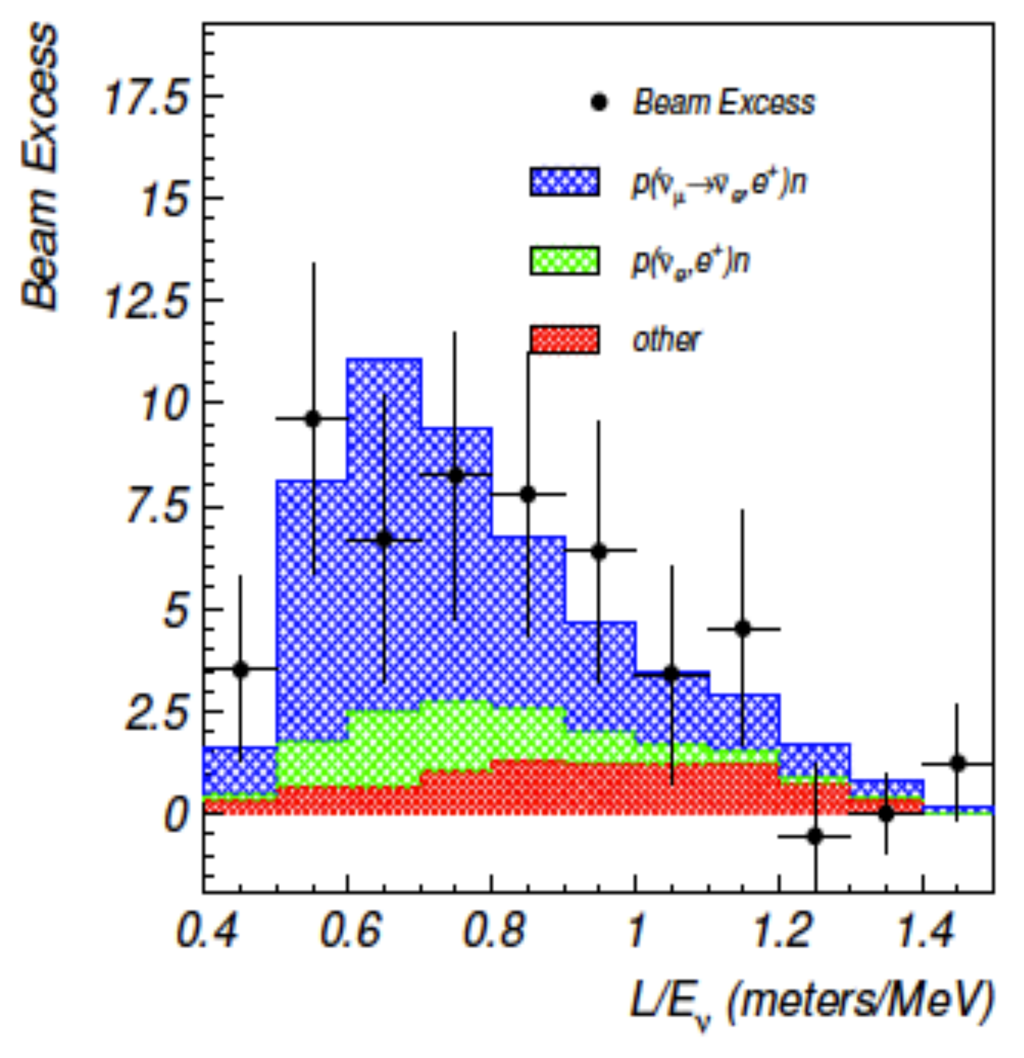
Hints for $\nu_\mu \longrightarrow \nu_e$ appearance

The LSND experiment

- Evidence for $\overline{\nu}_{\mu} \rightarrow \overline{\nu_e}$ oscillations

- Excess of ν_e events:

  87.9 ± 22.4 ± 6.0 (3.8σ)



L ~ 30m, E ~ 20-75 MeV

LSND Collab., PRD 64 (2001) 112007

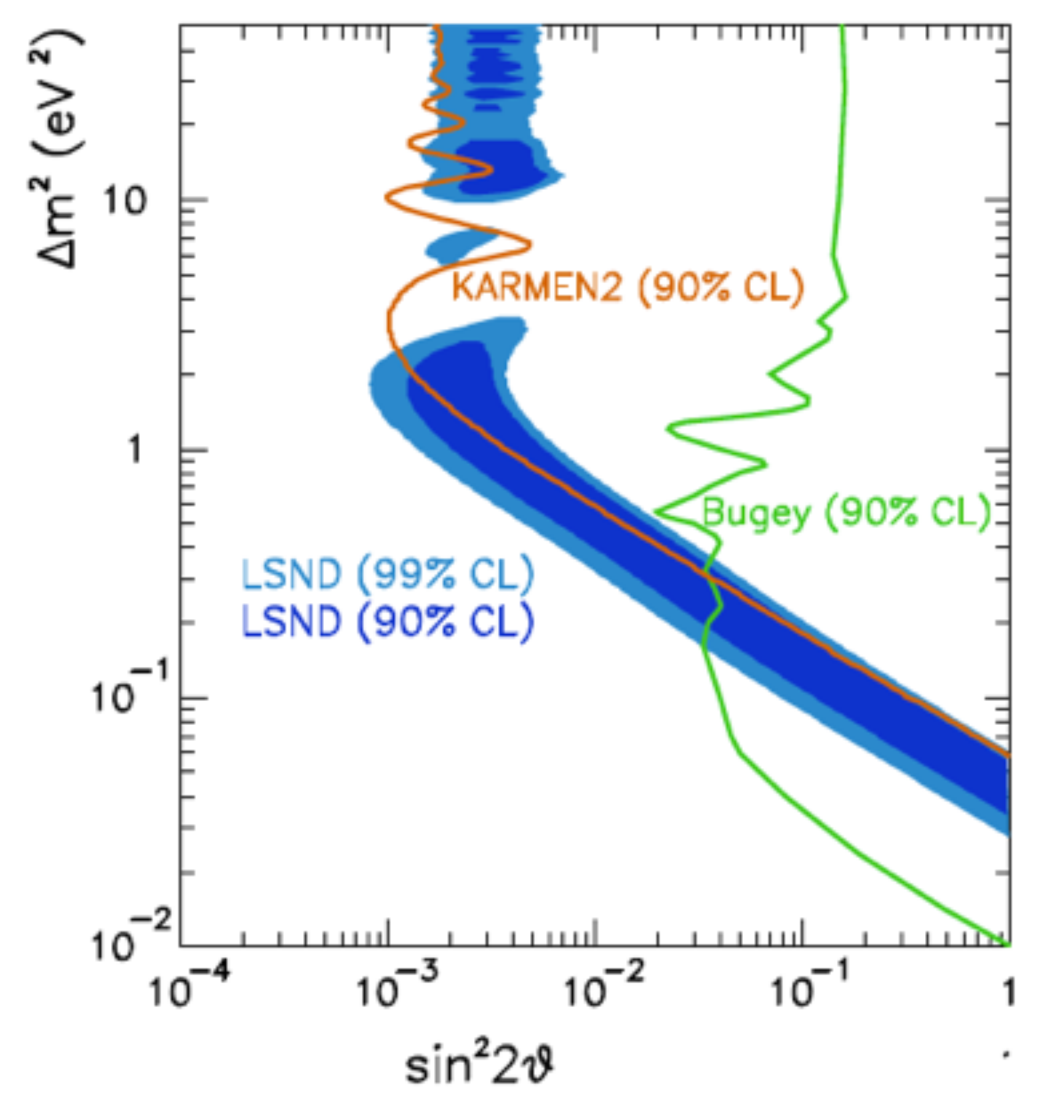
The LSND experiment

- Evidence for $\overline{\nu}_\mu \to \overline{\nu_e}$ oscillations

- Excess of ν_e events:
  $87.9 \pm 22.4 \pm 6.0\ (3.8\sigma)$

- Part of the allowed region excluded by other experiments.

- $\Delta m^2_{\mathrm{LSND}} \sim 0.2\text{–}10\ \mathrm{eV}^2$



L ~ 30m, E ~ 20-75 MeV

LSND Collab., PRD 64 (2001) 112007

The LSND experiment

- Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu_e}$ oscillations

- Excess of ν_e events:

  87.9 ± 22.4 ± 6.0 (3.8σ)

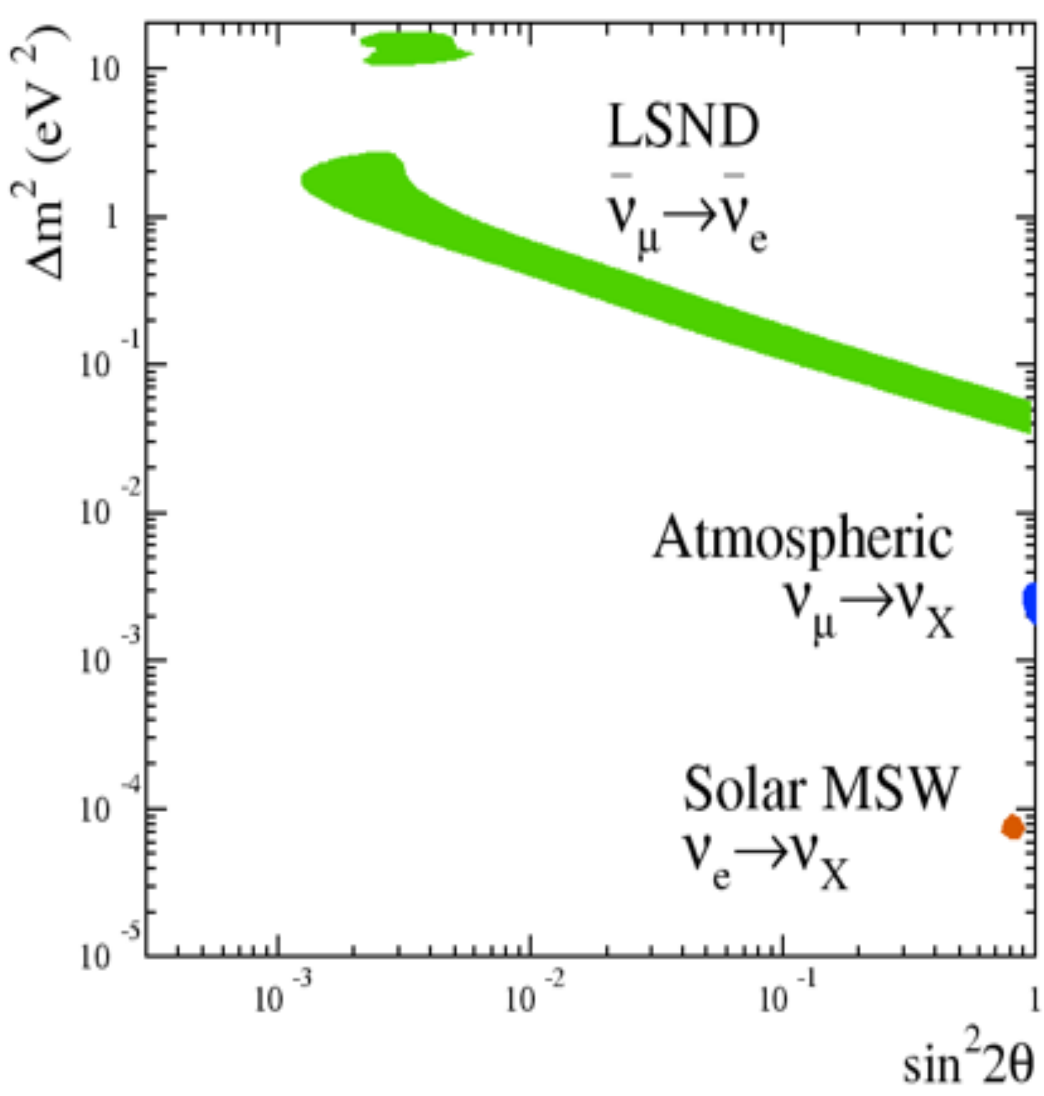
- Part of the allowed region excluded by other experiments.

- $\Delta m^2_{LSND} \sim 0.2\text{–}10\ eV^2$

  $\rightarrow \Delta m^2_{LSND} \neq \Delta m^2_{SOL},\ \Delta m^2_{ATM}$

  $\rightarrow \Delta m^2_{LSND} \neq \Delta m^2_{SOL} + \Delta m^2_{ATM}$

$\Rightarrow$ 4th sterile neutrino required !!

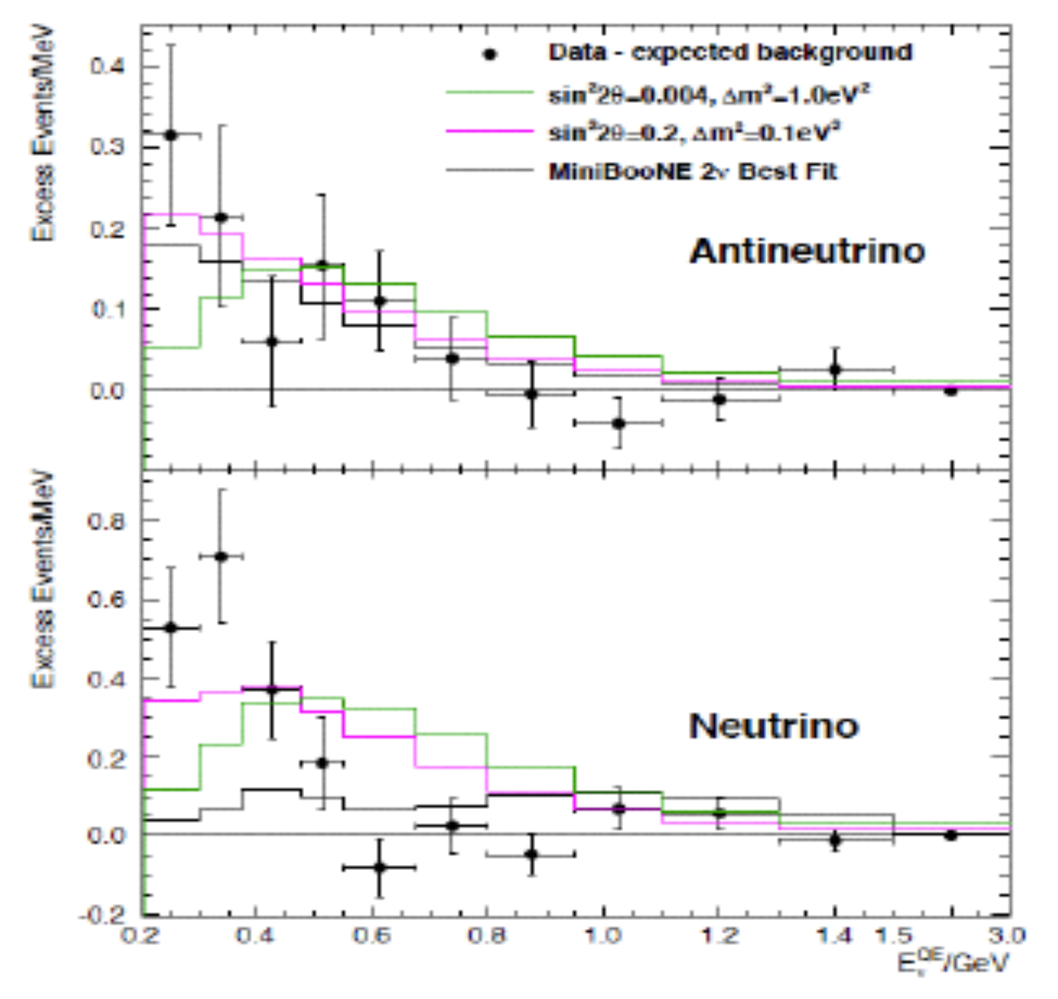


L ~ 30m, E ~ 20-75 MeV

LSND Collab., PRD 64 (2001) 112007

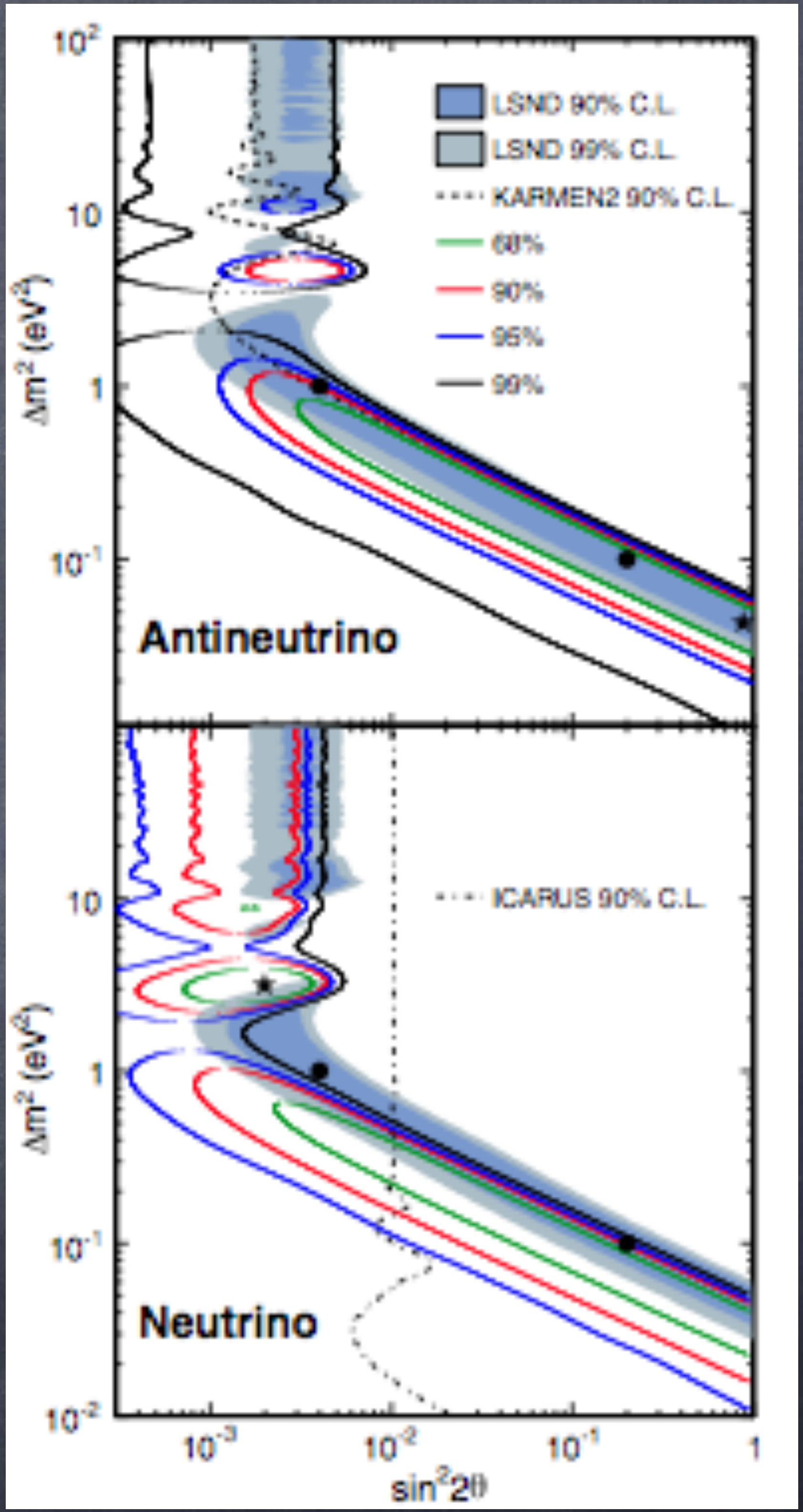
The MiniBooNE experiment

- Designed to test the LSND signal
- Runs in neutrino and antineutrino mode
- Observed excess:
  - ⇒ neutrino: 162 ± 47.8 (3.4σ)
  - ⇒ antineutrino: 78.4 ± 28.5 (2.8σ)



consistent with oscillations

marginal agreement with oscillations



MiniBooNE Collab., PRL 110 (2013) 161801

Global analysis of ν_e appearance data

- Global analysis using all data from ν_e appearance searches:

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E}, \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

-LSND

-MiniBooNE: neutrino + antineutrino

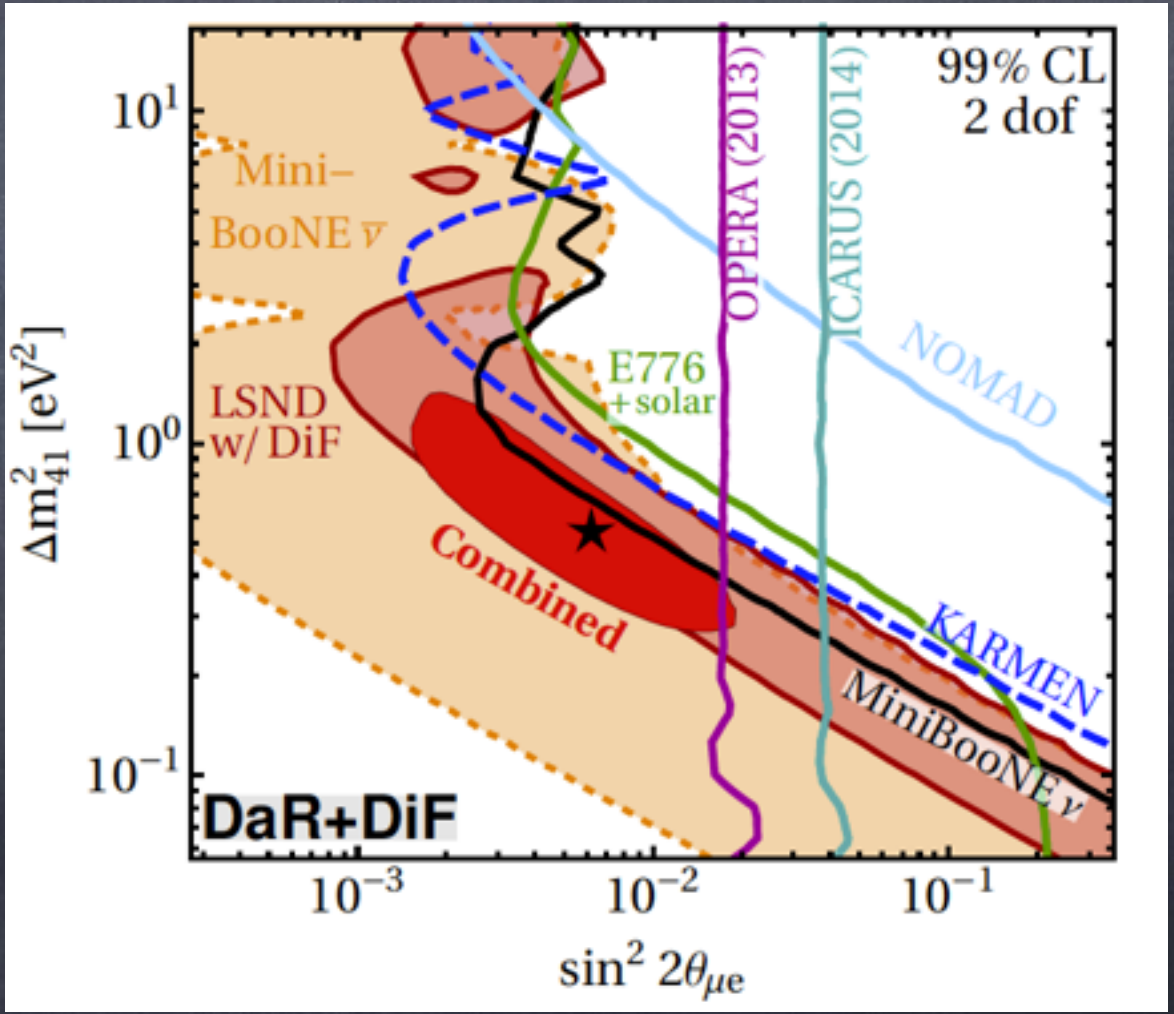
-KARMEN

-NOMAD

-ICARUS

-OPERA

no signal observed



Dentler et al, arXiv:1803.10661

→ Poor GOF, since MiniBooNE low-E excess can not be fitted in the 3+1 scenario

Hints for ν_e disappearance

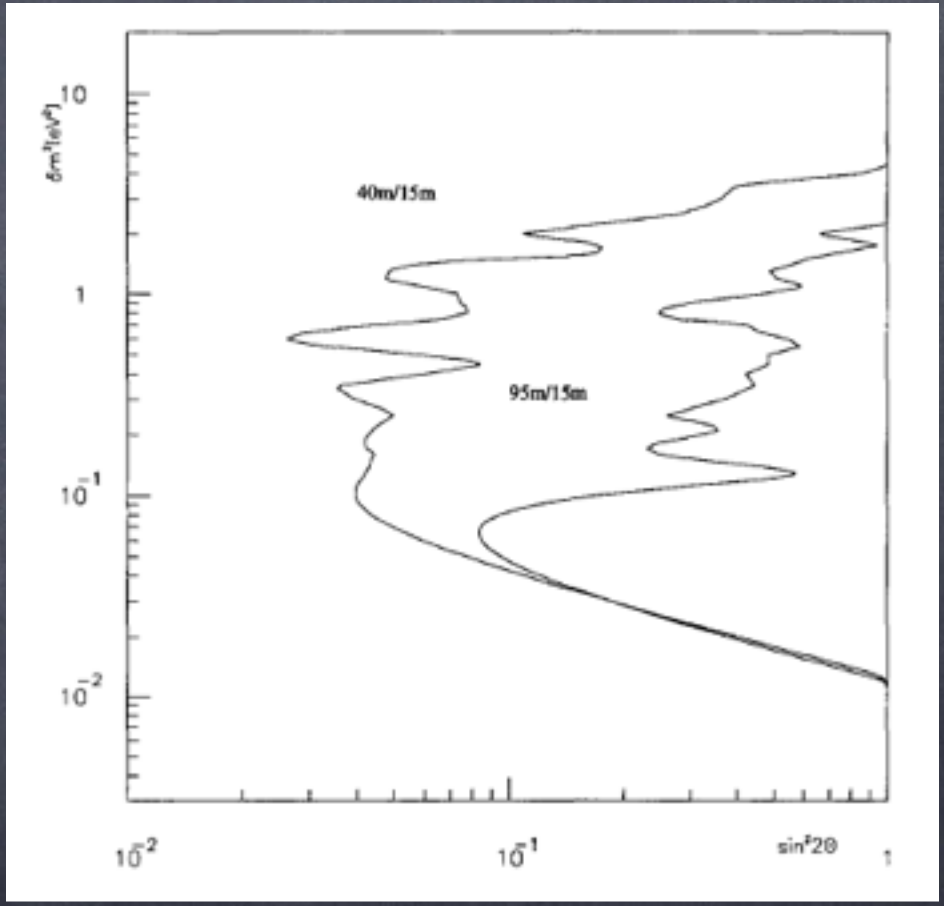
ν_e disappearance in reactor experiments

- Historically, very-short-baseline reactor neutrino experiments (10-100 m) have not observed any disappearance of reactor neutrinos.

Ex: Bugey experiment

- search for reactor ν disappearance at L = 15, 40, 95 m

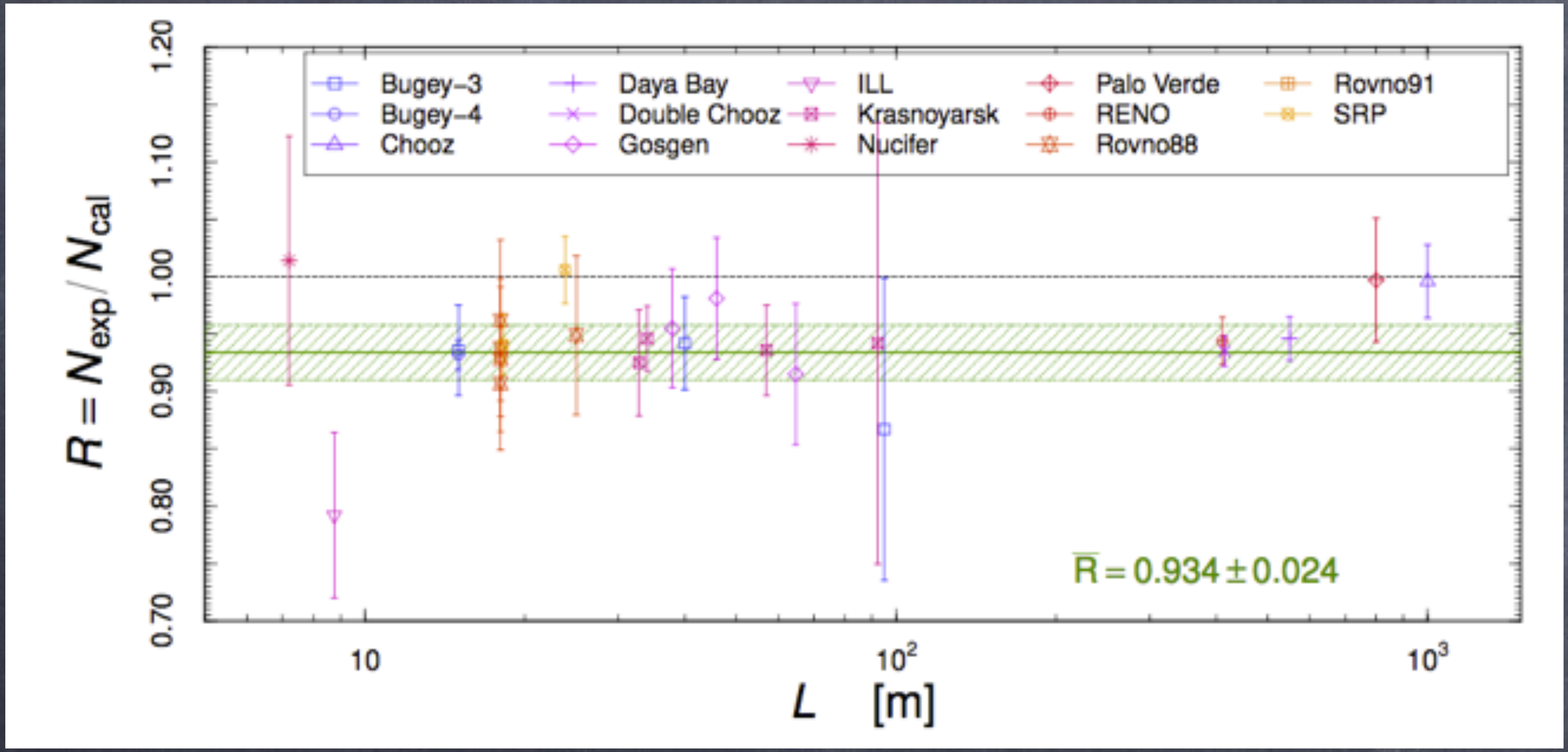
- results in agreement with theoretical fluxes: disappearance not observed



- However, recent (2011) theoretical re-evaluations of the produced neutrino flux at reactors result in higher fluxes, motivating a re-analysis of the reactor data.

The reactor antineutrino anomaly

- improved calculations of antineutrino fluxes report ~ 3% increase
  - Mueller et al, arXiv:1101.2663, Huber, arXiv 1106.0687



Gariazzo et al,
JHEP 2017

⇒ SBL reactor experiments show a deficit in the number of neutrinos detected: R = 0.927 ± 0.023 (3σ effect)

- can sterile neutrinos with $\Delta m^2 \sim 1$ eV^2 explain this anomaly ?

The Gallium anomaly

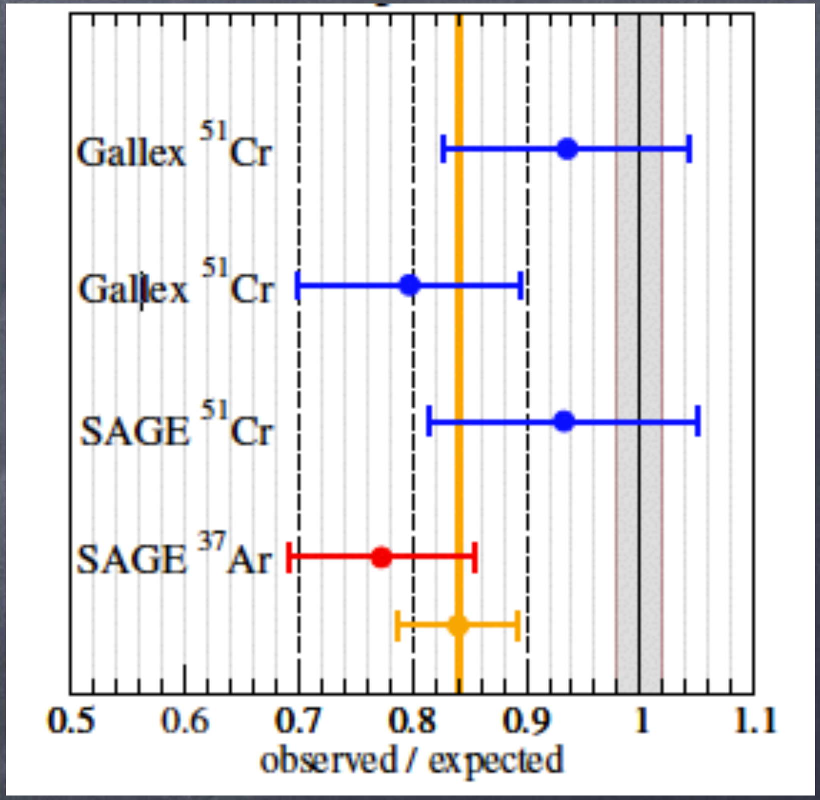
- Calibration of Gallium solar experiments GALLEX and SAGE with intense radioactive ν_e sources ^{51}Cr and ^{37}Ar in the process:

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

→ a reduction in the number of ν_e is observed

→ averaged deficit of ν_e:

R = 0.84 ± 0.05 (2.9σ)



- L ~ 1-2 m, E ~ 0.4-0.8 MeV

⇒ L/E similar to reactor anomaly

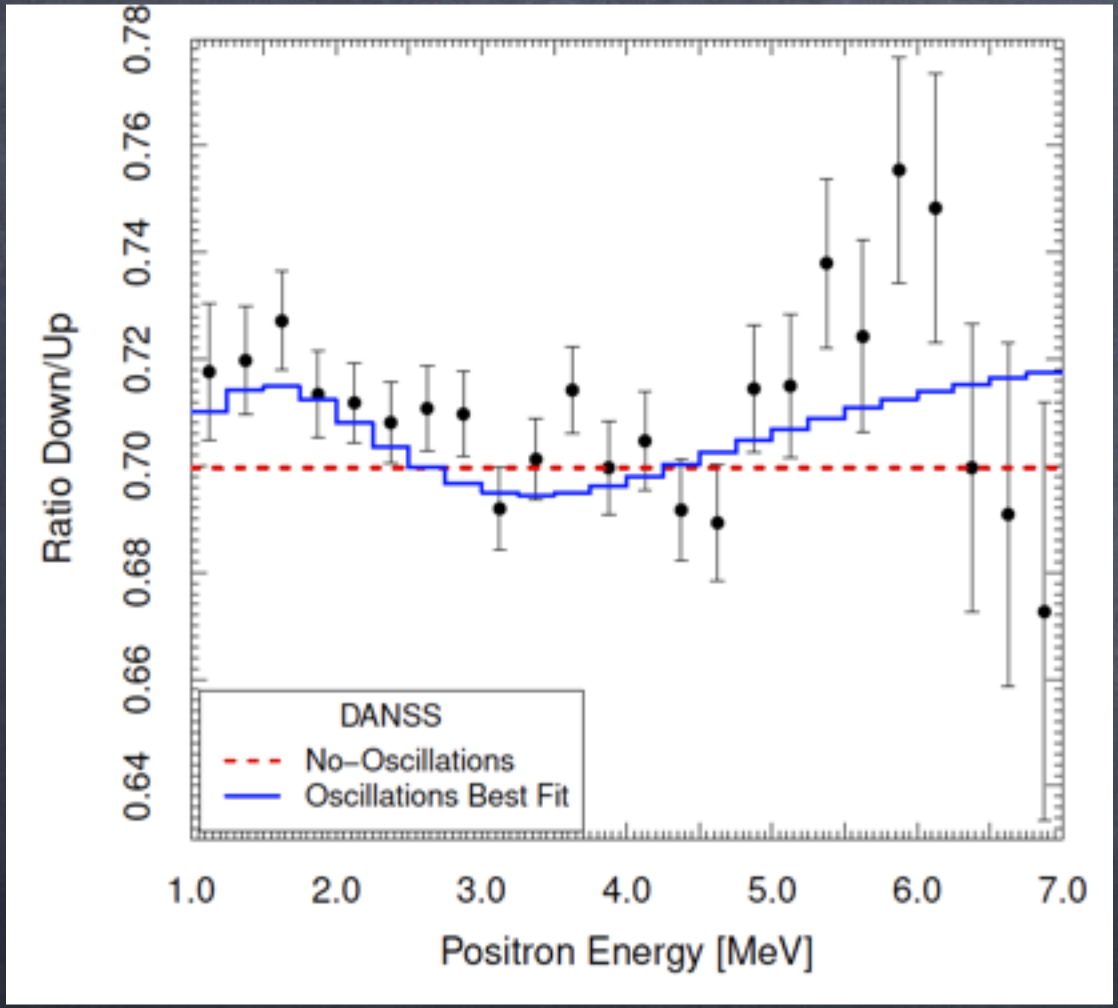
- oscillations with $\Delta m^2 \sim 1$ eV^2 can lead to reduction of the ν_e flux in the detector volume

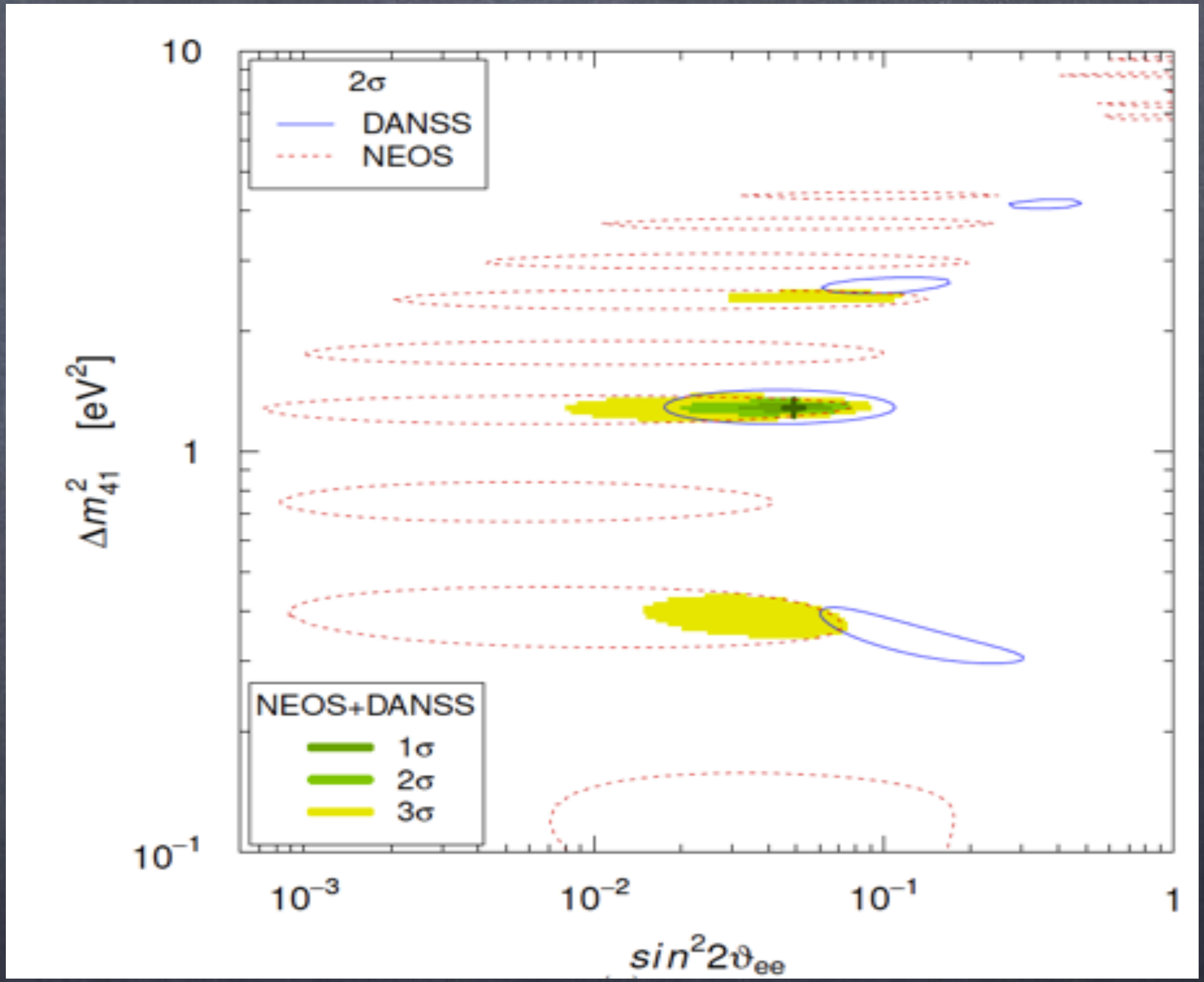
Recent indications: NEOS and DANNS

Observation of ratios of reactor antineutrino spectra at two baselines

Gariazzo et al, arxiv:0801.06467

10.7 m
vs
12.7 m





⇒ 3σ evidence of SBL ν_e oscillations based on comparisons of measured spectra at different baselines, independent of flux predictions.

Analysis of ν_e disappearance data

Dentler et al, arXiv:1803.10661

Global analysis using all data from ν_e disappearance searches:

-SBL reactor and gallium anomalies

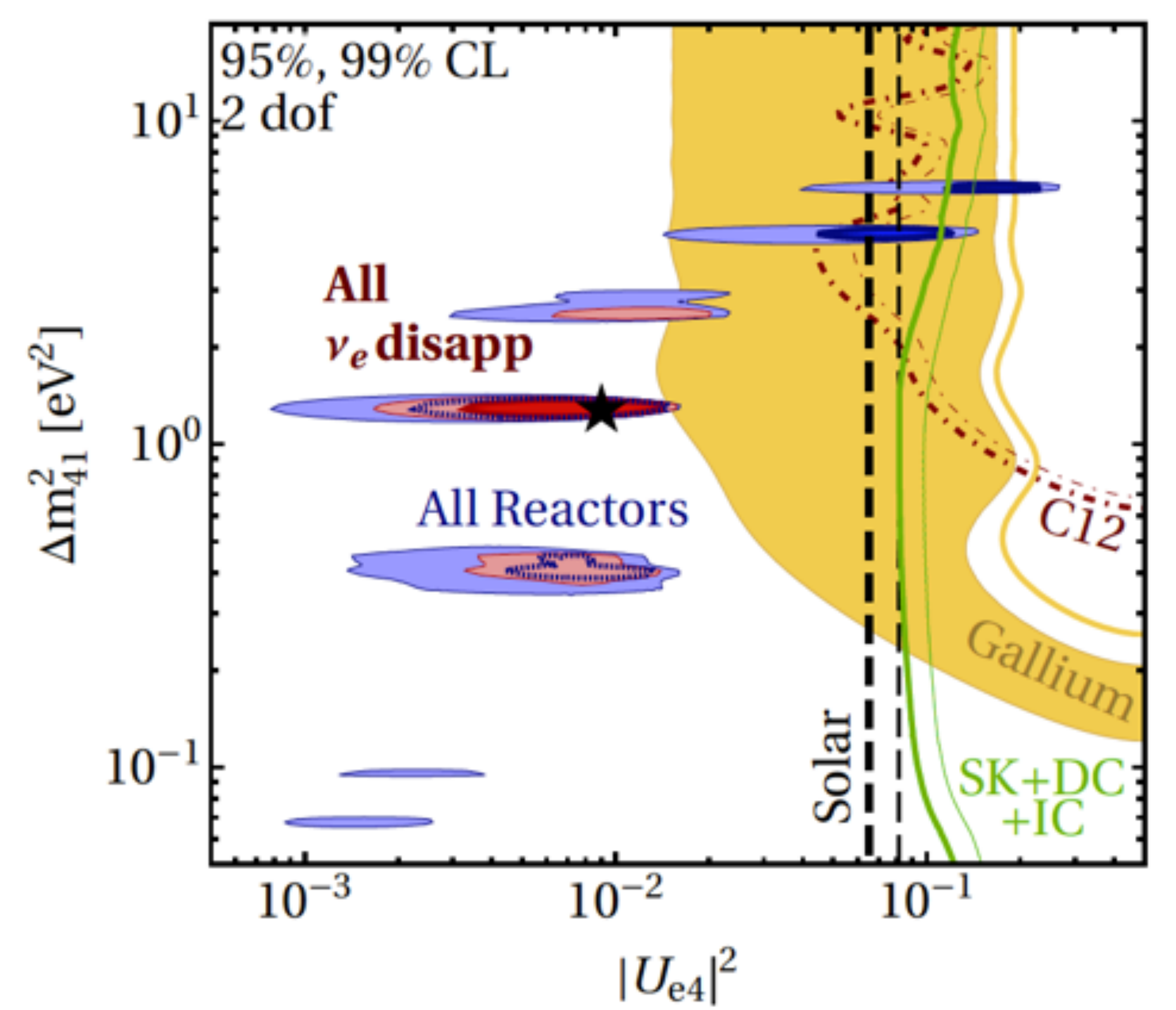
-Daya Bay FD & ND

-KamLAND (180 km)

-LSND and KARMEN ($\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$)

-recent DANNS and NEOS

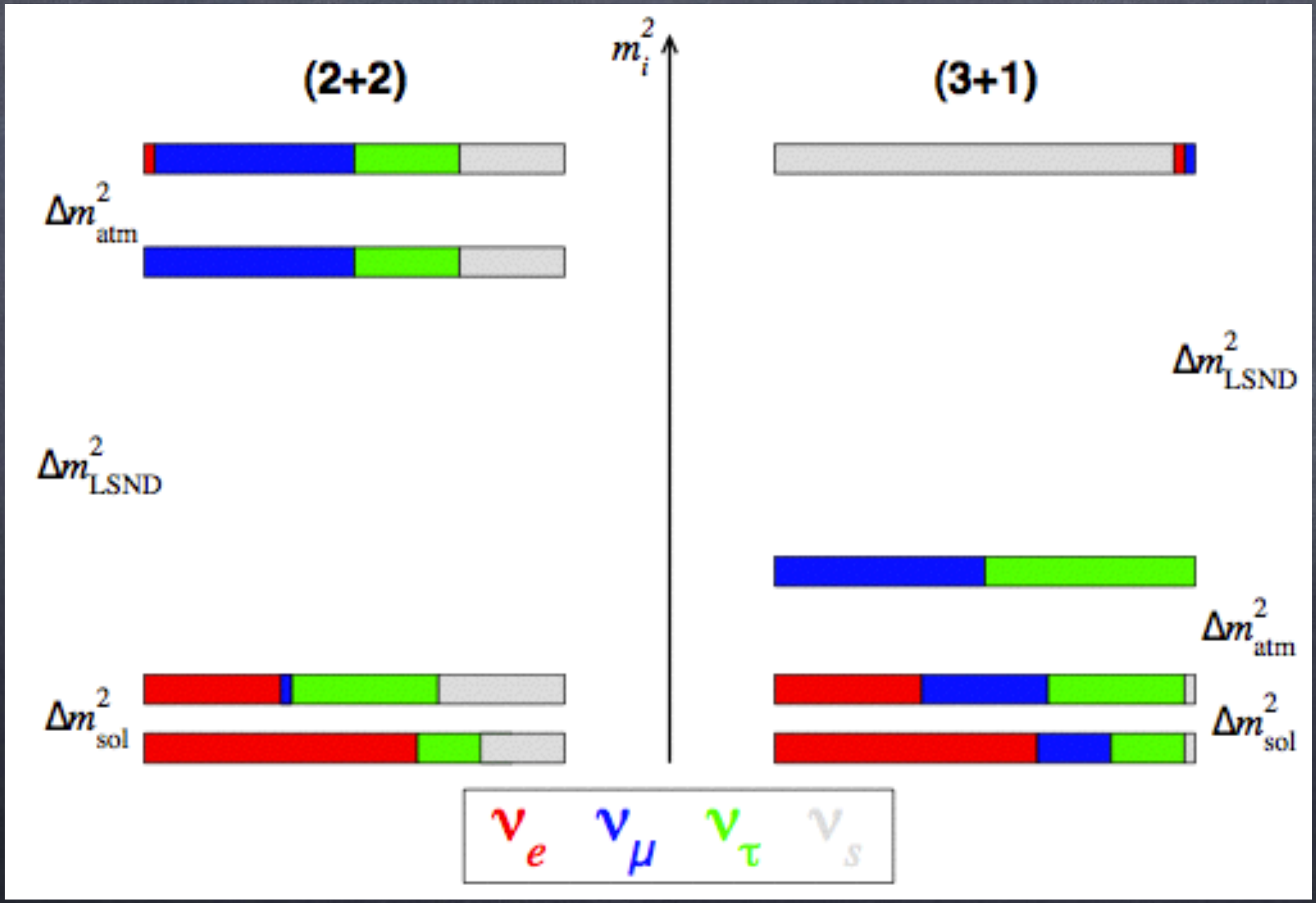
-(θ_{13}-θ_{14}) degeneracy in solar neutrinos



Best fit: $\Delta m^2_{41} = 1.3$ eV^2

Interpretation of the anomalies

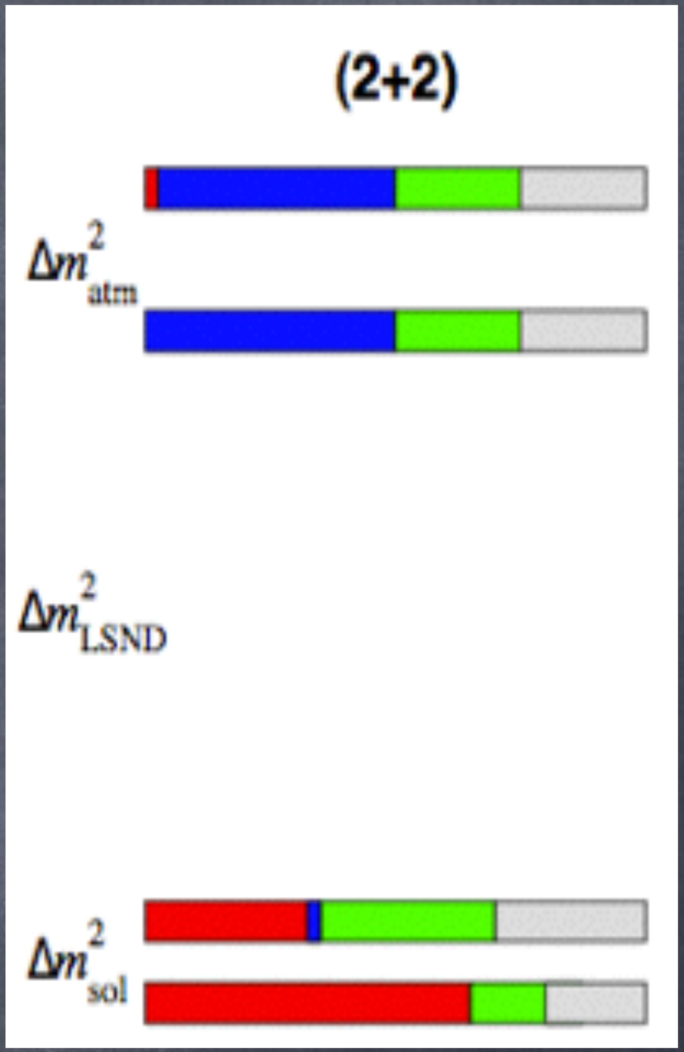
$\Delta m^2_{sol} \sim 8\times10^{-5}\ eV^2$ $\Delta m^2_{atm} \sim 2\times10^{-3}\ eV^2$ $\Delta m^2_{LSND} \sim 1\ eV^2$

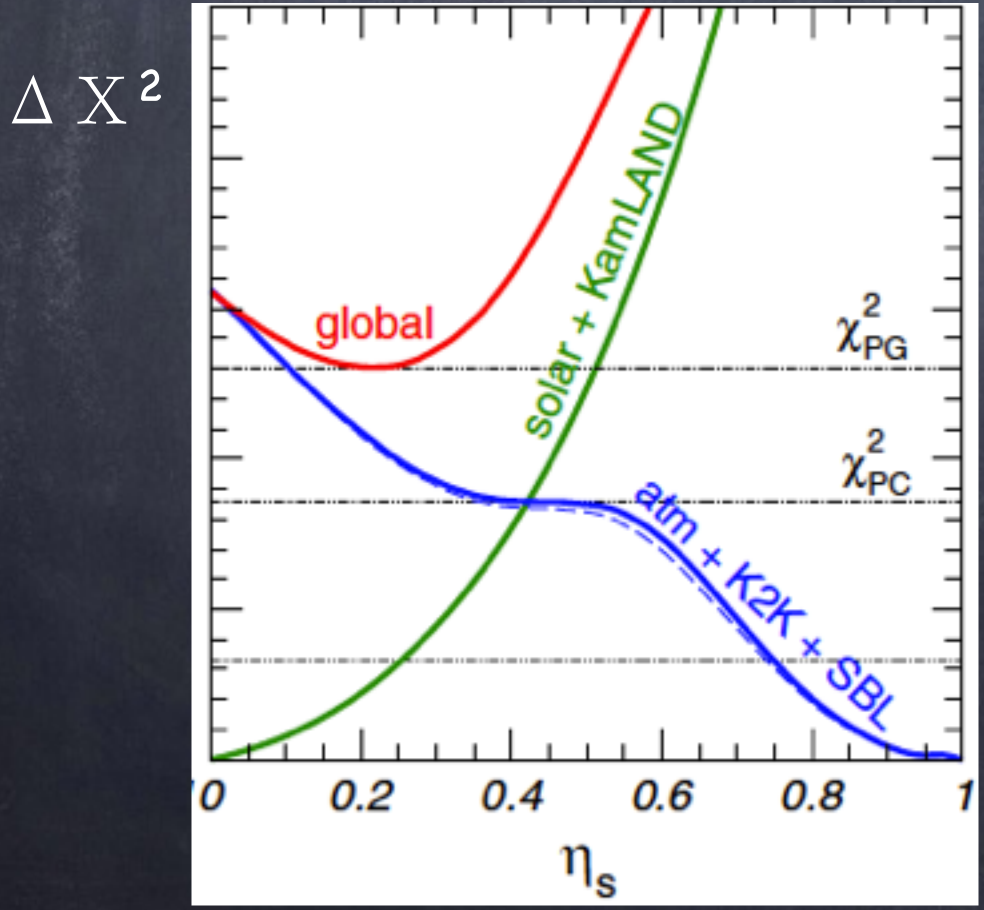


2+2 neutrino scheme

- This scheme requires the presence of sterile neutrinos either in solar or atmospheric neutrinos

- However, solar and atmospheric data show a strong preference for active oscillations



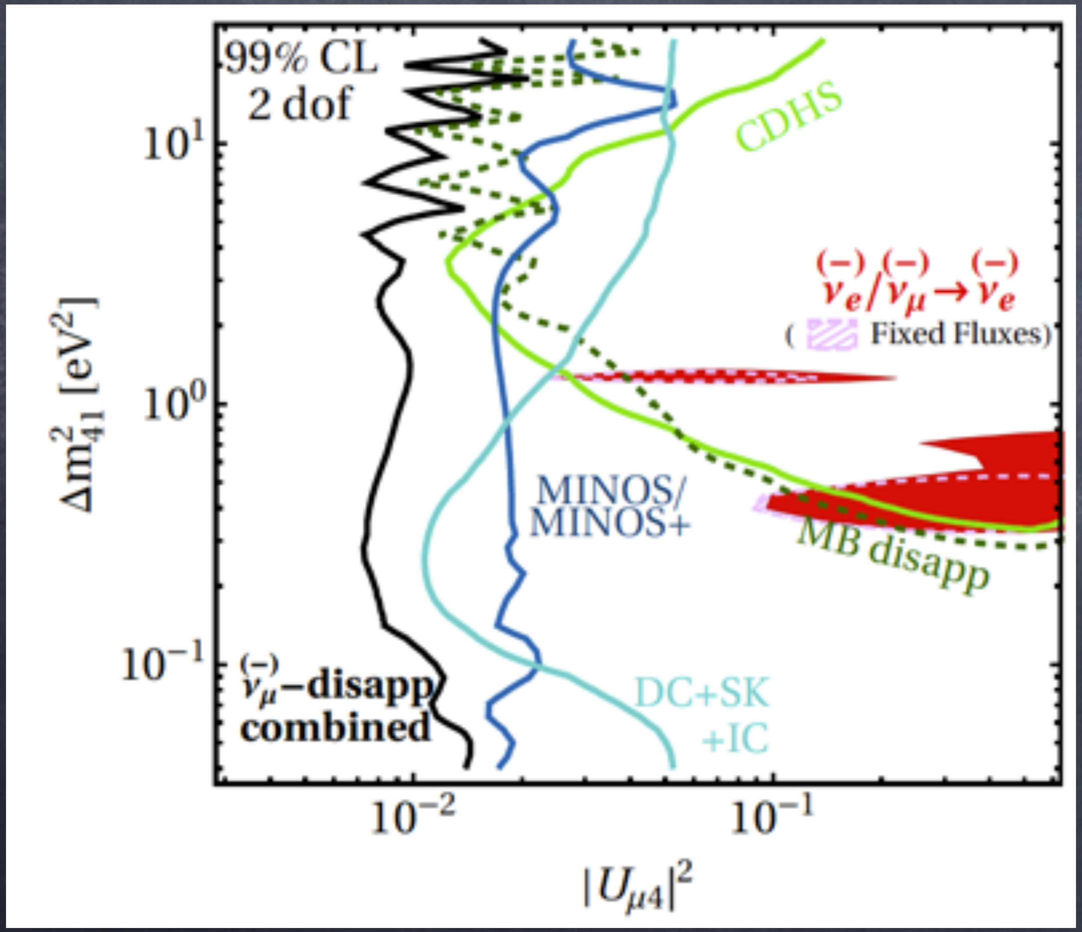


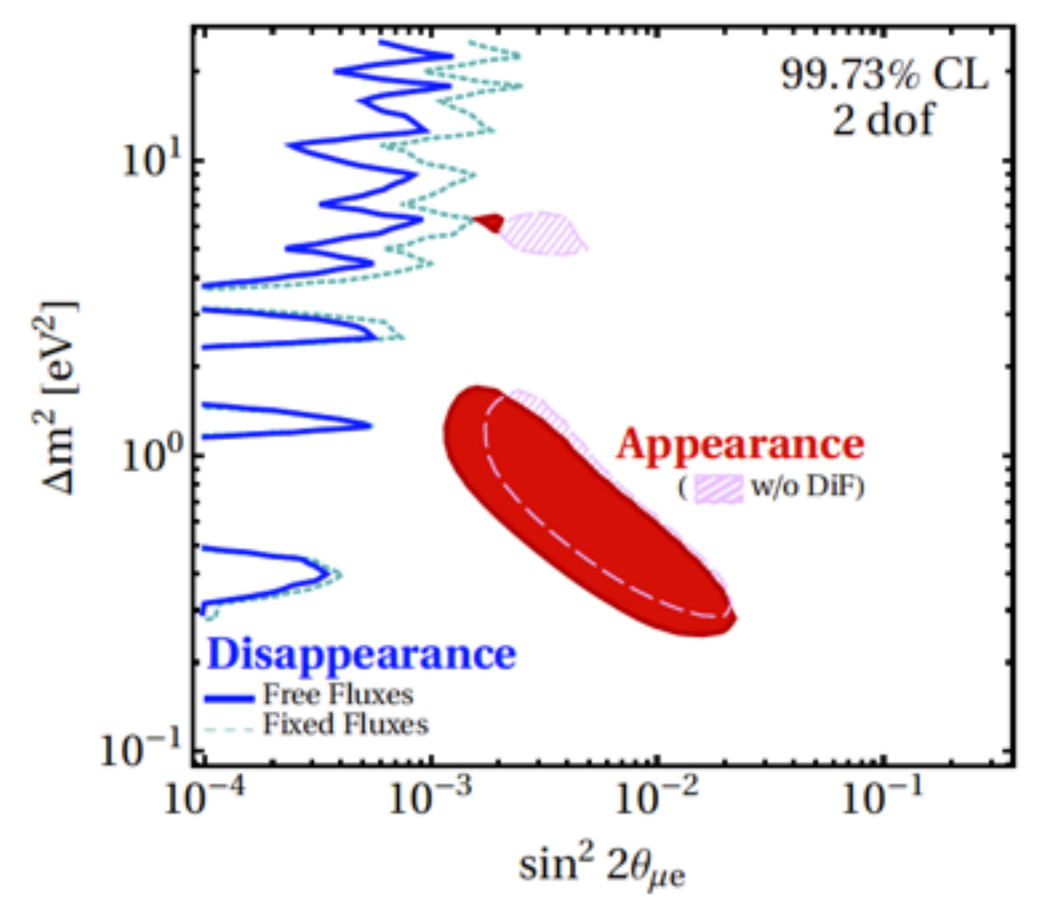
excluded by solar and atmospheric data

Maltoni et al, NPB643 (2003), NJP06 (2004)

Global fit in 3+1 neutrino scheme

- 3+1 spectra include the 3 active-neutrino scenario as limiting case.
- solar & atmos oscillations: mainly active ν + small sterile component
- disagreement between ν_μ appearance (LSND + MiniBooNE) and disappearance exp. (CDHS, SK, IceCube, MINOS/+, MiniBooNE-disap)





→ severe tension between appearance and disappearance results

Dentler et al, arXiv:1803.10661

eV-sterile neutrino in Cosmology

- In Cosmology, sterile neutrinos with eV masses would contribute to:

  $\sum m_\nu$ = sum of neutrino masses

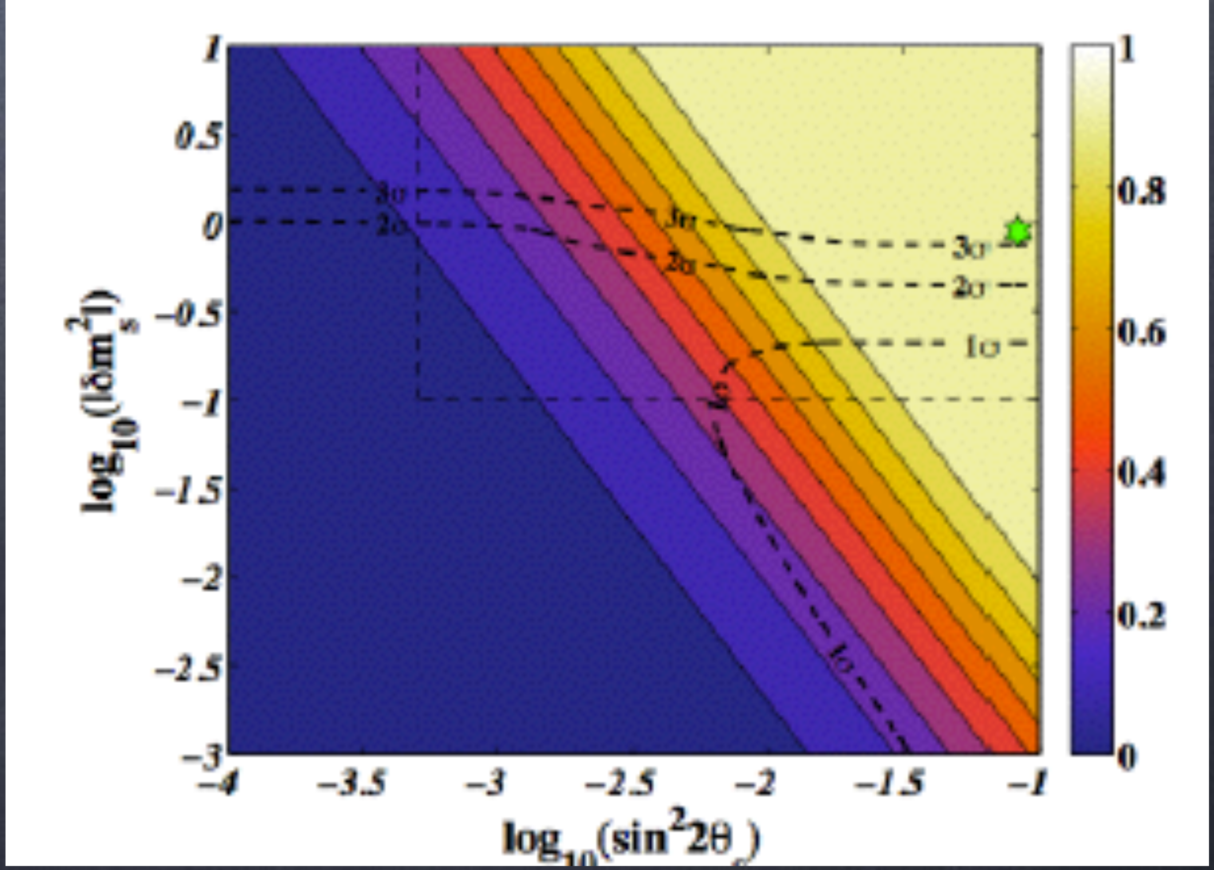
  N_{eff} = relativistic degrees of freedom.

- Cosmological bounds avoided if the mixing active-sterile neutrino is small.

- However, for mass & mixing parameters required to explain the anomalies, ν_s is fully thermalized in the early universe.

$$\rightarrow \sum m_\nu \gtrsim 0.05\text{eV} + \sqrt{\Delta m^2_{41}} > 1\text{ eV}$$

$$\rightarrow N_{eff} \approx 4$$



Hannestad et al, 1204.5861

Bounds from Cosmology

- recent limits on the sum of neutrino masses:

$\sum m_\nu < 0.13 - 0.72$ eV < 1 eV !!!! Lattanzi & Gerbino, arxiv:1712.07109

- recent limits on the effective number of relativistic dof:

  - PLANCK: $N_{eff} = 3.15 \pm 0.23$
  - PLANCK + LSS: $N_{eff} = 3.03 \pm 0.18$

Lattanzi & Gerbino, arxiv:1712.07109

- constraints can be avoided by preventing ν_s thermalization in the early universe, but it requires large modifications of cosmological model.

Example: new interactions in the sterile neutrino sector that suppress their thermalization in the early Universe

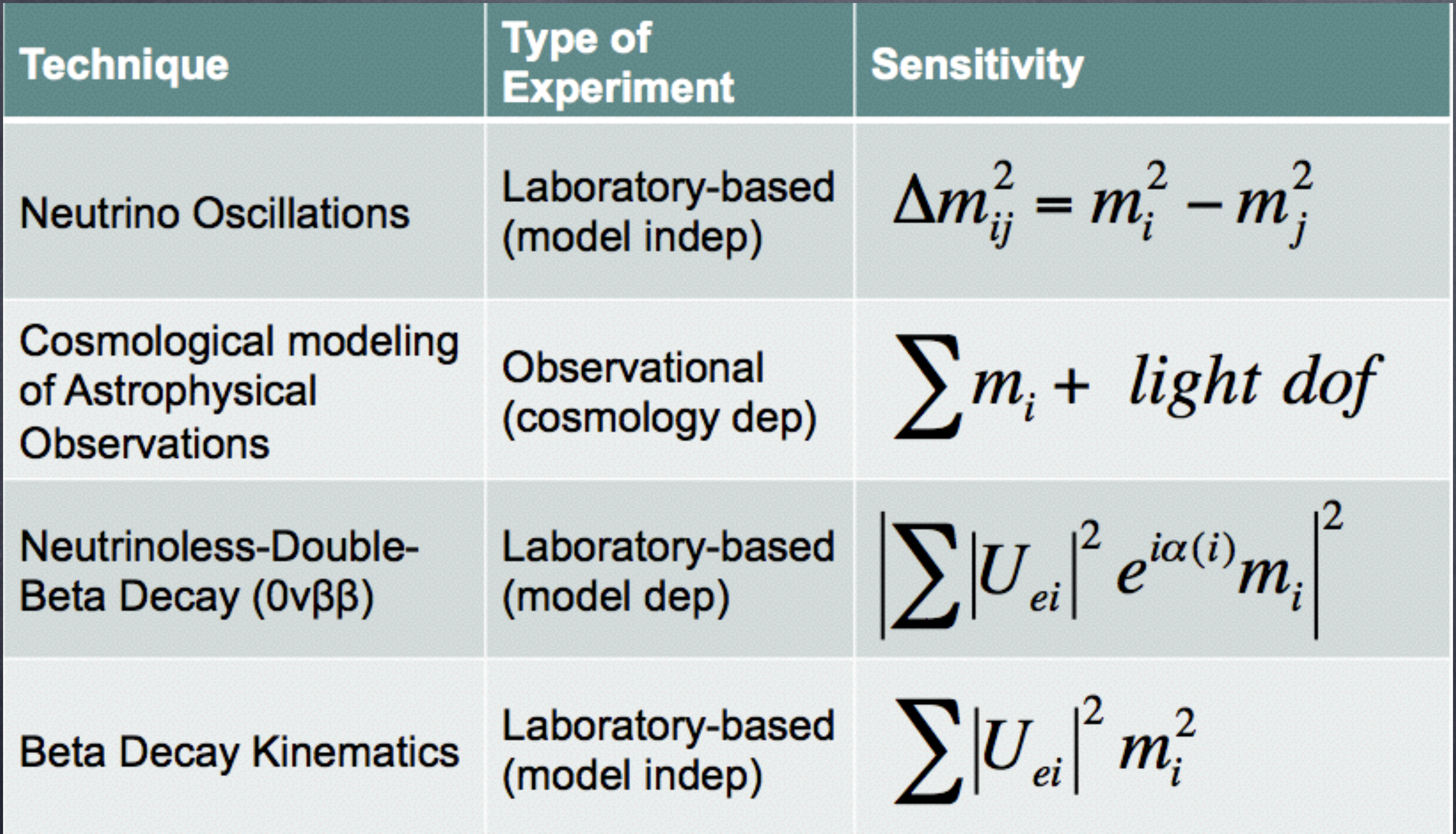
Dasgupta and Kopp, PRL112 (2014) 031803

However: these interactions also affect CMB!! Not easy to solve

Forastieri et al, JCAP 1707 (2017) 038

The absolute scale of neutrino mass

Constraints on neutrino masses



Technique	Type of Experiment	Sensitivity
Neutrino Oscillations	Laboratory-based (model indep)	$\Delta m_{ij}^2 = m_i^2 - m_j^2$
Cosmological modeling of Astrophysical Observations	Observational (cosmology dep)	$\sum m_i + \ light\ dof$
Neutrinoless-Double-Beta Decay (0vββ)	Laboratory-based (model dep)	$\left\lvert \sum \lvert U_{ei} \rvert^2 e^{i\alpha(i)} m_i \right\rvert^2$
Beta Decay Kinematics	Laboratory-based (model indep)	$\sum \lvert U_{ei} \rvert^2 m_i^2$

From oscillations: $m_\nu \geq \sqrt{\Delta m_{31}^2 + \Delta m_{21}^2} \gtrsim 0.05\,\mathrm{eV}$

Bounds from cosmology

- neutrino masses may affect cosmological observables:

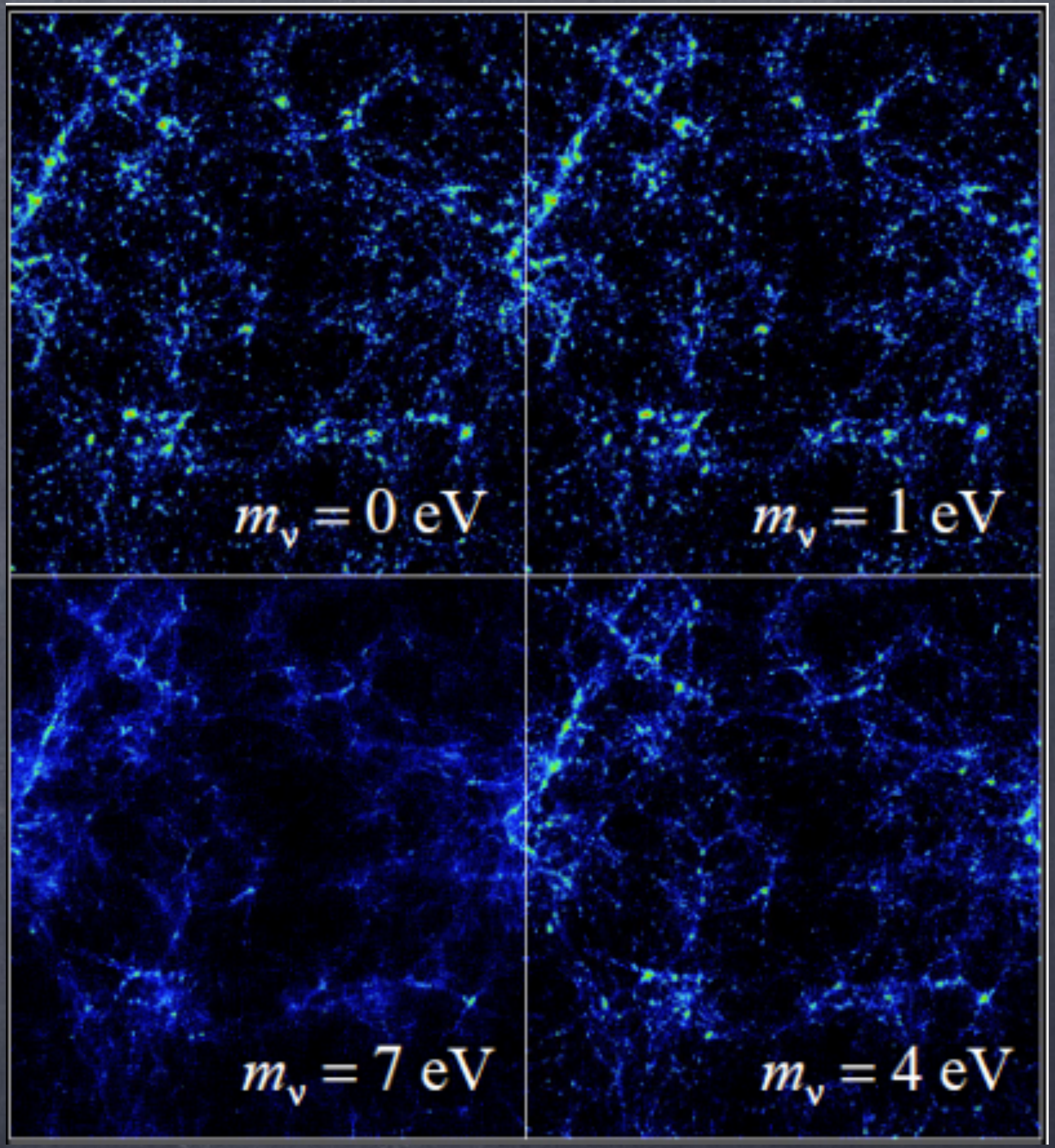
  → anisotropies in the CMB spectrum

  → Large Scale Structure formation

  → weak gravitational lensing

- Fit ΛCDM model + experimental data

$\sum m_{\nu i} < 0.13 - 0.72$ eV



Lattanzi & Gerbino, arxiv:1712.07109

Direct neutrino mass experiments

electron neutrino

endpoint β spectrum for

$^3H \rightarrow {}^3He + e^- + \nu_e$

$\rightarrow m_{\nu e} < 2$ eV (95% CL)

muon neutrino

measurement of p_μ in

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

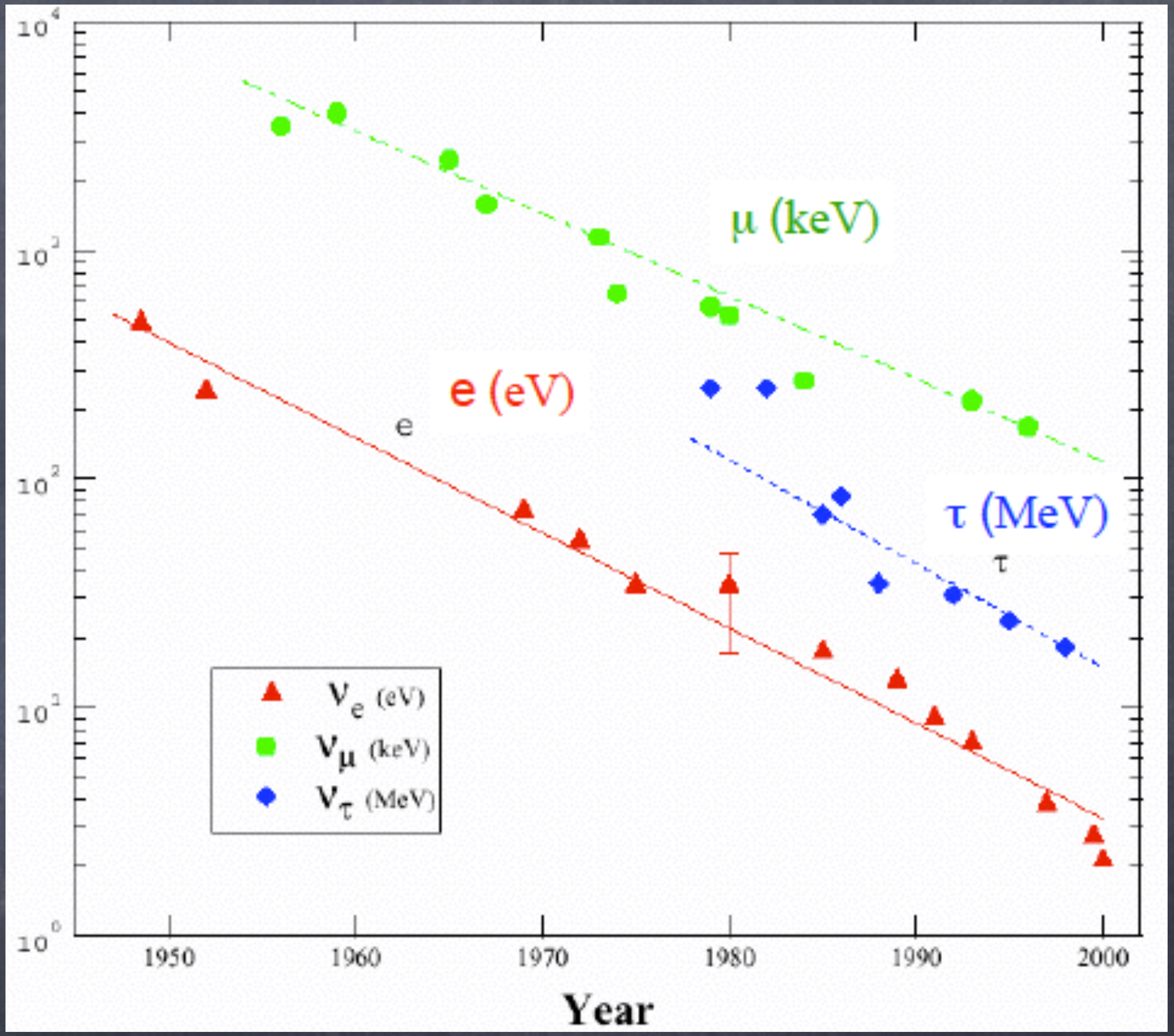
$\rightarrow m_{\nu\mu} < 190$ keV (90% CL)

tau neutrino

study $n\pi$ mass in

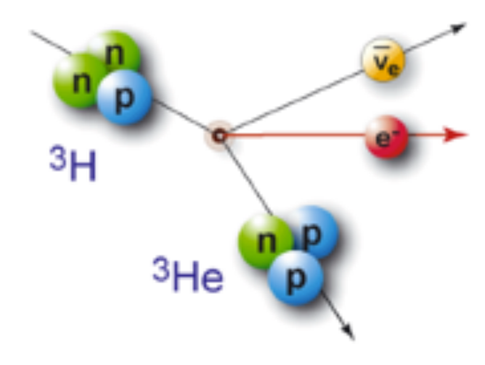
$\tau \rightarrow (n\pi) + \nu_\tau$

$\rightarrow m_{\nu\tau} < 18.2$ MeV (95% CL)



$$m(\nu_\alpha)^2 = \sum_i |U_{\alpha i}|^2 m(\nu_i)^2$$

Tritium beta decay experiments

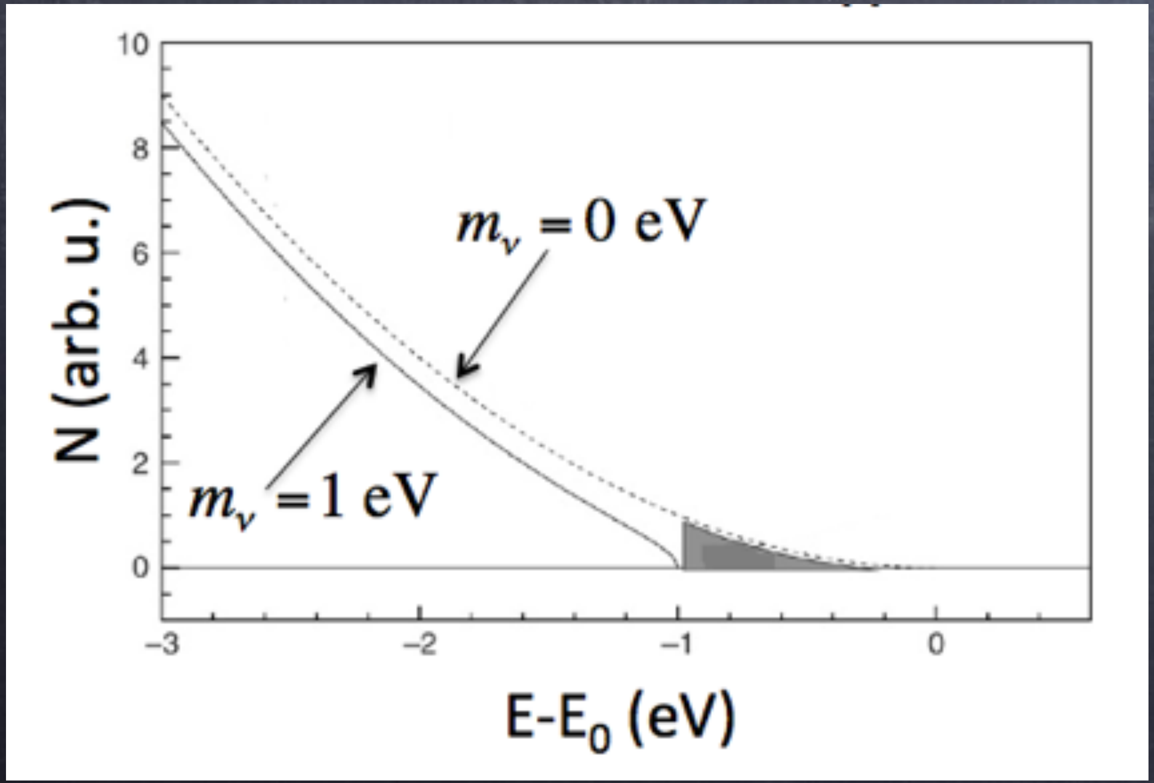


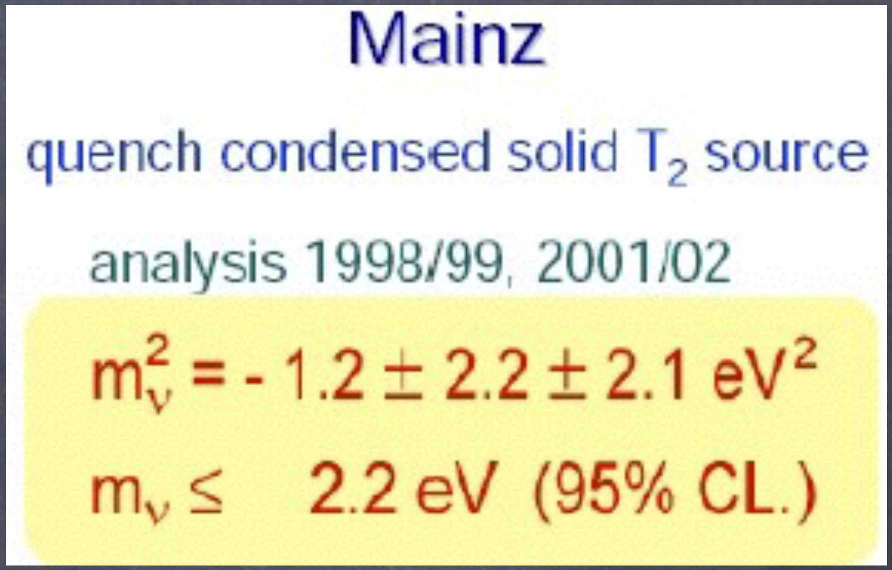
- β-decay spectrum close to the endpoint is very sensitive to m_ν

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \sqrt{(E_0-E_e)^2 - \text{"}m(\nu_e)\text{"}^2}$$

effective neutrino mass:

$$m(\nu_e)^2 = \sum_i |U_{ei}|^2 m(\nu_i)^2$$





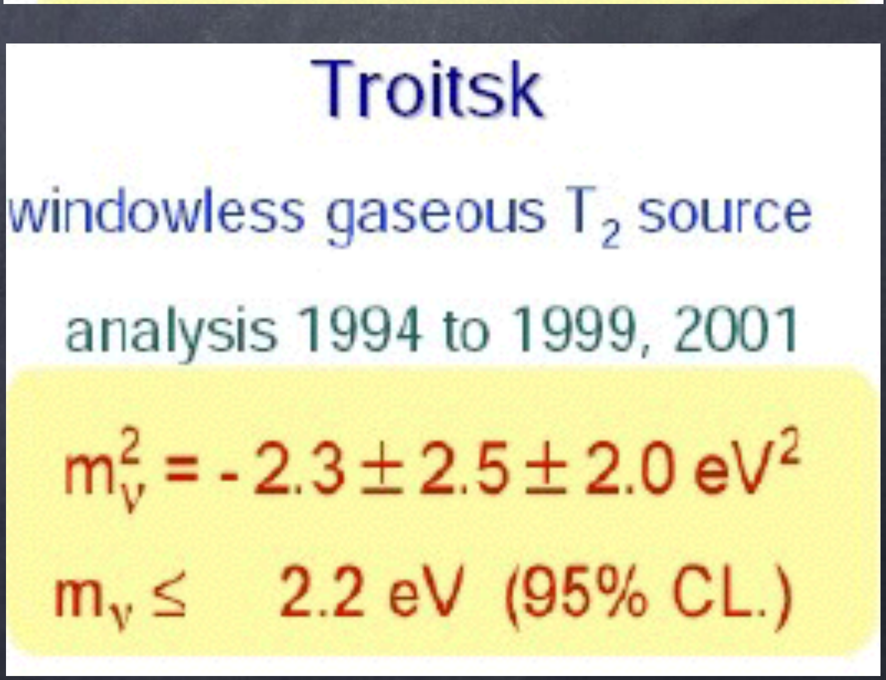
Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ \text{eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)



Troitsk

windowless gaseous T_2 source

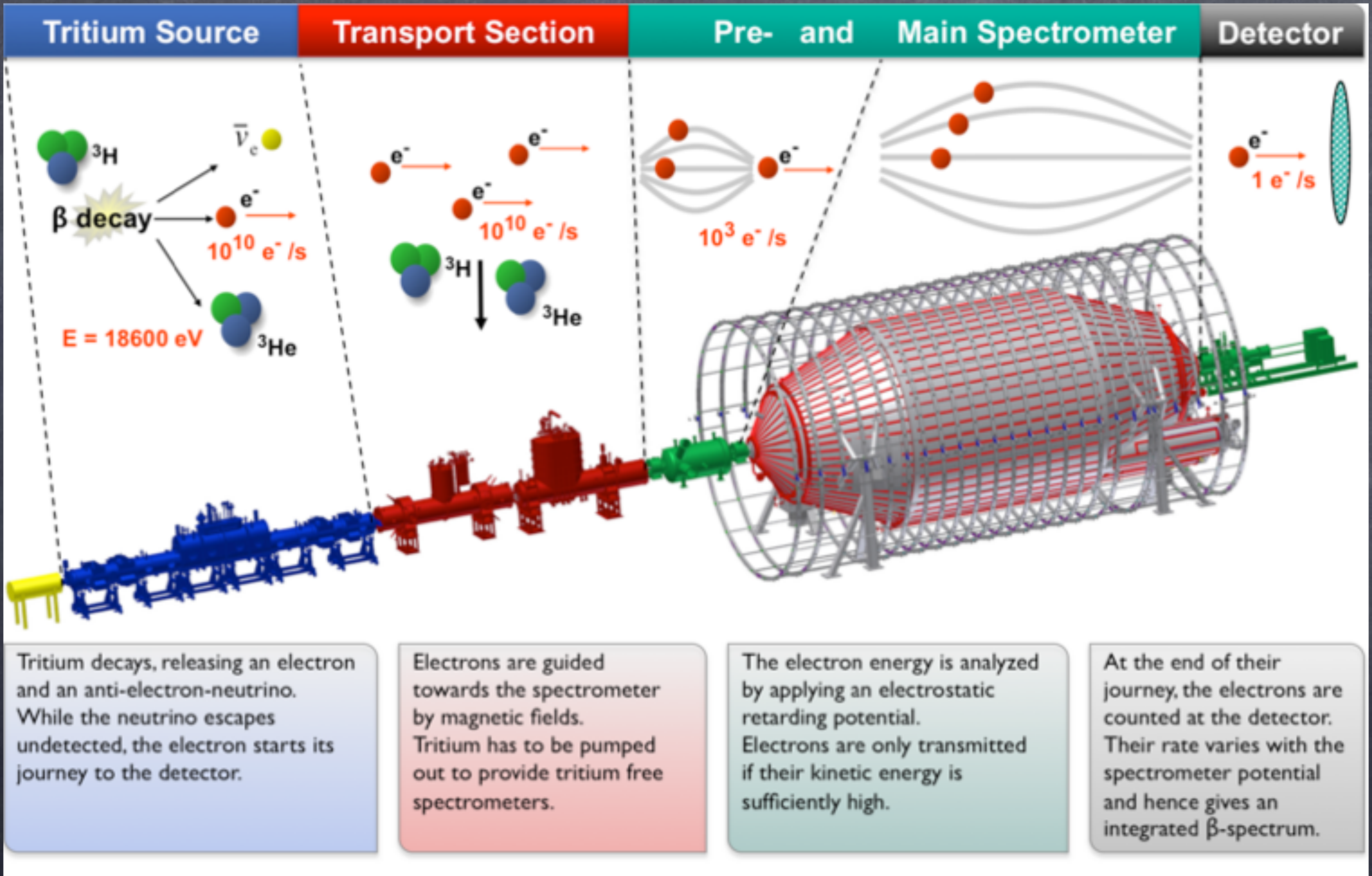
analysis 1994 to 1999, 2001

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0\ \text{eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)

The KATRIN experiment

(KArlsruhe TRItium Neutrino experiment)



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

sensitivity (90%CL)

$m_\nu < 0.2$ eV

discovery potential

$m_\nu = 0.35$ eV (5σ)

Inauguration

11 June 2018

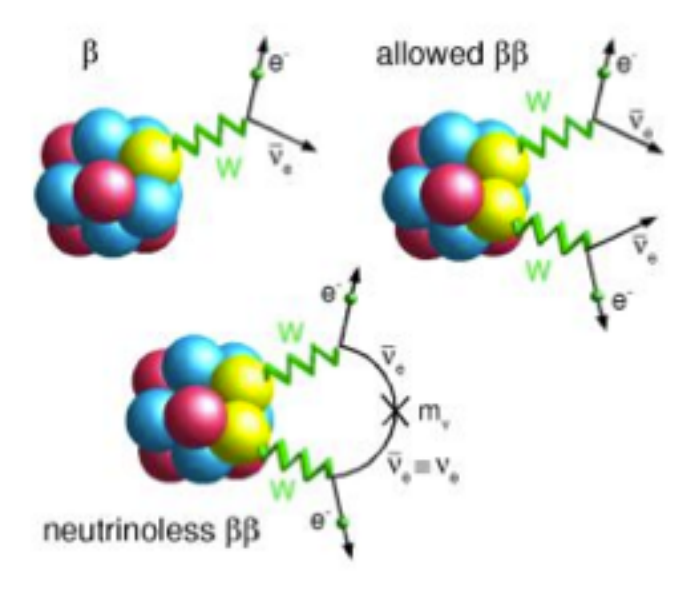
Neutrinoless double beta decay

- 2νββ: rare process in the SM with $t_{1/2} \sim 10^{21}$ years

- 0νββ: possible for massive Majorana neutrinos.

(A,Z) →(A,Z+2) + e^- + e^-

test ν nature

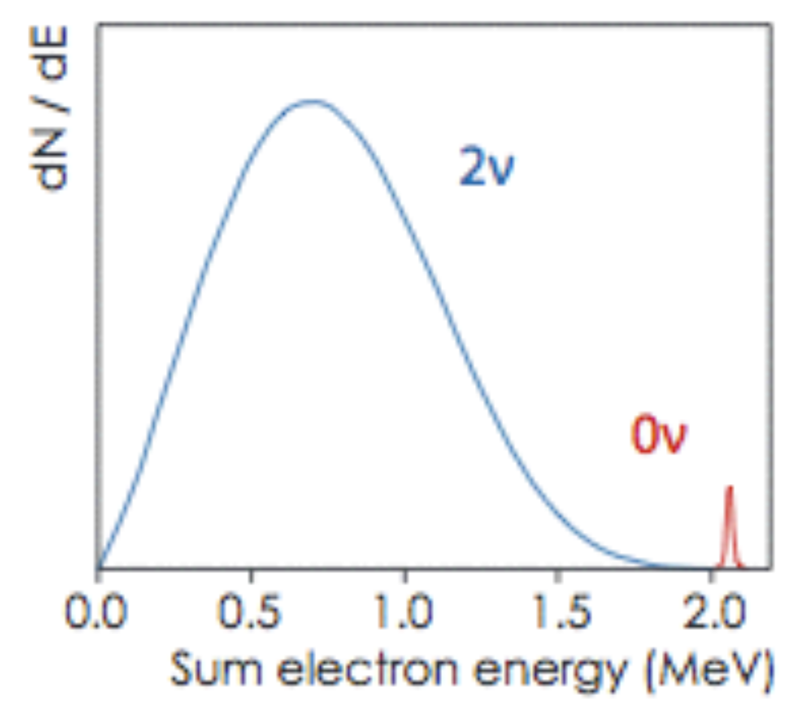


→ not observed yet

→ $t_{1/2} \sim 10^{26}$-10^{27}years

→ violates Lepton Number

→ rate depends on m_ν, unknown phases and nuclear mass matrix elements



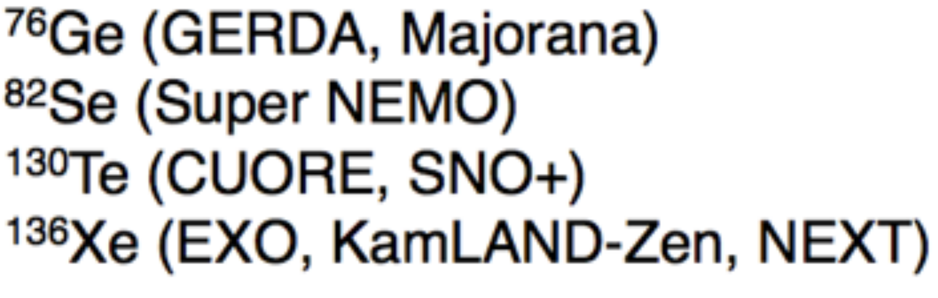
$$\Gamma_{0\nu\beta\beta} = G^{0\nu}|M^{0\nu}|^2 < m_{\beta\beta} >^2$$

$$< m_{\beta\beta} >= |\sum_i U_{ei}^2 m_i|$$

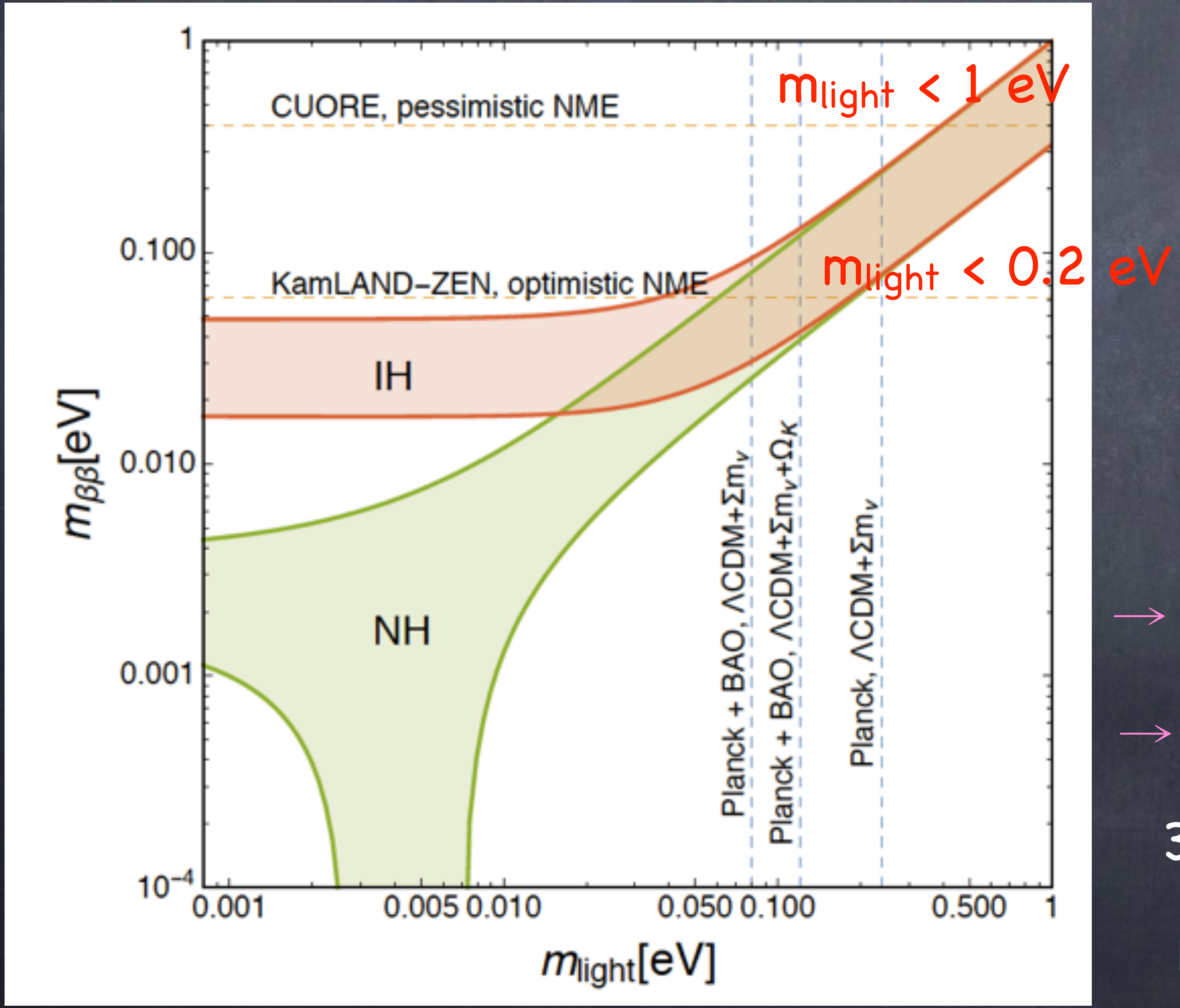
→ good separation 2νββ from 0νββ

→ low bg 0νββ peak region

Bounds from 0νββ decay experiments



^{76}Ge (GERDA, Majorana)
^{82}Se (Super NEMO)
^{130}Te (CUORE, SNO+)
^{136}Xe (EXO, KamLAND-Zen, NEXT)



$$< m_{\beta\beta} > = |\sum_i U_{ei}^2 m_i|$$

At 90% CL:

$m_{\beta\beta}$ < 140-400 meV CUORE

$m_{\beta\beta}$ < 147-398 meV EXO-200

$m_{\beta\beta}$ < 120-270 meV GERDA II

$m_{\beta\beta}$ < 61-165 meV KL-Zen

→ degenerate region explored

→ next generation: full IH region

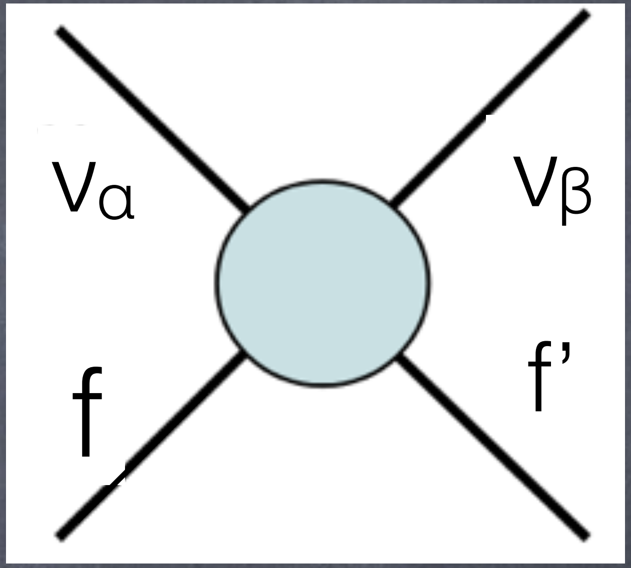
3σ discovery sensitivity 20 meV

Lattanzi & Gerbino, arxiv:1712.07109

Neutrino physics beyond the Standard Model

- Non-standard neutrino interactions
- Non-unitary neutrino mixing

Non-Standard Interactions (NSI)



- NSI appear in models of neutrino masses

- NSI may affect oscillation parameters,

  ⇒ precision measurements at current experiments

  ⇒ sensitivity reach of upcoming experiments

  (degeneracies and ambiguities)

- Information about the size of NSI could be very useful for neutrino model building

NSI: Notation

$$\boxed{\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\,\epsilon^{f f' X}_{\alpha\beta}\,(\bar{\nu}_\alpha\gamma^\mu P_L \ell_\beta)\left(\bar{f}'\gamma_\mu P_X f\right)}$$

⇒ may affect neutrino production and detection

$\epsilon^s_{\alpha\beta}$ (source) $\epsilon^d_{\alpha\beta}$ (detector)

$$\boxed{\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon^{f X}_{\alpha\beta}\,(\bar{\nu}_\alpha\gamma^\mu P_L \nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)}$$

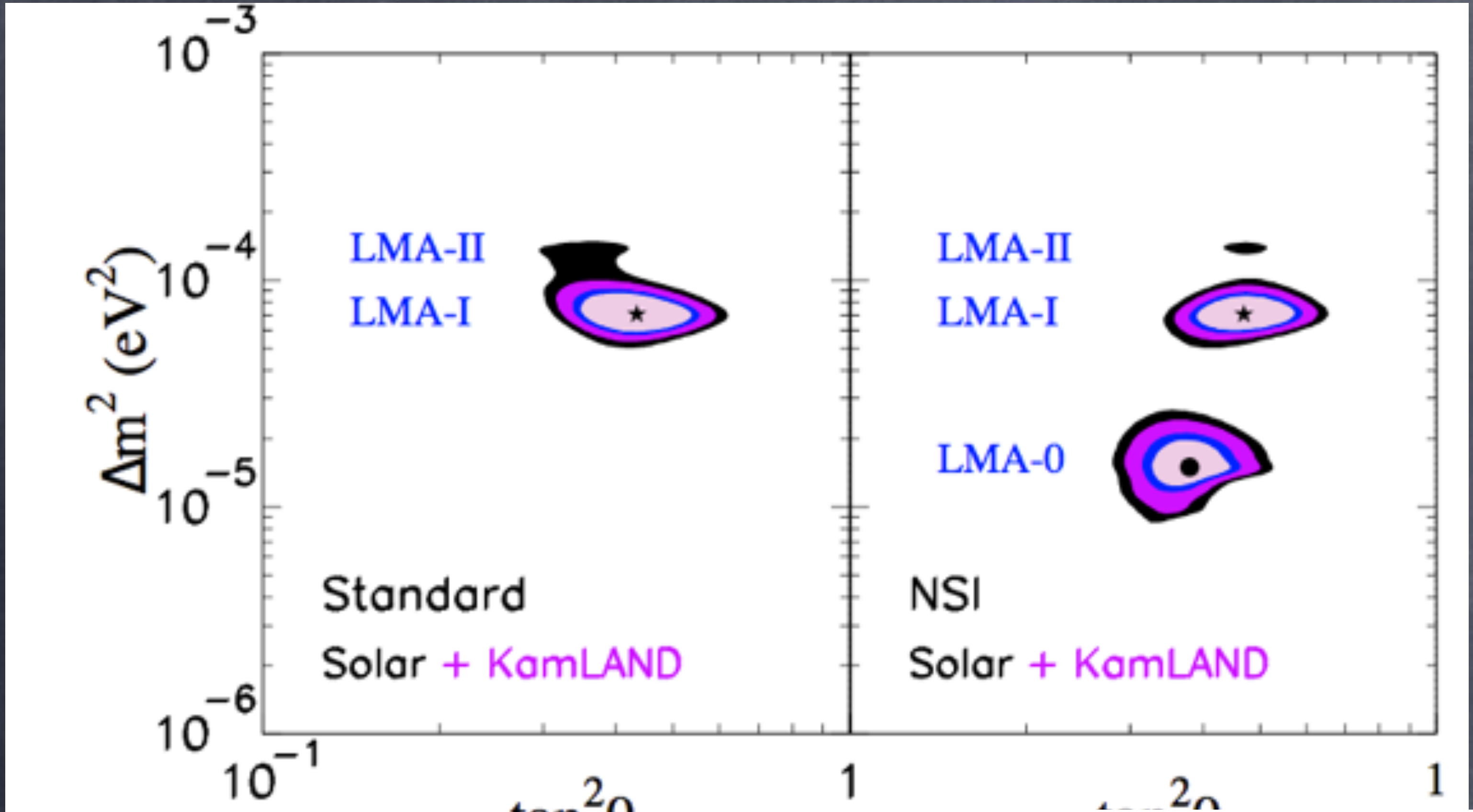
$\epsilon_{\alpha\beta} \neq 0$ → NSI violate lepton flavor (FC-NSI)

$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0$ → NSI violate LF universality (NU-NSI)

⇒ mainly affecting neutrino propagation in matter: $\epsilon^m_{\alpha\beta}$

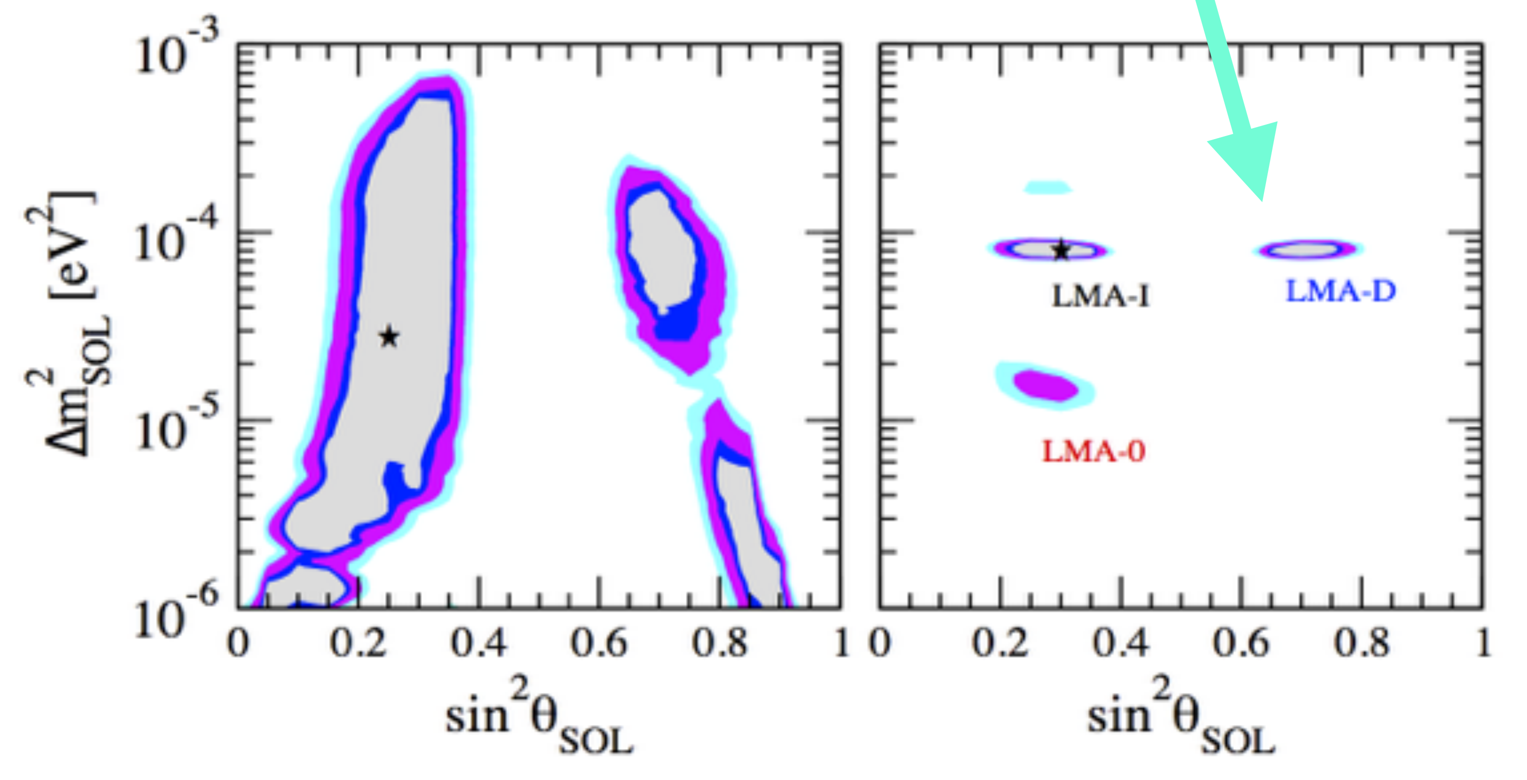
(but also detection, e.g., Super-K and Borexino)

NSI in the solar sector



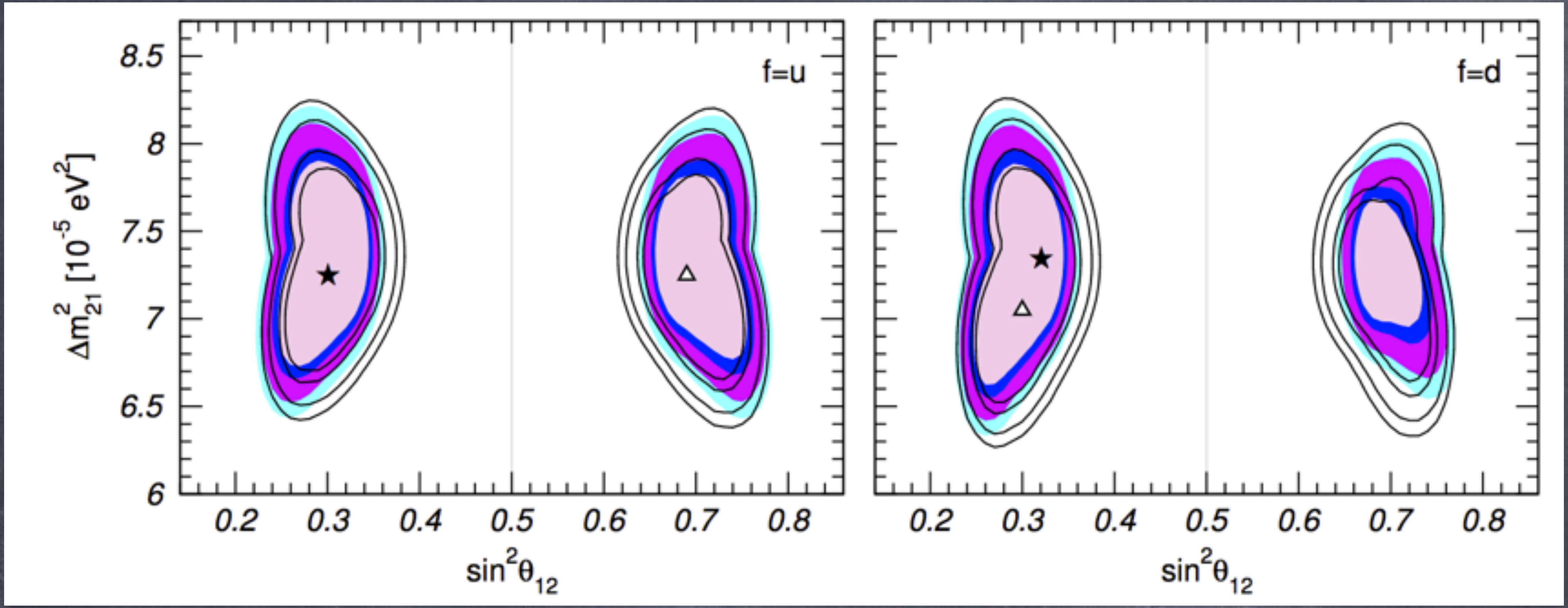
Friedland et al, PLB 2004

degenerate solution
LMA-Dark,
with $\theta_{12} > \pi/4$



Miranda et al, JHEP 2006

NSI in the solar sector



Gonzalez-Garcia et al, JHEP 2013

How to probe LMA-Dark?

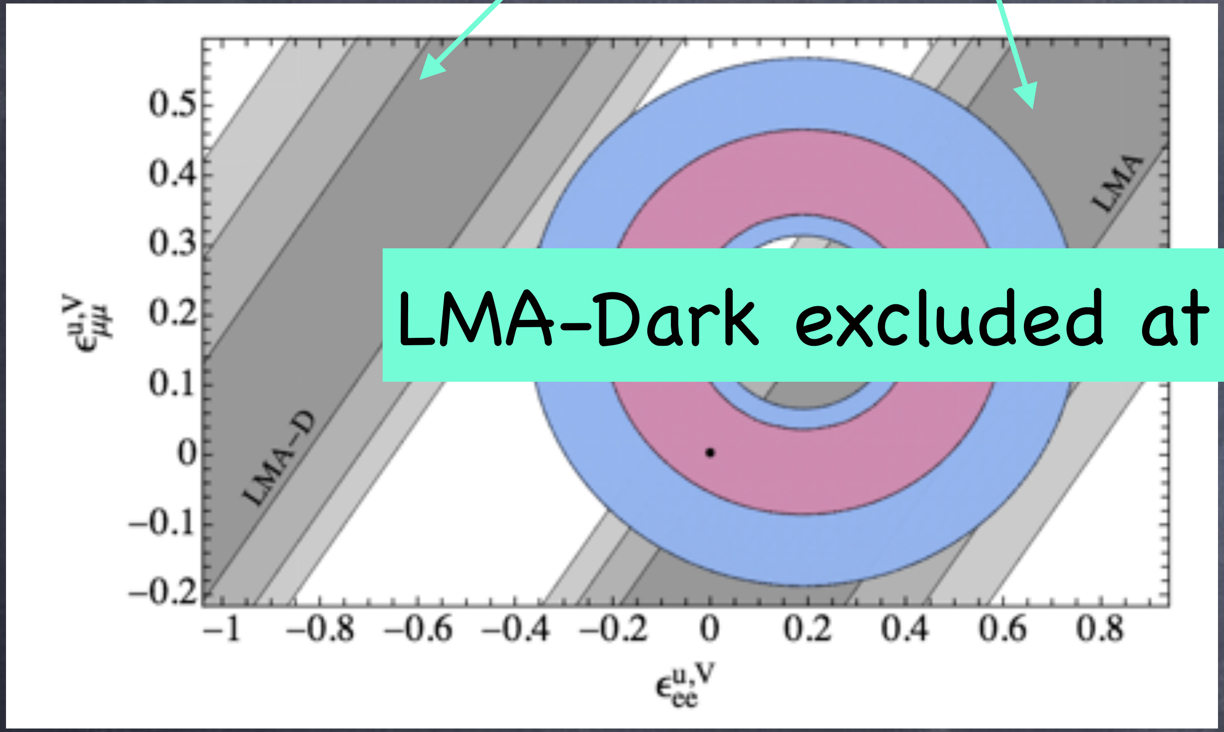
⇒ combination with neutrino scattering experiments: CHARM, NuTeV

Escrihuela et al, PRD 2009, Coloma et al, JHEP 2017

⇒ combination with coherent neutrino-nucleus scattering

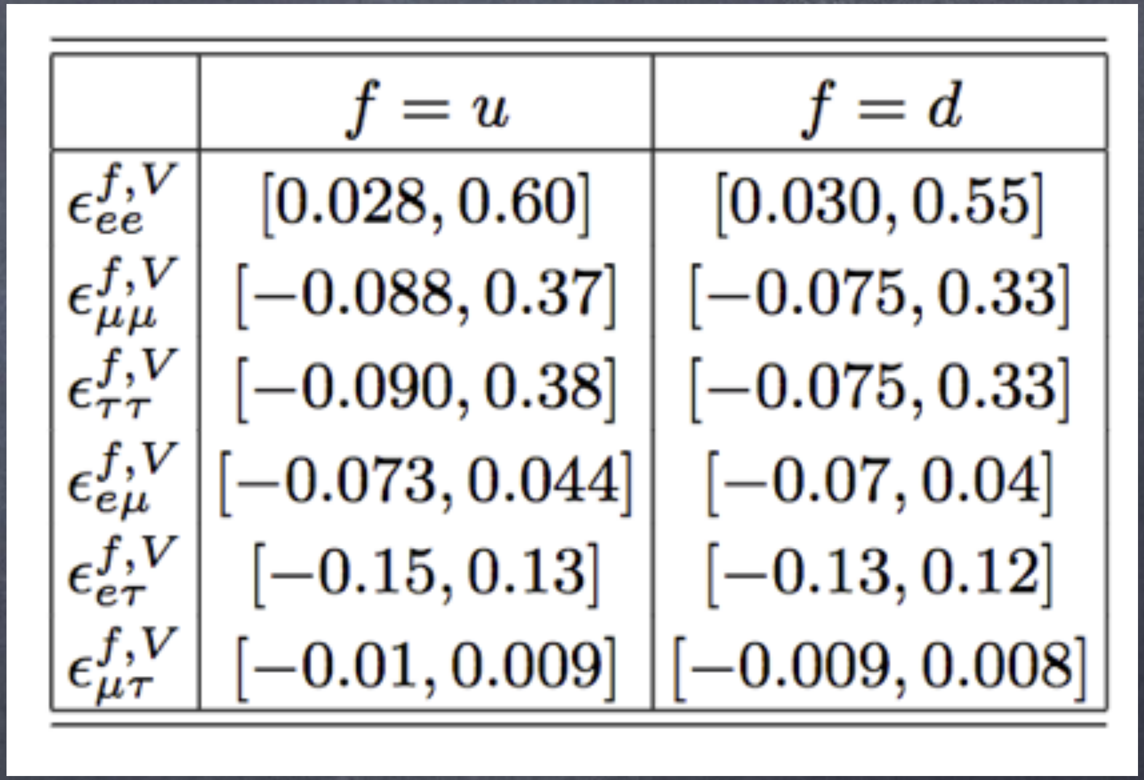
Coloma et al, PRD 2017

NSI in the solar sector: impact of COHERENT results



oscillations

LMA-Dark excluded at 3σ



	$f = u$	$f = d$
$\epsilon^{f,V}_{ee}$	$[0.028, 0.60]$	$[0.030, 0.55]$
$\epsilon^{f,V}_{\mu\mu}$	$[-0.088, 0.37]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{\tau\tau}$	$[-0.090, 0.38]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{e\mu}$	$[-0.073, 0.044]$	$[-0.07, 0.04]$
$\epsilon^{f,V}_{e\tau}$	$[-0.15, 0.13]$	$[-0.13, 0.12]$
$\epsilon^{f,V}_{\mu\tau}$	$[-0.01, 0.009]$	$[-0.009, 0.008]$

90% CL oscillation + COHERENT

Coloma et al, PRD 2017

caveats

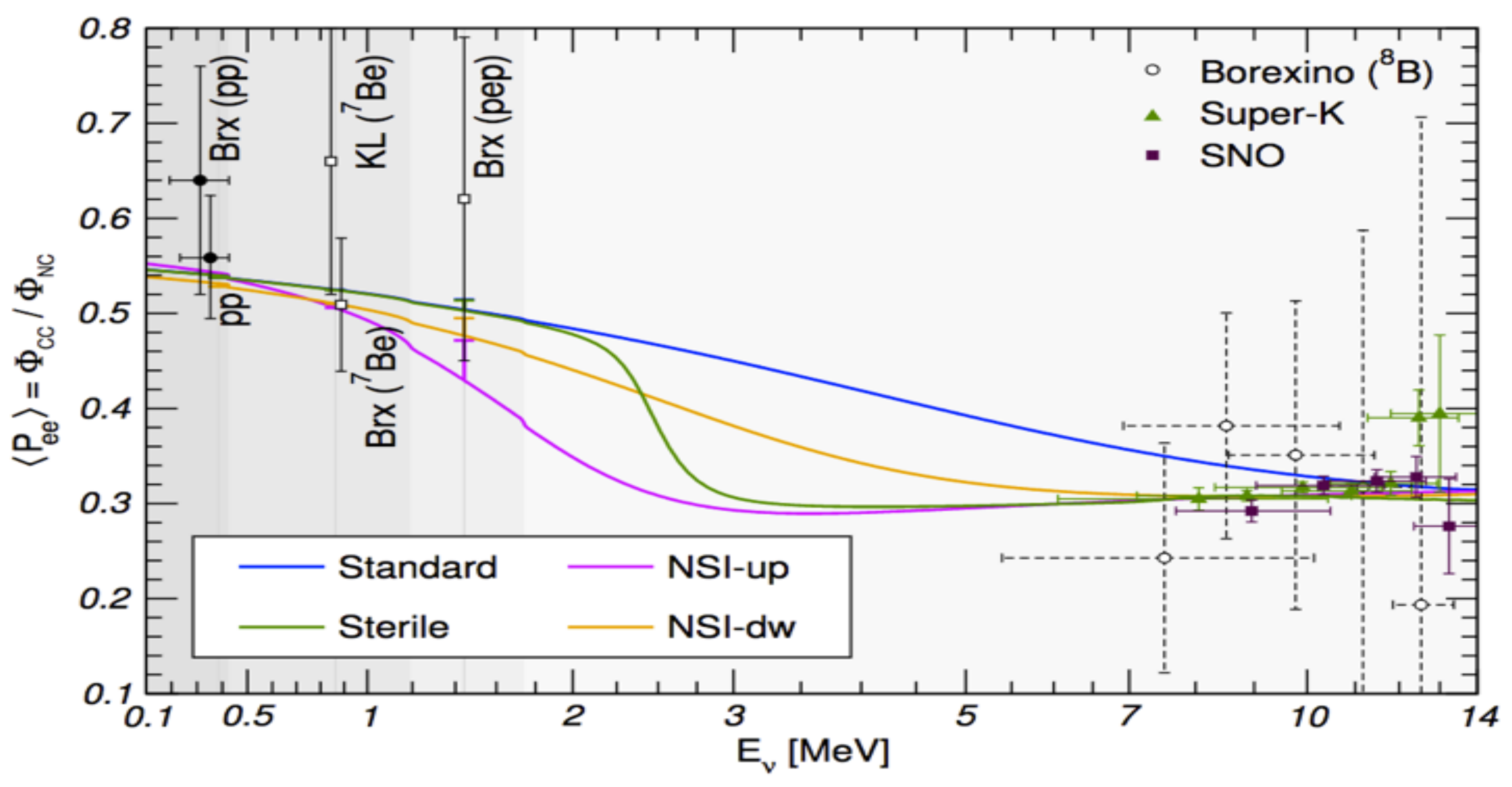
- NSI particle mediator lighter than 50 MeV
- degeneracies in (ε_d, ε_u)

Liao & Marfatia, PLB 2017

NSI in the solar sector

solar + KamLAND analysis prefer non-zero NSI

➡ spectrum flattening below 3 MeV and larger D/N asymmetry expected for NSI removes tension between KamLAND and solar data



Maltoni & Smirnov, EPJ 2015

NSI in the atmospheric sector

- From Super-K I & II phase data (2ν approx): Mitsuka et al, 2011

$$|\epsilon^{dV}_{\mu\tau}| < 0.011\,, \quad |\epsilon^{dV}_{\mu\mu} - \epsilon^{dV}_{\tau\tau}| < 0.049 \quad (90\%\,\mathrm{C.L.})$$

⇒ bounds relaxed in a 3-neutrino analysis Friedland et al 2004, 2005

- Three-neutrino analysis of Super-K data Gonzalez-Garcia et al, 2011

$$|\epsilon^{eV}_{\mu\tau}| < 0.035\,, |\epsilon^{eV}_{\tau\tau} - \epsilon^{eV}_{\mu\mu}| < 0.11 \quad (90\%\,\mathrm{C.L.})$$

- IceCube data can also constrain NSI couplings Esmaili & Smirnov, 2013

$$-0.006 < \epsilon^{dV}_{\mu\tau} < 0.0054 \quad (90\%\,\mathrm{C.L.})$$

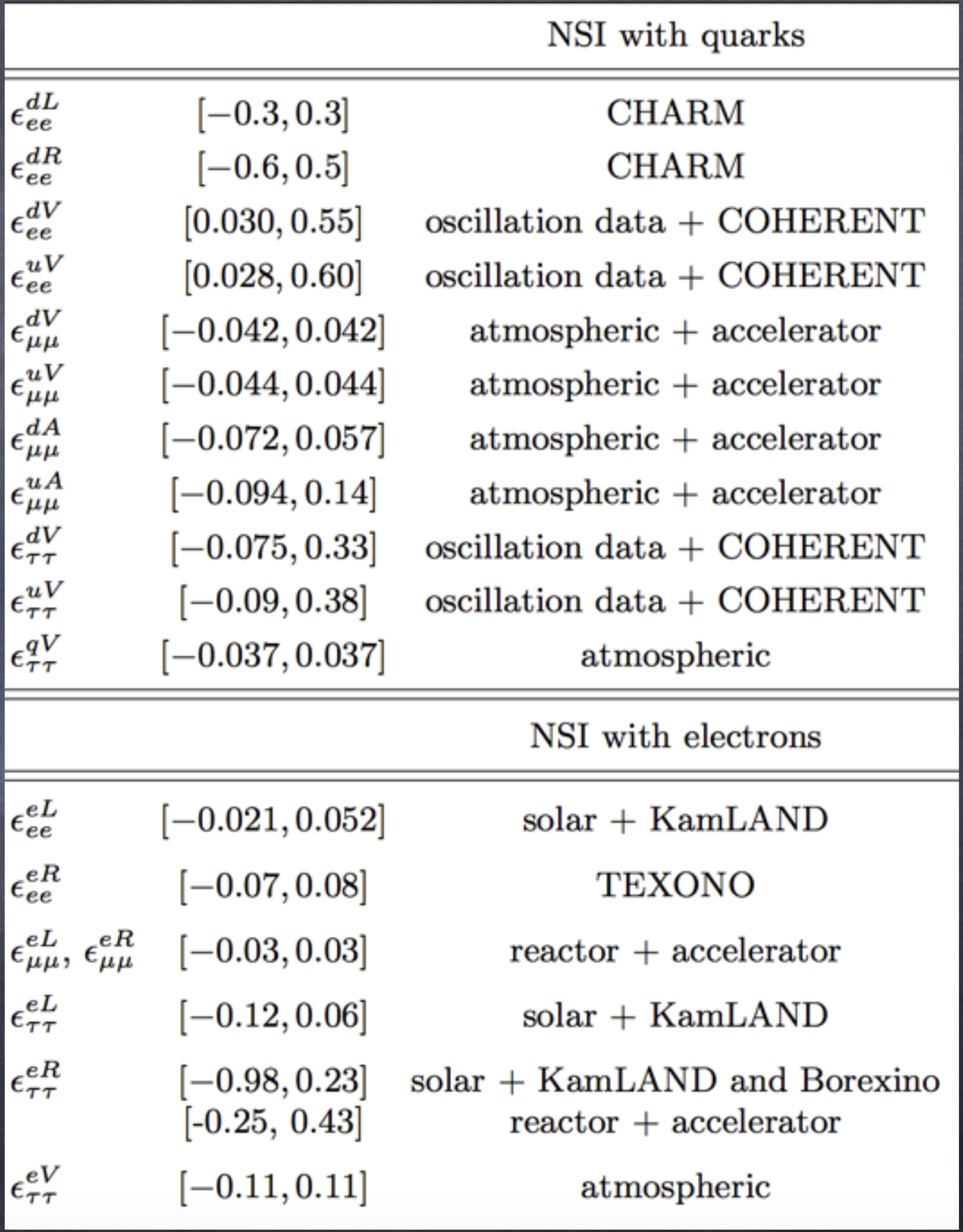
Salvado et al, 2017

⇒ best limit in $\mu\tau$ sector, obtained assuming $\epsilon_{\alpha\alpha} = 0$

90% C.L. bounds on NU-NSI

$$\epsilon^{fP}_{\alpha\alpha}$$

Y. Farzan and MT,
Frontiers in Physics 6 (2018) 10

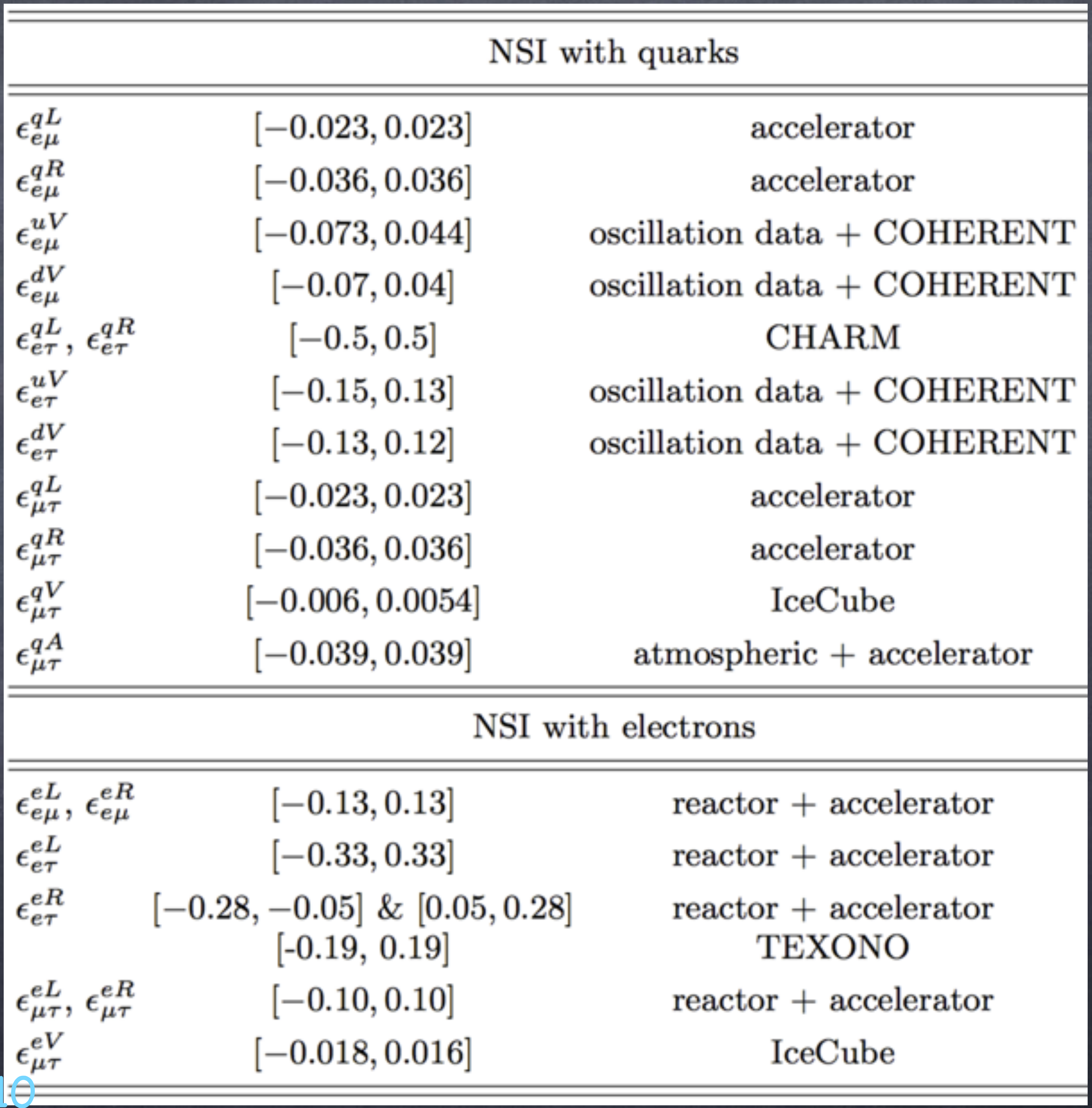


		NSI with quarks
ϵ^{dL}_{ee}	$[-0.3, 0.3]$	CHARM
ϵ^{dR}_{ee}	$[-0.6, 0.5]$	CHARM
ϵ^{dV}_{ee}	$[0.030, 0.55]$	oscillation data + COHERENT
ϵ^{uV}_{ee}	$[0.028, 0.60]$	oscillation data + COHERENT
$\epsilon^{dV}_{\mu\mu}$	$[-0.042, 0.042]$	atmospheric + accelerator
$\epsilon^{uV}_{\mu\mu}$	$[-0.044, 0.044]$	atmospheric + accelerator
$\epsilon^{dA}_{\mu\mu}$	$[-0.072, 0.057]$	atmospheric + accelerator
$\epsilon^{uA}_{\mu\mu}$	$[-0.094, 0.14]$	atmospheric + accelerator
$\epsilon^{dV}_{\tau\tau}$	$[-0.075, 0.33]$	oscillation data + COHERENT
$\epsilon^{uV}_{\tau\tau}$	$[-0.09, 0.38]$	oscillation data + COHERENT
$\epsilon^{qV}_{\tau\tau}$	$[-0.037, 0.037]$	atmospheric
		NSI with electrons
ϵ^{eL}_{ee}	$[-0.021, 0.052]$	solar + KamLAND
ϵ^{eR}_{ee}	$[-0.07, 0.08]$	TEXONO
$\epsilon^{eL}_{\mu\mu}$, $\epsilon^{eR}_{\mu\mu}$	$[-0.03, 0.03]$	reactor + accelerator
$\epsilon^{eL}_{\tau\tau}$	$[-0.12, 0.06]$	solar + KamLAND
$\epsilon^{eR}_{\tau\tau}$	$[-0.98, 0.23]$ [-0.25, 0.43]	solar + KamLAND and Borexino reactor + accelerator
$\epsilon^{eV}_{\tau\tau}$	$[-0.11, 0.11]$	atmospheric

90% C.L. bounds on FC-NSI

$\epsilon^{fP}_{\alpha\beta}$

Y. Farzan and MT,
Frontiers in Physics 6 (2018) 10

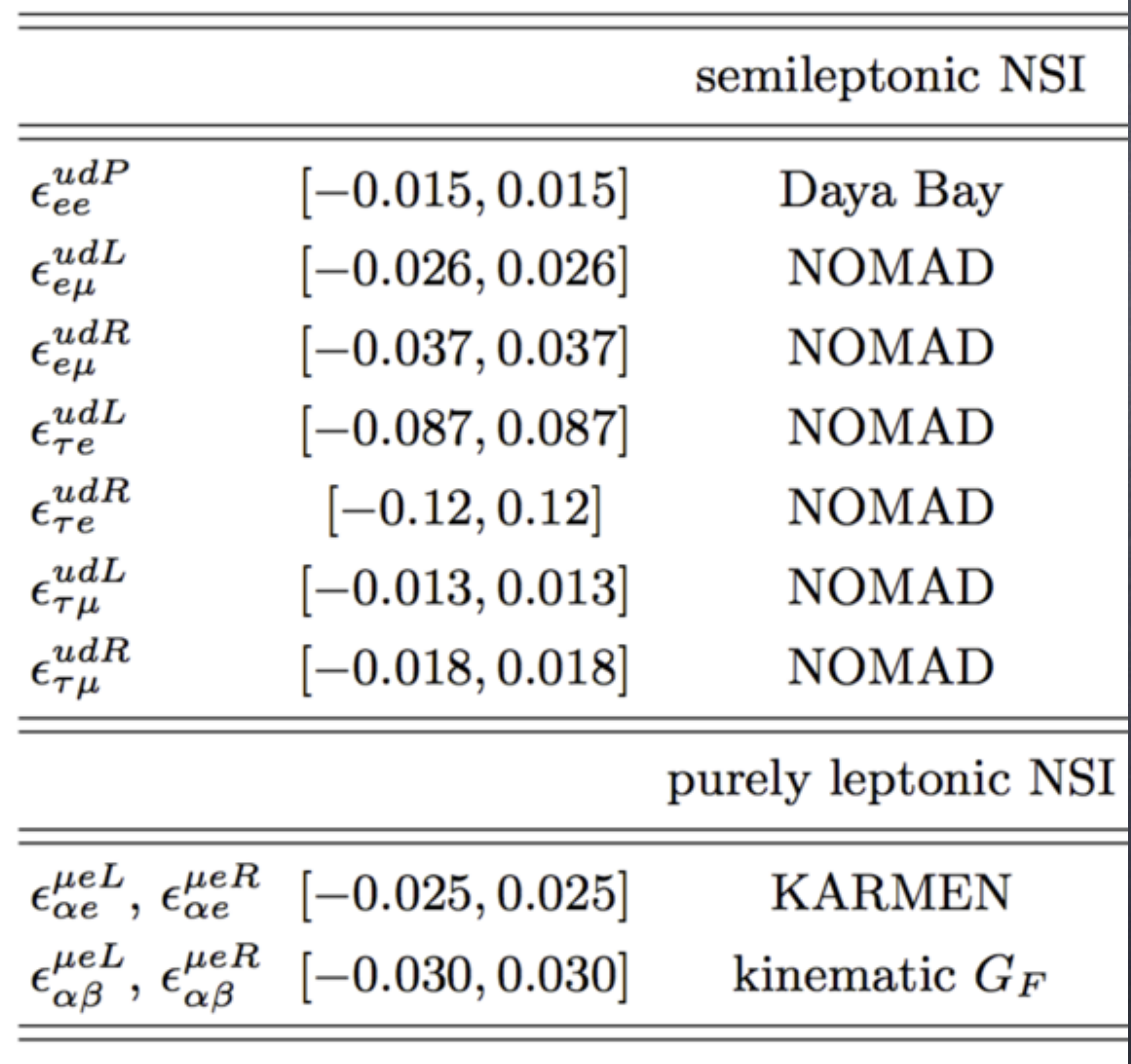


	NSI with quarks	
$\epsilon^{qL}_{e\mu}$	$[-0.023, 0.023]$	accelerator
$\epsilon^{qR}_{e\mu}$	$[-0.036, 0.036]$	accelerator
$\epsilon^{uV}_{e\mu}$	$[-0.073, 0.044]$	oscillation data + COHERENT
$\epsilon^{dV}_{e\mu}$	$[-0.07, 0.04]$	oscillation data + COHERENT
$\epsilon^{qL}_{e\tau}$, $\epsilon^{qR}_{e\tau}$	$[-0.5, 0.5]$	CHARM
$\epsilon^{uV}_{e\tau}$	$[-0.15, 0.13]$	oscillation data + COHERENT
$\epsilon^{dV}_{e\tau}$	$[-0.13, 0.12]$	oscillation data + COHERENT
$\epsilon^{qL}_{\mu\tau}$	$[-0.023, 0.023]$	accelerator
$\epsilon^{qR}_{\mu\tau}$	$[-0.036, 0.036]$	accelerator
$\epsilon^{qV}_{\mu\tau}$	$[-0.006, 0.0054]$	IceCube
$\epsilon^{qA}_{\mu\tau}$	$[-0.039, 0.039]$	atmospheric + accelerator
	NSI with electrons	
$\epsilon^{eL}_{e\mu}$, $\epsilon^{eR}_{e\mu}$	$[-0.13, 0.13]$	reactor + accelerator
$\epsilon^{eL}_{e\tau}$	$[-0.33, 0.33]$	reactor + accelerator
$\epsilon^{eR}_{e\tau}$	$[-0.28, -0.05]$ & $[0.05, 0.28]$	reactor + accelerator
	[-0.19, 0.19]	TEXONO
$\epsilon^{eL}_{\mu\tau}$, $\epsilon^{eR}_{\mu\tau}$	$[-0.10, 0.10]$	reactor + accelerator
$\epsilon^{eV}_{\mu\tau}$	$[-0.018, 0.016]$	IceCube

90% C.L. bounds on CC-NSI

$$\epsilon_{\alpha\beta}^{ff'P}$$

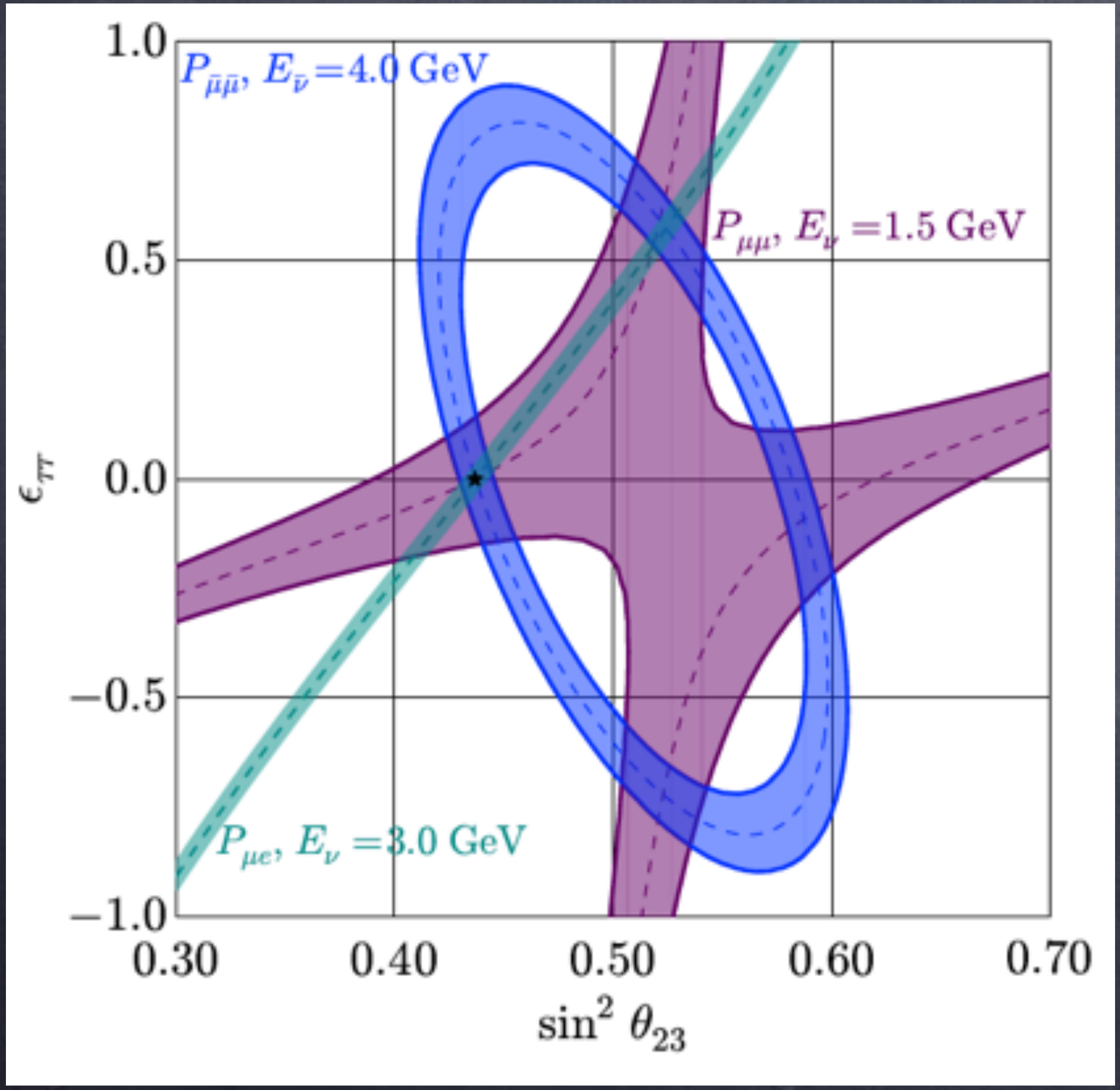
Y. Farzan and MT,
Frontiers in Physics 6 (2018) 10

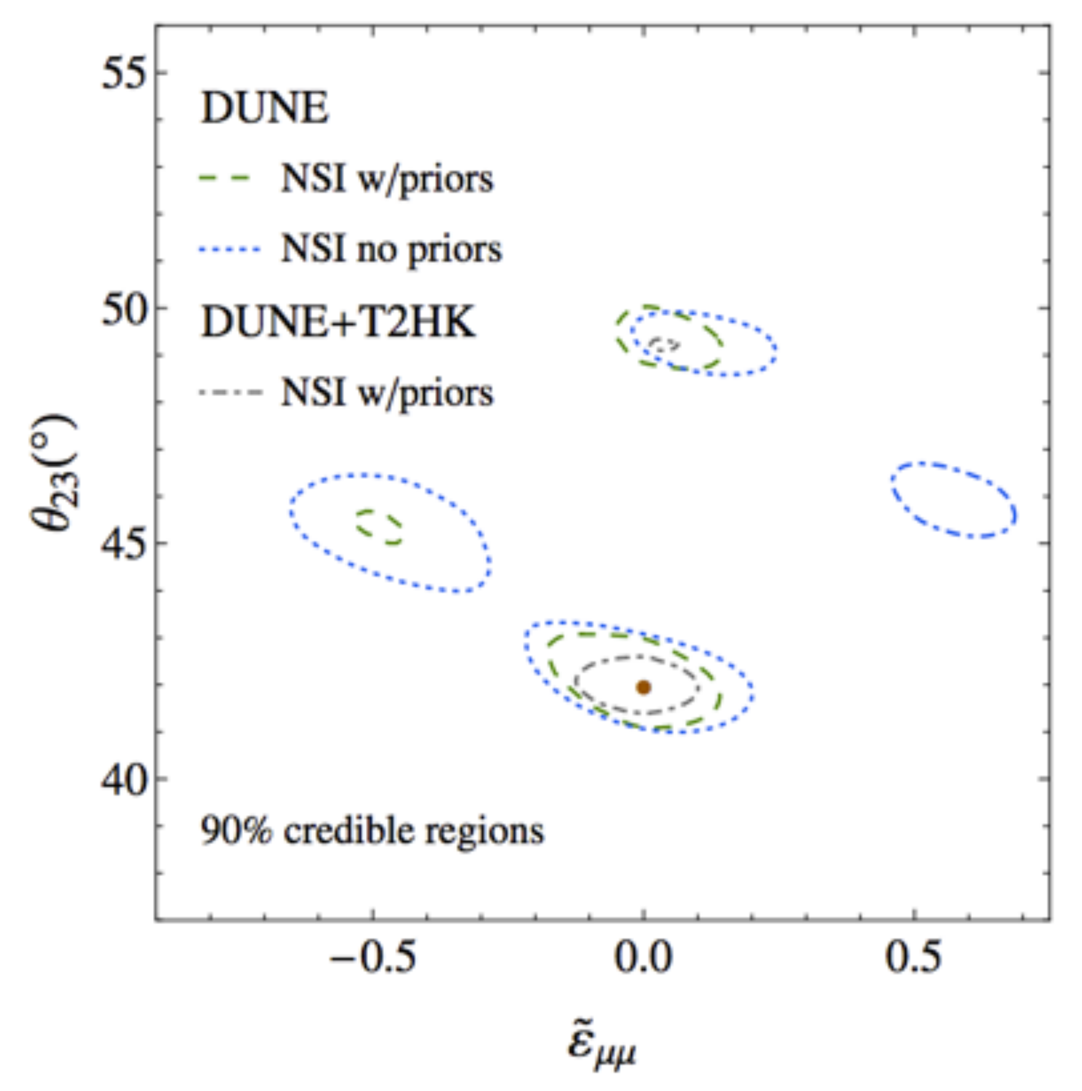


		semileptonic NSI
ϵ_{ee}^{udP}	$[-0.015, 0.015]$	Daya Bay
$\epsilon_{e\mu}^{udL}$	$[-0.026, 0.026]$	NOMAD
$\epsilon_{e\mu}^{udR}$	$[-0.037, 0.037]$	NOMAD
$\epsilon_{\tau e}^{udL}$	$[-0.087, 0.087]$	NOMAD
$\epsilon_{\tau e}^{udR}$	$[-0.12, 0.12]$	NOMAD
$\epsilon_{\tau\mu}^{udL}$	$[-0.013, 0.013]$	NOMAD
$\epsilon_{\tau\mu}^{udR}$	$[-0.018, 0.018]$	NOMAD
		purely leptonic NSI
$\epsilon_{\alpha e}^{\mu eL}$, $\epsilon_{\alpha e}^{\mu eR}$	$[-0.025, 0.025]$	KARMEN
$\epsilon_{\alpha\beta}^{\mu eL}$, $\epsilon_{\alpha\beta}^{\mu eR}$	$[-0.030, 0.030]$	kinematic G_F

NSI at future LBL experiments

(θ_{23}–$\epsilon_{\tau\tau}$) degeneracy in DUNE



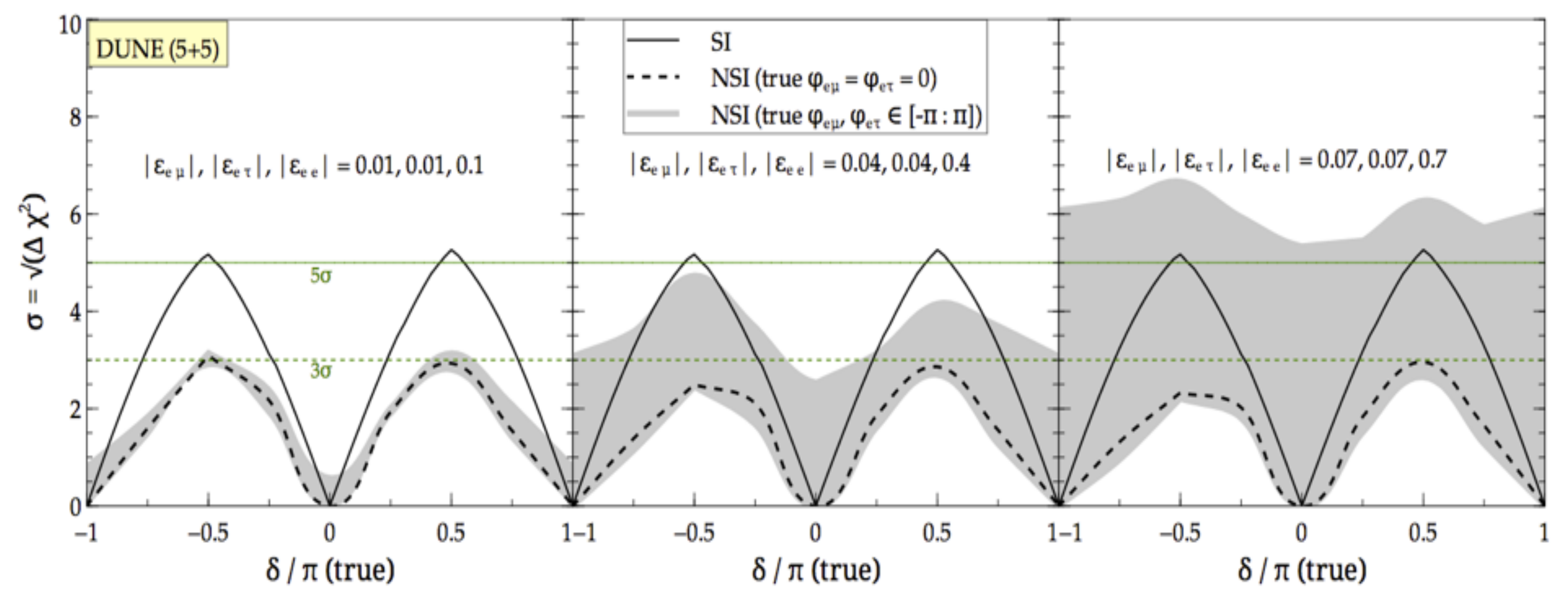


Gouvea and Kelly, NPB 2016

Coloma, JHEP 2016

NSI at future LBL experiments

NSI significantly spoil sensitivity to CP violation in DUNE



Masud and Mehta, PRD 2016

Non-unitary light neutrino mixing

- Most models of neutrino masses -> extra heavy states

Ex: type I seesaw, inverse seesaw

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

Minkowski 1977, Gell-Mann Ramond Slanski 1979, Yanagida 1979, Mohapatra Senjanovic 80, Schechter Valle 1980.

Mohapatra-Valle, 86

- NxN mixing matrix with:

  N(N-1)/2 mixing angles and (N-1)(N-2)/2 Dirac CP phases

$\rightarrow$ (3x3) light neutrino mixing matrix non-unitary in general

General parameterization of NU mixing

- NxN mixing matrix:

Okubo, PTP1962

$$U^{n\times n} = \omega_{n-1\,n}\,\omega_{n-2\,n}\;\ldots\;\omega_{1\,n}\,\omega_{n-2\,n-1}\,\omega_{n-3\,n-1}\;\ldots\;\omega_{1\,n-1}\;\ldots\;\omega_{2\,3}\,\omega_{1\,3}\,\omega_{1\,2}$$

ω_{ij} ≡ complex rotation matrix in the i-j plane

$$\omega_{13} = \begin{pmatrix} c_{13} & 0 & e^{-i\phi_{13}}s_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_{13}}s_{13} & 0 & c_{13} \end{pmatrix}$$

→

$$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix}$$

Hettmansperger et al, JHEP2011

and the (3x3) light block:

$$N = N^{NP}\,U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

See Xing, PRD2012 for n=6

Escrihuela et al, PRD92 (2015)

See also Fernandez-Martinez et al, PLB2007

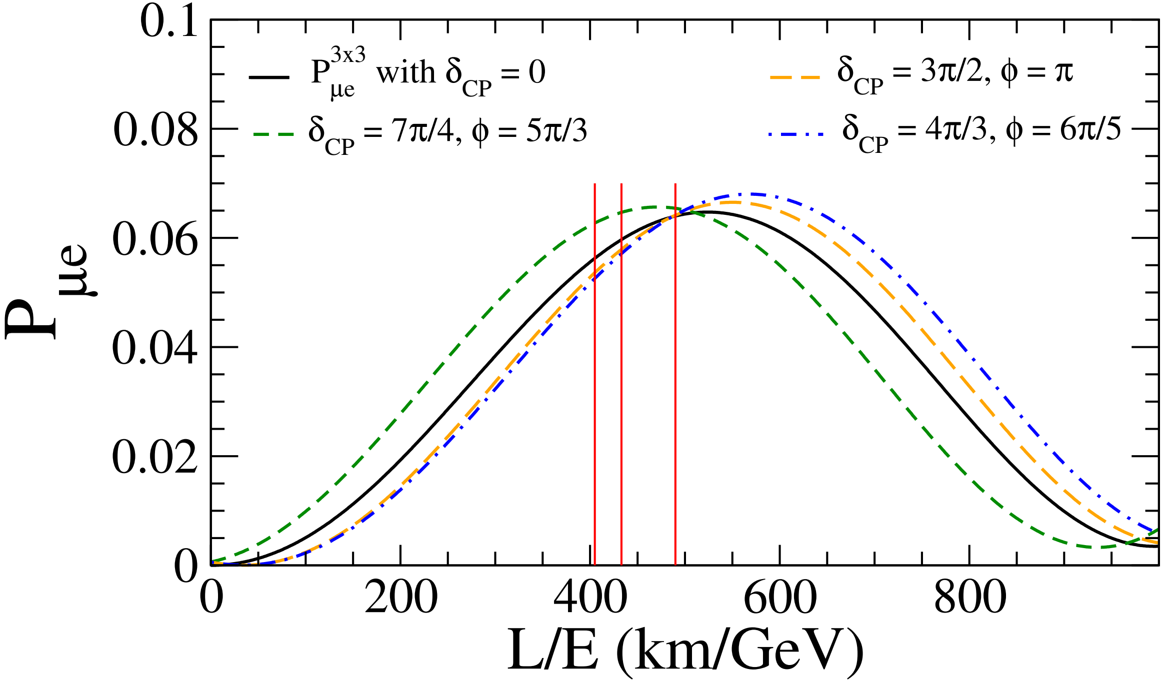
CP degeneracies in Pμe with NU

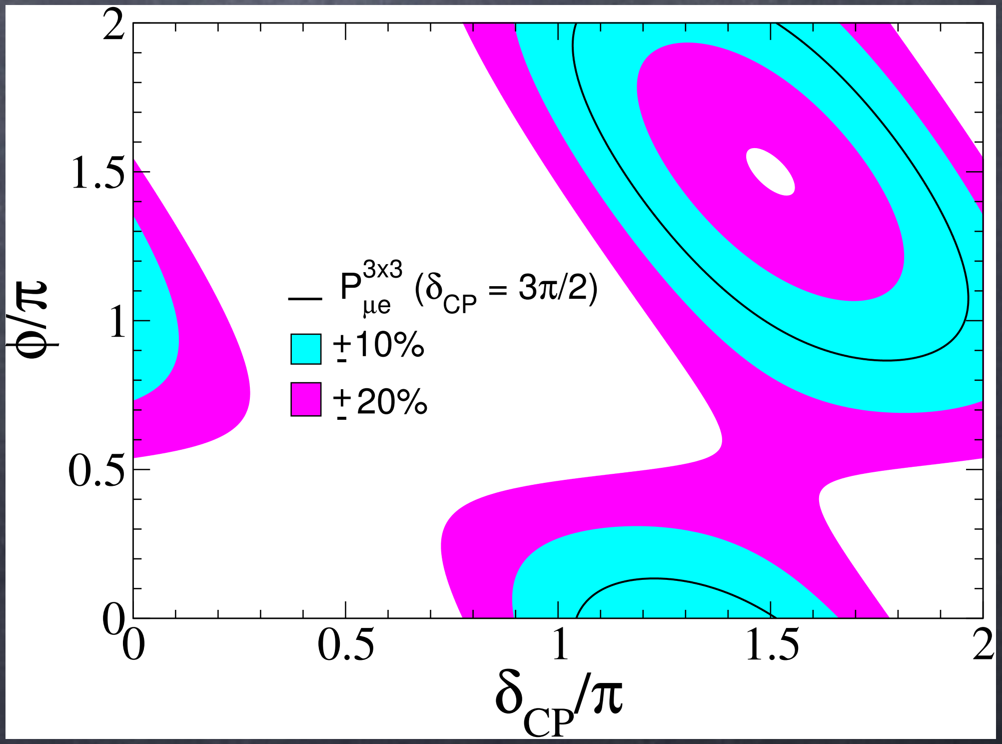
$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times3}_{\mu e} + \alpha_{11}^2\alpha_{22}|\alpha_{21}|P^{I}_{\mu e} + \alpha_{11}^2|\alpha_{21}|^2$$

$$\begin{aligned} P^{3\times3}_{\mu e} &= 4\left(\cos^2\theta_{12}\cos^2\theta_{23}\sin^2\theta_{12}\sin^2\Delta_{21} + \cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}\sin^2\Delta_{31}\right) \\ &+ \sin 2\theta_{12}\sin\theta_{13}\sin 2\theta_{23}\sin 2\Delta_{21}\sin\Delta_{31}\cos\left(\Delta_{31}+\delta_{\rm CP}\right) \end{aligned}$$

$$\begin{aligned} P^{I}_{\mu e} = & - 2\sin 2\theta_{13}\sin\theta_{23}\sin\Delta_{31}\sin\left(\Delta_{31}+\delta_{CP}+\phi\right) \\ & - \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}\sin 2\Delta_{21}\sin\phi \end{aligned}$$

→ degeneracies in the (δ, ϕ) plane



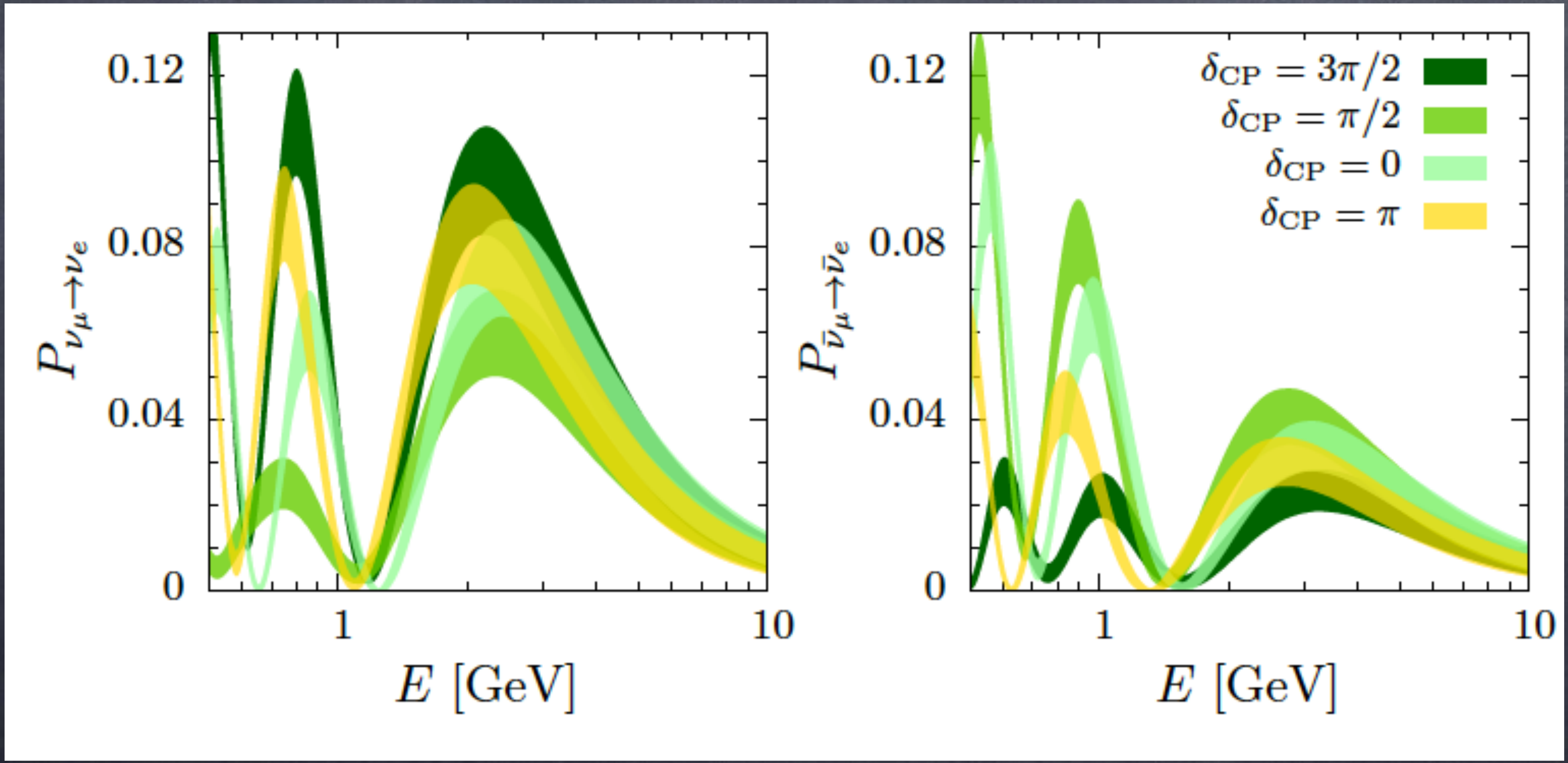


Miranda, MT, Valle, PRL 117 (2016)

NU neutrino oscillations in DUNE

The standard oscillation picture in DUNE gets modified due to NU

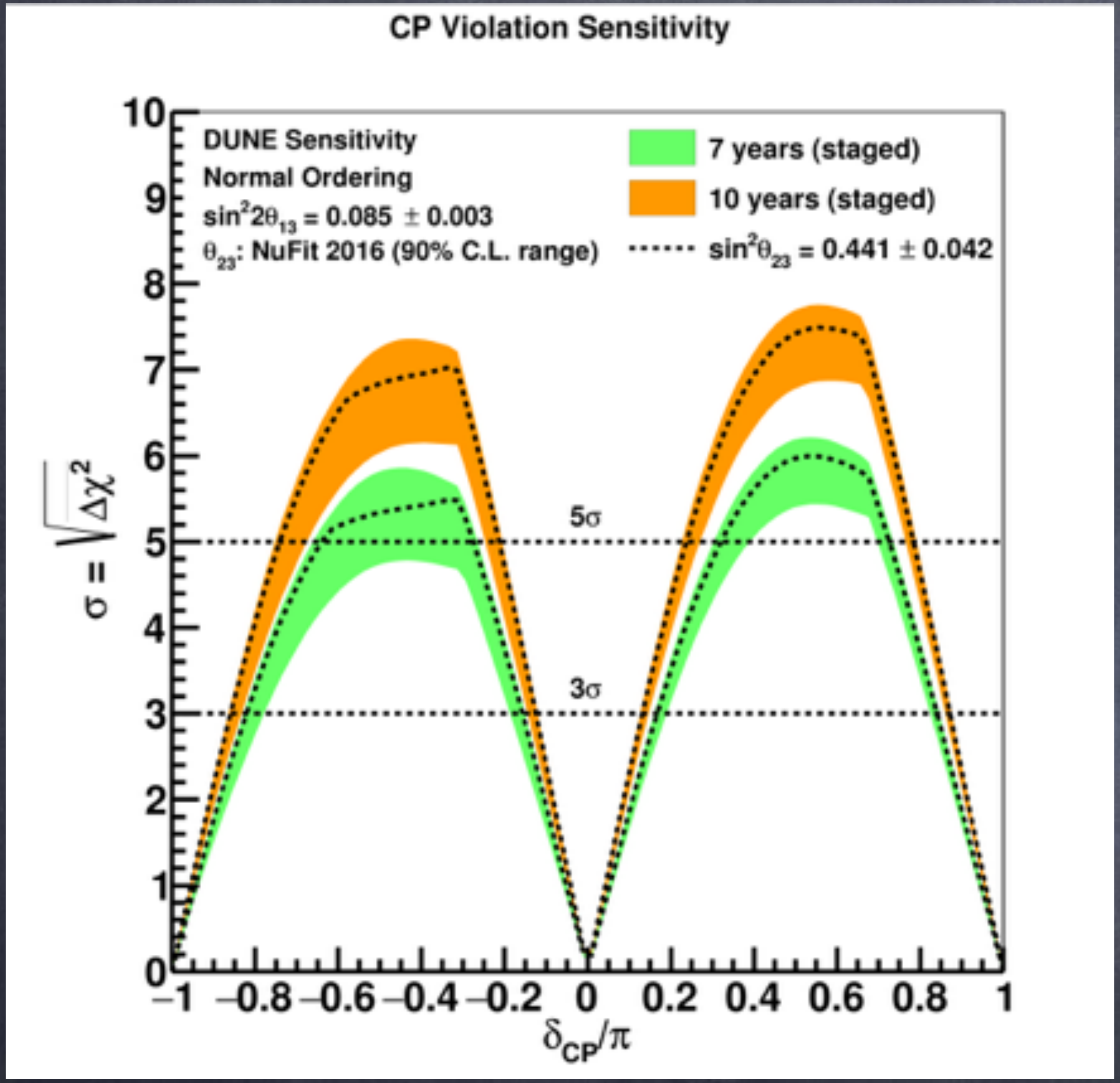
Here: α_{ii} = 1, $|\alpha_{21}|$ = 0.02, ϕ free (α_{3i} enter in $P_{\mu e}$ through matter effects)

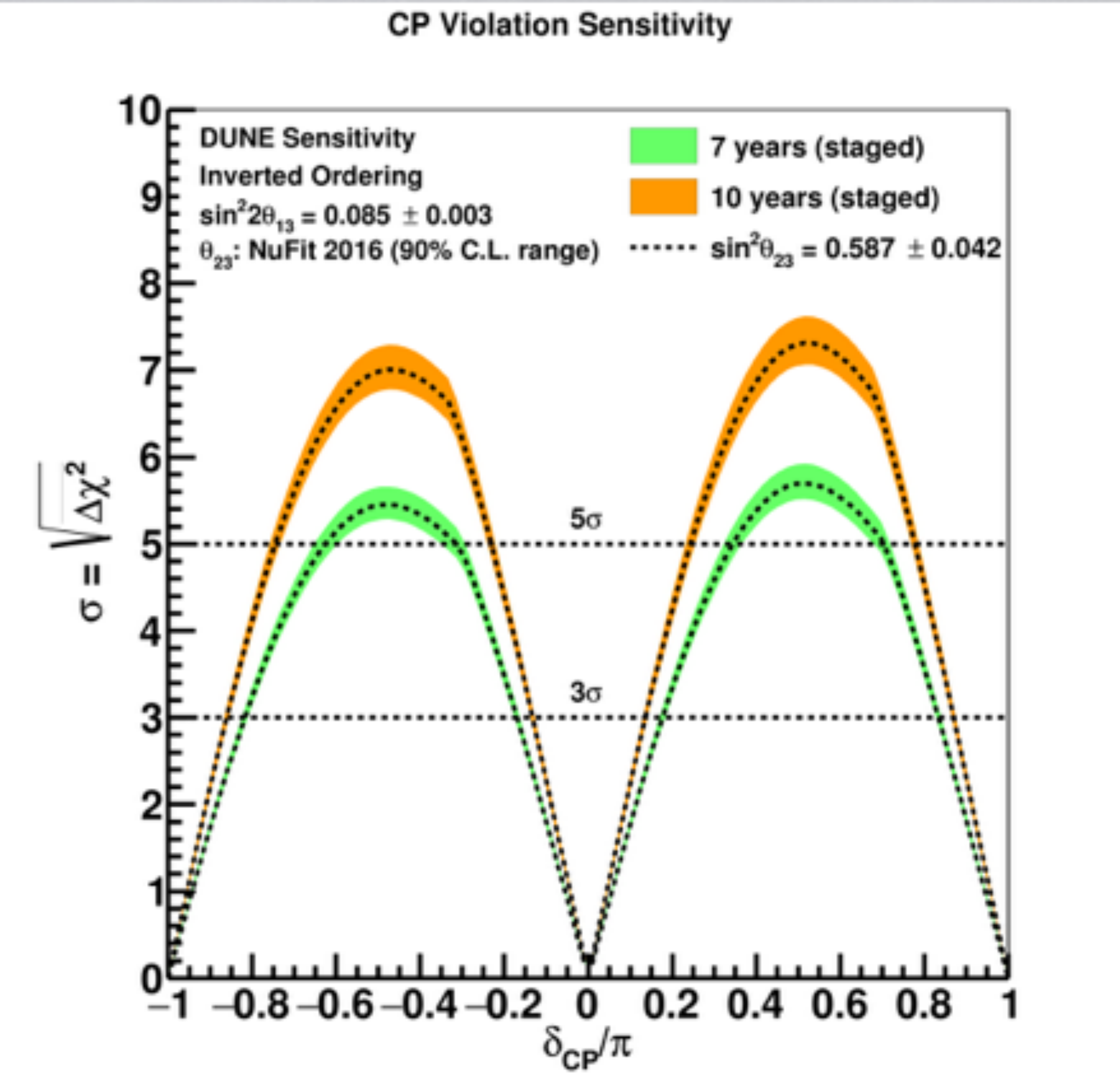


→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E$\gtrsim$ 3 GeV in both channels

Escrihuela et al, NJP 2017

CP violation searches in DUNE

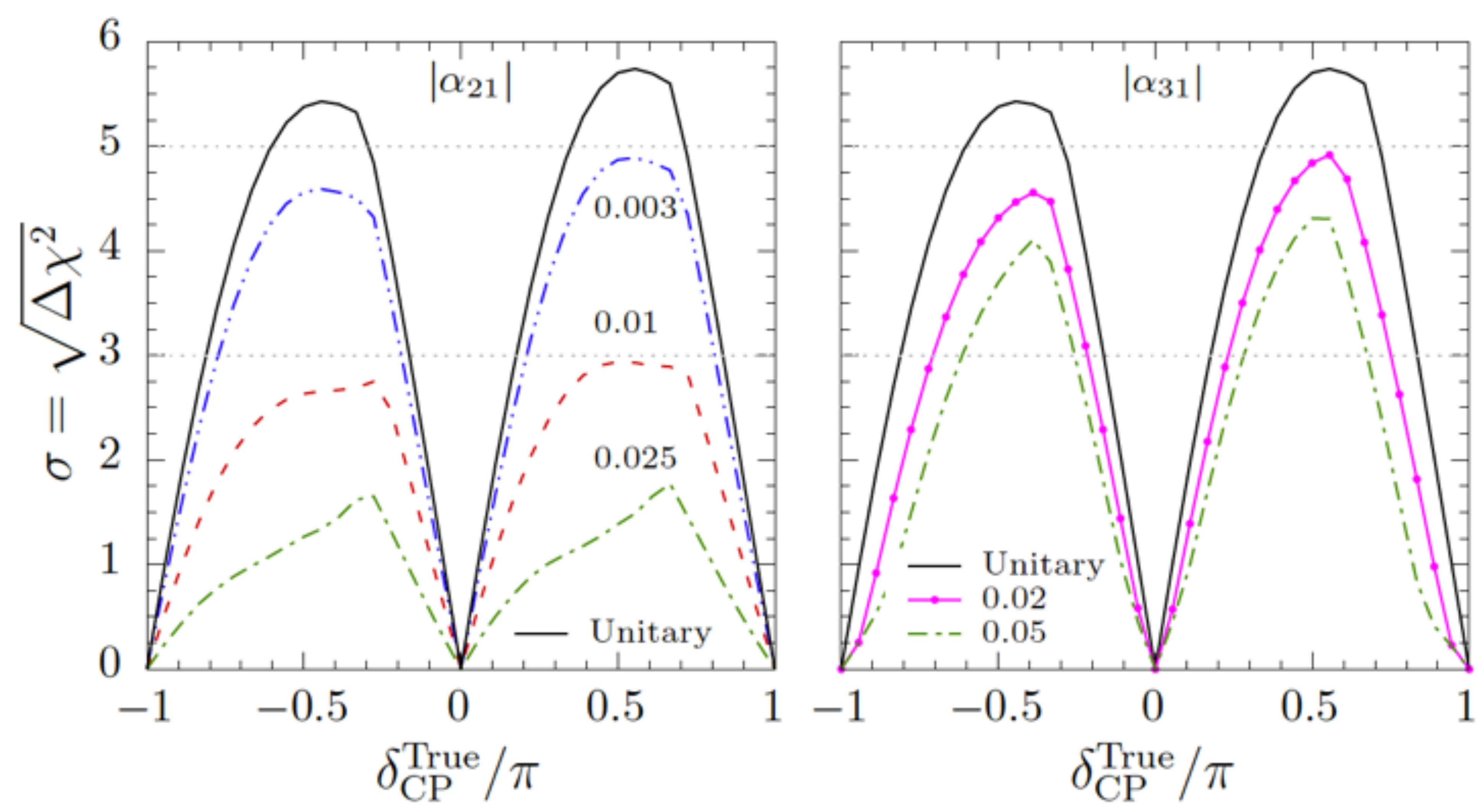




> 5σ sensitivity for some fraction of δ_{CP}

E. Worcester, DUNE Collaboration

DUNE CP sensitivity with NU



Escrihuela et al, NJP 2017

- ➡ probing maximal CP violation may be a challenge for large α_{21}.
- ➡ the impact of α_{31} and α_{32} is less relevant.
- ➡ weaker effect wrt probability analysis due to wide beam in DUNE

Summary (I)

- Neutrinos play an important role in many physical and astrophysical scenarios
- Important discoveries on neutrino physics along last century have provided the first evidence for physics beyond the Standard Model
- Extensions of the SM can explain the smallness of neutrino mass, although the flavor structure is not well understood yet
- Neutrino oscillations are well stablished with observations in several experiments, with natural and artificial sources.
- Oscillation parameters are measured quite accurately ($\lesssim$ 6%) by the combination of different experiments.
- First indications for normal mass ordering and maximal CP violation.

Summary (II)

- there are several indications for sterile neutrinos at eV scale.
- signal from ν_e disappearance at reactor and Gallium experiments are consistent, and not in disagreement with other data samples
- hint from $\nu_\mu \to \nu_e$ appearance in LSND and MiniBooNE are in disagreement with negative signals in ν_μ disappearance experiments.
- consistent picture of eV-sterile neutrinos in tension with cosmology
- the absolute scale of neutrino mass is bounded from cosmological and laboratory measurements, below 1 eV.
- new physics beyond the SM may affect significantly the current picture of neutrino oscillations.
- NSI with matter and Non-unitary mixing expected in models of neutrino masses may reduce the sensitivity at current and future experiments.