Neutrino Physics (II)

Mariam Tórtola

IFIC, Universitat de València/CSIC

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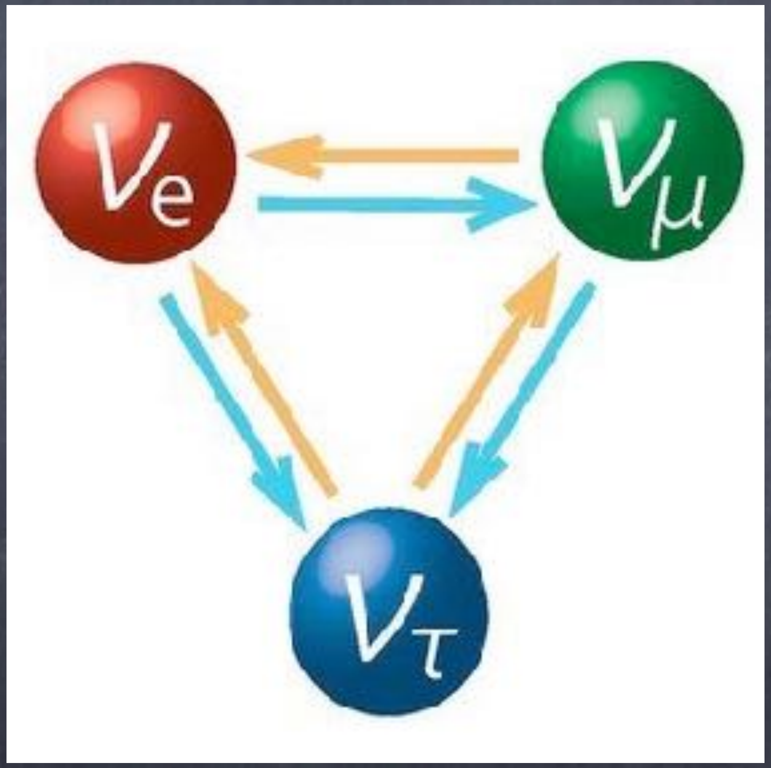
Outline

- Historical 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
- Beyond three-neutrino flavours: sterile neutrinos
- The absolute scale of neutrino mass
- Future prospects in neutrino oscillations
- Neutrino physics beyond the Standard Model

Three-flavour neutrino oscillations



two-neutrino approximation:

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

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

$\theta_{12}, \Delta m^2_{21}$	$\theta_{13}, \Delta m^2_{31}$	$\theta_{23}, \Delta m^2_{31}$
solar + KamLAND	SBL reactor	atmospheric + LBL

Precision measurements of parameters require full 3-nu analysis

three-neutrino analysis:

$\theta_{12}, \Delta m^2_{21}, \theta_{13}$	$\theta_{13}, \Delta m^2_{31}, \theta_{12}$	$\theta_{23}, \Delta m^2_{31}, \theta_{13}, \Delta m^2_{21}, \delta$

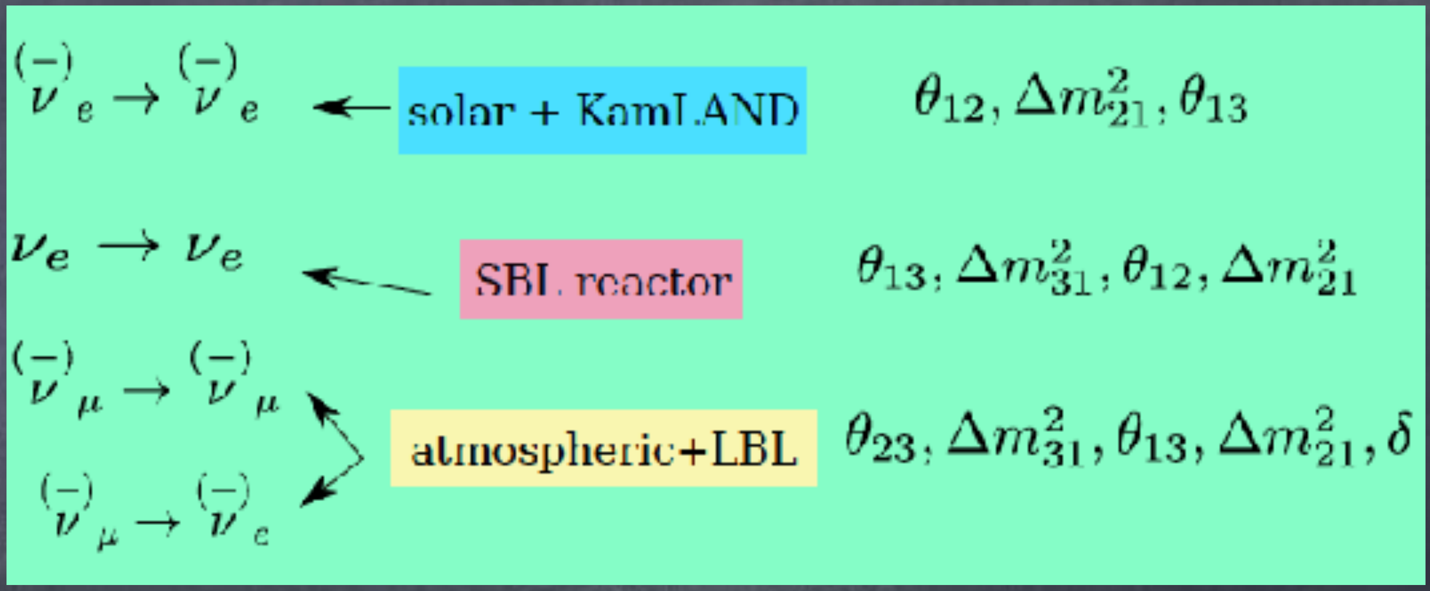
all data samples are connected → a global 3ν analysis is required.

Neutrino oscillation analysis methodology

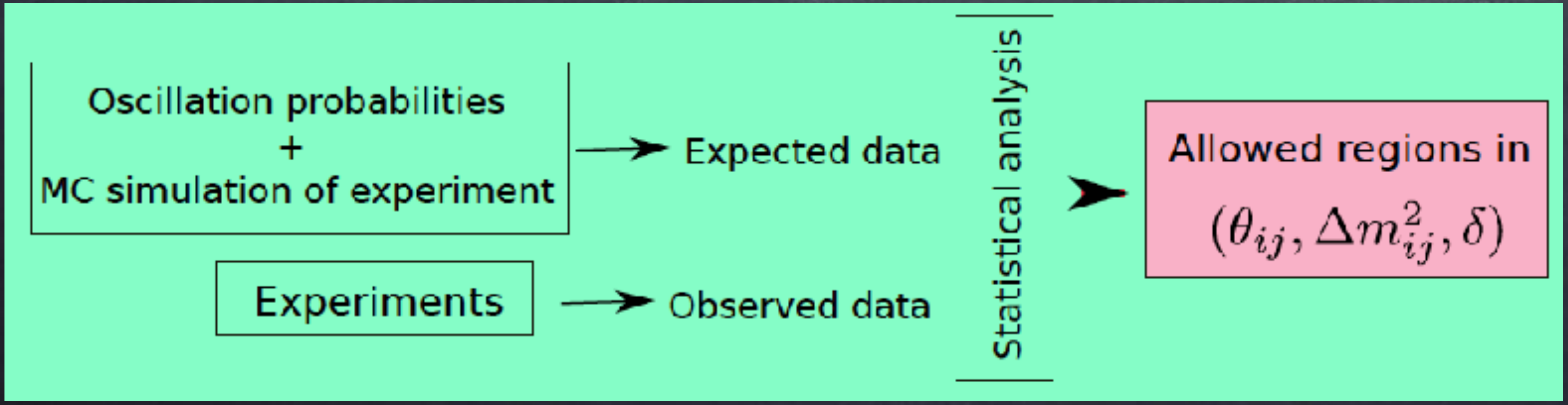
Experimental data

- solar: Homestake, Gallex/GNO, SAGE, Borexino, SNO, Super-K
- reactor: KamLAND, Double Chooz, RENO, Daya Bay
- atmospheric: Super-K, IceCube, ANTARES
- LBL: K2K, MINOS, T2K, NovA

Parameter sensitivity



Methodology



The solar neutrino sector

Solar neutrinos

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

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

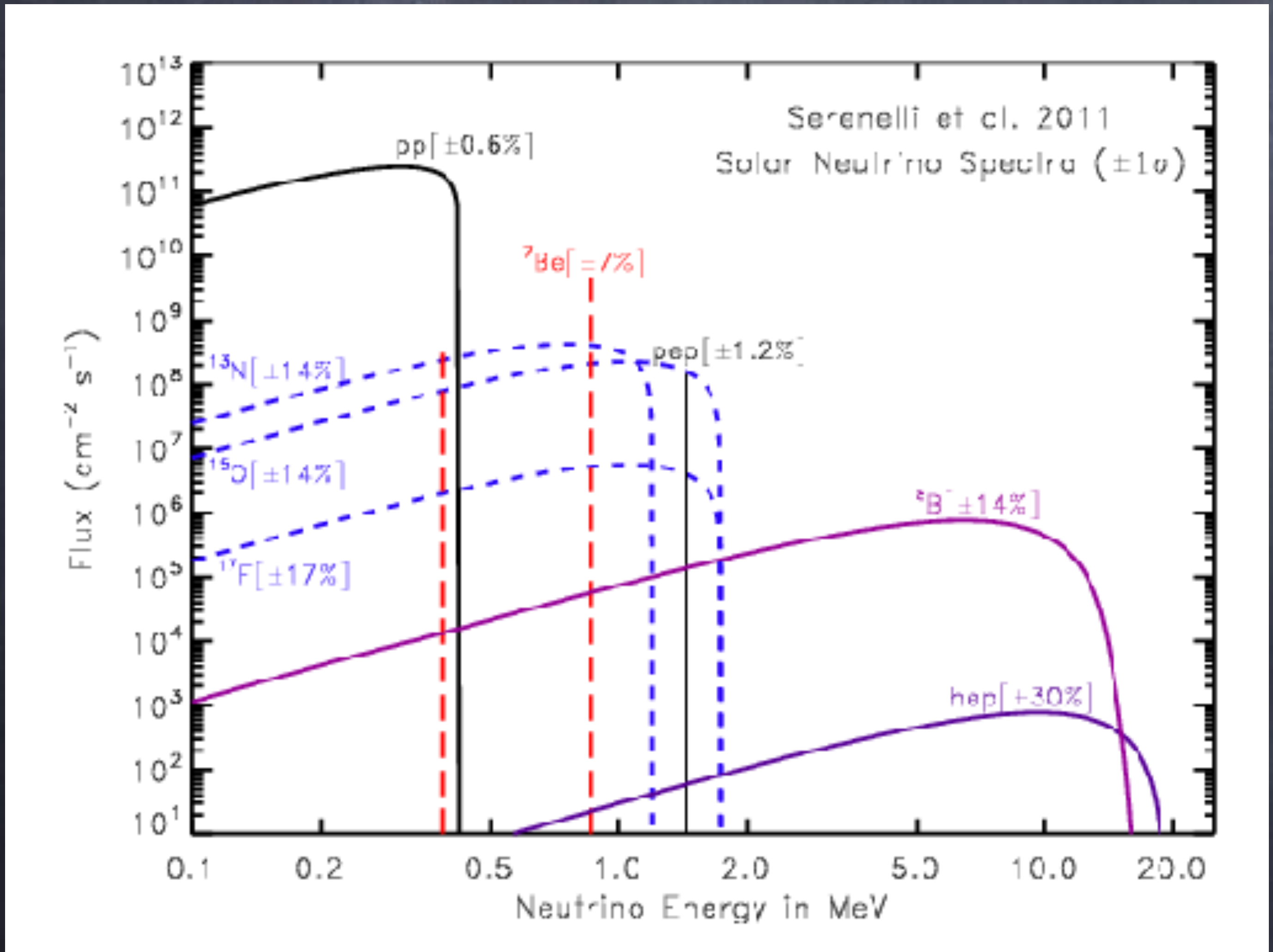
pp cycle

CNO

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

ν fluxes

SSM predictions



ν energy spectra

Radiochemical solar experiments

Homestake (Cl) experiment: 1967-2002

- gold mine in Homestake (South Dakota)
- 615 tons of perchloro-ethylene (C_2Cl_4)
- detection process (radiochemical)

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

$E_{th} = 0.814$ MeV

- only 1/3 of SSM prediction detected:

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

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

Gallium radiochemical experiments:

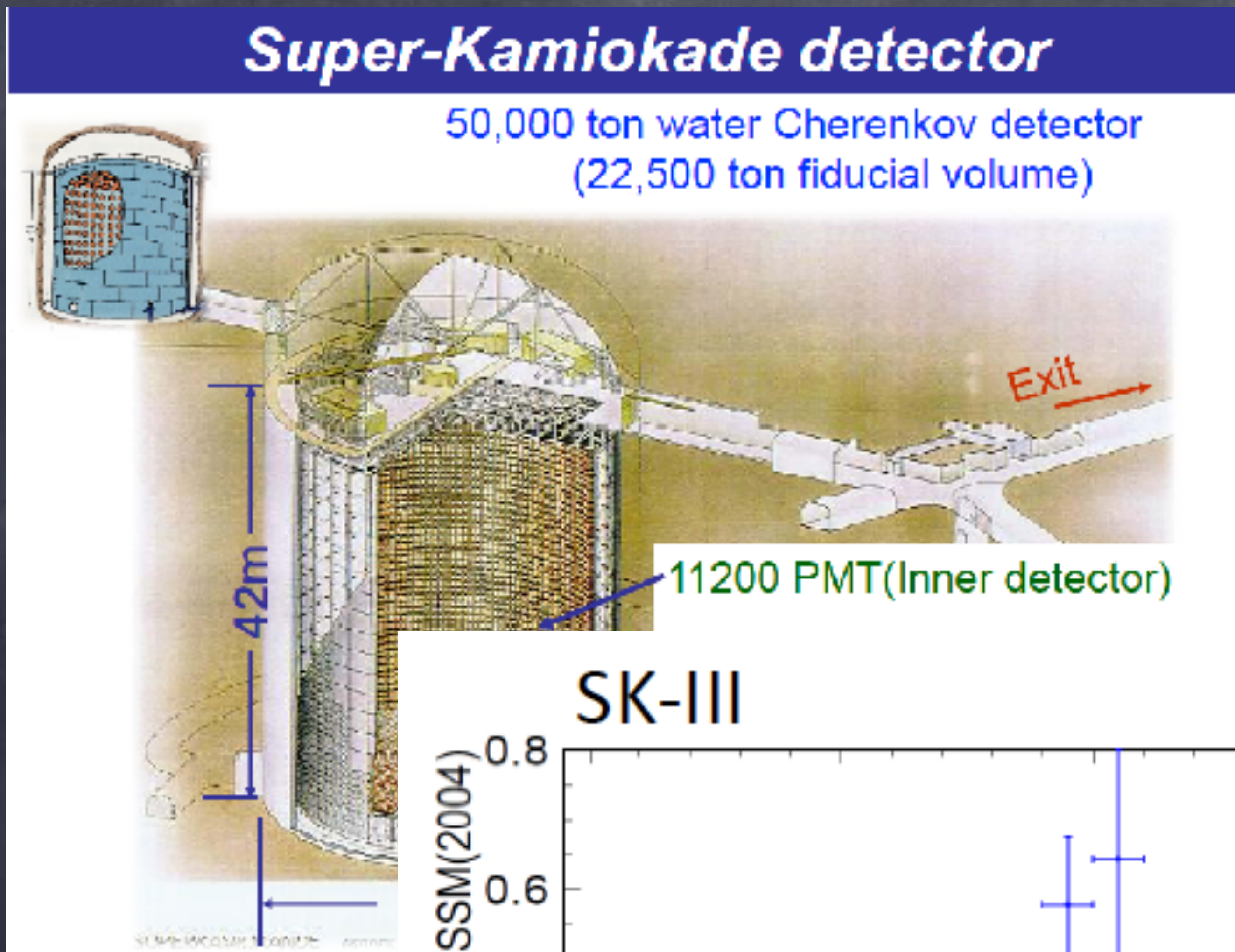
$$R_{SAGE} = 66.9 \pm 3.9 \text{ (stat.)} \pm 3.6 \text{ (syst.) SNU}$$

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

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

→ 50% deficit

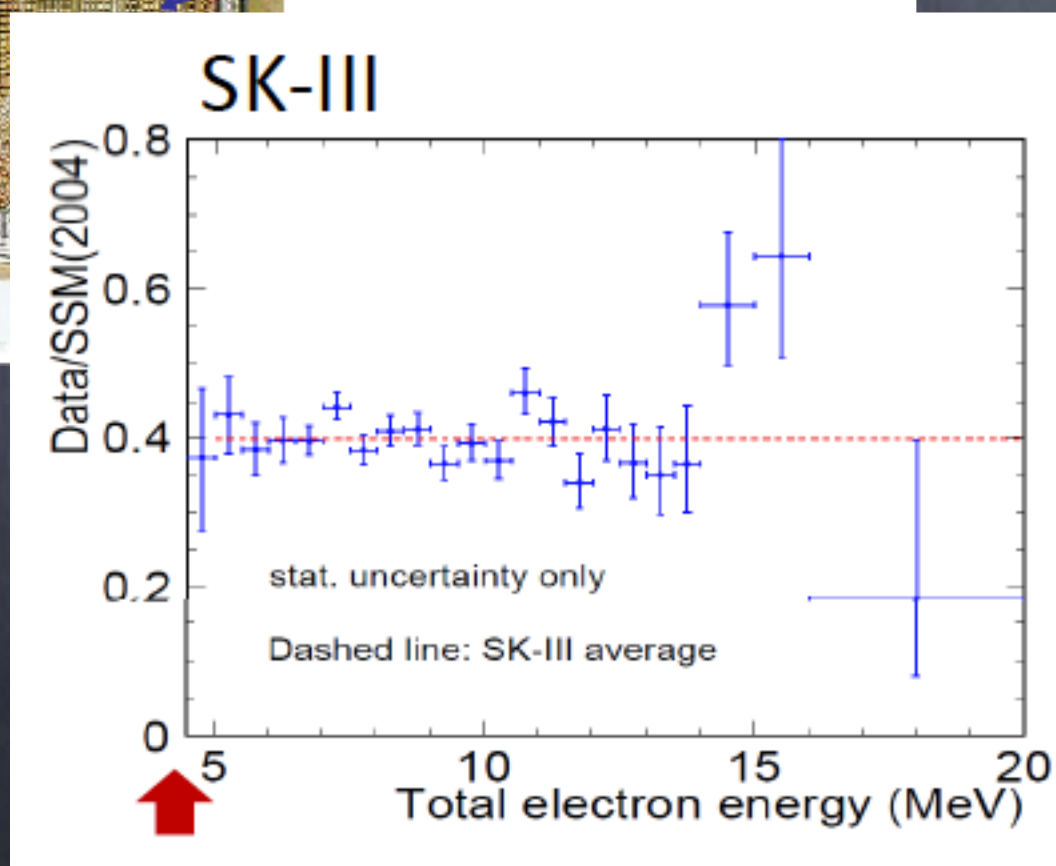
Solar neutrinos in Super-Kamiokande

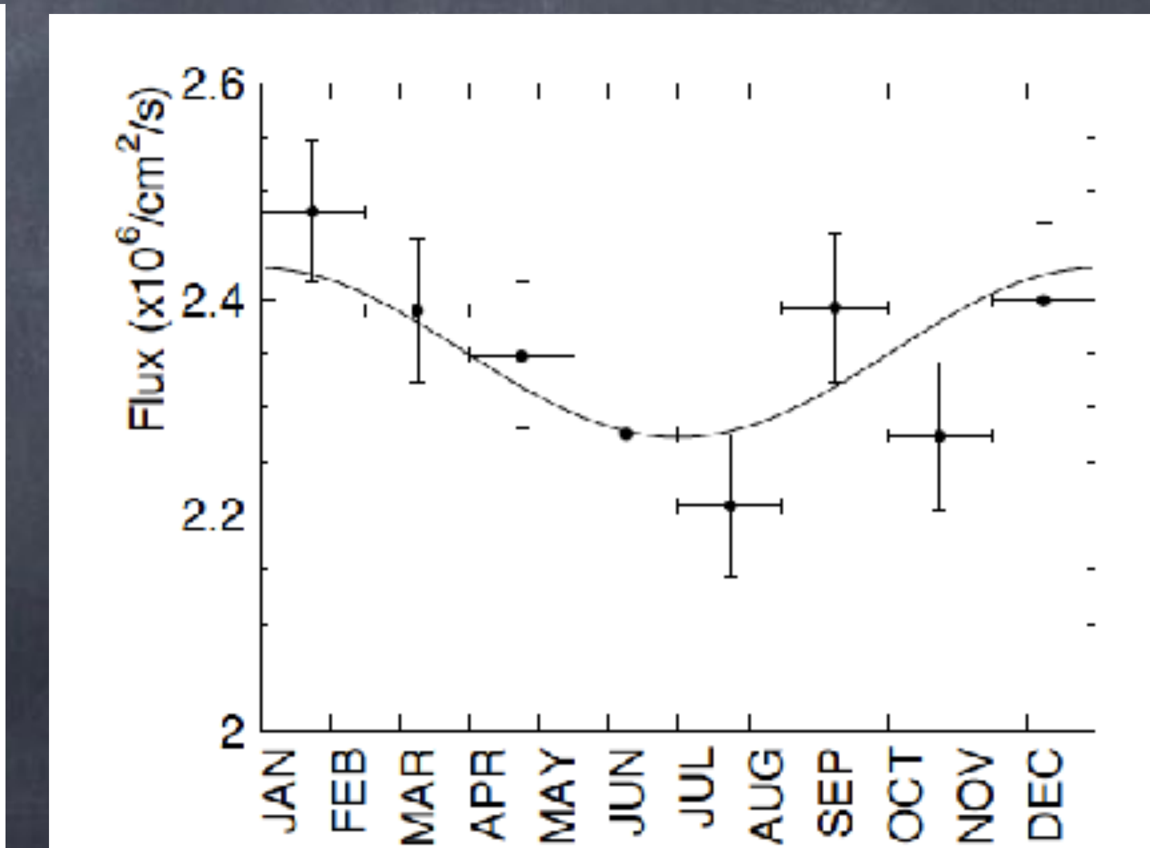


- water cherenkov detector
- sensitive to all neutrino flavors:

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

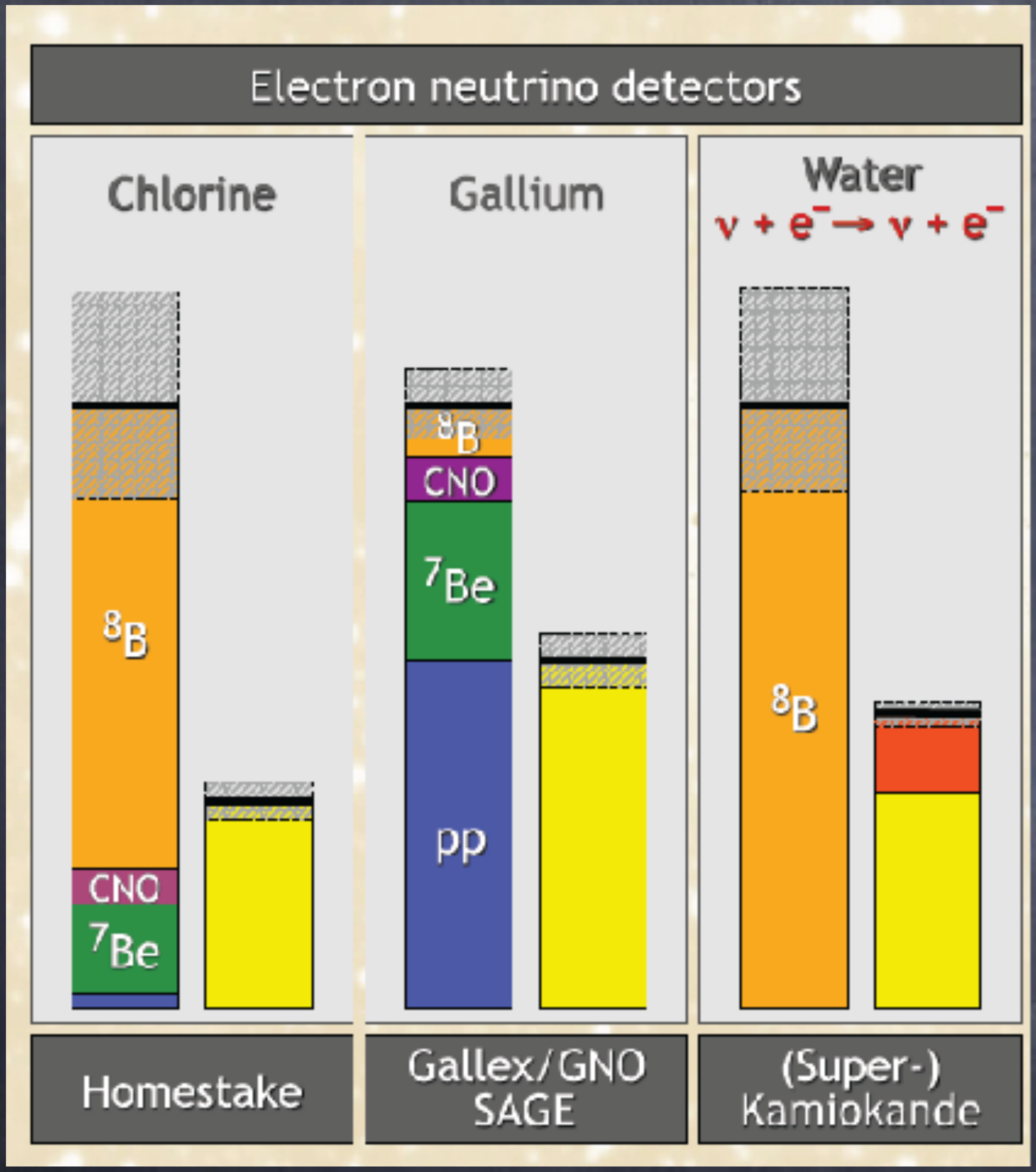
- threshold energy ~ 4-5 MeV
- real-time detector: (E, t)





➡ Super-Kamiokande detects less neutrinos than expected according to the SSM (40%)

The solar neutrino problem



~30% ~50% ~40%

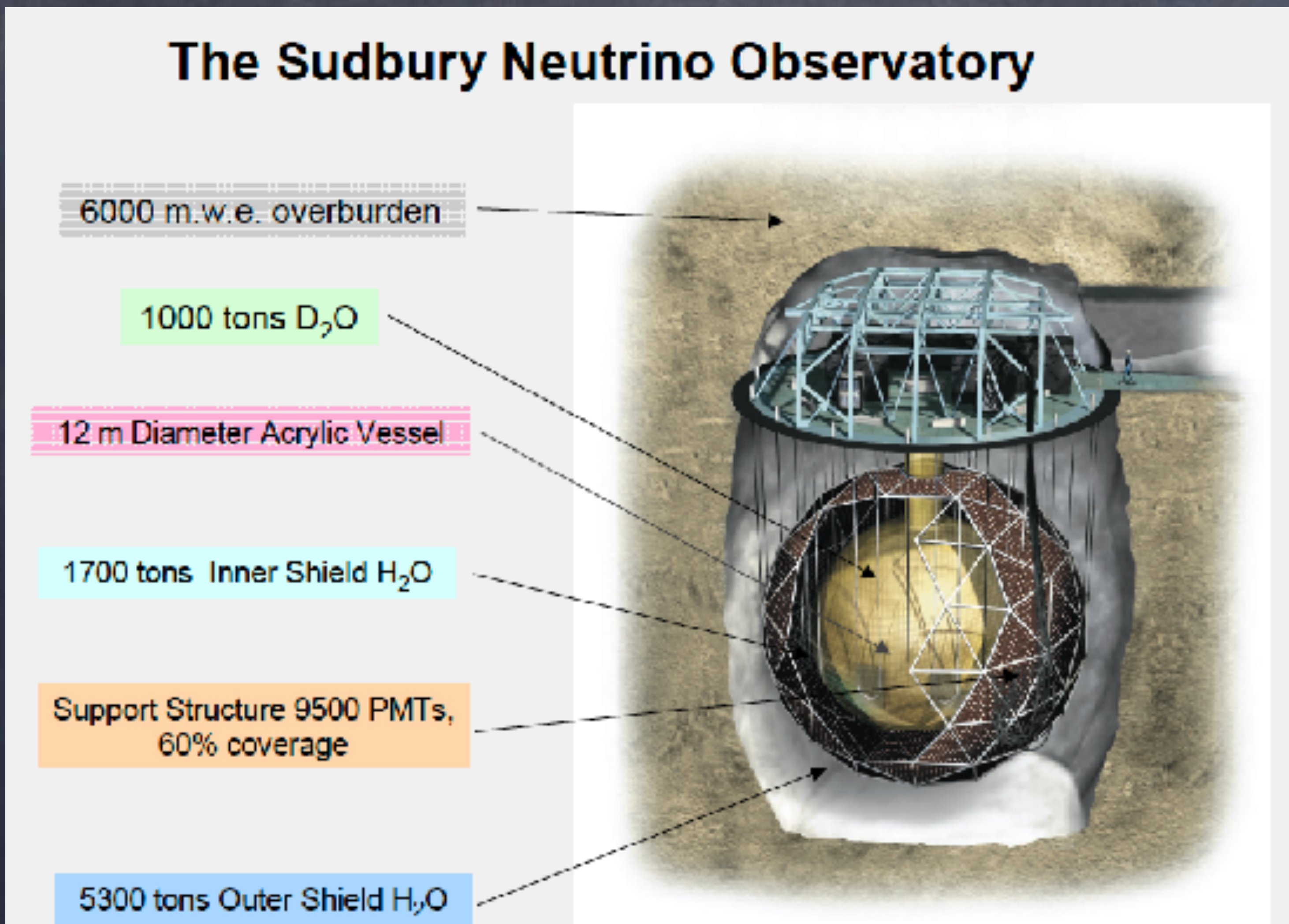
➡ All the experiments detect less neutrinos than expected (30-50%)

Why the deficit observed is different?

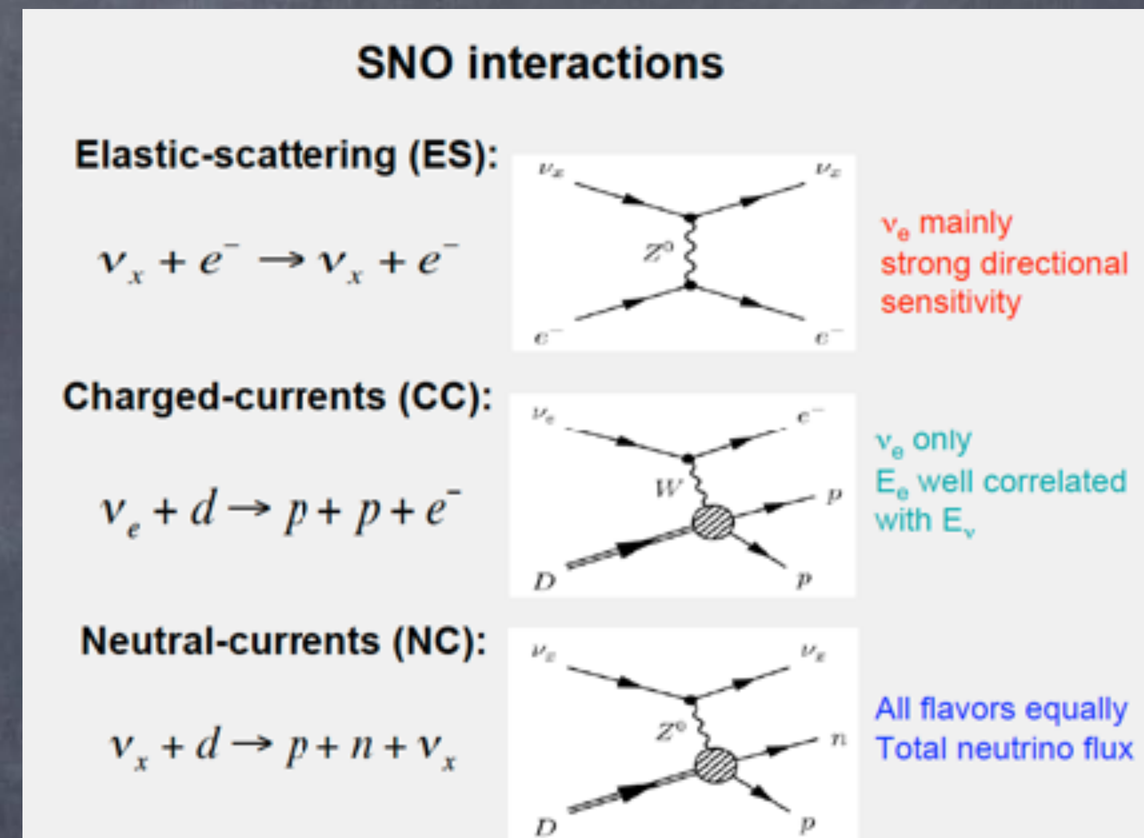
- different type of neutrinos observed
  - → radiochemical: ν_e while Super-K: ν_α
- different E-range sensitivity:
  - → Cl: E > 0.814 MeV
  - → Ga: E > 0.233 MeV
  - → Super-K: E > 5 MeV

Tutorials

The Sudbury Neutrino Observatory, SNO



SNO is sensitive to all ν flavors:



ν_e flux (CC):

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

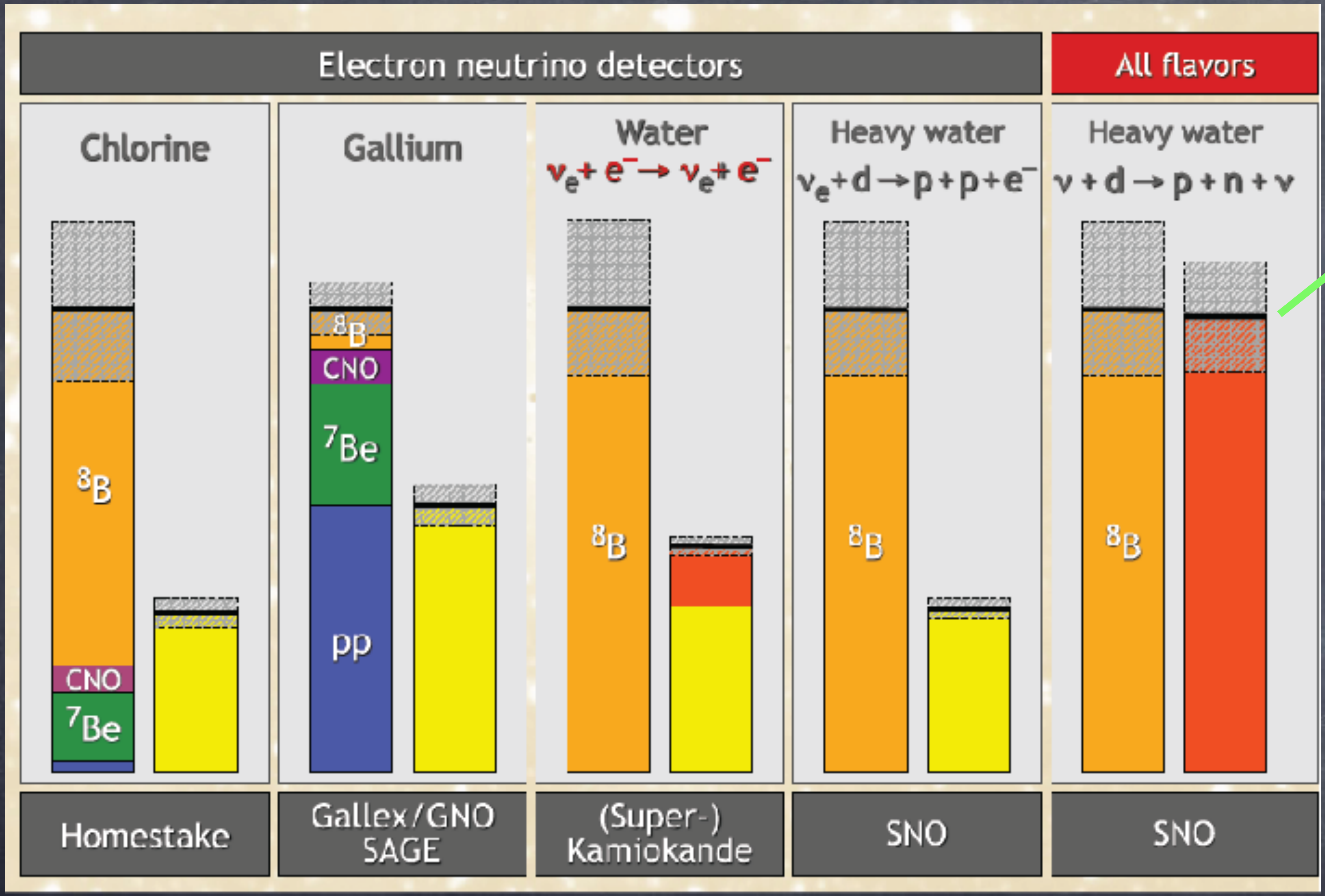
only 30% of the produced solar neutrinos are detected as ν_e

total ν flux (NC):

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

100% !!

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 ??

The KamLAND reactor experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector

* reactor experiment:

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

* 55 commercial power reactors

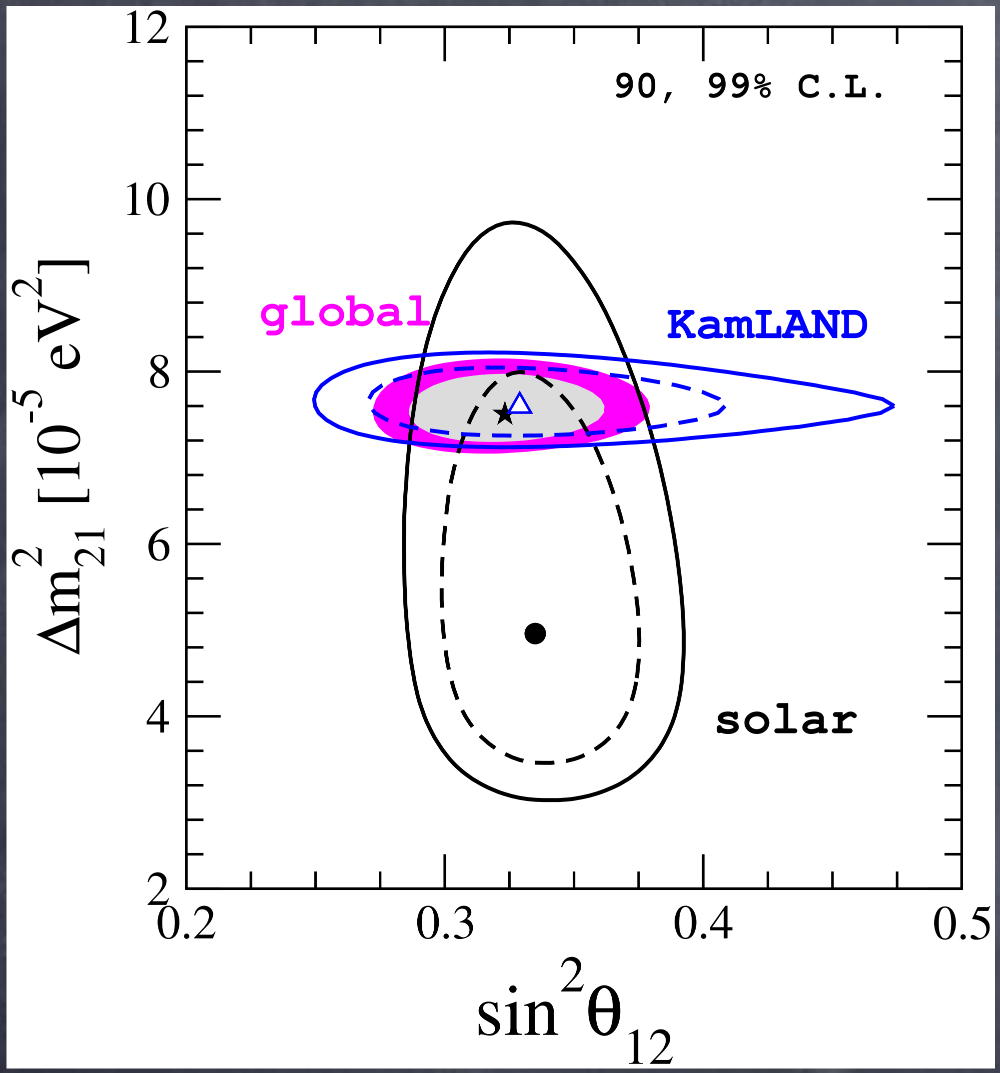
* average distance ~ 180 km

→ 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

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

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, PLB 782 (2018) 633

➡ 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

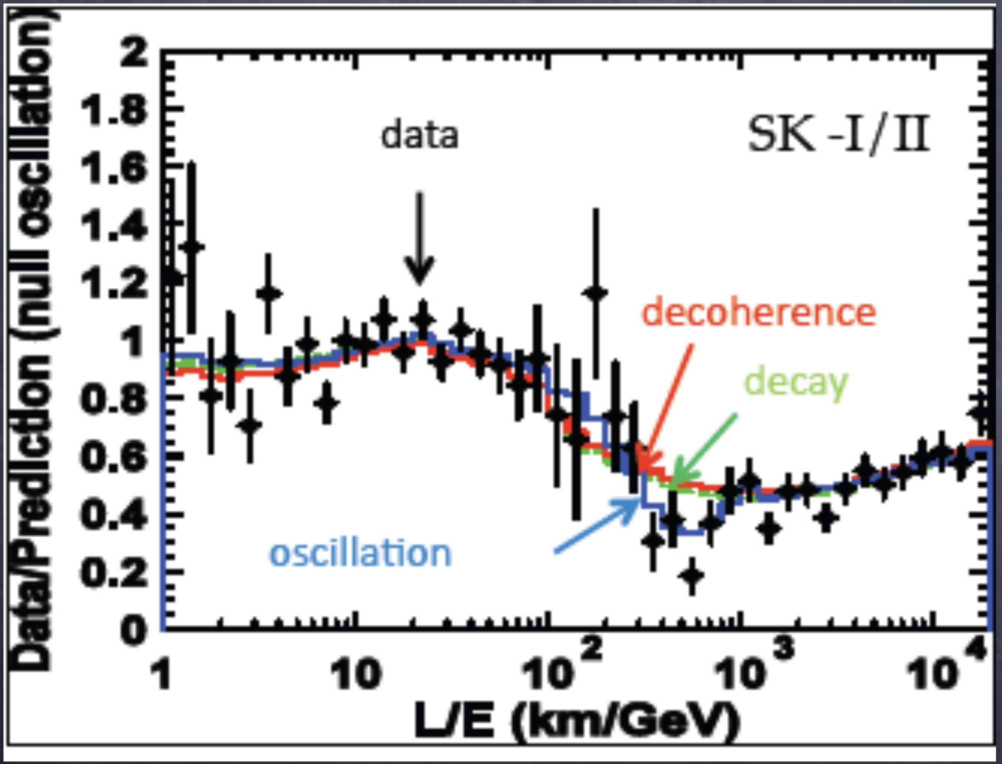
The atmospheric neutrino sector

Atmospheric neutrinos

1998: Evidence ν_μ oscillations at Super-K

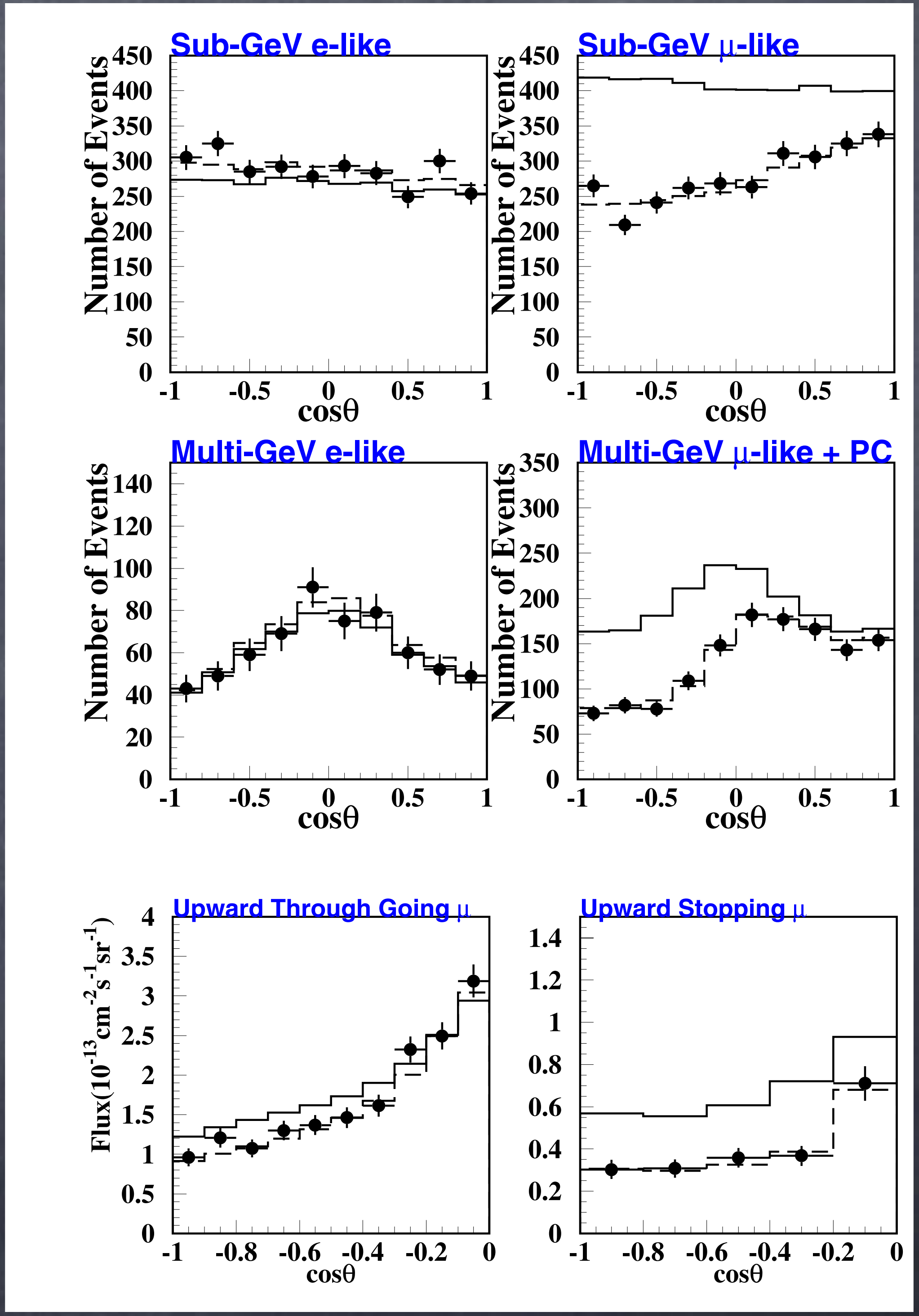
oscillation channel $\nu_\mu \rightarrow \nu_\tau$

2004: oscillatory L/E pattern



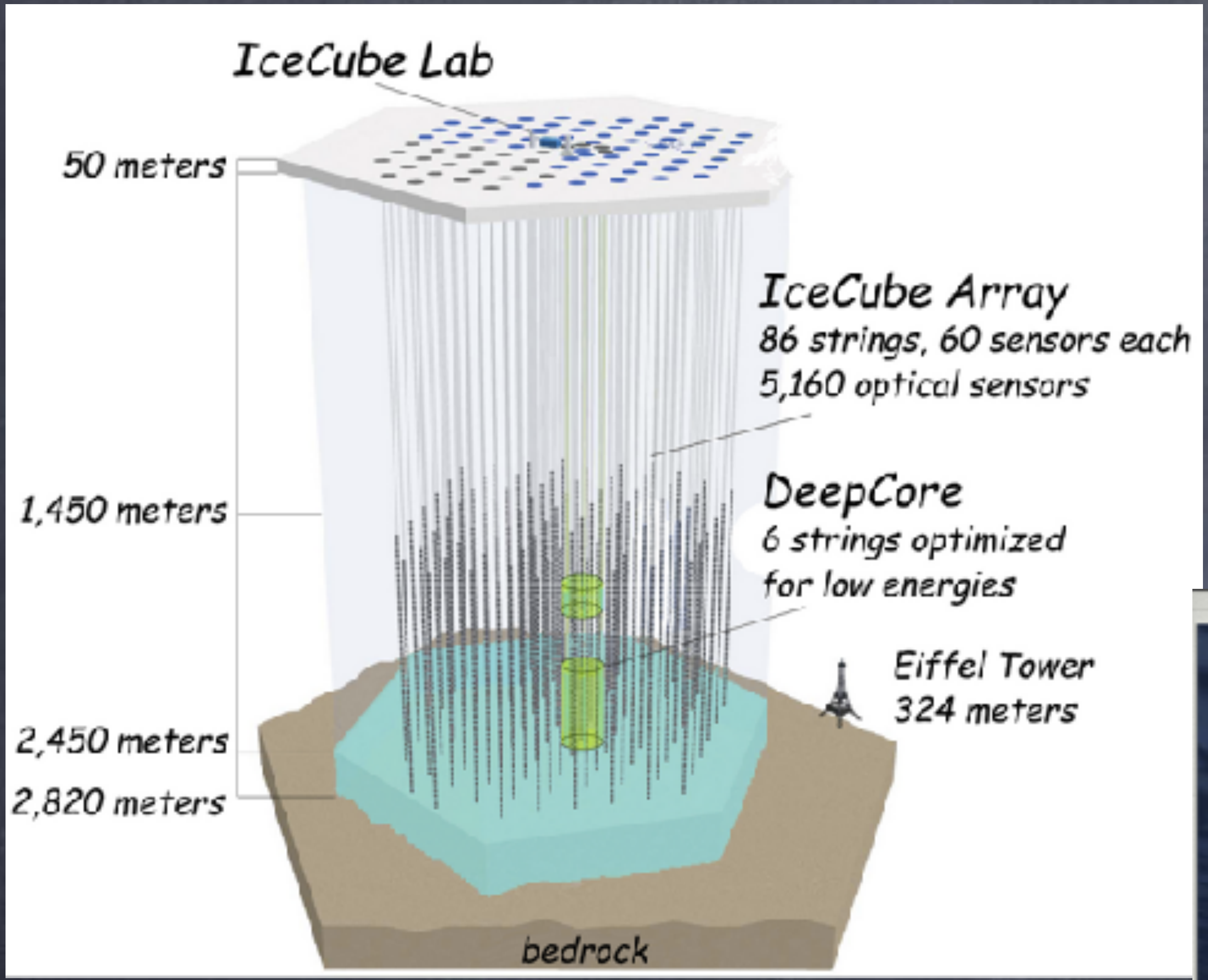
Super-K Coll, PRL93, 101801 (2004)

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

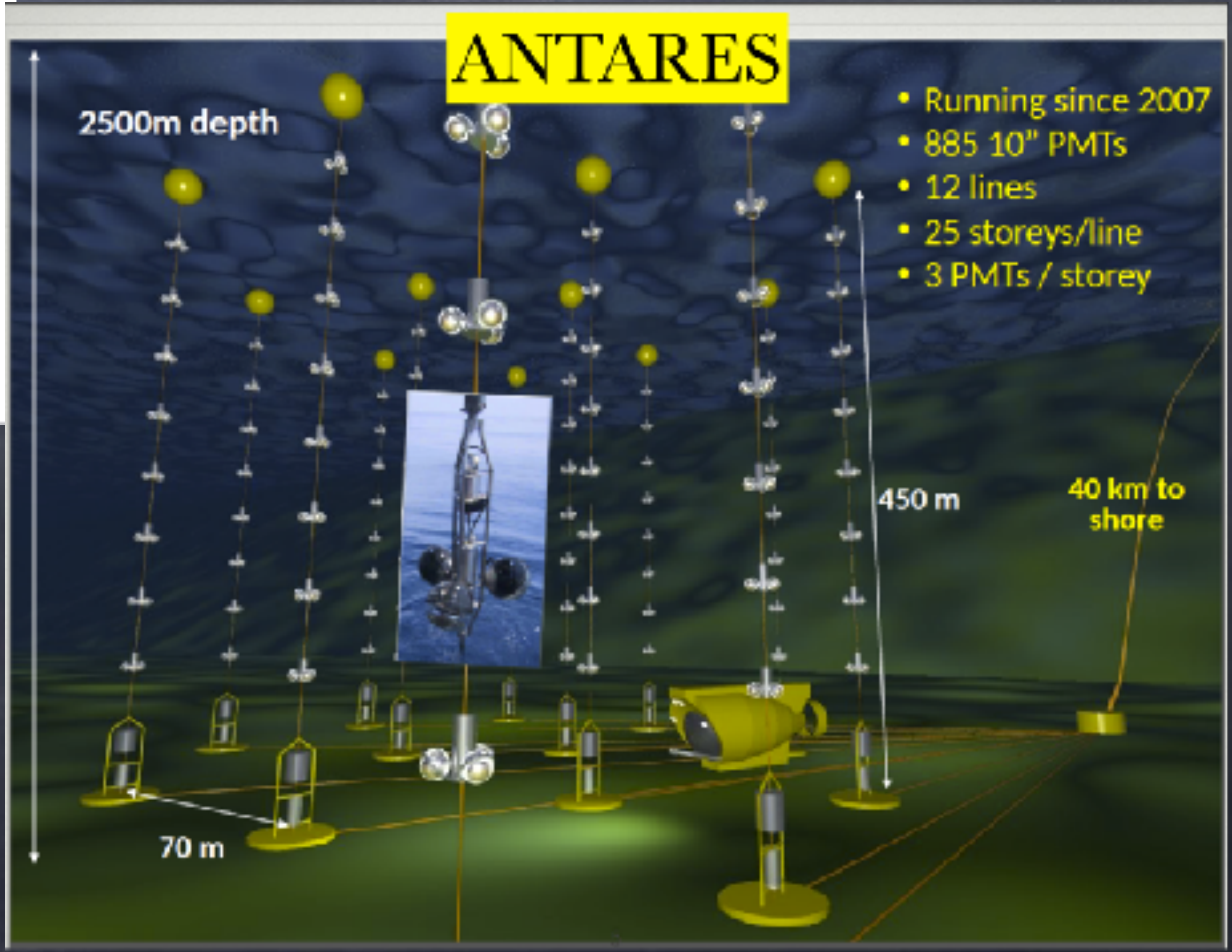


Super-K Coll., PRL 8 (1998) 1562.

Neutrino telescopes



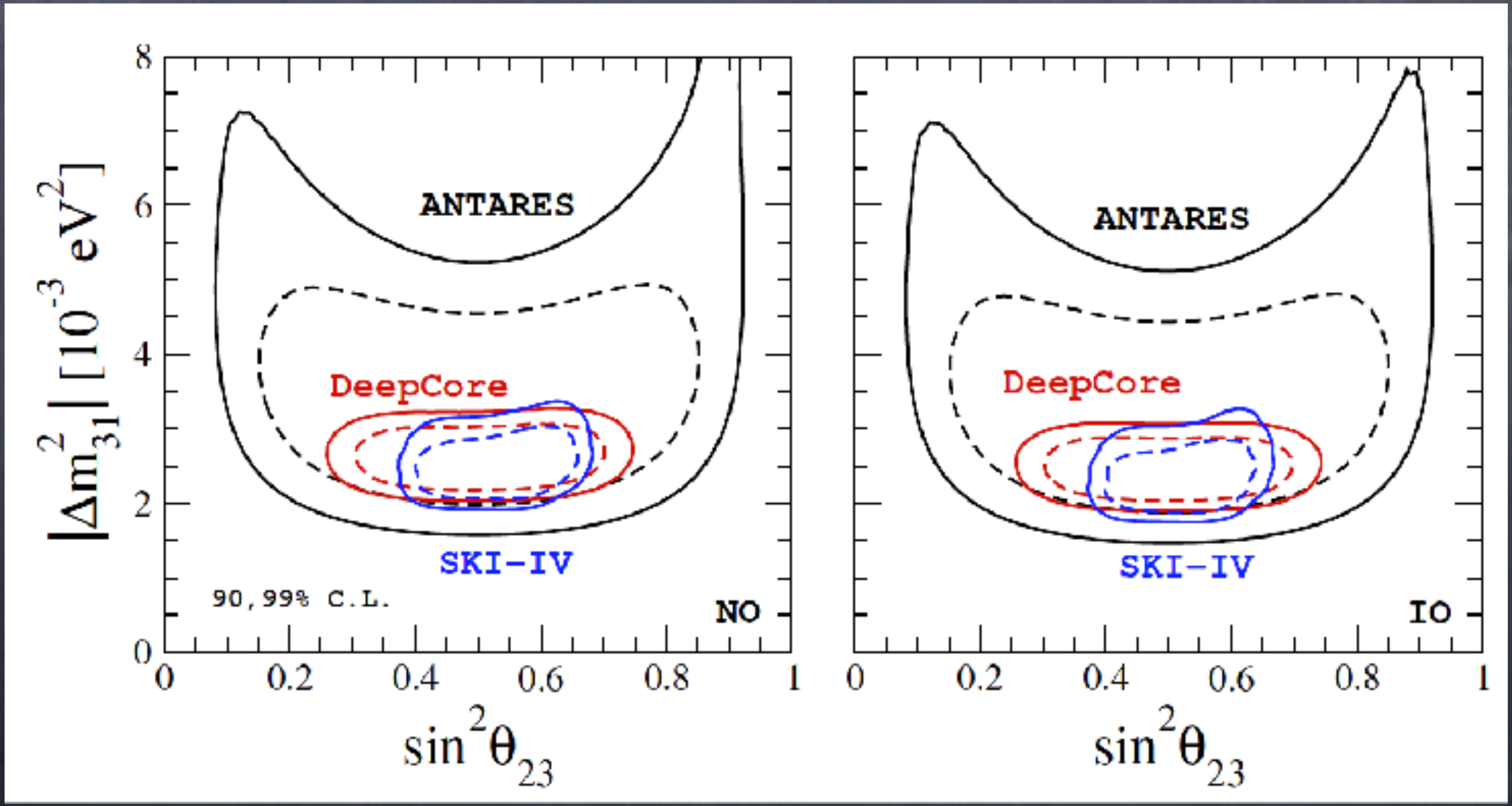
IceCube-DeepCore,
$E_\nu \in [6\text{–}56 \text{ GeV}]$



ANTARES
$E_\nu > 20$ GeV

Atmospheric neutrino experiments

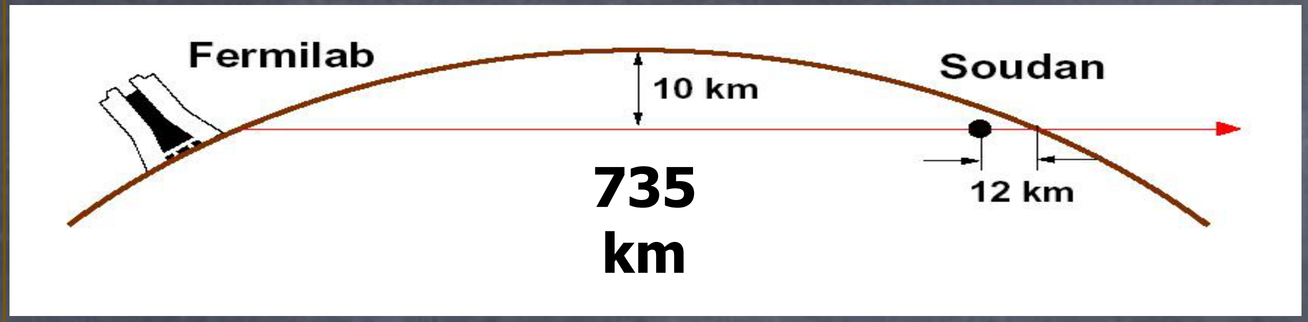
- Super-Kamiokande (phases I to IV) — Wendell et al, PRD81 (2010)
- IceCube-DeepCore (3 years of data) — Aartsen et al, arXiv:1410.7227
- ANTARES (863 days of data) — Adrián-Martínez et al, PLB 2012



de Salas et al, PLB 782 (2018) 633

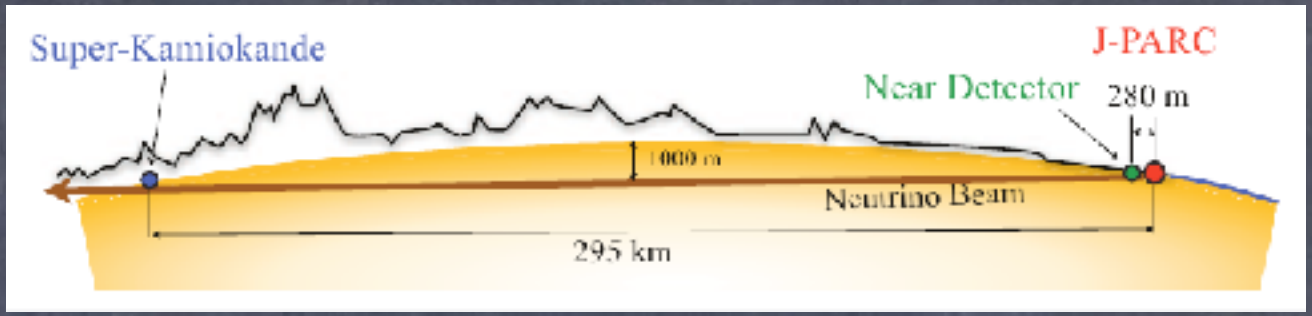
LBL accelerator neutrino experiments

MINOS



Feb2005 - Jun2016

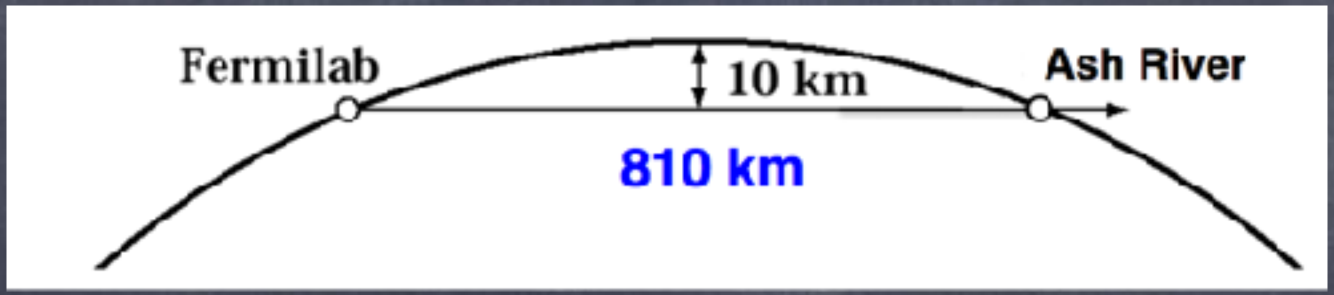
T2K



From Jan2010

running in antineutrino channel

NovA



From Oct2014

running in antineutrino channel

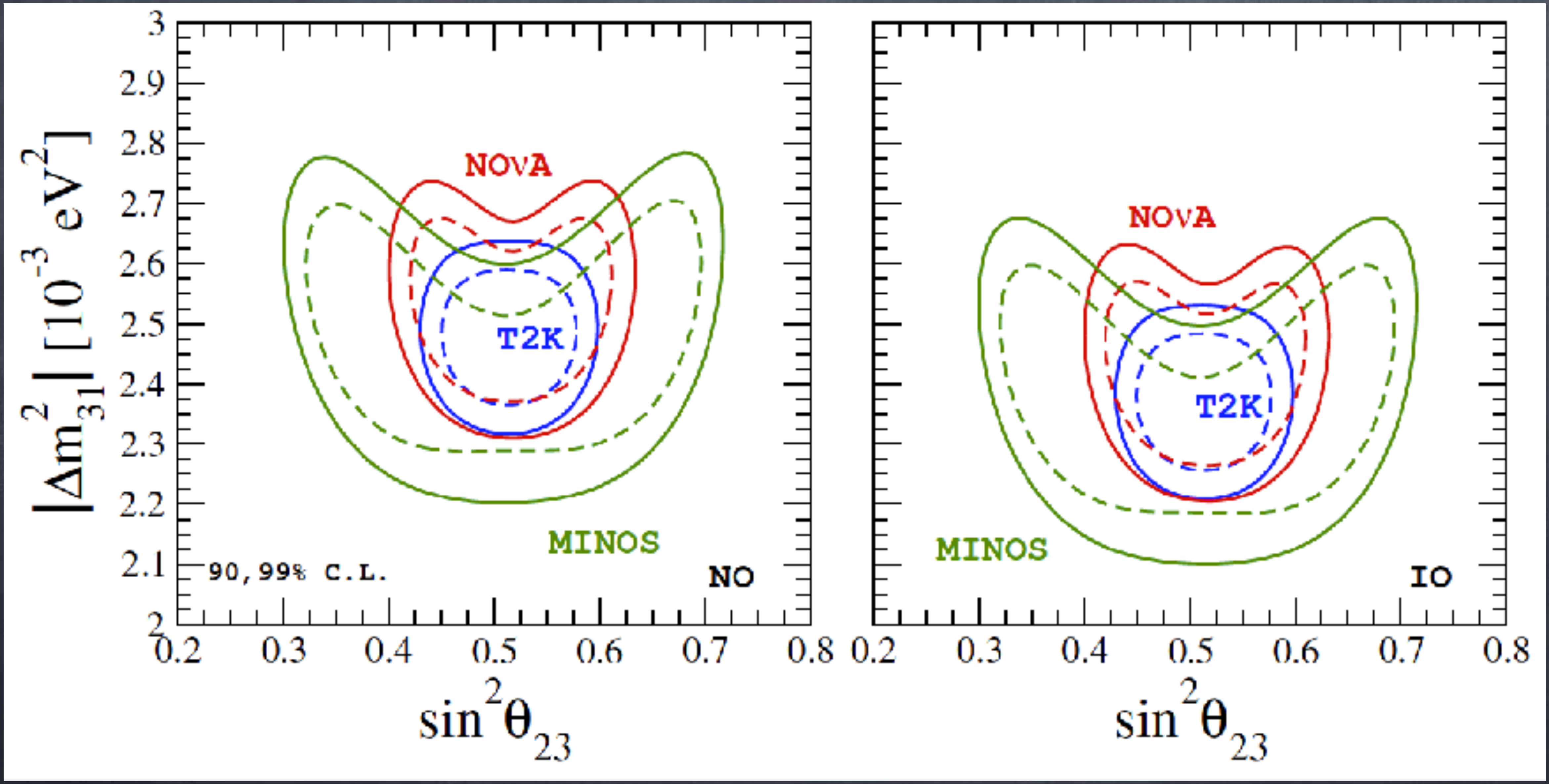
GOAL: observation of ν_μ disappearance, ν_e appearance and spectral distortions expected in the case of neutrino oscillations

→ consistent with atmospheric data

→ atm ν oscillations confirmed by laboratory exps

Accelerator LBL experiments

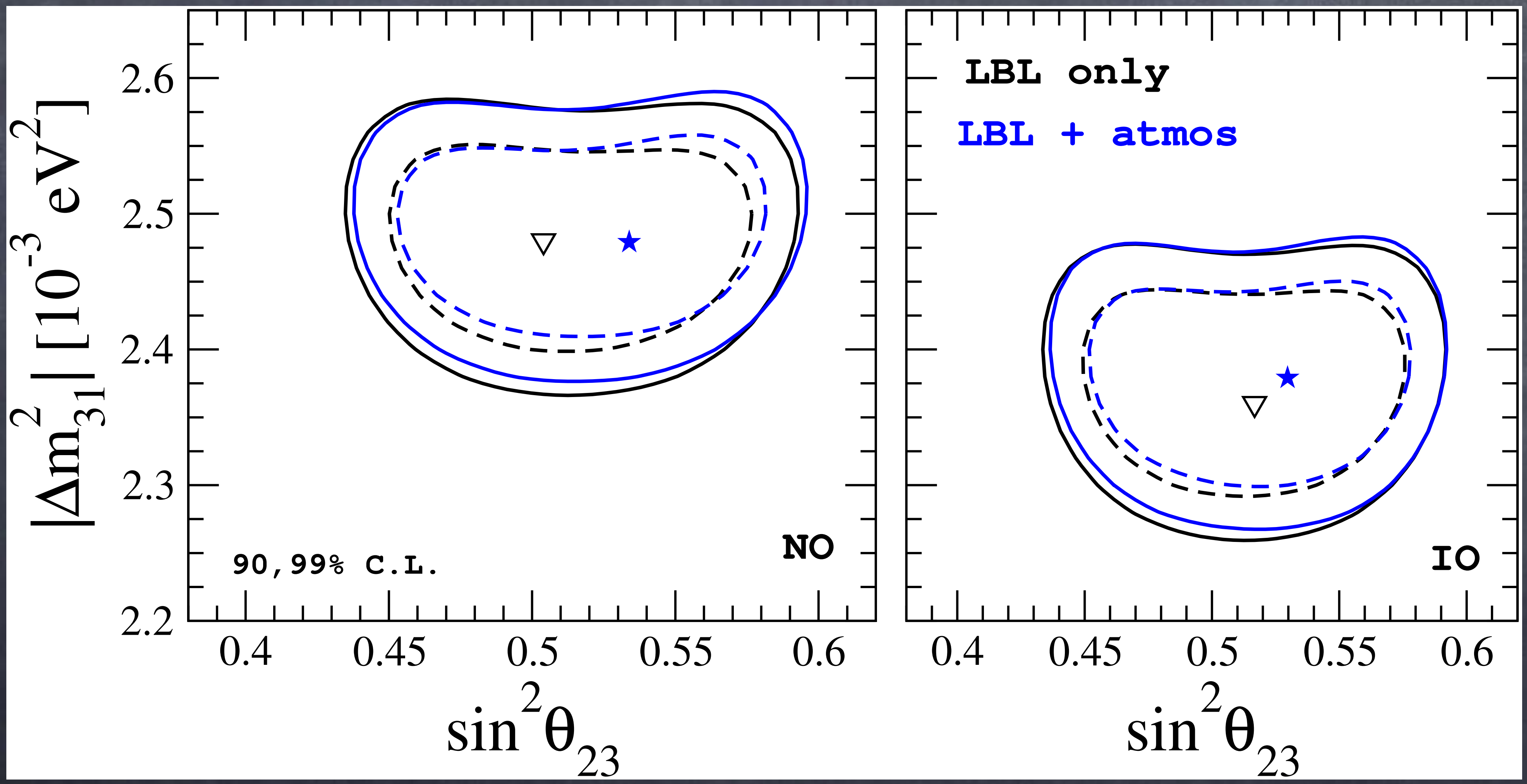
- MINOS + T2K (neutrino + antineutrino)
- NOvA (only neutrino data)



all experiments prefer mixing angle close to maximal

Atmospheric parameters

Combined analysis atmospheric + LBL data



atmospheric parameters are mostly constrained by LBL data

de Salas et al, PLB 782 (2018) 633

The reactor mixing angle θ_{13}

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

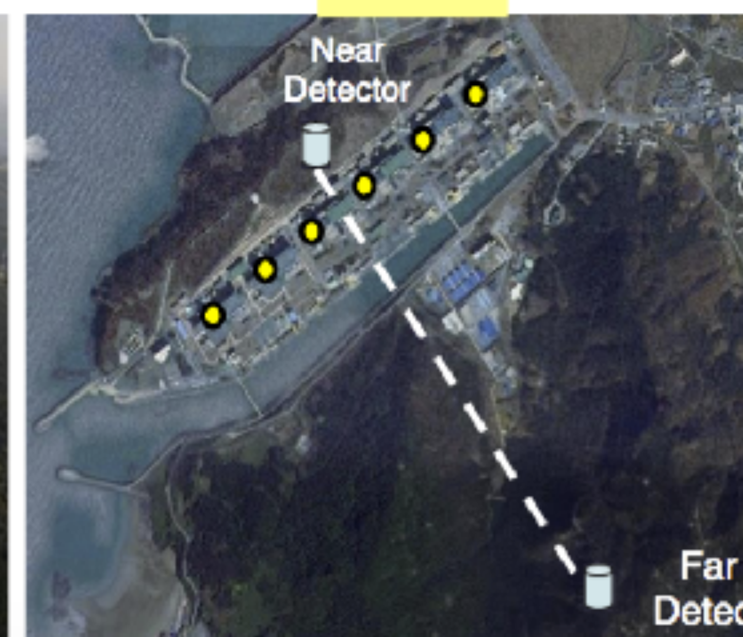
Daya Bay

6 cores + 4 ND + 4FD

Double Chooz

2 cores + 1 ND + 1 FD

Reno

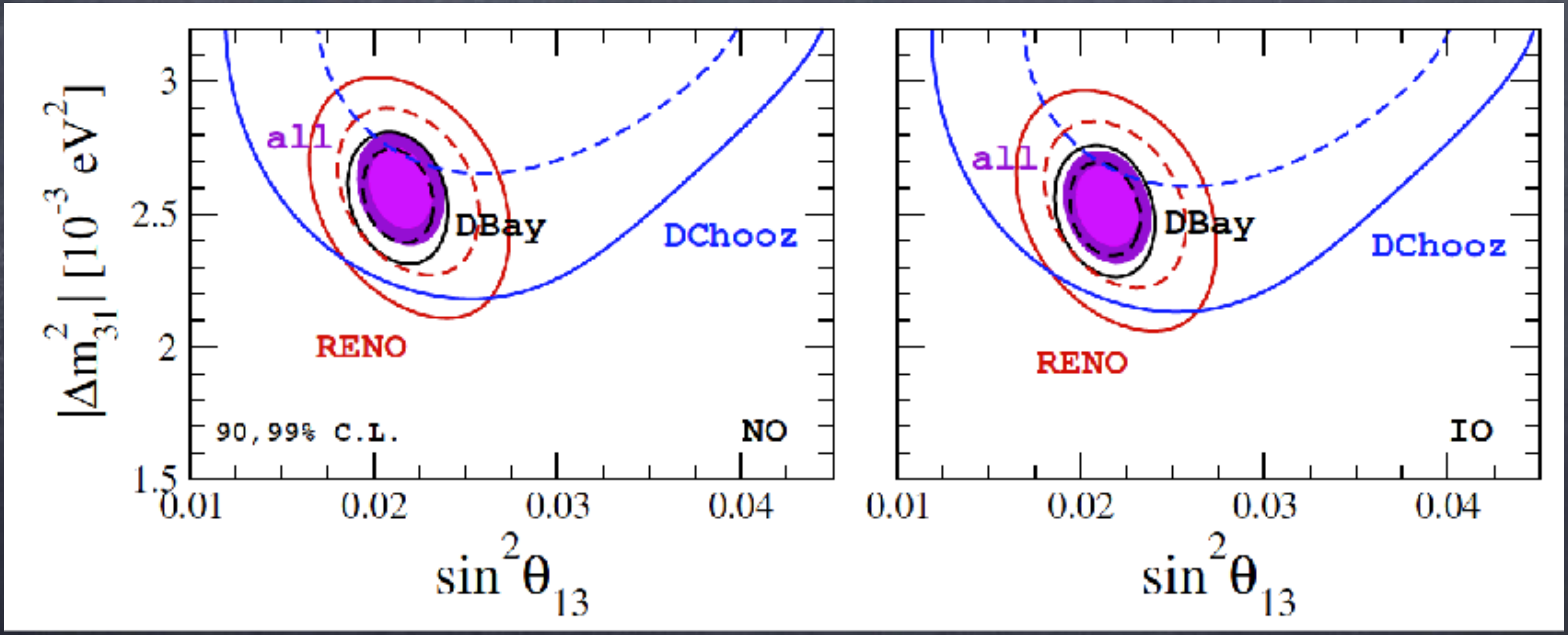


6 cores + 1 ND + 1 FD

Reactor sector

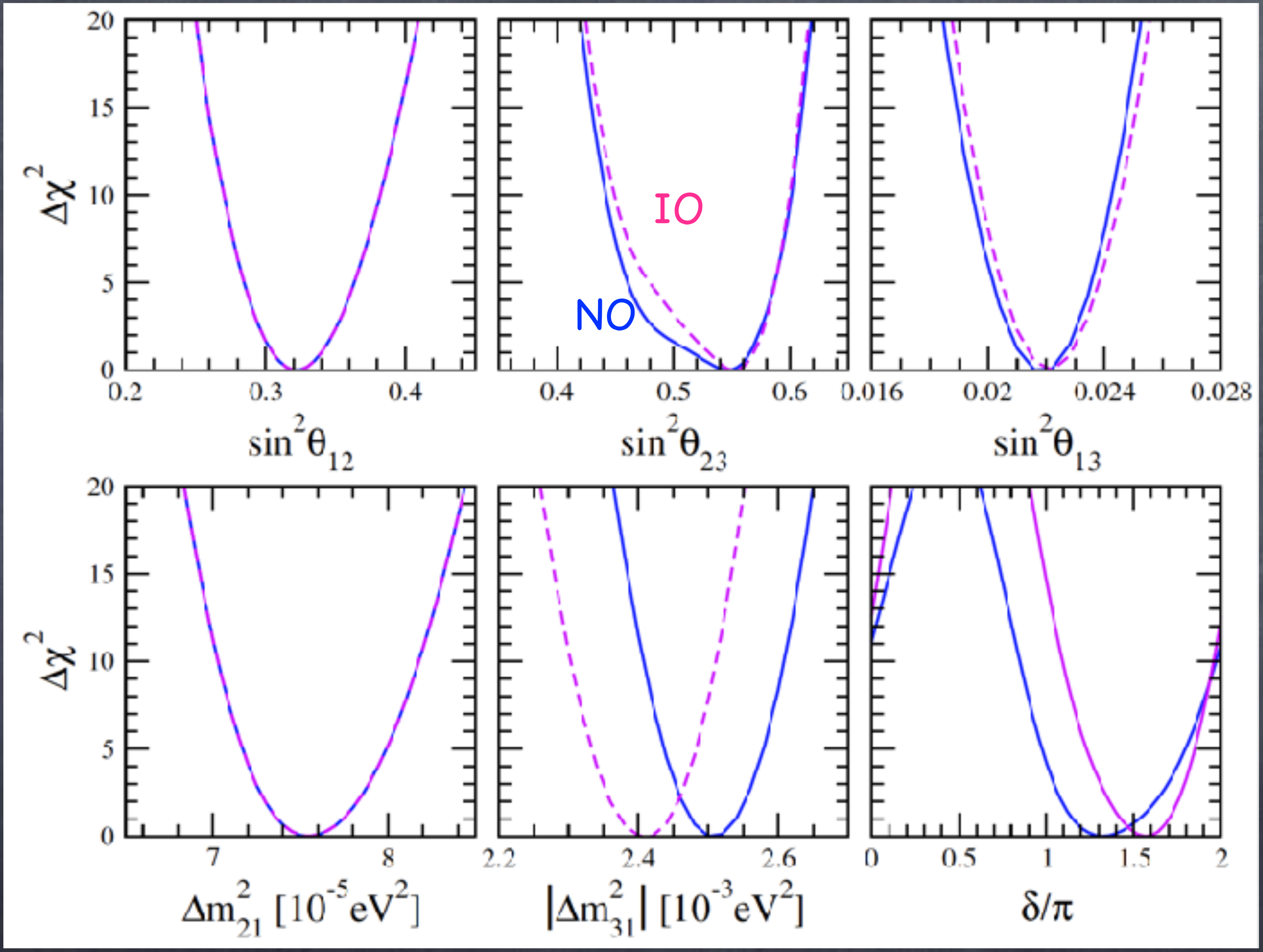
Daya Bay + RENO + Double Chooz

de Salas et al, PLB 782 (2018) 633



Precision dominated by Daya Bay

Updated global fit summary



- preference for Normal Ordering with $\Delta\chi^2$ (IO–NO) ≈ 11.7
  - ➡ Inverted Ordering disfavoured at 3.4σ

Updated global fit summary

parameter	best fit ± 1σ	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

relative 1σ

2.4%

1.3%

5.5%

4.7%

4.4%

3.5%

10%

9%

!!!

Beyond three-neutrino flavours: sterile neutrinos

How many neutrinos?

- according to LEP measurements of invisible Z decay width:

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

Experimental hints for a 4th sterile neutrino:

- LSND signal for $\overline{\nu}_\mu \rightarrow \overline{\nu_e}$ oscillations with E/L ~ 1 eV²

- MiniBooNE searches for $\overline{\nu}_\mu \rightarrow \overline{\nu_e}$ and $\nu_\mu \rightarrow \nu_e$ 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

$\rightarrow$ 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)

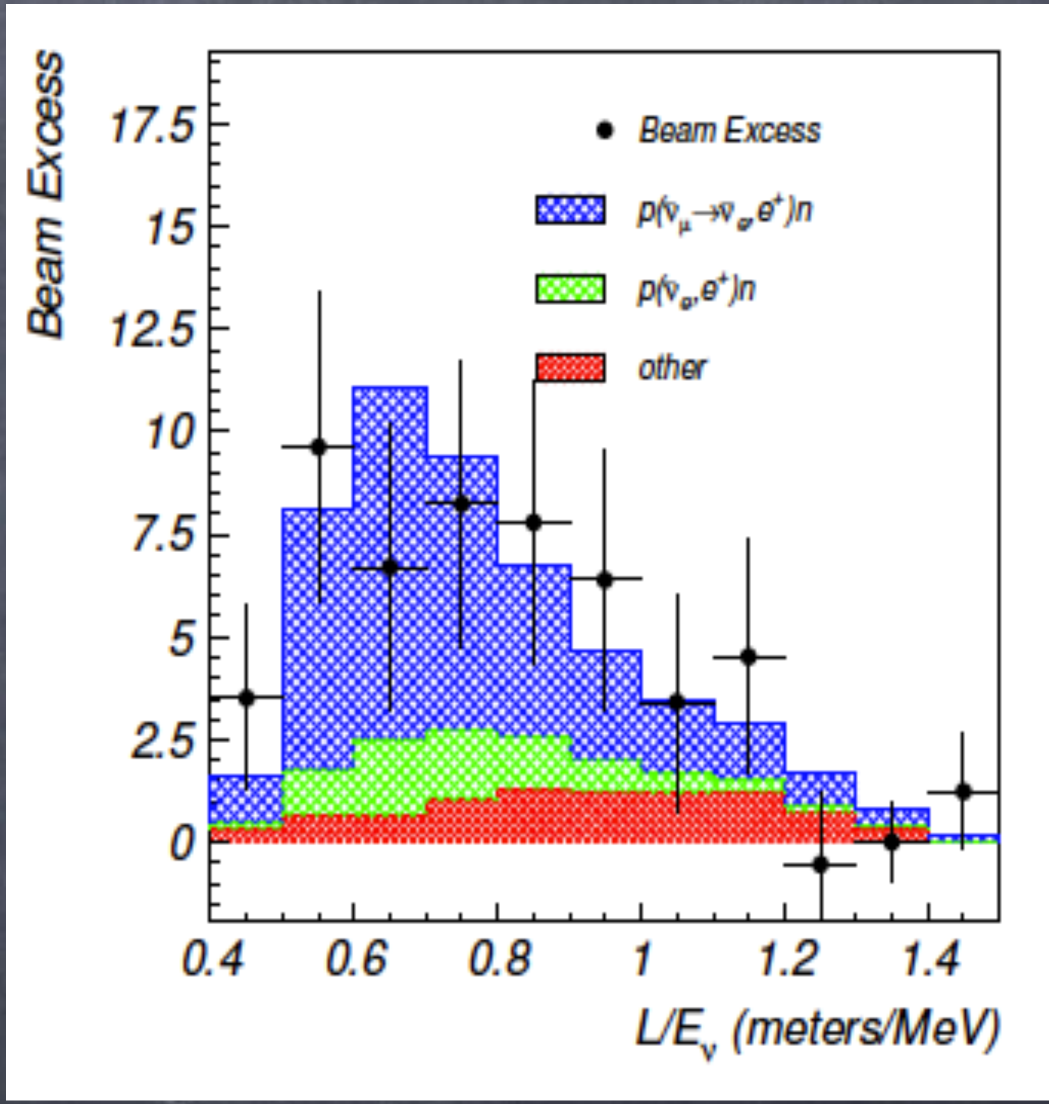
Hints for $\nu_\mu \rightarrow \nu_e$ appearance

The LSND anomaly

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

- Excess of ν_e events:

  $87.9 \pm 22.4 \pm 6.0$ (3.8σ)



L ~ 30m, E ~ 20-75 MeV

LSND Collab., PRD 64 (2001) 112007

The LSND anomaly

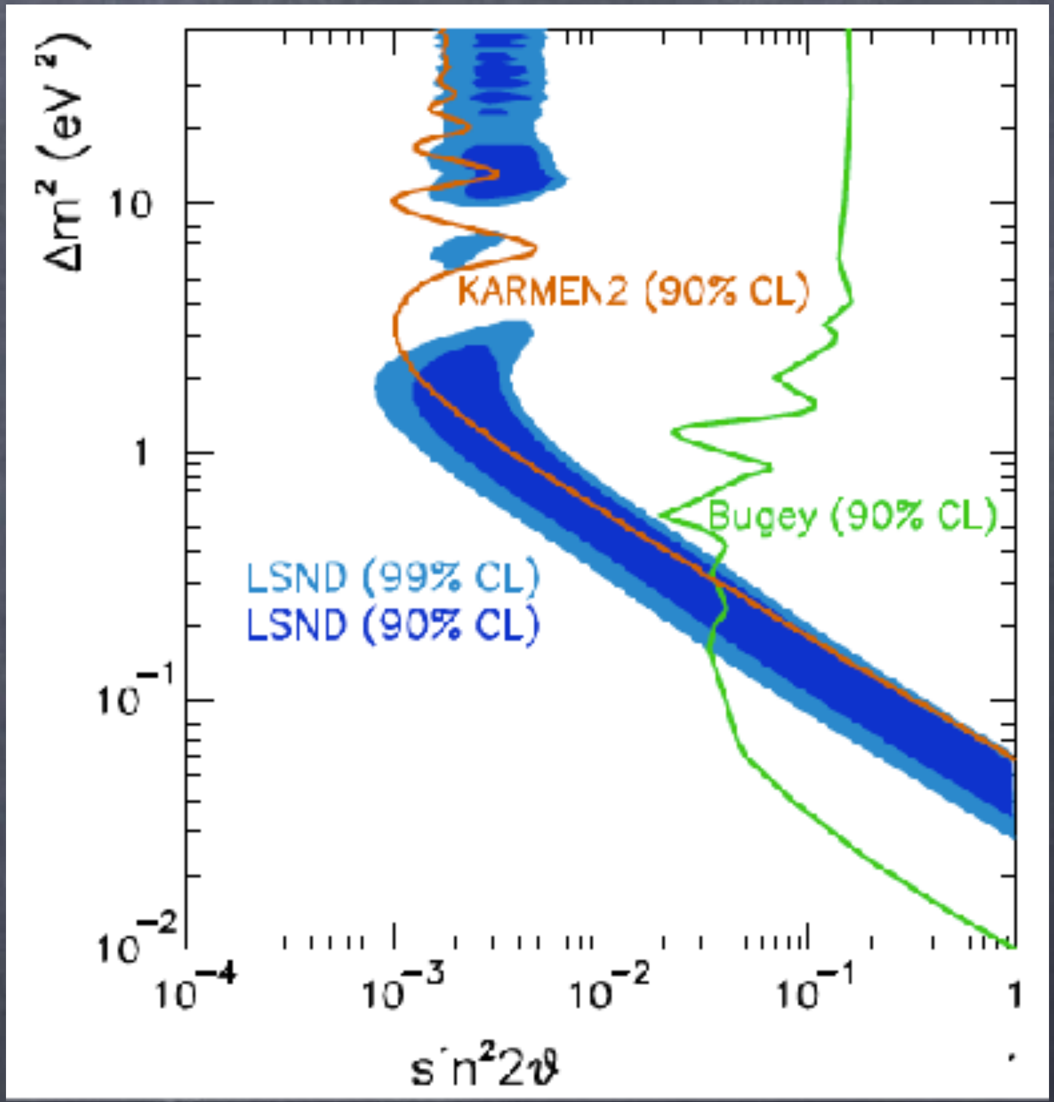
- Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu_e}$ oscillations

- 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.

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



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The LSND anomaly

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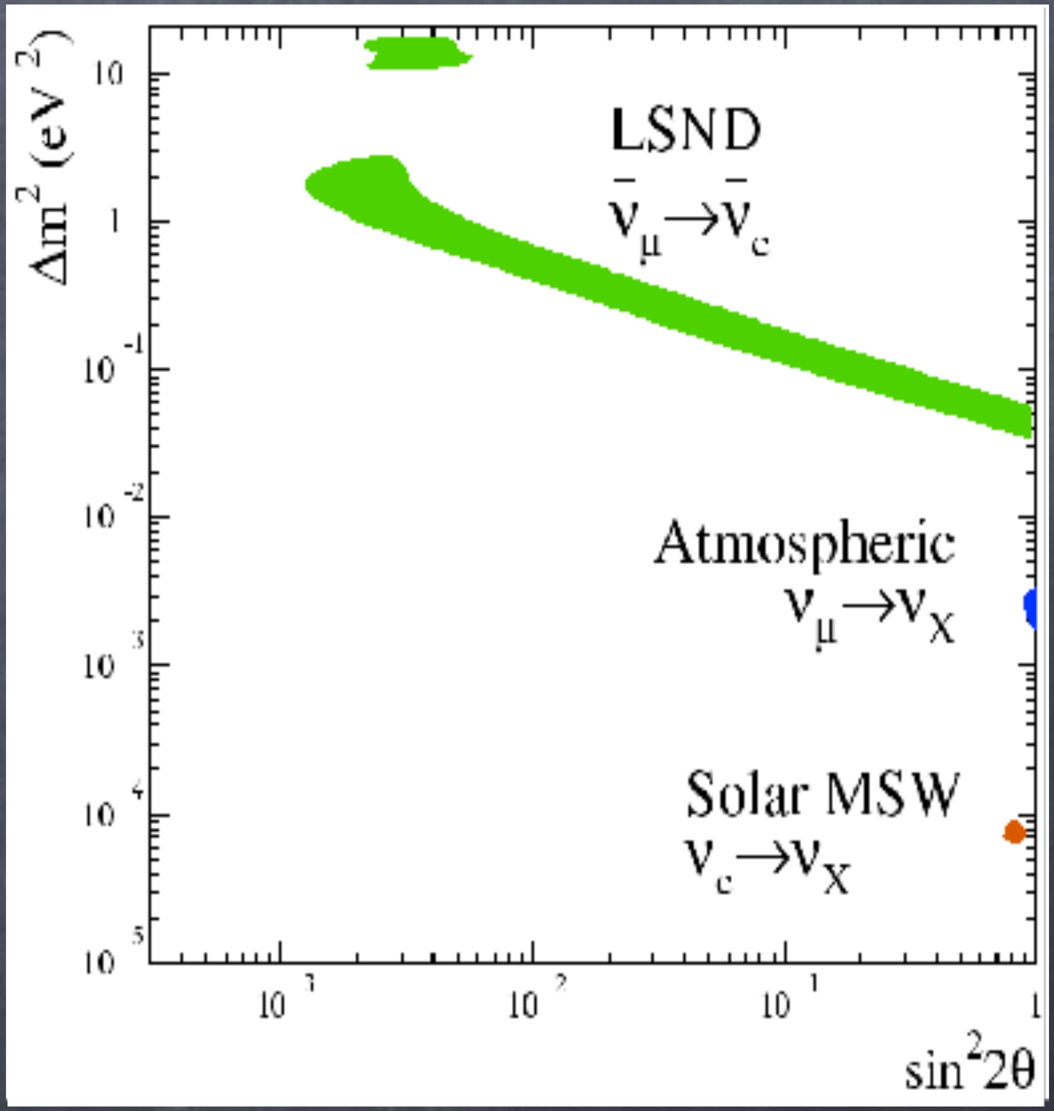
- Part of the allowed region excluded by other experiments.

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

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

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

$\Rightarrow$ 4th sterile neutrino required !!



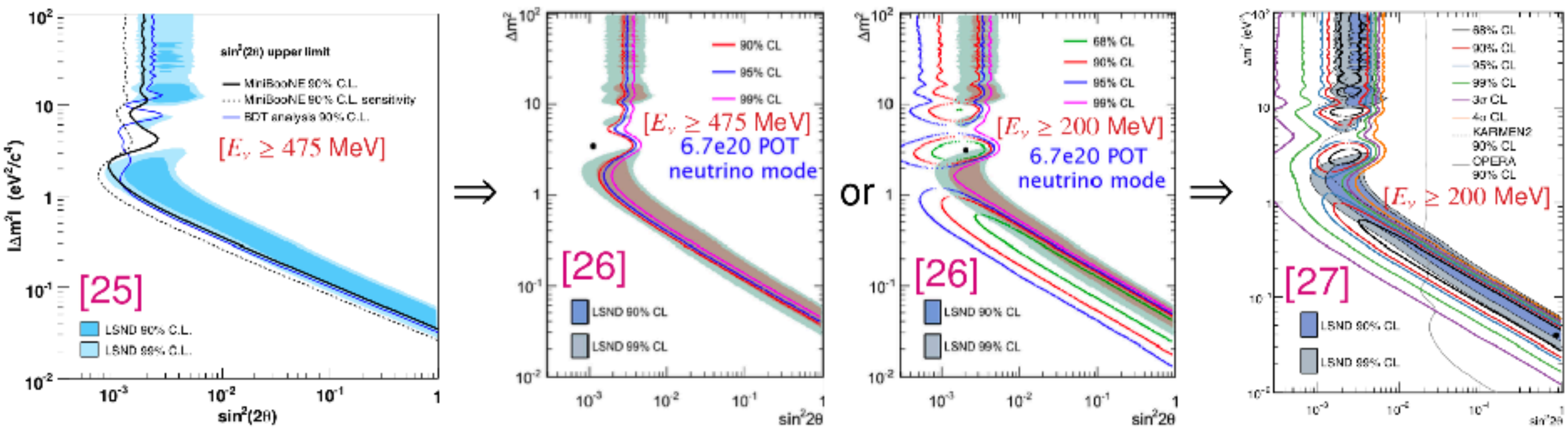
L ~ 30m, E ~ 20–75 MeV

LSND Collab., PRD 64 (2001) 112007

The MiniBooNE experiment

- Designed to test the LSND signal (similar L/E ratio)
- Runs in neutrino and antineutrino mode
- The neutrino channel results have been changing with time:

- is ν signal compatible with 2ν oscillations?
  - 2007: $P_{\text{osc}} \simeq 1\% \Rightarrow$ no it isn't [25];
  - 2012: $P_{\text{osc}} \simeq 6\% \Rightarrow$ maybe it is [26];
  - 2018: $P_{\text{osc}} \simeq 15\% \Rightarrow$ yes it is [27];
- do MB-ν rule out LSND-$\bar{\nu}$ signal? 2007: yes [25]; 2012: not really [26]; 2018: no [27].



Michele Maltoni, Neutrino-2018

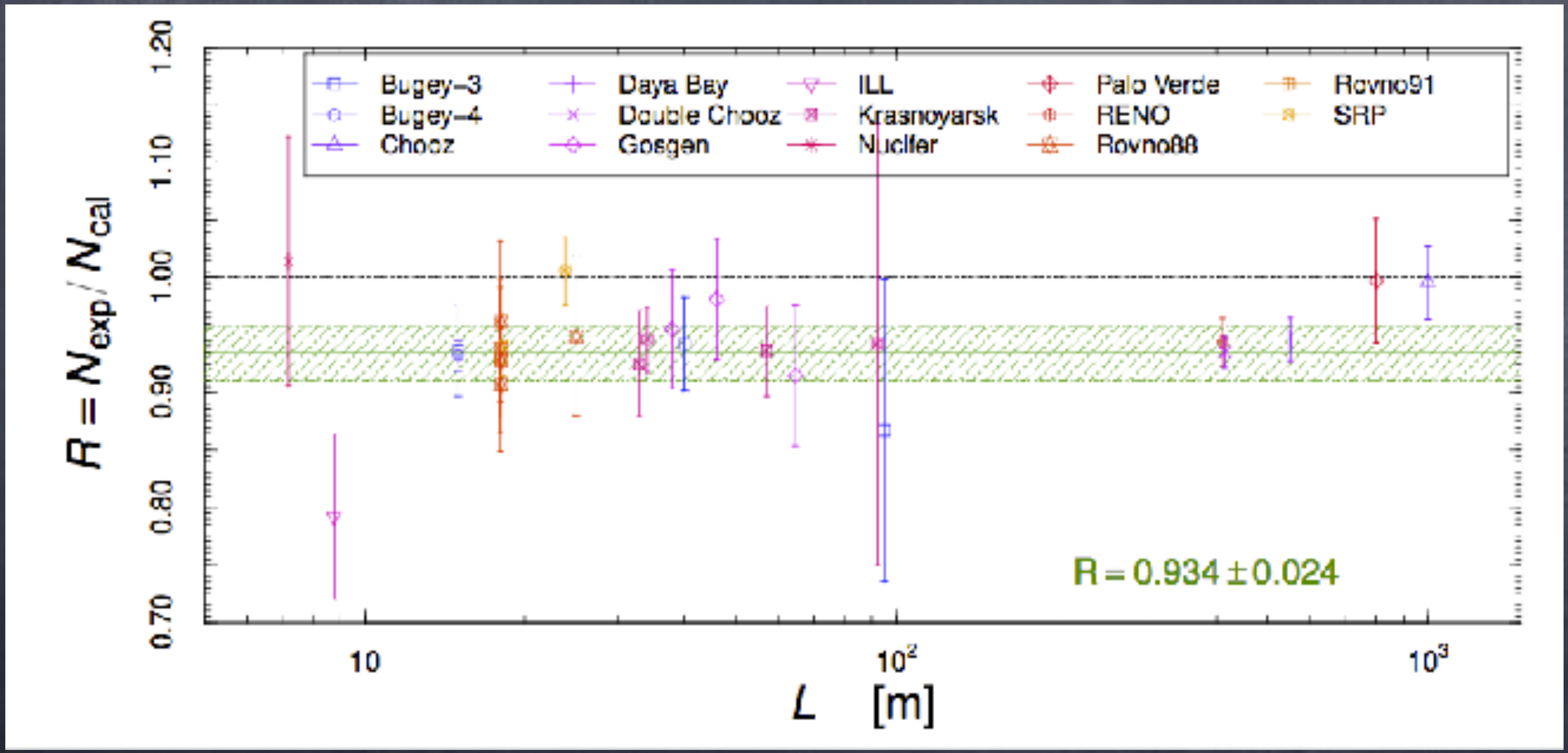
Hints for ν_e disappearance

$\bar{\nu}_e$ disappearance in reactor experiments

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

- 2011: improved calculations of antineutrino fluxes report 3% increase of the neutrino flux

Mueller et al, arXiv:1101.2663, Huber, arXiv 1106.0687



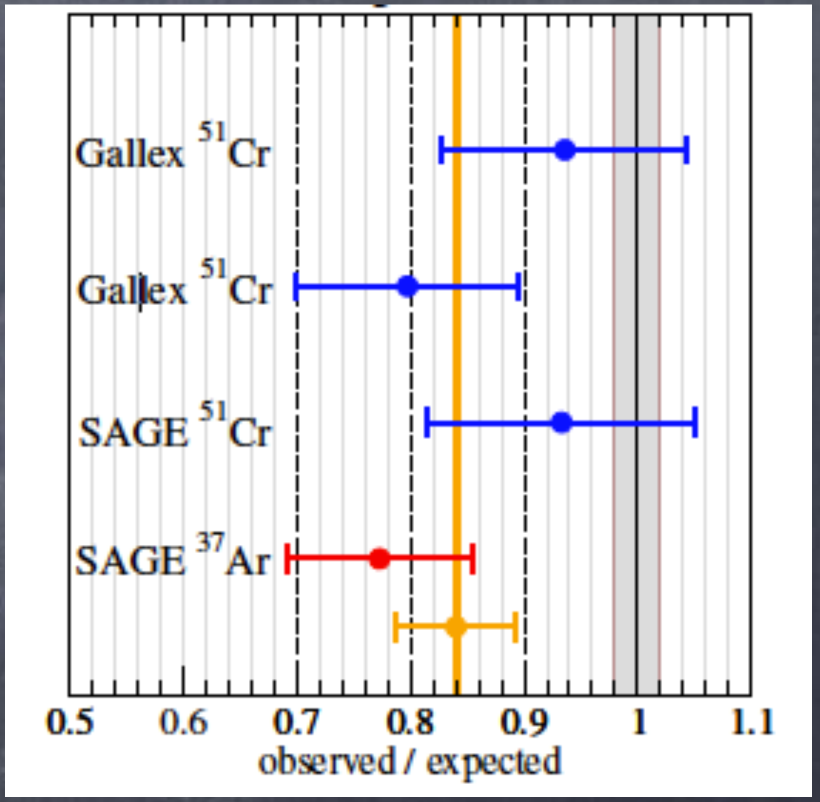
Gariazzo et al, JHEP 2017

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

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

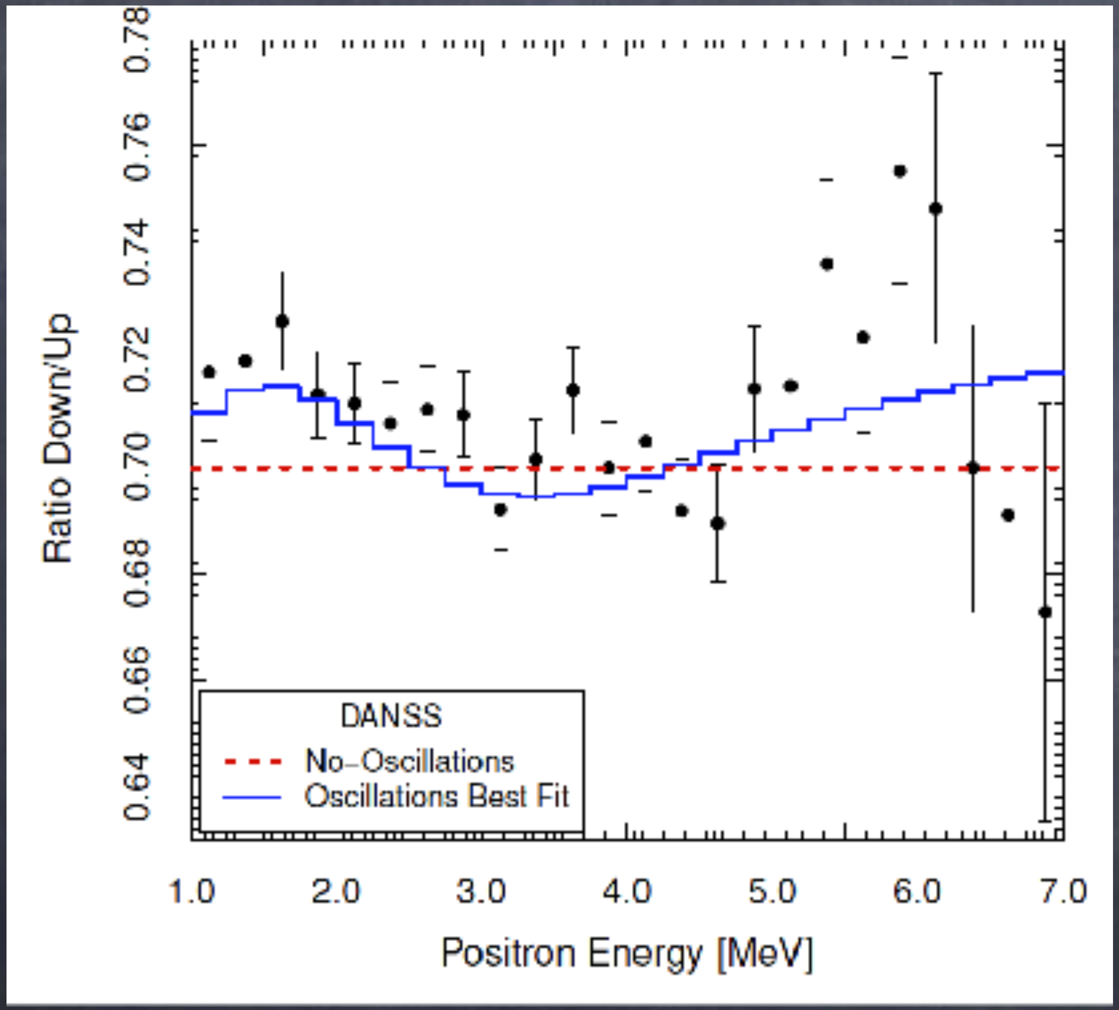
- oscillations with $\Delta m^2 \sim 1$ eV^2 can lead to reduction of the ν_e flux in the detector volume

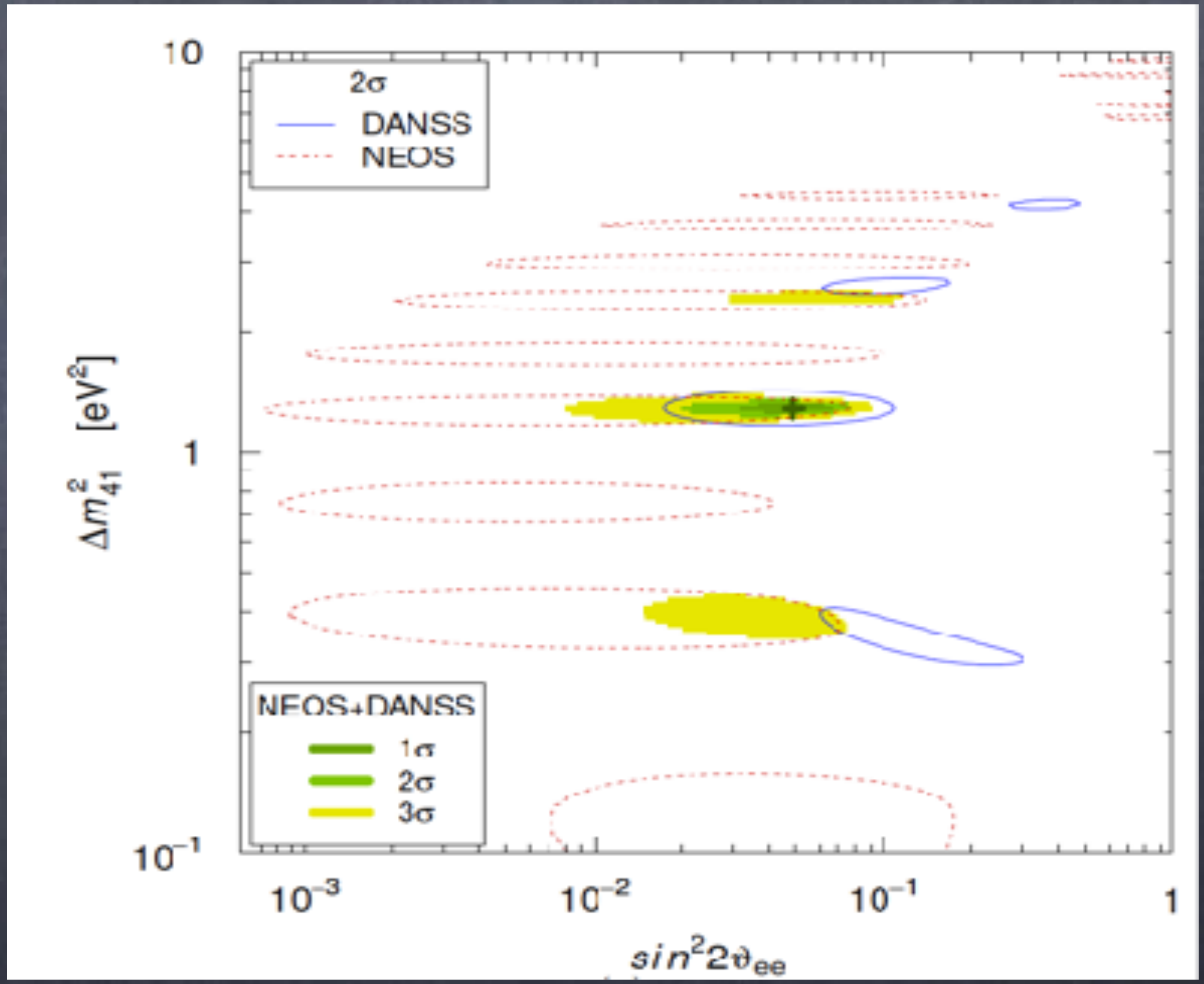
Recent indications: NEOS and DANNS

Observation of ratios of reactor antineutrino spectra at two baselines

Gariazzo et al, arxiv:1801.06467

10.7 m
vs
12.7 m

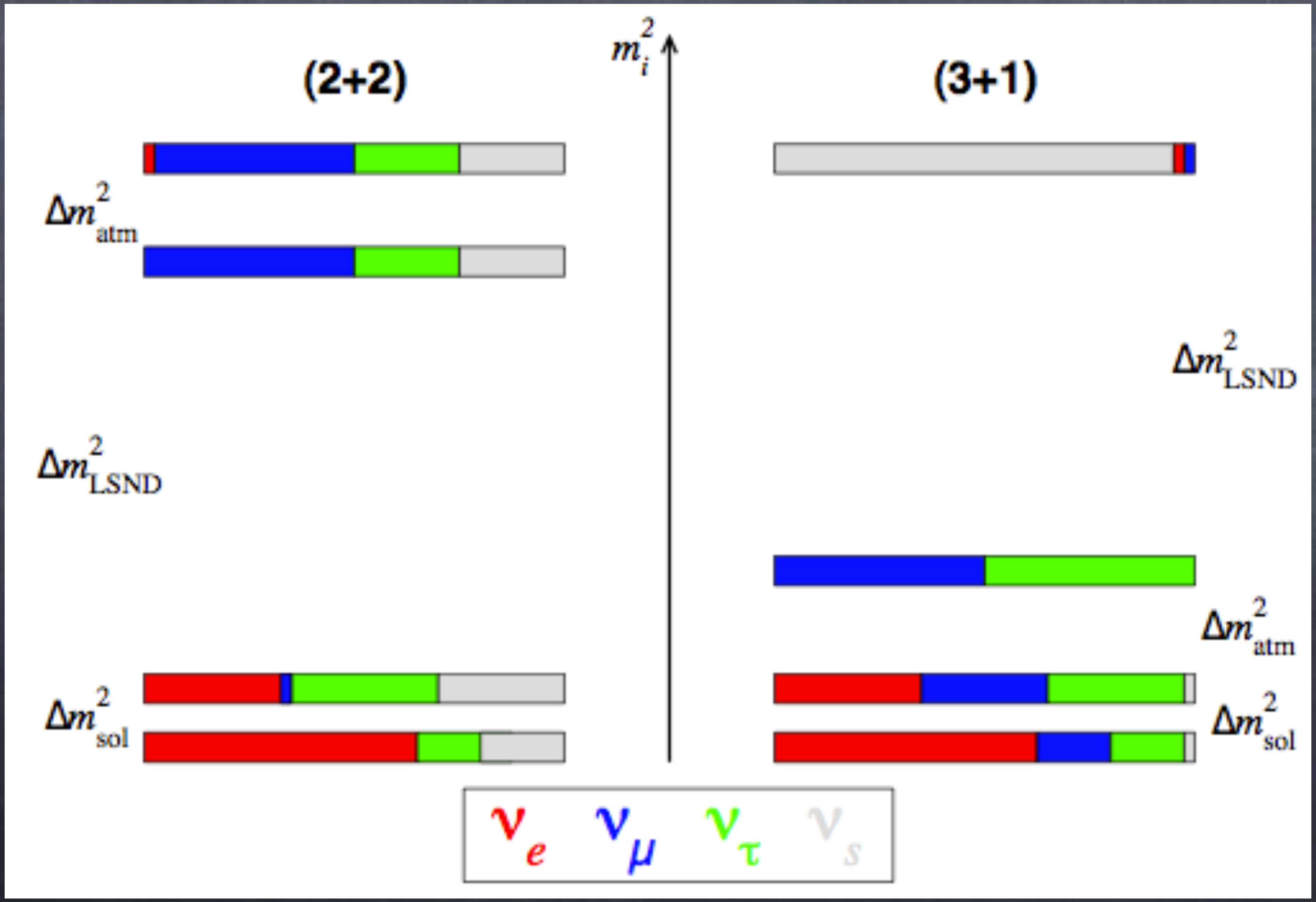




⇒ 3σ evidence of SBL ν_e oscillations based on comparisons of measured spectra at different baselines, independent of flux predictions.

Interpretation of the anomalies

$\Delta m^2_{sol} \sim 8x10^{-5}\ eV^2$ $\Delta m^2_{atm} \sim 2x10^{-3}\ eV^2$ $\Delta m^2_{LSND} \sim 1\ eV^2$

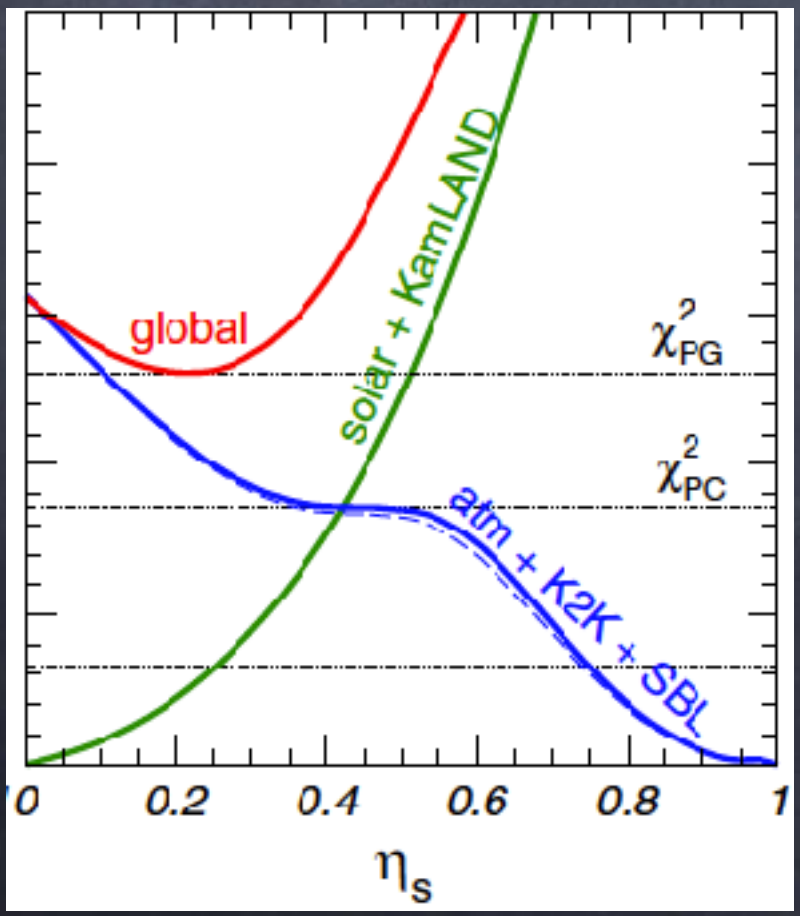


2+2 neutrino scheme

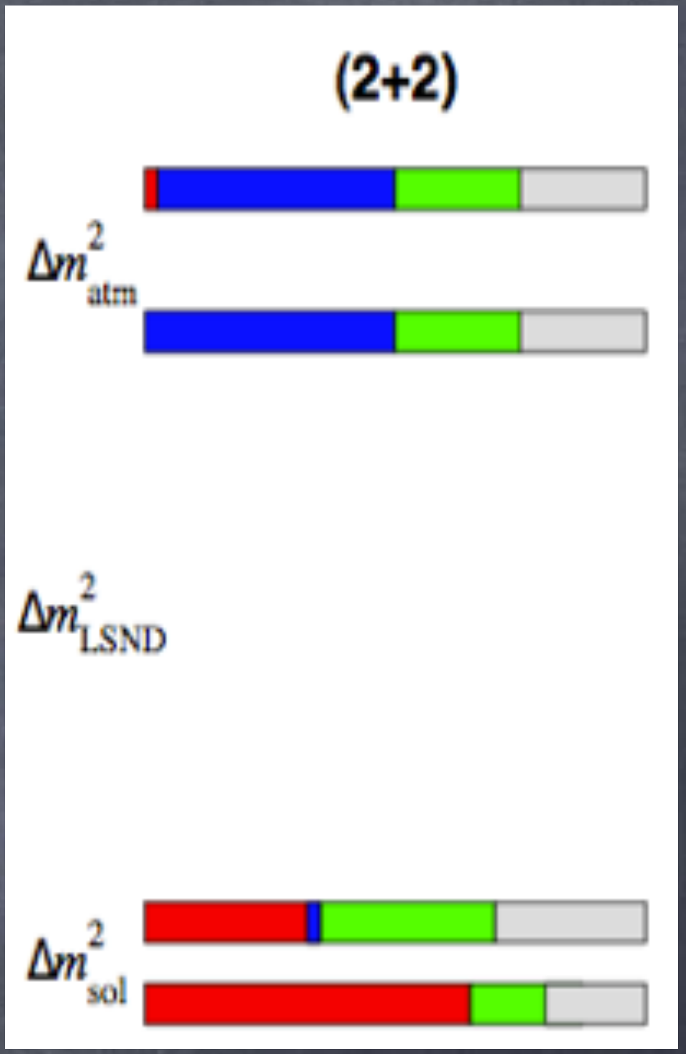
- This scheme requires the presence of sterile neutrinos either in solar or atmospheric neutrinos

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

ΔX^2



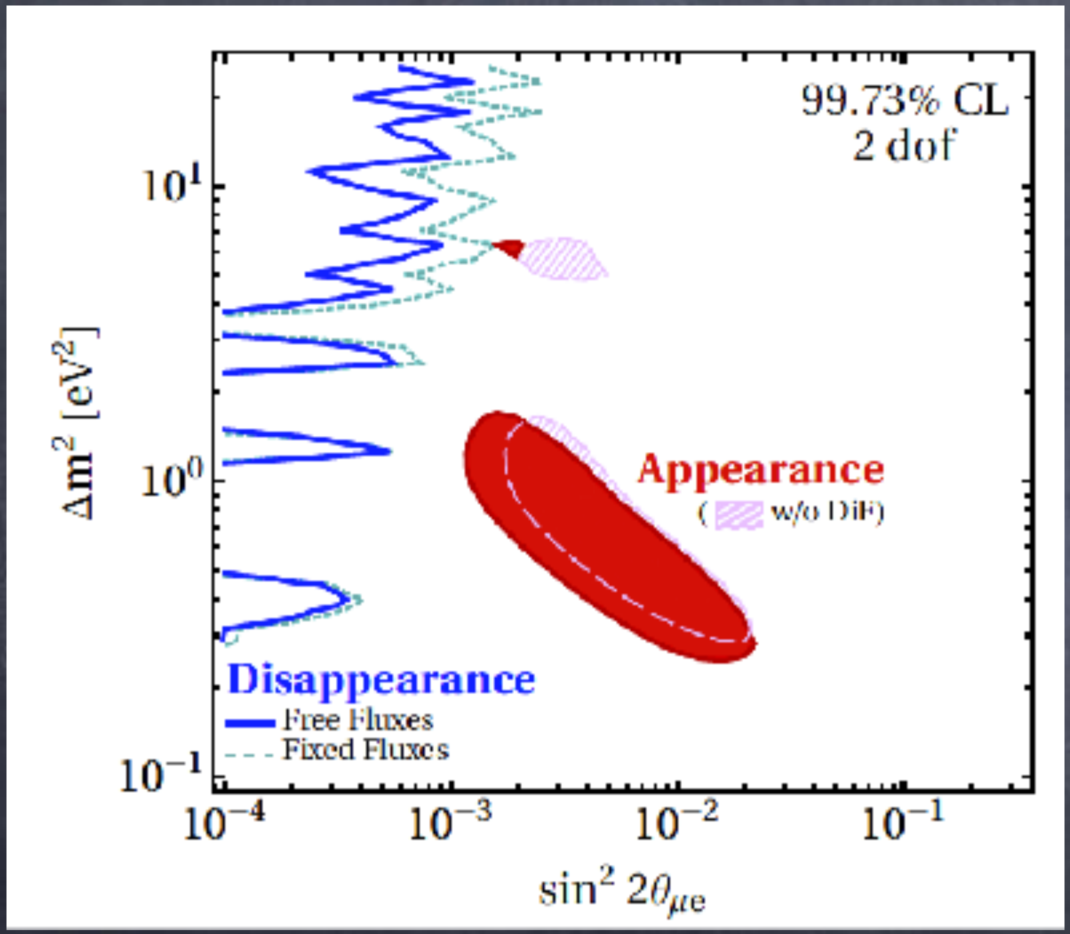
excluded by solar and atmospheric data



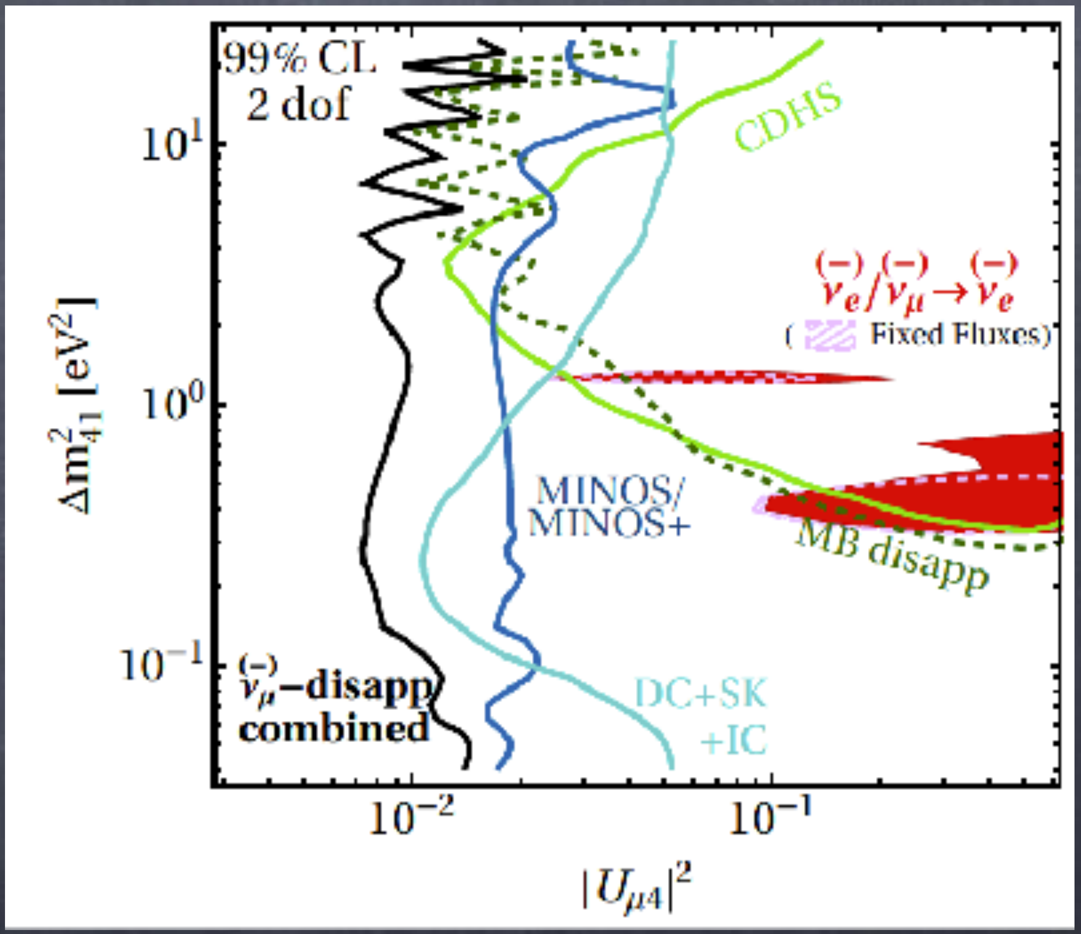
Maltoni et al, NPB643 (2003), NJP06 (2004)

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



strong tension between app (LSND/MB) and disapp exp. (CDHS, SK, IceCube, MINOS/+)



Disagreement between ν_e and ν_μ data

Dentler et al, arXiv:1803.10661

eV-sterile neutrino in Cosmology

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

  Σm_ν = sum of neutrino masses

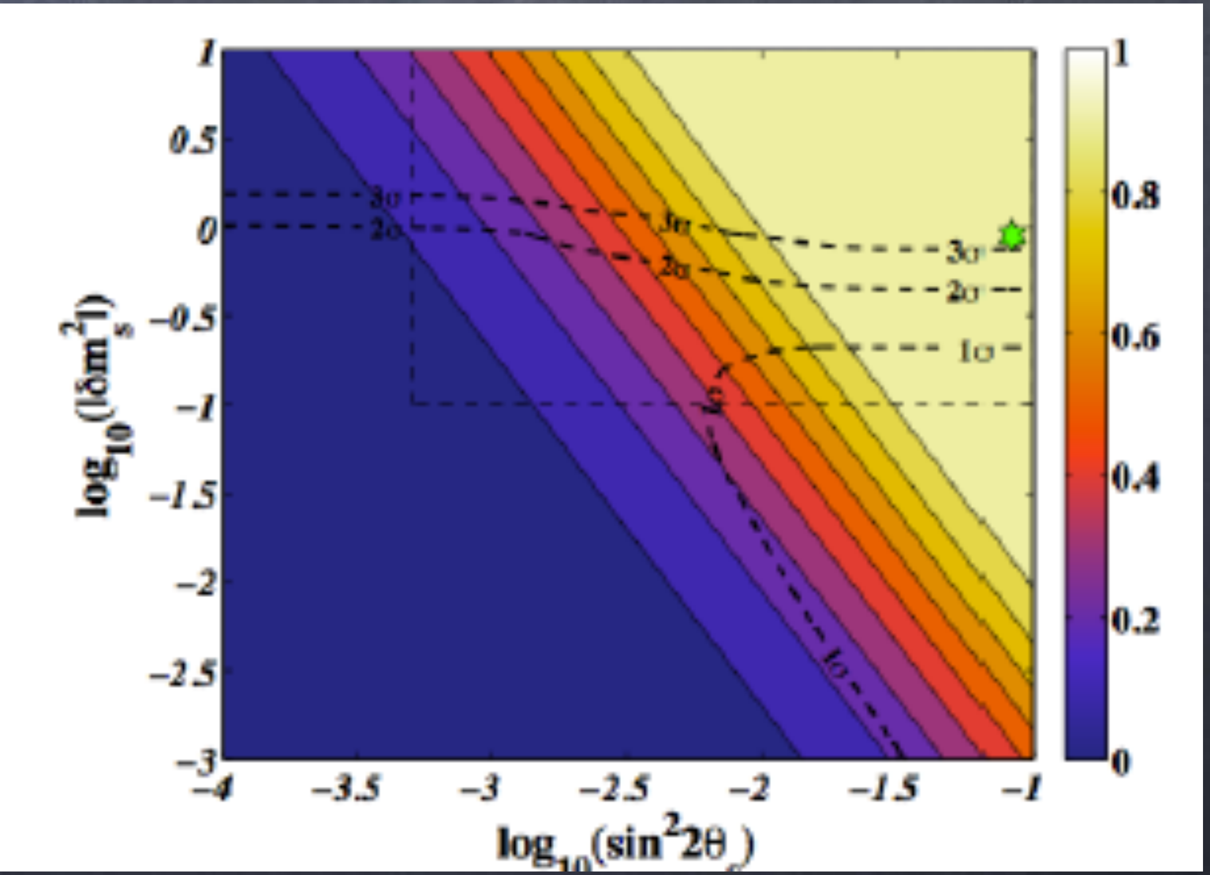
  N_{eff} = relativistic degrees of freedom.

- if the mixing active-sterile neutrino is small, one can relax limits from cosmology

- 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 eV

$\rightarrow N_{eff} \approx 4$



Hannestad et al, 1204.5861

Bounds from Cosmology

- recent limits on the sum of neutrino masses:

Σm_ν < 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 ± 0.23
– PLANCK + LSS: N_{eff} = 3.03 ± 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

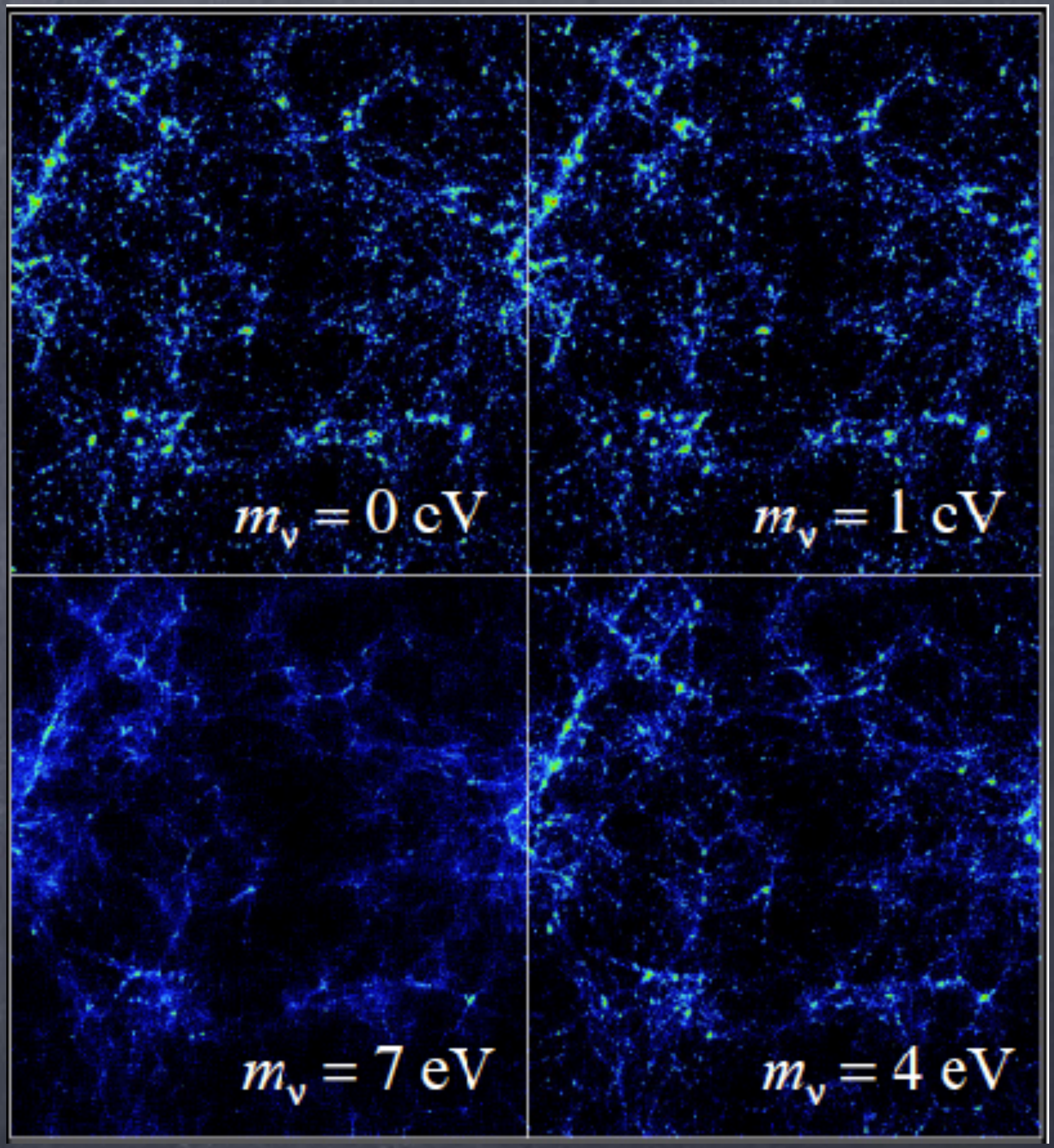
- neutrino masses may affect cosmological observables:

  → anisotropies in the CMB spectrum

  → Large Scale Structure formation

  → weak gravitational lensing

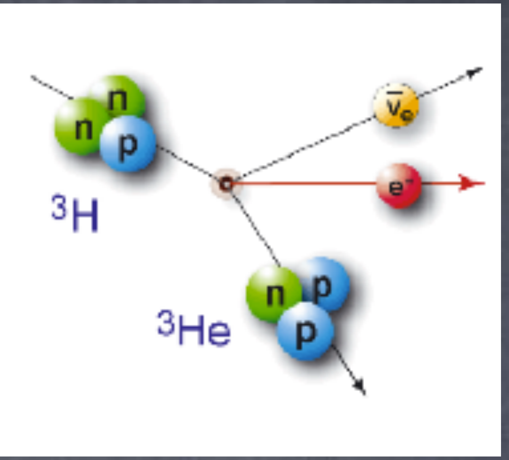
- Fit ΛCDM model + experimental data (WMAP, PLANCK, HST, LSS,...)



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

Lattanzi & Gerbino, arxiv:1712.07109

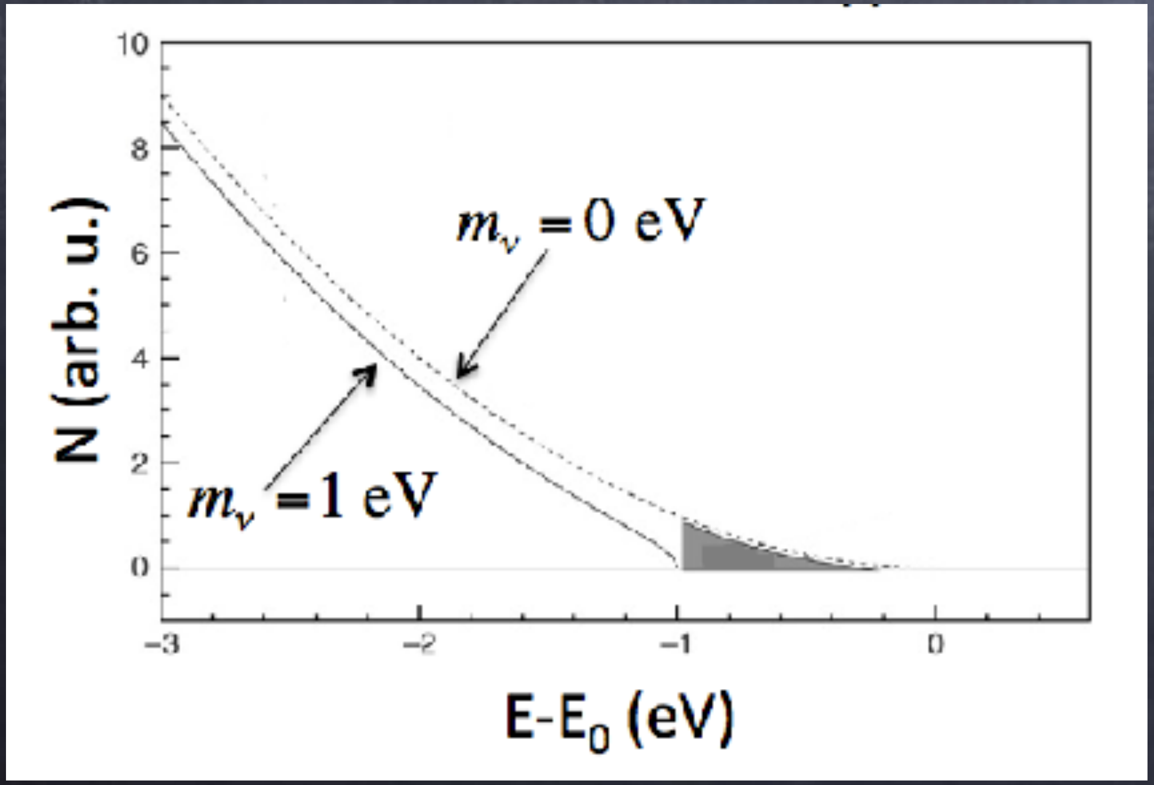
Tritium beta decay experiments



- β-decay spectrum close to the endpoint is very sensitive to neutrino mass:

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2}\, \Theta(Q_\beta - T - m_i) \right]^{1/2}$$

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

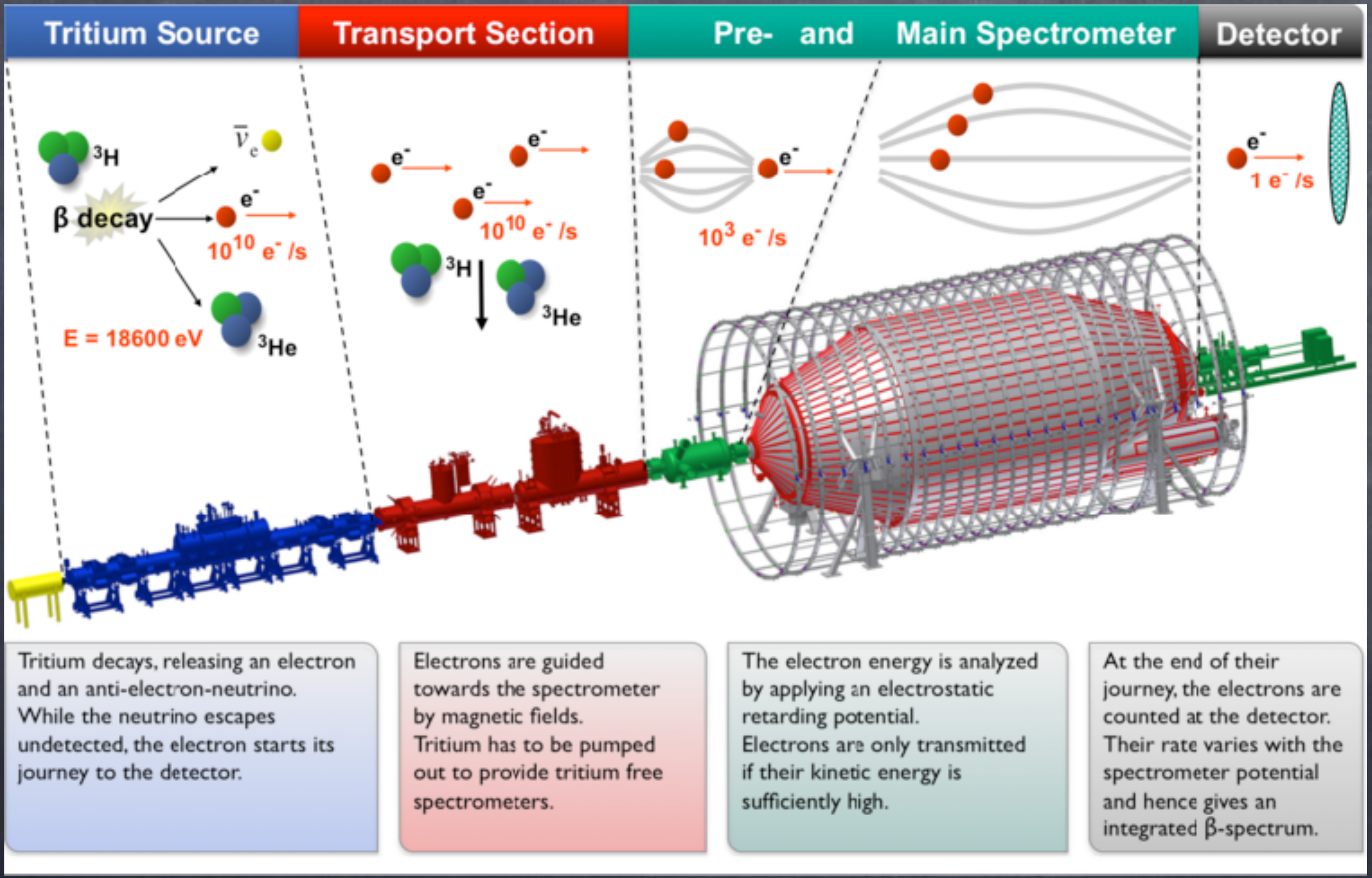


Mainz and Troitsk Experiments

$$m_\nu < 2.2\,\mathrm{eV}\ (95\%\,\mathrm{C.L.})$$

The KATRIN experiment

(KArlsruhe TRItium Neutrino experiment)



sensitivity (90%CL)

$m_\nu < 0.2$ eV

discovery potential

$m_\nu = 0.35$ eV (5σ)

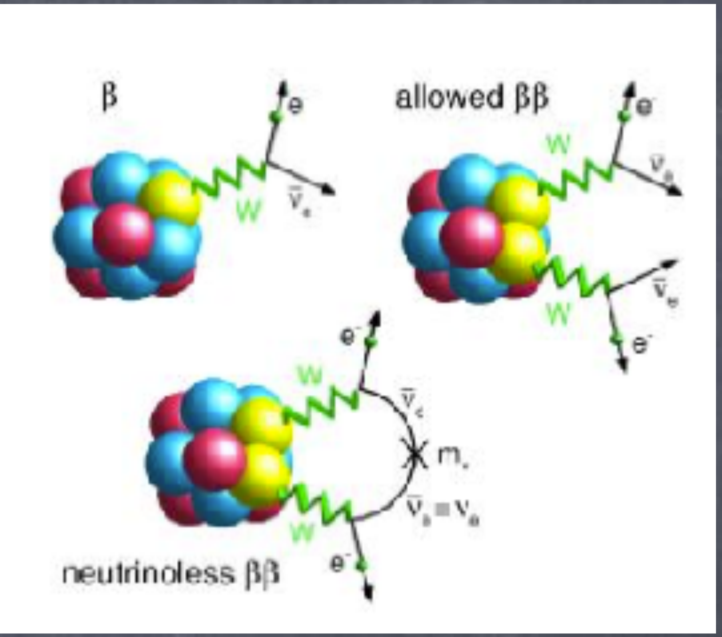
Inauguration
11 June 2018

Neutrinoless double beta decay

- $2\nu\beta\beta$: rare process in the SM with $t_{1/2} \sim 10^{21}$ years
- $0\nu\beta\beta$: possible for massive Majorana neutrinos.

(A,Z) →(A,Z+2) + e⁻ + e⁻

test ν nature



→ not observed yet

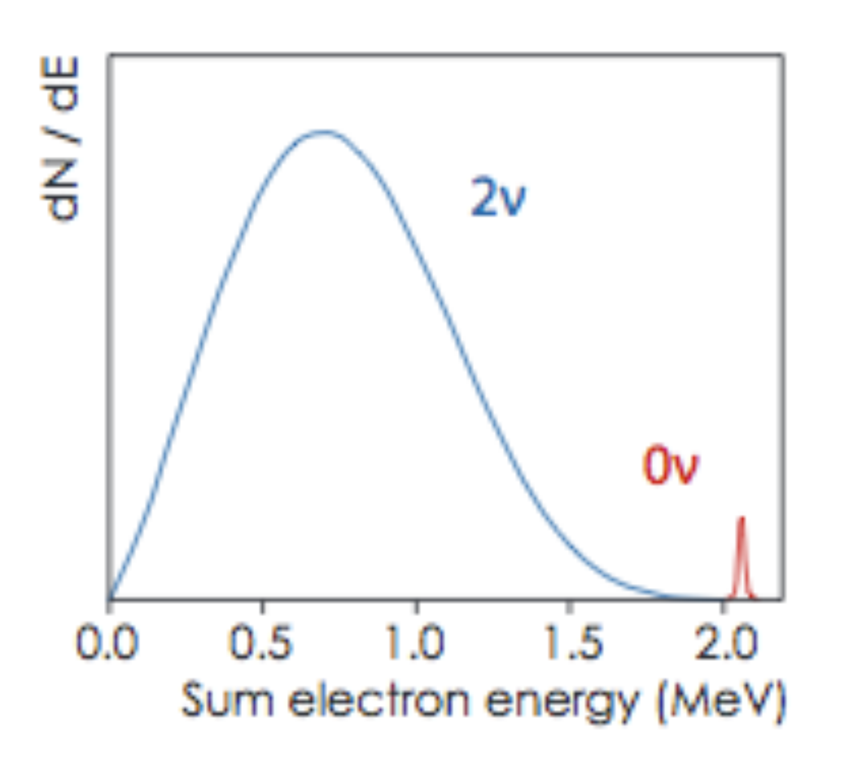
→ $t_{1/2} \sim 10^{26}$-10^{27} years

→ violates Lepton Number

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

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

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



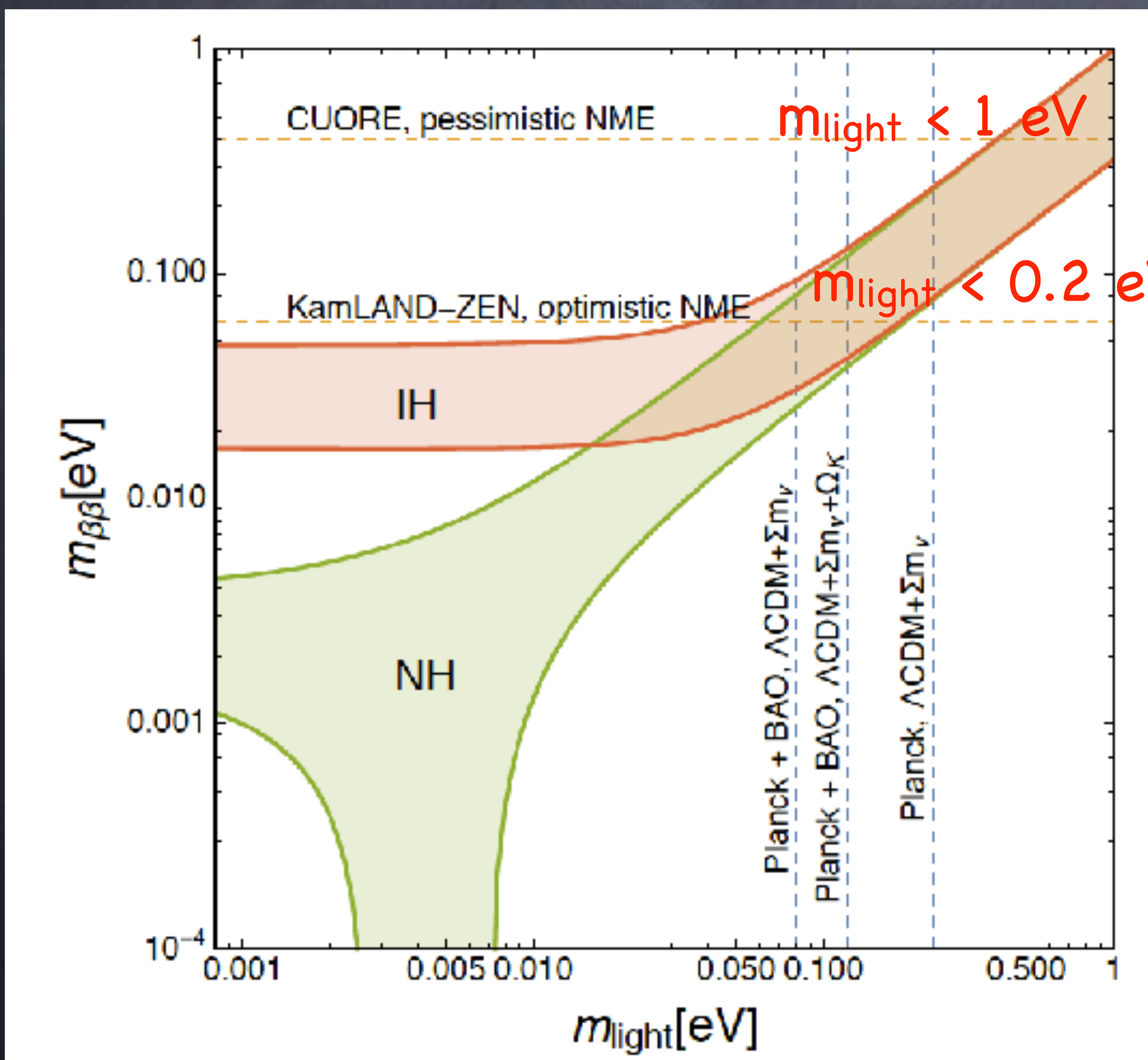
→ good separation $2\nu\beta\beta$ from $0\nu\beta\beta$

→ low bg $0\nu\beta\beta$ peak region

Bounds from $0\nu\beta\beta$ 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

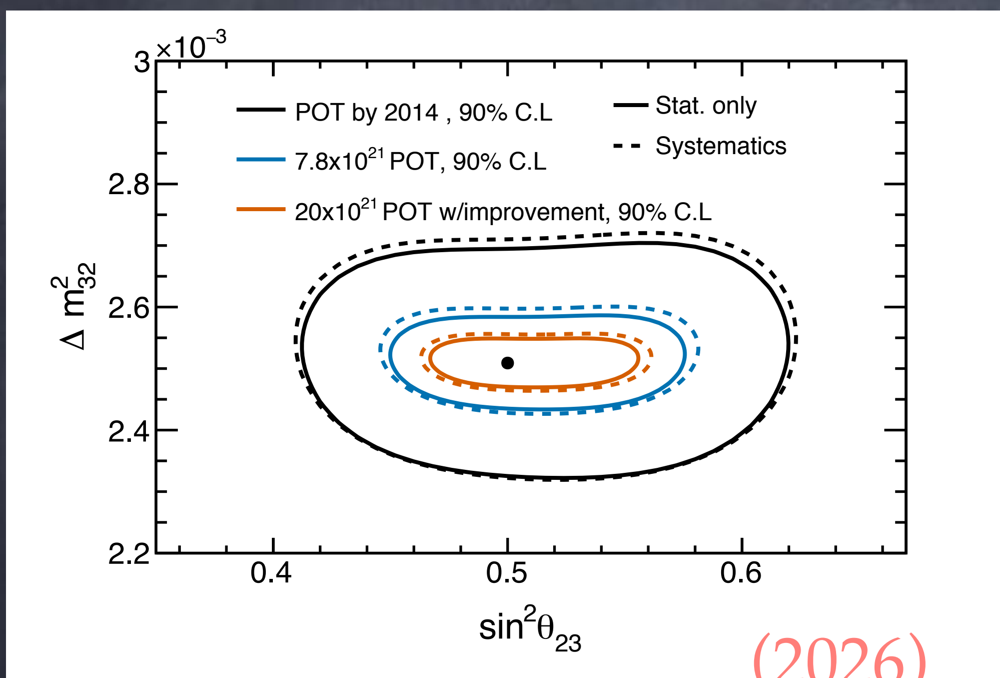
Lattanzi & Gerbino, arxiv:1712.07109

Future prospects in neutrino oscillations

Prospects for precision

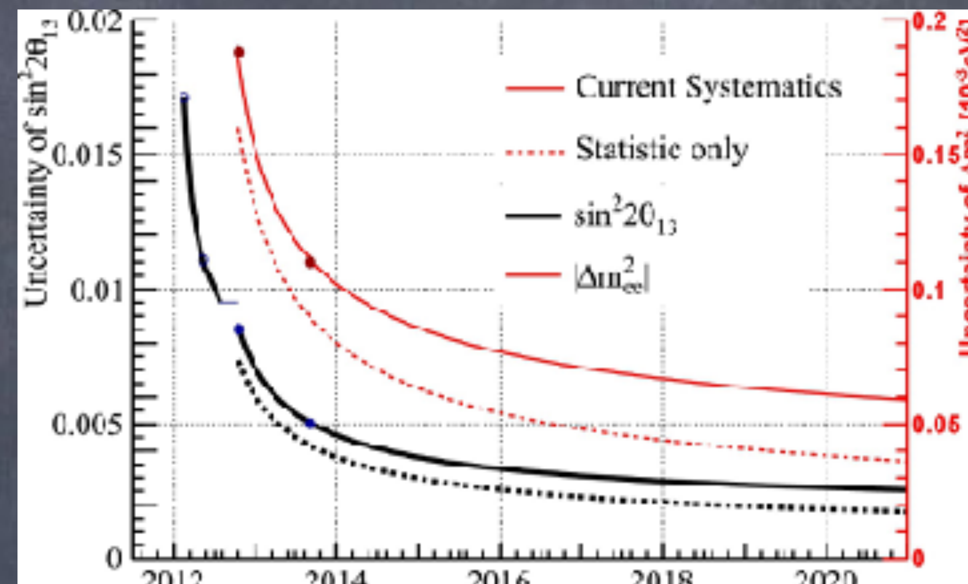
T2K-II

Abe et al, 1609.04111



~1% precision on Δm^2_{32}

~1-3% precision on $\sin^2\theta_{23}$



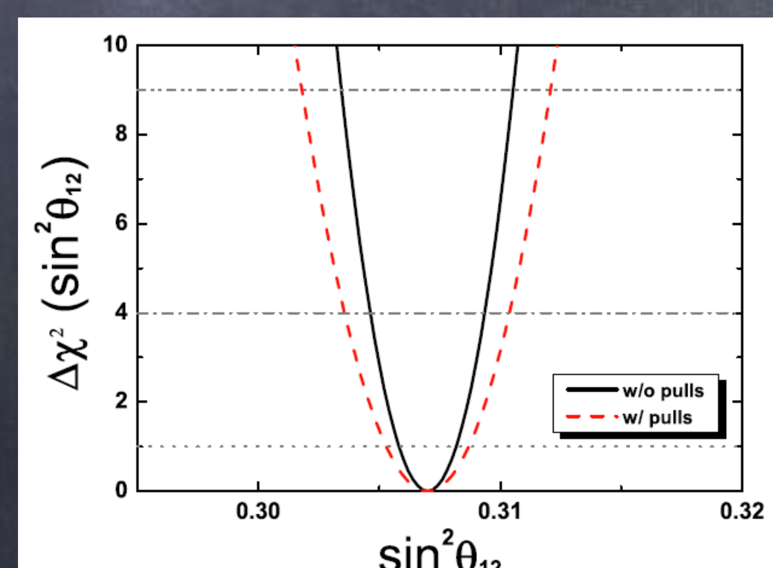
DayaBay

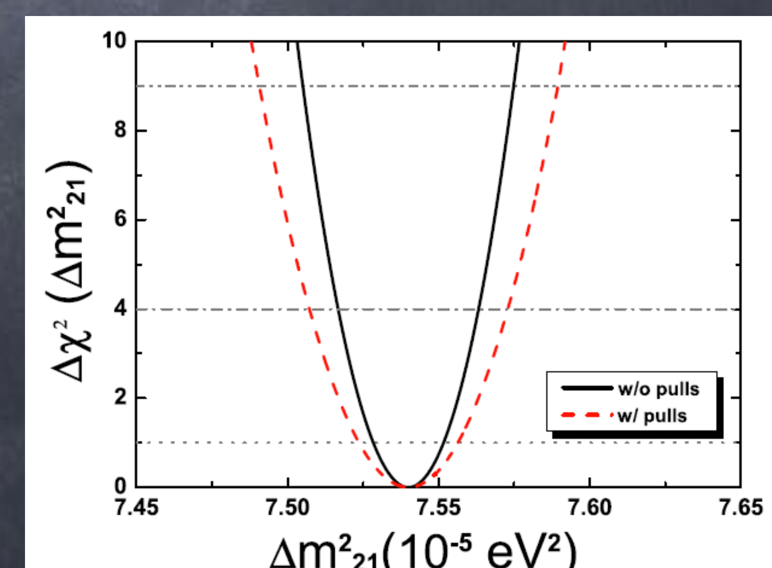
Cao and Luk, 1605.01502

< 3% precision in $\sin^2 2\theta_{13}$ and Δm^2_{ee} by 2020

JUNO

(6 years) **An et al, 1507.05613**

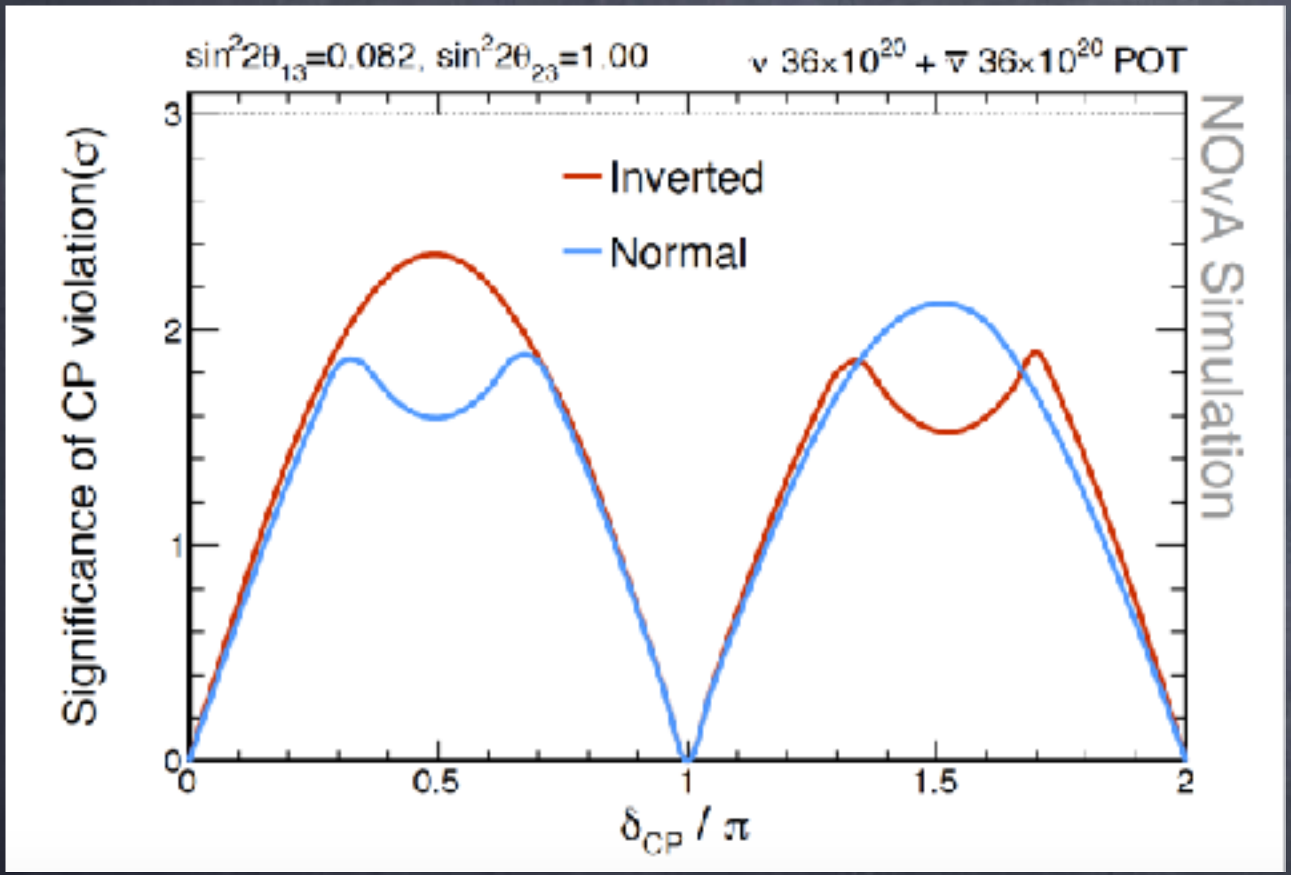




~0.7% precision on $\sin^2\theta_{12}$ ~0.6% precision on Δm^2_{21}

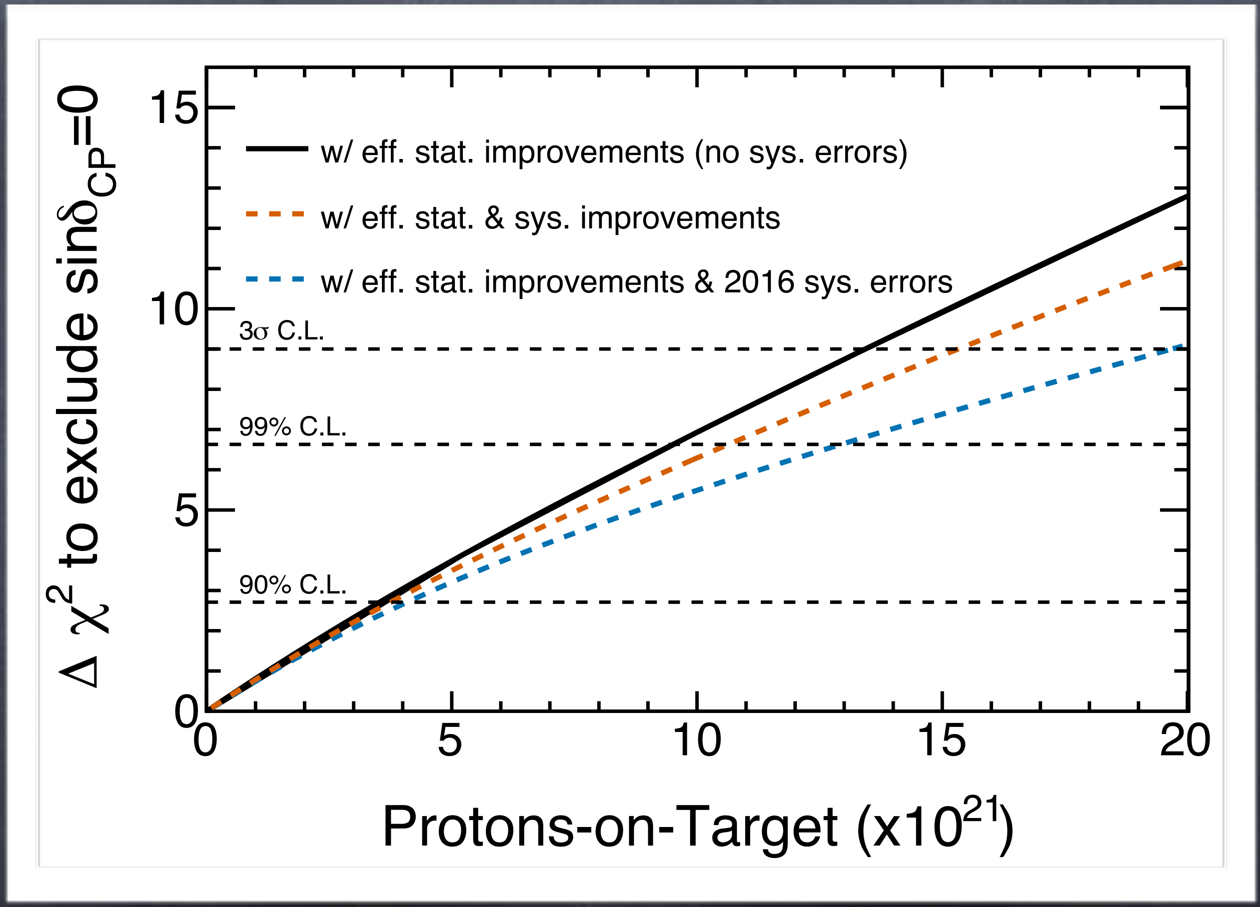
Prospects for CP violation

NOνA



- by 2024:
  > 2σ sensitivity on CP violation at max CP violation

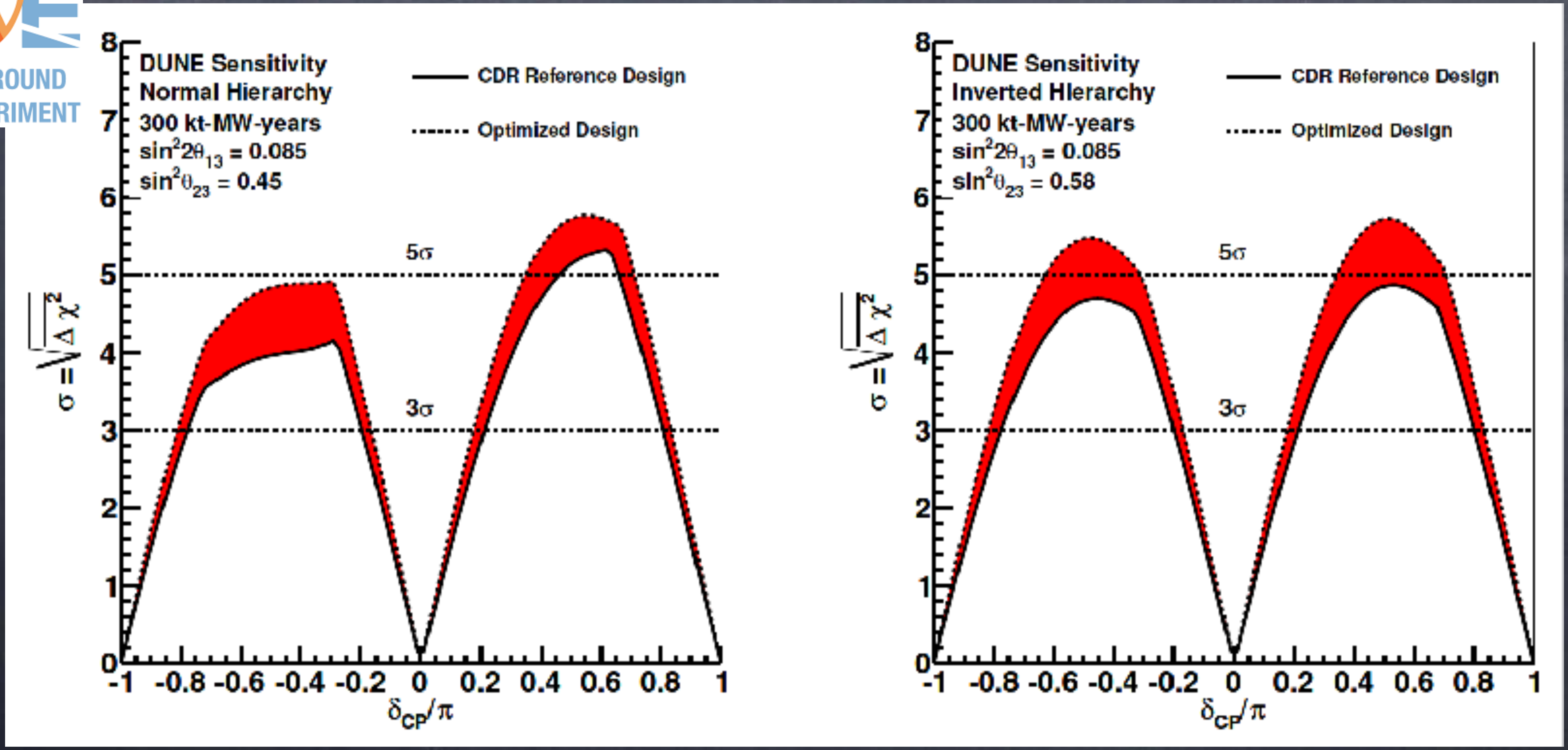
T2K-II



- by 2026 (20×10^21 POT):
  > 3σ sensitivity on CP violation

Prospects for CP violation

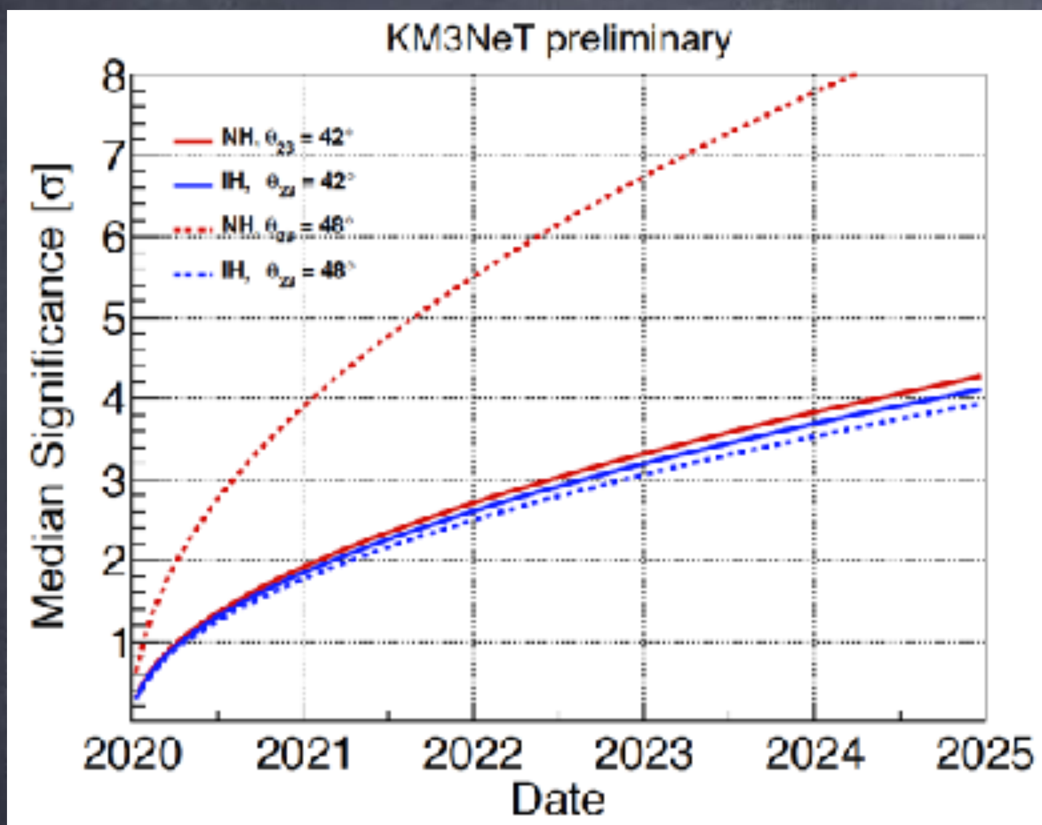
- for sensitivities above 3σ from a single experiment: DUNE, Hyper-K



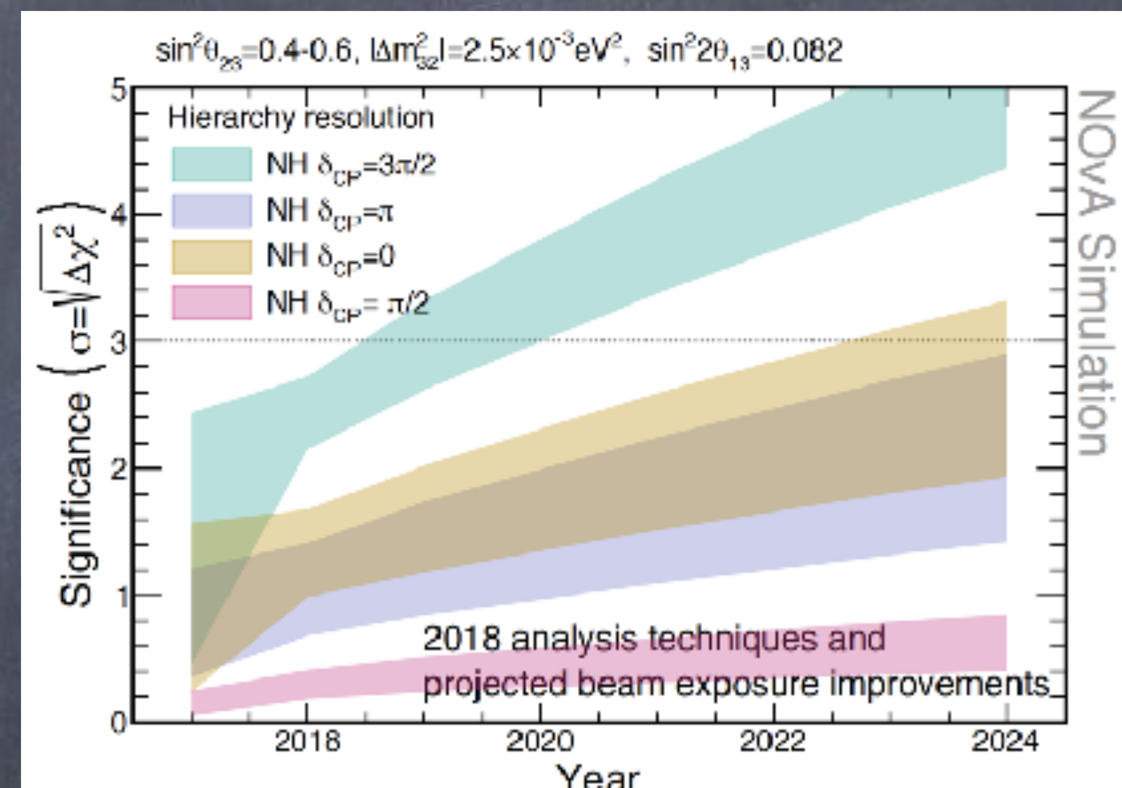
→ > 5σ sensitivity for some fraction of δ_{CP}

Prospects for mass ordering

ORCA upgraded ANTARES exp.



NOνA



- by 2023: 3σ determination of MO
  (similar results for PINGU)

- by 2020: 3σ sensitivity (NO and δ=3π/2)
- by 2024: 3σ sensitivity for 30/50% of δ

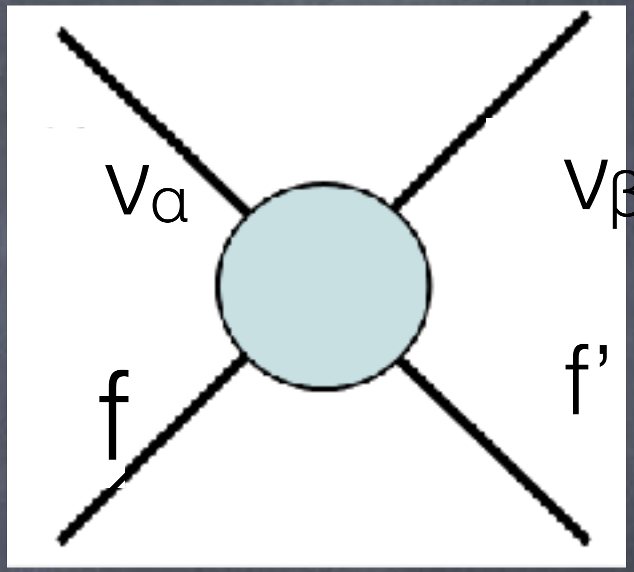
JUNO Reactor experiment with L=50 km

⇒ 3σ sensitivity on mass ordering after 6 years

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

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

$\Rightarrow$ may affect neutrino production and detection

$\epsilon_{\alpha\beta}^{s}$ (source) $\epsilon_{\alpha\beta}^{d}$ (detector)

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

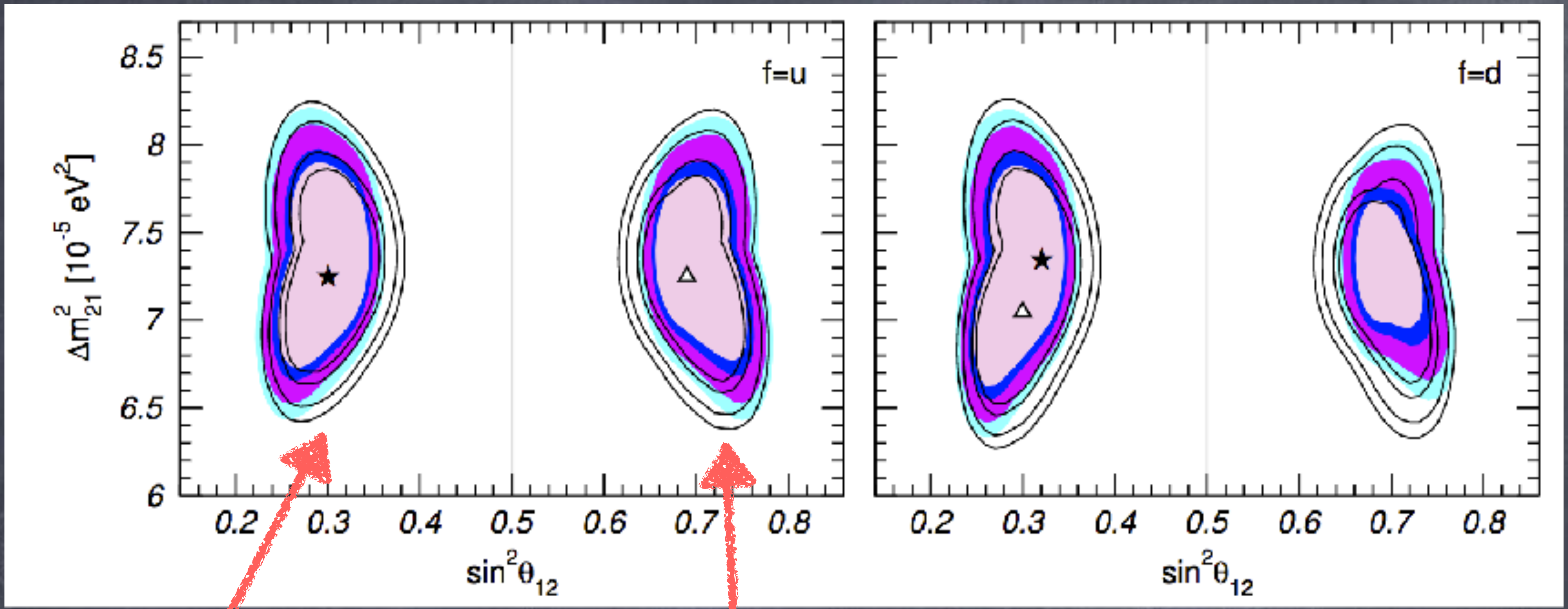
$\epsilon_{\alpha\beta} \neq 0$ $\rightarrow$ NSI violate lepton flavor (FC-NSI)

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

$\Rightarrow$ mainly affecting neutrino propagation in matter: $\epsilon_{\alpha\beta}^{m}$

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

NSI in the solar sector



Miranda et al, JHEP 2006

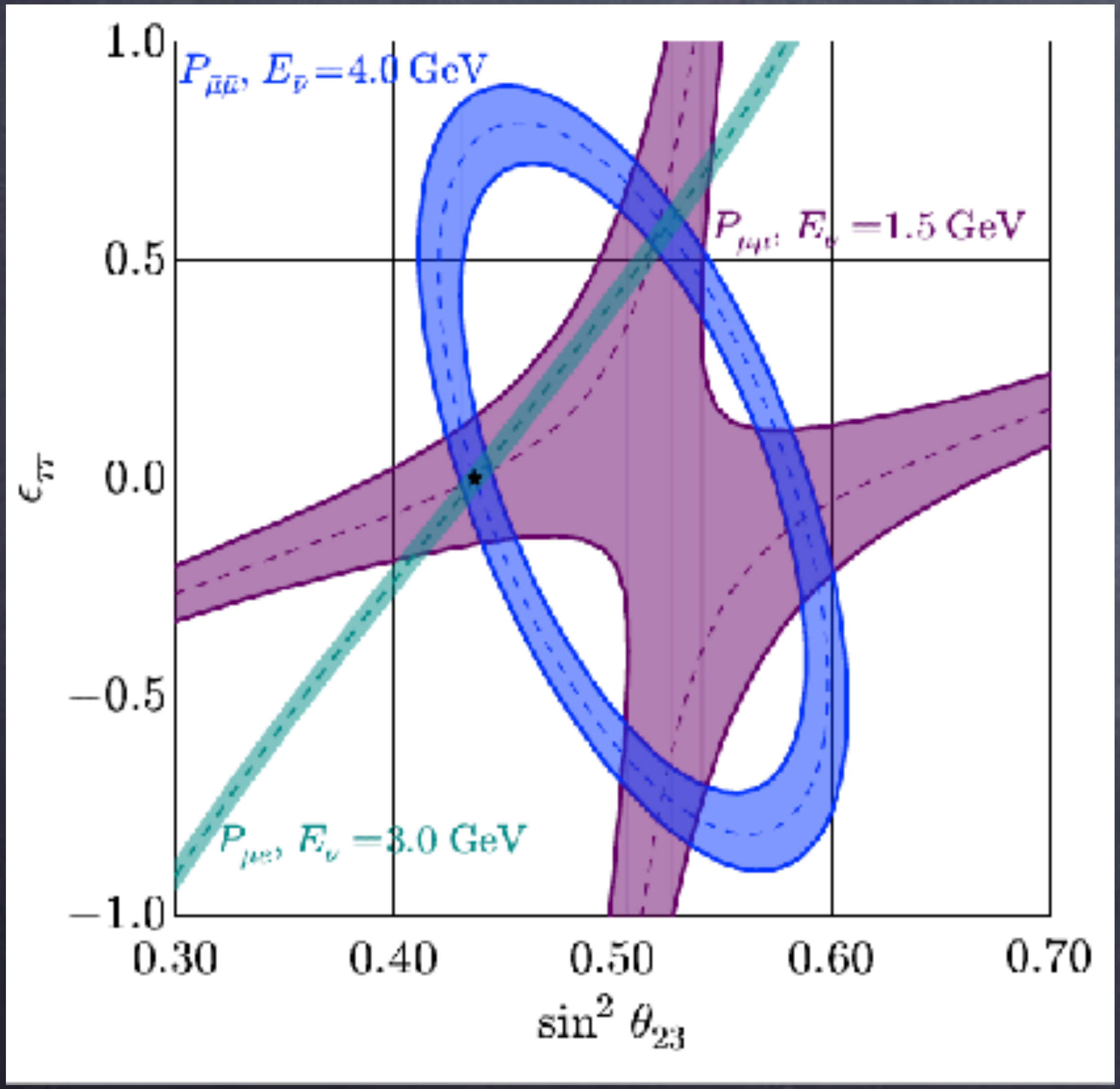
Gonzalez-Garcia et al, JHEP 2013

Standard solution without NSI

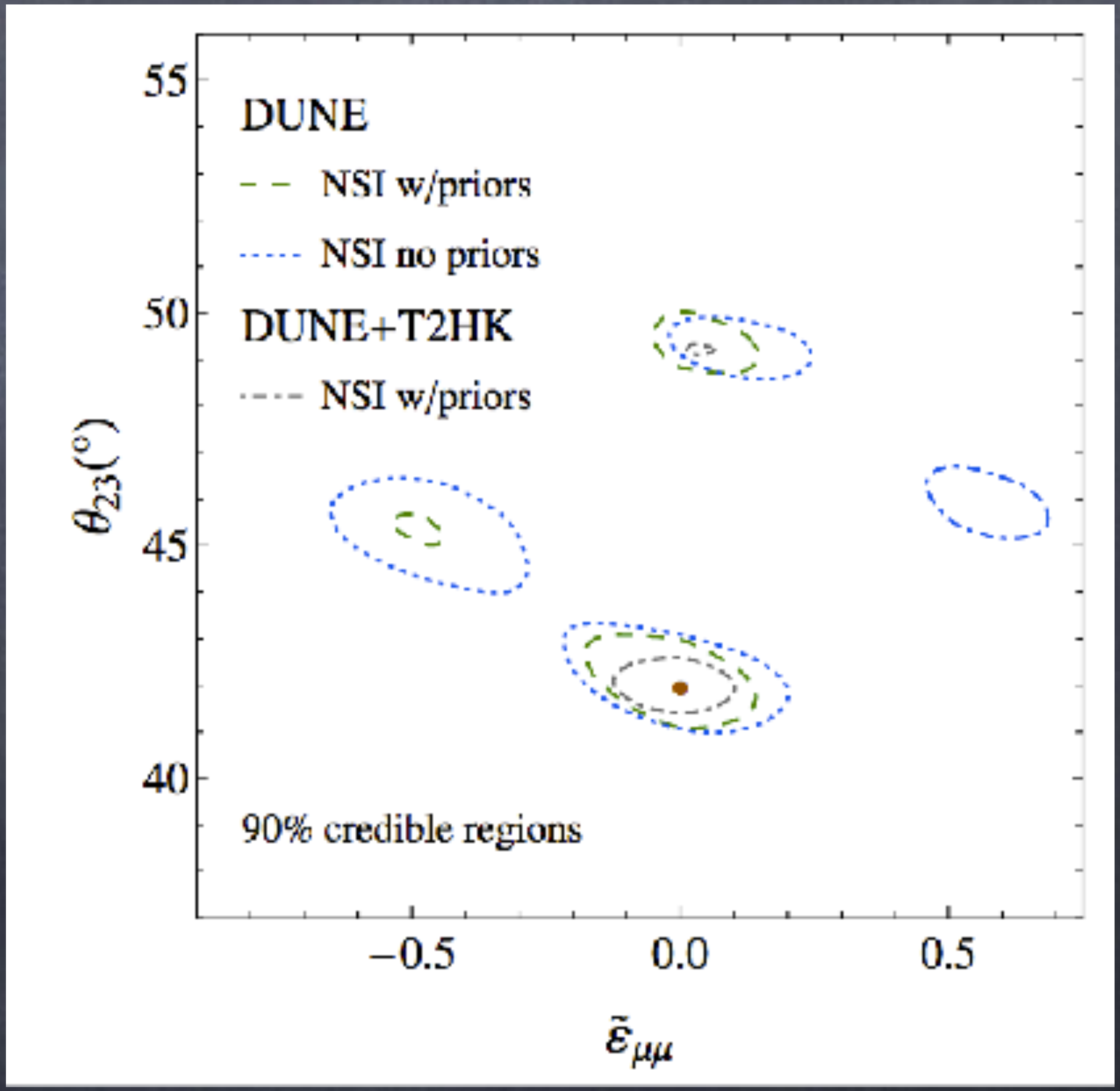
A degenerate solution appears, with $\theta_{12} > \pi/4$

NSI at future LBL experiments

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



Gouvea and Kelly, NPB 2016



Coloma, JHEP 2016

Non-unitary light neutrino mixing

- Most models of neutrino masses -> extra heavy states

  Ex: type I seesaw, inverse seesaw

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

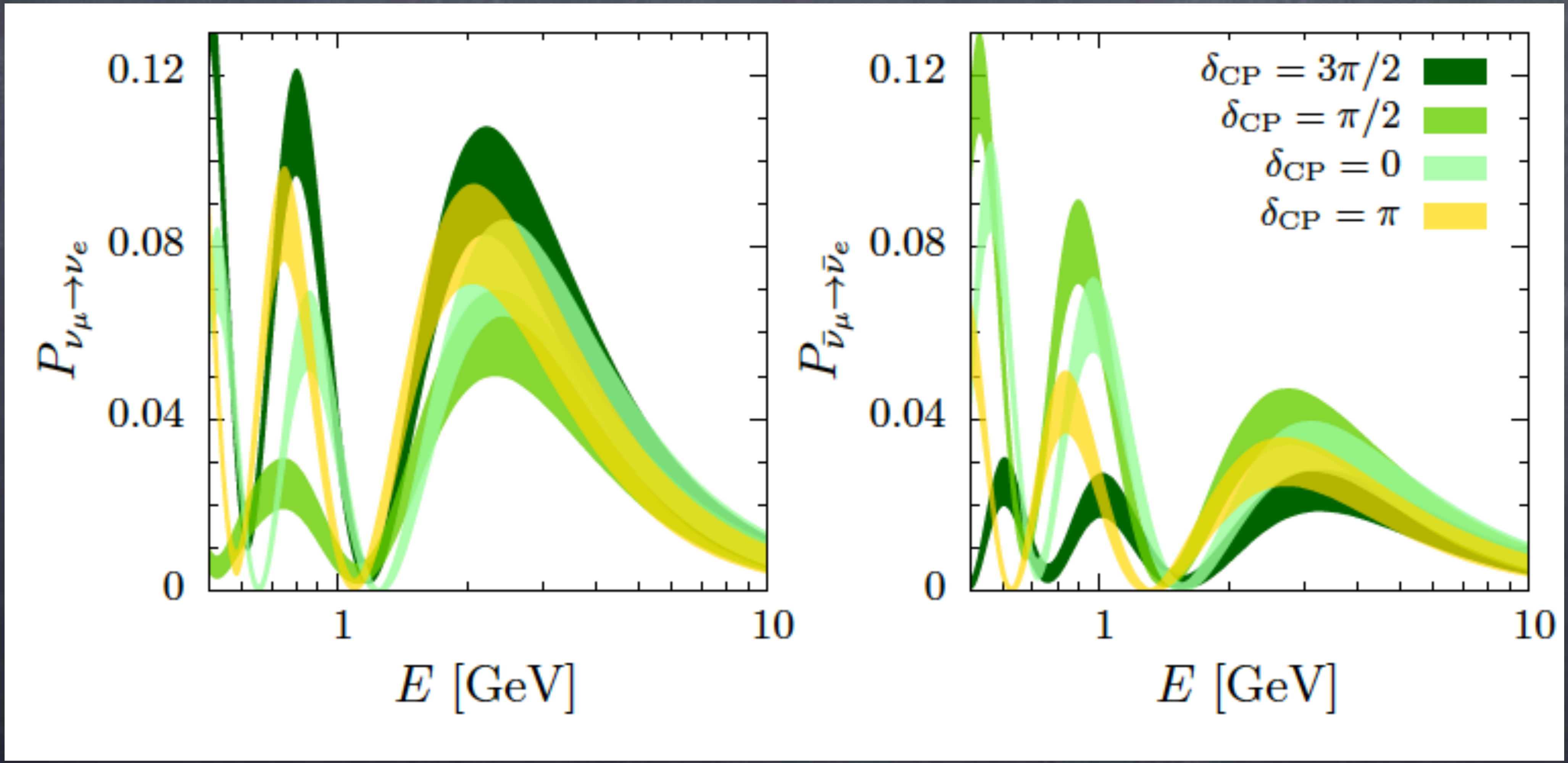
- NxN mixing matrix with:
  N(N-1)/2 mixing angles and (N-1)(N-2)/2 Dirac CP phases

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

$\rightarrow$ if U is non-unitary: 9 more parameters are needed to describe mixing: 6 new moduli + 3 new phases.

NU neutrino oscillations in DUNE

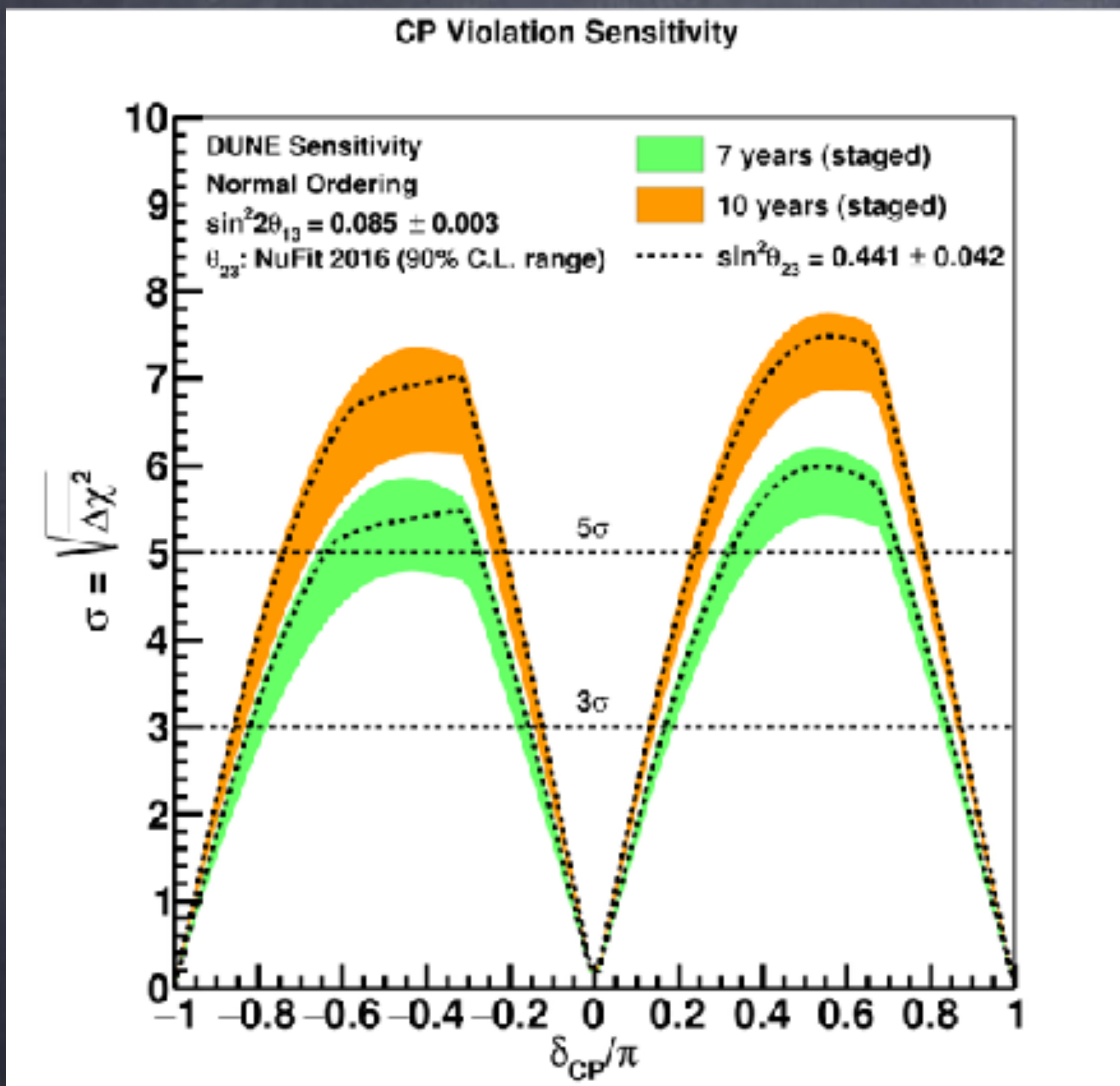
The new phases will modify the standard oscillation picture in LBL experiments, such as DUNE

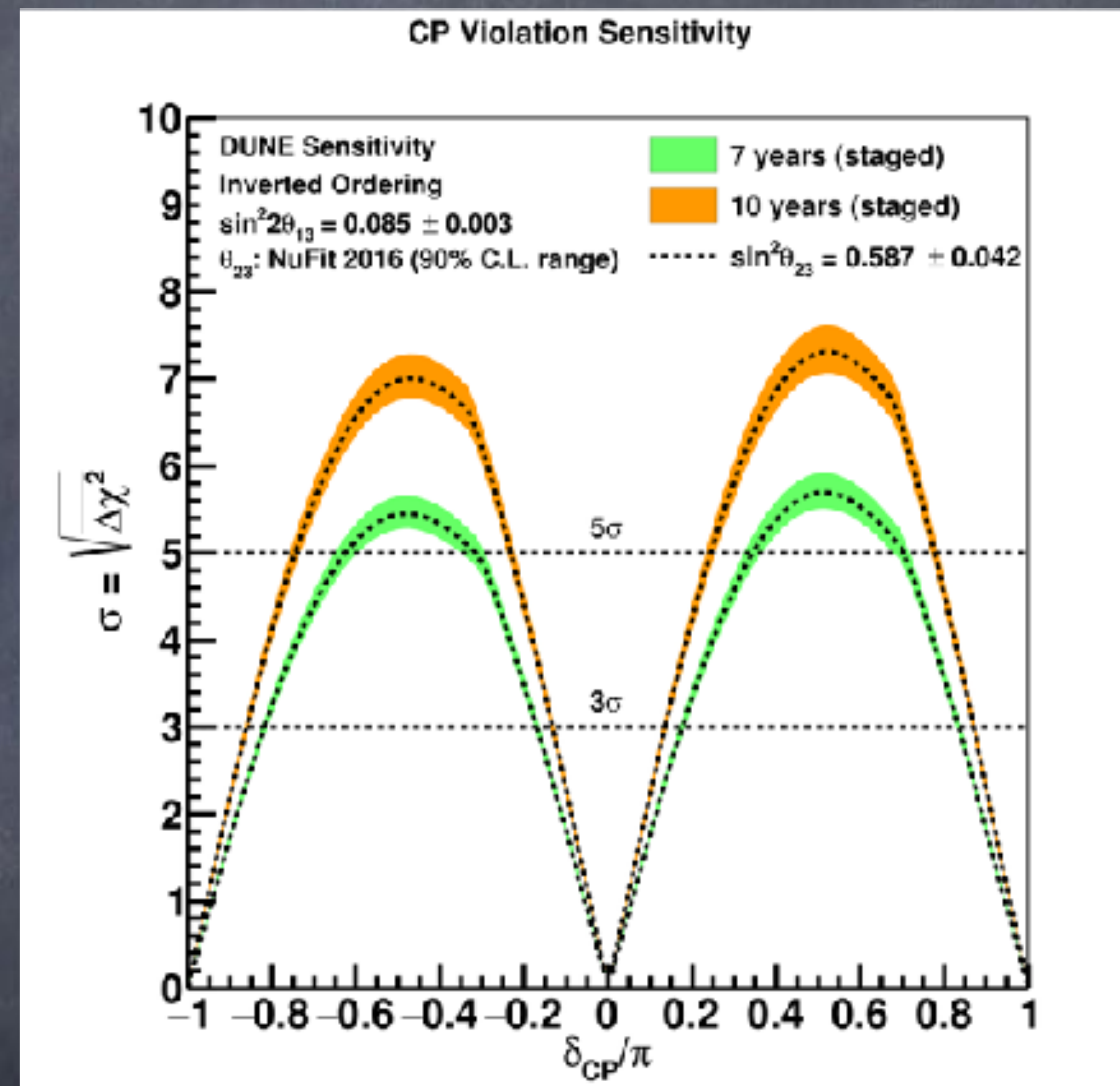


→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV spoil sensitivity to δ

Escrihuela et al, NJP 2017

CP violation searches in DUNE

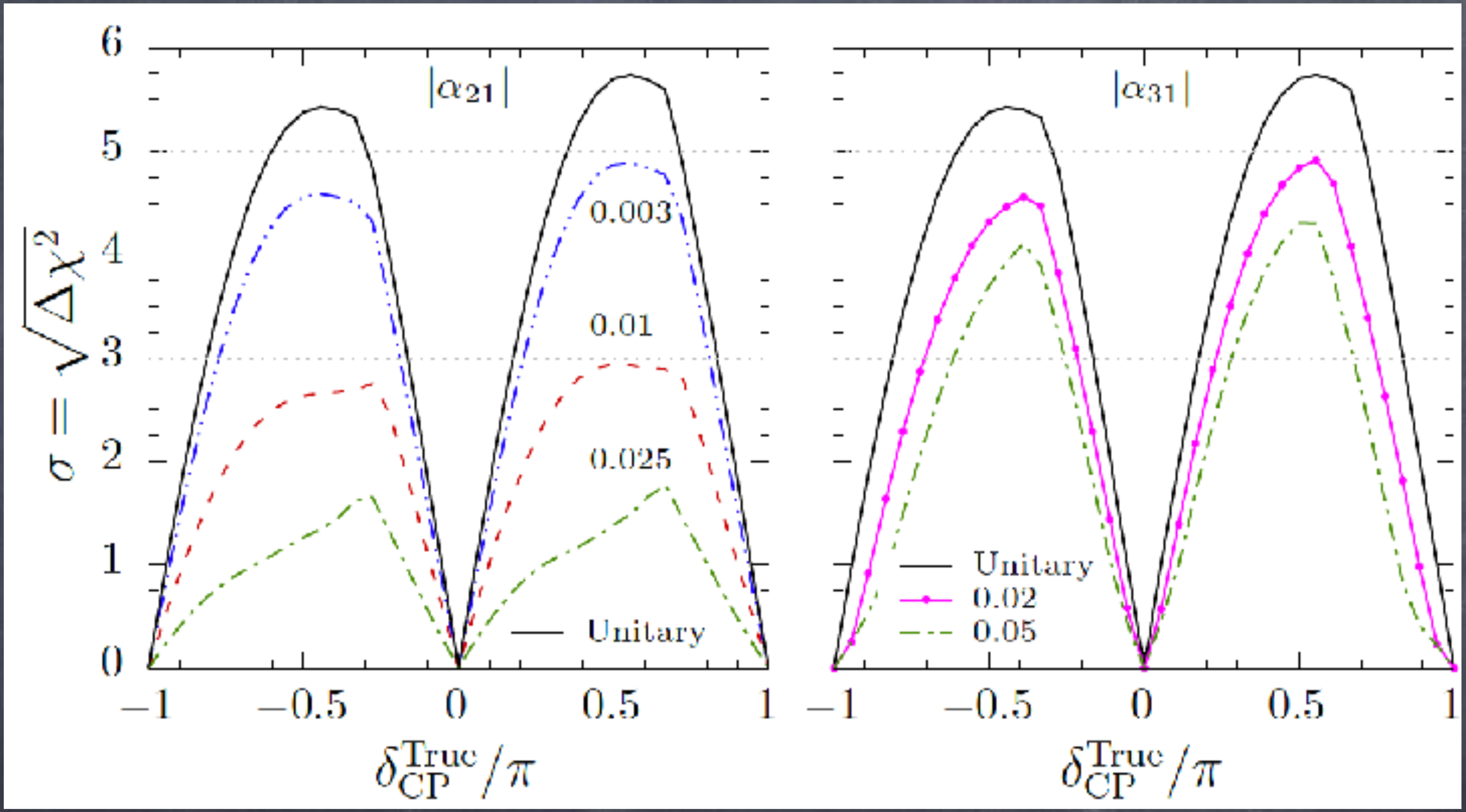




> 5σ sensitivity for some fraction of δ_{CP}

E. Worcester, DUNE Collaboration

DUNE CP sensitivity with NU



Escrihuela et al, NJP 2017

The sensitivity to CP violation might be significantly spoiled in the presence of NU

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 $\nu_\mu \rightarrow \nu_e$ 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 standard picture of neutrino oscillations.