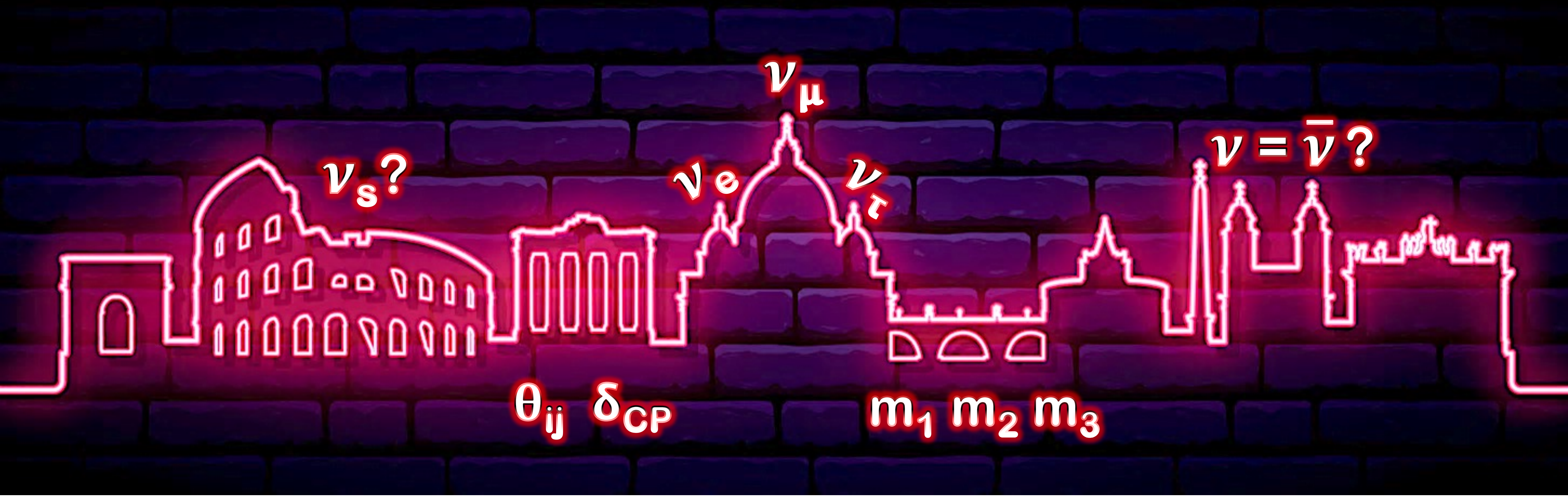
INFN
Istituto Nazionale di Fisica Nucleare
Sezione di Roma

The Rise of Particle Physics

23rd and 24th September 2024

Sapienza
Università di Roma

NEUTRINOS: THE RISE OF A NEW PARADIGM



Eligio Lisi
(INFN, Bari, Italy)

PROLOGUE

Last-century questions about fundamental ν properties (mass, spinorial d.o.f., families, charges):

How small is the neutrino mass?

Pauli, Fermi, ‘30s

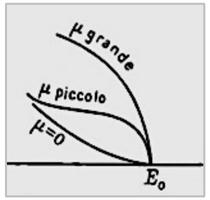
Is the neutrino its own antiparticle?

Majorana, ‘30s

Do ν of different flavors mix among them?

Pontecorvo, Maki, Nakagawa, Sakata, ‘60s





TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

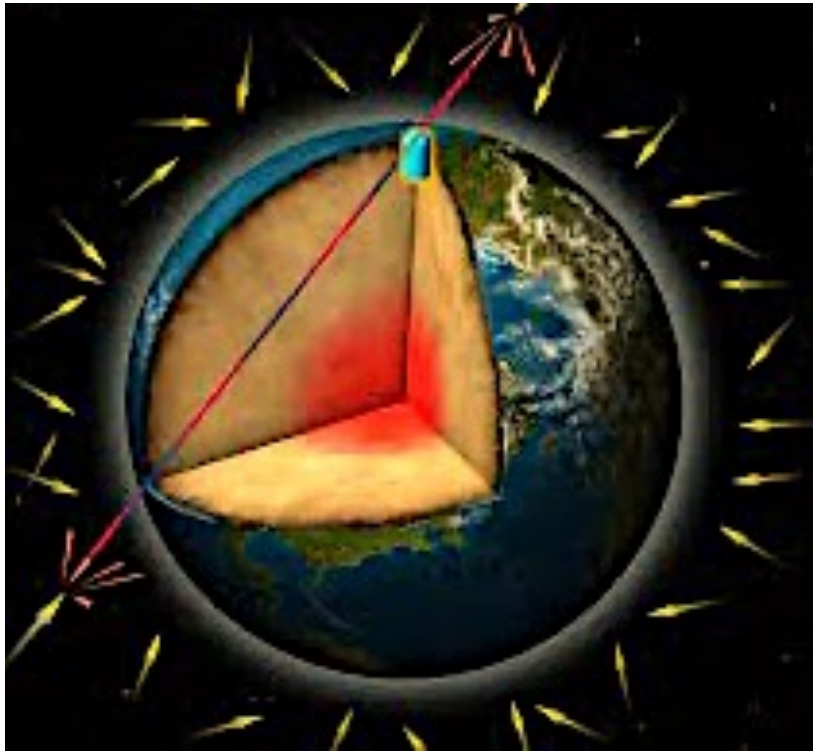
Nota di Ettore Majorana

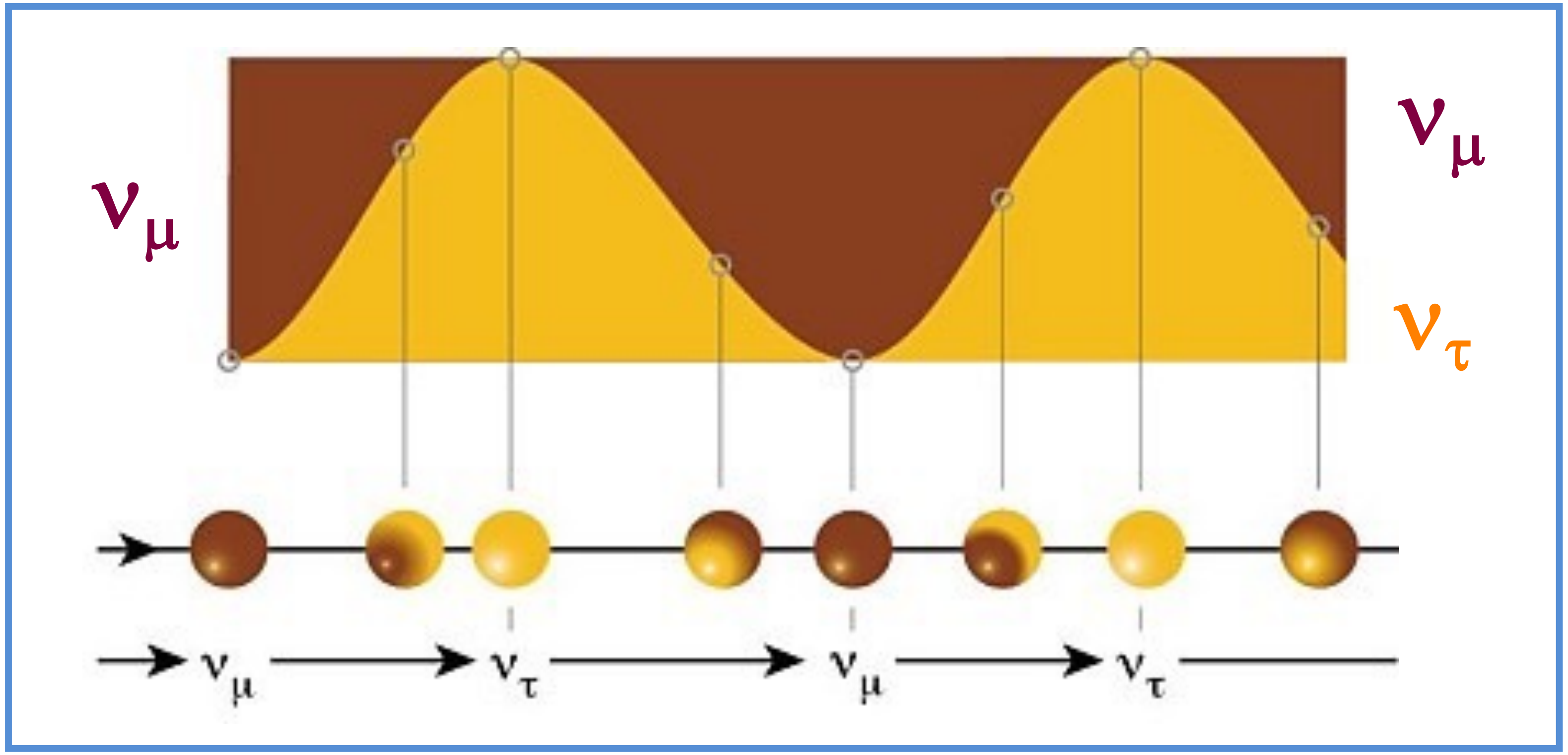



P M N S

Short answers (assumptions) in the “minimal” Standard Model were: Zero, NO, NO (respectively)

1998 discovery of atmospheric ν_μ-flavor oscillations in Super-Kamiokande started a new paradigm!





In 2ν approxim.: Oscillation **frequency** set by mass^2 difference Δm^2; amplitude set by mixing angle θ

[In a proper 3ν framework: further mass-mixing parameters]

Strong and long-lasting impact on the physics community (and beyond)

The New York Times

NEW YORK, FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, Friday, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter, the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Detecting Neutrinos

Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water ...

... and collide with other particles ...

... producing a cone-shaped flash of light.

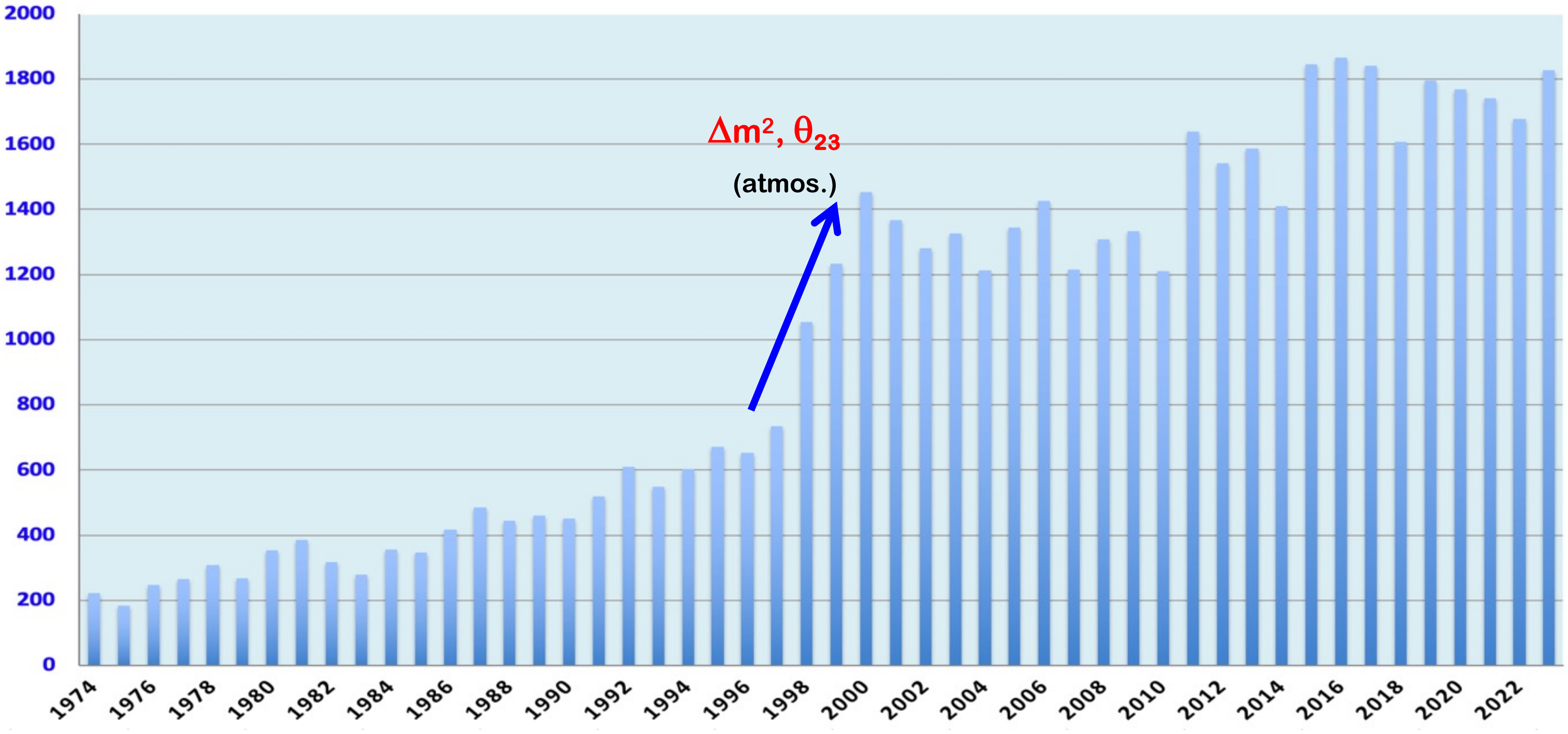
The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

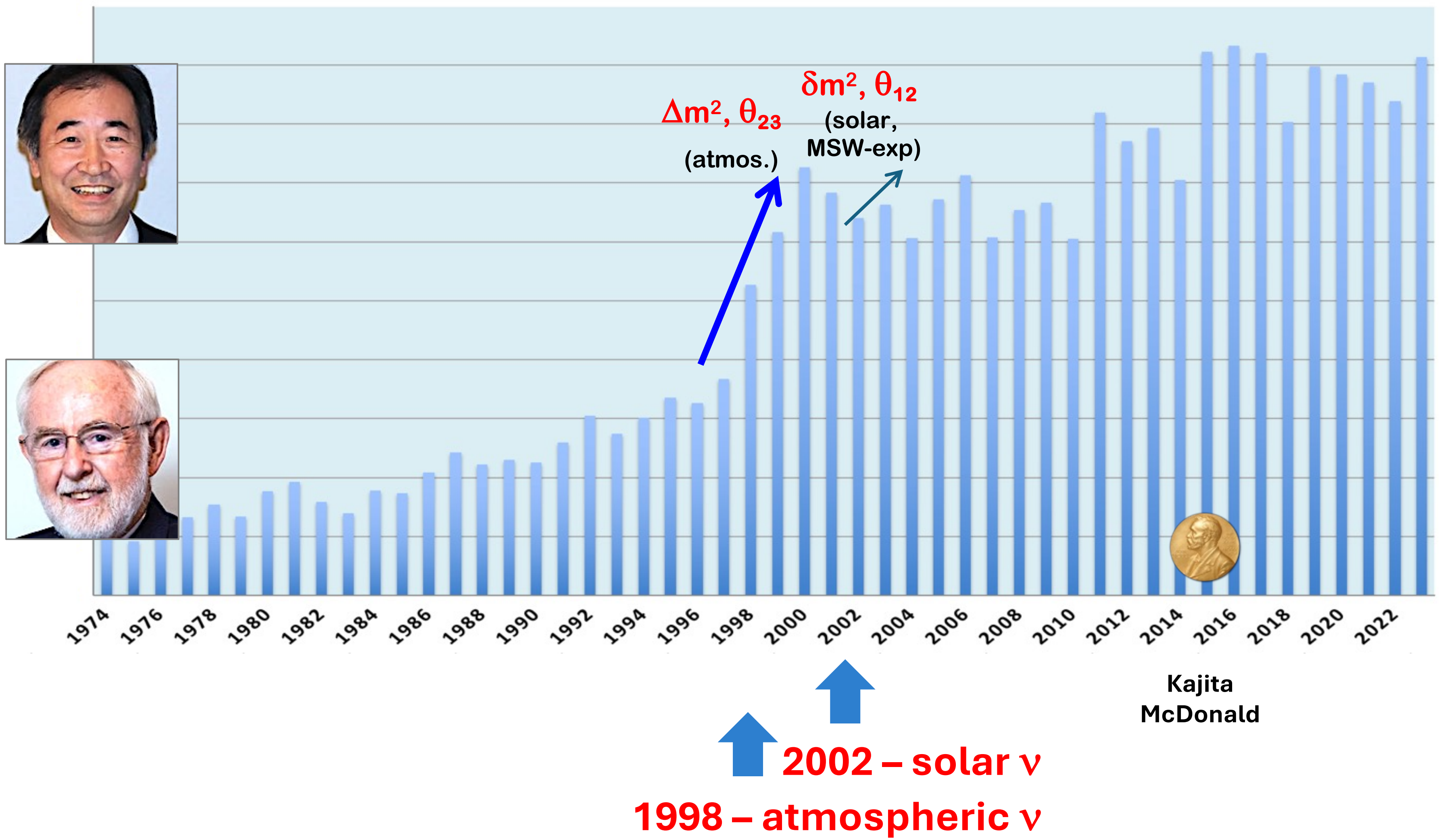
Source: University of Hawaii

\# papers with *neutrino* in the title, 50-yr trend from INSPIRE HEP

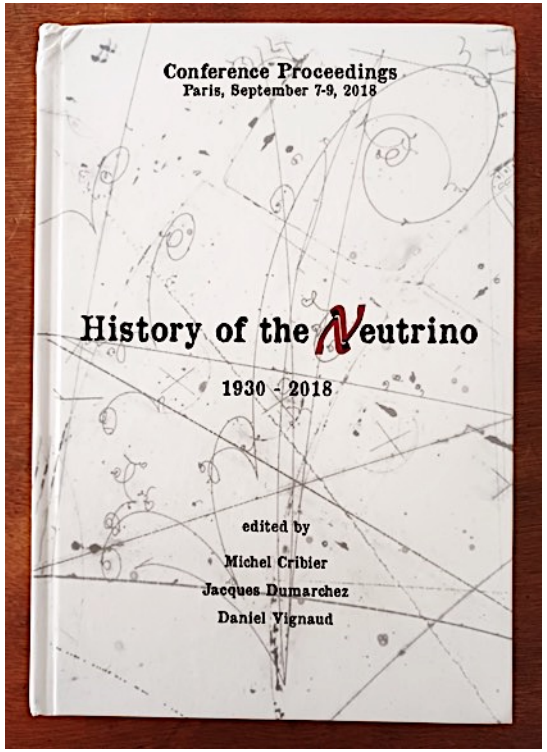


1998 – atmospheric ν

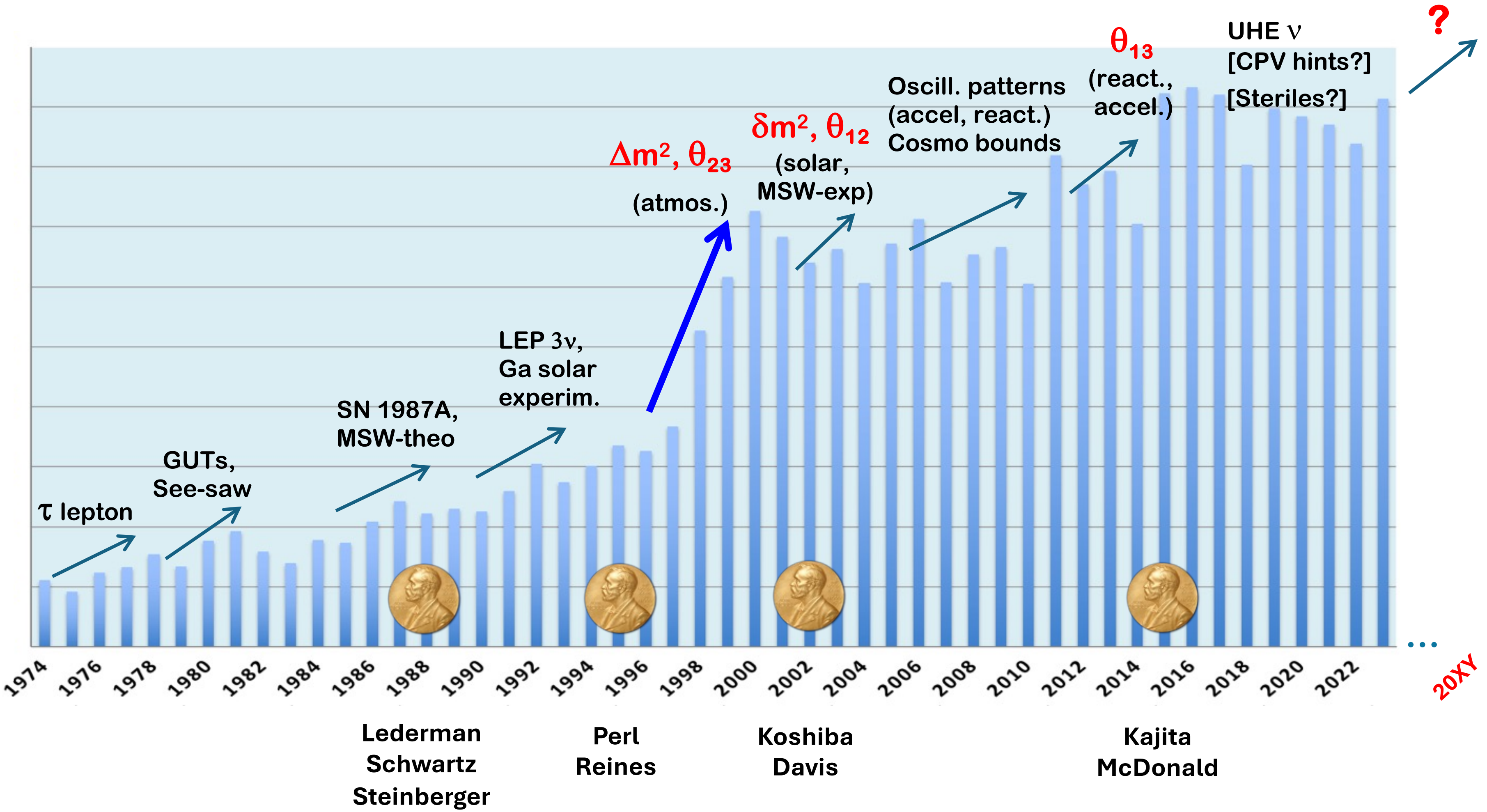
… followed by other crucial discoveries …



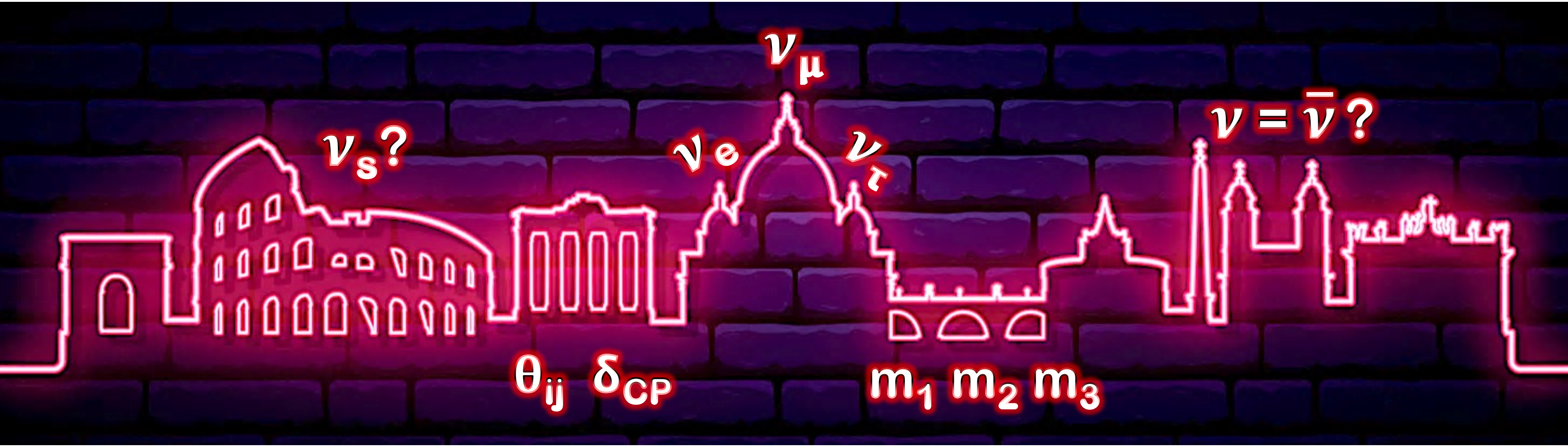
… that are part of a long and exciting scientific path



neutrino-history.in2p3.fr



Where Are We ?



Where Are We Going ?

3ν paradigm: oscillation parameters

Mixing matrix: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

2-3 rotation

1-3 rotation
+ CPV "Dirac" phase
U(ν) → U*($\overline{\nu}$)

1-2 rotation

Extra CPV phases
[if Majorana]
not tested in oscillat.

3ν paradigm: oscillation parameters

Mixing matrix: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

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2-3 rotation

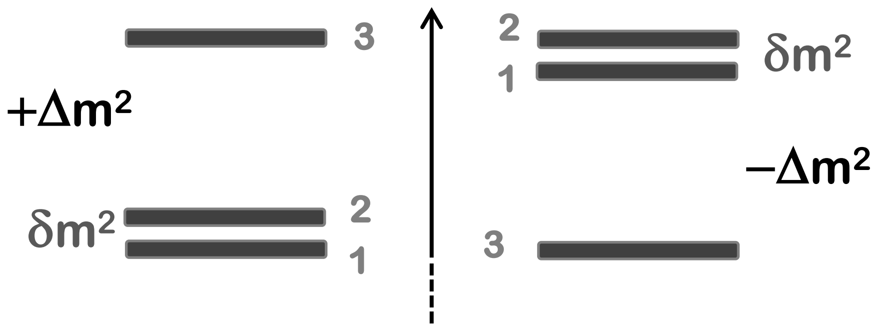
1-3 rotation
+ CPV "Dirac" phase
$U(\nu) \rightarrow U^*(\bar{\nu})$

1-2 rotation

Extra CPV phases
[if Majorana]
not tested in oscillat.

Mass [squared] spectrum (E ~ p + m²/2E + "MSW interaction energy")

"Normal"
Ordering
N.O.



"Inverted"
Ordering
I.O.

$$\delta m^2 = \Delta m^2_{21}, \quad \Delta m^2 = (\Delta m^2_{32} + \Delta m^2_{31})/2$$

+ interaction energy in matter → ~ $G_F \cdot E \cdot$ density
(Mykheev-Smirnov-Wolfenstein – MSW effect)

Sketchy 3ν status

5 knowns (robust):

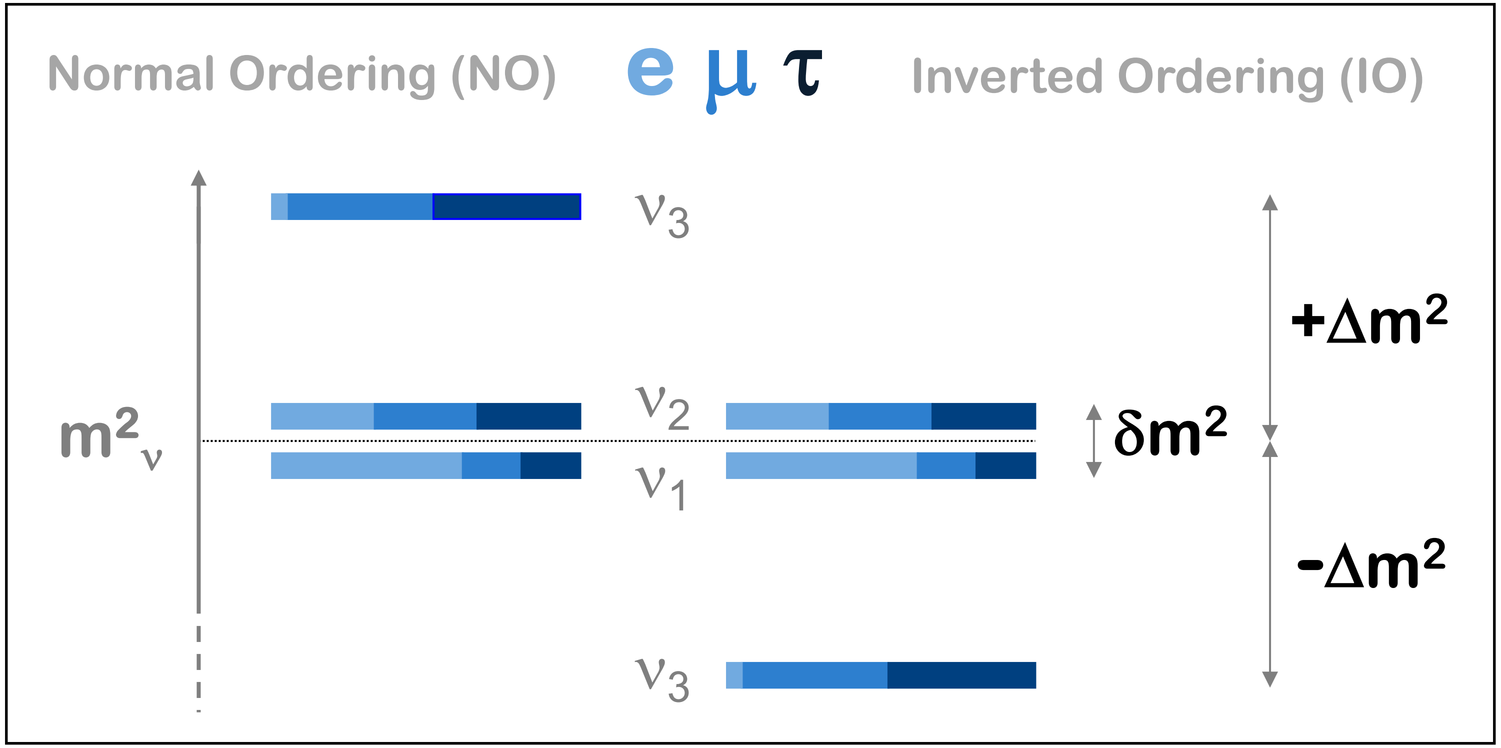
δm^2	~ 8 x 10^{-5} eV^2
$\vert\Delta m^2\vert$	~ 2 x 10^{-3} eV^2
$\sin^2\theta_{12}$	~ 0.3
$\sin^2\theta_{23}$	~ 0.5
$\sin^2\theta_{13}$	~ 0.02

Oscillations

Non-oscillat.

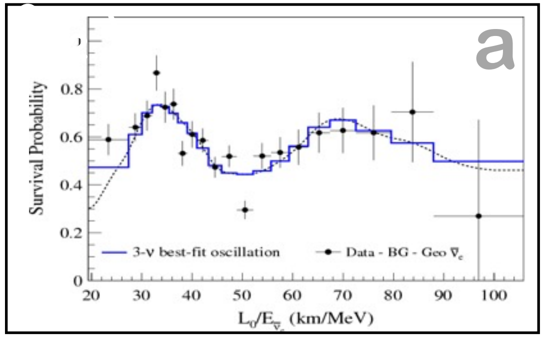
5 unknowns:

- **δ CPV** Dirac phase
- **sign(Δm^2)** → NO/IO
- **θ_{23} octant** degeneracy
- **absolute mass** scale
- **Dirac/Majorana** nature

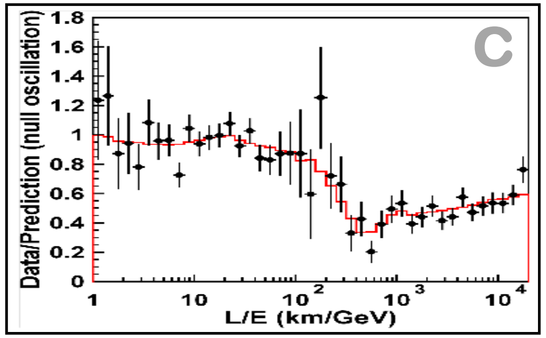


3ν oscillations probed by many experiments in different flavor channels…

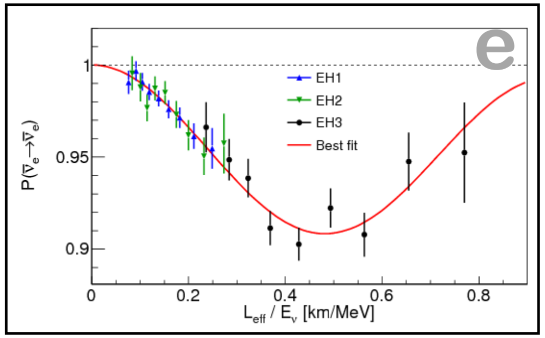
e→e (KamLAND, KL)



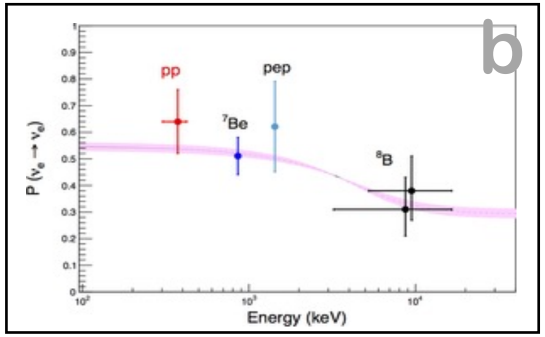
μ→μ (Atmospheric)



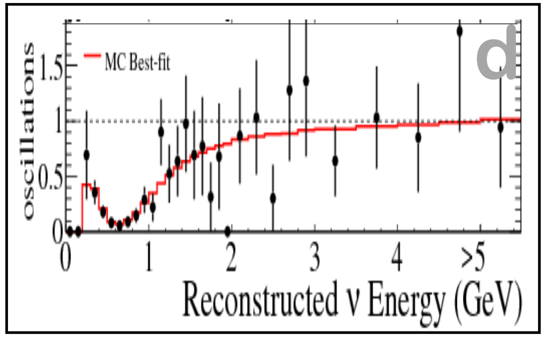
e→e (SBL Reac.)



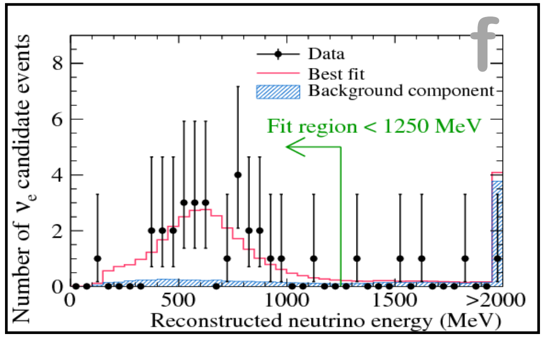
e→e (Solar)



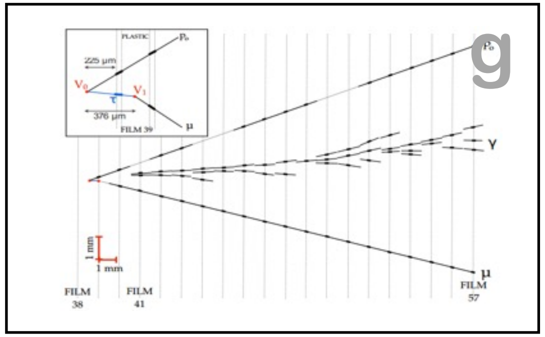
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

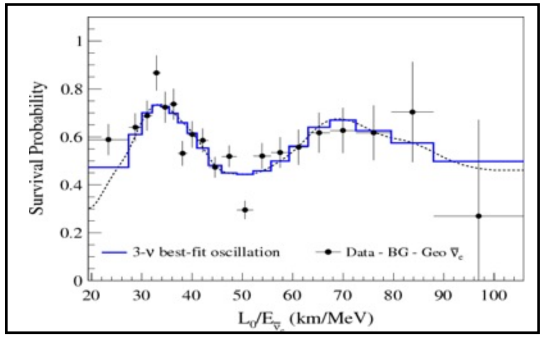


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

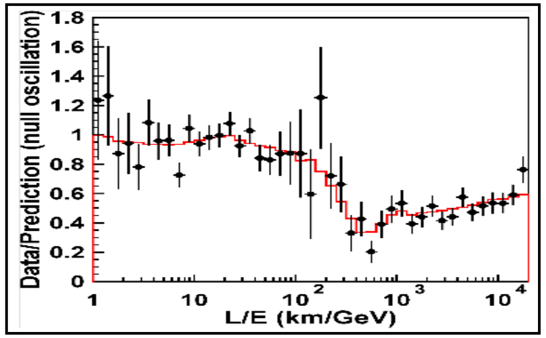
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

… with amplitude and frequency governed by 2 (or 3) leading parameters

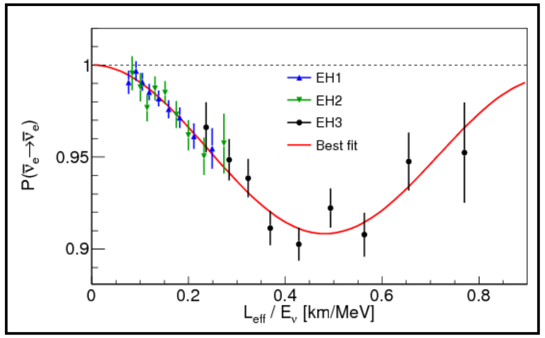
e→e (δm^2 , θ_{12})



μ→μ (Δm^2 , θ_{23})



e→e (Δm^2 , θ_{13})



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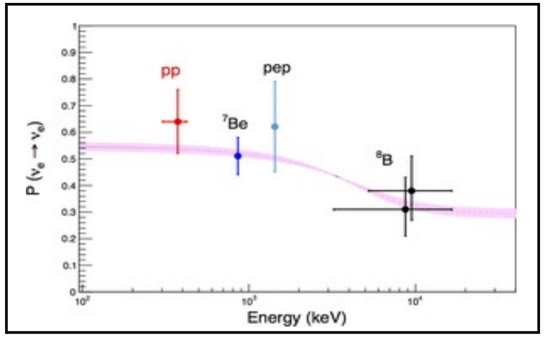
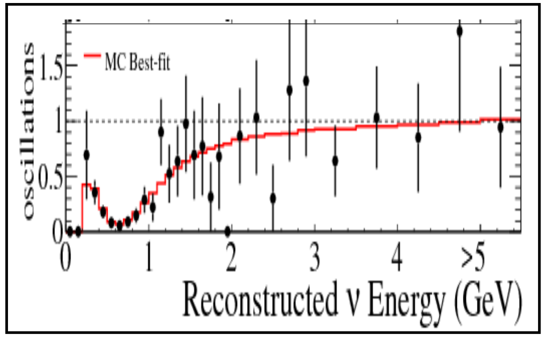
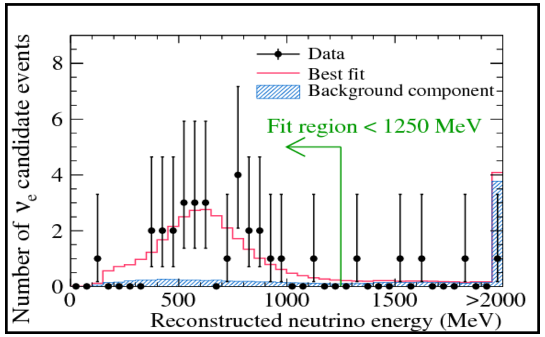


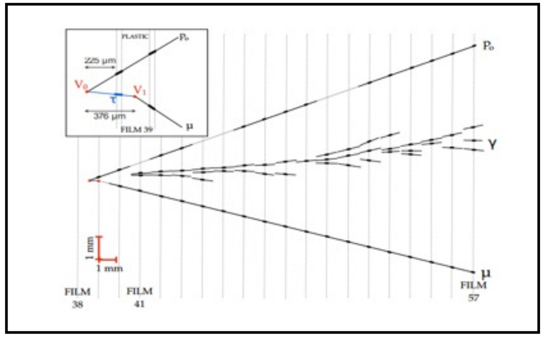
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



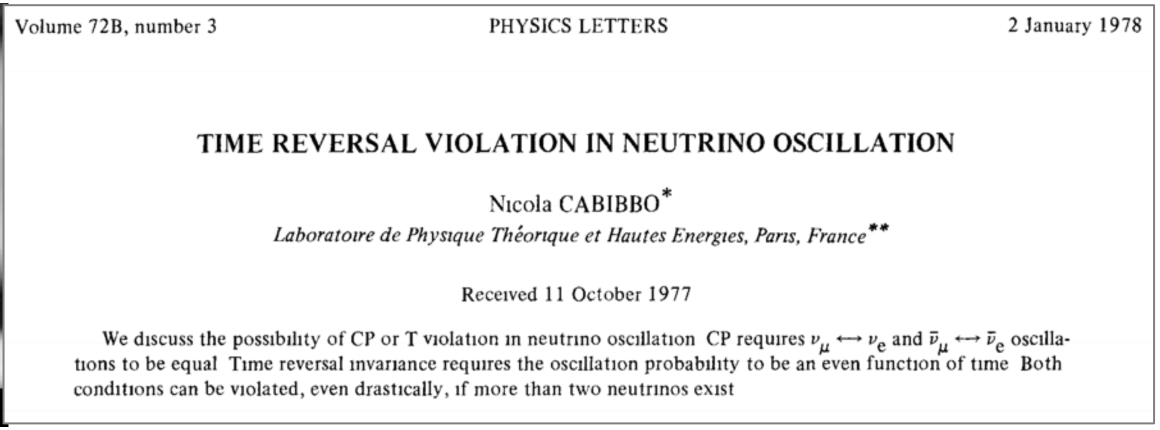
μ→τ (Δm^2 , θ_{23})



5 param.'s known & (over)constrained → consistency

Currently: focus on unknown par. & subleading effects, especially CPV via $\nu_\mu \to \nu_e$ in LBL accel. and atmos. expts and NO/IO mass spectrum via reactor + accel + atmos.

How do $\nu_\mu \rightarrow \nu_e$ appearance searches probe CPV?



Volume 72B, number 3 PHYSICS LETTERS 2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*
*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation CP requires $\nu_\mu \longleftrightarrow \nu_e$ and $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e$ oscillations to be equal Time reversal invariance requires the oscillation probability to be an even function of time Both conditions can be violated, even drastically, if more than two neutrinos exist

For two neutrinos, no CPV:

$$\overset{(-)}{\nu}_e = \cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2$$

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For two neutrinos, no CPV:

$$\overset{(-)}{\nu}_e = \cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2$$

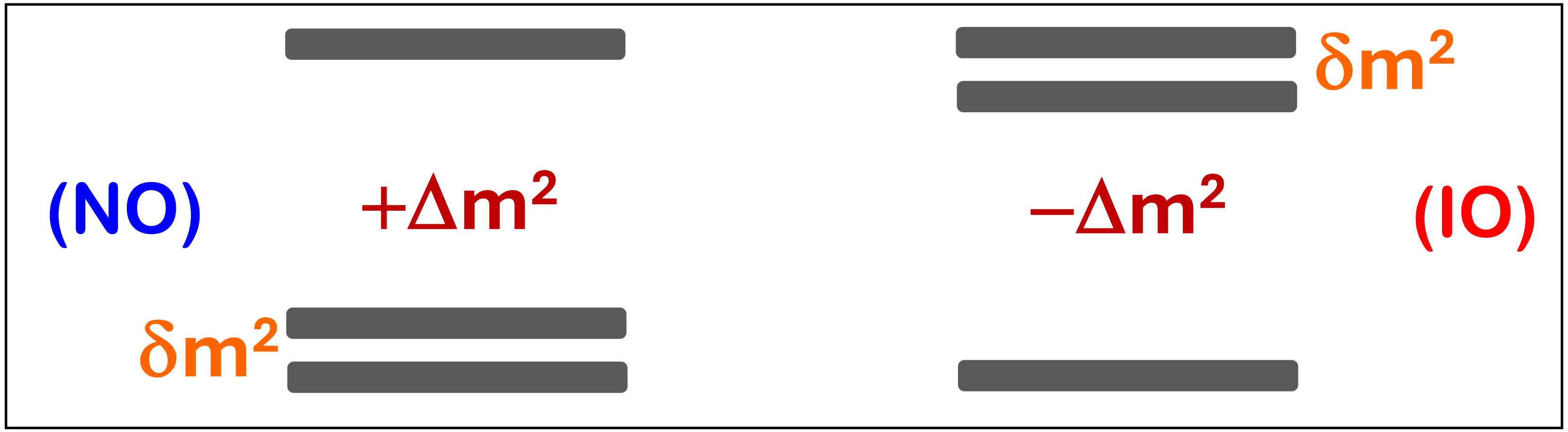
For three neutrinos: new possible CPV phase δ, tested via ν / $\bar{\nu}$

$$\overset{(-)}{\nu}_e = \cos\theta_{13}\, (\cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2) + e^{\pm i\delta} \sin\theta_{13}\, \nu_3$$

CPV is a genuine 3ν effect → all parameters (known+unknown) are involved/entangled

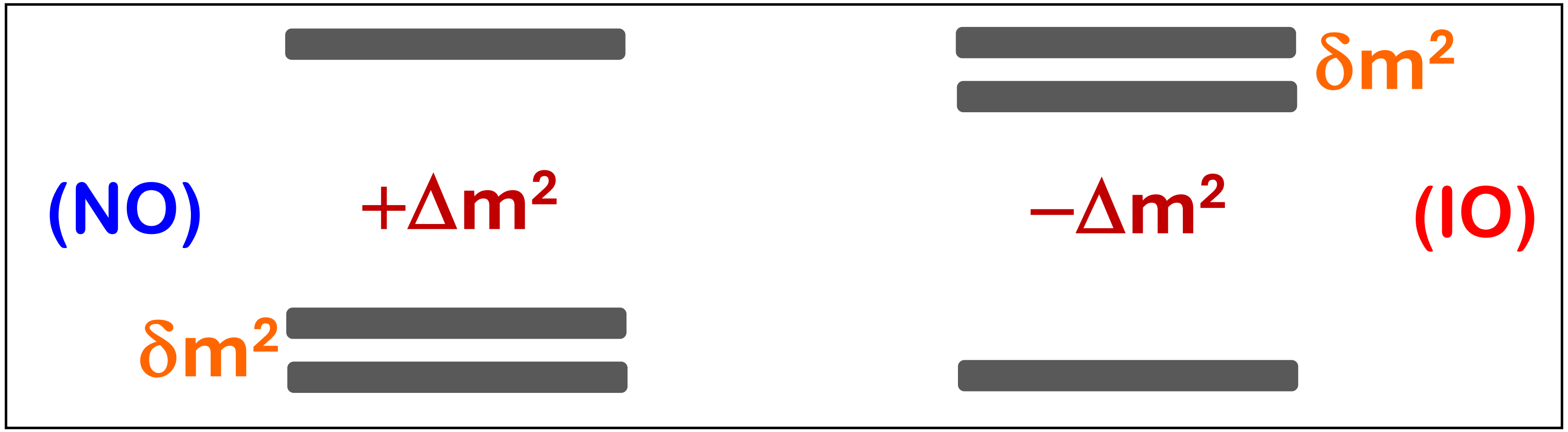
θ_{13} discovery at SBL reactors crucial! CPV currently tested in T2K, NOvA, atm. oscillations

How do oscillation searches probe mass ordering?



Observe interference effects of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity Q with <u>known sign</u>.

How do oscillation searches probe mass ordering?

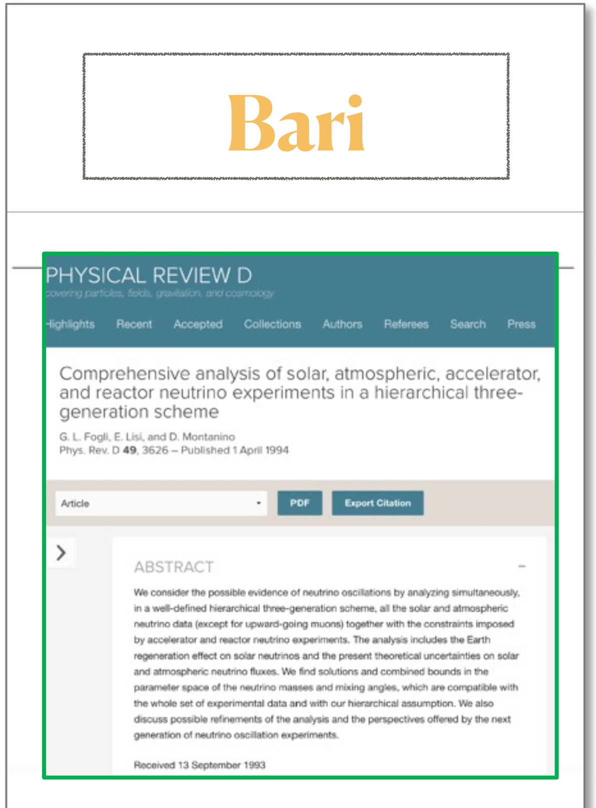


Observe interference effects of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity Q with known sign. Options:

$Q \sim \delta m^2$	(medium-baseline reactors → JUNO)
$Q \sim G_F N_e E$	(ν–matter effects → atm & LBL accel. expt.)
$Q \sim G_F N_\nu E$	(ν–ν collective effects → SN, rare & difficult!)

Additional handle: complementarity of different Δm^2 data in NO/IO
(should converge better in the true ordering than in the wrong one)

Status of known and unknown 3ν oscillation parameters [Global analyses]


Bari

PHYSICAL REVIEW D

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

G. L. Fogli, E. Lisi, and D. Montanino

Phys. Rev. D **49**, 3626 – Published 1 April 1994

Article PDF Export Citation

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

Slide from F. Vissani at NOW 2024, www.ba.infn.it/now

1994 global ν data analysis

Status of known and unknown 3ν oscillation parameters [Global analyses]

Valencia	NuFit	Bari

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2020 global reassessment of the neutrino oscillation picture

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ABSTRACT: We present an updated global fit of neutrino oscillation data in the simplest three-neutrino framework. In the present study we include up-to-date analyses from a number of experiments. Concerning the atmospheric and solar sectors, besides the data considered previously, we give updated analyses of IceCube DeepCore and Sudbury Neutrino Observatory data, respectively. We have also included the latest electron antineutrino data collected by the Daya Bay and RENO reactor experiments, and the long-baseline T2K 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 preference is milder than the one found in previous global analyses. These new results should be regarded as robust due to the agreement found between our Bayesian and frequentist approaches. Taking into account only oscillation data, there is a weak/moderate

https://doi.org/10.1007/JHEP02(2021)071

universe MDPI

Review

NuFIT: Three-Flavour Global Analyses of Neutrino Oscillation Experiments

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* Correspondence: concha@insti.physics.sunysb.edu (M.C.G.-G.); michele.maltoni@csic.es (M.M.); schwetz@kit.edu (T.S.)

Abstract: In this contribution, we summarise the determination of neutrino masses and mixing arising from global analysis of data from atmospheric, solar, reactor, and accelerator neutrino experiments performed in the framework of three-neutrino mixing and obtained in the context of the NuFIT collaboration. Apart from presenting the latest status as of autumn 2021, we discuss the evolution of global-fit results over the last 10 years, and mention various pending issues (and their resolution) that occurred during that period in the global analyses.

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

Unfinished fabric of the three neutrino paradigm

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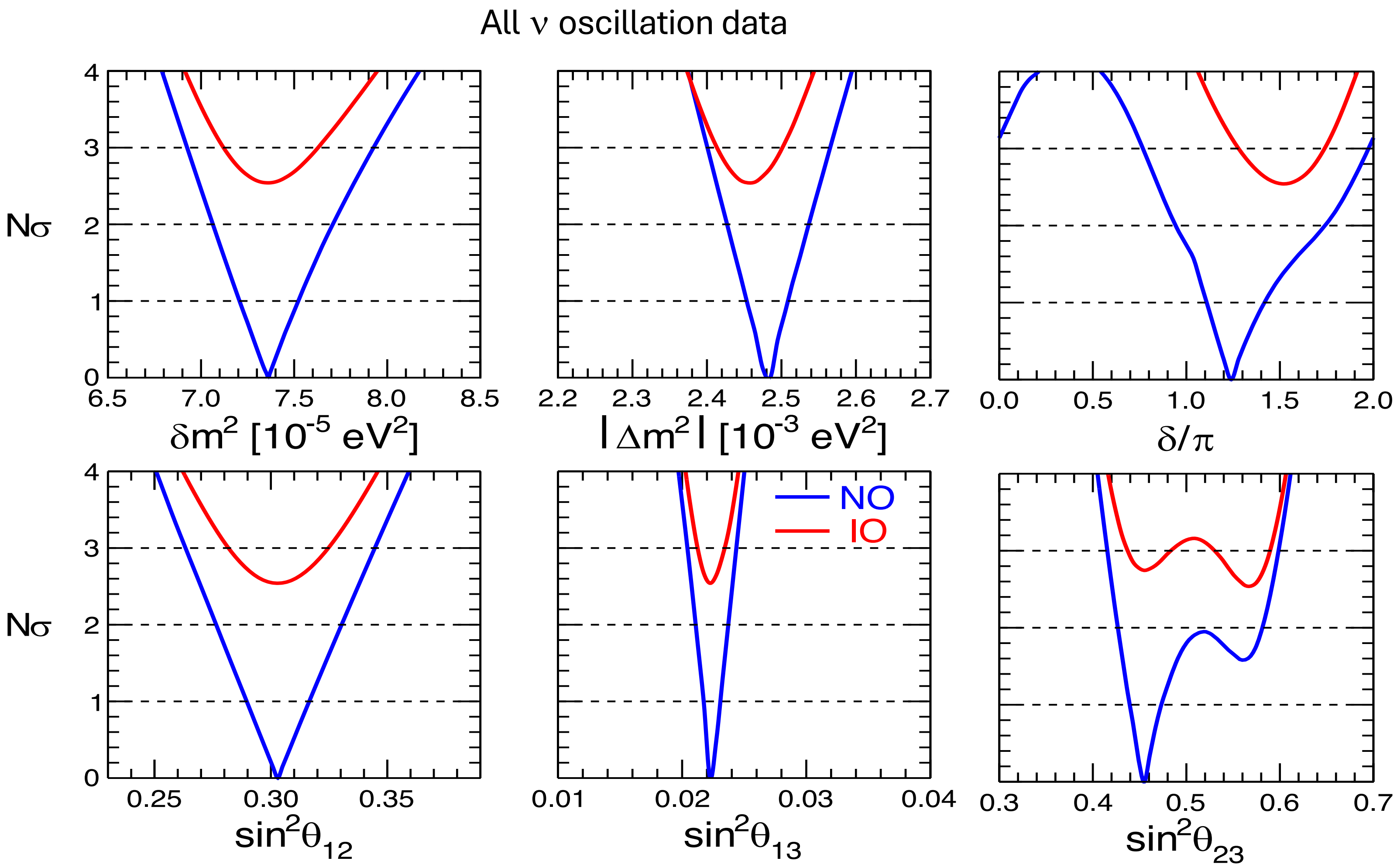
(Received 5 July 2021; accepted 24 September 2021; published 26 October 2021)

In the current 3ν paradigm, neutrino flavor oscillations probe three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$, one CP-violating phase δ, and two independent differences between the squared masses m_i^2, that can be chosen as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$, where sign$(\Delta m^2) = +(-)$ for normal (inverted) mass ordering. Absolute ν masses can be probed by the effective mass m_β in beta decay, by the total mass Σ in cosmology and—if neutrinos are Majorana—by another effective mass $m_{\beta\beta}$ in neutrinoless double beta decay. Within an updated global analysis of oscillation and nonoscillation data, we constrain these 3ν parameters, both separately and in selected pairs, and highlight the concordance or discordance among different constraints. Five oscillation parameters $(\delta m^2, |\Delta m^2|, \theta_{12}, \theta_{23}, \theta_{13})$ are consistently measured, with an overall accuracy ranging from ~1% for $|\Delta m^2|$ to ~6% for $\sin^2\theta_{23}$ (due to its persisting octant ambiguity). We find overall hints for normal ordering (at ~2.5σ), as well as for $\theta_{23} < \pi/4$ and for $\sin\delta < 0$ (both at 90% C.L.), and discuss some tensions among different datasets. Concerning nonoscillation data, we include the recent KATRIN constraints on m_β, and we combine the latest ^{76}Ge, ^{130}Te and ^{136}Xe bounds on $m_{\beta\beta}$, accounting for nuclear matrix element covariances. We also discuss some variants related to cosmic microwave background (CMB) anisotropy and lensing data, which may affect cosmological constraints on Σ and hints on sign(Δm^2). The default option, including all Planck results, irrespective of the so-called lensing anomaly, sets upper bounds on Σ at the level of $\sim 10^{-1}$ eV, and further favors 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.

Slide from F. Vissani at NOW 2024, www.ba.infn.it/now

All being updated after expt results at Neutrino 2024 in Milan, *neutrino2024.org*
Only slight changes expected.

Status of known and unknown 3ν oscillation parameters [Bari 2021 analysis]

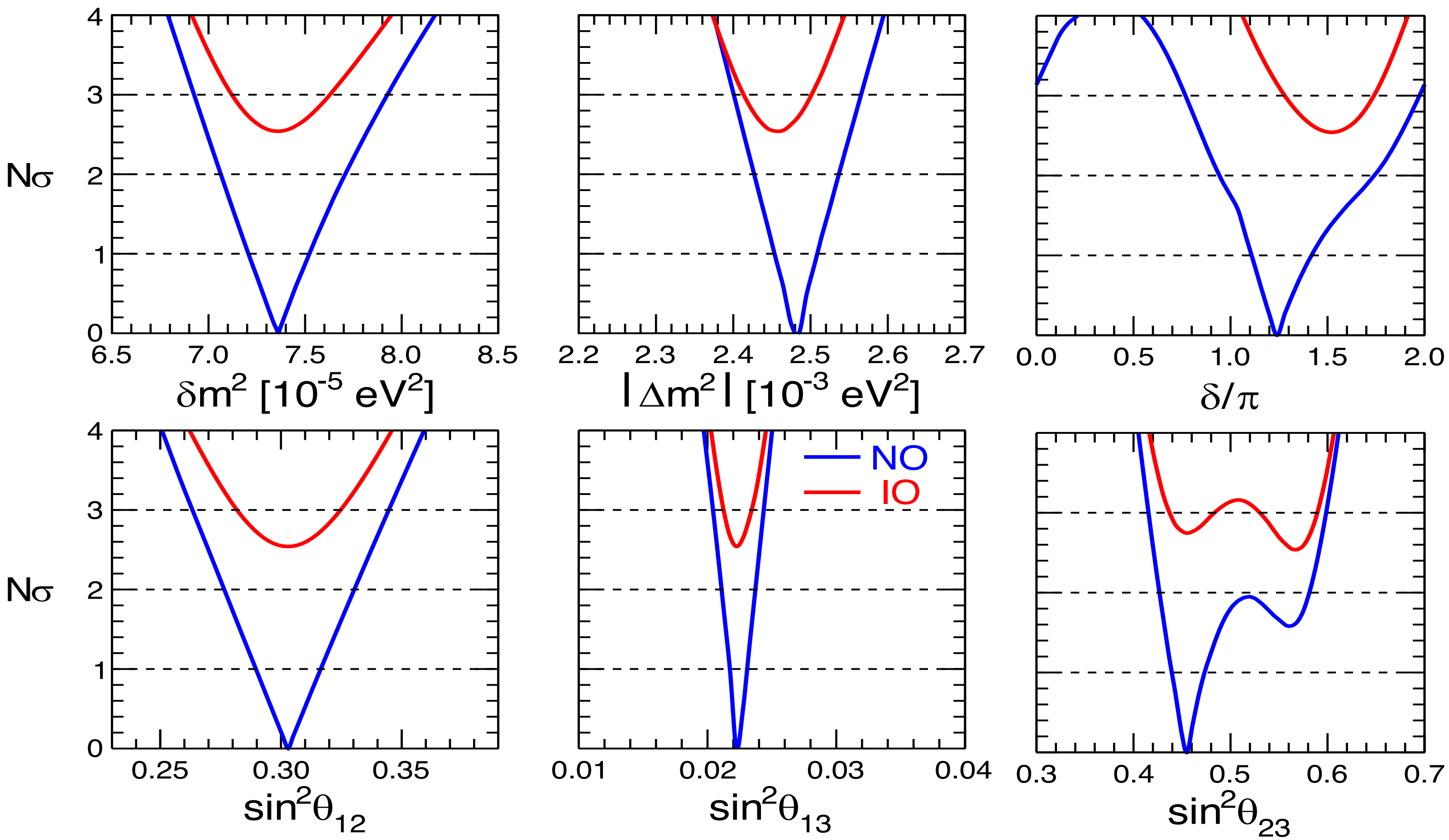


Status of known and unknown 3ν oscillation parameters [Bari 2021 analysis]

1σ error of **known** parameters

$\|\Delta m^2\|$	1.1%
δm^2	2.3%
θ_{13}	3.0%
θ_{12}	4.5%
θ_{23}	~ 6%

All ν oscillation data



knowns

3ν **oscill.**

unknowns

Hints on oscillation **unknowns**

NO	~99% CL
sinδ < 0	~90% CL
$\theta_{23} < \pi/4$	~90% CL

(Hints might be weaker including ν 2024 data)

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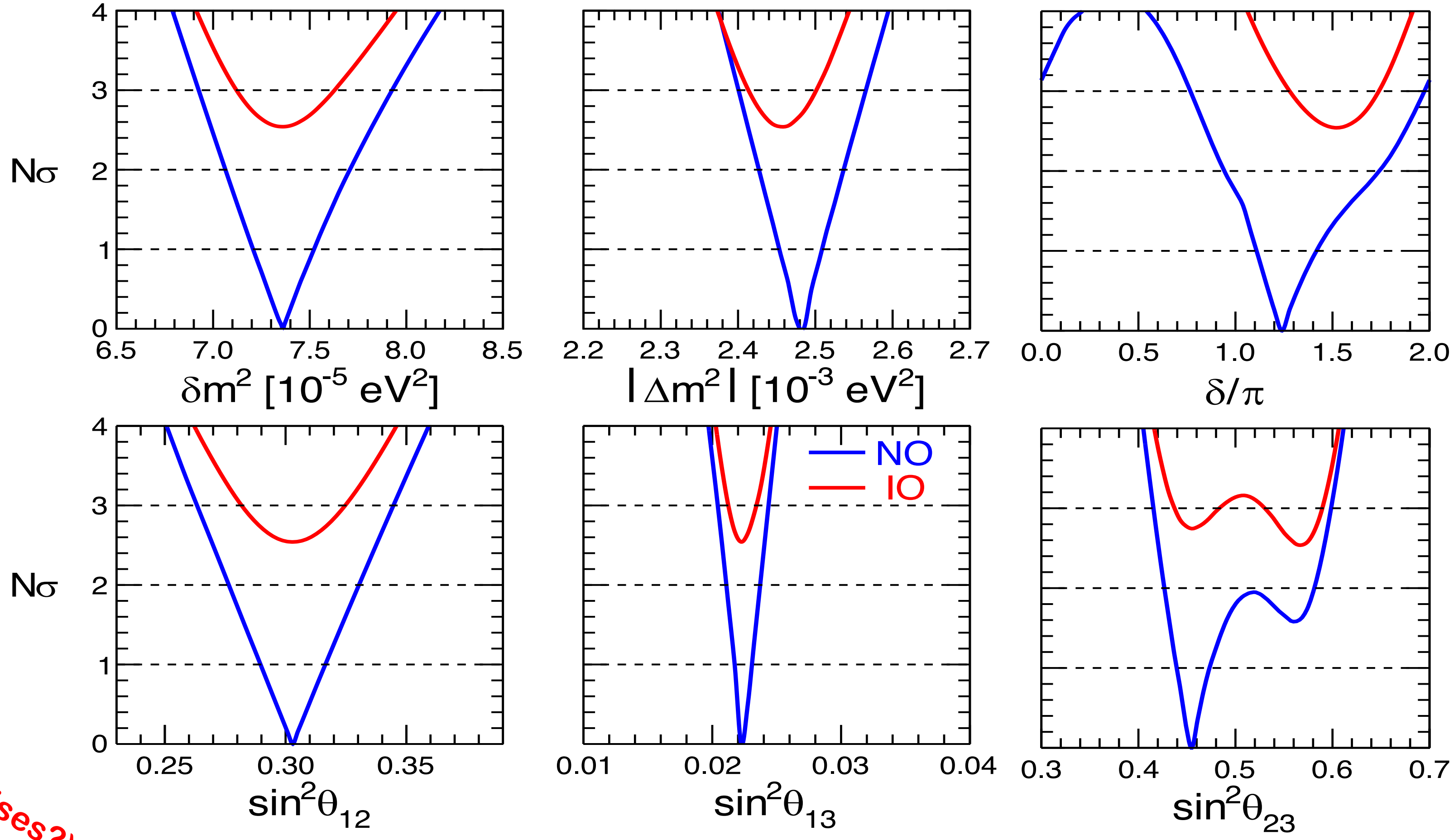
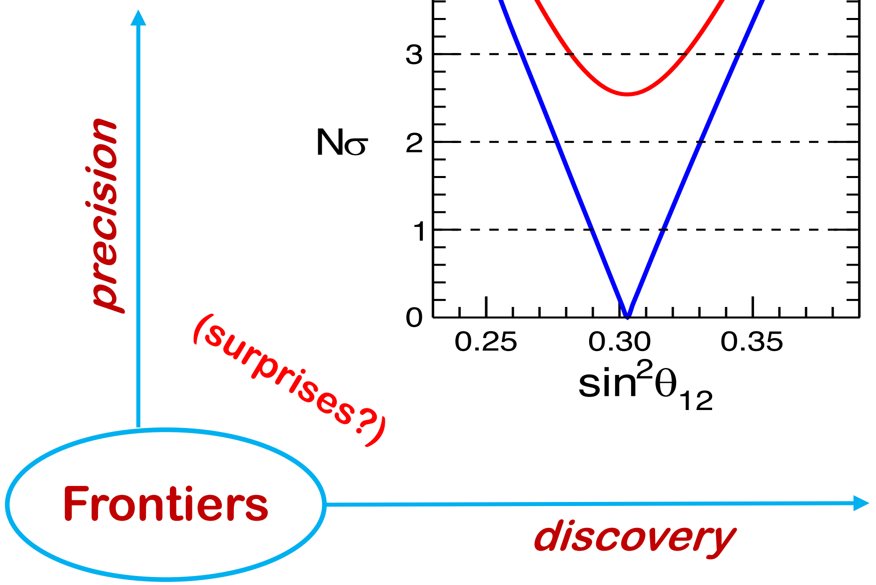




Hints on oscillation **unknowns**

NO	~99% CL
$\sin\delta < 0$	~90% CL
$\theta_{23} < \pi/4$	~90% CL

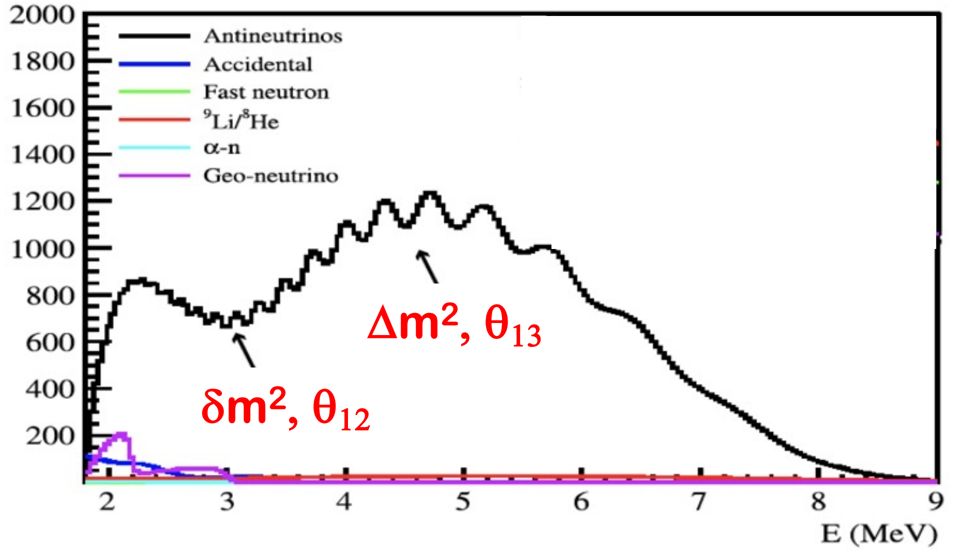
(Hints might be weaker including ν 2024 data)

E.g., frontiers for the JUNO reactor experiment

At “medium” baseline ~50 km, will probe two oscillations in ~vacuum

Main **discovery** goal: distinguish **NO vs IO at >3σ** in 6y.

May become **>5σ** in combination with atmospheric data.



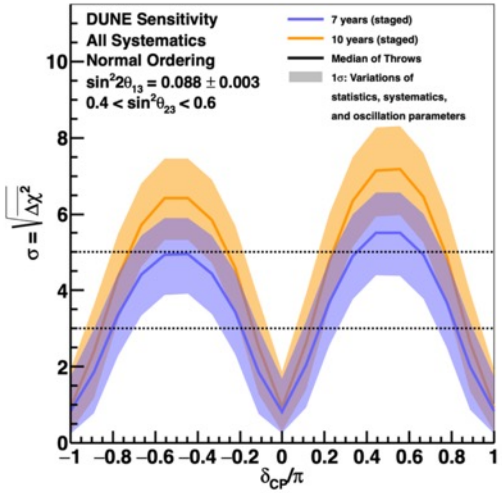
Significant better **precision** expected on 3 out of 4 oscillation parameters:

Parameter	1σ, now	JUNO in ~6y
δm^2	2.3 %	0.4 %
$\sin^2\theta_{12}$	4.4 %	0.5 %
Δm^2	1.1 %	0.2 %
$\sin^2\theta_{13}$	3.0 %	comparable

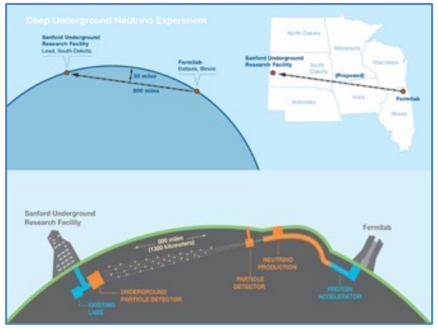
E.g., frontiers for DUNE LBL accelerator experiment

Disappearance + appearance, nu/antinu mode, matter effects at L~1300 km

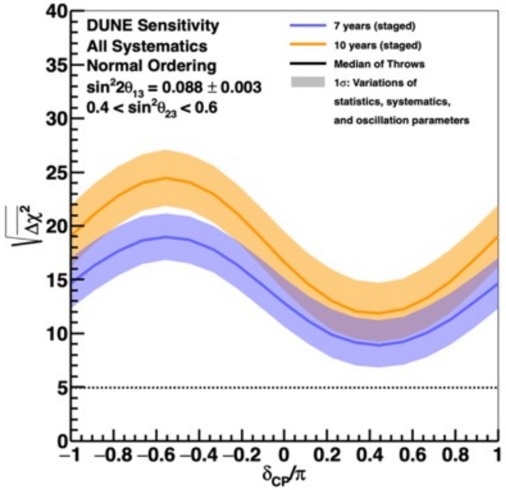
CPV



← Discovery goals →



NO vs IO



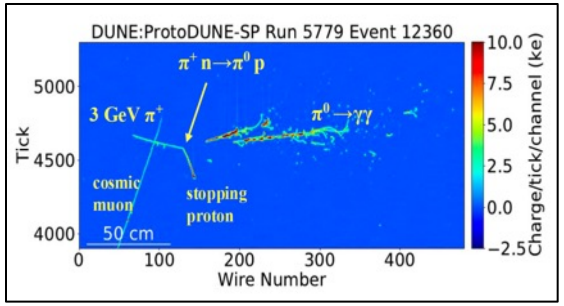
Precision frontier

↓

Parameter	1σ, now	DUNE in ~10 y [2002.03005]
Δm^2	1.1 %	factor ~1/4 reduction
$\sin^2\theta_{23}$	~ 6 %	factor ~1/4 reduction
$\sin^2\theta_{13}$	3.0 %	comparable

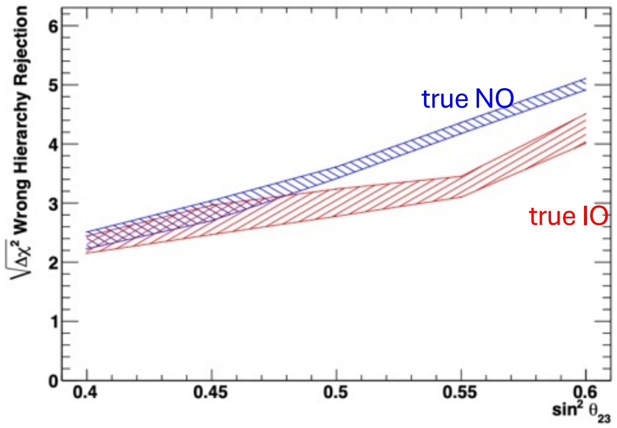
HK LBL: same ballpark. DUNE & HK will need precise cross sections!

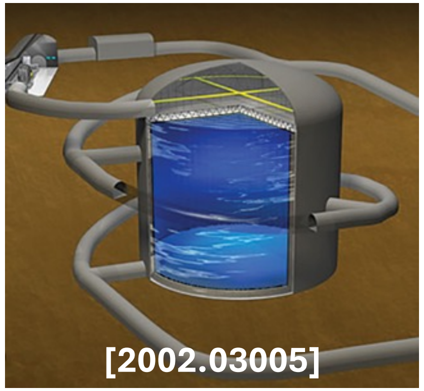
Worldwide activity to better understand **nuclear response to ν probes**



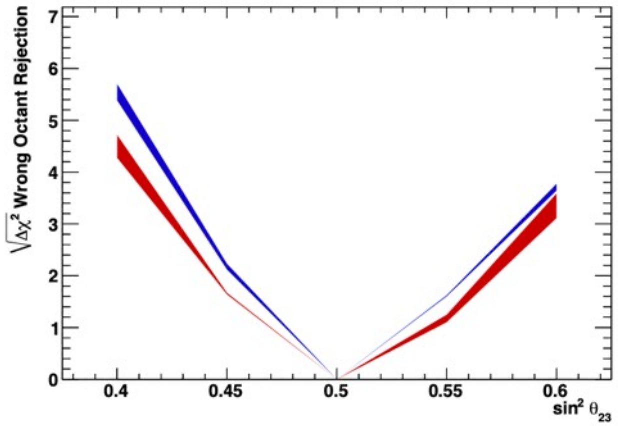
E.g., frontiers for Hyper-Kamiokande atmospheric ν oscillation signal…

Mass ordering





Octant resolution



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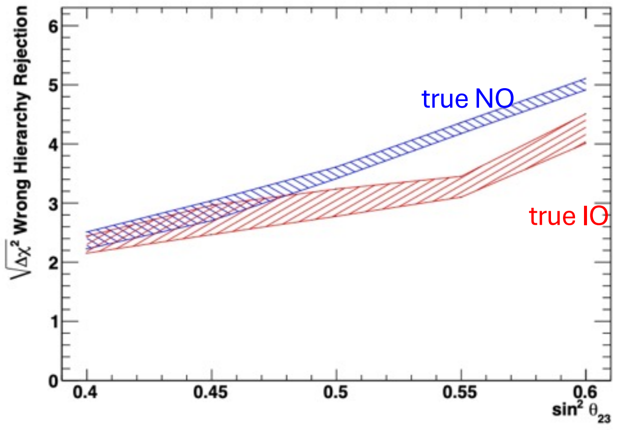
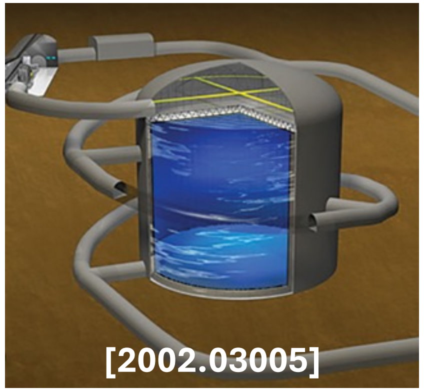
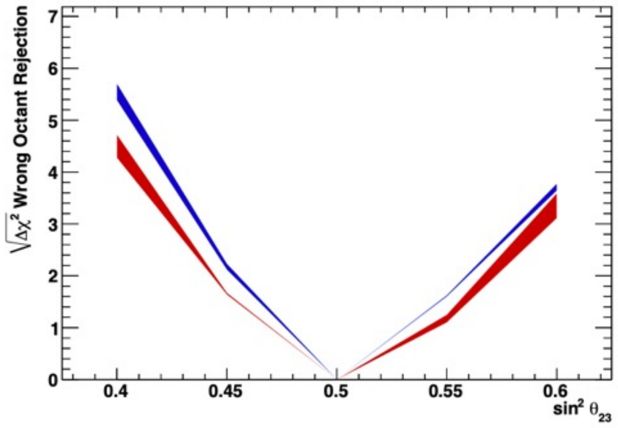
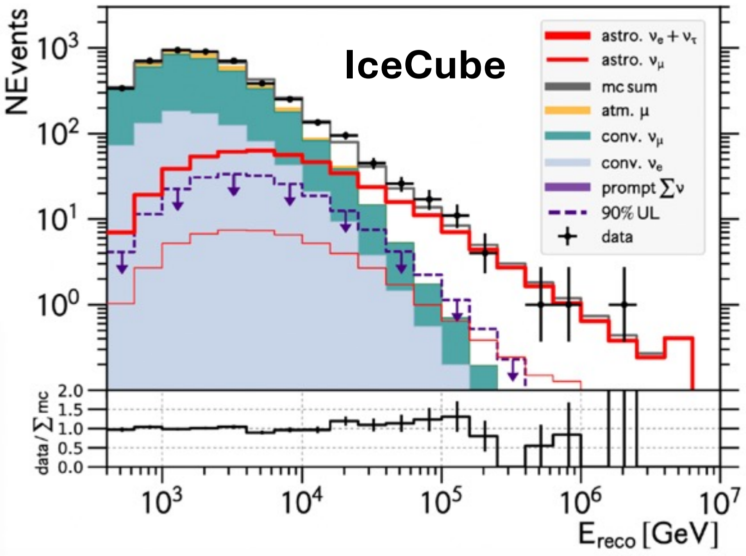


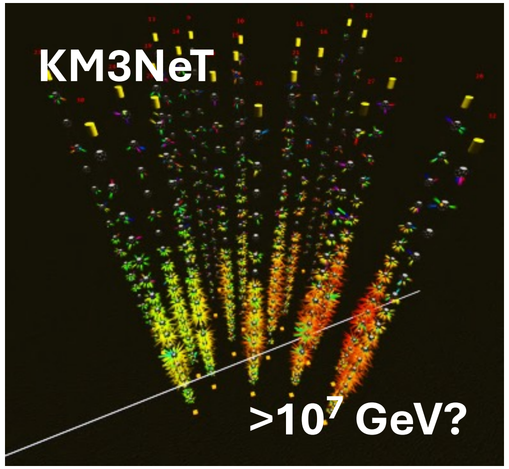


Octant resolution



… and atmospheric ν as background for HE frontier of cosmic ν detection





Surprises beyond the 3ν paradigm?

Advancing the precision and discovery frontiers in JUNO, DUNE, HK, IC, KM3NeT,…
we might either confirm the paradigm, or find "anomalous" results beyond it, e.g.,

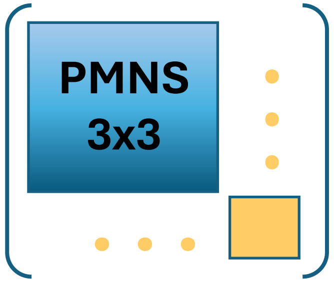
- new (sterile) neutrino states?
- nonstandard 4-fermion interactions (NSI)?
- violations of fundamental symmetries?
- …

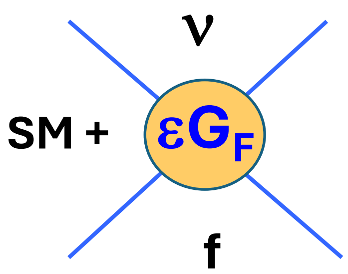
E.g., already in current data:

Saga of possible indications of sterile (~RH) neutrino state(s) at O(eV) scale
NSI terms $\sim\varepsilon_{\alpha\beta}G_F$ weakly preferred by SK solar data & by T2K vs NOvA tension
[not reviewed herein]

Even if you do not believe such hints… → Stress-tests of the 3ν paradigm

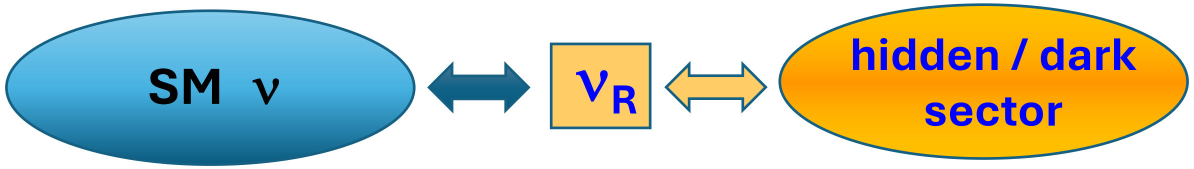
Testing the resilience of the 3ν paradigm to **extra ν states** or to **new interactions:**
Approach often involves PMNS unitarity violations or nonstandard FCNC, FDNC (NSI)





Extra parameters may dilute hints of PMNS unknowns: CPV, θ_{23} octant, ordering.
Rich phenomenology in (non)oscillation experiments + astrophysics & cosmology

Going further: consider both extra states and interactions: RH neutrinos as a **bridge** ("portal") to weakly coupled **BSM physics** ("hidden" or "dark" sector), e.g. **DM**



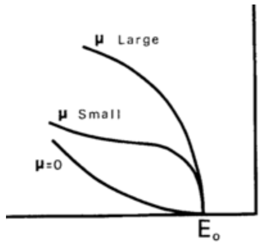
Low-scale BSM "portal" scenarios can provide new stress tests of the 3ν paradigm (as well as of $3\nu+1\nu_s$ models), e.g. via **modified neutrino dispersion relations.**

Absolute neutrino mass observables: (m_β , $m_{\beta\beta}$, Σ)

Probe absolute neutrino masses in different ways
May provide extra handles to distinguish NO vs IO

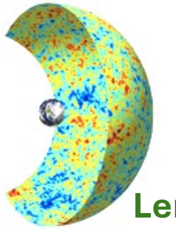
β decay (kinematics) - Sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



Cosmology (gravity) - Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$



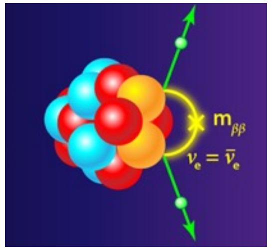
CMB

LSS

Lensing

0νββ decay: only if Majorana. "Effective Majorana mass" (+new CPV phases):

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



A <u>deep</u> question: Are neutrinos their own antiparticles?

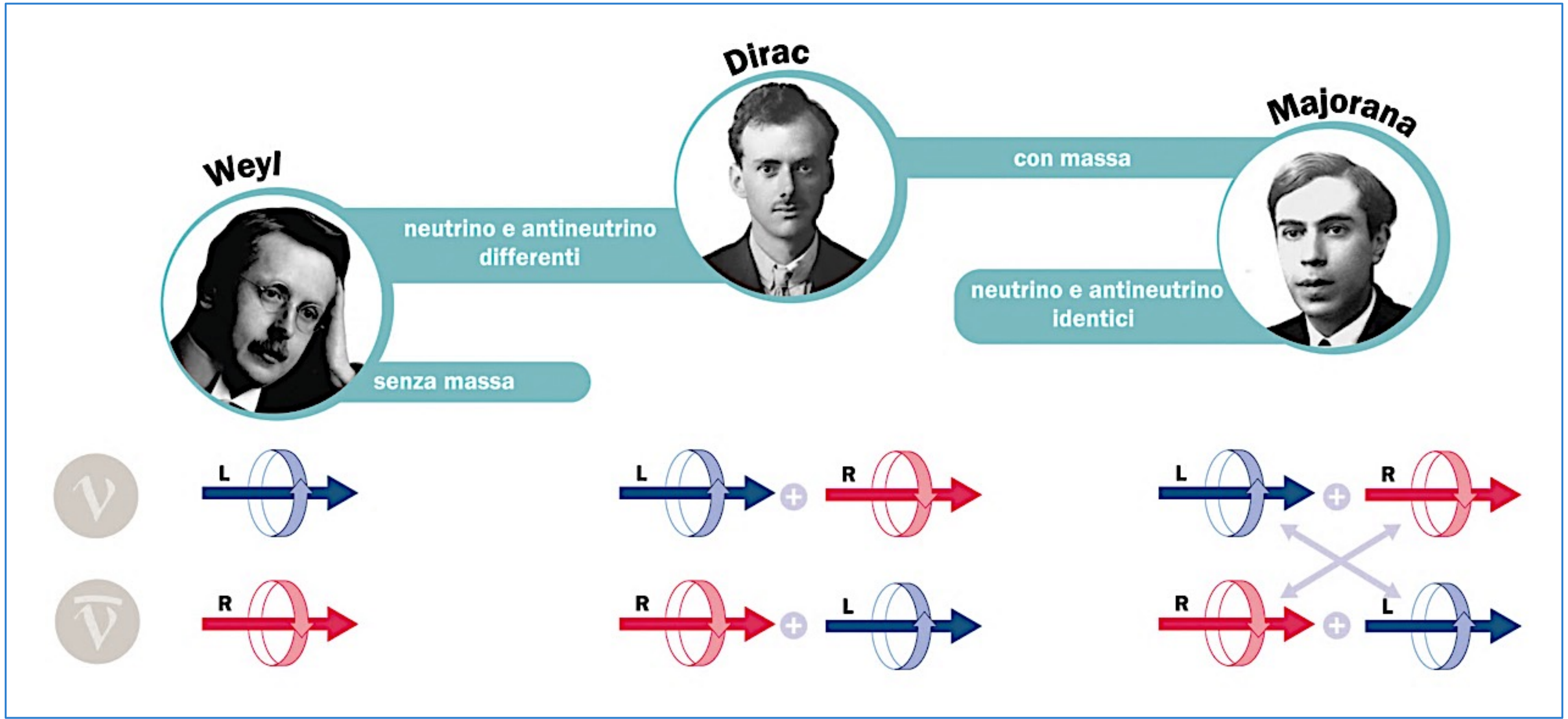
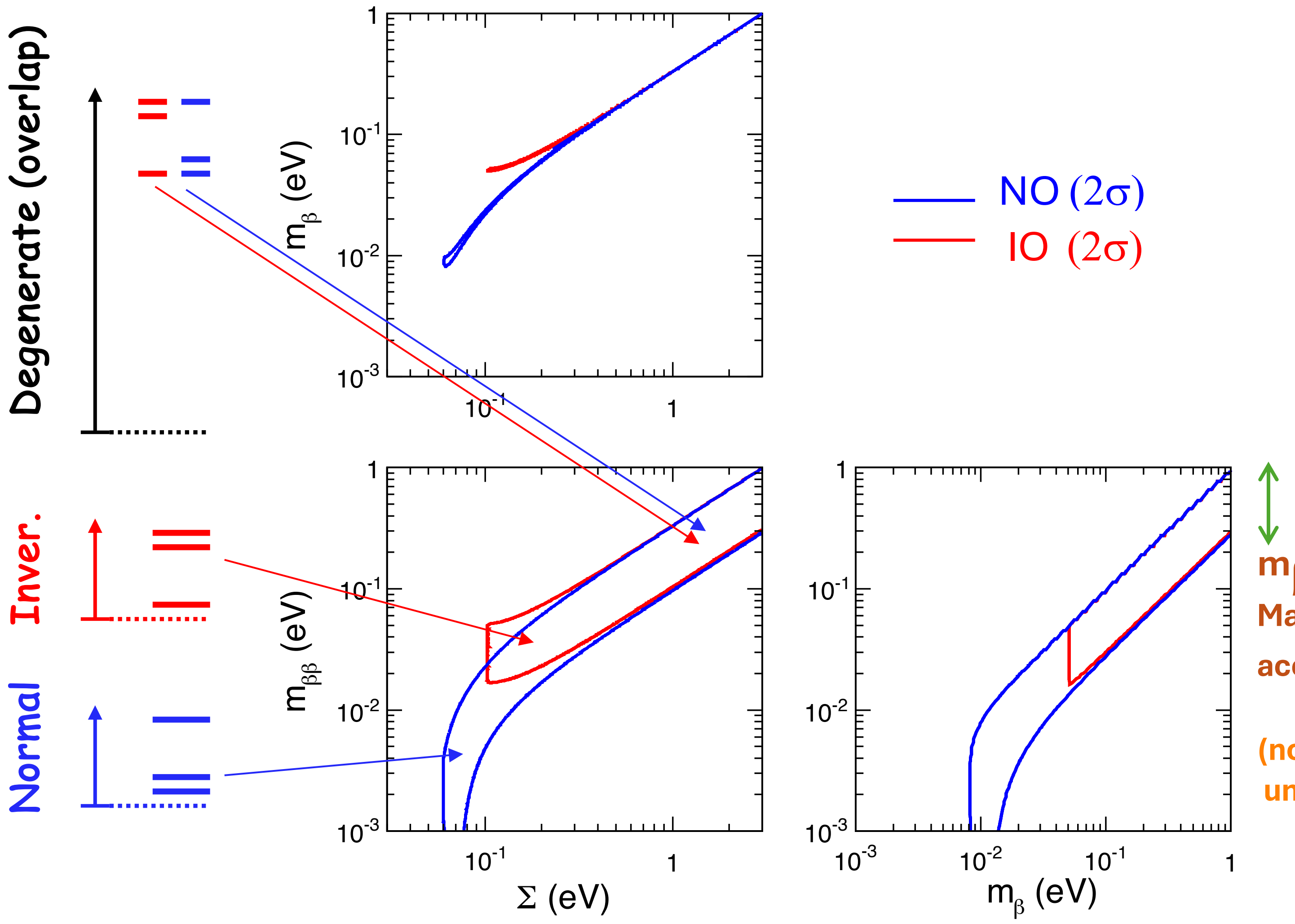


Image from Asimmetrie, Rivista dell'INFN, n. 29 (2020) - article by E.L.

Massless Weyl ν states are purely LH (nu) or RH (antinu)	Massive Dirac ν : both RH and LH components, different in nu vs antinu	Massive Majorana ν: RH and LH components of nu & antinu might be paired!

Standard Model: Higgs mechanisms → Dirac fermions. Majorana neutrinos → Beyond SM!

$(m_\beta$, $m_{\beta\beta}$, $\Sigma)$ observables: bands allowed by oscillations in NO/IO

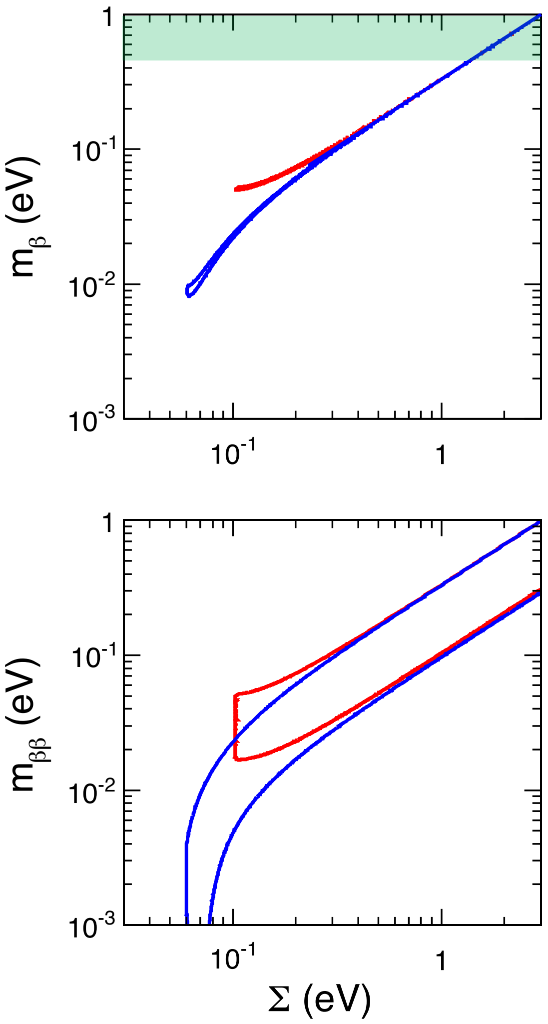


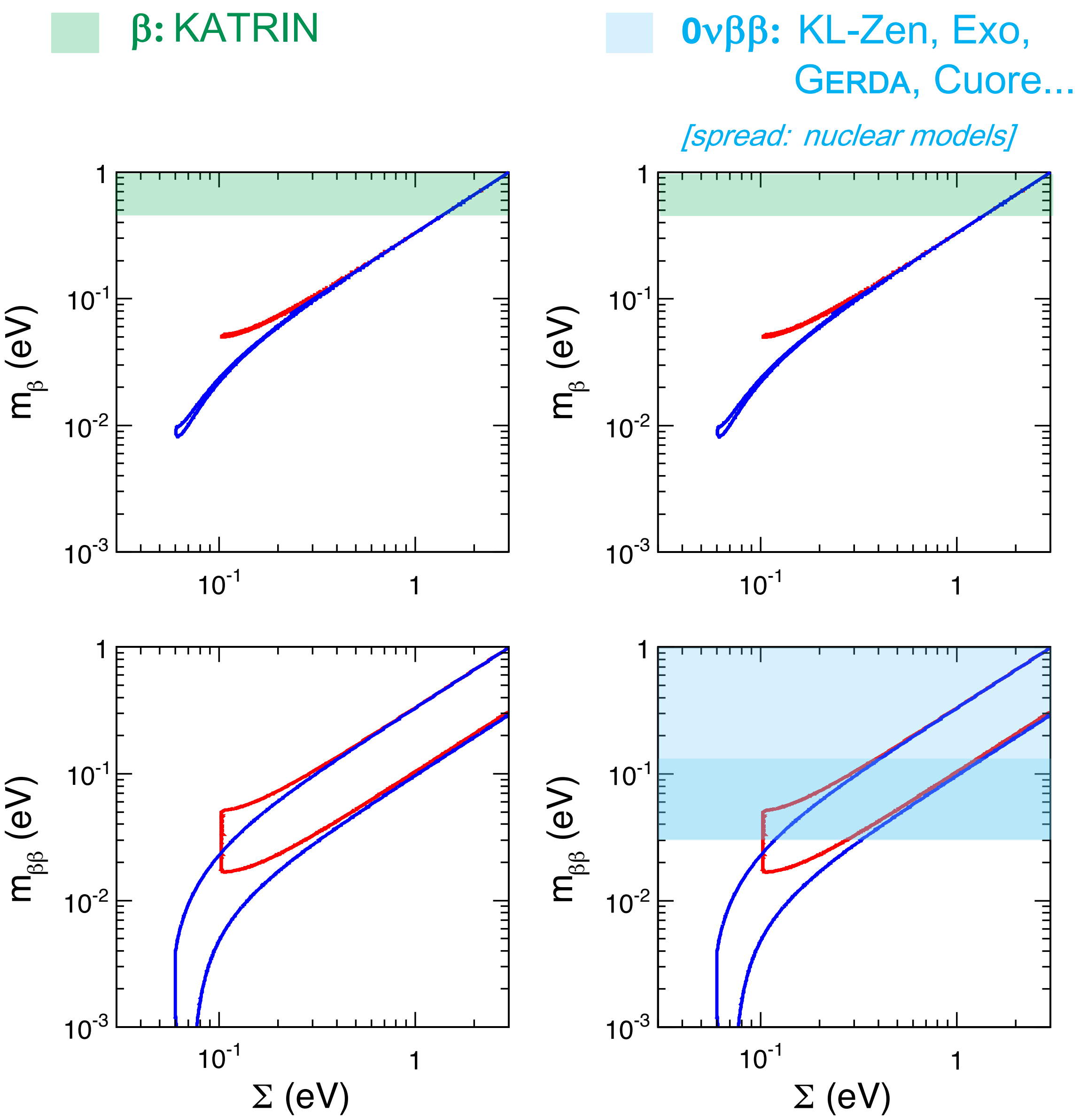
$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

(no nuclear matrix elem. uncert. included here!)

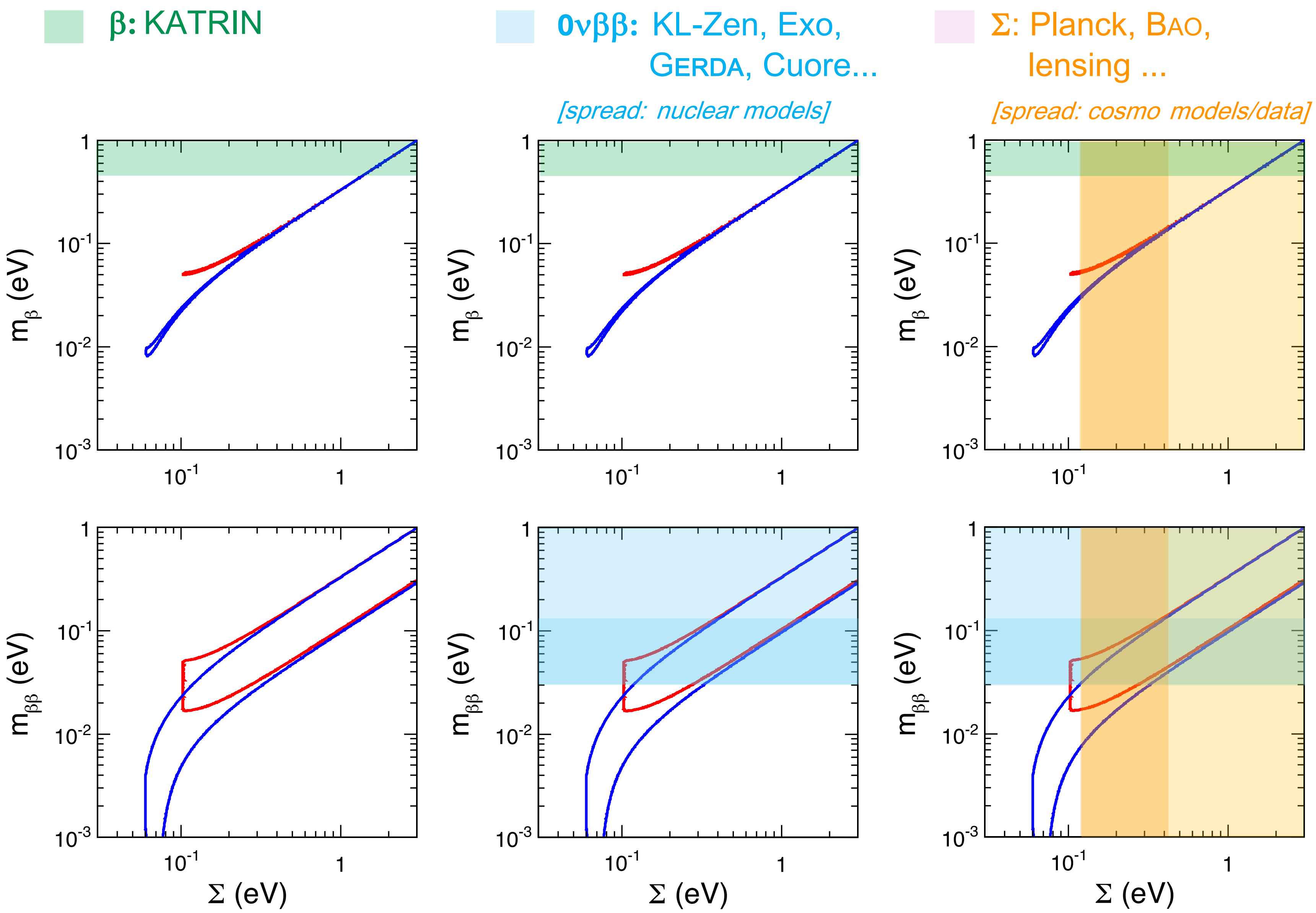
β: KATRIN

← **No signal so far. Current upper bounds from β decay**

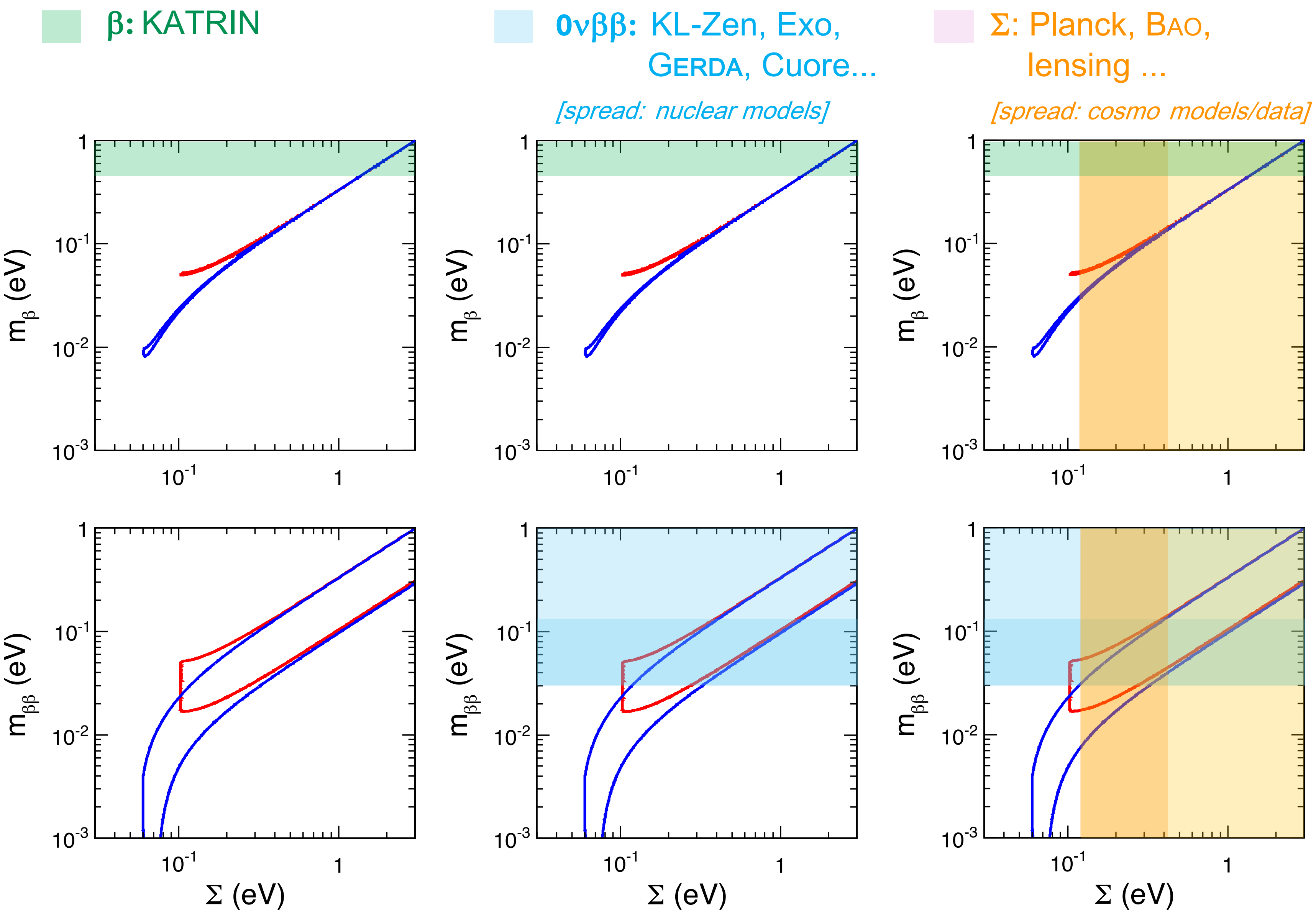




← **Current upper bounds from 0νββ decay**



IO "under pressure" from cosmo data. But: lively debate after recent (too strong?) DESI constraints

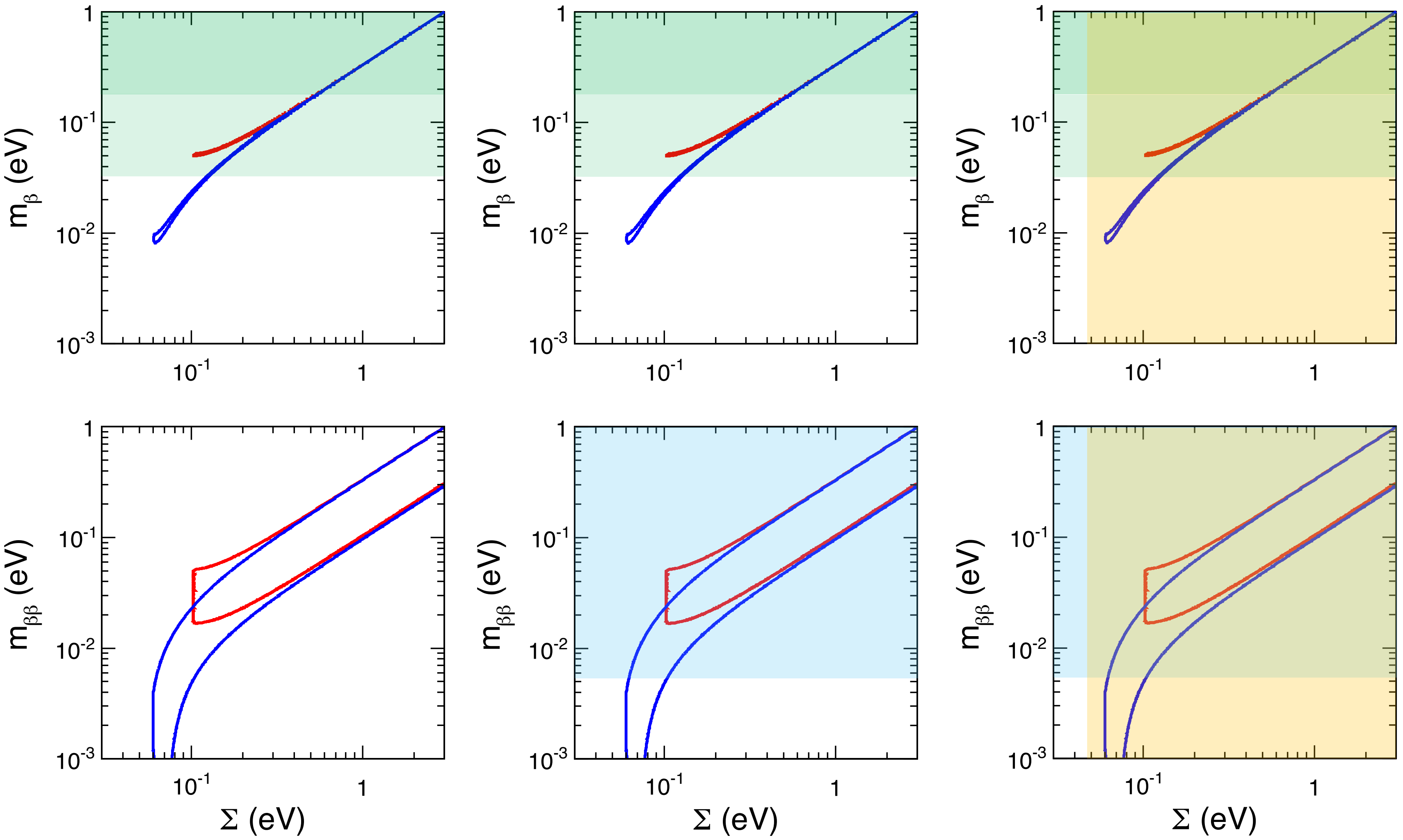


Frontiers for the next ~10-20 yrs →

β: ~0.2 eV (KATRIN) and hopefully below in ← **PROJECT 8**

0νββ: Well below IO limit @Ton scale **(LEGEND, NEXO, CUPID…)** w/ improved **NME**

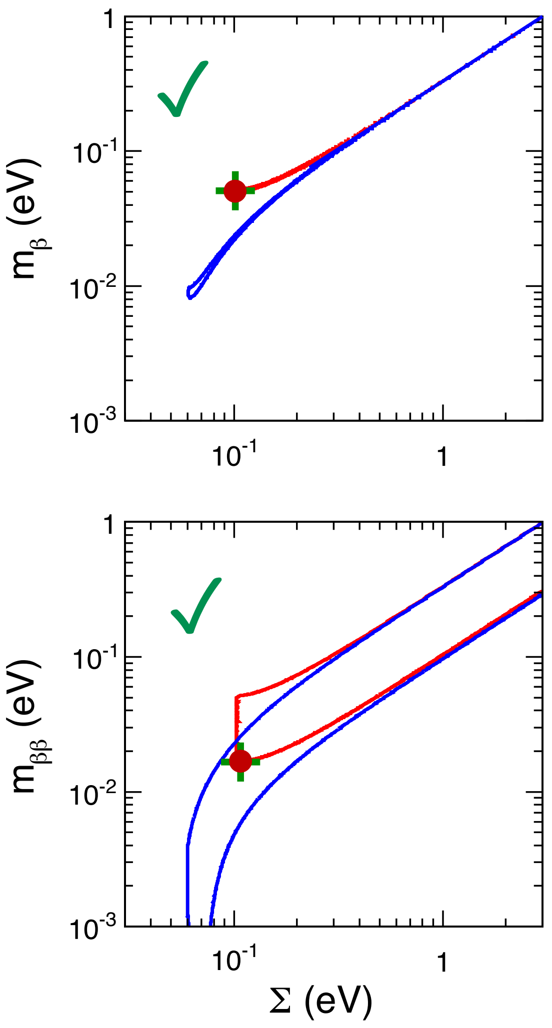
Σ: complete covering seems possible within a "robust" **cosmo model**



Large phase space for possible signal discoveries. First claims about absolute ν mass may come from cosmology, but laboratory detection via β (0νββ) decay is mandatory !

Future data ✚ dreams:

3ν convergence?



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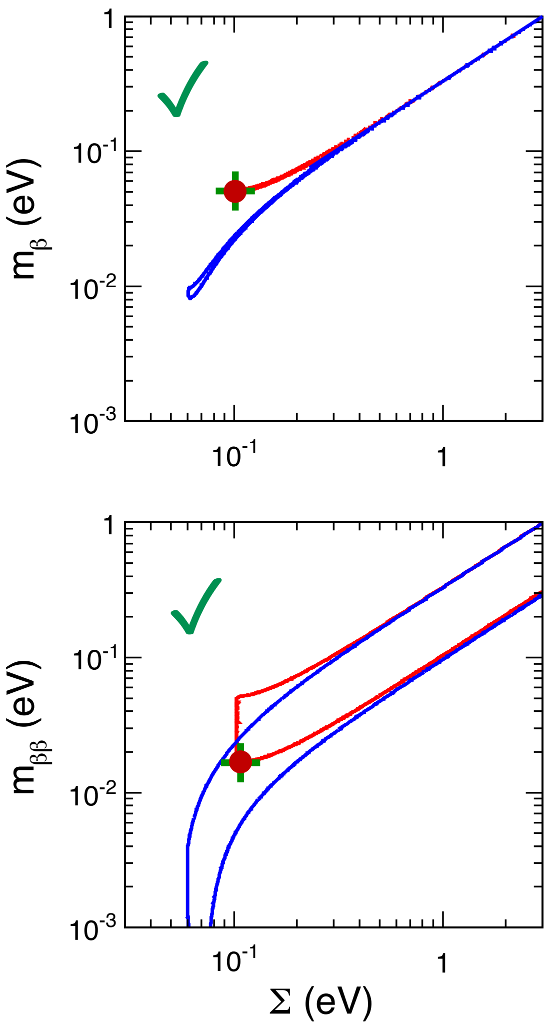
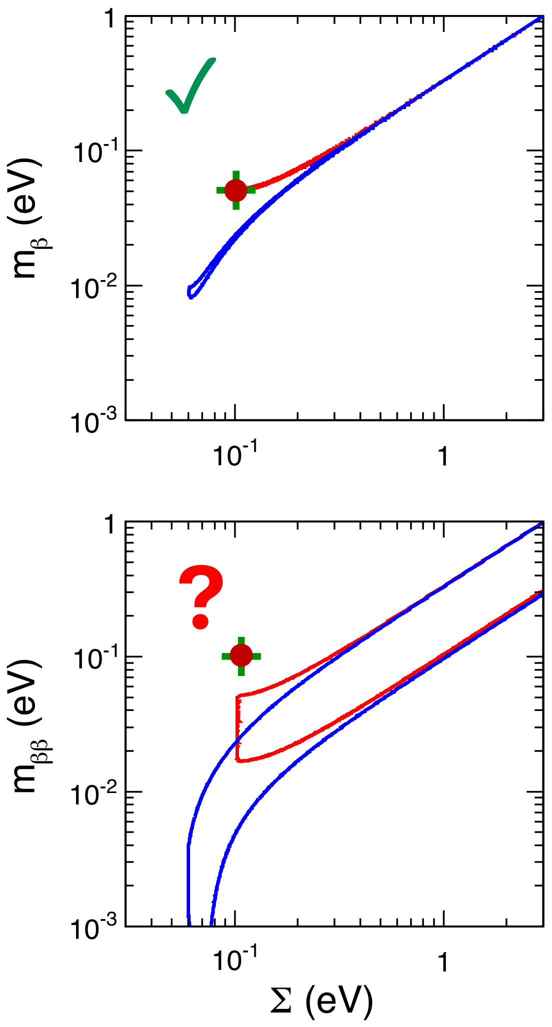


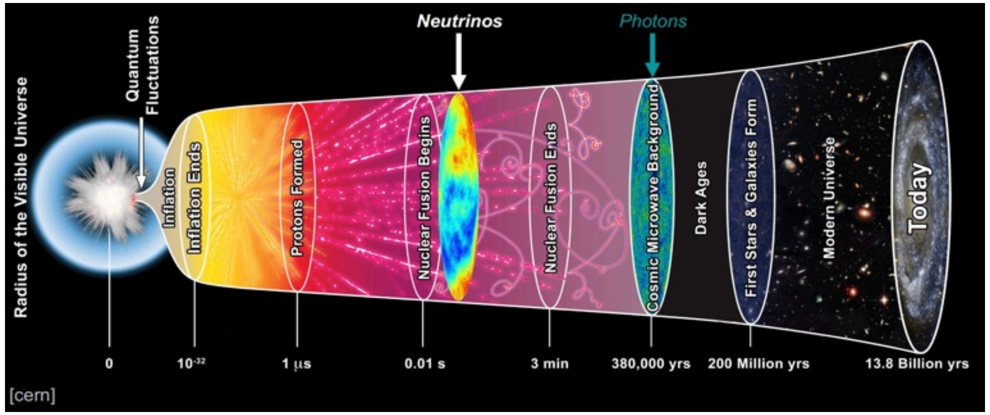
… or surprises?



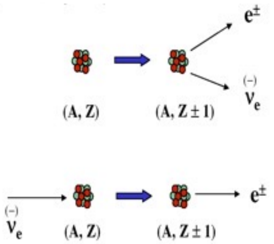
Lack of convergence might suggest new physics: e.g., **new cosmo model**, **nonstandard $0\nu\beta\beta$ …**

...Far-future dreams (β + cosmo): Capture big-bang relic neutrinos as "cold" as $T_\nu \sim O(10^{-4})$ eV

P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

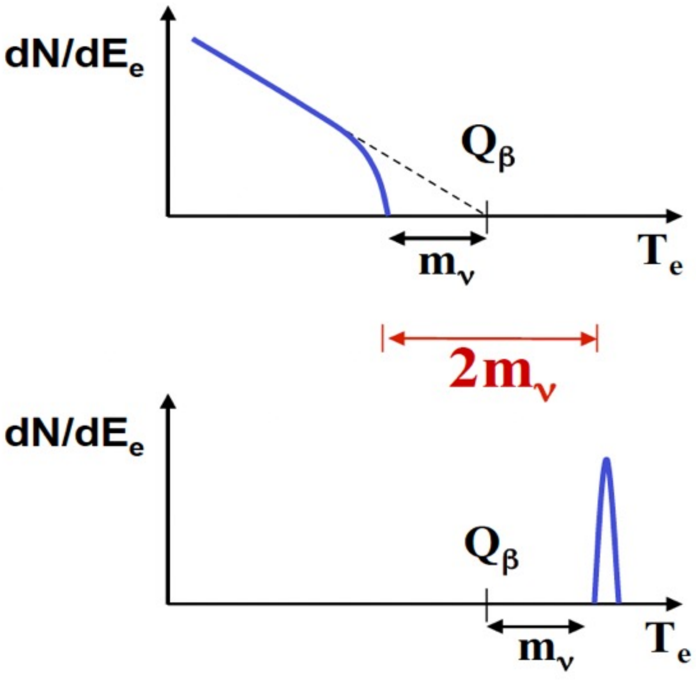


Nuclear Beta decay

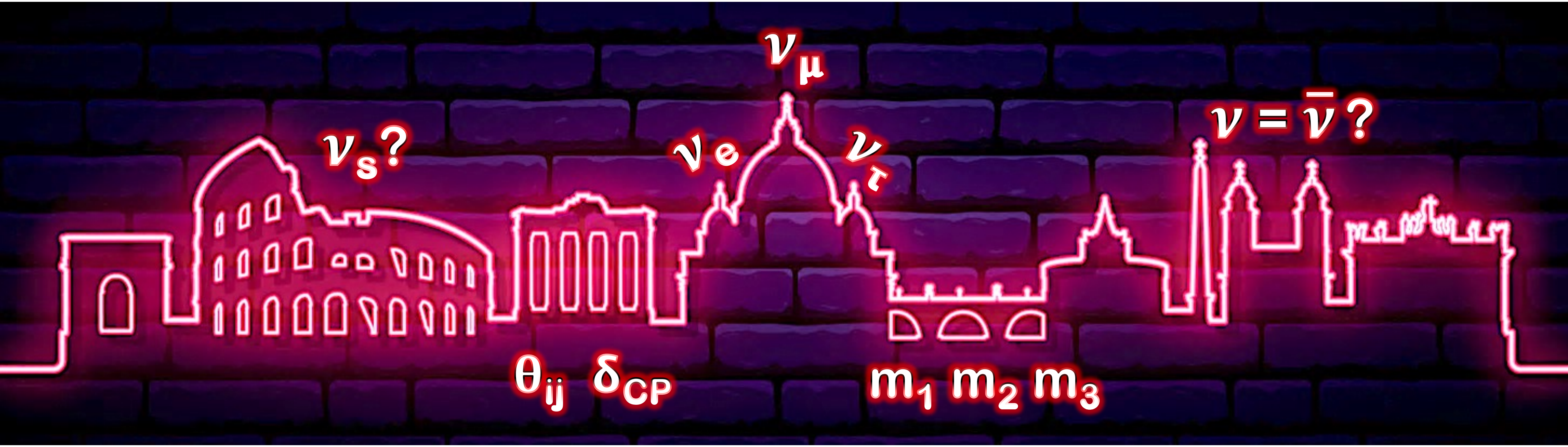


Neutrino Capture on a Beta Decaying Nucleus

No-threshold reaction!



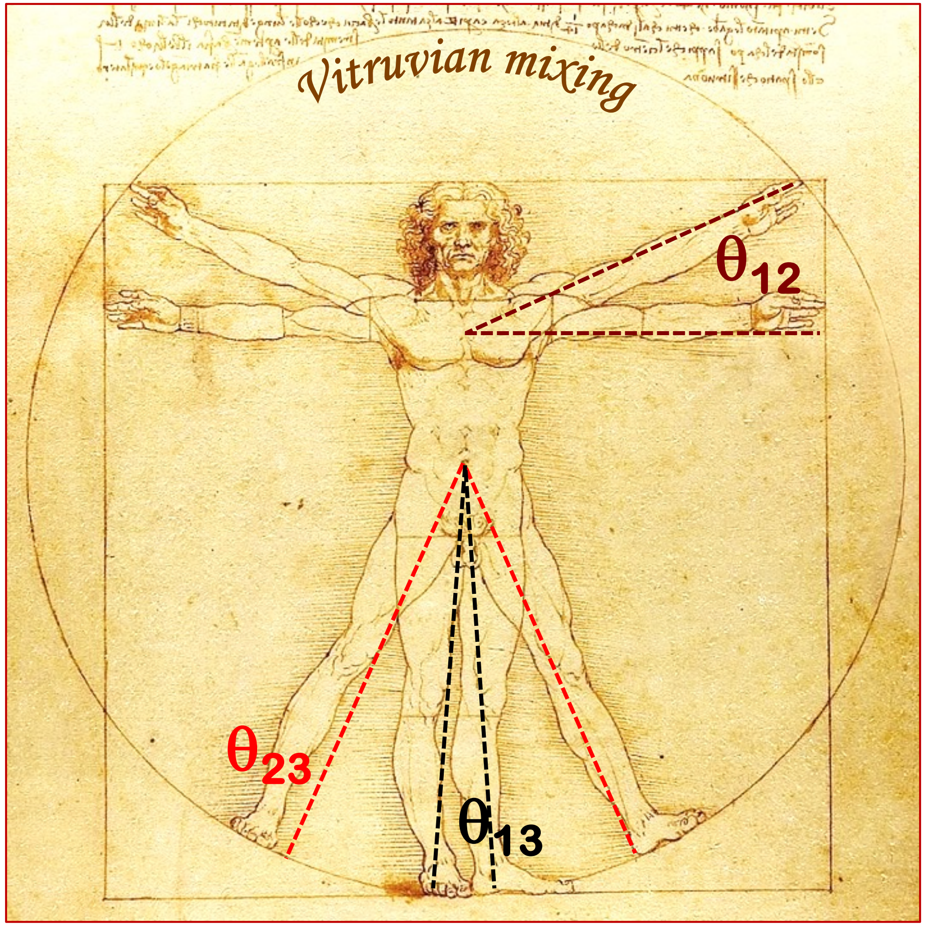
The PMNS paradigm...



...in a wider context

The SM lacks an organizing principle for flavor (Yukawa's Y).

Are the PMNS parameters "accidental", or suggestive of a "pattern"?



"Anarchy" or elaborated "symmetries" of leptons (+quarks)?

Many interesting ideas, but no obvious answer/guidance so far.

Subnuclear Physics: Past, Present and Future
Pontifical Academy of Sciences, Scripta Varia 119, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/sv119/sv119-altarelli.pdf

THE MYSTERY OF NEUTRINO MIXING

GUIDO ALTARELLI

"Finally, one could have imagined that neutrinos would bring a decisive boost towards the formulation of a comprehensive understanding of fermion masses and mixings. In reality it is frustrating that no real illumination was sparked on the problem of flavour. We can reproduce in many different ways the observations, in a wide range that goes from anarchy to discrete flavour symmetries) but we have not yet been able to single out a unique and convincing baseline for the understanding of fermion masses and mixings."

[But: the promising research line of modular symmetries just stemmed from Altarelli & Feruglio 2006 + Feruglio 2017...]

Time-honored ideas still illuminating the path forward…

perspective

NATURE PHYSICS | VOL 14 | FEBRUARY 2018

Symmetry and emergence

[**Edward Witten**, arXiv:1710.01791]

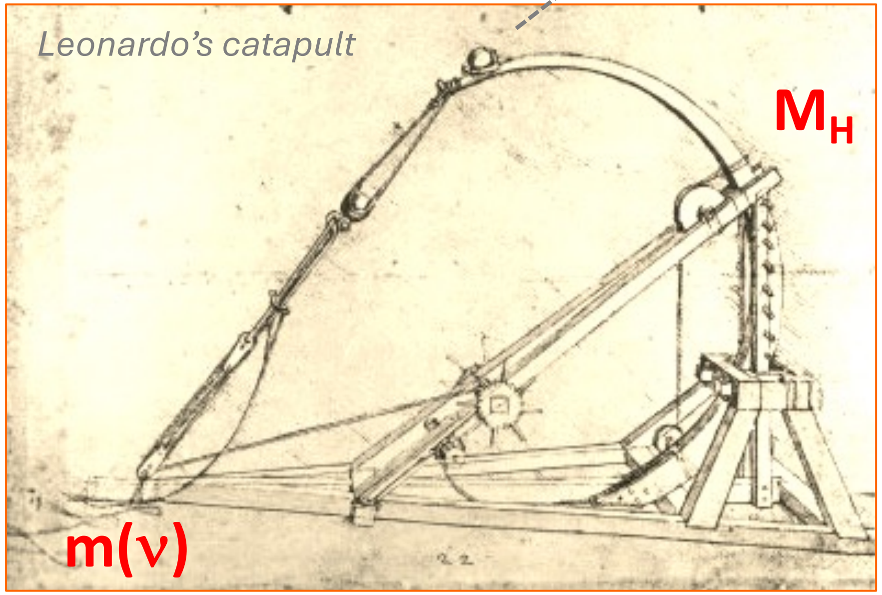
In a modern understanding of particle physics, global symmetries are approximate and gauge symmetries may be emergent. This view, which has echoes in condensed-matter physics, is supported by a variety of arguments from experiment and theory.

No reason for global symmetries to be exact, from different theoretical perspectives.

No global lepton number conservation	$\mathcal{L}_1 = \frac{1}{M} HHLL$	**Majorana neutrinos**
No global baryon number conservation	$\mathcal{L}_2 = \frac{1}{M^2} QQQL$	**Proton decay**
No a priori CP conservation in QCD	$\frac{\theta}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \mathrm{tr}\, F_{\mu\nu} F_{\alpha\beta}$	**Axion**

General arguments not weakened by absence of new physics at the LHC scale

Neutrinos masses may offer a great opportunity to jump beyond the EW framework via see-saw ...



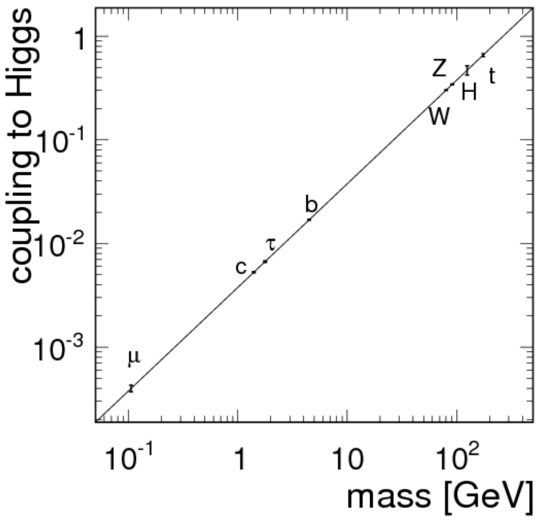
M ?

... and to address fundamental physics issues, such as:

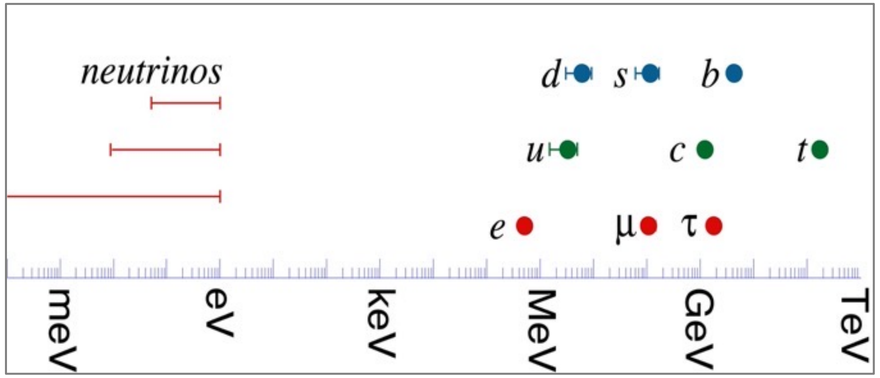
- new sources of CP violation at low and high energies
- lepton number violation and associated phenomena
- matter-antimatter asymmetry of the universe ...

Bridging two physics programs in collider and ν physics

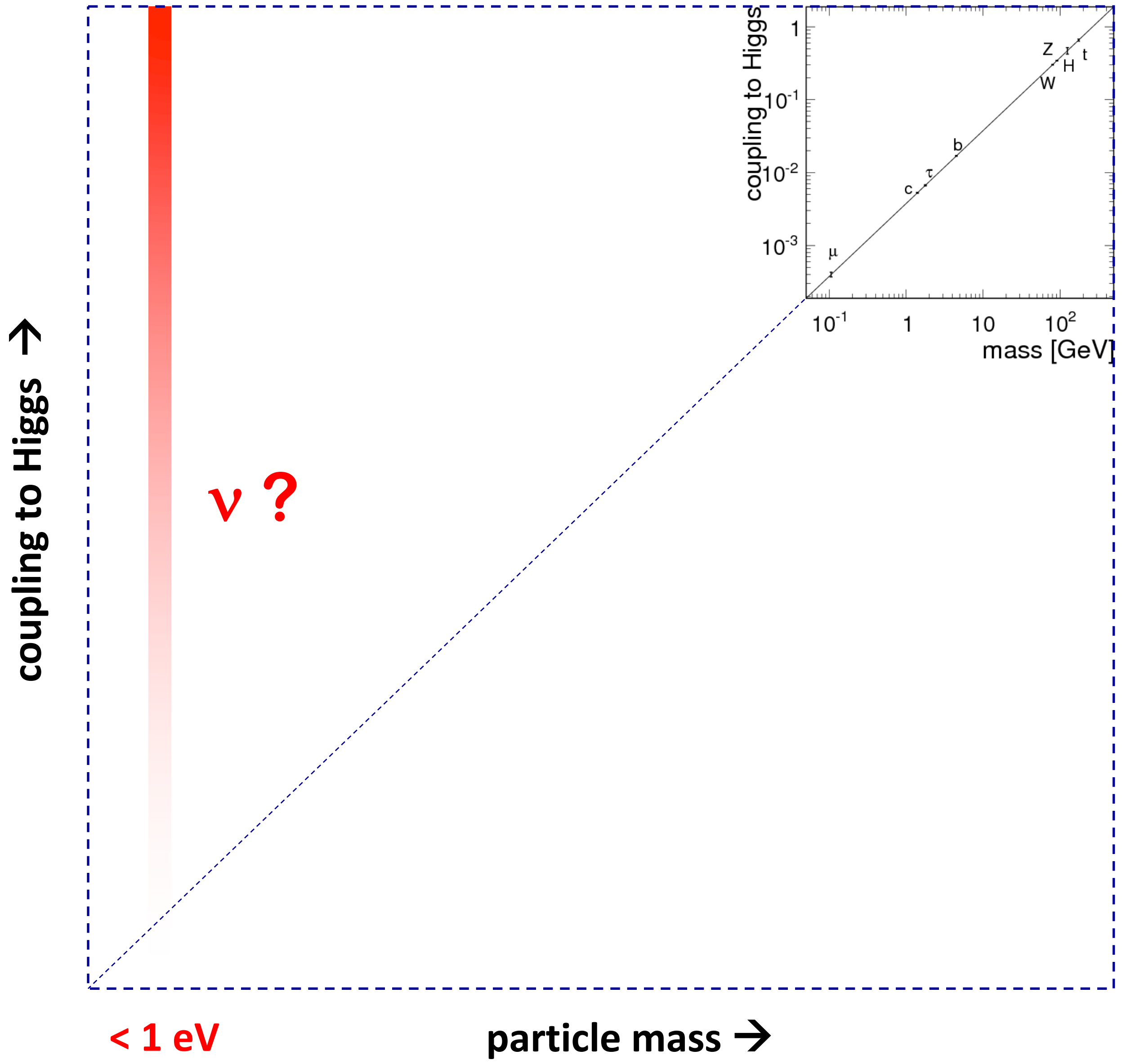
1. Test Higgs sector



2. Find ν masses



Why are the ν's so light? Where are they on this plot?



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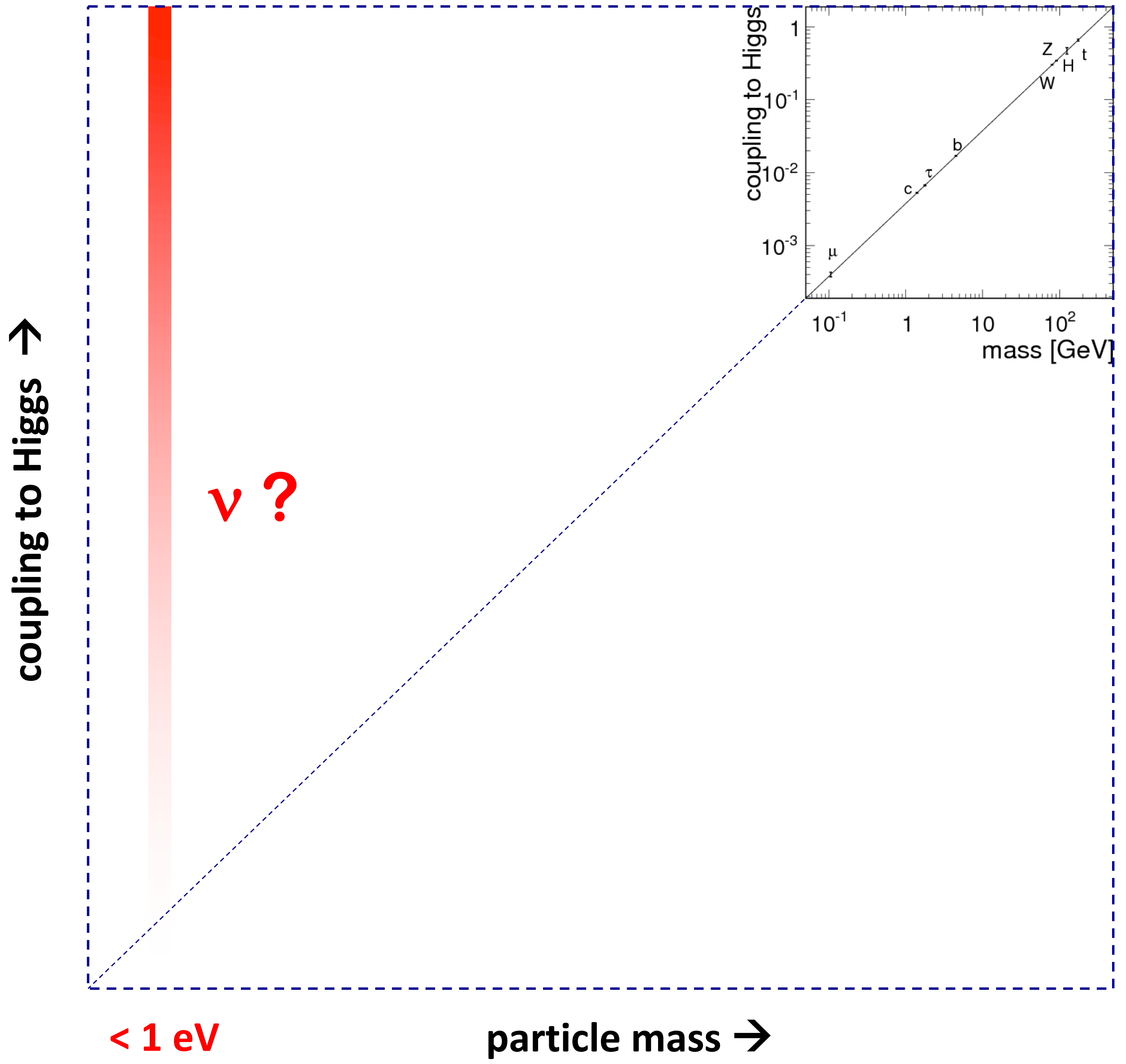
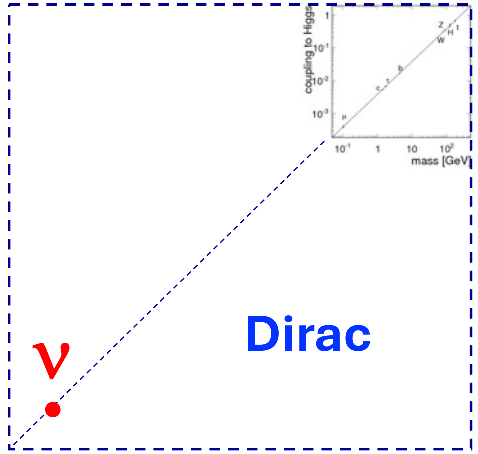


Neutrinos might just couple to the Higgs with tiny Yukawas…



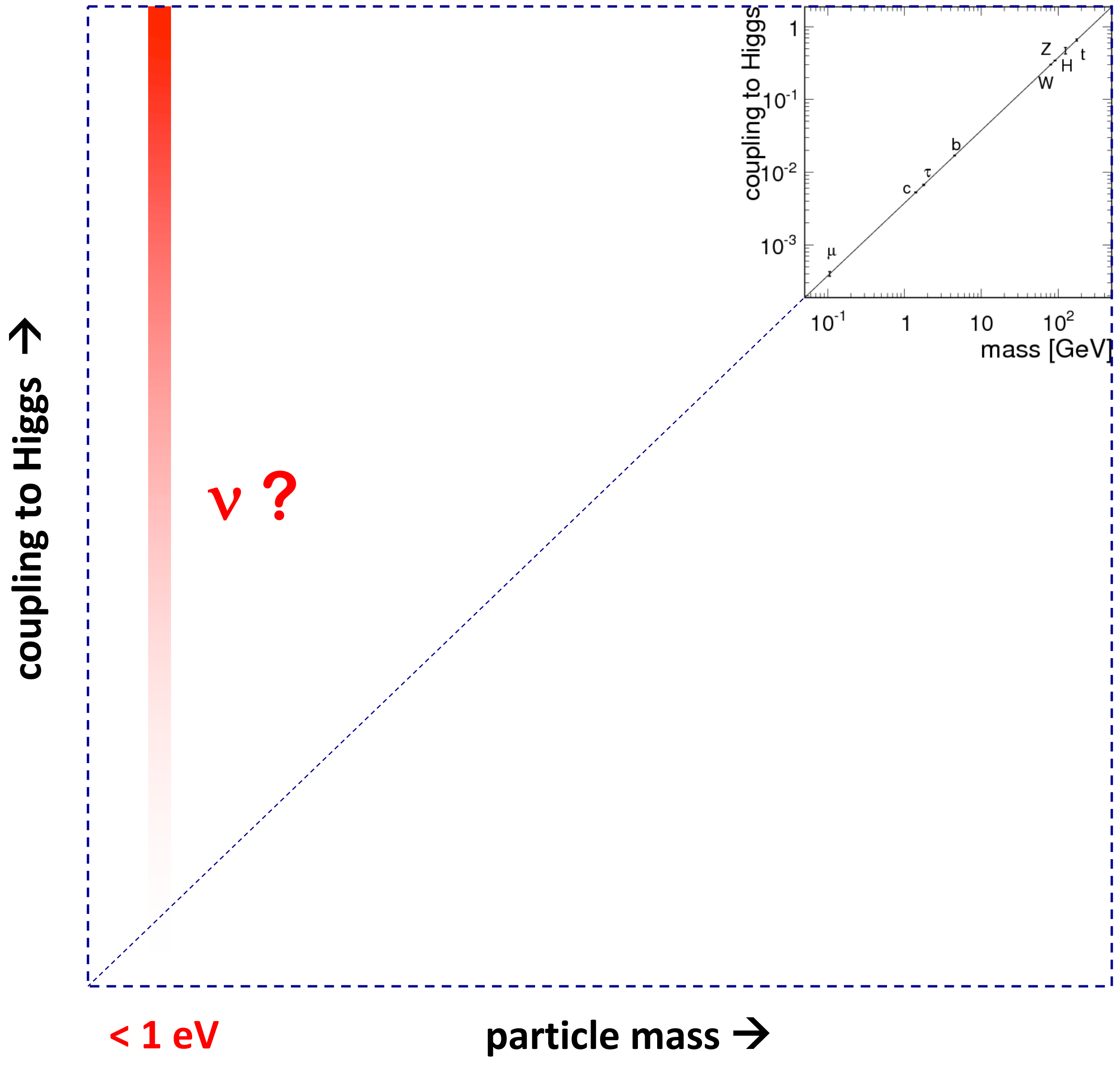
$$m_\nu \sim y M_H \;\; (y \sim 10^{-12})$$

Dante, *Inferno*:

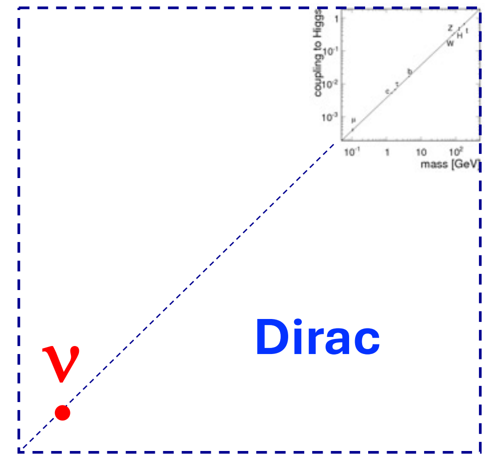
« … Vuolsi così colà dove si puote
ciò che si vuole, e più non dimandare »

«… It is so willed there where is power to do that which is willed; and farther ask not »

Why are the ν's so light? Where are they on this plot?

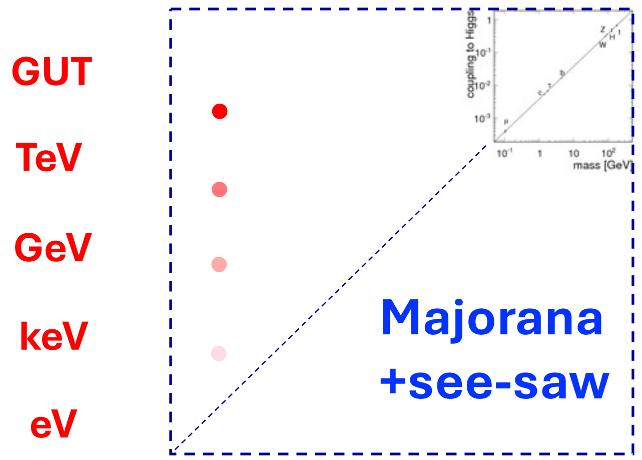


Neutrinos might just couple to the Higgs with tiny Yukawas...



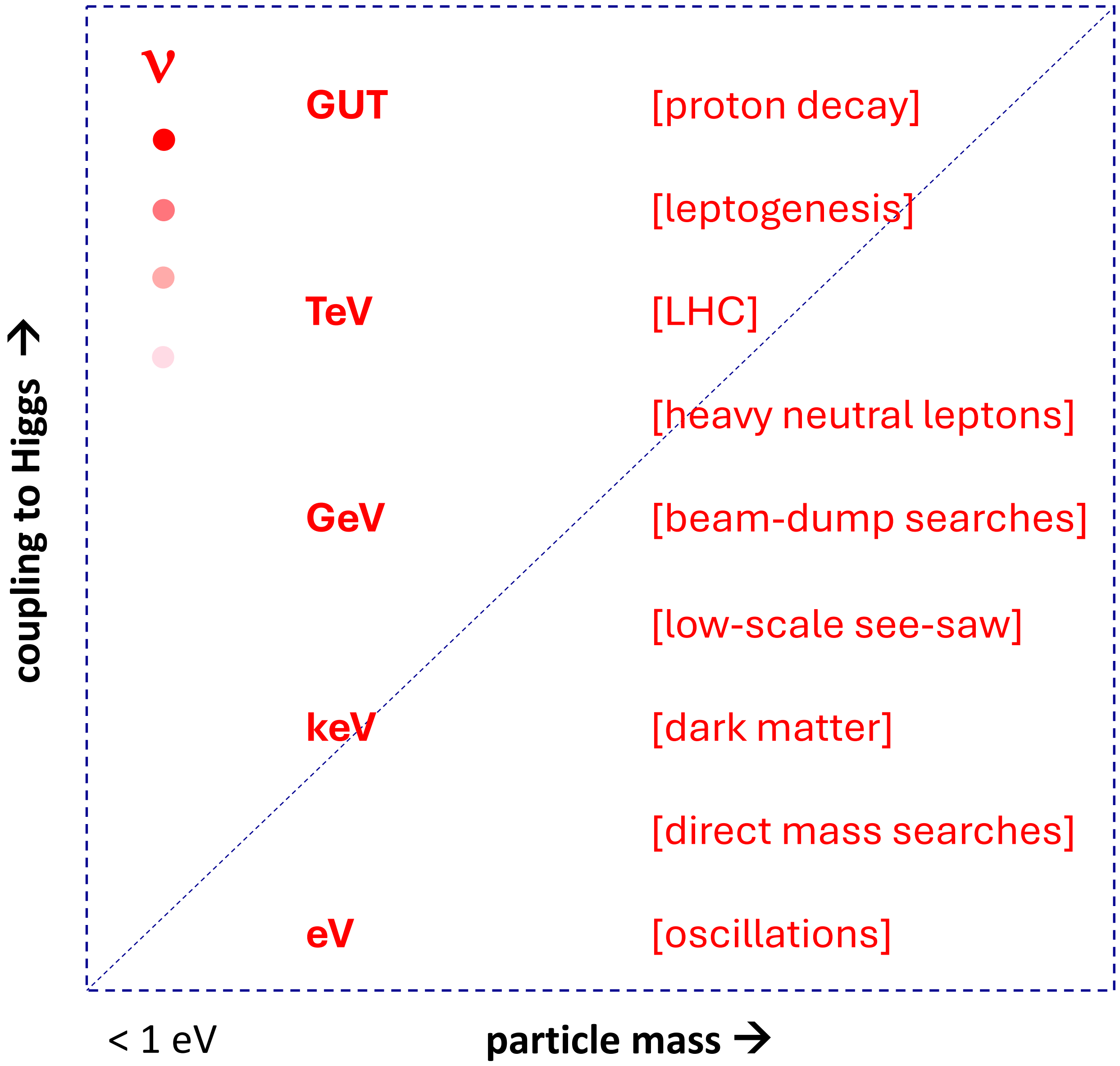
$$m_\nu \sim y M_H \;\; (y \sim 10^{-12})$$

...or talk to other physics scale(s), with new emerging mass states...



$$m_\nu \sim y M_H f \;\; (f \sim M_H/\Lambda)$$

Vast landscape of mass scales ...



ν

GUT [proton decay]

[leptogenesis]

TeV [LHC]

[heavy neutral leptons]

GeV [beam-dump searches]

[low-scale see-saw]

keV [dark matter]

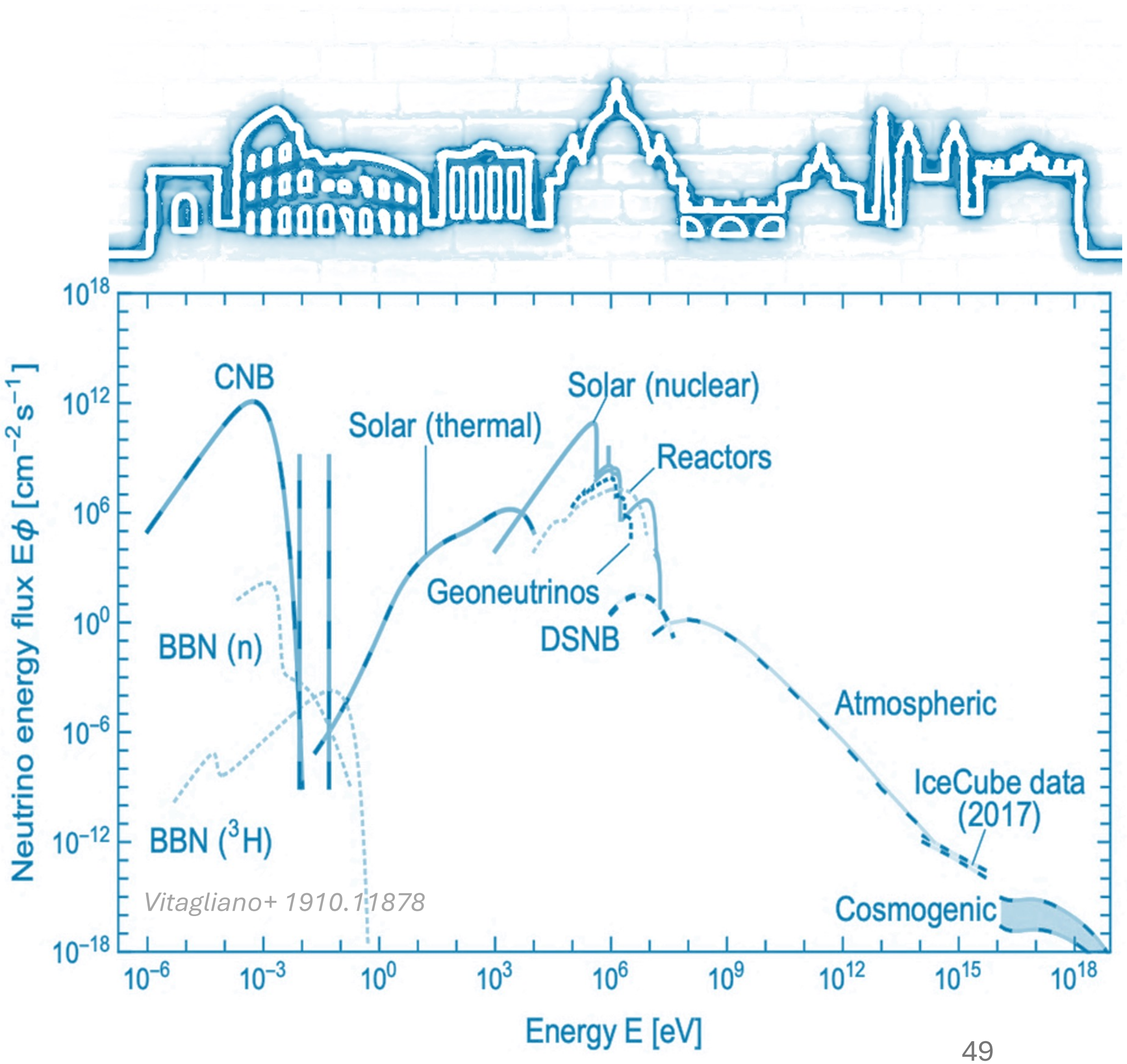
[direct mass searches]

eV [oscillations]

coupling to Higgs →

< 1 eV **particle mass →**

Vast landscape of mass scales ... and energies



Epilogue: The rise of the 3ν paradigm

Foundations

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$\Delta m^2 \sim 2\times10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

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Challenges

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute masses
Dirac vs Majorana

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A new paradigm?

new states
new interactions
new physics scales
flavor structure
origin of matter ...

Thank you for your attention

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