La physique des neutrinos

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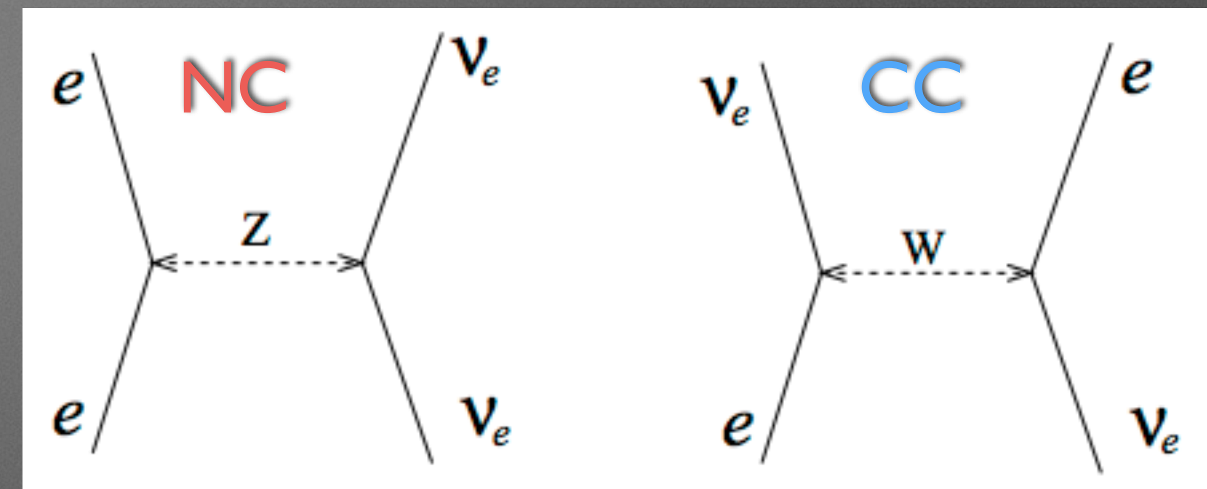
Journée de Physique de la SFP

22/11/2018

Neutrinos in the SM

Neutrinos are standard model particles → neutral cousin of the electron and of the other charged leptons

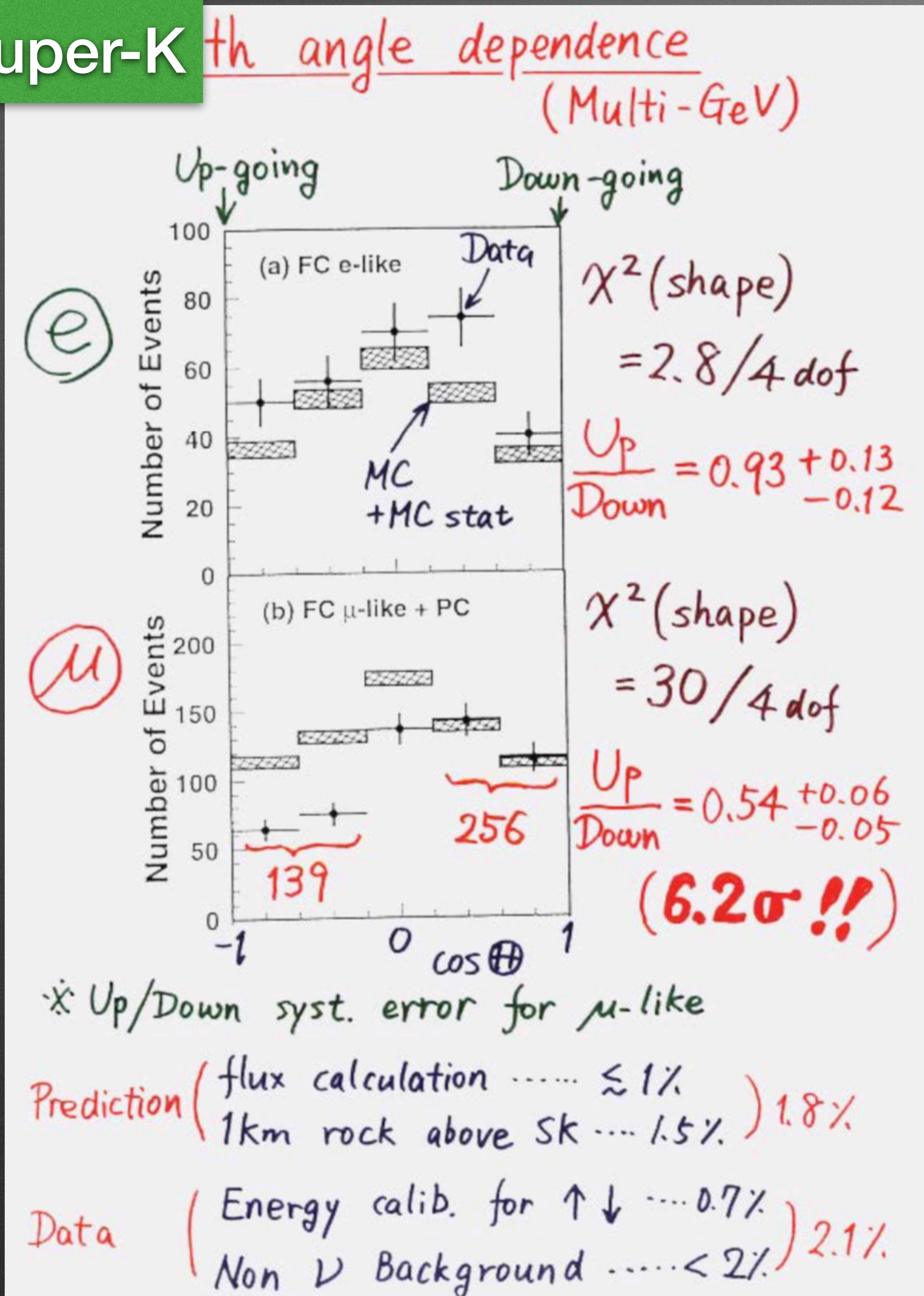


They interact only through weak interactions → Neutral current or Charged current

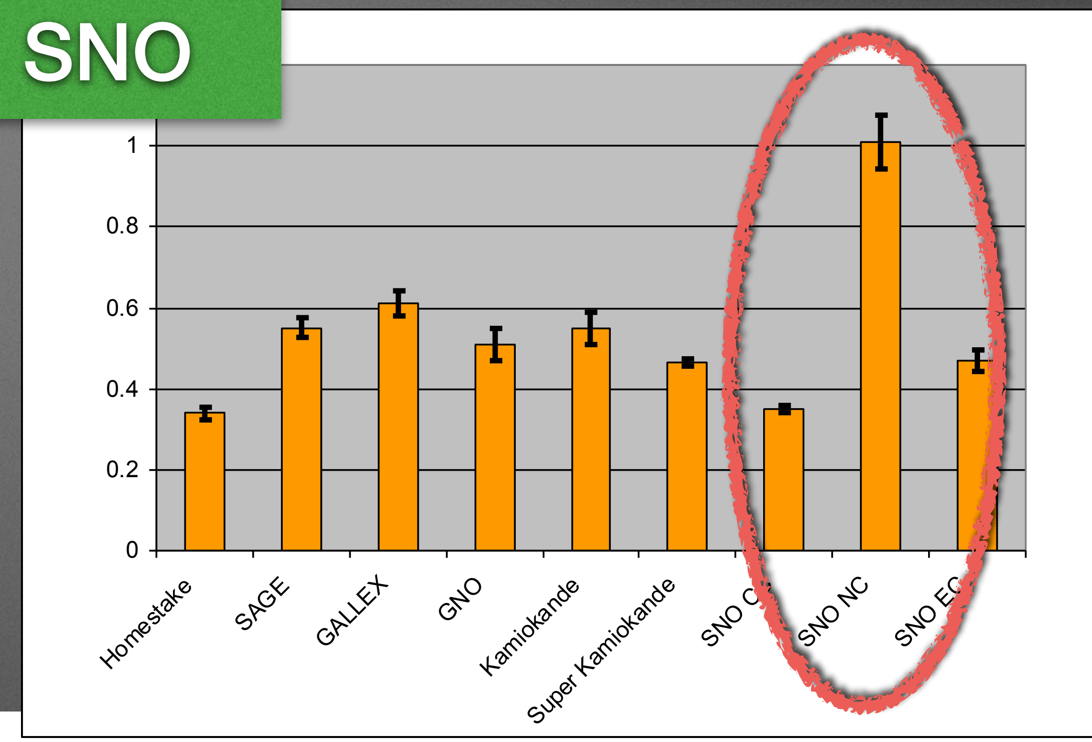
In the Standard Model neutrinos are massless particles → current limit on the sum of the neutrino masses ~1 eV → order of magnitudes lighter than the other fermions

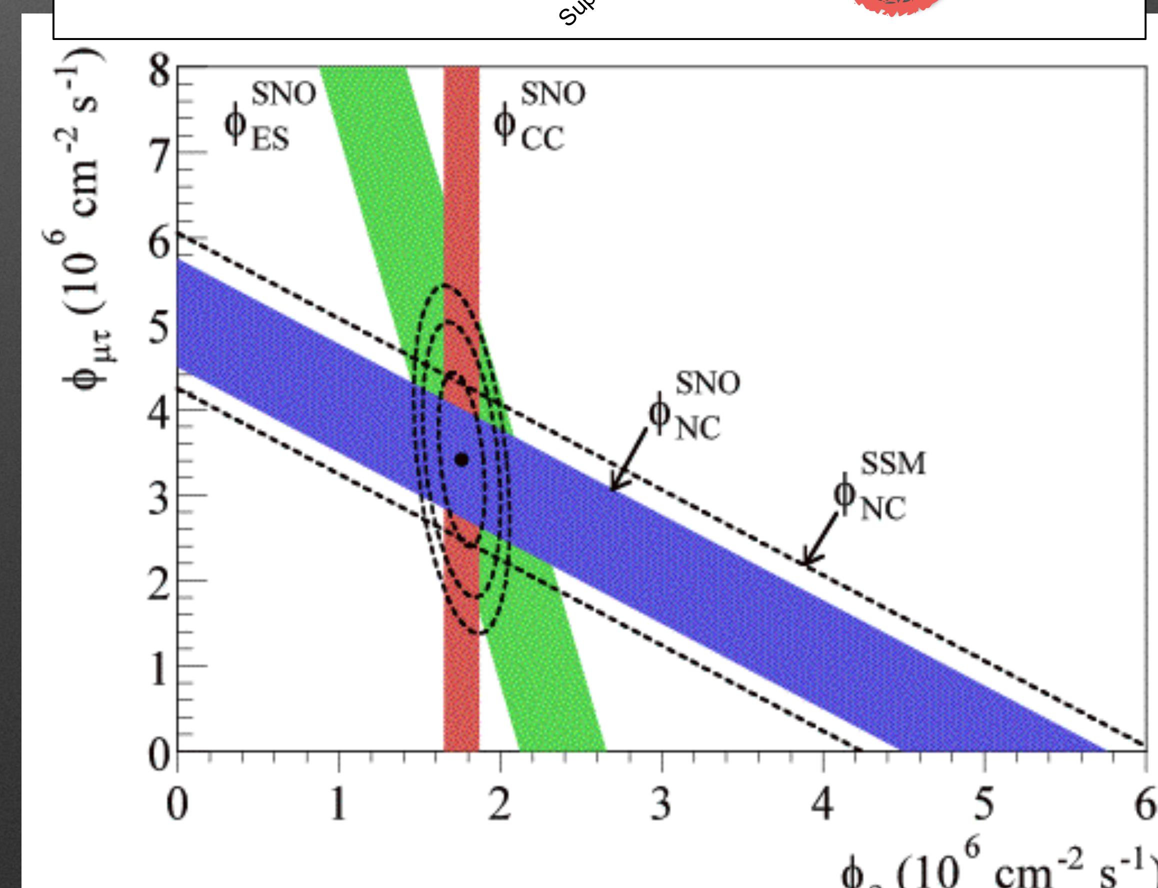
Discovery of ν oscillations

Super-K



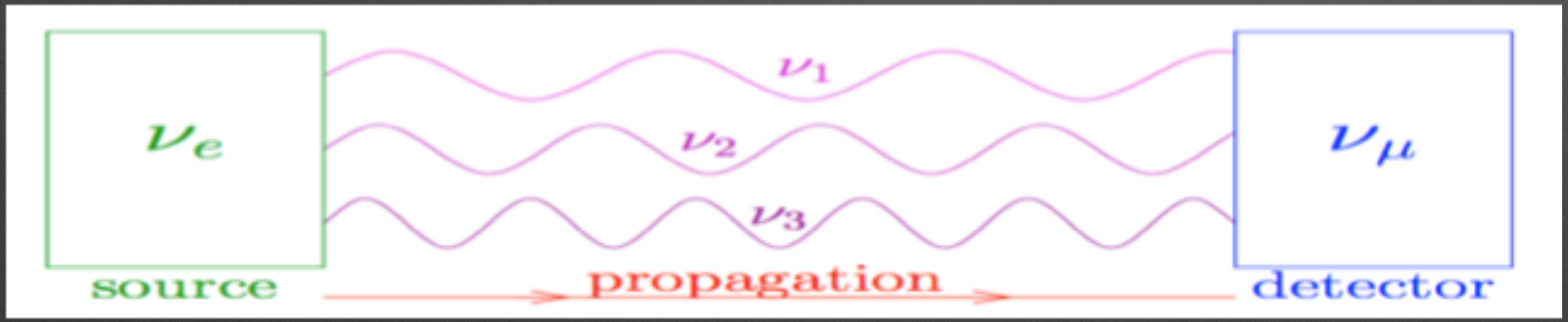
SNO

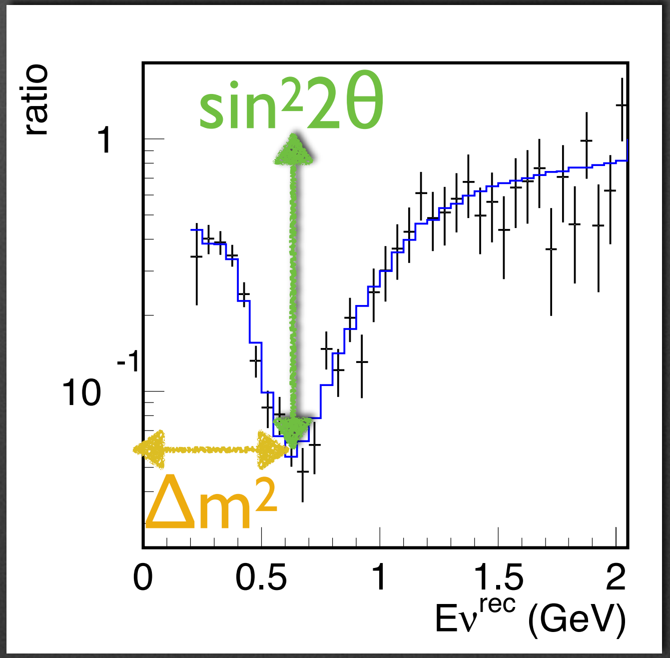




Neutrino oscillations

- First introduced by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates (ν_μ, ν_e, ν_τ) that are linear combination of mass eigenstates (ν_1, ν_2, ν_3)
- Neutrino propagate as mass eigenstates
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced





ν_e produced in a mixture of ν_1, ν_2, ν_3

ν_1, ν_2, ν_3 travel at different speed because they have different masses → interference

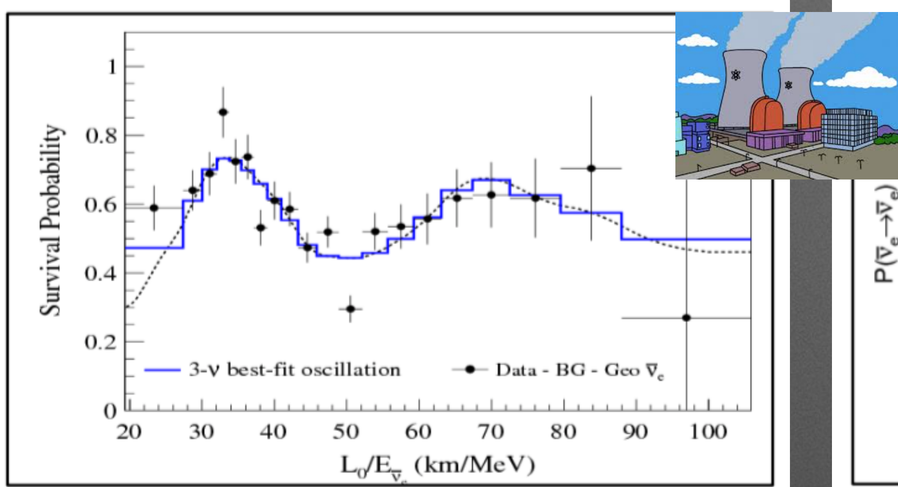
Different mixture of ν_1, ν_2, ν_3 → ν_μ is detected

Neutrino oscillation implies massive neutrinos

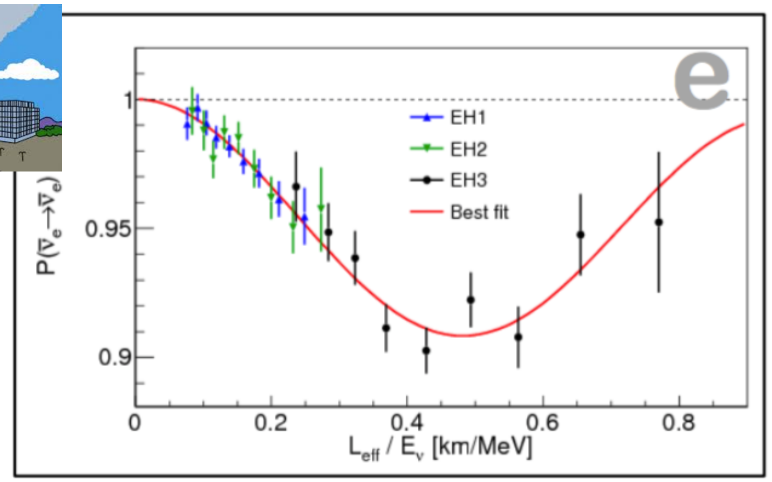
$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

Neutrino oscillations

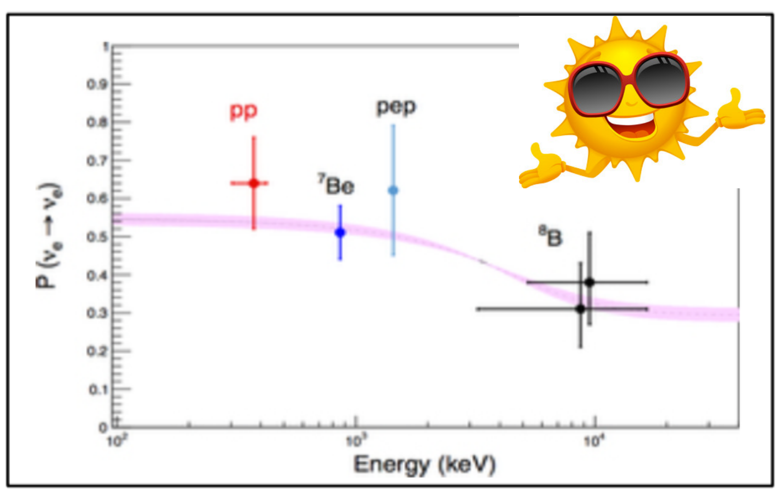
e→e (δm^2 , θ_{12})



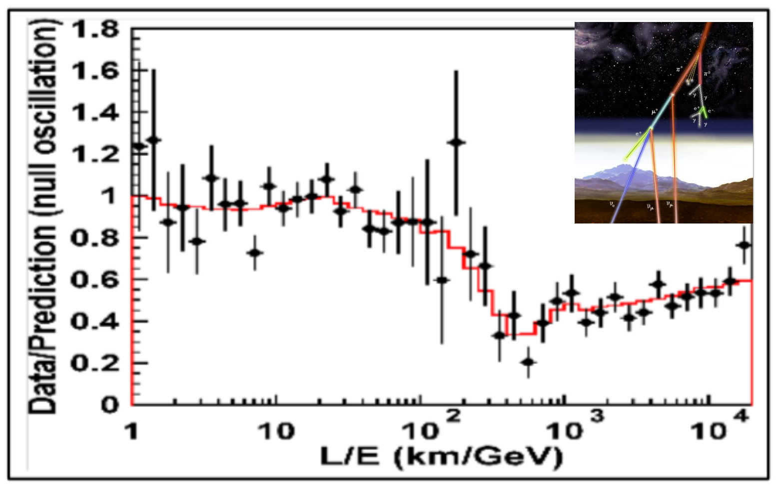
e→e (Δm^2 , θ_{13})



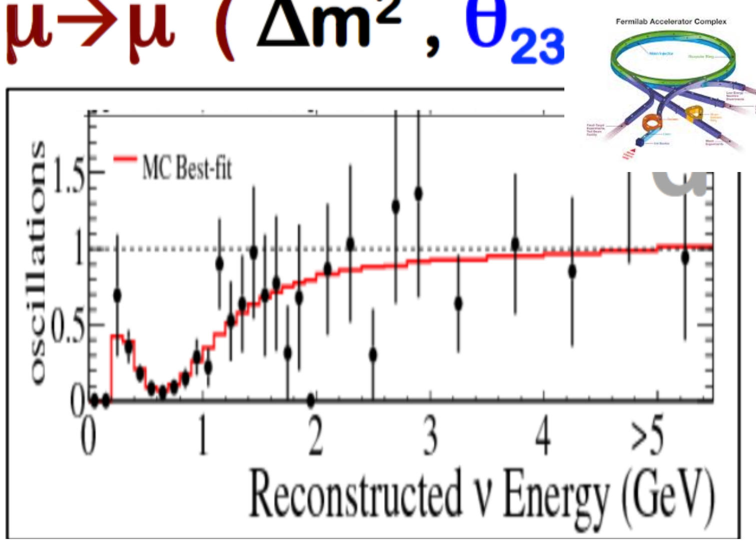
e→e (δm^2 , θ_{12})



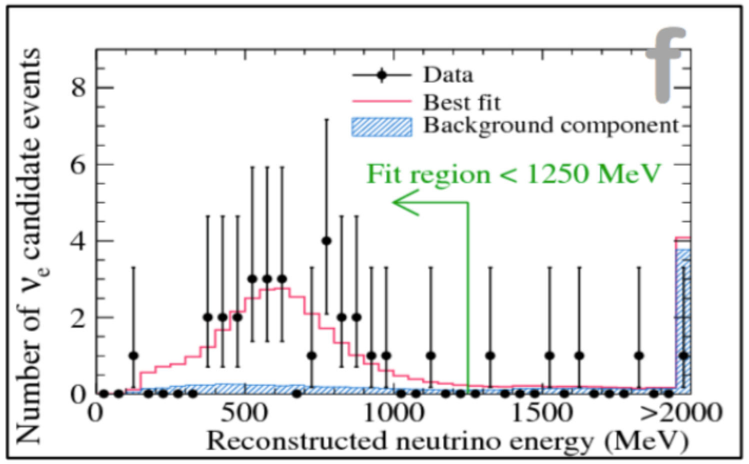
μ→μ (Δm^2 , θ_{23})



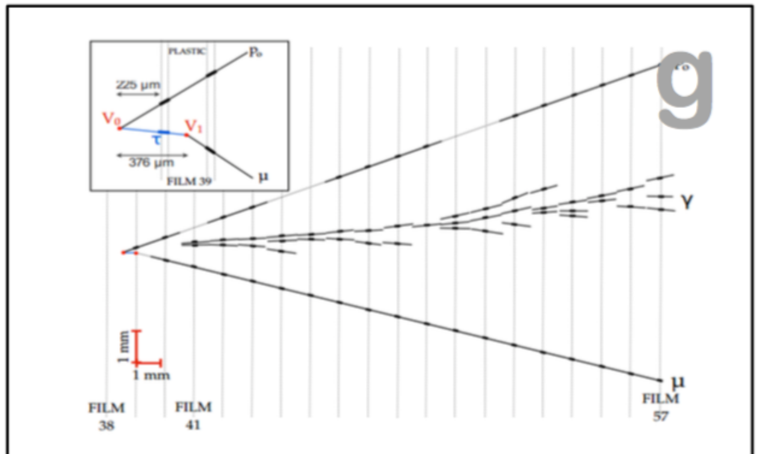
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



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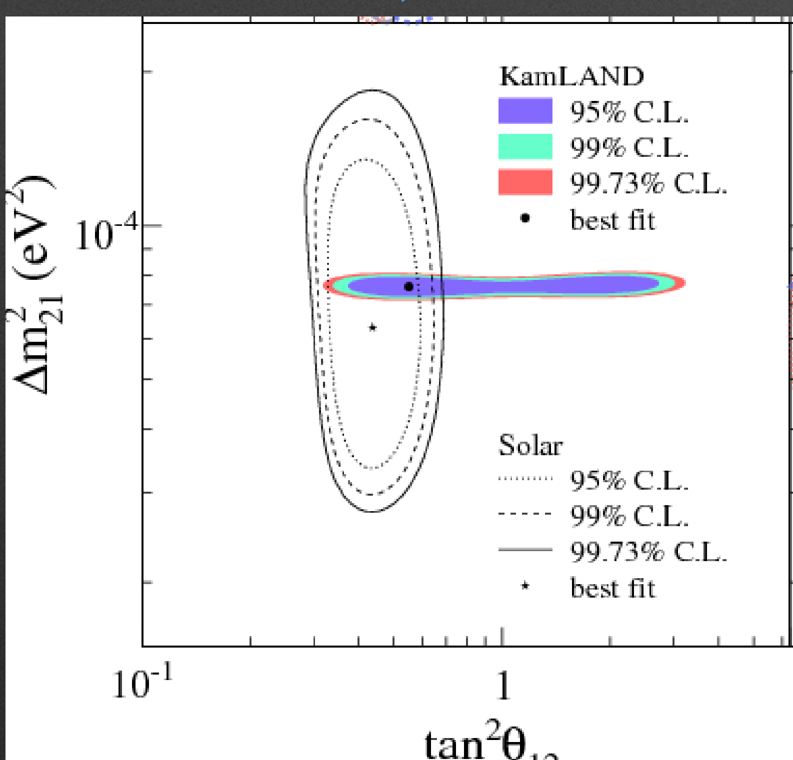
PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

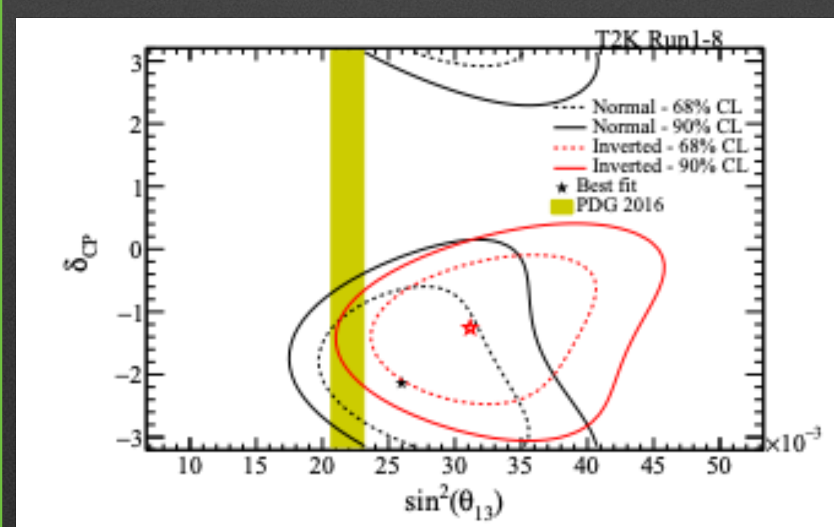
- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

θ_{13} is precisely known, some indications also for δ_{CP}

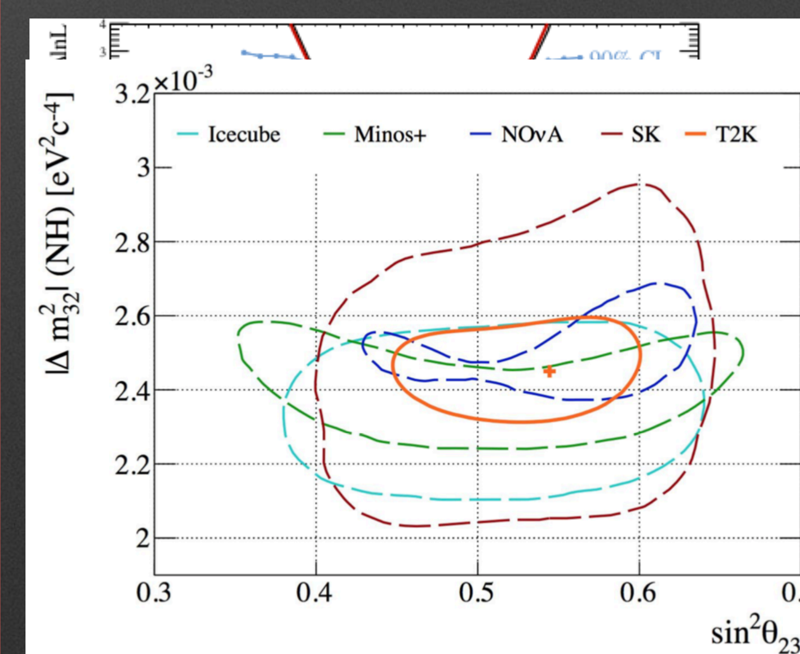
Solar (SNO, KamLand) → θ_{12}, Δm_{12}

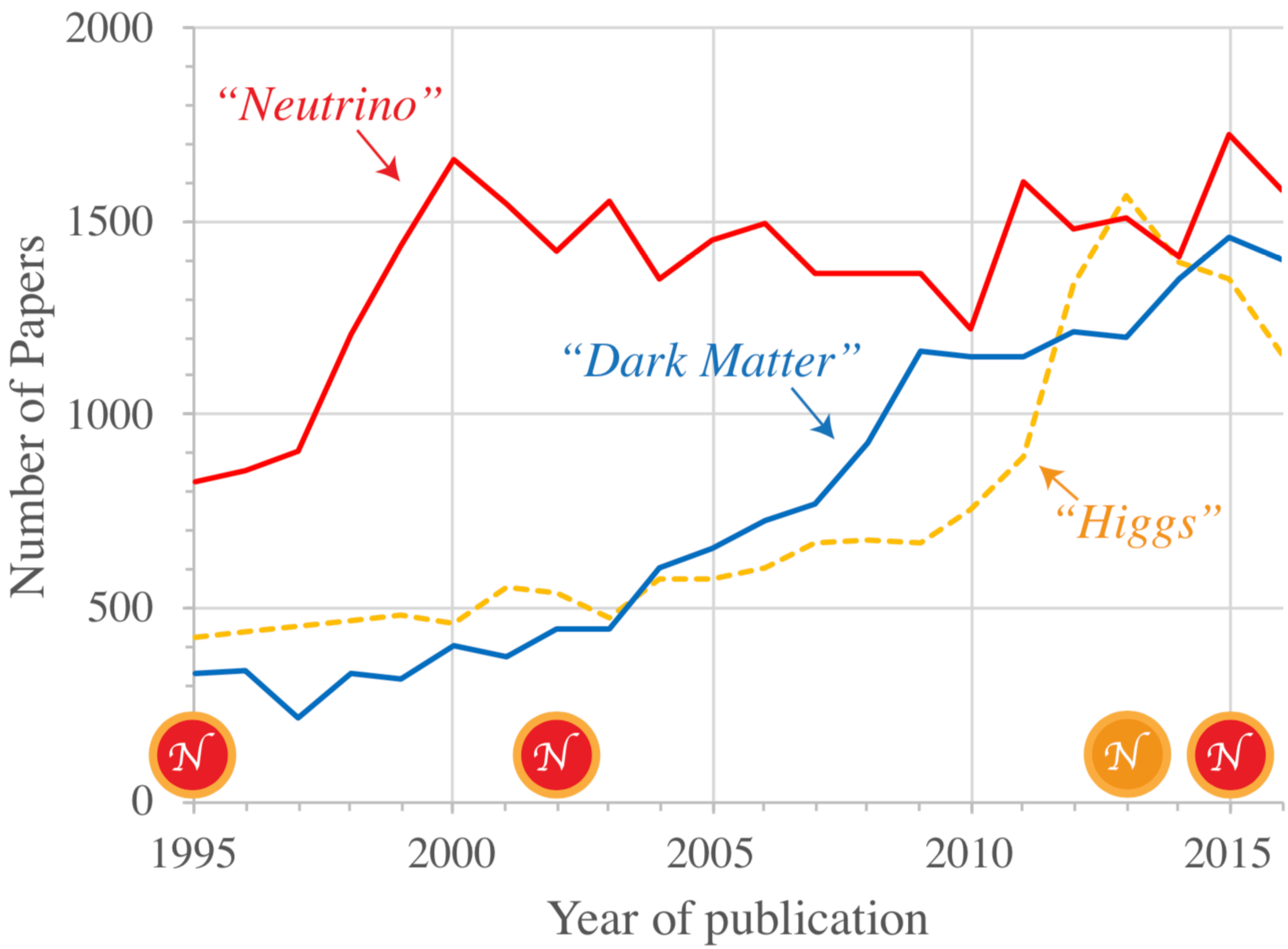


Reactors (Daya Bay, RENO, DChooz) → θ_{13}
LBL (T2K, NOνA) → θ_{13}, δ_{CP}



Atmospheric (SK, IceCUBE)
LBL (Minos, T2K, NOνA)
→ θ_{23}, Δm_{32}





From M. Messier @ NNN18

Data based on INSPIRES search "find ti Neutrino and date 2000", eg.

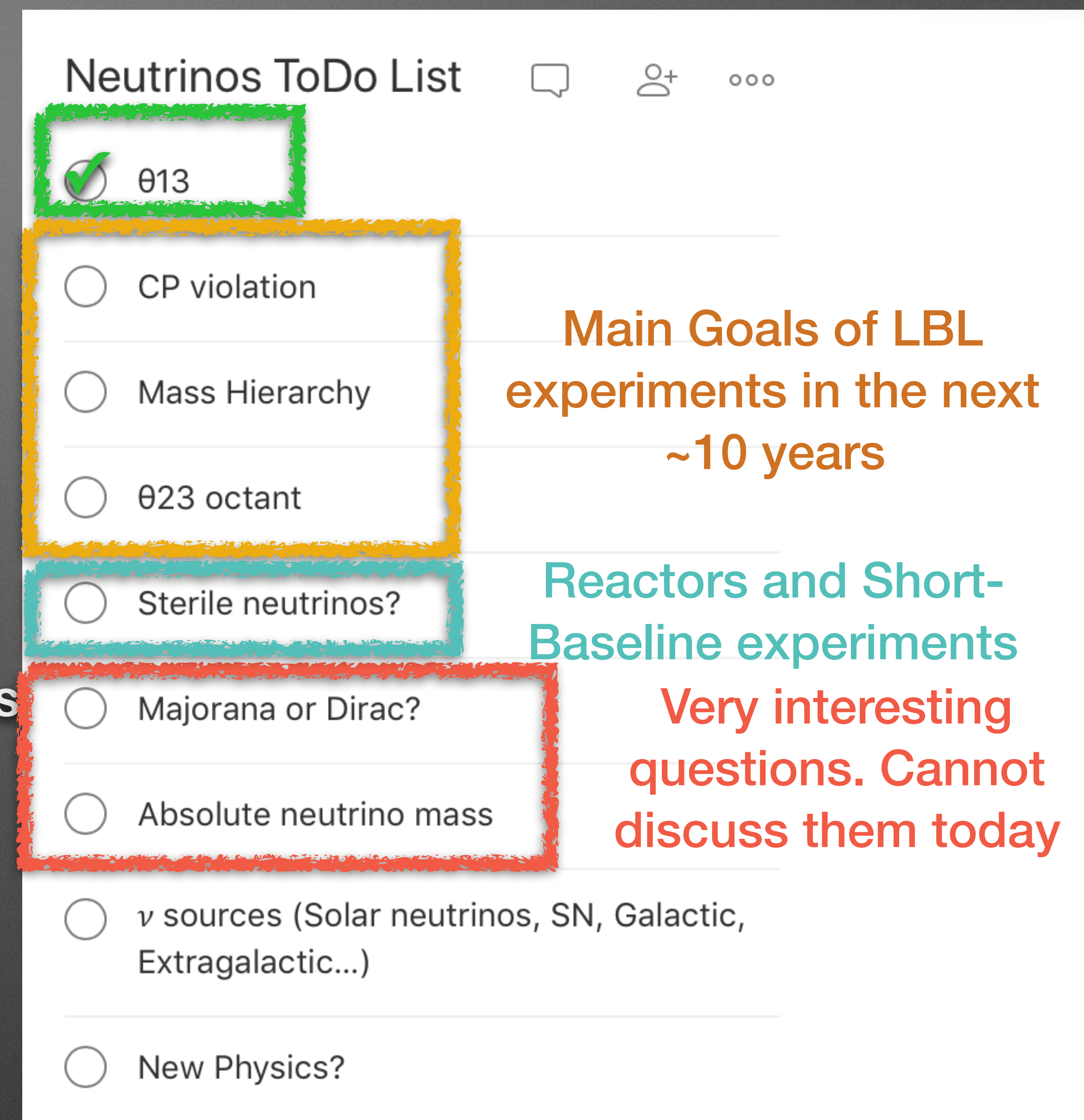
Artificial sources of neutrinos

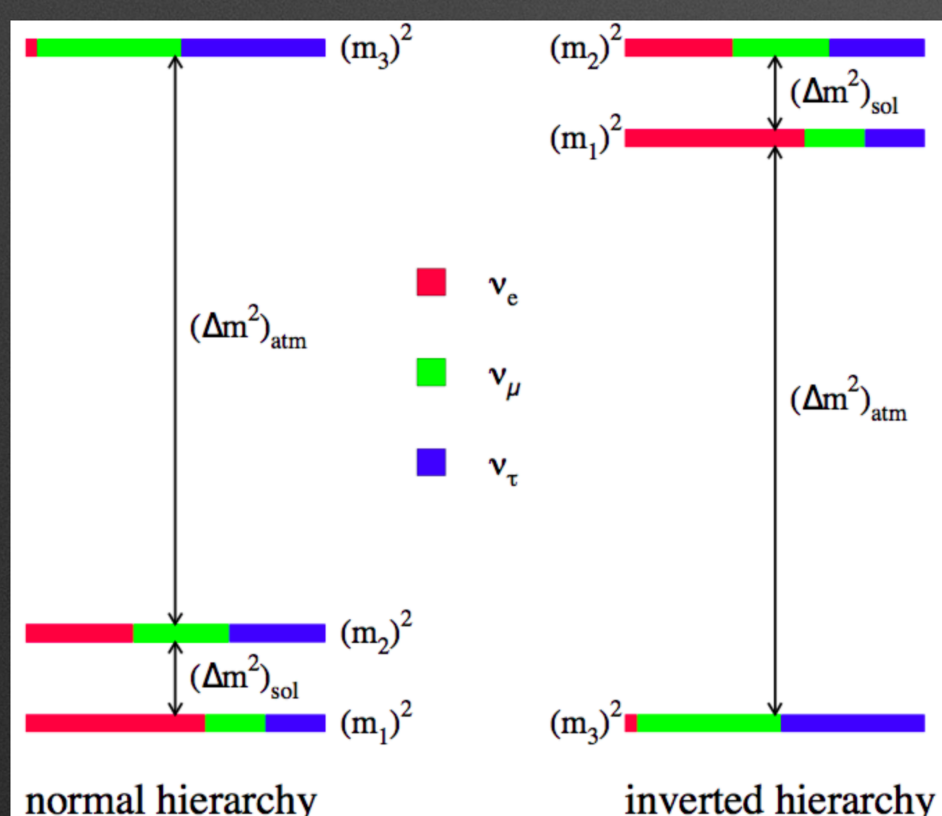
- Oscillations were discovered with solar and and atmospheric neutrinos
- Great sources of neutrinos → they come for free, just need to build a detector
  - Ideal for discoveries (span different ranges of $\Delta m2$)
  - Cannot be tuned → not the best sources for precision measurements
- Reactors → reactor spectrum is fixed but the distance can be tuned (KamLAND for θ_{12}, DB/DC/RENO for θ_{13}, Juno for mass ordering)
- Accelerators → can tune energy and distance
  - Well defined L/E → maximize oscillation probability (knowing $\Delta m2$)
  - Sensitive to 5 oscillation parameters (θ_{23}, θ_{13}, Δm^2_{23}, δ_{CP}, and mass ordering)
  - Can produce beam of ν_μ of $\bar{\nu}_\mu$ → study CP violation

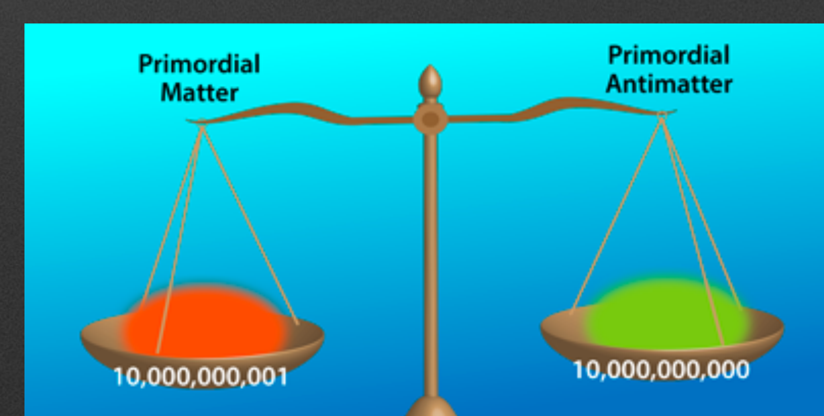
$$P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

Open questions

- Still many open questions related to neutrino oscillations → "guaranteed" measurements
- But we also don't know the nature of neutrinos (Dirac or Majorana) → $0\nu\beta\beta$ experiments
- Absolute mass of neutrinos → Katrin, Project-8, Cosmology
- Multi-messenger astronomy with neutrinos is starting now







Reactor experiments

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

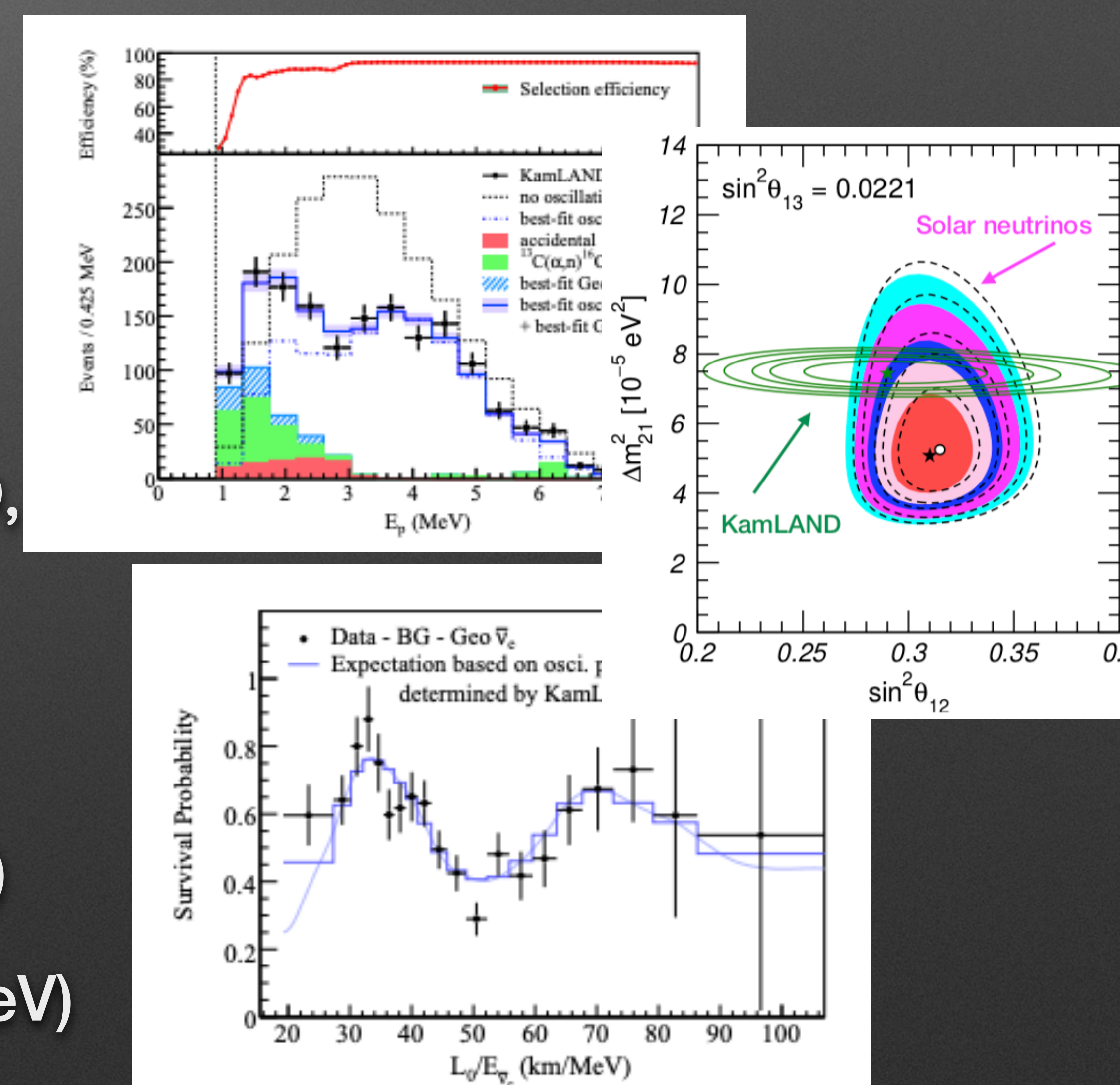
$\Delta m^2_{12} \sim 8\text{x}10^{-5}\ \text{eV}^2$ $\Delta m^2_{13} \sim 2.5\text{x}10^{-3}\ \text{eV}^2$

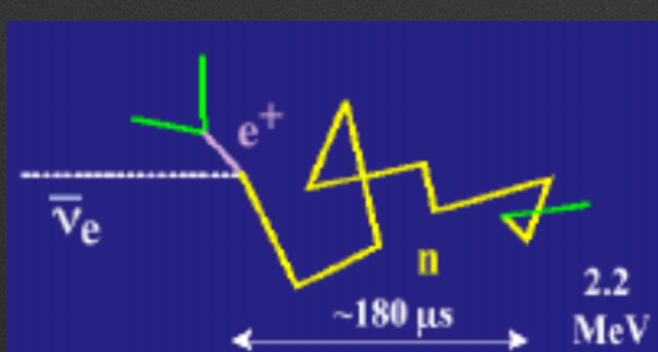
Max Posc → $\sin^2(1.27*\Delta m^2*L[km])/E[GeV]) = 1$

$\sin^2(1.27*\Delta m^2*L[km])/E[GeV]) \sim \pi/2$

- Reactor antineutrino spectrum ~ 4 MeV
- Δm^2_{12}, θ_{12} → distance of 200 km (KamLAND)
- Δm^2_{13}, θ_{13} → distance of ~1 km (Daya Bay, RENO, Double Chooz)

KamLAND



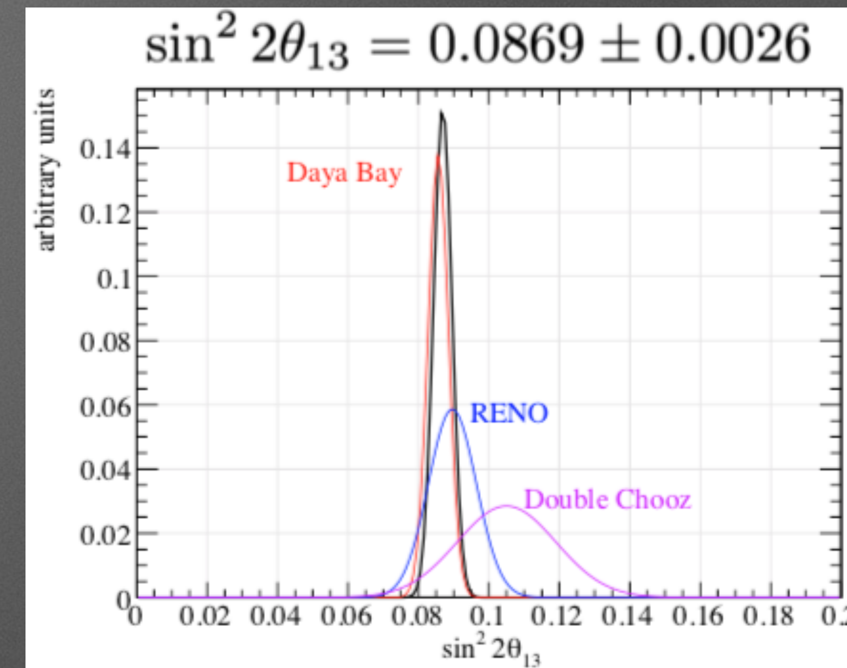


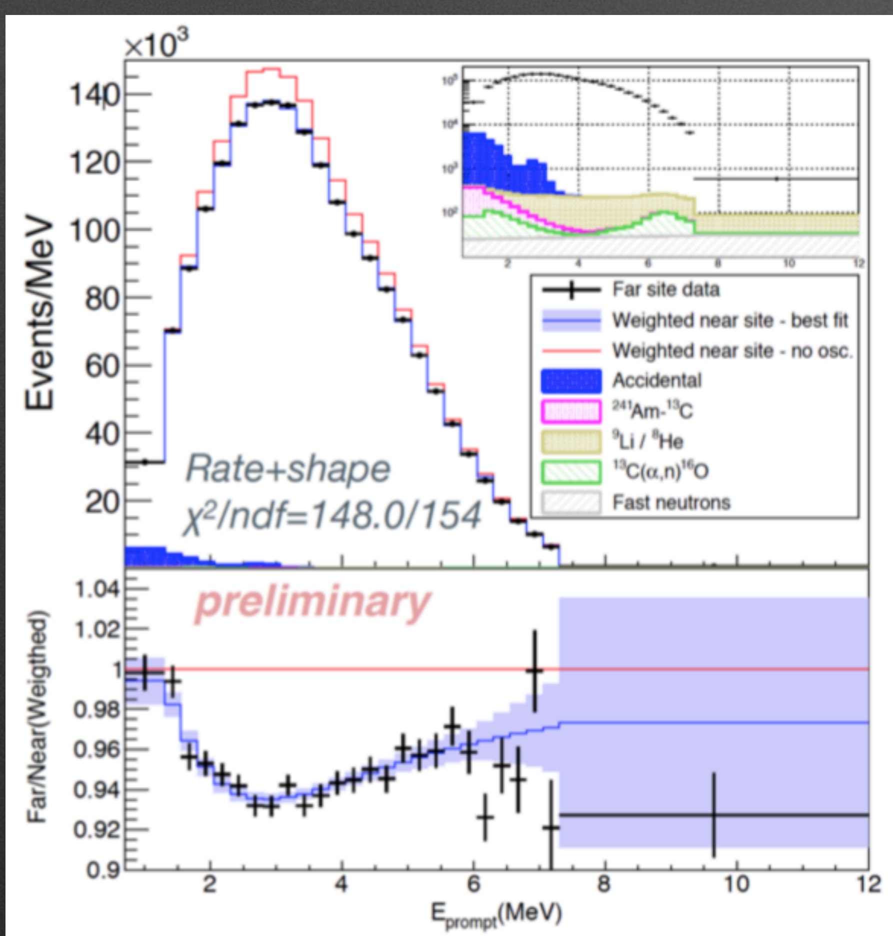
$\bar{\nu}_e + p \rightarrow e^+ + n$

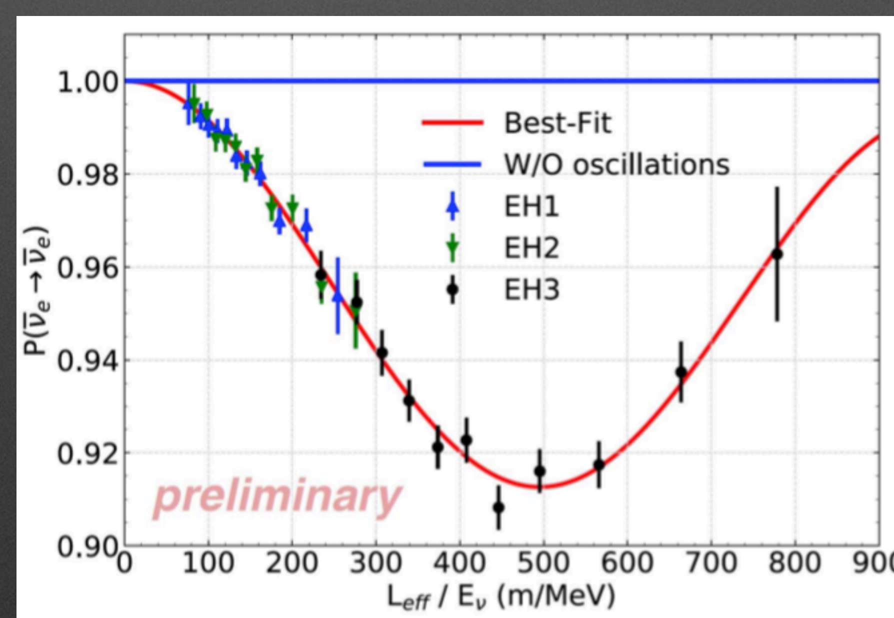
$n + p \rightarrow d + \gamma$ (2.2 MeV)

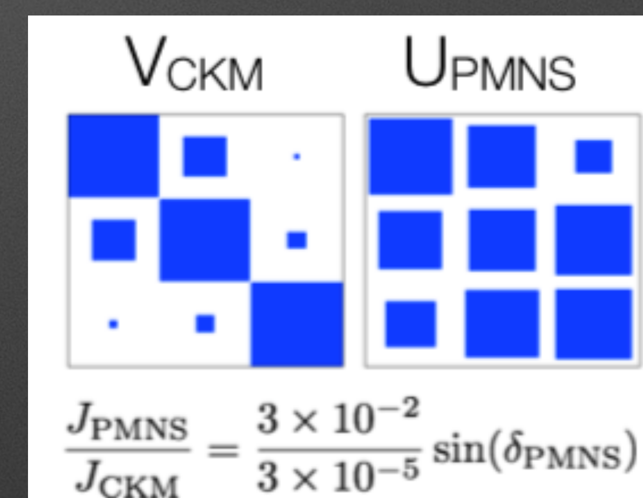
$n + Gd \rightarrow Gd^* + \gamma$ (8 MeV)

Measurement of θ_{13}





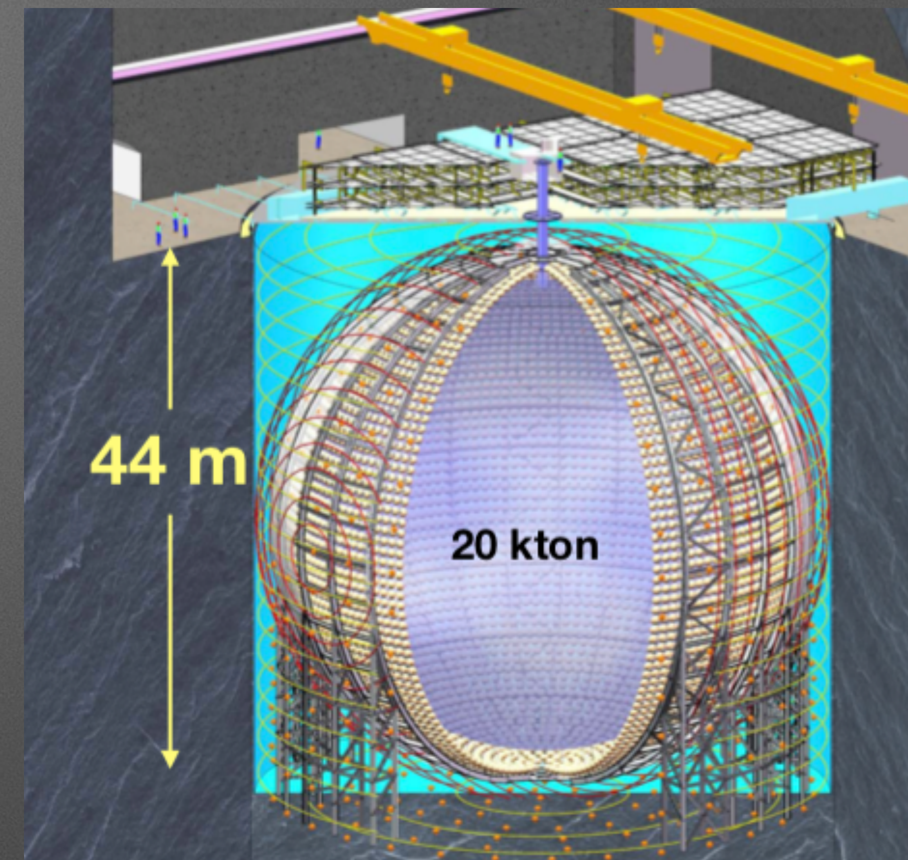


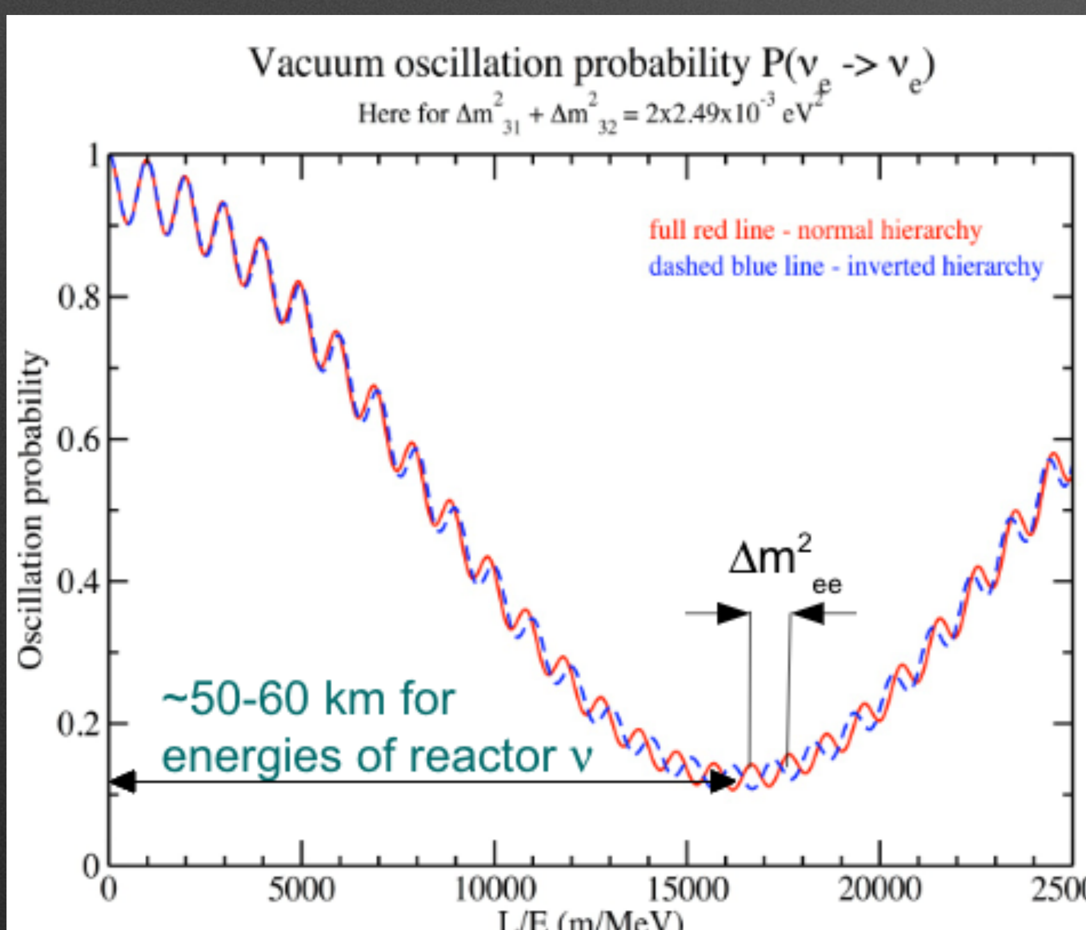


JUNO

IN2P3

- 20 kton Liquid Scintillator detector
- Installed at 53 km from nuclear reactor in China ("solar" oscillations) → very precise measurement of Δm^2_{21} and $\sin^2\theta_{12}$
- ~3σ sensitivity to the mass ordering → if energy resolution of 3% is achieved





	Δm^2_{21}	$\sin^2\theta_{12}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{13}$
Dominant experiment	KamLAND	SNO	T2K & NOvA /Daya Bay	Daya Bay
Individual 1σ	2.4%	6.7%	3.2%/3.5%	4.0%
Global 1σ *	2.2%	3.9%	1.2%	3.4%
JUNO expected 1σ	0.6%	0.7%	0.4%	~15%

Accelerator experiments

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Max Posc → $\sin^2(1.27 * \Delta m^2 * L[km])/E[GeV]) = 1$

$\sin^2(1.27 * \Delta m^2 * L[km])/E[GeV]) \sim \pi/2$

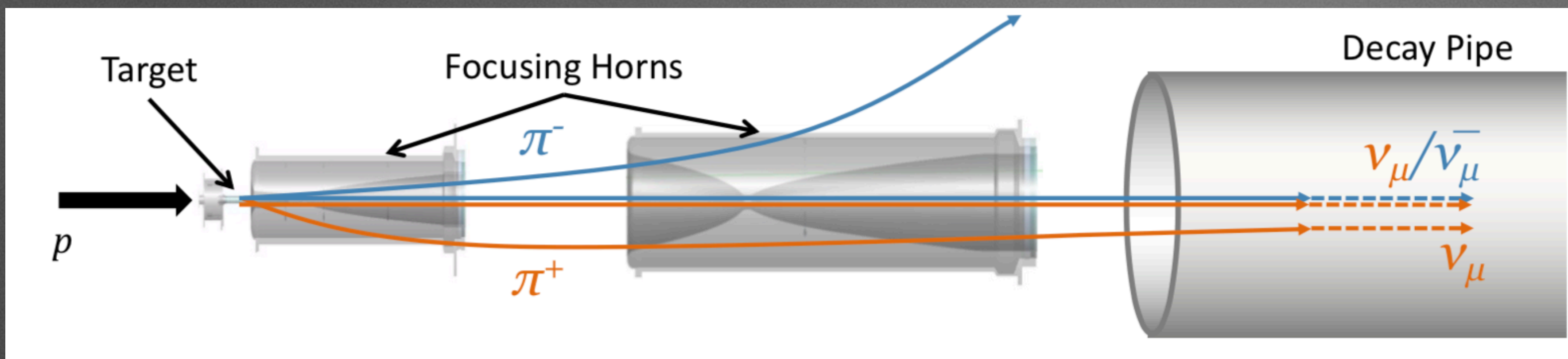
$\Delta m^2_{13} \sim \Delta m^2_{23} \sim 2.5 \times 10^{-3}$ eV^2

T2K
L = 295 km
Eν ~ 0.7 GeV

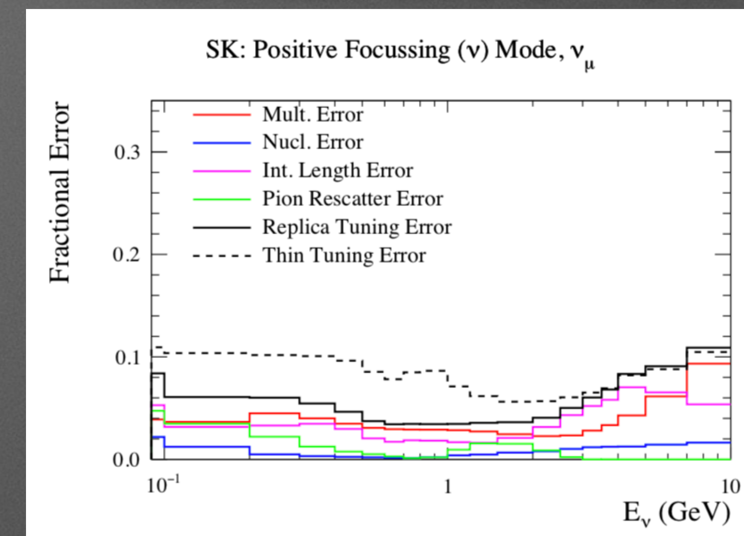
CEA+IN2P3

NOνA
L = 810 km
Eν ~ 2 GeV

Neutrino beams

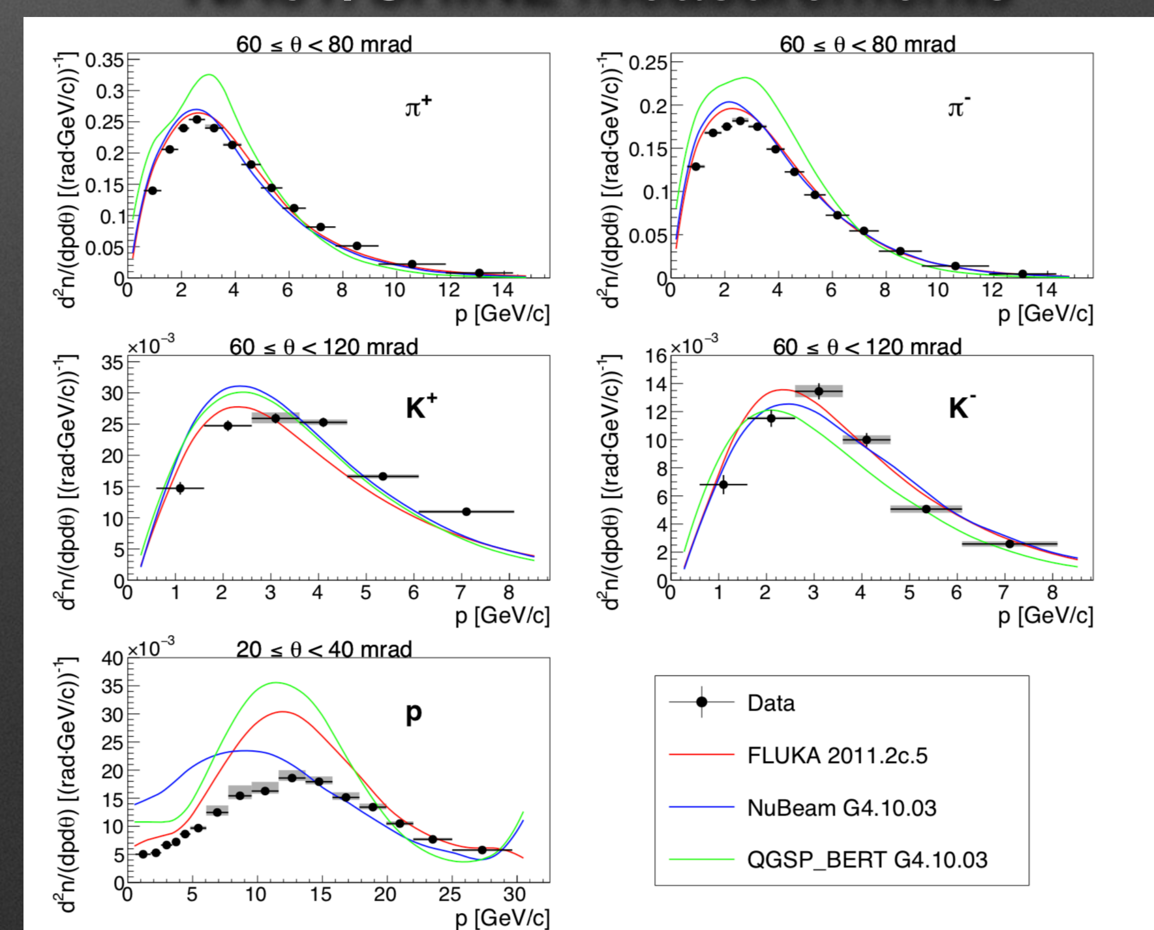


T2K flux errors ~ 5%

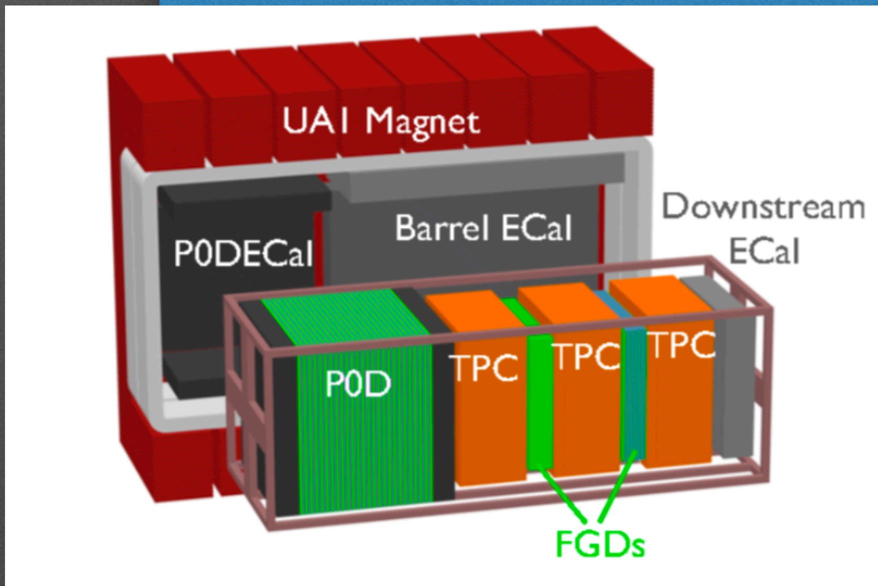


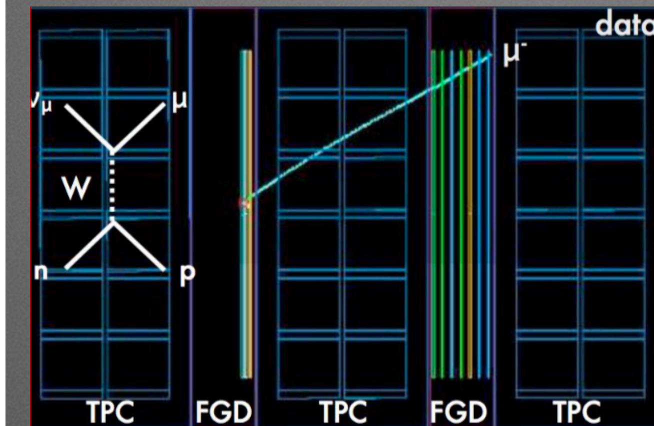
- Neutrino beams produced by striking a target with protons and then $\pi \rightarrow \mu + \nu_\mu$
- Main uncertainty → hadron-production cross-section
- Constrained with NA61/SHINE experiment at CERN
- Reduce flux uncertainties from ~25% to ~10% (5% expected very soon!)

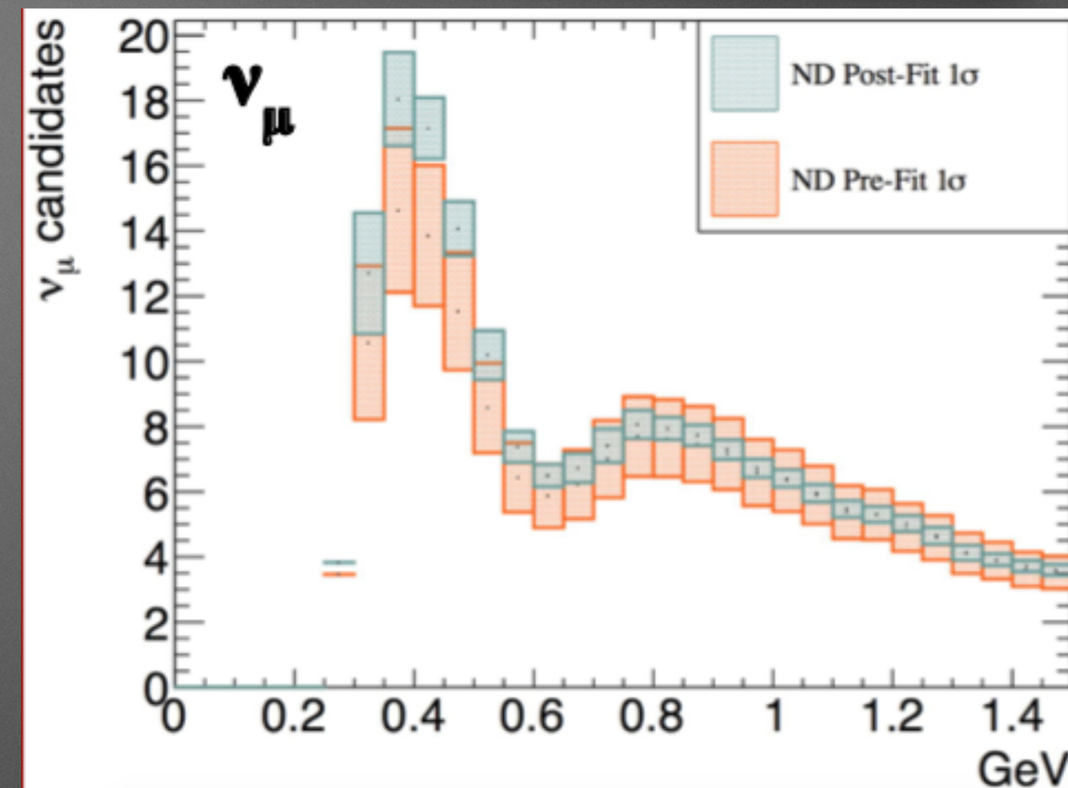
NA61/SHINE measurements

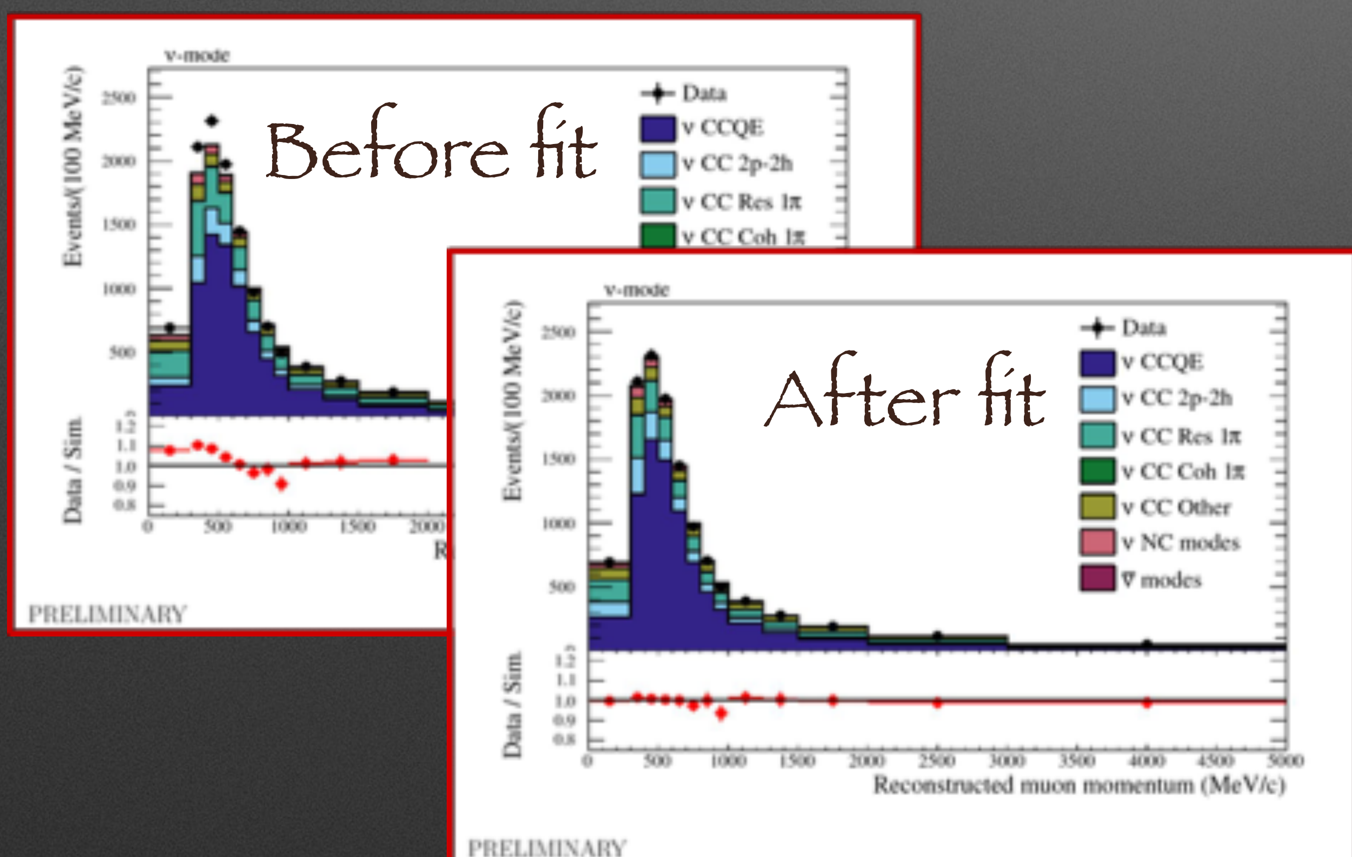


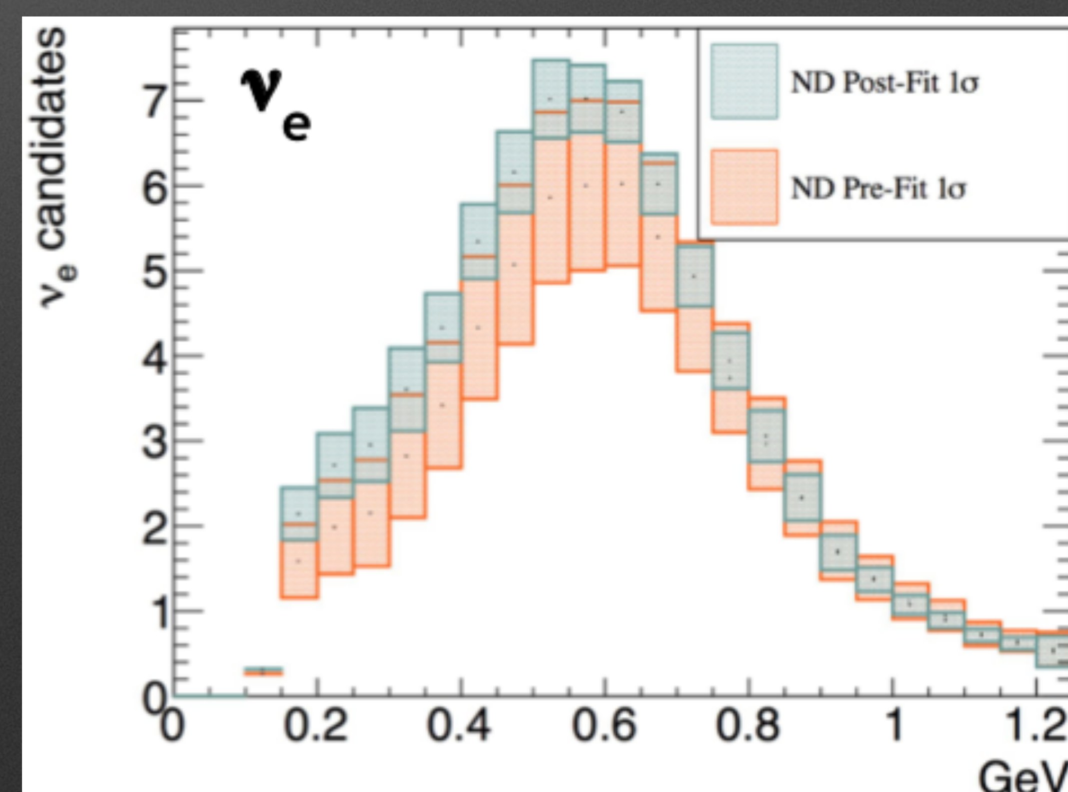
Near Detectors





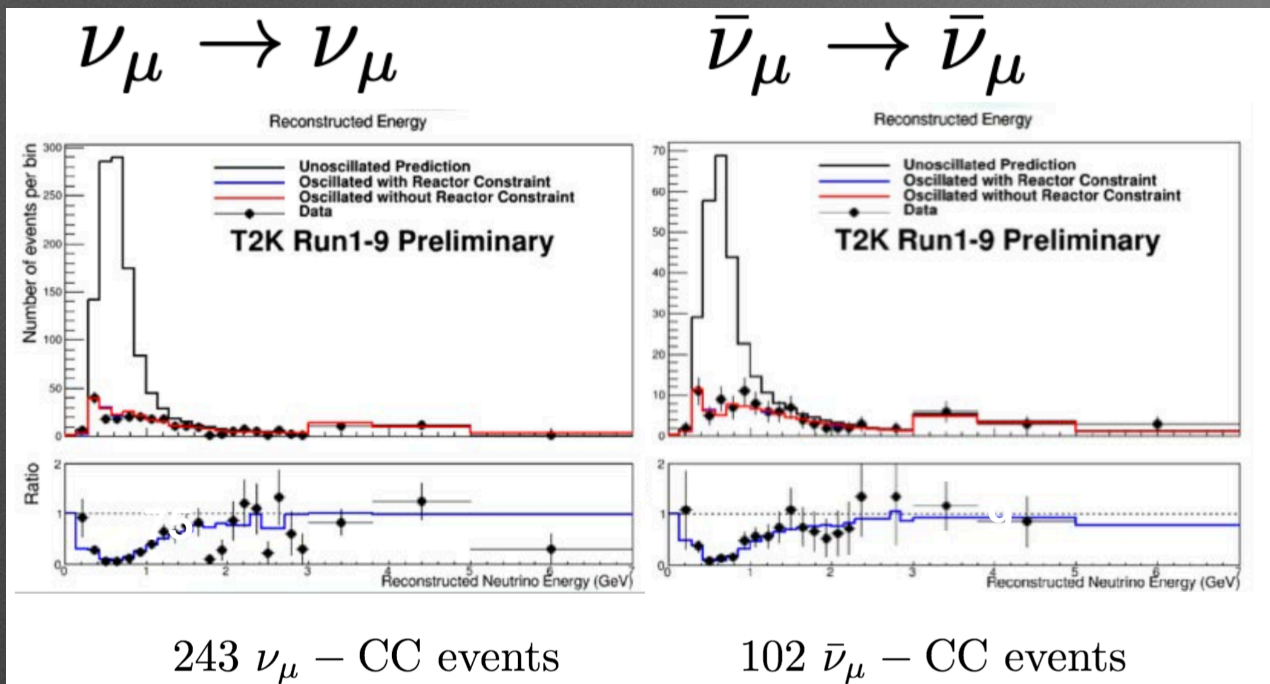


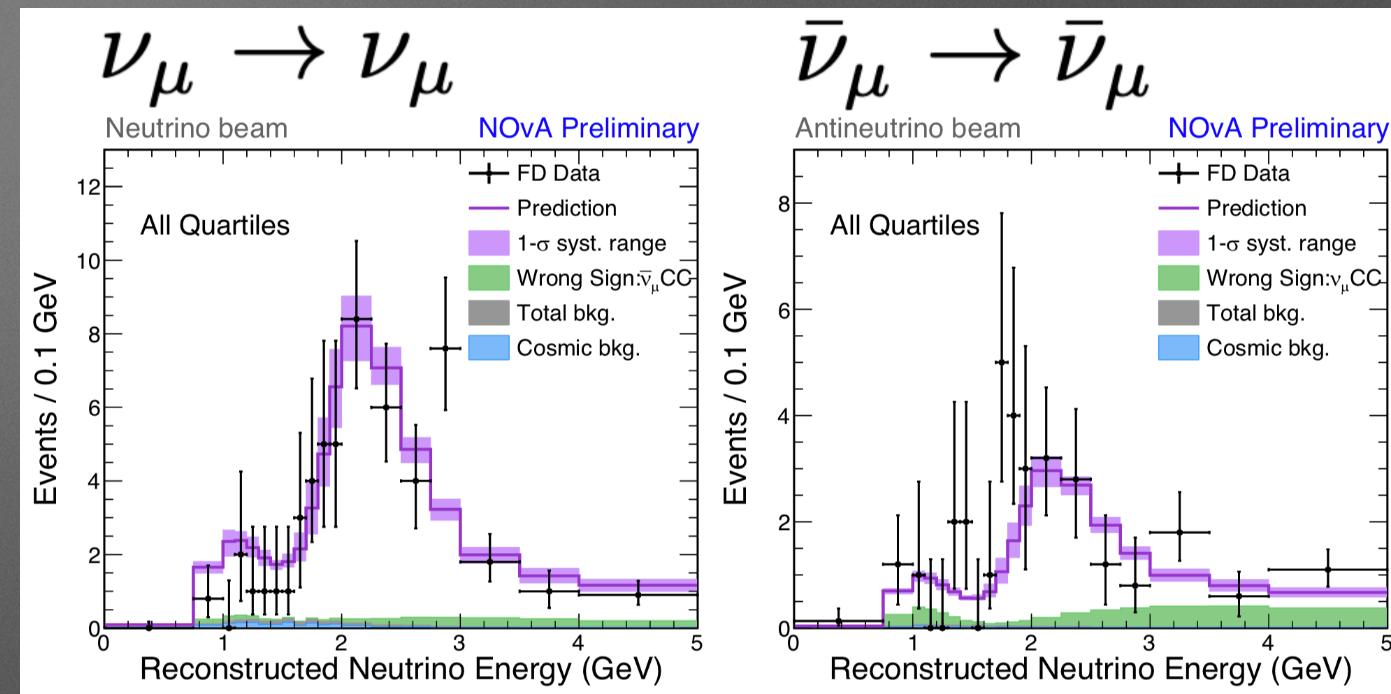




Reduce systematics uncertainties from ~15% to 5%

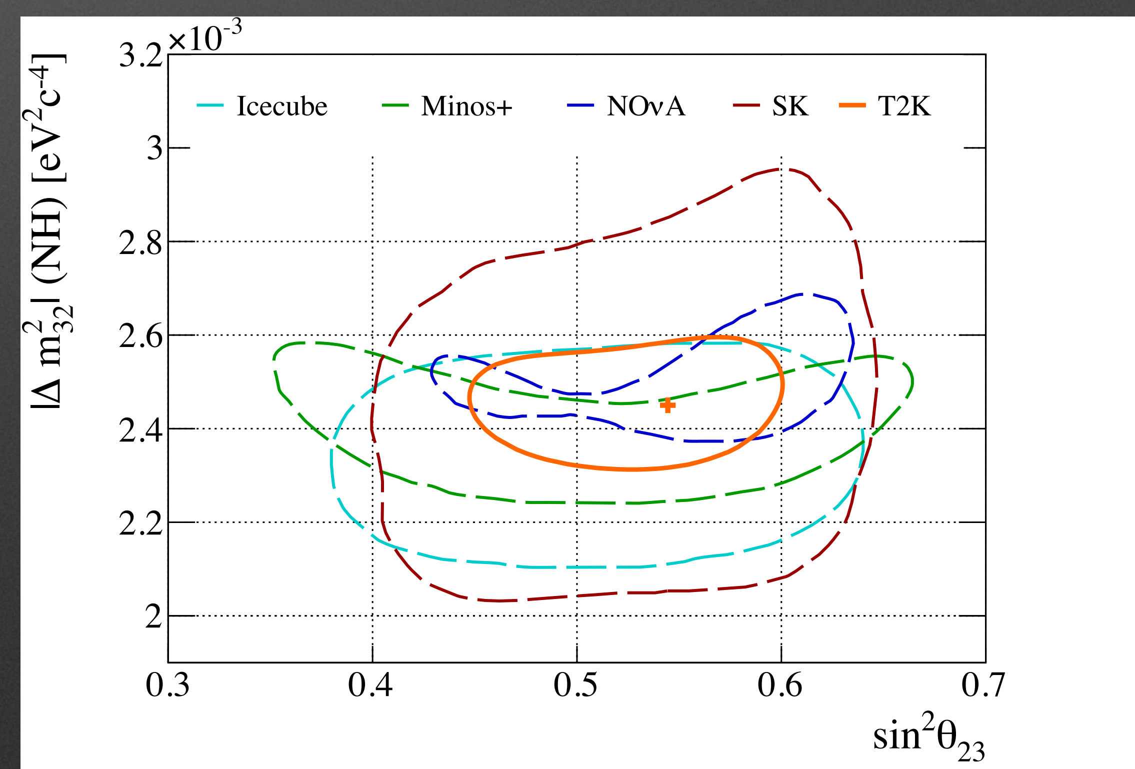
ν_μ disappearance: θ_{23}, Δm^2_{23}





* Dominated by LBL experiments

* All data compatible with $\sin^2(\theta_{23})=0.5$ → maximal mixing



ν_e appearance: CP violation, θ_{23} octant, mass ordering

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2\Delta_{31}$$

Leading term → θ_{13} * θ_{23}

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

CPV term

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

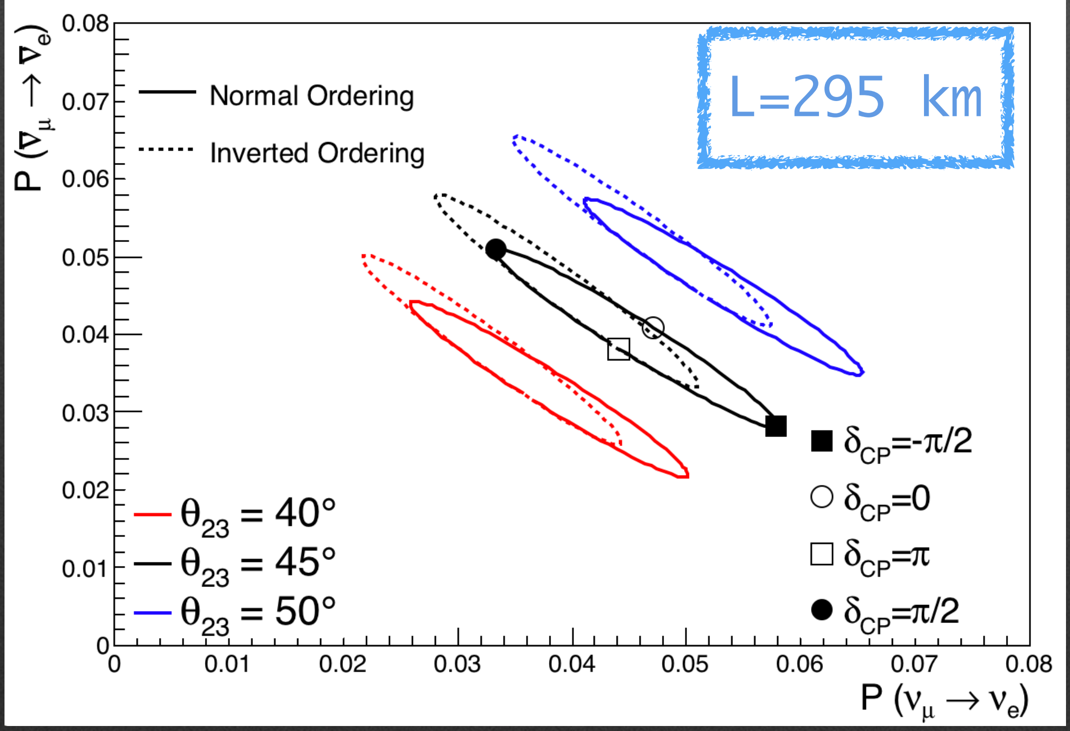
$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2\Delta_{21}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

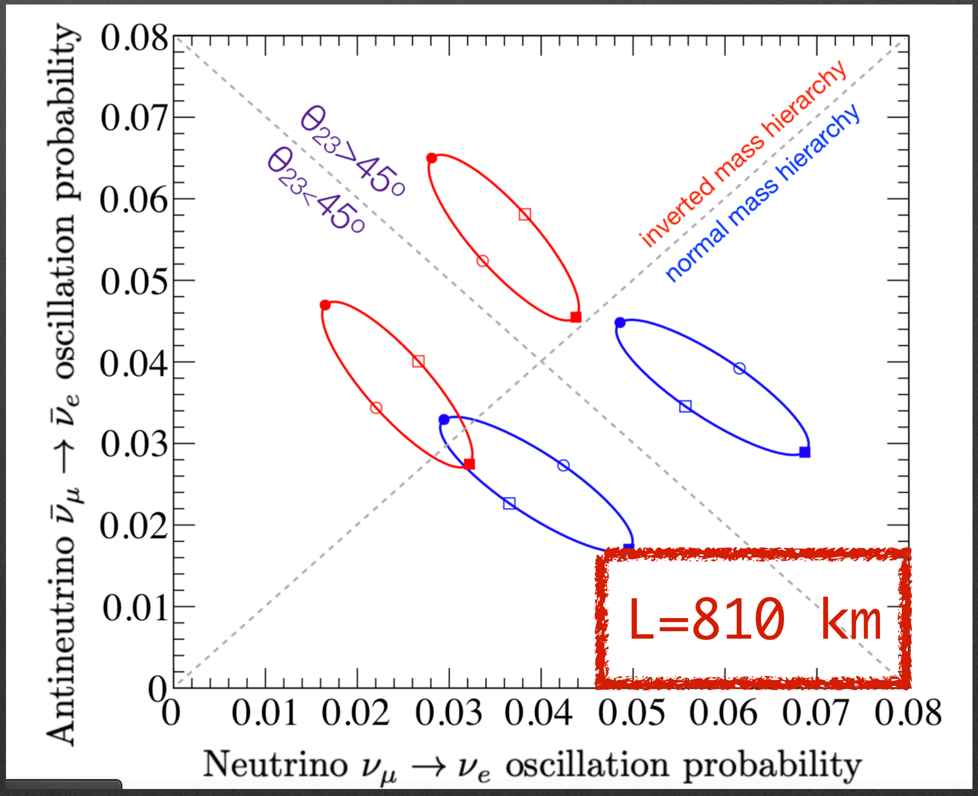
$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2\Delta_{31},$$

Matter effects ∝ distance

T2K almost no MH —>
~ clean measurement of CPV

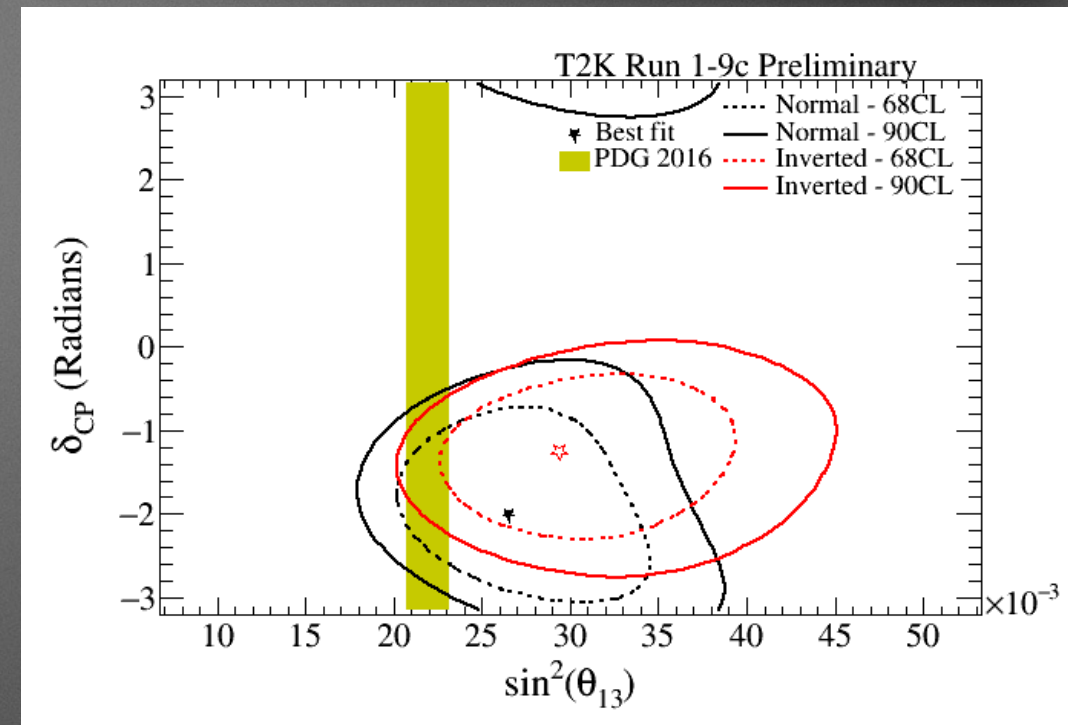


NOVA sensitive to MH and CPV
but with some degeneracies

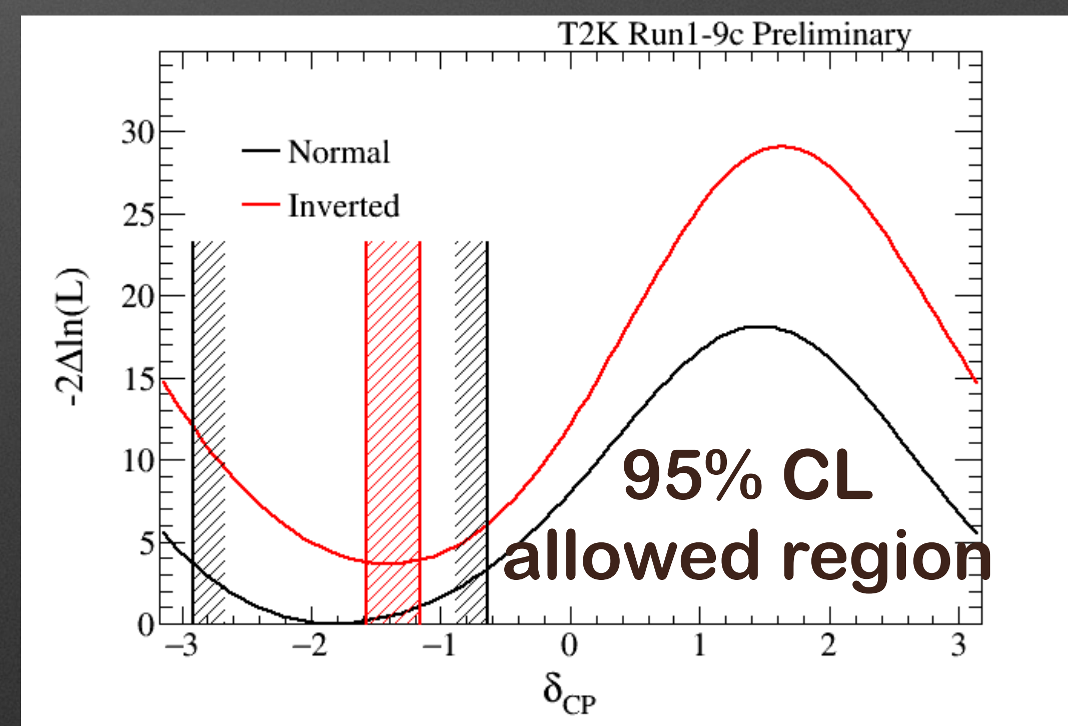


ν_e appearance: θ_{13}, δ_{CP}

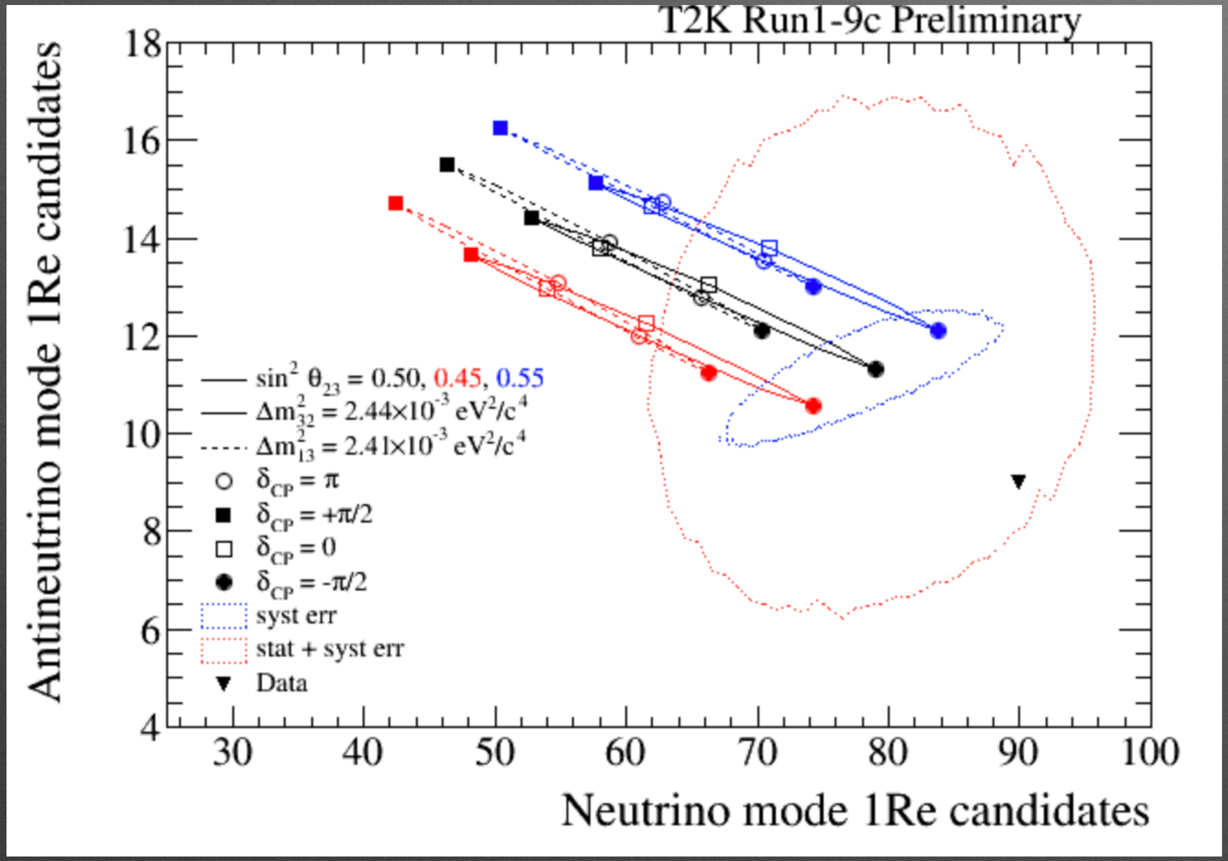
	Data	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν-mode e-like	75	73.8	61.6	50.0	62.2
ν-mode e-like+1π	15	6.9	6.0	4.9	5.8
$\bar{\nu}$-mode e-like	9	11.8	13.4	14.9	13.2

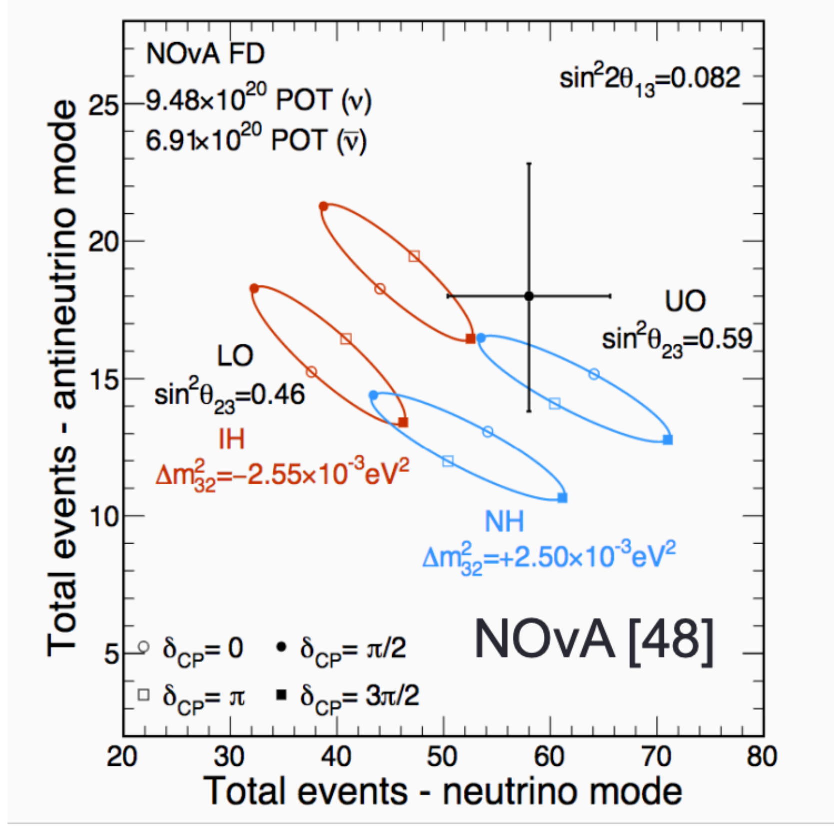


- T2K alone and T2K+reactor both prefer values of $\delta_{CP}\sim-\pi/2$
- Normal ordering is also favoured
- CP conserving values are excluded at >2 σ when reactor θ_{13} measurements are included



T2K/NOνA comparison





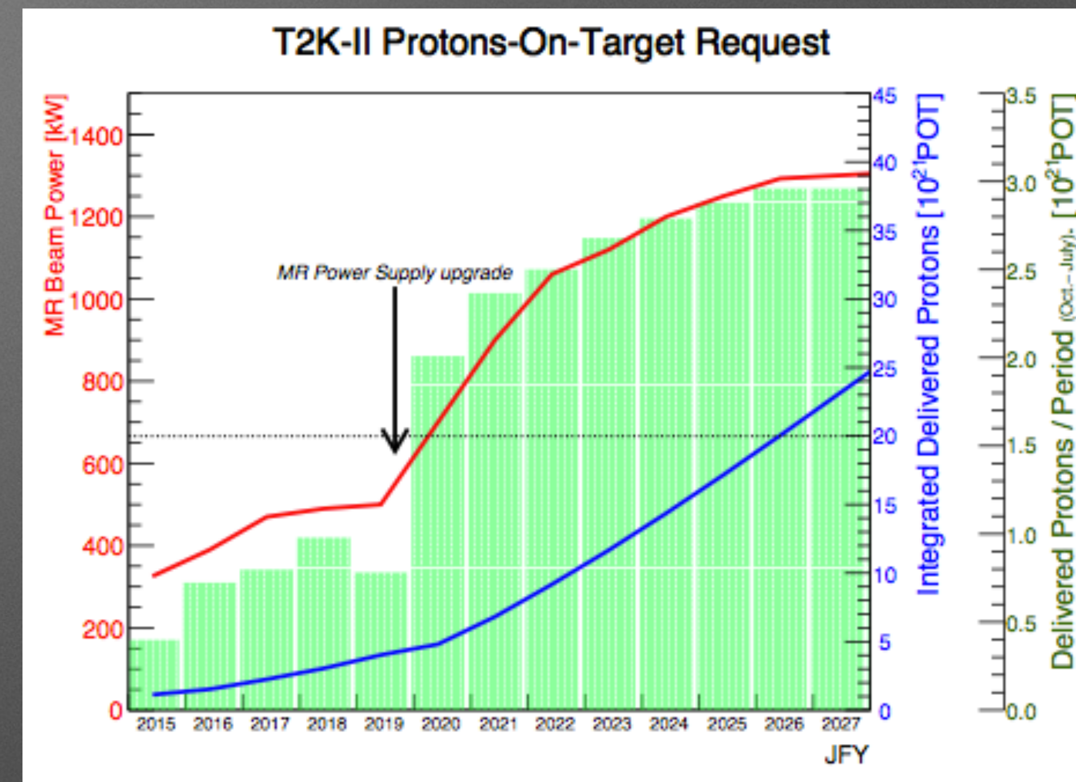
- Currently we both prefer normal ordering
- Preference for maximal CP violation in T2K not confirmed by NOνA
- More statistics is needed for both experiments!
- Plan to have combined T2K/NOνA Oscillation Analysis in 2022

T2K phase II

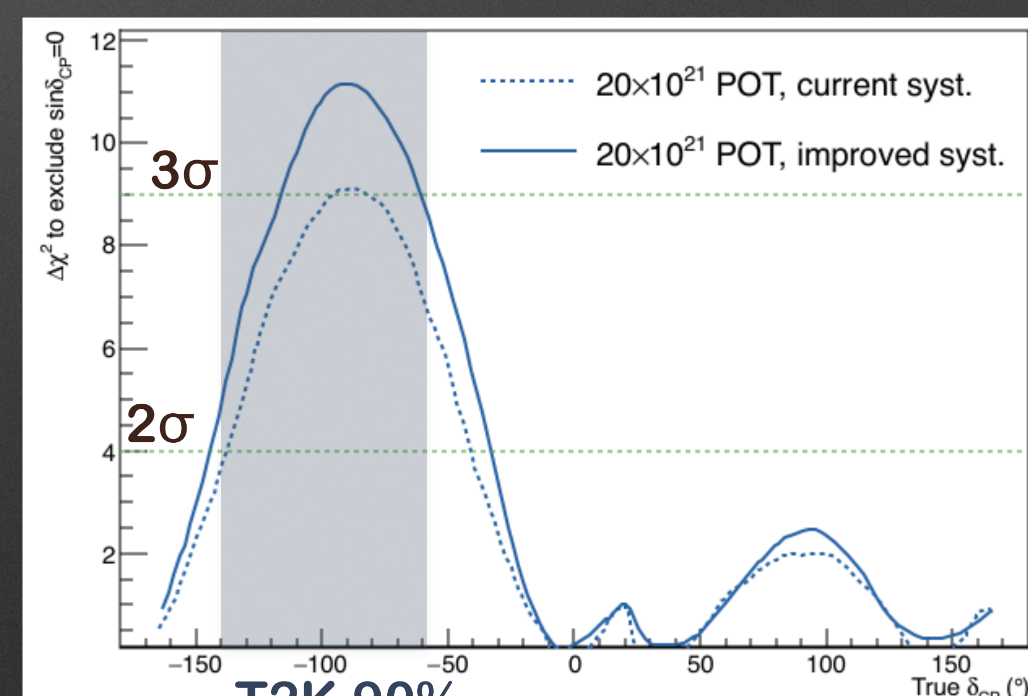
- T2K was originally approved to collect 7.8x10^{21} pot
  - Driven by sensitivity to θ_{13}
- Proposal for an extended run
  - T2K-II → 20x10^{21} pot
- Upgrade the Main Ring power supply to reach 1.3 MW operations

ν_e: 460 events ± 20% (δ_{CP} and ordering)

$\bar{\nu}_e$: 130 events ± 13% (δ_{CP} and ordering)

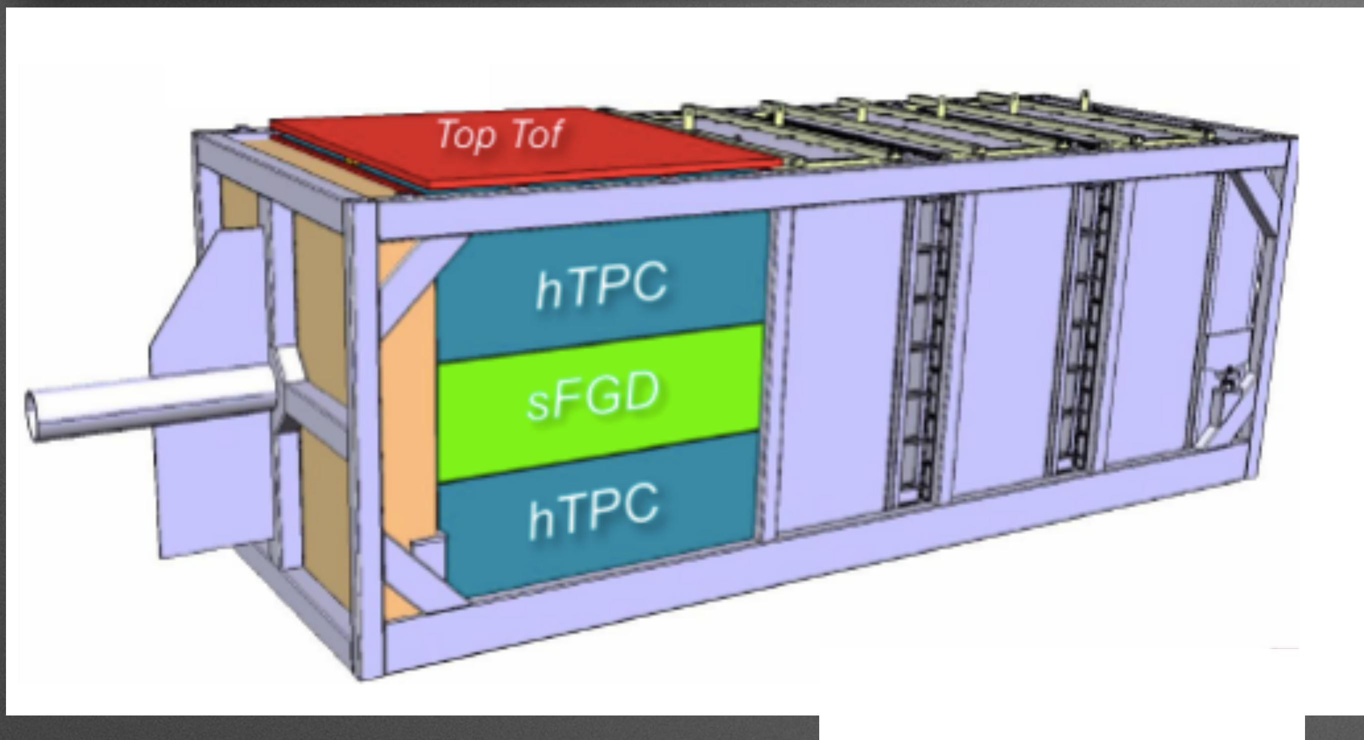


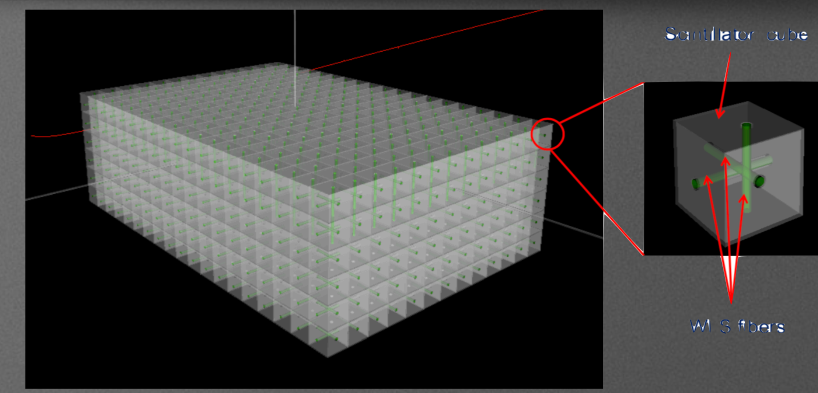
- >3σ measurement of CP violation (if δ_{CP} close to -π/2)
- Need to reduce systematics to ~4% (<3% from ND280)

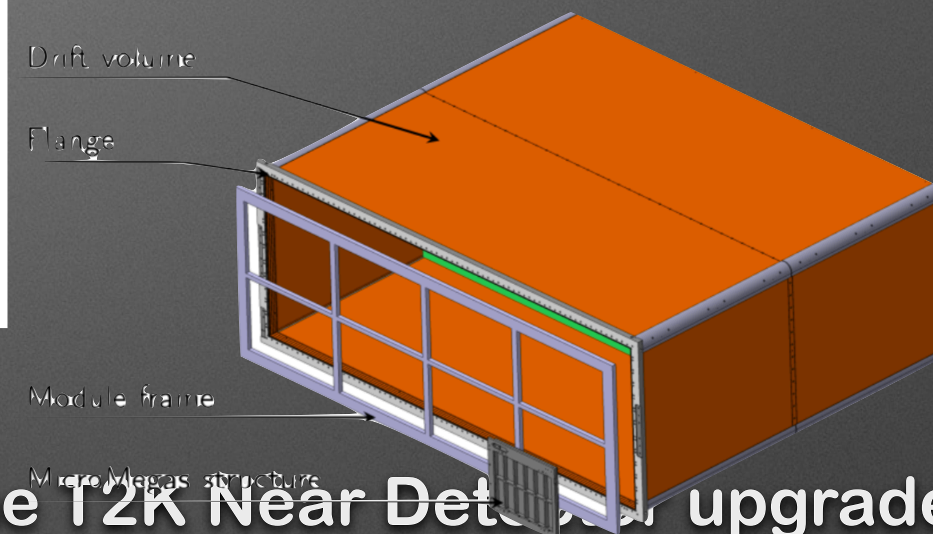


T2K 90% allowed region

Near Detector upgrade

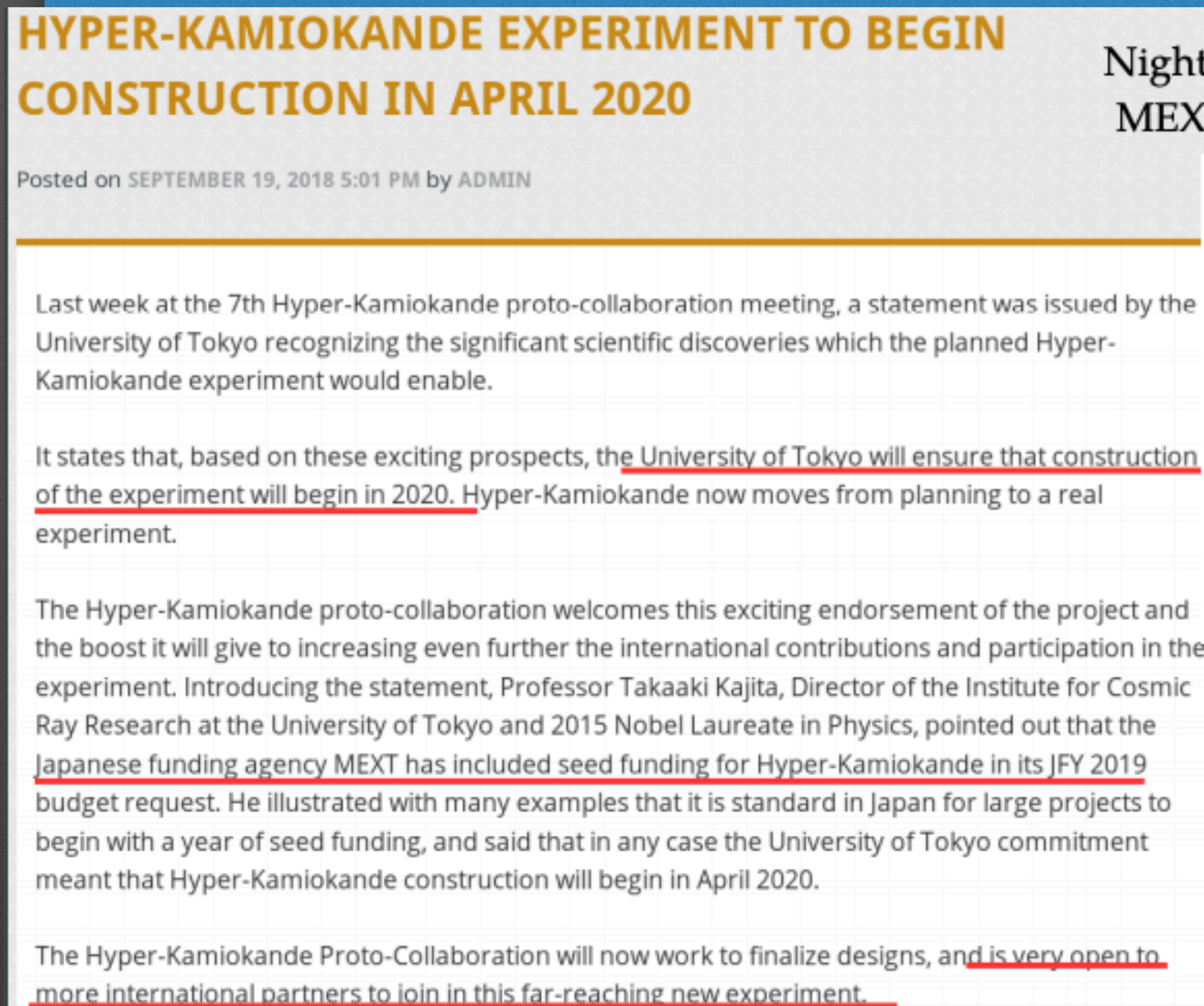






- T2K French groups heavily involved in the T2K Near Detector upgrade → to be installed in 2021
- Super-FGD (10^6 1cm^3 cubes) + horizontal TPC with resistive MicroMegas
- Expect to reduce systematics errors by ~30%
- No time to cover it today but all LBL experiments have also a large program of neutrino cross-section measurements → ND280 upgrade will contribute!

Next generation: Hyper-K



HYPER-KAMIOKANDE EXPERIMENT TO BEGIN CONSTRUCTION IN APRIL 2020

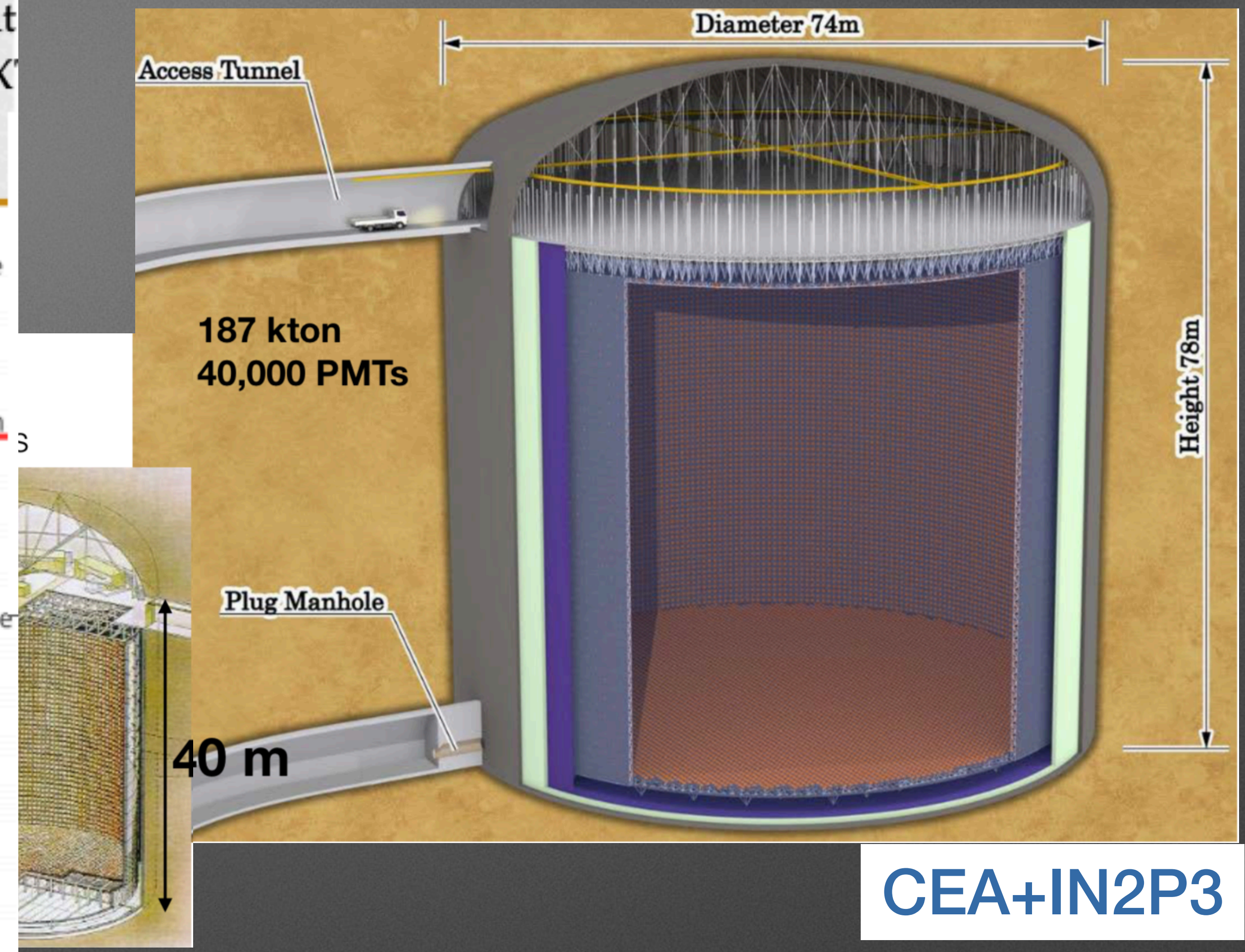
Posted on SEPTEMBER 19, 2018 5:01 PM by ADMIN

Last week at the 7th Hyper-Kamiokande proto-collaboration meeting, a statement was issued by the University of Tokyo recognizing the significant scientific discoveries which the planned Hyper-Kamiokande experiment would enable.

It states that, based on these exciting prospects, the University of Tokyo will ensure that construction of the experiment will begin in 2020. Hyper-Kamiokande now moves from planning to a real experiment.

The Hyper-Kamiokande proto-collaboration welcomes this exciting endorsement of the project and the boost it will give to increasing even further the international contributions and participation in the experiment. Introducing the statement, Professor Takaaki Kajita, Director of the Institute for Cosmic Ray Research at the University of Tokyo and 2015 Nobel Laureate in Physics, pointed out that the Japanese funding agency MEXT has included seed funding for Hyper-Kamiokande in its JFY 2019 budget request. He illustrated with many examples that it is standard in Japan for large projects to begin with a year of seed funding, and said that in any case the University of Tokyo commitment meant that Hyper-Kamiokande construction will begin in April 2020.

The Hyper-Kamiokande Proto-Collaboration will now work to finalize designs, and is very open to more international partners to join in this far-reaching new experiment.

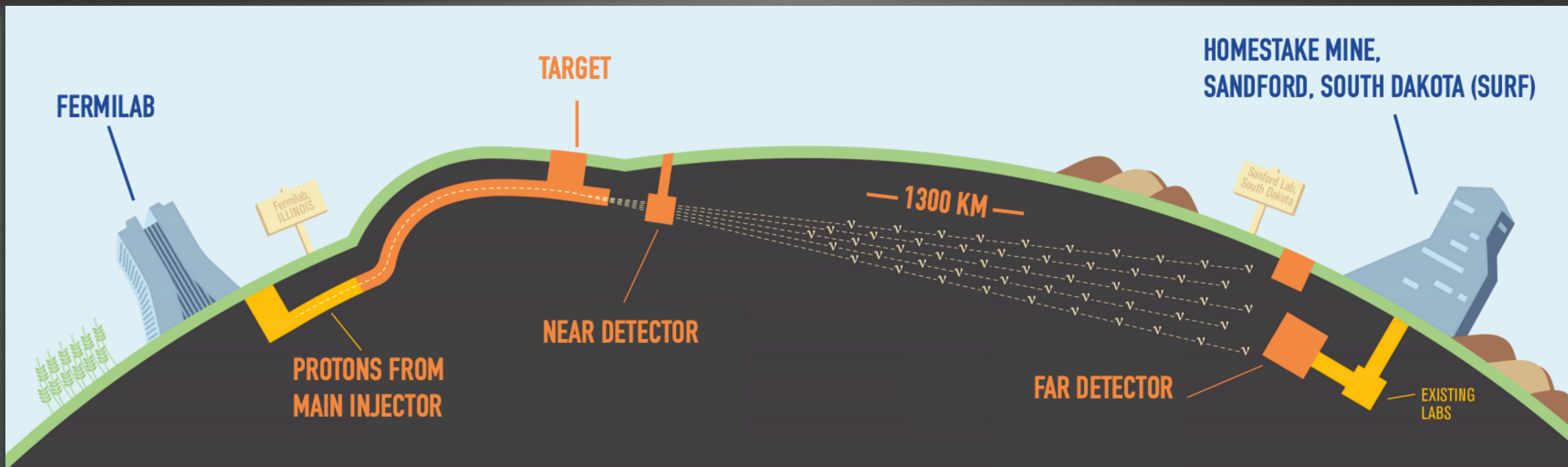


CEA+IN2P3

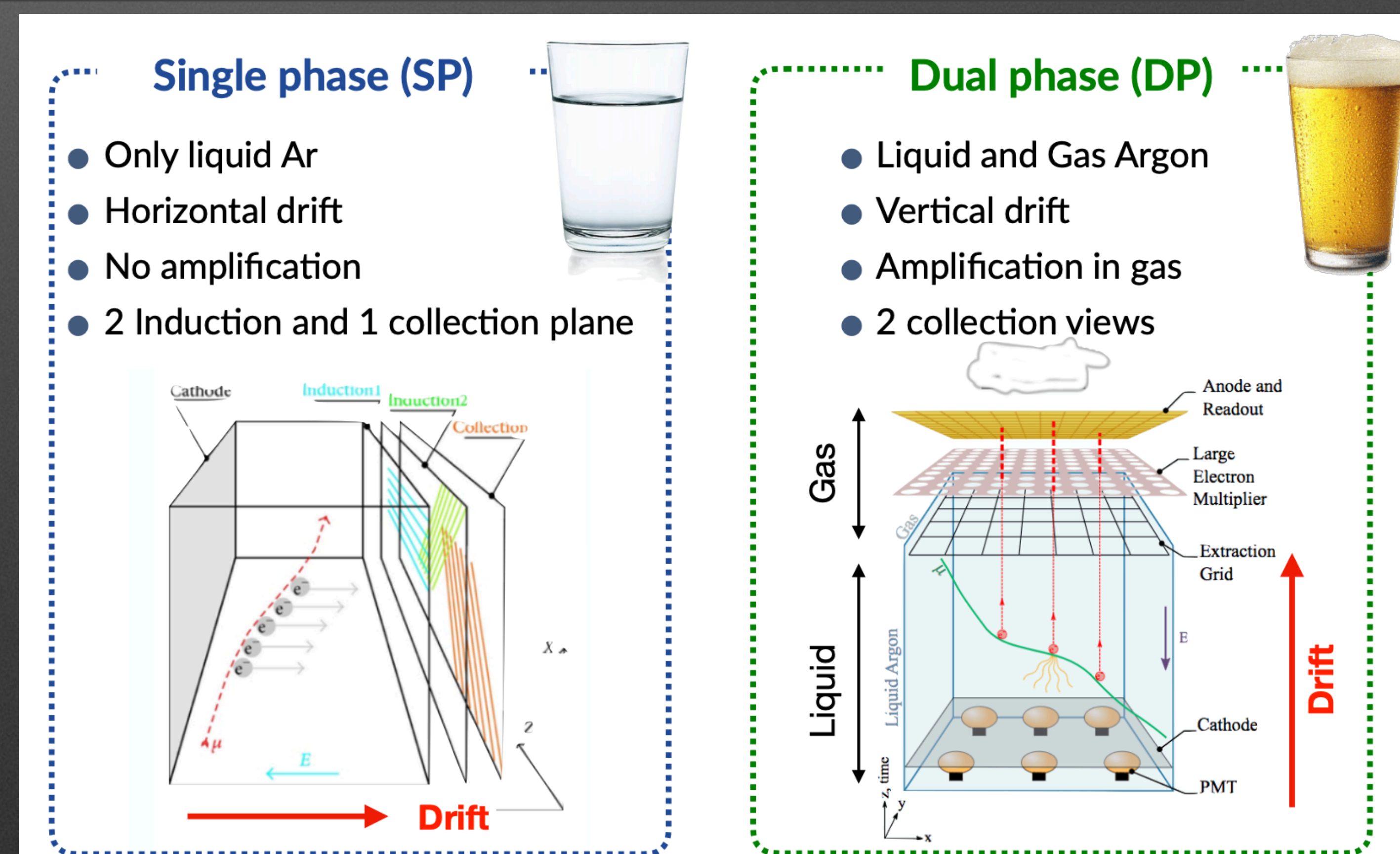
- ~10 times bigger than SK
- Upgraded beam from J-PARC (1.3 MW)
- Instrumented with 40k PMTs (R&D on-going)
- Approved to start construction in 2020, first data in 2026

Next generation: DUNE

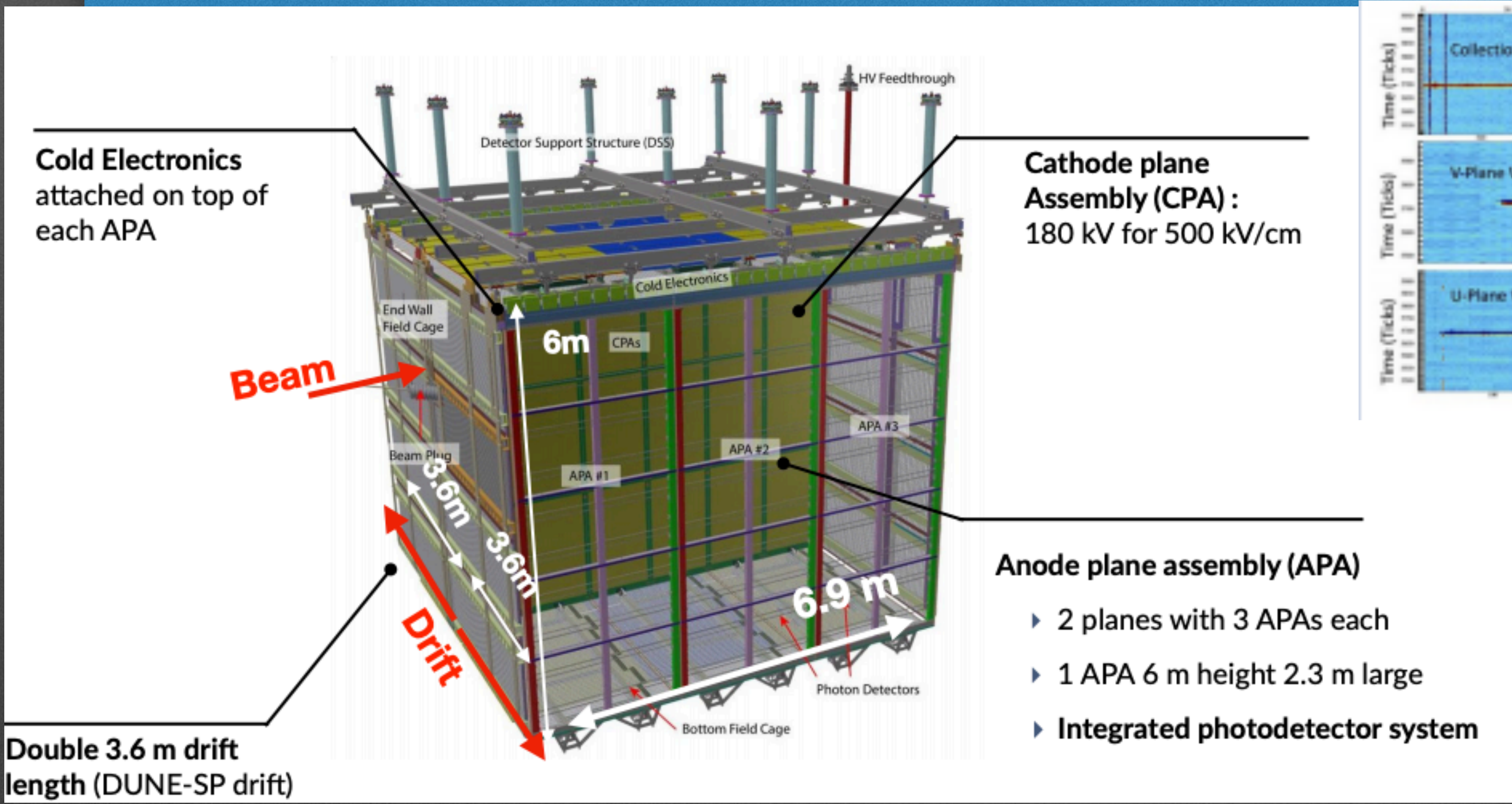
CEA+IN2P3

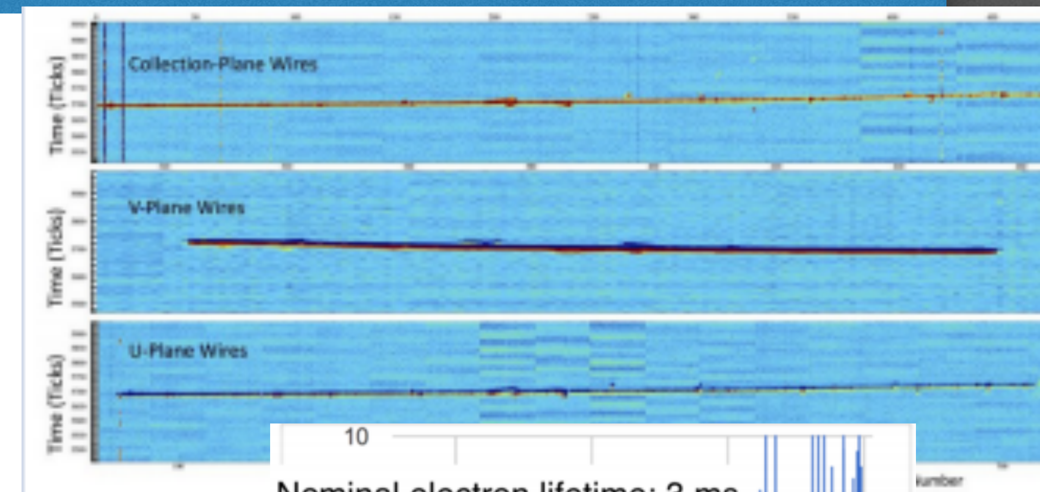


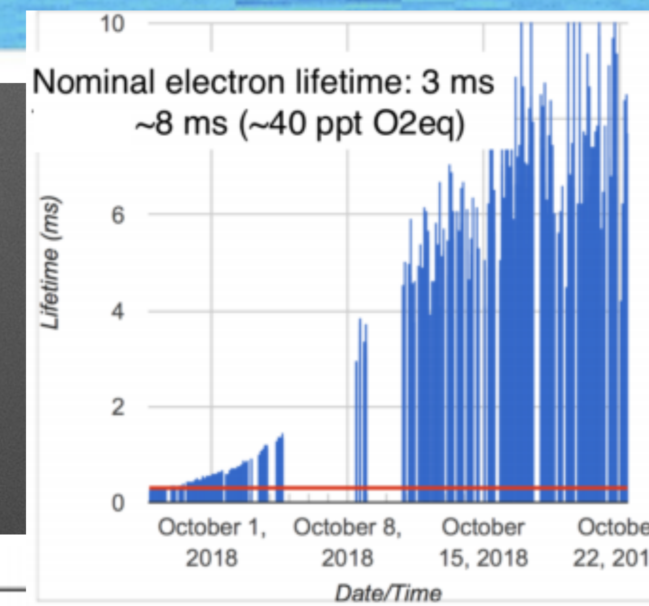
- ν beam produced at Fermilab
- Far detector at Homestake → 4*10 kton LAr TPCs
- Possible to have single and dual phases TPCs
- Expect to begin in 2026
- ~600 ton prototypes for SP and DP being built at CERN → TDR expected in 2019

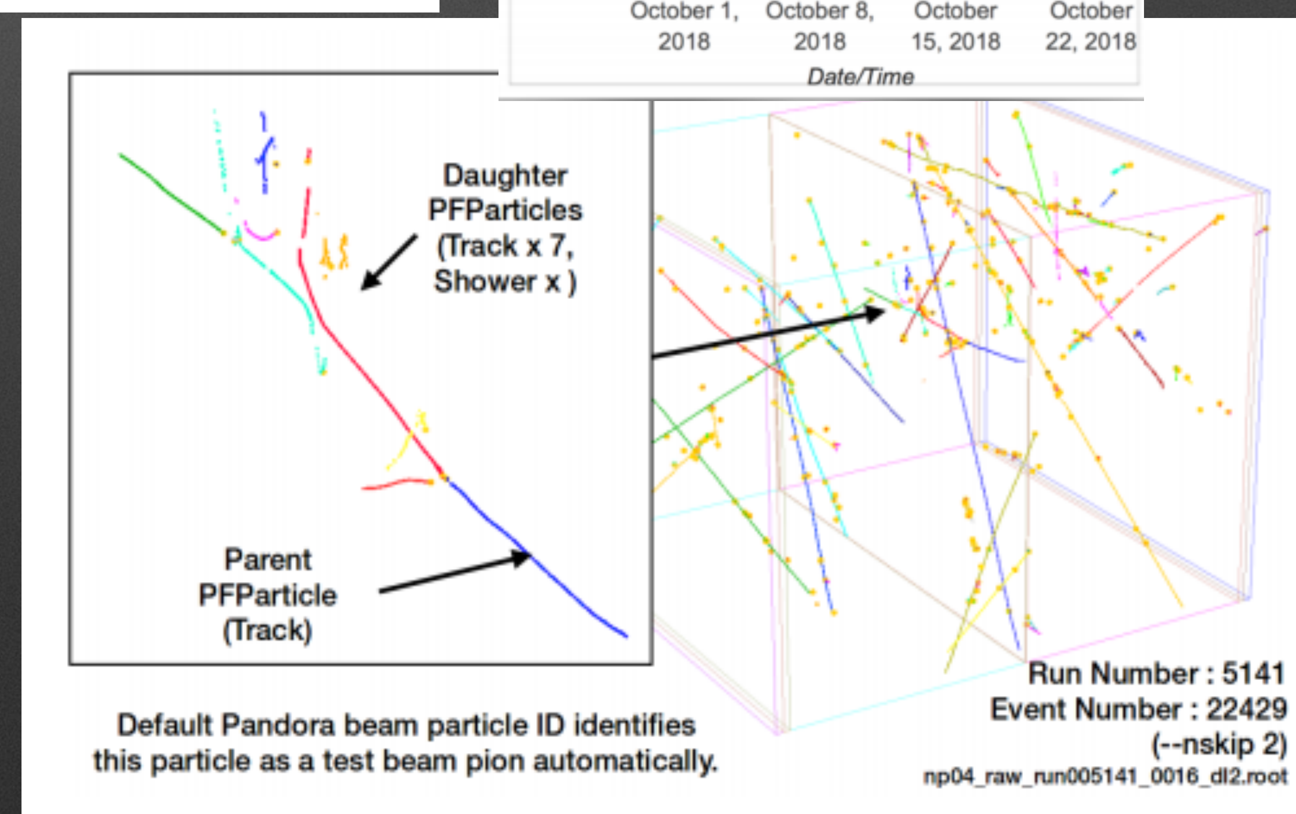


ProtoDUNE @ CERN









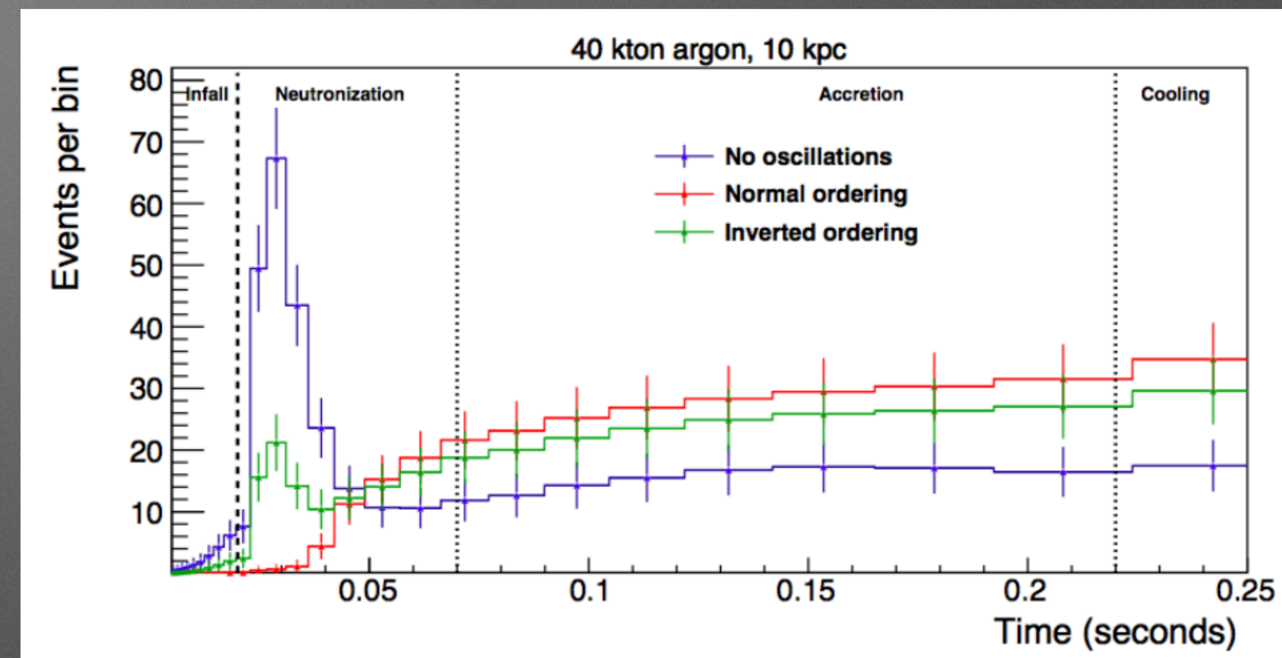
Default Pandora beam particle ID identifies this particle as a test beam pion automatically.

- SP prototype is already taking data at CERN
- DP prototype being assembled → will start data taking beginning fo 2019

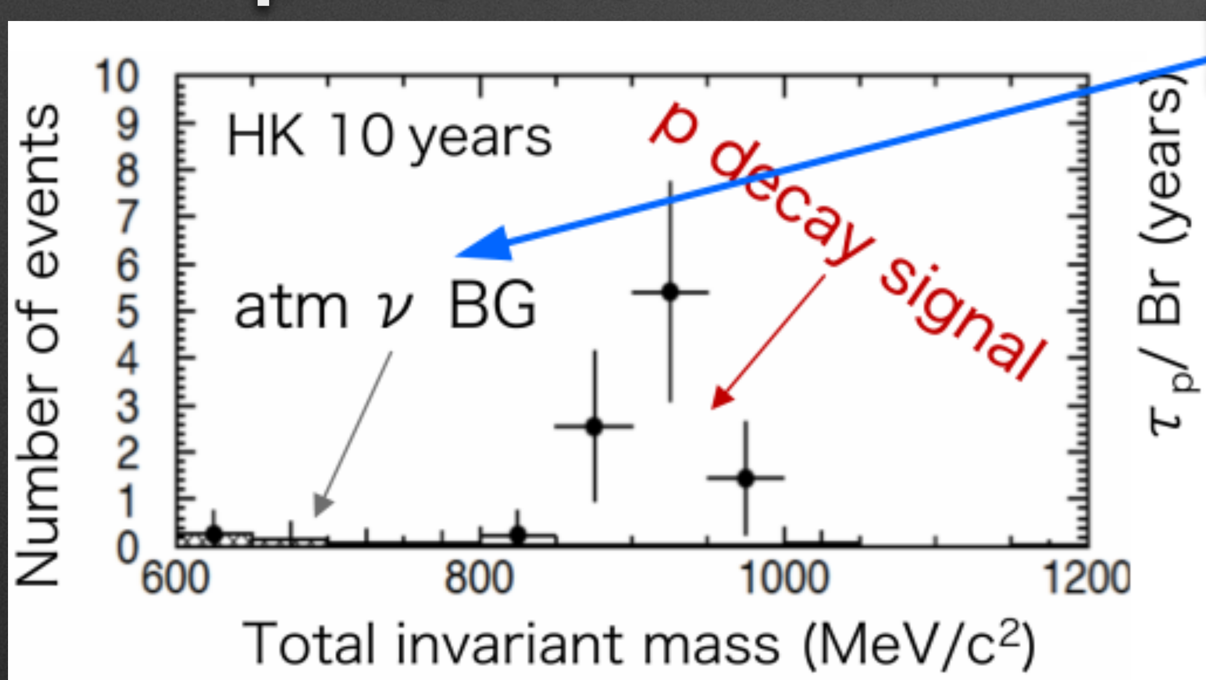
Non-PMNS physics goals

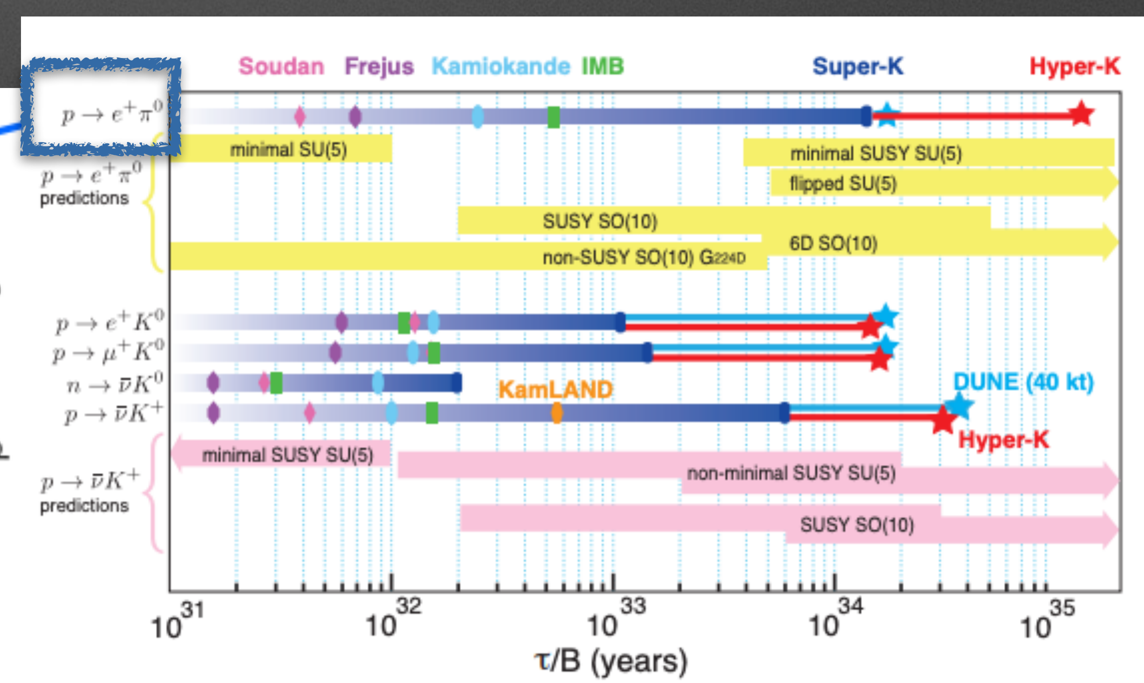
- DUNE and Hyper-K will have unprecedented sensitivities to proton decay, SN neutrinos, solar neutrinos, …

ν from SuperNovae in DUNE



$p \to e^+ + \pi^0$ in HK

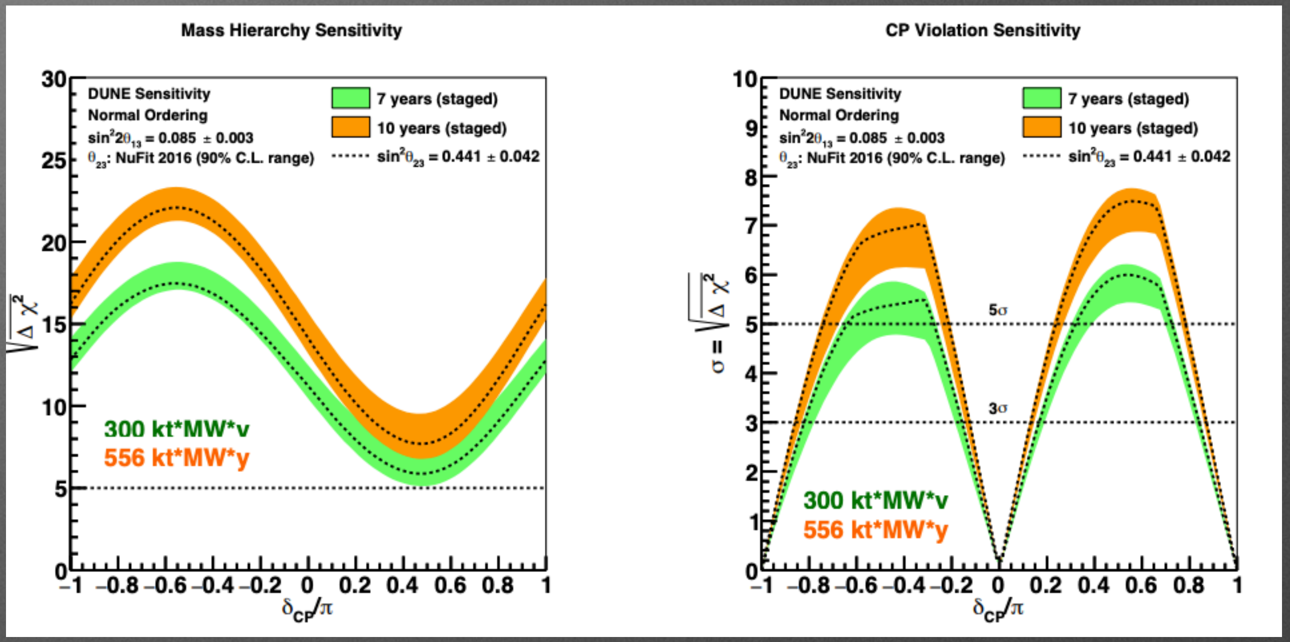


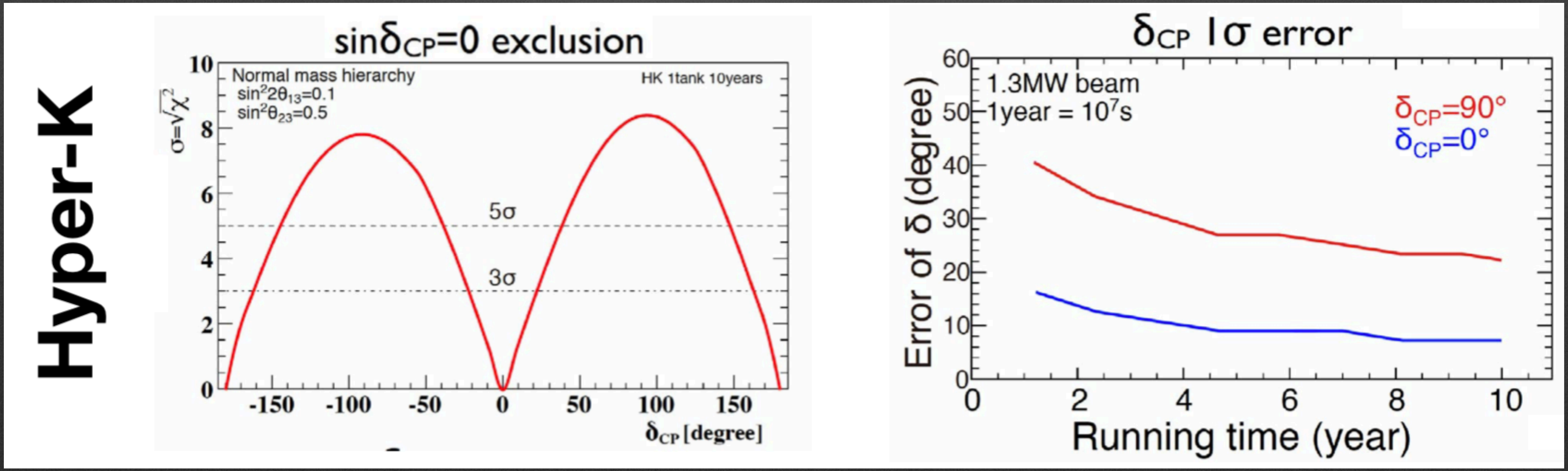


CP violation and mass ordering

- Thanks to the longer baseline DUNE will have a better sensitivity to the Mass Ordering (>5σ)

- Comparable sensitivities to CP violation





Prospects for mass ordering (<2025)

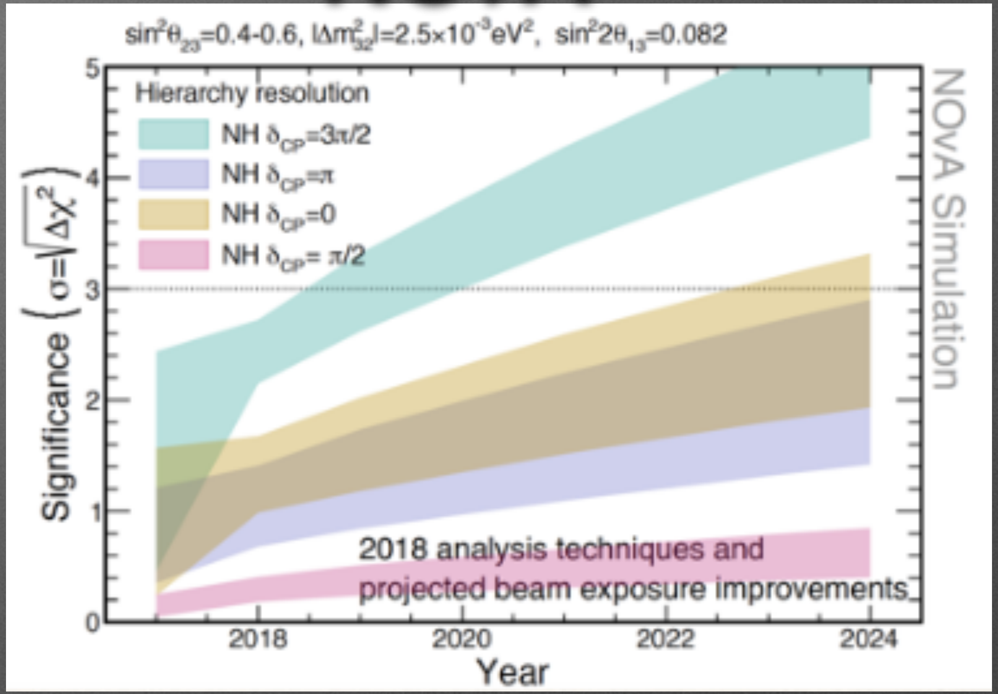
While CP violation can only be determined with LBL experiments different techniques can be used for determining the mass ordering

NOνA 3σ sensitivity by 2020 if $\delta_{CP}\sim-\pi/2$ with LBL experiments

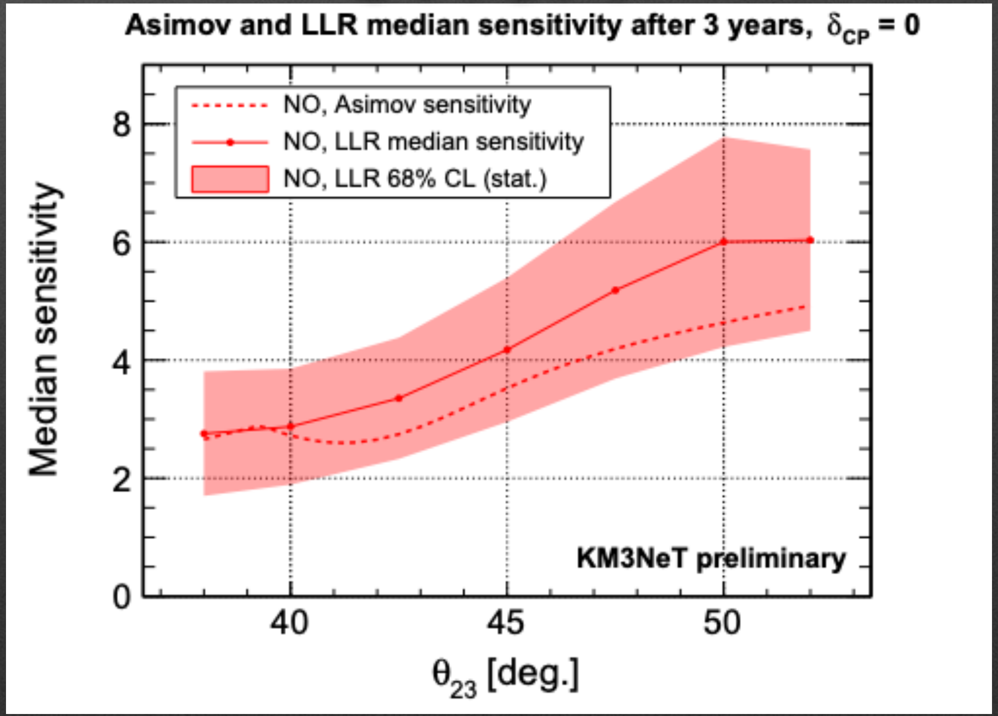
ORCA and PINGU >3σ sensitivity to mass ordering in ~2024 if $\theta_{23}>45°$ with atmospheric neutrinos

JUNO will also have 3-4 σ sensitivity to MO by 2024 (depending on the achieved energy resolution)

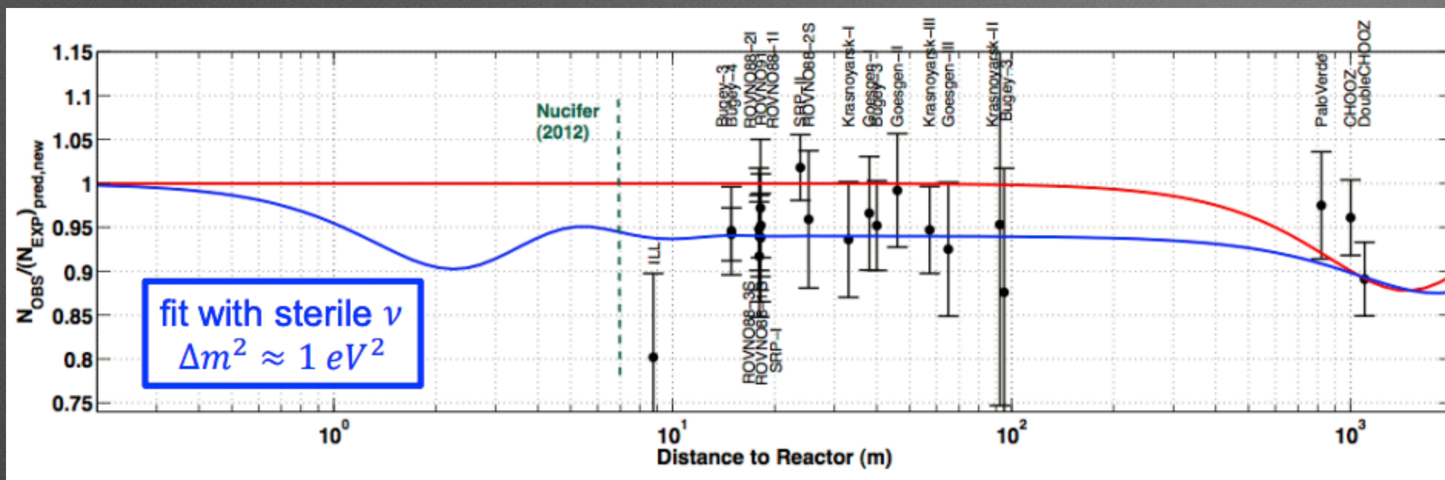
NOνA



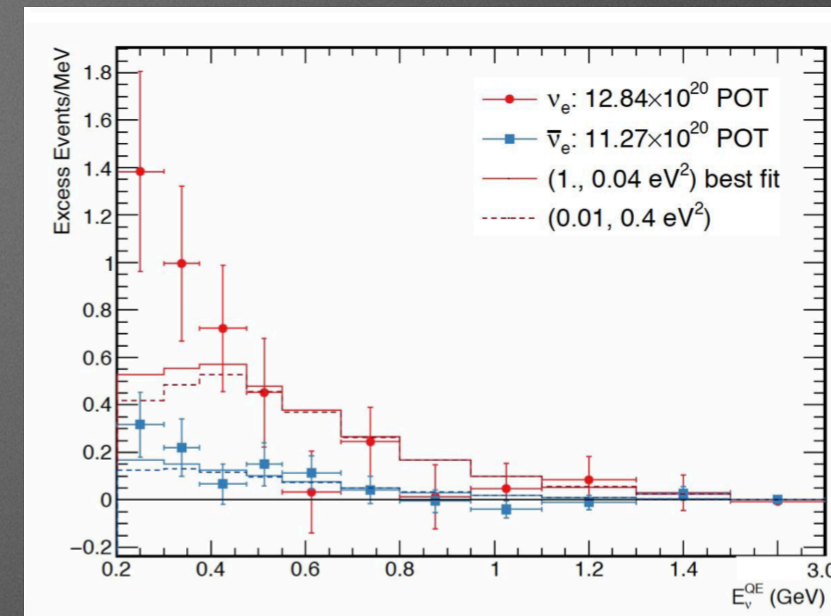
ORCA

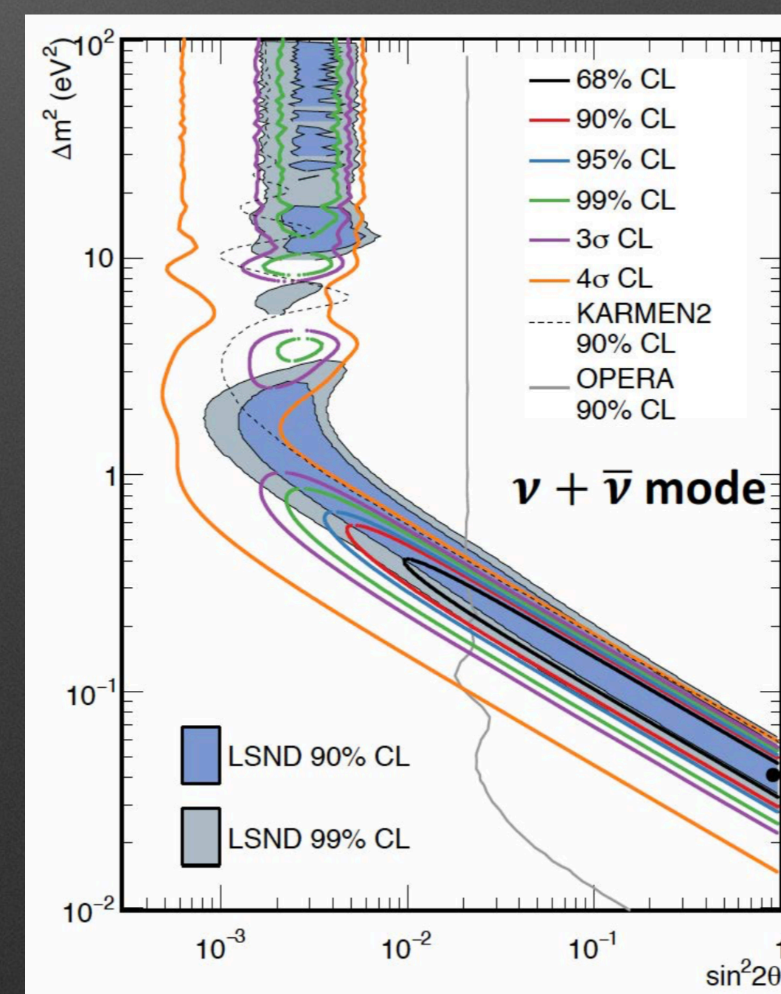


Sterile neutrinos



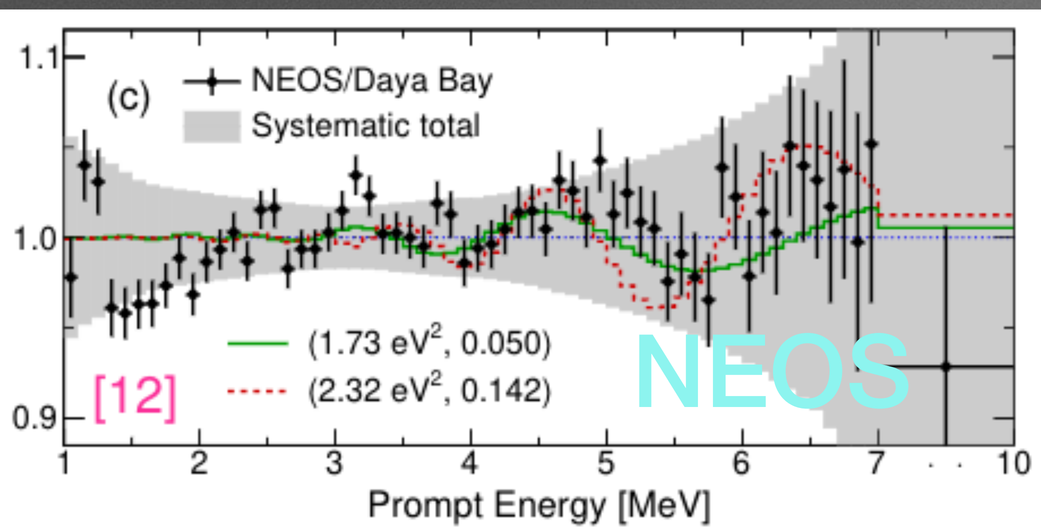
G. Mention et al.
Phys.Rev. D83 (2011) 073006

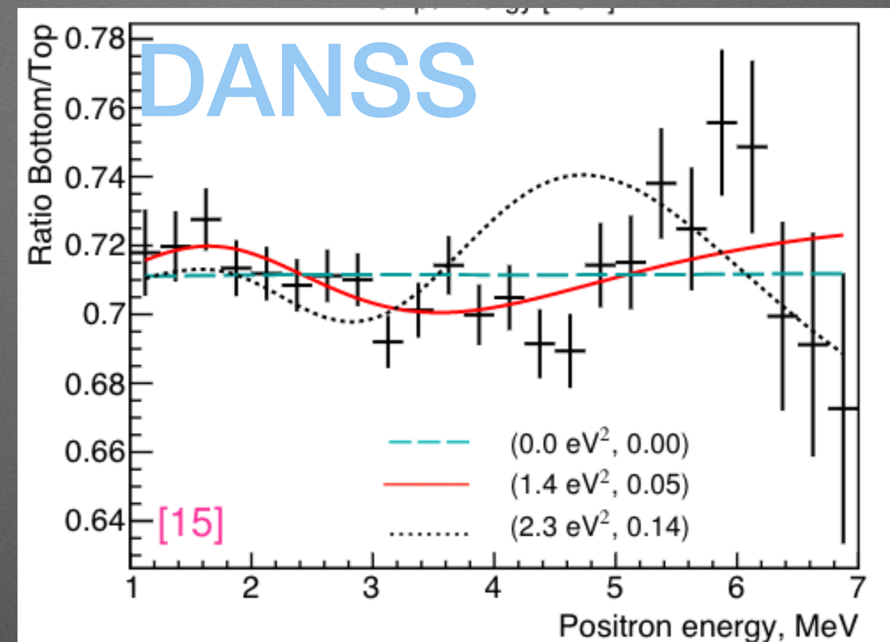


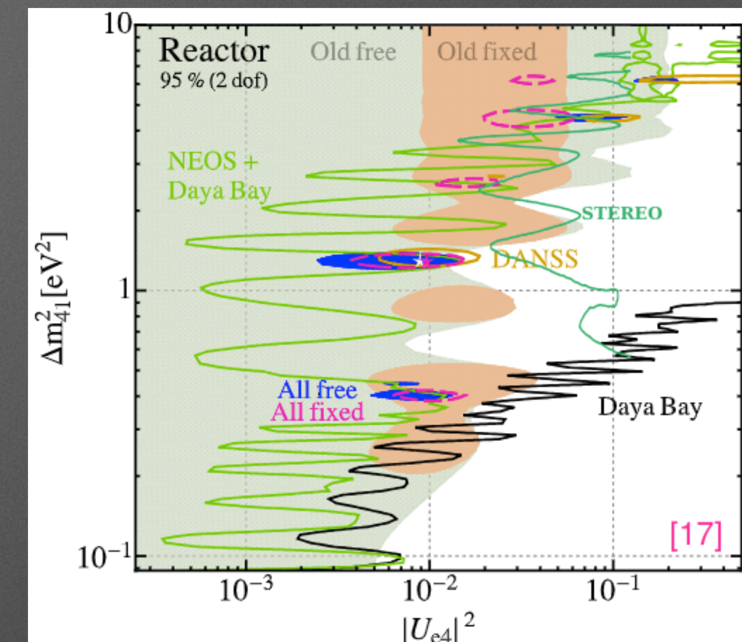


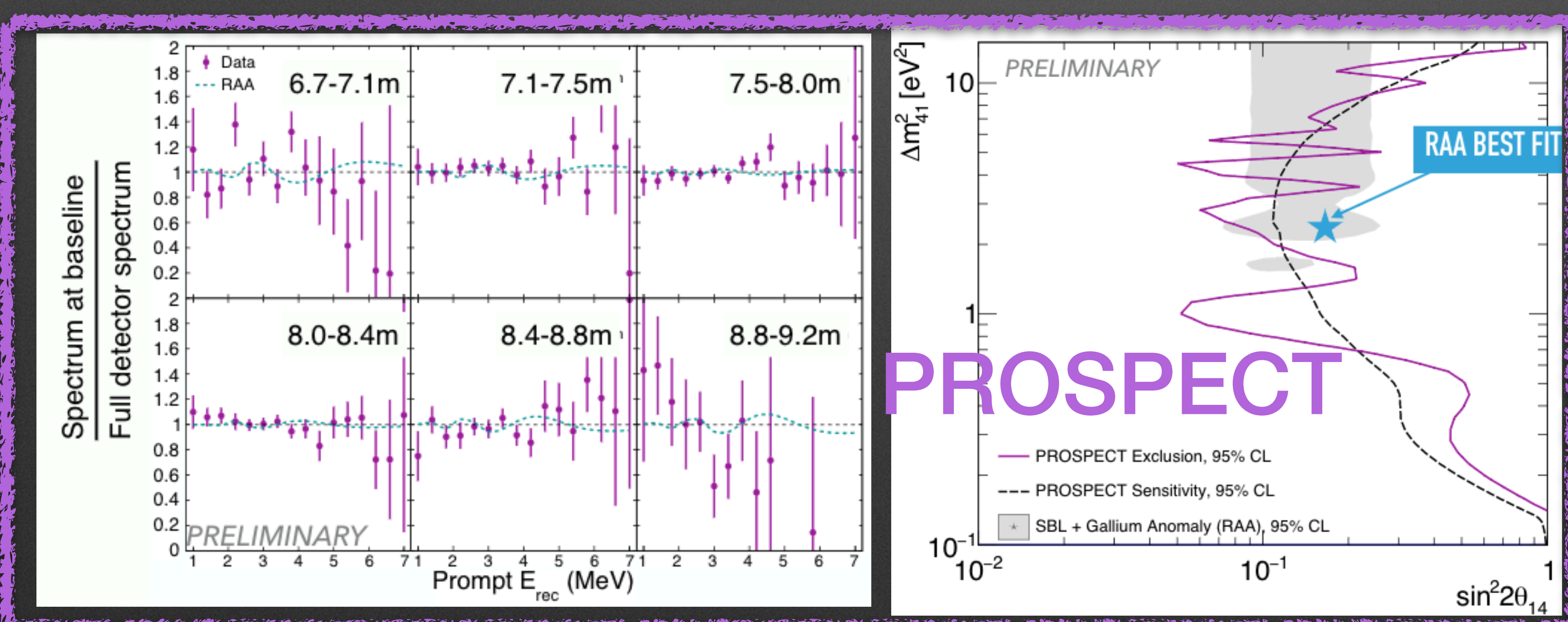
- 2 “anomalies” point to the existence of additional neutrino families (sterile neutrinos) with masses around ~1 eV
- Deficit of $\overline{\nu}_e$ flux from reactors
- ν_e and $\overline{\nu}_e$ excesses in short baseline experiment (LSND and MiniBooNE)

Reactor anomaly



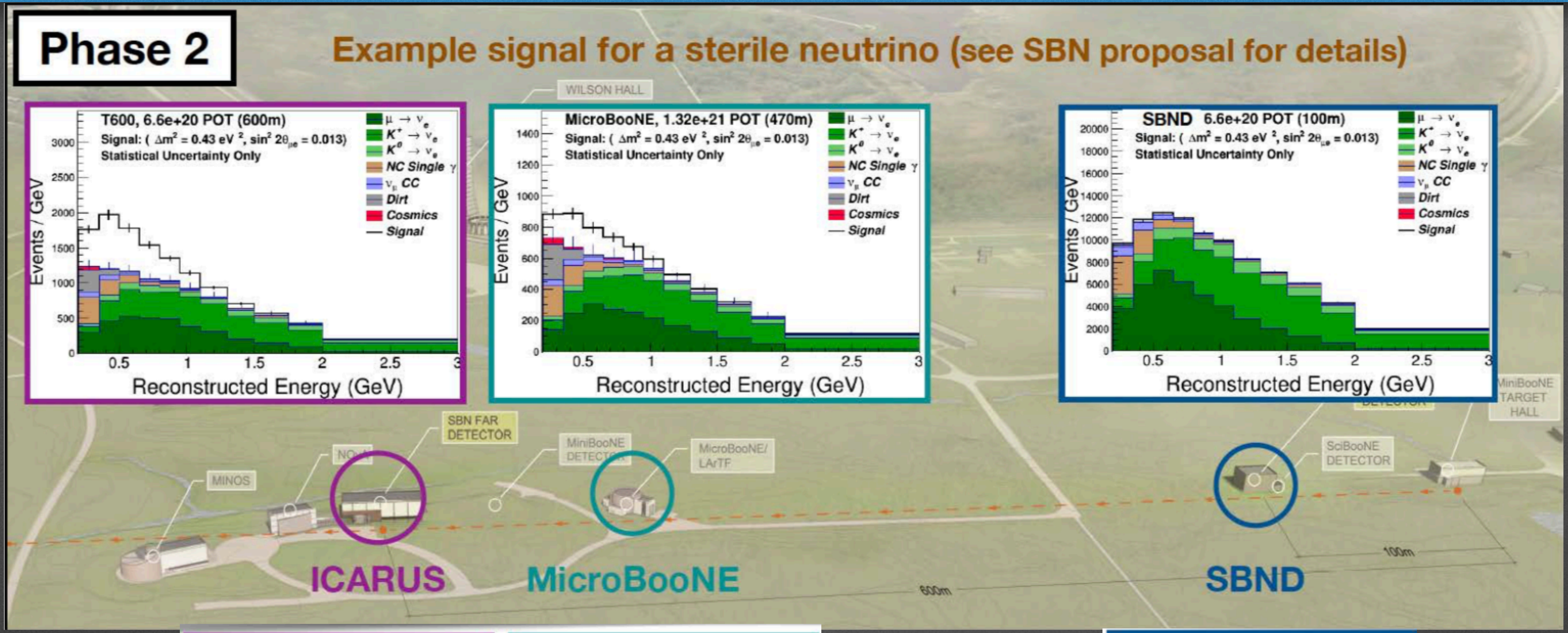


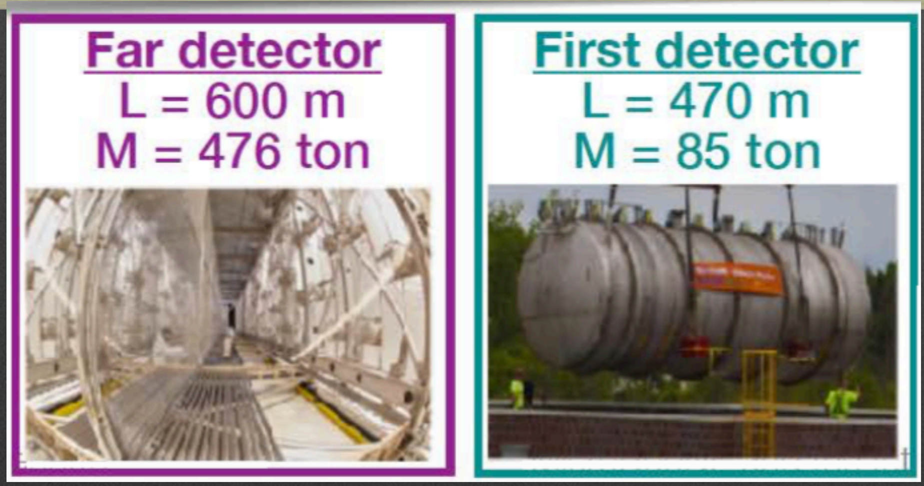


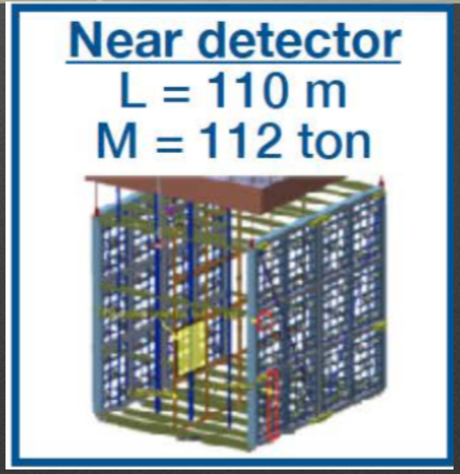


- Several experiments testing the reactor anomaly
- Best-fit point already excluded
- French groups involved in SOLID and STEREO
- Expect new results soon

Short baseline program at FNAL







- 3 LAr detectors at different baselines
- 3-5σ resolution of the LSND/MiniBooNE anomalies in 5 years

Summary

- In the last 20 years there have been huge progresses in neutrino oscillations physics
- The next 10 years will answer many of the remaining outstanding questions with a well defined accelerator-based program (T2K-II → Hyper-K and NOνA → DUNE)
  - Is CP violated?
  - Which is the mass ordering?
  - Is θ_{23} maximal?
  - Sterile neutrinos?
- The measurement of the neutrino mass and their nature (Dirac/ Majorana) will also actively pursued in the coming years
- Very interesting physics in front of us!