Neutrino masse and mixings: Status and challenges

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OUTLINE:

- Prologue
- The 3ν paradigm and its (un)knowns
- Global 3ν analysis of oscillation data
- Impact of nonoscillation constraints
- Beyond the 3ν paradigm
- Epilogue

Results based on the invited review article:

F. Capozzi, E. Lisi, A. Marrone, A. Palazzo,
"Current unknowns in the three-neutrino framework"
arXiv:1804.09678 [Prog. Part. Nucl. Phys., in press]

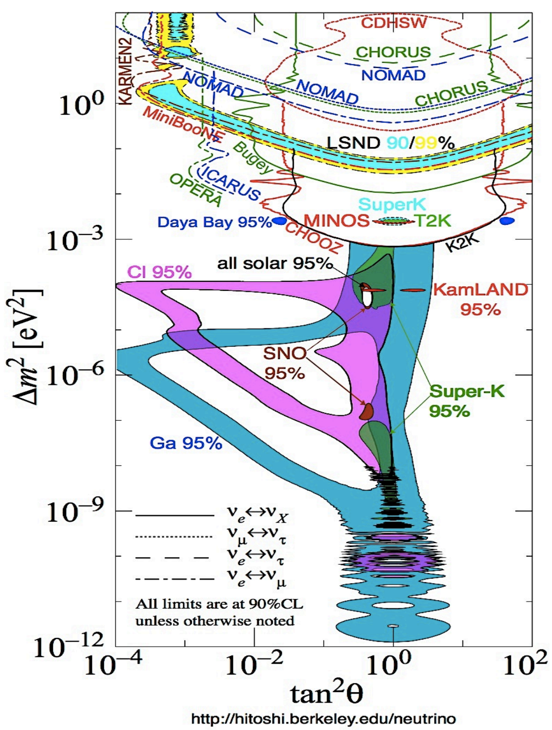
Prologue: The 2015 Nobel Prize in Physics

"for the discovery of neutrino oscillations ...

... which shows that neutrinos have mass"

Discovery phase ←→ Precision phase

broad-brush picture ... ⇄ ... **detailed** description



← from uncertainties spanning many decades...

... to few % accuracy on oscillation parameters →

← 3ν paradigm emerging with knowns and unknowns... →

Surprises?

δm^2	2.2 %
Δm^2	1.4 %
$\sin^2\theta_{12}$	4.4 %
$\sin^2\theta_{13}$	3.8 %
$\sin^2\theta_{23}$	~ 5 %

+

... 3ν unknowns ?
... Beyond 3ν ?
... Theo. challenges ?

3ν paradigm: parameters

Mixings and phases: 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

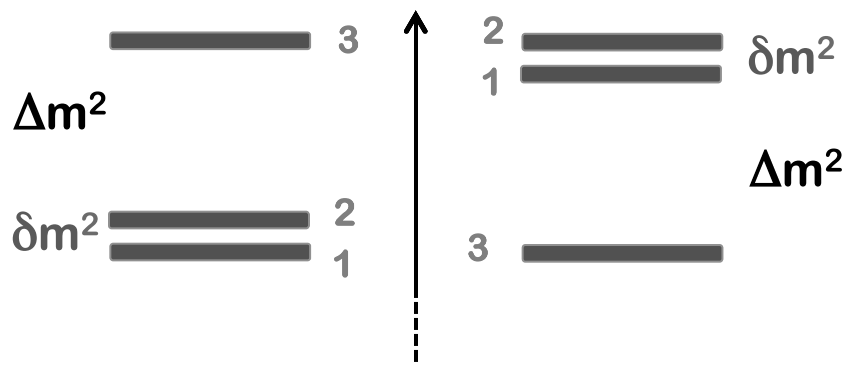
1-3 rotation
+ CPV "Dirac" phase

1-2 rotation

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

Mass [squared] spectrum (E ~ p + $m^2/2E$ + "interaction energy")

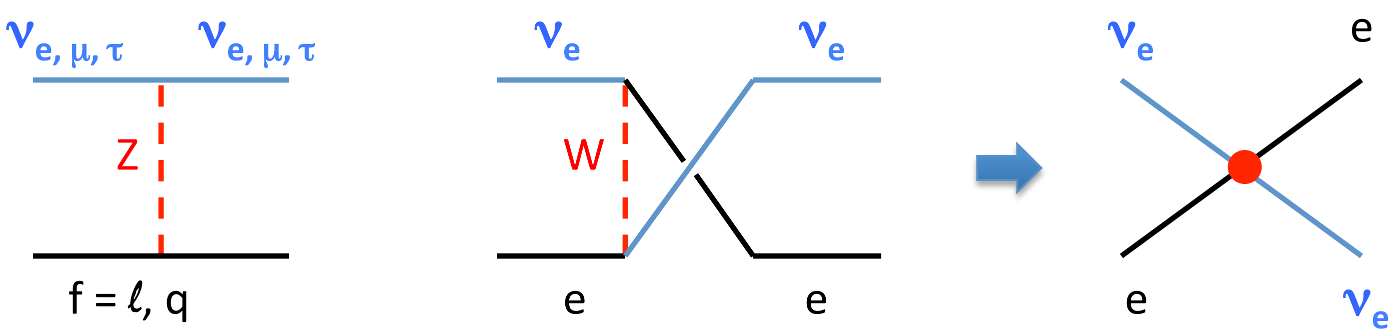
"Normal"
Ordering
N.O.



"Inverted"
Ordering
I.O.

+ interactions in matter → effective terms ~ G_F · E · density
+ absolute mass scale (not tested in oscillations)

Neutrino coherent forward scattering with (charged) background fermions f:



effect canceled out
(same for all flavors)

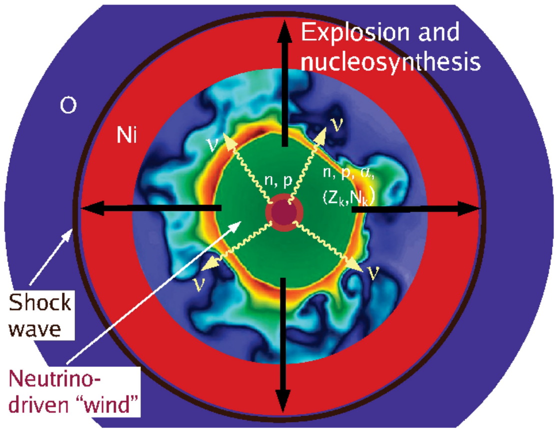
effect singled out
(no μ or τ in matter)

ν_e extra interaction energy ~ $G_F N_e E$
(changes sign for anti-ν)

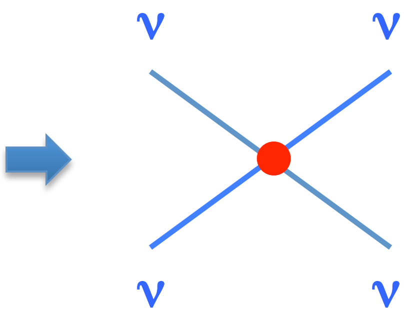
Mikheyev-Smirnov–Wolfenstein (MSW) effect → explored in a vast literature

[Difficult to say something really new, unless Nature reveals new NSI (non-standard interactions, leading to flavor-changing/conserving 4-fermion couplings ~ $\varepsilon_{\alpha\beta}\, G_F$]

Core-collapse SNe: for a few seconds, (anti)neutrino density can be dominant



...the only laboratory where weak interactions may become "strong"



ν extra interaction energies $\sim G_F N_\nu E$ (from a 4-ν vertex!)

Flavor evolution of ν depends on the ν background itself → **nonlinear problem**

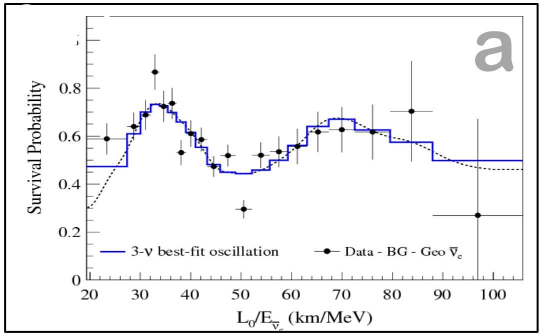
Formidable theoretical and computational difficulties: solutions still in their infancy.

Currently a narrow & specialized field, but will be boosted after the next galactic SN!

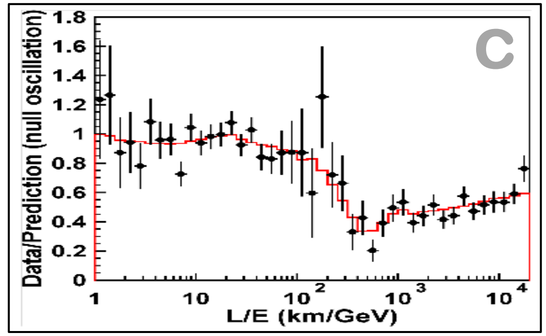
"Forensic analysis" of the SN ν signal will then become a discipline of its own...

ν flavor oscillation experiments: α → β in vacuum and matter

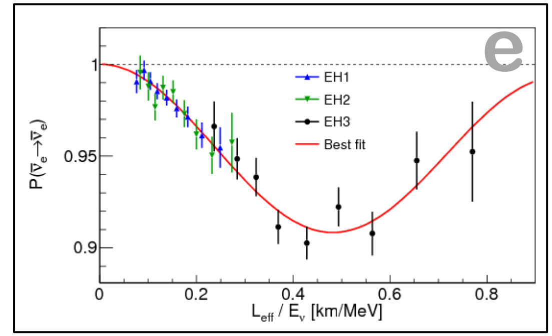
e→e (KamLAND)



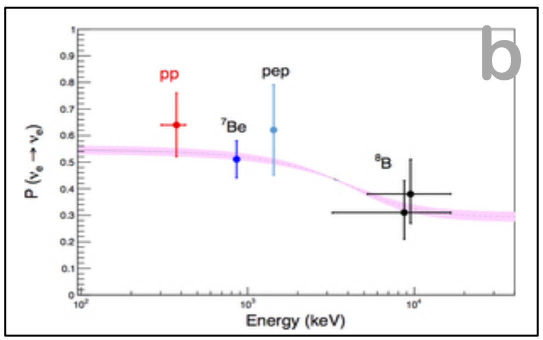
μ→μ (Atmospheric)



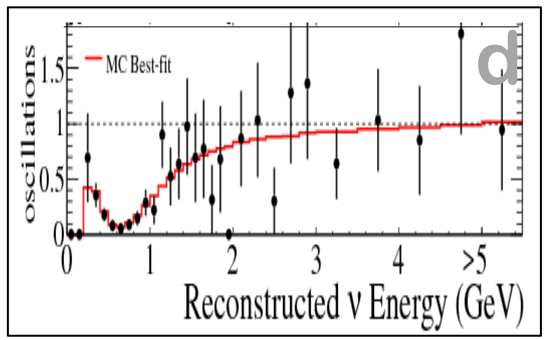
e→e (SBL Reac.)



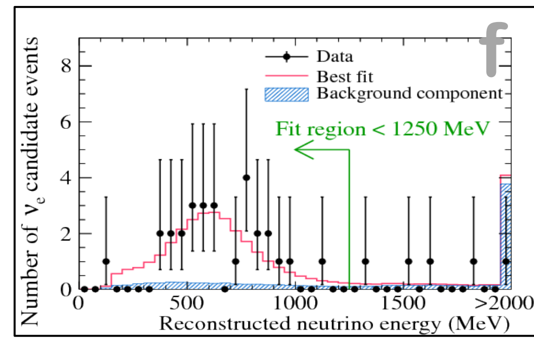
e→e (Solar)



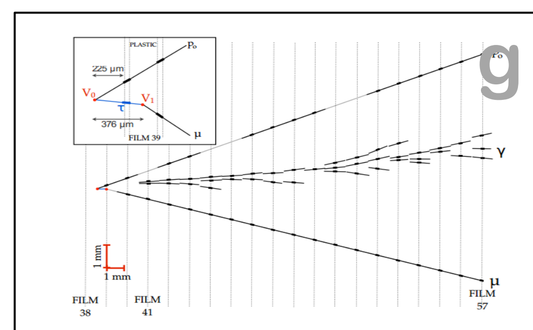
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK)

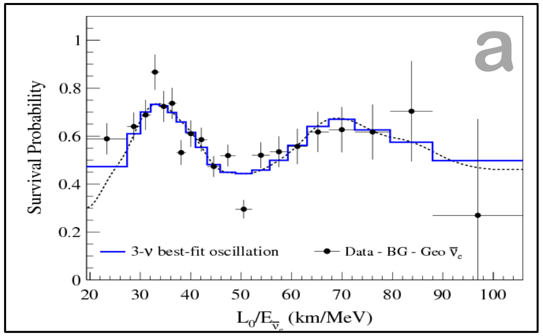


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

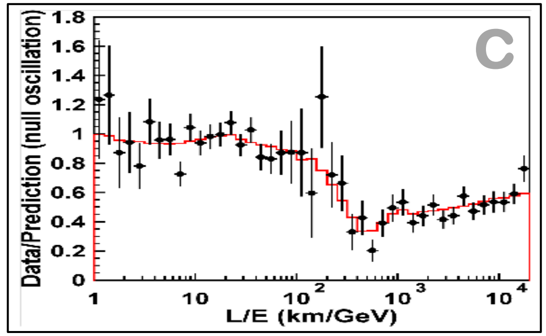
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

Leading sensitivities to 3ν oscillation parameters:

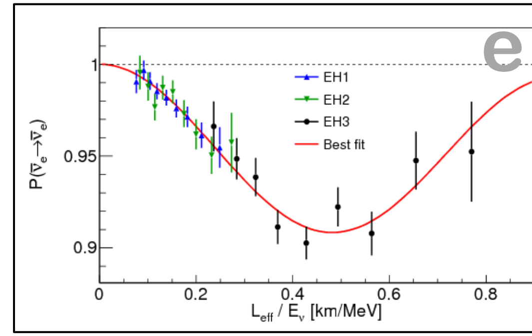
e→e (δm^2 , θ_{12})



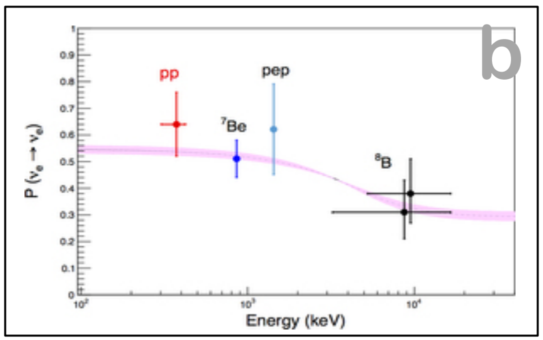
μ→μ (Δm^2 , θ_{23})



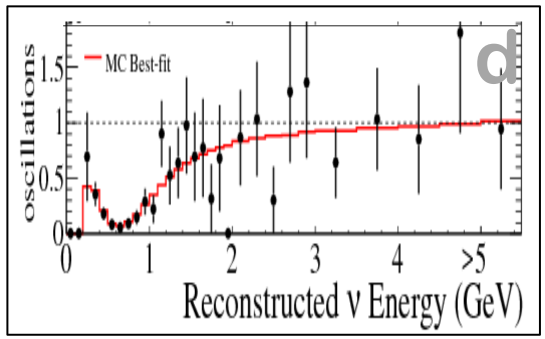
e→e (Δm^2 , θ_{13})



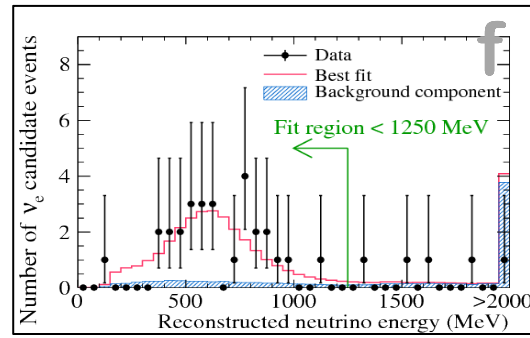
e→e (δm^2 , θ_{12})



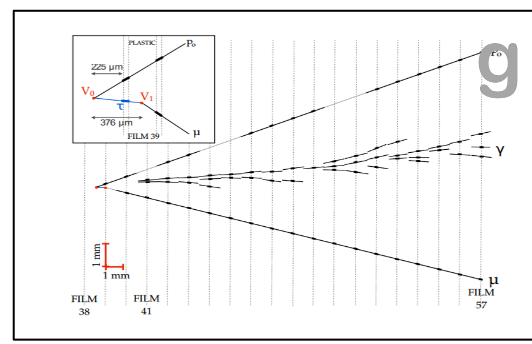
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



... + subleading sensitivities to **CPV** and **NO vs IO** difference, essentially via **μ→e** channel in LBL accel. and atmosph. expts

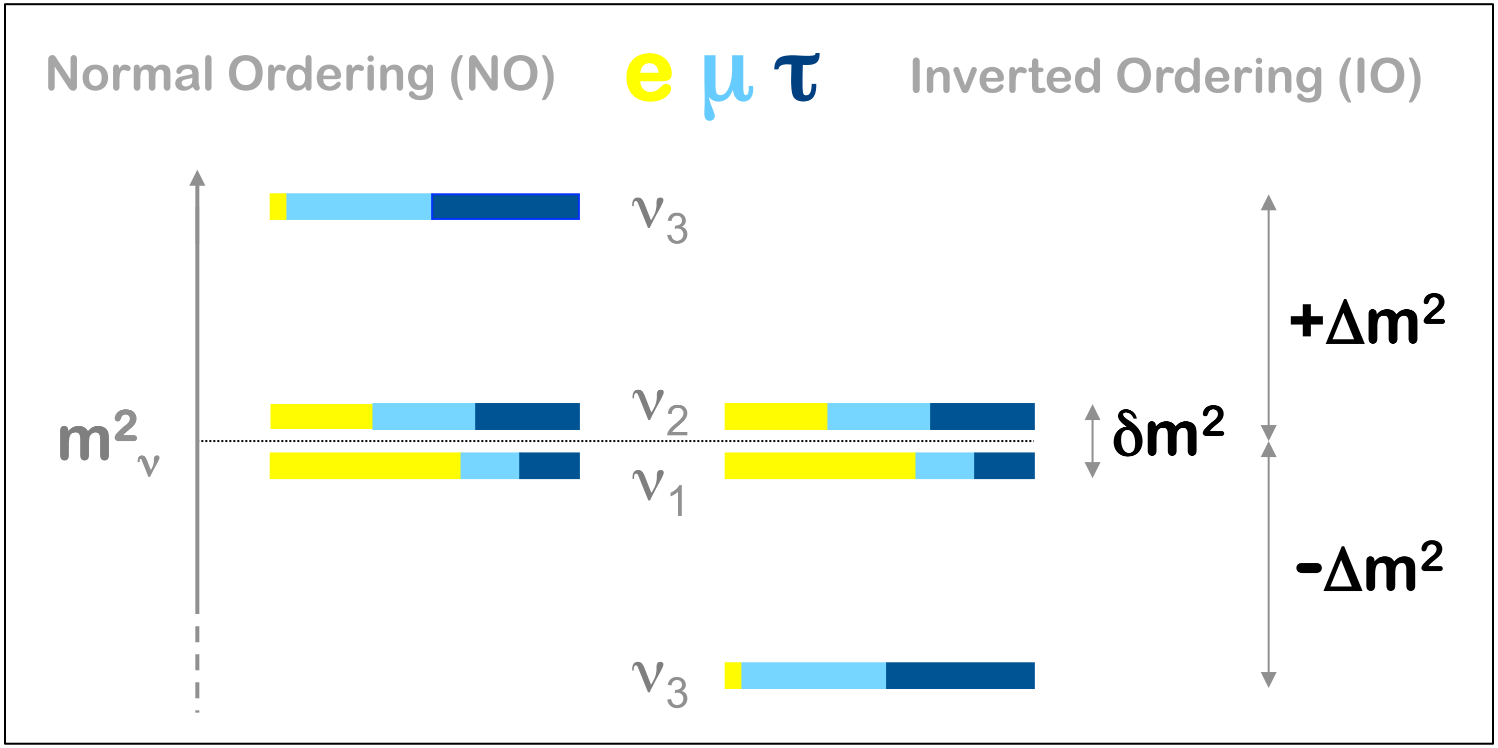
"Broad-brush" 3ν picture (with 1-digit accuracy)

Knowns:

$\delta m^2 \sim 7 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Unknowns:

δ = Dirac CPV phase
sign(Δm^2) = ordering
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature



Hi-res, larger picture → Global analysis of ν oscillation data

→

Analysis includes increasingly rich oscillation data sets:

LBL Accel + Solar + KL (KamLand)

LBL Accel + Solar + KL + SBL Reactor

LBL Accel + Solar + KL + SBL Reactor + Atmosph.

χ^2 metric adopted. Parameters not shown are marginalized away:

C.L.'s refer to $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3, \ldots$

Global fit results taken from 1804.09678. LBL = Long Baseline , SBL = Short Baseline.

LBL accelerators (T2K and NOvA) are dominantly sensitive to **(Δm^2 , θ_{13} , θ_{23})** but also probe δ and **NO vs IO**, provided that **(δm^2 , θ_{12})** are fixed by **solar+KL**.

$$\begin{aligned} P(\nu_\mu \to \nu_e) \;\; \simeq \;\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{A-\Delta m^2}\right)^2 \sin^2\left(\frac{A-\Delta m^2}{4E}x\right) \\ + \;\; & \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right)\sin\left(\frac{A}{4E}x\right)\sin\left(\frac{A-\Delta m^2}{4E}x\right)\cos\left(\frac{\Delta m^2}{4E}x\right)\cos\delta \\ - \;\; & \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right)\sin\left(\frac{A}{4E}x\right)\sin\left(\frac{A-\Delta m^2}{4E}x\right)\sin\left(\frac{\Delta m^2}{4E}x\right)\sin\delta \\ + \;\; & \cos^2\theta_{13}\sin^2 2\theta_{12}\left(\frac{\delta m^2}{A}\right)^2\sin^2\left(\frac{A}{4E}x\right) , \end{aligned} \quad (13)$$

where $A = 2\sqrt{2}G_F N_e E$ governs matter effects, with $A \to -A$ and $\delta \to -\delta$ for $\nu \to \overline{\nu}$, and $\Delta m^2 \to -\Delta m^2$ for normal to inverted ordering. At typical NOvA energies ($E \sim 2$ GeV) it is $|A/\Delta m^2| \sim 0.2$,

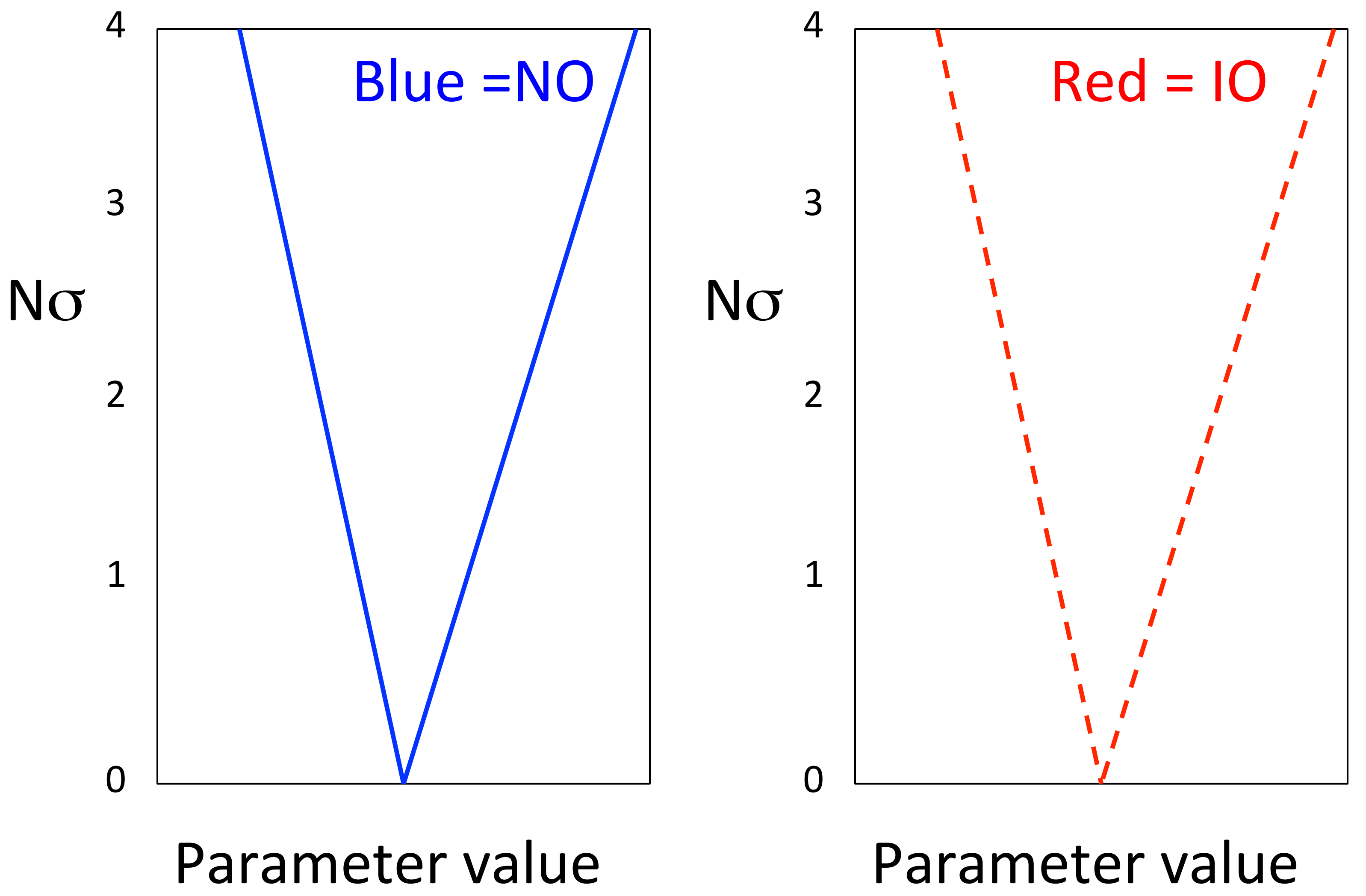
[Hereafter: $\Delta m^2 = (\Delta m^2_{31} + \Delta m^2_{32})/2$]

SBL reactors (Daya Bay, RENO, Double Chooz) are dominantly sensitive to **(Δm^2 , θ_{13})** and shrink the θ_{13} range dramatically, with correlated effects on the other parameters

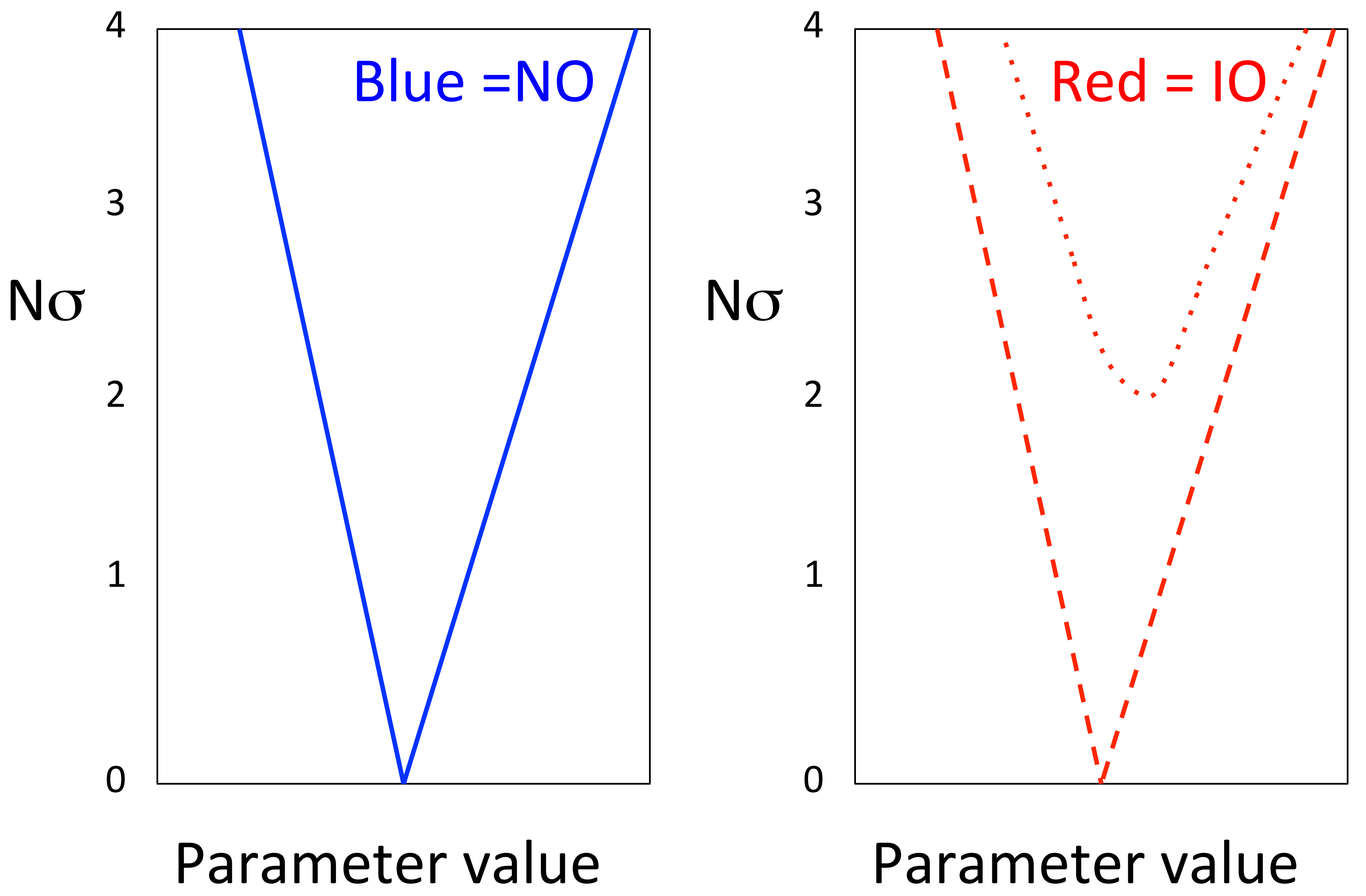
Atmospheric ν searches (mainly Super-Kamiokande) also contribute to probe and to constrain **(Δm^2 , θ_{13} , θ_{23} , δ)** as well as testing **NO vs IO.**

Relevant new result (2017-2018): Hints for Normal Ordering (NO) favored by data

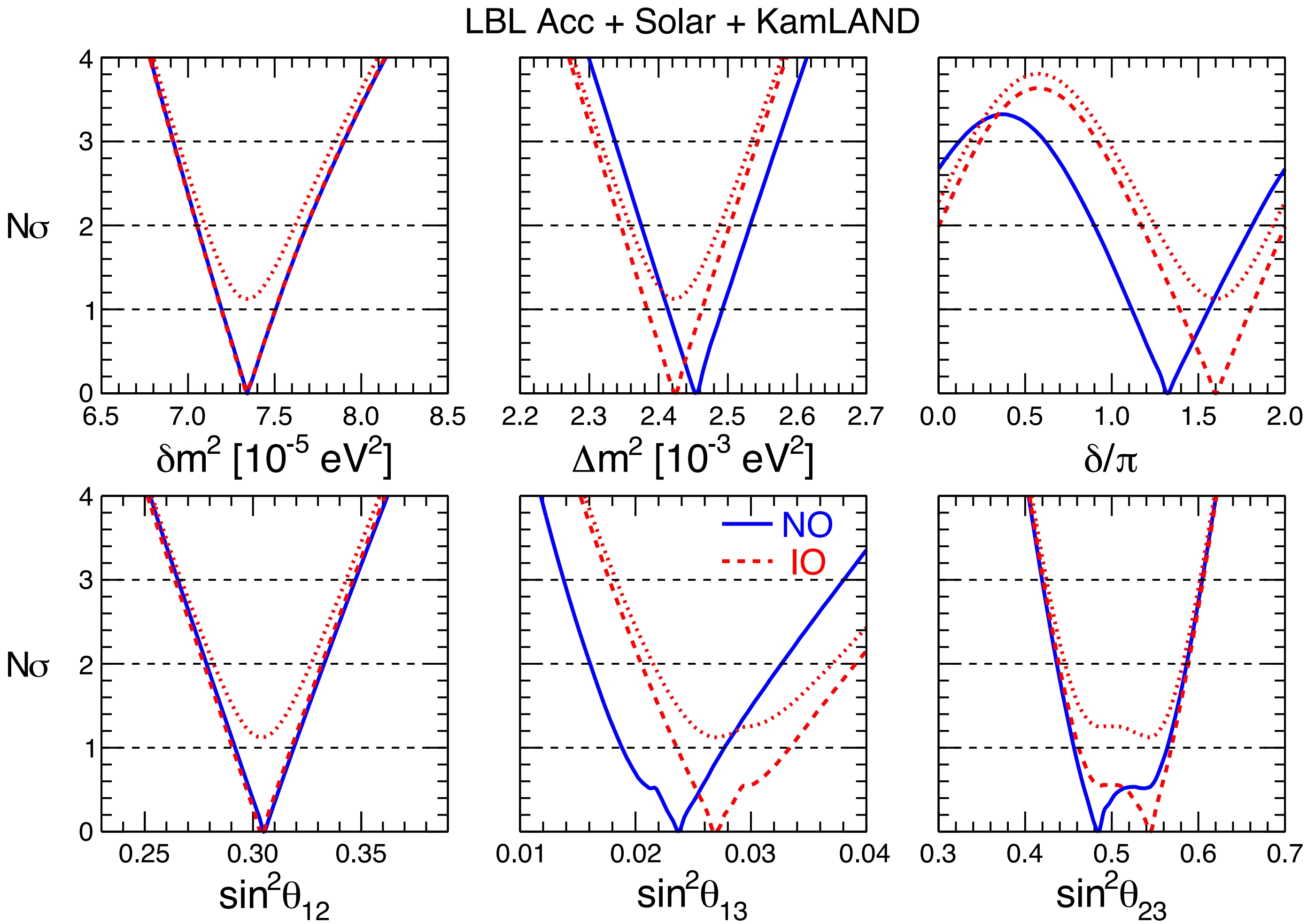
In the following figures: Typical bounds would be ~linear and symmetric for ~gaussian errors around the **separate best fits for both NO and IO.**



However, **bounds for IO move upwards** if one takes into account that currently **NO gives the absolute best fit**. Recall: **$N\sigma = \sqrt{\Delta\chi^2}$ = 1, 2, 3…**



Results from real data →

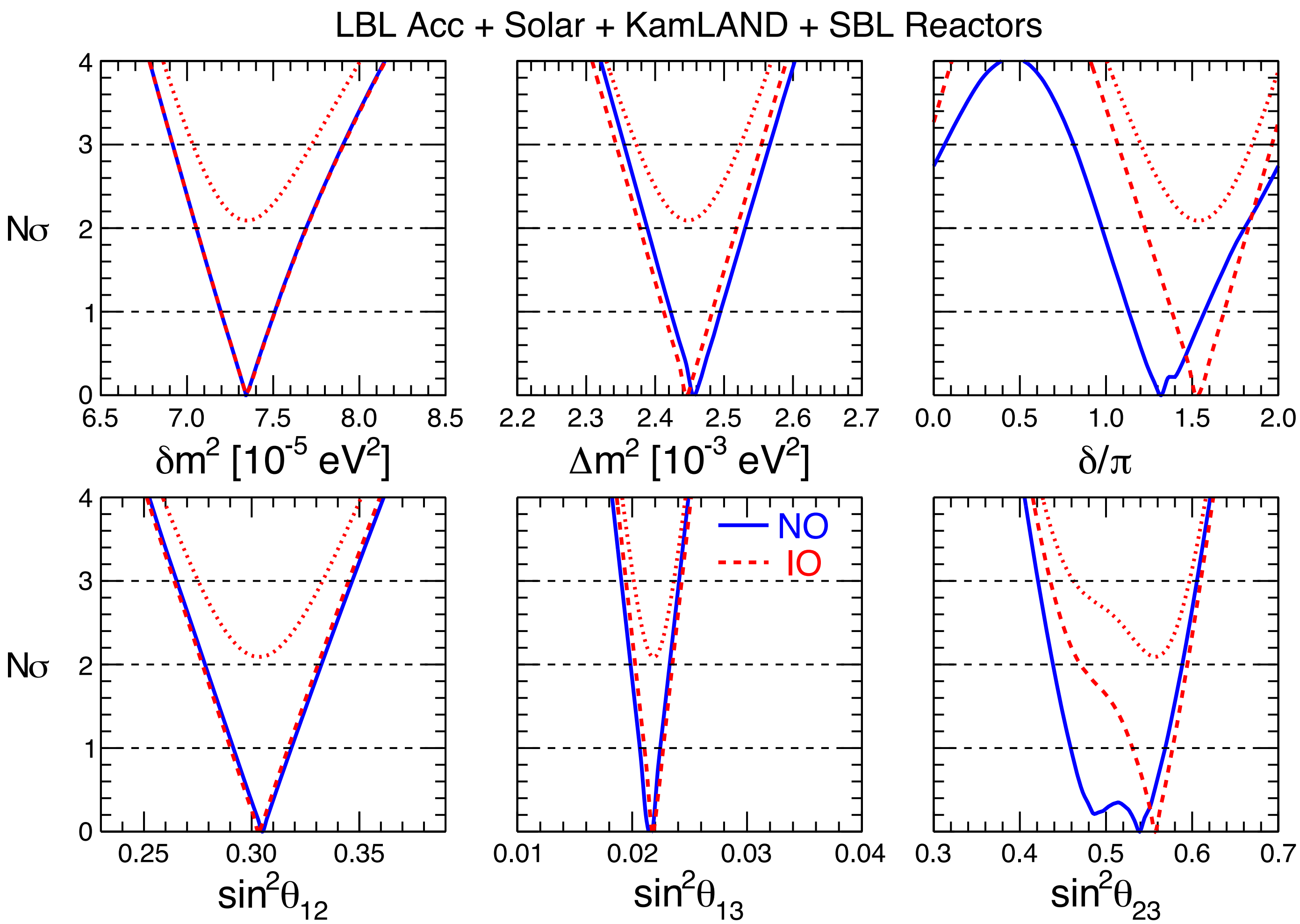


Two mass parameters and three mixing angles bound at >4σ level.

Largest mixing angle (2-3) close to π/4, but octant undetermined at 1σ.

CP phase favored around 3π/2 (max CPV with sinδ ~ -1).

IO slightly disfavored with respect to NO at ~1σ level.

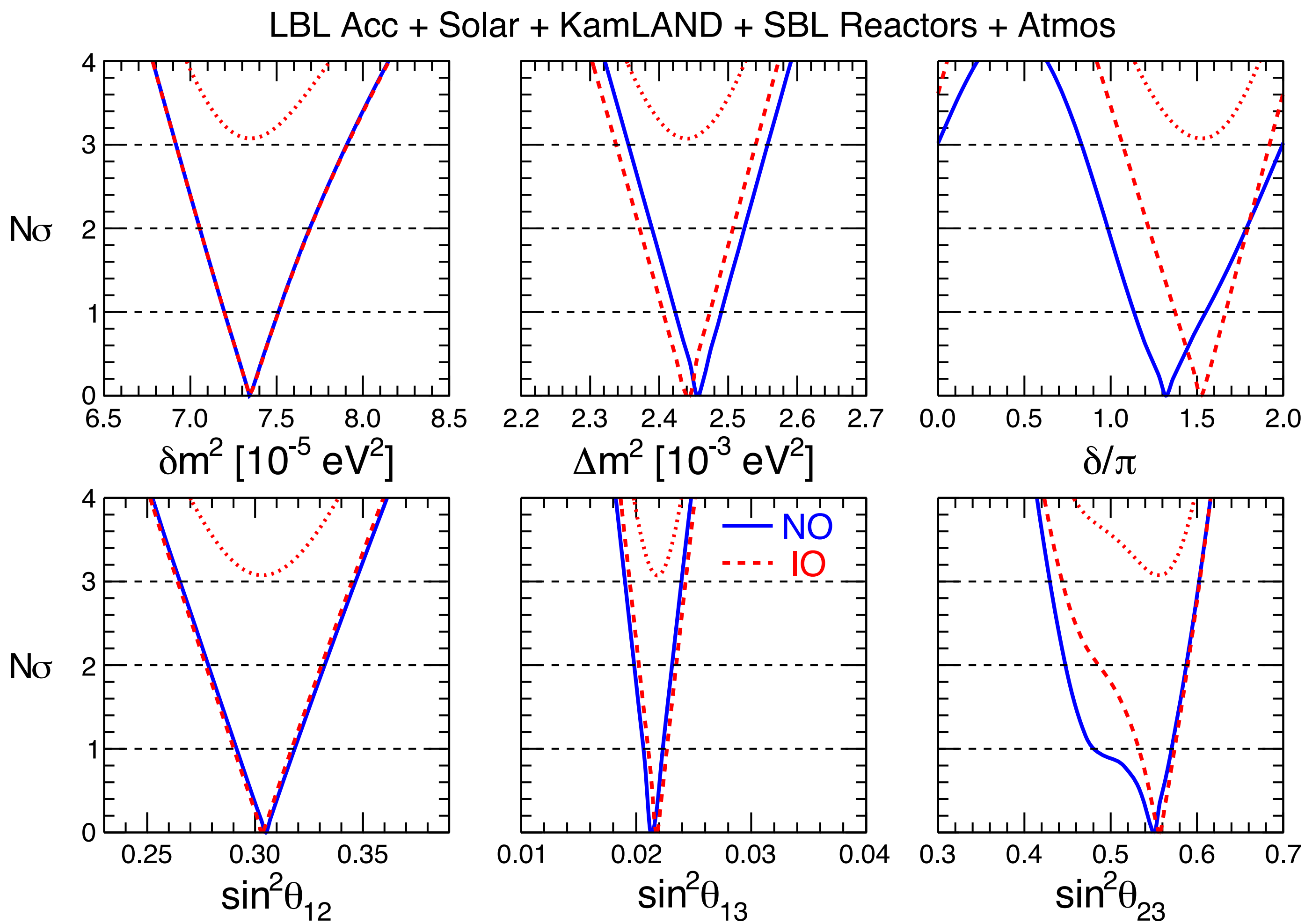


Range of smallest mixing angle (1-3) dramatically reduced

Largest mixing angle (2-3) close to $\pi/4$, but octant undetermined at 2σ.

Max CPV at ~$3\pi/2$ favored , CP conservation disfavored at ~2σ in NO.

IO disfavored with respect to NO at ~2σ level.



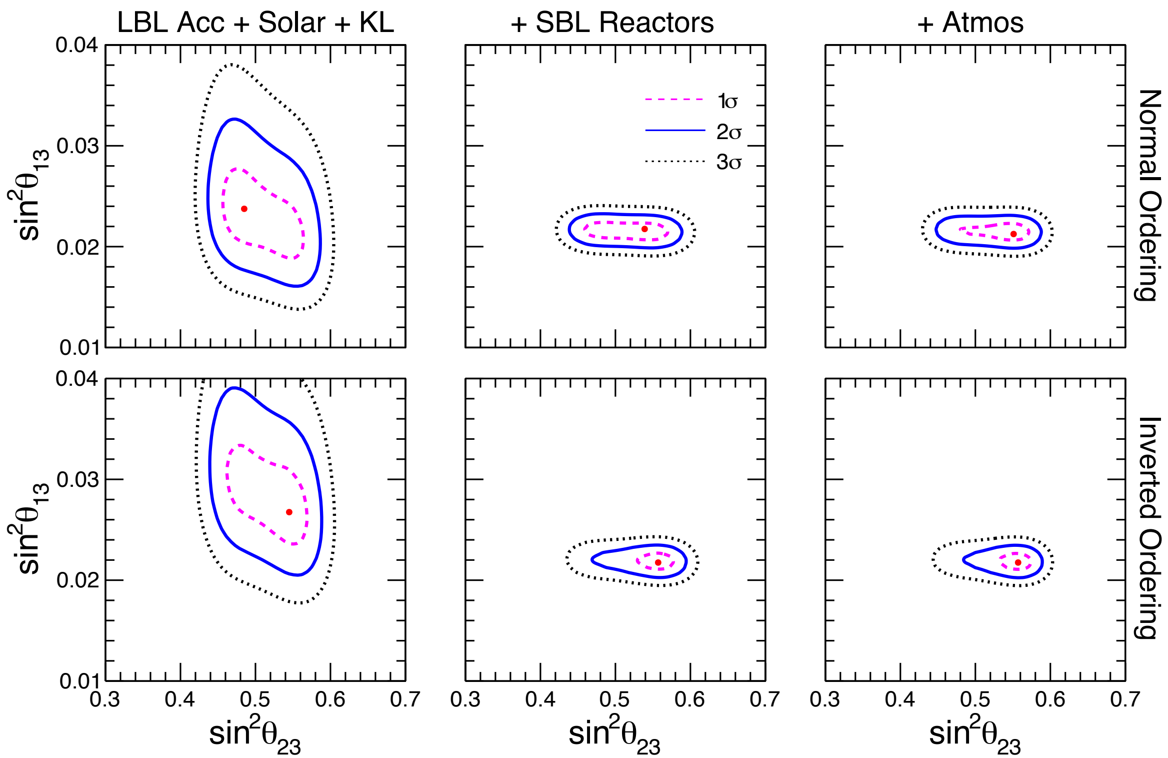
Further improvements for various parameters – bounds at few % level

Largest mixing angle (2-3) close to $\pi/4$, but octant undetermined at 2σ.

CPV: $\sin\delta$ ~ -1 favored, ~ 0 disfav., ~ +1 excl. Meaningful bounds at ~3σ.

IO significantly disfavored with respect to NO, at ~3σ level (but: caution!)

Understanding the accelerator + reactor (+atm.) impact on NO preference



NO

IO

Anticorrelation due to leading term in appearance channel at accelerators

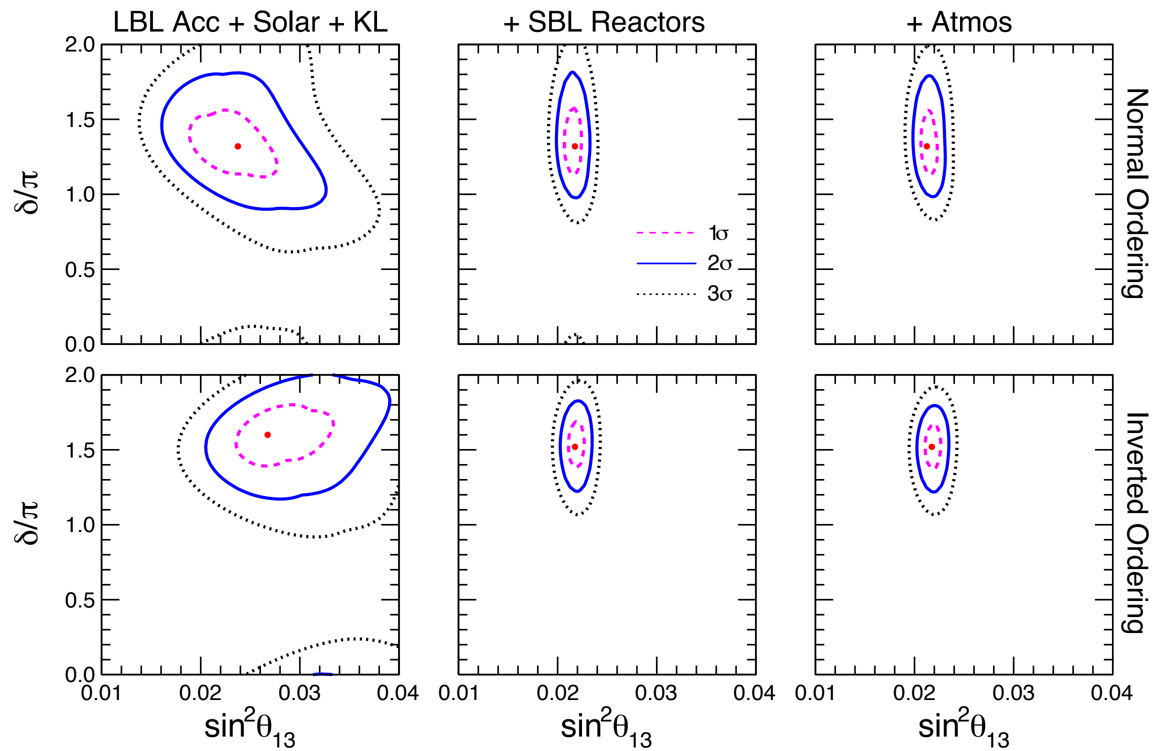
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{A-\Delta m^2}\right)^2 \sin^2\left(\frac{A-\Delta m^2}{4E}x\right)$$

Better agreement with reactors on y-axis for NO

Atmosph. data also contribute (but in a less intuitive way)

Running experiments can further corroborate this picture (if true)

Understanding the accelerator + reactor (+atm.) impact on CPV preference



NO

IO

CPV tested by sub leading terms at accelerators (nu-antinu difference)

$$\sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \left(\frac{\delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right) \sin\left(\frac{A}{4E}x\right) \sin\left(\frac{A-\Delta m^2}{4E}x\right) \sin\left(\frac{\Delta m^2}{4E}x\right) \sin\delta$$

Reactors not sensitive to CPV, but sharpen range

Atmosph. contribute to test CPV (but in a less intuitive way)

Running experiments can further corroborate this picture (if true)

Status of oscillation data analysis, circa 2018

Table 1: Best fit values and allowed ranges at $N\sigma = 1, 2, 3$ for the 3ν oscillation parameters, in either NO or IO. The latter column shows the formal "1σ accuracy" for each parameter, defined as 1/6 of the 3σ range divided by the best-fit value (in percent).

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\sin^2\theta_{12}$	NO	3.04	2.91 – 3.18	2.78 – 3.32	2.65 – 3.46	4.4
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.4
$\sin^2\theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23	1.98 – 2.31	1.90 – 2.39	3.8
	IO	2.18	2.11 – 2.26	2.02 – 2.35	1.95 – 2.43	3.7
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.455	2.423 – 2.490	2.390 – 2.523	2.355 – 2.557	1.4
	IO	2.441	2.406 – 2.474	2.372 – 2.507	2.338 – 2.540	1.4
$\sin^2\theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70	4.48 – 5.88	4.30 – 6.02	5.2
	IO	5.57	5.33 – 5.74	4.86 – 5.89	4.44 – 6.03	4.8
δ/π	NO	1.32	1.14 – 1.55	0.98 – 1.79	0.83 – 1.99	14.6
	IO	1.52	1.37 – 1.66	1.22 – 1.79	1.07 – 1.92	9.3

Known parameters constrained at few % level

"Unknown" CP phase maybe already "known" at O(10%) - if trend confirmed

Dramatic progress in the last two decades on the PMNS paradigm...

but still a long way to go to reach CKM-level accuracy and redundance!

Theoretical model building challenges

Underlying symmetries? A wide spectrum of options...

No organizing principle
("anarchy")

Discrete family simmetries
("geometry")

linear relations between
$\theta_{13}\cos\delta$ and θ_{12}, θ_{23}

Continuous flavor simmetries
("dynamics")

links between neutrino
spectra/angles/phases

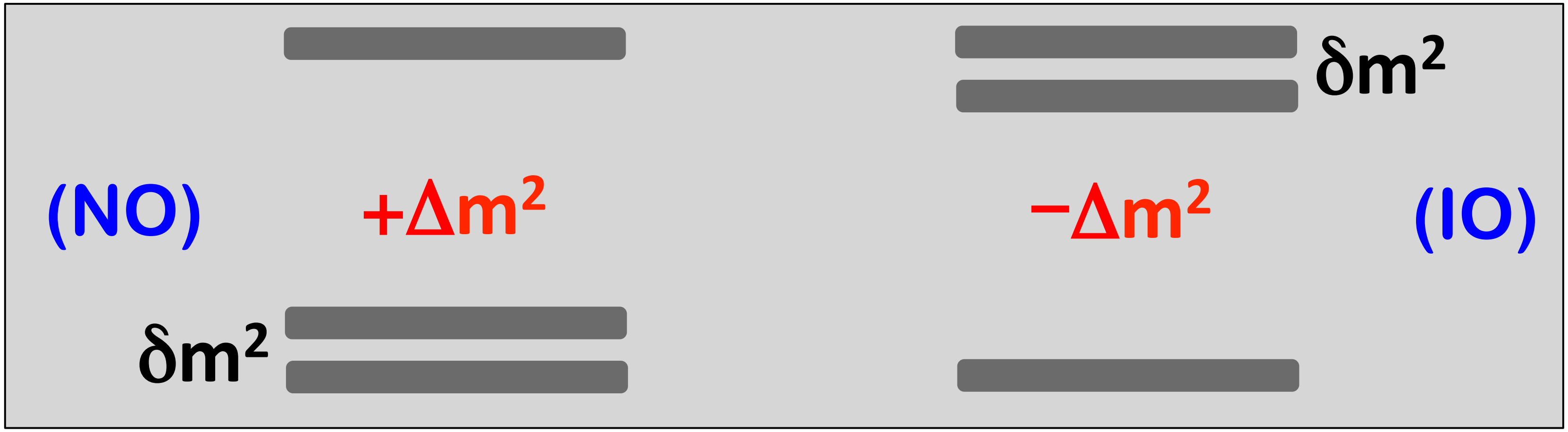
Common quark/lepton features
("complementarity")

links between
θ_{13} and θ_C

...model selection will benefit from new and more accurate data!

Experimental challenges, e.g., in testing mass ordering

Oscillation searches can directly access the sign of $\pm\Delta m^2$ ...



...if they can observe interference of oscill. driven by $\pm\Delta m^2$ with oscill. driven by a quantity Q having known sign. Three options:

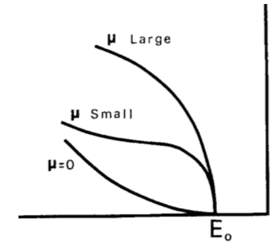
1) $Q \sim \delta m^2$	(medium-baseline reactors)
2) $Q \sim G_F\, E\, N_e$	(matter effects in accel./atmosph. ν)
3) $Q \sim G_F\, E\, N_\nu$	(self-interaction effects in supernovae)

1) **JUNO** experiment in construction (China). **Need nuclear theory progress on reactor spectra.**
2) **DUNE** (US), **HK** and **T2HK** (Japan), **EnuSSB** (EU) ... **Need progress on cross sections (also for CPV tests).**
3) Next galactic core-collapse **SN** in many experiments. **Need theory advance on self-interaction effects.**

3ν paradigm status via non-oscillation searches: absolute ν masses and observables (m_β , $m_{\beta\beta}$, Σ)

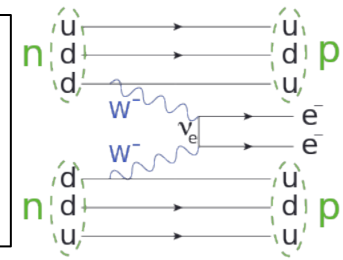
β decay, sensitive to the "effective electron neutrino mass":

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



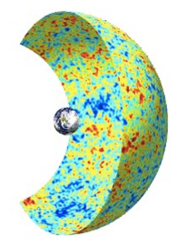
0νββ decay: only if Majorana. "Effective Majorana mass":

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



Cosmology: Dominantly sensitive to sum of neutrino masses:

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



Note 1: These observables may provide handles to distinguish NO/IO.
Note 2: Majorana case gives a new source of CPV (unconstrained)
Note 2: The three observables are correlated by oscillation data→

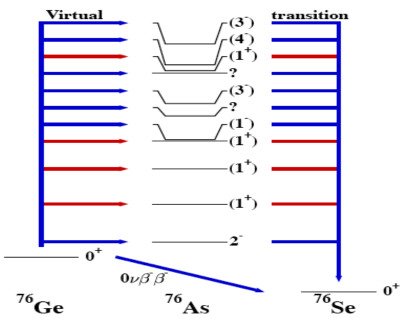
What sets the uncertainty of $m_{\beta\beta}$?

In case of positive signal, a major concern is the accuracy of the **nuclear matrix element |M|**, rather than the expt. uncertainty on the decay half life:

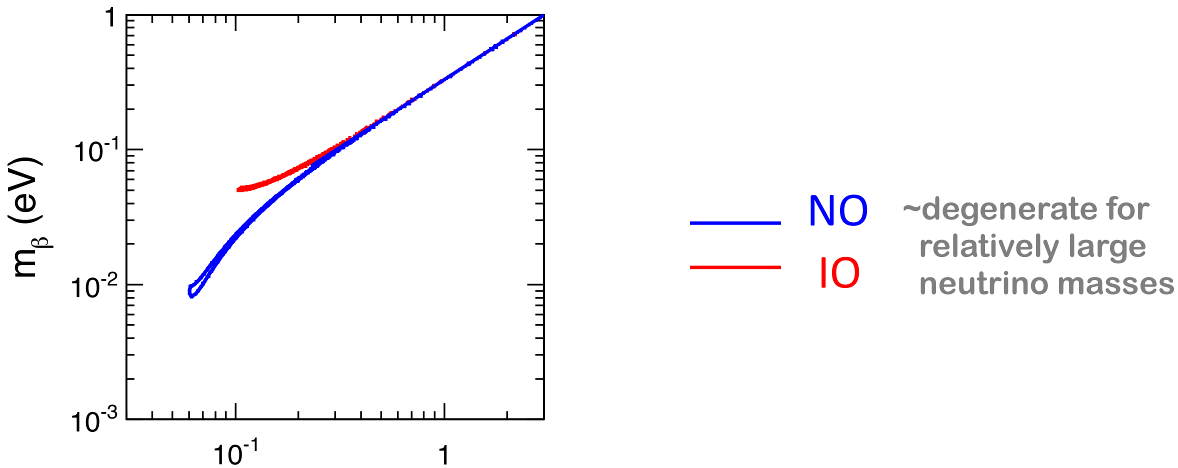
$$T_i^{-1} = G_i \, |M_i'|^2 \, m_{\beta\beta}^2$$

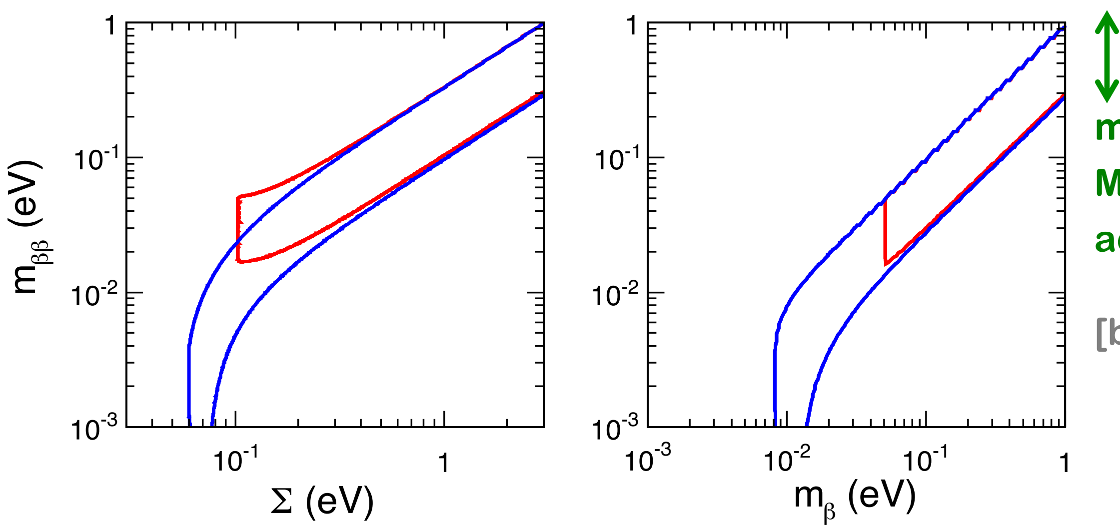
Half-life Phase space Nuclear matrix element

NME: Very difficult calculations. We have not (yet) a "standard nuclear model" ... **Medium term**: improve effective nuclear models via as many EW (+ other) test processes as you can: single and double beta decays, EC, muon capture, single and double charge exchange... **Long term**: improve nuclear models via lattice QCD simulations.



Constraints on nonoscillation observables from oscillation data

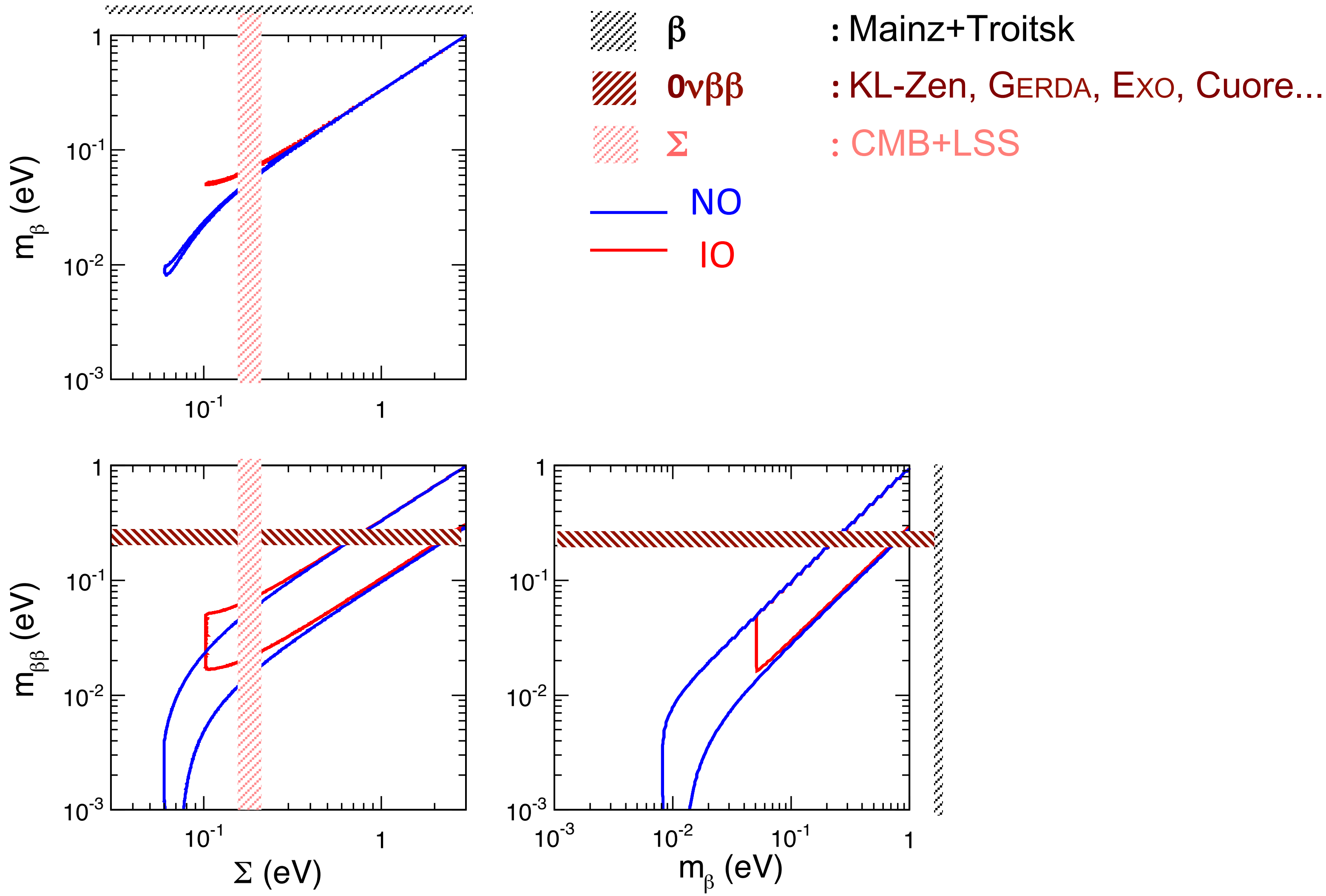




$m_{\beta\beta}$ spread due to
Majorana CP phase(s):
accessible in principle

[but no NME error here]

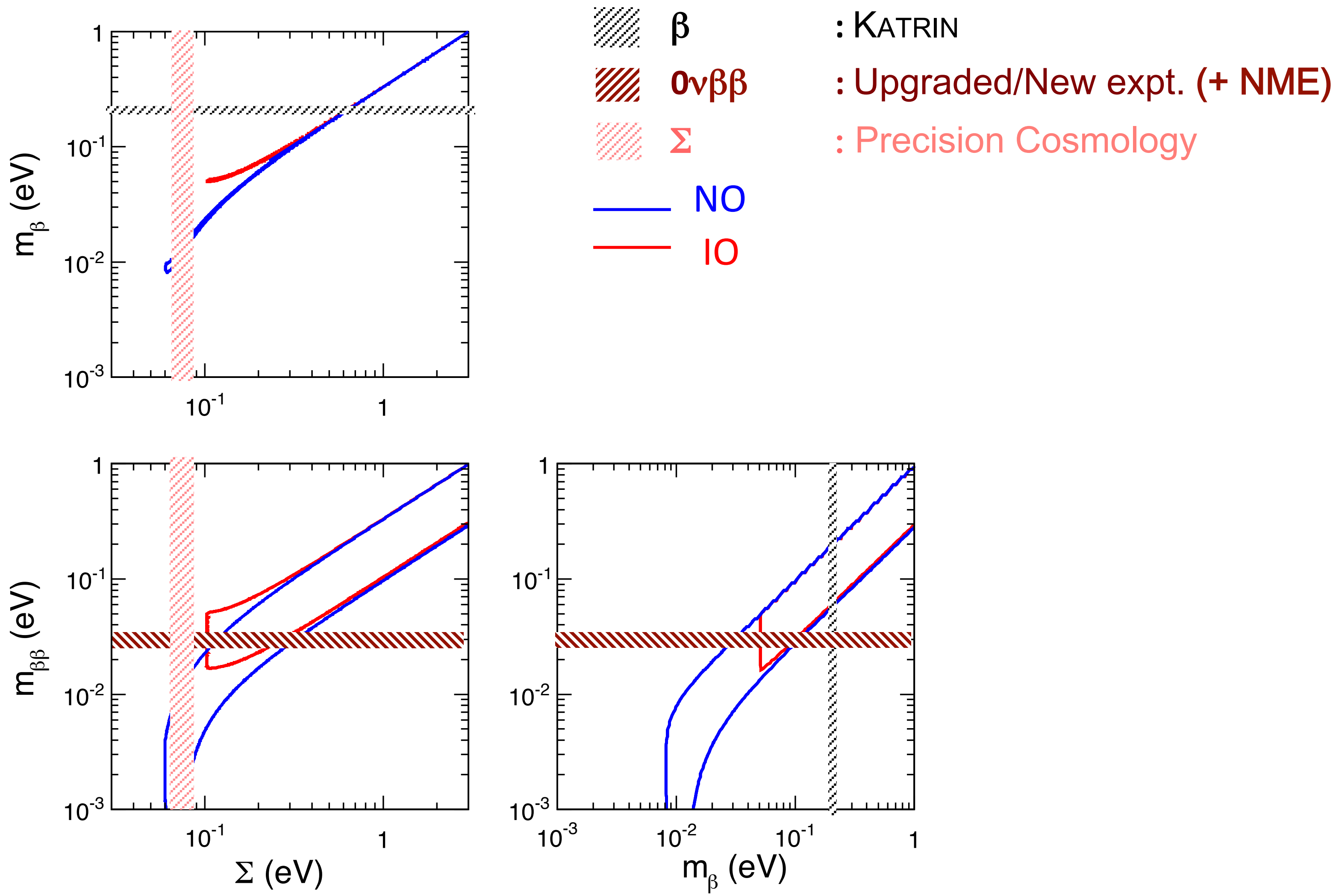
Upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.) + osc. constraints



Cosmo data already contribute to put IO "under pressure".

Major improvements expected in the next decade →

Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?



Large phase space for discoveries about ν mass and nature.

Theoretical challenges: cosmo high accuracy calculations/simulations, NME uncertainties

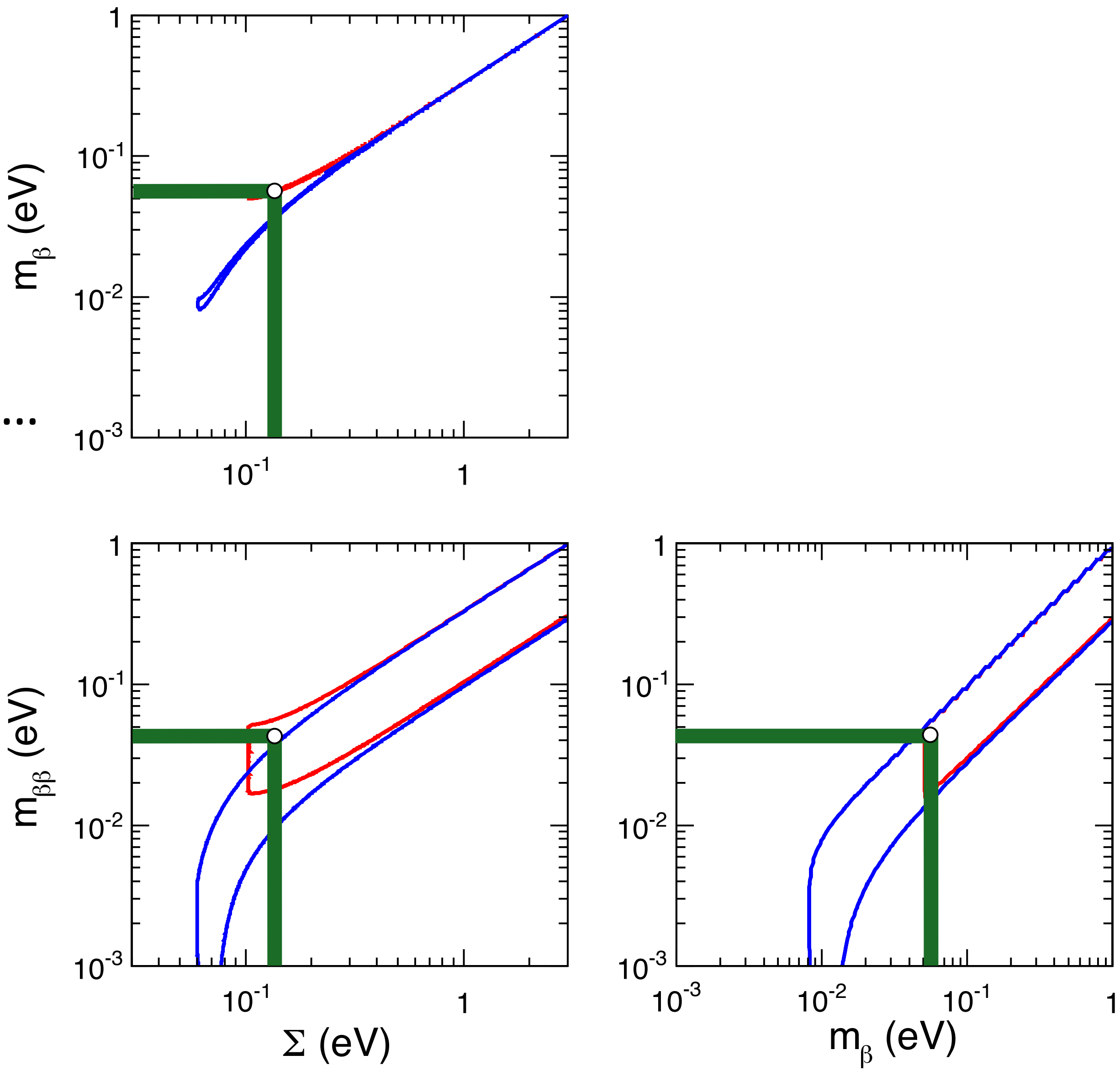
With "dreamlike" and converging data one could, e.g.

Determine the mass scale…

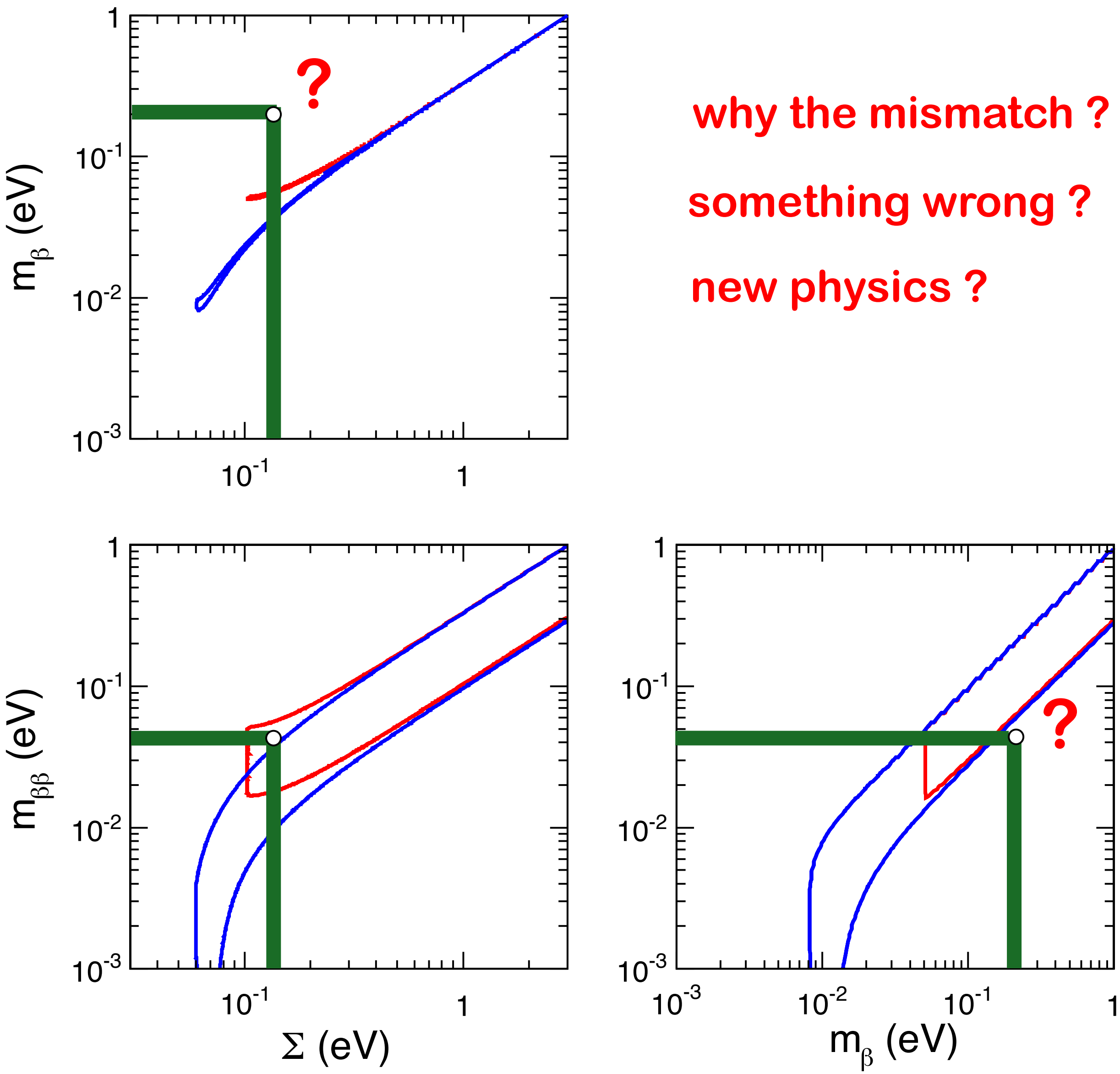
Check 3ν consistency …

Identify the hierarchy …

Probe the Majorana phase(s) …



But alternative situations (surprises!) might also occur....

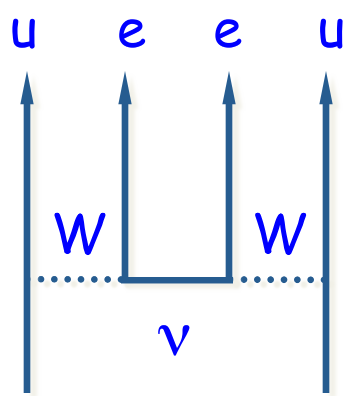


why the mismatch ?

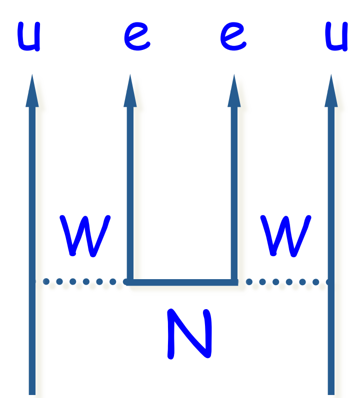
something wrong ?

new physics ?

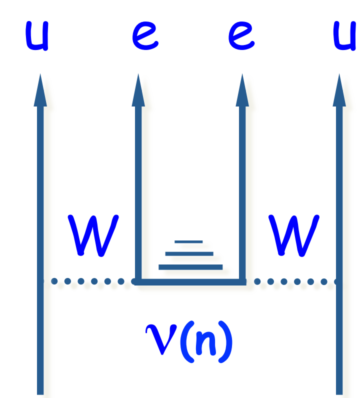
Physics beyond "3 light ν" should always be kept in mind, e.g., in neutrinoless double beta decay:



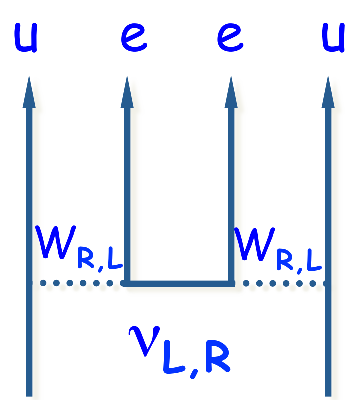
Standard



Heavy ν

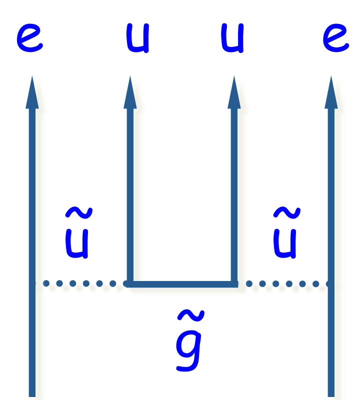


Kaluza-Klein

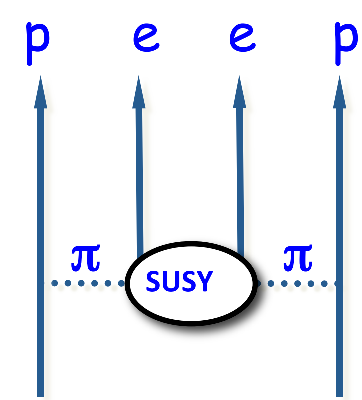


RHC λ,η

λ=RH had, η=LH had



SUSY $\tilde{g}$



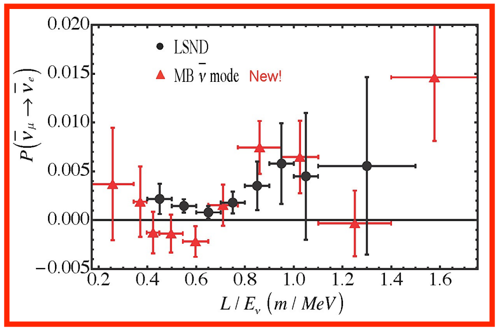
SUSY π

One scenario is under close scrutiny:

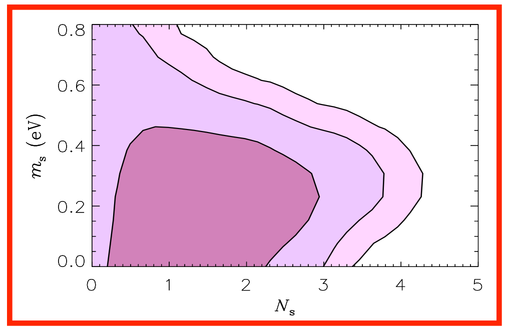
Sterile ν states at O(1 eV) scale, with small active-sterile mixing?

Prompted by some "anomalous" results still under investigation:

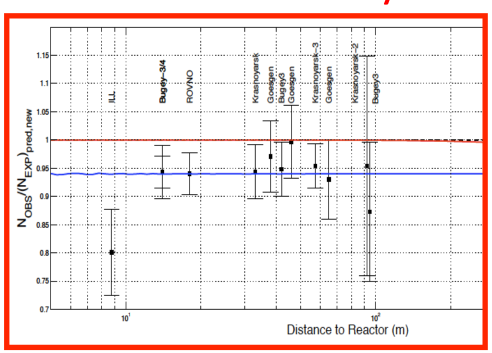
LSND/MiniBooNE (SBL)?



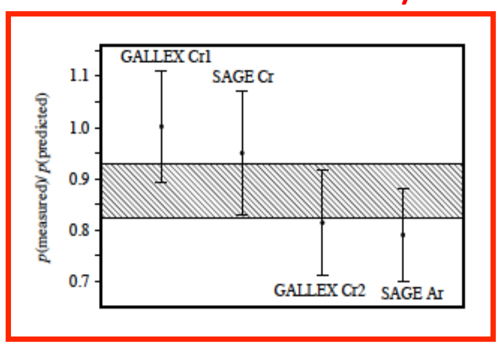
Extra cosm.radiation? (~obsolete)

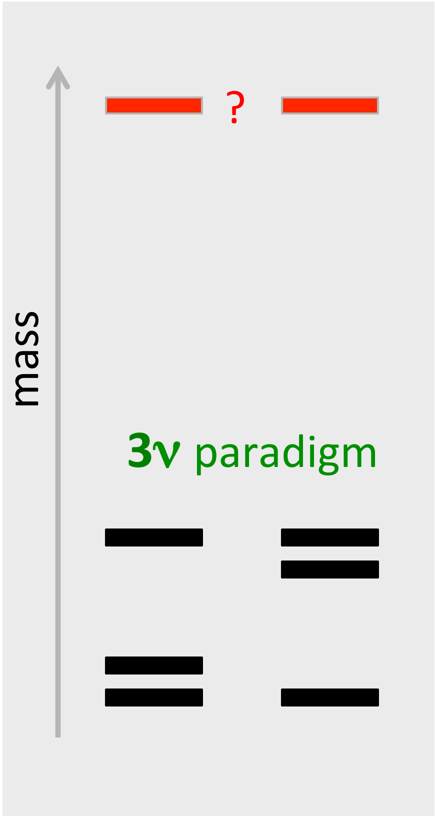


Reactor anomaly?

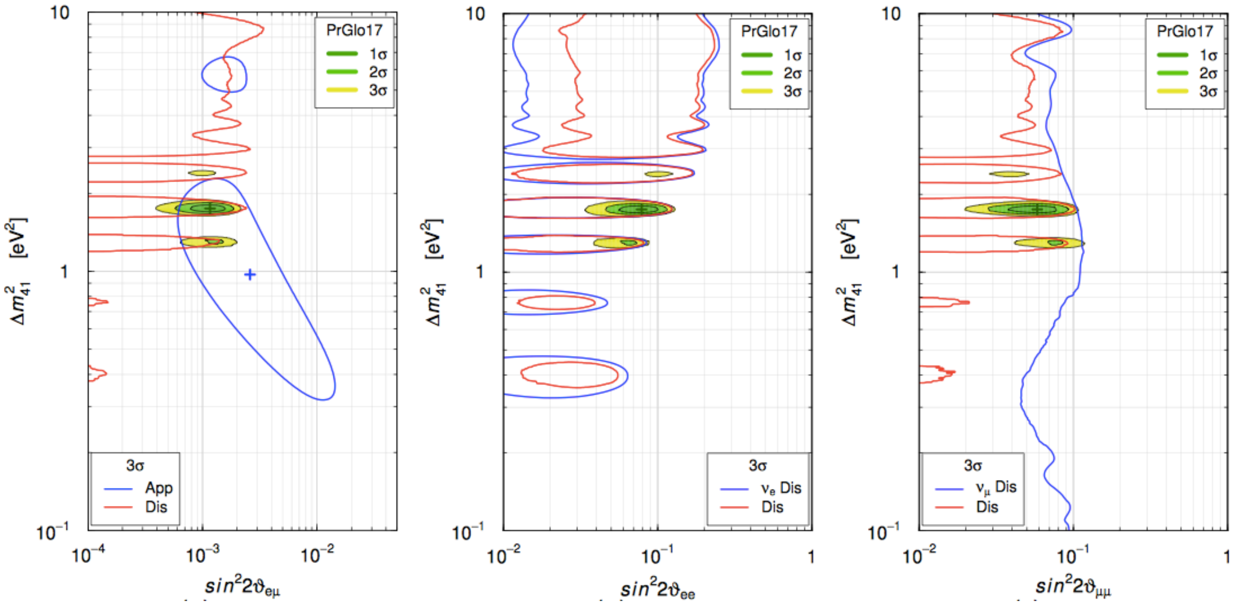


Gallium anomaly?





Sterile neutrinos: Appearance vs Disappearance... [from Giunti+ 2017]



... accuracy vs (possible) discoveries...

RECAP

- **Status of known 3ν oscillation parameters:**
  Precision era (but PMNS accuracy far from CKM)

- **Trends of unknown 3ν oscillation parameters:**
  Favoring **CPV** with $\sin\delta<0$ and **NO**; nearly max θ_{23}

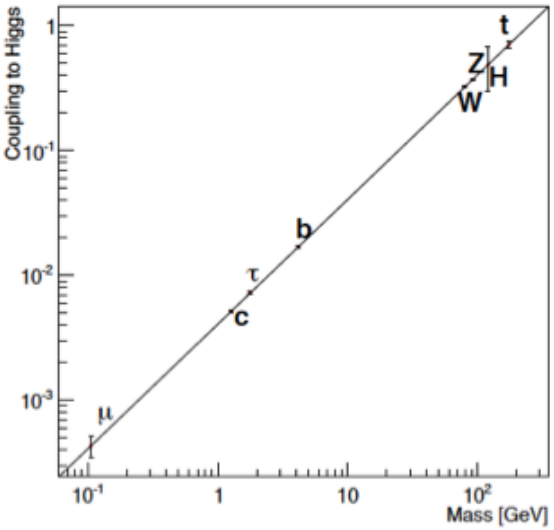
- **Status of 3ν abs. masses from $0\nu\beta\beta$ & Cosmology:**
  Sub-eV sensitivity but no positive detection yet

- **Experimental outlook:**
  Expect many **new results** within and beyond 3ν

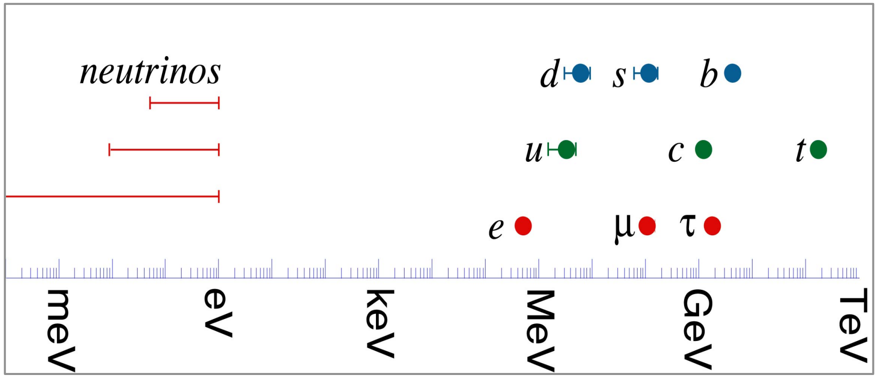
- **Theoretical outlook:**
  Expect **(better) understanding** within and beyond SM

EPILOGUE: Bridging two fundamental research programs

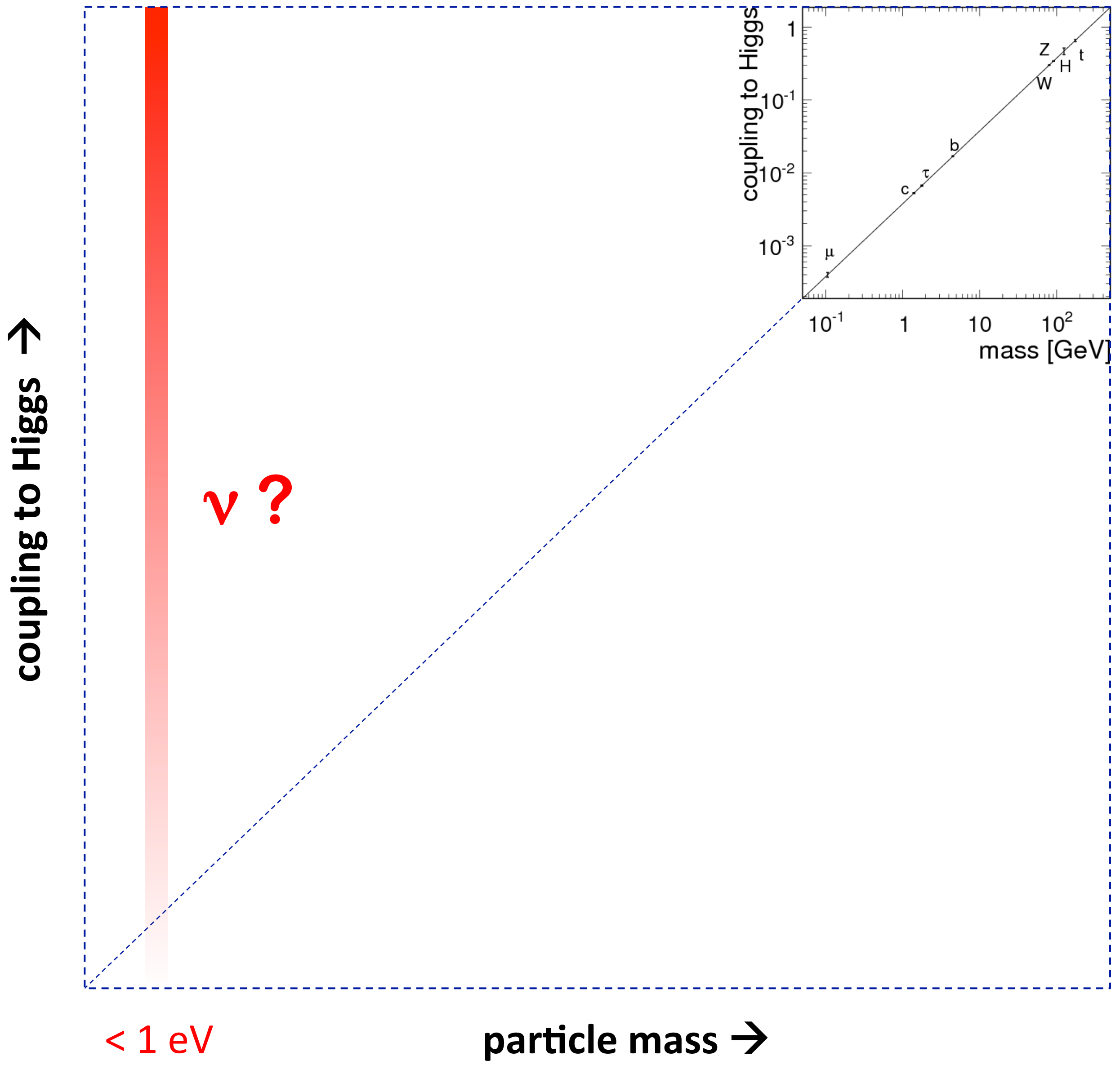
1. Test Higgs sector



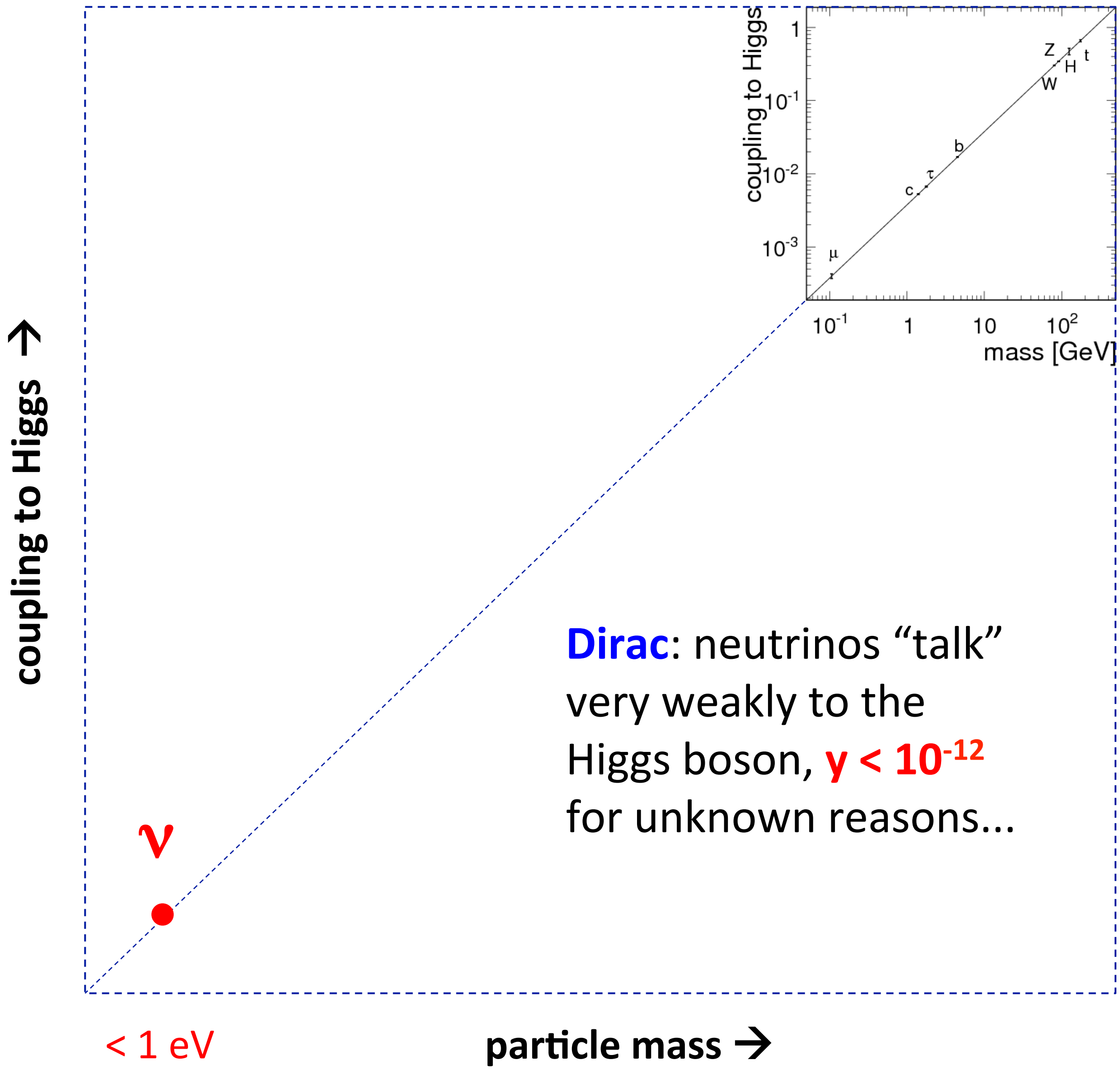
2. Find ν masses



1 + 2 **Where are the ν's on this plot? Why are they so light?**

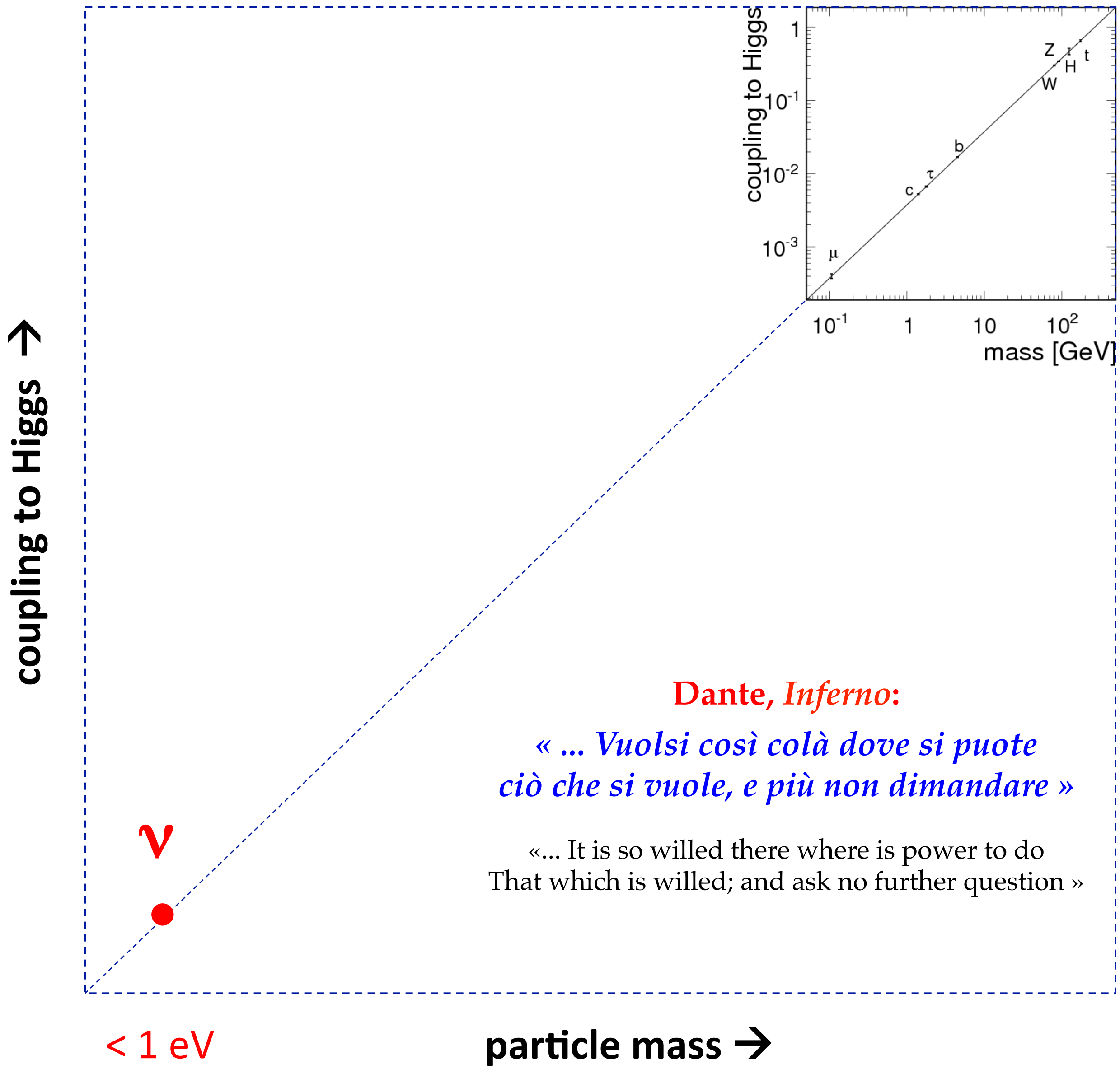


Option I



Dirac: neutrinos "talk" very weakly to the Higgs boson, **$y < 10^{-12}$** for unknown reasons...

Option I

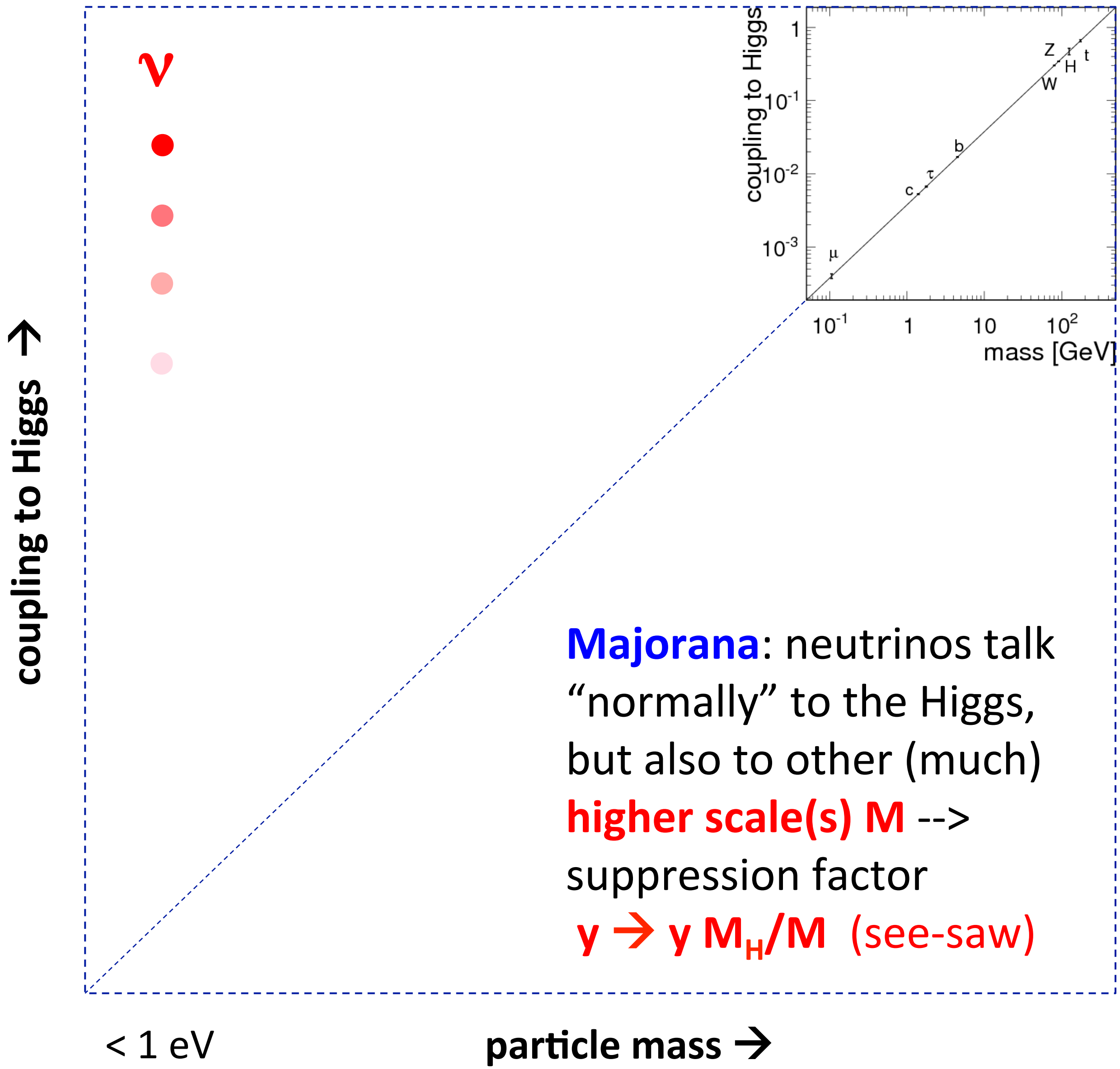


Dante, *Inferno*:

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

«... It is so willed there where is power to do
That which is willed; and ask no further question »

Option II



Majorana: neutrinos talk "normally" to the Higgs, but also to other (much) **higher scale(s) M** --> suppression factor

$y \rightarrow y\, M_H/M$ (see-saw)

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

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

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

M ~ GUT scale

CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis):
Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

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M ~ low scale

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) **additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP**

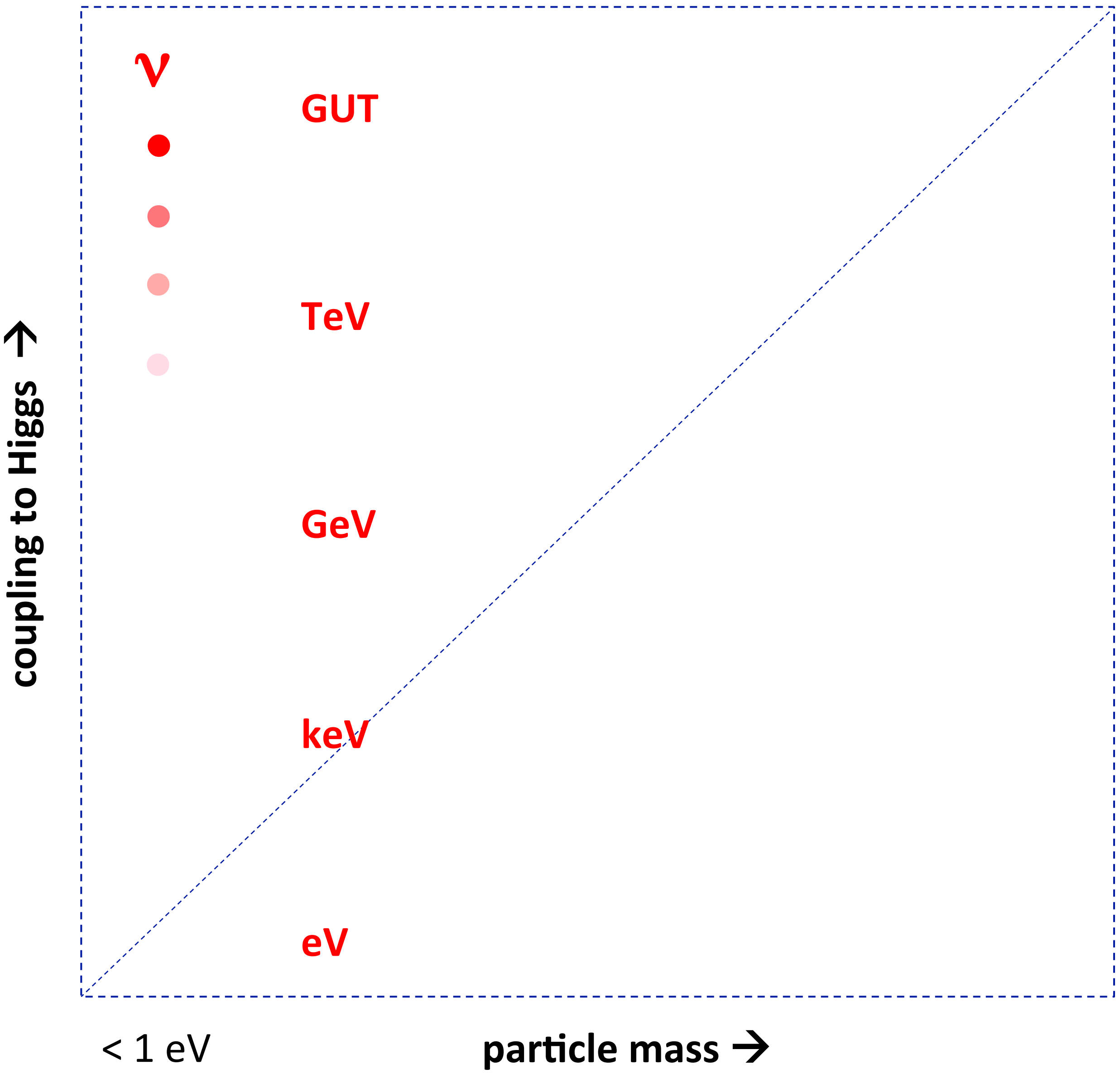
CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis). Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP

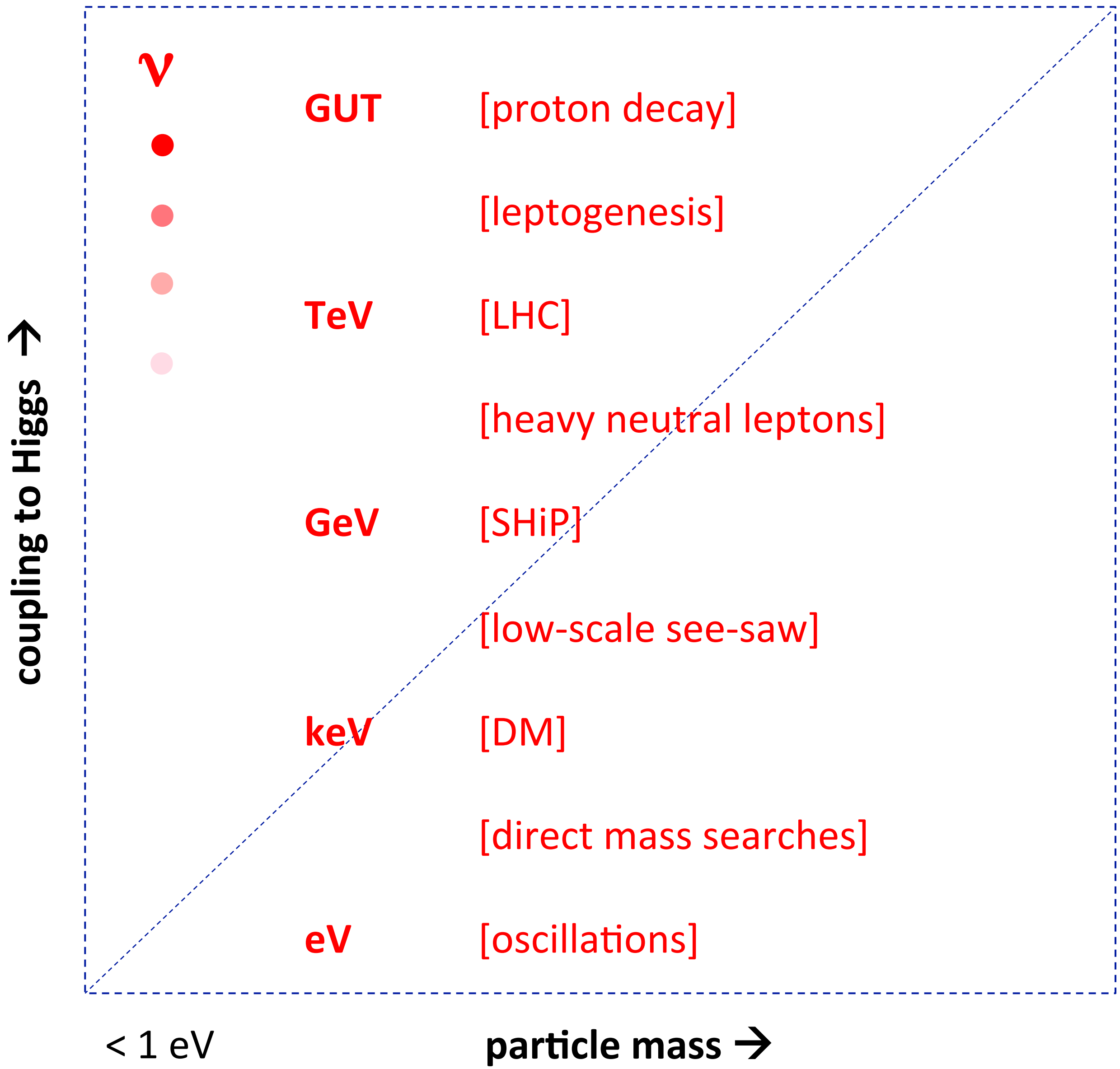
In principle, several sterile states might even be split among widely different energy scales, and affect various phenomena in (astro)particle physics.

Let us remain open-minded…

...New mass states could emerge at (different) new scales ...



… and contribute to a rich research program…

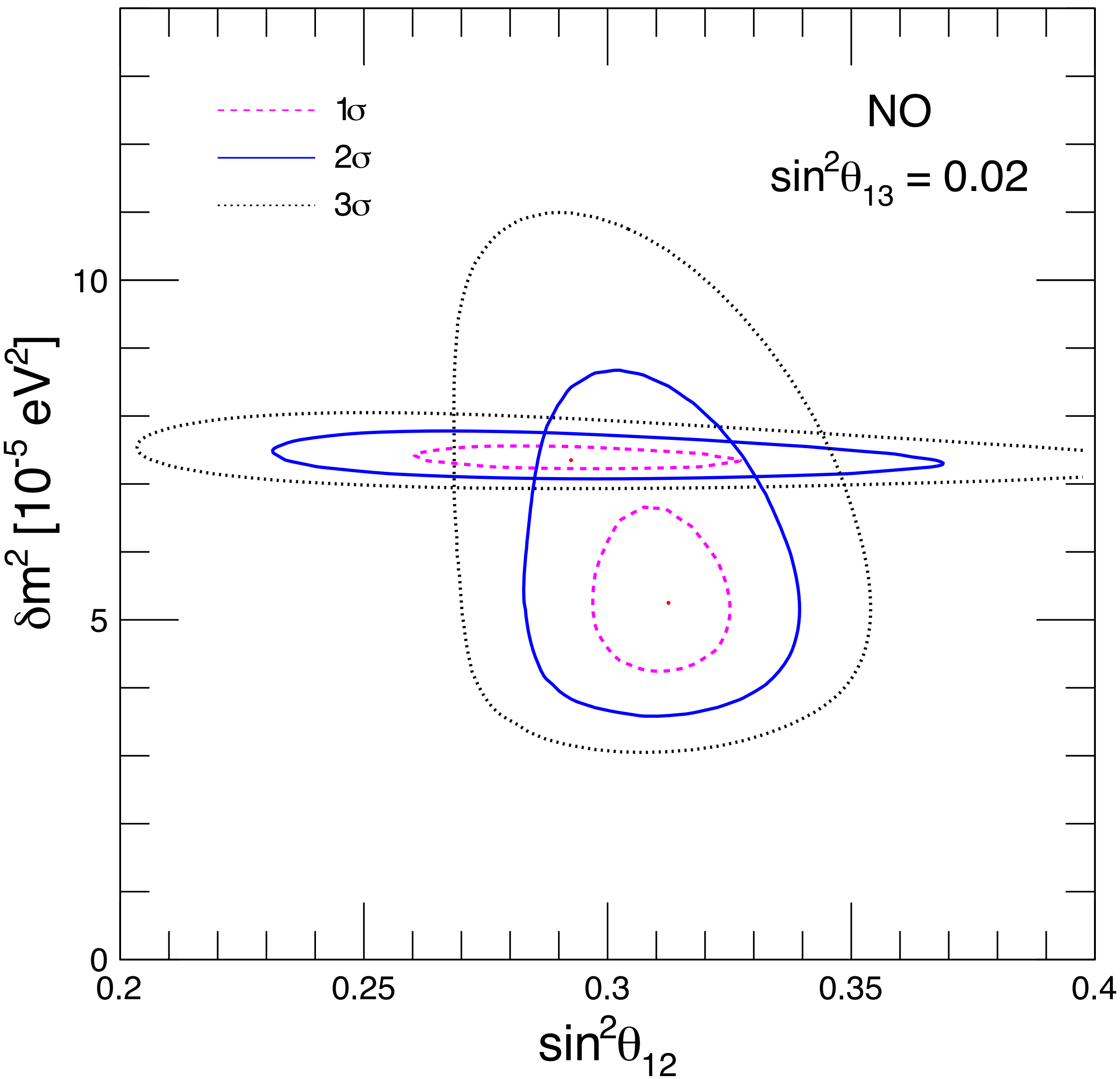


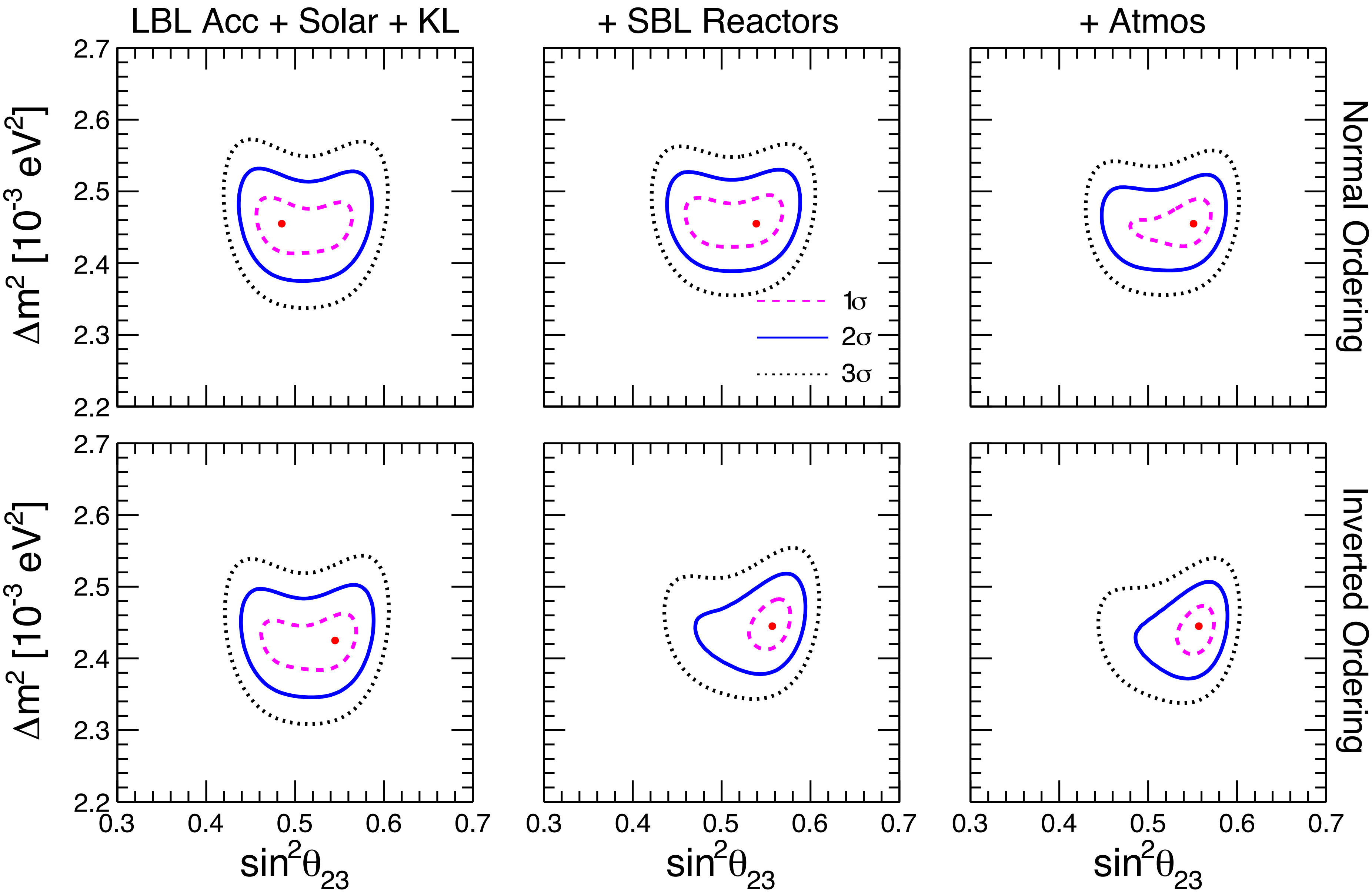
... that may lead to a novel, broad-brush picture beyond 3ν...


?
Thank you for your attention!

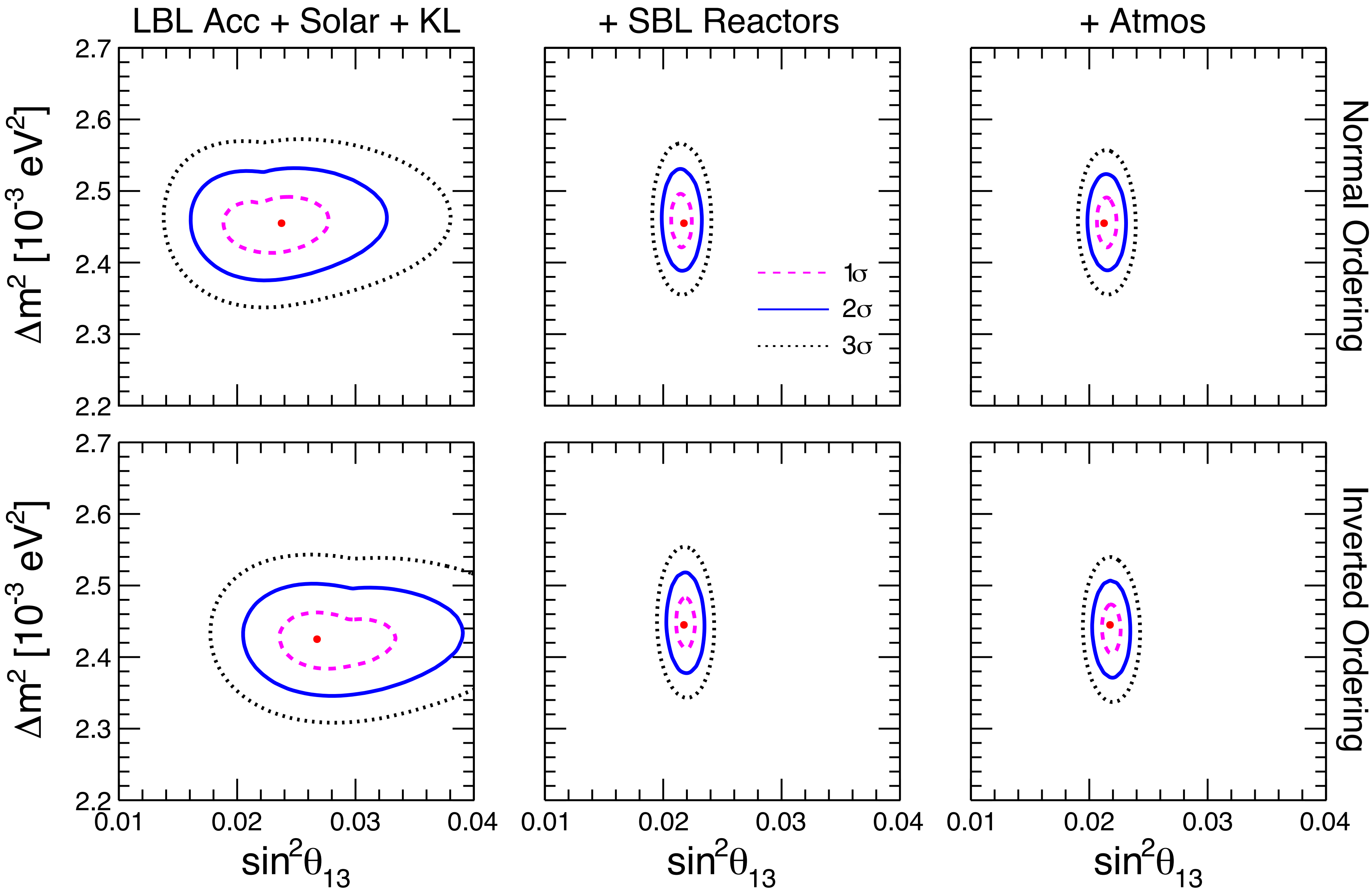
Extra slides

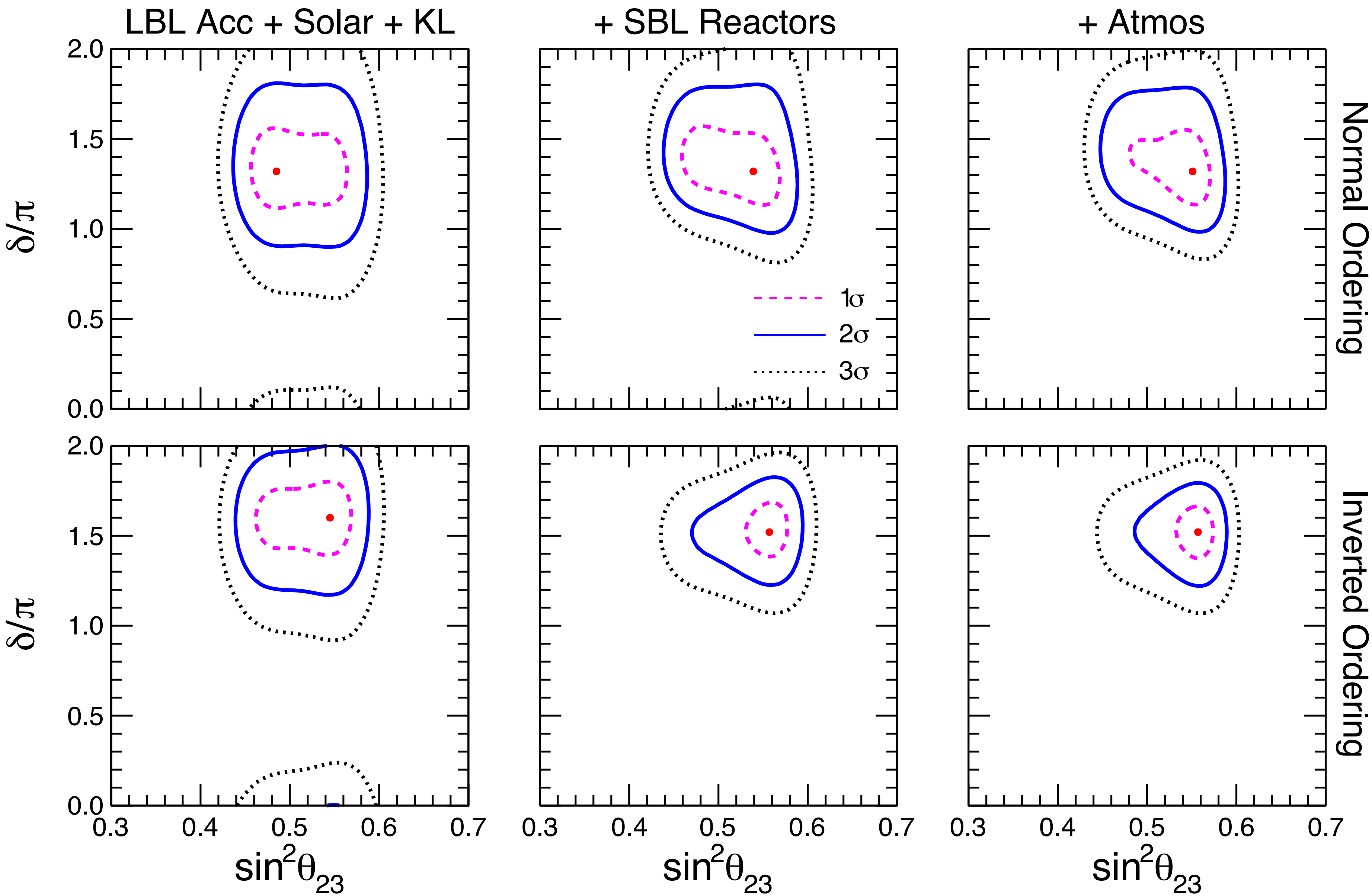
with further results related to arXiv:1804.09678


1σ
2σ
3σ
NO
sin²θ13 = 0.02
δm² [10⁻⁵ eV²]
0
5
10
0.2
0.25
0.3
0.35
0.4
sin²θ12

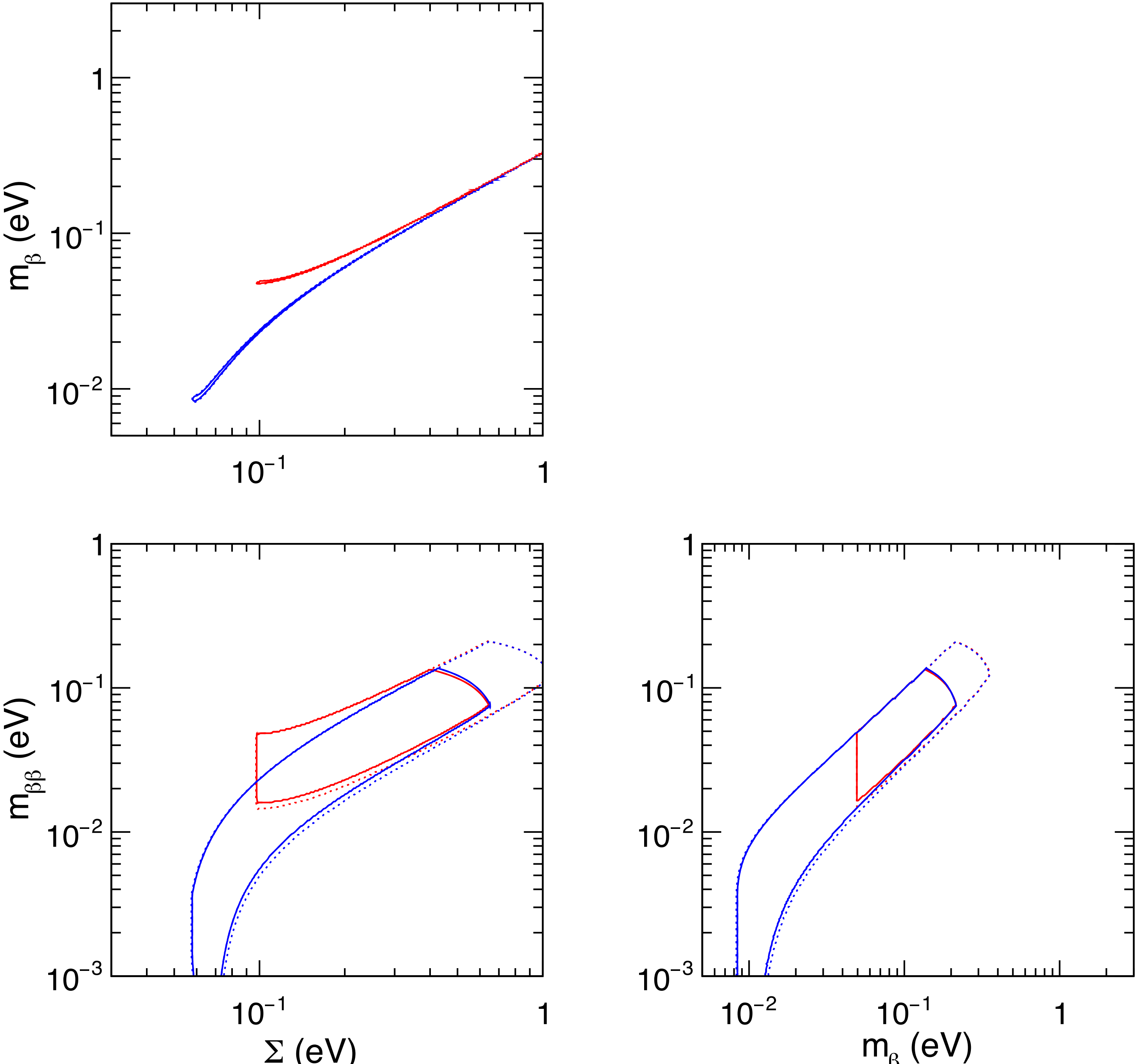


LBL Acc + Solar + KL
+ SBL Reactors
+ Atmos
Normal Ordering
Inverted Ordering
Δm² [10⁻³ eV²]
sin²θ₂₃
1σ
2σ
3σ
2.2
2.3
2.4
2.5
2.6
2.7
0.3
0.4
0.5
0.6
0.7

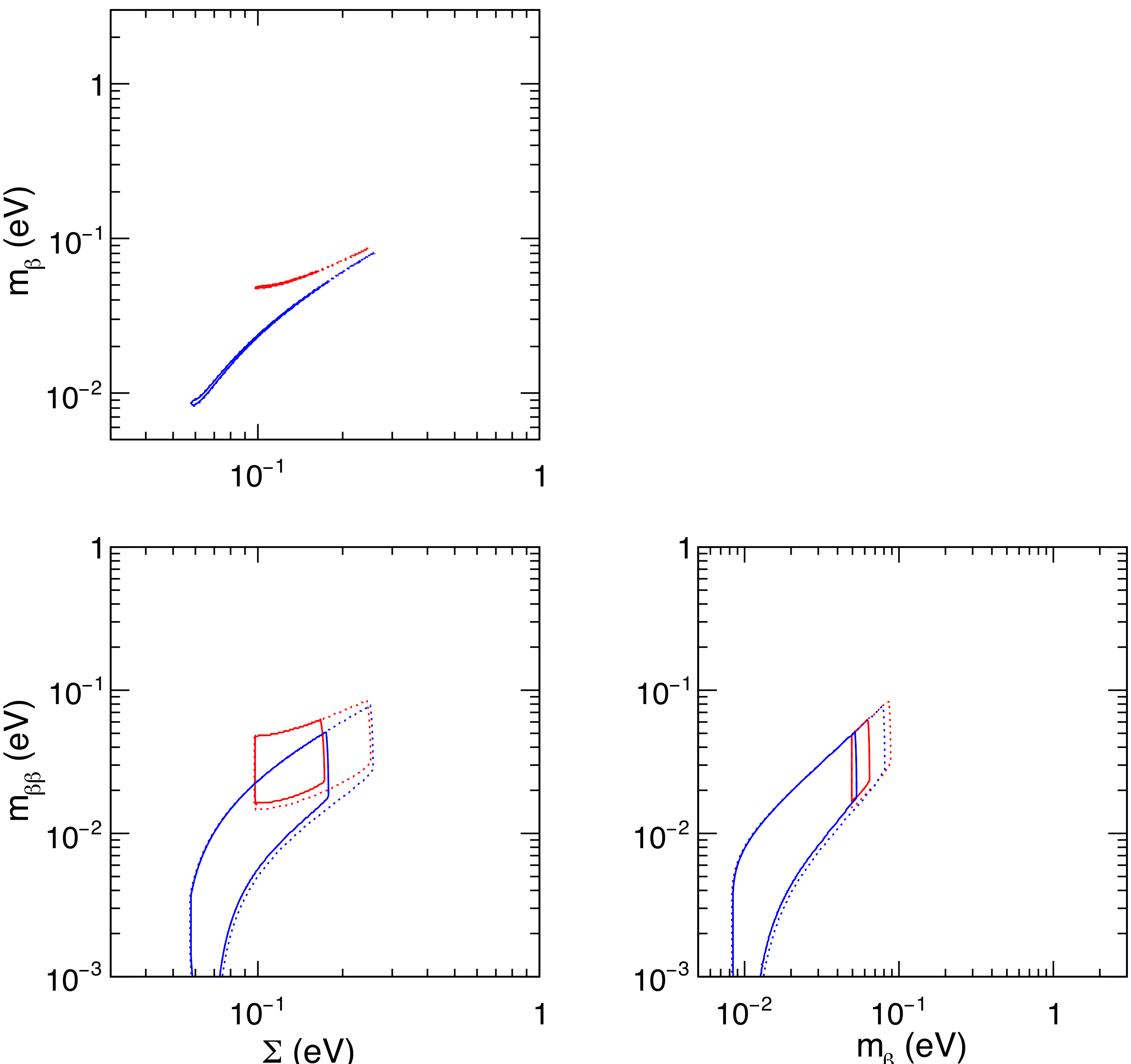

LBL Acc + Solar + KL
+ SBL Reactors
+ Atmos
Normal Ordering
Inverted Ordering
Δm2 [10-3 eV2]
sin2θ13
1σ
2σ
3σ
2.2
2.3
2.4
2.5
2.6
2.7
0.01
0.02
0.03
0.04



LBL Acc + Solar + KL
+ SBL Reactors
+ Atmos
Normal Ordering
Inverted Ordering
δ/π
δ/π
$\sin^2\theta_{23}$
$\sin^2\theta_{23}$
$\sin^2\theta_{23}$
1σ
2σ
3σ
0.0
0.5
1.0
1.5
2.0
0.3
0.4
0.5
0.6
0.7



1
10^{-1}
10^{-2}
m_β (eV)
10^{-1}
1
1
10^{-1}
10^{-2}
10^{-3}
$m_{\beta\beta}$ (eV)
10^{-1}
1
Σ (eV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
m_β (eV)



m_β (eV)
1
10^-1
10^-2
10^-1
1
m_ββ (eV)
1
10^-1
10^-2
10^-3
10^-1
1
Σ (eV)
1
10^-1
10^-2
10^-3
10^-2
10^-1
1
m_β (eV)