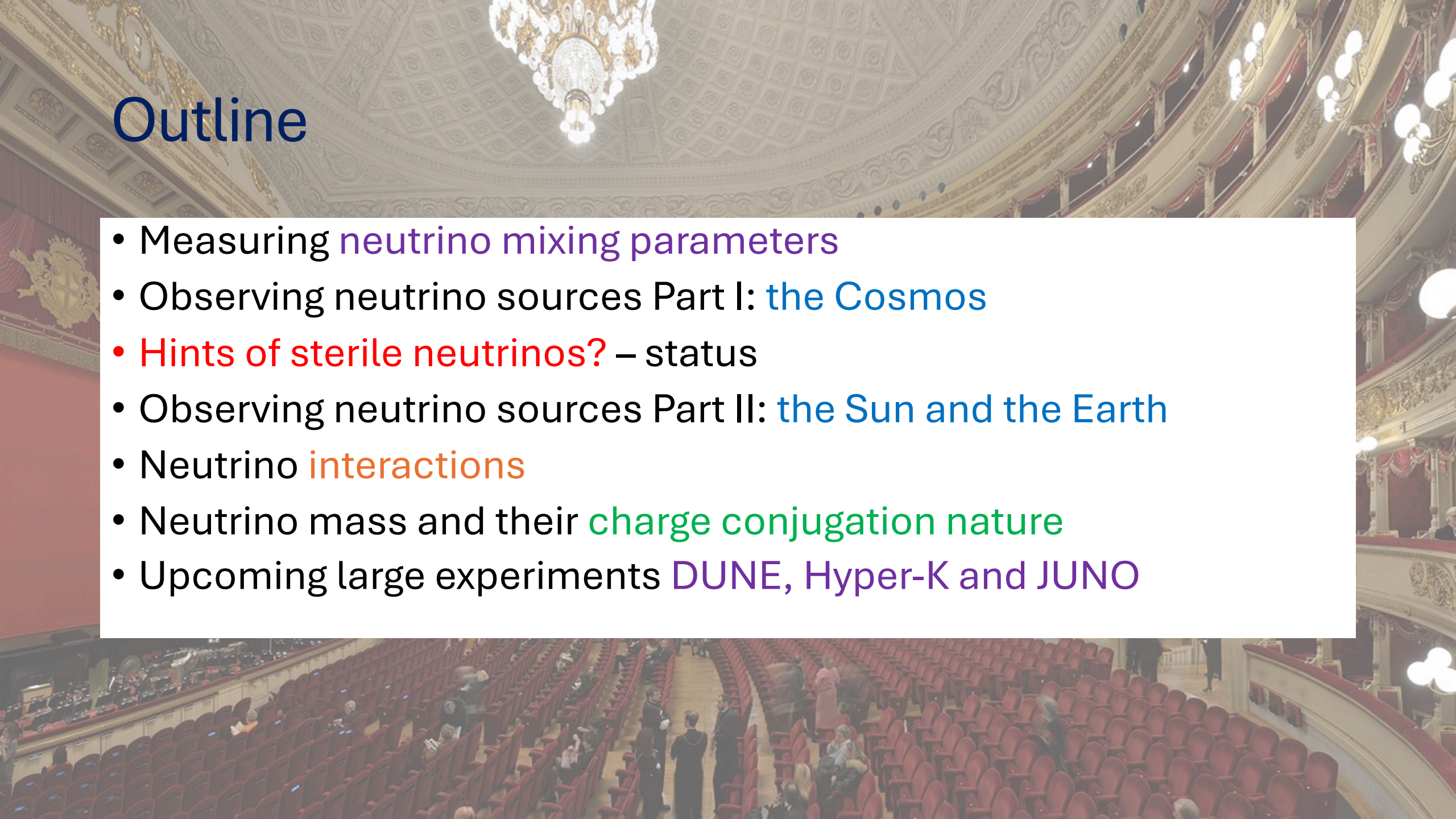
Overview of Neutrino Experiments: what's new after Neutrino 2024

Mark Chen

Queen's Univeristy

Selected highlights (experimental) from the Neutrino conference and future experiments we are eagerly anticipating



Outline

- Measuring neutrino mixing parameters
- Observing neutrino sources Part I: the Cosmos
- Hints of sterile neutrinos? – status
- Observing neutrino sources Part II: the Sun and the Earth
- Neutrino interactions
- Neutrino mass and their charge conjugation nature
- Upcoming large experiments DUNE, Hyper-K and JUNO

Neutrino Oscillation Paradigm
3-Flavour Mixing

PMNS Standard Convention:

From S. Parke

Atmospheric | Reactor | Solar | Majorana

Decreasing ν_e content

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}e^{i\eta_1} & 0 & 0\\ 0 & e^{i\eta_2} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

"easy to measure"

$$(U^2_{\alpha i}) = \begin{pmatrix} c^2_{13}c^2_{12} & c^2_{13}s^2_{12} & s^2_{13}\\ \cdots & \cdots & c^2_{13}s^2_{23}\\ \cdots & \cdots & c^2_{13}c^2_{23}\end{pmatrix}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}e^{i\eta_1} & 0 & 0\\ 0 & e^{i\eta_2} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Measured Values of Oscillation Parameters

Global fit to ν oscillation parameters

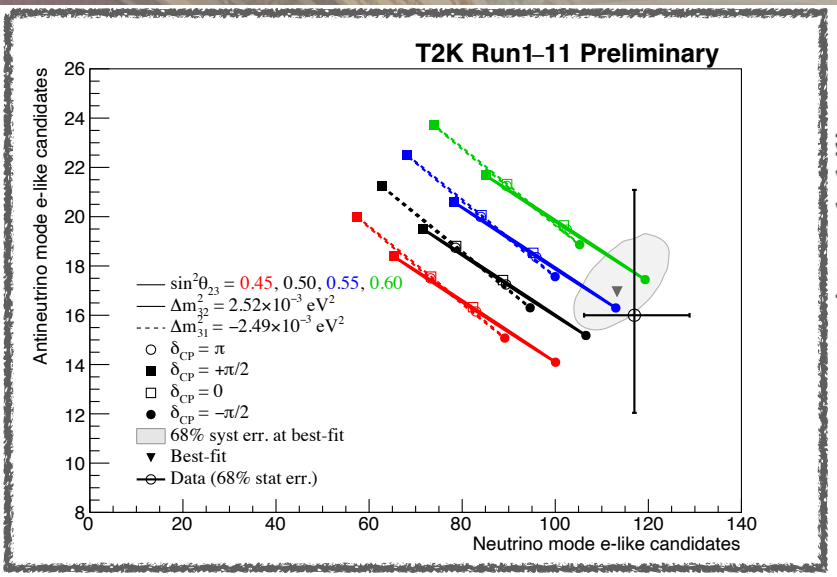
From M. Tórtola

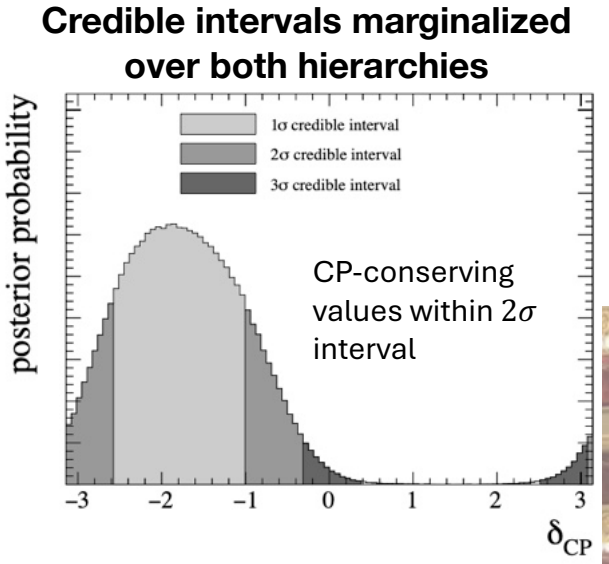
Valencia Global Fit (Pre-Nu2024)

parameter	best fit ± 1σ	3σ range	relative 1σ uncert	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7 %	
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	1.0 %	mass ordering?
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49		
$\sin^2\theta_{12}/10^{-1}$	$3.04^{\pm}0.16$	2.57–3.55	5.4%	
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	3-4%	octant?
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03		
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	2.6%	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38		
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	10-15%	maximal CP violation??
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87		

Presented by C. Giganti

T2K New Results and ND280 Upgrade

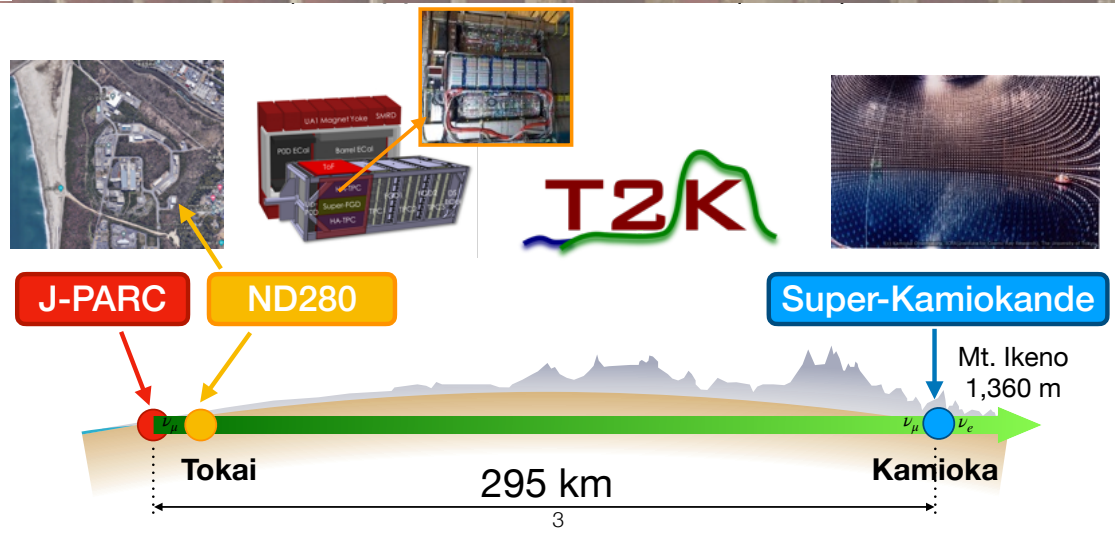




Mass ordering
NO/IO 3.3 Bayes Factor

Octant
Upper/Lower 2.6 BF

Beam power → 800 kW last week!
ND280 upgraded with new SuperFGD,
2 High-Angle TPCs, 6 ToF planes for neutrons
and taking data!



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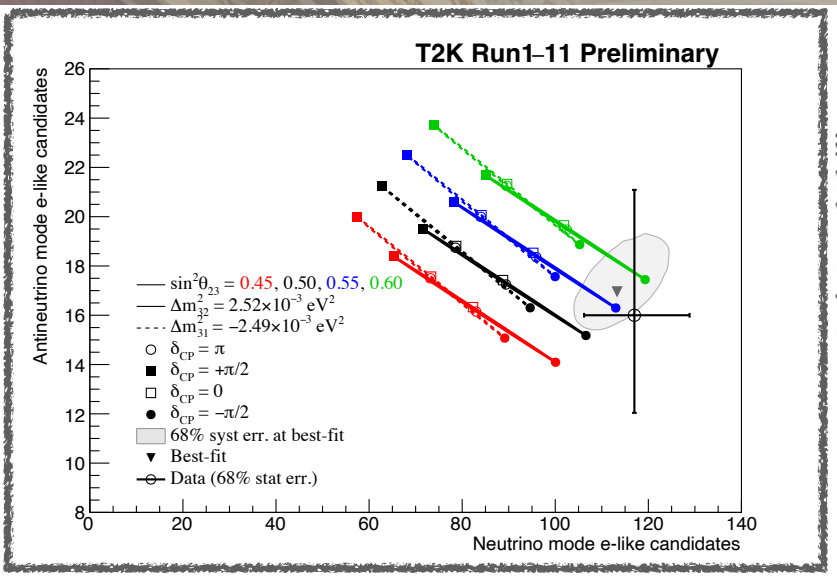

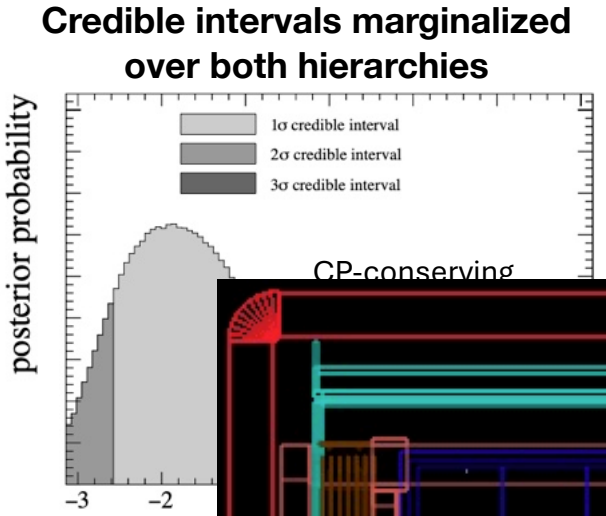

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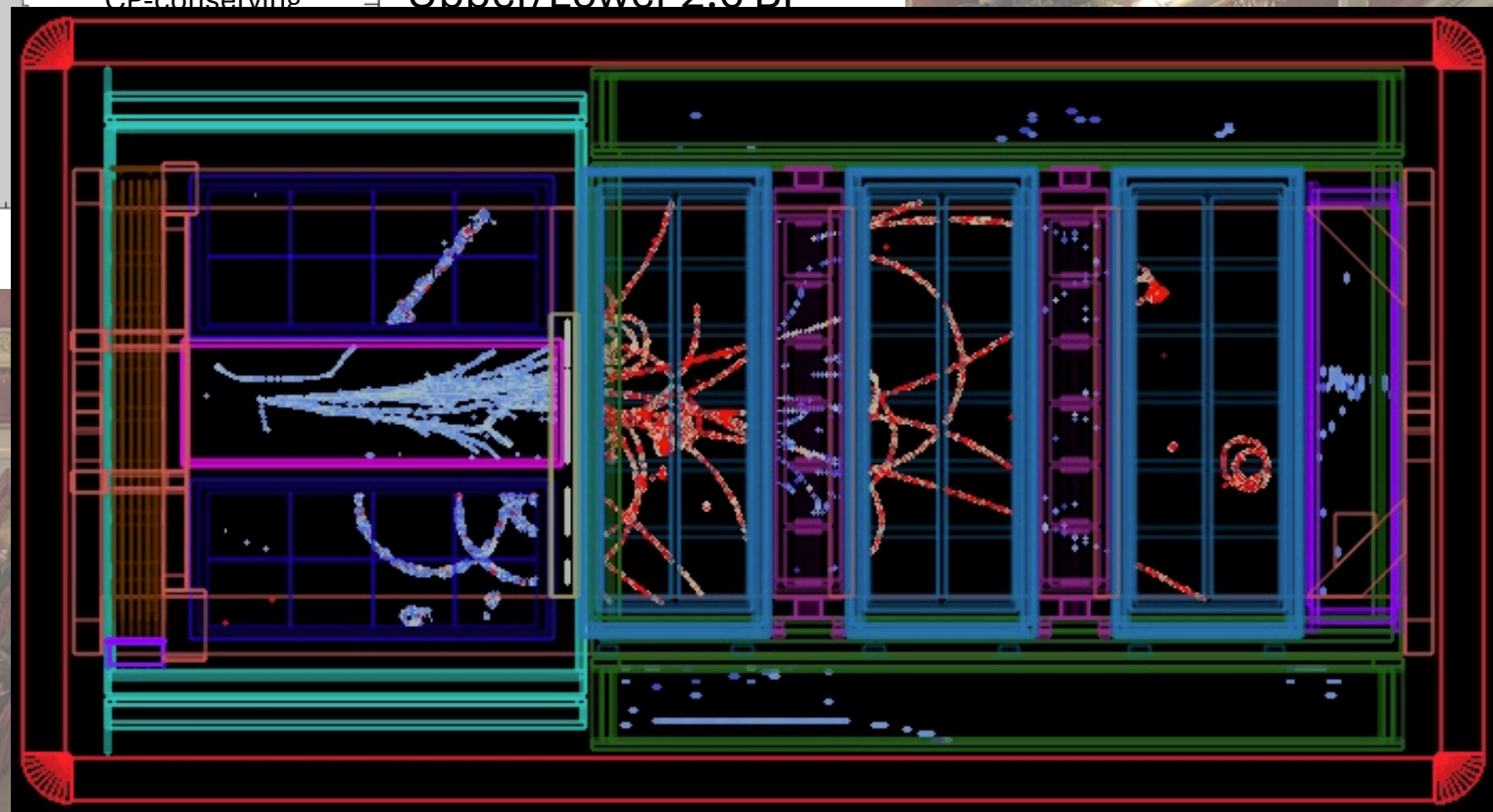
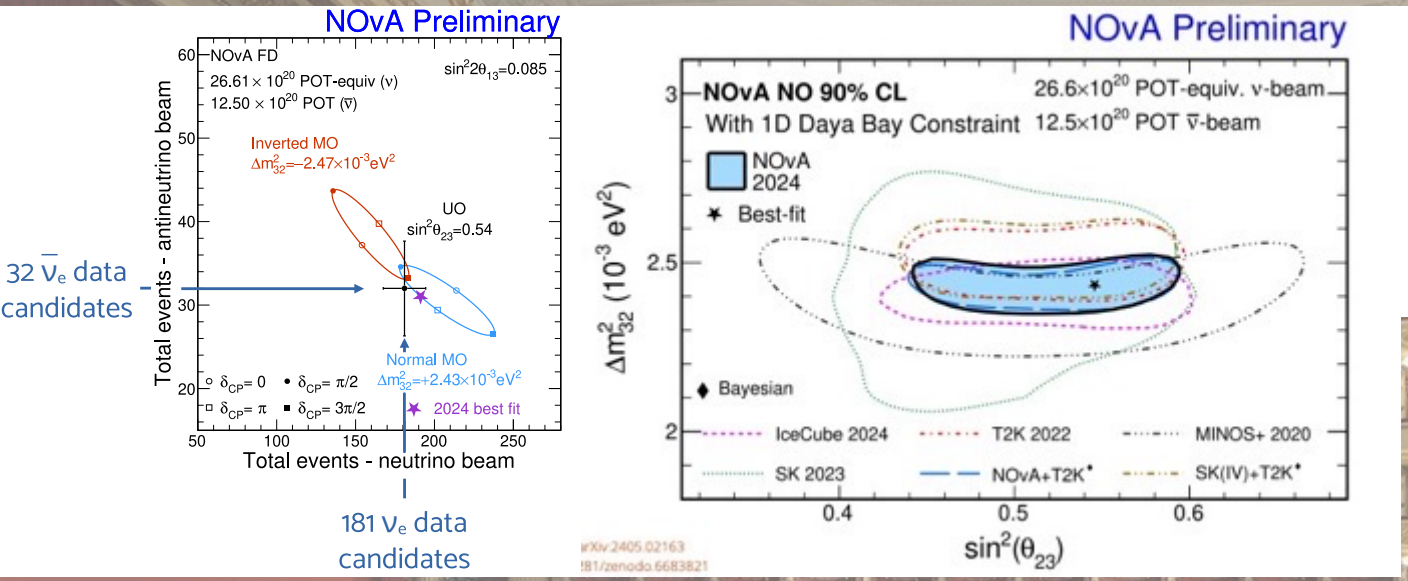


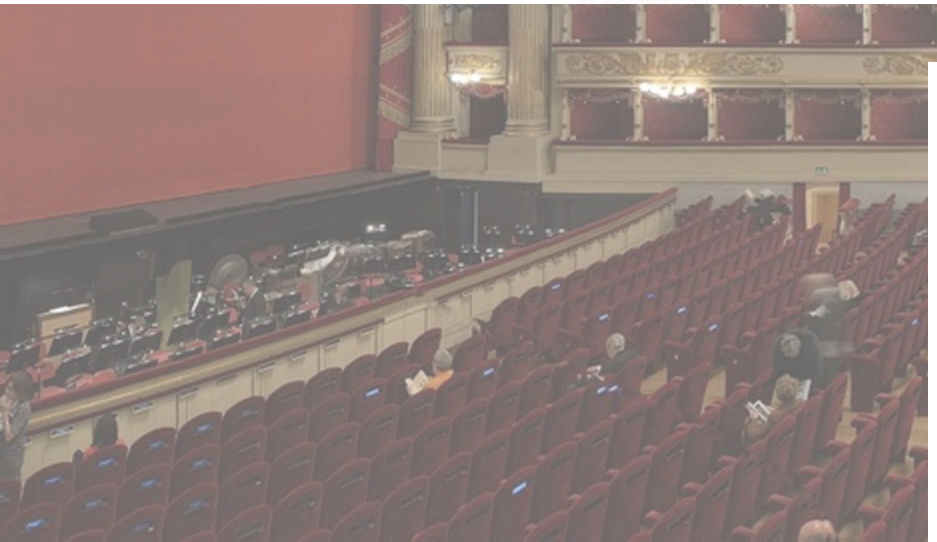
Presented by J. Wolcott

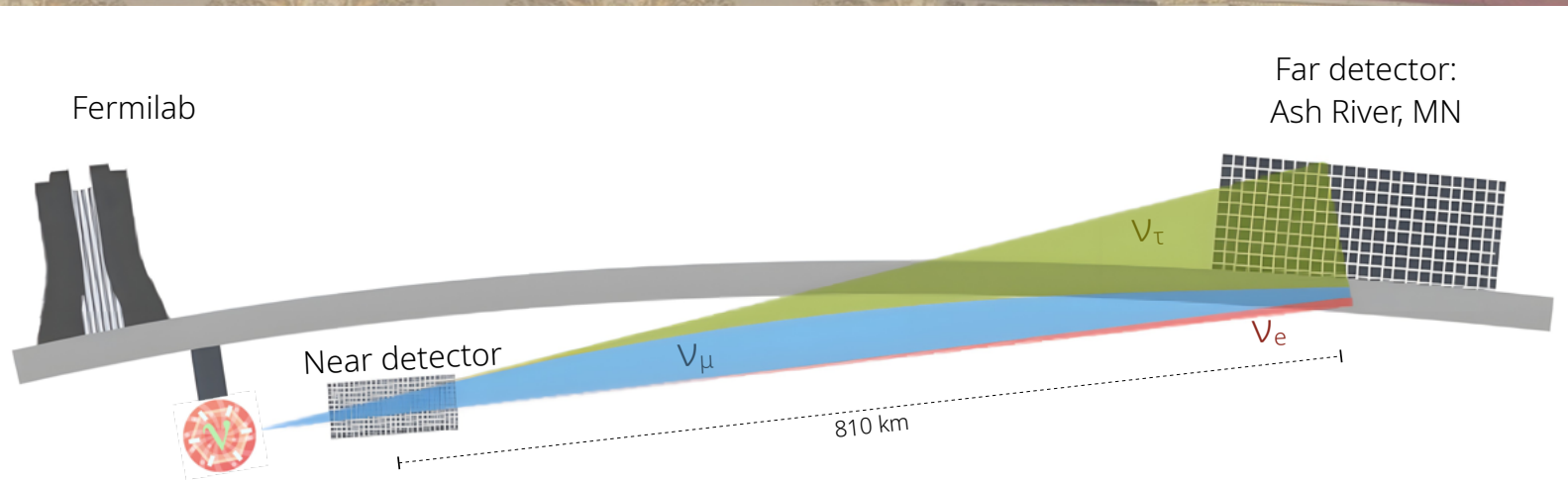
NOvA New Results with 10 yrs Data



Mass ordering (w/1D reactor)
NO/IO 3.2 Bayes Factor

Octant (w/1D reactor)
Upper/Lower 2.2 BF





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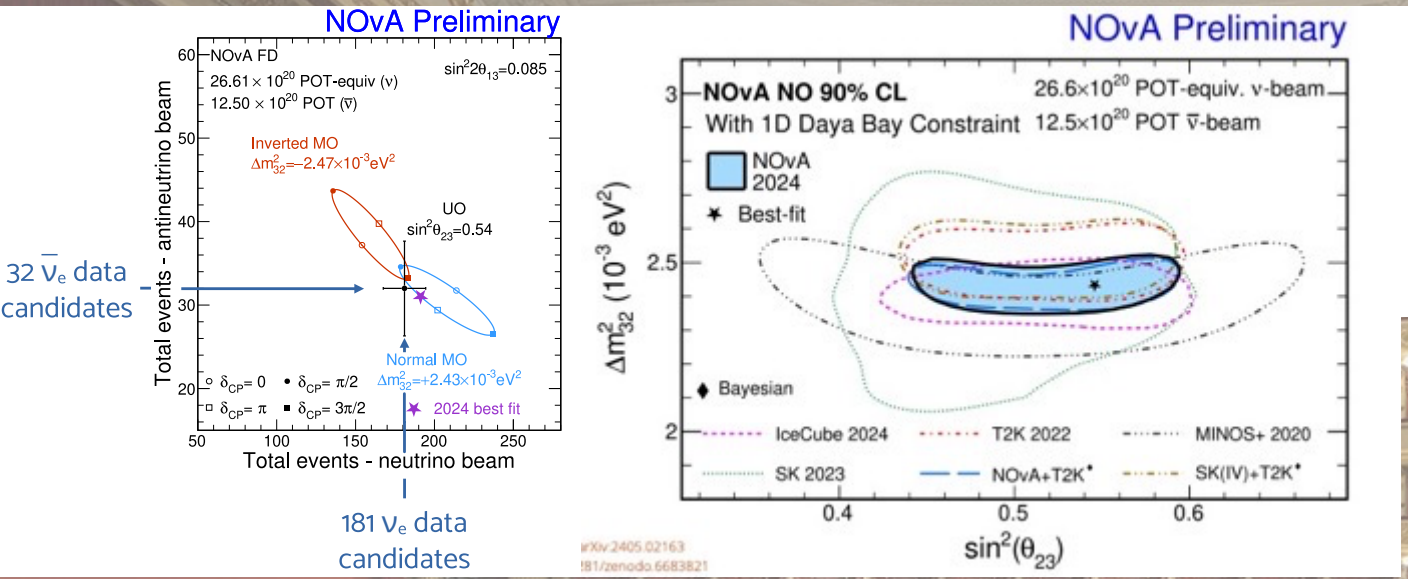

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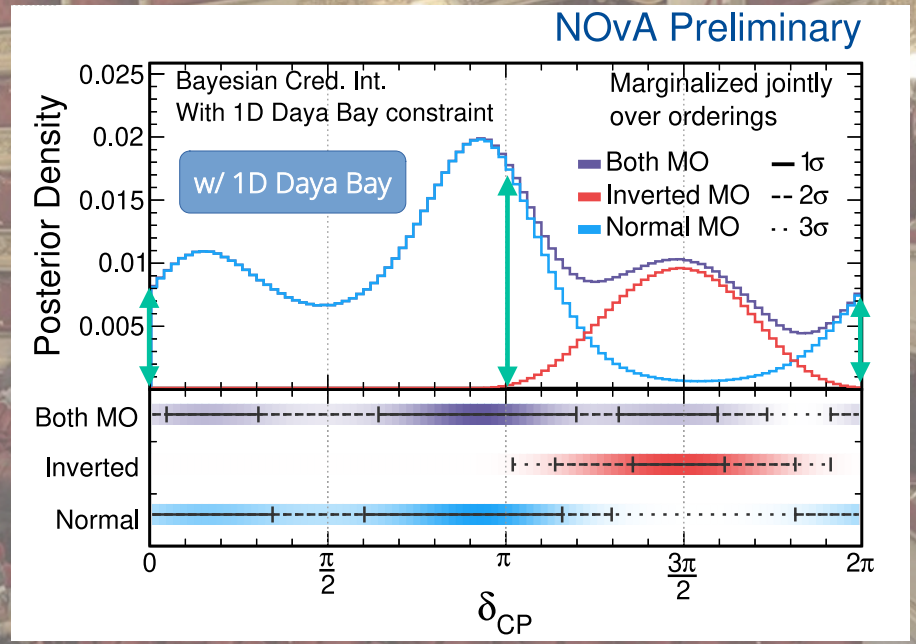
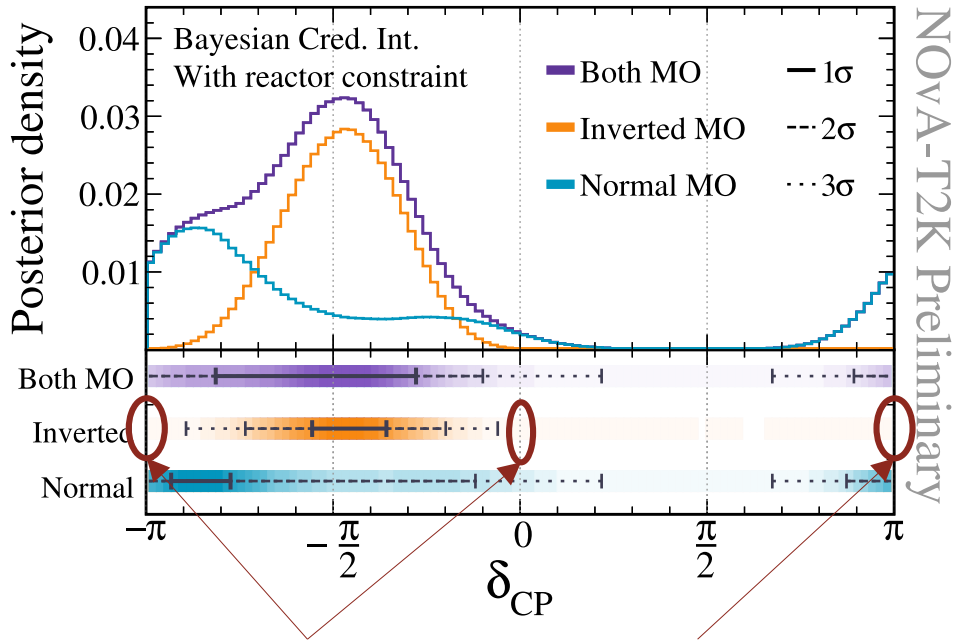


Most precise measurement Δm^2_{32} (±1.5%)
Data lies in region where matter effects and CP oppose
CP-conserving values favoured in NO (but outside 3σ interval in IO)

Presented by J. Wolcott

Joint Analysis: T2K+NOvA



CP-conserving points are *outside* 3σ intervals in IO

Expect CPV *if* ordering is inverted

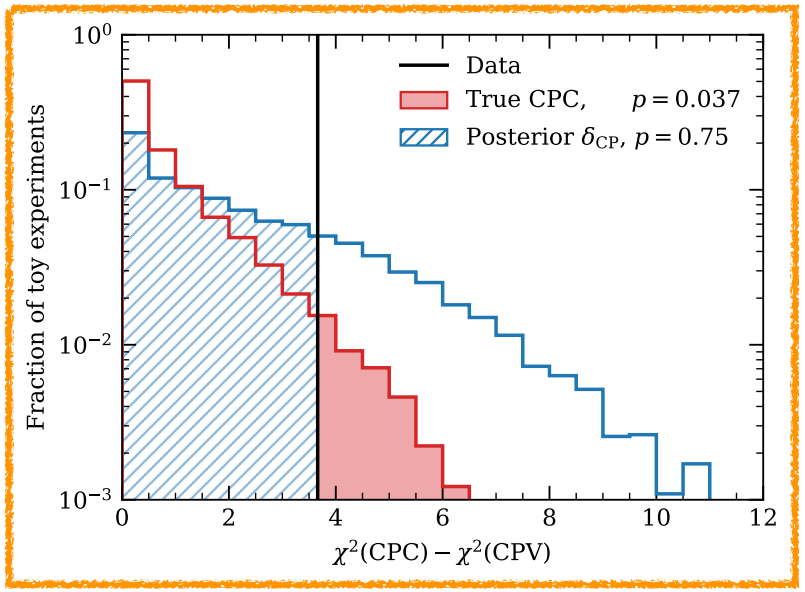
Mild preference for Inverted Ordering but **influenced by θ_{13} constraint**

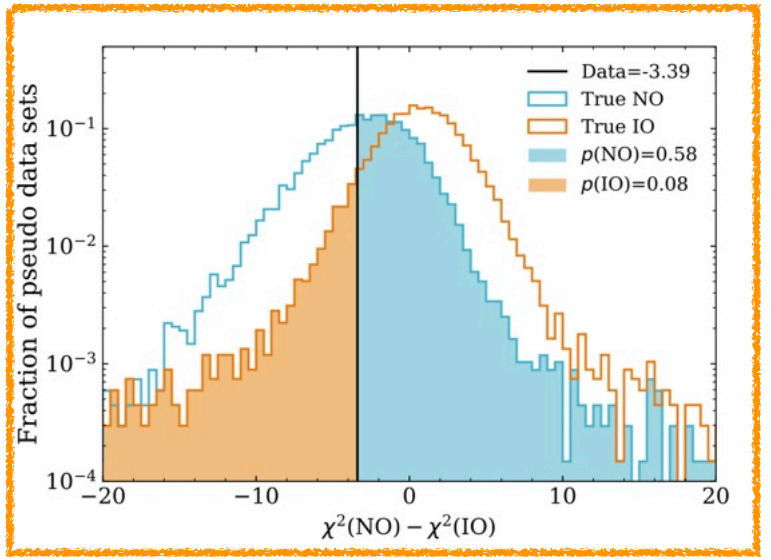
NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)

Presented by C. Giganti

Joint Analysis: T2K+SK

Same detector compels to unify model, systematic uncertainties, interaction model



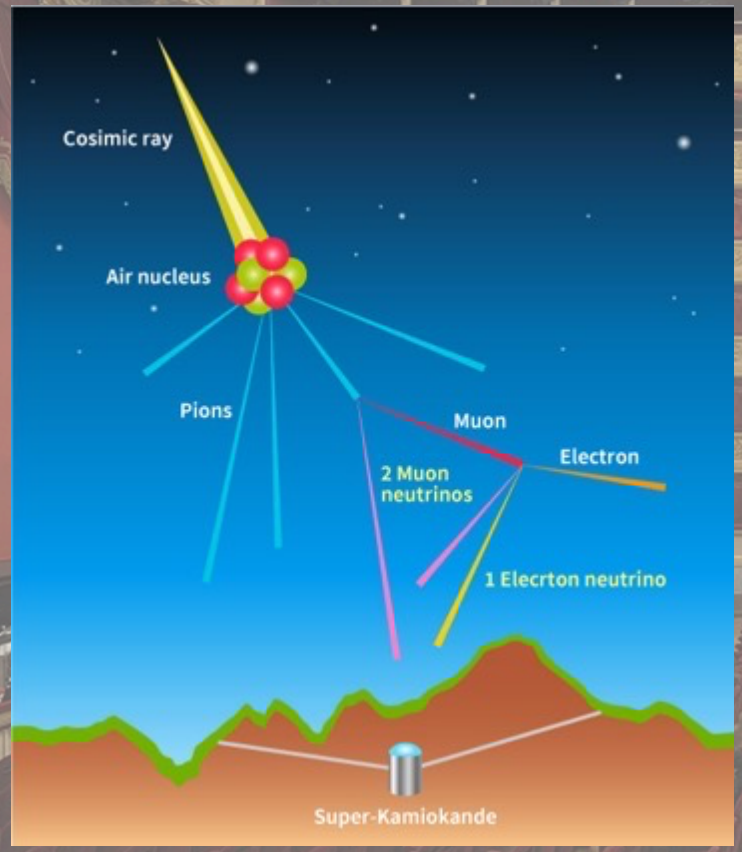


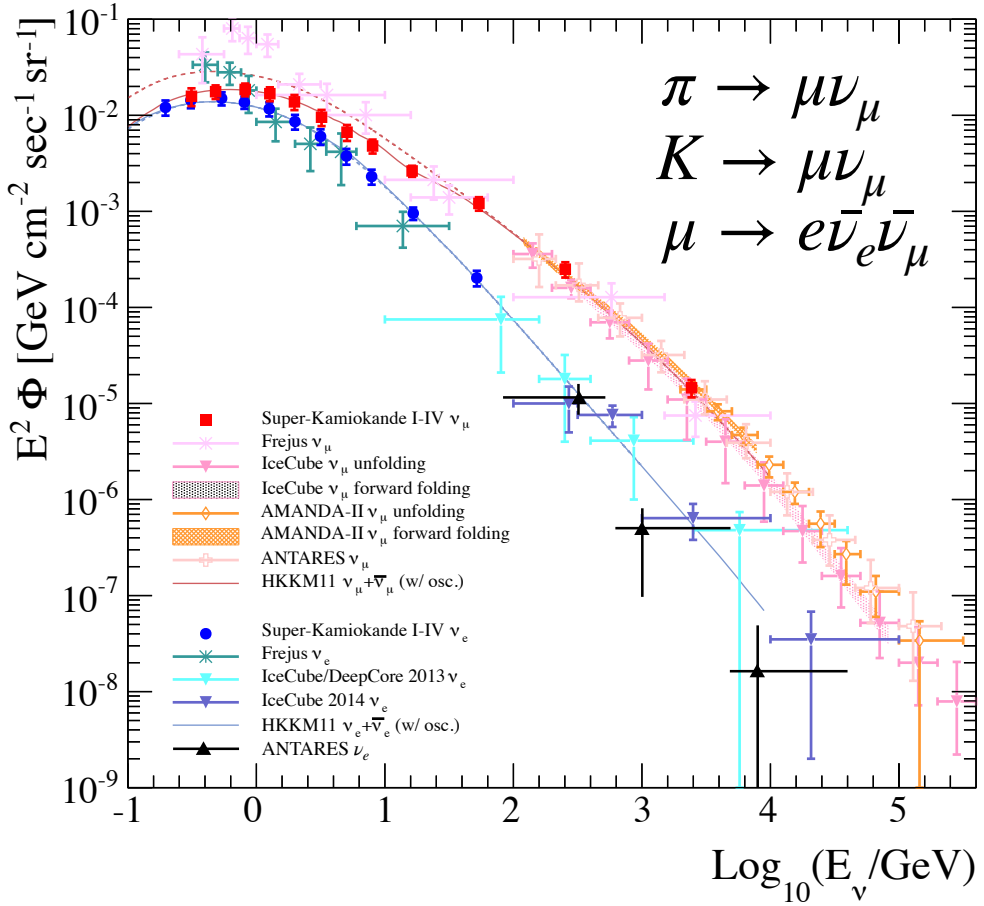
CP-conserving value disfavoured with significance 1.9-2.0σ
NO is preferred; IO p-value is 0.08

Presented by I. Martínez Soler

Atmospheric Neutrinos

Produced by cosmic rays colliding with the atmosphere





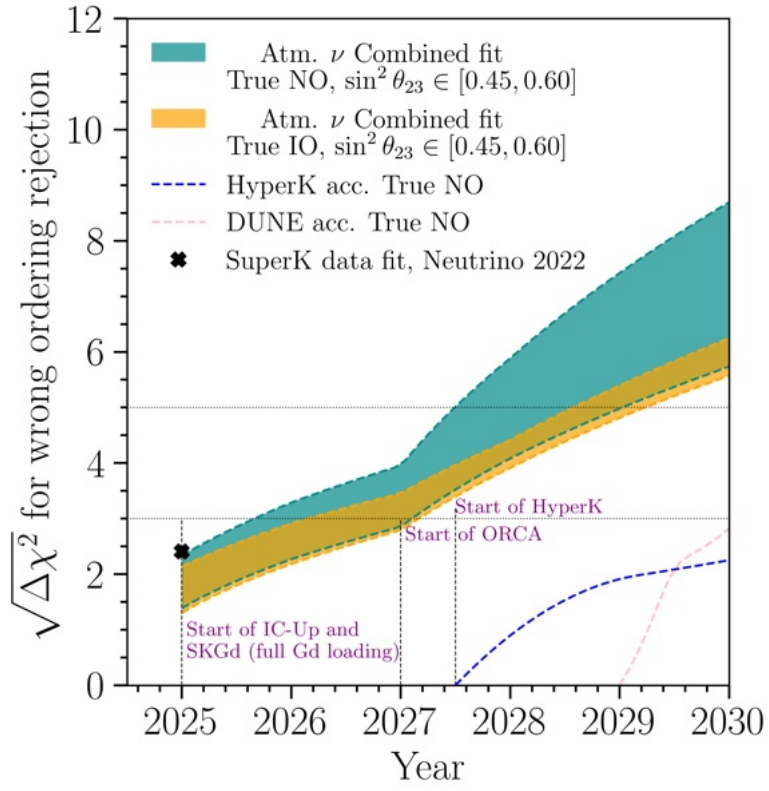
E. Richard et al. (SK), PRD 94 (2016) 5

Presented by I. Martínez Soler

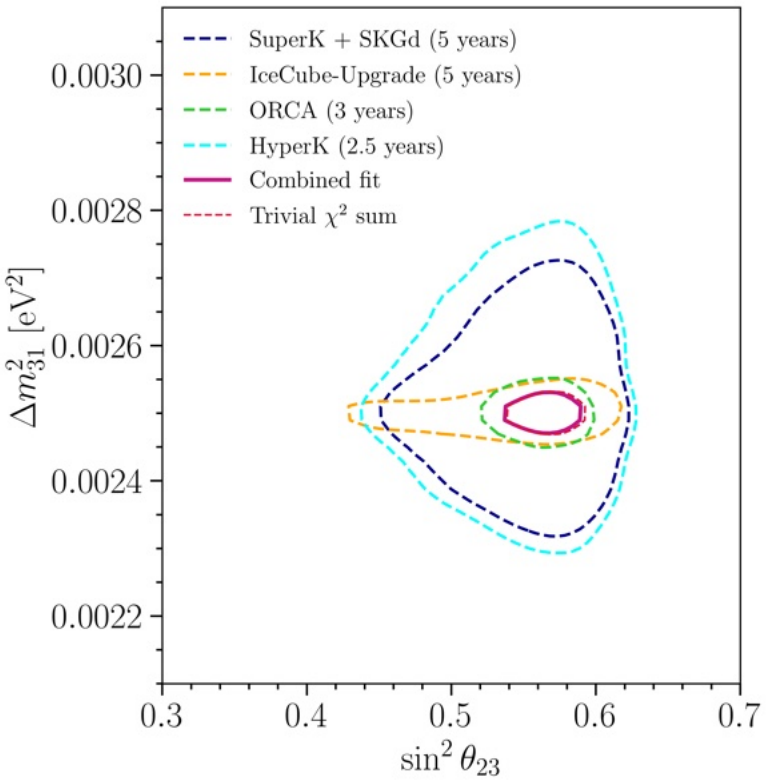
We will hear from C. Argüelles Delgado at this workshop!

Atmospheric Neutrinos

Provide good sensitivity to mass ordering (at ~6σ) in projections including future experiments; and to other oscillation parameters



Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)



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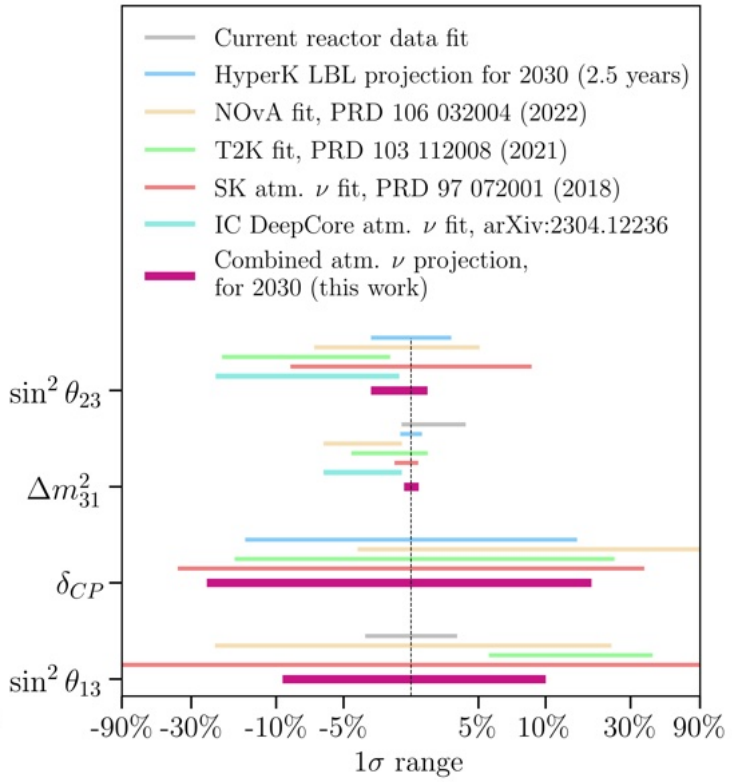
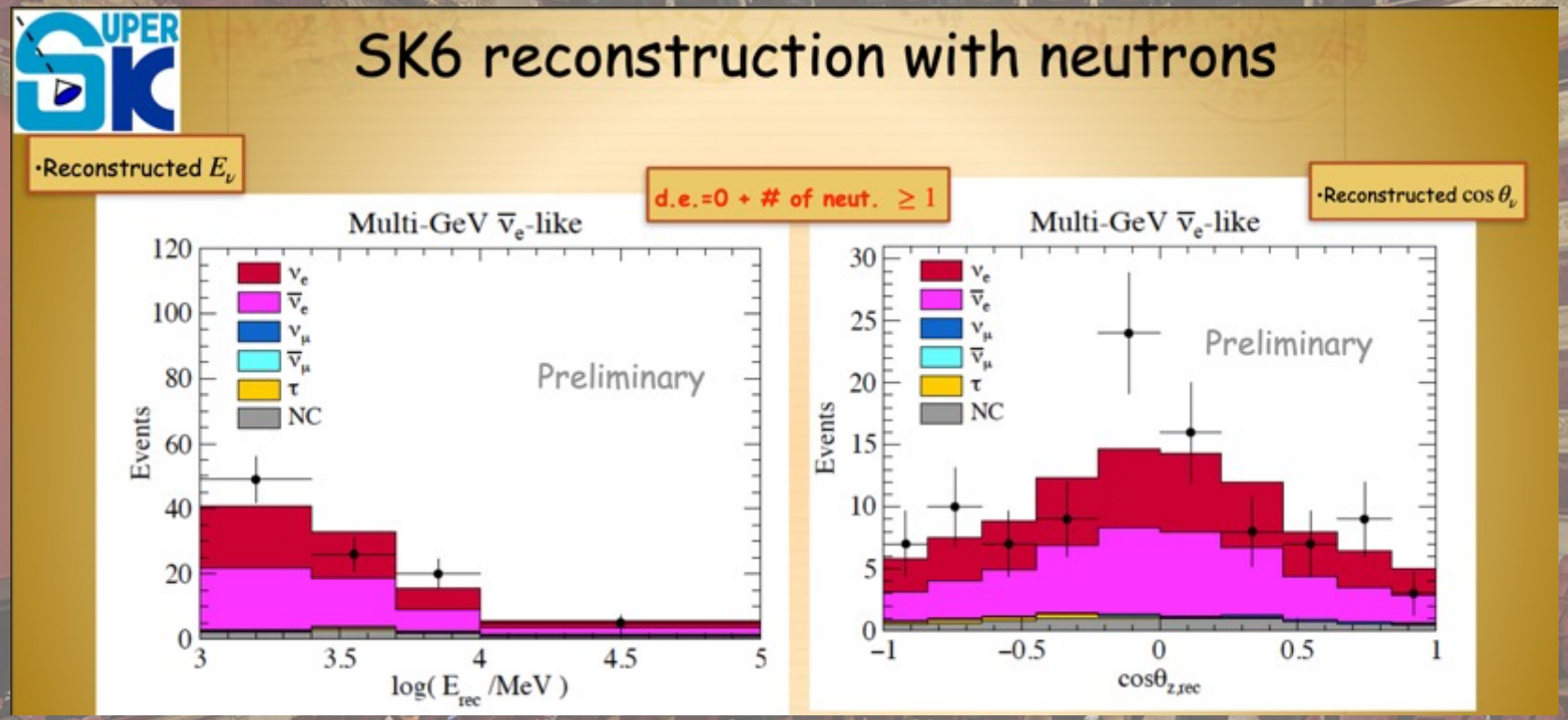


Argüelles, Fernandez, **IMS** and Jin, PRX 13 (2023)

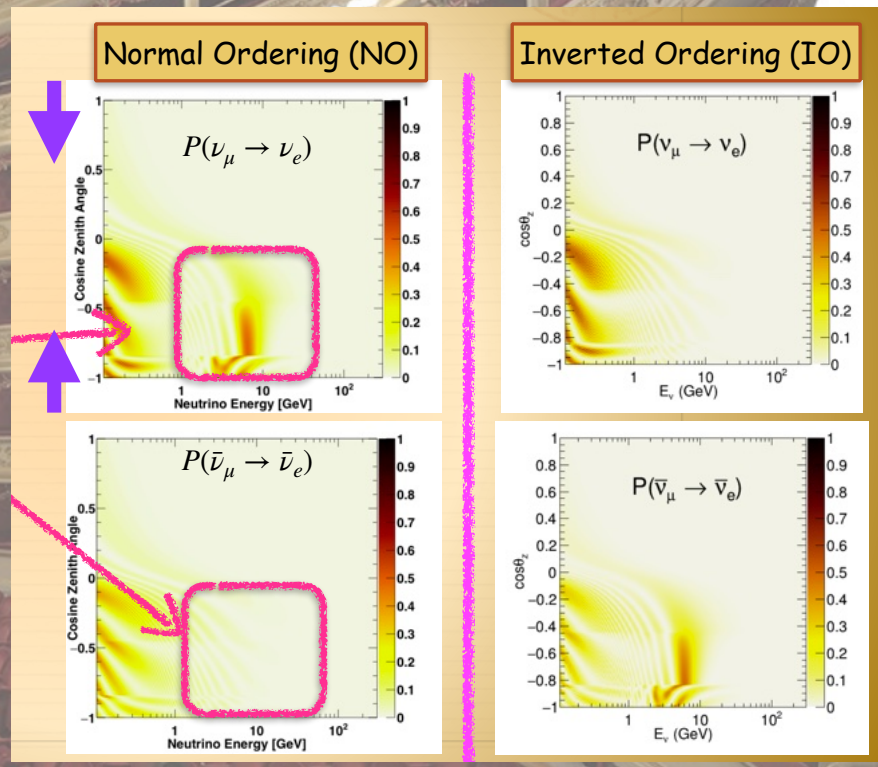
Presented by M. Posiadala-Zezula

Atmospheric Neutrinos w/Neutron Tagging

Enhancement of ν and $\bar{\nu}$ identification and improvement of E_ν reconstruction from neutrons on gadolinium



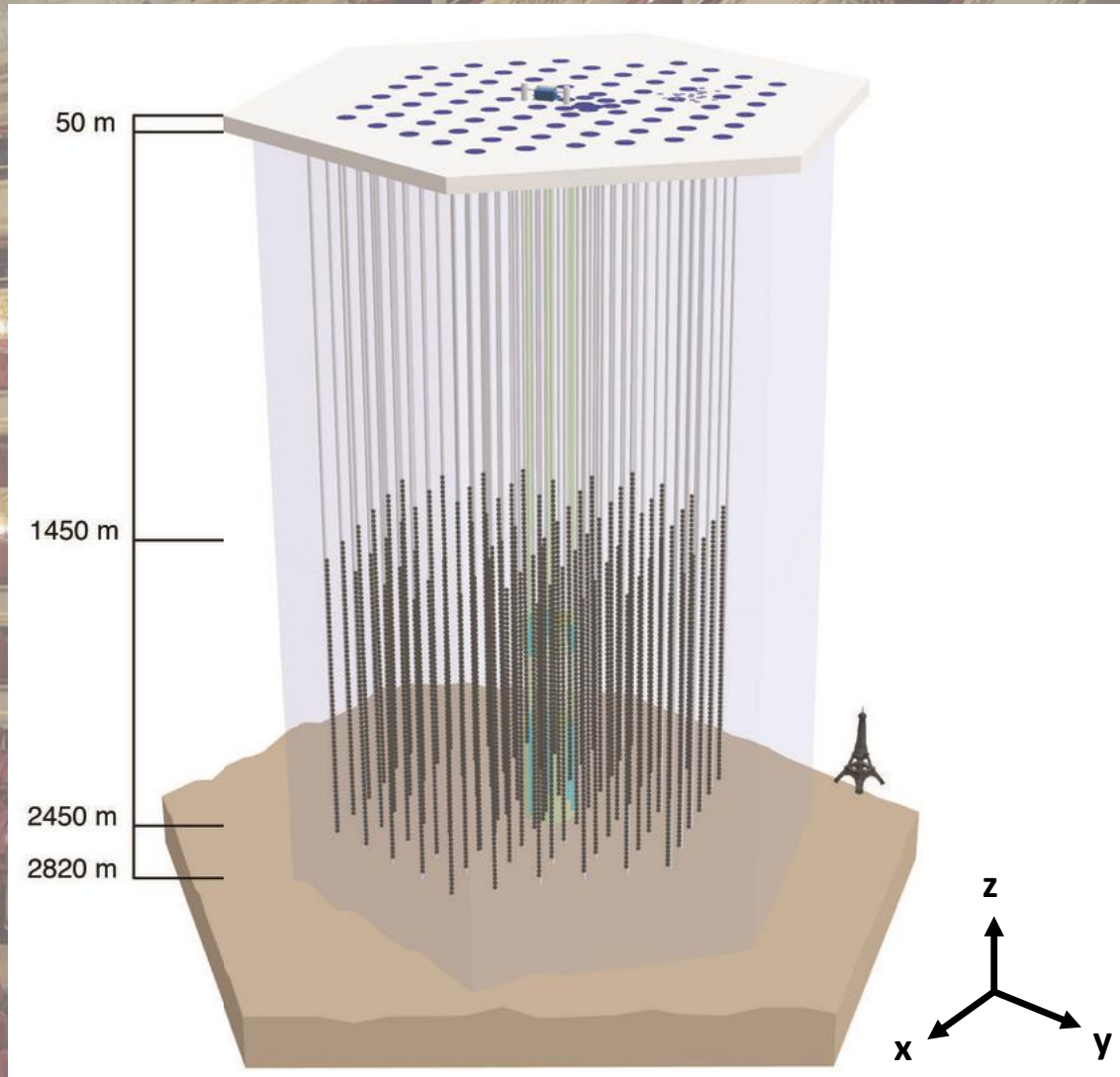
Oscillogram for Super-K



Presented by J. P. Yáñez

IceCube Atmospheric Oscillation Result

150,000 ν candidate events in 9 yrs data in oscillation analysis (also sterile ν searches)



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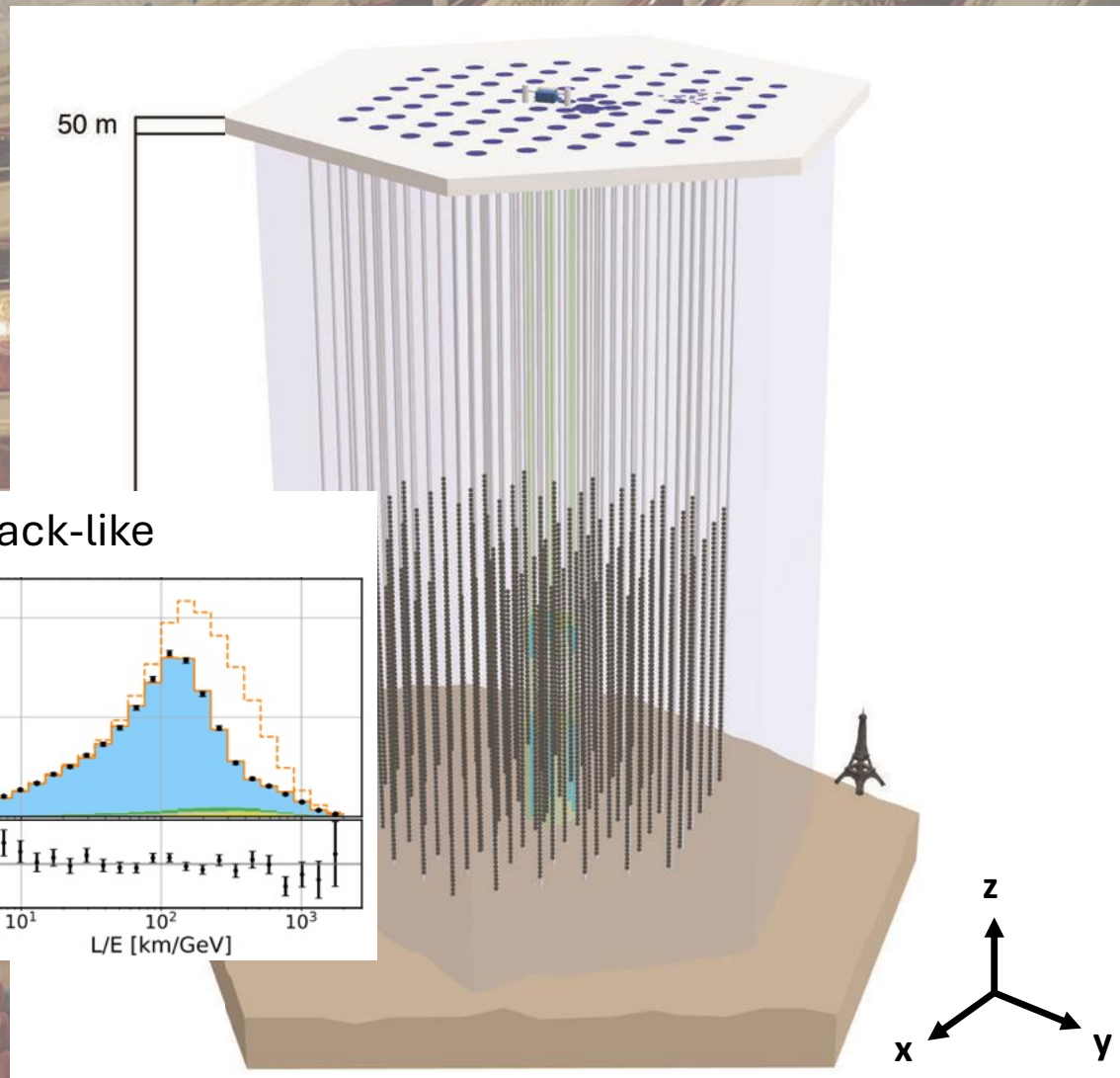
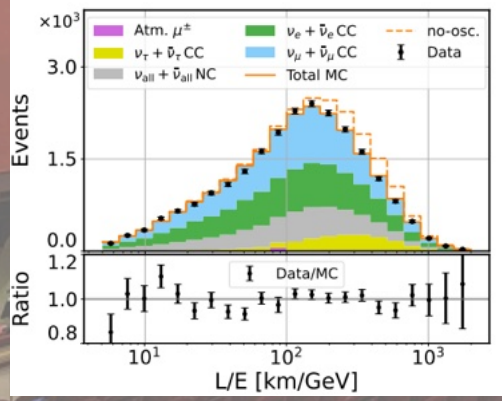
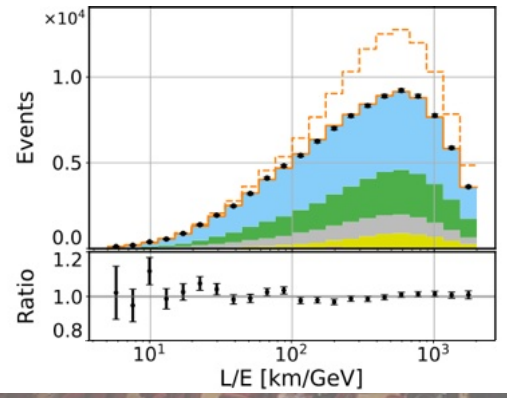


Cascade-like



Track- and cascade-like



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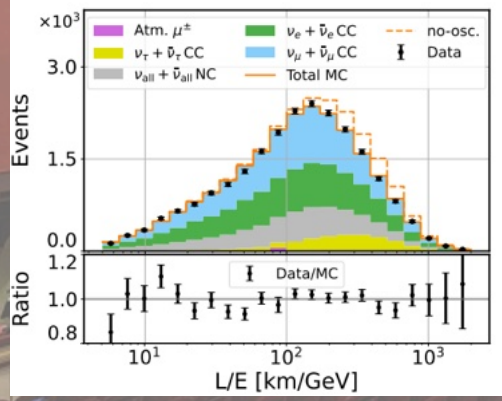

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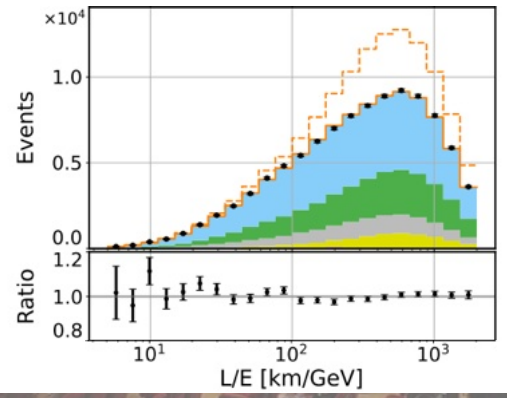
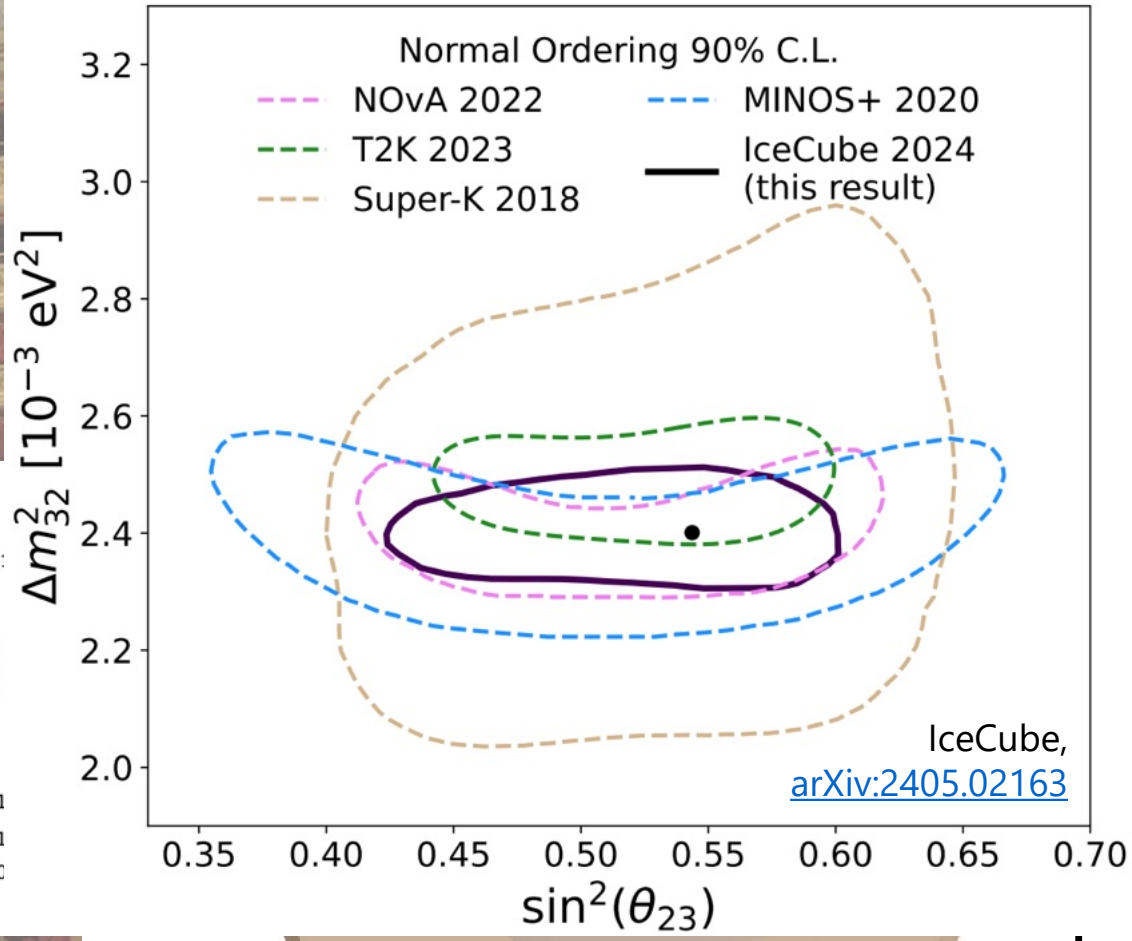
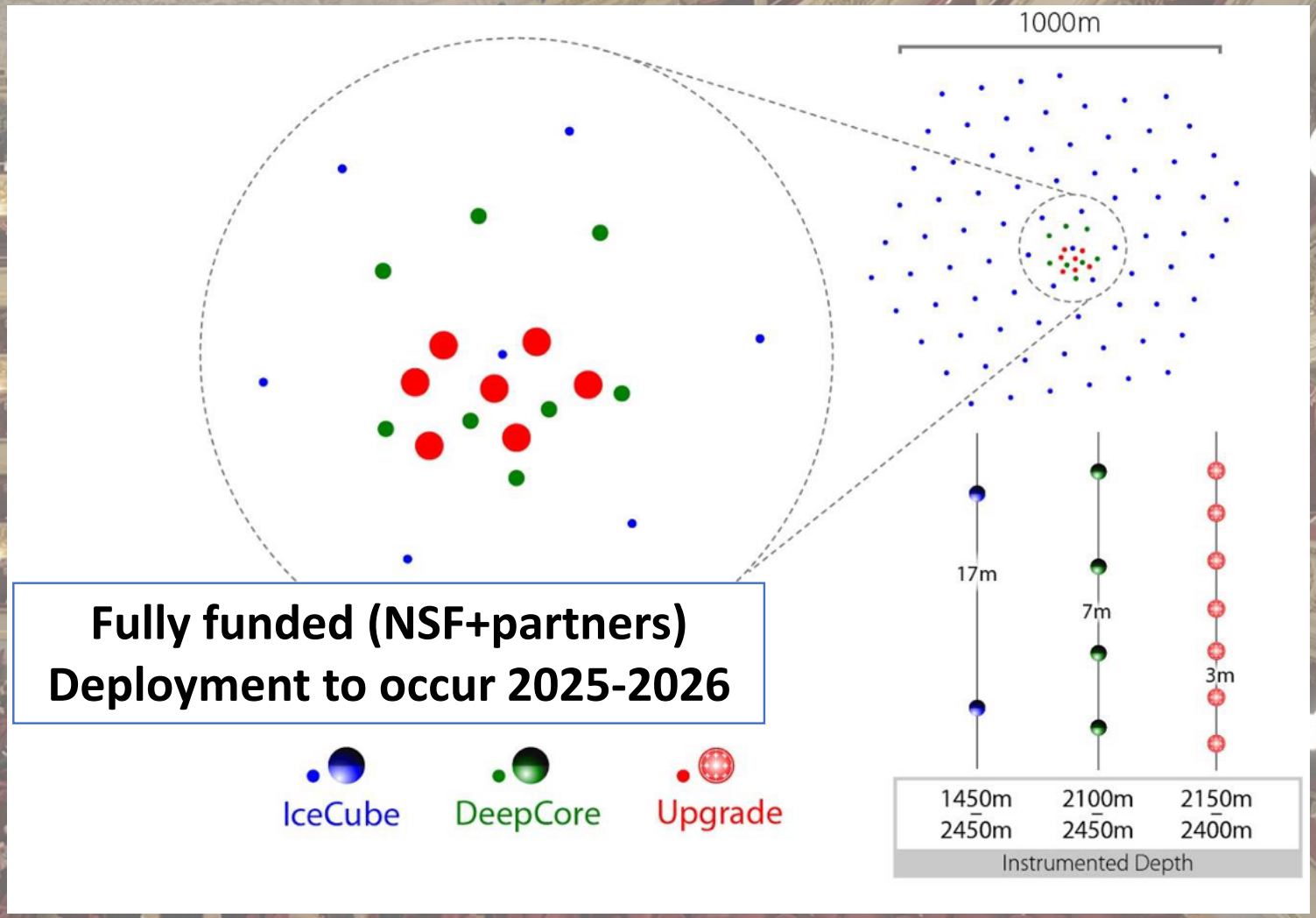




Presented by J. P. Yáñez, J.A. Aguilar

IceCube Upgrade

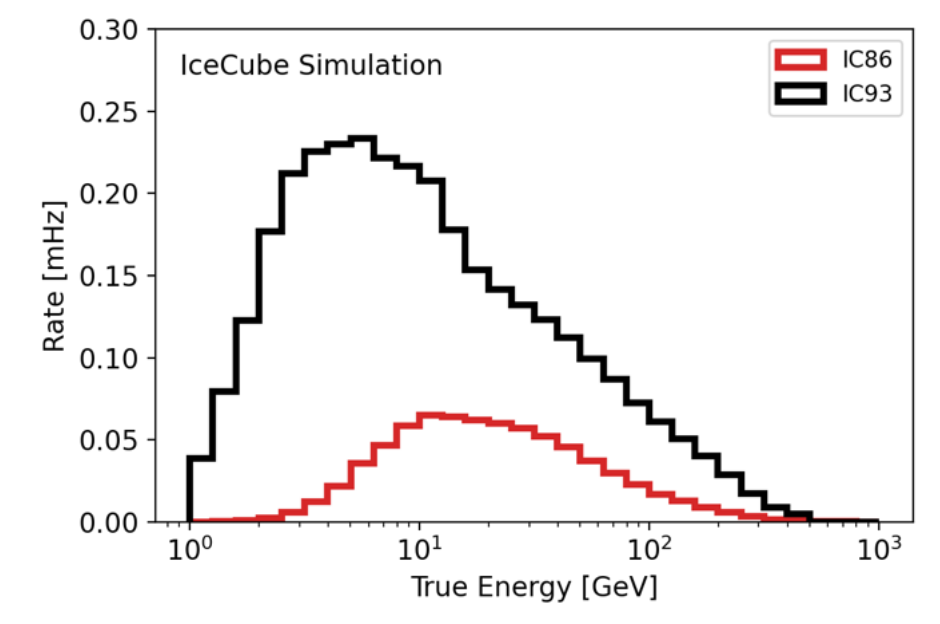
Detecting 2-100 GeV (atmospheric) neutrinos



Fully funded (NSF+partners)
Deployment to occur 2025-2026

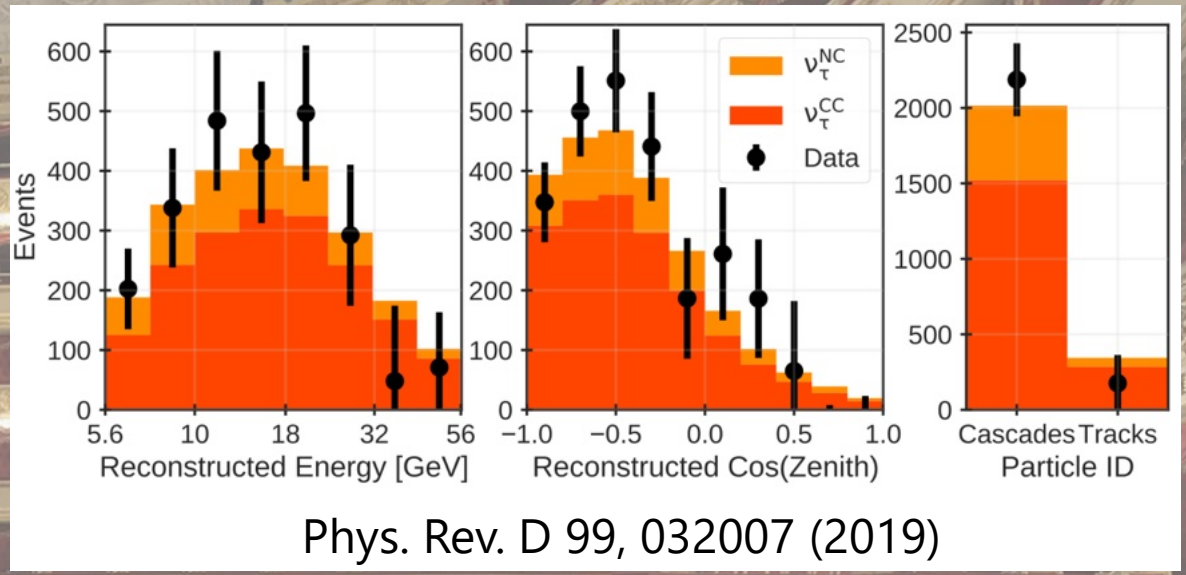
Presented by J. P. Yáñez

IceCube Upgrade



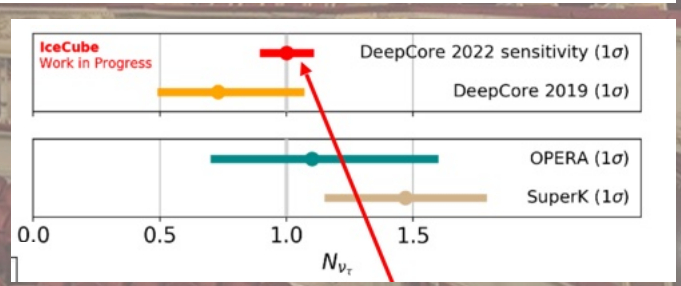
Significant increase of events at 10 GeV (and below)!

Oscillations to ν_τ in DeepCore



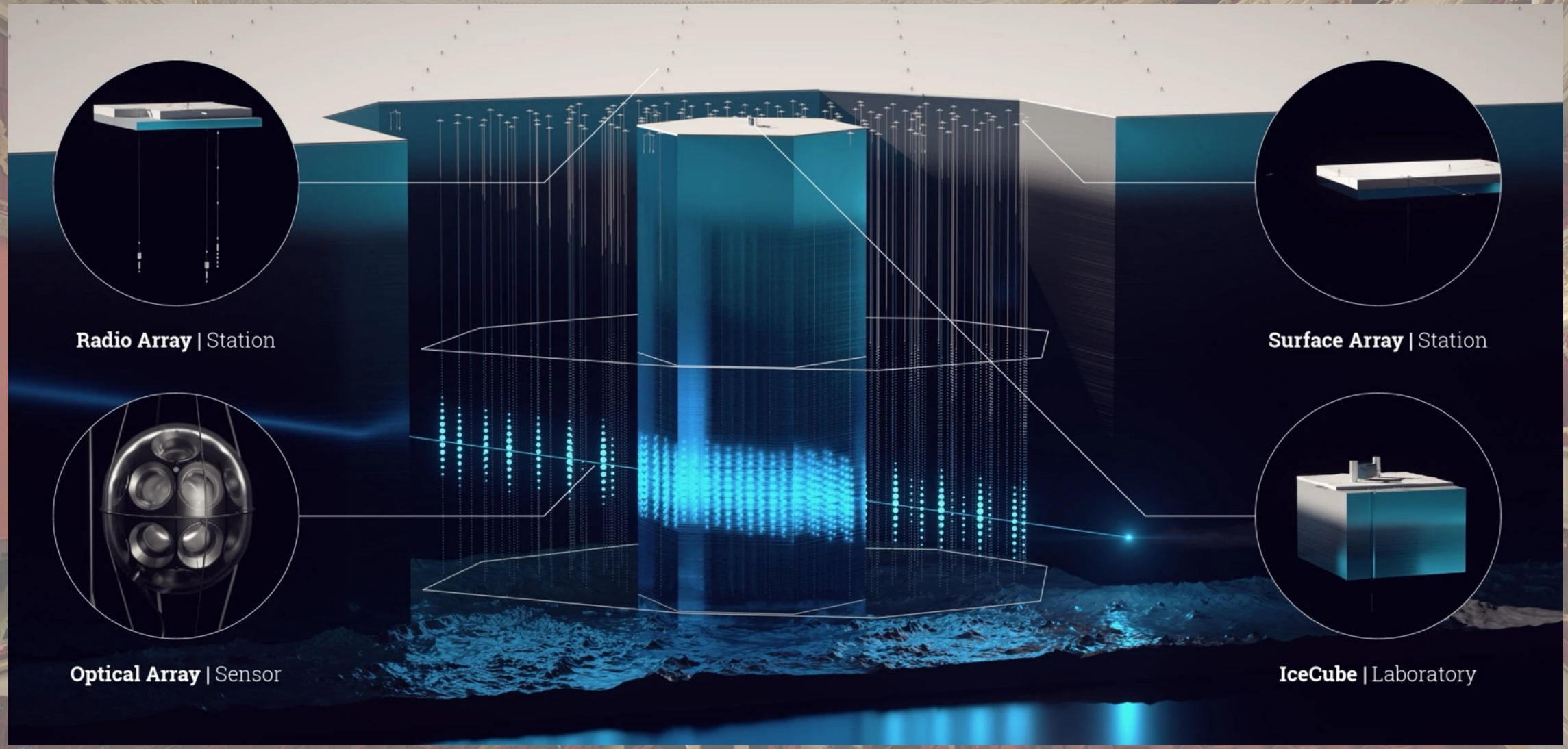
Phys. Rev. D 99, 032007 (2019)

Expecting world-leading precision with ~9,700 $\nu_{\tau,CC}$ events



Presented by J.A. Aguilar

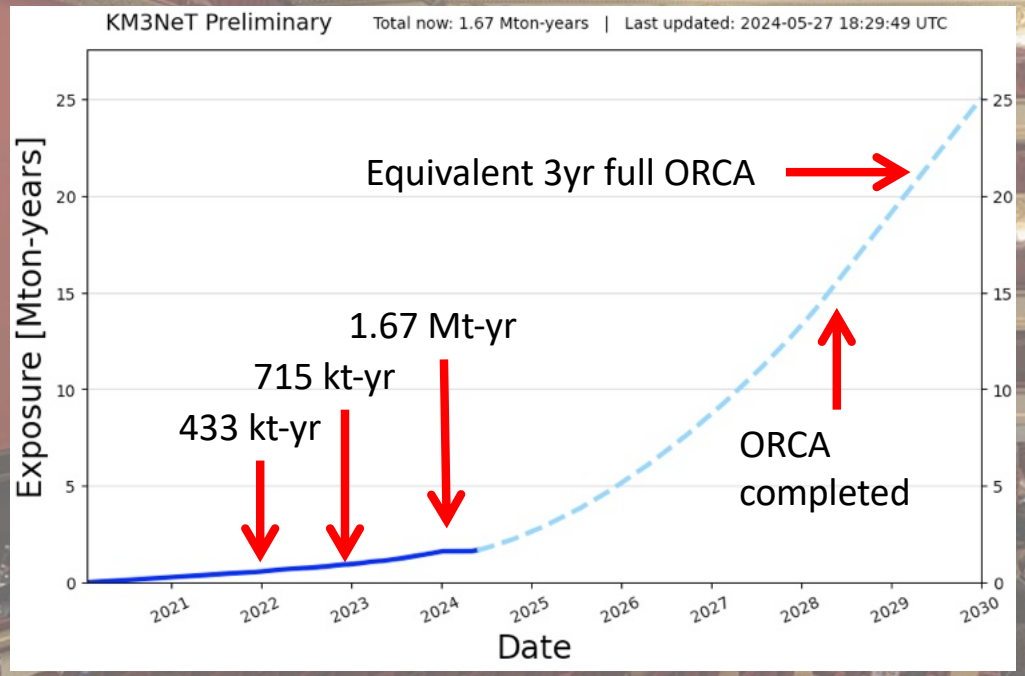
IceCube Gen2

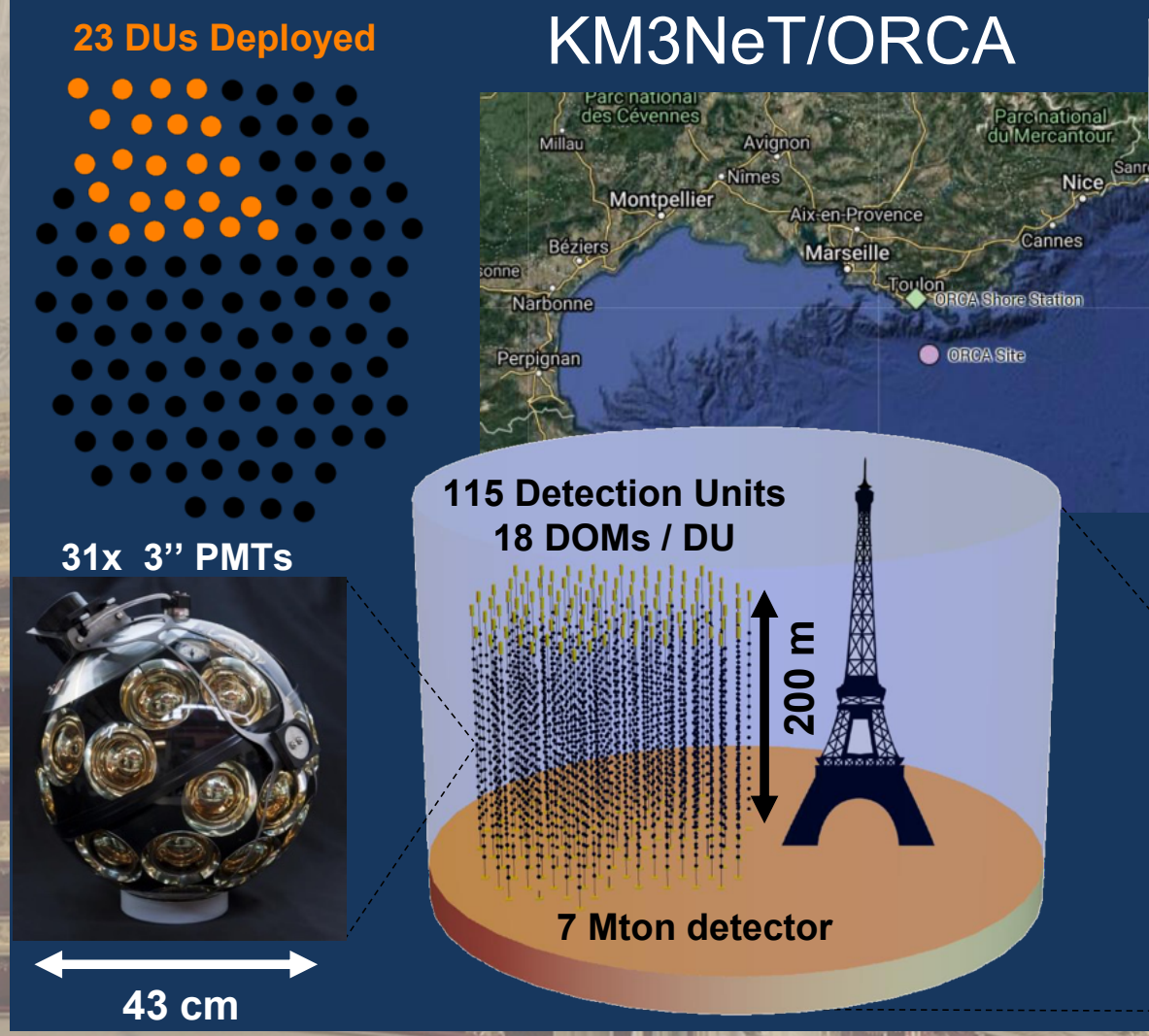


Presented by J. Brunner, J. Coelho

KM3NeT (ORCA)

Several 1000 ν_τ per year (10-40 GeV)
(coupling to 3rd family; new physics)





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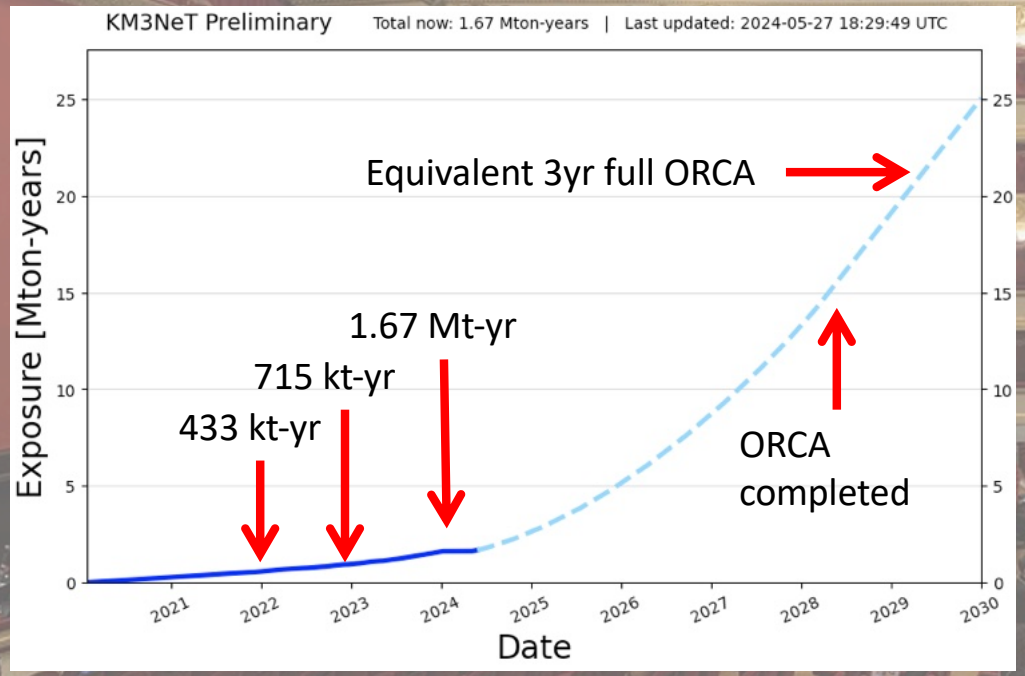

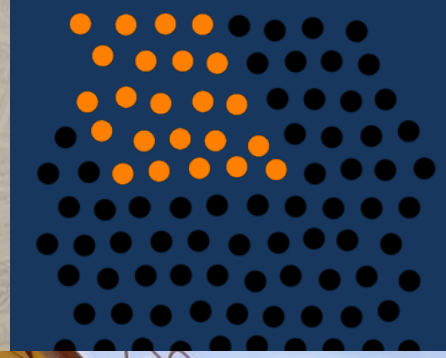

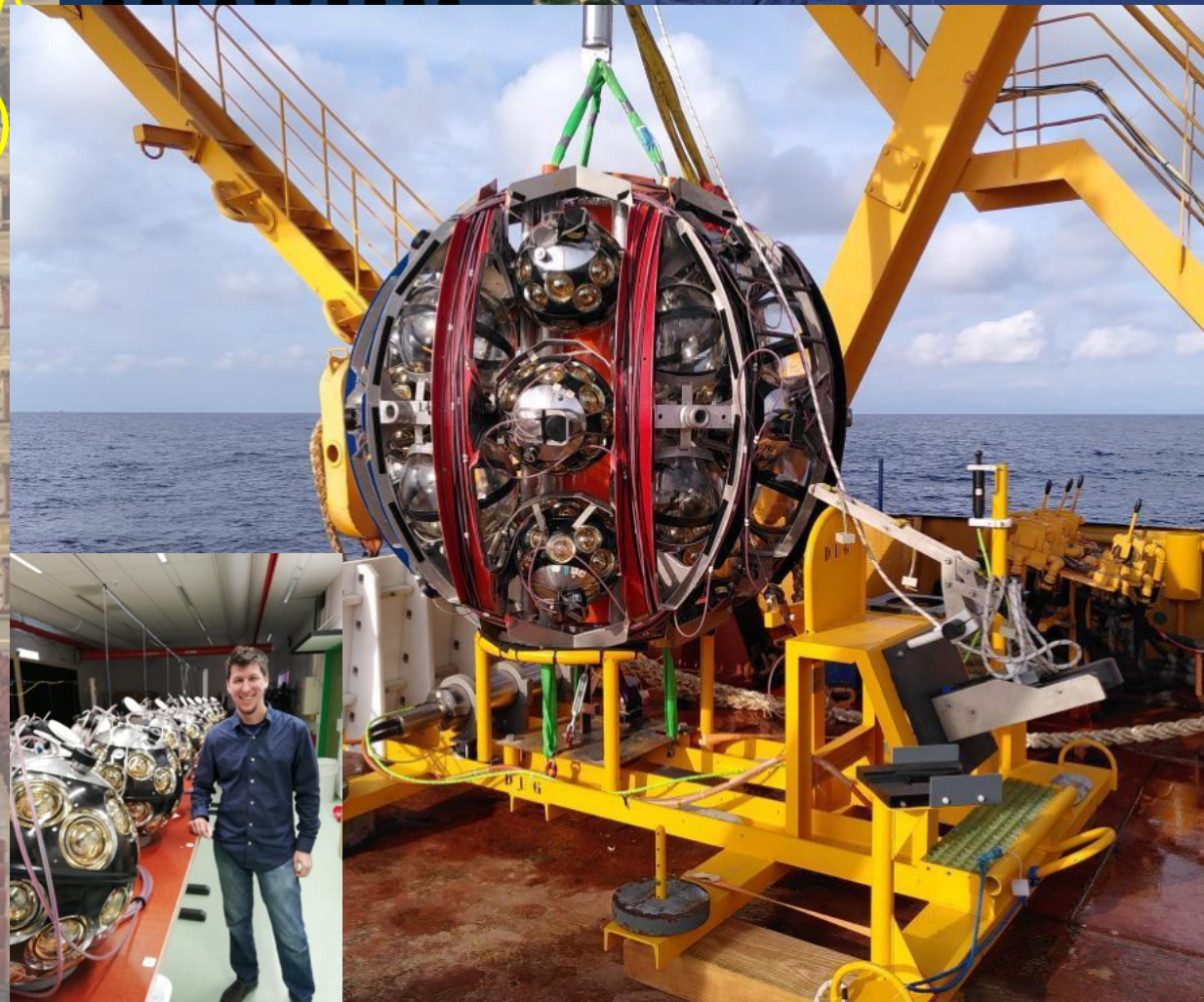

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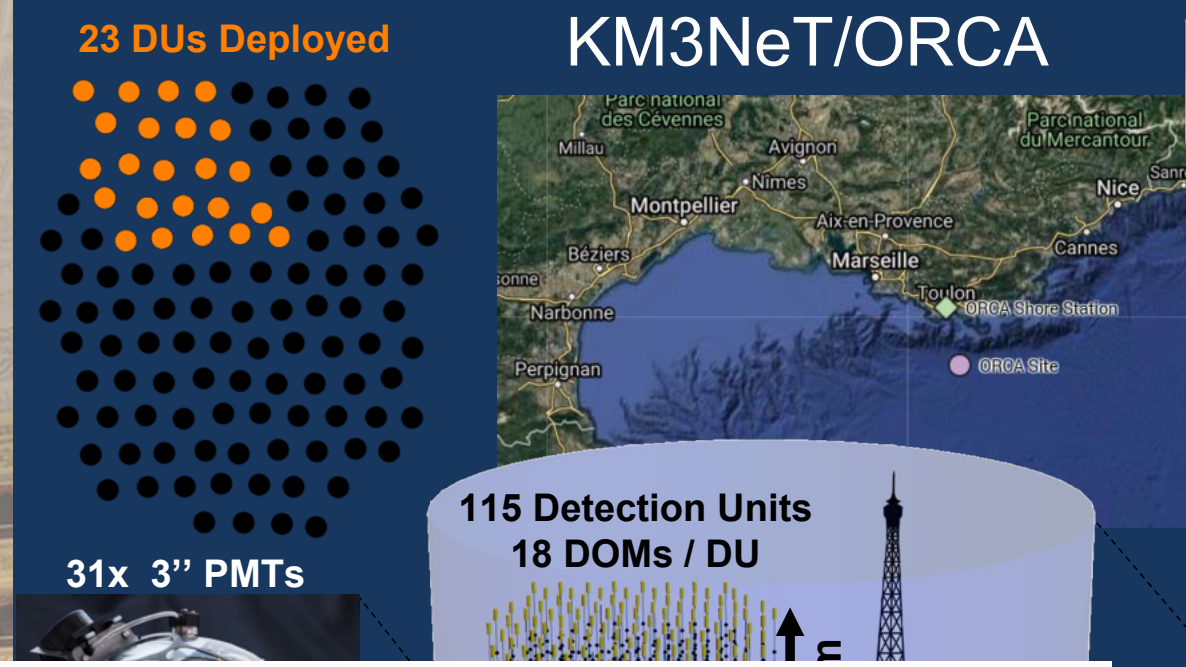

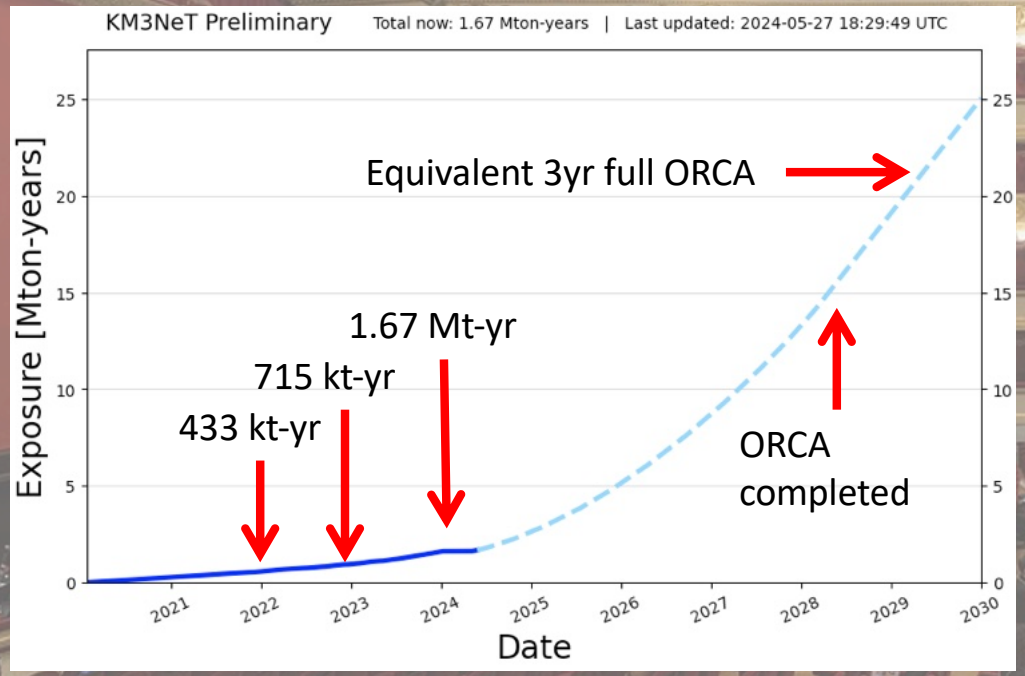

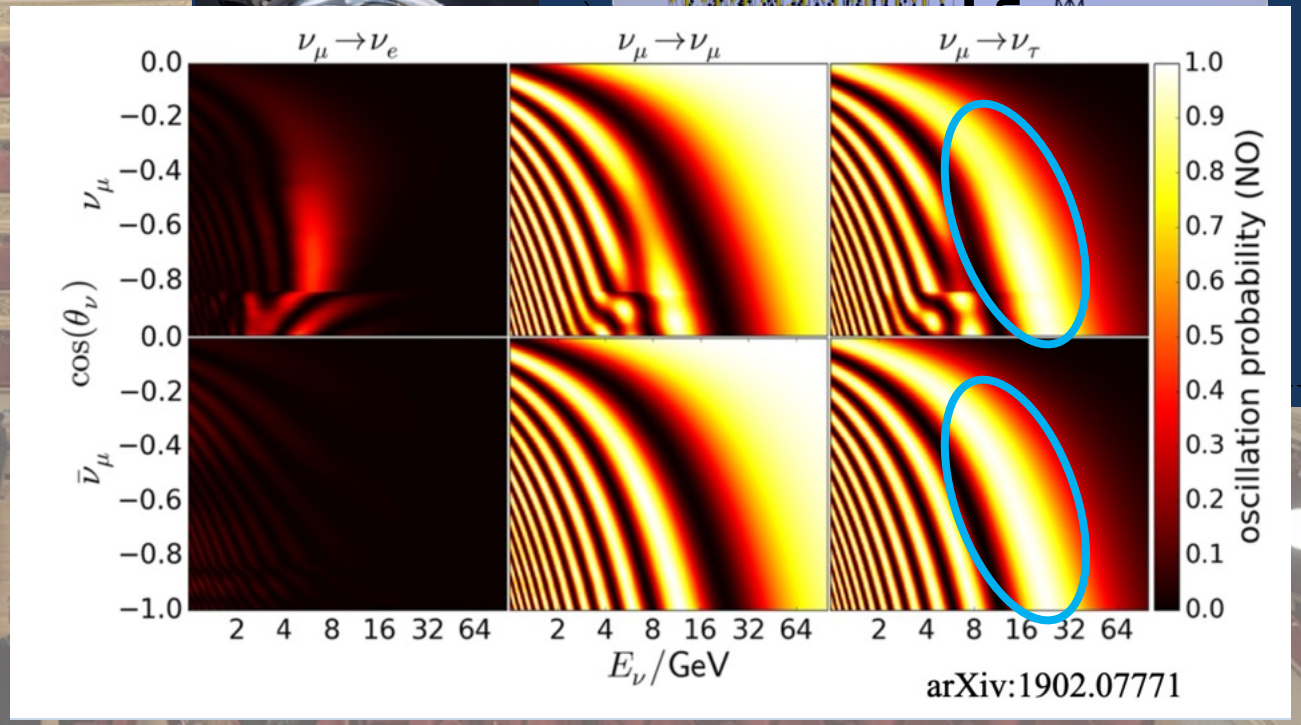

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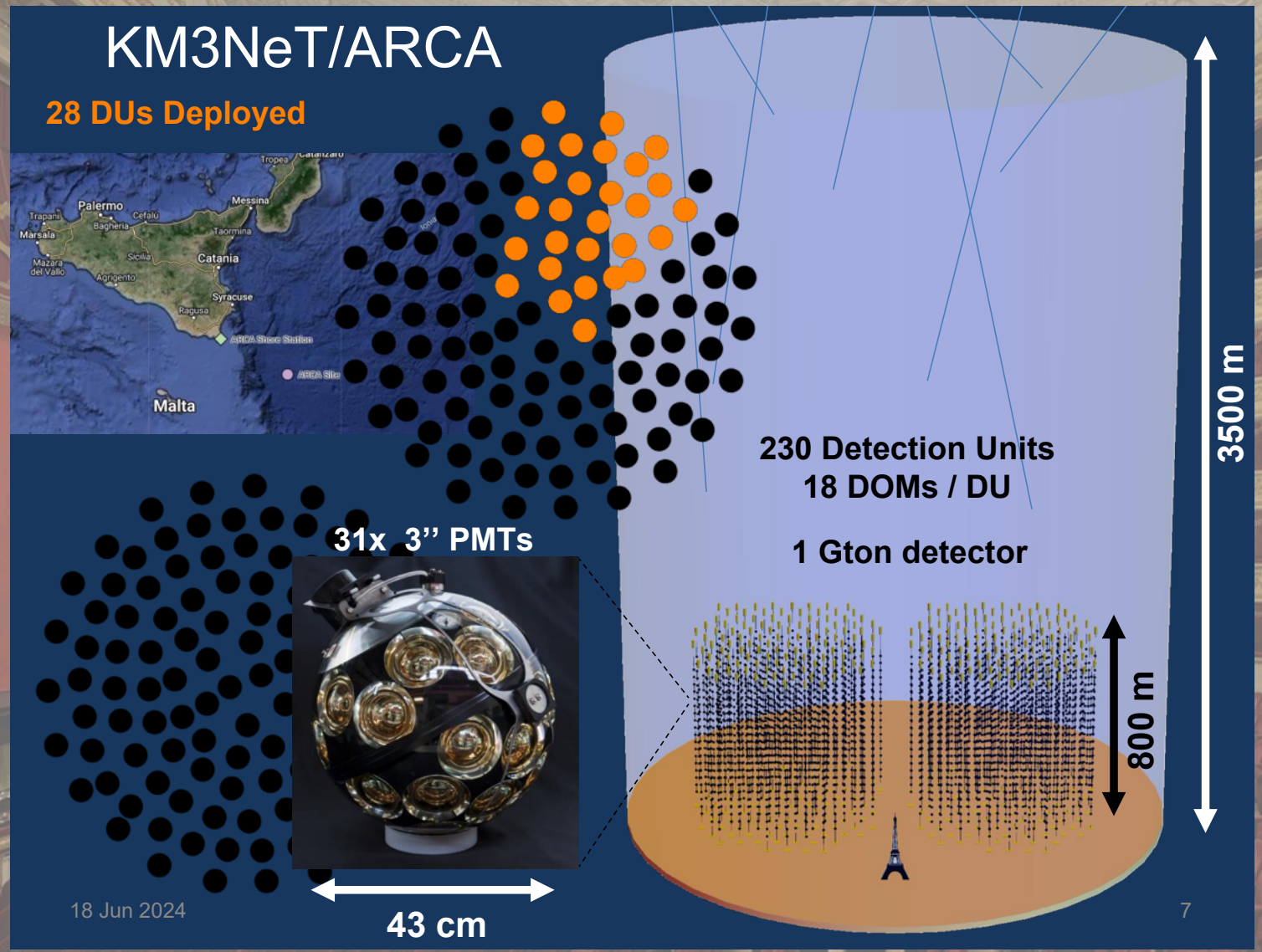
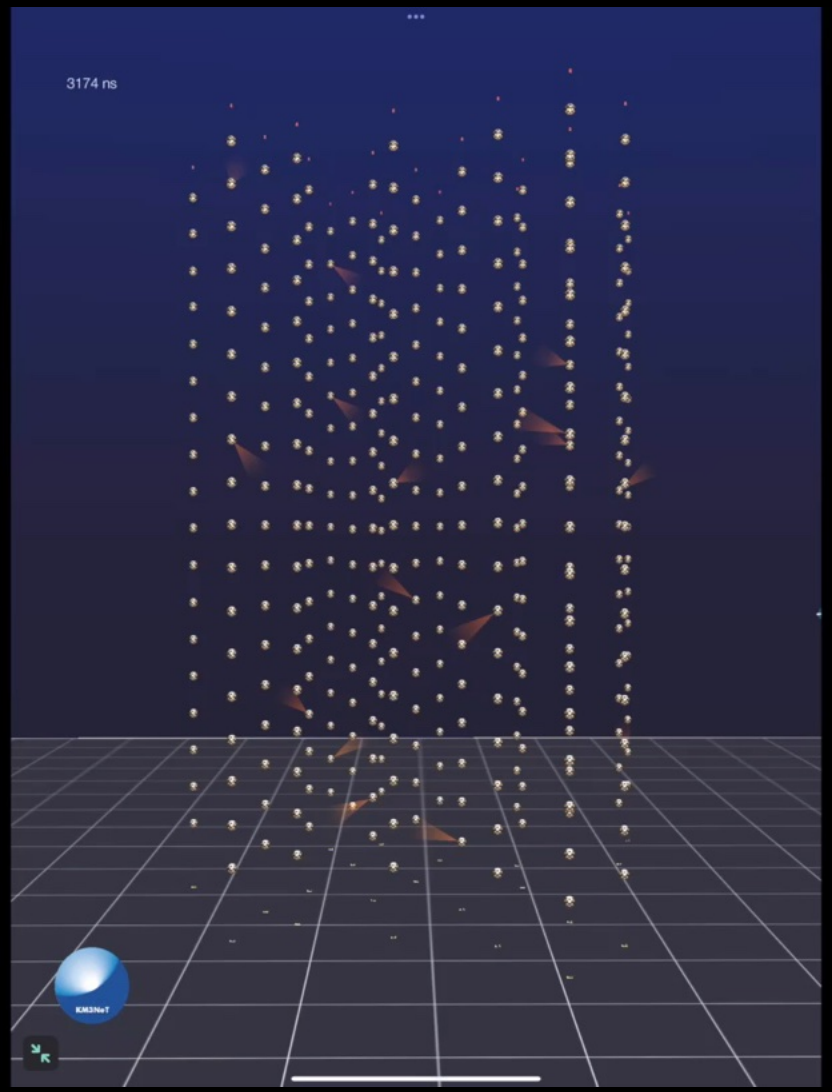
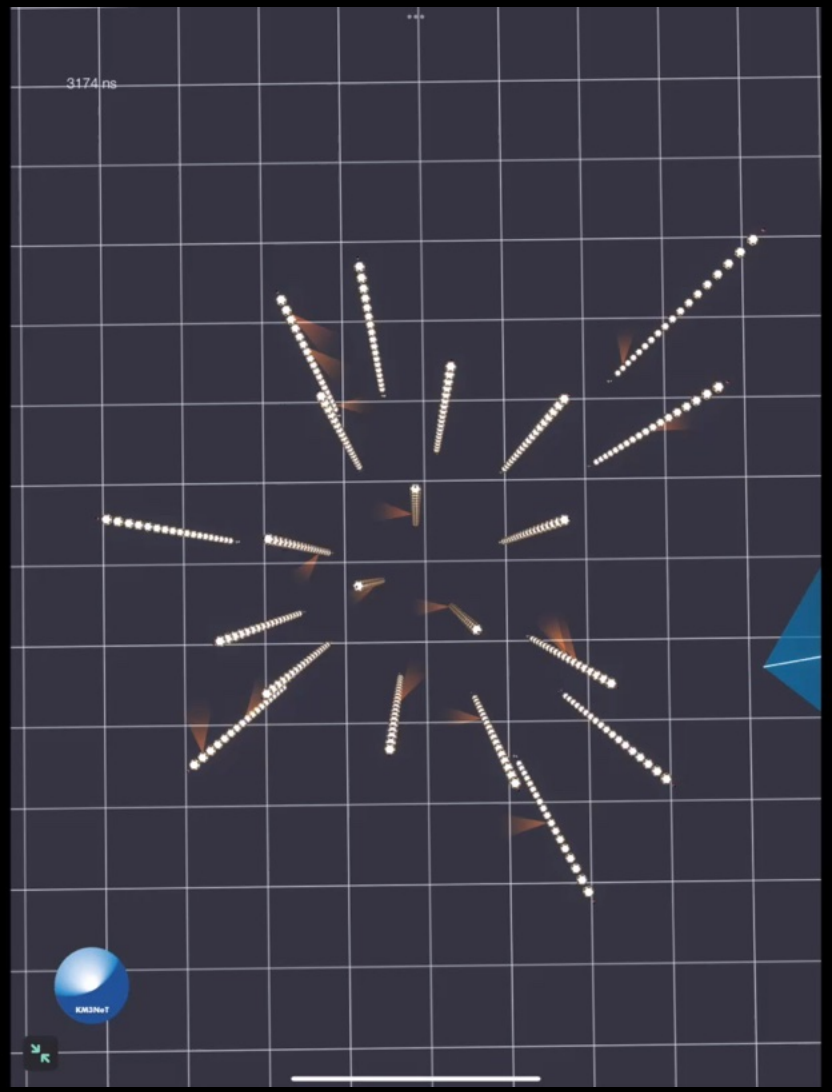


Uncharted Territory

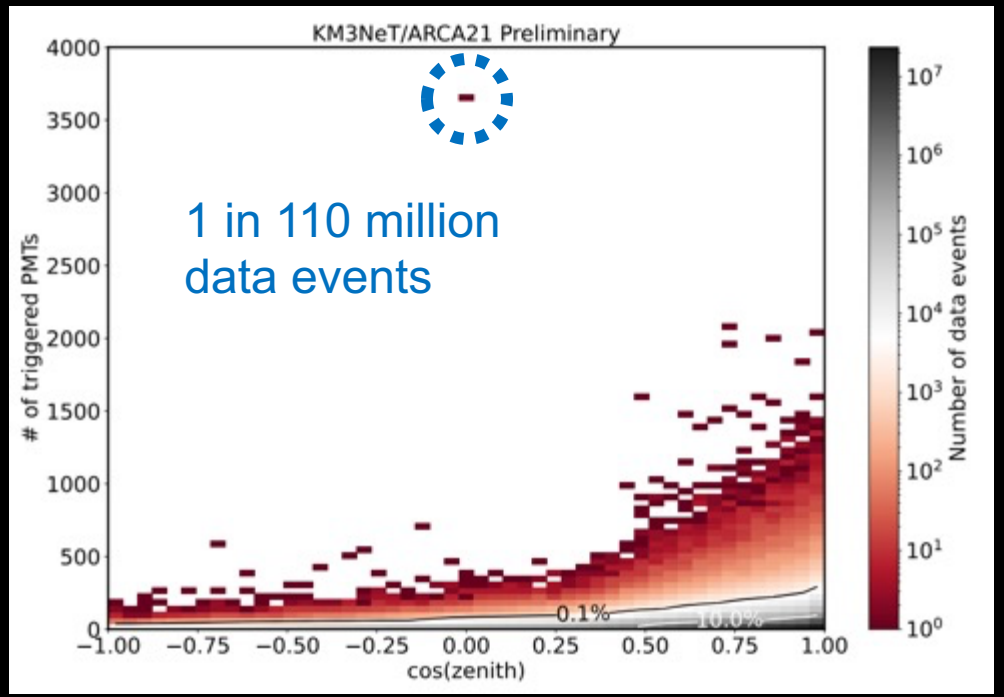


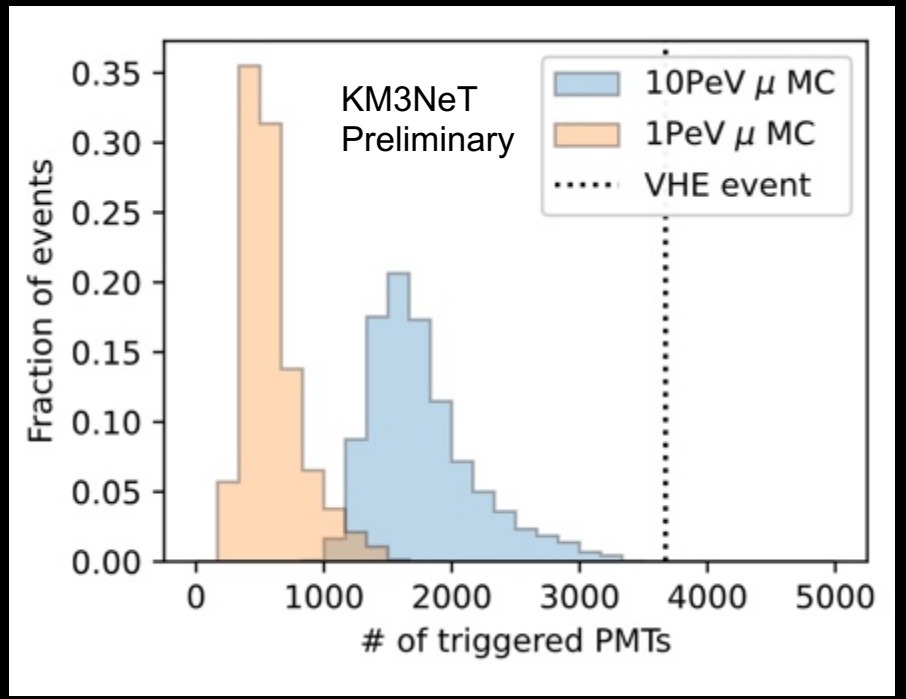


Presented by J. Coelho

Uncharted Territory

- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV





Presented by R. Dvornický

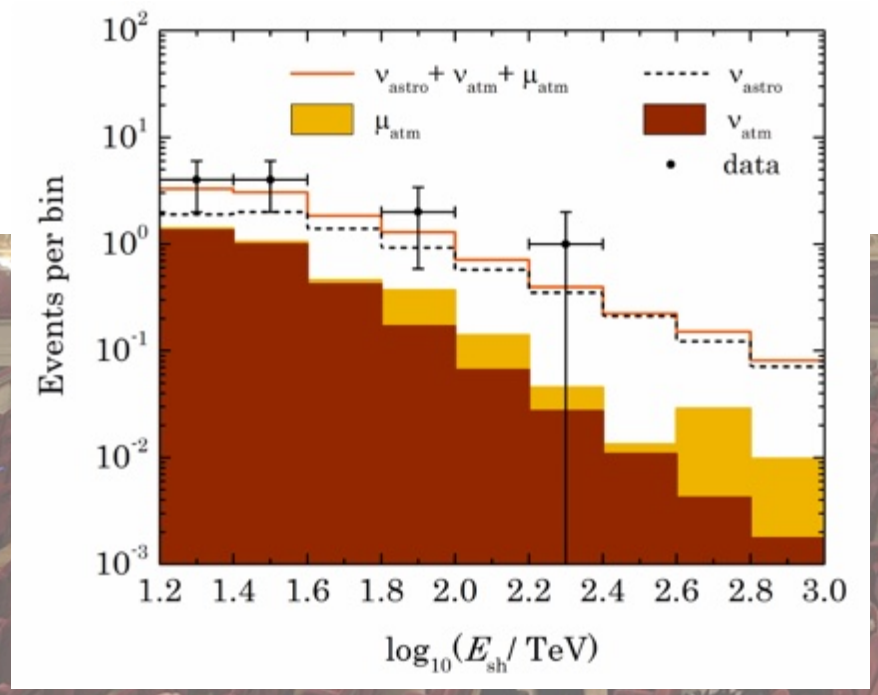
Baikal-GVD

Succesful 2024 deployment campaign 16/02 – 07/04

- 14 regular strings carrying 36 OMs installed
- 2 strings added to experimental (“optical”) cluster
- Pilot string for HUNT project

~0.6 km^3 detector volume
110 strings with 3960 Oms

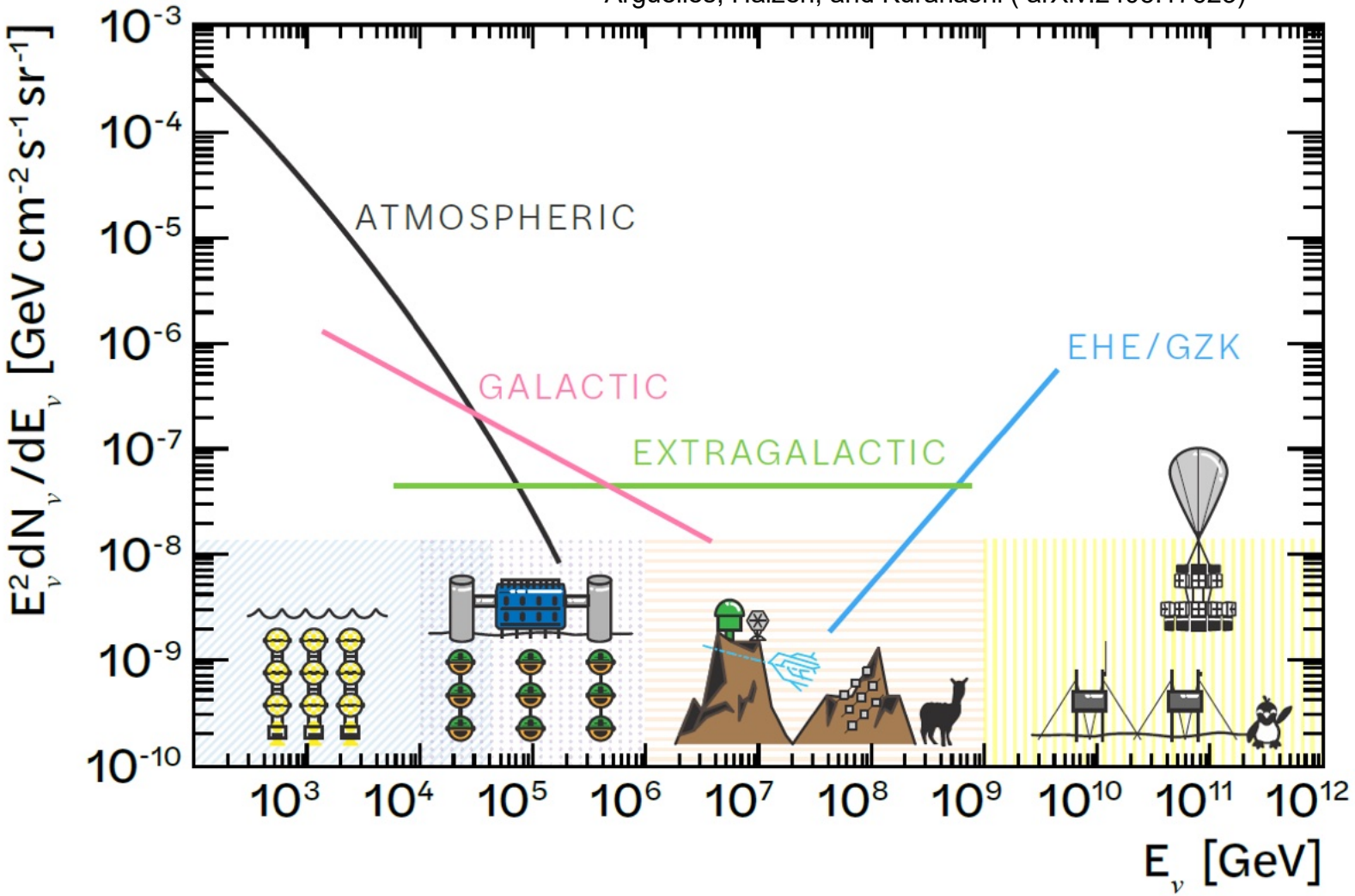
First “non-IceCube” evidence for diffuse astrophysical neutrino flux



Presented by J. Coelho, J.A. Aguilar, N. Kurahashi Neilson, K. Hughes

Dawn of Neutrino Astronomy

Argüelles, Halzen, and Kurahashi (arXiv:2405.17623)



Different detection technologies
Underwater Cherenkov
Under-ice Cherenkov
Horizontal shower
Radio detection

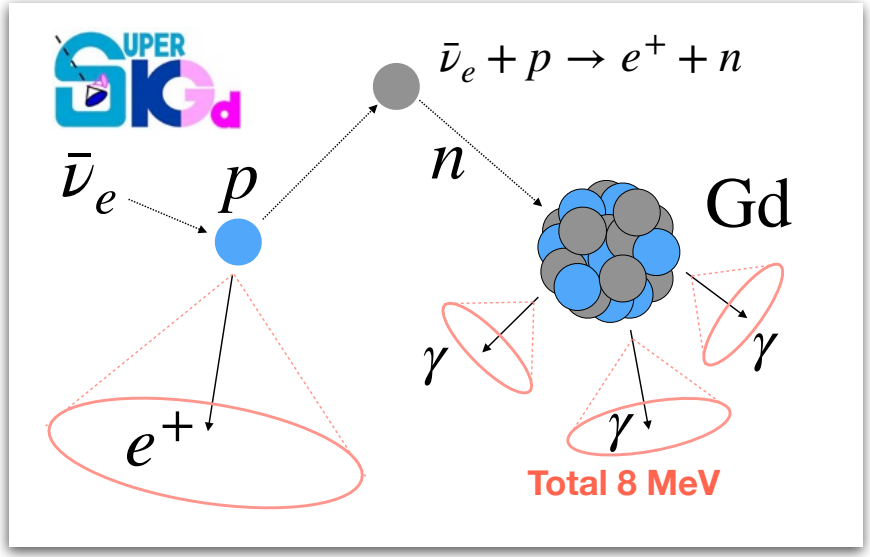
P-ONE
TRIDENT
HUNT
TAMBO
GRAND
BEACON
RNO-G
PUEO
…

possible future neutrino telescopes

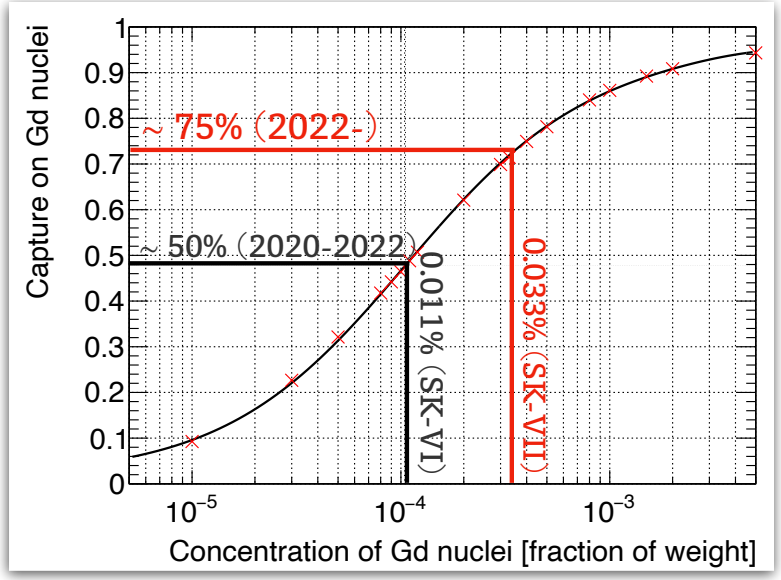
Presented by M. Harada

DSNB hint at ~2.3σ

- Phase: exposure with 22.5 kton times…
  - No neutron tagging (1996 - 2008): 3033 d (SK-I — III)
  - pure-water with neutron tagging (2008 - 2018): 2970 d (SK-IV)
  - **Gd-loaded water with neutron tagging (2020-present): >956 d (SK-VI, VII)**

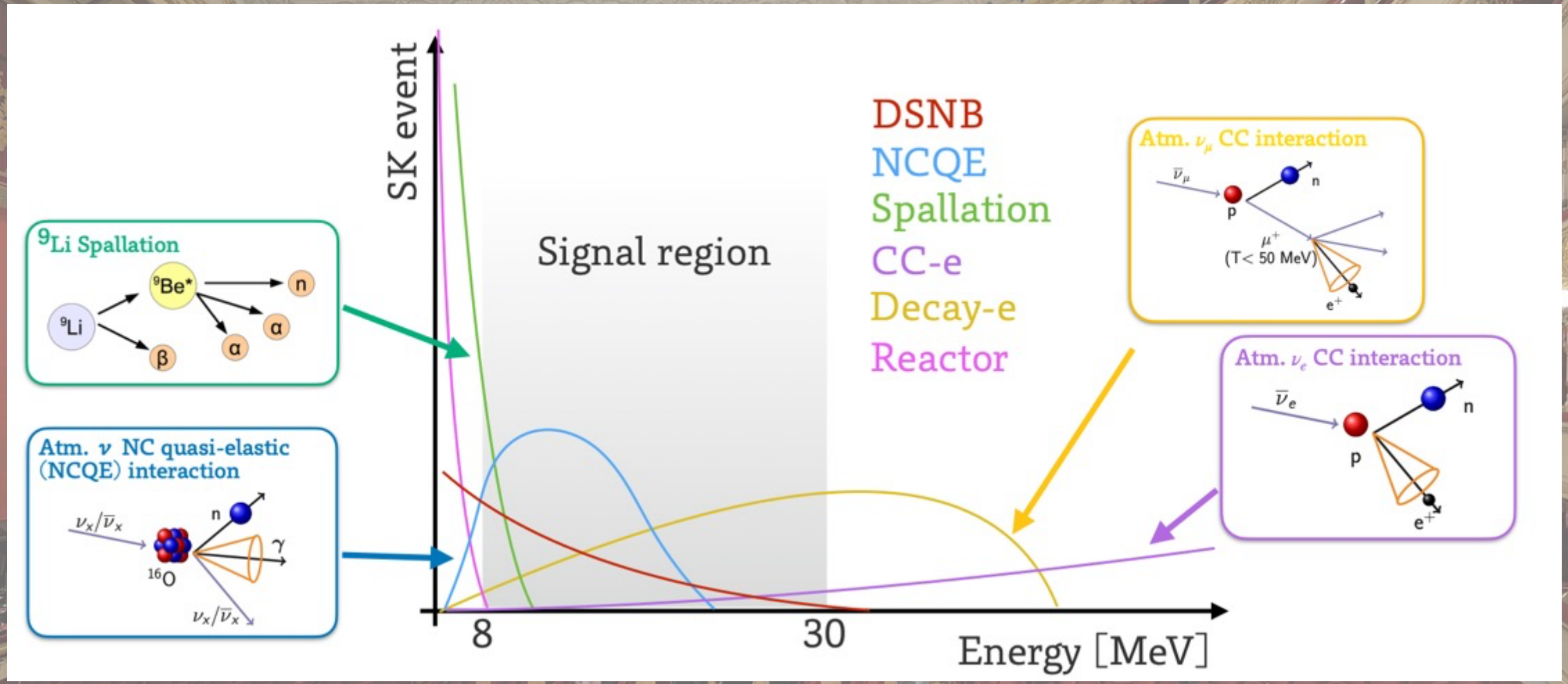


Beacom and Vagins (2004)



Presented by M. Harada

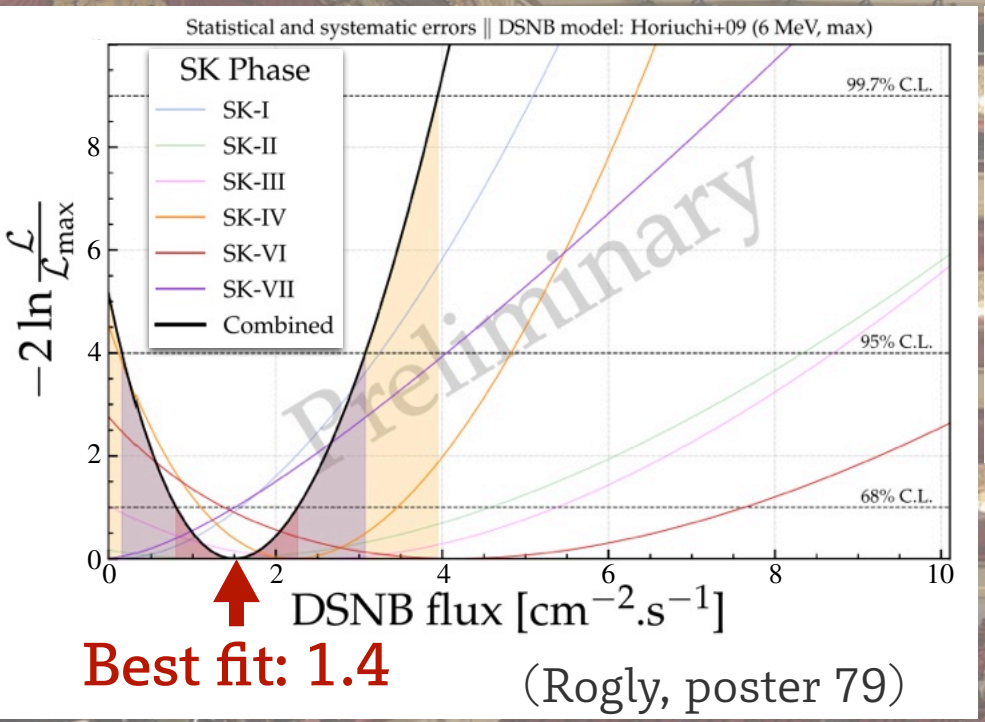
DSNB hint at ~2.3σ



Presented by M. Harada

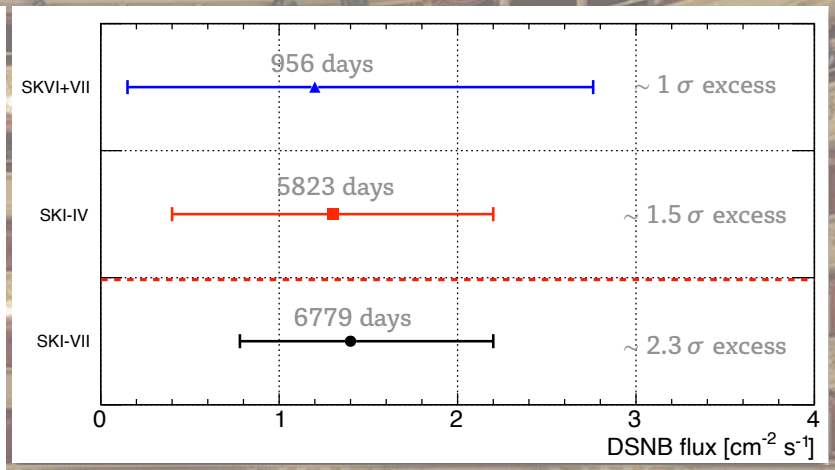
DSNB hint at ~2.3σ

SK-Gd and SK data combined



Best fit: 1.4

(Rogly, poster 79)



Presented by M. Harada

DSNB hint at ~2.3σ

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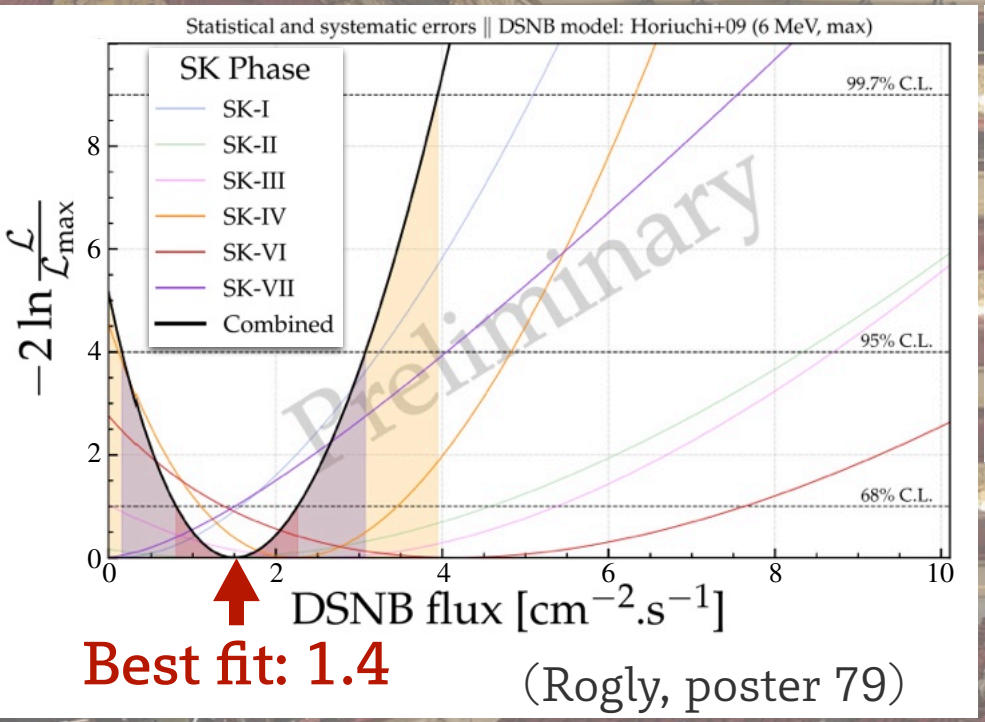

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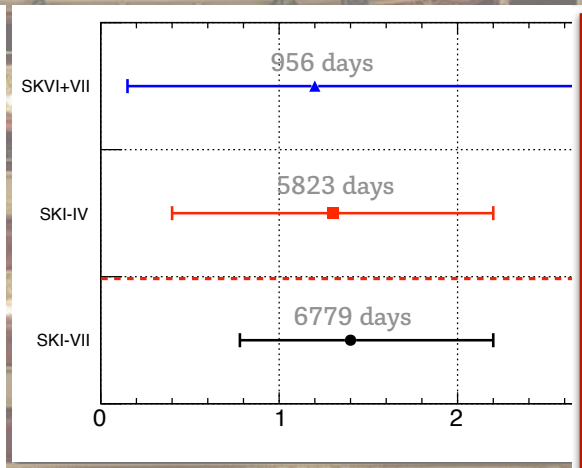
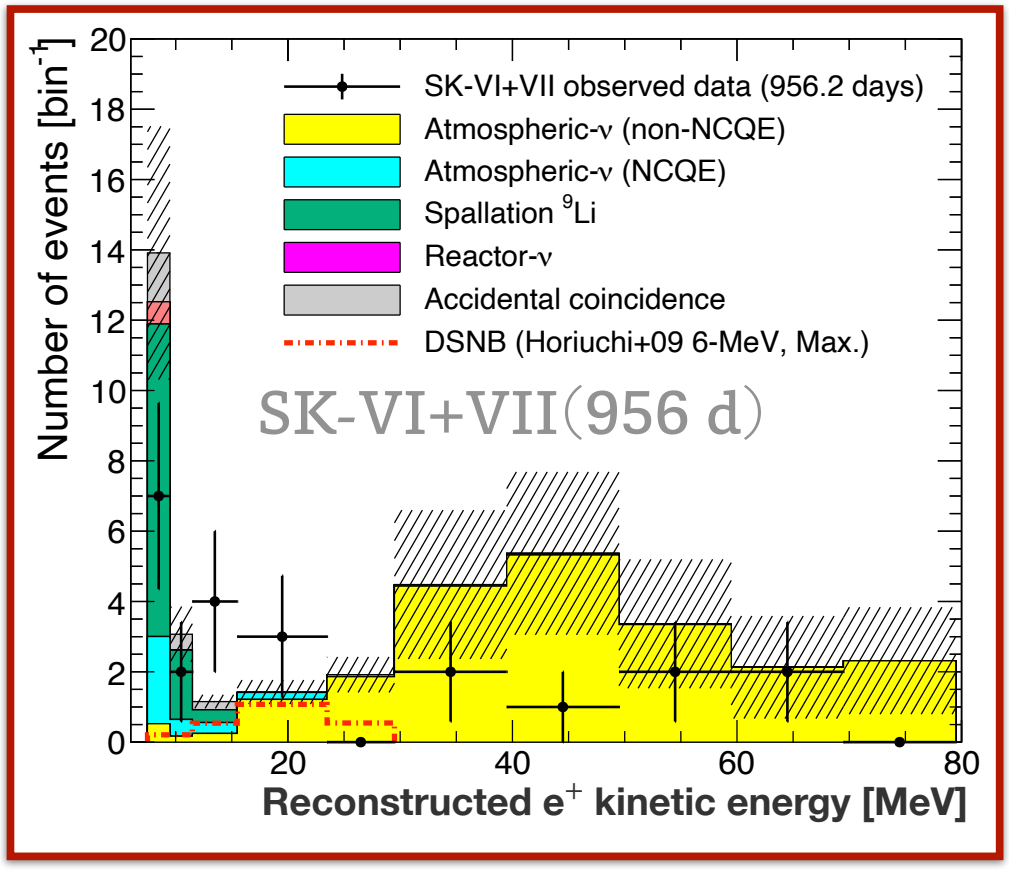
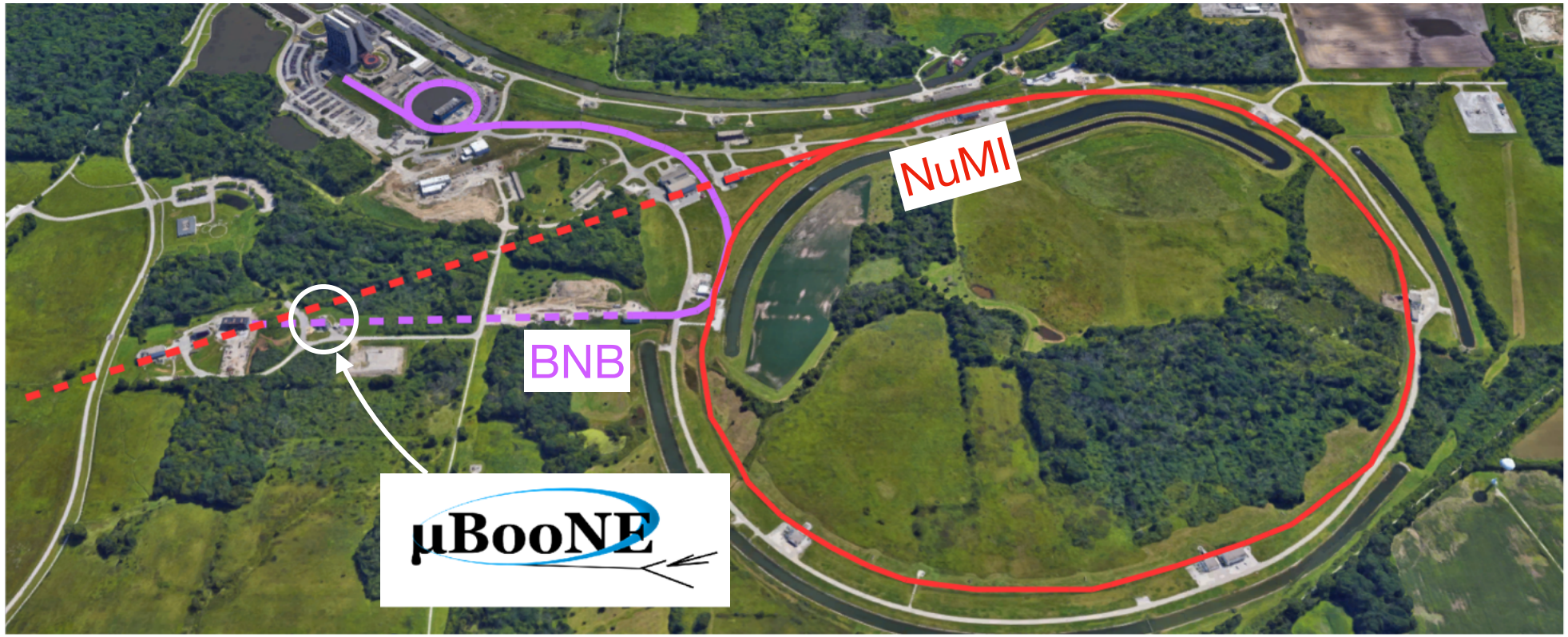




Presented by D. Caratelli

Short Baseline Experiments
MicroBooNE 5-yr Results

BNB & NuMI At MicroBooNE

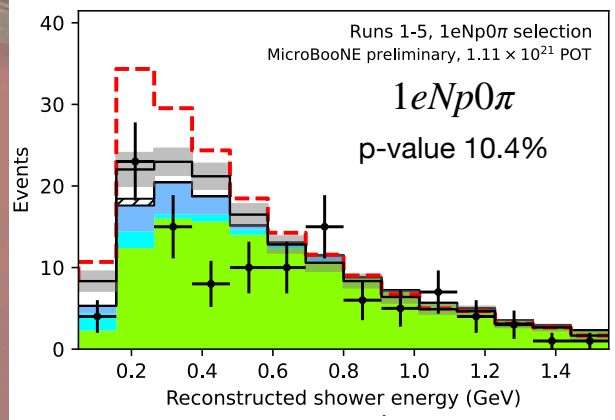


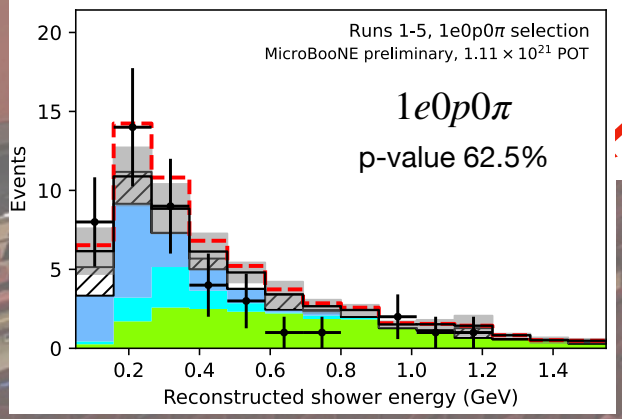
Presented by D. Caratelli

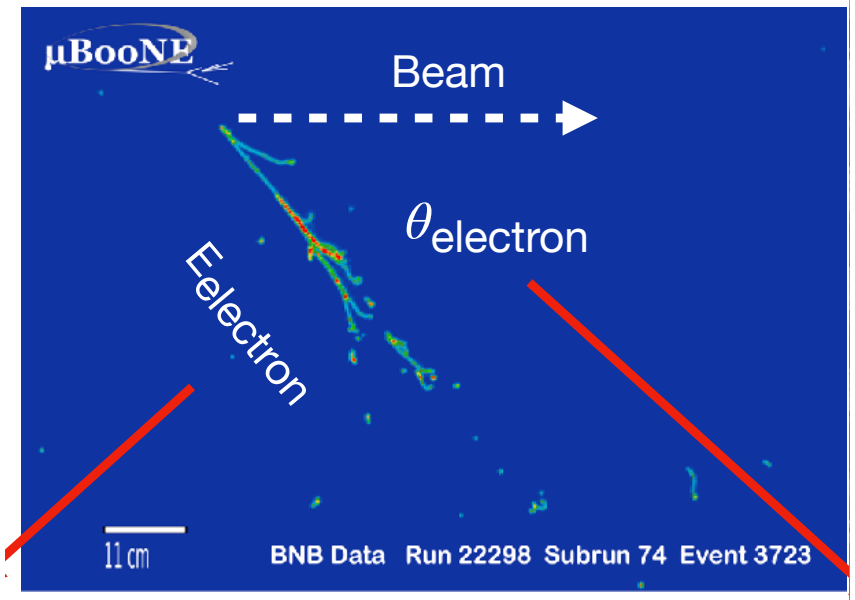
Short Baseline Experiments
MicroBooNE 5-yr Results

"Low-Energy Excess" search for pionless ν_e

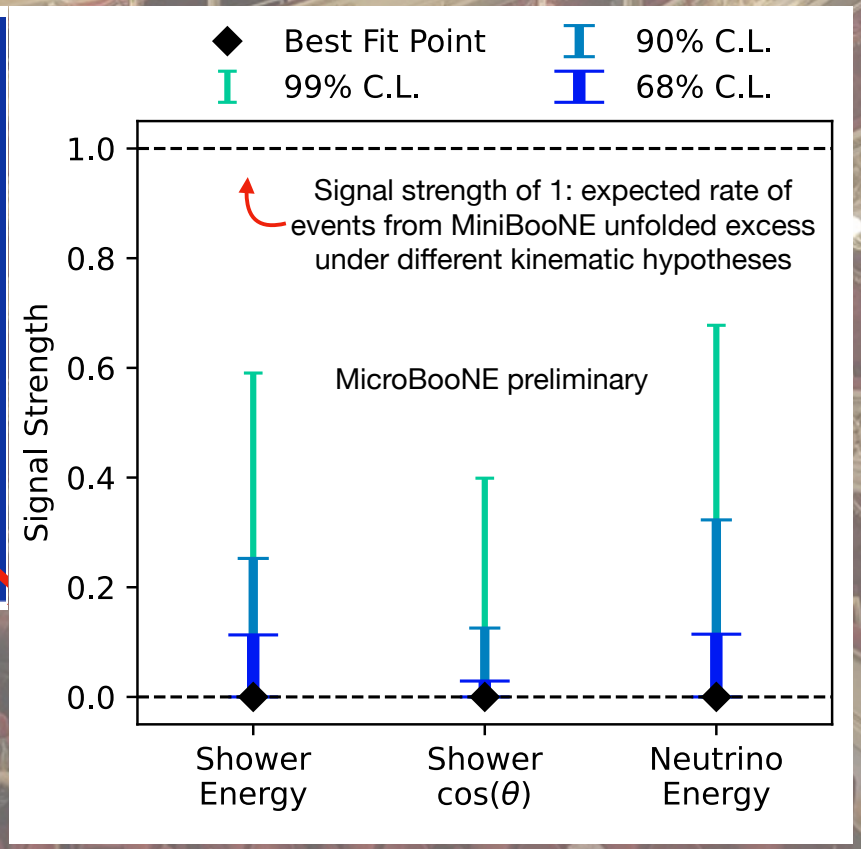
- 6.8e20 → 11.1e20 POT of BNB







data inconsistent with ν_e-like excess at >99% CL



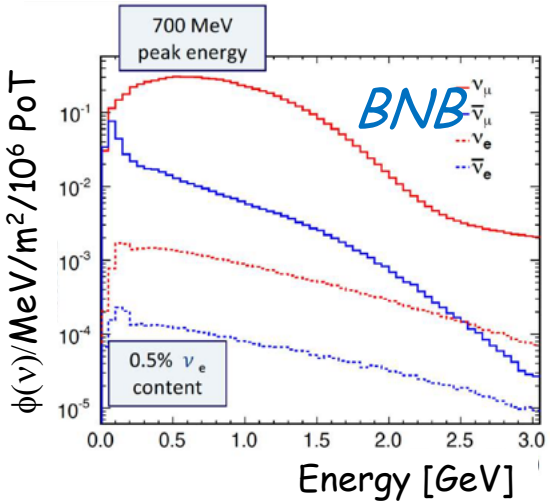
Presented by D. Gibin

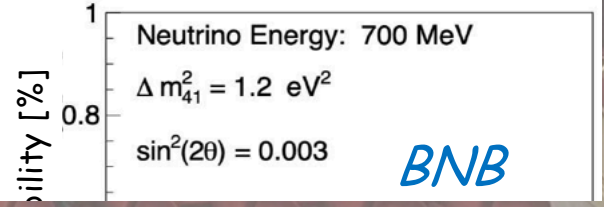
Short Baseline Experiments
ICARUS First Results

Short Baseline Neutrino (SBN) at FNAL BNB and NuMI beams:
a definitive answer to sterile neutrinos ?

ICARUS
600m baseline
470t active volume
Taking data

SBND
110m baseline
112t active volume
Commissioning



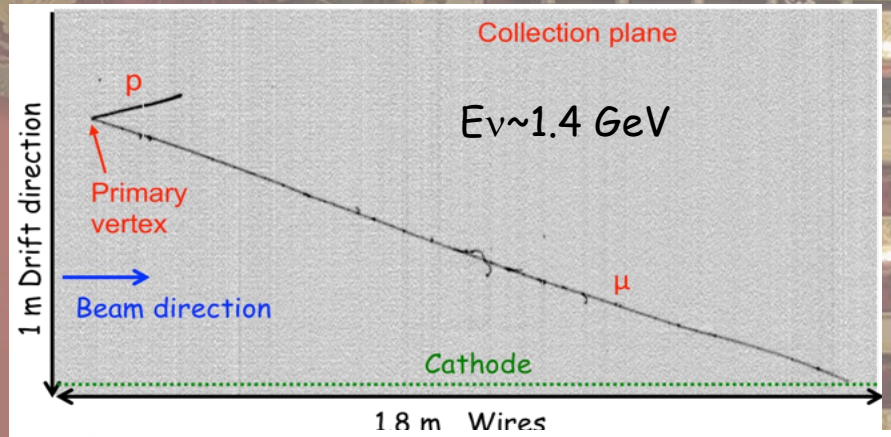


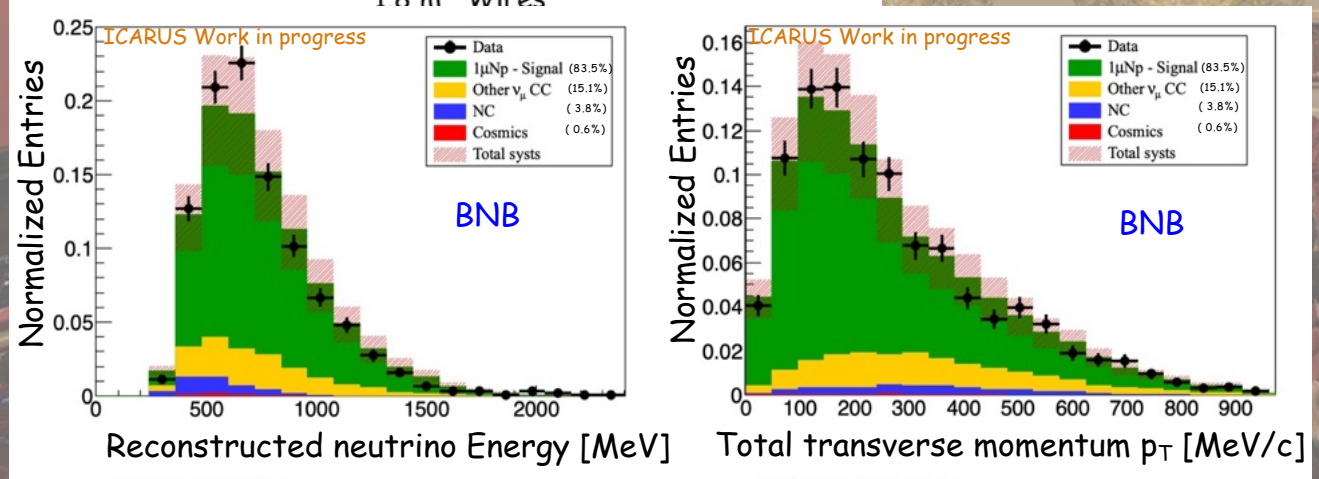
Presented by D. Gibin

Short Baseline Experiments
ICARUS First Results

Data with BNB and NuMI beams

study ν_μ disappearance while waiting for SBN





Presented by A. Sonzogni, D. Gorbunov, M. Danilov, Y. Oh

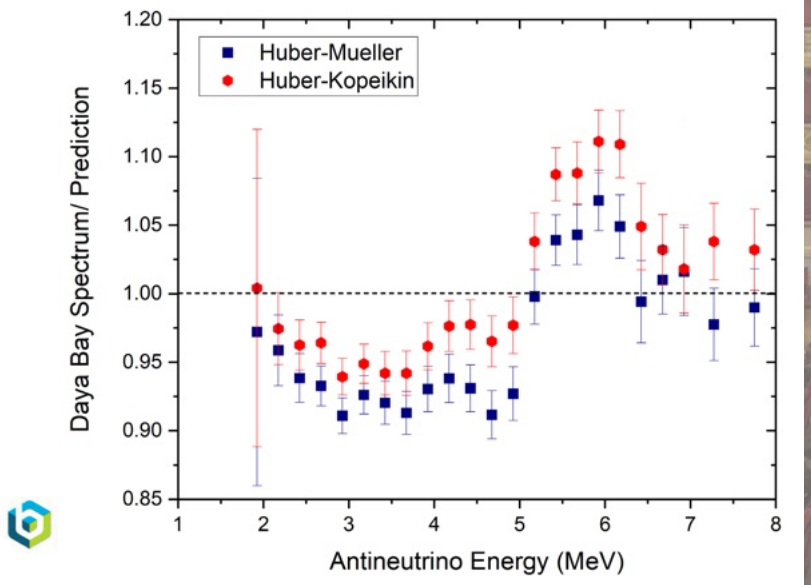
Reactor Antineutrino Anomaly and Sterile Neutrinos

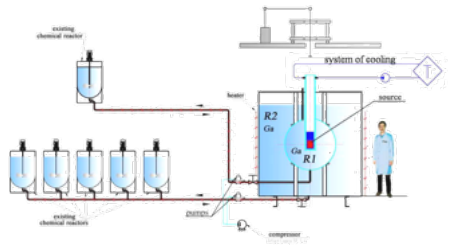
"Truth in contention"

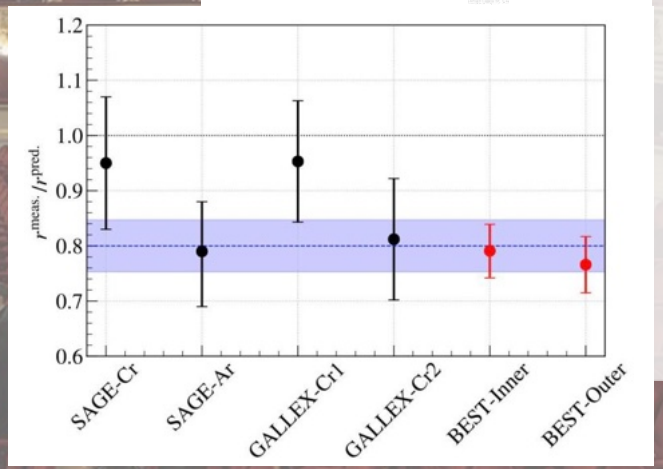
RAA is mostly understood now except for the ~5-6 MeV bump
(other features of the spectrum also to be better understood in the future)

BEST result (2021) not understood: $R_1 = 0.791 \pm 0.050$, $R_2 = 0.766 \pm 0.050$

- Ratio of ^{235}U to ^{239}Pu electron spectra is about 5% lower than ILL values.





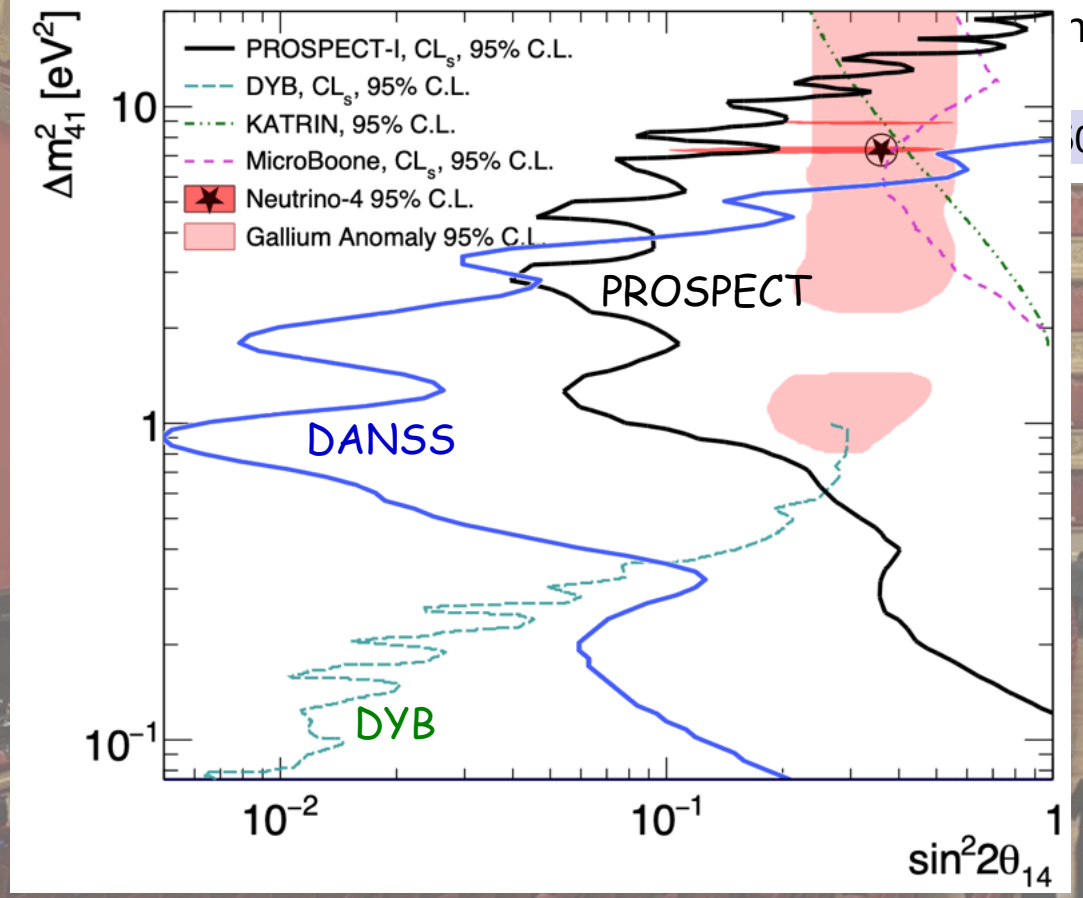


Presented by A. Sonzogni, D. Gorbunov, M. Danilov, Y. Oh

Reactor Antineutrino Anomaly and Sterile Neutrinos

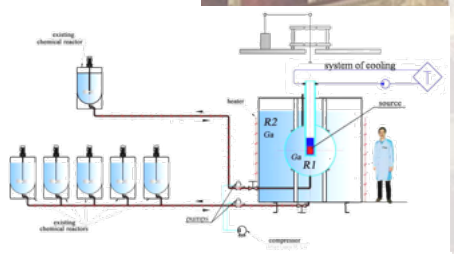
"Truth in contention"

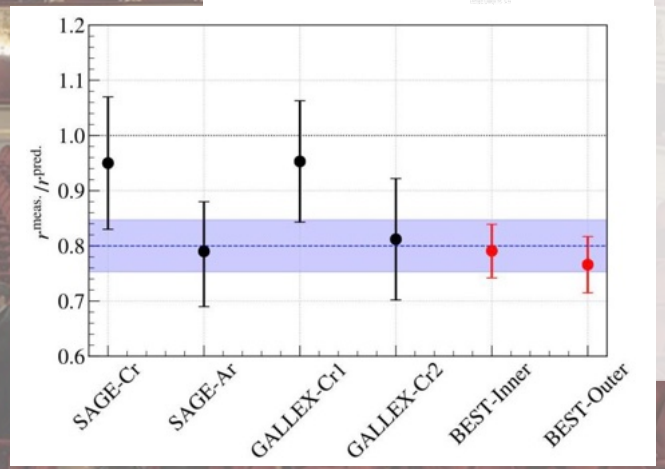
PROSPECT, Neutrino 2024, arXiv[2406.TBD]



MeV bump
nderstood in the future)

0, $R_2 = 0.766 \pm 0.050$

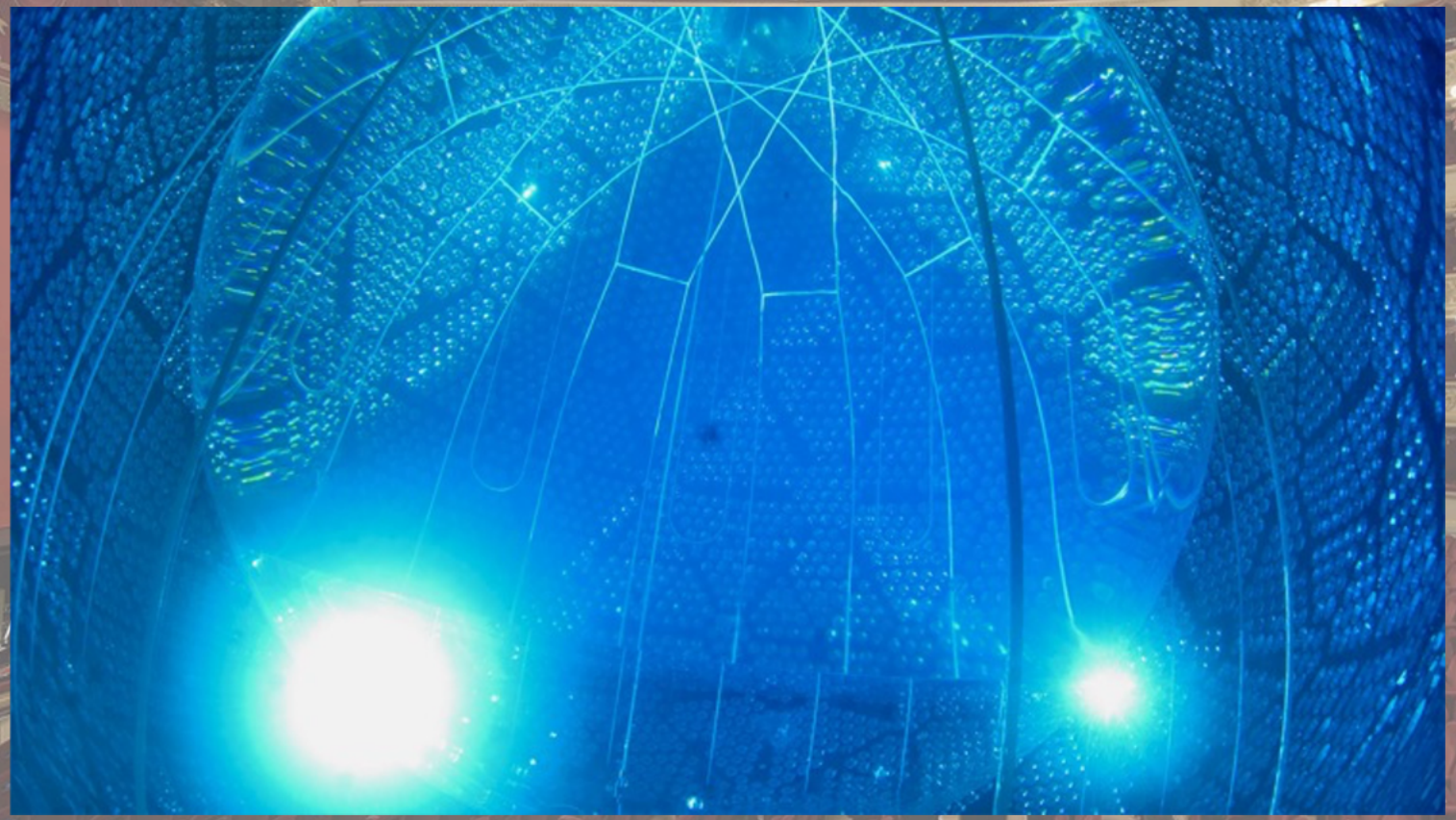




Presented by J. Maneira, L. Ludhova

The Sun and the Earth in Neutrinos

The SNO+ experiment presented new solar, reactor and geo neutrino results at Neutrino 2024.



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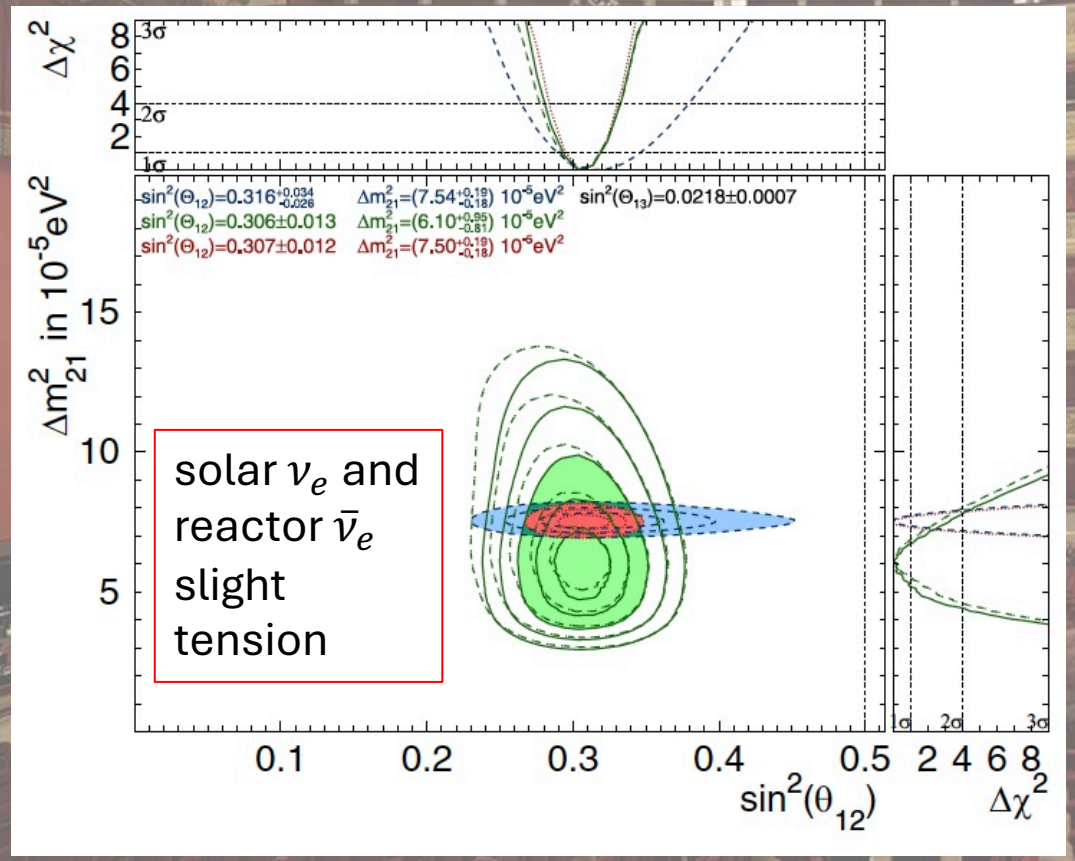


Presented by J. Maneira

The Sun and the Earth in Neutrinos

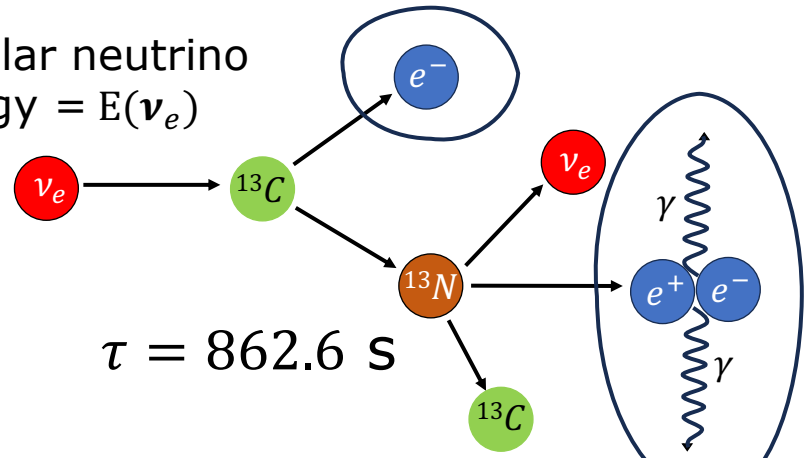
New results from SNO+ including:

- observing 2 events of CC ^{8}B solar ν_e on ^{13}C, the first time this channel has been used to detect neutrinos!

EXPECTED	BOX	LIKELIHOOD
BACKGROUND	0.31	0.17
SIGNAL	1.83	1.79

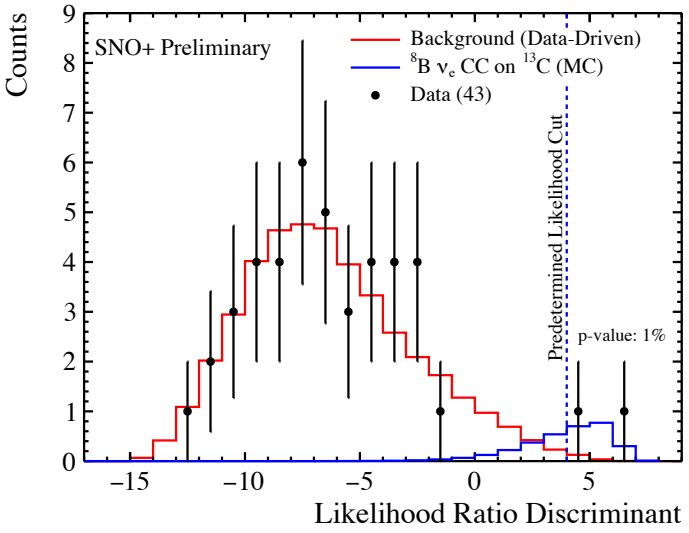
Prompt e$^-$ energy = $\mathrm{E}(\boldsymbol{\nu}_e) - 2.2\ MeV$

^{8}B solar neutrino energy = $\mathrm{E}(\boldsymbol{\nu}_e)$



$\tau = 862.6$ s

Delayed e$^+$ annihilation [1.01,2.20] MeV

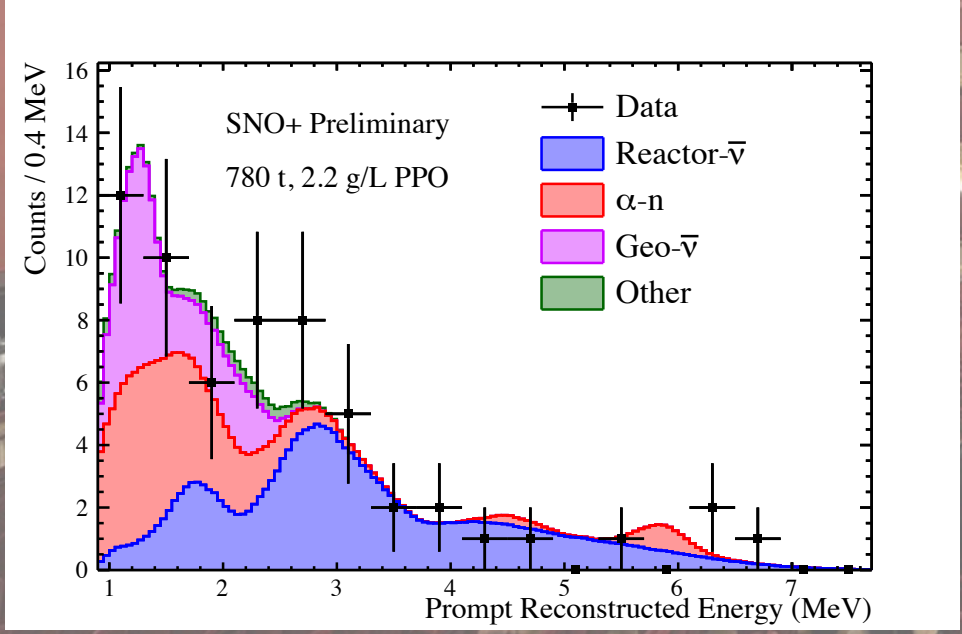


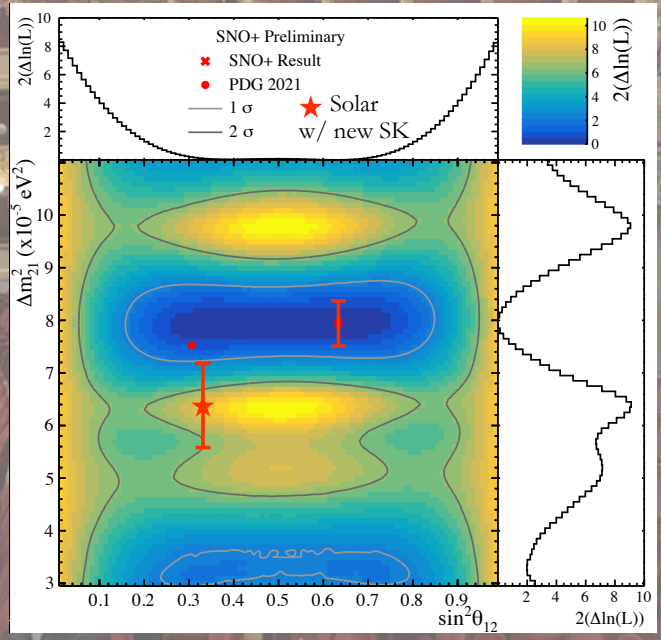
Presented by J. Maneira, L. Ludhova

The Sun and the Earth in Neutrinos

New results from SNO+ including:

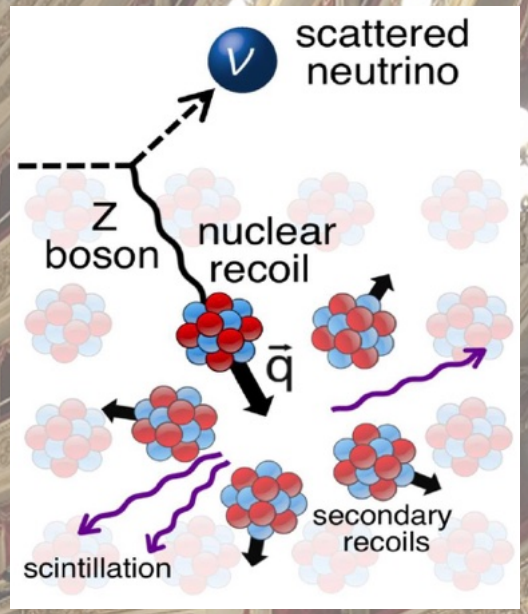
- <u>second</u> measurement of $\Delta m^2_{21} = 7.96^{+0.48}_{-0.41} \times 10^{-5}$ eV² with reactor $\bar{\nu}_e$
- prelim. geoneutrino flux measurement of 64 ± 44 TNU (refined analysis soon)





Presented by M. Green, I. Nasteva

Scattering

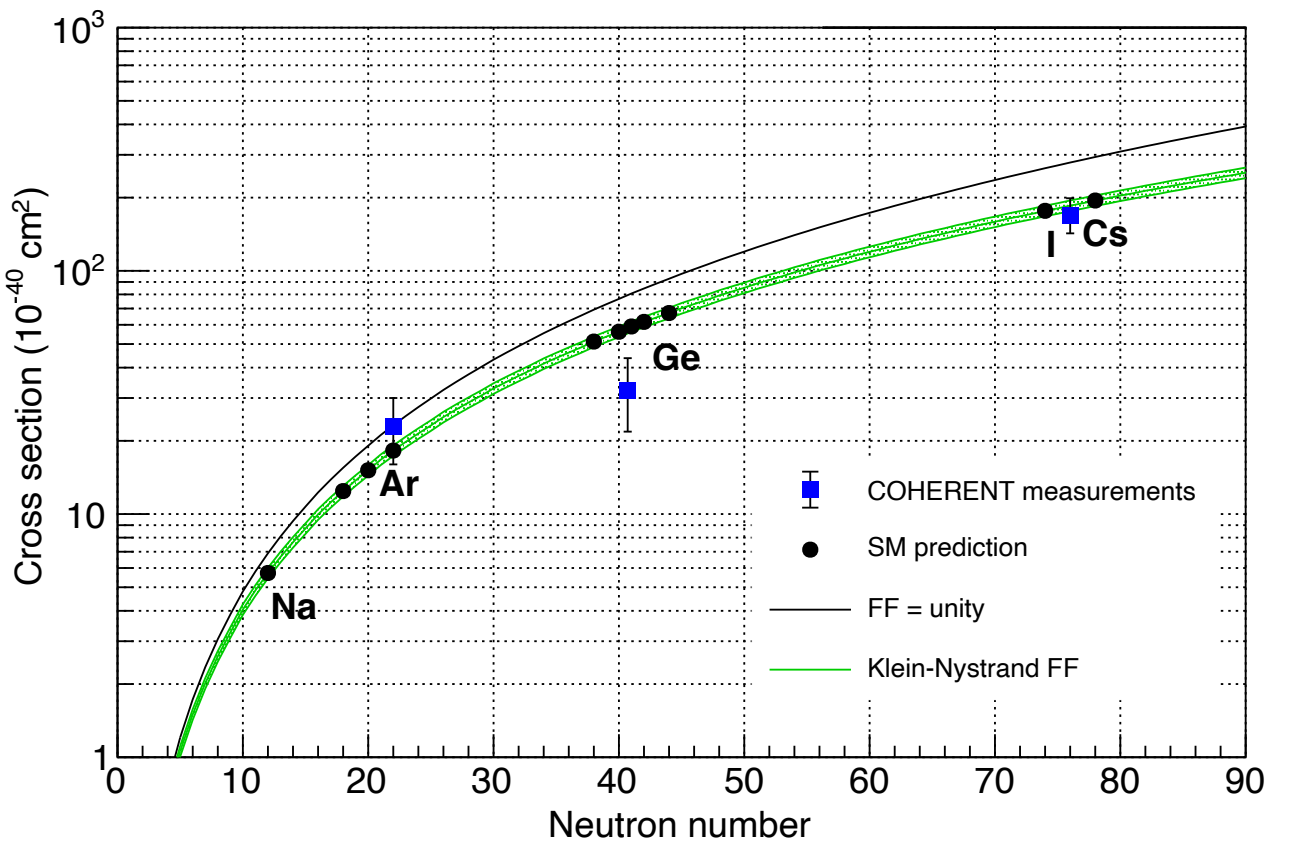


- At low energies, neutrinos scatter coherently off all neutrons in nucleus → cross section goes as N^2
- Many experiments making measurements at spallation sources (π DAR) and at reactors… so far, only the COHERENT Collaboration at the SNS (Oak Ridge) has seen signals over background

Presented by M. Green

Scattering

New Ge observation plus *many* new detectors sensitive to new physics



Presented by M. Green

Scattering

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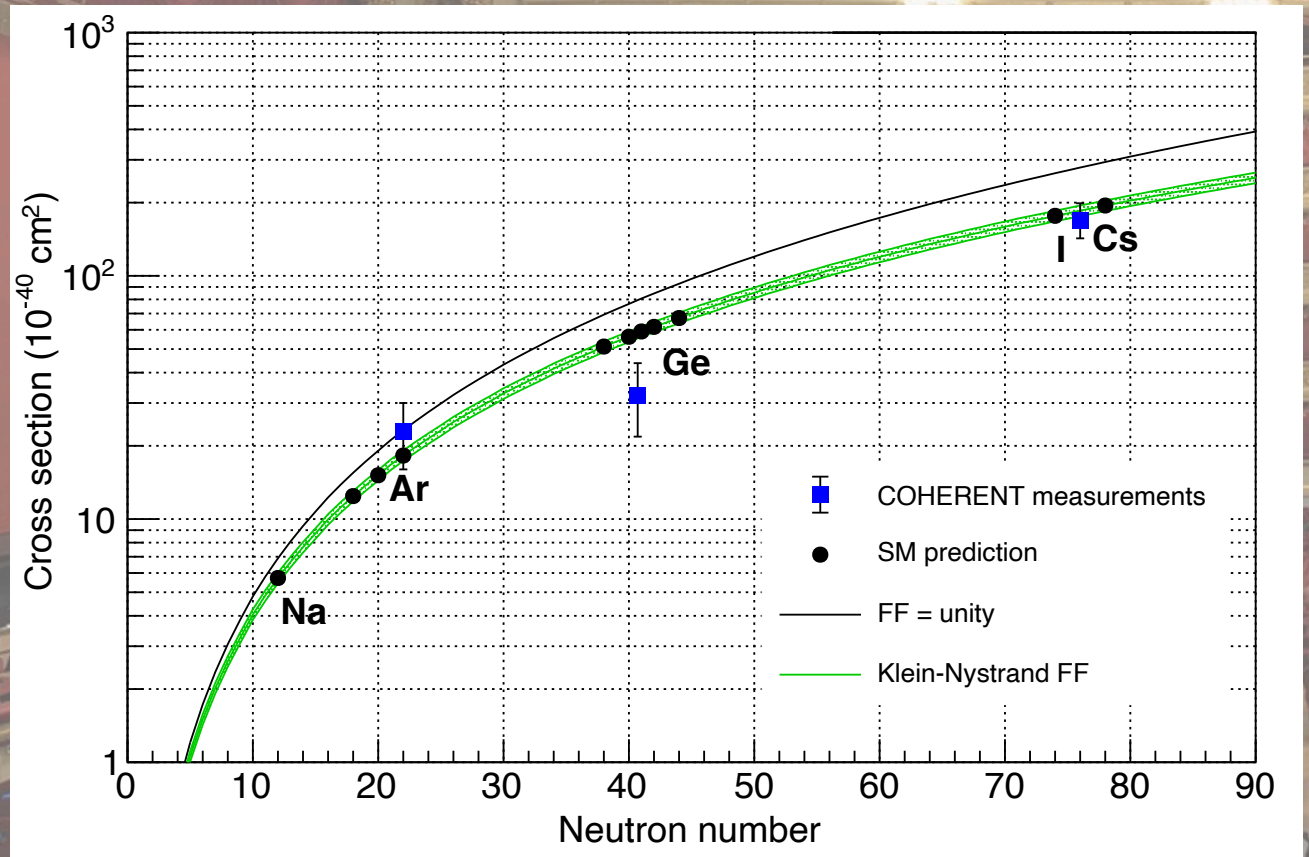
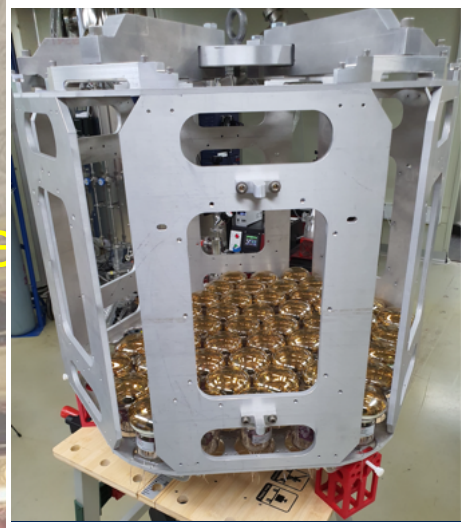
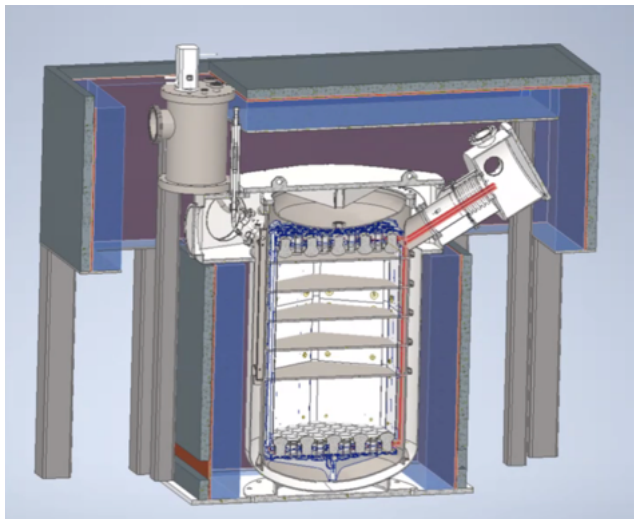


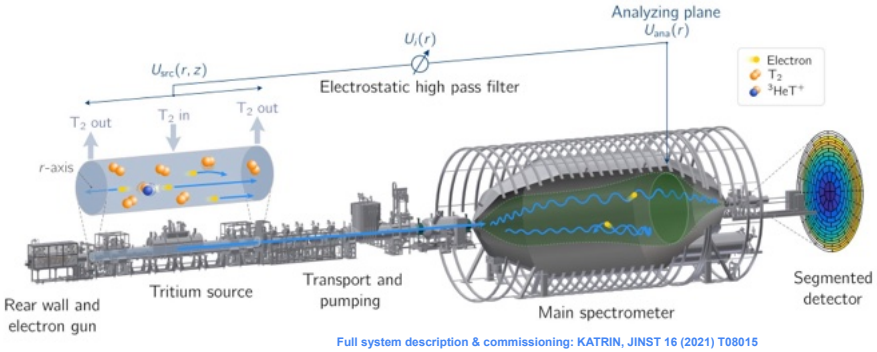




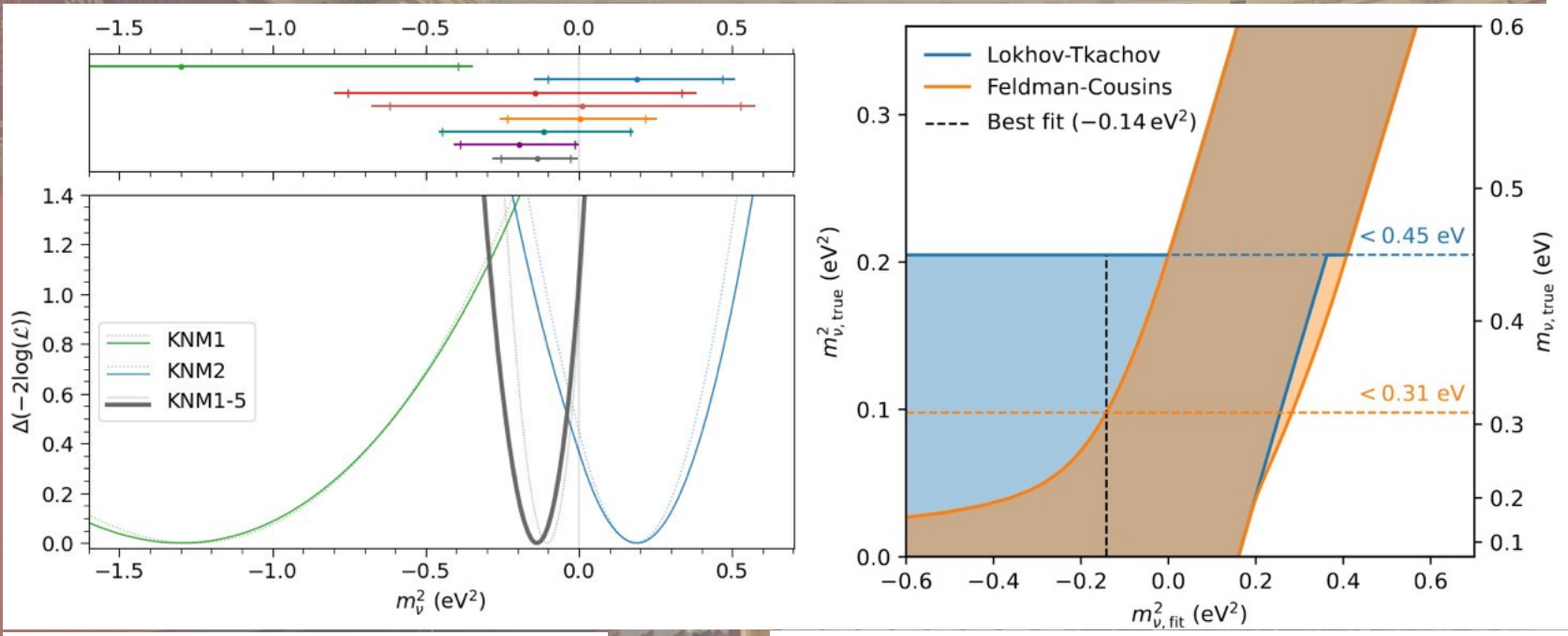
Presented by A. Lokhov

KATRIN New Result

The KATRIN experiment



Full system description & commissioning: KATRIN, JINST 16 (2021) T08015



$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$$

$$\rightarrow$$

$$m_\nu < 0.45\ \mathrm{eV}\ (90\,\%\ \mathrm{CL})$$

Presented by L. Pertoldi, I. Shimizu, C. Bucci

Double Beta Decay Updated Results at Neutrino 2024

- 1st year of LEGEND-200: combined with GERDA, Majorana:

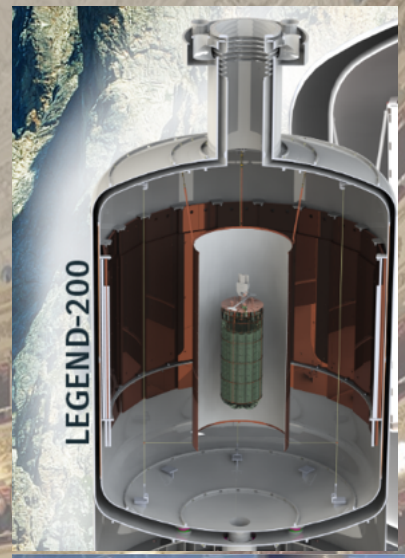
  ^{76}Ge $T_{1/2} > 1.9\times10^{26}$ yrs

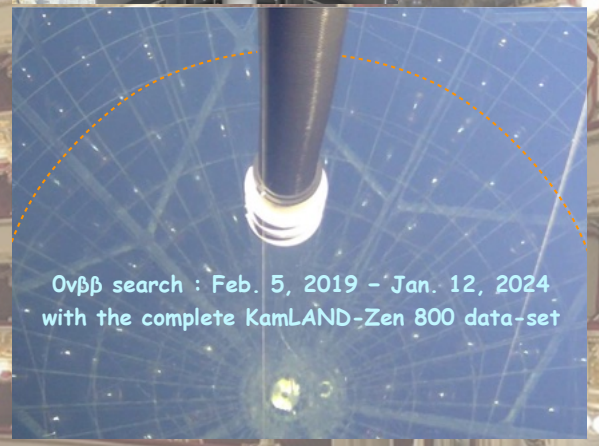
- New KamLAND-Zen 800 result:

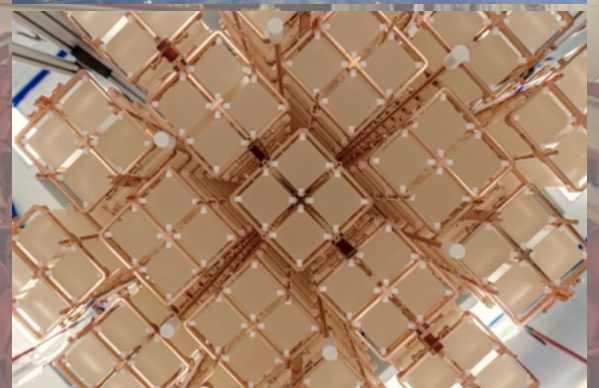
  ^{136}Xe $T_{1/2} > 3.8\times10^{26}$ yrs

- Latest CUORE 2024 result (data 05/2017 to 04/2023):

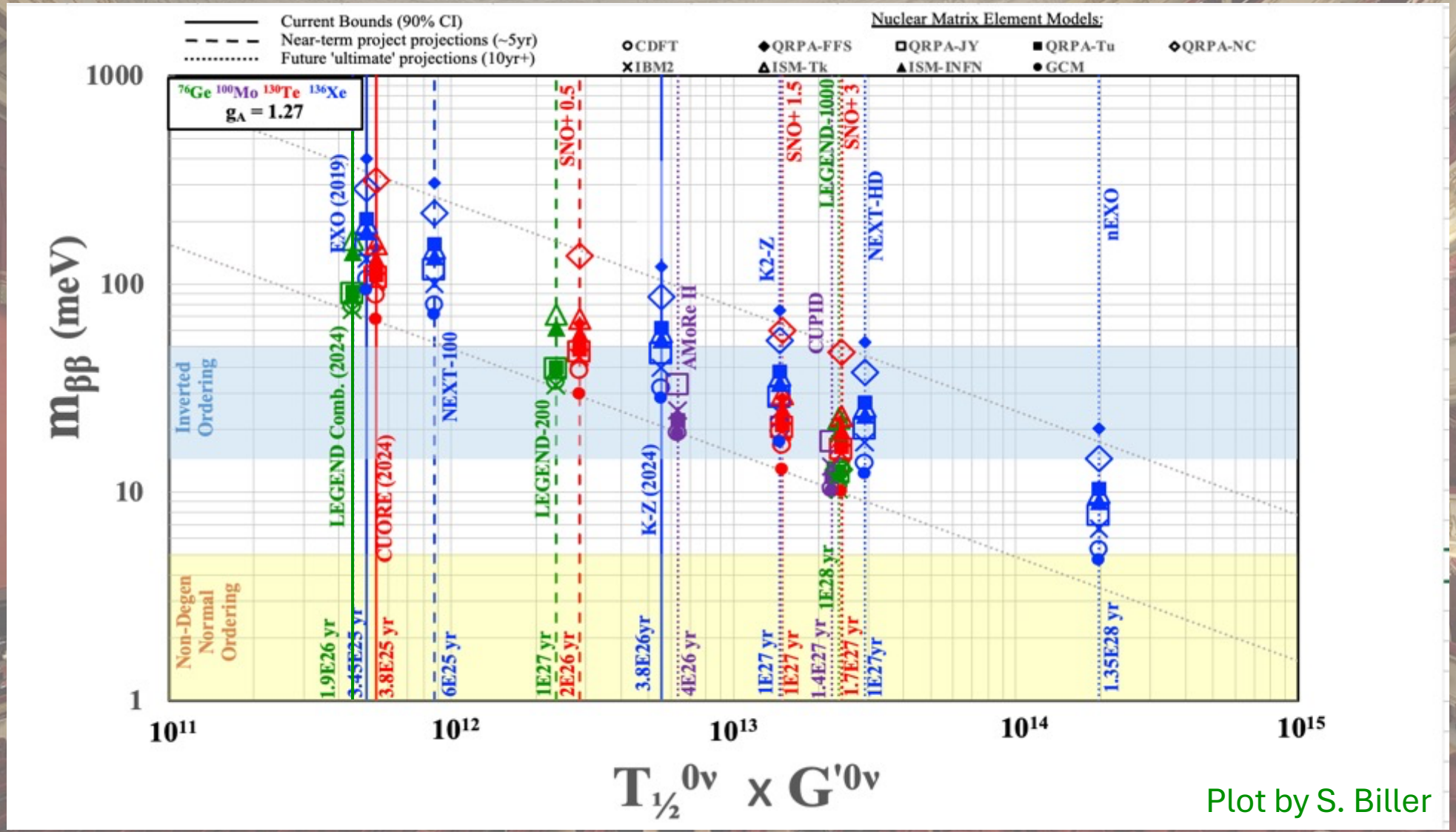
  ^{130}Te $T_{1/2} > 3.8\times10^{25}$ yrs







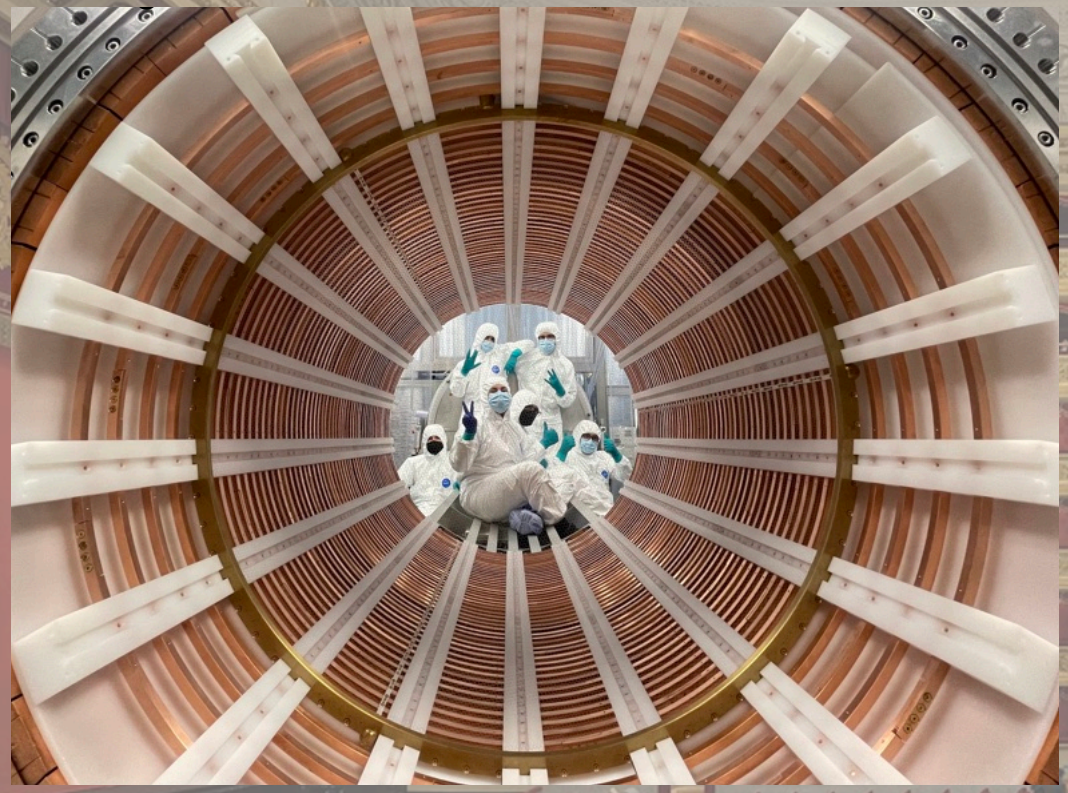
Double Beta Decay Comparison – Updated!



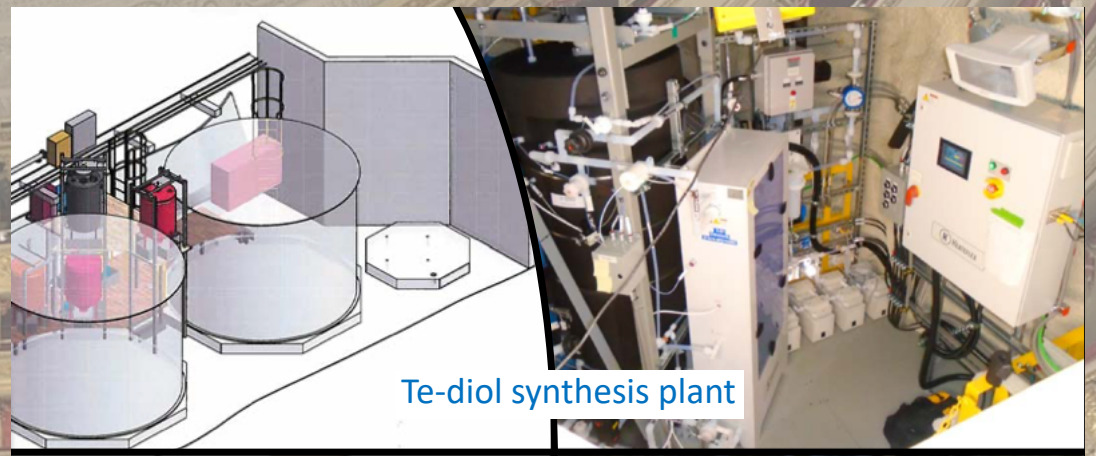
Plot by S. Biller

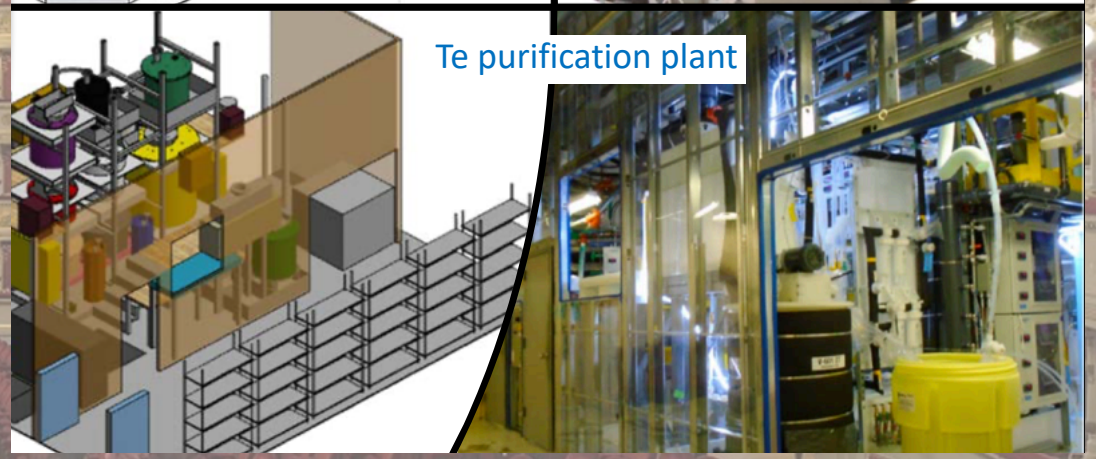
Presented by R. Guenette, MC also

Near-term New DBD Experiments



NEXT-100 fully built and under commissioning

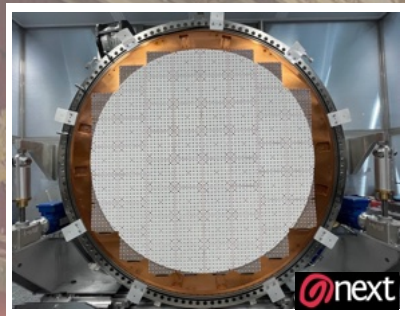


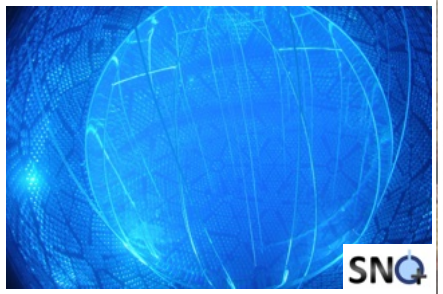


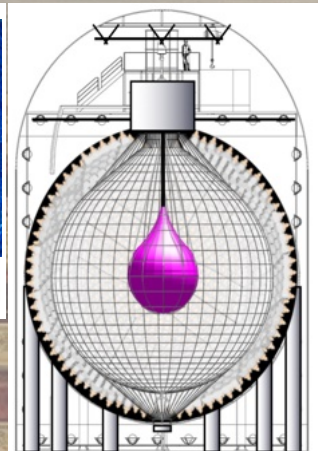
SNO+ Te systems built and undergoing full-scale testing; over 4,000 kg Te in-hand (underground since 2015) ready to deploy in 2025, after reviews and approvals

Presented by L. Pertoldi, I. Shimizu, C. Bucci R. Guenette, MC also

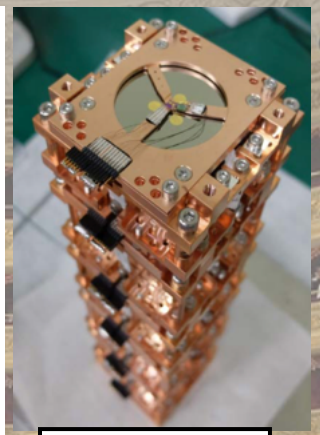
DBD Experimental Outlook





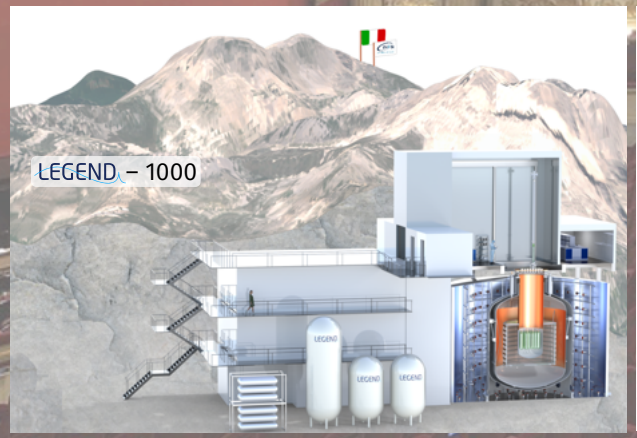


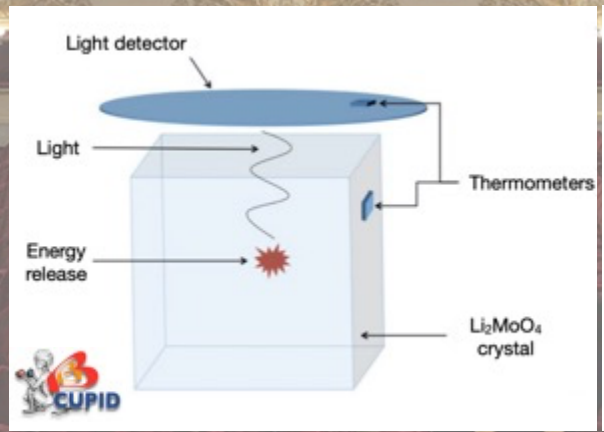
KamLAND2-Zen

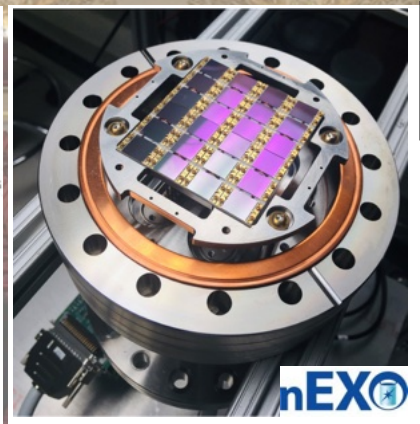


AMoRE-II

near-term new experiments



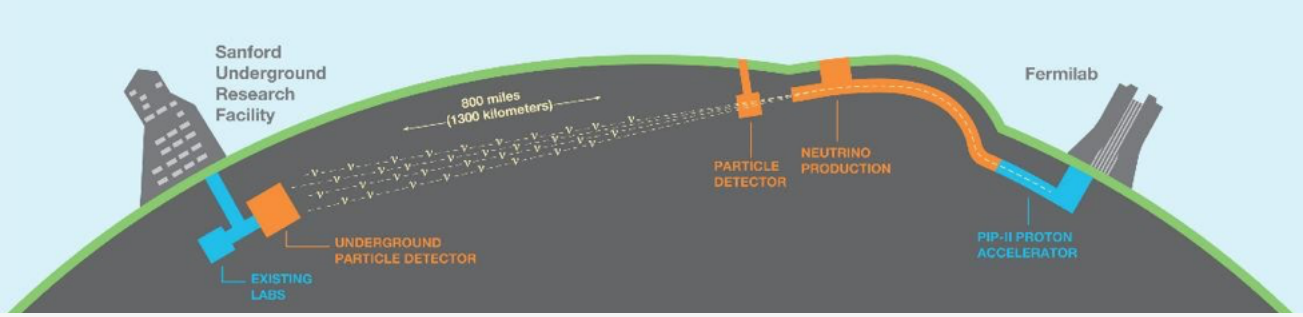




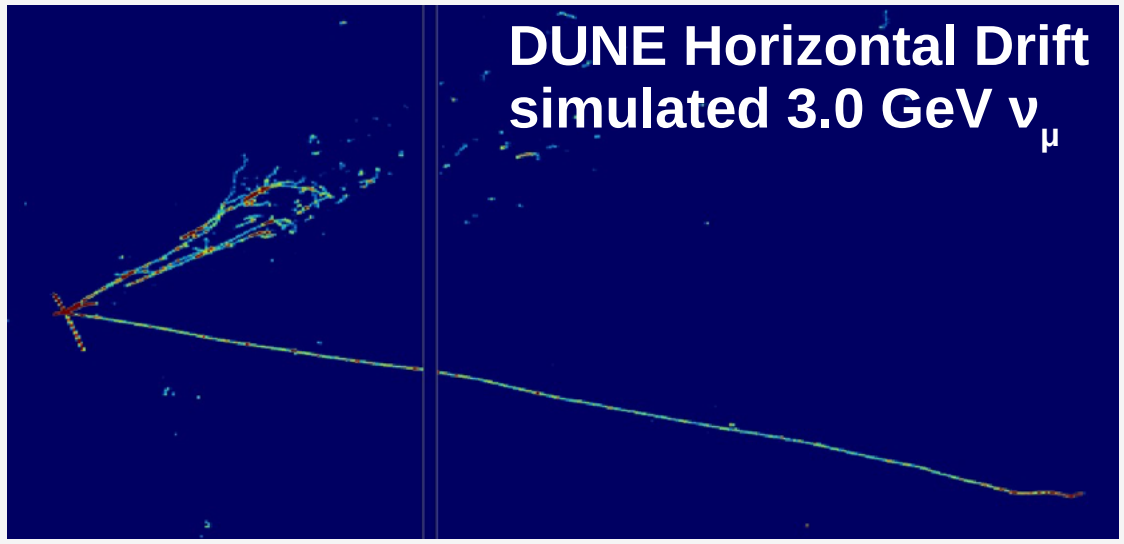
“ton-scale” program (US NSAC long-range plan)

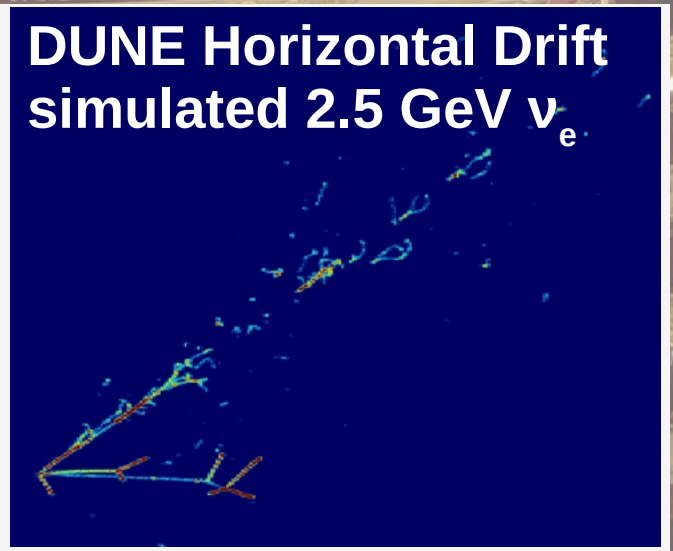
Presented by C. Marshall

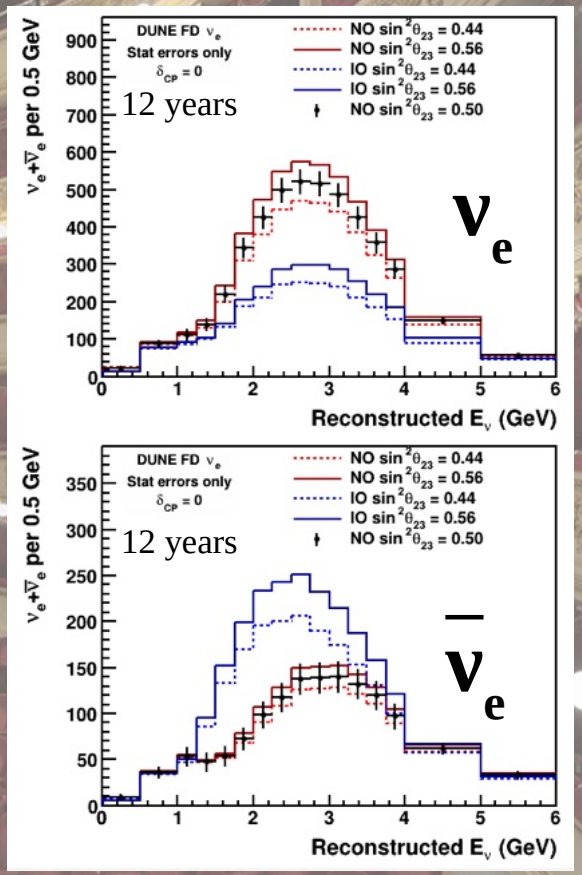
DUNE



Long baseline neutrino oscillations, solar, atmospheric, supernova, proton decay, BSM,...

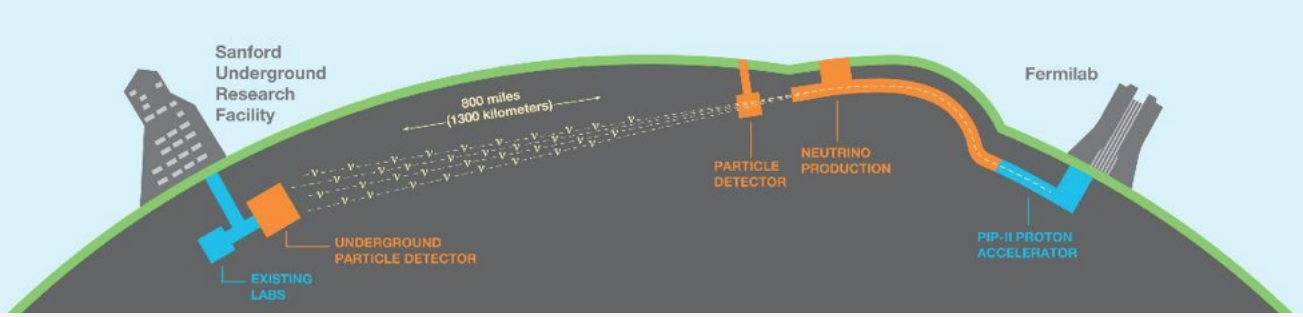




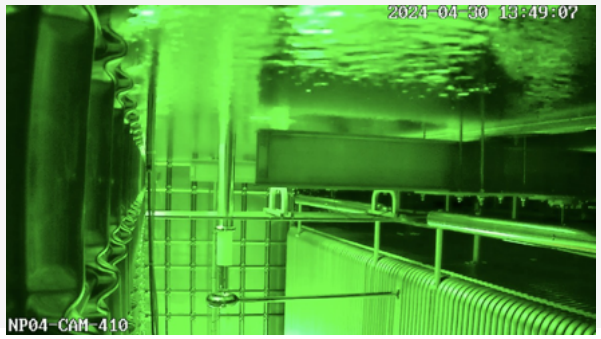


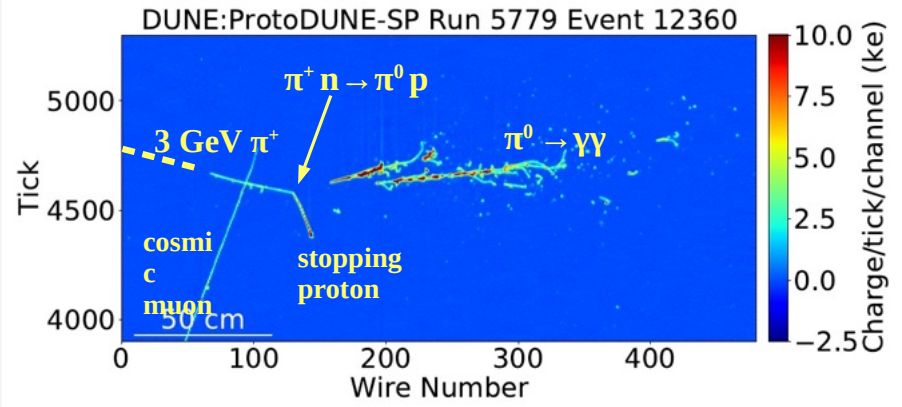
Presented by C. Marshall

DUNE

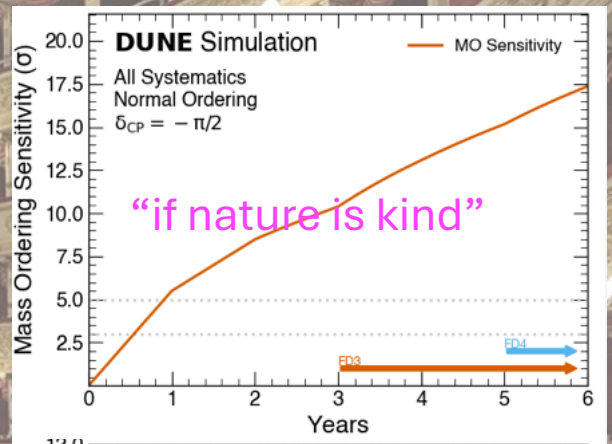


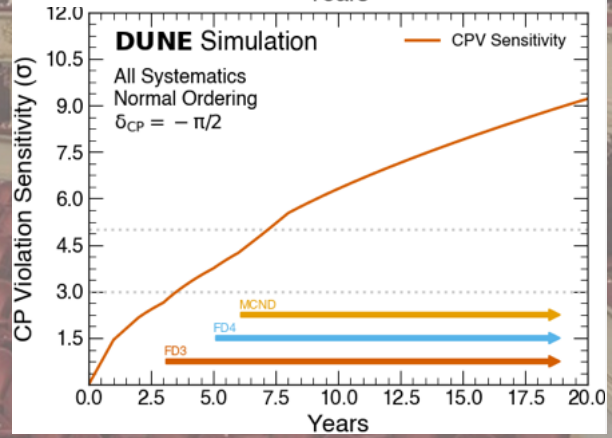
Long baseline neutrino oscillations, solar, atmospheric, supernova, proton decay, BSM,…





- Successful prototype of horizontal drift at CERN Neutrino Platform in 2018 (ProtoDUNE-SP)
- ProtoDUNE-HD completed filling 30th April, running since May, with beam turning on at 6pm tomorrow evening
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025

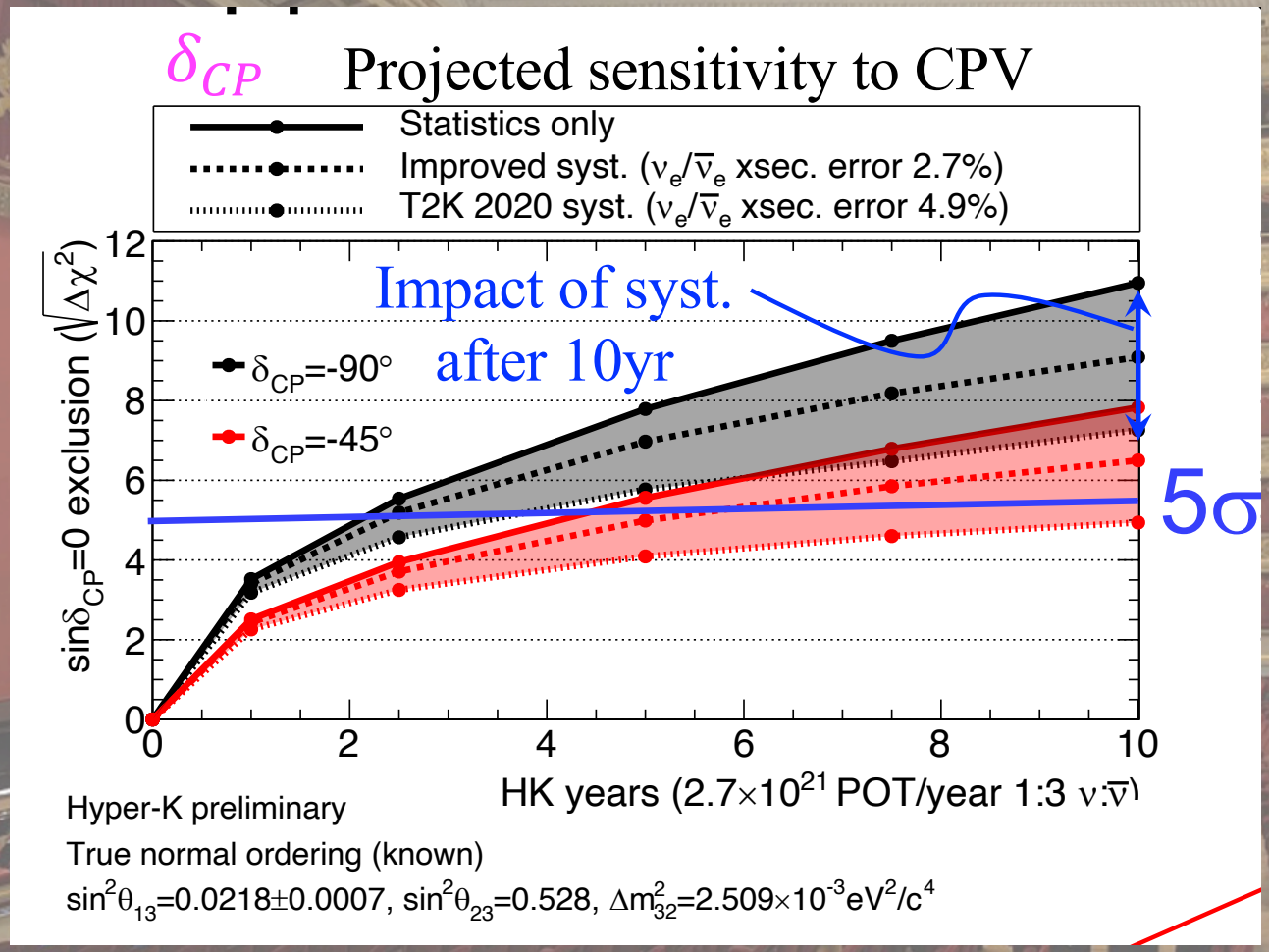




Presented by S. Moriyama

Hyper-K

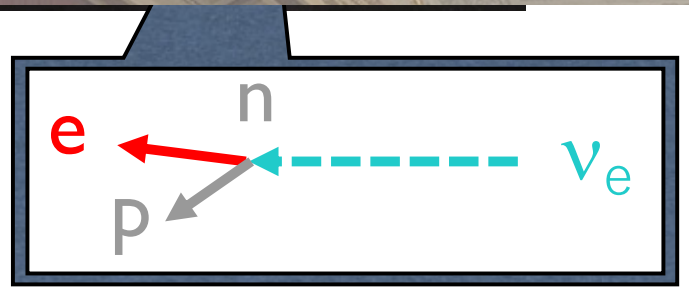
aiming for operational start in 2027



Presented by S. Moriyama

Hyper-K

aiming for operational start in 2027

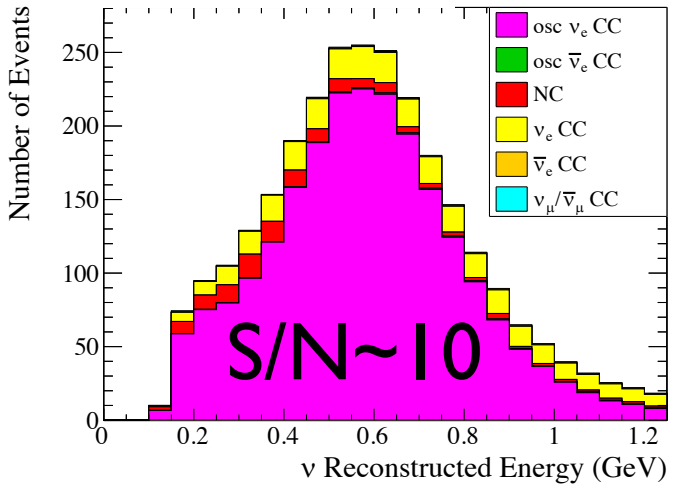


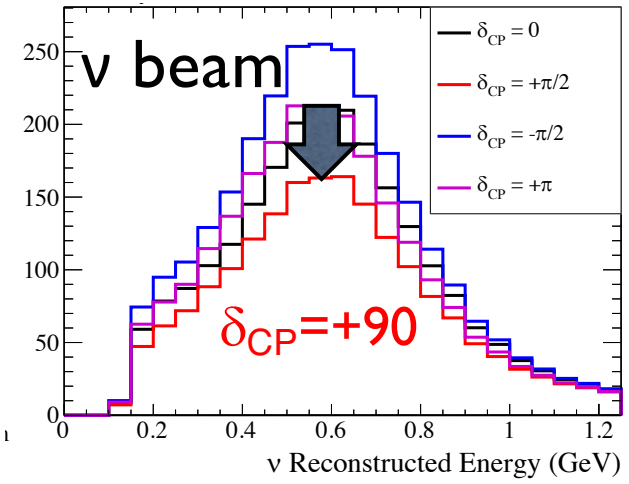
2.5 deg. off-axis

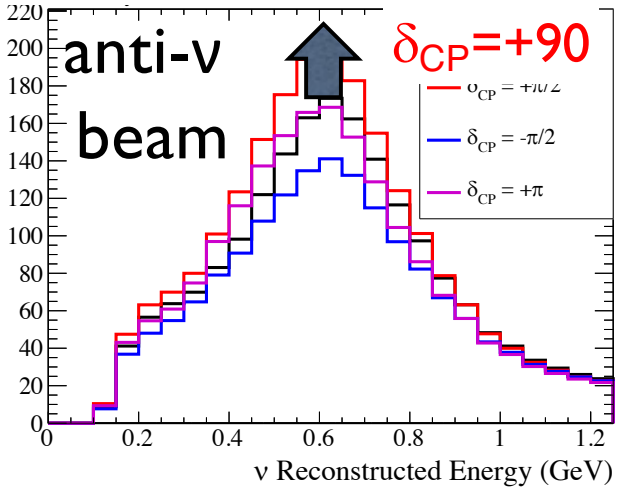
ν_e appearance signal = single e event

CCQE : $\nu_e + n \rightarrow e + p$

(dominant process at J-PARC beam energy)







Relatively Small matter Effect & Large CPV Effect

HK 10 yr, 2.7×10^{22} POT 1:3 ν:$\bar{\nu}$, 1-ring e-like + 0 decay e, > 1000 events each

Presented by S. Moriyama

Hyper-K

aiming for operational start in 2027

Oct. 3, 2023 Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)

PMT production ongoing, >10,000 delivered.
Screening both at Hamamatsu and Kamioka

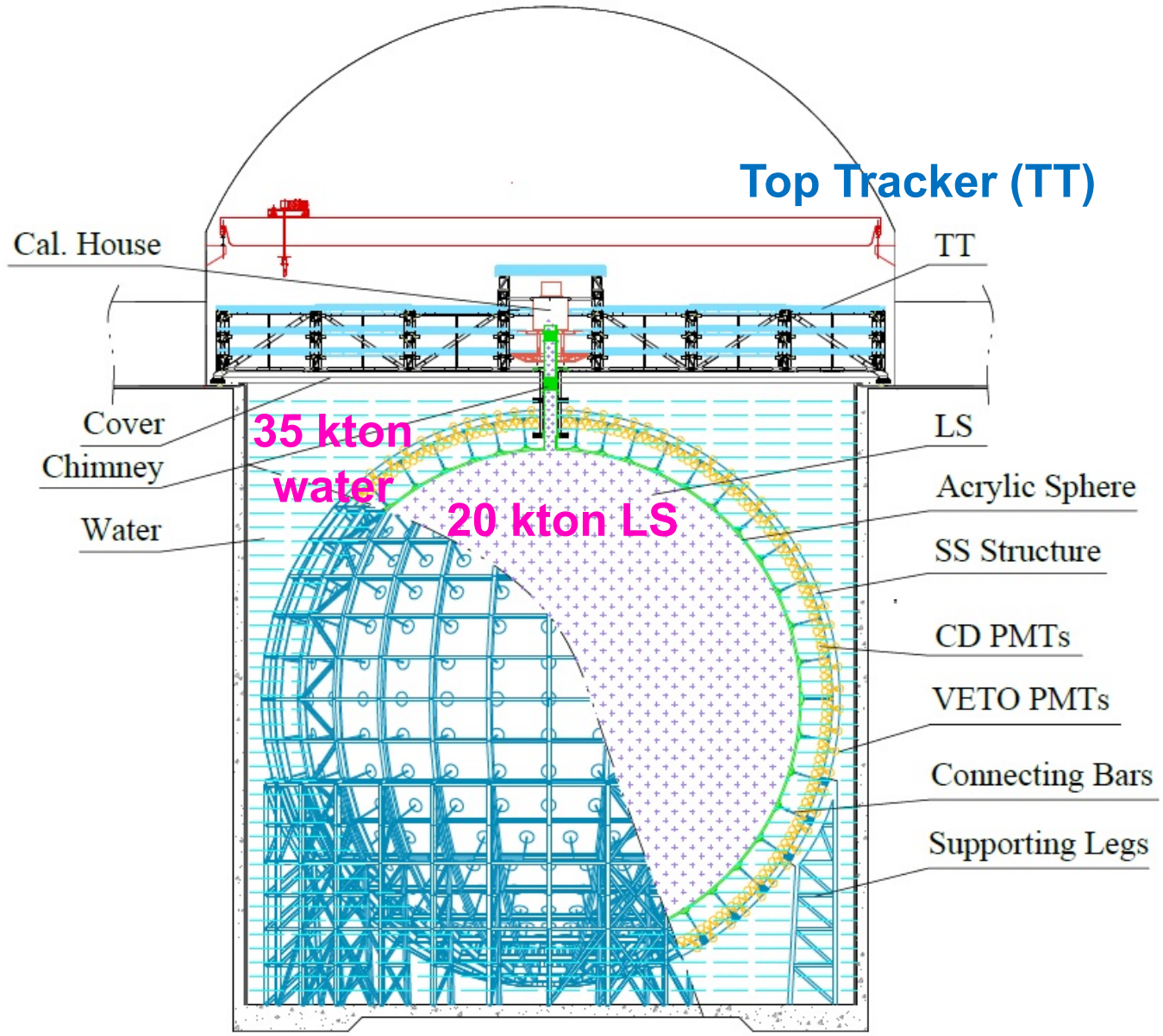
Excavation of the HK cavern will be completed by the end of this year!

Presented by J. Cao

JUNO

Aim to finish construction in 2024
and start filling

JUNO Detector



Presented by J. Cao

JUNO

Aim to finish construction in 2024
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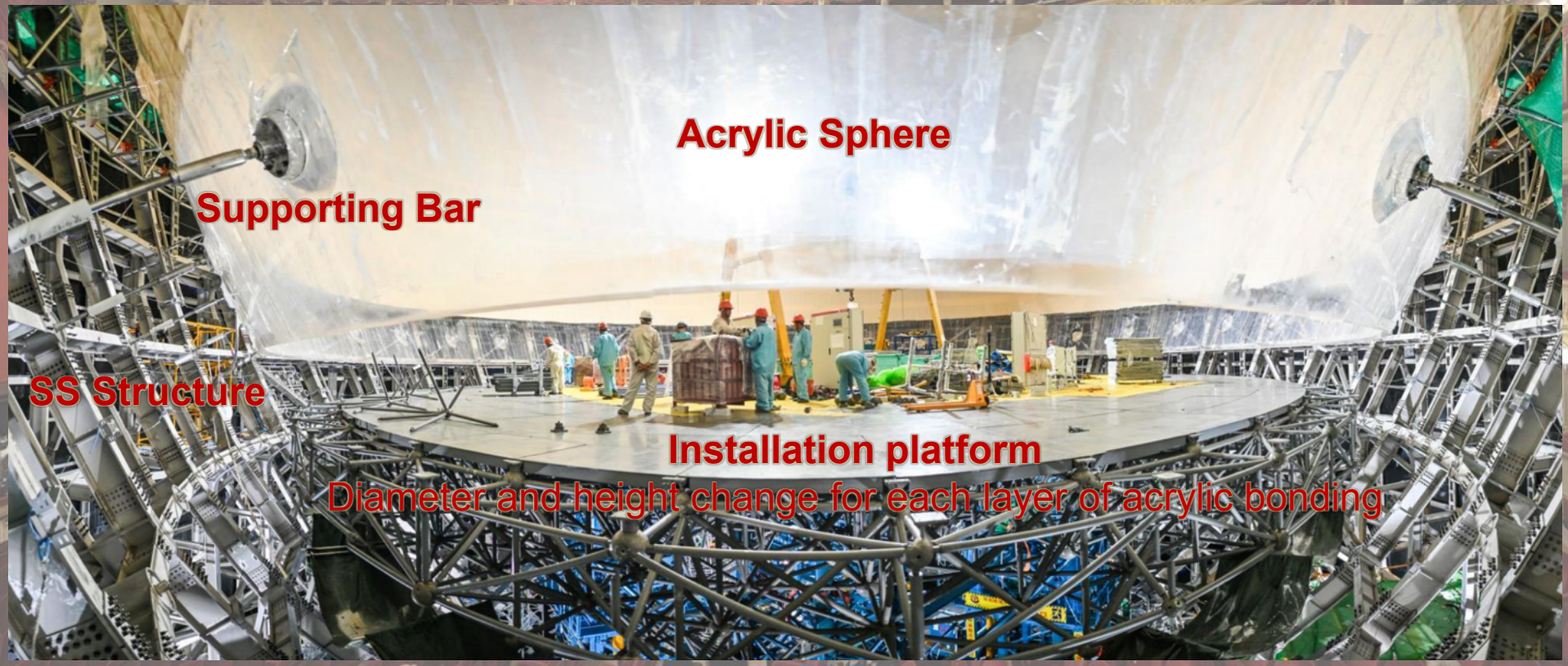


Presented by J. Cao

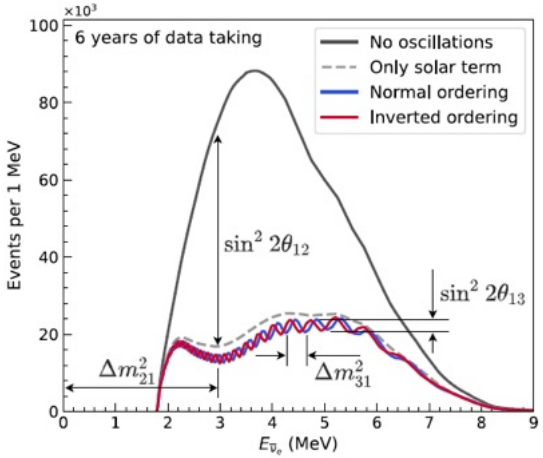
JUNO

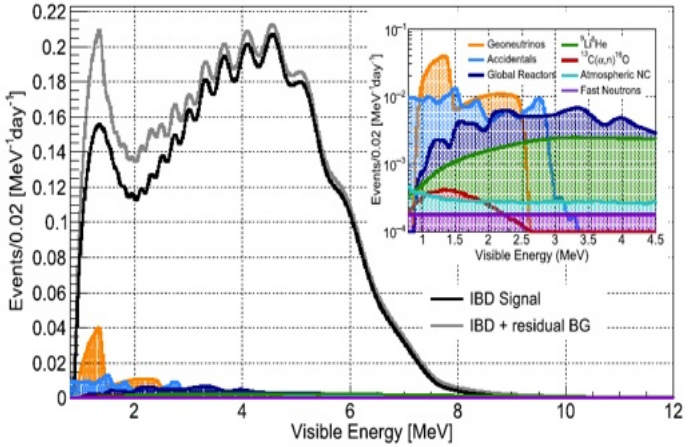
Precision Measurement of oscillation parameters

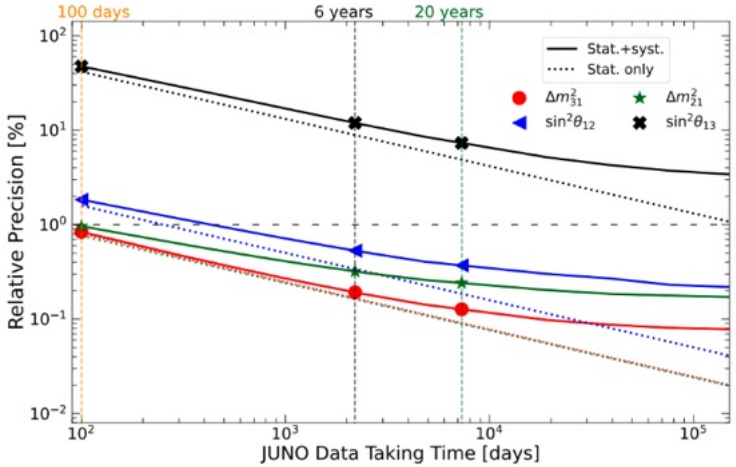
$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

ID#223, Precision Measurement

Chin. Phys. C46 (2022) 12, 123001







	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	$\pm$0.034 (1.3%)	$\pm$0.021 (0.8%)	$\pm$0.0047 (0.2%)	$\pm$0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	$\pm$0.18 (2.4%)	$\pm$0.074 (1.0%)	$\pm$0.024 (0.3%)	$\pm$0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	$\pm$0.013 (4.2%)	$\pm$0.0058 (1.9%)	$\pm$0.0016 (0.5%)	$\pm$0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	$\pm$0.0007 (3.2%)	$\pm$0.010 (47.9%)	$\pm$0.0026 (12.1%)	$\pm$0.0016 (7.3%)

$\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$, leading measurements in 100 days; precision <0.5% in 6 years

Conclusion

There were a lot of updates from neutrino experiments at the Neutrino conference!

The field has several large, important experiments being built, as well as experiments that are running, making measurements (or soon to be) and producing interesting results!

Experimental neutrino physics is a vibrant field with exciting future prospects!

Backup

- I did not mention these important topics
  - Existing θ_{13} reactor neutrino experiments
  - Each experiment searching for sterile neutrinos (at reactors)
  - Reactor monitoring and neutrinos for nuclear non-proliferation
  - Many secondary capabilities of many experiments
  - Neutrino and multi-messenger astronomy was under covered
  - Supernova (core collapse) neutrinos
  - Neutrino cosmology including $\sum m_\nu$
  - Neutrino hadroproduction and interactions – necessary for long baseline experiments and their systematics