Recent topics in the analysis of ν mass-mixing parameters

Eligio Lisi

INFN, Bari, Italy

Workshop on SM&B

Corfu, Sep 2nd, 2023

Image credit: Wikimedia

Outline

- Standard 3ν parameters: status and open issues *
- A nonstandard case with light + heavy neutrinos **
- Conclusions

* *Mainly based on Capozzi+ 2107.00532 and Lisi+ 2204.09569*

** *Mainly based on Lisi+ 2306.07671*

Standard 3ν 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*(ν̅)

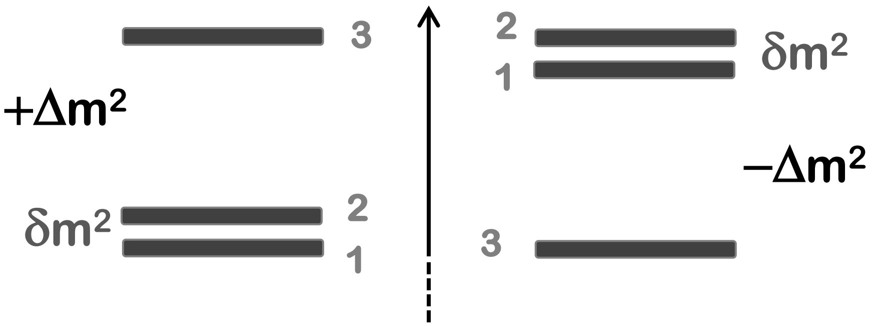
1-2 rotation

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

Mass [squared] spectrum

(E ~ p + $m^2/2E$ + "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
+ absolute ν mass scale (not tested in oscillations)

Sketchy 3ν status

5 knowns (robust):

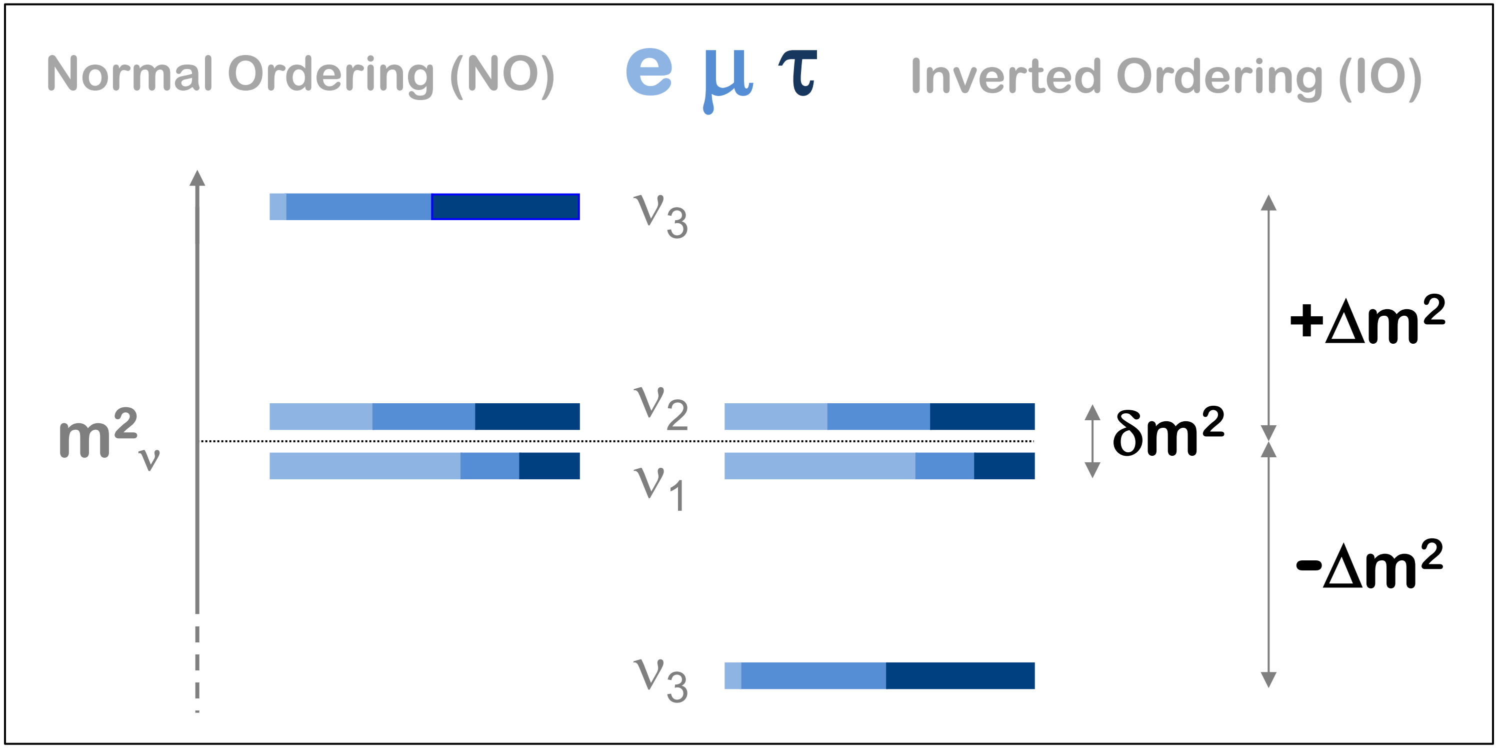
δm^2 ~ 8×10^{-5} eV^2
Δm^2 ~ 2×10^{-3} eV^2
$\sin^2\theta_{12}$ ~ 0.3
$\sin^2\theta_{23}$ ~ 0.5
$\sin^2\theta_{13}$ ~ 0.02

Oscillations

Non-oscillat.

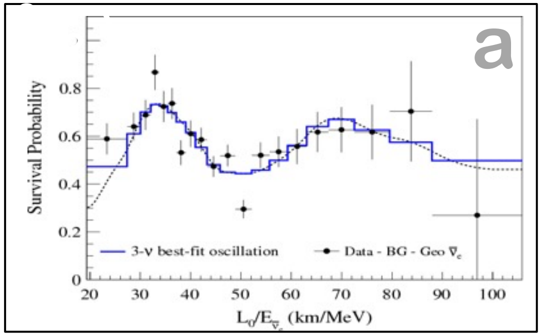
5 unknowns:

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

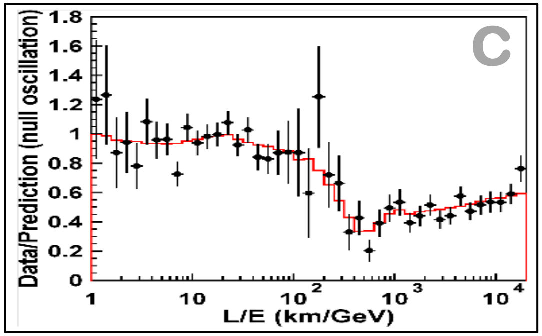


3ν oscillations probed by many experiments in different flavor channels…

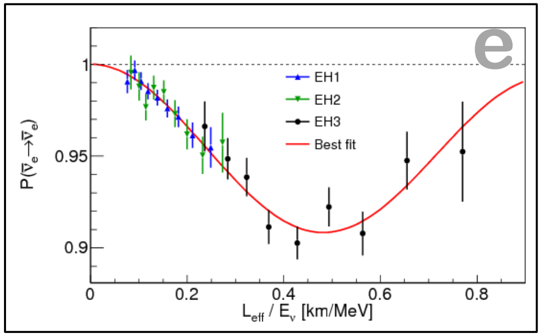
e→e (KamLAND, KL)



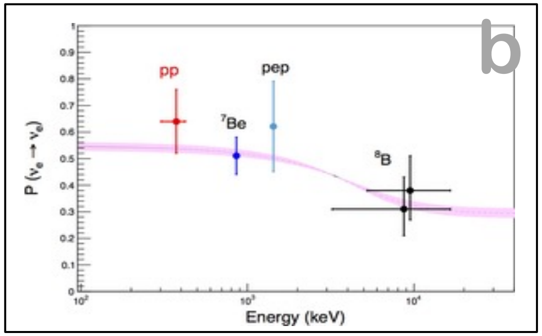
μ→μ (Atmospheric)



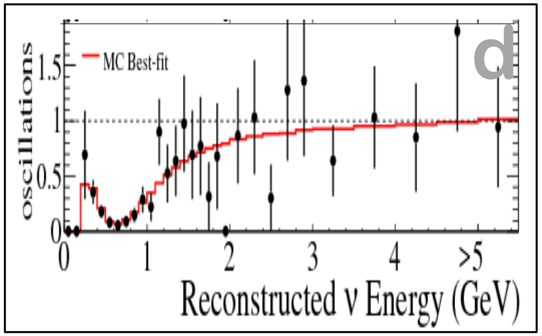
e→e (SBL Reac.)



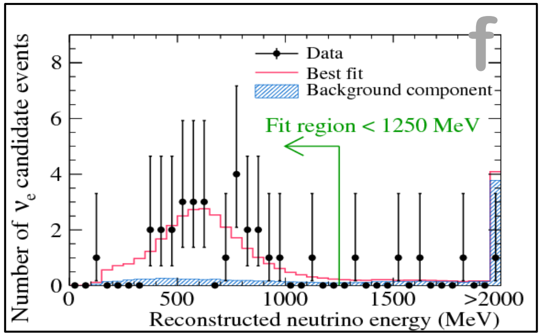
e→e (Solar)



μ→μ (LBL Accel)



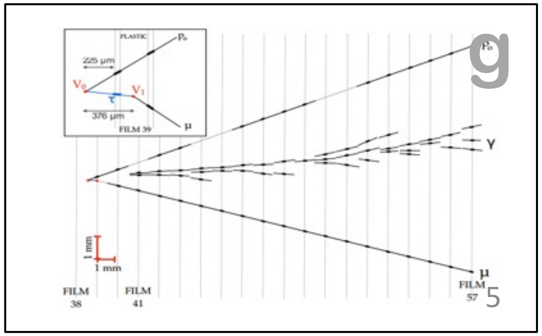
μ→e (LBL Accel)



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

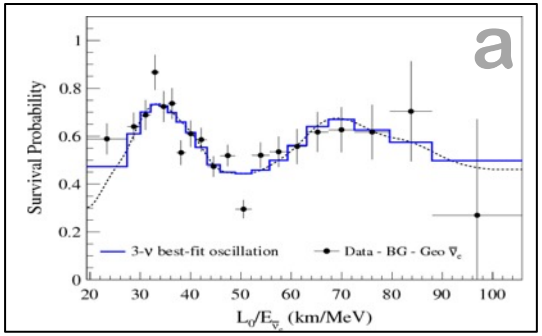
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot]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

μ→τ (OPERA, SK, DC)

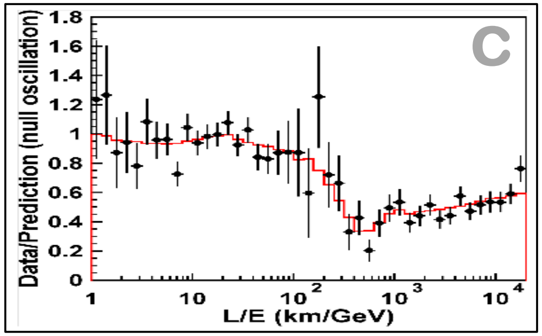


… with amplitude and frequency governed by 2 (or 3) leading parameters

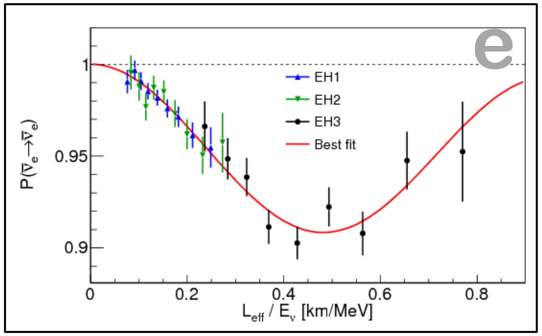
$e \to e$ (δm^2 , θ_{12})



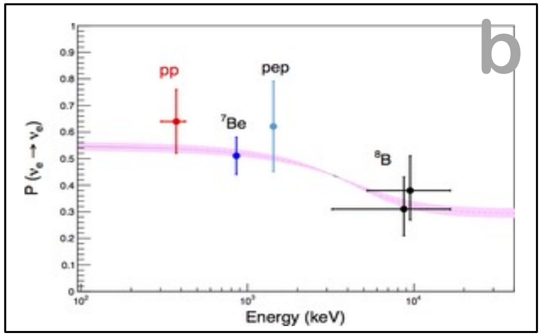
$\mu \to \mu$ (Δm^2 , θ_{23})



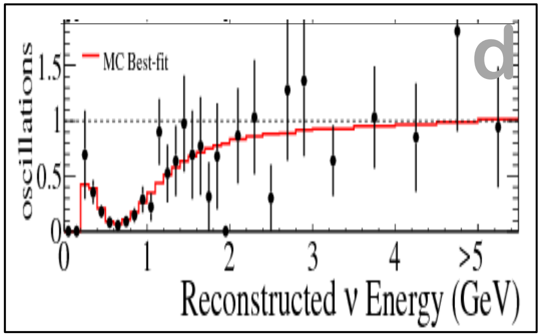
$e \to e$ (Δm^2 , θ_{13})



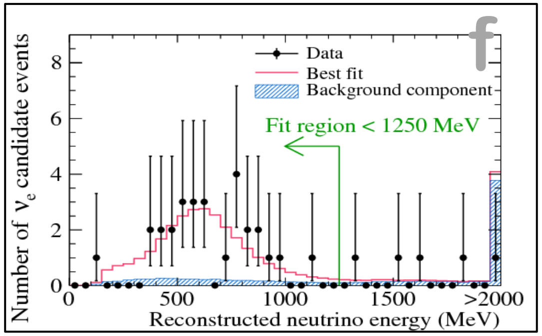
$e \to e$ (δm^2 , θ_{12})



$\mu \to \mu$ (Δm^2 , θ_{23})



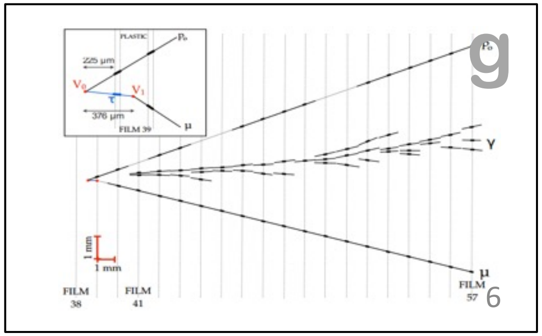
$\mu \to e$ (Δm^2 , θ_{13} , θ_{23})



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.

$\mu \to \tau$ (Δm^2 , θ_{23})

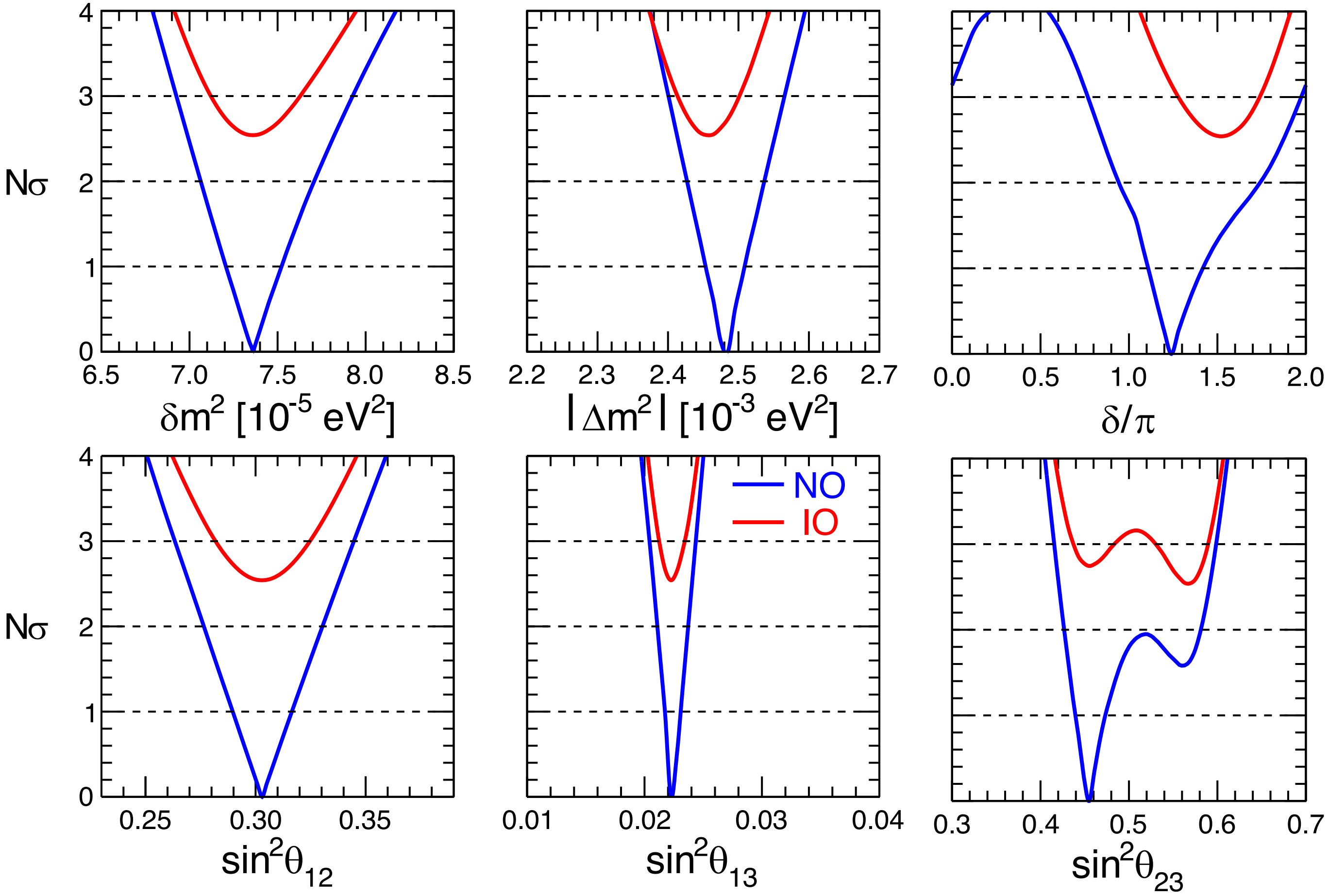


$N\sigma$ bounds on known and unknown 3ν osc. parameters: Global analysis ~2021*

1σ error of **known** parameters

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

All ν oscillation data

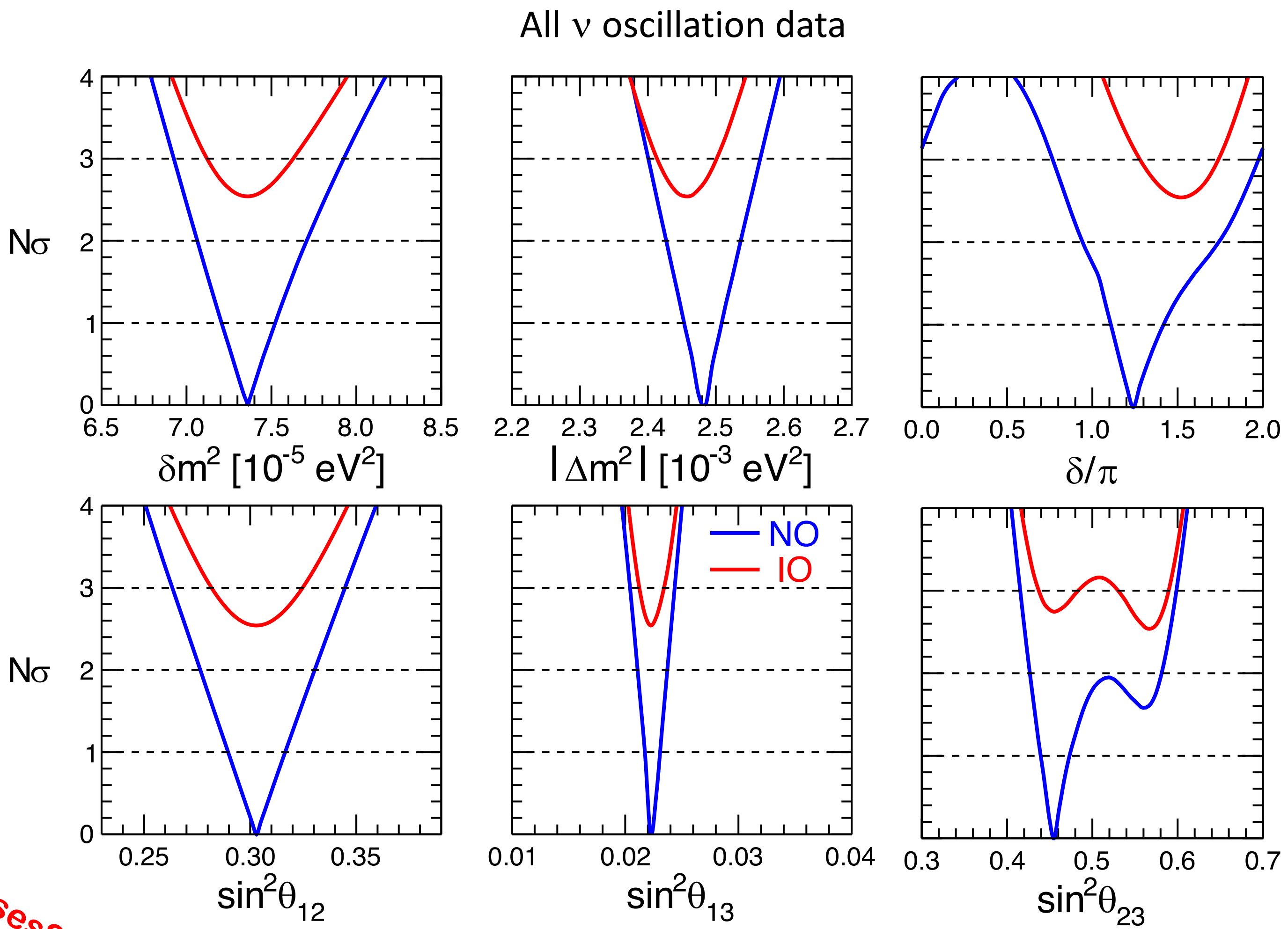


** Next relevant update: presumably in ~2024*

Hints on oscillation **unknowns** **(2021)**

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

Nσ bounds on **known** and **unknown** 3ν osc. parameters: **Global analysis ~2021**


All ν oscillation data

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%

precision

(surprises?)

Frontiers

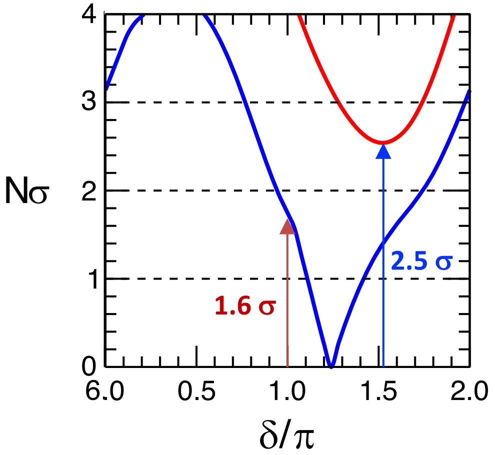
discovery

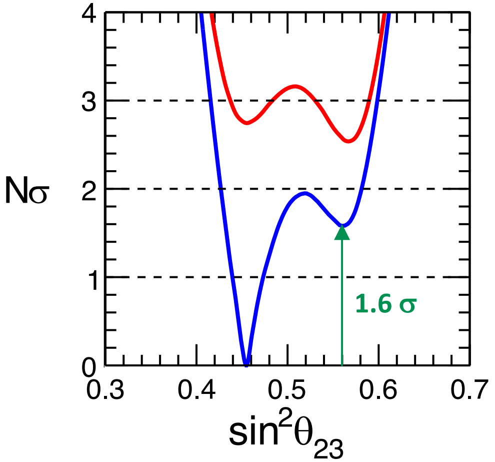
Hints on oscillation **unknowns** **(2021)**

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

Hints on oscillation **unknowns, 2021…**

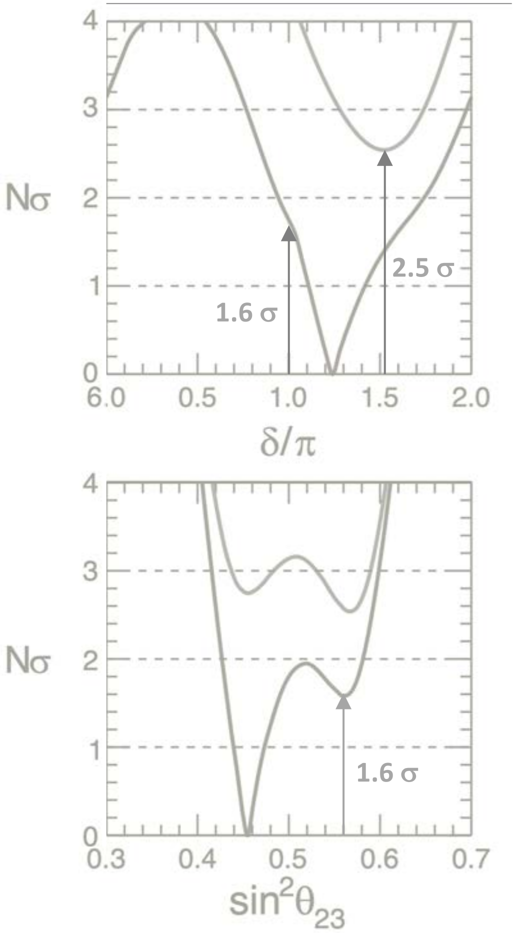
NO	~99% CL
sin$\delta < 0$	~90% CL
$\theta_{23} < \pi/4$	~90% CL





Hints on oscillation **unknowns, 2021…**

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



…Educated guess on **oscill. unknowns, after some recent data**

→ presumably >99% CL

→ presumably >90% CL

→ presumably flipped to > $\pi/4$

Main impact expected from ***new SK atmos. data in combination with T2K****, which may win over the T2K-NOvA tension:* ***Wait for T2K+NOvA new data and joint fit!***

Wait for full IC-DC atmospheric data set and NO/IO analysis!

Watch for synergy of various |Δm^2| measurements: *convergence / divergence in true/wrong ordering (& octant)*

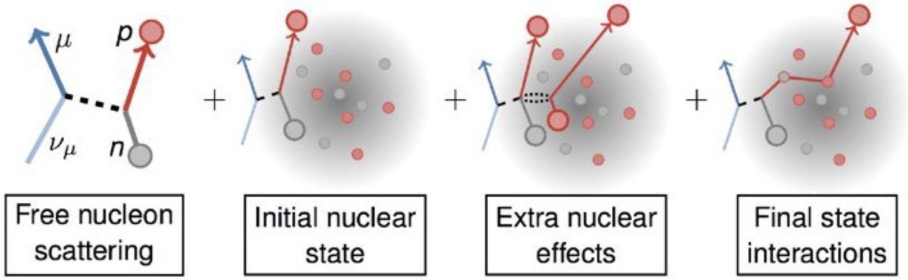
Expect global update in ~2024

Open issues in neutrino interaction physics

Oscillation phase ∝ $\Delta m^2/E$ → E-reconstruction uncertainties may bias Δm^2

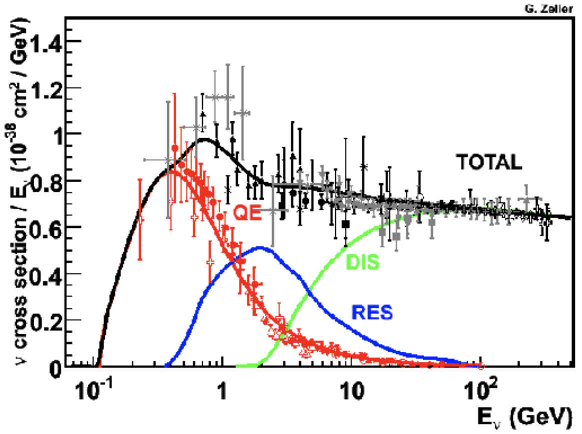
… and may affect central values and errors of other parameters via correlations

Theory: complex nuclear effects



Kajetan Niewczas @ NuFact2018

Experiment: relatively few data



Great effort to improve the situation through dedicated measurements and improved nuclear models, but non-negligible uncertainties remain

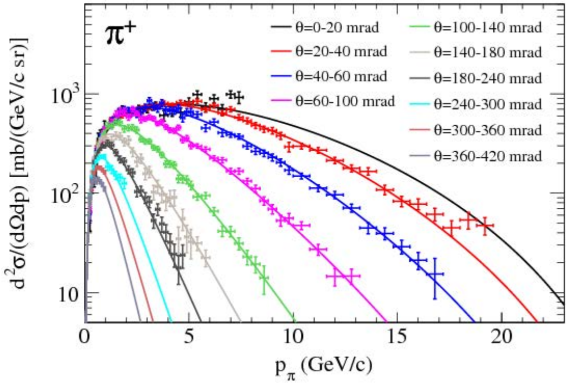
[Also relevant in the context of nonstandard neutrino interaction searches]

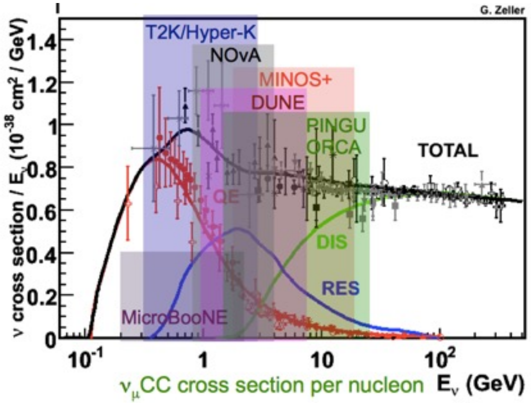
“Strong interaction” effects on “weak interaction” physics are ubiquitous…

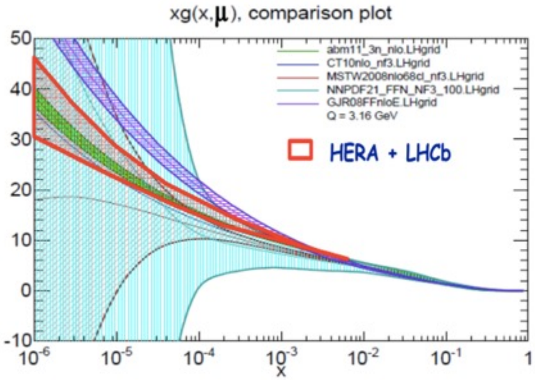
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atmos. and acceler. ν fluxes and errors

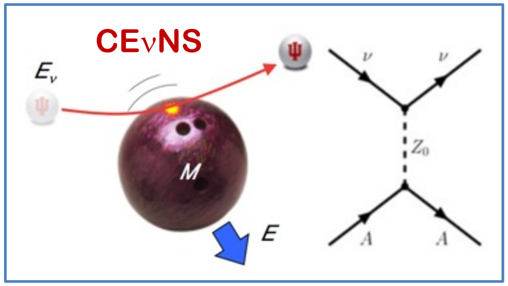
Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

Improved PDFs at low-x via ~forward charm production at LHCb essential to constrain prompt component in UHE ν



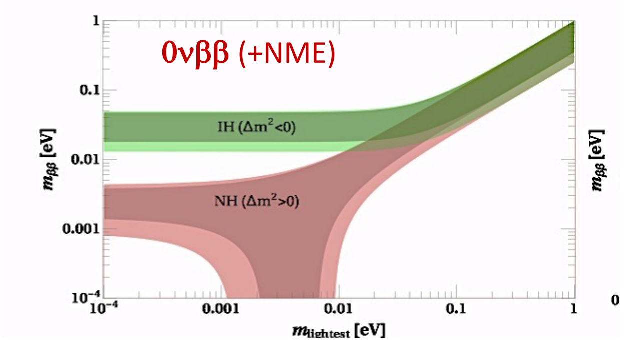






Control of nuclear EW response (e.g., form factors) relevant to interpret many low-energy data: CEvNS, reactor spect., 0ν2β

…



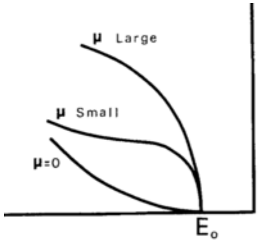
Progress requires further integration of different Expt+Theo communities:

→ (re)emerging field of “Electroweak Nuclear Physics”

Non-oscillation neutrino mass observables: (m_β , $m_{\beta\beta}$, Σ)

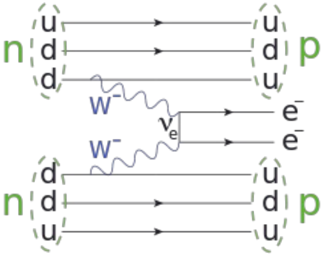
β decay, sensitive to the "effective electron neutrino mass":

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



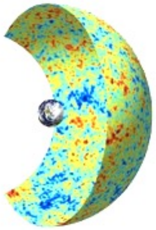
0νββ decay: **only if Majorana.** "Effective Majorana mass":

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



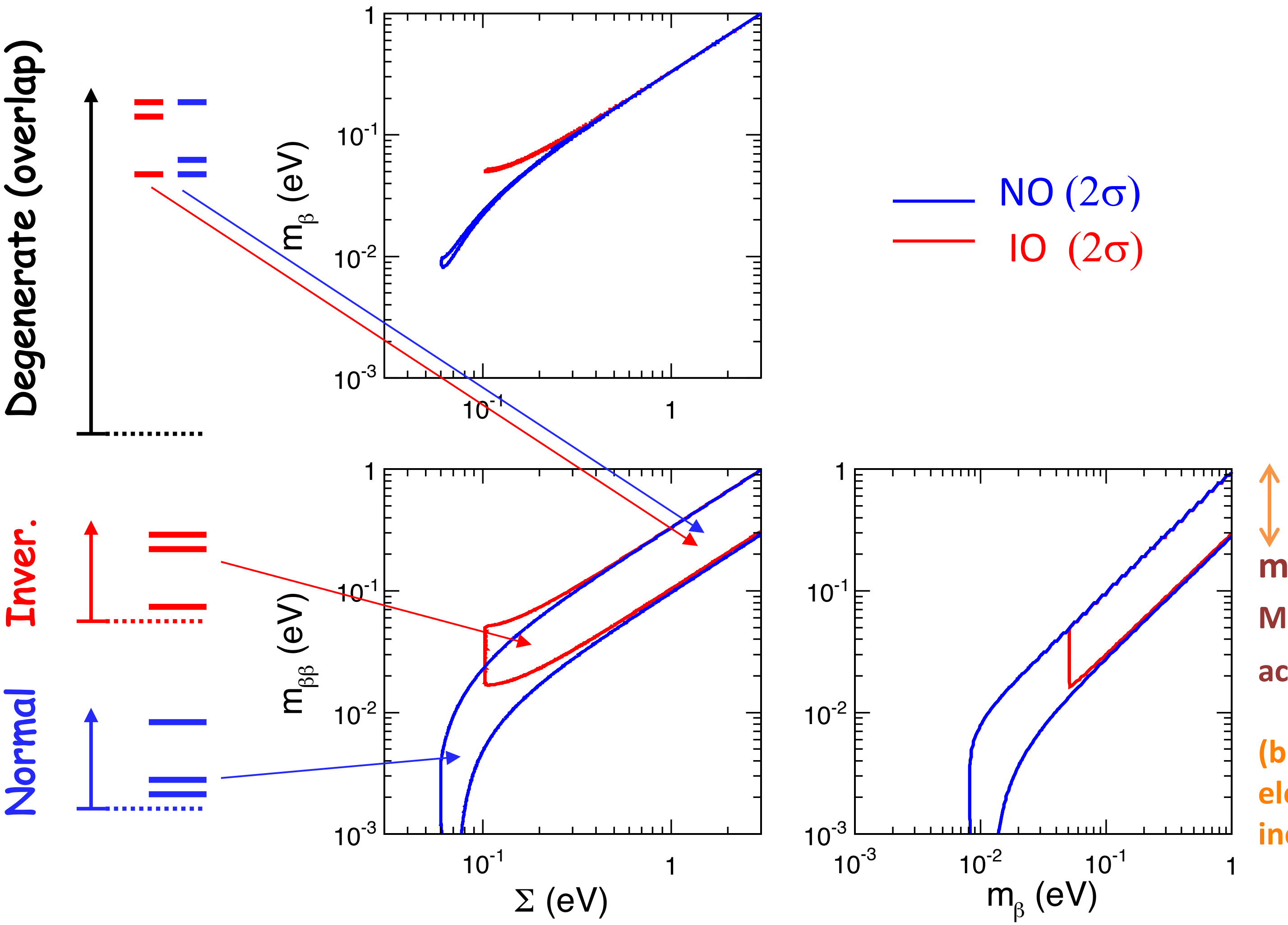
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



May provide additional handles to distinguish NO/IO!

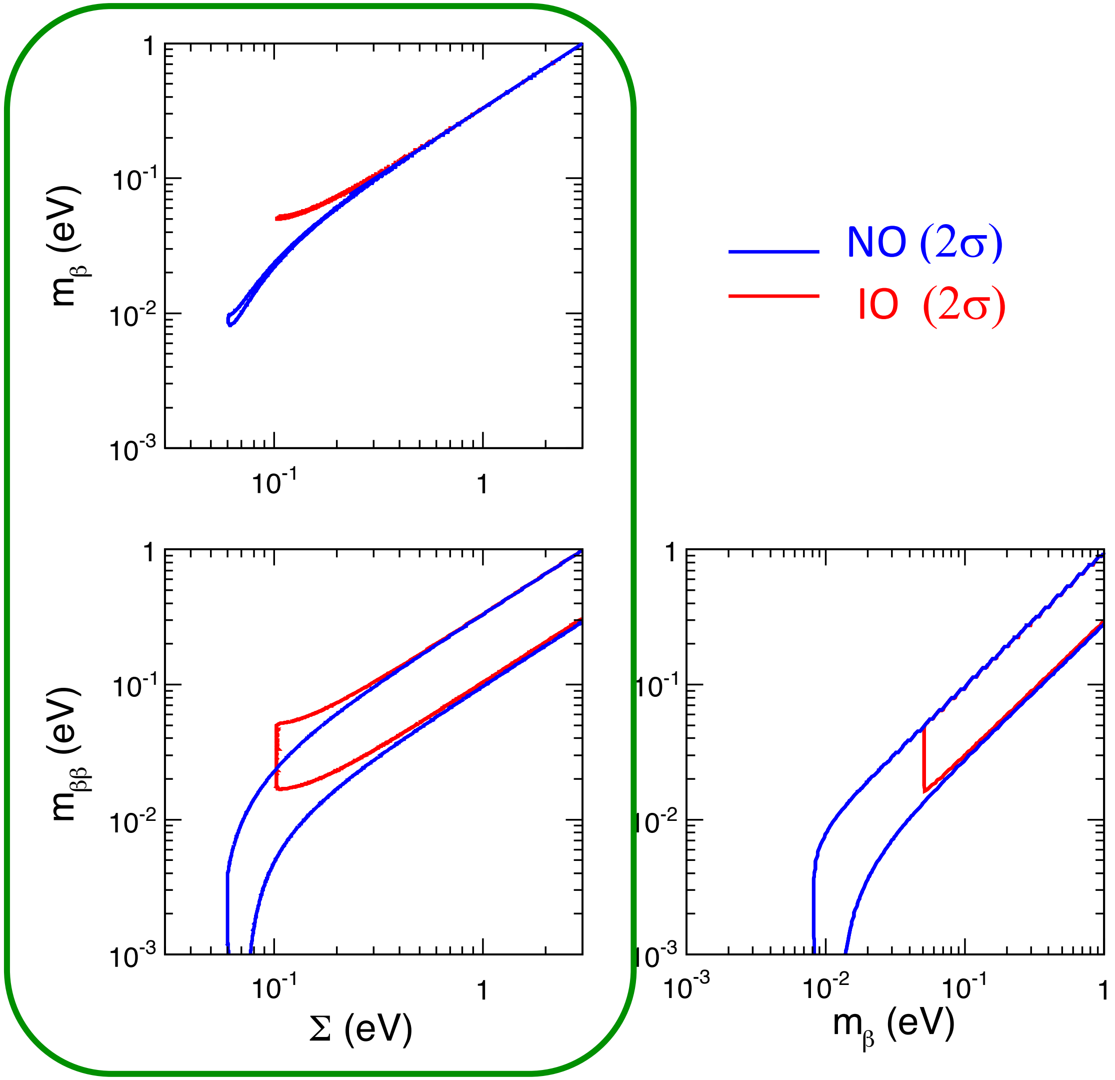
Absolute mass observables: bands allowed by oscillations in NO/IO



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

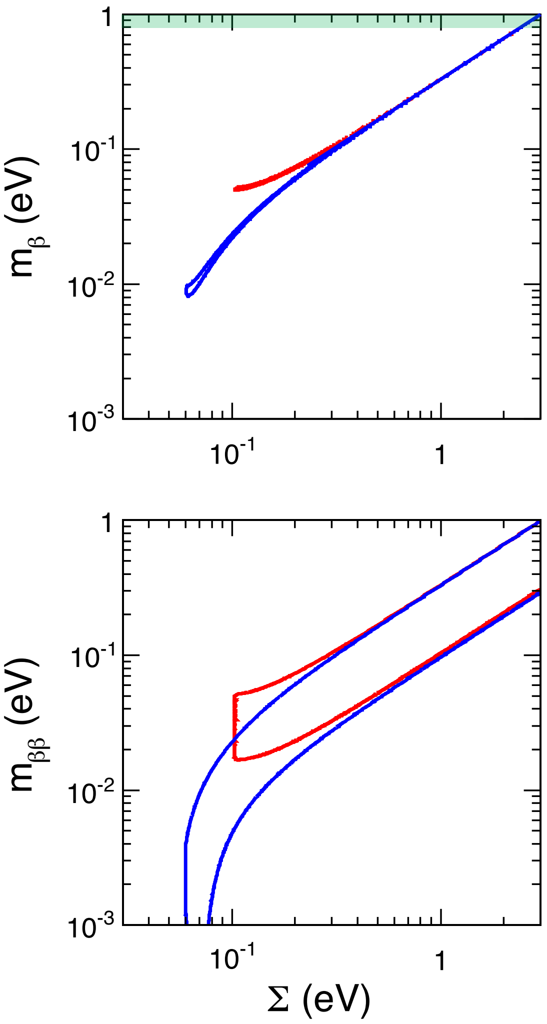
(but: no nuclear matrix element uncertainties included here!)

Absolute mass observables: currently, only upper bounds…



Focus on these planes

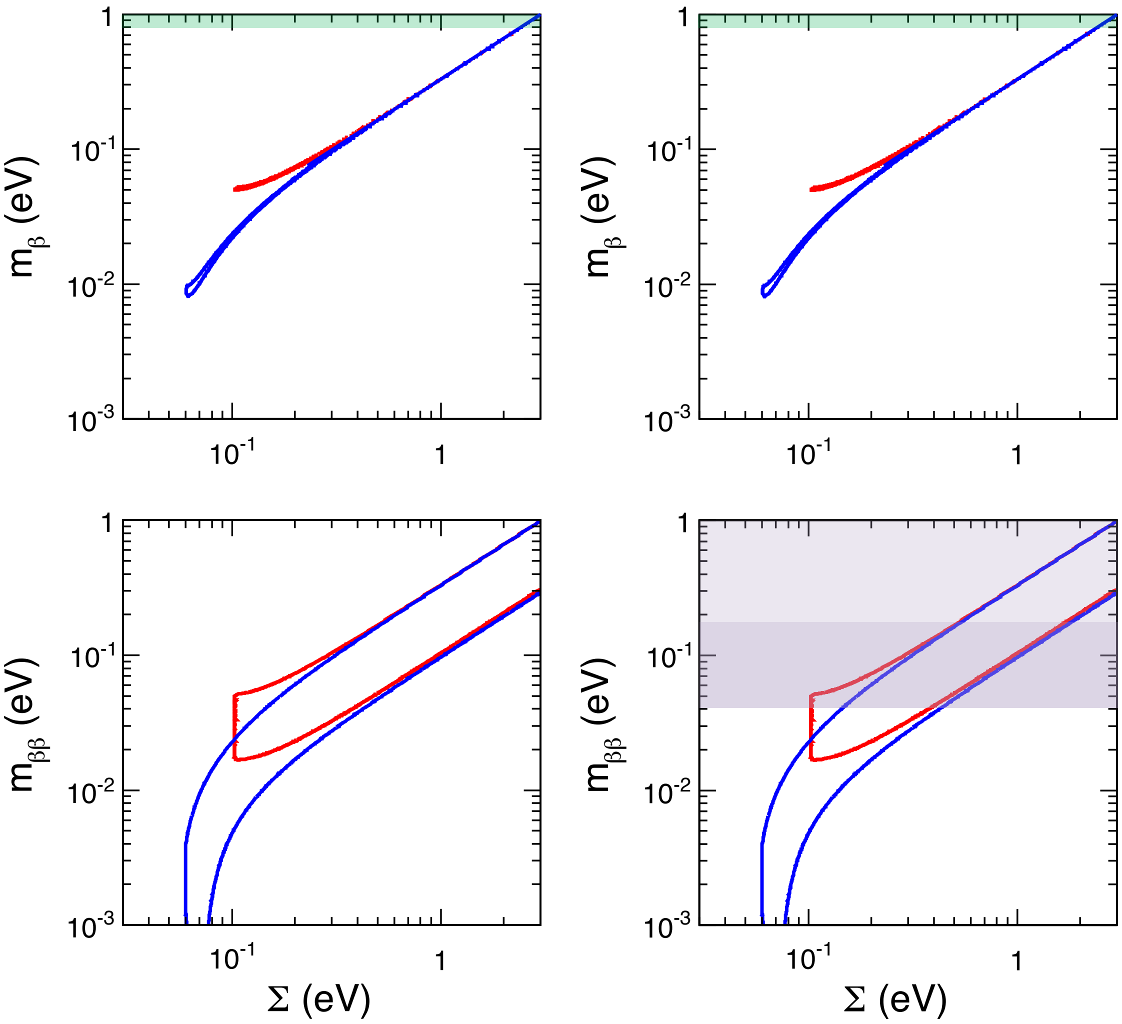
🟩 β : KATRIN



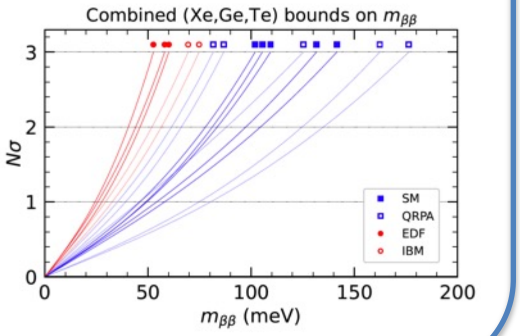
🟩 **β : KATRIN**

🟪 **$0\nu\beta\beta$: 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



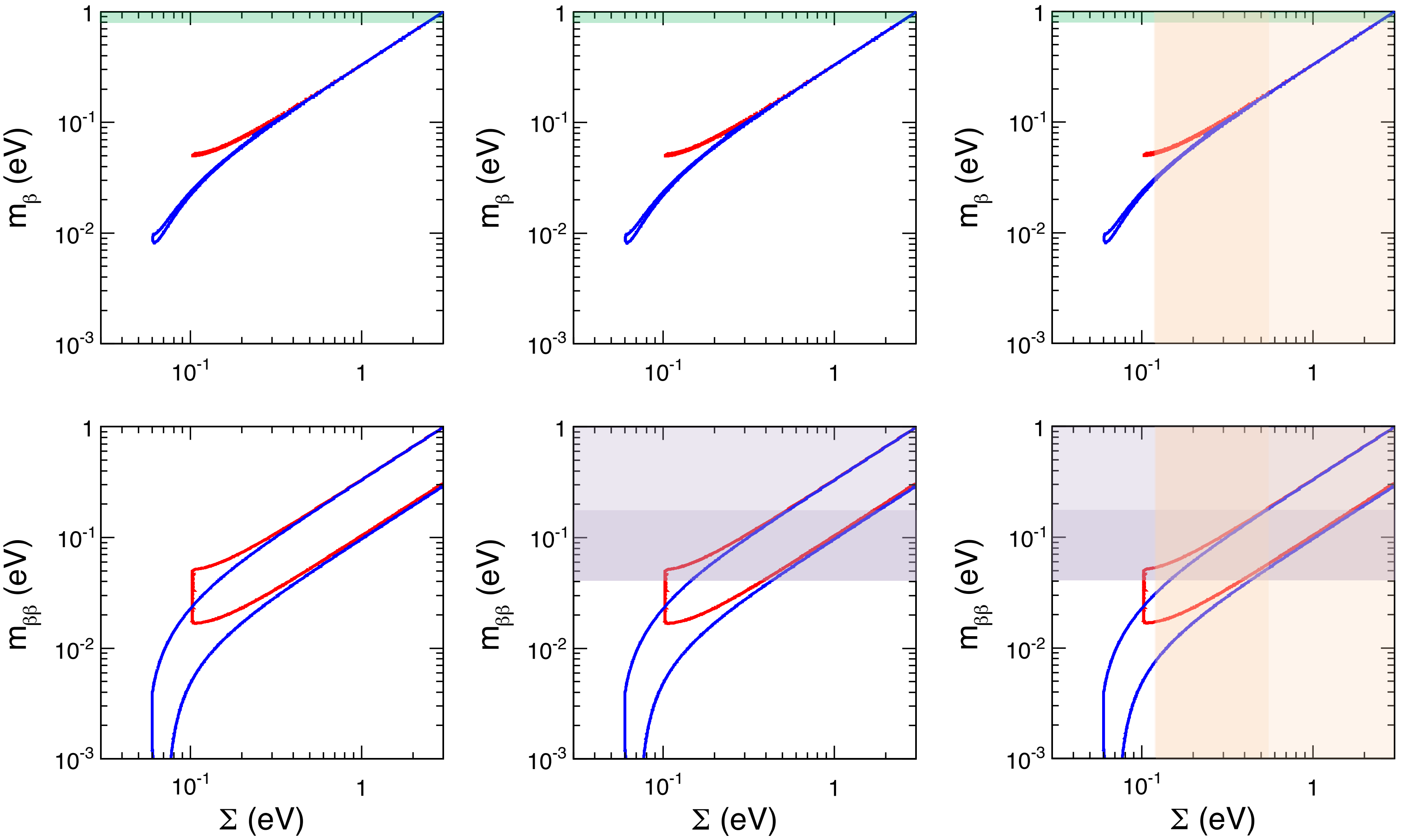
🟩 **β : KATRIN**

▨ **0νββ :** KL-Zen, Exo, GERDA, Cuore...

[spread: nuclear models]

▨ Σ: Planck, BAO, lensing ...

[spread: cosmo models/data]



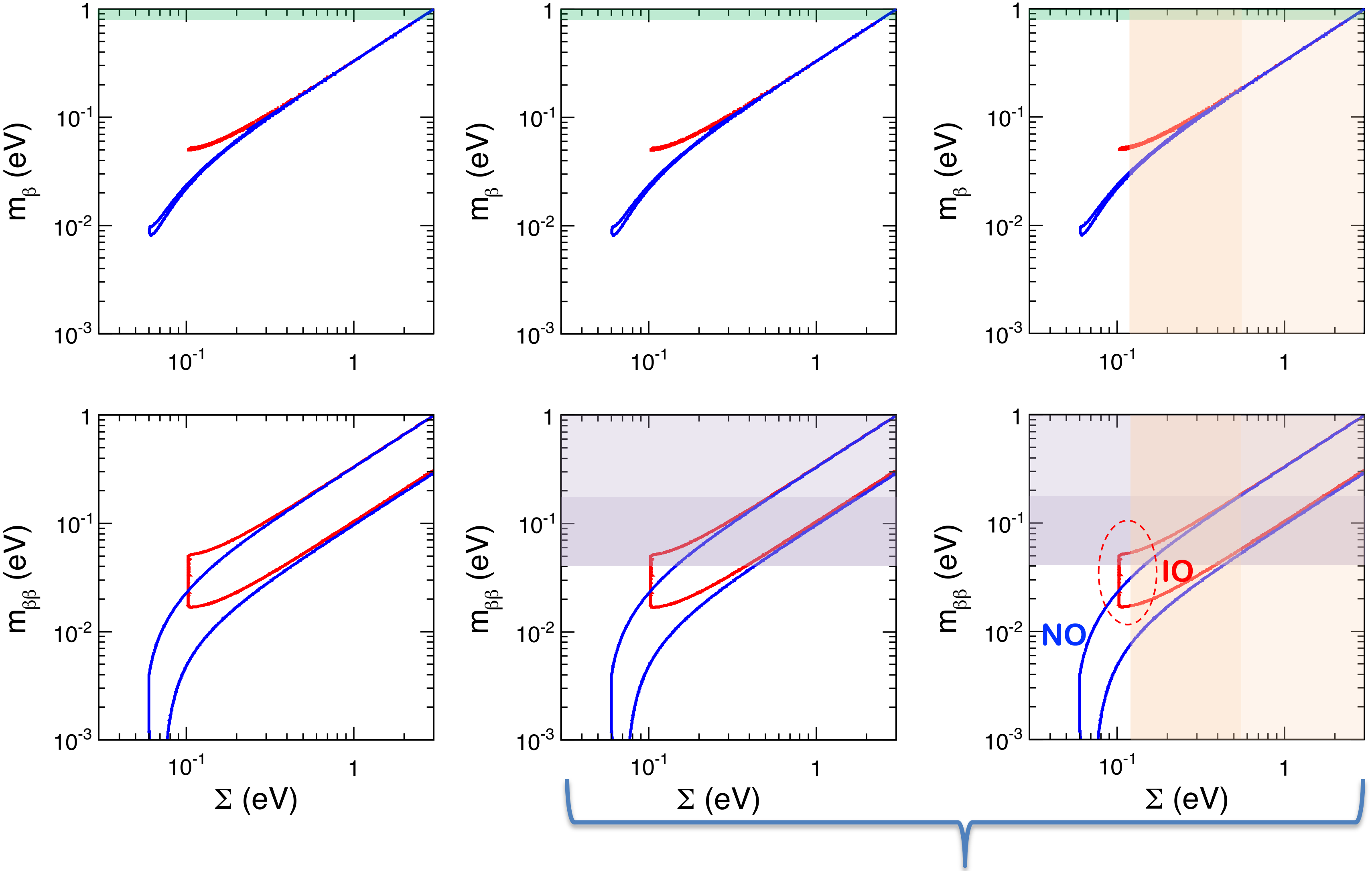
🟩 **β : KATRIN**

▨ **0νββ :** KL-Zen, Exo, GERDA, Cuore...

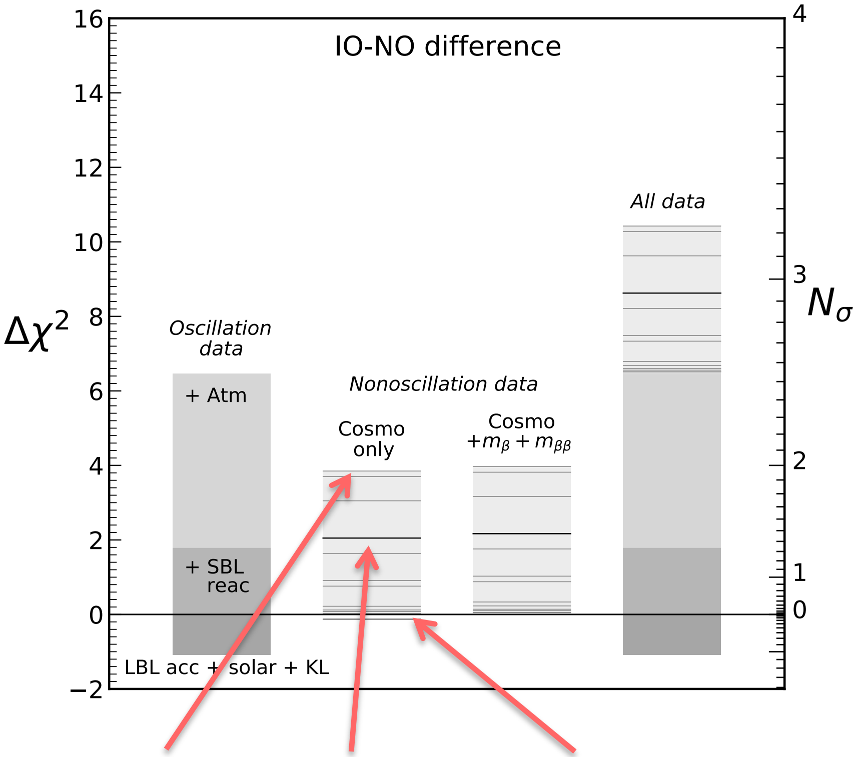
[spread: nuclear models]

▨ Σ: Planck, BAO, lensing ...

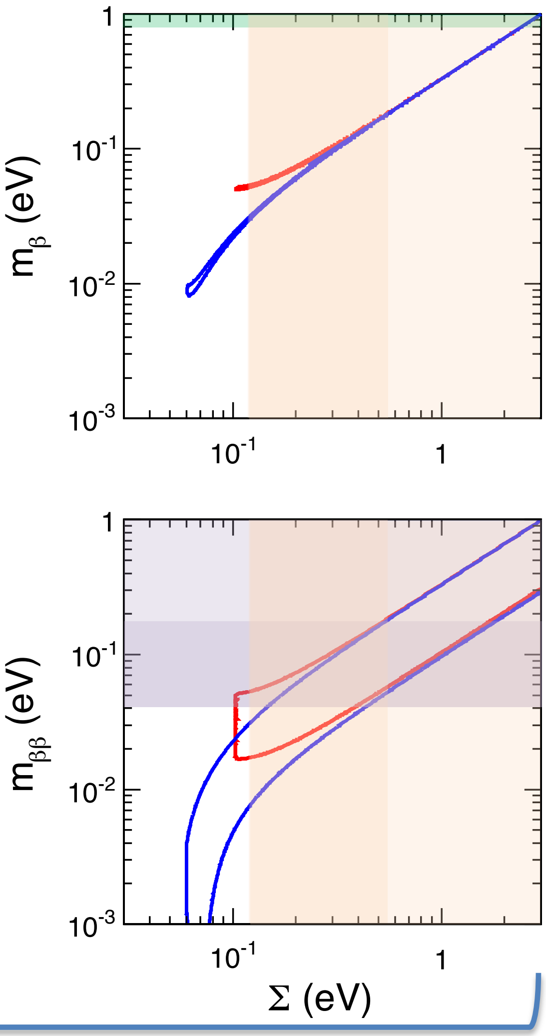
[spread: cosmo models/data]



IO "under pressure" but not excluded yet



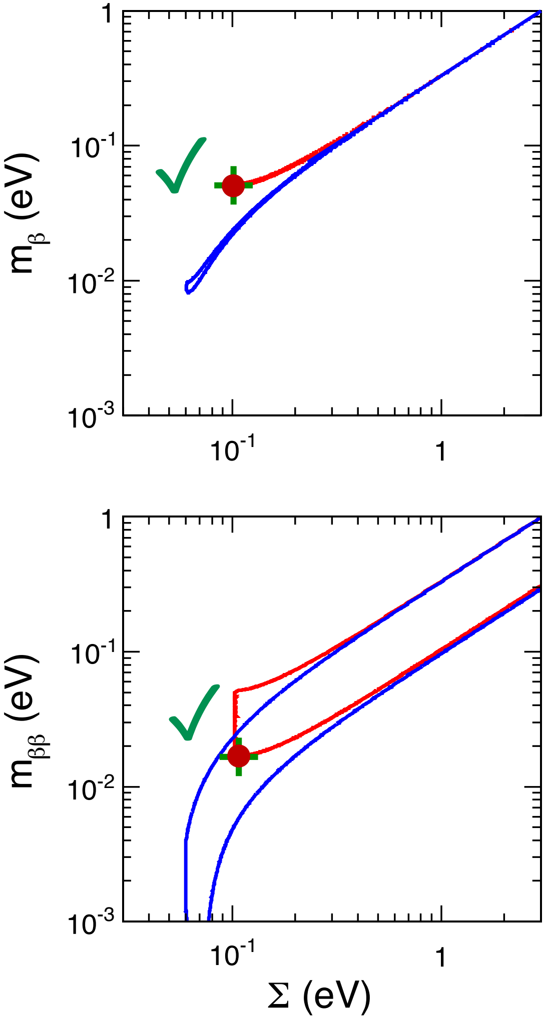
"aggressive" "default" "conservative" (cosmo)



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

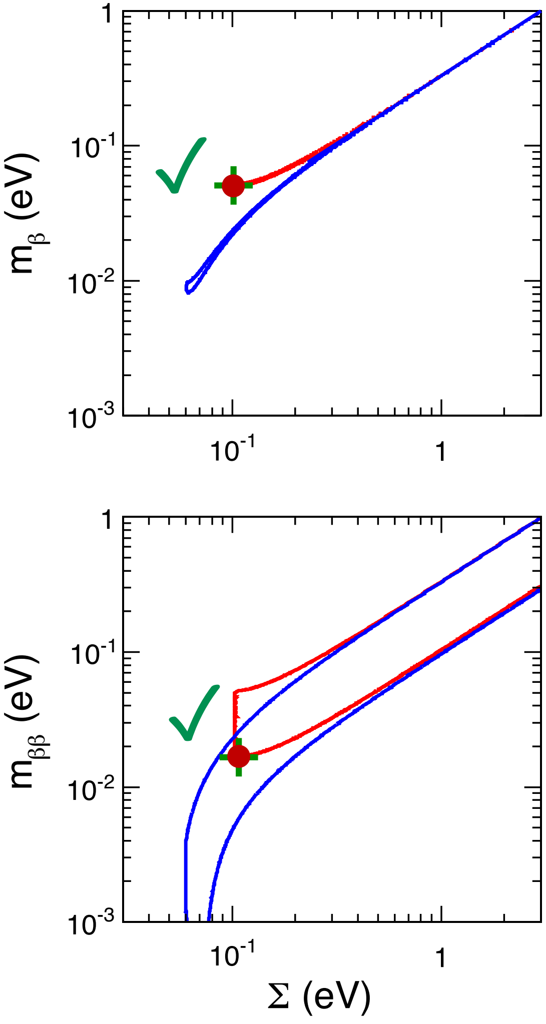
Far-future data dreams:

3ν convergence?

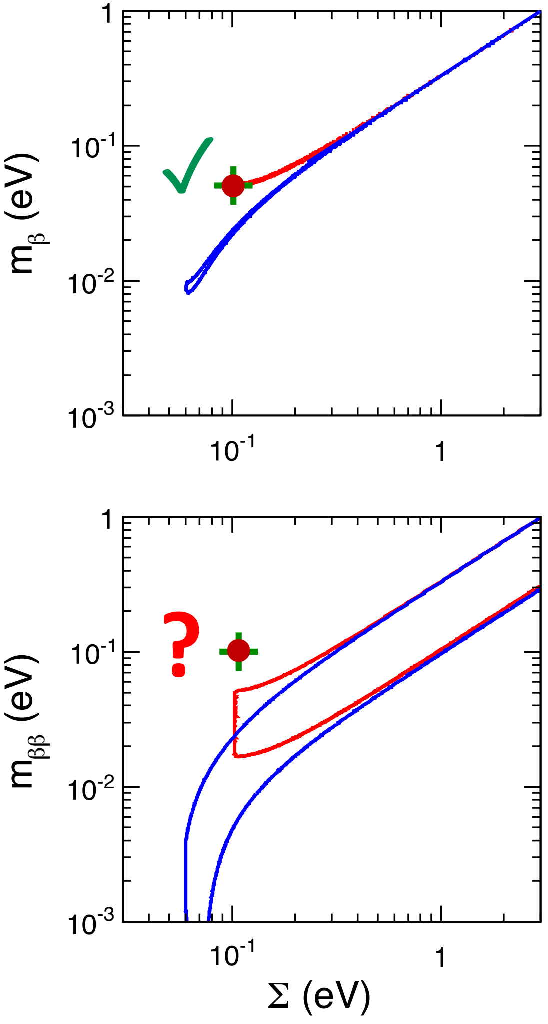


Far-future data dreams:

3ν convergence?

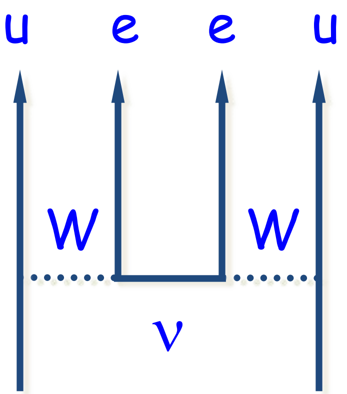


… or surprises?

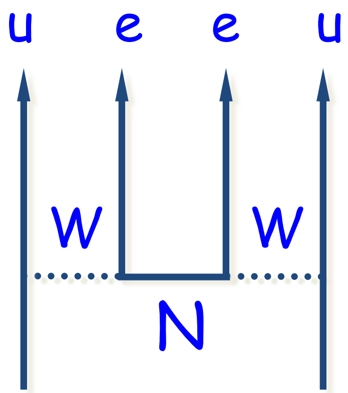


Lack of convergence might suggest new physics: e.g., **nonstandard 0νββ**

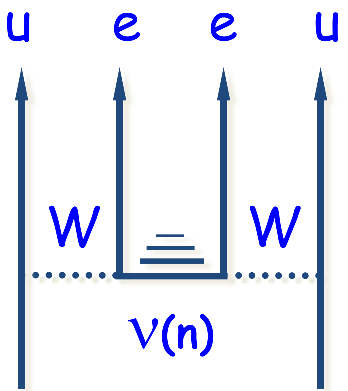
Examples of $0\nu\beta\beta$ decay induced by different mechanisms



Standard

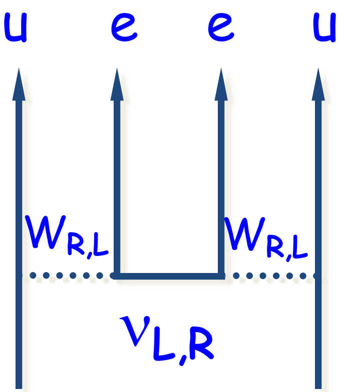


Heavy ν



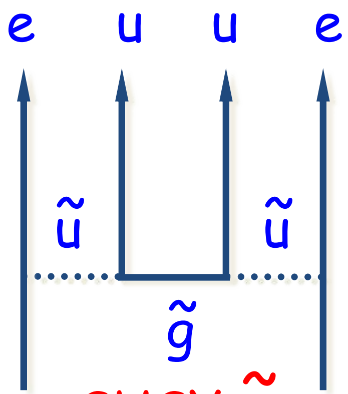
Kaluza-Klein

(KK±1 Brane:a=$10^{\pm1}$/GeV)

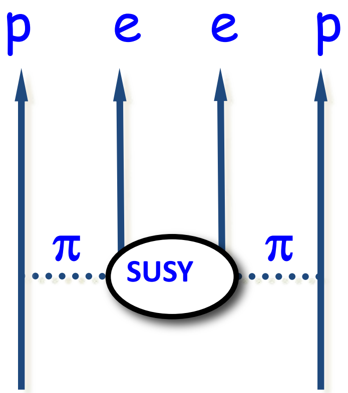


RHC λ,η

λ=RH had, η=LH had

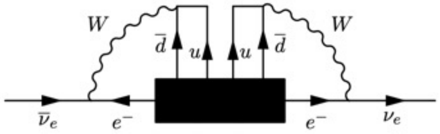


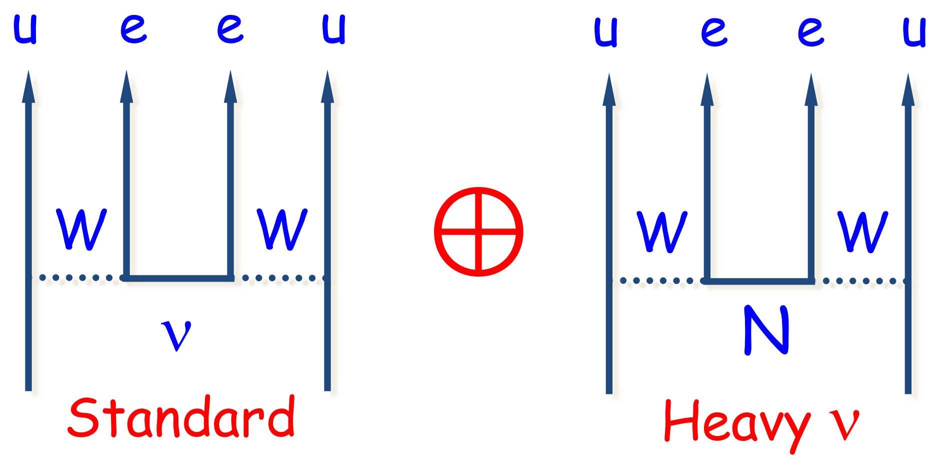
SUSY $\tilde{g}$



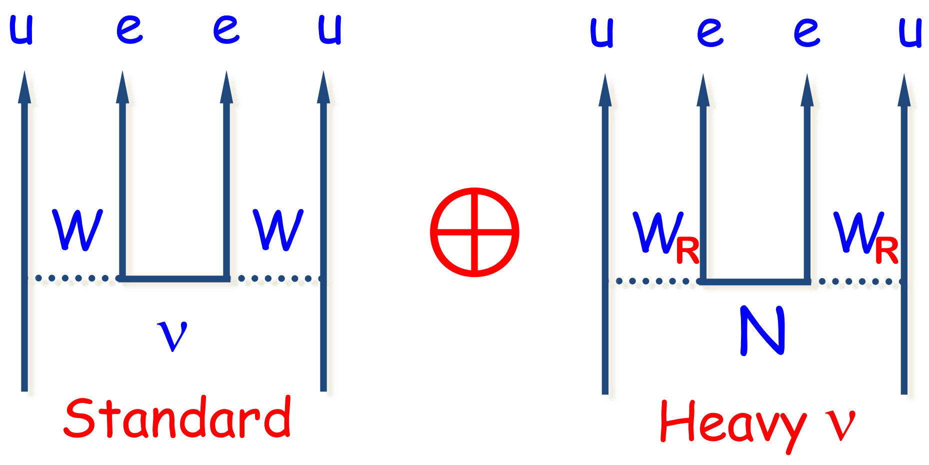
SUSY π

In any case, $0\nu\beta\beta$ decay implies Majorana ν:





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



Light and heavy ν exchange may be **non-interfering***, e.g. in LR-symmetric models.

In this case, for $0\nu\beta\beta$ decay in an isotope i=(Z, A):

Inverse half life ↓ | Signal strength ↓ | Phase space ↓ | Nuclear Matrix Element (**NME**) for light neutrinos ↓ | **NME** for heavy neutrinos ↓

$$\boxed{(T_i)^{-1} = S_i = G_i\ \left(M^2_{\nu,i}\, m^2_\nu\ + M^2_{N,i}\, m^2_N\right)}$$

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

Effective Majorana mass (light)

$$m_N = \frac{m^4_W}{m^4_{W_R}} \left|\sum_h V^2_{eh} \frac{m_p\, m_e}{M_h}\right|$$

Effective Majorana mass (heavy)

(* incoherent sum of two contributions)

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**

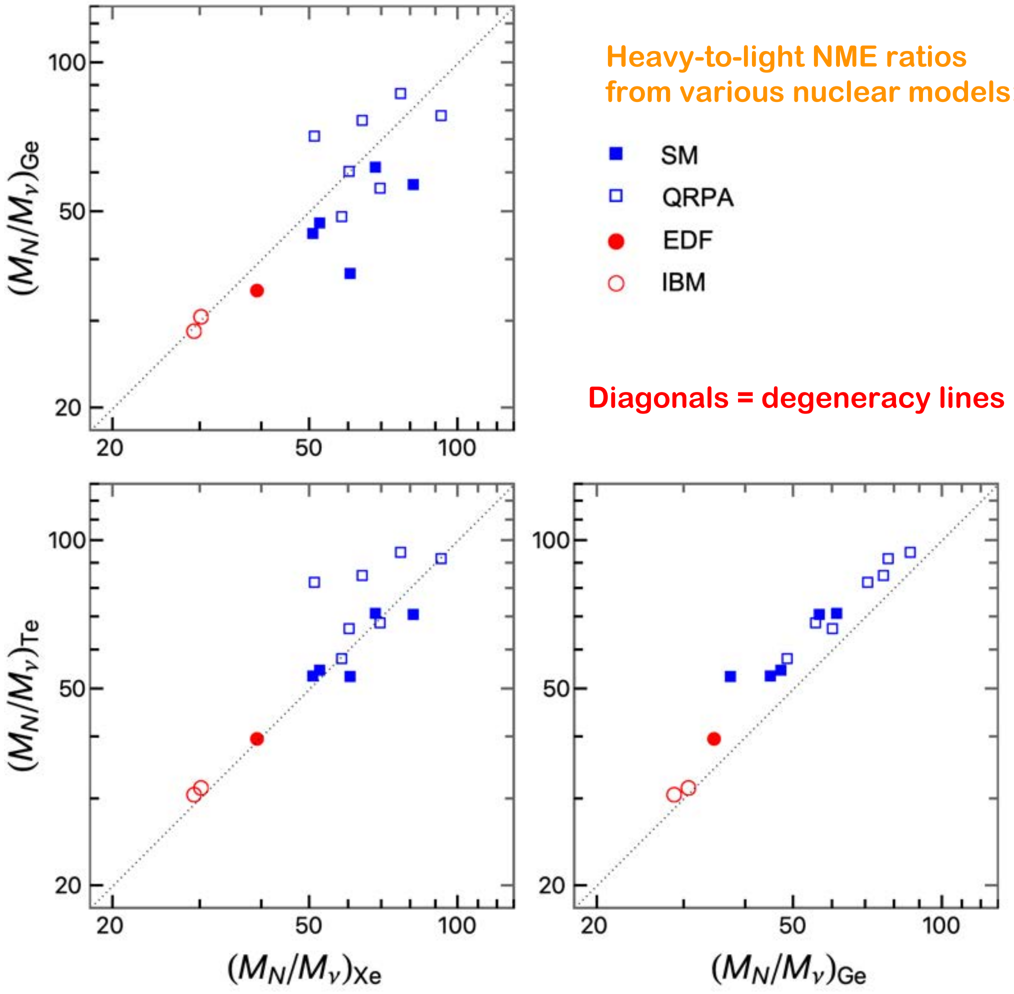
Non-degenerate solution iff matrix determinant is non-zero:

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

Issue of large NME uncertainties →

Isotopes in current leading expts:

^{76}Ge (GERDA, MAJORANA), ^{136}Xe (KamLAND, EXO), ^{130}Te (Cuore)



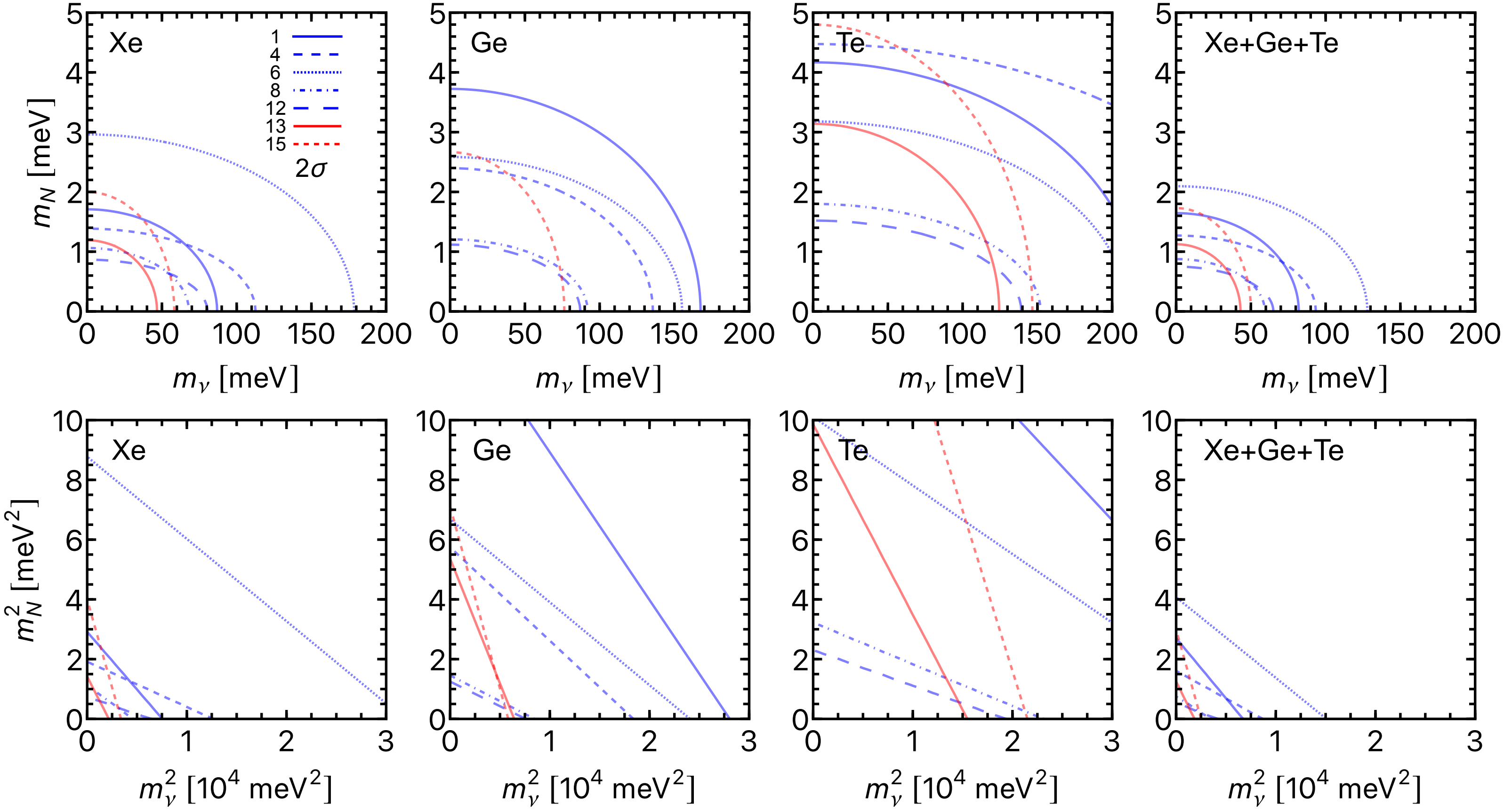
Heavy-to-light NME ratios
from various nuclear models:

- ■ SM
- □ QRPA
- ● EDF
- ○ IBM

Diagonals = degeneracy lines

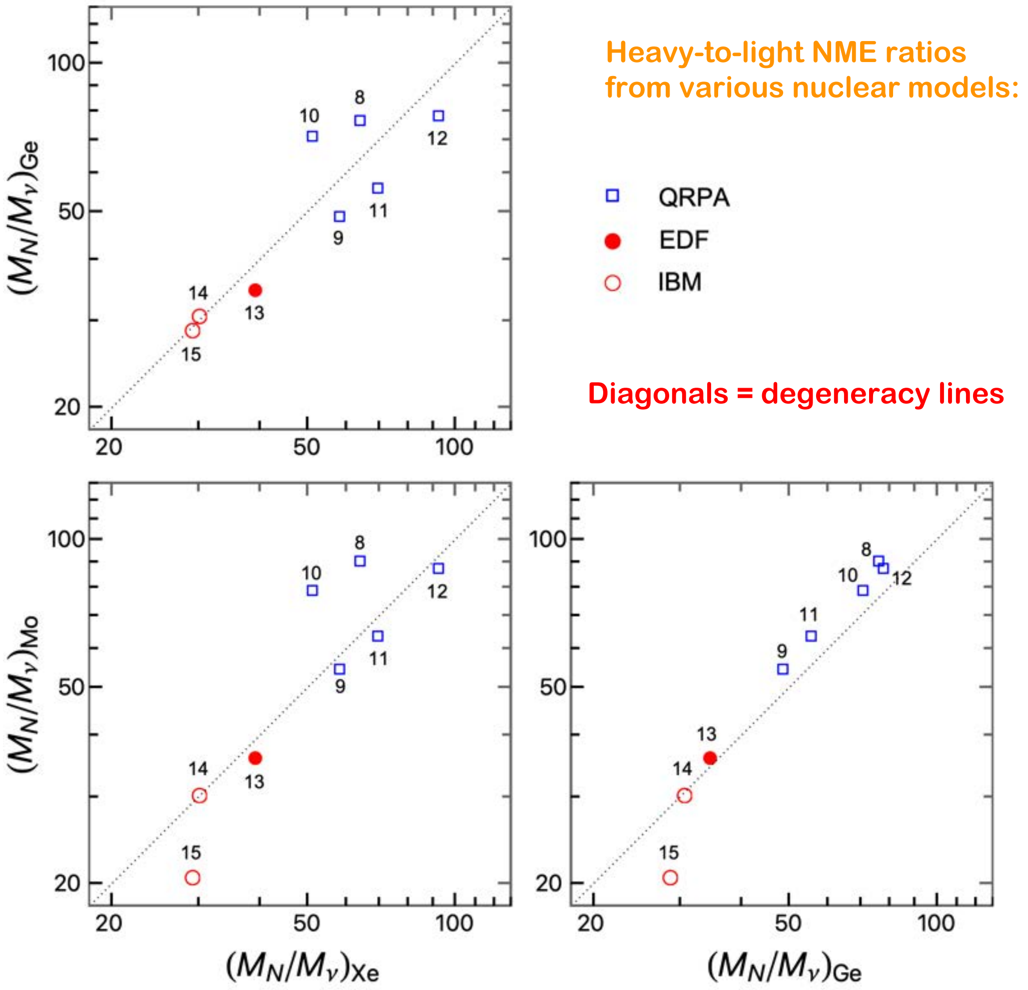
Large spread of NME ratios around the degeneracy lines

Current global bounds on light & heavy Majorana masses
for representative choices of NME



Smoothly interpolate between light and heavy neutrino limits (with no separation of the two contributions)

Isotopes for future ton-scale projects:
^{76}Ge (LEGEND), ^{136}Xe (nEXO), ^{100}Mo (CUPID)



Heavy-to-light NME ratios
from various nuclear models:

- □ QRPA
- ● EDF
- ○ IBM

Diagonals = degeneracy lines

Large spread of NME ratios around the degeneracy lines

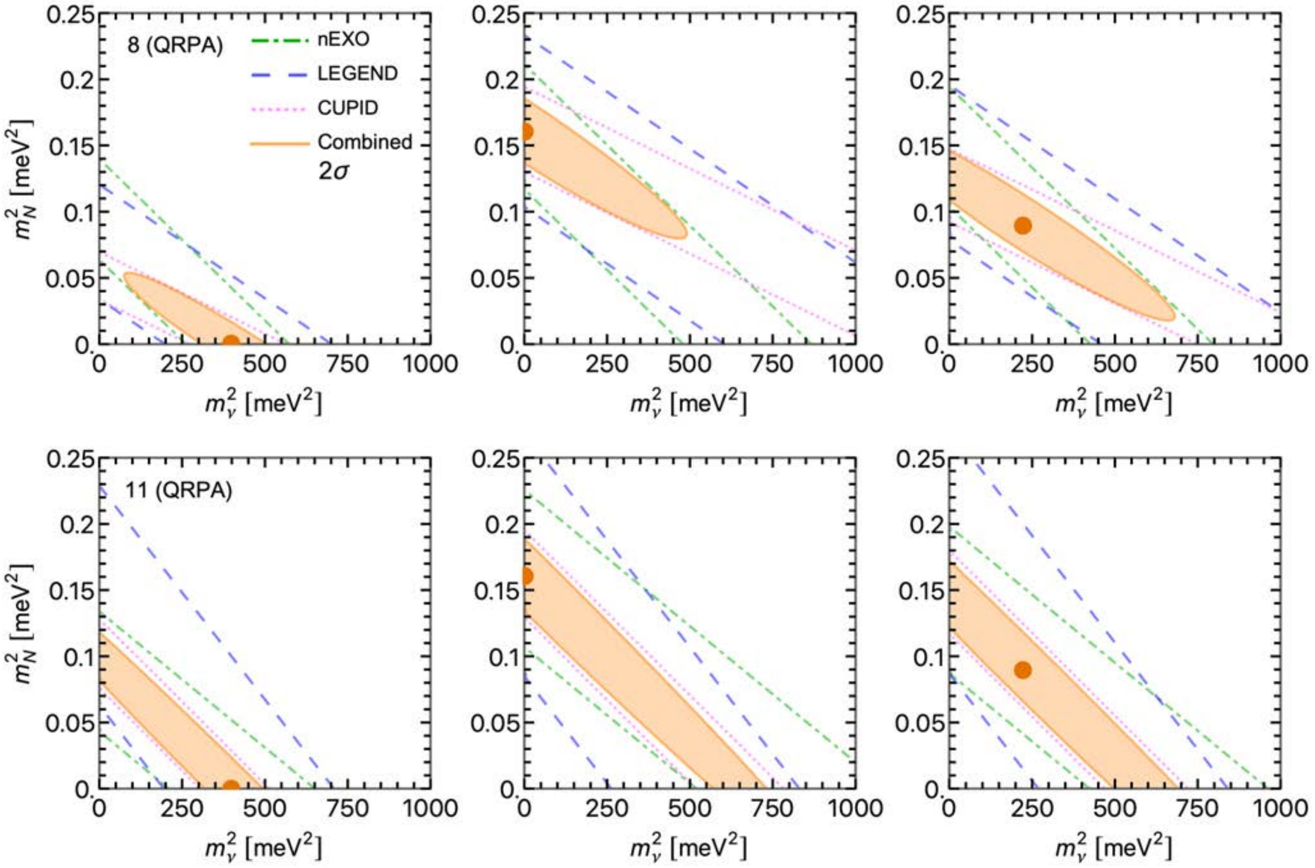
Simulated test cases for prospective >3σ measurements:

Only light ν **Only heavy ν** **Light + heavy ν**

Representative NME set

QRPA #8

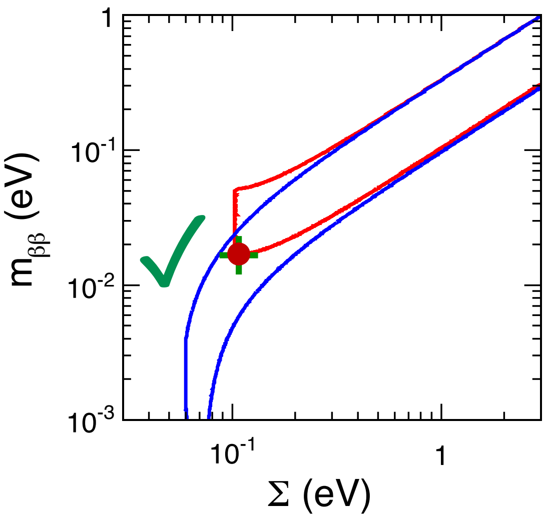
QRPA #11



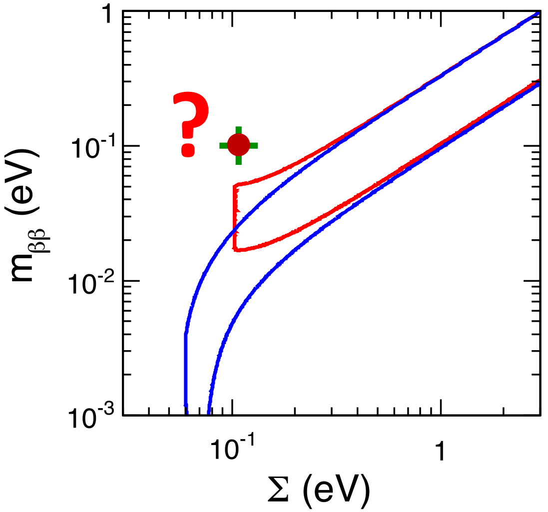
May -or may not- separate light and heavy ν contributions (depending on NME and their ratios)

Far-future data dreams:

3ν convergence?



… or surprises?

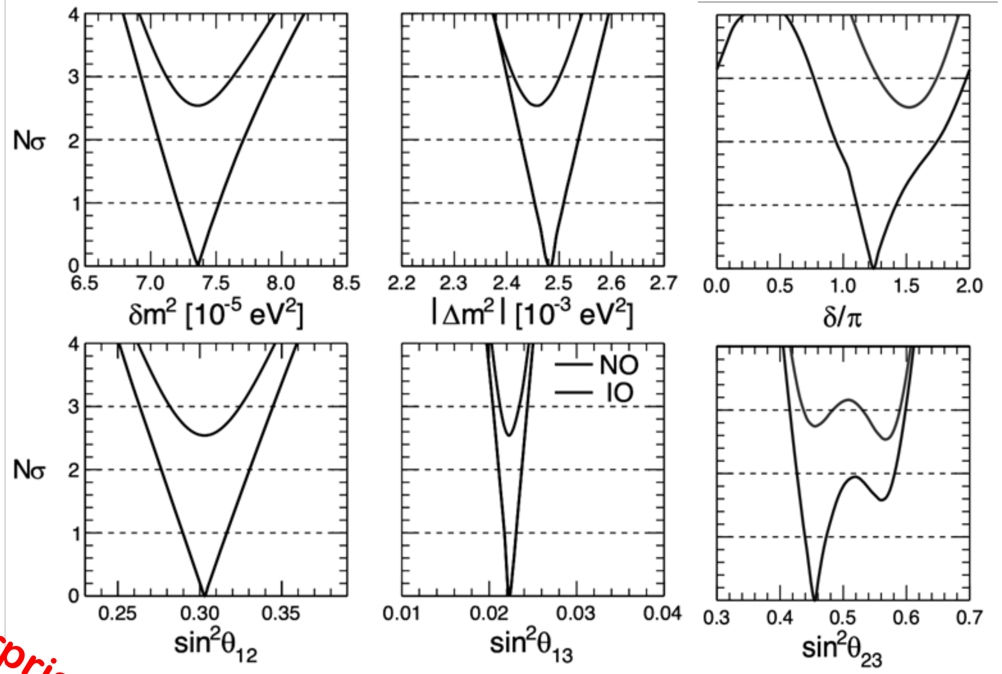


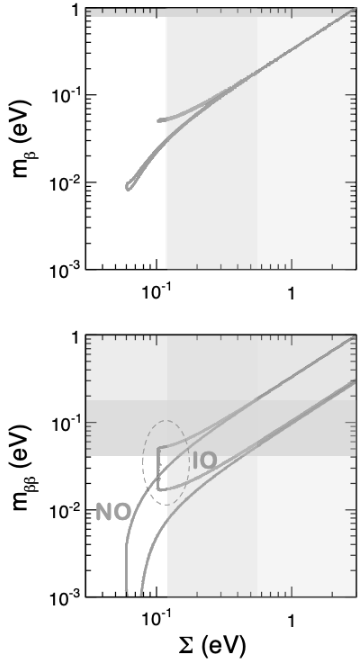
Identification of (non)standard 0νββ mechanisms will require major improvements in the calculation of NME with reliable (and significantly smaller) uncertainties, commensurate with the huge investment in future ton-scale experiments.

A vast and long-term program in nuclear physics is being envisaged to reach this goal. Key aspects: ab-initio calculations + nuclear model benchmarking.

[In the very far future: nuclear physics from lattice QCD…]

-epilogue-


Oscillation parameters


Non-osc. par.

precision

Surprises?

discovery

Frontiers

Progress in "electro-weak nuclear physics"
crucial to advance our frontiers in a vast range
of ν energies and (non)standard processes

Thank you for your attention!