18th Rencontres du Vietnam

Where are we now?
Where are we going?

Neutrino 2022

Sunny Seo, IBS

July 22, 2022

Neutrino Physics

2022 Quy Nohn

"Neutrino 2022"

Organized by IBS, KIAS & KPS

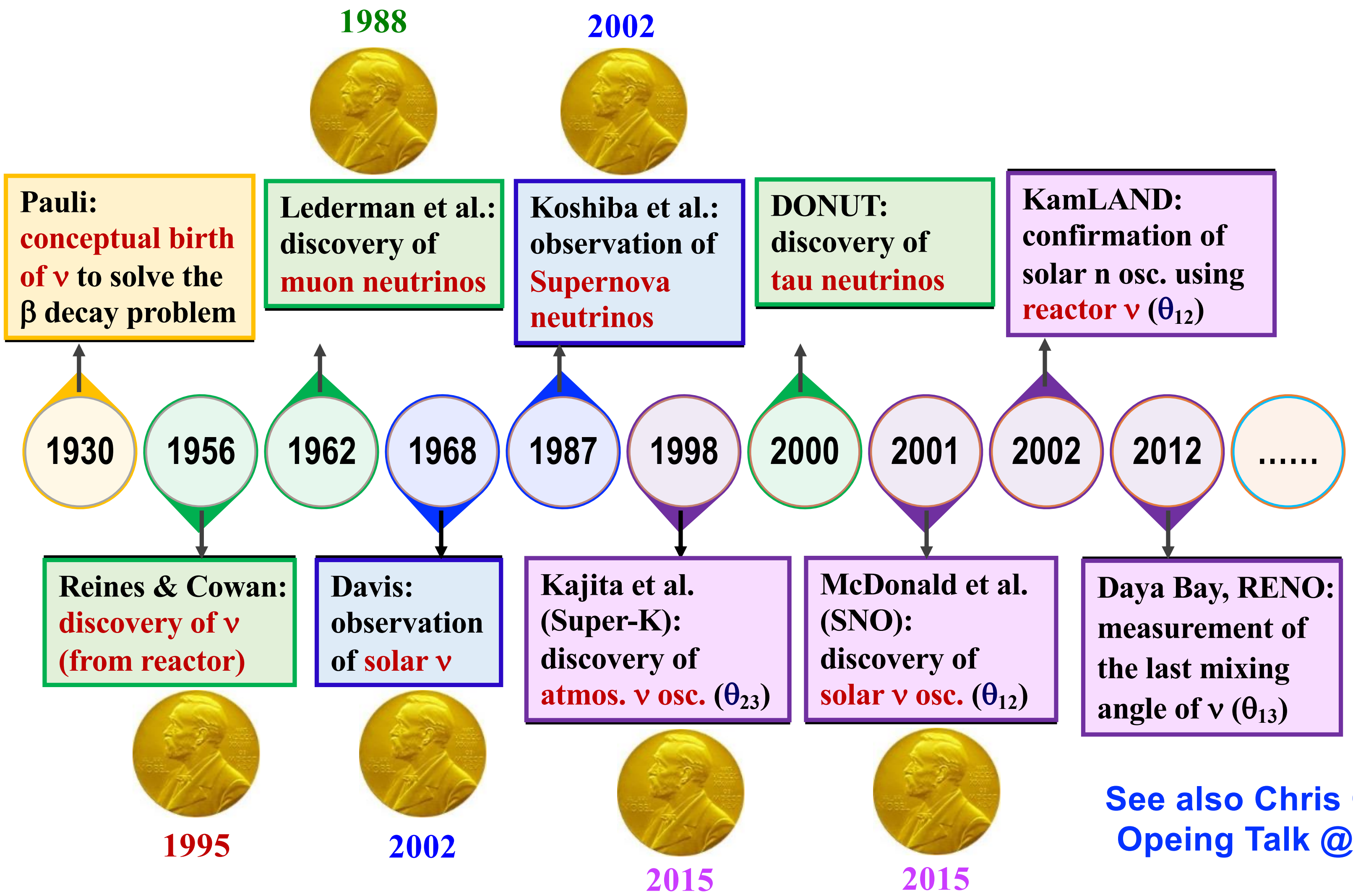
May 30 (M) – June 4 (Sat)
6 days
6 am – 23 pm (KST)

2nd Online meeting using Zoom (fee: 70 Euro)

- 1,382 people registered (44 countries)
- 84 talks (23 sessions)
- 661 posters (8 sessions w/ Virtual Reality)

Successfully finished !

Milestones of ν History



See also Chris Quigg's Opeing Talk @Nu2022

The last 90 years of
ν history has been amazingly great !

What problems
are
still remained & important ?

ν in the 2022 and beyond

- ❑ Neutrino oscillation: precision, MO, CPV
- ❑ # of neutrinos: sterile ν ?
- ❑ Abs. mass of ν: KATRIN, Project-8 etc.
- ❑ Dirac vs. Majorana: $0\nu\beta\beta$
- ❑ Neutrino interaction: CEvNS, ν x-section measurements
- ❑ Astrophysical ν: solar, Supernova, extra galactic ν etc.

- **Neutrino oscillation: precision, MO, CPV**
- # of neutrinos: sterile ν ?
- Abs. mass of ν: KATRIN, Ptolemy, etc.
- Dirac vs. Majorana: $0\nu\beta\beta$
- Neutrino interaction: CEvNS, ν x-section measurements
- Astrophysical ν: solar, Supernova, extra galactic ν etc.

Weak Eigen state **Mass Eigen state**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

PMNS matrix in 1962

- **P**ontecorvo
- **M**aki
- **N**akagawa
- **S**akata

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

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

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

Atmospheric	Reactor	Solar	Majorana
$\theta_{23} \approx 45°$	$\theta_{13} = 9°$	$\theta_{12} \approx 34°$	

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

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

Atmos. (ν_μ, $\overline{\nu}_\mu$ deficit)
Long baseline (ν_μ deficit)

Reactor ($\overline{\nu}_e$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

Solar (ν_e deficit)
Reactor ($\overline{\nu}_e$ deficit)

Short baseline (reactor term) **Medium baseline** (Solar term)

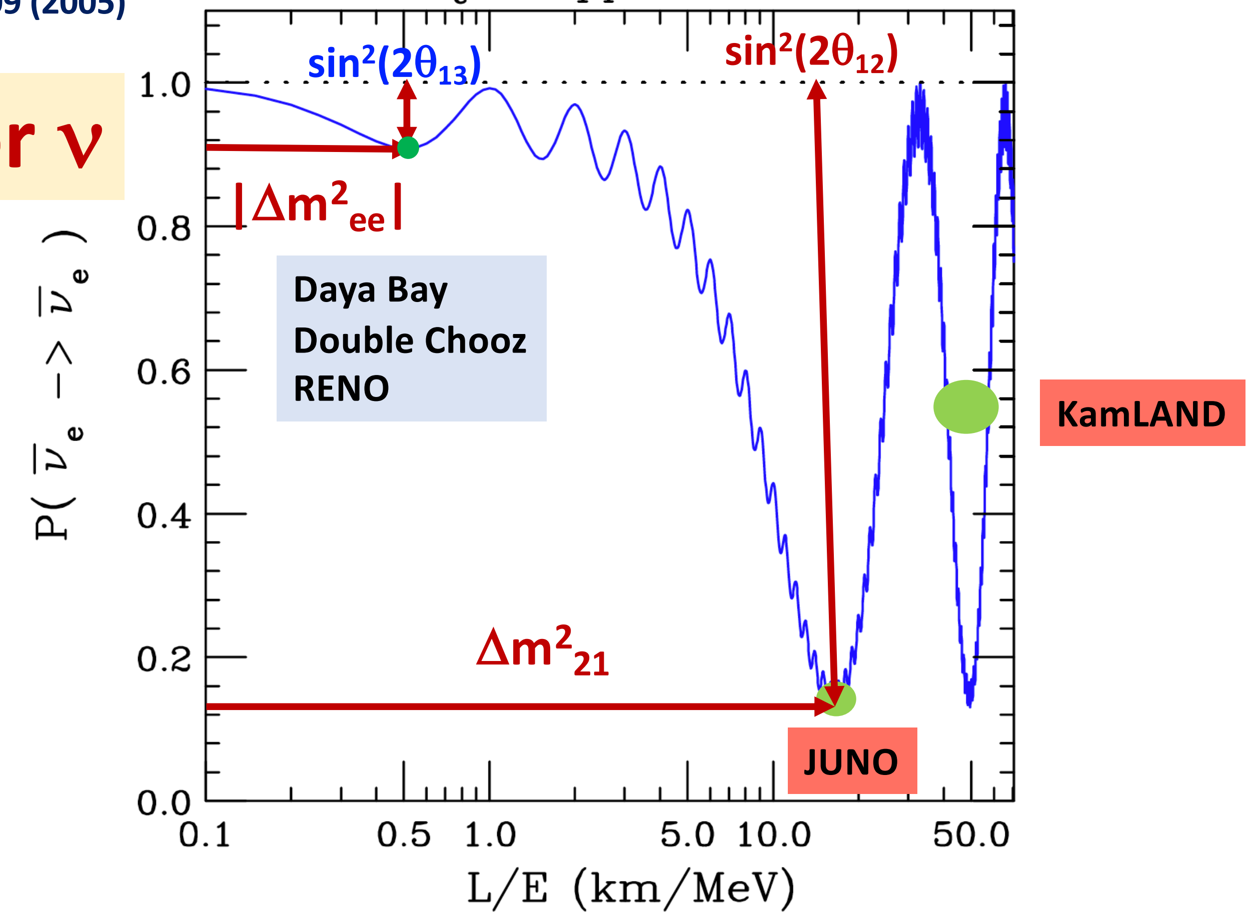
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{21} \frac{L}{4E})$$

Nunokawa, Parke, Funchal
PRD 72, 013009 (2005)

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Reactor ν

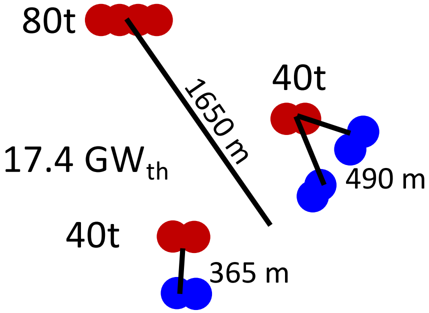
~2x10^{20} $\bar{\nu}_e$ per GW$_{th}$

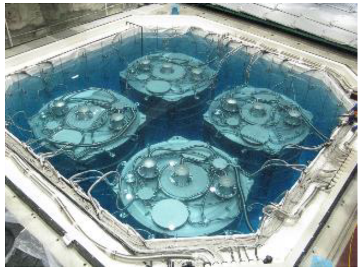


Daya Bay, Double Chooz, RENO for θ_{13}

Daya Bay

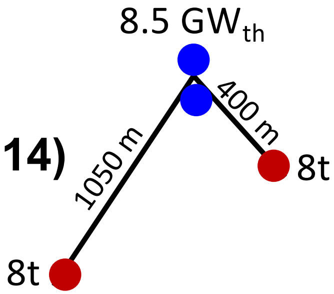
Nov. 2011
– Dec. 2021

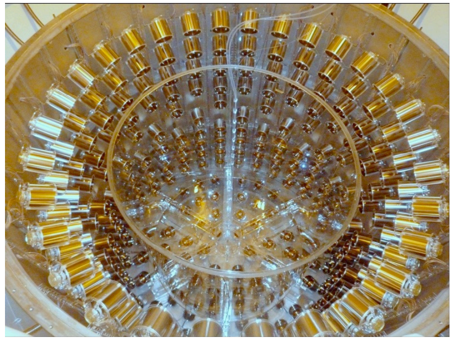




Double Chooz

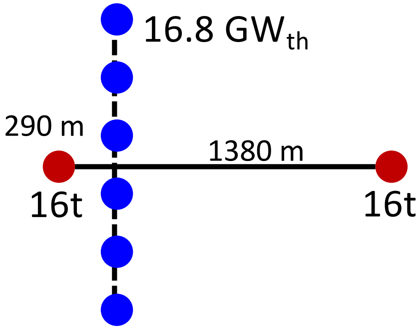
Apr. 2011
– Dec. 2017
(Near: Jan 2014)





RENO

Aug. 2011
– taking data



First θ_{13} measurements in 2012

~ 10 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%

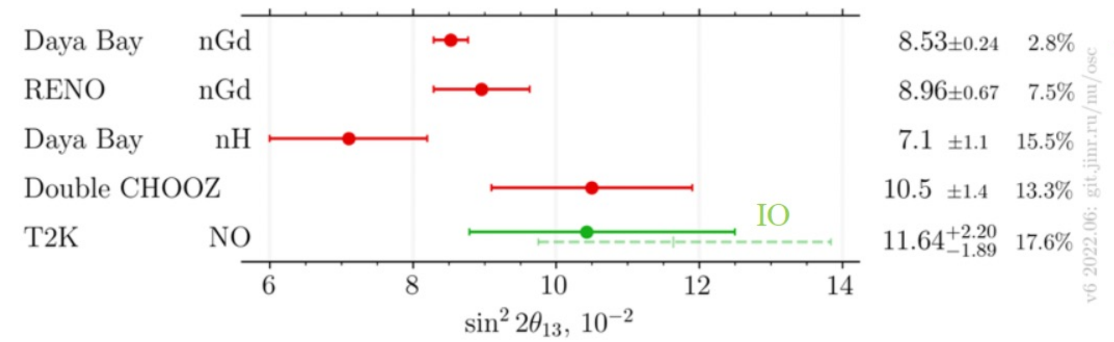
Precise θ_{13} measurements in 2022

	Double Chooz	Daya Bay	RENO
Publication	Neutrino 2020	Neutrino 2022	Neutrino 2022
$\sin^2(2\theta_{13})$	0.102	0.0853	0.0892
Stat. error	0.004 (F:1350/N:790 d)	--- (3158 cal.days)	0.0044 (2900 live days)
Syst. error	0.011	---	0.0045
Total err:	Total: 0.012	Total: 0.0024	Total: 0.0063
Precision:	11.5% (8.7σ)	2.8% (36σ)	7% (14σ)

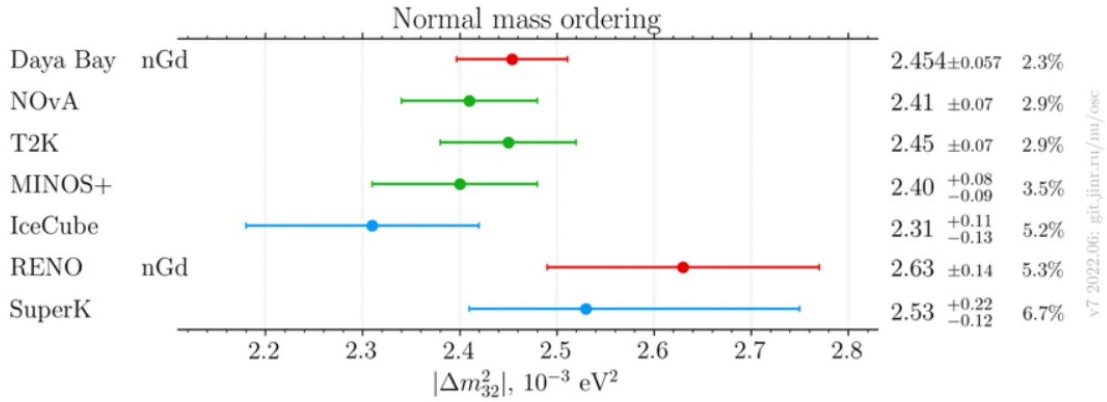
- Expected final precision on θ_{13}: 2.7% (Daya Bay)
  6.4% (RENO)

Kam-Biu Luk
@Nu2022

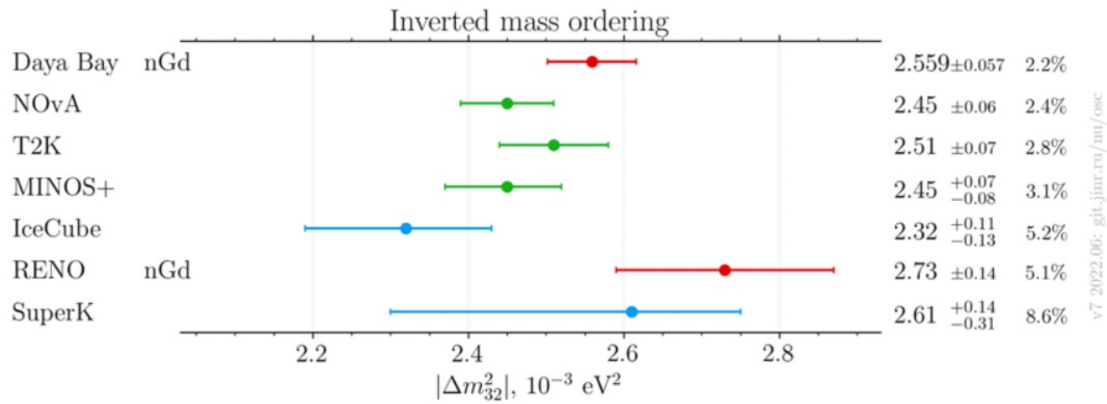
$\sin^2 2\theta_{13}$



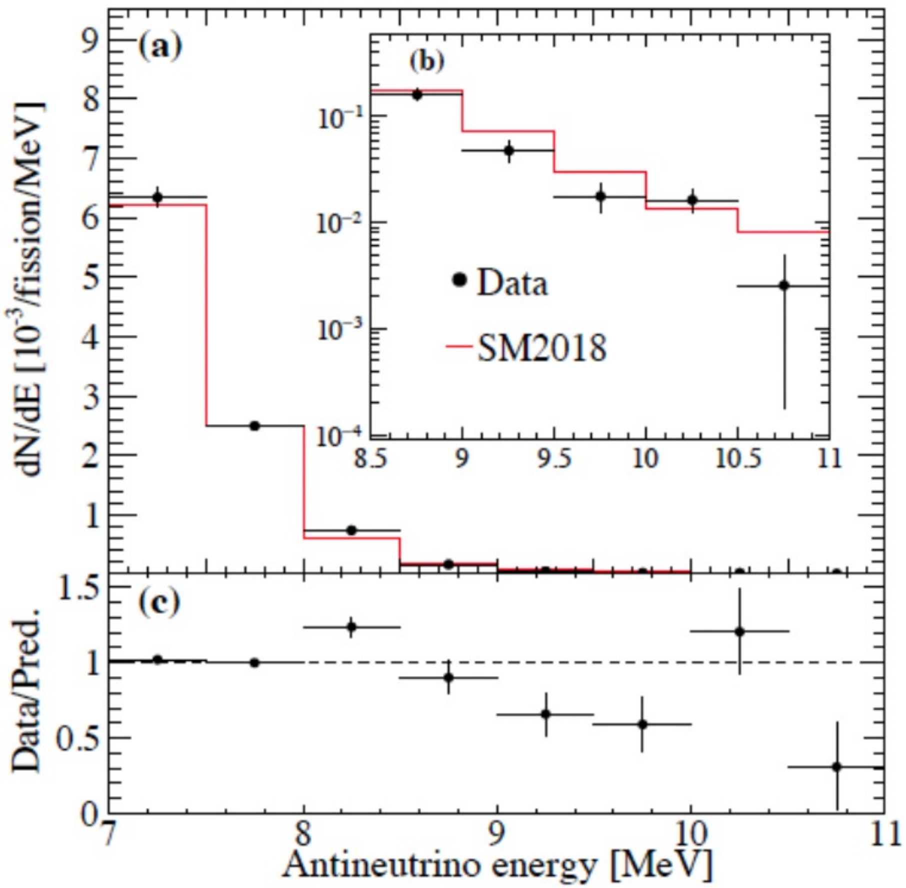
Δm^2_{32} (NO)



Δm^2_{32} (IO)



arXiv: 2203.0668 [hep-ex]
Poster 212



- Hypothesis of no reactor $\overline{\nu}_e$ with $E_\nu > 10$ MeV is ruled out at 6.2σ

Kam-Biu Luk
@Nu2022

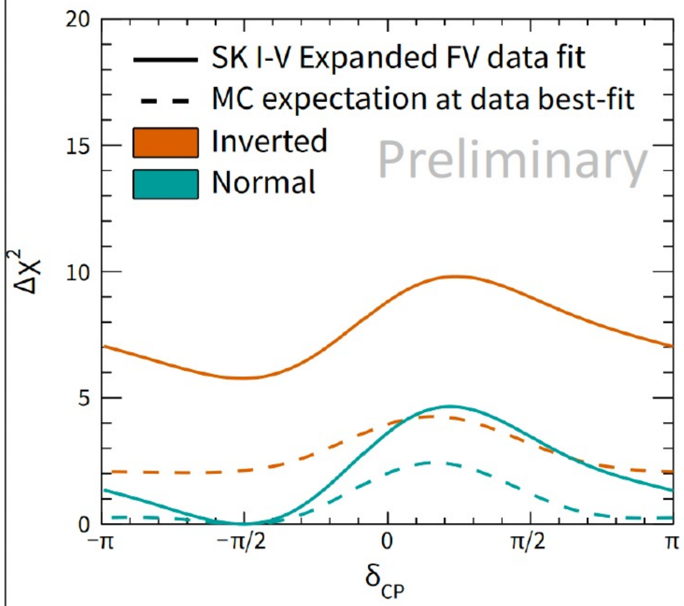
➢ Neutrinos w/ E_ν > 10 MeV can come from high-Q β-decay of short-lived isotopes, e.g. 88,90Br, 94,96,98Rb

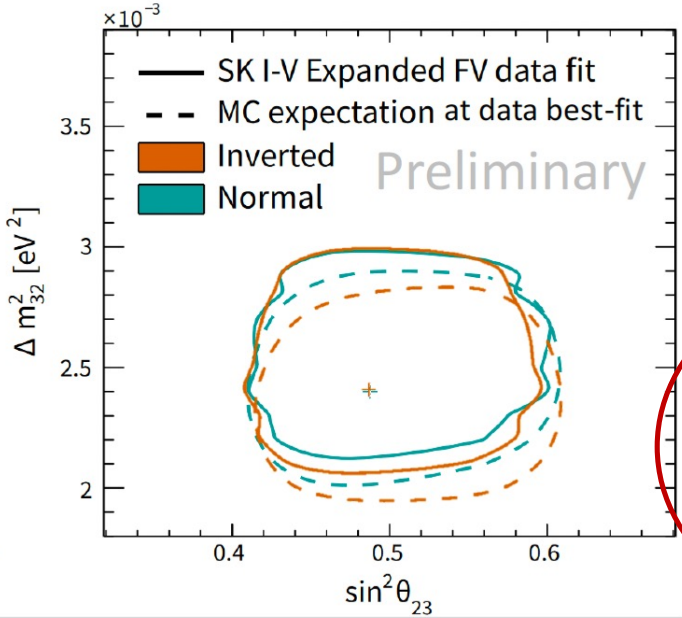
Atm. ν: Super-K

Linyan Wan
@Nu2022

❖ **SK-I ~ SK-V (1996-2020)
+ Expanded FV (+20%)**

Oscillation Measurements (SK only)





SK atmospheric neutrino data favors:

- maximal mixing
- $\delta_{CP} \approx -\frac{\pi}{2}$
- NO ($\Delta\chi^2 = 5.8$)

*Results on MO and δ_{CP} exceed sensitivity.

930 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK NO	1000.42	4.71	0.49	2.4×10^{-3} eV^2
SK IO	1006.19	4.71	0.49	2.4×10^{-3} eV^2

Preliminary

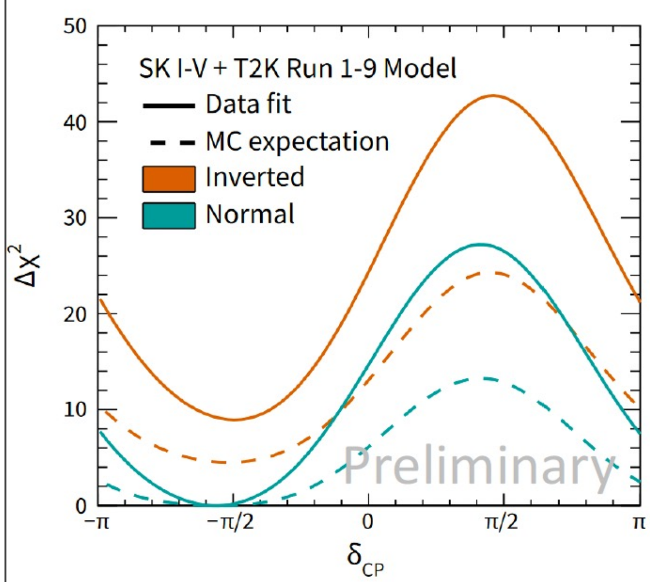
$\sin^2\theta_{13} = 0.0220 \pm 0.0007$

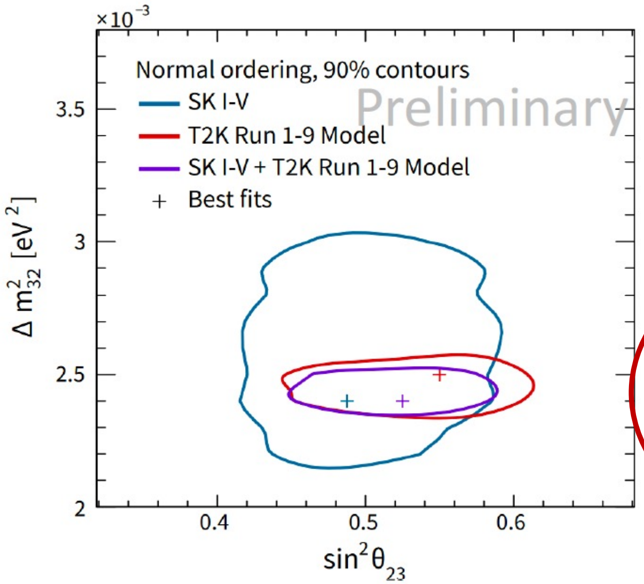
Atm. ν: Super-K

Linyan Wan
@Nu2022

❖ SK-I ~ SK-V (1996-2020)
+ Expanded FV (+20%)
❖ T2K: 2009-2017

Oscillation Measurements (SK+T2K)





1020 bins	χ^2	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23}
SK+T2K NO	1086.33	4.54	0.53	2.4×10^{-3} eV^2
SK+T2K IO	1095.25	4.71	0.53	2.4×10^{-3} eV^2

Preliminary

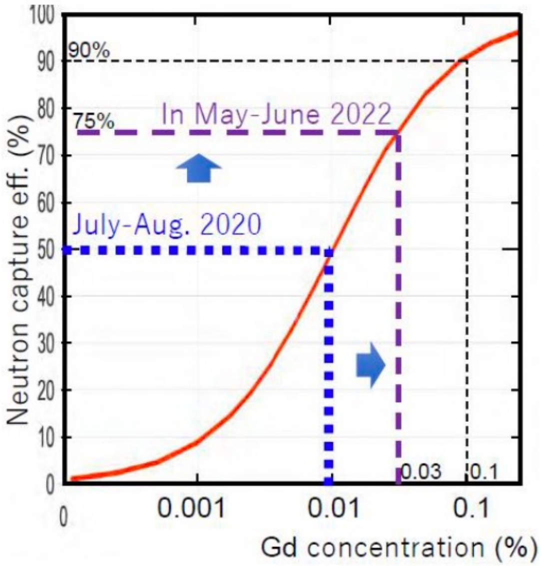
SK + external T2K constraints favor:

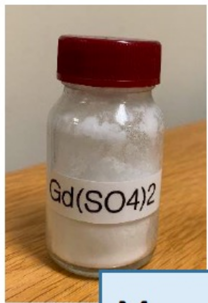
- maximal mixing
- $\delta_{CP} \approx -\frac{\pi}{2}$
- NO ($\Delta\chi^2 = 8.9$)

*Results from both experiments exceed sensitivity.

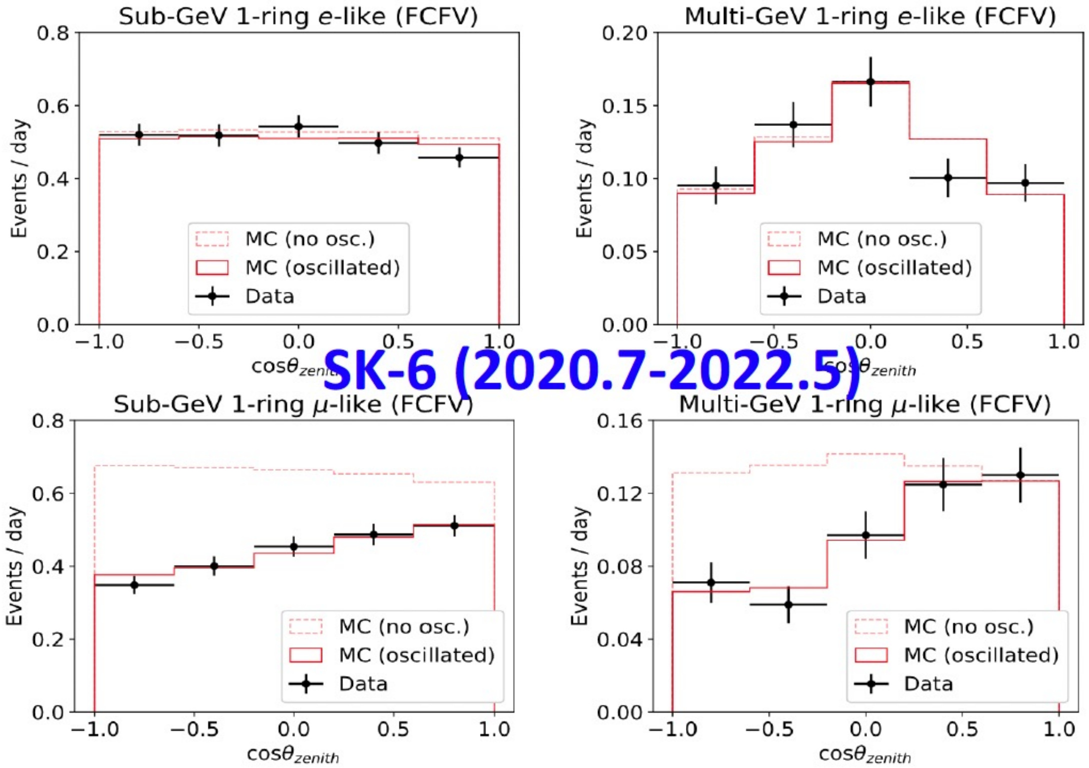
$\sin^2\theta_{13} = 0.0220 \pm 0.0007$

- Gd loading started in 2020.
- At **SK-6**, the Gd concentration is **0.011%**, corresponding to **~50%** neutron tagging efficiency.
- More Gd being loaded NOW!





More on SK-Gd:
Mark Vagins
June 2nd,
23:00 KST



- With 577 days of **data** in **SK-6**, the data quality is as expected in **MC**, and event rate is consistent with pure water phase.

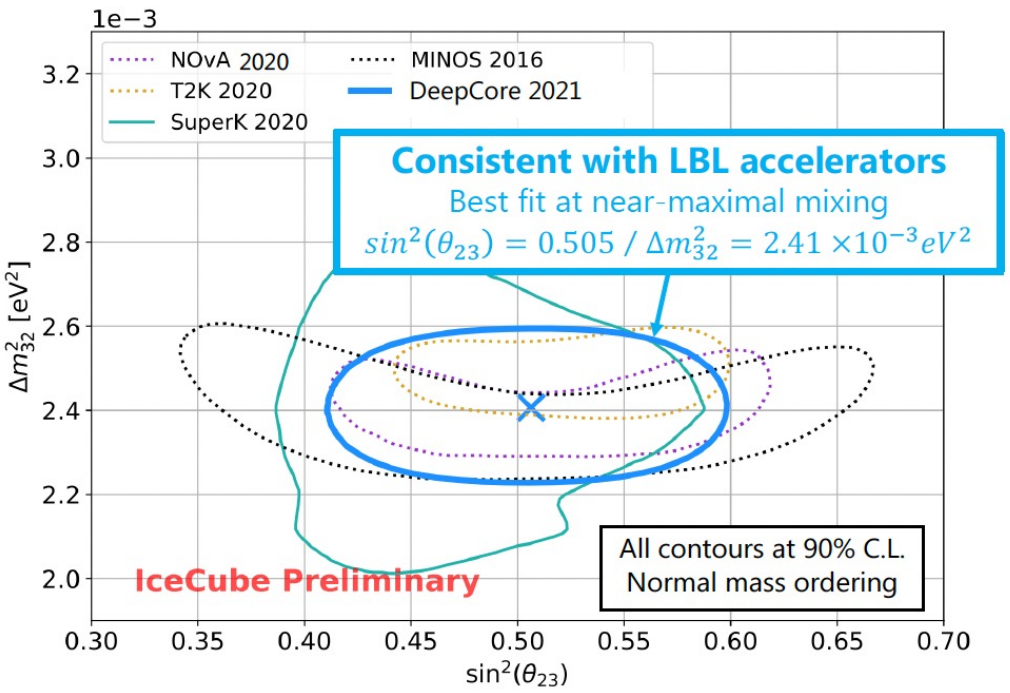
Linyan Wan @Nu2022

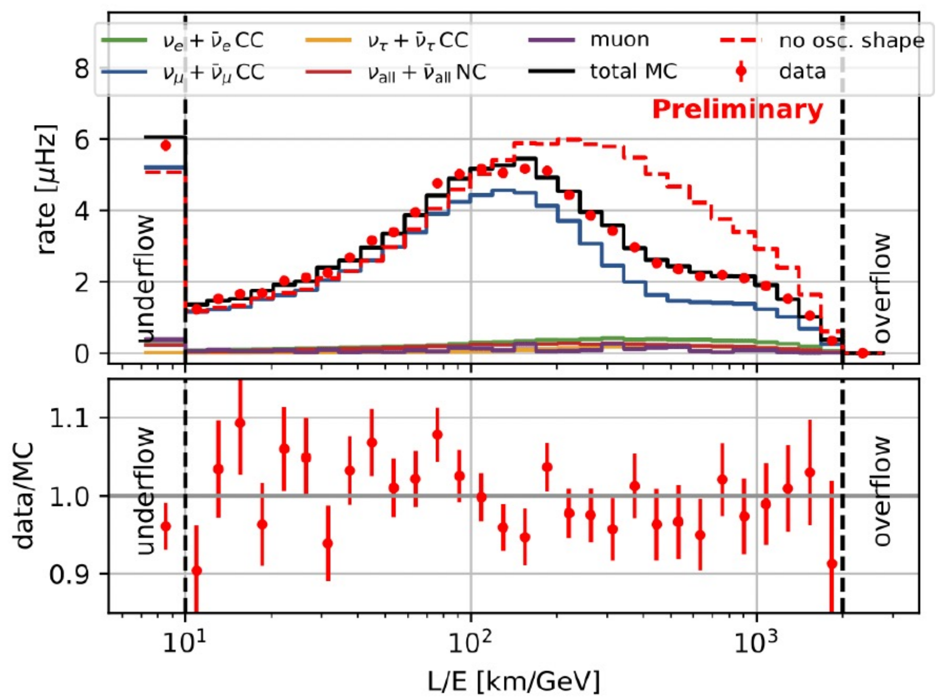
Atm. ν: IceCube

Tom Stuttart
@Nu2022

ν_μ disappearance: Latest results

- New measurement of **ν_μ disappearance with 8 years of IceCube data**
  - Uses a **"golden" sub-sample of ~23,000 track-like events**
  - Clean events with low levels of photon scattering → robust to ice modelling

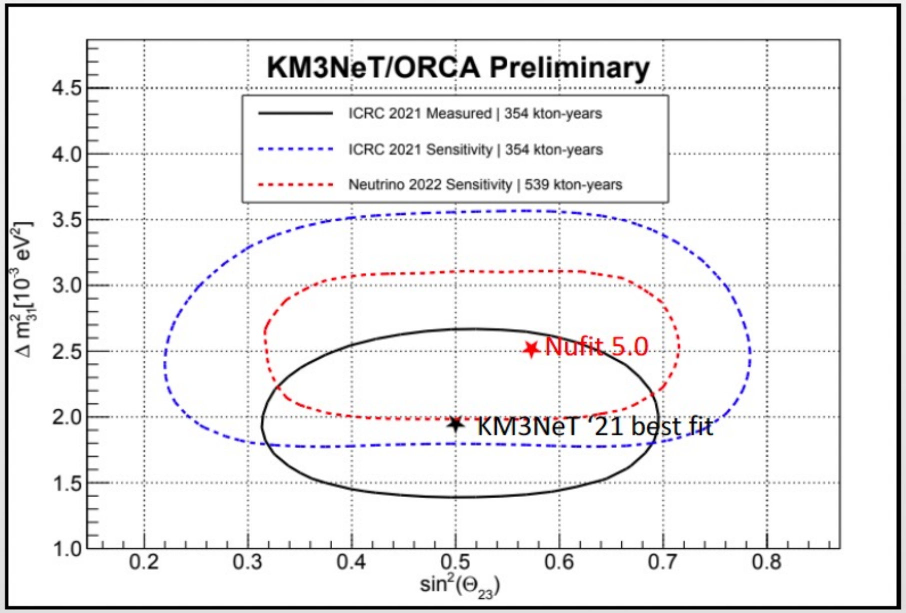


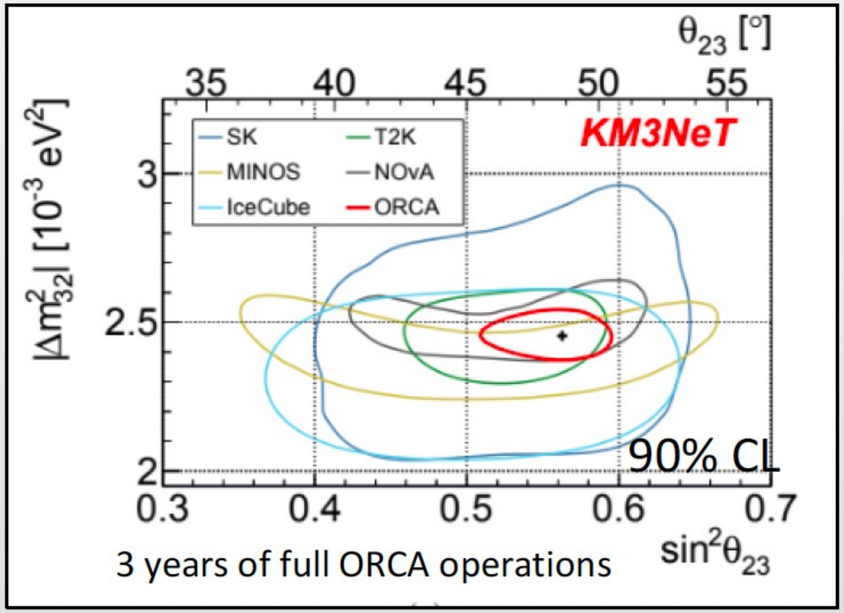


Atm. ν: KM3NeT

Aart Heijboer
@Nu2022

future improvement





soon

- More data 355 -> 540 days
- Better selection & particle identification
- Neutrino Sample increased by a factor 4
- Unblind in next months

later

- Completed ORCA detector will reach unprecedented sensitivity

Solar δm^2

	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

New result

Before 2020 → **Year 2020**

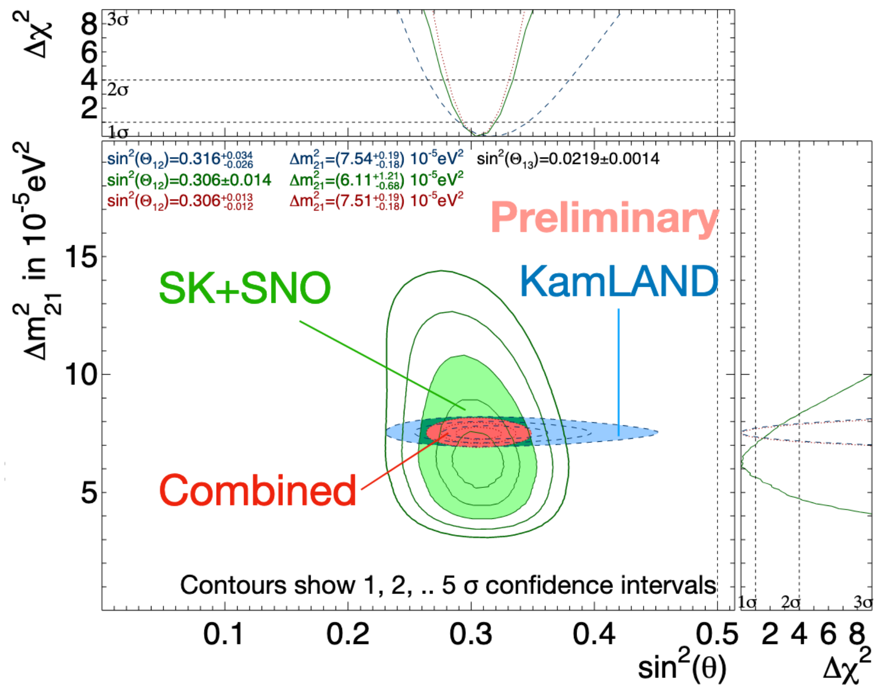
- Best fit values

KamLAND:

$$\Delta m^2_{21} = 7.50^{+0.20}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2,$$

SNO/SK:

$$\Delta m^2_{21} = 5.1^{+1.3}_{-1.0} \times 10^{-5}\ \mathrm{eV}^2,$$



~2 σ tension → **Tension decreased to 1.4 σ.**

(SK: 2055 days data)

(SK: 2970 days data)

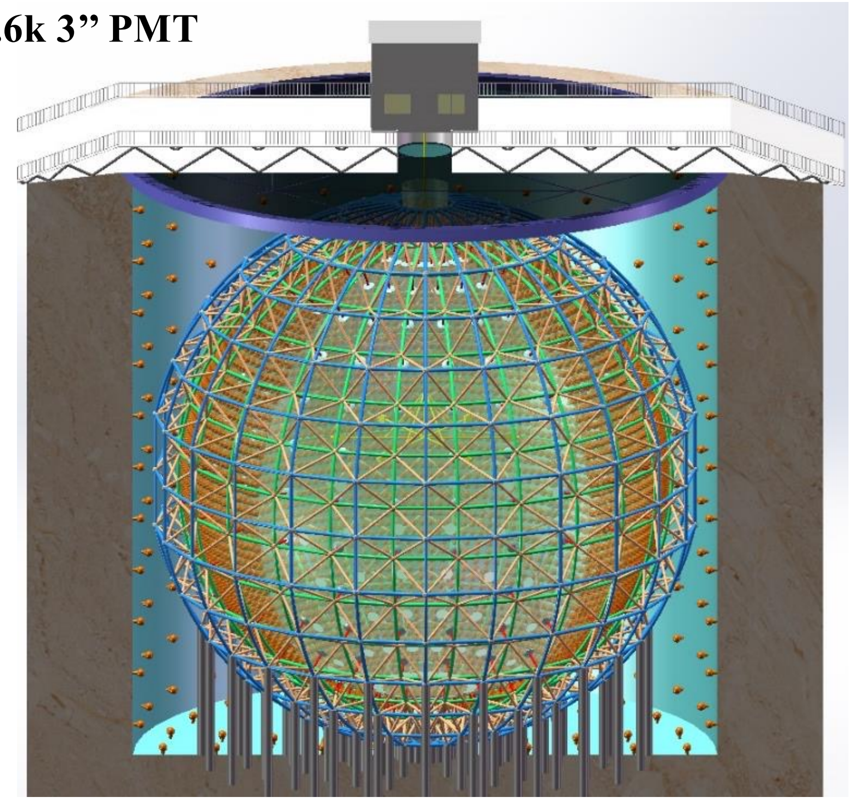
The JUNO Experiment

77 institutions
607 collaborators

Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013, 300 M$, online in 2024?

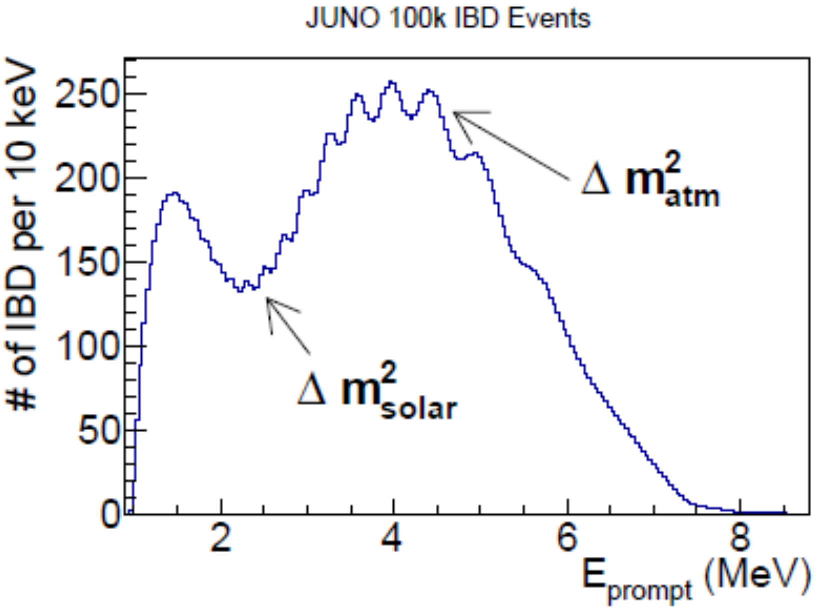
(75+3)% photo coverage

20k 20” PMT
25.6k 3” PMT



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

JUNO: Precision Measurements



Only JUNO can do!

	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%

➢ **MO: ~3 σ (6 yrs data)**

2018 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%

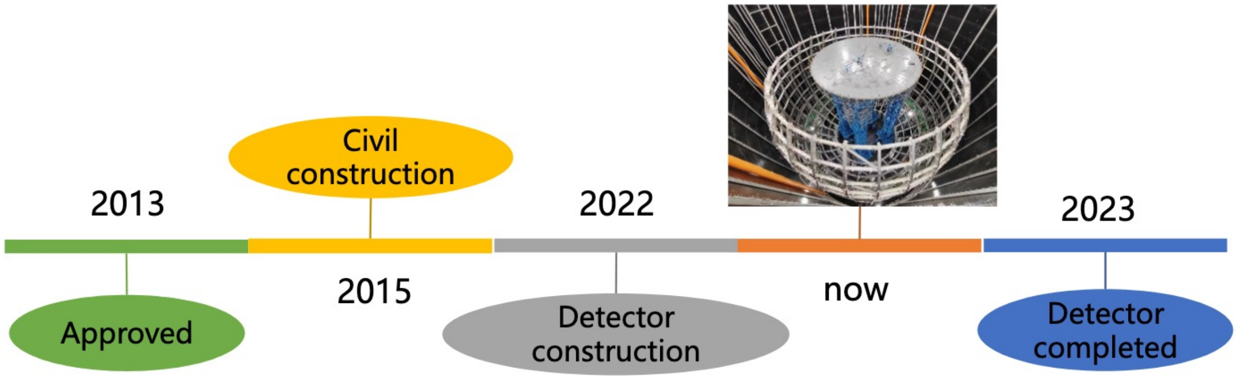
Probing the unitarity of U_{PMNS} to 1%, New physics?

JUNO Numbers and Sensitivity Changes

Jie Zhao
@Nu2022

	Design (J. Phys. G 43:030401 (2016))	Now (2022)
Thermal Power	36 GW_{th}	**26.6 GW_{th} (26%↓)**
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	**4 Hz (33%↑)**
Muon veto efficiency	83%	**93% (12%↑)**
Signal rate	60 /day	**47.1 /day (22%↓)**
Backgrounds	3.75 /day	**4.11 /day (10%↑)**
Energy resolution	3% @ 1 MeV	**2.9% @ 1 MeV (3%↑)**
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

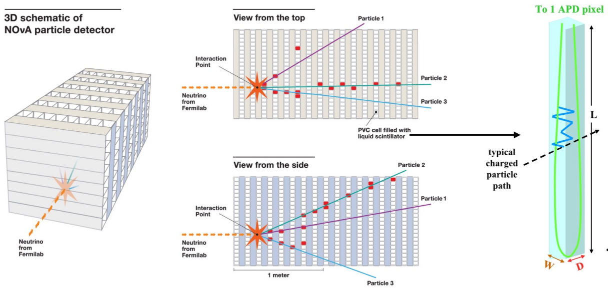
Phyiscs	Sensitivity
Mass Ordering	3σ (~1σ) in 6 yrs by reactor (atm.) ν
Osc. Parameters	Solar params & $\|\Delta m^2_{32}\|$< 0.5% in 6 yrs
SN Burst @10kpc	~5k IBD, ~300 eES, ~2k pES of all-falvor ν
DSNB	3σ in 3 yrs
Solar ν	Measure Be7, pep, CNO simultaneously, Measure B8 flux independently
Nucleon decays ($p \rightarrow \nu K^+$)	8.3x10^33 yrs (90% CL) in 10 yrs
Geo ν	~400/yr, 5% measurement in 10 yrs

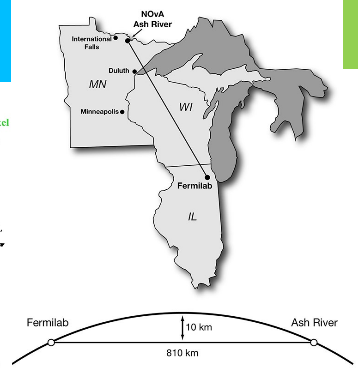


Current & Future Longbaseline ν experiments

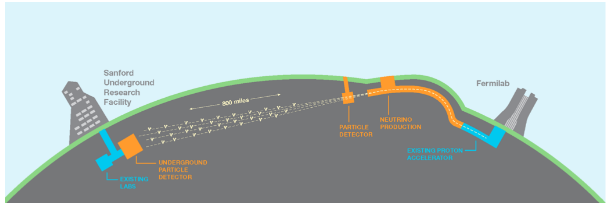
- θ_{23}, Δm^2_{31}, and CPV measurements

NOvA

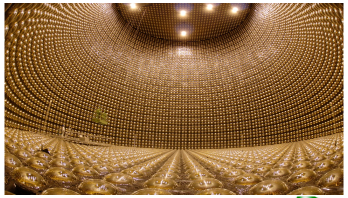




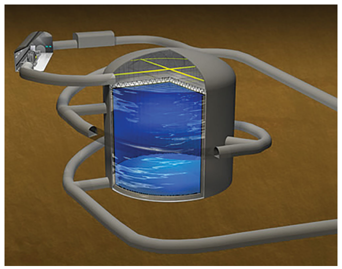
DUNE



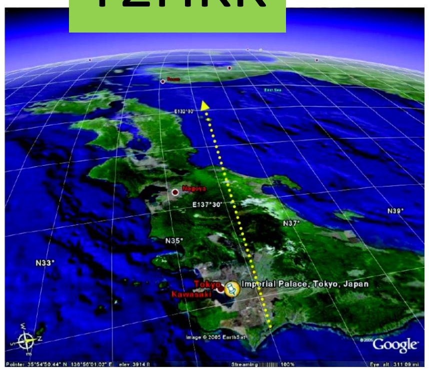
T2K



Hyper-K



T2HKK



Current & Future Longbaseline ν experiments

	T2K	NOvA	DUNE	Hyper-K	T2HKK/KNO
Beam	J-PARC	NuMi	NuMi	J-PARC	J-PARC
Beam power	515 kW (in 2020)	700 kW	1.2 → 2.4 MW	1.3 MW	1.3 MW
ν energy	< 2 GeV		< 8 GeV	< 2 GeV	< 2 GeV
Baselines	280m/295km	1km/810km	1300 km	280m/295km	280m/1100km
Off-axis angle	2.5^{o}	0.8^{o}	on-axis	2.5^{o}	1~3^{o}
Near Det.	ND280 (on-axis)		DUNE-Prism (on-/off-axis)	ND280 (on-axis)	ND280 (on-axis)
		0.3 kt			
Far Det.	Water Cherenkov	segmented sciintillator	LAr-TPC	Water Cherenkov	Water Cherenkov
	SK (50 kt)	14 kt	4 x 17 kt	260 kt	260 kt

operating (T2K, NOvA)

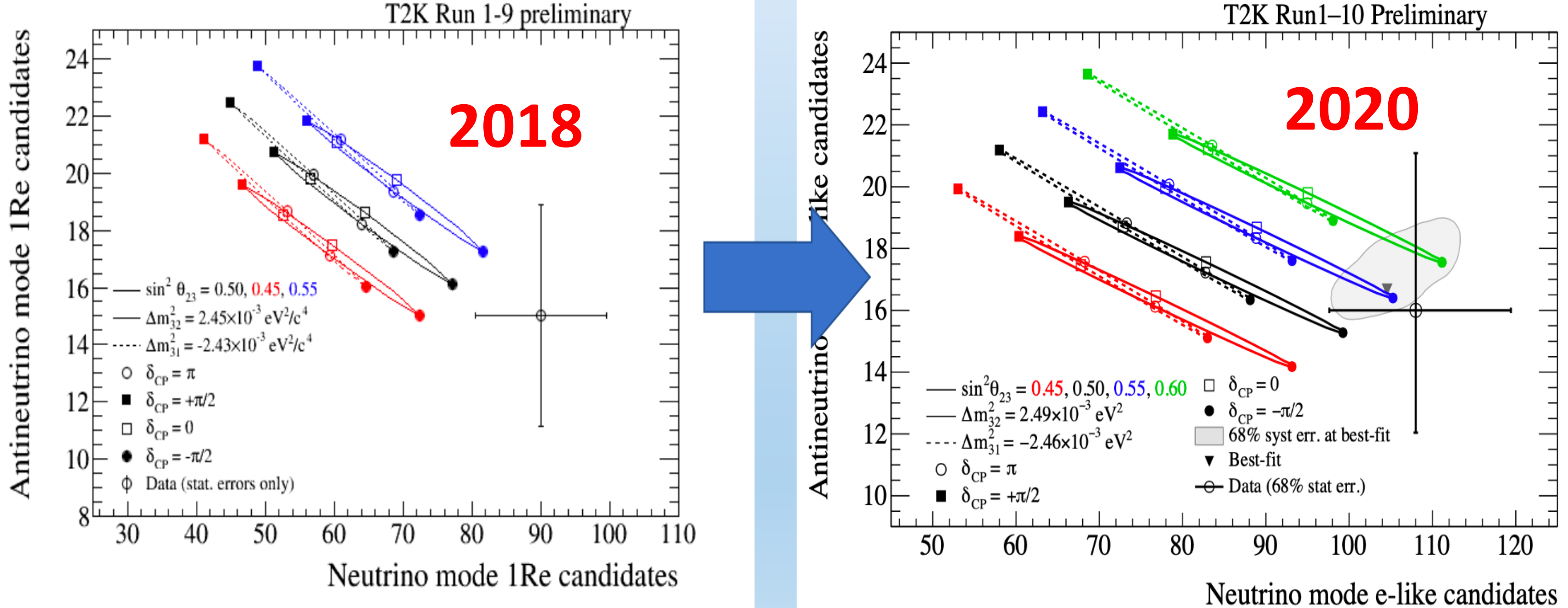
Construction phase (DUNE, Hyper-K)

IWC detector for HK (off-axis)

Comparison to previous result

T2K

- Data this year closer to PMNS prediction
  - See backup for details of effect of all changes made on results

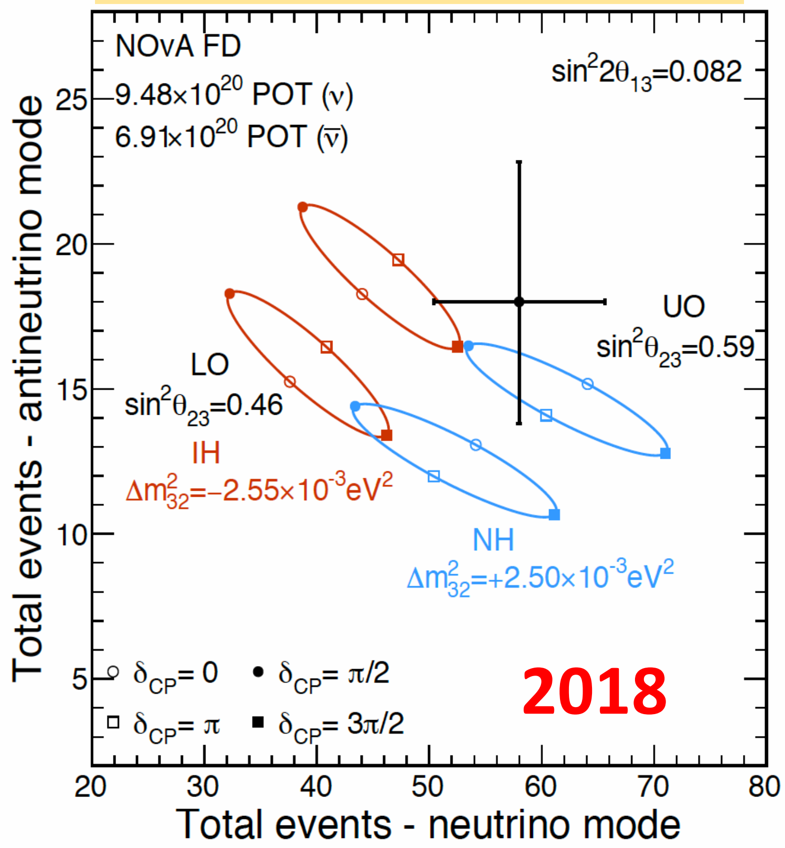


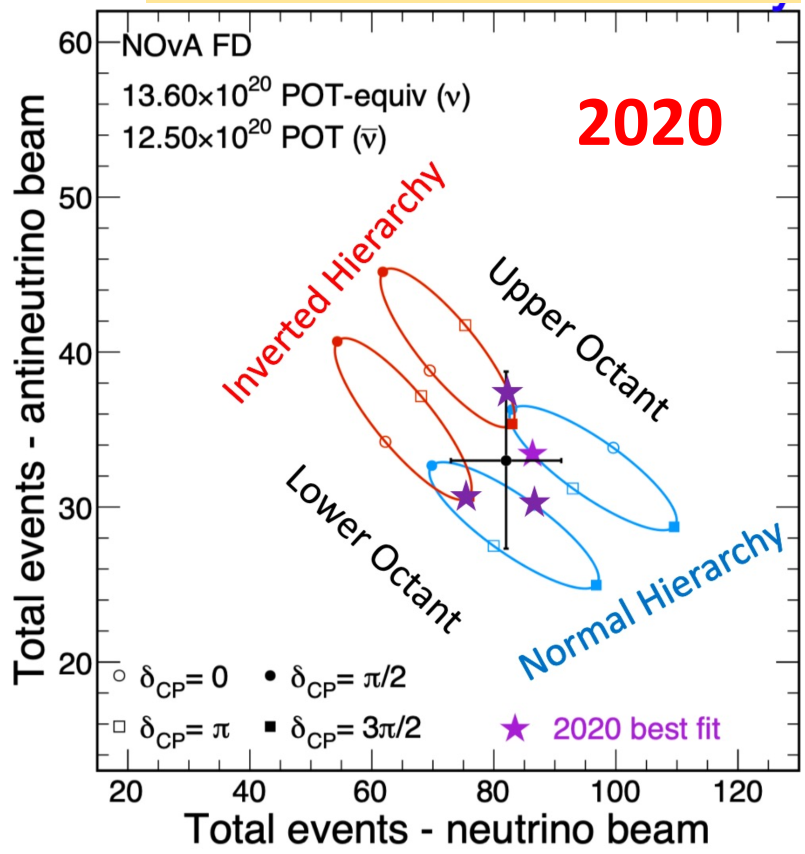
Before	After
Neutrinos: 14.9 x 10^{20} POT	Neutrinos: 19.7 x 10^{20} POT
Anti-nu : 16.3 x 10^{20} POT	Anti-nu : 16.3 x 10^{20} POT

NOvA Results: 2018 → 2020

Neutrinos: 8.85 x 10^{20} POT
Anti-nu : 6.9 x 10^{20} POT

Neutrinos: 13.6 x 10^{20} POT
Anti-nu : 12.5 x 10^{20} POT





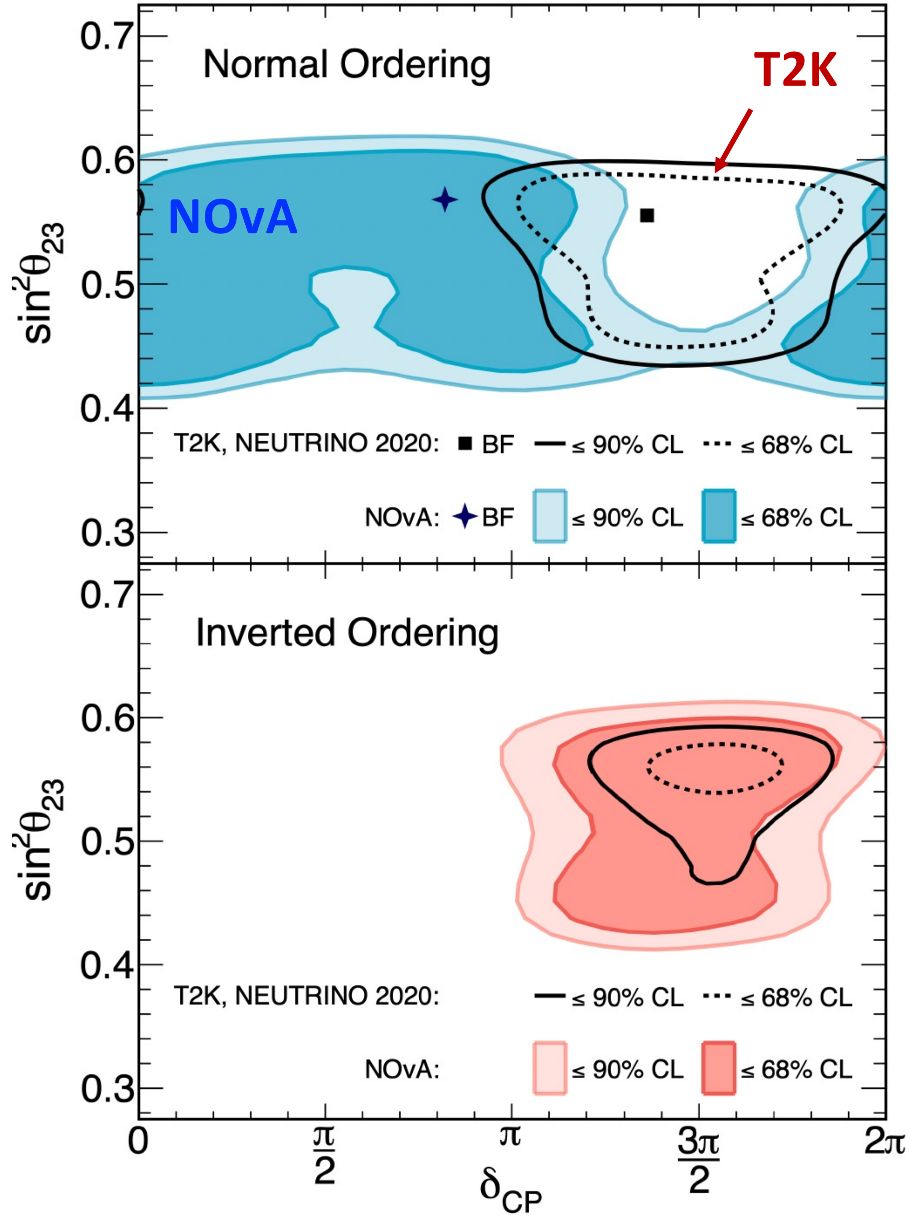
Statistical error dominant !

NOvA 2020

Jeff Hartnell
@Nu2022

- New 3-flavor oscillation results:
  - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ eV^2$
  - $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
  - exclude IH, $\delta = \pi/2$ at $> 3\sigma$,
  - disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$.

❑ Significant progress on joint fit with T2K
– coming this year (2022)

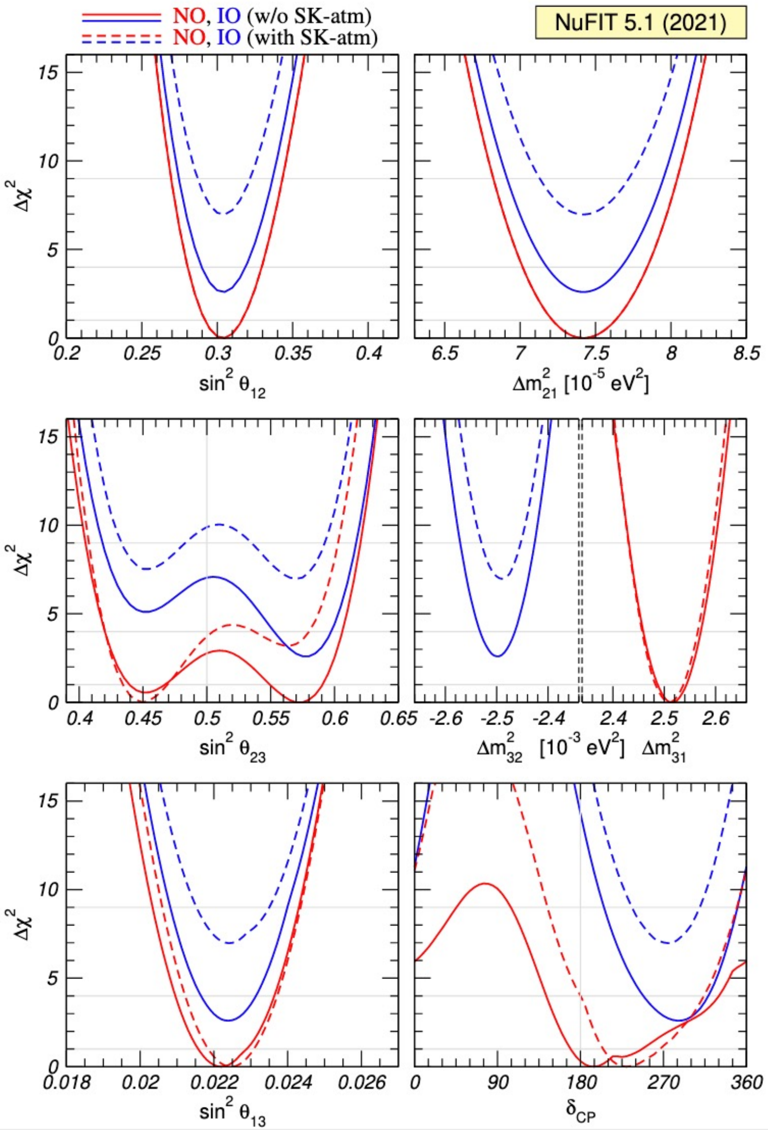


Three flavour oscillation parameters

global analysis **NuFIT 5.1 results** www.nu-fit.org

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$



comparable results:
Bari: e.g. Capozzi et al., 2107.00532
Valencia: e.g. deSalas et al., 2006.11237

Evolution of global 3 flavour fit

Gonzalez-Garcia, Maltoni, TS [arXiv:2111.03086]

	2012 NuFIT 1.0	2014 NuFIT 2.0	2016 NuFIT 3.0	2018 NuFIT 4.0	2021 NuFIT 5.1	improvement factor from 2012 to 2021
θ_{12}	15%	14%	14%	14%	14%	1.07
θ_{13}	30%	15%	11%	8.9%	9.0%	3.3
θ_{23}	43%	32%	32%	27%	27%	1.6
Δm^2_{21}	14%	14%	14%	16%	16%	0.88
$\lvert\Delta m^2_{3\ell}\rvert$	17%	11%	9%	7.8%	6.7% [6.5%]	2.5
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]	1 [1.2]
$\Delta\chi^2_{\text{IO-NO}}$	± 0.5	-0.97	$+0.83$	$+4.7$ [$+9.3$]	$+2.6$ [$+7.0$]	

w/o [w] SK atm data

relat. precision at 3σ : $\frac{2(x^+ - x^-)}{(x^+ + x^-)}$

improvement factor from 2012 to 2021

Thomas Schwetz
@Nu2022

3 ν Global Fit

Thomas Schwetz
@Nu2022

- results from global 3-flavour oscillation fit
  - robust determination of $\Delta m^2_{21}, |\Delta m^2_{31}|, \theta_{12}, \theta_{13}$
  - determination of mass-ordering, θ_{23}-octant, CP phase depends on sub-leading three-flavour effects — not yet statistically significant
  - interplay of accelerator / reactor / atmospheric data

NuFit 5.1

	best fit MO	$\Delta\chi^2$(MO)	best fit δ_{CP}	$\Delta\chi^2$(CPC)	oct. θ_{23}	$\Delta\chi^2$(oct.)
accelerator	IO	1.5	275°	2.0	2nd	2.2
+ reactors	NO	2.7	195°	0.4	2nd	0.5
+ atmospheric	**NO**	**7.1**	**230°**	**4.0**	**1st**	**3.2**

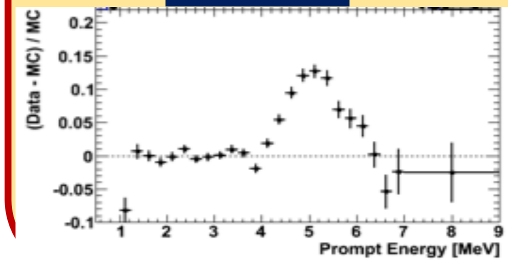
Neutrino Oscillation Physics in < 2040

	HK: JD Beam ν	HK: JD + KD Beam ν	HK: JD + KD Beam+ atm. ν	DUNE Beam ν
Baseline	295 km	295 km + ~ 1100 km	295 km + ~ 1100 km	1300 km
Detector Fiducial Vol.	190 kton water	2 x 190 kton water	2 x 190 kton water	40 kton LAr
POT (run time, $\nu:\bar{\nu}$)	2.7 x 10^{22} (10 yrs, 1:3)	2.7 x 10^{22} (10 yrs, 1:3)	2.7 x 10^{22} (10 yrs, 1:3)	556/ kt.MW.yr (10 yrs, 1:1)
δ_{CP} = $\pi/2$, $3\pi/2$ (known N.O.)	~ 8 σ	> 8 σ	> 8 σ	[7 σ, 8 σ]
δ_{CP} precision @ δ_{CP} = **$\pi/2$, $3\pi/2$**	22°	13~14°	~11°	~9°
δ_{CP} coverage (known NO)	~76 % at 3 σ	> 76 % at 3 σ	> 76 % at 3 σ	65 % at 3 σ
MO (true: NO)	> 1 σ for all δ_{CP}	> 6 σ for all δ_{CP}	> 7.5 σ for all δ_{CP}	> 8 σ for all δ_{CP}

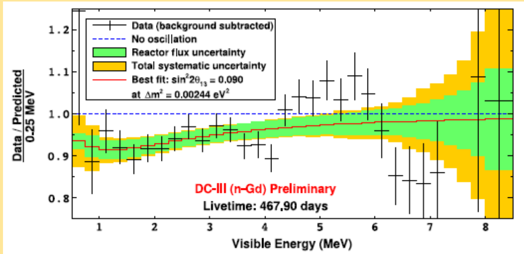
Reactor ν "Shape" Anomaly

The "5 MeV Excess" in 2014

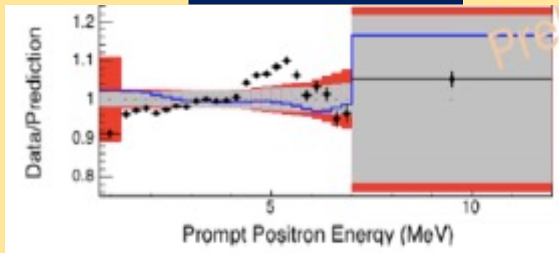
RENO



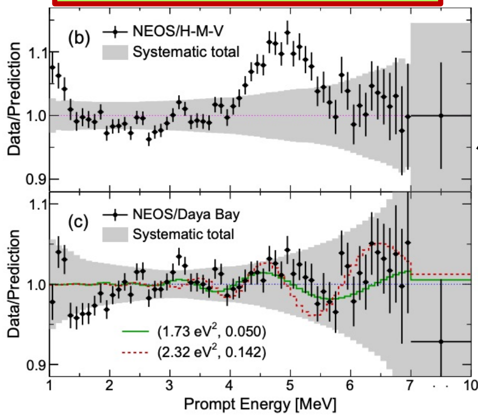
Double Chooz

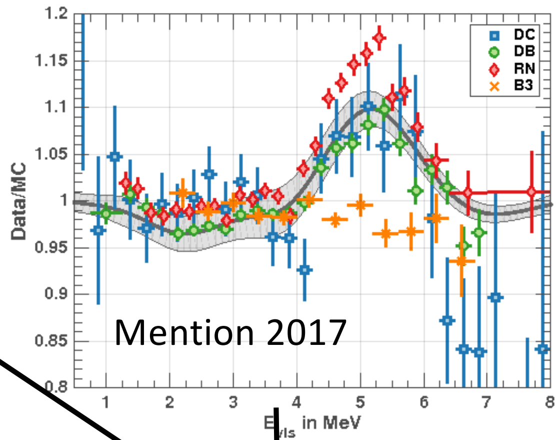


Daya Bay



NEOS in 2017





5 MeV excess compared to H&M model

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

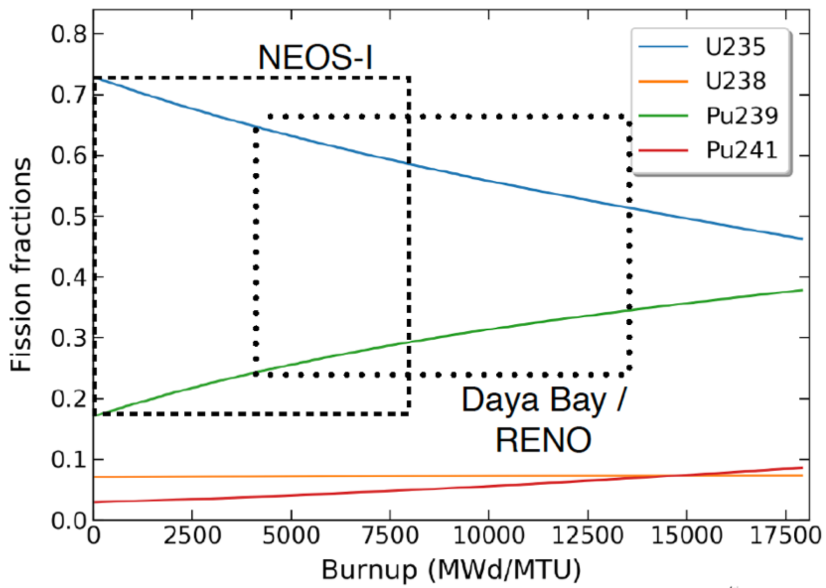
No relation w/ sterile neutrinos

❑ > 99 % reactor neutrinos are from 4 isotopes:
^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu

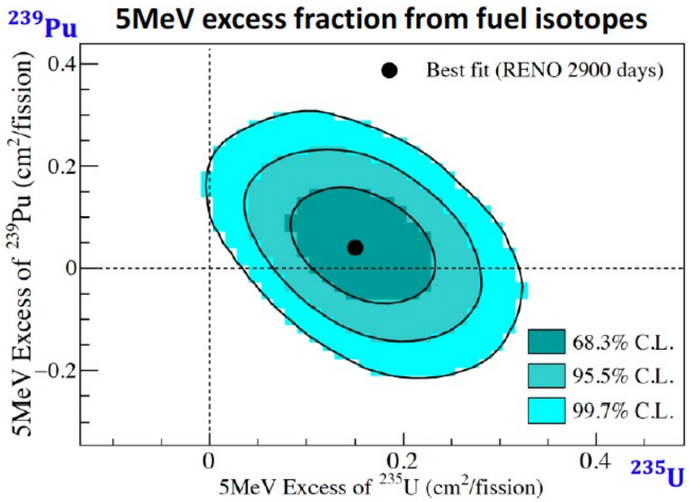
Which isotope(s) is responsible for the 5 MeV excess?

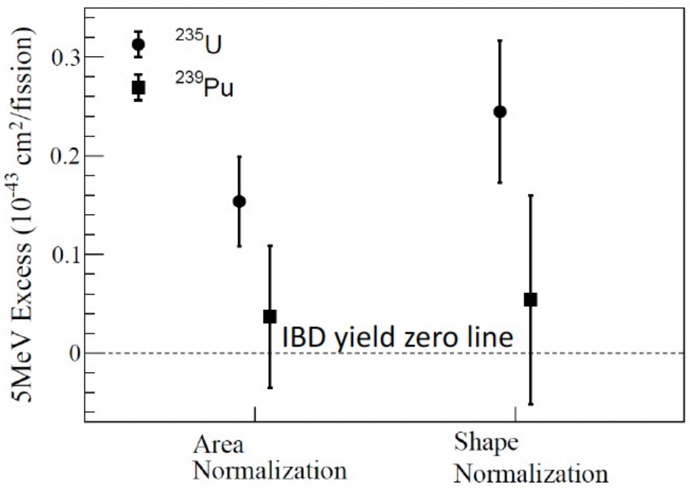
Commercial reactors:
Low Enriched ^{235}U (LEU)
3-5 % ^{235}U

Cf. Natural Uranium: 0.7% ^{235}U



5 MeV excess of ^{235}U and ^{239}Pu @RENO





- **5 MeV excess :**
  - ^{235}**U** = **(2.5 ±0.7) %** of the observed total flux (**3.9σ**)
  - ^{239}**Pu** = **(0.9 ± 1.7) %** to the observed total flux (**0.6σ**)

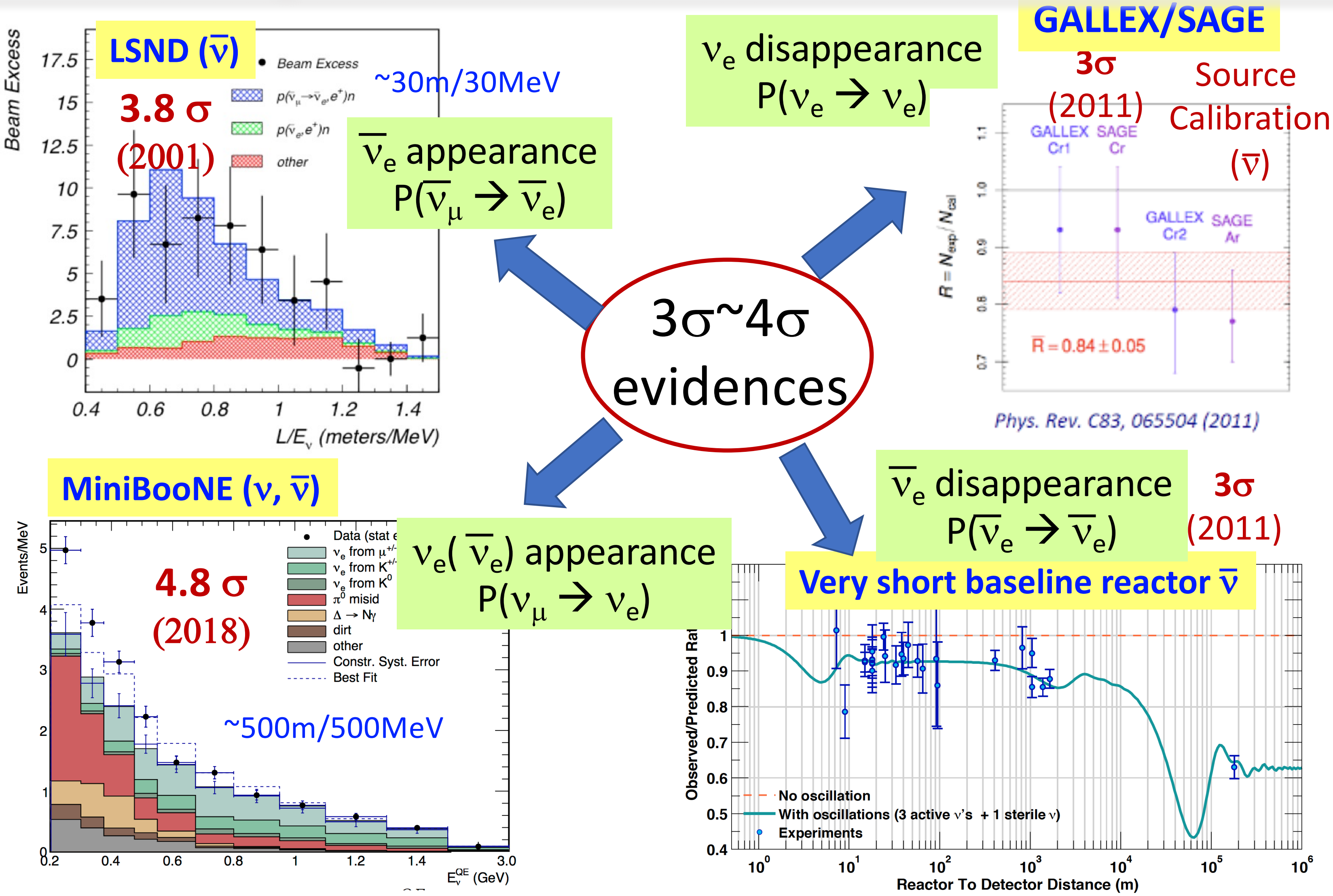
	Area normalization	Shape normalization (outside the excess)
5MeV excess of ^{235}U (cm^2/fission)	0.15 ± 0.05 ($2.5 \pm 0.7\,\%$)	0.24 ± 0.07 ($4.0 \pm 1.2\,\%$)
5MeV excess of ^{239}Pu (cm^2/fission)	0.04 ± 0.07 ($0.9 \pm 1.7\,\%$)	0.05 ± 0.11 ($1.3 \pm 2.5\,\%$)

Poster presentation **#599**
Seok-Gyeong Yoon, "Reactor Antineutrino Flux and Spectrum at RENO"

KKJoo
@Nu2022

- ❑ Neutrino oscillation: precision, MO, CPV
- ❑ **# of neutrinos: sterile ν ?**
- ❑ Abs. mass of ν: KATRIN, Ptolemy, etc.
- ❑ Dirac vs. Majorana: 0νββ
- ❑ Neutrino interaction: CEvNS, ν x-section measurements
- ❑ Astrophysical ν: solar, Supernova, extra galactic ν etc.

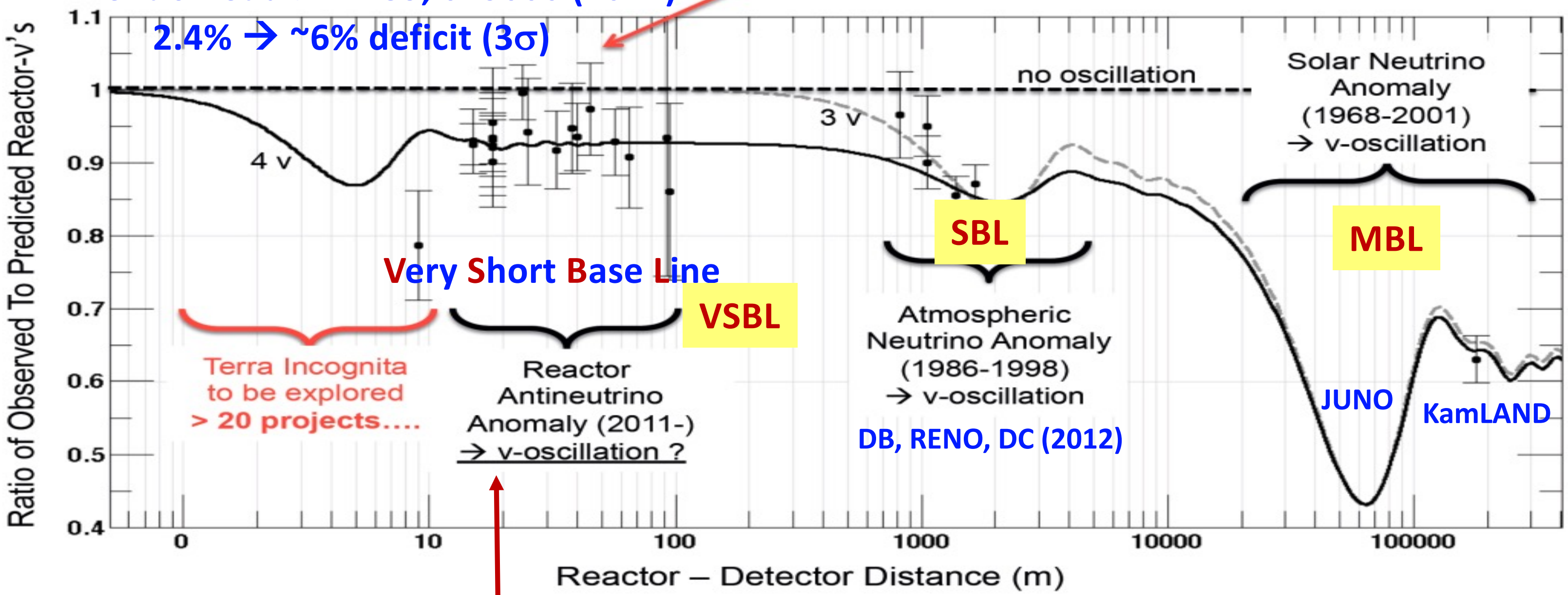
Smoking Guns of Sterile Neutrinos at ~eV?



Reactor ν "Flux" Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

Mention et al. PRD83, 073006 (2011)



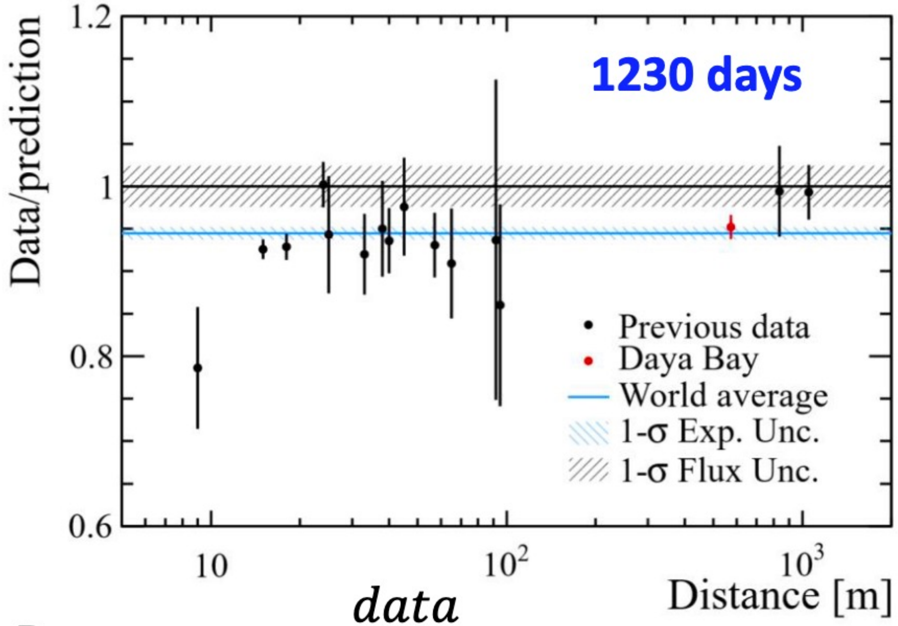
$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2 \left[1.27 \frac{\Delta m^2_{41} L}{E_\nu} \left(\frac{\mathrm{eV}^2 \cdot \mathrm{m}}{\mathrm{MeV}} \right) \right]$$

RAA = Reactor Antineutrino Anomaly

(3+1) ν RAA best fit: $\Delta m^2_{41} = 2.4\ \mathrm{eV}^2$, $\sin^2(2\theta_{14}) = 0.14$

Daya Bay

ND @ 500~600 m

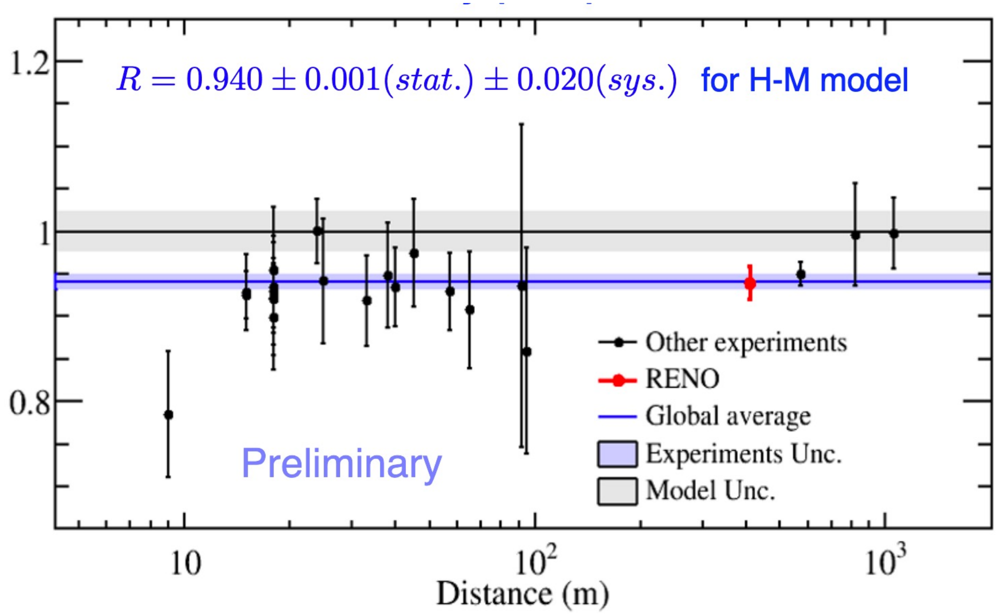


$$R = \frac{data}{Model\ (Huber + Mueller)}$$

$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

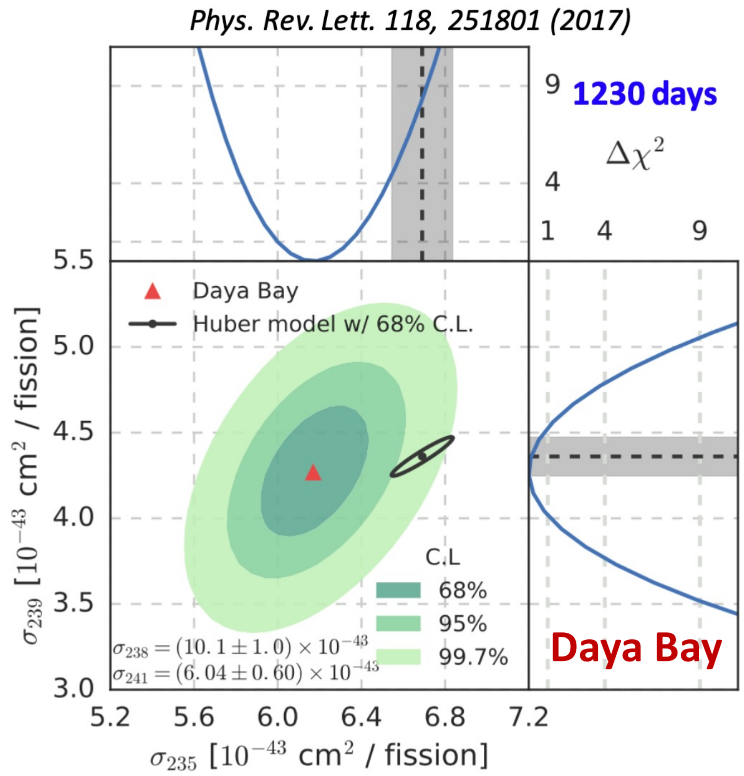
RENO

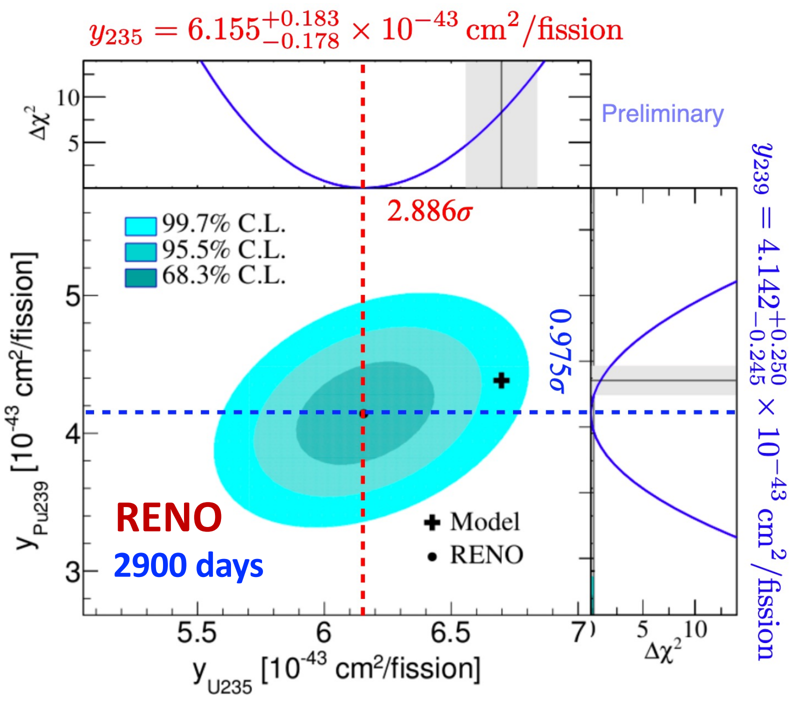
ND @ 400~500 m



R = 0.940 +/- 0.020 (*exp*)

→ 5~6% deficit @Near detector data



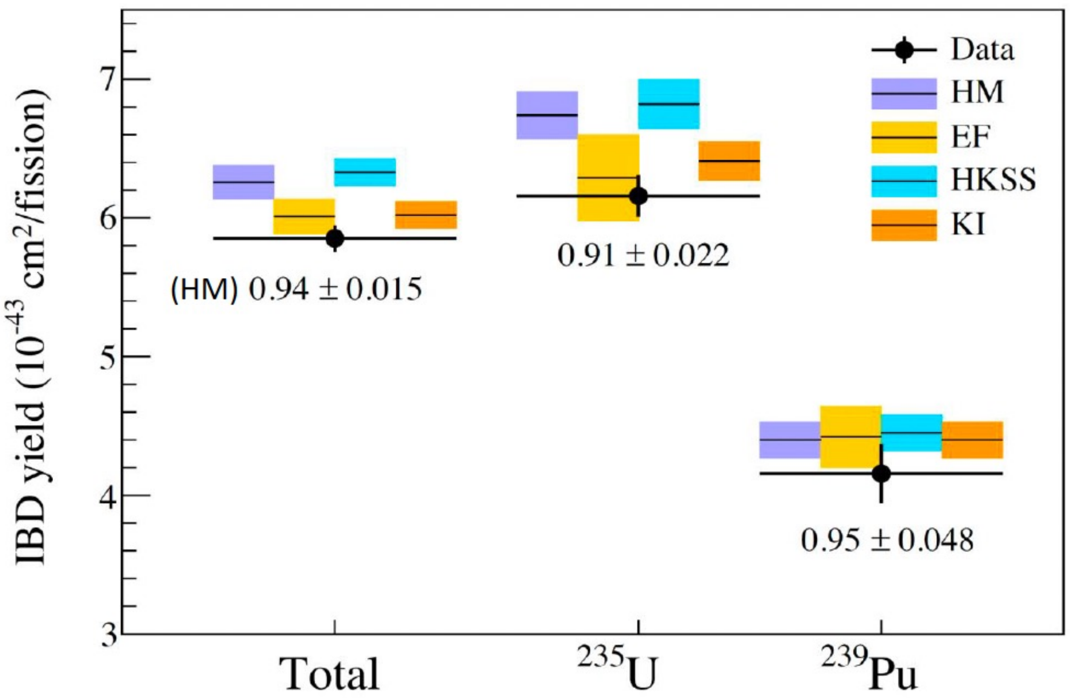


➢ Daya Bay and RENO results suggest that ν from ^{235}U is less by ~3 σ than HM model.

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

RENO IBD Yields

KKJoo @Nu2022



- Y_{235} = **(6.16 ± 0.15)** $\times 10^{-43}$cm^2/fission
  -> **0.91** of Huber model prediction (**4.1σ**)
- Y_{239} = **(4.16 ± 0.21)** $\times 10^{-43}$cm^2/fission
  -> **0.94** of Huber model prediction (**1.6σ**)
- **Similar flux deficit from ^{235}U (8.6±2.1%) and ^{239}Pu (5.5±4.7%)**

Daya Bay IBD Yields

arXiv:1704.01082

- y_{235} = 6.17 ± 0.17 [10^{-43}cm^2/fission]
  → 0.92 of HM model (~3 σ)
- y_{239} = 4.27 ± 0.26 [10^{-43}cm^2/fission]
  → consistent w/ HM

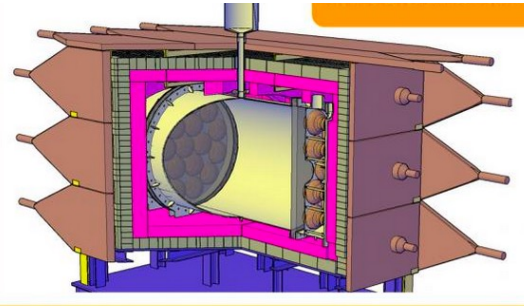
HM model

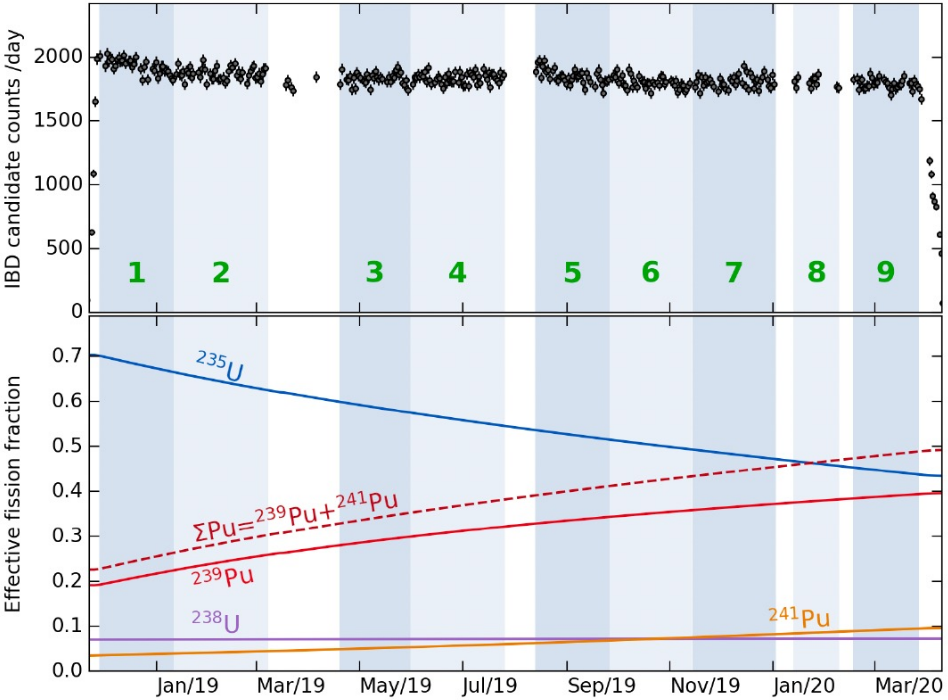
- y_{235} = 6.69 ± 0.15 [10^{-43}cm^2/fission]
- y_{239} = 4.36 ± 0.11 [10^{-43}cm^2/fission]

NEOS-II (2018 -- 2020)

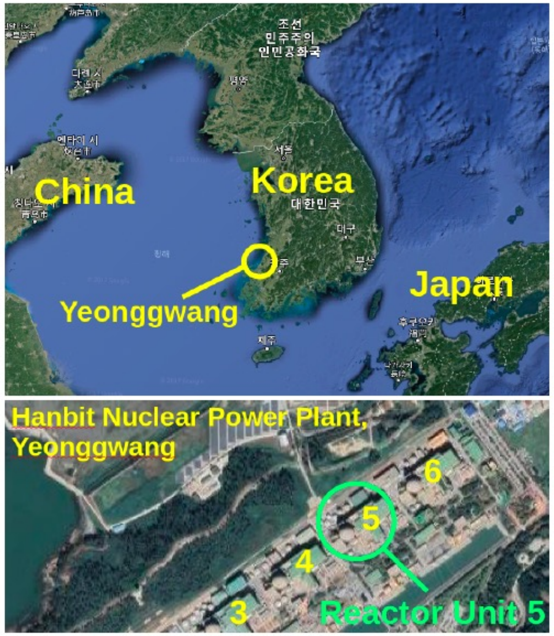
- Refurbished detector from NEOS-I.
- Took full fuel cycle (500 cal. days) + 2 OFF periods
- Time evolution of reactor ν flux/shape
- spectral decomposition (^{235}U, ^{239}Pu)
- Rate+Shape analysis

~1 kton Gd-LS
(4.5% Gd)

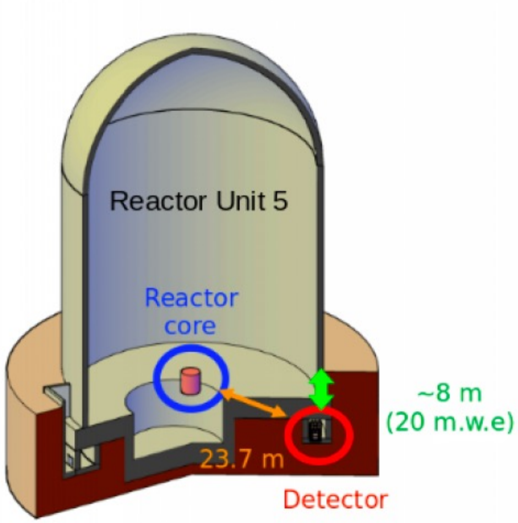




- Location



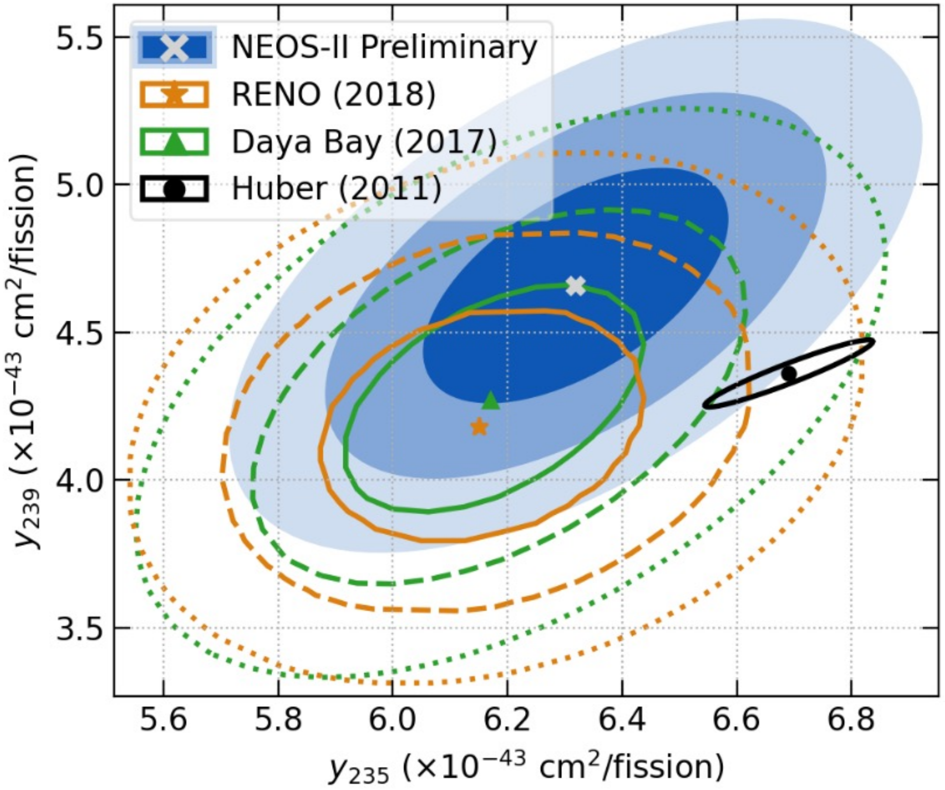
- Hanbit Reactor & Tendon Gallery

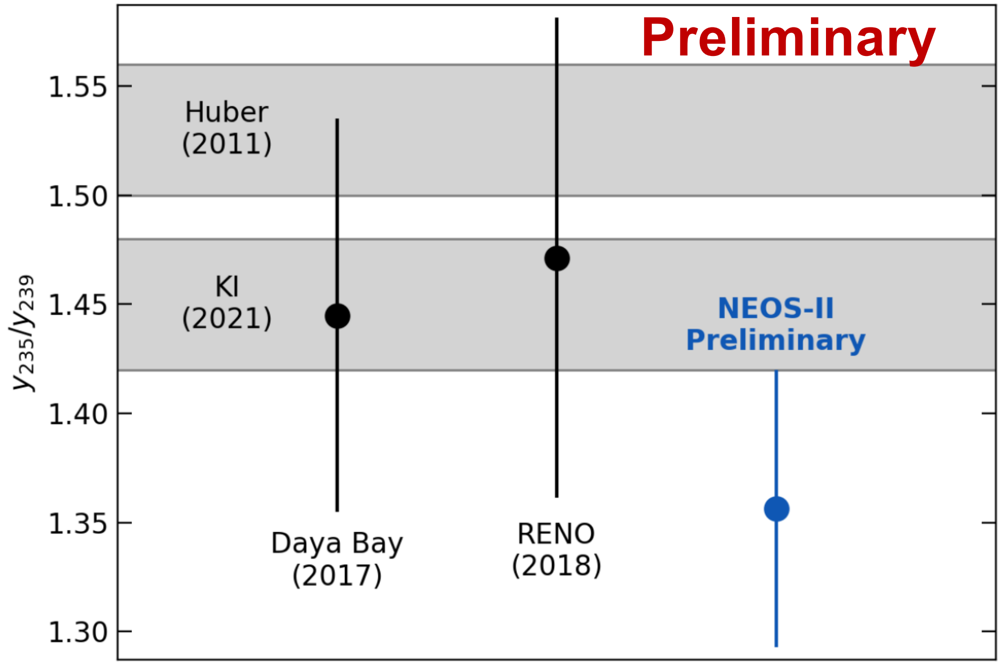


NEOS-II New Results

Jinyu Kim
@Nu2022

Preliminary



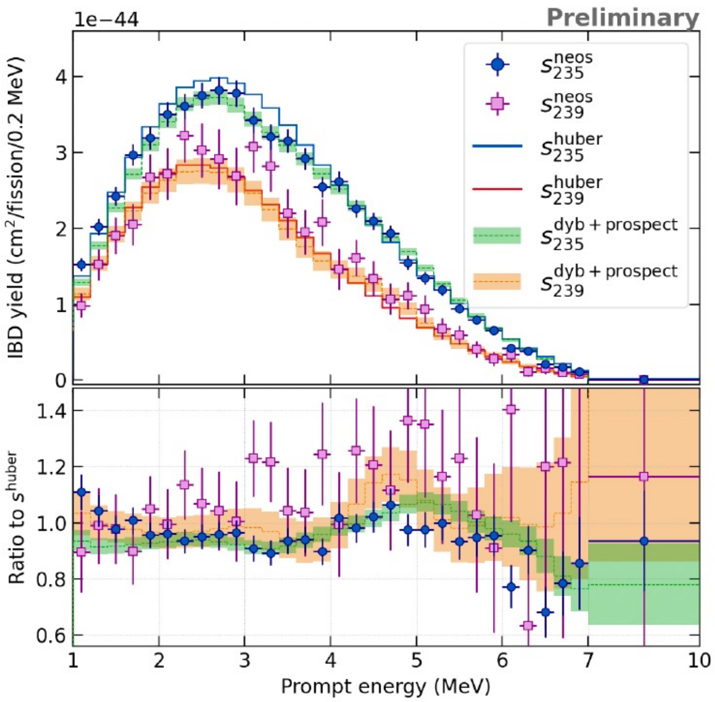


- Detection efficiency: $45 \pm 1.3\%$ (not finalized yet.)
- $y_{235}/y_{239} = 1.36 \pm 0.06$
  - $y_{235} = 6.32 \pm 0.18\ [10^{-43}\mathrm{cm}^2/\mathrm{fission}]$
  - $y_{239} = 4.66 \pm 0.26\ [10^{-43}\mathrm{cm}^2/\mathrm{fission}]$

^{235}U, ^{239}Pu Spectral Decomposition

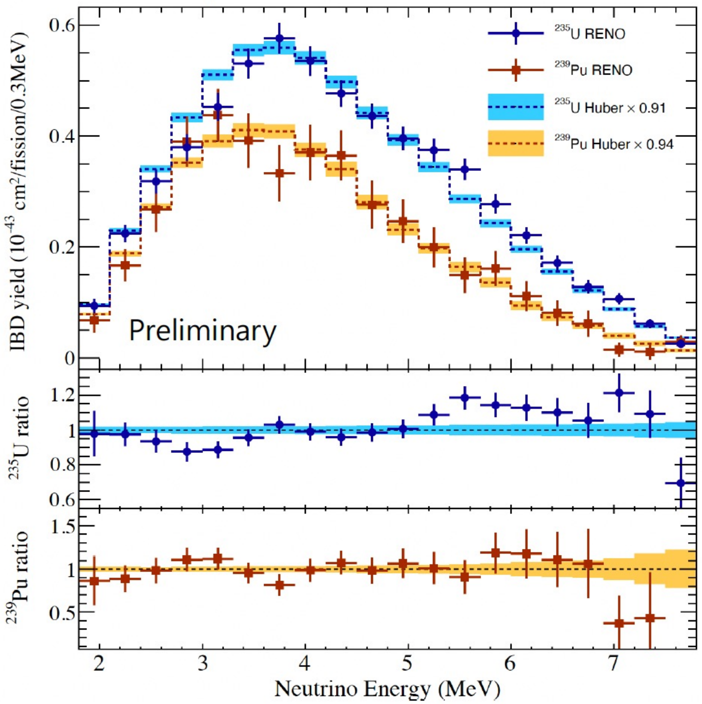
NEOS-II
@Nu2022

- ^{235}U & ^{239}Pu



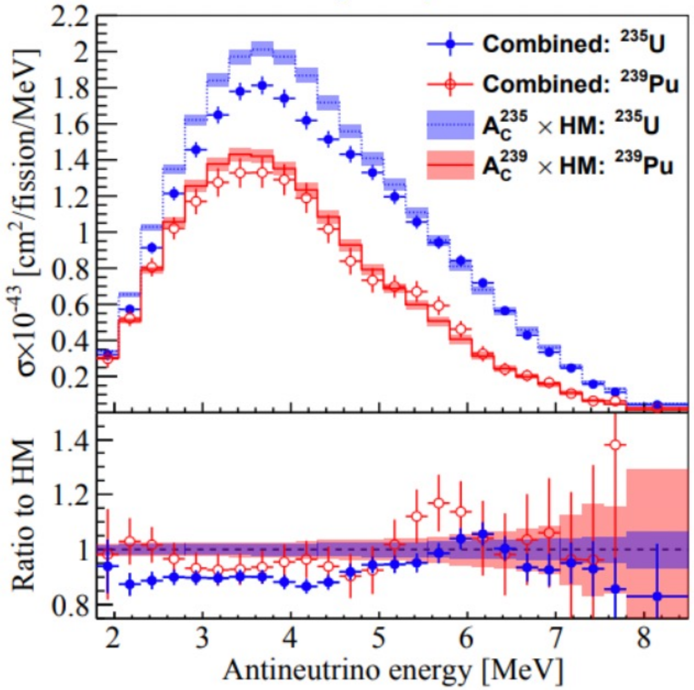
RENO
@Nu2022

Neutrino spectra



Daya Bay

PRL **128** (2022) 081801



Scintillation Detectors @VSBL

Liquid scintillator (LS)

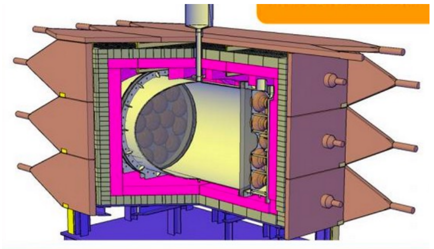
GdLS, ^{6}LiLS

(* : operating exp.)

Gd, Li → n-tagging

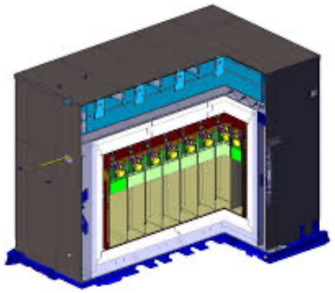
Homogeneous

NEOS,
Nucifer
(finished)



Segmented

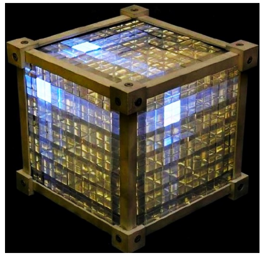
***Neutrino-4,**
***STEREO**
PROSPECT



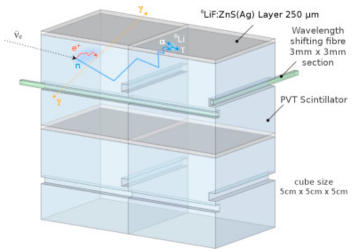
Plastic scintillator (PS)

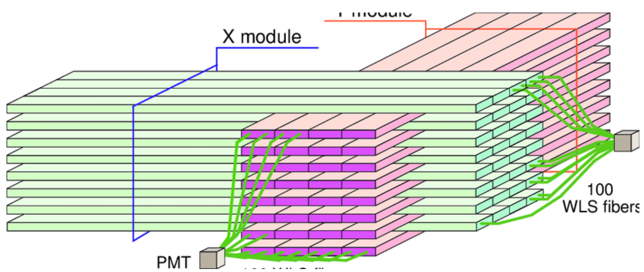
PS (Gd/^{6}Li sheet), ^{6}LiPS

Segmented



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

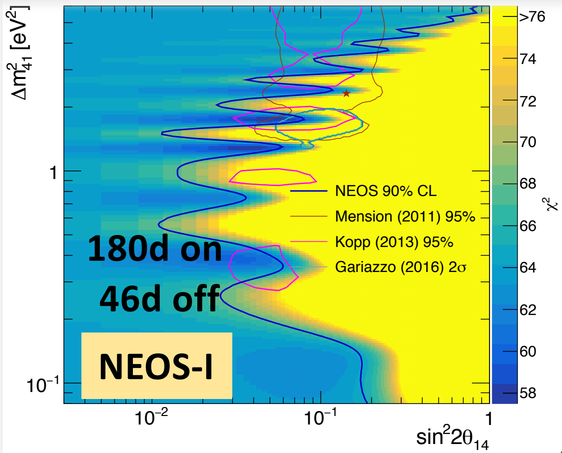




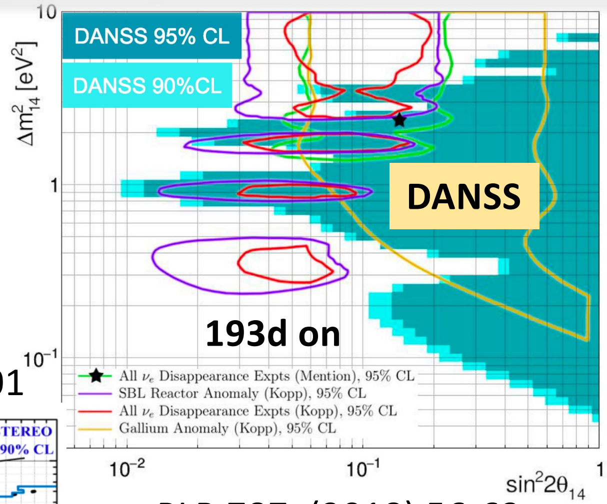
VSBL Reactor ν Experiments

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
PROSPECT	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

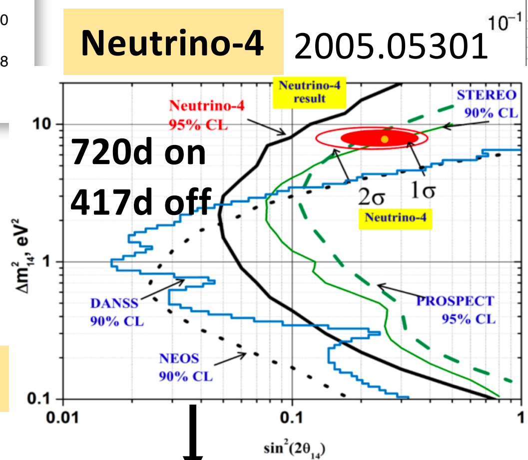
Current VSBL Reactor (3+1) ν Limits



PRL 118, 042502 (2017)



PLB 787, (2018) 56-63

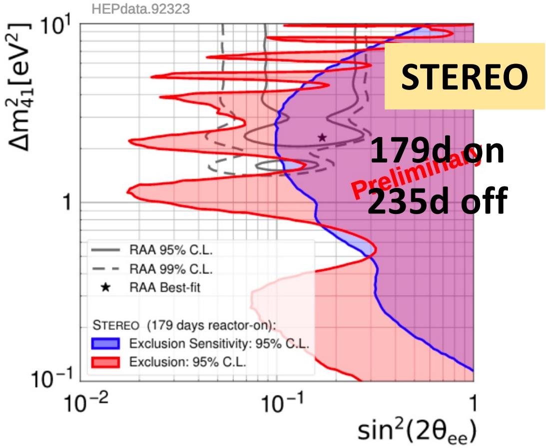


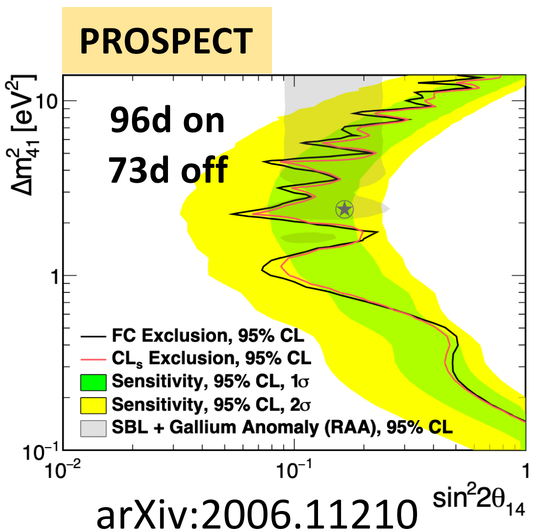
Best fit @~3σ

$\sin^2 2\theta_{14} = 0.36$,

$\Delta m_{41}{}^2 = 7.3$ eV^2

arXiv:1912.06582





arXiv:2006.11210

Baksan **E**xperiment on **S**terile **T**ransition

proposal: 1006.2103, 1204.5379, ...

artificial dichromatic source:

^{51}Cr of 3 MCi ($\Delta W/W < 0.5\%$)

neutrino flux measurment:

$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$

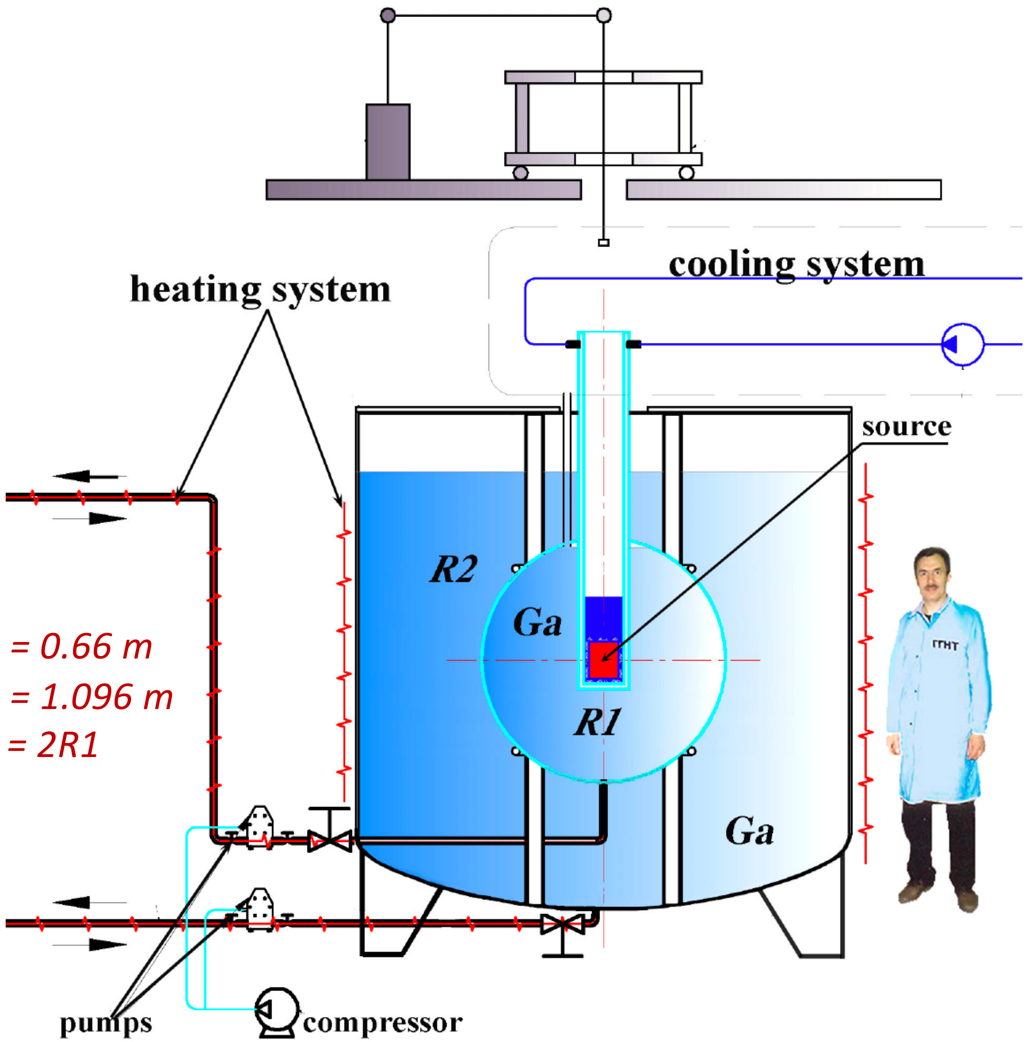
2 detector volumes:
for the flux cross check

geometry is chosen:
to search for $\simeq 1$ eV neutrino

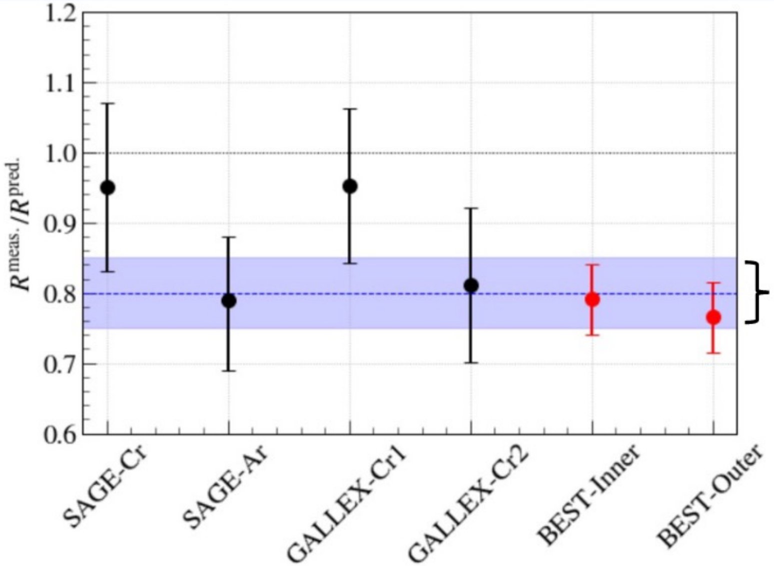
- *R1 = 0.66 m*
- *R2 = 1.096 m*
- *h = 2R1*

data taking:
July–September 2019

$\tau_{^{51}\mathrm{Cr}} = 27.7\mathrm{d}$



BEST



Steve Elliot @Nu2022

Combined result:
$R_0 = 0.80 \pm 0.05$

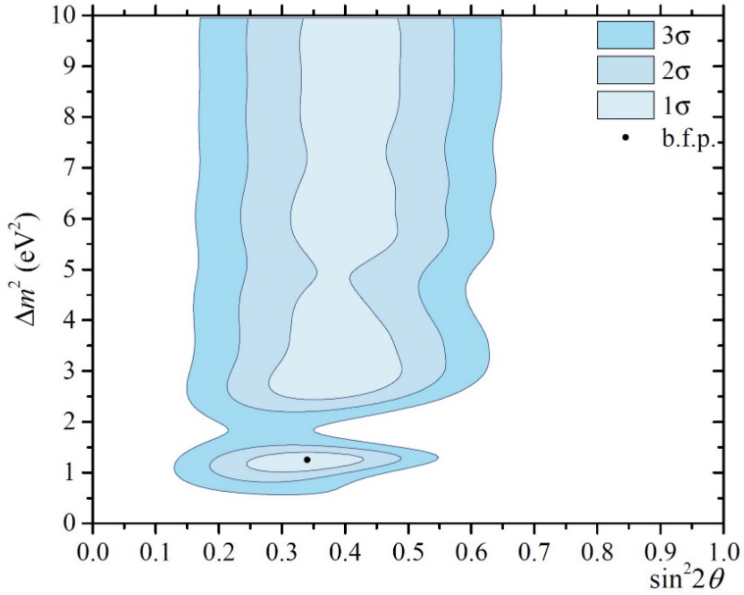


FIG. 8. Allowed regions for two GALLEX, two SAGE and two BEST results. The best-fit point is $\sin^2 2\theta$=0.33, $\Delta m^2 = 1.25$ eV^2 and is indicated by a point.

❖ **Possible alternative explanation was not identified.**

- Cross Section
- Source Strength
- Extraction Efficiencies
- Counting Efficiencies
- Average Path Length

❖ **Possible Future Plan**

^{65}Zn Source (PRD 97 (2018) 073001)

- Higher energy source (1.35 MeV vs. 0.75 MeV).
- Almost twice the cross section.
  - But adds a couple additional excited states.
- 13-14 kg of 95% enriched ^{64}Zn to produce 0.5 MCi.
- About 9x longer half life (244 d), many more events even with lower activity.

RAA = **R**eactor **A**ntineutrino **A**nomaly

(3+1) ν RAA best fit: $\Delta m^2_{41} = 2.4\ eV^2$, $\sin^2(2\theta_{14}) = 0.14$

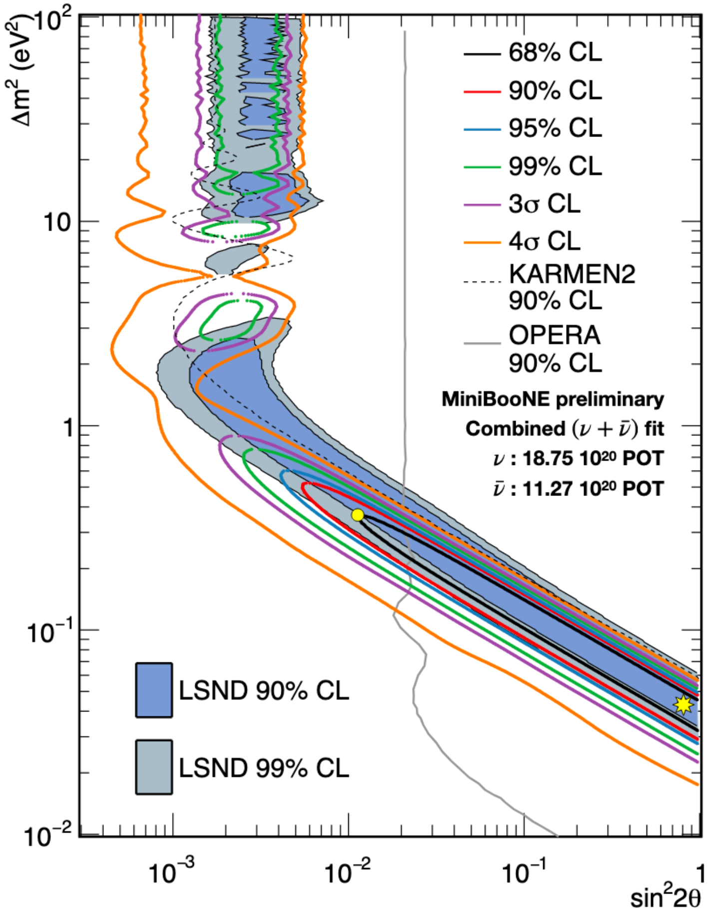
Neutrino-4: $\Delta m^2_{41} = 7.3\ eV^2$, $\sin^2(2\theta_{14}) = 0.36$

GALLEX+SAGE+BEST: $\Delta m^2_{41} = 1.25\ eV^2$, $\sin^2(2\theta_{14}) = 0.33$

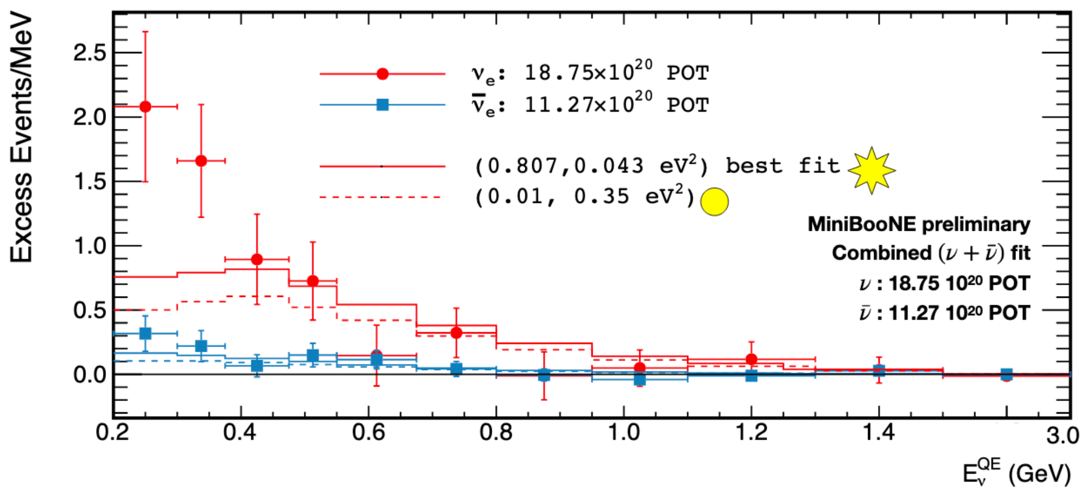
- These best fit values are exclued by several VSBL experiments.

MiniBooNE Results in 2020

- ➢ Total 17 years of data
- ➢ Total ~36 x 10^{20} POT roughly 1.66 : 1 in $\nu : \bar{\nu}$



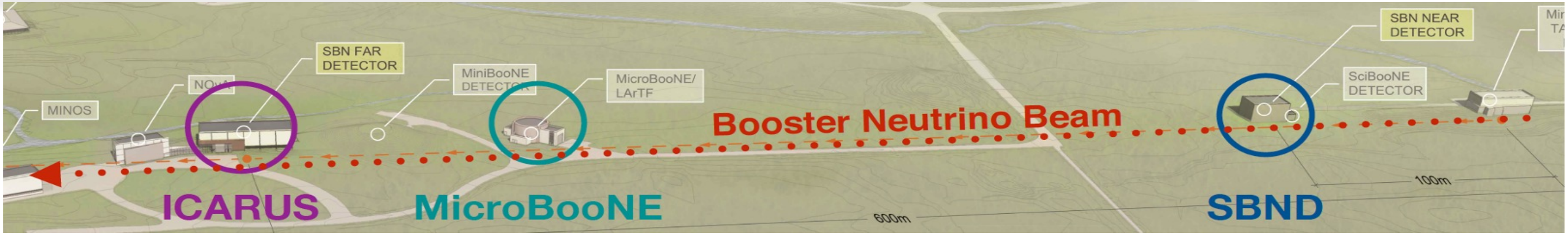
- Neutrino mode excess 4.7σ,
- **Neutrino+Anti-neutrino modes excess : 4.8σ**

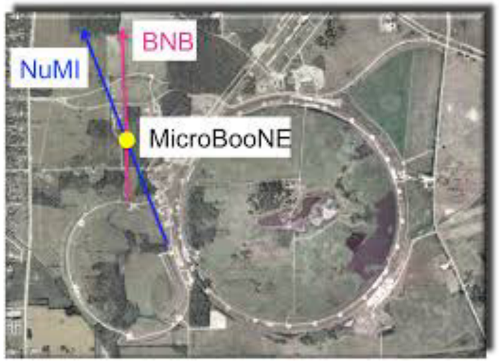


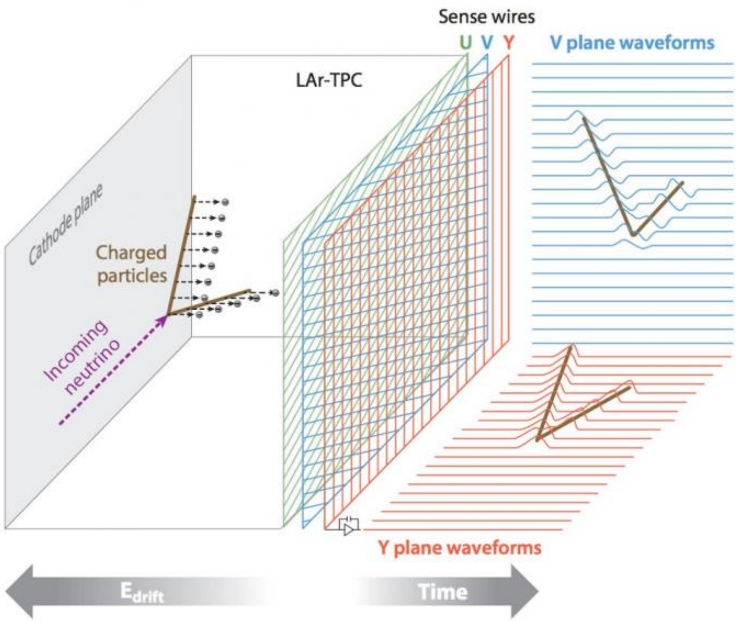
Neutrino + Anti-Neutrino Mode

$$(\Delta m^2, \sin^2 2\theta) = (0.043\ eV^2, 0.807)$$
$$\chi^2/ndf = 21.7/15.5\ (\text{prob} = 12.3\%)$$

MicroBooNE







LArTPC

- LAr: 150 ton (80 ton active)
- TPC: 3 wire planes
  (2.5 x 2.3 x 10.4 m^3)
  total 8256 wires

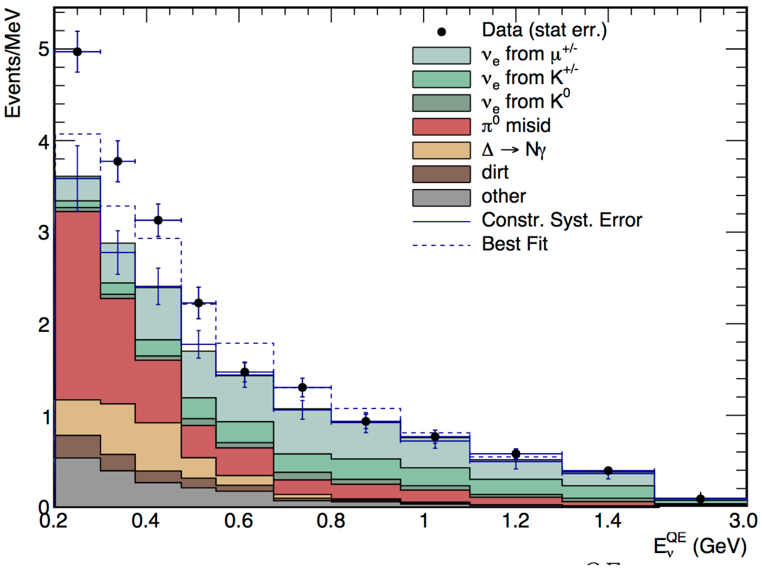
- ➢ Data taking: 2015 – 2019?
- ➢ Total **~1.32 x 10^{21} POT**

➢ MicroBooNE can distinguish e^- and γ.

MiniBooNE

- Data taking: 2002 - 2019

Total **~3.6 x 10^{21} POT** (1.66:1 in $\nu:\bar{\nu}$)



Electron-like excess (ν_e excess)

- Mismodeled/unknown process?
- Oscillation-driven excess?

Photon-like excess

- Mismodeled/unknown process producing photons, e.g. NC Δ resonance radiative decay?

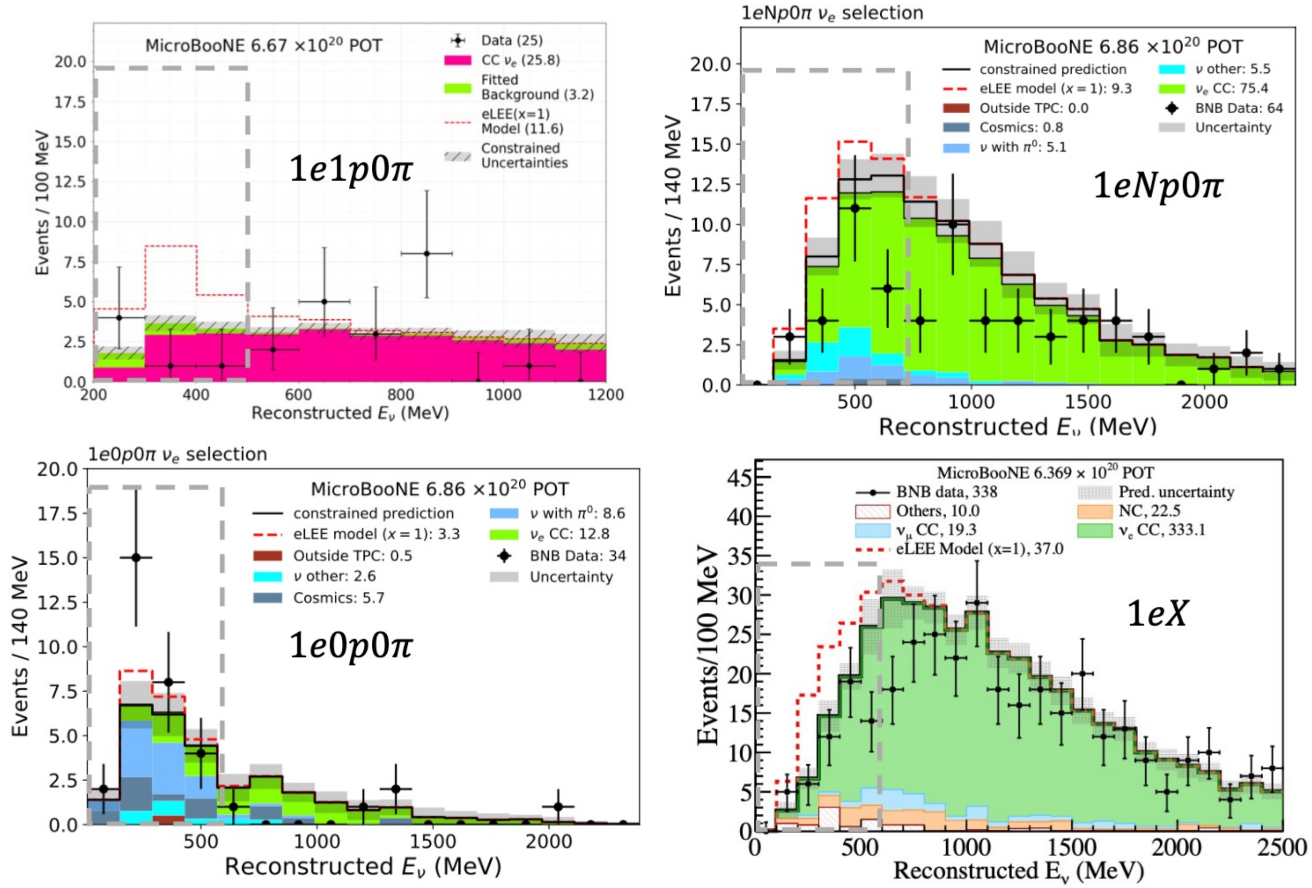
Hanyu Wei @Nu2022

MicroBooNE

arXiv:2110.14054

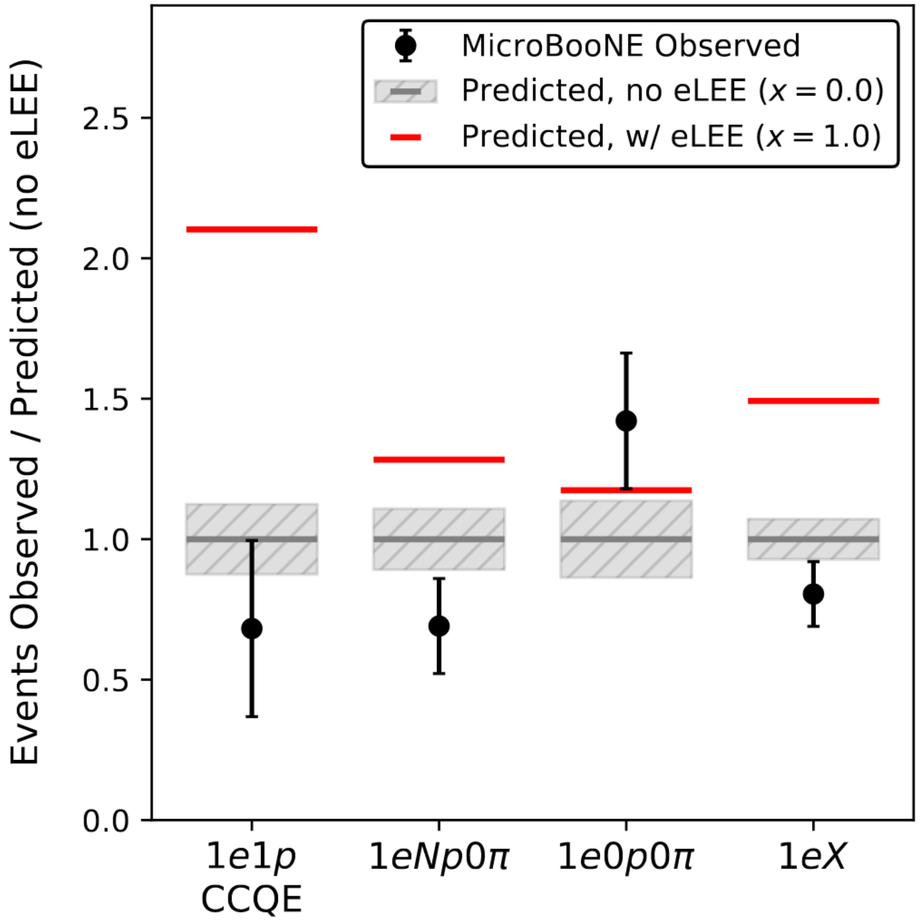
6.86 x 10^{20} POT

(50% data)



MicroBooNE eLEE Search Result

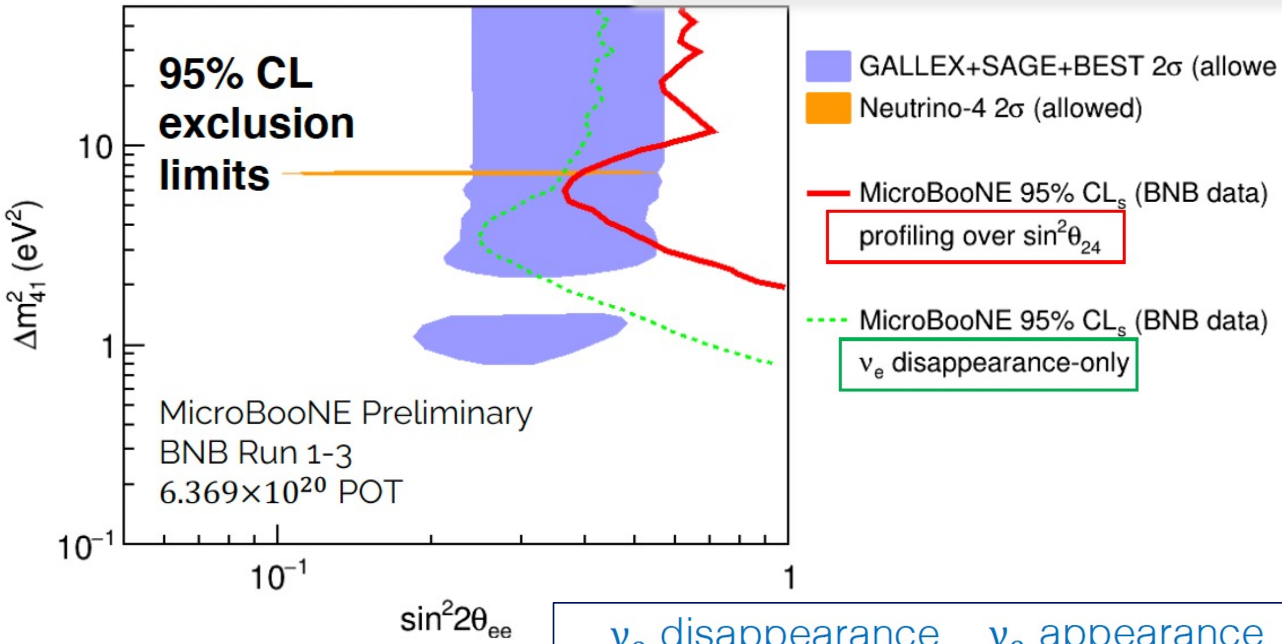
Hanyu Wei
@Nu2022



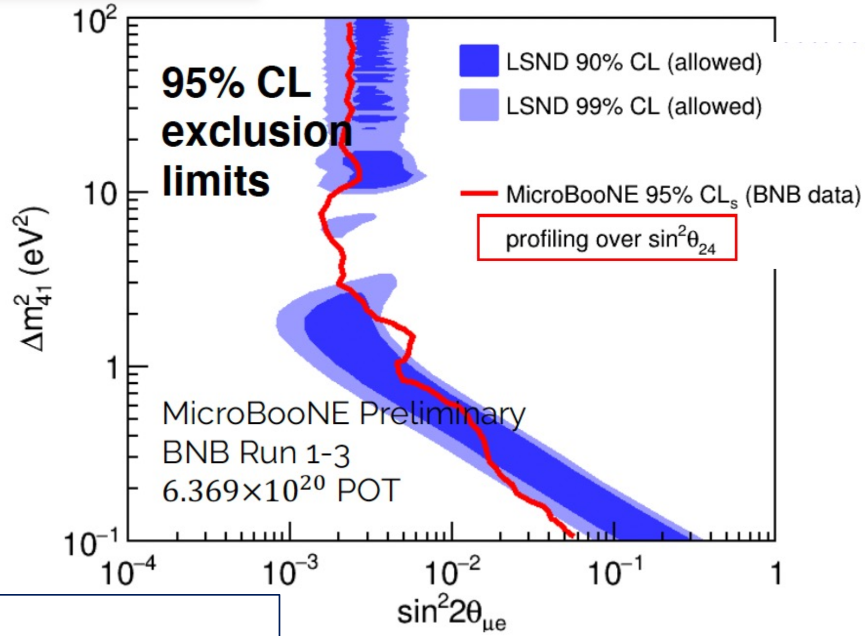
- Observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region

MicroBooNE (3+1) ν

ν_e **dis**appearance



ν_e appearance



ν_e disappearance $\quad$ ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}$$

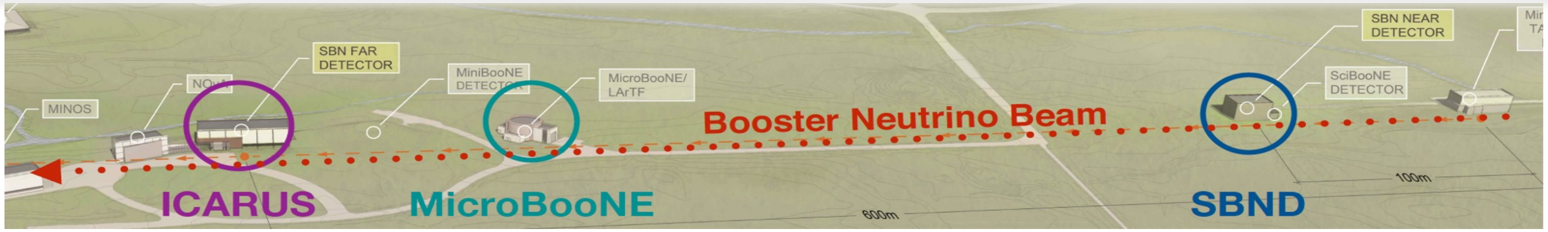
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + \boxed{\left(R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1 \right)} \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41} \right]$$

- **Degeneracy** when $\sin^2 \theta_{24}$ approaches R_{ν_e/ν_μ} which is the ratio of intrinsic ν_e and ν_μ in the neutrino flux
- **Sensitivity/exclusion limits gets much worse around the degeneracy point**

Hanyu Wei
@Nu2022

SBN (LarTPC) Status

Anne Schukraft @Nu2022

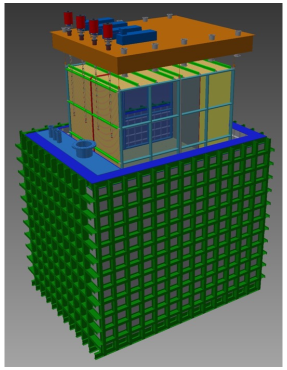


SBND

(110 m, 112 ton)

- Detector construction underway
- Detector installation: end of 2022
- Detector commissioning: 2023

← Systematic Constraint (~% level)



ICARUS

(600 m, 476 ton)

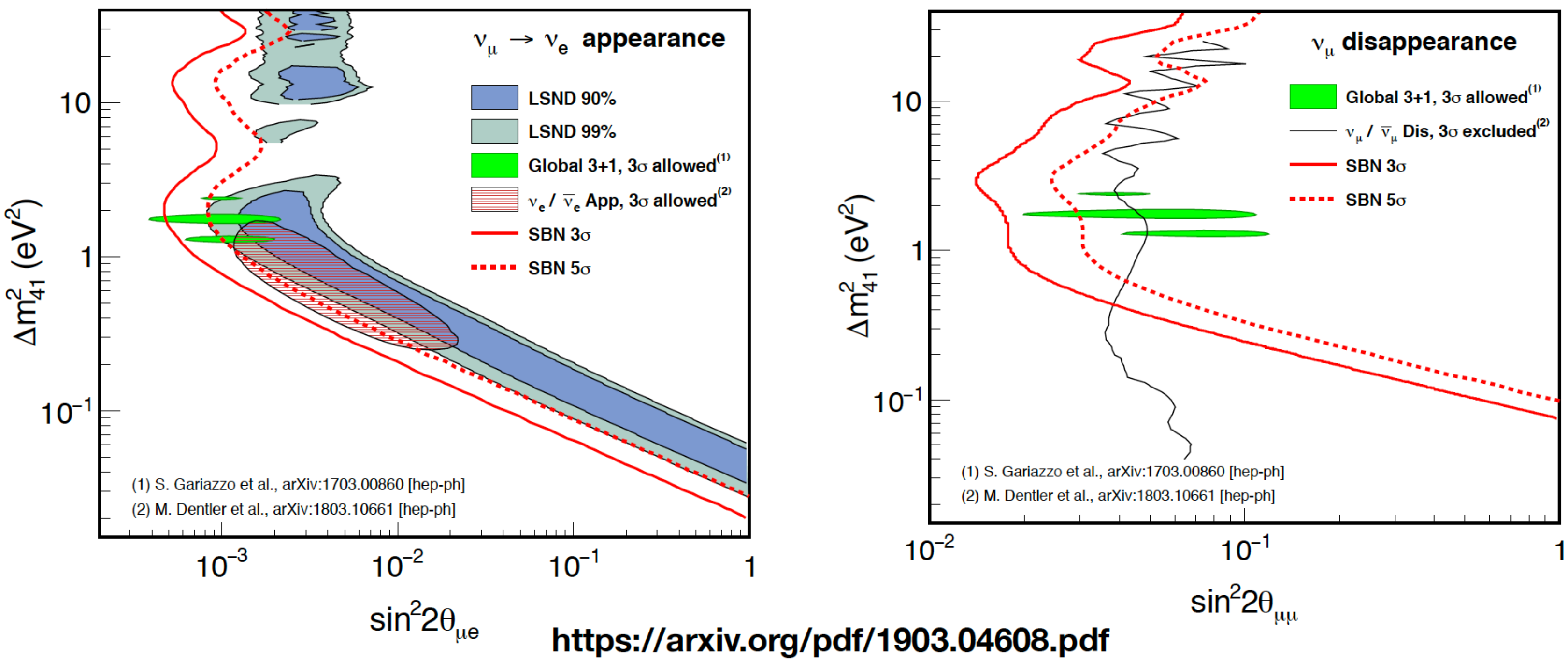
- Detector installation: July '18 – '19
- Detector commissioning: 2020
- 1st Physics data: June 2021
- Calibration campaign in process
- Preparing to start its physics run

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

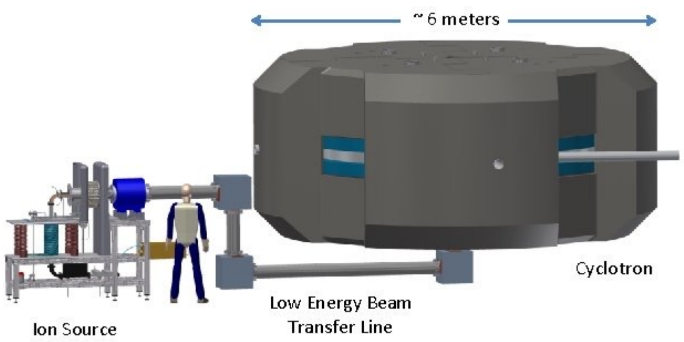
ν_e appearance **ν_μ disappearance**

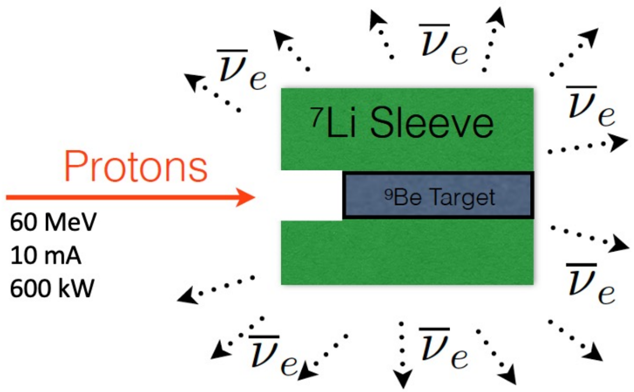


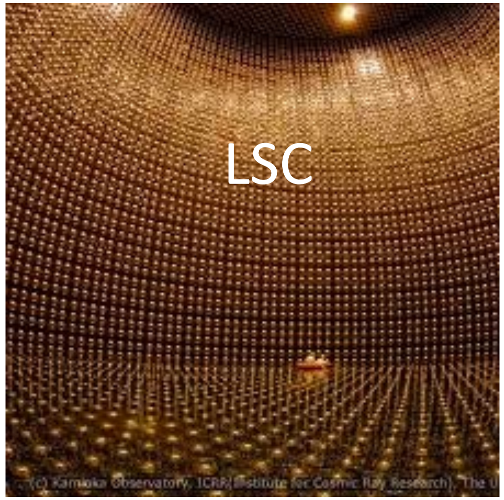
https://arxiv.org/pdf/1903.04608.pdf

❑ Sterile ν search w/ IsoDAR@Yemilab

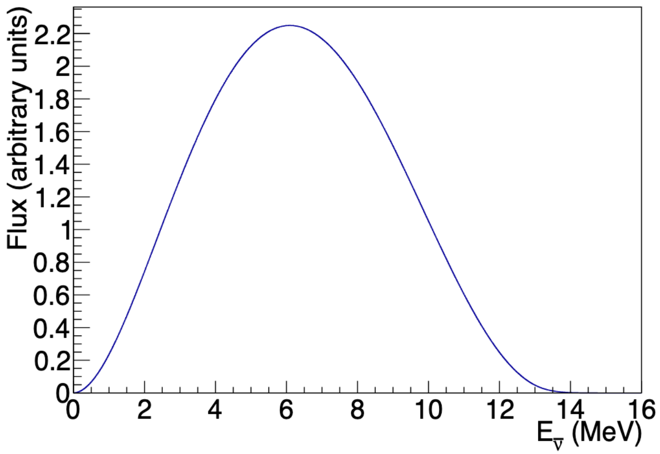
The IsoDAR Cyclotron and Ion Source

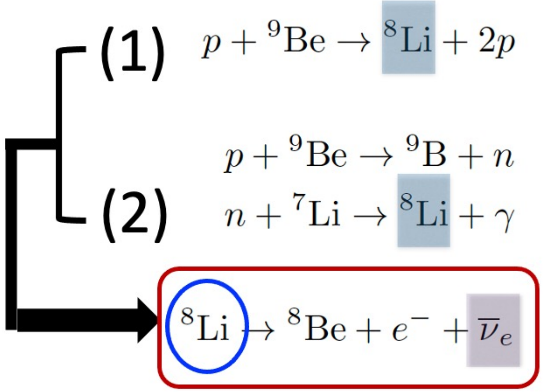






IsoDAR $\overline{\nu}$ spectrum





(1) $p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$

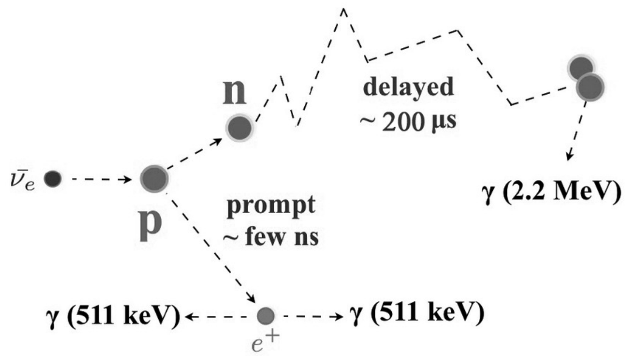
$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$

(2) $n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$

$${}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

IBD interaction

$$p^+ + \overline{\nu}_e \rightarrow e^+ + n^0$$

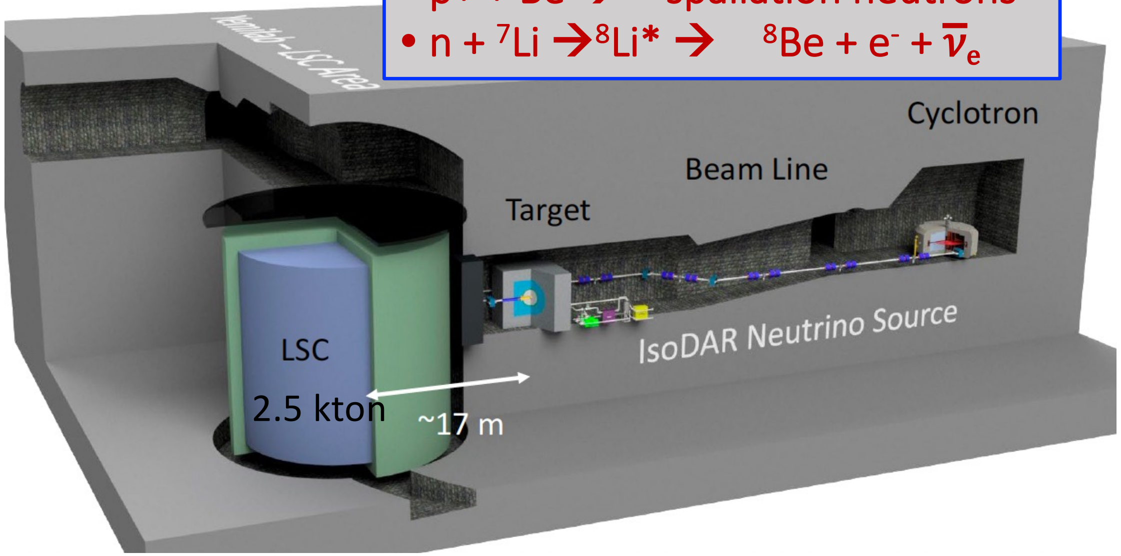


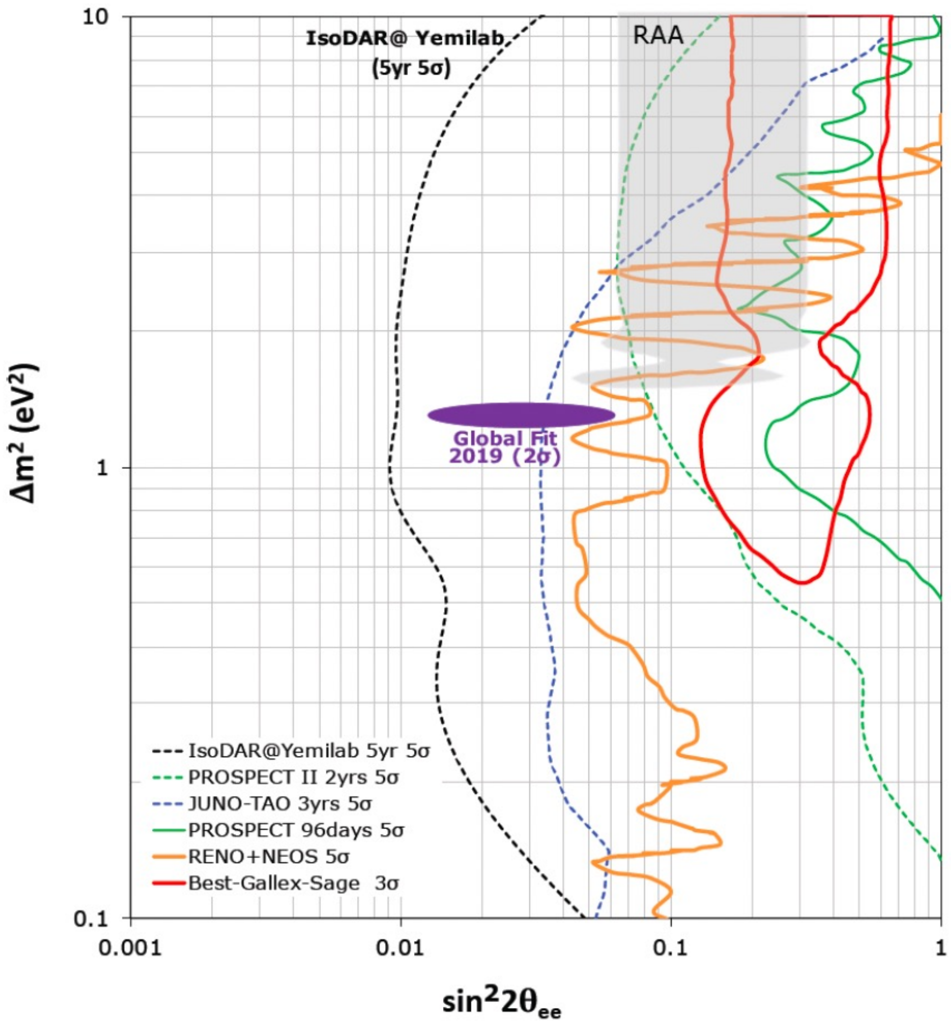
Future Sterile ν Sensitivities in $\nu_e \rightarrow \nu_e$

Daniel Winkleihner
@Nu2022

- On timescales from 2-5 years there are good prospects to cover the most important regions in parameter space
- 2y: PROSPECT-II → high Δm2
- 3y: JUNO-TAO → low Δm2
- 5y: IsoDAR@Yemilab → full coverage

- p+ + Be → spallation neutrons
- n + ^{7}Li → ^{8}Li* → ^{8}Be + e^- + $\bar{\nu}_e$





Sterile ν Search w/ IsoDAR@Yemilab

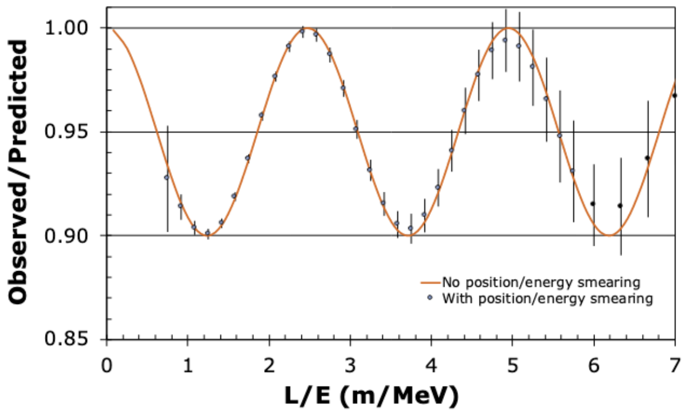
Daniel Winkleihner
@Nu2022

Possible Models & Signatures

arXiv:2111.09480
PRD 105 (2022) 5, 052009

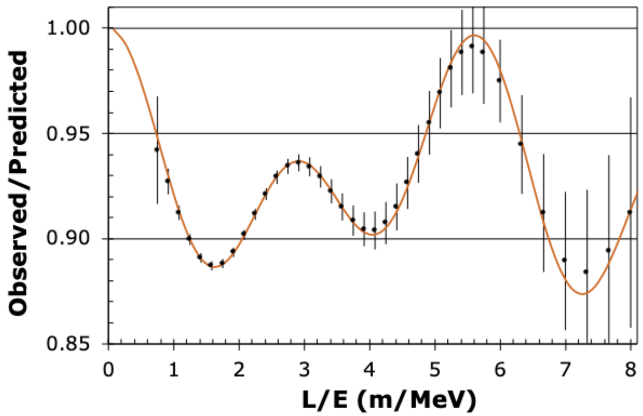
(3+1) ν

IsoDAR@ Yemilab: Δm^2 = 1 eV² and $\sin^2 2\theta$ = 0.1



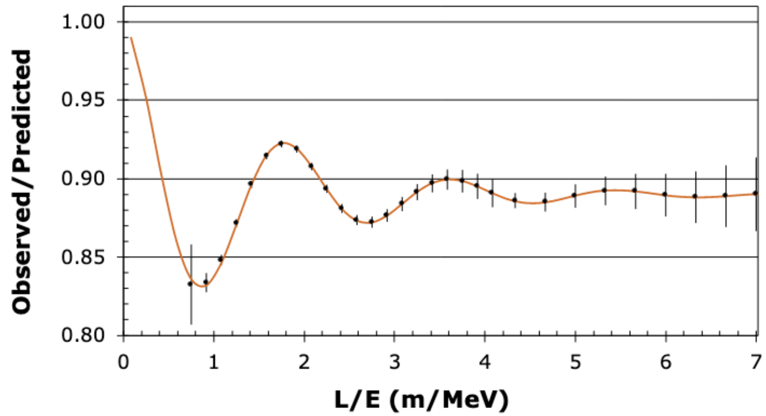
(3+2) ν

IsoDAR@Yemilab: (3+2) Model
with Kopp/Maltoni/Schwetz Parameters



(3+1) ν + ν_s decay

IsoDAR@Yemilab: (3+1) plus Decay Model
Δm^2 = 1.35 eV², $\sin^2 2\theta$ = 0.214 and τ = 4.5 eV⁻¹



→ IsoDAR@Yemilab can well distinguish different new physics models.

- The (3+1)+decay model significantly reduces the tension between appearance and disappearance experiments, improving the global-data goodness-of-fit.

1910.13456

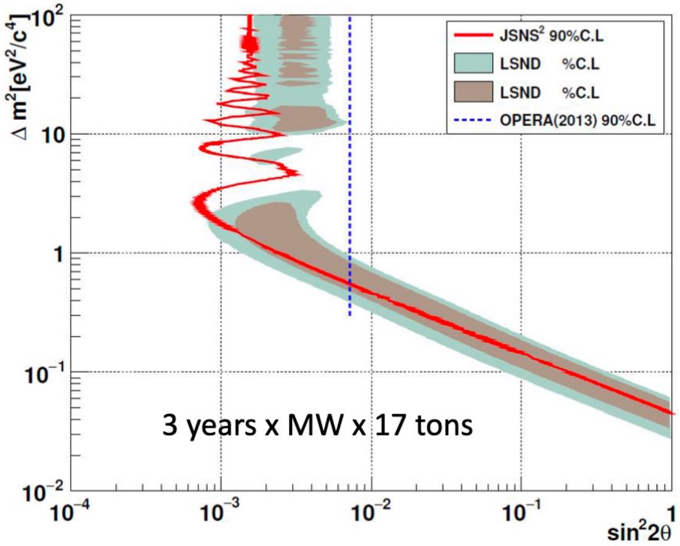
JSNS^2 @J-PARC

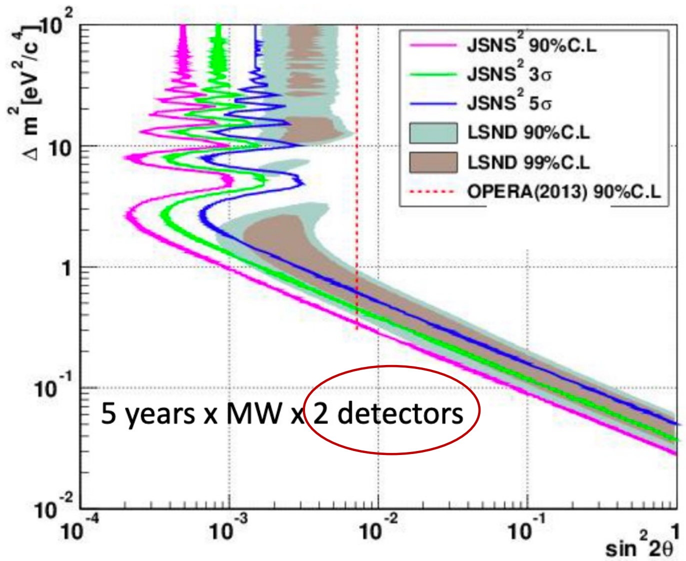
→ Direct tests for LSND

Experiment	ν-source	Energy E_ν	Distance L	Signal
LSND [1]	π DAR	40 MeV	30 m	$\bar{\nu}_\mu \to \bar{\nu}_e$
MiniBooNE [2]	π DIF	800 MeV	600 m	$\nu_\mu \to \nu_e$ / $\bar{\nu}_\mu \to \bar{\nu}_e$
FNAL SB program [7]	π DIF	800 MeV	110 m / 470 m / 600 m	$\nu_\mu \to \nu_e$ / $\bar{\nu}_\mu \to \bar{\nu}_e$
JSNS^2 [6]	π DAR	40 MeV	24 m	$\bar{\nu}_\mu \to \bar{\nu}_e$

- 17 ton GdLS target (cf. LSND = 167 ton LS)
- Better E resolution than LSND (2.4 % vs 7% at 45 MeV)

JSNS^2-II Data taking: End of 2023





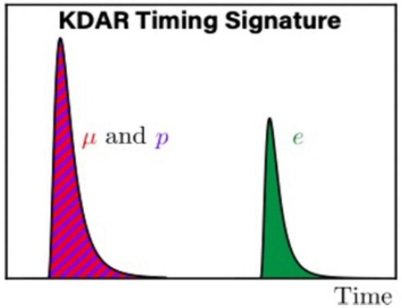
JSNS² KDAR

KDAR $K^+ \rightarrow \mu^+ + \nu_\mu$

Prompt $\nu_\mu + {}^{12}C \rightarrow X + \mu^-$

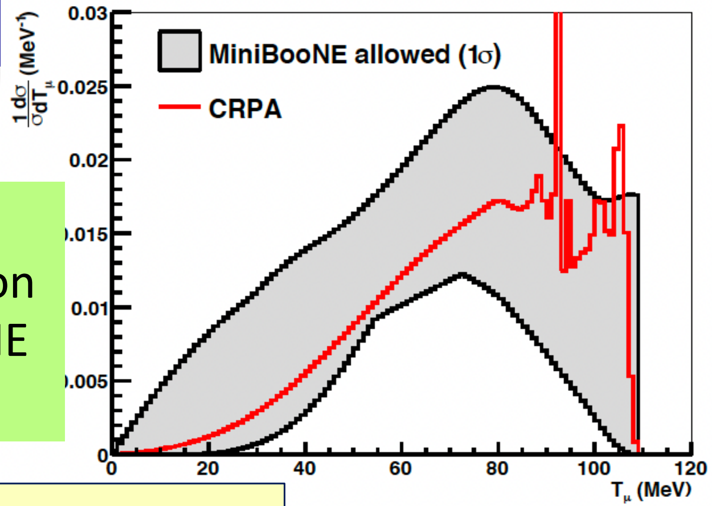
Delayed $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

E_ν(KDAR) = 236 MeV mono-energetic

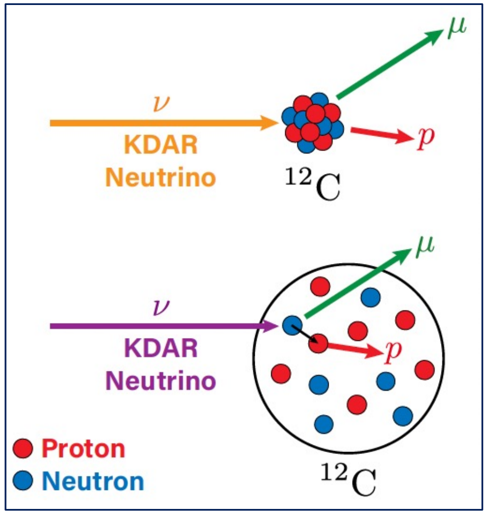


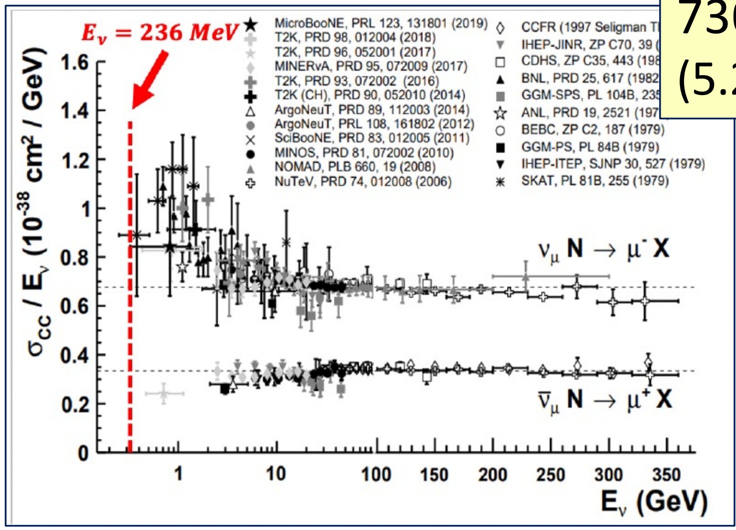
KDAR:
1st observation
by MiniBooNE
(3.9σ)

MiniBooNE, PRL 120 141802 (2018)



❖ Models and n generators
strongly disagree in this transition region.

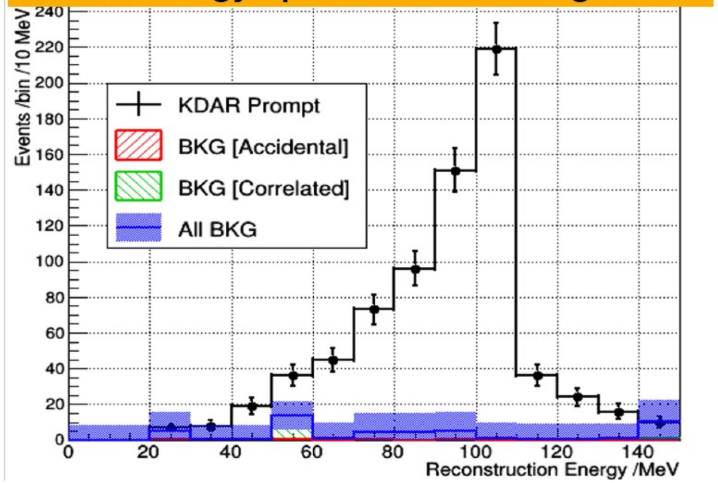




JSNS2:
KDAR clear observation
730 events
(5.2% BKG)

Jungsic Park
@Nu2022

Visible energy spectrum w/ backgrounds



keV Sterile ν Searches

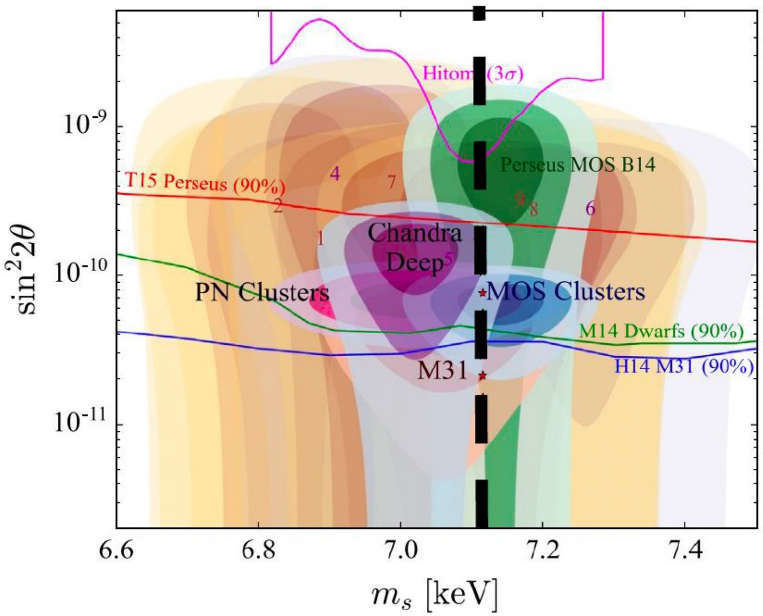
keV sterile ν → good candidate of warm DM

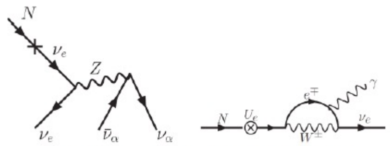
If purely keV sterile ν DM → m_ν > 0.4 keV

"Light" keV Searches (1 – 10 keV) – Hints?

Kyle Leech
@Nu2022

- Few keV mass neutrinos are strong WDM candidates
- Deep-field X-ray measurements of galactic clusters *hint* at a 3.5 keV line





R. Adhikari et al., JCAP **25** (2017)

Image Courtesy: Chandra/NASA

7.1 keV neutrino?

N. Cappellutiet al., Astrophys. J **854**, 179 (2018)
F.A. Aharonian et al., Astrophys. J **837**, L15 (2017)
A. Boyarsky et al., Phys. Rev. Lett. **113**, 251301 (2014)

Or something else?

Dessert *et al*., Science **367**, 1465–1467 (2020)

Image Courtesy: HITOMI/NASA

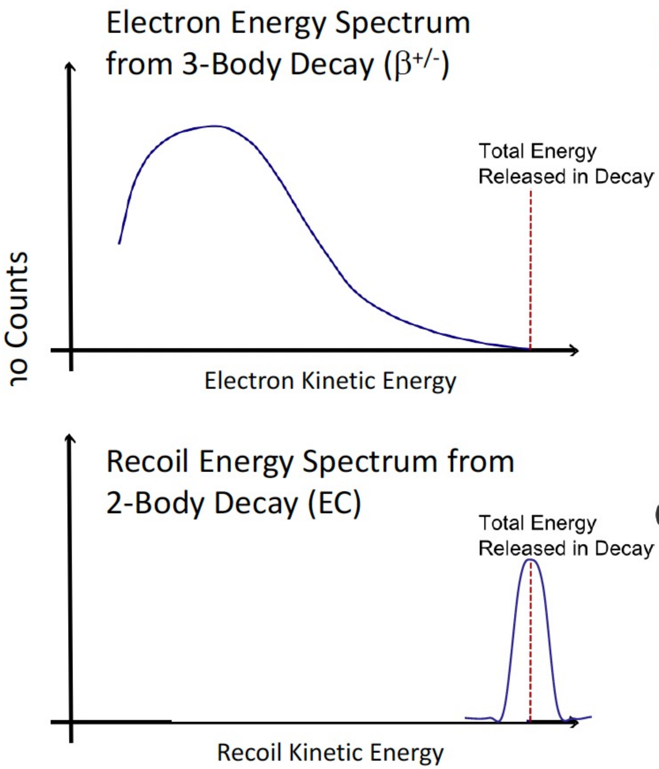
These measurements provide intriguing hints of new physics, BUT we need model independent measurements across a wide mass range for definitive searches….

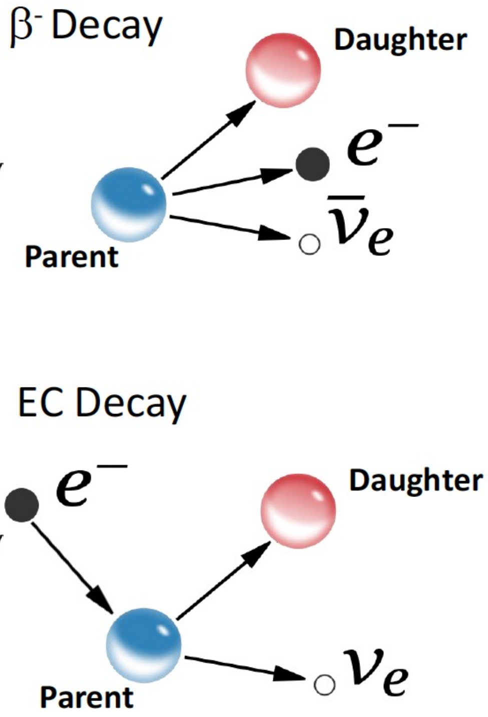
Here is where the power of beta decay plays a major role!

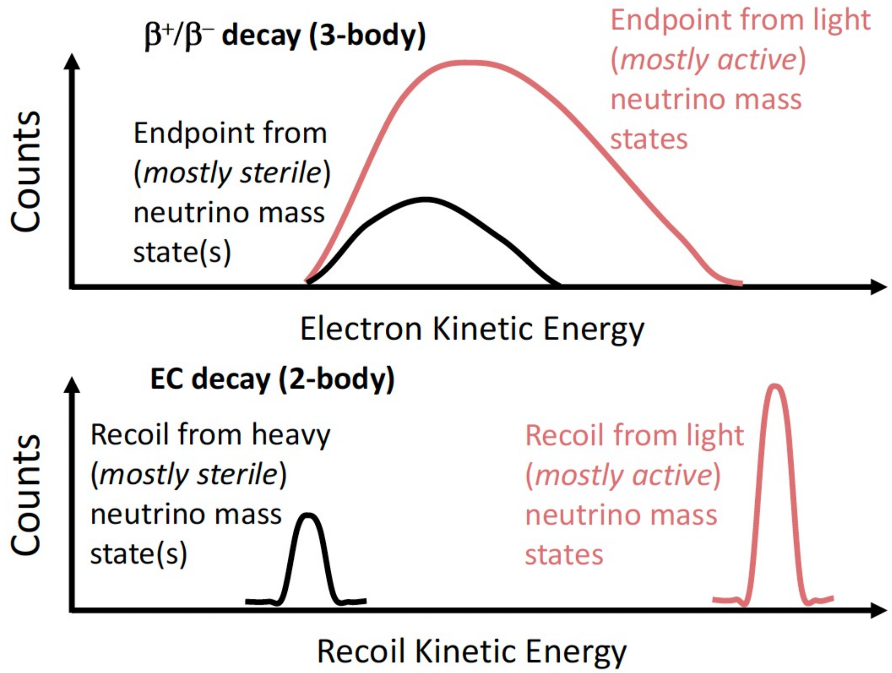
keV Sterile ν Searches

Kyle Leech
@Nu2022

- In Particle Phys. keV sterile ν are searched in beta decays (^{3}H, ^{241}Pu, etc) or EC

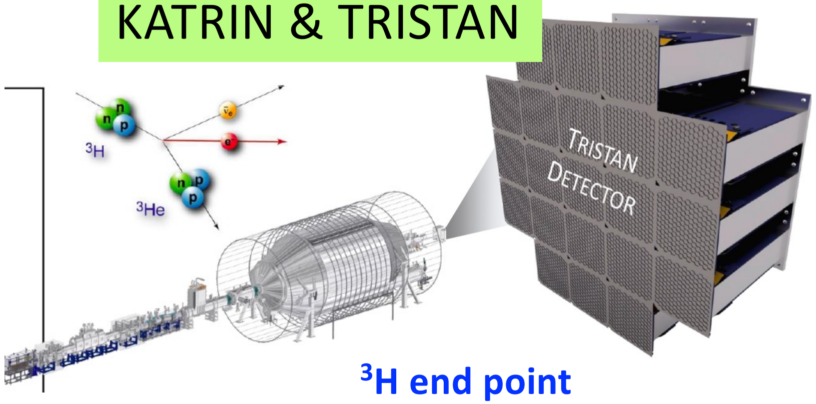






keV Sterile ν Search Experiments

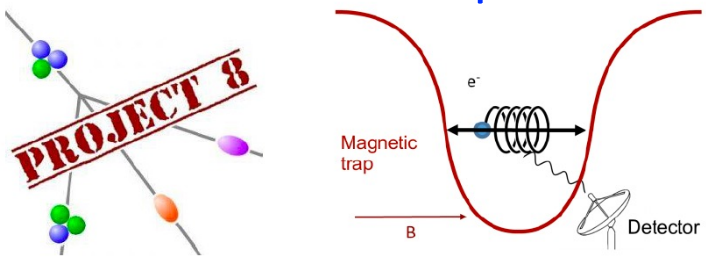
KATRIN & TRISTAN



^{3}H end point

PROJECT-8

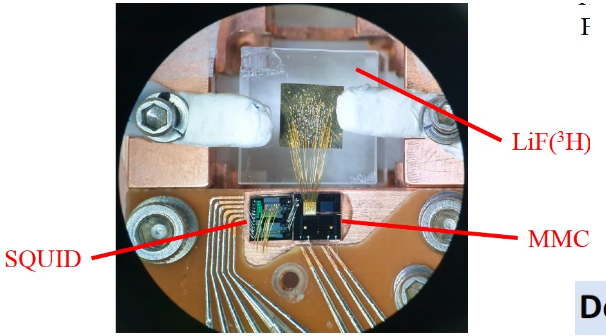
^{3}H end point

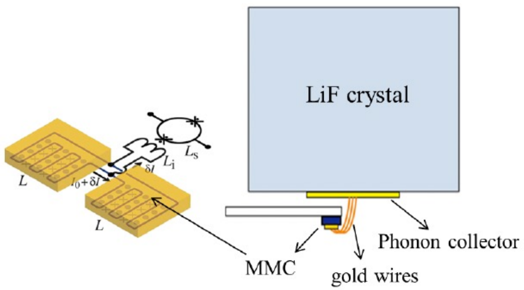


CUP Tritium Exp.

^{3}H end point

LiF + MMC

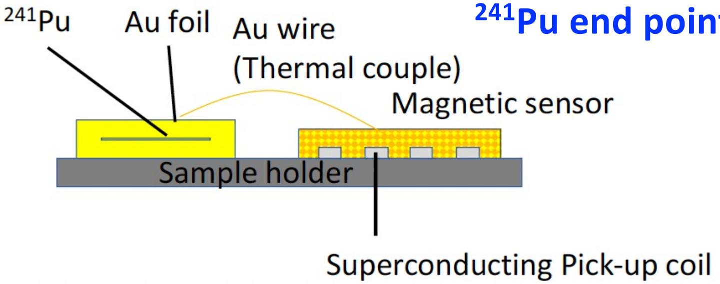




MAGNETO-ν

Detector: Magnetic Quantum Sensors with Gold foils

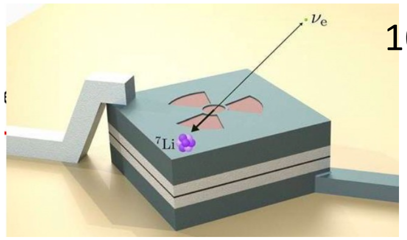
^{241}Pu end point

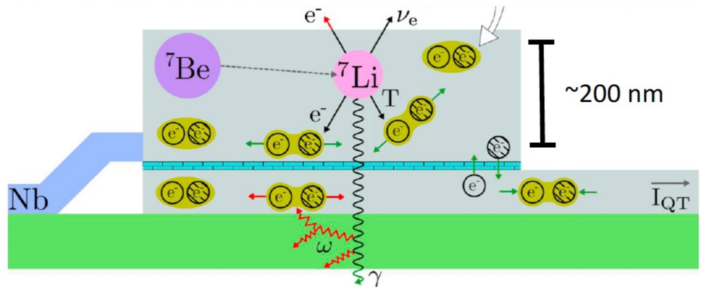


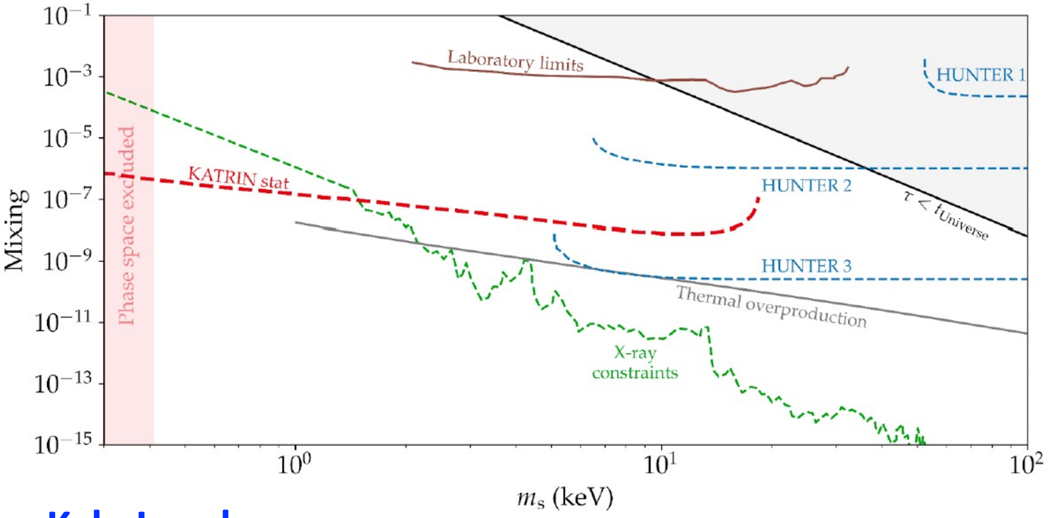
BeEST

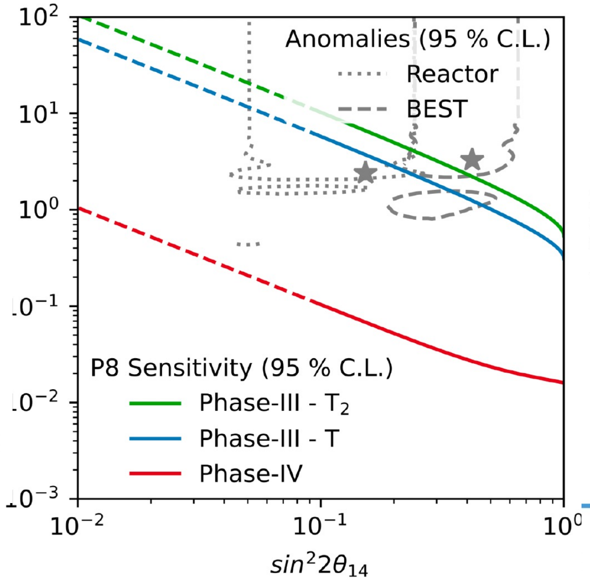
EC decay of ^{7}Be

10~100 keV

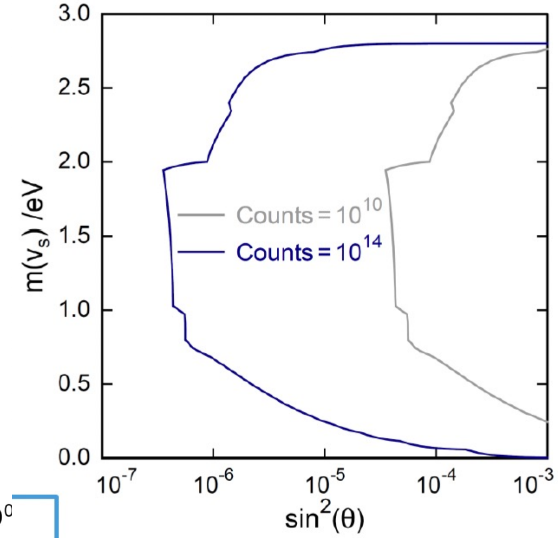






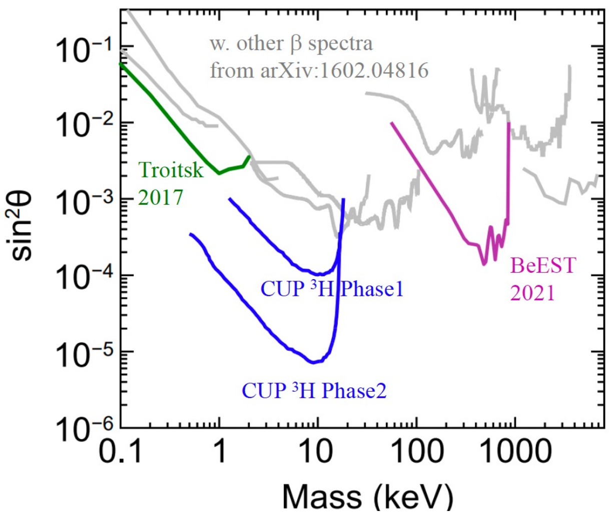


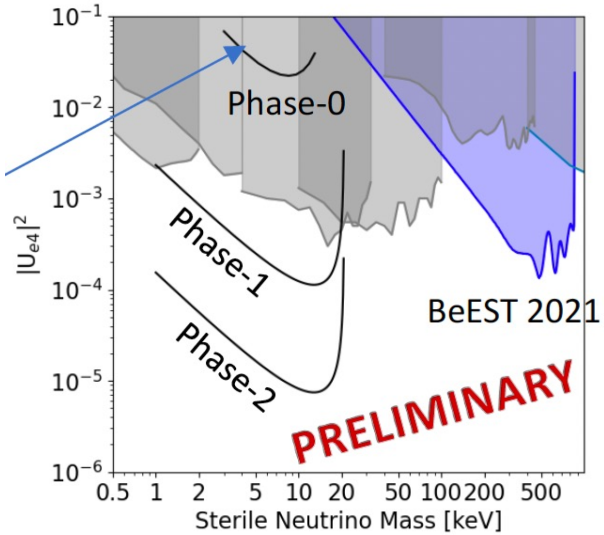
163Ho EC

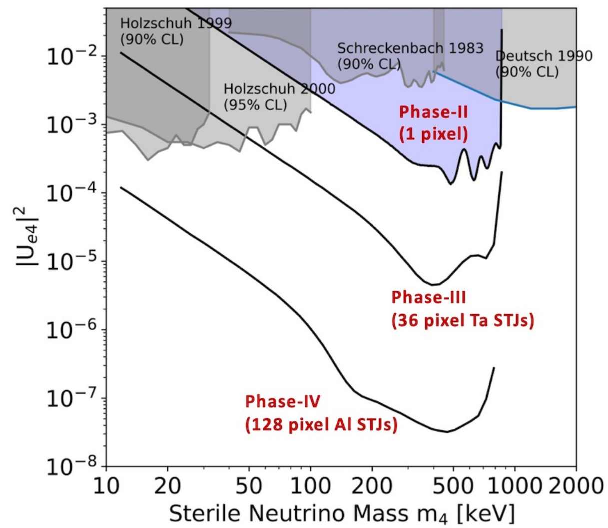


Kyle Leech
@Nu2022

3H end point
CUP tritium exp.







keV Sterile ν Searches: Conclusion & Outlook

Kyle Leech
@Nu2022

- Nuclear decay provides a powerful, model-independent probe in the keV – MeV mass range
- Significant progress in measurements over the past 3 years – enabled by quantum sensing
- Experiments poised to increase sensitivity by 5+ orders of magnitude in the next decade

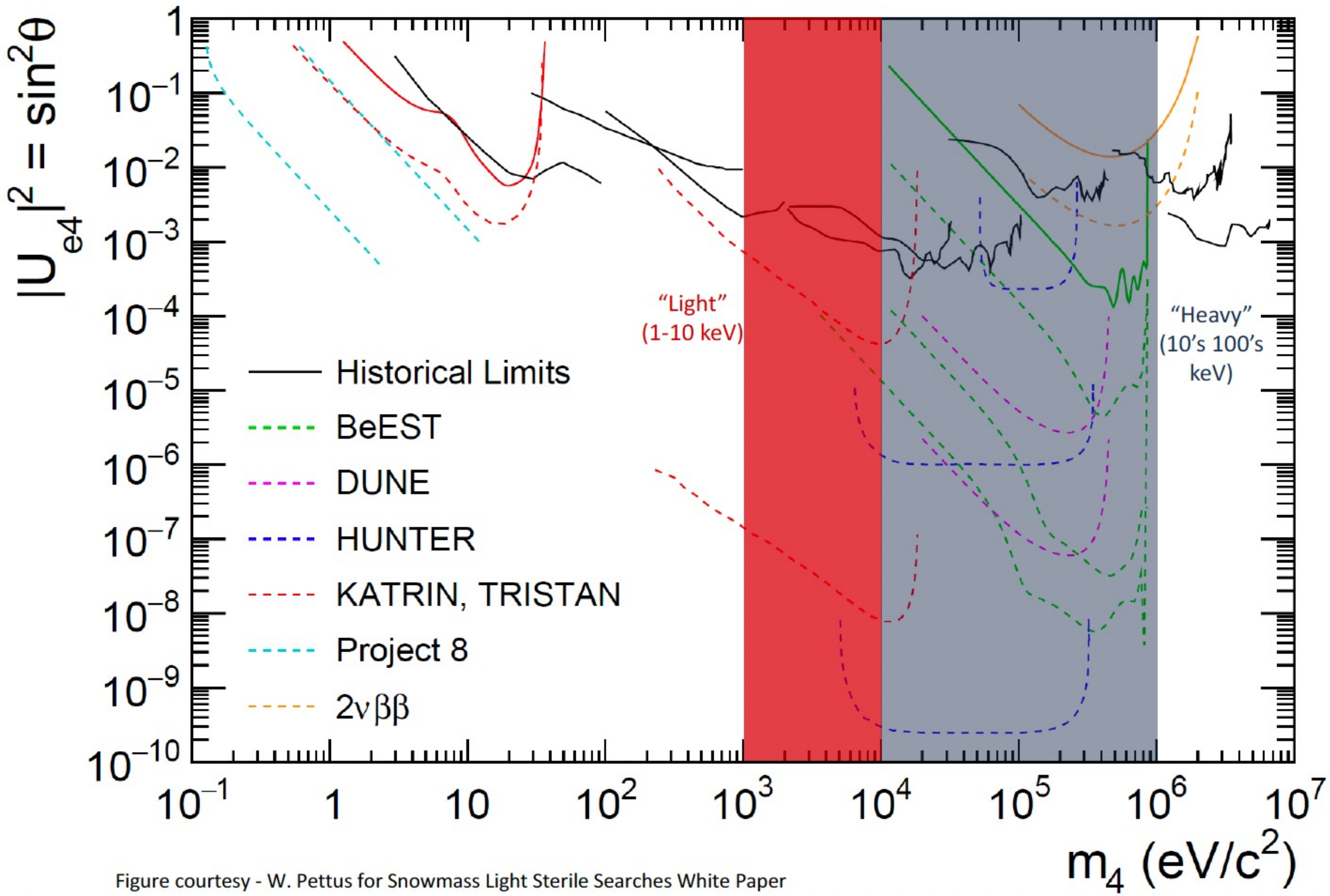


Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper

Cosmological Limits on N_{eff}

PDG 2021

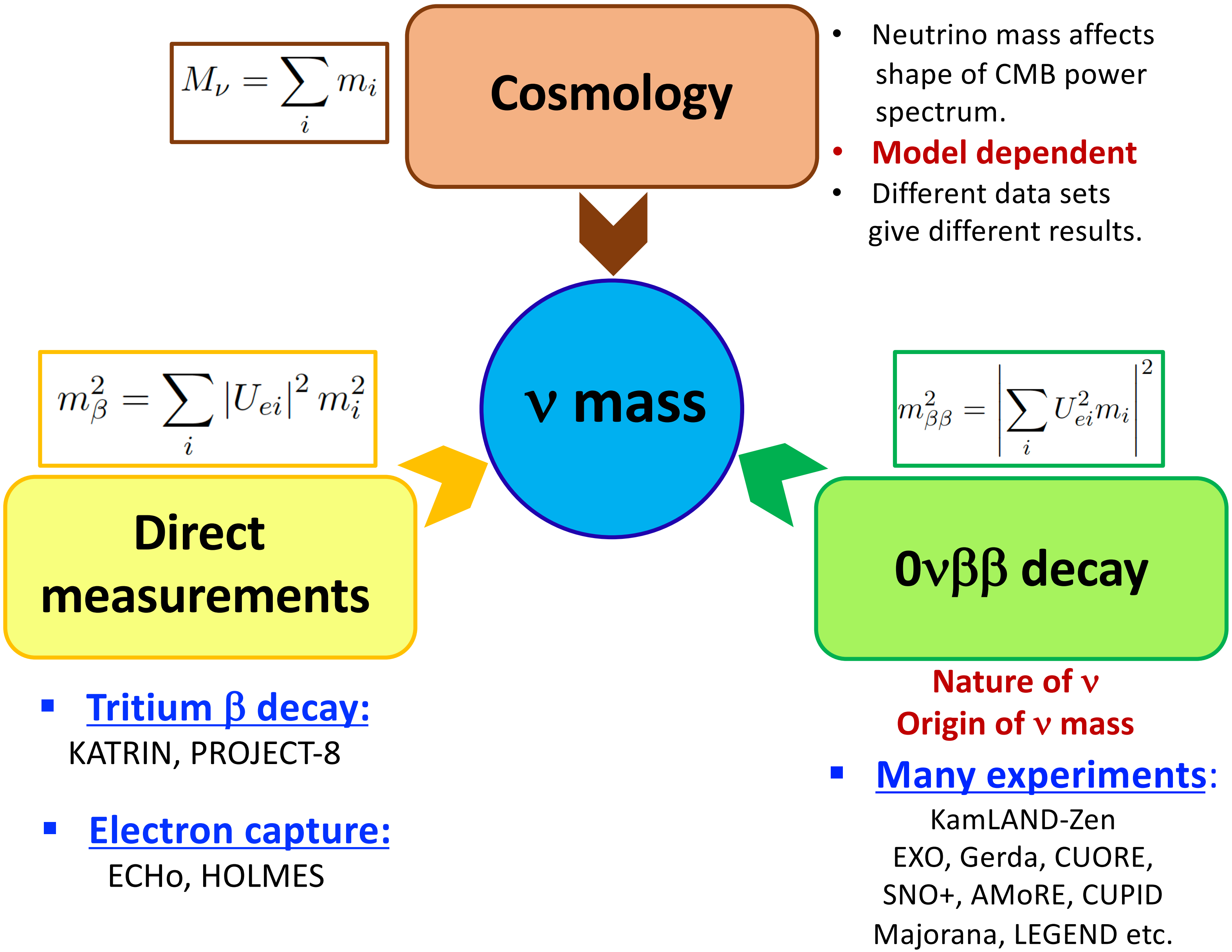
	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+N_{eff}	$2.92^{+0.36}_{-0.37}$	[22]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+N_{eff}	$2.99^{+0.34}_{-0.33}$	[22]
" + BAO + R21	ΛCDM+N_{eff}	3.34 ± 0.14 (68%CL)	[11]
"	" +5-params.	2.85 ± 0.23 (68%CL)	[23]

[11] N. Schöneberg et al. (2021), [arXiv:2107.10291.

[22] N. Aghanim et al. (Planck) (2018), [arXiv:1807.06209].

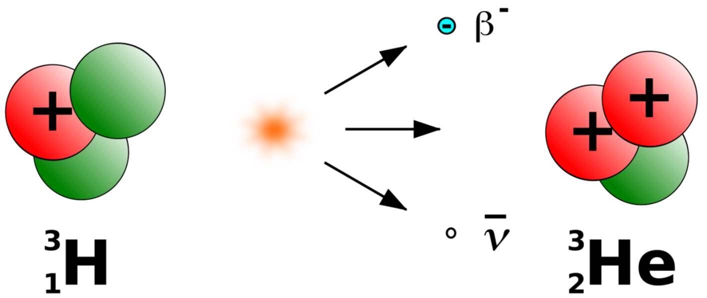
[23] E. Di Valentino, A. Melchiorri and J. Silk, JCAP 01, 013 (2020), [arXiv:1908.01391]

- ❑ Neutrino oscillation: precision, MO, CPV
- ❑ # of neutrinos: sterile ν
- ❑ **Abs. mass of ν: KATRIN, Project-8, etc.**
- ❑ Dirac vs. Majorana: 0νββ
- ❑ Neutrino interaction: CEvNS, ν x-section measurements
- ❑ Astrophysical ν: solar, Supernova, extra galactic ν etc.


$M_\nu = \sum_i m_i$
Cosmology
• Neutrino mass affects shape of CMB power spectrum.
• Model dependent
• Different data sets give different results.
ν mass
$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$
Direct measurements
▪ Tritium β decay:
KATRIN, PROJECT-8
▪ Electron capture:
ECHo, HOLMES
$m_{\beta\beta}^2 = \left|\sum_i U_{ei}^2 m_i\right|^2$
0νββ decay
Nature of ν
Origin of ν mass
▪ Many experiments:
KamLAND-Zen
EXO, Gerda, CUORE,
SNO+, AMoRE, CUPID
Majorana, LEGEND etc.

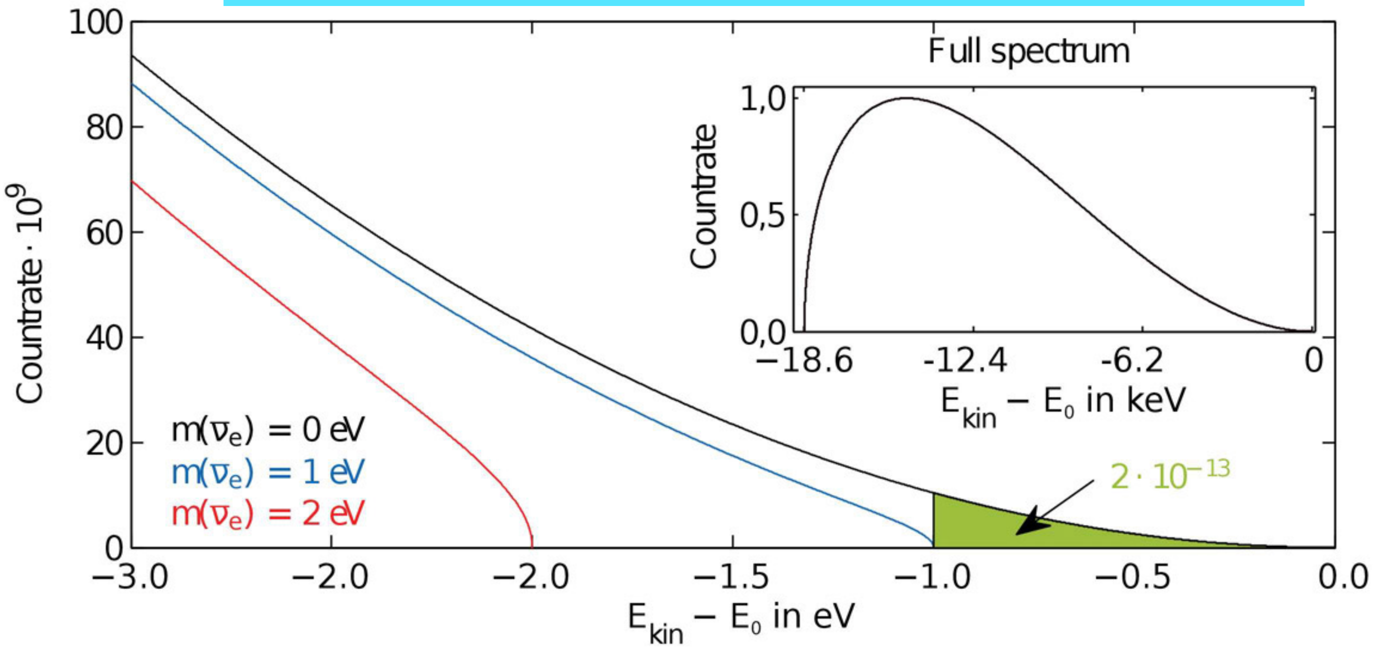
Tritium β Decay

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



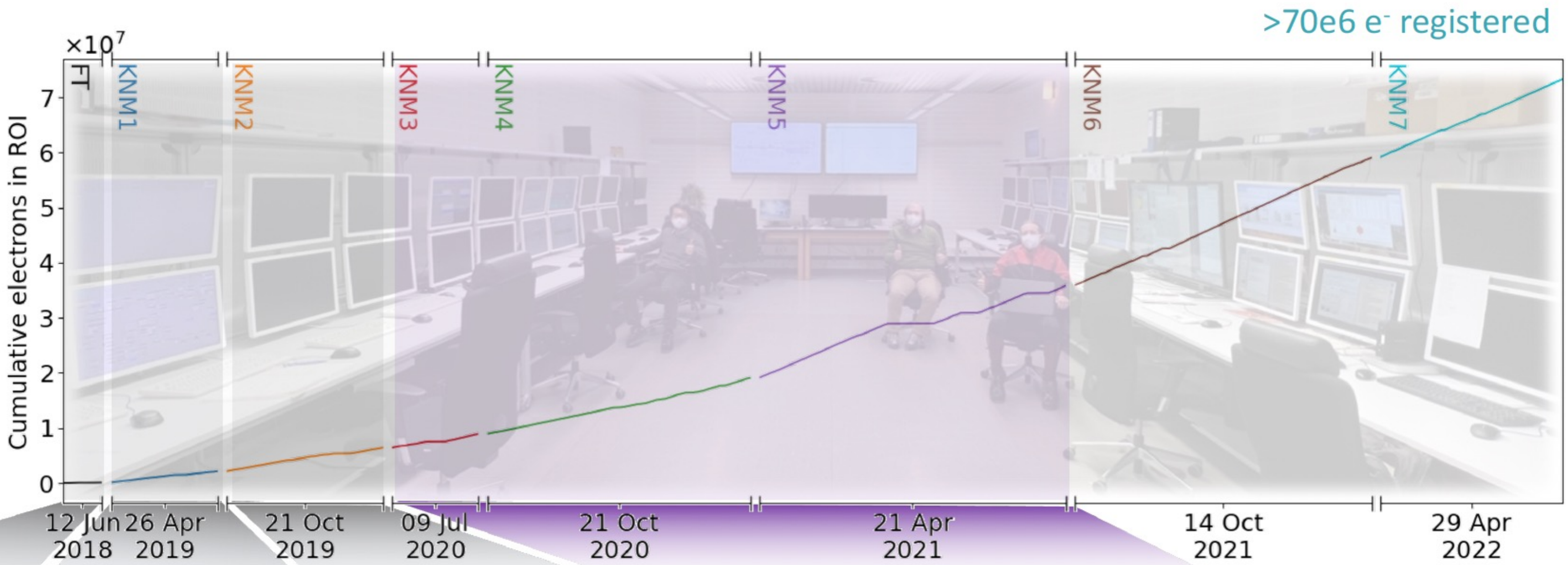
Q-value (E_0): 18.57 keV

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



KATRIN ν Mass Measurement

Thierry Lassere
@Nu2022



- commissioning
- only 0.5% tritium

EPJ C 80, 264 (2020)

- 1^{st} campaign

  2e6 e^- in ROI

- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

PRD. D 104, 012005 (2021)

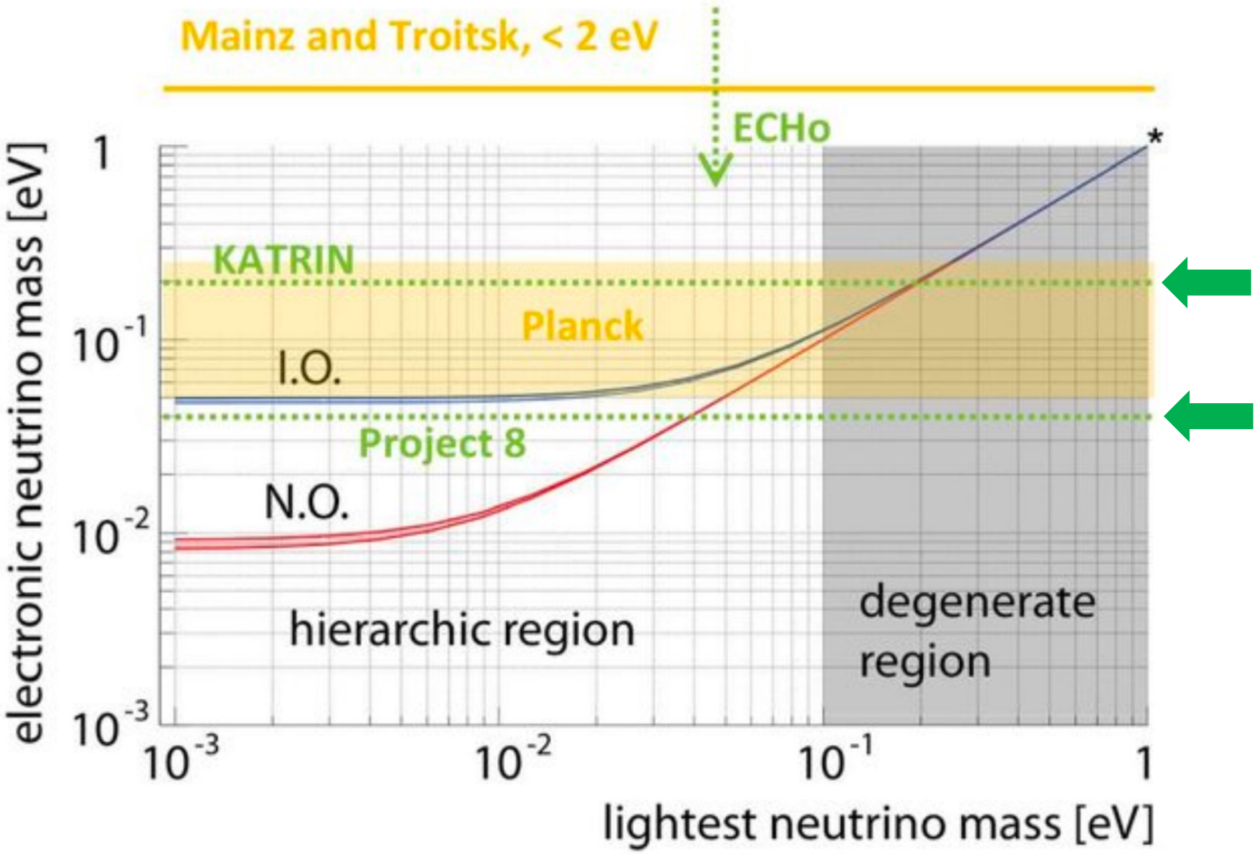
- $1^{st} + 2^{nd}$ campaigns
- 6e6 e^- in ROI
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

- next data unblinding in summer 2022
- 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5^{th} campaigns
- ~30e6 e^- in ROI

@Nu20222

Abs. ν Mass Sensitivity

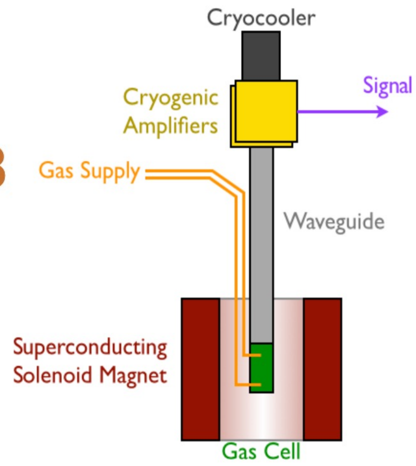


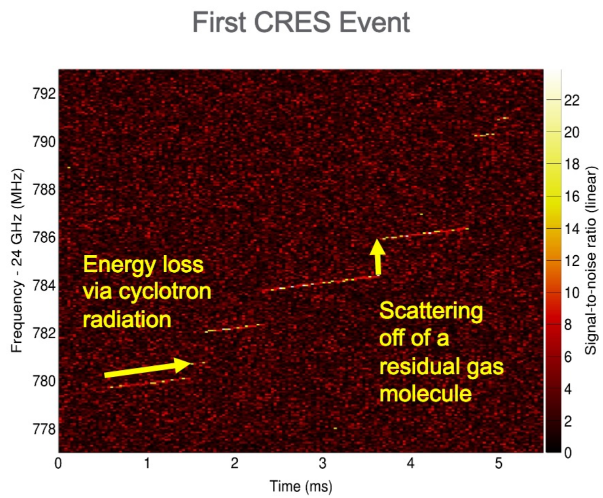
0.2 eV
(KATRIN)

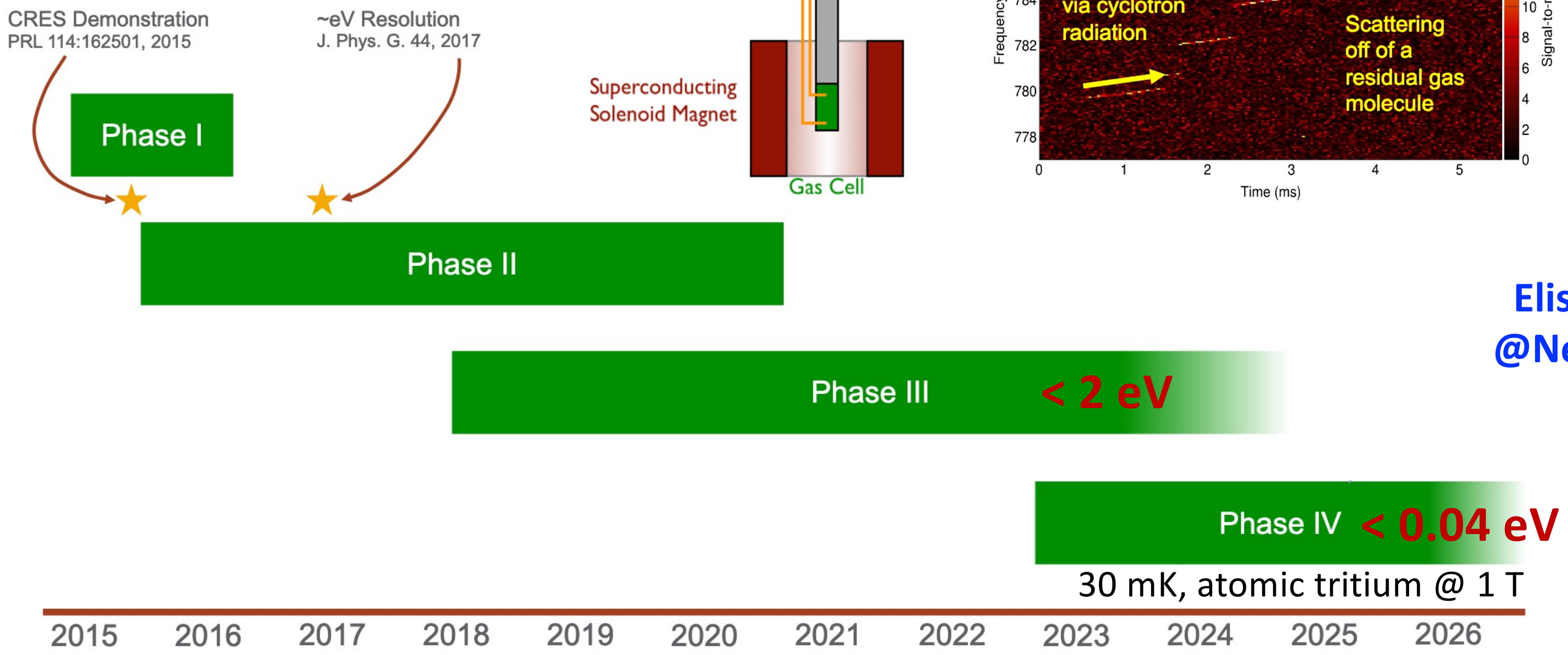
0.04 eV
(Project 8)

Pacific Northwest NATIONAL LABORATORY

The Project 8







Elise Novitski @Neutrino2022

Cyclotron Radiation Emission Spectroscopy (CRES) technique

Cosmological Limits on $M_\nu = \sum_i m_i$

PDG 2021

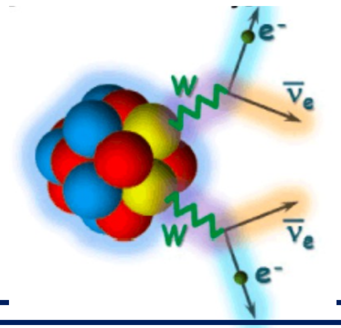
	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[22]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[22]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[43]
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[23]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[22]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[22]
CMB + probes of background evolution + LSS			
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[43]
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[44]
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13	[45]

[22] N. Aghanim et al. (Planck) (2018), [arXiv:1807.06209].
[23] E. Di Valentino, A. Melchiorri and J. Silk, JCAP 01, 013 (2020), [arXiv:1908.01391]
[43] S. Alam et al. (eBOSS), Phys. Rev. D 103, 8, 083533 (2021), [arXiv:2007.08991].
[44] N. Palanque-Delabrouille et al., JCAP 04, 038 (2020), [arXiv:1911.09073].
[45] T. M. C. Abbott et al. (DES) (2021), [arXiv:2105.13549

Dirac vs Majorana ν

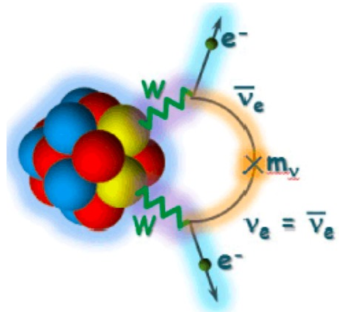
2νββ (1935)

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



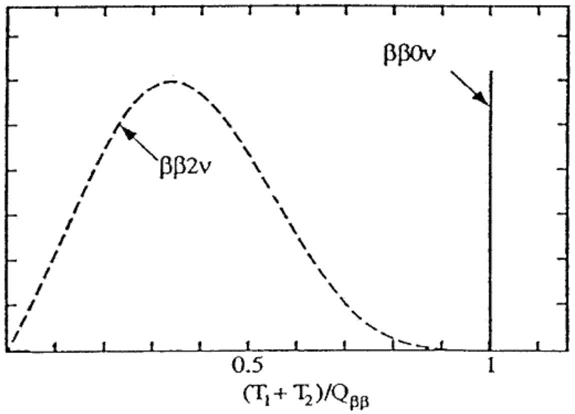
0νββ (1937/39)

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



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

$T_{1/2} = 10^{18} \sim 2\text{x}10^{21}$ yr



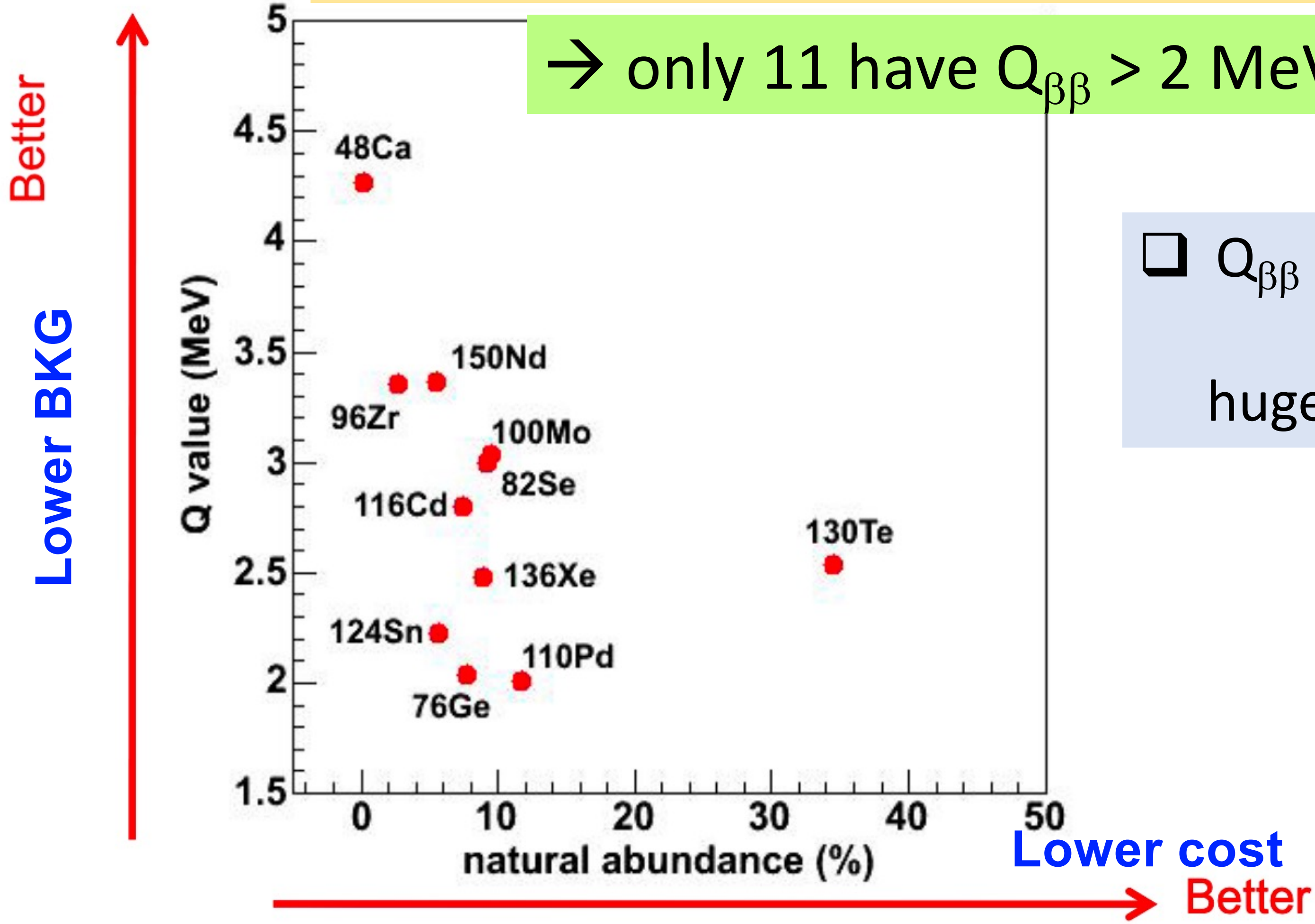
$$Q_{\beta\beta} \equiv M(A,Z) - M(A,Z+2)$$

0νββ → Majorana ν, LNV, absolute ν mass ($m_{\beta\beta}$)

ββ Emission Isotopes

- Total 33 ββ emission isotopes

→ only 11 have $Q_{\beta\beta}$ > 2 MeV



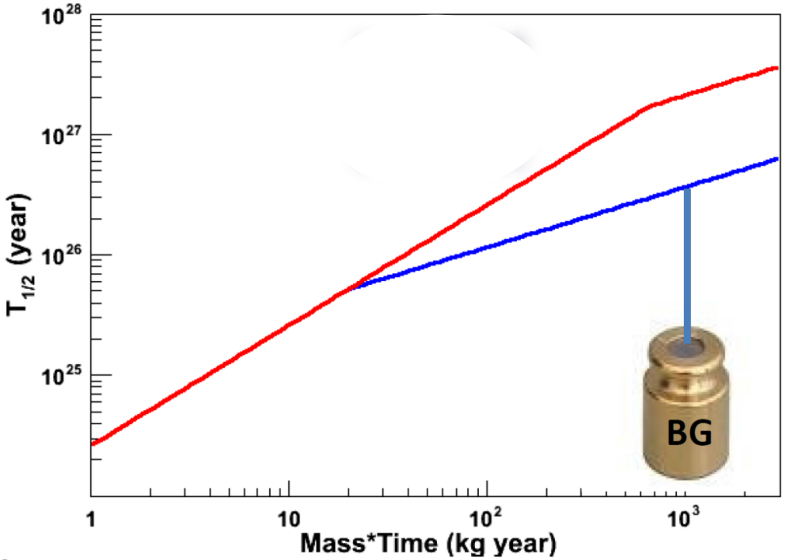
- $Q_{\beta\beta}$ > 3 MeV is better to avoid huge natural radio bkg.

Experimental Sensitivity of $T_{1/2}$ ($0\nu\beta\beta$)

❑ Sizeable background case:

$$T^{0\nu}_{1/2}(\exp) \sim a\varepsilon\sqrt{\frac{MT}{b\Delta E}}$$

- Isotopic Abundance → a
- Detection Efficiency → ε
- Detector Mass → M
- Time → T
- Background level (count/keV kg year) → b
- Energy Resolution → ΔE



❑ "zero background" case:

$$T^{0\nu}_{1/2}(\exp) \sim a\varepsilon\frac{MT}{n_{CL}}$$

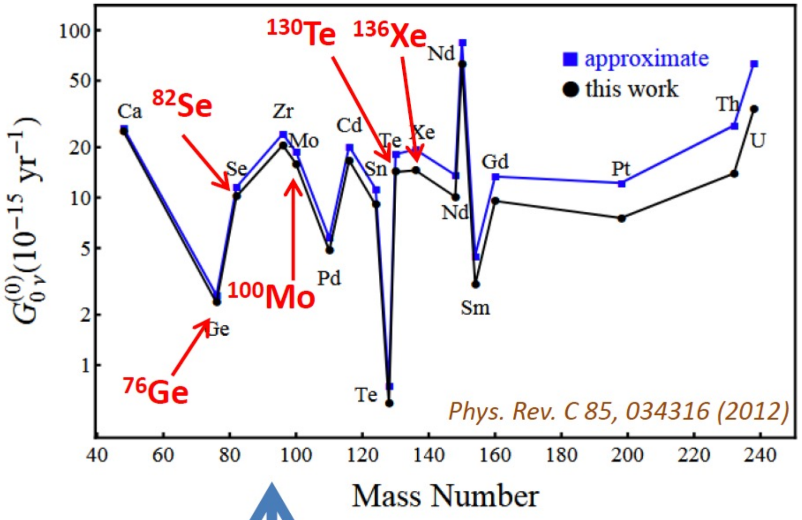
- $T_{1/2}$ (U, Th): ~10^{10} yrs
- $T_{1/2}$ ($2\nu\beta\beta$): 10^{18}~10^{21} yrs
- $T_{1/2}$ ($0\nu\beta\beta$): > 10^{24}, 10^{26} yrs

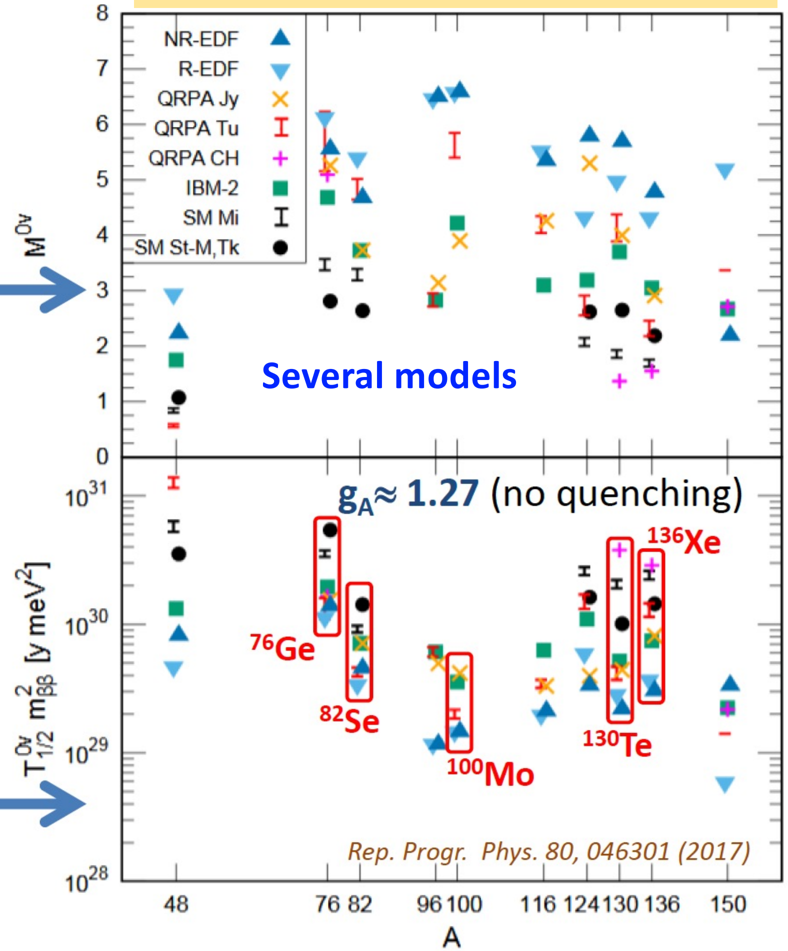
➢ Good energy resolution (< 3~5% FWHM), no/low BKG, high efficiency, etc will improve sensitivity of $0\nu\beta\beta$ search.

0νββ Challenge

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

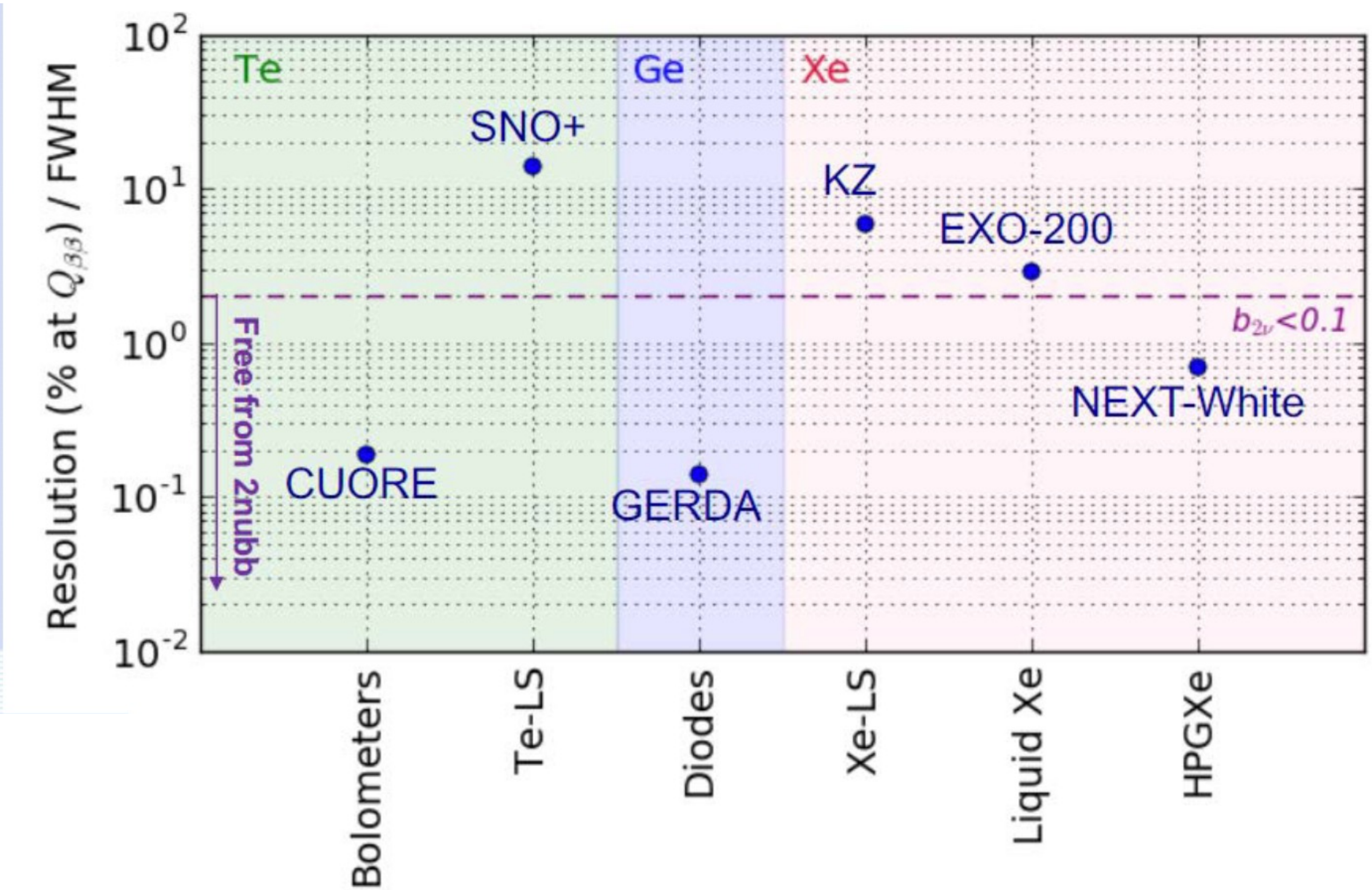
M: nuclear matrix element
Big uncertainty





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

Energy Resolution of 100-kg class 0νββ Experiments



Fedor Simkovic
@Nu2022

- Resolution better than 2% FWHM to fully reject 2νββ mode
- Solar ν is not an issue for 100 kg-class 0νββ experiments

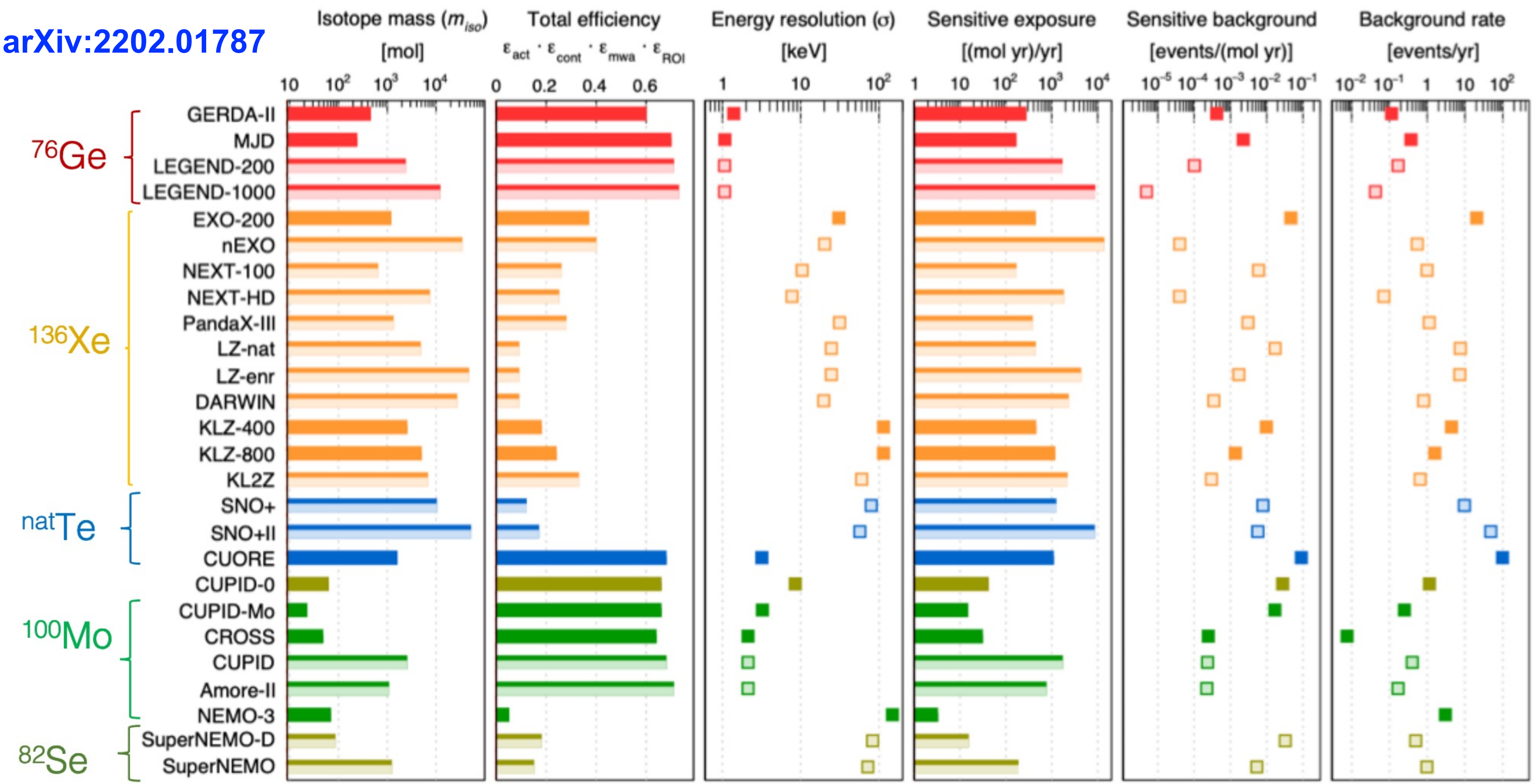
Current 0νββ Limits at 90% C.L.

Fedor Simkovic
@Nu2022

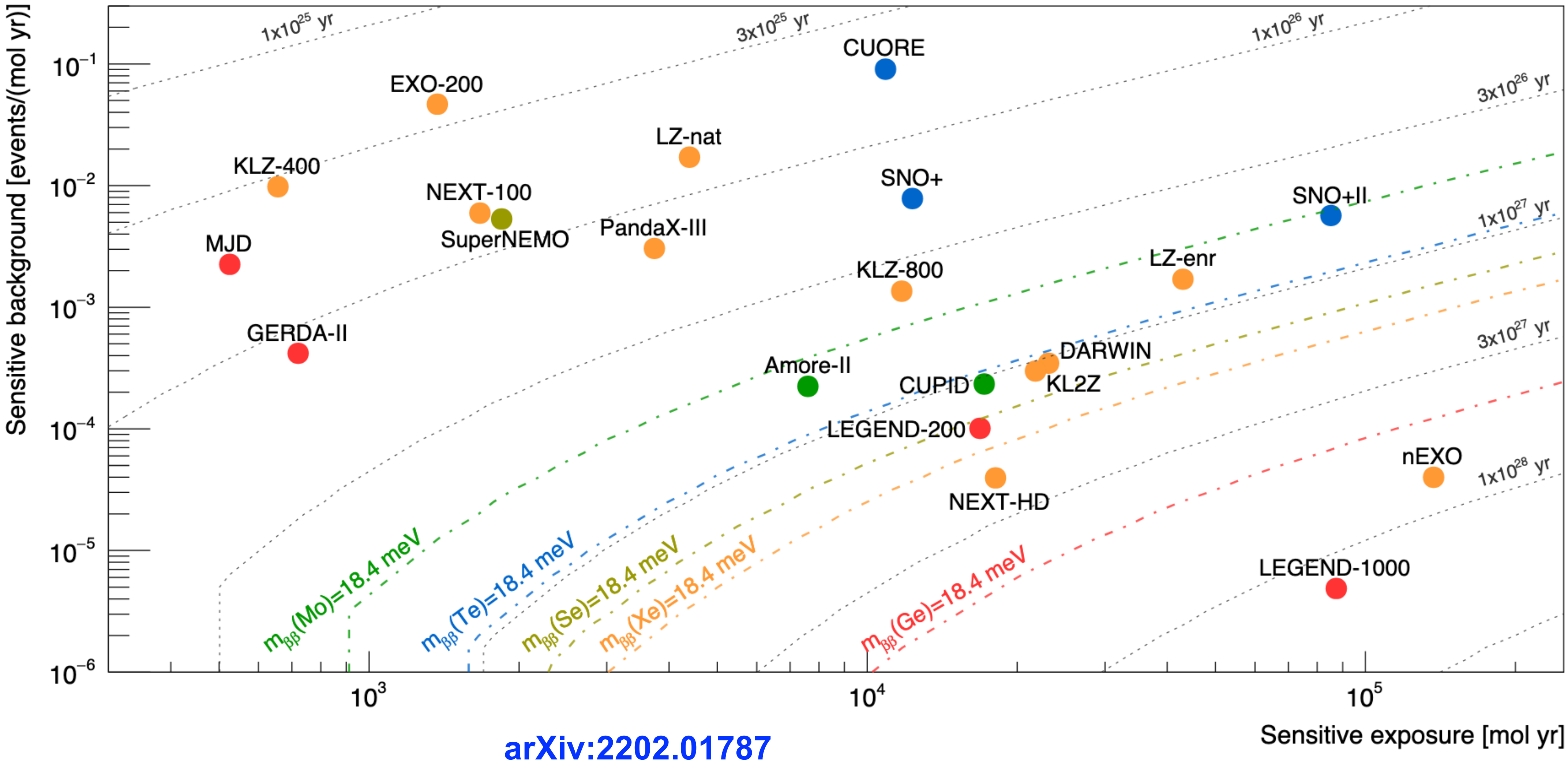
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

Isotope masses, efficiencies, sensitive background & exposure and backgrounds

arXiv:2202.01787



Sensitive background and exposure for recent & future Exp.

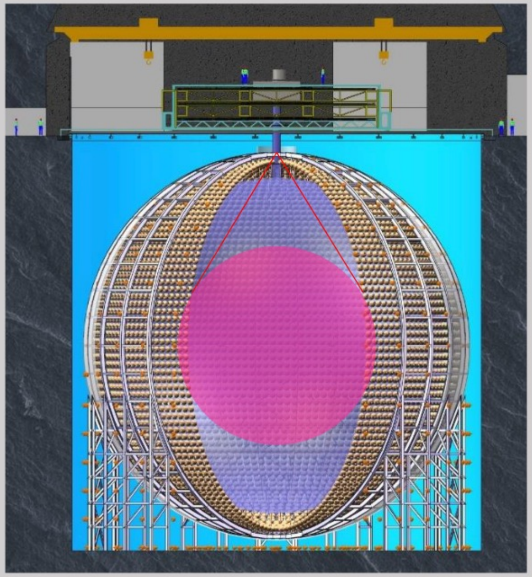


arXiv:2202.01787

Future prospect of JUNO

After the completion of the primary physics goals, JUNO can be upgraded by loading 0νββ isotope into LS, for searching for 0νββ (~2030)

The most sensitive to probe the Majorana nature of neutrinos, aiming at a sensitivity level of $|m_{\beta\beta}|$~ meV



Zhao et al., CPC 41 (2017) 053001

~10^2 tons of 0νββ target;

best LS shielding;

excellent energy resolution (3%/√E);

ultra-low background

	Isotope	mass (ton)	$<m_{\beta\beta}>$, meV
KamLAND-Zen	^{136}Xe	1	61-165
EXO	^{136}Xe	0.2	93-286
nEXO	^{136}Xe	5	7-22
GERDA	^{76}Ge	1	10-40
Majorana	^{76}Ge	1	10-40
SNO+	^{130}Te	8	19-46
JUNO-ββ	^{136}Xe	50	4-12
	^{130}Te	100-200	2-6 ?

Liangian Wen @WIN 2021

- Neutrino oscillation: precision, MO, CPV
- # of neutrinos: sterile ν
- Abs. mass of ν: KATRIN, Ptolemy, etc.
- Dirac vs. Majorana: 0νββ
- **Neutrino interaction: CEvNS, ν x-section measurements**
- Astrophysical ν: solar, Supernova, extra galactic ν etc.

Coherent Elastic ν-Nucleus Scattering

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi} Q_W^2 \left(1 - \frac{MT}{E_\nu^2} + \left(1 - \frac{T}{E_\nu}\right)^2\right)$$

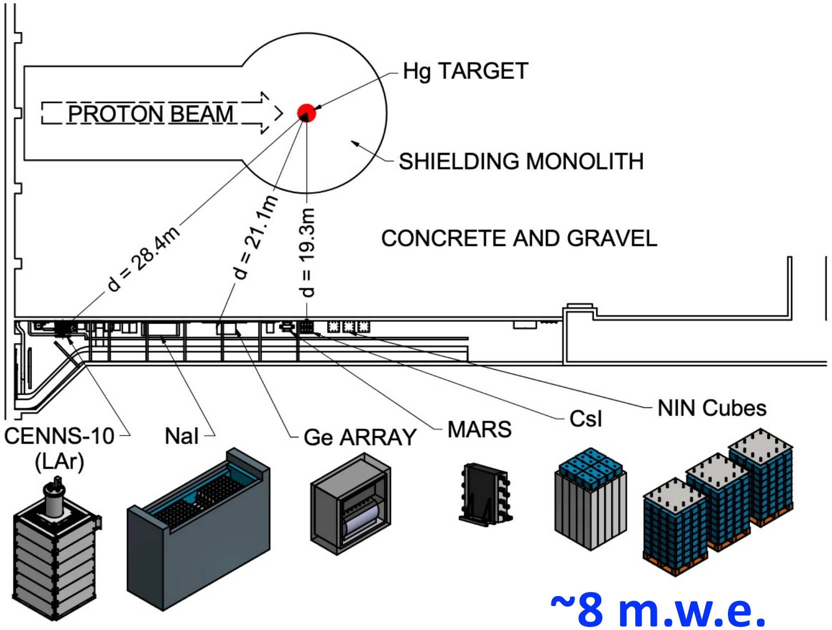
$$Q_W = (1 - 4\sin^2\theta_W) Z F_Z(Q^2) - N F_N(Q^2)$$

Predicted in 1974 (Freedman)

$$\frac{d\sigma}{dT} \propto N^2$$

Coherent up to ~ 50 MeV

COHERENT @ Oak Ridge SNS



~8 m.w.e.

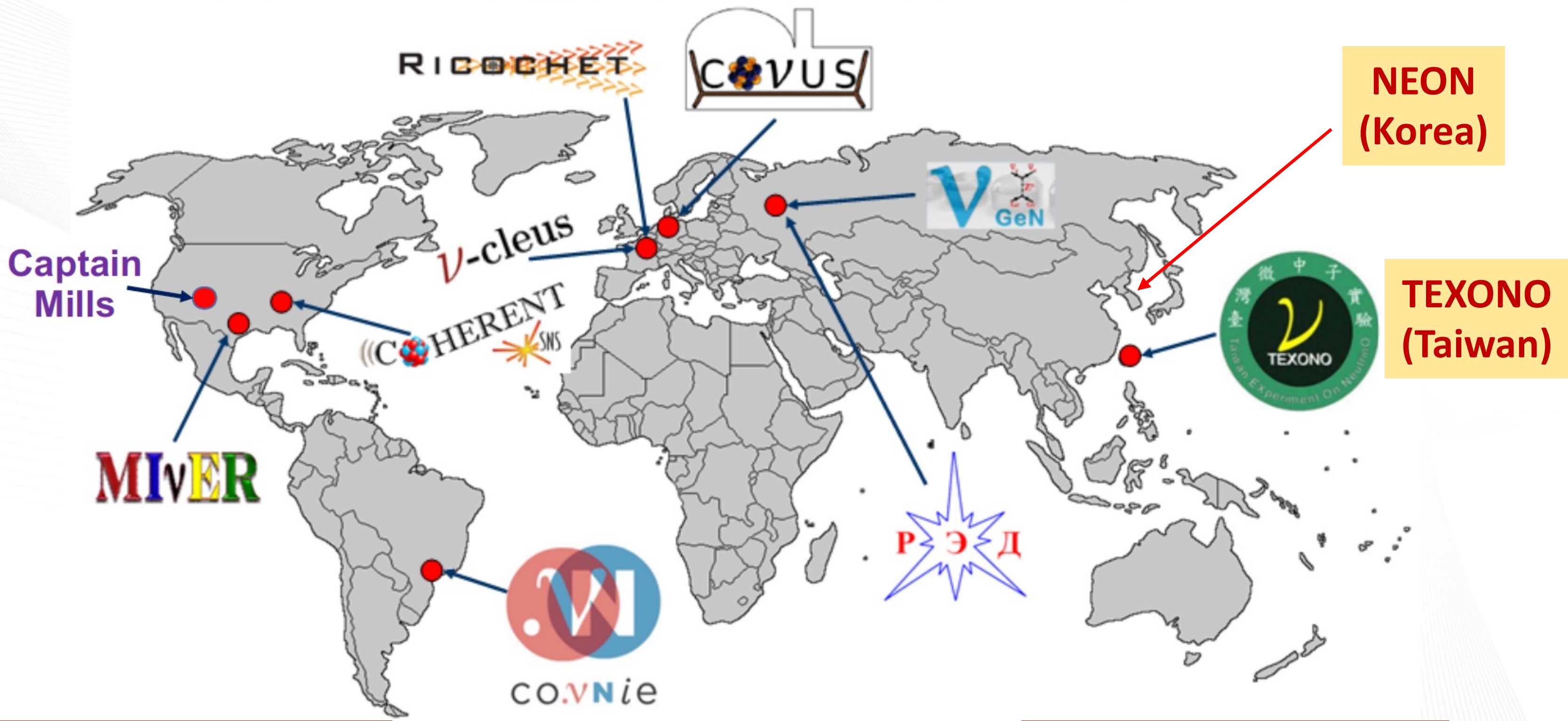
Far away from neutron beam lines.

- ✓ 2017: > 6 σ (CsI) discovery
- ✓ 2019: 4.9 σ (LAr)
- ✓ 2020: > 11 σ (CsI) w/ > x2 stat.

$$169^{+30}_{-26} \times 10^{-40}\ \mathrm{cm}^2$$

14.6 kg CsI crystal

World Wide Efforts to Detect CEvNS



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

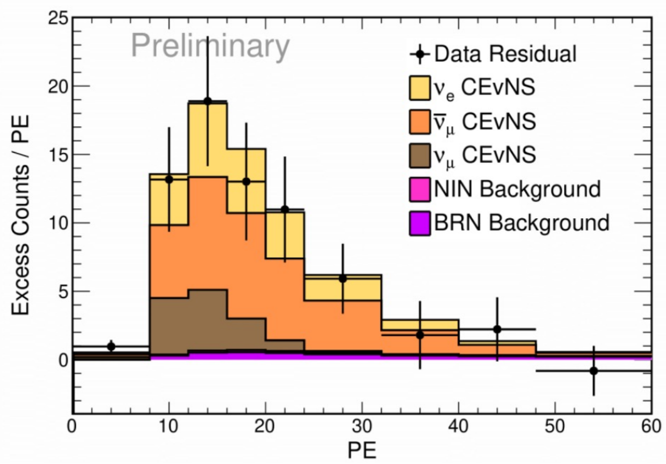
Nuclear reactors give large flux, but low energy neutrinos with a constant flux

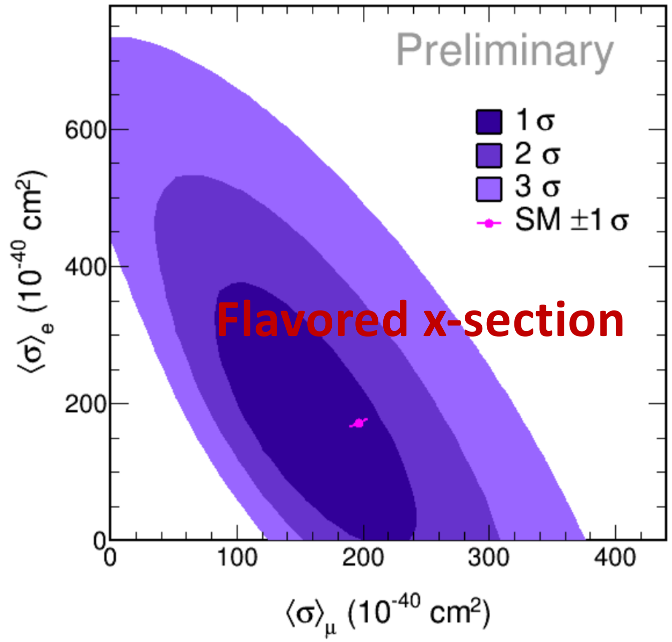
Various detector technologies are being investigated. We heard first indication of positive signal from the Conus experiment last year

Efremenko
@IAEA 2019

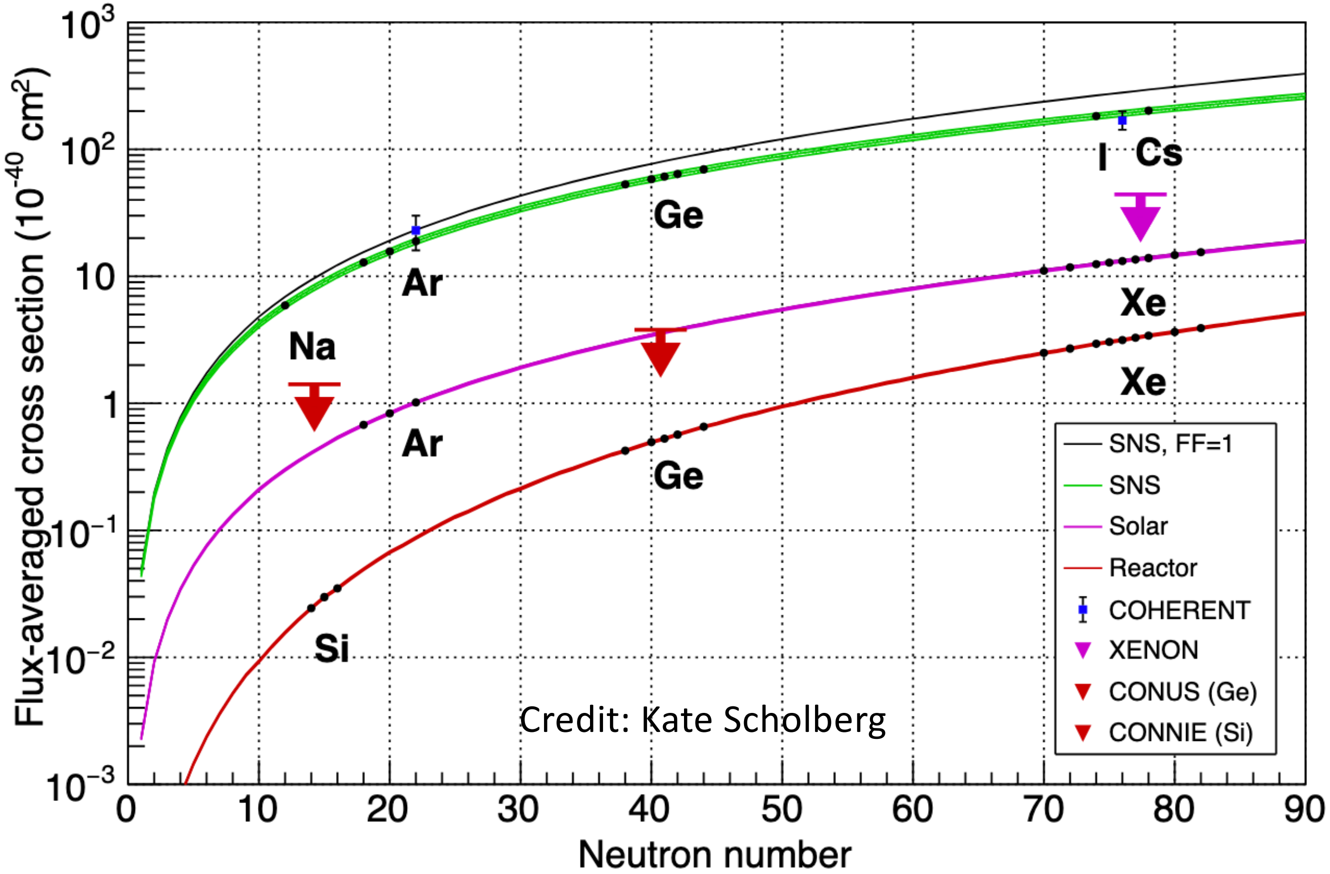
OAK RIDGE National Laboratory

CEvNS Detections and Future Prospects



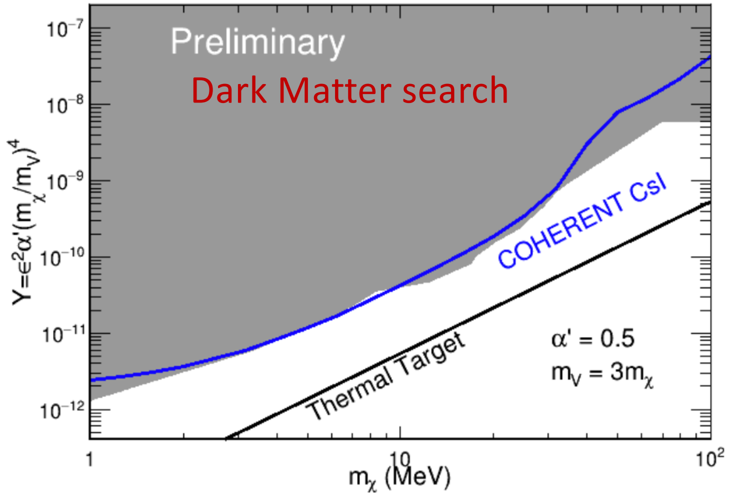


→ CsI data in 2020

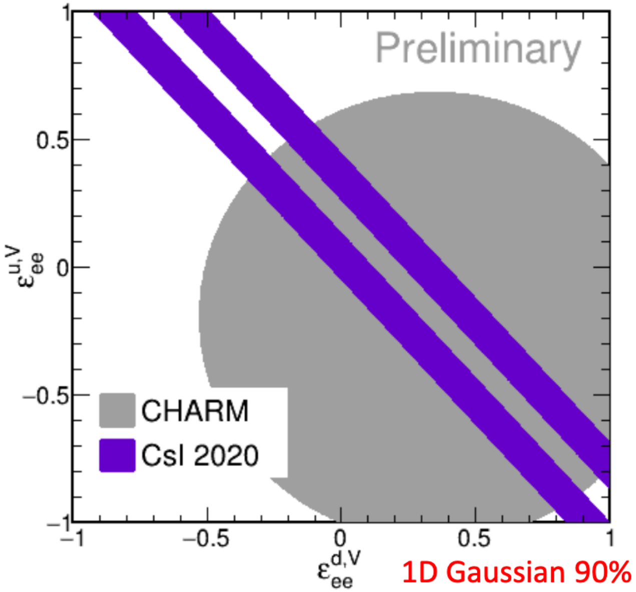


Physics with CEvNS

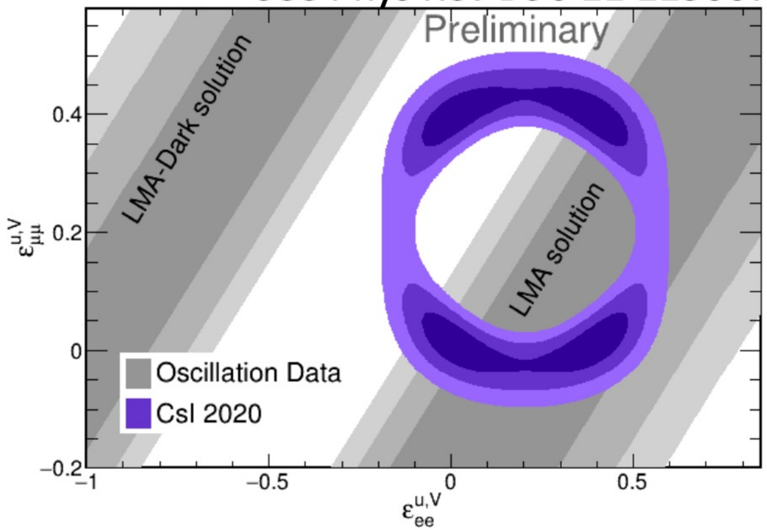
- Weak mixing angle (θ_W)
  → probe dark Z at low q^2
- Sterile neutrino search
- Neutrino magnetic moment
- NSI, DM, etc.



See Phys Rev D96 11 115007



1D Gaussian 90% critical up-values



CEvNS Prospects

- COHERENT is comissioning two detectors in 2021.
  → 16 kg **<u>Ge</u>** PPC, ton-scale **<u>NaI</u>** scintillator crystal

- The **<u>2nd target station</u>** is planned at SNS at Oak Ridge.
  → Very large detectors, new detector ideas could be realized.

- Many CEvNS experiments at reactor sites are expected
  to obtain new results in the near future.

- CEvNS: good test ground for BSM physics.

- “Magnificent CEvNS” workshop is held yearly basis.

ν X-section Measurements

Laura Fields
@Nu2022

NOvA

193 tons
PVC cells + **liquid scintillator**
$\bar{E}_\nu$ ~ **1.8 GeV**

T2K

On Axis
0.6 tons **H_2O**
0.3 ton plastic **scintillator**
100 ton **Fe**
$\bar{E}_\nu$ ~ **0.86 GeV**

Off Axis
1.5 tons **Plastic Scintillator**
0.5 tons **Water**
3 tons **Water** (PØD)
$\bar{E}_\nu$ ~ **0.6 GeV**

μBooNE

85 tons **Argon**
$\bar{E}_\nu$ ~ **0.8 GeV (BnB)**
$\bar{E}_\nu$ ~ **0.9 GeV (NuMI)**

MINERvA

0.2 tons **Carbon**
0.6 tons **Iron**
0.7 tons **Lead**
0.4 tons **Water**
0.2 tons Helium
5.5 tons **Plastic Scintillator**

E ~ 3 GeV (Low Energy)
E ~ 6 GeV (Med Energy)

WHAT'S NEXT

Laura Fields @Nu2022

NOvA

- Neutrino-electron scattering will **reduce flux uncertainties**
- **Testbeam measurements** will reduce detector systematics
- **Big focus on ratios** (e.g. $\nu/\bar{\nu}_\mu$, ν_e/ν_μ)
- Improved reconstruction -> **exclusive measurements**

T2K

- New **Wagasci/Babymind** detectors
- **ND280 upgrade** will bring larger angular acceptance, lower tracking threshold, neutron sensitivity
- Improved **statistics**

μBooNE

- **Multi-differential** cross sections
- Doubled **statistics**, better **reconstruction**
- **Special variables** (e.g. TKI)

MINERvA

- Completed data taking in 2019, but **30+ active analyses ongoing**
- **A-dependence** of 0-pi, 1-pi
- **Deep and shallow inelastic** scattering
- Data preservation project

- ❑ Neutrino oscillation: precision, MO, CPV
- ❑ # of neutrinos: sterile ν
- ❑ Abs. mass of ν: KATRIN, Ptolemy, etc.
- ❑ Dirac vs. Majorana: 0νββ
- ❑ Neutrino interaction: CEvNS, ν x-section measurements
- ❑ **Astrophysical ν: solar, Supernova, extra galactic ν etc.**

Borexino

- Operation: **2007 – 2021** @LNGS
- 300 ton LS (~2200 PMTs, ~6% @1MeV)
- Very low radioactive BKG

Isotope	2007-2010	2012-2020
^{238}U	$1.6 \pm 0.1 \quad 10^{-17}$ g/g	$< 9.4\ 10^{-20}$ g/g
^{232}Th	$5.1 \pm 1 \quad 10^{-18}$ g/g	$< 5.7\ 10^{-19}$ g/g
^{85}Kr	~ 30 cpd/100 t	~ 5 cpd/100 t
^{210}Bi	~ 40 cpd/100 t	~ 10 cpd/100 t

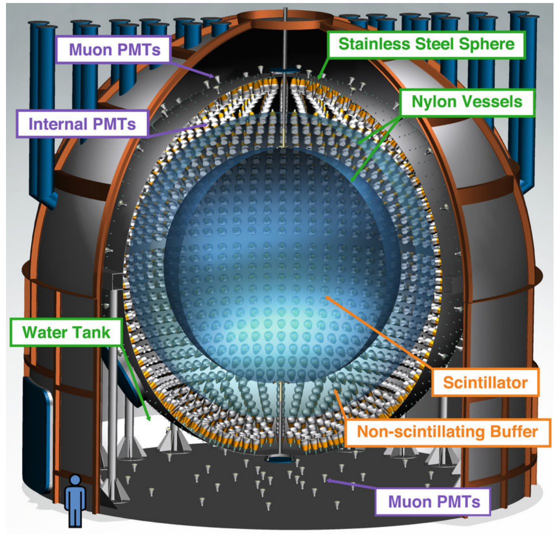
Data taking:

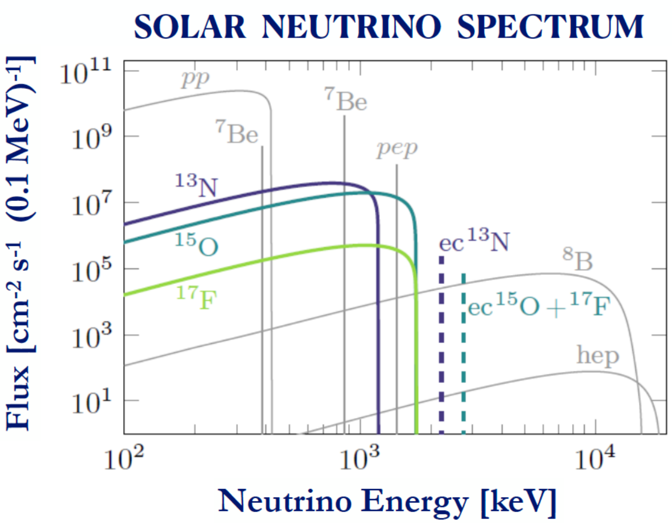
I : 2007 ~ 2010

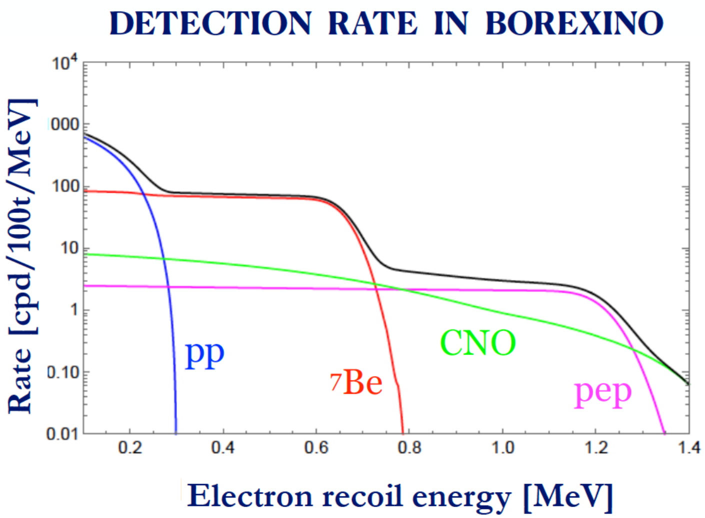
II : 2012 ~ 2015

III: 2017 ~ 2021

Oct. 2021: end of data taking

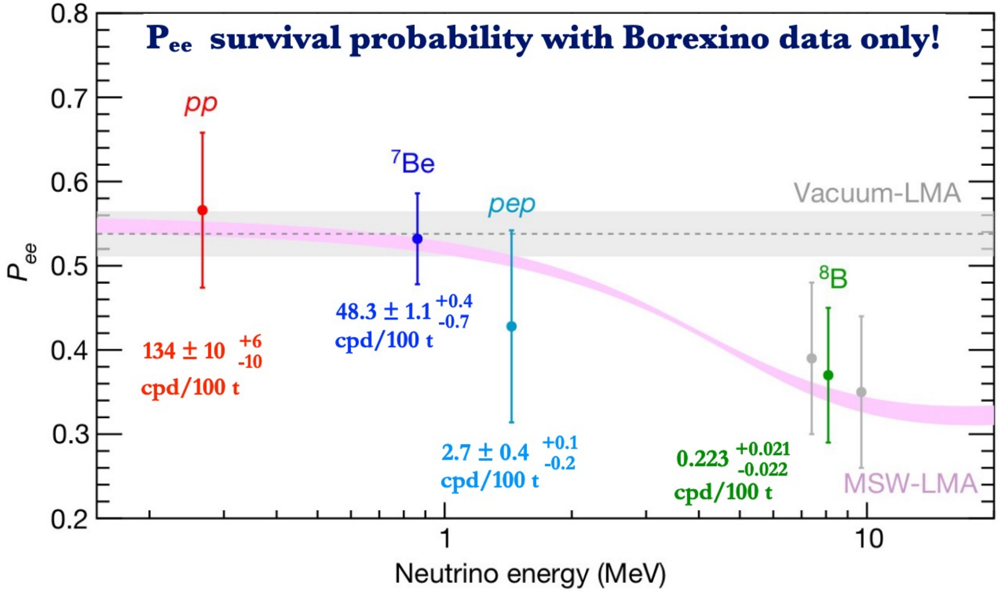






** Notable achievements of Borexino

Source	Count Rate [cpd/100t/d]	Comments on detection	First detection in BX
^{7}Be	~ 48	Clear signature on the shoulder	2007
^{8}B	< 1	Small, but high energy, low background	2010
pep	~ 3	Weak signature on top of ^{11}C	2012
pp	~ 140	Low energy, partially covered by ^{14}C	2014
CNO	~ 5	Small signal, migrating background (see talk)	2020
hep	Not measurable today	Signal too low, mostly covered by ^{8}B	never



Comprehensive chain:
Nature 562 (2018) 7728, 505.
Phys. Rev. D (2019)

pp:
Nature 512 (2014) 7515, 383.

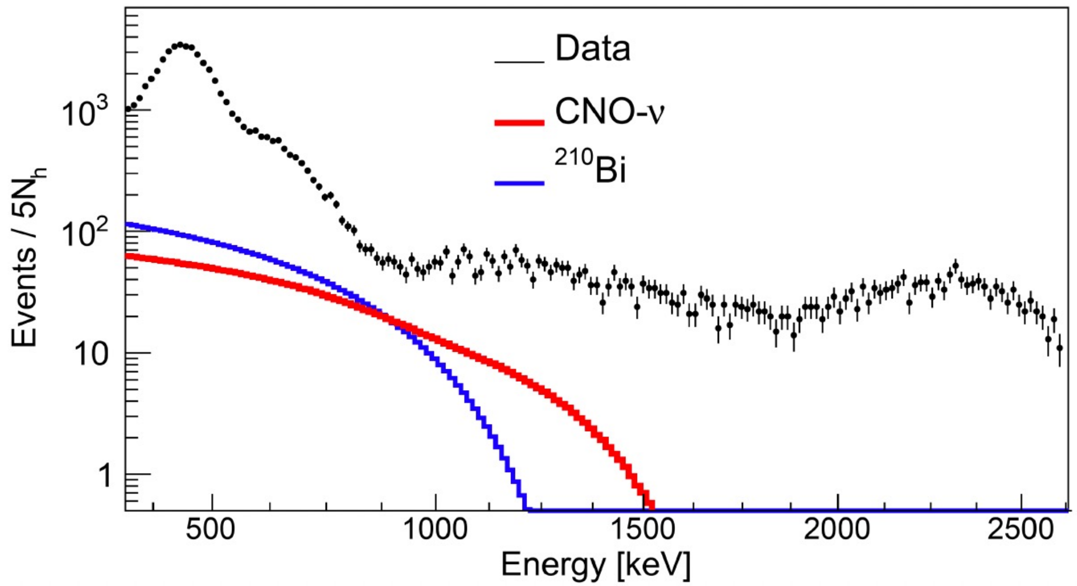
^{7}Be:
Phys. Lett. B658 (2008) 101
PRL 107 (2011) 141302

pep:
PRL 108 (2012) 051302

^{8}B:
Phys. Rev. D82 (2010) 033006

Borexino CNO ν Measurement

Final Phase-III dataset: Jan 2017-Sep 2021; N_{ev}= 110000



Barbara Caccianiga @Nu2022

CNO neutrinos: tagging ^{210}Bi with ^{210}Po

$^{210}Pb \rightarrow {}^{210}Bi + \beta^-$ (τ=33y)

$^{210}Bi \rightarrow {}^{210}Po + \beta^-$ (τ=7d)

$^{210}Po \rightarrow {}^{206}Pb + \alpha$ (τ=200d)

At secular equilibrium,

rate(^{210}Po) = rate(^{210}Bi);

Borexino CNO Update in 2022

Barbara Caccianiga @Nu2022

Results (including sys errors)

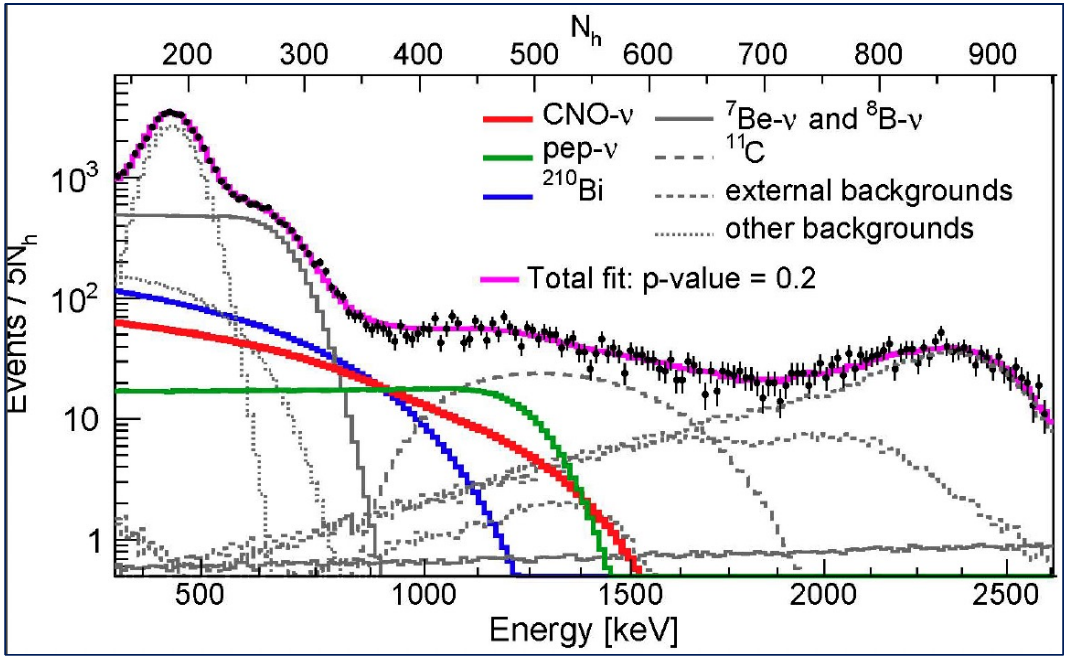
Rate(CNO)= $6.7^{+2.0}_{-0.8}$ cpd/100t

ϕ(CNO)= $6.6^{+2.0}_{-0.9} \times 10^{8}\ \nu\ cm^{-2}\ s^{-1}$

- Improved MC
- Increased exposure by ~33%
- Cleaner data set
- More stable temperature

→ More stringent limit on ^{210}Bi

R (^{210}Bi) < 10.8+/- 1.0 counts/day/100t

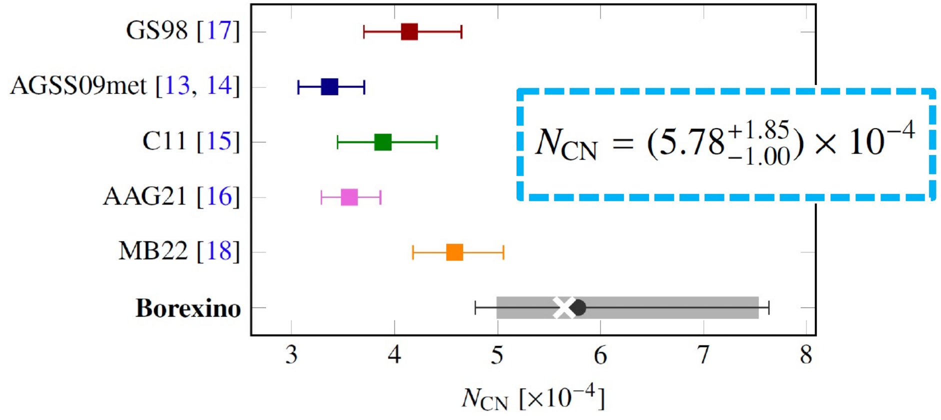


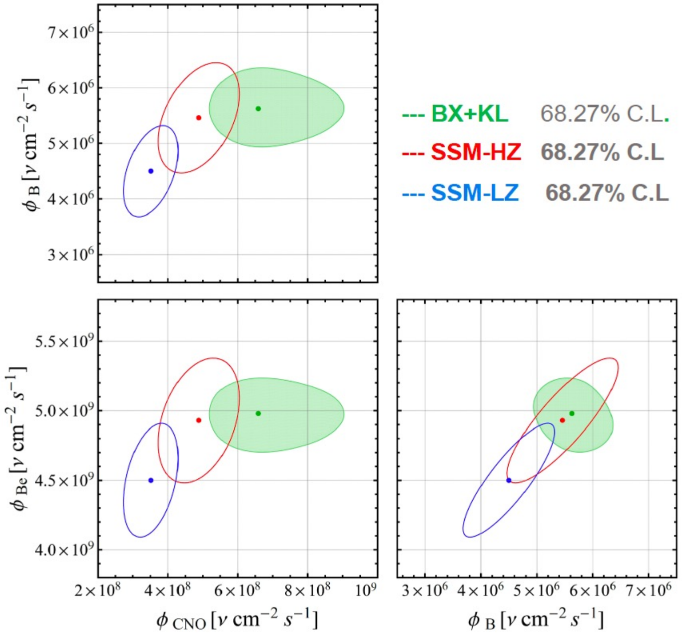
→ CNO-null hypothesis is excluded at ~ 7σ.

Borexino New Results

Barbara Caccianiga
@Nu2022

- CNO-null hypothesis excluded at ~ 7σ
- First measurement of N_{NC} in the Sun with solar neutrinos
- N_{NC} in good agreement with HZ photospheric measurements; ~2σ tension with the LZ photospheric measurements;
- CNO+7Be+8B neutrino flux results from BX disfavor SSM-LZ at 3.1σ (when compared to HZ-SSM)





LSC @Yemilab, Korea

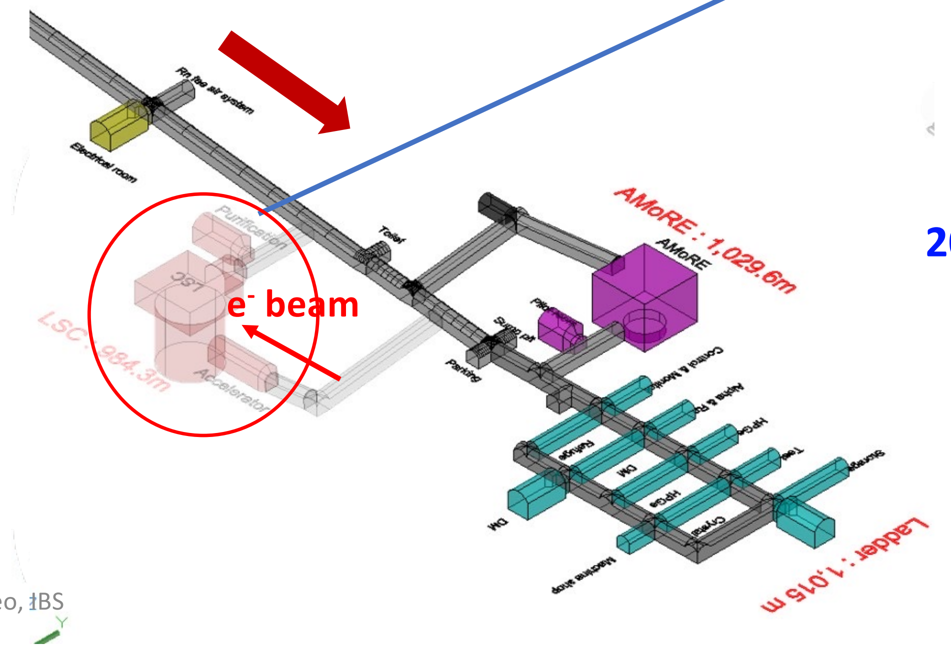
Yemilab: new underground lab in Korea (1 km overburden)

LSC = Liquid Scintillation Counter

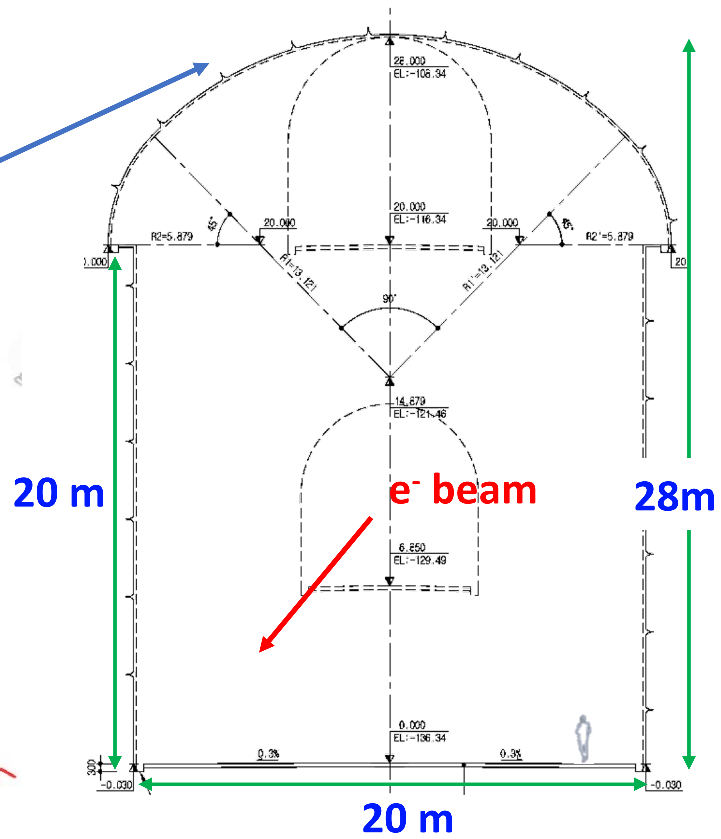
LSC Pit: 20 m (D) x 20 m (H)

LSC Hall construction: June – Nov. 2021

Tunnel entrance

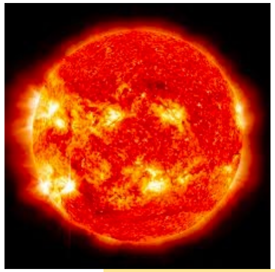


LSC Hall



Broad Physics Program @Yemilab

Solar ν



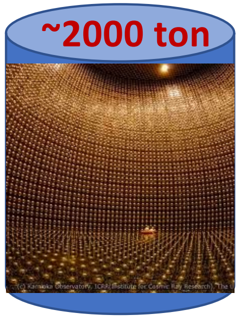
Supernova ν

S.H. Seo & Y.D. Kim
JHEP04(2021)135

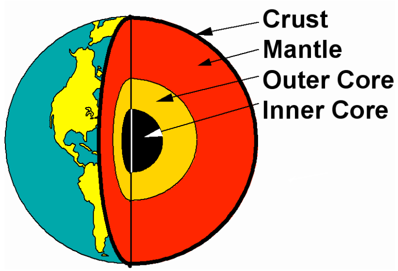
ν Telescope

e- beam

Dark Photon

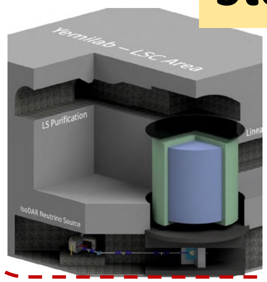


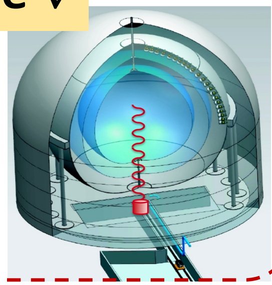
Geo ν



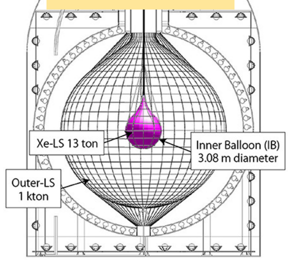
New step to Geo Science

Sterile ν



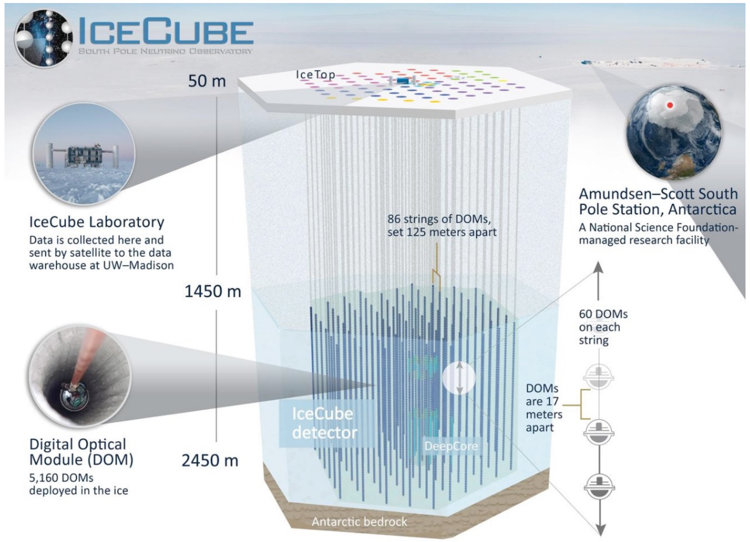


0νββ ?



IceCube

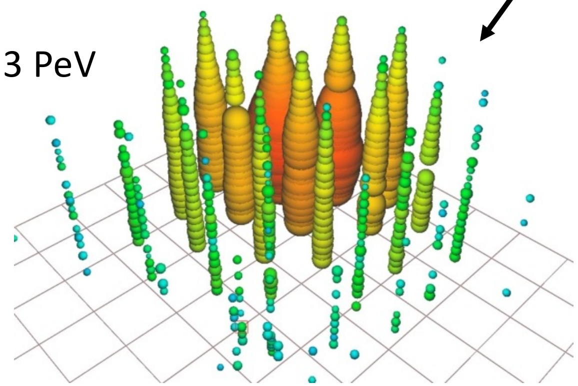
- Operation: **2005** – present @S. Pole
- 86 strings (60 DOMs/string) in 1km^3 → completion: **2011**

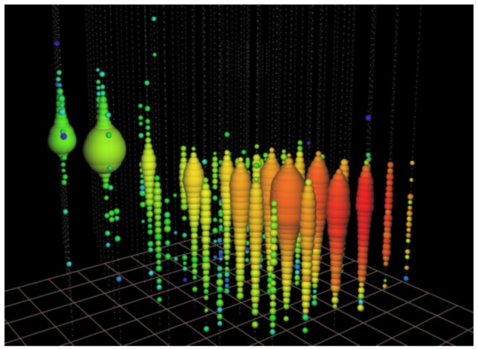


=== Notable achievements ===

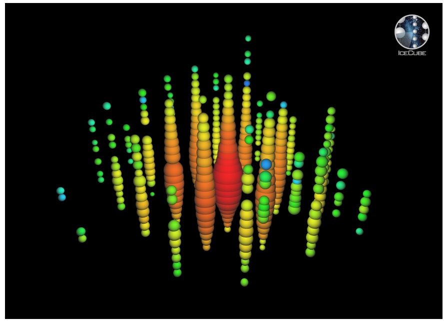
- Discovery of astrophysical ν events in **2013**
  → more events w/o source identification
- Identification of astrophysical ν source in **2018**
  Blazar TXS 0506+056: IC-170922A ν
  → open up multi-messenger astronomy
- <u>**Glashow resonance** event</u> at 6.3 PeV in 2016 data

6.3 PeV





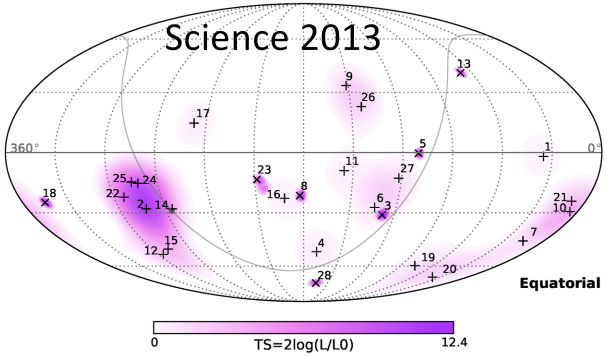
E_{vis}: 2.6 PeV (ν_μ: > 10 PeV, ν_τ: ~100 PeV)



E_ν: 1.14 PeV

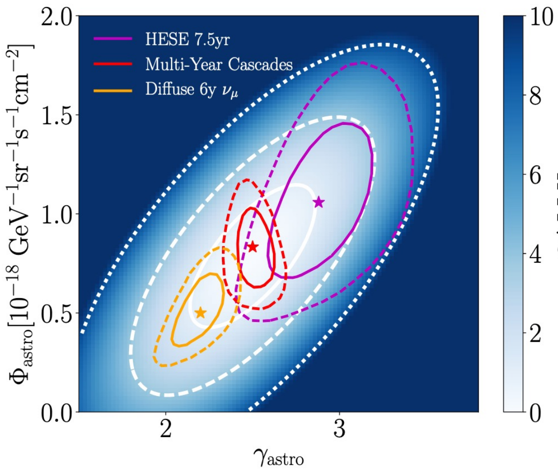
IceCube

Science 2013

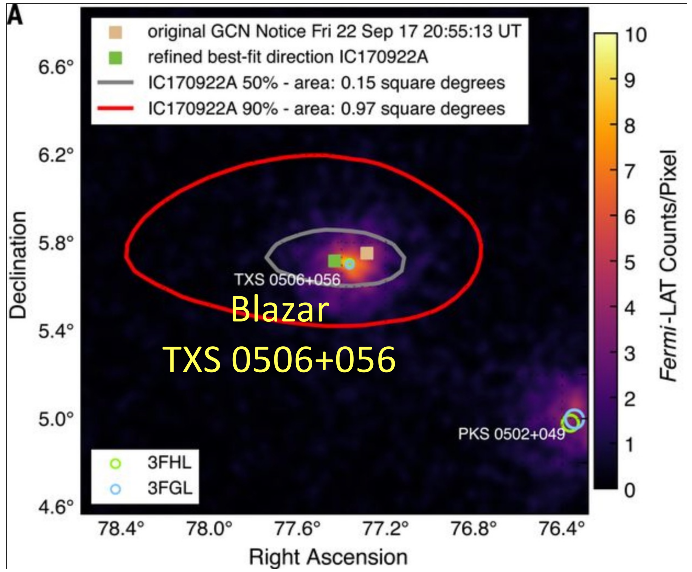


2005.12943

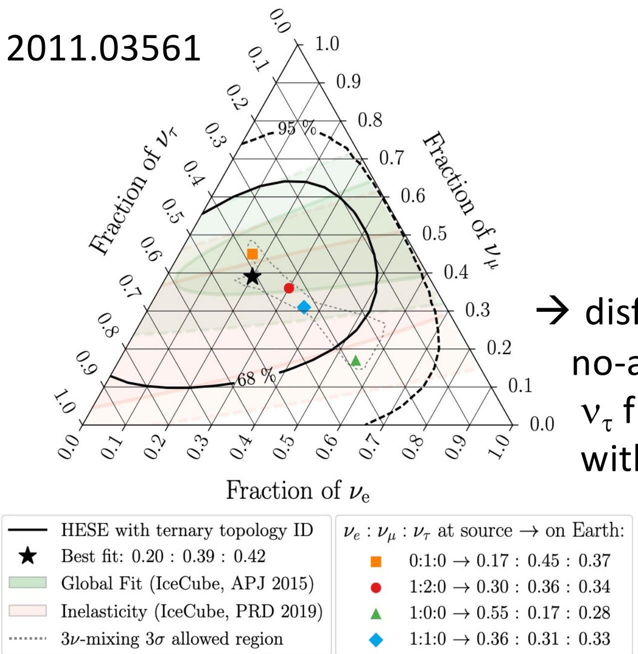
Phys. Rev. D 102, 052009 (2020)



Science 2018

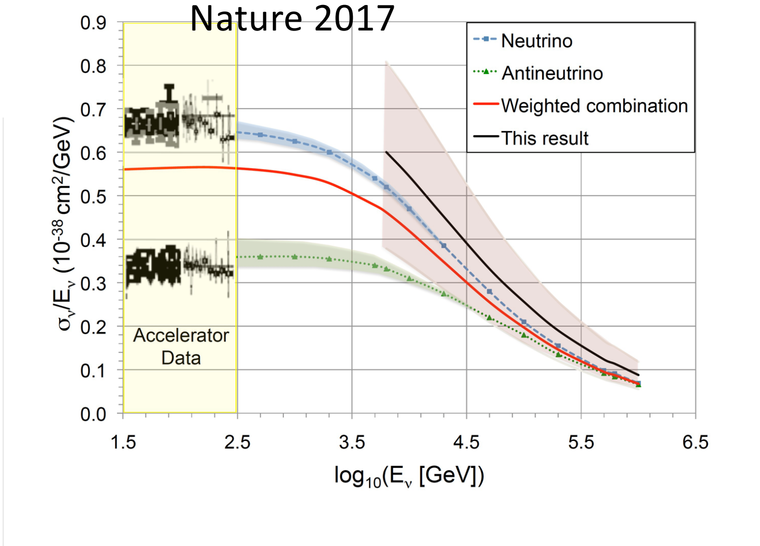


2011.03561

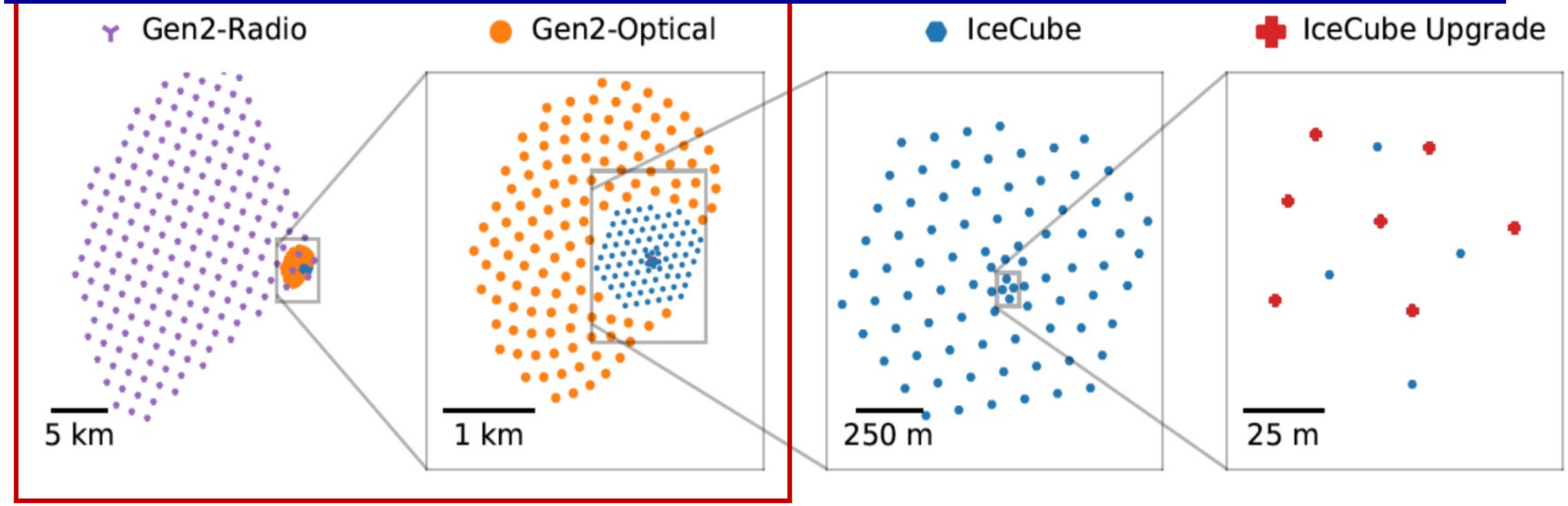


→ disfavoring a no-astrophysical ν_τ flux scenario with 2.8σ

Nature 2017



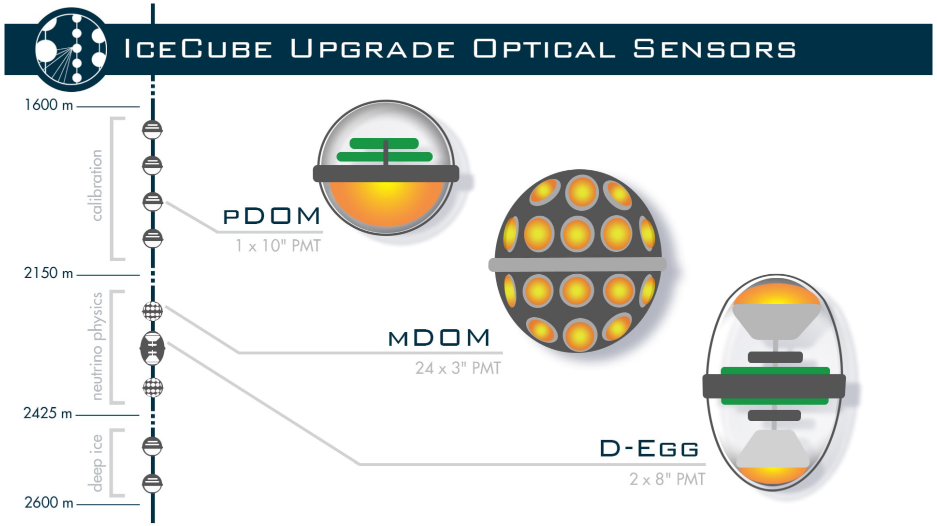
IceCube-Gen2



Gen2 Goals:

-- Identification of more astro. ν sources
-- Precise measurement of astro. ν spectral power law index & flavor ratio
-- Multi-messenger ν astronomy
etc.

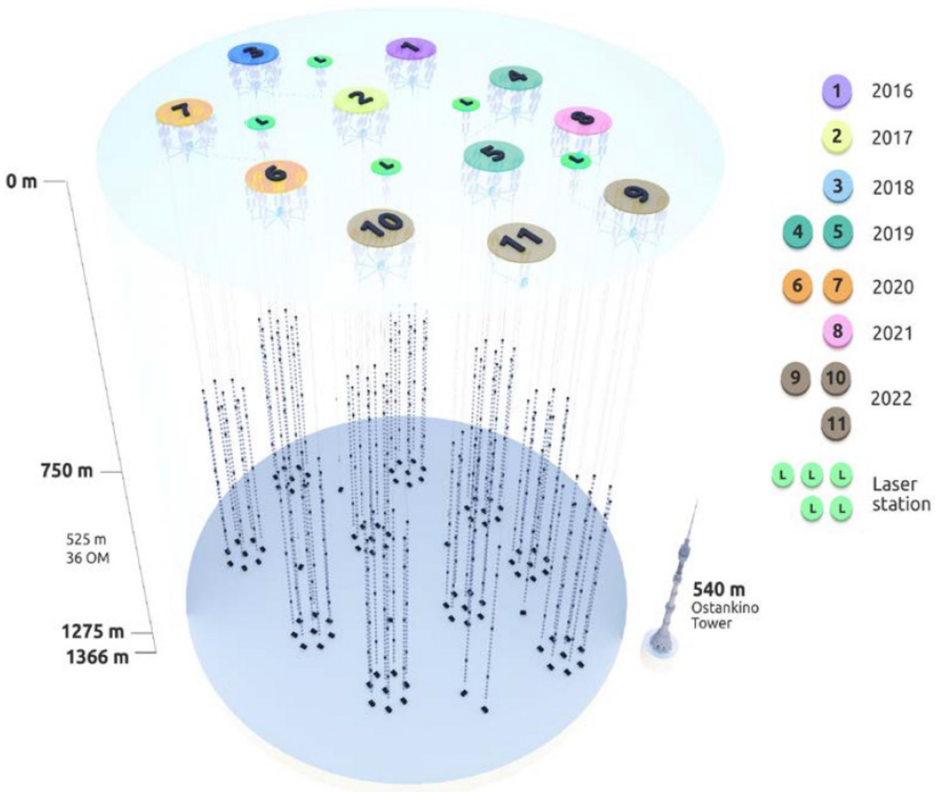
O(10) PeV neutrinos/year



Baikal-GVD construction status and schedule

Zhan Dzhikibayev
@Nu2022

Status 2022: 10 clusters, 5 laser stations, experimental strings



Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032
2025	16	4608
2026	18	5184

Baikal-GVD

Zhan Dzhikibayev
@Nu2022

- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere and growing
- Modular structure of GVD design allows a search for HE neutrinos and multimessenger studies at the early phases of array construction.
- Observations of atmospheric neutrinos by Baikal-GVD agree with expectations

❖ **Up-going events + down-going HE cascade events (2018-2021: 5522 live days in terms of one cluster)**

- First 25 astrophysics neutrino candidate events have been selected - Baikal-GVD confirms IceCube observation of astrophysical diffuse neutrino flux at 3σ level

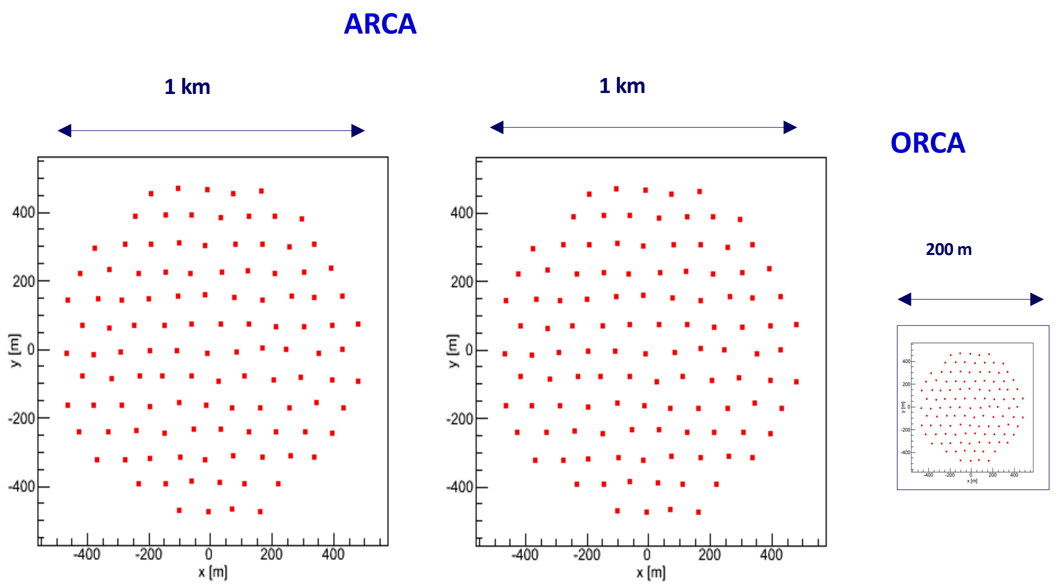
- **16 events are expected from IceCube E^(-2.46) diffuse astrophysical ν flux**

Plan

- 2025/2026 – ~ 1km^3 GVD with total of 16-18 clusters
- 2022-2024 – "Conceptual Design Report" for next generation neutrino telescope in Lake Baikal

KM3NeT

KM3NeT: 6 strings operating stably for one year



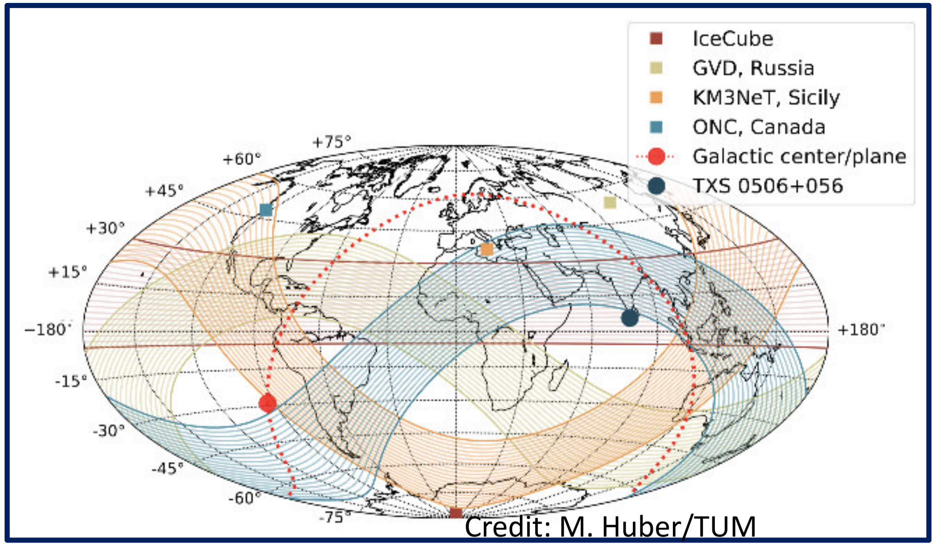
- ARCA (Astronomy) @French sea

-- 115 strings, 18 DOMs / string

-- 31 PMTs/DOM (Total: 64k*3¨ PMTs)

- ORCA @Italian sea

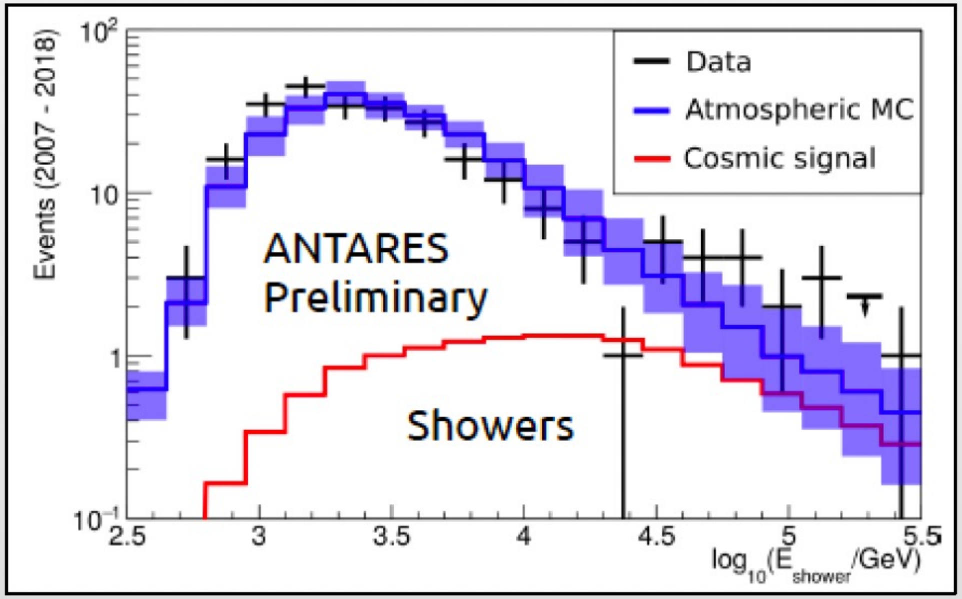
  -- NMO+ ν properties

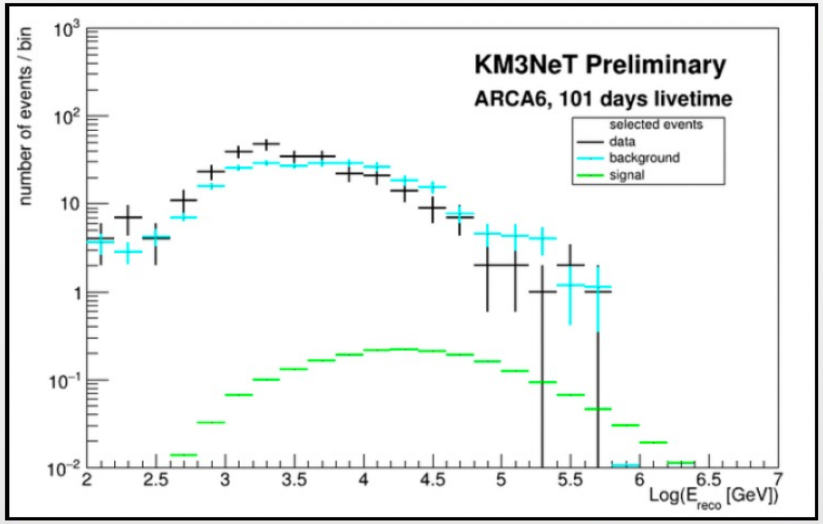


Antares & ARCA 6

Aart Heijboer
@Nu2022

Cosmic neutrinos





For the diffuse cosmic neutrino flux of [2]: 1.44 x 10^{-18} $(E/100TeV)^{-2.28}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]		Number of events
$\Phi_{90\%CL}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]	$\Phi_{5\sigma}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]	$N_{atm.mu\&nu}$ = 68.4
17.3 x 10^{-18}	51.4 x 10^{-18}	$N_{cosmic\ nu}$ = 1.3

Antares data fully compatible with comic flux

- Data: 50 events (27 tracks + 23 showers)
- Background : 36.1 ± 8.7

ARCA 6, 101 days

- Sample dominated by muon,
- No high-E excess due to neutrinos
- Results compatible with background

P0173

Neutrino 2022 Group Photo

The 50th Anniversary
NEUTRINO 2022
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

Hope ν continues !

The 50th Anniversary
NEUTRINO 2022
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

Nu1972

Feynman & Pontecorvo planting twin-oak trees

Nu2022

Twin-oak trees in 2021

Nu2072

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