Current and Future Experiments On Neutrino Physics

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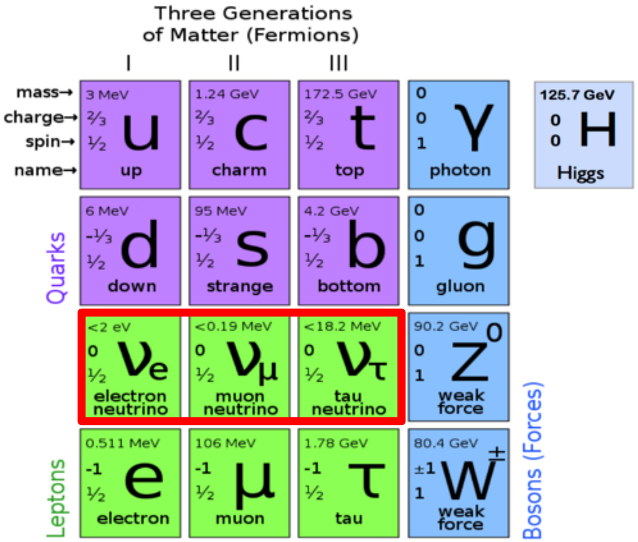
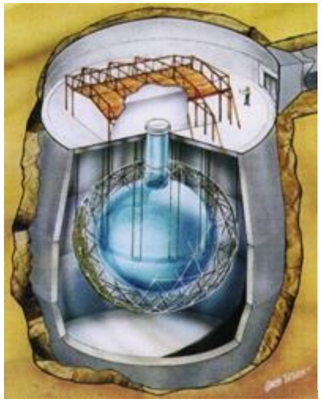
UC Berkeley and LBNL

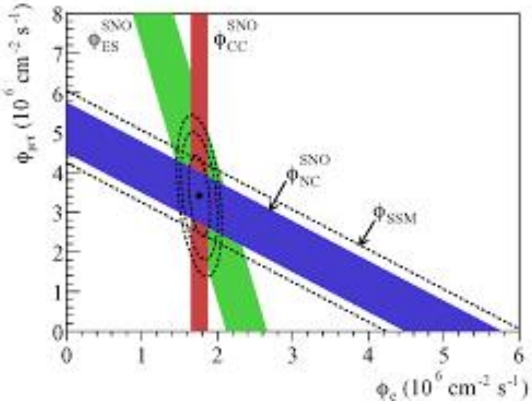
MicroPattern Gaseous Detector Conference
La Rochelle, France
7 May 2019

Neutrinos: Break the Standard Model

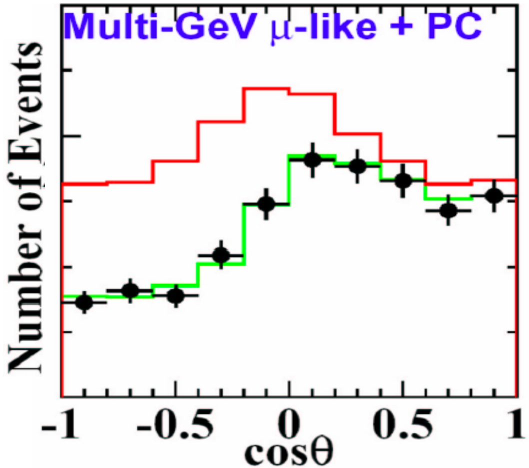


- Standard Model assumes
  - Massless neutrinos
  - Lepton number, L, conserves:
    - $L = L_e + L_\mu + L_\tau$





- SNO's results showed
  - Lepton number is still invariant
    - $\Delta L = 0$
  - Lepton flavour number violated
    - $\Delta L_\iota \neq 0$
- Super-K discovered
  - Neutrino oscillation
    - Neutrinos have mass

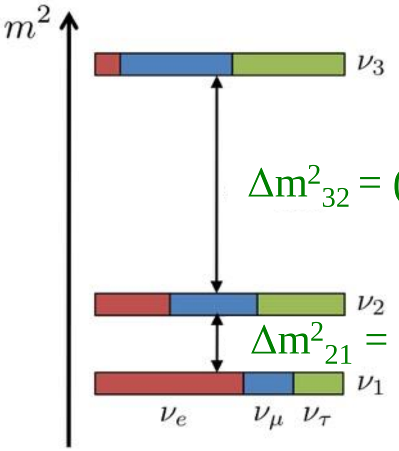


Learning More About The Neutrinos

- Neutrino mixing parameters for 3 generations
  - Mixing angles: θ_{12} (33.6° ± 0.8°), θ_{23} (38°-52°), θ_{13} (8.4° ± 0.1°)
  - Mass-squared differences: $\Delta m^2_{ij} = m_i^2 - m_j^2$ such that

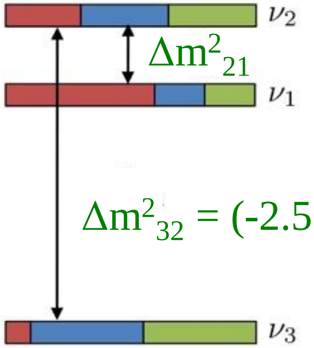
$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

Normal hierarchy or Inverted hierarchy



$\Delta m^2_{32} = (-2.56 \pm 0.04) \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$



Δm^2_{21}

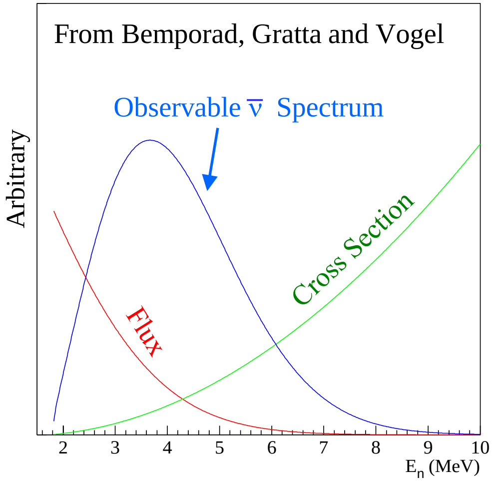
$\Delta m^2_{32} = (-2.56 \pm 0.04) \times 10^{-3}\ \mathrm{eV}^2$

  - CP-violating phase: δ
- Existence of sterile neutrinos
- Absolute mass of neutrinos
- Nature of neutrinos: Majorana or Dirac fermions

$\nu = \overline{\nu}$ $\nu \neq \overline{\nu}$

Neutrino Mixing

Reactor Neutrino Experiments



- Nuclear reactors are intense sources of pure low-energy electron anti-neutrinos
  - 1 $GW_{el} \Leftrightarrow 3\ GW_{th}$ produces ~6 x 10^{20} ν_e /s
  - $E_\nu \leq 10$ MeV

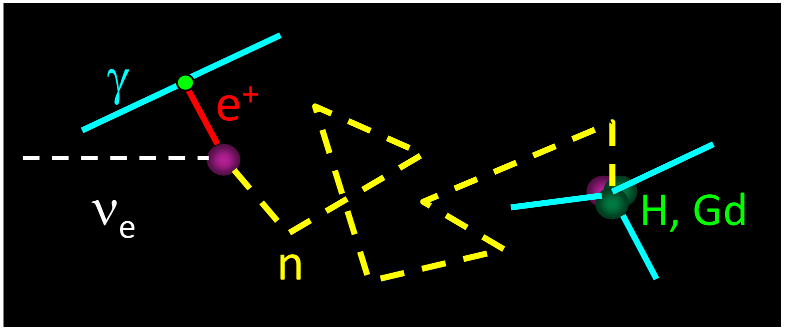
- Detect $\bar{\nu}_e$ via inverse β-decay reaction:

$$\nu_e + p \rightarrow e^+ + n$$

$\hookrightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$

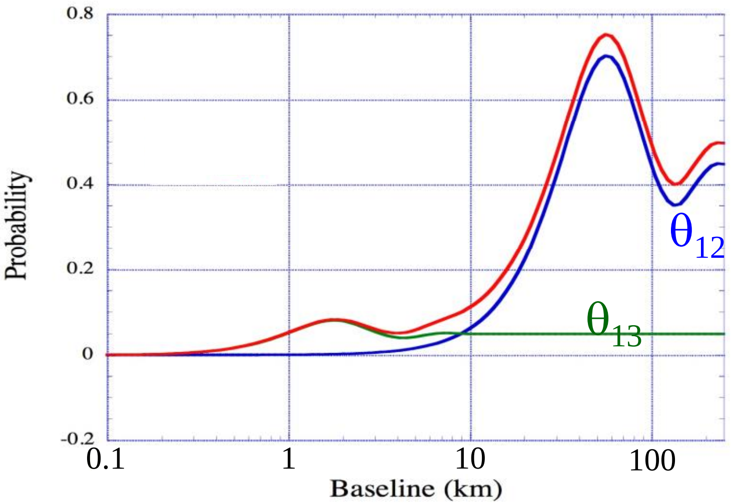
$\hookrightarrow + Gd \rightarrow Gd^*$

$\hookrightarrow Gd + \gamma\text{'s}(8\ \text{MeV})$



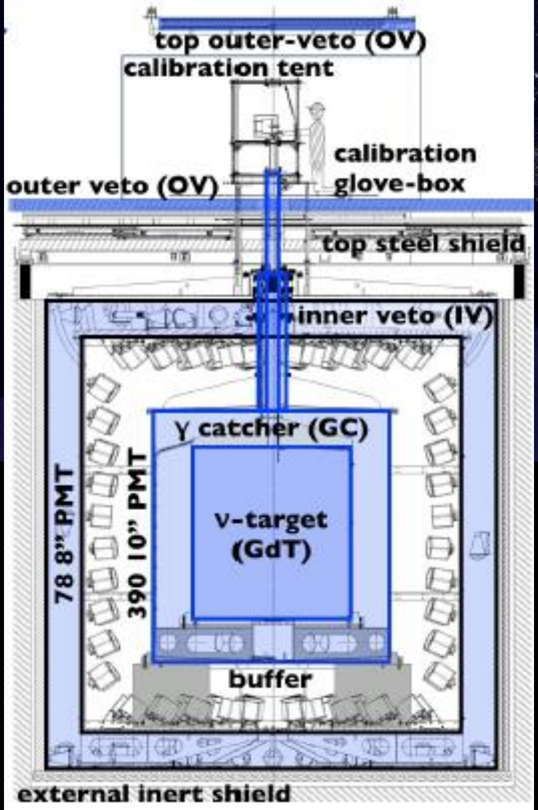
- Look for ν_e disappearance:

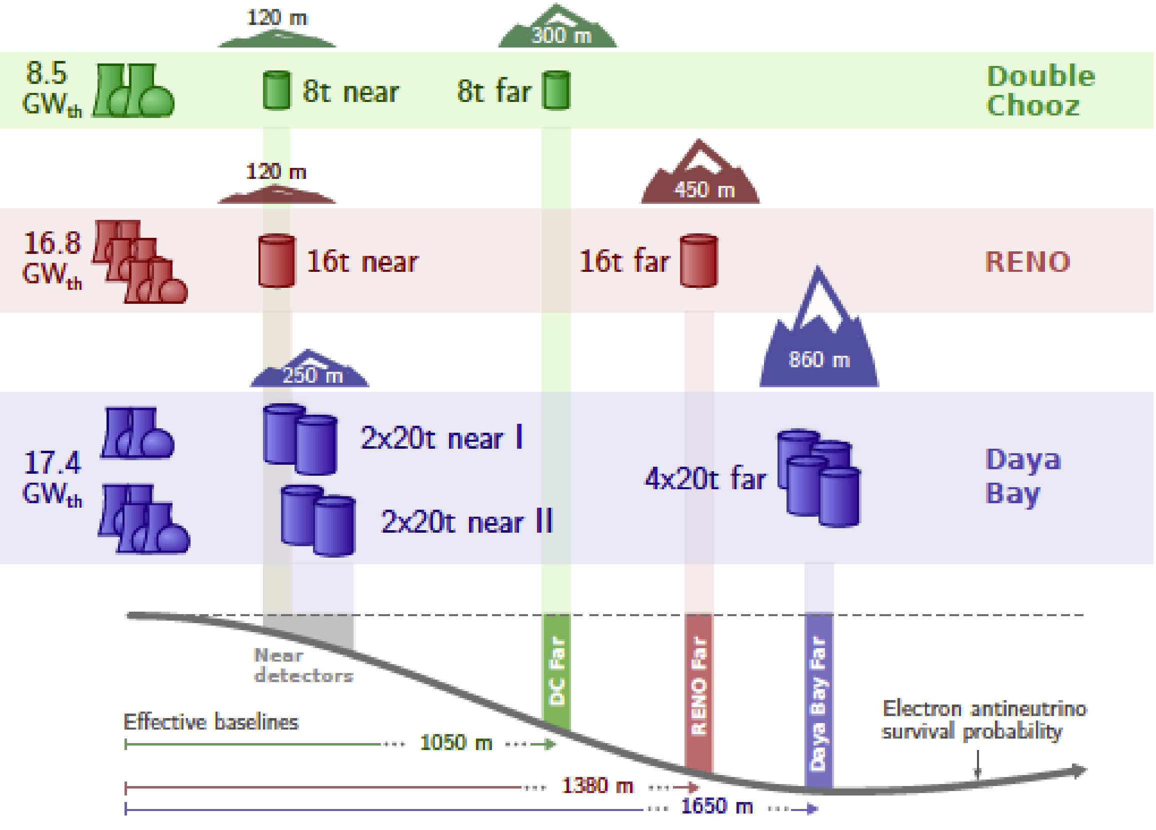
$$P_{ex} \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$



Current Reactor-based θ_{13} Experiments

- Use near and far detectors to reduce correlated errors
- Stable Gd-loaded liquid scintillators to detect inverse β-decay reactions
- Catcher to improve γ-ray detection
- Water-shielded detectors with redundant cosmic-ray taggers

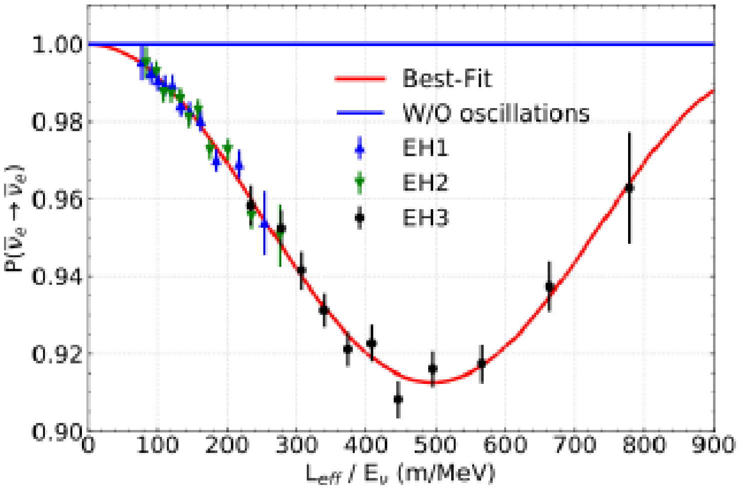




Mixing Parameters: θ_{13} and $|\Delta m^2_{32}|$

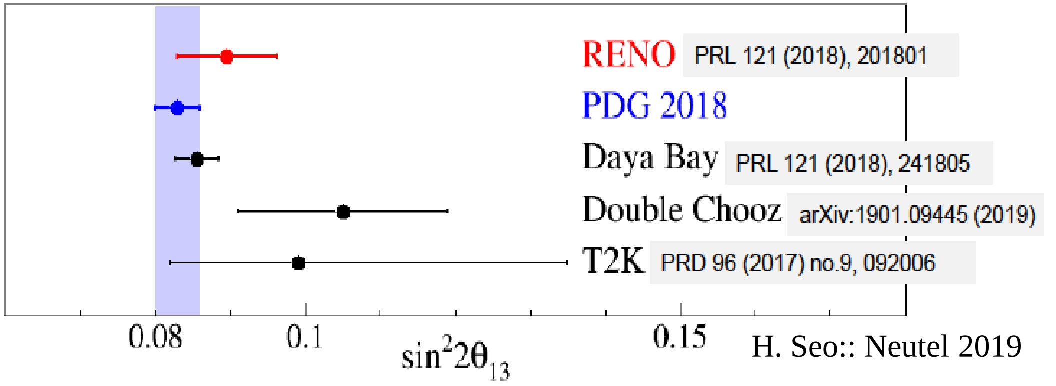
Daya Bay

PRL **121** (2018) 241805

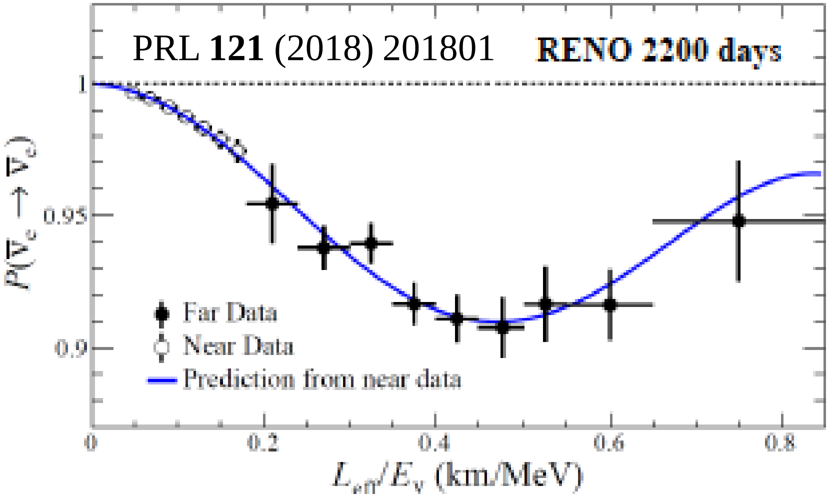


Daya Bay: $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

Ultimate precision: 0.0025



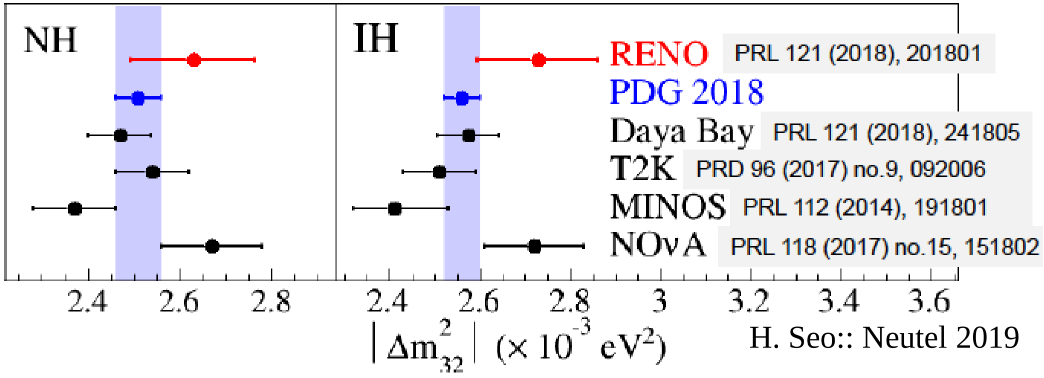
H. Seo:: Neutel 2019



Daya Bay: $\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}$ eV^2 (NH)

$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}$ eV^2 (IH)

Ultimate precision: 0.06×10^{-3} eV^2



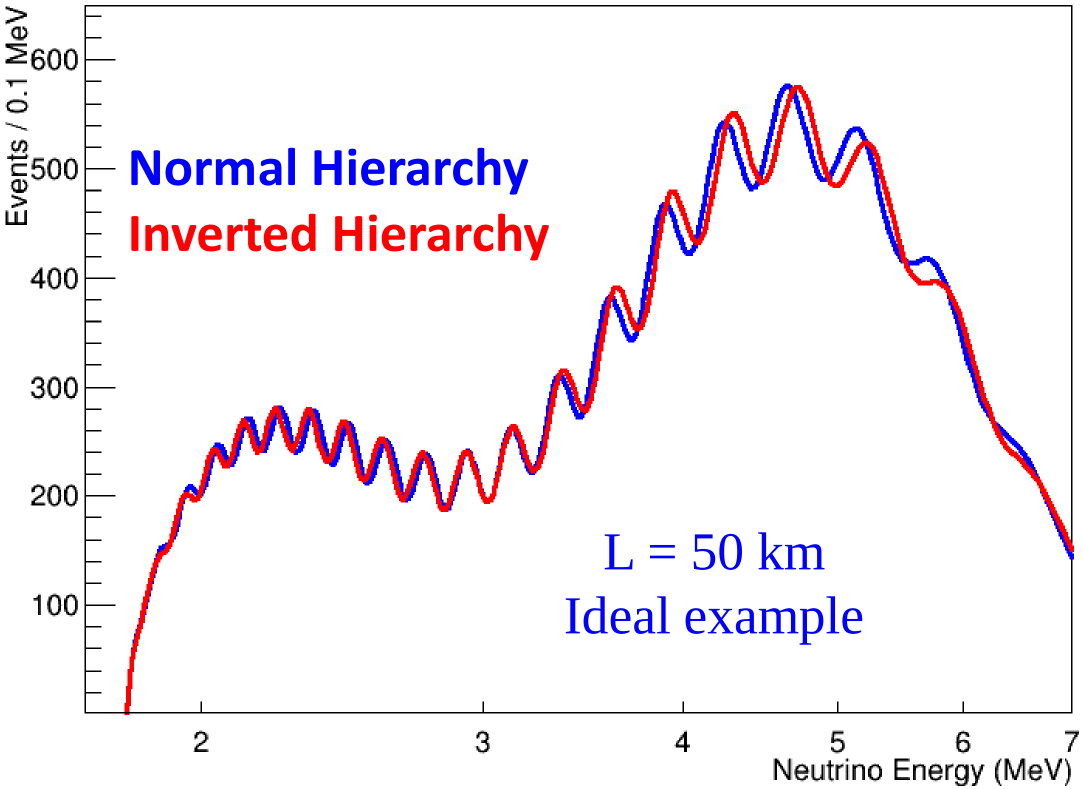
H. Seo:: Neutel 2019

Daya Bay and RENO will finish data taking by the end of 2020

Tackle Mass Hierarchy With Reactors

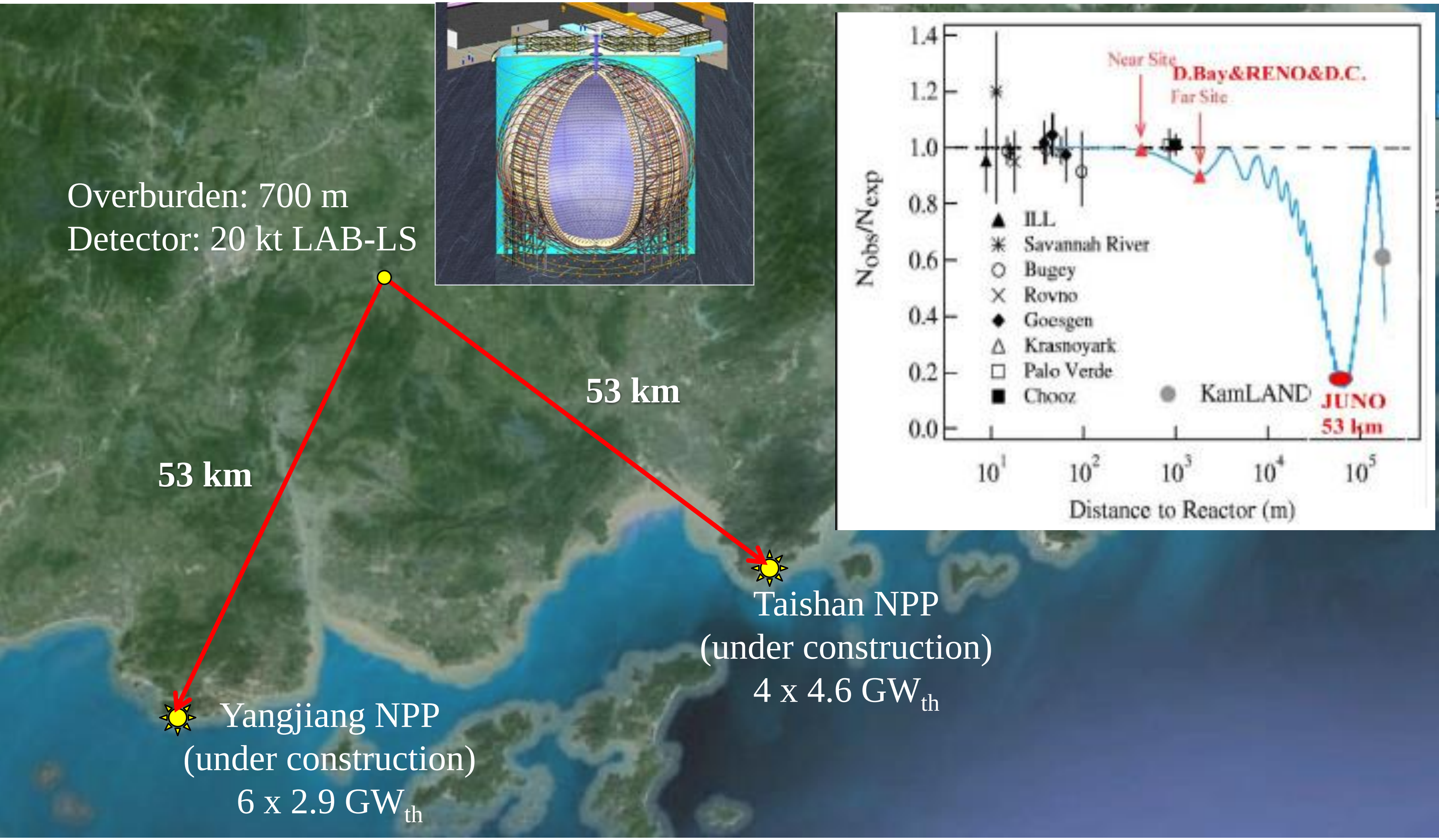
- Large θ_{13} enables determination of mass hierarchy with reactors [Petcov-Piai, PLB**533**(2002)94]
- Survival probability of $\overline{\nu}_e$ is given by:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left[\cos^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) + \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)\right] - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$



- Need high statistics and excellent energy measurement.

JUNO



Overburden: 700 m
Detector: 20 kt LAB-LS

53 km

53 km

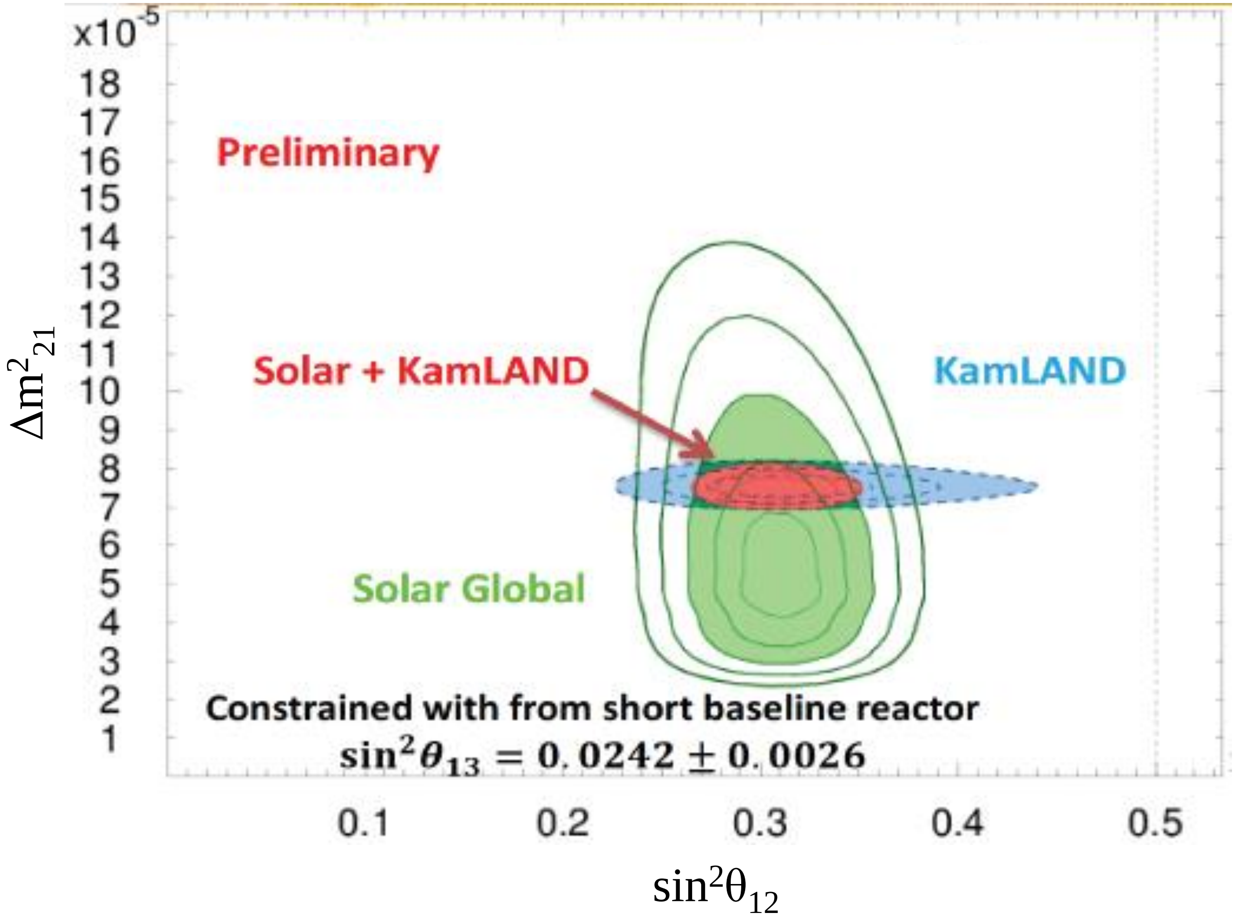
Taishan NPP
(under construction)
4 x 4.6 GW_{th}

Yangjiang NPP
(under construction)
6 x 2.9 GW_{th}

- Resolve mass hierarchy at 3-4 standard deviations in six years
- < 1% precision in $\sin^2 2\theta_{12}$, Δm^2_{21}, and Δm^2_{32}

Pinning Down Δm^2_{21}

Δm^2_{21} measured by KamLAND using reactor $\overline{\nu}_e$ disagrees with the one determined by solar-neutrino measurements by ~2 standard deviations



Constrained with from short baseline reactor $\sin^2\theta_{13} = 0.0242 \pm 0.0026$

$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.310 \pm 0.014$$
$$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60}$$
$$\sin^2\theta_{12} = 0.310 \pm 0.012$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17}$$

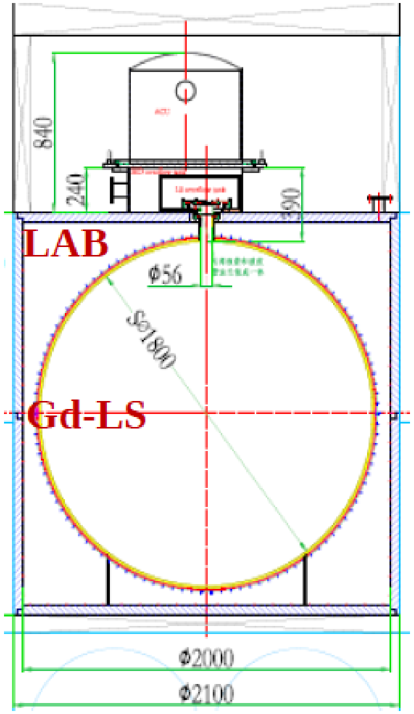
The unit of Δm^2_{21} is 10^{-5} eV^2

M.Ikeda, Neutrino 2018

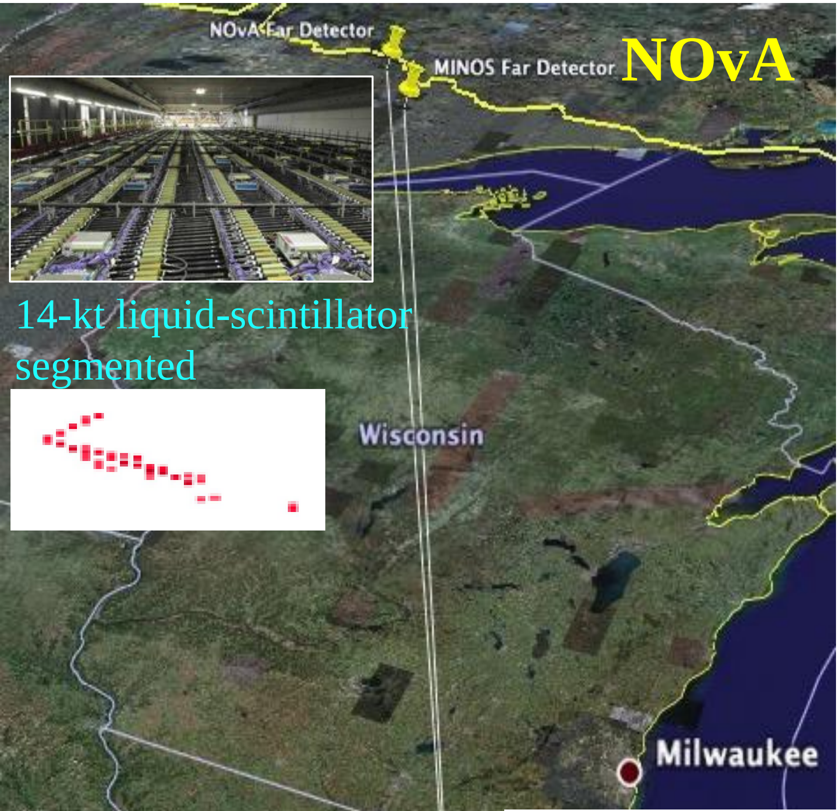
Status of JUNO

- Civil construction is ongoing
  - Verticle shaft and 40%-slope tunnel done
  - More than 54 m out of 70 m (H) of the cavern excavated.
- QE of 20” MCP-PMTs achieved >30%
- LAB-based liquid scintillator
  - Attenuation length of purified LAB measured: > 25 m.
  - R&D on reducing radio-activities (goal: ^{238}U/^{235}Th < 10^{-15} g/g, ^{40}K < 10^{-16} g/g)
- 1:12 prototype built for testing filling/circulation/overflow procedure
- Aim for energy resolution: 3%/√E
- Begin data taking in 2021

- TAO
  - 2.6 t Gd-LS
  - 30 m from a core of Taishan NPP
  - Full coverage with SiPMs at -50 C
  - Energy resolution of ~1.5%/√E
  - Ready by 2020
  - Measure energy spectrum precisely

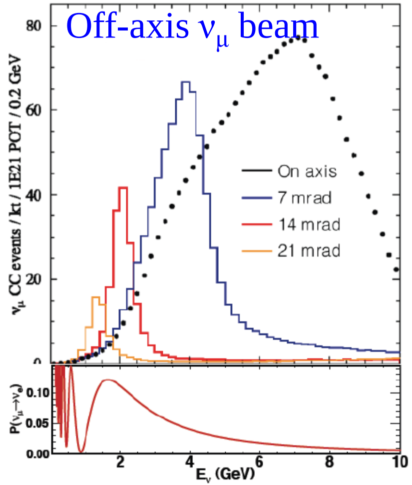


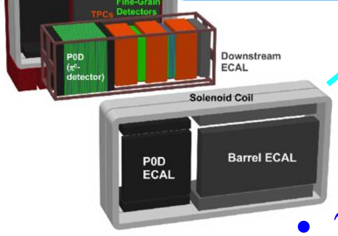
NOvA and T2K



14-kt liquid-scintillator segmented

300-ton functionally identical Near Detector



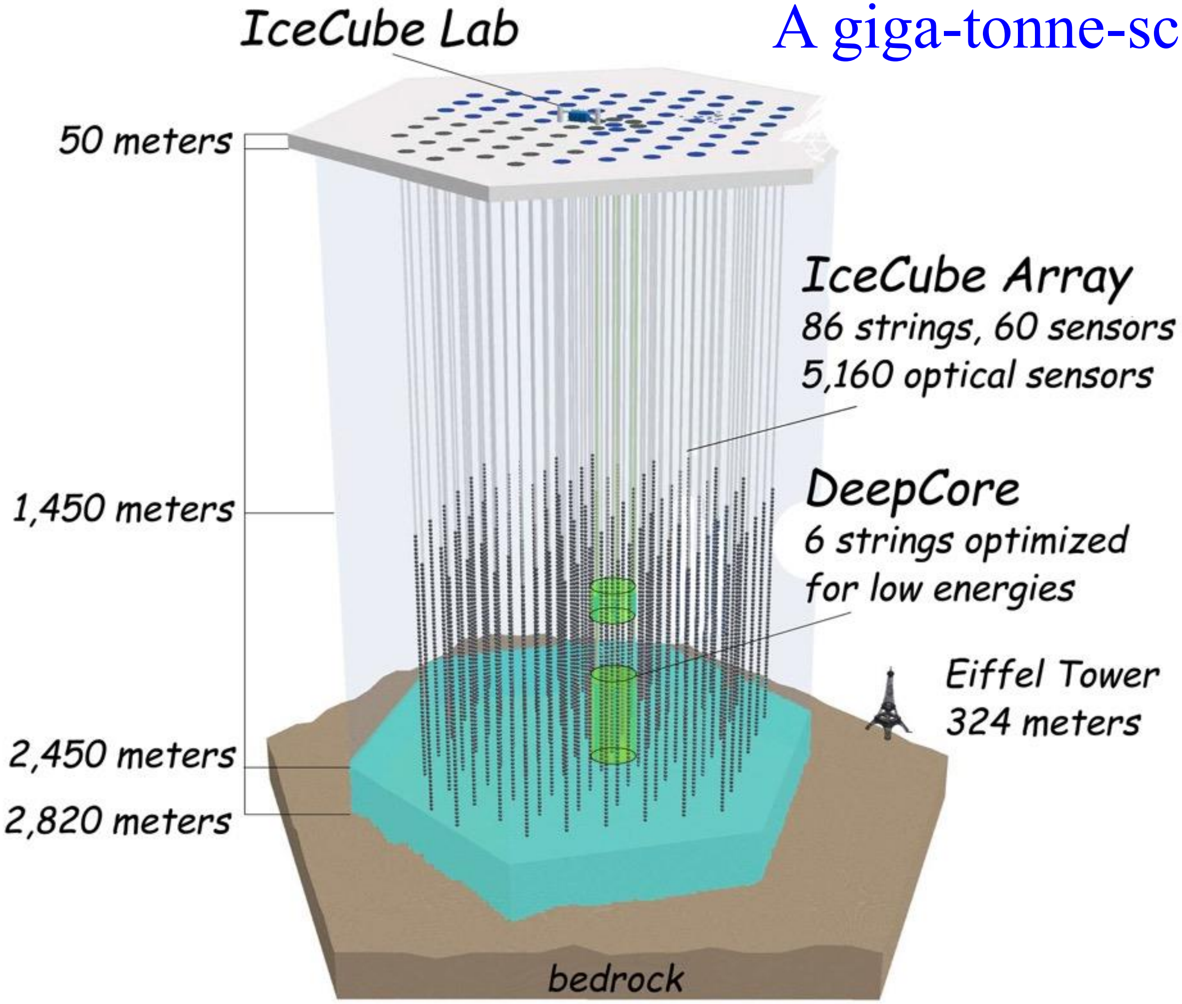


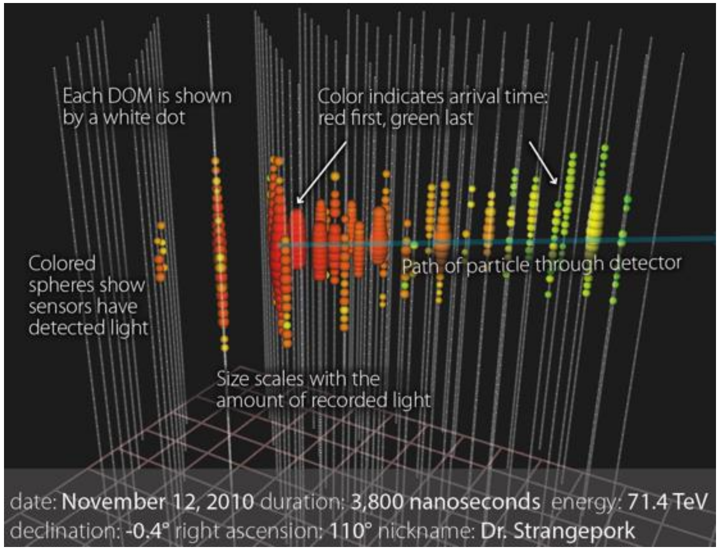
- Magnetized multi-purpose near detector
- 2.5° off-axis narrow-band ν_μ beam, 0.6 GeV peaked at first oscillation maximum

Matter effect ~10% for T2K and ~30% for NOvA, good for resolving degeneracies

IceCube-DeepCore

A giga-tonne-scale neutrino detector

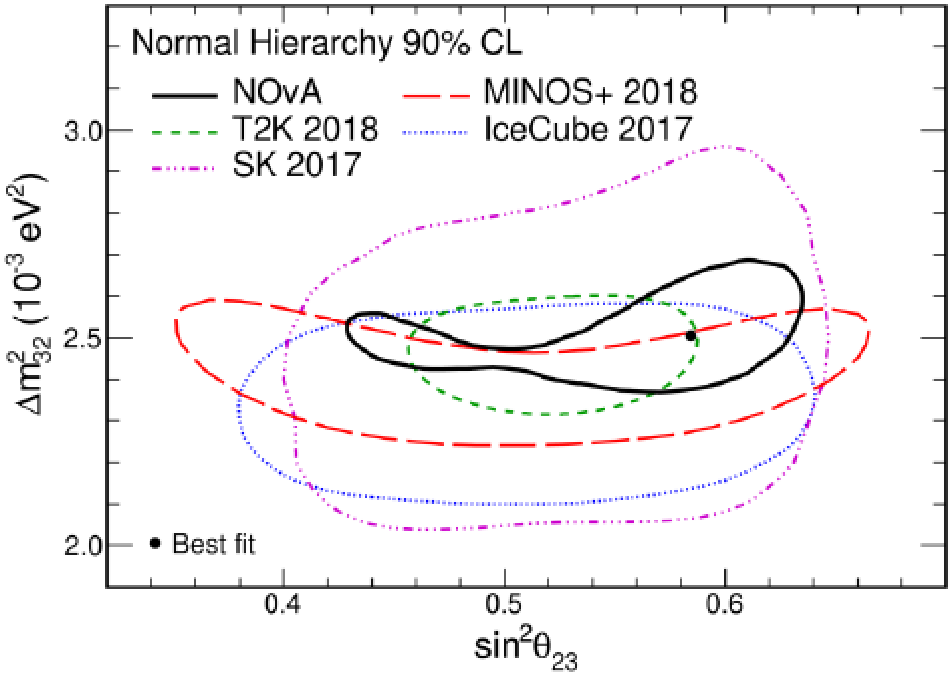




date: November 12, 2010 duration: 3,800 nanoseconds energy: 71.4 TeV
declination: -0.4° right ascension: 110° nickname: Dr. Strangepork

Update on θ_{23} & Δm^2_{32}

- T2K
  - has reduced uncertainties in the beam-flux and neutrino interaction model
  - error at Super-K site has gone down from ~15% to ~5% with improved analysis
- NOvA applied machine learning to improve analysis
- IceCube-DeepCore has used a different event selection and analysis to obtain new results, PRD **99**(2019)032007

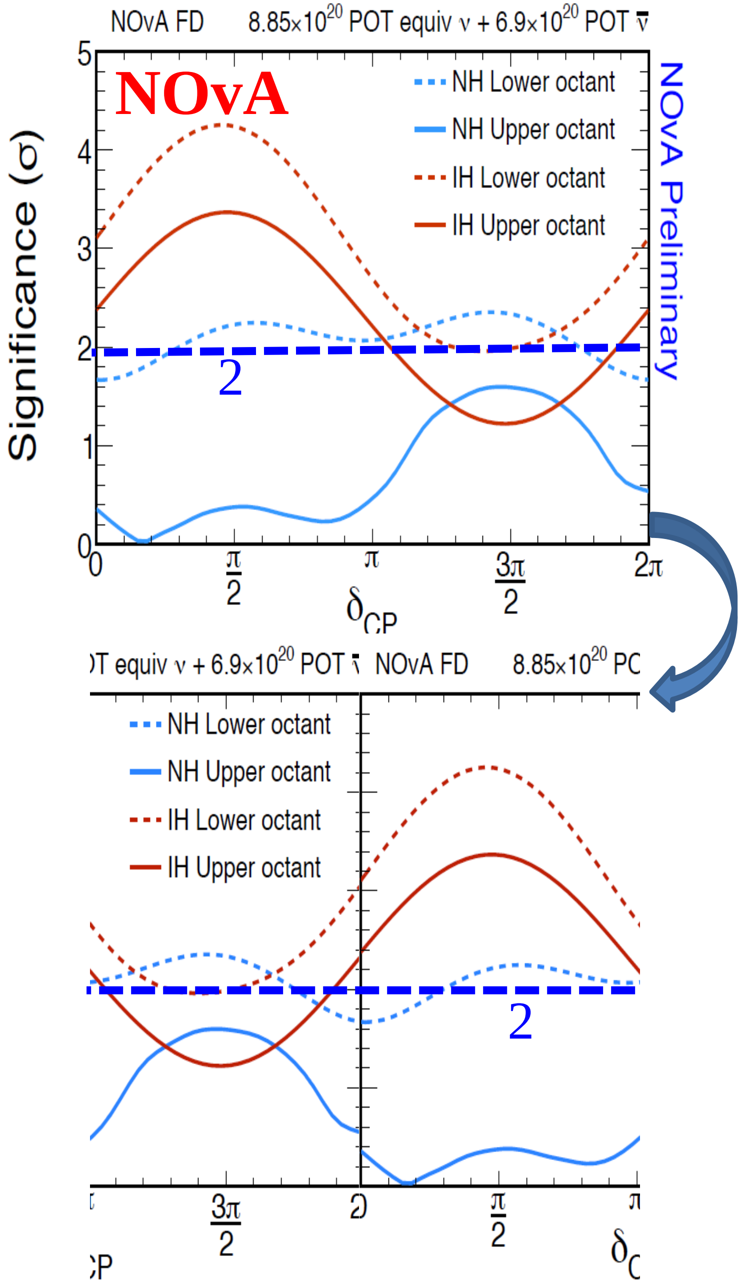


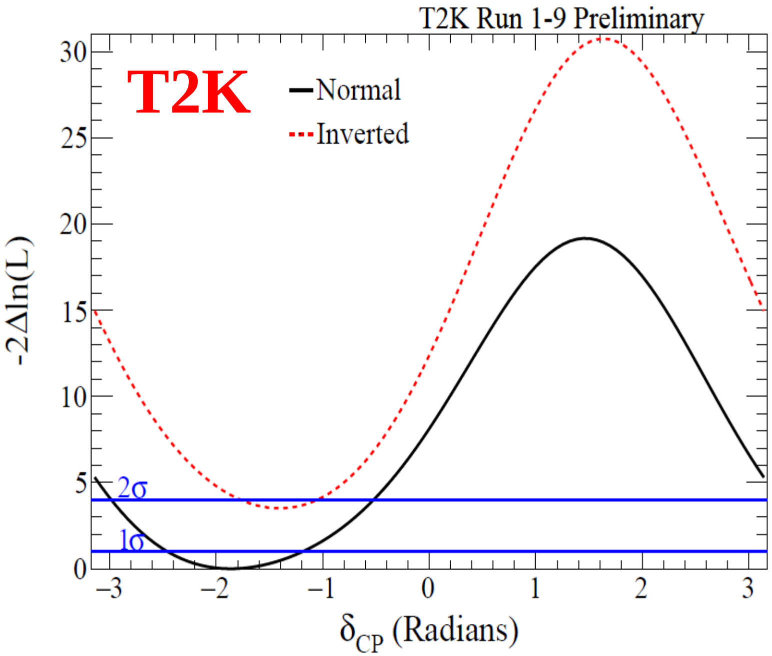
Aurisano: NeuTel 2019

NH	$\sin^2\theta_{23}$	$\Delta m^2_{32} \times 10^{-3}$ eV^2
T2K	$0.532^{+0.030}_{-0.037}$	$2.452^{+0.070}_{-0.071}$
NOvA	0.58 ± 0.03	$2.51^{+0.12}_{-0.0.8}$
IceCube-DeepCore 2019	$0.58^{+0.04}_{-0.13}$	$2.55^{+0.12}_{-0.11}$

All marginally disfavor maximal mixing and Lower Octant for θ_{23}

Mass Ordering and δ_{CP}



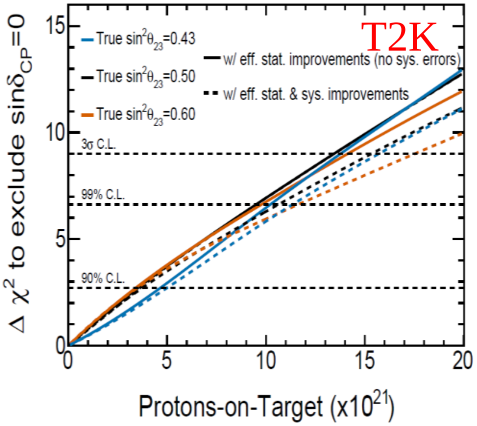


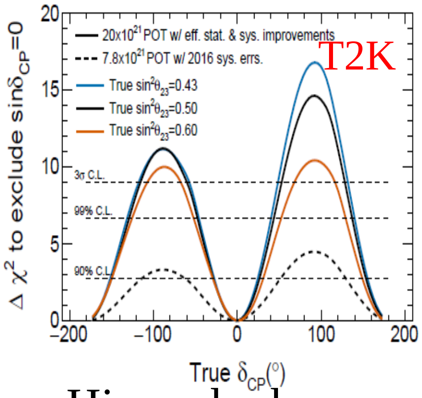
A.K. Ichikawa

- NOvA prefers NH at 1.8σ
- T2K
  - ruled out $\delta_{CP} = 0$ or π (CP conserves) by >2σ.
  - in favour of NH (89%) vs IH (11%)
- T2K+Super-K
  - best-fit $\delta_{CP} = 4.88^{+0.81}_{-1.48}$ radians

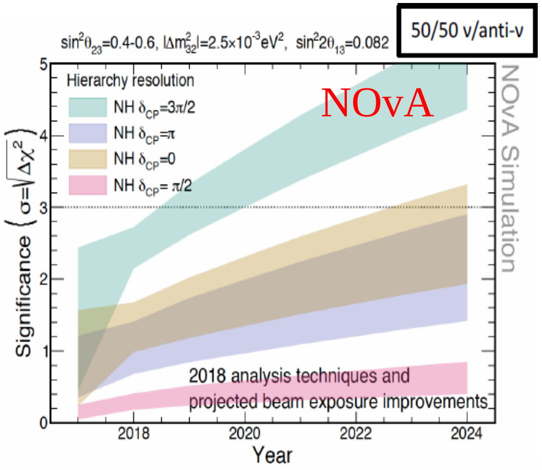
Prospects of NOvA and T2K

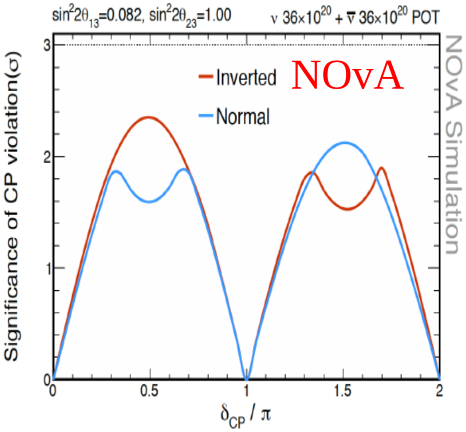
- NOvA
  - improve calibration with a test-beam program and better understanding of detector response
  - upgrade to high-power target in 2019, and PIP-II with beam power > 0.9 MW
- T2K
  - upgrade near detector by replacing PI0 and Barrel ECals to TPCs and Super-FGD
  - increase beam power from 0.5 MW to 1.3 MW
  - load Super-K detector with Gd to tag neutrino interactions





Hierarchy known

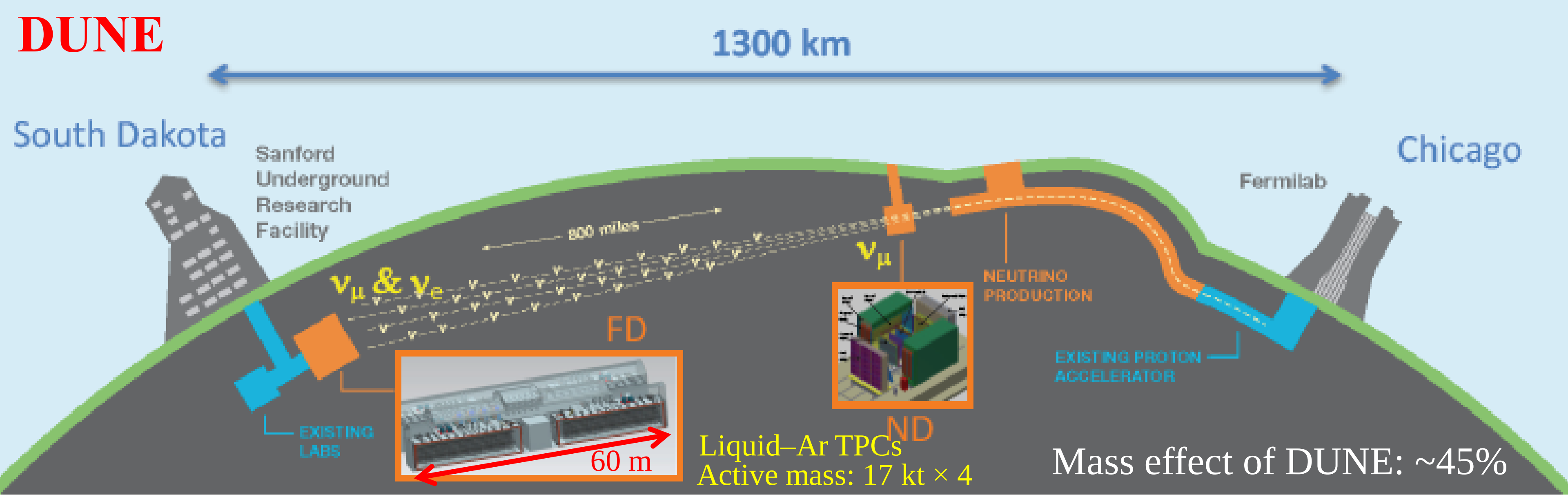




- NOvA and T2K
  - will continue to run till 2024
  - by then, may find CP violation and resolve mass hierarchy at 3σ

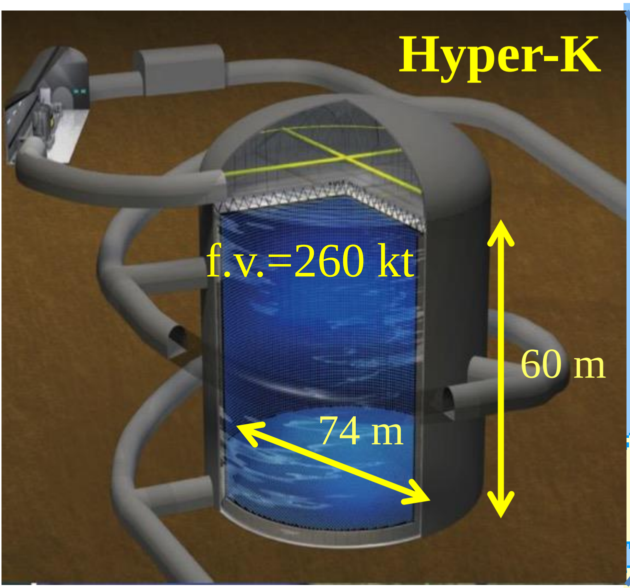
Future: DUNE and Hyper-K

DUNE



Liquid–Ar TPCs
Active mass: 17 kt × 4

Mass effect of DUNE: ~45%

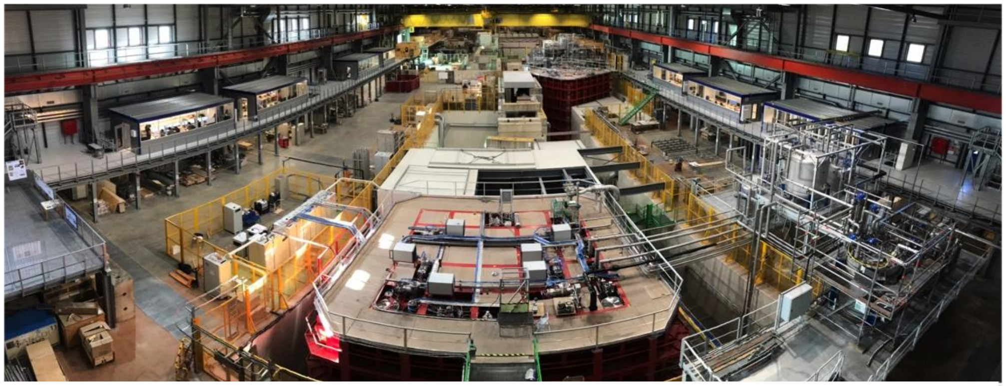


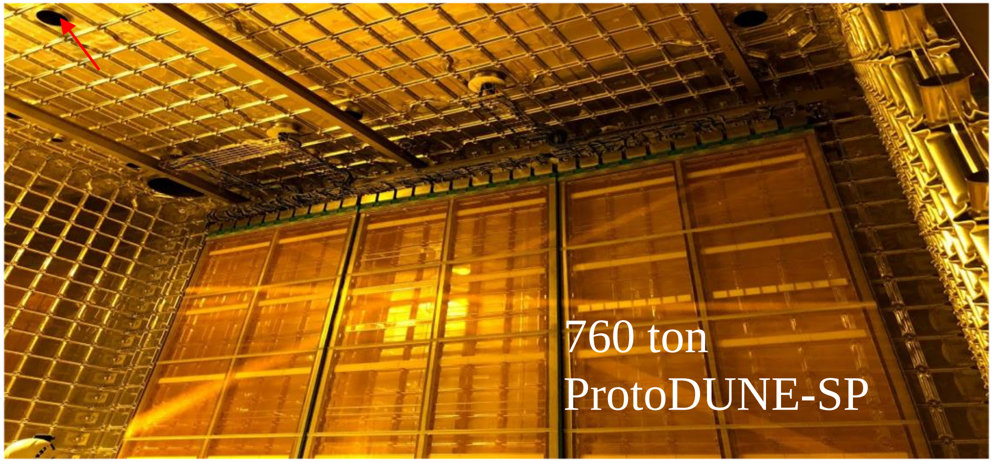
Mass effect of T2HK: ~10%

- Both experiments
  - are multi-purpose
    - accelerator neutrino
    - atmospheric neutrino
    - solar neutrino
    - supernova neutrino
    - nucleon decay
  - plan to start around 2026

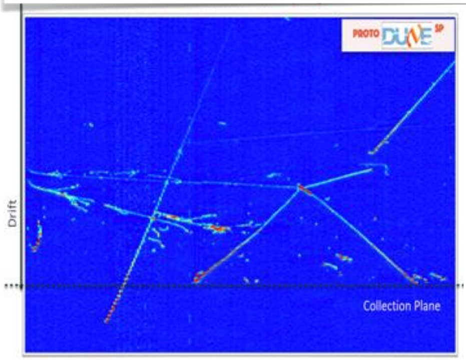
State-of-the-art Instrumentation

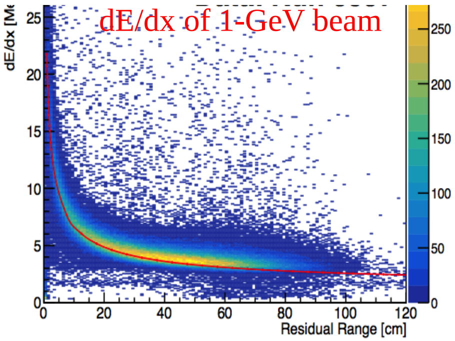
ProtoDUNE-SP (2018)





760 ton
ProtoDUNE-SP

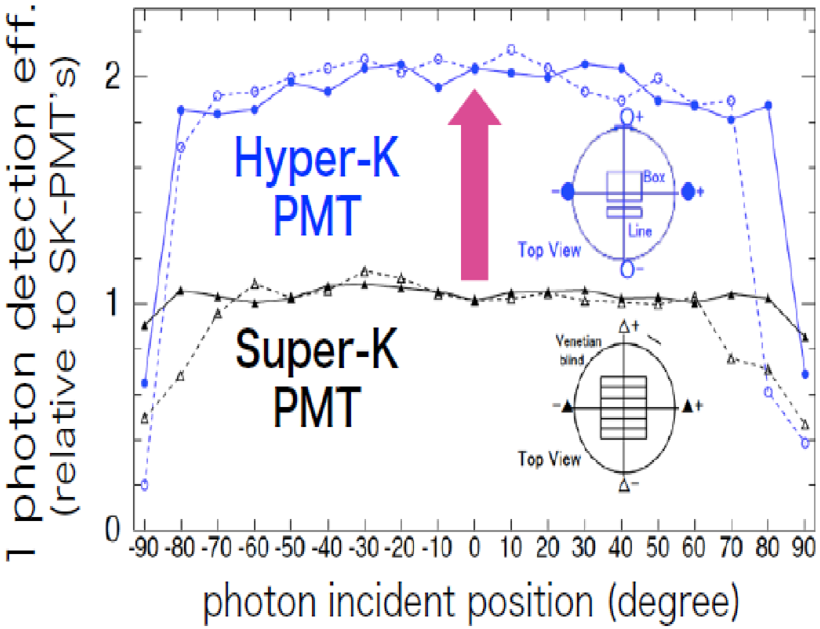




dE/dx of 1-GeV beam

Hyper-K

New 50cm PMT
- ×2 efficiency
- ×2 timing resolution
- ×2 pressure tolerance

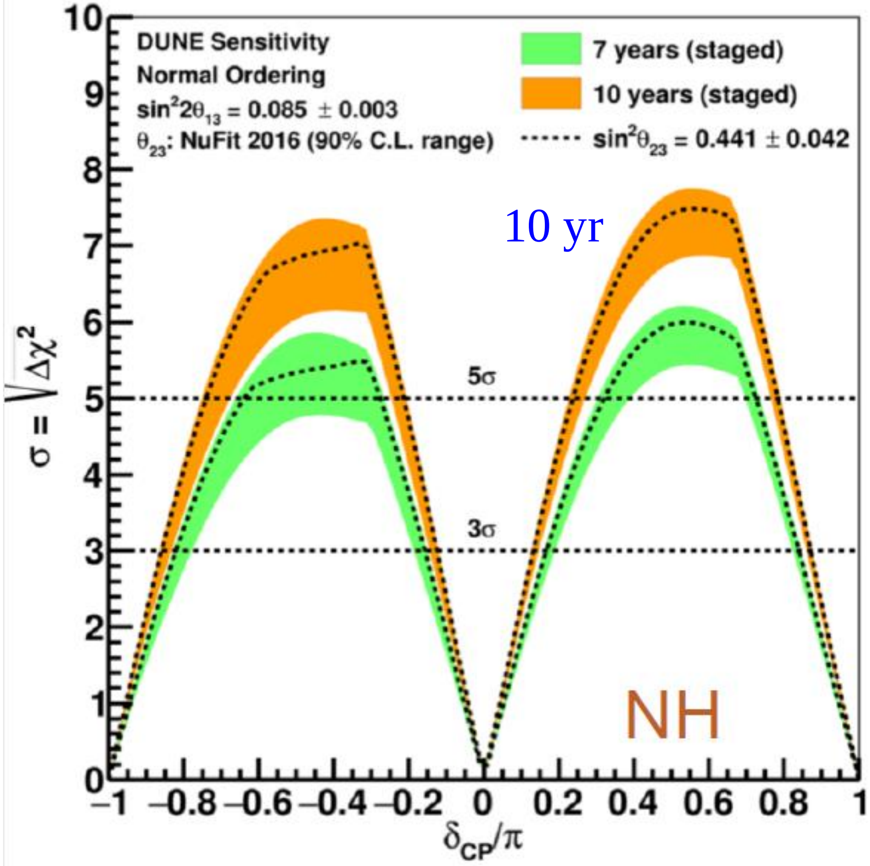


A.K. Ichikawa

DUNE and T2HK: Sensitivity in CP Violation

DUNE

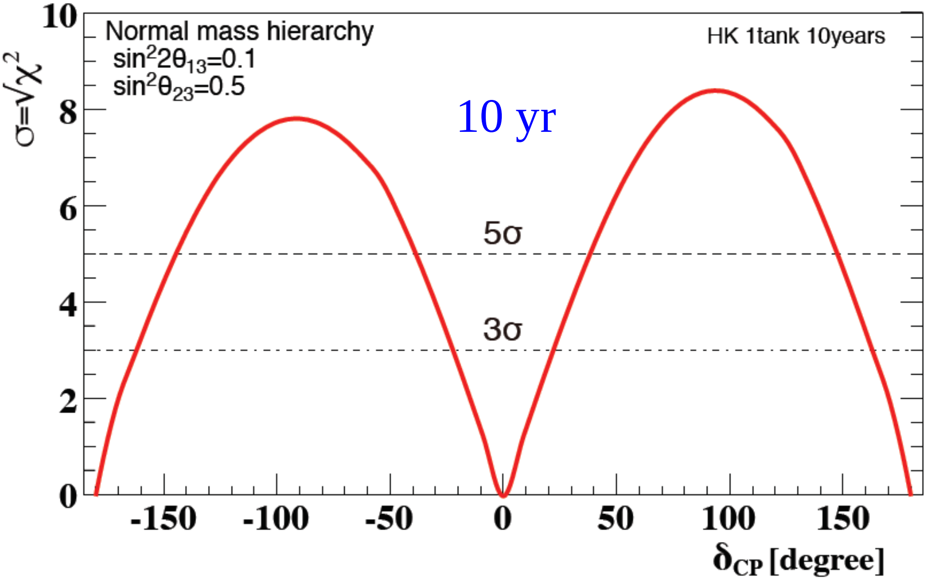
CP Violation



Width of band indicates variation in possible central values of θ_{23}

T2HK

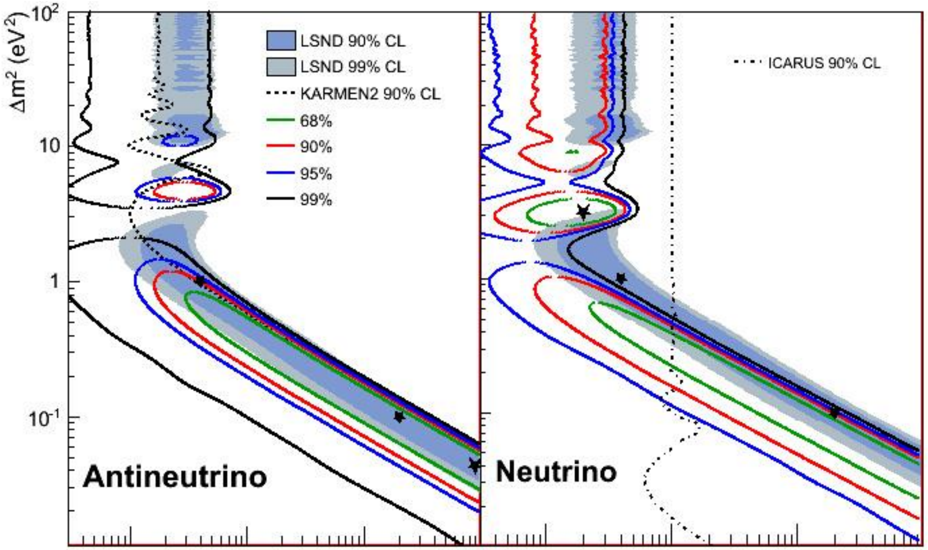
$\sin\delta_{CP}=0$ exclusion



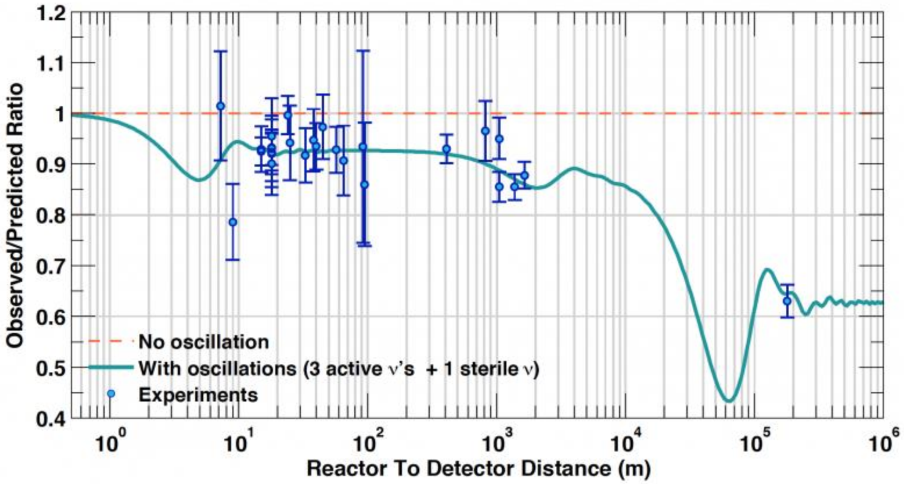
Sterile Neutrinos

Existence of Light Sterile Neutrinos ?

- Experimental hints:



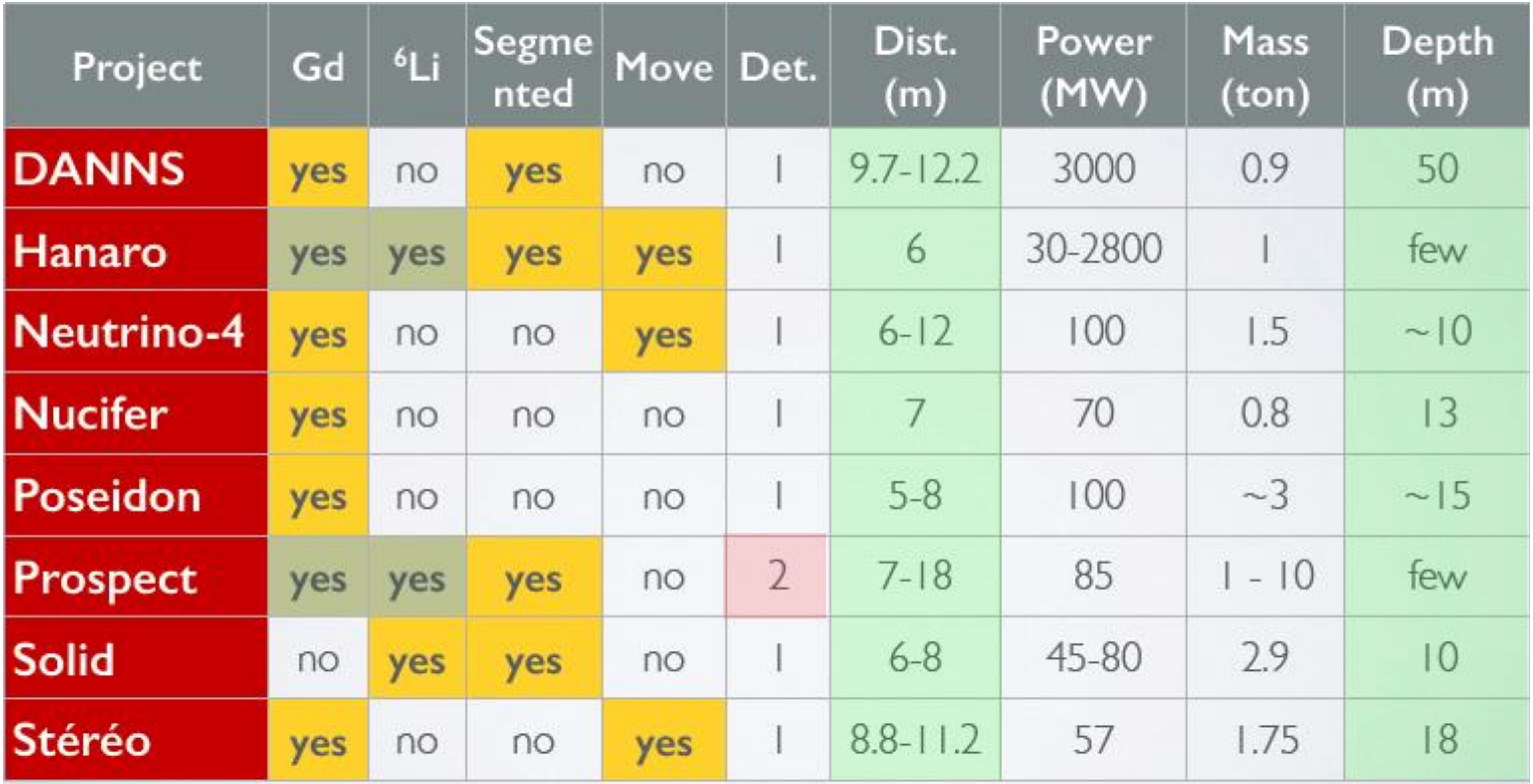
LSND/MiniBooNE Anomaly



Reactor Antineutrino Anomaly

Addressing Reactor Antineutrino Anomaly

- Very short-baseline reactor neutrino experiments & proposals to look for $\bar{\nu}_e$ disappearance

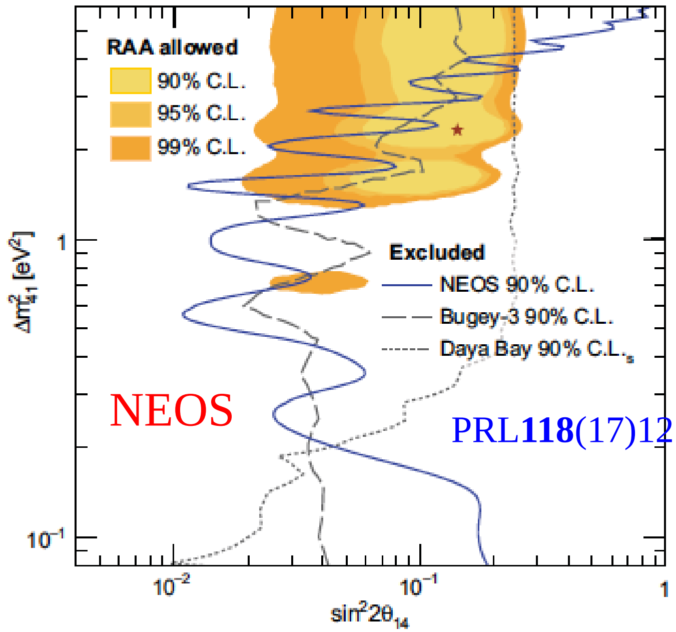


Project	Gd	^{6}Li	Segmented	Move	Det.	Dist. (m)	Power (MW)	Mass (ton)	Depth (m)
DANNS	yes	no	yes	no	1	9.7-12.2	3000	0.9	50
Hanaro	yes	yes	yes	yes	1	6	30-2800	1	few
Neutrino-4	yes	no	no	yes	1	6-12	100	1.5	~10
Nucifer	yes	no	no	no	1	7	70	0.8	13
Poseidon	yes	no	no	no	1	5-8	100	~3	~15
Prospect	yes	yes	yes	no	2	7-18	85	1 - 10	few
Solid	no	yes	yes	no	1	6-8	45-80	2.9	10
Stéréo	yes	no	no	yes	1	8.8-11.2	57	1.75	18

M. Pallavicini

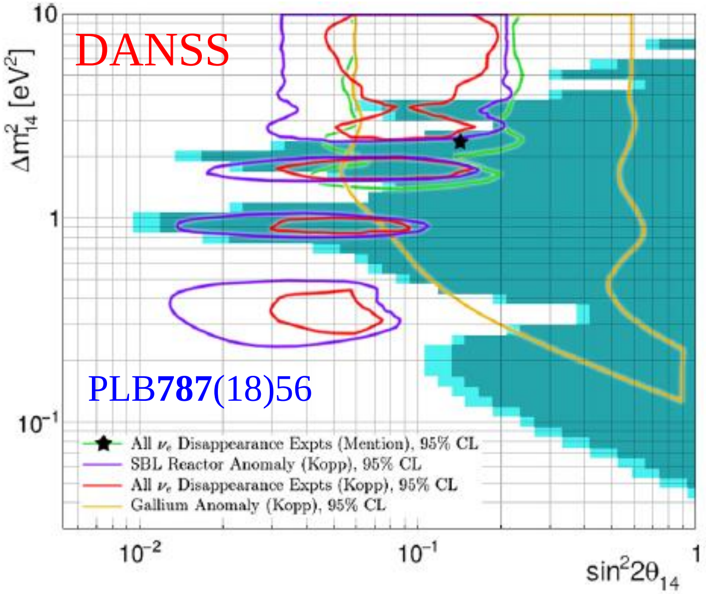
- Challenge: beat down background from reactor & cosmic ray

Empty-Handed First Results



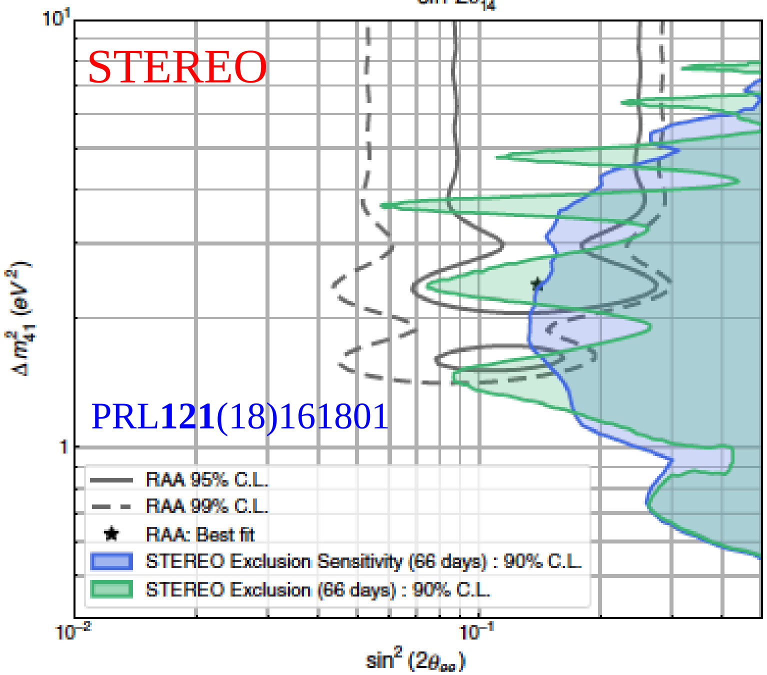
NEOS

PRL**118**(17)121802



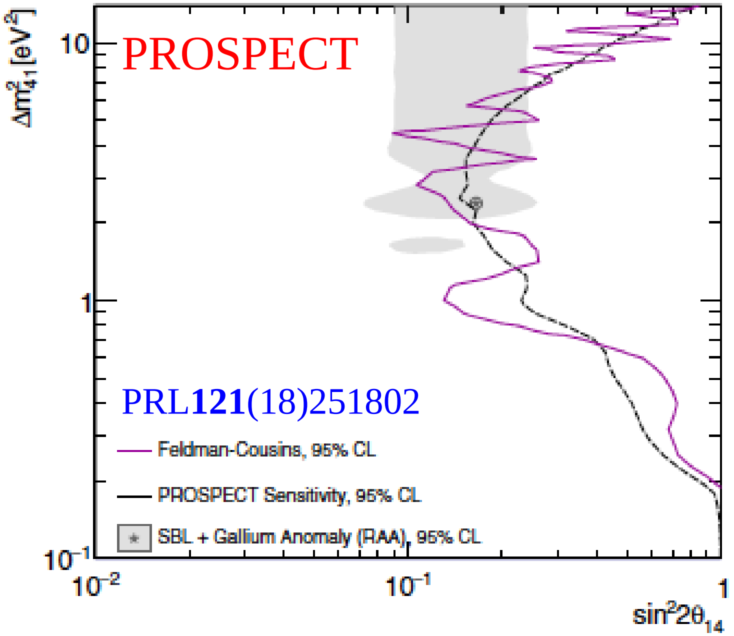
DANSS

PLB**787**(18)56



STEREO

PRL**121**(18)161801

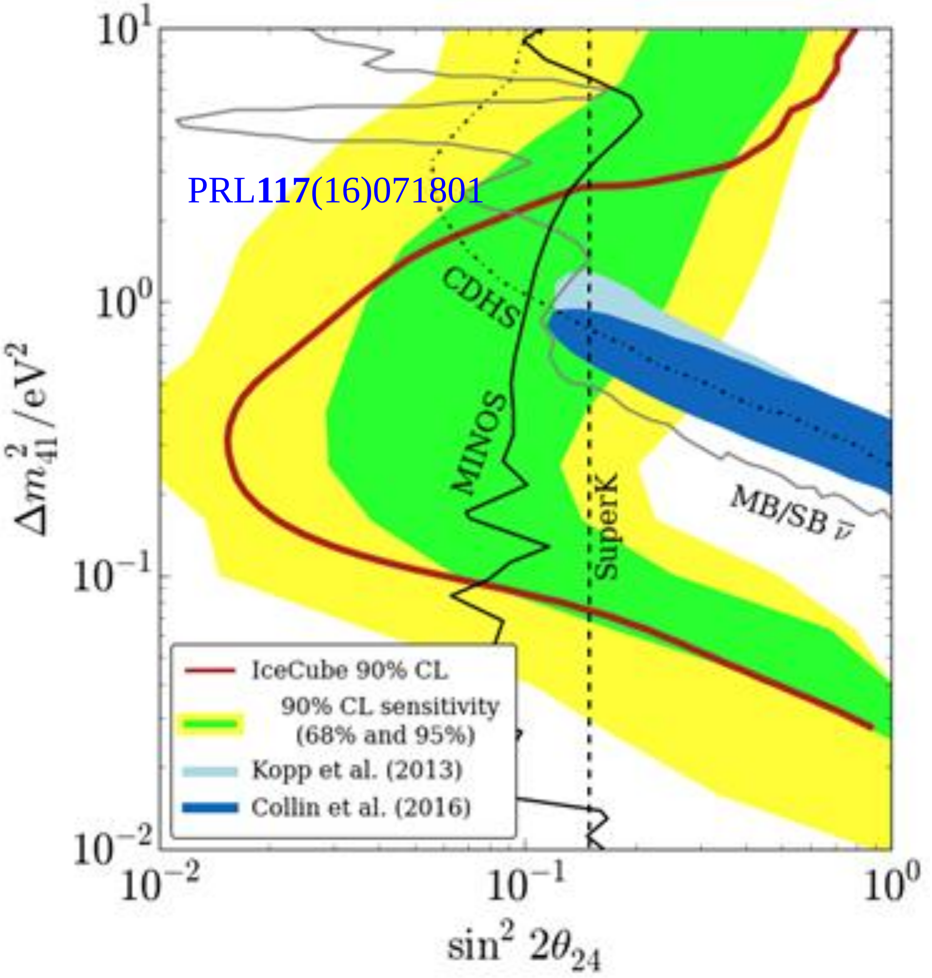


PROSPECT

PRL**121**(18)251802

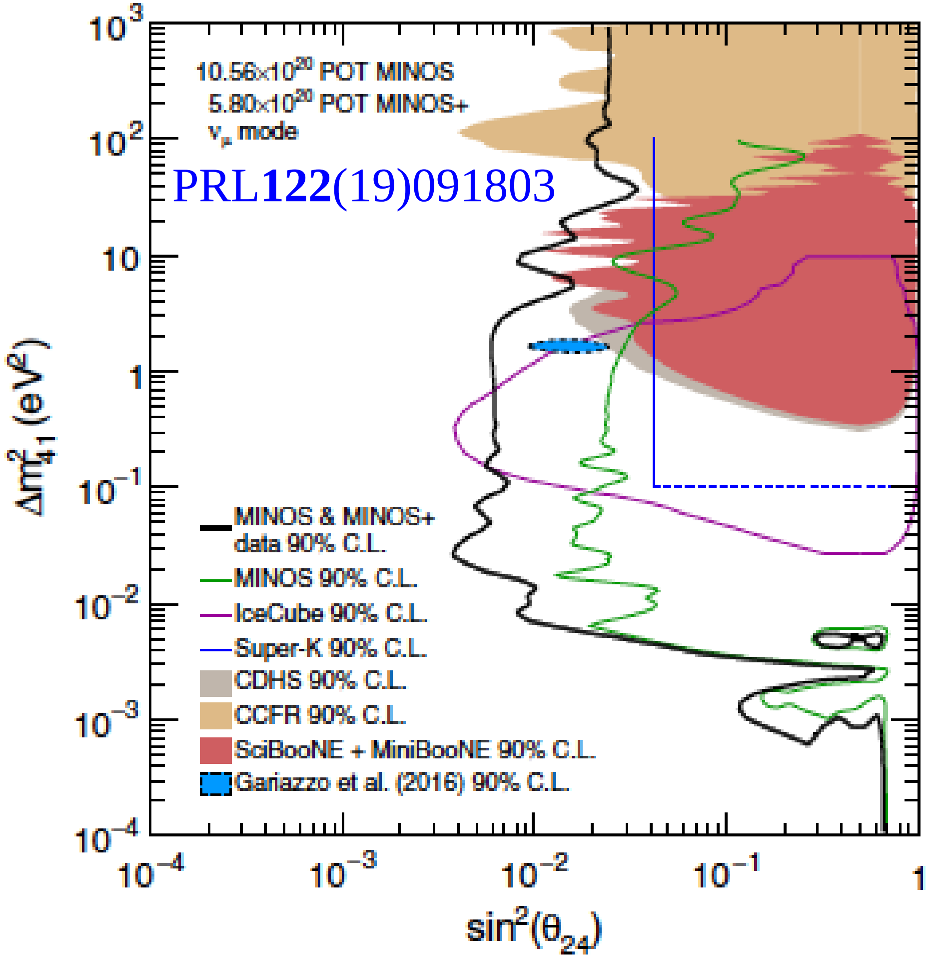
Other Null Results

IceCube



PRL**117**(16)071801

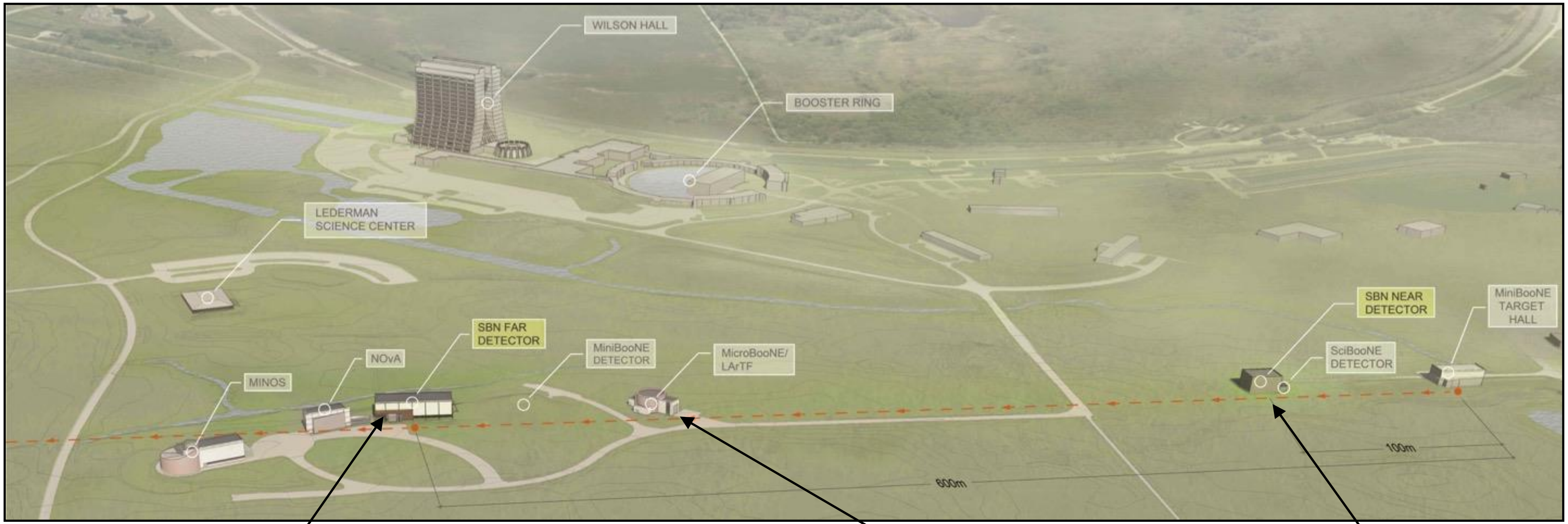
MINOS+MINOS+

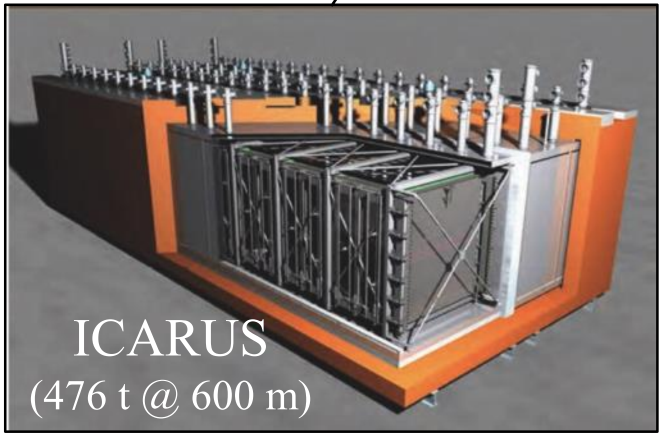


PRL**122**(19)091803

- Maltoni at Neutrino 2018: ‘Sterile neutrino models fail to simultaneously account for ν_e-to-ν_e data, the ν_μ-to-ν_e data, and the ν_μ-to-ν_μ data. This conclusion is robust.’

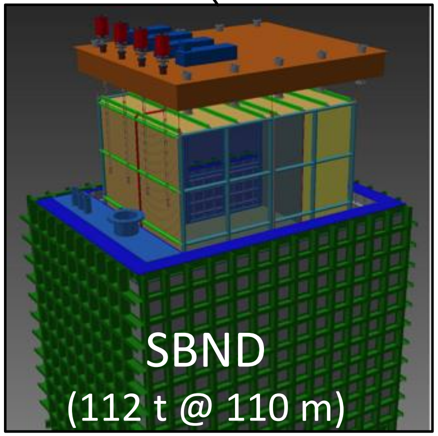
Short-Baseline Neutrino (SBN) Program





ICARUS
(476 t @ 600 m)

MicroBooNE
(89 t @ 470 m)

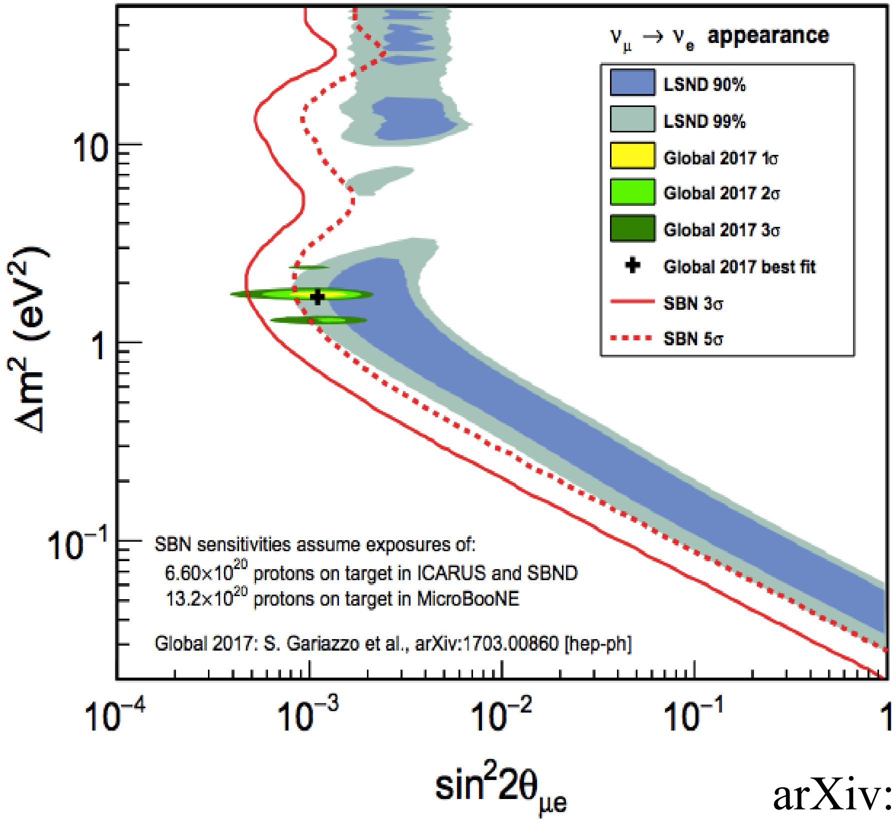


SBND
(112 t @ 110 m)

- All three detectors are liquid-argon TPCs
  - ICARUS will start data taking towards the end of 2019
  - Build a DUNE-style detector: SBND will see beam in 2020

Sensitivities of the SBN Program

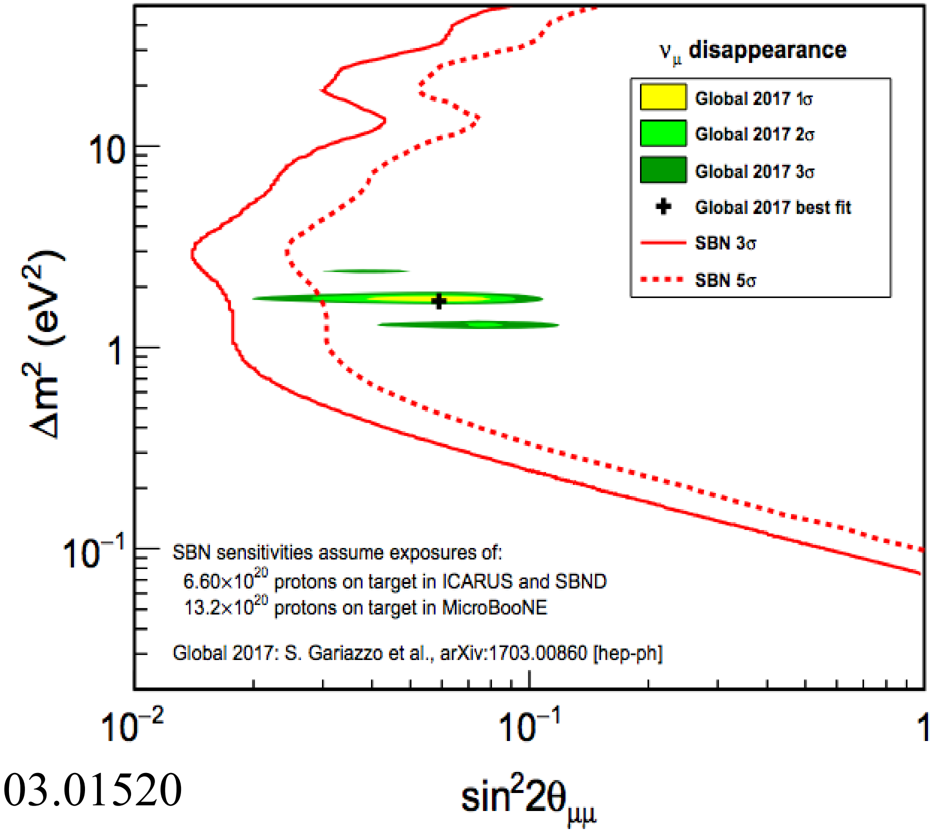
ν_e appearance



SBN sensitivities assume exposures of:
6.60×10^{20} protons on target in ICARUS and SBND
13.2×10^{20} protons on target in MicroBooNE

Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]

ν_μ disappearance



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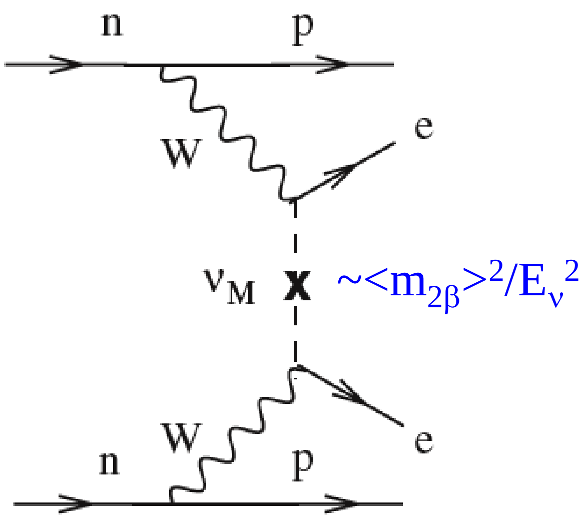
Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]

arXiv:1503.01520

- Appearance and disappearance measurements with the same detectors
- SBN has the potential to cover the entire range of interest

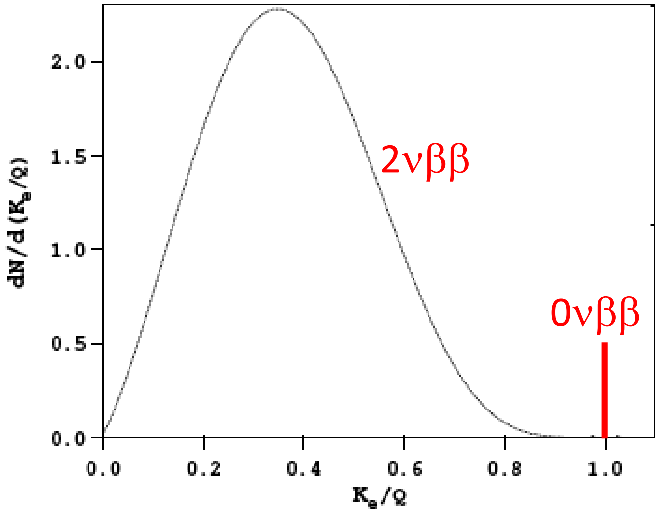
Neutrinoless Double Beta Decay

Neutrinoless Double Beta Decay



- The decay rate is given by:

$$W = \frac{2p}{\hbar}\left|M_{fi}(0n)\right|^2 r_2\left(Q_{2b},Z\right)\left\langle m_{2b}\right\rangle^2 \mu\ G_F^4 g_{n\bar{n}}^2 Q_{2b}^5 \left\langle m_{2b}\right\rangle^2$$



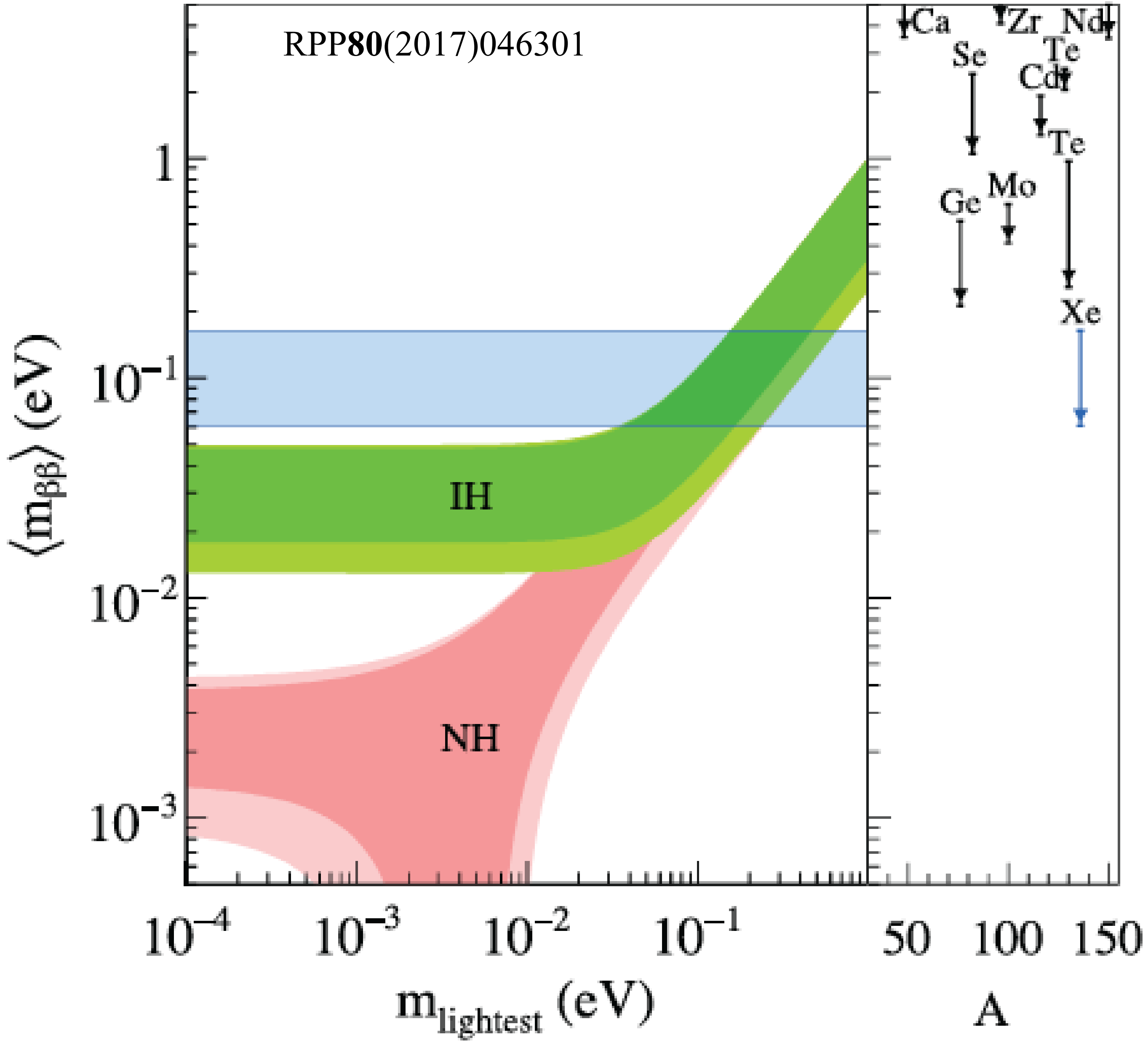
- Can only happen if
  - neutrinos have mass
  - neutrinos are Majorana particles
- It is a ΔL = 2 process.
- If 0νββ decay is observed:
  - it will determine the absolute neutrino mass *scale*.
  - measurements in a number of different isotopes can reveal the underlying interaction dynamics.

Experimental Techniques

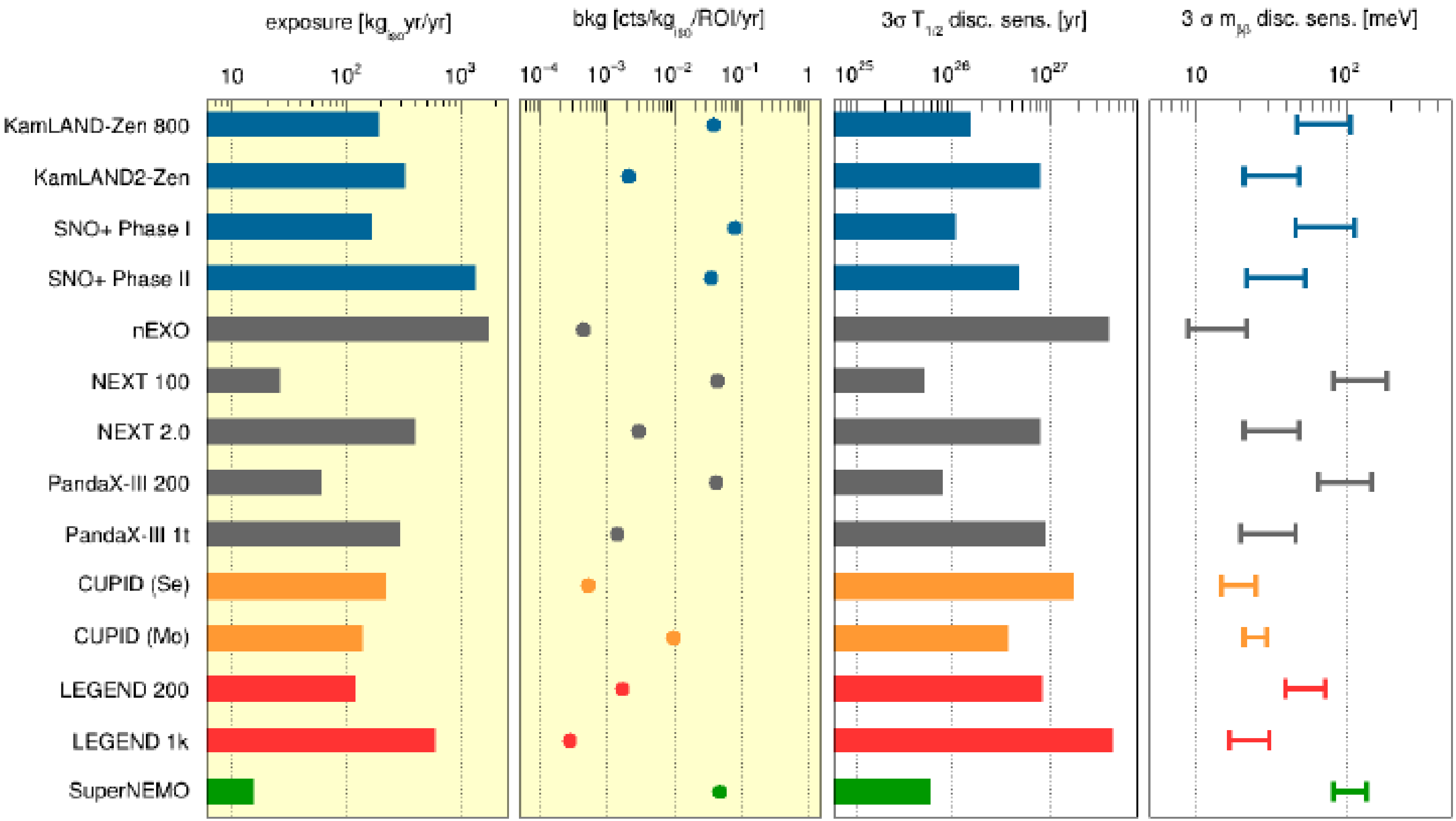
source = detector			NOW	MID-TERM	LONG-TERM
Scalability	Fluid embedded source	Xe-based TPC	EXO-200 NEXT-10	NEXT-100 PandaX-III	nEXO NEXT-2.0 PandaX-III 1t
		Liquid scintillator as a matrix	KamLAND-Zen 800 SNO+ phase I		KamLAND2-Zen SNO+ phase II
High ΔE and ε	Crystal embedded source	Germanium diodes	GERDA-II MJD	LEGEND 200	LEGEND 1000
		Bolometers	AMoRE pilot, I CUORE CUPID-0, CUPID-Mo	AMoRE II	CUPID

Giuliani: Neutrino 2018

Current Status

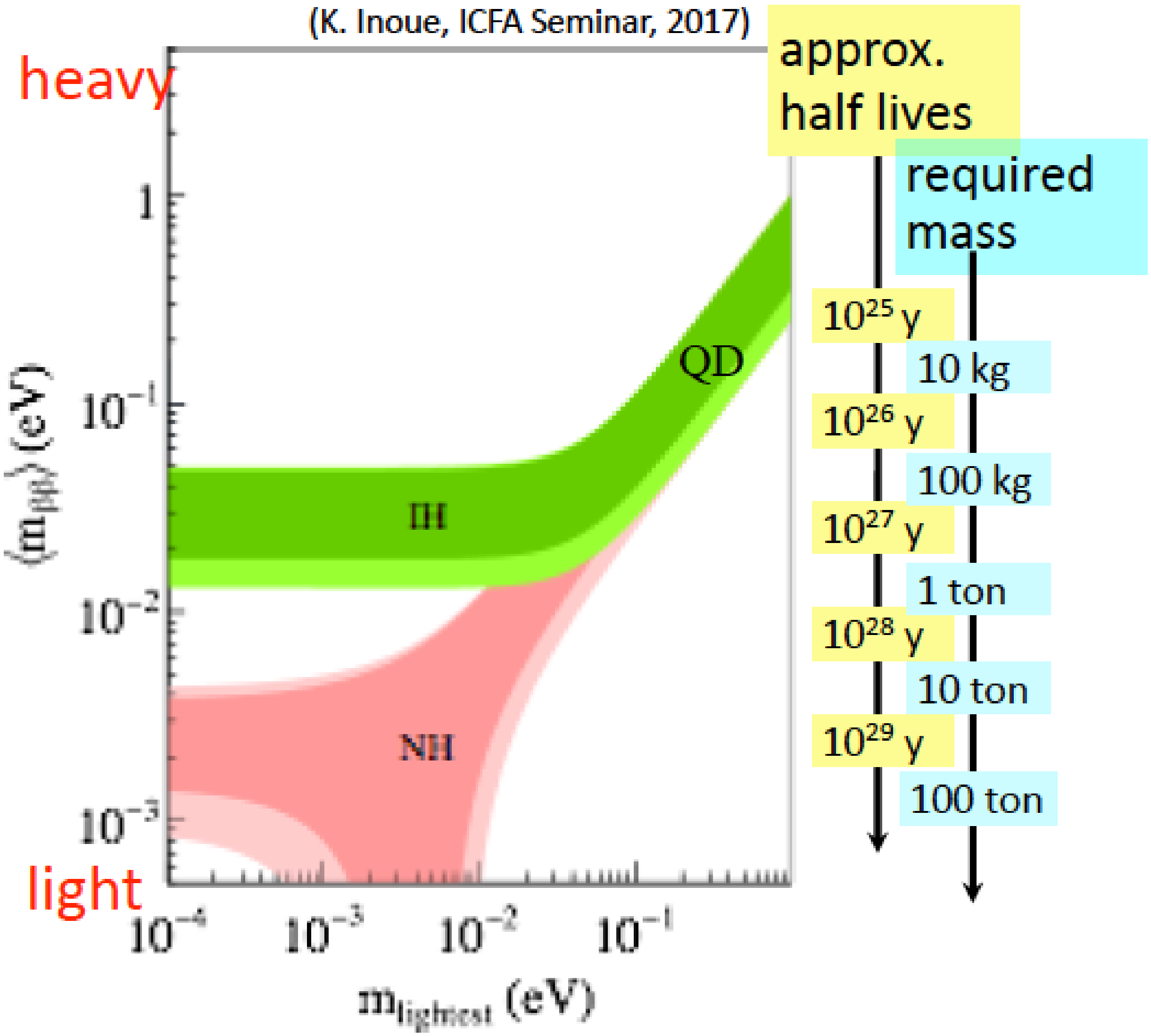


Comparison of Experiments



plot from M. Agostini

Getting To The NH Region


(K. Inoue, ICFA Seminar, 2017)

approx. half lives

required mass

10^{25} y

10 kg

10^{26} y

100 kg

10^{27} y

1 ton

10^{28} y

10 ton

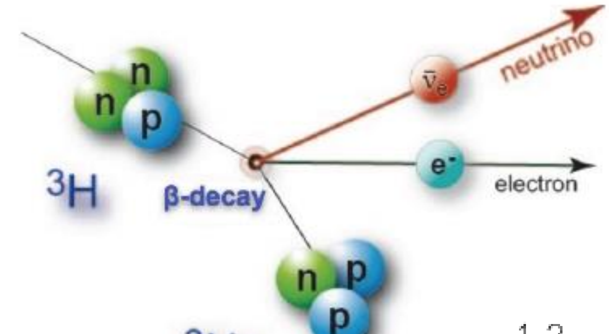
10^{29} y

100 ton

- Need to scale the current experiments by about 1000 times
- Must suppress background at least by (mass × time)$^{-1}$
- Need new approach

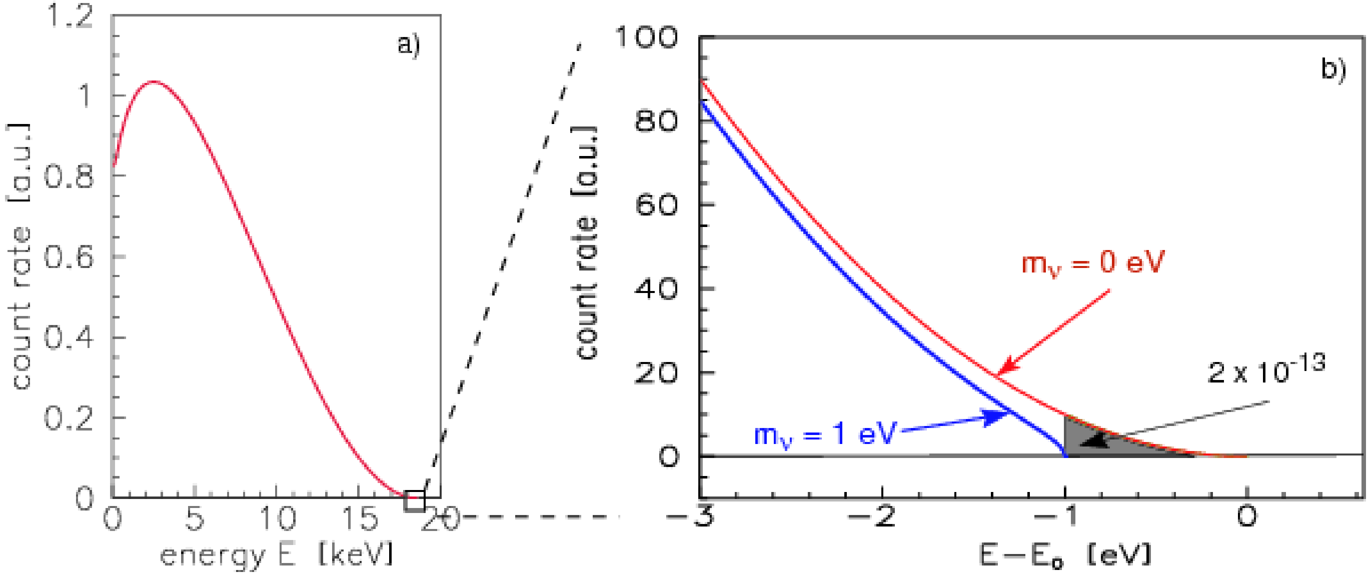
Absolute Neutrino Mass

Absolute Neutrino Mass



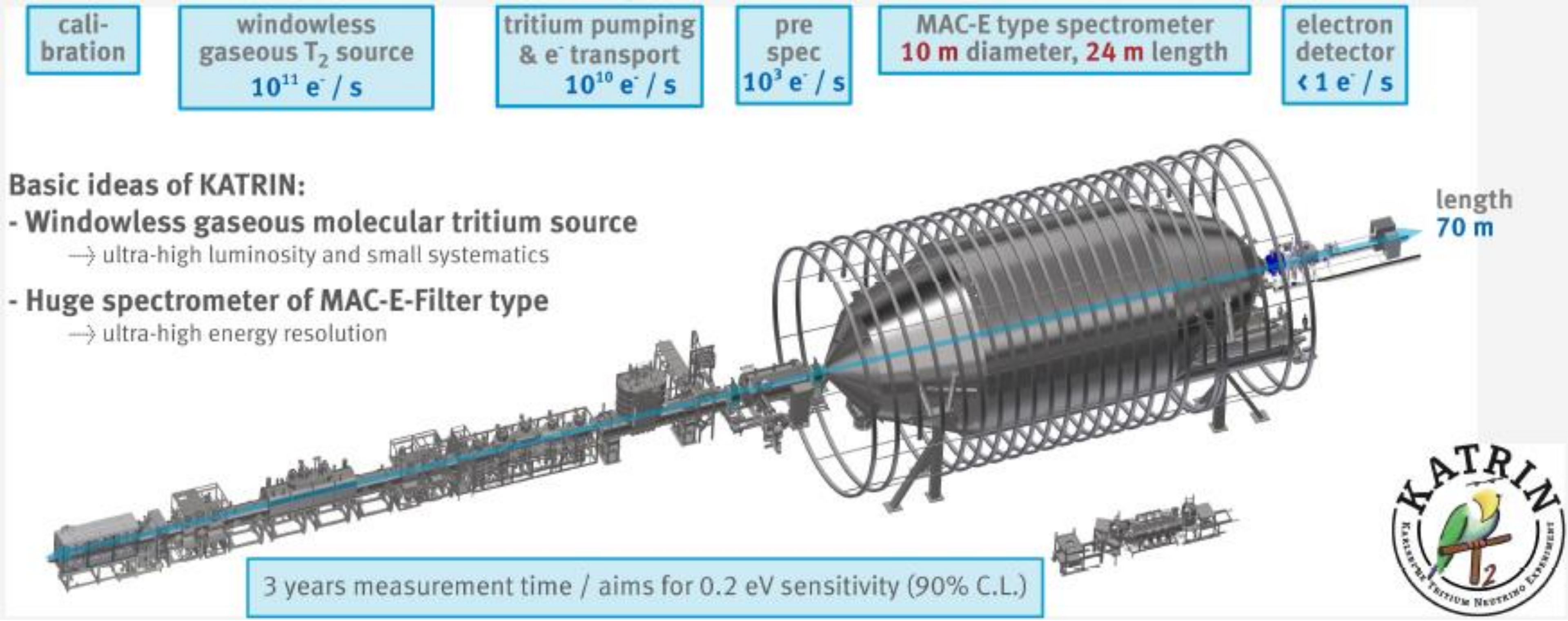
- The energy spectrum of the electron from a beta decay is

$$\frac{dN}{dE} \approx F(Z,E)\, p_e (E+m_e)\sqrt{(E-E_0)^2 - m_\nu^2}$$



- Need extremely high statistics and very good energy resolution
- Current limit: $m_\nu < 2.3$ eV

KATRIN



Basic ideas of KATRIN:

- **Windowless gaseous molecular tritium source**
  → ultra-high luminosity and small systematics
- **Huge spectrometer of MAC-E-Filter type**
  → ultra-high energy resolution

3 years measurement time / aims for 0.2 eV sensitivity (90% C.L.)

- First run in March/April 2019
- With 30 days of data, expect to reach m_ν < 1 eV

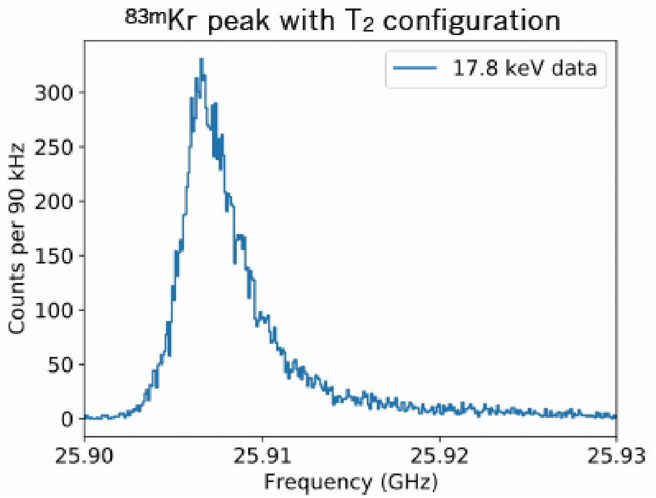
Project 8

- Store tritium gas in a magnetic trap
- Decay electrons circle around the field lines at cyclotron frequency

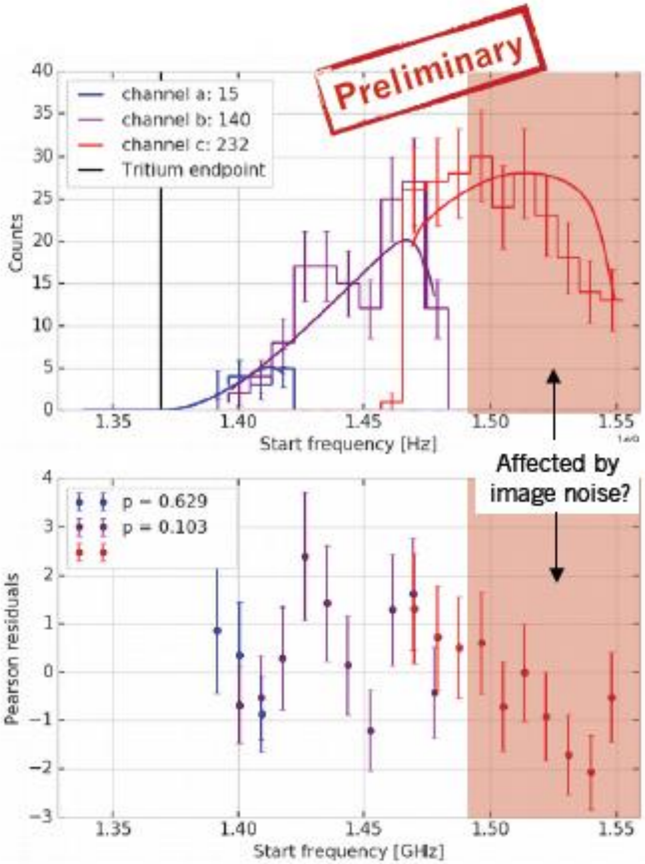
$$f_g = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_k}$$

with relativistic correction

- Detect cyclotron radiation, hence the energy spectrum.

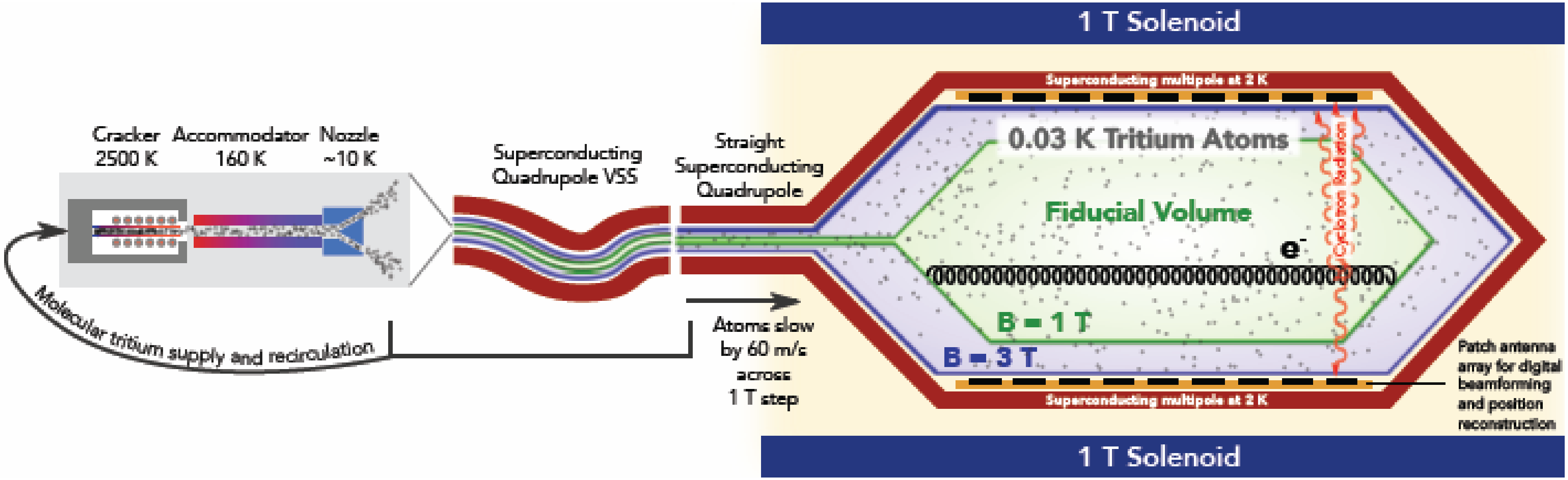


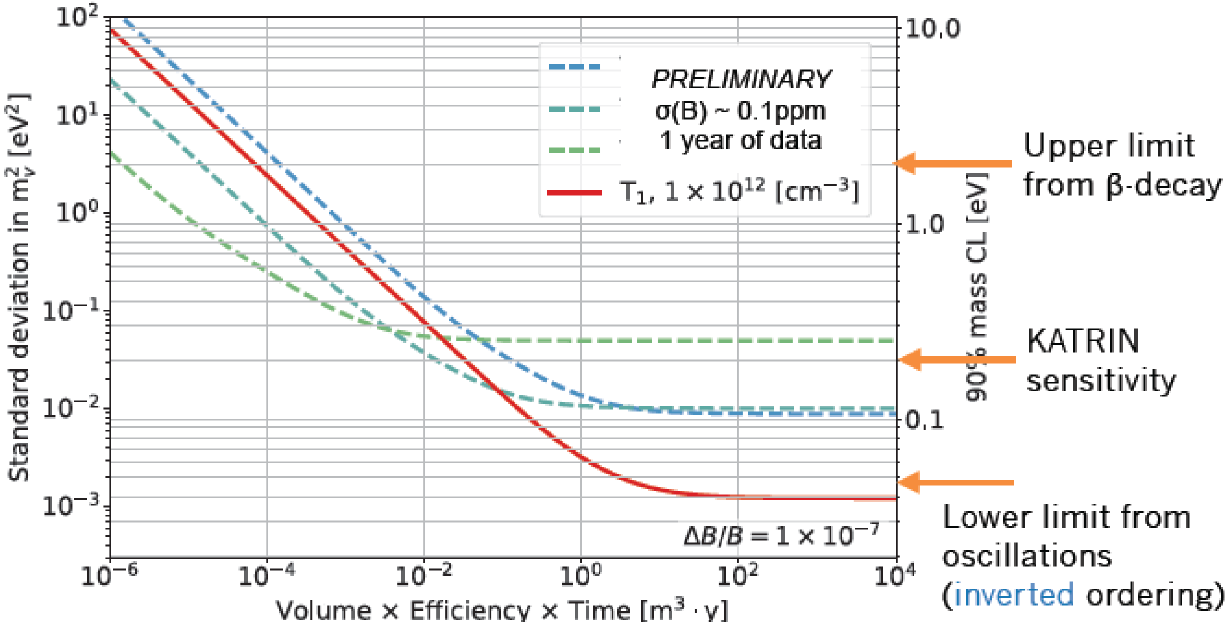
- T_2 run began on 8 Oct 2018
- Collected 417 events
- Spectrum consistent with expectation
- No background beyond end point



Prospects of Project 8

- Trap 10 m^3 at a density of 10^{12} cm^3 atomic T:





Upper limit from β-decay

KATRIN sensitivity

Lower limit from oscillations (inverted ordering)

Limited by

- rest gas interactions
- field homogeneity

Summary

- With the discoveries of neutrino oscillation,
  - neutrinos have tiny mass
  - lepton flavour number is violated
  - there is physics beyond the Standard Model
    - how do the neutrinos get their mass?
- To guide theoretical development,
  - determine the nature of the neutrinos
    - Dirac or Majorana fermions?
  - continue to look for sterile neutrinos
  - determine the absolute mass of the neutrinos
- This is a golden era of neutrino physics
- The future of neutrino physics is bright and rewarding
  - need some innovative ideas and technologies to break new ground