

Unveiling fundamental v properties



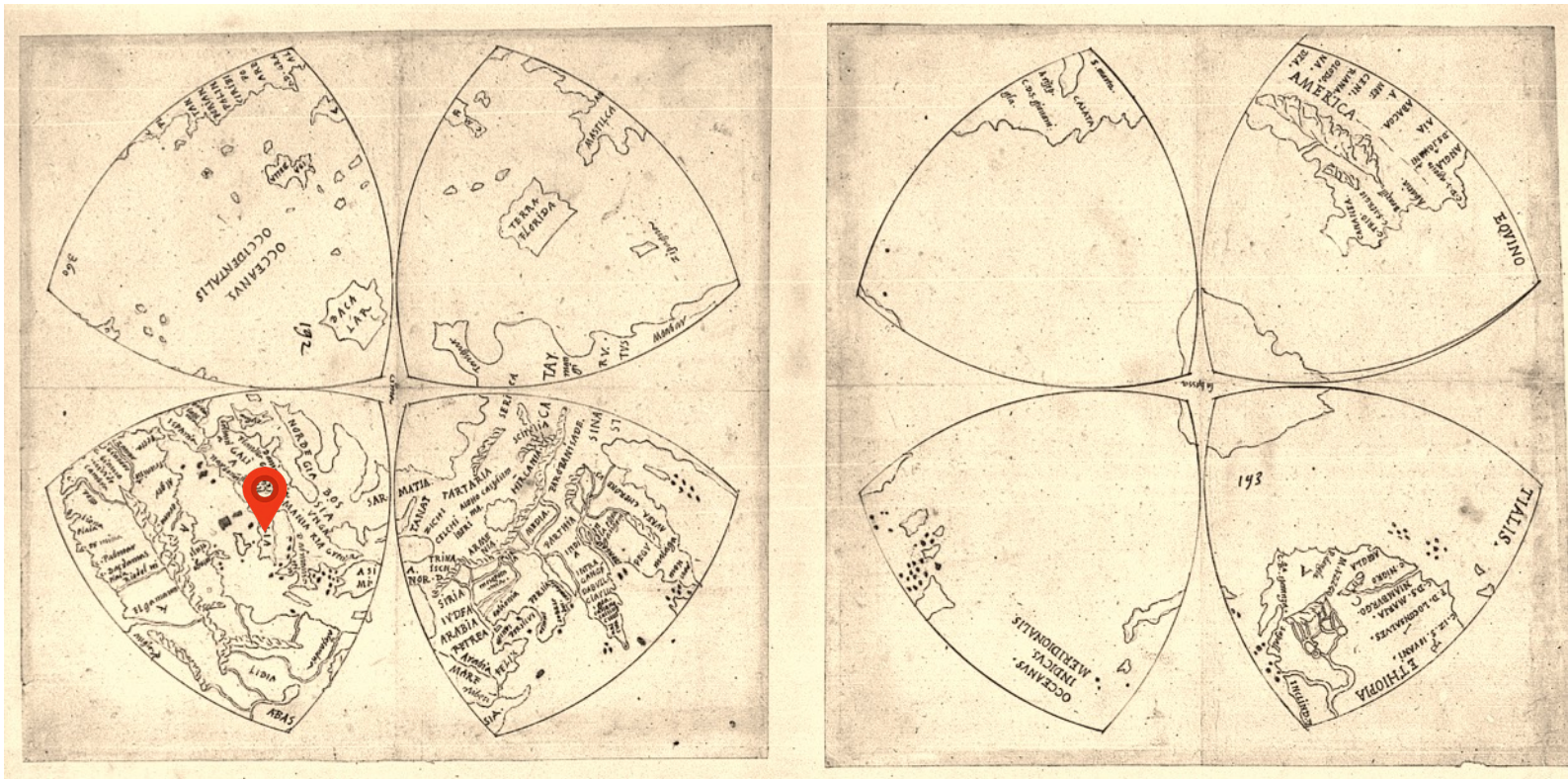

GSSI L'Aquila
Italy

Eligio Lisi

GSSI Colloquium, 21 April 2021


INFN Bari
Italy

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



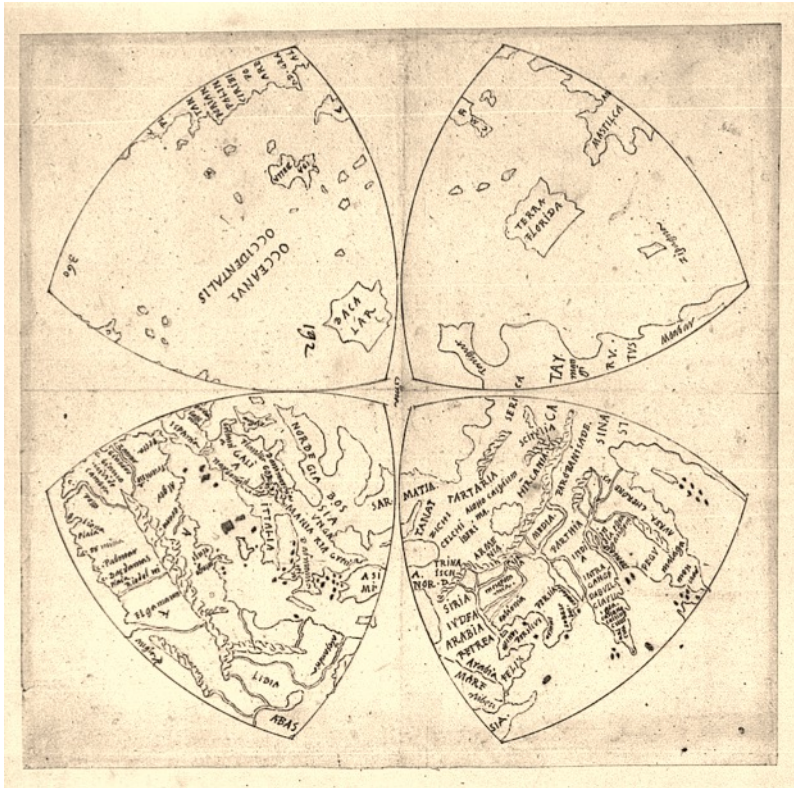
Northern hemisphere

Southern hemisphere

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

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

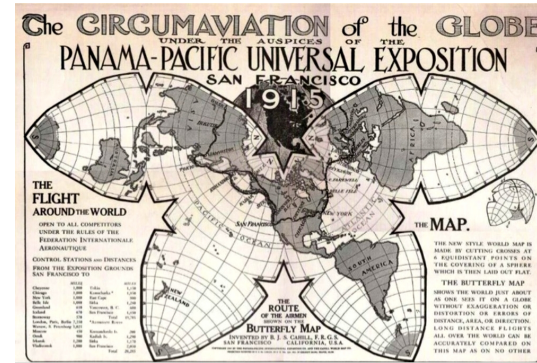
Earliest known world map ...



Leonardo's 1st sketch (Codex Atlant.)

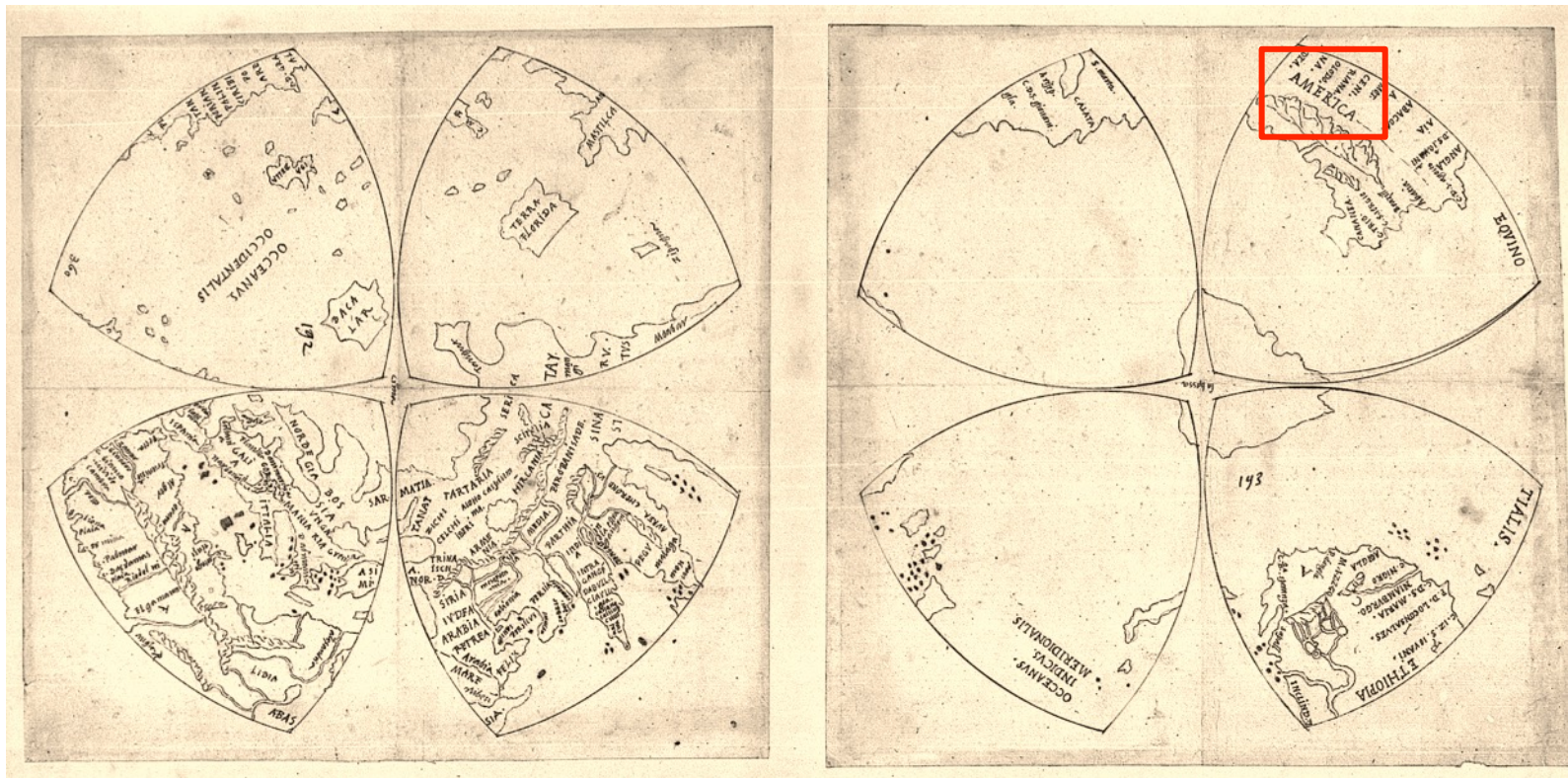


XX century octant map (Wikipedia)



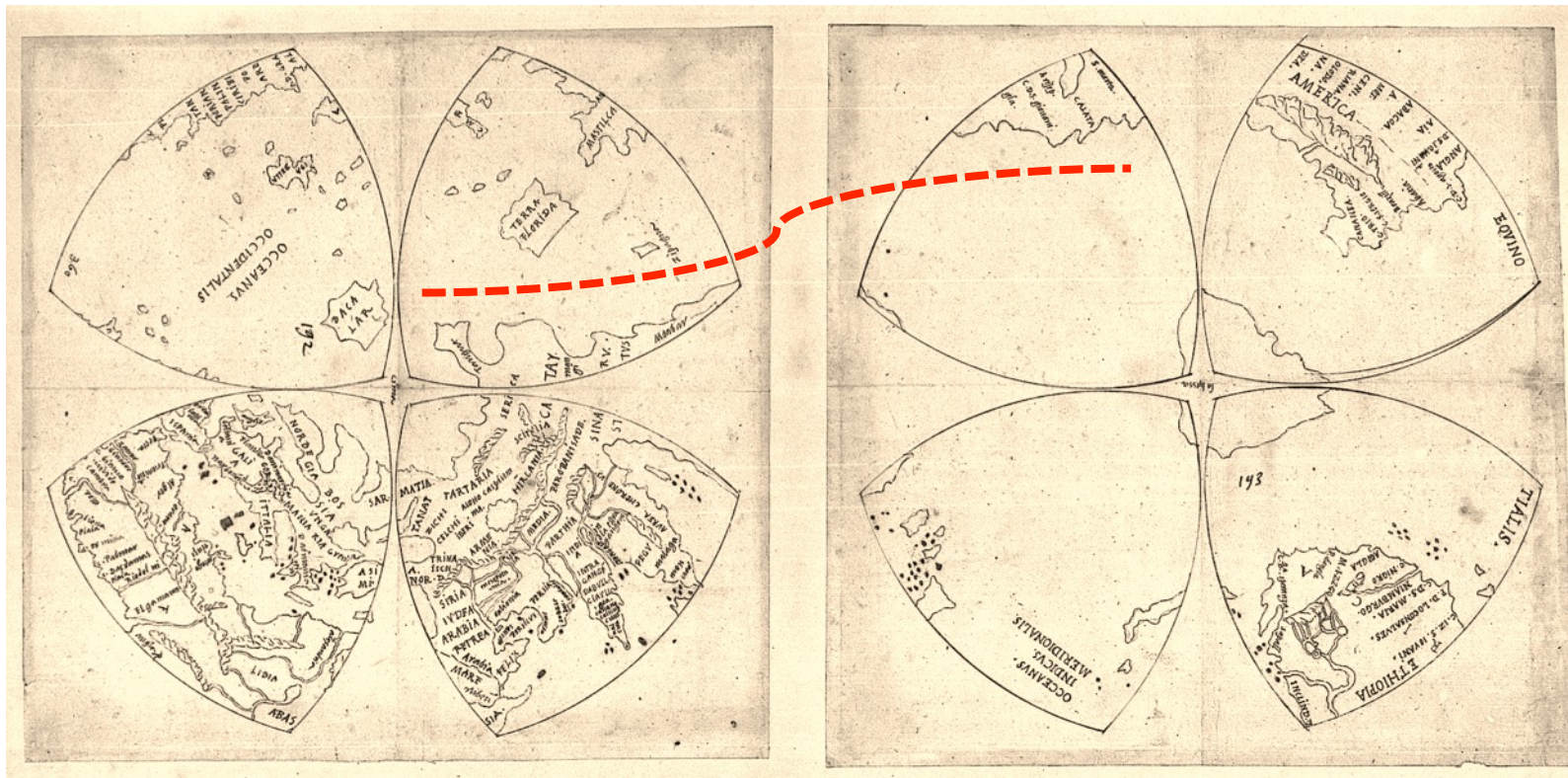
... made with octant projections (1/8's of the globe)

Earliest known world map ...



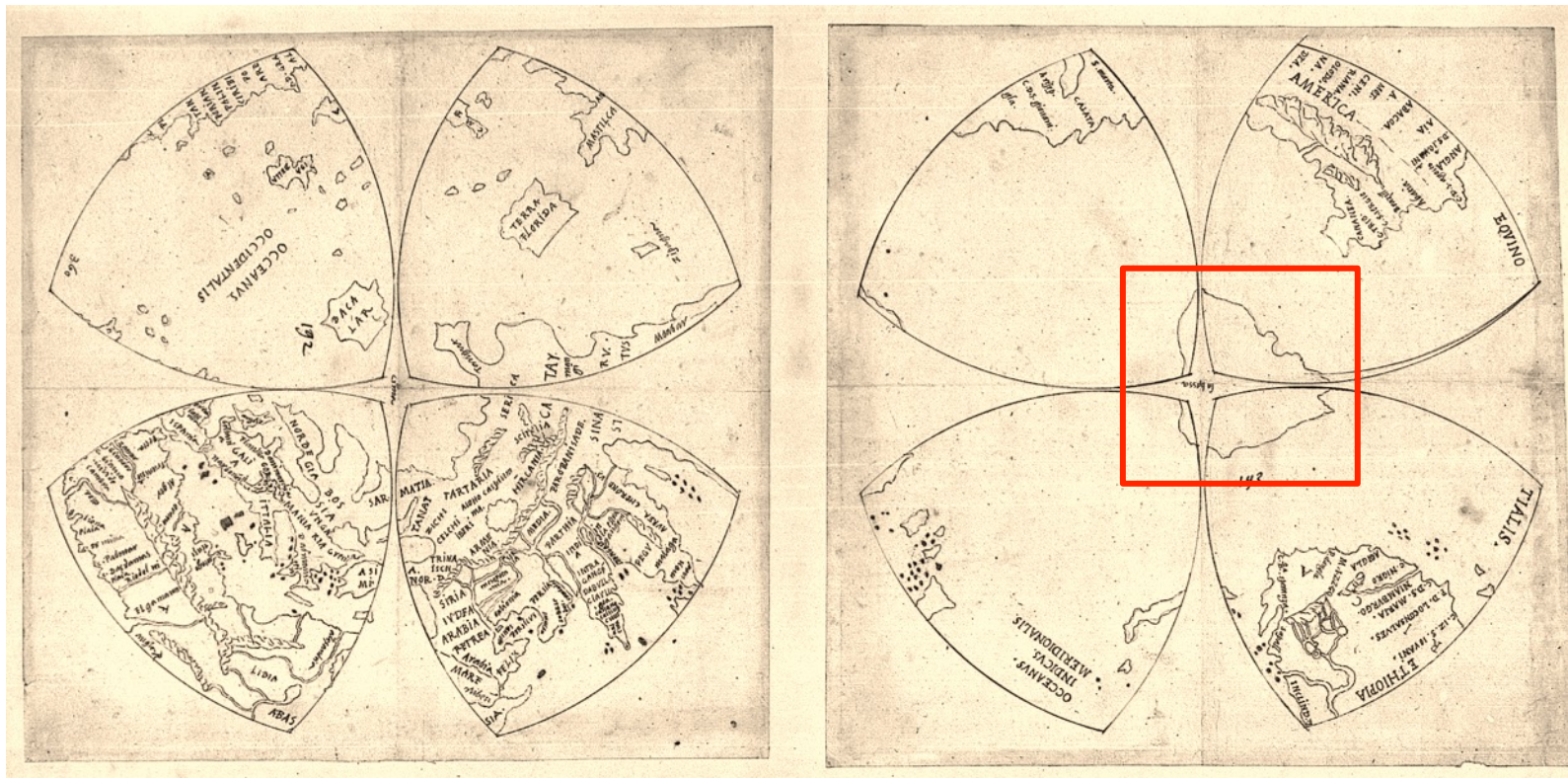
... made with octant projections (1/8's of the globe)
... showing the name "America" for the New World

Earliest known world map ...



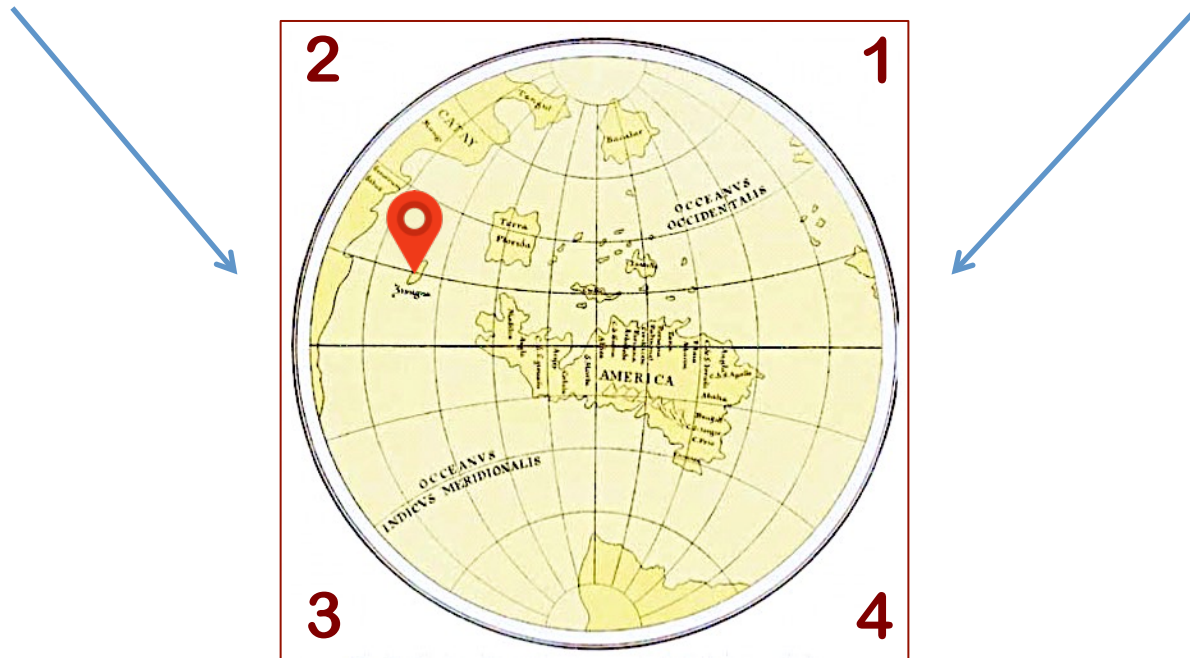
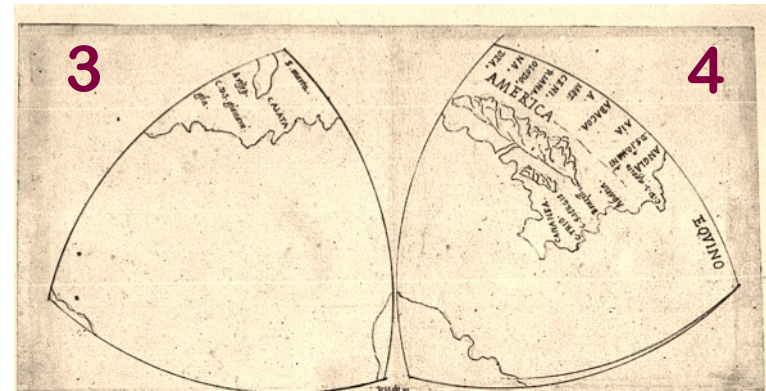
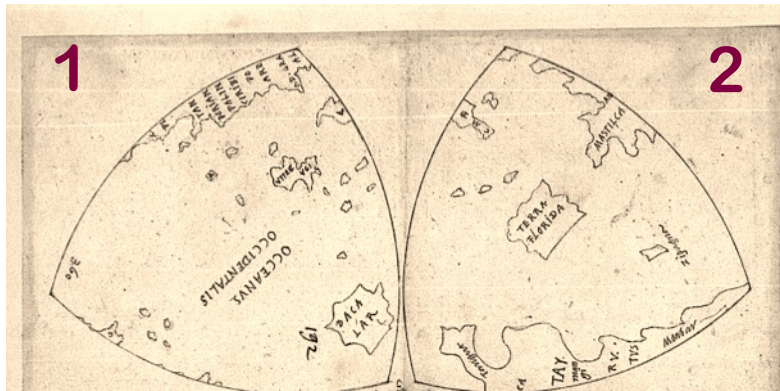
- ... made with octant projections (1/8's of the globe)
- ... showing the name "America" for the New World
- ... with America's west coast disconnected from Asia

Earliest known world map ...



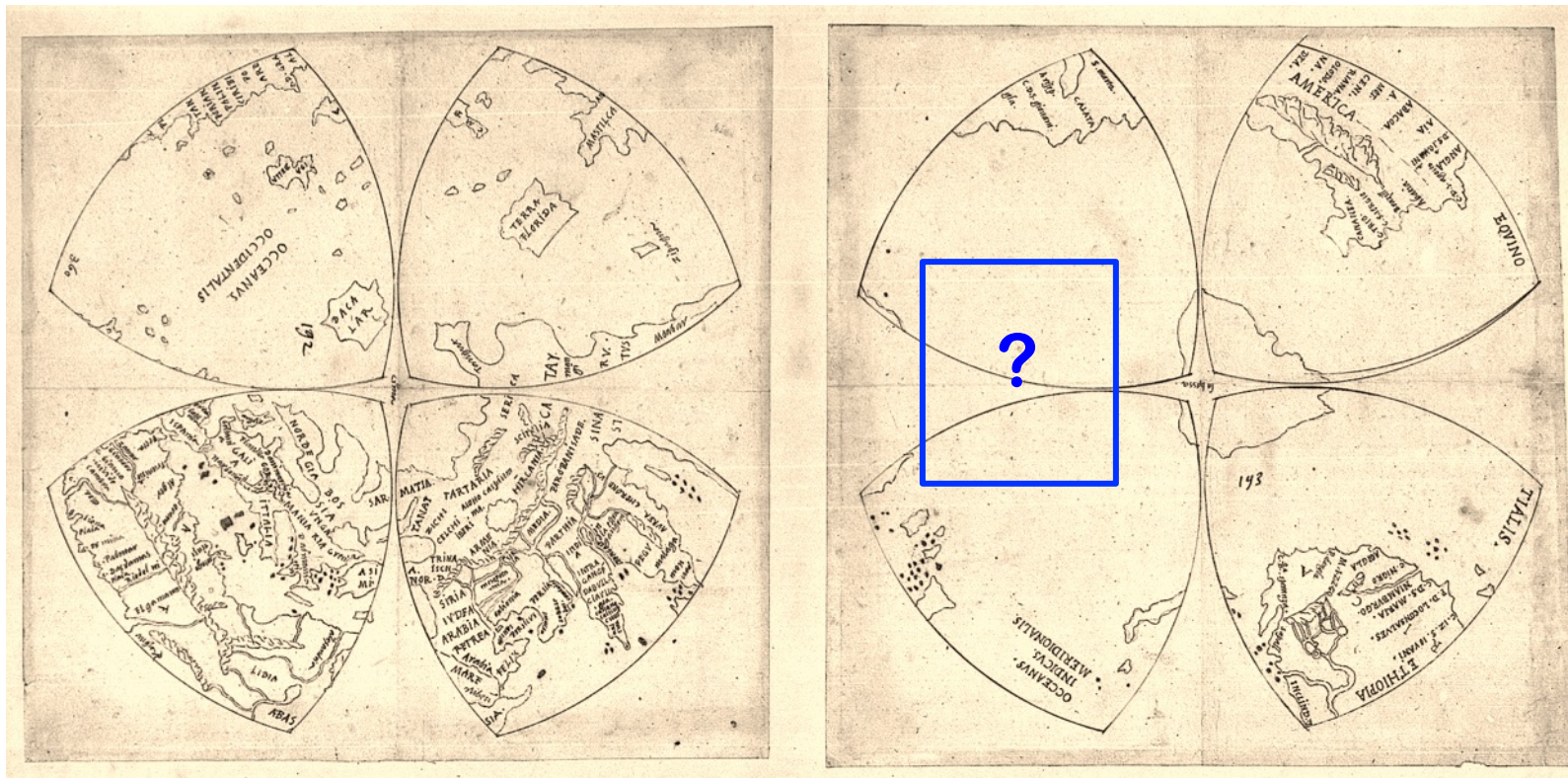
- ... made with octant projections (1/8's of the globe)
- ... showing the name “America” for the New World
- ... with America’s west coast disconnected from Asia
- ... indicating a large Southern continent (a bold guess!)

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...



... 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

After ~500 years...

...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 Cosmology & Astroparticle!

Cosmology

accelerated expansion
of the Universe

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

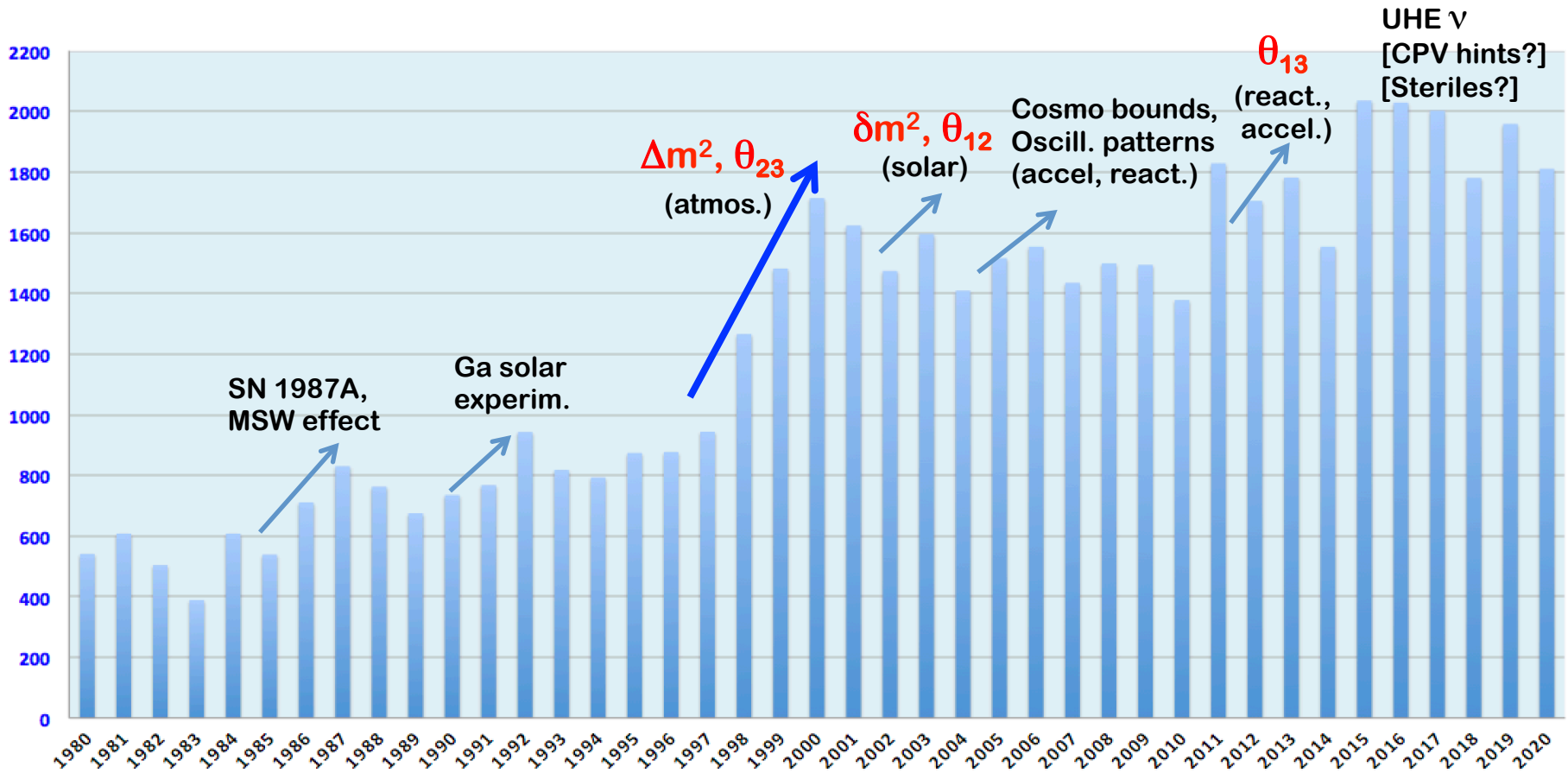
**Evidence for dark energy
from SN photon sources**

Astro Particle Physics

oscillations of
atmospheric neutrinos

$$\Delta m_{\text{atm}}^2 \sim (5 \times 10^{-2} \text{ eV})^2$$

**Evidence for neutrino mass
from CR-induced ν source**



$\Delta m_{ij}^2 L/E \sim$ oscillation phase in vacuum

$\nu_\alpha \rightarrow \nu_\beta$ (appearance)

$\sin^2 \theta_{ij} \sim$ oscill. amplitude in vacuum

$\nu_\alpha \rightarrow \nu_\alpha$ (disappear.)

→ standard ν paradigm established

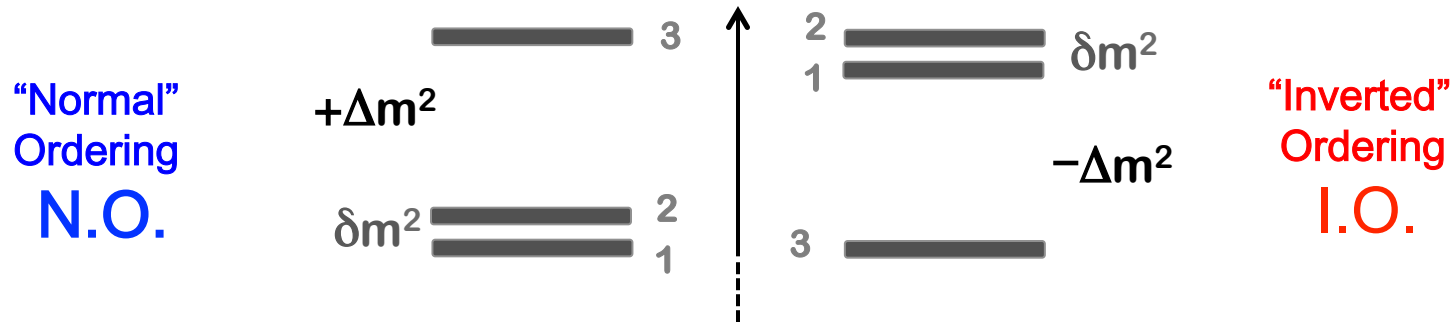
The standard 3ν paradigm: parameters

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”)

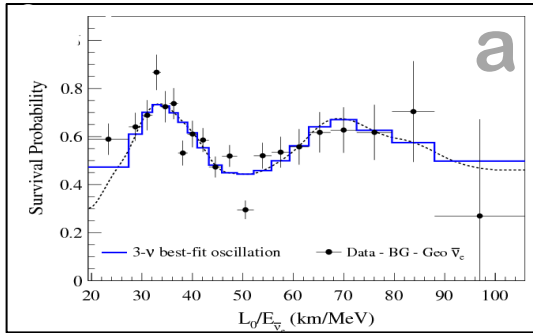


$$\delta m^2 = \Delta m_{21}^2, \quad \Delta m^2 = (\Delta m_{32}^2 + \Delta m_{31}^2)/2$$

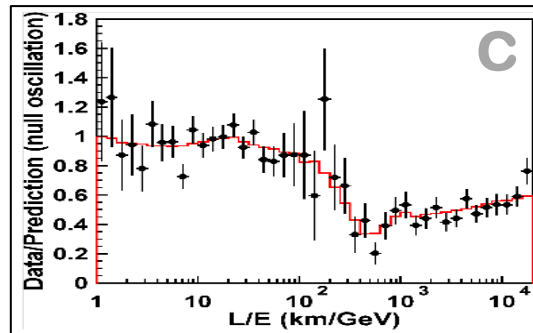
- + interactions in matter → effective terms ~ G_F · E · density
- + absolute neutrino mass scale (not tested in oscillations)

Beautiful ν oscillation data have established this 3ν paradigm...

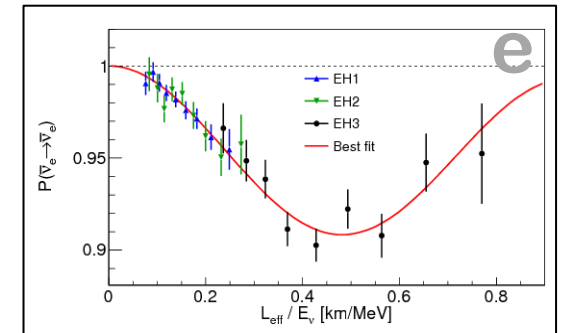
$e \rightarrow e$ (KamLAND, KL)



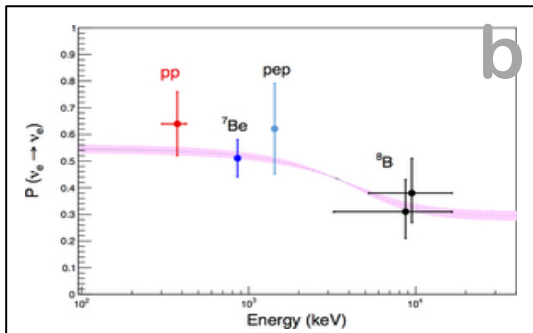
$\mu \rightarrow \mu$ (Atmospheric)



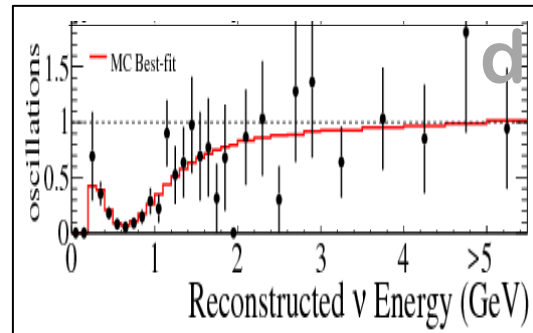
$e \rightarrow e$ (SBL React.)



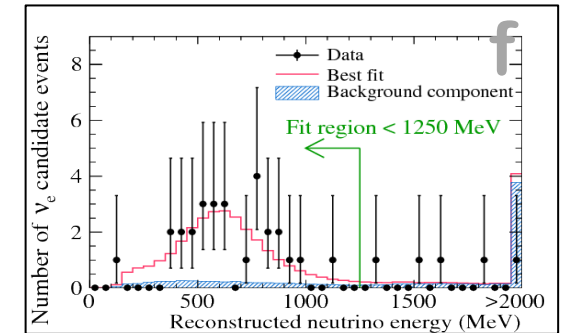
$e \rightarrow e$ (Solar)



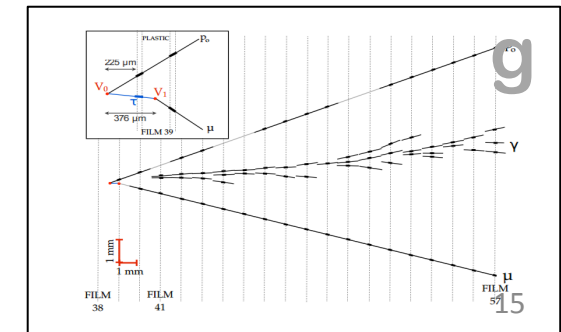
$\mu \rightarrow \mu$ (LBL Accel)



$\mu \rightarrow e$ (LBL Accel)



$\mu \rightarrow \tau$ (OPERA, SK, DC)

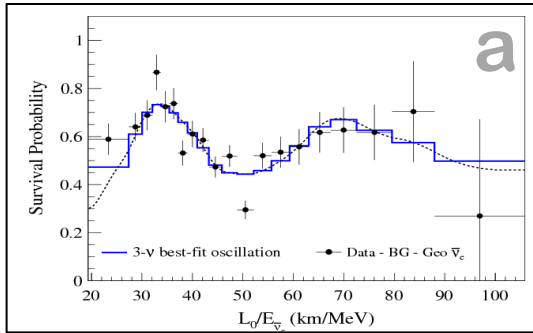


LBL = Long baseline (few x 100 km); SBL = short baseline (~1 km)

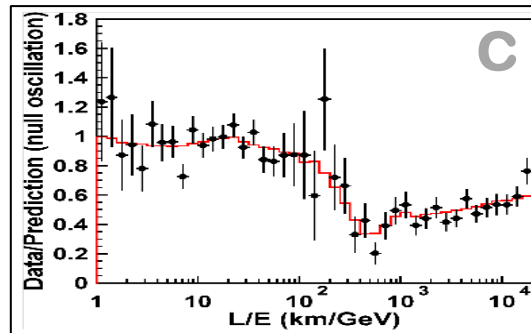
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K [plot], NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot]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

... and consistently measured five ν mass-mixing parameters

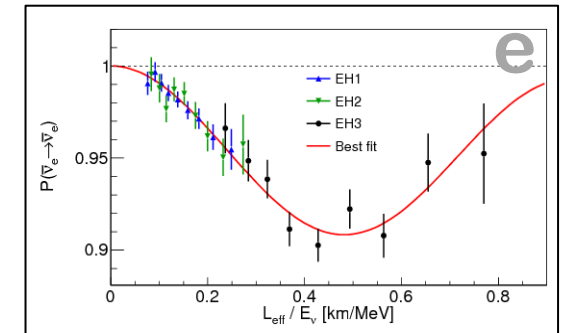
$e \rightarrow e$ ($\delta m^2, \theta_{12}$)



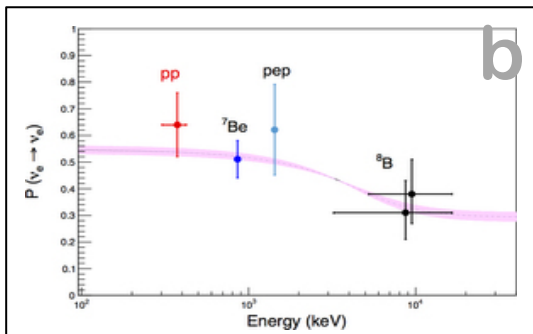
$\mu \rightarrow \mu$ ($\Delta m^2, \theta_{23}$)



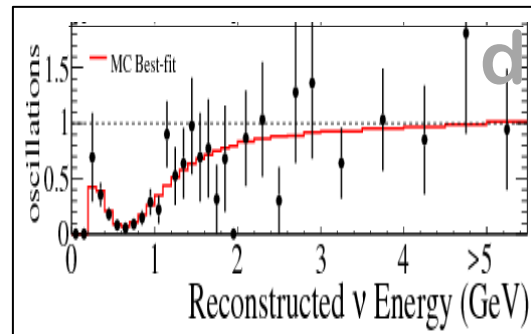
$e \rightarrow e$ ($\Delta m^2, \theta_{13}$)



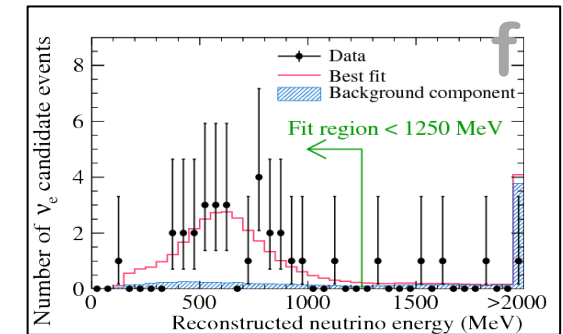
$e \rightarrow e$ ($\delta m^2, \theta_{12}$)



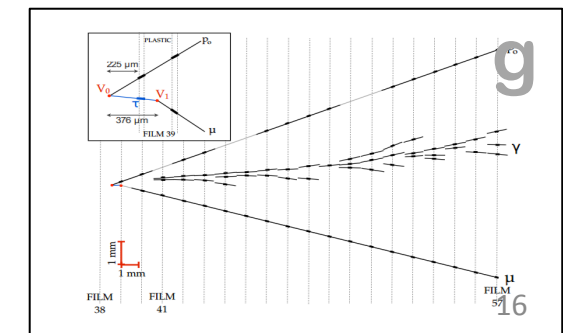
$\mu \rightarrow \mu$ ($\Delta m^2, \theta_{23}$)



$\mu \rightarrow e$ ($\Delta m^2, \theta_{13}, \theta_{23}$)



$\mu \rightarrow \tau$ ($\Delta m^2, \theta_{23}$)



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

Subleading effects involve CPV and NO vs IO difference, essentially via $\mu \rightarrow e$ in LBL accel. and atmospher. expts

CPV is a genuine 3ν effect; disappears in effective 2ν limit

$$\nu_e = \overbrace{\cos\theta_{13} (\cos\theta_{12} \nu_1 + \sin\theta_{12} \nu_2)}^{2\nu} + e^{-i\delta} \sin\theta_{13} \nu_3$$

$\underbrace{\hspace{15em}}_{3\nu}$

→ leptonic CPV ($\delta \neq 0, \pi$) observable in vacuum: different ν and $\bar{\nu}$ oscill.



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PHYSICS LETTERS

2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*

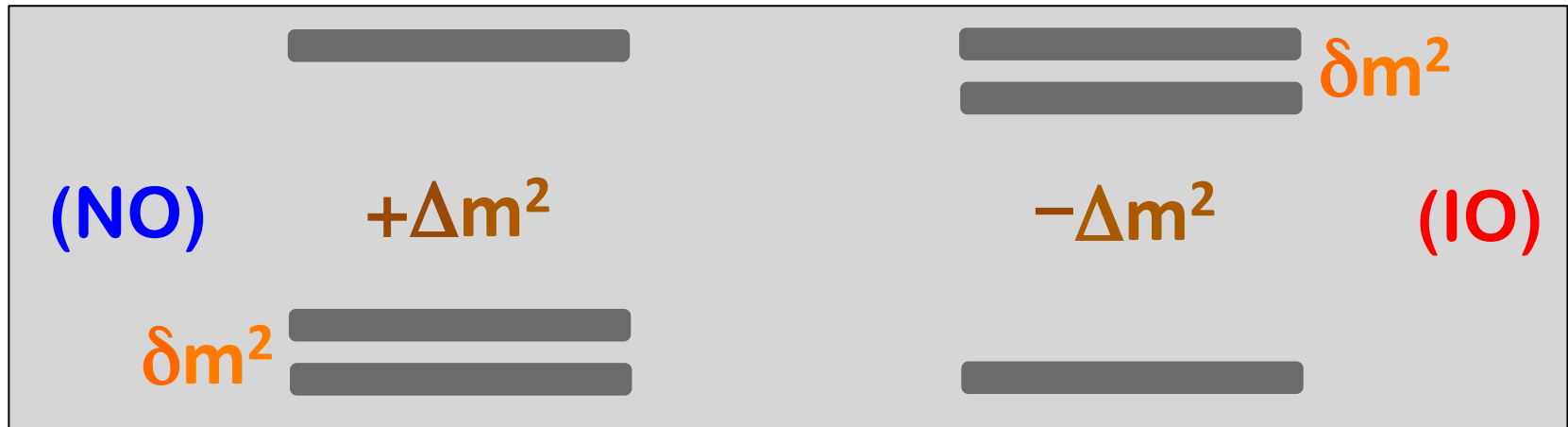
*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation. CP requires $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations to be equal. Time reversal invariance requires the oscillation probability to be an even function of time. Both conditions can be violated, even drastically, if more than two neutrinos exist.

Matter background is a “CPV nuisance” in this context

How do oscillation searches probe mass ordering?



Observe **interference effects** of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity **Q** with known sign. Options:

$Q \sim \delta m^2$ (medium-baseline reactors, as JUNO)

$Q \sim G_F N_e E$ (ν -matter effects in atm. & LBL accel. expt.)

$Q \sim G_F N_\nu E$ (collective ν - ν effects in SNe)

Non-oscillation data provide, in combination, additional handles.

Sketchy 3ν picture (with 1-digit accuracy)

Knowns:

$$\delta m^2 \sim 7 \times 10^{-5} \text{ eV}^2$$

$$\Delta m^2 \sim 2 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{12} \sim 0.3$$

$$\sin^2 \theta_{23} \sim 0.5$$

$$\sin^2 \theta_{13} \sim 0.02$$



Unknowns:

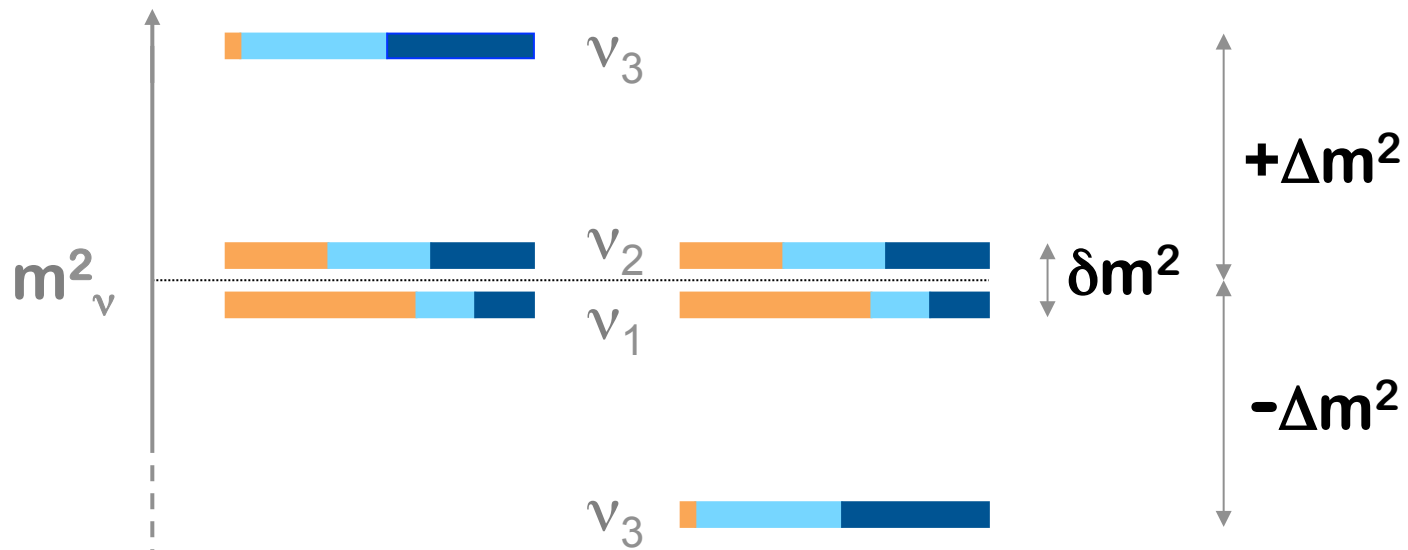
$\delta =$ Dirac CPV phase
 $\text{sign}(\Delta m^2) =$ ordering
 octant(θ_{23})

absolute mass scale
 Dirac/Majorana nature

Normal Ordering (NO)

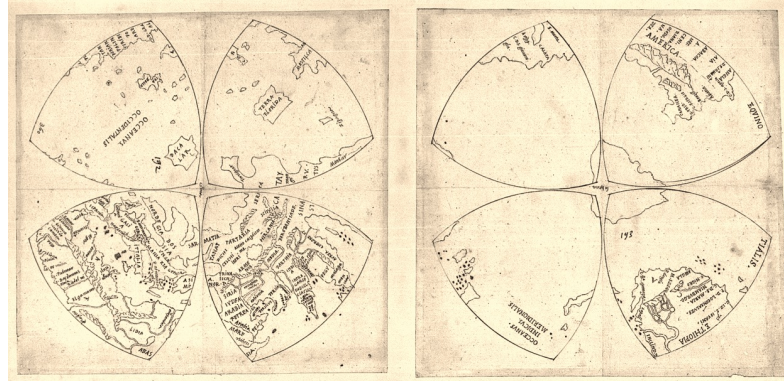
e μ τ

Inverted Ordering (IO)





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 →**

Fine Print 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; working on update.

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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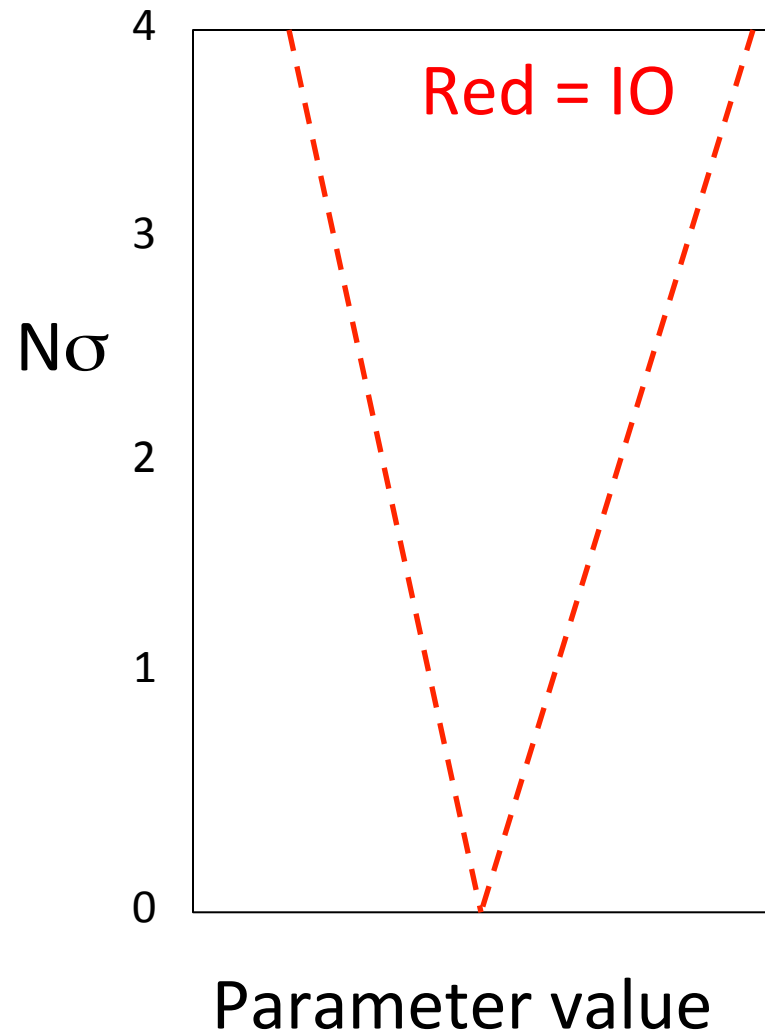
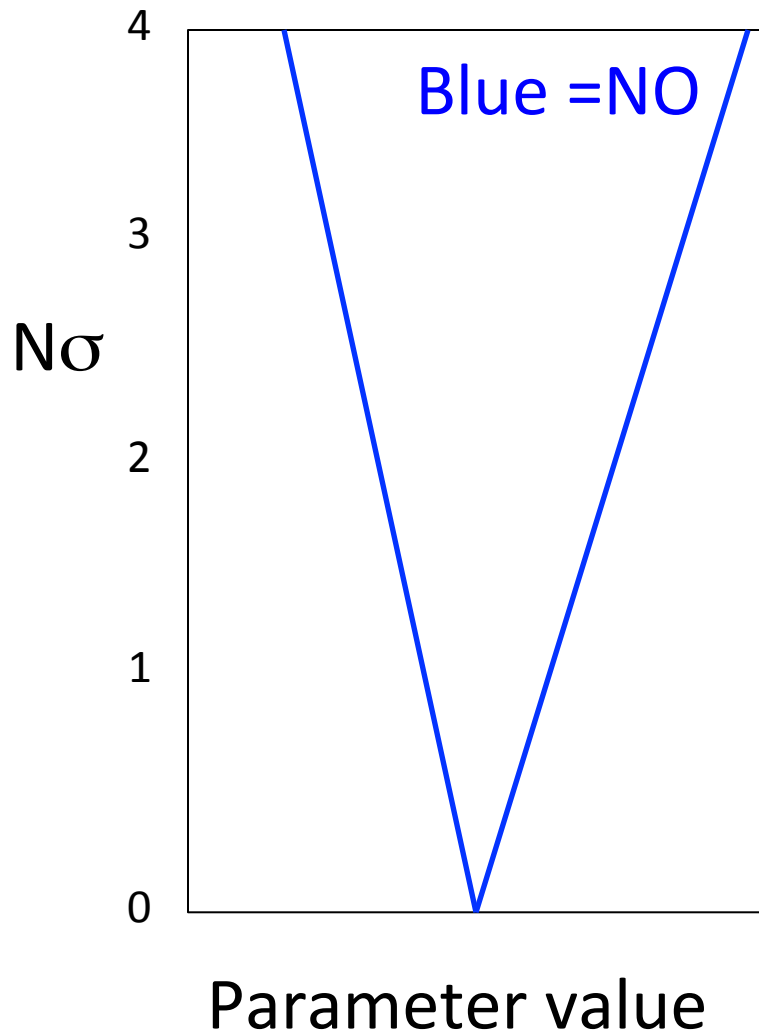
Statistics

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

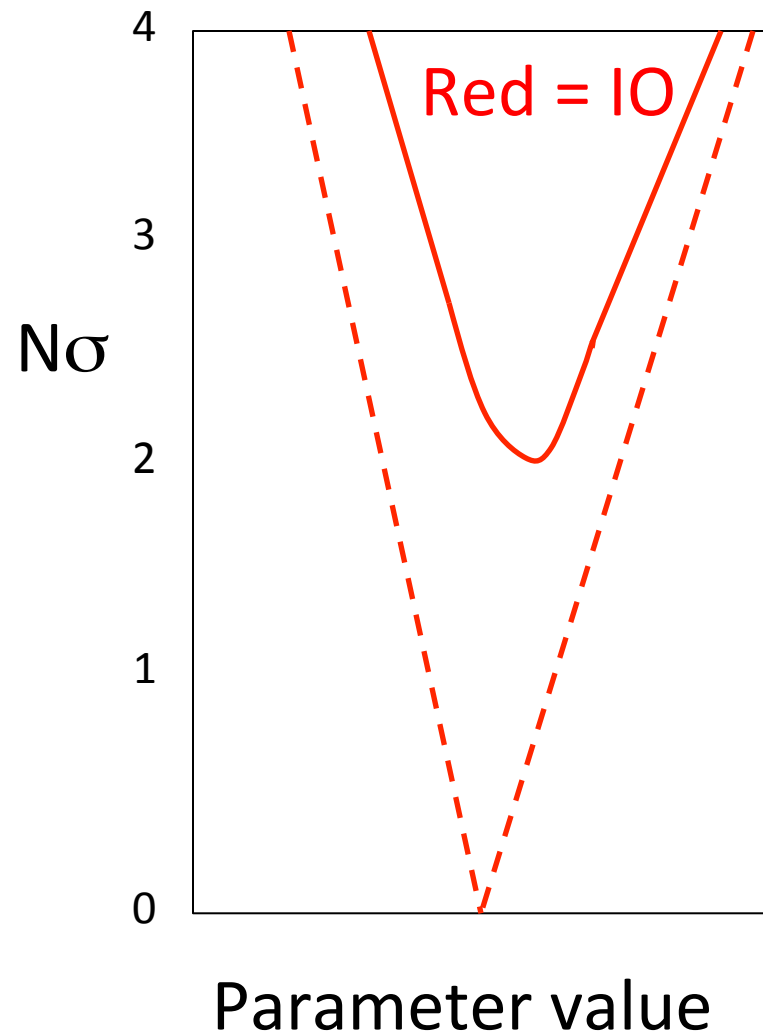
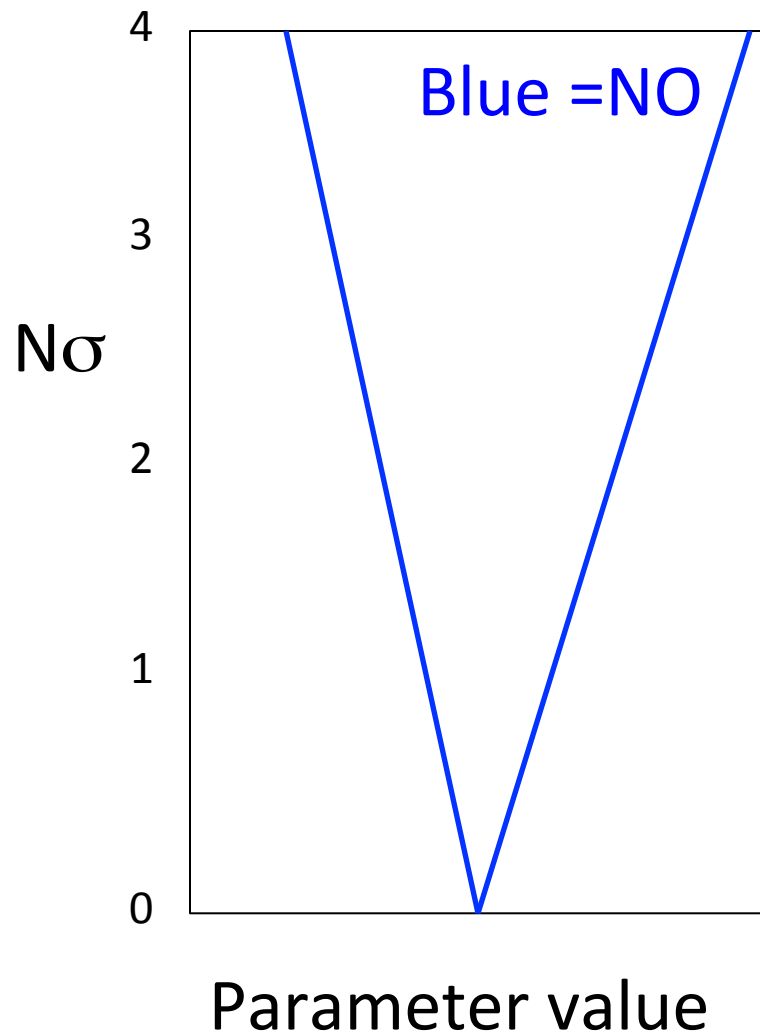
Undisplayed parameters are marginalized (projected) away

We shall discuss first “**single**” parameters and then “**pairs**” of parameters.

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



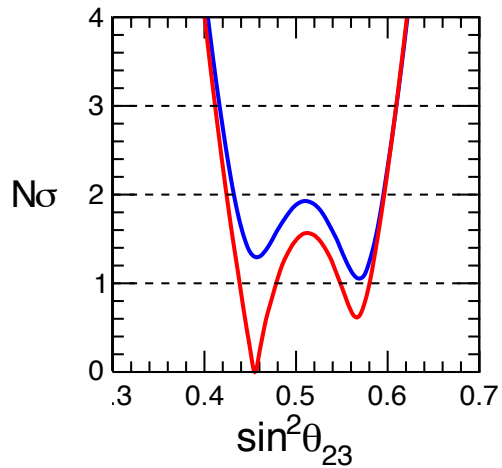
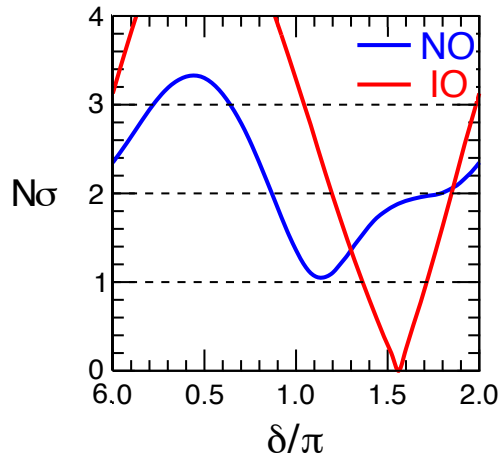
However, bounds for one given mass ordering move upwards,
if the other mass ordering is preferred, e.g.:



Results →

Focus on three unknowns: δ , NO/IO, θ_{23} octant

LBL Acc + Solar + KamLAND



IO favored at $\sim 1\sigma$

$\delta \sim 3\pi/2$ (**IO**), $\sim \pi$ (**NO**)

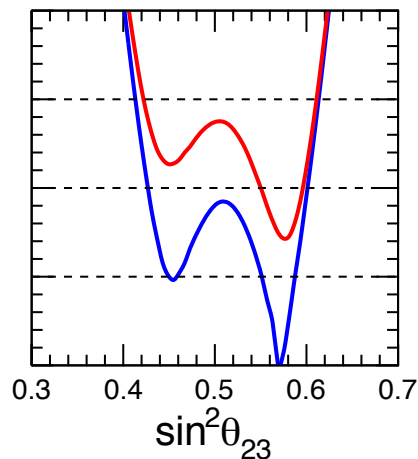
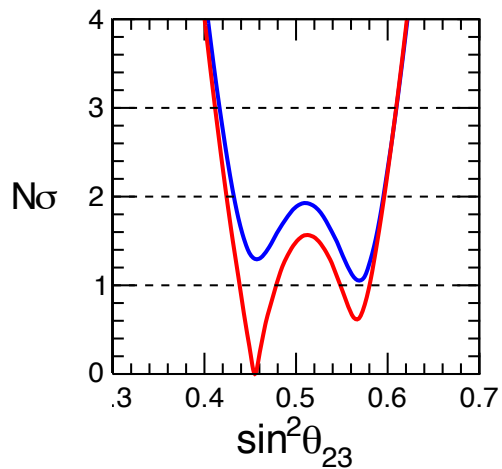
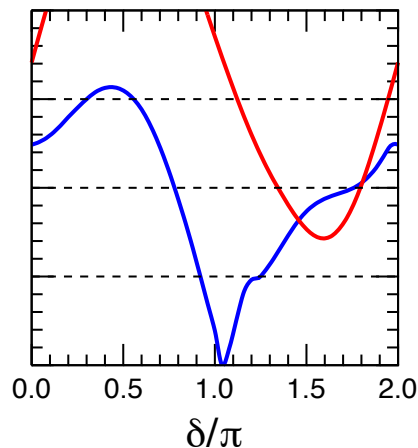
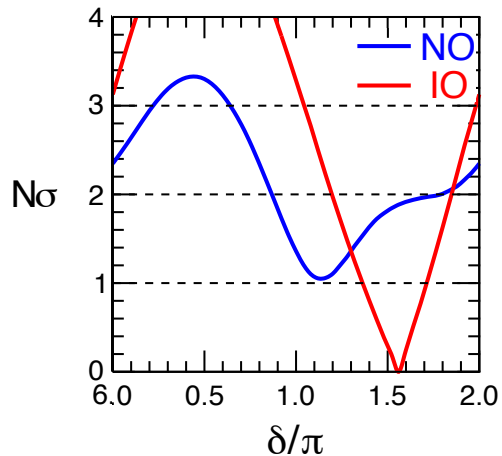
θ_{23} octants \sim degen.

Focus on three unknowns: δ , **NO/IO**, θ_{23} octant

LBL Acc + Solar + KamLAND



+ SBL Reactors



IO favored at $\sim 1\sigma$
 $\delta \sim 3\pi/2$ (**IO**), $\sim \pi$ (**NO**)
 θ_{23} octants \sim degen.

NO favored at $\sim 1.5\sigma$
 $\delta \sim 3\pi/2$ (**IO**), $\sim \pi$ (**NO**)
 2nd octant favored

Focus on three unknowns: δ , **NO/IO**, θ_{23} octant

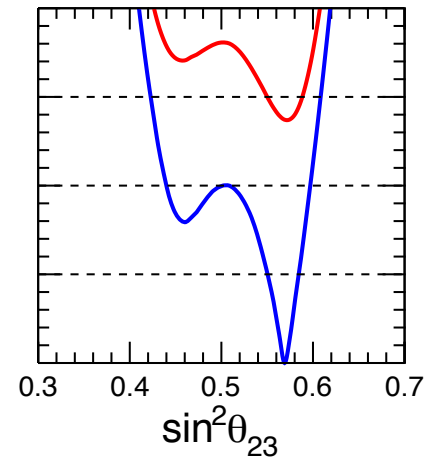
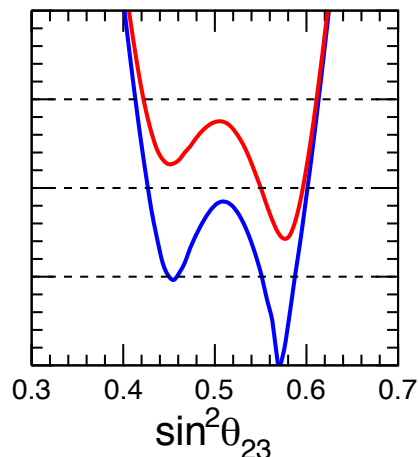
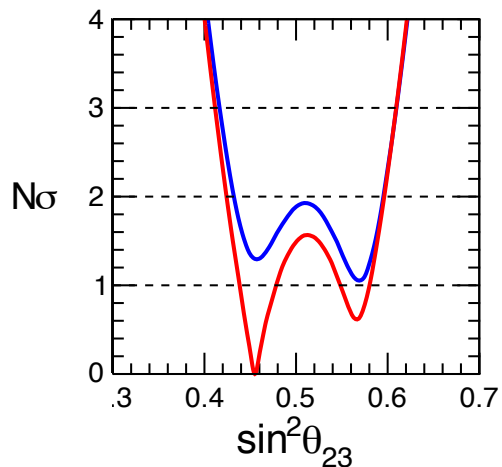
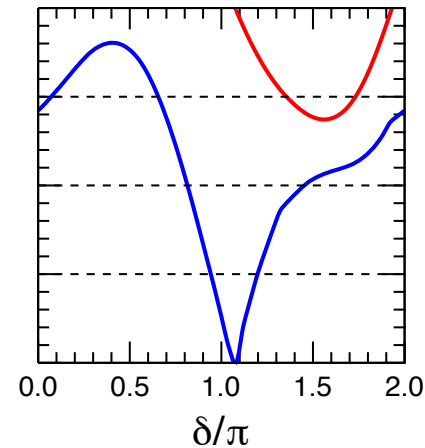
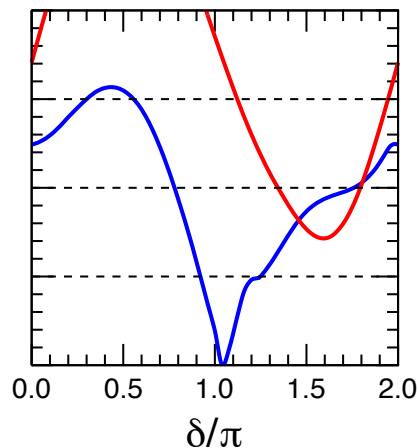
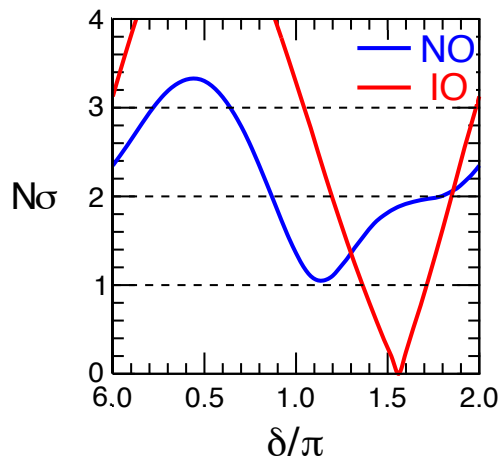
LBL Acc + Solar + KamLAND



+ SBL Reactors



+ Atmos



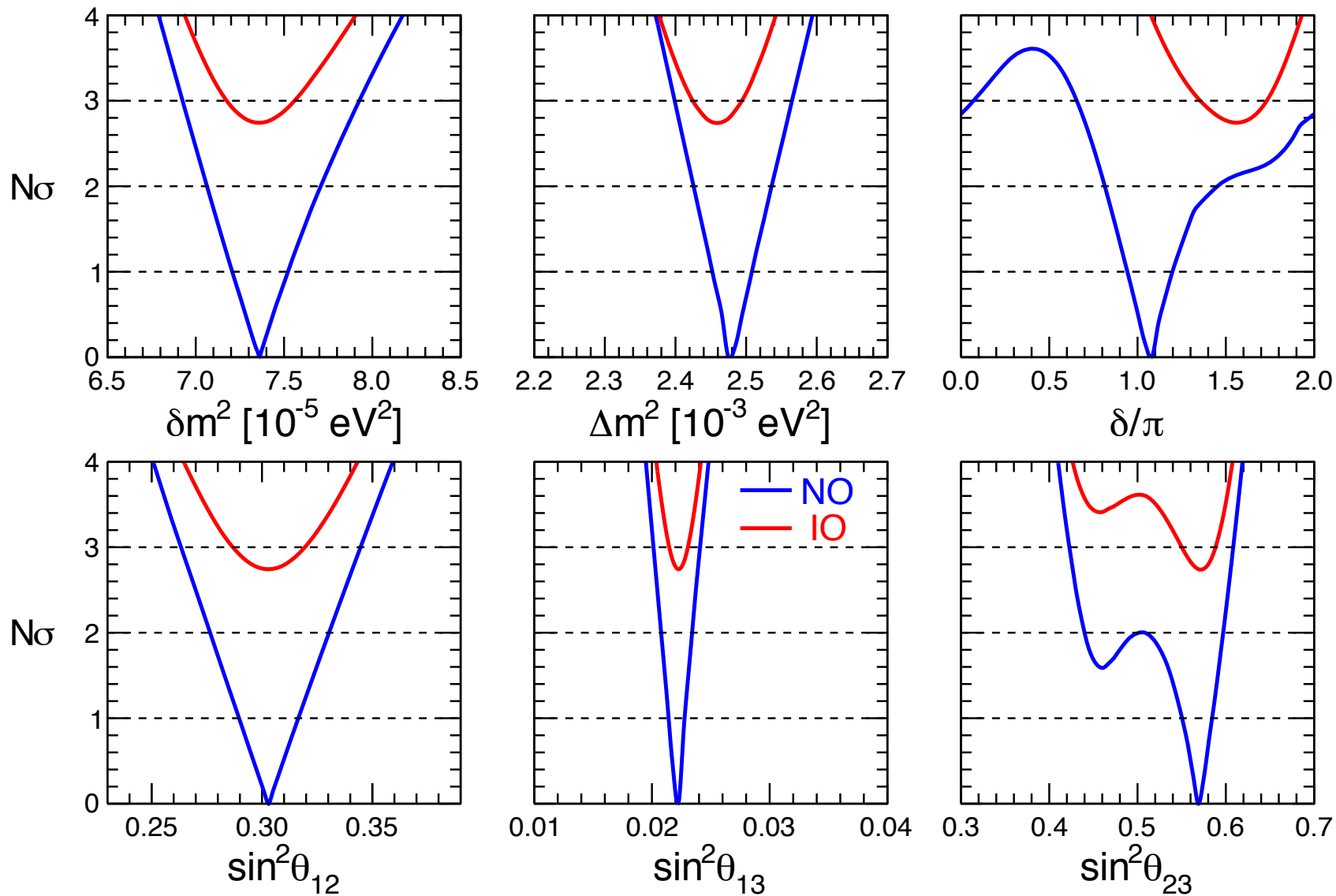
IO favored at $\sim 1\sigma$
 $\delta \sim 3\pi/2$ (**IO**), $\sim \pi$ (**NO**)
 θ_{23} octants \sim degen.

NO favored at $\sim 1.5\sigma$
 $\delta \sim 3\pi/2$ (**IO**), $\sim \pi$ (**NO**)
 2nd octant favored

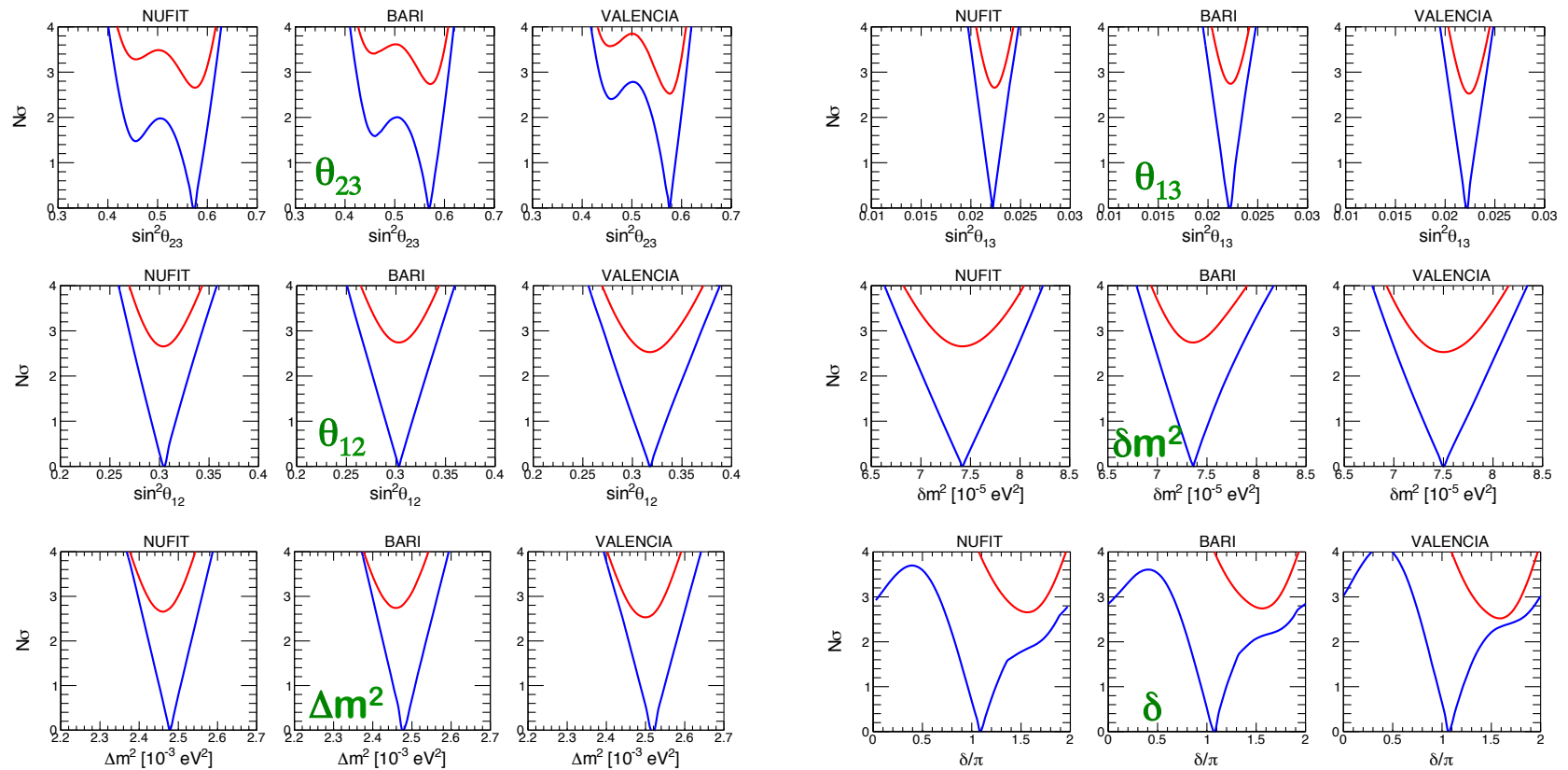
NO favored at $\sim 2.7\sigma$
 $\delta \sim 3\pi/2$ (**IO**), $\sim \pi$ (**NO**)
 2nd octant at $\sim 1.5\sigma$
 (fragile!)

Known and unknown oscillation parameters: global fit

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



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 ” (%)
$\delta m^2/10^{-5} \text{ eV}^2$	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
$ \Delta m^2 /10^{-3} \text{ 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 $\sim 1\%$!

Q1: Why adding SBL reactors flips preference from IO to NO, as these oscill. data are not sensitive to mass ordering?

Q2: δ , NO/IO, θ_{23} octant info: entangled in $\nu_{\mu} \rightarrow \nu_e$ oscillations. What are LBL accelerator expts telling us in this channel?

Q3: Can we really be confident about $\sim 1\%$ accuracy on Δm^2 ?

Answering requires **integrating** different pieces of information:

Covariance of oscillation parameters

Complementarity of different expts

Collaboration among expt & theo

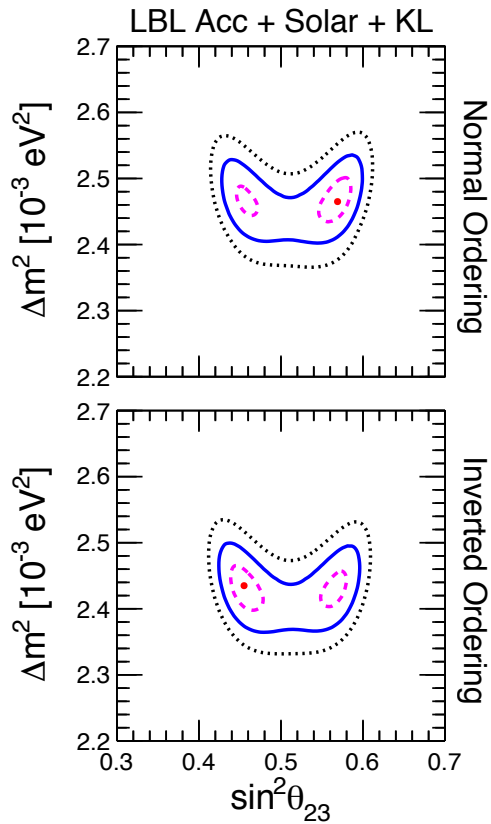
Pairs of parameters

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

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



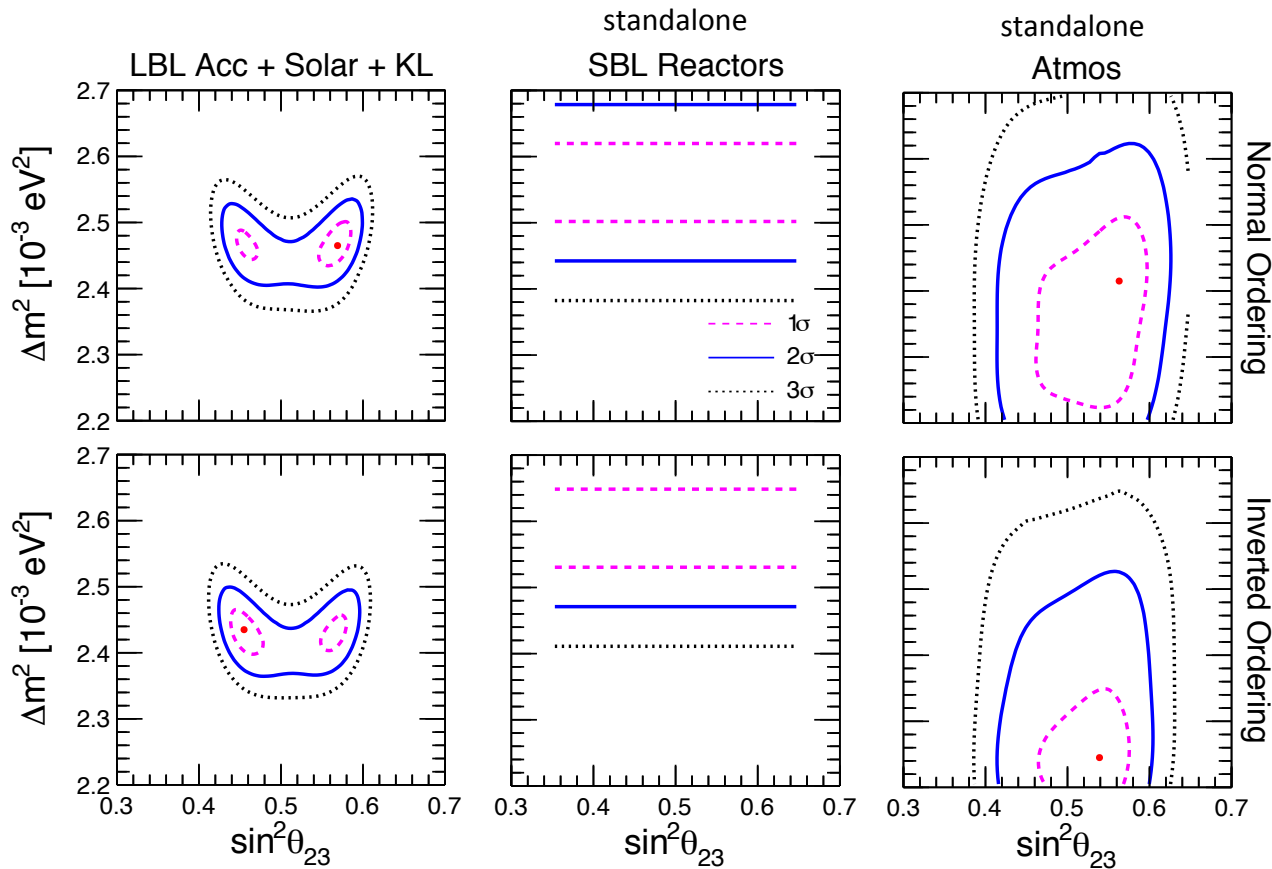
$(\pm\Delta m^2, \theta_{23})$ covariance



LBL accel. data: Best fit value of Δm^2 below $2.5 \times 10^{-3} \text{ eV}^2$.

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

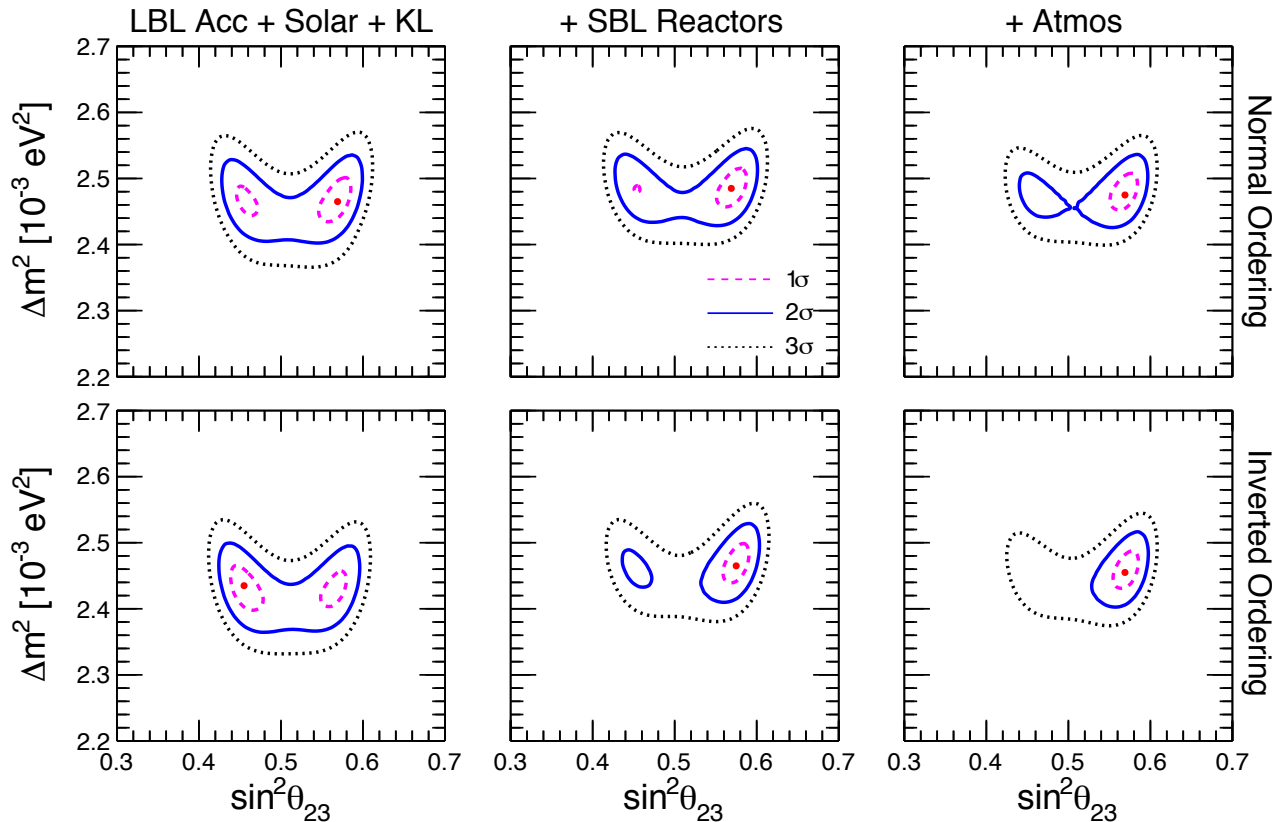
$(\pm\Delta m^2, \theta_{23})$ covariance



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

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

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



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

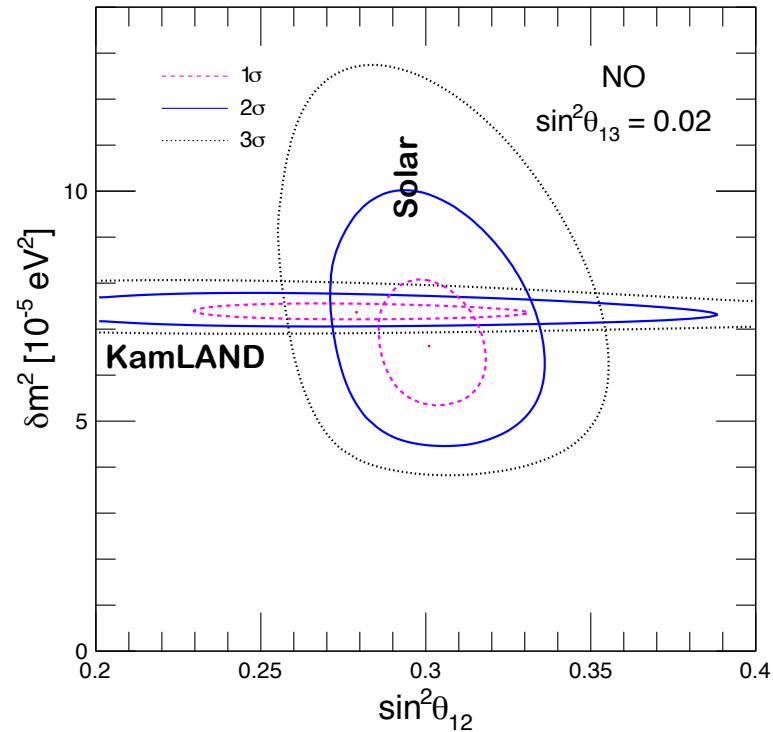
Relative difference is lower for **NO** and for **non-maximal θ_{23} mixing**

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

Accelerator/reactor complementarity at work!

Further complementarity at work:

$(\delta m^2, \theta_{12})$ 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 in solar neutrinos...]

- **trying to avoid distortions and biases...**

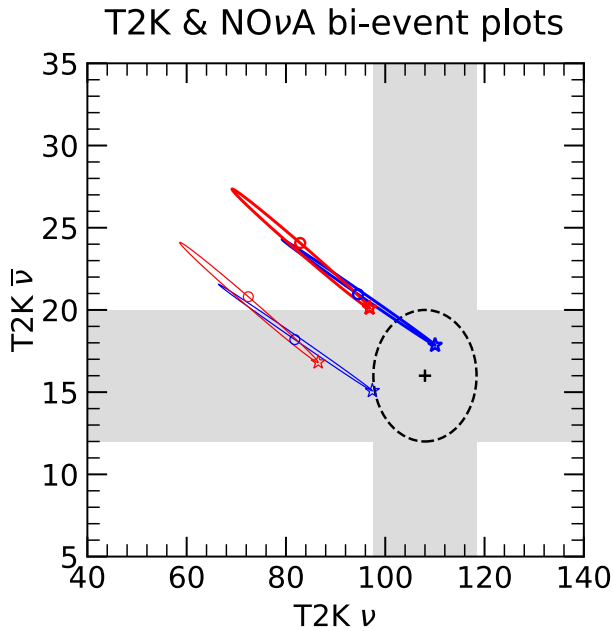
An interesting “data tension” emerges now within LBL accelerators **(T2K vs NOvA)** – whose differences in $\nu_{\mu} \rightarrow \nu_e$ results blur the (previously stronger) preference for NO and for CP violation.

→ 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]



$$s_{23}^2 = \begin{matrix} 0.57 \\ 0.45 \end{matrix} \quad \overline{\text{NO}} \quad \overline{\text{IO}} \quad \delta = \begin{matrix} \pi \\ 3\pi/2 \end{matrix} \begin{matrix} \circ \\ \star \end{matrix}$$

T2K ($\nu+\bar{\nu}$) prefers:

NO

$\delta \sim 3\pi/2$ (\sim max CPV)

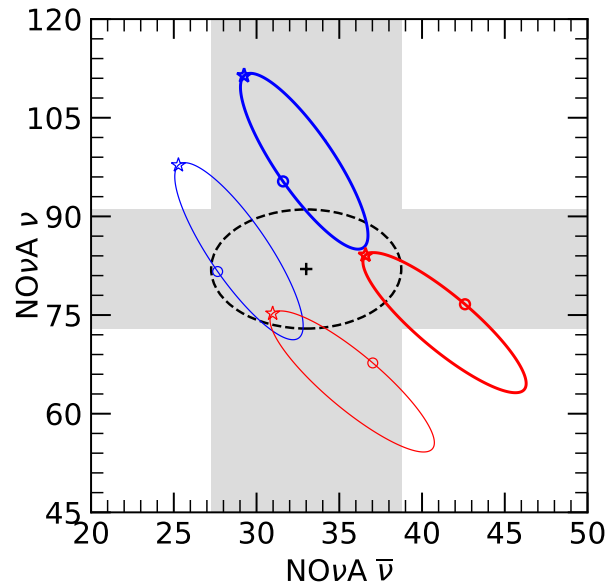
2nd octant

NOVA ($\nu+\bar{\nu}$) prefers:

NO

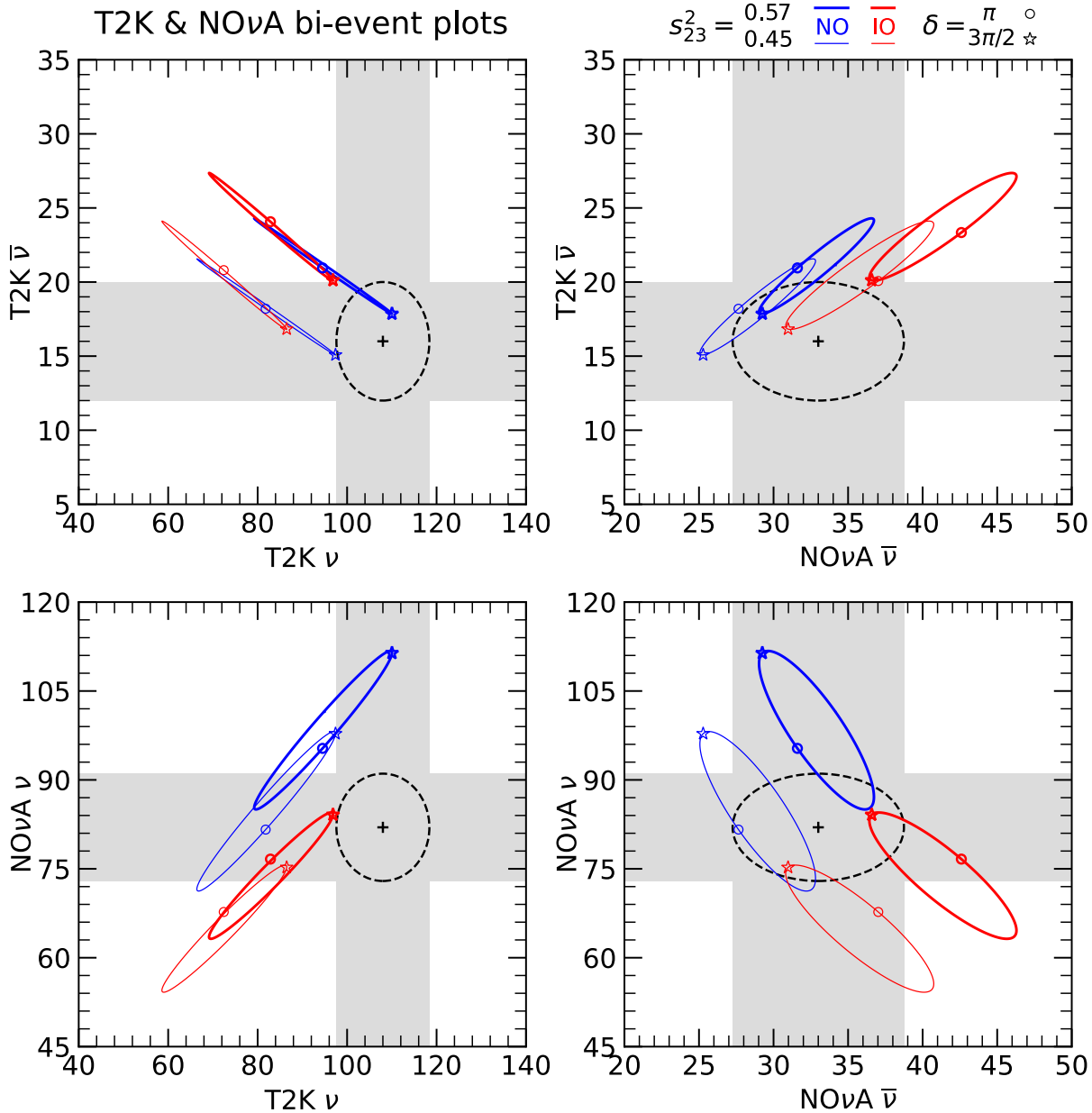
CP conservation

octants \sim degenerate



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

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



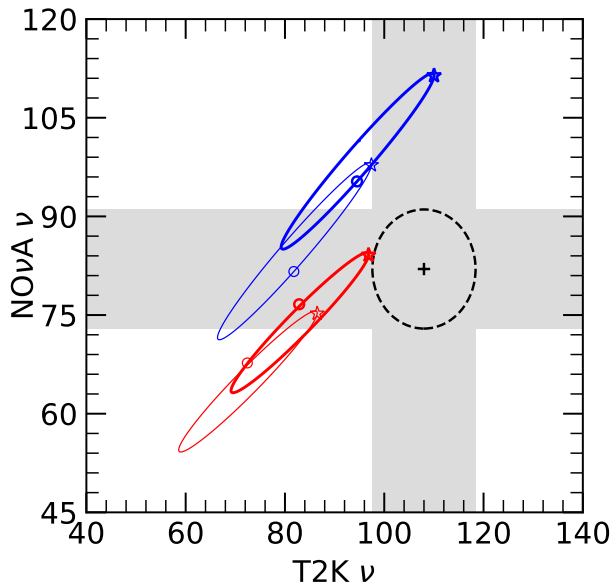
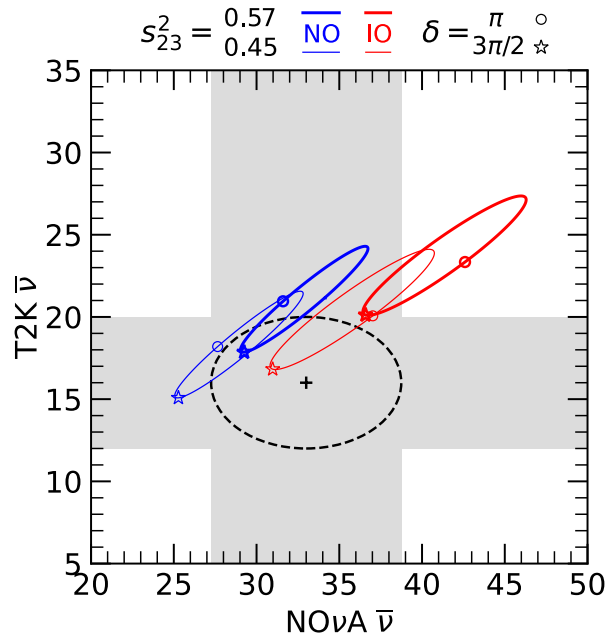
T2K & NOvA bi-event plots

T2K+NOvA (ν) prefer:

IO

$\delta \sim 3\pi/2$

1st octant



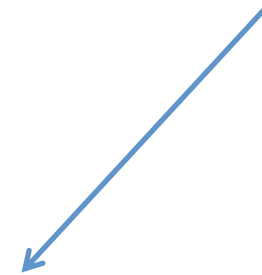
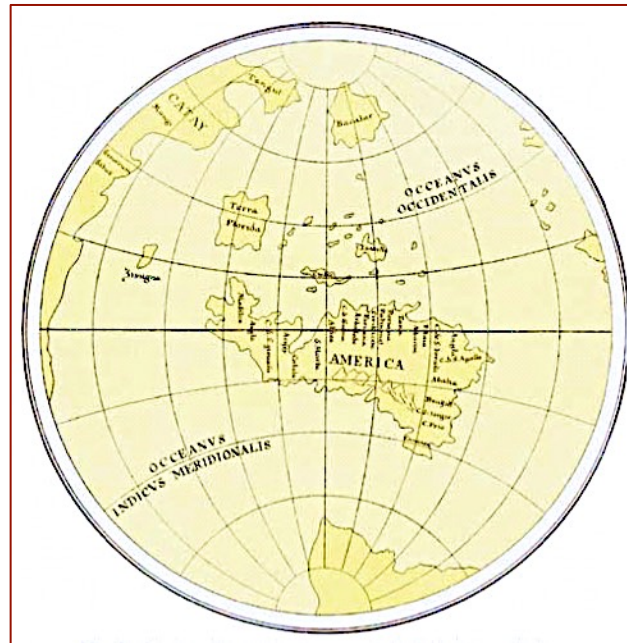
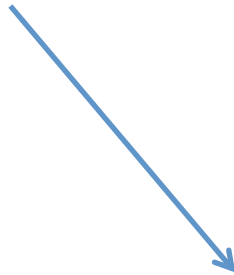
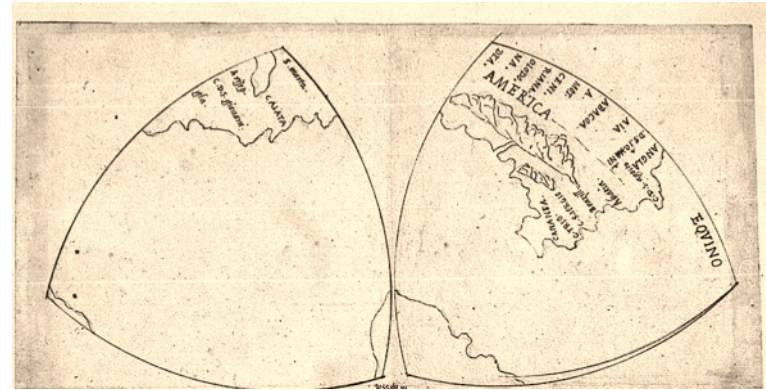
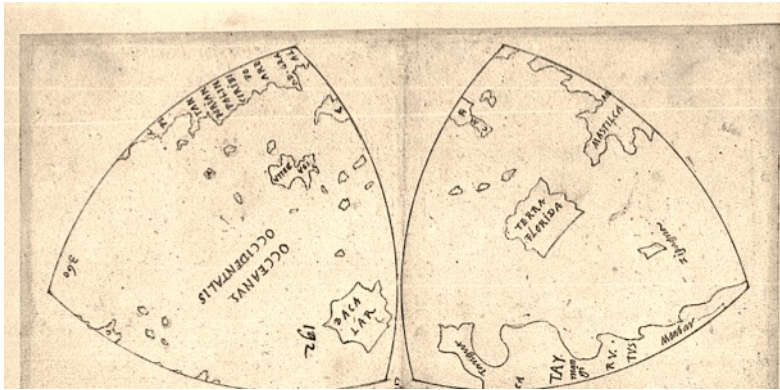
T2K+NOvA ($\bar{\nu}$) prefer:

IO

$\delta \sim 3\pi/2$

2nd octant

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



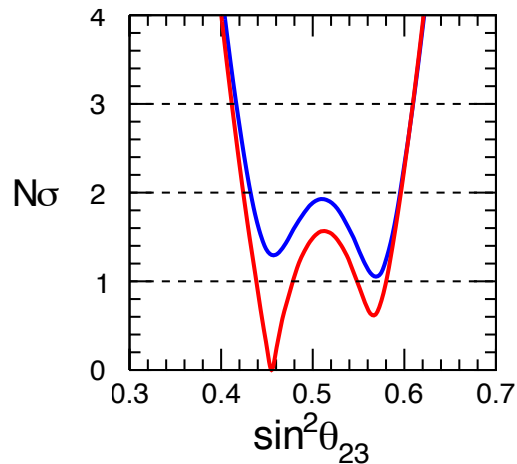
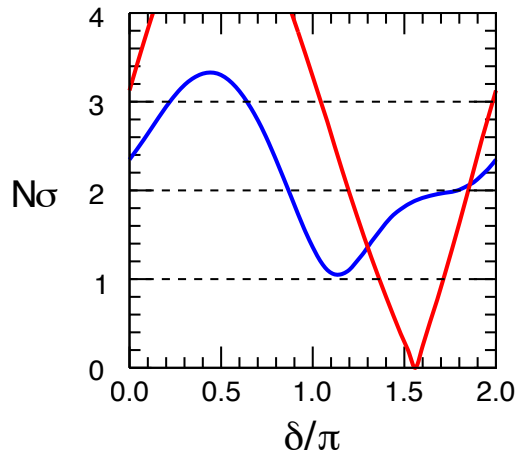
Not yet a clear transition from “*unknown*” to “*known*” subleading effects via $v_\mu \rightarrow v_e \dots$

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

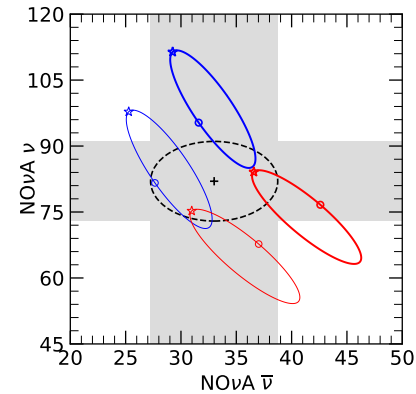
mass ordering (NO vs IO), θ_{23} octant and CP phase δ

Further data may tilt the current balance, or even point to new physics (NSI?)

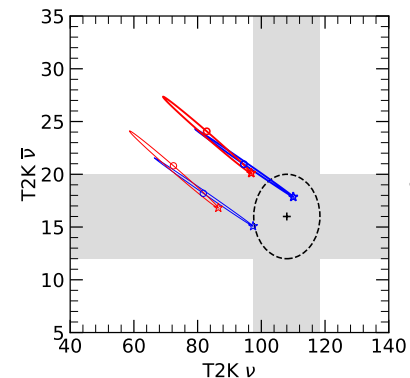
LBL Acc + Solar + KamLAND
(current)



NOvA close to different options within 1σ ...



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

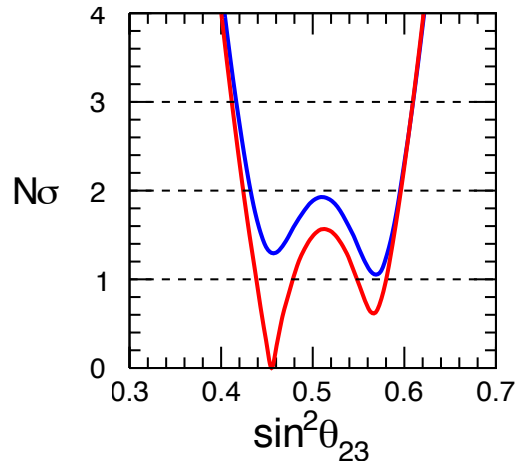
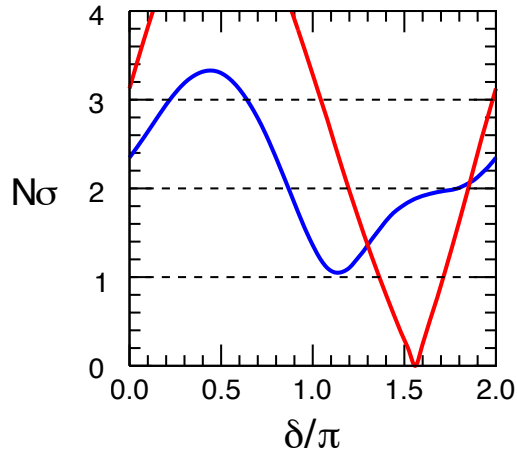


T2K + NOvA Joint analysis?

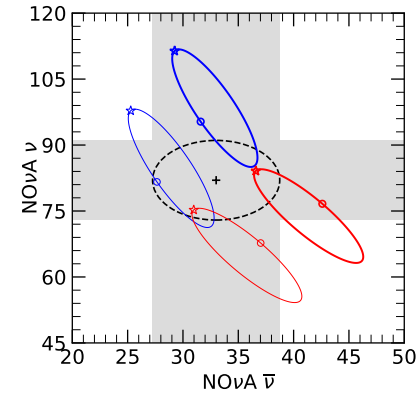
We'll learn a lot more from current LBL accel. (T2K+NOvA) + atmos. expts (SK, IC-DC), final SBL reactor data (DYB, RENO, DC), and future experiments (DUNE, HK, T2HK, IC-lowE upgrade, KM3NeT-Orca, JUNO ...). In the meantime:

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

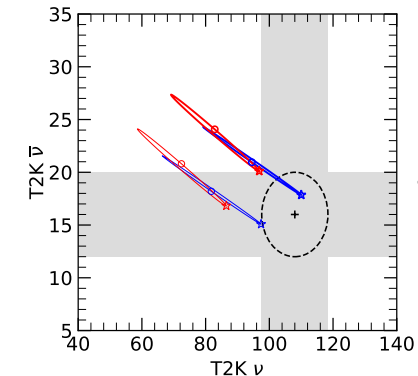
LBL Acc + Solar + KamLAND
(current)



NOvA close to different options within 1σ...



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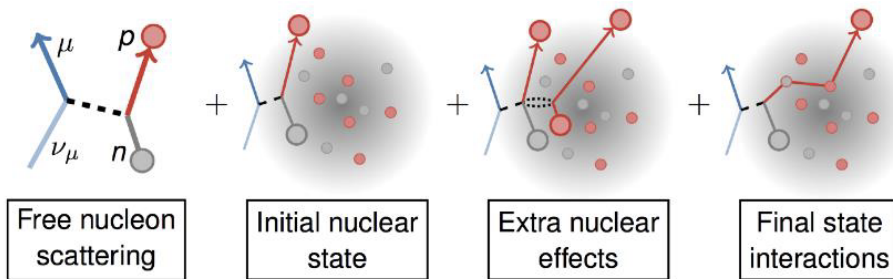


T2K + NOvA Joint analysis?

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

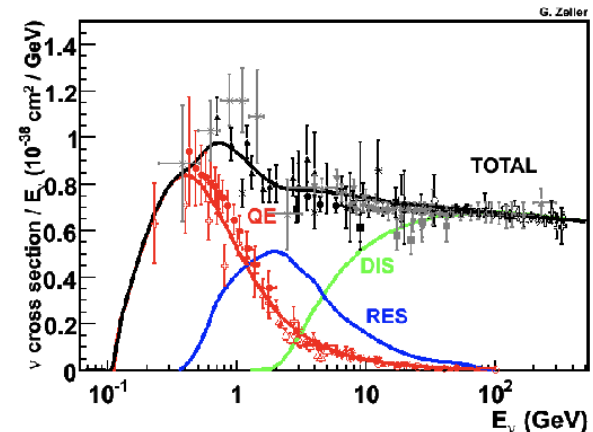
There is a general issue that affects all these (un)knowns:
neutrino interactions in nuclei are not understood as accurately as desired!

Theory: complex nuclear effects



Kajetan Niewczas @ NuFact2018

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.

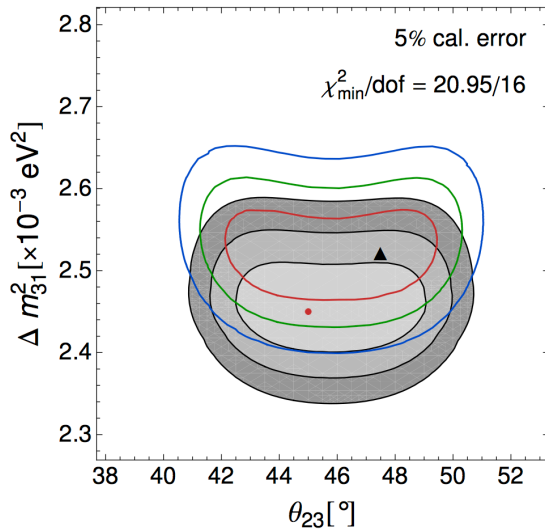
Neutrino-nuclear interactions and LBL accelerator experiments

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:

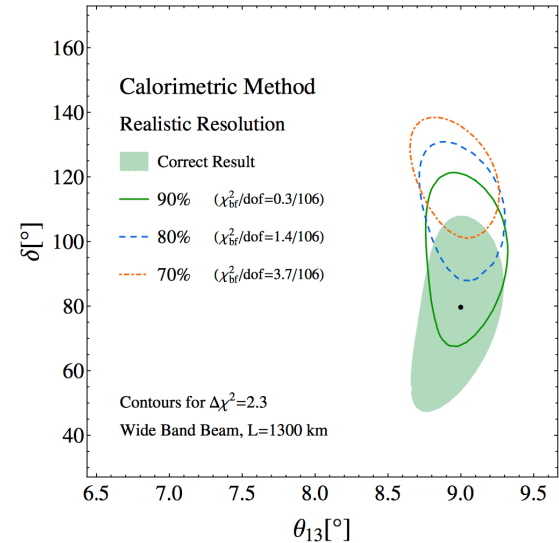
Generate data with one Xsec model and analyze them with a different model



← Biased →
ranges of

Δm^2 , θ_{23}
 δ

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



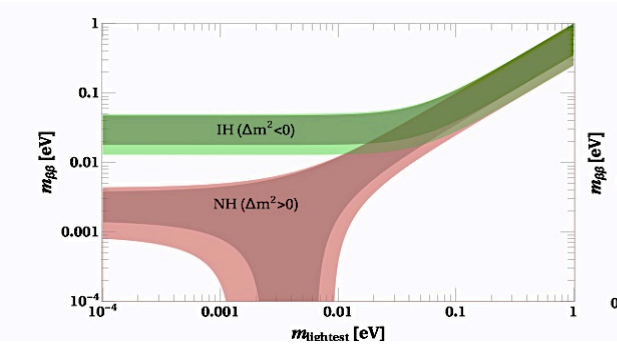
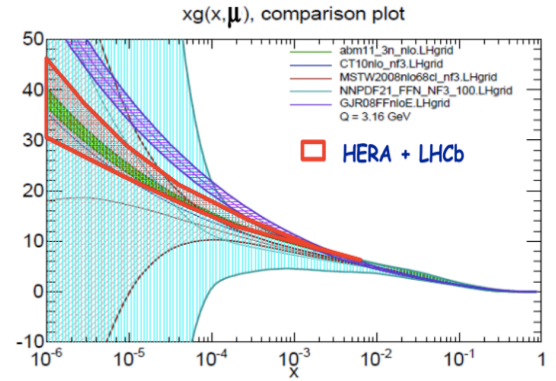
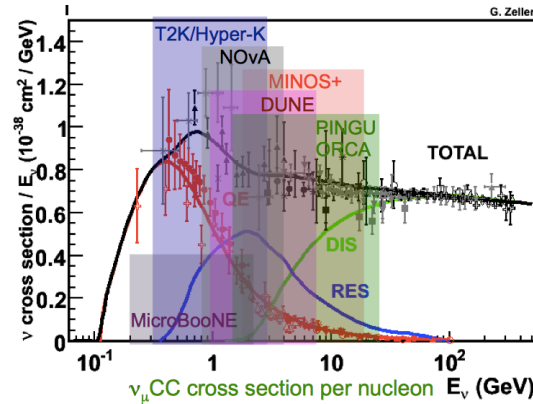
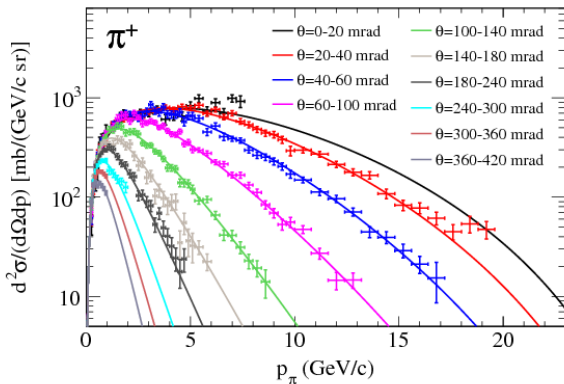
Effects reduced -but not zeroed- by tuning model(s) to ND data.
Remind: No model currently explains all available Xsection data!
Current 1% global-fit formal accuracy on Δm^2 might be optimistic

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

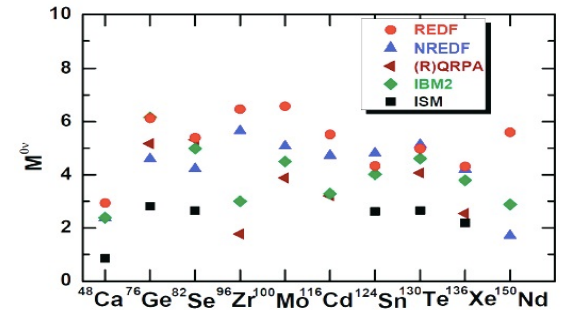
Need hadron production data, e.g. $pA \rightarrow \pi X$, +theory models to improve estimates of atm. and acceler. ν fluxes and errors

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 \sim 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 more COOPERATION from different EXPT+THEO communities:
→ emerging field of “Electroweak Nuclear Physics”; needs support!

There is much more than just cross sections for LBL accel. expts!

Need to know better the nuclear response to EW probes in various contexts

Beta decays for nuclear reactor spectra

Coherent Elastic Neutrino
Nucleus Scattering

Charge exchange processes for DBD NME

Neutrinos in very dense fermion
backgrounds (SN, mergers, early universe)

Effective neutrino axial current:
coupling strength and form factors

Nuclear astrophysics and neutrinos
(nucleosynthesis & solar reactions networks)

EFT vs QCD

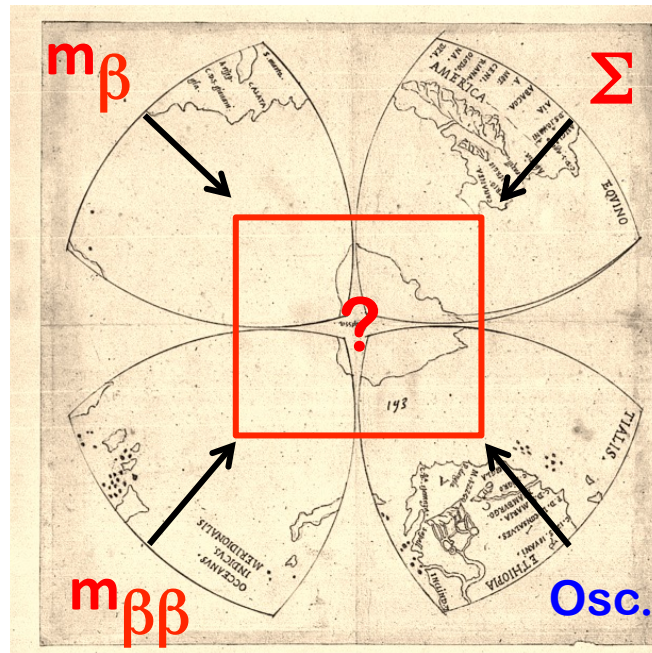
Ab initio nuclear structure

Connections with other EW probes
(gammas, electron, possible WIMPs...)

- 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

Absolute n masses ($m_i?$) and Dirac/Majorana nature ($\nu=\bar{\nu}?$):

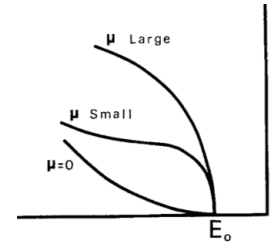
→ The last 3ν unknowns & their observables (m_β , $m_{\beta\beta}$, Σ)



(m_β , $m_{\beta\beta}$, Σ)

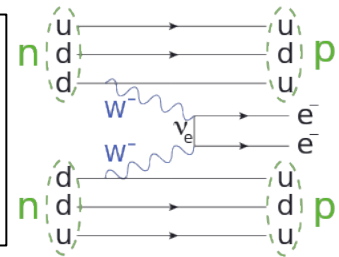
β decay, sensitive to the “effective electron neutrino mass”:

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



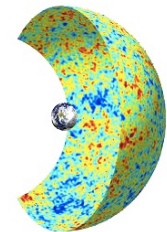
$0\nu\beta\beta$ decay: only if Majorana. “Effective Majorana mass”:

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



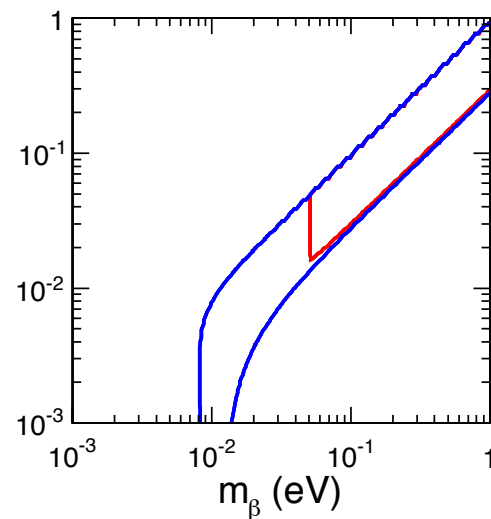
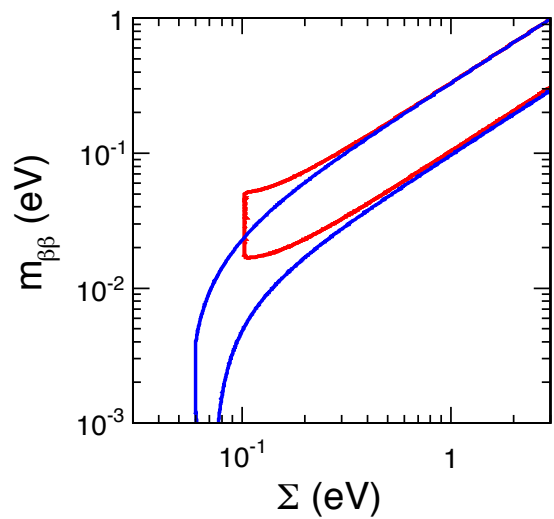
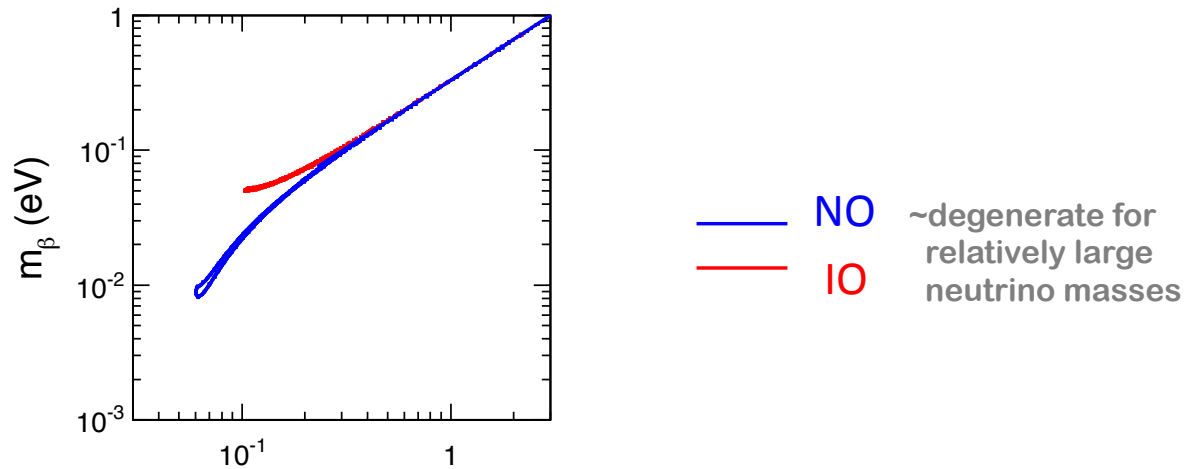
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



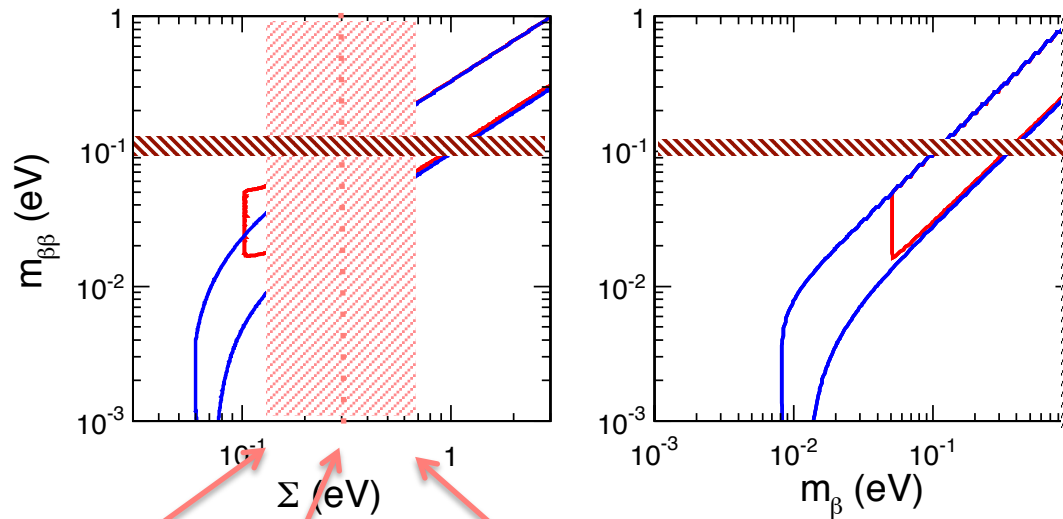
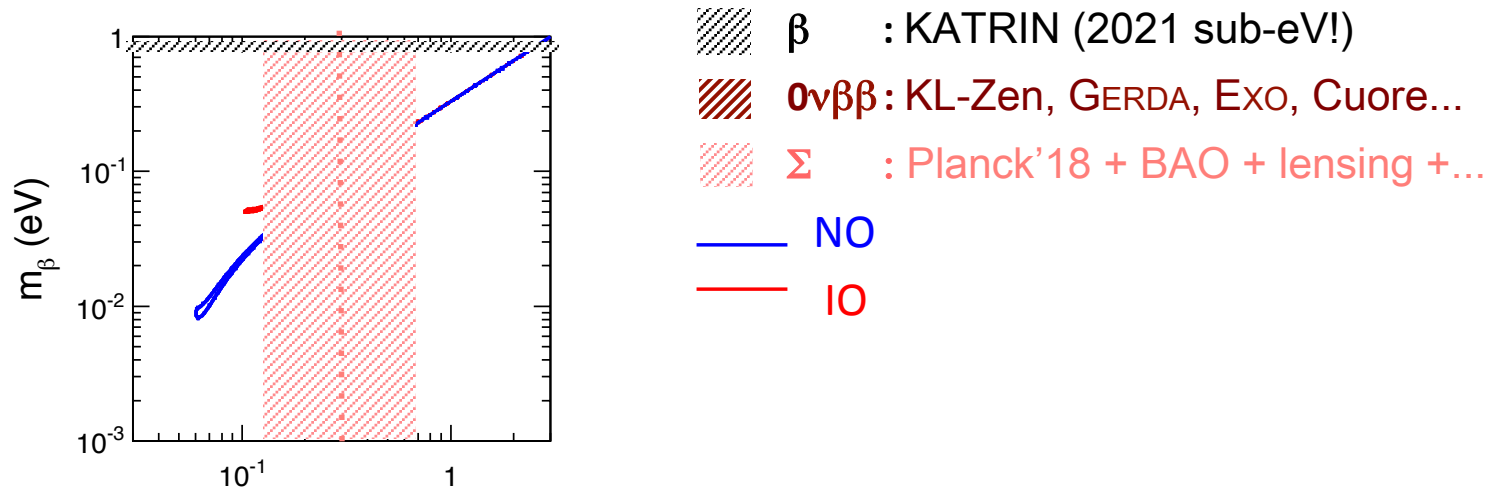
- Note 1: These observables may provide handles to distinguish NO/IO.
 2: Majorana case gives a new source of CPV (unconstrained)
 3: The three observables are correlated by oscillation data →

Impact of oscillations on non-oscillation parameter space



\updownarrow
 $m_{\beta\beta}$ 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.)

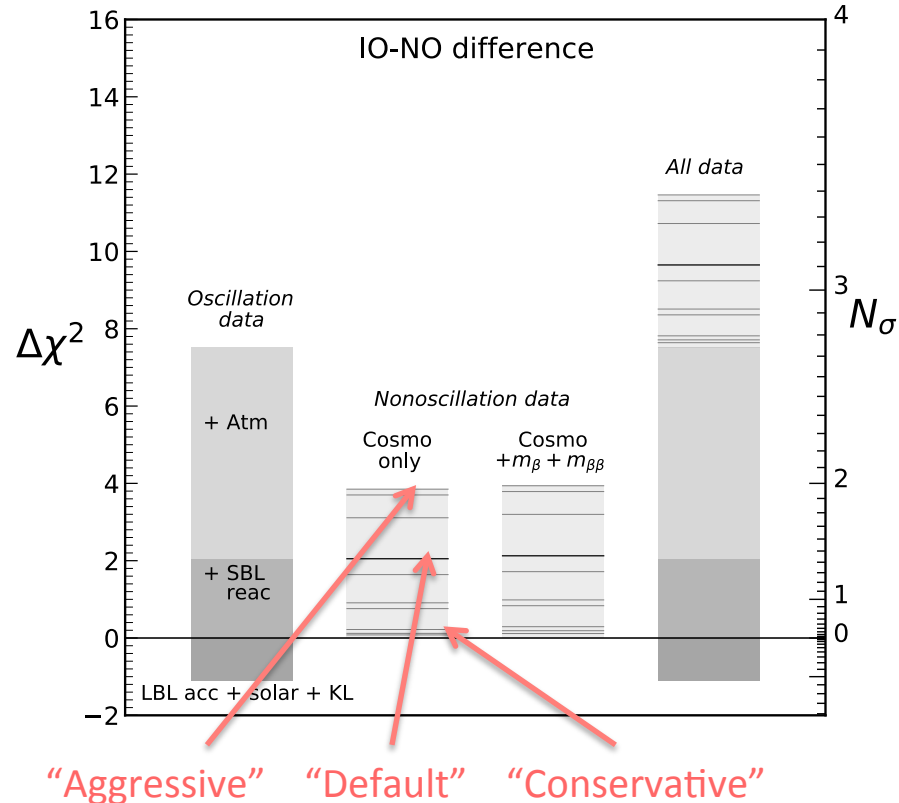


“Aggressive” “Default” “Conservative” cosmological limits

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

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

Update of 2003.08511 for this Colloquium:



Cosmo data can add from ~ 0 to $\sim 0.7\sigma$ to the $\sim 2.7\sigma$ oscillation preference for NO

→ overall $\sim 2.7\text{--}3.4\sigma$ hint for NO vs IO

[Work in progress: more emphasis on “conservative” cosmo cases]

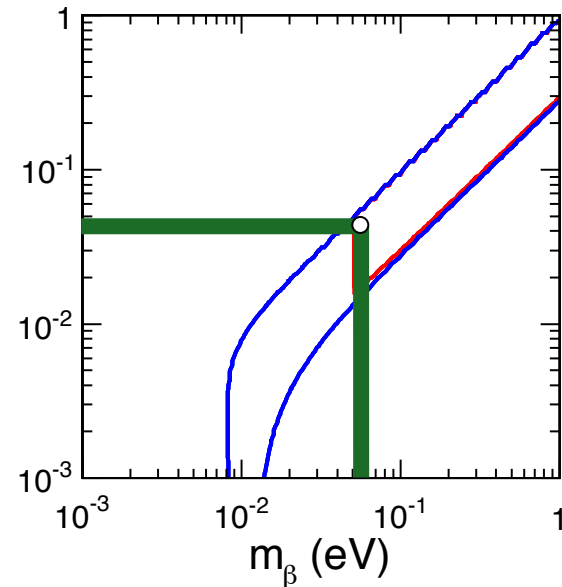
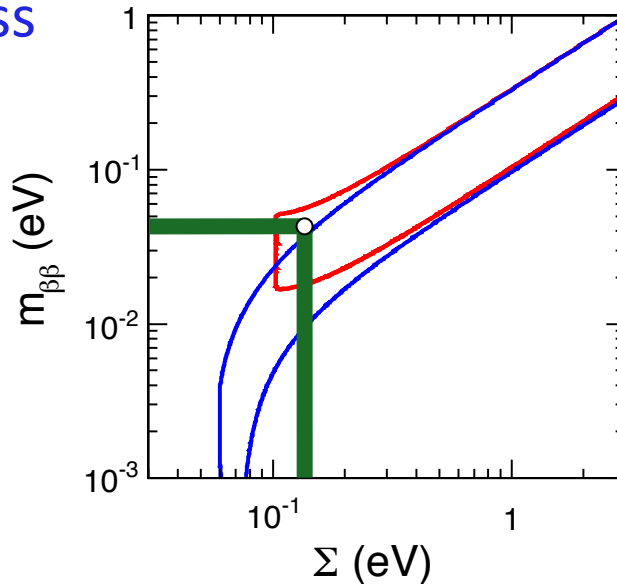
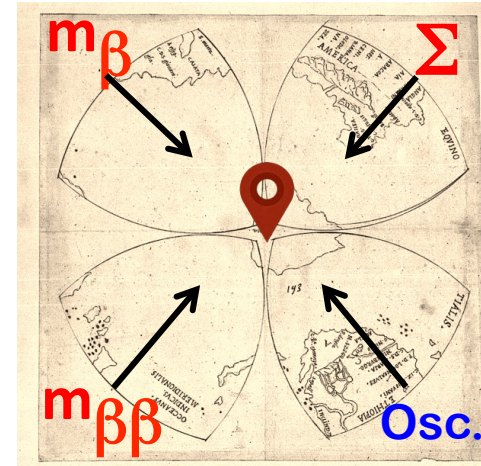
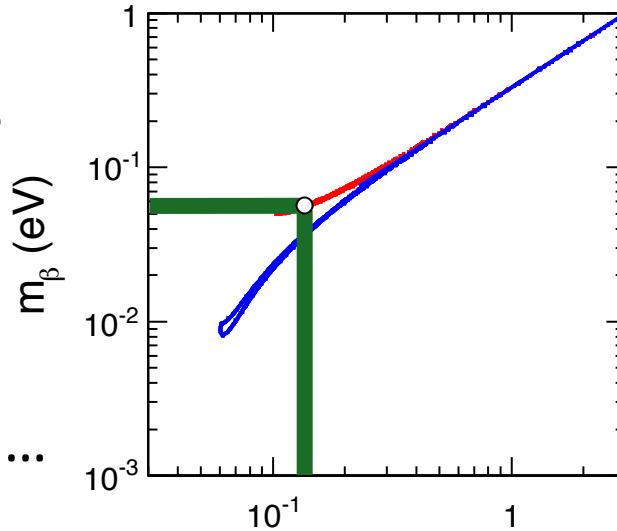
Far future: with precise and converging non-oscillation signals one could...

Determine the mass scale...

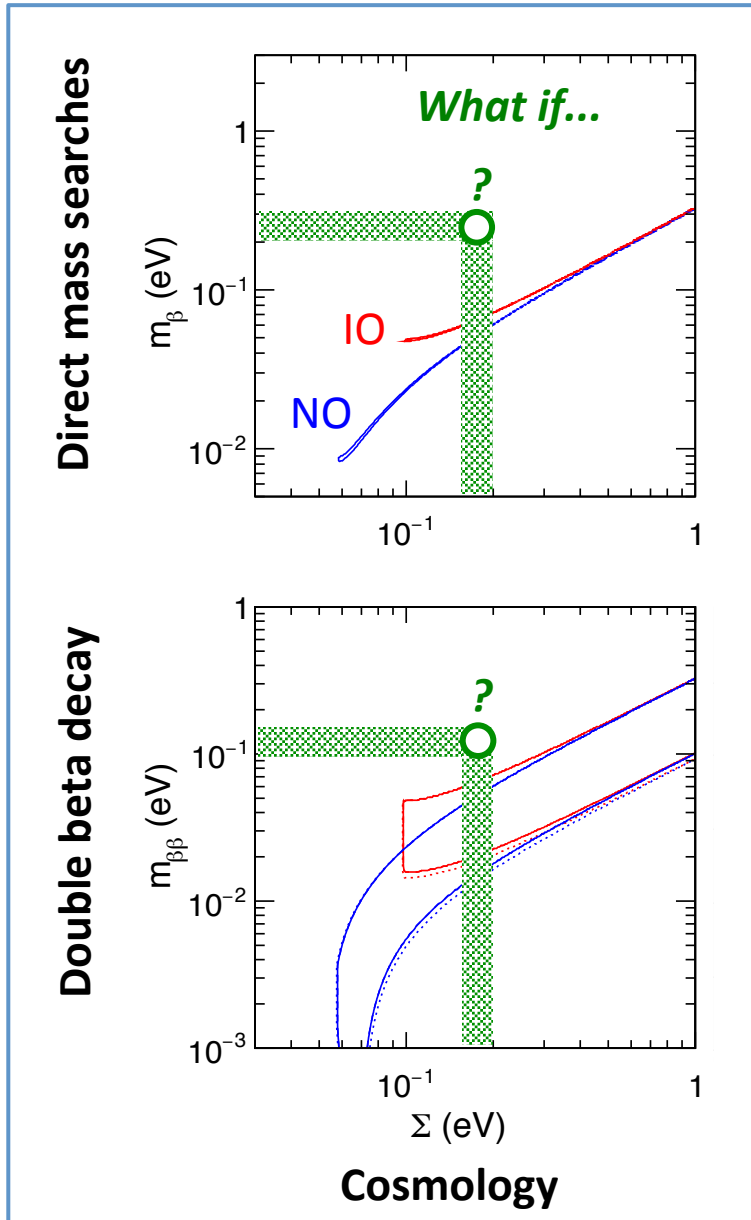
Check 3ν consistency ...

Identify mass ordering ...

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 Λ CDM*
- *New neutrino states*
- *New interactions*
- *Nonstandard ν properties*
- *New phenomena in propagation*
- ...

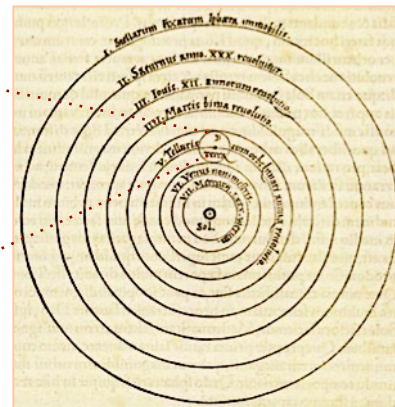
Main contender in current ν physics:
Light sterile ν at $O(\text{eV})$ scale
(Would require another colloquium...)

Towards the Epilogue...

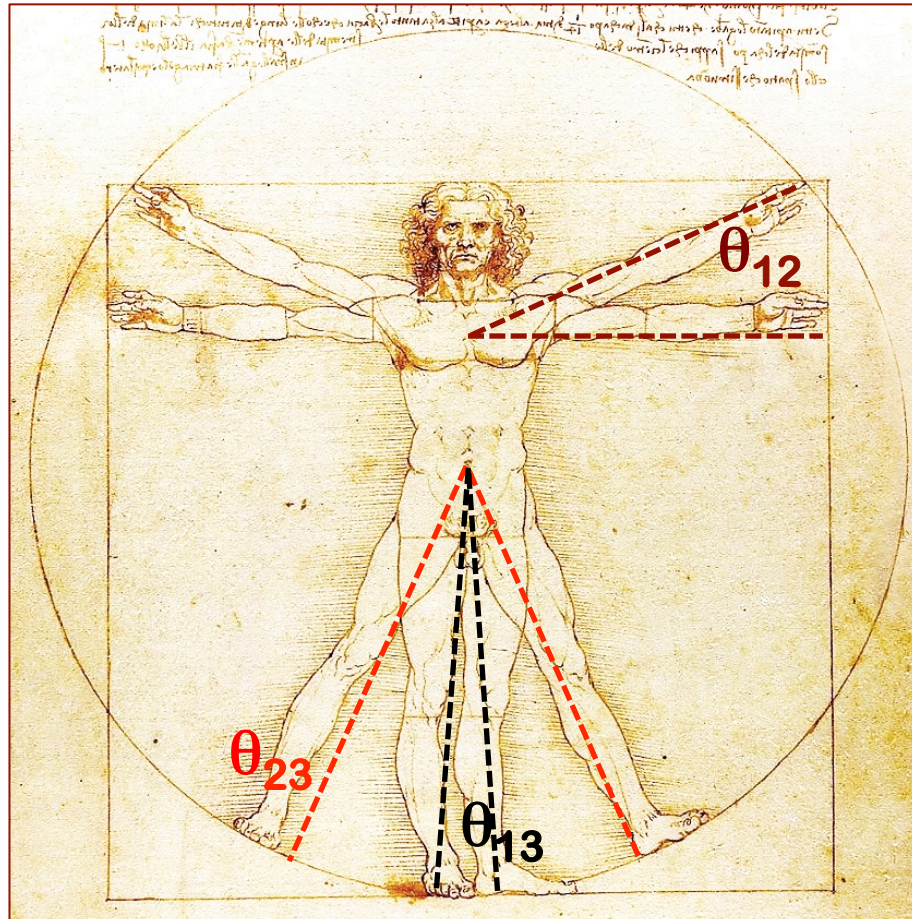
- being excited by a series of discoveries
- charting the newly discovered territories
- trying to avoid distortions and biases
- **seeking unknown lands and a bigger picture**



?



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 symmetries
 (“geometry”)

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

Continuous flavor symmetries
 (“dynamics”)

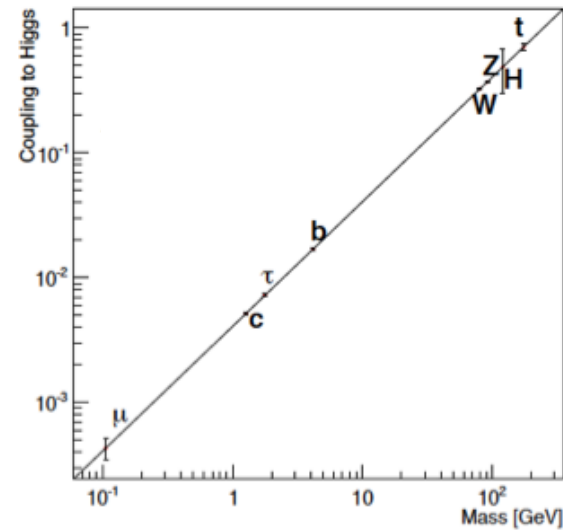
links between neutrino
masses/angles/phases

Common quark/lepton features
 (“complementarity”)

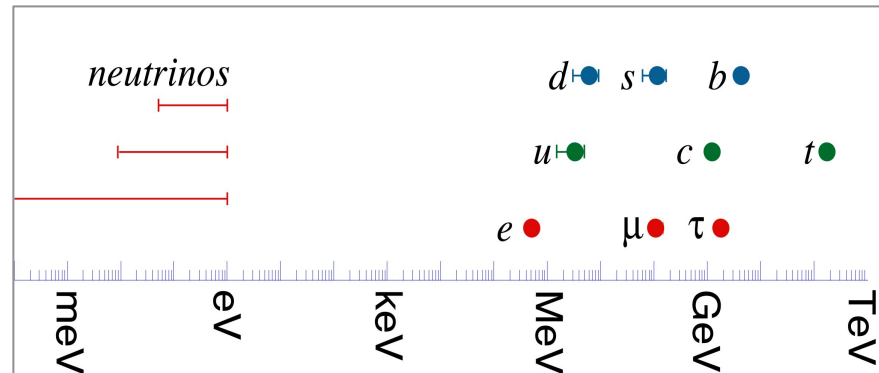
links between
 θ_{13} and θ_C

Masses: Linking two fundamental research expeditions

1. Test Higgs sector

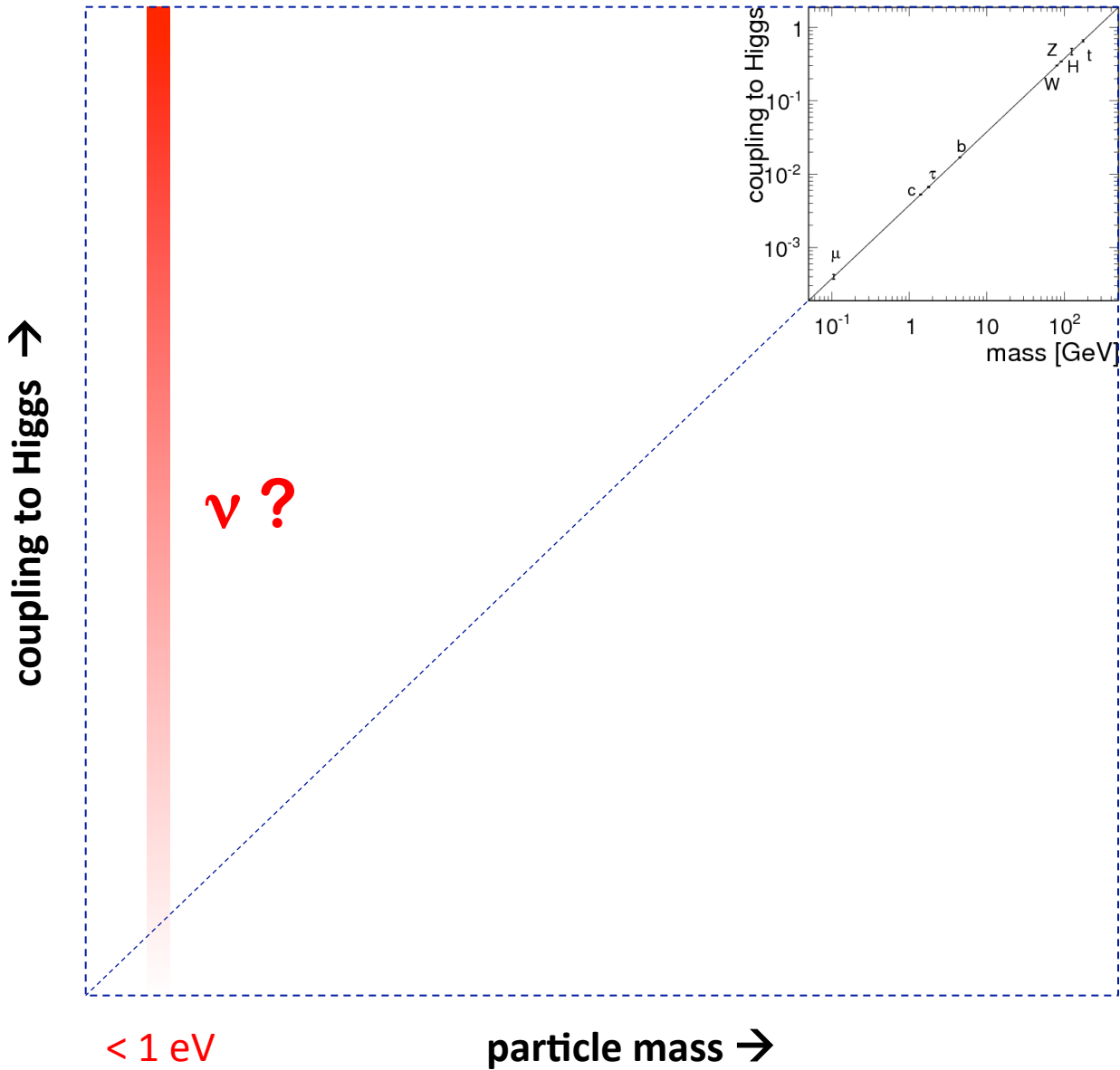


2. Fix ν masses

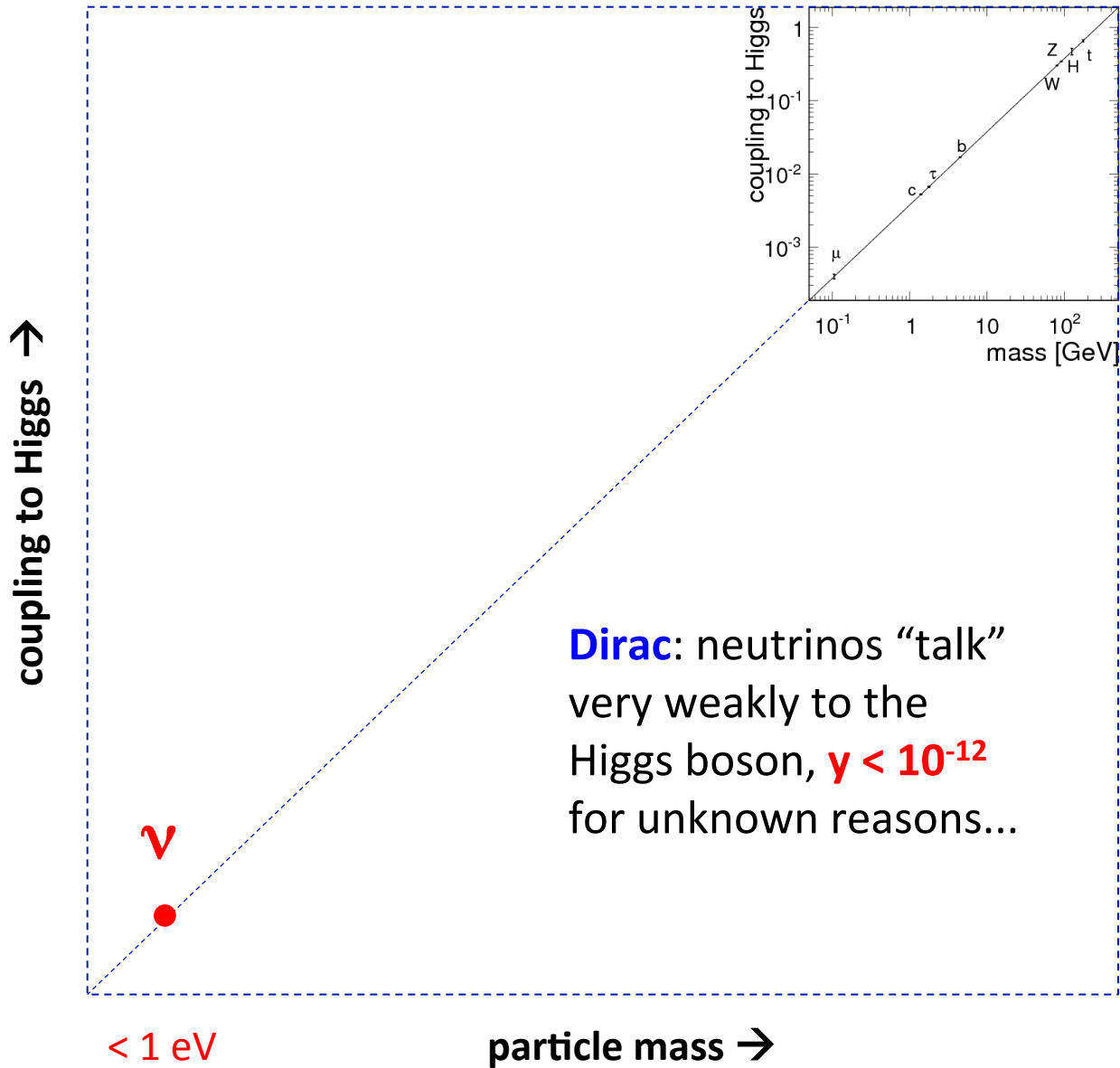


1 + 2

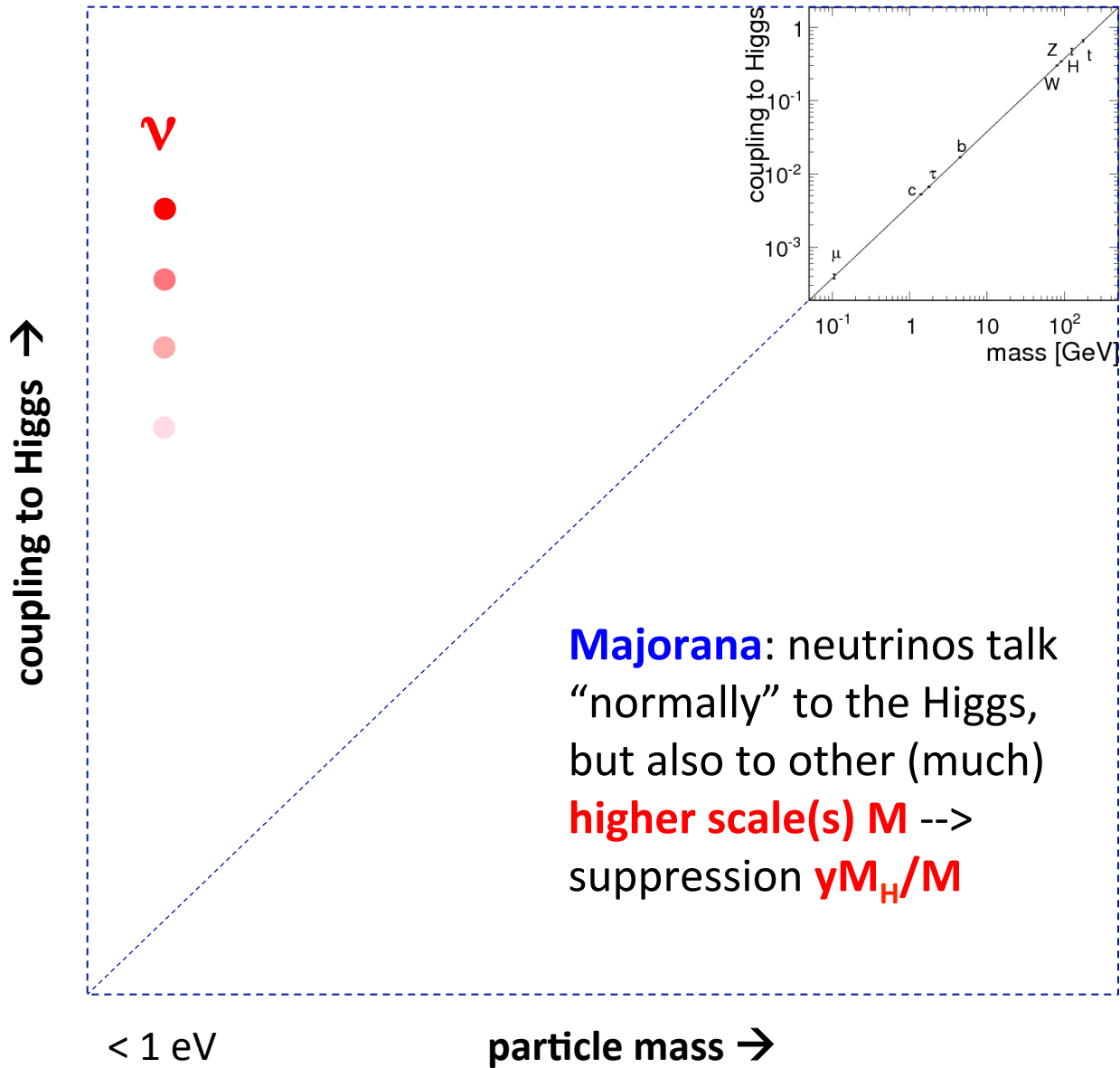
Where are the ν 's on this plot? Why are they so light?



Options:

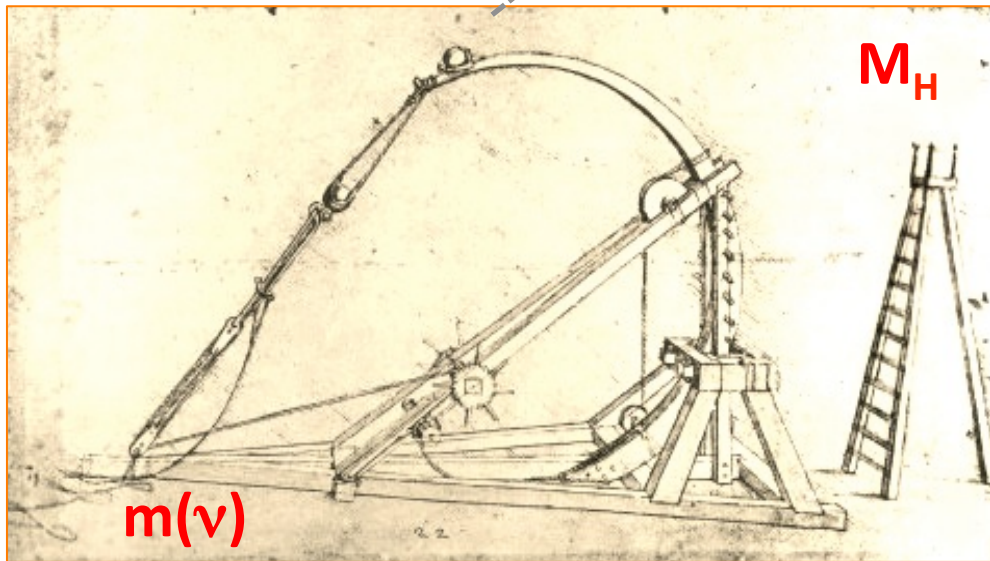


Options:



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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Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.



$M \sim$ 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

$$\delta m^2 \sim 7 \times 10^{-5} \text{ eV}^2$$

$$\Delta m^2 \sim 2 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{12} \sim 0.3$$

$$\sin^2 \theta_{23} \sim 0.5$$

$$\sin^2 \theta_{13} \sim 0.02$$

3ν Terra Cognita...



Epilogue

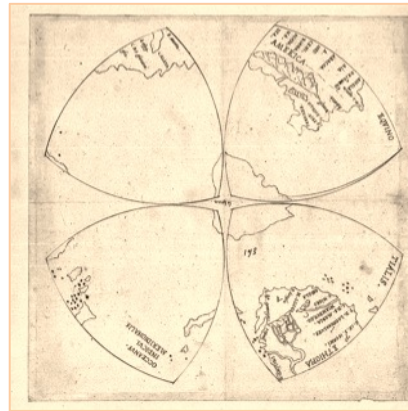
$$\begin{aligned}\delta m^2 &\sim 7 \times 10^{-5} \text{ eV}^2 \\ \Delta m^2 &\sim 2 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \theta_{12} &\sim 0.3 \\ \sin^2 \theta_{23} &\sim 0.5 \\ \sin^2 \theta_{13} &\sim 0.02\end{aligned}$$

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

3ν Terra Cognita...



3ν Terra Incognita...



Epilogue

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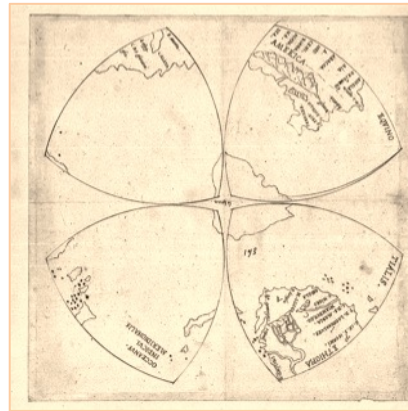
δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute masses
Dirac/Majorana

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

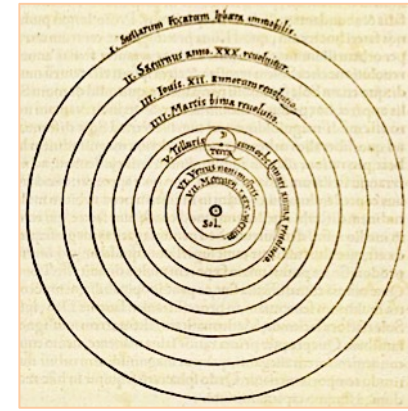
3ν Terra Cognita...



3ν Terra Incognita...



... and beyond



Epilogue

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

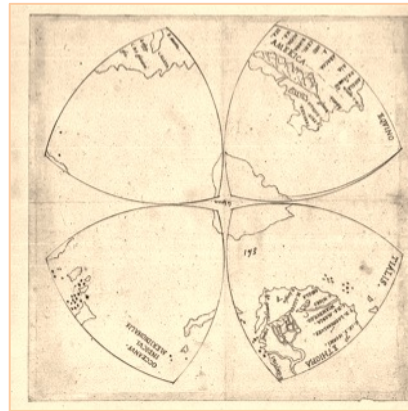
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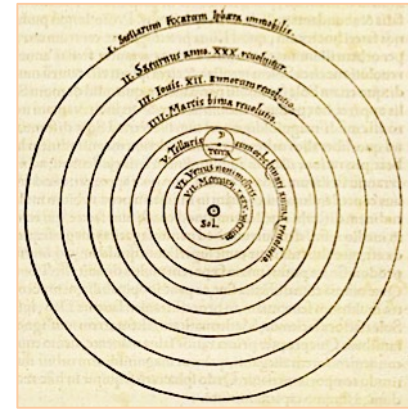
3ν Terra Cognita...



3ν Terra Incognita...



... and beyond



Thank you for your attention