Experimental Neutrino Physics

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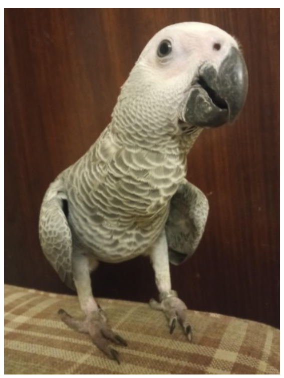
Outline

What are the big (experimental) questions in neutrino physics?

What's the status of answering them?

What do we still need to know?



Standard apology: There are enormous numbers of cool things going on in neutrino physics...

My plan is to **outline the big picture** and **pick out a few highlights** .... I'm sorry if I miss your favorite thing!

Science Drivers in Neutrino Physics

Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

Science Drivers in Neutrino Physics

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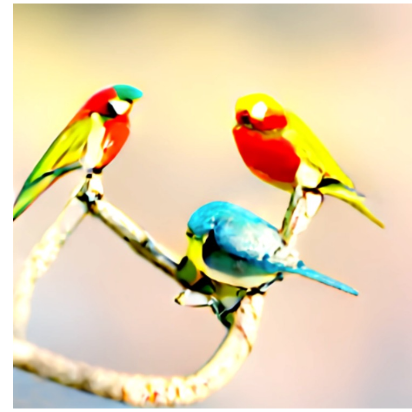
The three flavor paradigm

what's known,
what's left to measure?



Neutrino Oscillations
Latest 3-flavor results

Remaining unknowns in
the 3-flavor picture:
mass ordering (**MO) and CP** δ

The mass pattern

Absolute Mass
Status and prospects

The mass scale

Majorana vs Dirac?
Overview of NLDBD

The mass nature

Neutrino Mass and Oscillations in Three-Flavor Picture

Flavor states related to mass states by a unitary mixing matrix

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in weak interactions

unitary mixing matrix

eigenstates of free Hamiltonian

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate

Three-flavor oscillation probability

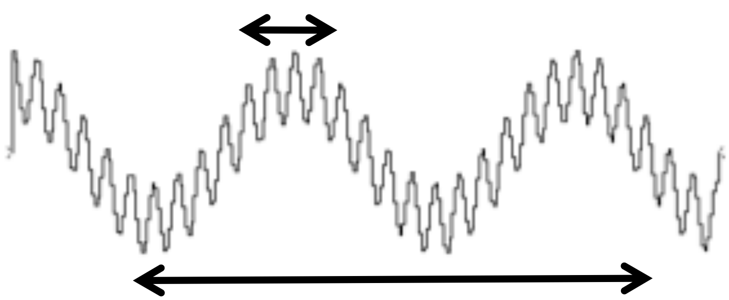
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*}|\nu_i\rangle$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$ (L in km, E in GeV, m in eV)

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4\sum_{i>j}\Re(U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*})\sin^2(1.27\Delta m_{ij}^2 L/E)$$

$$\pm\, 2\sum_{i>j}\Im(U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*})\sin(2.54\Delta m_{ij}^2 L/E)$$

oscillatory behavior in L and E



$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$ ➔ two frequency scales

Observables are neutrino ***flavor change*** (appearance or disappearance) as a function of baseline L and energy E_ν

Parameters in the 3-flavor neutrino paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

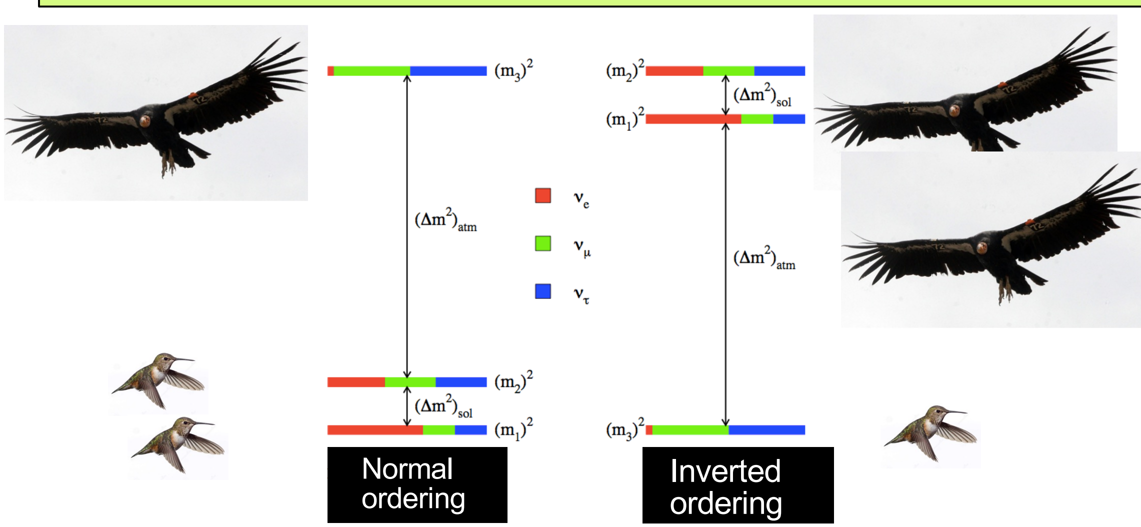
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$s_{ij} \equiv \sin\theta_{ij}, \; c_{ij} \equiv \cos\theta_{ij}$$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

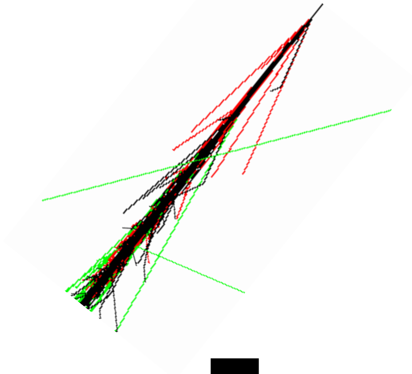
signs of the mass differences matter



Except Majorana phases, all parameters accessible by oscillation experiments

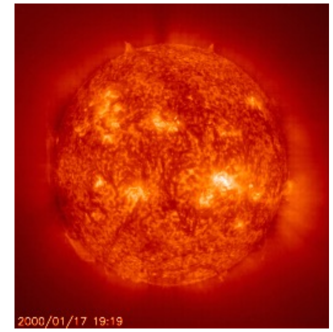
Multiple oscillation signatures from different neutrino sources

atmospheric



$\theta_{13,}$ the "twist in the middle"

solar



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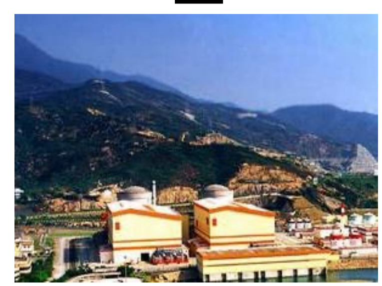
$$

Now precisely measured

beams



reactor

The three-flavor picture fits the data well

Global three-flavor fits to all data: atmospheric, solar, reactor, beams

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
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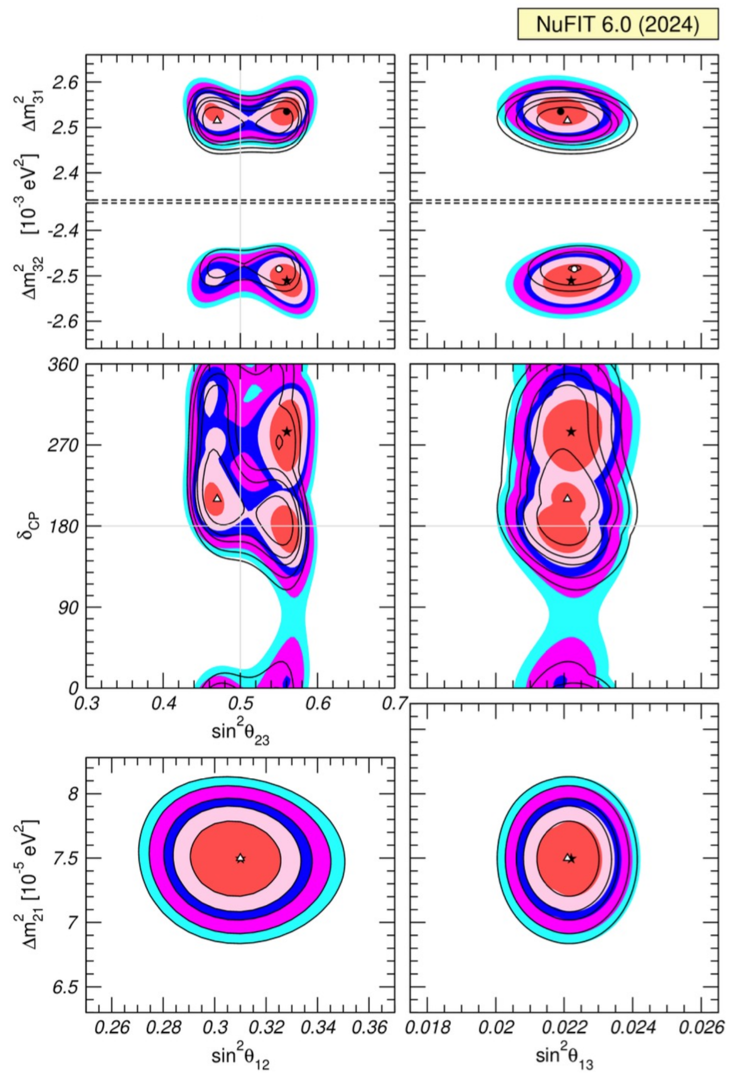
Esteban et al., JHEP 12 (2024) 216, 2410.05380 [hep-ph]



What do we *not* know about the three-flavor paradigm?

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sign of Δm^2 unknown (ordering of masses)

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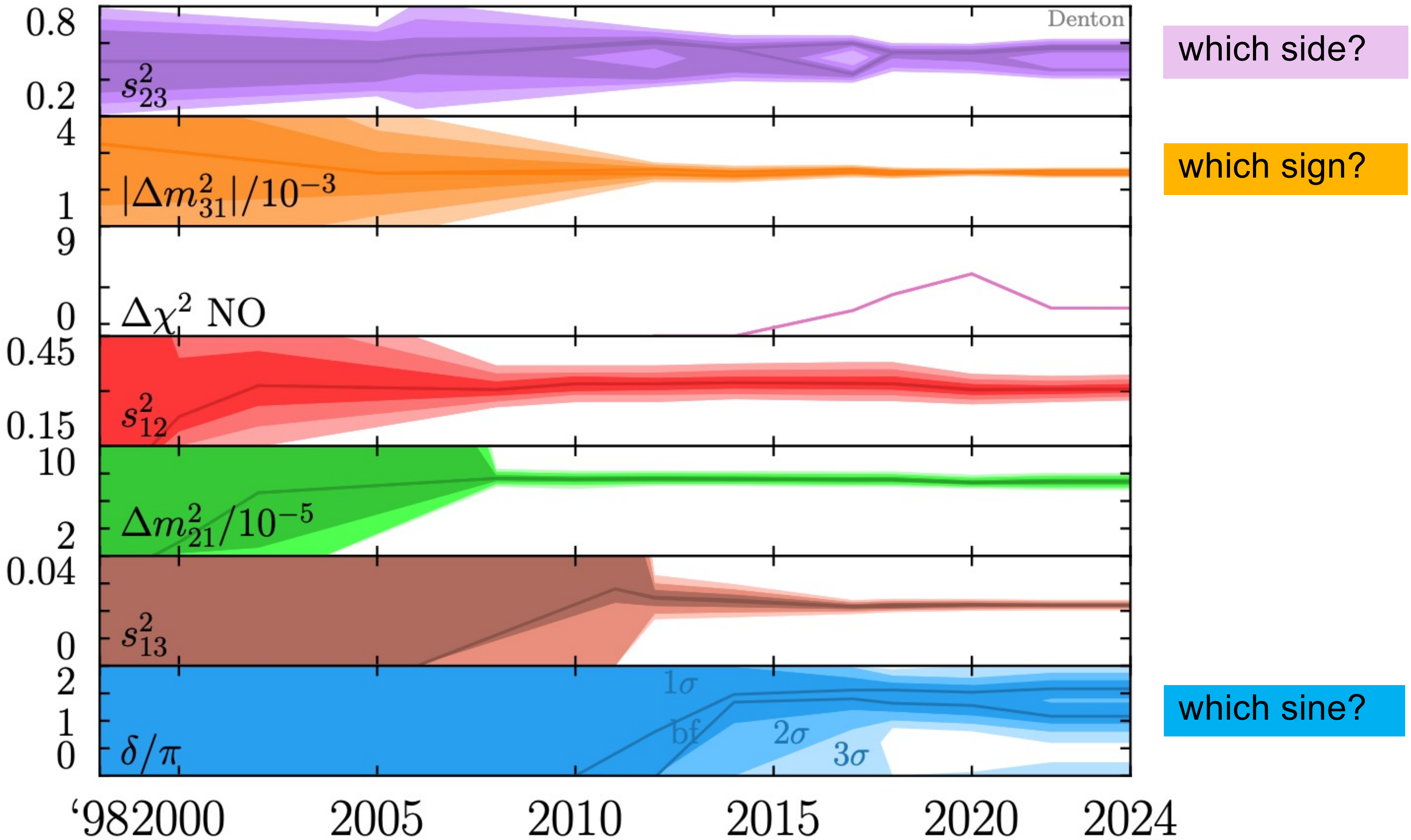
poor knowledge

sign of Δm^2 unknown (ordering of masses)



Peter Denton, CIPANP 2025 2212.00809 2501.08374

More and better info soon from:
beams [long-baseline], burns [solar, JUNO],
bangs [SNe]...

Where we are now with long-baseline experiments

Past → Current → Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

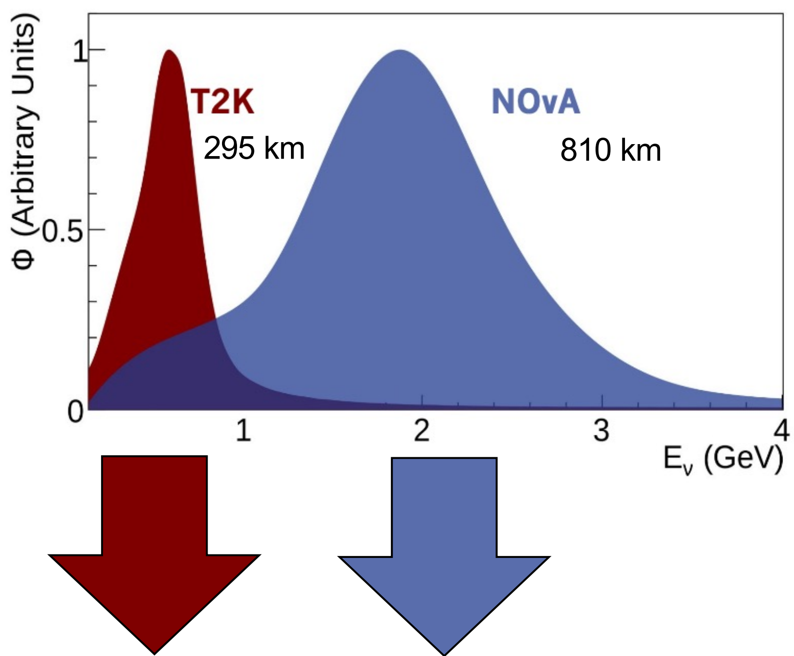
CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-900+ kW

T2K
J-PARC to Kamioka
295 km, 380-830 kW

T2K-NOvA joint analysis

Neutrino flux

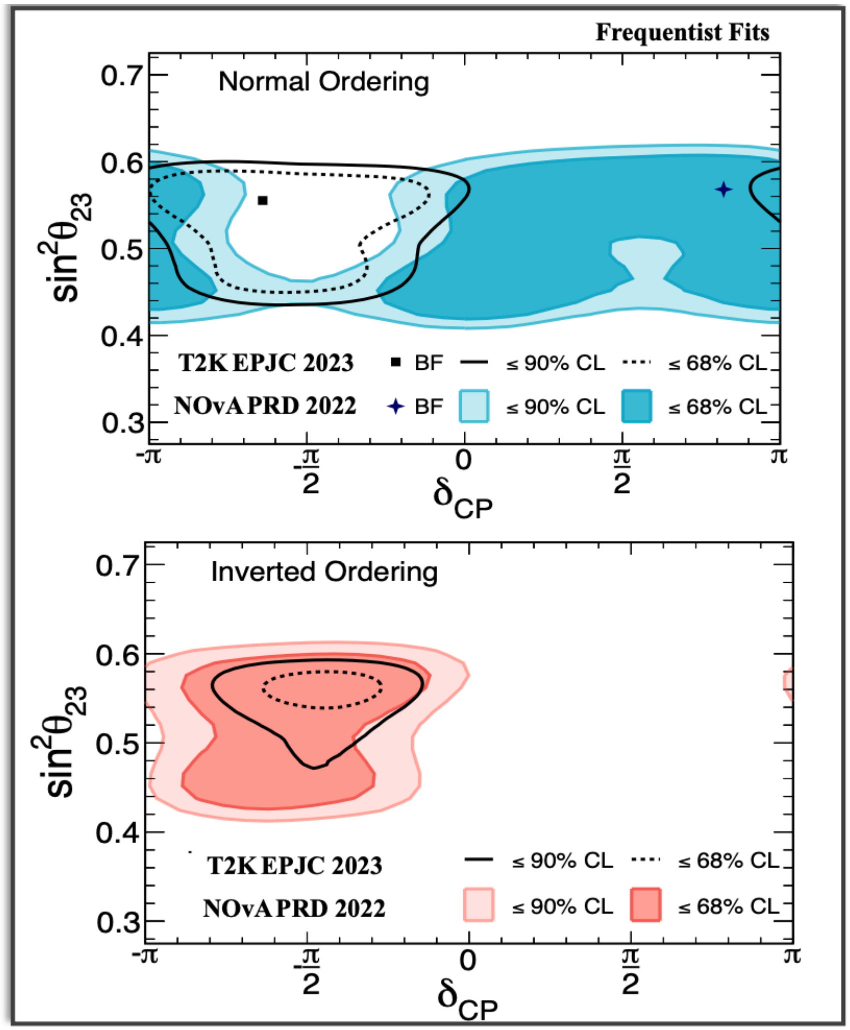


Shorter baseline, cleaner CPV effect

Longer baseline, more matter effect, more MO sensitivity

- ~Uncorrelated detector & flux systematics
- Analysis with and without Daya Bay reactor constraint

Individual results from NOvA/T2K 2020 datasets



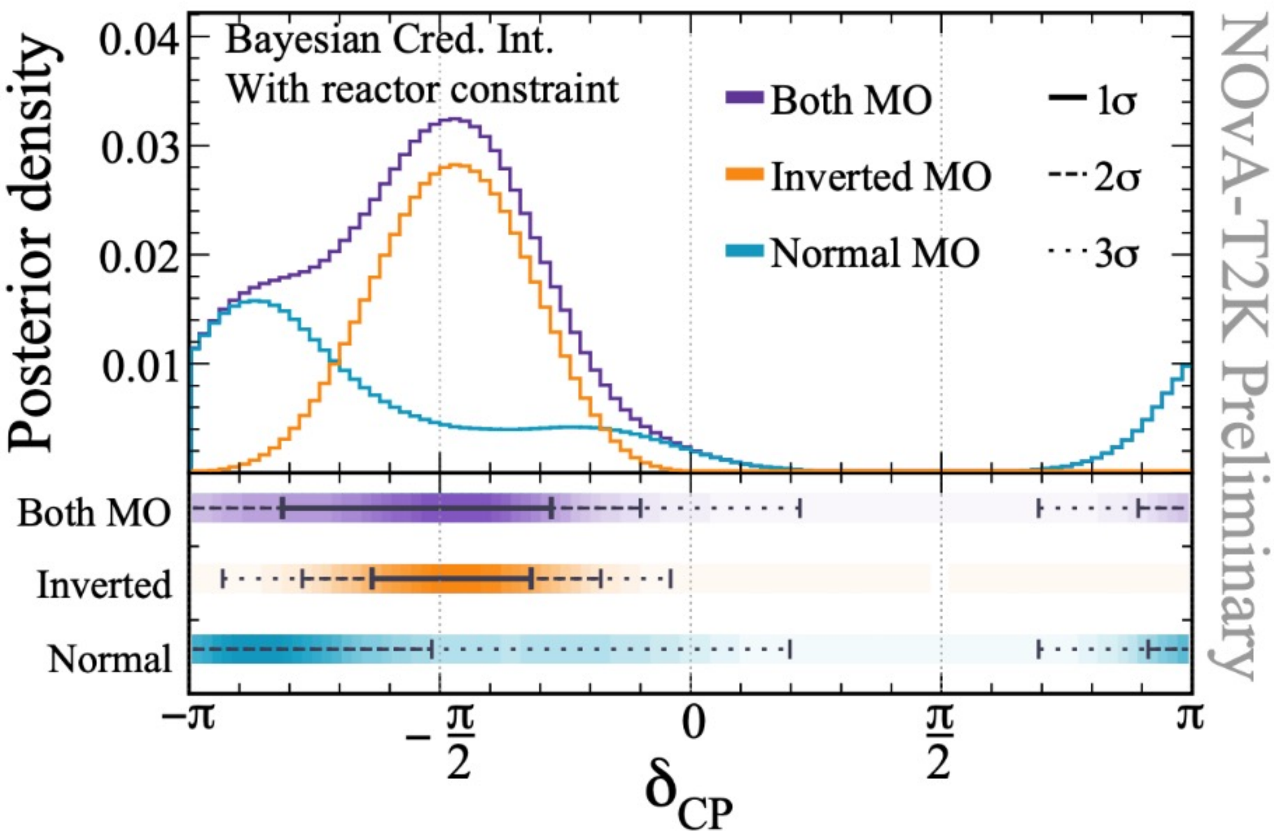
- both individually favor NO
- *mild* CP δ tension

Z. Vallari, CIPANP 2025

T2K-NOvA joint analysis results: joint fit describes both well

- **Octant**
  - ~No preference for octant for NOvA+T2K
  - Mild preference for upper octant with reactor constraint
- **Mass ordering**
  - NOvA+T2K has mild preference for IO
  - Preference for NO w/reactor included
- **CP-Violating Phase**
  - $\delta=\pi/2$ outside 3σ credible interval for any MO
  - For IO, CP-conserving $\delta=0$, π are outside 3σ; for NO, not so

Upshot: we're not there yet... more data needed!



One high-profile example... more joint fit oscillation parameter plots in backup

Z. Vallari, CIPANP 2025

And the future...

Past | Current | Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-900+ kW

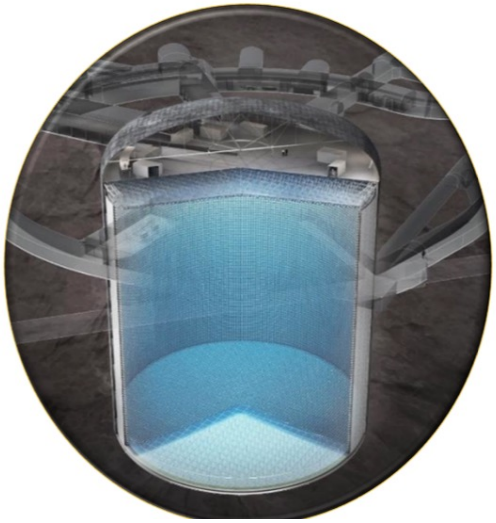
T2K
J-PARC to Kamioka
295 km, 380-830 kW ➔>1 MW

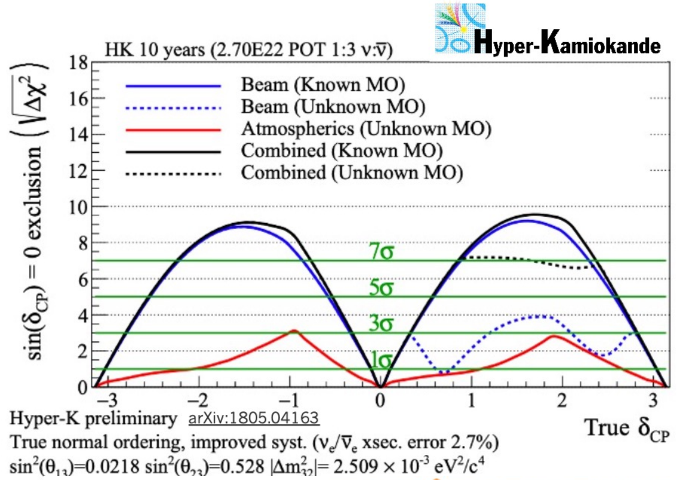
LBNF/DUNE
FNAL to Homestake
1300 km, 2-2.4 MW tunable

Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

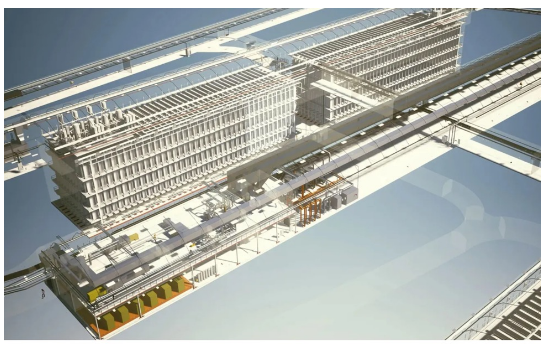
+ ESSνSB
+ farther future
nu factories...

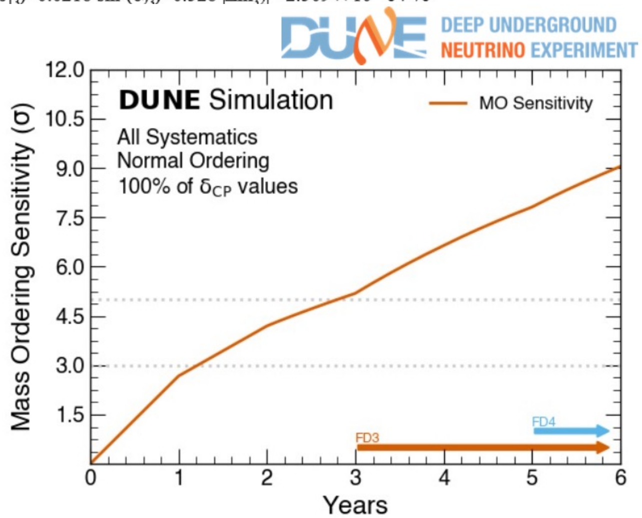
Next-generation long-baseline beam experiments





- 187 kt water
- Cavern nearing completion
- Excellent CPV but CPV/MO degeneracy





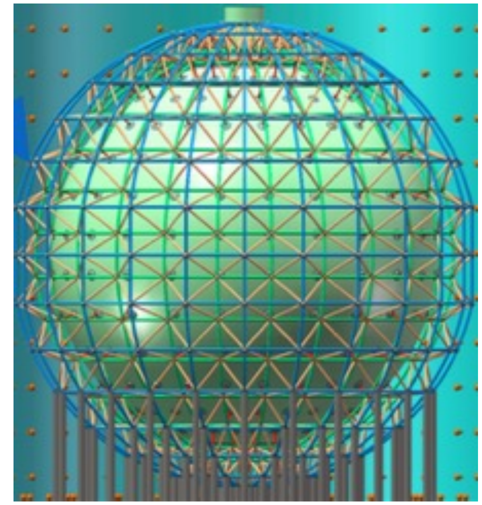
- 20-40 kt LAr
- Cavern completed
- Excellent MO sensitivity

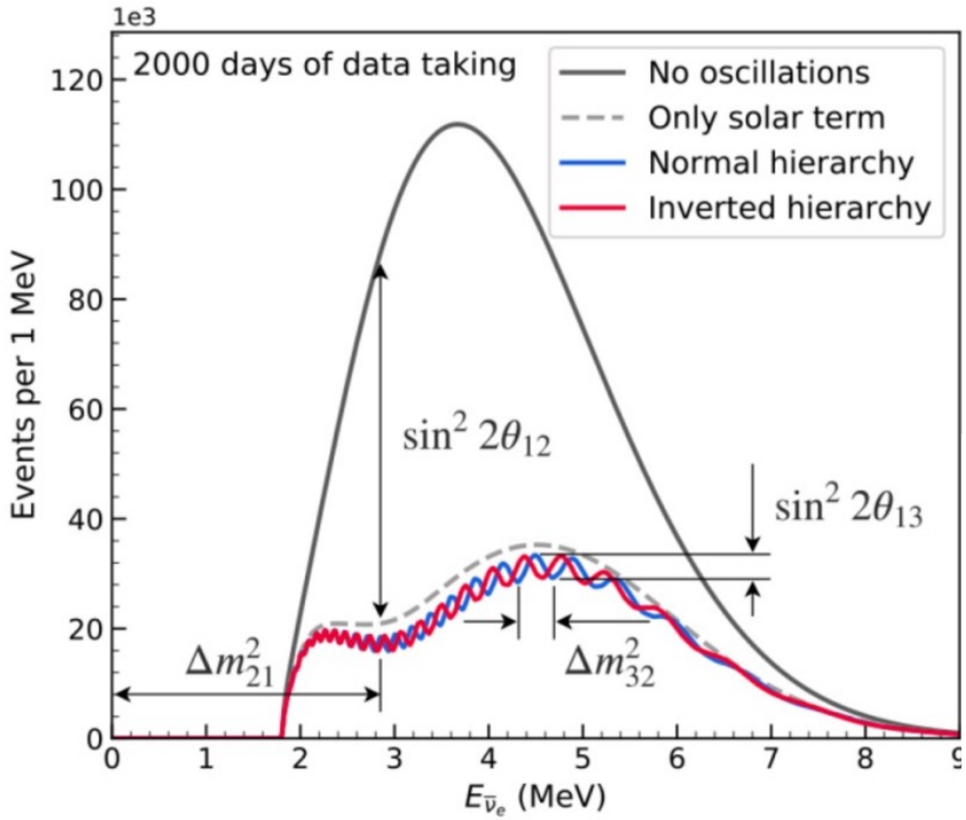
- both can also use atmospheric neutrinos*
- both have suite of diverse near detectors
- both will measure precision 2-3 parameters
- both have broad non-oscillation physics programs

[Long term eventual systematics wall... improve w/xscn, flux modeling, nu tagging (ENUBET)..]

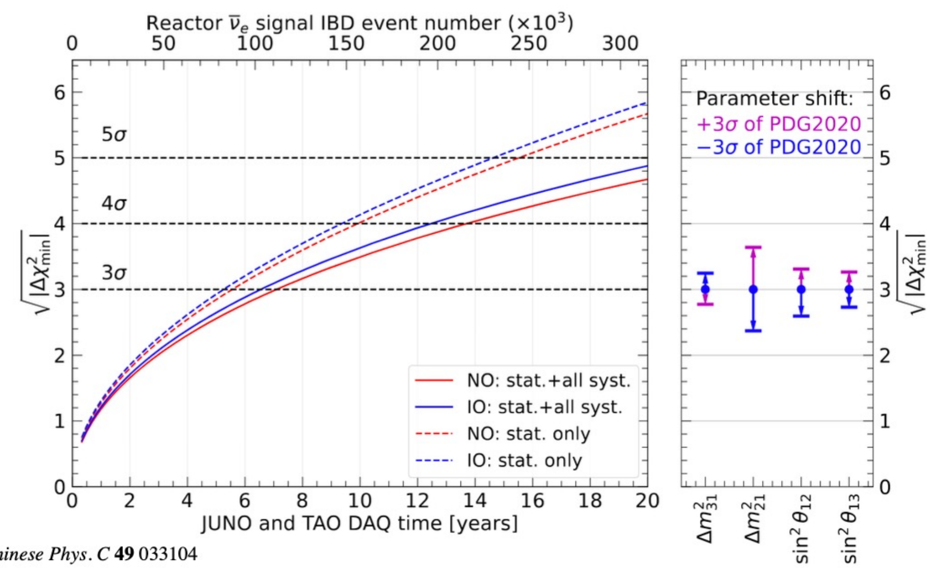
* Also KM3NeT, IceCube atmnus

And **JUNO** in China approaches MO differently with reactor ν_e-bar disappearance





- 20 kt liquid scintillator
- 53 km from 26.6 GW reactor
- water → LS this summer



Chinese Phys. C **49** 033104

Also precision 1-2 parameters and broad non-oscillation physics program

Neutrino Oscillations

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Remaining unknowns in the 3-flavor picture: **MO and CP δ**

Beyond 3-flavor?

Absolute Mass

Status and prospects

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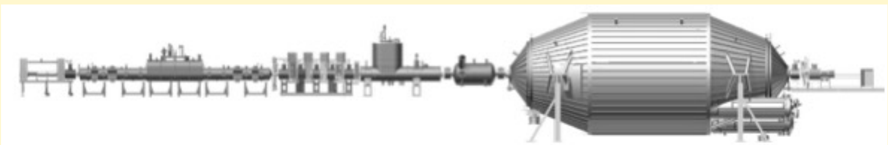
Kinematic neutrino mass approaches

Tritium spectrometer: KATRIN

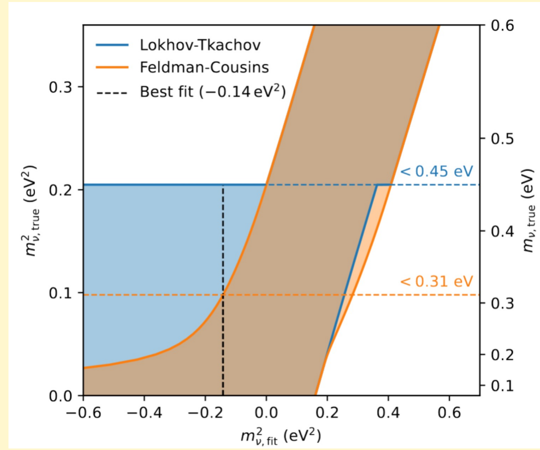
$^{3}\mathrm{H} \rightarrow ^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$

18.6 keV endpoint



Sensitivity to ~0.3 eV

Ongoing results, taking more data



KATRIN collab., *Science* 388 (2025) 180-185

$$m_\nu < 0.45\ \mathrm{eV}\ (90\%\ \mathrm{C.L.})$$

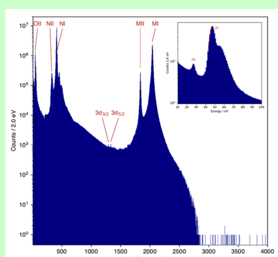
Holmium

e.g., **ECHo, HOLMES**

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

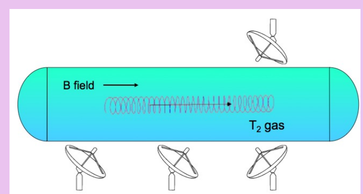
metallic magnetic calorimeter or TES sensors



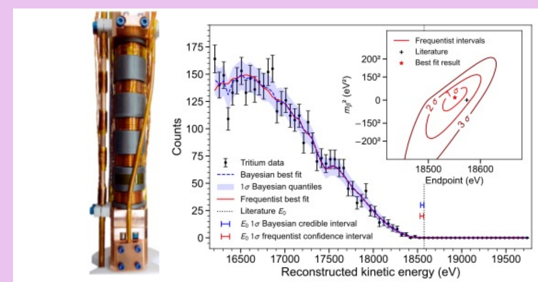
Electron capture decay,
ν mass affects deexcitation spectrum

R&D, m_β< 19, 27 eV

Cyclotron radiation tritium spectrometer: Project 8, QTNM



Long-term potential ~40 meV



Project 8 Collaboration, Phys. Rev. Lett. (2023)
Project 8 Collaboration, Phys. Rev. C (2024)

R&D, m_β < 155 eV

+KATRIN++ (atomic tritium), PTOLEMY

Neutrino Oscillations

Latest 3-flavor results

Remaining unknowns in the 3-flavor picture: **MO and CP δ**

Beyond 3-flavor?

The mass pattern

Absolute Mass

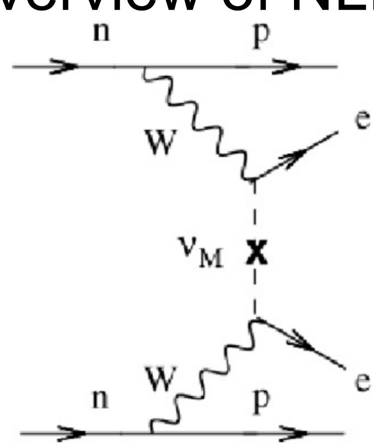
Status and prospects

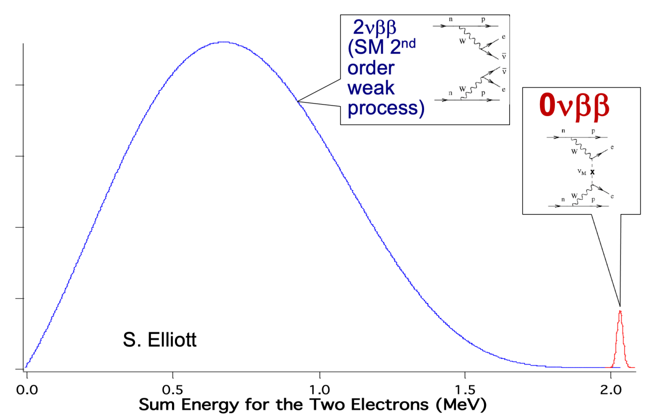
The mass scale

Majorana vs Dirac?

Overview of NLDBD

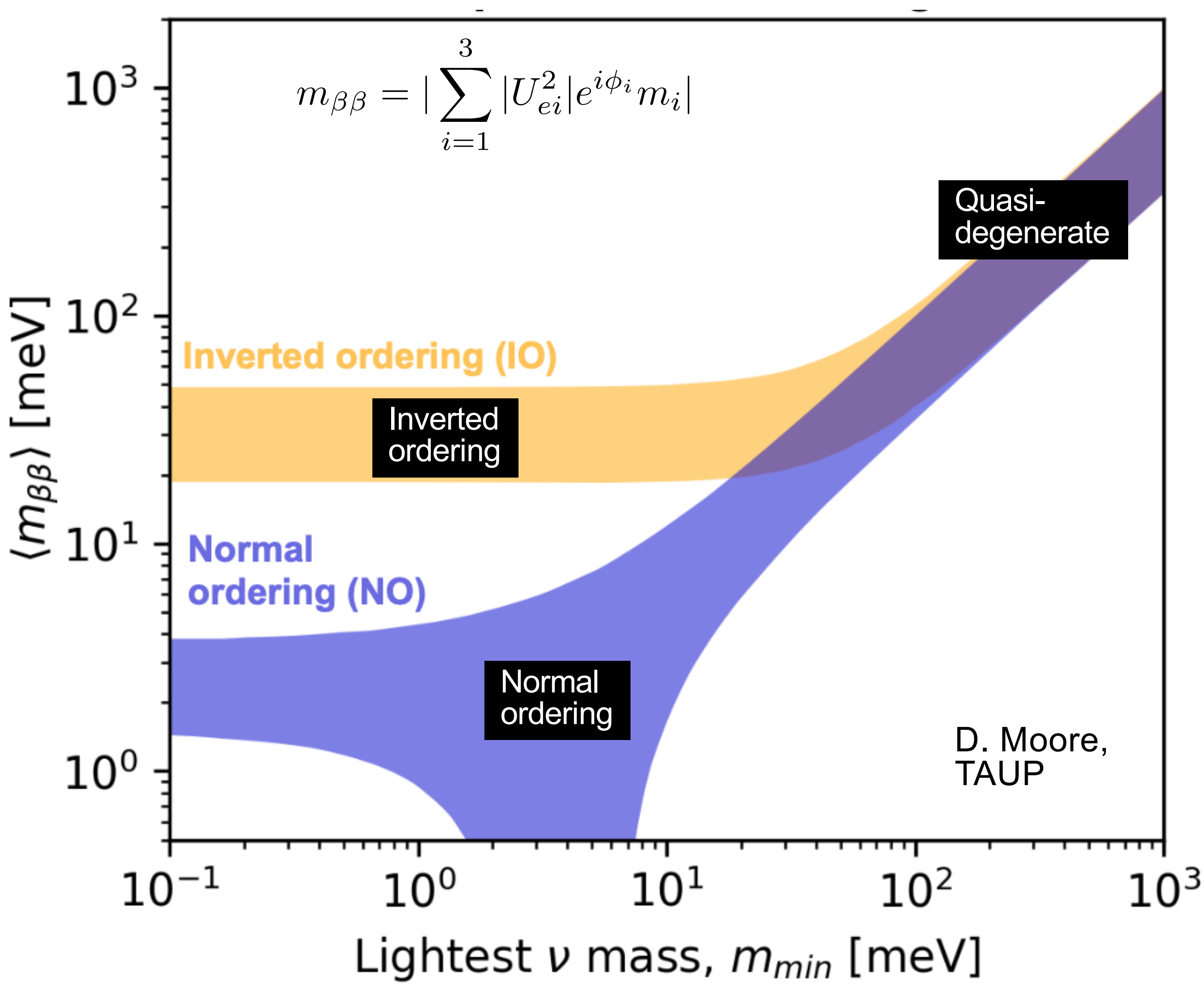
The mass nature





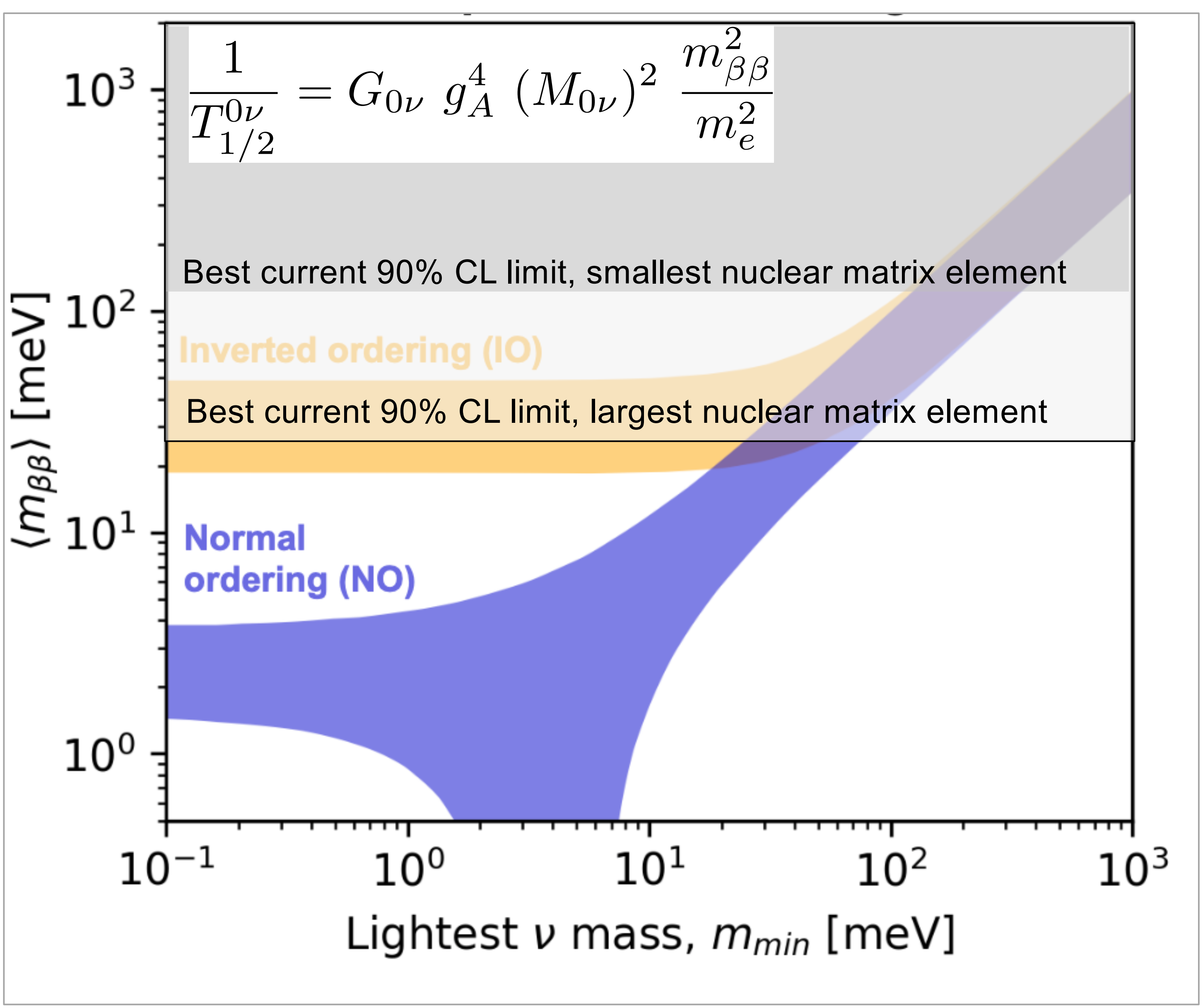
kinematic signature of rare decay

(A) Neutrinoless Double Beta Decay T-Shirt Plot



***If* neutrinos are Majorana, experimental results must fall in the shaded regions**

Extent of the regions determined by
uncertainties on Majorana phases and mixing matrix elements



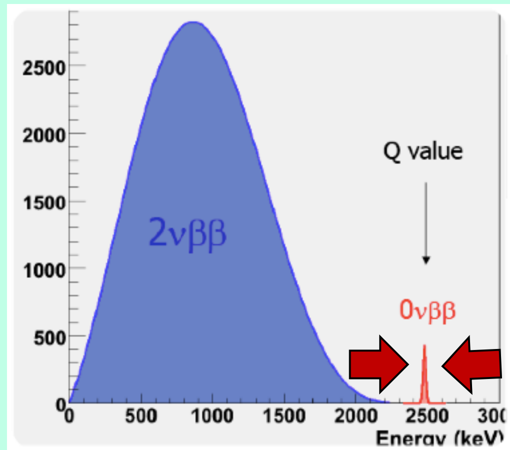
Observed half-life requires knowledge of nuclear matrix elements

General NLDBD experiment strategies

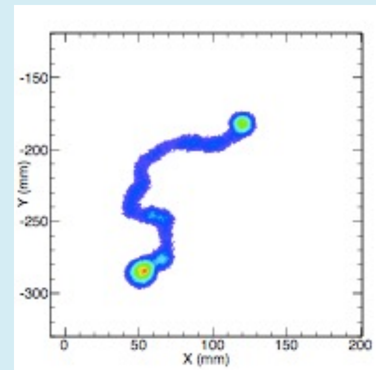
$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

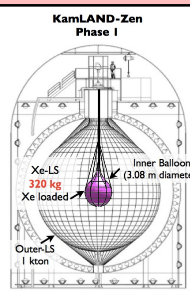
The "Brute Force" Approach

The "Peak-Squeezer" Approach

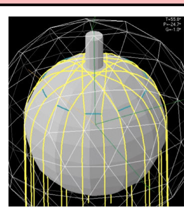


The "Final-State Judgement" Approach

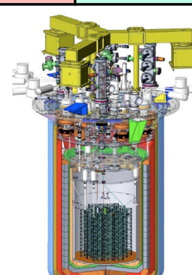




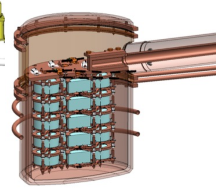
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)



CUORICINO/ CUORE (^{130}Te)

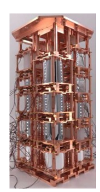


MAJORANA (^{76}Ge)

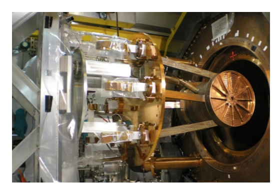
CUPID (^{82}Se)

CUPID -Mo (^{100}Mo)

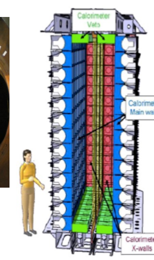
GERDA (^{76}Ge)



AMORE (^{100}Mo)



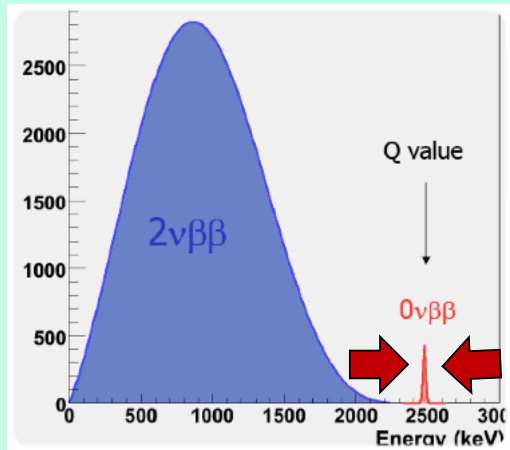
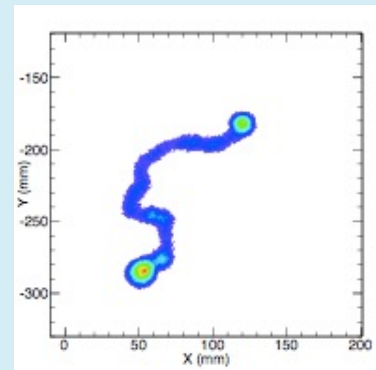
EXO (^{136}Xe)

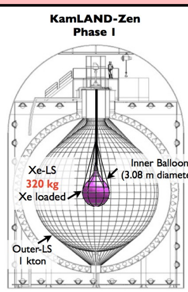


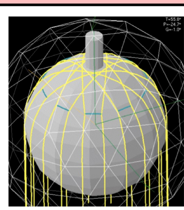
NEMO/ SuperNEMO (various/^{82}Se)

General NLDBD experiment strategies

$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

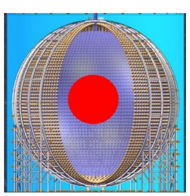
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		



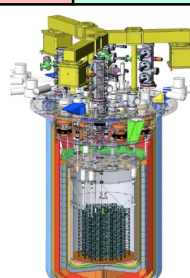


SNO+ (^{130}Te)

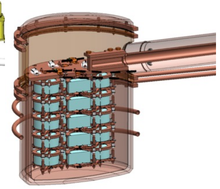
KamLAND-Zen (^{136}Xe)



JUNO-ββ (^{136}Xe, ^{130}Te)



CUORICINO/ CUORE (^{130}Te)



MAJORANA (^{76}Ge)

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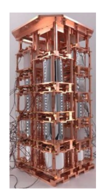
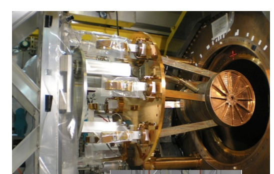
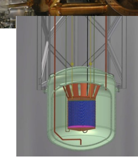


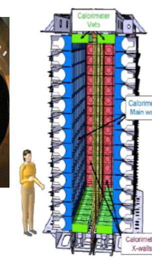
AMORE (^{100}Mo)

LEGEND (^{76}Ge)

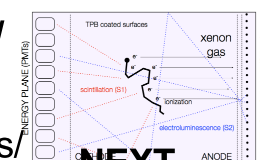




nEXO (^{136}Xe)



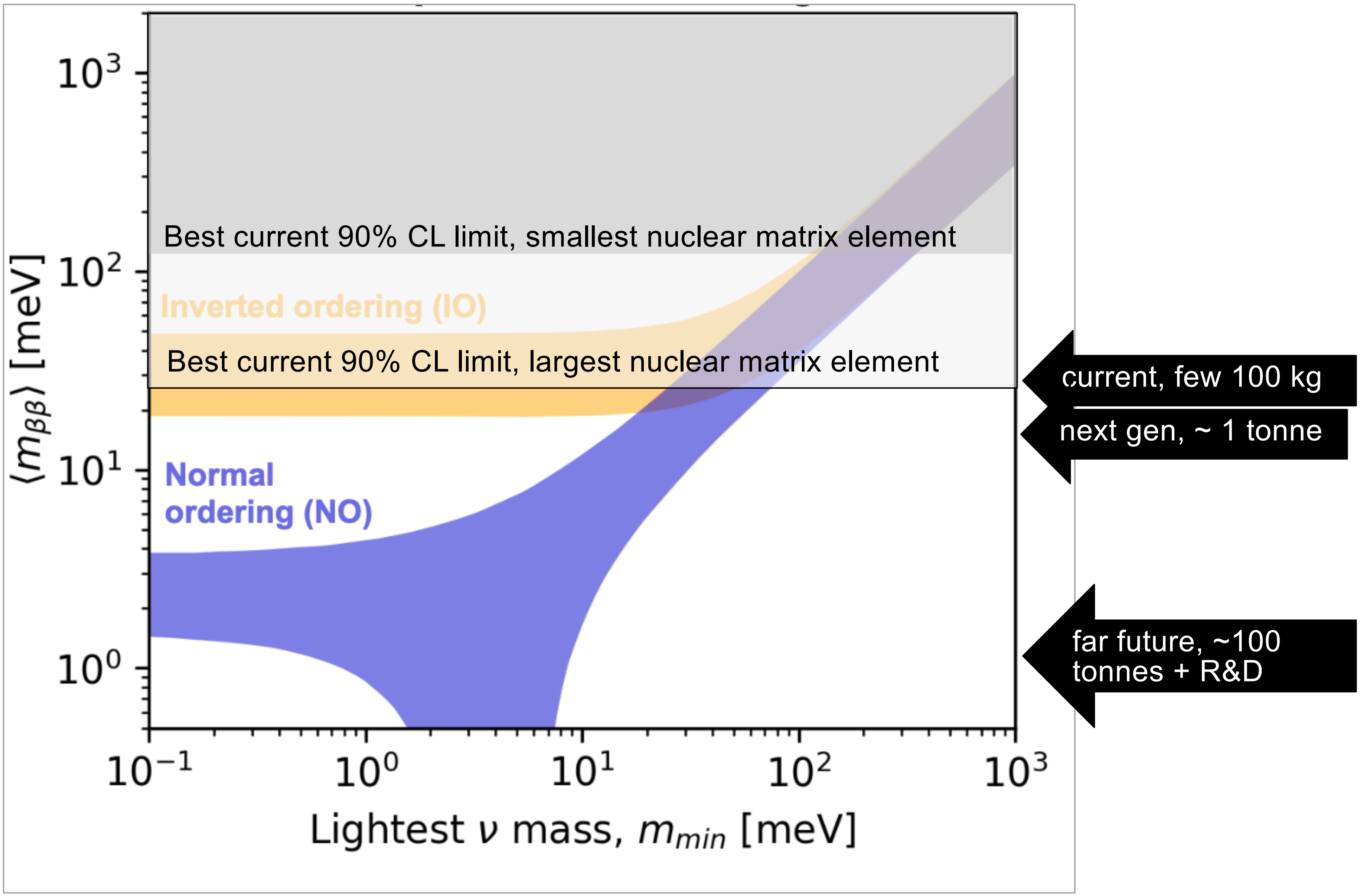
NEMO/ Super NEMO (various/ ^{82}Se)



NEXT (^{136}Xe)

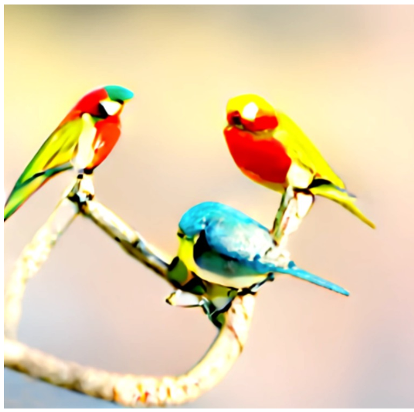
+more, see backup...

Overall Long-Term Prospects for NLDBD



In the long term will need more than one isotope...
theory needed too!

Science Drivers in Neutrino Physics



Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

There are already some slightly uncomfortable data that **don't fit that paradigm**...

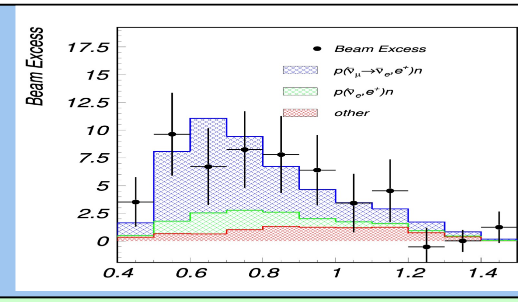
... various appearance and disappearance signatures at different L, E

... **sterile neutrinos** (no SM weak interactions) are primary suspects...

Status of attempts to resolve anomalies...

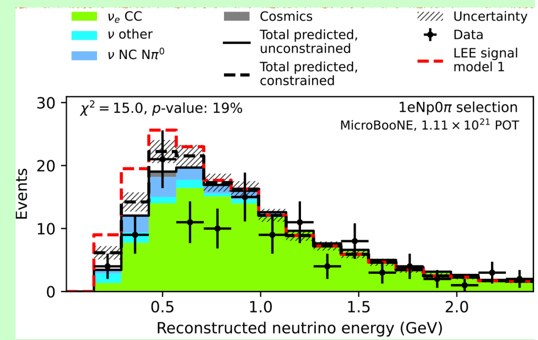
LSND @ LANL (~30 MeV, 30 m) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess

Unresolved... JSNS^2 will test ~directly

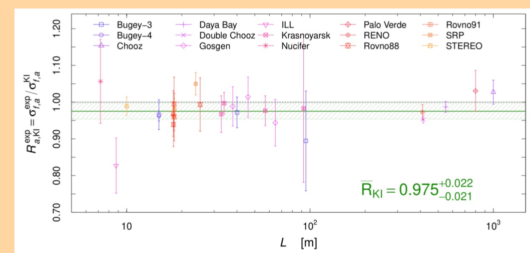


MiniBooNE @ FNAL ($\nu,\bar{\nu}$ ~1 GeV, 0.5 km)
electron flavor excess ~consistent w/LSND

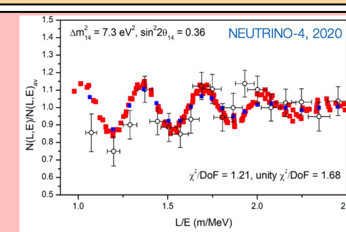
Unresolved.... MicroBooNE LArTPC @ FNAL **does not see excess of ν_e**, investigation of photon channel underway...
.more data from FNAL SBN (ICARUS, SBND) soon



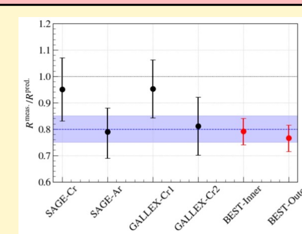
"Reactor flux anomaly" deficit of reactor $\bar{\nu}_e$
Resolved with new input β-decay spectra
from 235-U fission



"Reactor spectral anomaly" spectral wiggle in $\bar{\nu}_e$
~Unresolved... **new data disfavor**.. more data coming...
PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER, Neutrino-4,....

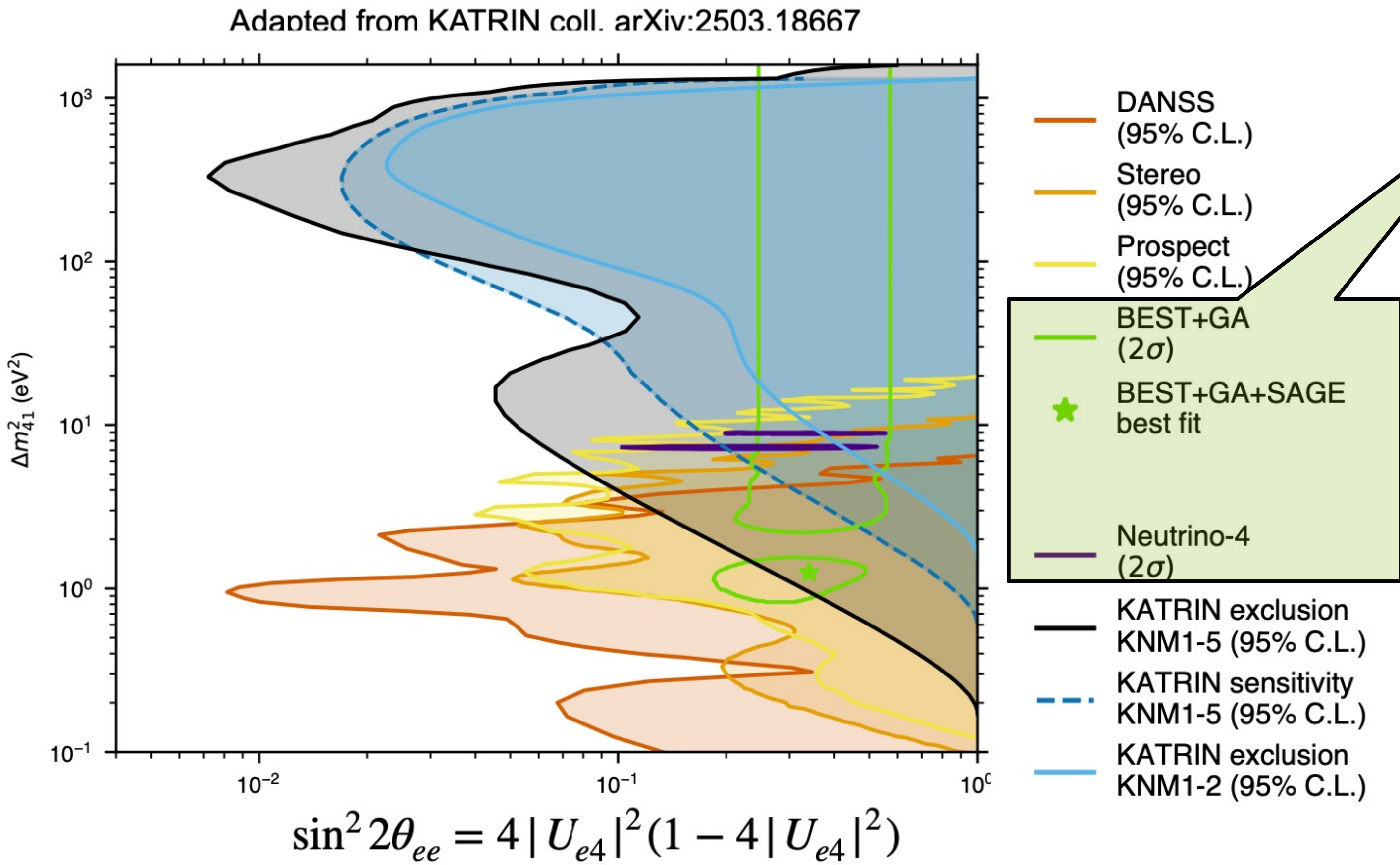


"Gallium anomaly" ν_e suppression from Ga source
Unresolved... new BEST results (5σ) confirm
...no baseline dependence



(One) example of sterile-oscillation parameter space:

From M. Hostert, CIPANP 2025



sterile oscillation hints

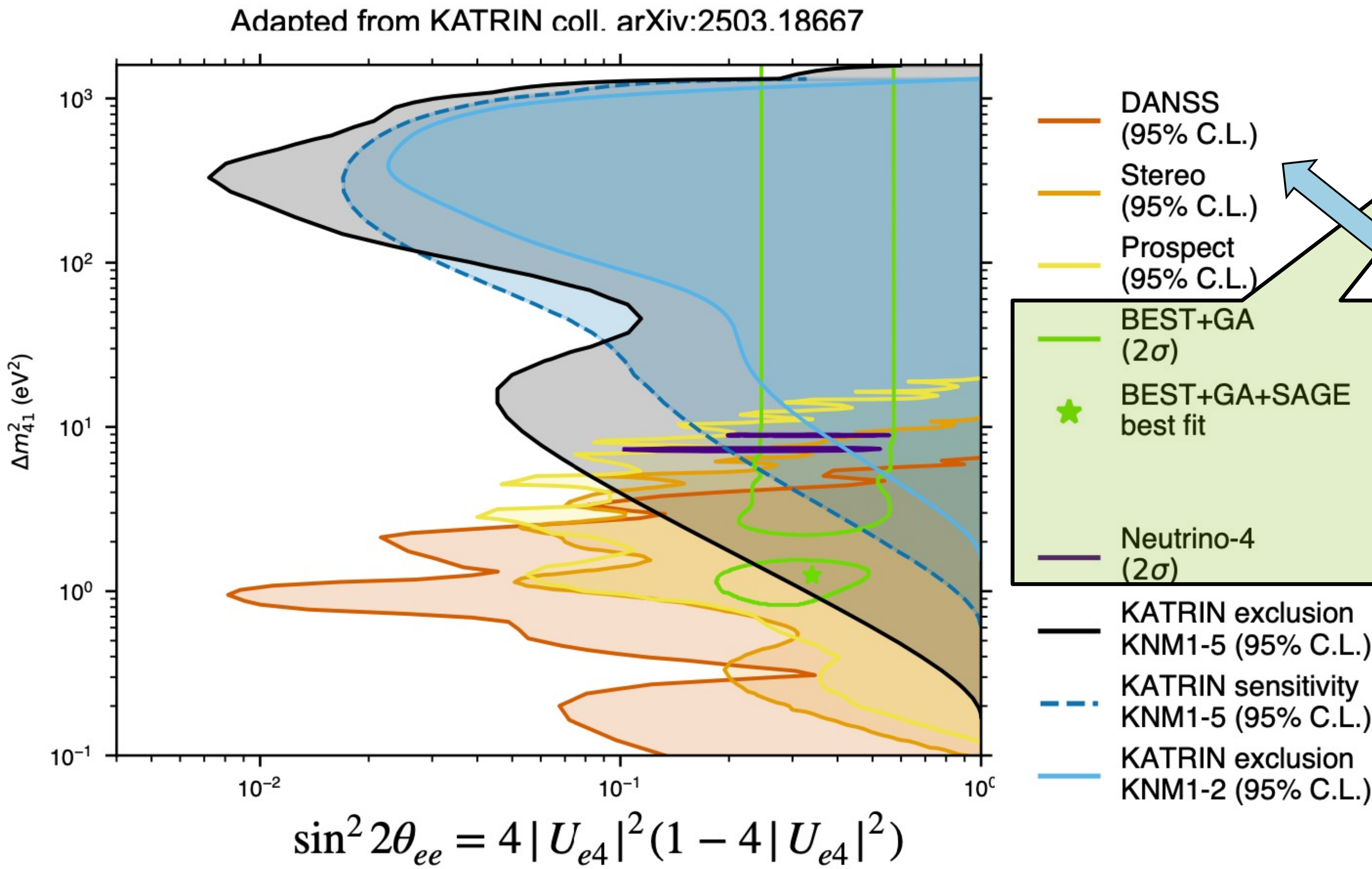
Sterile oscillation fits to “all” the data are uncomfortable...

No consistent sterile-oscillation picture

it's either something mundane,
or something new (or both...)

(One) example of sterile-oscillation parameter space:

From M. Hostert, CIPANP 2025



sterile oscillation hints

almost completely wiped out by other experiments

Sterile oscillation fits to “all” the data
are uncomfortable...

No consistent sterile-oscillation picture
it's either something mundane,
or something new (or both...)

Science Drivers in Neutrino Physics

Three-flavor paradigm: filling in the remaining pieces

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Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

Beyond the Standard Model with Neutrinos

BSM in the neutrino sector *and* BSM search opportunities in neutrino detectors

- sterile neutrinos over wide range of masses (also "heavy neutral leptons")
- neutrino decay
- PMNS non-unitarity
- anomalous ν electromagnetic properties
- non-standard ν interactions, effective field theories
- new physics in double beta decay

- baryon number violation in large detectors
- dark sector searches (beams, natural sources, cosmogenic)
  - Axion-like particles
  - Light DM
  - Light Z'

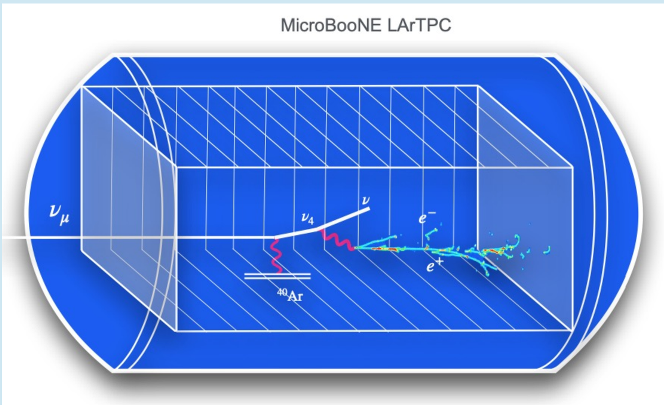
(categories are not crisply separated...)

Very wide array of experimental signatures & approaches

See J. Kopp ESPP talk

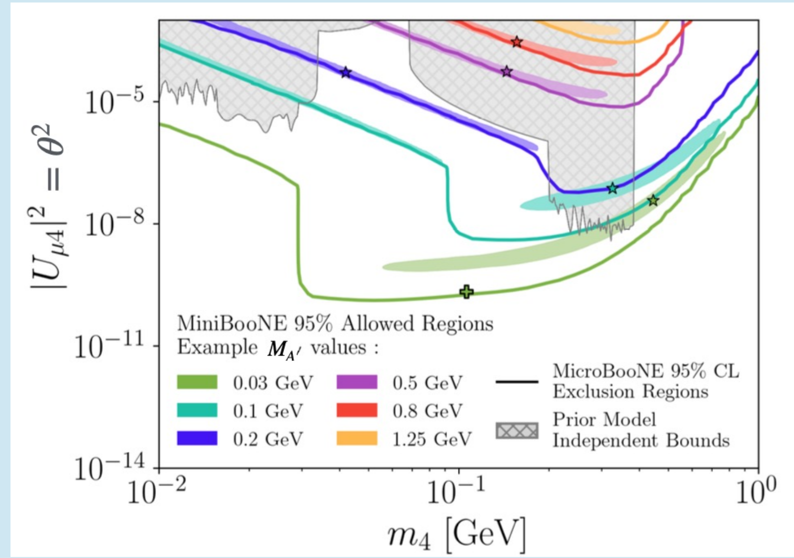
Just two BSM search examples, of very very many...

Look for scattering + $\nu_4 \rightarrow \nu e^+ e^-$ topology in LArTPC

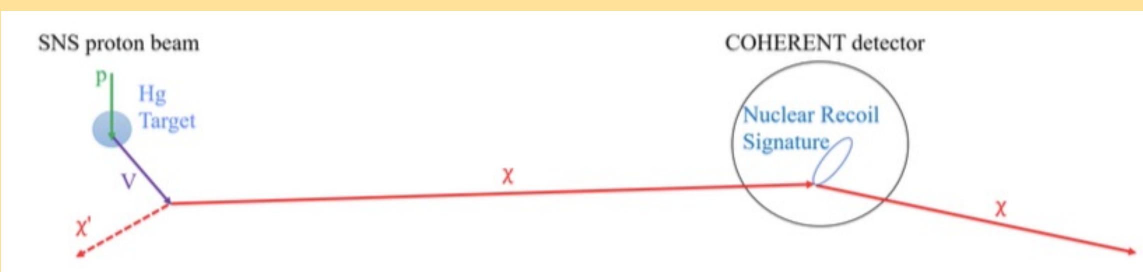


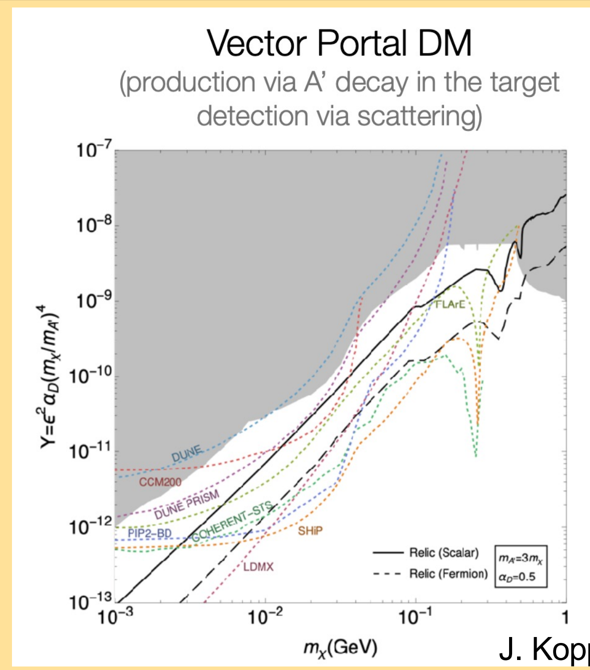
M. Hostert, CIPANP 2025

MicroBooNE arXiv:2502.10900



Look for nuclear recoil signatures of vector-portal DM in low-threshold CEvNS detectors





J. Kopp ESPP

Science Drivers in Neutrino Physics

Three-flavor paradigm: filling in the remaining pieces

Hunting down **anomalies**

Searching for **BSM** physics

Understanding **astrophysics** and **cosmology**

Multi-Messenger Astrophysics

Many, many sources

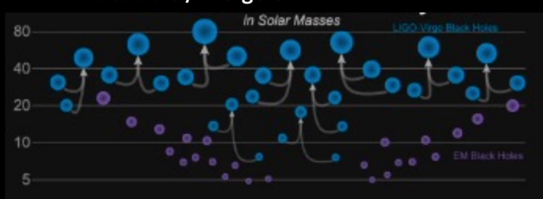
Supernovae + α

Supernova remnants

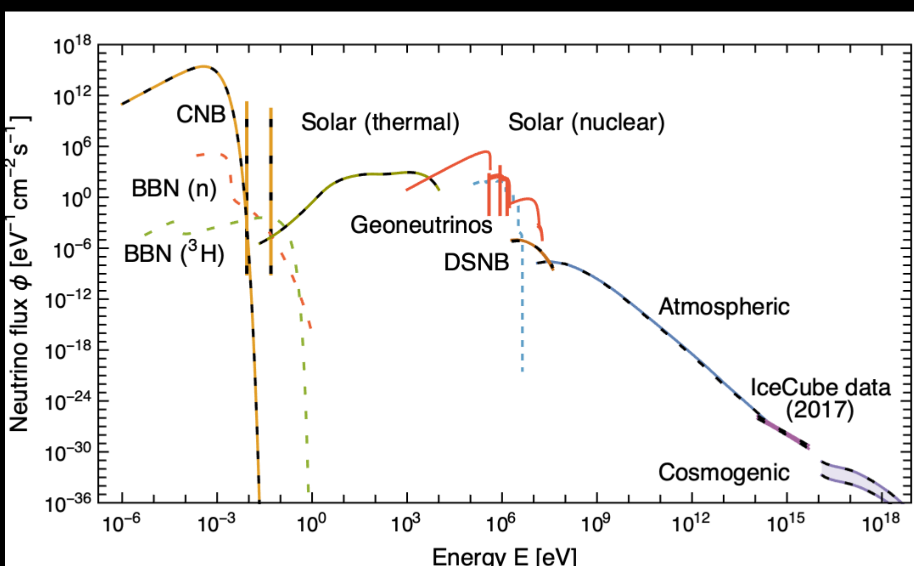
Neutron star, magnetar

Dark matter
Primordial BH

Black hole / mergers



Supermassive black hole



Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF

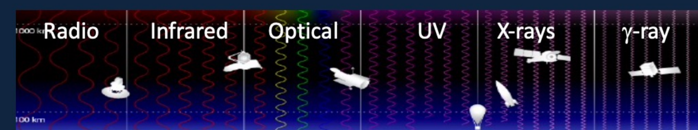
Many, many detectors

ν
SuperK + gadolinium
JUNO
DUNE
Hyper-Kamiokande
KM3NeT
IceCube-gen2
ARA

CR
LHAASO
PUEO
GRAND
TAMBO
POEMMA

GW
KAGRA
LIGO-India
LIGO Voyager
Cosmic Explorer
Einstein Telescope
LISA

γ



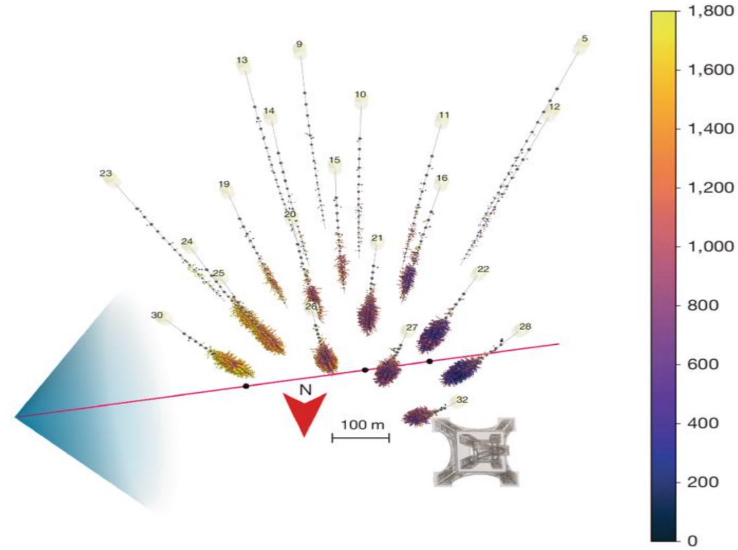
Radio: LAST, SKA
Infrared: JWST
Optical: LSST, TMT, ELT
X-rays: Athena
γ-ray: CTA, SWGO

Shunsaku Horiuchi

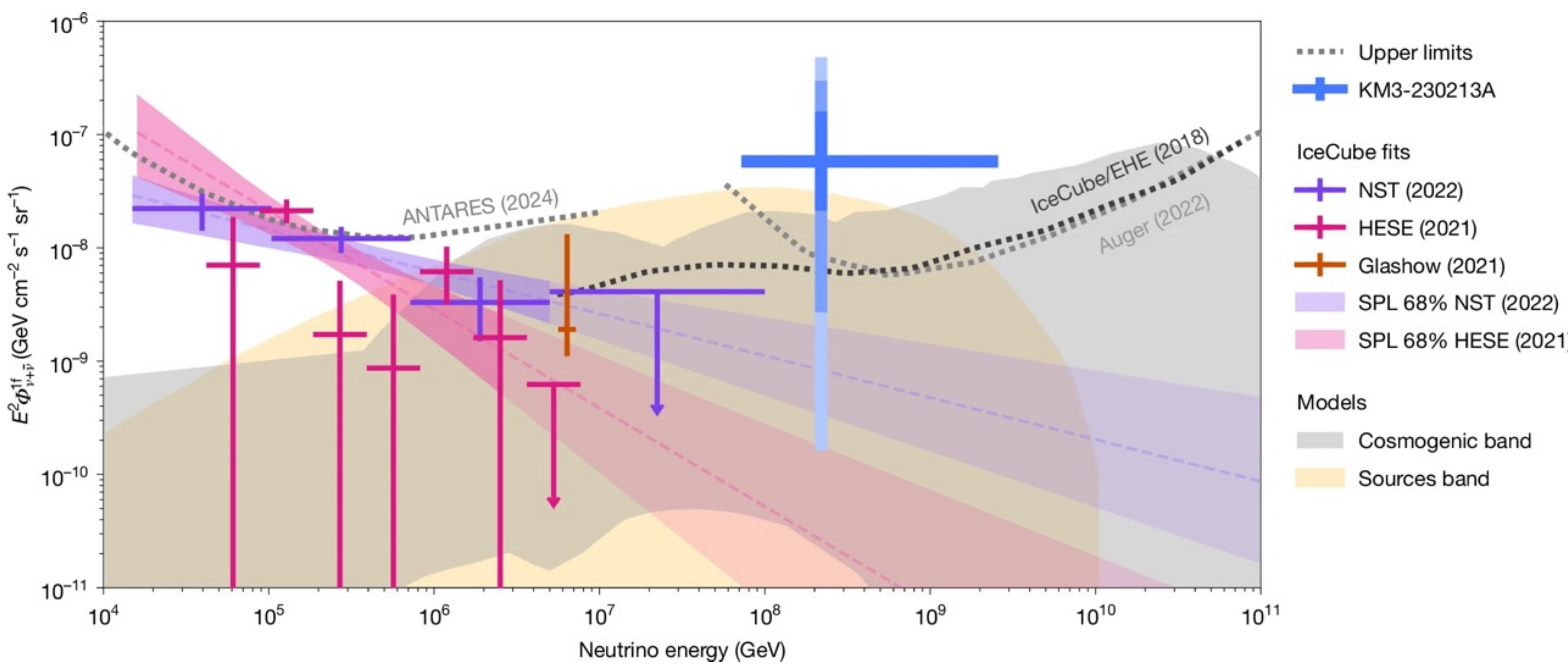
- Neutrinos are tools to understand the sources
- Natural neutrino sources are messengers of *physics*

Highlight example:

an amazing neutrino event seen by KM3NeT!



Nu energy 220^{+570}_{-110} PeV

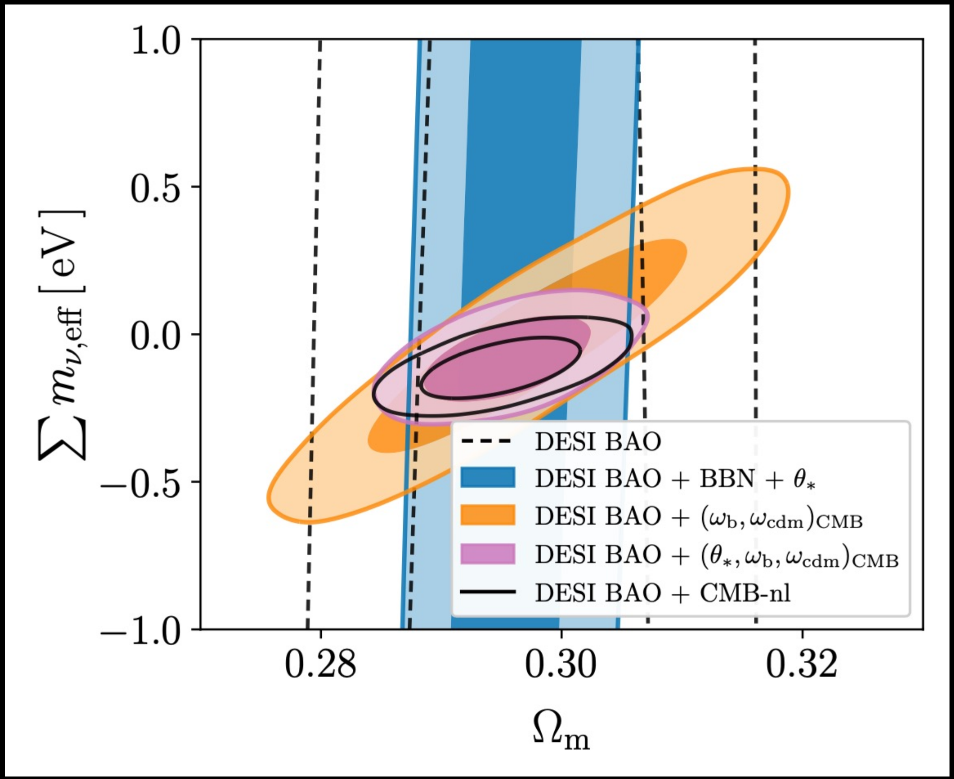


Plenary by Annarita Margiotta on Tuesday

Neutrinos and Cosmology

Fits to multiple cosmological measurements can tell us about ν properties, notably:

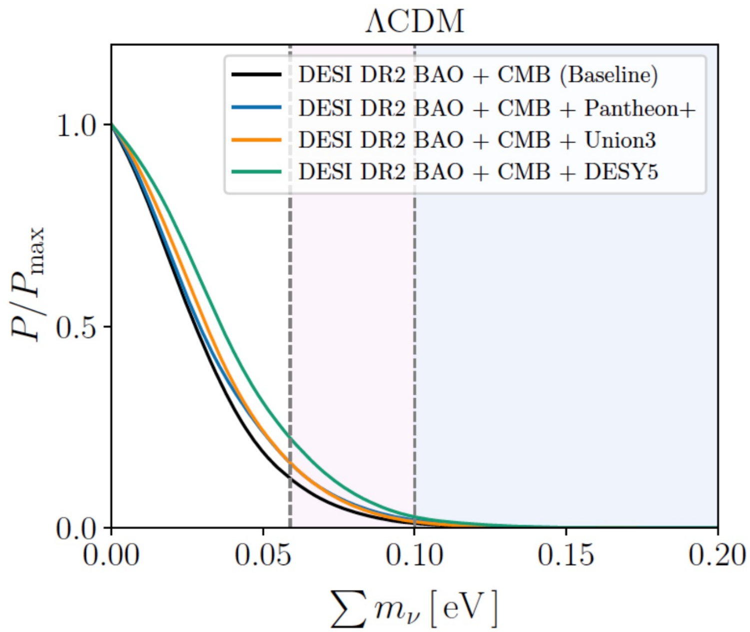
- Absolute neutrino mass scale
- N_{eff}, effective number of relativistic species



arXiv:2503.14744v2

Latest cosmology data, including new DESI results, tend to favor very small neutrino mass scale....

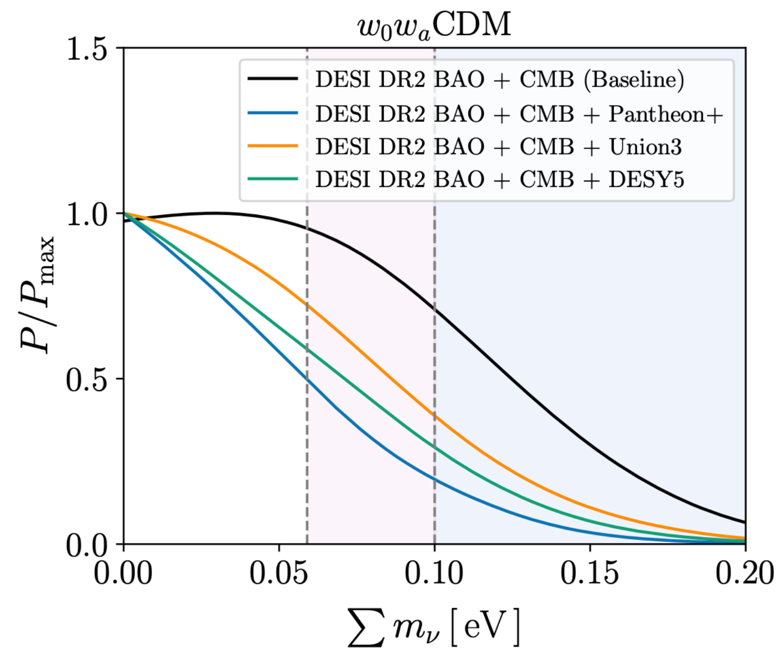
arXiv:2503.14744v2



$$\sum m_\nu < 0.053 \text{ eV}$$

in some tension
with 3-flavor oscillations....

However, modified cosmology can relieve the tension...



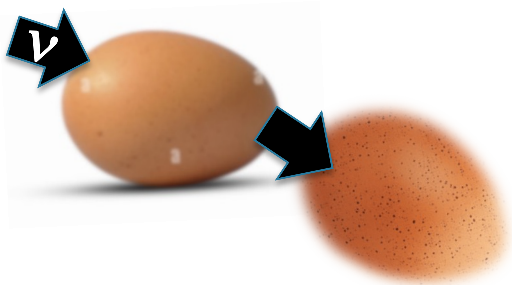
Laboratory neutrino measurements can provide constraints to cosmology

Neutrino interactions with matter
must be understood over a range of energies...
osc interpretation+BSM+astro motivations... **many efforts!**

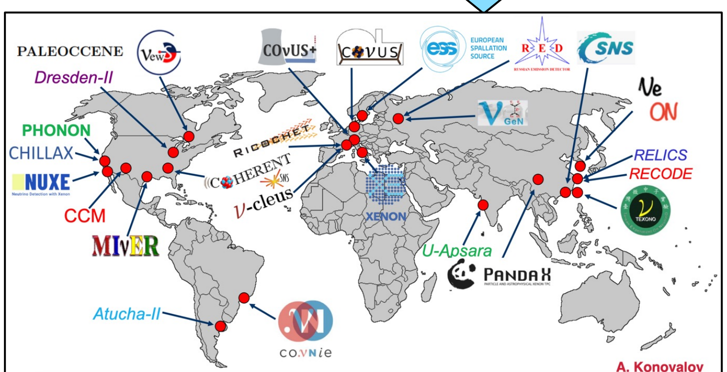
keV MeV GeV TeV PeV

Some dedicated
to cross sections,
some with day jobs

Neutrino interactions with matter
must be understood over a range of energies...
osc interpretation+BSM+astro motivations... **many efforts!**



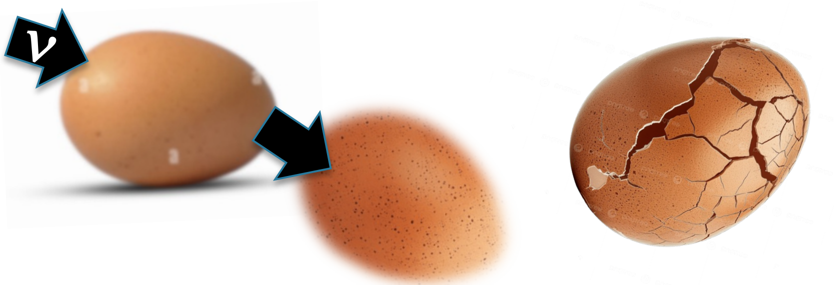
keV MeV GeV TeV PeV



World of CEvNS experiments

Some dedicated
to cross sections,
some with day jobs

Neutrino interactions with matter
must be understood over a range of energies...
osc interpretation+BSM+astro motivations... **many efforts!**



keV MeV GeV TeV PeV

World of CEvNS experiments

Coherent Captain Mills

Some dedicated to cross sections, some with day jobs

Neutrino interactions with matter

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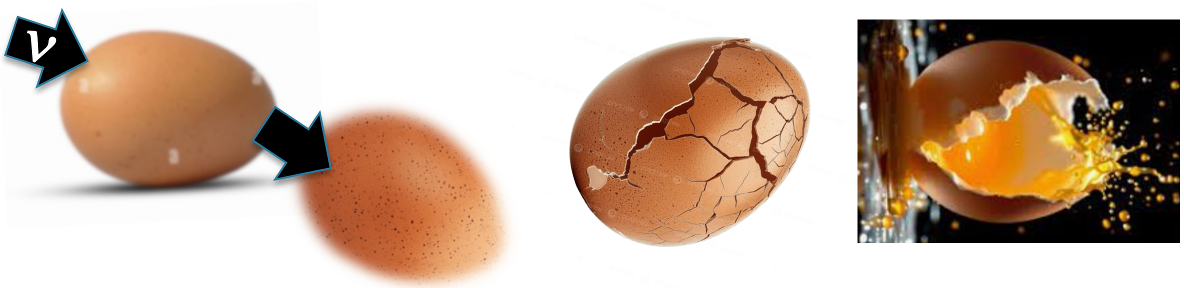

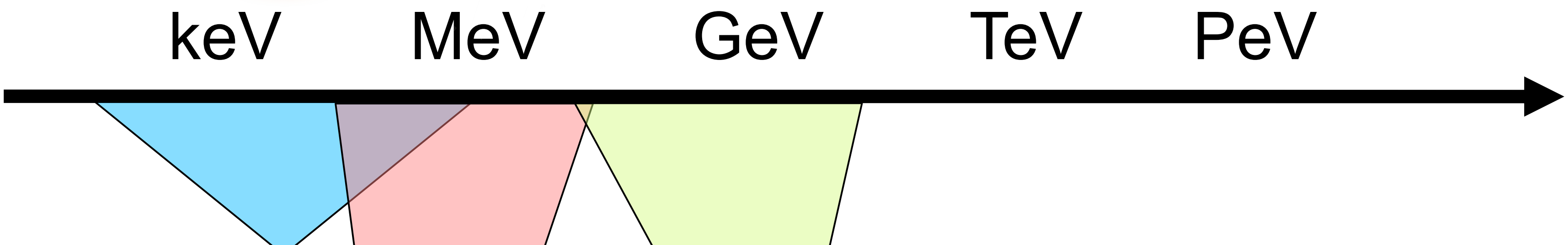

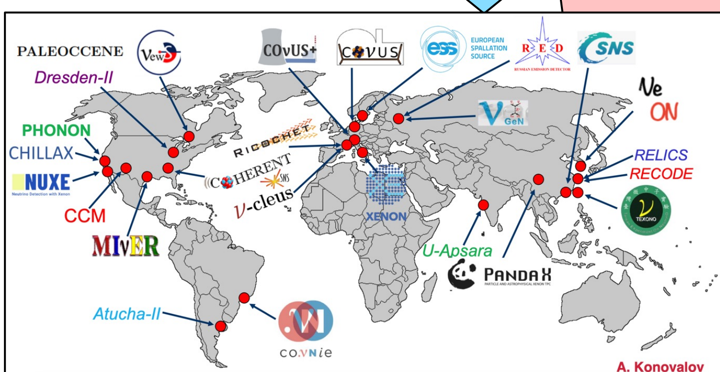

World of CEvNS experiments

COHERENT
JSNS²
J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source

Coherent Captain Mills

MINERvA
SBND Short-Baseline Near Detector
NINJA
ICARUS
T2K
μBooNE
νSTORM
NOvA

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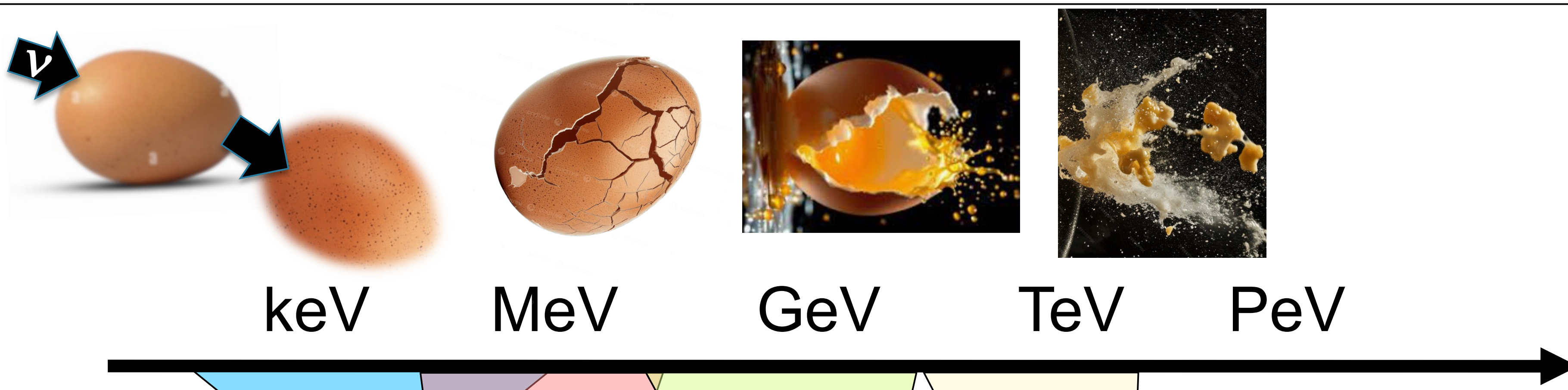
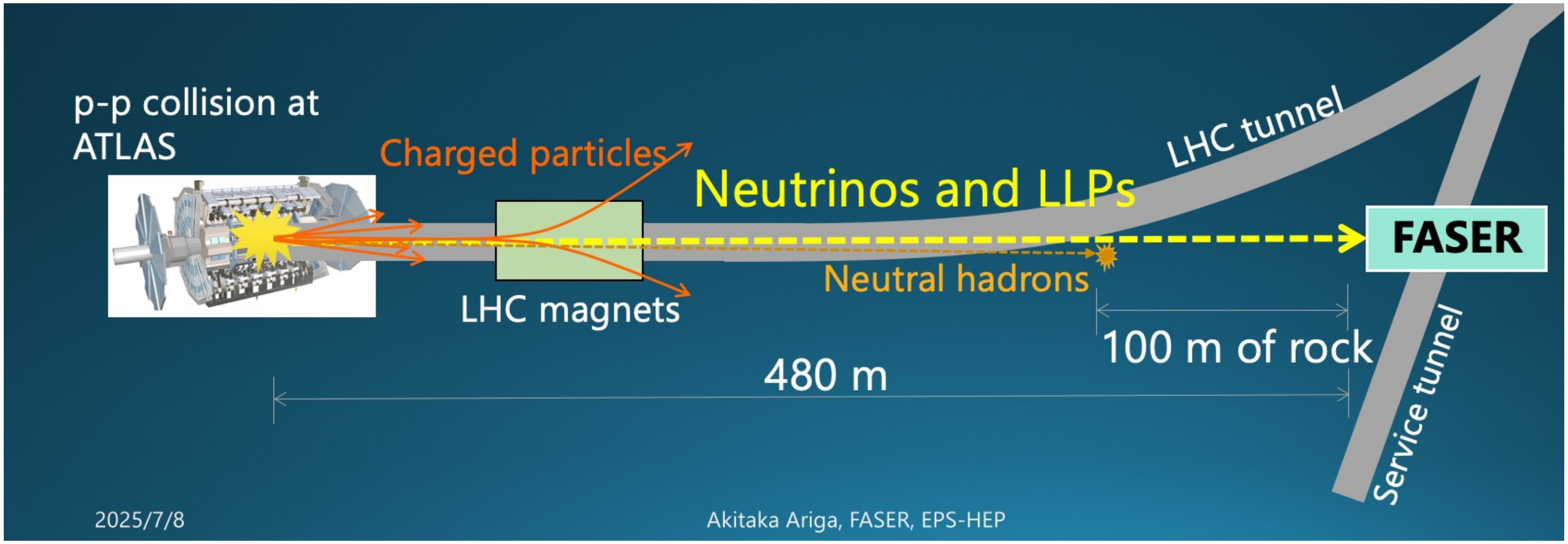


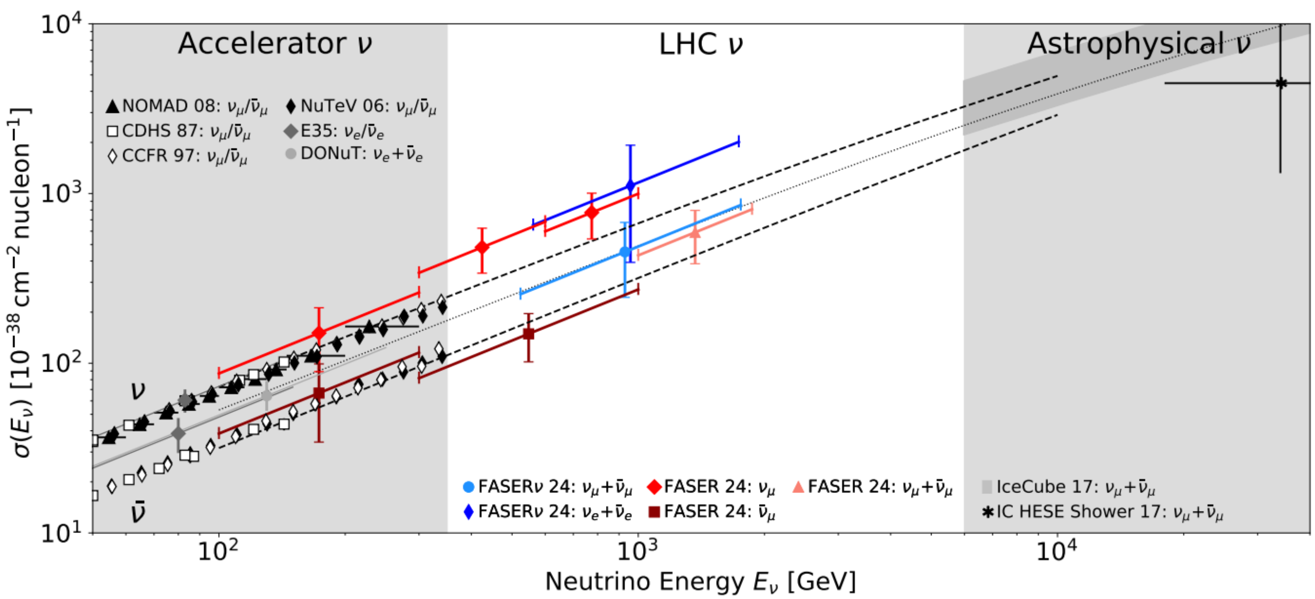
World of CEvNS experiments

Coherent Captain Mills

Some dedicated to cross sections, some with day jobs

One last specific highlight: **new results from FASER**

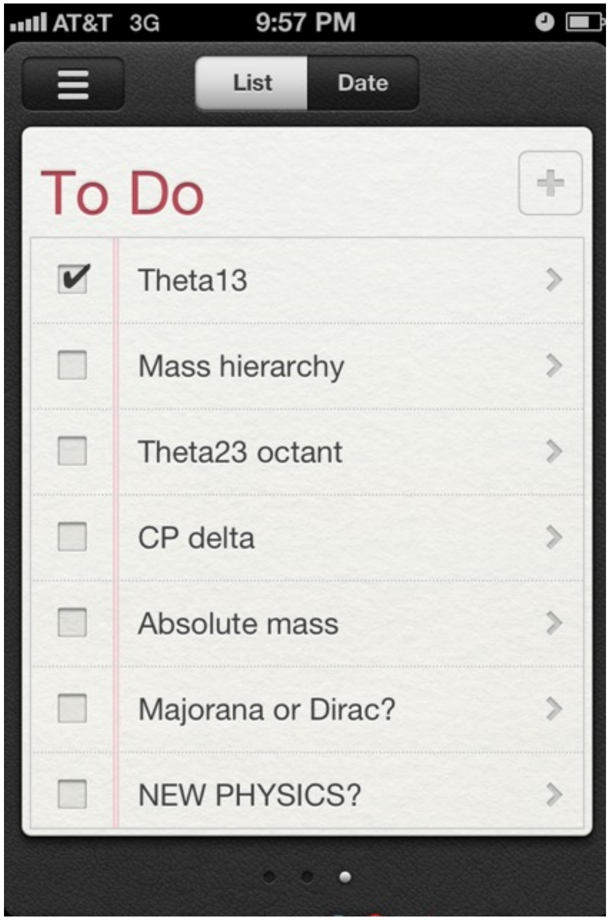




Measure flux-averaged cross section → interpret as cross-section *or* flux measurement

Overall Summary

Huge progress in understanding of neutrinos over the last 30 years, **but still many outstanding questions**



My IPhone from ~15 years ago!*

*I have never found a good to-do list app...

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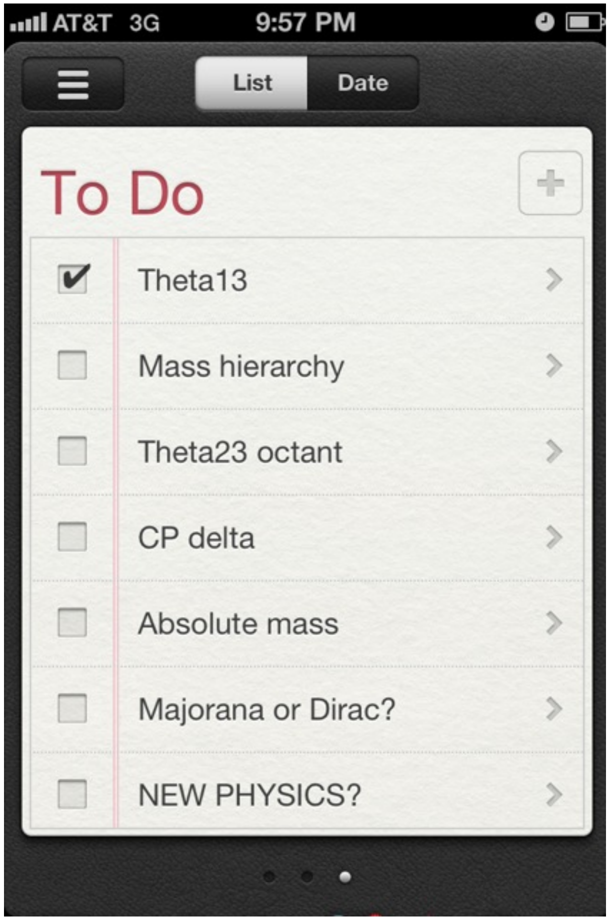

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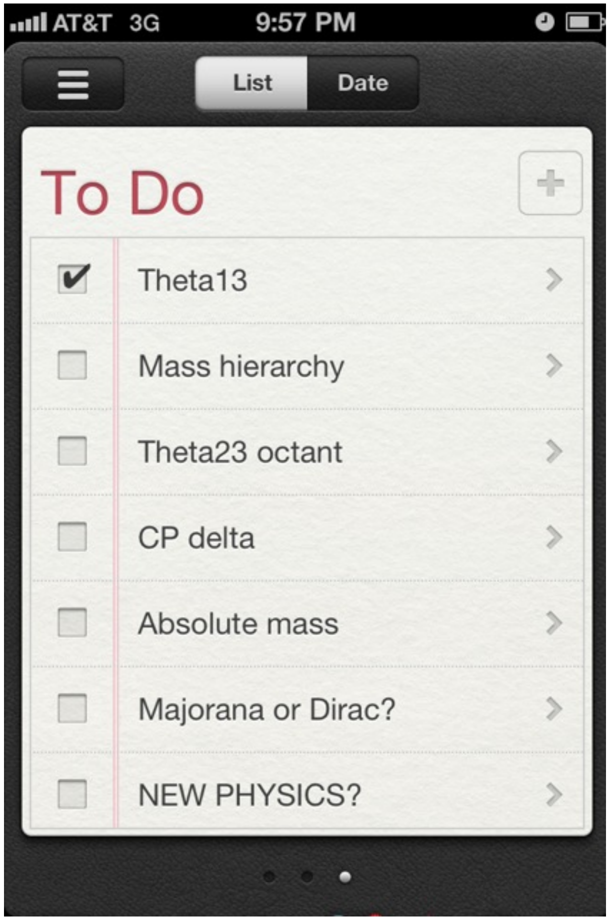

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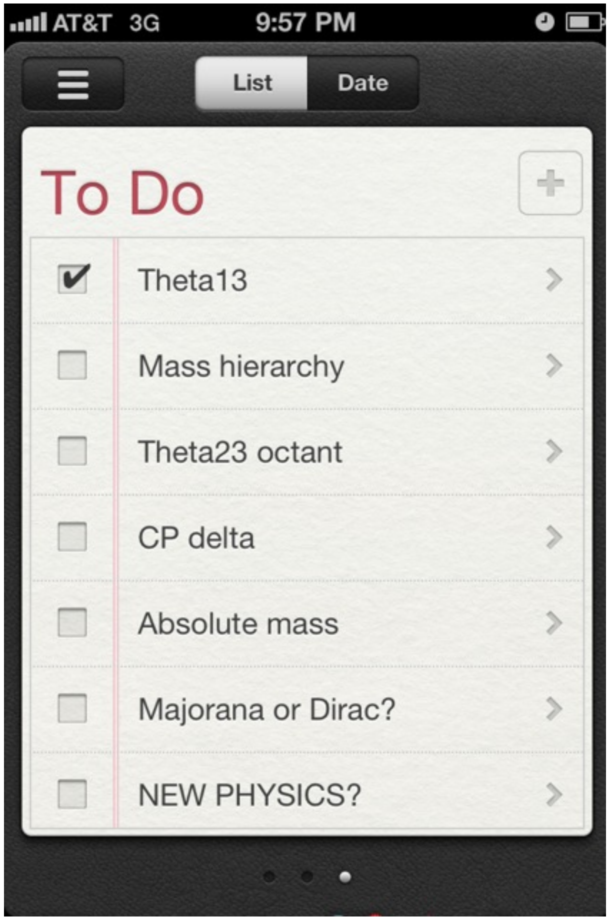

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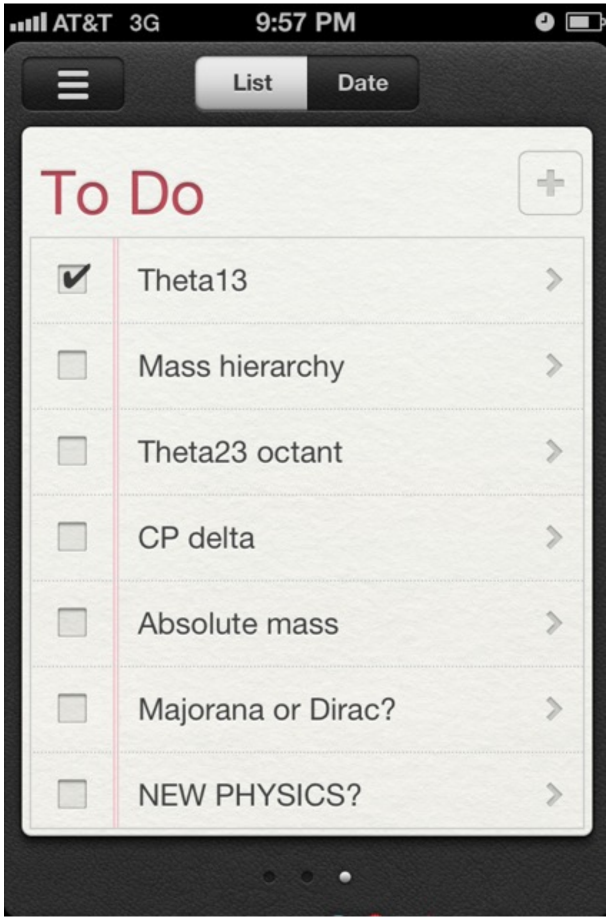

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We must keep pushing on the paradigm and searching broadly for BSM

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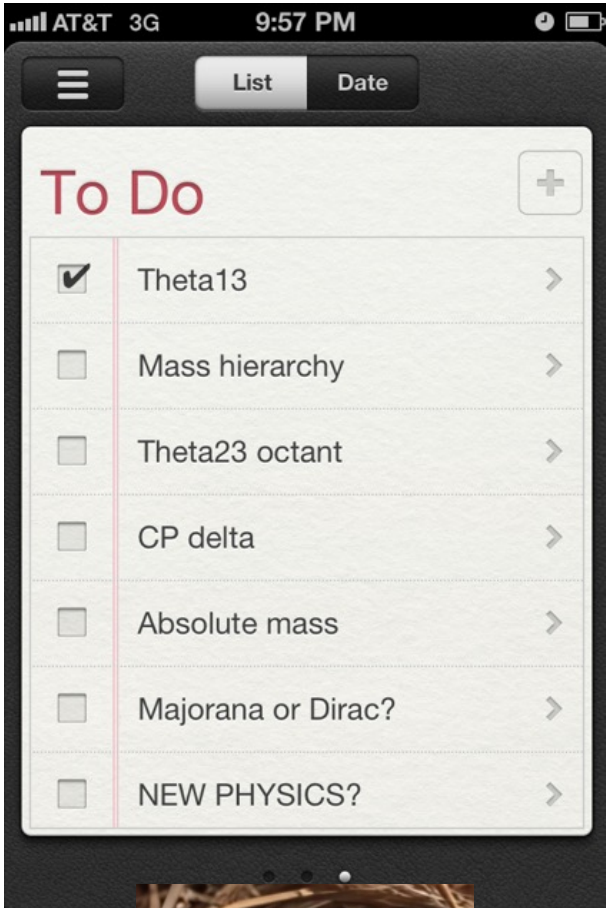

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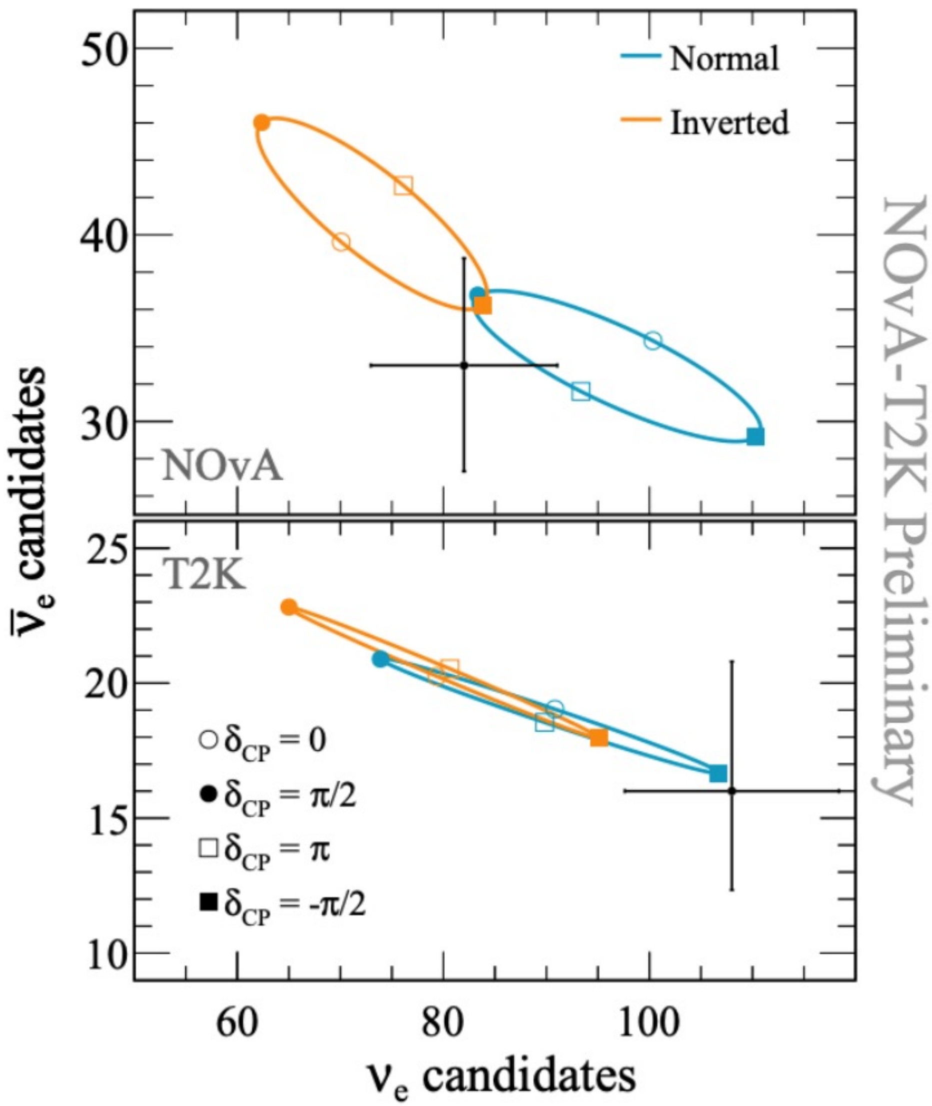
Tonne-scale NLDBD program

We must keep pushing on the paradigm and searching broadly for BSM

And Nature may still hold surprises for us!

Extras/Backups

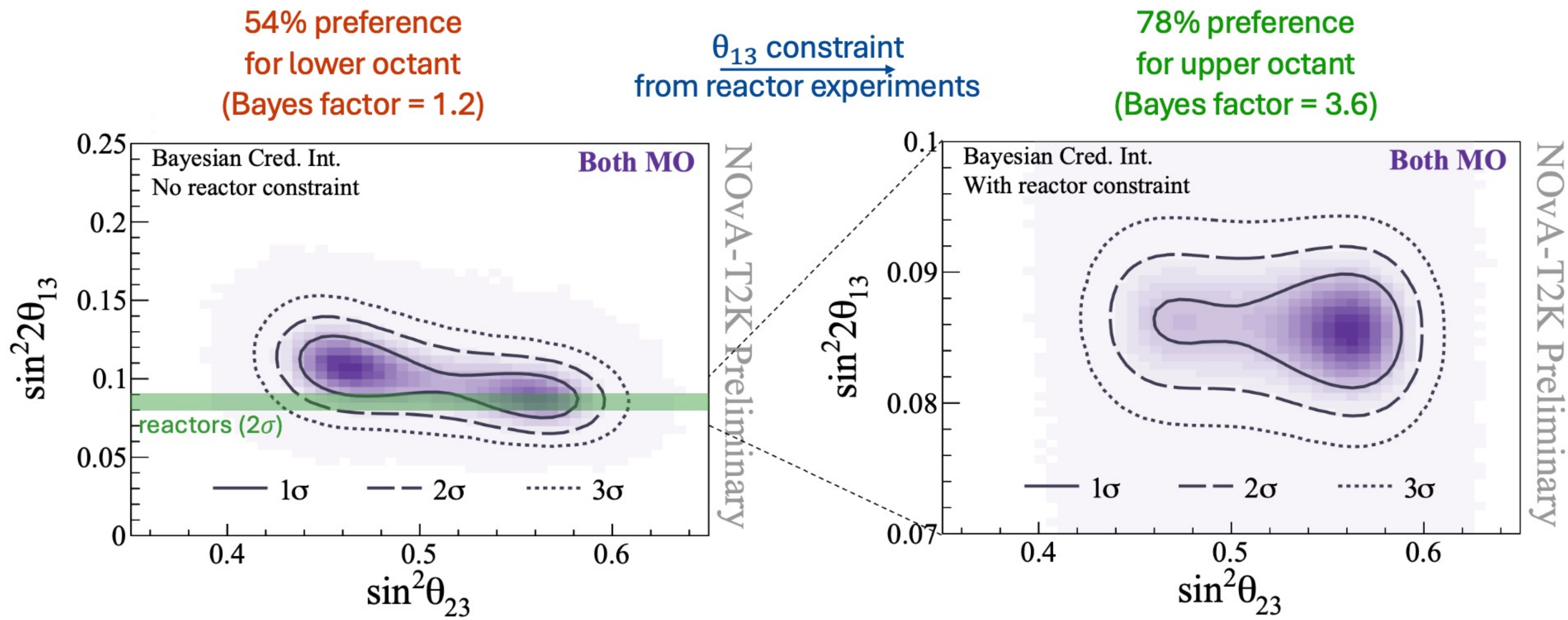
Individual T2K and NOvA datasets



Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137

Z. Vallari, CIPANP 2025

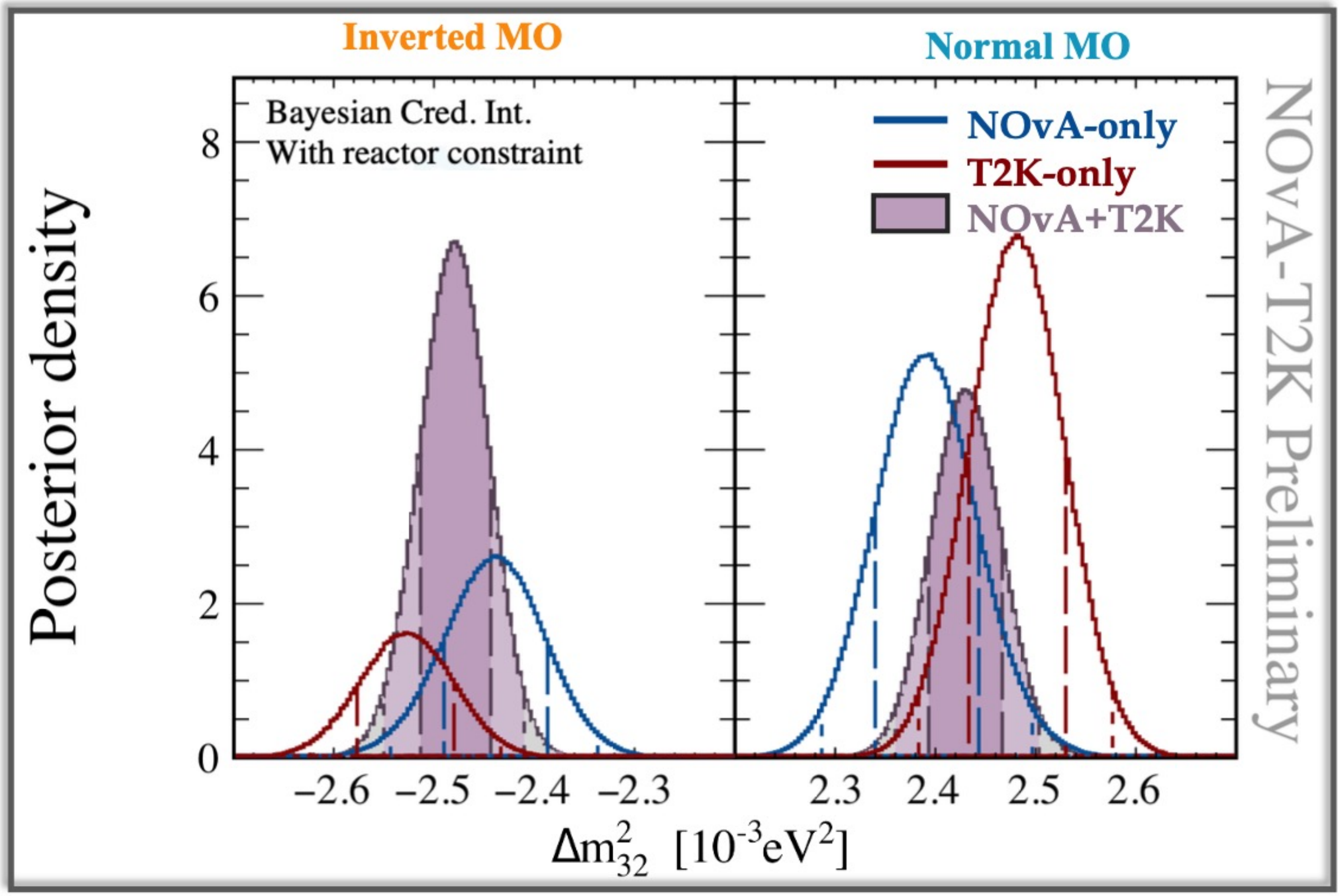
Octant fit, with and without reactor constraint



Z. Vallari, CIPANP 2025

Mass ordering result from joint T2K-NOvA fit

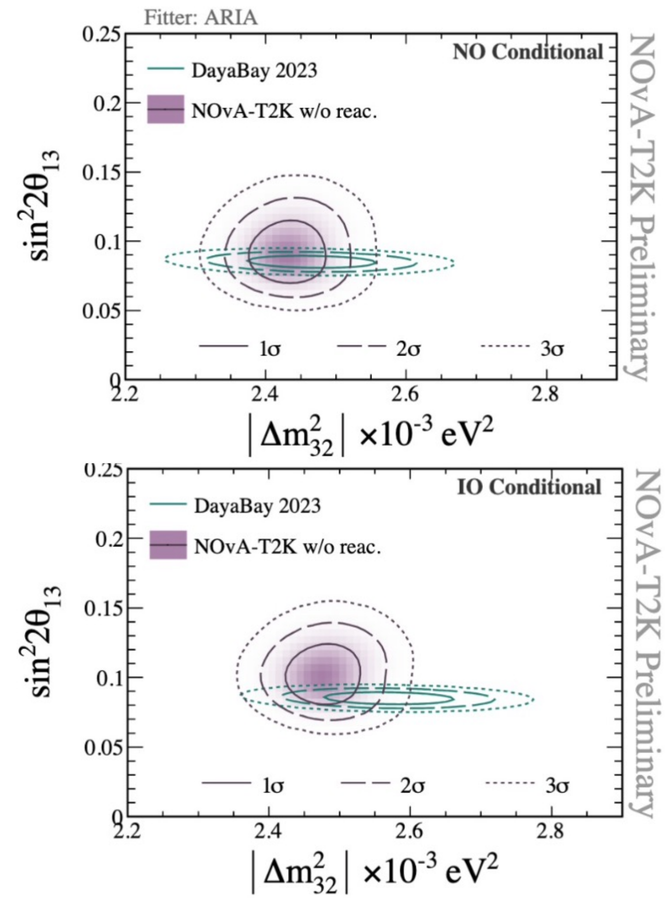
With reactor θ_{13} constraint



	NOvA only	T2K only	NOvA+T2K
Bayes factor	**2.07** Normal/Inverted ~67% : ~33% posterior	**4.24** Normal/Inverted ~81% : ~19% posterior	**1.36** Inverted/Normal ~58% : ~42% posterior

Z. Vallari, CIPANP 2025

Including the reactor constraint restores the preference for normal ordering

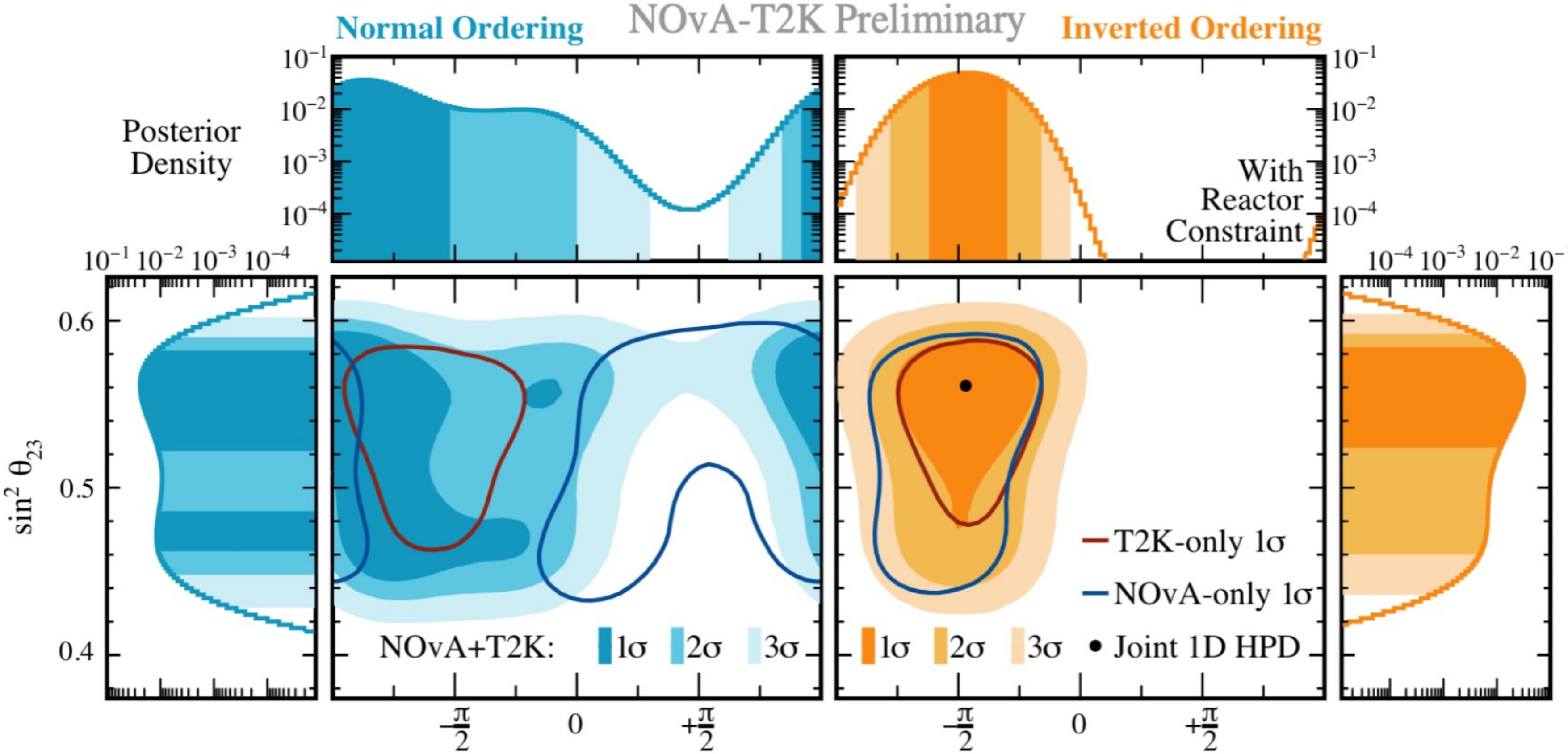


	NOvA - T2K w/o Daya Bay	NOvA – T2K w/ θ_{13} Daya Bay	NOvA - T2K w/ $(\theta_{13}, \Delta m^2_{32})$ Daya Bay
Bayes factor	**2.47** Inverted/Normal ~71% : ~29% posterior	**1.34** Inverted/Normal ~57% : ~43% posterior	**1.44** Normal/Inverted ~59% : ~41% posterior

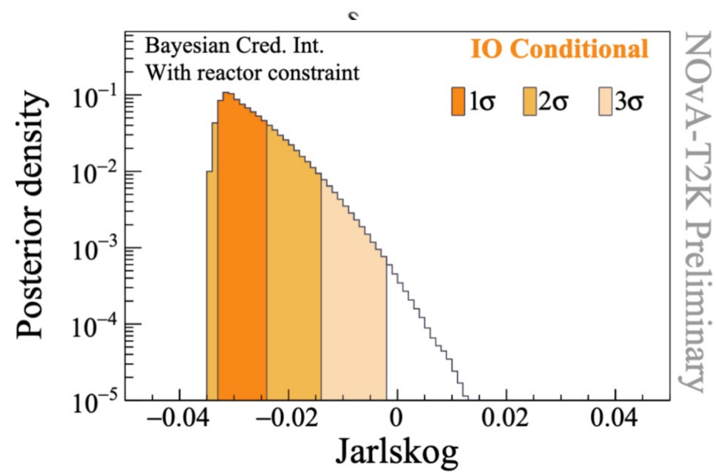
Z. Vallari, CIPANP 2025

Joint T2K-NOvA CPδ fit results

With reactor θ_{13} constraint



HPD = Highest Posterior Density



Z. Vallari, CIPANP 2025

Neutrinoless Double Beta Decay Experiments

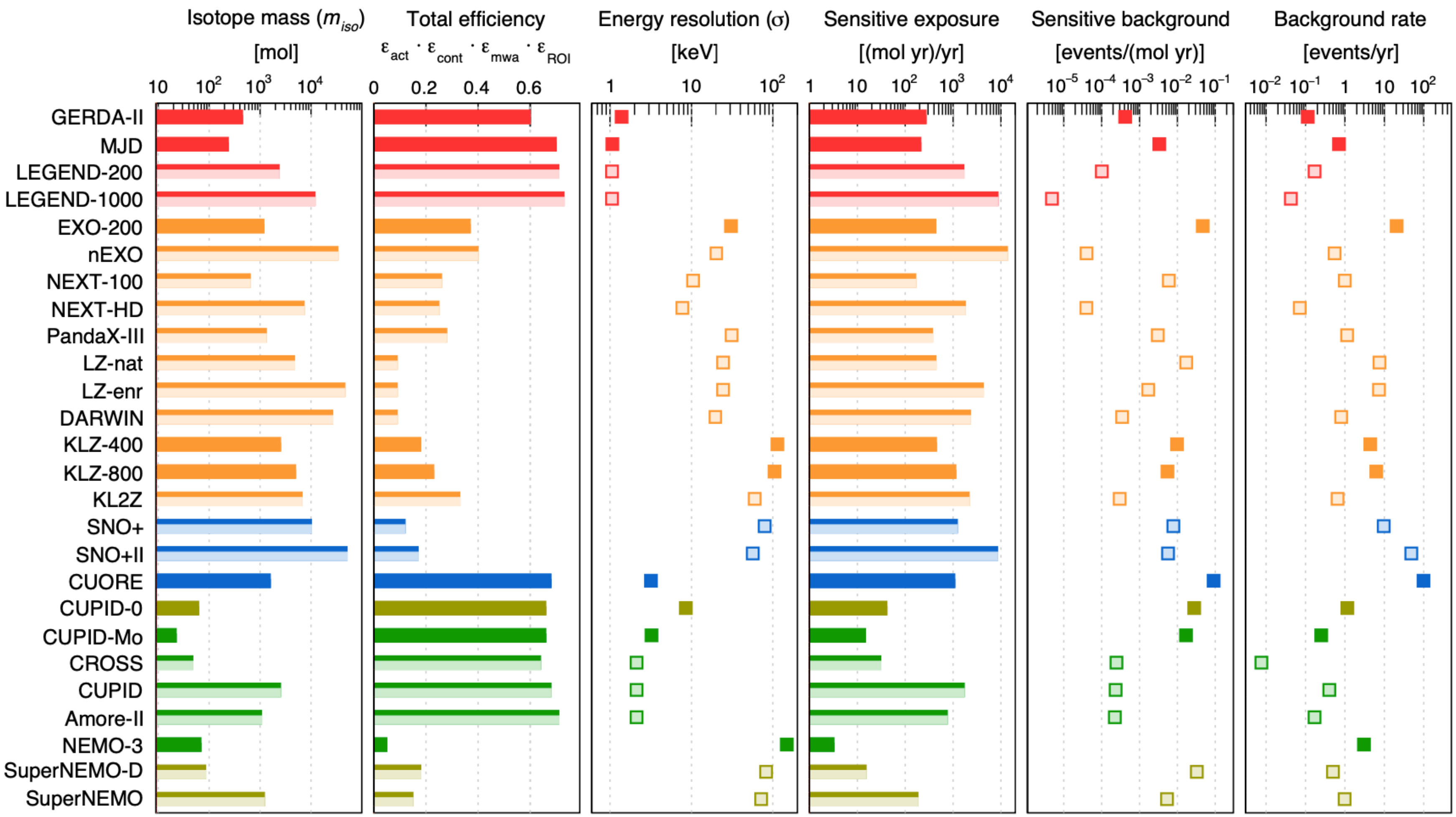
many, many isotopes and technologies

Recent and future experiments

Experiment	Isotope	Status	Lab	m_{iso} [mol]	ε_{act} [%]	ε_{cont} [%]	ε_{mva} [%]	σ [keV]	ROI [σ]	ε_{ROI} [%]	$\mathcal{E}$ $\left[\frac{mol\cdot yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{events}{mol\cdot yr}\right]$	λ_b $\left[\frac{events}{yr}\right]$	$T_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
High-purity Ge detectors (Sec. VI.B)															
GERDA-II	^{76}Ge	completed	LNGS	$4.5\cdot10^{2}$	88	91	79	1.4	-2,2	95	273	$4.2\cdot10^{-4}$	$1.1\cdot10^{-1}$	$1.2\cdot10^{26}$	93-222
MJD	^{76}Ge	completed	SURF	$3.1\cdot10^{2}$	91	91	86	1.1	-2,2	95	212	$3.3\cdot10^{-3}$	$7.1\cdot10^{-1}$	$4.7\cdot10^{25}$	149-355
LEGEND-200	^{76}Ge	construction	LNGS	$2.4\cdot10^{3}$	91	91	90	1.1	-2,2	95	1 684	$1.0\cdot10^{-4}$	$1.7\cdot10^{-1}$	$1.5\cdot10^{27}$	27-63
LEGEND-1000	^{76}Ge	proposed		$1.2\cdot10^{4}$	92	92	90	1.1	-2,2	95	8 736	$4.9\cdot10^{-6}$	$4.3\cdot10^{-2}$	$1.3\cdot10^{28}$	9-21
Xenon time projection chambers (Sec. VI.C)															
EXO-200	^{136}Xe	completed	WIPP	$1.2\cdot10^{3}$	46	100	84	31	-2,2	95	438	$4.7\cdot10^{-2}$	$2.1\cdot10^{+1}$	$2.4\cdot10^{25}$	111-477
nEXO	^{136}Xe	proposed	SNOLAB	$3.4\cdot10^{4}$	64	100	66	20	-2,2	95	13 700	$4.0\cdot10^{-5}$	$5.5\cdot10^{-1}$	$7.4\cdot10^{27}$	6-27
NEXT-100	^{136}Xe	construction	LSC	$6.4\cdot10^{2}$	88	76	49	10	-1.0,1.8	80	167	$5.9\cdot10^{-3}$	$9.9\cdot10^{-1}$	$7.0\cdot10^{25}$	66-281
NEXT-HD	^{136}Xe	proposed		$7.4\cdot10^{3}$	95	89	44	7.7	-0.5,1.7	65	1 809	$4.0\cdot10^{-5}$	$7.2\cdot10^{-2}$	$2.2\cdot10^{27}$	12-50
PandaX-III-200	^{136}Xe	construction	CJPL	$1.3\cdot10^{3}$	77	74	65	31	-1.2,1.2	76	374	$3.0\cdot10^{-3}$	$1.1\cdot10^{+0}$	$1.5\cdot10^{26}$	45-194
LZ-nat	^{136}Xe	construction	SURF	$4.7\cdot10^{3}$	14	100	80	25	-1.4,1.4	84	440	$1.7\cdot10^{-2}$	$7.5\cdot10^{+0}$	$7.2\cdot10^{25}$	64-277
LZ-enr	^{136}Xe	proposed	SURF	$4.6\cdot10^{4}$	14	100	80	25	-1.4,1.4	84	4302	$1.7\cdot10^{-3}$	$7.3\cdot10^{+0}$	$7.1\cdot10^{26}$	20-87
Darwin	^{136}Xe	proposed		$2.7\cdot10^{4}$	13	100	90	20	-1.2,1.2	76	2 312	$3.5\cdot10^{-4}$	$8.0\cdot10^{-1}$	$1.1\cdot10^{27}$	17-72
Large liquid scintillators (Sec. VI.D)															
KLZ-400	^{136}Xe	completed	Kamioka	$2.5\cdot10^{3}$	44	100	97	114	0,1.4	42	450	$9.8\cdot10^{-3}$	$4.4\cdot10^{+0}$	$3.3\cdot10^{25}$	95-408
KLZ-800	^{136}Xe	taking data	Kamioka	$5.0\cdot10^{3}$	55	100	100	105	0,1.4	42	1 143	$5.5\cdot10^{-3}$	$6.2\cdot10^{+0}$	$2.0\cdot10^{26}$	38-164
KL2Z	^{136}Xe	proposed	Kamioka	$6.7\cdot10^{3}$	80	100	97	60	0,1.4	42	2 176	$3.0\cdot10^{-4}$	$6.5\cdot10^{-1}$	$1.1\cdot10^{27}$	17-71
SNO+I	^{130}Te	construction	SNOLAB	$1.0\cdot10^{4}$	20	100	97	80	-0.5,1.5	62	1 232	$7.8\cdot10^{-3}$	$9.7\cdot10^{+0}$	$1.8\cdot10^{26}$	31-144
SNO+II	^{130}Te	proposed	SNOLAB	$5.1\cdot10^{4}$	27	100	97	57	-0.5,1.5	62	8 521	$5.7\cdot10^{-3}$	$4.8\cdot10^{+1}$	$5.7\cdot10^{26}$	17-81
Cryogenic calorimeters (Sec. VI.E)															
CUORE	^{130}Te	taking data	LNGS	$1.6\cdot10^{3}$	100	88	92	3.2	-1.4,1.4	84	1 088	$9.1\cdot10^{-2}$	$9.9\cdot10^{+1}$	$5.1\cdot10^{25}$	58-270
CUPID-0	^{82}Se	completed	LNGS	$6.2\cdot10^{1}$	100	81	86	8.5	-2,2	95	41	$2.8\cdot10^{-2}$	$1.2\cdot10^{+0}$	$4.4\cdot10^{24}$	283-551
CUPID-Mo	^{100}Mo	completed	LSM	$2.3\cdot10^{1}$	100	76	91	3.2	-2,2	95	15	$1.7\cdot10^{-2}$	$2.5\cdot10^{-1}$	$1.7\cdot10^{24}$	293-858
CROSS	^{100}Mo	construction	LSC	$4.8\cdot10^{1}$	100	75	90	2.1	-2,2	95	31	$2.5\cdot10^{-4}$	$7.6\cdot10^{-3}$	$4.9\cdot10^{25}$	54-160
CUPID	^{100}Mo	proposed	LNGS	$2.5\cdot10^{3}$	100	79	90	2.1	-2,2	95	1 717	$2.3\cdot10^{-4}$	$4.0\cdot10^{-1}$	$1.1\cdot10^{27}$	12-34
AMoRE-II	^{100}Mo	proposed	Yemilab	$1.1\cdot10^{3}$	100	82	91	2.1	-2,2	95	760	$2.2\cdot10^{-4}$	$1.7\cdot10^{-1}$	$6.7\cdot10^{26}$	15-43
Tracking calorimeters (Sec. VI.F)															
NEMO-3	^{100}Mo	completed	LSM	$6.9\cdot10^{1}$	100	100	11	148	-1.6,1.1	42	3	$9.4\cdot10^{-1}$	$3.0\cdot10^{+0}$	$5.6\cdot10^{23}$	505-1485
SuperNEMO-D	^{82}Se	construction	LSM	$8.5\cdot10^{1}$	100	100	28	83	-4.2,2.4	64	15	$3.3\cdot10^{-2}$	$5.0\cdot10^{-1}$	$8.6\cdot10^{24}$	201-391
SuperNEMO	^{82}Se	proposed	LSM	$1.2\cdot10^{3}$	100	100	28	72	-4.1,2.8	54	185	$5.3\cdot10^{-3}$	$9.8\cdot10^{-1}$	$7.8\cdot10^{25}$	67-131

ABDMV, RMP 2022, arXiv:2202.01787

Summary of recent and future experiments



ABDMV, RMP 2022, arXiv:2202.01787

Limits from US Long Range Plan

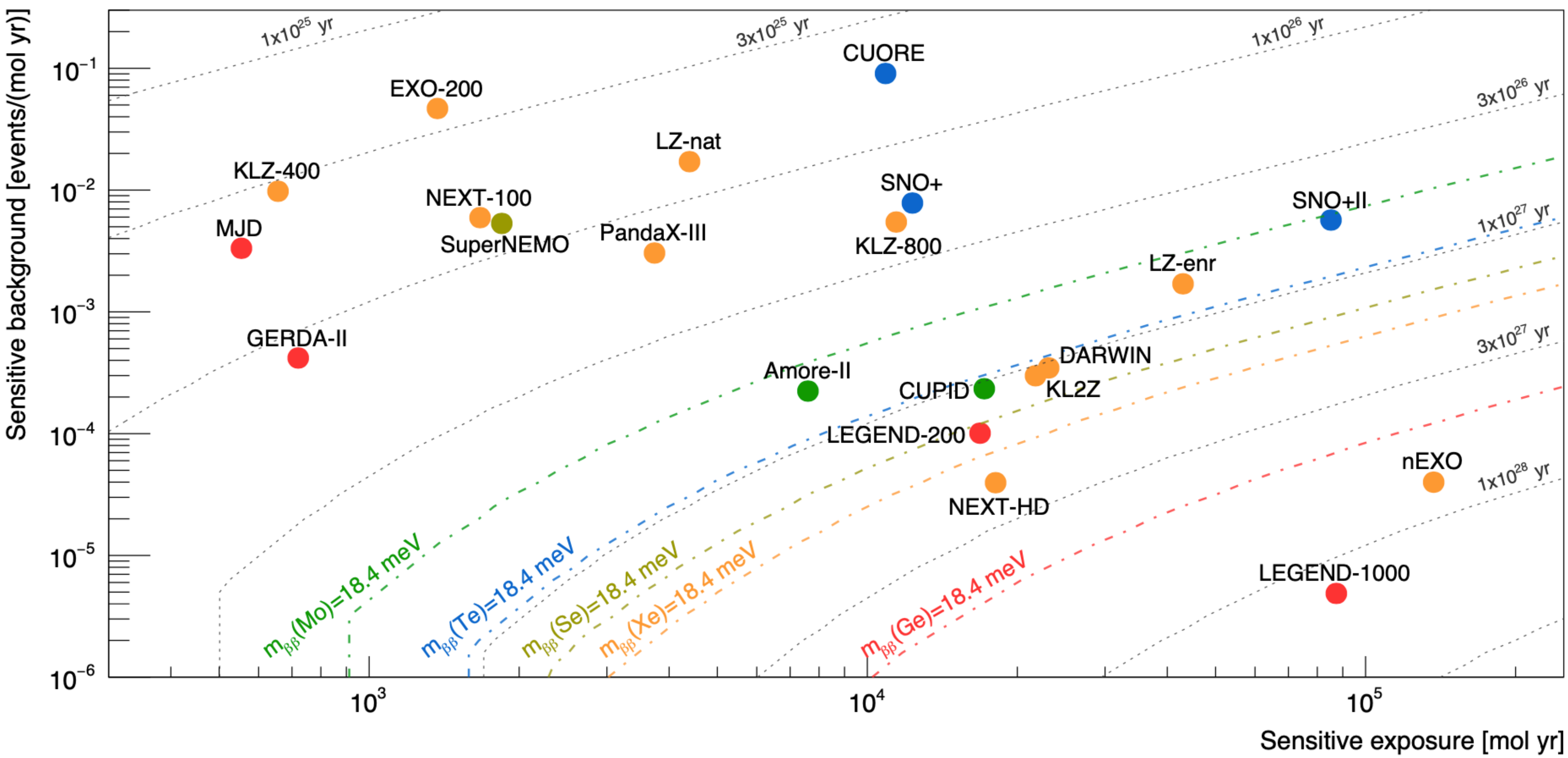
Experiment	Isotope	Half-life limit (1026 years)	mββ limit (meV)
MAJORANA	Germanium-76	0.83	113–269
GERDA	Germanium-76	1.8	79–180
EXO-200	Xenon-136	0.35	93–286
KamLAND-Zen	Xenon-136	2.3	36–156
CUORE	Tellurium-130	0.22	90–305

Updates:

LEGEND-200: 1.9 x 10^{26} yr arXiv:2505.10440
KL-ZEN: 28-122 meV

Sensitive background and exposure for recent and future experiments

ABDMV, RMP 2022, arXiv:2202.01787



Grey dashed lines: discovery sensitivity on the NLDBD $T_{1/2}$ (isotope-independent)

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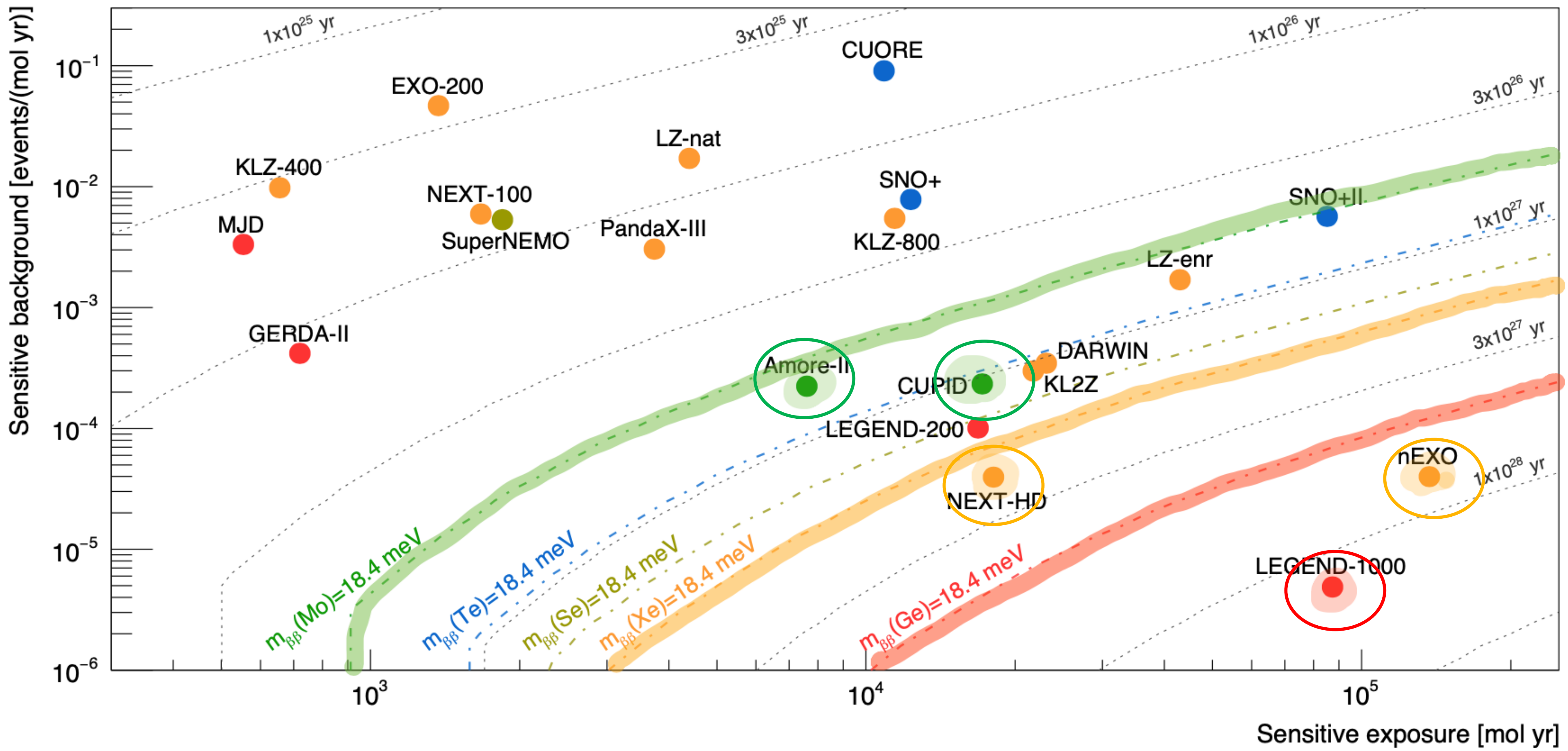

Grey dashed lines: discovery sensitivity on the NLDBD $T_{1/2}$ (isotope-independent)
Colored dashed lines: $m_{\beta\beta}$ sensitivities to **get to the bottom of the IO region** for *specific isotopes*, taking into account NME & phase space

[specific ~optimistic NME assumption] → **want to be to the lower right of *your* colored line!**