Outlook on ν theory and phenomenology

- Reflections from / for a long-term project -


Image credit: Wikimedia

Eligio Lisi
(INFN, Bari, Italy)

PRIN PANTHEON
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN Istituto Nazionale di Fisica Nucleare

Prologue

The Duomo of Milan

Duomo: not a static monument, but a never-ending construction, la “Veneranda Fabbrica del Duomo”…

…started from a visionary idea in 1386 (G.Visconti)

Credit: Wikimedia


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… evolved in unforeseen ways during centuries

…continues with state-of-the-art approaches:


Credit: Duomomilano

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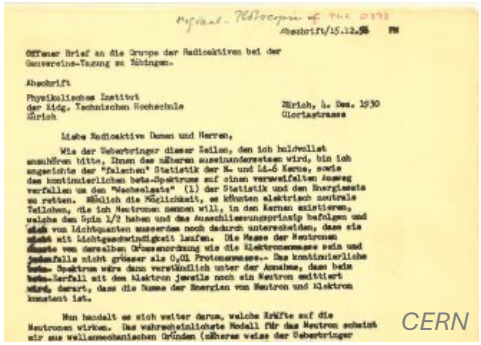
Neutrino physics: a long-term research activity…

…started from a visionary idea in 1930 (W. Pauli)


Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen das näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müssten von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta-Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

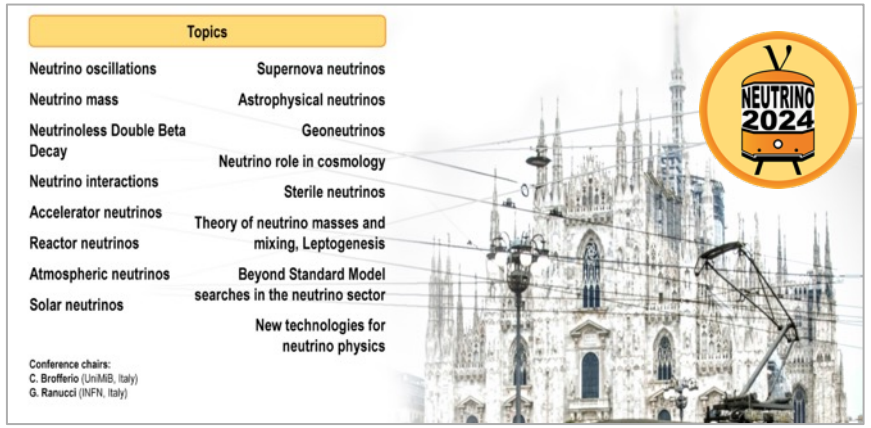
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer

CERN


Credit: CERN

… evolved in unforeseen ways during decades

…continues with state-of-the-art approaches:



Outline

In analogy (or in contrast) with the Duomo construction

Building pillars

Seeking patterns

Assessing levels

Rebuilding structures

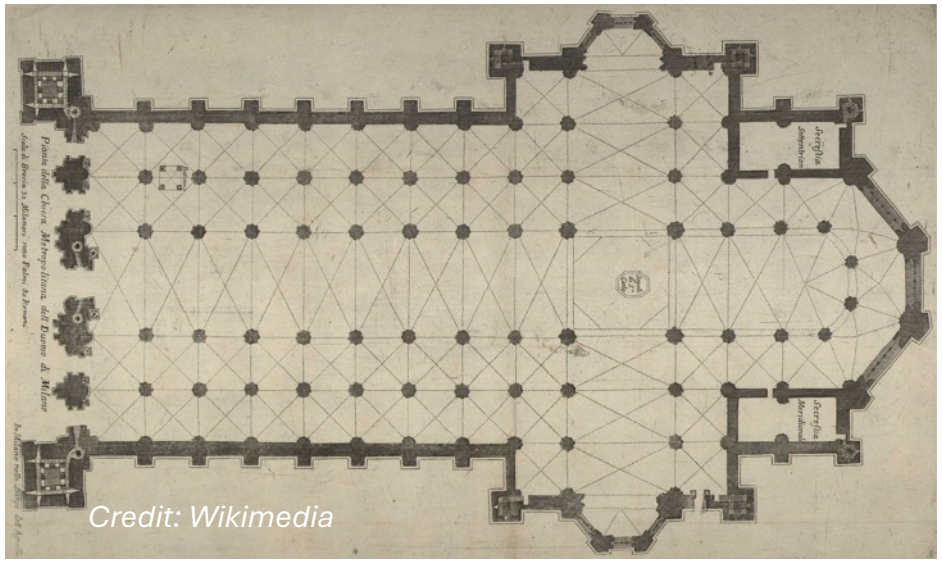
Illuminating darkness

Engaging with society

With apologies to many talks [and all posters] not cited in the following ~25'…

Building pillars

Define the basic template of the structure,
+allowance/constraints for possible variants



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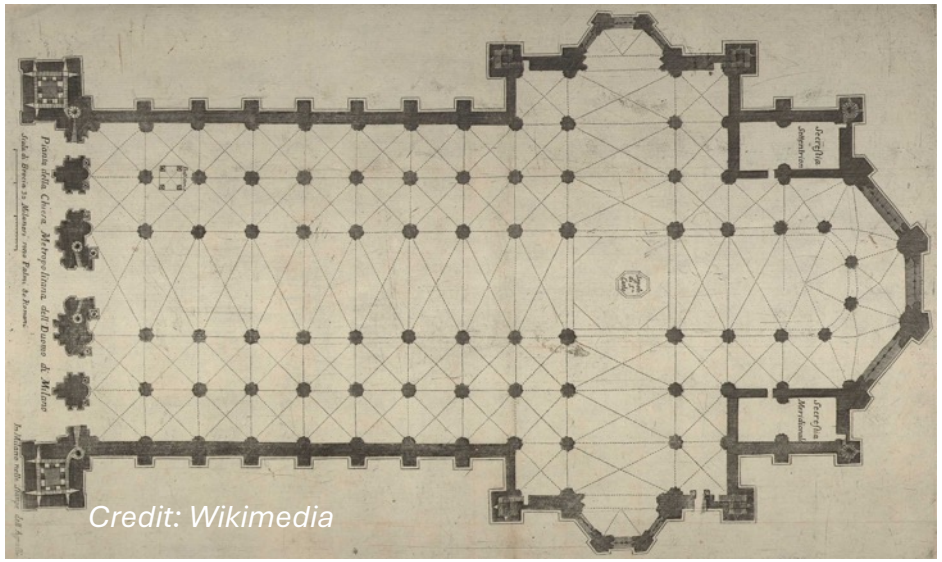


→ Standard 3ν oscillation framework

Our basic paradigm since 1998,
still resisting many stress tests (beyond 3ν)

Five pillars have been raised and will be further refined: δm^2, $|\Delta m^2|$, θ_{12}, θ_{13}, θ_{23}

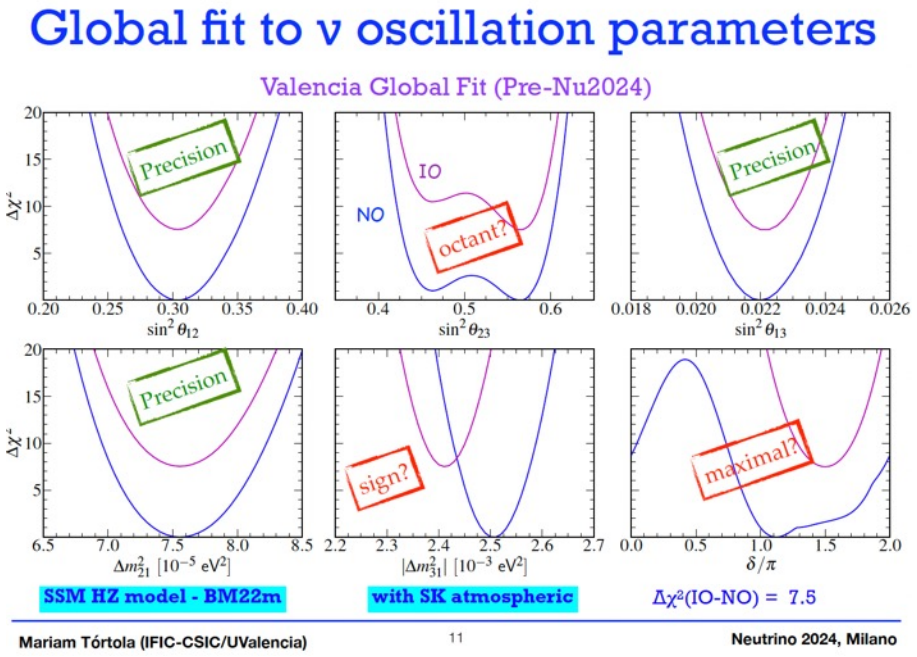
(θ_{23} still a bit unstable, consolidation will take some time…)

Two more pillars are under construction: **mass ordering, CP phase**

In Milan, we have seen construction in the making…

Pre-Nu2024 hints on octant, ordering, CP

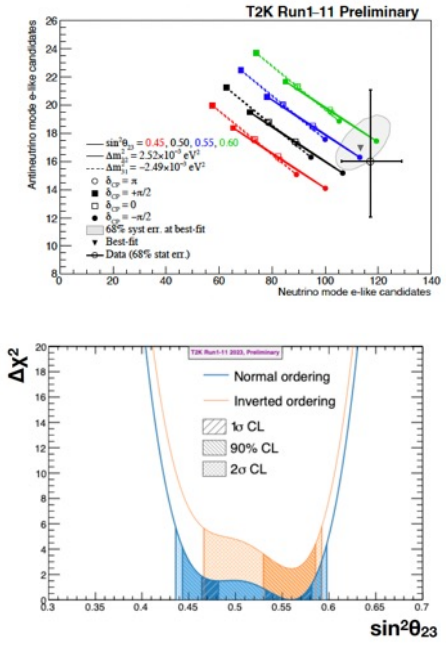
[Tortola]



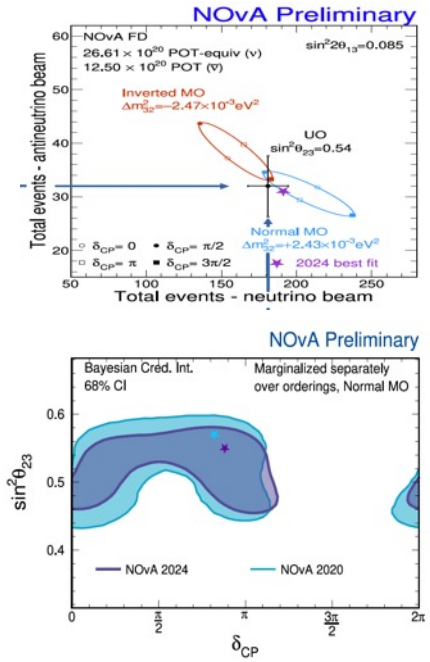
Hints perturbed by new T2K and NOvA data

→ Call for updated analyses

[Giganti, T2K]



[Wolcott, NOvA]



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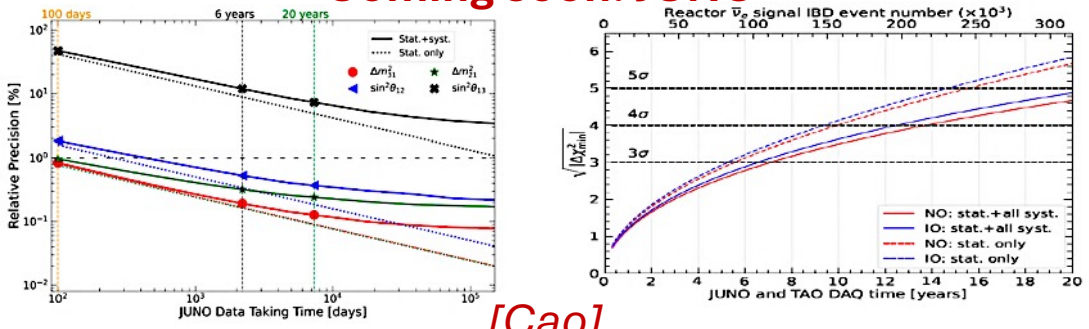
… and exciting plans + guaranteed results for decades!

Both precision and discovery frontiers

Coming soon: JUNO



[Cao]

Expt frontiers with strong impact on theory/pheno

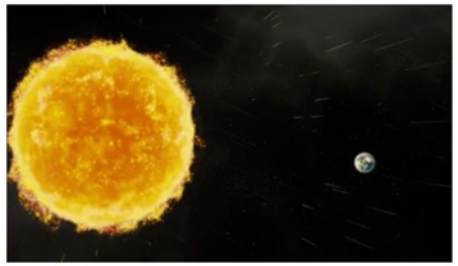
[Tortola, global analysis]
[Soler, Brunner, Yanez, atmos. analysis]
[Ding, flavor symmetries]
[Worcester, LBL pheno]
[Menendez, Guenette, $0\nu\beta\beta$ pheno]
[Maneira, solar ν]
[Expt. talks…]

Each pillar supported by ≥2 classes of expts

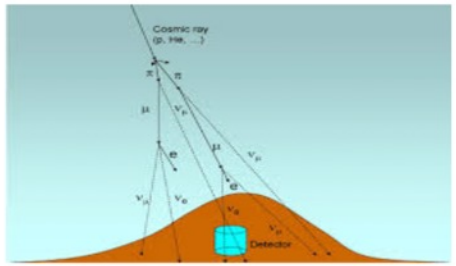
→ Learn from ≥2 datasets via joint/global analyses

[Tortola]

Solar sector: θ_{12}, θ_{13}, Δm^2_{21}

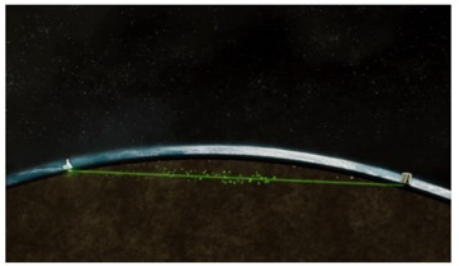


Atmospheric sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



Reactor sector: θ_{13}, Δm^2_{31}

Accelerator sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



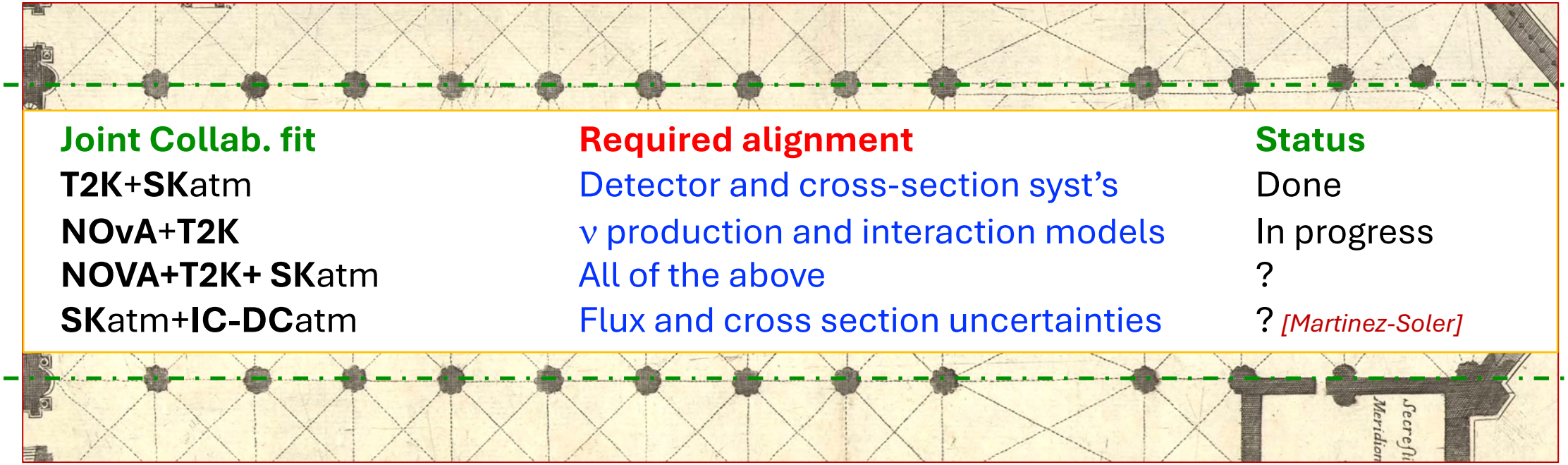
Joint oscillation analysis *[McDonald]*

- Different energies, baselines can resolve the degeneracies between mass ordering and δ_{CP} and/or θ_{23} octant and δ_{CP}
- It is important to study possible correlations in the systematics errors between the experiments

← *Can be studied also by "external users" [Tortola]*

← *Should be jointly carried out by Collaborations*

At (sub)percent error level, need to align common features & avoid "pillar mismatch", e.g:



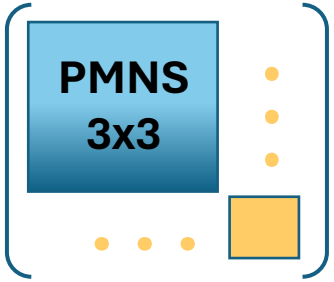
Joint Collab. fit	**Required alignment**	**Status**
T2K+**SK**atm	Detector and cross-section syst's	Done
NOvA+**T2K**	ν production and interaction models	In progress
NOVA+T2K+ SKatm	All of the above	?
SKatm+**IC-DC**atm	Flux and cross section uncertainties	? *[Martinez-Soler]*

… also to exploit powerful synergy/complementarity in larger combinations (e.g., +JUNO)

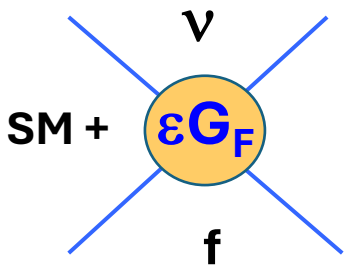
Beyond 3ν precision and discovery: Stress-tests of the 3ν pillars. Surprises?

Testing the resilience of the 3ν paradigm to **extra ν states** or to **new interactions, e.g.:**

non-unitarity

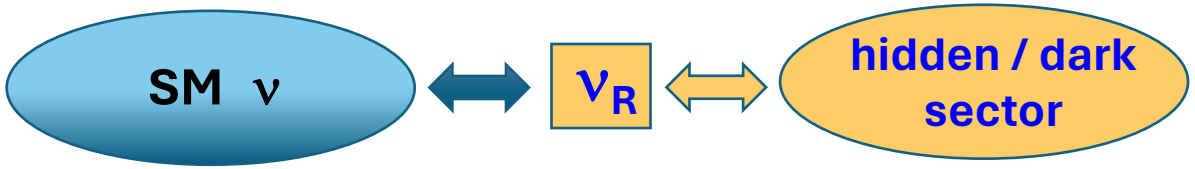


NSI



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**: e.g., RH ν 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 3ν paradigm (also 3+1), e.g. via **modified ν dispersion relations, decays, new particles …**

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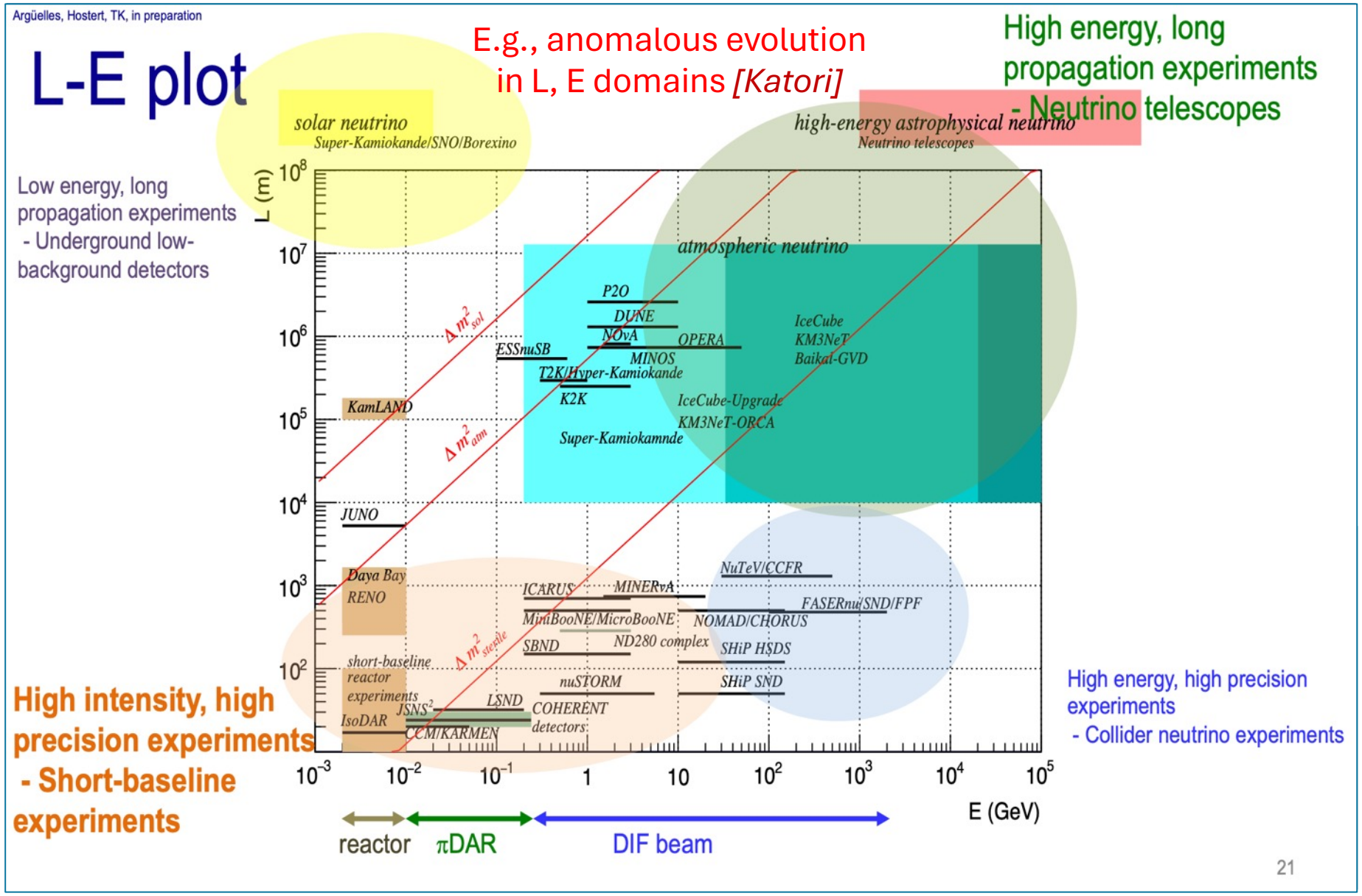

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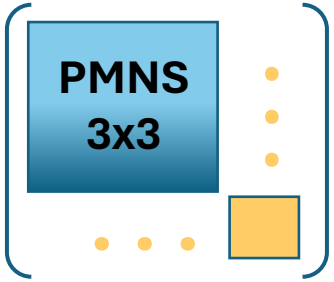

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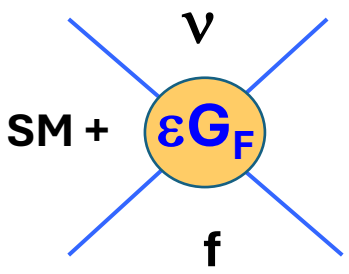

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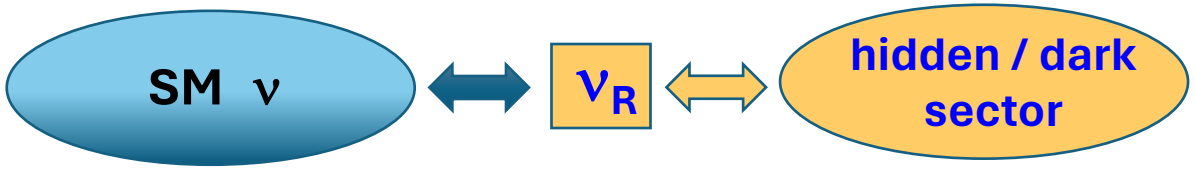

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No evidence so far, except for possible **O(eV) sterile ν** anomalies [next slide]

Important to keep 3ν "under pressure" via theory variants

Unexpected results may come any time!

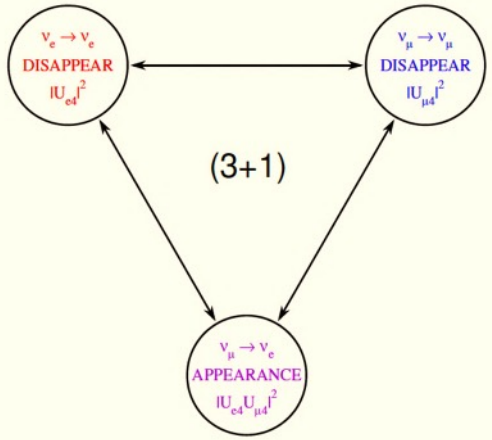
[Tortola, global analyses]
[Fernandez-M., ν BSM]
[Katori, ν BSM]
[Gariazzo, Cosmology]
[Caratelli, MicroBoone]
[…]

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

(3+1): appearance versus disappearance

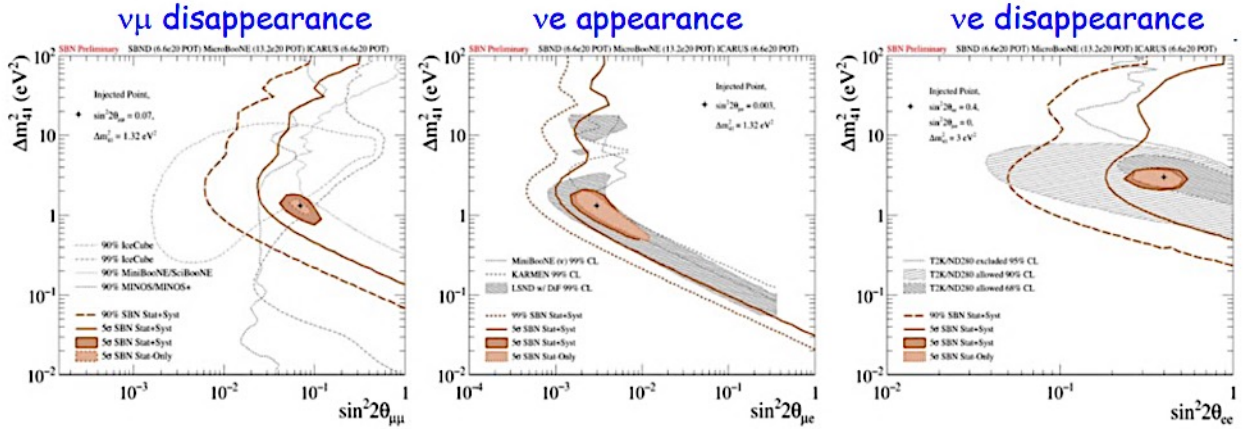
- (3+1): $P_{\nu_\mu \to \nu_e} \propto |U_{e4} U_{\mu 4}|^2$ with $\begin{cases} |U_{e4}|^2 \propto P_{\nu_e \to \nu_e} , \\ |U_{\mu 4}|^2 \propto P_{\nu_\mu \to \nu_\mu} ; \end{cases}$
- hence, $P_{\nu_\mu \to \nu_e} > 0$ requires $\begin{cases} P_{\nu_e \to \nu_e} > 0 , \\ P_{\nu_\mu \to \nu_\mu} > 0 ; \end{cases}$

¿? 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]

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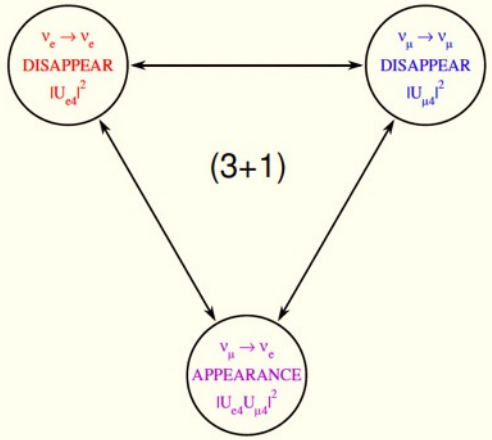

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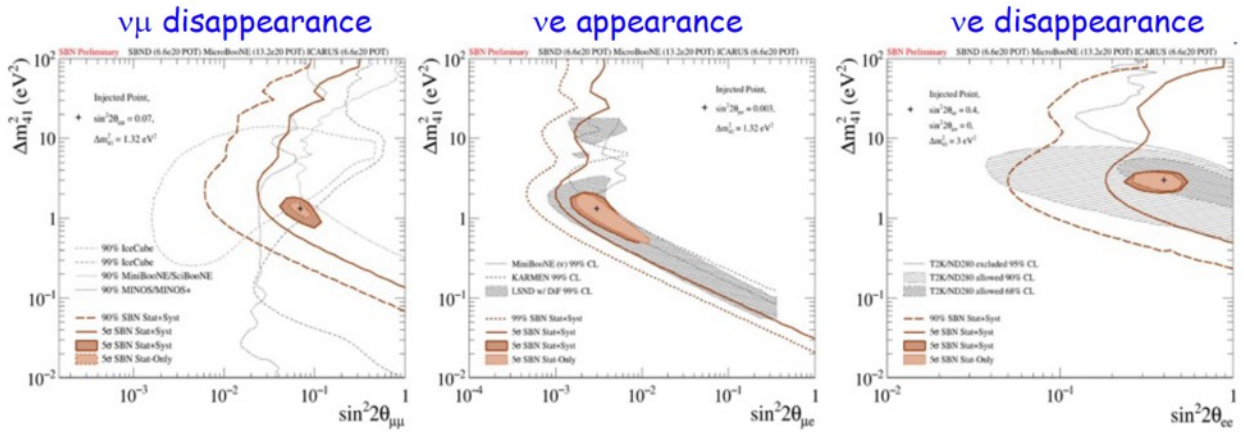

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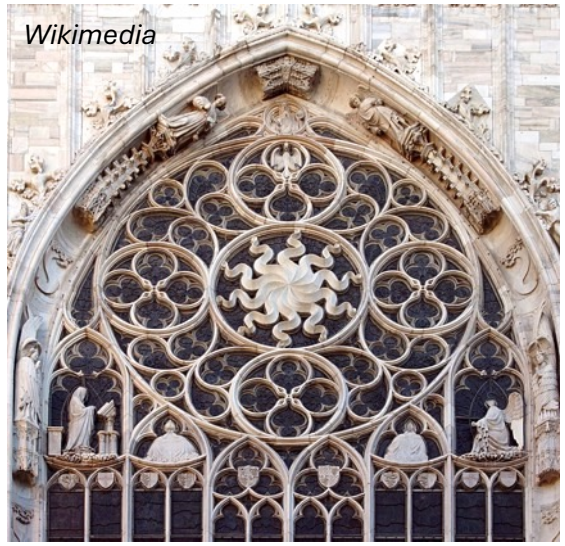
[Gibin, Icarus+SBND]

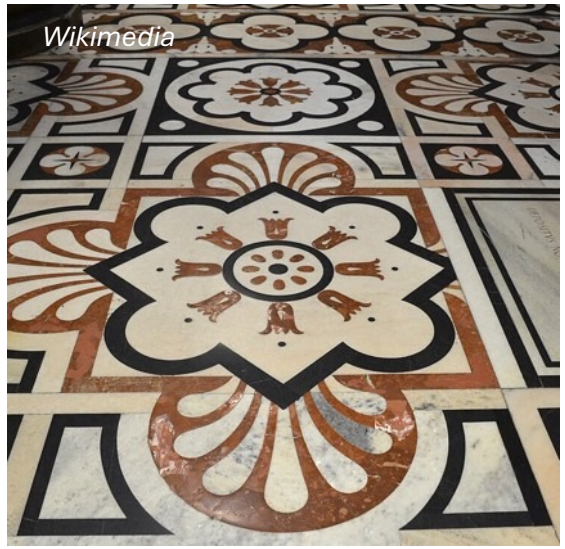
Sterile ν status largely discussed

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

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

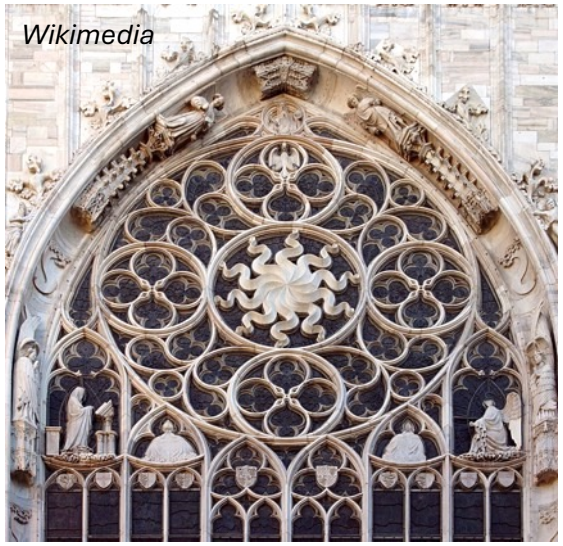
If false, should trigger retrospective review in Neutrino 20XY: **What went wrong?**





Seeking patterns

Patterns and (a)symmetries are an essential part of Duomo architecture and decoration



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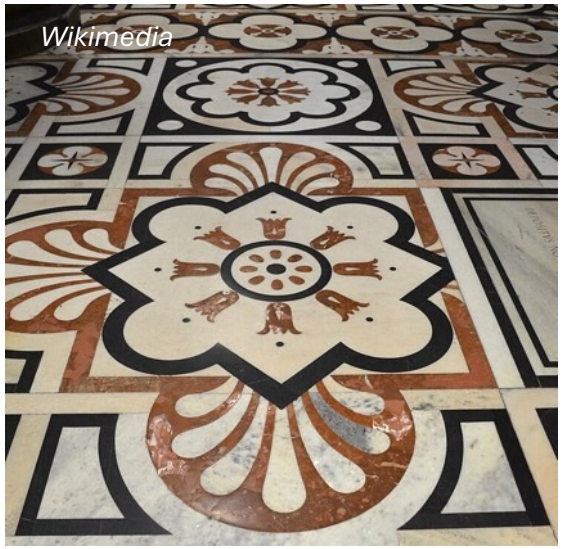


→ **Patterns in the 3ν framework?**

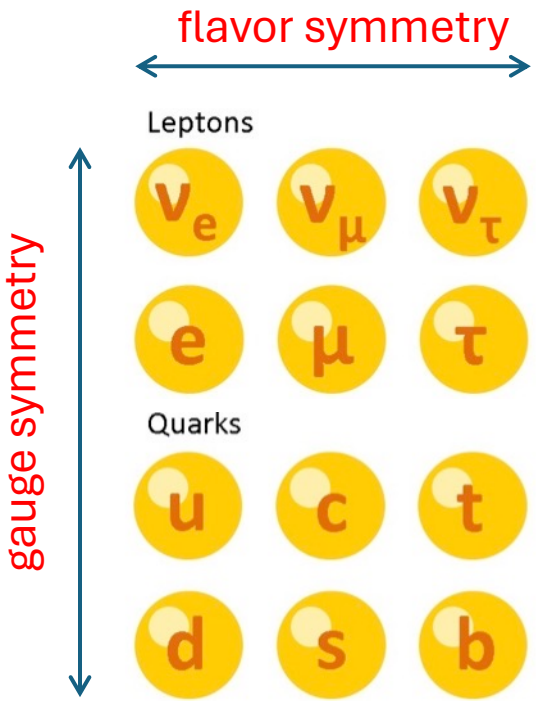
Do they exist? If so, any hope to unravel them?

→ **The most fundamental ν symmetry…**

Particle = antiparticle?

Model building by assuming symmetries

New scale(s) with higher symmetries



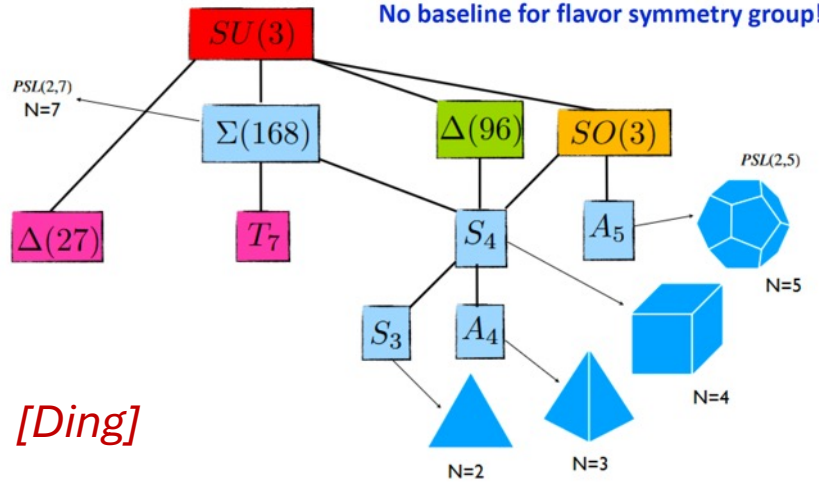
Flavor symmetries: group patterns

$$\mathcal{G}_f$$

$$\mathcal{G}_l \quad \mathcal{G}_\nu$$

$$\mathcal{U}_l \quad \mathcal{U}_\nu$$

$$\mathcal{U}_{PMNS} = \mathcal{U}_l^+ \mathcal{U}_\nu$$



[Ding]

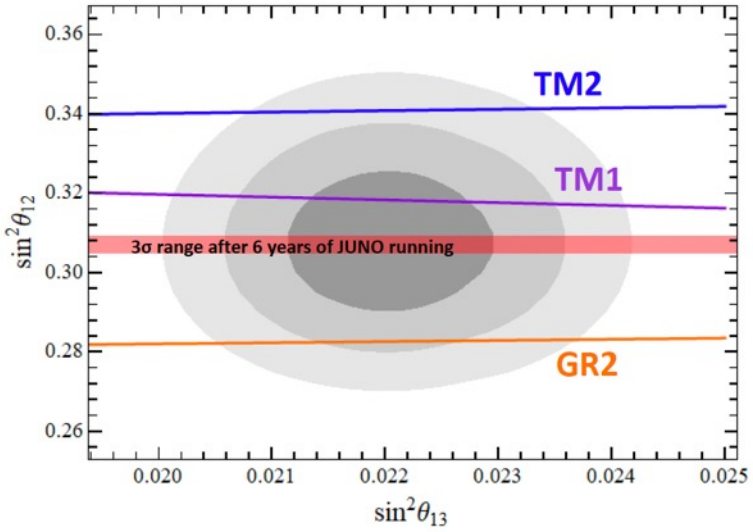
Hope to "explain" at least lepton,
+ possibly also quark flavor sector,
with relatively few new d.o.f.

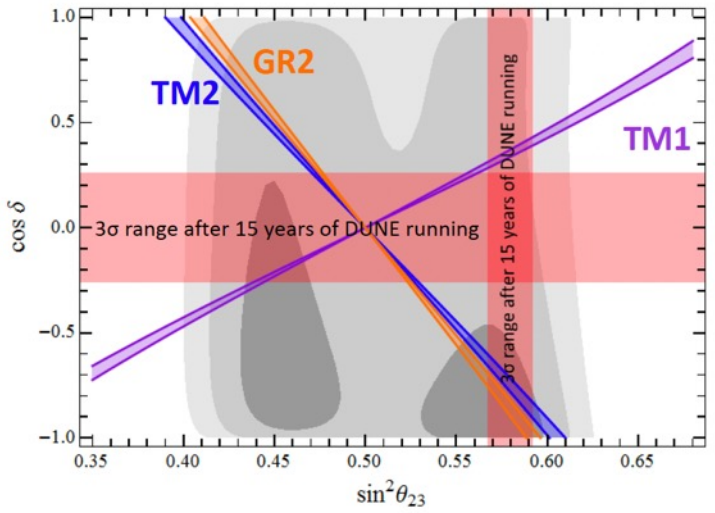
$G_l \rtimes H_{CP}^l$	$G_\nu \rtimes H_{CP}^\nu$	U	# parameters
Z_n	$K_4 \times CP$	$Q_l^\dagger P_l^T \Sigma_l^\dagger \Sigma_\nu P_\nu Q_\nu$	0
Z_n	$Z_2 \times CP$	$Q_l^\dagger P_l^T \Sigma_l^\dagger \Sigma_\nu R_{23}(\theta) P_\nu Q_\nu$	1
$Z_2 \times CP$	$K_4 \times CP'$	$Q_l^\dagger P_l^T R_{23}^T(\theta_l) \Sigma_l^\dagger \Sigma_\nu P_\nu Q_\nu$	
$Z_2 \times CP$	$Z_2 \times CP'$	$Q_l^\dagger P_l^T R_{23}^T(\theta_l) \Sigma_l^\dagger \Sigma_\nu R_{23}(\theta_\nu) P_\nu Q_\nu$	2
Z_2	$K_4 \times CP$	$Q_l^\dagger P_l^T U_{23}^\dagger(\theta_l, \delta_l) \Sigma_l^\dagger \Sigma_\nu P_\nu Q_\nu$	
Z_n	CP	$Q_l^\dagger P_l^T \Sigma_l^\dagger \Sigma_\nu O_3(\theta_1, \theta_2, \theta_3) Q_\nu$	3
CP	$K_4 \times CP'$	$Q_l^\dagger O_3^T(\theta_1, \theta_2, \theta_3) \Sigma_l^\dagger \Sigma_\nu Q_\nu$	
Z_2	$Z_2 \times CP$	$Q_l^\dagger P_l^T U_{23}^\dagger(\theta_l, \delta_l) \Sigma_l^\dagger \Sigma_\nu R_{23}(\theta_\nu) P_\nu Q_\nu$	

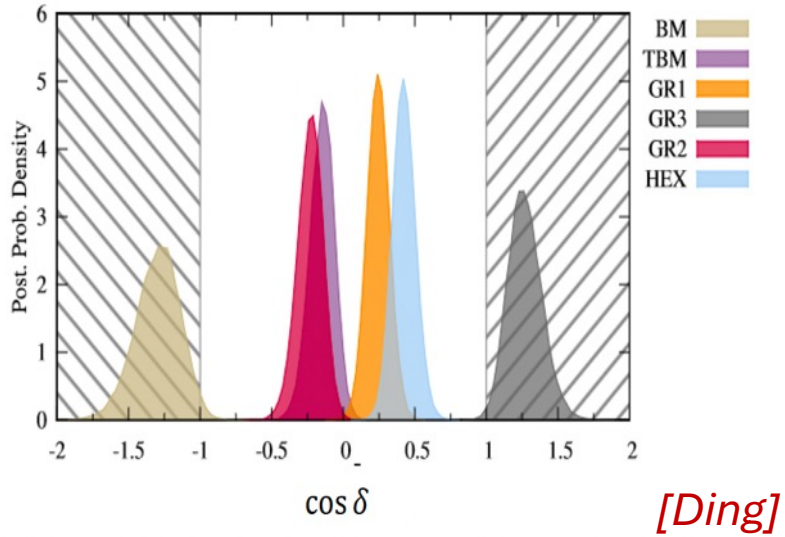
Testability and accuracy: two extreme viewpoints…

If there is no particular structure but **random entries** in the PMNS matrix (“anarchy”): higher precision data would bring **no further insights.**

If there is an underlying symmetry: PMNS known parameters become **correlated** and unknown ones are **predicted**. Future precise data could **select models:**



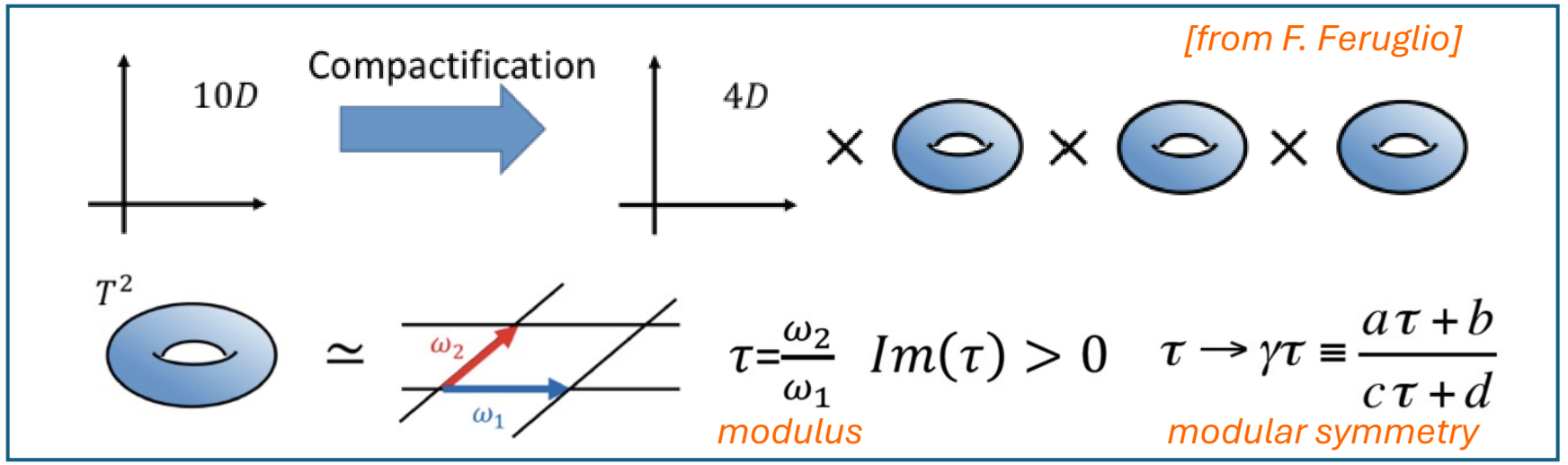




[Ding]

Various symmetry attempts "unified" under the concept of "modular symmetry" (MS)

[inspired by string theory & compactified extra dimensions; requires supersymmetry.]



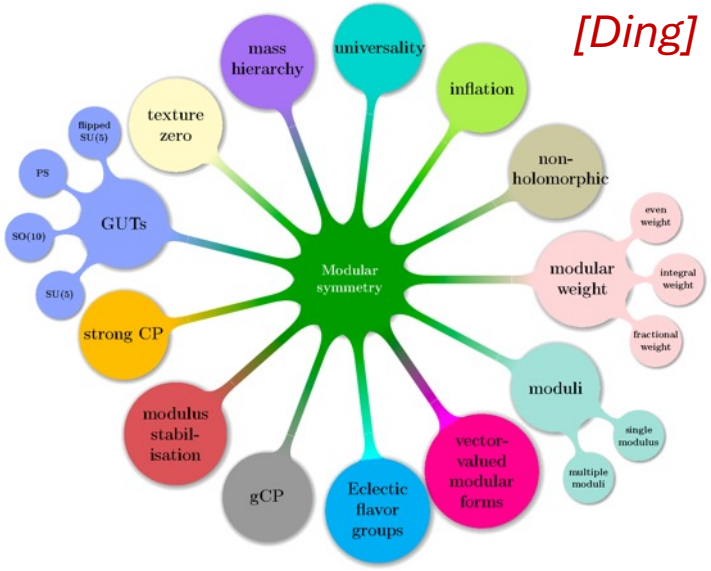
Successful realizations of MS are rather constraining on neutrino flavor sector **(including $0\nu\beta\beta$ and Majorana phases)**

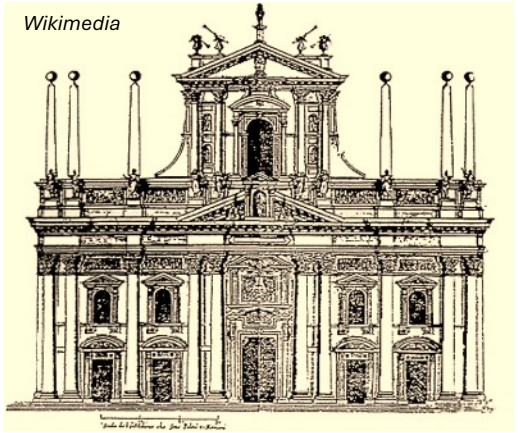
Dimensionless τ → no obvious scale, many options … →

In a sense…

SM: tell EW scale, but not flavor structure

MS: may tell us flavor structure, but scale?



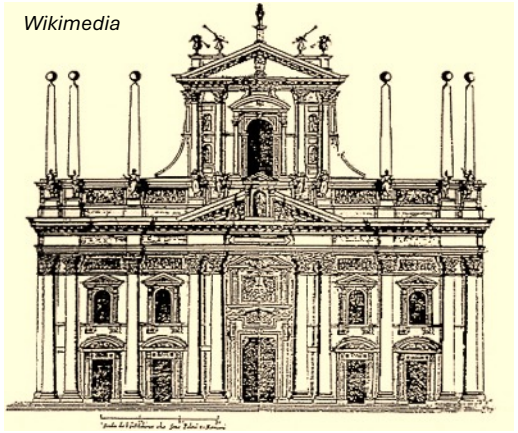


Tibaldi project ~1580, Roman style,
three levels

Buzzi project ~1651, Gothic style,
further levels and high side towers

Assessing levels

Assessing the Duomo **façade and its levels** involved evaluation of many projects, spanning several centuries and cultural approaches



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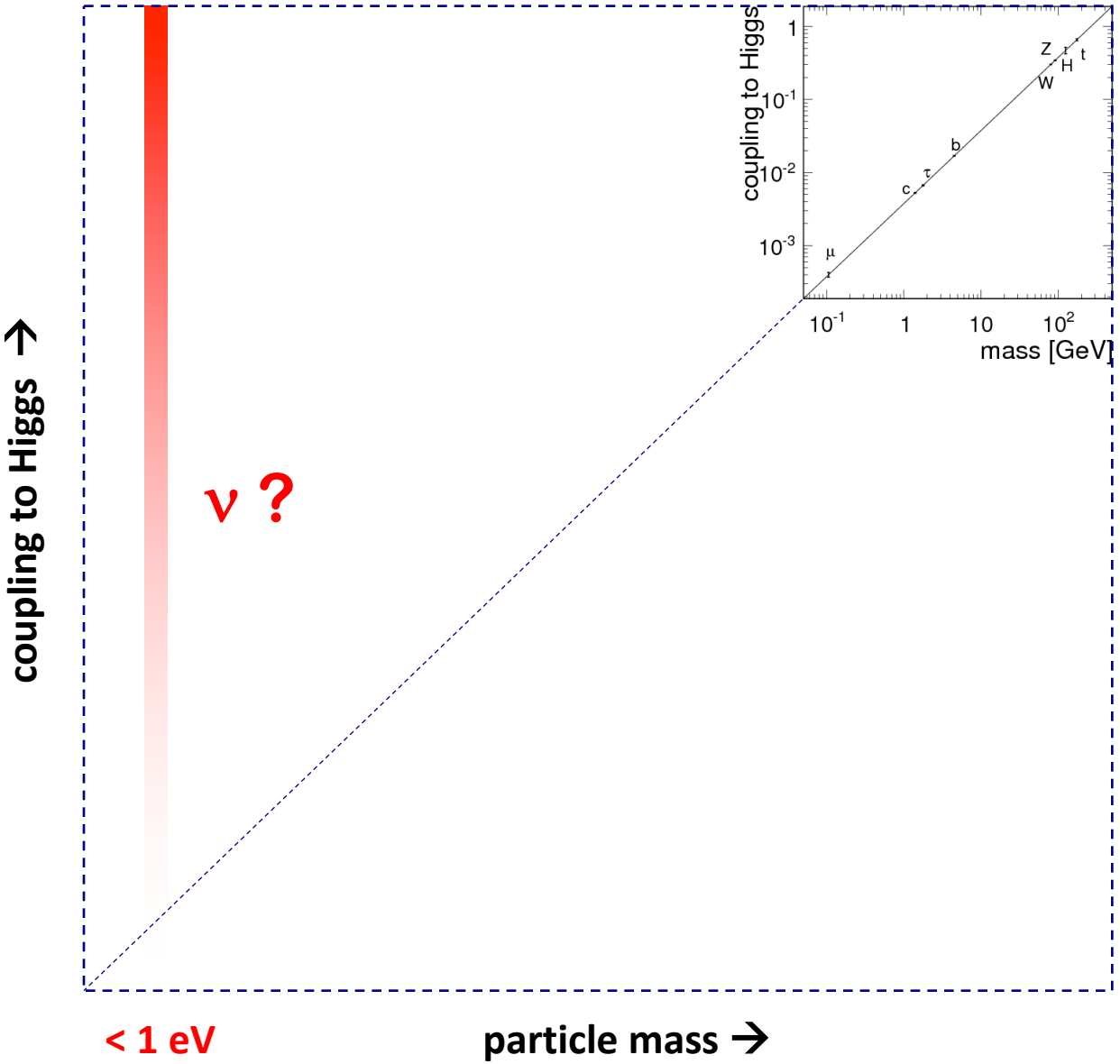
Assessing levels

Assessing the Duomo **façade and its levels** involved evaluation of many projects, spanning several centuries and cultural approaches

→ Searching absolute ν mass scale(s)

Assessing the scale of known **light ν** and possibly **heavier scales,** involves searches spanning a variety of expt. domains and theory approaches

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



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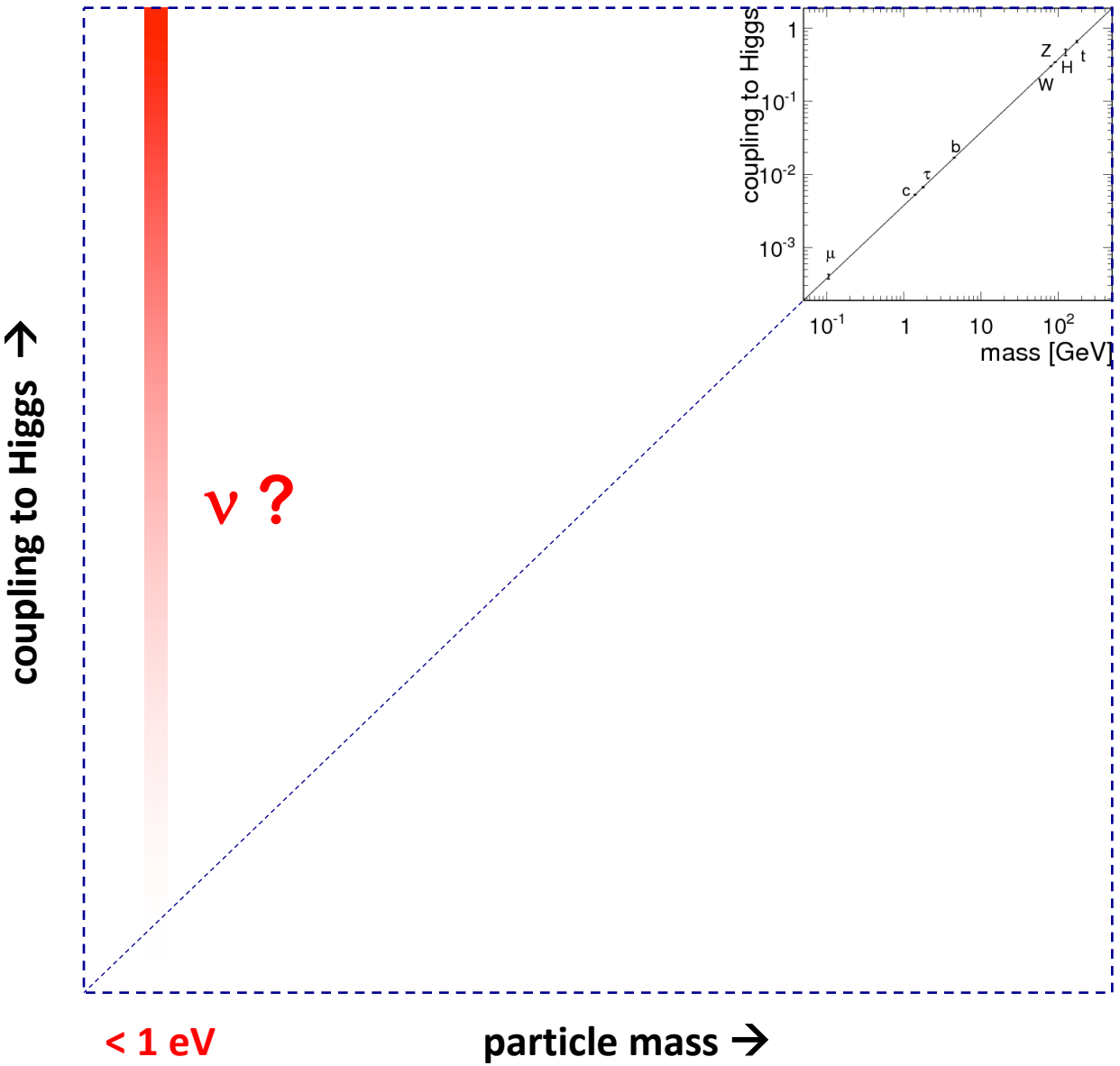
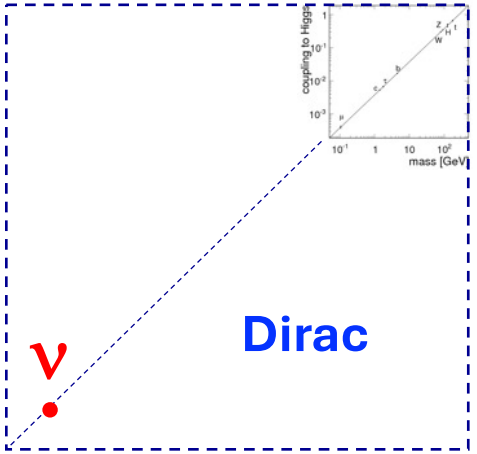


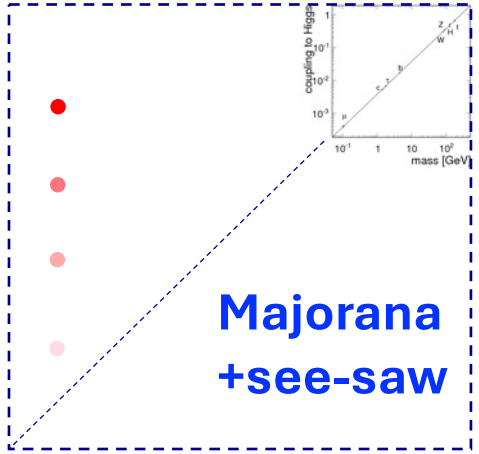
Neutrinos might just couple to the Higgs with tiny Yukawas…



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

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

Λ
GUT
TeV
GeV
keV
eV

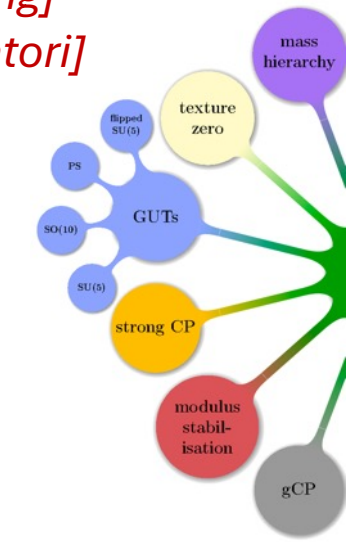


$$m_\nu \sim y M_H f \ (f \sim M_H/\Lambda)$$

Long-term mass scale exploration program…

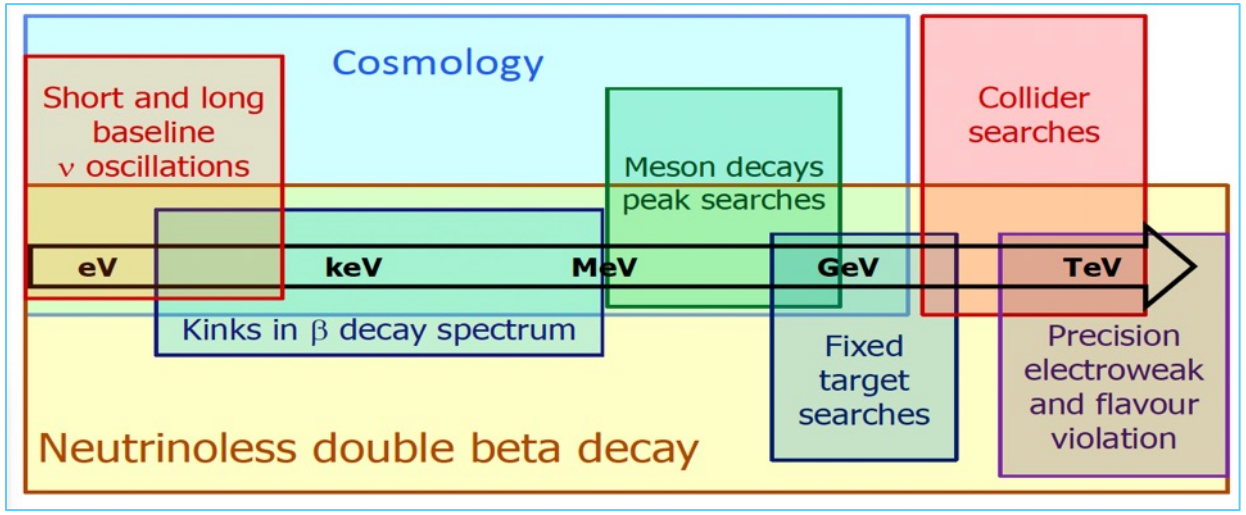
Theory exploration up to "far" scales

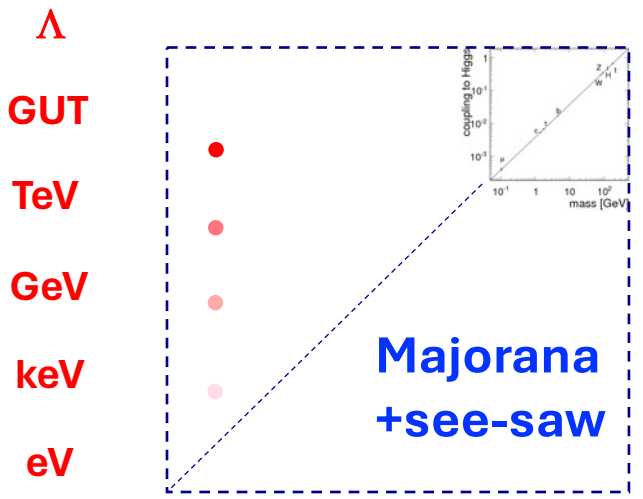
[Ding]
[Katori]



[Fernandez-M.]
[De Roeck]

Expt exploration of "near" scales





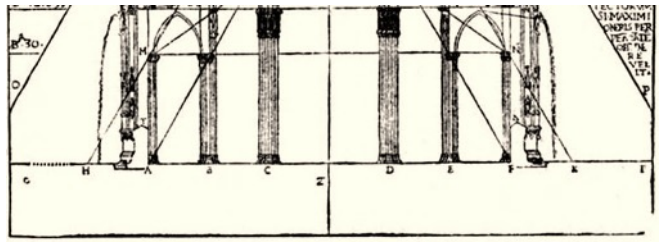
$$m_\nu \sim y M_H f \ \ (f \sim M_H/\Lambda)$$

A long-term challenge to higher levels: the Duomo lantern construction…

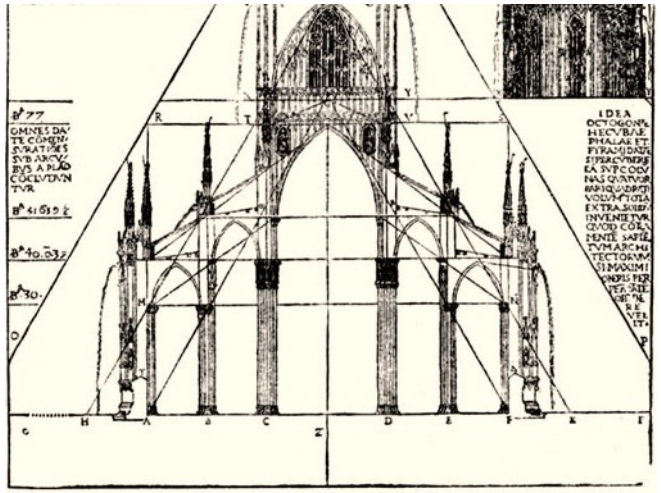
1487: Lantern project competition
(Leonardo da Vinci among other candidates)

Leonardo 1487

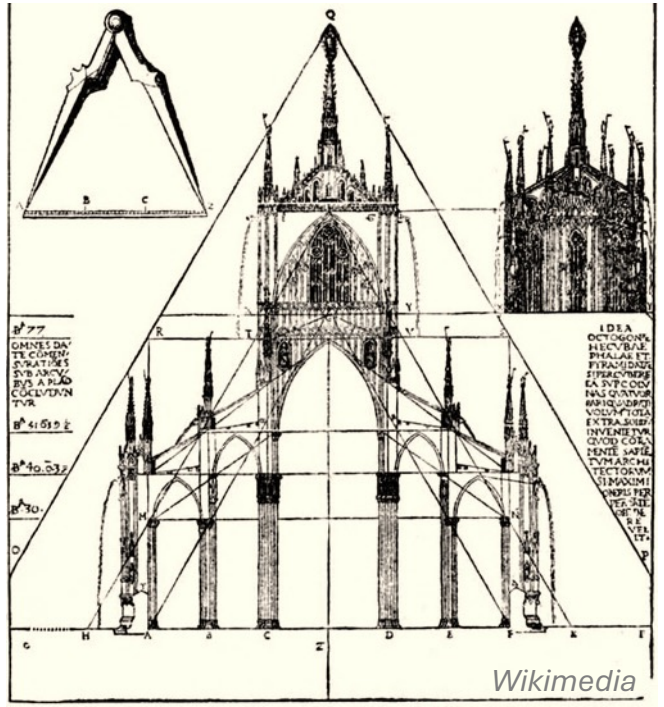
Codex Atlanticus f.850r



1490-1500: Lantern construction
(Winner architects Amedeo & Dolcebuono)

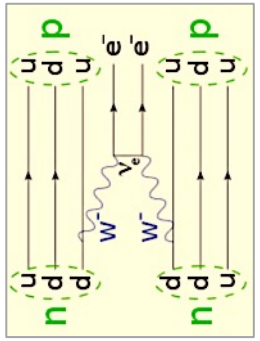


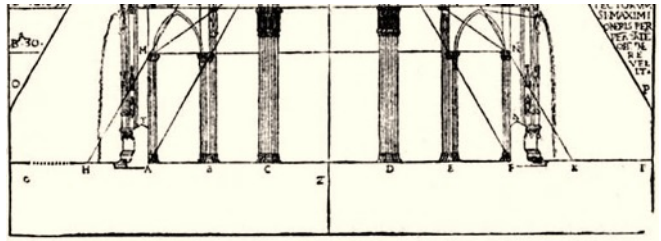
1765-1769: Main Spire above
(after stability study by R. Boscovich)



… the challenge of probing Majorana neutrinos with $0\nu\beta\beta$ decay

A bold theoretical idea…

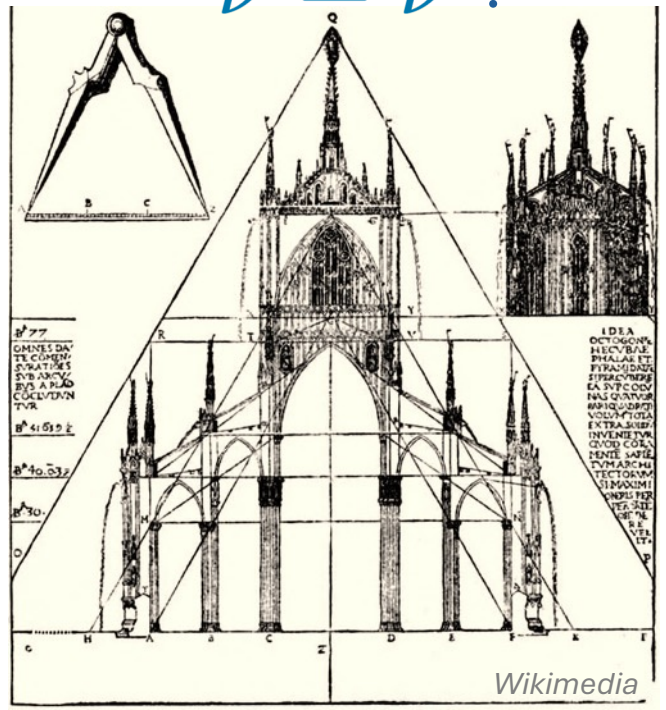




….takes great ν architects

… to lead to new heights

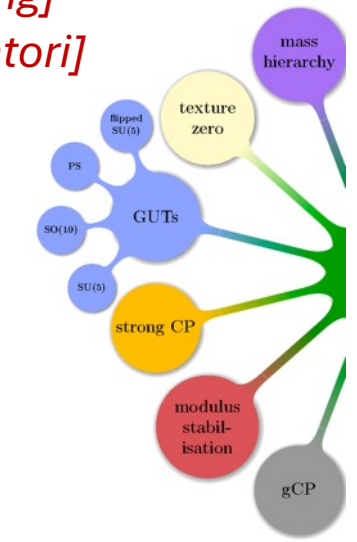
$\nu = \overline{\nu}$?



Long-term mass scale exploration program…

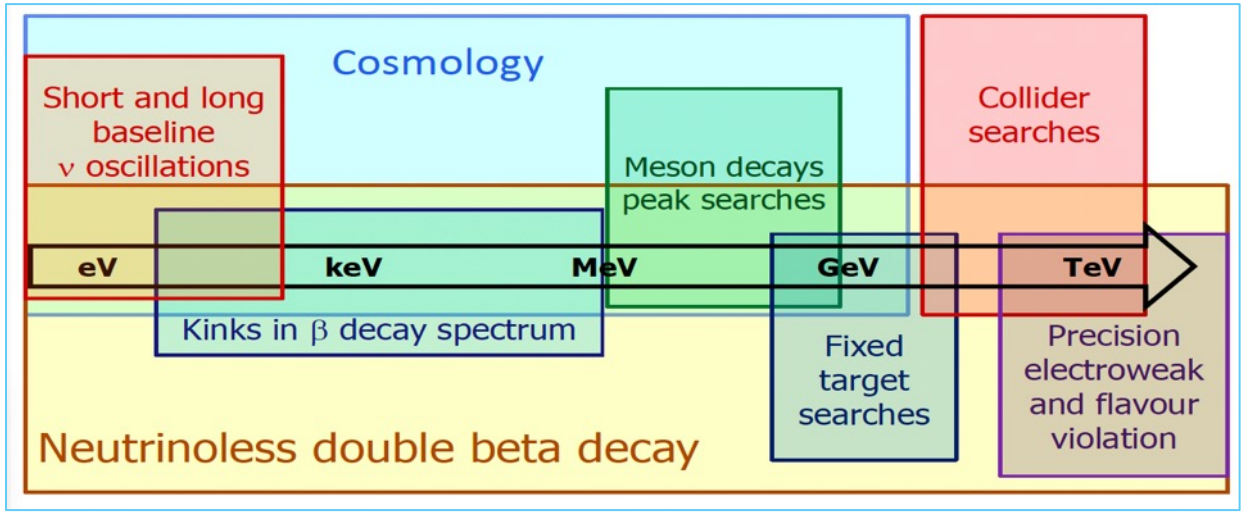
Theory exploration up to "far" scales

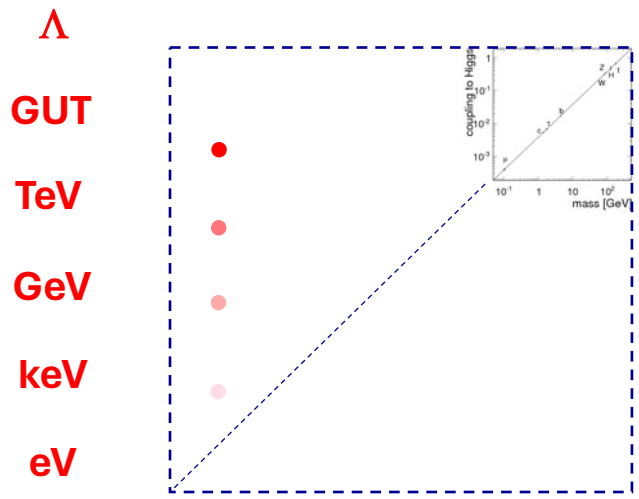
[Ding]
[Katori]



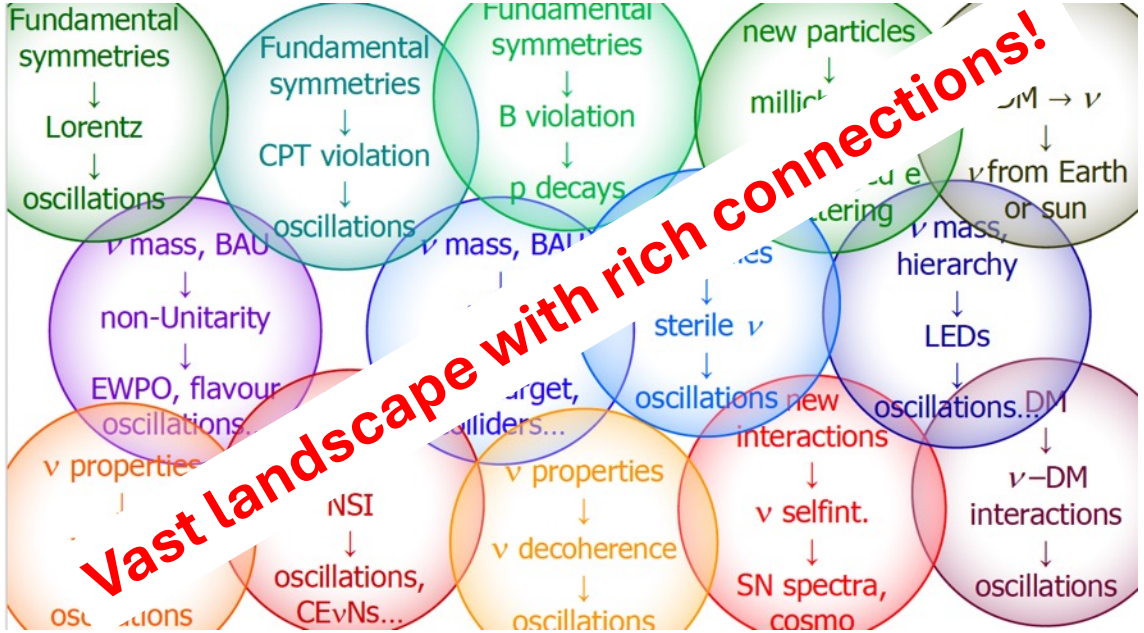
[Fernandez-M.]
[De Roeck]

Expt exploration of "near" scales





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



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[De Roeck]

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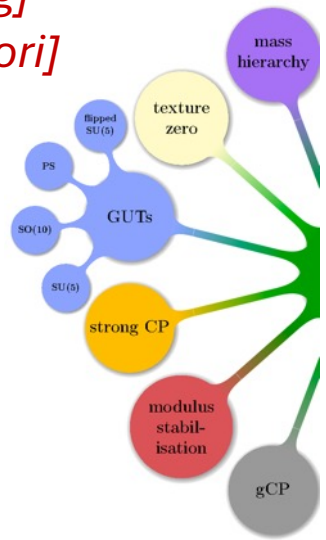

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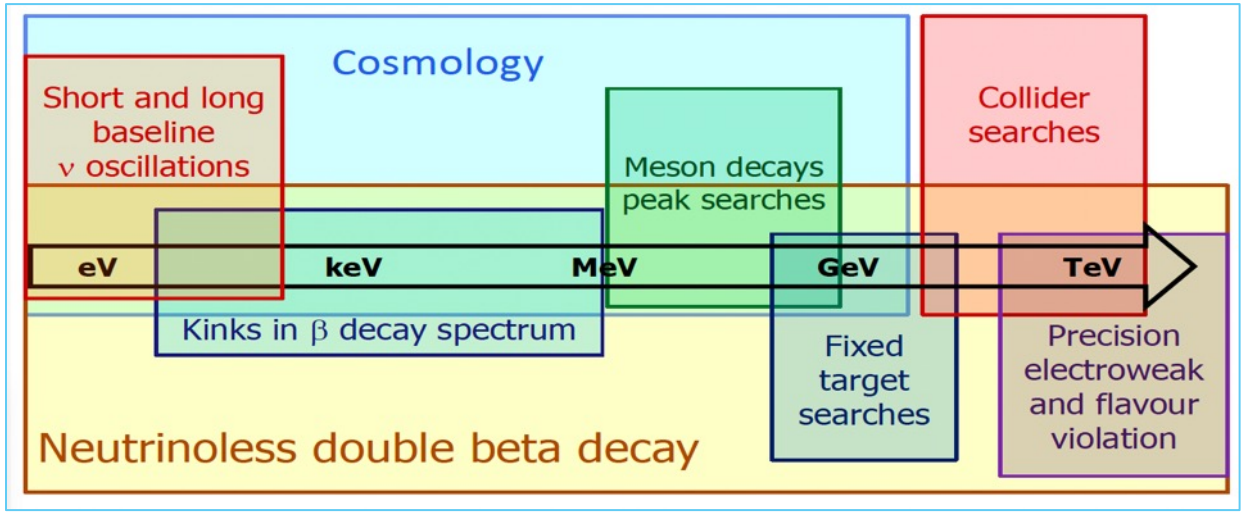

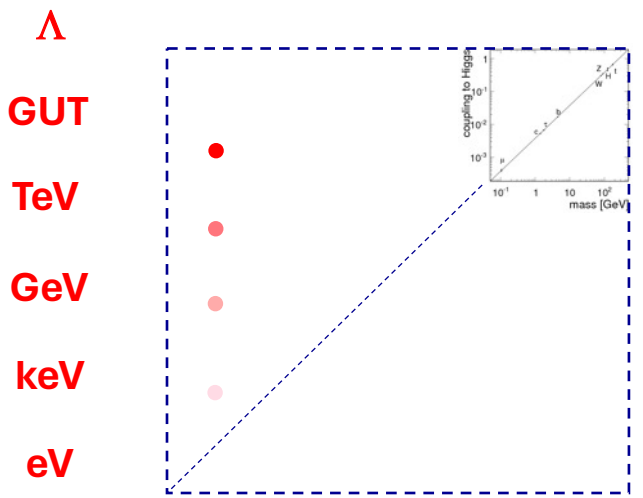

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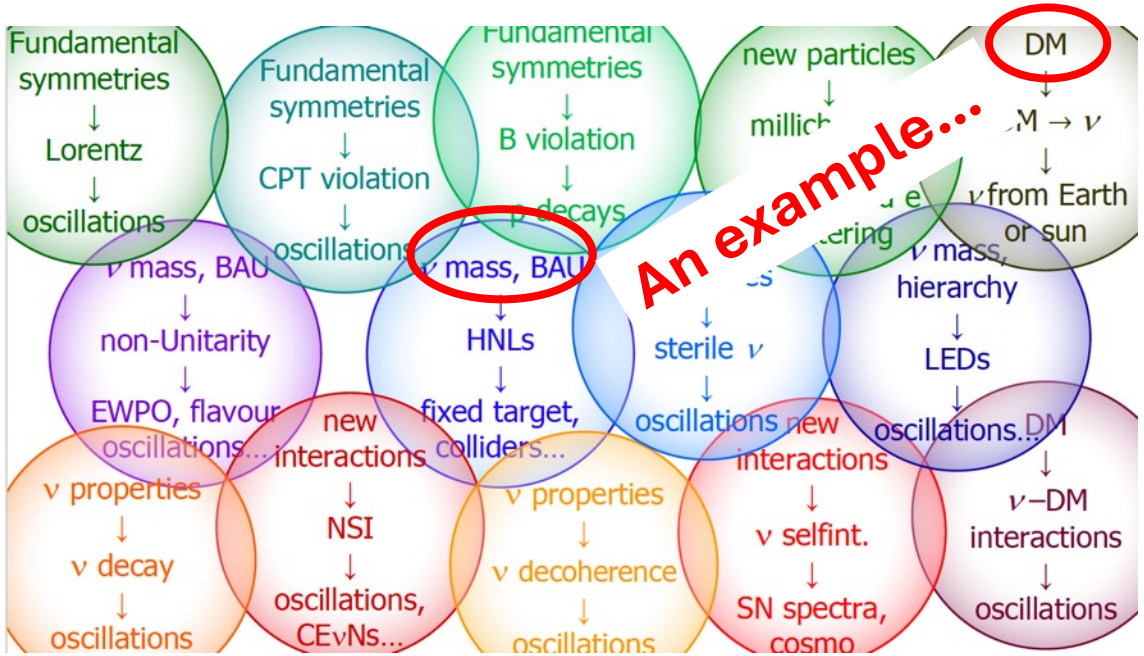

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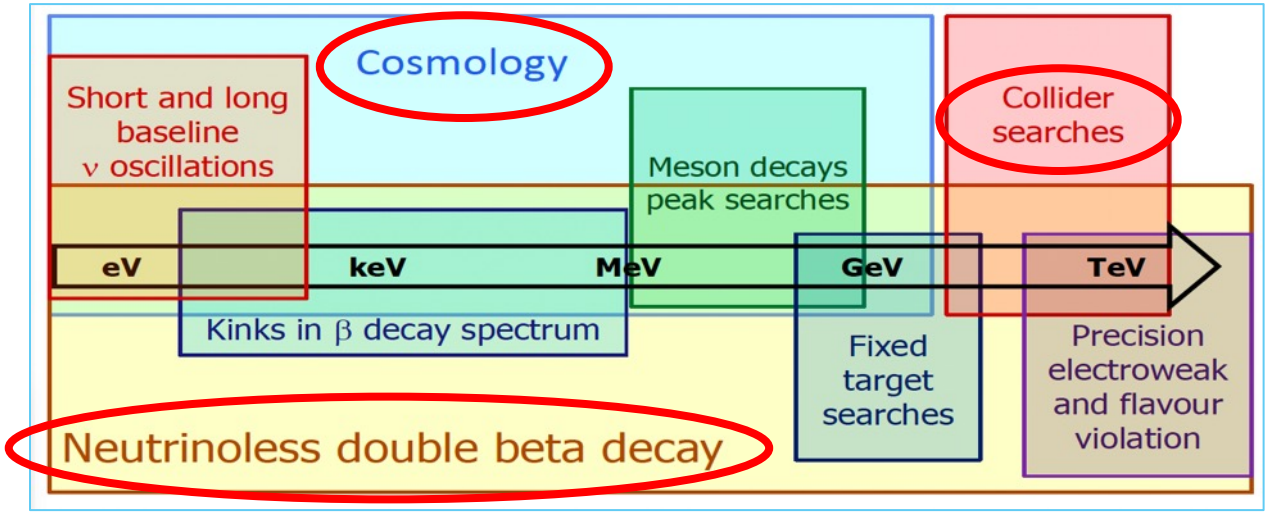
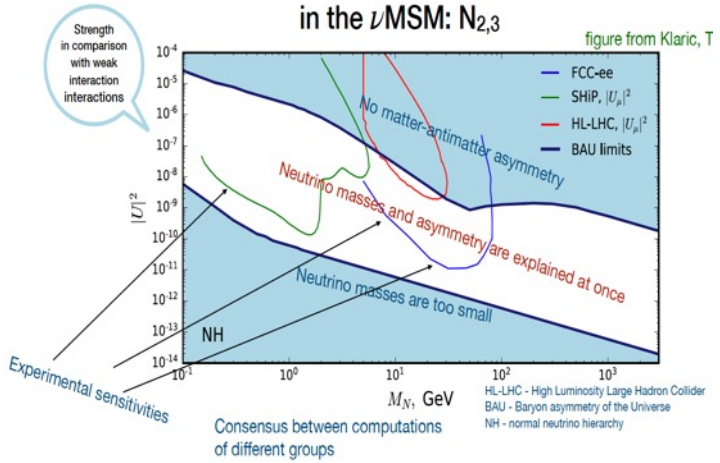
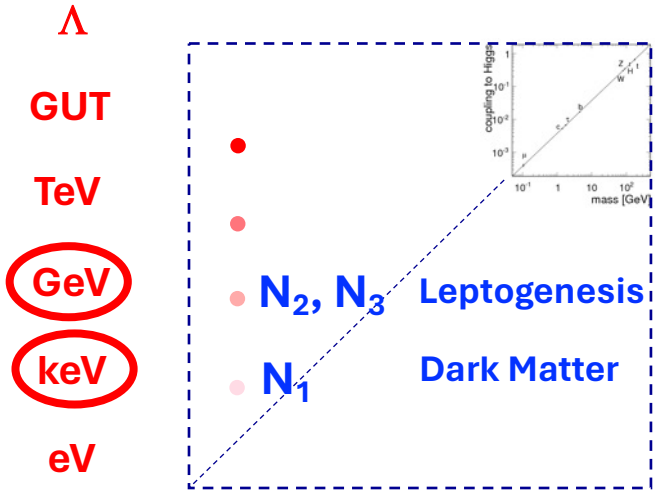




A minimal model linked to GeV-keV scales

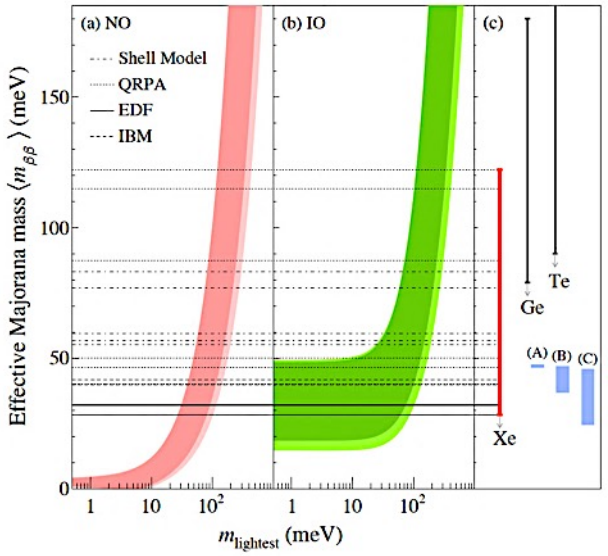
[Shaposhnikov]



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

Down to the "ground" level: masses of the known neutrinos. Nu2024 highlights:

$m_{\beta\beta}$



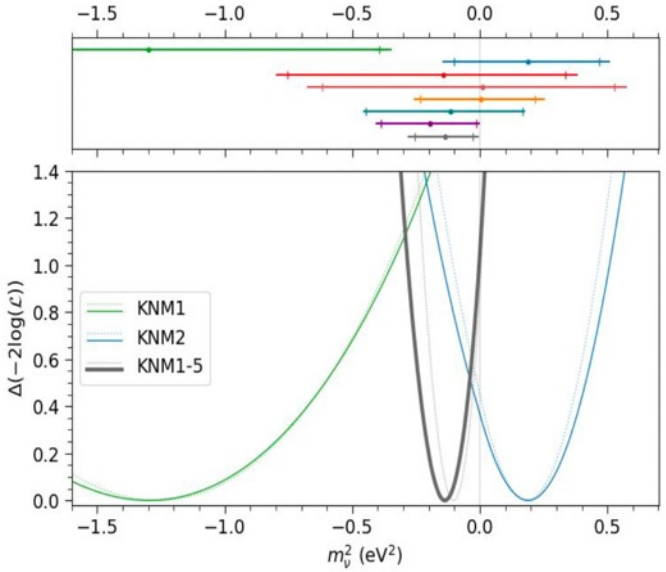
KamLAND-Zen (^{136}Xe)

$\langle m_{\beta\beta} \rangle$ < 28–122 meV

m_{lightest} < 84–353 meV

[Shimizu]

m_{β}

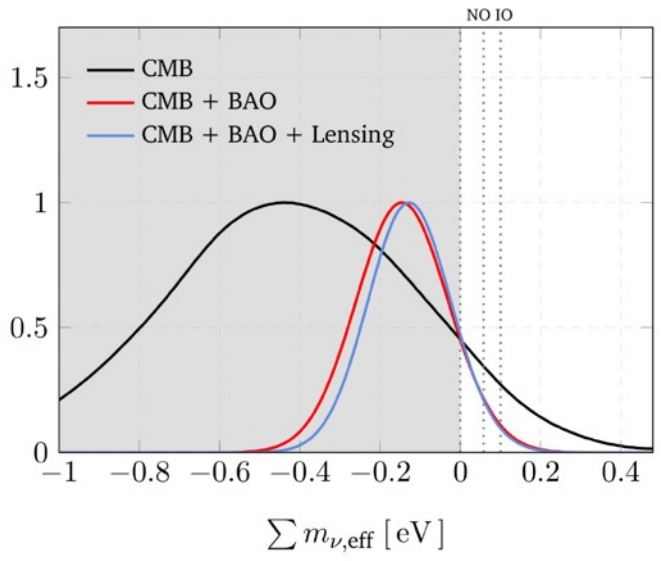


KATRIN's **new** upper limit

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

[Lokhov]

Σ



$$\sum m_\nu < 0.072\,\text{eV}$$

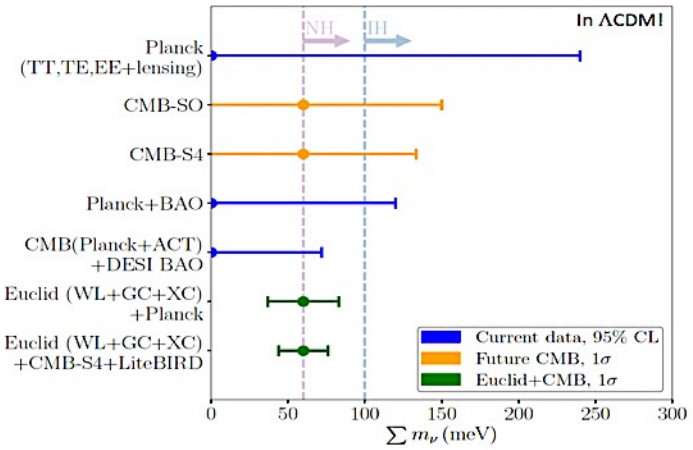
~3σ tension with min(Σ)

[Elbers, DESI]

All best-fits above in the unphysical region. *[For KL-Zen, my guess: S=(S+B)-B < 0]*

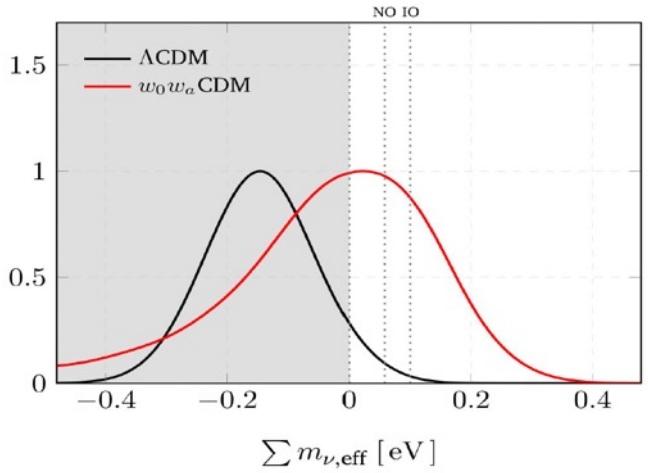
Not worrying (yet) for β and ββ, but what about cosmology?

Euclid, standard physics



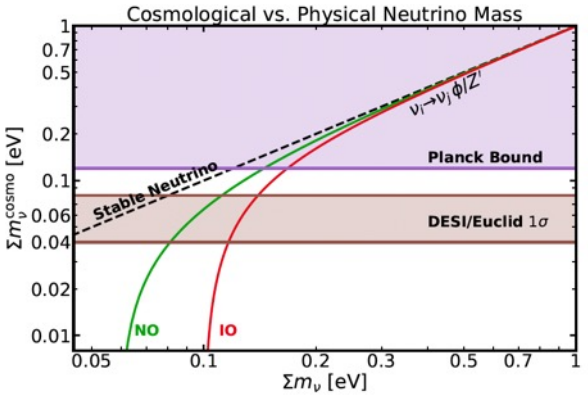
[Archidiacono]

New physics in cosmology



[Elbers]

New ν physics in cosmology



[Gariazzo]

Personal viewpoint:

- If DESI indication $\Sigma<0$ disconfirmed by Euclid: **another "internal" cosmo data tension**
  → Unstable bounds on Σ until tension is understood and resolved
- If DESI indication confirmed by Euclid: **really unexpected ν surprise in cosmology!**
  → But no robust conclusion on Σ until new underlying physics (cosmo, ν) is identified
- In both cases: increasing importance **of lab searches for NO/IO, m_β and $m_{\beta\beta}$**
  → **m_β** and NO/IO: input to cosmology; also important to reduce NME theory error in $m_{\beta\beta}$

Rebuilding structures

At any time, a fraction of Duomo is **under restoration** of Candoglia marble stones, or **major reconstruction** of structures, using both traditional and new techniques

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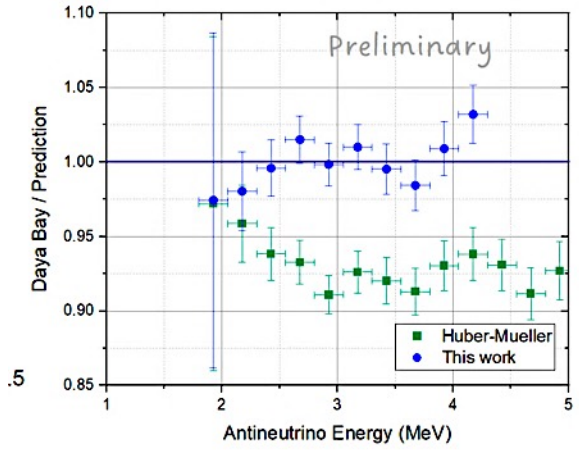
→ Electroweak nuclear physics

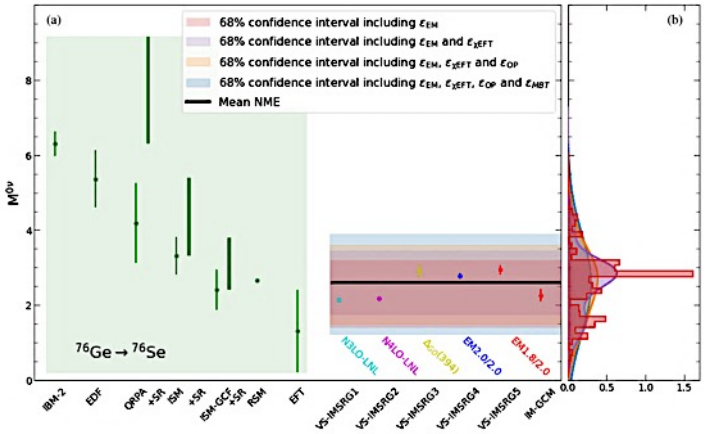
Major areas of **theory/pheno renovation** concern developments in our understanding of **ν interactions in nuclei** (and in dense media) with new approaches

Improve reactor spectra



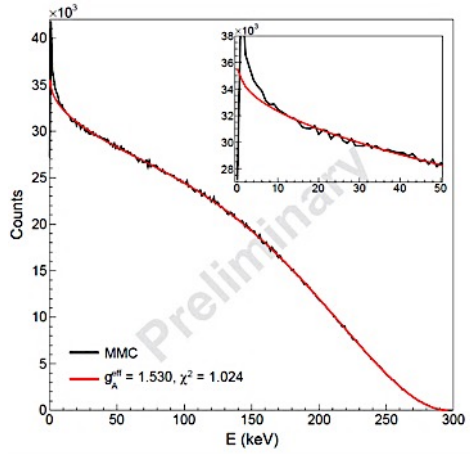
[Sonzogni]

Get NME from ab-initio methods



[Menendez]

Refine β spectra



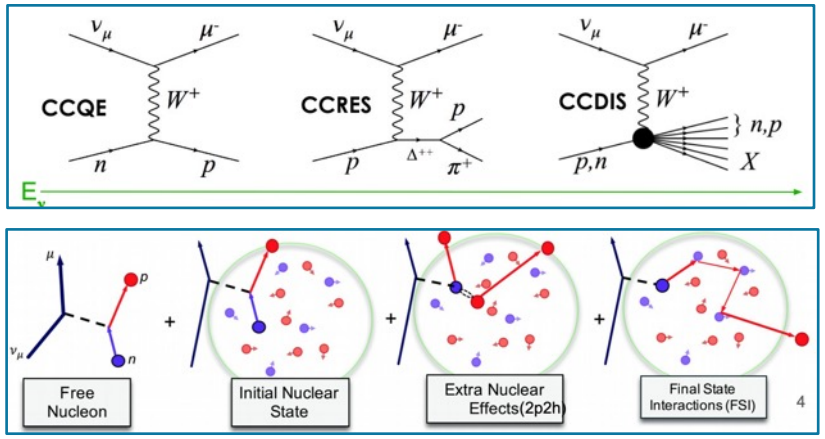
[Mougeot]

Advance interac. theory

- Ongoing progress:
  - Lattice and perturbative QCD
  - Effective Field Theory
  - Phenomenological models
  - Monte Carlo simulations

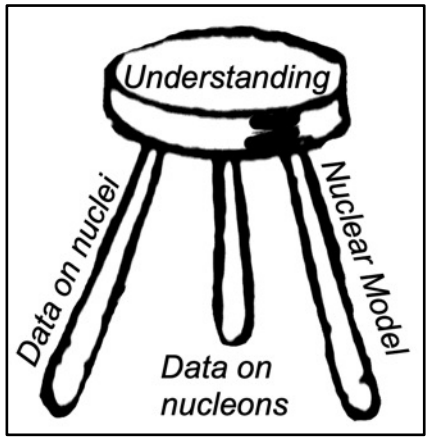
[Alvarez-Ruso]

Account for microscopic complexity



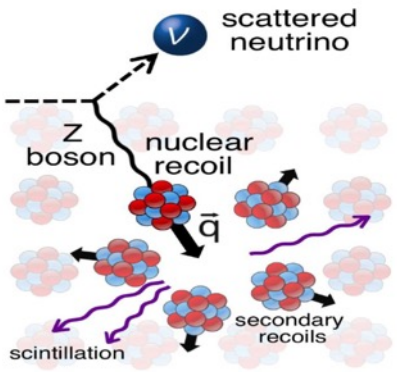
[Buizza-Avanzini]

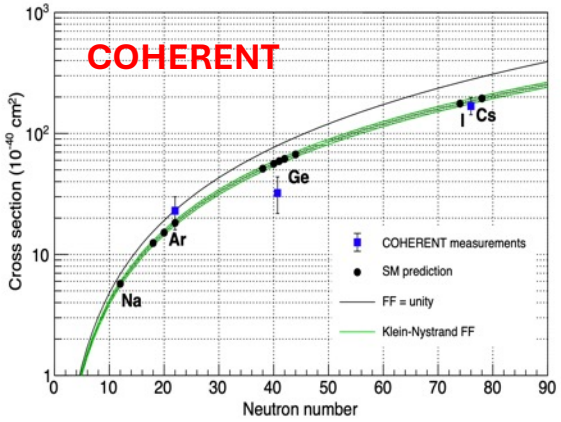
Benchmark nucl. models

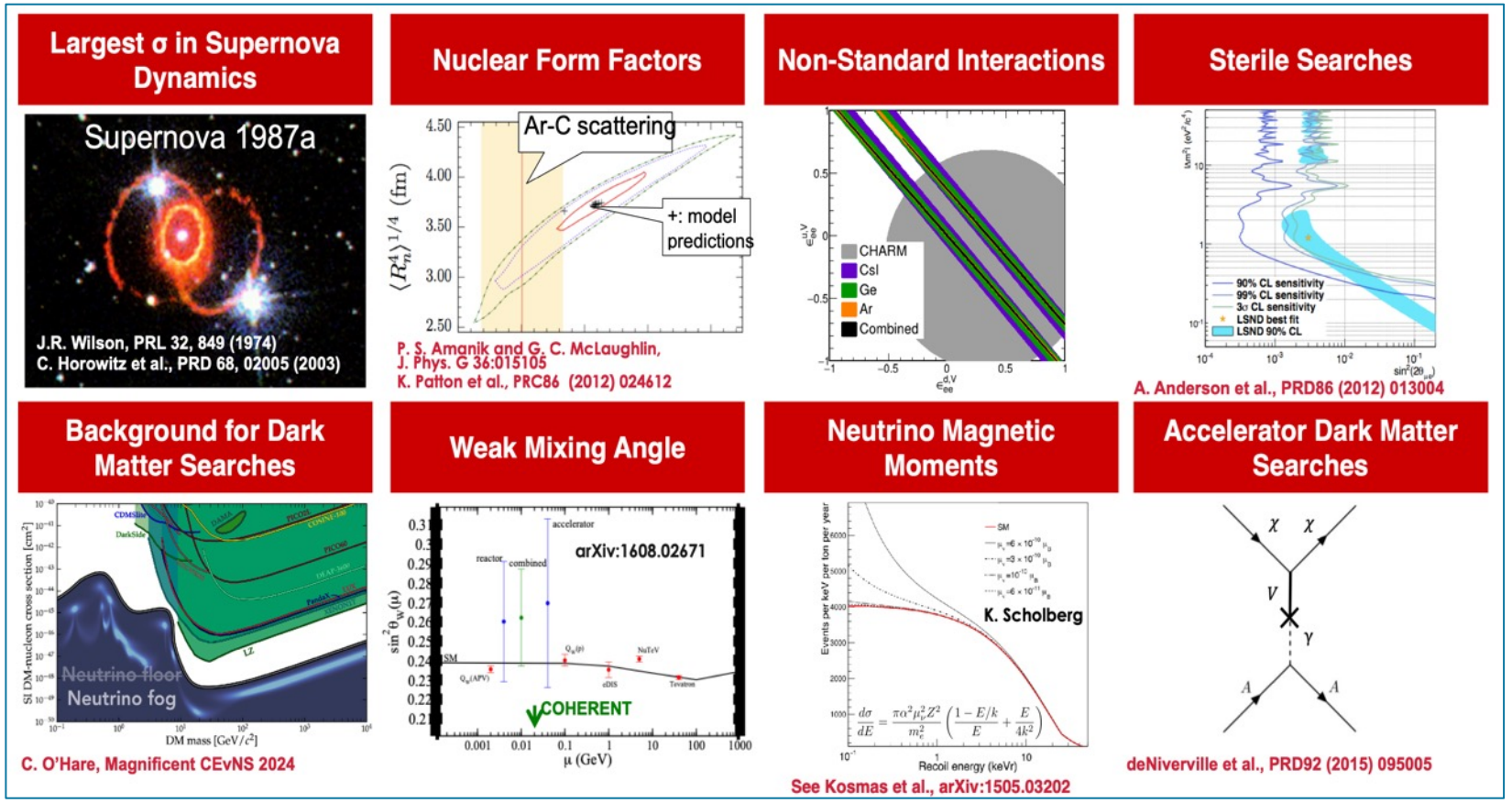


[McFarland]

CEvNS: renovating entire research lines along new (non)standard directions!





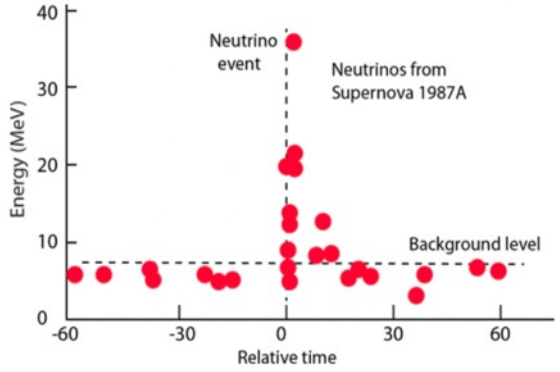


How low-E data … can lead to a vast set of theo/pheno connections!

[Nasteva, Green]

From nuclei to dense media: neutrinos in the SN environment

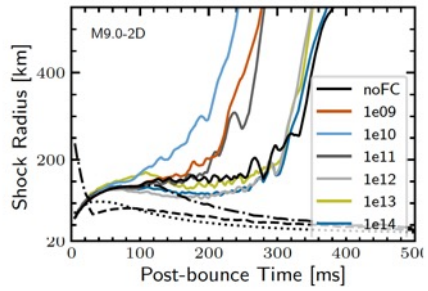
First and *only* SN nu detection: SN1987A



[Lunardini]

Collective oscillations: r < 1000 Km

- Impact on r-process nucleosynthesis
- *Fast mode* (r < 100 Km) : impact on shock-revival
  - Increased or de-creased neutrino heating behind shock (depending on progenitor star)

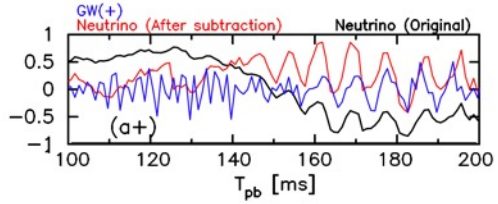


Complexities...

- Resonant interplays of collective and matter-driven effects
- Late time/large radii phenomena
  - Adiabaticity breaking at shockwave front
  - Turbulent matter density profile behind shock
  - Decoherence
- Progenitor-dependent effects
  - non-adiabatic H-resonance in ONeMg-core Sne

GW + neutrinos: enhanced potential

- Improve alert: timing, localization
- test near-core physics: SASI, neutron star cooling, ...



Need to improve theoretical description, to get the most from next SN event(s)

[hopefully multimessenger...]

Illuminating darkness

XIV-XX century: Construction of stained-glass windows that provide diffuse light in Duomo

1786: A hole in the roof to provide a sunlight beam crossing the meridian line (at noon)

Illuminating darkness

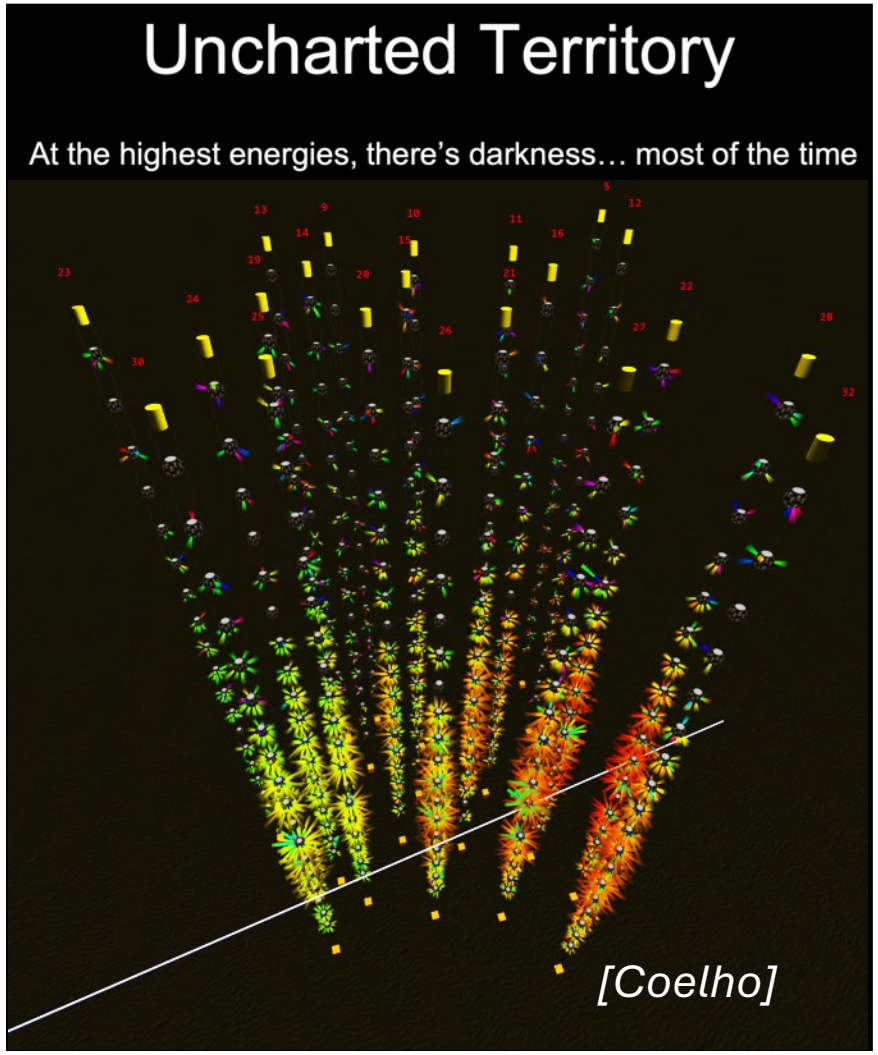
XIV-XX century: Construction of stained-glass windows that provide diffuse light in Duomo

1786: A hole in the roof to provide a sunlight beam crossing the meridian line (at noon)

→ **Diffuse and localized ν sources**

→ **(Multi-messenger) ν astronomy**

A new window to our Universe. Can probe peculiar environments, distances, phenomena!



Illuminating darkness

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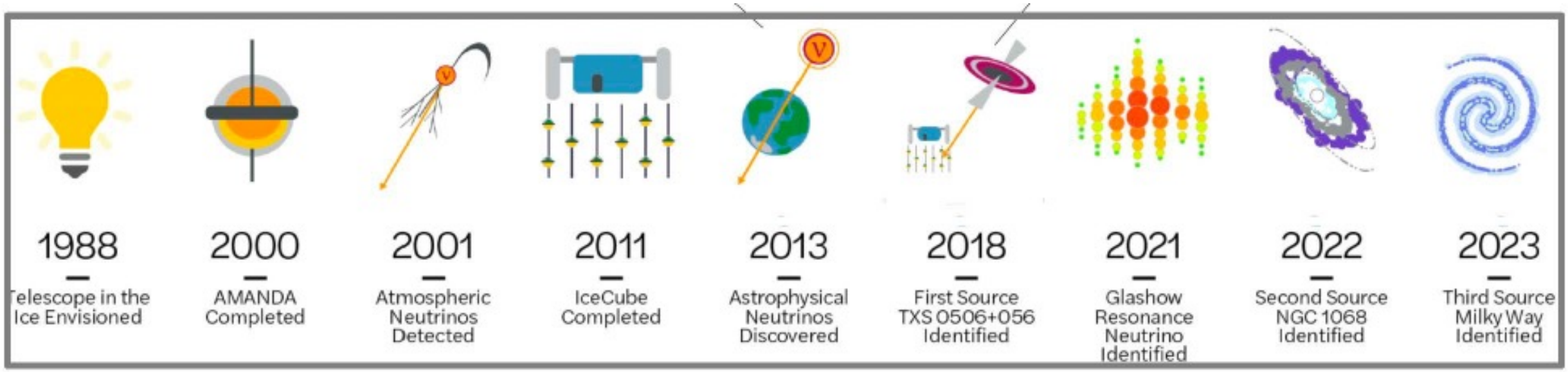
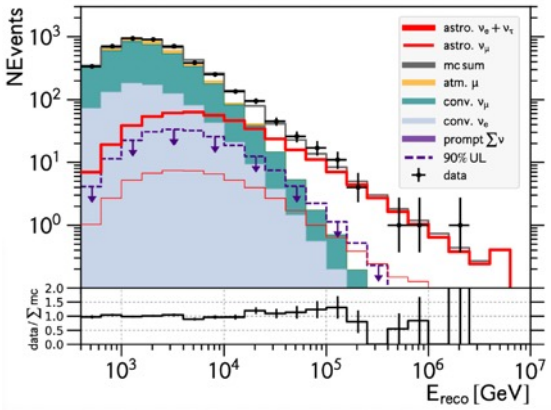
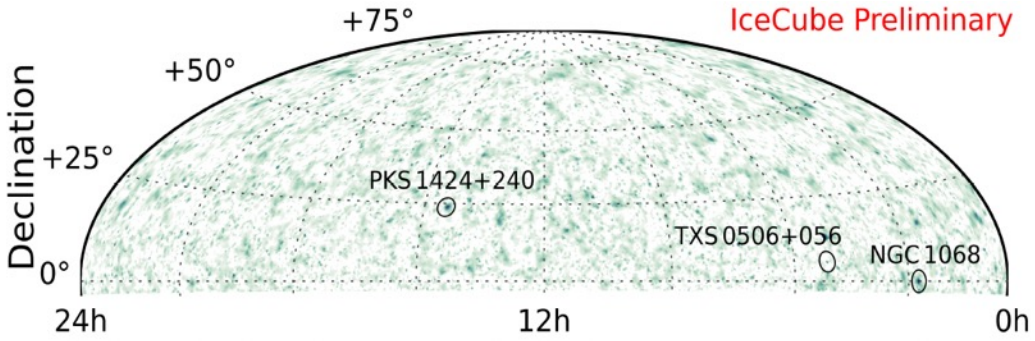
Congrats to KM3NeT!

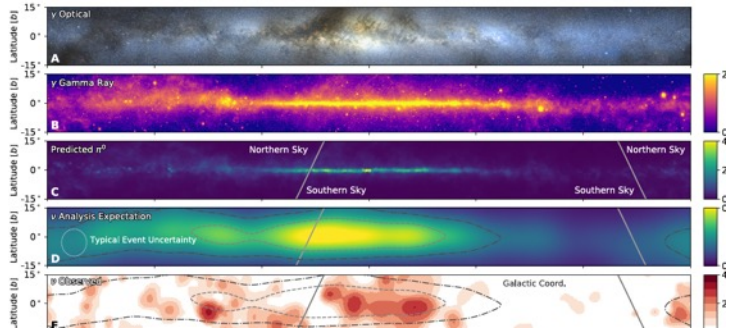
Illuminating the high-energy ν sky: building a "catalog" of sources



Diffuse **Point** **Point** **Diffuse**







[Neilson, Aguilar]

When you start a catalog, you never know where you will end up...

Barkas and Rosenfeld UCRL-8030 Table I

Masses and mean lives of elementary particles; November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

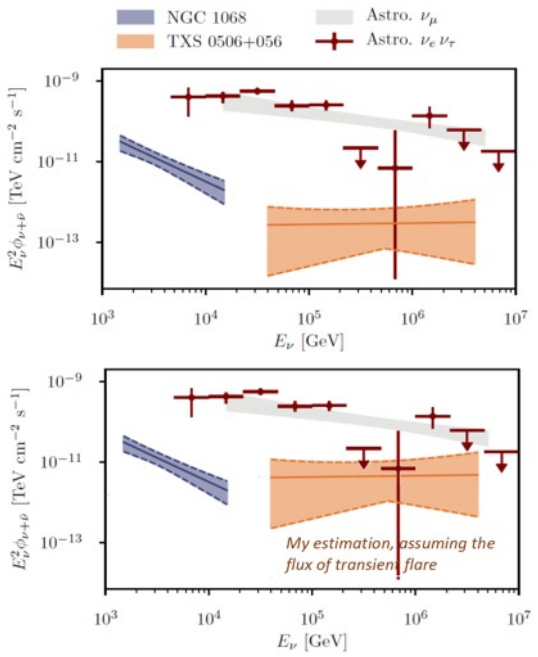
	Particle	Spin	Mass (Errors represent standard deviation) (Mev)	Mass difference (Mev)	Mean life (sec)	Decay rate (number per second)
Photon	γ	1	0		stable	0
Leptons	ν	$\frac{1}{2}$	0		stable	0
	e^-	$\frac{1}{2}$	0.510976 (a)		stable	0
	μ^-	$\frac{1}{2}$	105.70 ±0.06 (a)		(2.22 ±0.02) $\times 10^{-6}$	0.45 $\times 10^6$
Mesons	π^+	0	139.63 ±0.06 (a)	4.6 (a)	(2.56 ±0.05) $\times 10^{-8}$ (a)	0.39 $\times 10^8$
	π^0	0	135.04 ±0.16 (a)		< 4 $\times 10^{-16}$ (d)	> 2.5 $\times 10^{15}$
	K^+	0	494.0 ±0.2 (g)	0.4 ± 1.8	(1.224±0.013)$\times 10^{-8}$ (h)	0.815 $\times 10^8$
	K^0	0	494.4 ±1.8 (i)		K_1: (0.95 ±0.08) $\times 10^{-10}$ (e)	1.05 $\times 10^{10}$
					K_2: (4 < τ < 13) $\times 10^{-8}$ (c)	(0.07 < τ < 0.25) $\times 10^8$
Baryons	p	$\frac{1}{2}$	938.213 ±0.01 (a)		stable	0.0
	n	$\frac{1}{2}$	939.506 ±0.01 (a)		(1.04 ±0.13) $\times 10^{+3}$ (a)	0.96 $\times 10^{-3}$
	Λ	$\frac{1}{2}$	1115.2 ±0.14 (j)		(2.77 ±0.15) $\times 10^{-10}$ (k)	0.36 $\times 10^{10}$
	Σ^+	$\frac{1}{2}$	1189.4 ±0.25 (l)	7.1 ± 0.4	(0.83 $^{+.06}_{-.05}$) $\times 10^{-10}$ (m)	1.21 $\times 10^{10}$
	Σ^-	$\frac{1}{2}$	1196.5 ±0.5 (n)		(1.67 ±0.17) $\times 10^{-10}$ (o)	0.60 $\times 10^{10}$
	Σ^0	$\frac{1}{2}$	1190.5 $^{+0.9}_{-1.4}$ (p)	6.0 $^{+1.4}_{-0.9}$	(< 0.1) $\times 10^{-10}$ (b) theoretically ~10^{-19}	> 10 $\times 10^{10}$ theoretically ~10^{19}
	Ξ^-	?	1320.4 ± 2.2 (q)		(4.6 < τ < 200) $\times 10^{-10}$ (f)	(>0.005, <0.2) $\times 10^{10}$
	Ξ^0	?	?		?	

Particle Data Book 1957...

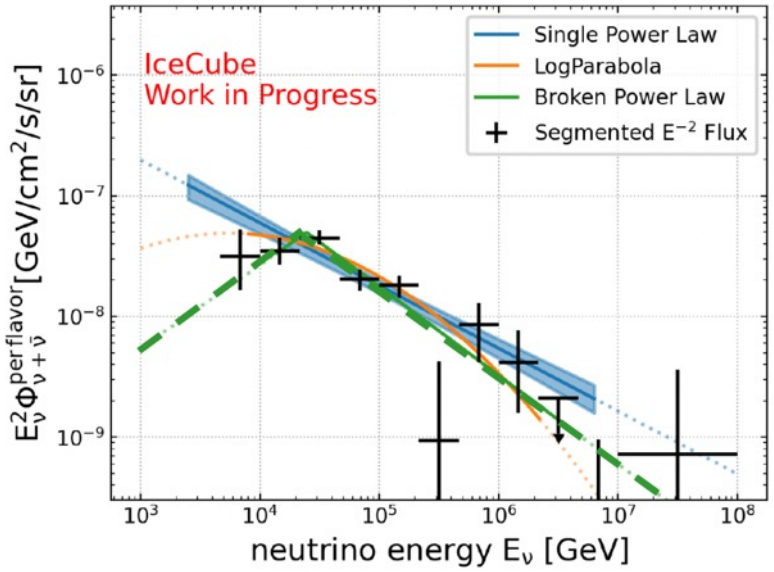
... and later editions

Many open questions:

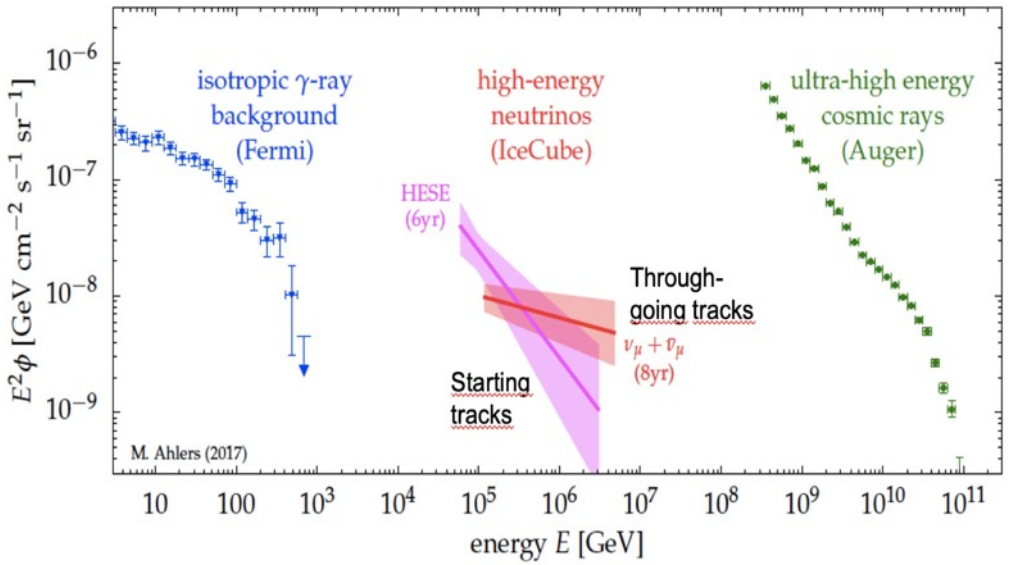
Transients?



Energy spectrum?



Links with CR and gammas?



What are the ν sources, and where? Can we detect other messengers?

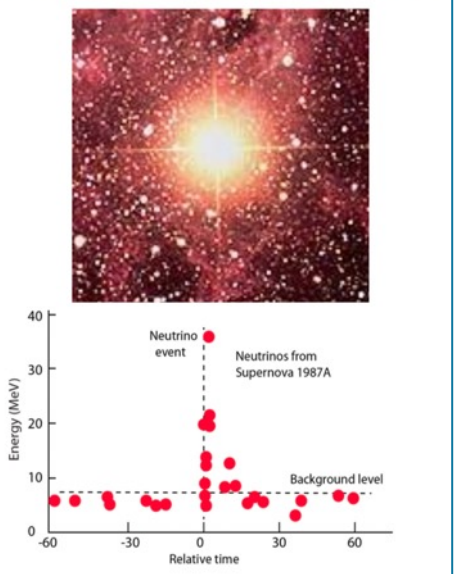
We are just at the beginning…

[Spurio, Aguilar, Franckowiak, Neilson]

Illuminating the low-energy ν sky with SN….

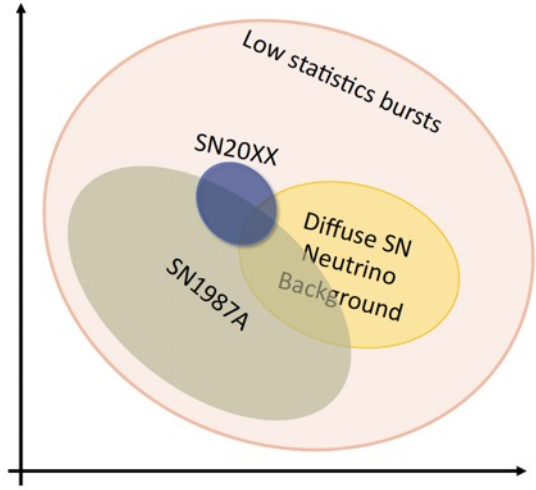
Localized…

First and *only* SN nu detection: SN1987A



From one to many: toward a population study

- The future: global analysis of multiple data sets
  - Test stellar *population*
  - Disentangle stellar physics from neutrino/particle physics

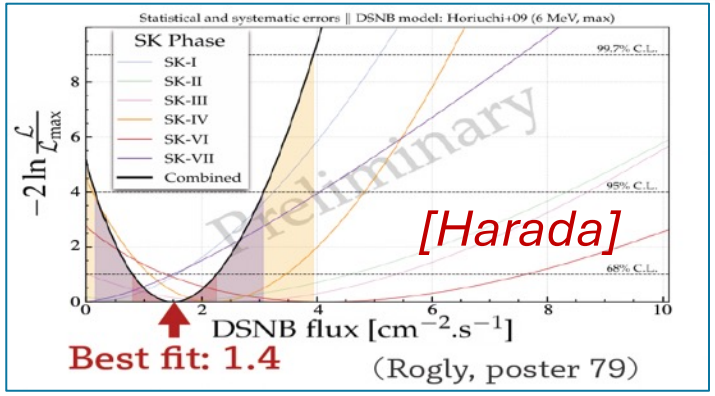


Diffuse… NEW hint!

Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is $1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1} for E_ν > 17.3 MeV

➡ exhibit ~2.3 σ excess!!

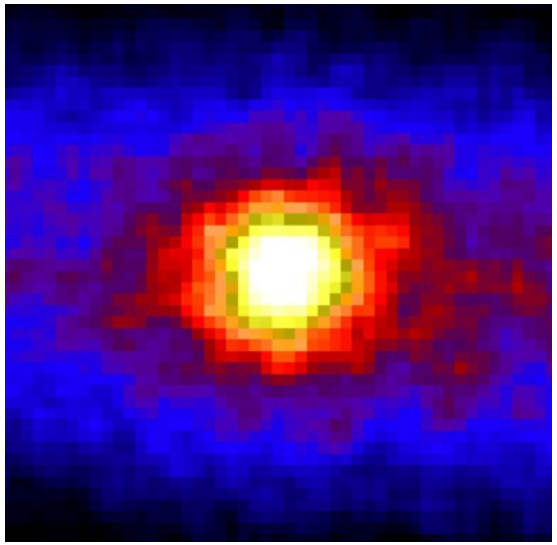


In the long term…combined!

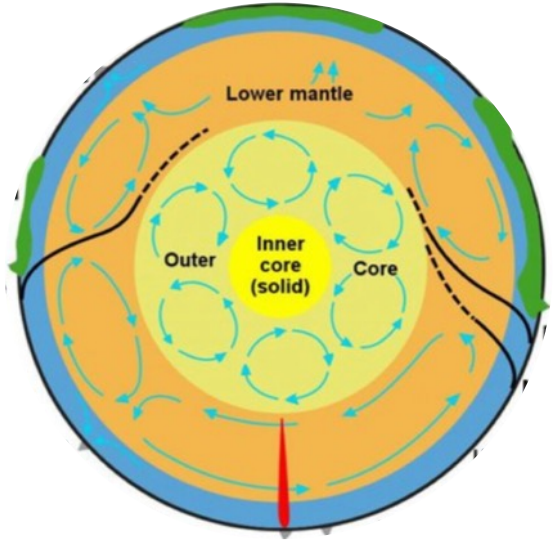
[Lunardini, Franckowiak]

… and with time-honored, stationary sources

The Sun as a neutrino star



The Earth as an antineutrino star



We are still learning from them!

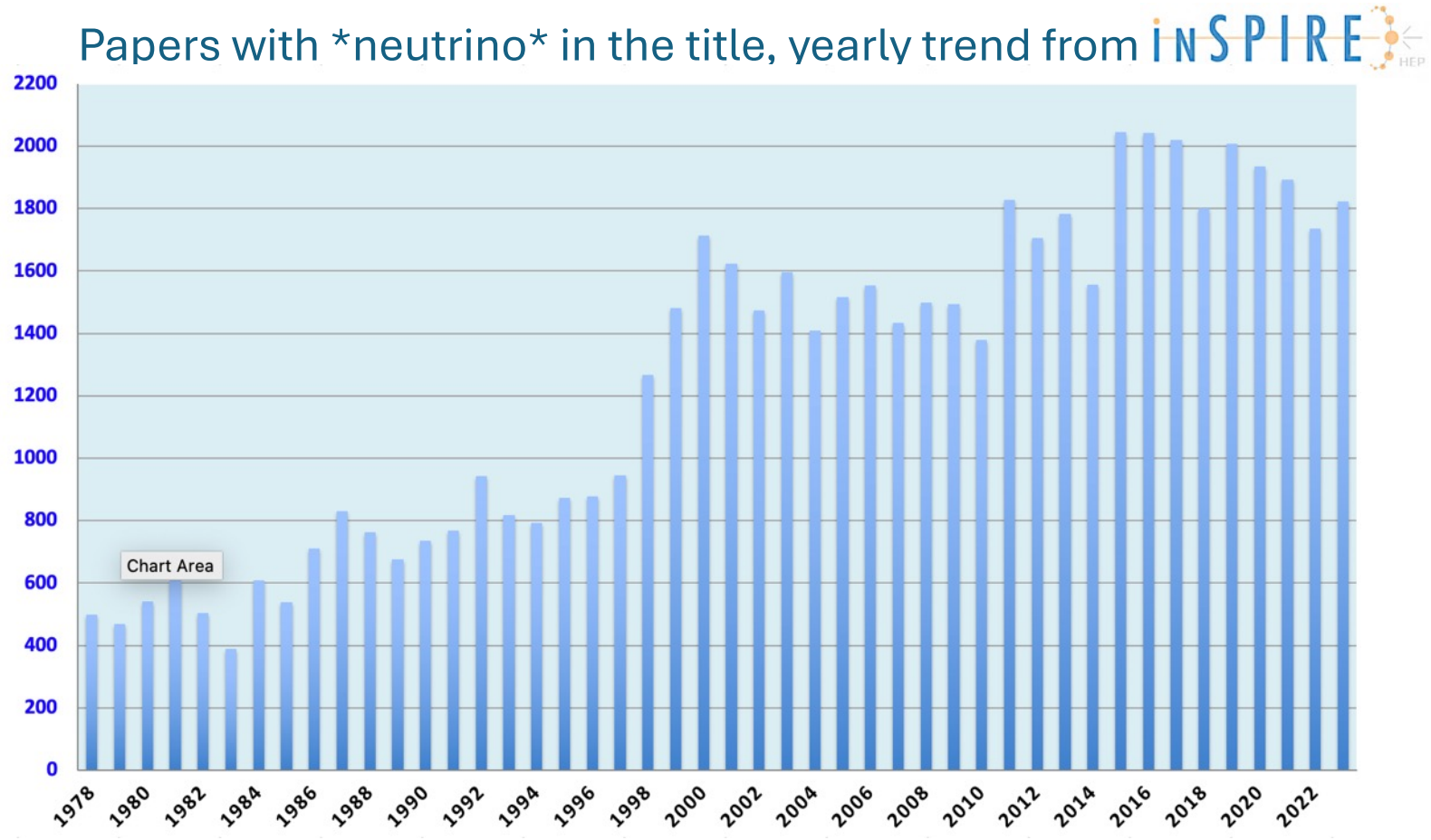
[Bellini, Maneira, Ludhova]

Epilogue:

Engaging with society

The Duomo continues to be an appreciated masterpiece, although not necessarily for the same reasons (or in the same way) as for people living centuries ago with a different mindset and culture. **Perceptions may change!**

Interest in ν physics (expt+theo) will remain high in the scientific community...



... and we should strive to transfer it into society at all levels, especially in a time of great changes

Organization of successful outreach events is increasingly important!

1. **Public Event:** “Quei piccoli enigmatici neutrini”
2. **Lecture for students:** “The genesis of the neutrino concept”
3. **Activity for kids:** “Che fisiche!”

1. Speakers: Silvia Pascoli, Elisa Resconi, Guido Tonelli. Moderator: Giuliana Galati
2. Lecturers: Francesco Vissani
3. Authors: Ilaria Canobbio and Cecilia Orsera

Also in the spirit of: “Science with no borders” *[S. Ragazzi, memories of E. Fiorini]*

Let me thank Chiara, Gioacchino and the LOC for an exciting conference week…

…and all of you for your attention!

PRIN PANTHEON

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INFN Istituto Nazionale di Fisica Nucleare