Karlsruher Institut für Technologie

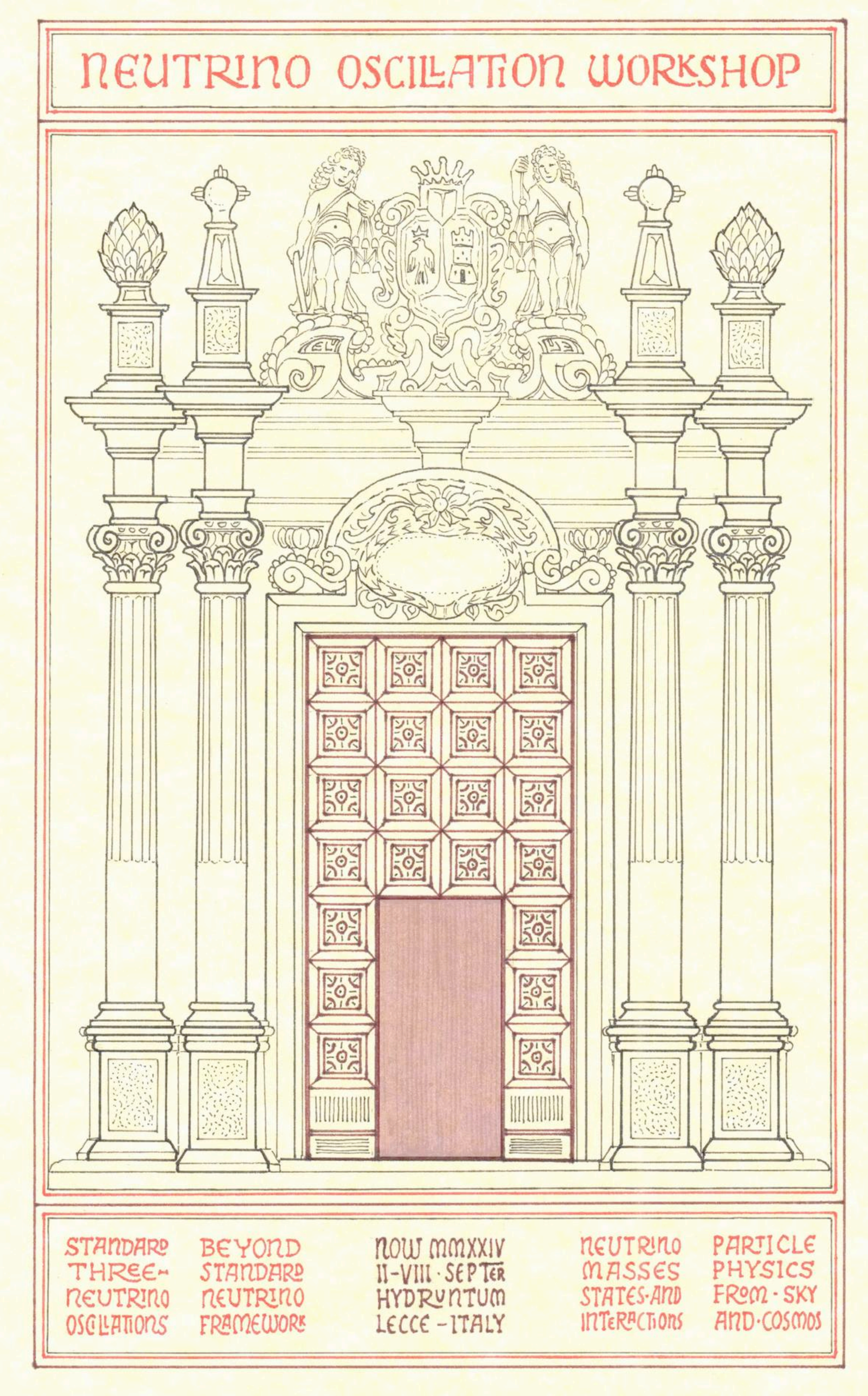
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

NOW 2024 — Concluding Talk

Otranto, 7 Sept 2024

Thomas Schwetz

Karlsruhe Institute of Technology
Institute for Astroparticle Physics



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not „Summary Talk“!

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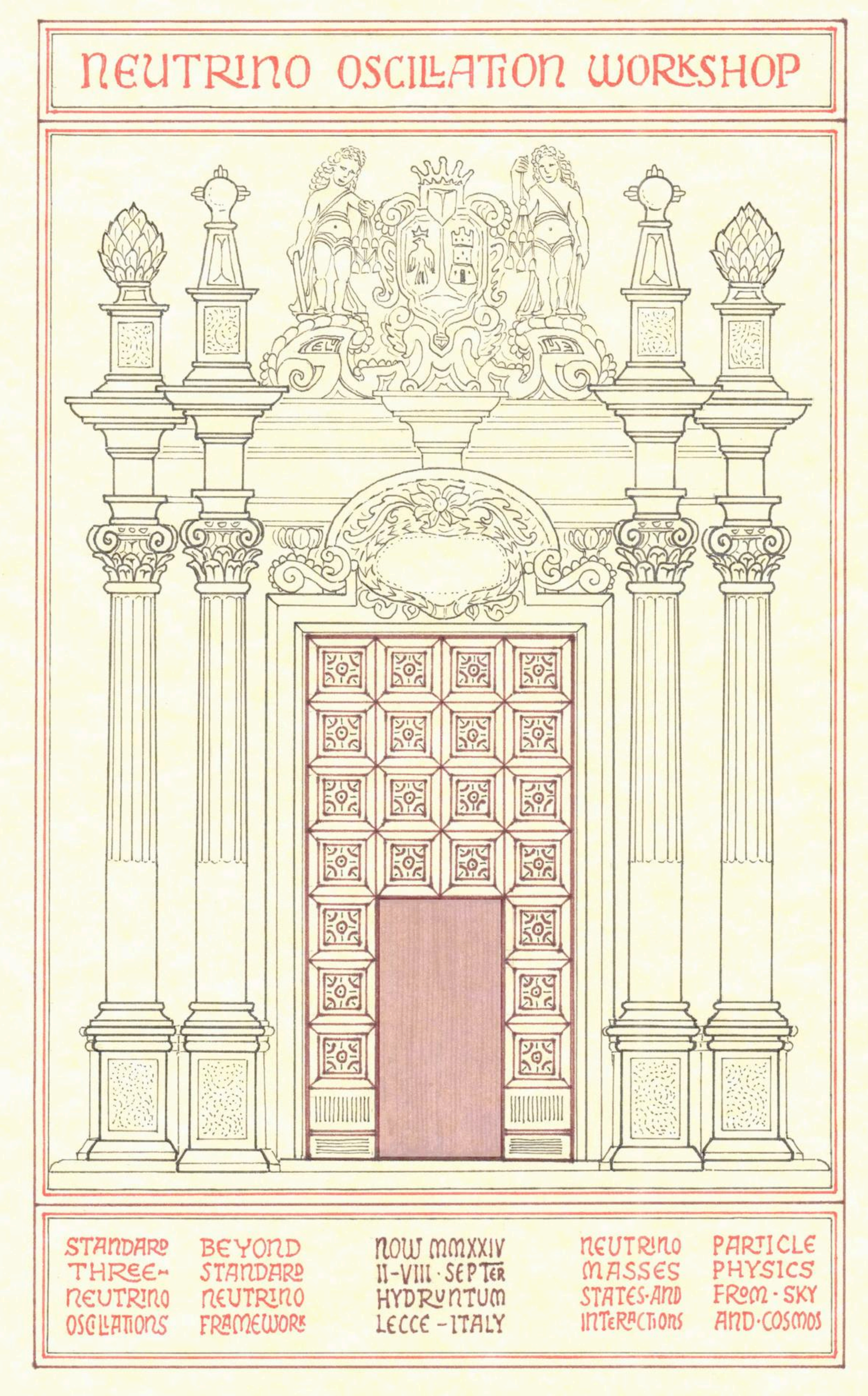

email from NOW2024 organizers

„The concluding talk is not meant to summarize the NOW 2024 contributions, although you may refer to some of the workshop talks if you wish. The talk is mainly expected to convey your personal "vision" for the short-term and especially long-term prospects in neutrino physics and, more generally, in astroparticle physics.“

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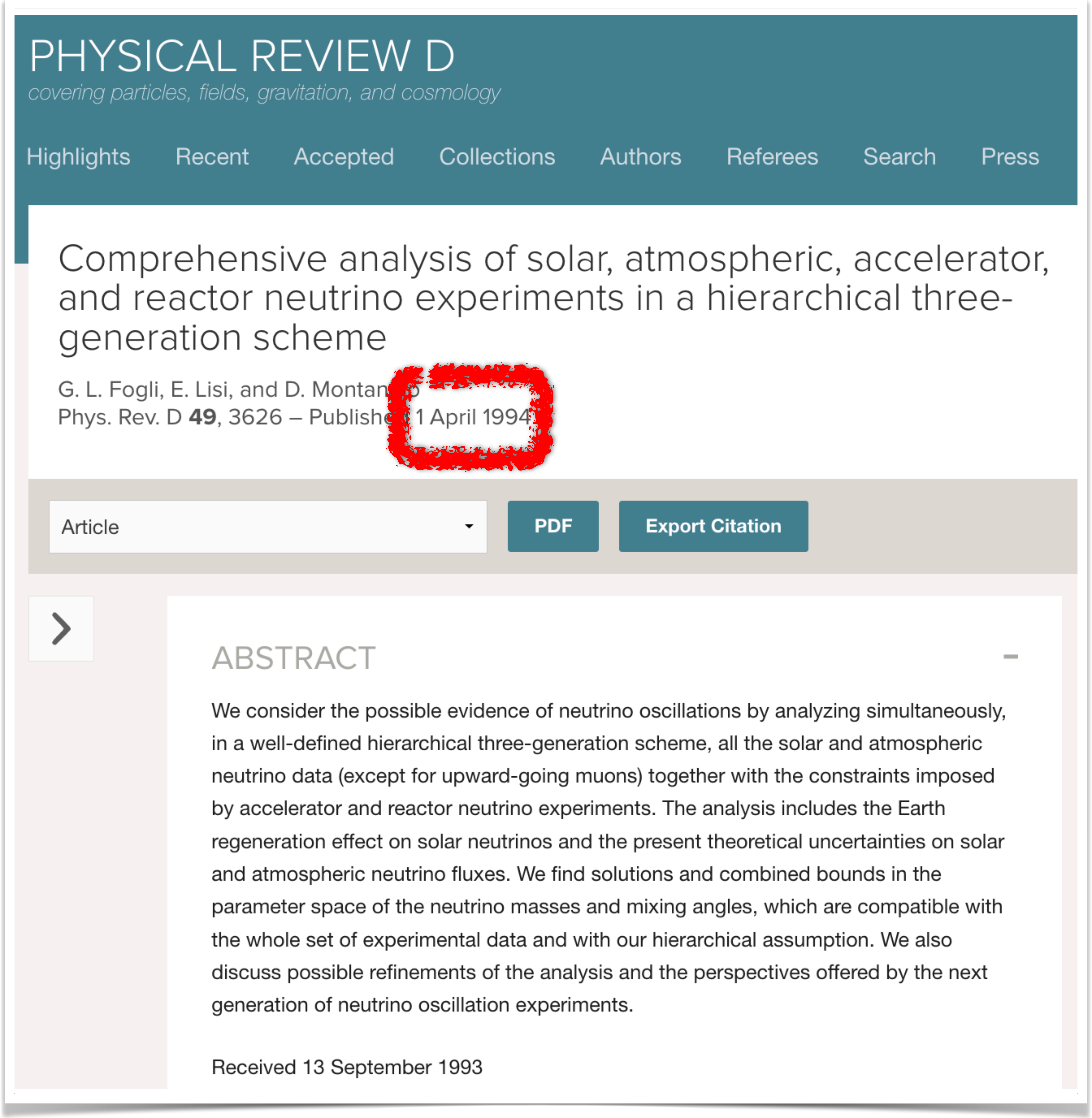
⇒ my talk will be very personally biased,
apologizes for omissions and incompleteness

an anniversary: 30 years of global analyses

. . . .

- *Nobel 1995 to Cowan for neutrino observation*
- *Nobel 2002 to Davis and Koshiba for neutrino astronomy*
- *Nobel 2015 to Kajita & McDonald for neutrino oscillations*

F. Vissani



Comprehensive analysis of solar, atmospheric, accelerator, and reactor neutrino experiments in a hierarchical three-generation scheme

G. L. Fogli, E. Lisi, and D. Montan
Phys. Rev. D **49**, 3626 – Publishe 1 April 1994

ABSTRACT

We consider the possible evidence of neutrino oscillations by analyzing simultaneously, in a well-defined hierarchical three-generation scheme, all the solar and atmospheric neutrino data (except for upward-going muons) together with the constraints imposed by accelerator and reactor neutrino experiments. The analysis includes the Earth regeneration effect on solar neutrinos and the present theoretical uncertainties on solar and atmospheric neutrino fluxes. We find solutions and combined bounds in the parameter space of the neutrino masses and mixing angles, which are compatible with the whole set of experimental data and with our hierarchical assumption. We also discuss possible refinements of the analysis and the perspectives offered by the next generation of neutrino oscillation experiments.

Received 13 September 1993

Valencia **NuFit** **Bari**

JHEP Published for SISSA by Springer

Received: *June 30, 2020*
Revised: *November 27, 2020*
Accepted: *December 29, 2020*
Published: *February 9, 2021*

2020 global reassessment of the neutrino oscillation picture

P.F. de Salas,[a] **D.V. Forero,**[b] **S.**
C.A. Ternes,[c,d] **M. Tórtola**[c,e] **an**

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AlbaNova, 10691 Stockholm, Swede
[b] *Universidad de Medellín,*
Carrera 87 N° 30-65, Medellín, C
[c] *Instituto de Física Corpuscular, C*
46980 Paterna, Spain
[d] *INFN, Sezione di Torino,*
Via P. Giuria 1, I-10125 Torino,
[e] *Departament de Física Teòrica, U*
46100 Burjassot, Spain
E-mail: pablo.fernandez@fysi
gariazzo@to.infn.it, pamarmi
chternes@ific.uv.es, mariam

Abstract: We present an updat
three-neutrino framework. In th
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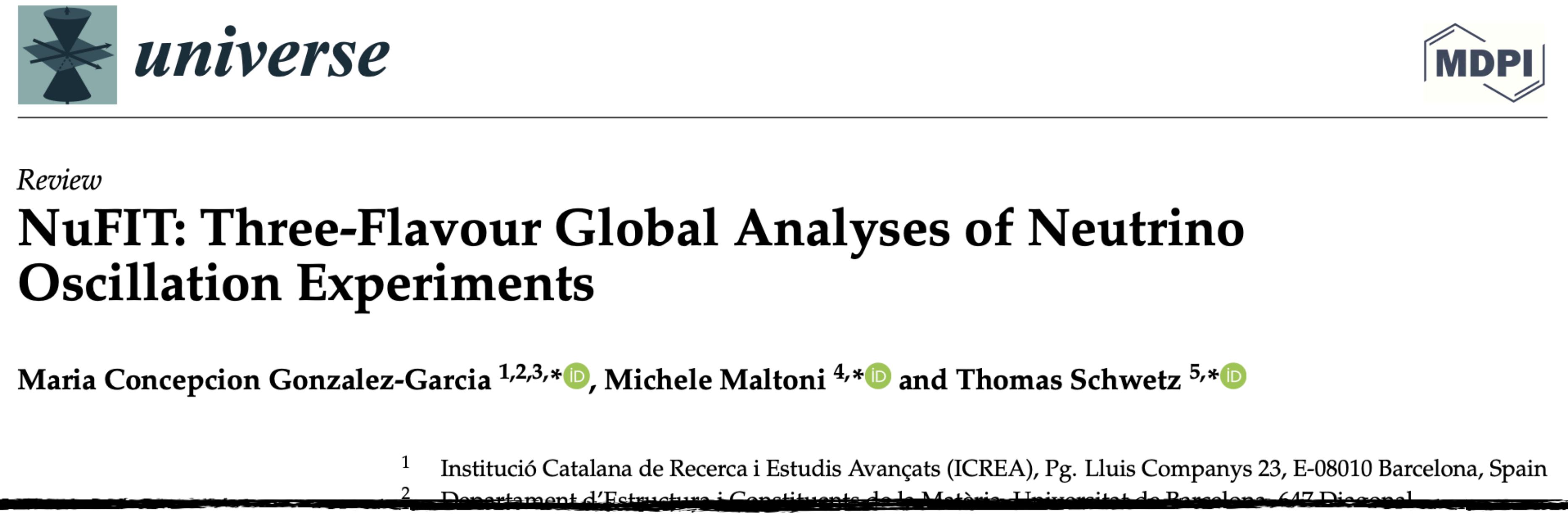
data collected by the Daya Bay an
and NOνA measurements, as reported in the Neutrino 2020 conference. All in all, these new analyses result in more accurate measurements of θ_{13}, θ_{12}, Δm^2_{21} and $|\Delta m^2_{31}|$. The best fit value for the atmospheric angle θ_{23} lies in the second octant, but first octant solutions remain allowed at $\sim 2.4\sigma$. Regarding CP violation measurements, the preferred value of δ we obtain is 1.08π (1.58π) for normal (inverted) neutrino mass ordering. The global analysis still prefers normal neutrino mass ordering with 2.5σ statistical significance. This



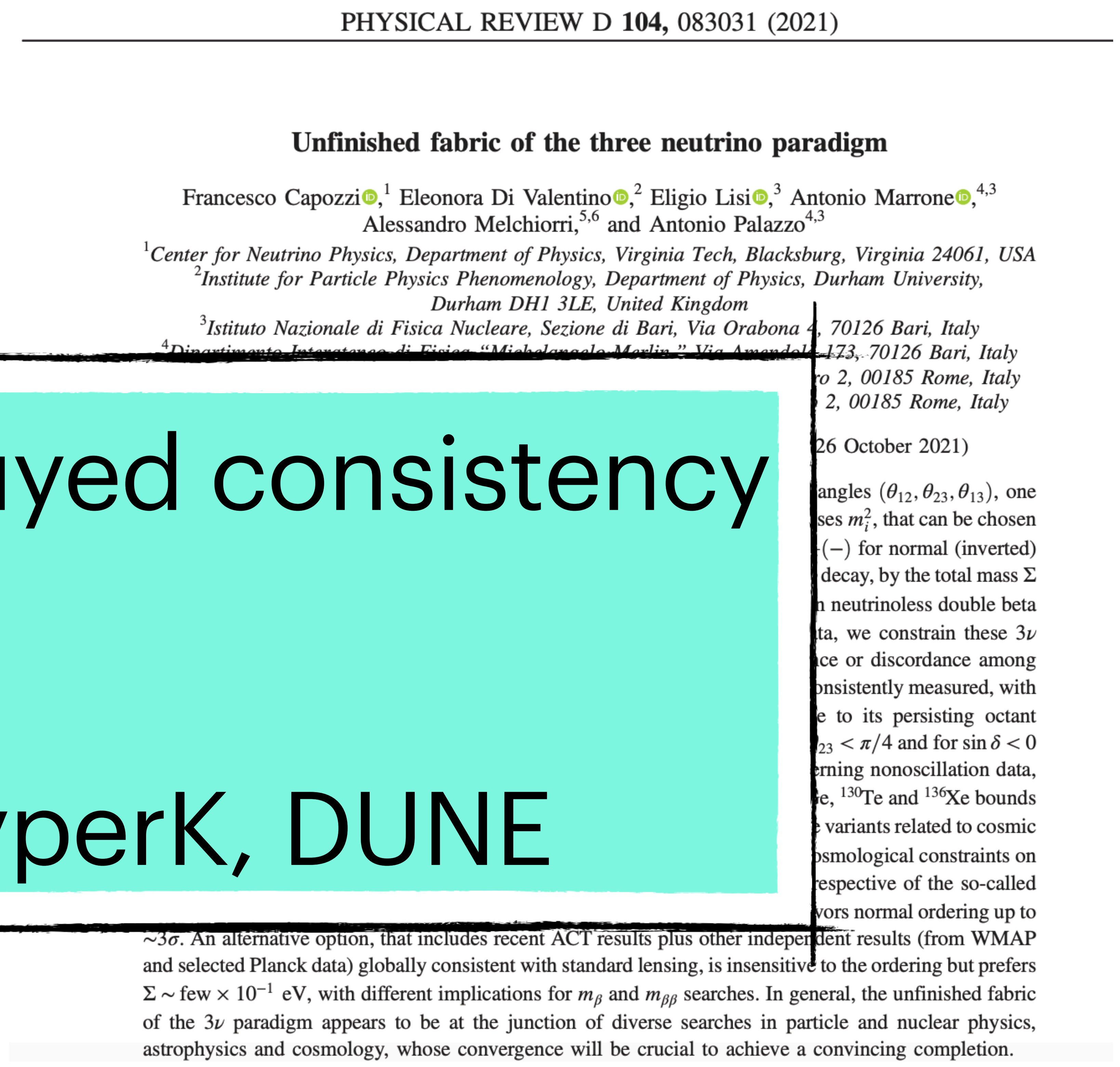
universe MDPI

Review

NuFIT: Three-Flavour Global Analyses of Neutrino Oscillation Experiments

Maria Concepcion Gonzalez-Garcia [1,2,3,*], **Michele Maltoni** [4,*] **and Thomas Schwetz** [5,*]

[1] Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluis Companys 23, E-08010 Barcelona, Spain



PHYSICAL REVIEW D **104,** 083031 (2021)

Unfinished fabric of the three neutrino paradigm

Francesco Capozzi,[1] Eleonora Di Valentino,[2] Eligio Lisi,[3] Antonio Marrone,[4,3]
Alessandro Melchiorri,[5,6] and Antonio Palazzo[4,3]

[1] *Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*
[2] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom*
[3] *Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Via Orabona 4, 70126 Bari, Italy*
173, 70126 Bari, Italy
o 2, 00185 Rome, Italy
2, 00185 Rome, Italy

26 October 2021)

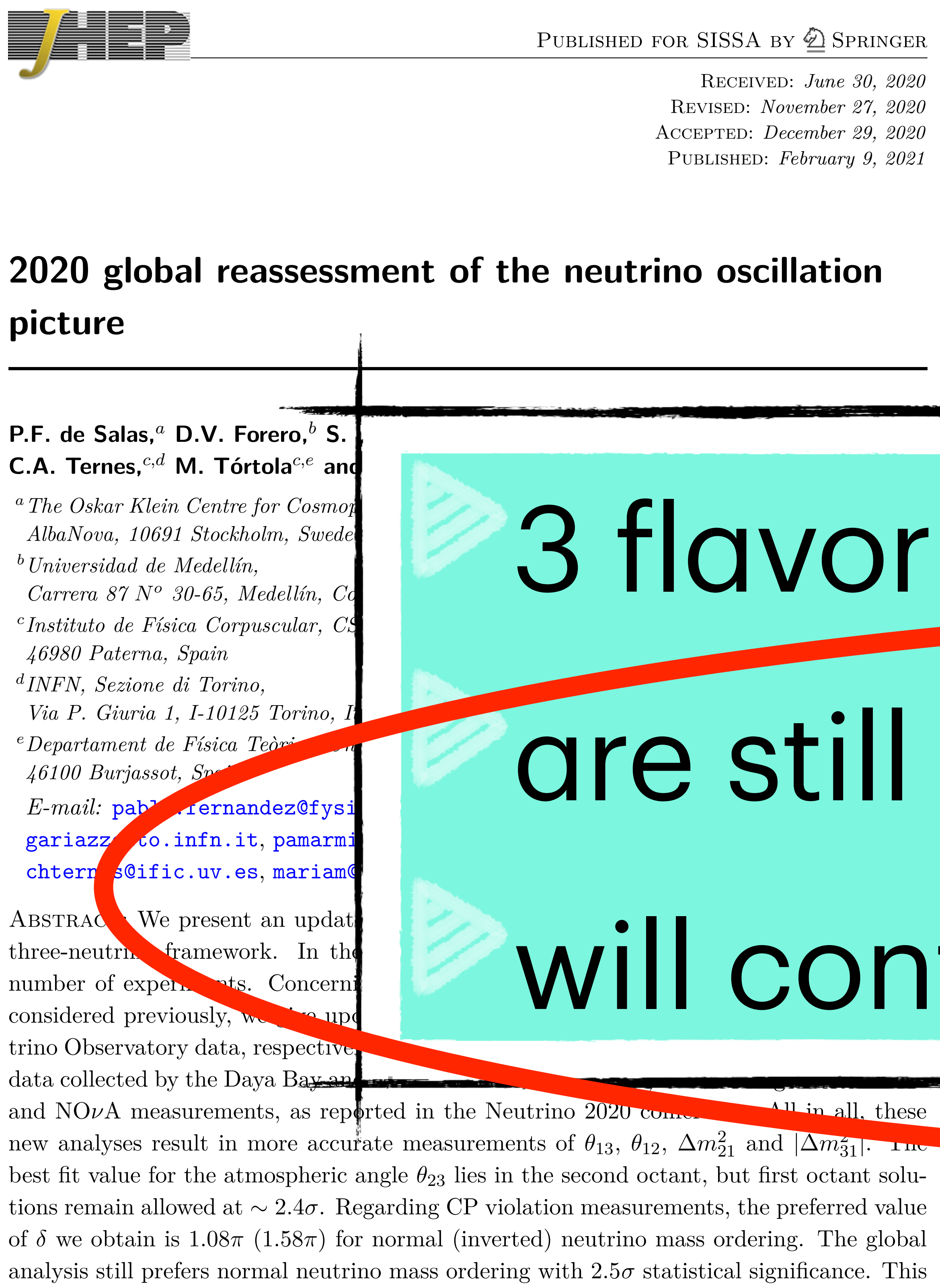
angles ($\theta_{12}, \theta_{23}, \theta_{13}$), one
ses m_i^2, that can be chosen
$(-)$ for normal (inverted)
decay, by the total mass Σ
neutrinoless double beta
ta, we constrain these 3ν
ce or discordance among
nsistently measured, with
e to its persisting octant
$_{23} < \pi/4$ and for $\sin\delta < 0$
rning nonoscillation data,
e, ^{130}Te and ^{136}Xe bounds
variants related to cosmic
smological constraints on
espective of the so-called
vors normal ordering up to
$\sim 3\sigma$. An alternative option, that includes recent ACT results plus other independent results (from WMAP and selected Planck data) globally consistent with standard lensing, is insensitive to the ordering but prefers $\Sigma \sim$ few $\times 10^{-1}$ eV, with different implications for m_β and $m_{\beta\beta}$ searches. In general, the unfinished fabric of the 3ν paradigm appears to be at the junction of diverse searches in particle and nuclear physics, astrophysics and cosmology, whose convergence will be crucial to achieve a convincing completion.

- 3 flavor analyses have always displayed consistency
- are still crucial after so many years
- will continue to be so after JUNO, HyperK, DUNE

F. Vissani

s. also talk by W. Shorrock

Valencia | **NuFit** | **Bari**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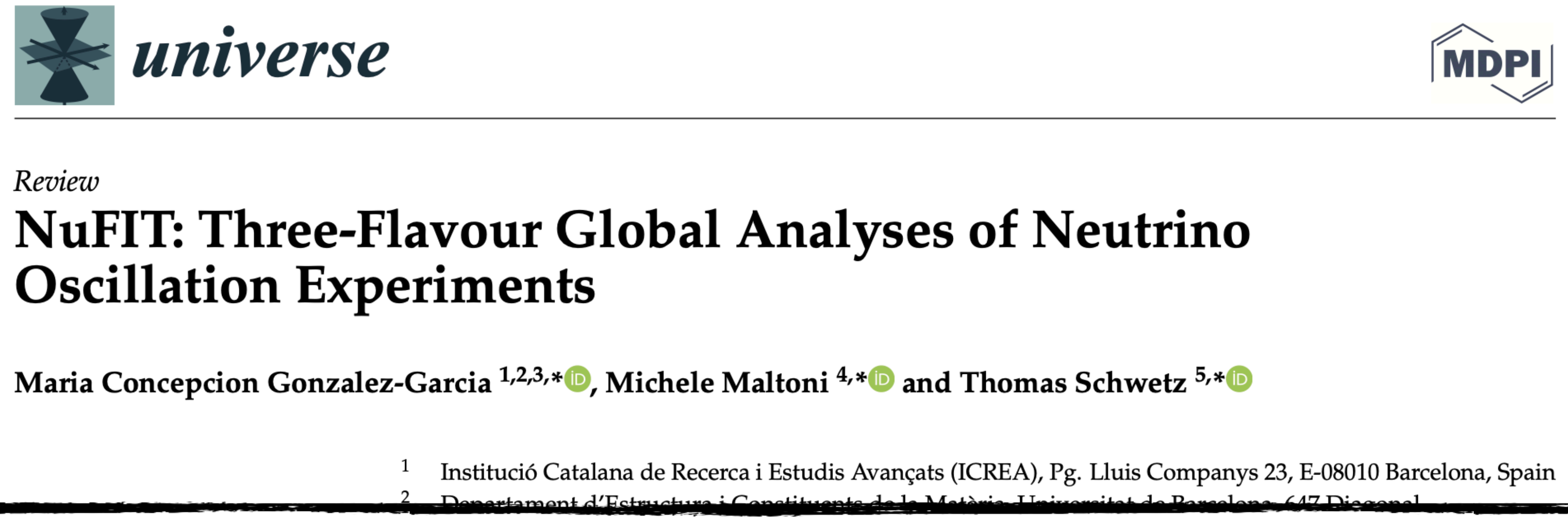
universe

MDPI

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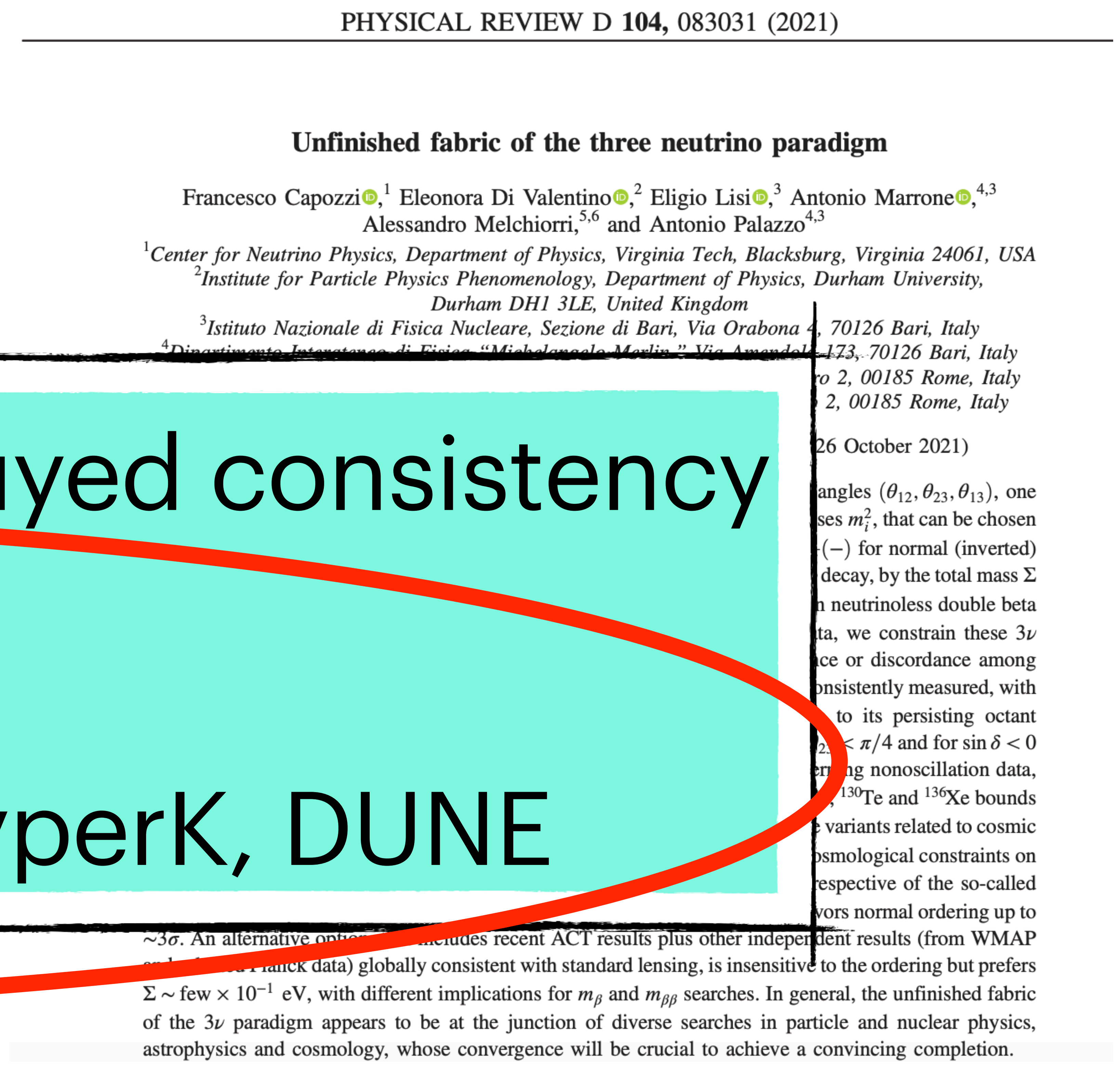
Maria Concepcion Gonzalez-Garcia [1,2,3,*], Michele Maltoni [4,*] and Thomas Schwetz [5,*]

1 Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluis Companys 23, E-08010 Barcelona, Spain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~3σ. An alternative option includes recent ACT results plus other independent results (from WMAP and Planck data) globally consistent with standard lensing, is insensitive to the ordering but prefers $\Sigma \sim$ few $\times 10^{-1}$ eV, with different implications for m_β and $m_{\beta\beta}$ searches. In general, the unfinished fabric of the 3ν paradigm appears to be at the junction of diverse searches in particle and nuclear physics, astrophysics and cosmology, whose convergence will be crucial to achieve a convincing completion.

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F. Vissani

s. also talk by W. Shorrock

Karlsruher Institut für Technologie

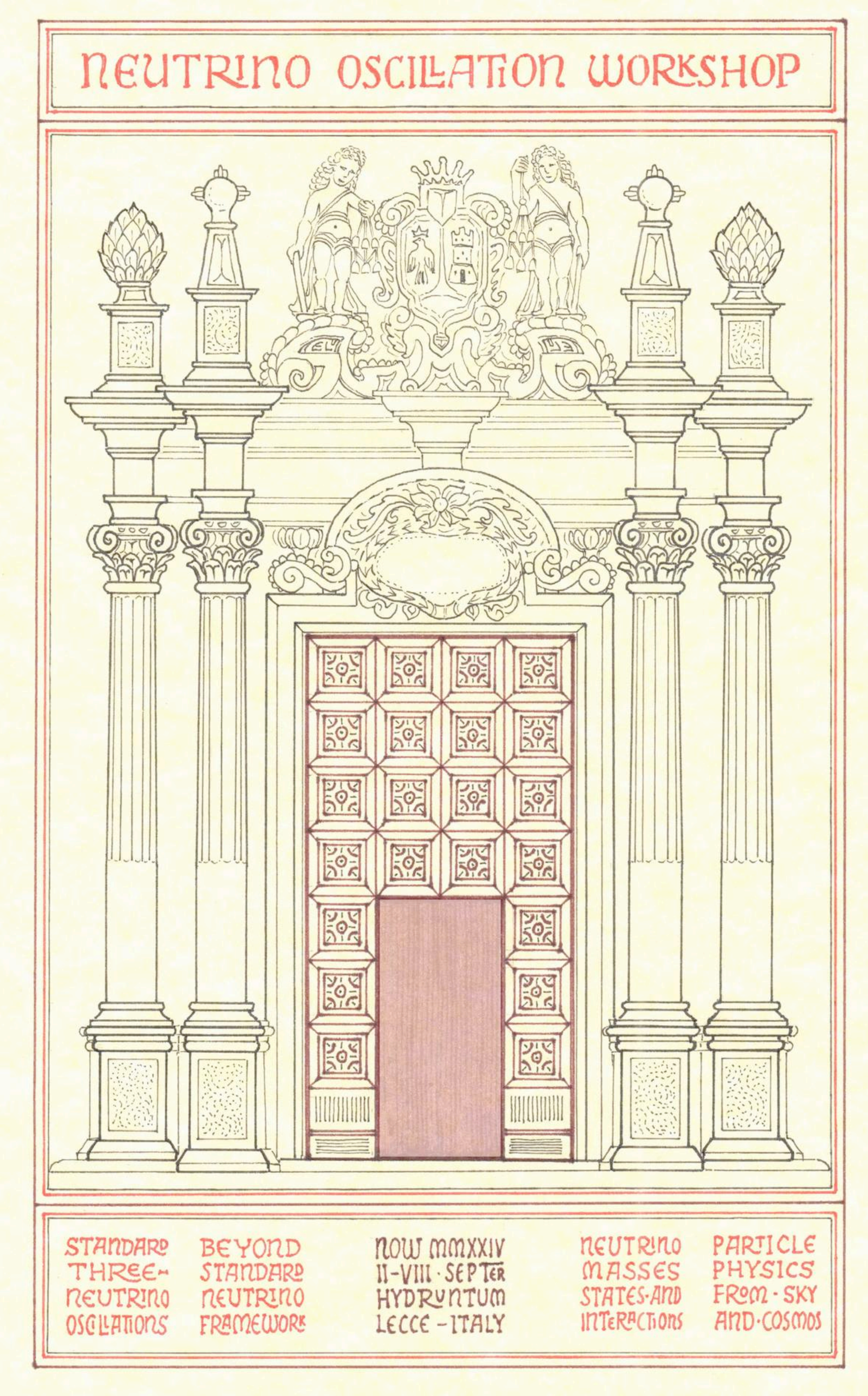
HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

NOW 2024 — Concluding Talk:
Global analyses now and in the future

Otranto, 7 Sept 2024

Thomas Schwetz

Karlsruhe Institute of Technology
Institute for Astroparticle Physics

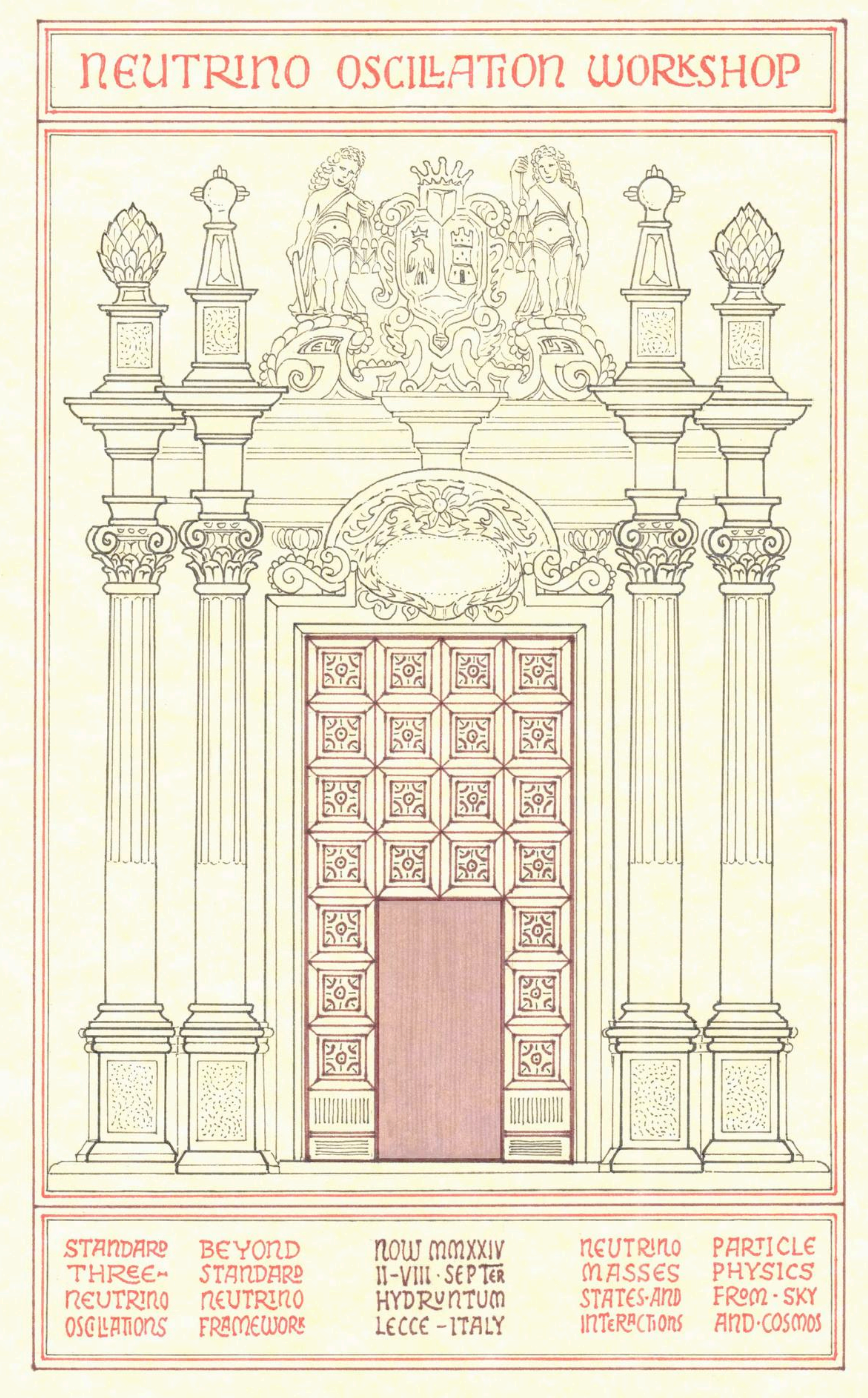


Outline

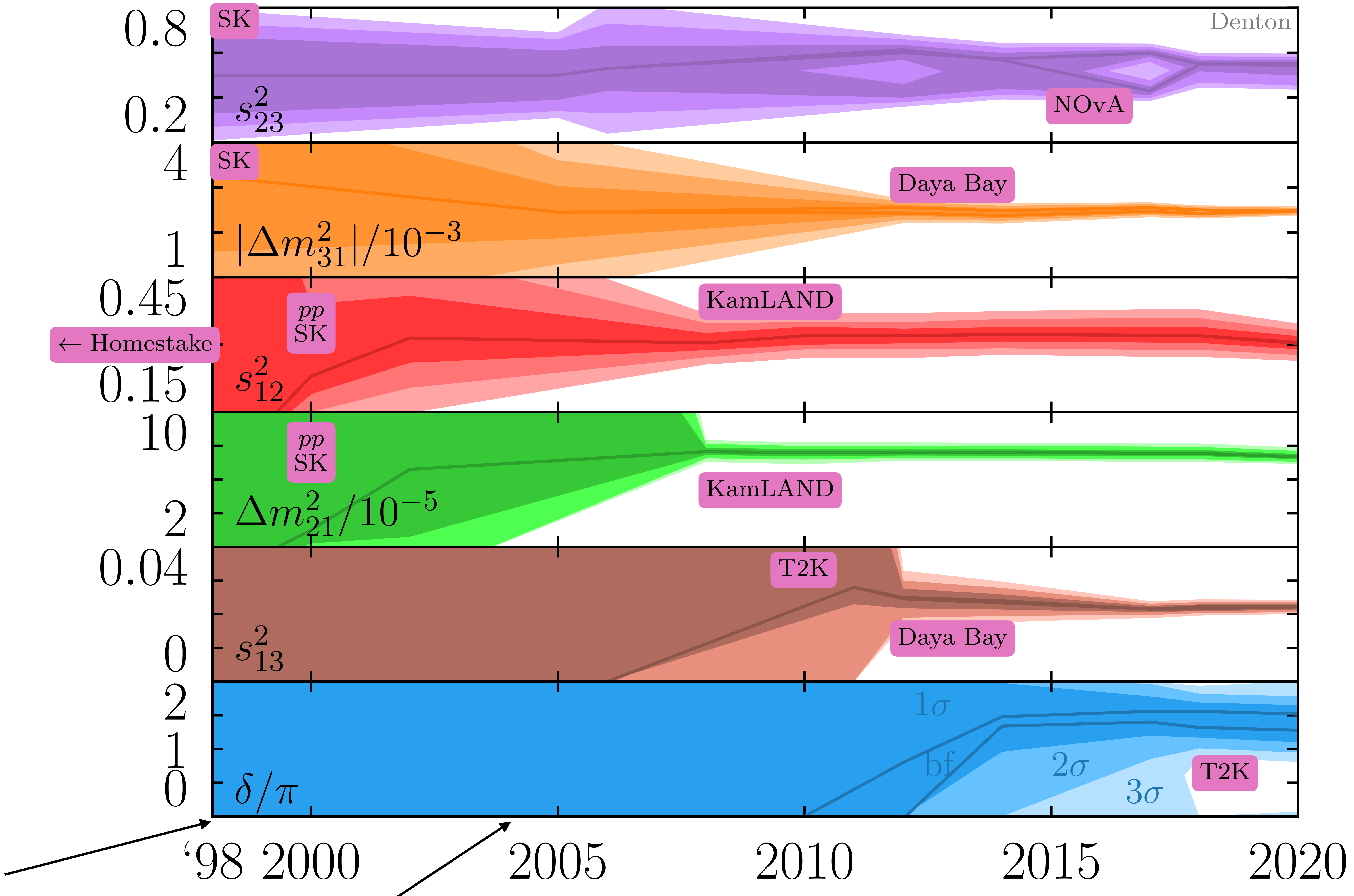
- Selected comments on **current** global analyses
  - three-flavour fit
  - a ``doubtful case'': sterile neutrinos

- Selected comments on **near-term** future
  - the JUNO era
  - neutrino mass from cosmology

- Selected comments on **long-term** future
  - search for lepton number violation
  - search for CP (or T) violation



Huge progress in neutrino oscillations

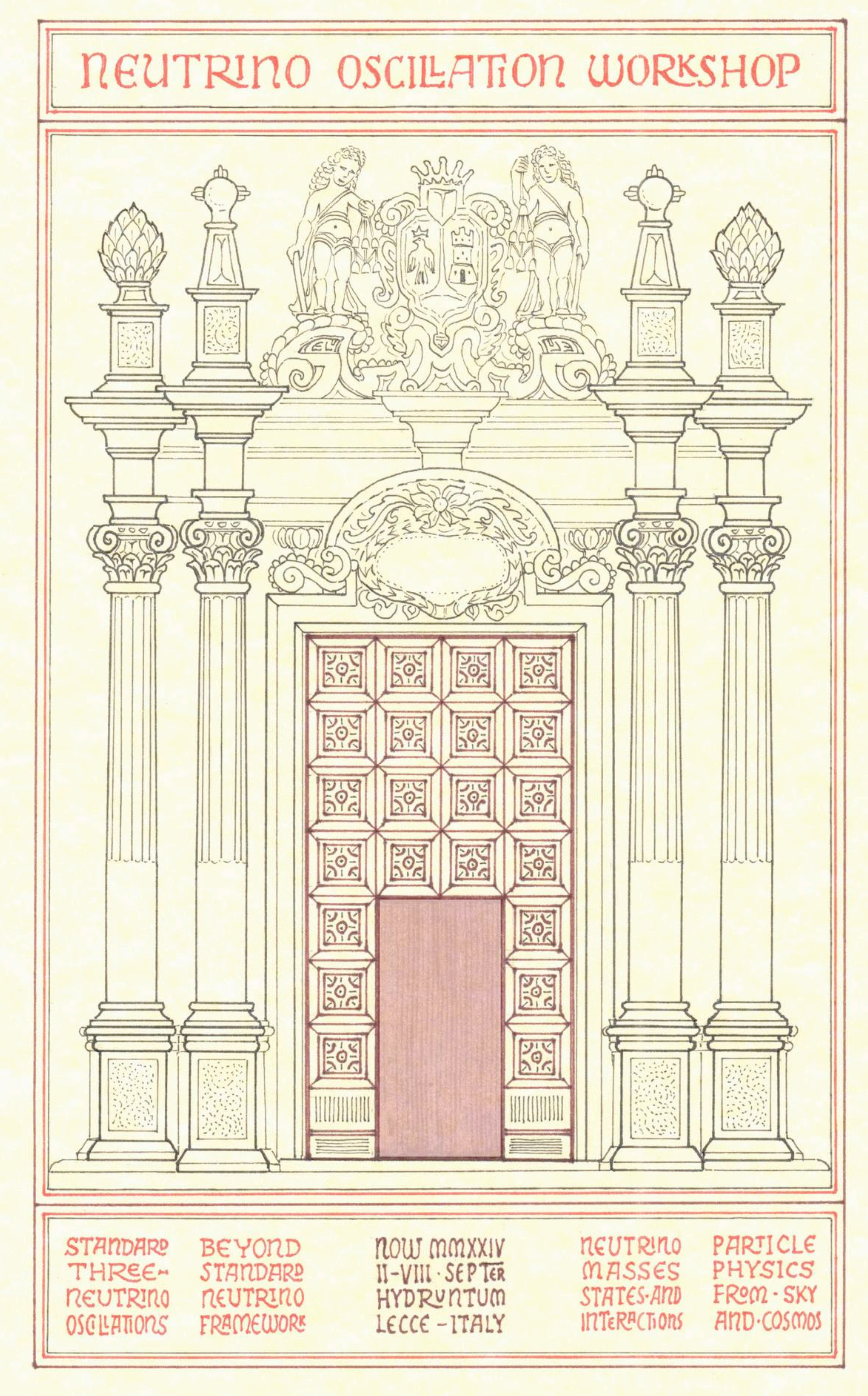


P. Denton

first NOW

my first NOW

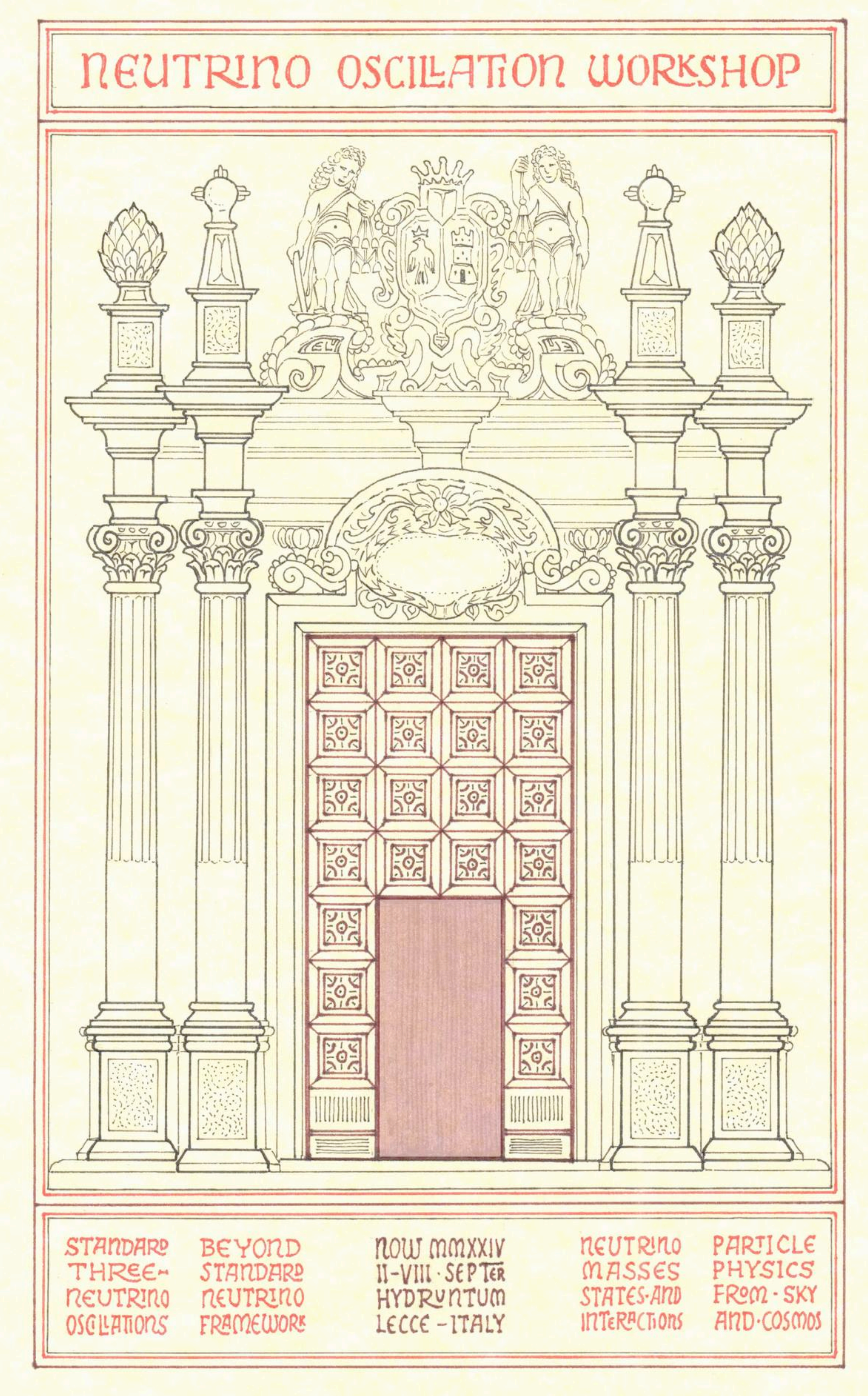
The neutrino portal is open…



The neutrino portal is open…

…but

- we cannot yet see inside



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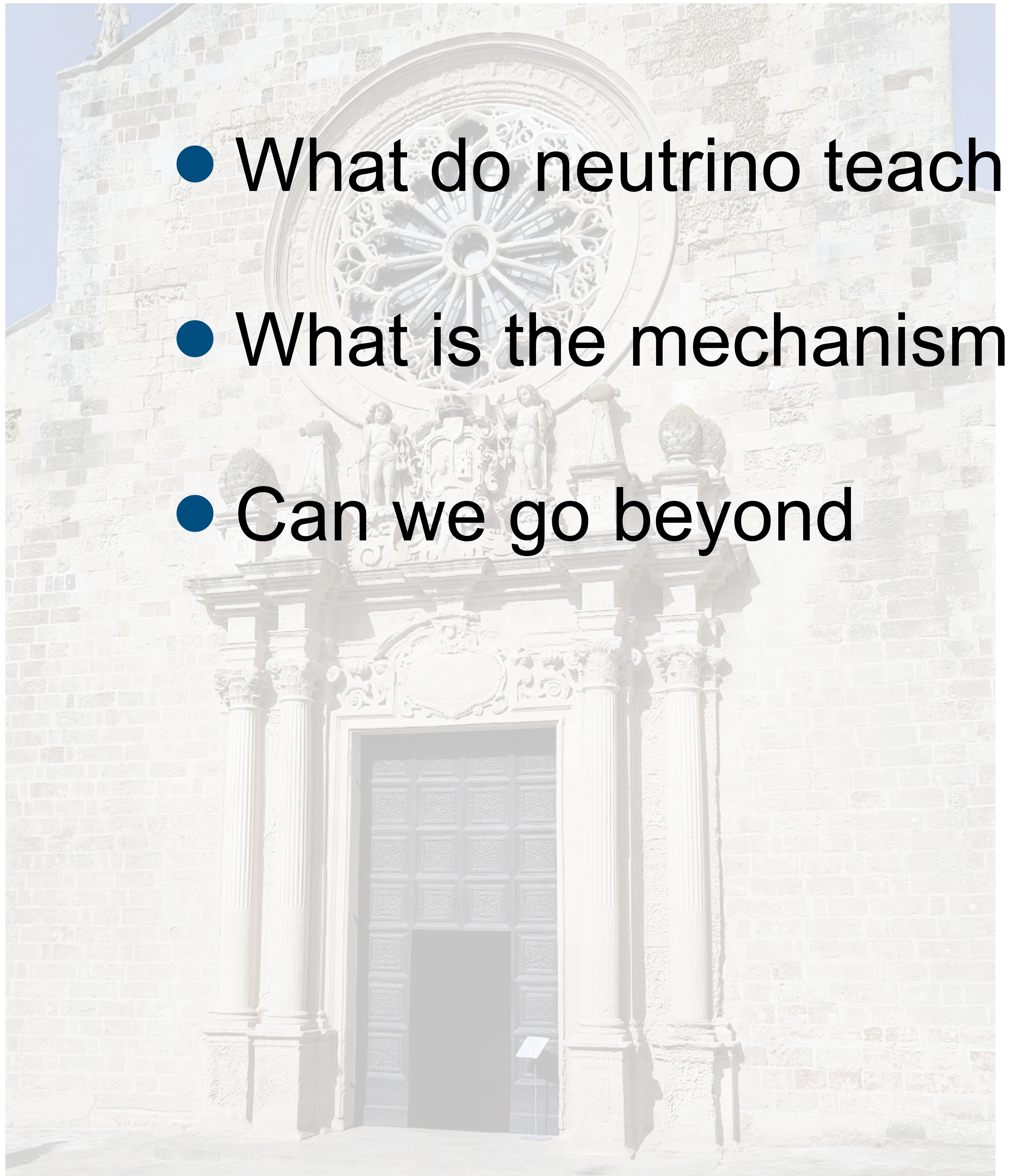
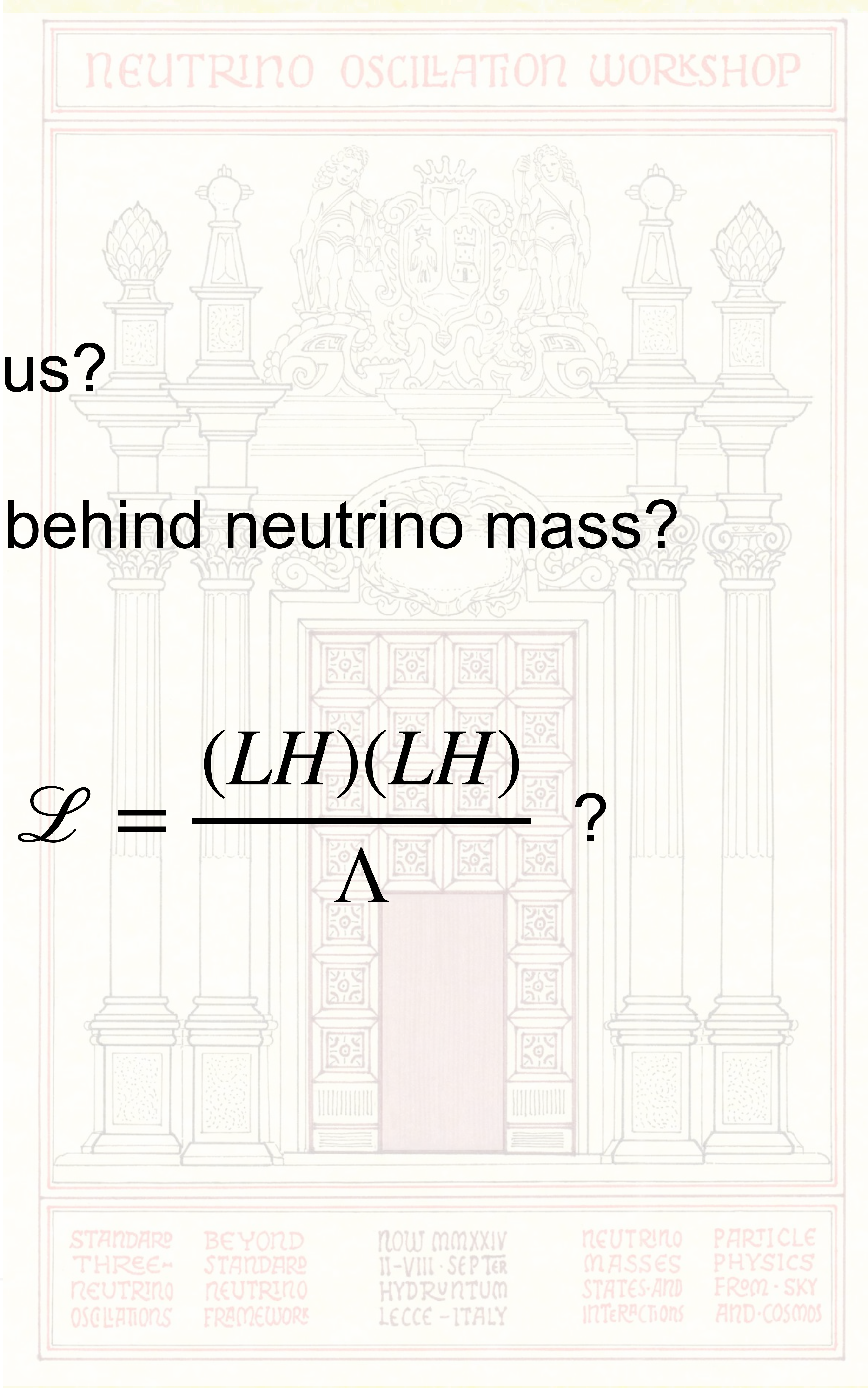


- What do neutrino teach us?
- What is the mechanism behind neutrino mass?
- Can we go beyond

$$\mathscr{L} = \frac{(LH)(LH)}{\Lambda} \; ?$$



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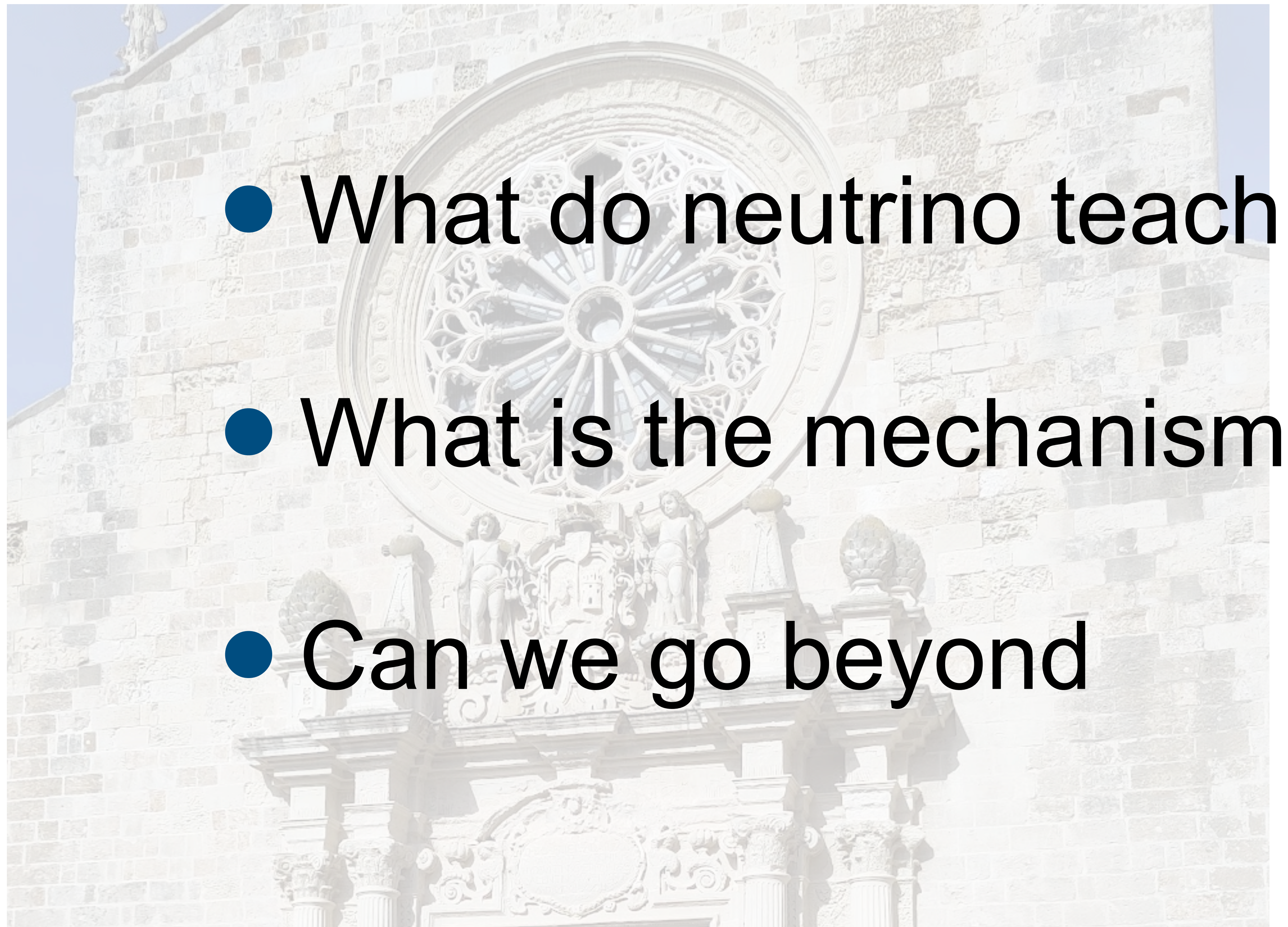

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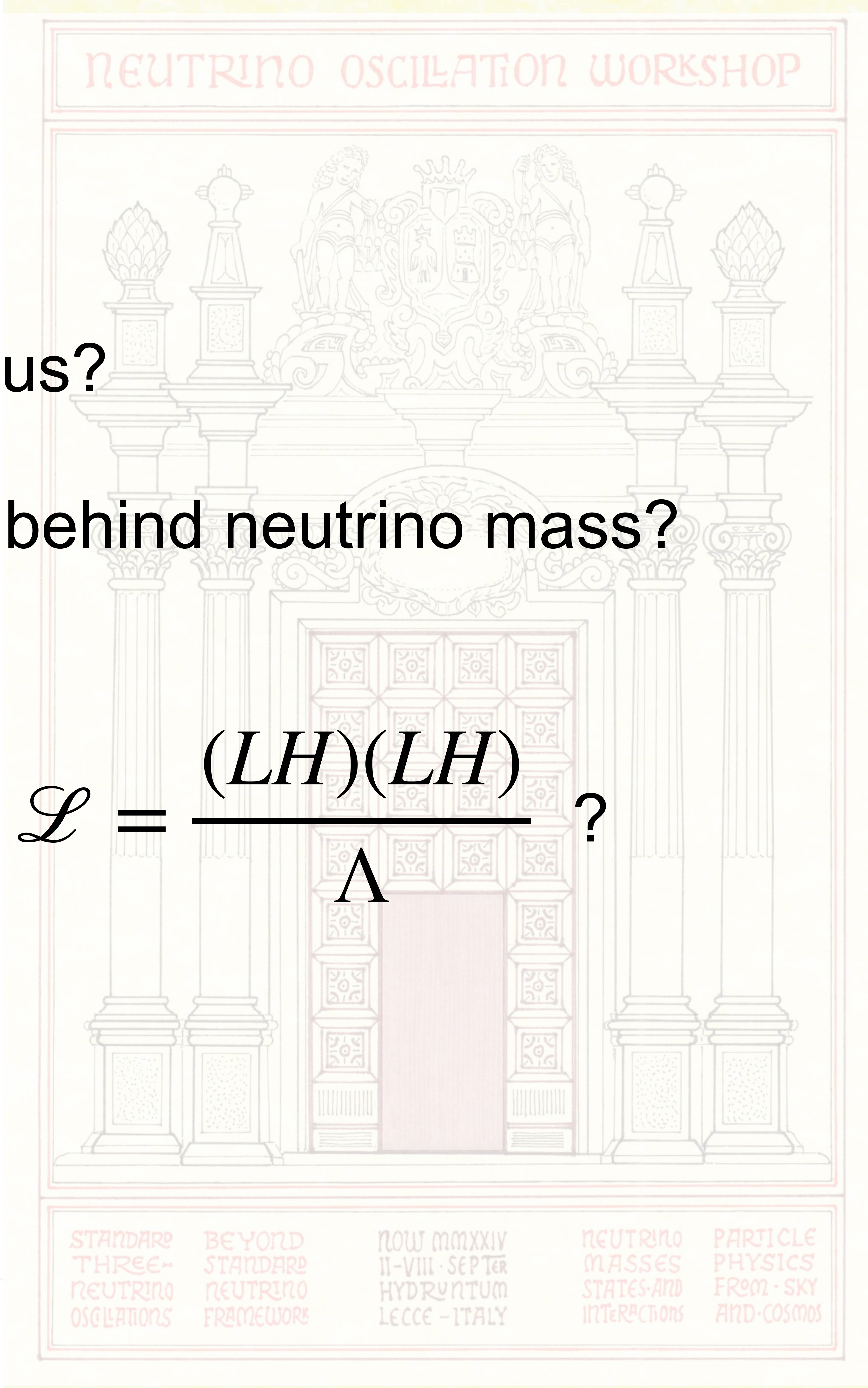
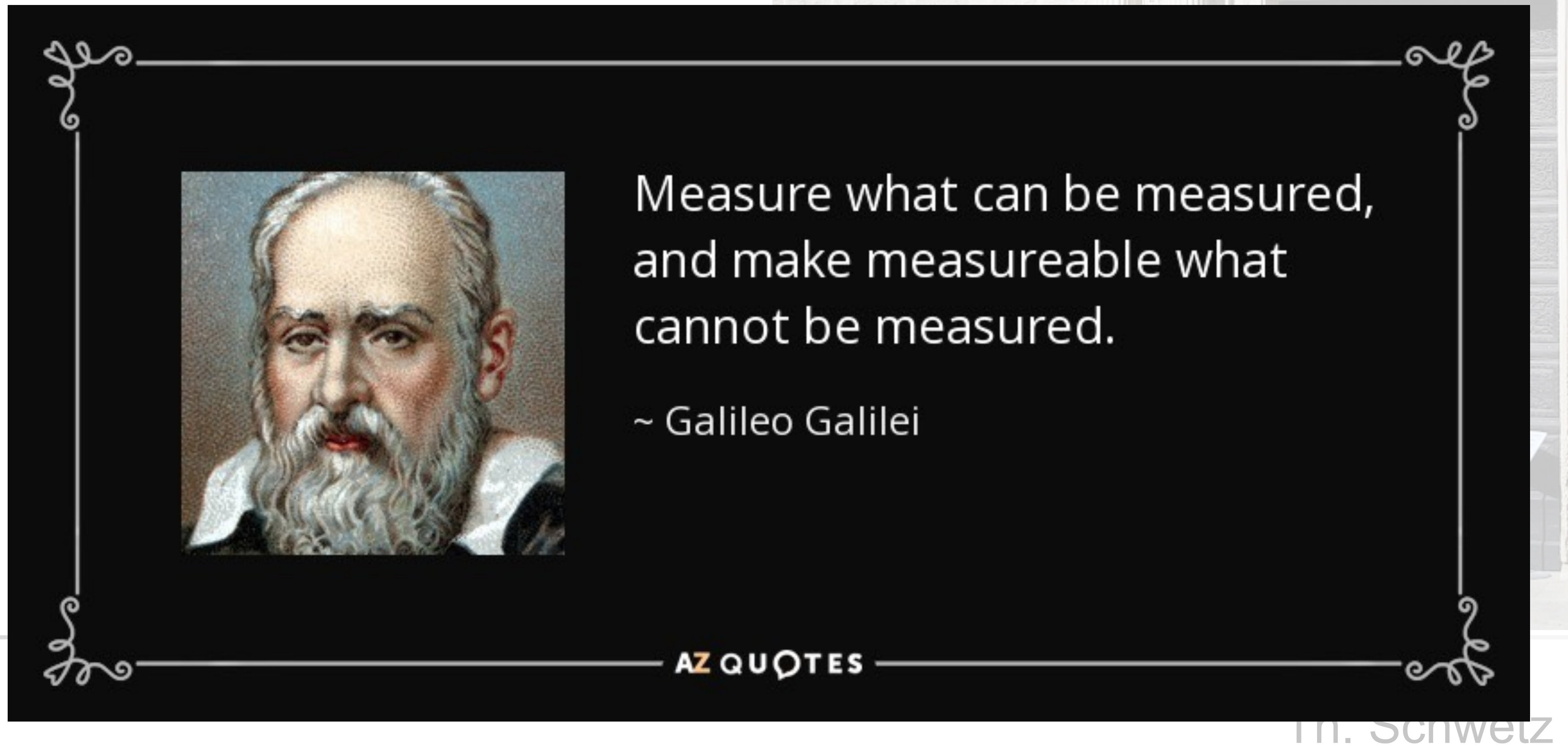


https://www.azquotes.com/quote/905195



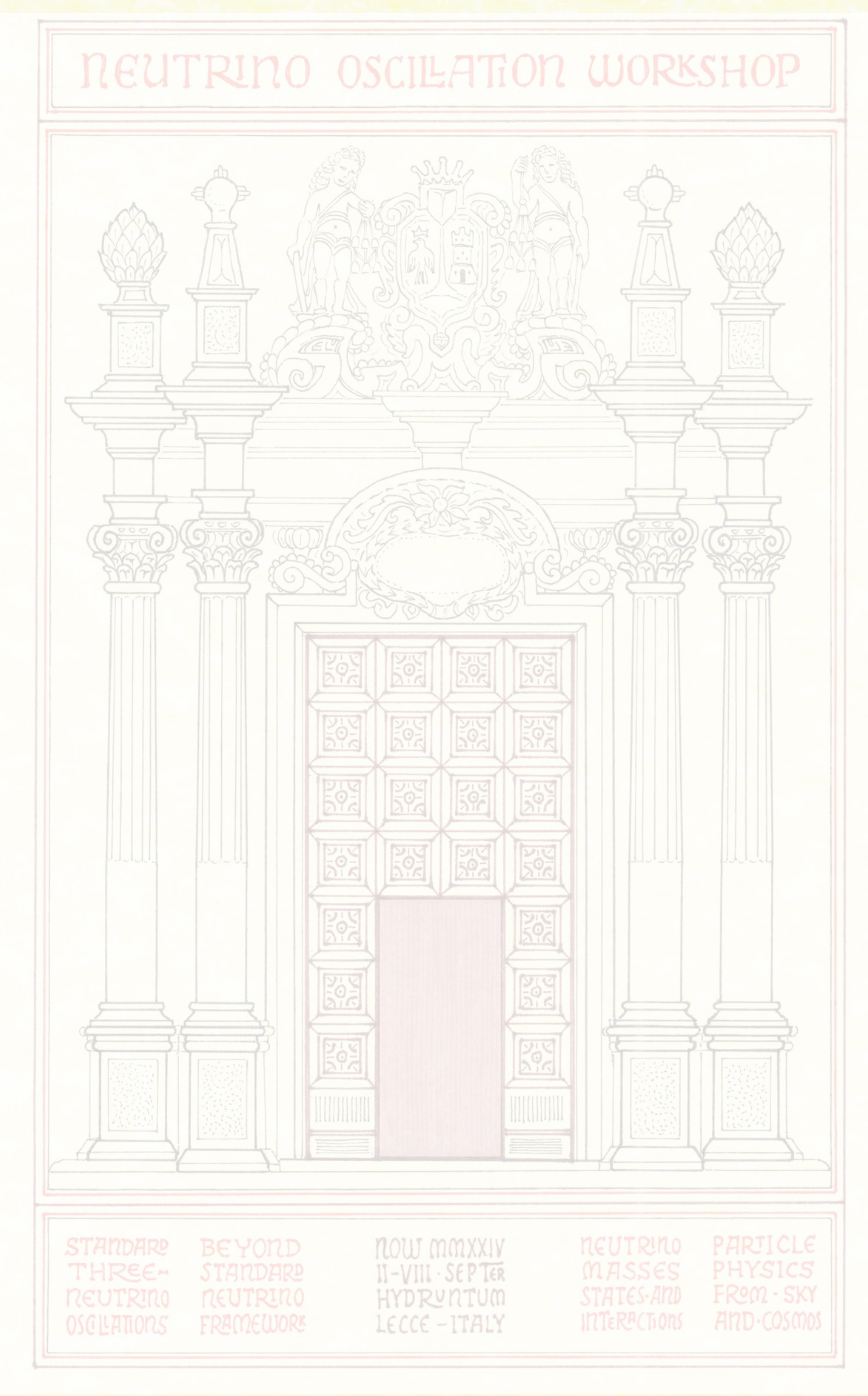
Measure what can be measured, and make measureable what cannot be measured.

~ Galileo Galilei

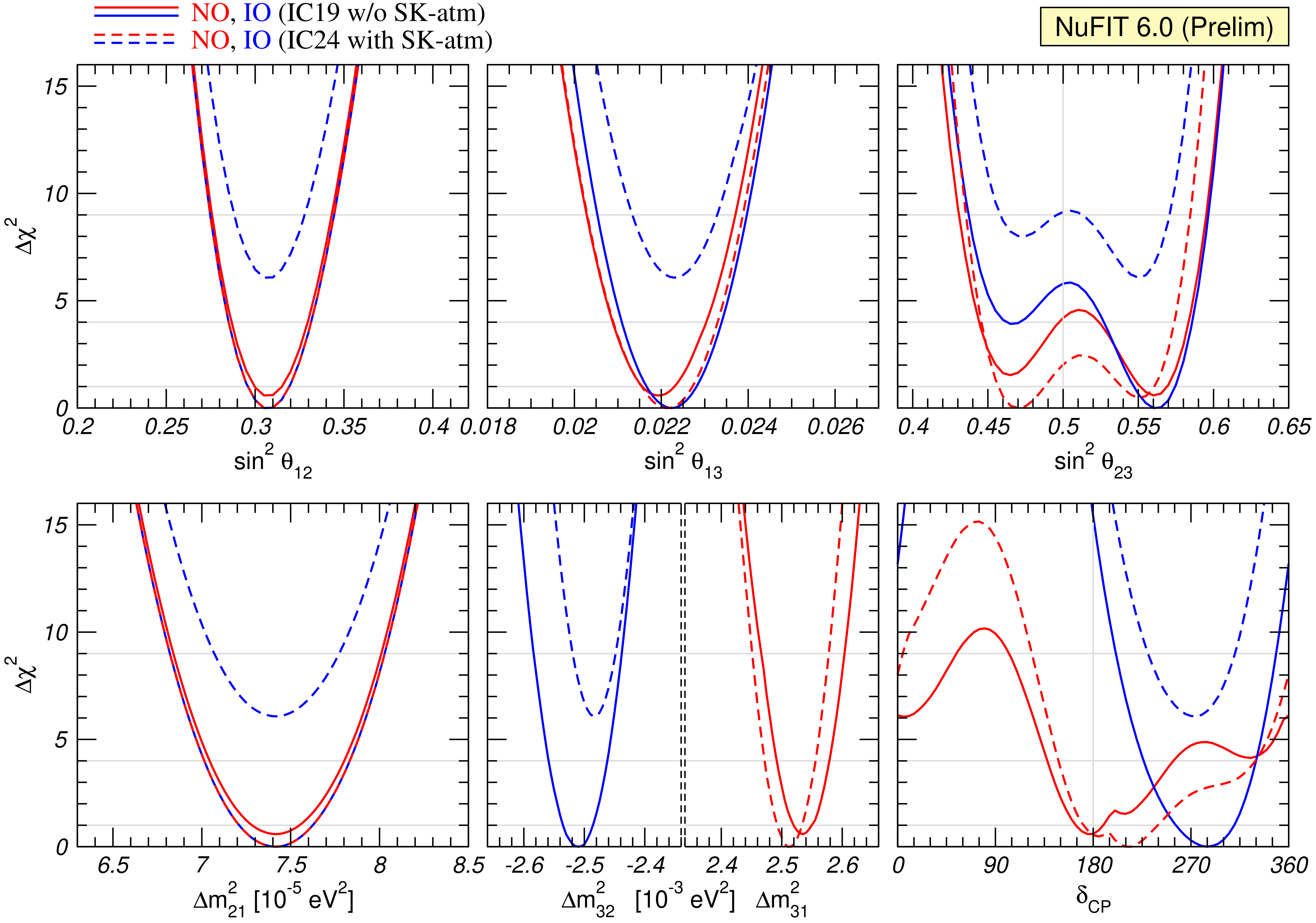
Comments on global fit to current data

thanks to my NuFit collaborators:

Ivan Esteban
Concha Gonzalez-Garcia,
Michele Maltoni
Ivan Martinez-Soler
Joao Pinheiro



post NEUTRINO24 NuFIT global analysis (preliminary!)



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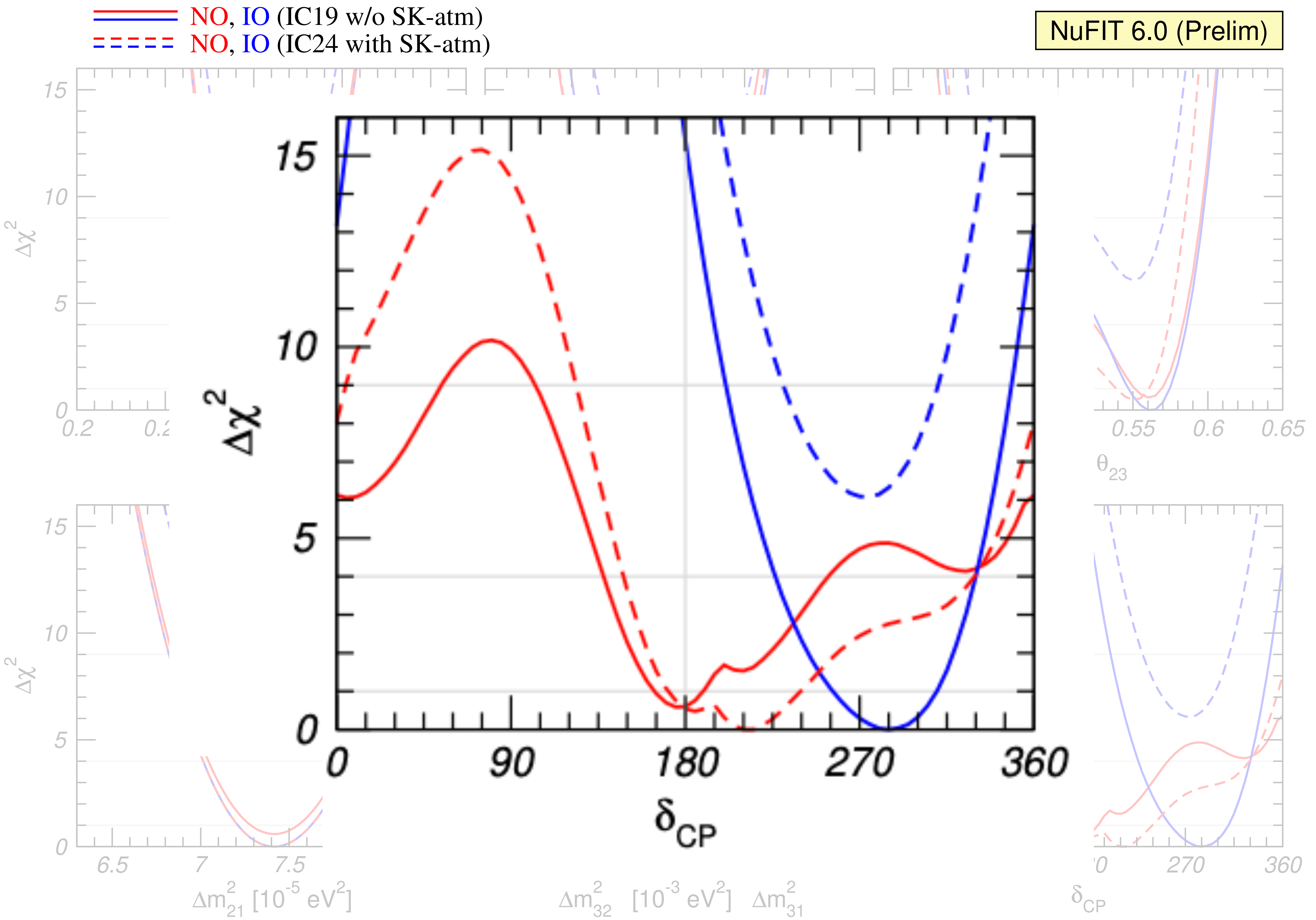


Show case: mass ordering

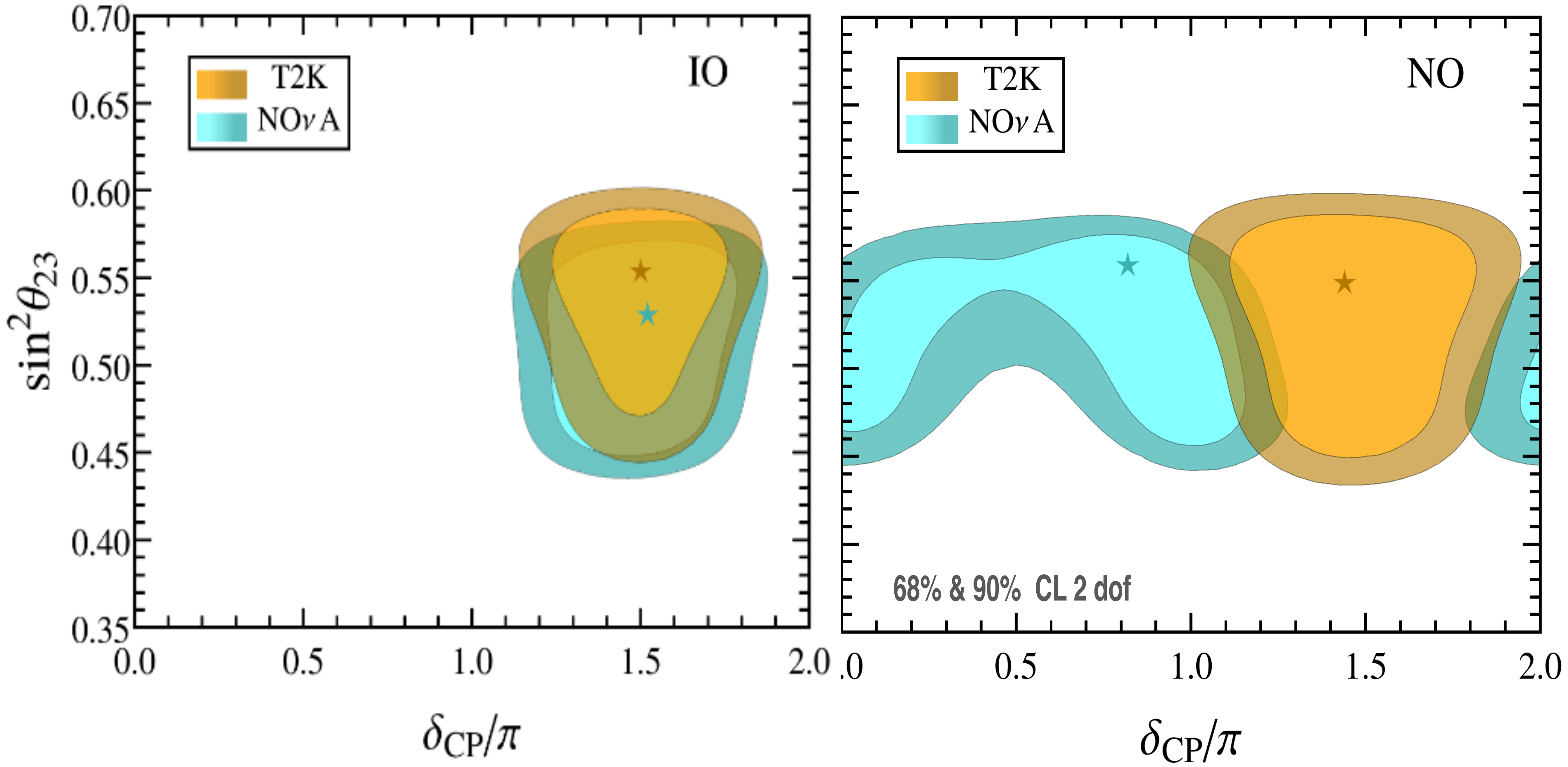
the power (and the pitfalls) of global analyses

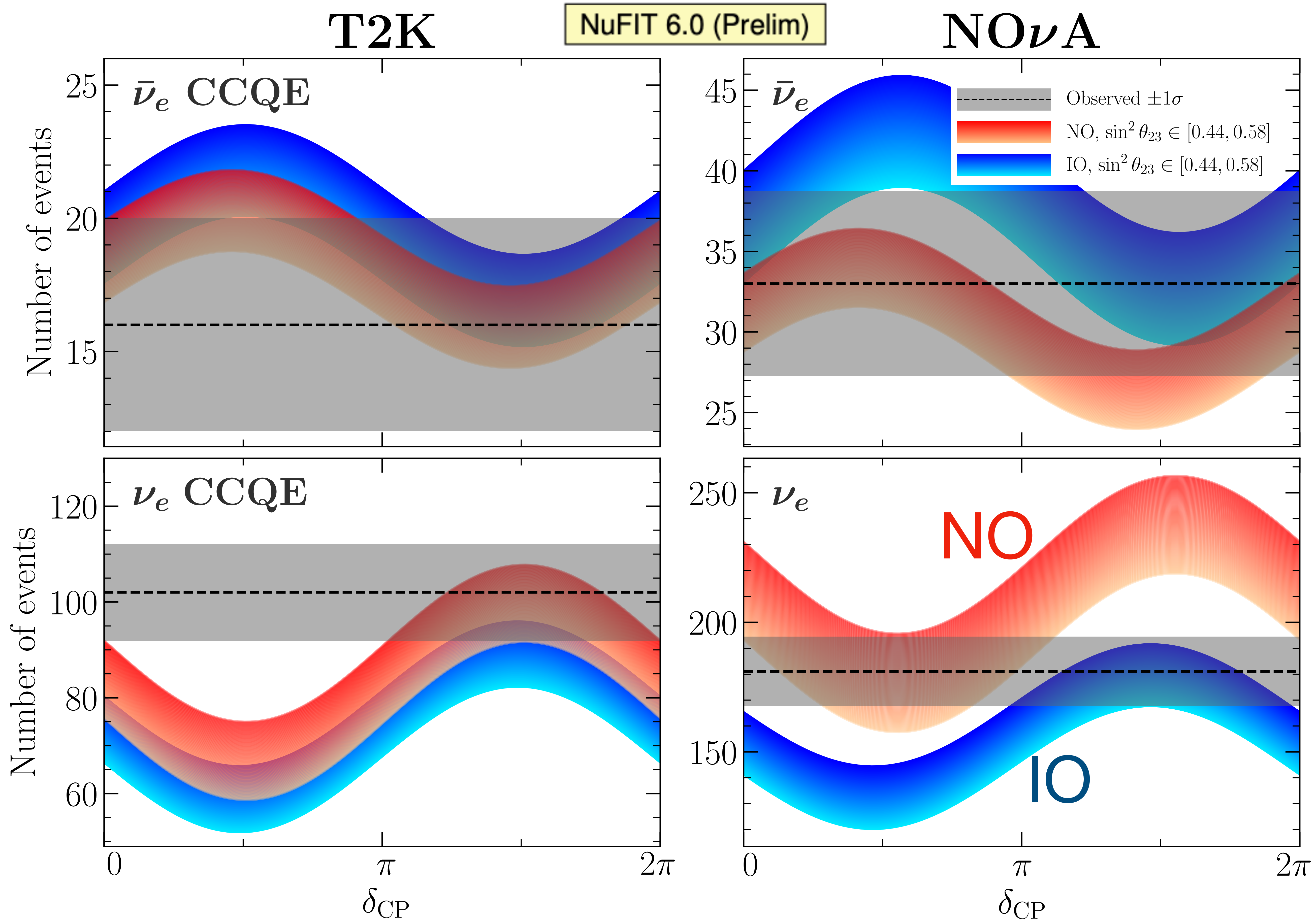
- different tendencies in global fit
  - T2K & NOvA combination prefer inverted ordering
  - Reactor vs accelerator disappearance prefer normal ordering
  - SuperK and IC24 atmospheric prefer normal ordering

- final result in global fit is sensitive to changes in the data

T2K and NOvA better consistency for IO

A. Palazzo



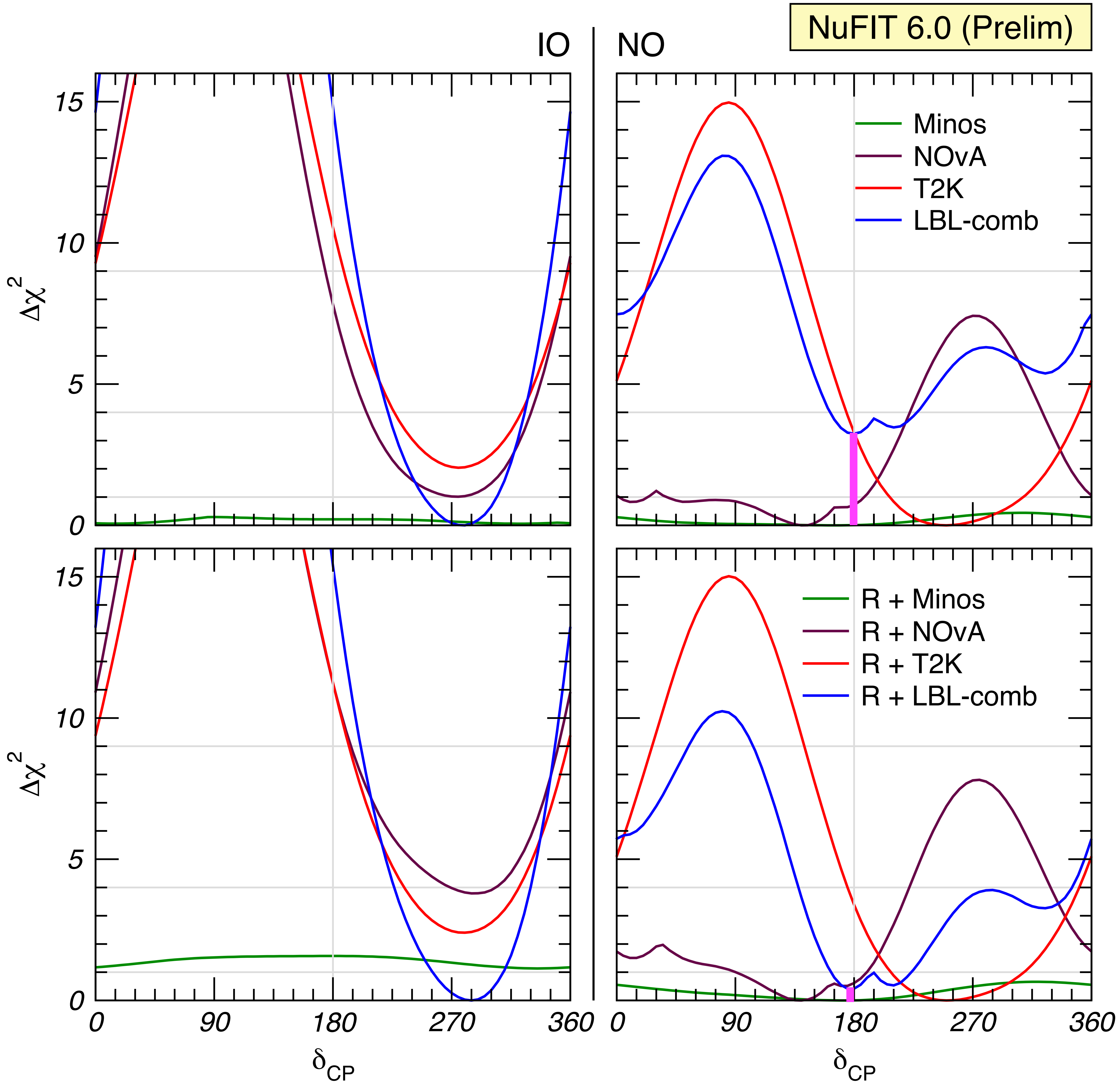


Consistent combined analyses

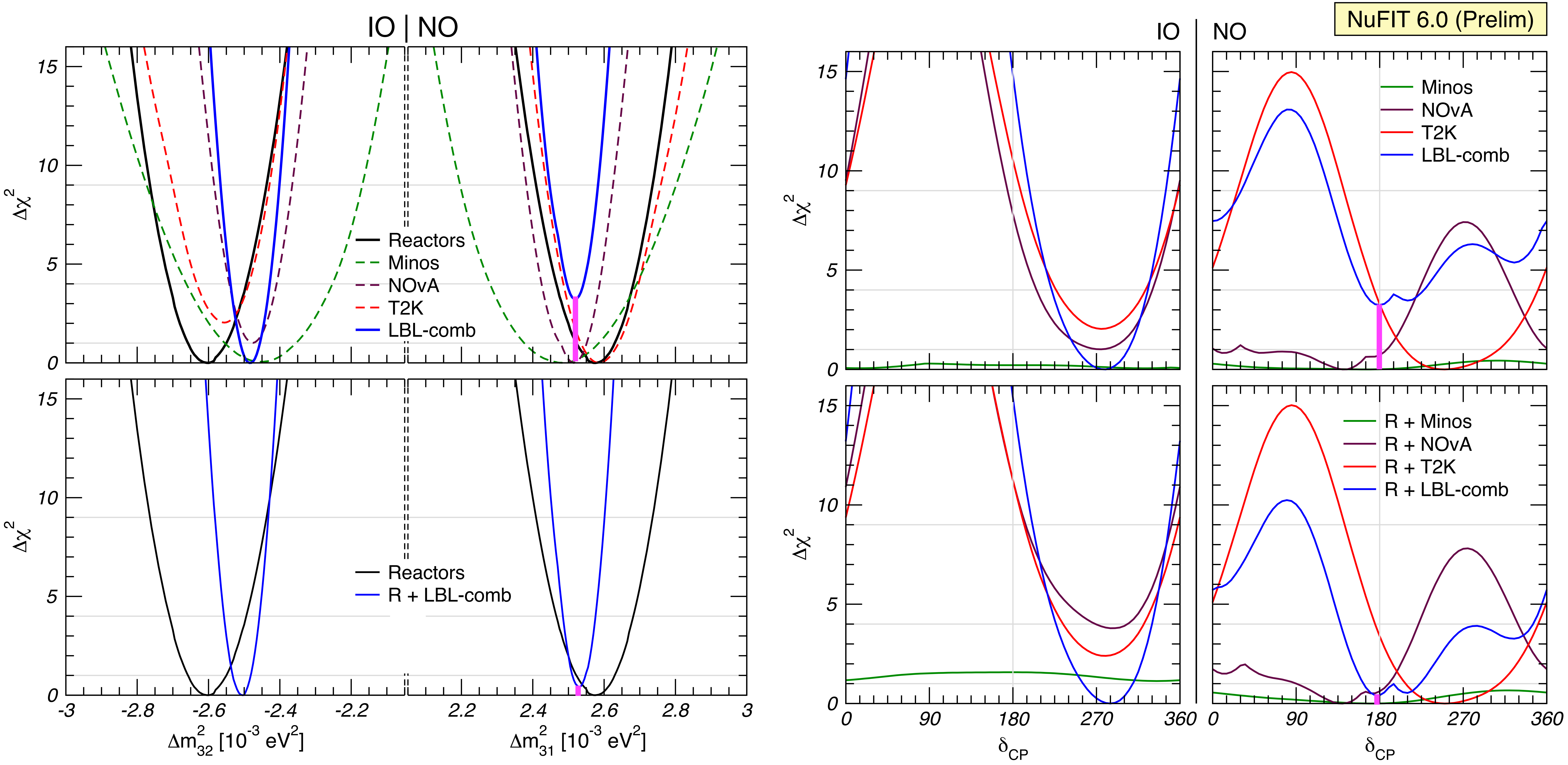
- ``naive'' LBL+reactor combination (θ_{13} prior): $\Delta\chi^2_{\mathrm{IO-NO}} \approx -3$

  was ≈ -1.5 pre-NEUTRINO24

- consistent LBL+reactor combination including full parameter dependence: $\Delta\chi^2_{\mathrm{IO-NO}} \approx -0.7$



better agreement of $|\Delta m^2_{31}|$ for NO

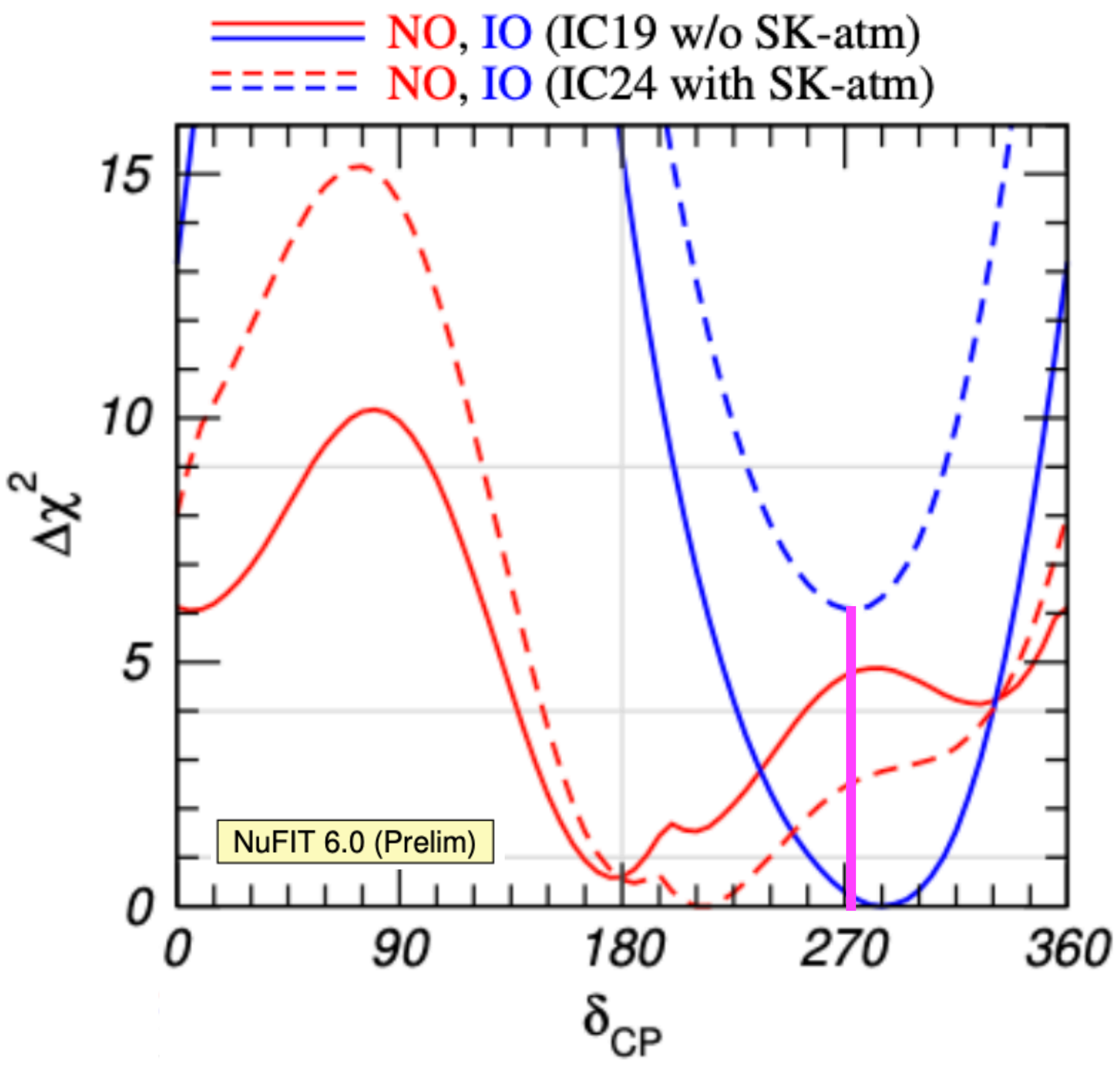


Show case: mass ordering

- different tendencies in global fit
  - T2K & NOvA combination: inverted ordering
  - React. vs accelerator disapp.: normal ordering
  - SK and IC24 atmospheric: normal ordering

- overall preference for normal ordering with $\Delta\chi^2_{\mathrm{IO-NO}} \approx 6$ (preliminary)

NuFit 5.3 (2024 pre-NU24): 9.1
NuFit 5.2 (2022): 6.4
NuFit 5.0 (2020): 7.1
Valencia (Tortola@NU24): 7.1
Bari (Capozzi et al 2021): 6.5



SK: 484.2 kt yr [2311.05105]
IC24: 9.3 yr [2405.02163]
IC19: 3 yr [1902.07771]

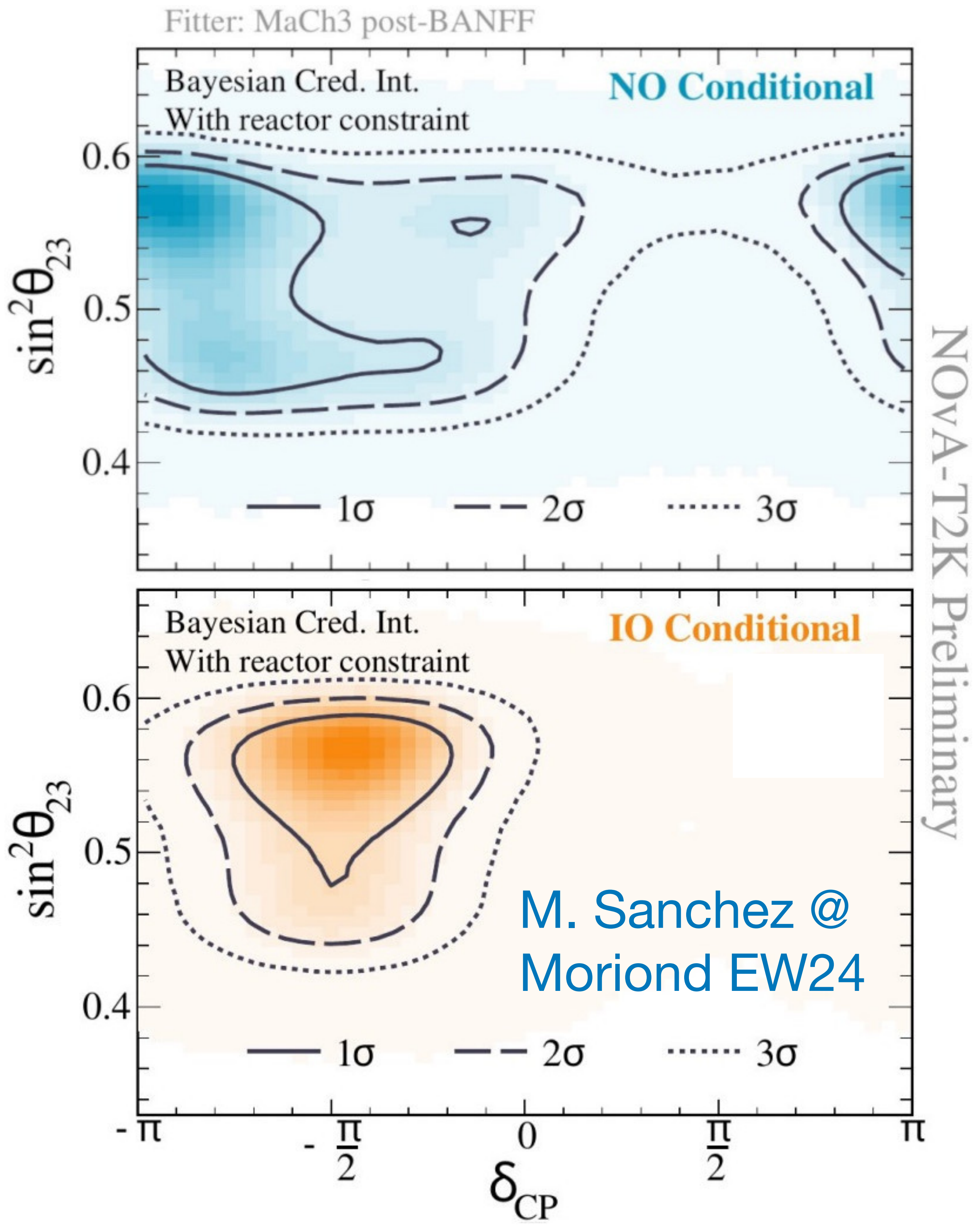
Should you trust global fits by phenomenologists?

Collaborations start performing (partial) combined analyses, e.g.:

- T2K + NOvA
- T2K + SK-atmospheric
- NOvA + DayaBay

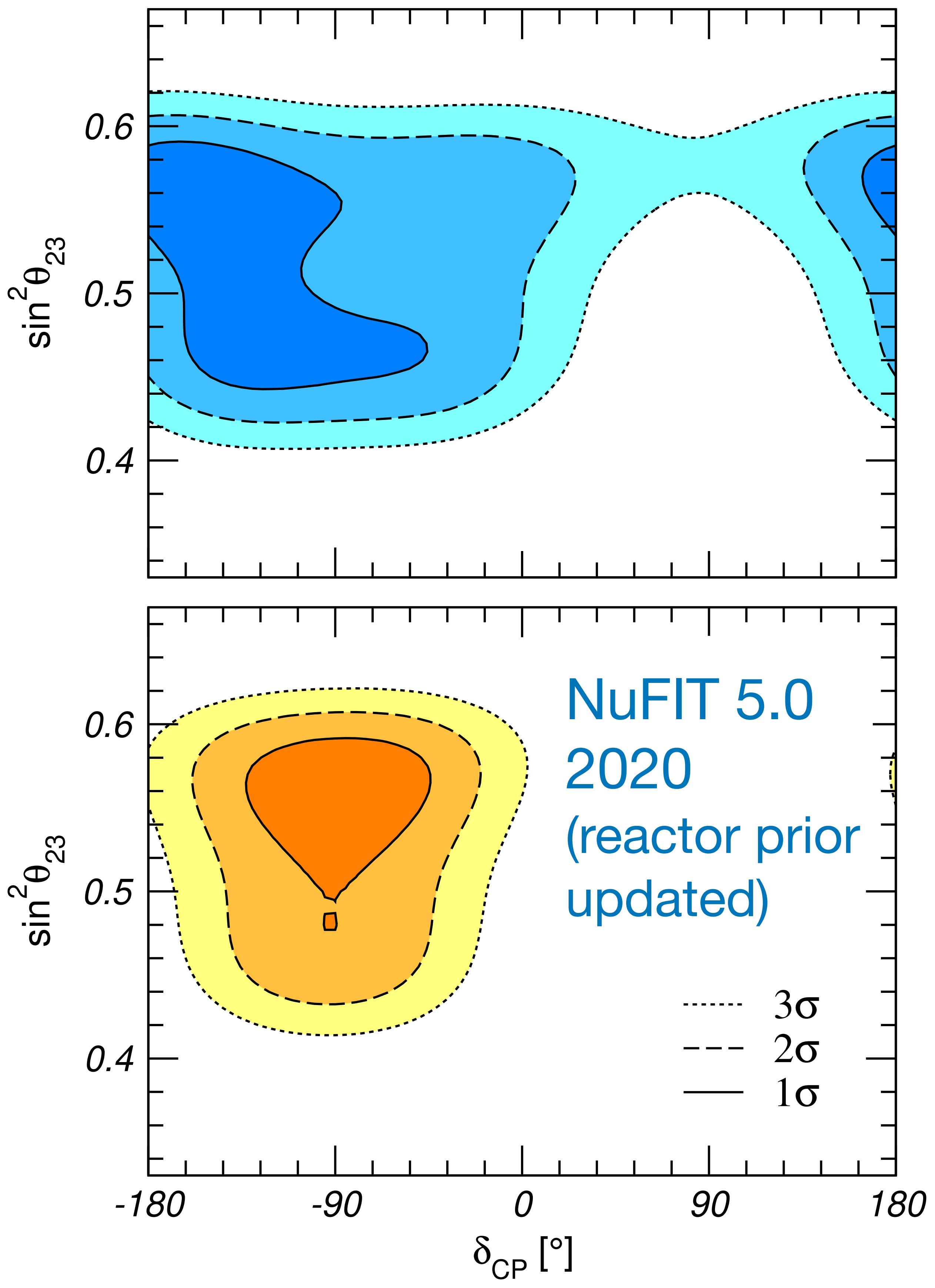
D. Barrow, L. Kolupaeva

joint NOvA T2K analysis (2020 data) became available in 2024



M. Sanchez @ Moriond EW24

$$\Delta\chi^2_{\mathrm{IO-NO}} = -1.34$$



NuFIT 5.0 2020 (reactor prior updated)

(1d react. prior)

$$\Delta\chi^2_{\mathrm{IO-NO}} \approx -1.5$$

a ``doubtful case” [Vissani]: eV sterile neutrino oscillations

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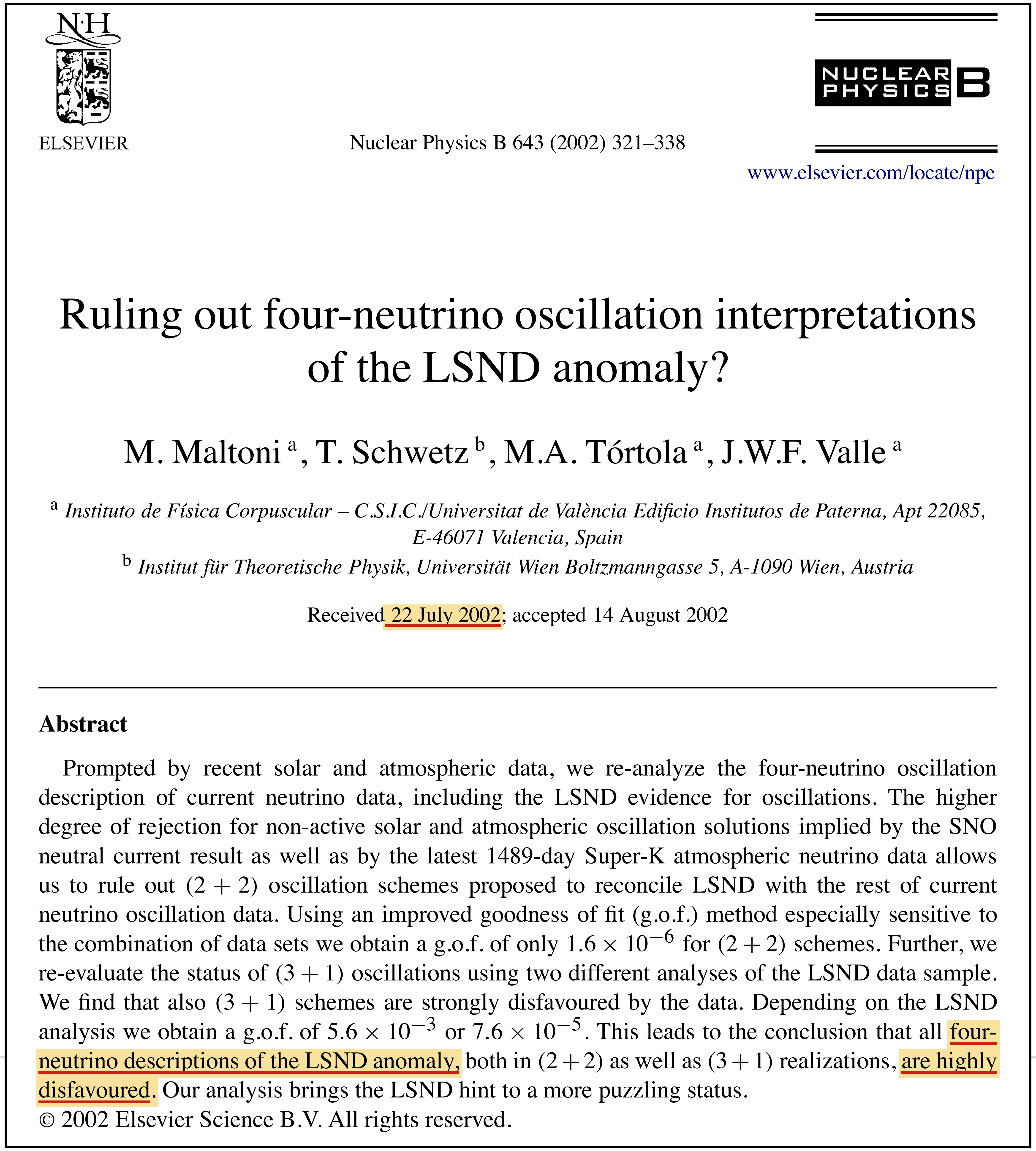

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NUCLEAR PHYSICS B

Nuclear Physics B 643 (2002) 321–338

www.elsevier.com/locate/npe

Ruling out four-neutrino oscillation interpretations of the LSND anomaly?

M. Maltoni [a], T. Schwetz [b], M.A. Tórtola [a], J.W.F. Valle [a]

[a] *Instituto de Física Corpuscular – C.S.I.C./Universitat de València Edificio Institutos de Paterna, Apt 22085, E-46071 Valencia, Spain*

[b] *Institut für Theoretische Physik, Universität Wien Boltzmanngasse 5, A-1090 Wien, Austria*

Received 22 July 2002; accepted 14 August 2002

Abstract

Prompted by recent solar and atmospheric data, we re-analyze the four-neutrino oscillation description of current neutrino data, including the LSND evidence for oscillations. The higher degree of rejection for non-active solar and atmospheric oscillation solutions implied by the SNO neutral current result as well as by the latest 1489-day Super-K atmospheric neutrino data allows us to rule out $(2+2)$ oscillation schemes proposed to reconcile LSND with the rest of current neutrino oscillation data. Using an improved goodness of fit (g.o.f.) method especially sensitive to the combination of data sets we obtain a g.o.f. of only 1.6×10^{-6} for $(2+2)$ schemes. Further, we re-evaluate the status of $(3+1)$ oscillations using two different analyses of the LSND data sample. We find that also $(3+1)$ schemes are strongly disfavoured by the data. Depending on the LSND analysis we obtain a g.o.f. of 5.6×10^{-3} or 7.6×10^{-5}. This leads to the conclusion that all four-neutrino descriptions of the LSND anomaly, both in $(2+2)$ as well as $(3+1)$ realizations, are highly disfavoured. Our analysis brings the LSND hint to a more puzzling status.

a ``doubtful case'' [Vissani]: eV sterile neutrino oscillations

- global analyses disfavoured eV sterile neutrino oscillations already 20 years ago
- after 20 years of joined theory & pheno & experiment effort:
  - reactor anomaly: came and went away
  - LSND/MiniB: (largely) unsolved
  - Gallium anomaly at 5σ: unsolved
  - strong tension with cosmology
- was it a waisted effort or did we learn something?
- similar theory arguments which ``disfavour'' eV sterile neutrinos ``disfavoured'' also large lepton mixing angles

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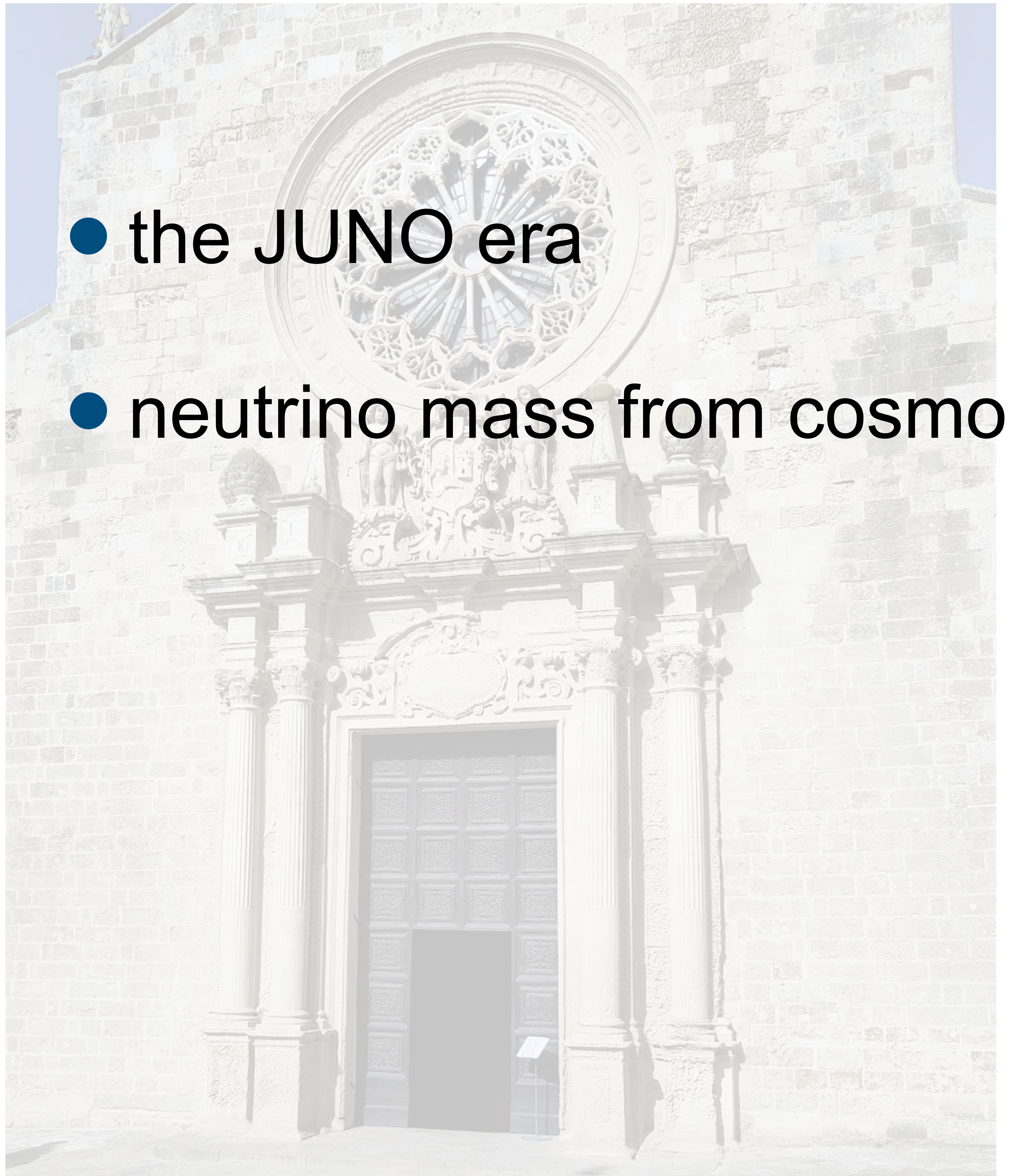
You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you will be sorry.

S. Weinberg, quoted by Z-z. Xing

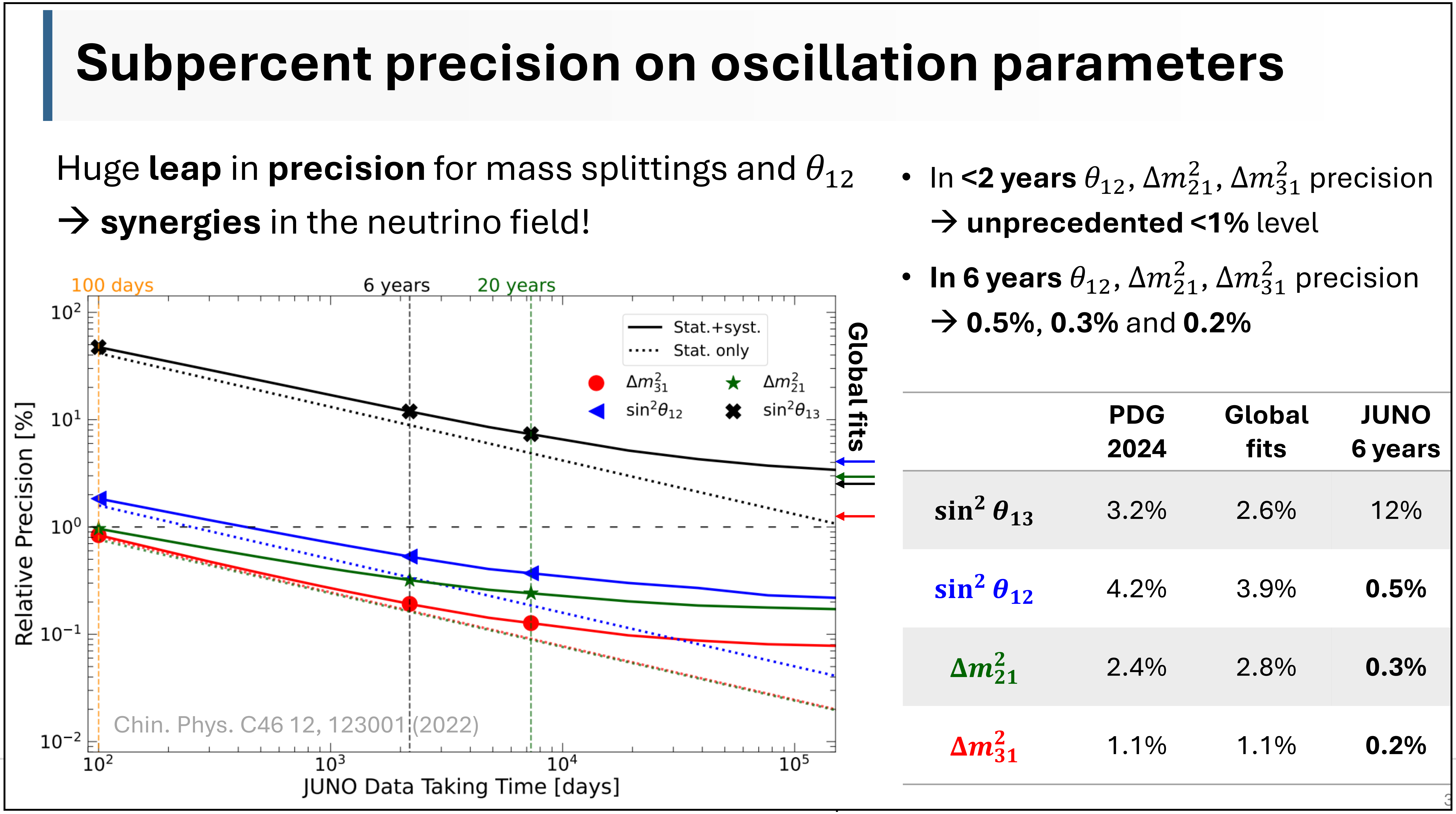
Comments on near-term future

- the JUNO era
- neutrino mass from cosmology



The upcoming JUNO precision revolution

A. Serafini, V. Cerrone



Subpercent precision on oscillation parameters

Huge **leap** in **precision** for mass splittings and θ_{12}
→ **synergies** in the neutrino field!

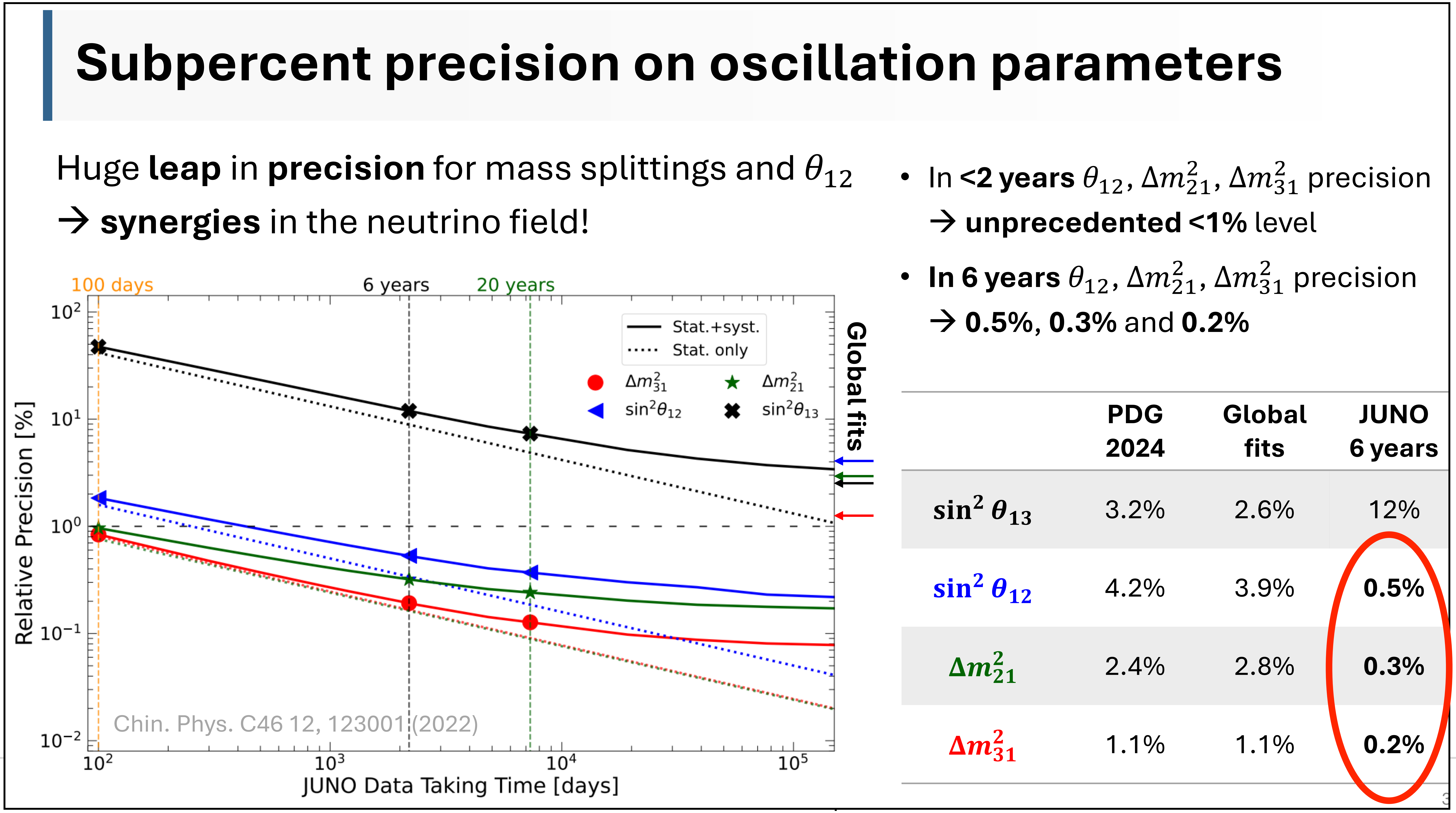
Chin. Phys. C46 12, 123001 (2022)

- In **<2 years** θ_{12}, Δm^2_{21}, Δm^2_{31} precision
  → **unprecedented <1%** level
- **In 6 years** θ_{12}, Δm^2_{21}, Δm^2_{31} precision
  → **0.5%, 0.3%** and **0.2%**

	PDG 2024	**Global fits**	**JUNO 6 years**
$\sin^2\theta_{13}$	3.2%	2.6%	12%
$\sin^2\theta_{12}$	4.2%	3.9%	**0.5%**
Δm^2_{21}	2.4%	2.8%	**0.3%**
Δm^2_{31}	1.1%	1.1%	**0.2%**

The upcoming JUNO precision revolution

A. Serafini, V. Cerrone



Subpercent precision on oscillation parameters

Huge **leap** in **precision** for mass splittings and θ_{12}
→ **synergies** in the neutrino field!

Chin. Phys. C46 12, 123001 (2022)

- In **<2 years** θ_{12}, Δm^2_{21}, Δm^2_{31} precision
  → **unprecedented <1%** level
- **In 6 years** θ_{12}, Δm^2_{21}, Δm^2_{31} precision
  → **0.5%, 0.3%** and **0.2%**

	PDG 2024	**Global fits**	**JUNO 6 years**
$\sin^2\theta_{13}$	3.2%	2.6%	12%
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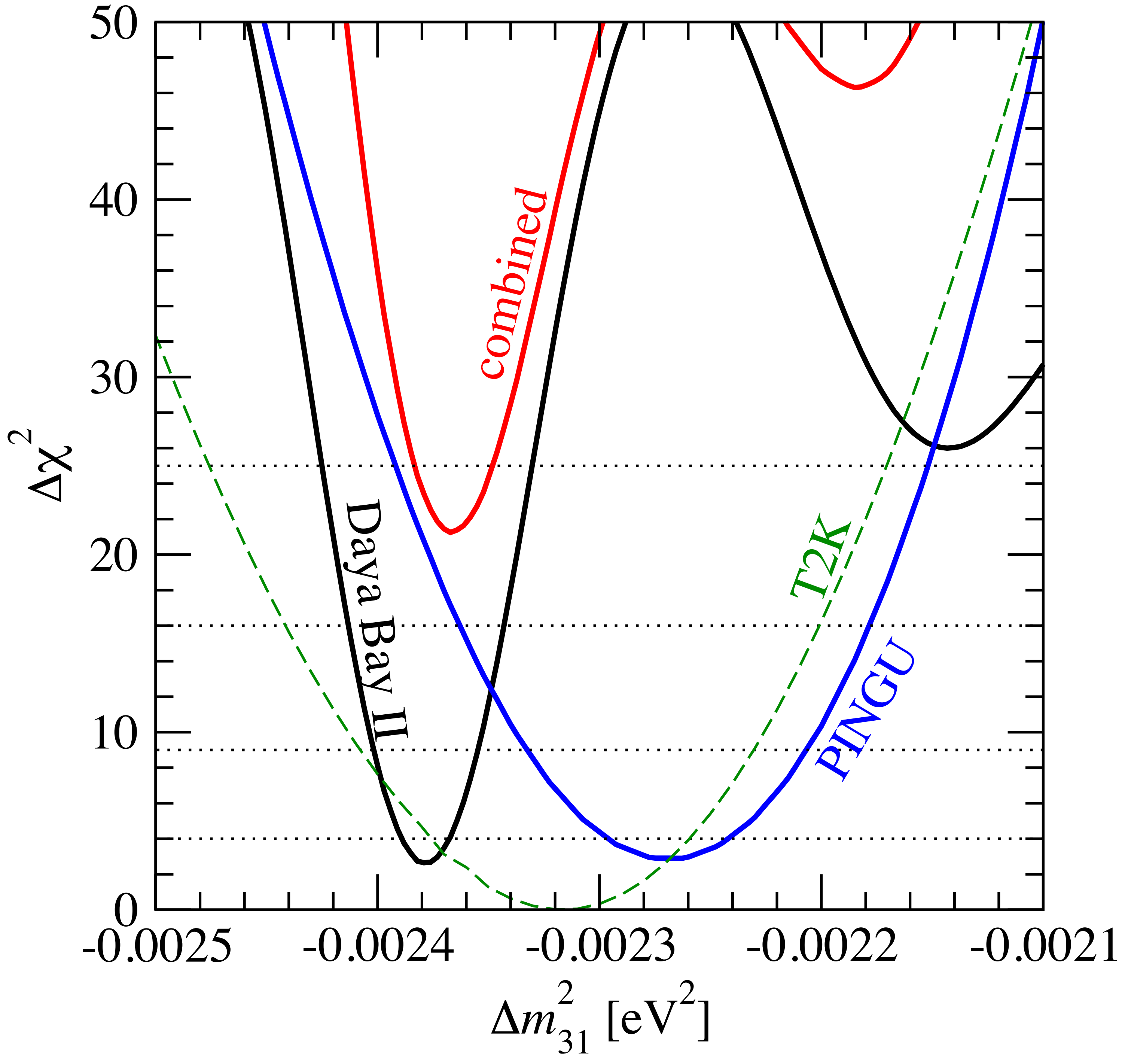
Combined analyses in the JUNO era

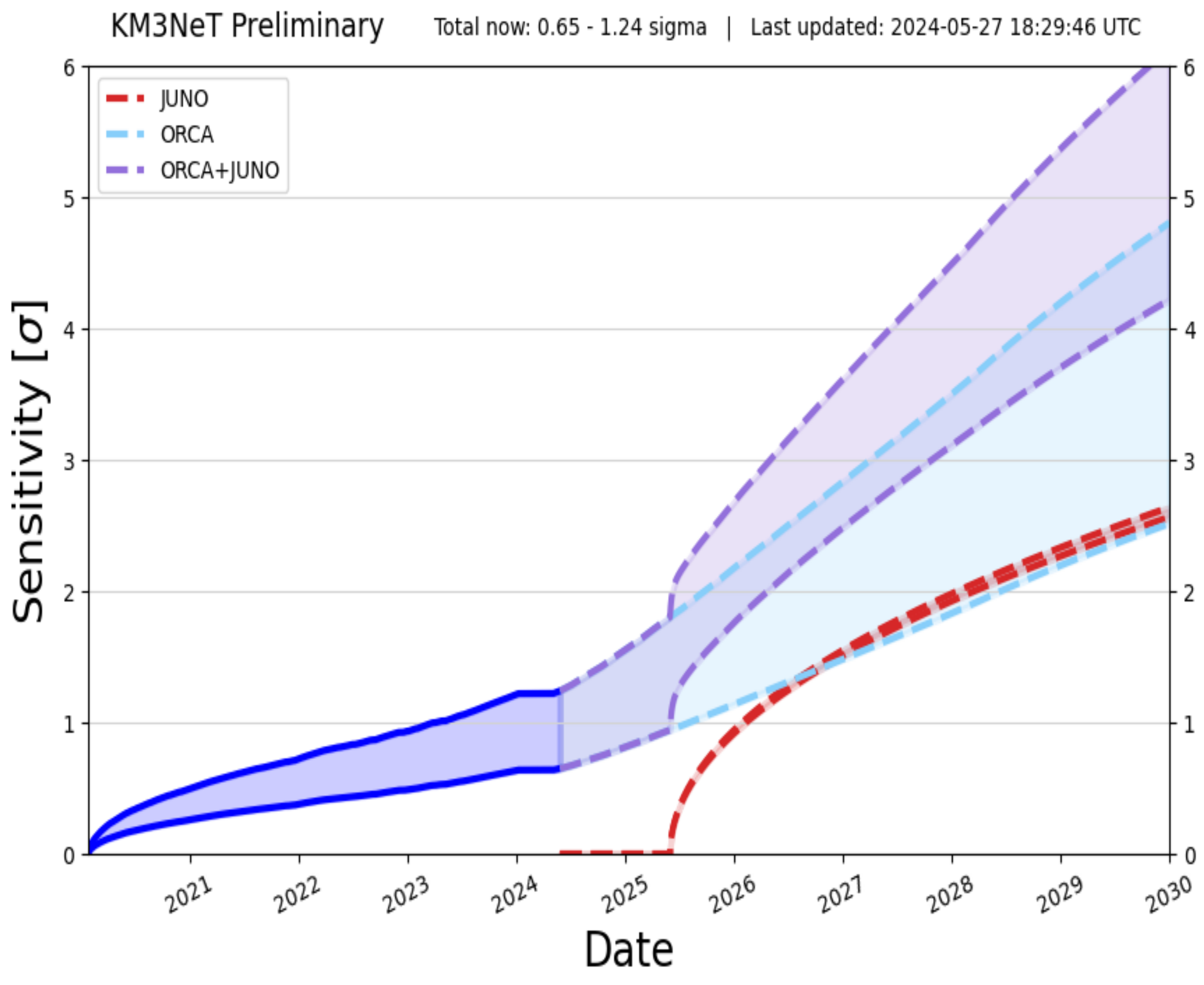
- mass ordering from combination of reactor and atmospheric neutrinos (and accelerators)

Blennow, Schwetz,1306.3988



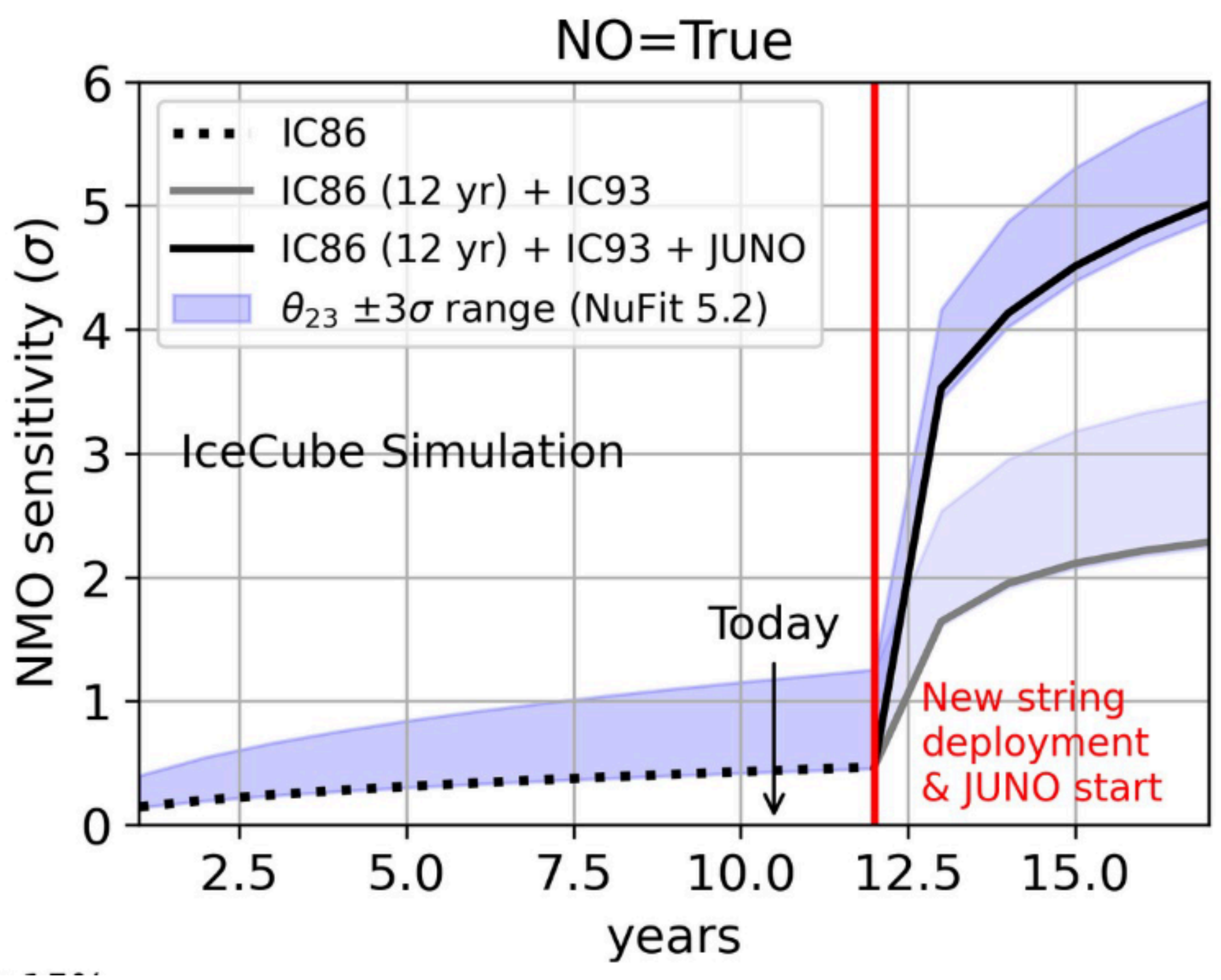
JUNO & KM3NET/ORCA

[2108.06293] talk by P. Migliozzi



JUNO & IceCube

[1911.06745] talk by A. Terliuk

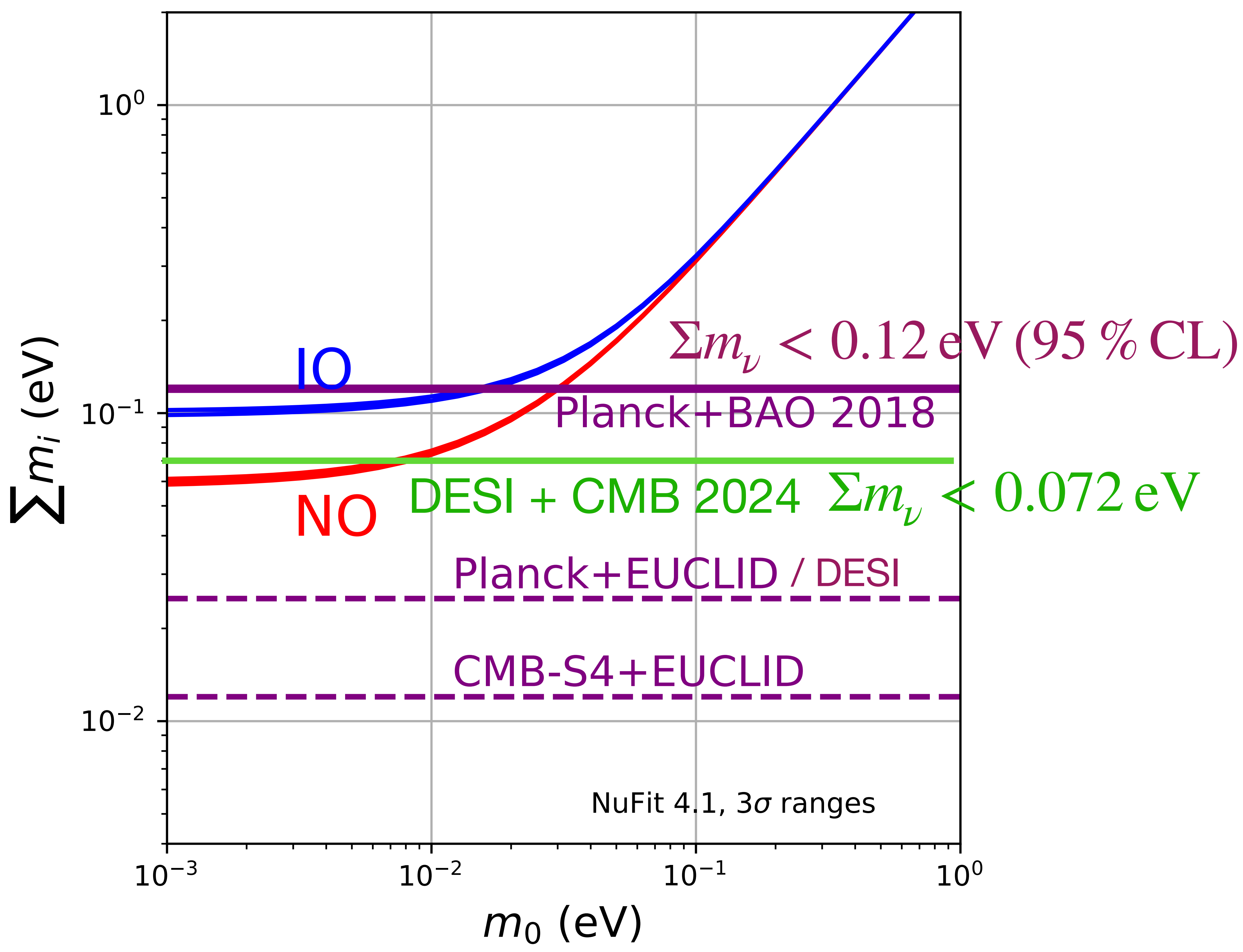


Neutrino mass from cosmology

Lattanzi, Pamuk

- CMB + BAO observations reach the critical sensitivity to observe neutrino masses as predicted by oscillations NOW!
- potential to discover neutrino mass soon

- showcase for
  - the power of global analyses to break parameter degeneracies
  - interplay of cosmology and particle physics



Neutrino mass from cosmology

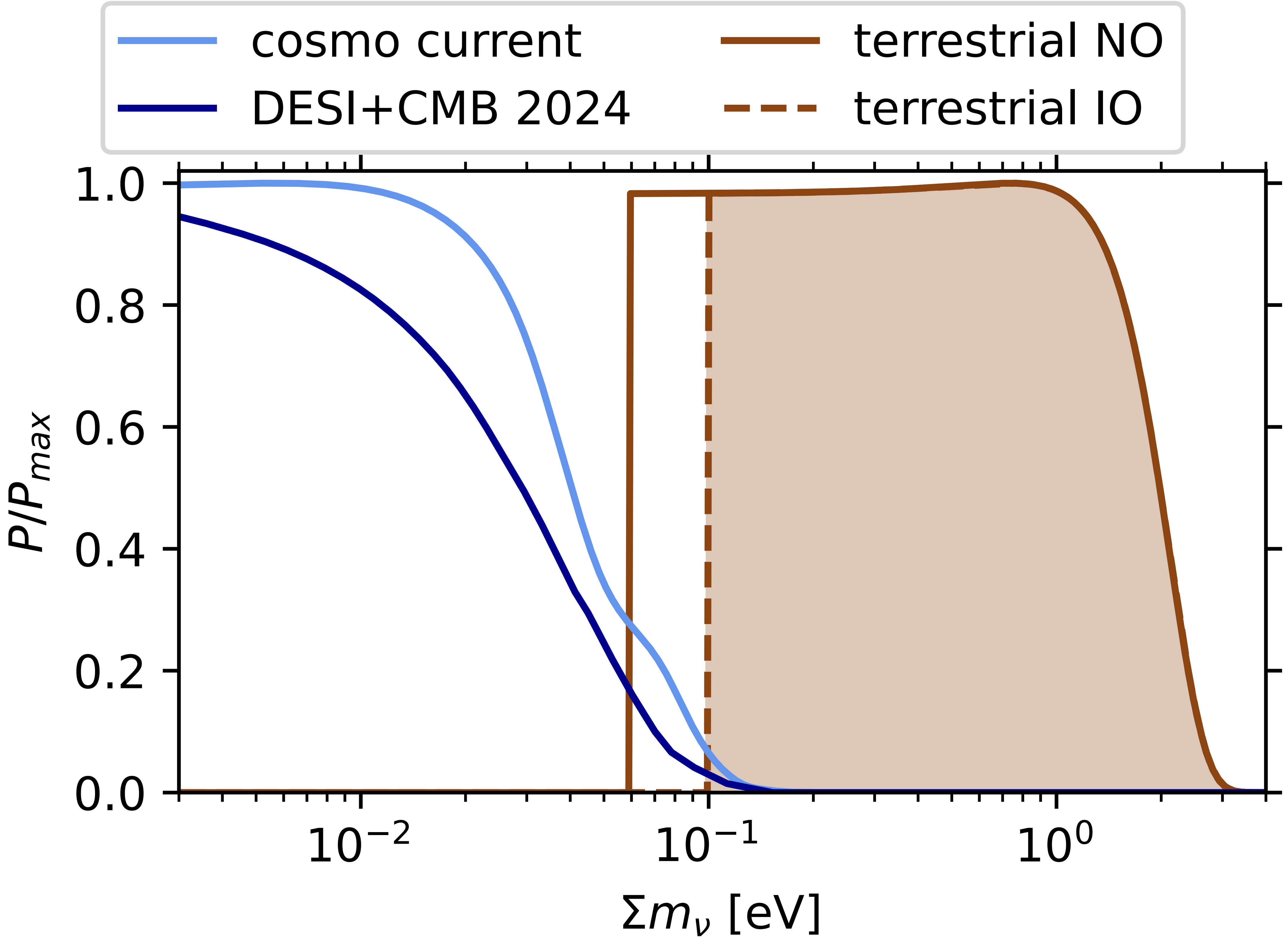
Lattanzi, Pamuk

- current results: preference for $\sum m_\nu = 0$

  $\Rightarrow$ tension between cosmology and oscillations for both orderings

- if this trend continues it could imply
  - nonstandard cosmology [Lattanzi]
  - exotic neutrino properties [talk by M. Sen, Escudero, TS, Terol-Calvo, 23]

- direct neutrino mass determinations are crucial to have independent information $\Rightarrow$ quest to go beyond KATRIN! [talks by Schlösser, Ferri, Salomon]



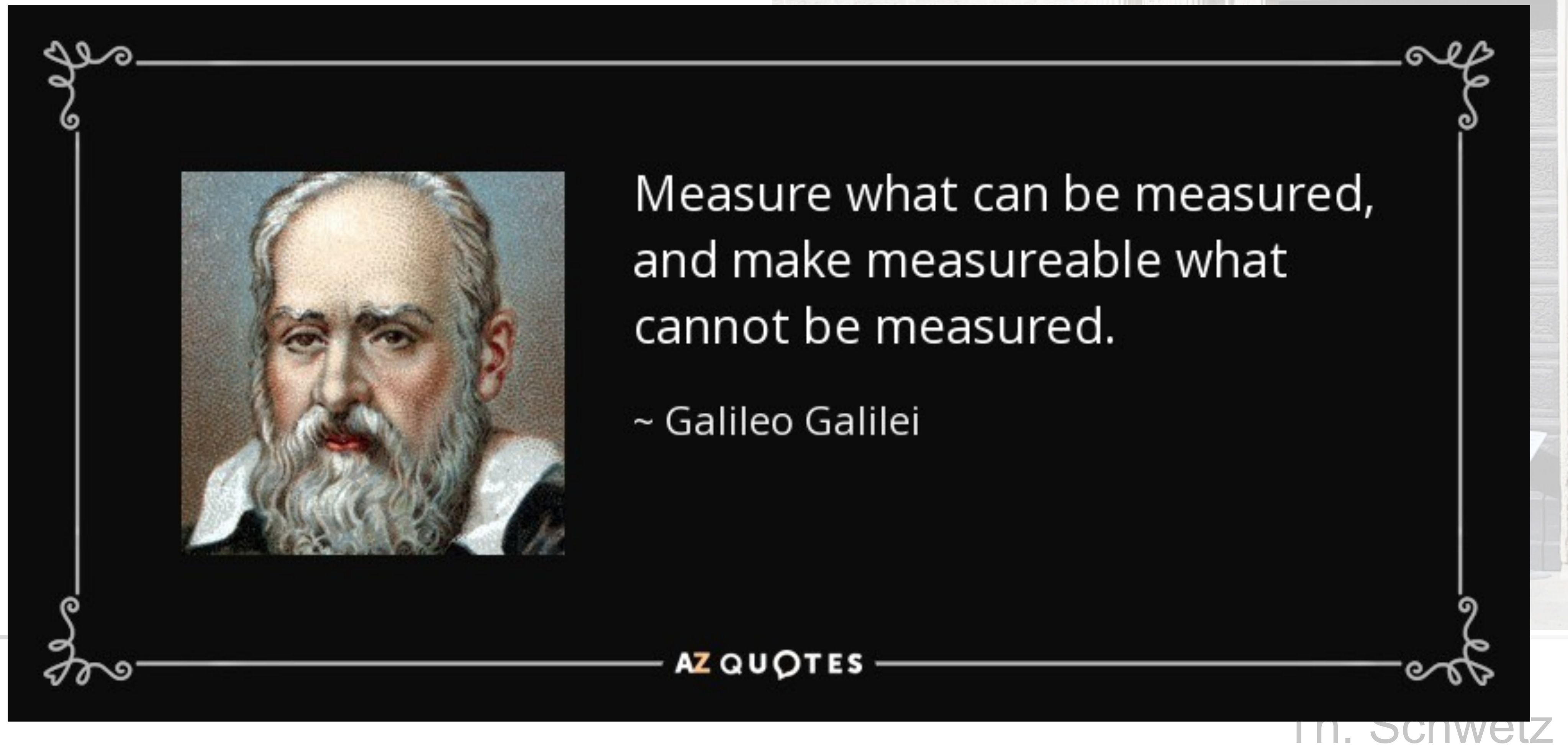
Gariazzo, Mena, TS, 2302.14159

Comments on long-term future: LNV and CPV

- What do neutrino teach us?
- What is the mechanism behind neutrino mass?
- Can we go beyond

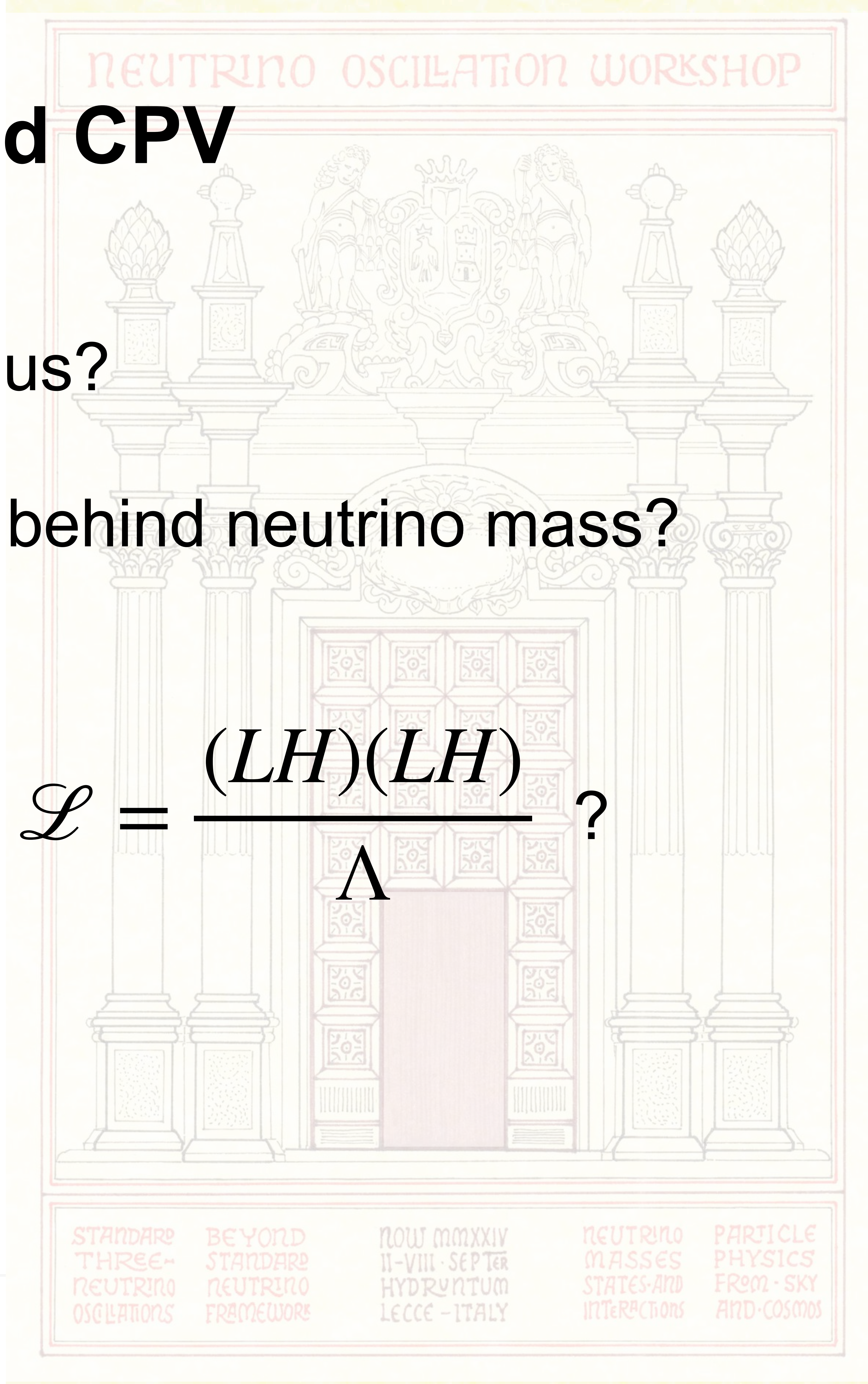
$$\mathscr{L} = \frac{(LH)(LH)}{\Lambda} \; ?$$

https://www.azquotes.com/quote/905195

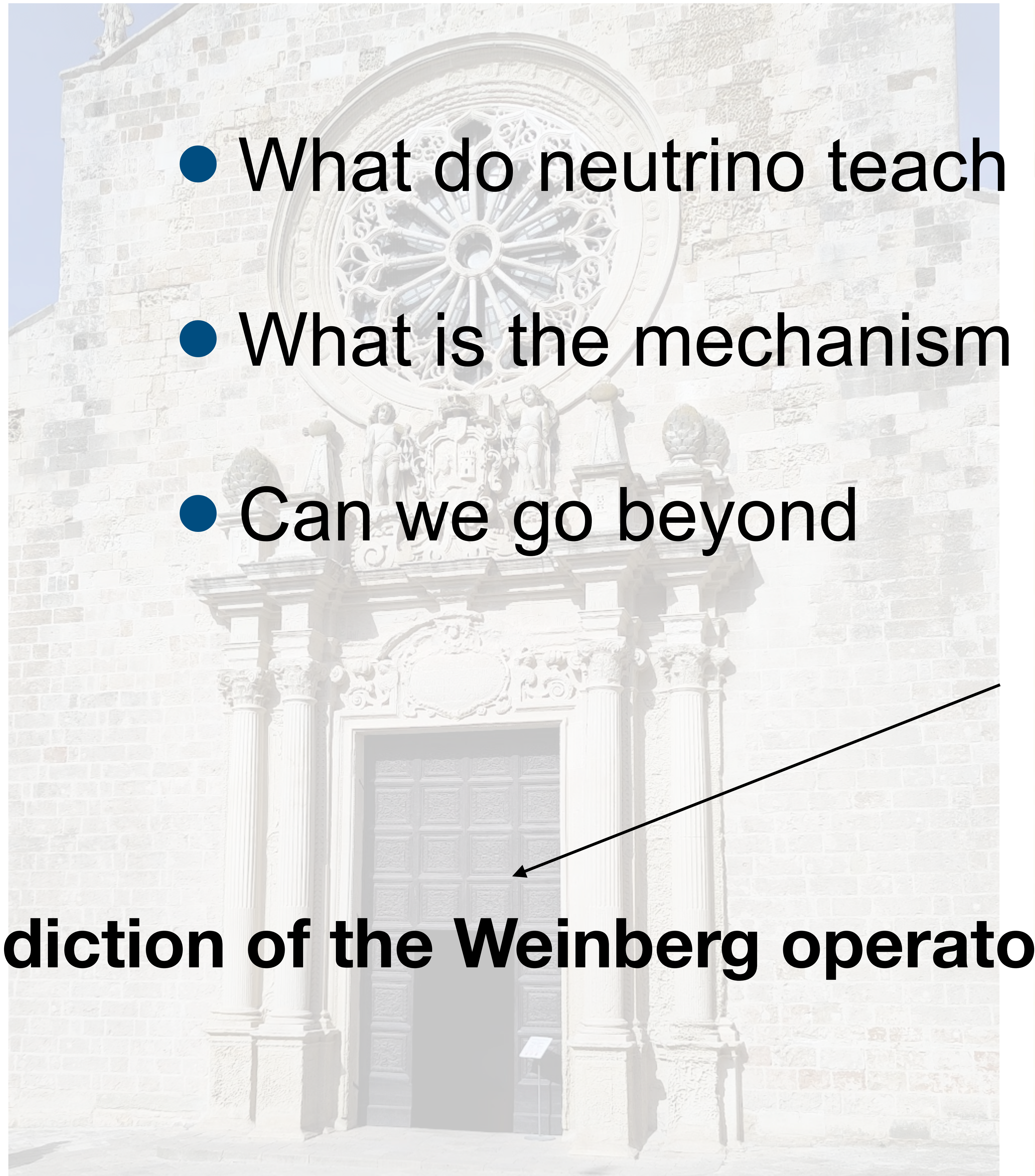


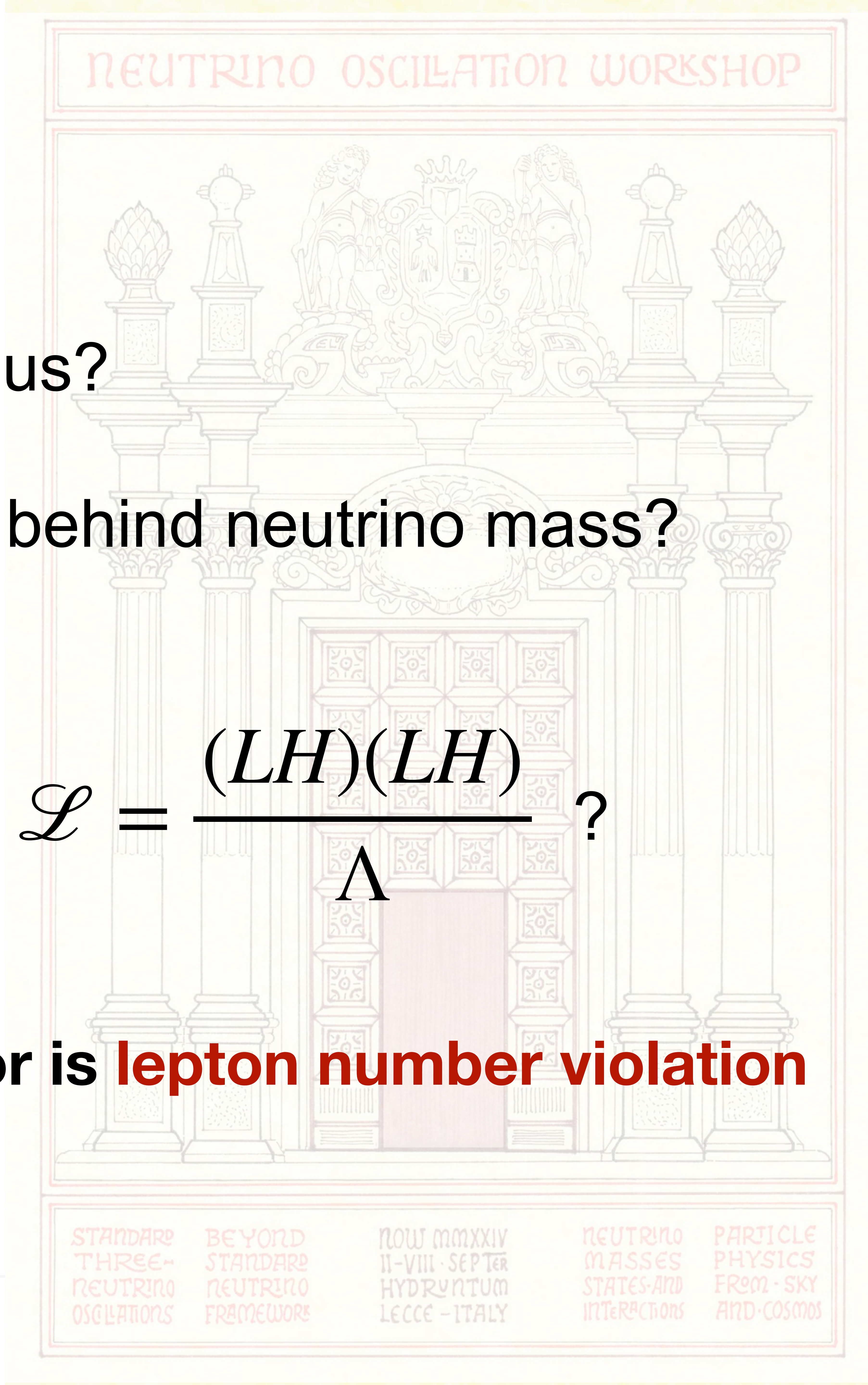
Measure what can be measured, and make measureable what cannot be measured.

~ Galileo Galilei



Comments on long-term future: LNV





- What do neutrino teach us?
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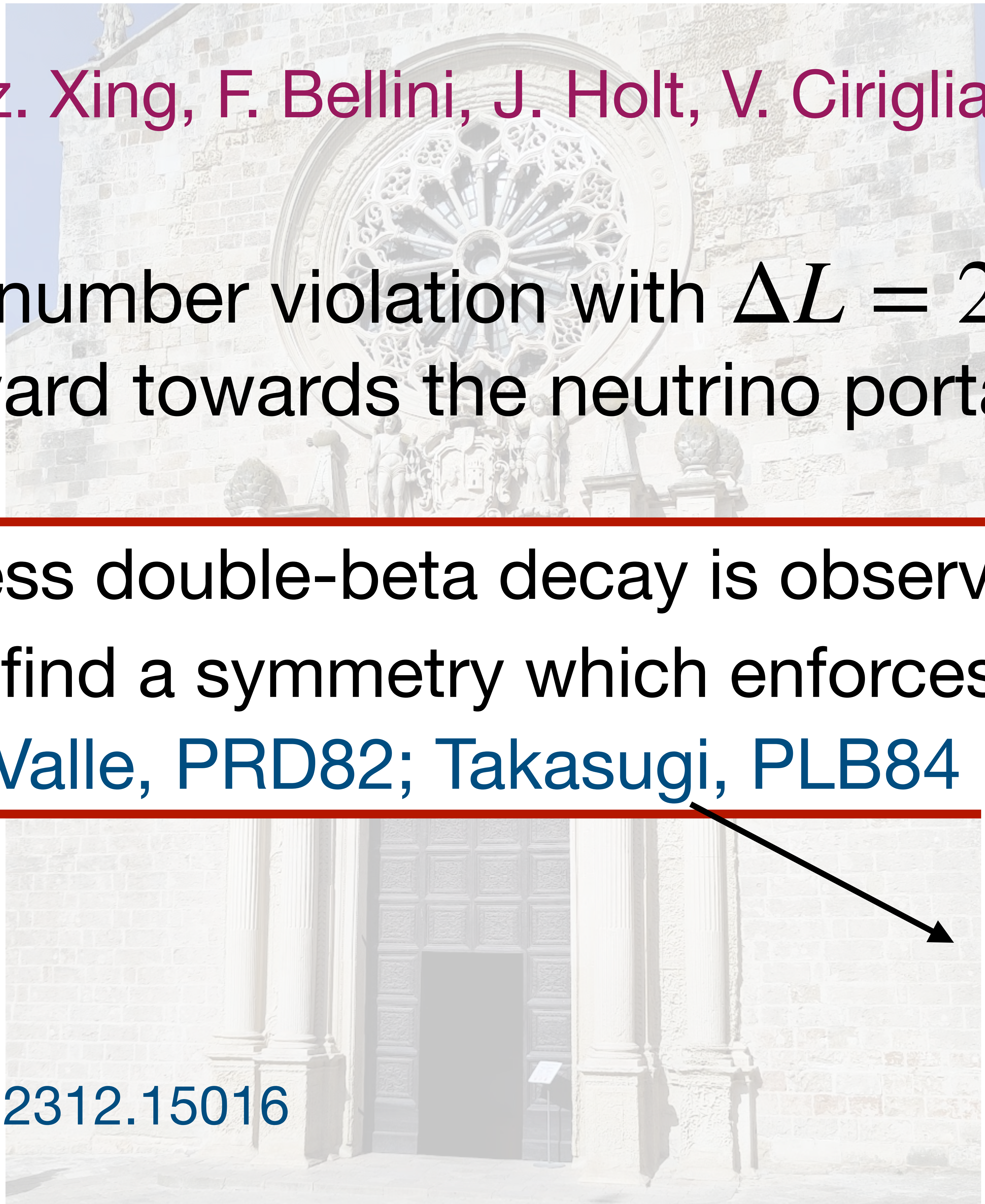
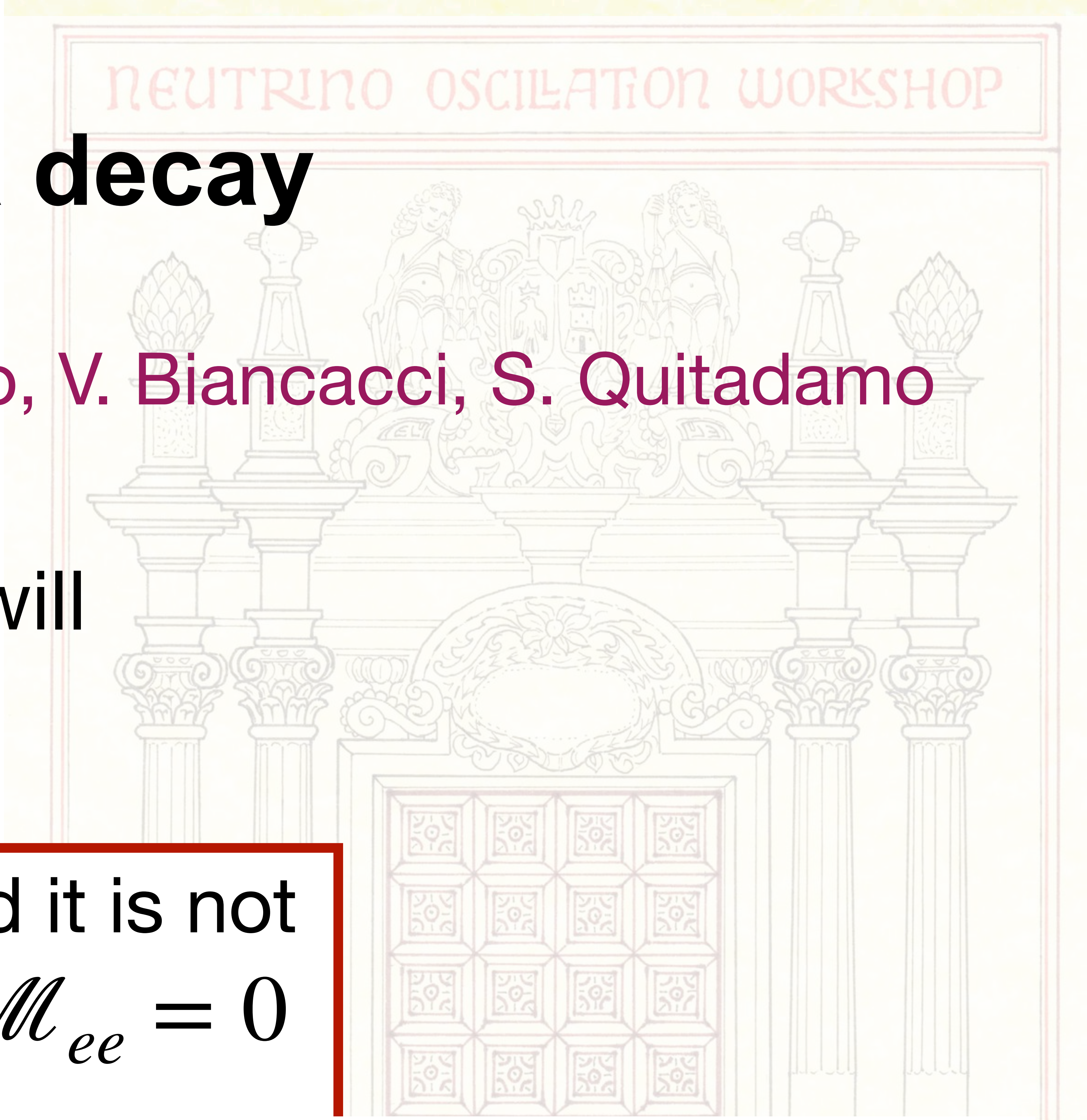
$$\mathscr{L} = \frac{(LH)(LH)}{\Lambda} \; ?$$

the most specific prediction of the Weinberg operator is lepton number violation

unique role of neutrinoless double-beta decay

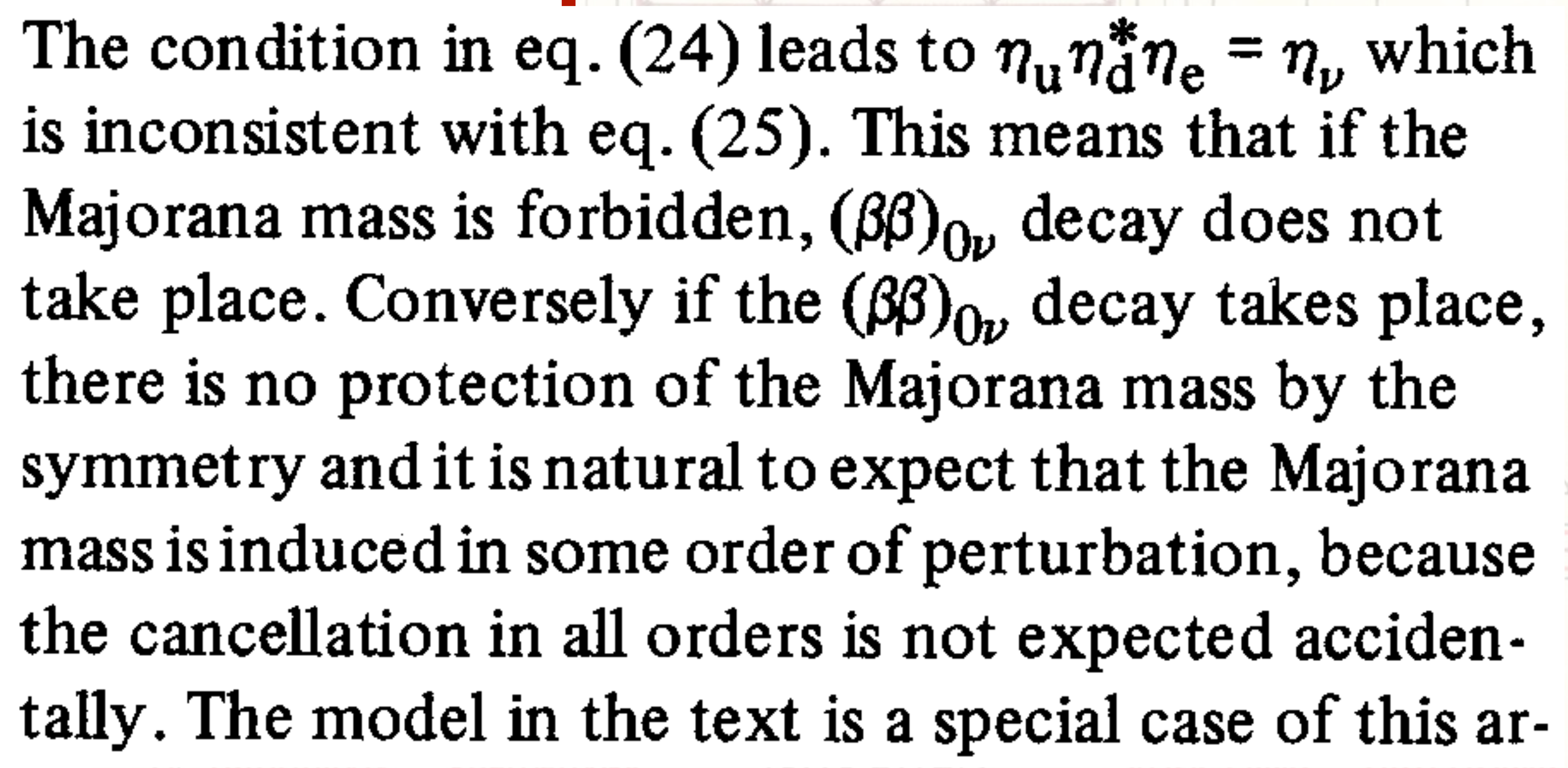




talks by F. Vissani, Z-z. Xing, F. Bellini, J. Holt, V. Cirigliano, V. Biancacci, S. Quitadamo

Establishing lepton number violation with $\Delta L = 2$ will be a huge step forward towards the neutrino portal

If neutrinoless double-beta decay is observed it is not possible to find a symmetry which enforces $\mathscr{M}_{ee} = 0$
Schechter, Valle, PRD82; Takasugi, PLB84



The condition in eq. (24) leads to $\eta_u \eta_d^* \eta_e = \eta_\nu$, which is inconsistent with eq. (25). This means that if the Majorana mass is forbidden, $(\beta\beta)_{0\nu}$ decay does not take place. Conversely if the $(\beta\beta)_{0\nu}$ decay takes place, there is no protection of the Majorana mass by the symmetry and it is natural to expect that the Majorana mass is induced in some order of perturbation, because the cancellation in all orders is not expected accidentally. The model in the text is a special case of this ar-

for a curious loophole see
Graf, Jana, Scholer, Volmer, 2312.15016

unique role of neutrinoless double-beta decay

talks by F. Vissani, Z-z. Xing, F. Bellini, J. Holt, V. Cirigliano, V. Biancacci, S. Quitadamo

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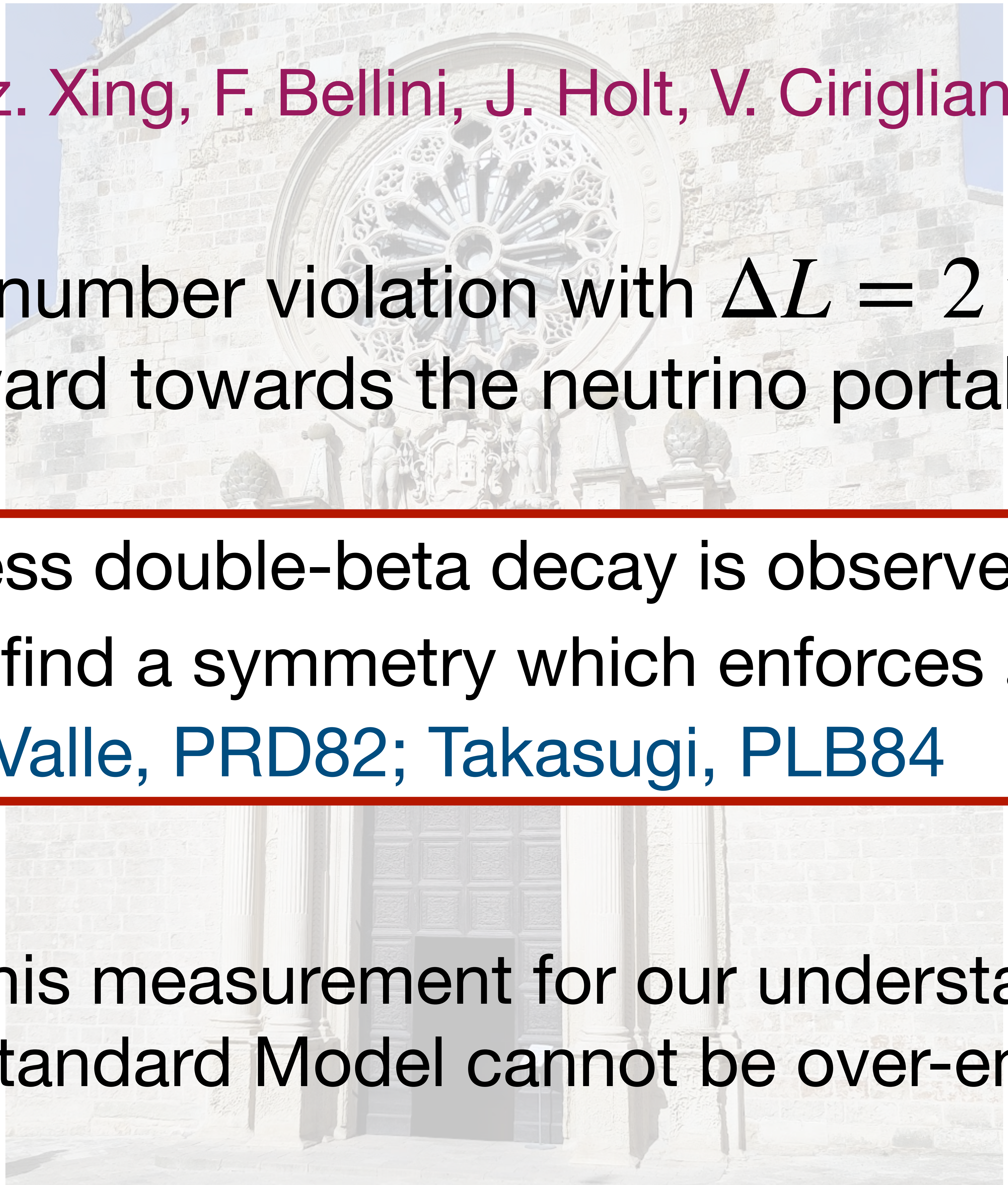
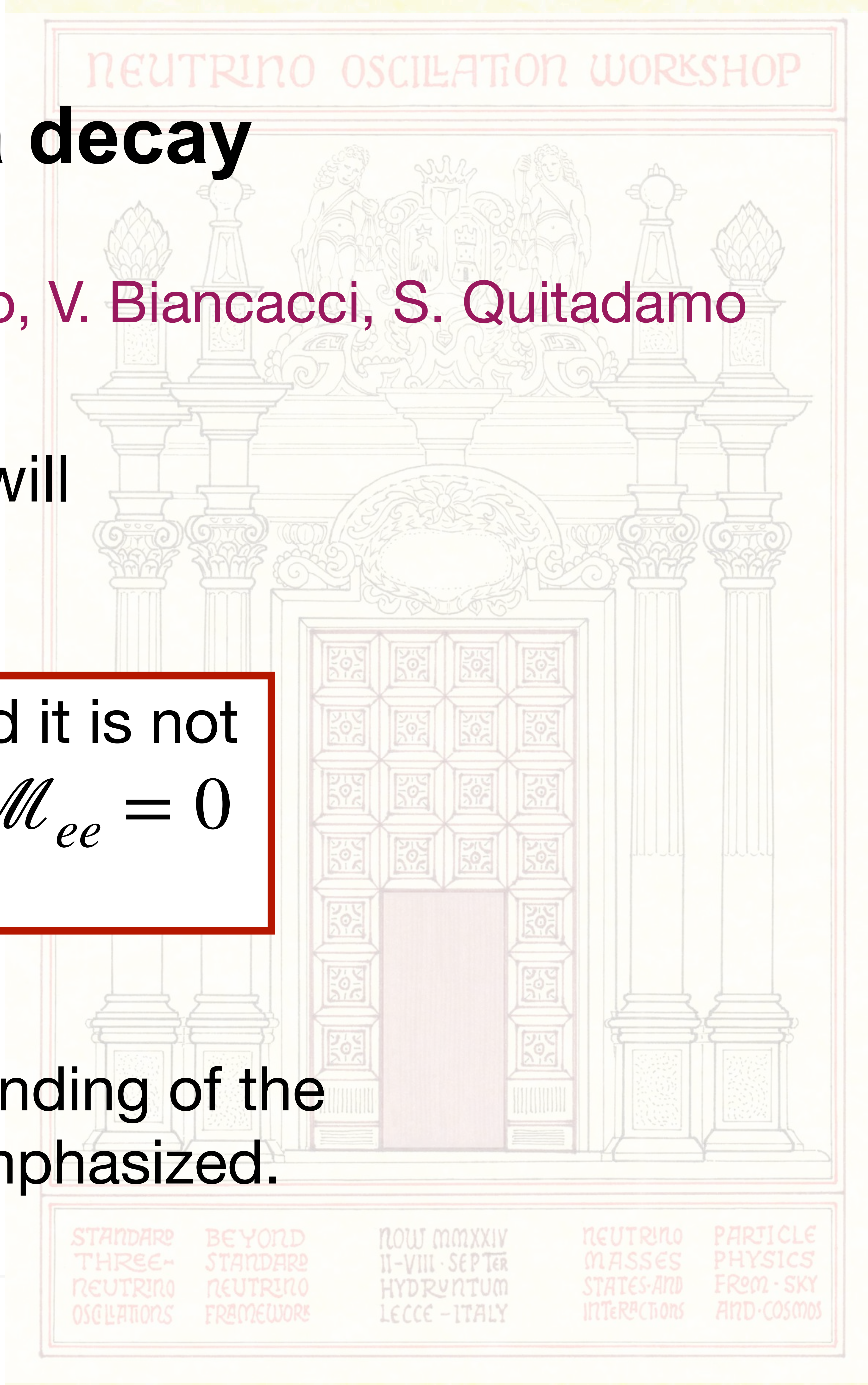
The importance of this measurement for our understanding of the symmetries of the Standard Model cannot be over-emphasized.





unique role of neutrinoless double-beta decay

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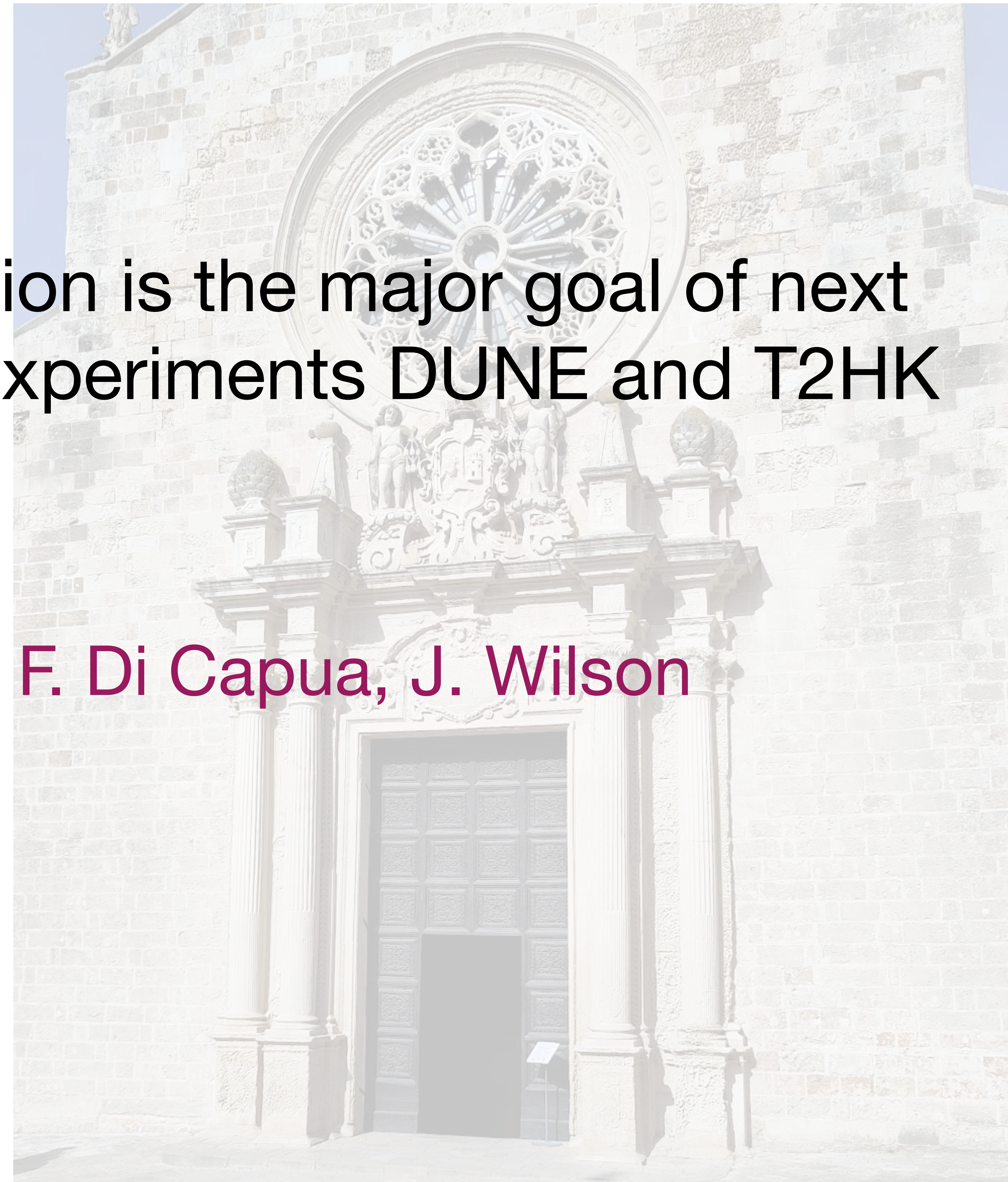
Establishing lepton number violation with $\Delta L = 2$ will be a huge step forward towards the neutrino portal

- covering inverted ordering region is challenging
- remarkable progress in experiments and NME theory

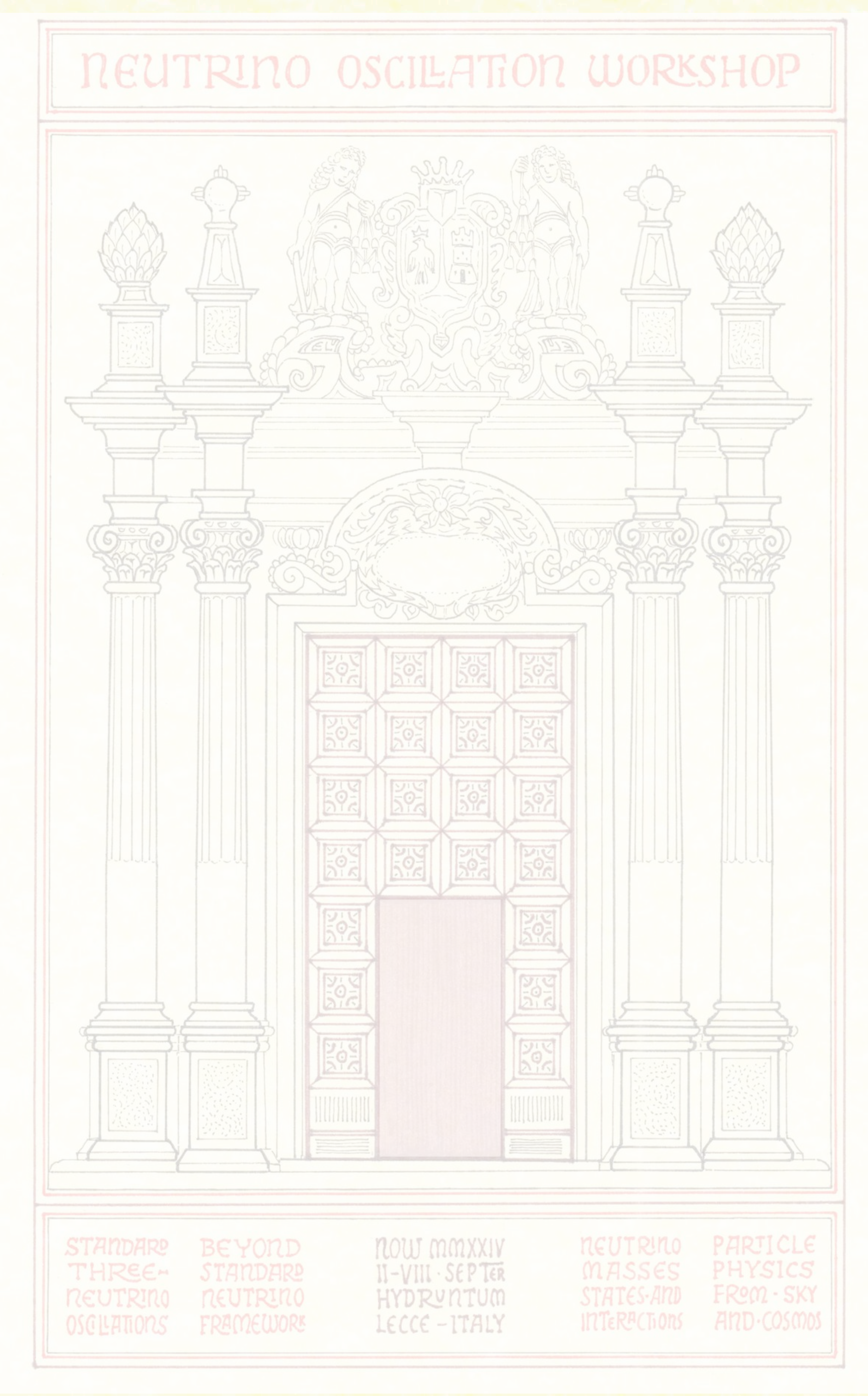
- global analyses of results from different isotopes will be important to
  - check for consistency, improve sensitivity
  - provide additional information on NME calculations
    [talk by J. Holt; Pompa, TS, Zhu, 23; Lisi, Marrone, 22]

Comments on long-term future: CPV

search for CP violation is the major goal of next generation of LBL experiments DUNE and T2HK



talks by F. Di Capua, J. Wilson



Comment on the search for CP (and T) violation

The „standard approach“ is highly model dependent:

no model-independent CPV observable → assume:

- minimal three-flavour (unitary) scenario
- standard neutrino interactions

perform a parametric fit of combined accelerator/reactor data

- determine allowed range for $\delta_{\rm CP}$
- CPV $\Leftrightarrow$ excluding values of 0 and π for $\delta_{\rm CP}$

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perform a parametric fit of combined accelerator/reactor data

- determine allowed range for δ_{CP}
- CPV ⇔ excluding values of 0 and π for δ_{CP}

Can we find a ``model-independent” observable to test CP (or T) violation in oscillation experiments?

A proposal of a T-violating observable

A. Segarra, TS, Phys. Rev. Lett. **128** (2022) 091801 [arXiv:2106.16099]
A. Segarra, TS, Phys. Rev. D **105** (2022) 055001 [arXiv:2112.08801]
S. Chatterjee, S. Patra, TS, K. Sharma, arXiv:2408.06419

impractical experimentally
(need a μ-based neutrino factory)

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$$\mathrm{T}[P_{\nu_\alpha\to\nu_\beta}(L)] = P_{\nu_\beta\to\nu_\alpha}(L) = P_{\nu_\alpha\to\nu_\beta}(-L)$$

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use that

$$\mathrm{T}[P_{\nu_\alpha\to\nu_\beta}(L)] = P_{\nu_\beta\to\nu_\alpha}(L) = P_{\nu_\alpha\to\nu_\beta}(-L)$$

- measure oscillation probabilities at several distances but at the same energy
- search for a T-odd (L-odd) component of the oscillation probability

Segarra, TS, 22

Model-independent test of T violation

- general parameterisation of the transition probabilities:

$$c_i^\alpha \equiv (N_{\alpha i}^{\mathrm{det}})^* N_{\mu i}^{\mathrm{prod}}$$

$$P_{\mu\alpha} = \left|\sum_{i=1}^{3} c_i^\alpha e^{-i\lambda_i L}\right|^2$$

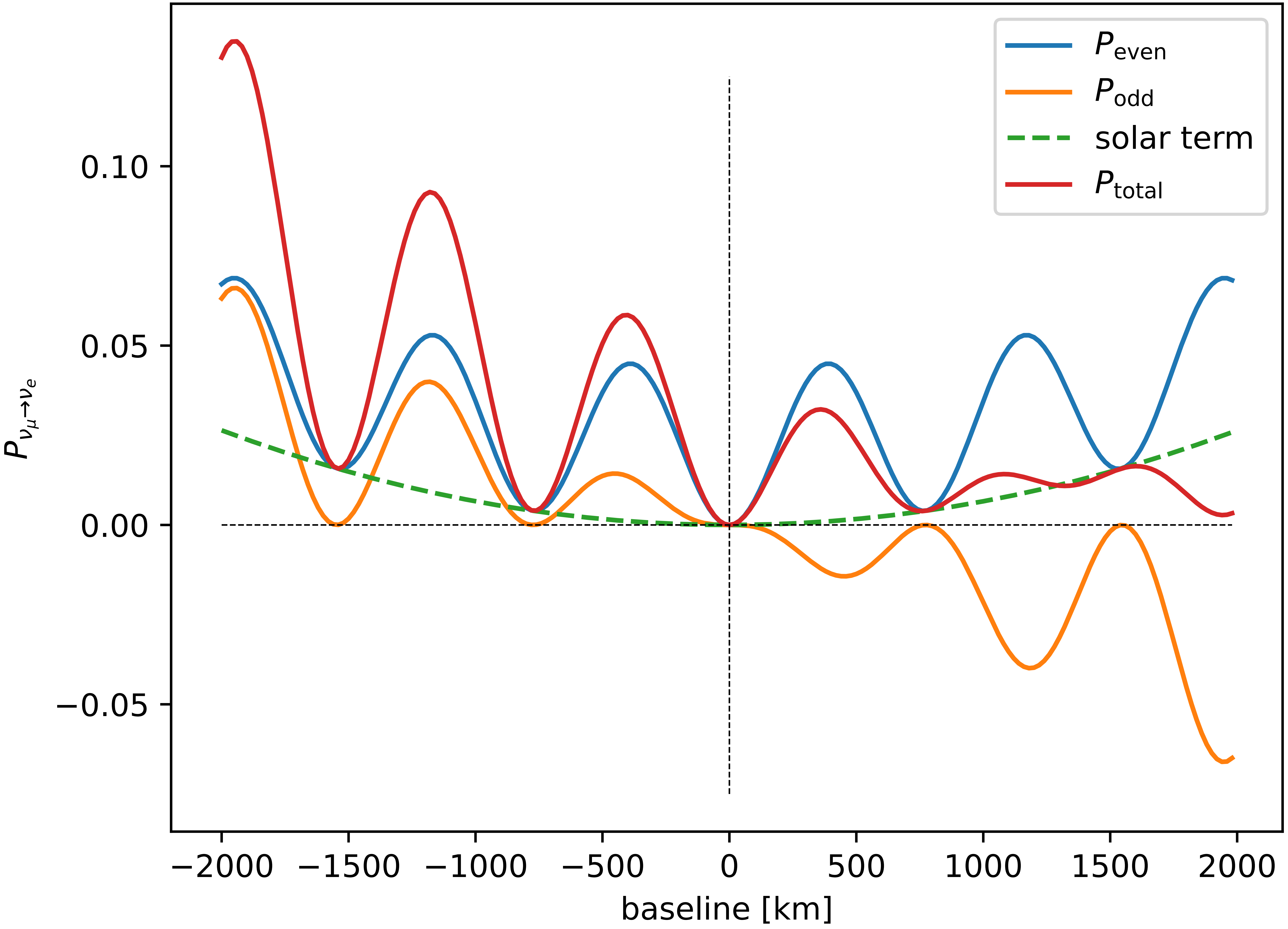
T-even

T-odd

$$= \sum_i |c_i^\alpha|^2 + 2\sum_{j<i} \mathrm{Re}(c_i^\alpha c_j^{\alpha *}) \cos(\omega_{ij} L) - 2\sum_{j<i} \mathrm{Im}(c_i^\alpha c_j^{\alpha *}) \sin(\omega_{ij} L)$$

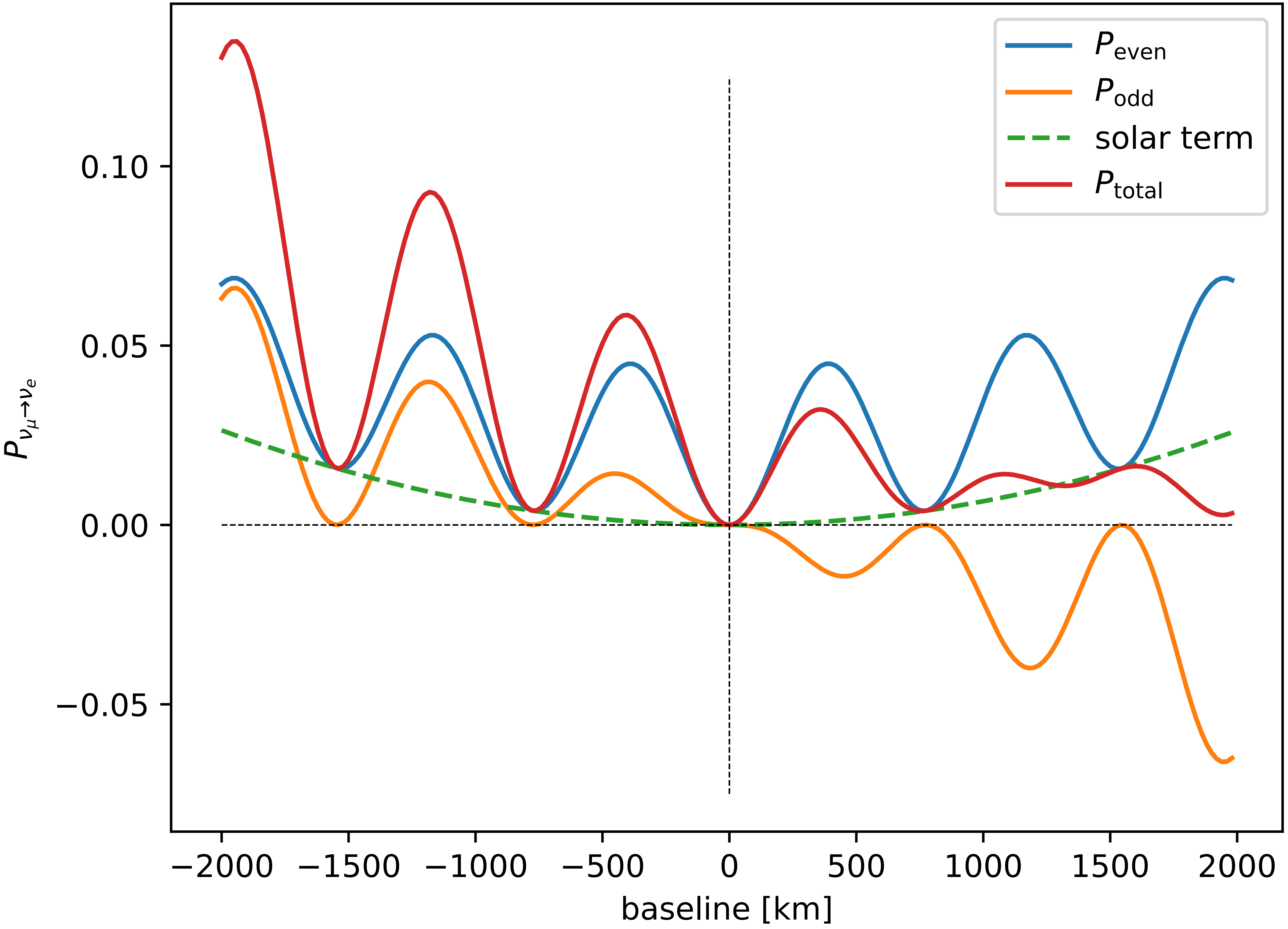
if data cannot be fitted only with the L-even part, fundamental T violation is established model-independently

- Example:
  3-flavour vacuum probability for
  $\delta_{\rm CP} = \pi/2$
  $E_\nu = 0.75\,{\rm GeV}$



- Example:
  3-flavour vacuum probability for
  $\delta_{\mathrm{CP}} = \pi/2$
  $E_\nu = 0.75\,\mathrm{GeV}$

- How many data points do we need to establish that a T-odd component is present?



Need just two experiments!

Chatterjee, Patra, TS, Sharma, 2408.06419

- consider

$$X_T \equiv P_{\text{even}}(L_2) - P_{\text{even}}(L_1) - \delta_0 P_{\text{even}}^{L=0}$$

$$= c_2^2\delta_2 + c_3^2\delta_3 + c_2c_3\delta_{23}$$

where δ_i are known functions of $(\Delta m_{ij}^2)_{\text{eff}} L_{1,2}/E_\nu$

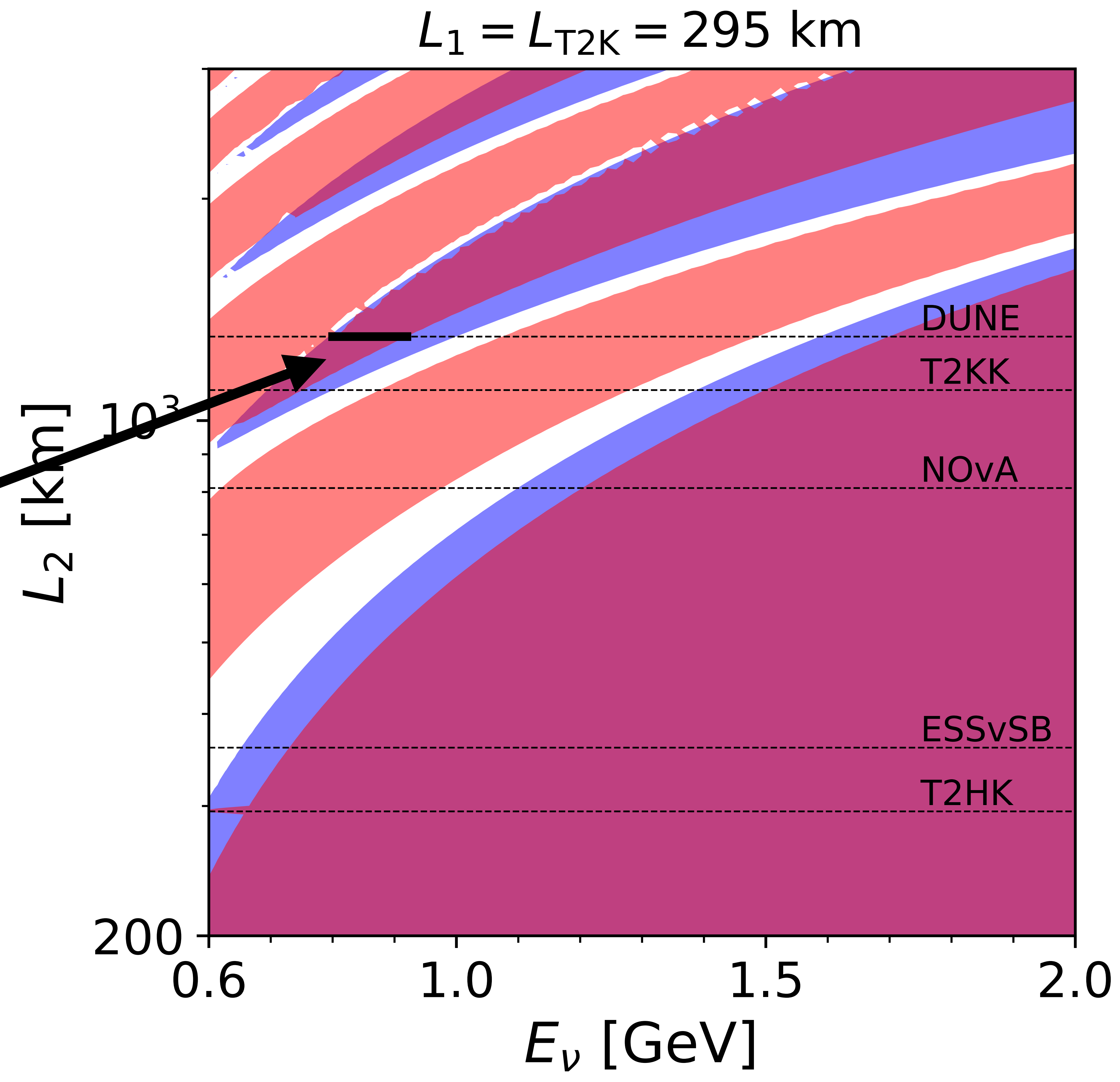
$\Rightarrow \quad X_T \geq 0$ if $\delta_2, \delta_3 > 0$ and $\delta_{23}^2 < 4\delta_2\delta_3$

- T has to be violated if $X_T^{\text{observed}} < 0$ and the δ_i-conditions are satisfied.

Chatterjee, Patra, TS, Sharma, 2408.06419

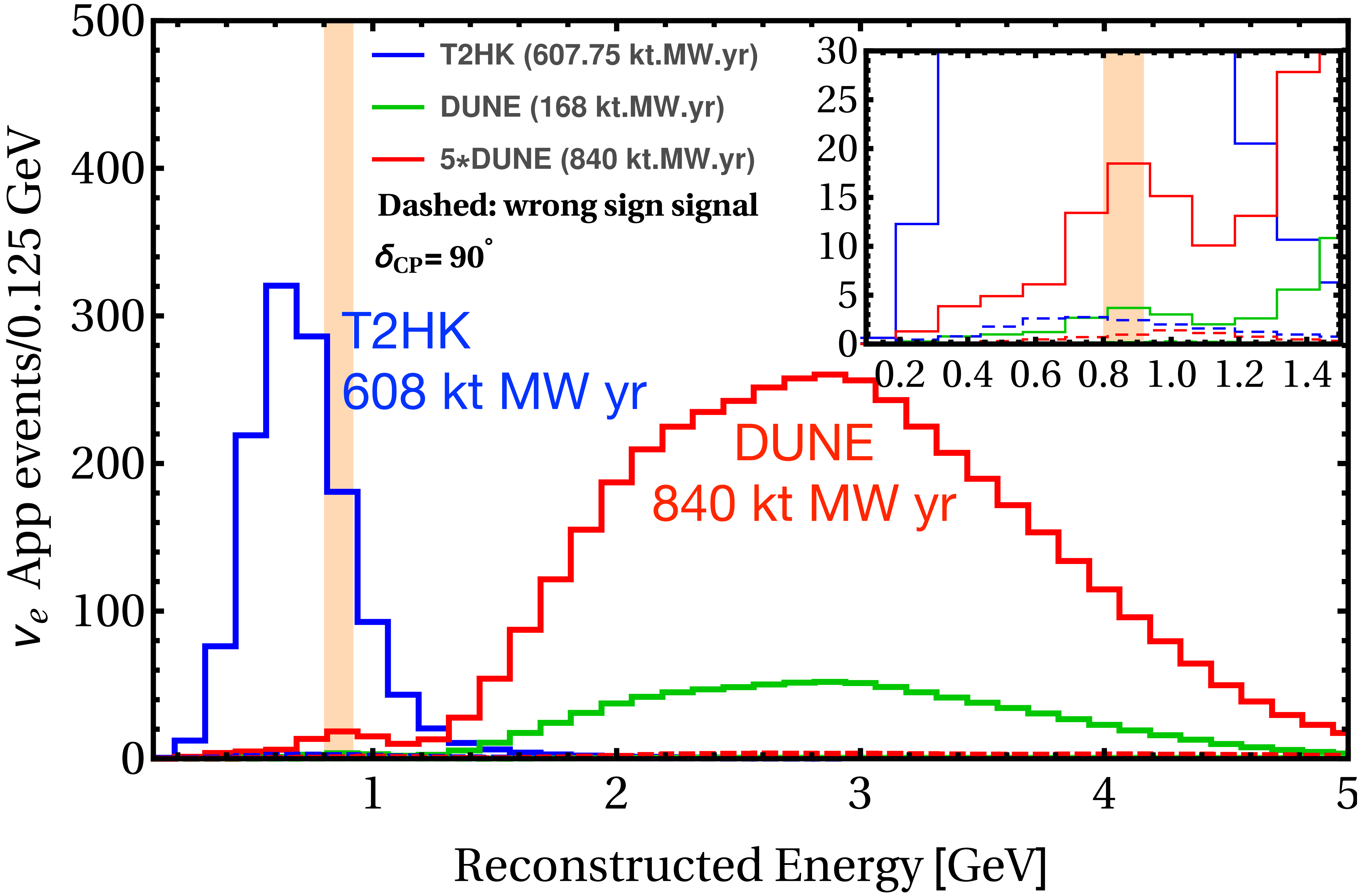
- where are the conditions $\delta_2, \delta_3 > 0$ and $\delta_{23}^2 < 4\delta_2\delta_3$ satisfied? (both)

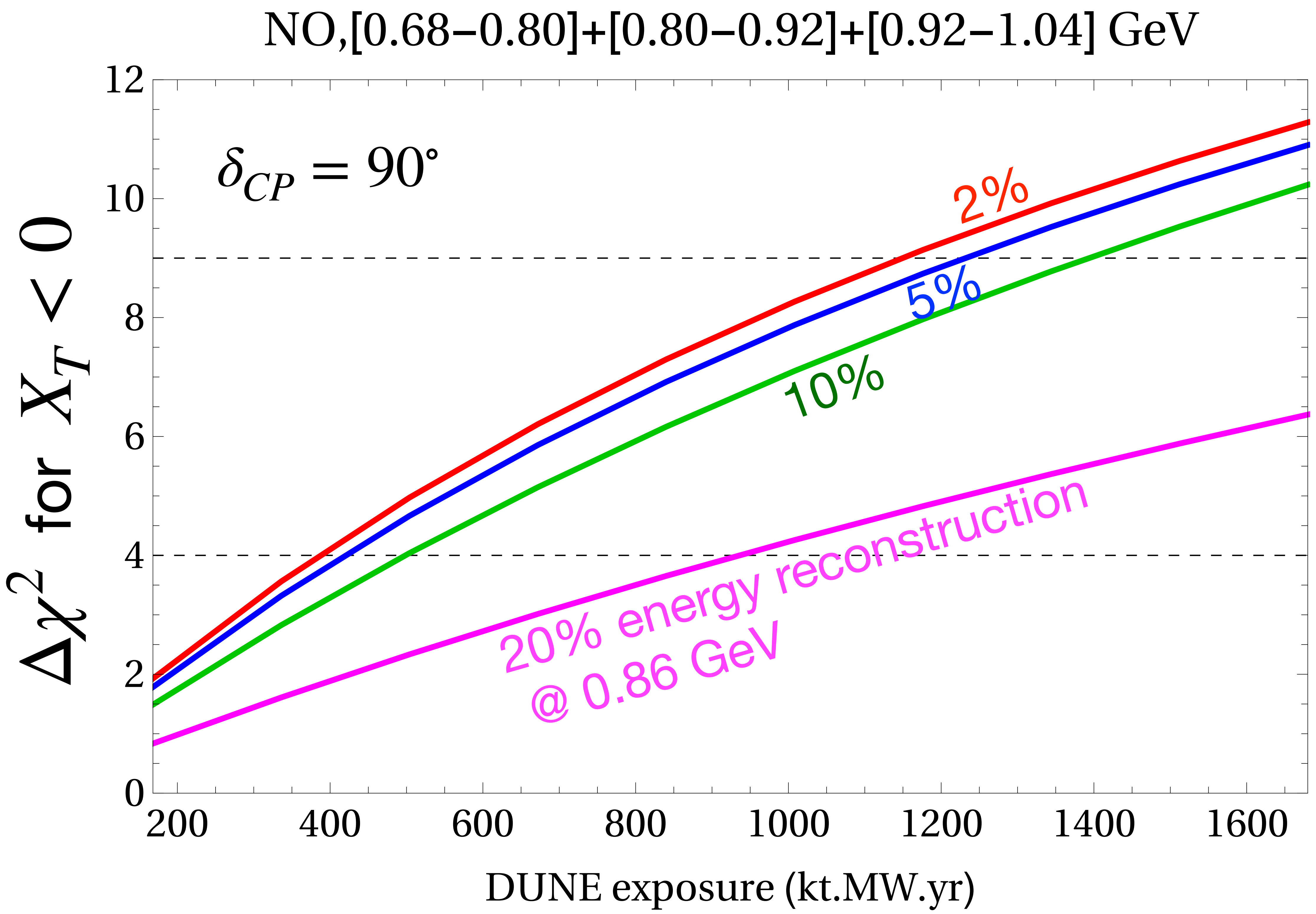
- sweet spot for T2HK and DUNE for $E_\nu \approx 0.86$ GeV



$\Rightarrow$ If we can establish experimentally that $P_{\mu e}(\mathrm{DUNE}) < P_{\mu e}(\mathrm{T2HK})$ at $E_\nu \approx 0.86$ and $P_{\mu e}(L = 0)$ is sufficiently small then T has to be violated.

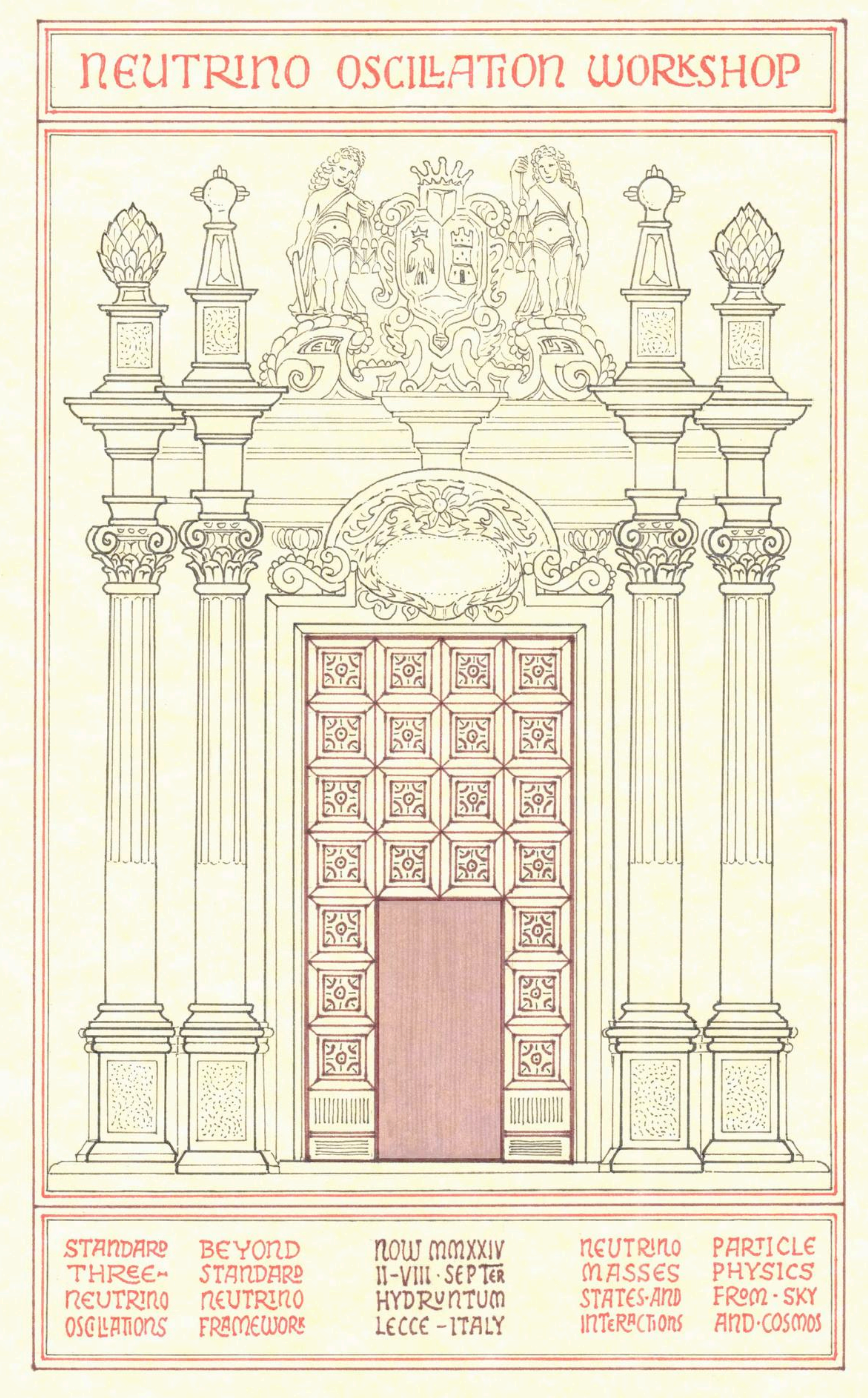
Can it work in real life?





need to collect enough statistics in DUNE at $E_\nu \approx 0.86$ GeV,
and achieve good energy resolution

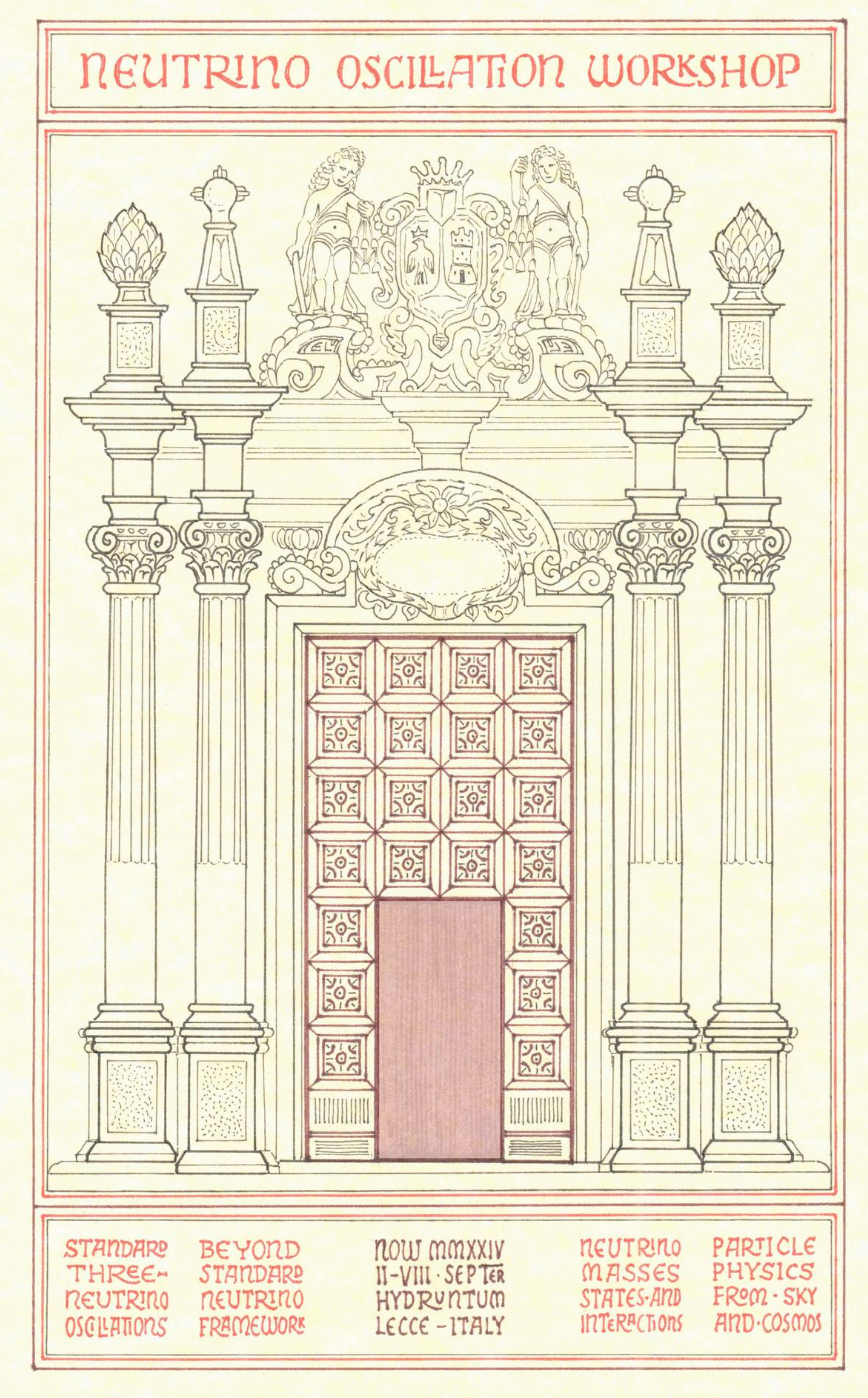
The neutrino portal is open…



The neutrino portal is open…

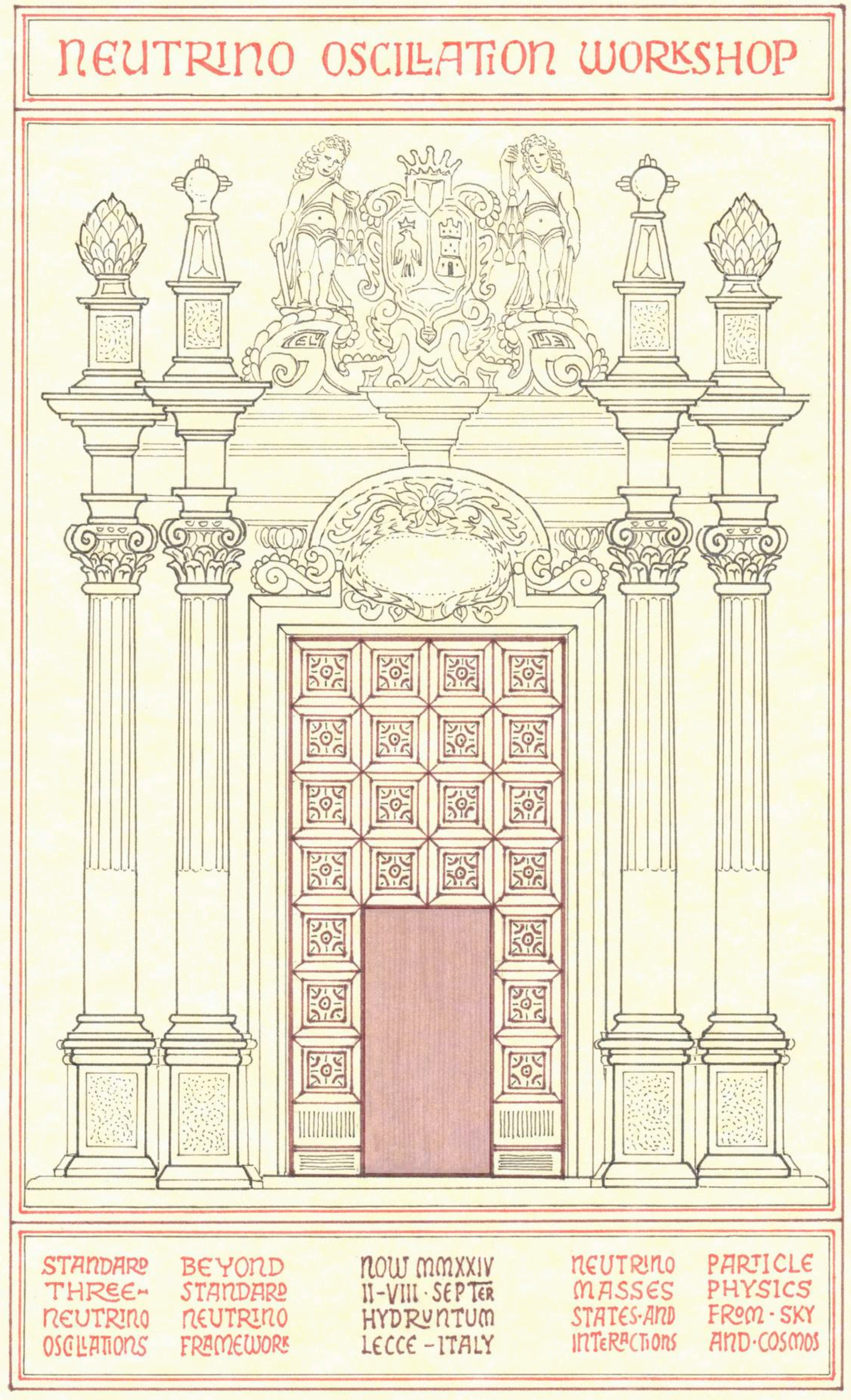
…but

- we cannot yet see inside
- the entrance is small and surrounded by strong walls

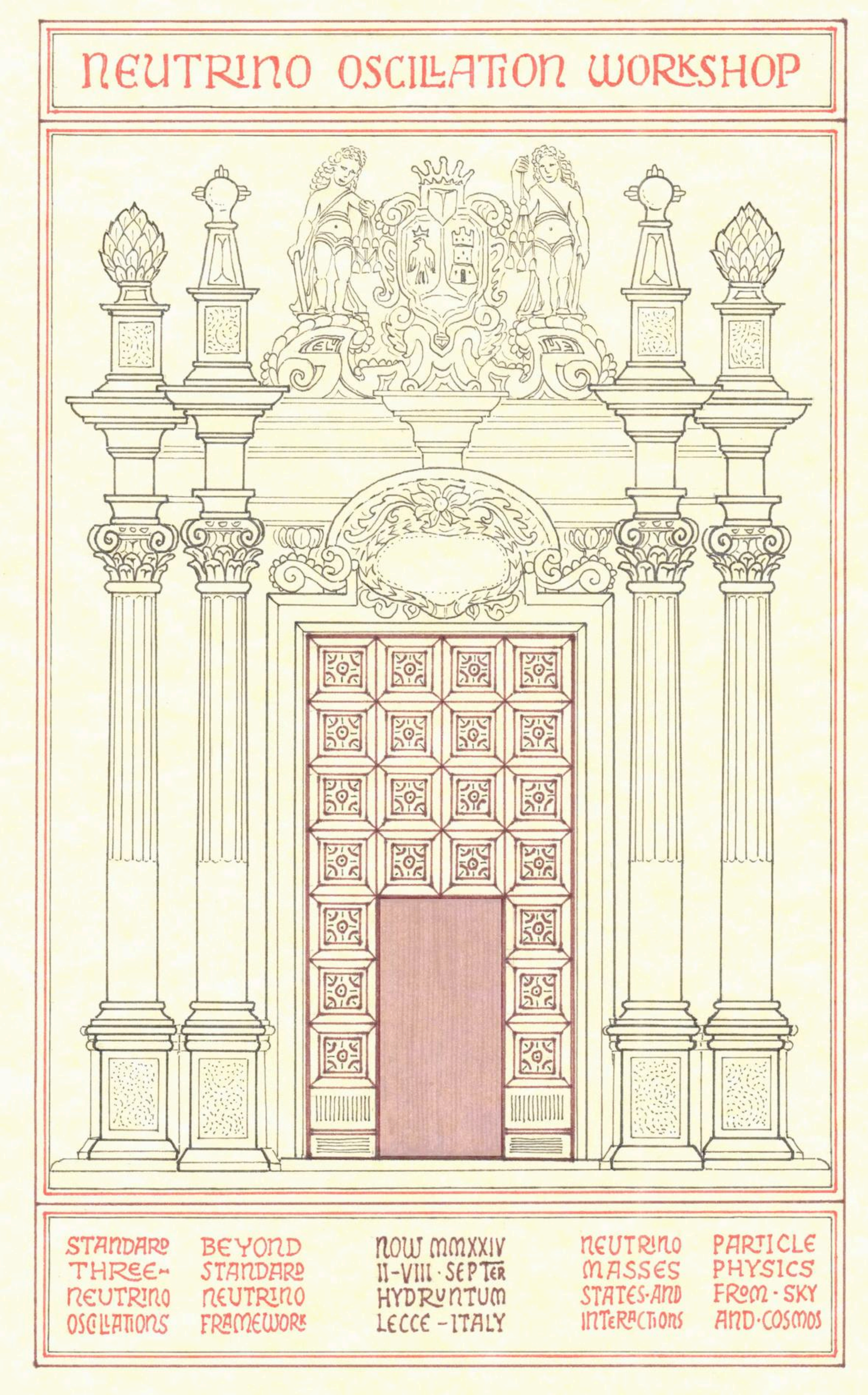


The neutrino portal is open…

Let's enter the portal to find out what's behind it, and what neutrinos ultimately will teach us!



- **Congratulations to the Bari group for 30 years of influential work on global analyses**
- **Thanks to the organizers for another fantastic edition of the NOW series!**



backup

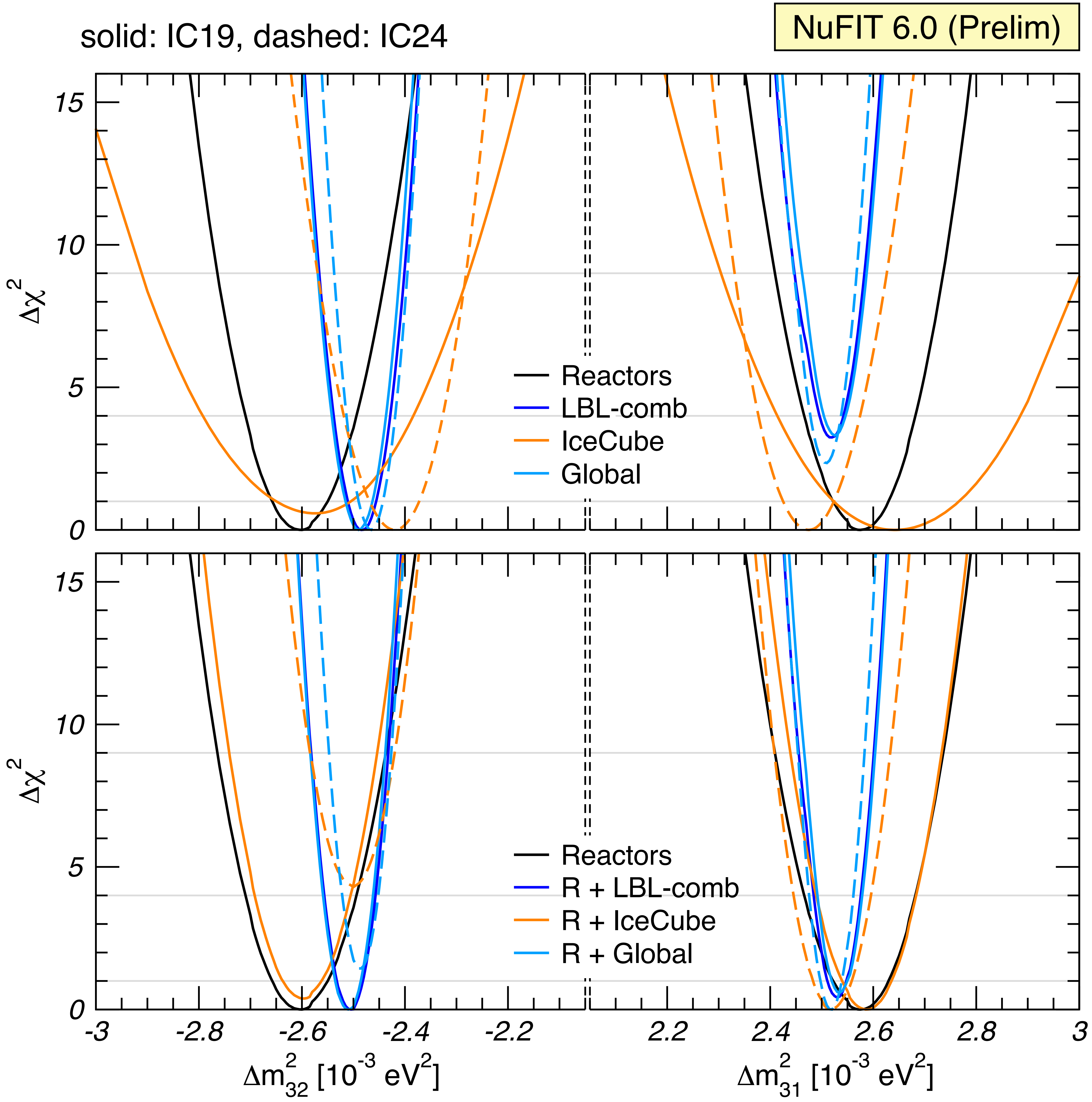
IceCube/DeepCore impact on MO global fit

IC24: 9.3 yr data [2405.02163]

$\Delta\chi^2$ table provided by collaboration

IC19: 3 yr data [1902.07771]

our analysis



Segarra, TS, 22

Assumptions for T violation search

- assume evolution equation $i\partial_t|\psi\rangle = H(E_\nu)|\psi\rangle$ $(H = H^\dagger$, unitary evolution)
- position independent Hamiltonian (approx. constant matter density)
→ matter effect does not introduce environmental T violation
- allow for arbitrary (non-standard) matter effect
- allow for arbitrary (non-unitary) mixing between flavour and energy eigenstates (different for production and detection): $|\nu_\alpha\rangle = \sum_i N_{\alpha i}^{\text{prod,det}}|\nu_i\rangle$
- only 2 independent frequencies are present, deviation from standard 3-flavour is „small“: $(\Delta m^2_{21})_{\text{eff}}$, $(\Delta m^2_{31})_{\text{eff}}$ close to SM