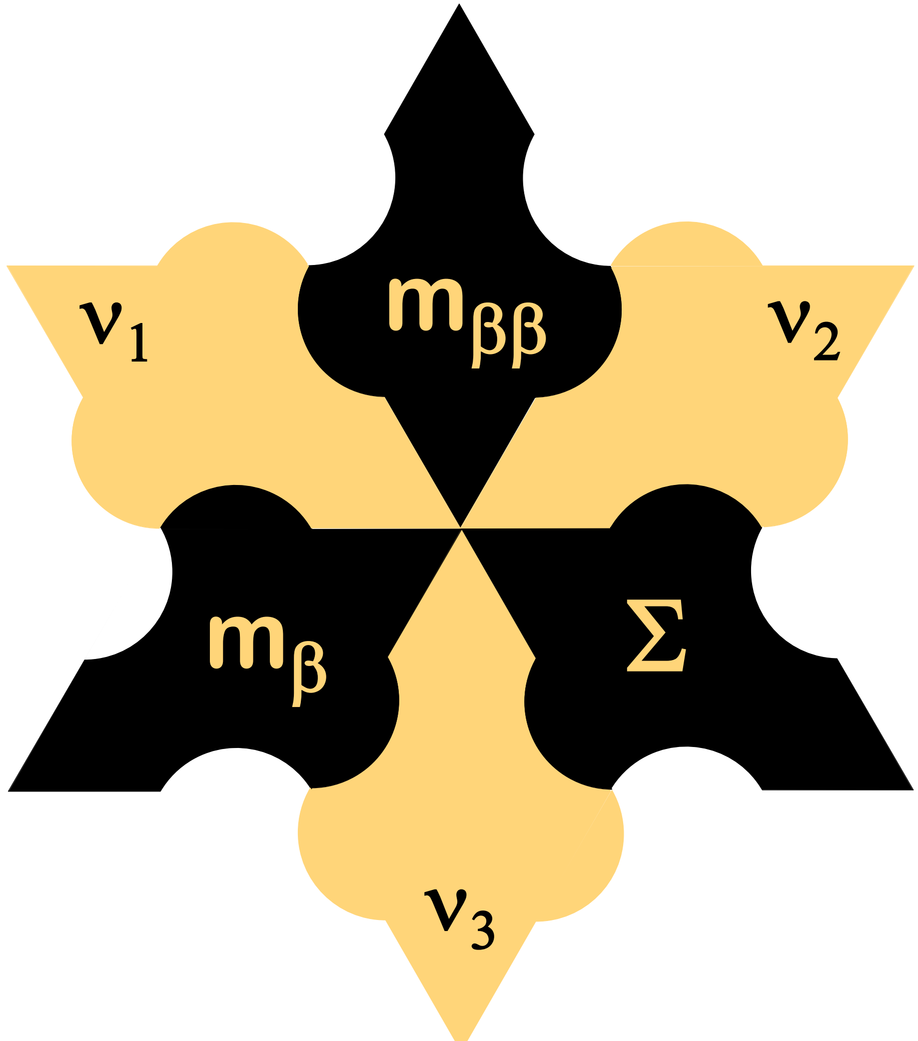
Towards a global analysis of absolute ν masses



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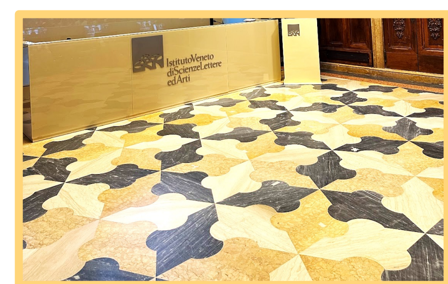


Eligio Lisi (INFN, Bari, Italy)

XX Int. Workshop on Neutrino Telescopes – Palazzo Franchetti, Venezia, 27 Oct 2023

In perspective, the global analysis of absolute 3ν masses from:

Oscillations

+

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

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

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

involves several issues that are worth discussing,
in the light of (far) future m_β, $m_{\beta\beta}$, Σ signals
…and of possible new physics

Outline:

Graphs of 3ν osc. bounds

Towards a Σ signal

Towards a m_β signal

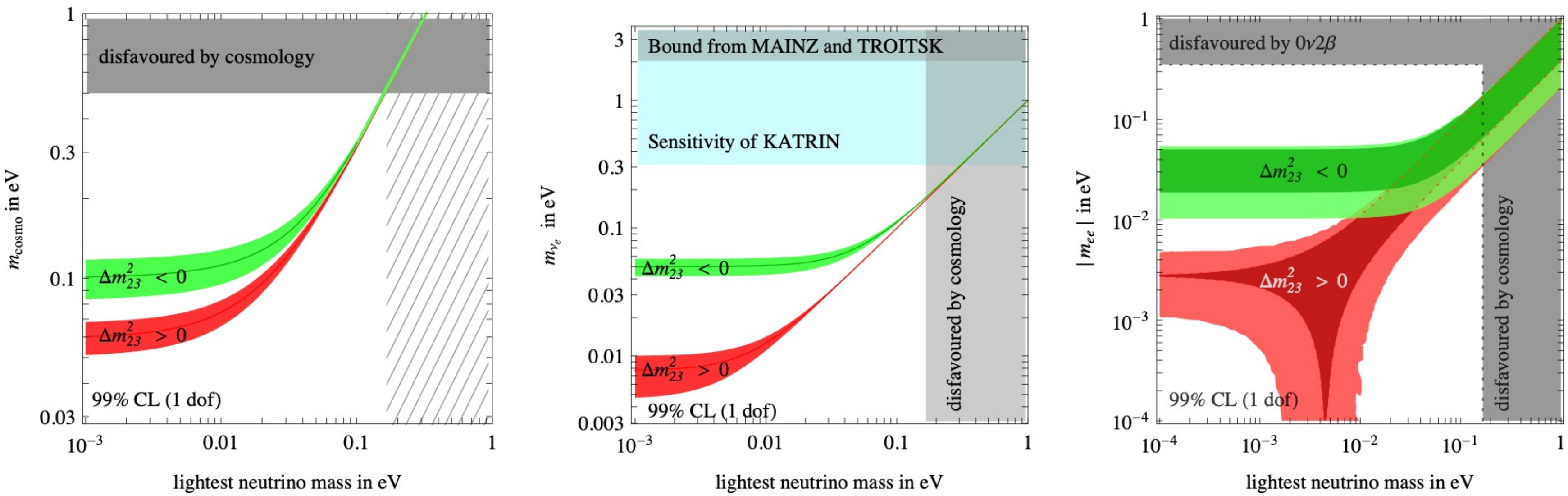
Towards $m_{\beta\beta}$ (& beyond 3ν)

Epilogue

Graphs of 3ν osc. bounds (1): $(m_\beta, m_{\beta\beta}, \Sigma)$ vs $m_{lightest}$ in NO/IO

Σ and m_β lines

$m_{\beta\beta}$ bands
(construct./destructive interfer.)



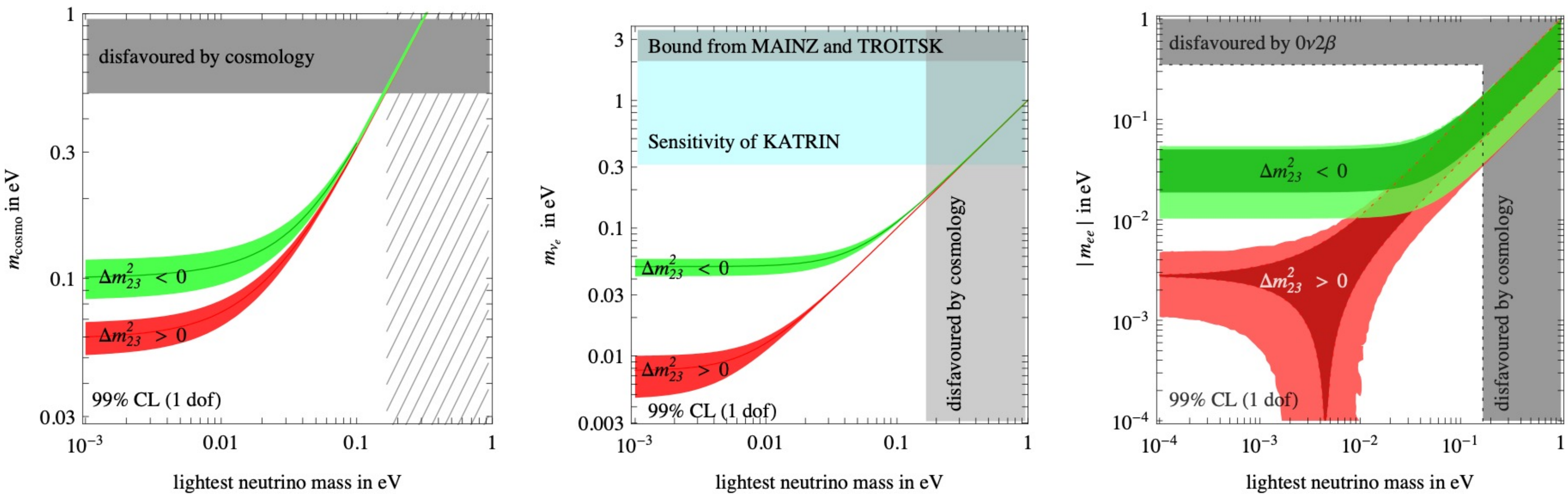
Lines and bands somewhat **smeared** by oscillation parameter uncertainties

Figure from Strumia & Vissani, hep-ph/0606054

Precise oscillometry in next decade → Negligible smearing & NO/IO selection

Only one Σ and m_β line

Only one $m_{\beta\beta}$ band



→ Progress in these planes will be driven only by absolute mass observables

(within the standard 3ν framework)

Comment on mass ordering through oscillations

No bump/dip/kink… but small/smooth differences in spectral templates S(E)

→ requires statistical comparison of template shapes vs data

Probes:	Templates:	Oscill. physics:
(1) MBL reactors:	S(E)	$\pm\Delta m^2$ vs δm^2
(2) LBL acceler.:	S(E, flavor)	$\pm\Delta m^2$ vs **MSW**, δm^2
(3) Atmospheric:	S(E, flavor, zenith)	$\pm\Delta m^2$ vs **MSW**, δm^2

In addition, "synergy" or "complementarity" of different probes:

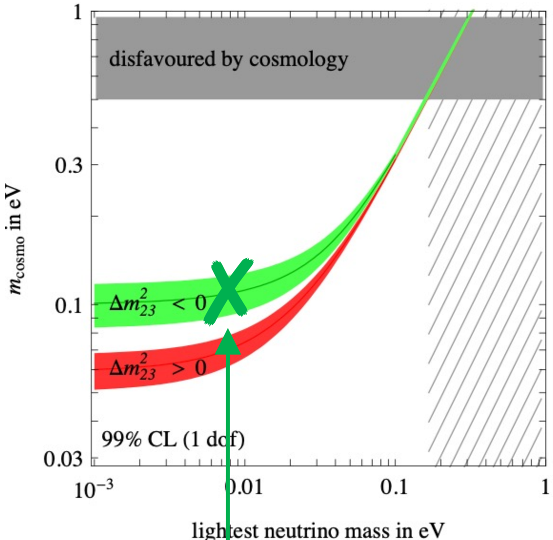
(4) ≥ 2 probes:	Spread of $\{+\Delta m^2_i\}$ vs $\{-\Delta m^2_i\}$ smaller for true ordering

Currently: Some hints from (2-4), sum up to $\sim 2.5\sigma$ in favor of $+\Delta m^2$

Future: from hints to discovery, as lines of evidence (1 - 4) grow & converge

See also talk by S. Parke

In the meantime… avoid **“jargon”** and **“statistical temptations”** …e.g.:

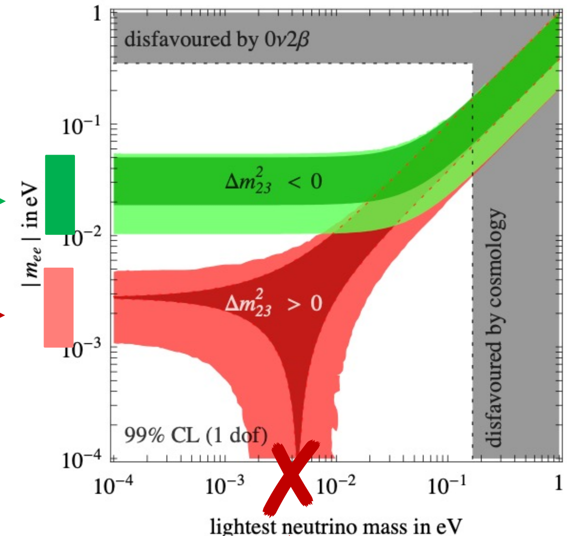


Jargon:

“IO region”

“NO region”

as if: **IO ∩ NO =** $\{0\}$
while it is: **IO ⊆ NO**



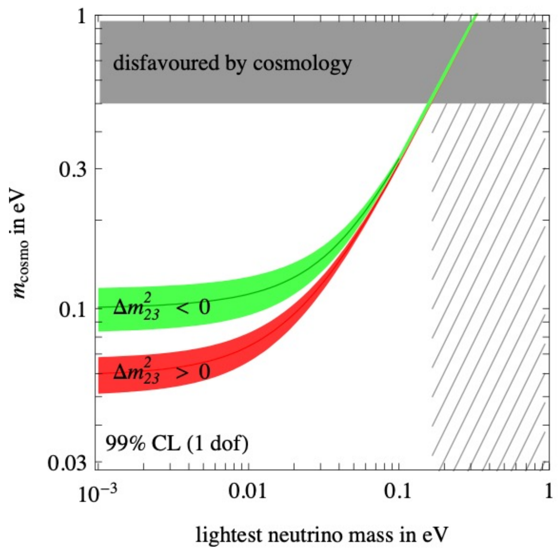
Statistical temptations:

“IO already rejected by cosmology”

“Region where $m_{\beta\beta} \to 0$
(named: well, funnel, throat…)
unlikely, due to fine - tuned cancellations”

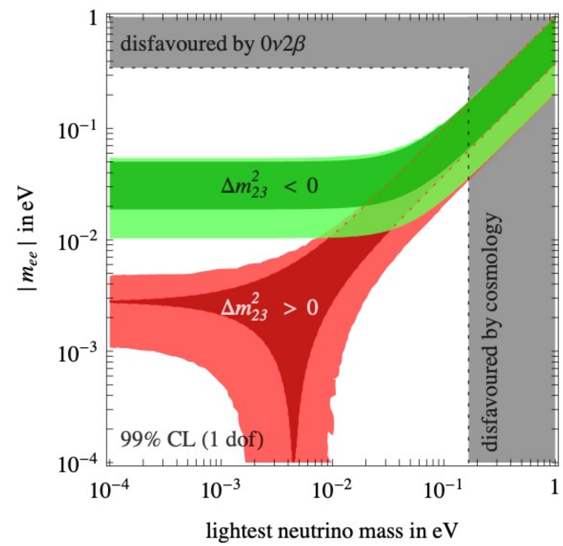
Nature does not care about our “naturalness” criteria or phase-space (under)sampling!

… also notice that $m_{lightest}$ **is not really measured**

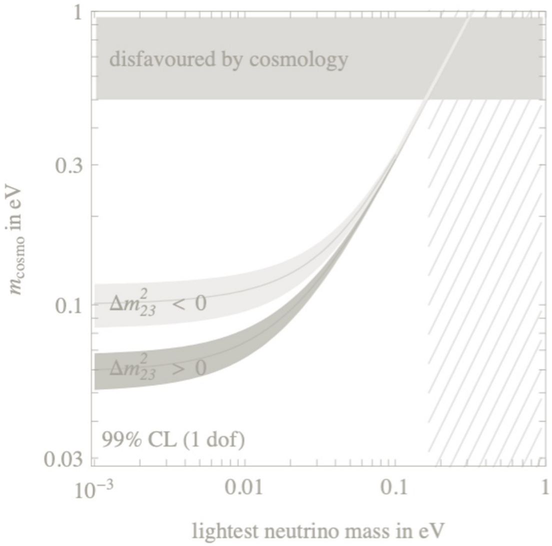


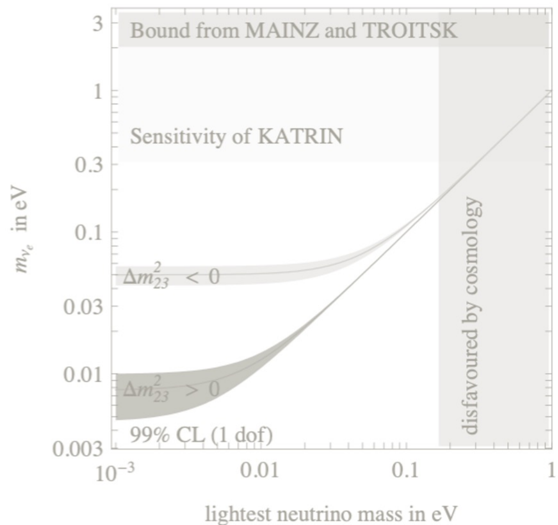
Phenomenologically:
How can you tell
$m_{lightest}$=**0.1** meV
from **1** meV
or even **a few** meV?

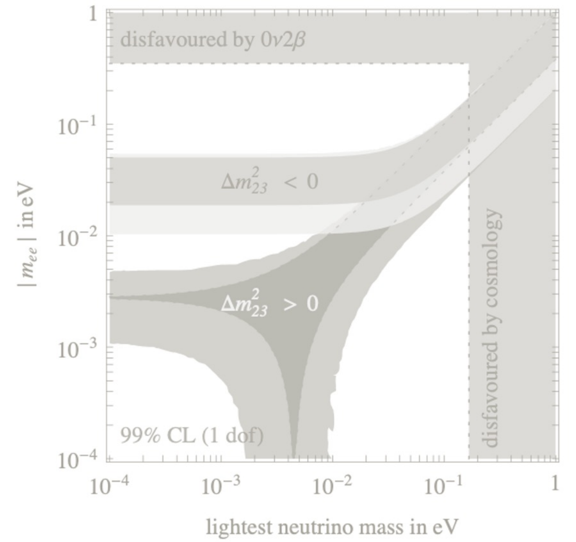
Also: log($m_{lightest}$) scale
amplifies NO/IO differ.



It makes sense to project away $m_{lightest}$ →







It makes sense to project away $m_{lightest}$ →

But *… keep in mind that the case* ***$m_{lightest}$ = 0*** *guarantees futuristic implications:*

- *a* ***relativistic CνB component*** *up to redshift z=0 ($m_{lightest} < T_\nu \sim$ 0.1 meV suffices)*
- *a* ***0νββ lower bound in NO*** *$m_{\beta\beta}$ > 1 meV ($m_{lightest}$ < 1 meV suffices)*
- *a* ***ν component with v=c*** *from multimessenger astrophysical sources*

Graphs of 3ν osc. bounds (2): $(m_\beta, m_{\beta\beta}, \Sigma)$ without $m_{lightest}$

Only measurable quantities; graphically amplified structures are squeezed away

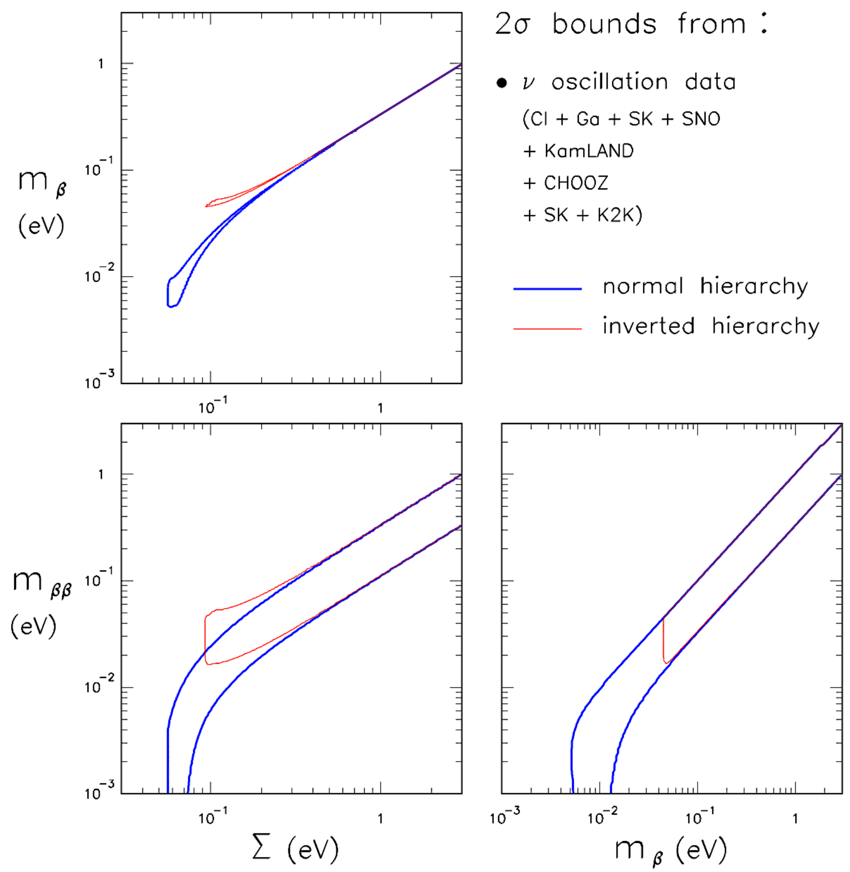
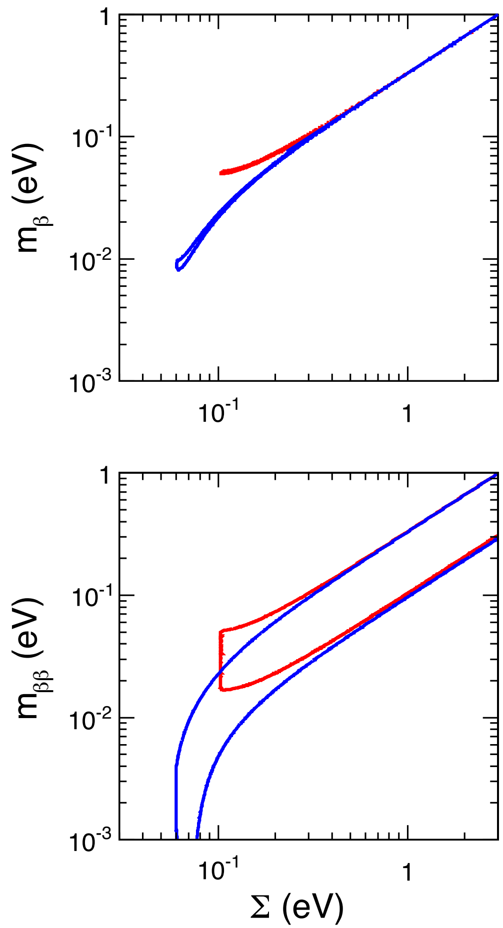
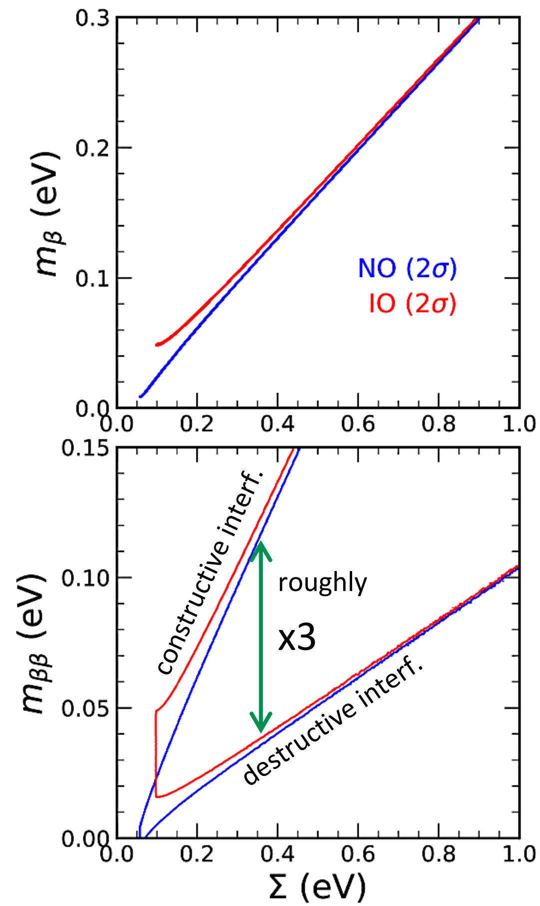


Figure from Fogli, Lisi, Marrone, Melchiorri, Palazzo, Serra and Silk, hep-ph/0408045

In perspective:

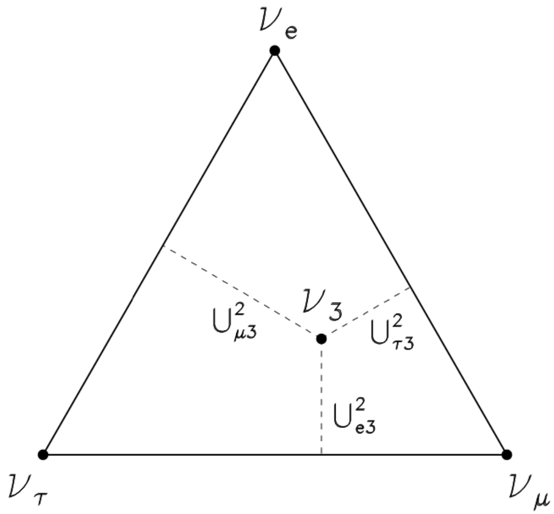
Log scale → Linear scale



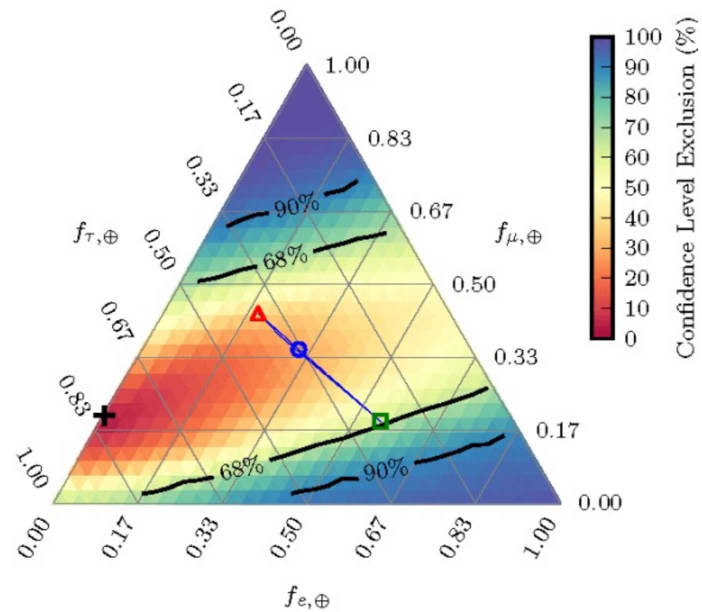


Right figure from Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo 2107.00532

Some plots may take time to get popular, but eventually…

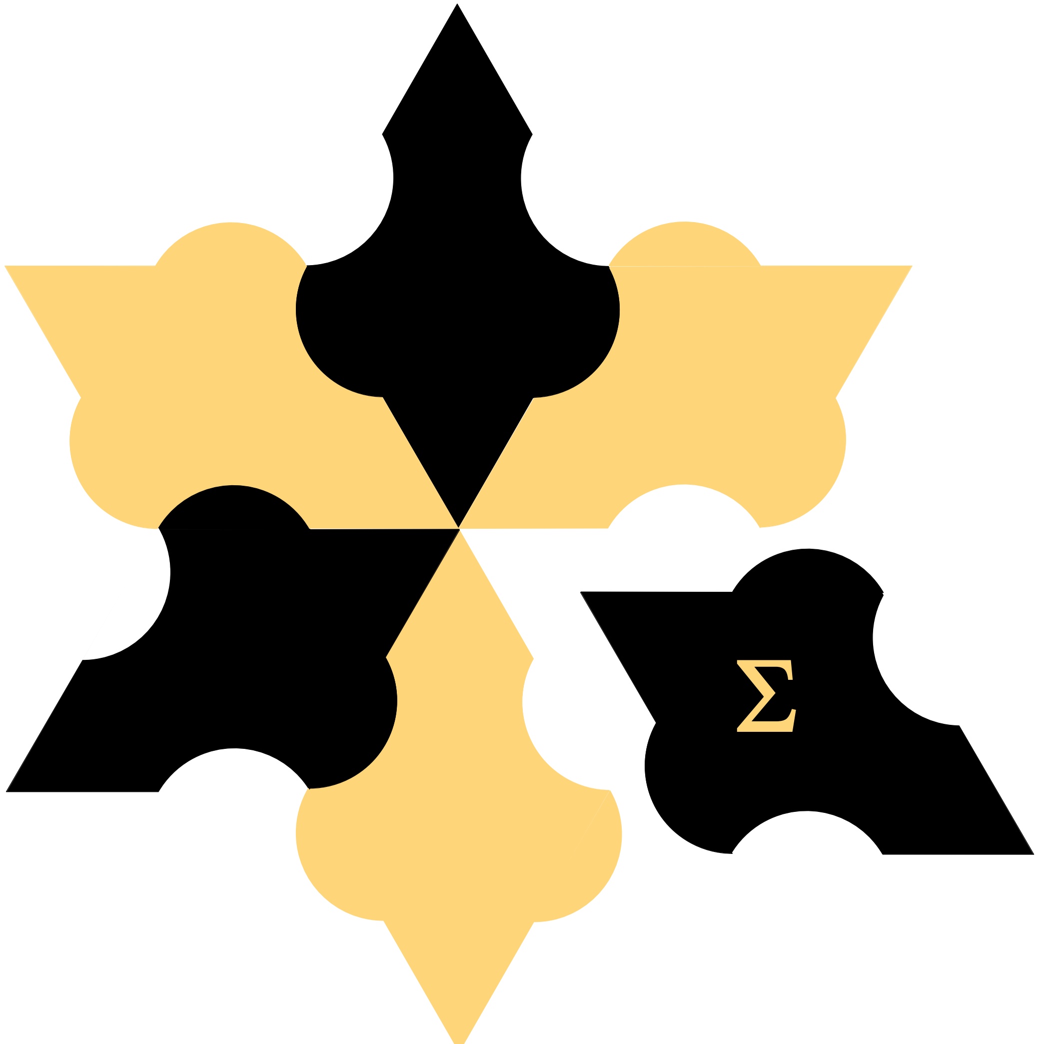


Fogli, Lisi, Scioscia
Phys.Rev.D 52 (1995) 5334
+later papers in the 90's



IceCube webpage

Towards a Σ signal



Current bounds: freely adapted from PDG quoted values and from 2107.00532
Forecasts: mainly adapted from M. Lattanzi, talks at NOW 2022 and TAUP 2023
See also talks by O. Mena and R. Laureijs at this Workshop

Σ signal is guaranteed:

$$\min \Sigma \simeq \begin{cases} 60 \text{ meV} & \text{(NO)} \\ 100 \text{ meV} & \text{(IO)} \end{cases}$$

But: Σ = **output** of a multi-parameter **fit** to cosmological data within ΛCDM,

$\mathcal{L}(\Sigma)$ → (roughly) $\Sigma \simeq \Sigma_0 \pm \sigma$

Currently: Variants in #parameters, datasets, model… → **various 95% CL limits:**

$\Sigma_i < \Sigma_{0i} + 2\sigma_i$, $i \in \{\text{variants}\}$

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + m_β + $m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\text{IO}-\text{NO}}$	Σ (2σ)	$\Delta\chi^2_{\text{IO}-\text{NO}}$
0	ΛCDM + Σ	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	ΛCDM + Σ	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	ΛCDM + Σ	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	ΛCDM + Σ	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	ΛCDM + Σ	Planck TT, TE, EE + lensing + H_0(R19)	< 0.13 eV	3.9	< 0.13 eV	4.0
5	ΛCDM + Σ	Planck TT, TE, EE + BAO + H_0(R19)	< 0.13 eV	3.1	< 0.13 eV	3.2
6	ΛCDM + Σ	Planck TT, TE, EE + BAO + lensing + H_0(R19)	< 0.12 eV	3.7	< 0.12 eV	3.8
7	ΛCDM + Σ + A_{lens}	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	ΛCDM + Σ + A_{lens}	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	ΛCDM + Σ + A_{lens}	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2
10	ΛCDM + Σ	ACT + WMAP + τ_{prior}	< 1.21 eV	−0.1	< 1.00 eV	0.1
11	ΛCDM + Σ	ACT + WMAP + Planck lowE	< 1.12 eV	−0.1	< 0.87 eV	0.1
12	ΛCDM + Σ	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

E.g., Capozzi+ 2107.00532

	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[22]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[22]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[43]
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[23]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[22]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[22]
CMB + probes of background evolution + LSS			
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[43]
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[44]
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13	[45]

Lesgourgues, Verde PDG 2022

+talk by Olga Mena

Σ signal is guaranteed:

$$\min \Sigma \simeq \begin{cases} 60 \text{ meV} & \text{(NO)} \\ 100 \text{ meV} & \text{(IO)} \end{cases}$$

But: Σ = **output** of a multi-parameter **fit** to cosmological data within ΛCDM,

$$\mathcal{L}(\Sigma) \rightarrow \text{(roughly) } \Sigma \simeq \Sigma_0 \pm \sigma$$

Currently: Variants in #parameters, datasets, model… → **various 95% CL limits:**

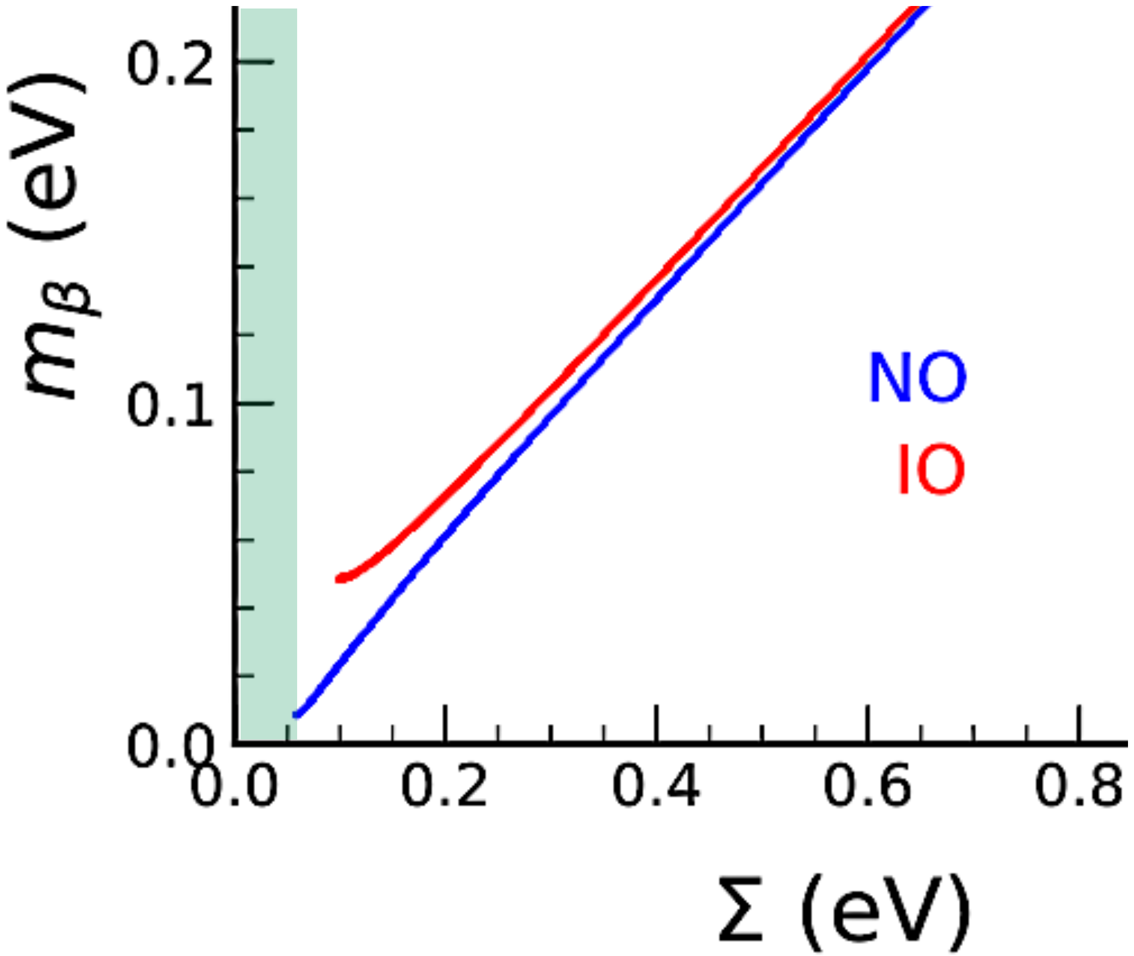
$$\Sigma_i < \Sigma_{0i} + 2\sigma_i \quad , \quad i \in \{\text{variants}\}$$

Strongest current limits [PDG, $\Sigma_i < 90$–130 meV at 2σ] roughly correspond to:

$$\Sigma_{0i} \sim 0 \text{ meV}$$
$$\sigma_i \sim 45\text{–}65 \text{ meV}$$

Weaker limits involve **larger uncertainties** σ_i and/or **nonzero best fits** $\Sigma_{0i} \sim O(\sigma_i)$

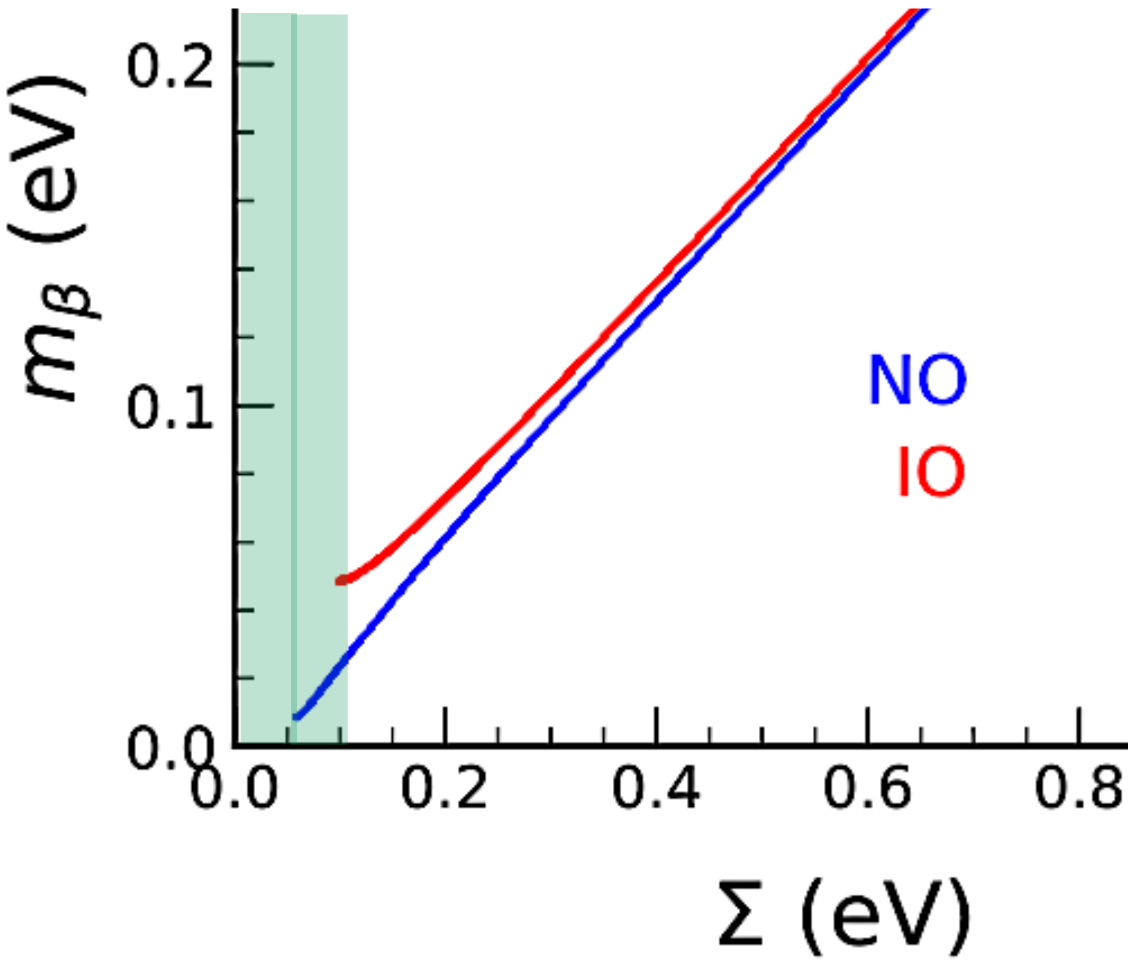
Implications of a current strong limit, e.g., **$\Sigma = 0 \pm 60$ meV:**



Unphysical best fit, but … compatible with min(NO) at $\sim 1\sigma$ and min(IO) at $<2\sigma$

To some extent, best fit may be an artifact of degenerate mass approximation →

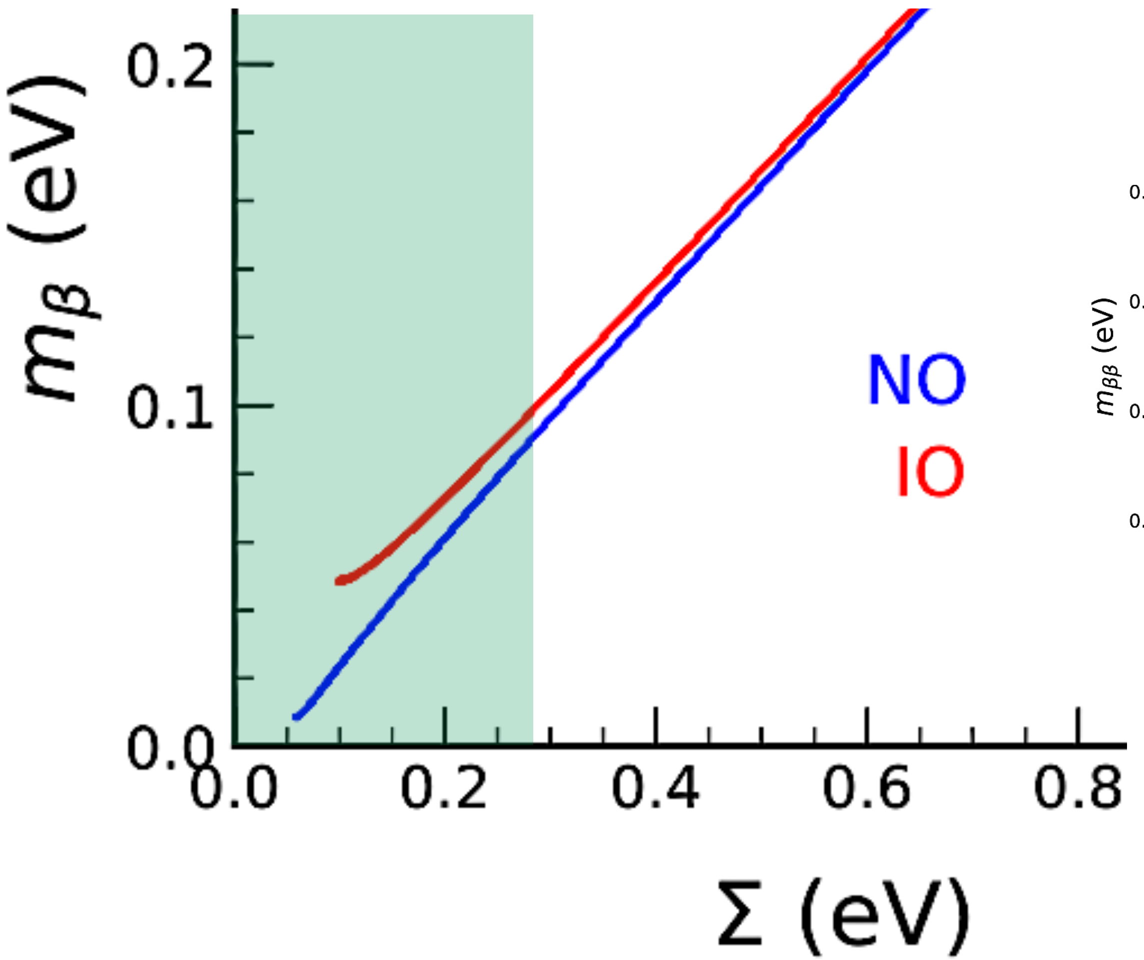
For nondegenerate ν masses get, e.g., $\Sigma = 60 \pm 60$ **meV:**

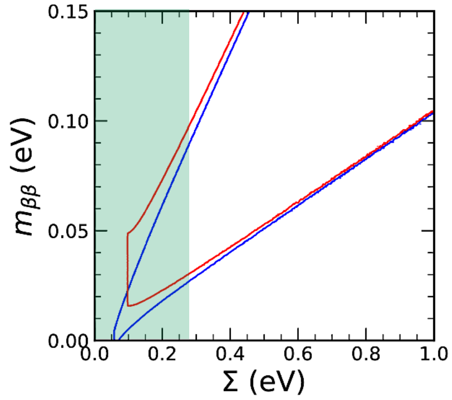


Physical best fit sitting at min(NO), compatible with min(IO) at $<1\sigma$

Note: *small but nonzero fit difference by taking Σ=60=**0+9+51** rather than **20+20+20***

More variants can cover up to, say, $\Sigma < 270$ **meV at** 1σ (akin to weakest PDG limits)





Rather conservative Σ bound, implying m_β and $m_{\beta\beta}$ (much) below 100 meV

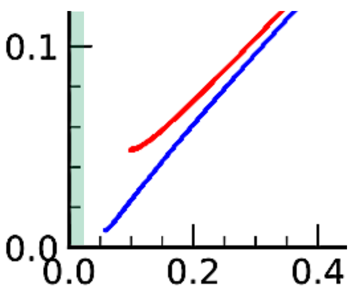
Mass ordering undecided by cosmology

Next ~10 years: expect a significant reduction of σ from both CMB and LSS data

σ ~ 45-65 meV (now) → σ ~ 30 meV (baseline) → σ ~ 20 meV (goal)

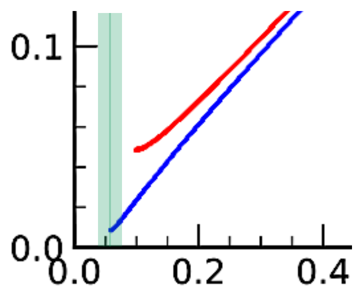
Different (and very interesting!) implications, depending on central value of Σ, e.g.:

Σ = 0 ± 20 meV



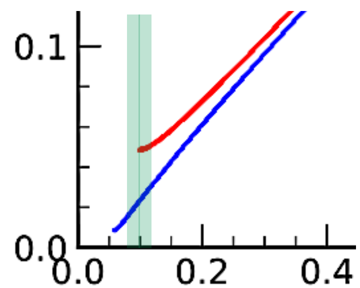
Unphysical at 3σ.
A new tension
in cosmology?

Σ = 60 ± 20 meV



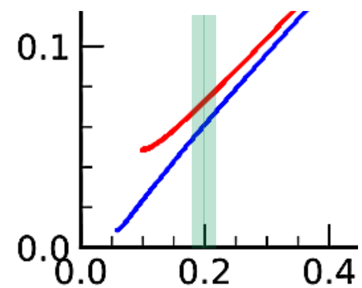
Min(NO) signal at 3σ.
IO disfavored at 2σ.
Consistent with oscill.?

Σ = 100 ± 20 meV



Mass signal at 5s.
NO/IO ~undecided
by cosmology

Σ = 200 ± 20 meV



Mass signal at > 5s.
NO/IO undecided
by cosmology

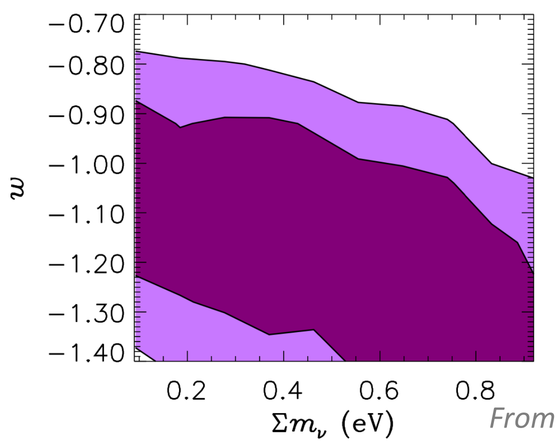
*Always useful to compare the **degenerate** mass approximation with the full-fledged **nondegenerate** case including oscillation Δm^2_{ij}.*

Any such result/implication will emerge gradually, and not without debate.

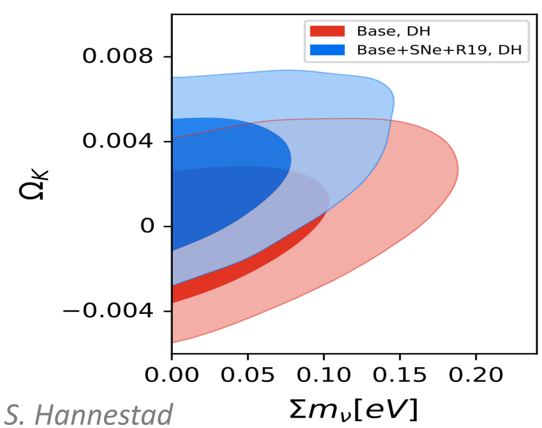
Saga of multi-parameter fit **variants** is likely to continue *(focus: from limits to signals):*

- Old tensions (e.g., H_0) might not be solved by new data; new tensions may appear
- The ΛCDM model might evolve into a richer model as DE and DM get “understood”
- New model parameters (e.g., $w \neq -1$, curvature...) may be correlated with Σ (see below)
- “Statistical temptations” might enhance claims about Σ signal significance

Negative correlation with ***w***



Positive correlation with $\boldsymbol{\Omega_k}$



From S. Hannestad

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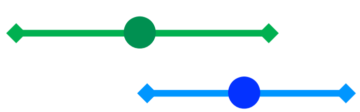
- New model parameters (e.g., $w \neq -1$, curvature…) may be correlated with Σ
- "Statistical temptations" might enhance claims about Σ signal significance

What will it take to get a convincing signal $\Sigma \simeq \Sigma_0 \pm \sigma$?

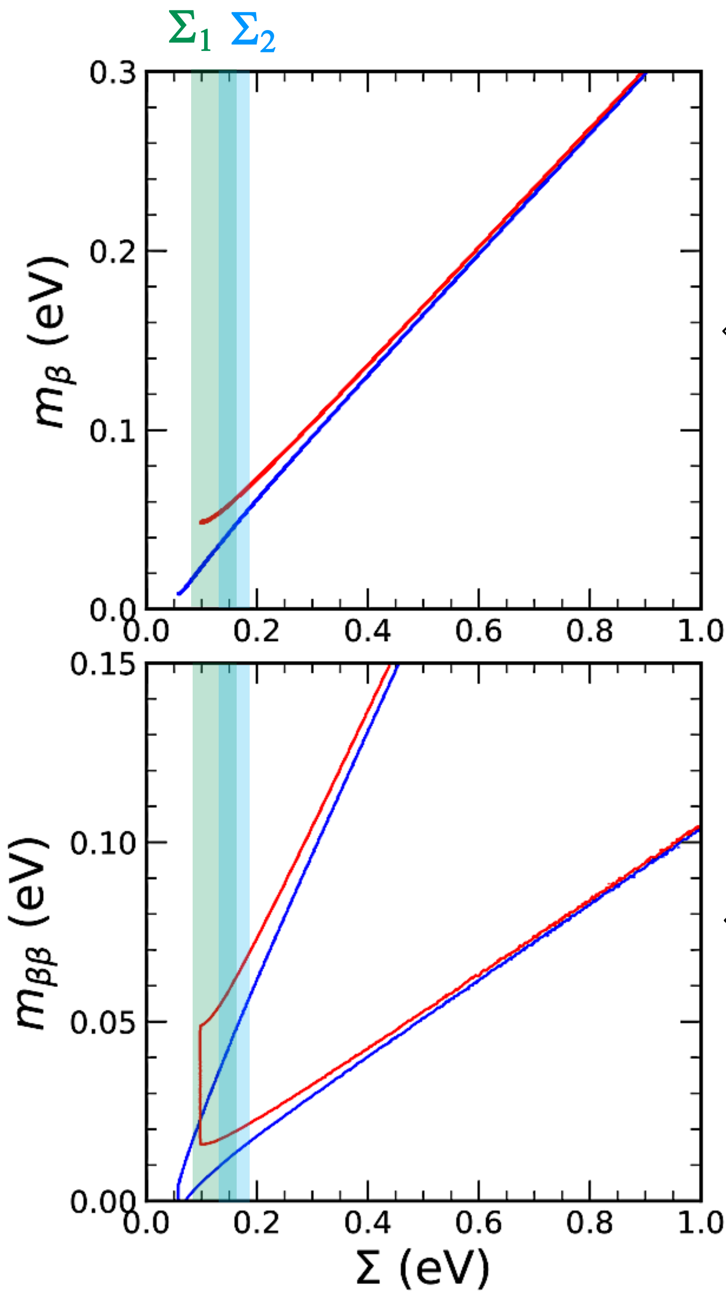
As for oscill(NO/IO): **convergence of ≥2** quasi-independent **lines of evidence** helps!



Σ_1 from dataset$_1$ (e.g., mostly CMB or high-z data or else …)

Σ_2 from dataset$_2$ (e.g., mostly LSS or low-z data or else …)

especially if robust w.r.t. additional model parameter: demanding requirements!



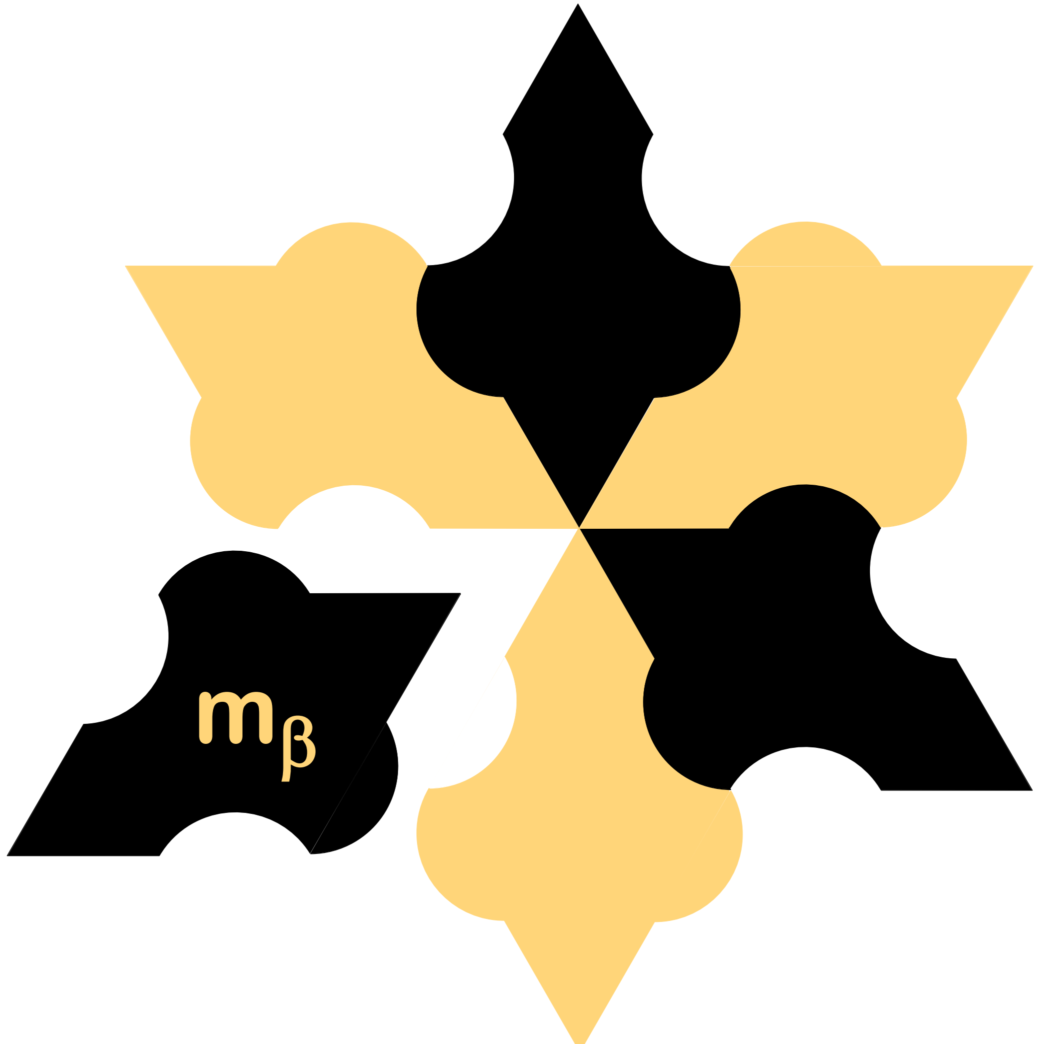
In any case: for settled NO/IO, any estimate for Σ will be in one-to-one correspondence with a m_β estimate

Viceversa, a m_β measurement can (dis)confirm Σ and (de)stabilize this corner of cosmology.

Weaker correspondence of Σ with $m_{\beta\beta}$, due to x3 variation from interference of unknown Majorana phases.

Viceversa: $m_{\beta\beta}$ >0 signal with less than x3 error may constrain cases of max constructive vs destructive interfer.

Towards a m_β signal



m_β signal is guaranteed: $\min \mathbf{m}_\beta \simeq \begin{cases} 9\ \text{meV} & \text{(NO)} \\ 50\ \text{meV} & \text{(IO)} \end{cases}$

While $\boldsymbol{\Sigma}$ requires to model the whole universe, $\mathbf{m}_\beta$ requires to model source + detector
→ Instrinsically robust and pivotal role of β decay.

One must find the $\mathbf{m}_\beta$ signal at any cost!

m_β signal is guaranteed: min $m_\beta \simeq \begin{cases} 9\ \text{meV} & \text{(NO)} \\ 50\ \text{meV} & \text{(IO)} \end{cases}$

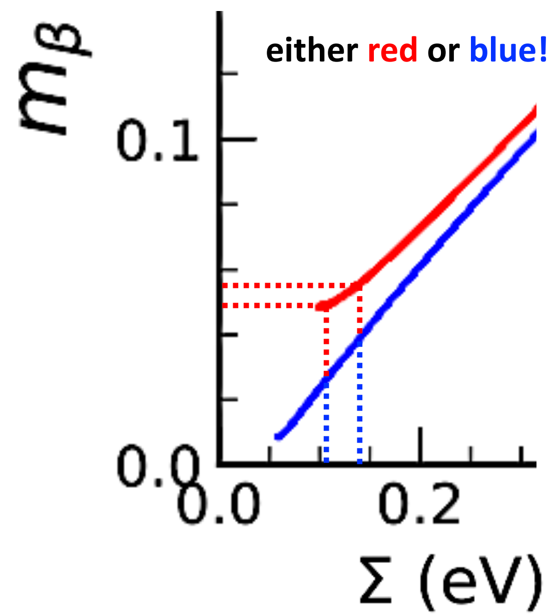
While Σ requires to model the whole universe, m_β requires to model source + detector
→ Instrinsically robust and pivotal role of β decay.

One must find the m_β signal at any cost!

There is realistic path to go from ~200 meV (KATRIN) to ~50 meV (PROJECT 8)
Timescale: ~10 yrs. Other projects explored, in R&D phase (J. Formaggio's talk)

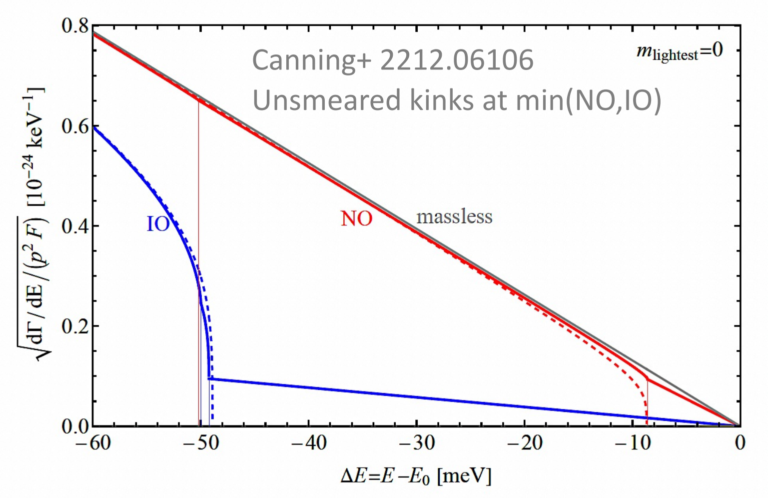
*If lucky, in **203X** we might see*
up to two absolute mass signals
and analyze them in fine details:
a new frontier of global fits

*If not: **path m_β ~50 → ~9 meV***
needs to be envisaged.
Hard but absolutely necessary!



Fine details in future global analyses…

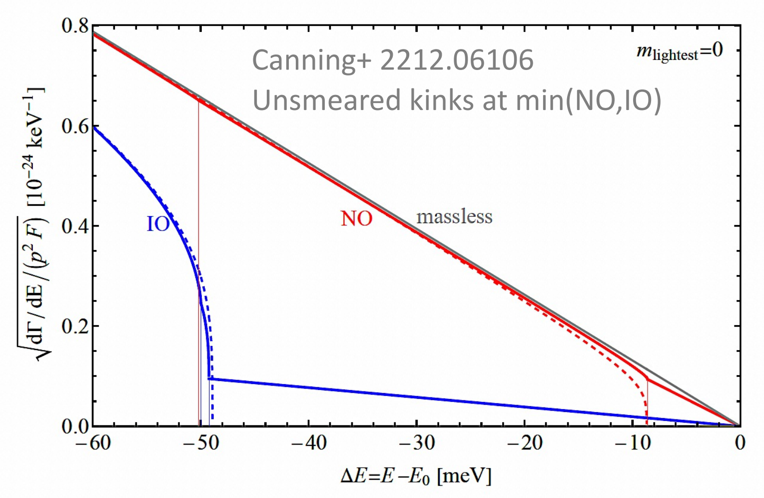
Improvements in m_β sensitivity might come with improvements in resol. ΔE_β from current **$\Delta E_\beta \sim 1$ eV** (KATRIN) to, hopefully, **$\Delta E_\beta \sim O(\sqrt{\Delta m^2}) \sim 50$ meV** or less
→ possible sensitivity to **kink(s) info** rather than just overall smeared distortion



Concerning **Σ**: as noted, it will be worthwhile to check small differences between the **degenerate** mass approximation and **nondegenerate** masses

Fine details in future global analyses…

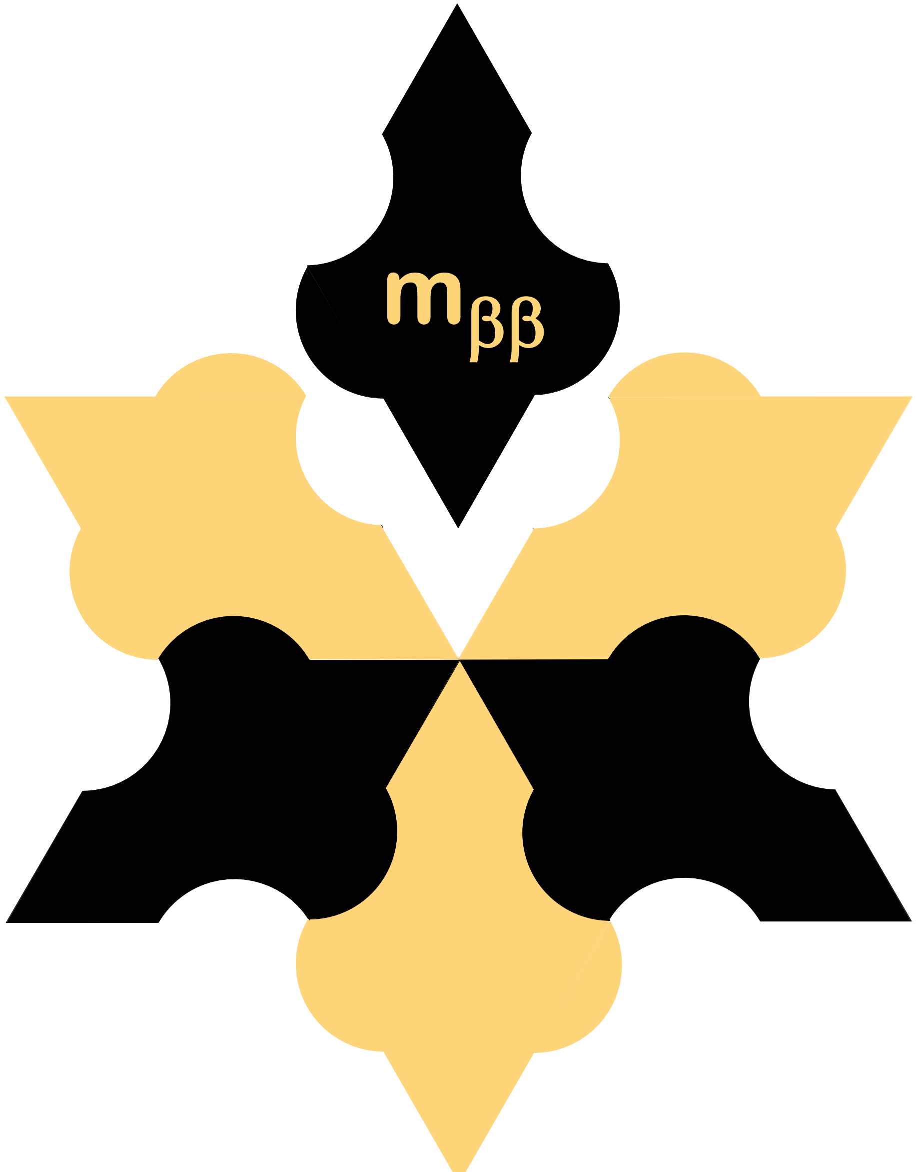
Improvements in $\mathbf{m_\beta}$ sensitivity might come with improvements in resol. ΔE_β from current ΔE_β **~1 eV** (KATRIN) to, hopefully, **ΔE_β ~O(√Δm²) ~50 meV** or less → possible sensitivity to **kink(s) info** rather than just overall smeared distortion



Concerning Σ: as noted, it will be worthwhile to check small differences between the **degenerate** mass approximation and **nondegenerate** masses

There may be a little bit more information than just 2 param. (m_β and Σ)!
Possible slight sensitivity to the ν_i **mass distribution**, hopefully consistent with the one dictated by the true mass ordering + oscillation splittings.

Towards $m_{\beta\beta}$ …



Towards $m_{\beta\beta}$ … and beyond 3ν

$m_{\beta\beta}$ signal is not guaranteed: min $m_{\beta\beta}$ (iff Majorana) $\simeq \begin{cases} 0\ \text{meV} & \text{(NO)} \\ 18\ \text{meV} & \text{(IO)} \end{cases}$

But Majorana/Dirac discrimination is of fundamental importance! (talks: M. Agostini, S. Petcov)

Signal estimates depend on **nuclear model of (Z,A)** + model of source/detector

$$\boxed{i = (Z, A): \qquad S_i = 1/T_i = G_i M_i^2 m_{\beta\beta}^2}$$

Signal strength ↑

$\propto$ decay counts

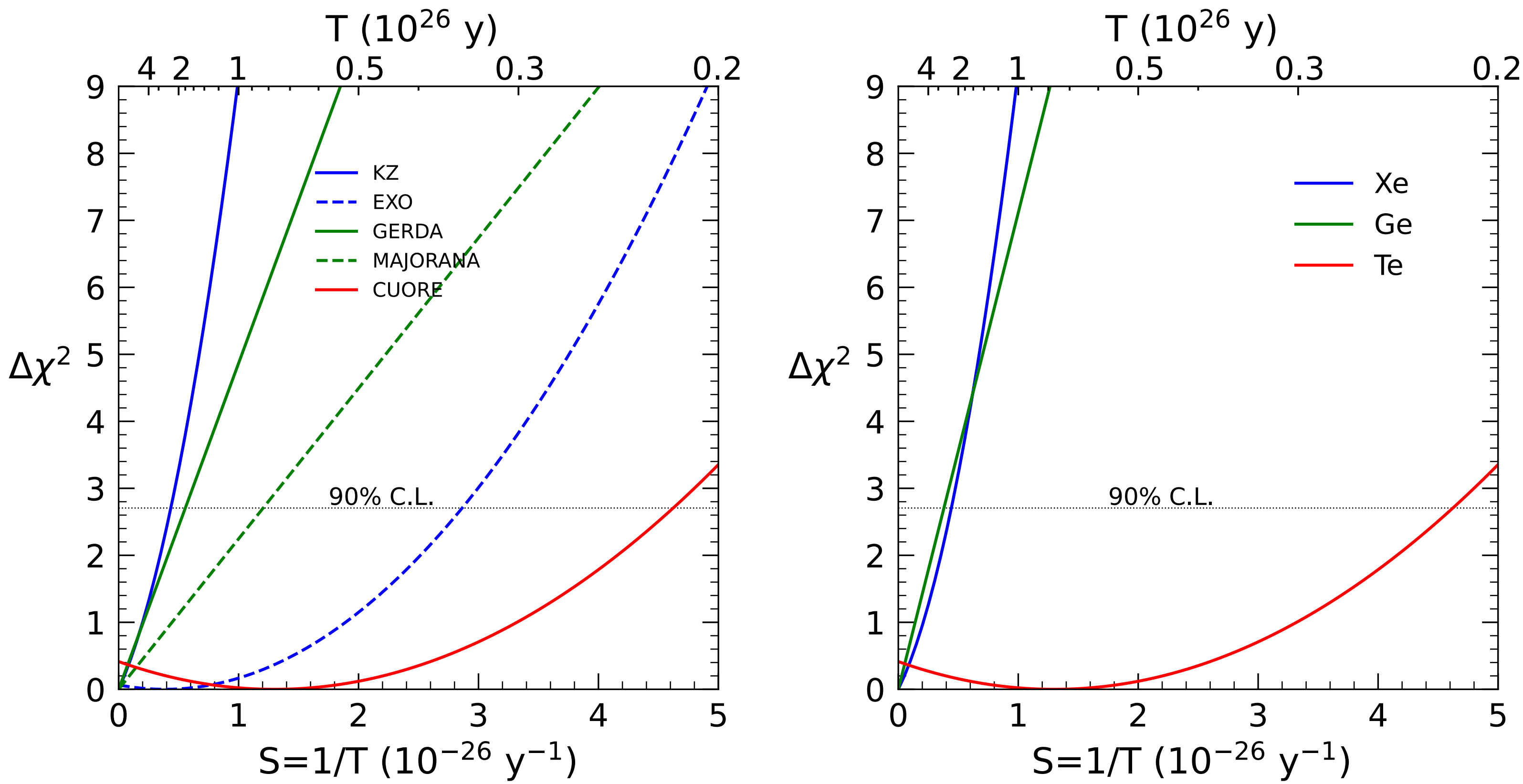
Main source of stat. error for $\mathbf{m}_{\beta\beta}$

NME ↑

nuclear dynamics

Main source of syst. error for $\mathbf{m}_{\beta\beta}$

Signal strength likelihood for latest results



Best fit at (or close to) null signal → NME-dependent upper limits on $m_{\beta\beta}$

A plea to experimentalists: please always publish **$\mathcal{L}$(S)**, not just S at 90% CL!

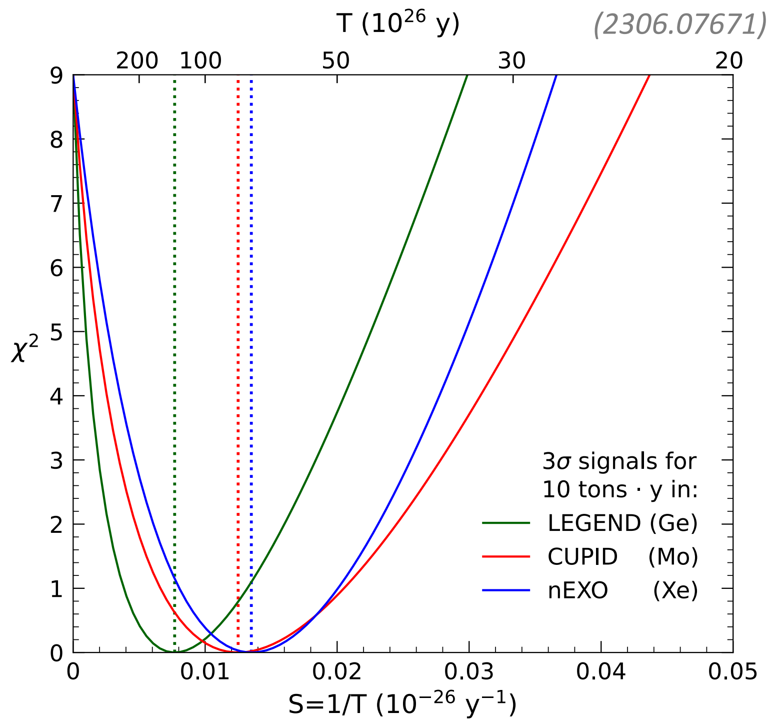
Otherwise: impossible to combine independent results, even in same (Z,A)

Lisi, Marrone, Nath, 2306.07671

Realistic path to reach ≥3σ evidence down to $m_{\beta\beta}$~18 meV, even for lowest known NME:
Ton-scale masses, 10-year time scale → **10 ton yr exposure** *(talk by M. Agostini)*

Signal strength likelihood for prospective 3σ evidence:

(2306.07671)

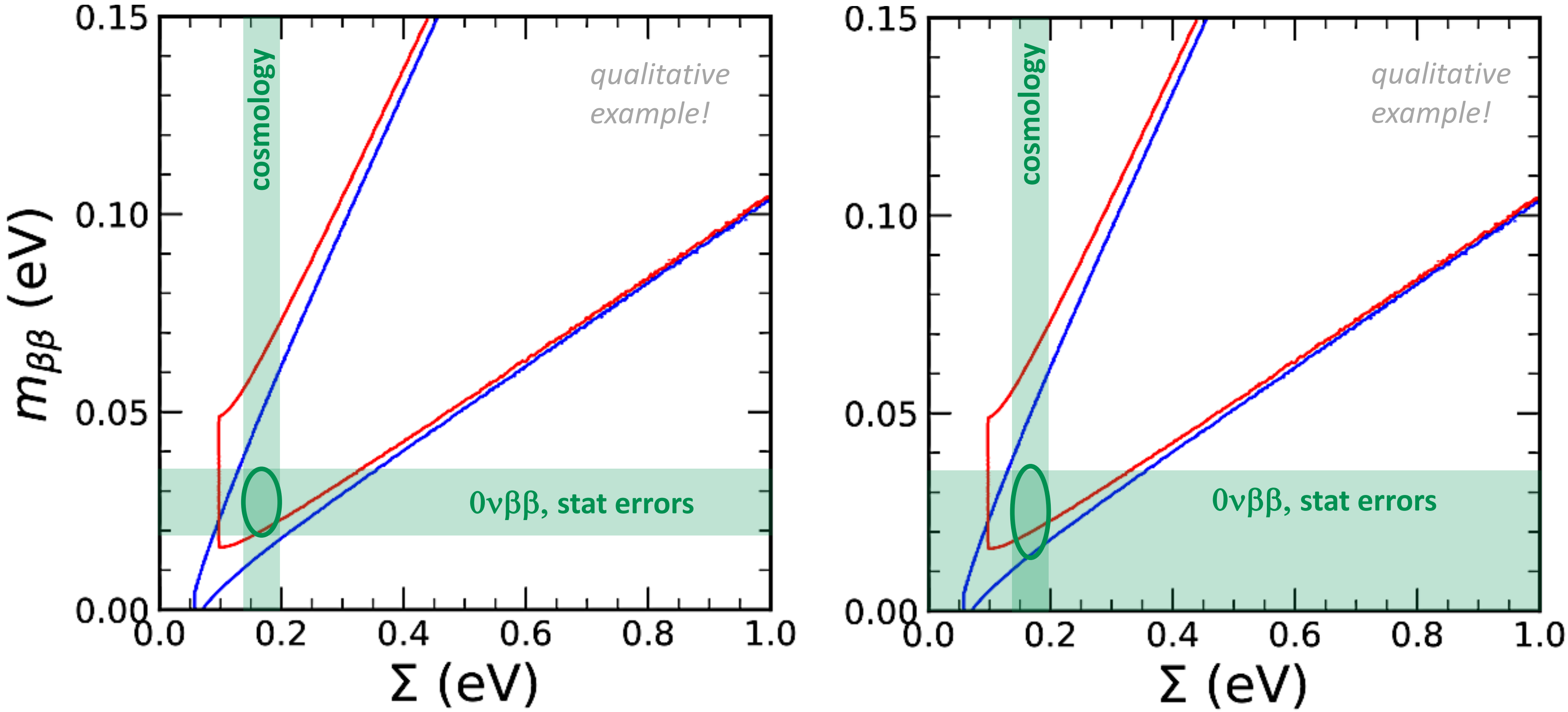


In each expt., ±1σ stat. spread of $m_{\beta\beta} \propto \sqrt{S}$ smaller than "x3 variation"
(even better for >3σ evidence, or by combining ≥ 2 experiments)

In **combination** with a signal for Σ (of for m_β, or both)

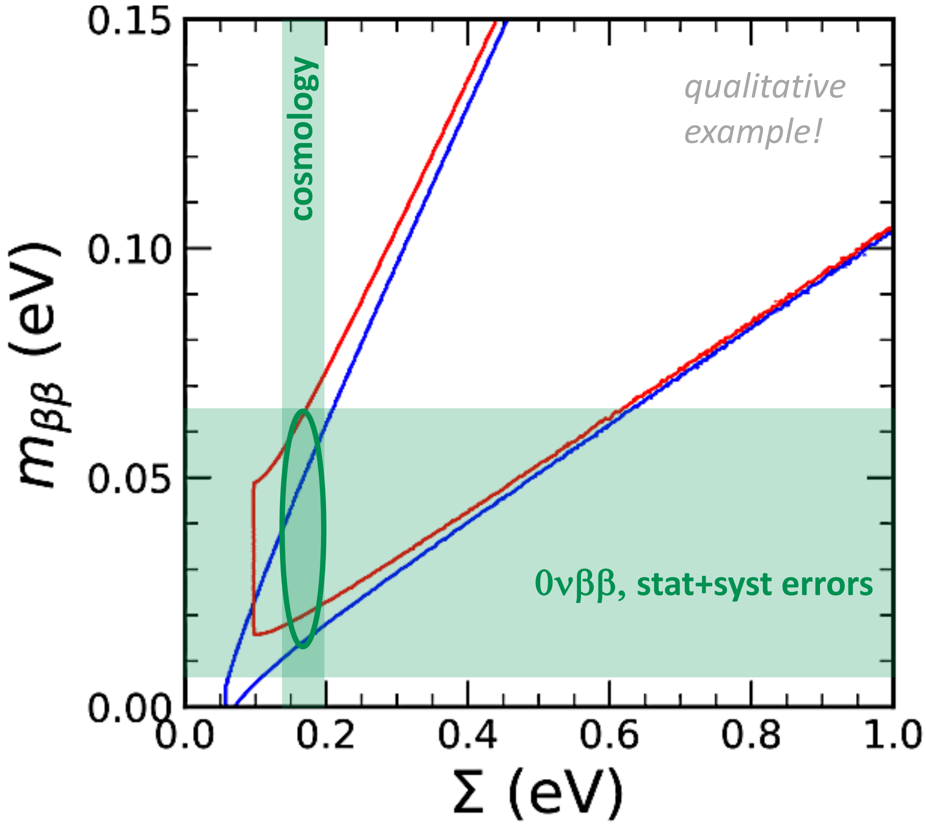
some constraints on Majorana phases may emerge

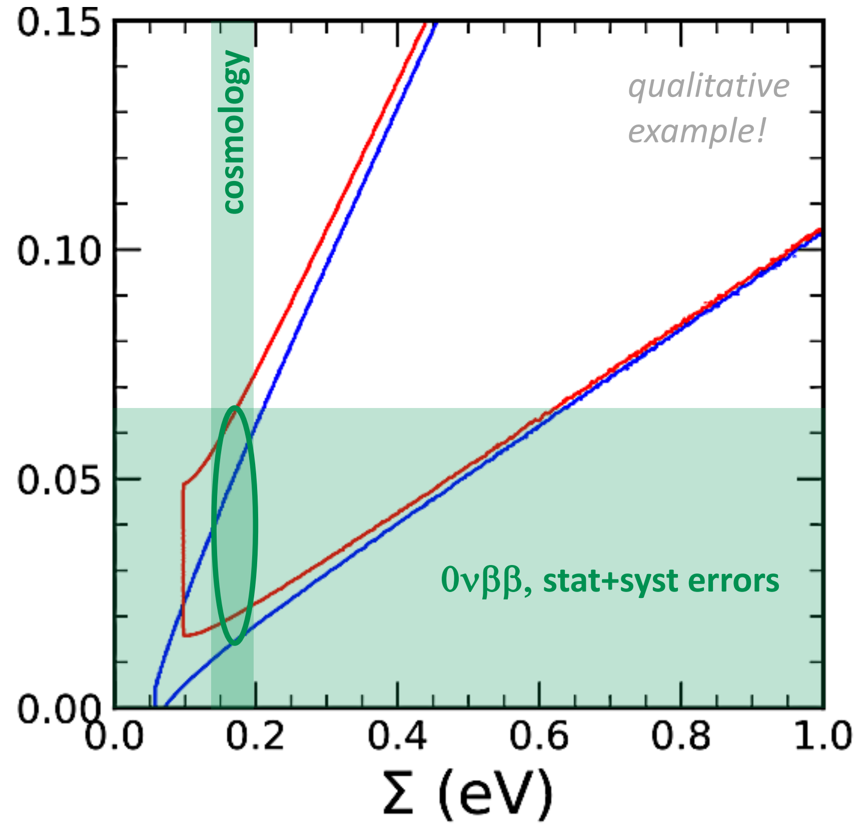
(even for *upper limits only* on $m_{\beta\beta}$)



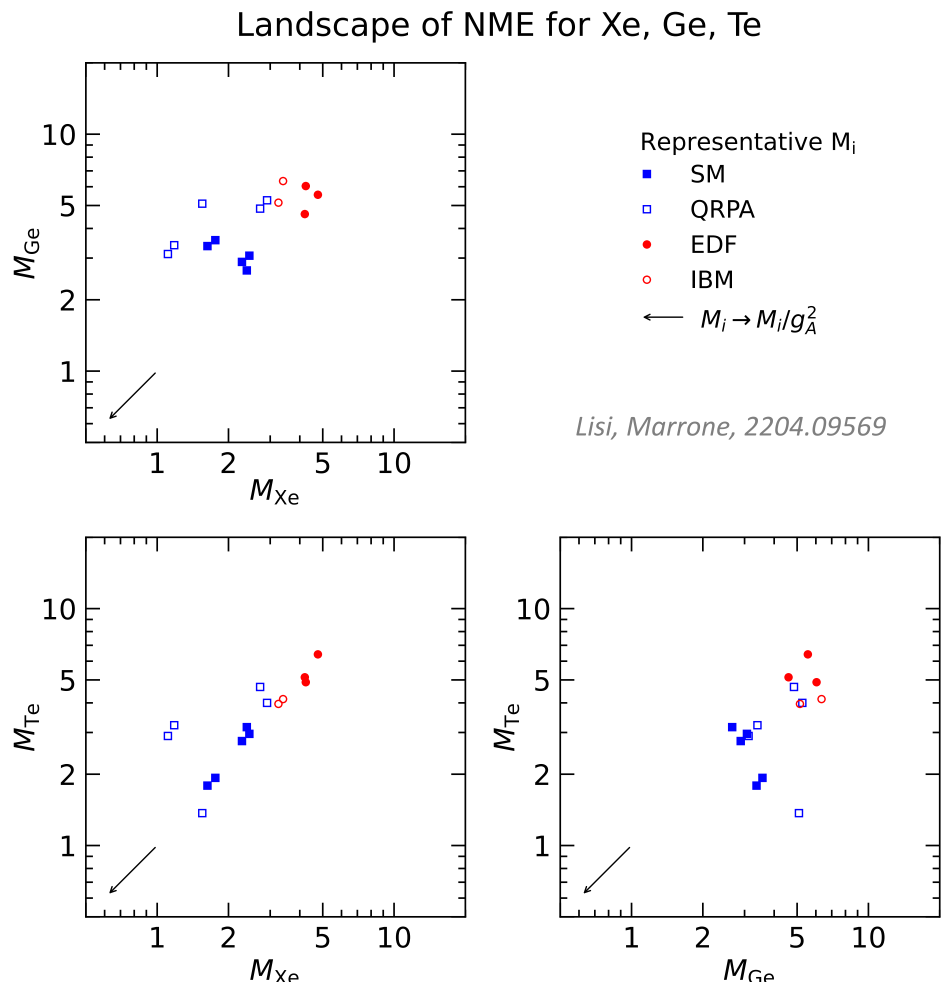
Unfortunately…

washed out by <u>current</u> x3 spread of NMEs

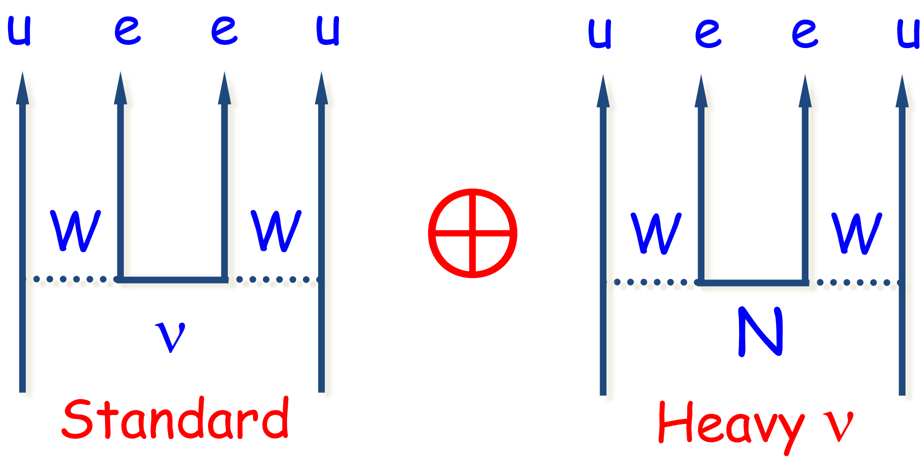




M_i spread dangerous because it's: (1) large; (2) correlated among i=(Z,A)

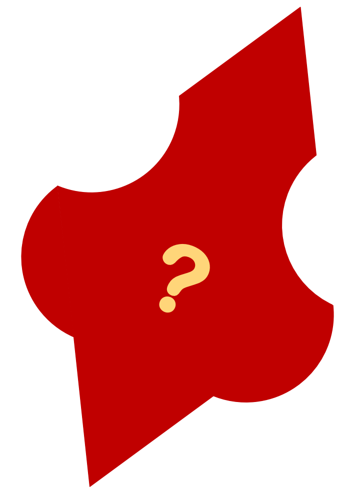


The **fully correlated error** component $M_i \rightarrow M_i\,\xi$ is degenerate with $m_{\beta\beta} \rightarrow m_{\beta\beta}/\xi$ and **is not reduced** by combining multi-isotope signals *(Faessler+, 1103.2504)*

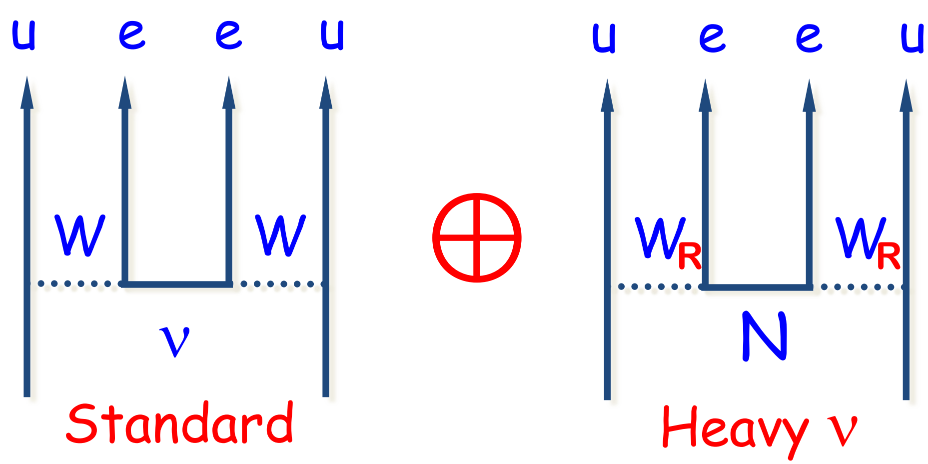


New physics beyond 3ν?

E.g., possible to have both **light and heavy ν** in many theo. models, e.g. see-saw



Large and correlated NME spread may also prevent discrimination of **new physics contributions** (if any)



Light and heavy ν exchange may be **~non-interfering***, e.g. in LR-symmetric models:
(*simplest case, no extra phases)

Signal strength — NME for **light** neutrinos — **NME** for heavy neutrinos

$$\boxed{S_i = G_i \left(M_{\nu,i}^2\, m_\nu^2 \; + M_{N,i}^2\, m_N^2 \right)}$$

$$m_\nu = \left| \sum_{k=1}^{3} U_{ek}^2 m_k \right|$$

Effective Majorana mass (light)

$$m_N = \frac{m_W^4}{m_{W_R}^4} \left| \sum_h V_{eh}^2 \frac{m_p\, m_e}{M_h} \right|$$

Effective Majorana mass (heavy)

Need two equations *(two isotopes i,j)* for two mass unknowns:

$$\begin{bmatrix} S_i G_i^{-1} \\ S_j G_j^{-1} \end{bmatrix} = \begin{bmatrix} M_{\nu,i}^2 & M_{N,i}^2 \\ M_{\nu,j}^2 & M_{N,j}^2 \end{bmatrix} \begin{bmatrix} m_\nu^2 \\ m_N^2 \end{bmatrix}$$

DATA
+kinematics

NME
(nuclear physics)

Majorana masses
(particle physics)

With three (or more) isotopes: can make further checks.

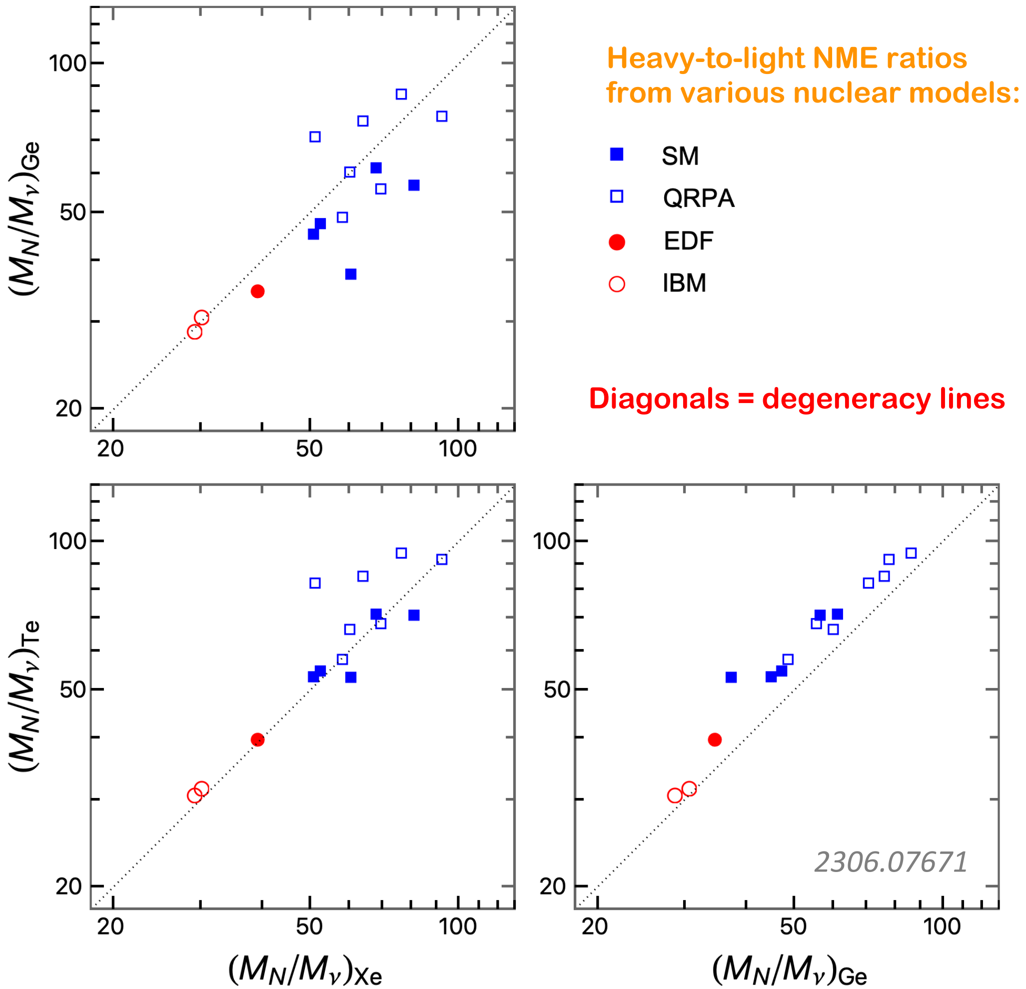
→ **Need multi-isotope 0νββ decay searches**

Non-degenerate solution iff matrix determinant is non-zero:

$$\frac{M_{N,i}}{M_{\nu,i}} \neq \frac{M_{N,j}}{M_{\nu,j}}$$

NME heavy/light <u>ratio</u> uncertainties →

Large spread of heavy/light ratios of NME around the degeneracy lines:



→ Difficult to separate heavy ν contribution - and new physics in general

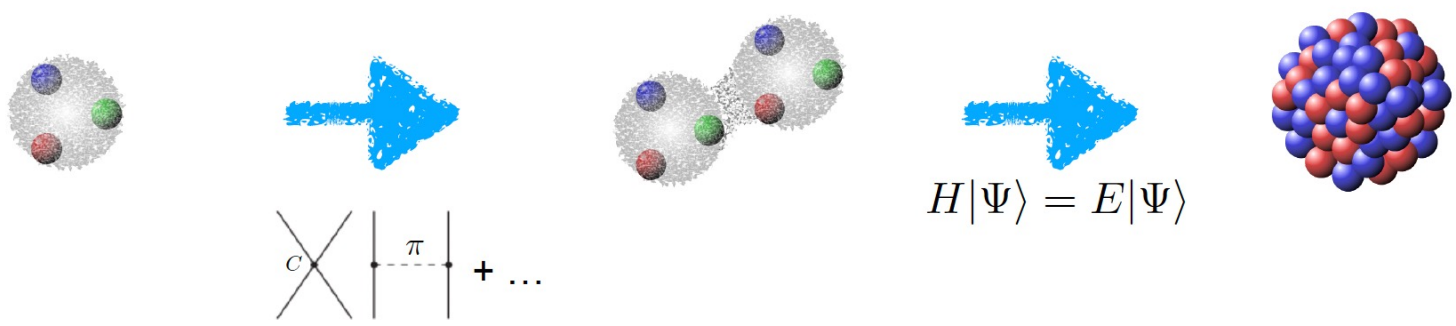
[Taming degeneracy by error control will be easier for largely off-diagonal central values]

But…there is a realistic path towards improved NME estimates
in the wider context of ab-initio approaches in nuclear physics

2203.12169

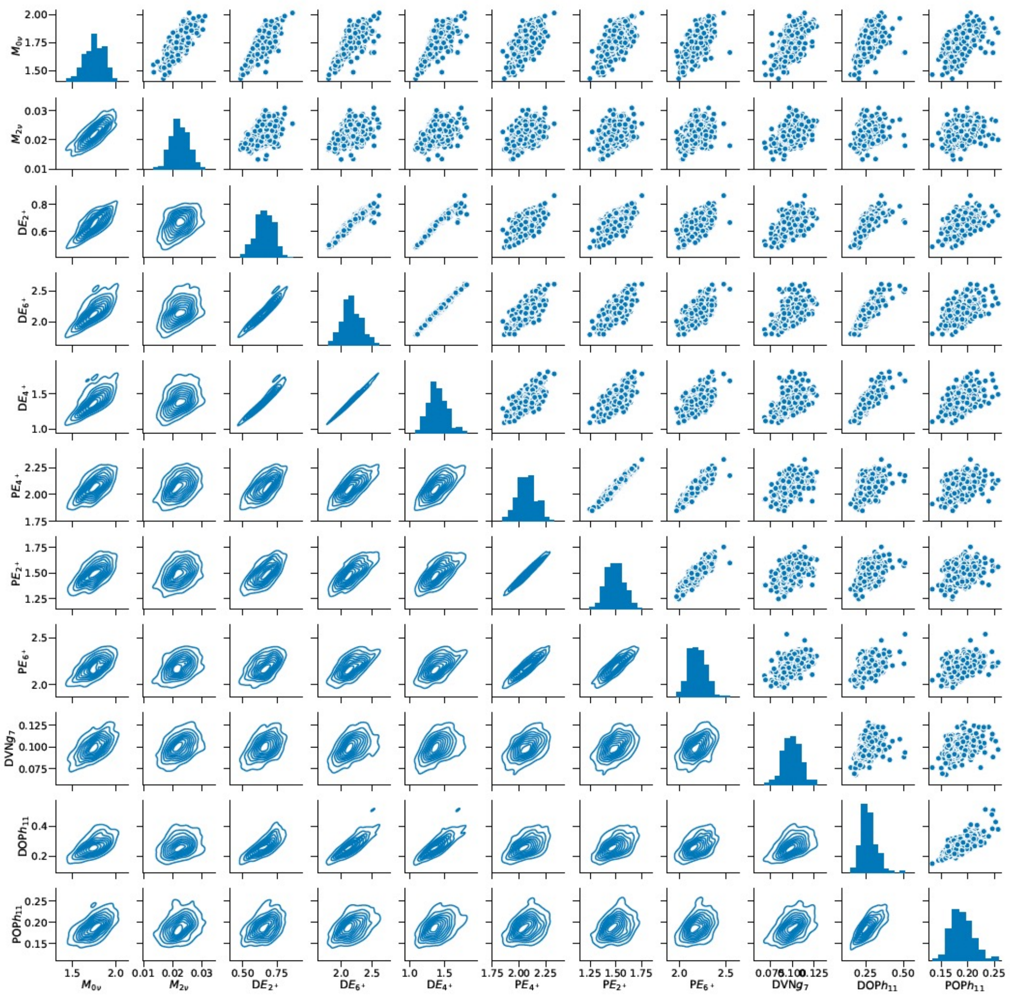
Neutrinoless Double-Beta Decay:
A Roadmap for Matching Theory to Experiment

Ab-initio approaches: start from well-motivated $\mathcal{N}\mathcal{N}$ and $\mathcal{N}\mathcal{N}\mathcal{N}$ forces and solve multi-$\mathcal{N}$ Schroedinger equation with systematically improvable methods



See talks by T. Miyagi at ISPUN 2023
J. Menendez at HADRON 2023
A. Ekstrom at HIRSCHEGG 2023

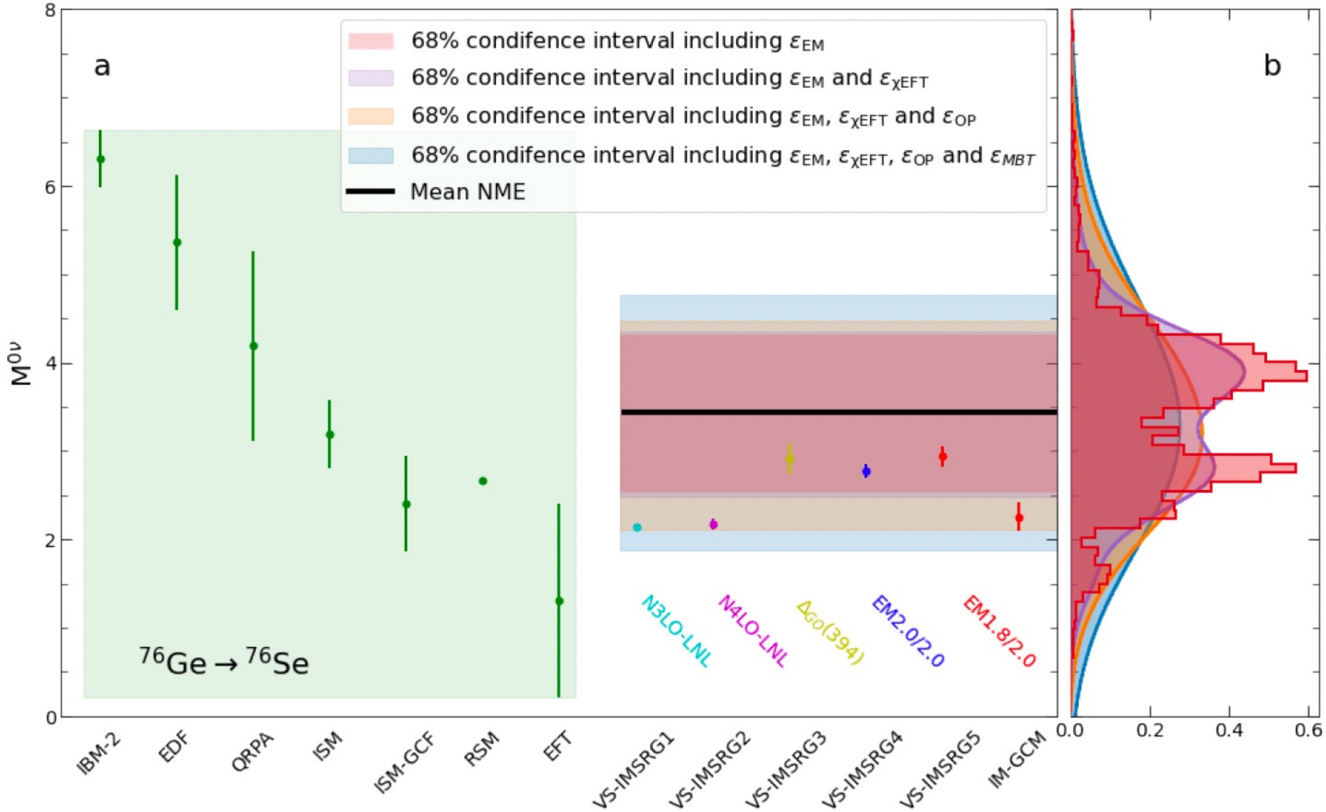
Benchmark method(s) with a variety of nuclear data and processes (including $2\nu\beta\beta$)



E.g., Horoi+ 2302.03664

Obtain probability distribution for calculated NME (not yet correlations etc.)

E.g., Belley+ 2308.1564 for ^{76}Ge



Already improvements w.r.t. usual x3 spread. Room for significant progress.

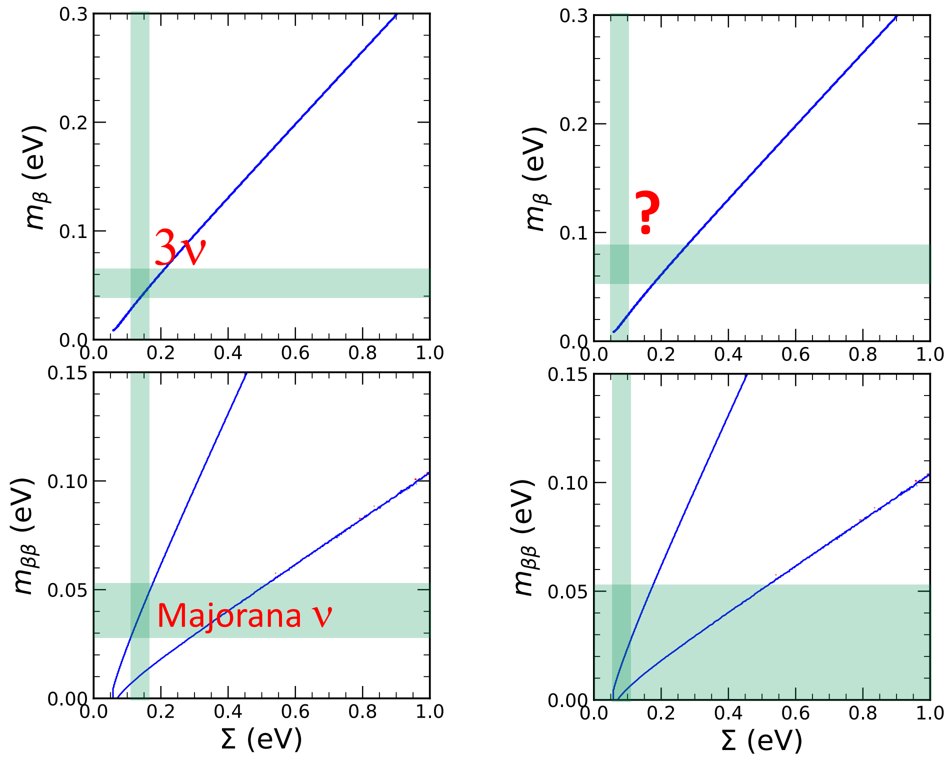
We may hope in NME (co)variances commensurate to ton-scale requirements.

Epilogue

Conceivable to dream about scenarios like these at **NEUTEL 203X:**

We may experience some nightmares, as well as **surprises**…

… but we will learn **a lot new from nature** at very different scales



Epilogue

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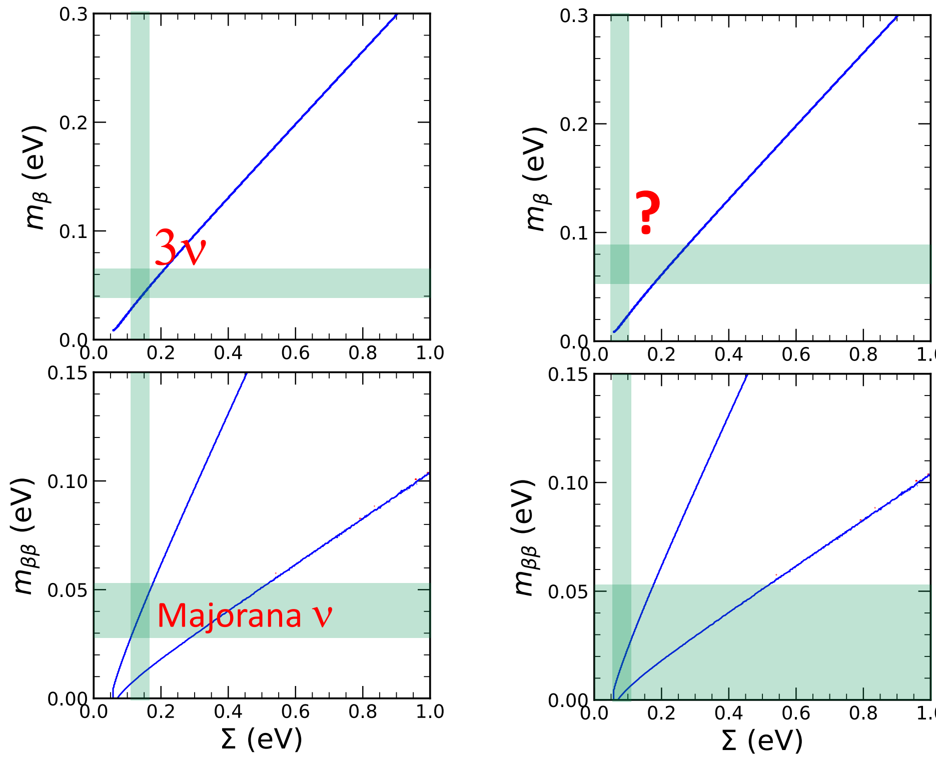

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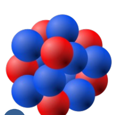
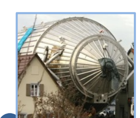
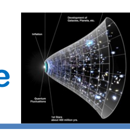


nuclei



laboratory

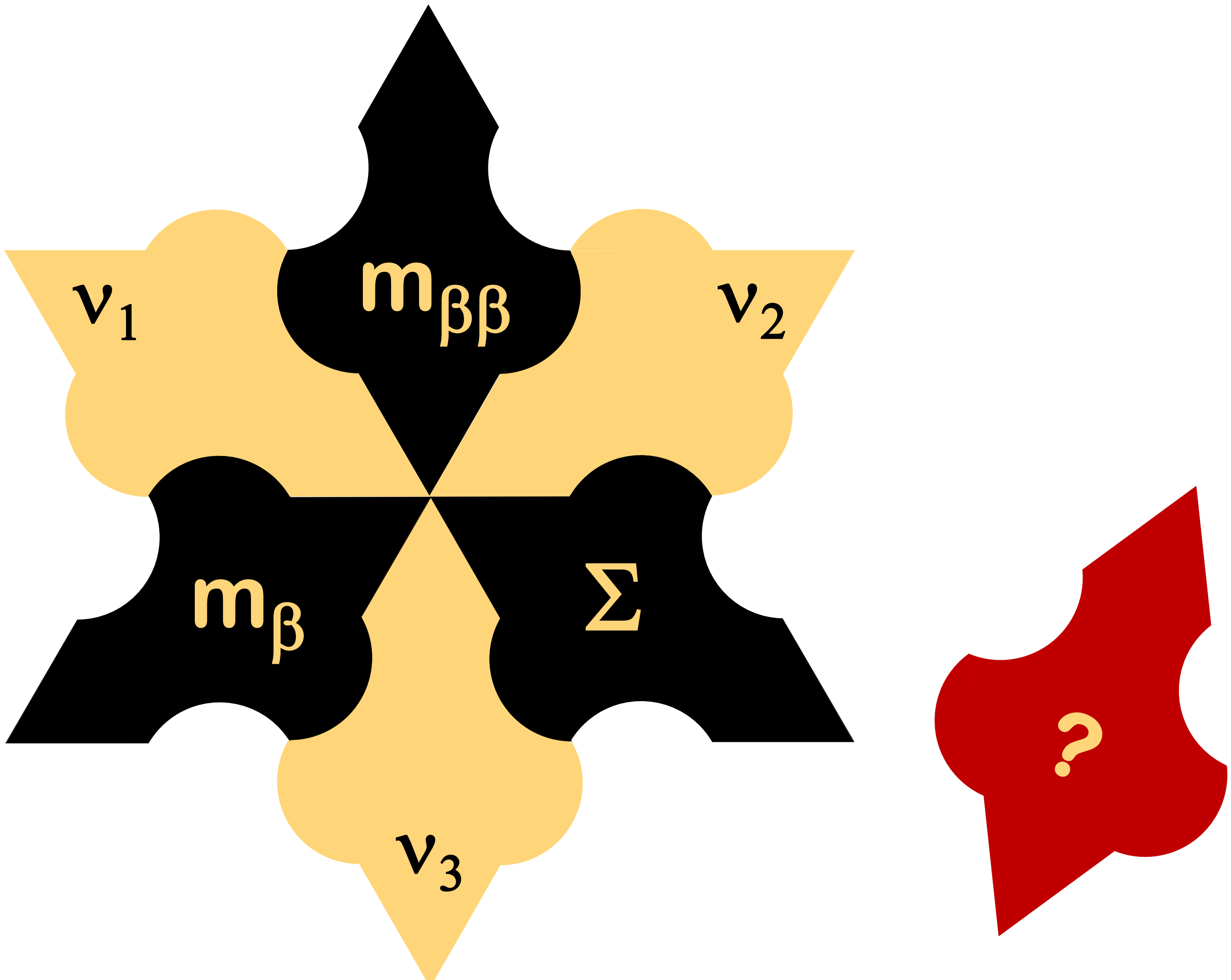
visible universe



10^{-15} 10^{0} 10^{15} 10^{30} m

[… here, a log scale is appropriate!]

Thank you for your attention!



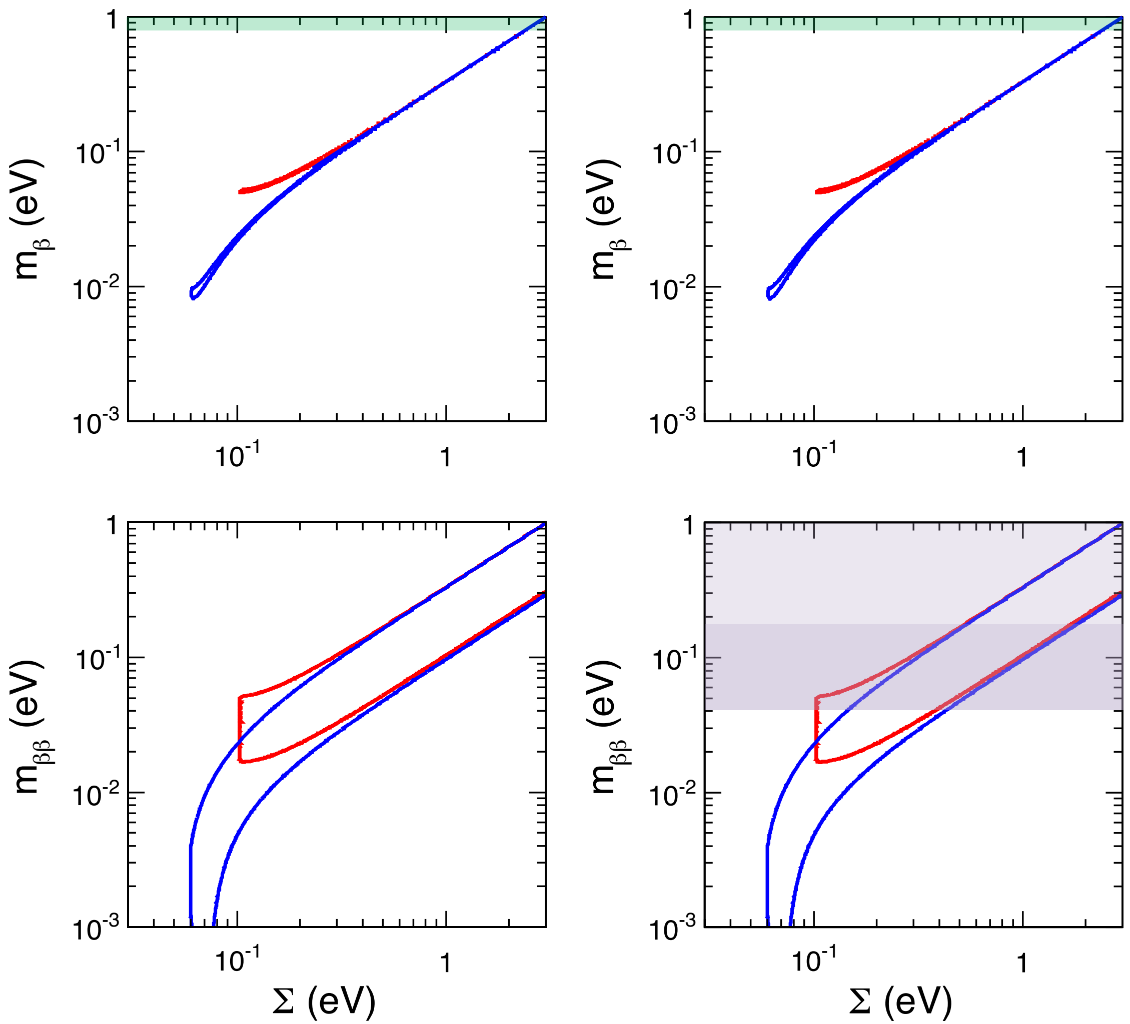
Work supported by PRIN 2022 "PANTHEON" (Italian MUR) & Network "TASP" (INFN)

Extras

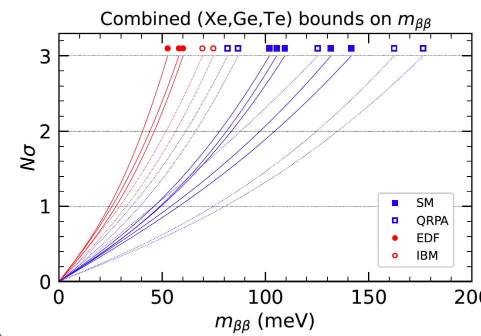
β : KATRIN

$0\nu\beta\beta$: KL-Zen, Exo, GERDA, Cuore...

[spread: nuclear models]



E.g., spread of upper bounds from Xe+Ge+Te data by using 15 nuclear matrix elements from 4 classes of nucl. models. e-print 2204.09569



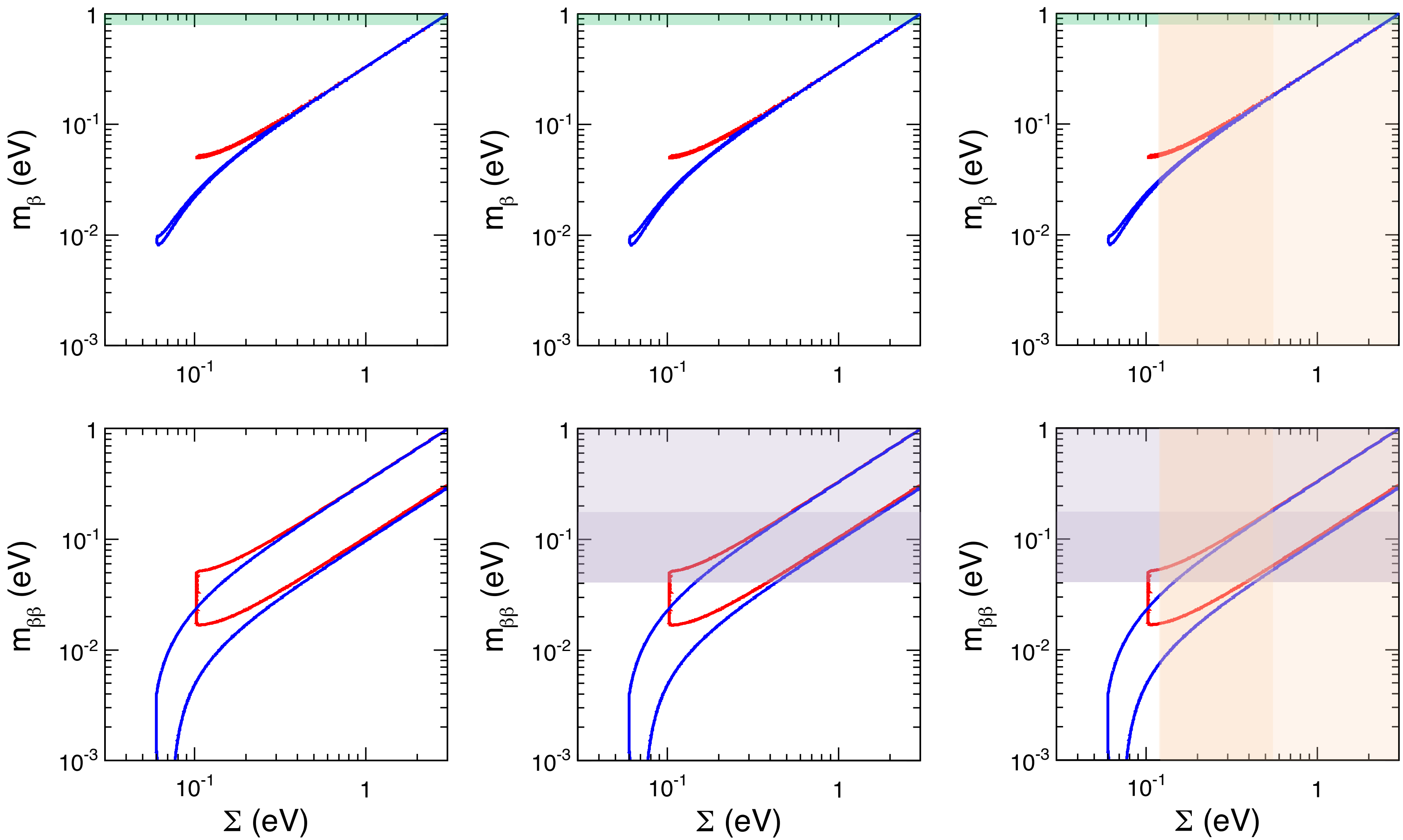
β : KATRIN

0νββ: KL-Zen, Exo, GERDA, Cuore...

[spread: nuclear models]

Σ: Planck, BAO, lensing ...

[spread: cosmo models/data]



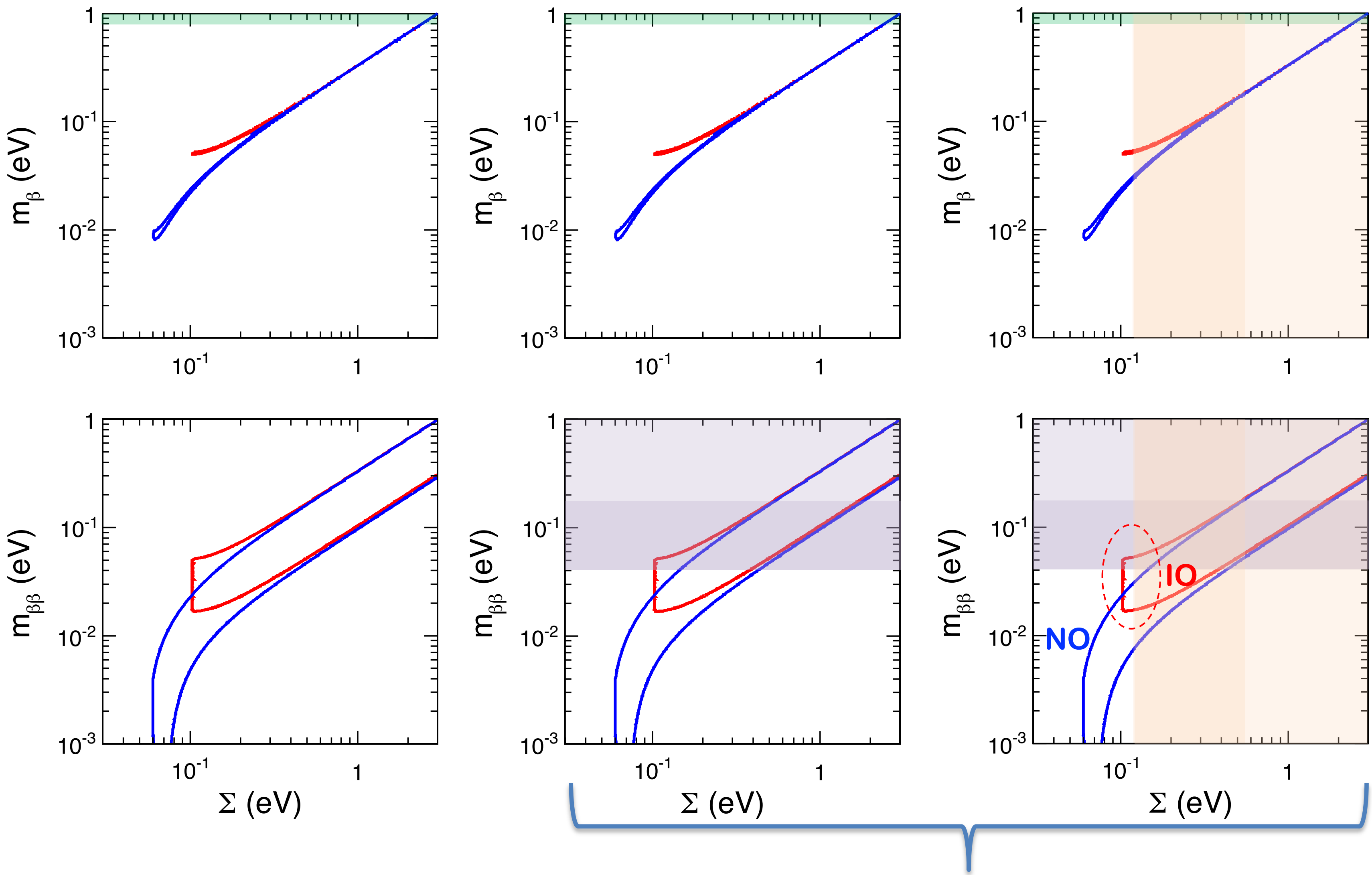
β : KATRIN

0νββ: KL-Zen, Exo, GERDA, Cuore...

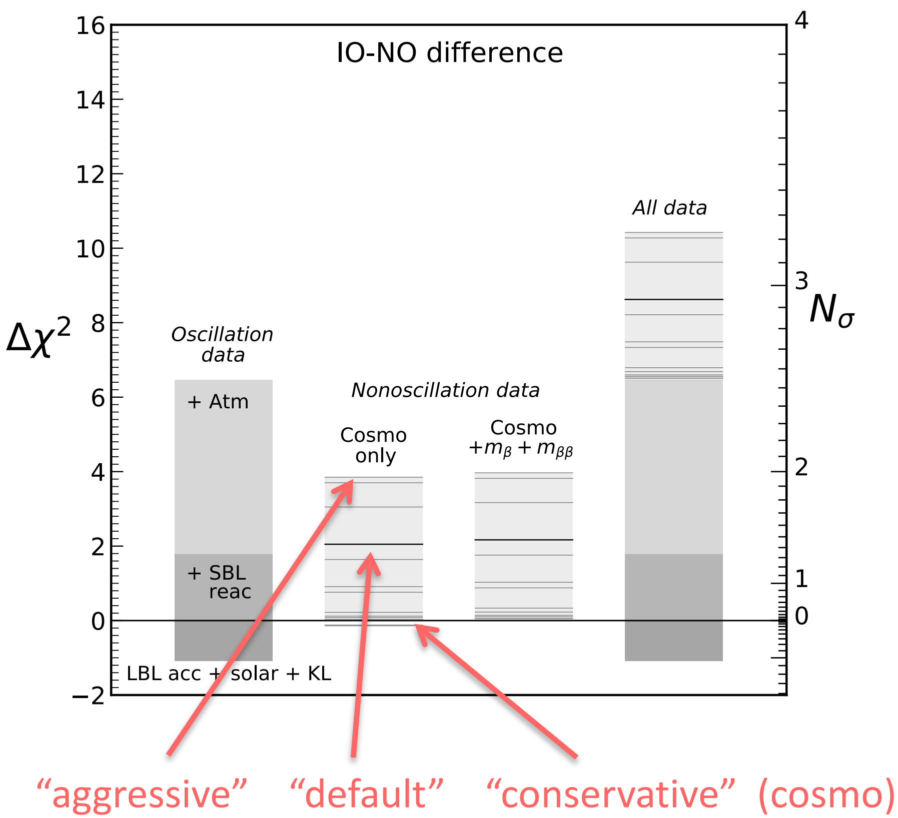
Σ: Planck, BAO, lensing ...

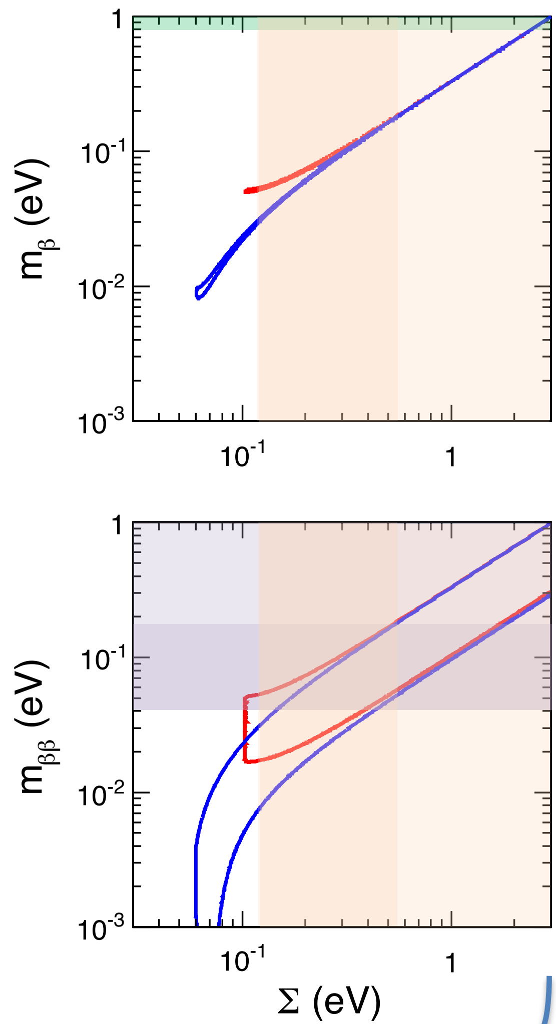
[spread: nuclear models]

[spread: cosmo models/data]



IO "under pressure" but not excluded yet





IO currently disfavored at ~3σ by combining oscillation + nonoscillation data