

Disclaimer: this is not  
a comprehensive  
summary of all talks

# Experimental Outlook after Neutrino 2024

Mark Chen  
Queen's University

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

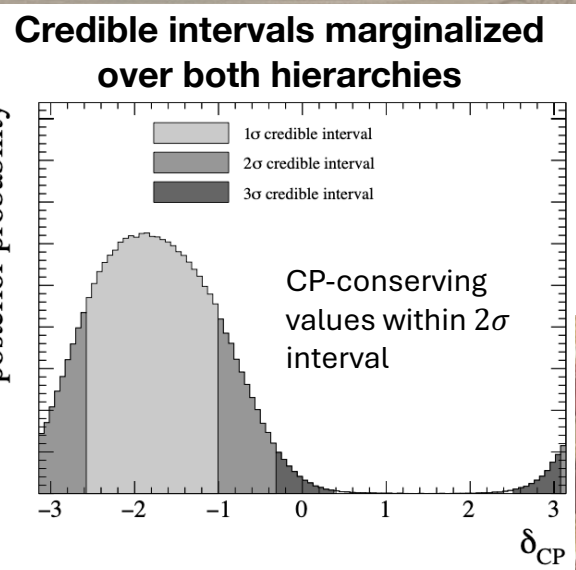
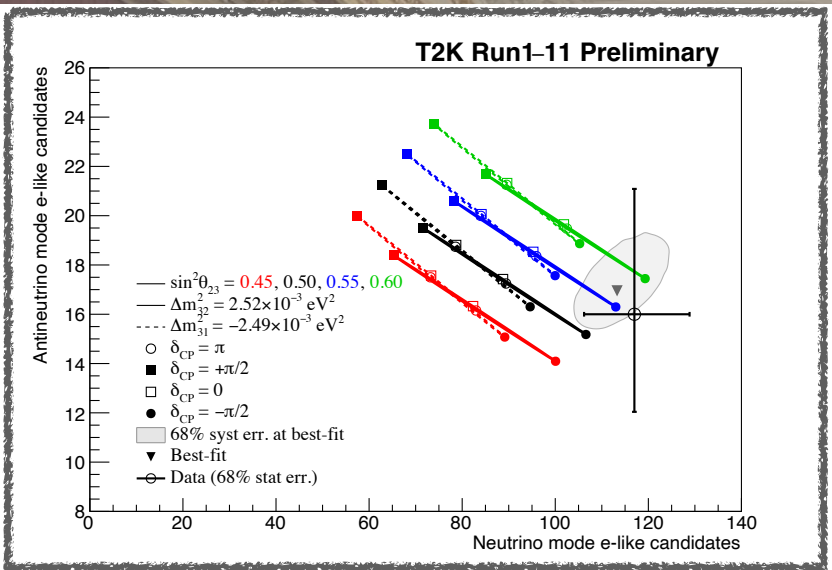
# Experimental Neutrino Physics and Opera “la musica lirica”

Theory (physics) is like music

Experimental neutrino physics is like music *with props...*  
and stunning sets and backdrops  
plus heros and characters!



# T2K New Results and ND280 Upgrade



Mass ordering  
NO/IO 3.3 Bayes Factor

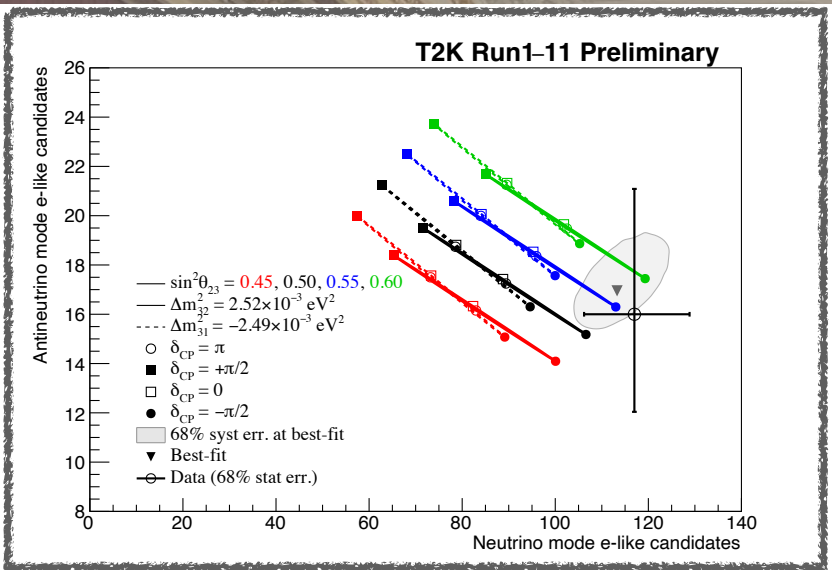
Octant  
Upper/Lower 2.6 BF



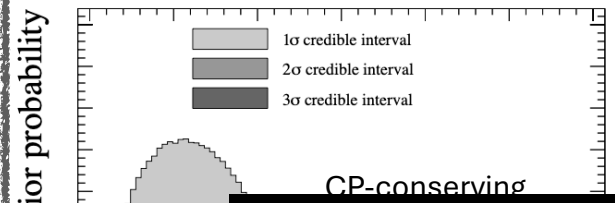
Beam power  $\rightarrow$  800 kW last week!  
 ND280 upgraded with new SuperFGD,  
 2 High-Angle TPCs, 6 ToF planes for neutrons  
 and taking data!



# T2K New Results and ND280 Upgrade



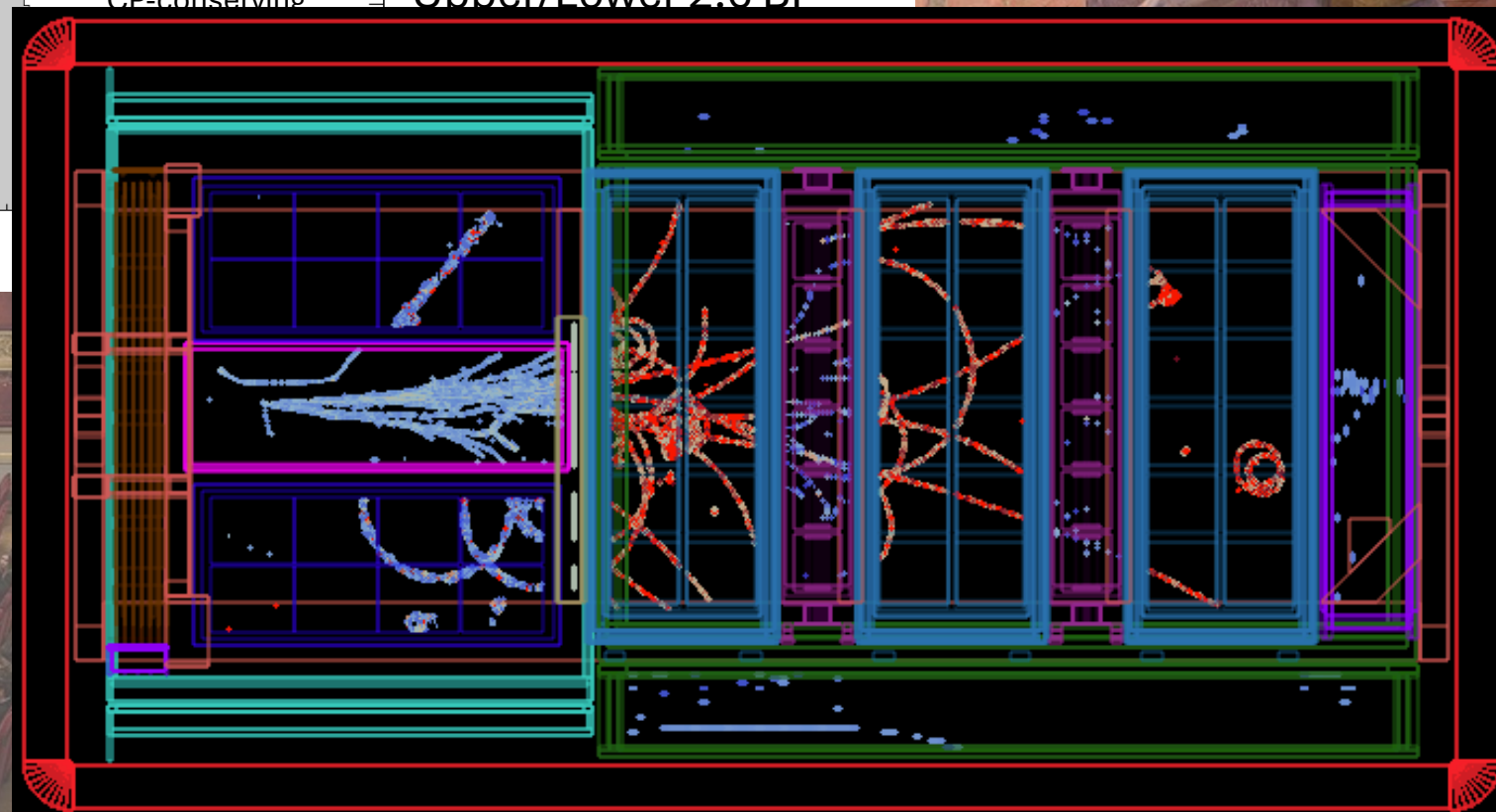
Credible intervals marginalized over both hierarchies



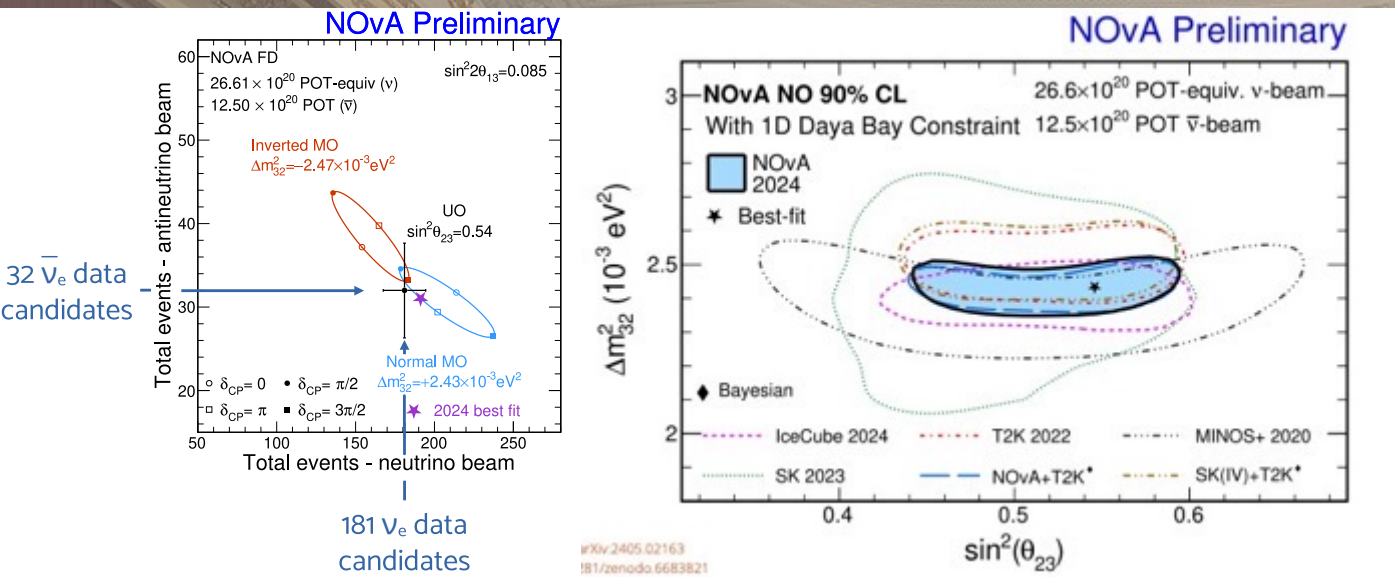
Mass ordering  
NO/IO 3.3 Bayes Factor

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!



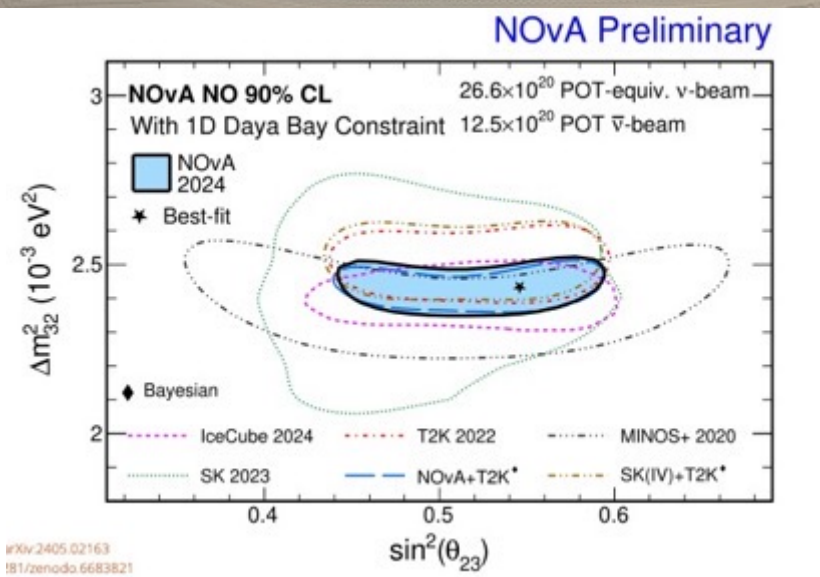
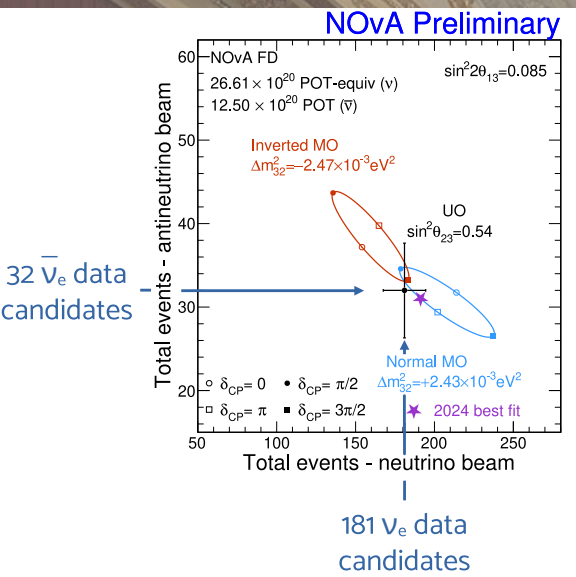
# NOvA New Results with 10 yrs Data



Most precise measurement  $\Delta m_{32}^2 (\pm 1.5\%)$   
 Data lies in region where matter effects and CP oppose  
 CP-conserving values favoured in NO (but outside  $3\sigma$  interval in IO)

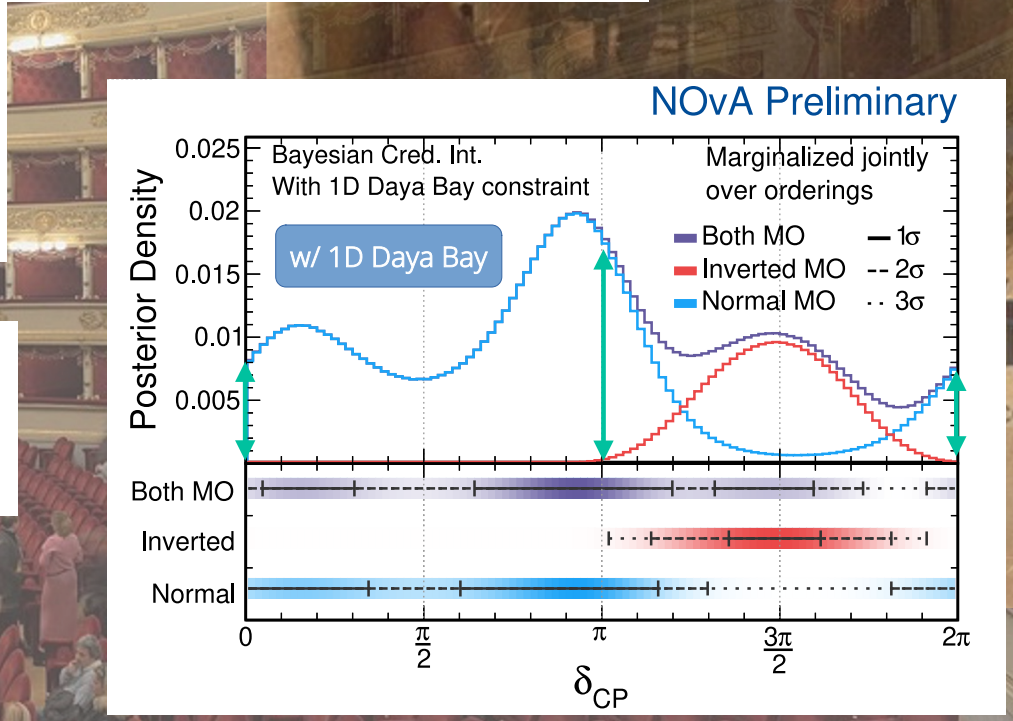


# NOvA New Results with 10 yrs Data



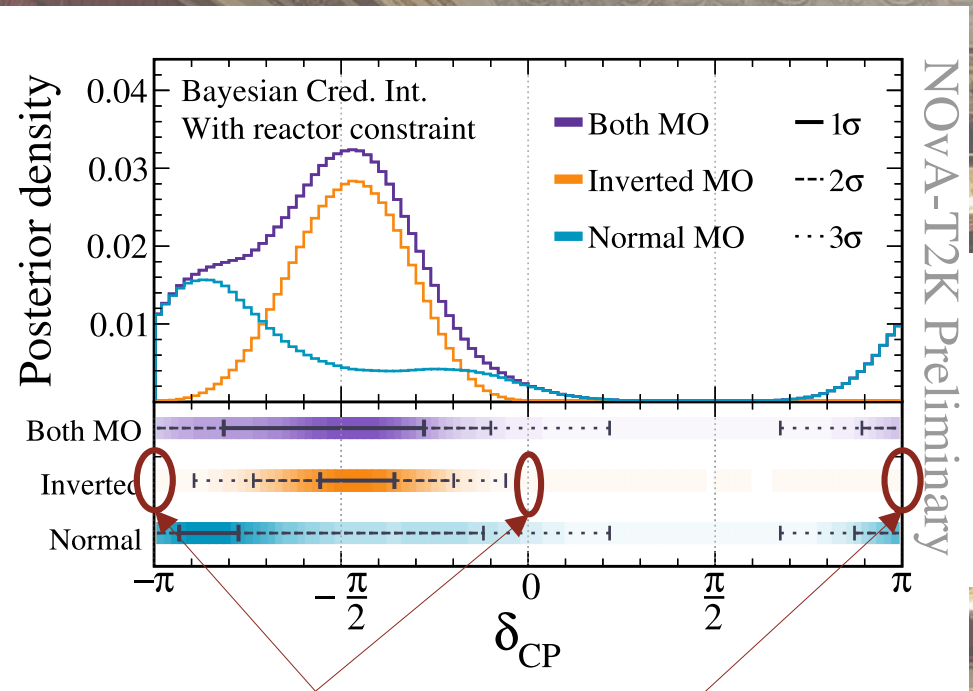
Mass ordering (w/1D reactor)  
 NO/IO 3.2 Bayes Factor

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



Most precise measurement  $\Delta m_{32}^2$  ( $\pm 1.5\%$ )  
 Data lies in region where matter effects and CP oppose  
 CP-conserving values favoured in NO (but outside  $3\sigma$  interval in IO)

# Joint Analysis: T2K+NOvA



Mild preference for Inverted Ordering but influenced by  $\theta_{13}$  constraint

NOvA+T2K only	NOvA+T2K + 1D $\theta_{13}$	NOvA+T2K + 2D ( $\theta_{13}, \Delta m^2_{32}$ )
IO (71%)	IO (57%)	NO (59%)

CP-conserving points are *outside*  $3\sigma$  intervals in IO  
Expect CPV if ordering is inverted

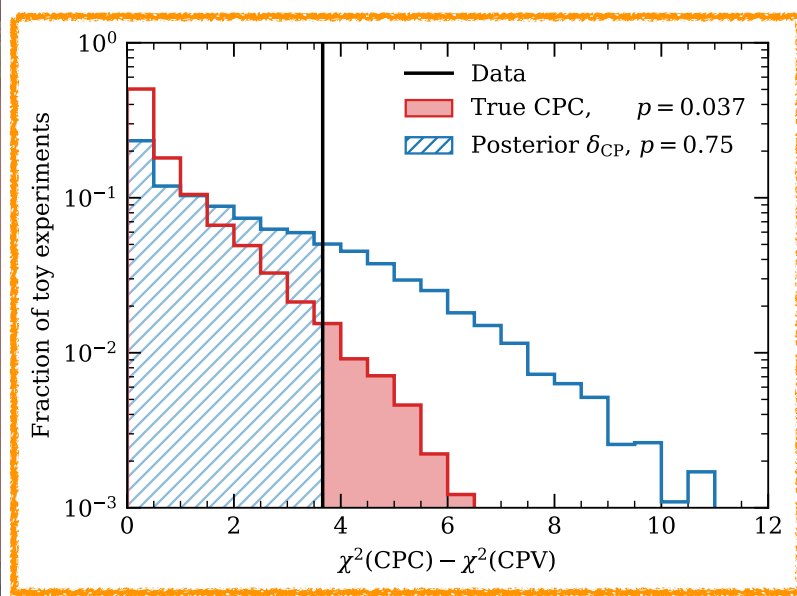


*W. A. Mozart  
Le Nozze di Figaro*

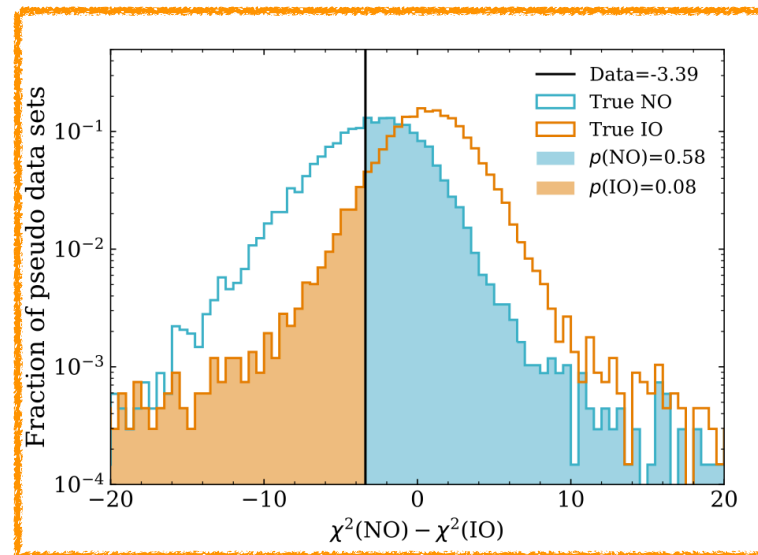


# Joint Analysis: T2K+SK

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



23



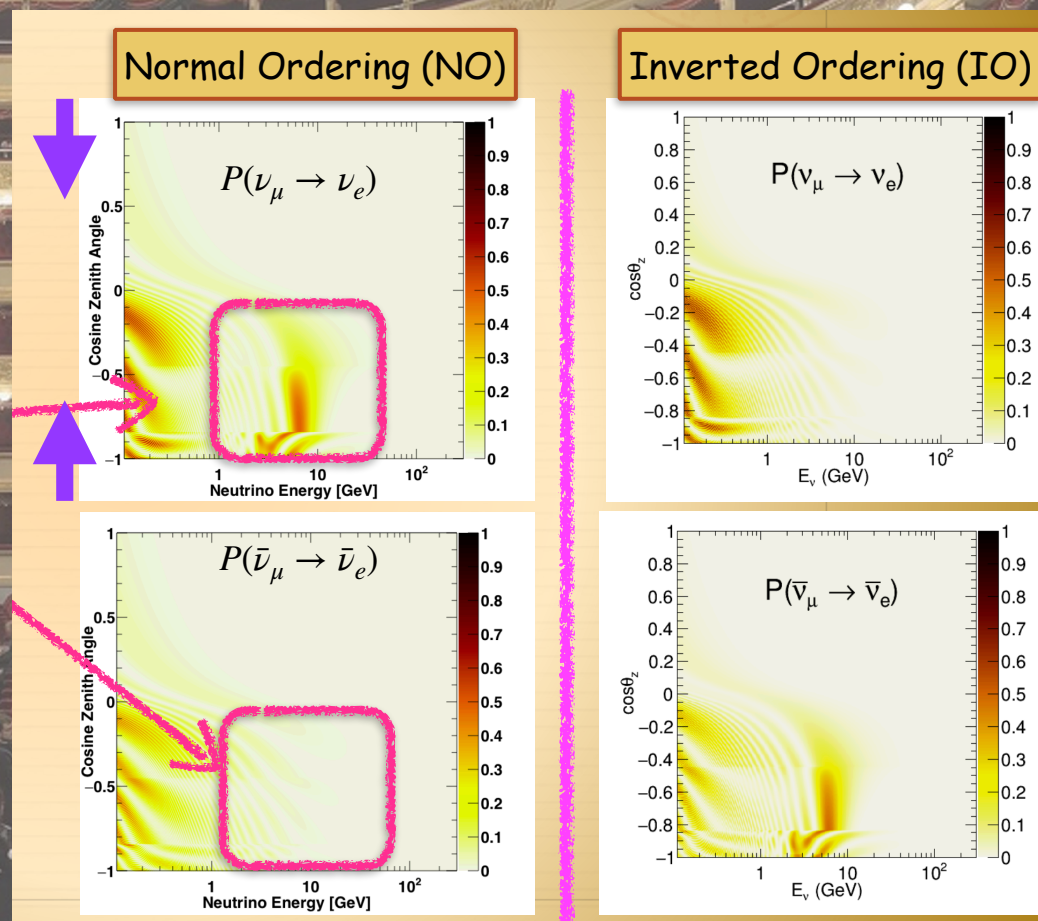
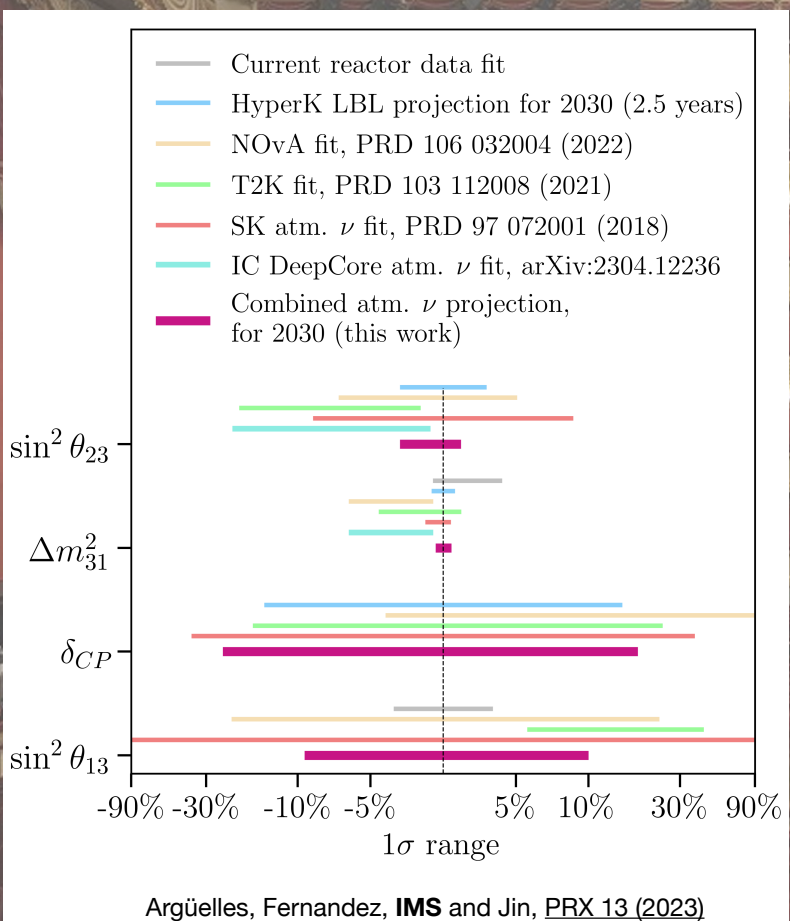
*W. A. Mozart  
Le Nozze di Figaro*

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



# Atmospheric Neutrinos

Provide good sensitivity to mass ordering (at  $\sim 6\sigma$ ) in projections including future experiments; and to other oscillation parameters



Oscillogram for Super-K

# Atmospheric Neutrinos w/Neutron Tagging

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

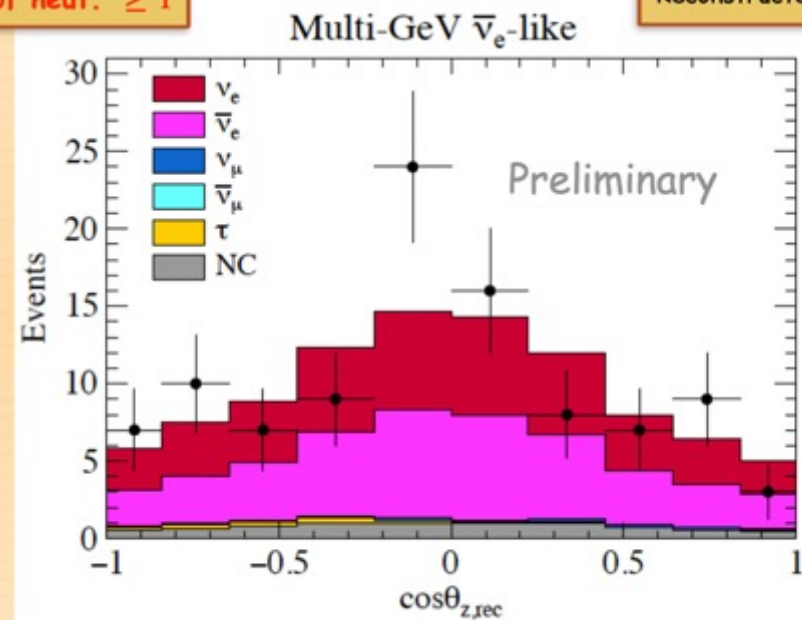
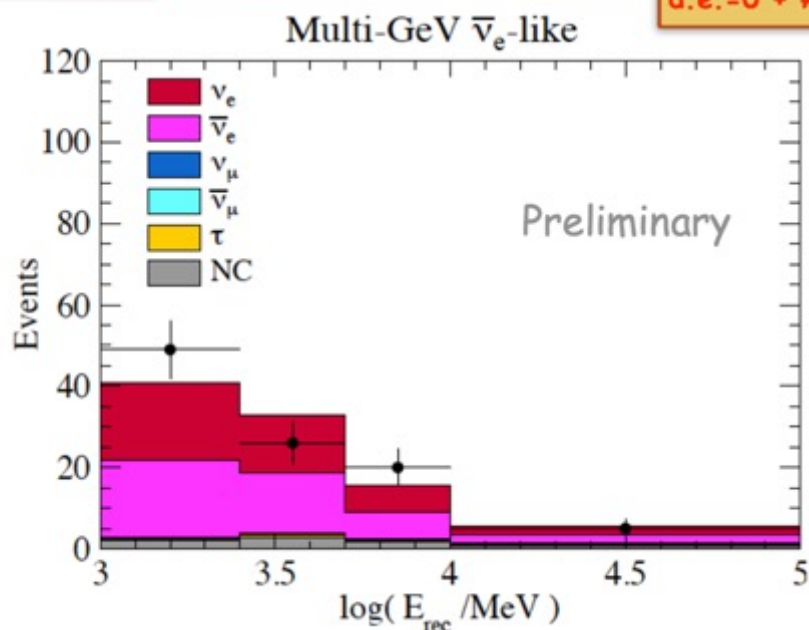


## SK6 reconstruction with neutrons

•Reconstructed  $E_\nu$

d.e.=0 + # of neut.  $\geq 1$

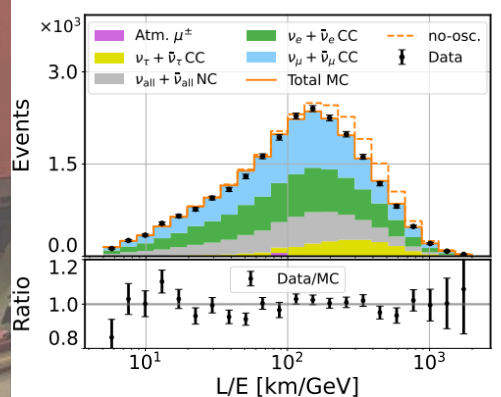
•Reconstructed  $\cos \theta_\nu$



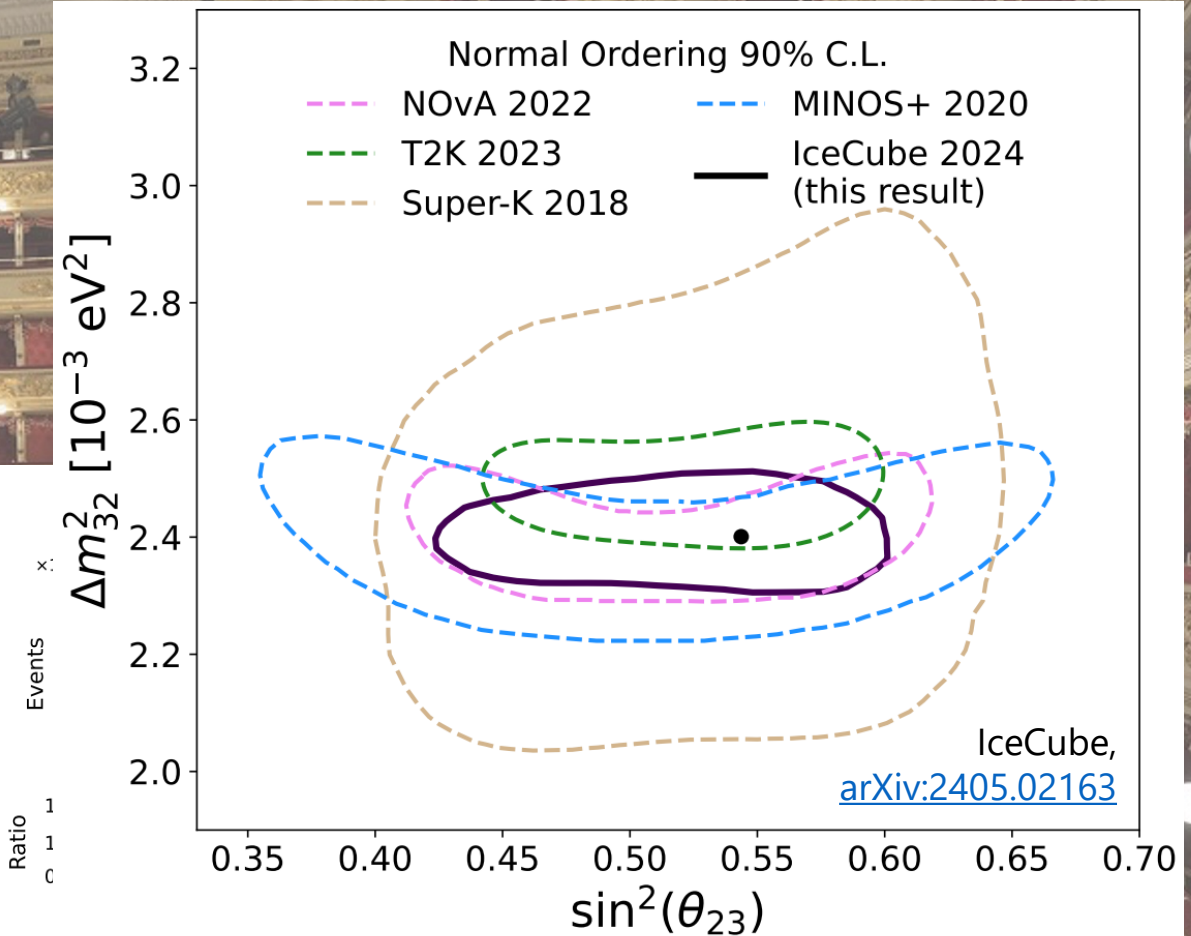
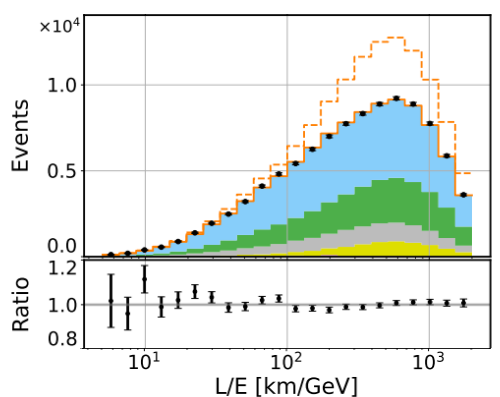
# IceCube Atmospheric Oscillation Result

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

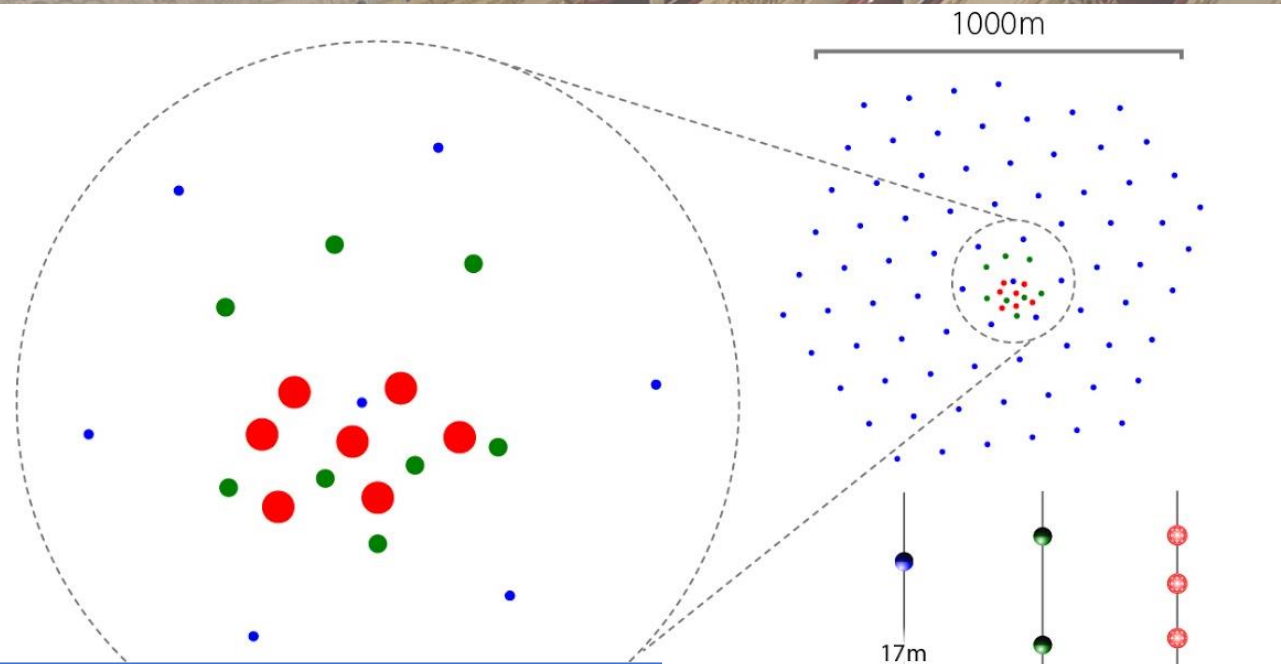
### Cascade-like



### Track- and cascade-like



# IceCube Upgrade



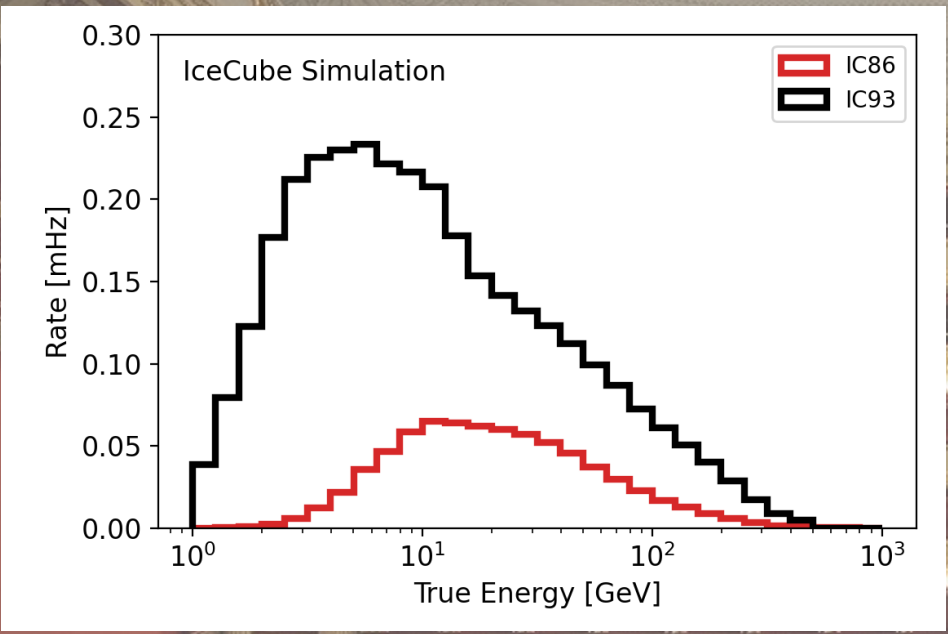
**Fully funded (NSF+partners)  
Deployment to occur 2025-2026**

● IceCube    ● DeepCore    ● Upgrade

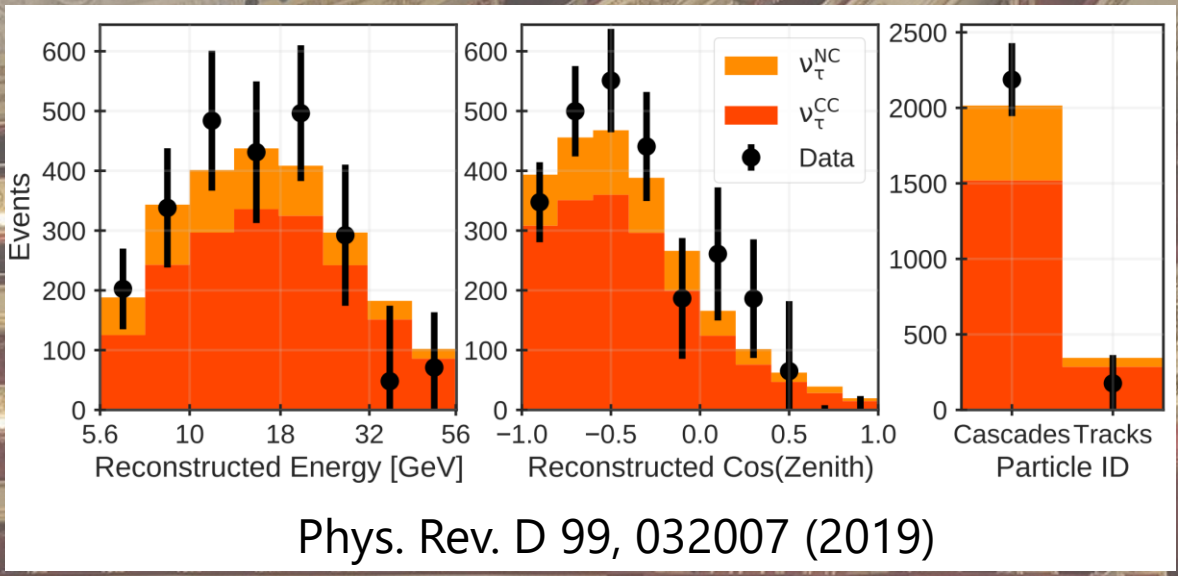
1450m	2100m	2150m
2450m	2450m	2400m
Instrumented Depth		

Detecting 2-100 GeV (atmospheric) neutrinos

# IceCube Upgrade

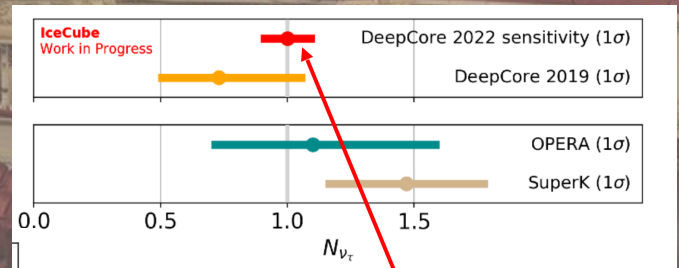


## Oscillations to $\nu_\tau$ in DeepCore

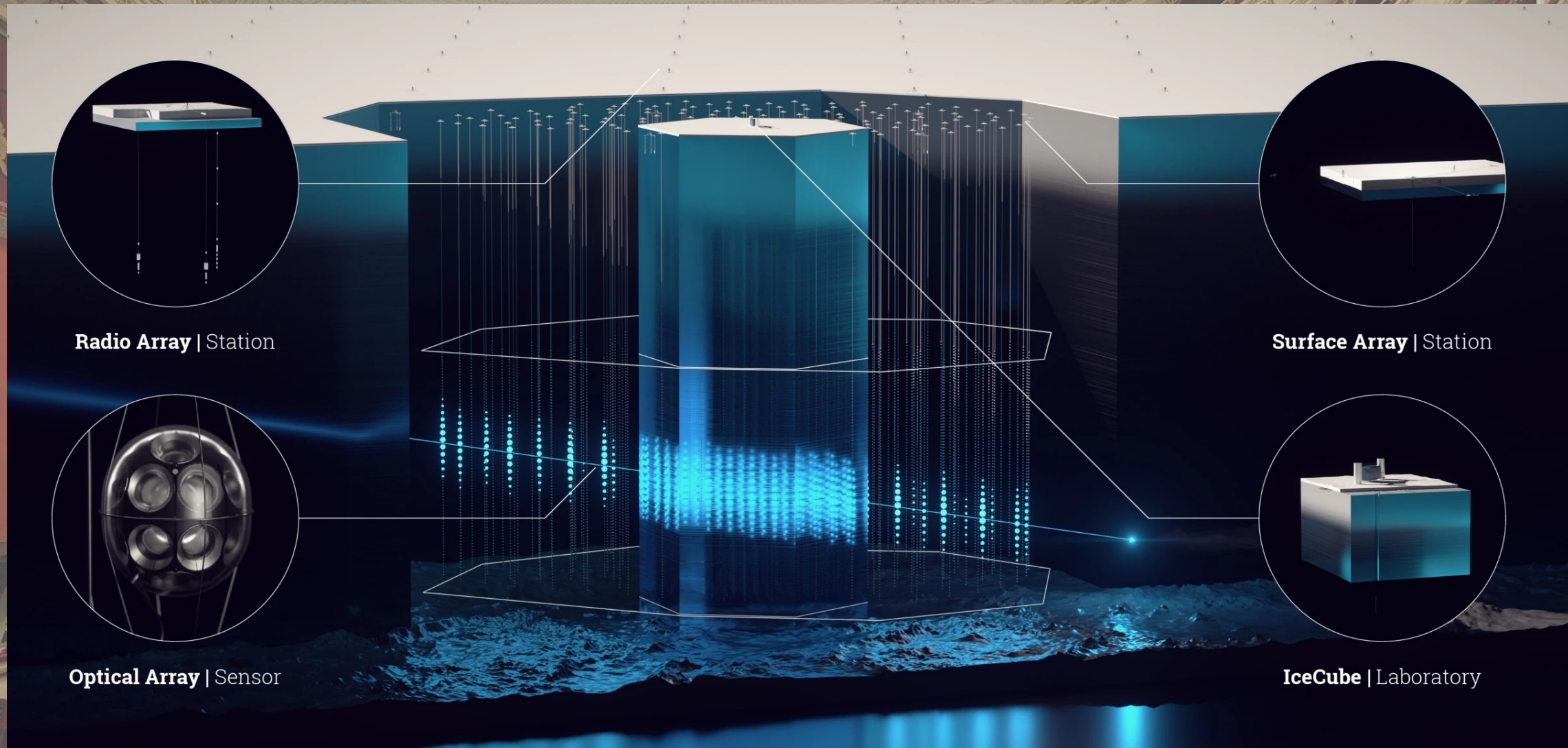


Significant increase of events at 10 GeV (and below)!

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



# IceCube Gen2



**Radio Array | Station**

**Surface Array | Station**

**Optical Array | Sensor**

**IceCube | Laboratory**

# KM3NeT (ORCA)

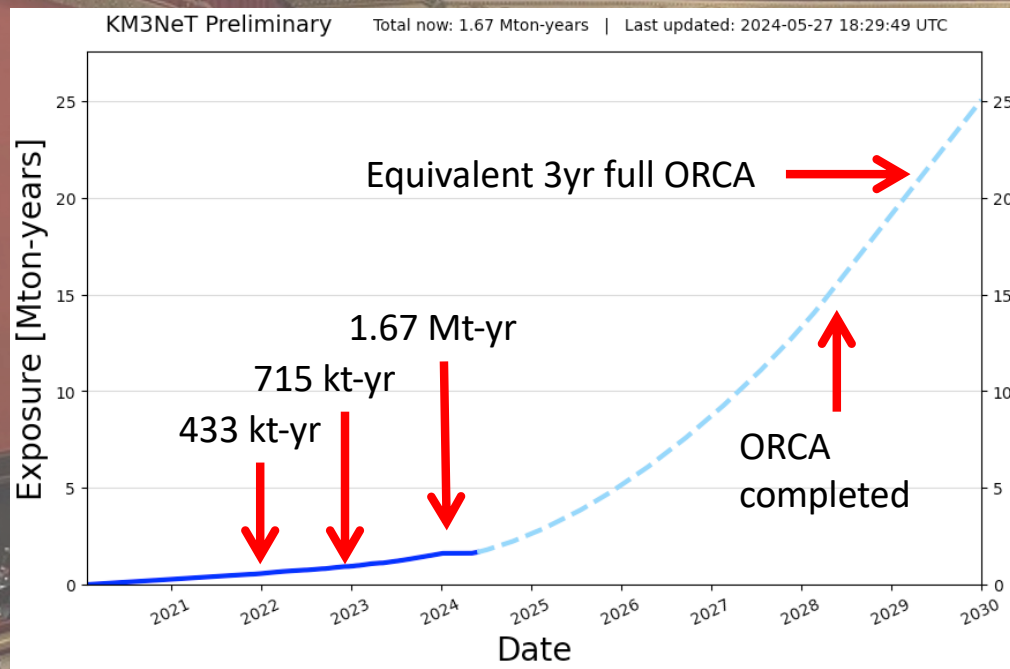
Several 1000  $\nu_\tau$  per year (10-40 GeV)  
(coupling to 3<sup>rd</sup> family; new physics)

OCEANA

Commedia fantastica in tre atti di Silvio Benco

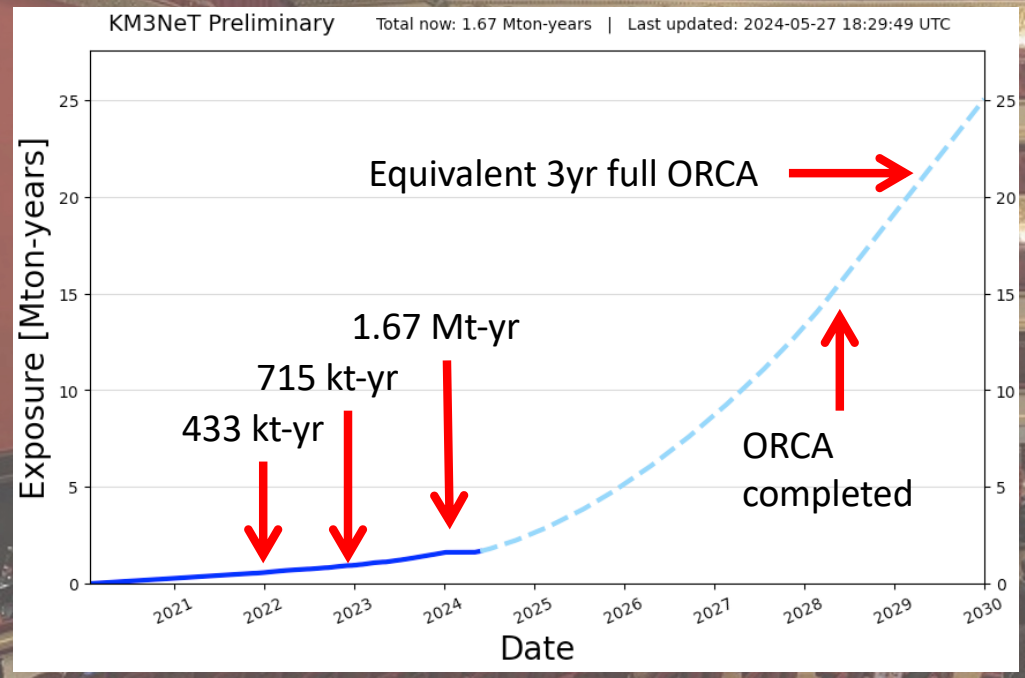
Musica di Antonio SMAREGLIA

Milano Teatro alla Scala, 22 gennaio 1903



# KM3NeT (ORCA)

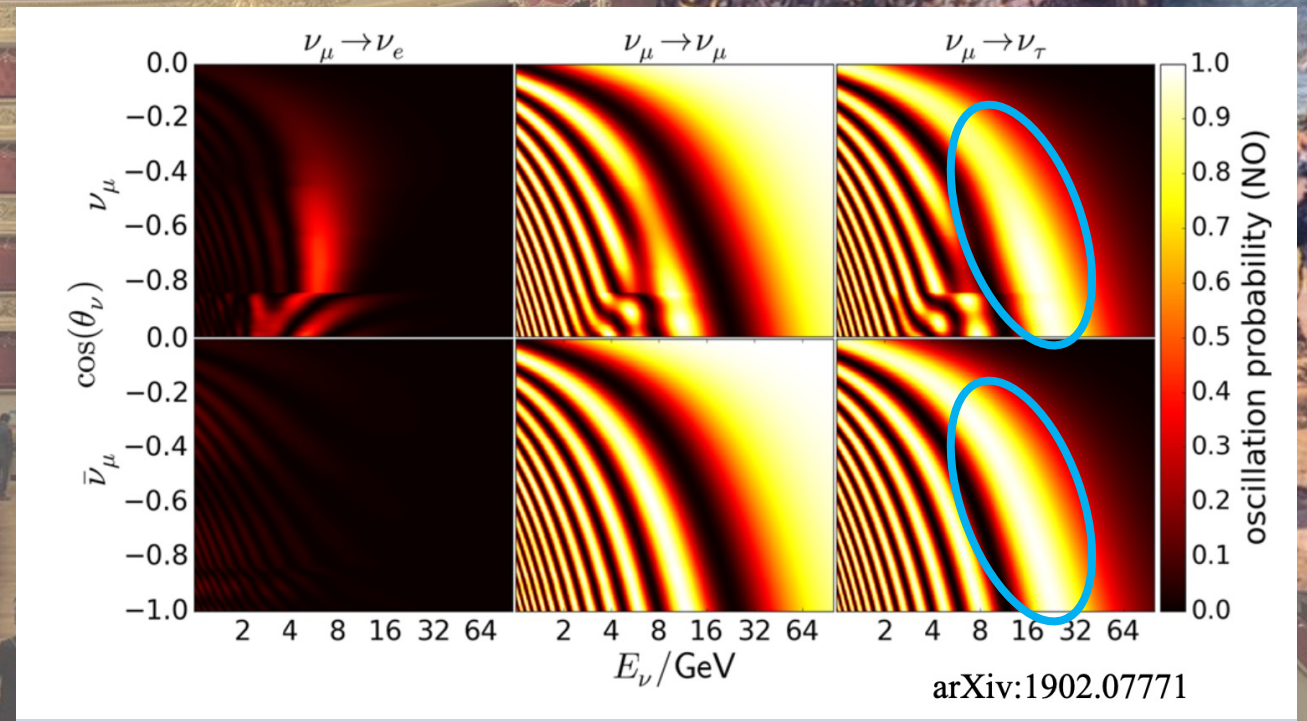
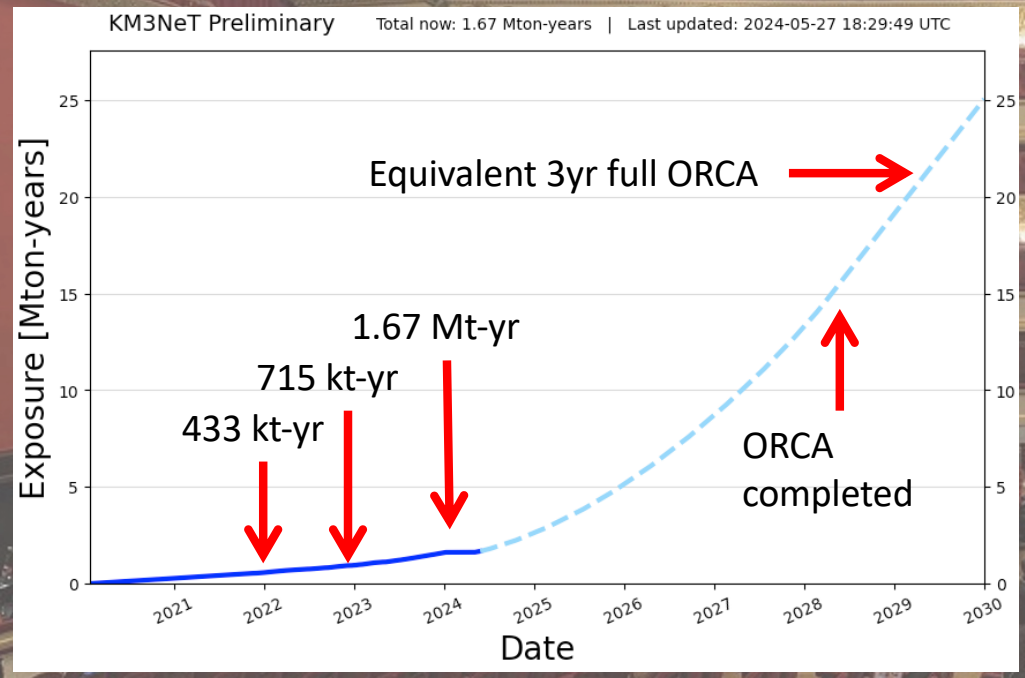
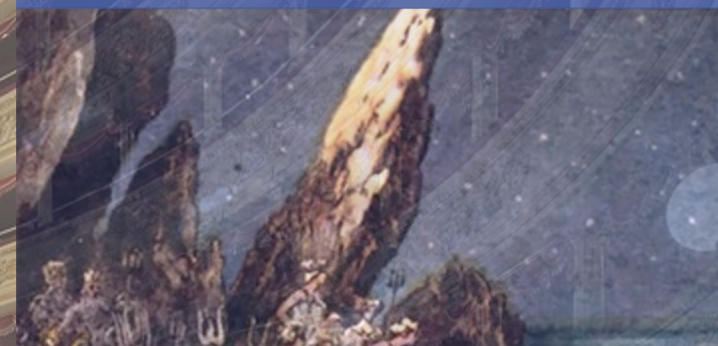
Several 1000  $\nu_\tau$  per year (10-40 GeV)  
(coupling to 3<sup>rd</sup> family; new physics)



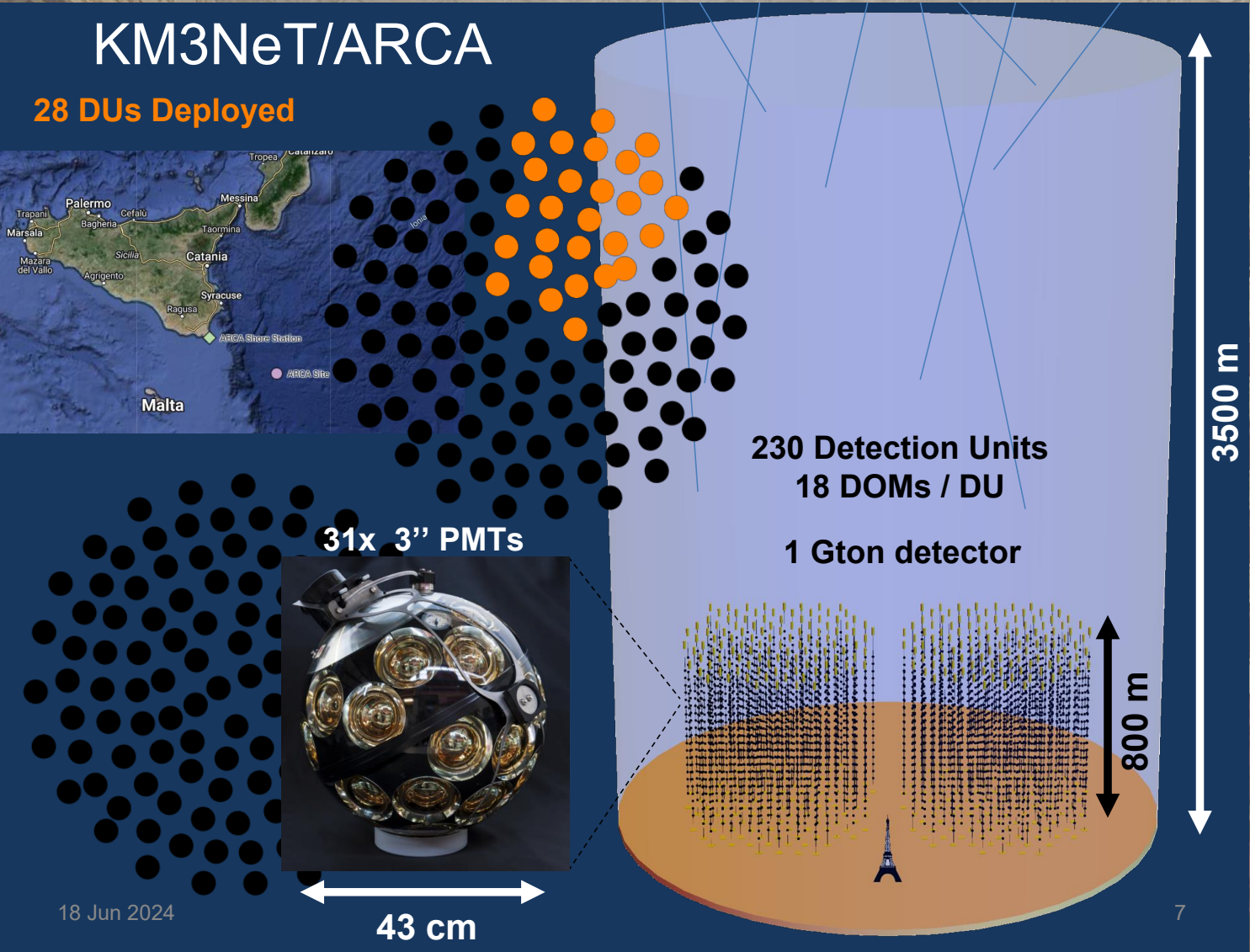


# KM3NeT (ORCA)

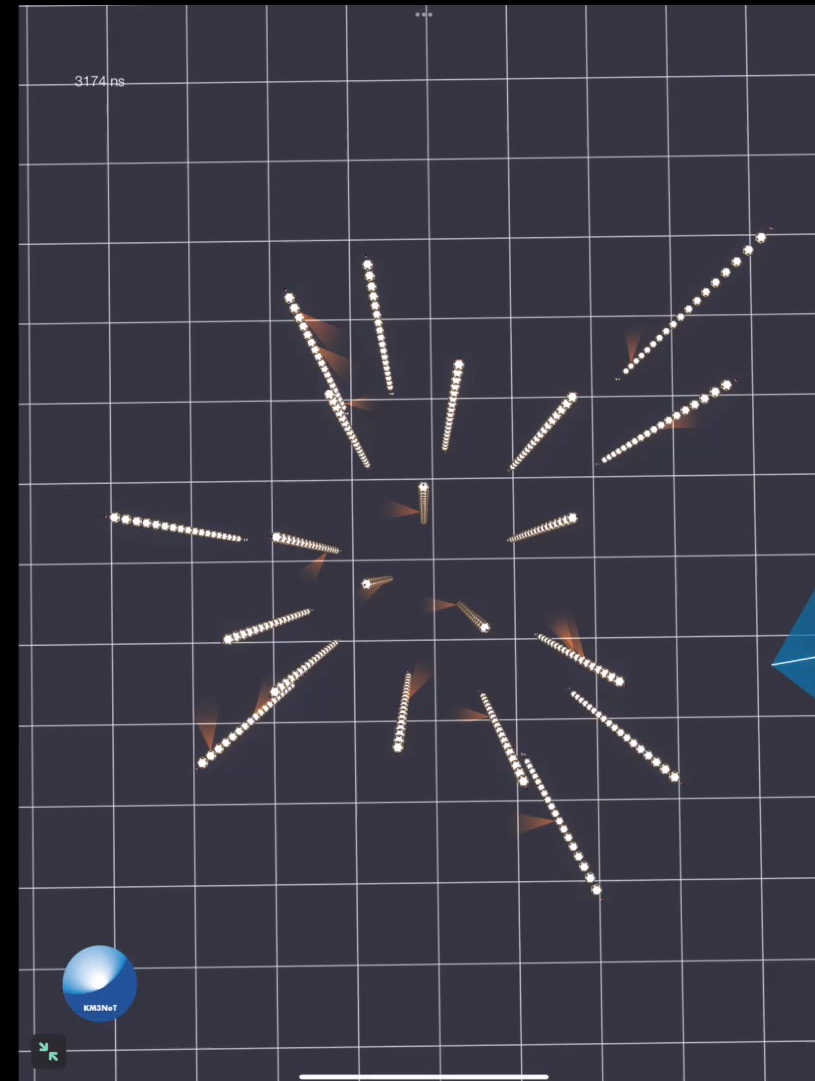
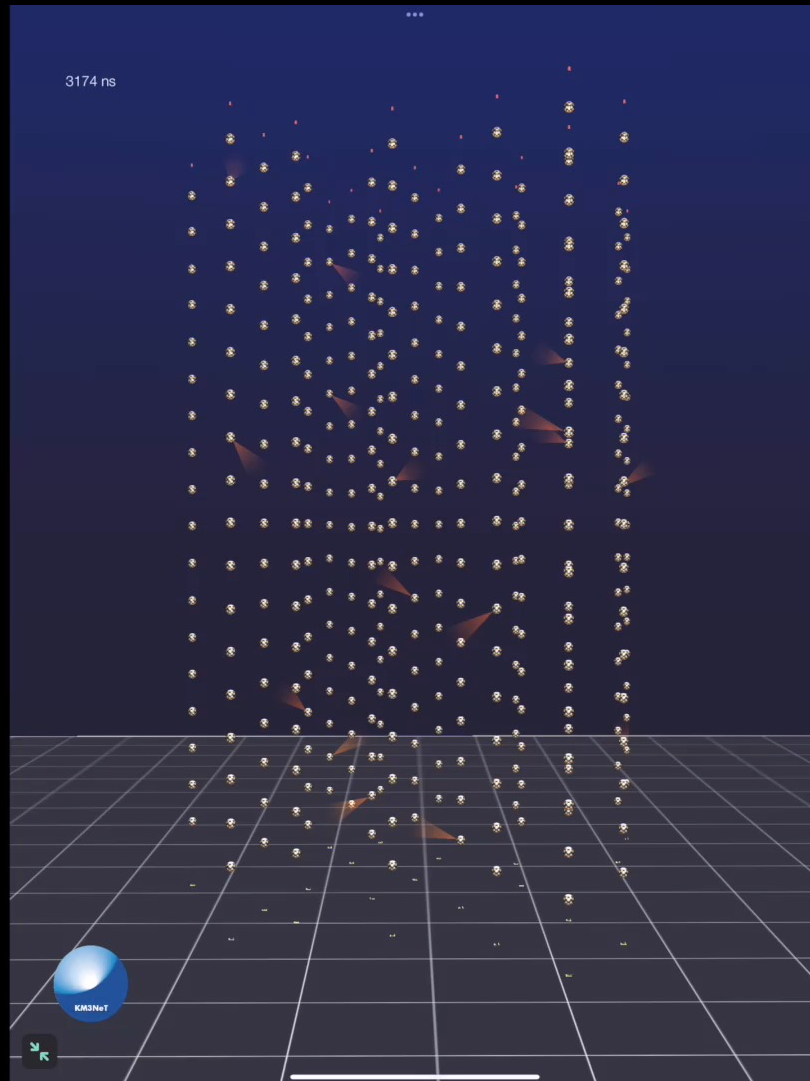
Several 1000  $\nu_\tau$  per year (10-40 GeV)  
(coupling to 3<sup>rd</sup> family; new physics)



# KM3NeT (ARCA)

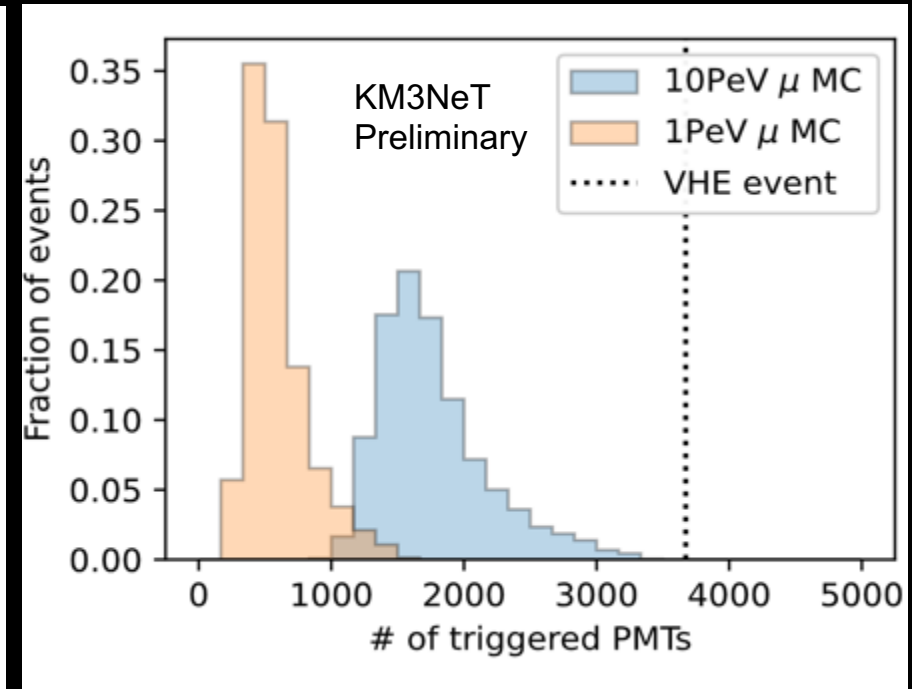
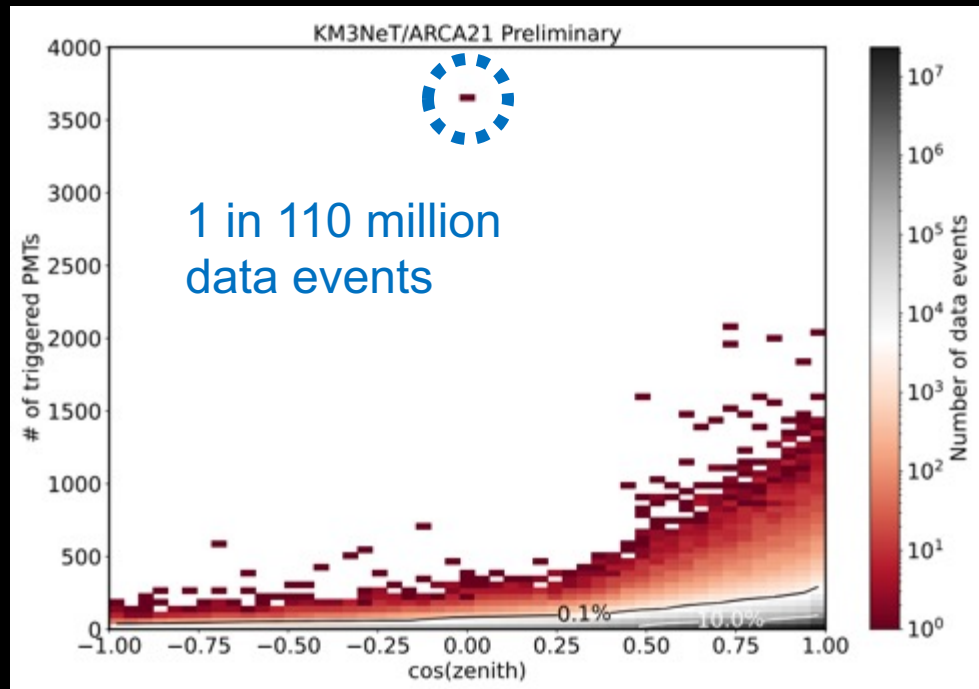


# Uncharted Territory



# Uncharted Territory

- Significant event observed with huge amount of light
- Horizontal event ( $1^\circ$  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



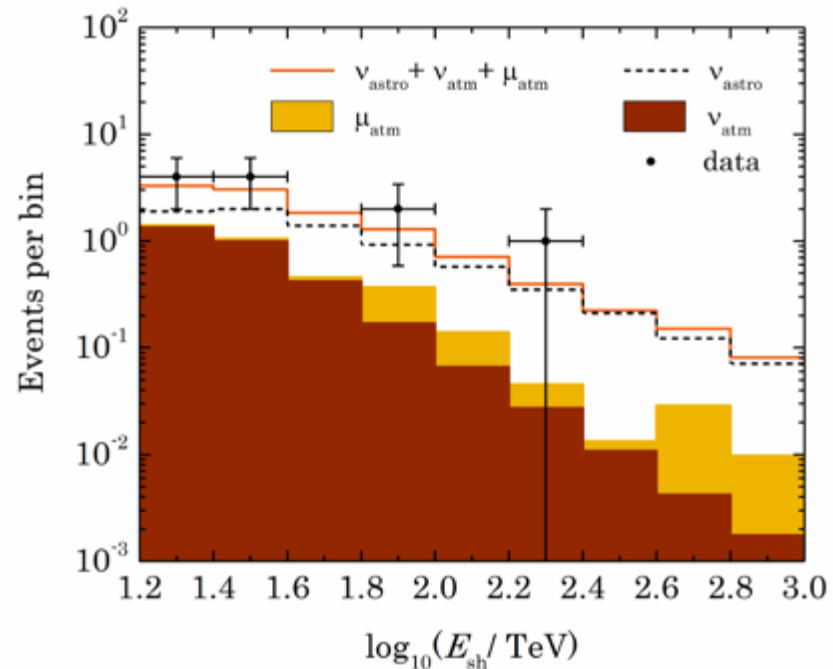
# Baikal-GVD

## Successful 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<sup>3</sup> detector volume  
110 strings with 3960 OMs

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



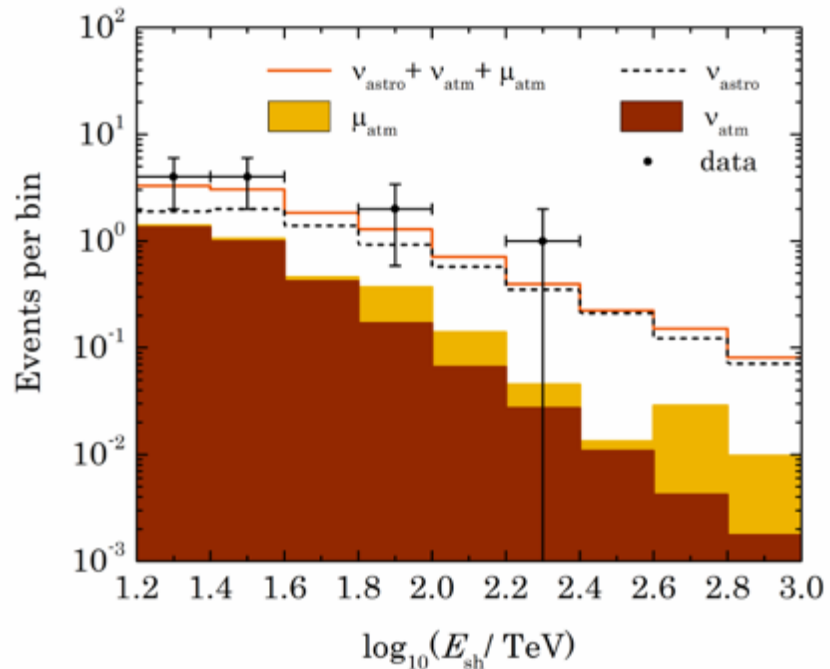
# Baikal-GVD

## Successful 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

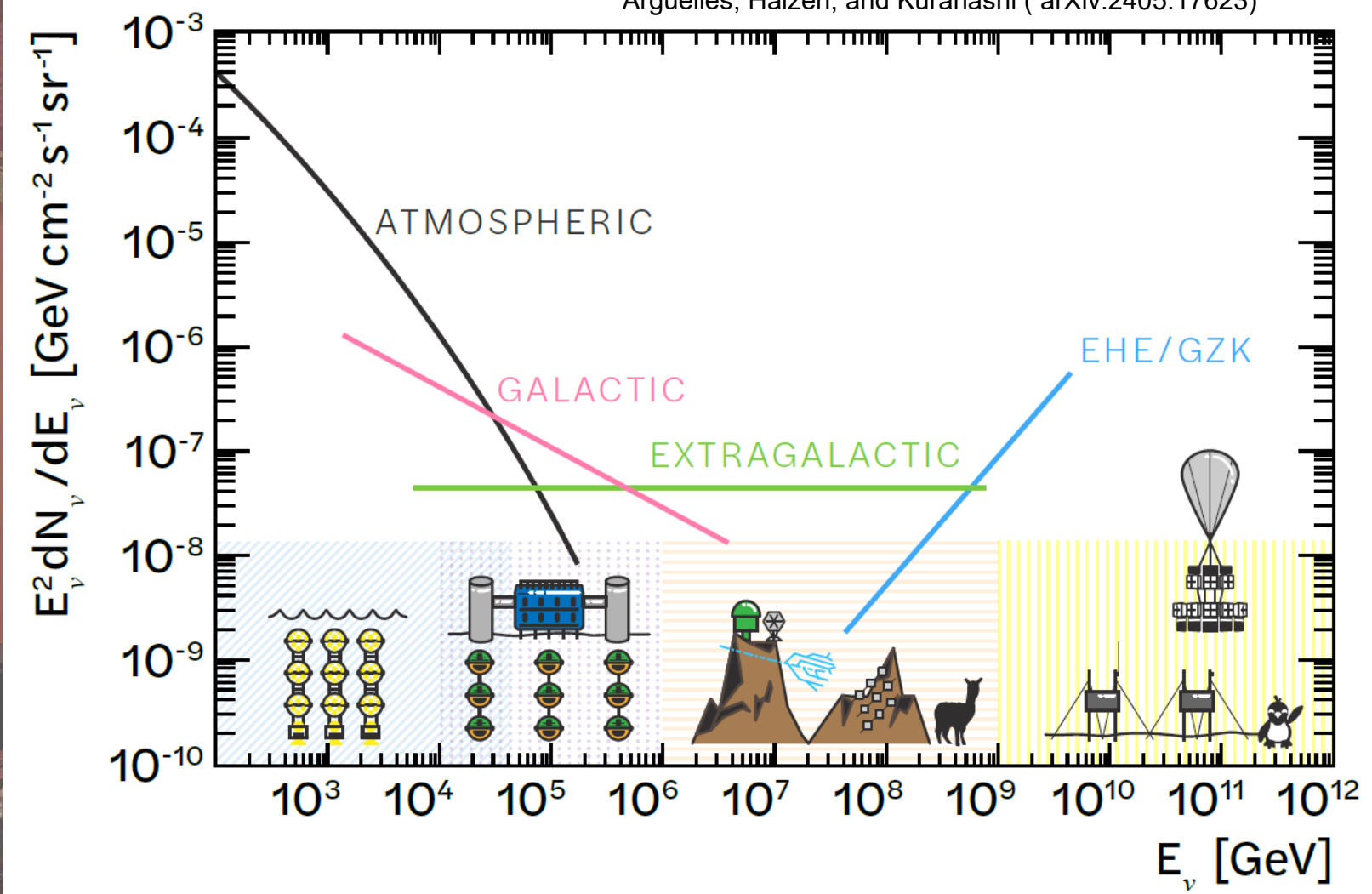
~0.6 km<sup>3</sup> detector volume  
110 strings with 3960 OMs

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



# Dawn of Neutrino Astronomy

Argüelles, Halzen, and Kurahashi ( arXiv:2405.17623)



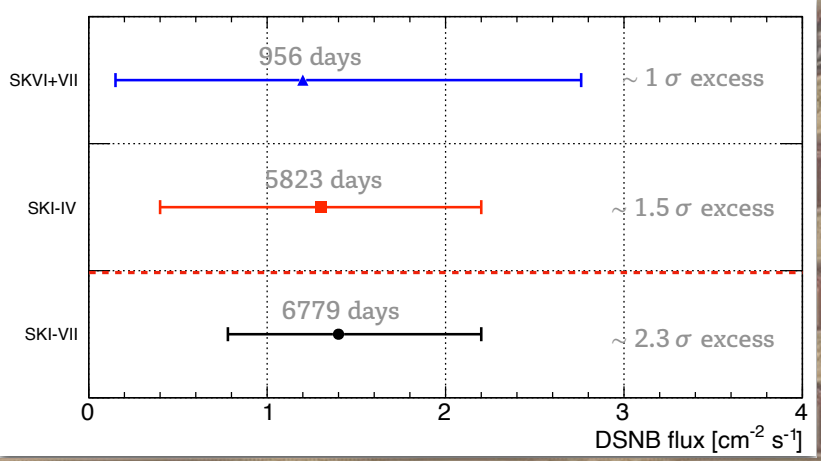
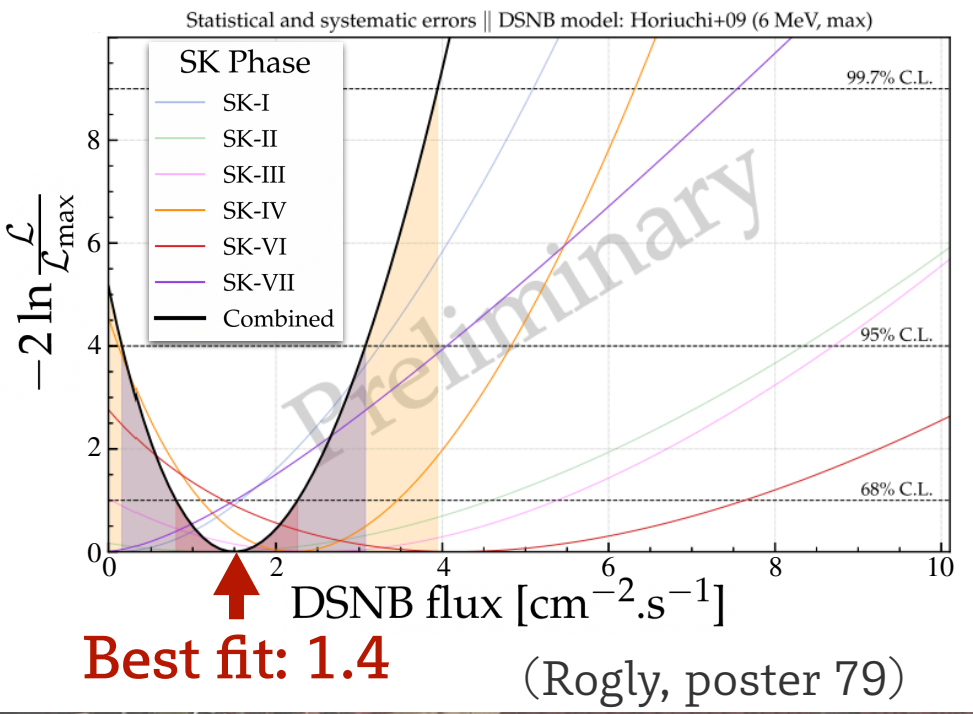
- P-ONE
- TRIDENT
- HUNT
- TAMBO
- GRAND
- BEACON
- RNO-G
- PUEO
- ...

possible future  
neutrino  
telescopes



# DSNB hint at $\sim 2.3\sigma$

## SK-Gd and SK data combined

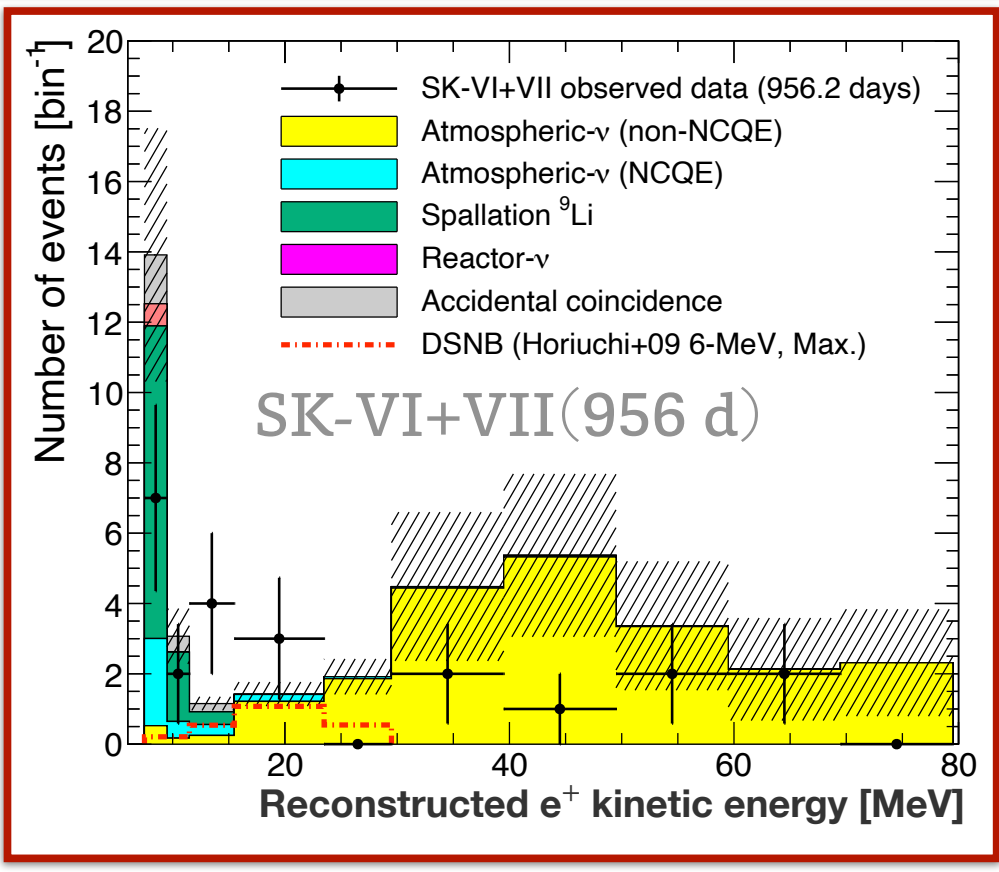
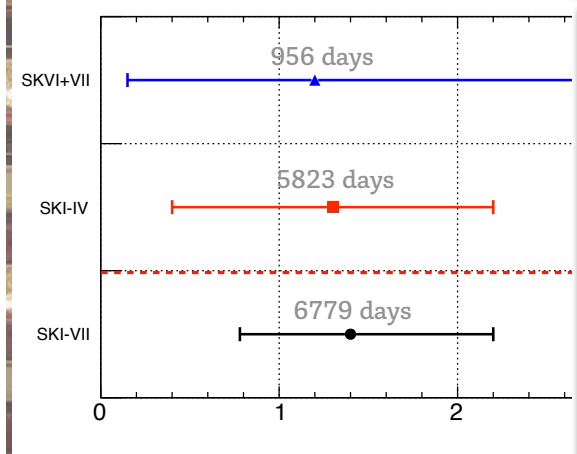
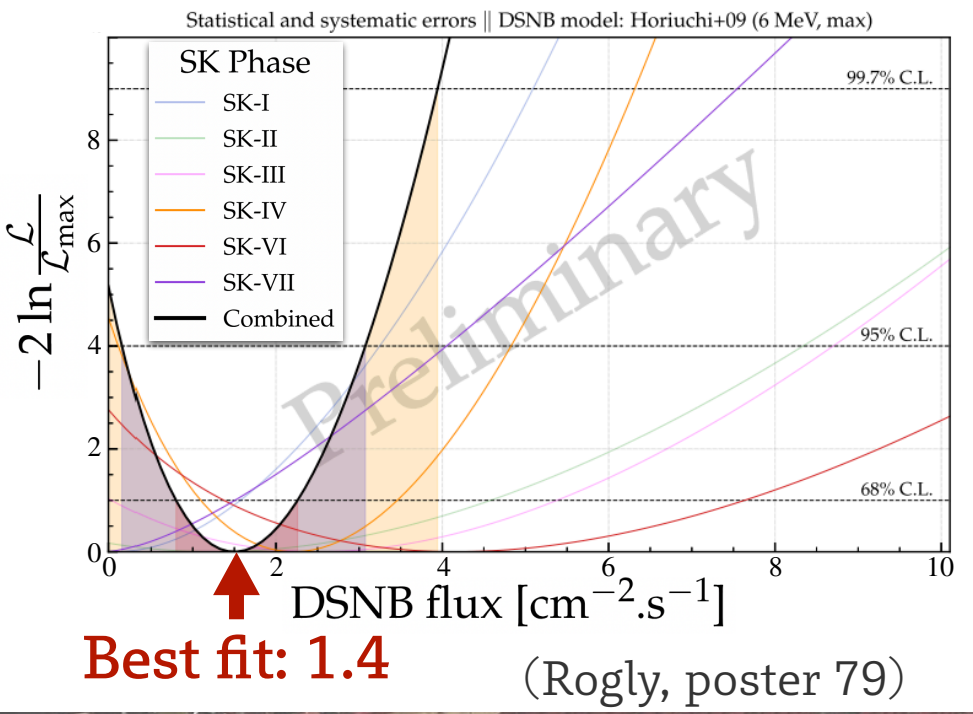






# DSNB hint at $\sim 2.3\sigma$

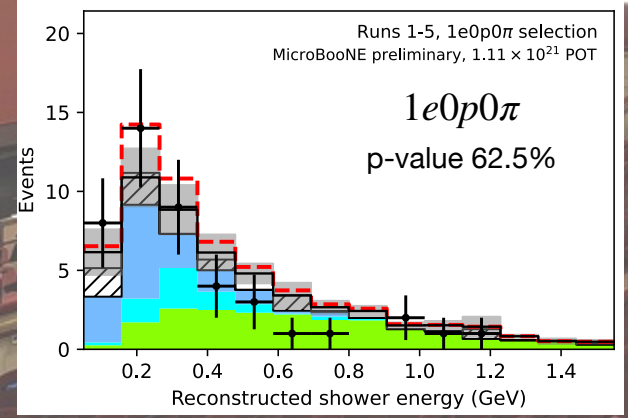
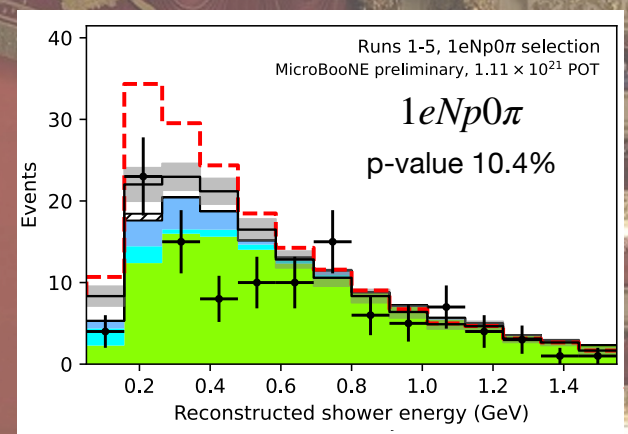
## SK-Gd and SK data combined



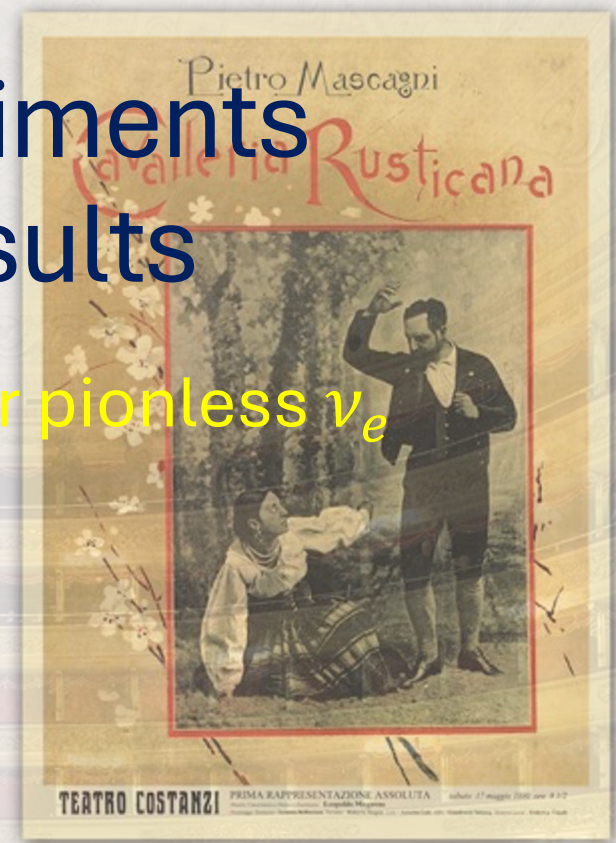
# Short Baseline Experiments MicroBooNE 5-yr Results

“Low-Energy Excess” search for pionless  $\nu_e$

- $6.8e20 \rightarrow 11.1e20$  POT of BNB



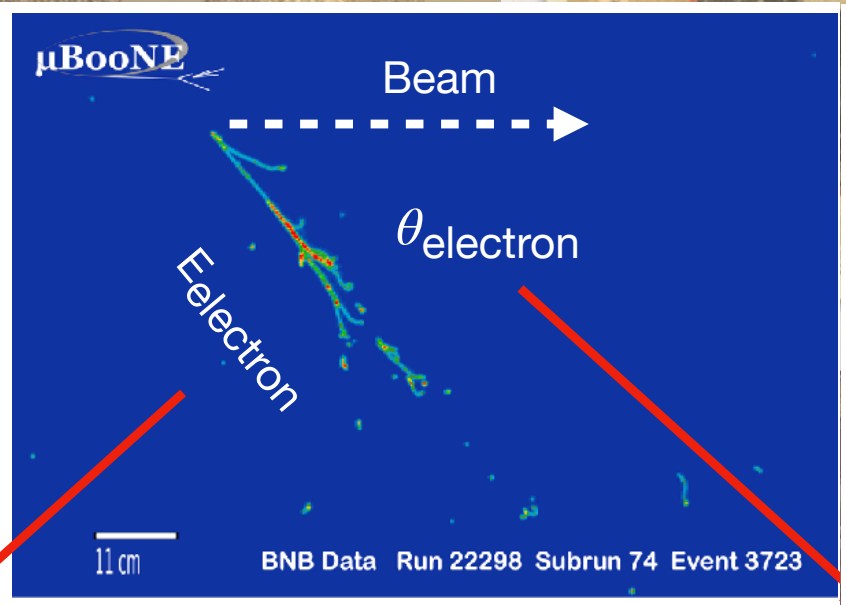
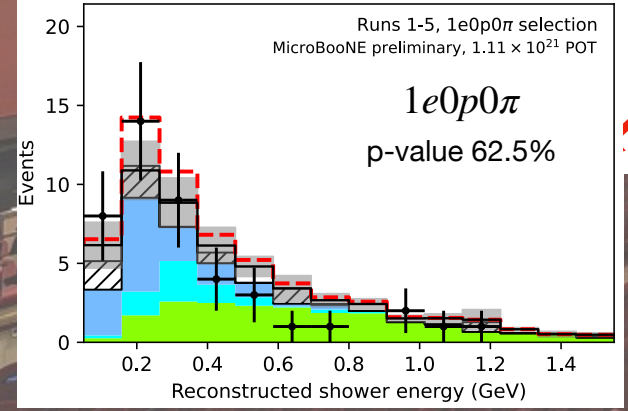
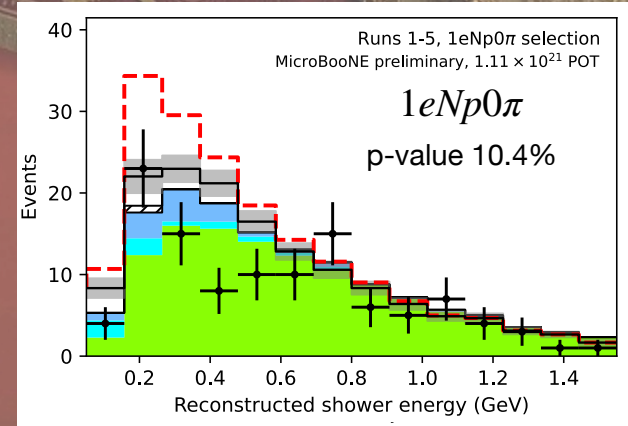
data inconsistent with  $\nu_e$ -like  
excess at >99% CL



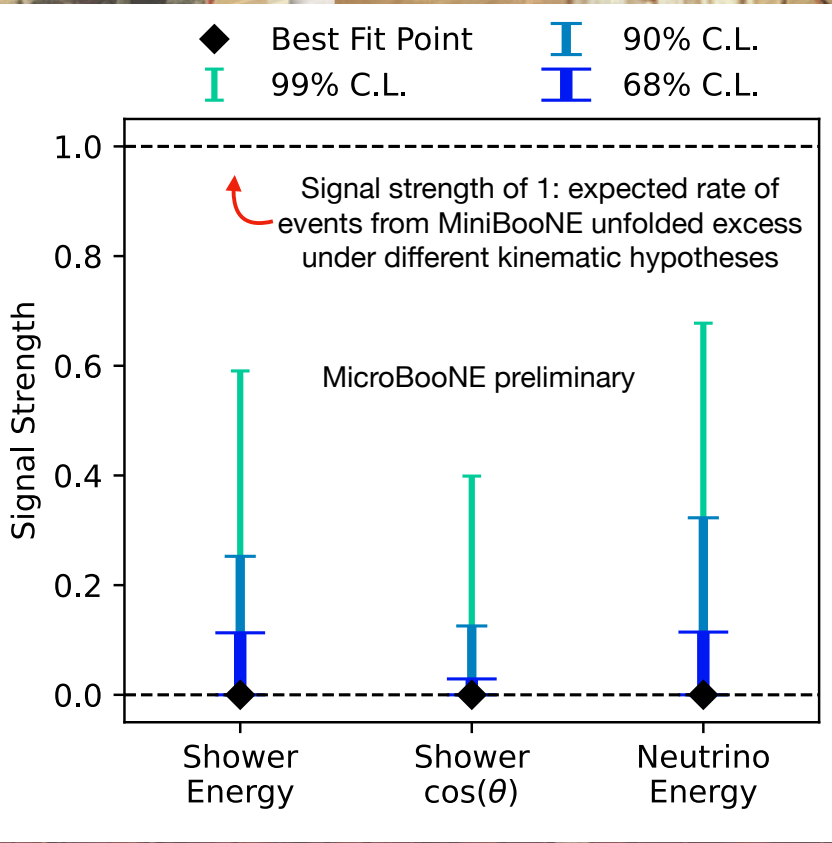
# Short Baseline Experiments MicroBooNE 5-yr Results

“Low-Energy Excess” search for pionless  $\nu_e$

- 6.8e20  $\rightarrow$  11.1e20 POT of BNB



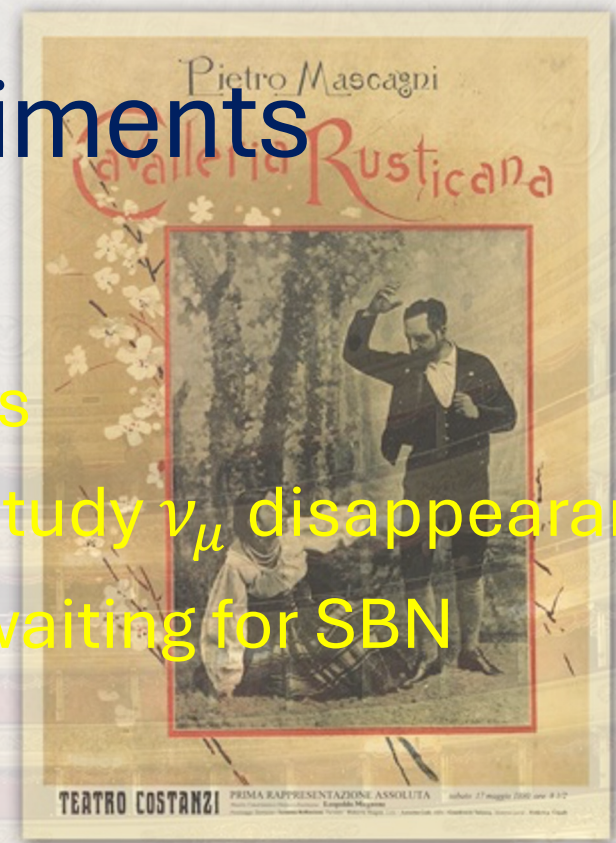
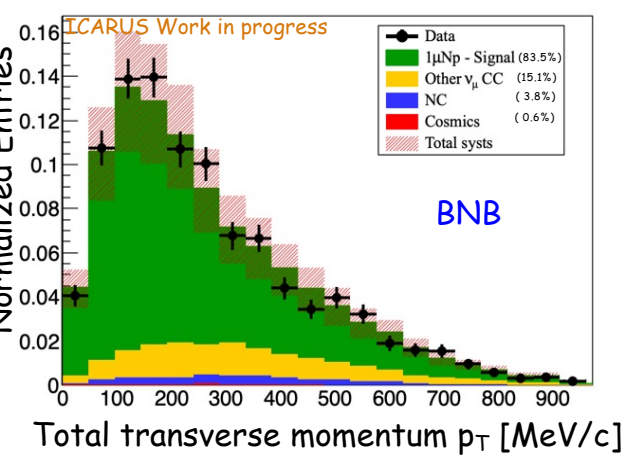
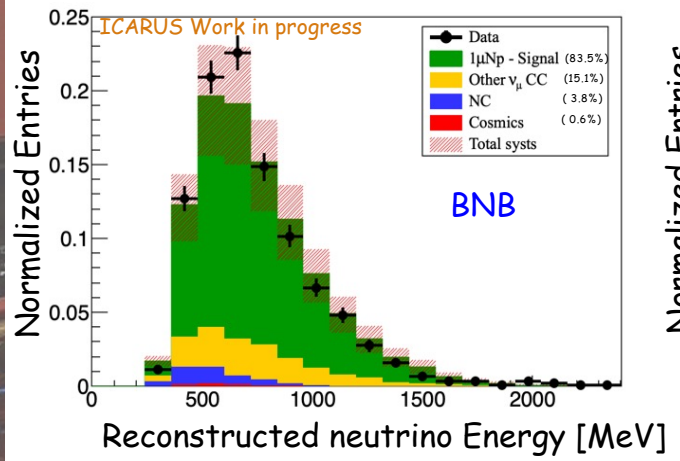
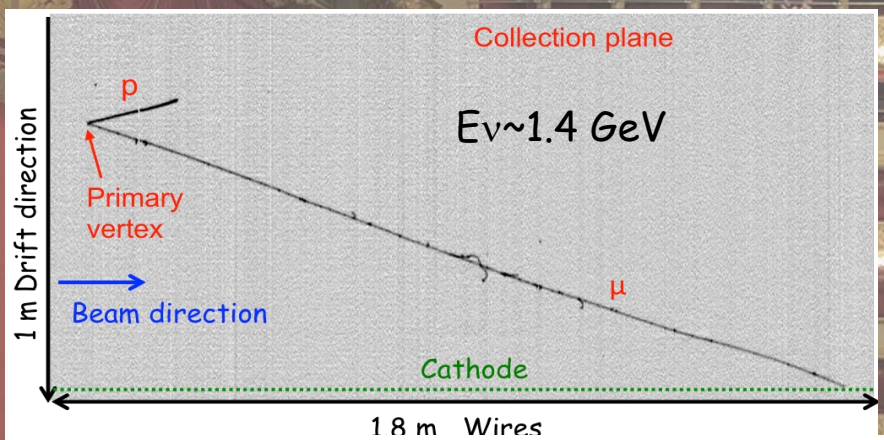
data inconsistent with  $\nu_e$ -like excess at >99% CL



# Short Baseline Experiments ICARUS First Results

Data with BNB and NuMI beams

study  $\nu_\mu$  disappearance while waiting for SBN



# Double Beta Decay Results

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

$${}^{76}\text{Ge } T_{1/2} > 1.9 \times 10^{26} \text{ yrs}$$

- **New KamLAND-Zen 800 result:**

$${}^{136}\text{Xe } T_{1/2} > 3.8 \times 10^{26} \text{ yrs}$$

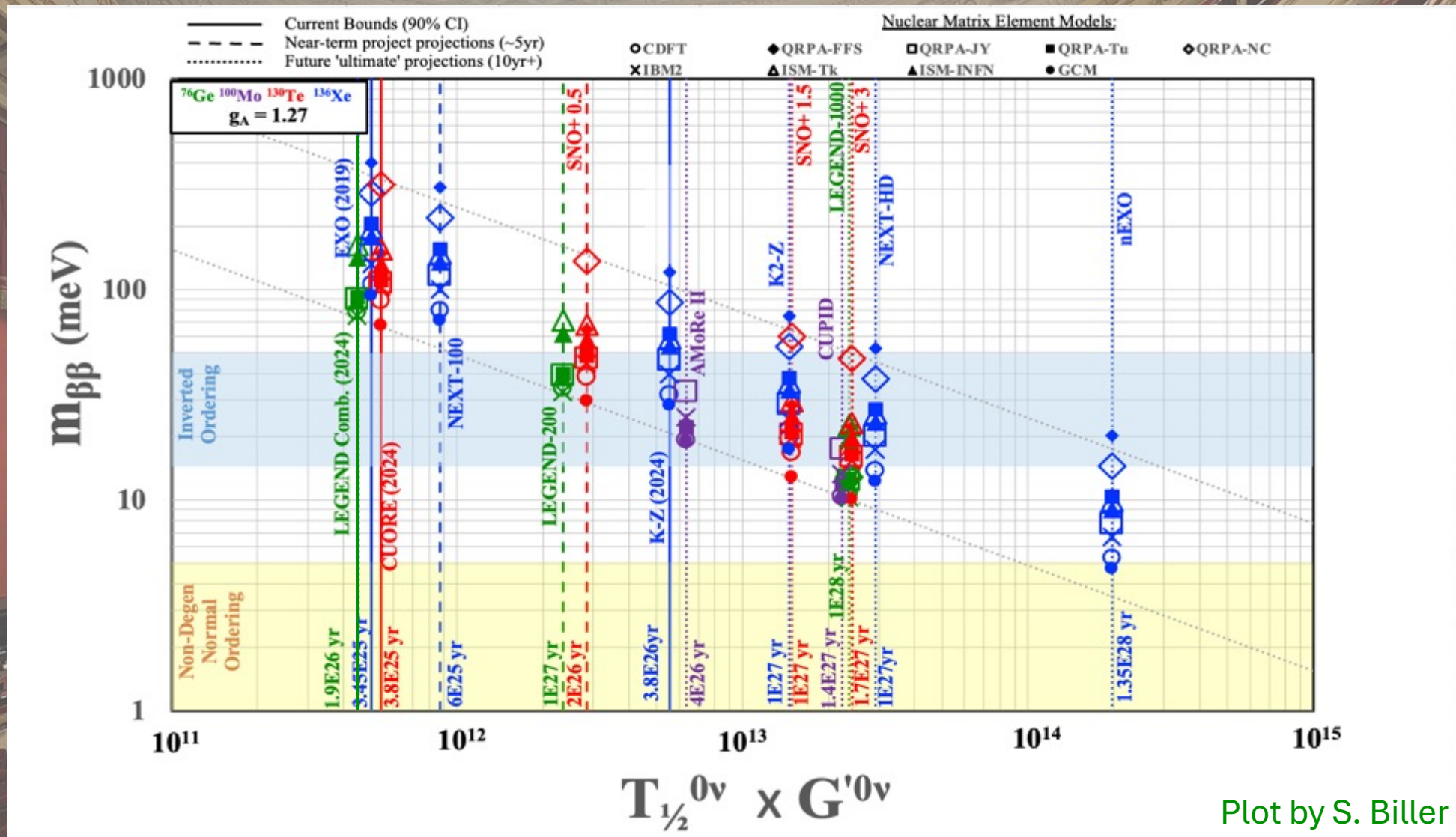
- Latest CUORE 2024 result (data 05/2017 to 04/2023):

$${}^{130}\text{Te } T_{1/2} > 3.8 \times 10^{25} \text{ yrs}$$

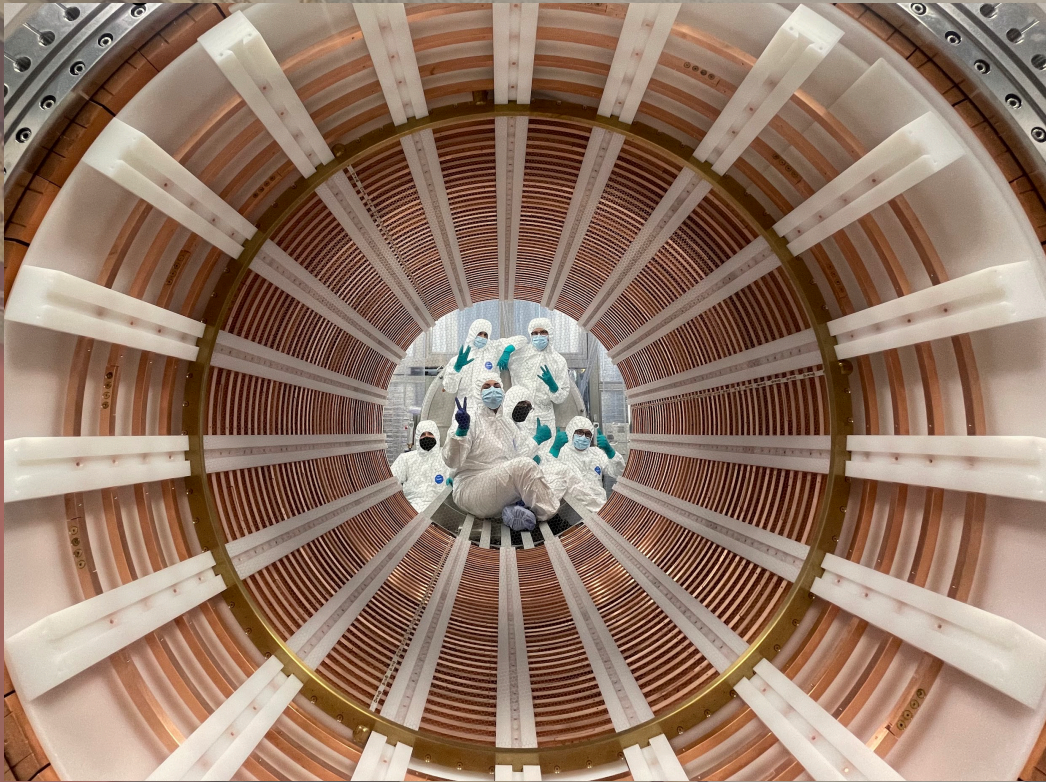


*R. Wagner  
Die Walküre*

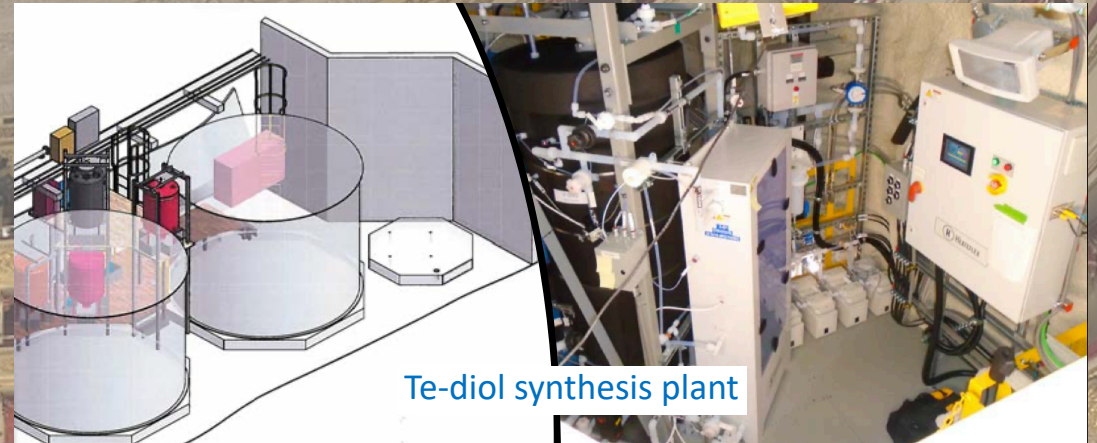
# Double Beta Decay Comparison – Updated!



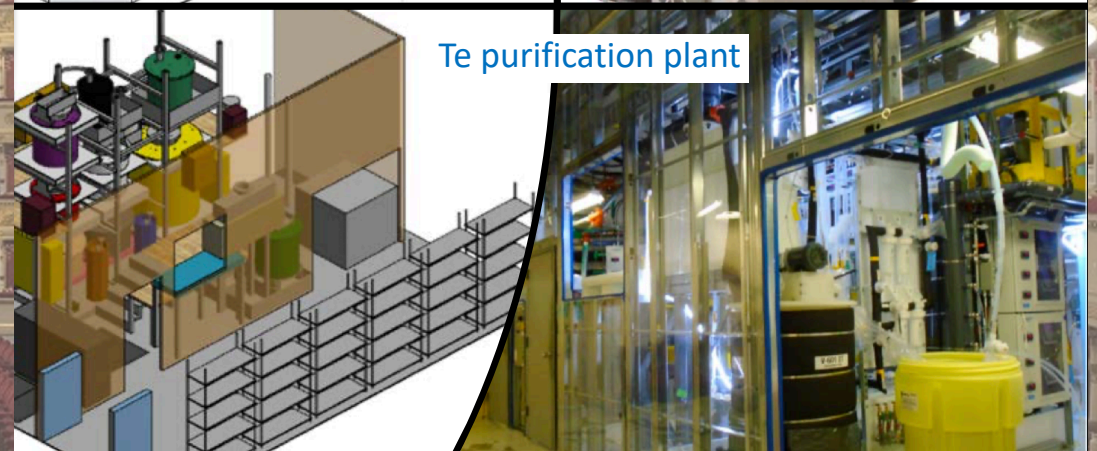
# Near-term New DBD Experiments



NEXT-100 fully built and under commissioning



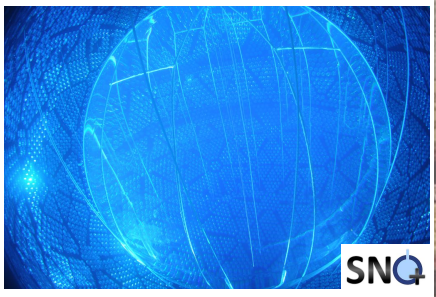
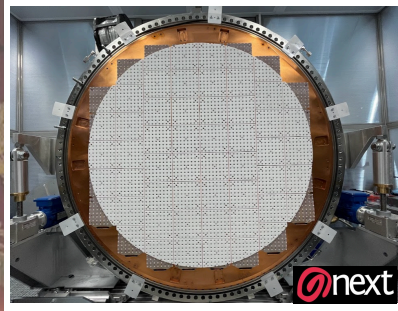
Te-diol synthesis plant



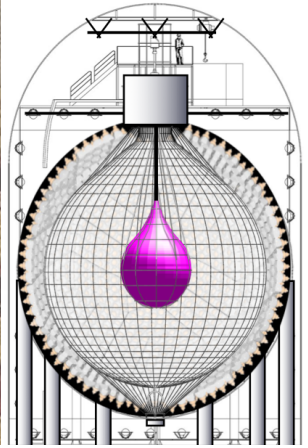
Te purification plant

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

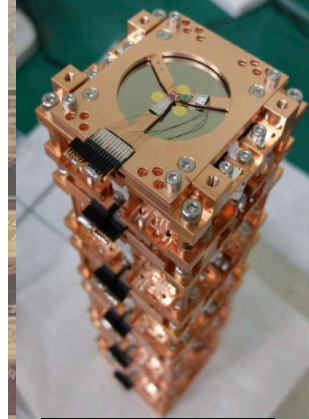
# DBD Experimental Outlook



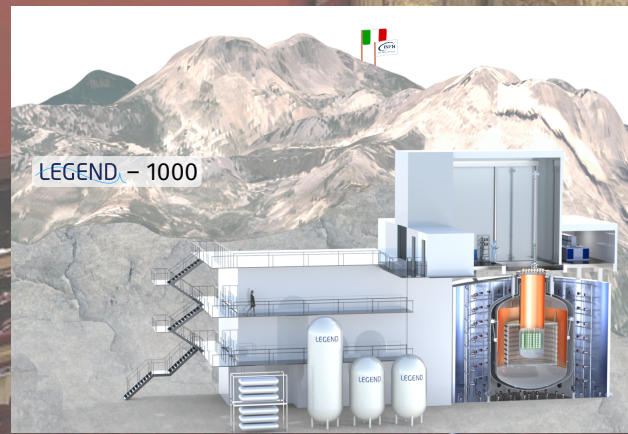
SNQ



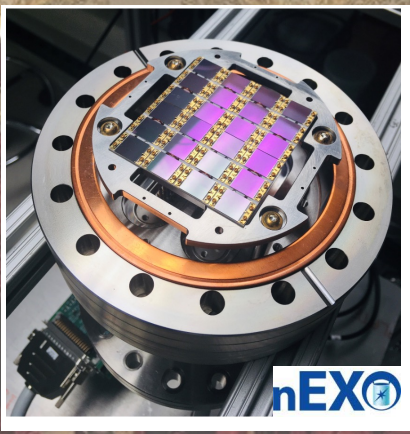
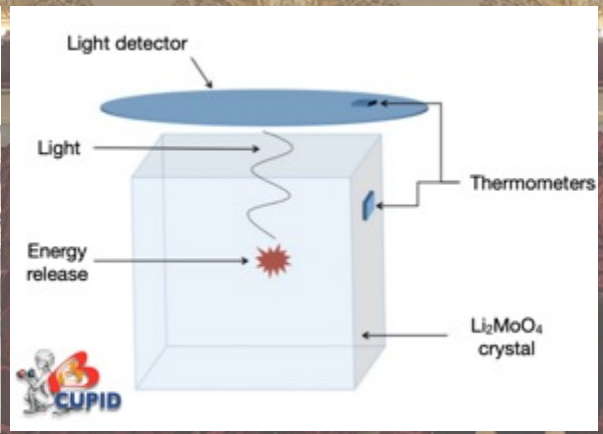
KamLAND2-Zen



AMoRE-II



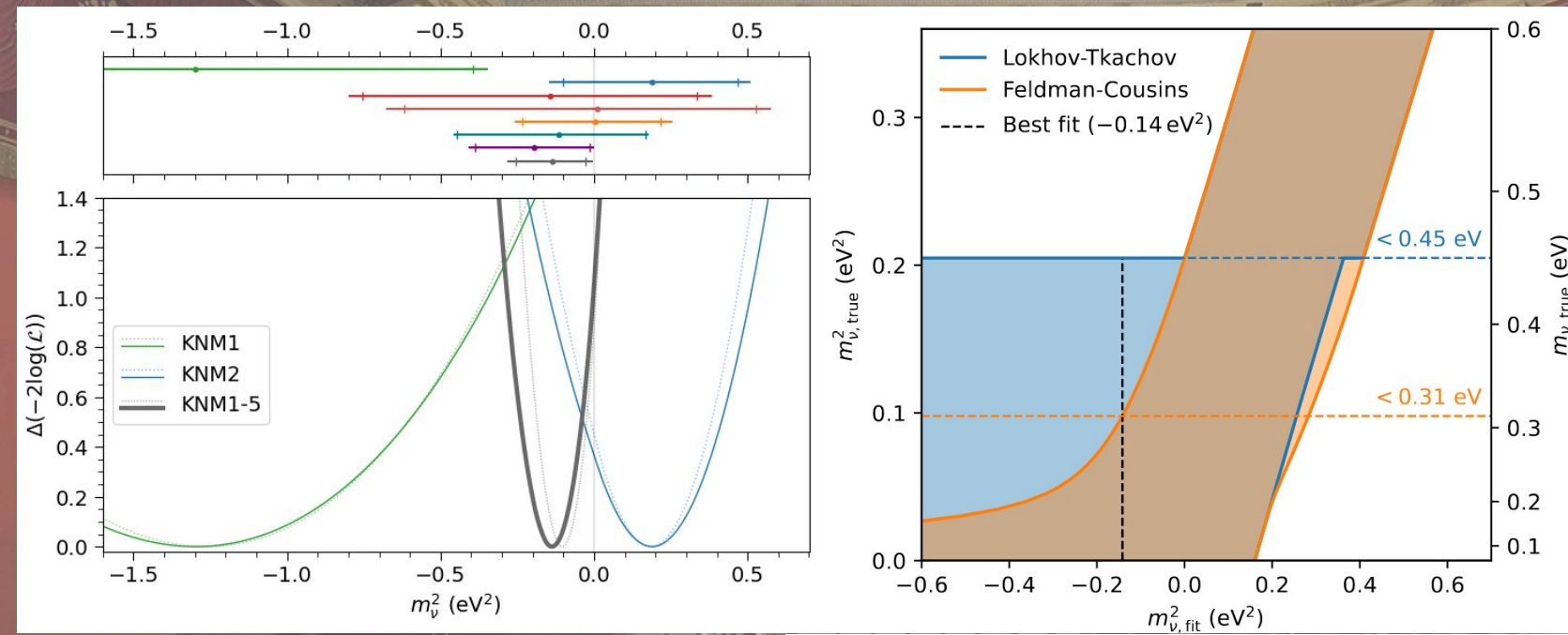
LEGEND - 1000



known as the "ton-scale"  
(see US NSAC long-range plan)



# KATRIN New Result



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

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

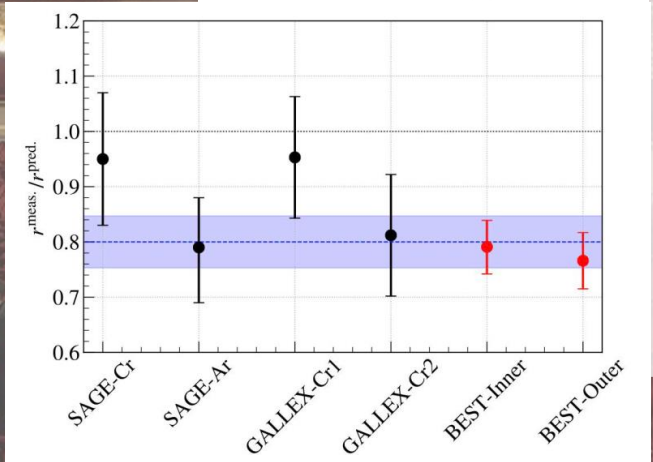
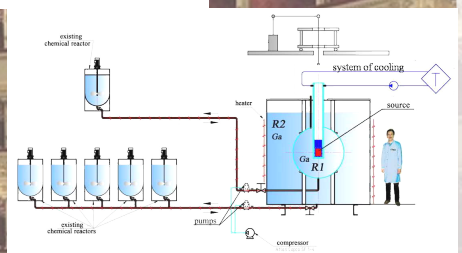


# Reactor Antineutrino Anomaly and Sterile Neutrinos

“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:  $R_1 = 0.791 \pm 0.050$ ,  $R_2 = 0.766 \pm 0.050$



**A. VIVALDI**

LA VERITA'  
IN CIMENTO

*Drama per Musica*

DA RAPPRESENTARSI  
Nel Teatro di S. Angelo

*L'Autunno dell' Anno 1710.*

DEDICATO

A SUA ECCELLENZA

*Il Signer Conte*

SAVA WLADISLAVICH

CONSIGL. AUL. DI S. M. TZAR. Etc.



IN VENEZIA, MDCCXX.

Per Marino Roffetti in Merzeria  
all'Insegna della Pace.

Con Licenza de' Superiori.

# Reactor Antineutrino Anomaly and Sterile Neutrinos

“Truth in contention”

**A. VIVALDI**

**LA VERITA' IN CIMENTO**

*Drama per Musica*

DA RAPPRESENTARSI Nel Teatro di S. Angelo

*L'Autunno dell' Anno 1710.*

DEDICATO

A SUA ECCELLENZA

*Il Signer Conte*

**SAVA WLADISLAVICH**

CONSIGL. AUL. DI S. M. Tzar. Eccl.

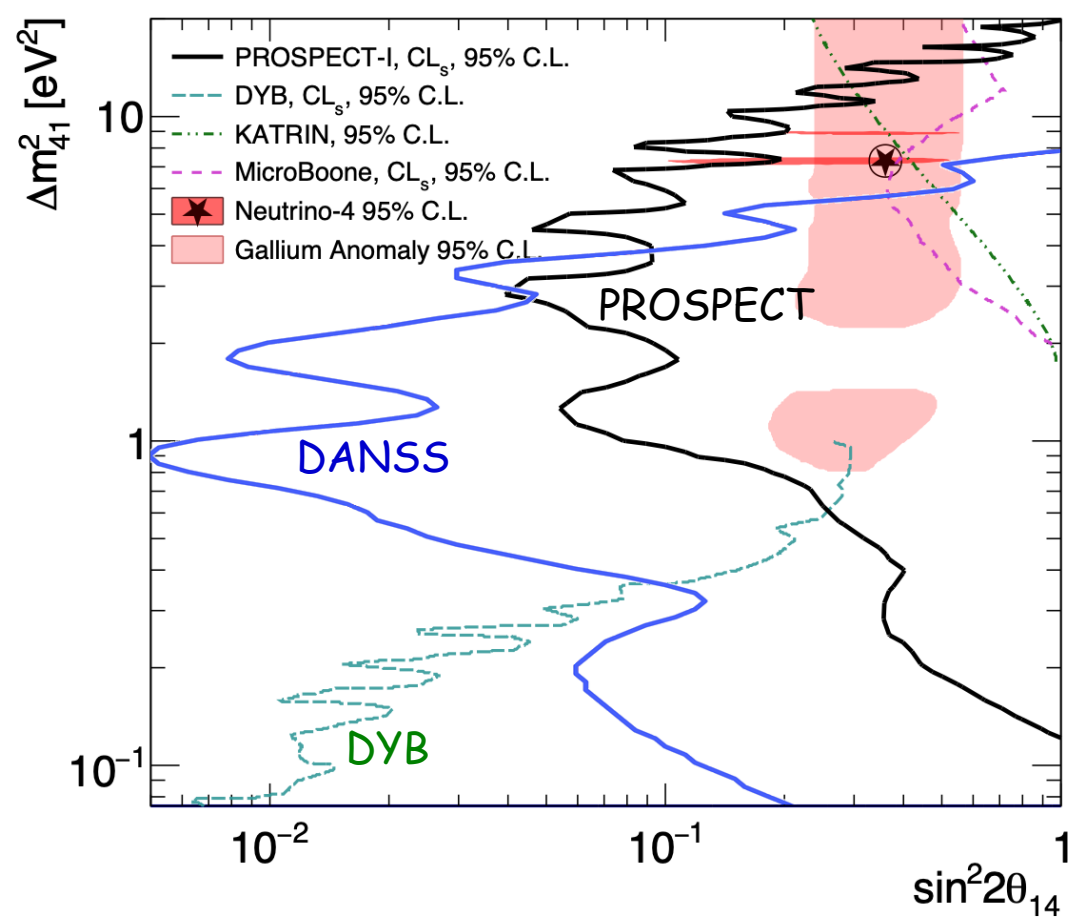


**IN VENEZIA, MDCCXX.**

Per Marino Roffetti in Merzeria all'Insegna della Pace.

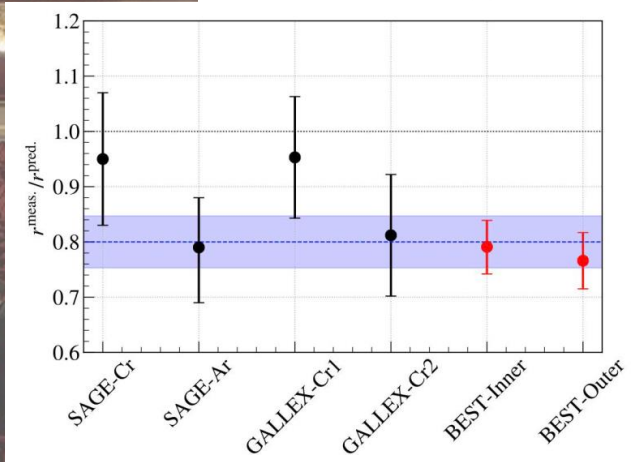
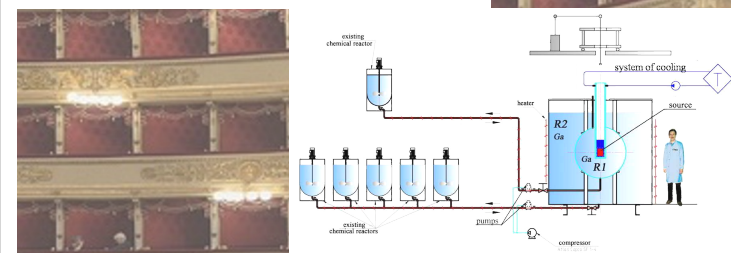
Con Licenza de' Superiori.

PROSPECT, Neutrino 2024, arXiv[2406.TBD]

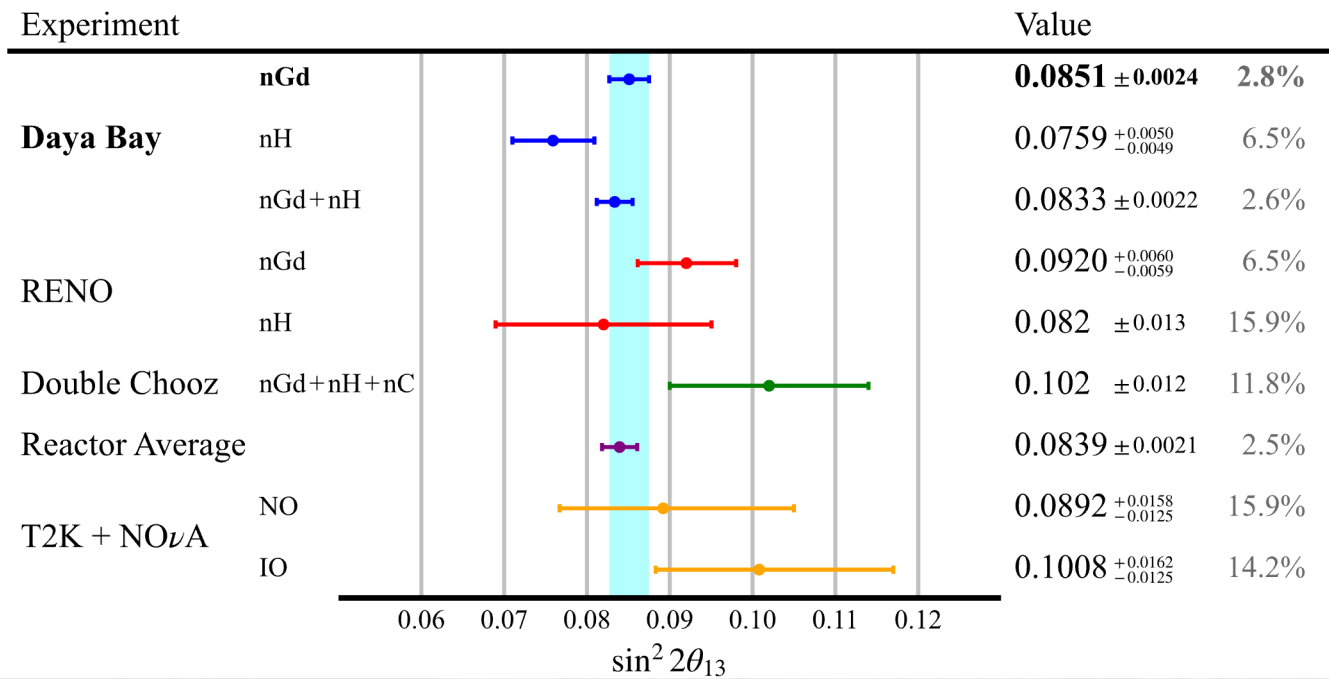


leV bump  
(understood in the future)

$$R_2 = 0.766 \pm 0.050$$



# Precision Oscillation Parameters for New Physics?



# Precision Oscillation Parameters for New Physics?

Experiment	
	nGd
Daya Bay	nH
	nGd+nH
RENO	nGd
	nH
Double Chooz	nGd+nH+nC
Reactor Average	
T2K + NO $\nu$ A	NO
	IO

0.06

Under ongoing experimental demonstration & exploration via the CLOUD experiment

## SuperChooz experimental setup...

the Ardennes mountains

the Meuse river

European Innovation Council | UK Research and Innovation

AM-Otech project [EIC-UKRI]  
CLOUD experiment

1 Dec 2022

**Chooz-A: Cavern Reactor Core**

**Chooz-B: Reactor Cores**

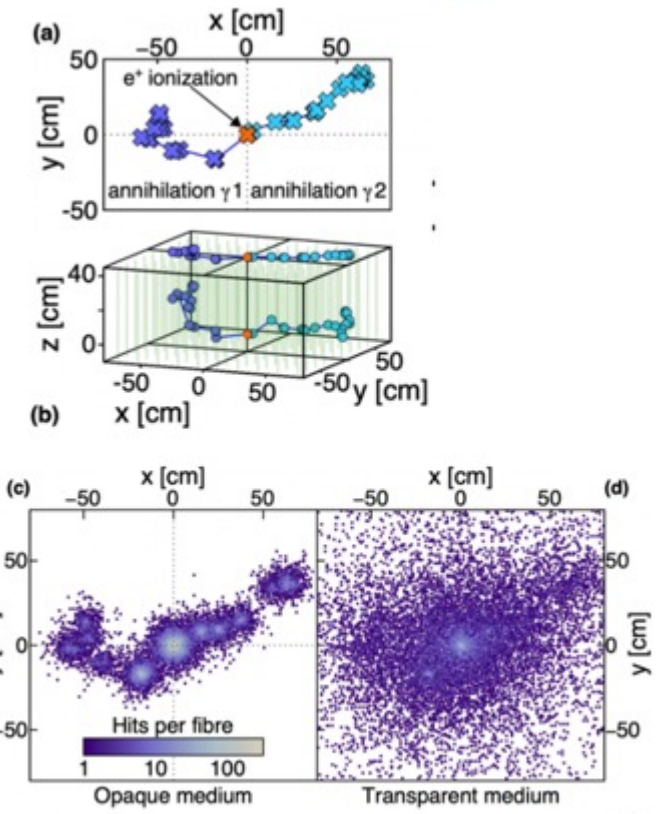
**Ultra Near Detectors @ Chooz-B:**

- LiquidO technology
- Mass:  $\leq 5$  tons
- Overburden:  $\leq 5$ m
- Baseline:  $\leq 30$ m

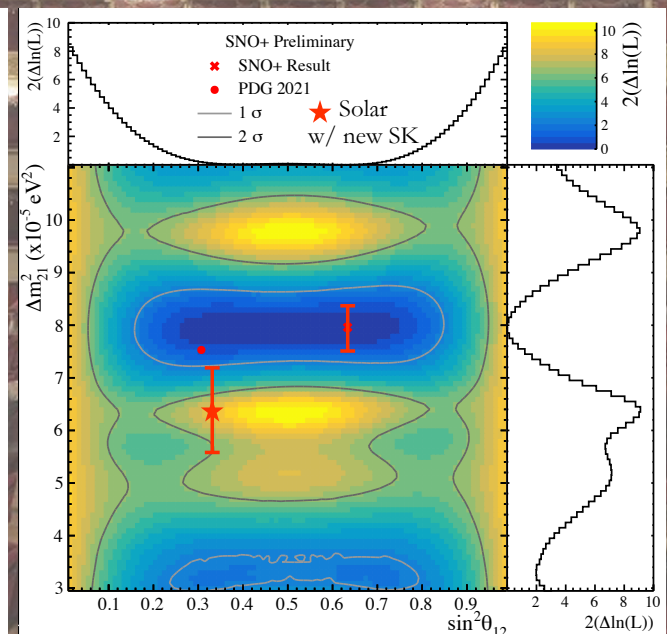
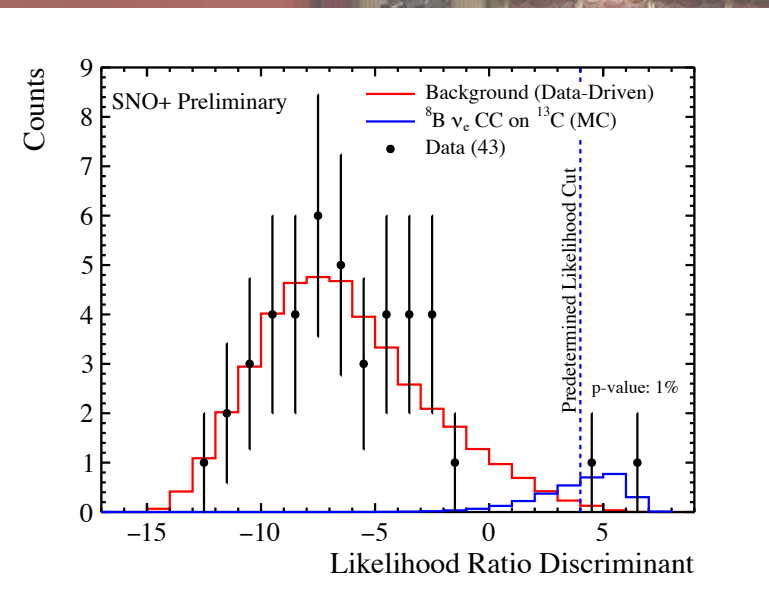
**Super Far Detector @ Chooz-A**

- LiquidO technology
- Mass:  $\sim 10,000$  tons
- Overburden:  $\leq 100$ m
- Baseline:  $\sim 1$ km

FD cavern is already built



# The Sun and the Earth in Neutrinos

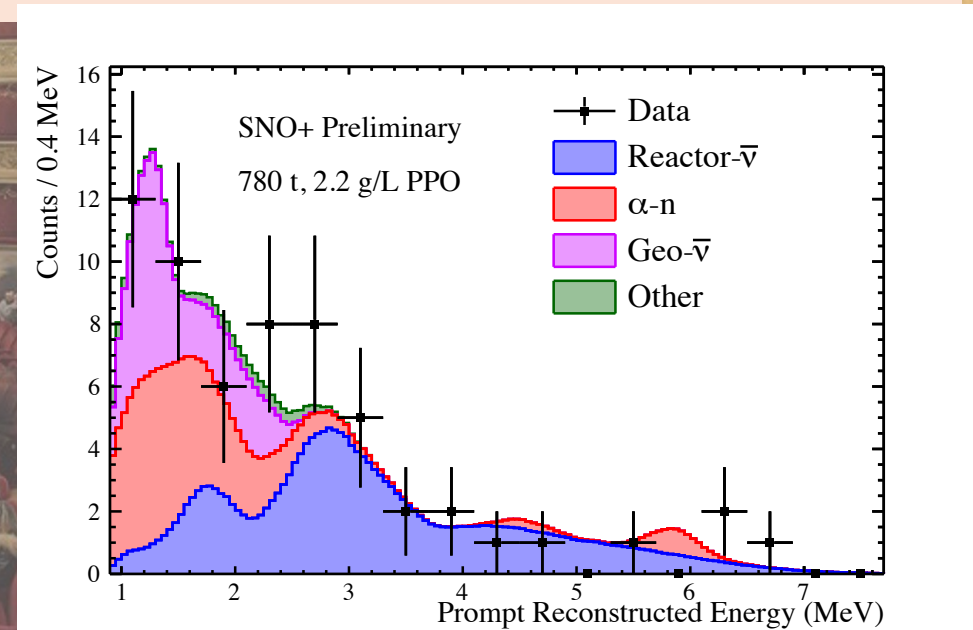
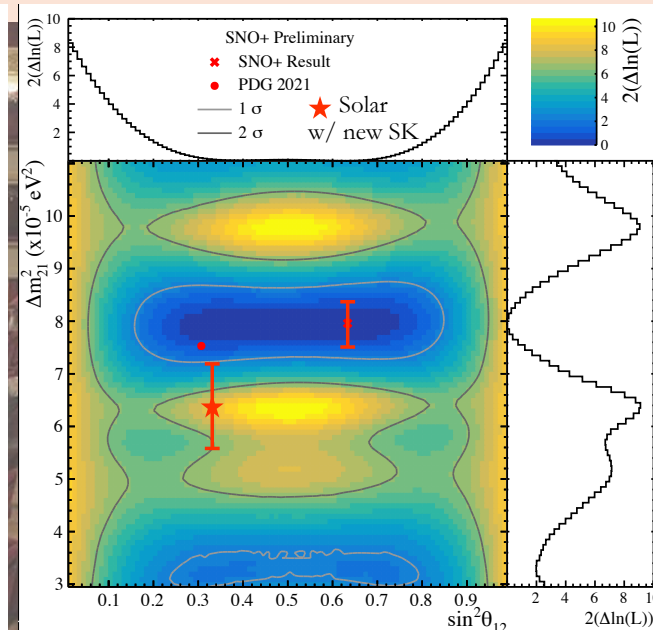
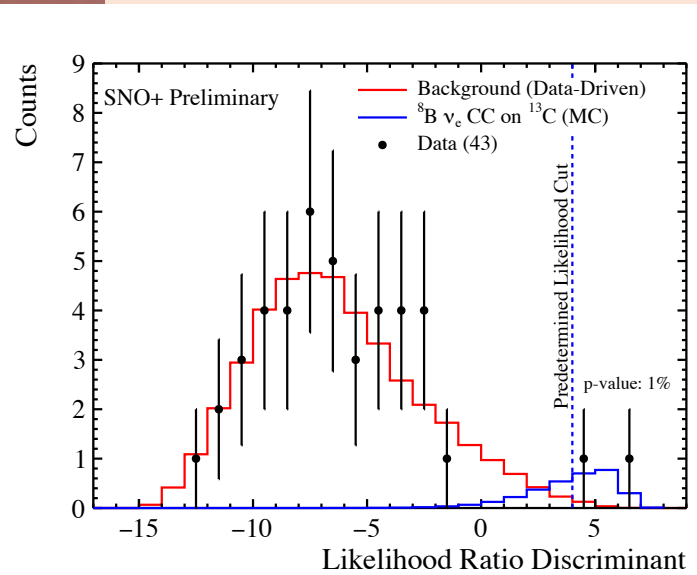




# The Sun and the Earth in Neutrinos

New results from SNO+ including:

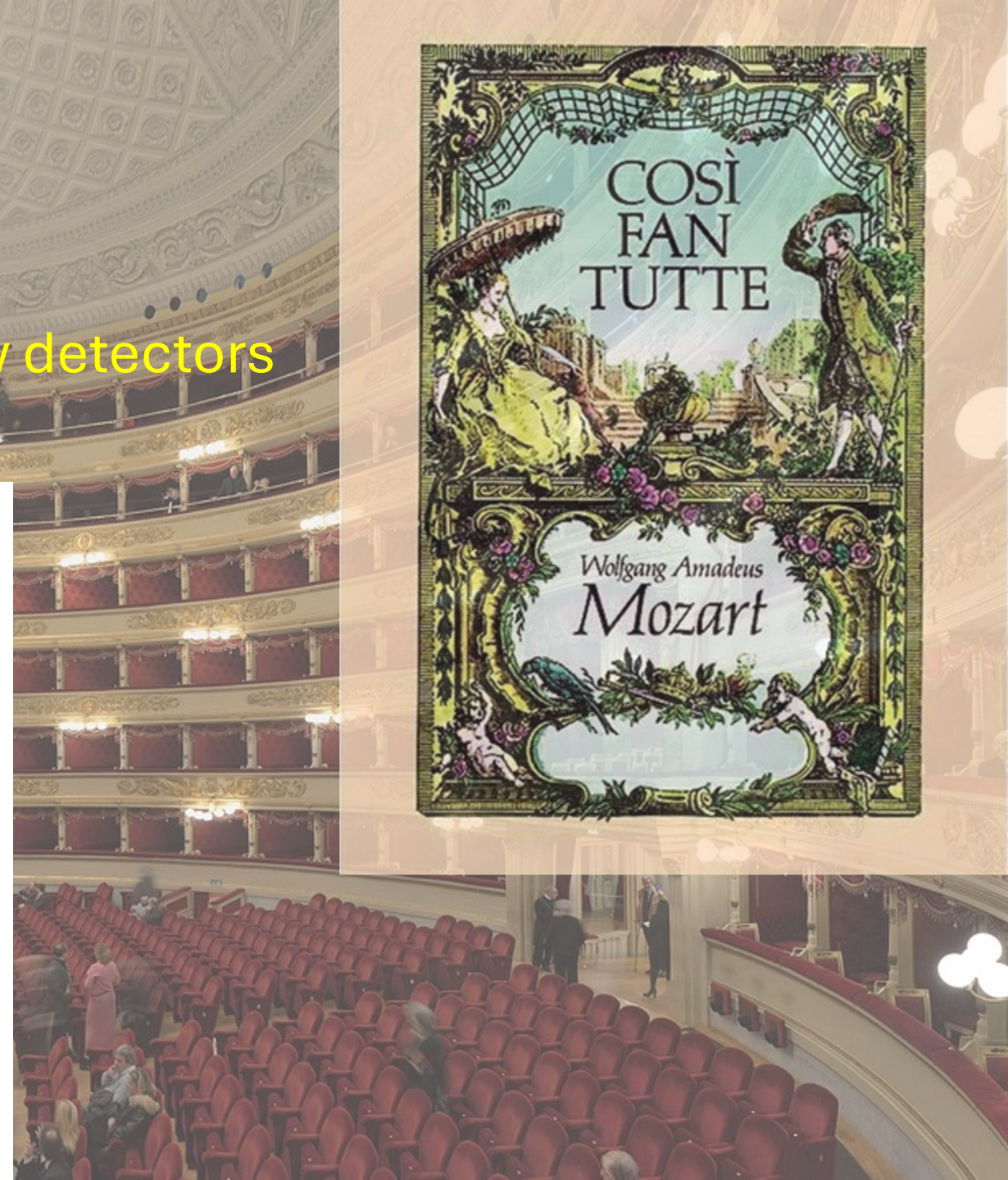
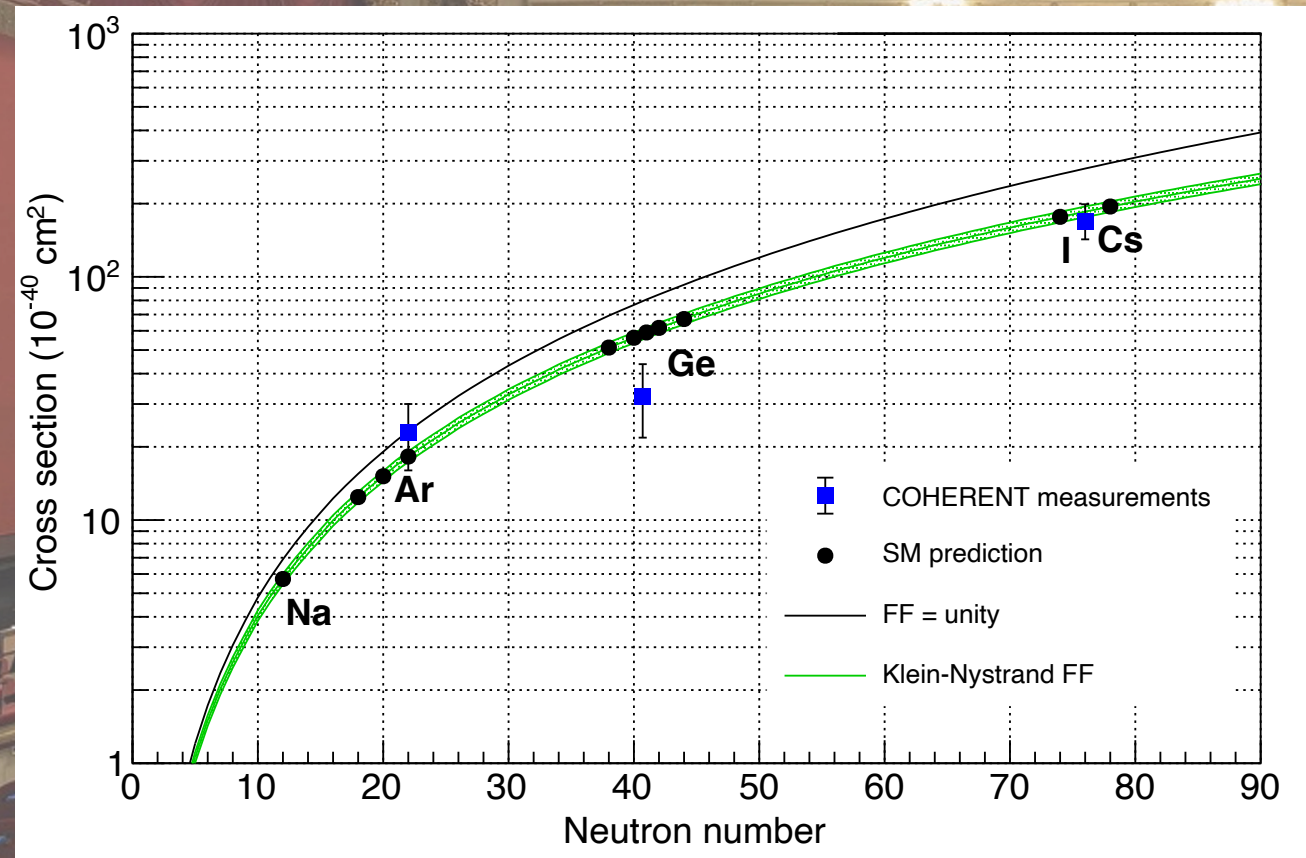
- observing 2 events (background 0.17) of CC  $^8\text{B}$  solar  $\nu_e$  on  $^{13}\text{C}$ , the first time this channel has been used to detect neutrinos!
- second measurement of  $\Delta m_{21}^2 = 7.96_{-0.41}^{+0.48} \times 10^{-5} \text{ eV}^2$  with reactor  $\bar{\nu}_e$
- prelim. geoneutrino flux measurement of  $64 \pm 44 \text{ TNU}$  (refined analysis soon)





# Scattering

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



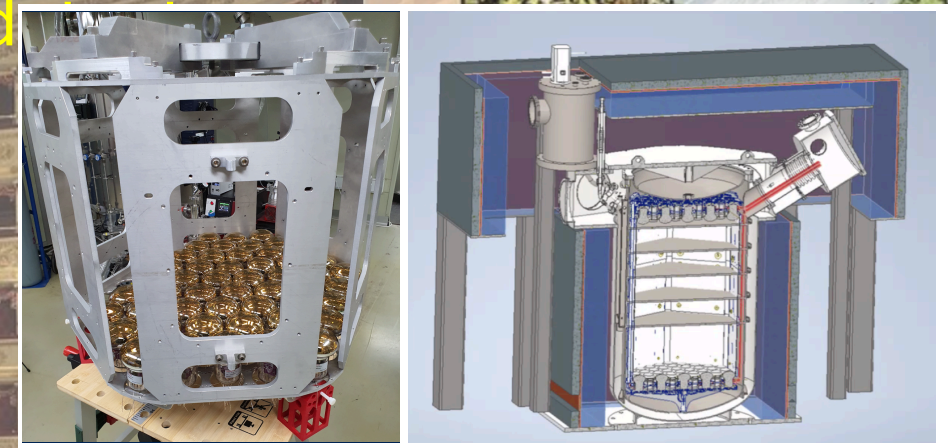
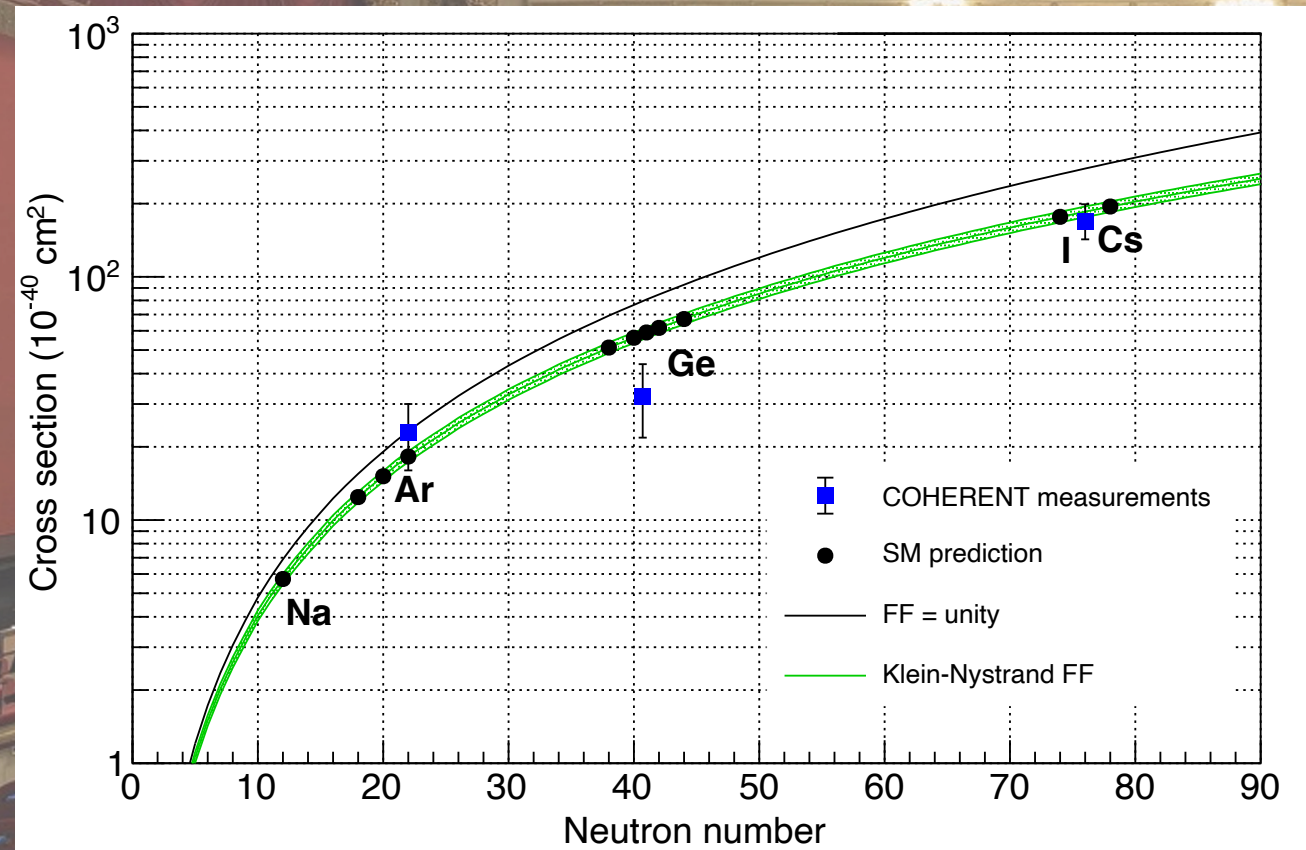




# Scattering



New Ge observation plus *many* new data points sensitive to new physics



# DUNE

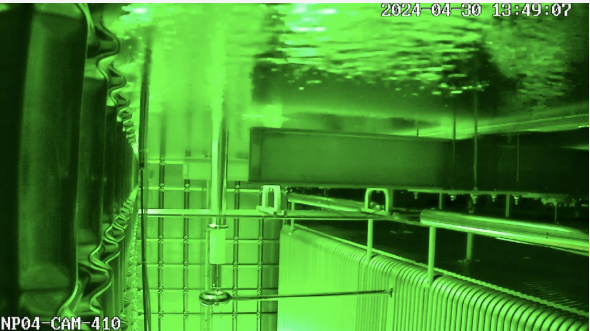
Long baseline neutrino oscillations, solar, atmospheric, supernova, proton decay, BSM,...

**G. VERDI**  
**AIDA**

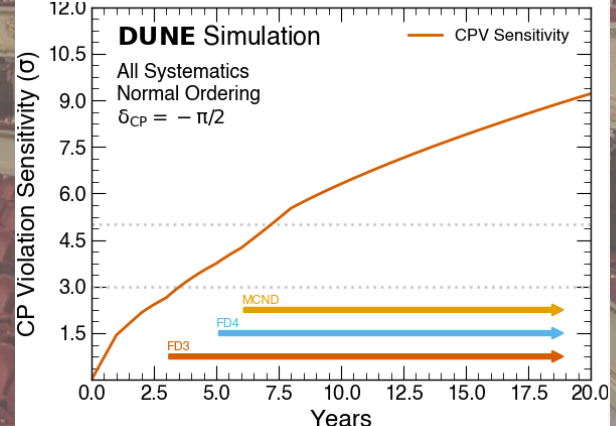
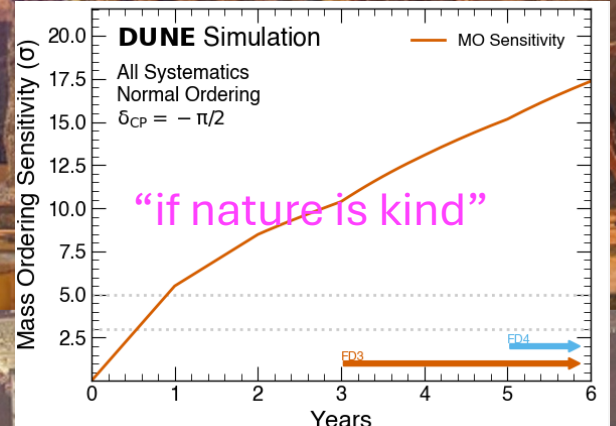
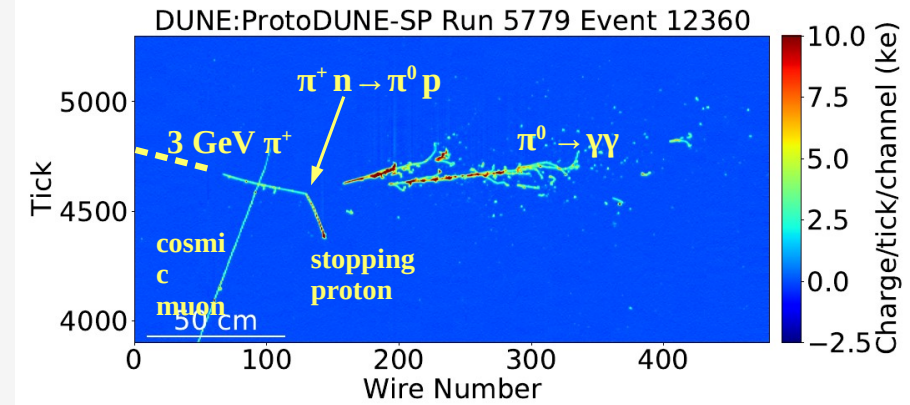


# DUNE

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

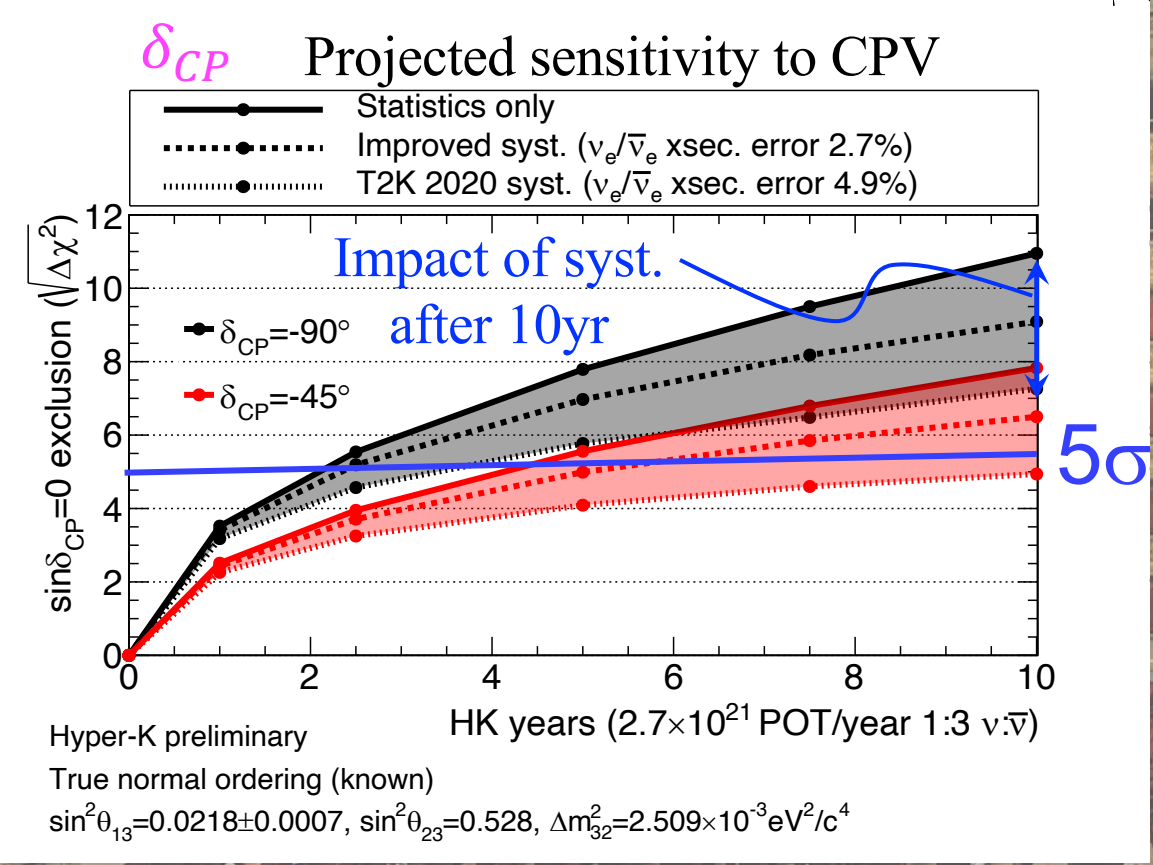


- Successful prototype of horizontal drift at CERN Neutrino Platform in 2018 (ProtoDUNE-SP)
- ProtoDUNE-HD completed filling 30<sup>th</sup> April, running since May, with beam turning on at 6pm tomorrow evening
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025



aiming for operational start in 2027

# Hyper-K



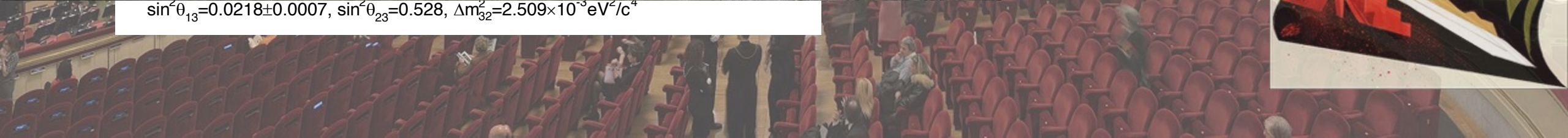
aiming for operational start in 2027

# Hyper-K



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

$$\sin^2\theta_{13}=0.0218\pm 0.0007, \sin^2\theta_{23}=0.528, \Delta m_{32}^2=2.509\times 10^{-5}\text{eV}^2/c^4$$



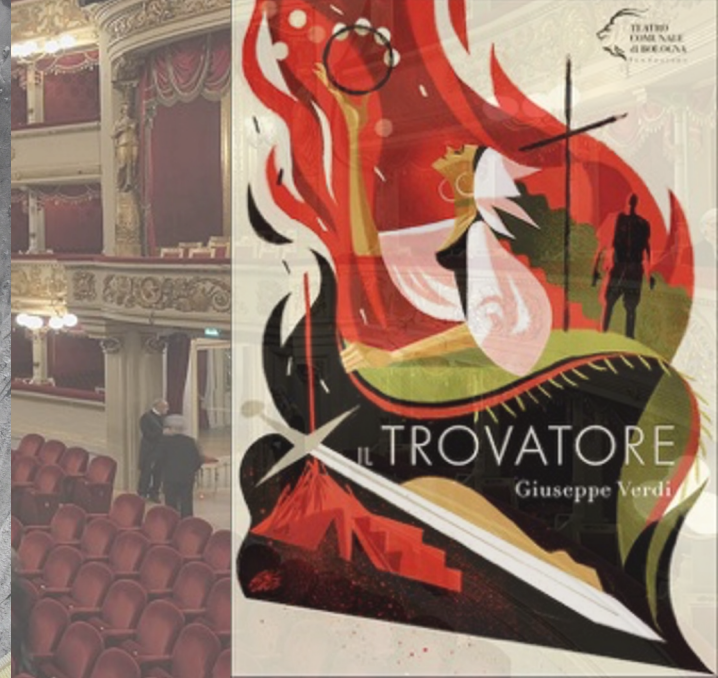
aiming for operational start in 2027

# Hyper-K



Oct. 3, 20

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



aiming for operational start in 2027

# Hyper-K



Oct. 3, 20

Excavation of the HK cavern with



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



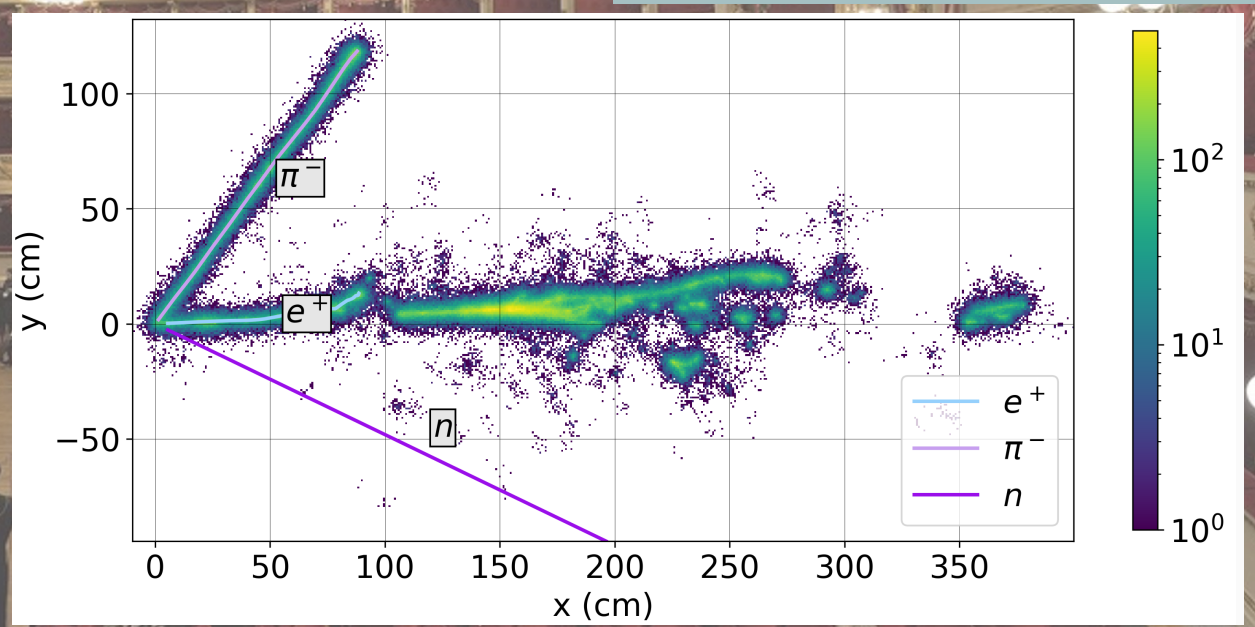
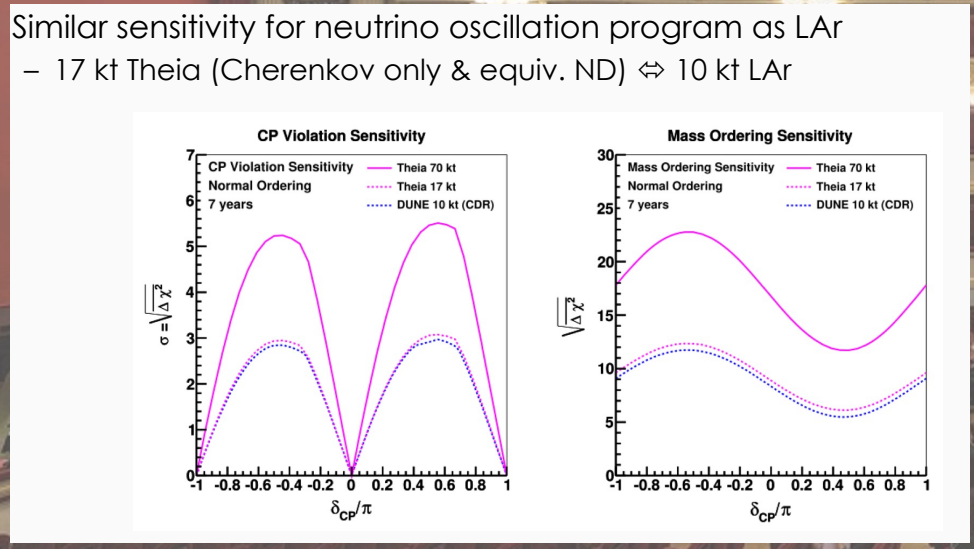
# Other Future Long Baseline Projects

- Korea Neutrino Observatory
- FD4 – DUNE 4<sup>th</sup> module
  - “module of opportunity”
- THEIA



*R. Wagner  
Götterdämmerung*

LiquidO





Presented by J. Cao

# JUNO

Aim to finish construction in 2024  
and start filling



*G. Puccini  
Turandot*

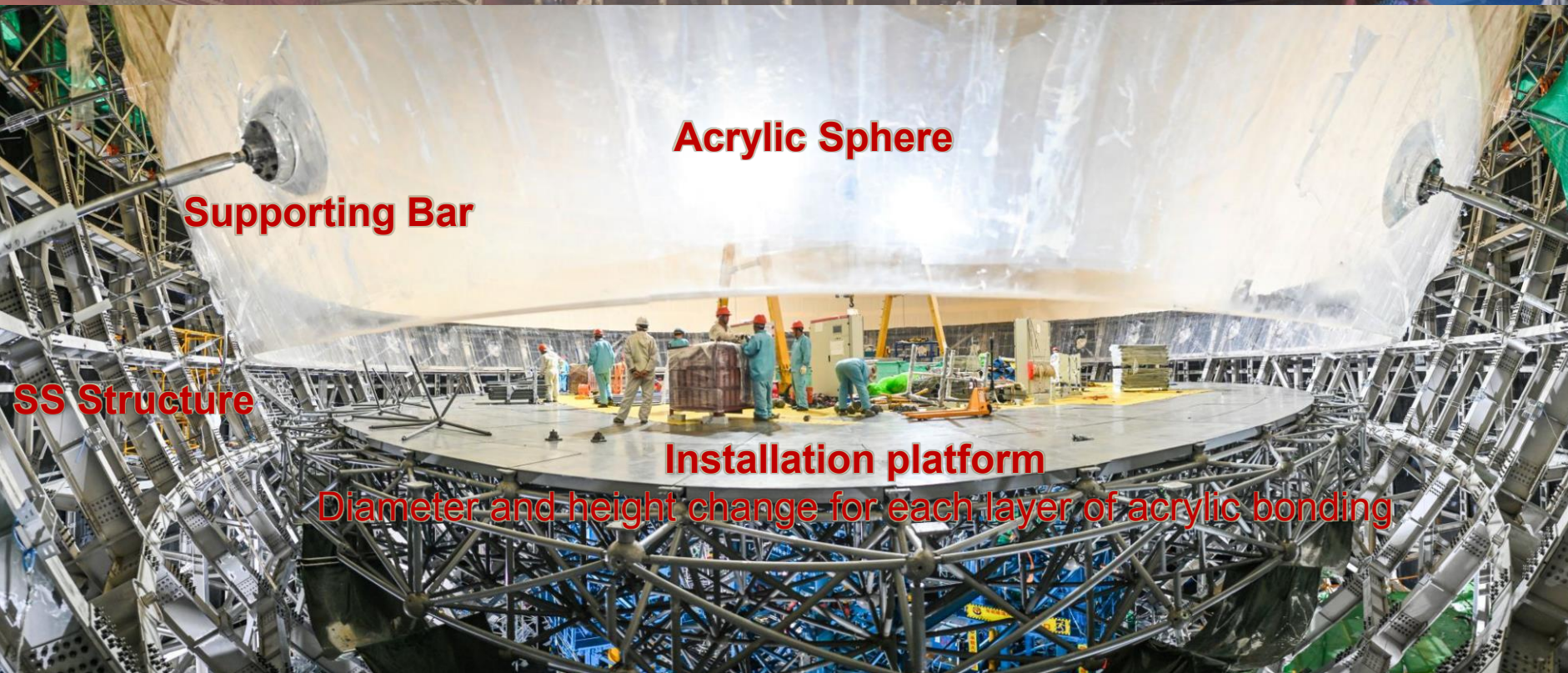


# JUNO

Aim to finish construction in 2024  
and start filling



*G. Puccini  
Turandot*



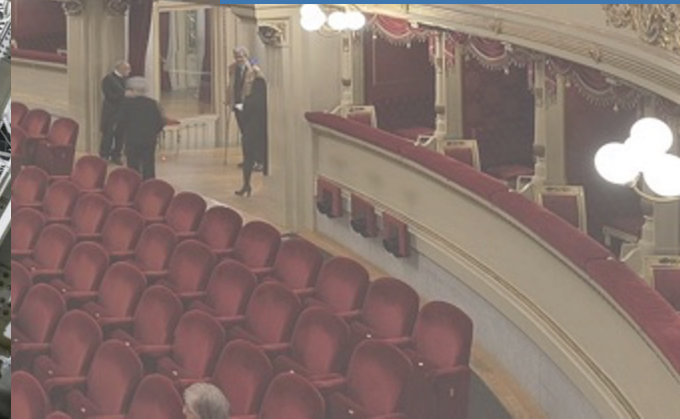
**Acrylic Sphere**

**Supporting Bar**

**SS Structure**

**Installation platform**

**Diameter and height change for each layer of acrylic bonding**



# JUNO

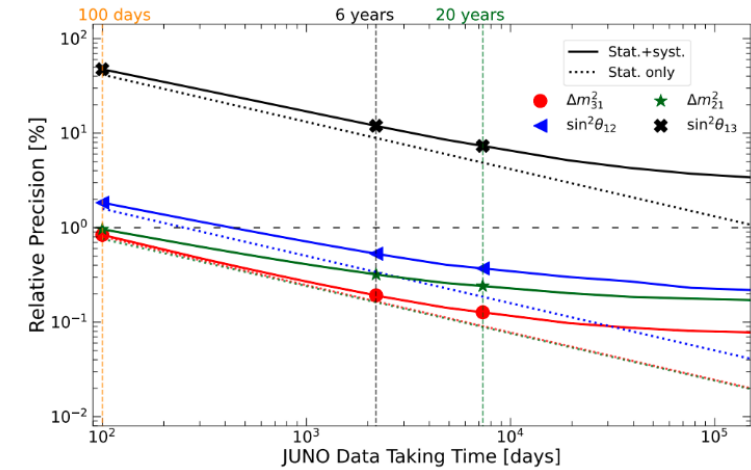
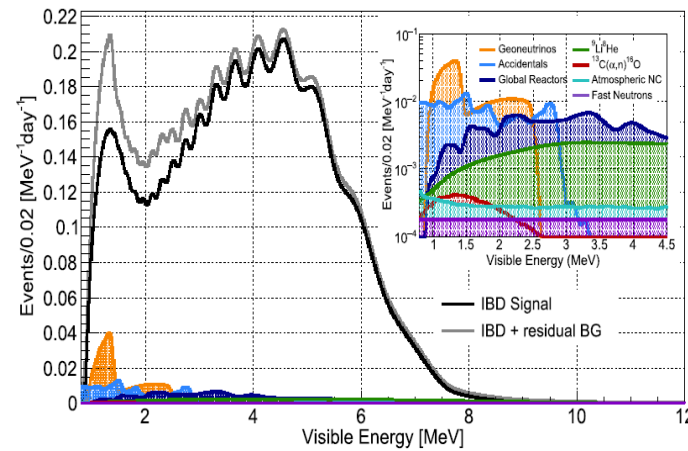
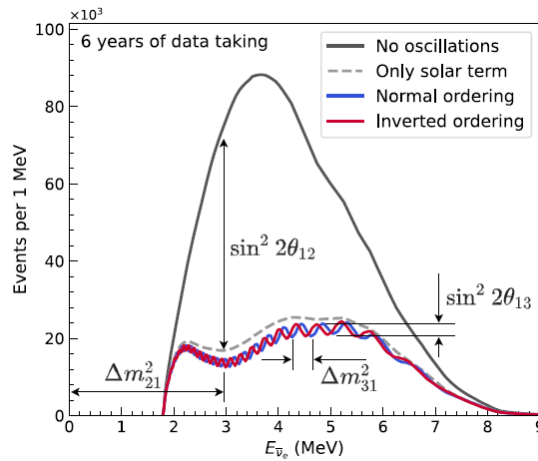


## Precision Measurement of oscillation parameters

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

ID#223, Precision Measurement

Chin. Phys. C46 (2022) 12, 123001



	Central Value	PDG2020	100 days	6 years	20 years
$\Delta m_{31}^2$ ( $\times 10^{-3}$ eV <sup>2</sup> )	2.5283	$\pm 0.034$ (1.3%)	$\pm 0.021$ (0.8%)	$\pm 0.0047$ (0.2%)	$\pm 0.0029$ (0.1%)
$\Delta m_{21}^2$ ( $\times 10^{-5}$ eV <sup>2</sup> )	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%)

$\sin^2 2\theta_{12}$ ,  $\Delta m_{21}^2$ ,  $|\Delta m_{32}^2|$ , leading measurements in 100 days; precision <math>< 0.5\%</math> in 6 years

*Arrivederci a tutti! Alla prossima volta!*

