Neutrino masses, mixings & Electroweak Nuclear Physics

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OUTLINE:

Status of the 3ν paradigm

The role of nuclear physics

A suggestion for this field

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Status of the 3ν paradigm

The role of nuclear physics

A suggestion for this field

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

Knowns:

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

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

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

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

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

Unknowns:

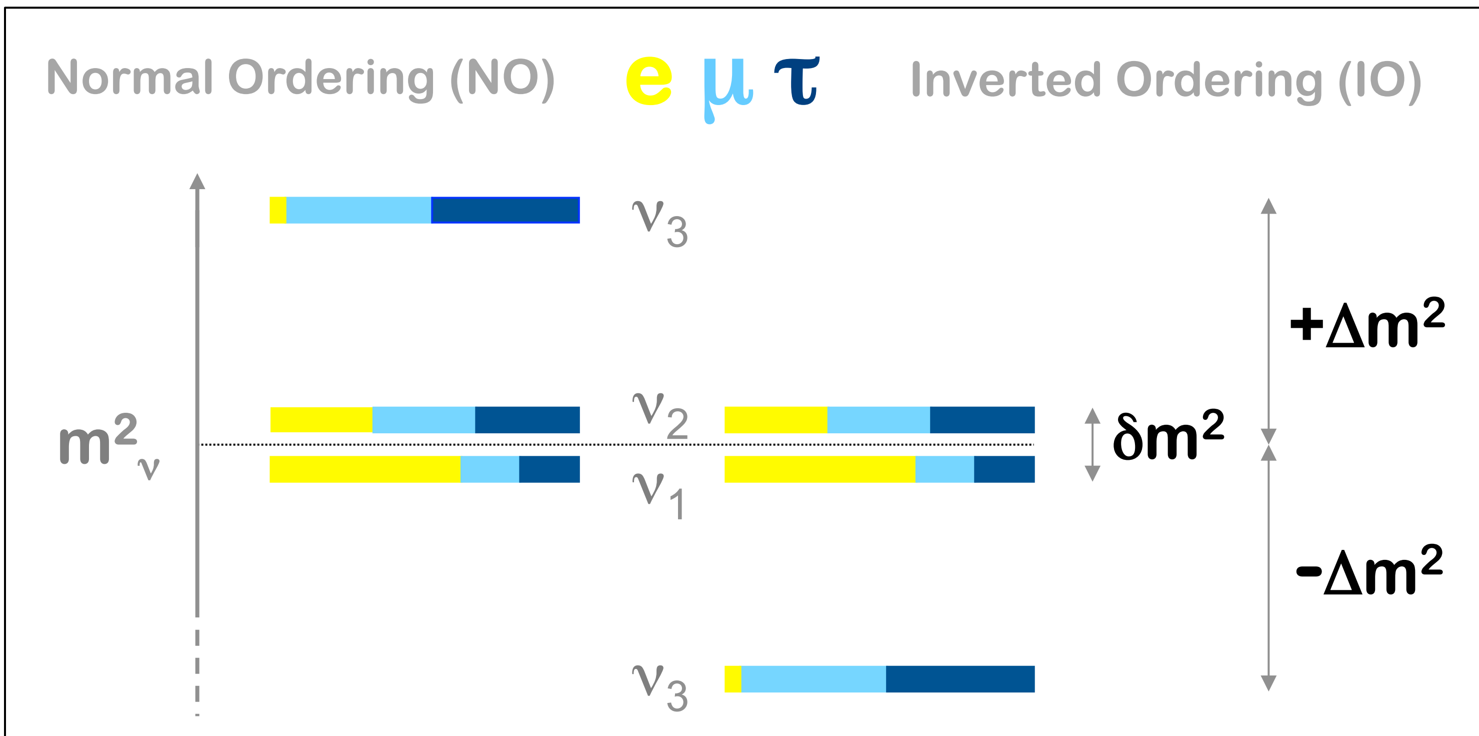
δ = Dirac CPV phase

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: 1804.09678 by F. Capozzi, E. Lisi, A. Marrone, A. Palazzo, PPNP 102, 48 (2018)

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**.

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

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 $|A/\Delta m^2| \sim 0.2$,

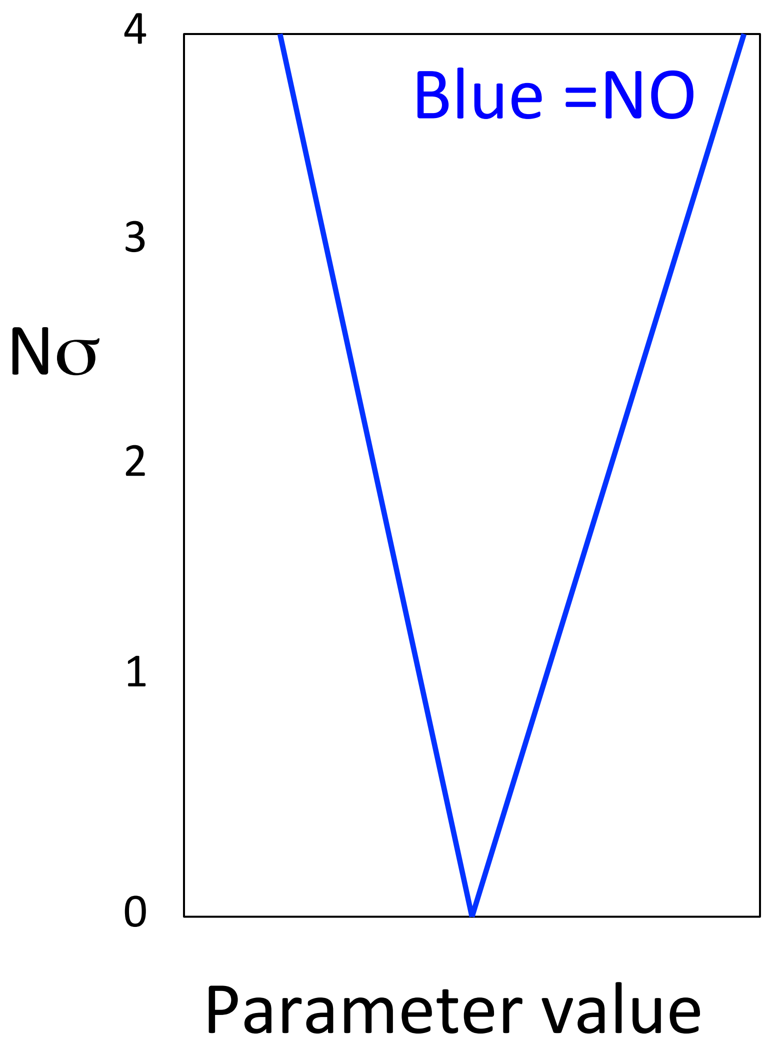
[Hereafter: $\Delta m^2 = (\Delta m^2_{31} + \Delta m^2_{32})/2$]

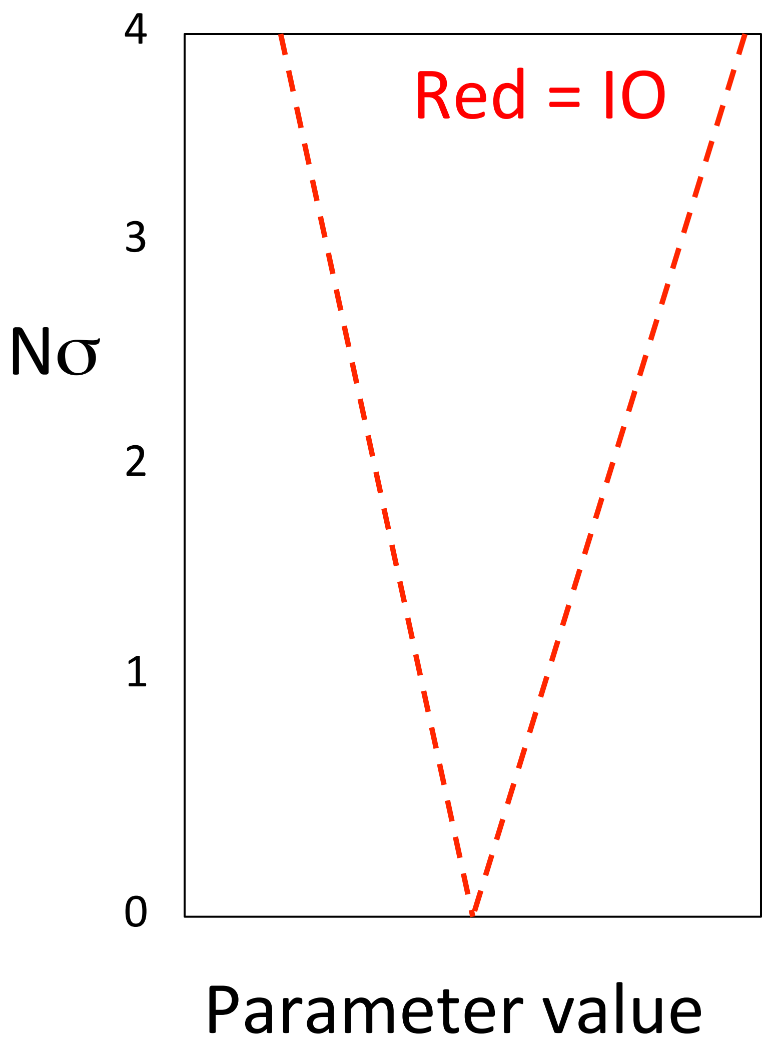
SBL reactors (Daya Bay, RENO, Double Chooz) are dominantly sensitive to (Δm^2 , θ_{13}) and shrink the θ_{13} range dramatically, with correlated effects on the other parameters

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.**

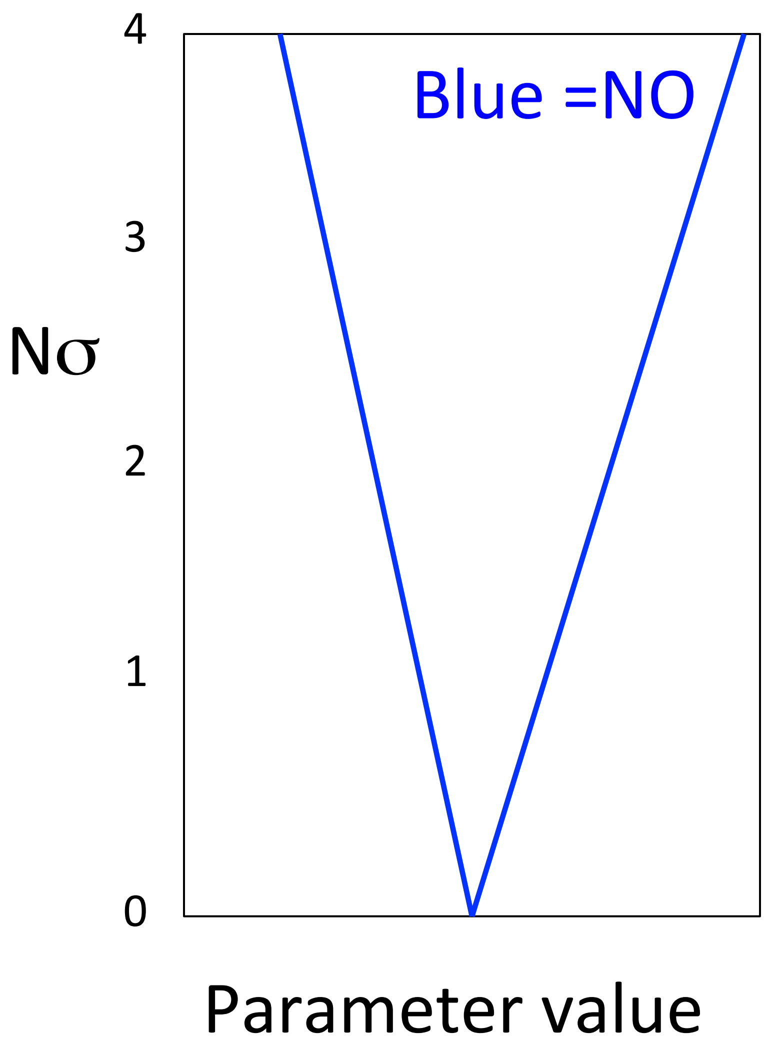
Relevant new result (2017-2018): Hints for CPV and Normal Ordering (NO)

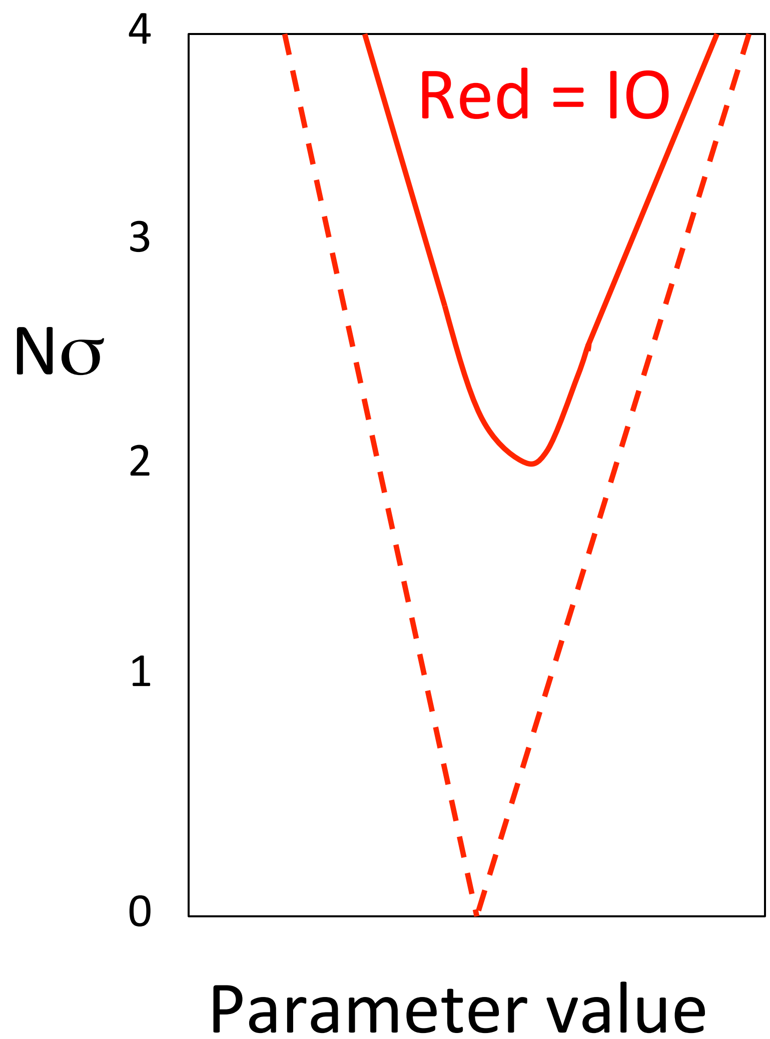
In the following figures: Typical bounds would be ~linear and symmetric for ~gaussian errors around the **separate best fits for both NO and IO.**



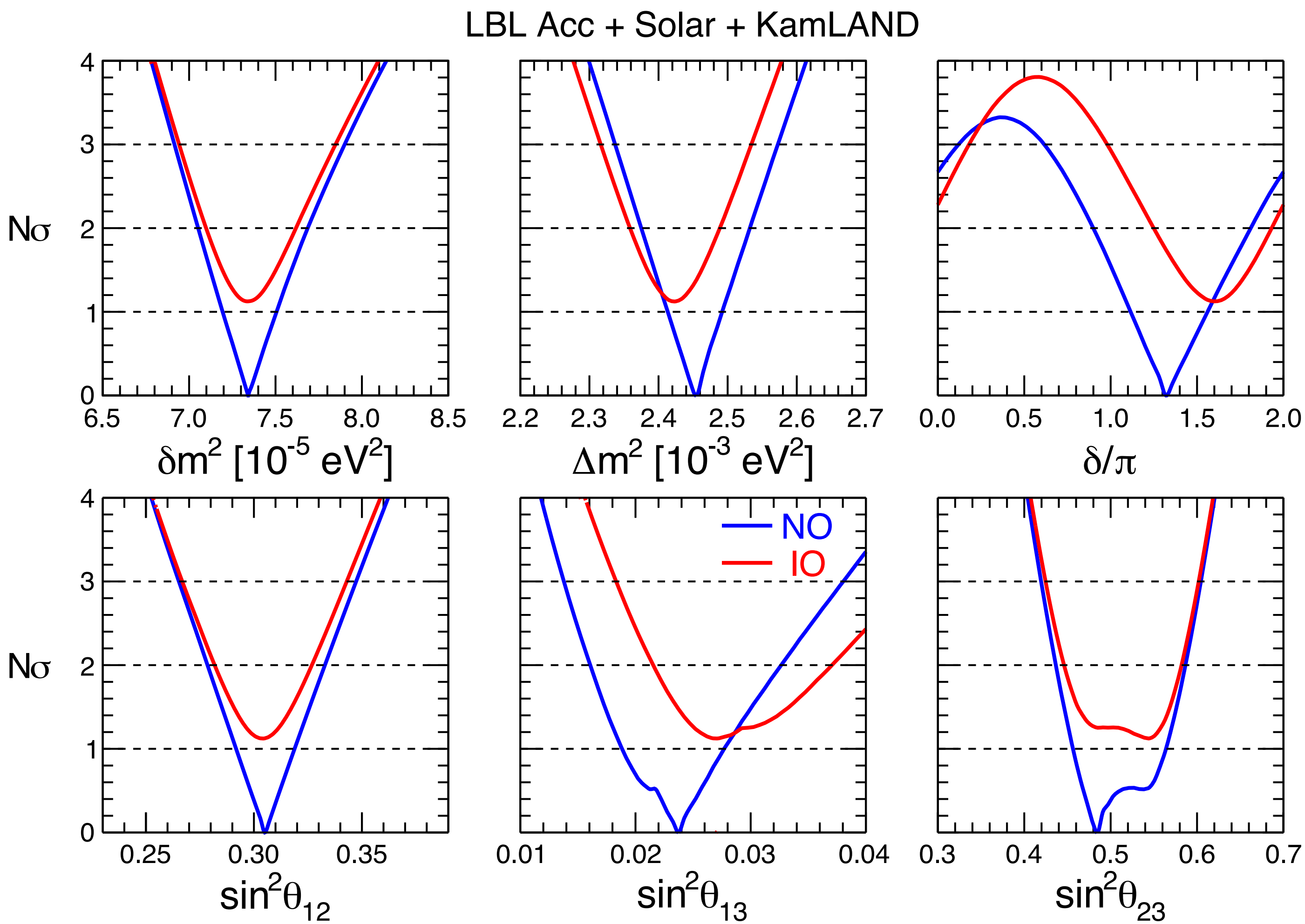


However, **bounds for IO move upwards** if one takes into account that currently **NO gives the absolute best fit**. Recall: **$N\sigma = \sqrt{\Delta\chi^2}$ = 1, 2, 3…**





Results from real data →

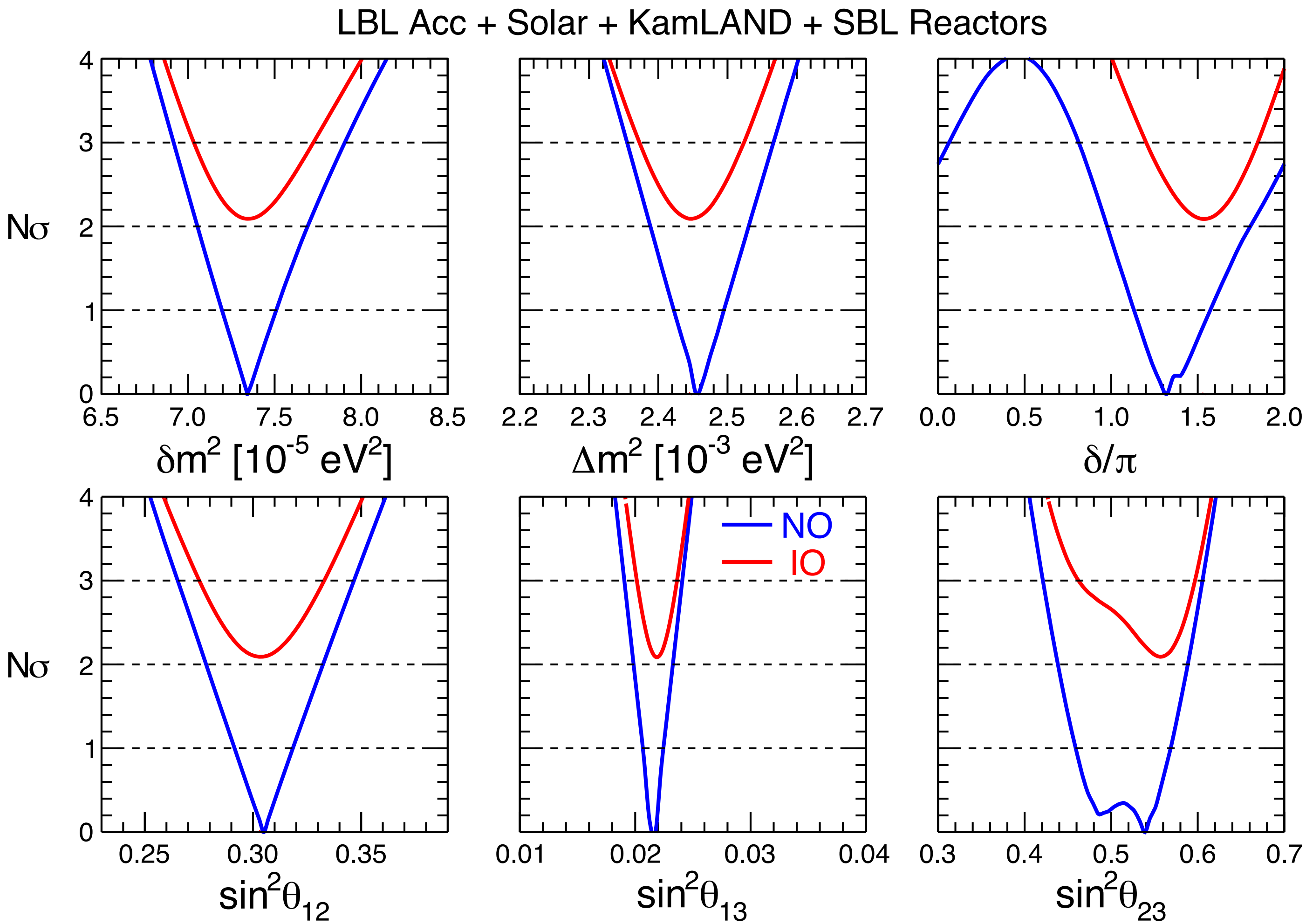


The 2 mass[2] parameters and the 3 mixing angles bound at >4σ level.

Largest mixing angle θ_{23} close to $\pi/4$, but octant undetermined at 1σ.

CP phase favored around $3\pi/2$ (max CPV with $\sin\delta \sim -1$).

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

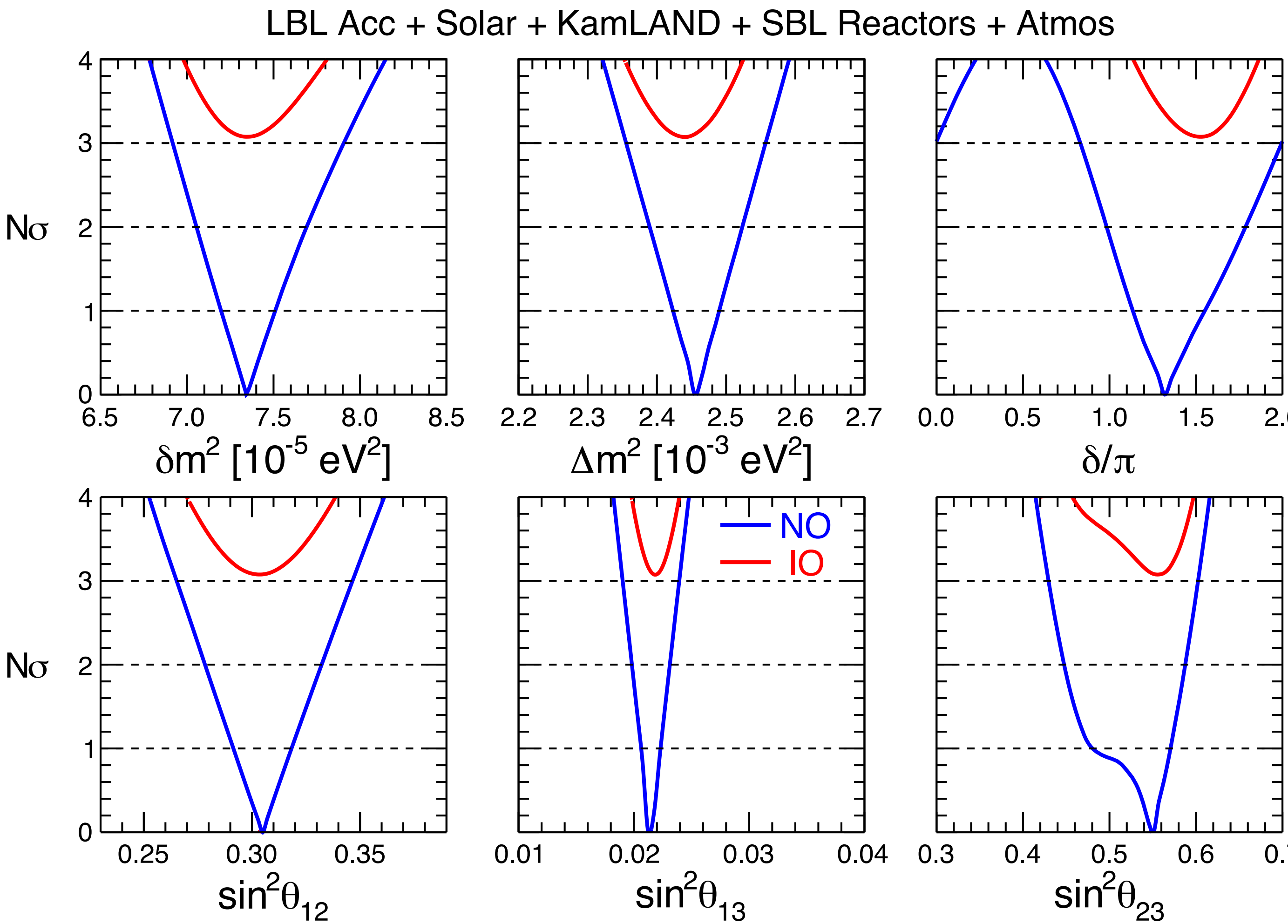


Range of smallest mixing angle θ_{13} dramatically reduced

Largest mixing angle θ_{23} close to $\pi/4$, but octant undetermined at 2σ.

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

IO disfavored with respect to NO at $\sim 2\sigma$ level.



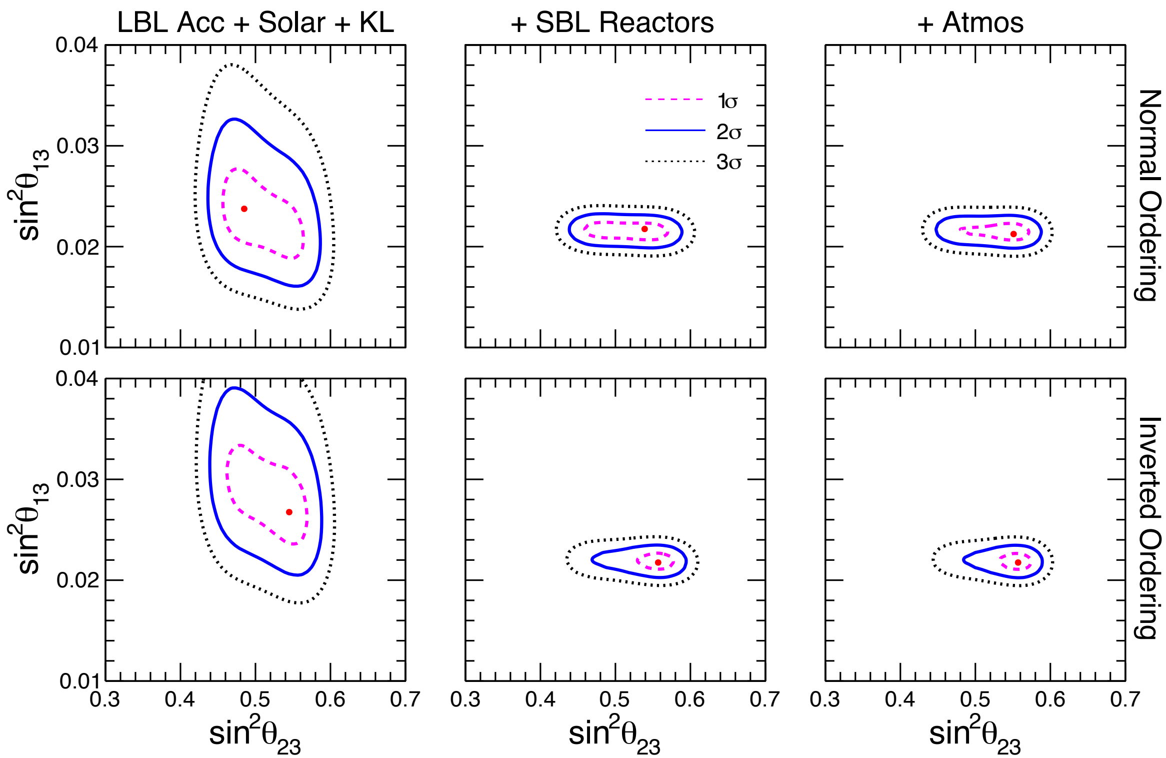
Further improvements for various parameters: 1σ bounds at few % level

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

CPV: sinδ ~ -1 favored, ~ 0 disfav., ~ +1 exclud. 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

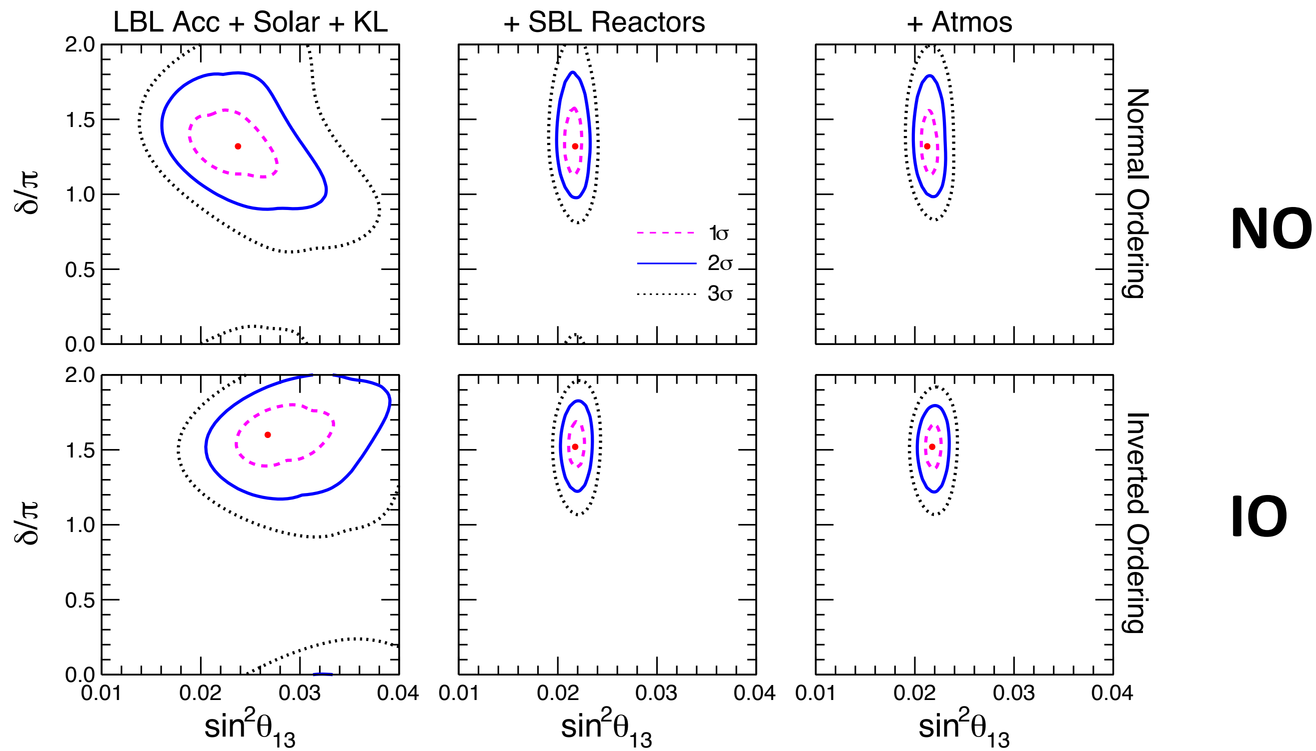
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{A-\Delta m^2}\right)^2 \sin^2\left(\frac{A-\Delta m^2}{4E}x\right)$$

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



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)

3ν oscillation parameters, 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
$\|\Delta m^2\|/10^{-3}$ 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 – Precision era!

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

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

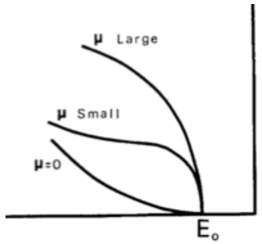
but still a long way to go to reach CKM-level accuracy and redundance!

Hints for nearly maximal CPV and NO will be at center stage in next years

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

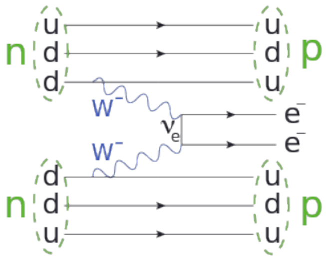
β decay, sensitive to the "effective electron neutrino mass":

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



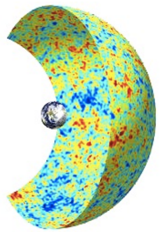
0νββ decay: only if Majorana. "Effective Majorana mass":

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



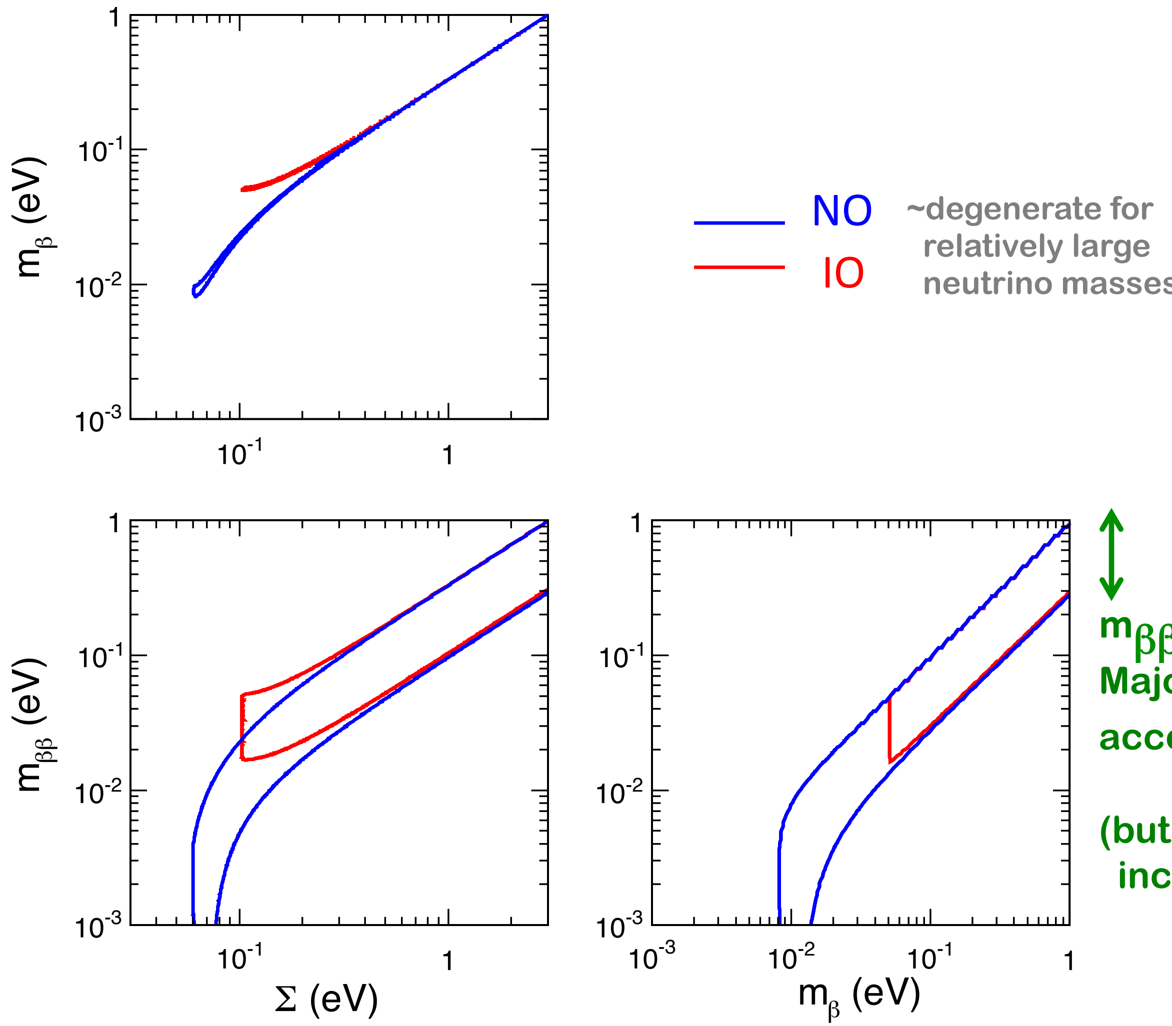
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



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→

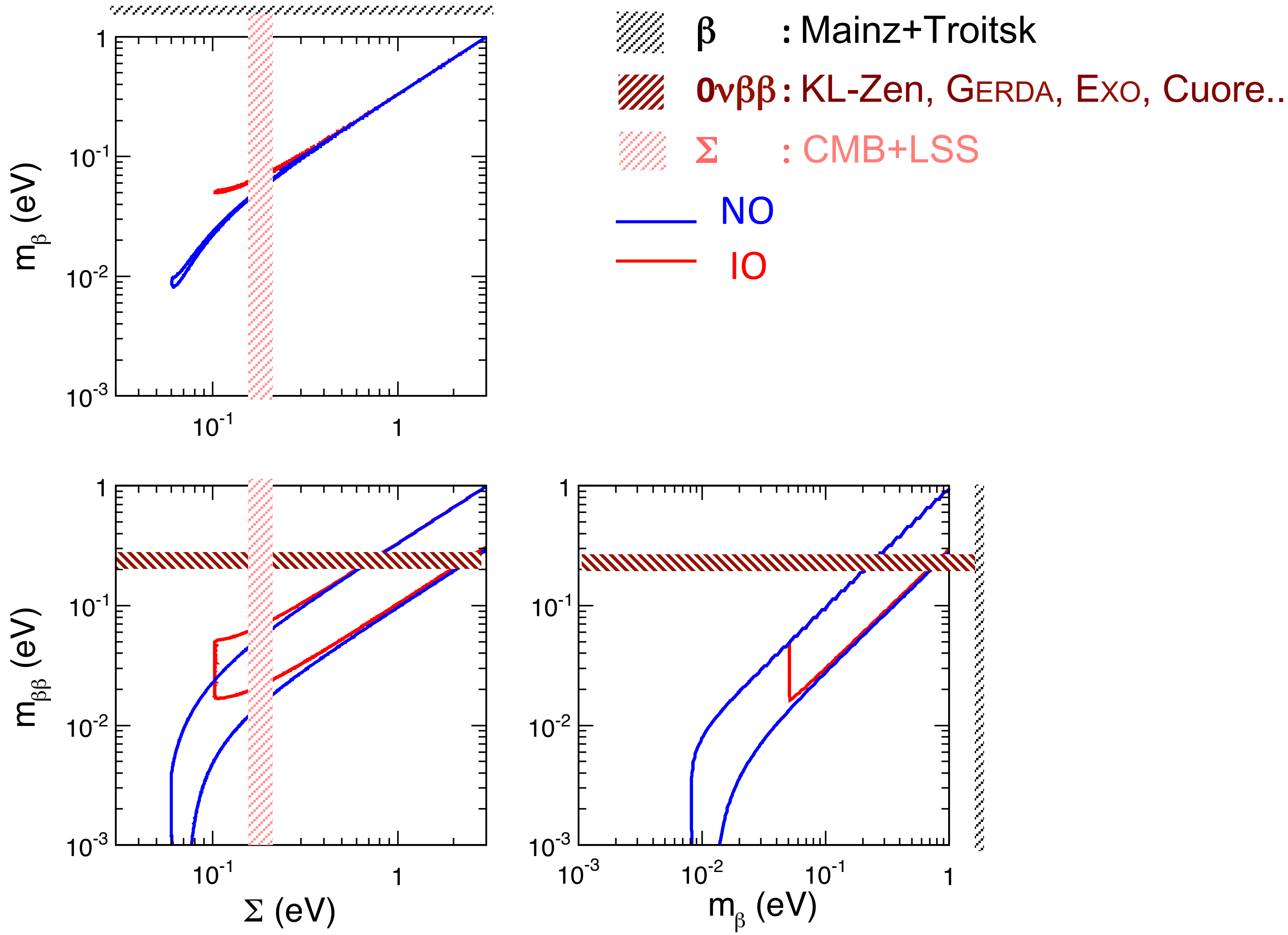
Constraints on nonoscillation observables from oscillation data



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

(but: no NME errors included here!)

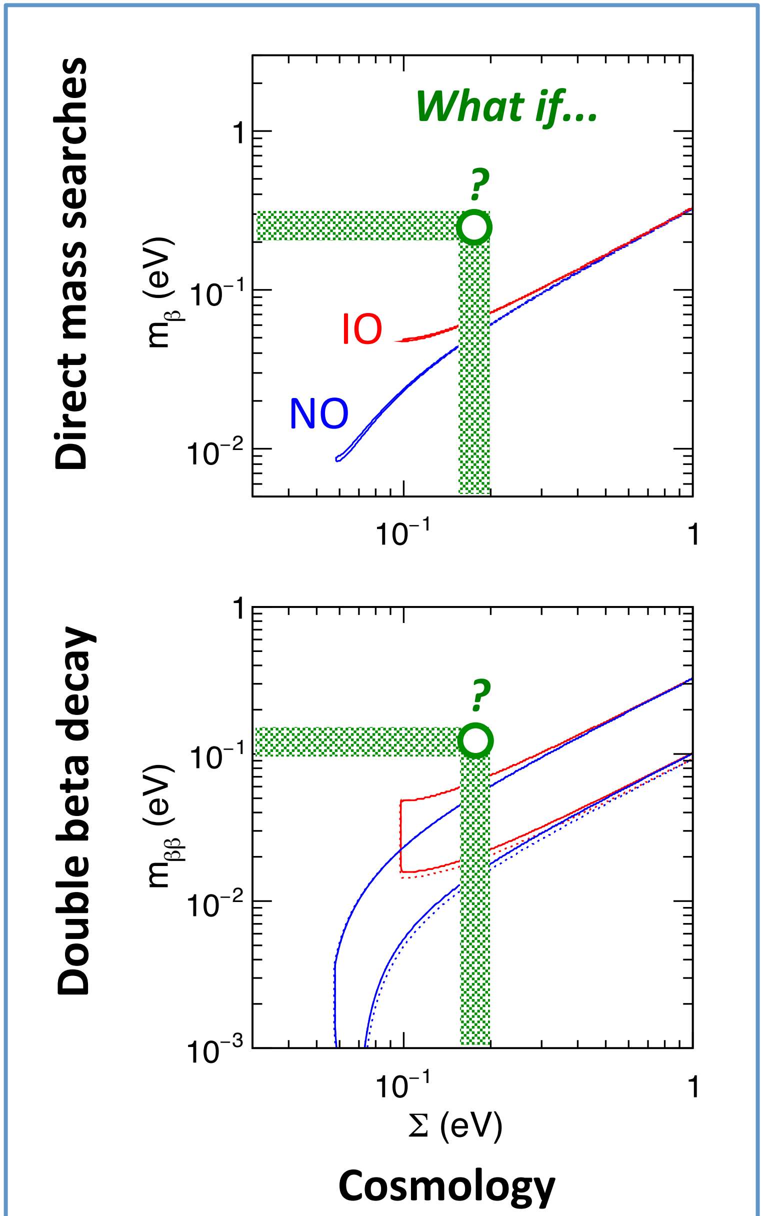
Upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.) + osc. constraints



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

Major improvements expected in the next decade...

… 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:

- *Nonstandard $0\nu\beta\beta$ mechanisms*
- *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
from some SBN oscillation hints

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A suggestion for this field

Let me report a few slides from Neutrino 2018...

Neutrino fireworks and illumination

Eligio Lisi

Istituto Nazionale di Fisica Nucleare (INFN, Italy), Sezione di Bari

XXVIII International Conference on Neutrino Physics and Astrophysics (Heidelberg, Germany, 2018)

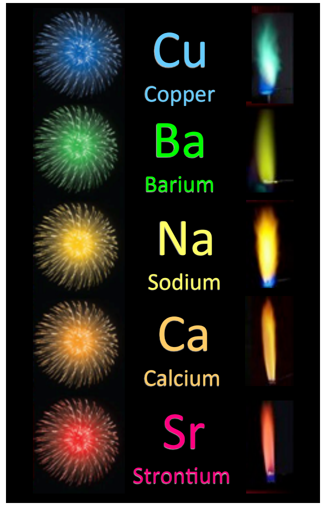
Neutrino Firework Session Chart 2018

Size

When νs meet gravity and astrophysics

[Prologue]
Supernova ν
Gravit. waves
ν Astro/Cosmo

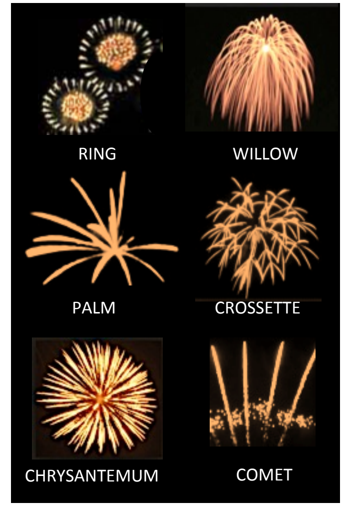
Colors



When νs meet chromodynamics and nuclear physics

Coherent ν
New detectors
Cross sections
0ν double beta

Shapes



When νs meet the many facets of particle physics

Solar, Atmos.
Reactor, Accel.
Lab. ν mass
Phenomenology

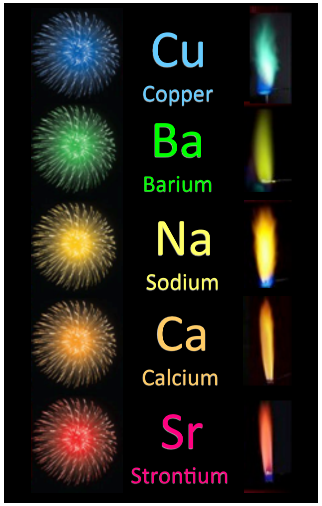
Illumination

When νs meet new physics and energy scales

Theory
Sterile ν
Dark matter
[Epilogue]

Colors

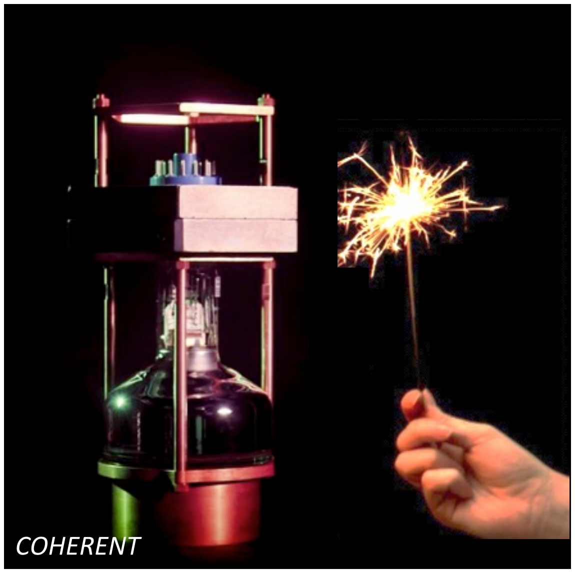
When νs meet chromodynamics and nuclear physics

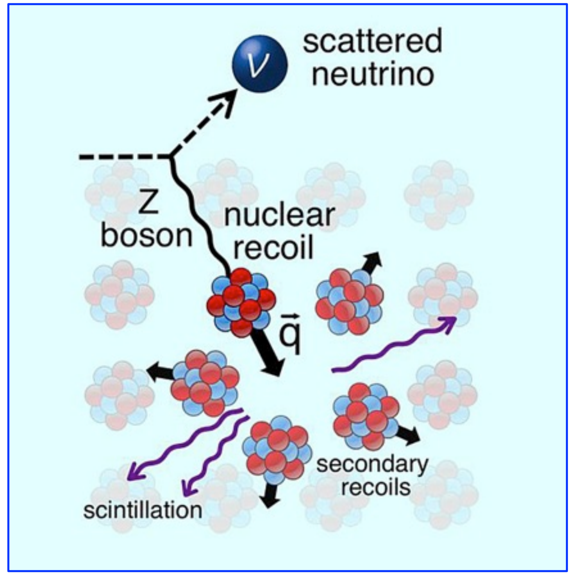


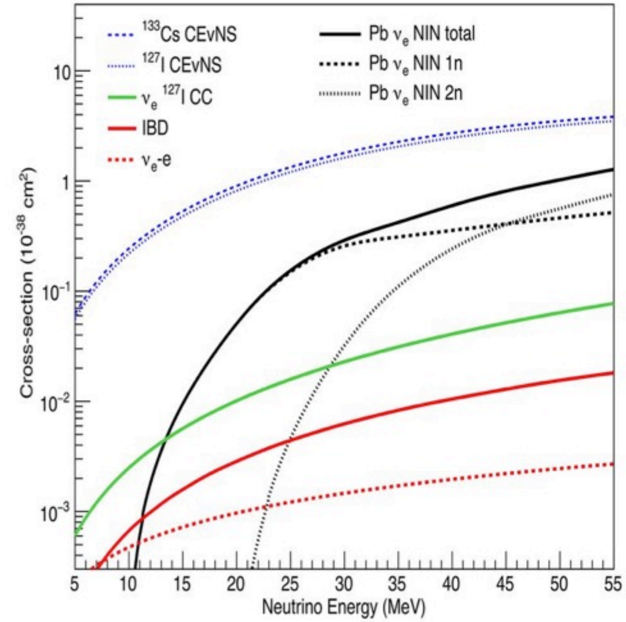
Coherent ν
New detectors
Cross sections
0ν double beta

After the largest... the smallest: Coherent Elastic ν Nucleus Scattering

Detector size ~ sparkler! ...probing **small** energies/recoils... but **large** cross sections

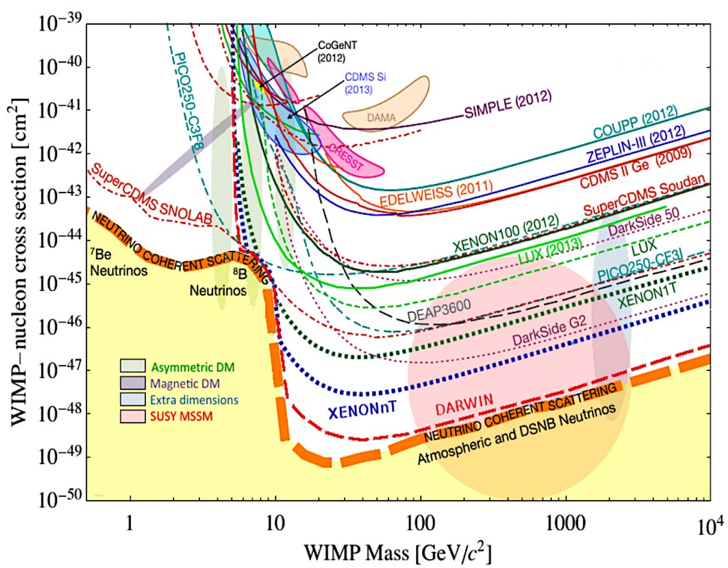






"Yesterday's discovery is today's calibration..."

(R. Feynman)

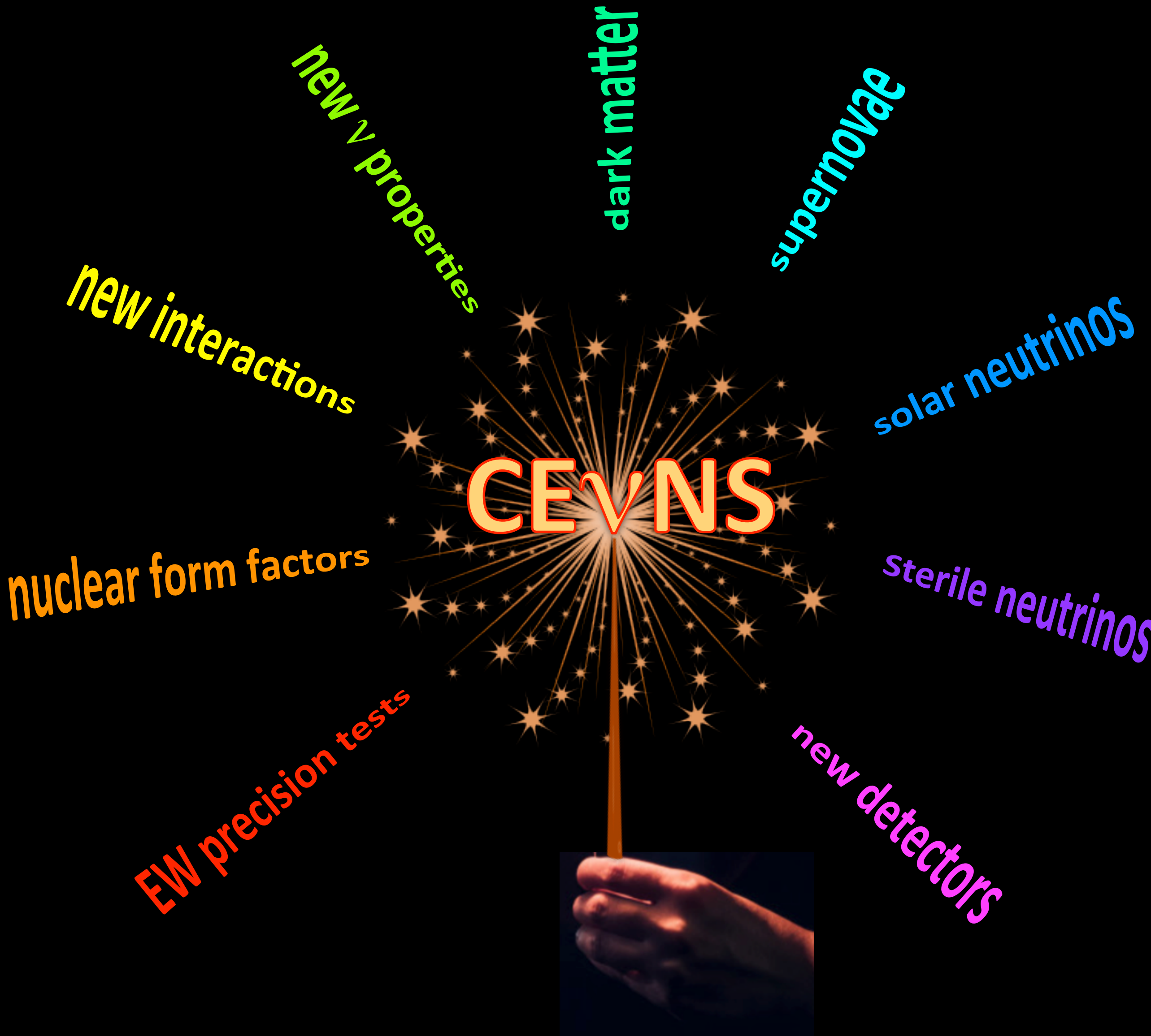


"...and tomorrow's background."

(V. Telegdi)

A new portal to (non)standard particle and nuclear physics

... small but multicolor !

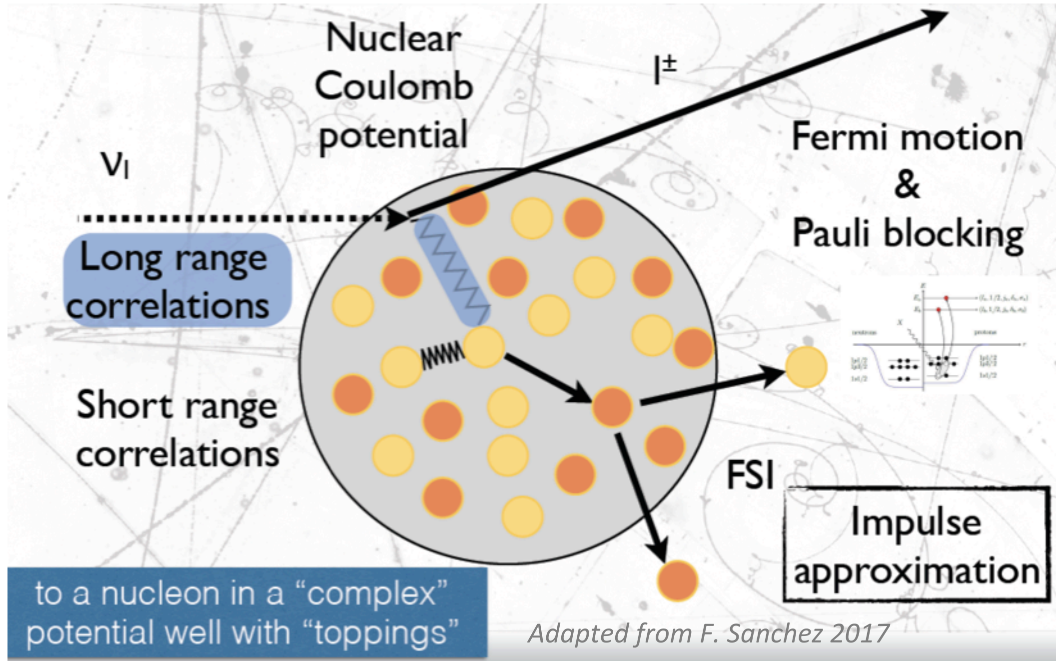


From the nucleus as a whole to its inner part(on)s

Cross sections

A complex and interdisciplinary issue in ν physics, both expt and theo

From a free nucleon in a potential well…



We have “standard models” for particle physics and for cosmology, but
but not yet for the nuclear response to electroweak probes

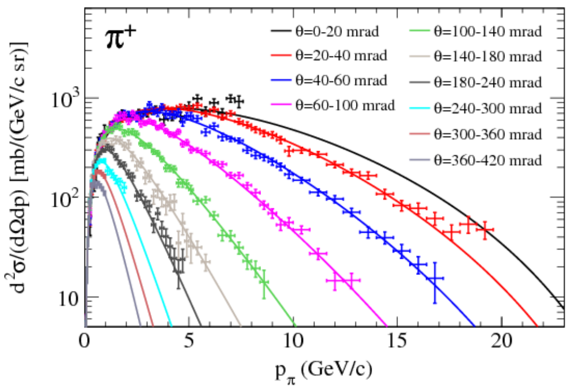
Progress in this field is crucial to get the most out of many ν−related data

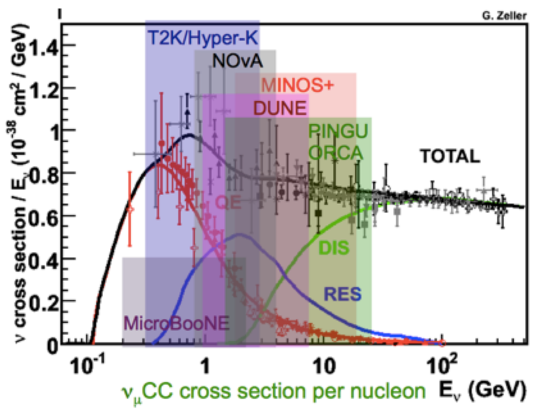
“Strong interaction” effects on “weak interaction” physics are ubiquitous...

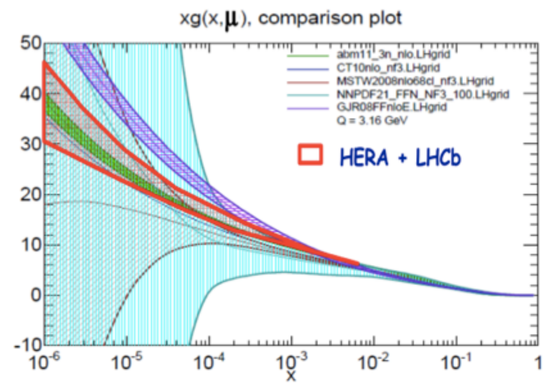
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atm. and acceler. ν fluxes and errors

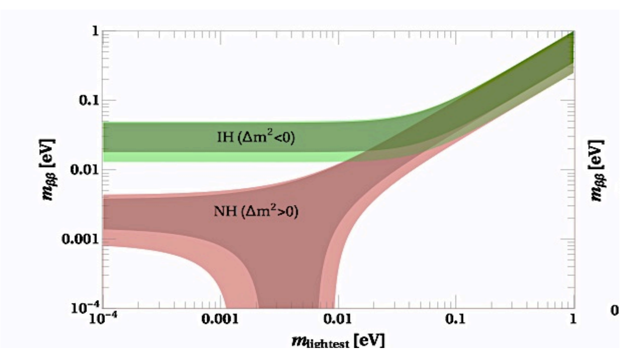
Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

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

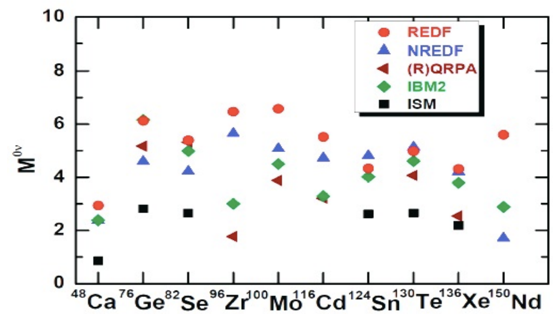








Better control of nuclear EW response (e.g., $\mathbf{g_A}$) relevant to interpret 2β data and to connect them with other data



...

Progress requires joint contributions from different disciplines & communities

In the long-term: Lattice QCD? Recent calculations of axial coupling and form factor (g_A, m_A)

... not just cross sections but much more ...

Beta decays for nuclear reactor spectra

Xsec shape uncertainties for statistical analyses

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

EC processes and neutrino mass

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

A really exciting, data-rich,

multifaceted and interdisciplinary

field of research, at the junction of

neutrino and nuclear physics

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multifaceted and interdisciplinary

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neutrino and nuclear physics

But...

... you know, when seen from "outside":

multifaceted = fragmented / dispersive

...and when it comes to fundings and jobs:

interdisciplinary = nobody's child

→ *"ancillary" at most...*

Deserves more proper recognition!

OUTLINE:

Status of the 3ν paradigm

The role of nuclear physics

A suggestion for this field

Learning from another field
(admittedly much wider)
that suffered from being
multifaceted and interdisciplinary:

ASTROPARTICLE PHYSICS

Interconnected aspects of
Particle physics, Astrophysics
Cosmic ray physics, Cosmology,
were not covered under the unifying "name" of...

ASTROPARTICLE PHYSICS

... until it was recognized that important problems
(dark matter, baryon asymmetry and stability, neutrino masses ...)
required to join different communities and competences

Adam giving names (Genesis 2:19)
Artist unknown. Phillip Medhurst Collection

The term "Astroparticle Physics" came into existence in the late '80s, early '90s:

1987	**A. De Rujula and D.V. Nanopoulos (Erice School)**
1988	**A. Salam**
1990	**V.A. Rubakov**
1991	**D.H. Perkins**
1992	**D. Cline and R. Peccei**
1992	**F. Halzen**
1994	**H. Ejiri**

Became a widely recognized "unifying name" around ~2000.

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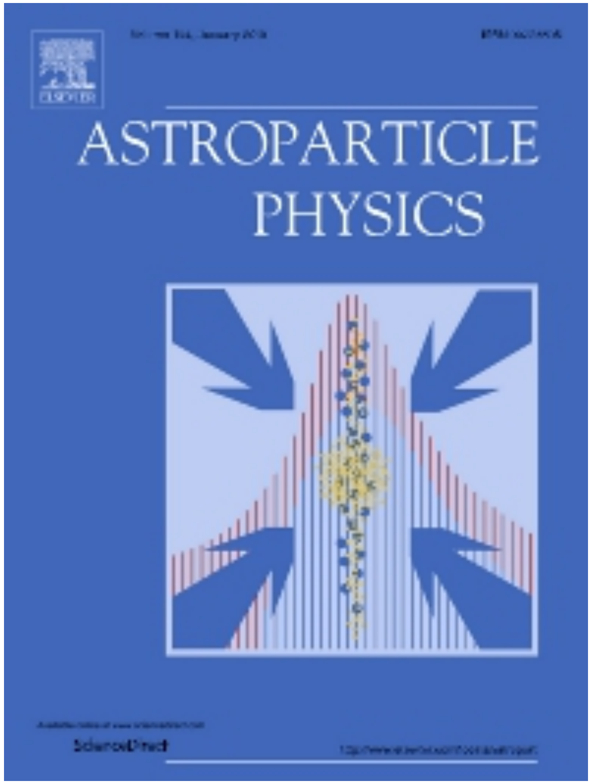
In about the same period, within INFN:

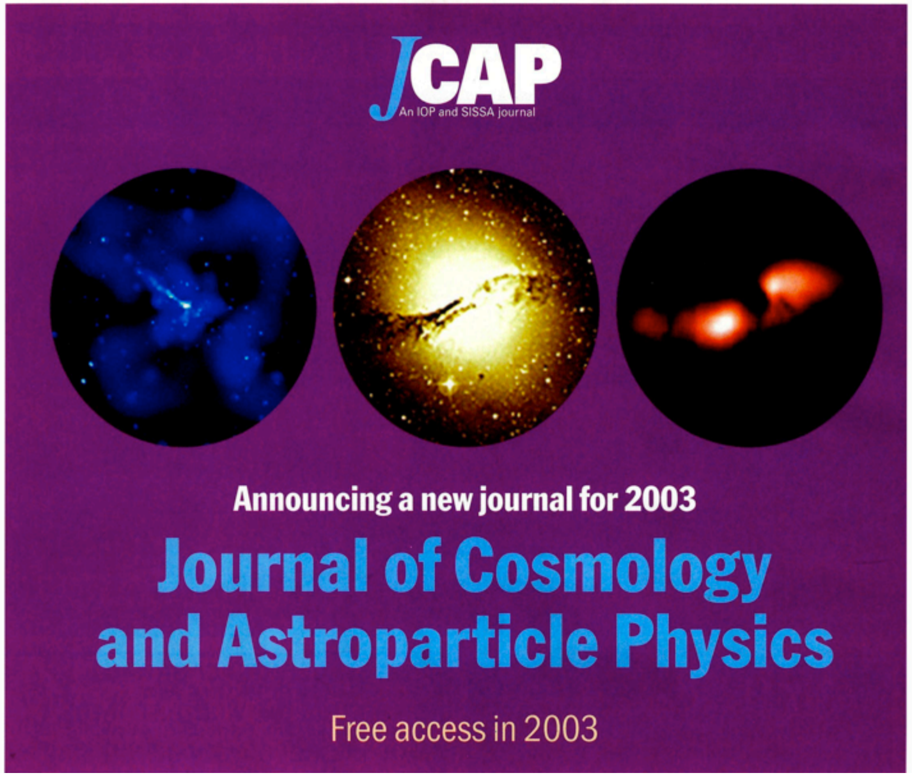
Experimental Committee II: transition from "negative" to "assertive" wording:
Non-accelerator physics → Astroparticle physics

Theoretical Committee IV: includes the topic "Theoretical Astroparticle Physics"
Dedicated PhD courses, Schools, Workshops...

Also: Two dedicated international Journals



1992+



2003+

These actions helped to establish a common scientific language
and sinergies of different competences and communities
that recognized themselves within the same "Astroparticle" field

Astroparticle Physics European Consortium

August 2017

appec.org

Executive Summary

Astroparticle physics is the fascinating field of research at the intersection of astronomy, particle physics and cosmology. It simultaneously addresses challenging questions relating to the micro-cosmos (the world of elementary particles and their fundamental interactions) and the macro-cosmos (the world of celestial objects and their evolution) and, as a result, is well-placed to advance our understanding of the Universe beyond the *Standard Model of particle physics* and the *Big Bang Model of cosmology*.

One of its paths is targeted at a better understanding of cataclysmic events such as: supernovas – the titanic explosions marking the final evolutionary stage of massive stars; mergers of multi-solar-mass black-hole or neutron-star binaries; and, most compelling of all, the violent birth and subsequent evolution of our infant Universe. This quest is pursued using the combined and often complementary power of all 'cosmic' messengers: *cosmic rays*, *electromagnetic waves* (i.e. 'light' but also photons at all energies), *neutrinos* and *gravitational waves*. Another path aims to elucidate long-standing mysteries such as the true nature of *Dark Matter* and *Dark Energy*, the intricacies of *neutrinos* and the occurrence (or non-occurrence) of *proton decay*.

The field of astroparticle physics has quickly established itself as an extremely successful endeavour. Since 2001 four Nobel Prizes (2002, 2006, 2011 and 2015) have been awarded to astroparticle physics and the recent – revolutionary – first direct detections of gravitational waves is literally opening an entirely new and exhilarating window onto our Universe. We look forward to an equally exciting and productive future.

Many of the next generation of astroparticle physics research infrastructures require substantial capital investment and, for Europe to remain competitive in this rapidly evolving global field of research both on the ground and in space, a clear, collective, resource-aware strategy is essential. As a relatively new field, European astroparticle physics does not benefit from a natural and strong inter-governmental

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In the current landscape of (sub)nuclear physics and astrophysics, maybe it's worth trying to better characterize the field(s) at the junction of

neutrino and nuclear physics

in analogy with the astroparticle physics experience *(albeit on a smaller scale)*, having in mind long-term and ambitious goals, including e.g. a possible

"unified model" for the nuclear response to EW probes

It is left to further discussion (if any!) to evaluate if such perspective is worthwhile.
I have no practical suggestions, but let me just give my two cents for a general name:

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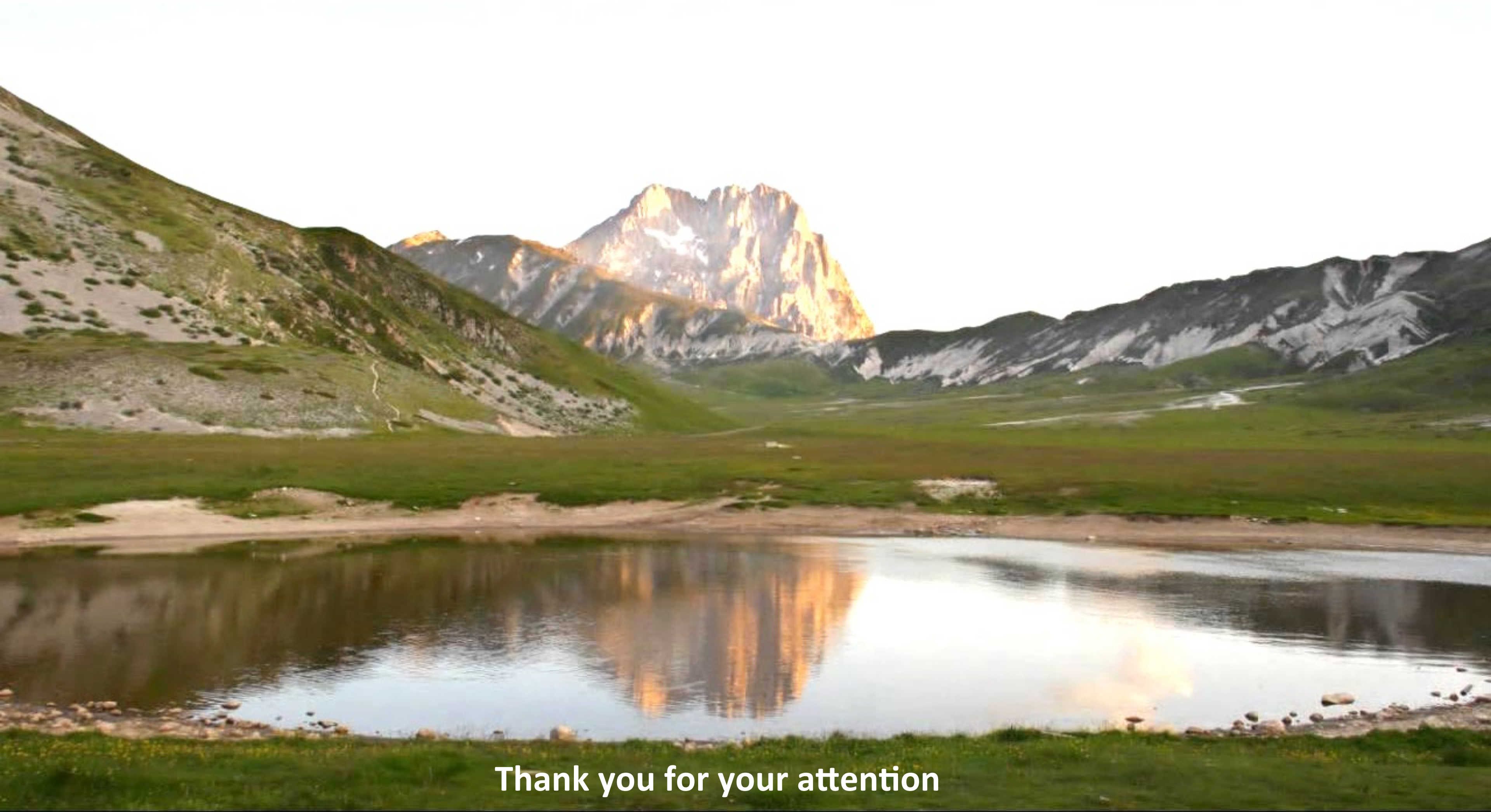


Thank you for your attention

EXTRA

3ν paradigm: parameters

Mixings and phases: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

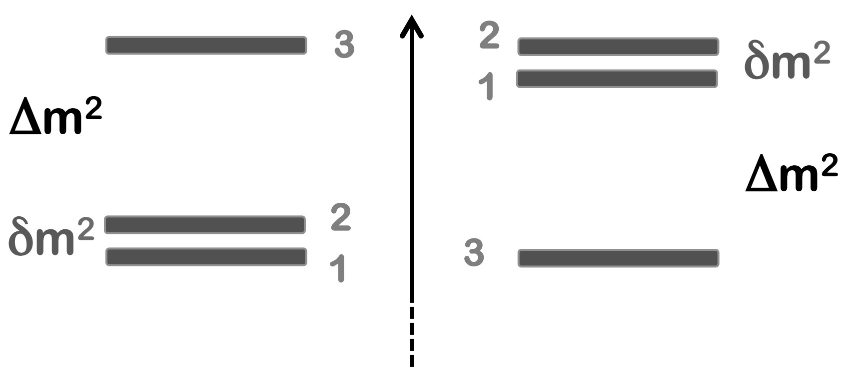
$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

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

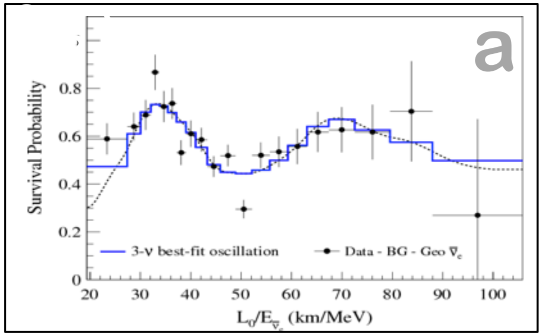
I.O.

+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density

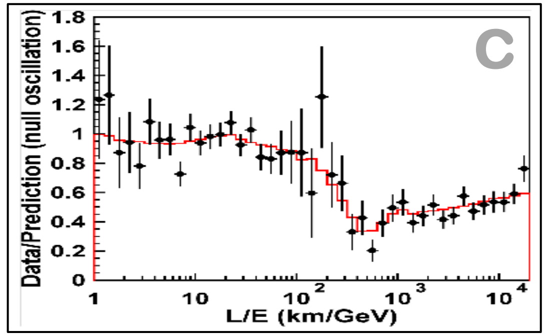
+ absolute mass scale (not tested in oscillations)

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

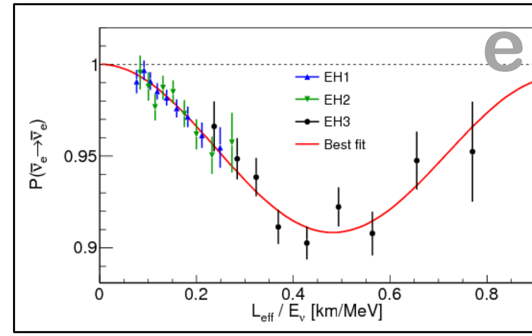
e→e (KamLAND)



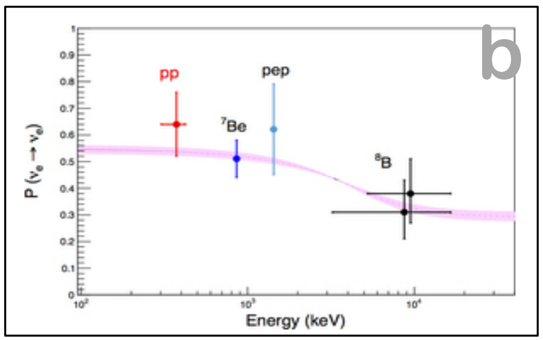
μ→μ (Atmospheric)



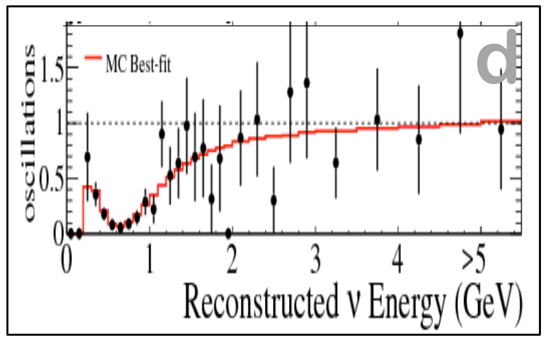
e→e (SBL Reac.)



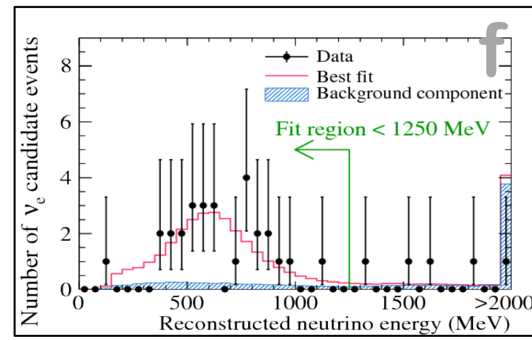
e→e (Solar)



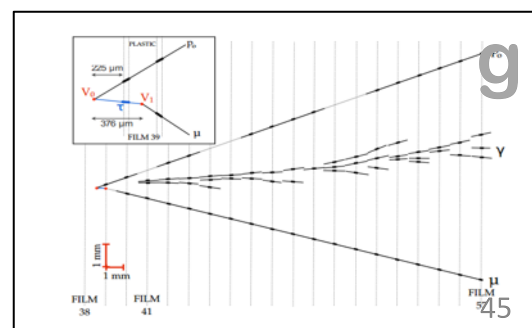
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK)

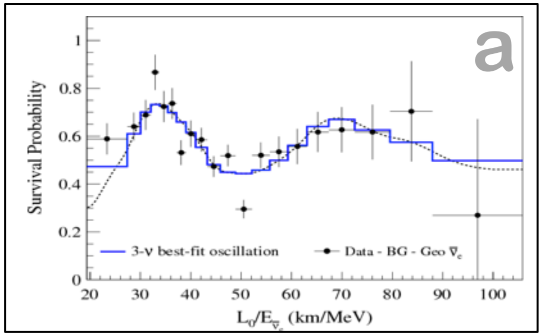


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline LBL accelerator, (e) short-baseline SBL reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

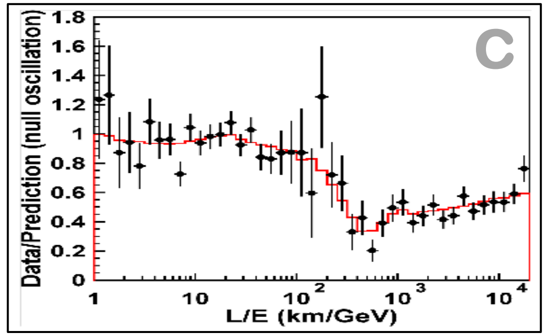
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

Leading sensitivities to 3ν oscillation parameters:

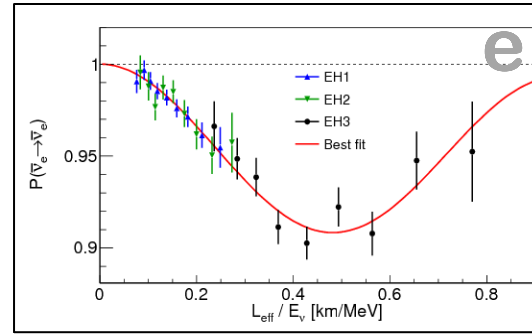
e→e (δm^2 , θ_{12})



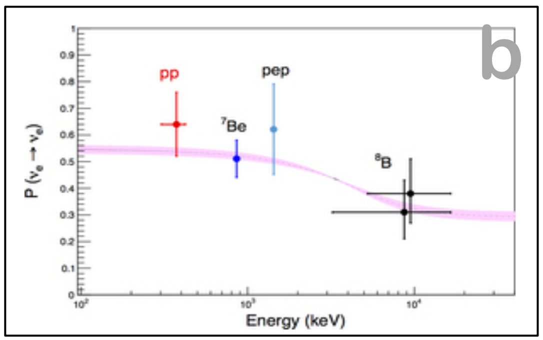
μ→μ (Δm^2 , θ_{23})



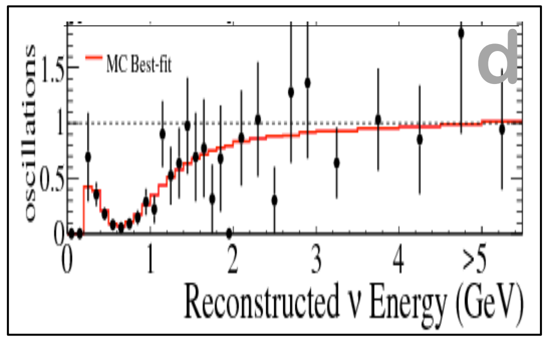
e→e (Δm^2 , θ_{13})



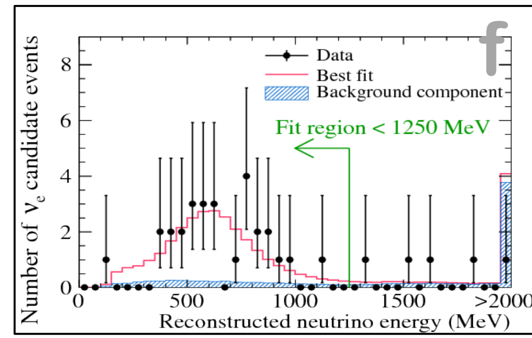
e→e (δm^2 , θ_{12})



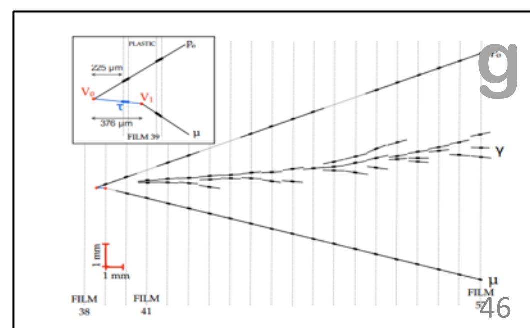
μ→μ (Δm^2 , θ_{23})



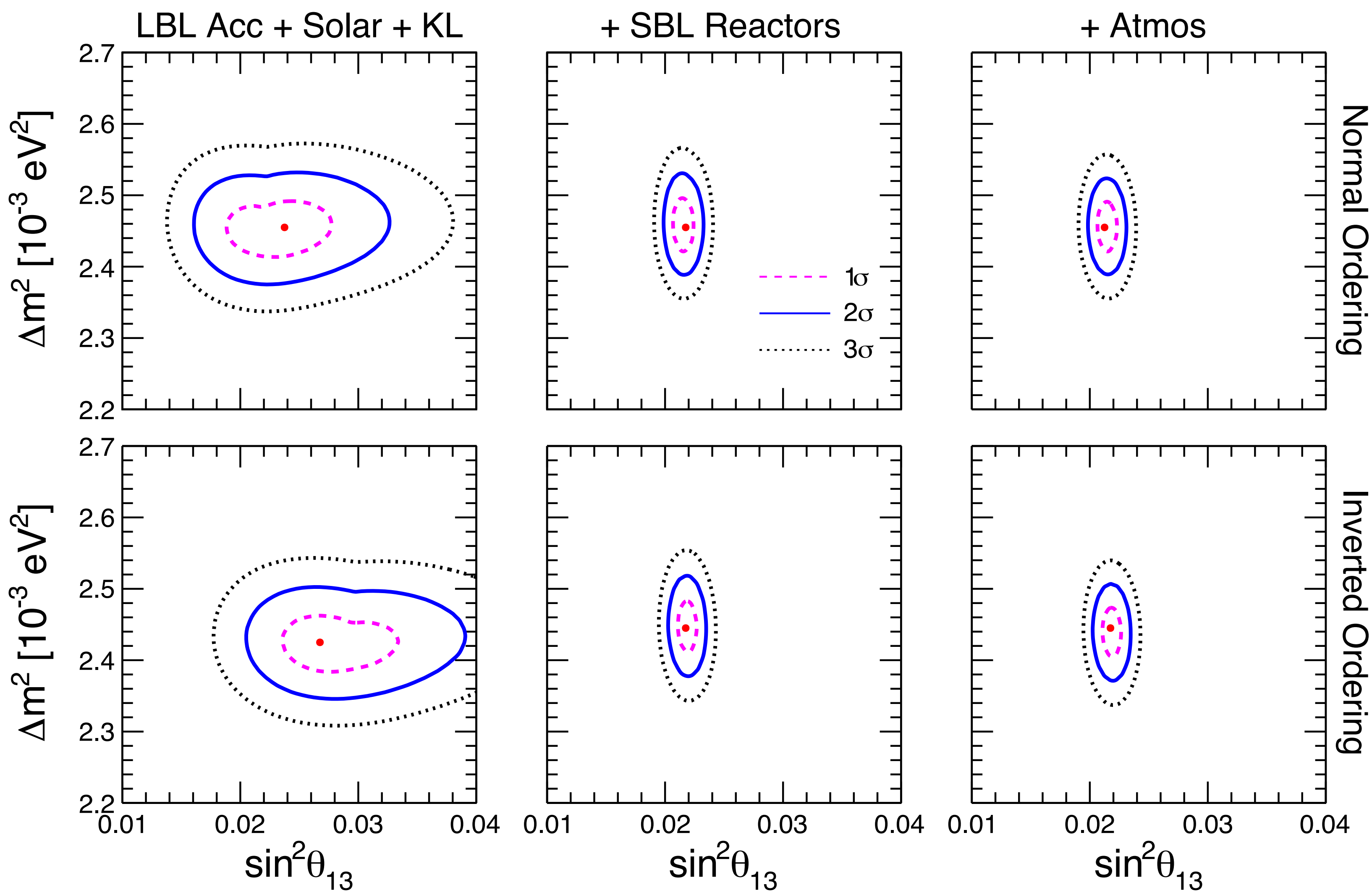
μ→e (Δm^2 , θ_{13} , θ_{23})



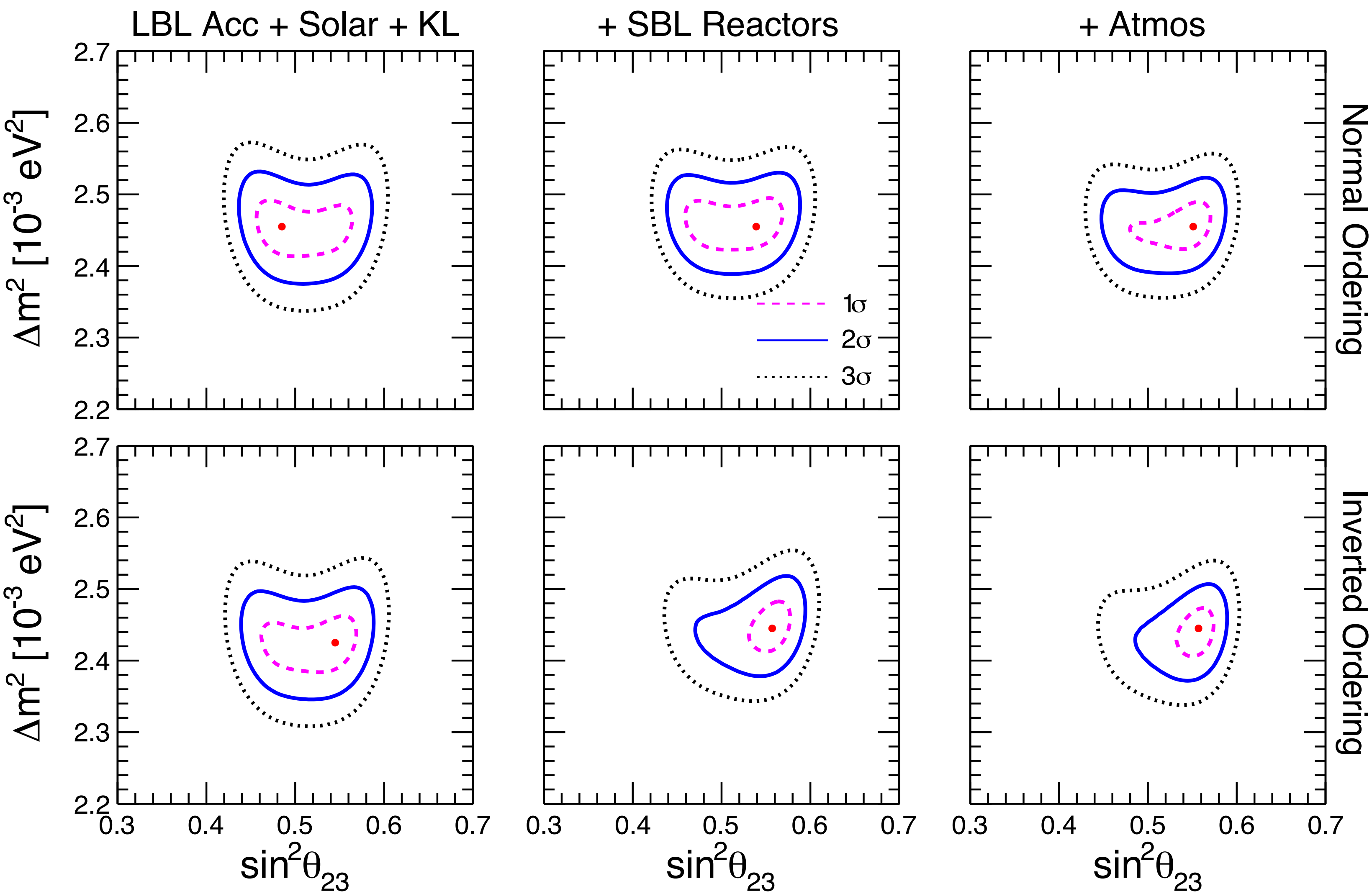
μ→τ (Δm^2 , θ_{23})



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



LBL Acc + Solar + KL
+ SBL Reactors
+ Atmos
Normal Ordering
Inverted Ordering
Δm^2 [10^{-3} eV^2]
$\sin^2\theta_{13}$
2.2
2.3
2.4
2.5
2.6
2.7
0.01
0.02
0.03
0.04
1σ
2σ
3σ


LBL Acc + Solar + KL
+ SBL Reactors
+ Atmos
Normal Ordering
Inverted Ordering
Δm^2 [10^{-3} eV^2]
$\sin^2\theta_{23}$
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