Overview
Neutrino Experiments

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IBS

2019.06.03

WIN 2019 @Bari

Why ν ?

1. Simple

2. Mysterious

- Key to unveil secret of our universe ?

Why matter dominant in our universe now ?

- Dirac or Majorana
- Absolute mass ?

3. Surprises

- Evidence of 4^{th} family of ν
- Neutrino flux deficit
- ν spectral shape anomaly (5MeV excess)

To unveil the mysteries, and
To understand the surprises
We need bigger detectors !

→ Challenging technically
& in budget

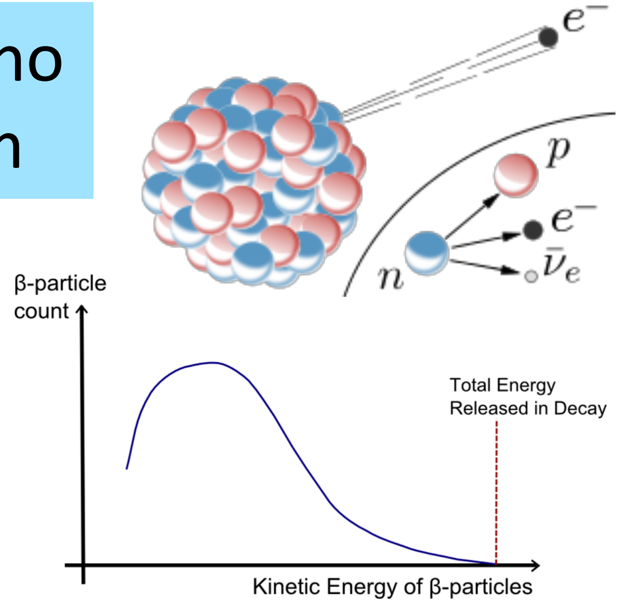
We have known neutrinos for ~ 90 years.
We learned a lot about neutrinos,
but still there are very important questions
to be answered.

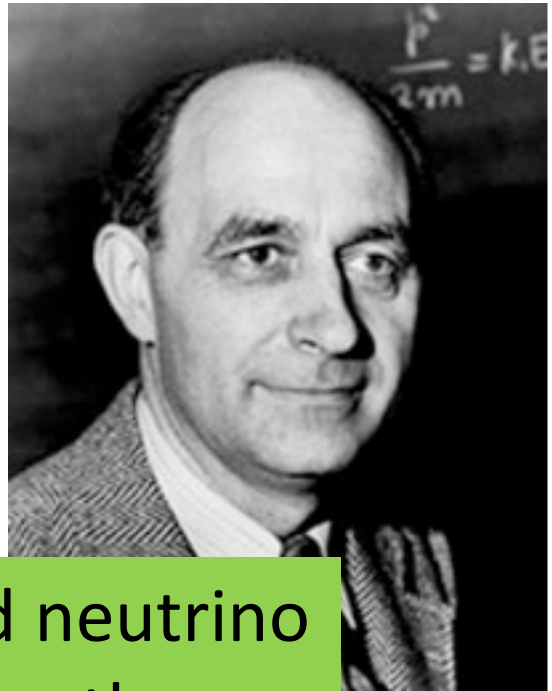
In this talk,

Neutrino oscillations	-- Oscillation parameters -- CPV, MO
4^{th} family of neutrinos	-- Several smoking guns
Dirac or Majorana	-- $0\nu\beta\beta$
Absolute ν mass	

****I do apologize to the experiments not covered here due to lack of time.**

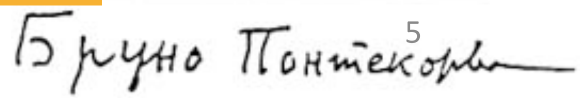
1930 Pauli postulated neutrino
to explain beta decay problem





1933 Fermi baptized neutrino
In his weak interaction theory

1957 Pontecorvo suggested
Neutrino mass and oscillation

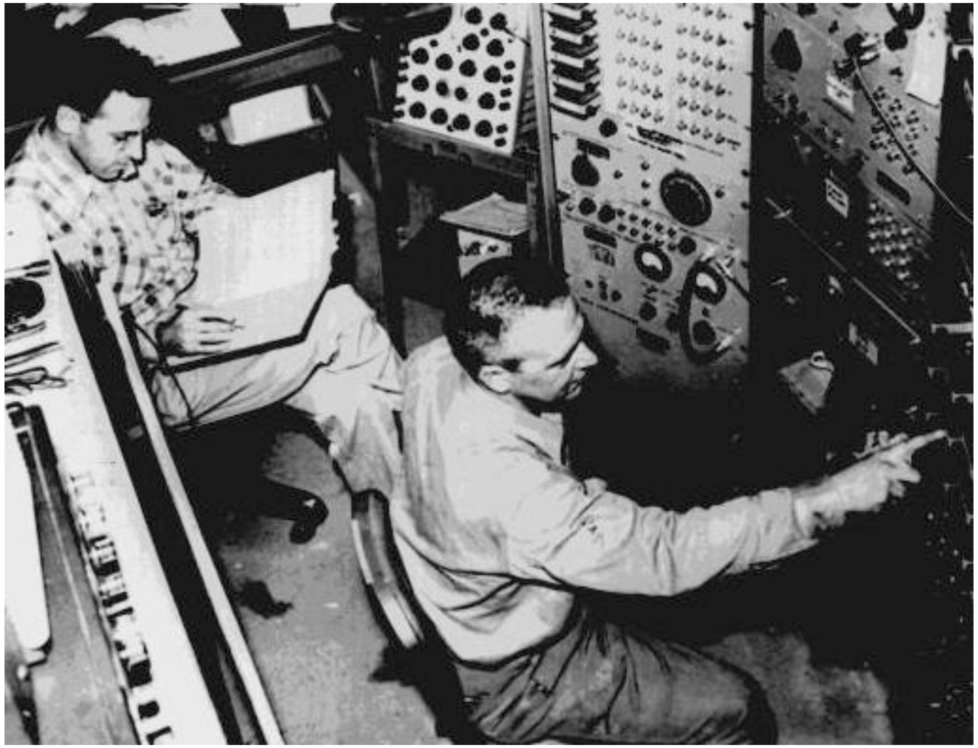


First discovery of neutrino is from reactor neutrinos !

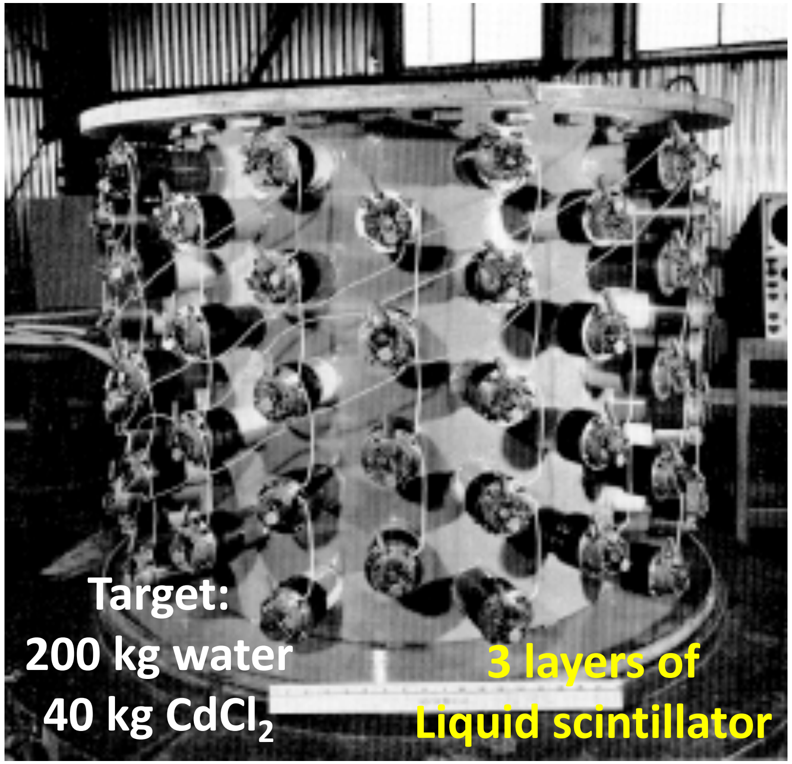
Nobel Prize in 1995

in **1956** @Savannah river, S. Carolina
By Reines and Cowan

"Project Poltergeist"



Liquid scintillator



$2\text{x}10^{20}\ \overline{\nu}_e/GW_{th}$

Weak Eigen state

Mass Eigen state

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

PMNS matrix in 1962

- Pontecorvo
- Maki
- Nakagawa
- Sakata

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

Atmospheric: $\theta_{23} \approx 45°$

"CP" sector: $\theta_{13} = 9°$

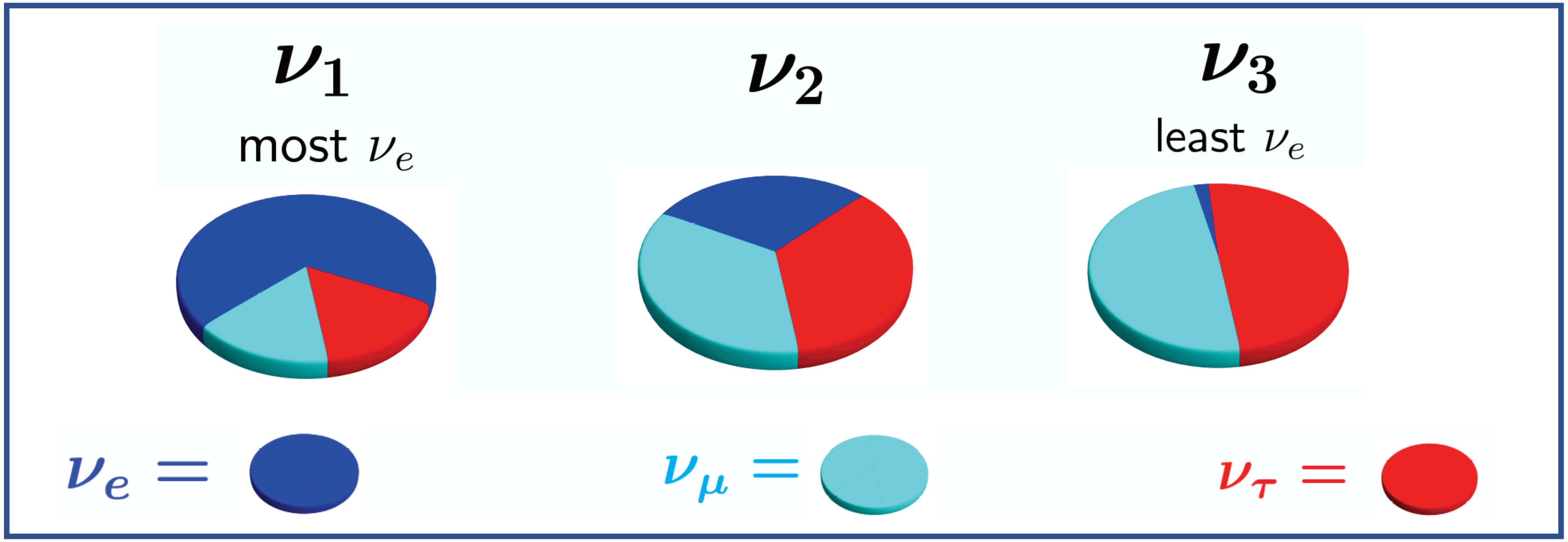
Solar: $\theta_{12} \approx 34°$

Majorana

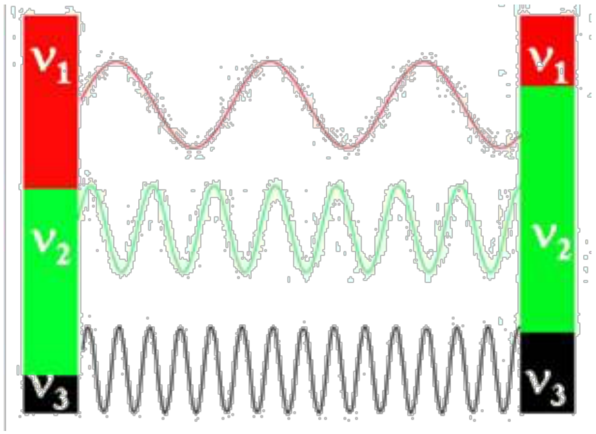
$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ eV^2$

$\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ eV^2$

Mixing angles (θ_{12}, θ_{23}, θ_{13})
determine flavor contents of the mass eigen-state.



$$|\nu_e\rangle =$$



$$= c_1|\nu_e\rangle + c_2|\nu_\mu\rangle + c_3|\nu_\tau\rangle$$

Neutrino Oscillation Milestones

Neutrino has mass & oscillation

1957
B. Pontecorvo

Atmos. Neutrino Oscillation

θ_{23}

T. Kajita

~45º (1998)
Super-K; K2K

2015 Nobel Prize

Solar Neutrino Flavor Conversion

(arXiv:1609.02386)

θ_{12}

A. McDonald

34º (2001)
SNO, Super-K;
KamLAND

Reactor Neutrino Oscillation

θ_{13}

9º (2012)
Daya Bay, RENO
Double Chooz, T2K

❑ 3ν oscillation paradigm:

→ **6 oscillation parameters**

Known: $|\Delta m^2_{32}|$ θ_{23} Δm^2_{21} θ_{12} θ_{13} → need precise measurements

Unknown: δ_{CP}, ν mass ordering → need discoveries

Current status of precision

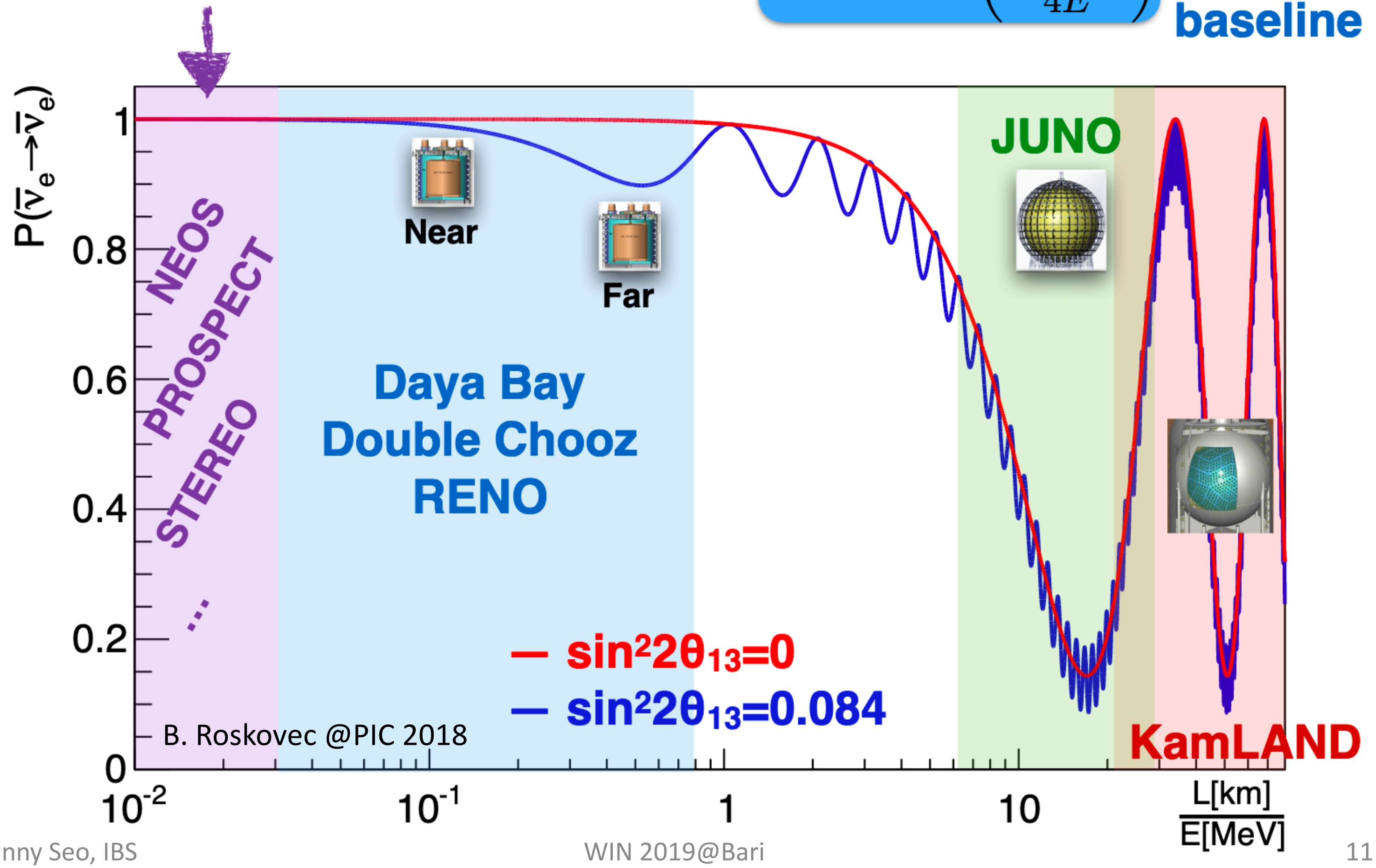
	Δm^2_{21}	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%

Reactor ν Oscillation (3 ν)

Two modes of oscillations: $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E}\right)$ **Medium baseline**

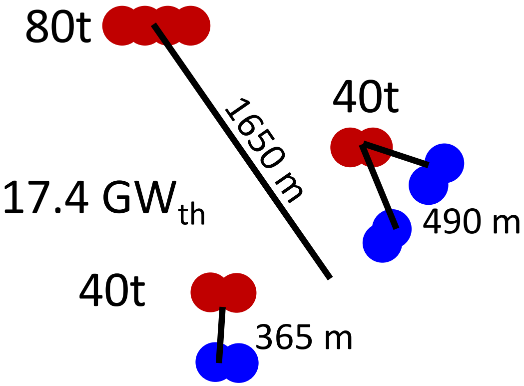
$- \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{ee} L}{4E}\right)$ **Short baseline**

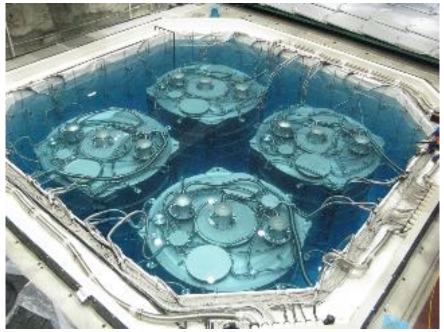
Is there 3rd mode?!?



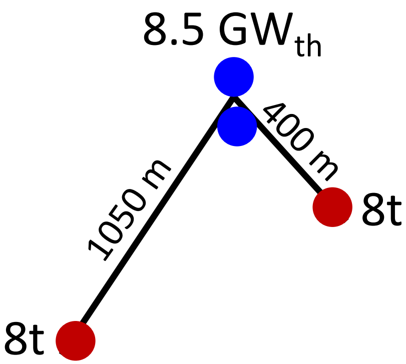
Daya Bay, Double Chooz, RENO for θ_{13}

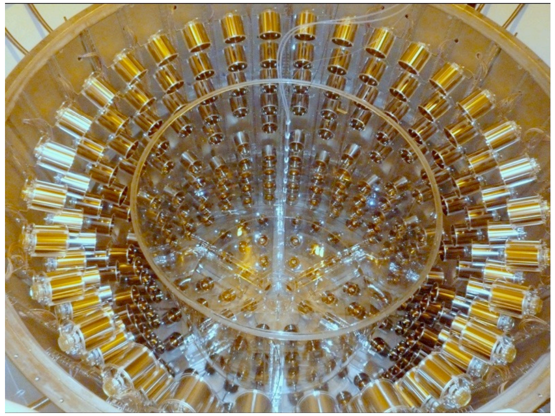
Daya Bay



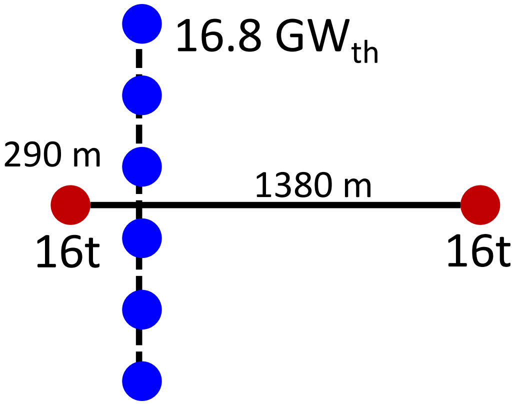


Double Chooz

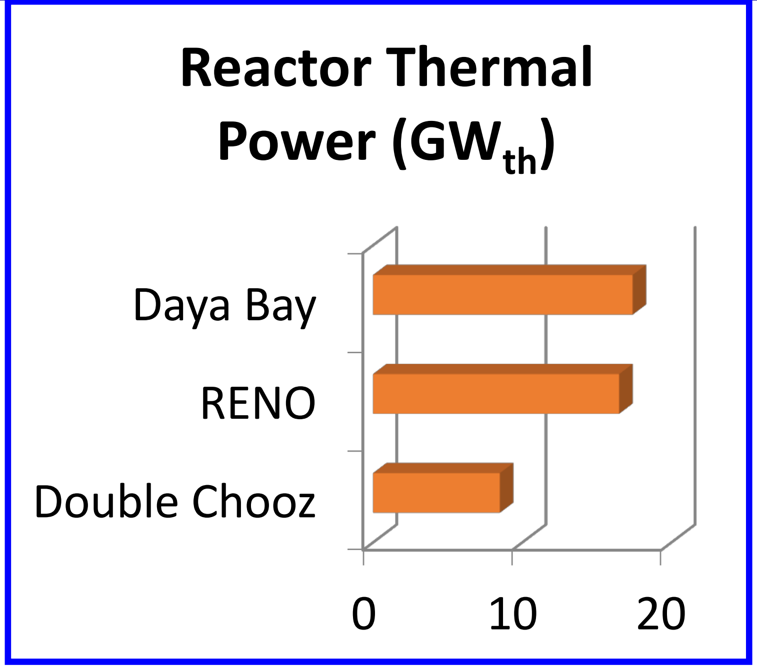


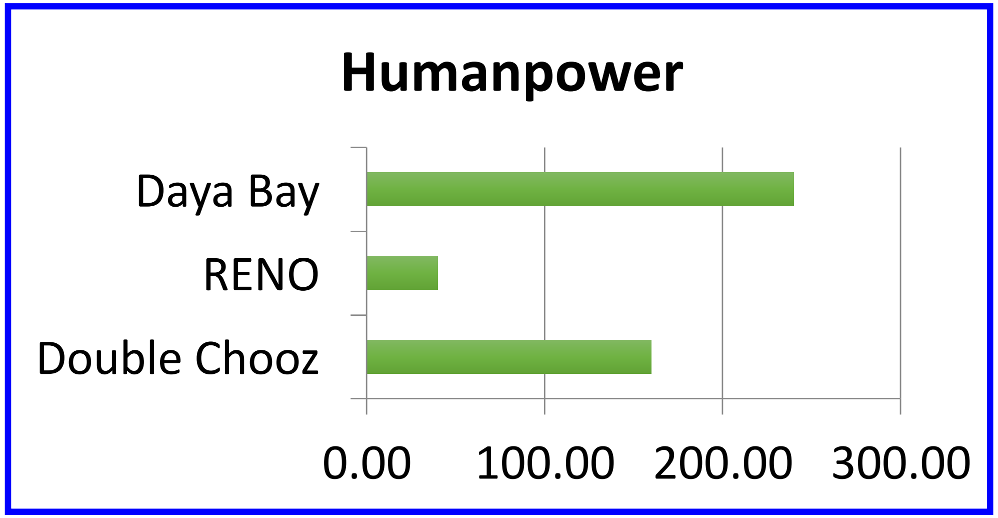


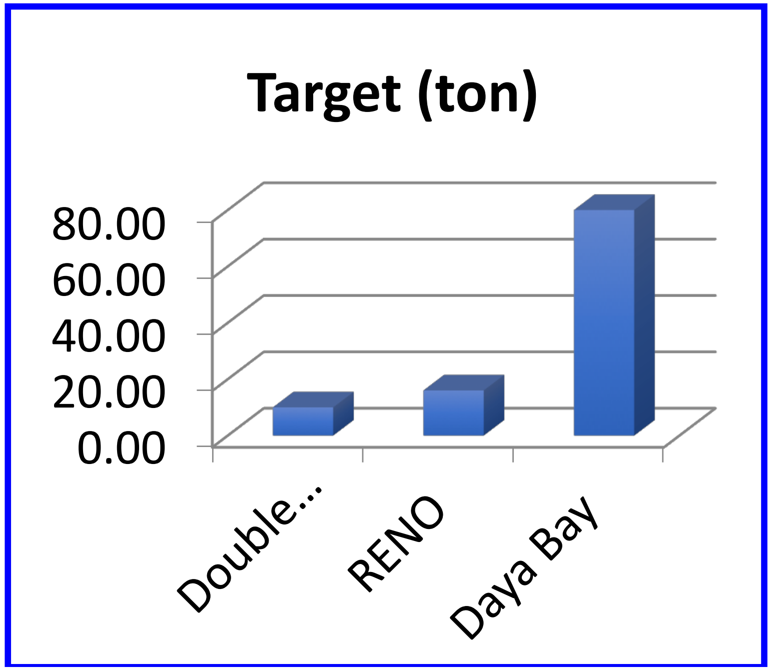
RENO

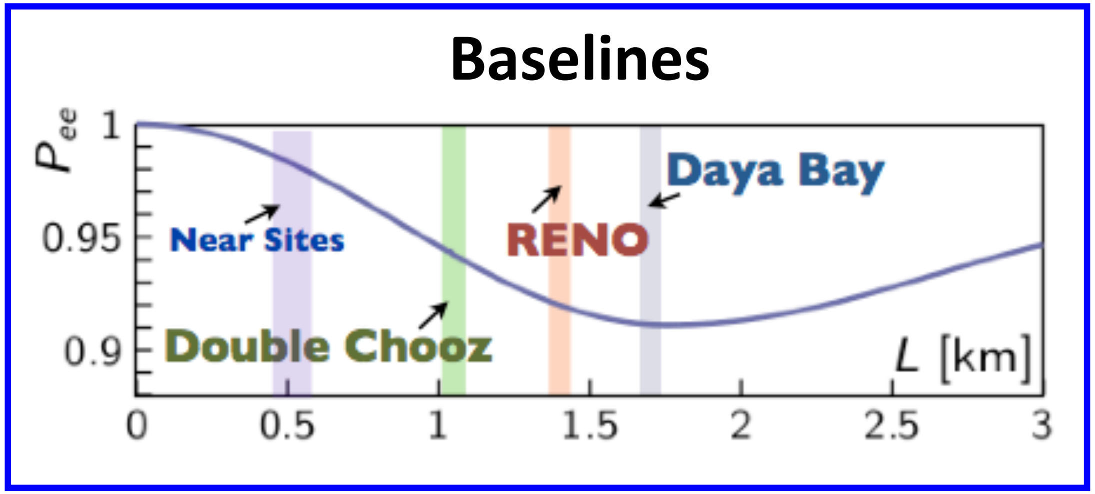


Comparisons

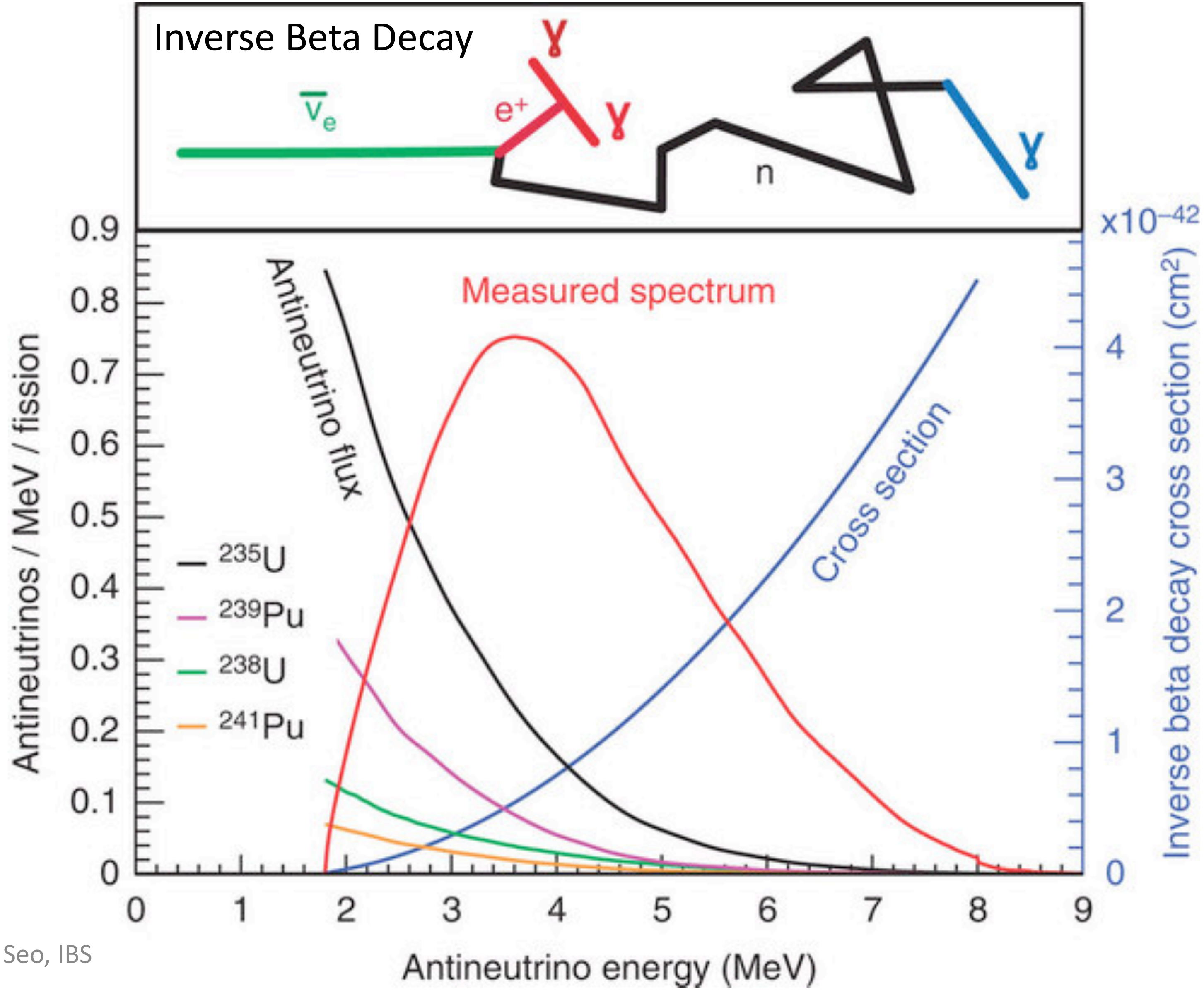








> 99.9% reactor anti-neutrinos are produced from 4 isotopes: ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu

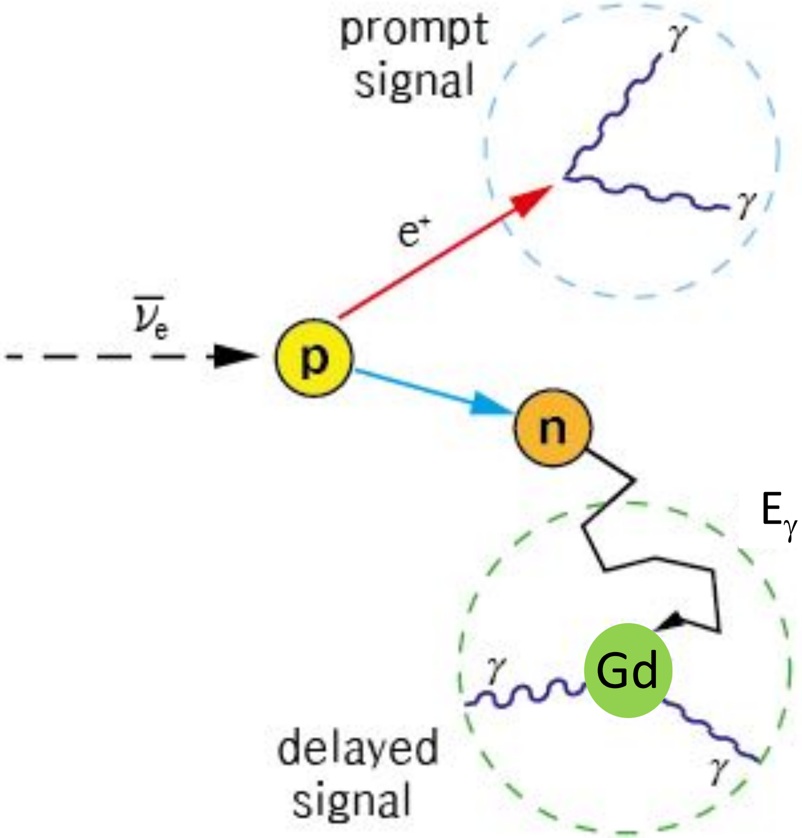


Detection Principle of Reactor Neutrinos

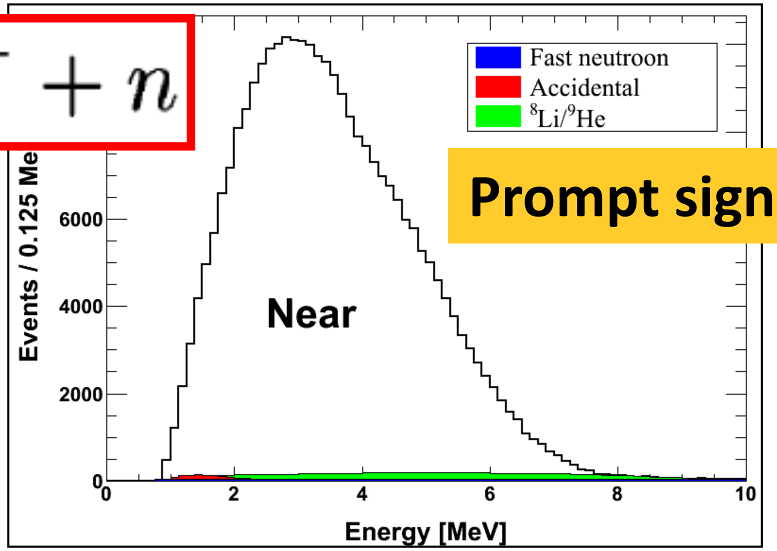
IBD process

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

(E_ν > 1.8 MeV)



E_γ = 8MeV



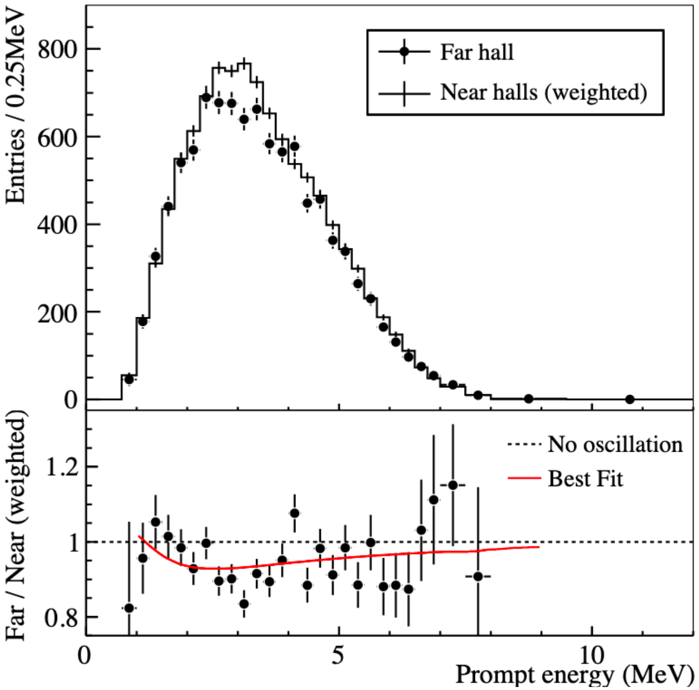
Prompt signal

E_p = 1~10 MeV

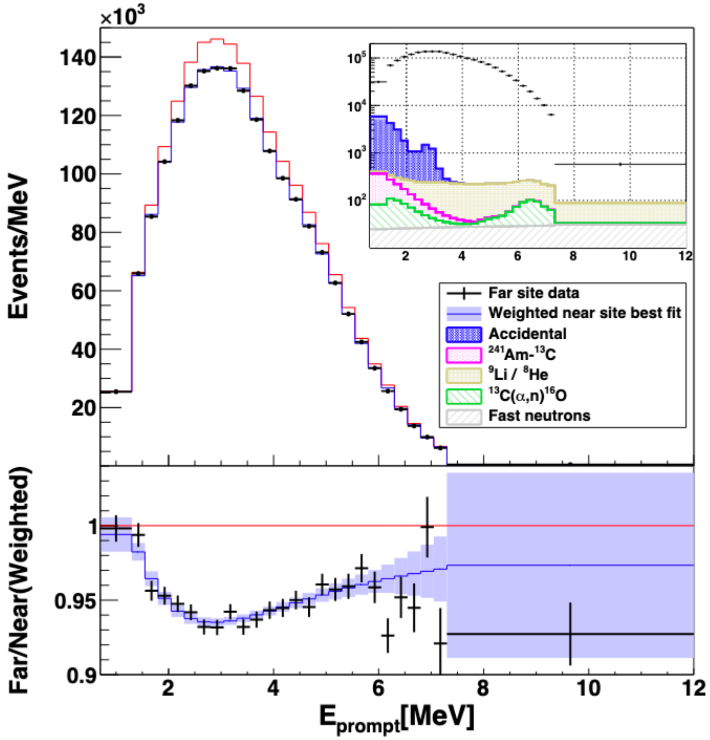
Delayed signal

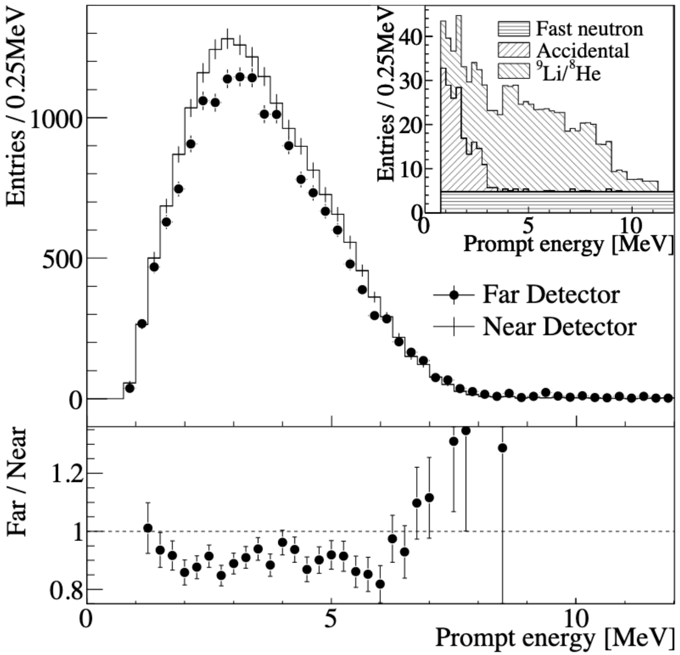
n-Gd	n-H
~30 μs	~200 μs
~8 MeV	~2.2 MeV

IBD Prompt Spectrum 2012 vs 2018

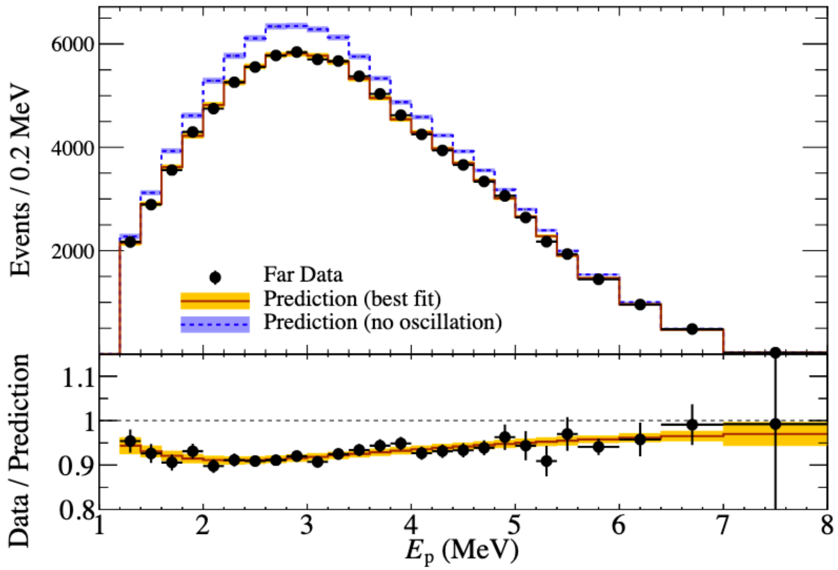


Daya Bay





RENO



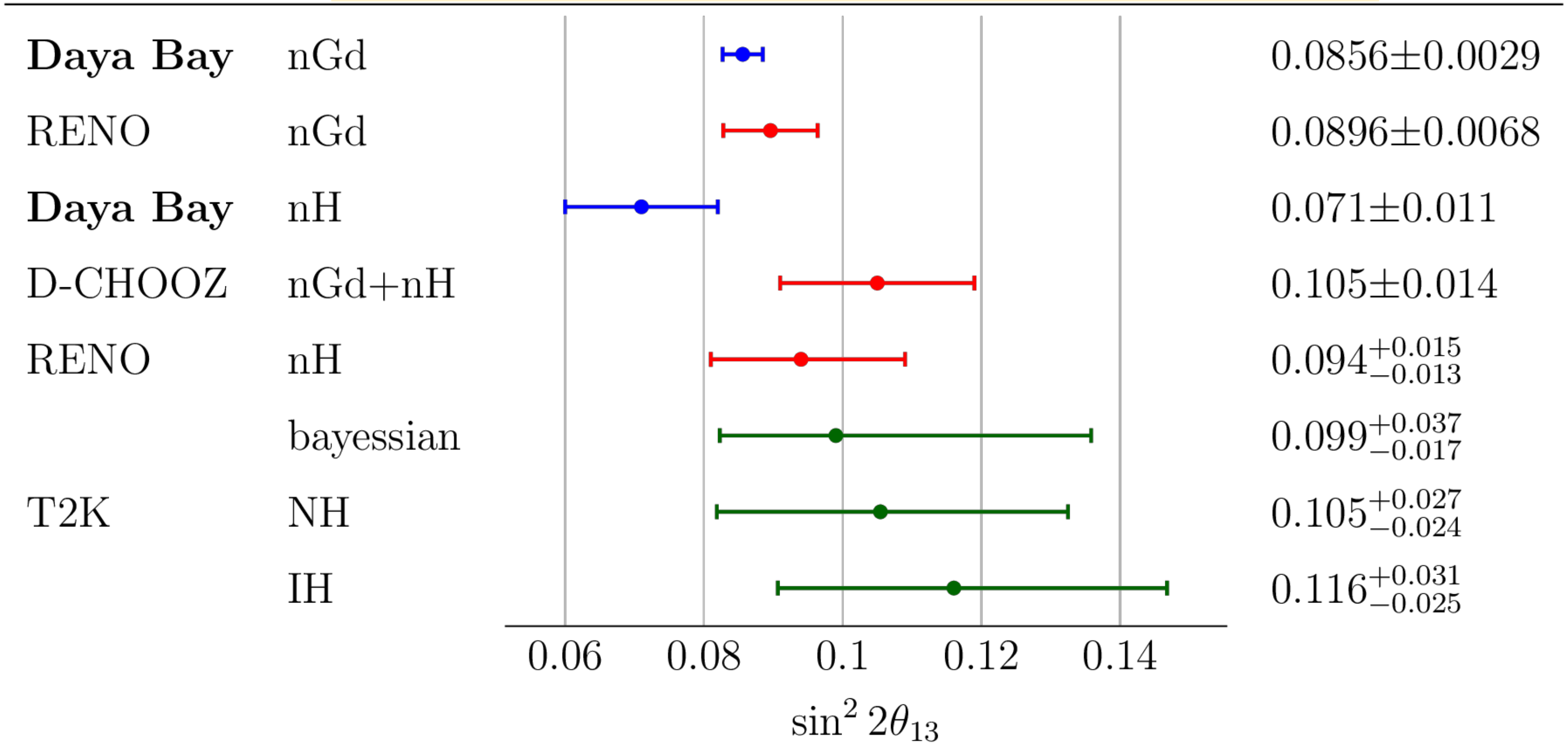
First θ_{13} measurements in 2012

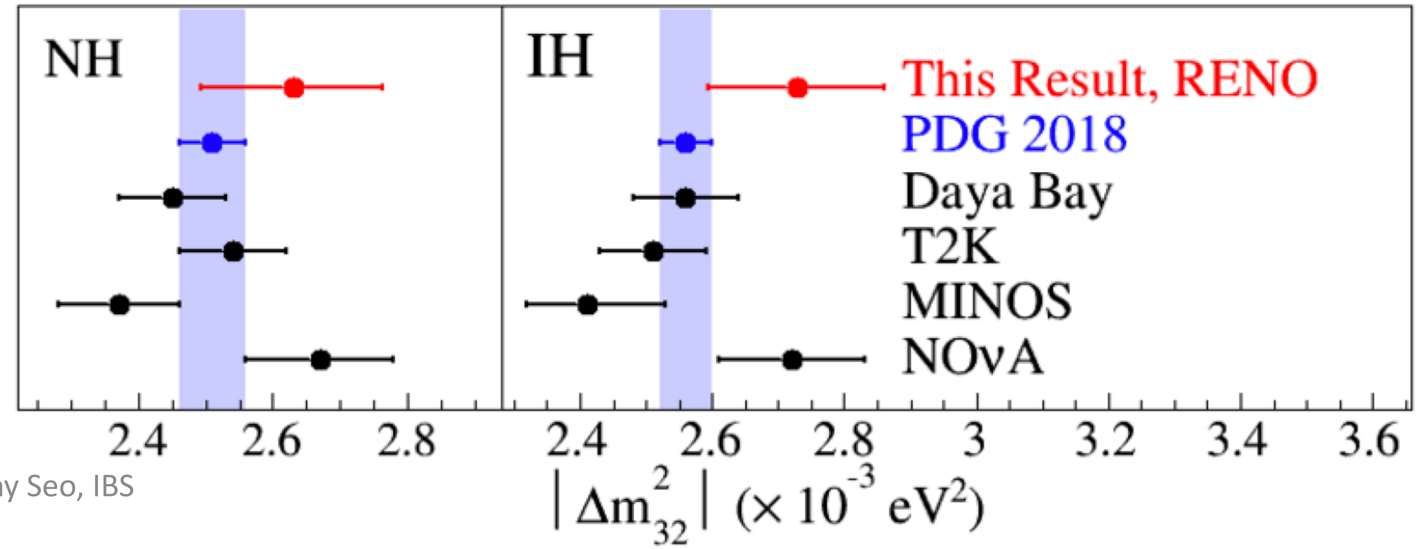
~ 7 years ago

	Double Chooz	**Daya Bay**	**RENO**
Publication	PRL 108, 131801 (Mar. 30, 2012)	PRL 108, 171803 (Apr.27, 2012)	PRL 108, 191802 (May 11, 2012)
$\sin^2(2\theta_{13})$	0.086	0.092	0.113
Stat. error	0.041 (101 days)	0.016 (49 days)	0.013 (220 days)
Syst. error	0.030 (flux uncert.)	0.005 (MC driven)	0.019 (data driven)
Significance	1.7 σ	5.2 σ	4.9 σ

➢ $\sin^2(2\theta_{13})$ precision in 2012: 18%

$\sin^2(2\theta_{13})$ precision in 2018: 3.4%



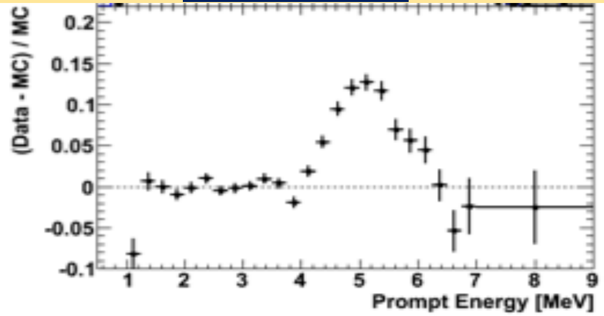


2.7%

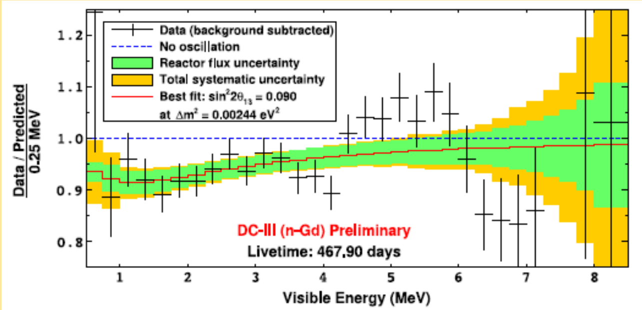
Reactor ν "Shape" Anomaly

The "5 MeV Excess" in 2014

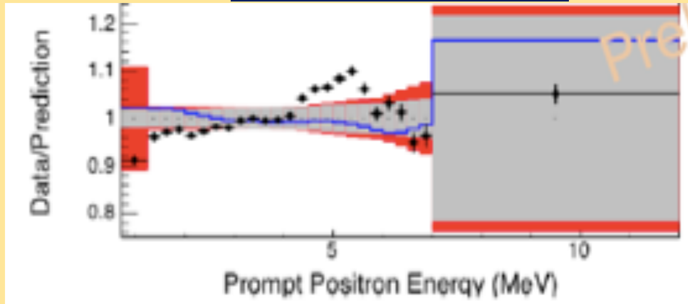
RENO



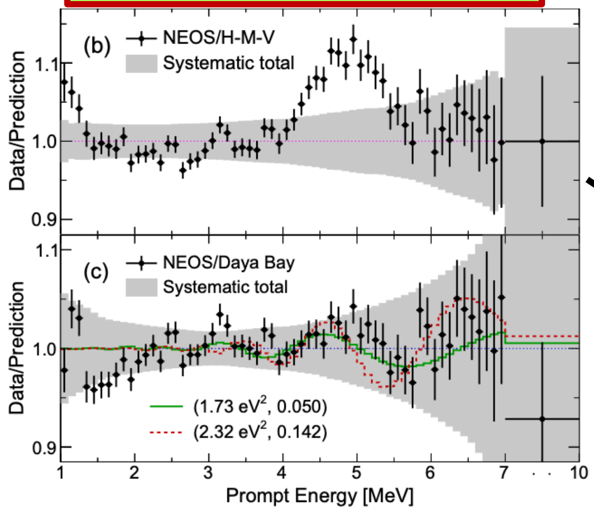
Double Chooz

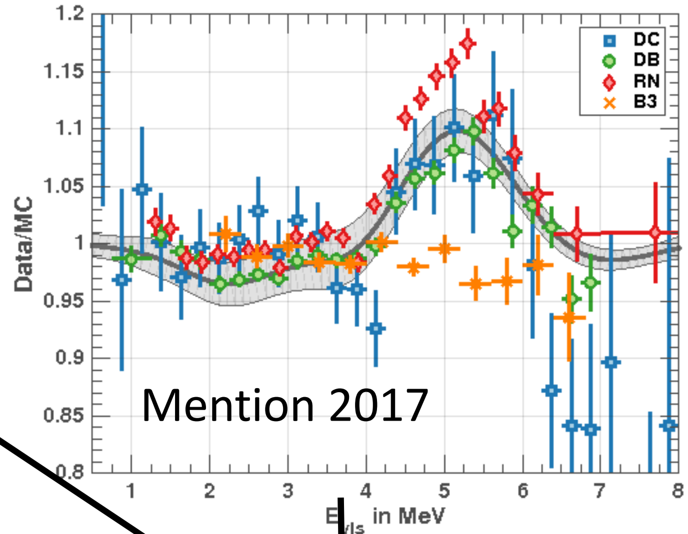


Daya Bay



NEOS in 2017



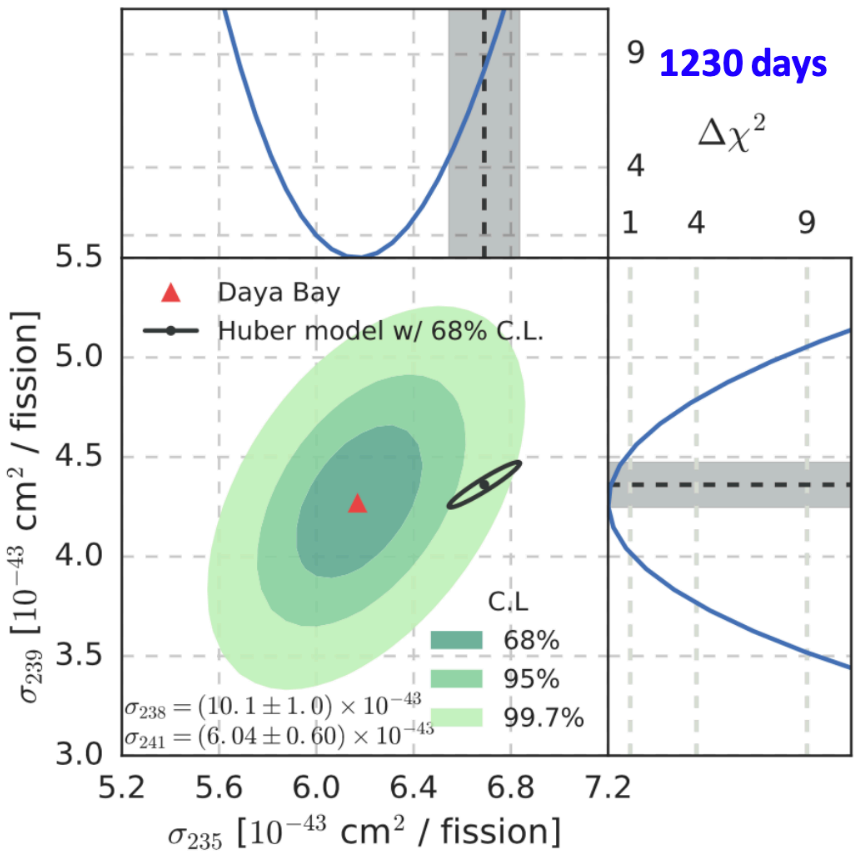


5 MeV excess compared to H&M model

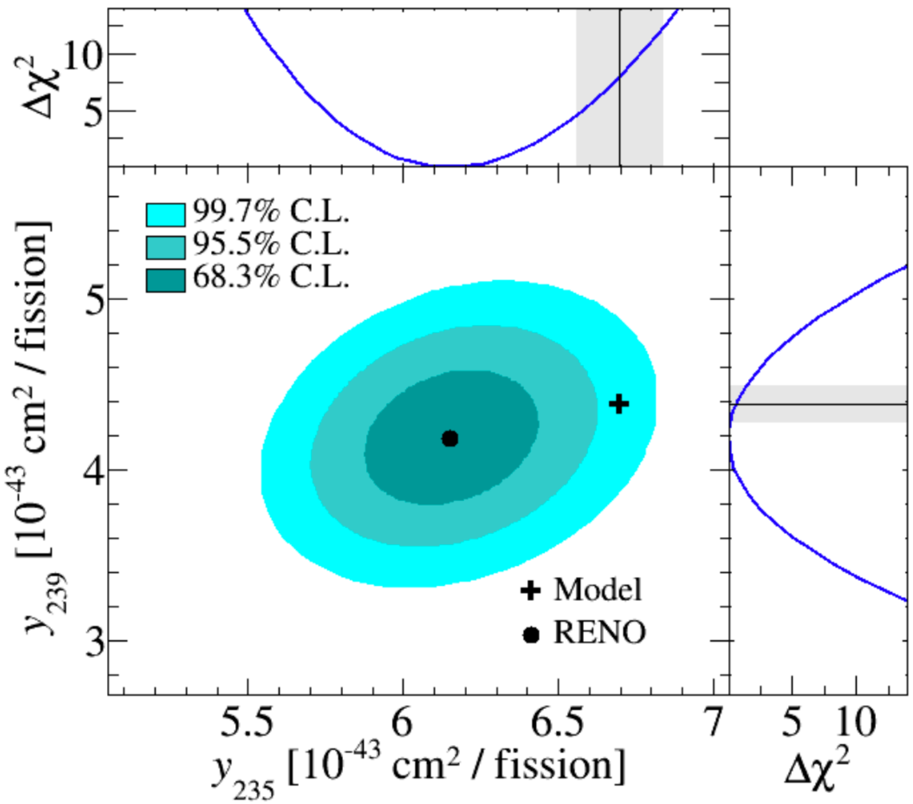
NEOS is the only VSBL (<100m) exp. which observed the 5 MeV excess.

No relation w/ sterile neutrinos

Phys. Rev. Lett. 118, 251801 (2017)



1807.9 days of near data

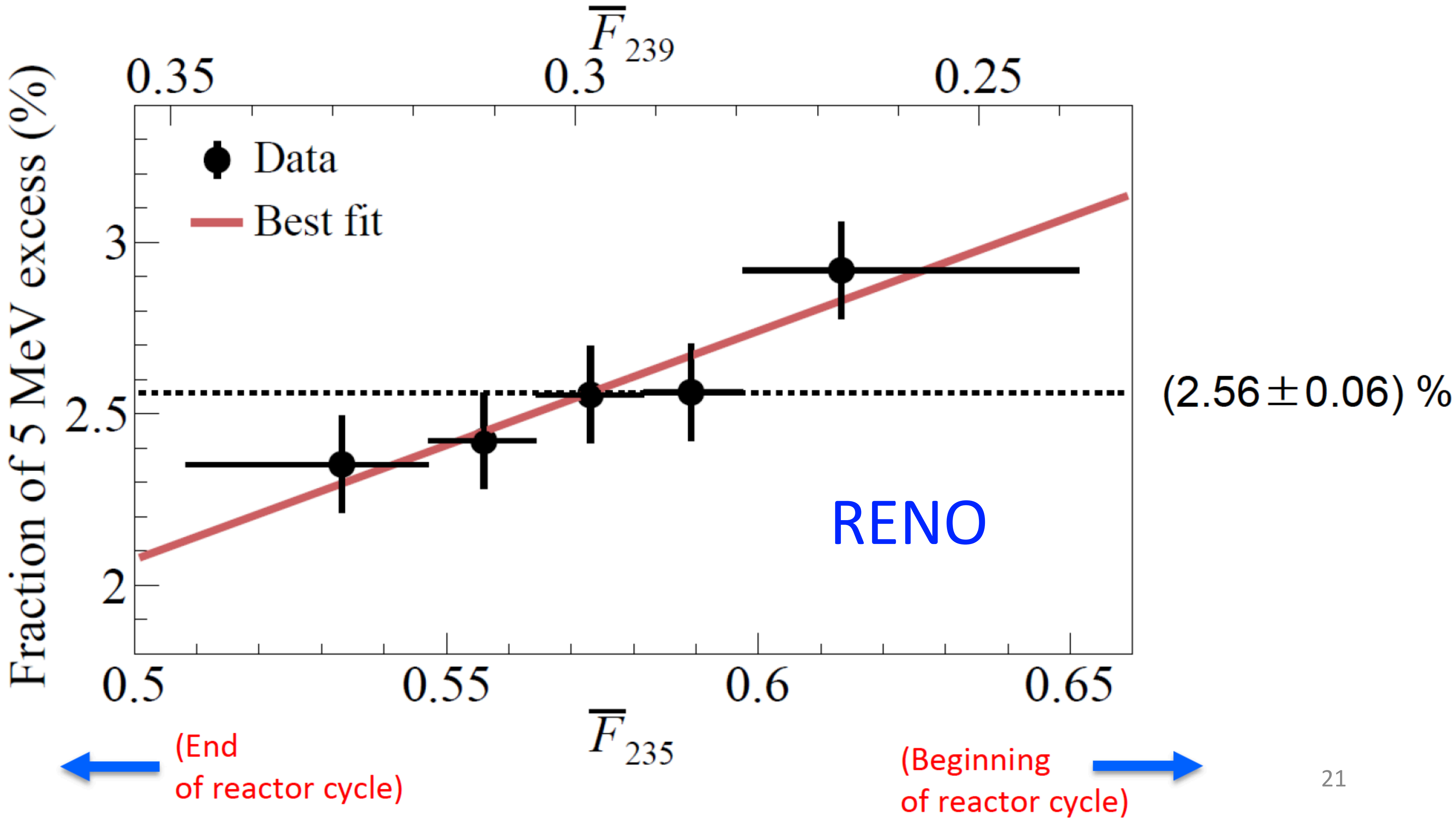


➢ Daya Bay and RENO results suggest that ν from ^{235}U is less by ~3 σ than HM model.

→ Need HEU reactors (20-90% ^{235}U), i.e., research reactors to thoroughly test this.

Correlation of 5 MeV excess with fuel ^{235}U

2.9σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission !!



θ_{13} and Future ν Osc. Experiments

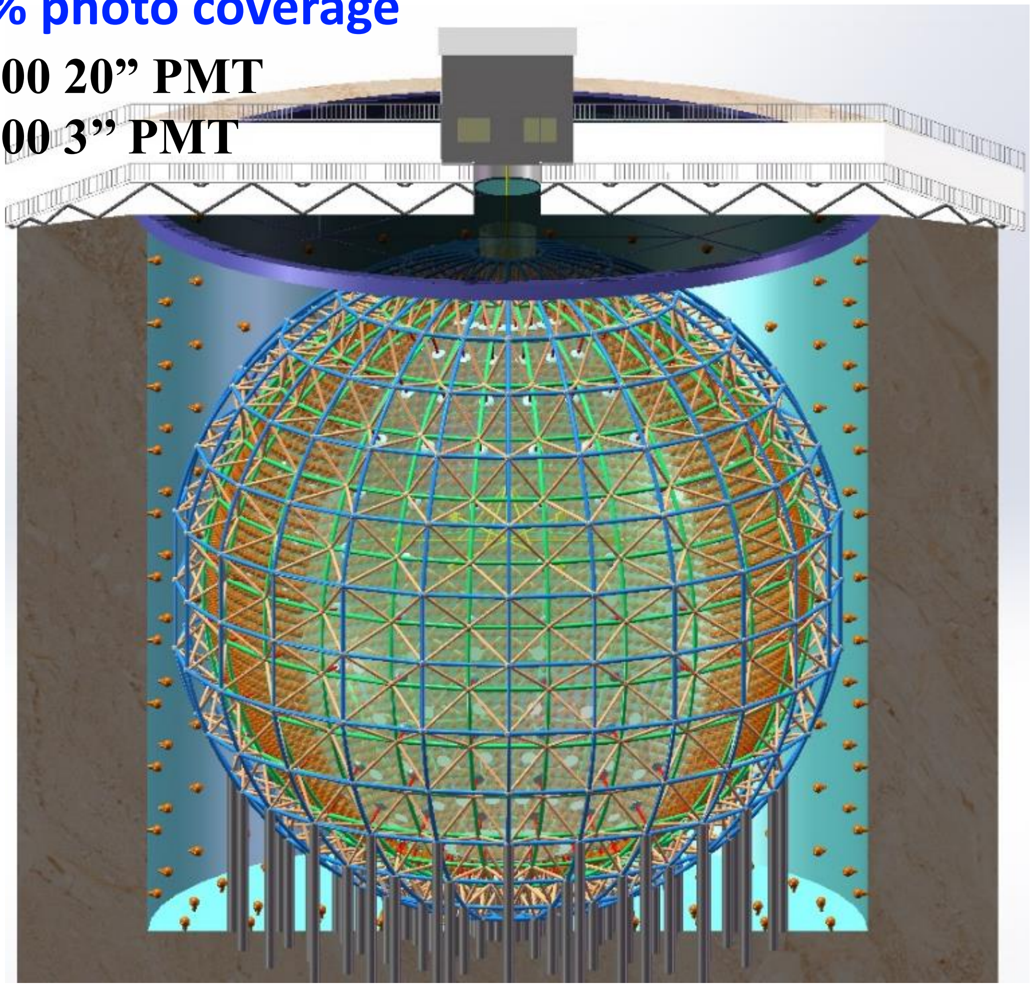
The JUNO Experiment

77 institutions
607 collaborators

Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013, 300 M$, online in 2021

78% photo coverage

18000 20” PMT
25000 3” PMT

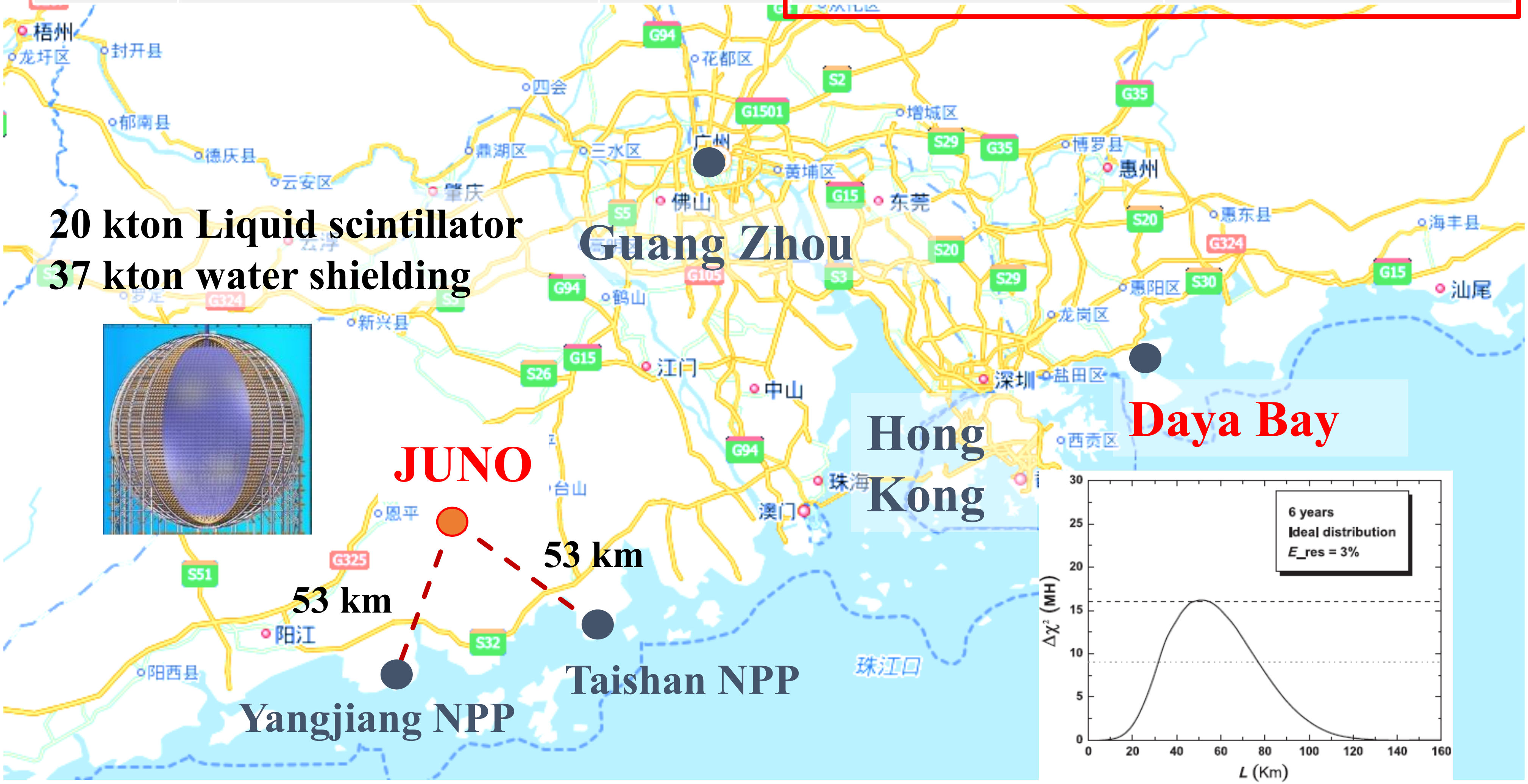


- **20 kton LS detector**
- **700 m underground**
- **3% energy resolution**
- **Rich physics possibilities**
  - **Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters**
  - **Supernova neutrino**
  - **Geo-neutrino**
  - **Solar neutrino**
  - **Atmospheric neutrino**
  - **Proton decay**
  - **Exotic searches**

Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007,2009

JUNO Site

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Determine MO with reactors

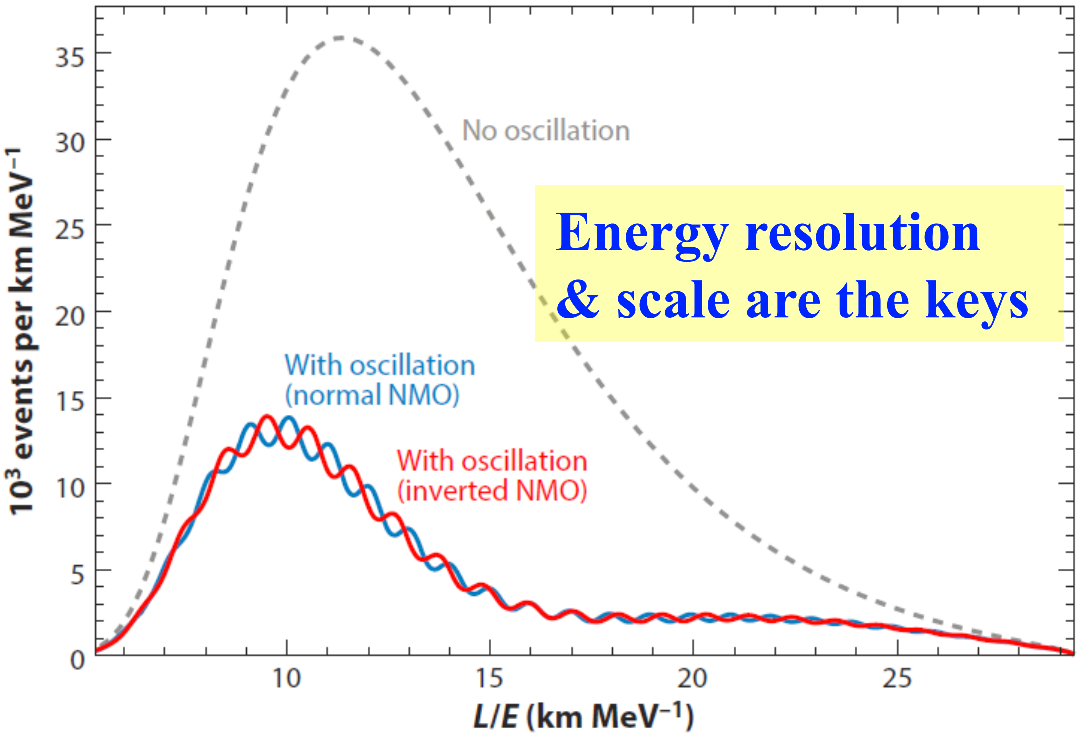
Independent on CP phase and θ_{23} (Acc. & Atm. do)

- Measure energy spectrum at 53 km from reactors
  - **Very high precision measurement**
  - **Interplay of Δm^2_{31} and Δm^2_{32}, frequencies differ by 3%**

** Sensitivity: 3-4σ in 6 years, 5σ in 10 years

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$



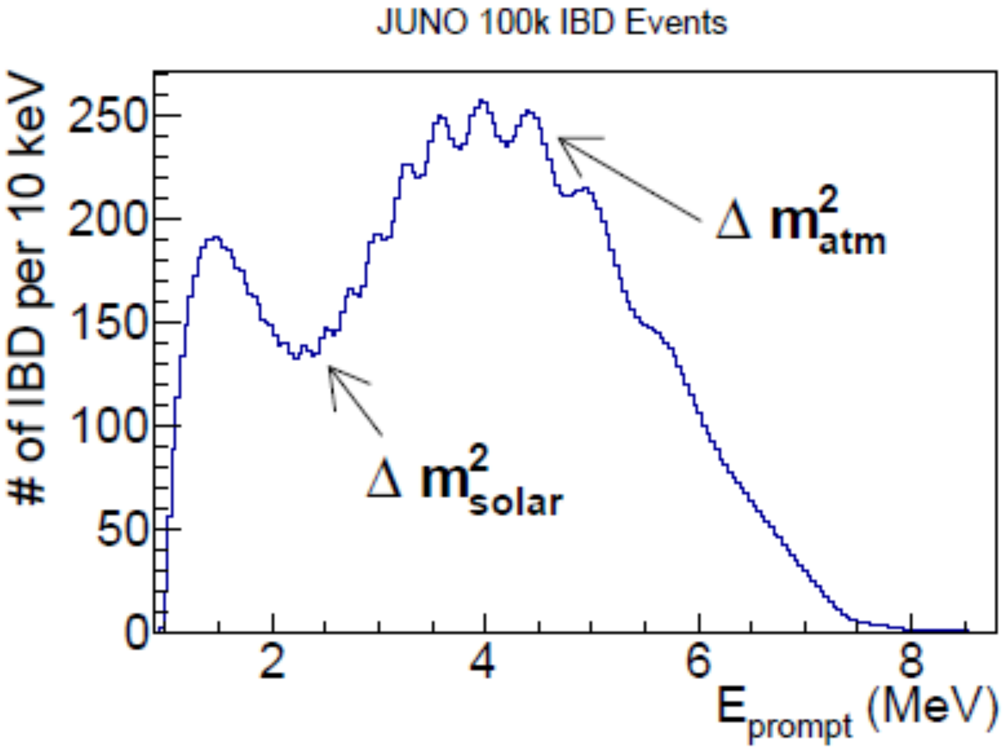
Energy resolution & scale are the keys

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
Y.F Li et al, PRD 88, 013008 (2013)
…

2) Precision Measurements

Current precision	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%

Probing the unitarity of U_{PMNS} to 1%, New physics?



	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%

Only JUNO can do!

Why Leptonic CPV ?

1. Which flavor symmetry model ?

Understanding pattern of ν mixing

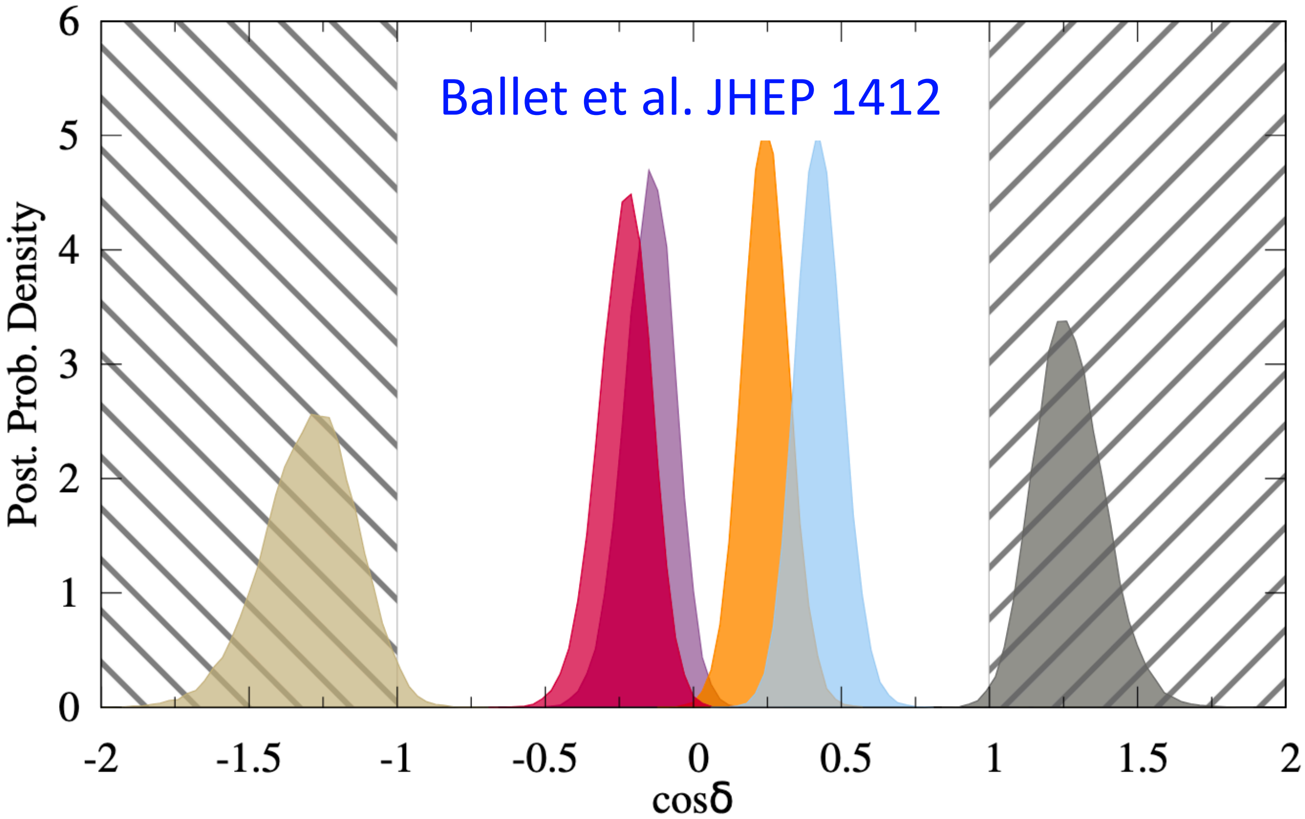
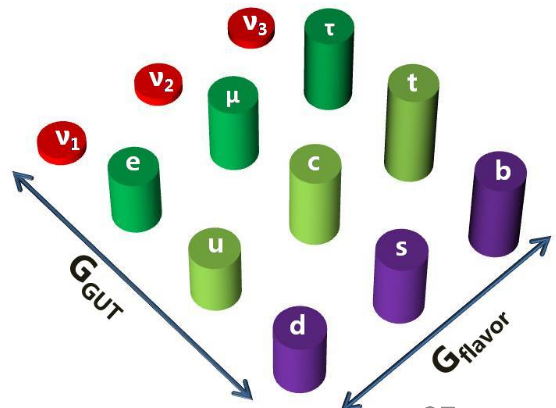


Image credit: T. Ohlsson @KTH

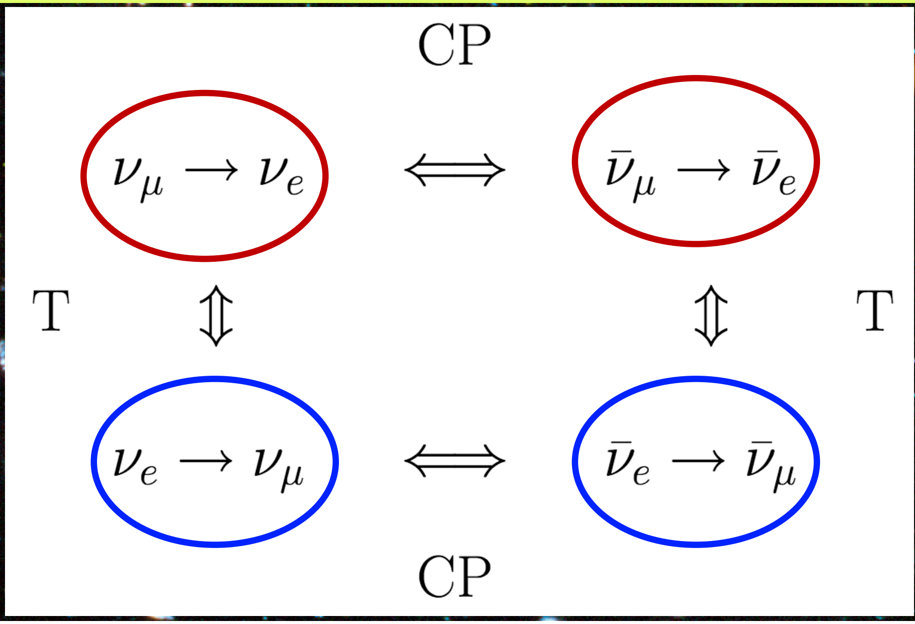


Why CPV in Lepton Sector?

- CP structure in quark sector is well known.
  → Small CPV in quark sector (< 10^{-7} %)
  can not explain baryon asymmetry of the universe.

- However, **leptogenesis** may explain baryon asymmetry, provided with large CPV in lepton sector.

- There is **hint** of maximal CPV in lepton sector.
  (~ 2sigma @T2K, NOvA)



$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

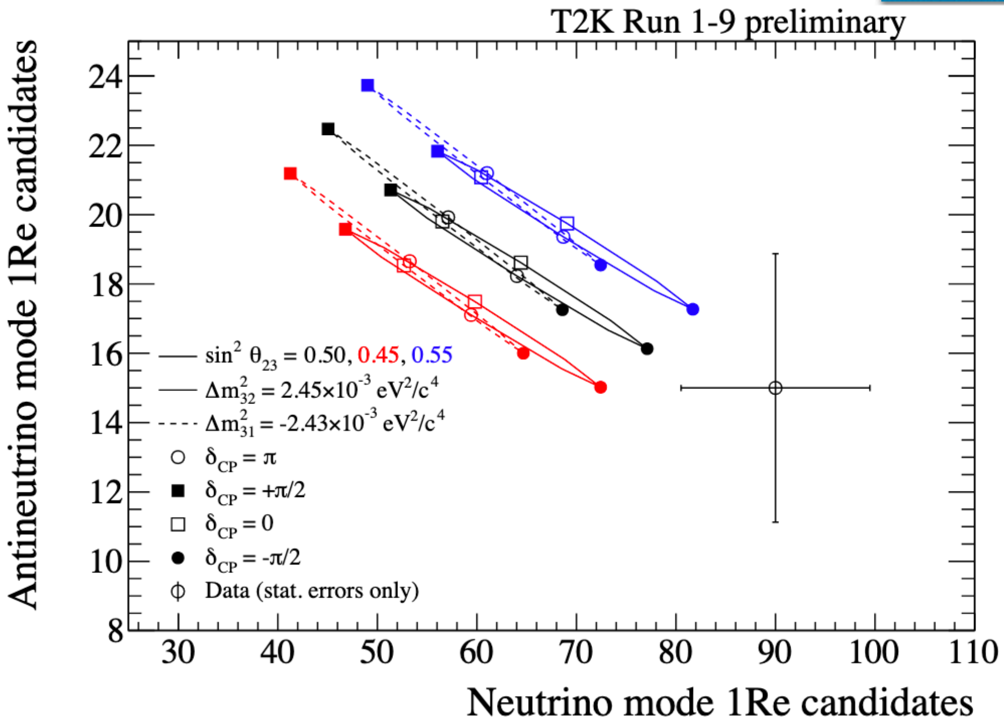
T2K (2010 --)

- Beam: J-PARC ν beam (480 kW)
- Baseline: 295 km w/ 2.5° off-axis
- Far detector: Super-K (50 kton water) in 1 km depth
- Near detectors: ND280, INGRID → to reduce σ_{syst}
- Discovery of ν_e appearance in 2013

Recent T2K Results

- **Comparison of # of ν_e and $\bar{\nu}_e$ appearance candidates**

	Obs.		Expectation			
			$\delta=-\pi/2$	$\delta=\pi$	$\delta=\pi/2$	$\delta=0$
$\nu_\mu \rightarrow \nu_e$ candidates	90	↔	81.4	68.6	55.5	68.3
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ candidates	15	↔	17.1	19.3	21.7	19.4
			CPV	CPC	CPV	CPC



ν-mode : 14.9×10^{20} POT

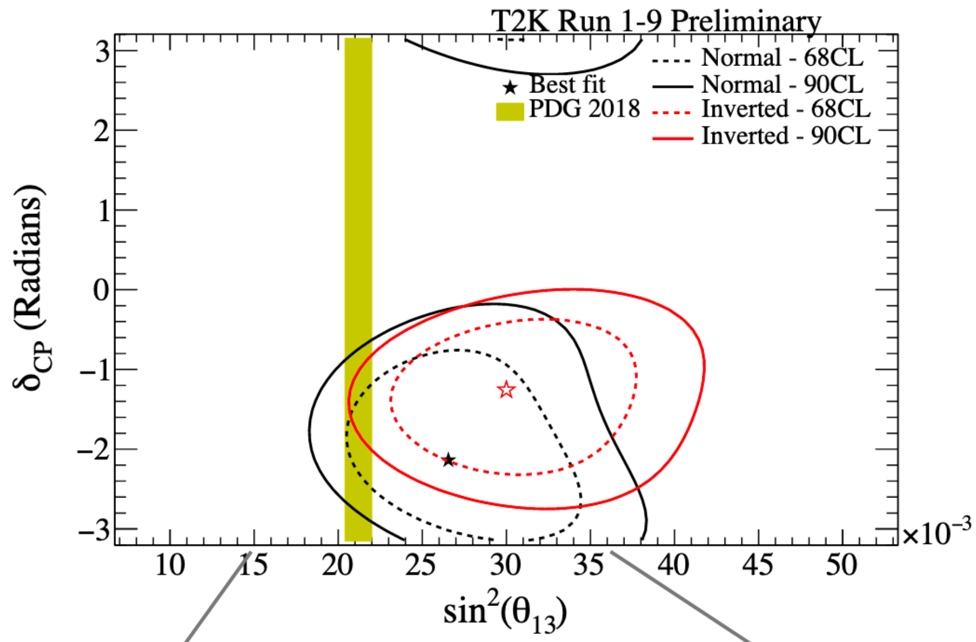
$\bar{\nu}$-mode : 16.3×10^{20} POT

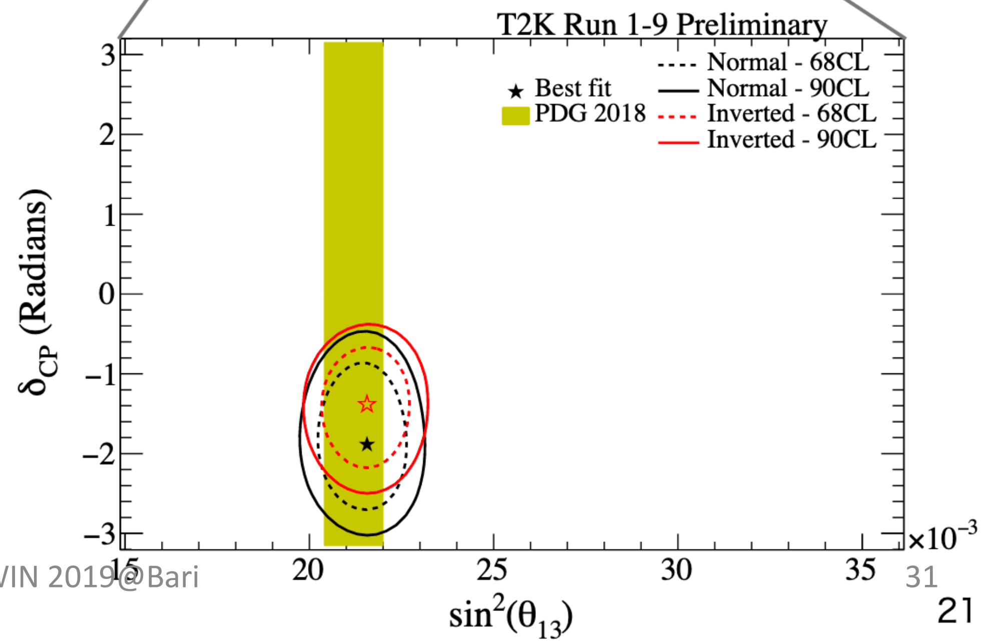
➡ *oscillation parameters are extracted using all event samples (not only ν_e samples but also ν_μ samples)*

Recent T2K Results

δ_{CP} vs $\sin^2\theta_{13}$

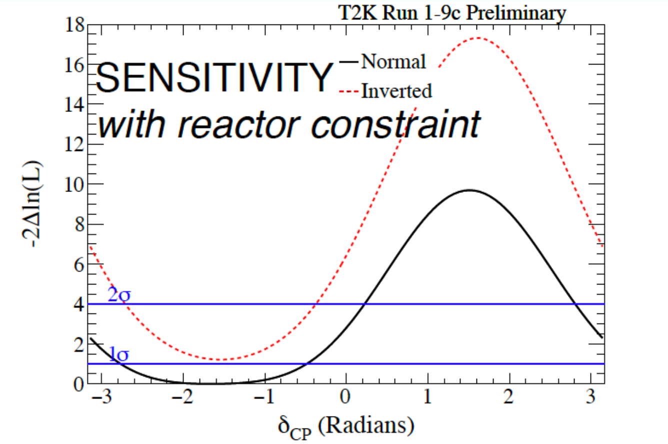
- Contours for δ_{CP} and $\sin^2(\theta_{13})$ w/ all the data samples
- Top plot shows only T2K allowed region
- Bottom plot shows with reactor constraints on $\sin^2(\theta_{13})$ (PDG2018)





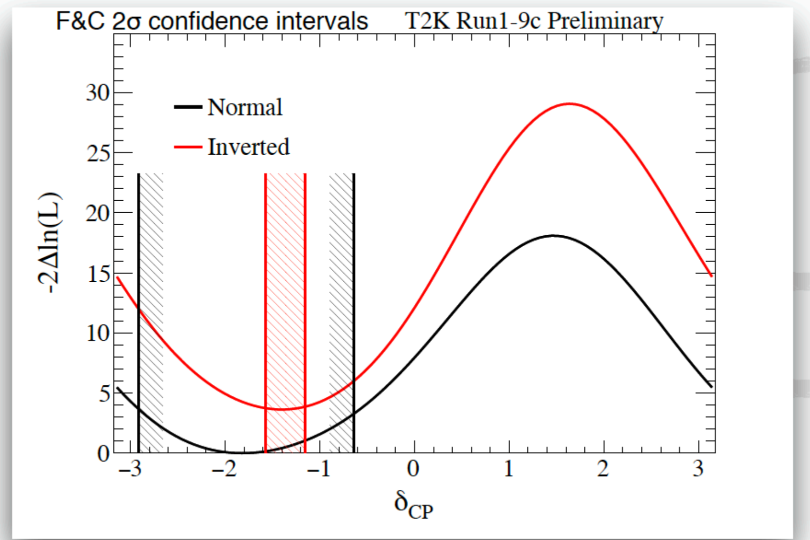
Recent T2K Results

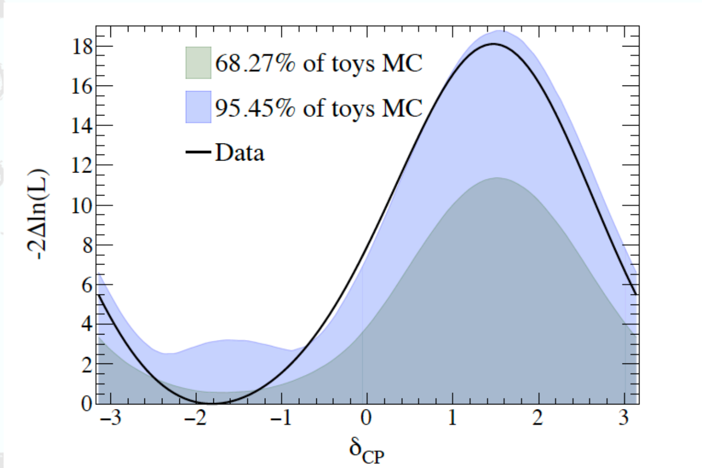
δ_{CP} 1D contours



- CP conserving values outside of 2σ region for both hierarchies
- 19% of toys exclude CP conservation at 2σ CL (both δ_{CP}=0 & δ_{CP}=π)

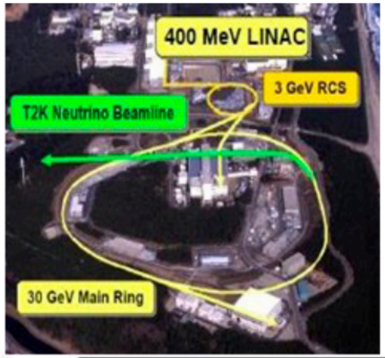
DATA FIT with reactor constraint



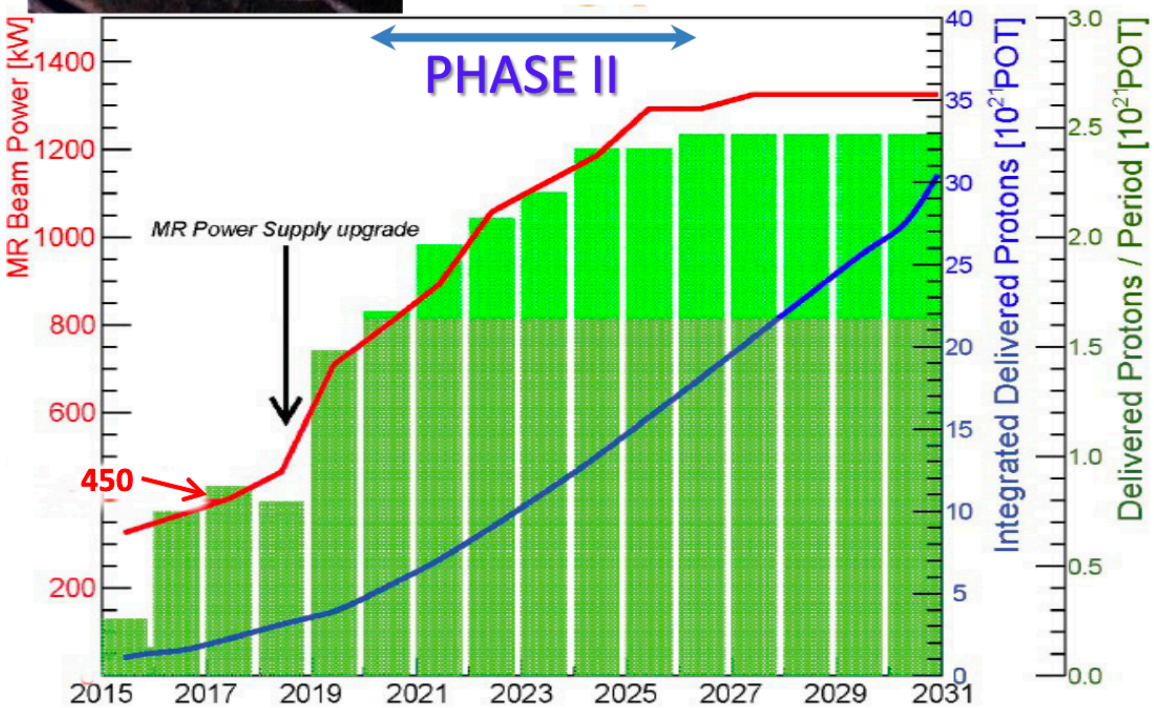


δ_{CP}	Hierarchy	90%	2σ
0	NH	0.421	0.288
π	NH	0.388	0.248
0	IH	0.768	0.660
π	IH	0.783	0.685

J-PARC Beam Upgrade Plan



Beam Upgrades (MR power supply, upgrade MR RF, …)



Step by step

- Decrease bunch intervals from 2.48 sec to 1.3 sec, then 1.16 sec
- Increase protons/bunch from 2.7 10^{14} to 3.2 10^{14}
- Increase horn current form 250 kA to 320 kA

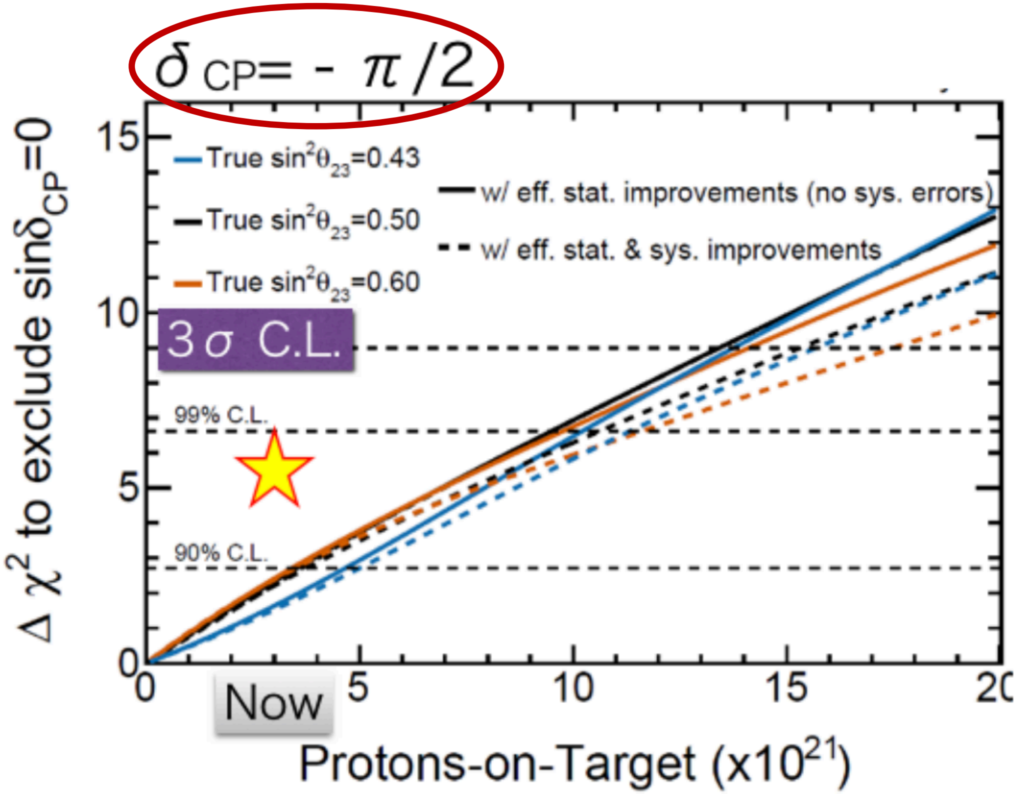
Proposal for T2K phase II @ 1.3 MW (funded)

Increase total delivered protons from 7.8×10^{21} to 20.0×10^{21}

T2K-II Prospects

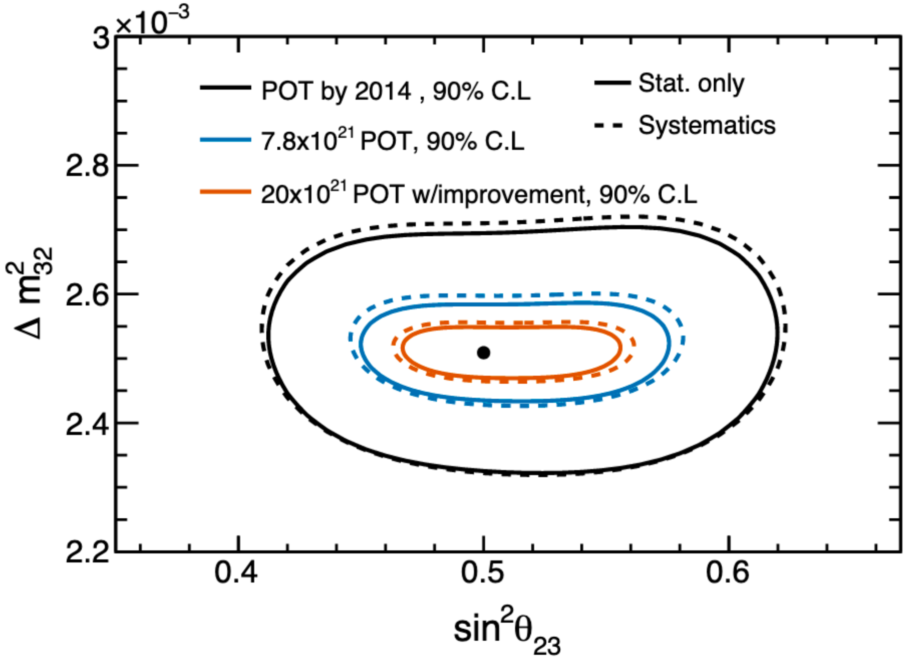
with ND280 upgrade

Sensitivity to exclude sin δ_{CP}=0



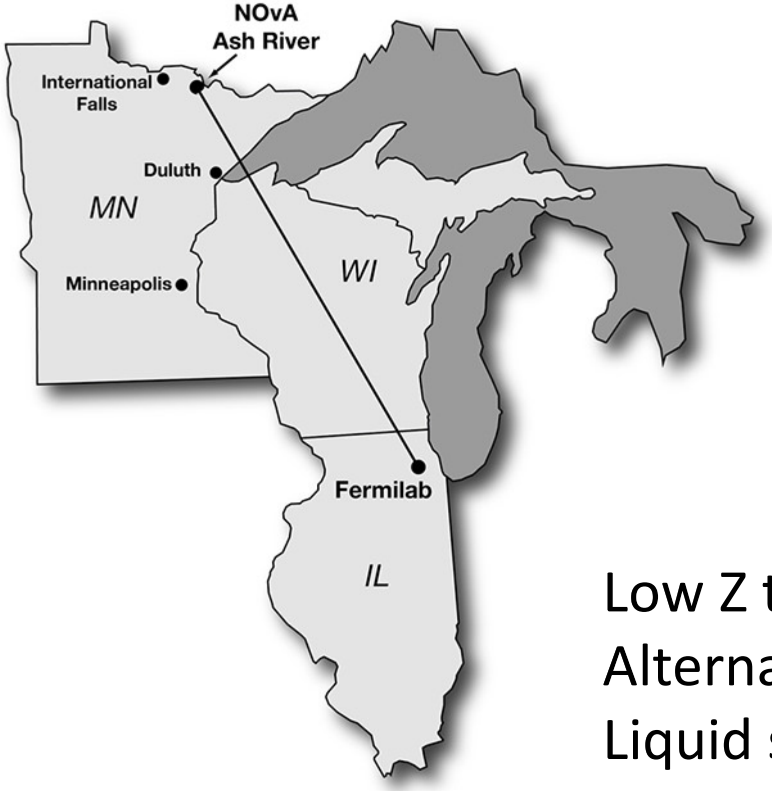
>3σ CPV sensitivity

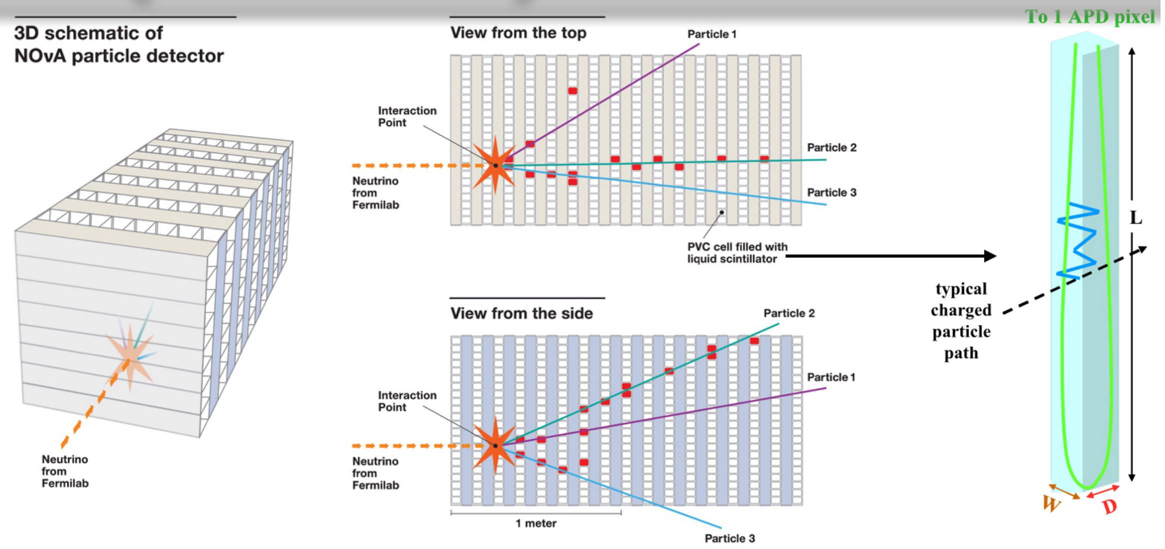
Sensitivity of $\sin^2\theta_{23}$, Δm^2_{32}



~1% precision of Δm^2,
0.5°-1.7° precision of θ_{23}
(depends on true value)

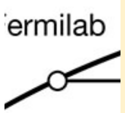
NOvA (2010 --)





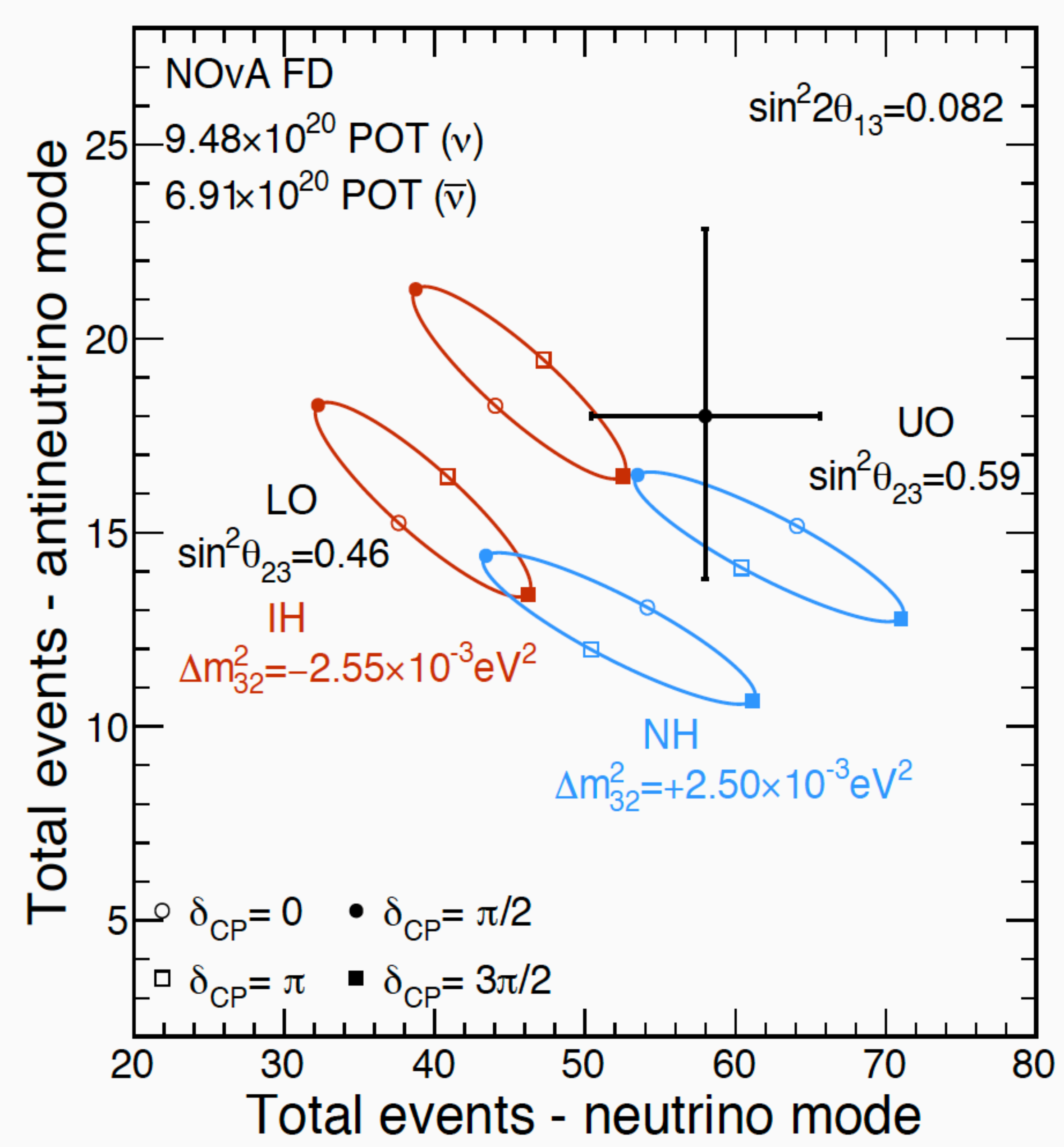
Low Z tracking calorimeter composed of
Alternating horizontal & vertical planes of
Liquid scintillator filled cells.

~344 k ch



- Beam: Fermilab NuMi ν beam (700 kW)
- Baseline: 810 km w/ 0.8° (14 mrad) off-axis
- Far detector: segmented scintillator in PVC (14 kton)
- Near detector: 0.3 kt @1km → to reduce σ_{syst}
- 4σ observation of $\overline{\nu}_e$ appearance in 2018

NOvA Results in 2018



Neutrinos: 8.85x 10^{20} POT

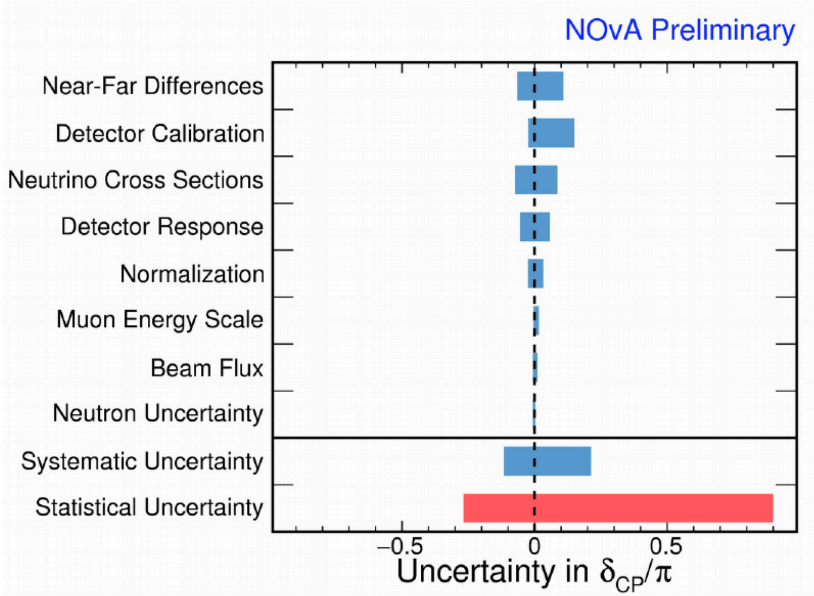
(Feb. 2014 -- Feb. 2017)

Feb.2019 --

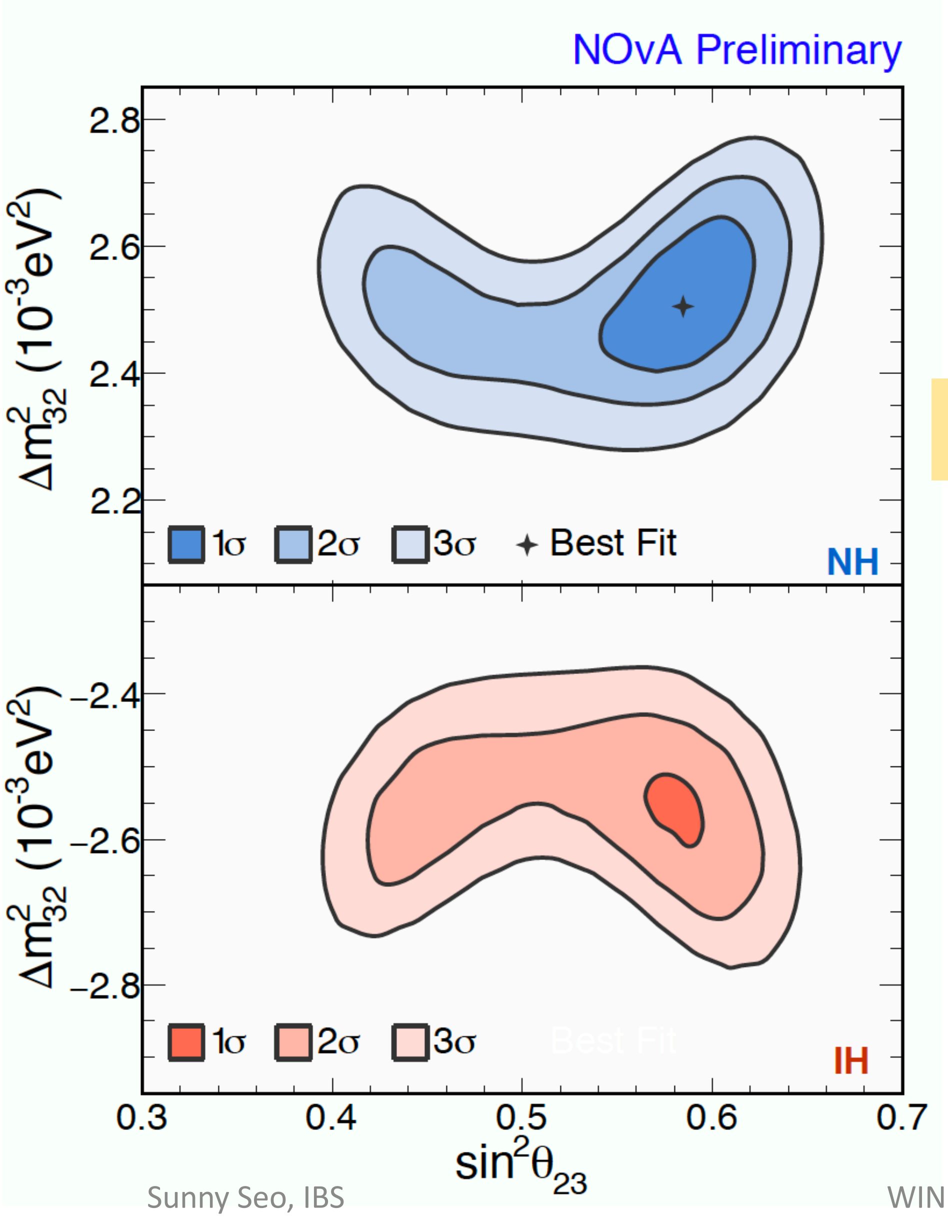
Anti-nu : 6.9x 10^{20} POT

(Feb. 2017 -- Apr. 2018)

Statistical error dominant !



NOvA Results in 2018

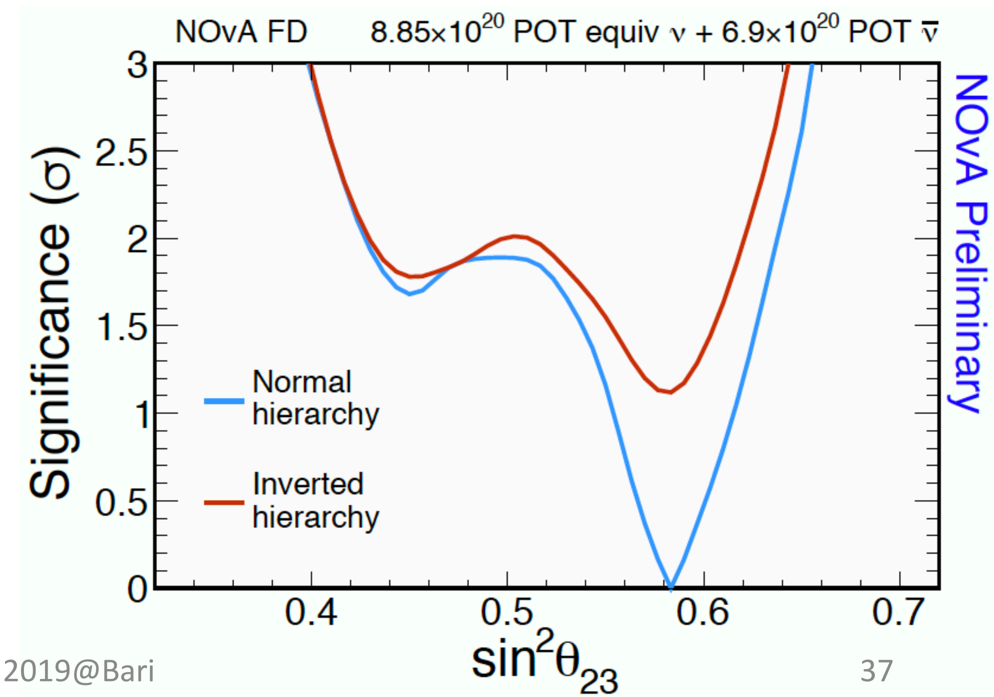


Best fit:

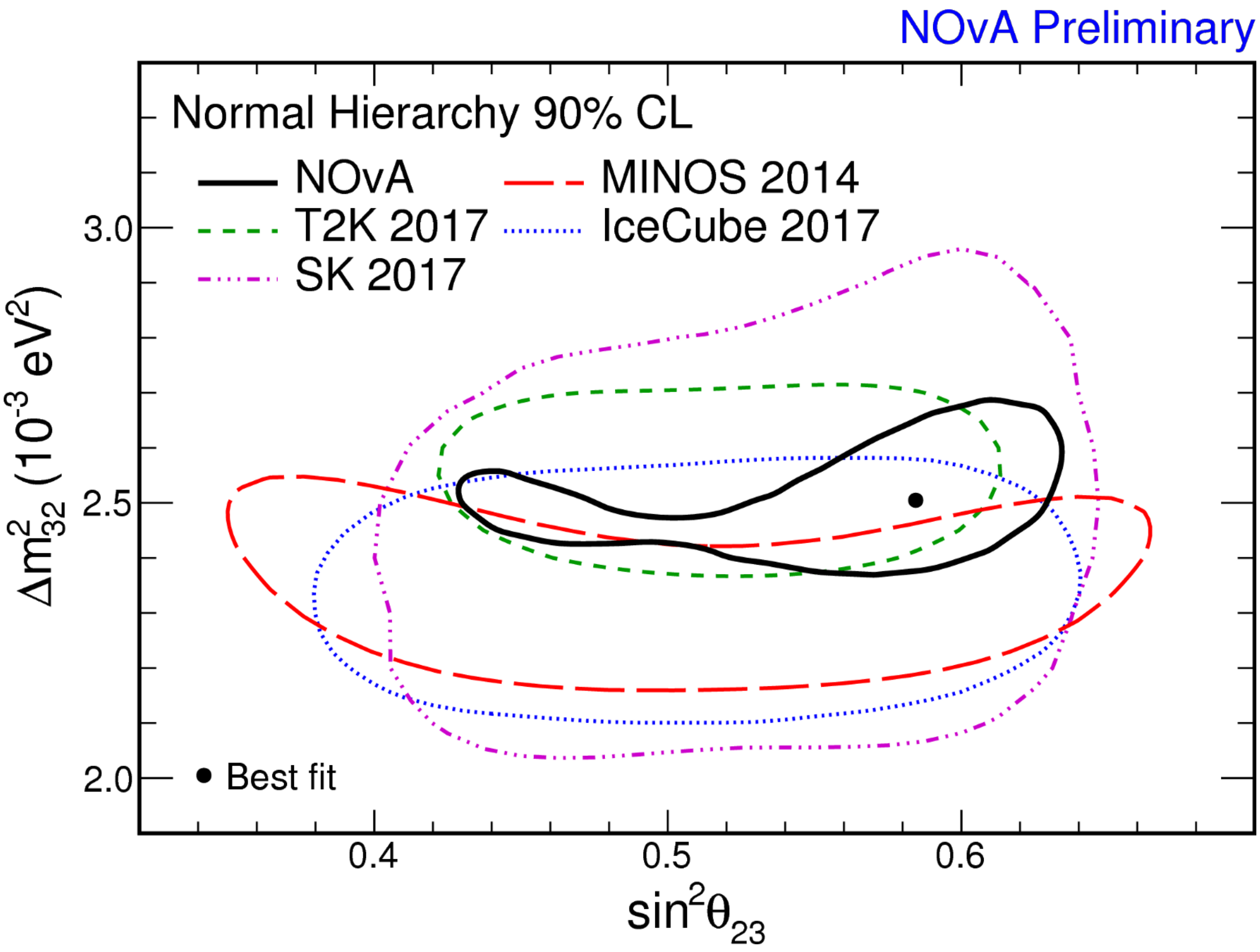
- Normal Ordering
- $\sin^2(2\theta_{13})$ = 0.58 +/- 0.03

  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2

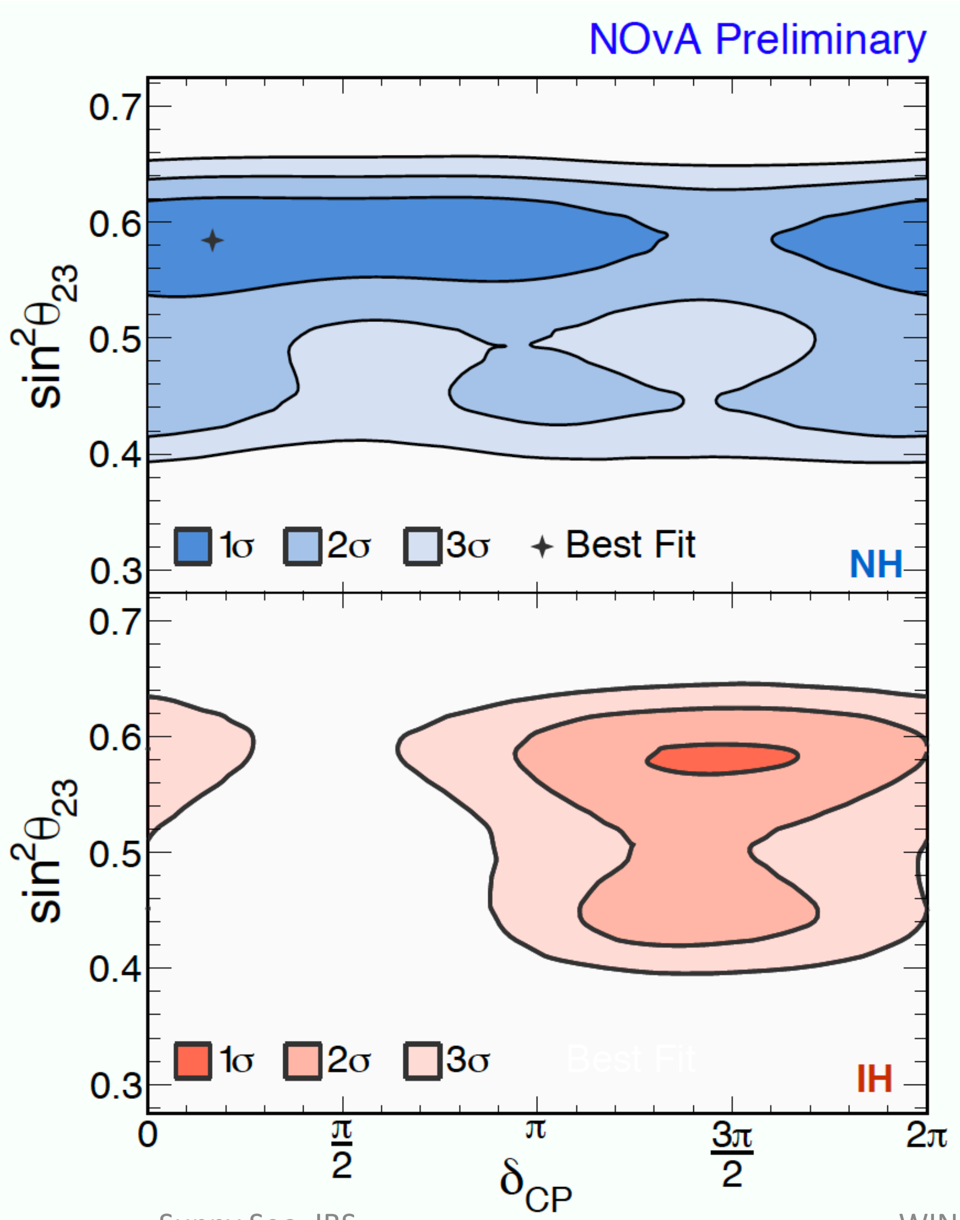
Non-maximal θ_{23} is favorable at 1.8σ.



Status: Δm^2_{32} vs $\sin^2\theta_{23}$



NOvA Results in 2018

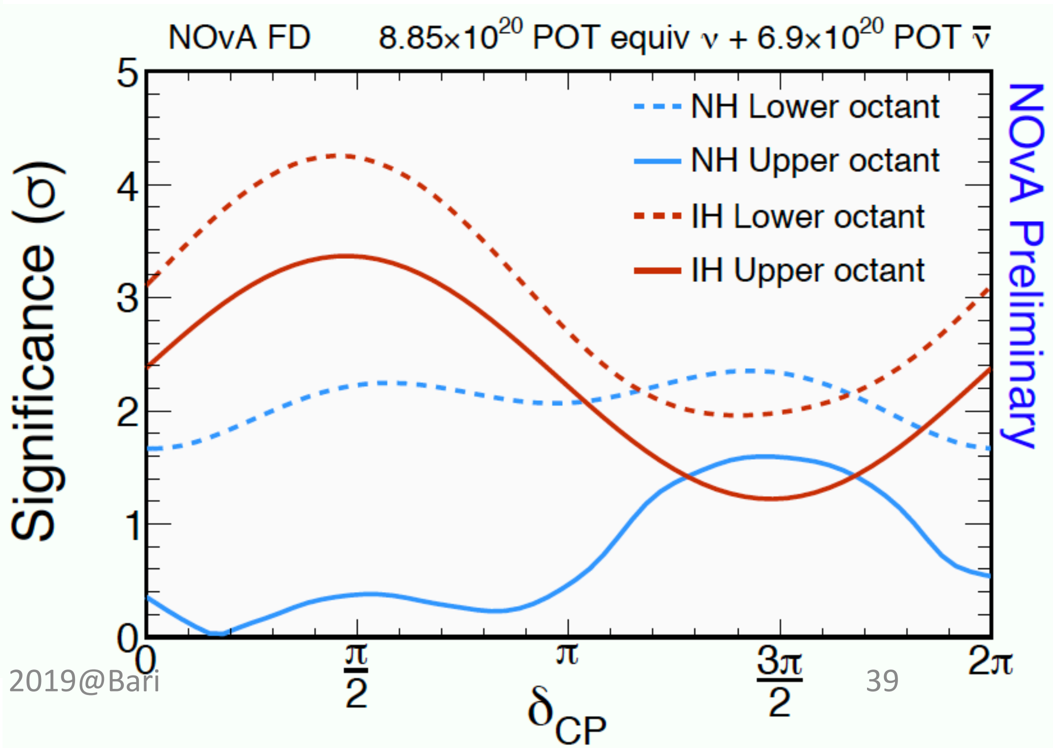


Best fit at N.O. (favored at 1.8σ)

- $\delta_{CP} = 0.17\,\pi\ (\sim 30^o)$
- $\sin^2(2\theta_{13})$ = 0.58 +/- 0.03

  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08})\text{x}10^{-3}\ eV^2$

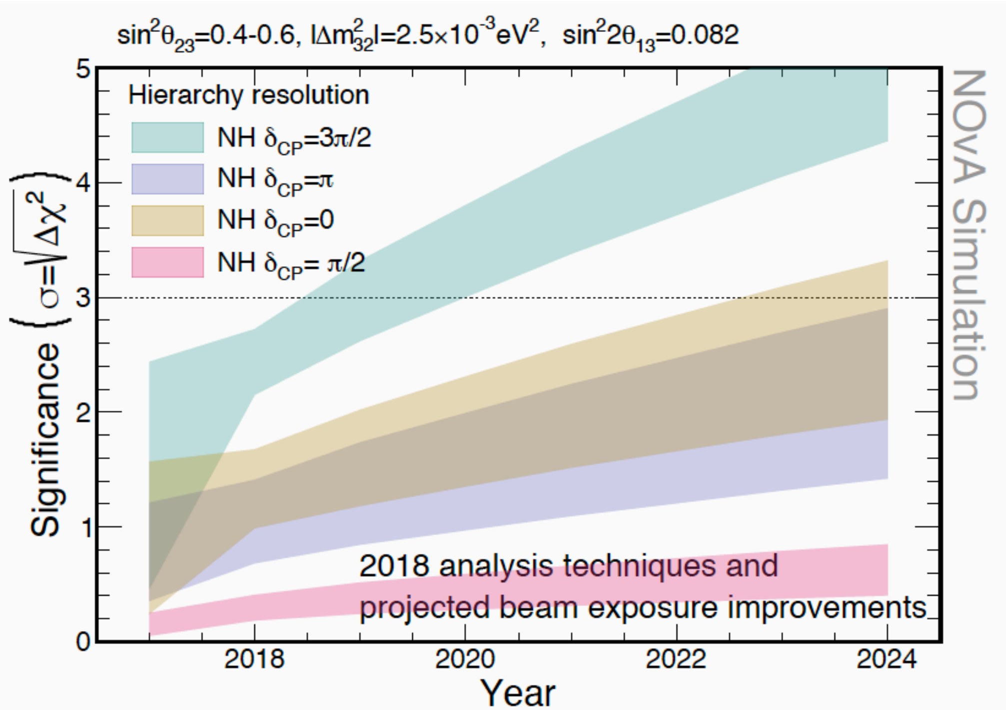
Excluding $\delta_{CP}=\pi/2$ at IO > 3σ

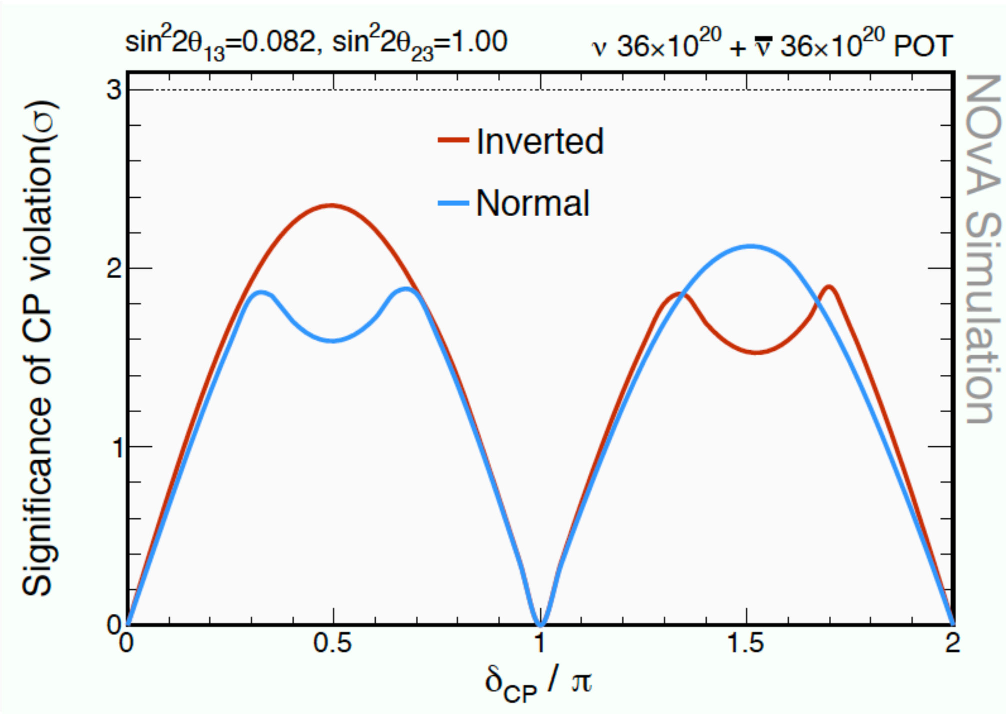


NOvA Plan & Sensitivity

Running until 2025

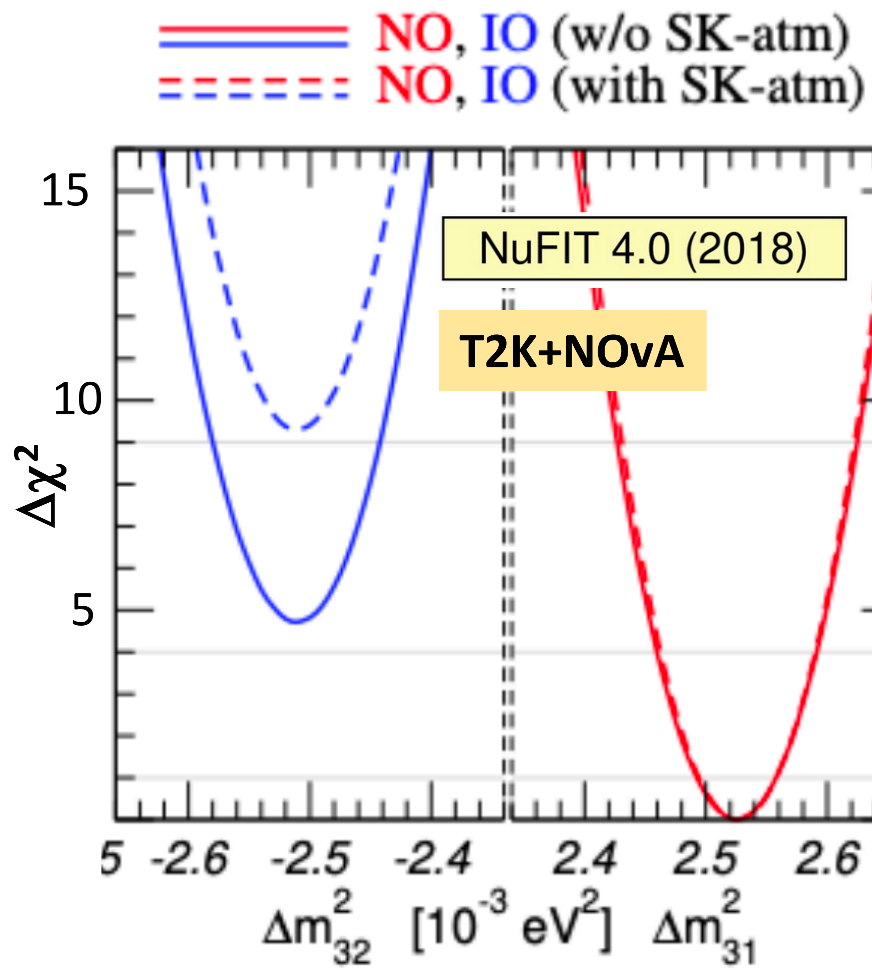
$\nu : \bar{\nu} = 1 : 1$

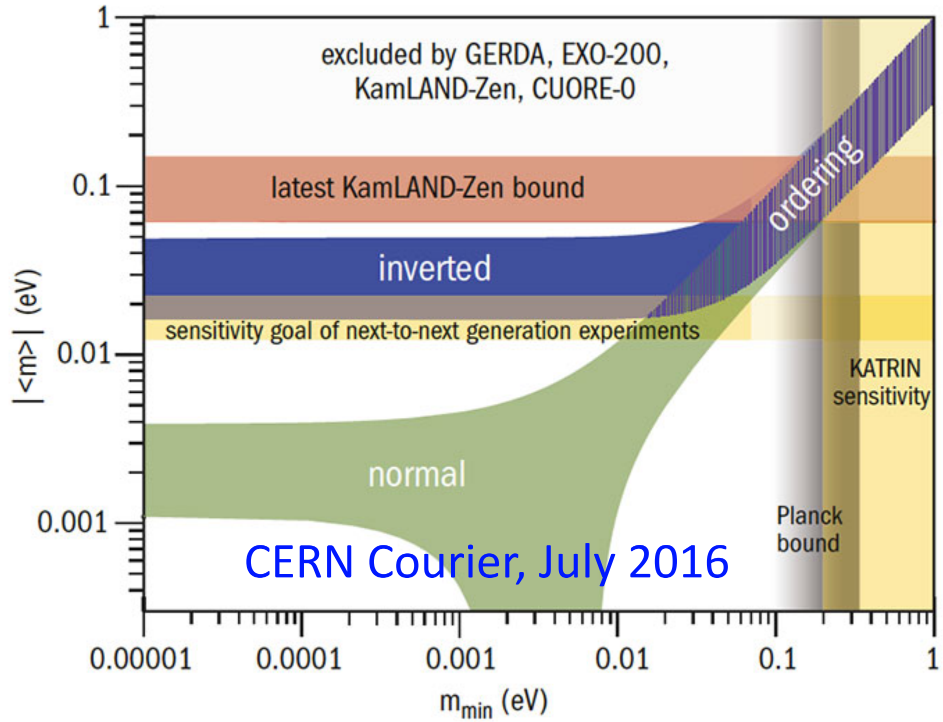




2021: aim to do T2K + NOvA analysis

Current Status of ν MO





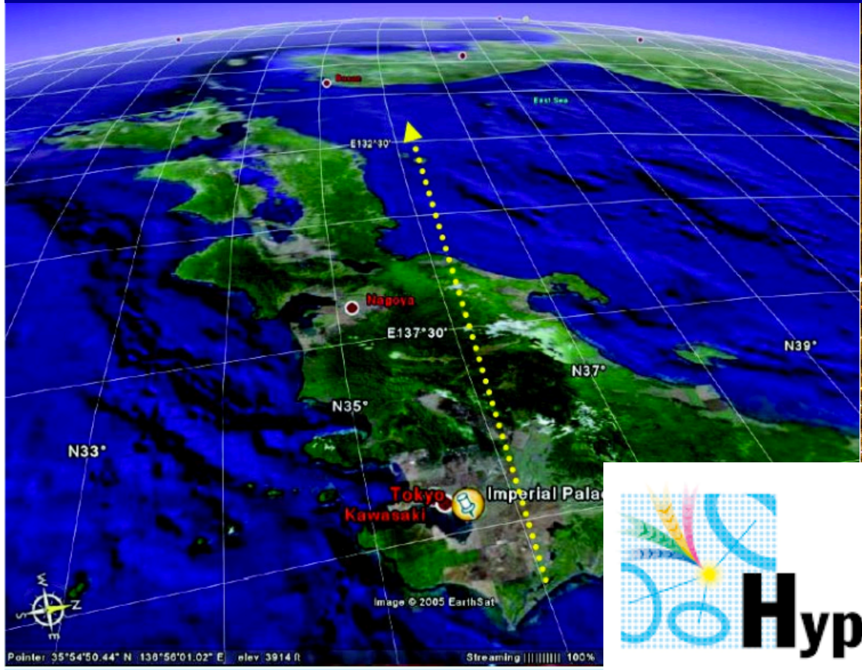
** Cosmological measurement
(indirect / independent)
favors normal ordering 3 times
more from sum of ν mass

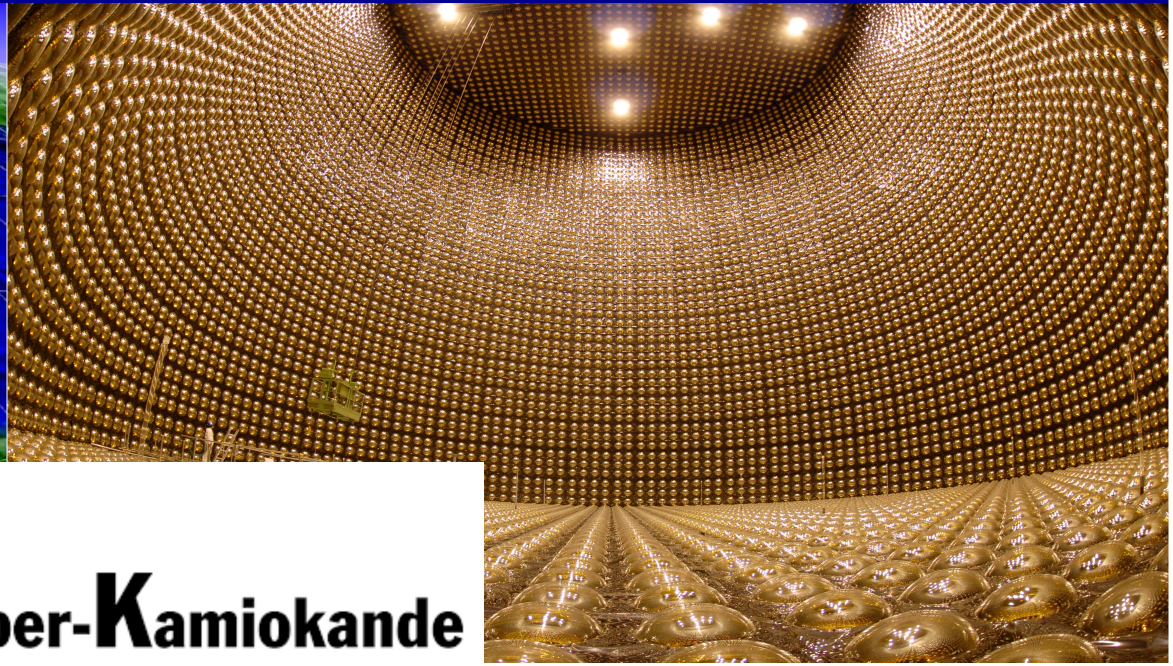
➢ Current best fit: normal ordering at **3.4 σ** from global fit

Front. Astron. Space Sci., 09 October 2018

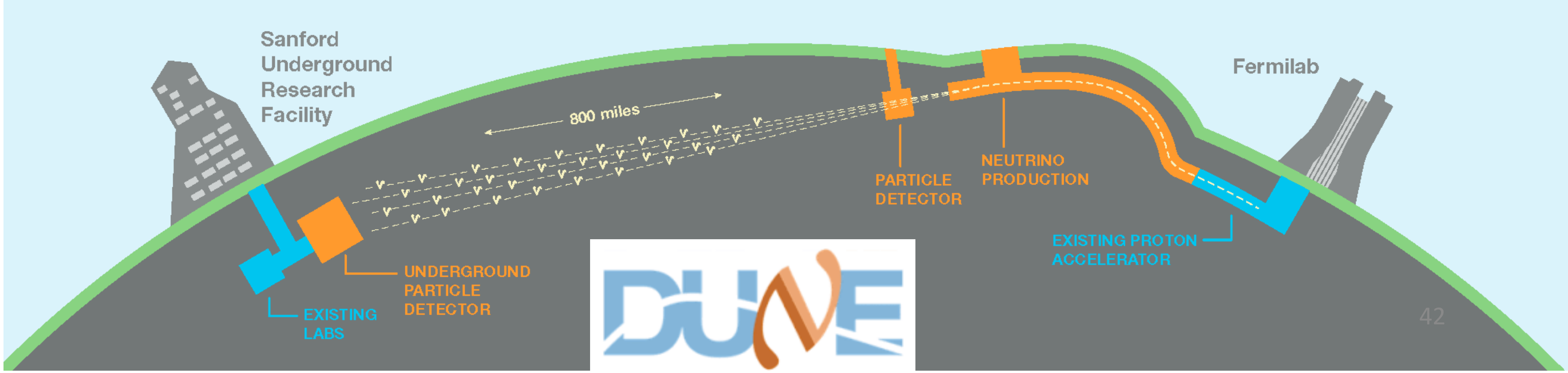
(T2K, NOvA) + (SK) + (DB, RENO, DC)

Future Long Baseline ν Experiments



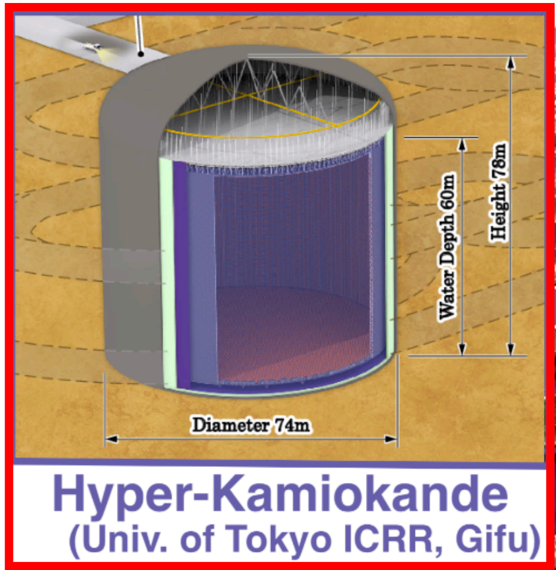


Hyper-Kamiokande



DUNE

Hyper-K (~2027 --)

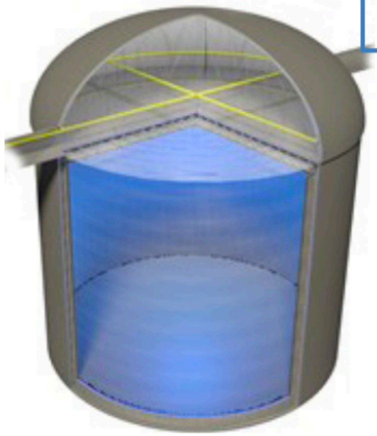


~300 collaborators in 15 countries

J-PARC Main Ring
(KEK-JAEA, Tokai)

- Beam: upgraded J-PARC ν beam (1.3 MW)
- Baseline: 295 km w/ 2.5^{o} off-axis (E_{ν} = 0.6 GeV)
- Far detector: HK (260 kton water) in 600 m depth
- Near detectors: upgraded ND280, INGRID
- Intermediate WC det. 1 kton @ ~1 km → to reduce σ_{syst}
- Very far 2nd detector: T2HKK in Korea (~1100 km)

T2HK systematic errors for oscillation analysis



Estimations and simulations will be based
on *T2K and SK studies with real data*

ν-mode ν_e candidates

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.48%
SKDet only	2.28%
FSI+SI only	2.63%
Flux	3.67%
2p-2h (corr)	3.90%
2p-2h bar (corr)	0.05%
NC other (uncorr)	0.15%
NC 1gamma (uncorr)	1.47%
XSec nue/numu (uncorr)	2.61%
XSec Tot (corr)	4.26%
XSec Tot	5.21%
Flux+XSec (ND280 constrained)	2.90%
Flux+XSec (All)	4.17%
Flux+XSec+SKDet+FSI+SI	5.45%
Flux+XSec+SKDet+FSI+SI (pre-fit)	12.1%
Oscillations	4.20%
All	6.91%
All (pre-fit)	12.6%

$\overline{\nu}$-mode $\overline{\nu}_e$ candidates

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.95%
SKDet only	3.11%
FSI+SI only	2.43%
Flux	3.84%
2p-2h (corr)	3.04%
2p-2h bar (corr)	2.36%
NC other (uncorr)	0.33%
NC 1gamma (uncorr)	2.95%
XSec nue/numu (uncorr)	1.46%
XSec Tot (corr)	4.46%
XSec Tot	5.55%
Flux+XSec (ND280 constrained)	3.20%
Flux+XSec	4.60%
Flux+XSec+SKDet+FSI+SI	6.28%
Flux+XSec+SKDet+FSI+SI (pre-fit)	13.5%
Oscillations	4.00%
All	7.38%
All (pre-fit)	14.1%

Goal

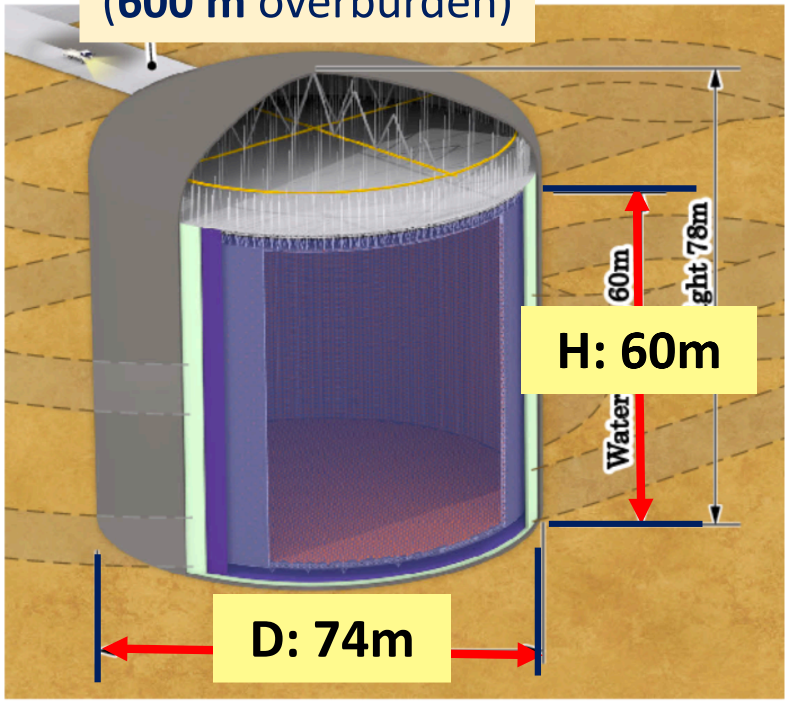
Reduction from ~ 6-7% in T2K

to ~ 3-4% in T2HK for the expected number of events.

Beam flux, XSections, HK Detector, New Near Detectors.

Hyper-K Detector

@Tochibora site
(**600 m** overburden)

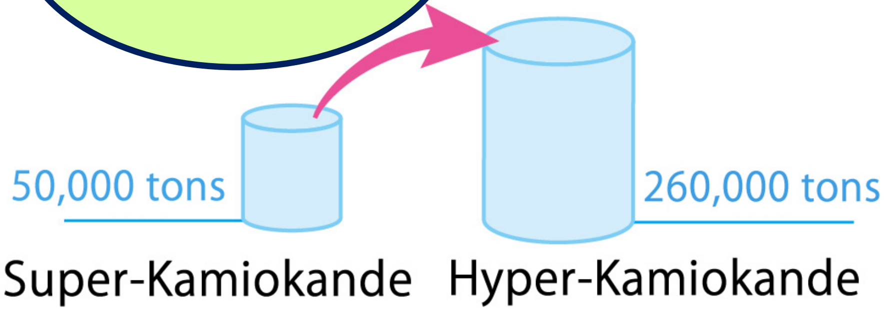


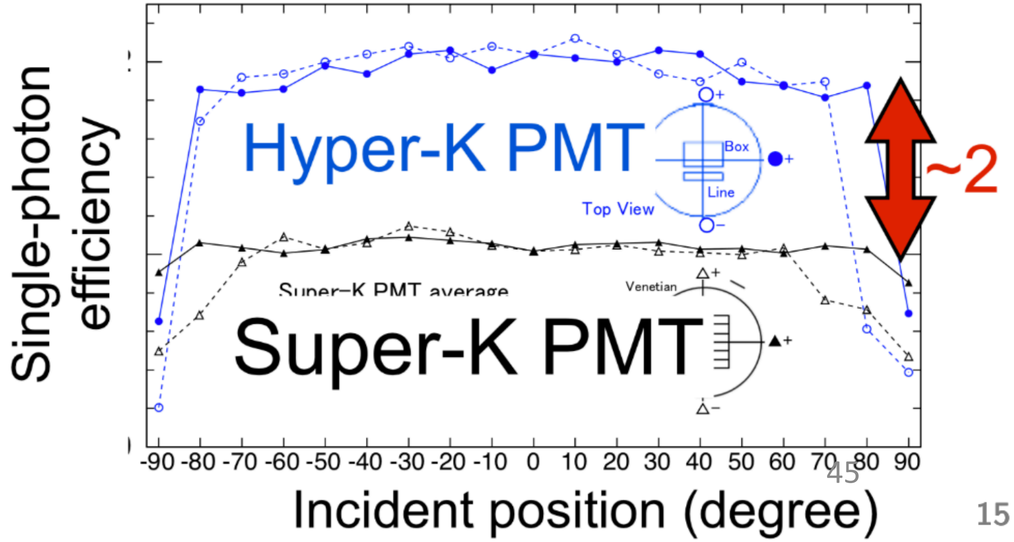
- **20~40%** photo-coverage
  (20 inch + mPMTs)
- **190 kton** fiducial vol.

Hamamatsu B&L PMT (20”)

mPMT (19x 3”)

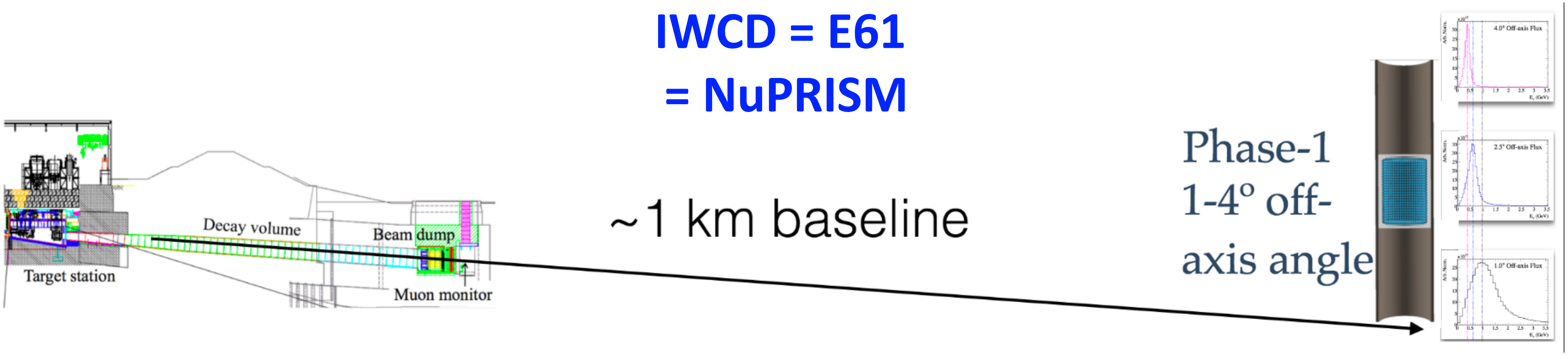
Fiducial Vol.
HK = SK **x 8**





Intermediate Water Cherenkov Detector

IWCD = E61
= NuPRISM



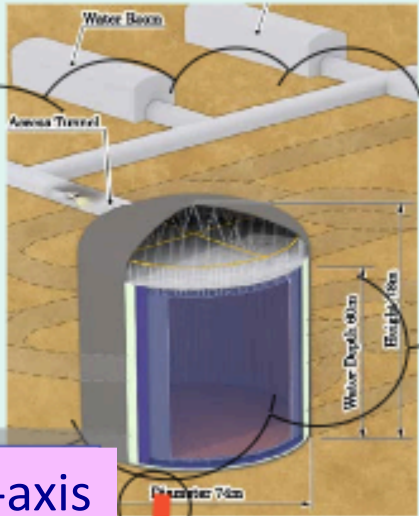
- ~1 km baseline
- 1~4° off-axis angles in 50m vertical tunnel
- 1 kton WC detector
- 480 mPMTs
- Detector optimization is on-going.

❑ To precisely measure $\nu_e / \bar{\nu}_e$ cross-section
❑ To measure neutron production in ν-nucleus scattering

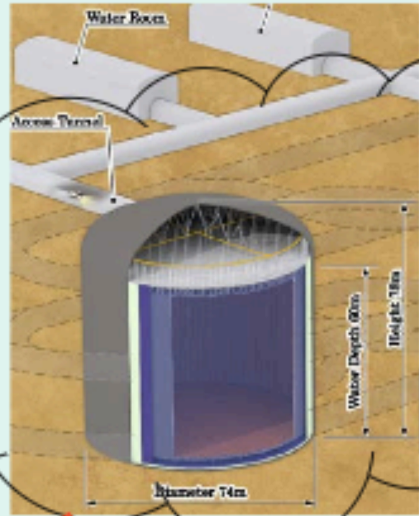
Hyper-K Two Detectors

T2HKK

KNO
Korean
Neutrino
Observatory



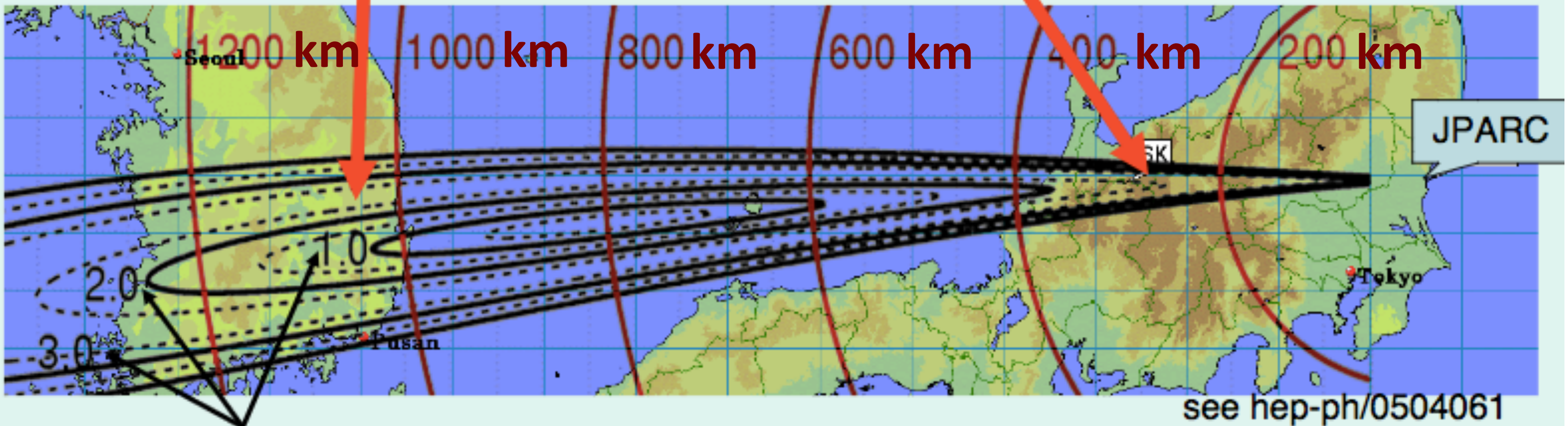
1~3 deg. off-axis



Hyper-K

2.5 deg. off axis

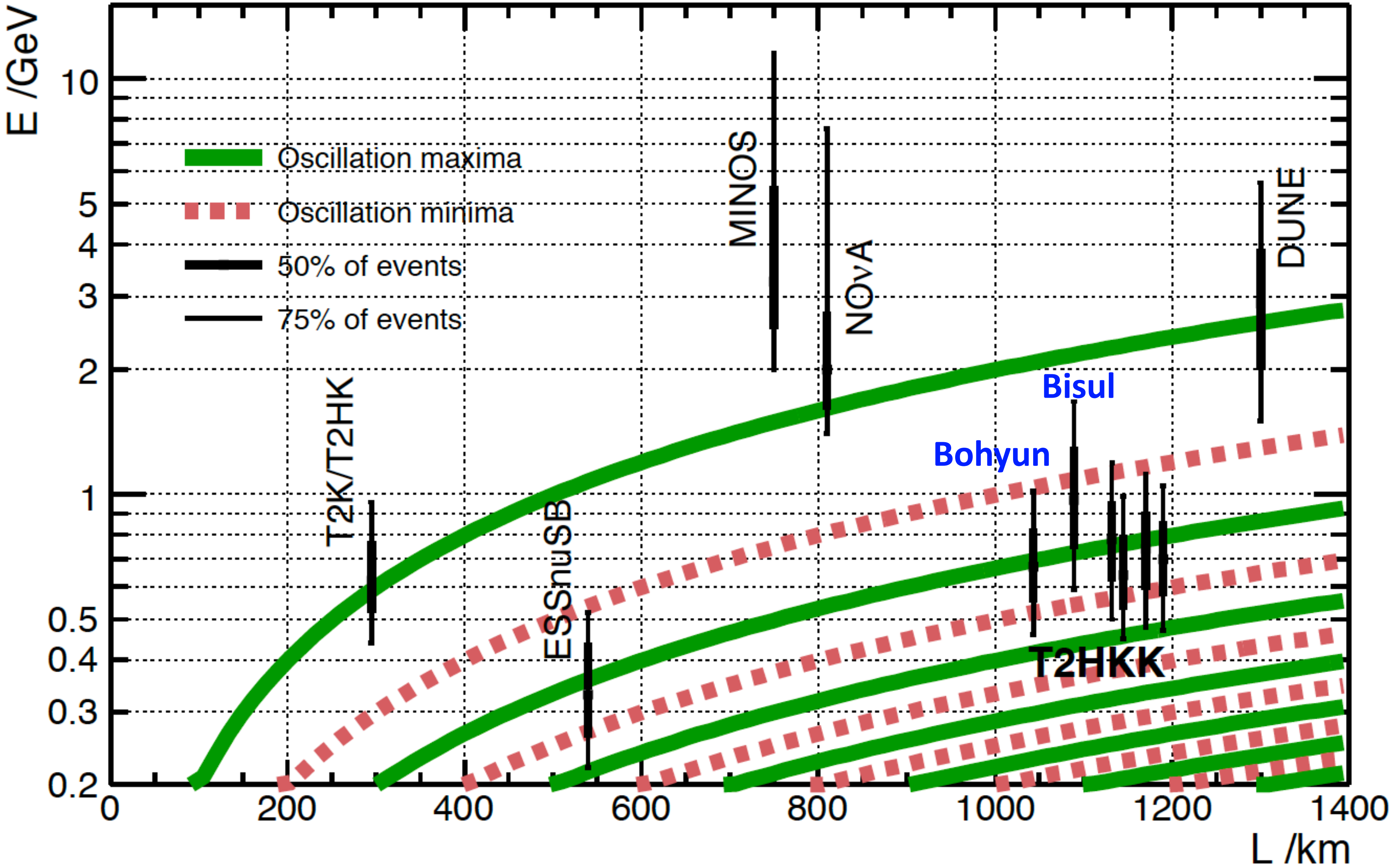
The J-PARC ν beam comes to Korea.



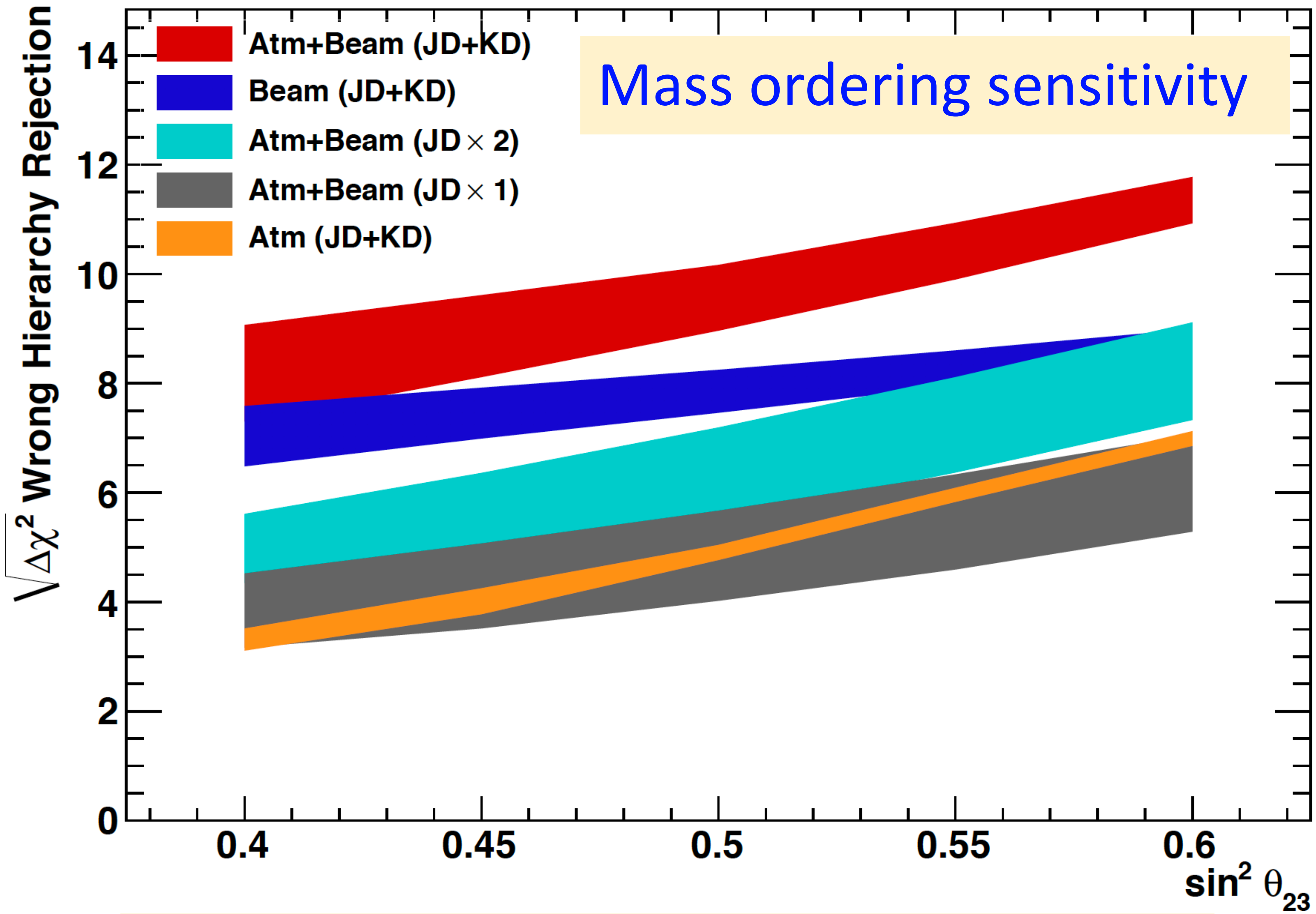
Off-axis angle

see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

Energy vs. Baseline



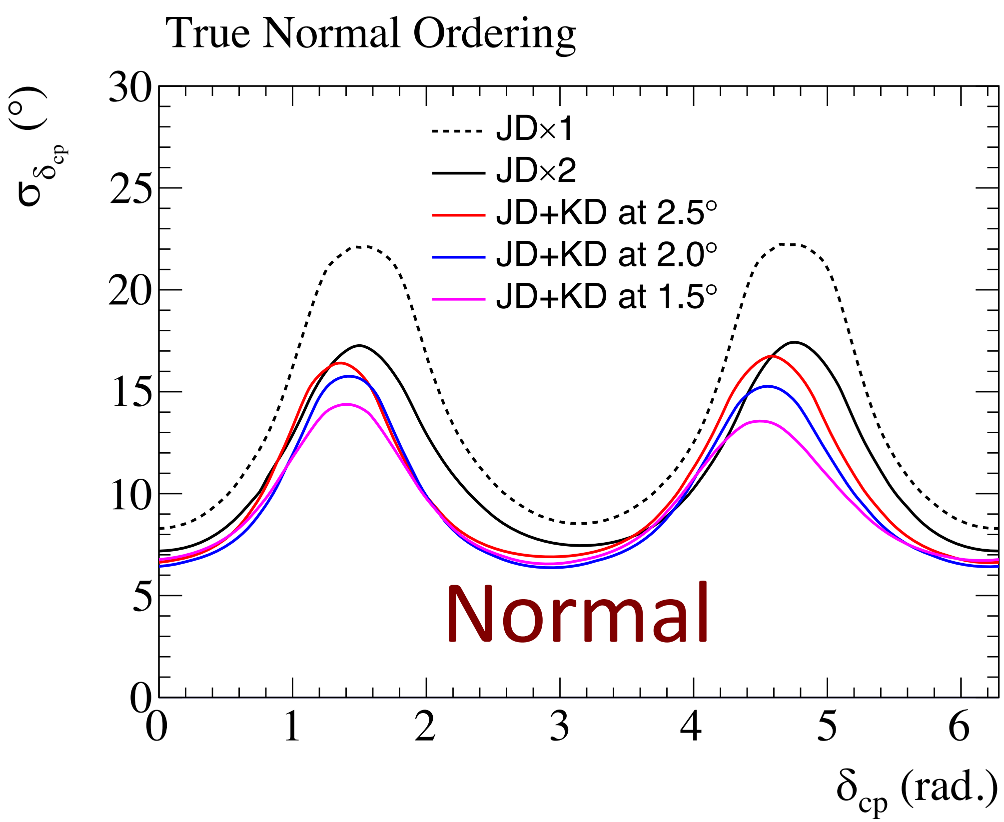
Beam + Atm. ν Data

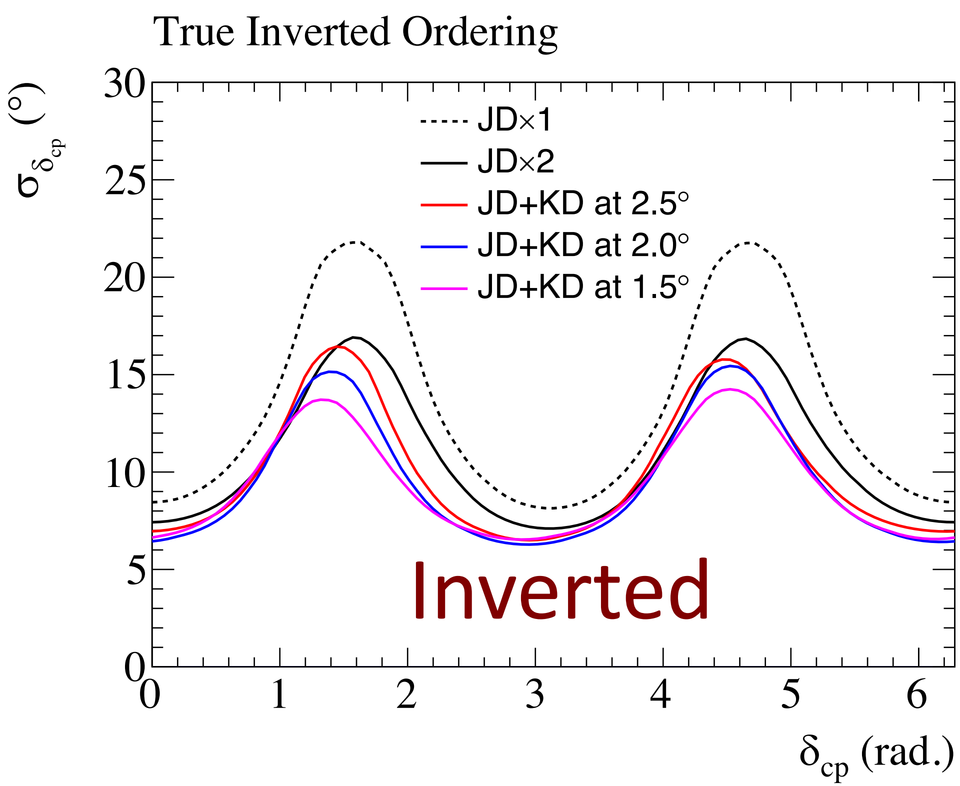


→ Best way to determine ν mass ordering among [[ν oscillation, 0νββ, cosmology]]

δ_{CP} Precision Sensitivities

→ Very important for flavor symmetry model of neutrino mixing
S. Petcov in ICHEP 2018



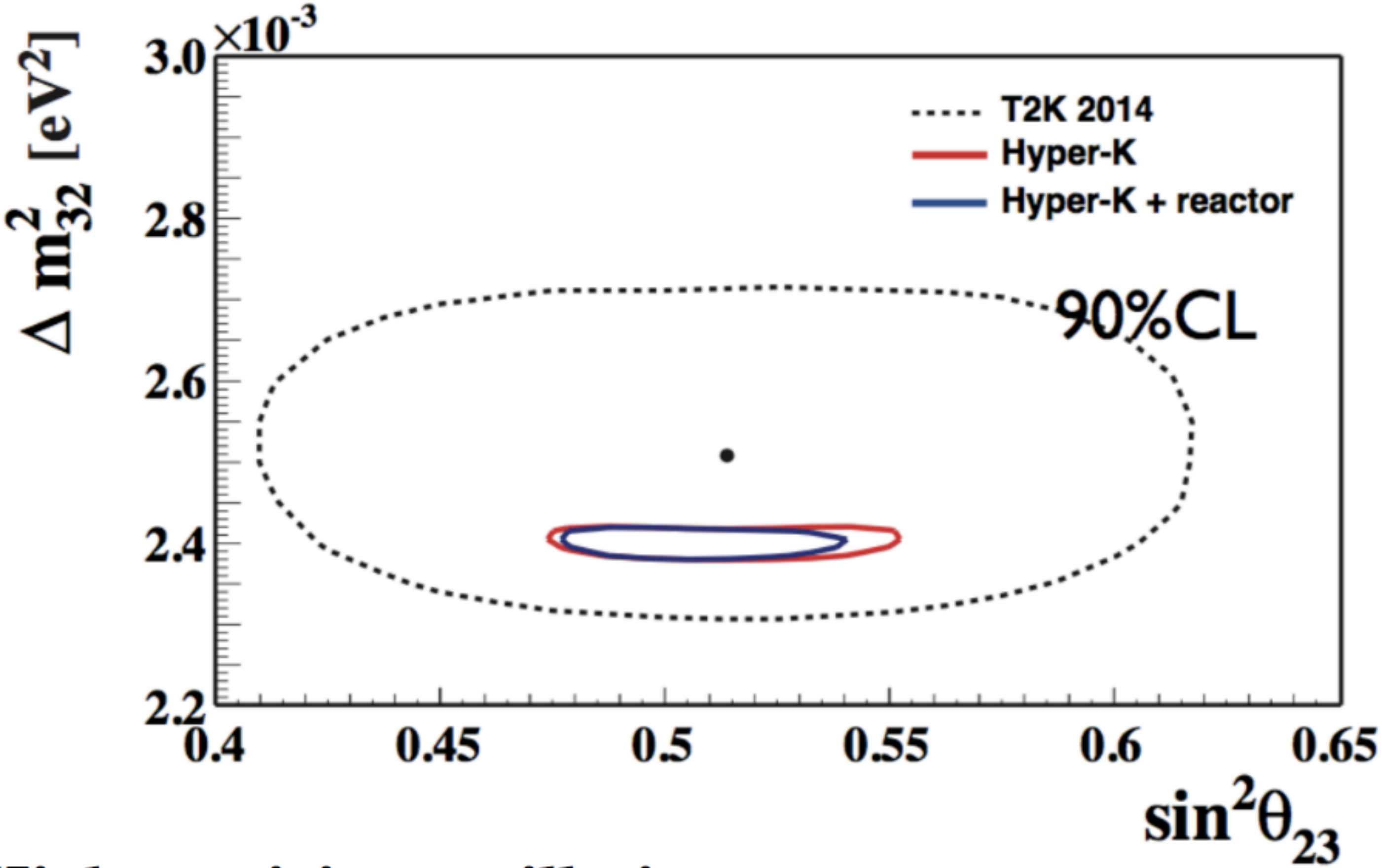


PTEP 2018, 6, 1-56

At maximum CP violation: JD+KD 1.5°: $\sigma(\delta_{CP})$ = 13~14 degree
JD x 2 : $\sigma(\delta_{CP})$ ~ 17 degree
JD x 1 : $\sigma(\delta_{CP})$ ~ 22 degree

Atmospheric Parameter Sensitivity

Neutrino oscillation parameters



High precision oscillation parameter measurement:

1.3% $\delta(\sin^2\theta_{23}) \sim 0.006$ (for $\sin^2\theta_{23}$=0.45)

3% $\delta(\sin^2\theta_{23}) \sim 0.015$ (for $\sin^2\theta_{23}$=0.50)

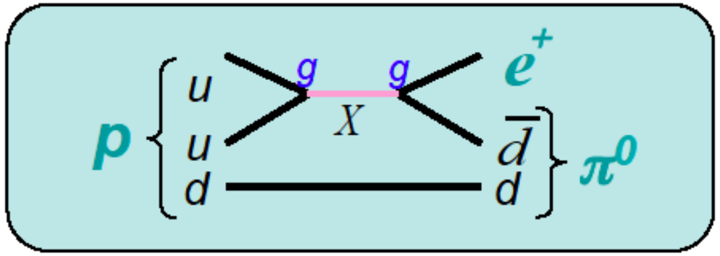
$\delta(\Delta m^2_{32}) \sim 1.4\times10^{-5}\text{eV}^2$ 15

~0.6%

Why Proton Decay Search ?

- Only way to directly probe Grand Unified Theory
- Two major modes predicted by many models

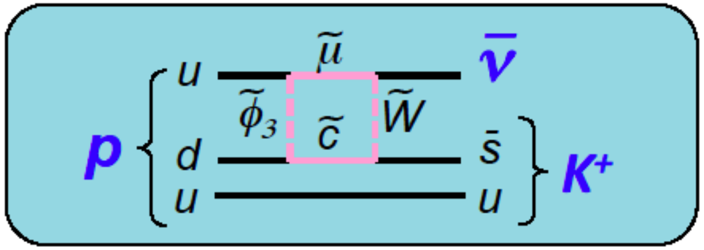
Mediated by gauge bosons



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

$$\Gamma(p \to e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY mediated



$p \to \nu K^+$

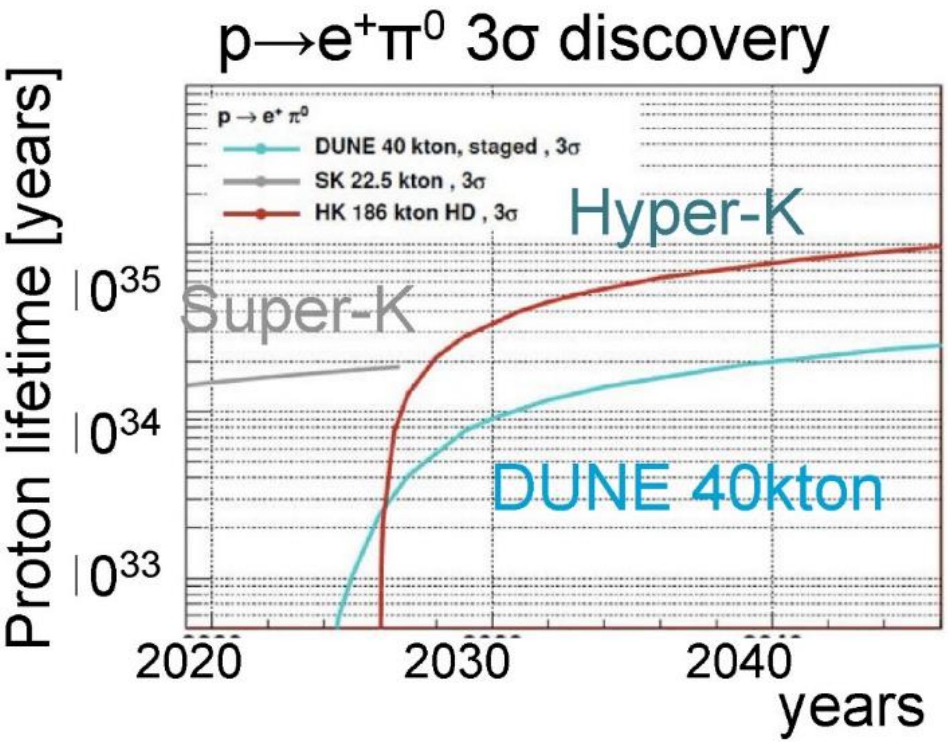
$$\Gamma(p \to \bar{\nu} K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

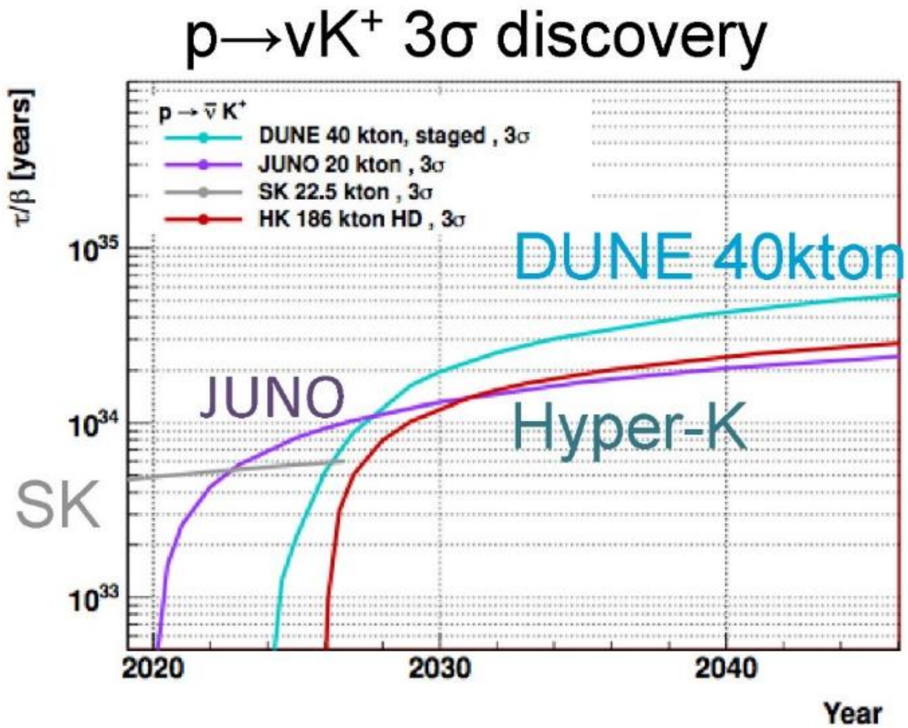
- Need broad searches including other possible modes

See F. Di Lodovico's proton decay talk on this Friday.

7) Proton Decay

- **Proton decay: physics at very high energy scale, where neutrino mass/mixing might be related with.**
- **Hyper-K: $\tau \sim 10^{35}$ years for $e\pi^0$**
- **DUNE: JUNO: $\tau \sim 2\times10^{34}$ years for νK^+**





Takaaki Kajita, Neutrino2018

Hyper-K Status

東京大学
THE UNIVERSITY OF TOKYO

The University of Tokyo
Hongo, Bunkyo-ku, Tokyo 113-8654, Japan

September 12th, 2018

Concerning the Start of Hyper-Kamiokande

Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project's importance and value both nationally and internationally.

The neutrino research that lead to Nobel prizes for Special University Professor Emeritus Koshiba and Distinguished University Professor Kajita has entered a new era. The international community has demonstrated the need for Hyper-Kamiokande. The considerable expertise and achievements of the University of Tokyo and Japan, and unique and invaluable contributions from national and international collaborators will ensure the project will make significant contributions to the intellectual progress of the world.

Makoto Gonokami
President, The University of Tokyo

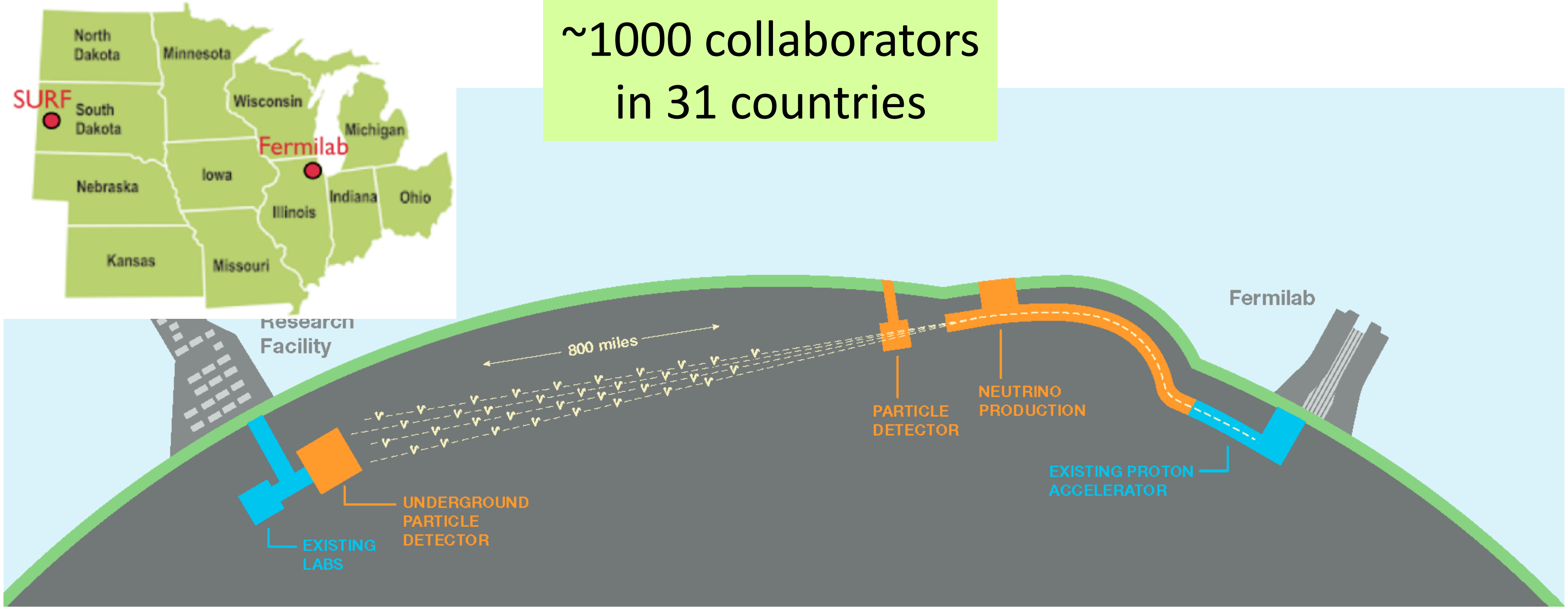
On Sept. 12th 2018,
U. Tokyo president & Kajita-san visited HK Collab. Meeting, and announced the start of HK construction.

- Seed funding in 2019 JFY
- Construction starts in 2020
- Data taking in ~2027

** HK Technical Design Report will be ready soon.

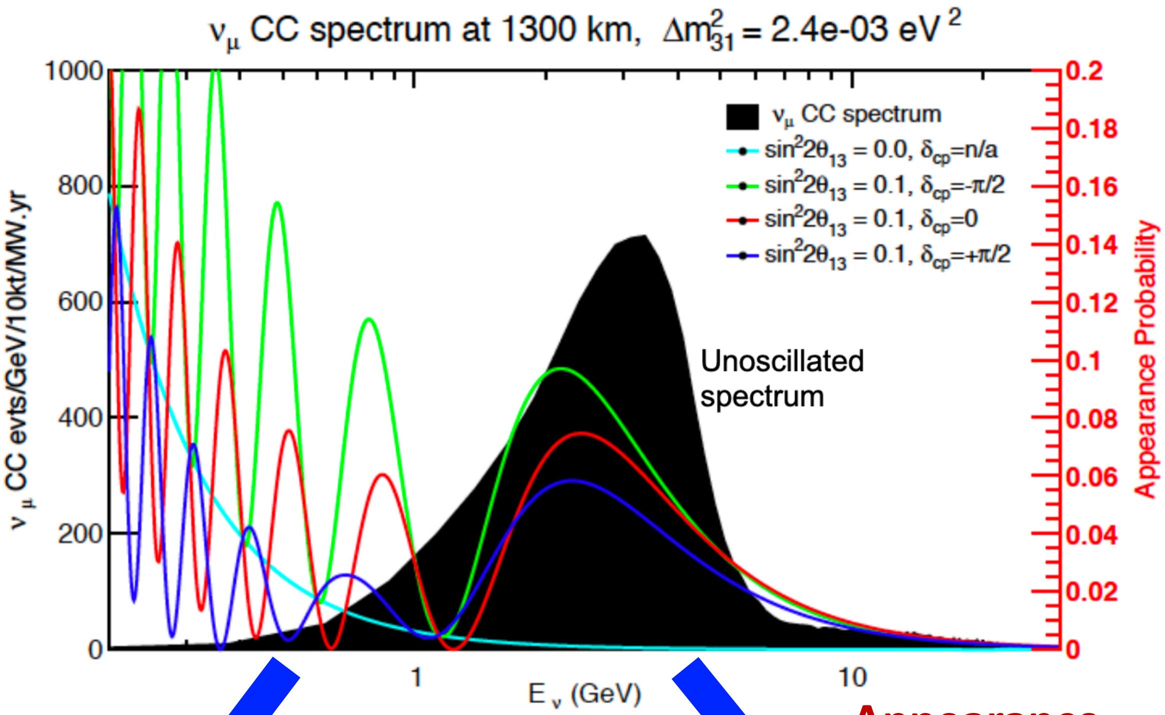
Deep Underground ν Exp. (2026~)

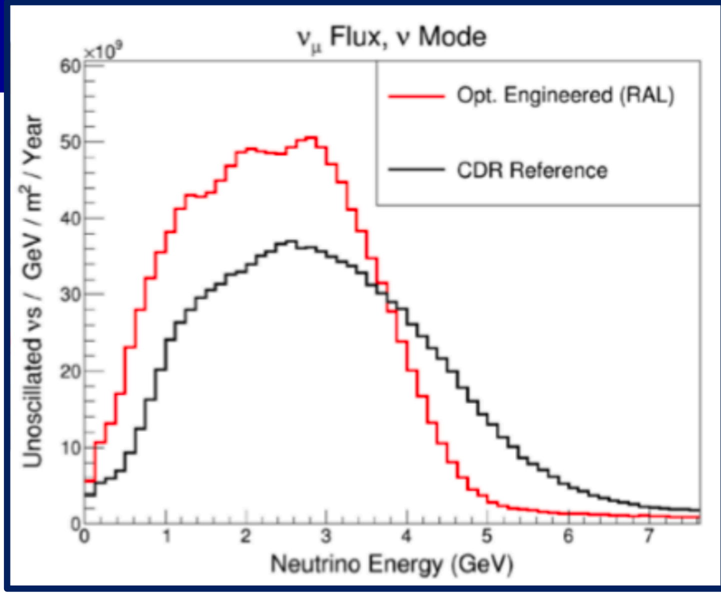
~1000 collaborators
in 31 countries

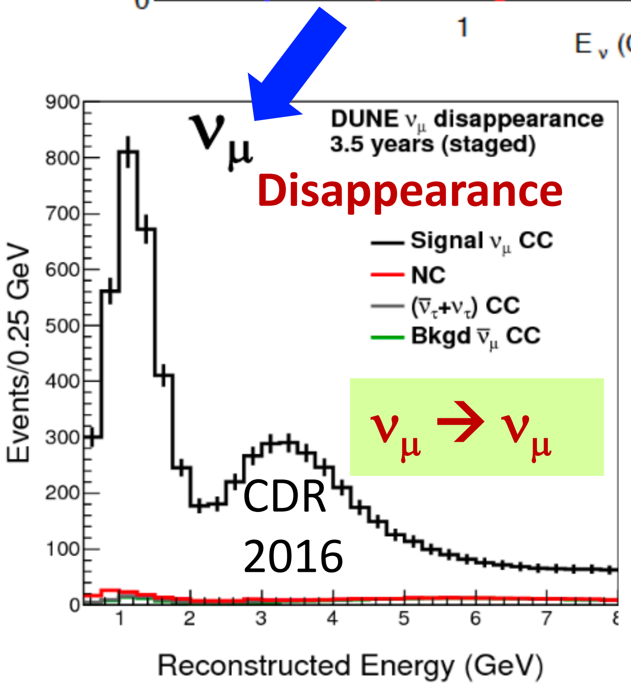


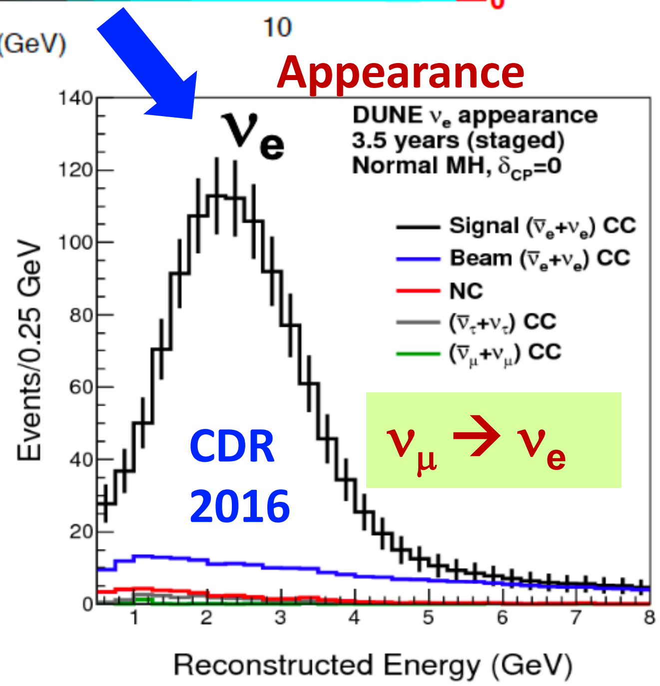
- Beam: nuMI ν beam (1.2 → 2.4 MW upgradable)
- Baseline: 1300 km w/ on-axis ν beam (E_ν < 8 GeV)
- Far detector: 4 x 10 kton (fiducial) LArTPC in 1.5 km depth
  (single or double phase TPC)
- Near detector: designing phase → to reduce σ_{syst}

DUNE ν Spectra

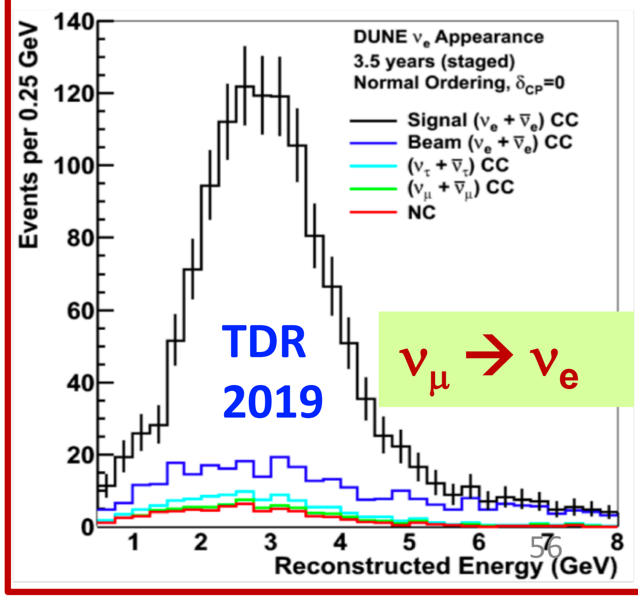




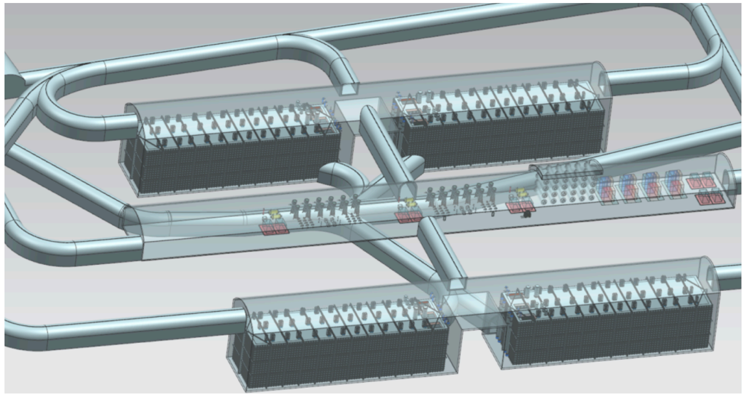




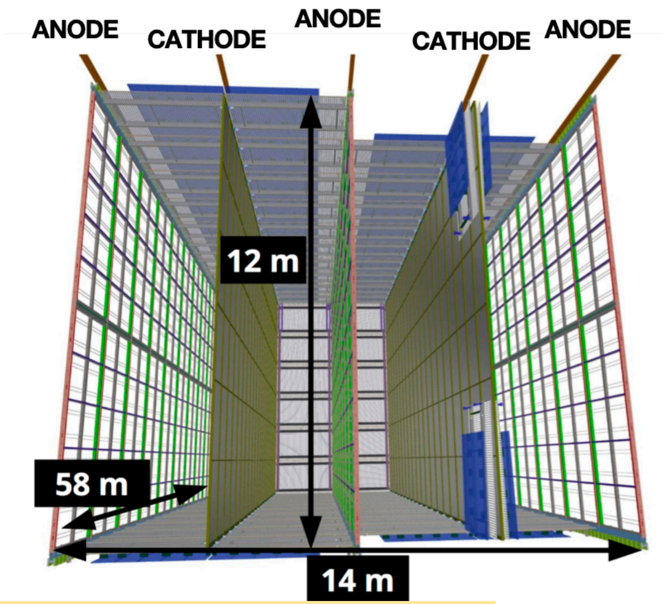
Technical Design Report (2019):
Full simulation reconstruction+ chain and CVN event selection



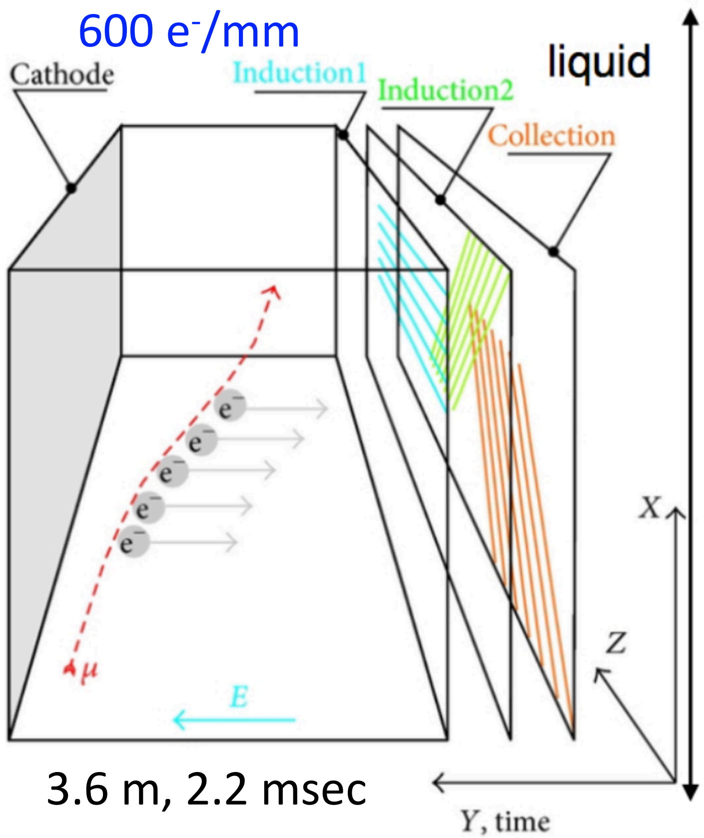
DUNE Far Detector



17 kt LAr/module
(10 kt fiducial vol.)



mip ionization:
600 e^-/mm



- ❑ LAr: scint. Light (PD) → triggering, t0
- ❑ TPC: tracking

Total 150 APA (Anode Plane Assembly) /module

- 1 APA = 6 m x 2.8 m
- 2,560 SiPM channels/APA

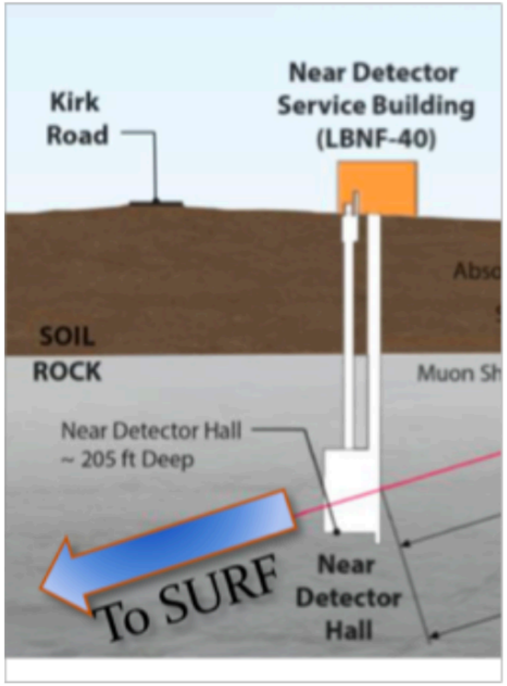
- ➢ e^- drifts horizontally to Anode.
  $\langle V_d \rangle$ = 1.63 m/ms
- ➢ 500 V/cm → 180 kV at cathode

DUNE Near Detector

- Constrain systematic uncertainties for long baseline oscillation analysis
- Also enables high precision neutrino interaction physics

1.3 km baseline

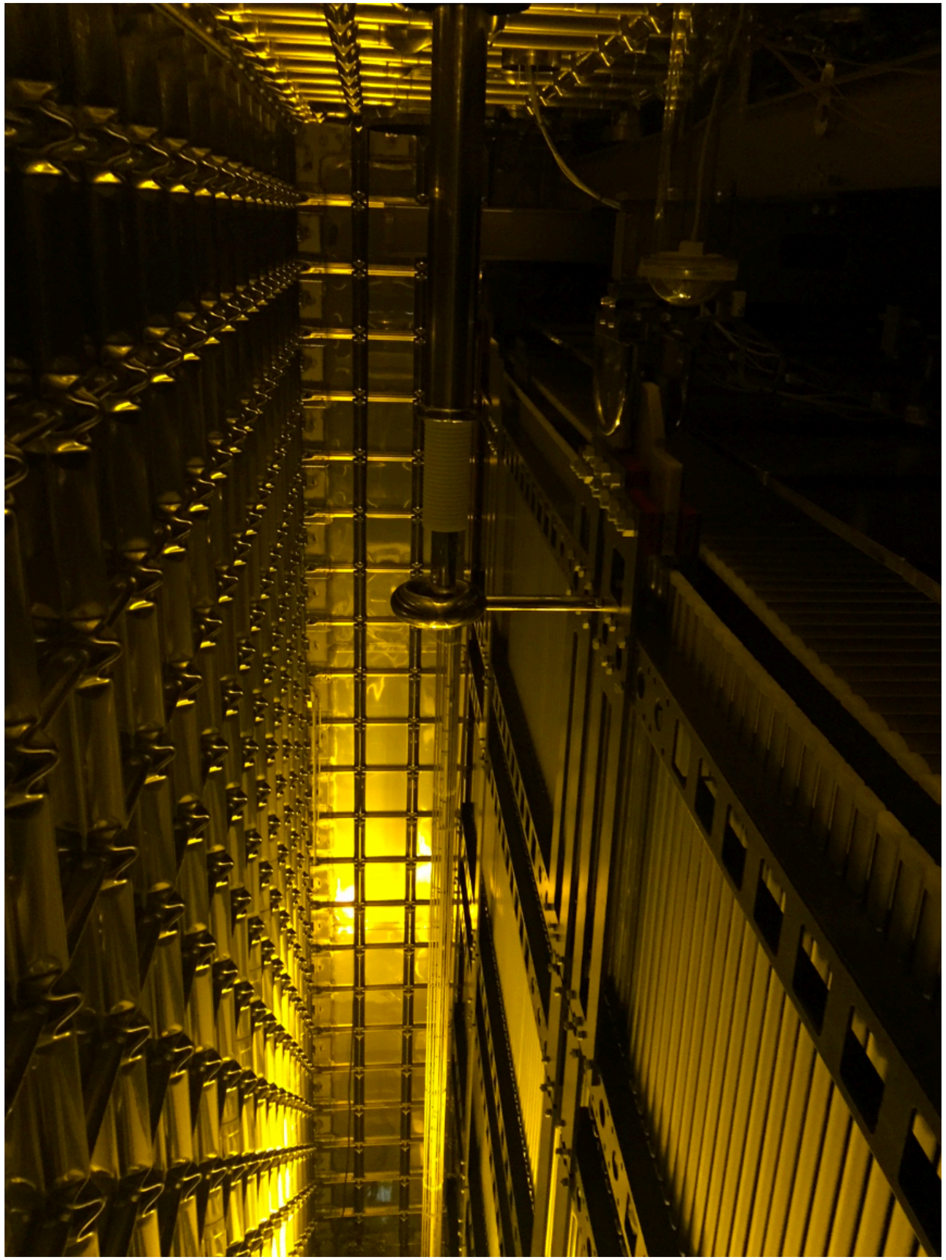
- Current Concept is an integrated system composed of multiple detectors
  - Highly segmented Liquid Argon Time Projection Chamber (~75 t)
  - Magnetized multi-purpose tracker w/ High Pressure Ar-CH_4 TPC (~1 t) surrounded by electromagnetic calorimeter and muon tagger
  - Magnetized 3D scintillator tracker (~6 t)



- Capability for the LArTPC to be moveable off axis is being investigated
- ND Conceptual Design Report (CDR) planned for 2019

B. Svoboda @Prospects in Neutrino Physics 2019

ProtoDUNE @CERN



Thanks to "Neutrino Platform" @CERN

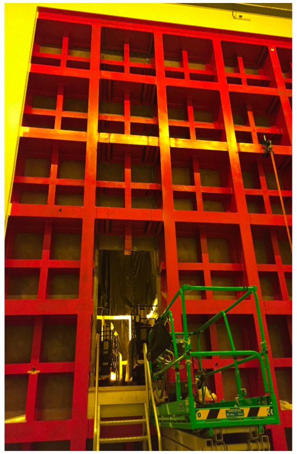
ProtoDUNE construction: 2016 – 2018

- 1 kton LArTPC SP (6x6x7m^3)
- Beam data taking: Sept.-Nov. 2018
- Cosmic μ data: until early 2021

(due to CERN Long Shutdown 2)

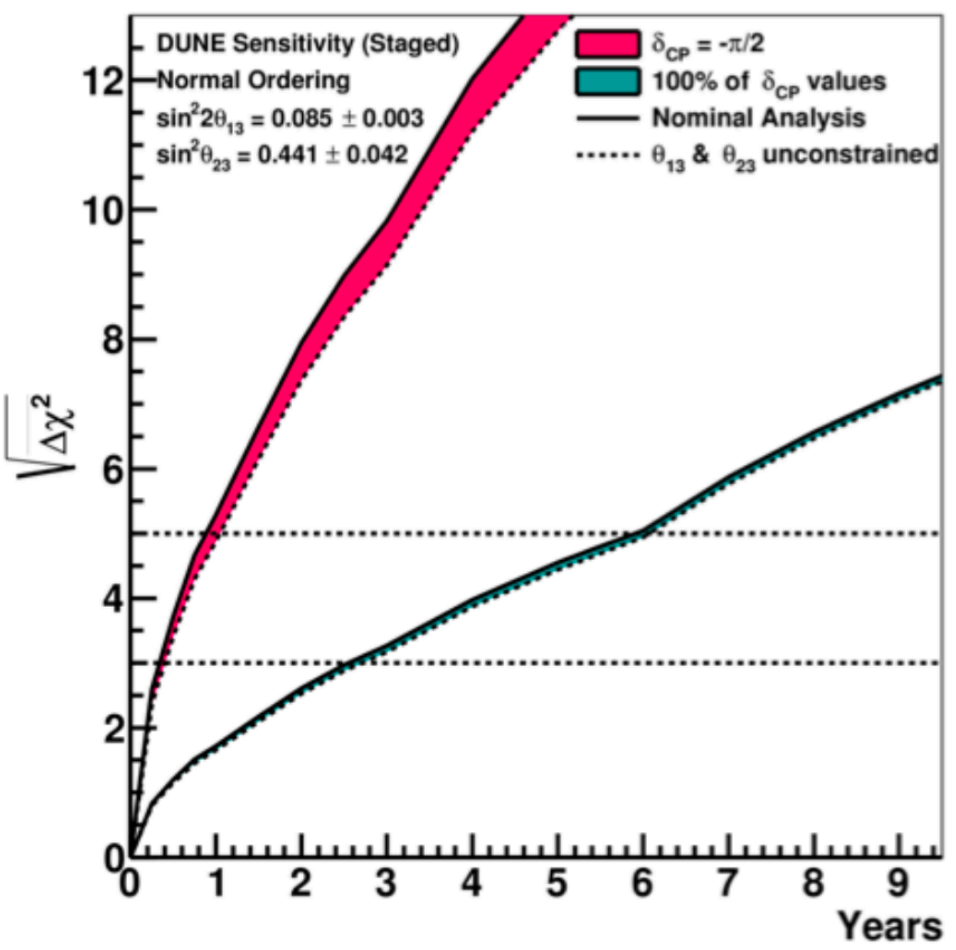
Purpose:

- Validation of design
- Understand detector response
- Long term stability, etc.

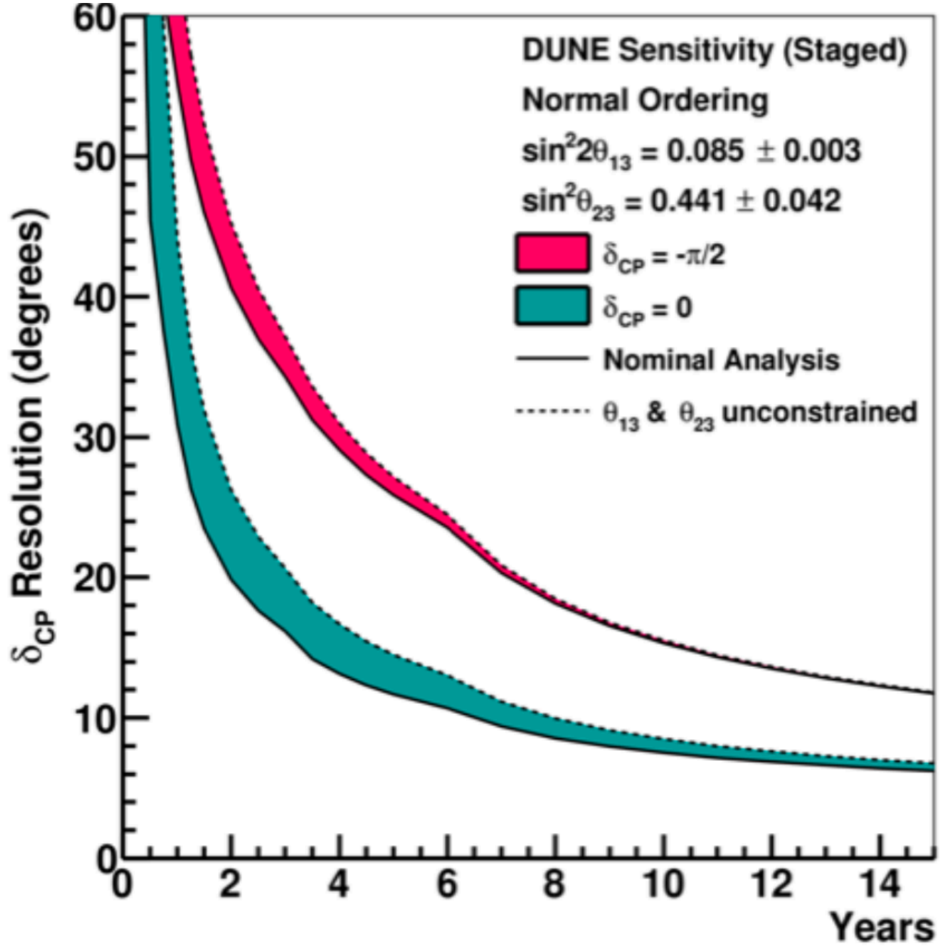


DUNE Sensitivities

Mass Ordering



δ_{CP}



DUNE Status

- Ground breaking: July 2017 (pre-excavation underway)
- Cavern excavation: 2021-2024
- Near site construction starting in 2020
- Ground breaking for MW proton linac: Mar 2019

  → Neutrino beam available in 2026/27

- ProtoDune-SP successfully constructed at CERN (NuPlatform)
- Double phase ProtoDUNE will take cosmic data summer 2019.

- **Module 1**: **single** phase installation: summer 2024

  (data taking in 2025 for SuperNova burst, atm. Nu)
- **Module 2**: **double** phase LArTPC
- **Module 3**: **single** phase LArTPC
- **Module 4**: "module of opportunity" w/ different design

For example, WbLS detector (THEIA)

** DUNE Technical Design Report will be ready in summer 2019.

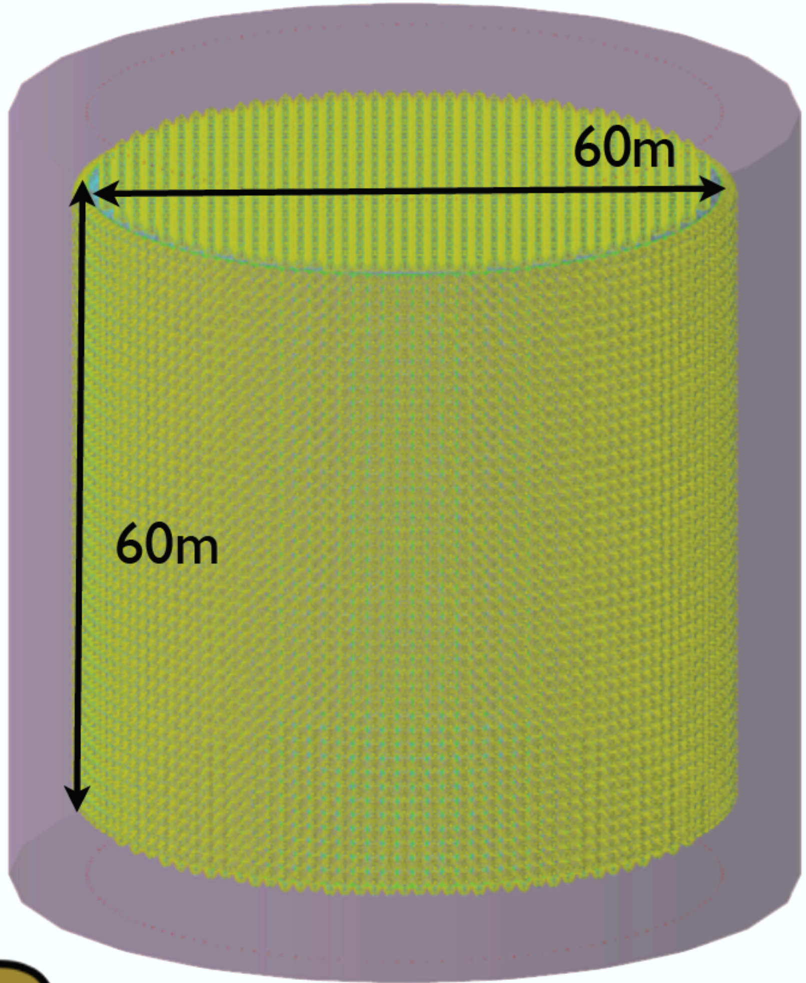
THEIA:

G. Orebi Gann talk, 2015

A realisation of the Advanced Scintillation Detector Concept (ASDC)

- Large-scale detector (50-100 kton)
- WbLS target
- Fast, high-efficiency photon detection with high coverage
- Deep u/ground (Pyhäsalmi, Homestake)
- Isotope loading (Gd, Te, Li...)
- *Flexible*! Target, loading, configuration

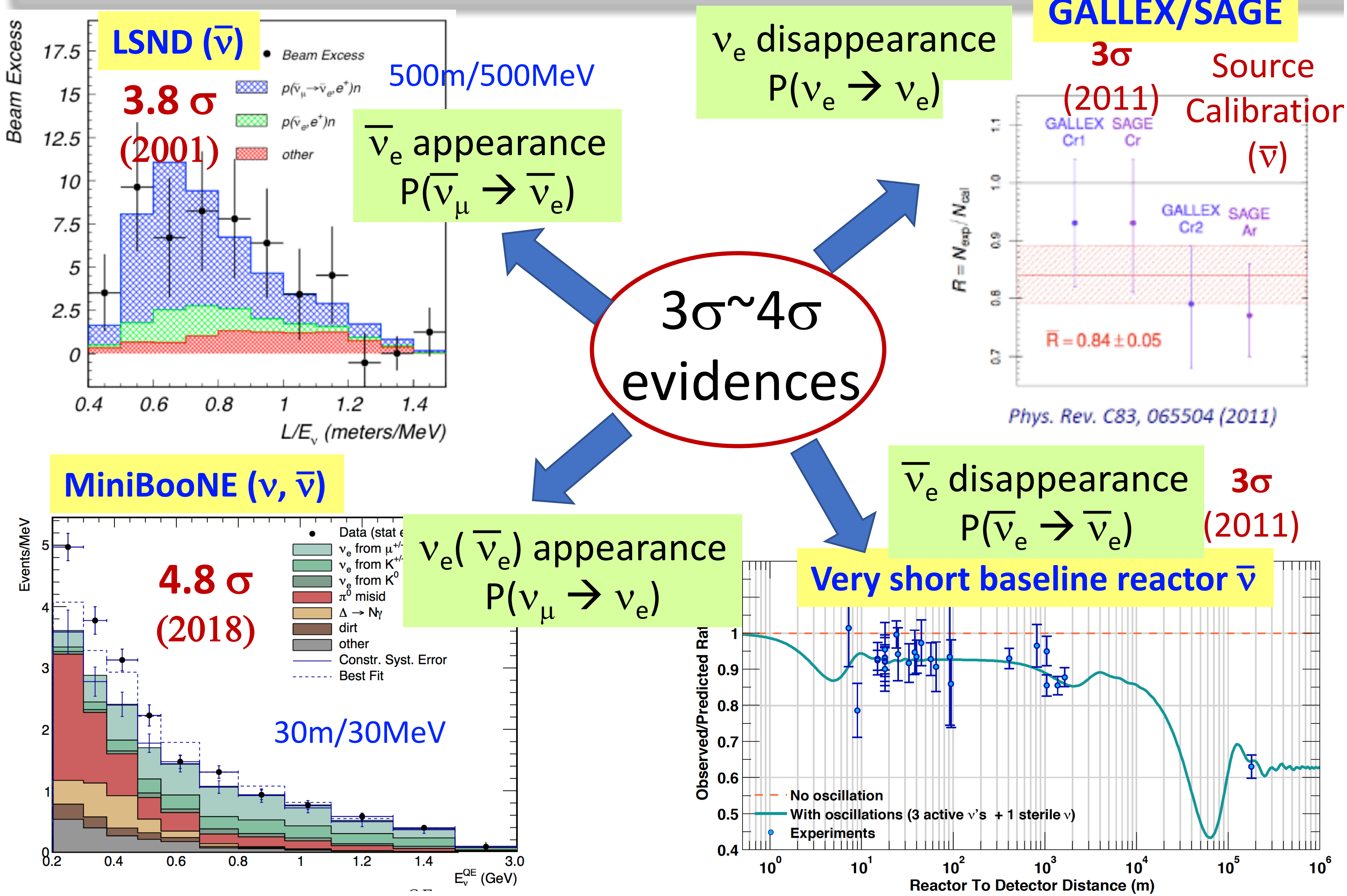
➡ **Broad physics program!**



Detector image product of RAT-PAC

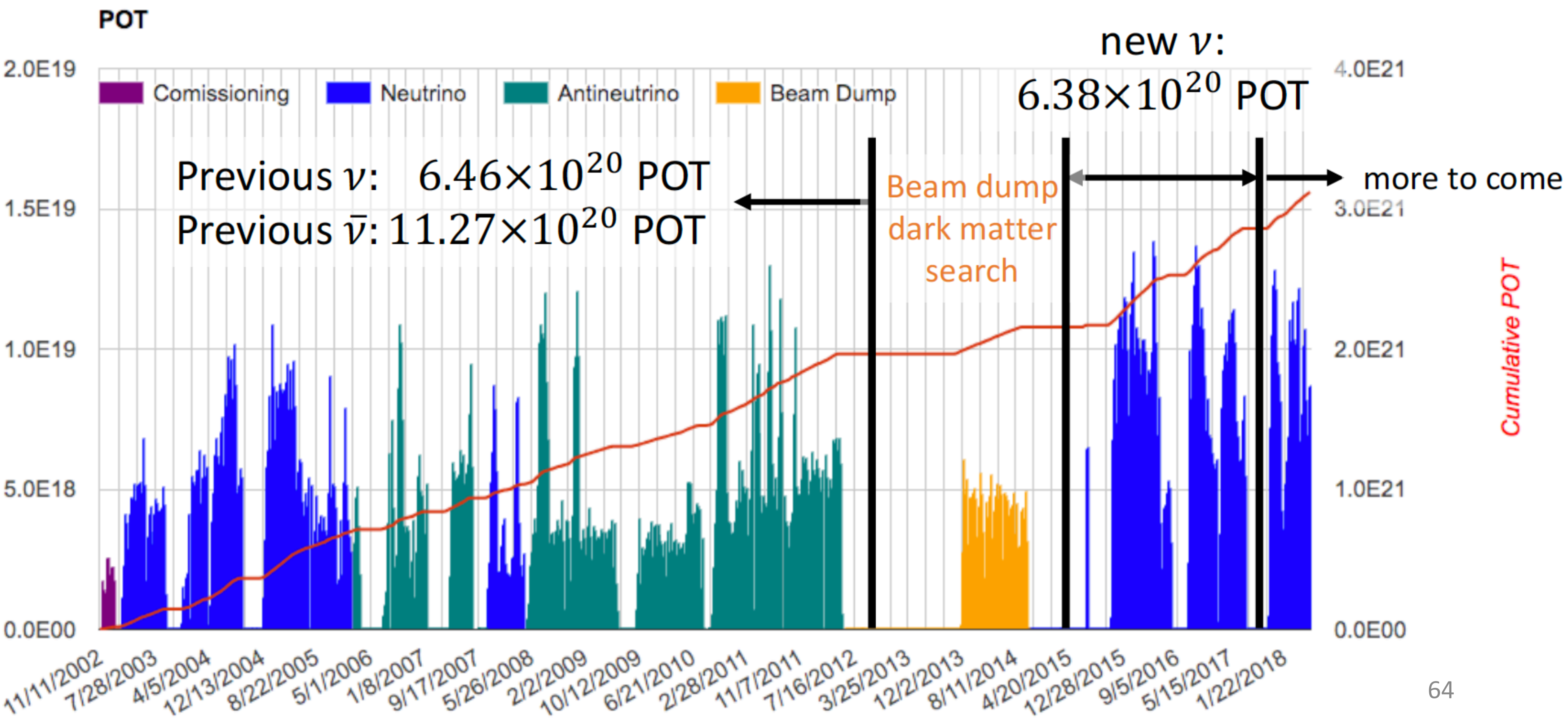
Concept paper - arXiv:1409.5864

Sterile Neutrinos at ~eV ?

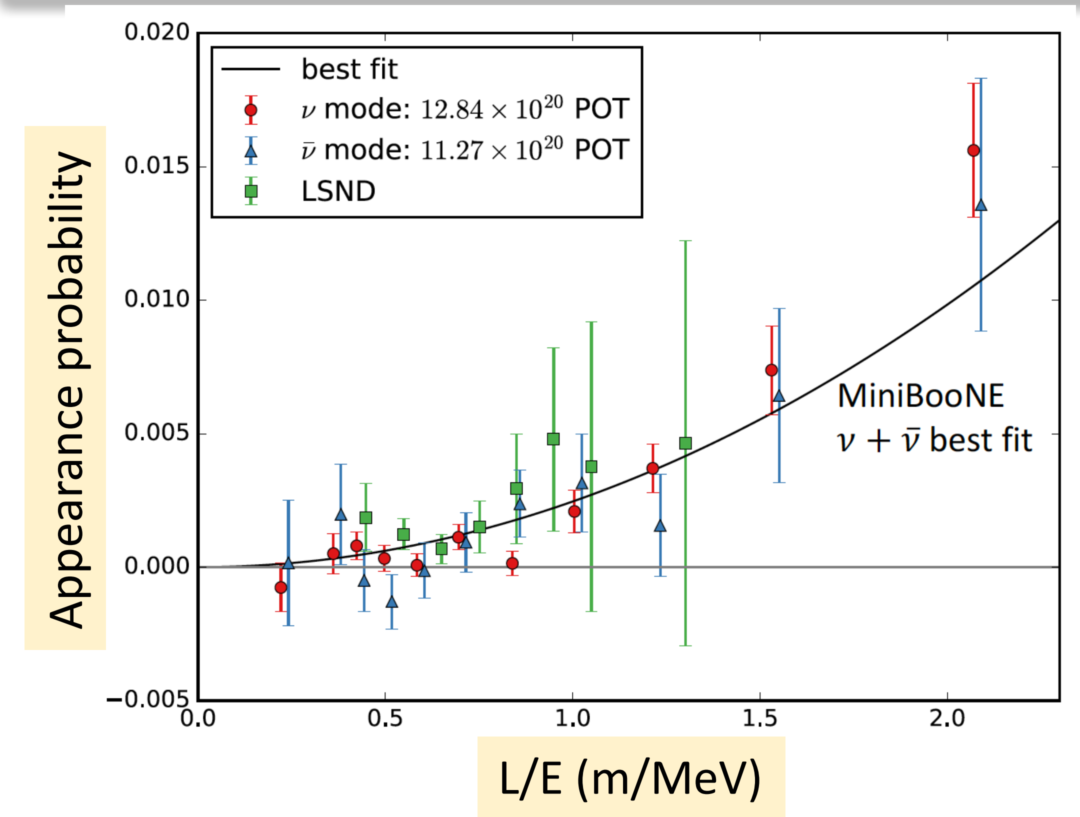


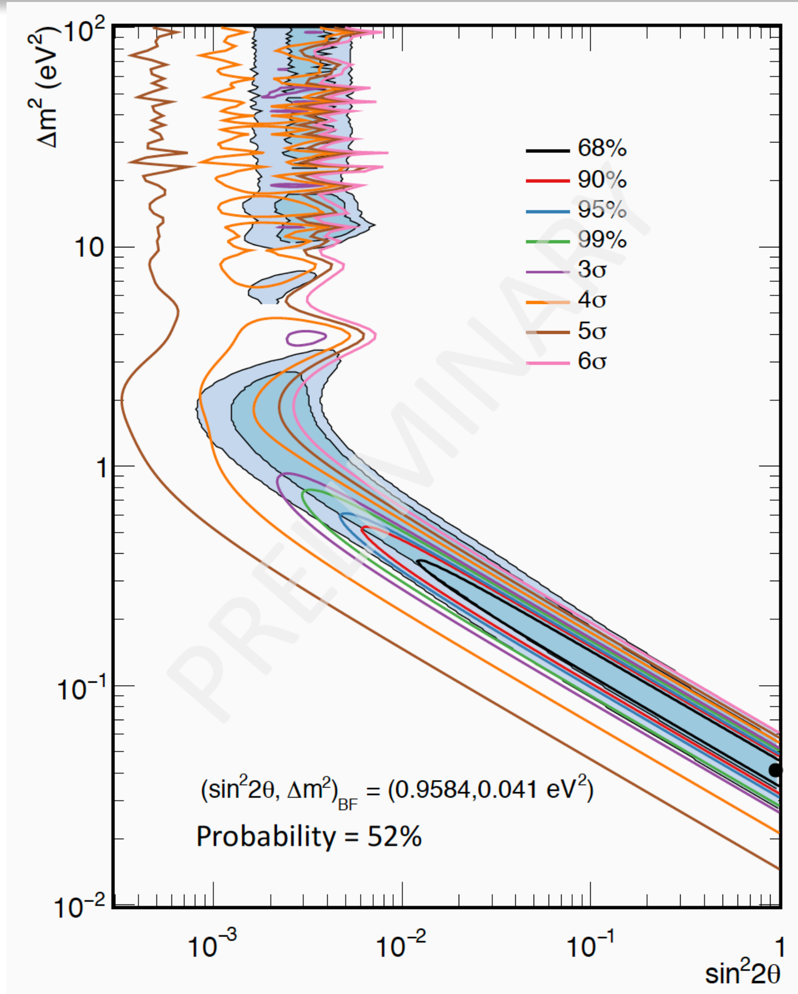
MiniBooNE Data by 2018

- 15+ years of taking data
- Total 30 x 10^{20} POT roughly 1 : 1 in $\nu : \bar{\nu}$
  where, new ν data of 6.38 x 10^{20} POT



MiniBooNE Results in 2018



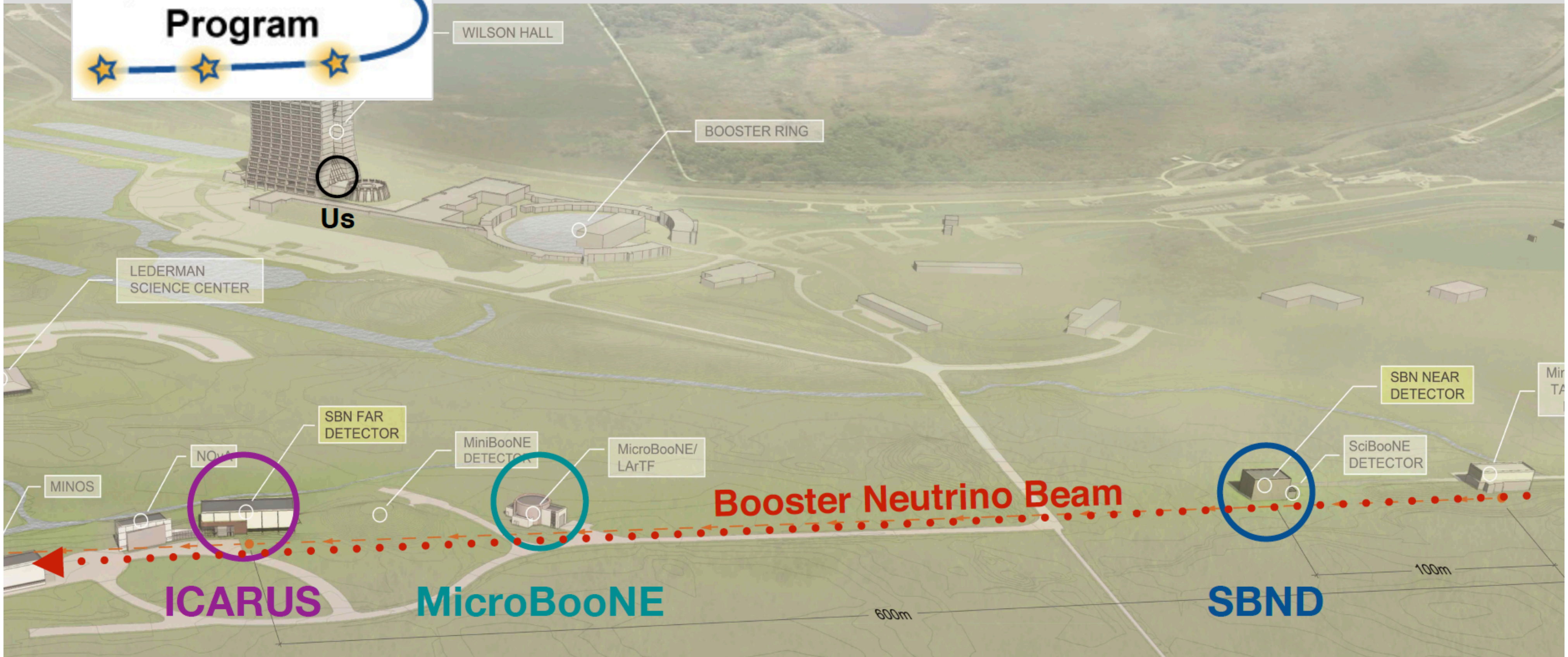


➢ Large $\sin^2 2\theta$ value is unphysical for 3+1 ν osc. frame.

- Total excess for neutrino + antineutrino: $460.5 \pm 95.8 (4.8\sigma)$
- Combined with LSND (3.8σ), total significance is at 6.1σ

Three LArTPCs in the BNB

SBN Program

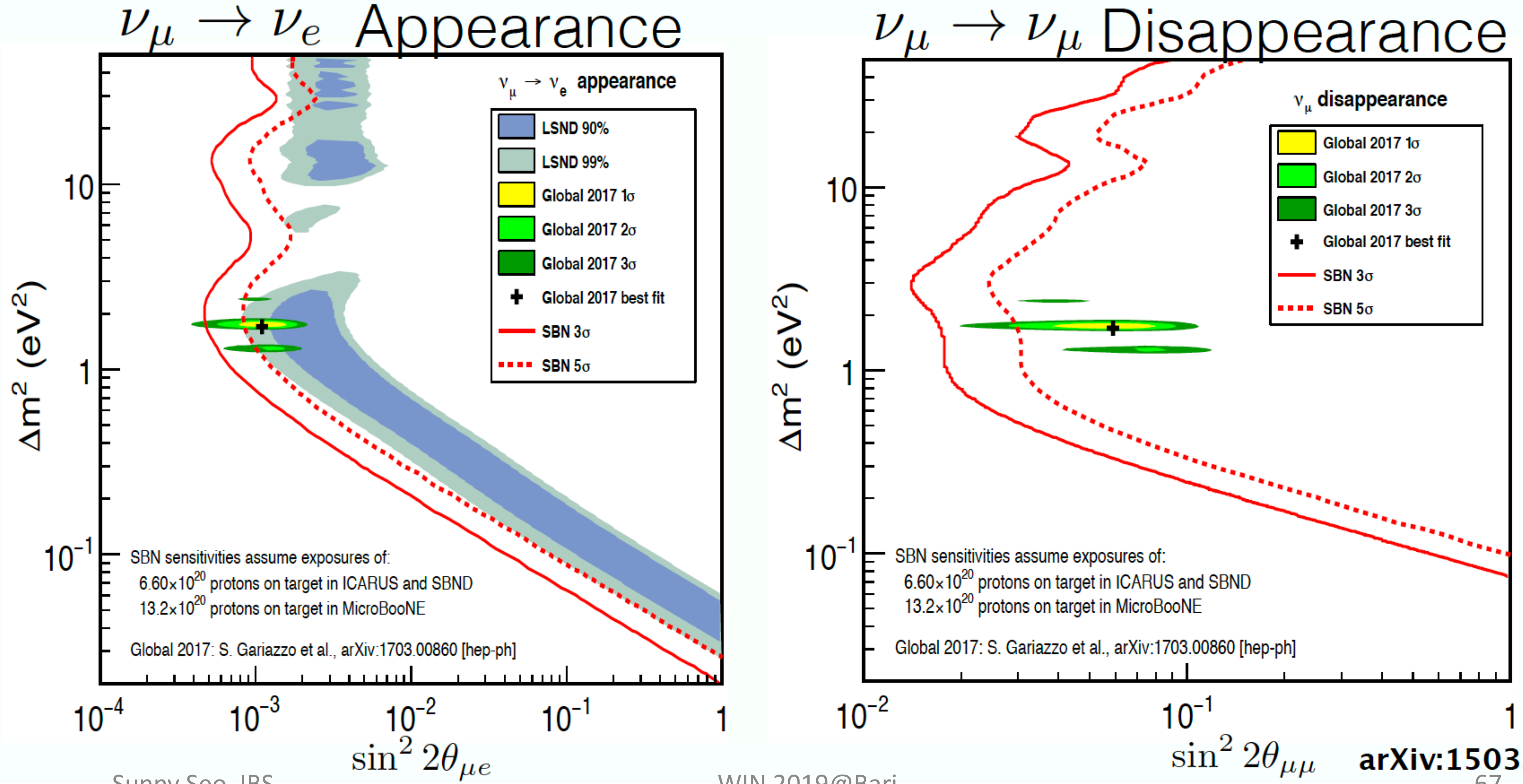


ICARUS	µBooNE	SBND
L = 600 m M = 476 ton	L = 470 m M = 85 ton	L = 110 m M = 112 ton

SBN Sensitivities

- Reach of full program
  - SBND/ICARUS (6.6e20 POT ~ 3 years)
  - MicroBooNE (13.2e20 POT ~ 6 years)

Appearance and disappearance tested in one program

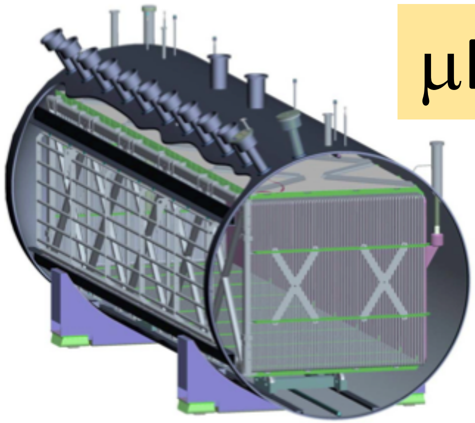


arXiv:1503.01520

SBN Status

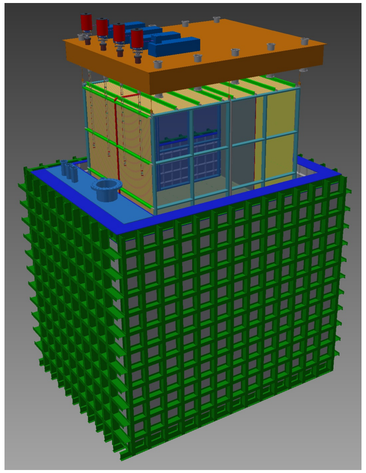
SBND

- Performing R&D w/ candidate DUNE technologies
- Detector construction underway
- Data taking: ~2020



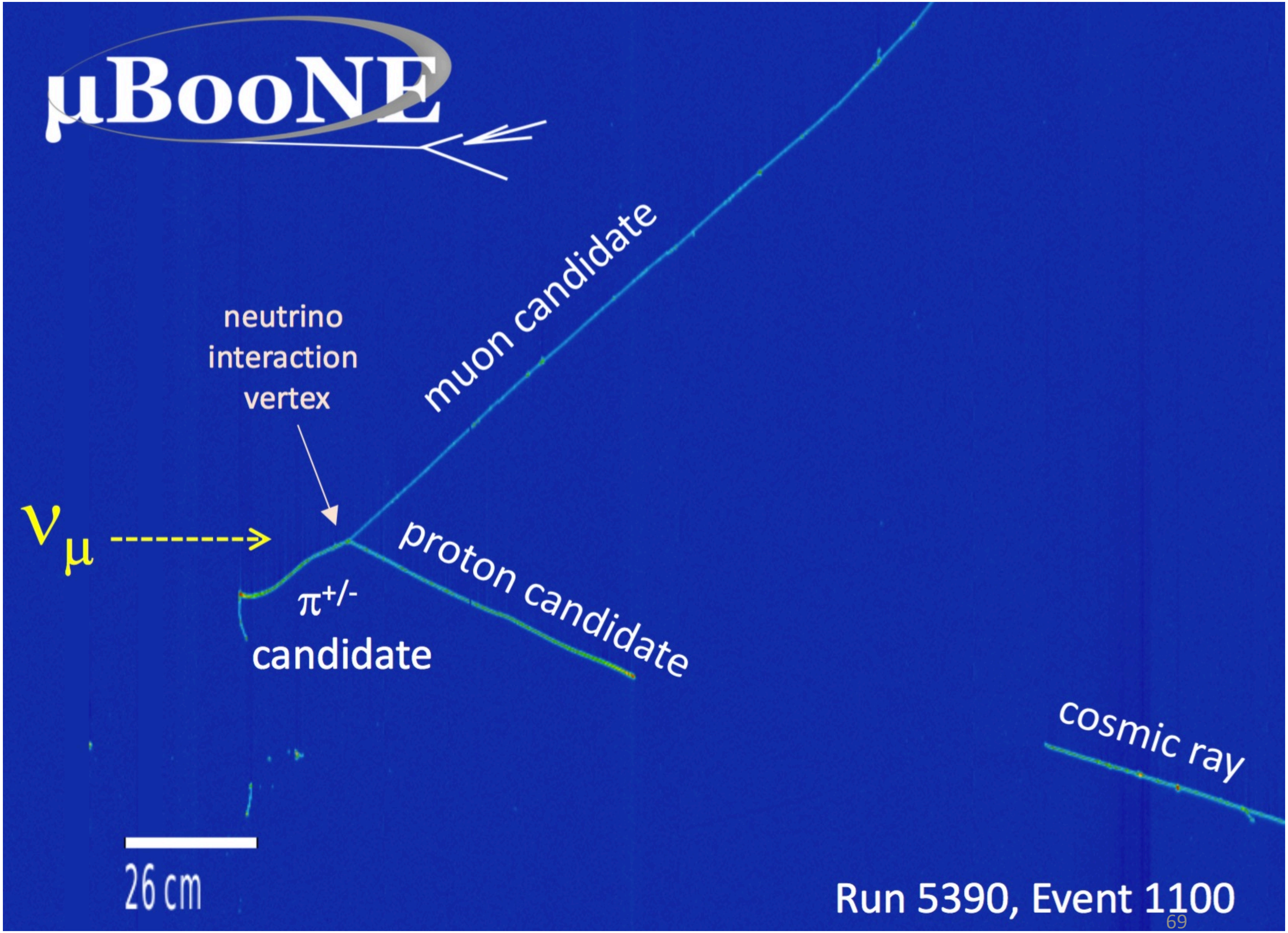
μBooNE → High muon rate is a challenge !

- Detector operating smoothly
- 9.4×10^{20} POT a year ago (> 95% DAQ up time)
- Improvements: detector response, reconstruction
- Confirm or refute MiniBooNE in 2019~2020 ?

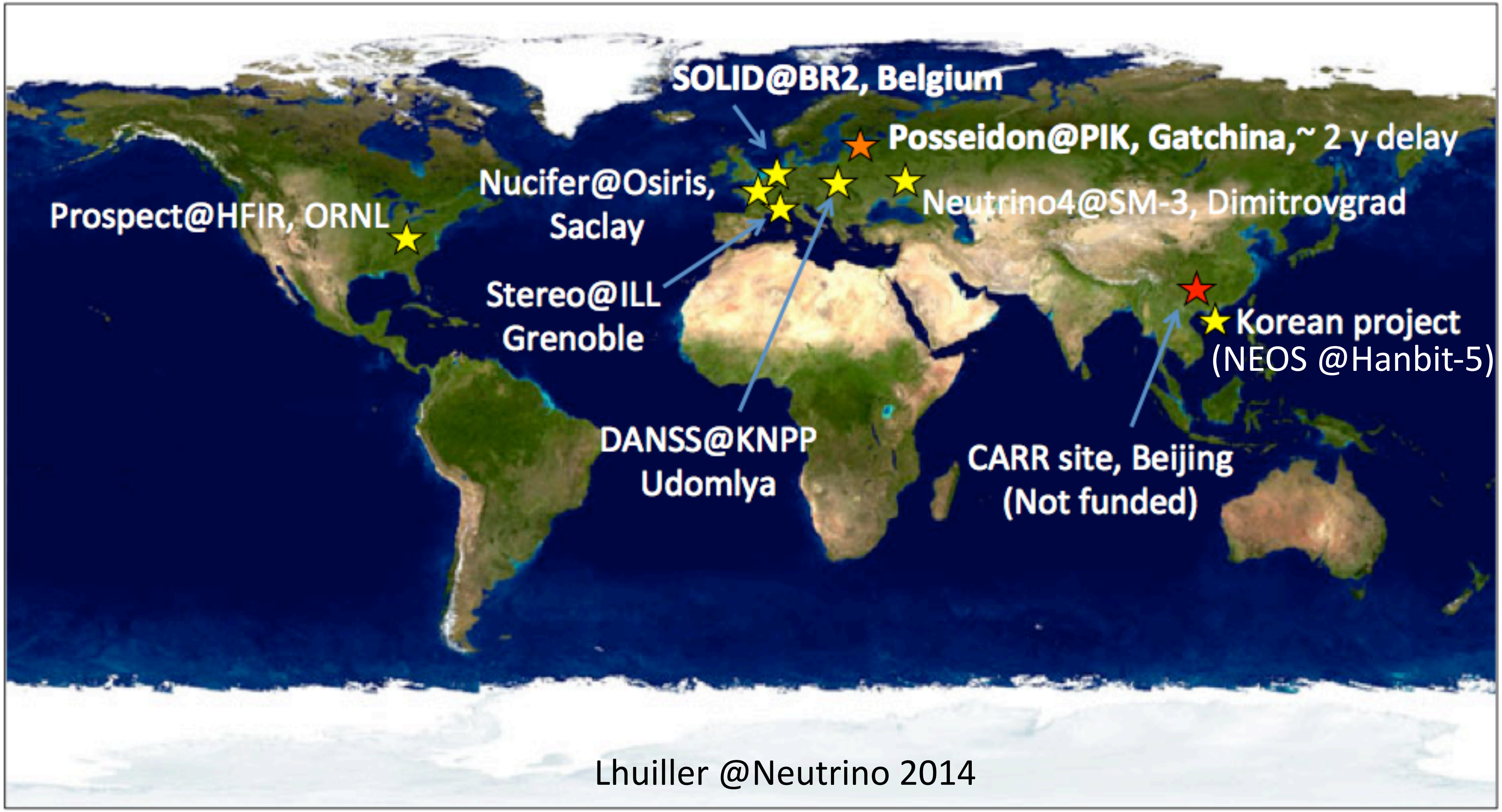


ICARUS

- Detector construction underway
- Detector installation: July 2018 --
- Data taking: ~2019


μBooNE
muon candidate
neutrino
interaction
vertex
ν_μ
$\pi^{+/-}$
candidate
proton candidate
cosmic ray
26 cm
Run 5390, Event 1100

Very Short Baseline Reactor ν Exp. Sites



Scintillation Detectors @VSBL

Liquid scintillator (LS)

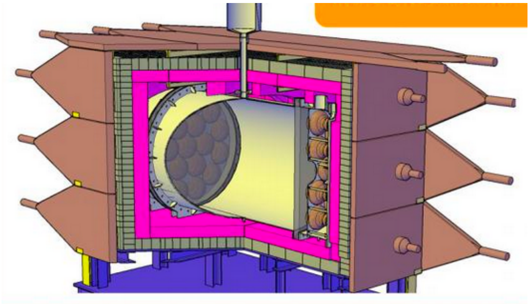
GdLS, ^{6}LiLS

(* : operating exp.)

Gd, Li → n-tagging

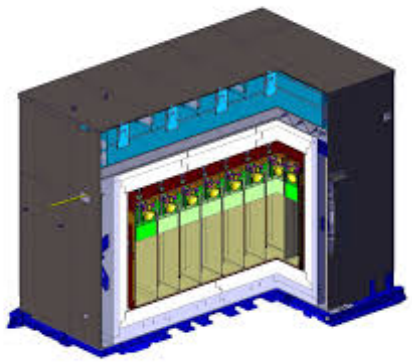
Homogeneous

***NEOS,**
Nucifer
(finished)



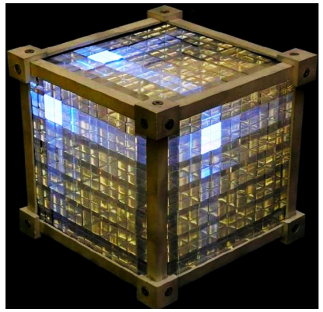
Segmented

***Neutrino-4,**
***PROSPECT,**
***Stereo**



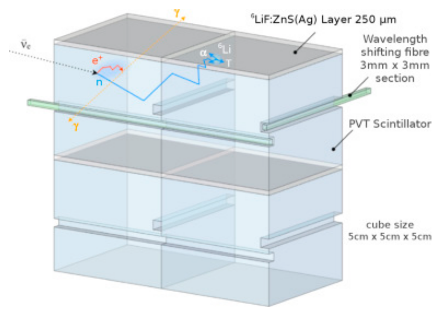
Plastic scintillator (PS)

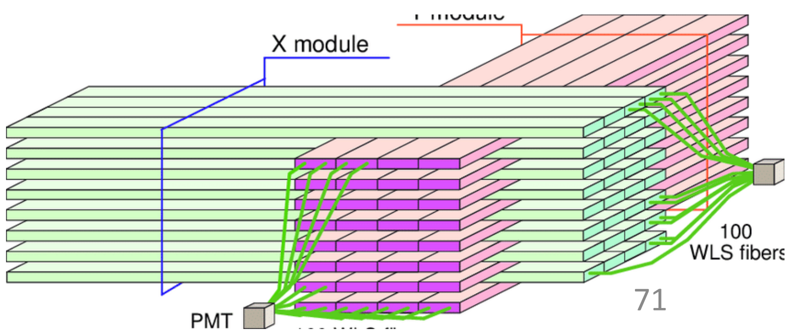
PS (Gd/^{6}Li sheet), ^{6}LiPS



Segmented

***DANSS,**
***SoLid,**
NuLat (R&D),
Chandler (R&D)

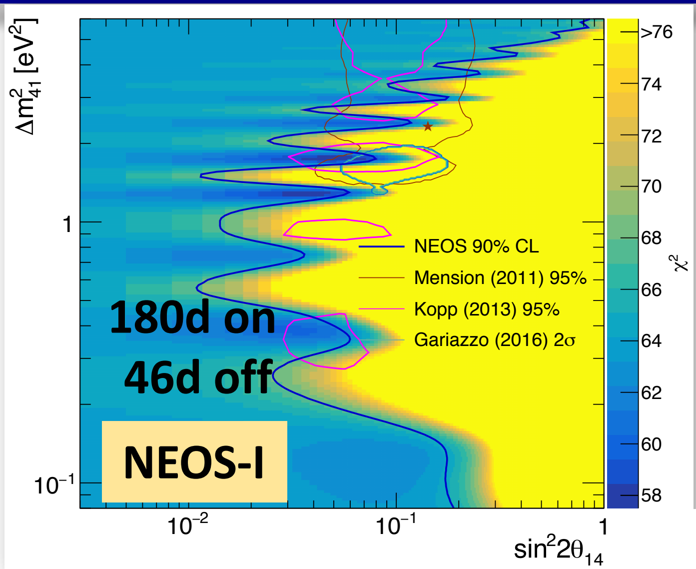




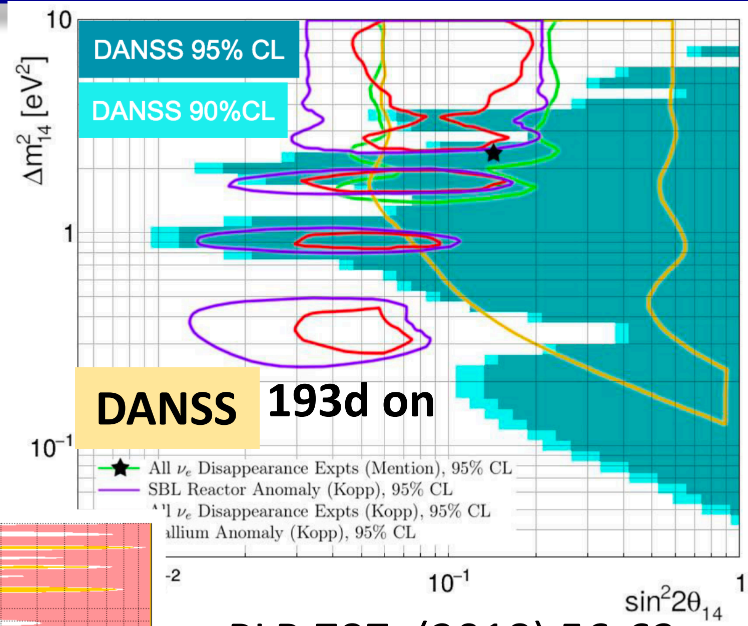
VSBL Reactor ν Experiments

Experiment	Thermal power [MW_{th}]	Baseline [m]	Target Mass, Vol	Target material	Segment
NEOS	2800	24	~1 m^3	GdLS	None
DANSS	3000	10-12	1 m^3	PS(Gd layer)	2D
Neutrino-4	100	6-12	1.8 ton	GdLS	2D
PROSPET	85	7-12	4 ton	^{6}LiLS	2D
SoLid	72	6-9	1.6 ton	PS(^{6}Li layer)	3D
STEREO	57	9-11	2.4 m^3	GdLS	1D
NuLat	Moving ν lab	any	0.9 ton	^{6}LiPS	3D
Chandler	Moving ν lab	any	?	PS(^{6}Li layer)	3D

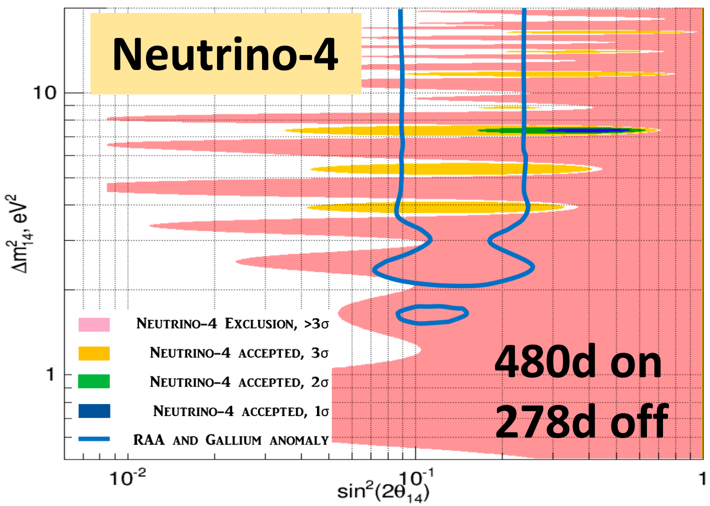
Current VSBL Reactor (3+1) ν Limits



PRL 118, 042502 (2017)

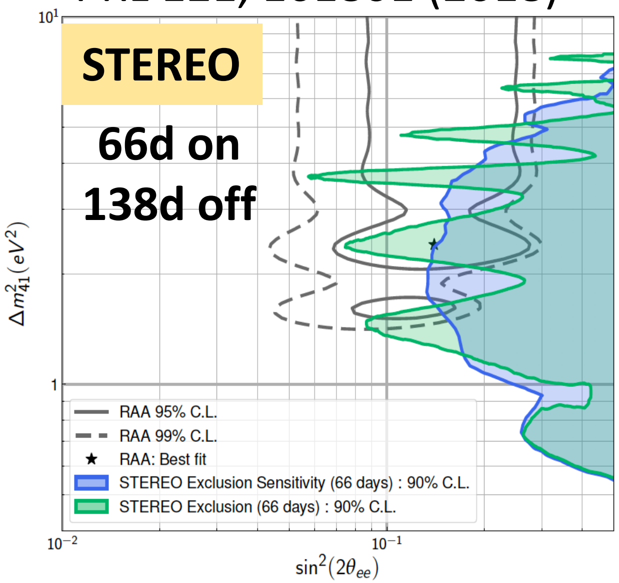


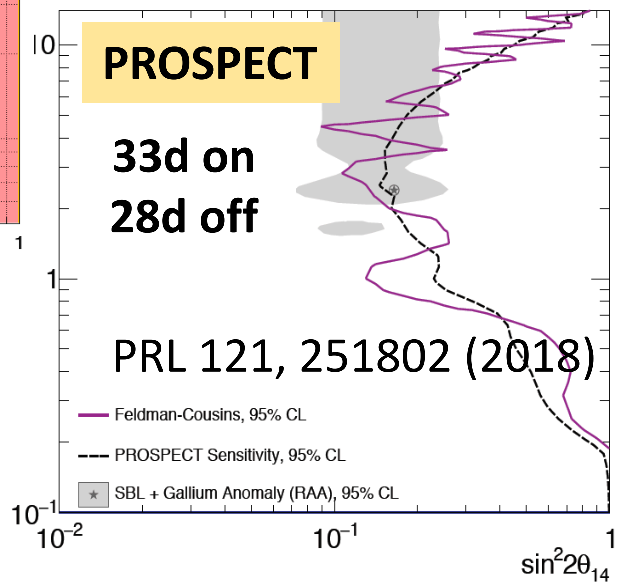
PLB 787, (2018) 56-63



arXiv:1809.10561
Accepted in JTEP

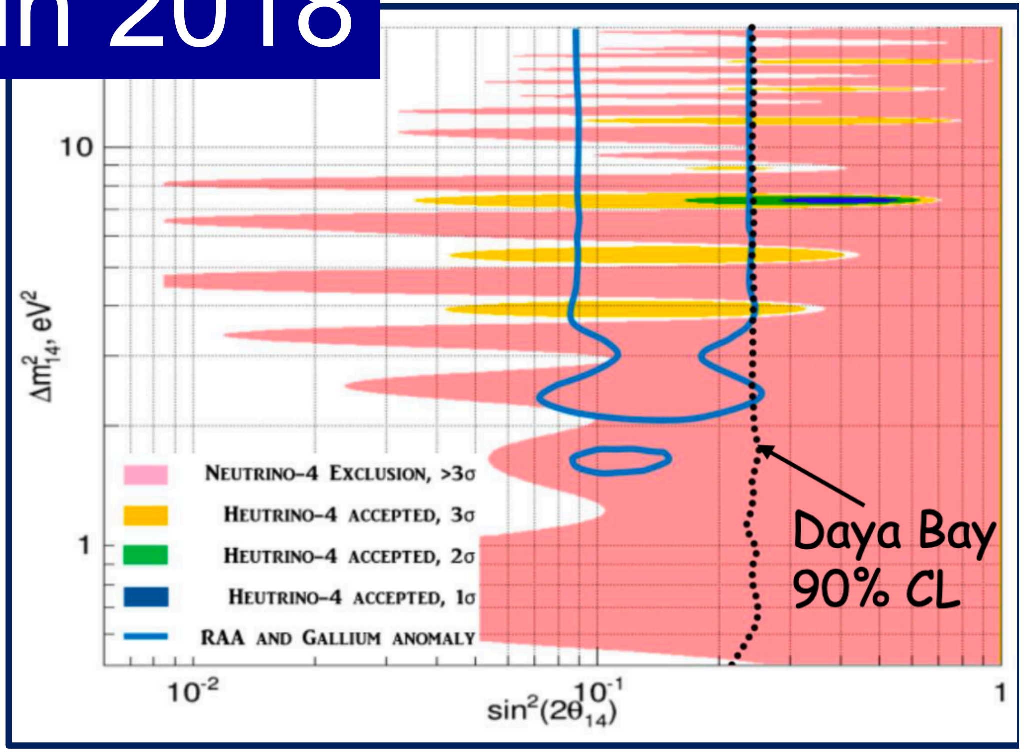
PRL 121, 161801 (2018)





PRL 121, 251802 (2018)

Neutrino-4 Results in 2018



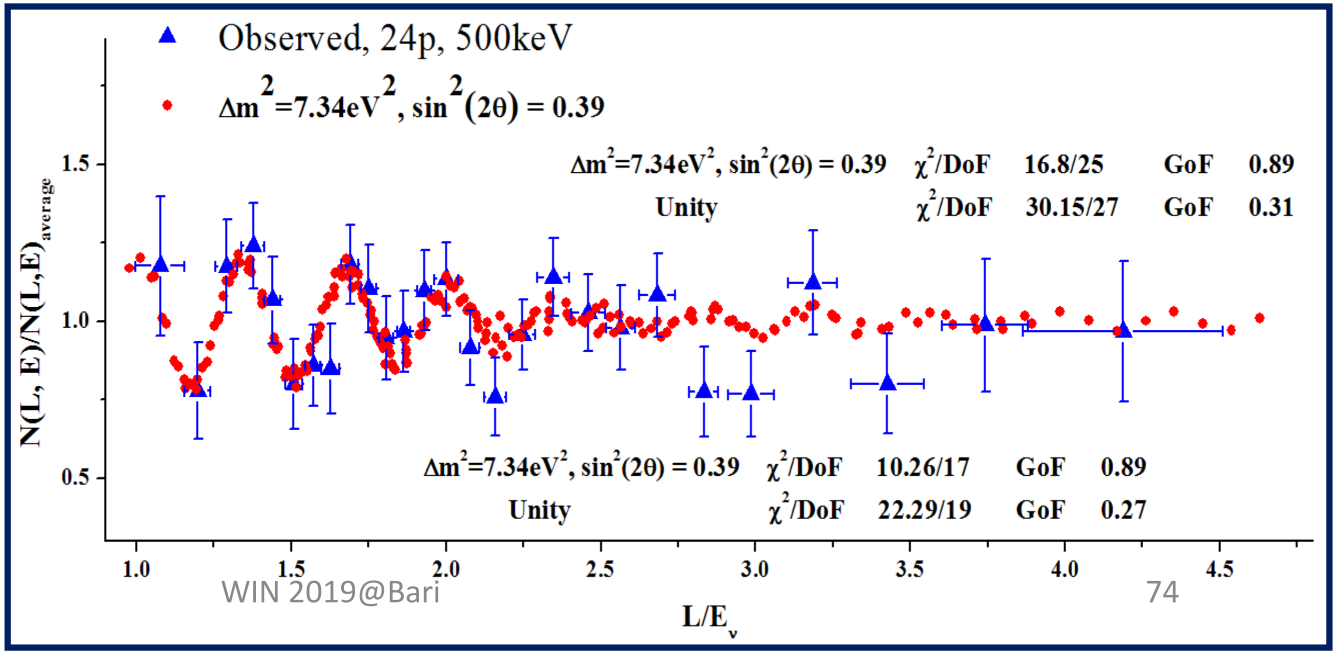
480(288) days On(OFF) data

Oscillation effect
C.L. 99.7% (3σ):

$$\Delta m^2_{14} \approx 7\text{eV}^2 \quad \sin^2 2\theta_{14} \approx 0.4$$

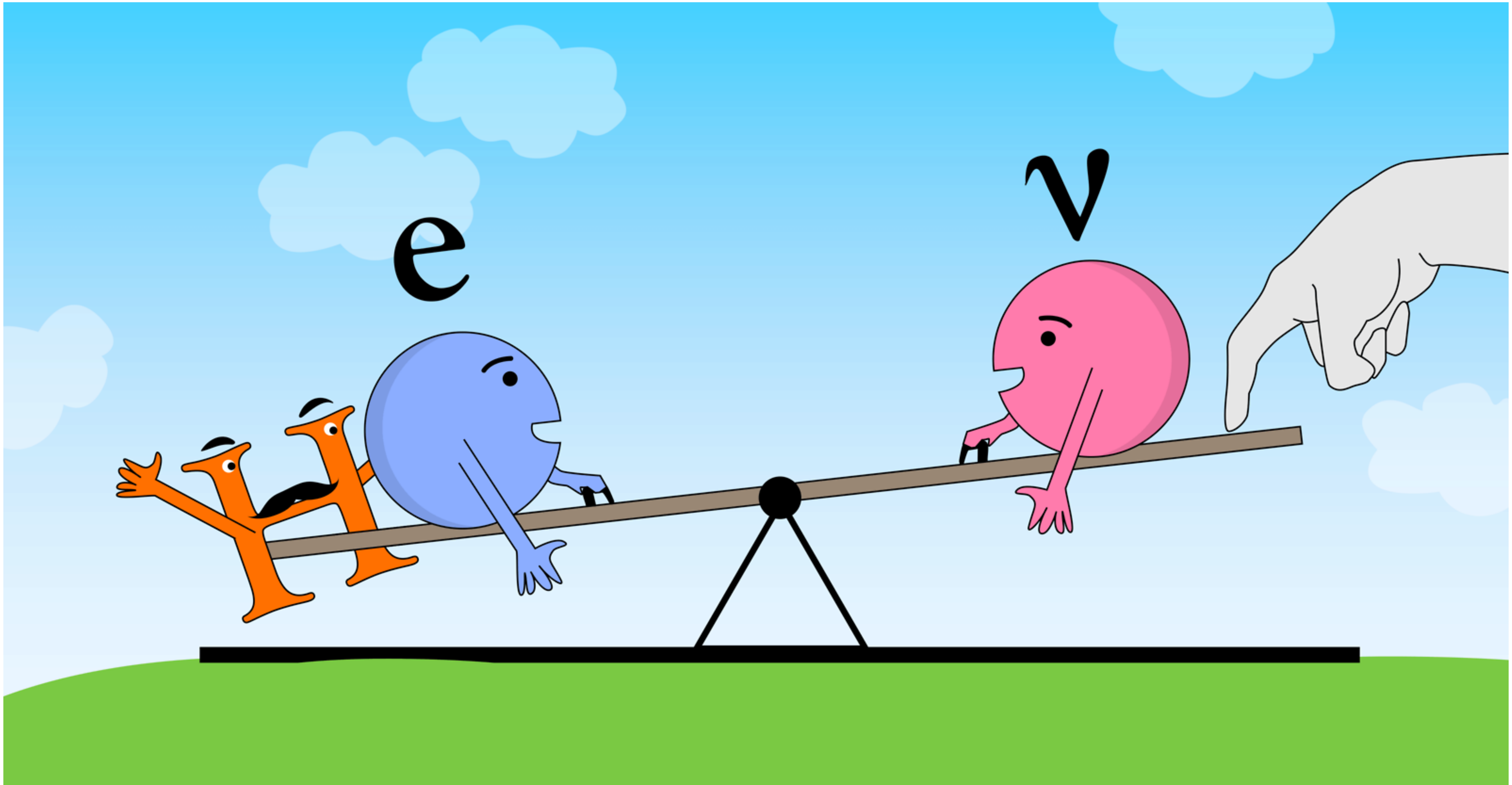
✓ **20% deficit contradicts to DYB & RENO results !**

Data taking continues.

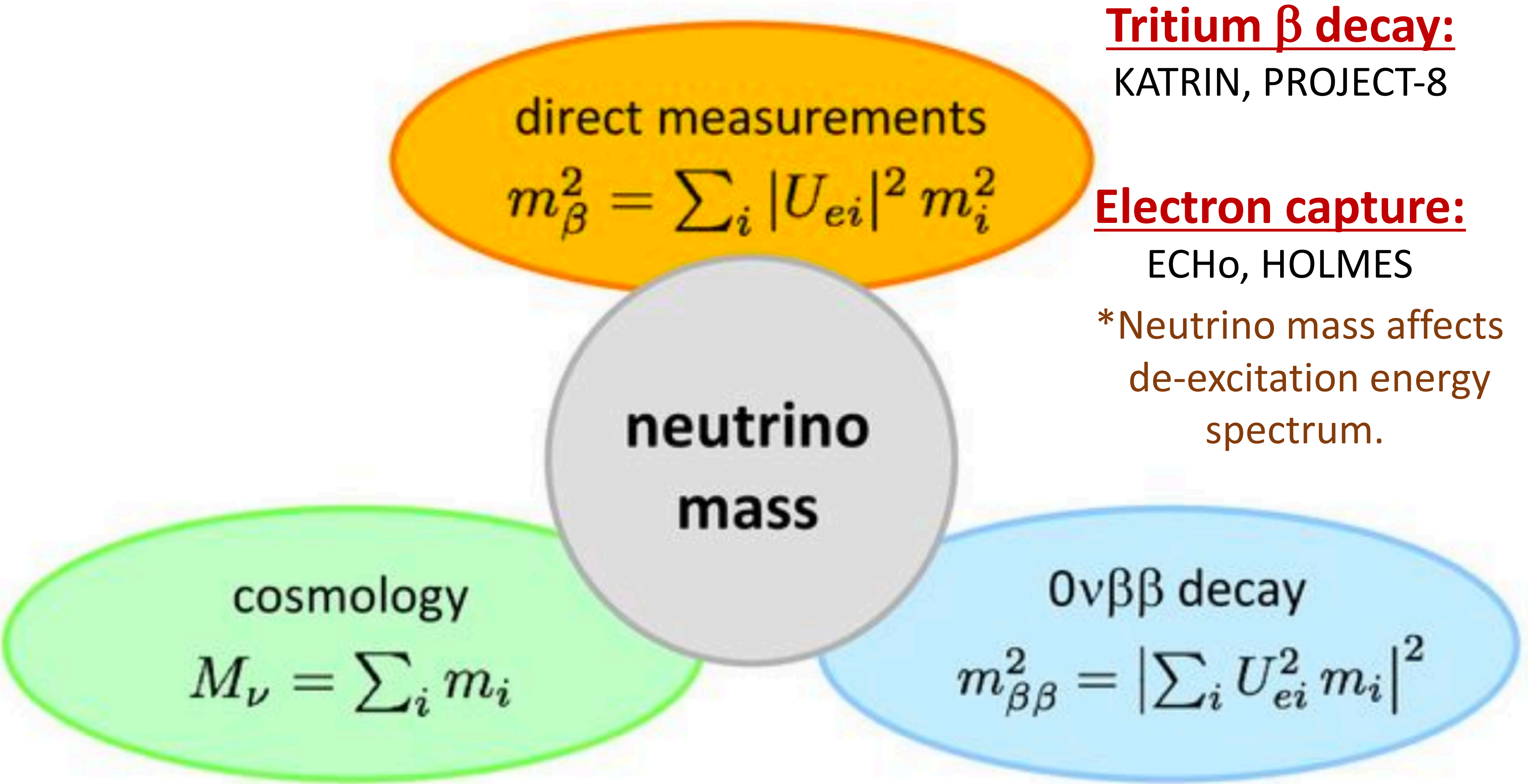


Which mechanism gives mass to neutrinos ?

See W. Rodejohan's ν theory talk (Mon.) & F. Vissani's Majorana ν talk (Fri.)



Credit: Symmetry Magazine, 2013



Tritium β decay:

KATRIN, PROJECT-8

Electron capture:

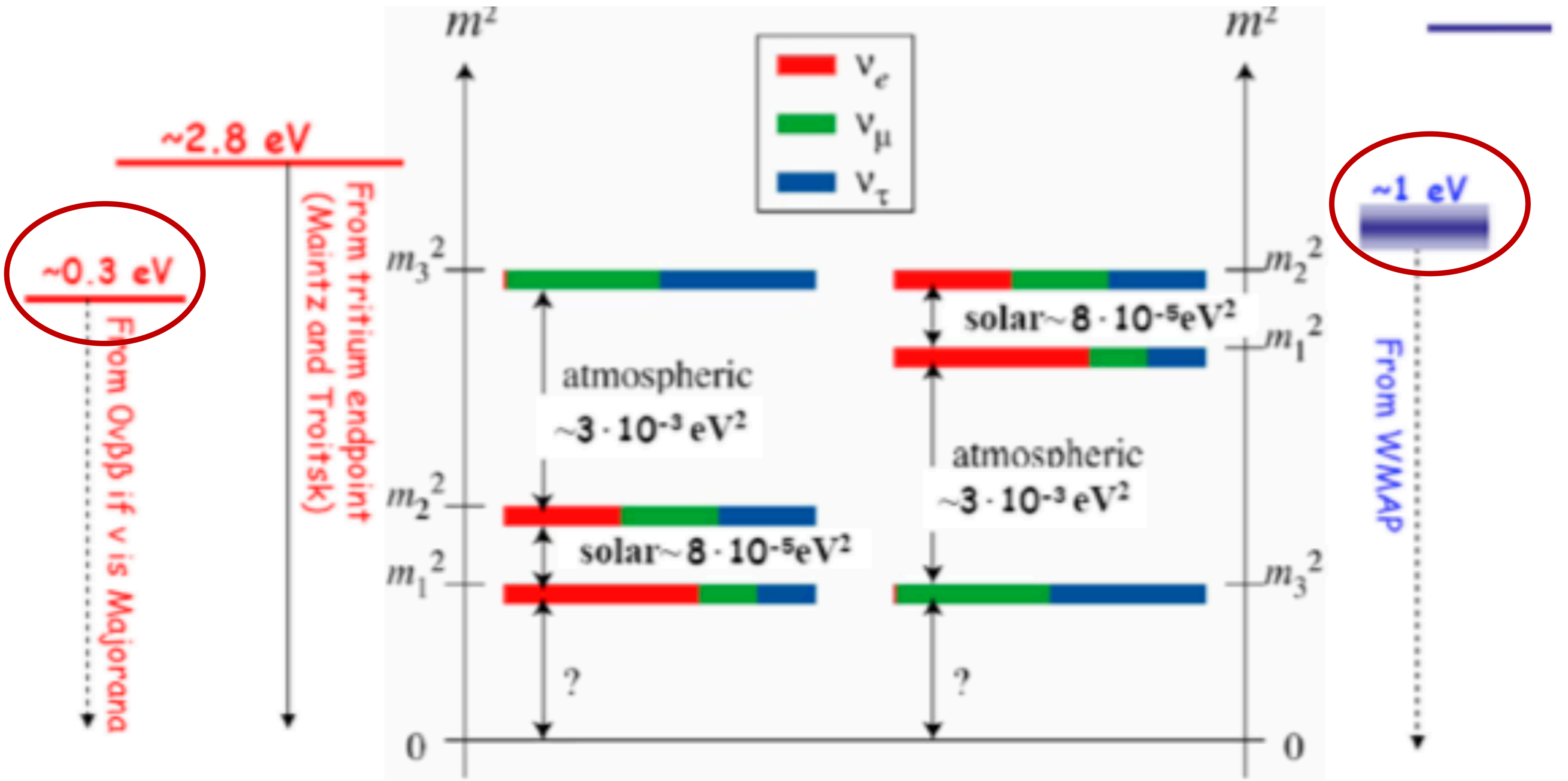
ECHo, HOLMES

*Neutrino mass affects de-excitation energy spectrum.

- Neutrino mass affects shape of CMB power spectrum.
- Model dependent
- Different data sets give different results.

Many experiments:

KamLAND-Zen
EXO, Gerda, CUORE,
SNO+, AMORE,
Majorana, etc.



F. Aviniogne's talk in 2014

0νββ: ~0.3 eV (2014) → ~0.23 eV at 90% C.L. (2018)

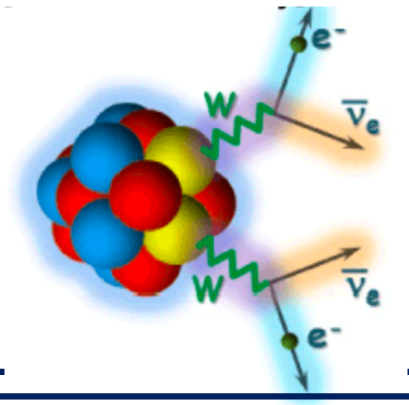
WMAP: ~1 eV (2014)
→ Planck (2018): 14~50 meV (IO), 0~30 meV (NO)

A.S. Barabash
Front. In Phys. (2019)

Dirac vs Majorana ν

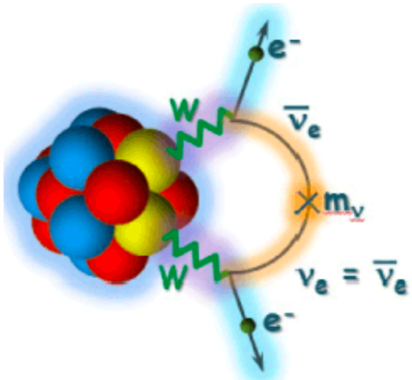
2νββ (1935)

M. Goeppert-Mayer
PRL, 48 (1935), 512



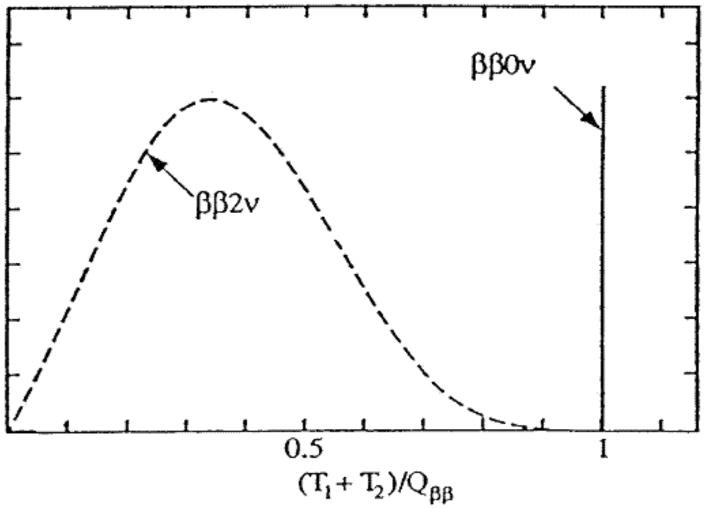
0νββ (1937/39)

G. Racah,
Nuovo Cimento,
14, (1937) 171
W. H. Furry
PRL, 56, (1939) 1184



1st observation of 2νββ in **1987** for 11 nuclei

$T_{1/2}$ = 10^{19} ~2×10^{21} yr

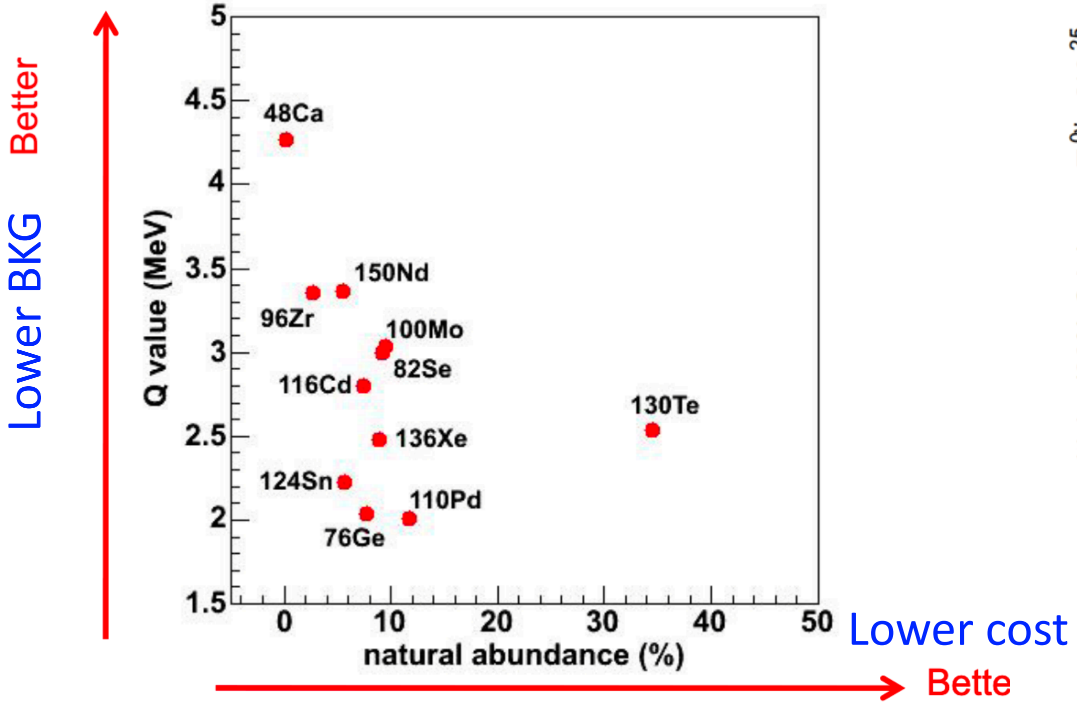


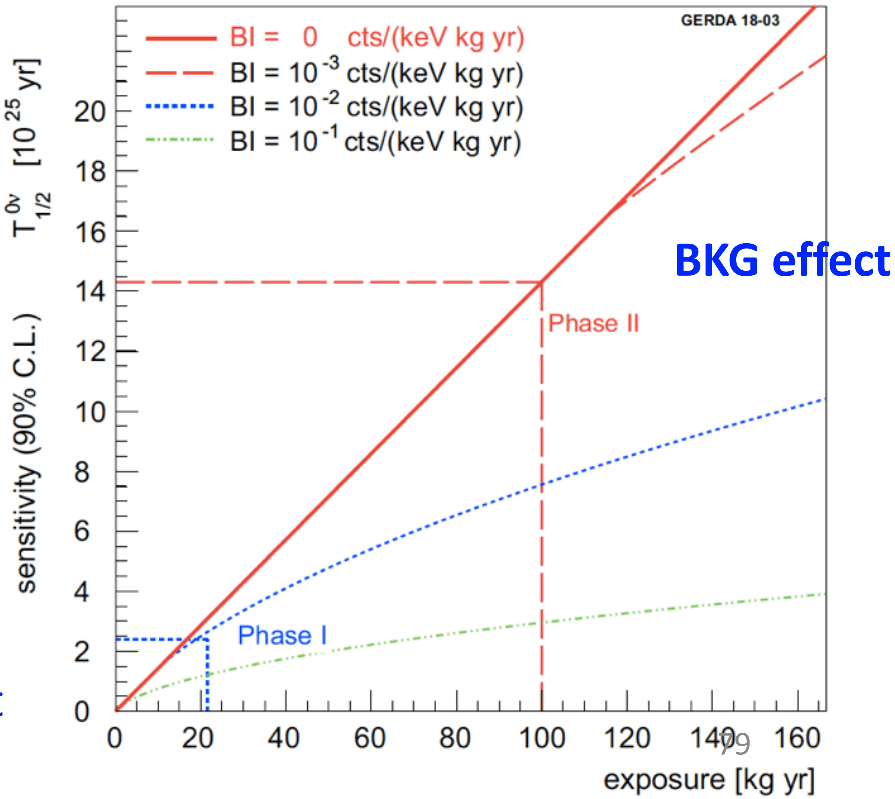
$$Q_{\beta\beta} \equiv M(A,Z) - M(A,Z+2)$$

0νββ = Majorana ν, LNV, absolute ν mass

$0\nu\beta\beta$ Exp. Design Conditions

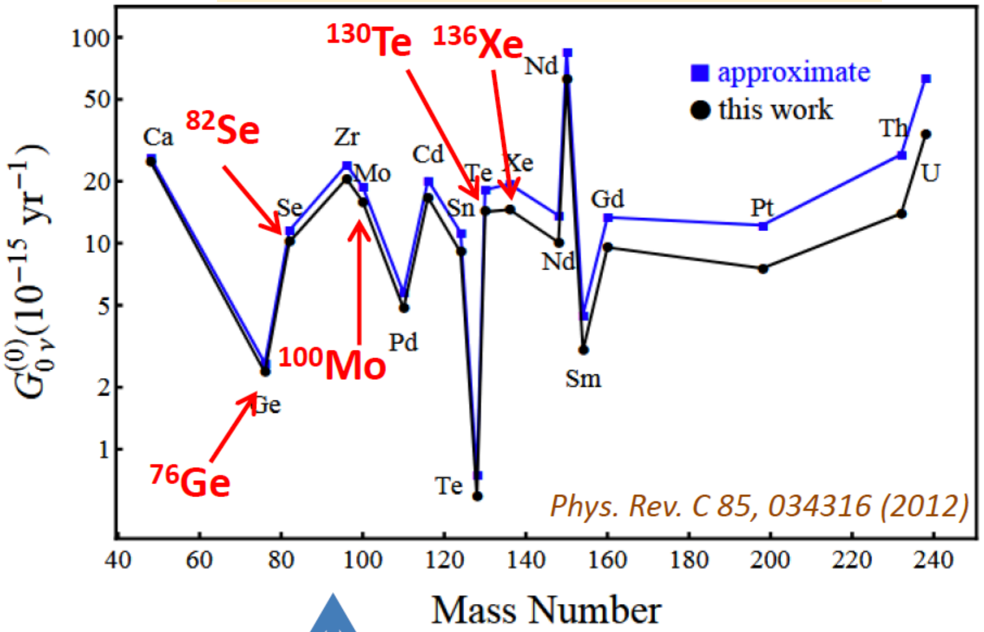
- Need radioactive isotopes with $\beta\beta$ emission.
  → Total 33 isotopes, only 11 have $Q_{\beta\beta}$ > 2 MeV
- $Q_{\beta\beta}$ > 3 MeV is better to avoid huge natural radio bkg.
- Good energy resolution (< 3~5% FWHM) ,
  no/low BKG, high efficiency, etc improve sensitivity.



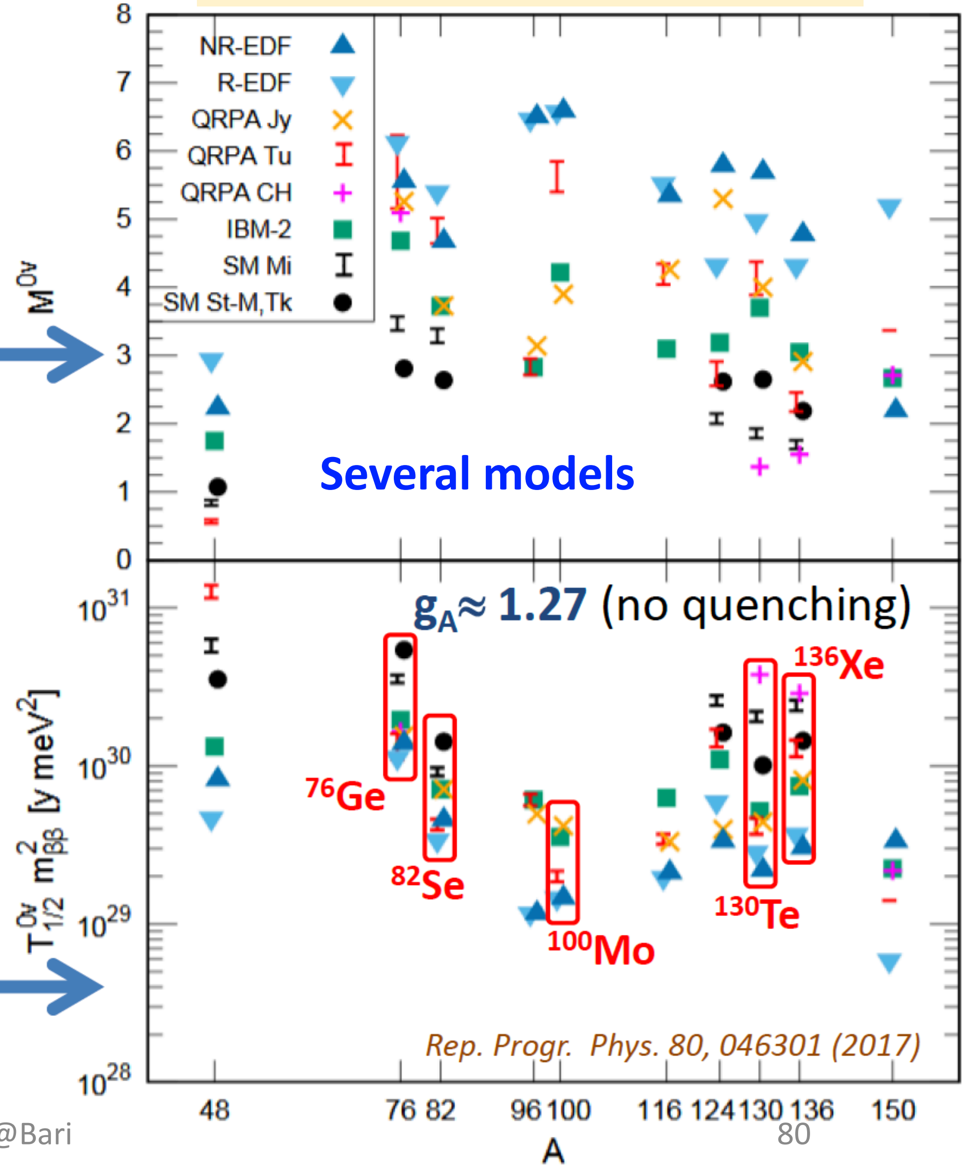


0νββ Challenge

G(Q,Z): phase-space factor
well calculated



M: nuclear matrix element
Big uncertainty

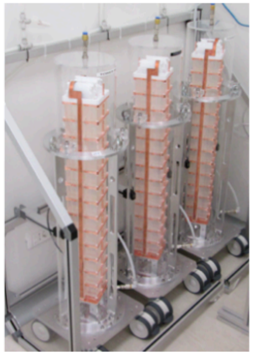


$$1/\tau = G(Q,Z)\ g_A^{\ 4}\ |M_{nucl}|^2\ m_{\beta\beta}^{\ 2}$$

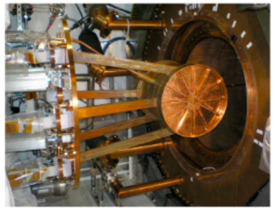
See W. Rodejohan's ν theory talk (Mon.)

0νββ Experiments

CUORE



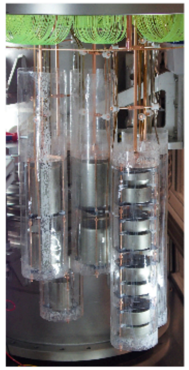
EXO200



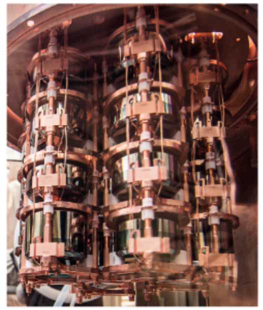
KamLAND Zen

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - III	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

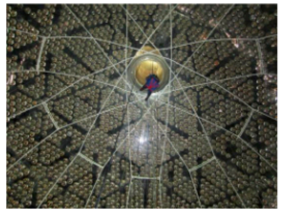
GERDA



MAJORANA



SNO+

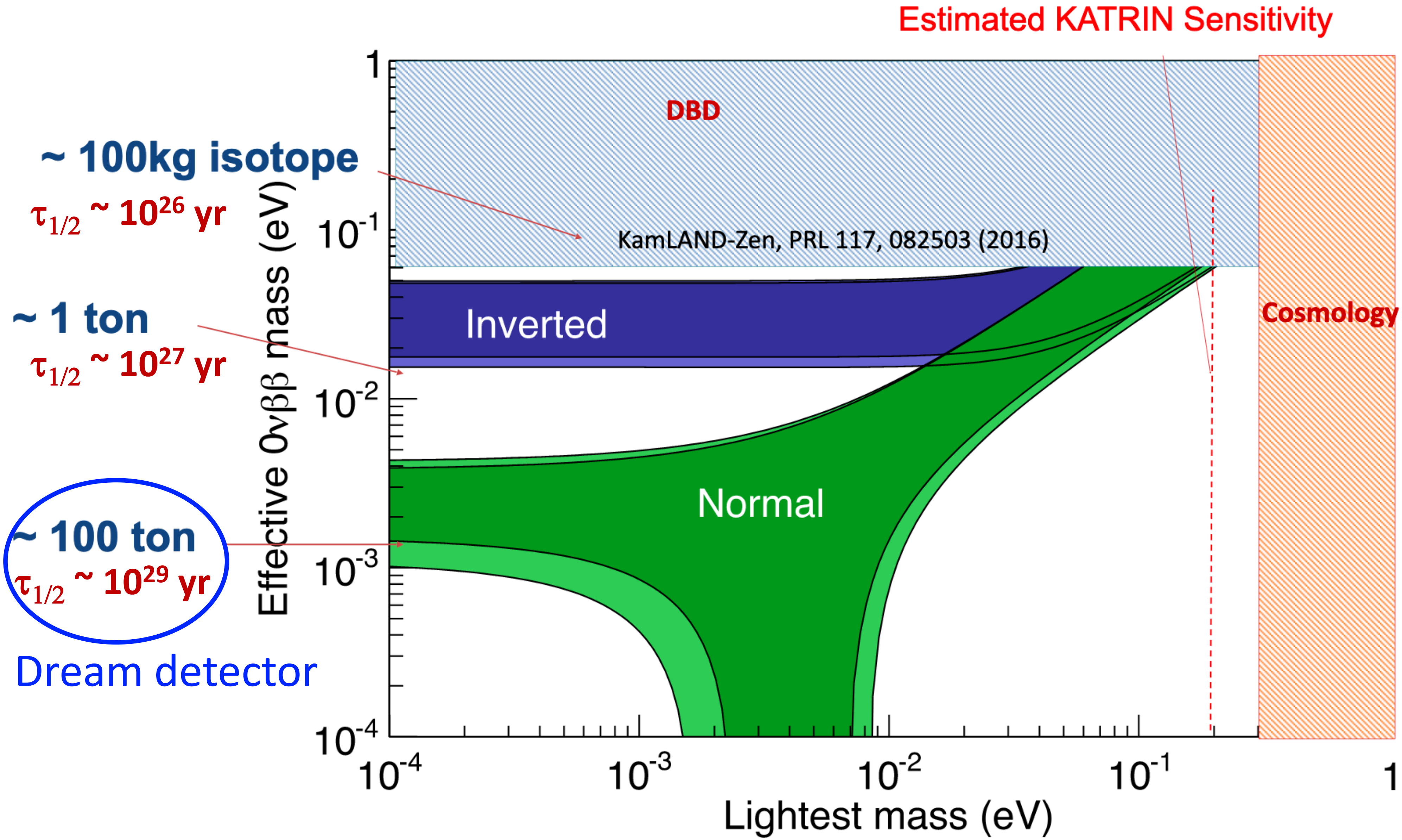


J.F. Wilkerson

Current (2018) Limits at 90% C.L.

Isotope	$Q_{2\beta}$, keV	$T_{1/2}$, yr	$\langle m_\nu \rangle$, eV	Experiment
^{48}Ca	4267.98	$> 5.8 \times 10^{22}$	$< 3.1 - 15.4$	CANDLES
^{76}Ge	2039.00	**$> 5.8 \times 10^{25}$**	**$< 0.14 - 0.37$**	GERDA-I+GERDA-II
		$(> 8 \times 10^{25})$	$(< 0.12 - 0.31)$	
^{82}Se	2997.9	$> 2.4 \times 10^{24}$	$< 0.4 - 0.9$	CUPID-0/Se
^{96}Zr	3355.85	$> 9.2 \times 10^{21}$	$< 3.6 - 10.4$	NEMO-3
^{100}Mo	3034.40	$> 1.1 \times 10^{24}$	$< 0.33 - 0.62$	NEMO- 3
^{116}Cd	2813.50	$> 2.2 \times 10^{23}$	$< 1 - 1.7$	AURORA
^{128}Te	866.6	$> 1.5 \times 10^{24}$	$2.3 - 4.6$	Geochem. exp.
^{130}Te	2527.52	**$> 7 \times 10^{24}$**	**$< 0.19 - 0.74$**	CUORICINO +
		$(> 1.5 \times 10^{25})$	$(< 0.13 - 0.50)$	CUORE0 + CUORE
^{136}Xe	2457.83	**$> 5.6 \times 10^{25}$**	**$< 0.08 - 0.23$**	KamLAND-Zen
		$(> 1.07 \times 10^{26})$	$(< 0.06 - 0.16)$	
^{150}Nd	3371.38	$> 2 \times 10^{22}$	$< 1.6 - 5.3$	NEMO-3

A.S. Barabash
Frontiers in Physics (2019)

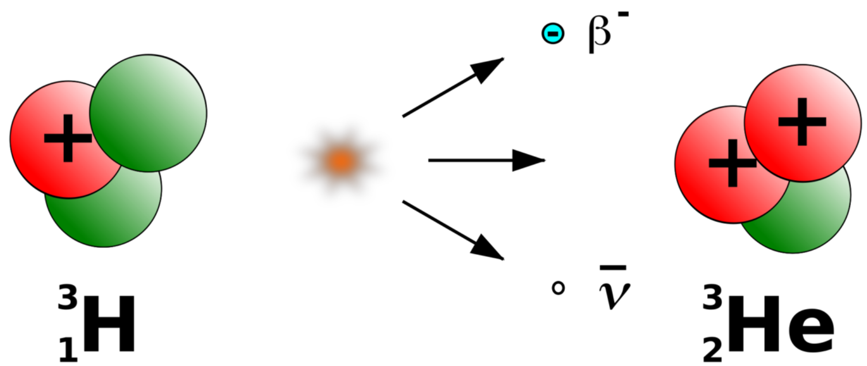


~ 1 ton next generation experiments:

nEXO, NEXT-2.0, PandaX-III 1t, Kamland2-ZEN, SNO+-II, LEGEND-1000, CUPID

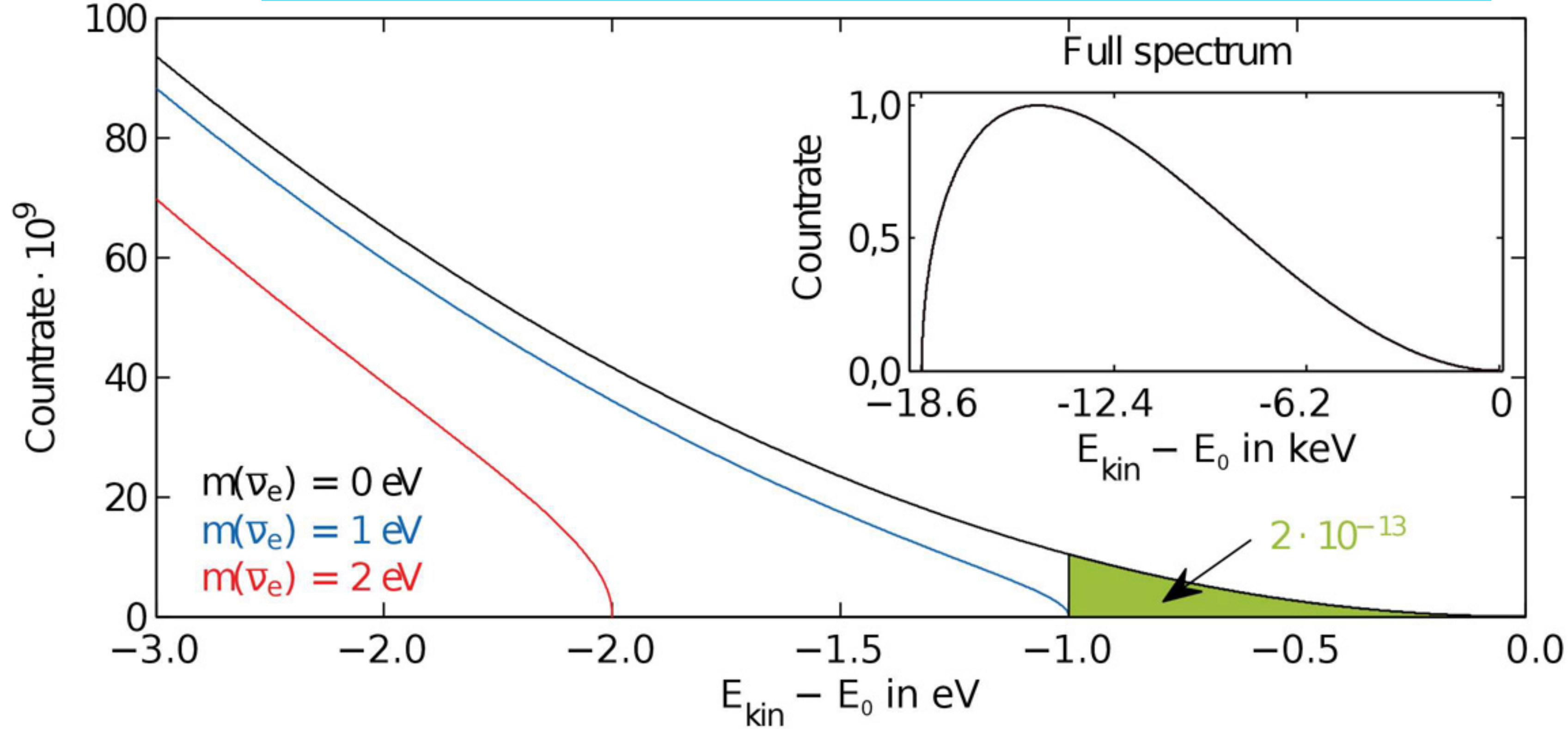
Tritium β Decay

$\tau_{1/2}$ (^{3}H) = 12.3 yrs



Q-value (E_0): 18.57 keV

If m_ν = 0, then β^- end point is 18.57 keV.

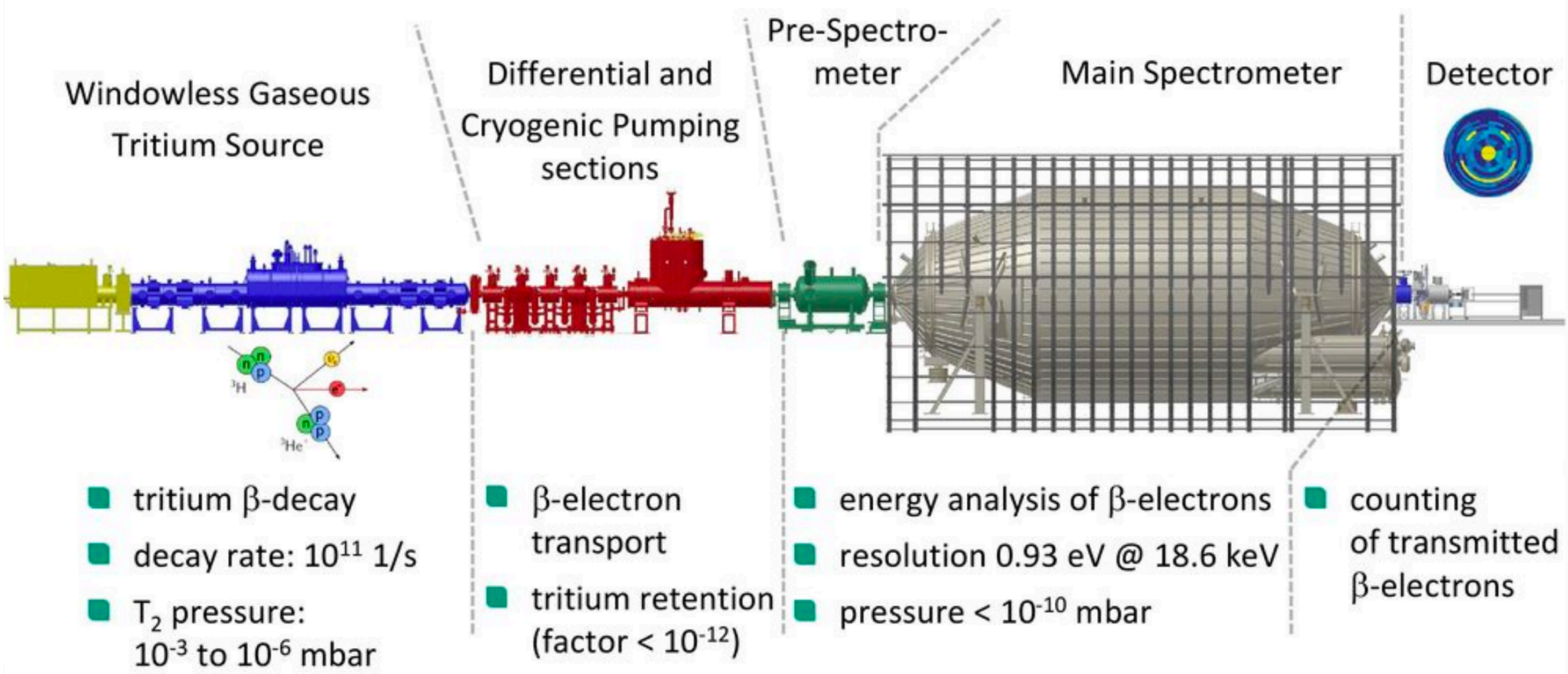


KATRIN Detector

KArlsruhe **TRI**tium **N**eutrino experiment

Sensitivity: m_ν = **0.2 eV** at 90% C.L.

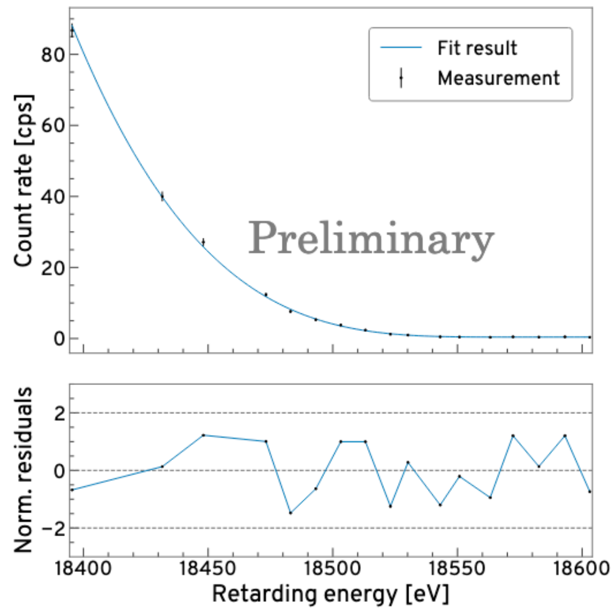
~70 m



KATRIN Status

- Very successful measurement campaigns
  - Spectral scanning with ^{83m}Kr
  - Background studies

July 2017

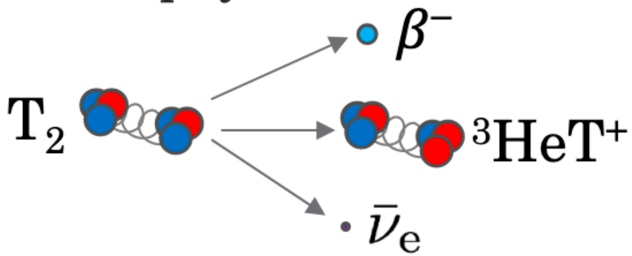


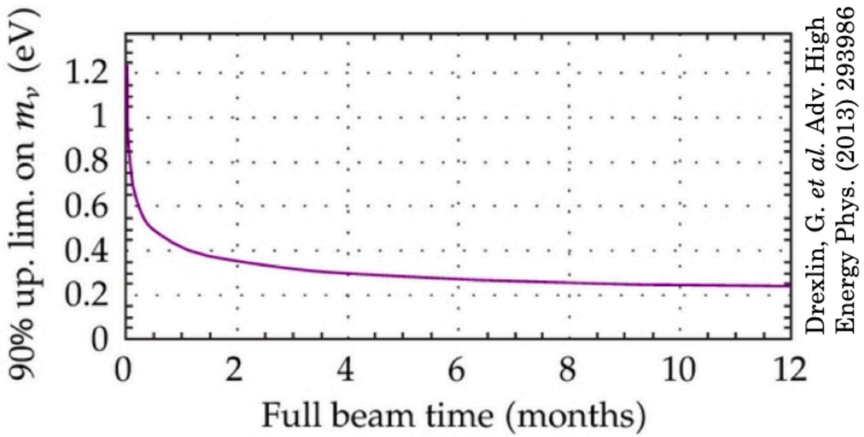
- First tritium

May 2018

  - Apparatus meets stability requirements
  - Preliminary spectra agree with expectations
  - Data-taking is happening right now!
  - Commissioning will continue this year 2018

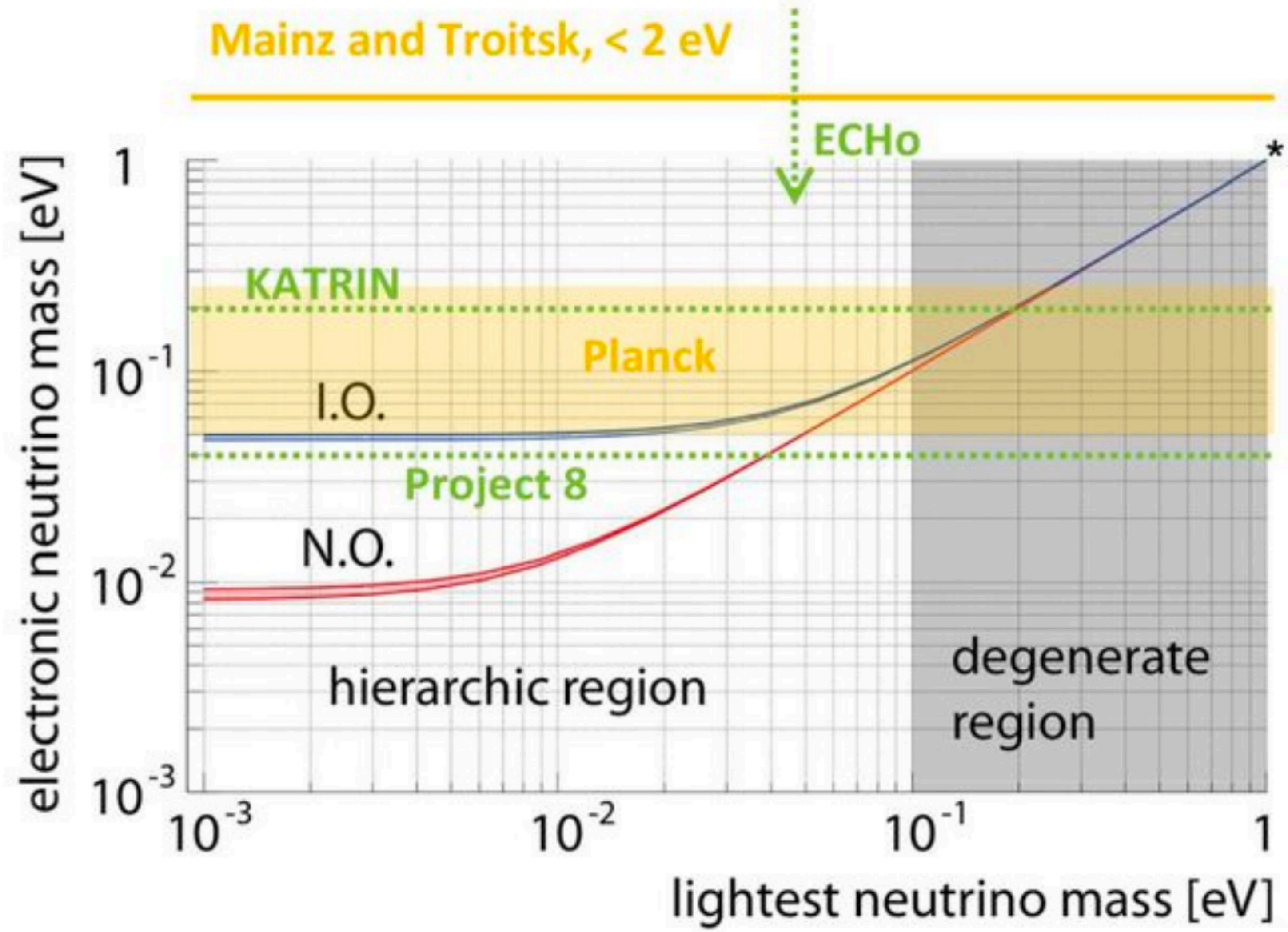
- 5 years of measurements planned, looking for:
  - Effective neutrino mass
  - Sterile neutrinos
  - BSM physics





Kippenbrock talk at PASCOS 2018

Abs. ν Mass Sensitivity

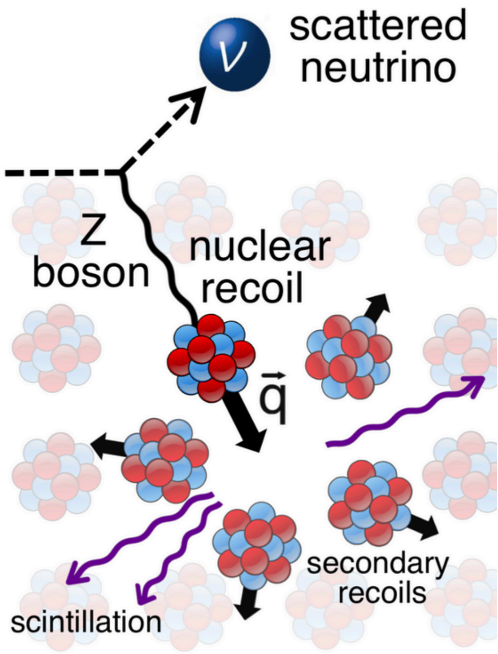


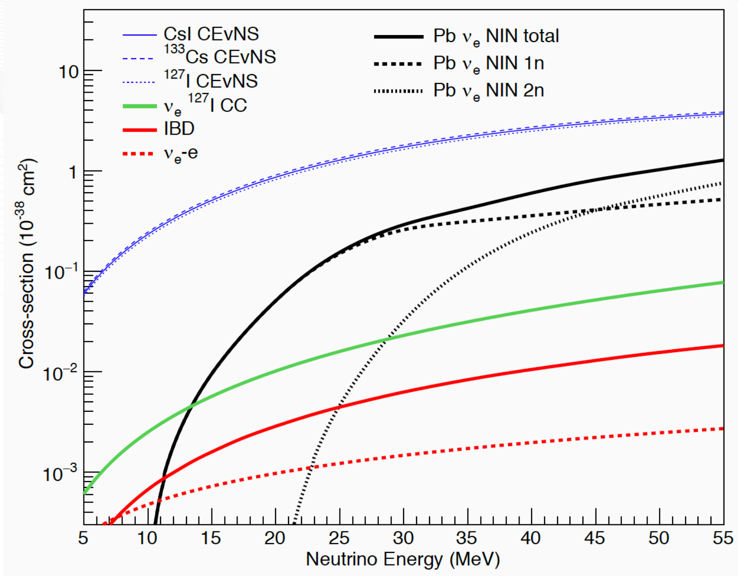
0.2 eV
(KATRIN)

0.04 eV
(Project 8)

CEvNS

Coherent Elastic veutrino-Nucleus Scattering

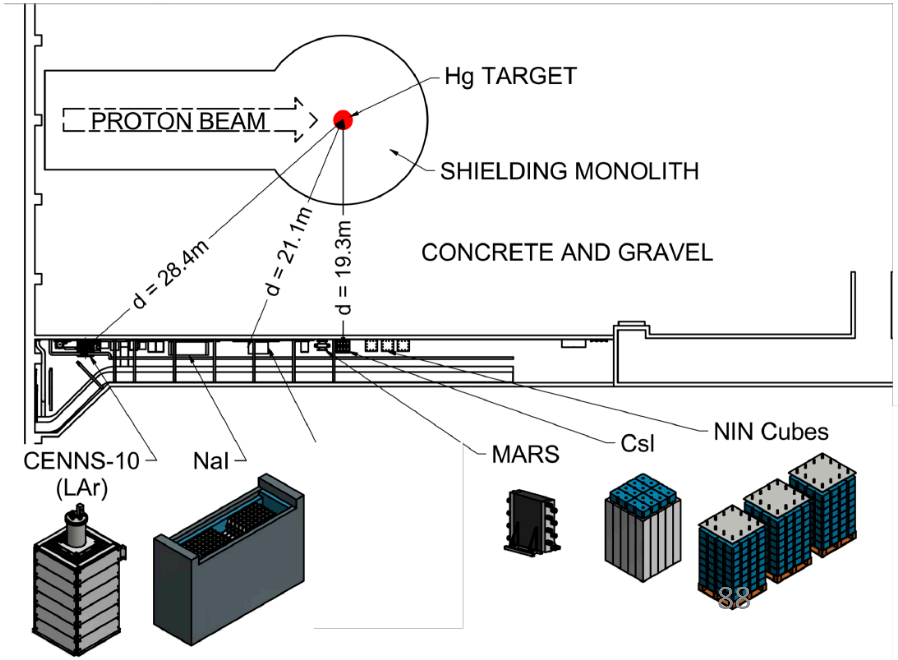




Observed in 2017

by COHERENT @OAK RIDGE NL

coherent up to $E_\nu \sim 50$ MeV



CEvNS does exists
However, nobody doubt that !!!

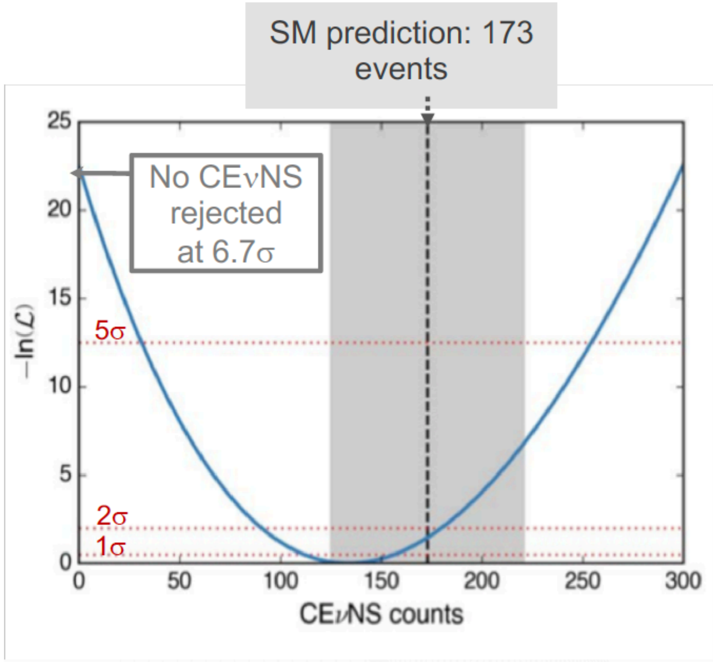
1974
Freedman

"It's a real thrill that something that I predicted 43 years ago has been realized experimentally,"

Some Details About the First CEvNS Detection

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, 2D likelihood fit	134 ± 22 (16%)
Predicted SM signal counts	173 ± 48 (28%)

Uncertainties on signal and background predictions	
Event selection (signal acceptance)	5%
Form Factor	5%
Neutrino Flux	10%
CsI Quenching Factor (QF)	25%
Total uncertainty on signal prediction	28%



All uncertainties except neutrino flux are detector specific and could be much less for other technologies

To unlock high precision CEvNS program we need to calibrate SNS neutrino flux, measure QF well and accumulate large statistics on multiple targets

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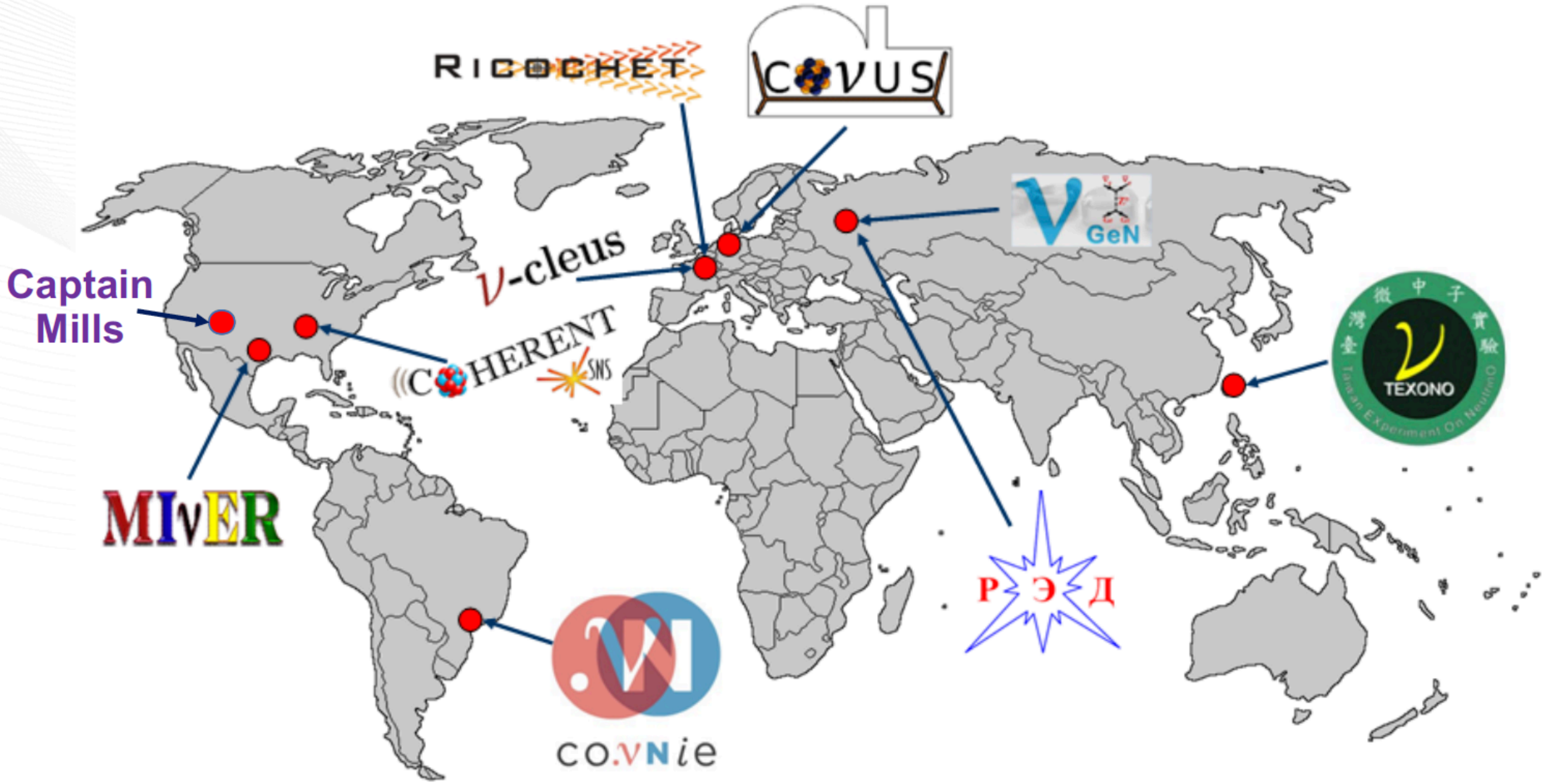
OAK RIDGE National Laboratory

Efremenko @IAEA 2019

World Wide Efforts to Detect CEvNS



Except COHERENT and CM collaborations, all others attempting to use nuclear reactors as a neutrino source

Nuclear reactors give large flux, but low energy neutrinos with a constant flux

Various detector technologies are being investigated. We heard first indication of positive signal from the Conus experiment last year

OAK RIDGE National Laboratory

Summary (I)

- θ_{13} can be best measured by short baseline reactor neutrino exp.
  → Legacy measurement (~3%) by 2021

- Reactor ν flux (6% deficit at 3σ) spectral anomaly (5MeV excess) needs to be understood.

- JUNO will be the largest ever LS detector (20 kton).

→ Most precise measurements (<1%) of osc. parameters before 2030.

- **<u>eV scale sterile neutrino searches</u>**:

→ Need more precise measurements by VSBL reactor ν exp.
→ μBooNE should identify low E excess events seen by MiniBooNE
→ Additionally, SBN detectors will be good demonstrators for DUNE.

- T2K/NOvA will provide evidences (~3 σ level) of CPV and MO by 2027.

Summary (II)

➢ CPV & MO will be determined by Hyper-K and DUNE before 2040.
dCP = -π/2 ? Normal Ordering ?

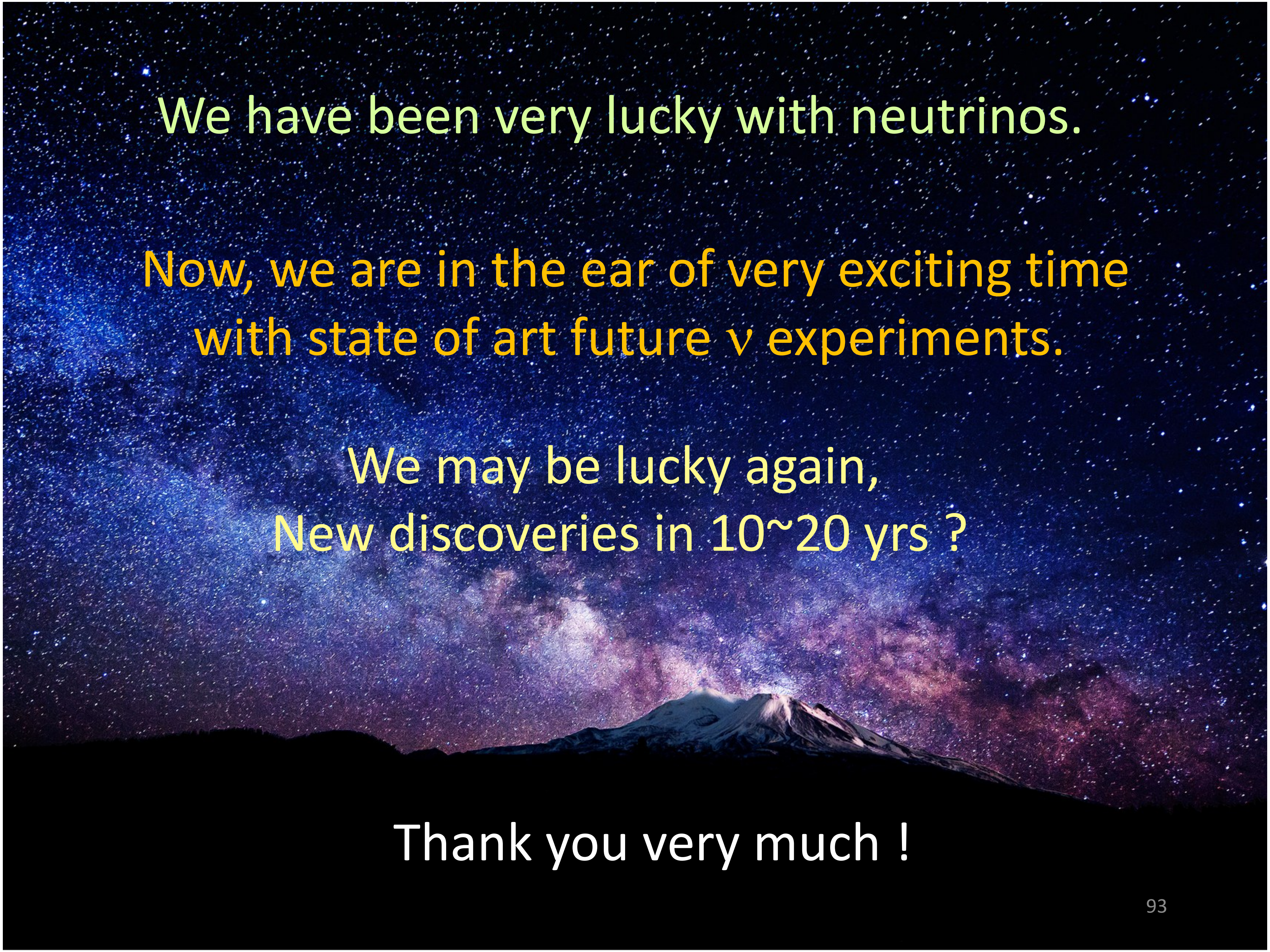
- Hyper-K: the biggest ever water Cherenkov detector (260 kton)
- DUNE: noble technology detector (LArTPC, 4 x 17 kton)
- T2HKK/ESSnuSB gives unique opportunity for 2^{nd} osc. Max.

➢ Whether neutrinos are Dirac vs Majorana is very fundamental question.
→Need bigger detector with no or tiny background
→CUPID, KamLAND2-ZEN, LEGEND, nEXO, SNO+-II, NEXT-2.0, etc

➢ Absolute mass measurements → very challenging
KATRIN (> 0.2 eV), PROJECT-8 (> 0.04 eV), ECHo, HOLMES

➢ CEvNS is observed (6.7σ) by COHERENT in 2017: 1σ tension w/ predict.
This field grows rapidly with different technologies also using reactor ν.

➢ **Multi-messenger astronomy** → see Astroparticle Overview Talks


We have been very lucky with neutrinos.
Now, we are in the ear of very exciting time
with state of art future ν experiments.
We may be lucky again,
New discoveries in 10~20 yrs ?
Thank you very much !