Status and Prospects of Neutrino Physics

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

International Workshop “Invisibles 2024”

Bologna, Italy, July 1 - 5, 2024

This project has received funding from the European Unions Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 860881.

Research in Neutrino Physics: we strive to understand at deepest level what are the origins of neutrino masses and mixing and what determines the pattern of neutrino mixing and of neutrino mass squared differences that emerged from the neutrino oscillation data in the recent years. And we try to understand what are the implications of the remarkable discovery that neutrinos have mass, mix and oscillate for elementary particle physics, cosmology and for better understanding of the Earth, the Sun, the stars, formation of Galaxies, the Early Universe, i.e., for better deeper understanding of Nature in general.

The Current Status

Reference 3-ν Mixing Scheme

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\,\nu_{j\mathrm{L}} \qquad l = e, \mu, \tau.$$

Data: 3 νs are light: $\nu_{1,2,3}$, $m_{1,2,3} \lesssim 0.5$ eV;
KATRIN: $m_{\bar{\nu}_e} < 0.45$ eV;
Cosmology: $\sum_j m_j <$ 0.12 - 0.77 eV (95% CL; 2107.00532).

The value of $\mathrm{min}(m_j)$ and "mass ordering" unknown.

Δm^2_{21}, $|\Delta m^2_{31}|$ - **known ($\mathrm{sgn}(\Delta m^2_{31})$ - unknown).**

ν_j, $m_j \neq 0$: **nature - Dirac or Majorana - unknown.**

The PMNS matrix U - 3×3 unitary: θ_{12}, θ_{13}, θ_{23} - known; CPV phases δ, α_{21}, α_{31} - unknown.

Thus, 5 known + 4 unknown parameters + MO.
"Known" = measured; "unknown" = not measured.

m_e, m_μ, m_τ **also known - used as input.**

Compellings Evidence for $\nu-$Oscillations

$-\nu_{\text{atm}}$: SK UP-DOWN ASYMMETRY

θ_Z-, $L/E-$ **dependences of** $\mu-$**like events**

Dominant $\nu_\mu \rightarrow \nu_\tau$ **K2K, MINOS, T2K; CNGS (OPERA)**

$-\nu_\odot$: **Homestake, Kamiokande, SAGE, GALLEX/GNO**
Super-Kamiokande, SNO, BOREXINO

$-\bar{\nu}_e$ (from reactors): **KamLAND, Daya Bay, RENO, Double Chooz**

Dominant $\bar{\nu}_e \rightarrow \bar{\nu}_{\mu,\tau}$

T2K, MINOS, NOνA (ν_μ from accelerators): $\nu_\mu \rightarrow \nu_{e,\mu}$

T2K, NOνA ($\bar{\nu}_\mu$ from accelerators): $\bar{\nu}_\mu \rightarrow \bar{\nu}_{e,\mu}$

Idea of neutrino oscillations:
B. Pontecorvo, 1957, 1958, 1967;
Z. Maki, M. Nakagawa, S. Sakata, 1962.

$$|\nu_l>= \sum_{j=1}^{n} U^{*}_{lj}\,|\nu_j> , \quad \nu_j : \; m_j \neq 0 ; \quad l = e, \mu, \tau ; \quad n \geq 3 ;$$

$$\nu_{l\mathrm{L}}(x) = \sum_{j=1}^{n} U_{lj}\, \nu_{j\mathrm{L}}(x) , \quad \nu_{j\mathrm{L}}(x) : \; m_j \neq 0 ; \quad l = e, \mu, \tau \, .$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix.

ν_j, $m_j \neq 0$: Dirac or Majorana particles.

Data: at least 3 νs are light: $\nu_{1,2,3}$, $m_{1,2,3} \lesssim 0.5$ eV.

The Charged Current Weak Interaction Lagrangian:

$$\mathcal{L}^{CC}(x) = -\frac{g}{2\sqrt{2}} \sum_{l=e,\mu,\tau} \bar{l}(x)\gamma_\alpha\,(1-\gamma_5)\,\nu_{l\mathrm{L}}(x)\,W^\alpha(x) + \text{h.c.}\,,$$

$$\nu_{l\mathrm{L}}(x) = \sum_{j=1}^{n} U_{lj}\,\nu_{j\mathrm{L}}(x)\,, \quad \nu_{j\mathrm{L}}(x):\; m_j \neq 0\,; \quad l = e,\mu,\tau\,.$$

These data imply that

$$m_{\nu_j} <<< m_{e,\mu,\tau}, m_q, \; q = u, c, t, d, s, b$$

For $m_{\nu_j} \lesssim 0.5$ **eV:** $m_{\nu_j}/m_{l,q} \lesssim 10^{-6}$

For a given family: $10^{-2} \lesssim m_{l,q}/m_{q'} \lesssim 10^2$

This suggests that

- ν_j get their masses from a mechanism which differs from that generating the masses of $m_{e,\mu,\tau}, m_q$ in the SM;

- the smallness of m_{ν_j} is related to the existence of a new fundamental mass scale in particle physics, i.e., to the existence of New Physics beyond the SM.

Natural to assume ν_j "differ" from $m_{e,\mu,\tau}, m_q$ because they are Majorana particles (e, μ, τ, quarks are Dirac particles).

The observation of, e.g., $(\beta\beta)_{0\nu}-$ decay would be a proof.

These ideas are realised in many theoretical models which predict massive Majorana ν_j: seesaw (N_j, H, T), HTP (H^{--}, H^{-}), models of lepton flavour.

The observed patterns of $\nu-$mixing and of $\Delta m^2_{\rm atm}$ and $\Delta m^2_{\odot}$ can be related to Majorana ν_j and a new fundamental (approximate flavour) symmetry, e.g.,

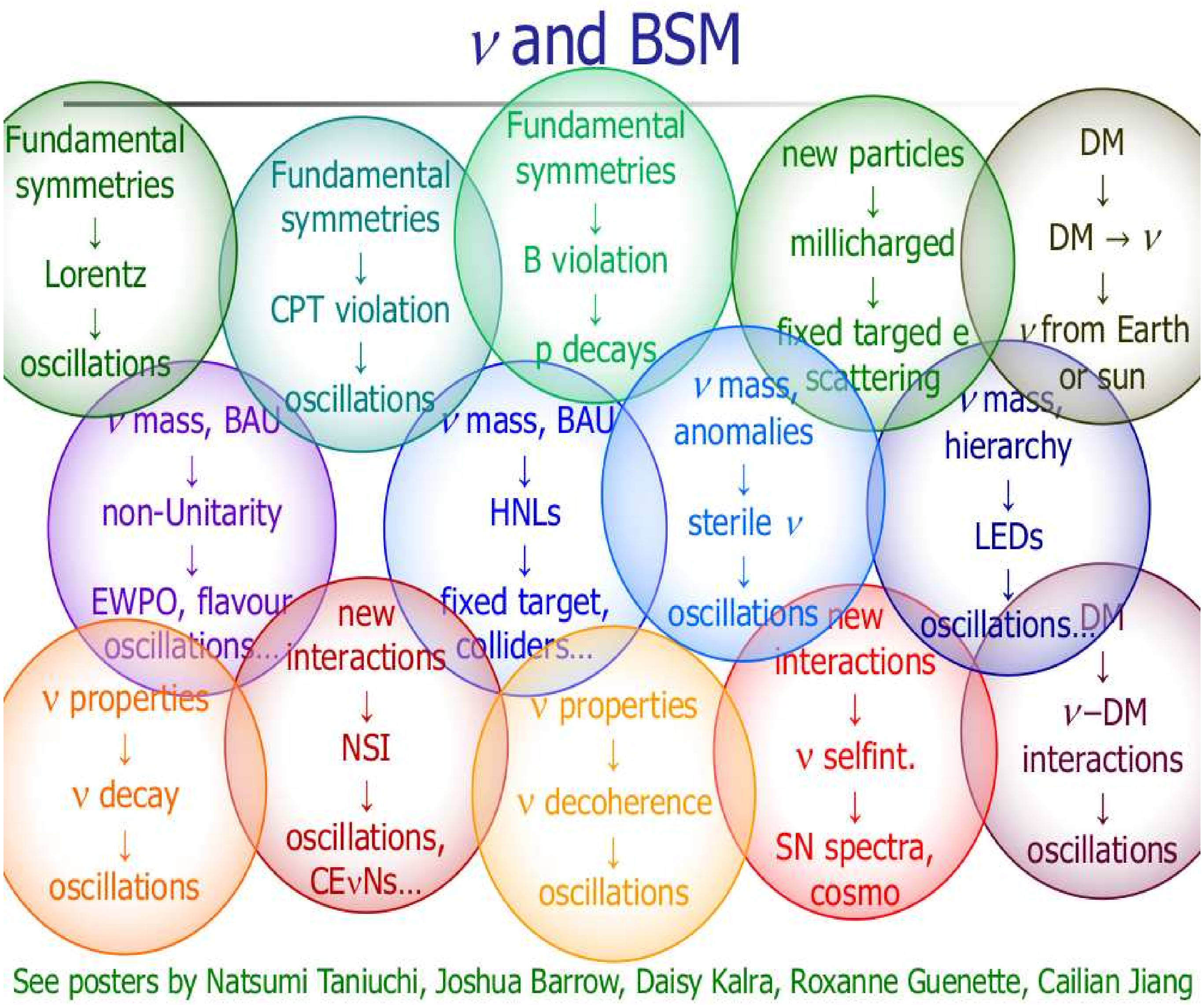
$$A_4\ (\sim \Gamma_3),\ S_4\ (\sim \Gamma_4), ...,\ U(1)_{L'}\ (L' = L_e - L_\mu - L_\tau), ...$$

These discoveries suggest the existence of New Physics beyond that of the ST.

The New Physics can manifest itself (can have a variety of different “flavours”):

- In the existence of more than 3 massive neutrinos: $n > 3$ ($n = 4$, or $n = 5$, or $n = 6$,...).
- In the observed pattern of neutrino mixing and in the values of the CPV phases in the PMNS matrix.
- In the Majorana nature of massive neutrinos.
- In the existence of LFV processes: $\mu \to e + \gamma$, $\mu \to 3e$, $\mu - e$ conversion, etc., which proceed with rates close to the existing upper limits.
- In the existence of new particles, e.g., at the TeV scale: heavy Majorana Neutrinos N_j, doubly charged scalars,...

- In the existence of new (FChNC, FCFNSNC) neutrino interactions.
- In the existence of “unknown unknowns”...



ν and BSM

Fundamental symmetries ↓ Lorentz ↓ oscillations

Fundamental symmetries ↓ CPT violation ↓ oscillations

Fundamental symmetries ↓ B violation ↓ p decays

new particles ↓ millicharged ↓ fixed targed e scattering

DM ↓ DM → ν ↓ ν from Earth or sun

ν mass, BAU ↓ non-Unitarity ↓ EWPO, flavour oscillations...

ν mass, BAU ↓ HNLs ↓ fixed target, colliders...

ν mass, anomalies ↓ sterile ν ↓ oscillations

ν mass, hierarchy ↓ LEDs ↓ oscillations...

ν properties ↓ ν decay ↓ oscillations

new interactions ↓ NSI ↓ oscillations, CEνNs...

ν properties ↓ ν decoherence ↓ oscillations

new interactions ↓ ν selfint. ↓ SN spectra, cosmo

DM ↓ ν–DM interactions ↓ oscillations

See posters by Natsumi Taniuchi, Joshua Barrow, Daisy Kalra, Roxanne Guenette, Cailian Jiang

E. Fernandez-Martinez, talk at Neutrino 2024, June 17-22, Milano

We can have $n > 3$ ($n = 4$, or $n = 5$, or $n = 6$,...) if, e.g., sterile ($SU(2)_L$ singlet states) ν_R, $\tilde{\nu}_L$ exist and they mix with the active flavour neutrinos ν_l ($\tilde{\nu}_l$), $l = e, \mu, \tau$.

Two (extreme) possibilities:

i) $m_{4,5,...} \sim 1$ eV;
in this case $\nu_{e(\mu)} \rightarrow \nu_S$ oscillations are possible (hints from LSND and MiniBooNE experiments, re-analises of SBL reactor $\bar{\nu}_e$ oscillation data with "new" fluxes of $\bar{\nu}_e$ ("RAA"), data of radioactive source callibration of the solar neutrino SAGE and GALLEX experiments ("Gallium anomaly"); Neutrino-4 claim; tests (SBLNP (Fermilab, ICARUS + 2 detectors), JSNS2 (at KEK), DANSS, NEOS, PROSPECT, STEREO,...).

ii) $M_{4,5,...} \sim (1 - 10^3)$ GeV, low-scale seesaw models;

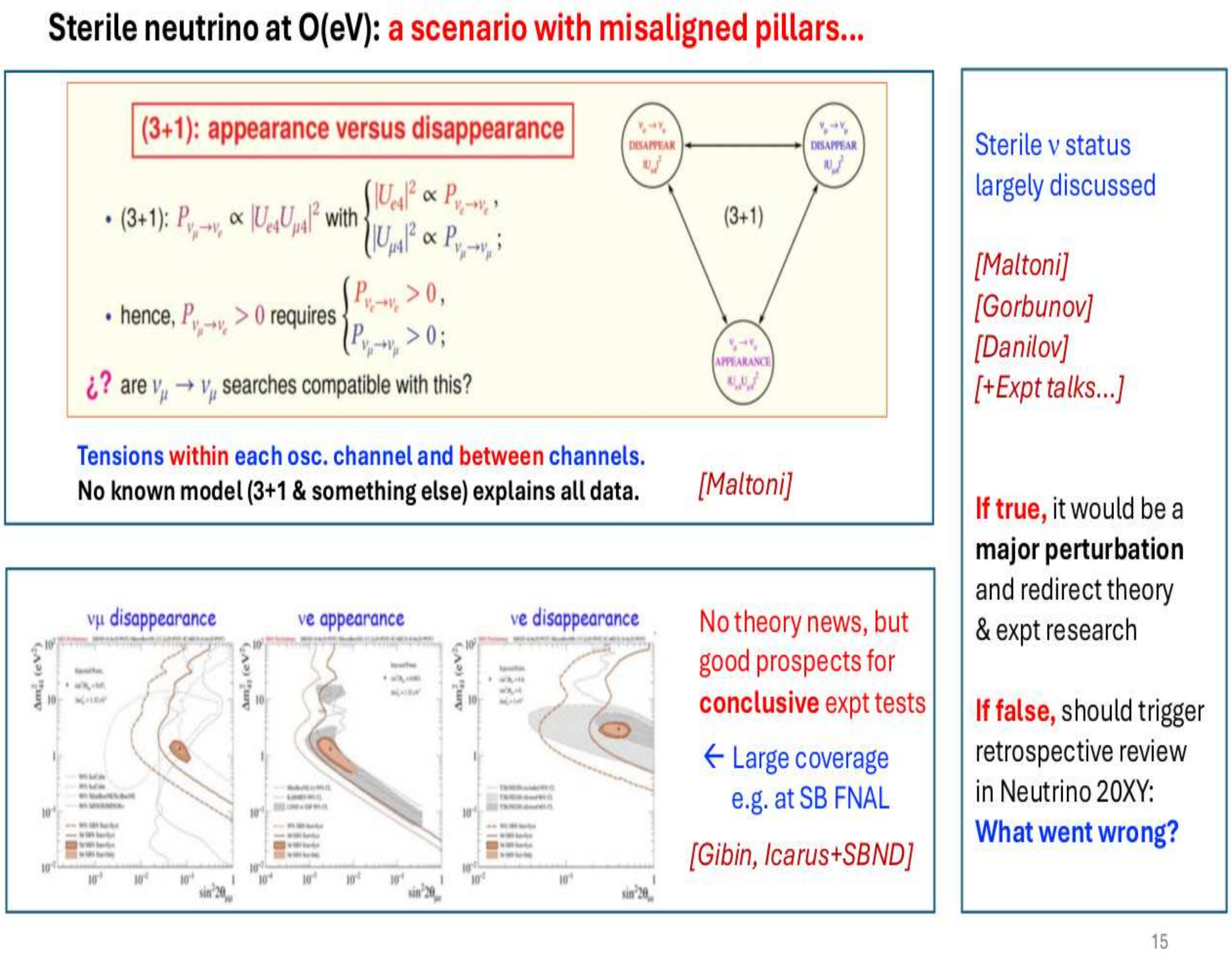
$M_{4,5,...} \sim (10^6 - 10^{14})$ GeV, high-scale seesaw models.

We can also have, in principle:

$m_4 \sim 3$ keV (DM), $M_{5,6} \sim (1 - 10^3)$ GeV (seesaw).

Results on $\nu_{e(\mu)} \rightarrow \nu_S$ oscillations presented at Neutrino 2024 - still inconclusive.

Talks by M. Maltoni (review), D. Gorbunov (review of positive hints), M. Danilov (review of negative hints), D. Lhuillier (reactor $\bar{\nu}_e$ flux) + talks by ICARUS, JESNS2, MicroBooNE, NEOS II collaborations.



Sterile neutrino at O(eV): a scenario with misaligned pillars...

(3+1): appearance versus disappearance

- (3+1): $P_{\nu_\mu\to\nu_e} \propto |U_{e4}U_{\mu4}|^2$ with $\begin{cases}|U_{e4}|^2 \propto P_{\nu_e\to\nu_e}\,, \\ |U_{\mu4}|^2 \propto P_{\nu_\mu\to\nu_\mu}\,;\end{cases}$
- hence, $P_{\nu_\mu\to\nu_e} > 0$ requires $\begin{cases}P_{\nu_e\to\nu_e} > 0\,, \\ P_{\nu_\mu\to\nu_\mu} > 0\,;\end{cases}$

¿? are $\nu_\mu \to \nu_\mu$ searches compatible with this?

Tensions within each osc. channel and between channels.
No known model (3+1 & something else) explains all data. *[Maltoni]*

No theory news, but good prospects for **conclusive** expt tests

← Large coverage e.g. at SB FNAL

[Gibin, Icarus+SBND]

Sterile ν status largely discussed

[Maltoni]
[Gorbunov]
[Danilov]
[+Expt talks...]

If true, it would be a **major perturbation** and redirect theory & expt research

If false, should trigger retrospective review in Neutrino 20XY: **What went wrong?**

E. Lisi, summary talk at Neutrino 2024

There are several indications of a new neutrino with $\Delta m^2 \sim 1\ \mathrm{eV}^2$, $\mathrm{Sin}^2 2\theta_{ee} \sim 0.1$, Must be Sterile since $\Gamma_Z \rightarrow N_\nu = 3$

1. LSND, MiniBooNE: ν_e ($\bar{\nu}_e$) appearance in ν_μ ($\bar{\nu}_\mu$) beams: > 6σ
   Not confirmed by MicroBooNE arXiv:2110.14054v2 but not excluded
   Increased sensitivity with NuMI beam but not sufficient
   FNAL SBNP and JSNS2 will clarify the situation

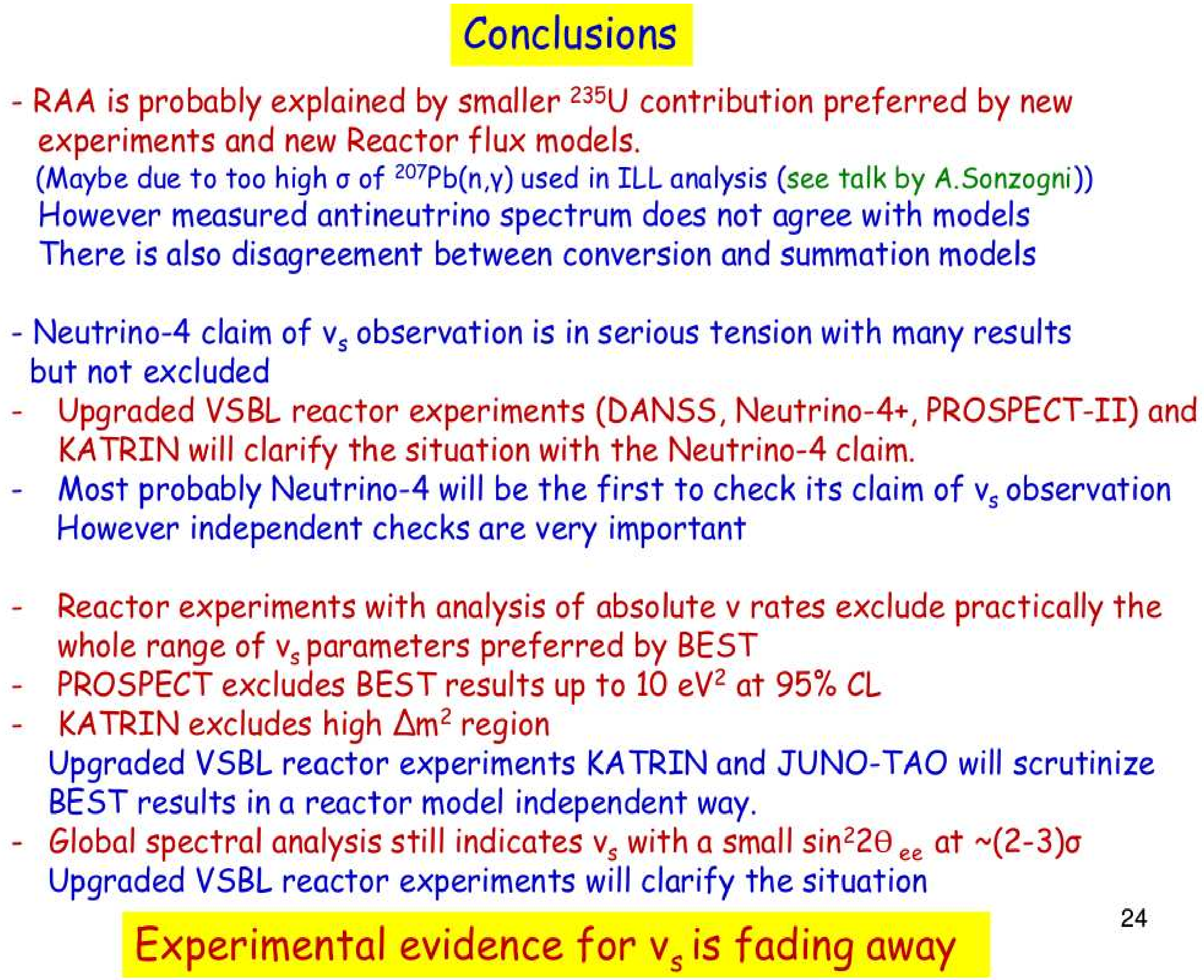
2. SAGE and GALEX ν_e deficit (GA) confirmed by BEST: > 5σ
   arXiv: 2109.11482, arXiv: 2201.07364 , PRL 128.232501
   GA looks solid, but ν_s explanation is practically excluded

3. Reactor ν_e deficit (RAA): ~ 3σ
   Explained by KI (arXiv:2103.01684), DayaBay, RENO, STEREO experiments
   and new reactor neutrino flux models?

4. Neutrino-4 claim of sterile neutrino observation
   $\Delta m^2 = 7.3 \pm 1.17\mathrm{eV}^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$ 2.7σ Phys.Rev.D 104, 032003 (2021)
   Serious tension with many experiments but not excluded

These are statistically strongest laboratory indications of physics BSM!

M. Danilov, talk at Neutrino 2024



Conclusions

- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments and new Reactor flux models.
  (Maybe due to too high σ of ^{207}Pb(n,γ) used in ILL analysis (see talk by A.Sonzogni))
  However measured antineutrino spectrum does not agree with models
  There is also disagreement between conversion and summation models

- Neutrino-4 claim of ν_s observation is in serious tension with many results but not excluded
- Upgraded VSBL reactor experiments (DANSS, Neutrino-4+, PROSPECT-II) and KATRIN will clarify the situation with the Neutrino-4 claim.
- Most probably Neutrino-4 will be the first to check its claim of ν_s observation
  However independent checks are very important

- Reactor experiments with analysis of absolute ν rates exclude practically the whole range of ν_s parameters preferred by BEST
- PROSPECT excludes BEST results up to 10 eV^2 at 95% CL
- KATRIN excludes high Δm^2 region
  Upgraded VSBL reactor experiments KATRIN and JUNO-TAO will scrutinize BEST results in a reactor model independent way.
- *Global spectral analysis still indicates ν_s with a small $\sin^2 2\theta_{ee}$ at ~(2-3)σ*
  Upgraded VSBL reactor experiments will clarify the situation

Experimental evidence for ν_s is fading away

M. Danilov, talk at Neutrino 2024

Three Neutrino Mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}} \ .$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- U - $n \times n$ unitary:

		2	3	4
	n	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6
CP-violating phases:				
• ν_j- Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• ν_j- Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$: 1 Dirac and
2 additional CP-violating phases, Majorana phases

S.M. Bilenky, J. Hosek, S.T.P., 1980

PMNS Matrix: Standard Parametrization

$$U = V\,P\,, \qquad P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix},$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CPV phase, $\delta = [0, 2\pi]$; CP inv.: $\delta = 0, \pi, 2\pi$;
- α_{21}, α_{31} - Majorana CPV phases; CP inv.: $\alpha_{21(31)} = k(k')\pi$, $k(k') = 0, 1, 2...$

S.M. Bilenky et al., 1980

- $\Delta m^2_{\odot} \equiv \Delta m^2_{21} \cong 7.34 \times 10^{-5}$ eV$^2 > 0$, $\sin^2\theta_{12} \cong 0.305$, $\cos 2\theta_{12} \gtrsim 0.306$ (3σ),
- $|\Delta m^2_{31(32)}| \cong 2.448\ (2.502) \times 10^{-3}$ eV^2, $\sin^2\theta_{23} \cong 0.545\ (0.551)$, NO (IO) ,
- θ_{13} - the CHOOZ angle: $\sin^2\theta_{13} = 0.0222\ (0.0223)$

F. Capozzi et al. (Bari Group), arXiv:2003.08511.

- $\text{sgn}(\Delta m^2_{\text{atm}}) = \text{sgn}(\Delta m^2_{31(32)})$ not determined

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{31} > 0, \quad \text{normal mass ordering (NO)}$$

$$\Delta m^2_{\text{atm}} \equiv \Delta m^2_{32} < 0, \quad \text{inverted mass ordering (IO)}$$

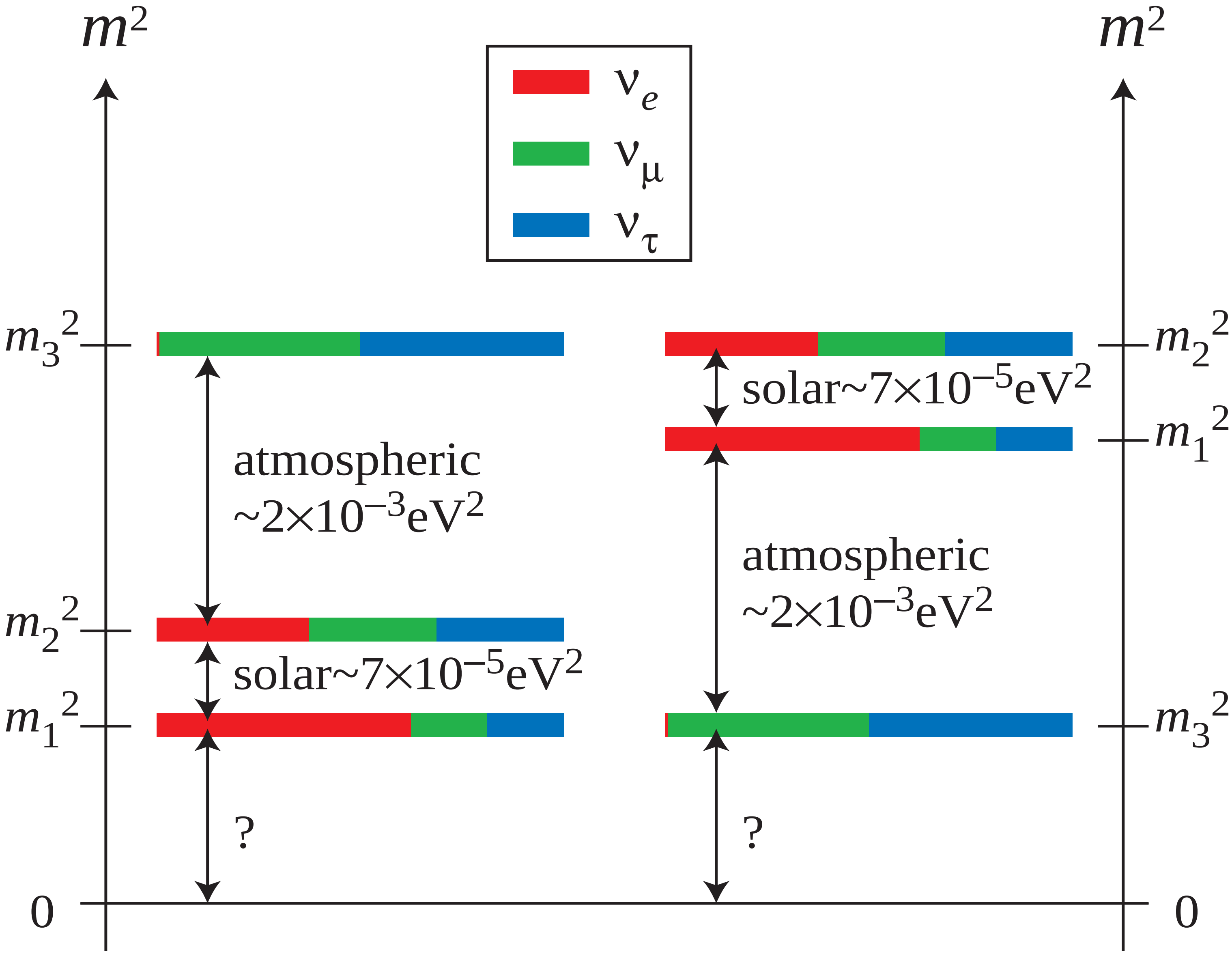
Convention: $m_1 < m_2 < m_3$ - NO, $m_3 < m_1 < m_2$ - IO

$$m_1 \ll m_2 < m_3, \qquad \text{NH},$$

$$m_3 \ll m_1 < m_2, \qquad \text{IH},$$

$$m_1 \cong m_2 \cong m_3, \;\; m^2_{1,2,3} >> |\Delta m^2_{31(32)}|, \;\; \text{QD}; \;\; m_j \gtrsim 0.10 \text{ eV}.$$

- $m_2 = \sqrt{m_1^2 + \Delta m^2_{21}}$, $m_3 = \sqrt{m_1^2 + \Delta m^2_{31}}$ - NO;
- $m_1 = \sqrt{m_3^2 + \Delta m^2_{23} - \Delta m^2_{21}}$, $m_2 = \sqrt{m_3^2 + \Delta m^2_{23}}$ - IO;


m^2
m^2
🟥 ν_e
🟩 ν_μ
🟦 ν_τ
m_3^2
atmospheric
$\sim 2\times10^{-3}\mathrm{eV}^2$
m_2^2
solar$\sim 7\times10^{-5}\mathrm{eV}^2$
m_1^2
?
0
m_2^2
solar$\sim 7\times10^{-5}\mathrm{eV}^2$
m_1^2
atmospheric
$\sim 2\times10^{-3}\mathrm{eV}^2$
m_3^2
?
0

- **Dirac phase** δ: $\nu_l \leftrightarrow \nu_{l'}, \bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}, \; l \neq l'$; $A^{(l,l')}_{\rm CP} \propto J_{\rm CP} \propto \sin\theta_{13} \sin\delta$:

3ν—mixing: P.I. Krastev, S.T.P., 1988

$$A^{(l,l')}_{\rm CP} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) \;, \quad l \neq l' = e, \mu, \tau$$

$$A^{(l,l')}_{\rm T} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\nu_{l'} \rightarrow \nu_l), \; l \neq l'$$

$$A^{(e,\mu)}_{\rm CP(T)} = A^{(\mu,\tau)}_{\rm CP(T)} = -A^{(e,\tau)}_{\rm CP(T)}$$

In vacuum: $A^{(e,\mu)}_{\mathrm{CP(T)}} = 4\, J_{\mathrm{CP}} F^{vac}_{osc} \quad (A^{(e,\mu)}_{\mathrm{CP(T)}} = A^{(\mu,\tau)}_{\mathrm{CP(T)}} = -\, A^{(e,\tau)}_{\mathrm{CP(T)}})$

$$J_{CP} = \mathrm{Im}\left\{U_{e1}\, U_{\mu 2}\, U^{*}_{e2}\, U^{*}_{\mu 1}\right\} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

$$F^{vac}_{osc} = \sin(\frac{\Delta m^2_{21}}{2E} L) + \sin(\frac{\Delta m^2_{32}}{2E} L) + \sin(\frac{\Delta m^2_{13}}{2E} L)$$

P.I. Krastev, S.T.P., 1988

In matter: **Matter effects violate**

$$\mathrm{CP:} \qquad P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$$

$$\mathrm{CPT:} \qquad P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_{l'} \rightarrow \bar{\nu}_l)$$

P. Langacker et al., 1987

Can conserve the T-invariance (constant density or density profile symmetric relative to the middle point, e.g., Earth)

$$P(\nu_l \rightarrow \nu_{l'}) = P(\nu_{l'} \rightarrow \nu_l),\ l \neq l'$$

In matter with constant density (T2K, NOνA, T2HK, DUNE):

$$\mathrm{J}^{\mathrm{mat}}_{\mathrm{CP}} = \mathrm{J}^{\mathrm{vac}}_{\mathrm{CP}}\ \mathrm{R}_{\mathrm{CP}}, \quad \mathrm{A}^{(\mathrm{e},\mu)}_{\mathrm{T}} = \mathrm{J}^{\mathrm{mat}}_{\mathrm{CP}} \mathrm{F}^{\mathrm{mat}}_{\mathrm{osc}}$$

R_{CP}- real, does not depend on θ_{23} and δ; $|R_{CP}| \lesssim 2.5$

P.I. Krastev, S.T.P., 1988

2018: $R_{CP} > 0$, $R_{CP} \leq 1.2$; **numerically** R_{CP}**=Naumov-HS factor (from 1991).**

S.T.P., Y.-L. Zhou, 1806.09112

Current data: $|J_{CP}| \lesssim$ 0.040 (can be relatively large!); b.f.v. with $\delta = 3\pi/2$: $J_{CP} \cong -0.035$.

- **Majorana phases** α_{21}, α_{31}:
  - $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$ not sensitive;

S.M. Bilenky, J. Hosek, S.T.P.,1980;
P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

  - $|<m>|$ in $(\beta\beta)_{0\nu}$−decay depends on α_{21}, α_{31};
  - $\Gamma(\mu \rightarrow e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
  - BAU, leptogenesis scenario: $\delta, \alpha_{21,31}$!

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	7.21 − 7.52	7.06 − 7.71	6.93 − 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.90 − 3.16	2.77 − 3.30	2.63 − 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.485	2.454 − 2.508	2.427 − 2.537	2.401 − 2.565	1.1
	IO	2.455	2.430 − 2.485	2.403 − 2.513	2.376 − 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 − 2.30	2.11 − 2.37	2.04 − 2.44	3.0
	IO	2.23	2.17 − 2.29	2.10 − 2.38	2.03 − 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.40 − 4.73	4.27 − 5.81	**4.16 − 5.99**	6.7
	IO	5.69	5.48 − 5.82	4.30 − 5.94	**4.17 − 6.06**	5.5
δ/π	NO	1.24	1.11 − 1.42	0.94 − 1.74	0.77 − 1.97	16
	IO	1.52	1.37 − 1.66	1.22 − 1.78	**1.07 − 1.90**	9
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+6.5 (2.5σ)				

Global 3ν analysis of oscillation parameters: best-fit values and allowed ranges at $N_\sigma = 1$, 2 and 3, for either NO or IO, including all data. The latter column shows the formal "1σ fractional accuracy" for each parameter, defined as 1/6 of the 3σ range, divided by the best-fit value and expressed in percent. We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that $\delta \in [0, 2\pi]$ (cyclic). The last row reports the difference between the χ^2 minima in IO and NO.

F. Capozzi et al. (Bari Group), arXiv:2107.00532.

θ_{12}, θ_{23} - **large**, θ_{13} - **small (very different from the quark mixing angles).**
$\sin^2\theta_{23}$ - **relatively large uncertainty.**

$$\Delta m^2_{21}/|\Delta m^2_{31}| \cong 1/30.$$

2020 global analyses after Nu2020: combine latest T2K and NOνA data.

Results on CPV due to δ and NO vs IO spectrum - inconclusive.

K.J. Kelly, P.A. Machado, S.J. Parke, Y.F. Perez Gonzalez and R. Zukanovich-Funchal,
"Back to (Mass-)Square(d) One: The Neutrino Mass Ordering in Light of Recent Data," **arXiv:2007.08526 [hep-ph].**

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou,
"The fate of hints: updated global analysis of three-flavor neutrino oscillations," **arXiv:2007.14792 [hep-ph].**

Result on CPV, b.f.v.: $\delta = 197^\circ$, NO; $\delta = 282^\circ$, IO.

At 3σ: δ is found to lie in $[120^\circ, 369^\circ]$ ($[193^\circ, 352^\circ]$), NO (IO).

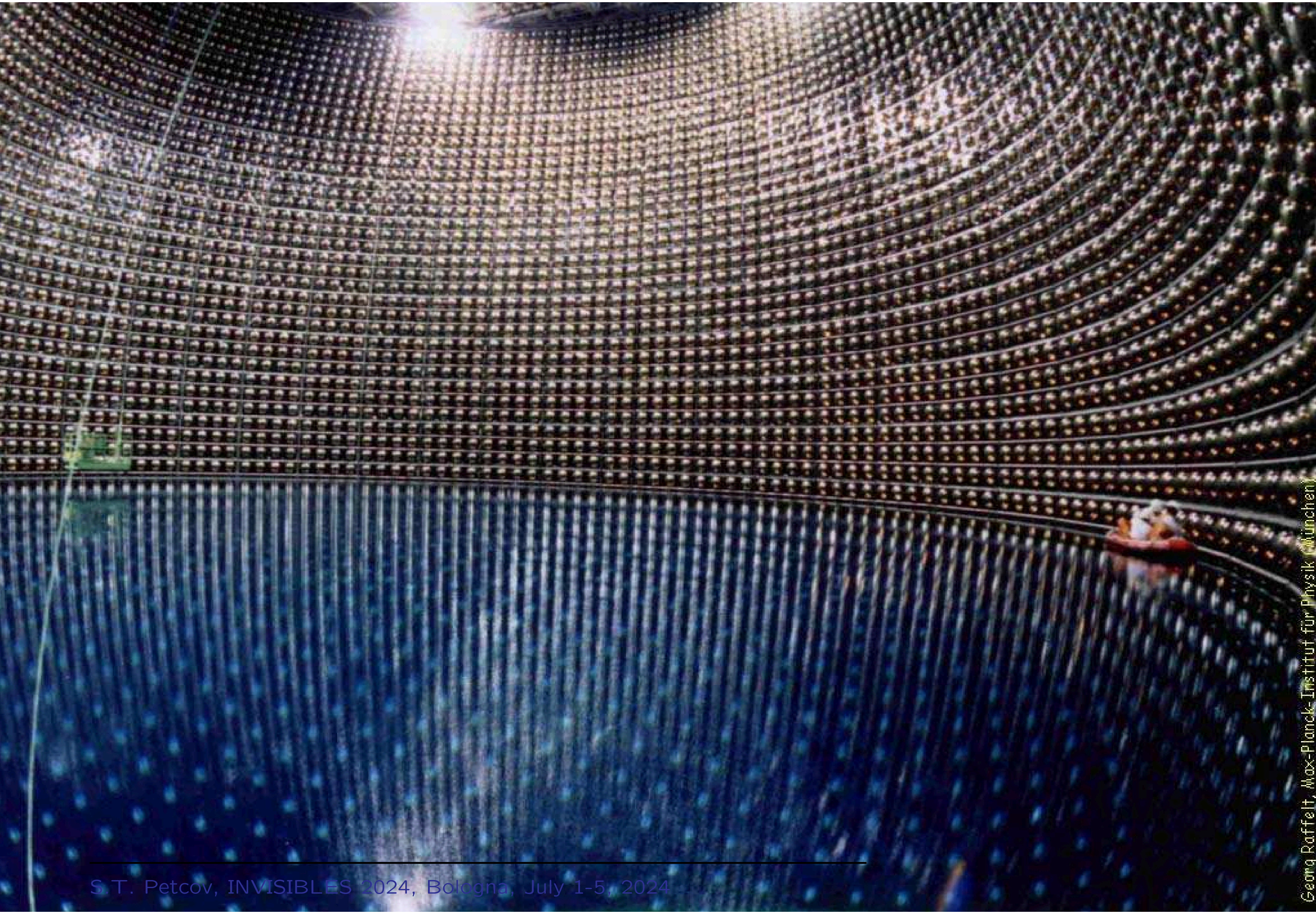
IO: CPV due to δ at 3σ.

IO disfavored at 1.6σ with respect to NO (2.7σ including SuperK ν_{atm} data).

T2K and NOνA presented new results at Neutrino 2024 (June 17-22, Milano)

T2K: Tokai - Super Kamiokande

NOνA: Fermilab - site in Minnesota (810 km)


Georg Raffelt, Max-Planck-Institut für Physik (München)

T2K: Tokai - Super Kamiokande; off-axis ν beam, $E = 0.6$ GeV, $L \cong 295$ km, 50 kt water Cherenkov detector.

NOνA: Fermilab - site in Minnesota; off-axis ν beam, $E = 2$ GeV, $L \cong 810$ km, 14 kt liquid scintillator detector.

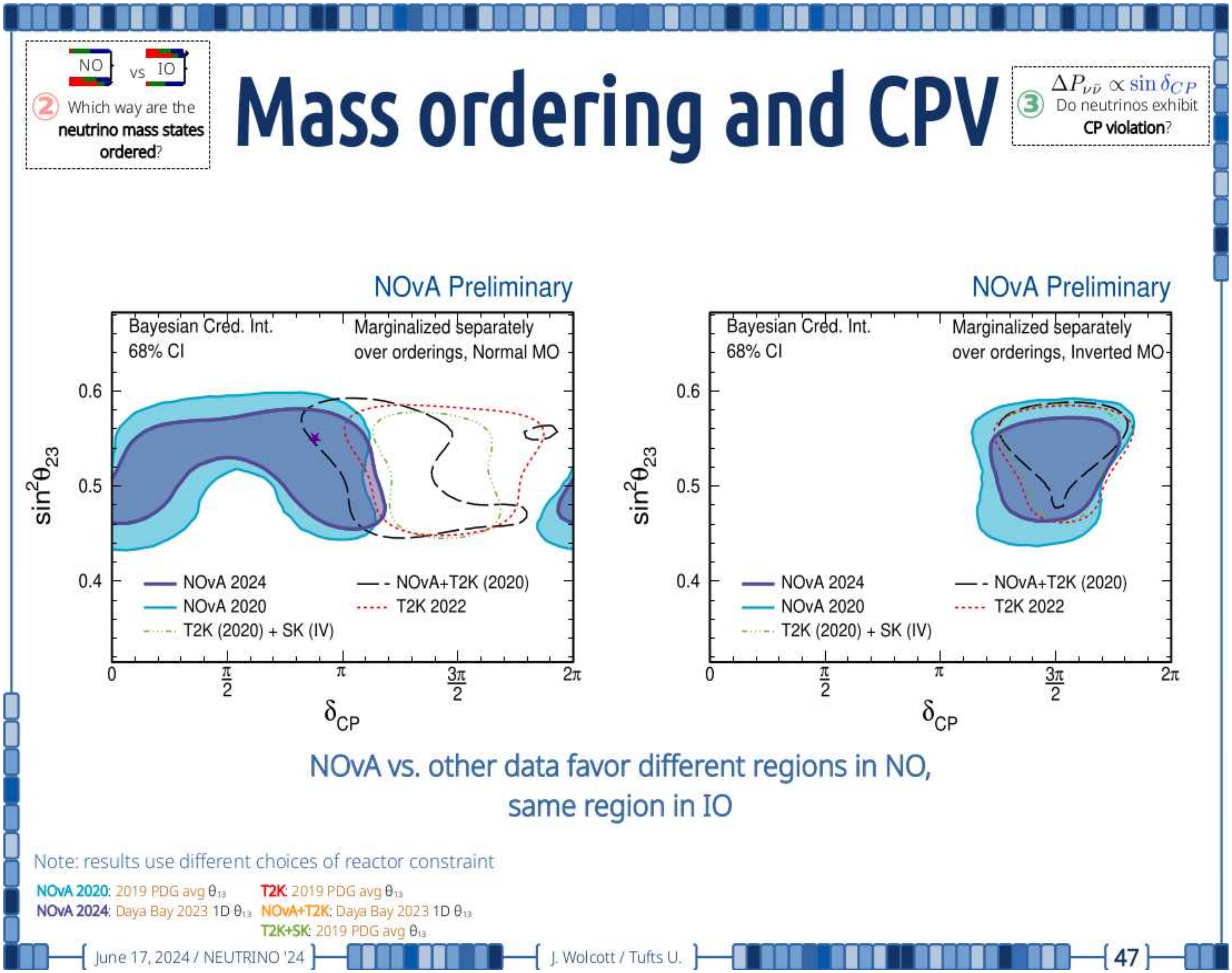
SK experiment (50 kt water Cerenkov) studying atmospheric ν_μ, $\tilde{\nu}_\mu$, ν_e, $\tilde{\nu}_e$ ($E \cong 0.1 \div 100$ GeV), and solar ν_e ($E \cong 5 \div 14$ MeV) oscillations.

T2K: 10% more statistics in the ν_μ mode with repect to that used for 2020 results (19.7 (16.3) $\times 10^{20}$ pot in ν_μ ($\bar{\nu}_\mu$) mode).
Joint analysis of T2K and SK atmospheric ν data.
T2K has sensitivity to δ_{CP}, but weak sensitivity to MO. SK has better sensitivity to MO (IO disfavoted at 1.4σ) but not on δ_{CP}.
Exclude CP conserving value of J_{CP} invariant at between 1.9σ and 2σ C.L.
"Slight preference for NO and upper octant for θ_{23}, but none of them is significant."
No significant change of the results from 2022 (2020).

C. Gigante and M. Posiadala-Zezula, talks at Neutrino 2024

NOνA (10 y of data): 384 ν_μ (11.3 bckg) and 106 $\bar{\nu}_\mu$ (1.7 bckg) candidates; 181 ν_e (61-63 bckg) and 32 $\bar{\nu}_e$ (11-13 bckg) candidates.
T2k and NOνA performed also a joint analysis of their data.

J. Wolcott, talk at Neutrino 2024; the next 4 figures are from this talk.



Mass ordering and CPV

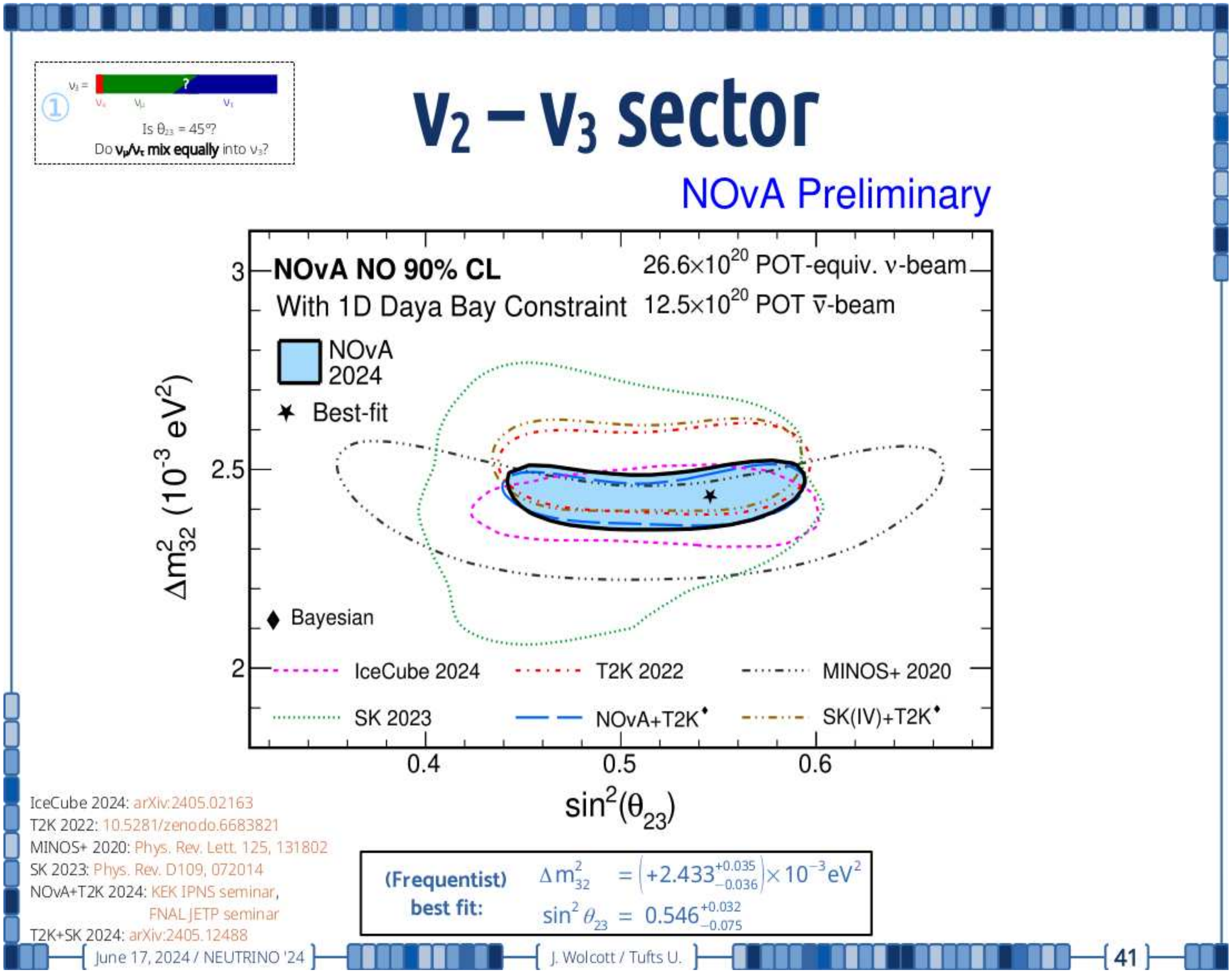
② Which way are the **neutrino mass states ordered**?

$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$
③ Do neutrinos exhibit **CP violation**?

NOvA vs. other data favor different regions in NO, same region in IO

Note: results use different choices of reactor constraint

NOvA 2020: 2019 PDG avg θ_{13}
NOvA 2024: Daya Bay 2023 1D θ_{13}
T2K: 2019 PDG avg θ_{13}
NOvA+T2K: Daya Bay 2023 1D θ_{13}
T2K+SK: 2019 PDG avg θ_{13}



①

Is $\theta_{23} = 45°$?

Do **ν_μ/ν_τ mix equally** into ν_3?

$\nu_2 - \nu_3$ sector

NOvA Preliminary

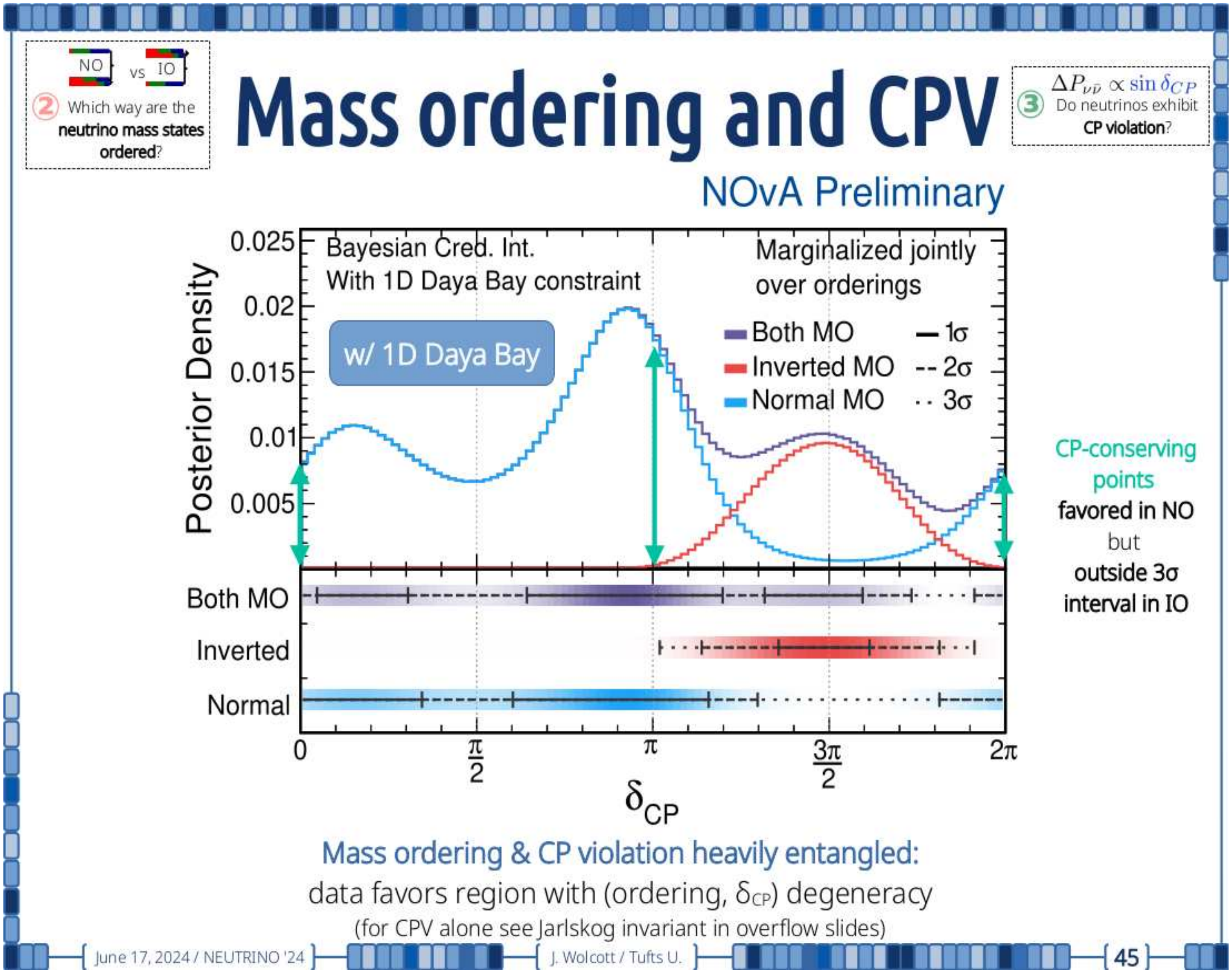
IceCube 2024: arXiv:2405.02163
T2K 2022: 10.5281/zenodo.6683821
MINOS+ 2020: Phys. Rev. Lett. 125, 131802
SK 2023: Phys. Rev. D109, 072014
NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar
T2K+SK 2024: arXiv:2405.12488

(Frequentist) best fit:

$$\Delta m^2_{32} = \left(+2.433^{+0.035}_{-0.036}\right)\times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.546^{+0.032}_{-0.075}$$

June 17, 2024 / NEUTRINO '24 | J. Wolcott / Tufts U. | 41



NO vs IO

② Which way are the **neutrino mass states ordered**?

Mass ordering and CPV

$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$

③ Do neutrinos exhibit **CP violation**?

NOvA Preliminary

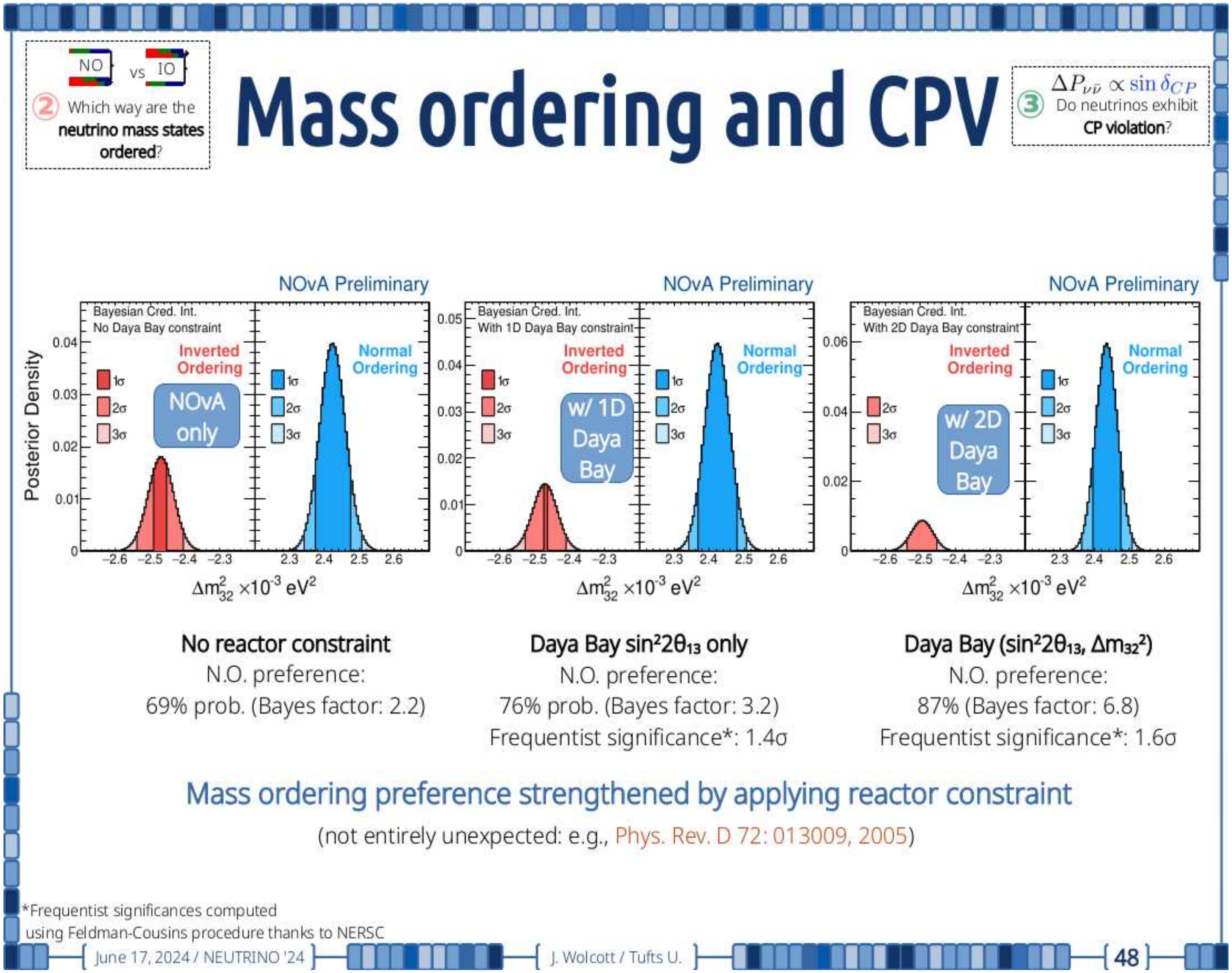
CP-conserving points **favored in NO** but **outside 3σ interval in IO**

Mass ordering & CP violation heavily entangled:

data favors region with (ordering, δ_{CP}) degeneracy

(for CPV alone see Jarlskog invariant in overflow slides)

June 17, 2024 / NEUTRINO '24 — J. Wolcott / Tufts U. — 45



② Which way are the **neutrino mass states ordered**?

Mass ordering and CPV

$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$

③ Do neutrinos exhibit **CP violation**?

No reactor constraint
N.O. preference:
69% prob. (Bayes factor: 2.2)

Daya Bay $\sin^2 2\theta_{13}$ only
N.O. preference:
76% prob. (Bayes factor: 3.2)
Frequentist significance*: 1.4σ

Daya Bay ($\sin^2 2\theta_{13}$, Δm^2_{32})
N.O. preference:
87% (Bayes factor: 6.8)
Frequentist significance*: 1.6σ

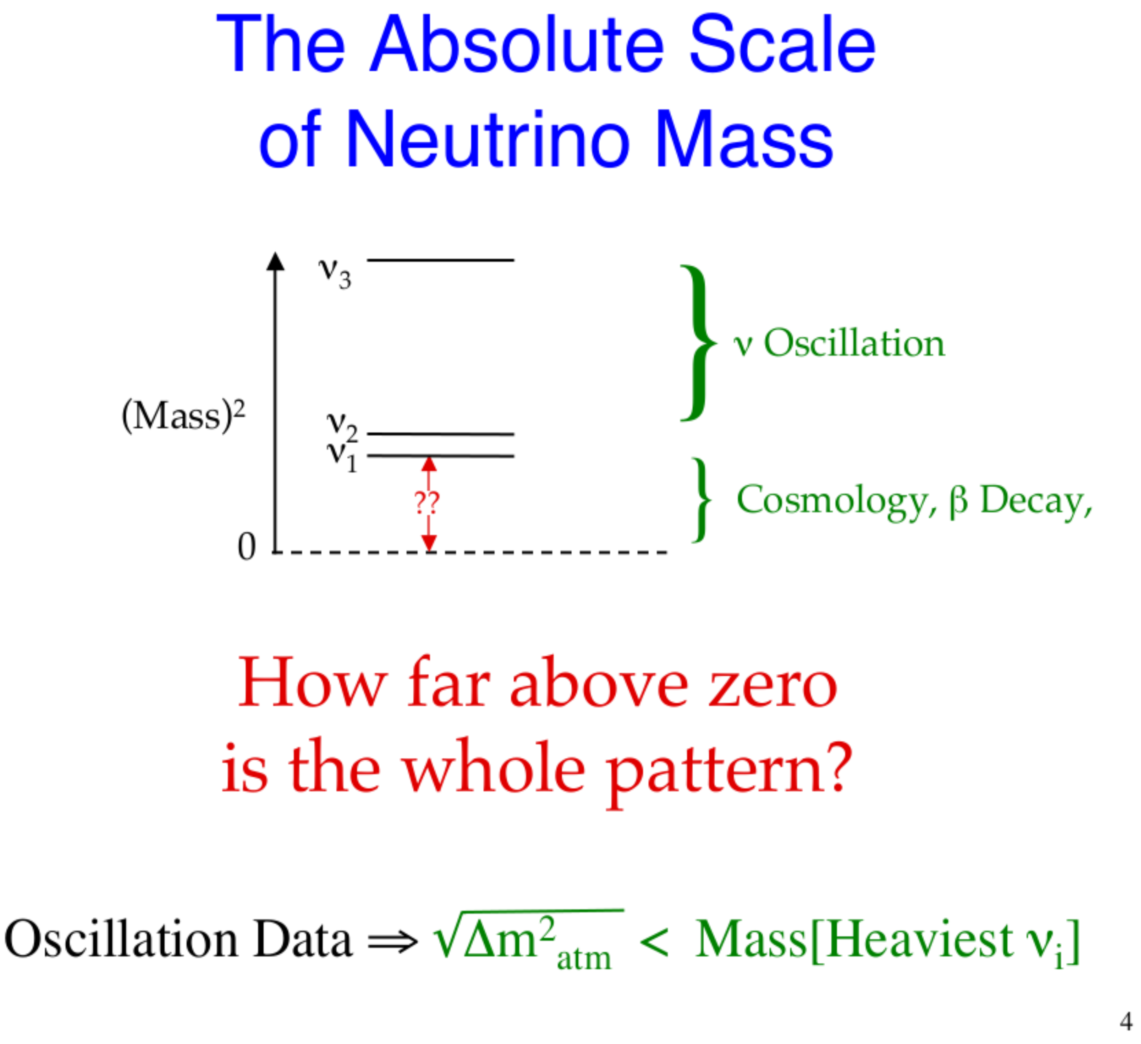
Mass ordering preference strengthened by applying reactor constraint

(not entirely unexpected: e.g., Phys. Rev. D 72: 013009, 2005)

*Frequentist significances computed using Feldman-Cousins procedure thanks to NERSC

June 17, 2024 / NEUTRINO '24 J. Wolcott / Tufts U. 48

Absolute Neutrino Mass Scale



The Absolute Scale of Neutrino Mass

How far above zero is the whole pattern?

$$\text{Oscillation Data} \Rightarrow \sqrt{\Delta m^2_{\text{atm}}} < \text{Mass}[\text{Heaviest } \nu_i]$$

4

Due to B. Kayser

Absolute Neutrino Mass Measurements

Experiments on e^--spectrum in $^3\mathrm{H} \to ^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$

(super-allowed $^3\mathrm{H} \to ^3\mathrm{He}$ transition, NME - constant, $E_0 \simeq 18574.3 \pm 1.7$ eV, half-life 12.3 years)

$$m_{\bar{\nu}_e} < 2.2 \text{ eV} \qquad (95\%\ \text{C.L.})\ \text{Troitzk, Mainz.}$$

We have $m_{\bar{\nu}_e} \cong m_{1,2,3}$ in the case of QD spectrum.

The KATRIN experiment (11/06/2018) is planned to reach sensitivity

$$\textbf{KATRIN:} \quad m_{\bar{\nu}_e} \sim \textbf{0.2 eV}$$

i.e., it will probe the region of the QD spectrum.

KATRIN data (2022):

$$m_{\bar{\nu}_e} < 0.81 \text{ eV} \qquad (90\%\ \text{C.L.})$$

Latest KATRIN data (2024):

$$m_{\bar{\nu}_e} < 0.45 \text{ eV} \qquad (90\%\ \text{C.L.})$$

E. Lokhov et al., talk at Neutrino 2024 (June 17-22, 2024, Milano)

$$\frac{d\,\Gamma({}^3\mathrm{H} \rightarrow {}^3\,\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}}{d\,\mathbf{E_e}} = \sum_\mathrm{i} |\mathrm{U_{ei}}|^2 \;\; \frac{d\,\Gamma(\mathrm{m_i})}{d\,\mathrm{E_e}}\,,$$

$$\frac{d\,\Gamma(\mathrm{m_i})}{d\,\mathrm{E_e}} = \mathrm{C\,p_e\,(E_e + m_e)\,(E_0 - E_e)}\sqrt{(E_0 - E_e)^2 - m_i^2}\,\mathrm{F(E_e)}\,\theta(\mathrm{E_0 - E_e - m_i})\,.$$

Here $E_e \leq E_0 - m_i$ is the kinetic energy of the electron, E_0 is the energy released in the decay, p_e is the electron momentum, m_e is the mass of the electron, $F(E_e)$ is the Fermi function which takes into account the Coulomb interaction of the final state particles, and C is a constant. $(E_0 - E_e)$ is the neutrino energy and $p_i = \sqrt{(E_0 - E_e)^2 - m_i^2}$ is the momentum of neutrino with mass m_i.

Usually

$$\mathrm{m}_\beta \equiv \mathrm{m}_{\bar{\nu}_\mathrm{e}} = \sqrt{\sum_i |U_{ei}|^2 \; m_i^2} \;\; (\simeq \mathrm{m}_{1,2,3}, \quad \mathrm{QD\;\; spectrum})$$

is considered as the neutrino mass related observable in β-decay experiments.

Future plans ($\gtrsim$ 2027): KATRIN++, 50 g of ^{3}H (use of atomic ^{3}H); goal: reach sensitivity to $m_\beta < 0.04$ eV.

In development: PROJECT 8 (CRES technique, B. Monreal, J. A. Formaggio, Phys.Rev.D 80(2009) 051301):

$$2\pi\, f(E_\beta) = \frac{eB}{E_\beta + m_e};\ \textbf{Energy resolution:}\ \frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$

CRES technique demonstrated by Project 8 for e^- magnetically trapped inside a wave guide; best E-resolution $\Delta E_{FWHM} = 1.7$ eV at 18 keV.
Limit obtained $m_\beta < 152$ eV; goal: $m_\beta < 0.04$ eV.

In development: HOLMES and ECHo e^- capture calorimetric experiments,
$^{163}Ho \rightarrow ^{163}Dy[H_i] + \nu_e$, $^{163}Dy[H_i] \rightarrow ^{163}Dy + E_c$,
H_i =M1, M2, N1, N2, O1, O2, P1; EC from shell $\geq$ M1.
$Q = 2863.2 \pm 0.6$ eV; $\tau_{1/2} \cong 4570$ years; 2×10^{11} ^{163}Ho nuclei $\leftrightarrow$ 1 Bq.
End-point rate and m_β sensitivity depend on $Q - E_b(M1)$.
Current limits $m_{\nu_e} < 28$ eV (HOLMES), 19 eV (ECHo) (90% C.L.)

A. Nicciotti, talk at Neutrino 2024

Mass and Hierarchy from Cosmology

Cosmological and astrophysical data on $\sum_j m_j$ - the current most stringent constraints (Planck CMB + BAO data + lensing data + the Hubble constant datum [H0(R19)] + ΛCDM (6 parameter) model + assuming 3 light massive neutrinos):

$$\sum_j m_j \equiv \Sigma < 0.12 \text{ eV} \quad (95\% \text{ C.L.})$$

The upper limit depends on the data set and assumptions used. According to F. Capozzi et al., arXiv:2107.00532, it reads:

$$\sum_j m_j \equiv \Sigma < 0.12 - 0.77 \text{ eV} \quad (95\% \text{ C.L.})$$

where 0.77 eV corresponds to the data set used which leads to one of the most conservative result (Λ CDM+Σ+ A_{lens}+Planck+lensing data).

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP, Planck and currently taking data EUCLID experiments might allow to determine

$$\sum_j m_j : \qquad \delta \cong (0.01 - 0.04) \text{ eV}.$$

Similar sensitivity ($\delta \cong 0.03$ eV) is planned to be reached in CMB-S4 experiment, and/or combining data from DESI and CMB-S4 experiments ($\delta \cong 0.012 - 0.020$ eV).

Talks by M. Archidiacono and W. Elbers at Neutrino 2024, June 17-22, Milano

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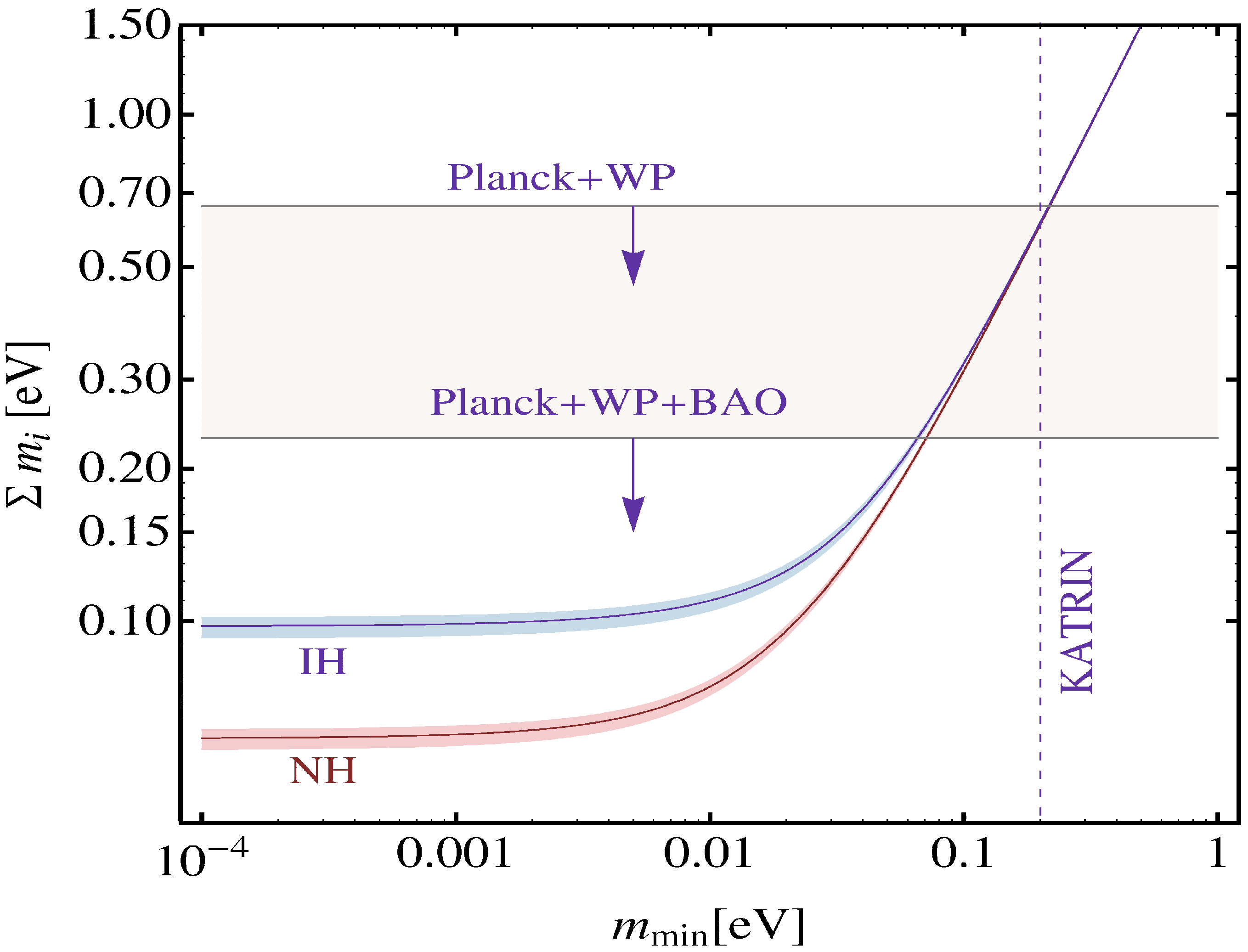
Mass and Hierarchy from Cosmology



NH ($m_1 \cong 0$): $\sum_j m_j \cong m_2 + m_3 = \sqrt{\Delta m^2_{21}} + \sqrt{\Delta m^2_{31}} \cong 0.061$ **eV** (3σ **max**);

IH ($m_3 \cong 0$): $\sum_j m_j \cong m_1 + m_2 \cong 2\sqrt{\Delta m^2_{23}} \cong 0.098$ **eV** (3σ **min**); $\sum_j m_j \gtrsim 0.098$ **eV.**

Determining the Nature of Massive Neutrinos.

Determining the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos is one of the most challenging and pressing problems in present day elementary particle physics.

Establishing that the total lepton charge $L = L_e + L_\mu + L_\tau$ is not conserved in particle interactions by observing the $(\beta\beta)_{0\nu}-$decay would be a fundamental discovery (similar to establishing baryon number nonconservation (e.g., by observing proton decay)).

Establishing that ν_j are Majorana particles would be of fundamental importance, as important as the discovery of $\nu-$ oscillations, and would have far reaching implications.

ν_l oscillations are not sensitive to the nature of ν_j.

The Majorana nature of ν_j can manifest itself in the existence of $\Delta L = \pm 2$ processes:

$$K^+ \rightarrow \pi^- + \mu^+ + \mu^+$$
$$\mu^- + \ (\mathsf{A,Z}) \rightarrow \mu^+ + \ (\mathsf{A,Z-2})$$

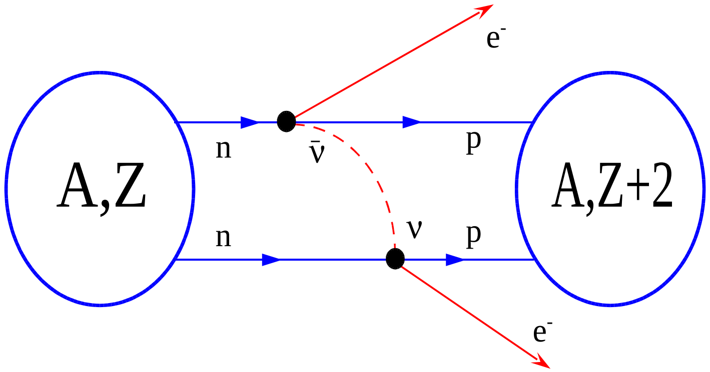
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$-decay

$$(\mathsf{A,Z}) \rightarrow (\mathsf{A,Z+2}) + e^- + e^-$$

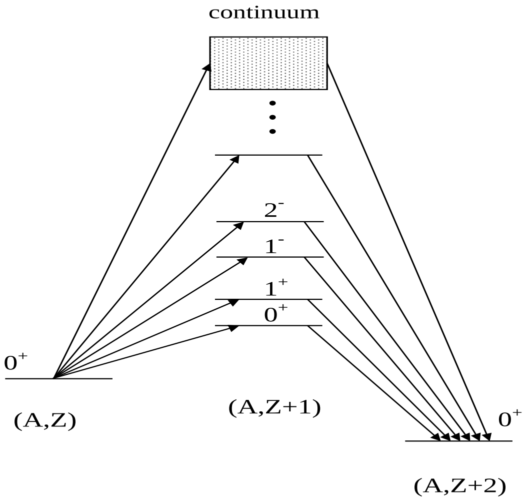
of even-even nuclei, ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd.

$2n$ from (A,Z) exchange a virtual Majorana ν_j (via the CC weak interaction) and transform into $2p$ of (A,Z+2) and two free e^-.

Nuclear $0\nu\beta\beta$-decay



strong in-medium modification of the basic process
$dd \to ue^-e^-(\overline{\nu}_e\overline{\nu}_e)$



virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

Figure due to V. Rodin

$(\beta\beta)_{0\nu}-$Decay Experiments:

- $L-$**nonconservation, Majorana nature of** ν_j**.**
- **Type of** $\nu-$**mass spectrum (NH, IH, QD)**
- **Absolute neutrino mass scale**

^{3}H β-**decay, cosmology:** min(m_i) **(QD, IH)**

- **CPV due to Majorana CPV phases**

$A(\beta\beta)_{0\nu} \sim G_F^2 {<}m{>}$ **M(A,Z),** **M(A,Z) - NME,**

$$|{<}m{>}| = |\textstyle\sum_k U_{ek}^2\, m_k| = \left|m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2\ e^{i\alpha_{21}} + m_3 |U_{e3}|^2\ e^{i\alpha_{31}}\right|$$

$$= \left|m_1\ c_{12}^2\ c_{13}^2 + m_2\ s_{12}^2\ c_{13}^2\ e^{i\alpha_{21}} + m_3\ s_{13}^2\ e^{i\alpha_{31}}\right|,\ \ \theta_{12} \equiv \theta_\odot,\ \theta_{13}\text{- CHOOZ}$$

α_{21}, α_{31} $((\alpha_{31} - 2\delta) \to \alpha_{31})$ **- the two Majorana CPVP of the PMNS matrix.**

$$|{<}m{>}| = |{<}m{>}|\ (\min(m_j), \alpha_{21,31}, MO)$$

CP-invariance: $\alpha_{21} = 0, \pm\pi$, $\alpha_{31} = 0, \pm\pi$;

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

relative CP-parities of ν_1 and ν_2, and of ν_1 and ν_3 .

L. Wolfenstein, 1981;
S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;
B. Kayser, 1984.

$A(\beta\beta)_{0\nu} \sim G_F^2 < m >$ M(A,Z), M(A,Z) - NME,

$$|<m>| \cong \left|\sqrt{\Delta m^2_{21}}\sin^2\theta_{12}e^{i\alpha_{21}} + \sqrt{\Delta m^2_{31}}\sin^2\theta_{13}e^{i\alpha_{31}}\right| , \; m_1 \ll m_2 \ll m_3 \text{ (NH)},$$

$$|<m>| \cong \sqrt{m_3^2 + \Delta m^2_{23}}\left|\cos^2\theta_{12} + e^{i\alpha_{21}}\ \sin^2\theta_{12}\right| , \; m_3 < (\ll) m_1 < m_2 \text{ (IH)},$$

$$|<m>| \cong m\left|\cos^2\theta_{12} + e^{i\alpha_{21}}\ \sin^2\theta_{12} + \sin^2\theta_{13}\ e^{i\alpha_{31}}\right| ,$$
$m_{1,2,3} \cong m \gtrsim 0.10$ eV (QD).

CP-invariance: $\alpha_{21} = 0, \pm\pi, \; \alpha_{31} = 0, \pm\pi;$

$$1.3 \times 10^{-3} \lesssim |<m>| \lesssim 5.0 \times 10^{-3} \text{ eV, NH } (3\sigma);$$

$$\sqrt{\Delta m^2_{23}}\cos 2\theta_{12} \cong 0.015 \text{ eV} \lesssim |<m>| \lesssim \sqrt{\Delta m^2_{23}} \cong 0.051 \text{ eV, IH } (3\sigma);$$

$$m\cos 2\theta_{12} \lesssim |<m>| \lesssim m, \; m \gtrsim 0.03 \text{ eV, QD } (3\sigma).$$

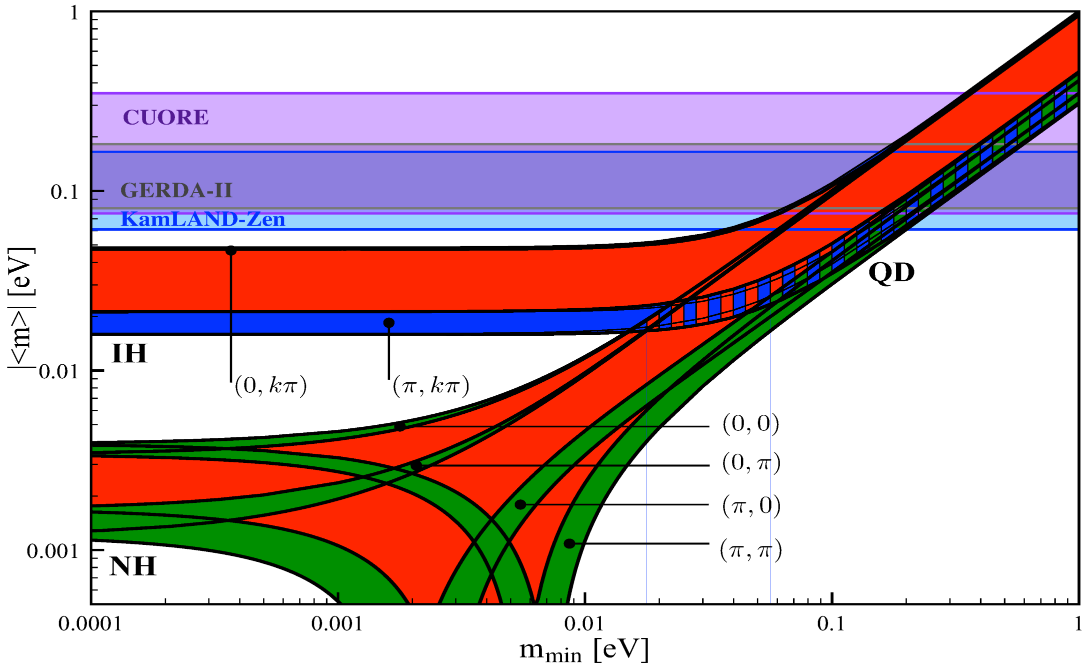
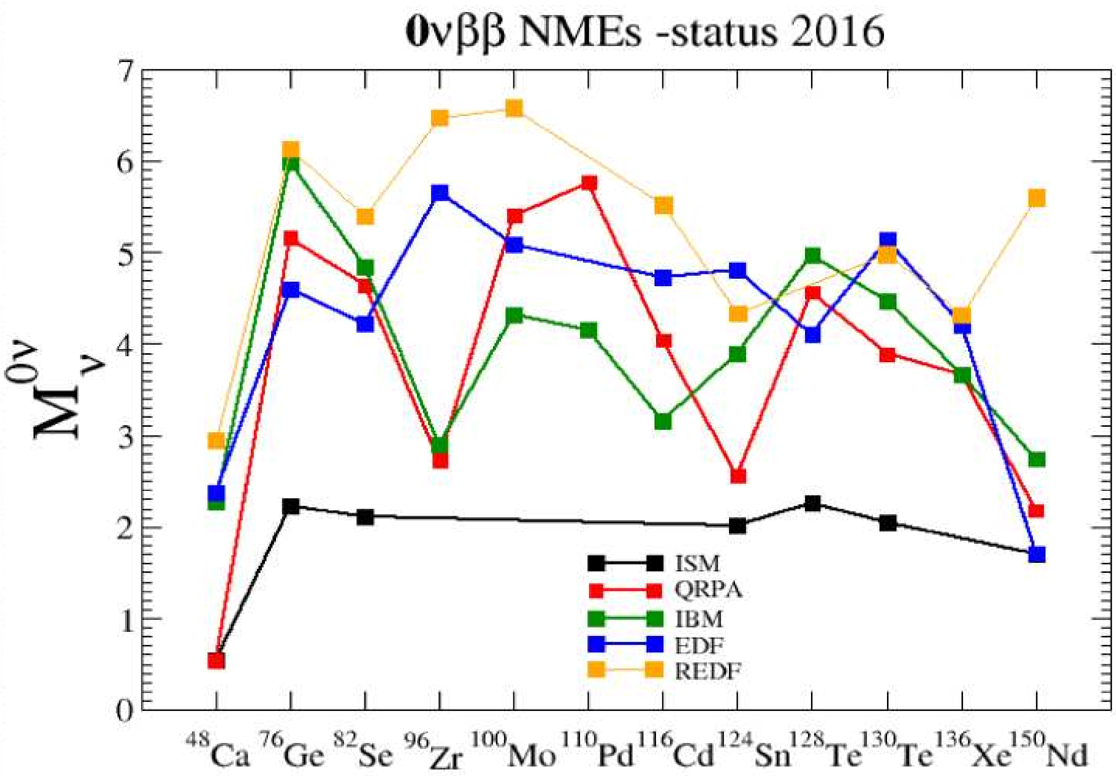


Figure by S. Pascoli, 2020

The figure is obtained using the b.f.v. and the 1σ ranges of allowed values of Δm^2_{21}, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$ and $|\Delta m^2_{31(32)}|$ from F. Capozzi et al., arXiv:2003.08511, propagated to $<m>$ and then taking a 2σ uncertainty. α_{21} and $(\alpha_{31} - 2\delta)$ are varied in the interval [0,2π]. The predictions for the NH, IH and QD spectra as well as the CUORE, GERDA-II and KamLAND-Zen limits are indicated. The black lines determine the ranges of values of $|<m>|$ for the CP conserving values $(\alpha_{21}, \alpha_{31} - 2\delta) = (0,0)$, $(0,\pi)$, $(\pi,0)$ and (π,π). The red regions correspond to α_{21} and/or $(\alpha_{31} - 2\delta)$ having a CP violating value. (Update by S. Pascoli of a figure from S.Pascoli, STP, Phys. Rev. D77 (2008) 113003.)

NMEs for Light ν Exchange



	mean field meth.	**ISM**	**IBM**	**QRPA**
Large model space	yes	no	yes	yes
Constr. Interm. States	no	yes	no	yes
Nucl. Correlations	limited	all	restricted	restricted

F. Simkovic, 2017

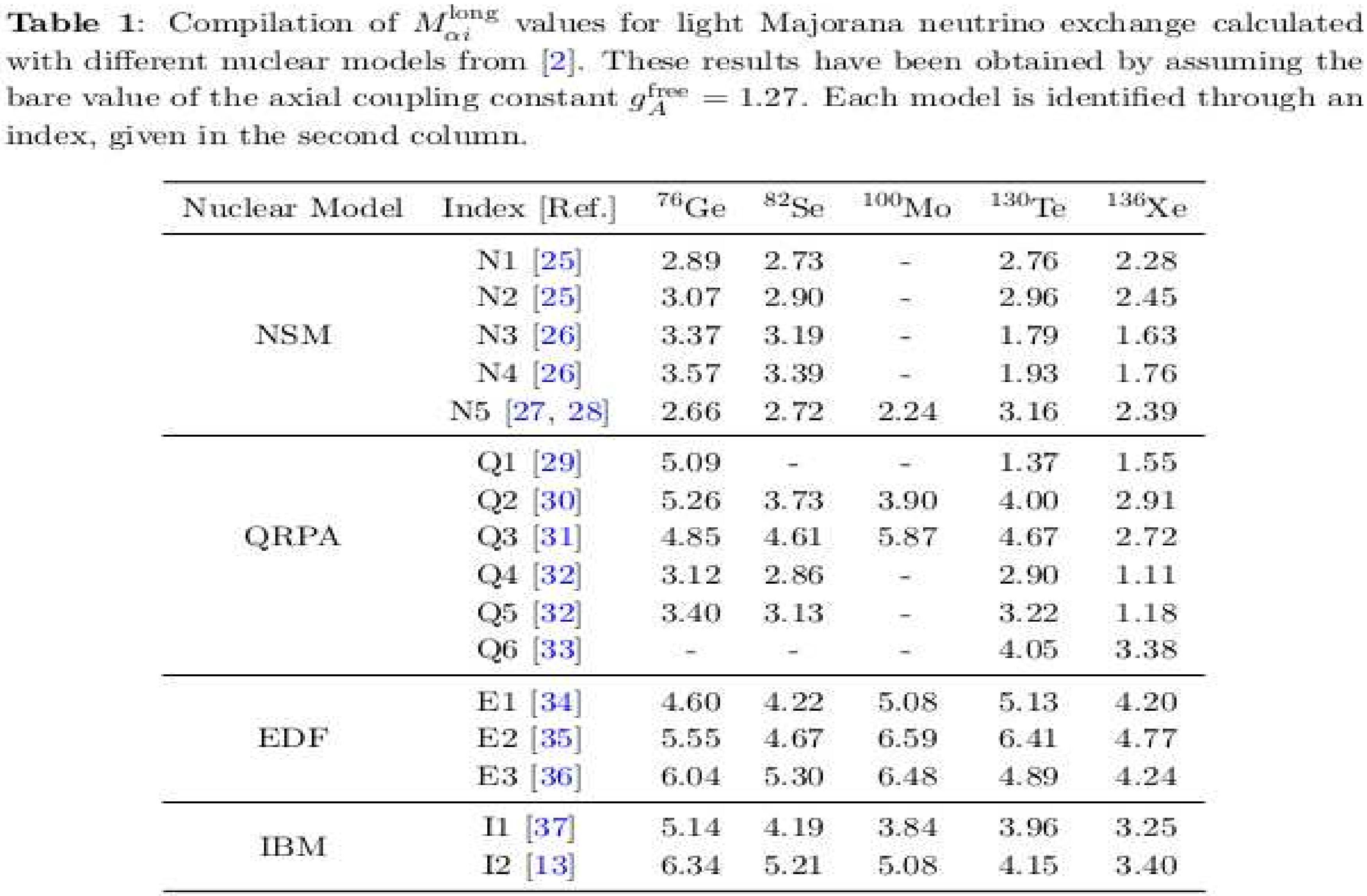


Table 1: Compilation of $M^{\text{long}}_{\alpha i}$ values for light Majorana neutrino exchange calculated with different nuclear models from [2]. These results have been obtained by assuming the bare value of the axial coupling constant $g_A^{\text{free}} = 1.27$. Each model is identified through an index, given in the second column.

Nuclear Model	Index [Ref.]	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
NSM	N1 [25]	2.89	2.73	-	2.76	2.28
	N2 [25]	3.07	2.90	-	2.96	2.45
	N3 [26]	3.37	3.19	-	1.79	1.63
	N4 [26]	3.57	3.39	-	1.93	1.76
	N5 [27, 28]	2.66	2.72	2.24	3.16	2.39
QRPA	Q1 [29]	5.09	-	-	1.37	1.55
	Q2 [30]	5.26	3.73	3.90	4.00	2.91
	Q3 [31]	4.85	4.61	5.87	4.67	2.72
	Q4 [32]	3.12	2.86	-	2.90	1.11
	Q5 [32]	3.40	3.13	-	3.22	1.18
	Q6 [33]	-	-	-	4.05	3.38
EDF	E1 [34]	4.60	4.22	5.08	5.13	4.20
	E2 [35]	5.55	4.67	6.59	6.41	4.77
	E3 [36]	6.04	5.30	6.48	4.89	4.24
IBM	I1 [37]	5.14	4.19	3.84	3.96	3.25
	I2 [13]	6.34	5.21	5.08	4.15	3.40

M. Agostini et al., arXiv:2202.01787

It has been noticed in 2019 that in addition to the known long-range light virtual Majorana neutrino exchange contribution to the $(\beta\beta)_{0\nu}$-decay amplitude, also a short-range contribution to amplitude appears when one combines SM effective field theory method with chiral perturbation theory for taking into account low-energy strong interaction effects. This new contribution is not related to heavy lepton-number violating beyond-standard model physics inducing $(\beta\beta)_{0\nu}$-decay, but appears already in the minimal "standar" scenario, with only three light Majorana neutrinos with non-zero masses being present.

V. Cirigliano et al., 1907.11254 and 2107.13354

Taking into account this additional contribution one has:

$$A(\beta\beta)_{0\nu} \propto G_{\mathrm{F}}^2 \left[g_A^2 \, M_{\mathrm{GT}}^{0\nu} + g_\nu^{\mathrm{NN}} \, m_\pi^2 \, M_{\mathrm{cont}}^{0\nu} \right] \frac{<m>}{m_e} \,.$$

g_ν^{NN} is unknown constant, m_π is the pion mass and $M_{\mathrm{cont}}^{0\nu} > 0$ is the NME of the new contact term. The estimated uncertainty in the knowledge of $M_{\mathrm{cont}}^{0\nu}$ is the same as that for the "standrad" mechanism NME $M_{\mathrm{GT}}^{0\nu}$, namely, a factor of $\sim (2-3)$. **Information about the constant g_ν^{NN} can be obtained, in particular, from QCD calculations on the lattice. Results of calculations using different nuclear physics techniques (shell model, QRPA, etc.) obtained for some of the nuclei of interest, ^{48}Ca, ^{76}Ge, ^{130}Te and ^{136}Xe, suggest that g_ν^{NN} is positive and that the contact term can enhance by a factor of ~(20% - 40%) the magnitude of $A(\beta\beta)_{0\nu}$ (increasing the sensitivity rearch of the experiments.**

See arXic:2207.05108, arXiv:2210.05809, arXiv:2112.08146 and references quoted therein.

The searches for $(\beta\beta)_{0\nu}-$ decay have a long history.

See, e.g., S.T.P., arXiv:1910.09331 and A. Barabash, arXiv:1104.2714

Results from IGEX (^{76}Ge), NEMO3 (^{100}Mo), CUORICINO+CUORE-0 (^{130}Te):

IGEX ^{76}Ge: $|<m>| < (0.33 - 1.35)$ eV **(90% C.L.).**

Data from NEMO3 (^{100}Mo):

$T(^{100}Mo) > 1.1 \times 10^{24}$ **yr,** $|<m>|$ $<$**(0.3–0.6) eV;**

Best Sensitivity Results

$$\mathbf{T(^{136}Xe)} > 1.6 \times 10^{25}\text{yr at } 90\% \text{ C.L., EXO}$$

$$\mathbf{T(^{136}Xe)} > 3.8 \times 10^{26}\text{y at } 90\% \text{ C.L., KamLAND} - \text{Zen}$$

$$|<m>| < (0.028 - 0.122) \text{ eV}.$$

H. Shimizu, talk at Neutrino 2024, June 17-22, Milano

$$\mathbf{T(^{76}Ge)} > 1.8 \times 10^{26}\text{yr at } 90\% \text{ C.L., GERDA II}.$$

$$|<m>| < (0.079 - 0.182) \text{ eV}.$$

S. Calgora, Talk at NuTel, October 2023

$$\mathbf{T(^{76}Ge)} > 1.9 \times 10^{26}\text{yr at } 90\% \text{ C.L., LEGEND} - 200.$$

L. Pertoldi, talk at Neutrino 2024, June 17-22, Milano

(GERDA + MAJORANA → LEGEND)

$$\mathbf{T(^{130}Te)} > 4.4 \times 10^{25}\text{yr at } 90\% \text{ C.L.},$$

$$|<m>| \; < (0.070 - 0.240) \text{ eV}, \;\; \text{CUORE}$$

C. Bucci, talk at Neutrino 2024, June 17-22, Milano

Constraints on min(m_j)

$$\mathbf{T(^{136}Xe)} > 3.8 \times 10^{26}\text{yr at } 90\% \text{ C.L.}, \;\; \text{KamLAND} - \text{Zen}$$

$$|<m>| \; < (0.028 - 0.122) \text{ eV}.$$

$|<m>| \; < 0.122$ eV, **QD region:**

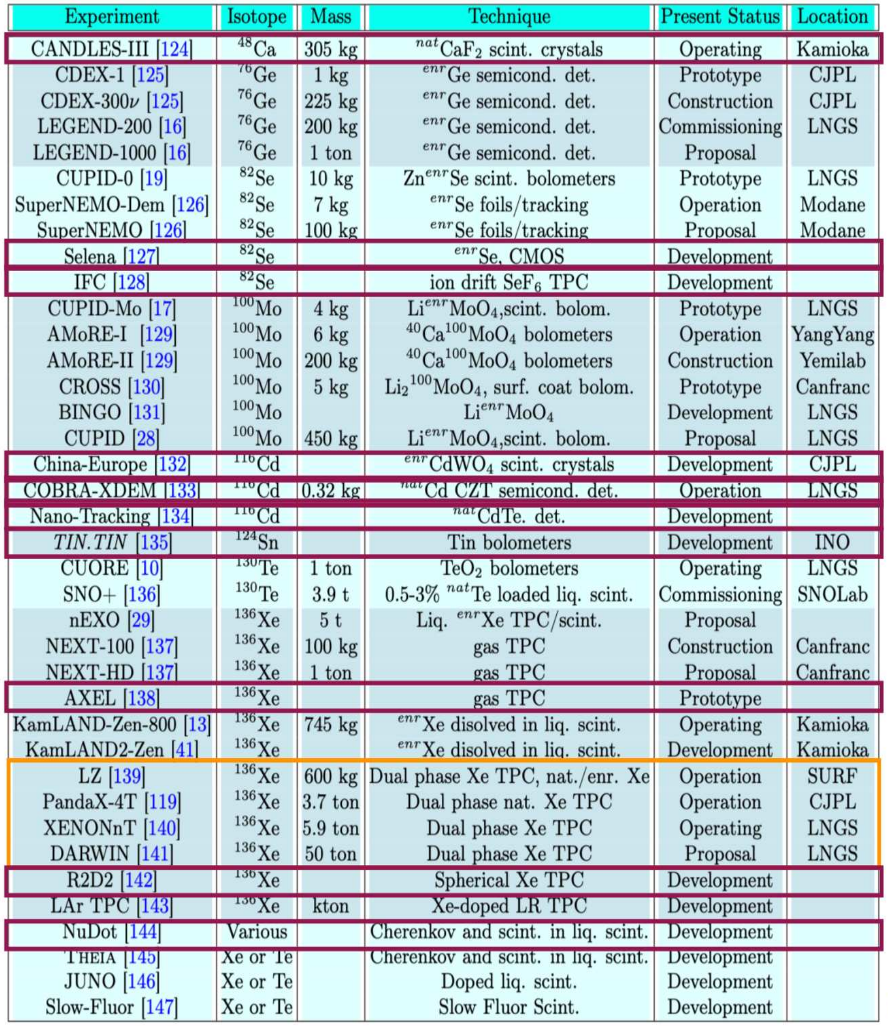
$$m_{1,2,3} < \frac{0.122 \text{ eV}}{\cos 2\theta_{12}} \cong 0.384 \text{ eV} \;\; (\cos 2\theta_{12} \gtrsim 0.318, \;\; 3\sigma)$$

Large number of experiments: $|<m>|$ $\sim$ (0.01-0.05) eV

CUORE - ^{130}Te;
*CUPID - ^{100}Mo (250 kg; CUPID-IT: 1000 kg (8×10^{27} yr);
LEGEND - ^{76}Ge (LEGEND-200; LEGEND-1000);
KamLAND-ZEN - ^{136}Xe (750 kg, 4.6×10^{26} yr);
*nEXO - ^{136}Xe (5 tons, 9×10^{27} yr);
NEXT-100 - ^{136}Xe (NEXT-HD (10^{27} yr); NEXT-BOLD (10^{28} yr));
SNO+ - ^{130}Te (800 tons of LS loaded with (0.5%) Te, 33.8% ^{130}Te);
AMoRE - ^{100}Mo (200 kg of XMoO4 crystals);
PANDAX-III - ^{136}Xe (200 kg of Xe enriched at 90% in ^{136}Xe);
CANDLES - ^{48}Ca;
*SuperNEMO - ^{82}Se (100 kg of ^{82}S, 20 modules);
DCBA - ^{82}Se, ^{150}Nd;
XMASS - ^{136}Xe;
ZICOS - ^{96}Zr;
MOON - ^{100}Mo;
...

See, e.g., A. Giuliani et al., 1910.04688; M. Agostini et al., 2202.01787

And many more ideas



Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	^{48}Ca	305 kg	^{nat}CaF$_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300ν [125]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [126]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [127]	^{82}Se		^{enr}Se, CMOS	Development	
IFC [128]	^{82}Se		ion drift SeF$_6$ TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	Li^{enr}MoO$_4$,scint. bolom.	Prototype	LNGS
AMoRE-I [129]	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ bolometers	Operation	YangYang
AMoRE-II [129]	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ bolometers	Construction	Yemilab
CROSS [130]	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [131]	^{100}Mo		Li^{enr}MoO$_4$	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	Li^{enr}MoO$_4$,scint. bolom.	Proposal	LNGS
China-Europe [132]	^{116}Cd		^{enr}CdWO$_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	^{116}Cd		^{nat}CdTe. det.	Development	
TIN.TIN [135]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO$_2$ bolometers	Operating	LNGS
SNO+ [136]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [137]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe disolved in liq. scint.	Development	Kamioka
LZ [139]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [143]	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA [145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	

I did not have time to discuss these, but they all have unique features....

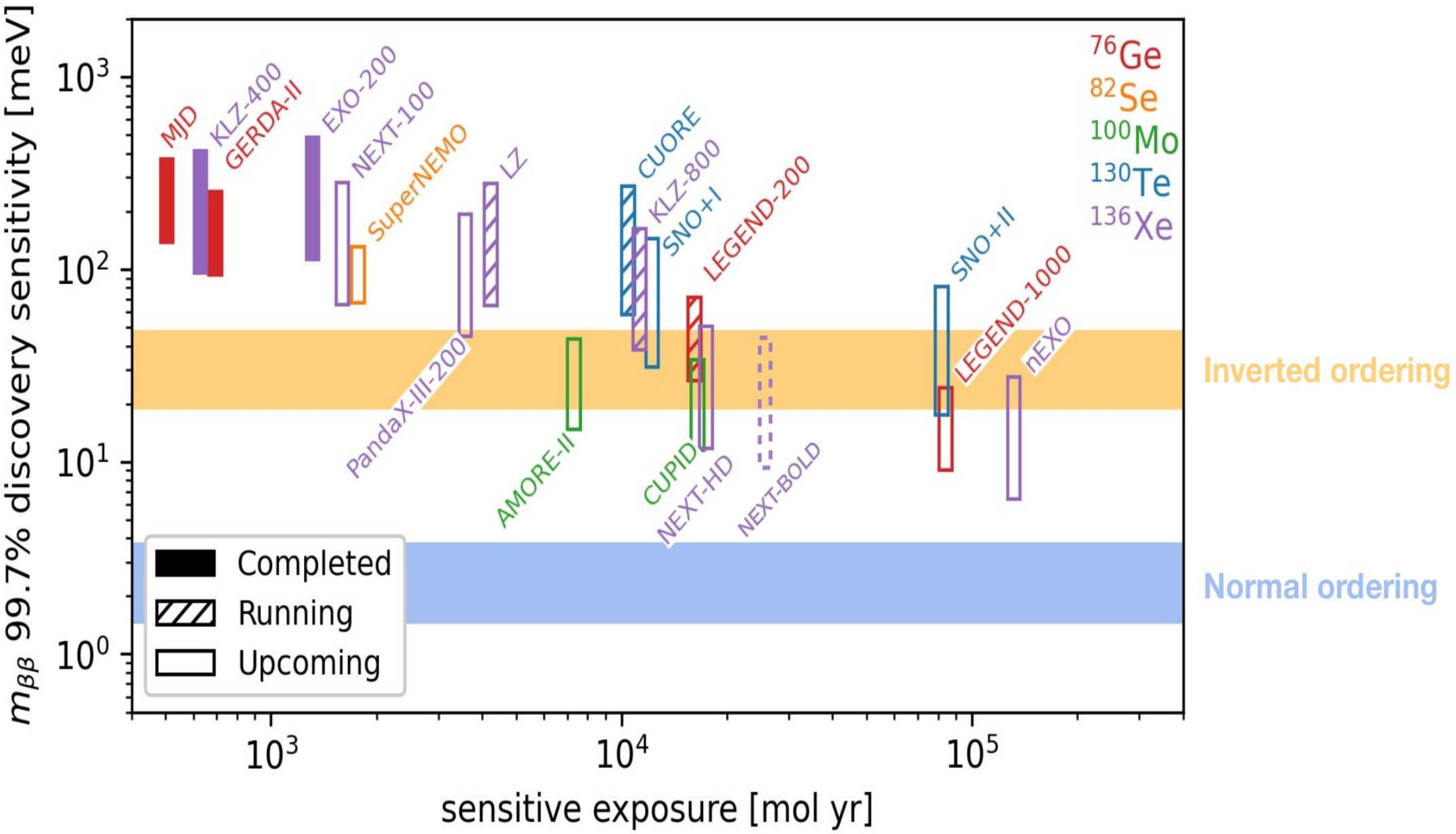
Opportunistic searches with Dark Matter experiments: L. Baudis' talk on Friday

arXiv:2212.11099

R. Guinette, talk at Neutrino 2024

Conquering the inverted ordering

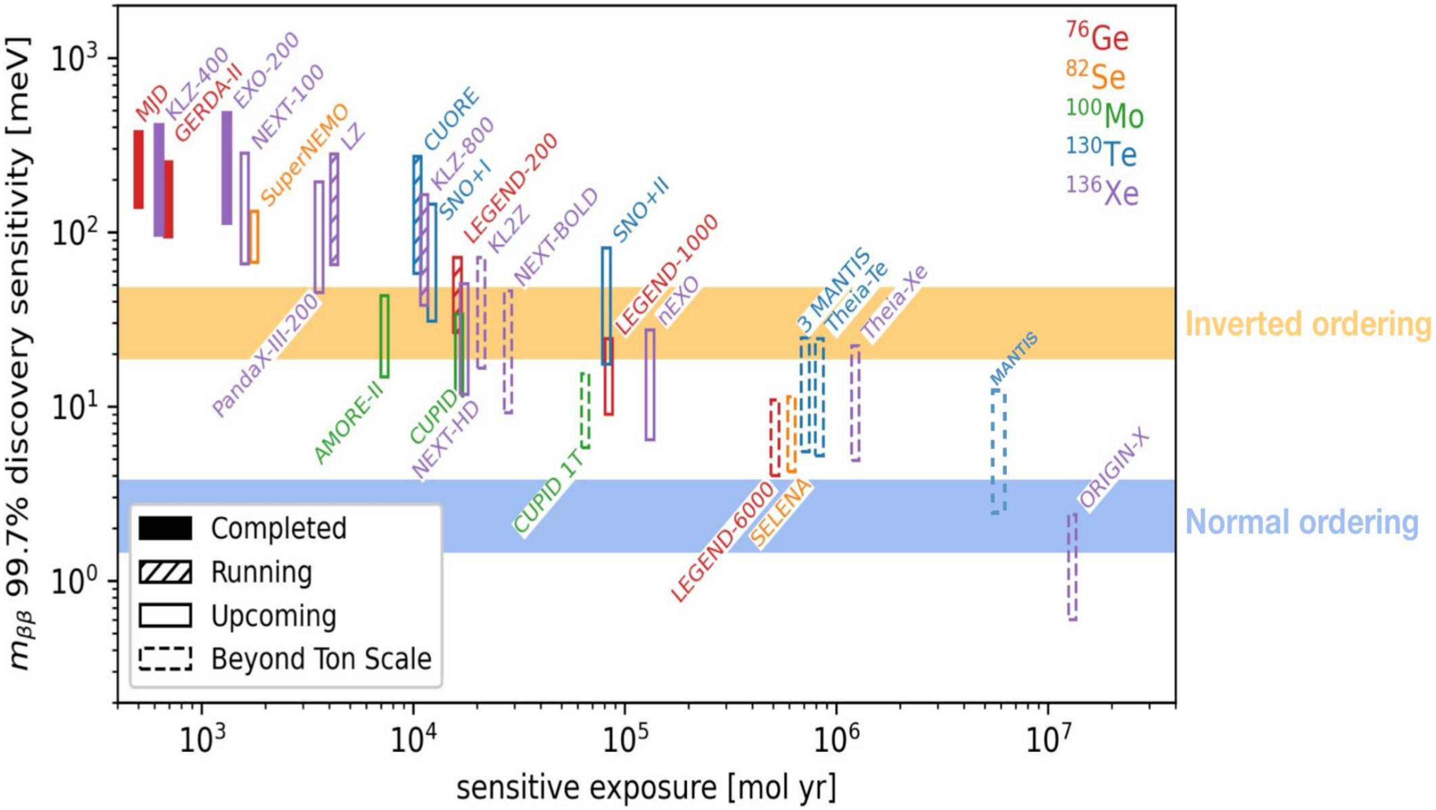
- Next generation will *cover* the inverted ordering



Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

R. Guinette, talk at Neutrino 2024

Next next step: Attempt the Normal Ordering

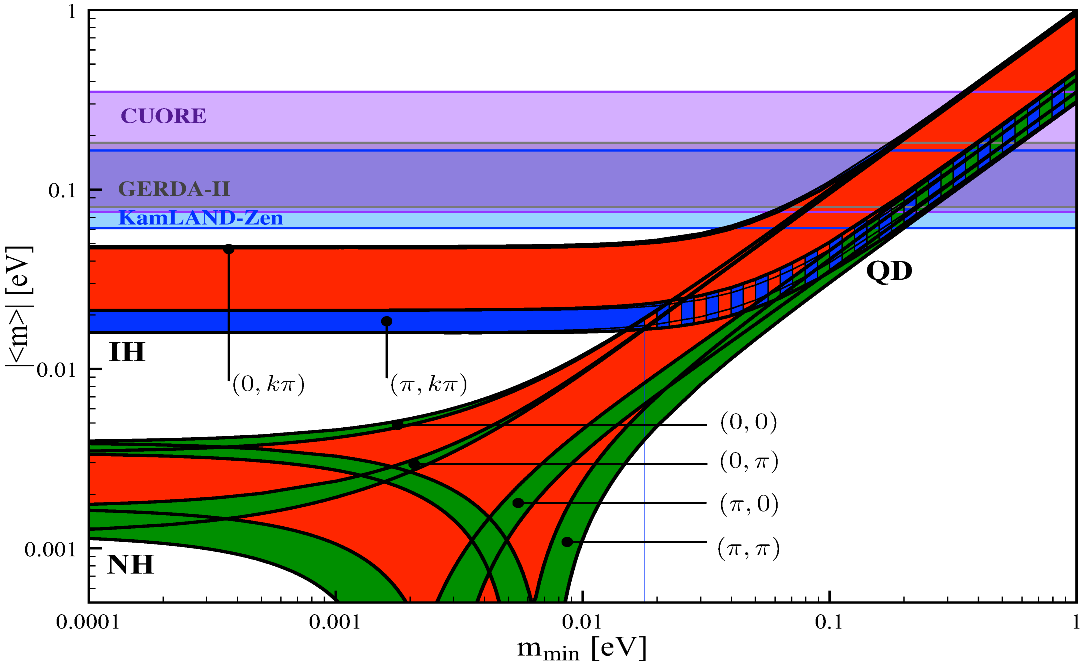


Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

R. Guinette, talk at Neutrino 2024

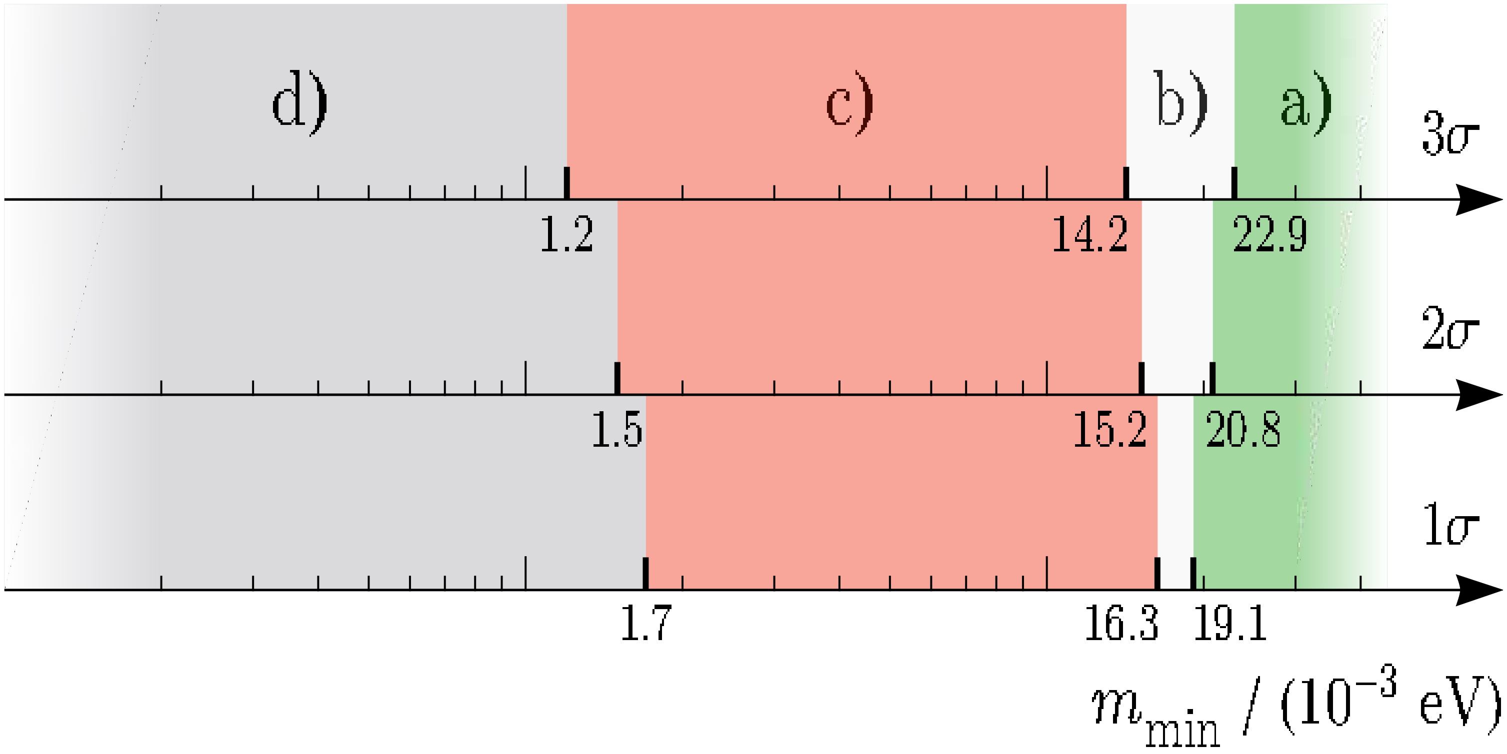
If $|<m>| \; < 0.01$ eV, the next frontier will be $|<m>| \sim(1.0 - 5.0)\times 10^{-3}$ eV

Experiments: nEXO, LEGEND-1000, CUPID-IT, NEXT-BOLD



Under what conditions $|<m>| \; \geq 1.0 \; (5.0) \times 10^{-3}$ eV,
or how not to "fall" in the "well of non-obsevability".

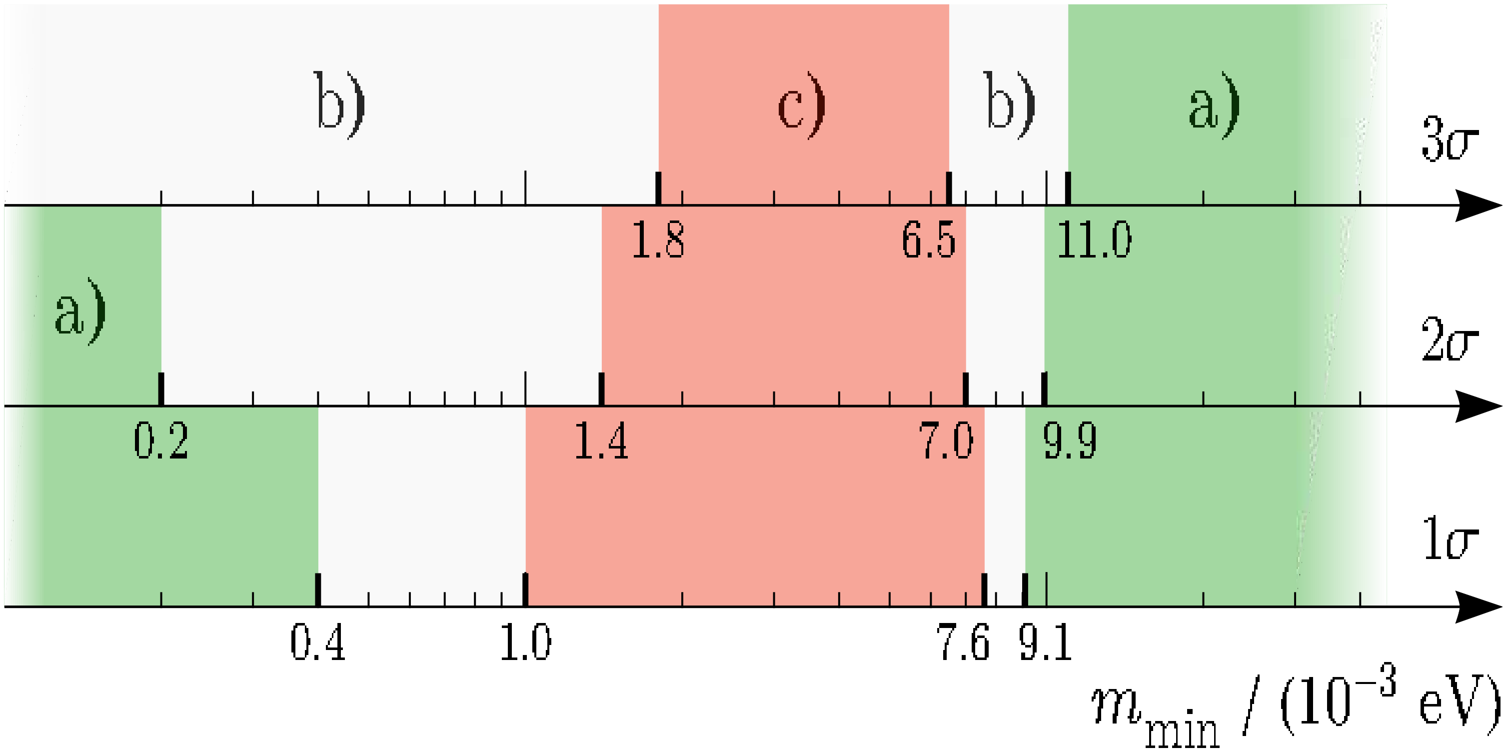
S. Pascoli, STP, arXiv:0711.4993; J. Penedo, STP, PL B786 (2018) 410



Ranges of $m_{\rm min}$ for a NO spectrum and for oscillation parameters inside their $n\sigma$ ($n = 1, 2, 3$) intervals for which: in green, a) $|<m>| > 5 \times 10^{-3}$ eV for all values of θ_{ij}, Δm^2_{ij}, and $\alpha^{(\prime)}_{ij}$ from the corresponding allowed or defining intervals; in grey, b) there exist values of θ_{ij}, Δm^2_{ij} from the 1σ, 2σ and 3σ allowed intervals and values of $\alpha^{(\prime)}_{ij}$ such that $|<m>| < 5\times10^{-3}$ eV and in red, c) for all values of θ_{ij} and Δm^2_{ij} from the corresponding allowed intervals there exist values of the phases α_{21} and α'_{31} for which $|<m>| < 5\times10^{-3}$ eV. In darker grey d), ranges of $m_{\rm min}$ for which one has $|<m>| < 5\times10^{-3}$ eV independently of the values of oscillation parameters and CPV phases.

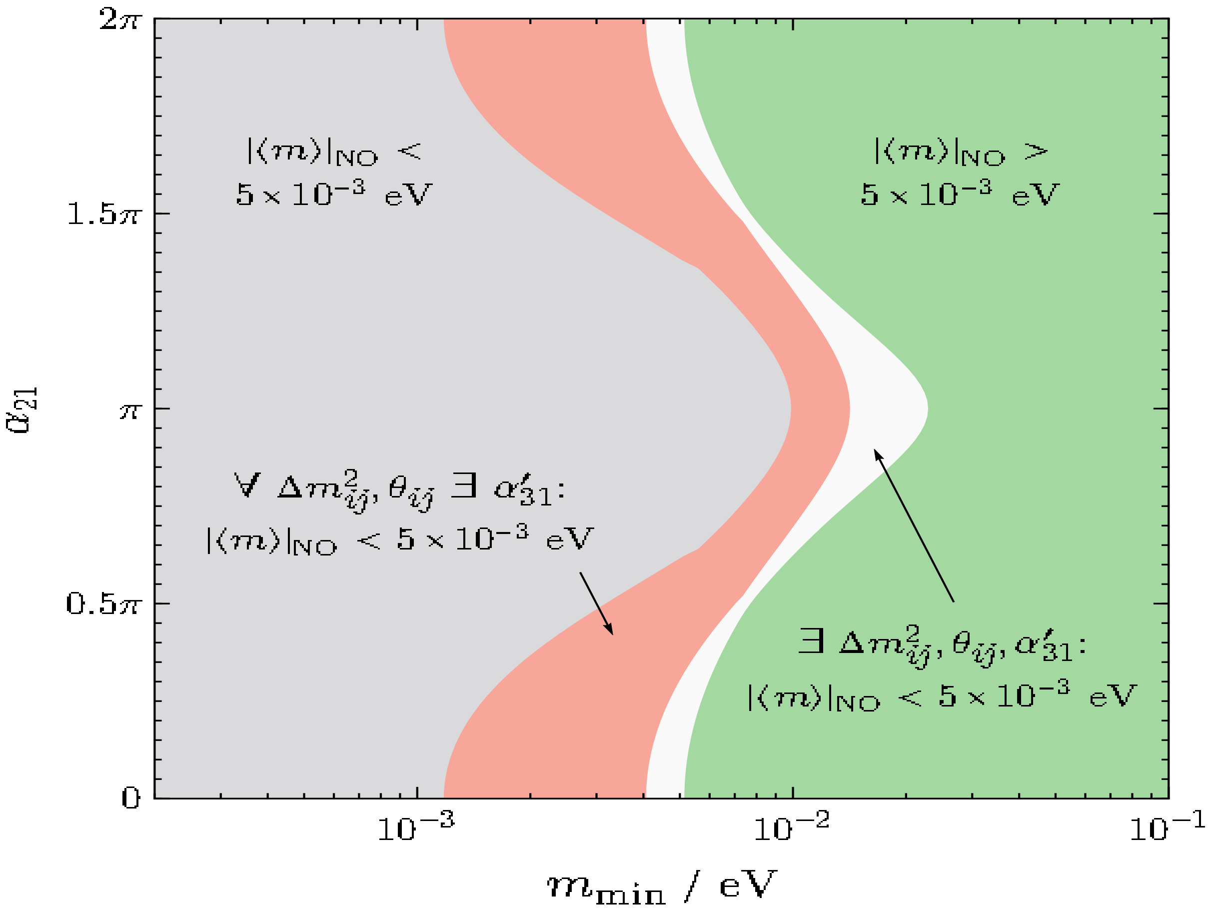
J. Penedo, STP, PL B786 (2018) 410

$|<m>| > 5 \times 10^{-3}$ eV if $m_{\rm min} > 0.0229$ eV, or if $\sum m_j \geq 0.1$ eV (3σ).



Ranges of m_{min} for a NO spectrum and for oscillation parameters inside their $n\sigma$ ($n = 1, 2, 3$) intervals for which: in green, a) $|{<}m{>}| > |{<}m{>}|_{ref} = 10^{-3}$ eV for all values of θ_{ij}, Δm^2_{ij}, and $\alpha^{(\prime)}_{ij}$ from the corresponding allowed or defining intervals; in grey, b) there exist values of θ_{ij}, Δm^2_{ij} from the 1σ, 2σ and 3σ allowed intervals and values of $\alpha^{(\prime)}_{ij}$ such that $|{<}m{>}| < |{<}m{>}|_{ref} = 10^{-3}$ eV; and in red, c) for all values of θ_{ij} and Δm^2_{ij} from the corresponding allowed intervals there exist values of the phases α_{21} and α'_{31} for which $|{<}m{>}| < |{<}m{>}|_{ref} = 10^{-3}$ eV.

$|{<}m{>}| > 10^{-3}$ eV if $m_{\mathrm{min}} > 0.011$ eV, or if $\sum m_j \geq 0.08$ eV (3σ).



J. Penedo, STP, PL B786 (2018) 410

$\sum m_j \geq 0.1$ **eV implies** $|<m>|\ \geq 5\times10^{-3}$ **eV (3σ);**

$\sum m_j \geq$ **0.08 eV implies** $|<m>|\ \geq 10^{-3}$ **eV (3σ).**

If it is experimentally established that

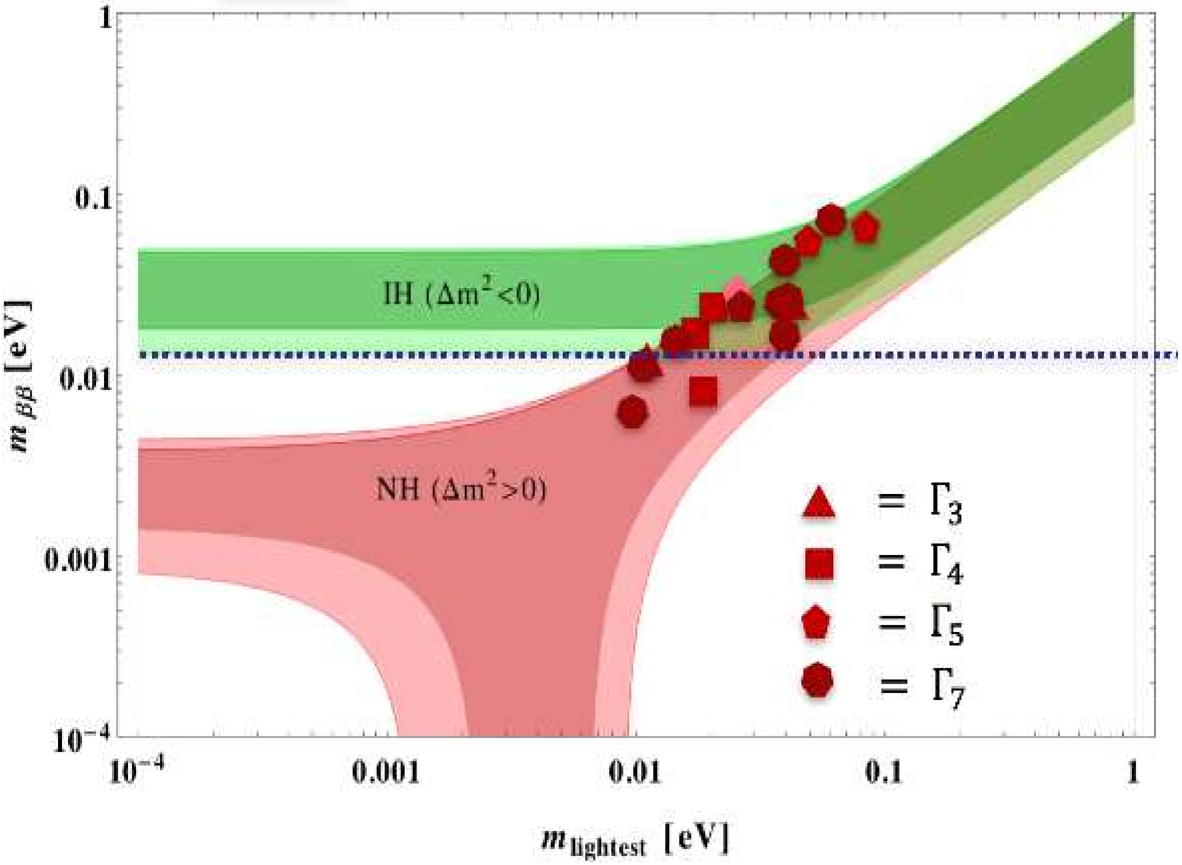
$$\Sigma_j m_j \gtrsim 0.10\ (0.08)\ \text{eV},$$

this would imply for NO ν mass spectrum that

$$|{<}m{>}| \ \geq 5 \times 10^{-3}\ (10^{-3})\ \text{eV}$$

J.T. Penedo, STP, arxiv:1806.03203

Predictions of modular invariant theories of lepton flavour



F. Feruglio, talk at Bethe Colloquium, 18/06/2020

New approach to neutrino and charged lepton masses, lepton (neutrino) mixing and leptonic CP violation (for a review see, e.g., F. Feruglio and A. Romanino, arXiv:1912.06028). Has been intensively developed in the last two years. Models typically predict $m_1 > 0.01$ eV for NO spectrum (see, e.g., J. Penedo, STP, arXiv:1806.1040, P. Novichkov et al., arXiv:1811.04933).

Of fundamental importance are:

- determining the status of CP symmetry in the lepton sector and high precision measurement of δ (T2K, NOνA T2HK, DUNE); leptonic CPV might be at the origin of matter-antimatter (or baryon) asymmetry of the Universe; critical test of symmetry origin of the ν-mixing pattern.

- the determination of the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos (which is one of the most challenging and pressing problems in present day elementary particle physics) (LEGEND (GERDA, MJORANA), KamLAND-Zen II, CUORE (CUPID), nEXO (EXO), SNO+, NEXT, ...);

- determination of the type of spectrum neutrino masses possess, or the "neutrino mass ordering" (T2K + NOνA; JUNO; ORCA; T2HK+HK(atm.data); DUNE; INO);

- determination of the absolute neutrino mass scale, or $\min(m_j)$ (KATRIN, new ideas; cosmology).

- High precision determination of $\sin^2\theta_{23}$ (T2HK+HK(atm.data); DUNE) - relevant, e.g., for ν-osc. tomography of the Earth (ORCA), and $\sin^2\theta_{12}$ (JUNO); both crucial for tests of ideas on origin of the ν-mixing pattern.

The program of research extends beyond 2035.

- Understanding at fundamental level the mechanism giving rise to the $\nu-$masses and mixing and to the L_l-non-conservation. Includes understanding

  – the origin of the observed patterns of ν-mixing and ν-masses ;

  – the physical origin of CPV phases in U_{PMNS} ;

  – Are the observed patterns of ν-mixing and of $\Delta m^2_{21,31}$ related to the existence of a new symmetry?

  – Is there any relations between $q-$mixing and $\nu-$ mixing? Is $\theta_{12} + \theta_c = \pi/4$?

  – Is $\theta_{23} = \pi/4$, or $\theta_{23} > \pi/4$ or else $\theta_{23} < \pi/4$?

  – Is there any correlation between the values of CPV phases and of mixing angles in U_{PMNS}?

- Progress in the theory of ν-mixing might lead to a better understanding of the origin of the BAU.

  – Can the Majorana and/or Dirac CPVP in U_{PMNS} be the leptogenesis CPV parameters at the origin of BAU?

BS3νRM: eV scale sterile ν's; NSIs; ChLFV processes ($\mu \to e + \gamma$, $\mu \to 3e$, $\mu^- - e^-$ conversion on (A,Z)); $\nu-$related BSM physics at the TeV scale (N_{jR}, H^{--}, H^-, etc.).

Future Developments

JUNO

20 kt LS detector of reactor $\bar{\nu}_e$ via IBD
$\bar{\nu}_e + p \to n + e^+$; $E_{res} = 3\%/\sqrt{E}$; $L \cong 53$ **km;**
thermal power of the used reactors: 26.6 GW;
Sphere with a diameter of 38 m.
Cost: 300×10^6 **US Dollars.**
Built in China by international collaboration of more than 700 scientists from 74 Institutions in 17 countries/regions. Expected to start data-taking at the beginning of 2025.
After 6 years of operation: NMO at 3σ **(using reactor** ν **data only). Adding** ν_{atm} **data can improve the sensitivity by** $(0.8 - 1.4)\sigma$**.**

The idea put forward in S.T.P., M. Piai, PLB 553 (2002) 94 (hep-ph/0112074).

Based on: $P_{NO}(\bar{\nu}_e \to \bar{\nu}_e) \neq P_{IO}(\bar{\nu}_e \to \bar{\nu}_e)$

$$P^{NO}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{13}\left(1 - \cos\frac{\Delta m^2_{atm}\,L}{2\,E_\nu}\right) - \frac{1}{2}\cos^4\theta_{13}\sin^2 2\theta_{12}\left(1 - \cos\frac{\Delta m^2_{\odot}\,L}{2\,E_\nu}\right)$$

$$+ \frac{1}{2}\sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos\left(\frac{\Delta m^2_{atm}\,L}{2\,E_\nu} - \frac{\Delta m^2_{\odot}\,L}{2\,E_\nu}\right) - \cos\frac{\Delta m^2_{atm}\,L}{2\,E_\nu}\right), \quad \Delta m^2_{\odot} \equiv \Delta m^2_{21},$$

$$P^{IO}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta_{13}\left(1 - \cos\frac{\Delta m^2_{atm}\,L}{2\,E_\nu}\right) - \frac{1}{2}\cos^4\theta_{13}\sin^2 2\theta_{12}\left(1 - \cos\frac{\Delta m^2_{\odot}\,L}{2\,E_\nu}\right)$$

$$+ \frac{1}{2}\sin^2 2\theta_{13}\cos^2\theta_{12}\left(\cos\left(\frac{\Delta m^2_{atm}\,L}{2\,E_\nu} - \frac{\Delta m^2_{\odot}\,L}{2\,E_\nu}\right) - \cos\frac{\Delta m^2_{atm}\,L}{2\,E_\nu}\right).$$

$\Delta m^2_{\rm atm} = \Delta m^2_{31(32)}(NO)$, $\Delta m^2_{\rm atm} = \Delta m^2_{32(31)}(IO)$,

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

Spectrum of e^+ - sensitive to the difference between $P^{NO}(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ and $P^{IO}(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ - can be used to determine neutrino mass ordering. Optimal L exists.

S.T.P., M. Piai, 2001

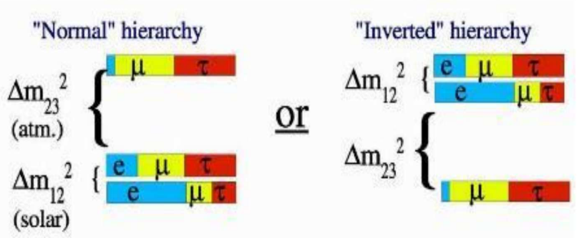
JUNO (China, International collaboration)

S. Choubey, S.T.P., M. Piai, PRD 68 (2003) 113006 ((hep-ph/0306017):
can measure $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} with exceptionally high precision.
After 6 years of dataking:
$\sin^2\theta_{12}$**: 0.5%;** Δm^2_{21}**: 0.3%;** Δm^2_{31}**: 0.2%** **(**1σ**)**
(Y. Wang, talk given at CERN on March 20, 2024).

Wide program of research: atmospheric ν oscillations, solar neutrinos, SN neutrinos, geo-neutrinos, nucleon decay; distant future: $(\beta\beta)_{0\nu}$ decay.

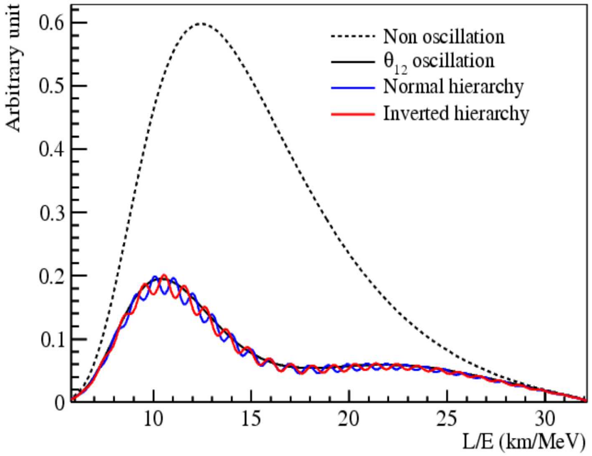

Huizhou
Guangzhou
Guang Zhou
Dongguan
Zhaoqing
CNS
2.5 h drive
Shen Zhen
Huizhou NPP
Lufeng NPP
Daya Bay NPP
Zhongshan
Zhu Hai
Zhujiang River Estuary
Hong Kong
Hong Kong
Macau
Macau
JUNO site
53 km
53 km
Taishan NPP
Yangjiang NPP
N

Mass Ordering by Reactor Neutrinos

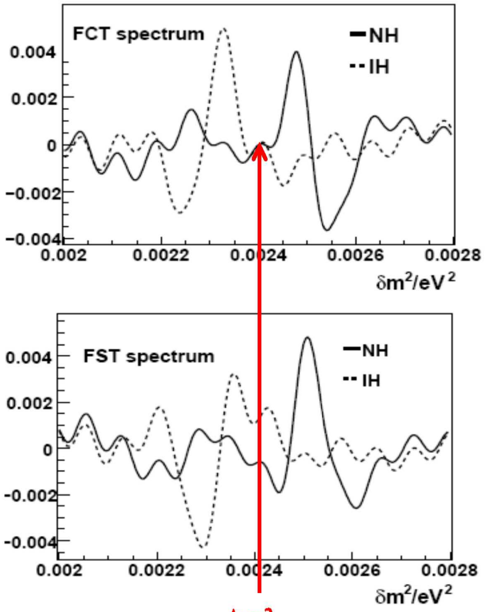


$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$

$$\boxed{\frac{\Delta m^2_{21}}{|\Delta m^2_{32}|} \sim 3\%}$$



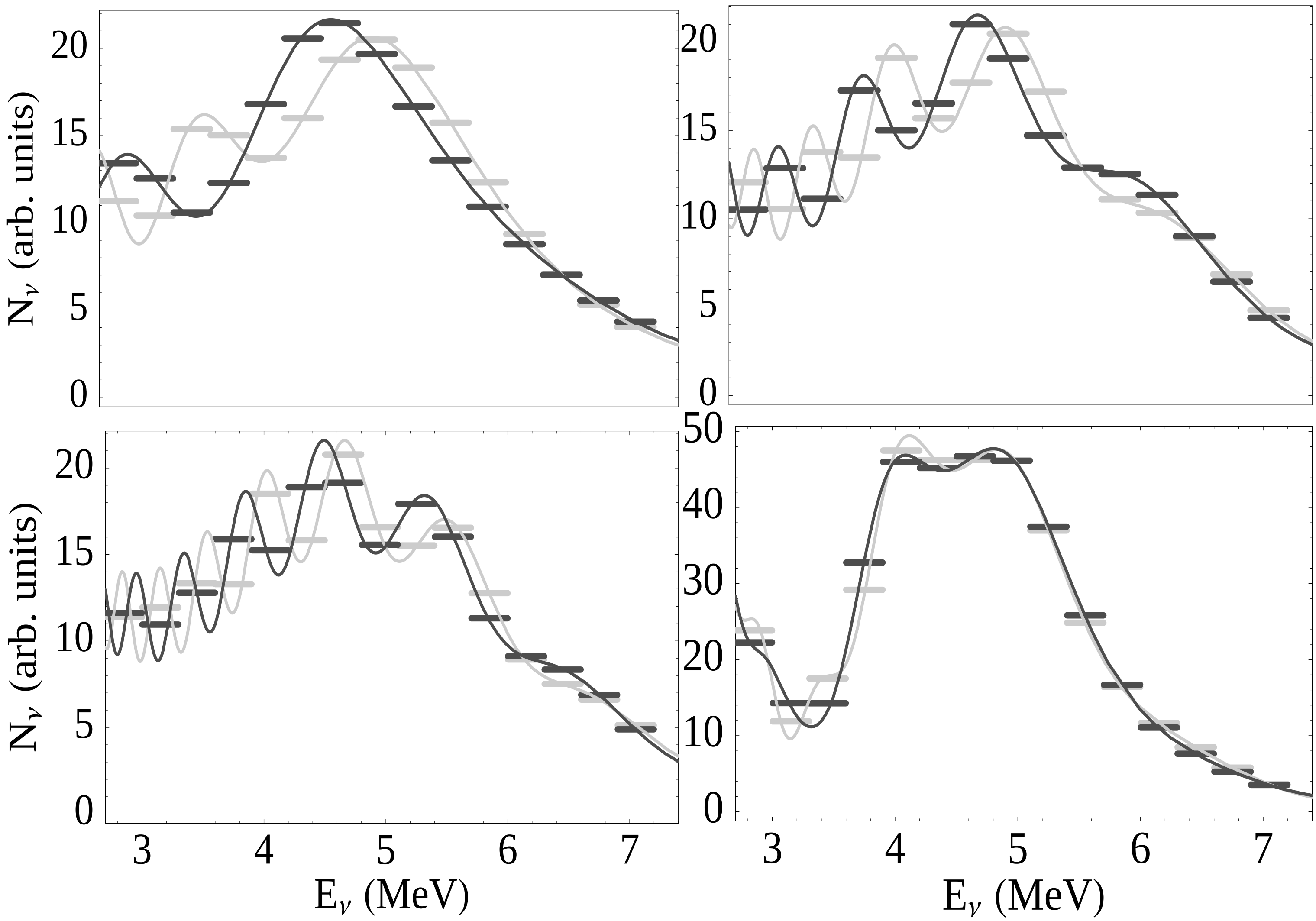
$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$



Δm^2_{32}

S. Petcov and Piai, Phys. Lett. B 553, 94-106(2002)
J. Learned et al., PRD 78(2008)071302
L. Zhan, YFW et al., PRD 78(2008)111103

Y. Wang, talk given at CERN on March 20, 2024

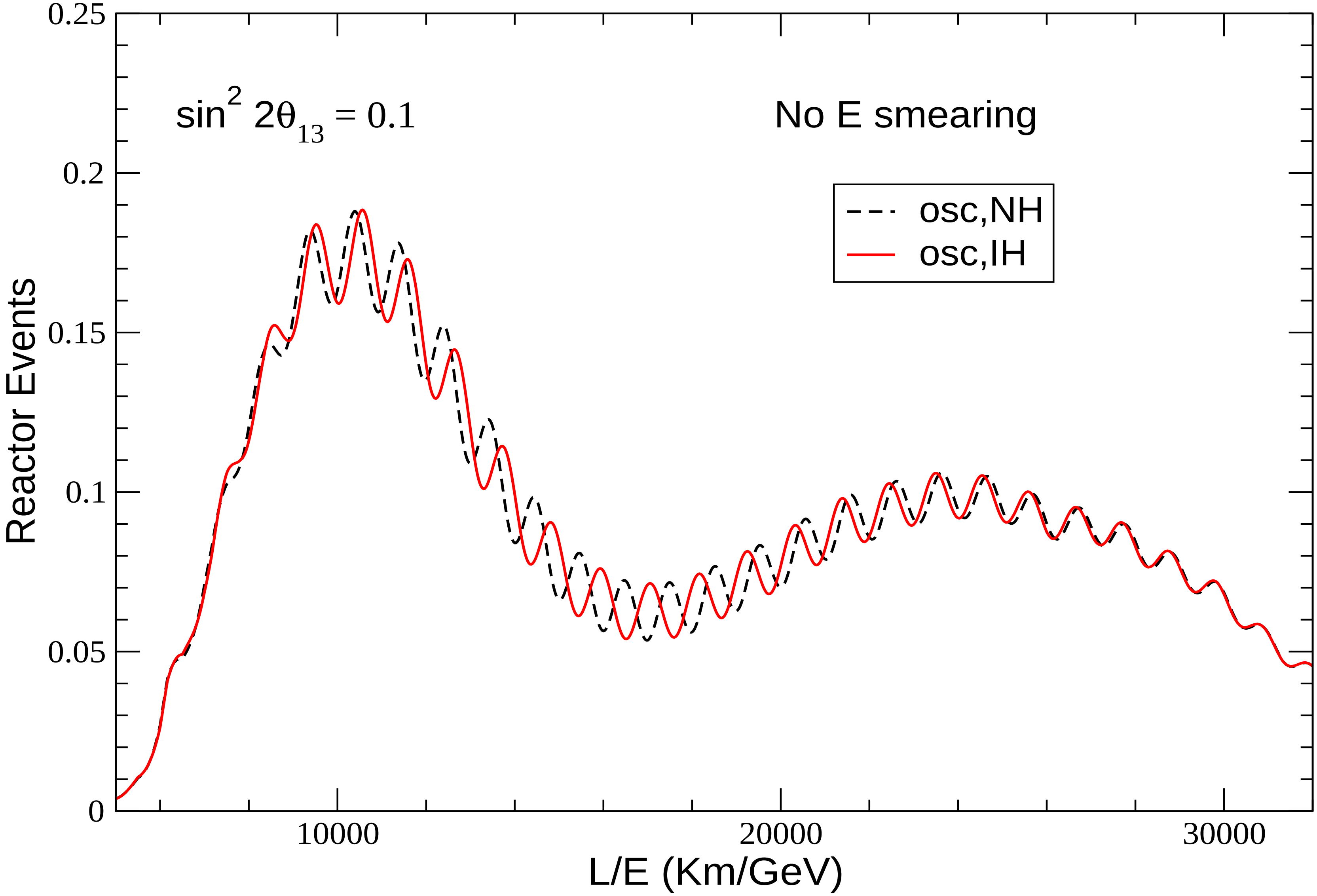


S.T.P., M. Piai, PLB 553 (2002) 94 (hep-ph/0112074)

$\Delta m^2_{21} = 2 \times 10^{-4}$ eV^2, $\Delta m^2_{31} = 1.3; 2.5; 3.5 \times 10^{-3}$ eV^2;

$\Delta m^2_{21} = 6 \times 10^{-4}$ eV^2, $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2; $\sin^2\theta_{12} = 0.8$;$\sin^2\theta_{13} = 0.05$.

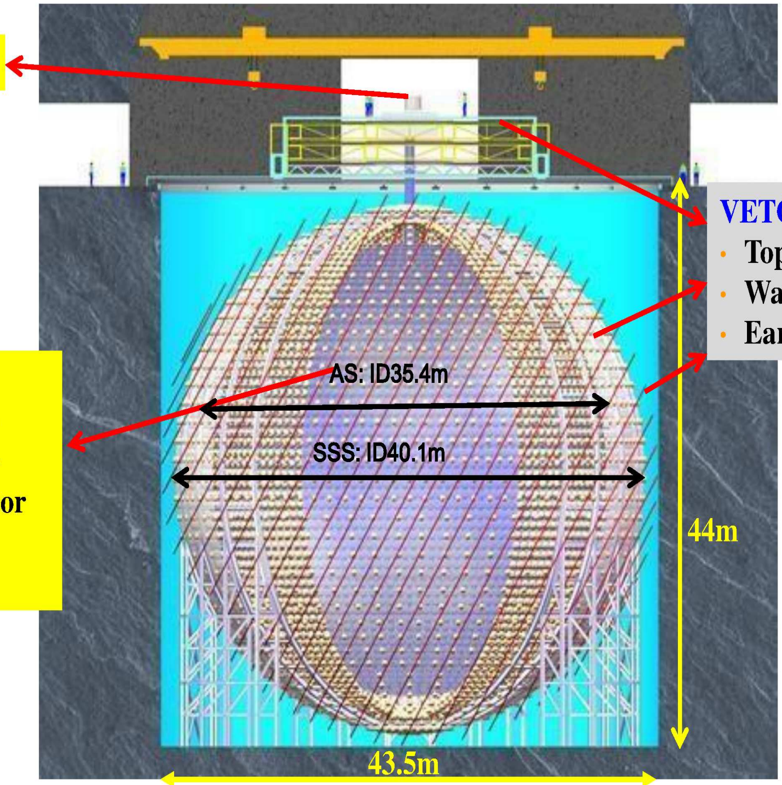
“However, as it is well known, “Only those who wager can win.” (W. Pauli, Letter to Participants of a Physics Meeting in Tubingen, Germany, December 4, 1930.”



P. Ghoshal, S.T.P., JHEP 03 (2011) 058 (arXiv:1011.1646)

Concept of JUNO for Mass Ordering

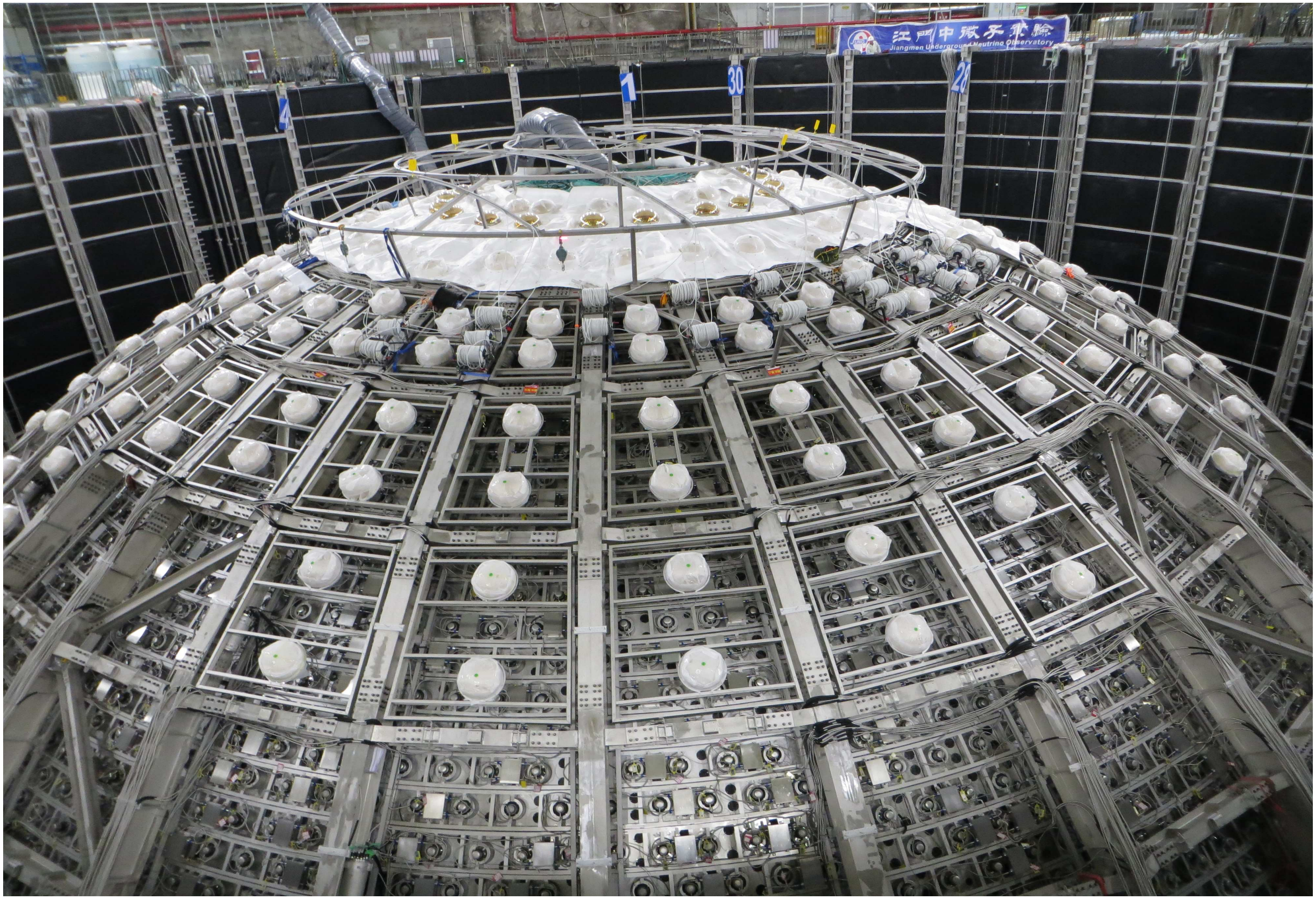
- Two-layer structure for simplicity and cost: stainless steel frame + Acrylic tank
- Water as VETO and Buffer ➔ radiopurity control of water



Calibration

Central detector
- Steel structure (SSS)
- Acrylic sphere(AS) + 20kt Liquid scintillator
- 17612 20” PMT
- 25600 3” PMT

VETO system
- Top Tracker
- Water VETO with 2400 20” PMT
- Earth Magnetic Field shielding coils


Jiangmen Underground Neutrino Observatory
4
1
30
28

8
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1
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28
Jiangmen Underground Neutrino Observatory

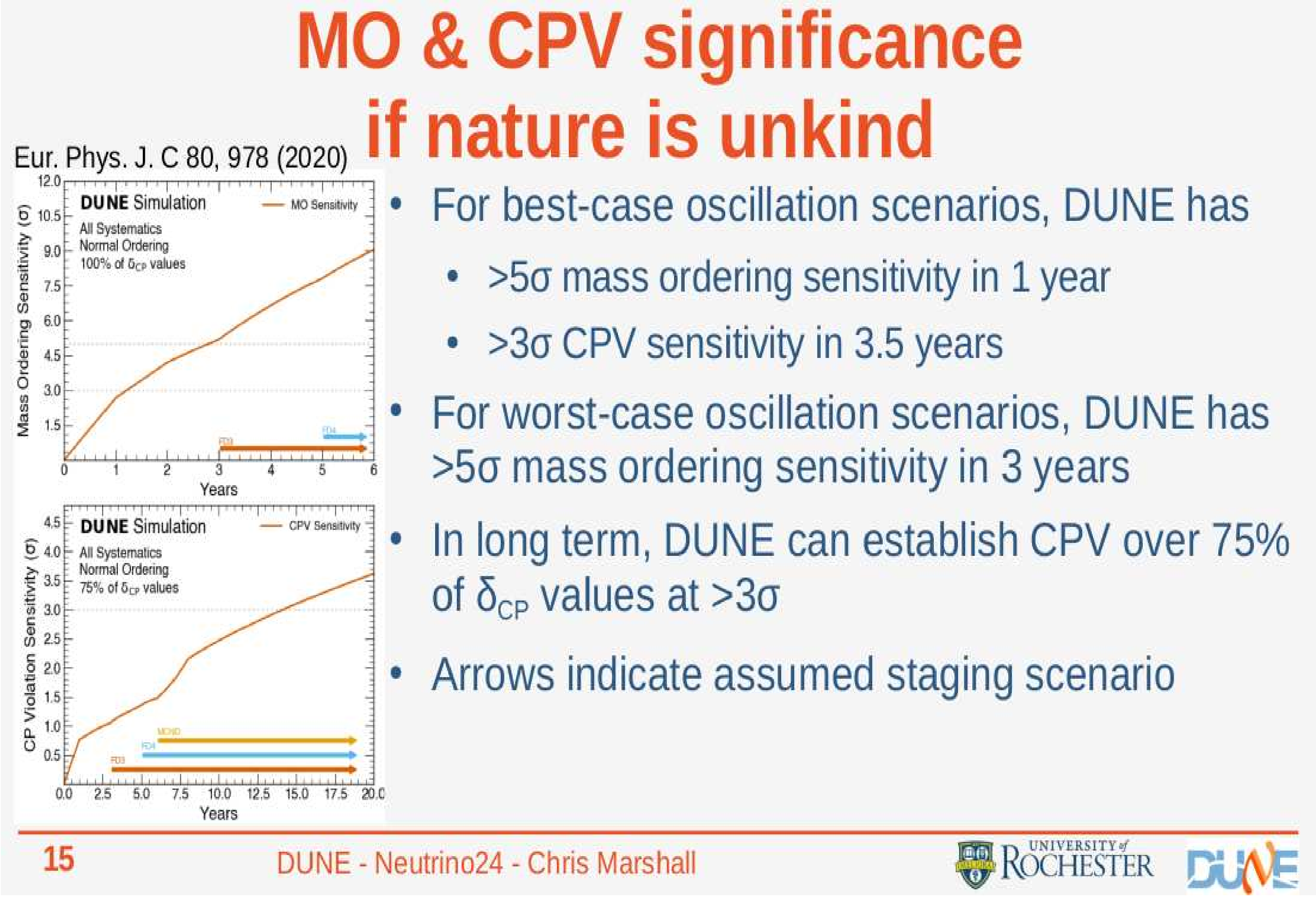
DUNE

DUNE (LBNE): Fermilab-DUSEL, $L = 1290$ km, 1.2 MW (2.3 MW) proton beam, wide band ν beam (first and second osc. maxima at $E = 2.4$ GeV and 0.8 GeV); 34 kt fiducial volume LAr detecors; plans to run 5 years with ν_μ and 5 years with $\bar{\nu}_\mu$; 2028-2029

DUNE could have very good sensitivity to CP-violation with a 60% coverage at 3σ in the allowed range of values of $\sin^2 2\theta_{13}$ (assuming it will run for 5 years in neutrinos and 5 years in antineutrinos).

DUNE could achieve the determination of the NMO at 3σ in less then a year.

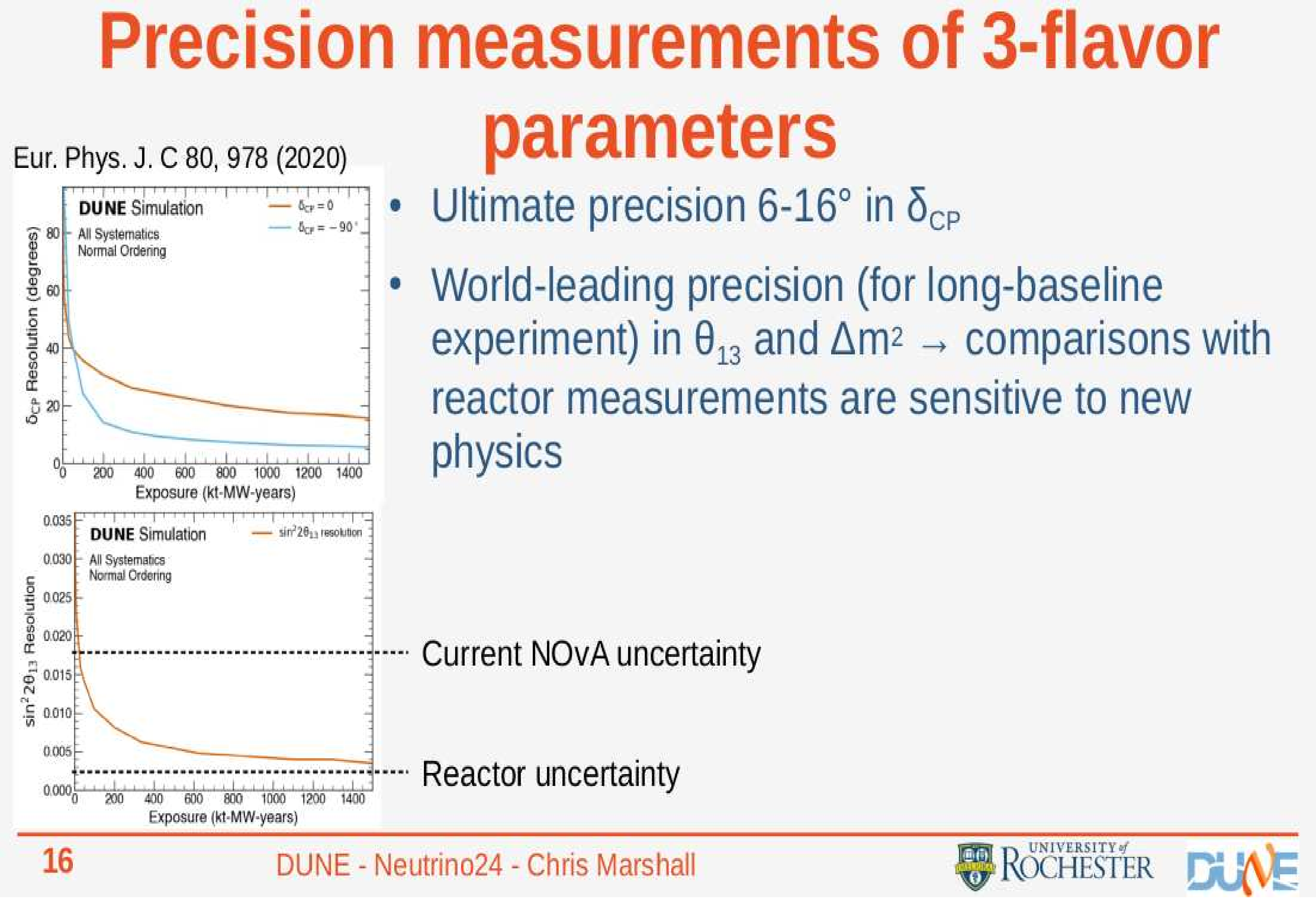
The next slides on DUNE are from the talk by Ch. Marshall at Neutrino 2024.



MO & CPV significance if nature is unkind

Eur. Phys. J. C 80, 978 (2020)

- For best-case oscillation scenarios, DUNE has
  - >5σ mass ordering sensitivity in 1 year
  - >3σ CPV sensitivity in 3.5 years
- For worst-case oscillation scenarios, DUNE has >5σ mass ordering sensitivity in 3 years
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3σ
- Arrows indicate assumed staging scenario



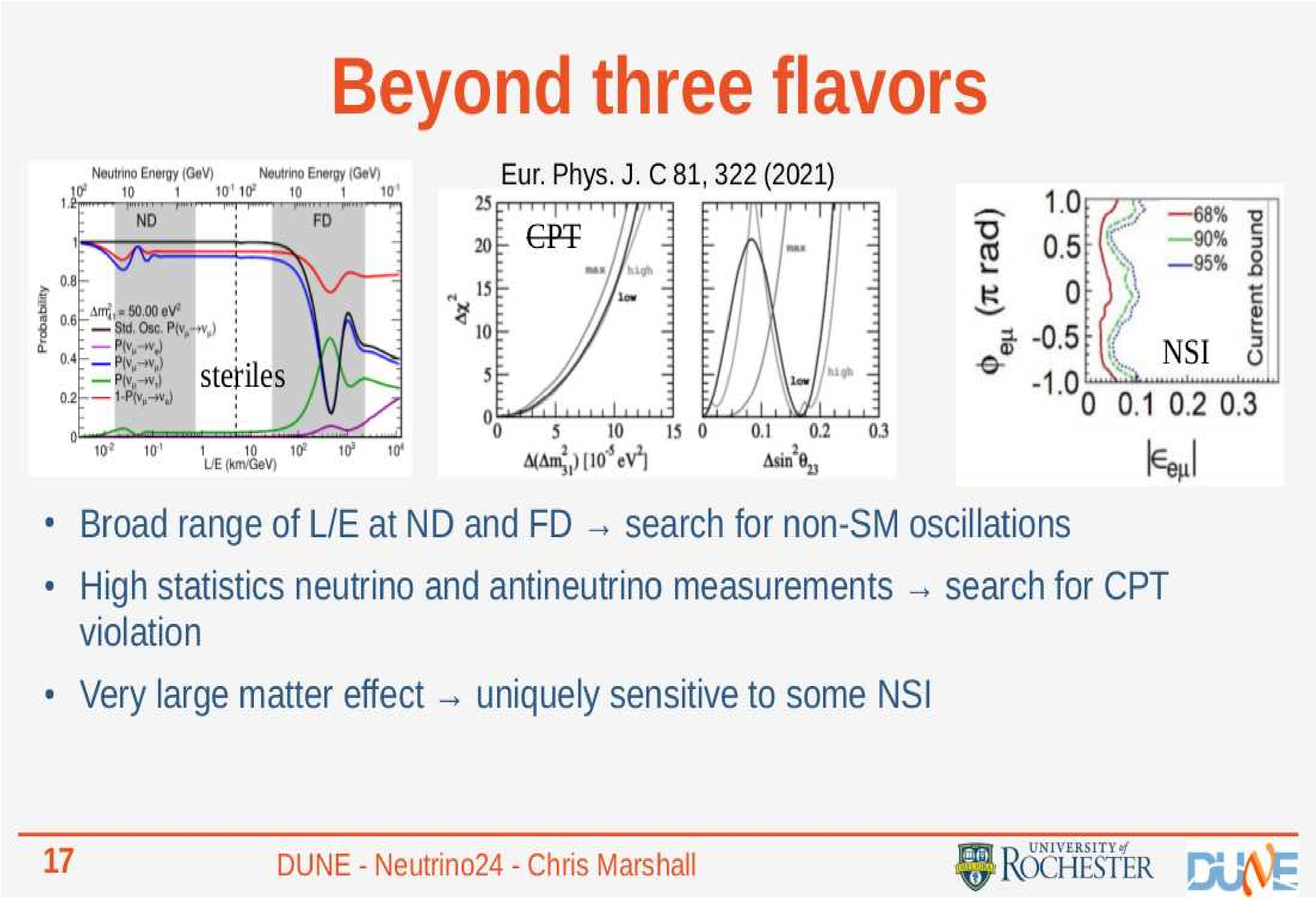
Precision measurements of 3-flavor parameters

Eur. Phys. J. C 80, 978 (2020)

- Ultimate precision 6-16° in δ_{CP}
- World-leading precision (for long-baseline experiment) in θ_{13} and Δm^2 → comparisons with reactor measurements are sensitive to new physics

Current NOvA uncertainty

Reactor uncertainty

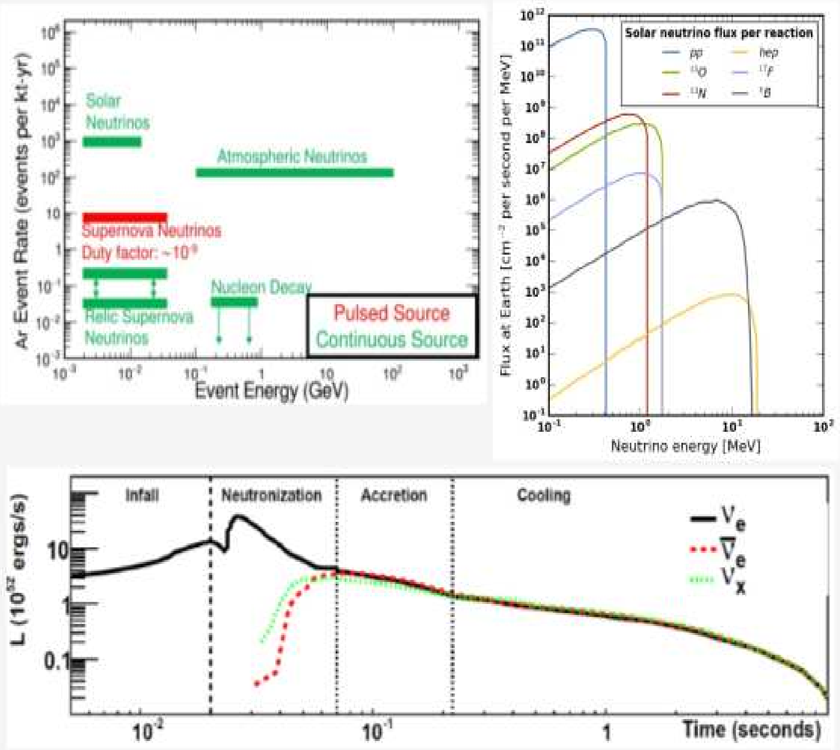


Beyond three flavors

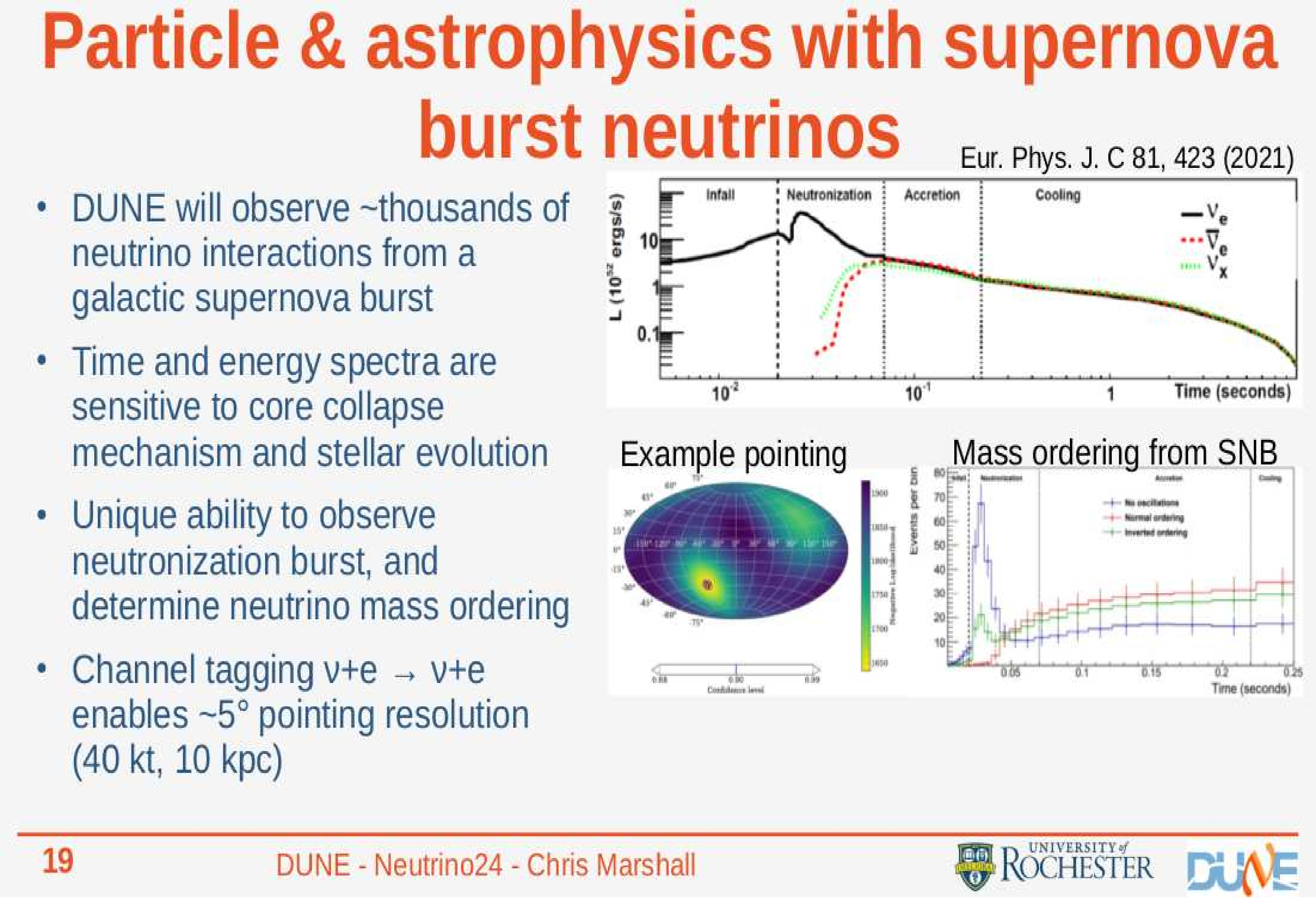
Eur. Phys. J. C 81, 322 (2021)

- Broad range of L/E at ND and FD → search for non-SM oscillations
- High statistics neutrino and antineutrino measurements → search for CPT violation
- Very large matter effect → uniquely sensitive to some NSI

Natural neutrino sources at DUNE FD



- DUNE FD will observe atmospheric, solar, and supernova neutrinos
- Argon target gives unique sensitivity to MeV-scale electron neutrinos
  - $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ ($E_\nu > 1.5$ MeV)
  - $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$ ($E_\nu > 7.5$ MeV)
  - $\nu_x + e^- \rightarrow \nu_x + e^-$ (pointing)
- Highly complementary to other experiments (Hyper-K, JUNO) that predominantly see $\bar{\nu}_e$ via IBD



Particle & astrophysics with supernova burst neutrinos

Eur. Phys. J. C 81, 423 (2021)

- DUNE will observe ~thousands of neutrino interactions from a galactic supernova burst
- Time and energy spectra are sensitive to core collapse mechanism and stellar evolution
- Unique ability to observe neutronization burst, and determine neutrino mass ordering
- Channel tagging ν+e → ν+e enables ~5° pointing resolution (40 kt, 10 kpc)

UNIVERSITY of ROCHESTER

DUNE

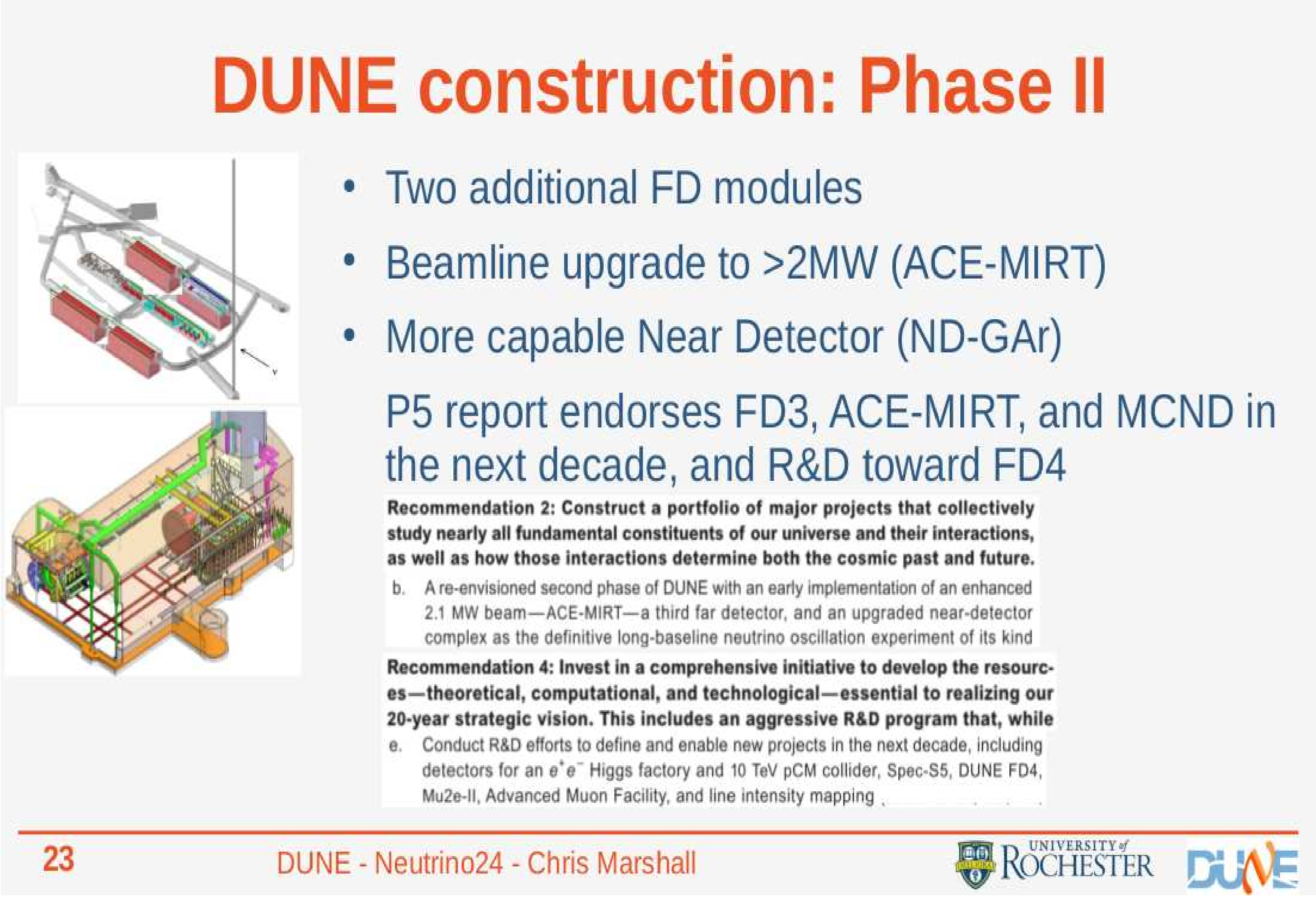
DUNE construction: Phase I

- Full Near and Far Site facility
- Two LArTPC modules (VD & HD), each 17 kt Ar
- 1.2 MW upgradeable neutrino beamline
- Movable LArTPC ND+muon catcher, SAND

Completing Phase I is highest priority in P5 report:

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos.



DUNE construction: Phase II

- Two additional FD modules
- Beamline upgrade to >2MW (ACE-MIRT)
- More capable Near Detector (ND-GAr)

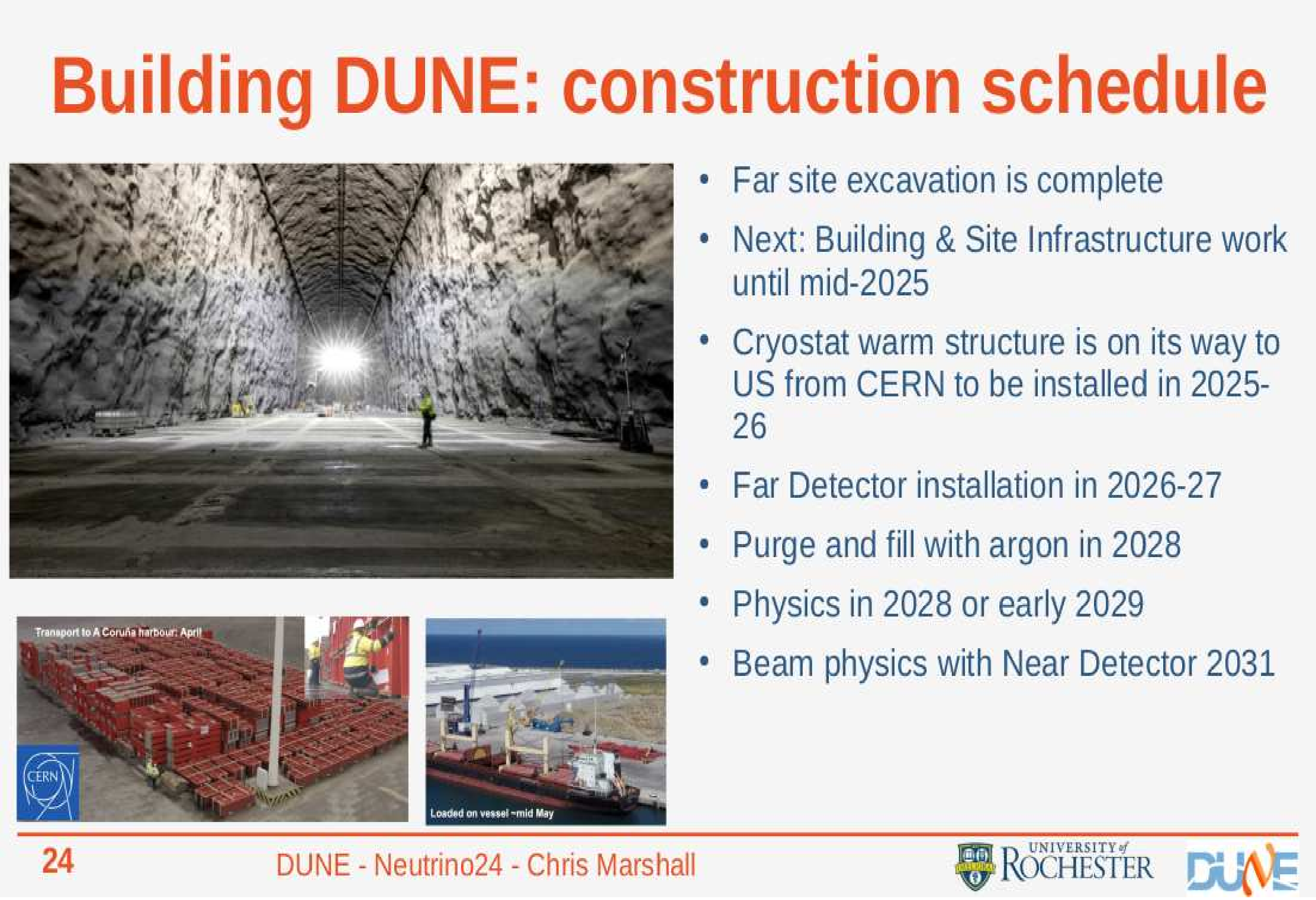
P5 report endorses FD3, ACE-MIRT, and MCND in the next decade, and R&D toward FD4

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

b. A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind

Recommendation 4: Invest in a comprehensive initiative to develop the resources—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an aggressive R&D program that, while

e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping



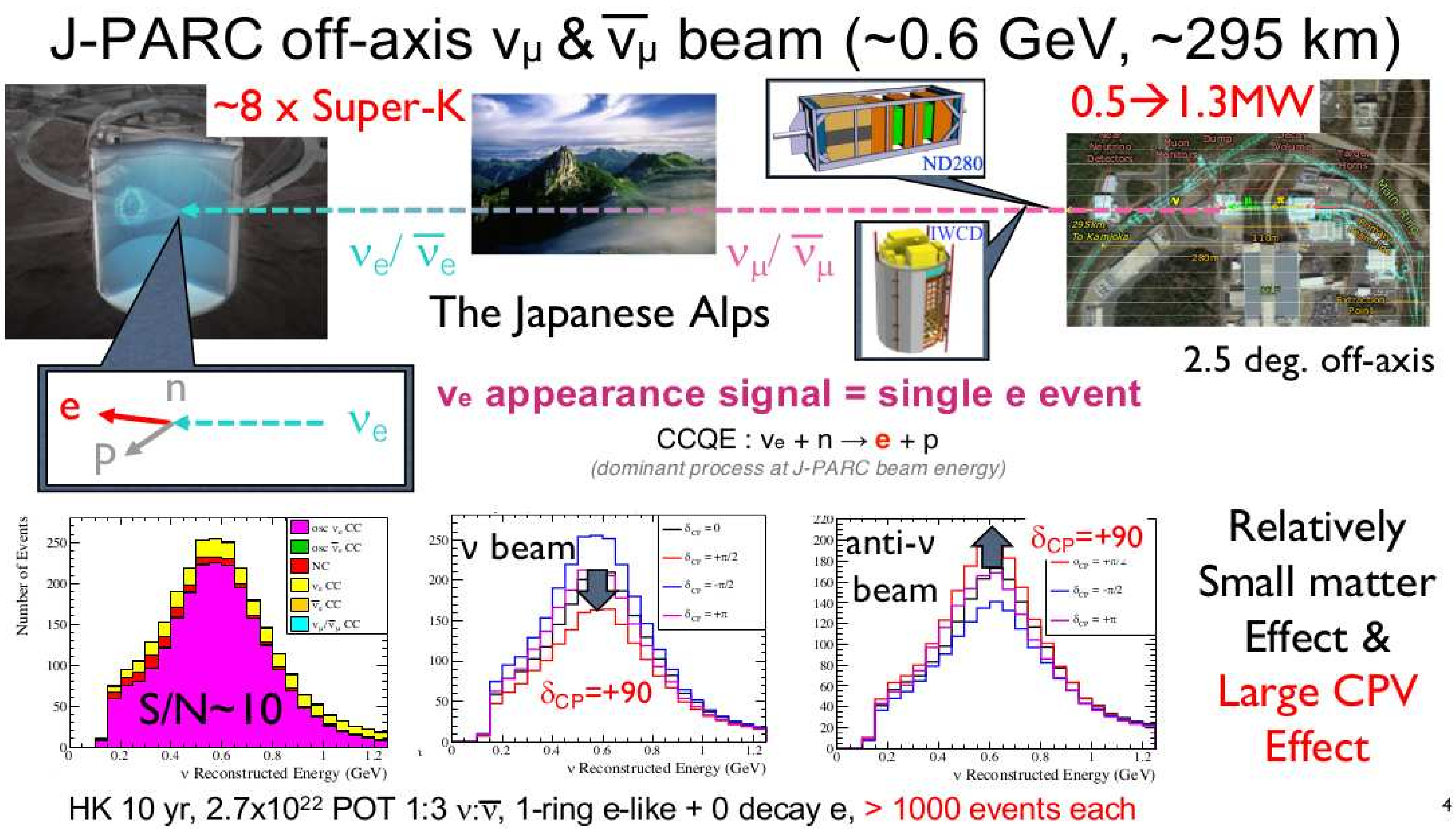
Building DUNE: construction schedule

- Far site excavation is complete
- Next: Building & Site Infrastructure work until mid-2025
- Cryostat warm structure is on its way to US from CERN to be installed in 2025-26
- Far Detector installation in 2026-27
- Purge and fill with argon in 2028
- Physics in 2028 or early 2029
- Beam physics with Near Detector 2031

Hyper-Kamiokande and T2HK

Hyper-Kamiokande: water-Cherenkov, $\sim$ 025 Mton, fiducial $\sim$ 0.2 Mton; 2027; T2HK.

The next slides are from the talk by S. Muriyama at Neutrino 2024.



J-PARC off-axis ν_μ & $\overline{\nu}_\mu$ beam (~0.6 GeV, ~295 km)

~8 x Super-K

0.5→1.3MW

$\nu_e / \overline{\nu}_e$

$\nu_\mu / \overline{\nu}_\mu$

The Japanese Alps

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 $\nu:\overline{\nu}$, 1-ring e-like + 0 decay e, > 1000 events each

Atmospheric 3-flavor ν beam (0.1-10^3 GeV, 10-13,000 km)

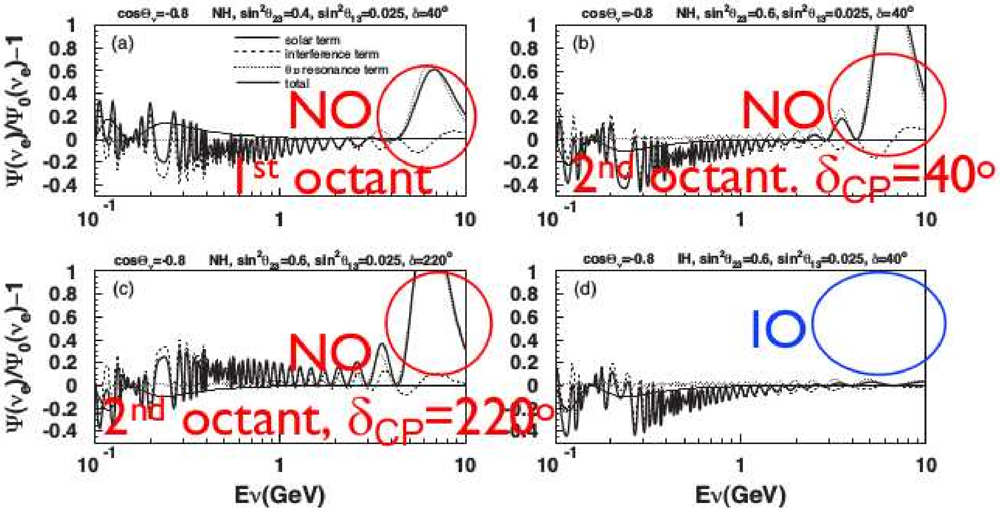
- The wide range of E (0.1~10^3 GeV) and L (10 km⬇~13,000 km⬆) provide an excellent opportunity to study various properties of ν.
- Study of the earth matter effect to determine neutrino mass ordering
- Unique tests of exotic properties

~80 events/day

Oscillation studies with wide range of E and L. The matter effect solves MO.

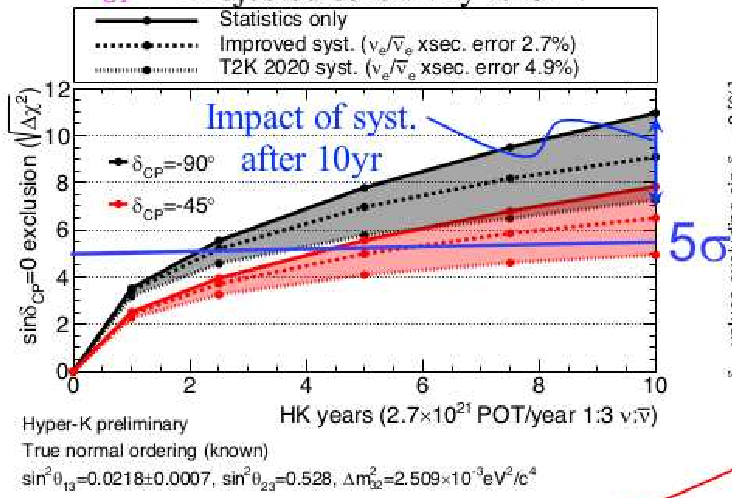
In case of $\cos\Theta_\nu$=-0.8, the effect of MO can be observed.

Effect of Mass Ordering (MO) and $\not{C}P$ on ν_e flux



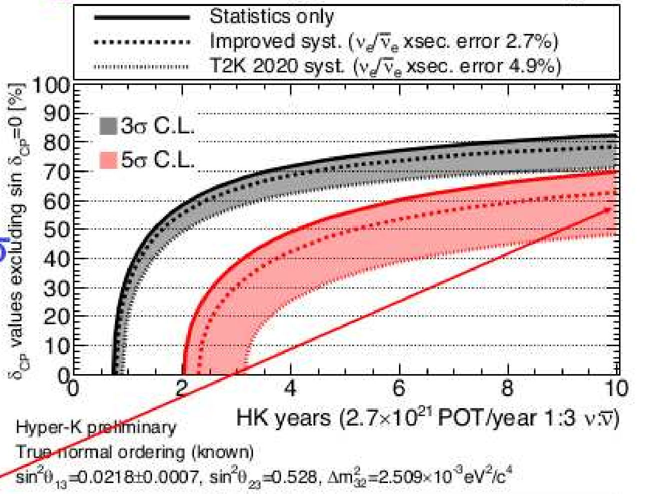
Precision measurement of neutrino oscillations

δ_{CP} Projected sensitivity to CPV



Hyper-K preliminary
True normal ordering (known)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

δ_{CP} Fraction of δ_{CP} to exclude $\sin\delta_{CP}=0$



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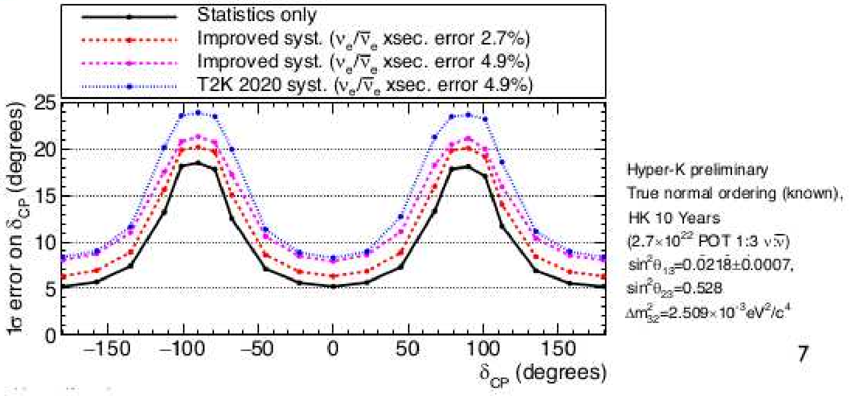
Discovery of CP violation at >5 σ for >60% of δ_{CP}

1σ resolution of δ_{CP} in 10 yrs

~20° for $\delta_{cp} = -90°$ / ~6° for $\delta_{cp} = 0°$

Reduction of systematic uncertainty has sizable impact:

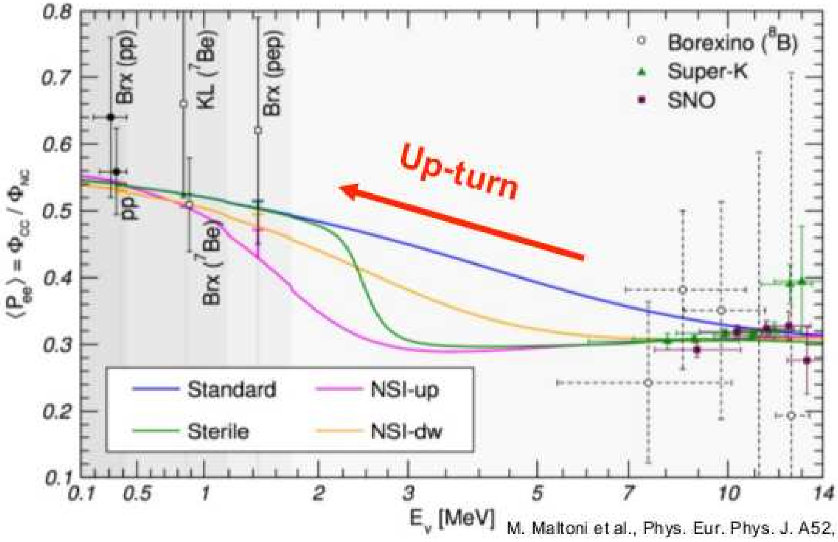
- Upgrade of ND280 + ~600 ton Intermediate Water Cherenkov detector (IWCD)
- Aim to suppress detector error below 1%



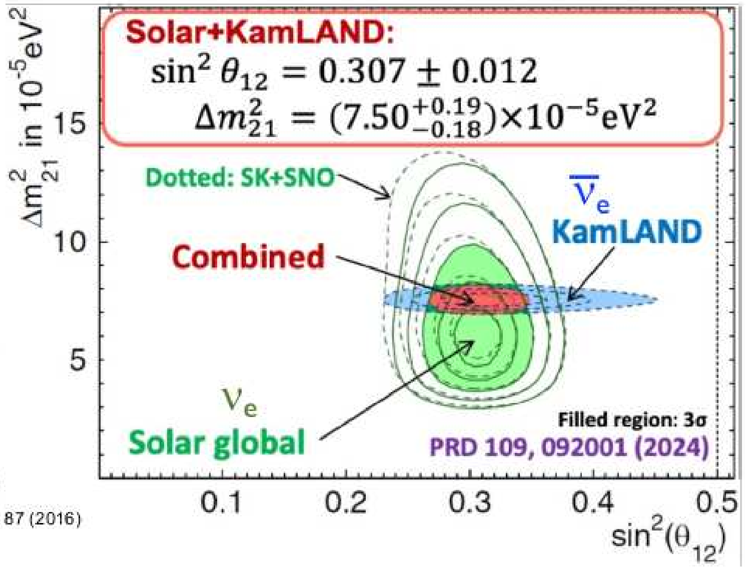
Solar ν spectrum & possible differences in $\nu_e/\bar{\nu}_e$ oscillation

Confirm MSW effect by observing spectrum distortion "up-turn"

Compare ν_e, $\bar{\nu}_e$ oscillation (currently ~1.5σ tension in solar/reactor ν)



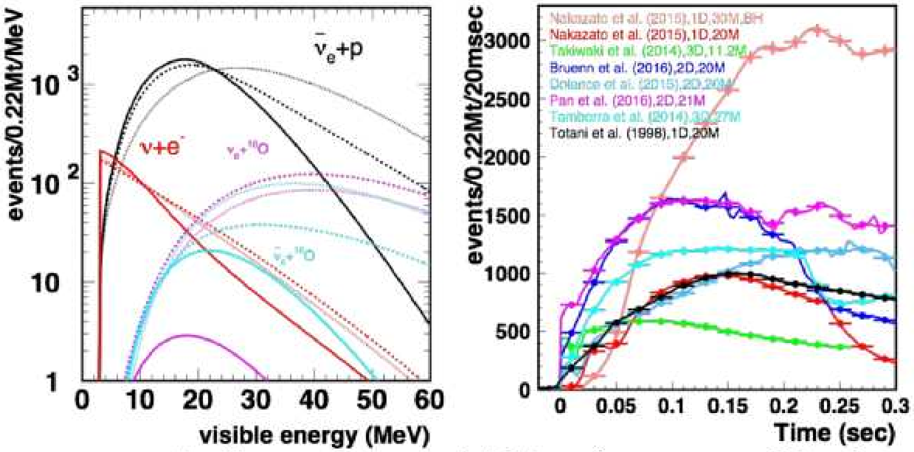
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)



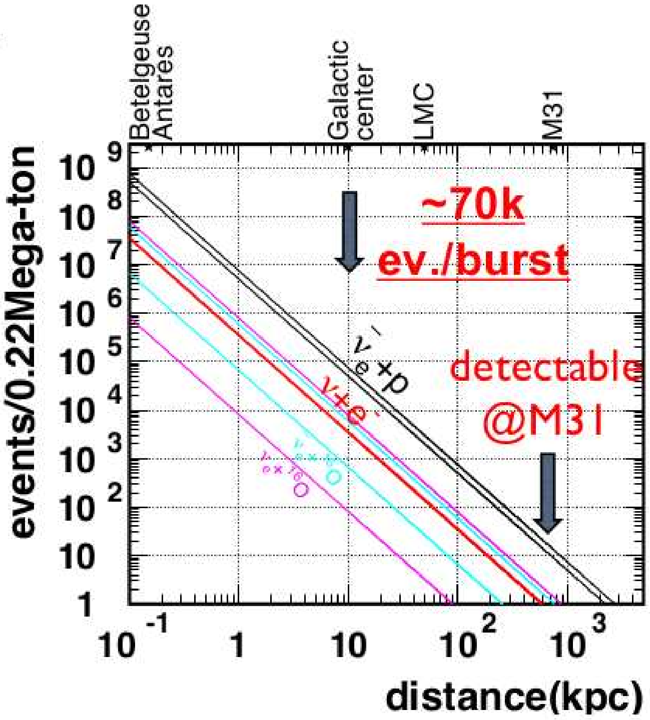
~130 events/day

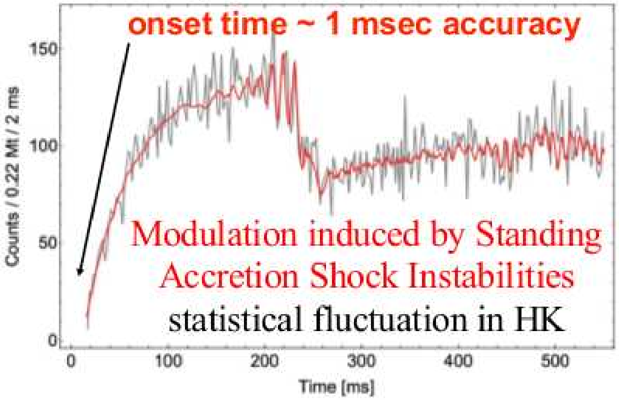
- > 3σ sensitivity for the spectrum up-turn in 10 yrs (E_{th}=4.5 MeV).
- ~2σ day/night sensitivity expected for the difference in $\nu_e/\bar{\nu}_e$ osc. in 20 yrs.

Astrophysics: Supernova burst ν



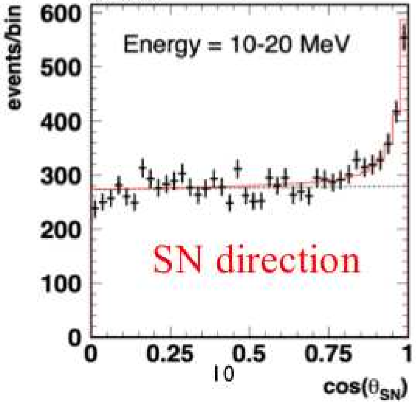
galactic supernova at 10 kpc (our r_{galaxy}= 8 kpc)





Modulation induced by Standing Accretion Shock Instabilities

statistical fluctuation in HK



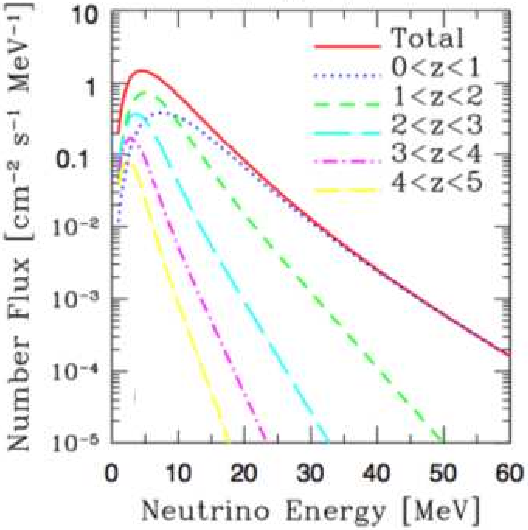
SN direction

~70k events/burst at 10 kpc

- explosion mechanism,
- BH/NS formation,
- alert with 1° pointing

Diffuse Supernova Neutrino Background (DSNB)

DSNB energy spectrum
including red shift

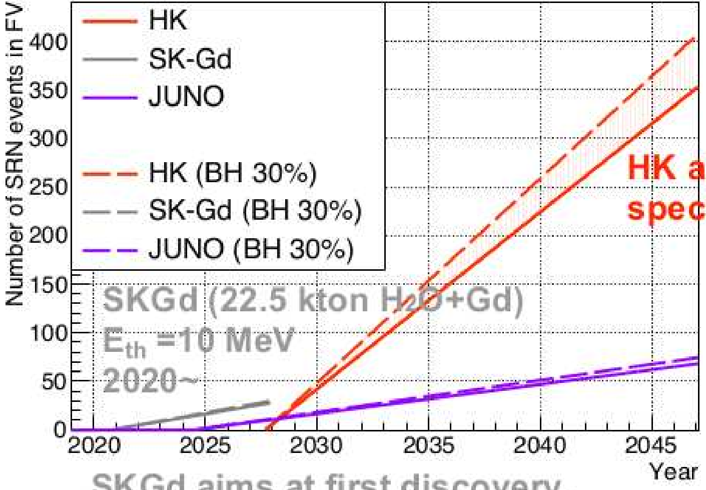


S. Ando and K. Sato, New J. Phys. 6, 170 (2004)

$$\frac{dF_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{\rm max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}\frac{dz}{\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}},$$

Neutrinos from supernova explosions
in the early universe to the present day
integrated flux ~10 $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$

Number of DSNB events
before neutron tagging



HK (187 kton H_2O)
E_{th} =16 MeV
2027~

HK aims for precise flux & spectrum measurement.

SKGd (22.5 kton H_2O+Gd)
E_{th} =10 MeV
2020~

JUNO (20 kt LS)
E_{th} =12 MeV
2024~

SKGd aims at first discovery.

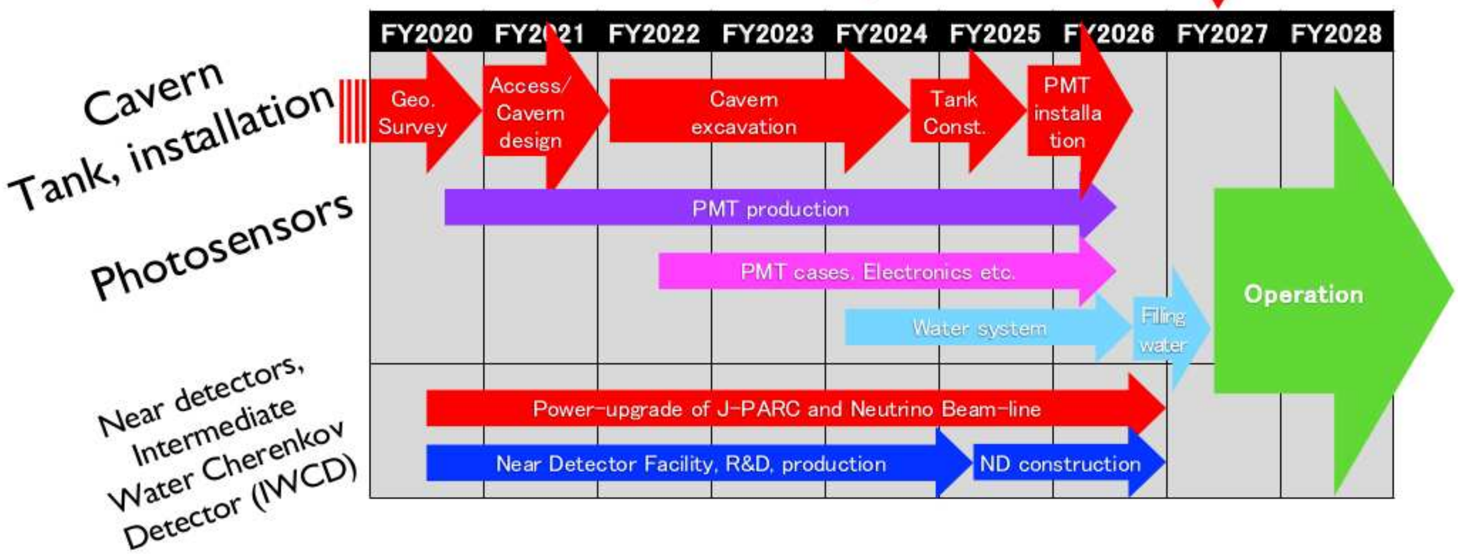
~4 ev/yr after neutron tagging w/ H_2O

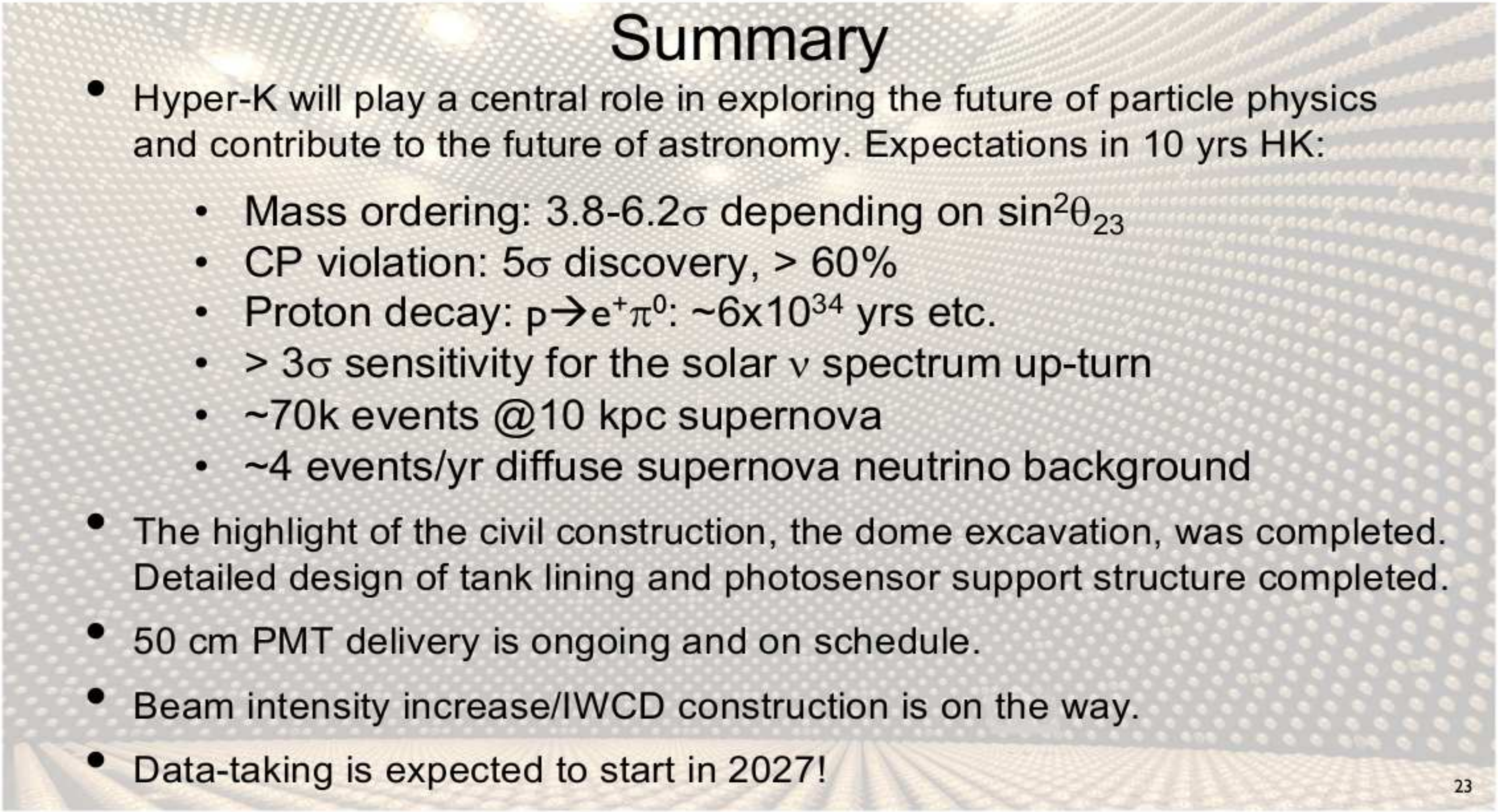
- Stellar collapse
- Star formation rate
- Heavy element synthesis

Construction Schedule

- We are here June 2024

- Aiming at operation start in 2027.





Summary

- Hyper-K will play a central role in exploring the future of particle physics and contribute to the future of astronomy. Expectations in 10 yrs HK:
  - Mass ordering: 3.8-6.2σ depending on $\sin^2\theta_{23}$
  - CP violation: 5σ discovery, > 60%
  - Proton decay: $p \rightarrow e^+\pi^0$: ~$6\text{x}10^{34}$ yrs etc.
  - > 3σ sensitivity for the solar ν spectrum up-turn
  - ~70k events @10 kpc supernova
  - ~4 events/yr diffuse supernova neutrino background
- The highlight of the civil construction, the dome excavation, was completed. Detailed design of tank lining and photosensor support structure completed.
- 50 cm PMT delivery is ongoing and on schedule.
- Beam intensity increase/IWCD construction is on the way.
- Data-taking is expected to start in 2027!

The Neutrino Mixing Problem

The most elegant, simple and testable solution of the neutrino mixing problem is arguably provided by the non-Abelian discrete symmetry approach.

In what concerns the lepton flavour problem, in the last 5 years a very successful and attractive approach based on Modular Invariance has been and continues to be developed.

The measurement of the Dirac phase in the PMNS mixing matrix, together with an improvement of the precision on the mixing angles θ_{12}, θ_{13} and θ_{23}, can provide unique information about the possible existence of new fundamental symmetry in the lepton sector at the origin of the pattern of neutrino mixing (1405.6006, 1410.8056, 1504.00658, 1711.10806, 1711.02107, 1804.00182...).

Prospective (useful/requested) precision:

$\delta(\sin^2\theta_{12}) = 0.7\%$ **(JUNO),**

$\delta(\sin^2\theta_{13}) = 3\%$ **(Daya Bay),**

$\delta(\sin^2\theta_{23}) = 3\%$ **(T2HK, DUNE; T2K+NOνA(?)).**

$\delta(\delta) \leq 14^\circ$ **at** $\delta = 3\pi/2$

(THKK?; DUNE: accounting for both the 1st and 2nd probability maxima, Jogesh Rout, Poonam Mehta et al., PRD 2021, S. Goswami et al., 2012.04958; ESSnuSB)

Together with the determination of the NMO and the value of $\min(m_{\nu_i})$ **– power tests of theories of** ν**-mixing and, more generally, of lepton flavour.**

Conclusions

We are heading to a period in which some of the fundamental questions in neutrino physics, and more genereally, in particle and astroparticle physics - the status of CP symmetry in the lepton sector and its possible implications for the generation of BAU, the type of spectrum neutrino masses obey, the origin of the patterns of neutrino masses and mixing (symmetry?), the value of the absolute neutrino mass scale, and possibly the nature - Dirac or Majorana - of massive neutrinos, will be answered. This will have profound implications for particle and astroparticle physics, for astrophysics and cosmology.

The program of research in neutrino physics extends beyond 2035.

The future of neutrino physics is bright.