Known and unknown neutrino mass-mixing properties

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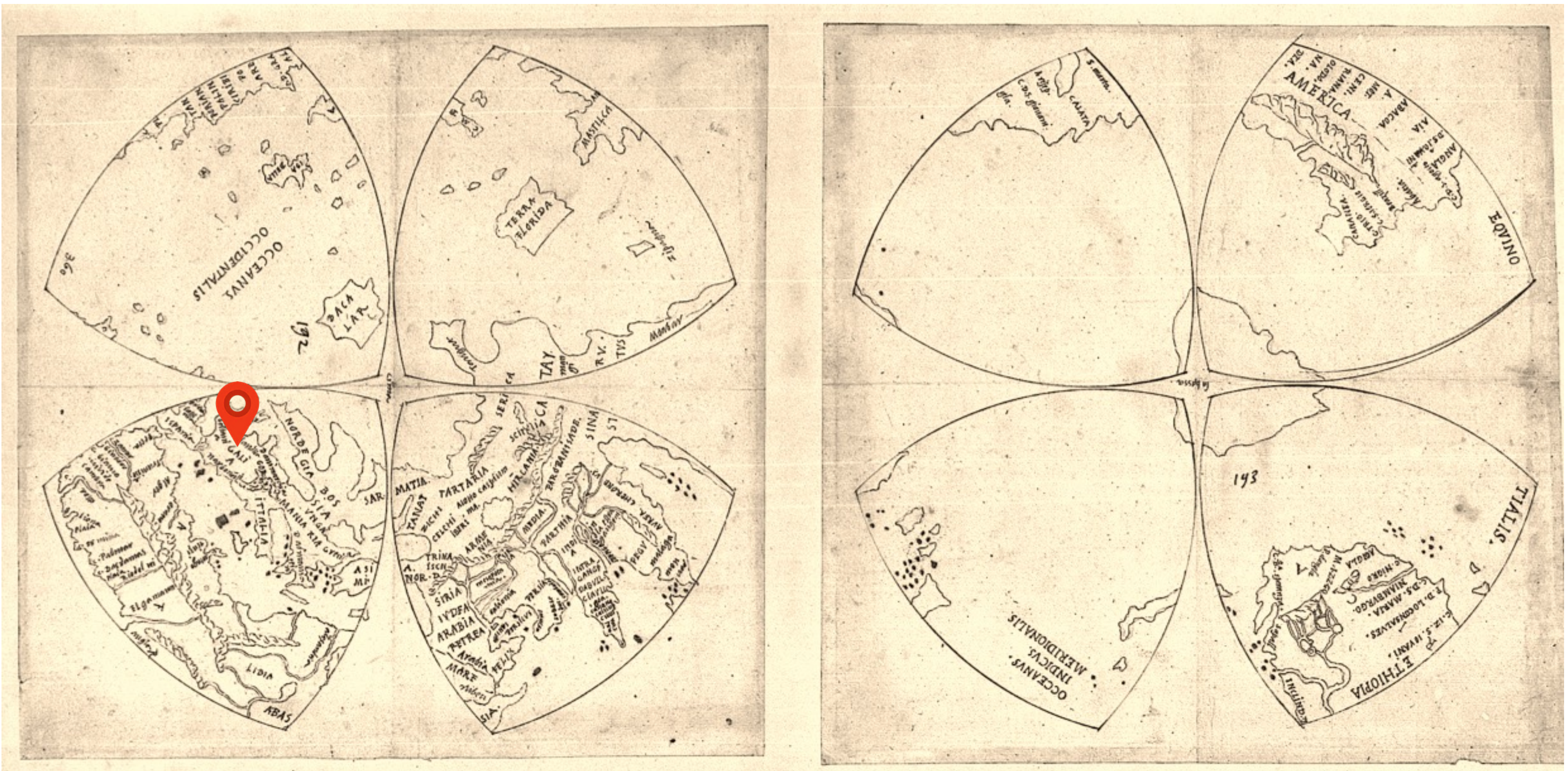
APC Colloquium, 9 April 2021

PROLOGUE: A remarkable world map (~ 1514)...

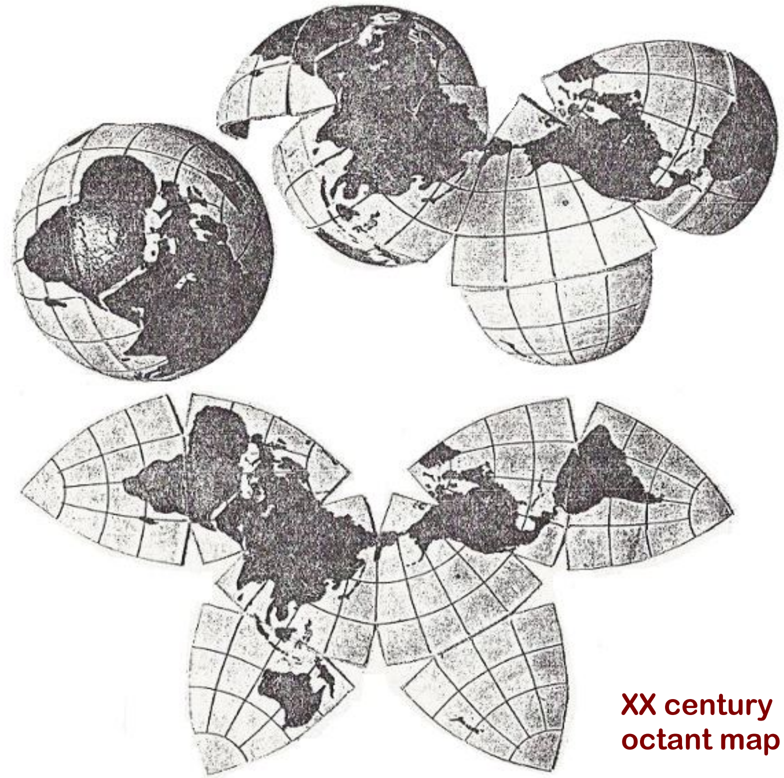


Northern hemisphere **Southern hemisphere**

... attributed to Leonardo da Vinci [1452-1519]

[Now at the Royal Library, Windsor Collection. Executed by one of Leonardo’s assistants.]

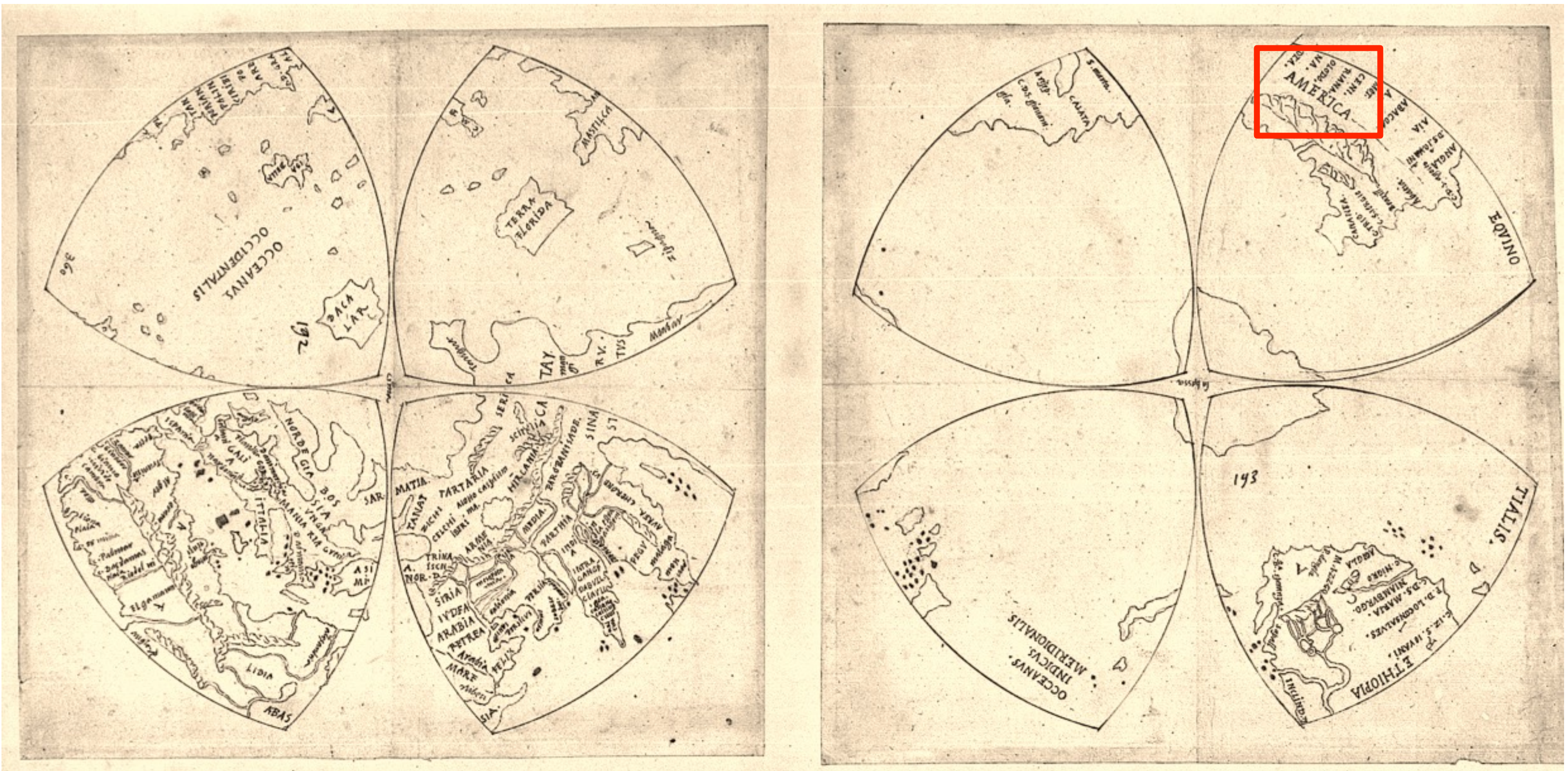
Earliest known world map …



XX century octant map

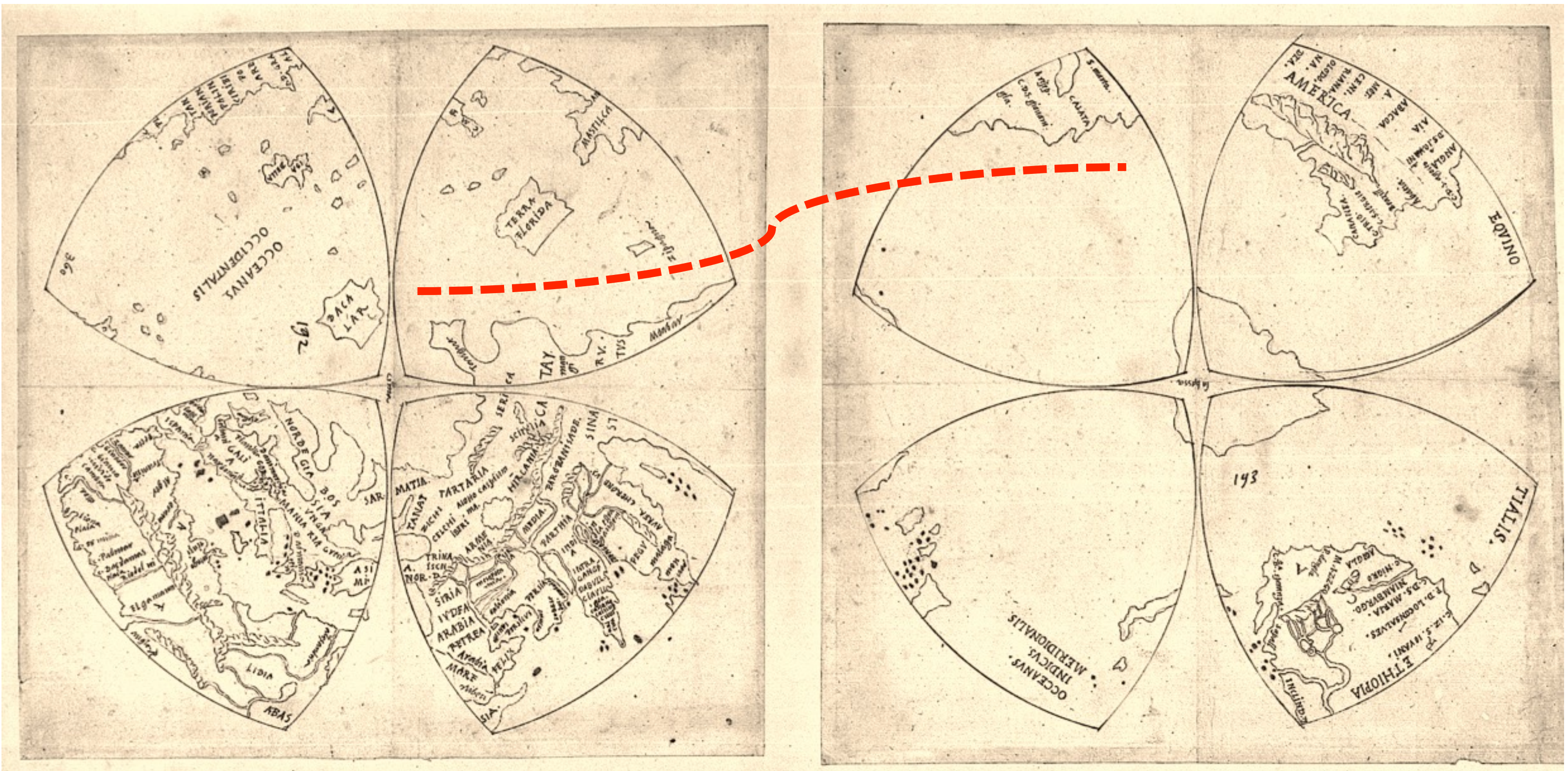
… made with octant projections (1/8's of the globe)

Earliest known world map ...



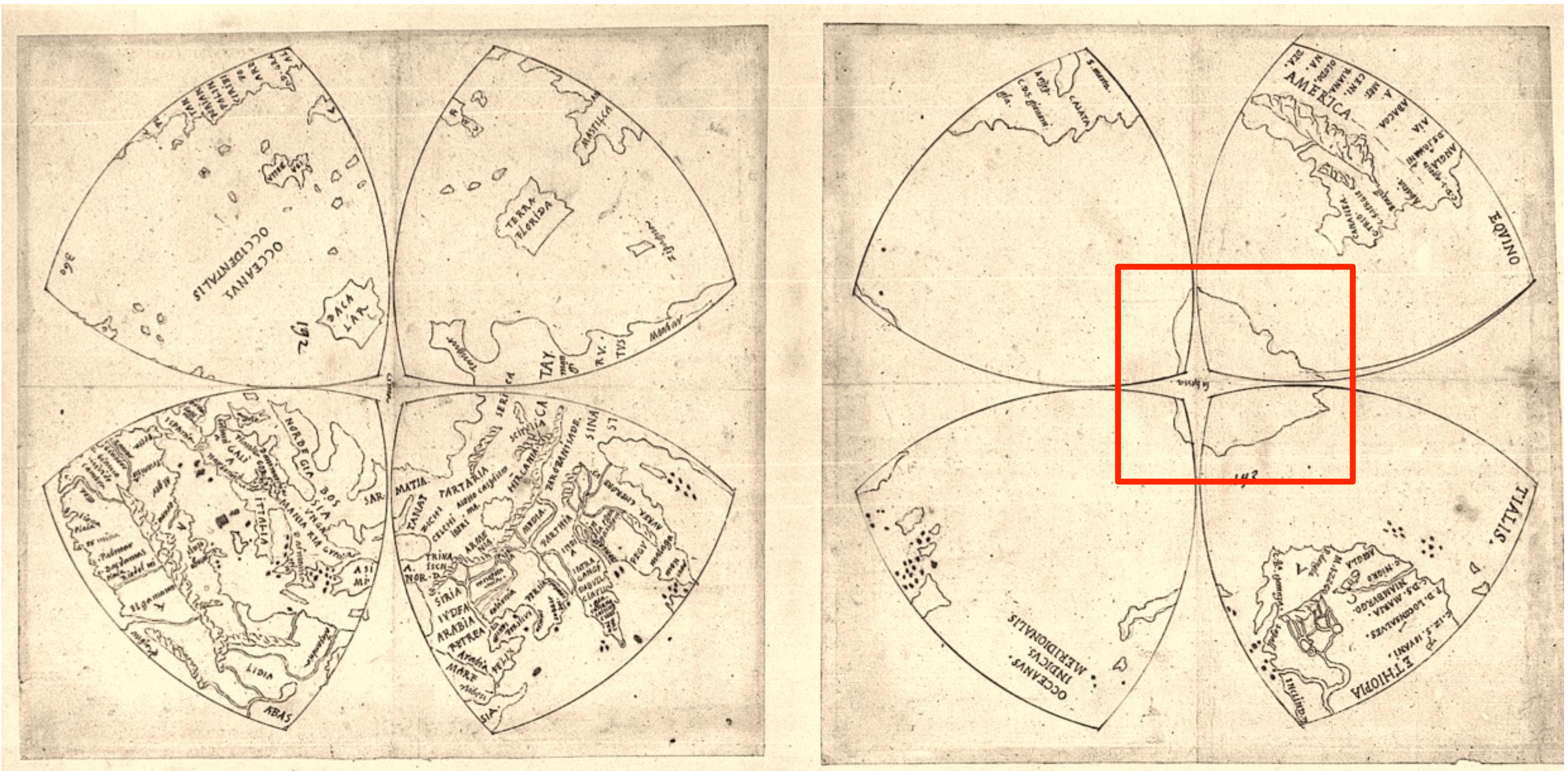
... made with octant projections (1/8's of the globe)
... showing the name "America" for the New World

Earliest known world map ...



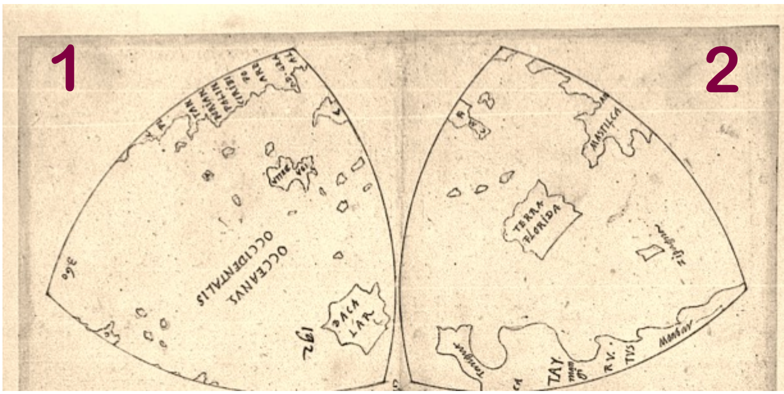
... made with octant projections (1/8's of the globe)
... showing the name "America" for the New World
... with America's west coast disconnected from Asia

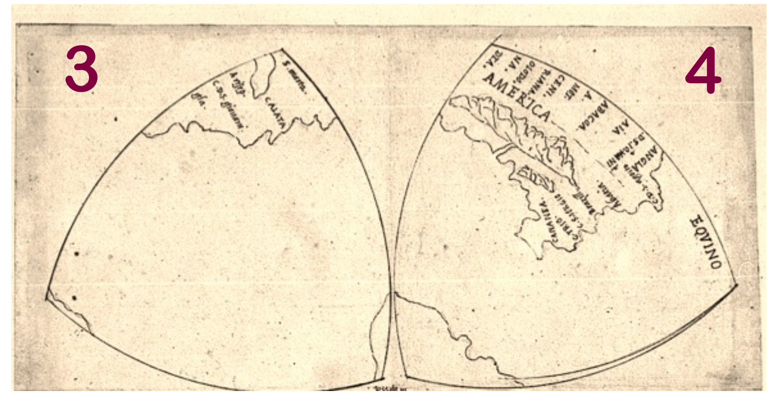
Earliest known world map ...



... made with octant projections (1/8's of the globe)
... showing the name "America" for the New World
... with America's west coast disconnected from Asia
... indicating a large Southern continent (a bold guess!)

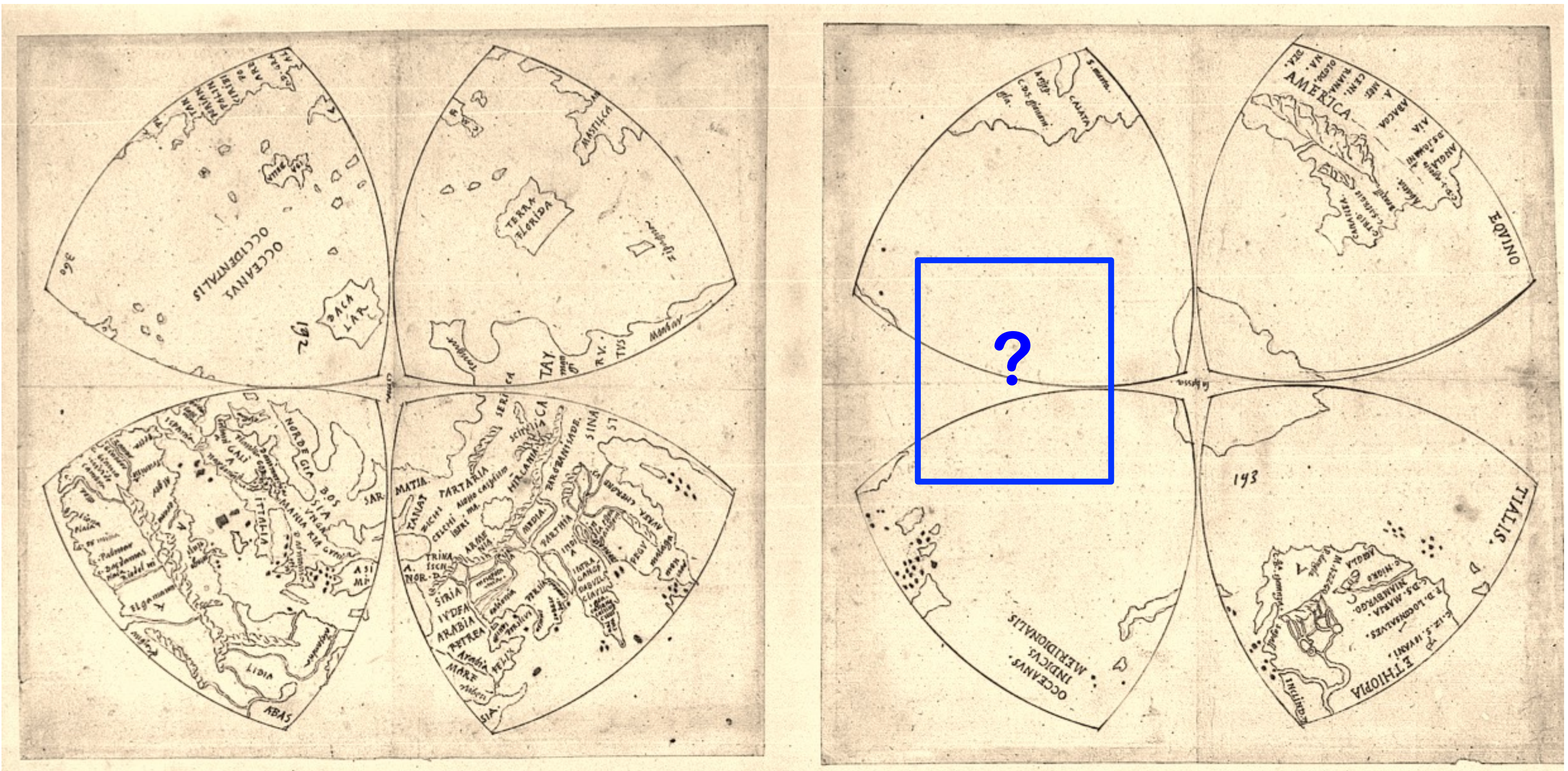
But Leonardo could not yet...





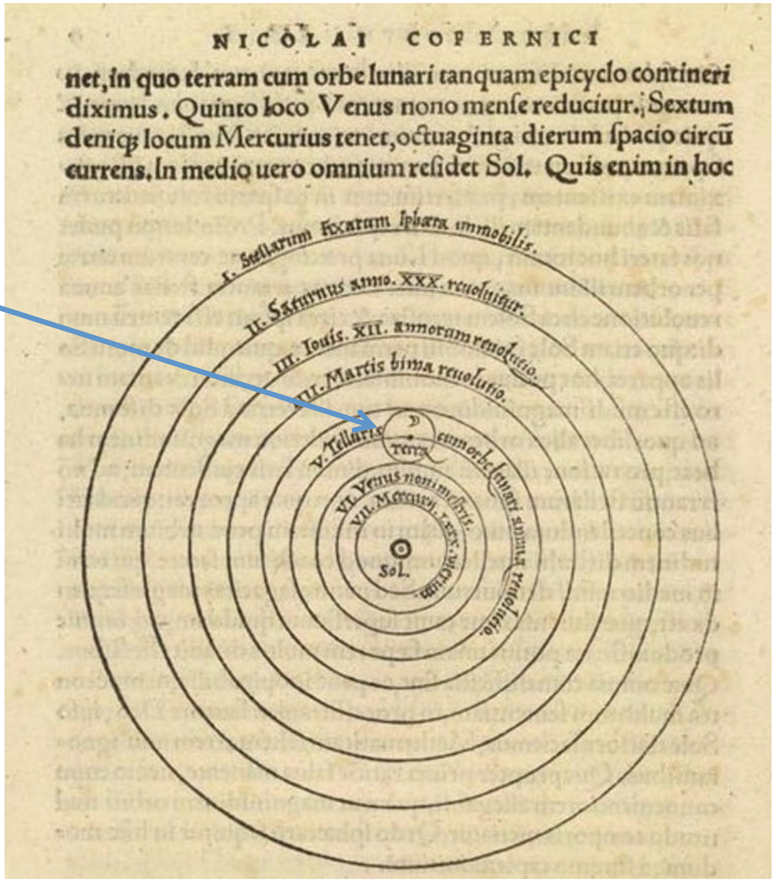
... avoid mapping distortions and biases

But Leonardo could not yet...



... know about Australian continent (~ 90 years later)

But Leonardo could not yet...



NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri
diximus. Quinto loco Venus nono mense reducitur. Sextum
deniq; locum Mercurius tenet, octuaginta dierum spacio circũ
currens. In medio uero omnium residet Sol. Quis enim in hoc

... fully grasp a bigger picture of the world
(Copernicus, ~30 years later)

After ~500 years...

...we are experiencing a similar situation in ν physics:

- being excited by a series of discoveries
- charting the newly discovered territories
- trying to avoid distortions and biases
- seeking unknown lands and a bigger picture

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…we are experiencing a similar situation in ν physics:

- being excited by a series of discoveries
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…which is also the thread of this Colloquium:
an interplay between known and unknown neutrino properties

• being excited by a series of discoveries

1998: Annus Mirabilis for "**APC**"

"C"

accelerated expansion of the Universe

$$\varrho_{\rm vac} \sim (2 \times 10^{-3}\ {\rm eV})^4$$

Evidence for dark energy

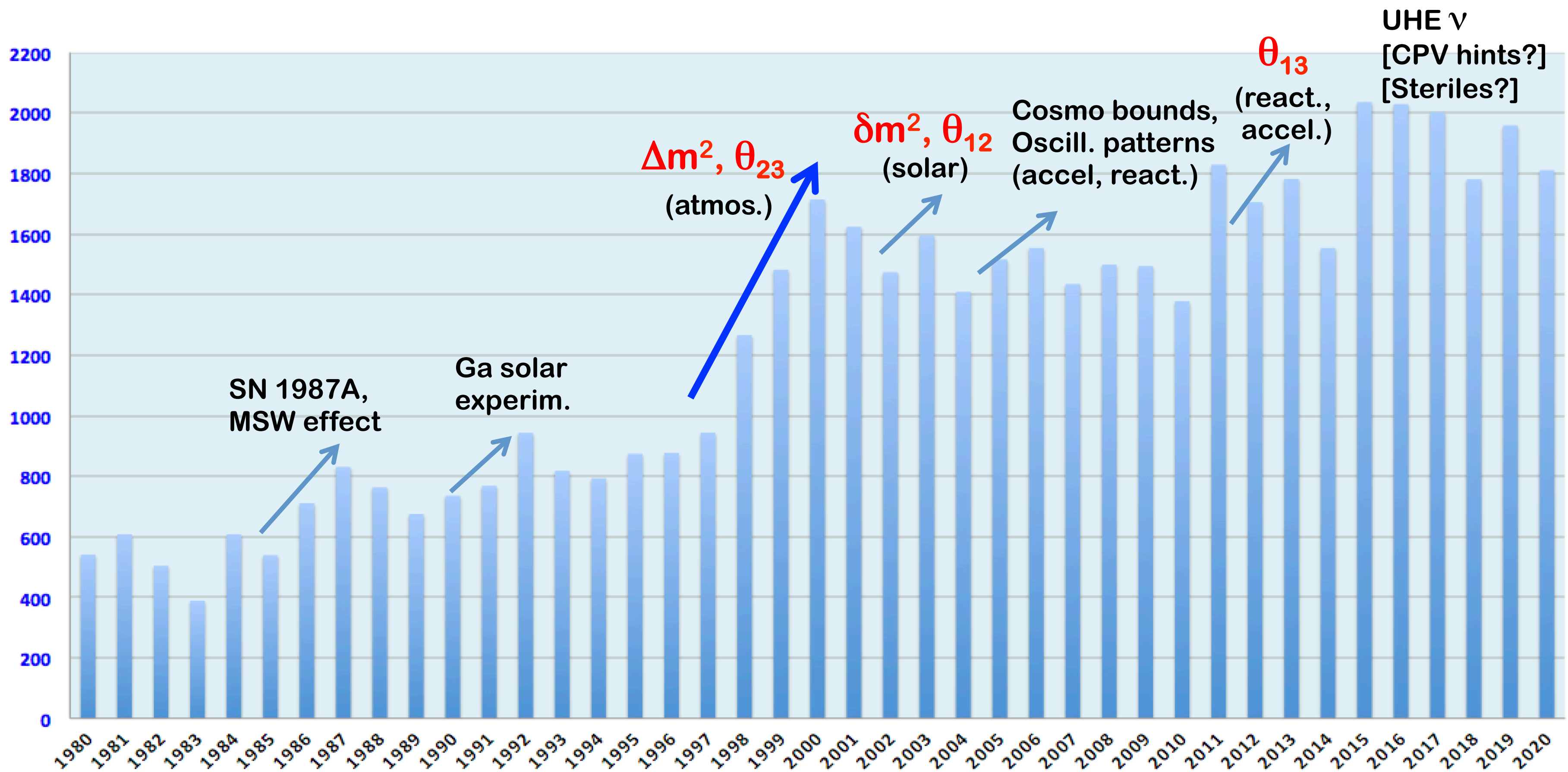
"AP"

oscillations of atmospheric neutrinos

$$\Delta m^2_{\rm atm} \sim (5 \times 10^{-2}\ {\rm eV})^2$$

Evidence for neutrino mass

Papers with *neutrino* in the title, 40-yr trend from INSPIRE HEP



$\Delta m^2_{ij} L/E \sim$ oscillation phase in vacuum $\quad \nu_\alpha \to \nu_\beta$ (appearance)

$\sin^2\theta_{ij} \sim$ oscill. amplitude in vacuum $\quad \nu_\alpha \to \nu_\alpha$ (disappear.)

→ **standard ν paradigm established**

The standard 3ν paradigm: parameters

Mixings 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

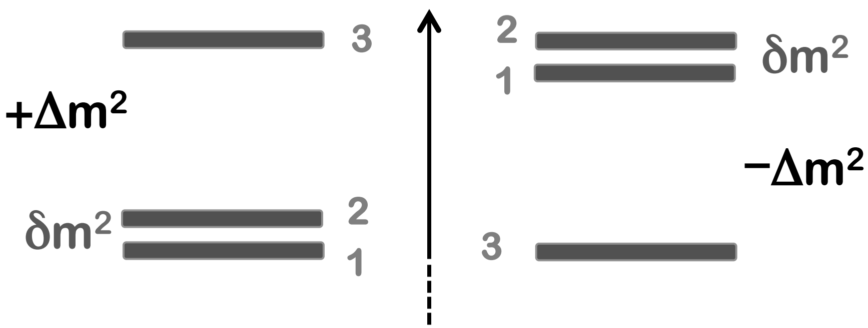
1-3 rotation
+ CPV "Dirac" phase

1-2 rotation

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

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

"Normal" Ordering
N.O.



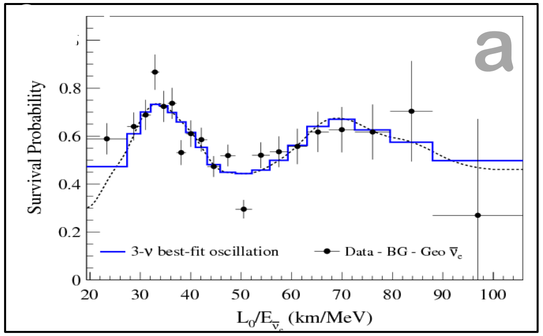
"Inverted" Ordering
I.O.

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

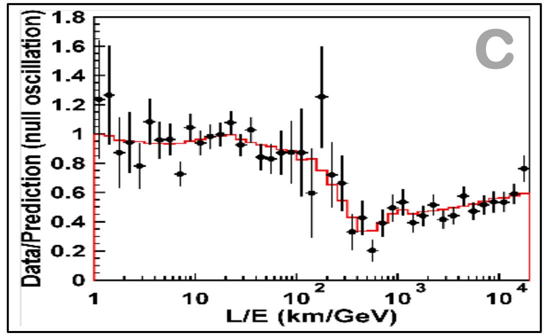
+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density
+ absolute neutrino mass scale (not tested in oscillations)

Beautiful ν oscillation data have established this 3ν paradigm…

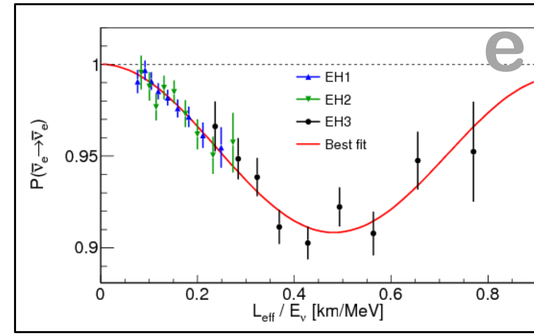
e→e (KamLAND, KL)



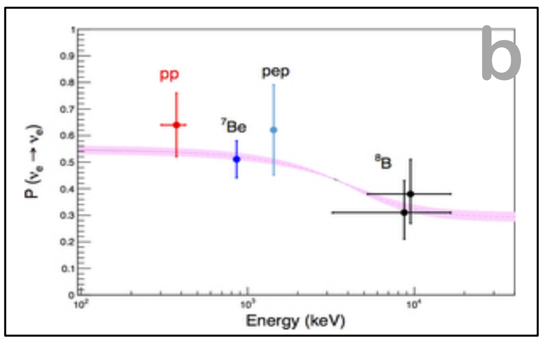
μ→μ (Atmospheric)



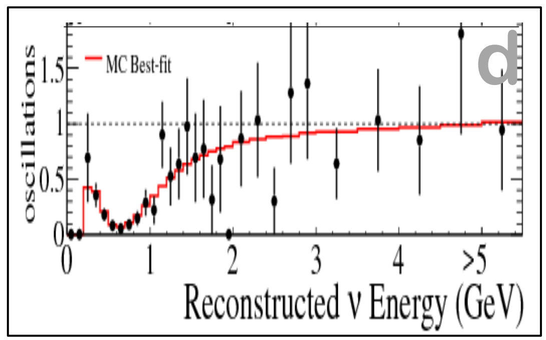
e→e (SBL Reac.)



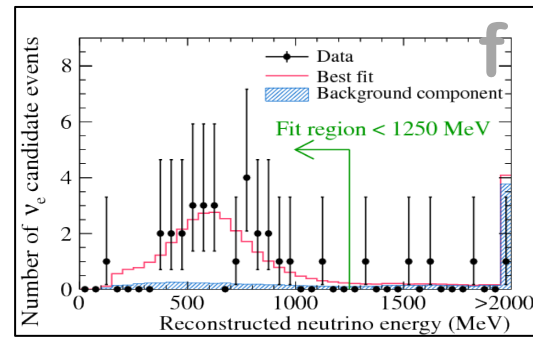
e→e (Solar)



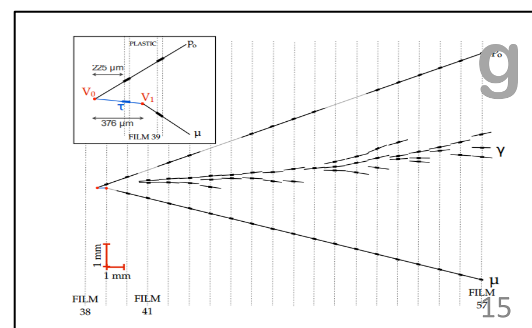
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

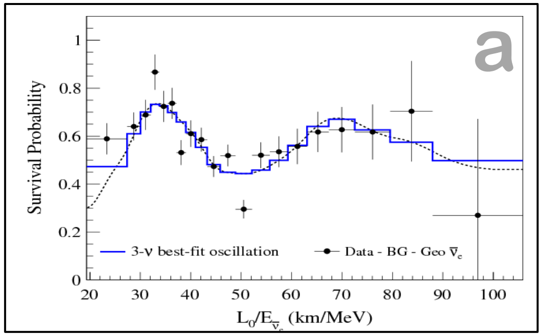


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

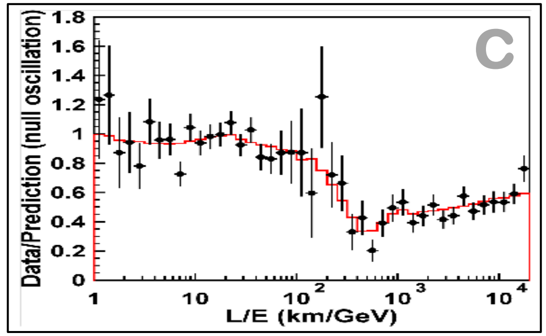
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot]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

… and consistently measured five ν mass-mixing parameters

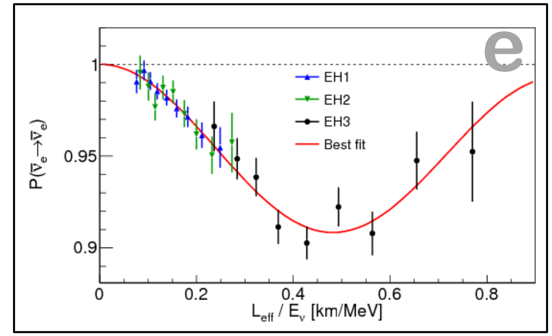
e→e (δm^2 , θ_{12})



μ→μ (Δm^2 , θ_{23})



e→e (Δm^2 , θ_{13})



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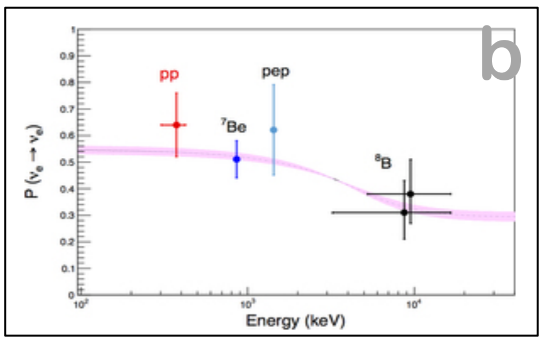

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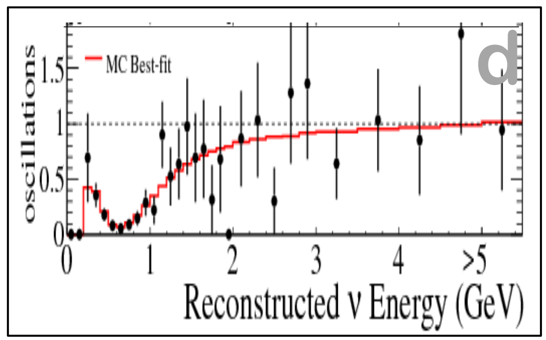
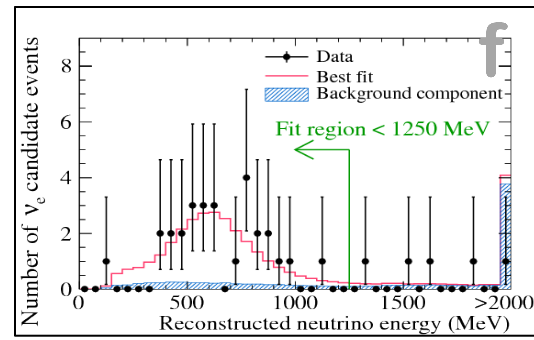
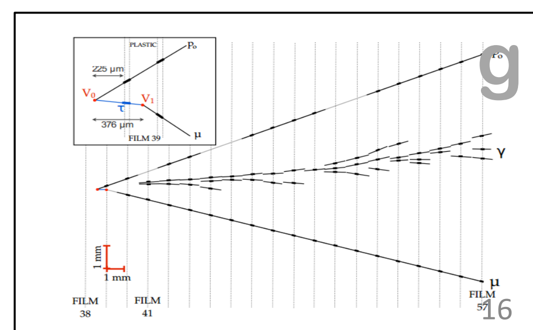


μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



Each leading oscillation parameters (over)constrained by at least two classes of measurements → 3ν consistency

Subleading effects involve **CPV** and **NO vs IO** difference, essentially via **μ→e** in LBL accel. and atmospher. expts

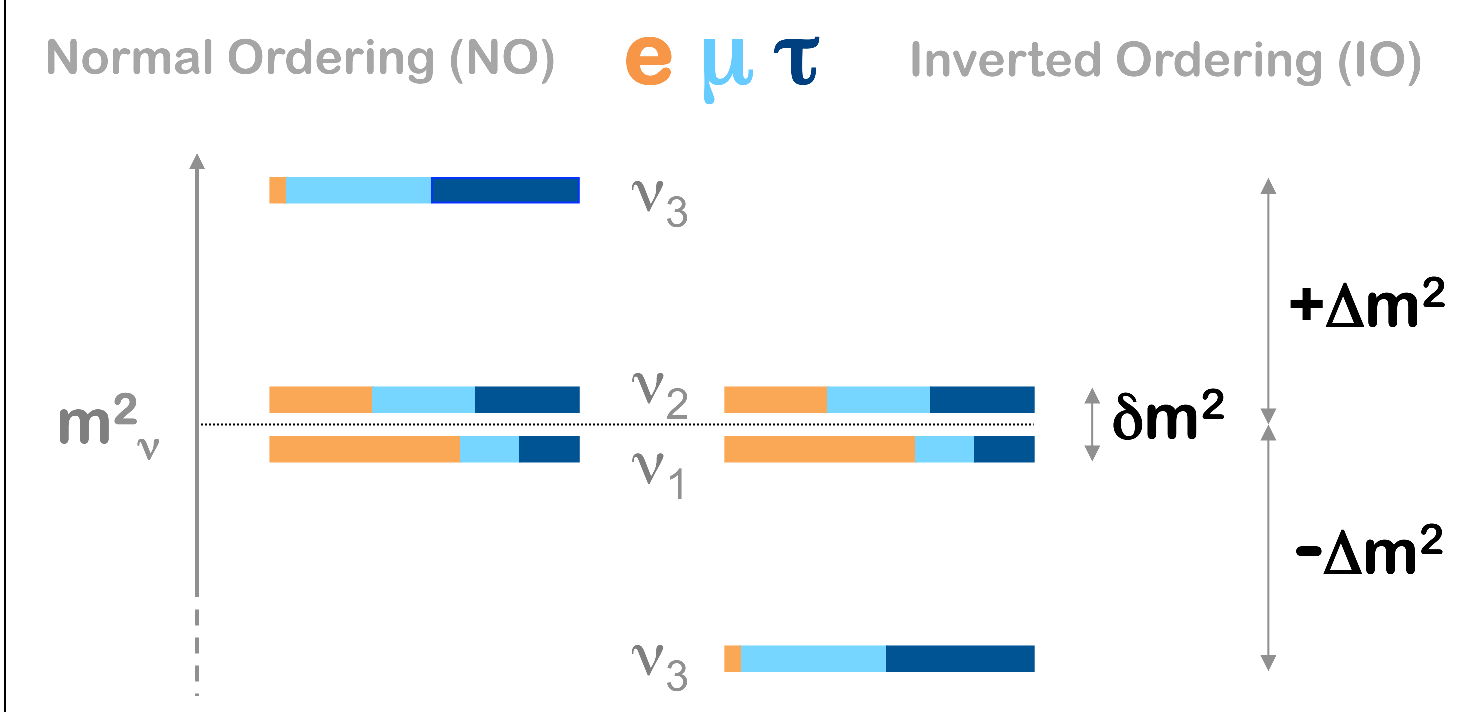
Sketchy 3ν picture (with 1-digit accuracy)

Knowns:

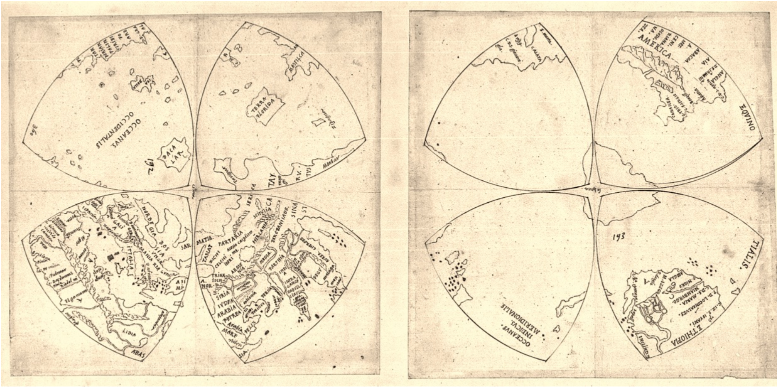
$\delta m^2 \sim 7 \times 10^{-5}\ eV^2$
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Unknowns:

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



from sketch
to full map →
combine info
from all ν data
"global analysis"



Global 3ν analysis: mainly based on work in collaboration with
F. Capozzi, E. Di Valentino, A. Marrone, A. Melchiorri, A. Palazzo;
hep-ph 2003.08511 (PRD 101, 2020) + work in progress (2021)

- charting the newly discovered territories →

For experts: Results of 2003.08511 are here updated with oscill. data from Neutrino 2020 (SK solar, T2K, NOvA, RENO). Still working on inclusion of latest SK-IV atmos. Non-oscillation data are the same as in 2003.08511 in this Colloquium.

Methodology

Useful to analyze oscillation data in the following sequence:

LBL Accel + Solar + KL (KamLAND)

minimal set sensitive to all osc. param.: δm^2, Δm^2, θ_{13}, θ_{23}, θ_{12}, δ, NO/IO

LBL Accel + Solar + KL + SBL Reactor

add sensitivity to Δm^2, θ_{13} and affect other parameters via correlations

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

add sensitivity to Δm^2, θ_{23}, δ, NO/IO (but: entangled information in atmos.)

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

add sensitivity to Δm^2, θ_{23}, δ, NO/IO (but: entangled information in atmos.)

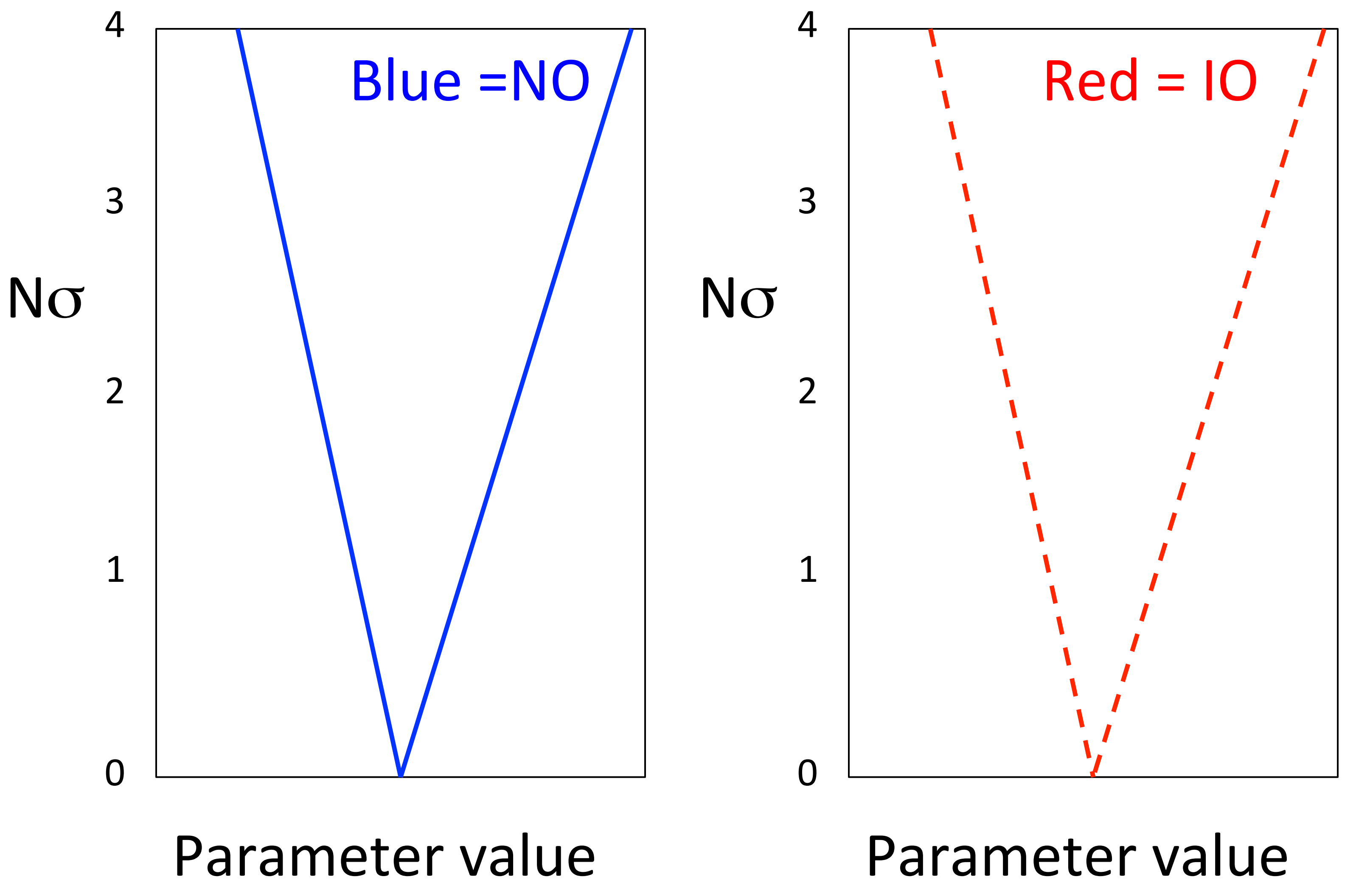
Statistics

Bounds/contours in terms of $N\sigma$ around best fit: $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3\ldots$

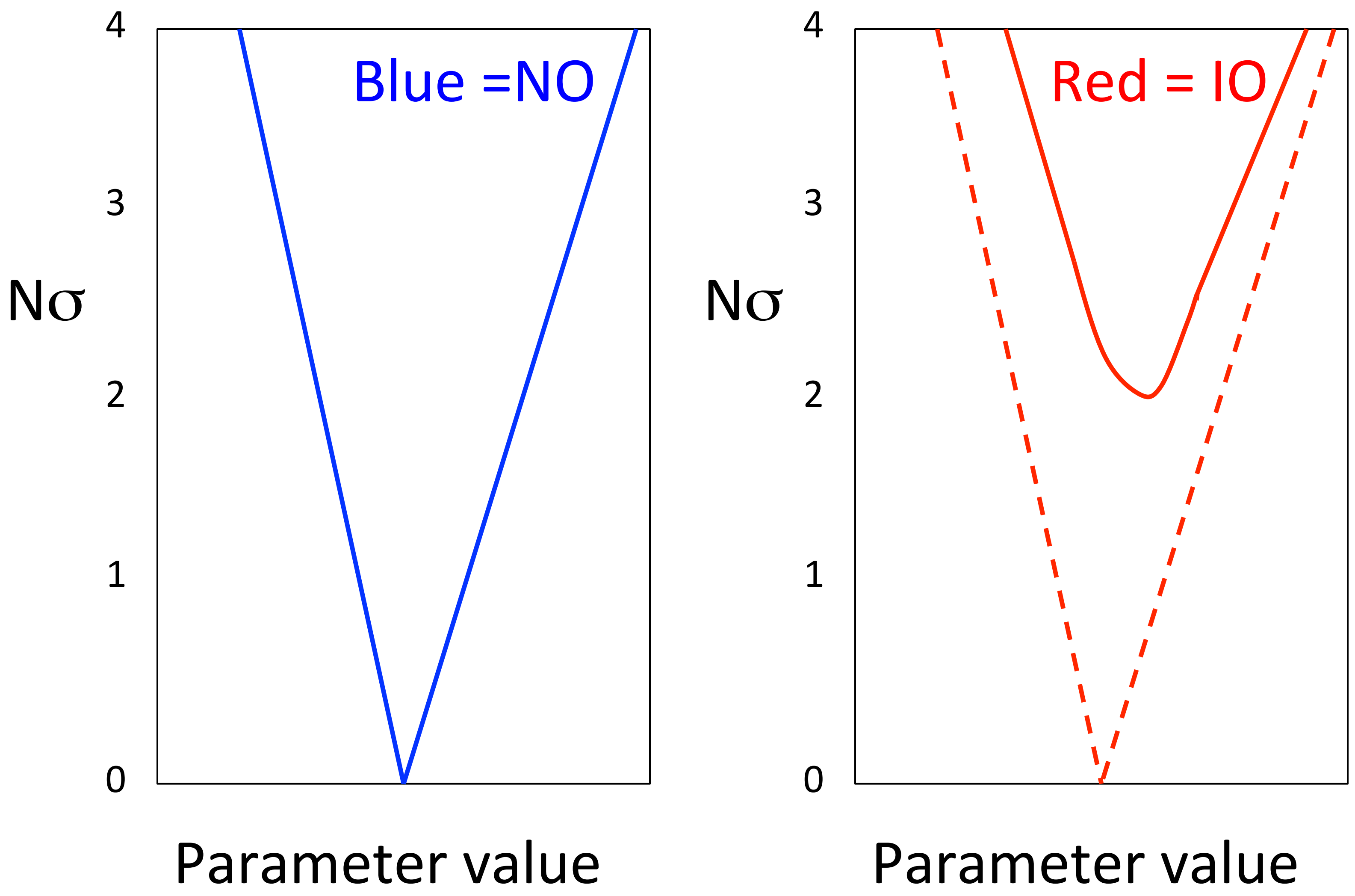
Undisplayed parameters are marginalized (projected) away

We shall discuss first "single" parameters and then "pairs" of parameters.

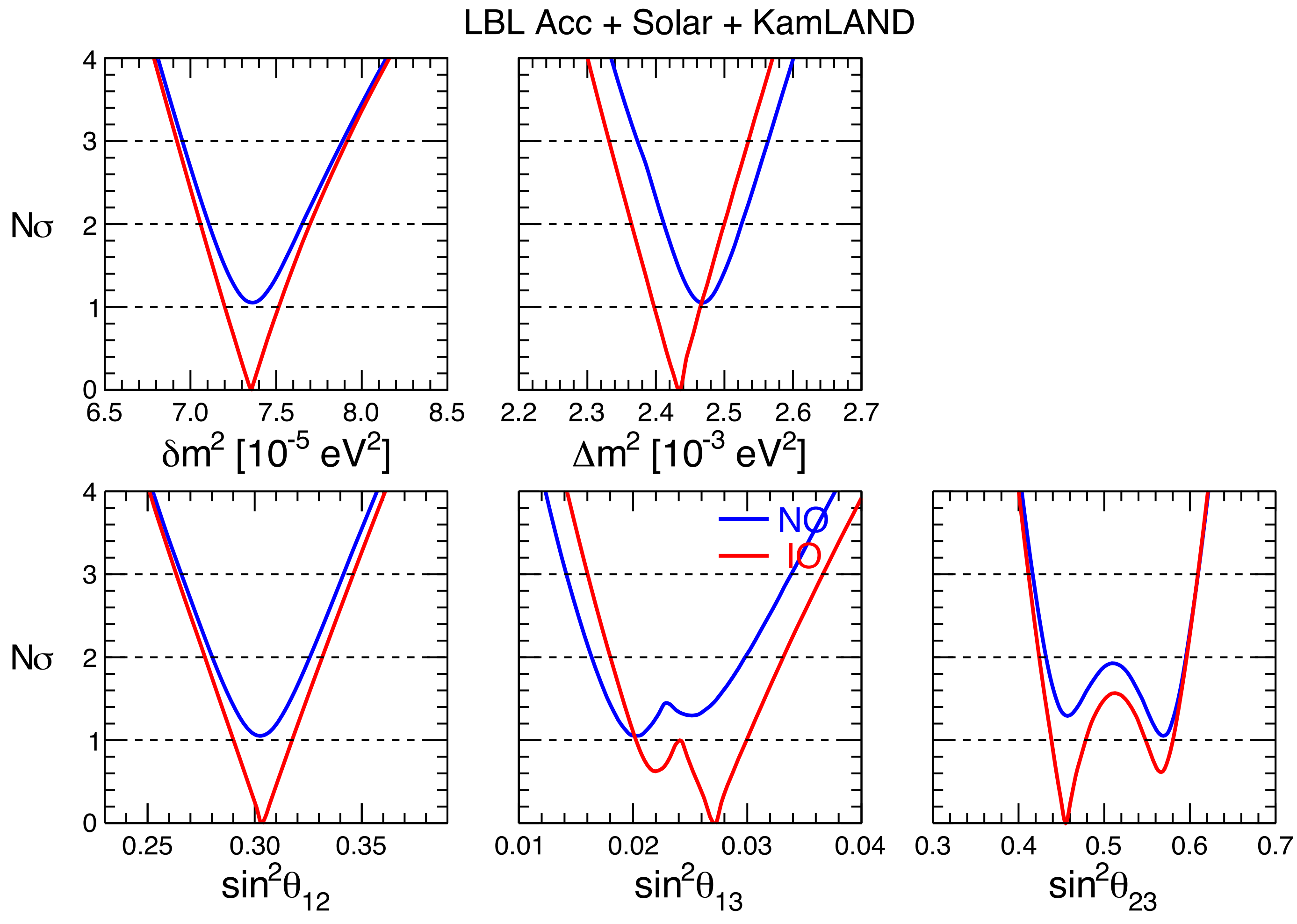
Single-parameter bounds would scale linearly (and symmetrically) in the limit of ~ gaussian errors around best fit values.



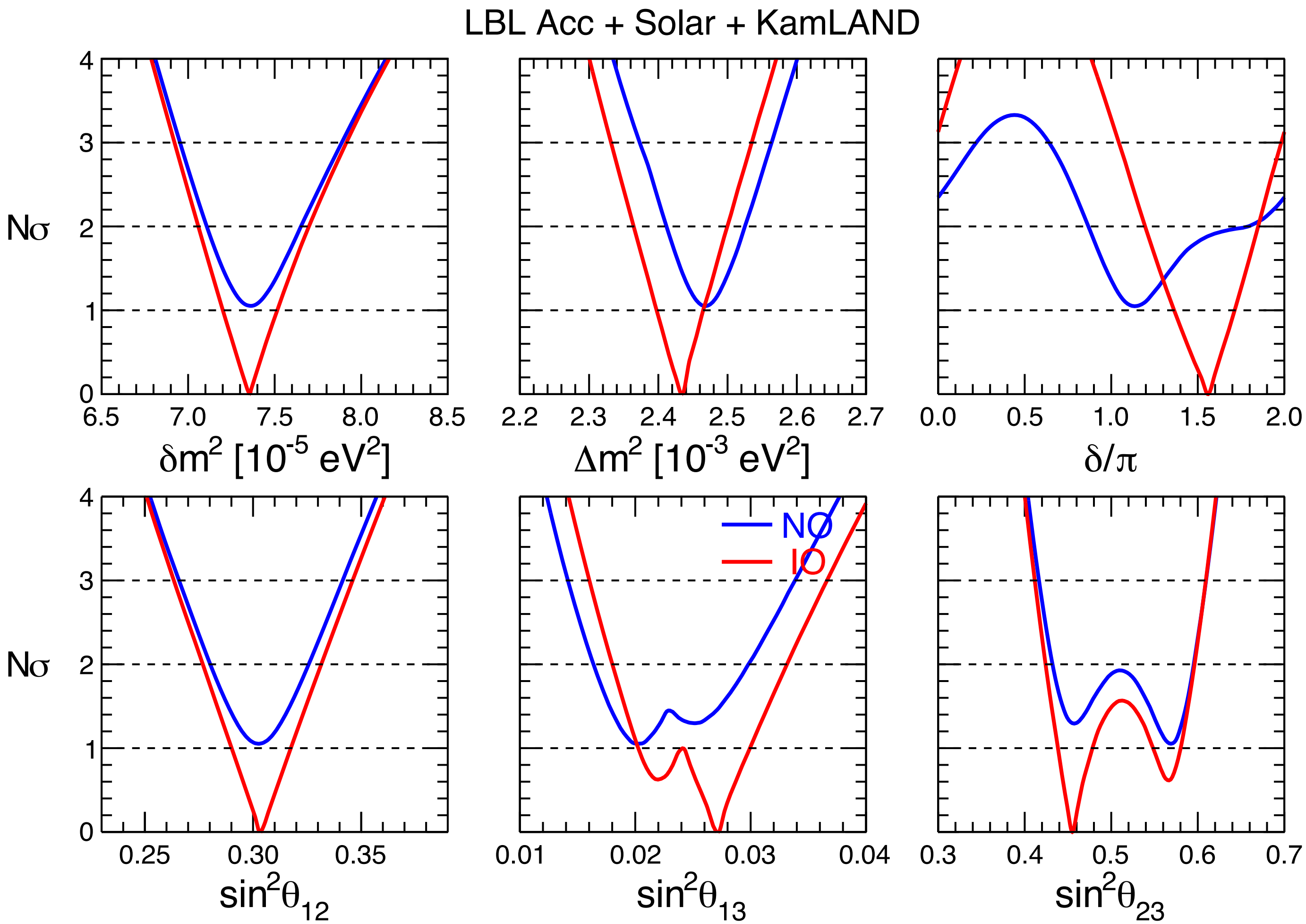
However, bounds for one given mass ordering move upwards,
if the other mass ordering is preferred, e.g.:



Results→



- Upper and and lower bounds at >>3σ for **δm^2, Δm^2, θ_{12}, θ_{13}, θ_{23}**
- Weak preference for **IO** at ~1σ. Note different **Δm^2** in NO/IO
- Octant degeneracy of **θ_{23}** also affects **θ_{13}** via correlations in $\nu_\mu \rightarrow \nu_e$



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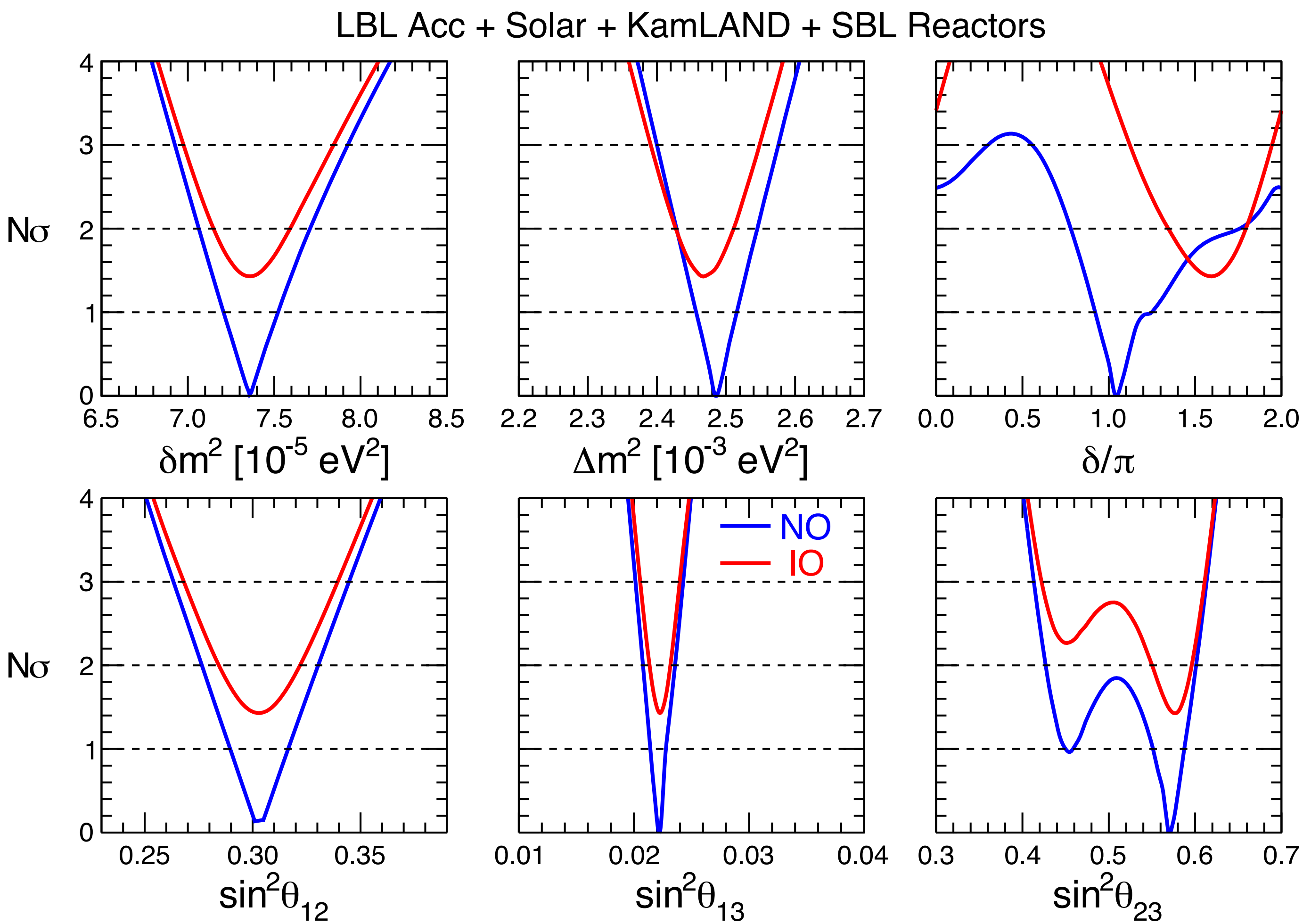
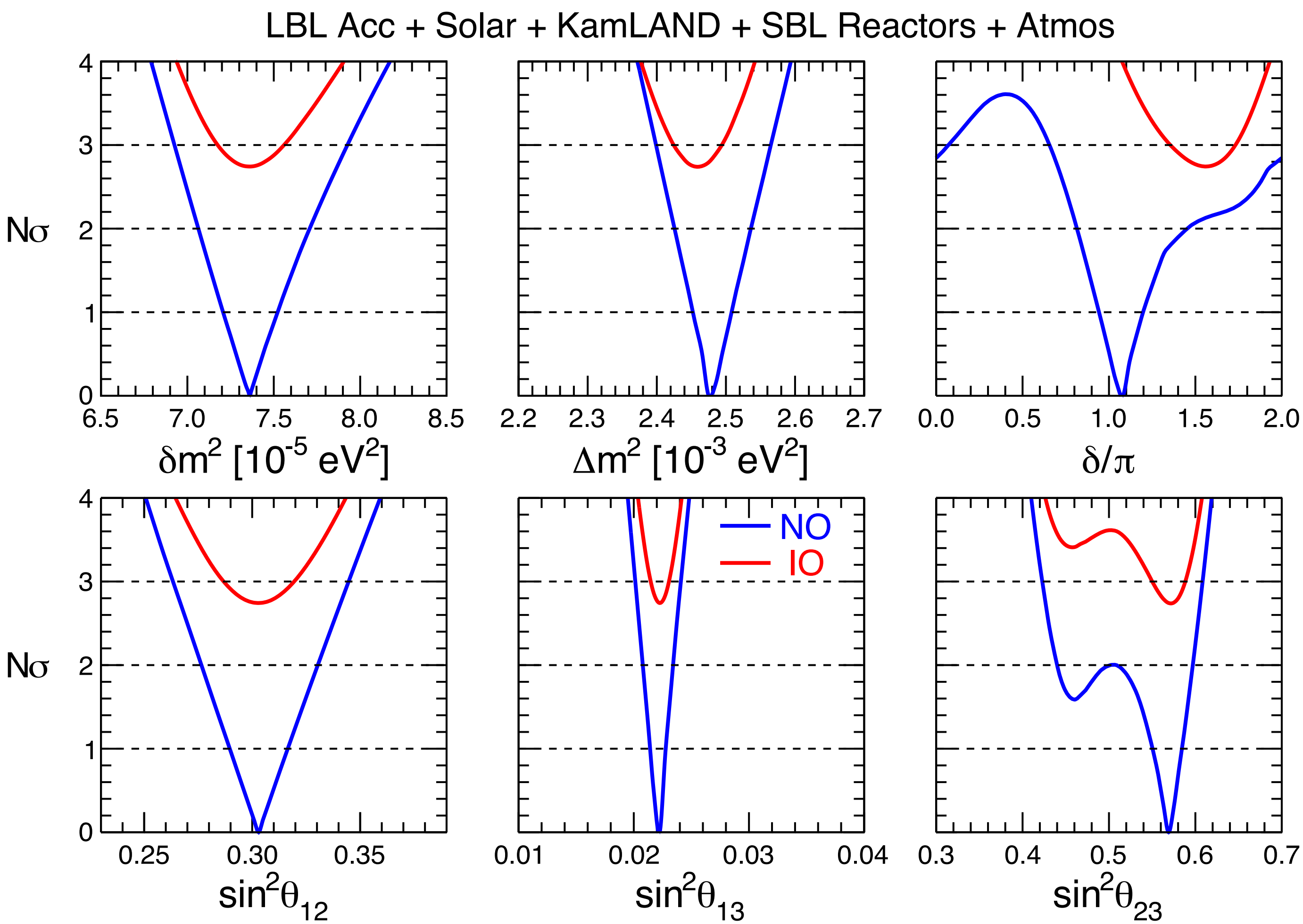
- Weak preference for **IO** at ~1σ. Note different **Δm^2** in NO/IO
- Octant degeneracy of **θ_{23}** also affects **θ_{13}** via correlations in $\nu_\mu \rightarrow \nu_e$
- Preference for **δ~3π/2** (CP violation) in **IO**, but not in NO

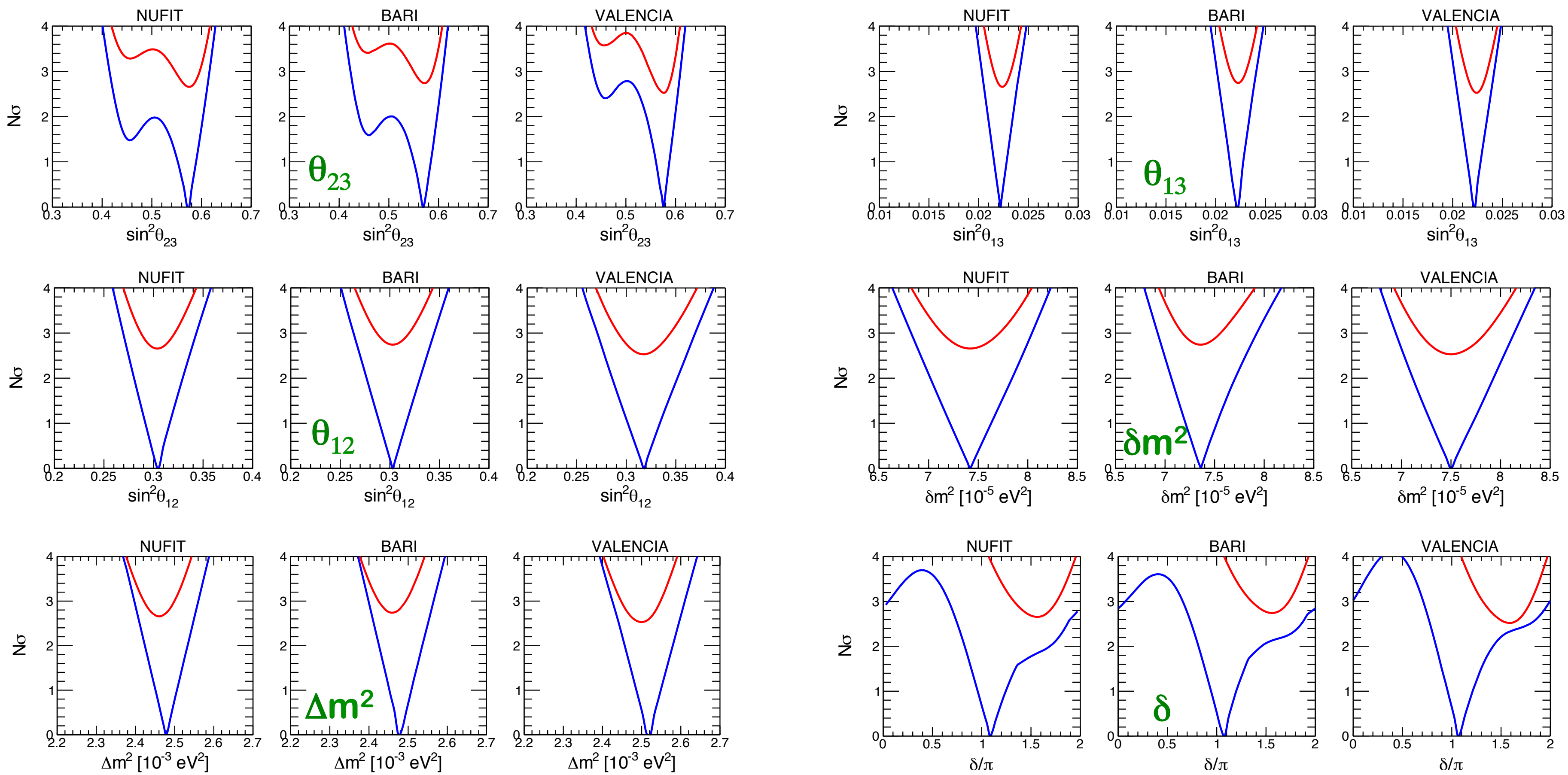


- Bounds on θ_{13} and Δm^2 strengthened
- Preference for **NO** at $\sim 1.5\sigma$. Note overall higher Δm^2 in both NO and IO
- Octant degeneracy of θ_{23} weakly broken, 2^{nd} octant preferred at $\sim 1\sigma$
- Preference for $\delta \sim \pi$ (CP conservation) in **NO**, while $\delta \sim 3\pi/2$ in IO



- Increased preference for **NO** (2.7σ)
- Increased preference for 2nd octant of θ_{23} (1.6σ)
- CP phase: best fits still around $\delta\sim\pi$ in **NO** and $\delta\sim3\pi/2$ in **IO**

Comparison among independent global neutrino oscillation data analyses



BARI: 2003.08511 [updated for this Colloquium]

NUFIT: 2007.19742 [with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]

VALENCIA: 2006.11237v2 [with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]

Precision 3ν cartography: Five parameters known at (few)% level

TABLE I: **Updated for this Colloquium from Capozzi+ arXiv:2003.08511 [hep-ph]**

Global 3ν analysis of oscillation data, in terms of best-fit values and allowed ranges at $N_\sigma = 1,\ 2,\ 3$ for the mass-mixing parameters, in either NO or IO. The last 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). We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and $\delta/\pi \in [0,\ 2]$ (cyclic).

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.475	2.453 – 2.508	2.426 – 2.536	2.399 – 2.565	1.1
	IO	2.455	2.431 – 2.487	2.403 – 2.516	2.374 – 2.545	1.2
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.15 – 2.28	2.08 – 2.34	2.01 – 2.41	3.0
	IO	2.23	2.16 – 2.29	2.10 – 2.35	2.03 – 2.42	2.9
$\sin^2\theta_{23}/10^{-1}$	NO	5.69	5.50 – 5.84	4.40 – 5.97	4.23 – 6.08	5.4
	IO	5.69	5.54 – 5.85	5.28 – 5.98	4.25 – 6.08	5.4
δ/π	NO	1.08	0.94 – 1.20	0.82 – 1.45	0 – 0.07 $\oplus$ 0.65 – 2	22
	IO	1.56	1.40 – 1.70	1.22 – 1.83	1.06 – 1.94	9

Most accurate parameter is Δm^2: "formal" uncertainty as small as ~1% !

Q.: Is such accuracy "robust"? Any bias? More later.

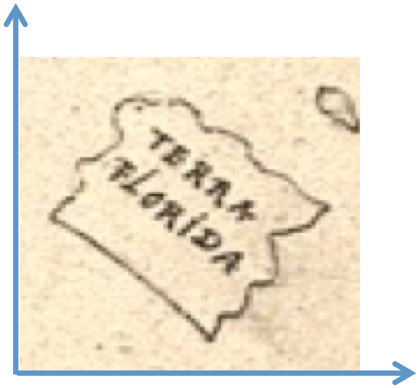
Pairs of parameters

Some relevant covariances:

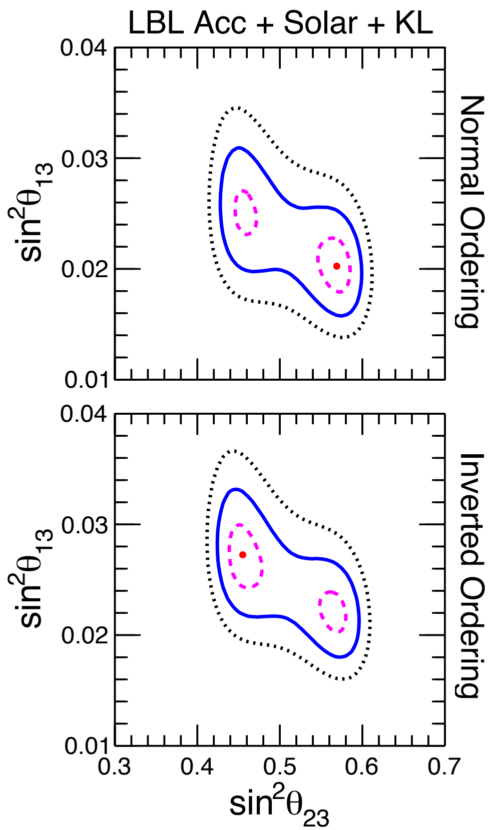
$(\theta_{13}, \theta_{23})$

$(\theta_{13}, \pm\Delta m^2)$

$(\theta_{12}, \delta m^2)$



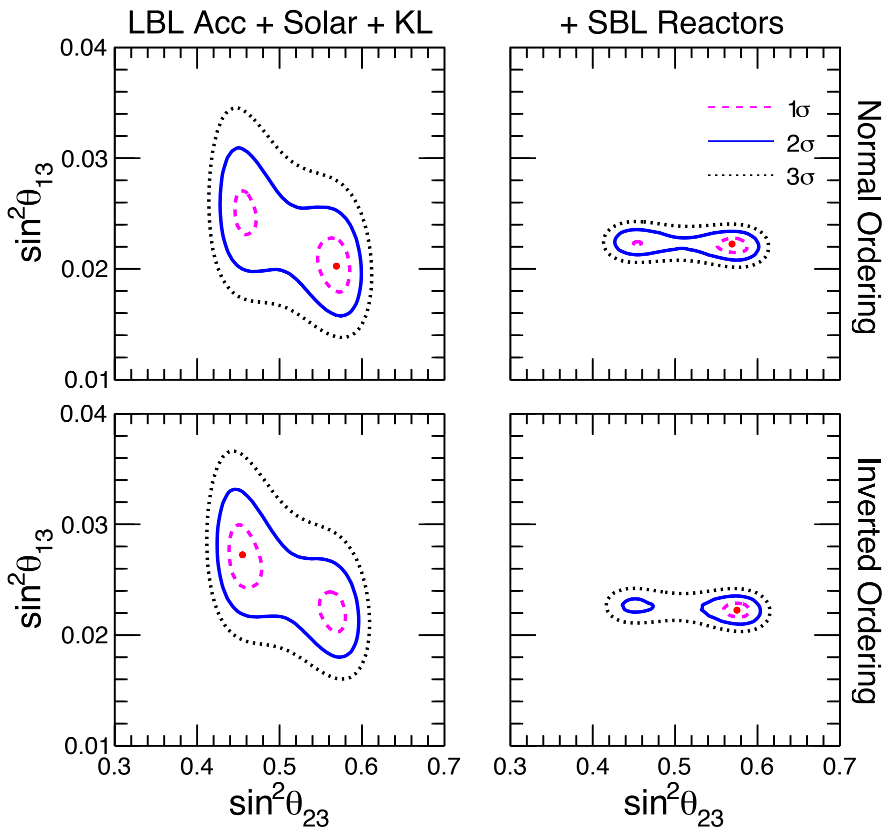
(θ_{13} , θ_{23}) covariance



Anticorrelation due to leading $\nu_\mu \to \nu_e$ term

$\sim \sin^2\theta_{23} \sin^2 2\theta_{13}$

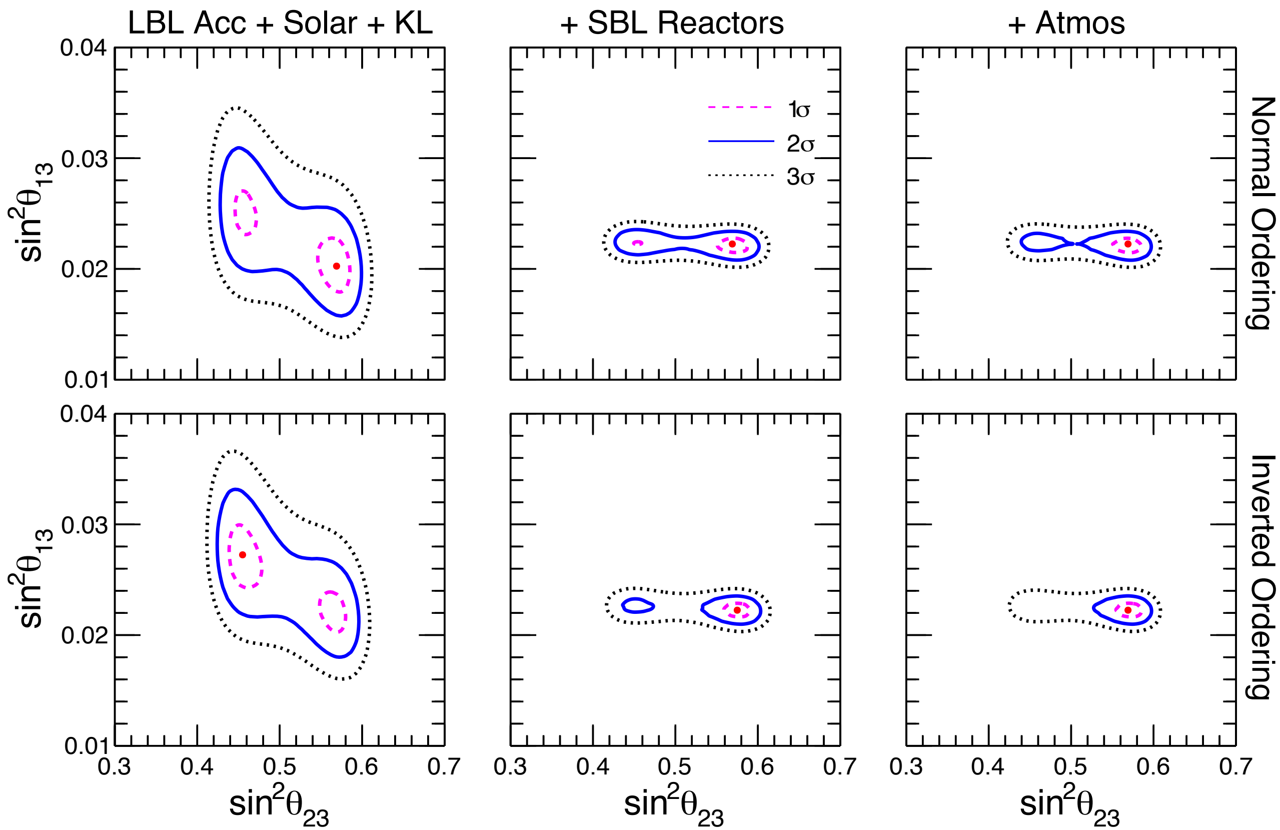
(θ_{13} , θ_{23}) covariance



Anticorrelation due to leading $\nu_\mu \rightarrow \nu_e$ term $\sim \sin^2\theta_{23}\ \sin^2 2\theta_{13}$

Narrow and "low" θ_{13} reactor angle selects 2nd octant

(θ_{13} , θ_{23}) covariance



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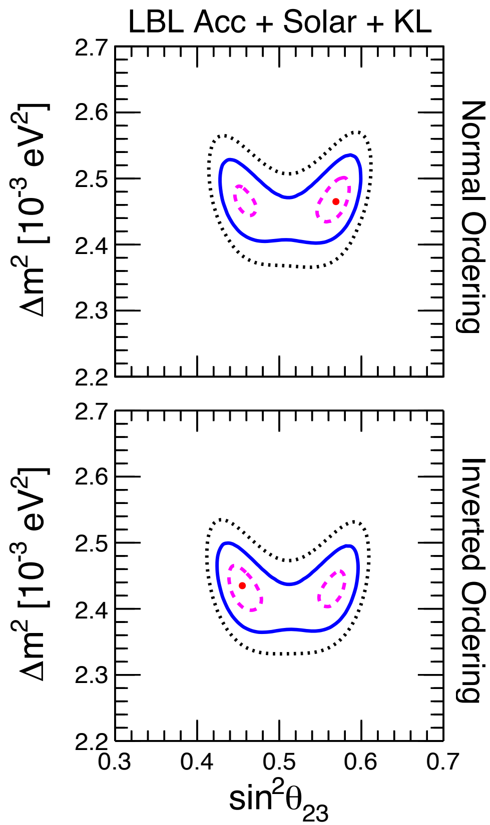
Narrow and "low" θ_{13} reactor angle selects 2nd octant

2nd octant confirmed by atmospheric data in both NO and IO (but: fragile!)

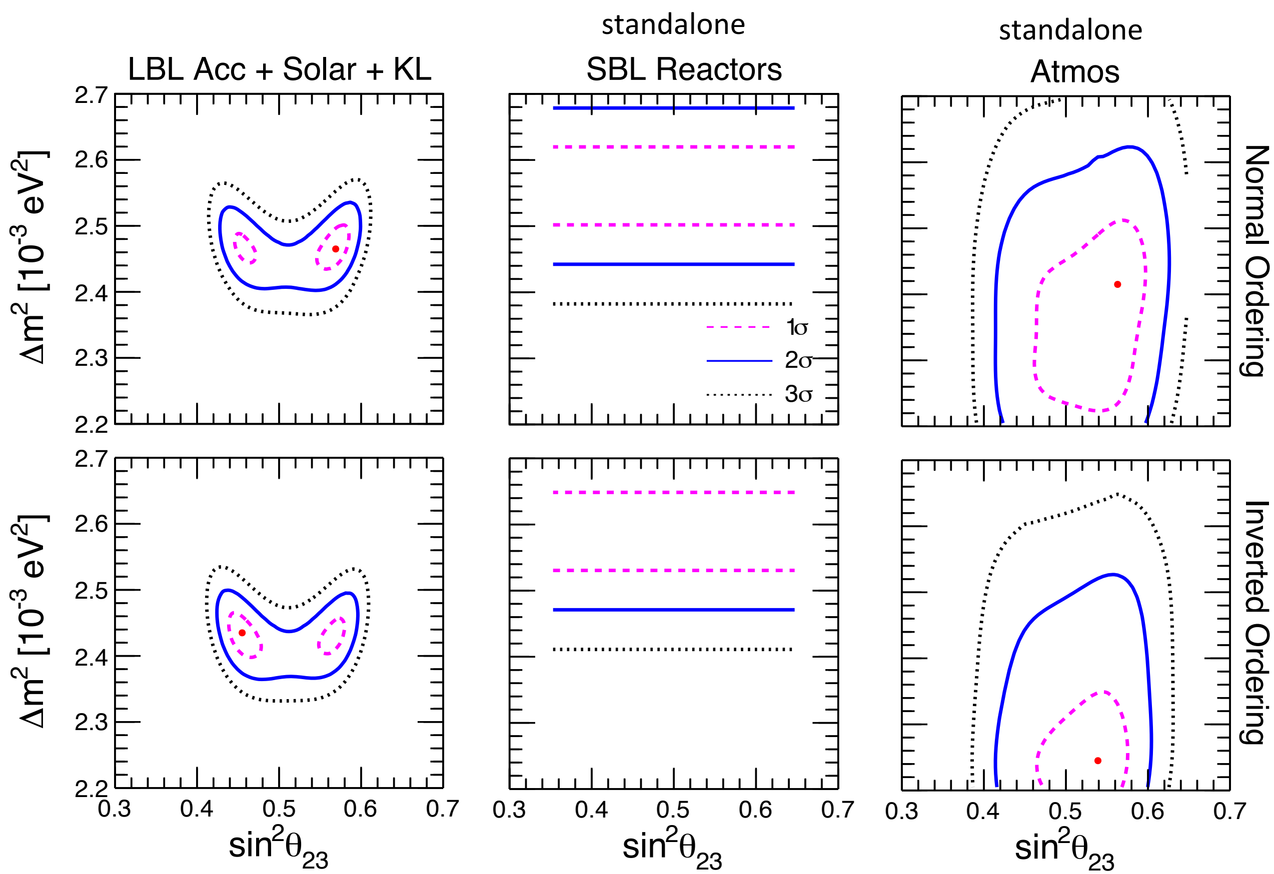
(θ_{23} , $\pm\Delta m^2$) covariance



LBL data: Best fit value of Δm^2 below 2.5 x 10^{-3} eV^2.

The higher is Δm^2 , the more non-max is θ_{23}. Note octant ambiguity.

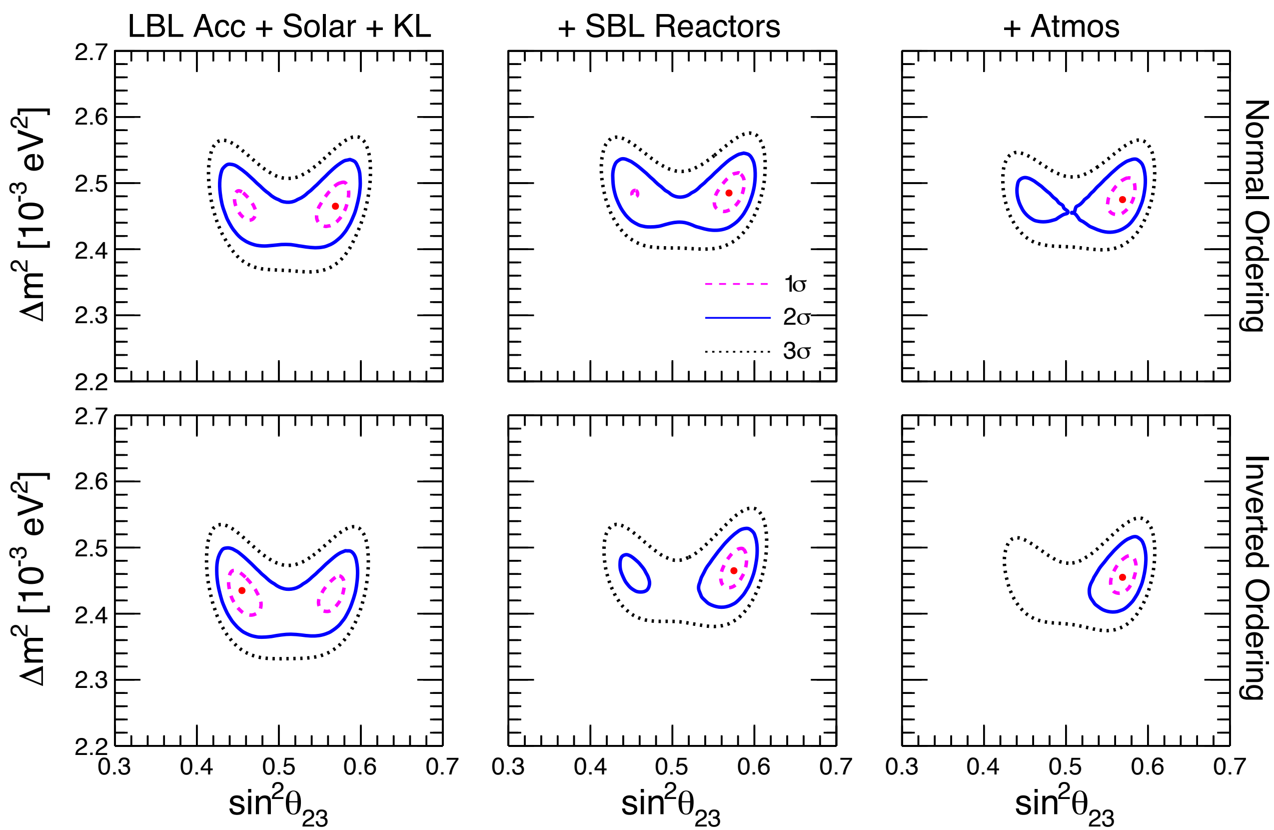
(θ_{23} , $\pm\Delta m^2$) covariance



Reactors prefer higher Δm^2 (>2.5 x 10^{-3} eV^2) than LBL accel. and atmos. exts.

Relative difference is lower for **NO** and for non-maximal θ_{23} mixing

(θ_{23} , $\pm\Delta m^2$) covariance



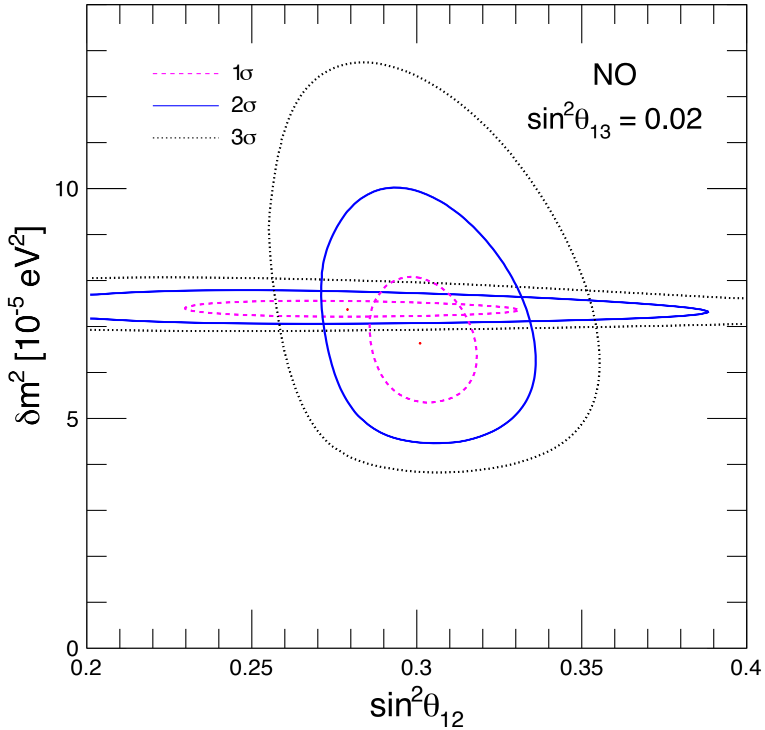
Reactors prefer higher Δm^2 (>2.5 x 10^{-3} eV^2) than LBL accel. and atmos. exts.

Relative difference is lower for **NO** and for non-maximal θ_{23} mixing

→ Better convergence reached for **NO**, nonmax θ_{23}, intermediate Δm^2

Accelerator/reactor complementarity at work!

(θ_{12}, δm^2) covariance



After the latest SK solar neutrino data (Neutrino 2020), there is
no longer "tension" between δm^2 values of Solar vs KamLAND

[Tension might have pointed to new physics, like NSI, in solar neutrinos...]

• trying to avoid distortions and biases...

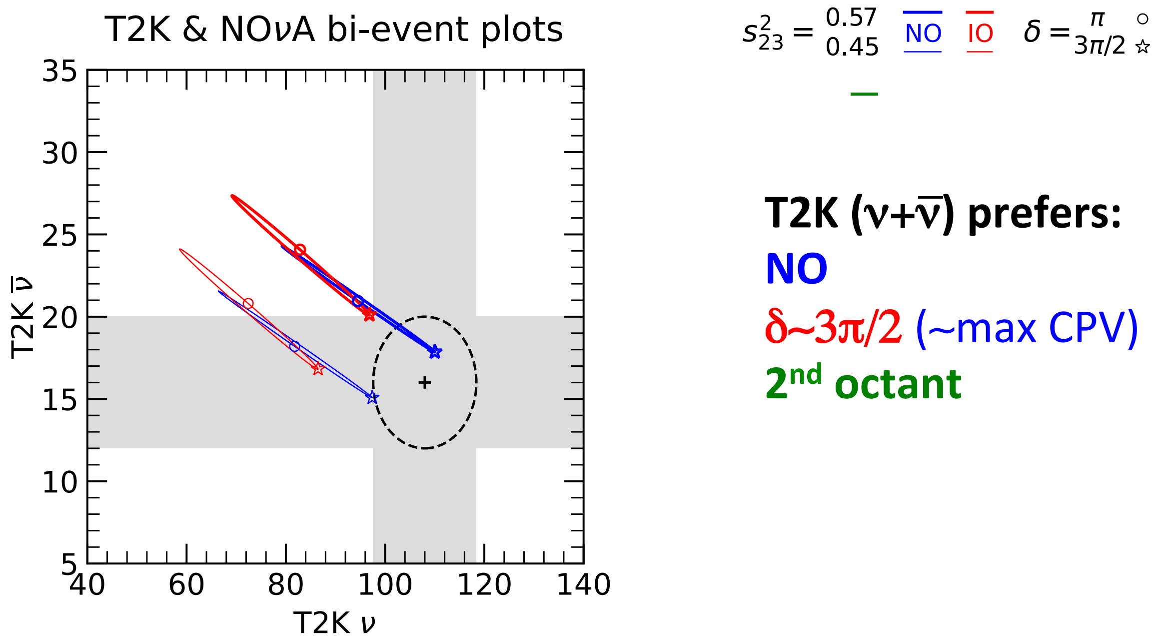
An interesting "data tension" emerges now within LBL accelerators **(T2K vs NOvA) –** whose differences in $\nu_\mu \rightarrow \nu_e$ findings blur the the (previously stronger) preference for NO and for CP violation.

→ **some details for experts (bi-event plots)**

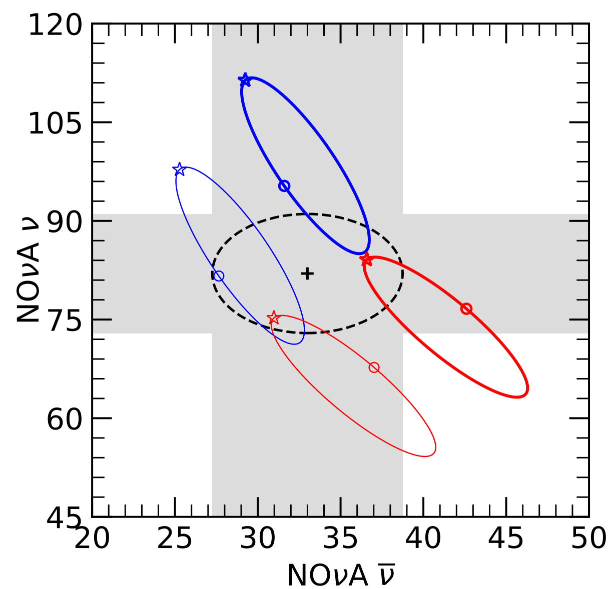
Speculations on a possible role of **ν interaction** uncertainties

→ **general comments for all (EW nuclear physics)**

Integrated info on ν and $\bar{\nu}$, stat. errors only. [Not used in fits]



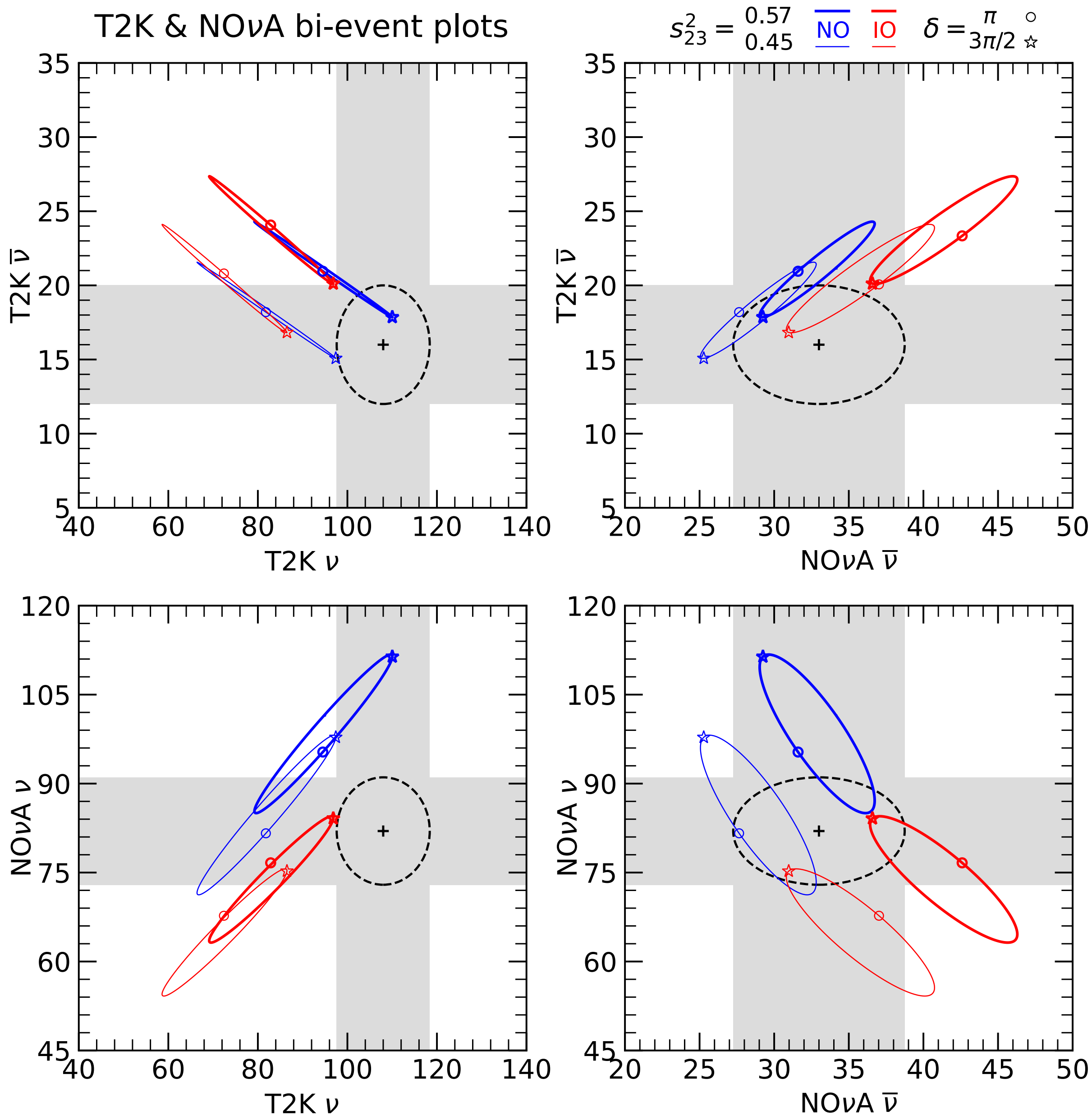
T2K (ν+$\bar{\nu}$) prefers:
NO
δ~3π/2 (~max CPV)
2nd octant



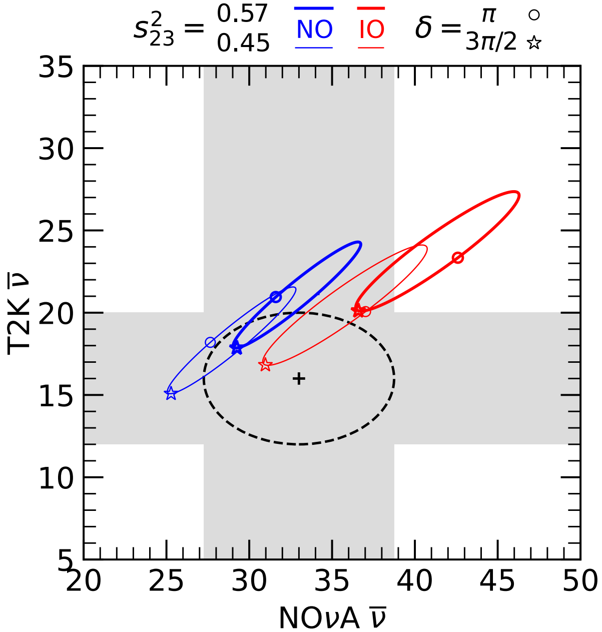
NOVA (ν+$\bar{\nu}$) prefers:
NO
CP conservation
octants ~degenerate

→ T2K and NOVA, separately: NO preferred; CP and octant ambiguous

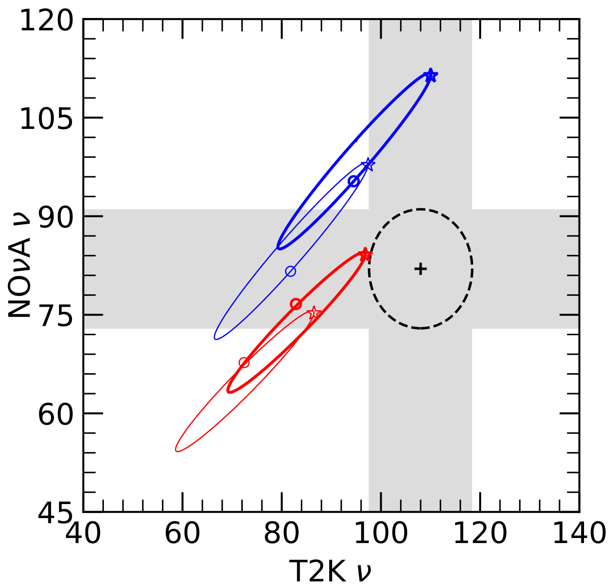
The same info can be reorganized in terms of T2K vs NOvA:



T2K & NOνA bi-event plots

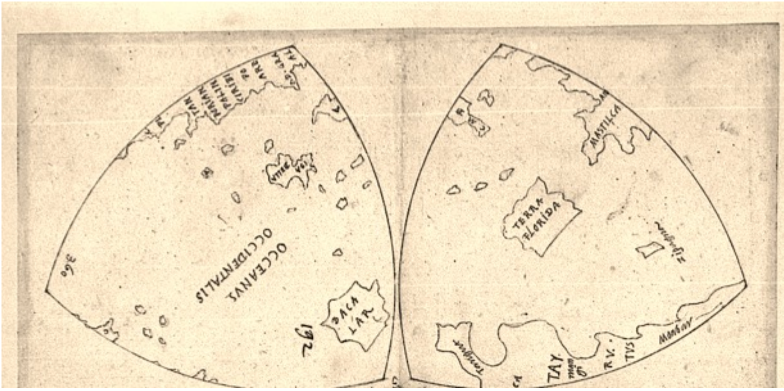


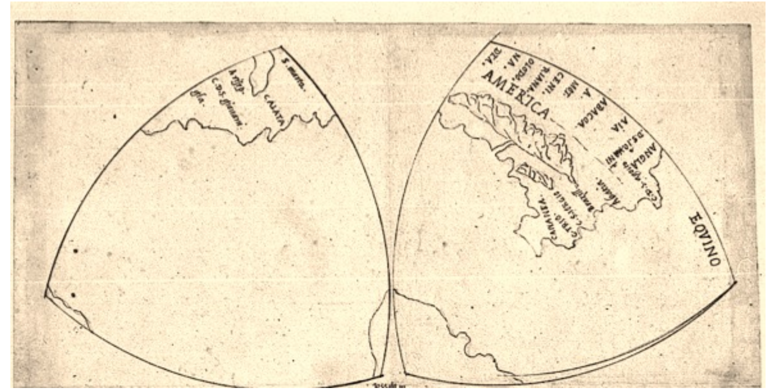
T2K+NOvA (ν) prefer:
IO
δ~3π/2
1st octant

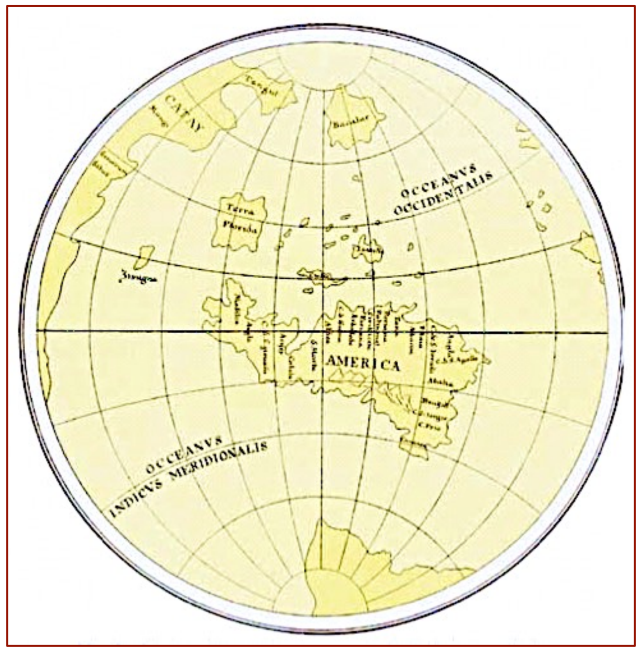


T2K+NOvA ($\bar{\nu}$) prefer:
IO
δ~3π/2
2nd octant

→ T2K and NOVA, jointly: IO and CPV preferred; octant ambiguous







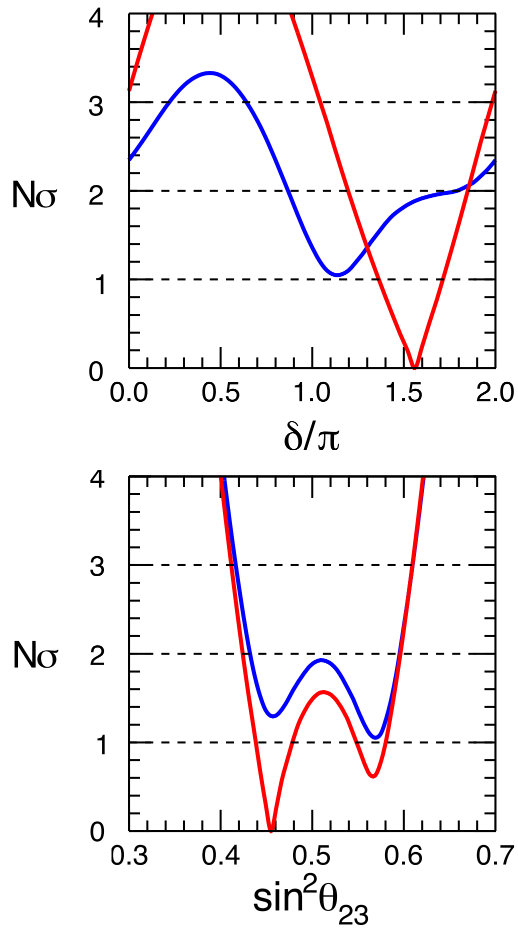
Not yet a convincing transition from "unknown" to "known" lands…

...In the T2K+NOvA combination, still unstable results on three unknowns:

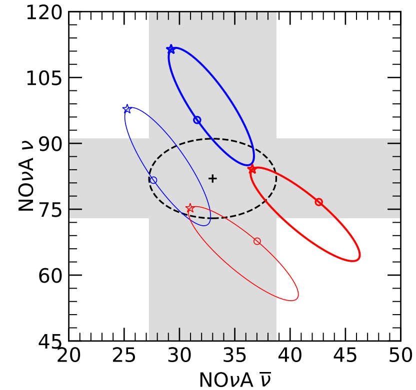
mass ordering (NO vs IO), θ_{23} octant and CP phase δ

Further data may tilt the current balance...

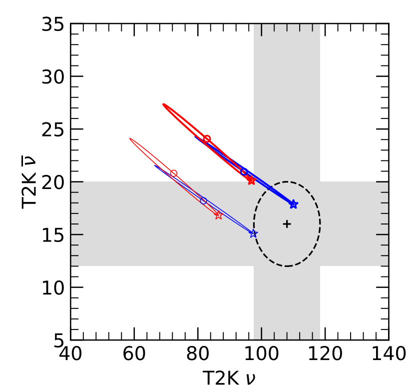
LBL Acc + Solar + KamLAND
(current)



NOvA close to different options within 1σ...



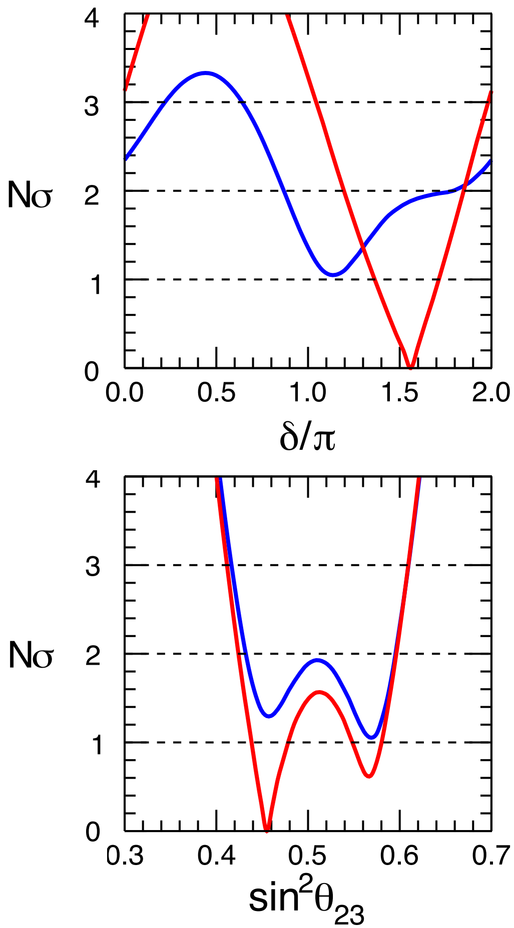
T2K close to the edge of expected Asimov sensitivity...



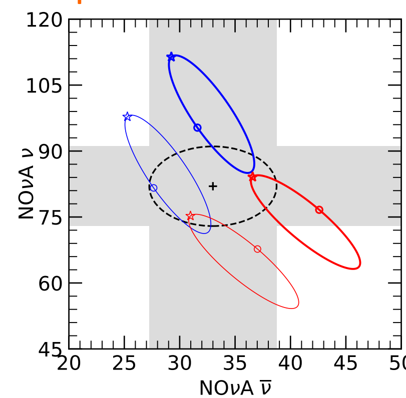
We'll learn a lot more from current LBL accel. (T2K+NOvA) + atmos. expts (SK, IC-DC), final SBL reactor data (DYB, RENO, DC), and future experiments (DUNE, HK, T2HK, IC-lowE upgrade, KM3NeT-Orca, JUNO ...). In the meantime:

Q.: Is there only statistics behind the T2K/NOvA tension?

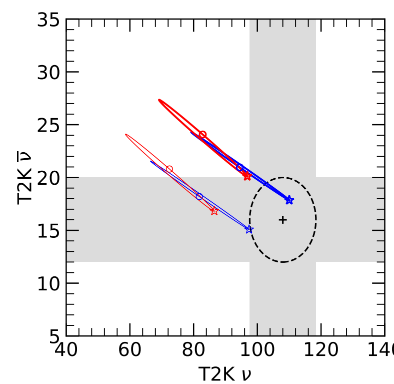
LBL Acc + Solar + KamLAND (current)



NOvA close to different options within 1σ...



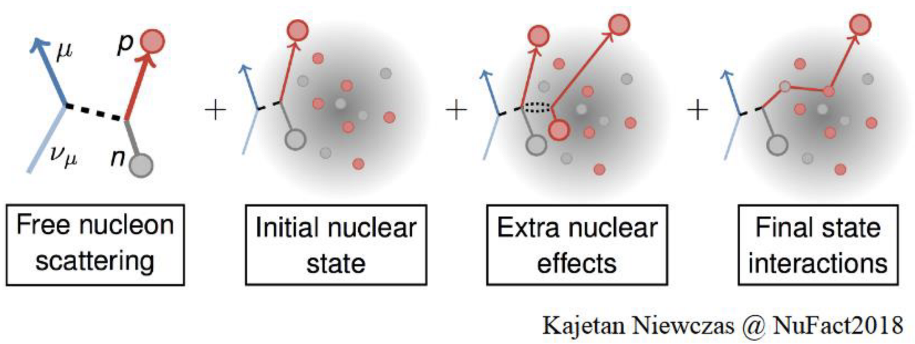
T2K close to the edge of expected Asimov sensitivity...



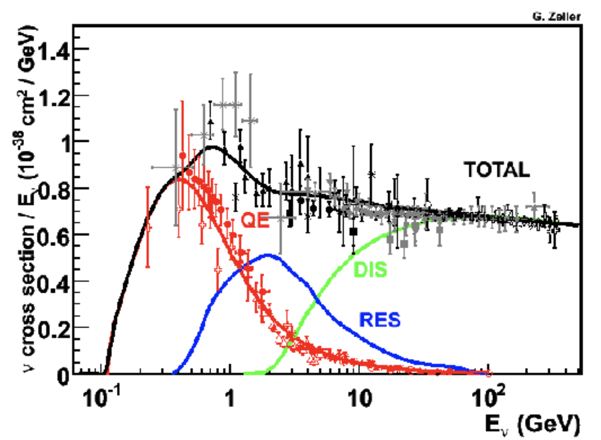
Parameter covariances and data tensions show the delicate interplay between 2 knowns [**Δm^2, θ_{23}**] and 3 unknowns [**NO/IO, δ, sign ($\theta_{23} - \pi/4$)**]

There is a general issue that affects all these (un)knowns:
neutrino interactions in nuclei are not understood as accurately as desired!

Theory: complex nuclear effects



Experiment: relatively few data



Great effort to improve the situation through dedicated experiments (including near detectors, ND) and improved nuclear models (including tuning to the above experiments), but non-negligible uncertainties remain.

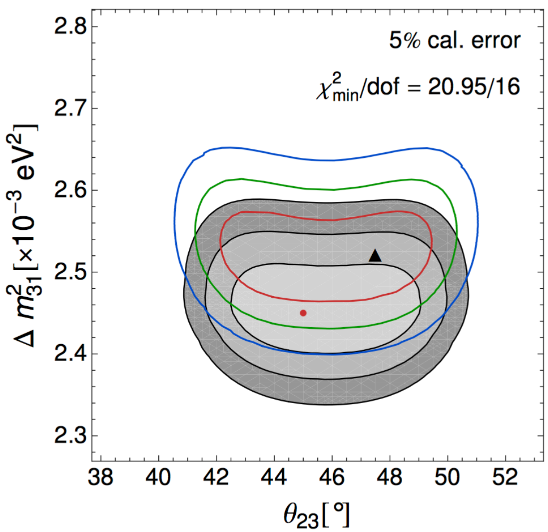
Neutrino-nuclear interactions and LBL accelerator experiments

Cross section uncertainties may affect:

Δm^2 (via E_{rec}), θ_{23} (via spectral norm+shape), δ (via $\nu - \bar{\nu}$ interaction differences)

Exercise to estimate bias:

Generate data with one Xsec model and analyze them with a different model

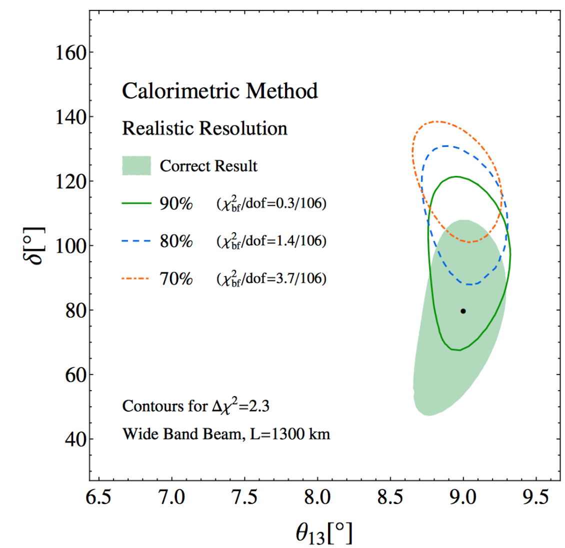


← Biased →
ranges of

Δm^2, θ_{23}

δ

[Benhar+ 1501.06448, Alvarez+ 1706.03621, and refs. therein]



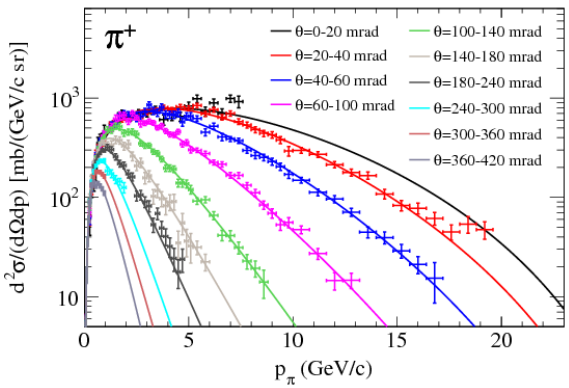
Effects reduced -but not zeroed- by tuning model(s) to ND data.
Remind: No model currently explains all available Xsection data!
Current 1% global-fit formal accuracy on Δm^2 might be optimistic

But... there is much more than just cross sections for HEP!

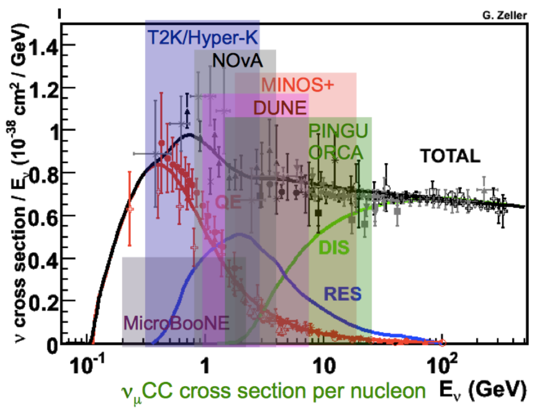
- Beta decays for nuclear reactor spectra
- Coherent Elastic Neutrino Nucleus Scattering
- Charge exchange processes for DBD NME
- Effective neutrino axial current: coupling strength and form factors
- Neutrinos in very dense fermion backgrounds (SN, early universe)
- Nuclear astrophysics and neutrinos (nucleosynthesis & solar reactions networks)
- EFT vs QCD
- Ab initio nuclear structure
- EC processes and neutrino mass
- Connections with other EW probes (gammas, electron, possible WIMPs...)

"Strong interaction" effects on "weak interaction" physics are ubiquitous...

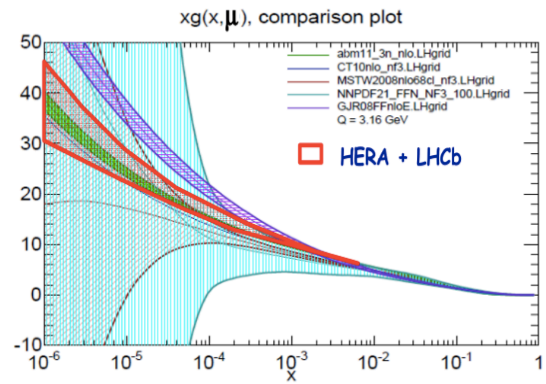
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atm. and acceler. ν fluxes and errors

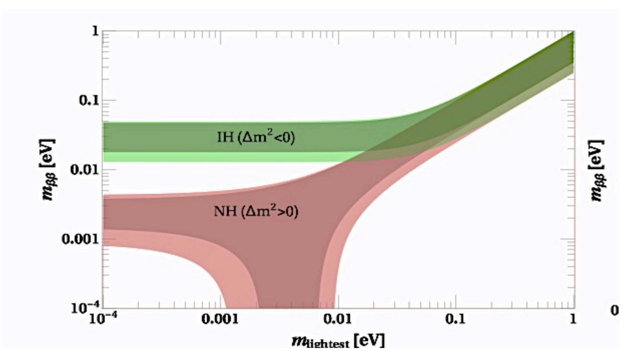


Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

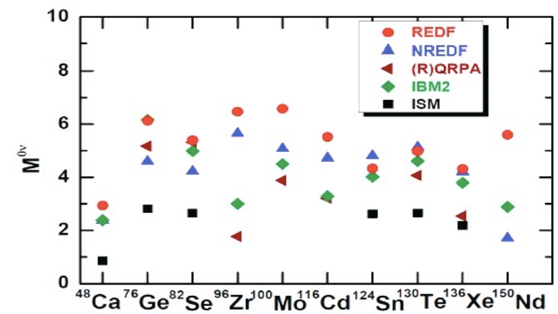


Improved PDFs at low-x via ~forward charm production at LHCb essential to constrain prompt component in UHE ν





Better control of nuclear EW response (e.g., g_A) relevant to interpret 2β data and to connect them with other data, including reactor spectra...



Progress requires joint contributions from different disciplines & communities:

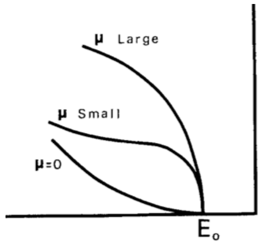
→ emerging field of "Electroweak Nuclear Physics"; needs support!

Absolute neutrino mass and Dirac/Majorana nature:

The last 3ν unknowns & their observables (m_β , $m_{\beta\beta}$, Σ)

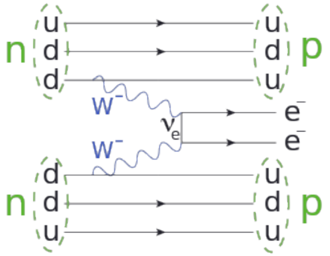
β decay, sensitive to the "effective electron neutrino mass":

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



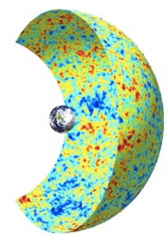
0νββ decay: only if Majorana. "Effective Majorana mass":

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



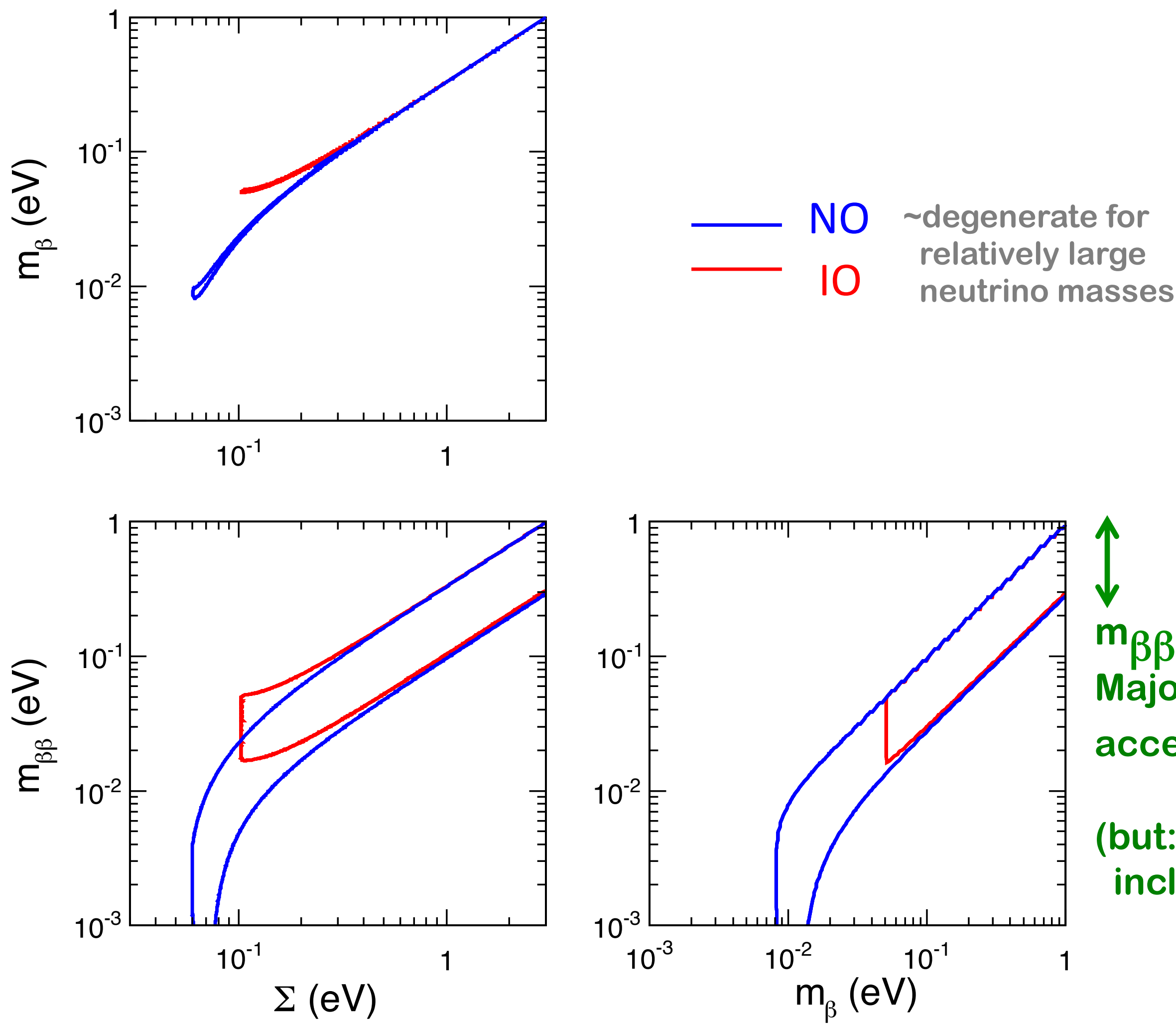
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



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→

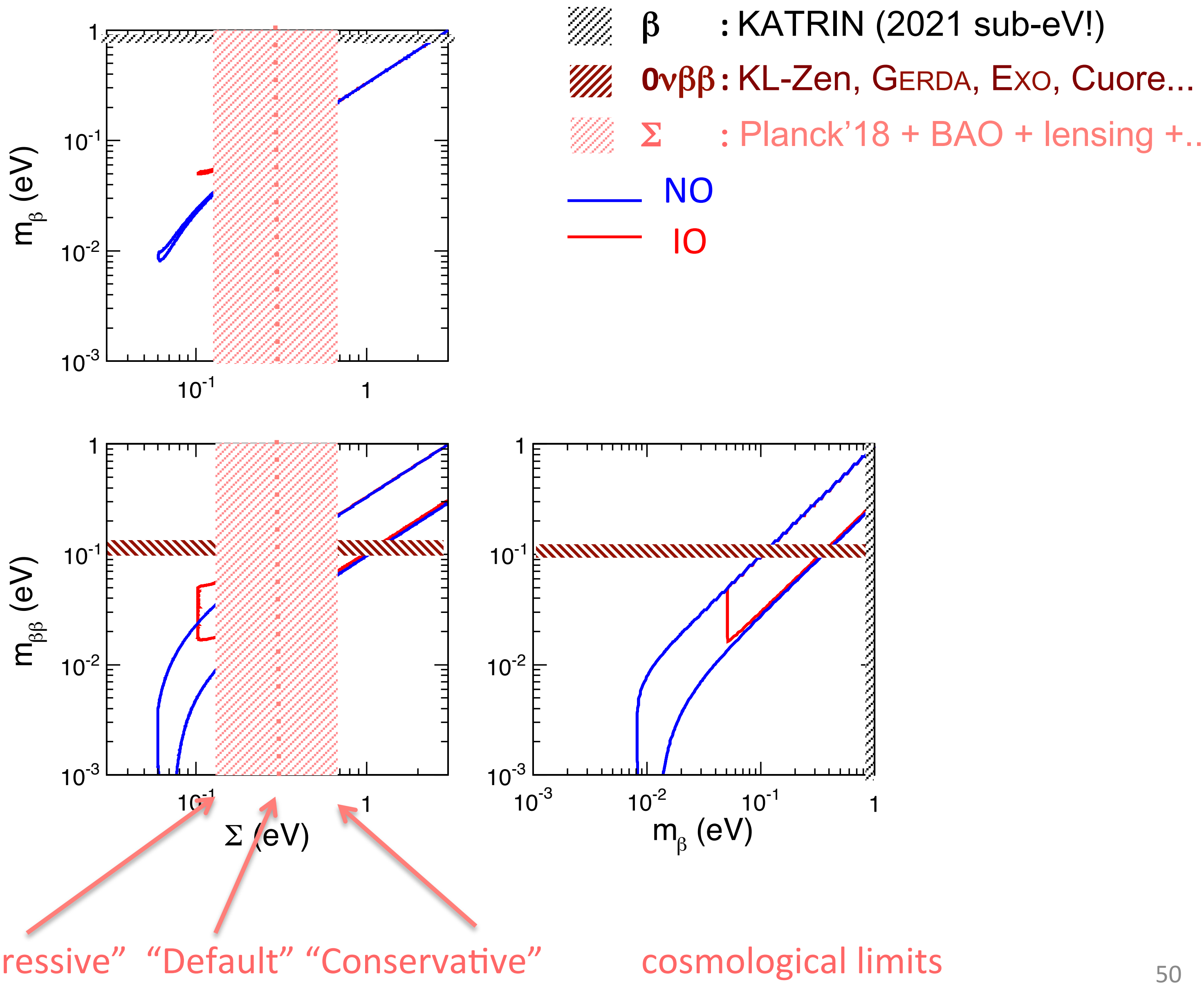
Impact of oscillations on non-oscillation parameter space



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

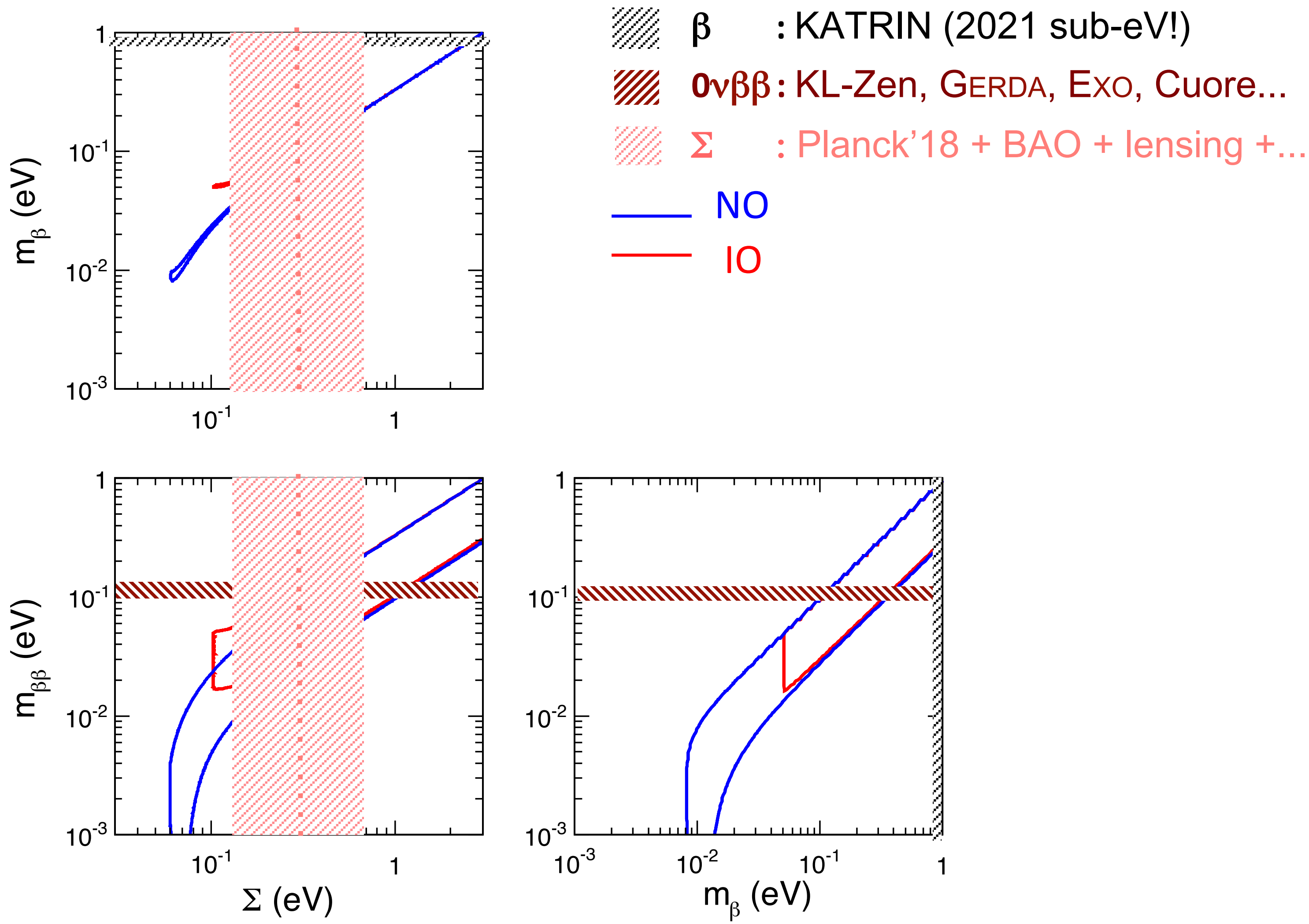
(but: no NME errors included here!)

No signal (yet), but upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.)



cosmological limits

No signal (yet), but upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.)

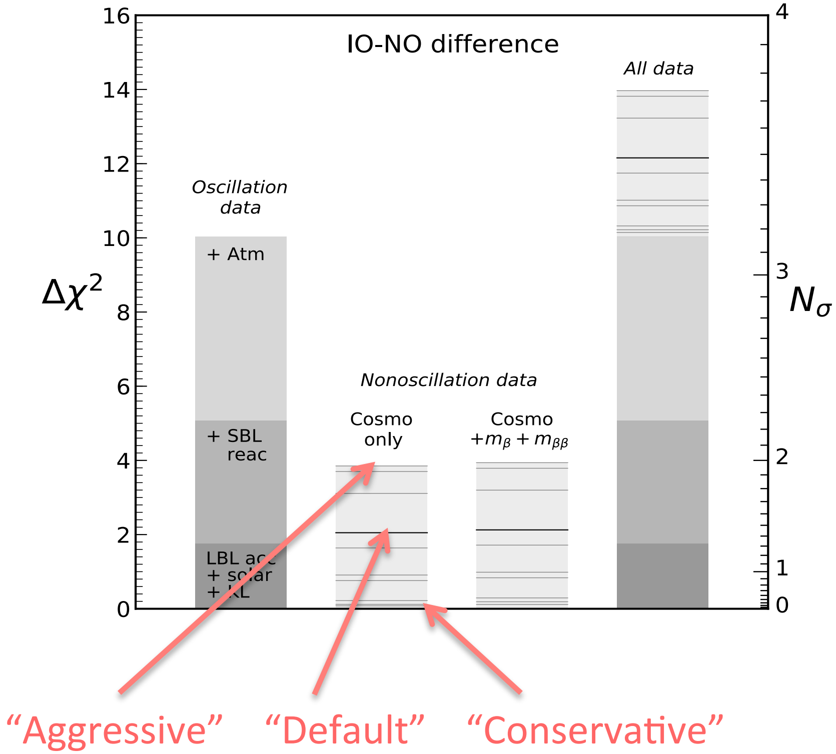


Cosmo data constrain masses and generally put IO "under pressure" →

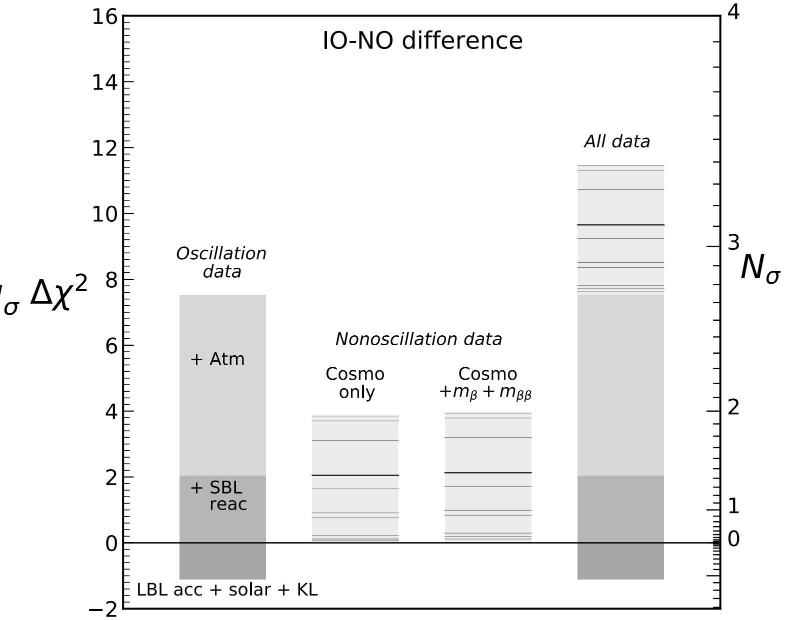
Impact of cosmology on global oscillation fit, w.r.t. IO-NO difference

(envelope of conservative, default, aggressive case = horizontal lines)

arXiv:2003.08511 (pre ν2020)



Update for this Colloquium



Cosmo data may add from ~0 to ~0.7σ
to the ~2.7σ oscillation preference for NO
→ overall typical ~3σ hint for NO vs IO

Update of cosmological bounds with latest CMB data, and with emphasis on conservative cases wrt to possible future β and ββ signals: in progress.

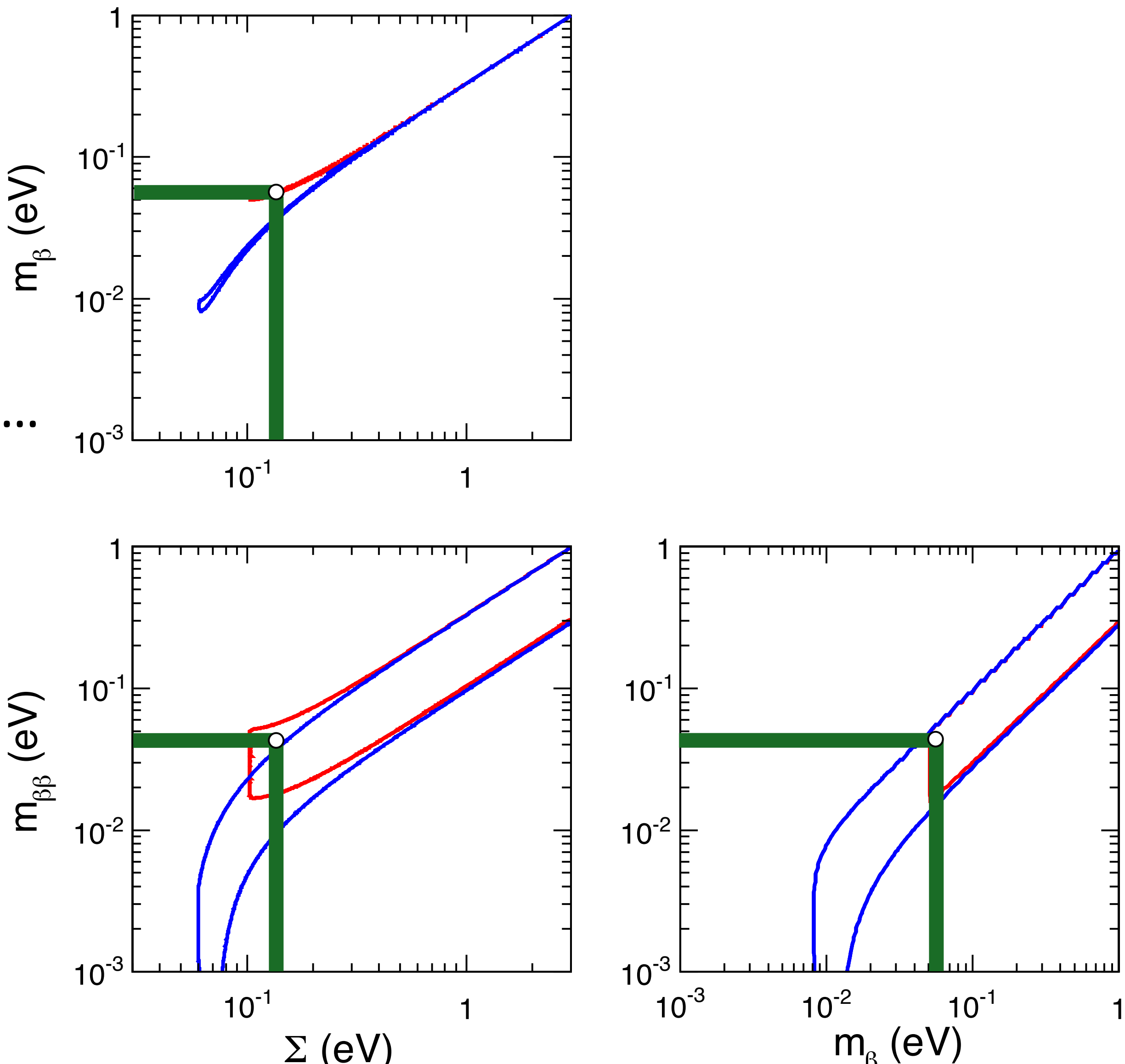
Far future: with precise and converging non-oscillation signals one could…

Determine the mass scale…

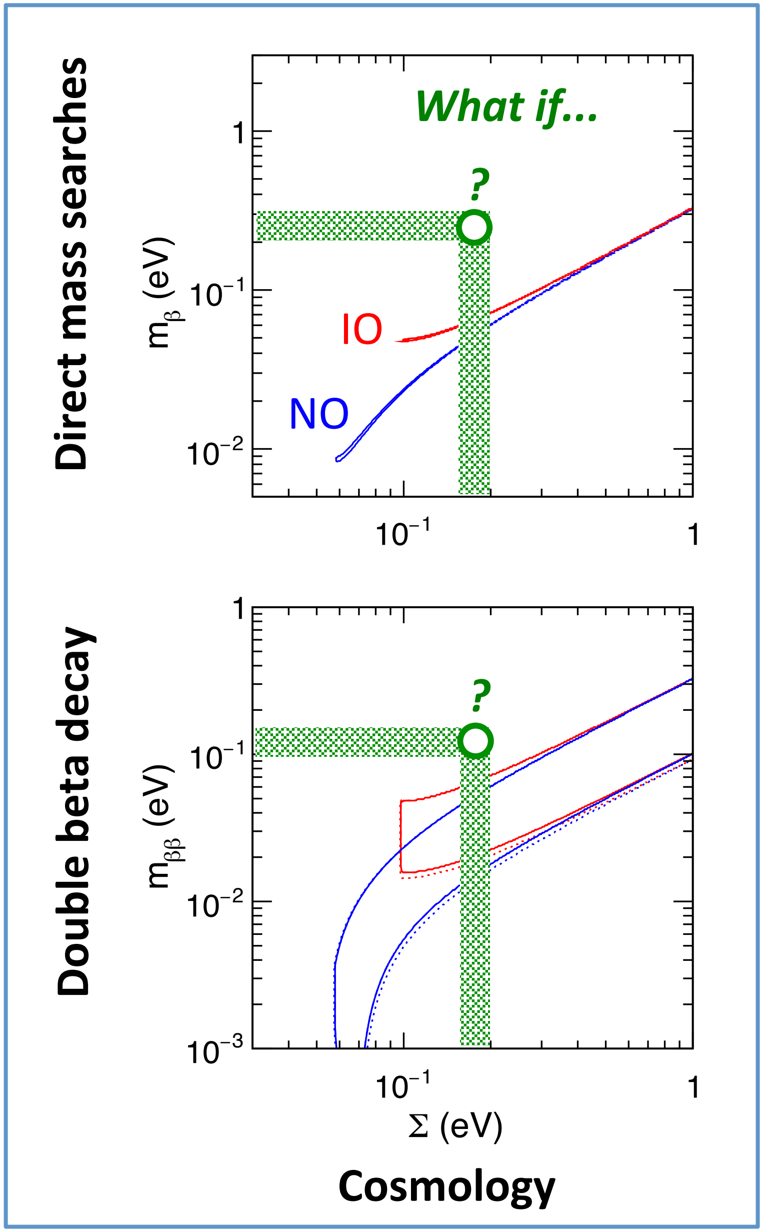
Check 3ν consistency …

Identify the hierarchy …

Probe the Majorana phase(s) …



... but data might well bring us beyond 3ν and re-shape the field!



Lack of convergence among data (barring expt mistakes) might point towards new possibilities:

- *Cosmology beyond ΛCDM*
- *New neutrino states*
- *New interactions*
- *Nonstandard ν properties*
- *New phenomena in propagation*
- *...*

Main contender in current ν physics:

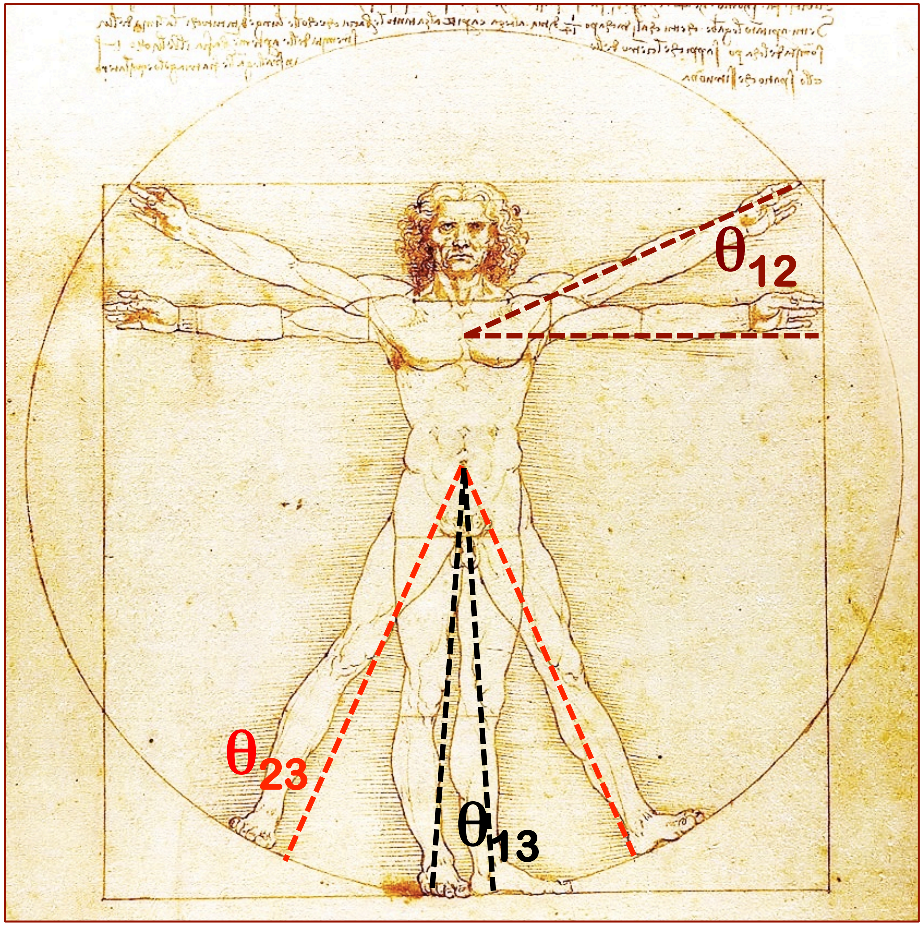
Light sterile ν at O(eV) scale

(Would require another colloquium...)

Towards the epilogue...

- being excited by a series of discoveries
- charting the newly discovered territories
- trying to avoid distortions and biases
- **seeking unknown lands and a bigger picture**

Mixings: are they suggestive of some "simmetry"…



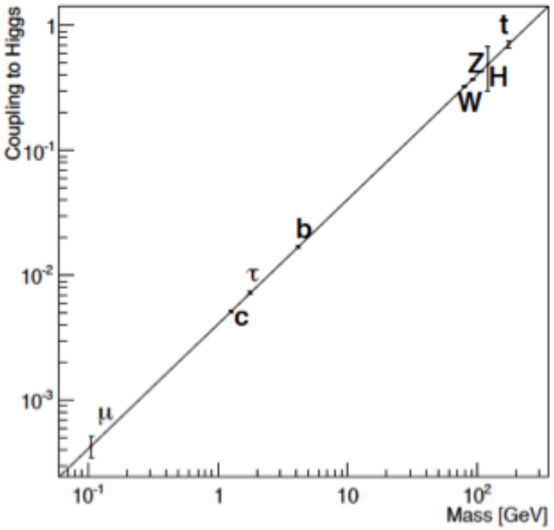
…or the symmetry is only in our mind, and there is just randomness?

Many interesting ideas, but still looking for an "illumination"...

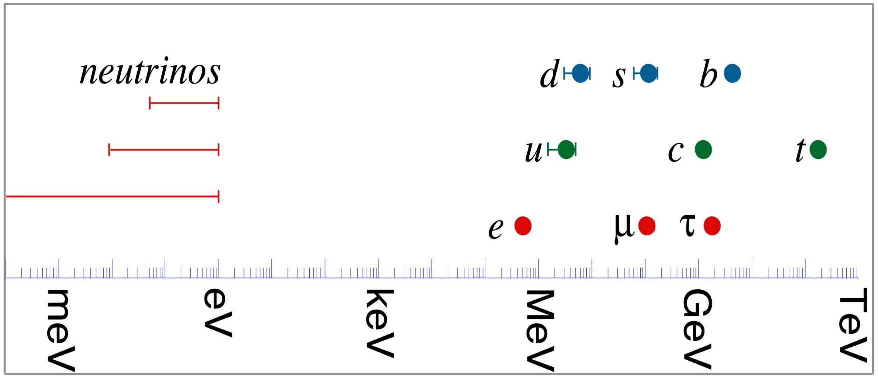
No organizing principle ("anarchy")	
Discrete family simmetries ("geometry")	linear relations between $\theta_{13}\cos\delta$ and θ_{12}, θ_{23}
Continuous flavor simmetries ("dynamics")	links between neutrino masses/angles/phases
Common quark/lepton features ("complementarity")	links between θ_{13} and θ_C

Masses: Linking two fundamental research expeditions

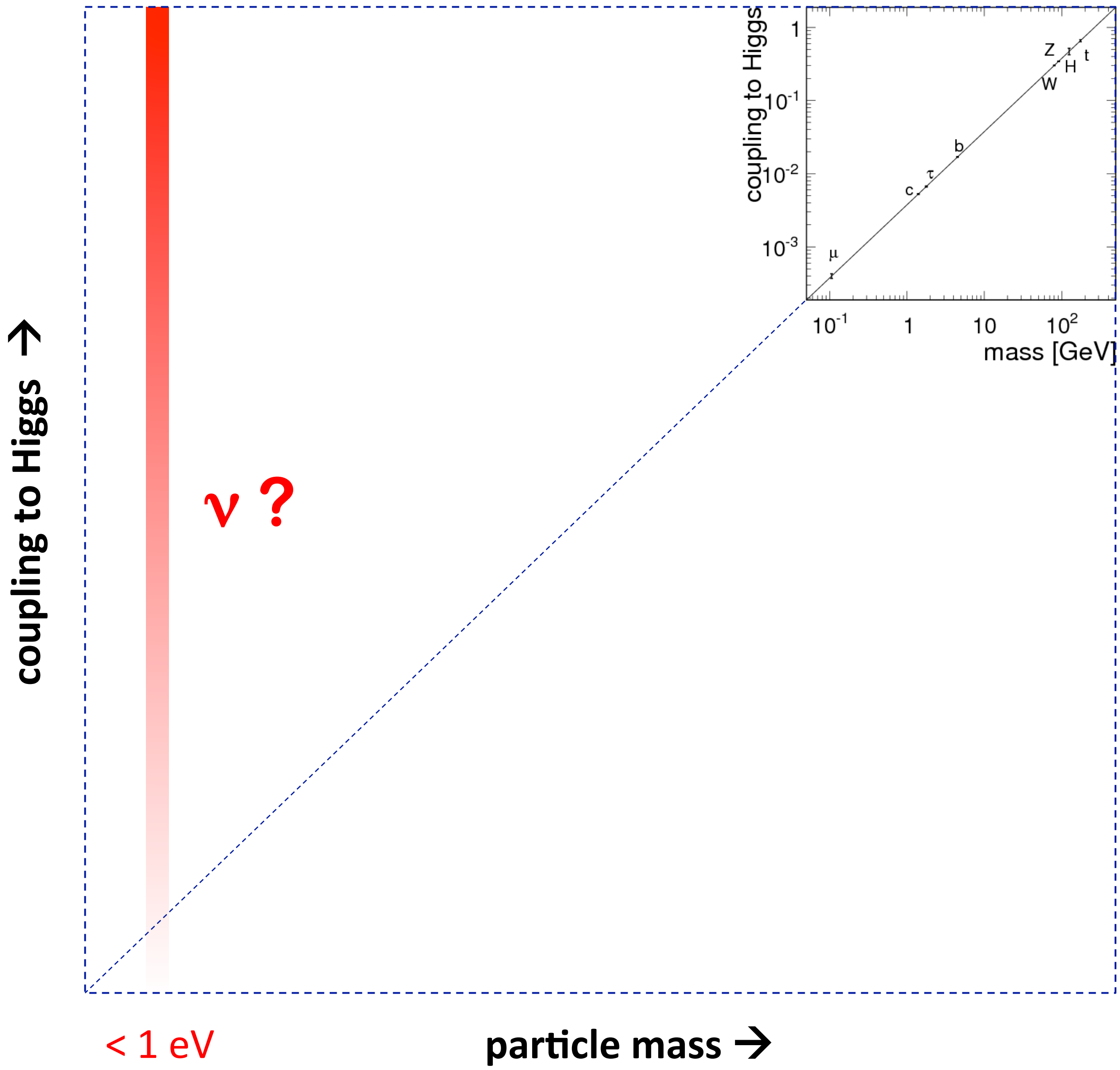
1. Test Higgs sector



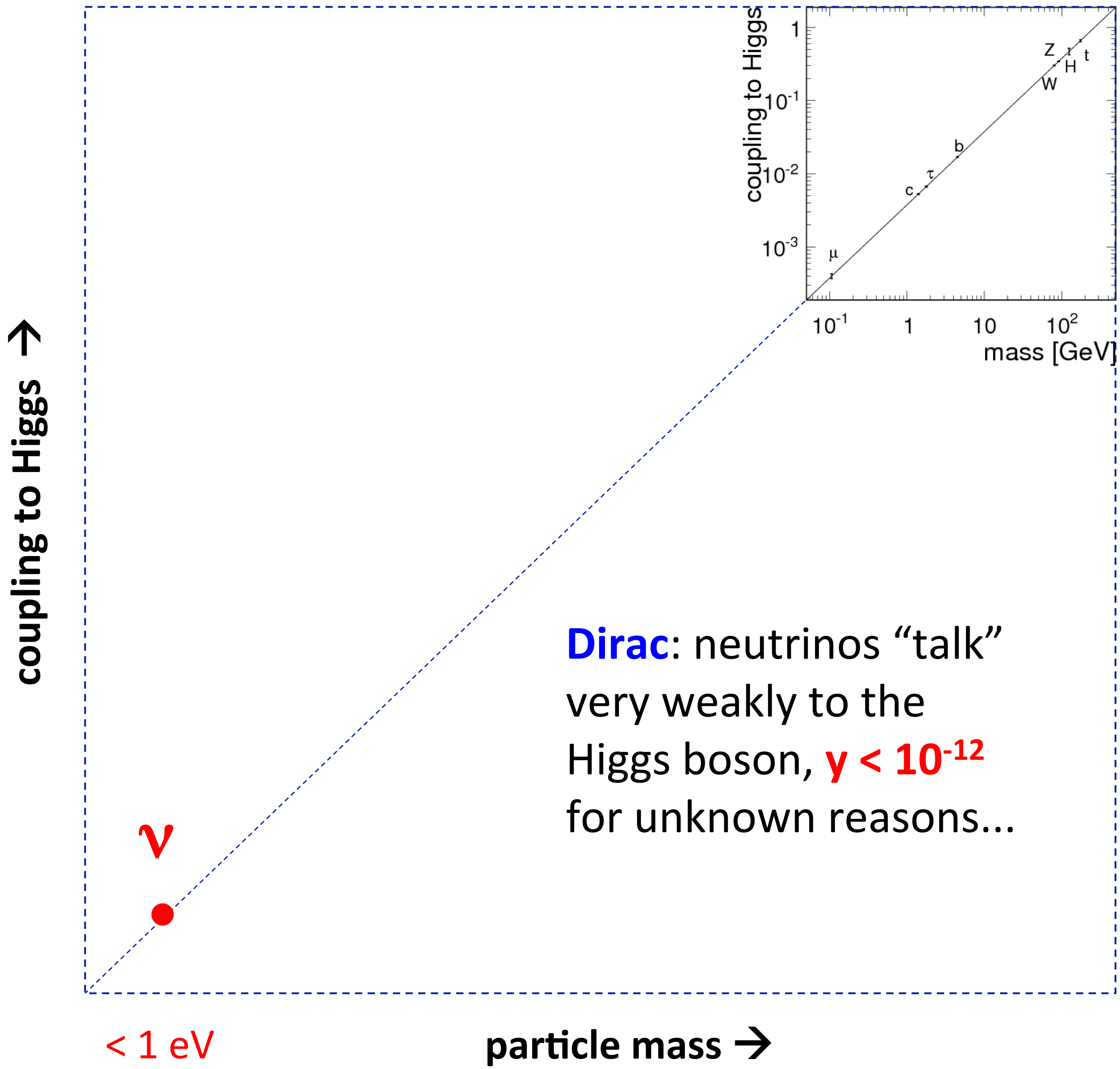
2. Fix ν masses



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

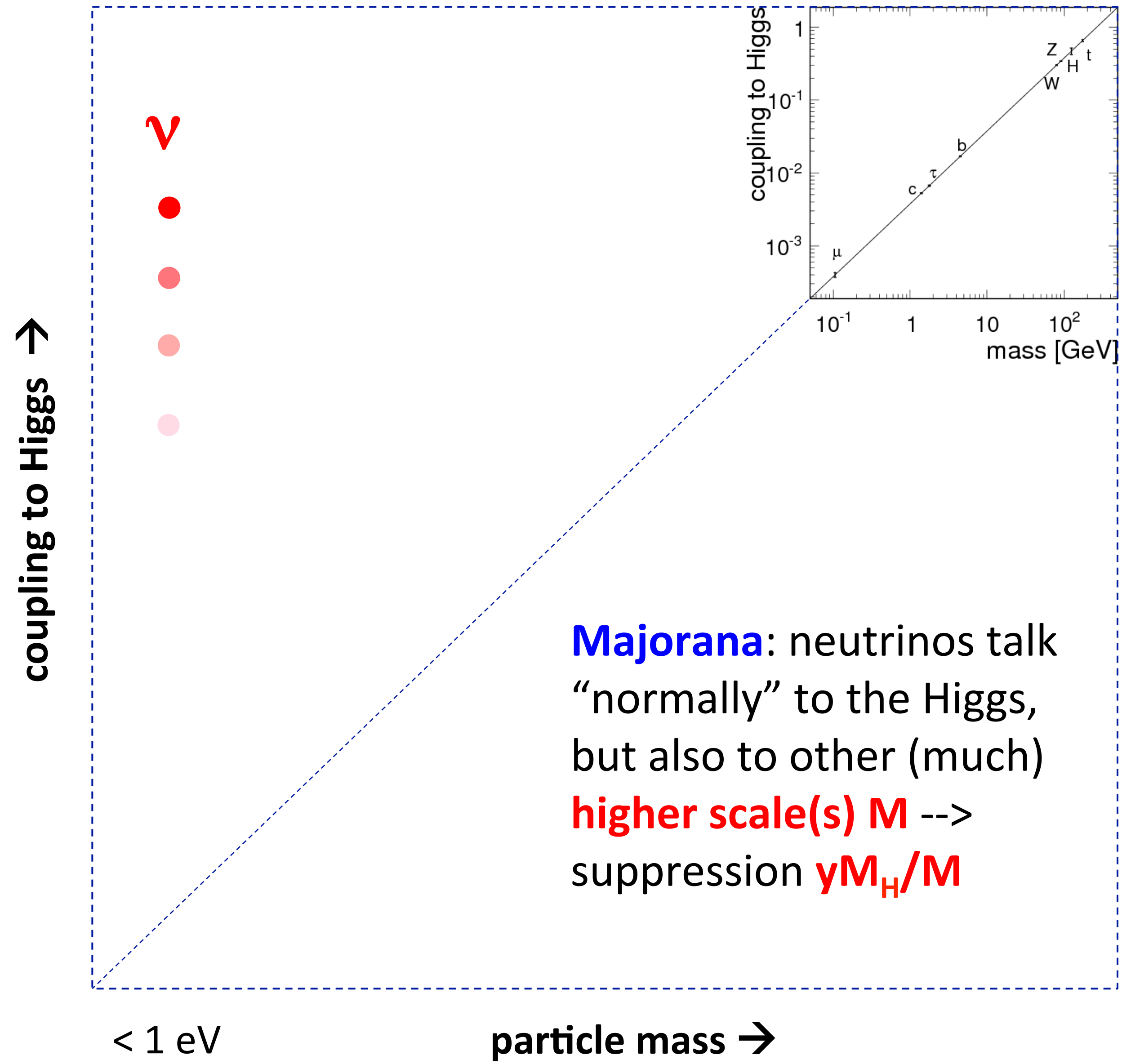


Options:



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

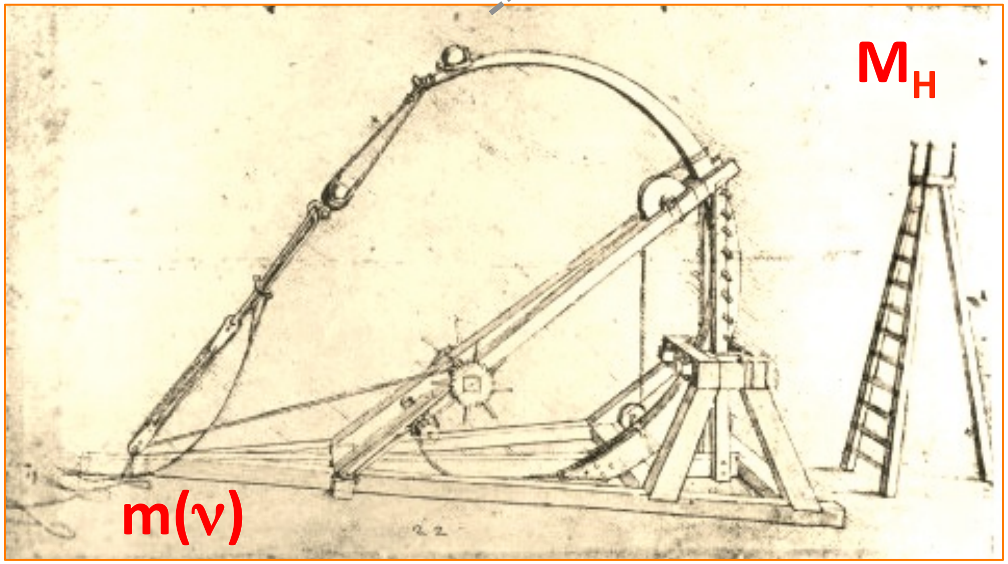
Options:



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

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

M



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

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

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!

Epilogue

$\delta m^2 \sim 8\text{x}10^{-5}\ eV^2$
$\Delta m^2 \sim 2\text{x}10^{-3}\ eV^2$
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

3ν Terra Cognita...

Epilogue

$\delta m^2 \sim 8\text{x}10^{-5}$ eV^2
$\Delta m^2 \sim 2\text{x}10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
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3ν Terra Cognita...

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

3ν Terra Incognita...

Epilogue

$\delta m^2 \sim 8 \times 10^{-5}\ eV^2$
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$
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3ν Terra Cognita...

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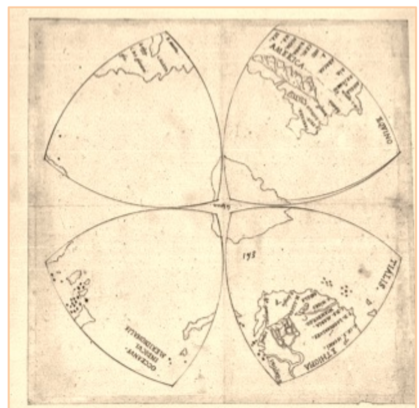
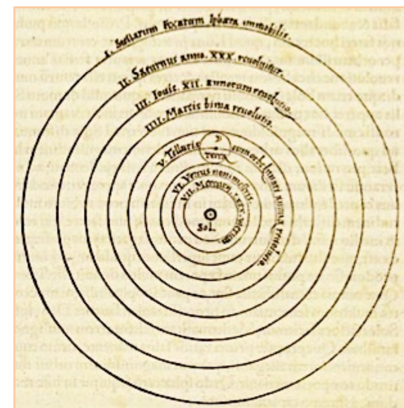
octant(θ_{23})
absolute masses
Dirac/Majorana

3ν Terra Incognita...



new light states
new interactions
new heavy scales
flavor structure
origin of matter

... and beyond



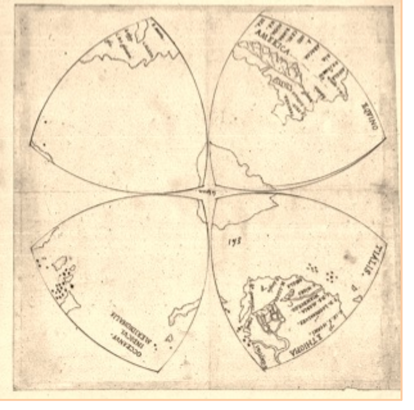
Epilogue

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

3ν Terra Cognita...

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

3ν Terra Incognita...



new light states
new interactions
new heavy scales
flavor structure
origin of matter

... and beyond

Thank you for your attention