

Question

Could quarks also undergo flavour oscillations like neutrinos?

Lecture 4

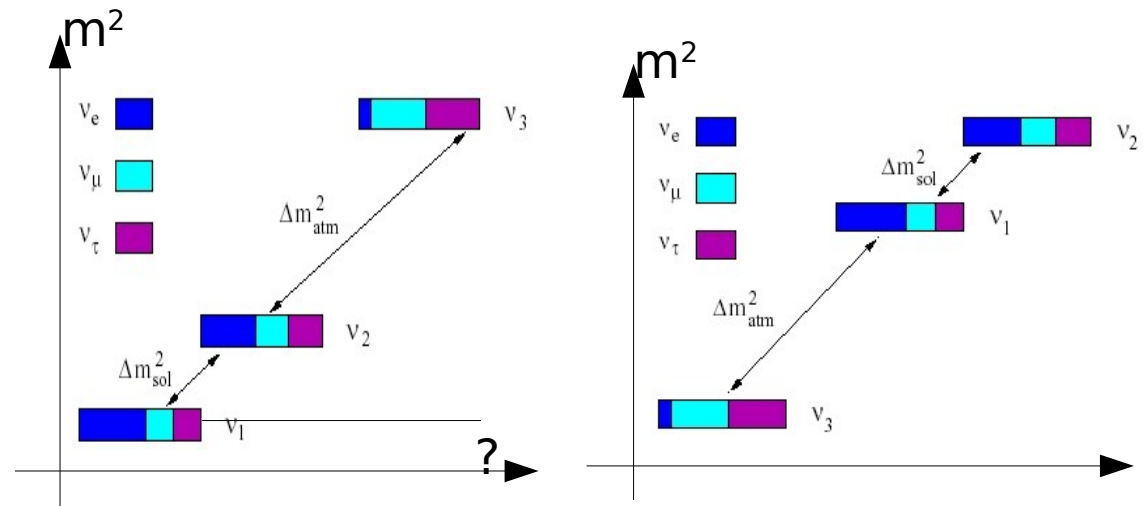
To Infinity and Beyond!

The Quest

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

Value of δ ?

Normal or Inverted mass hierarchy?



$$U_{PMNS} \approx \begin{pmatrix} 0.82 & 0.54 & 0.14 \\ 0.35 & 0.56 & 0.68 \\ 0.35 & 0.55 & 0.69 \end{pmatrix} ?$$

$$U_{CKM} = \begin{pmatrix} 0.975 & 0.222 & 0.004 \\ 0.221 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

- Better estimates of the oscillation parameters using accelerators
- Is θ_{23} maximal?
- Is the neutrino Majorana?
- What is the absolute mass?

Current Experiments

T2K

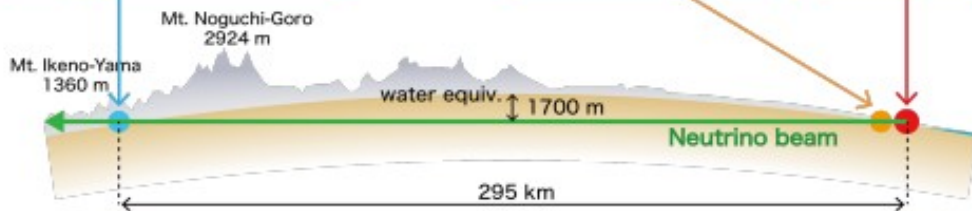
Japan



Super Kamiokande

Near Detector

J-PARC



25 kton water Cerenkov

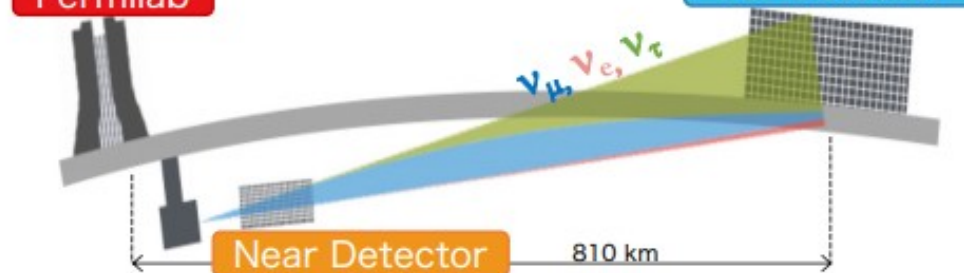


USA



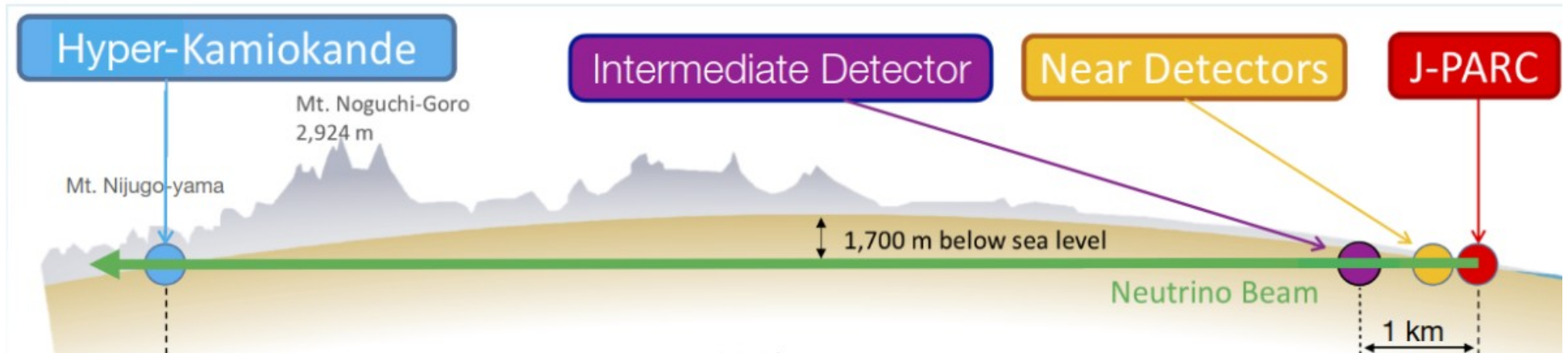
Fermilab

Far Detector



14 kton liq. scint.

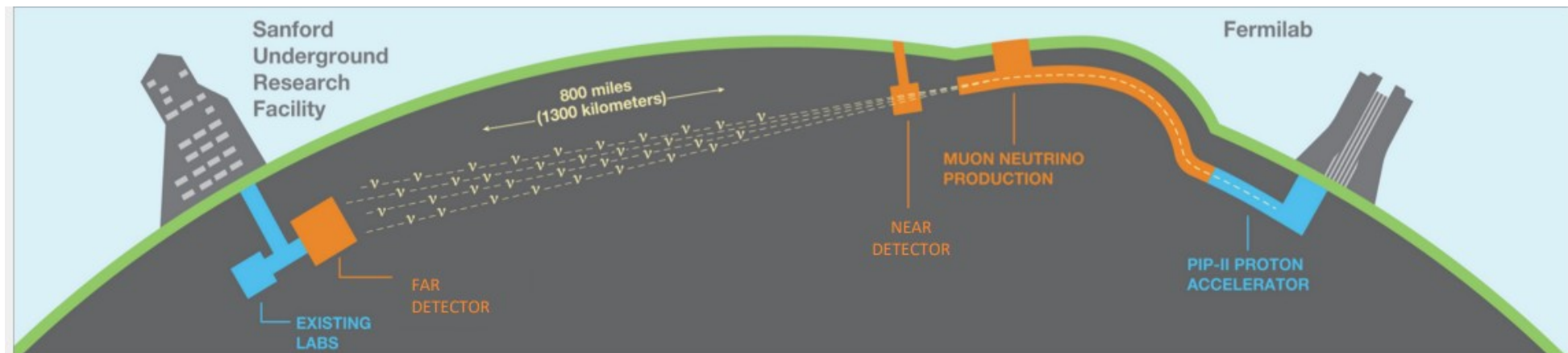
Next generation



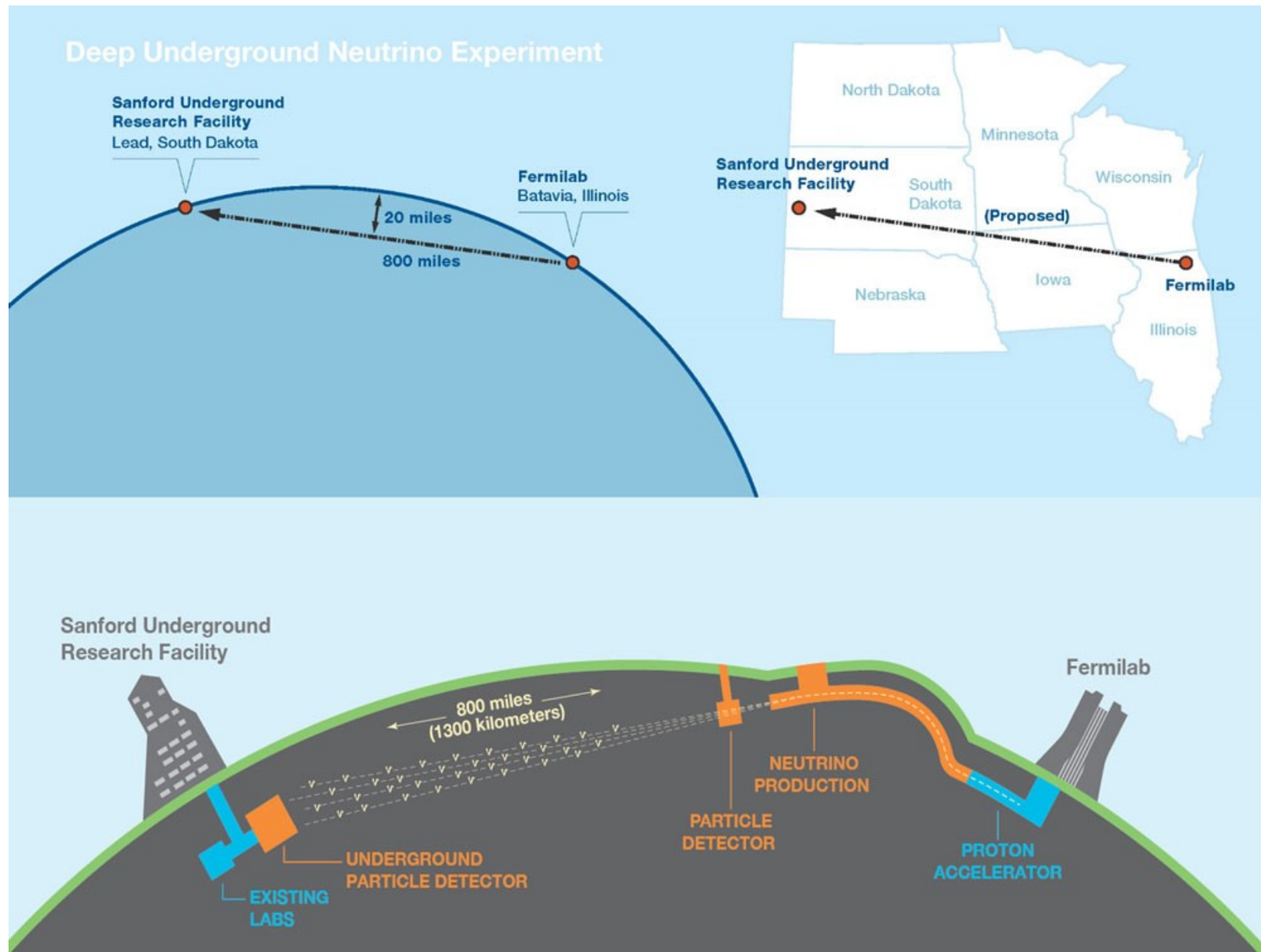
DUSEL Underground
Neutrino Experiment (DUNE)
1300 km baseline



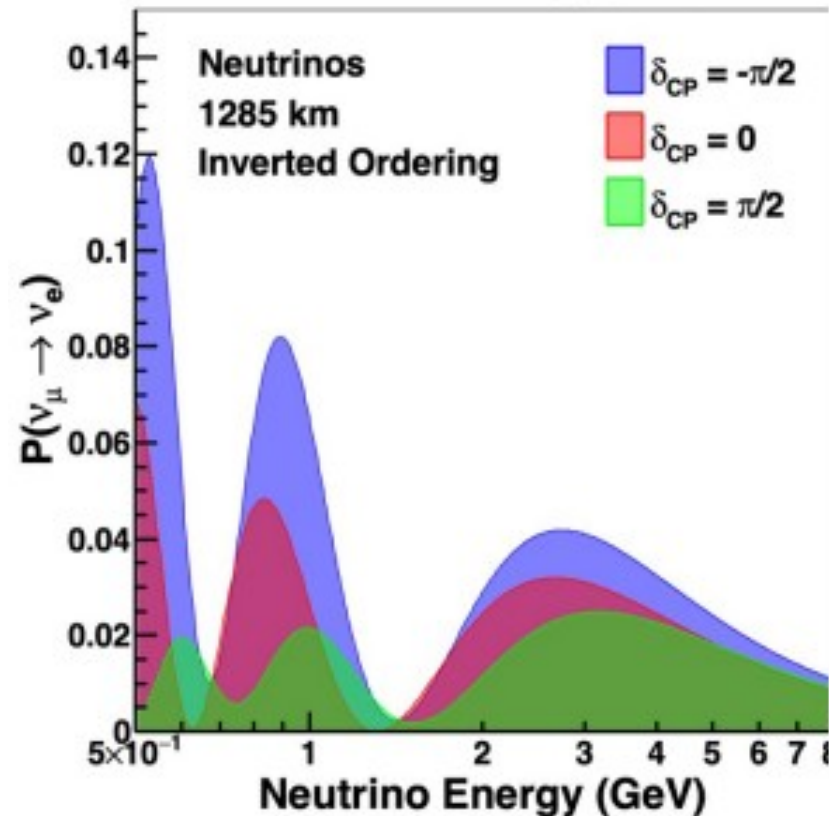
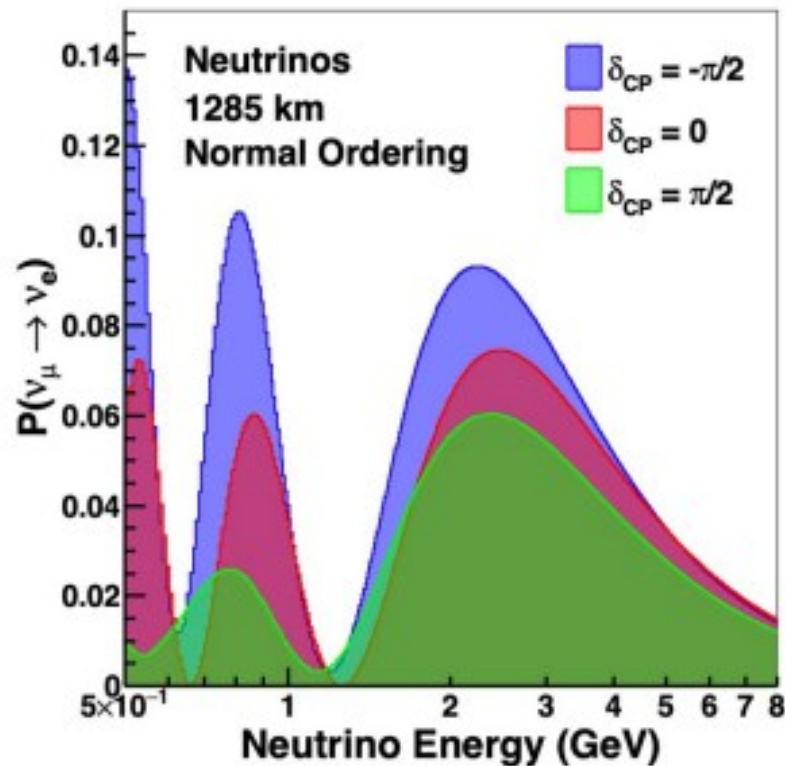
Hyper-Kamiokande
300 km baseline



DUNE in the USA

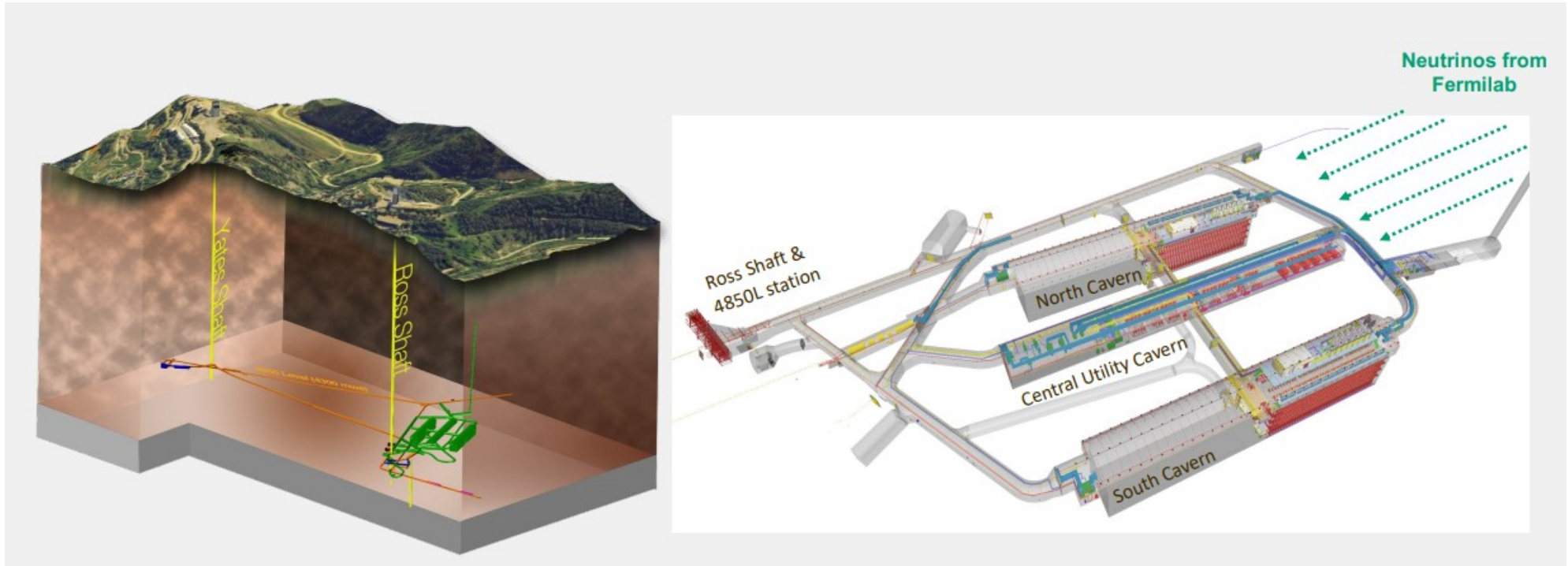


DUNE Beam



- ▶ DUNE operates a wide-band beam between 0 and 8 GeV, peaking at about 2.5 GeV at the FD.
- ▶ Comparison of the peaks of the first AND second oscillation maxima can be used to measure the mass ordering and δ_{CP}
- ▶ At high energies (>3 GeV) degeneracies become less of a problem.

DUNE Far Detector



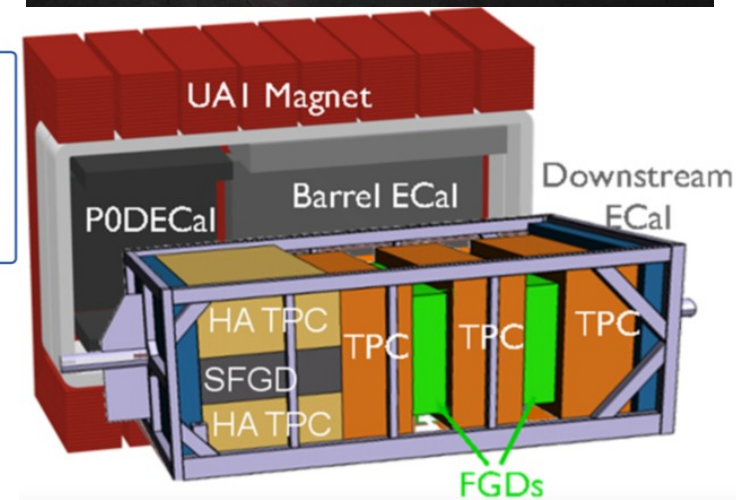
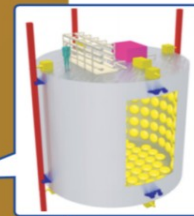
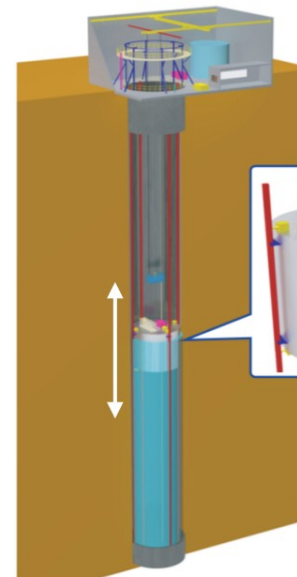
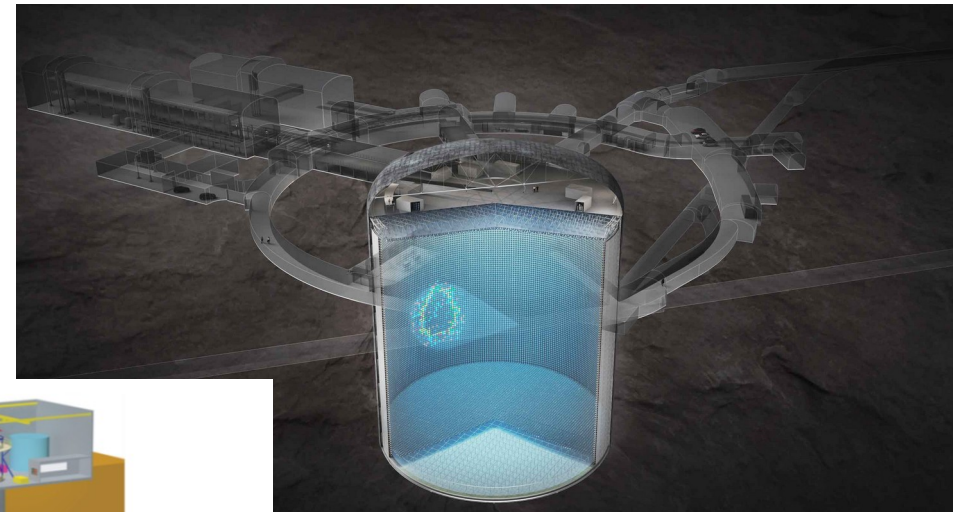
- ▶ Phased development (due to lack of ready cash)
 - ▶ 2 17 kton LAr TPC operating by 2030 (Atm+Solar)
 - ▶ 1.2 MW beam operational by end of 2031
 - ▶ 2 more modules (perhaps diff. technology) by mid-2032
 - ▶ 2.4 MW beam + complete near detector suite by mid-2032

SURF



Hyper-Kamiokande

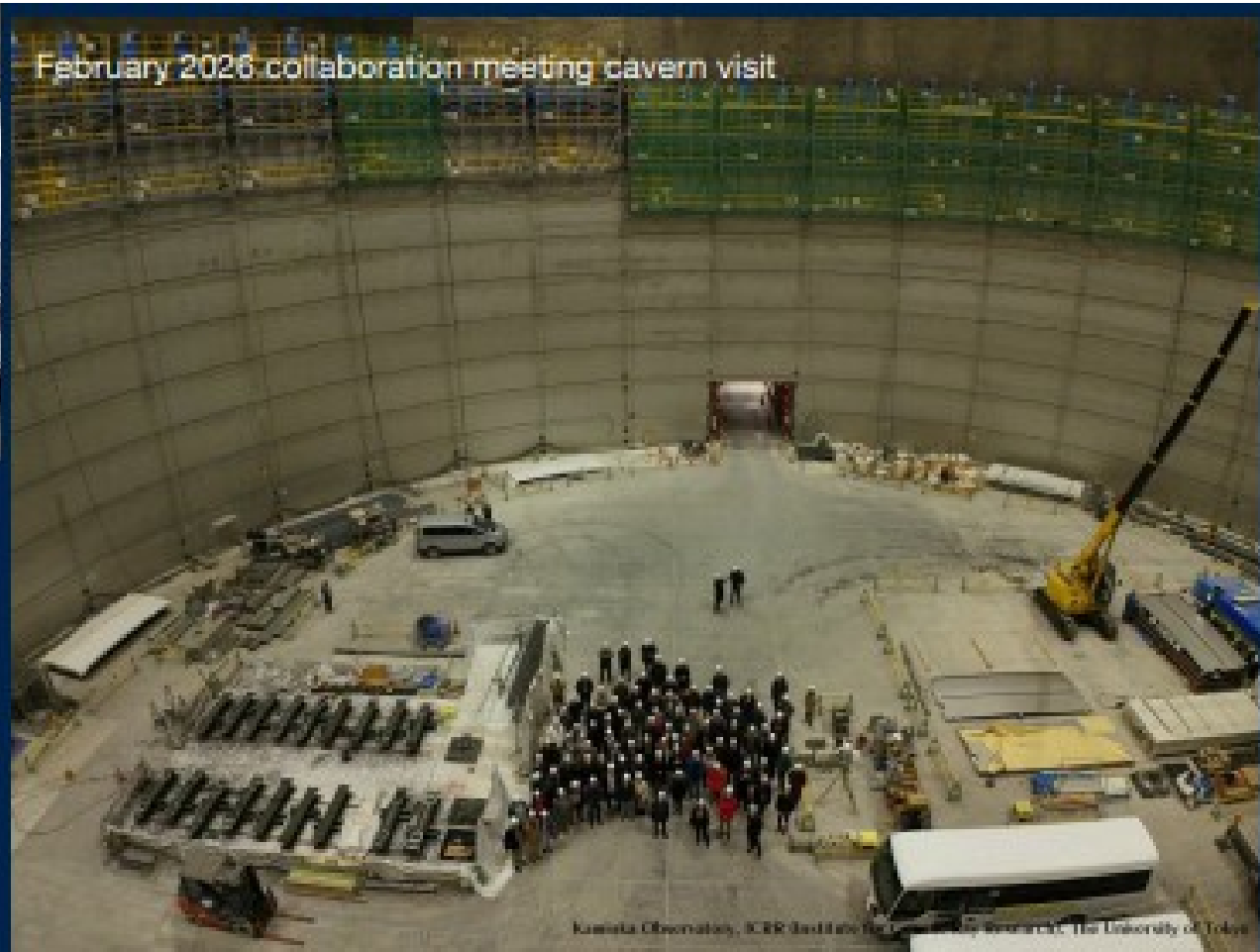
- ▶ Three detectors:
 - ▶ HK Far Detector
 - ▶ Upgraded Near detector
 - ▶ New “Intermediate” detector
- ▶ FarDet complete : 2028
- ▶ Beam upgrades complete : 2028
- ▶ First beam data : 2028-2029



Construction through to 2028'ish

Super-K : 25 kton water
Hyper-K : 200 kton

HyperK



Dune / HK Comparison

	DUNE	Hyper-K	T2K
Beam Energy	3 GeV	0.6 GeV	0.6 GeV
Baseline (L)	800 km	295 km	295 km
Beam Power	1.2 MW → 2 MW	1.3 MW	0.5 MW
Type of Beam	Wideband	Off-axis	Off-axis
Mass of far detector	40 kton (P1) up to 80 kton (P2)	190 kton	22.5 kton
Technology	Liquid Ar TPC	Water Cerenkov	Water Cerenkov
Running from	2031'ish	2028'ish	Now

CP violation and the Mass Hierarchy

Measuring δ_{CP} is the ultimate goal of neutrino oscillation experiments. How? δ_{CP} shows up in the imaginary part of the PMNS matrix.

$$Prob(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\Delta m_{ij}^2 \frac{L}{4E})$$

$$+ 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\Delta m_{ij}^2 \frac{L}{2E})$$

= 0 if $\alpha = \beta$

CP violation can only take place in *appearance* experiments

Look for $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

In all it's naked glory

$$P(\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2 \theta_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_{-+}} \right)^2 \sin^2 \left(\frac{B_{-+}}{2} L \right)$$

$$P_2 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A} \right)^2 \sin^2 \left(\frac{A}{2} L \right)$$

$$P_3 = J \cos \delta \cos \left(\frac{\Delta_{23}}{2} L \right) \left(\frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_{-+}} \right) \sin \left(\frac{A}{2} L \right) \sin \left(\frac{B_{-+}}{2} L \right)$$

$$P_4 = \pm J \sin \delta \sin \left(\frac{\Delta_{23}}{2} L \right) \left(\frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_{-+}} \right) \sin \left(\frac{A}{2} L \right) \sin \left(\frac{B_{-+}}{2} L \right)$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E}$$

$$A = \sqrt{2} G_F N_e$$

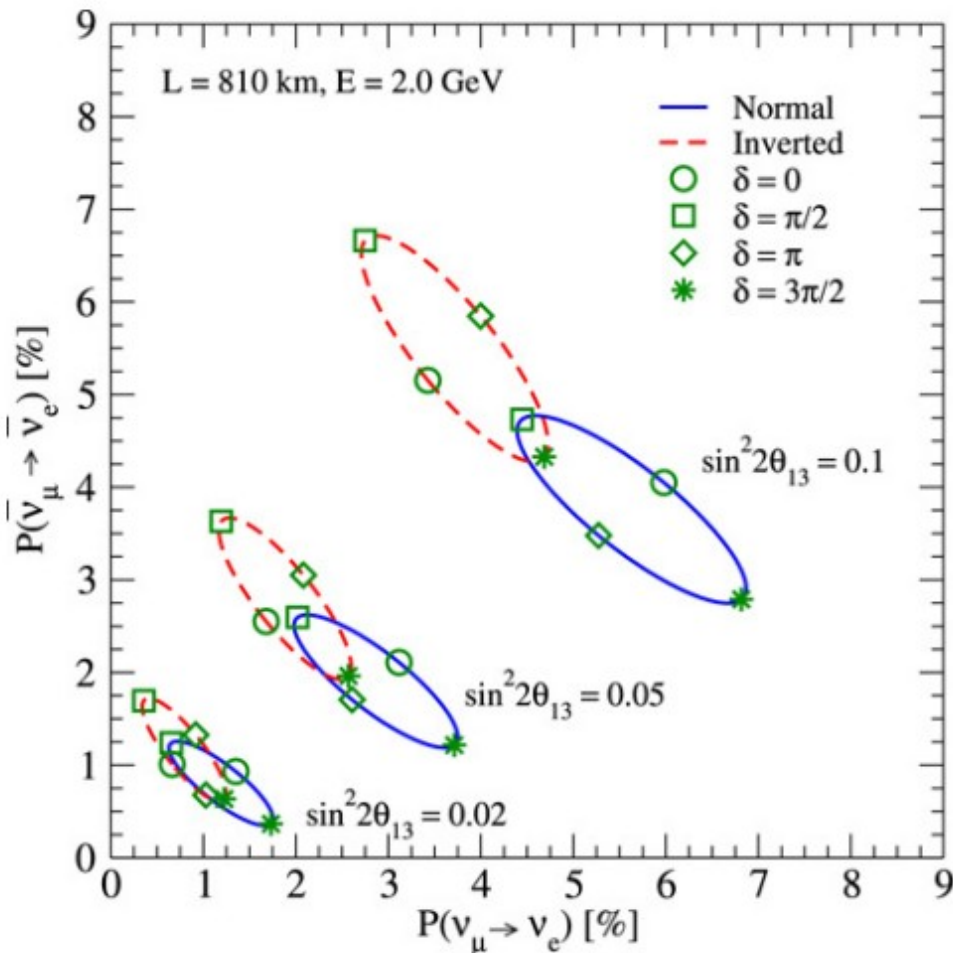
$$B_{-+} = |\Delta_{13} \mp A|$$

$$J = \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

- θ_{13}
- $\theta_{23} > 45$ or $\theta_{23} < 45$
- $\text{Sign}(\Delta m_{23}^2)$
- δ_{MNSP}

Degeneracies

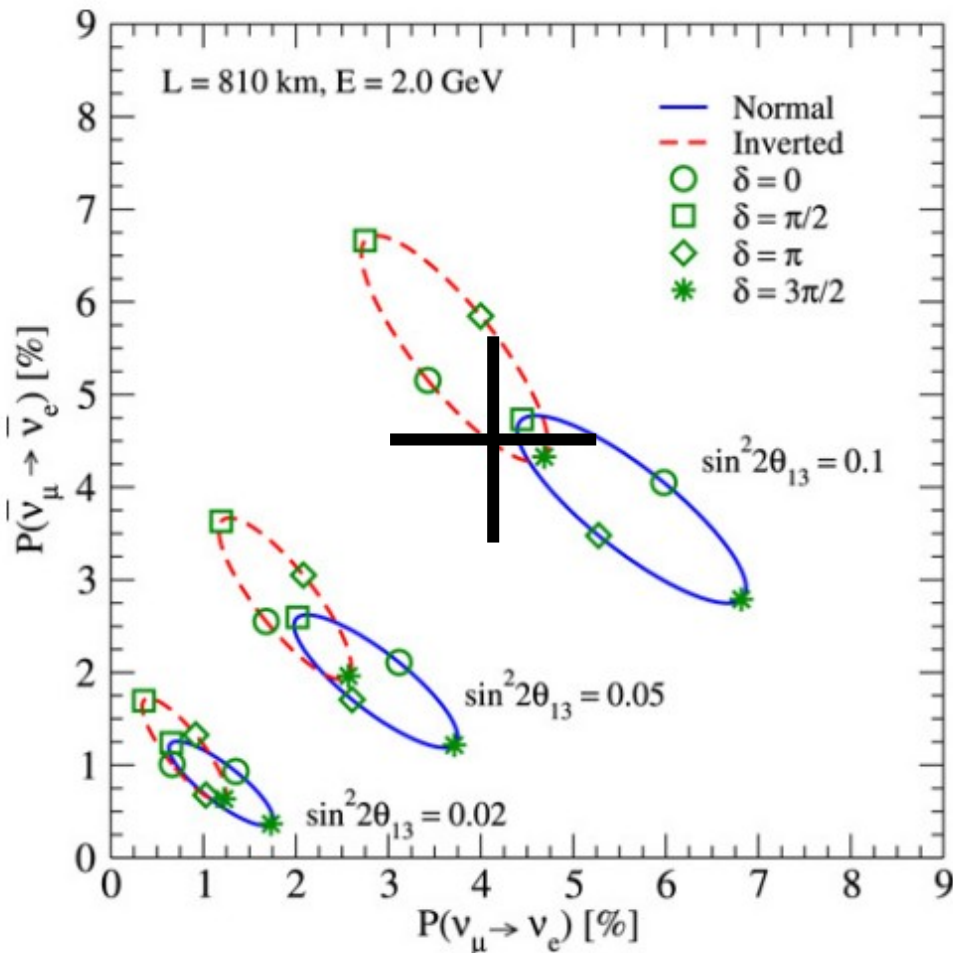
Experiments only measure at most two numbers; but probability has three unknowns and parameters with errors.



Need more than one measurement at different L/E to disentangle the parameter space

Degeneracies

Experiments only measure at most two numbers; but probability has three unknowns and parameters with errors.



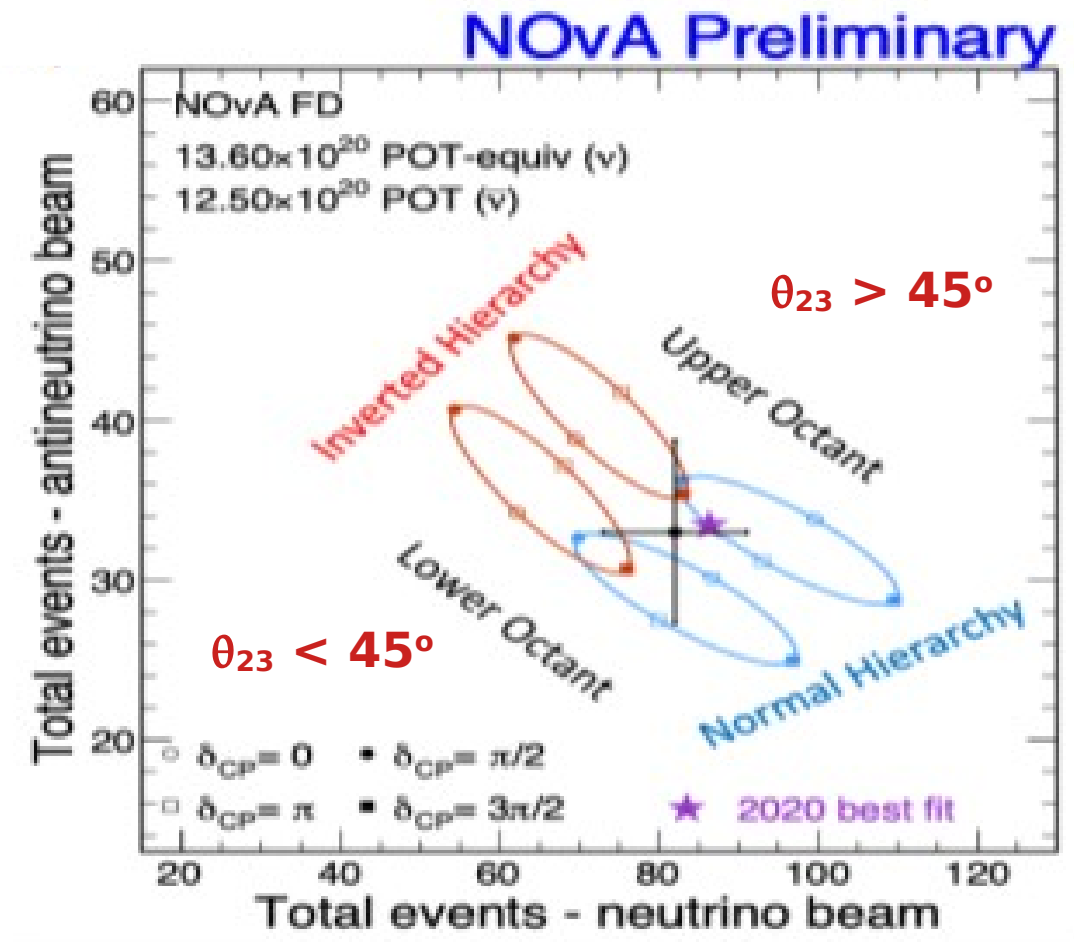
Need more than one measurement at different L/E to disentangle the parameter space

Mass Hierarchy measurements

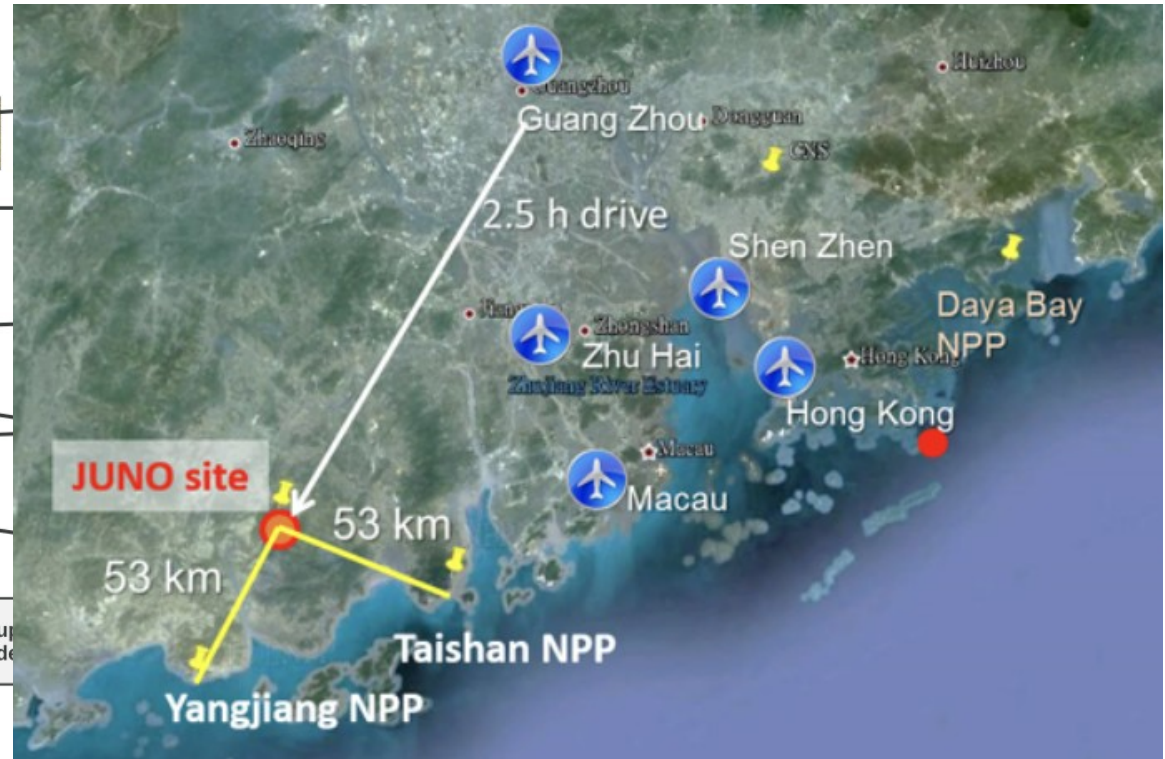
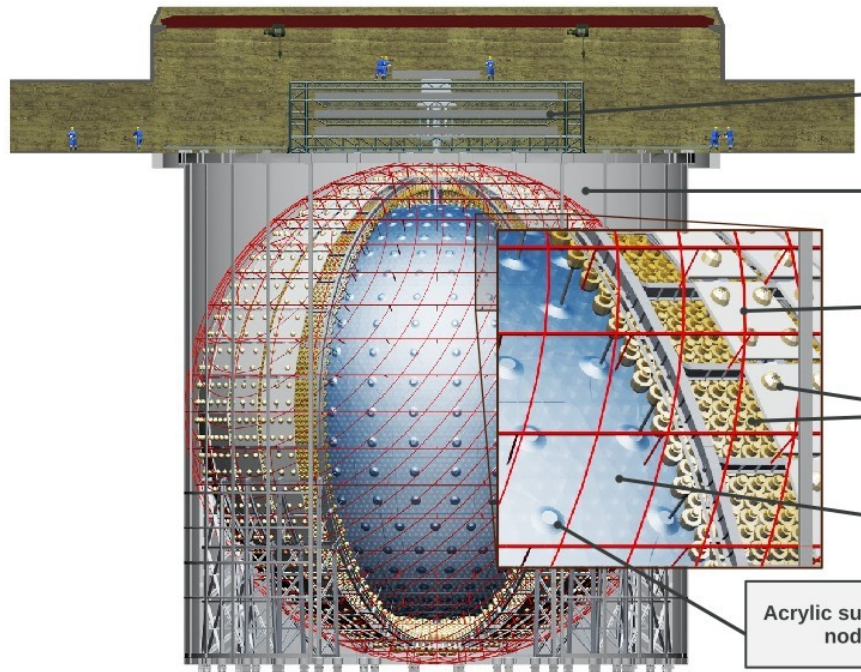
As baseline grows,
matter effects increase

At distances of around
1000 km we can
unambiguously
identify the mass
hierarchy

Once we've done
that we need to
determine CP phase



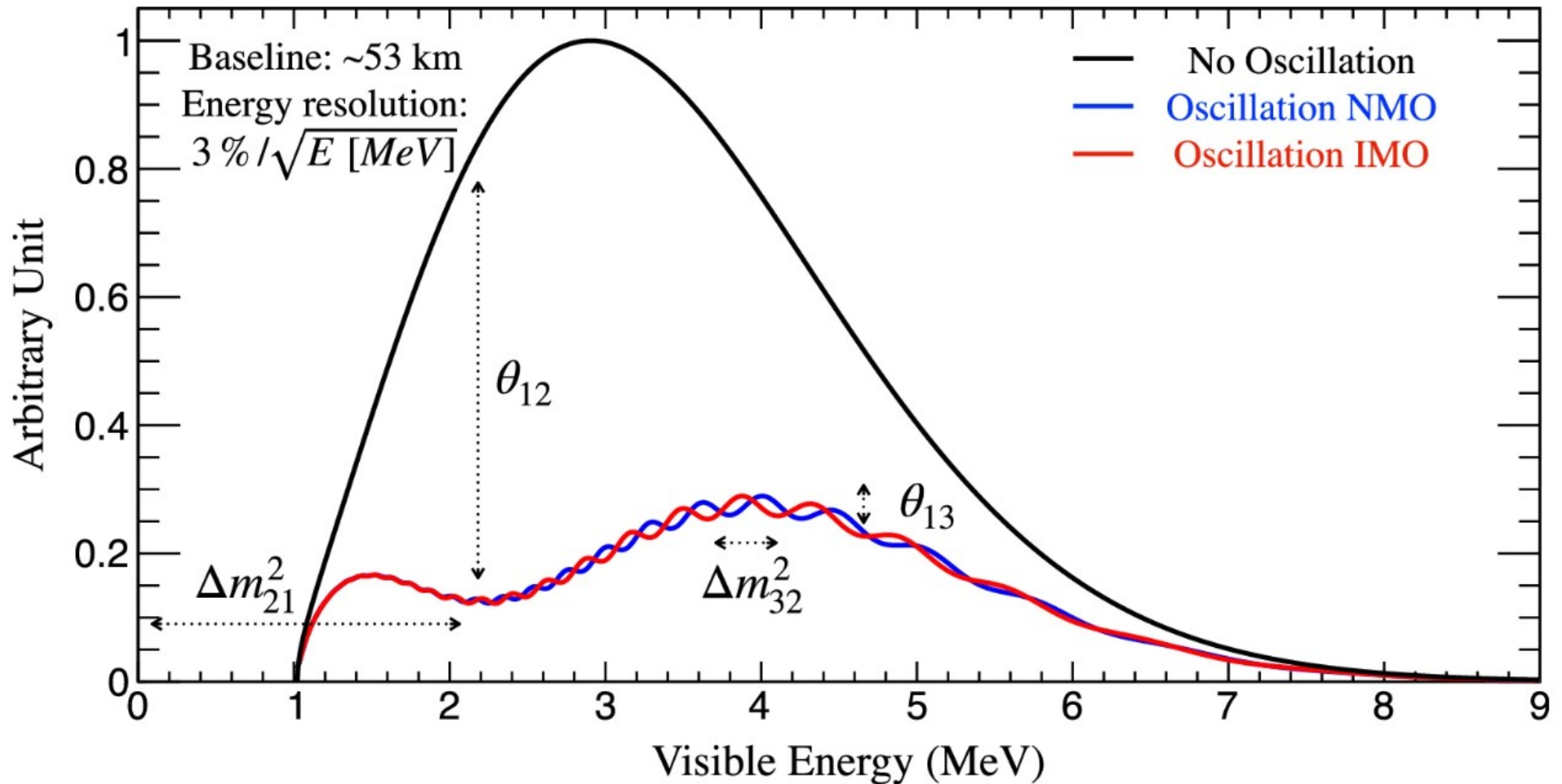
JUNO



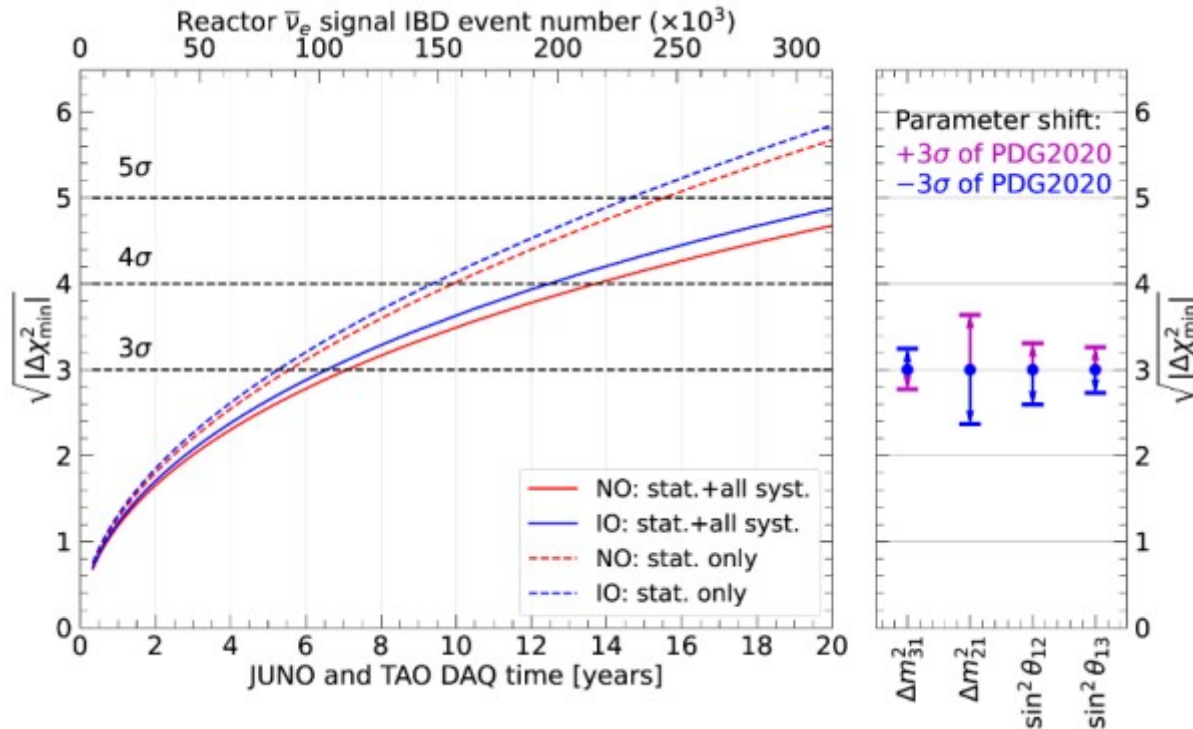
- ▶ 20 kton of liquid scintillator
- ▶ Largest liquid scintillator detector ever built

- ▶ Determine mass hierarchy
- ▶ Precisely measure solar oscillation parameters

JUNO Goal



JUNO

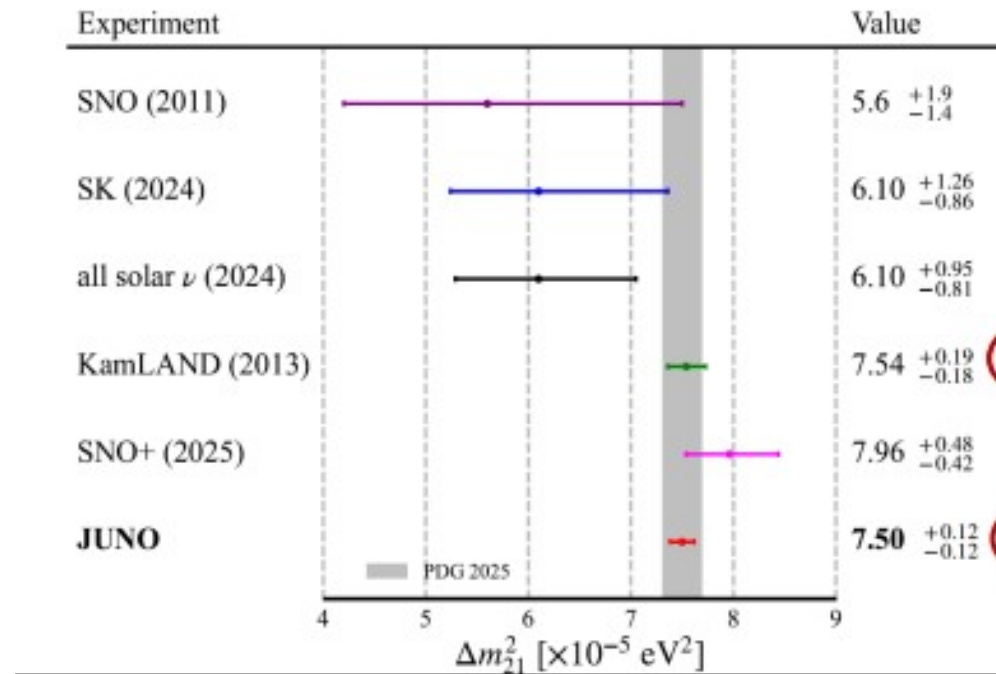
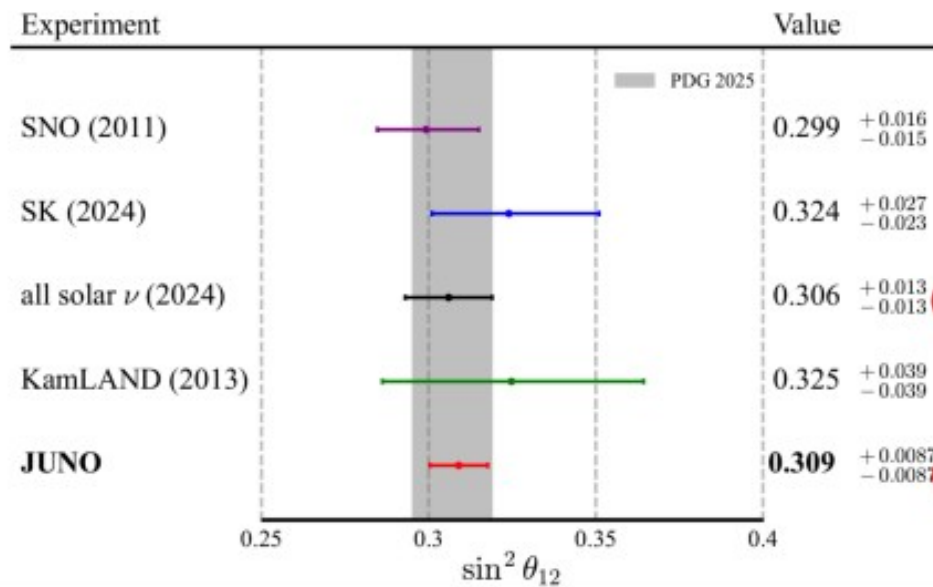


Parameter	PDG 2025	JUNO 6 years
$ \Delta m_{32}^2 $	1.2%	0.2%
Δm_{21}^2	2.4%	0.3%
$\sin^2 \theta_{12}$	4.0%	0.5%
$\sin^2 \theta_{13}$	3.2%	12.1%

- ▶ Determine mass hierarchy
- ▶ 3 σ in 7 years (faster if combined with SK / T2K / NOVA)
- ▶ Precisely measure solar oscillation parameters

Data taking started in 2025

JUNO 1st Results



- ▶ First JUNO results from 59 days of data
- ▶ Already the most precise solar neutrino oscillation parameter measurements ever.

Current Experiments



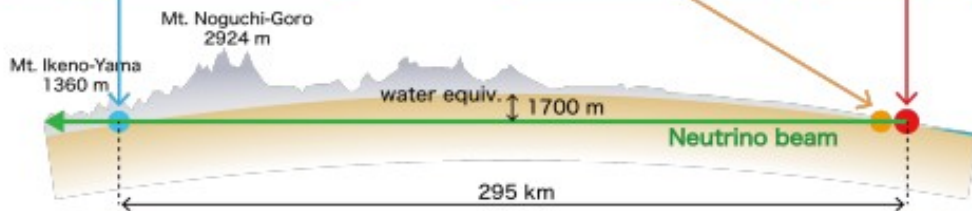
Japan



Super Kamiokande

Near Detector

J-PARC



25 kton water Cerenkov

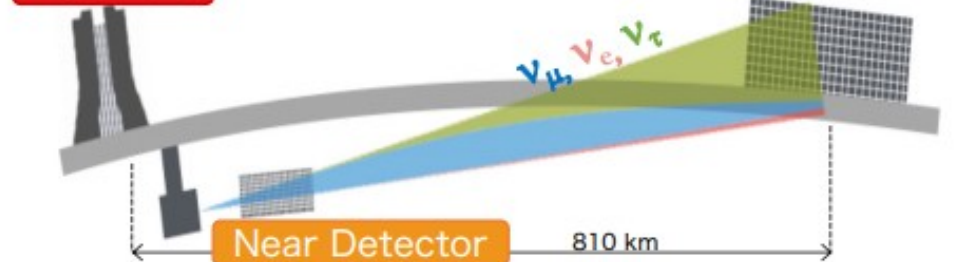


USA



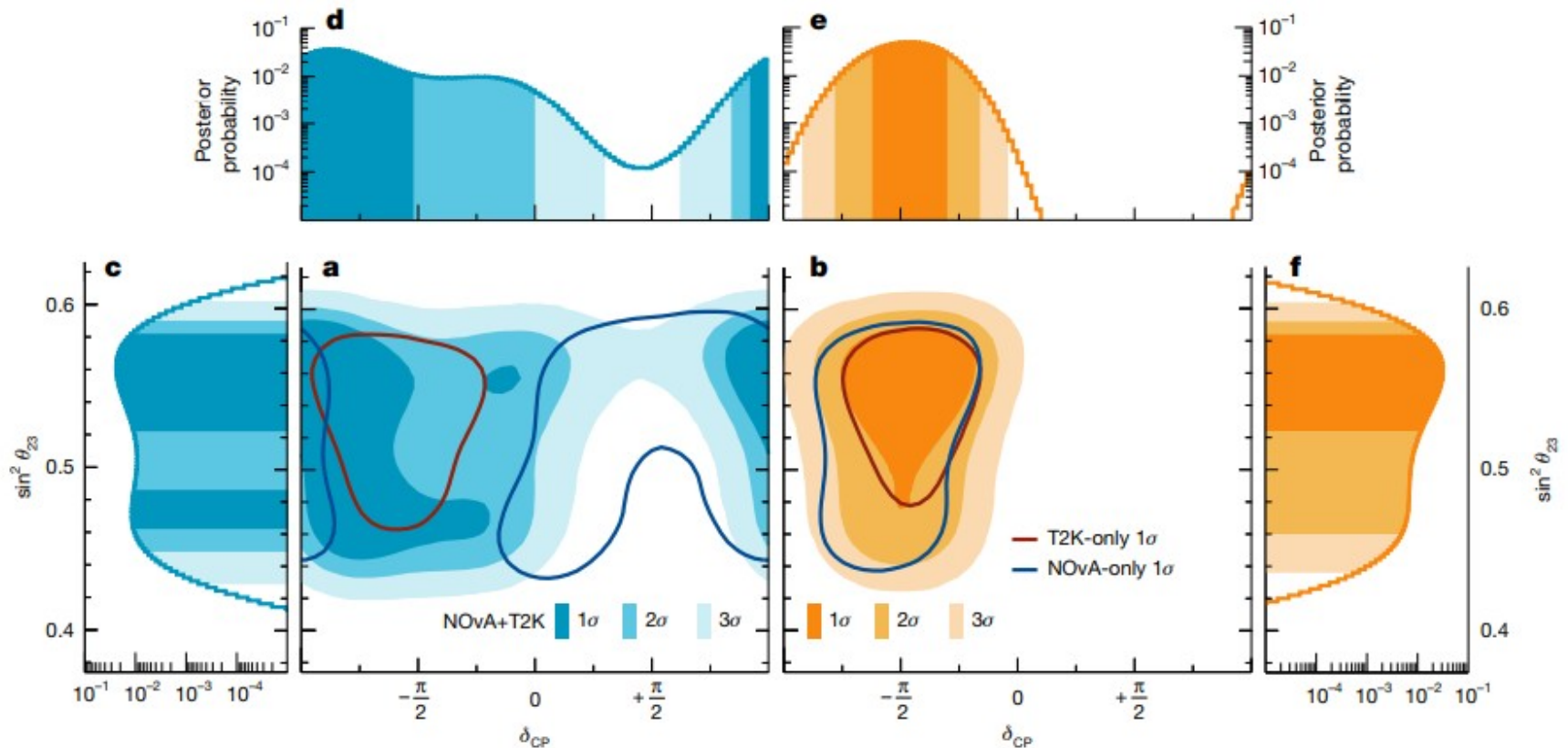
Fermilab

Far Detector



14 kton liq. scint.

T2K and NOvA



Normal hierarchy

3σ credibility interval

$$\delta_{CP} : [-1.38\pi, 0.3\pi]$$

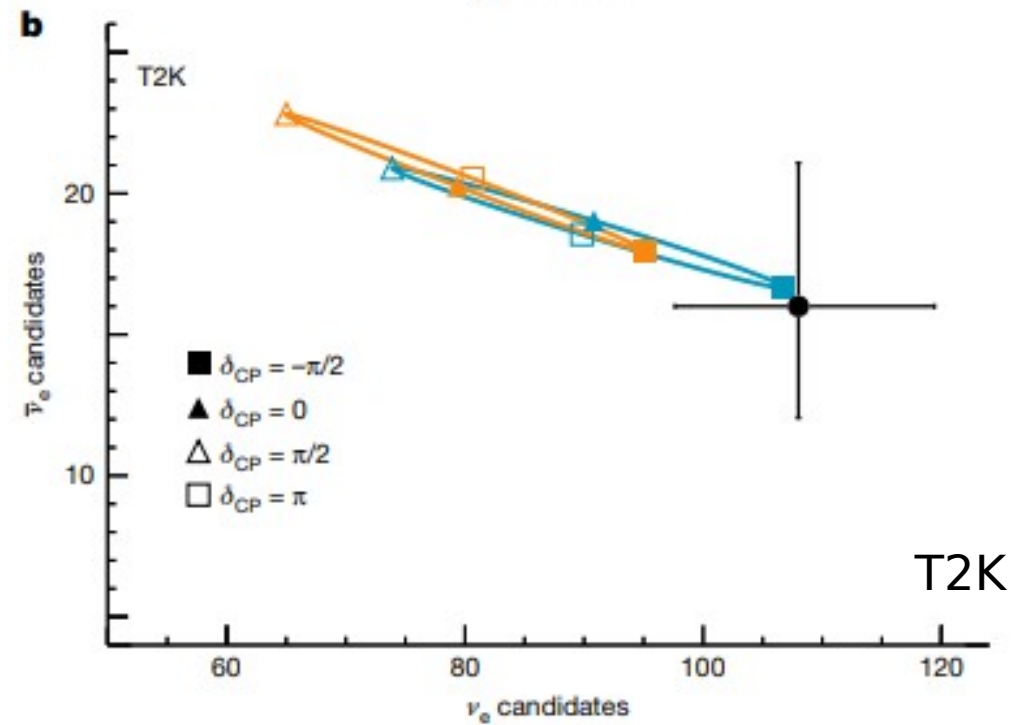
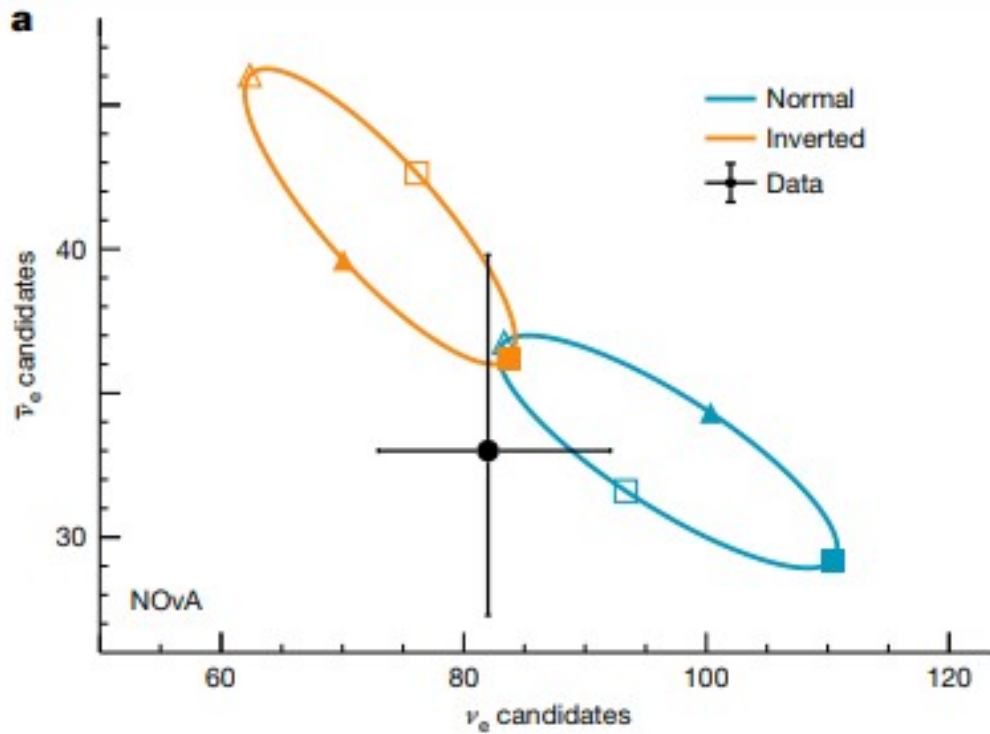
No significant preference for mass ordering
Weak preference for $\sin^2 \theta_{23} > 0.5$

Inverted hierarchy

3σ credibility interval

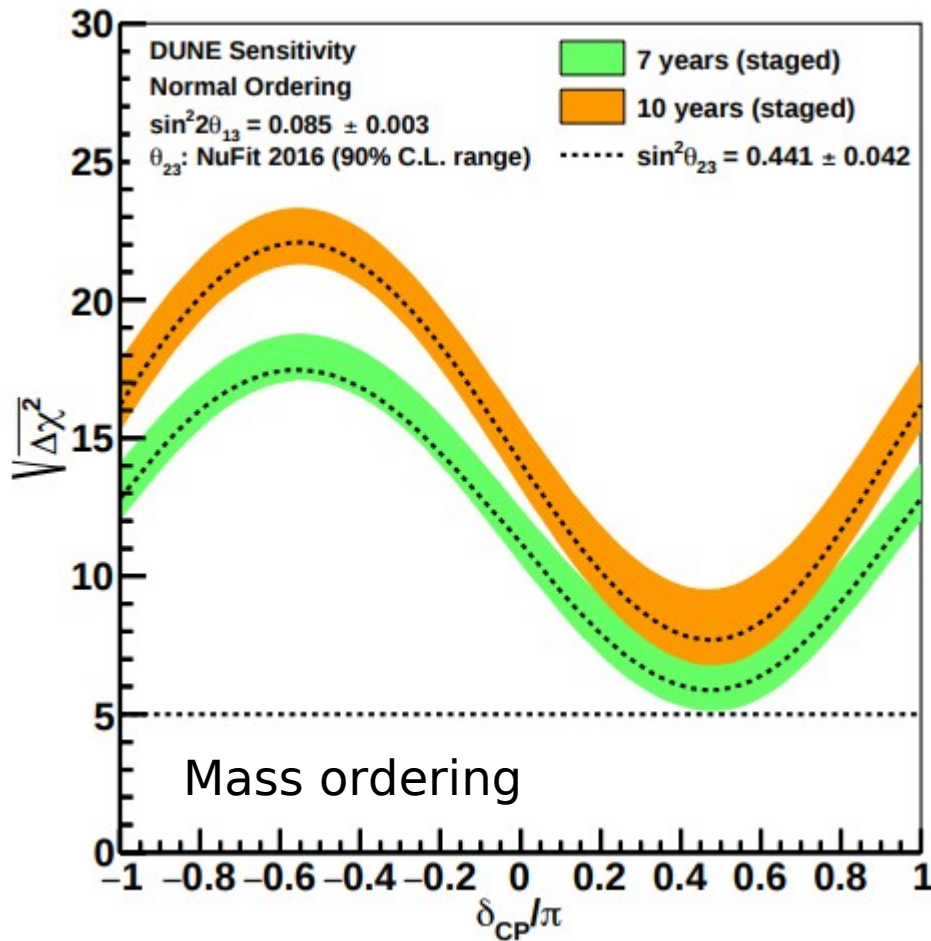
$$\delta_{CP} : [-0.92\pi, -0.04\pi]$$

T2K and NOvA

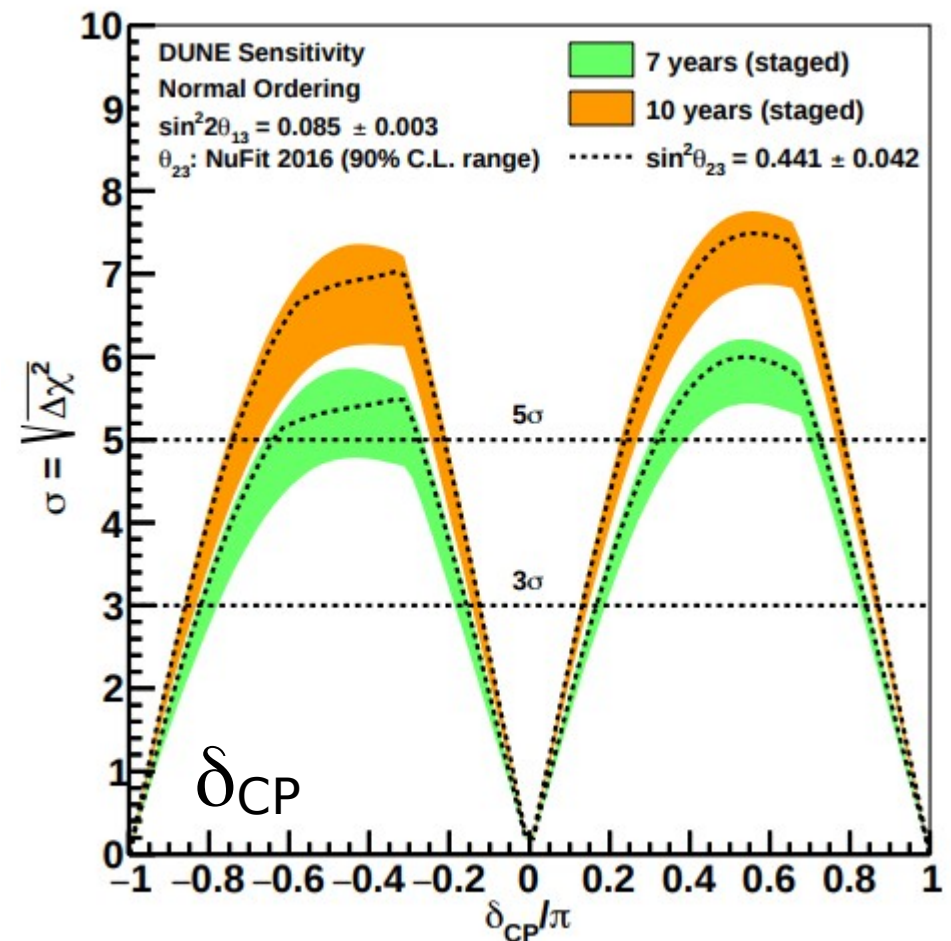


Future project sensitivities

δ_{CP} : DUNE Sensitivity

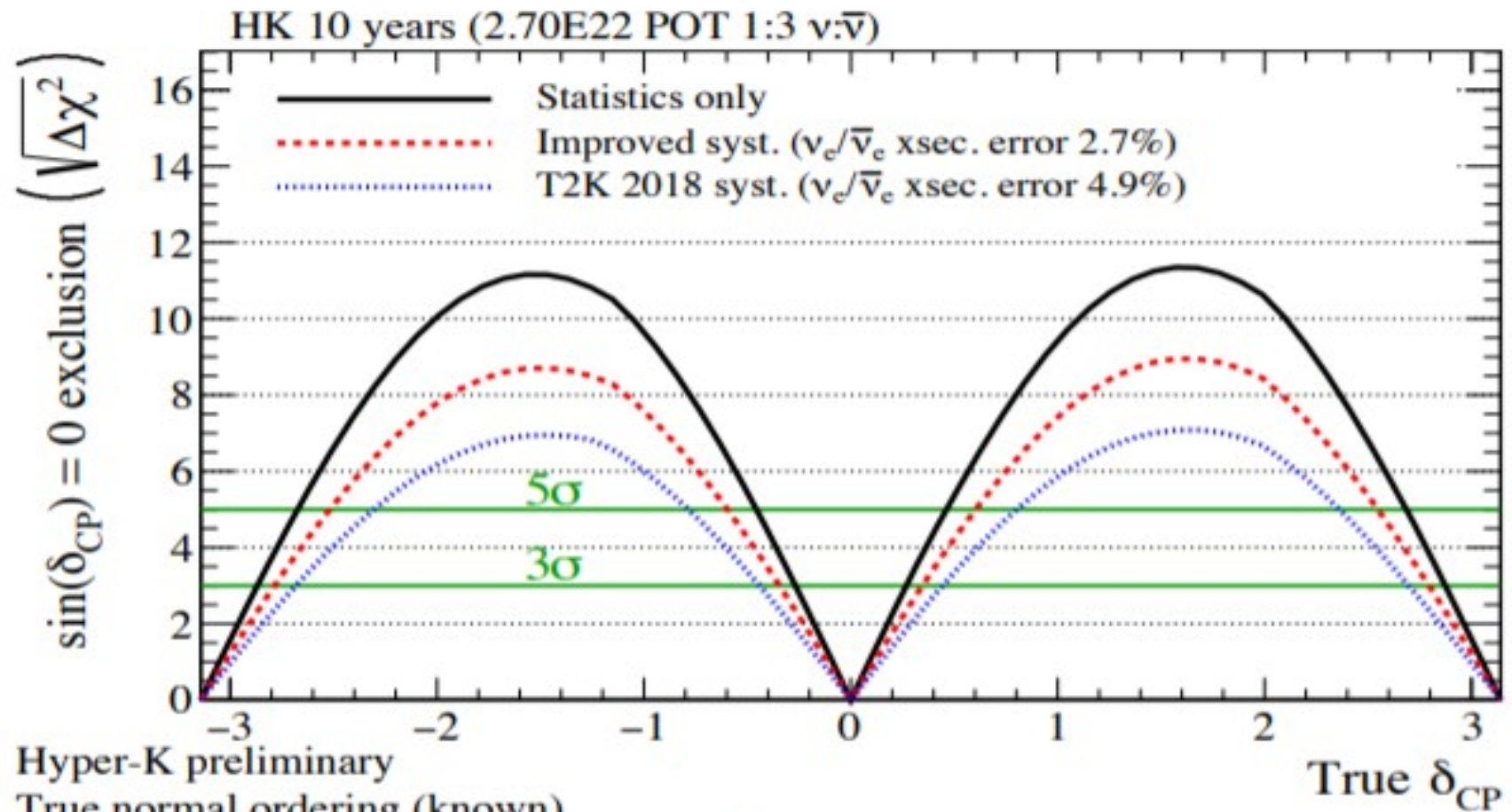


$> 5 \sigma$ reach after 7 years of running over entire δ_{CP} range



$> 5 \sigma$ reach after 10 years if δ_{CP} exists in $\pm[0.2-0.8]\pi$

HK δ_{CP} Sensitivity



Hyper-K preliminary

True normal ordering (known)

$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m_{32}^2| = 2.509E-3$

A return to $0\nu\beta\beta$ decay

m_2

m_1

m_3

$$\Gamma(0\nu\beta\beta) \propto |\langle m_{\nu_e} \rangle|^2 = \left| \sum_i |U_{ei}^2| m_i e^{i\phi_i} \right|^2$$

In the **inverted ordering**: $m_3 \ll m_1 \approx m_2$, $\Delta m_{13}^2 \approx \Delta m_{23}^2$ and m_3 is the lightest mass state, so we can write

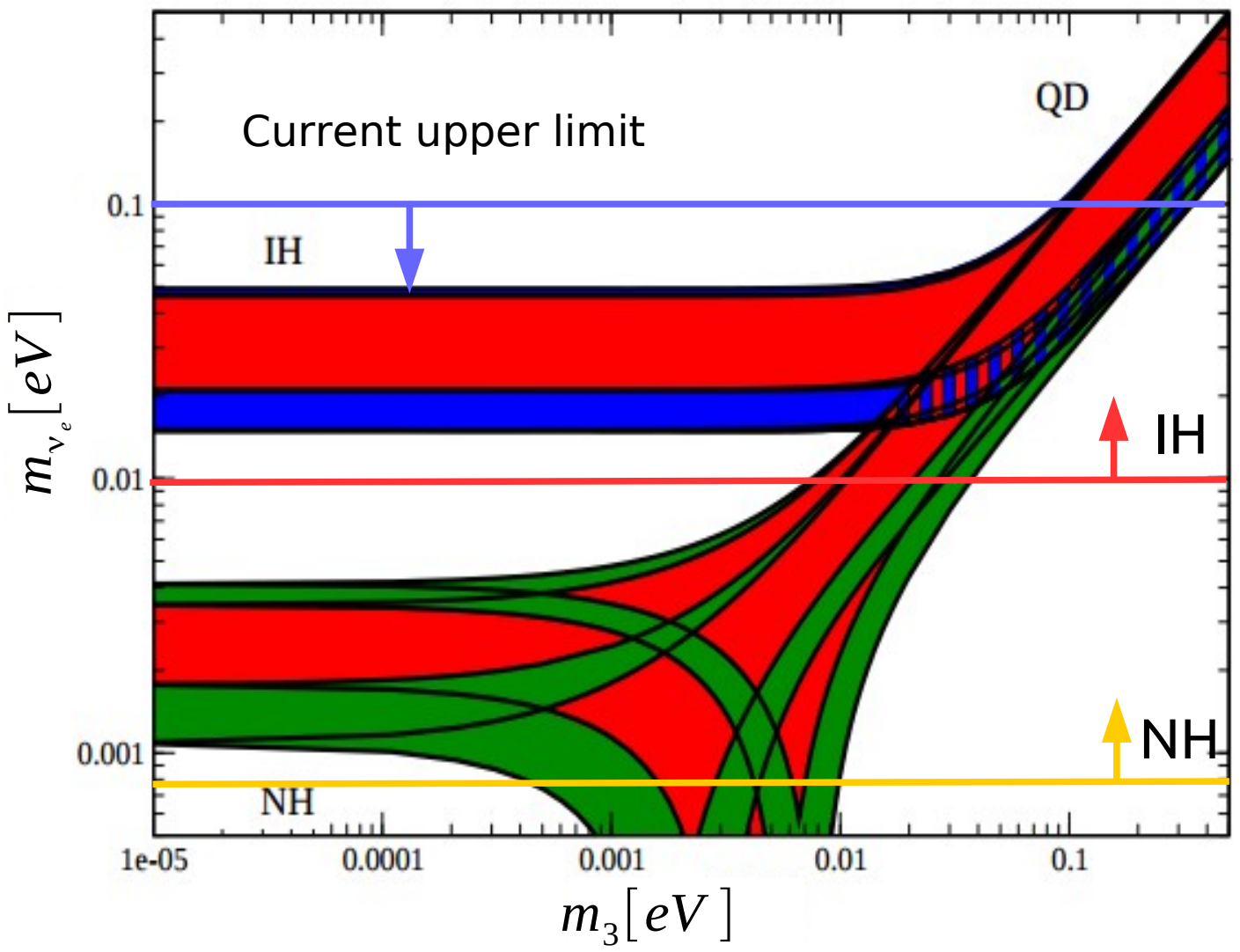
$$m_{\nu_e}^2 = \left| |U_{e1}|^2 \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e2}|^2 e^{i\alpha_2} \sqrt{m_3^2 + \Delta m_{23}^2} + |U_{e3}|^2 e^{i\alpha_3} m_3^2 \right|^2$$

Setting m_3 to zero (not a bad approximation) one can show that

$$m_{\nu_e} > \sqrt{\Delta m_{23}^2} \cos^2 \theta_{13} (1 - 2 \sin^2 \theta_{12})$$

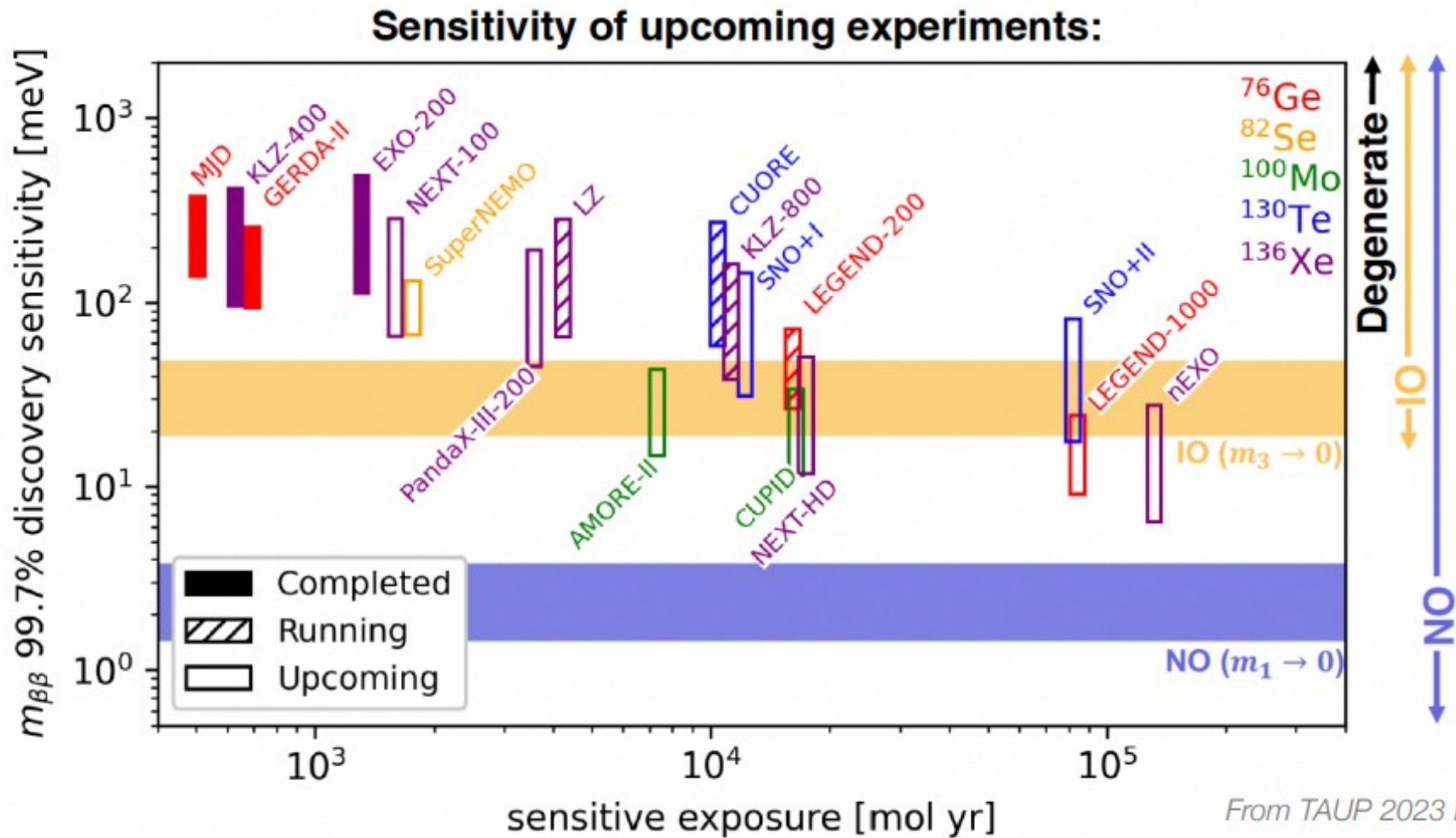
i.e for the inverted hierarchy, the average electron neutrino mass would have a *lower limit at small m_3*

Mass hierarchy & $0\nu\beta\beta$ decay



- ▶ Experimental limit needs to decrease by a factor of 10
- ▶ Limit scales with mass and run time
- ▶ Experiments need to be 10 times bigger and run 10 times longer
- ▶ These are being built now.

Exp. sensitivities



From TAUP 2023 D. Moore

Mass Hierarchy Determination

A number of different experiments, both accelerator and $0\nu\beta\beta$ decay focused, are now trying to determine the mass hierarchy.

Timescale : ~ 3-5 years from now for 3σ determination
from NOVA + SK + JUNO

Measurement of δ_{CP}

Next generation of experiments are being planned to measure this

Timescale : 4-5 years from now (including construction) for 3σ sensitivity to distinguish from no CP-violation scenario (if true δ_{CP} is $\pi/2$).

12-15 years for a measurement of δ_{CP} to a precision of 20° (if true δ_{CP} is $\pi/2$).

The Roadmap - 2005

We are at the beginning of a global coordinated effort to unravel the neutrino sector



Now

Measure θ_{23} sector to 10%
MINOS, K2K, OPERA, miniBoone



2009

Measure θ_{13} ; Probably need 2 measurements at different L/E and an antineutrino measurement to unravel ambiguities.
T2K/NOvA, Reactor experiments



2015
2020

Precision measurements of all parameters
Phase 2 Superbeams, β beams, Neutrino Factories

The next 20 years - 2009

Measurement	Method	Experiments	Why?	When
$ \Delta m_{23}^2 $	ν_μ Disapp.	MINOS	More precise Estimates	2007
θ_{23}	ν_μ Disapp.	T2K, NovA	Is it maximal?	2009
θ_{13}	ν_e Appear.	T2K, NovA	Equal to 0? Can't measure δ_{CP} if it is	2012
	Anti- ν_e Disapp.	Reactor		2012
$\text{Sgn}(\Delta m_{23}^2)$	$\nu_e / \text{anti-}\nu_e$	T2KK, neutrino Factory, ???	Unification, GUT Lepton asymmetry	2025?
δ_{CP}				

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	Anti- ν_e Disapp.	Reactor		2012	✓
$\text{Sgn}(\Delta m_{23}^2)$	$\nu_e / \text{anti-}\nu_e$	T2KK, neutrino Factory, ???	Unification, GUT Lepton asymmetry	2025?	✗
δ_{CP}					

The next 20 years - 2024

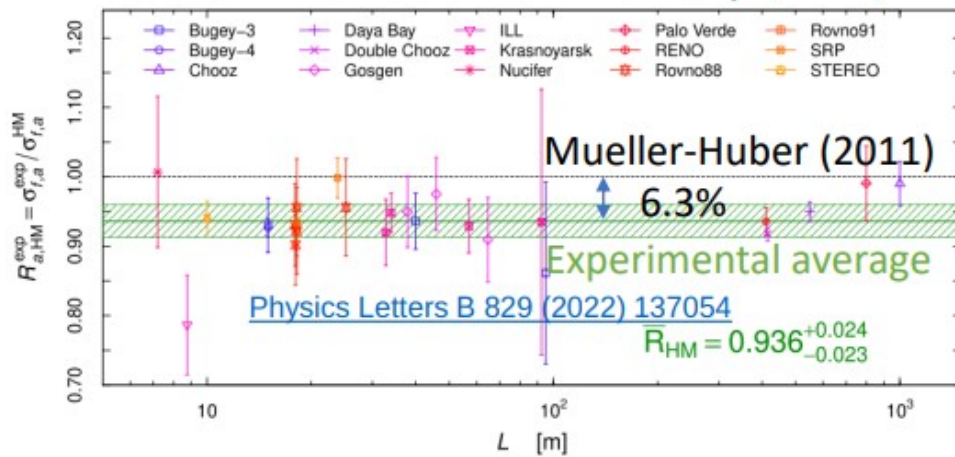
Measurement	Method	Experiments	Why?	When	
$ \Delta m_{23}^2 $	ν_μ Disapp.	MINOS	More precise Estimates	2007	✓
θ_{23}	ν_μ Disapp.	DUNE, HK, JUNO		2030's	✗
θ_{13}	ν_e Appear.	T2K, NovA	Equal to 0? Can't measure δ_{CP} if it is	2012	✓
	Anti- ν_e Disapp.	Reactor		2012	✓
$\text{Sgn}(\Delta m_{23}^2)$ δ_{CP}	ν_e / anti- ν_e	DUNE, HK, JUNO		2030's	✗

ANOMALIES

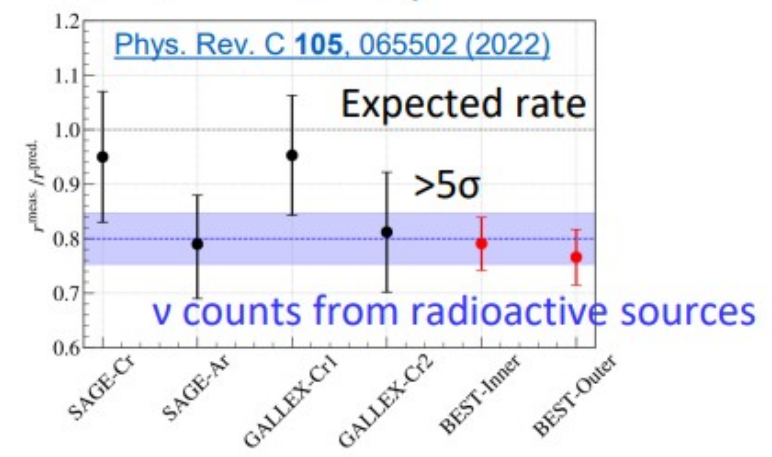


ANOMALIES EVERYWHERE

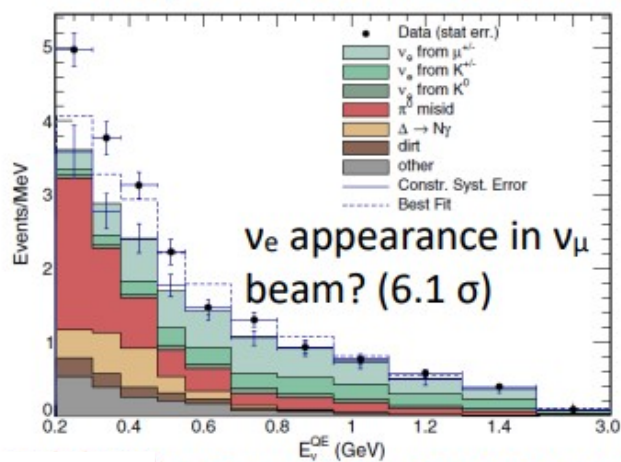
• Reactor Antineutrino Anomaly (RAA)



• Gallium Anomaly

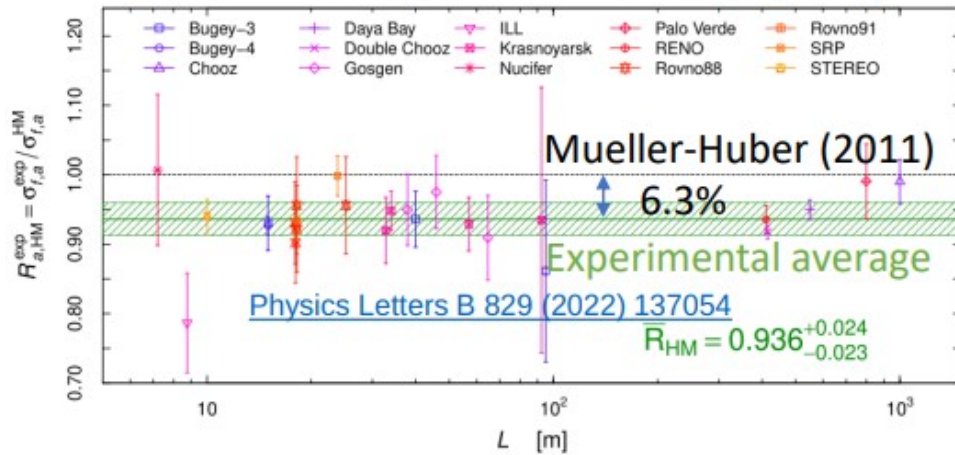


• LSND/MiniBooNE Anomaly

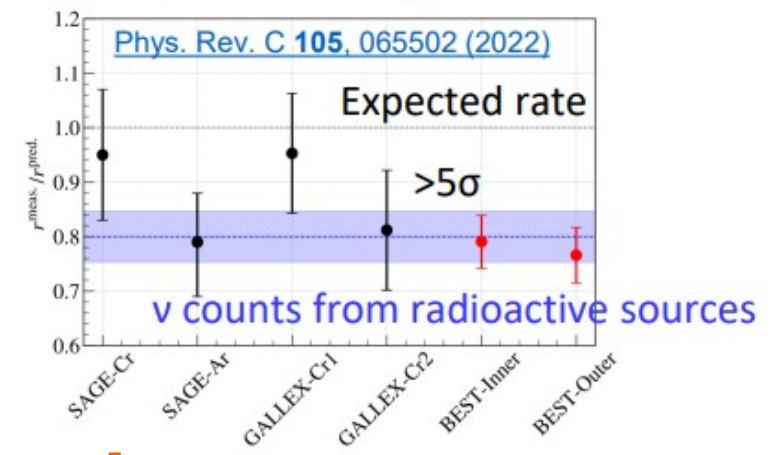


[Phys. Rev. Lett. 121, 221801 \(2018\)](#)

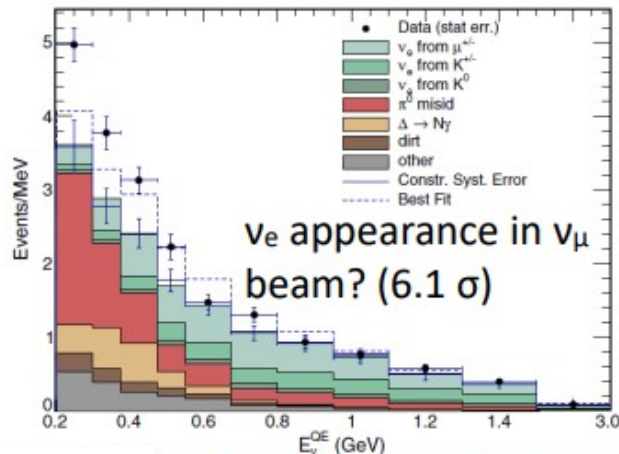
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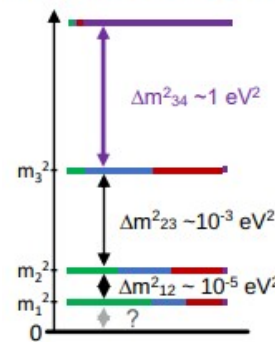


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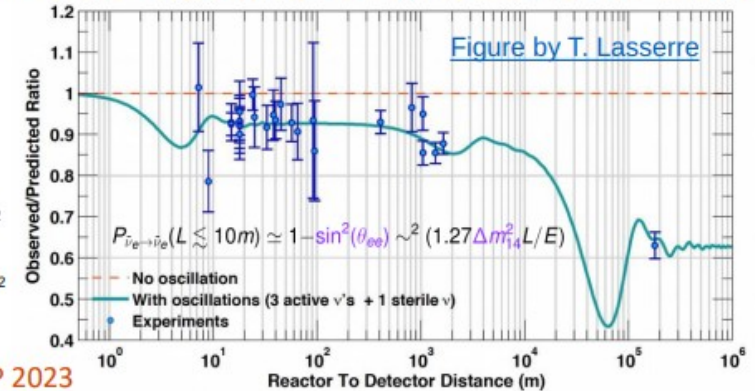


Phys. Rev. Lett. 121, 221801 (2018)

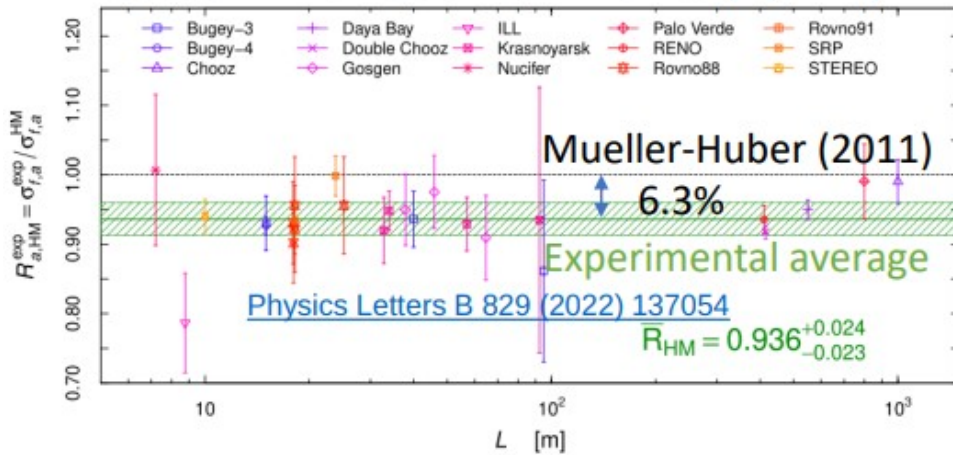
New 0.1-1 eV neutrino, consisting of a sterile flavor



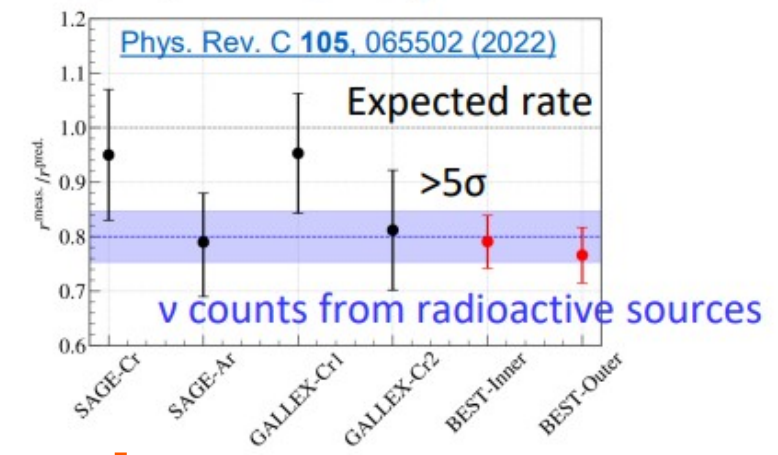
sterile Neutrino @ TAUP 2023



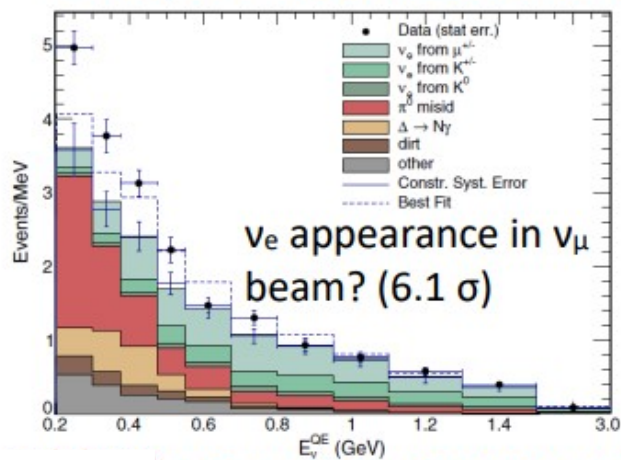
• Reactor Antineutrino Anomaly (RAA)



• Gallium Anomaly



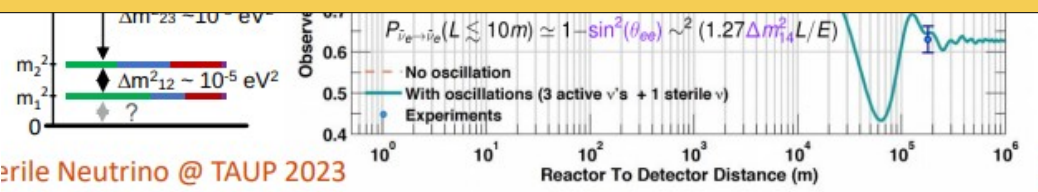
• LSND/MiniBooNE Anomaly



Phys. Rev. Lett. 121, 221801 (2018)

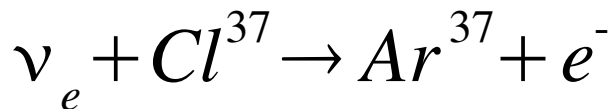
New 0.1-1 eV neutrino, consisting of a sterile flavor

Or do they?

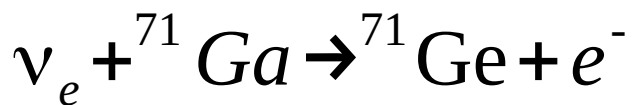


The Gallium Anomaly

We've discussed the Homestake experiment which studied

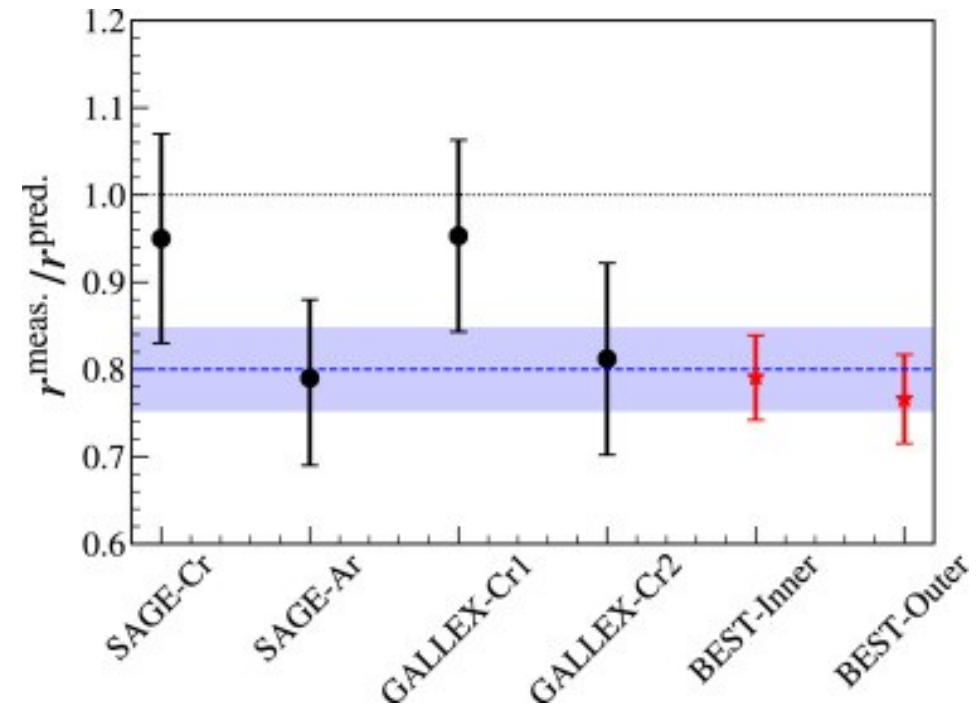


A couple of experiments (SAGE and GALLEX) also studied



In early 2000's the response of GALLEX was being tested using MCI radioactive sources.

Sources emitted ν_e which were then observed using the standard Ge signature



$$L/E \approx 0.1 \text{ m}/0.1 \text{ MeV} \rightarrow \Delta m^2 \approx 1 \text{ eV}^2$$

(or is it our understanding of the low energy ν -Ga cross section, or is it just bad luck?)

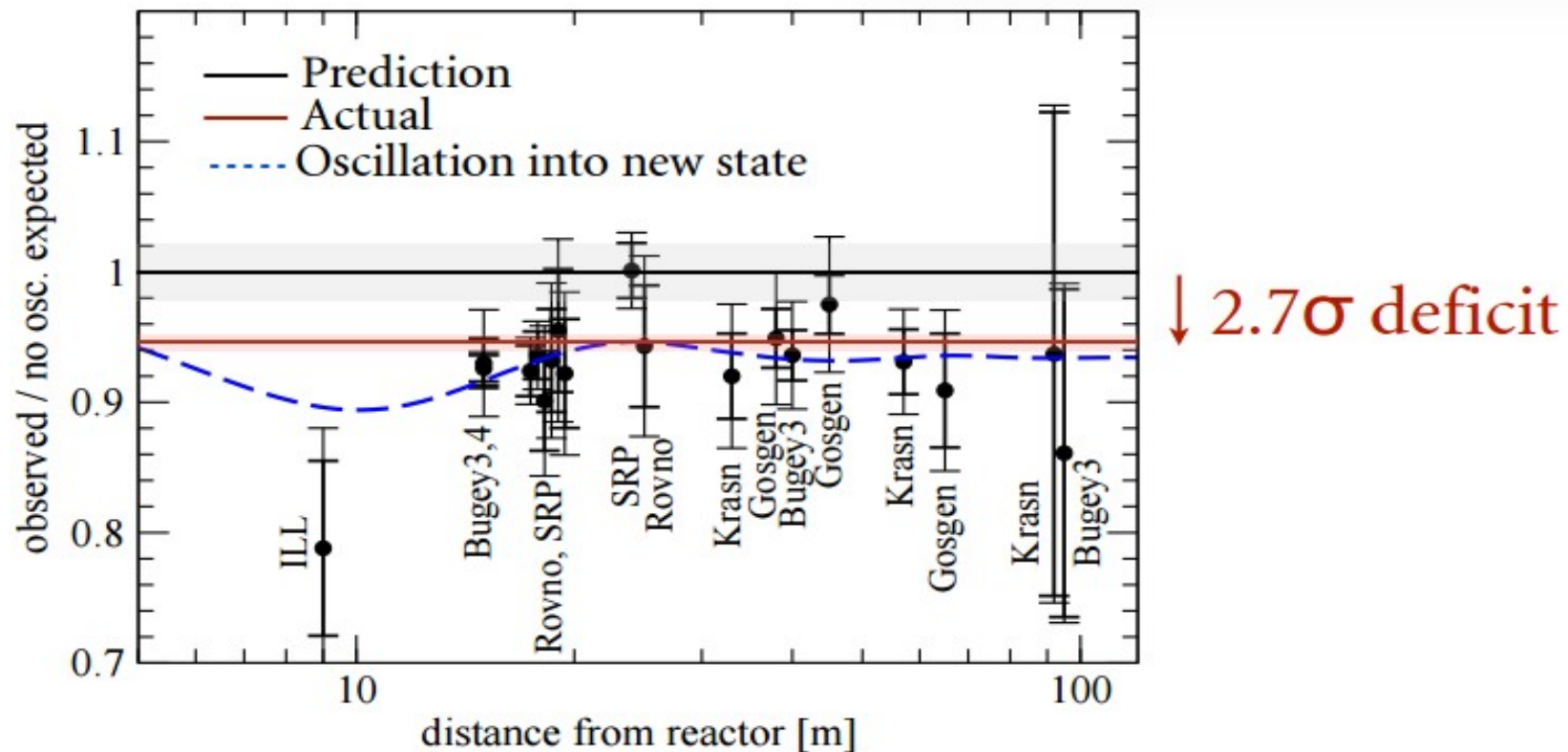
The reactor anomalies

- ▶ pre-2011 : measurement of the total neutrino flux from reactors agreed with expectation.
- ▶ In 2011, new techniques in modelling nuclear reactions led to a re-evaluation of the expected electron antineutrino flux. The new estimate was about 6% **higher** than the old.
- ▶ Suddenly all the experiments now observed a general **deficit** of electron antineutrinos being detected at the detector

$$N(\bar{\nu}_e) = \Phi^{old}(\bar{\nu}_e) \sigma \longrightarrow \Phi^{new}(\bar{\nu}_e) \sigma \times P(\bar{\nu}_e \rightarrow \nu_s)$$

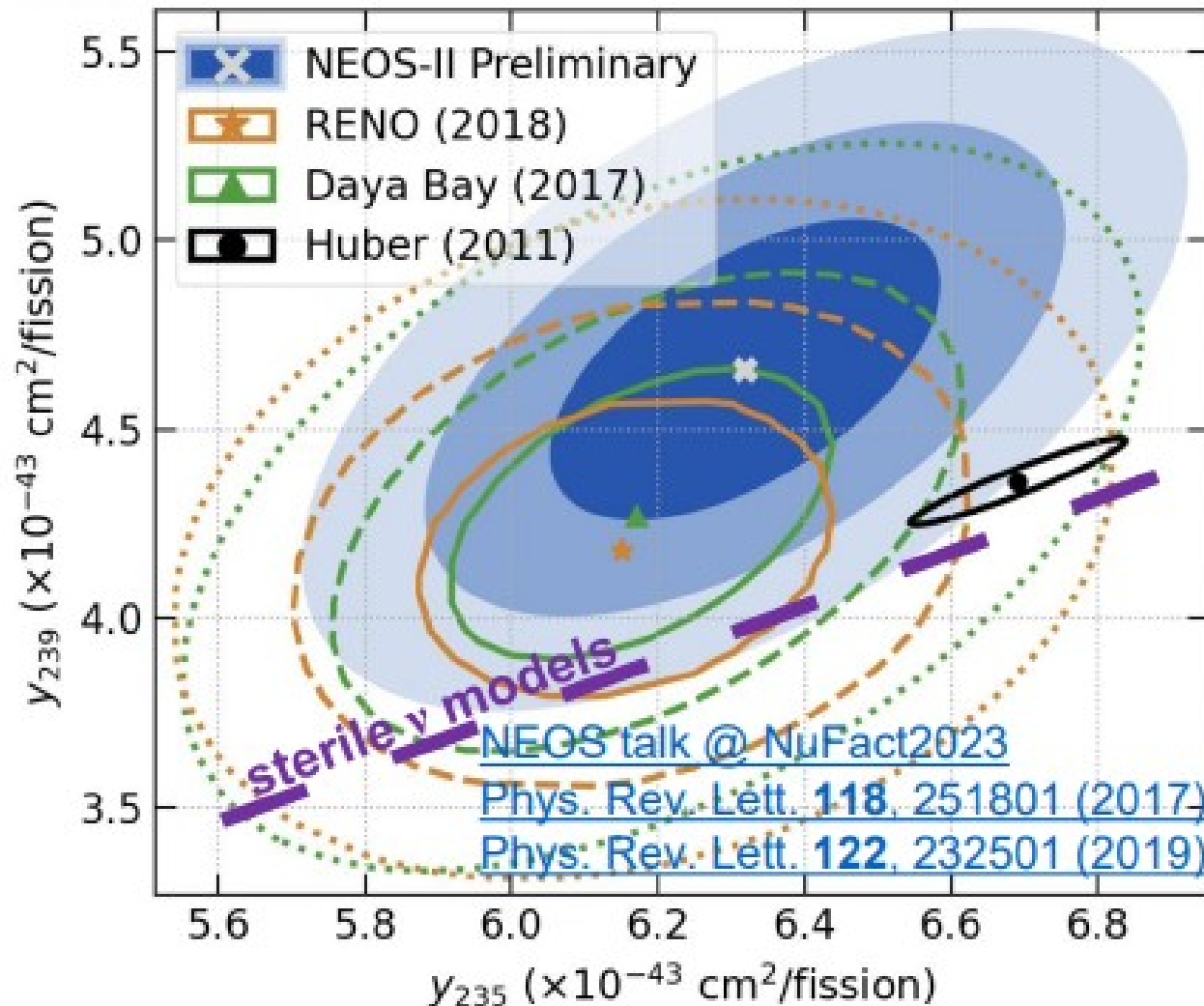
- ▶ Could this be (i) the new flux estimate is just a bit dodgy or (ii) we have short baseline neutrino oscillations to a sterile state?

Reactor Anomaly



Deficit consistent with a sterile state with $\Delta m^2 \sim 1.5 \text{ eV}^2$
Reactor antineutrino flux calculations are VERY hard to do
It's almost certain that this is an issue with the calculation of the antineutrino flux NOT steriles.

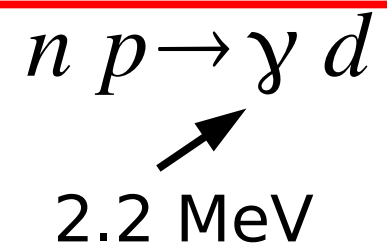
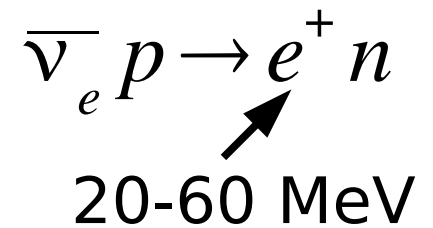
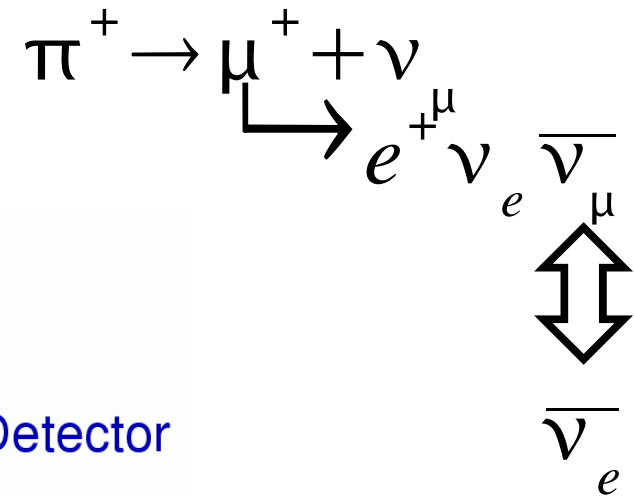
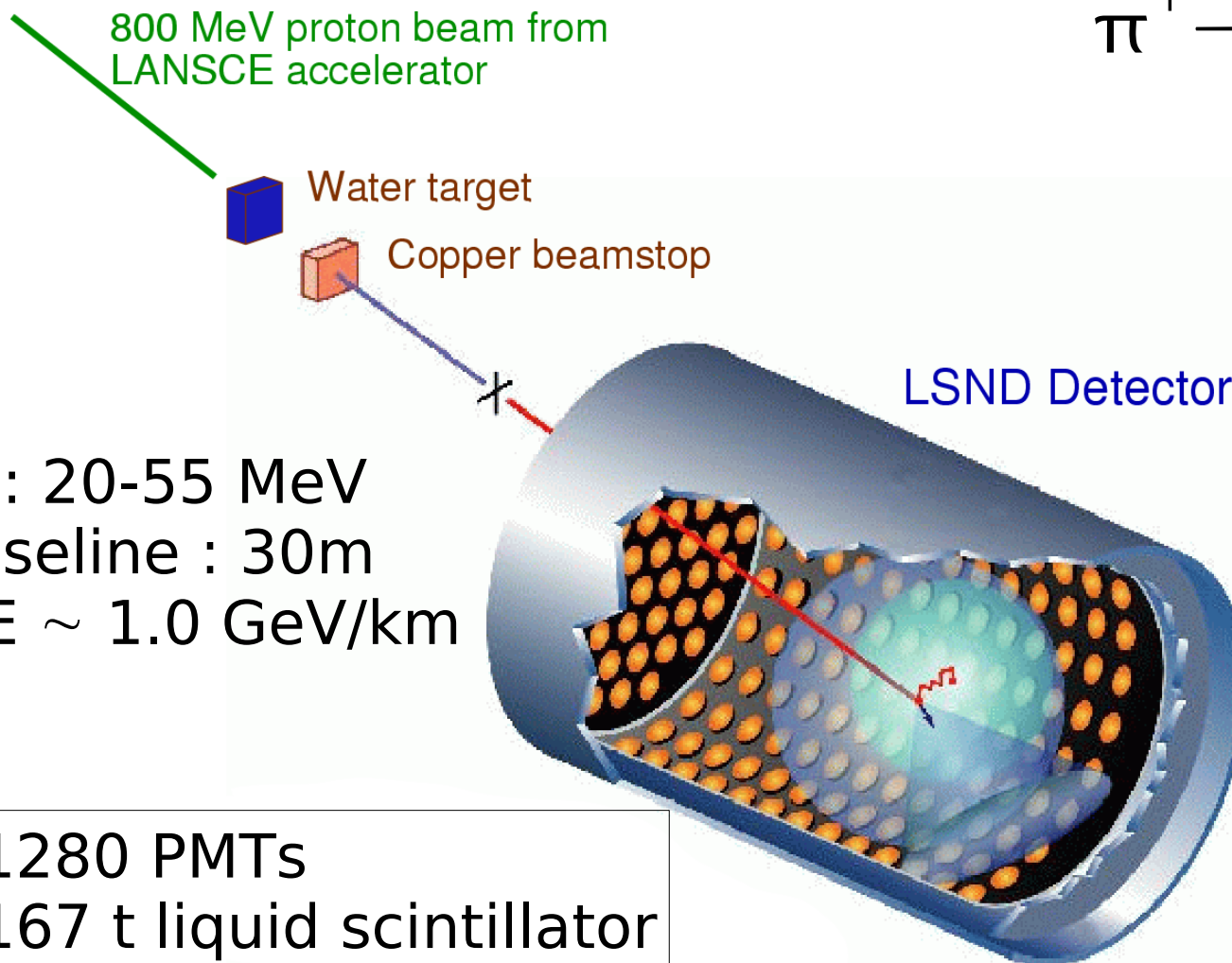
New fluxes - again



- ▶ Reactor flux deficit has probably gone away now
- ▶ “New” 2011 flux overestimated the flux from U-235
- ▶ New flux measurements suggest that the reactor flux deficit was not real

LSND

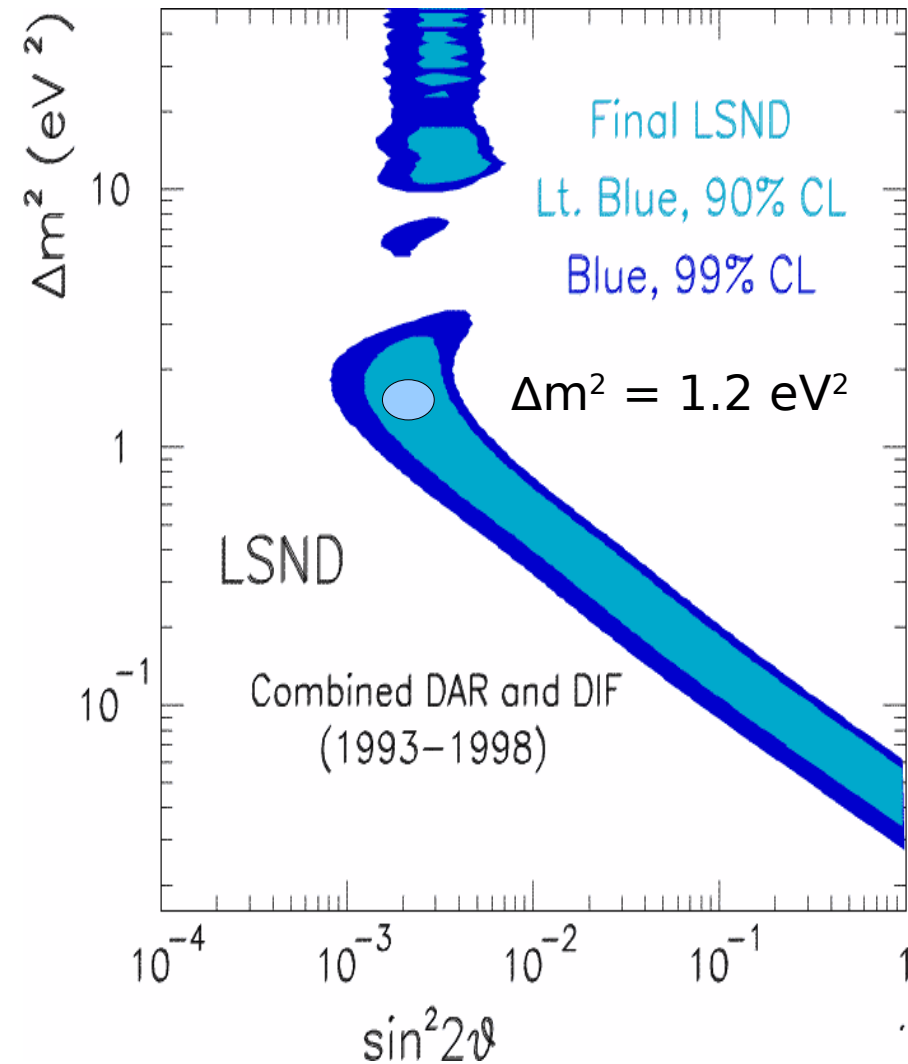
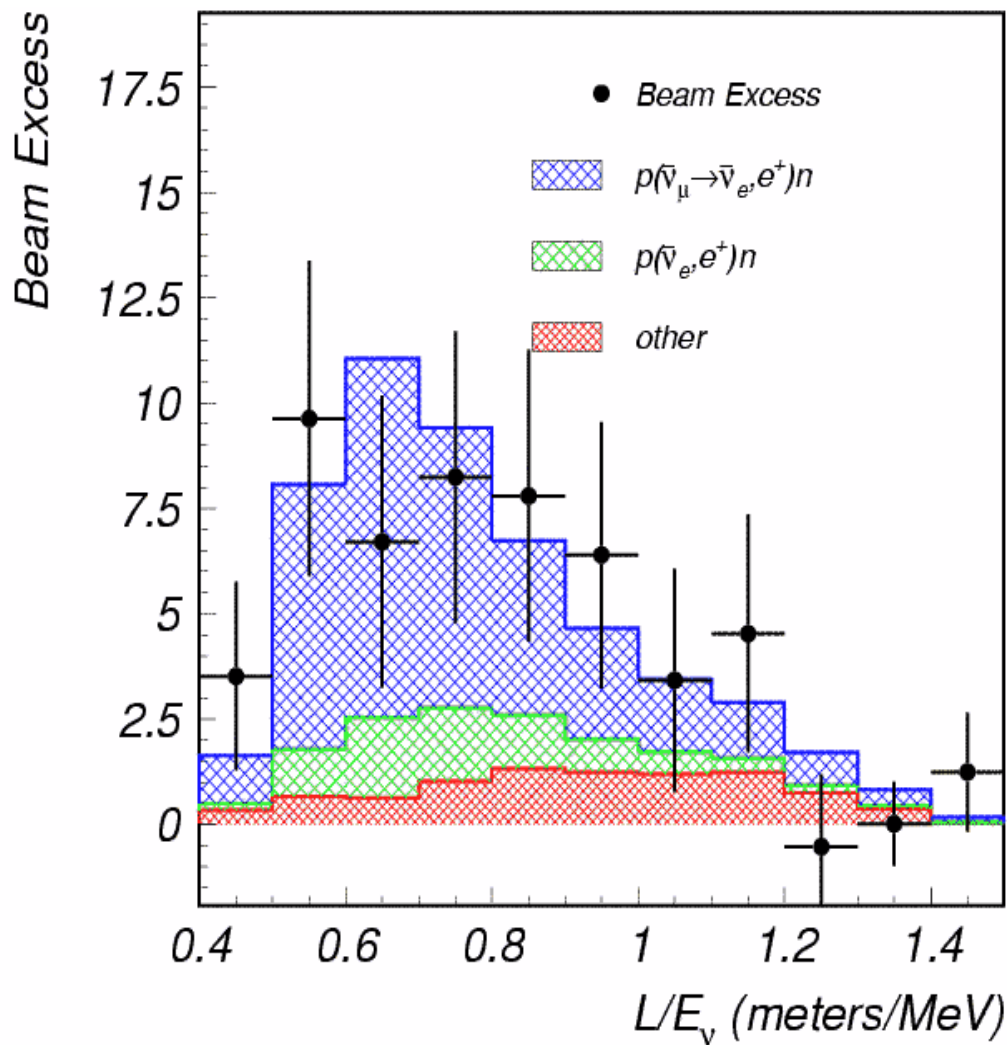
The LSND experiment was the first accelerator experiment to report a positive appearance signal



LSND Result (1997)

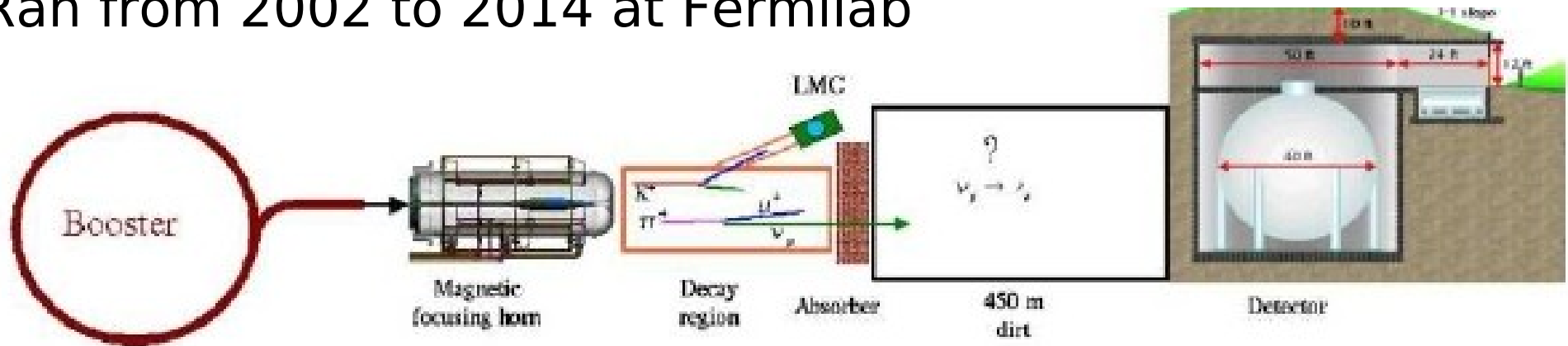
$87.9 \pm 22.4 \pm 6$ excess events
from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

3.3 σ evidence for
oscillations



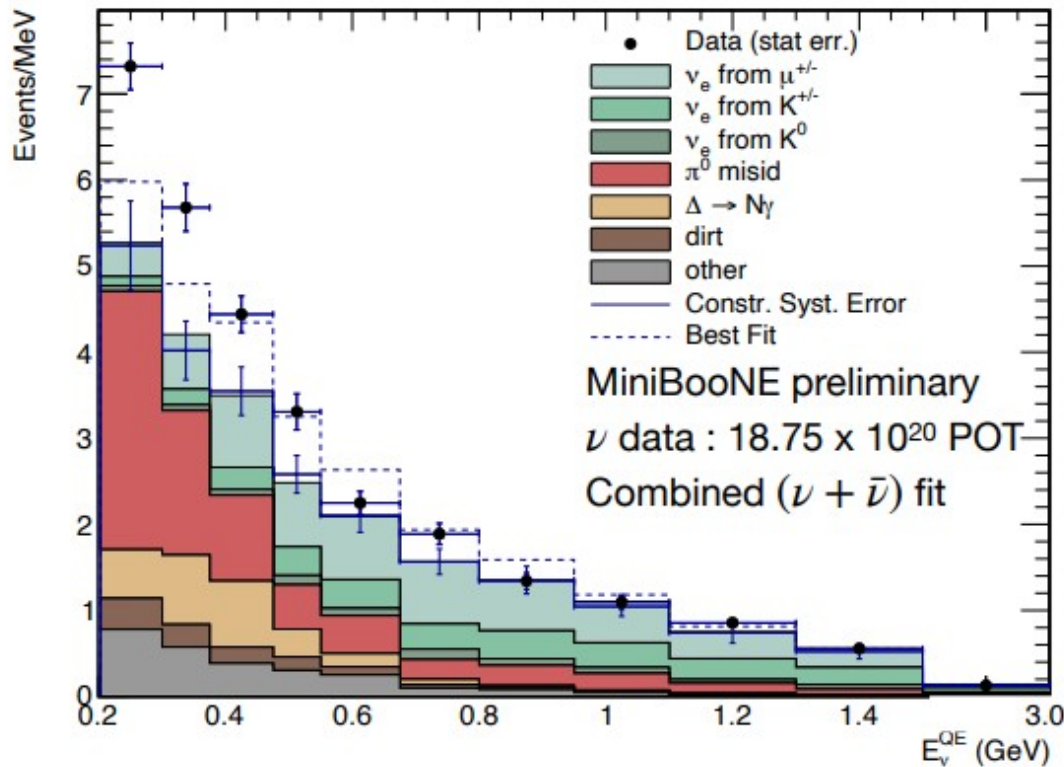
MiniBooNE

Ran from 2002 to 2014 at Fermilab

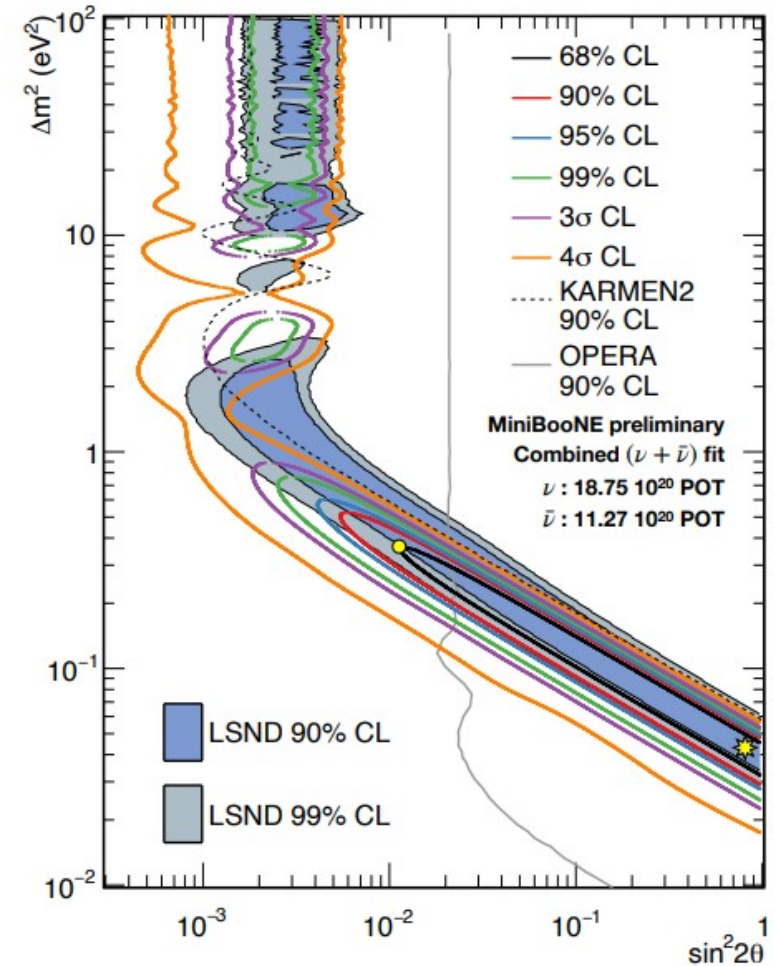


- Average neutrino energy ≈ 1 GeV
- L/E the same as LSND
- Same technology as LSND
- Different energy = different event types = different systematics

miniBooNE Results



Excess of low energy electrons
at the level of 4.8σ

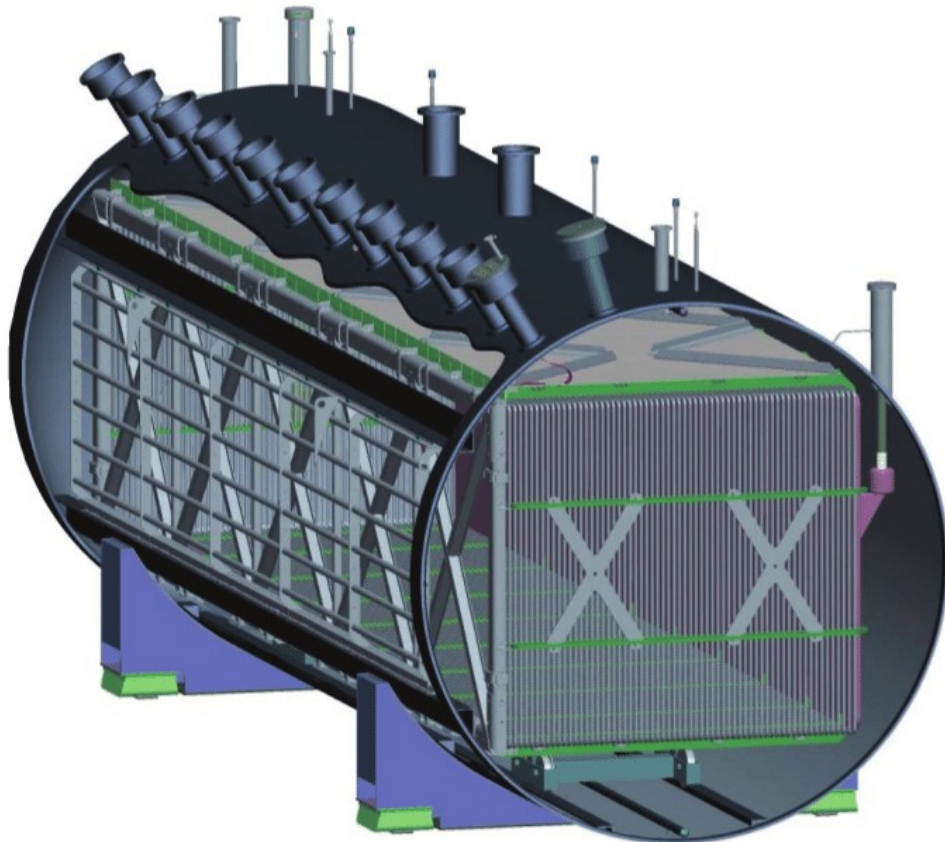


Neutrino + Anti-Neutrino Mode

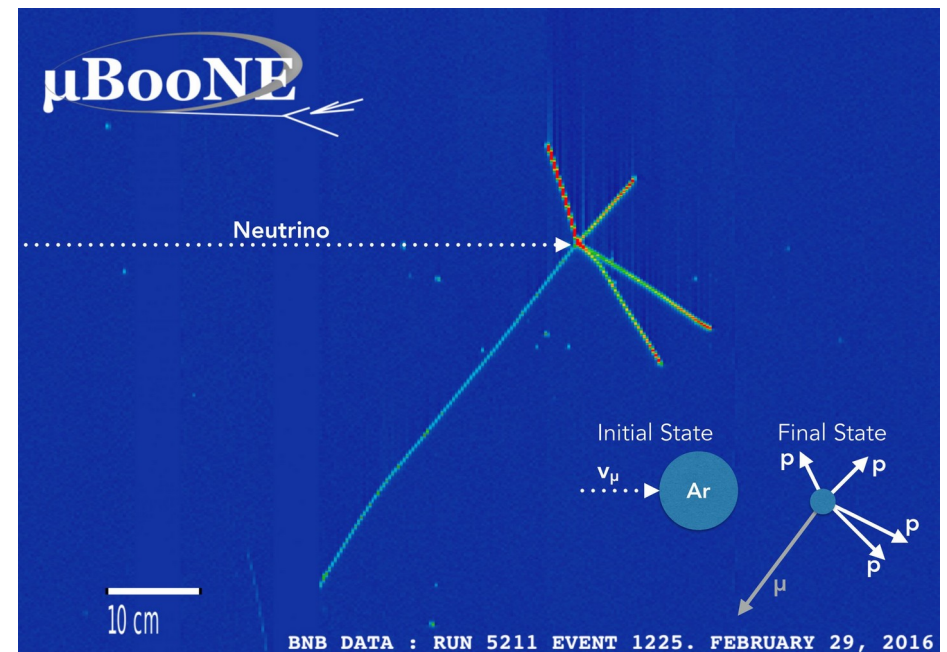
$$(\Delta m^2, \sin^2 2\theta) = (0.043 \text{ eV}^2, 0.807)$$

$$\chi^2/ndf = 21.7/15.5 \text{ (prob} = 12.3\%)$$

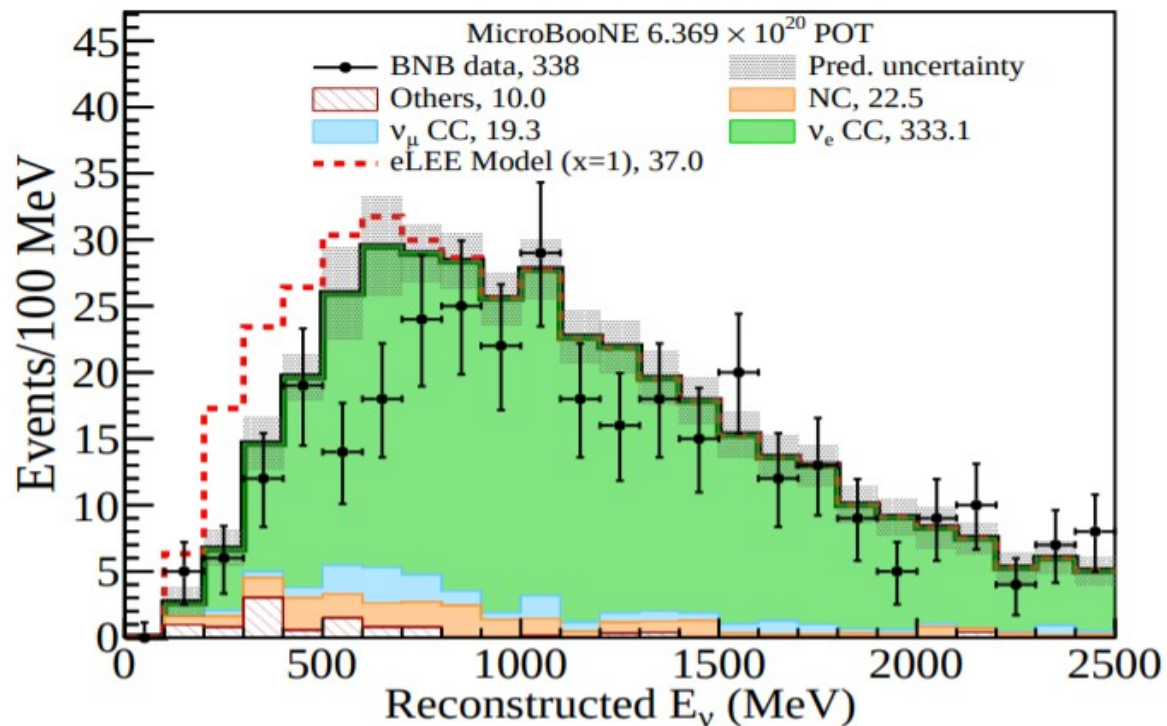
MicroBooNE



- ▶ 170 ton LAr TPC
- ▶ Operating in the same beam as LSND and miniBooNE
- ▶ Capable of reconstructing electrons and photons



Low Energy Excess



▶ No sign of excess of low energy electrons or photons.

▶ ??????

▶ LSND/MiniBoone are seeing something though. What?

Reconstructed energy spectrum for inclusive ν_e event sample

3+1 sterile?

3+2 ?

3+n ?

CPT Violation?

*Decaying sterile
neutrinos?*



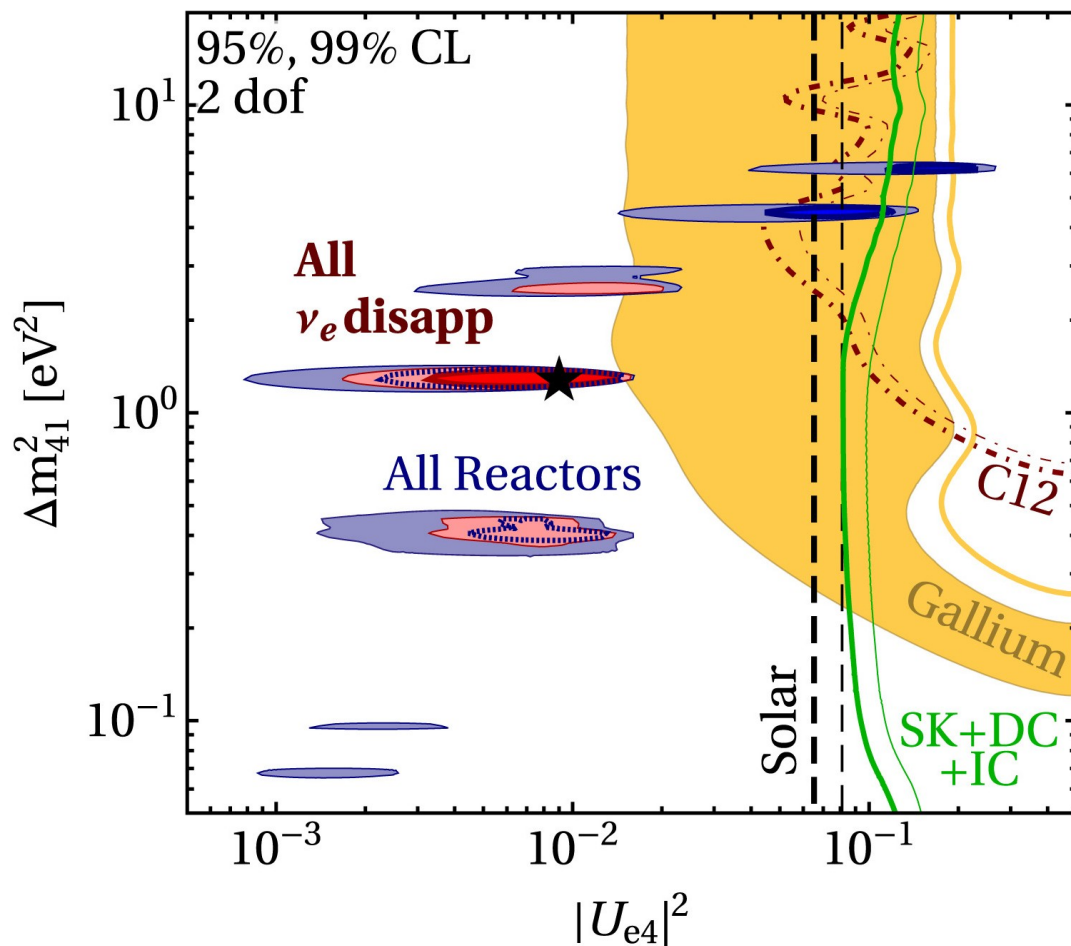
Lorentz violation?

Extra dimensions?

*Experimental
problems?*

?

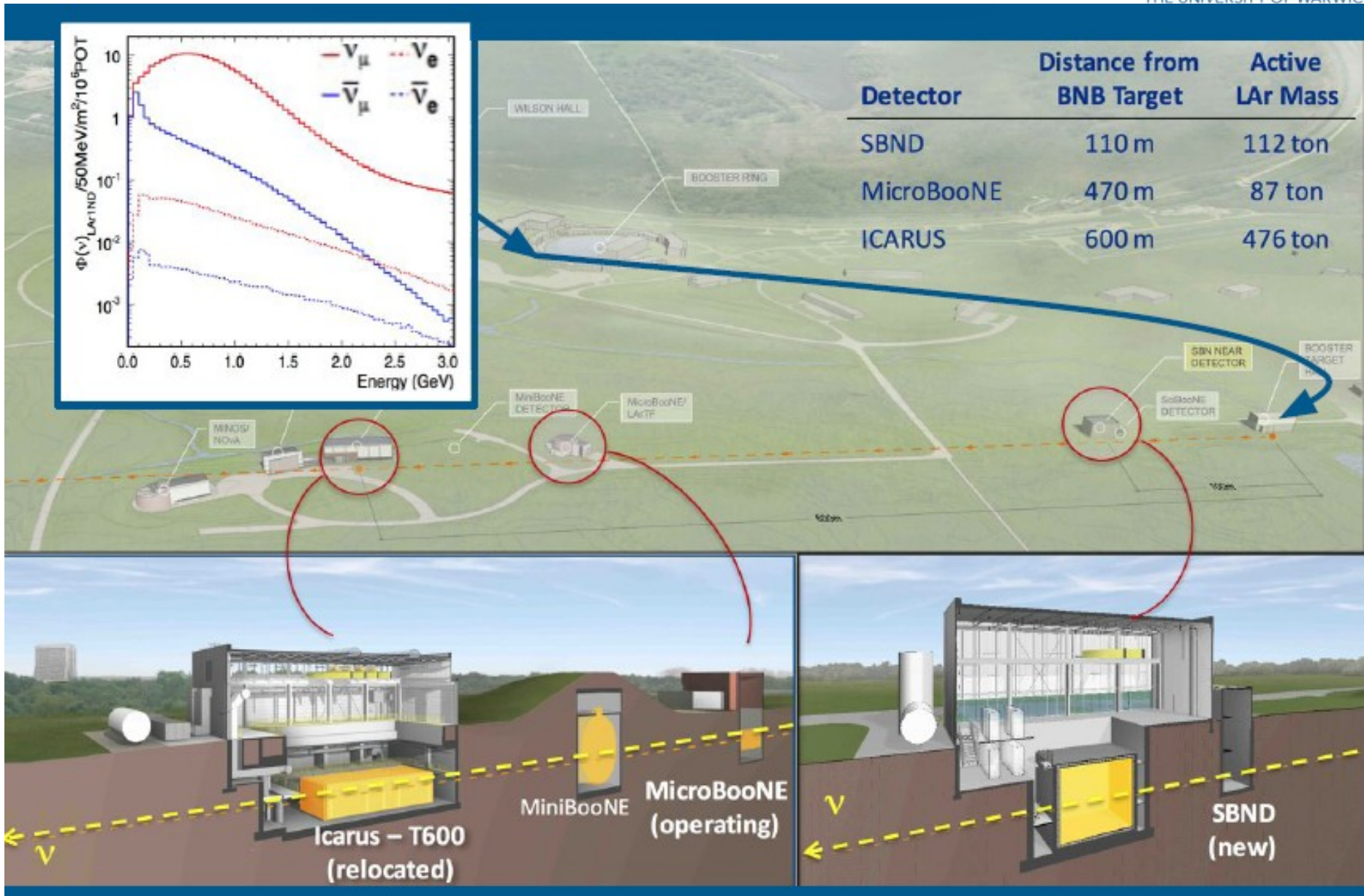
Global analysis



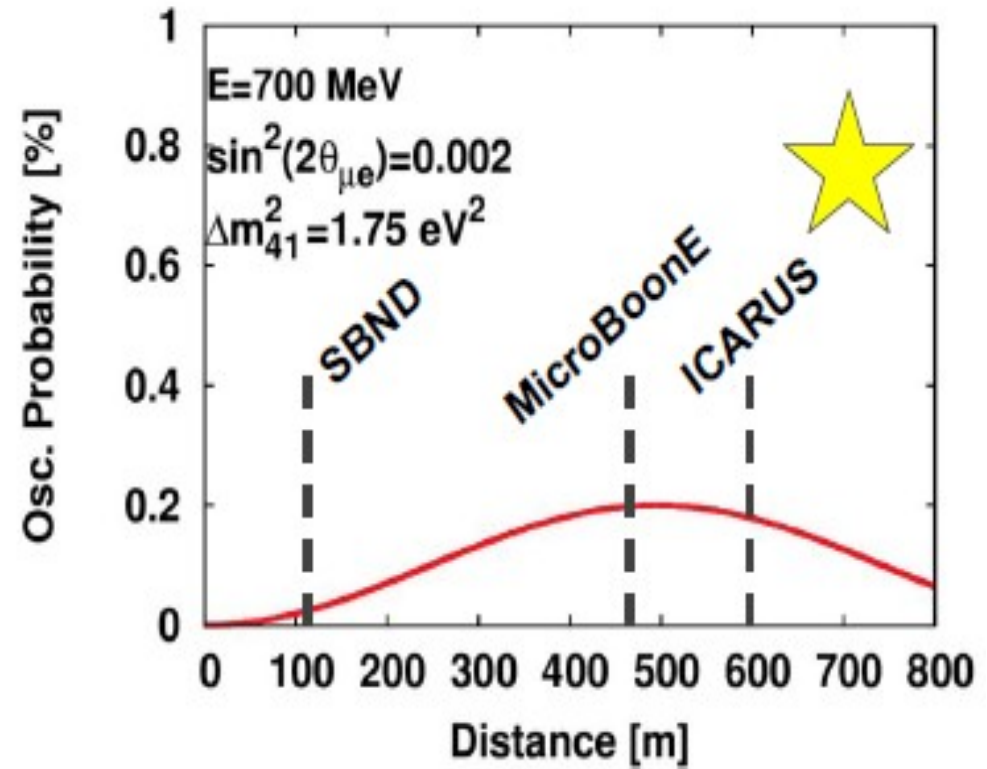
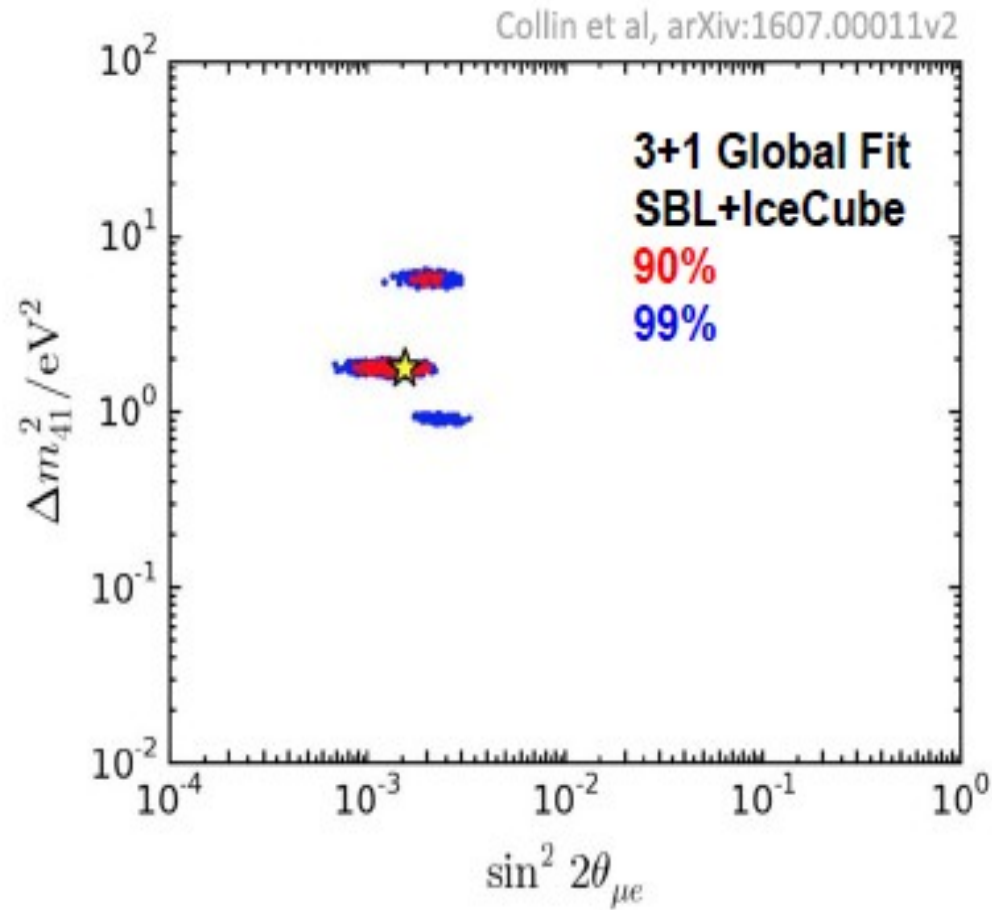
▶ it's very hard to fit all of the data to a 3+1 (or other) models.

▶ A consistent picture does not leap out from all these anomalies.

SBN Program

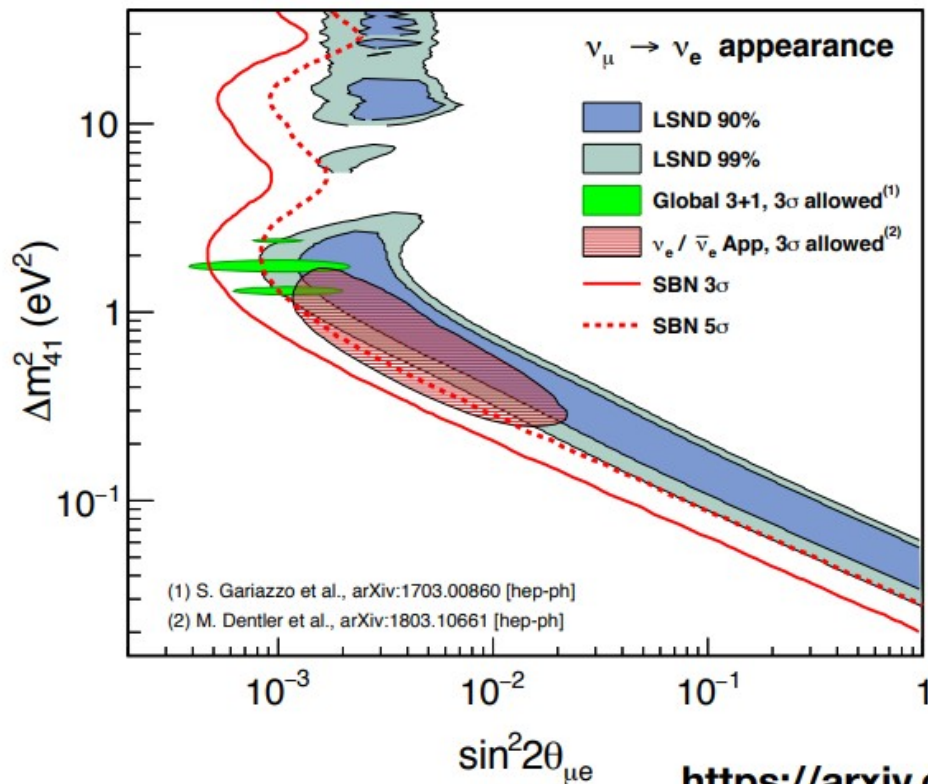


SBND

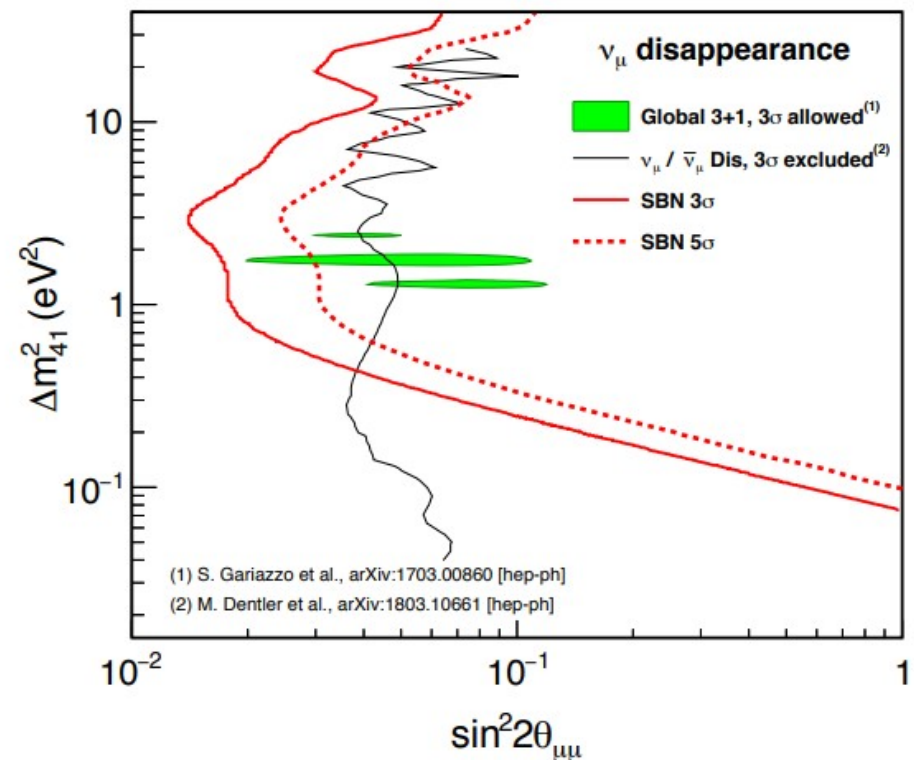


SBN Program

ν_e appearance



ν_{μ} disappearance



<https://arxiv.org/pdf/1903.04608.pdf>

- SBN cover much of the parameters allowed by past anomalies at $>5\sigma$ significance
- ▶ Has started data taking - already has the largest sample of ν -Ar interactions

Sterile summary

- ▶ A couple of anomalies exist which may be interpreted as the existence of a sterile neutrino in flavour oscillations
- ▶ A single sterile hypothesis cannot account for all the anomalies collectively AND agree with all other current data
 - ▶ Gallium anomaly clashes with solar/reactor data
 - ▶ MiniBooNE data clashes with LSND data clashes with microBooNE data; low energy excess cannot be explained by oscillations alone.
- ▶ In general to explain all this using steriles some other new physics is also needed

Evidence for existence of a ν_s at a Δm^2 of 1 eV^2 is fading; but not yet completely excluded.

What I have omitted

- ▶ Any mention of the neutrino observatories :
 - ▶ IceCube, Antares, KM3Net/Orca
- ▶ Any mention of reactor experiments (apart from Daya Bay / JUNO) :
 - ▶ Stereo, SoLid, Prospect, Neutrino4, DANSS, NEOS
- ▶ To my shame : any mention of neutrino interaction cross section work
 - ▶ T2K, MicroBooNE/ArgoNeut, MINERvA

Concluding Remarks

- ▶ Neutrinos are massive → extensions needed to the Standard Model
- ▶ Neutrino oscillation parameters still need to be better measured; δ_{CP} and mass ordering have to be measured.
- ▶ Next generation of experiments will hopefully get a handle on these parameters : data coming from 2029 and the early 2030's.
- ▶ Many opportunities for BSM in the neutrino sector
- ▶ We are getting perilously close to a neutrino mass measurement – perhaps in the next 5-10 years?
- ▶ Majorana or Dirac? We may be lucky with an intensive $0\nu\beta\beta$ program; look out for LEGEND 1000
- ▶ New neutrino machines may be coming with muon storage ring technology