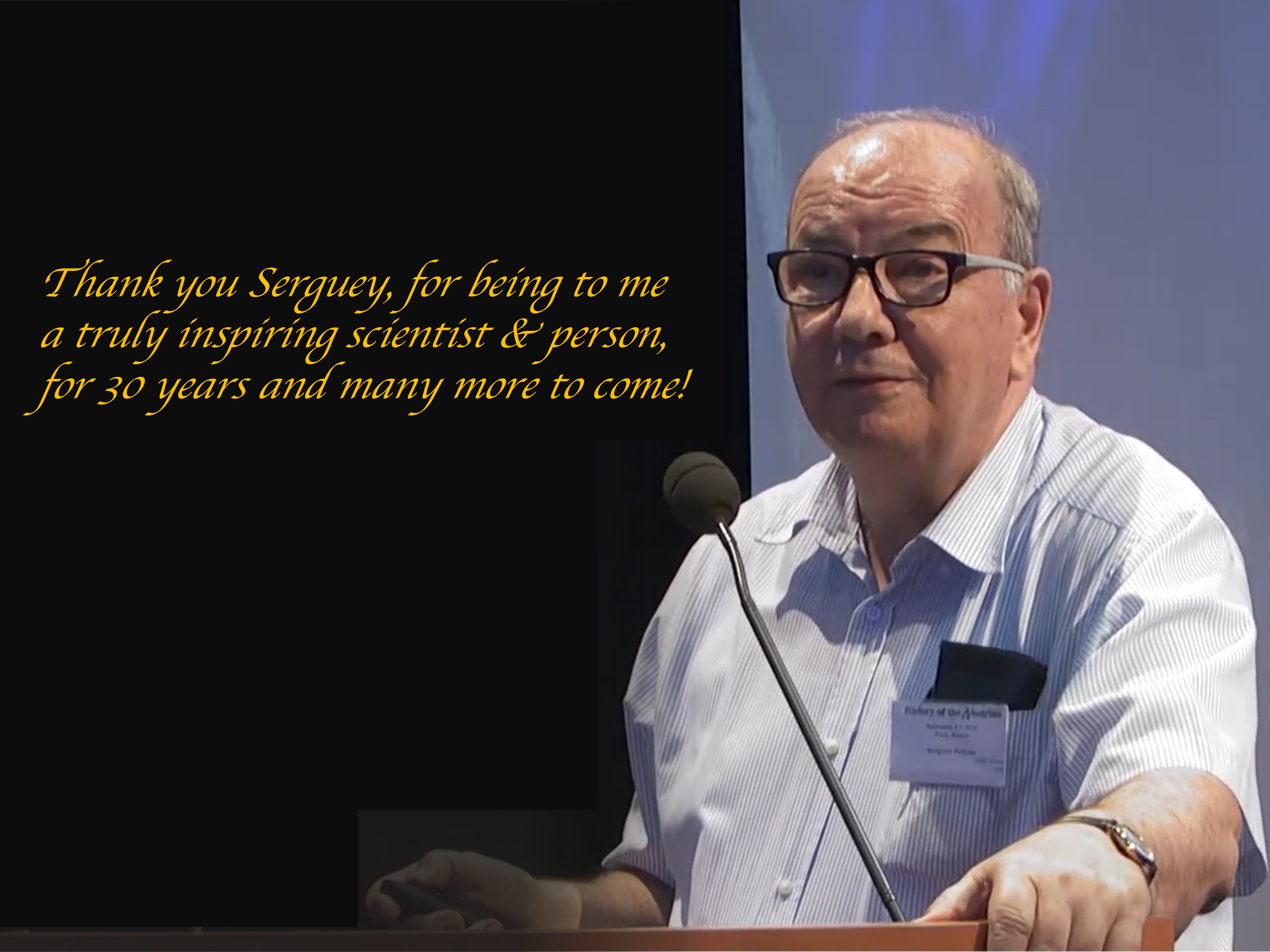
Overview of

my intersections with Serguey in

ν phenomenology

Eligio Lisi
INFN, Bari, Italy

PetcovFEST 2023


Thank you Serguey, for being to me
a truly inspiring scientist & person,
for 30 years and many more to come!

30 years ago, during my PhD work… a turning point

(non)standard EW precision physics

→ neutrino and astroparticle physics

(following a wise suggestion by Gianluigi Fogli)

30 years ago, during my PhD work… a turning point

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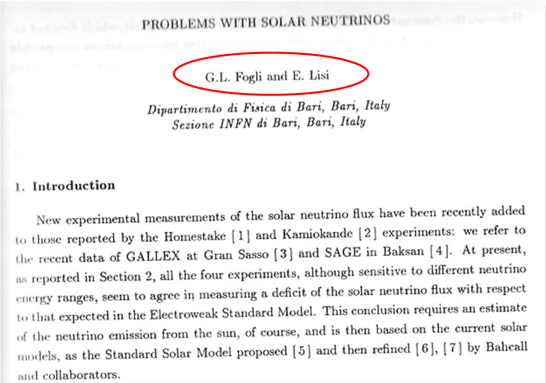
Papers on my desk at that time:

- …***Besides*** 1-loop EW effects from R-conserving SUSY:

- ***Kuo & Pantaleone***: ν oscillations and MSW review
- ***Bahcall & Pinsonneault***: SSM review
- ***Guzzo-Masiero-Petcov***: ν NSI from R-violating SUSY, an inspiring new possibility w.r.t. collider BSM searches!

Results: SUSY NSI effects on solar ν at Neutrino Telescopes 1993 (Venice, Italy):



PROBLEMS WITH SOLAR NEUTRINOS

G.L. Fogli and E. Lisi

Dipartimento di Fisica di Bari, Bari, Italy
Sezione INFN di Bari, Bari, Italy

1. Introduction

New experimental measurements of the solar neutrino flux have been recently added to those reported by the Homestake [1] and Kamiokande [2] experiments: we refer to the recent data of GALLEX at Gran Sasso [3] and SAGE in Baksan [4]. At present, as reported in Section 2, all the four experiments, although sensitive to different neutrino energy ranges, seem to agree in measuring a deficit of the solar neutrino flux with respect to that expected in the Electroweak Standard Model. This conclusion requires an estimate of the neutrino emission from the sun, of course, and is then based on the current solar models, as the Standard Solar Model proposed [5] and then refined [6], [7] by Bahcall and collaborators.

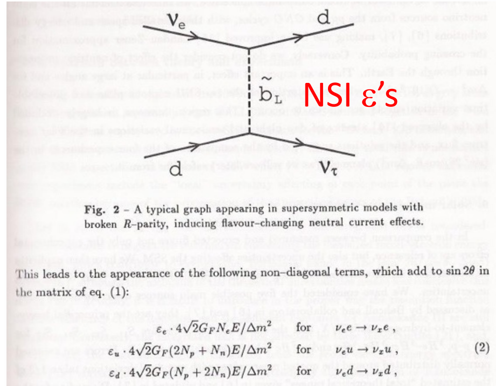
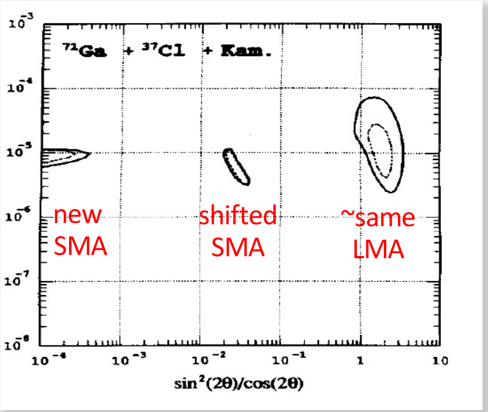


Fig. 2 – A typical graph appearing in supersymmetric models with broken *R*-parity, inducing flavour-changing neutral current effects.

This leads to the appearance of the following non-diagonal terms, which add to $\sin 2\theta$ in the matrix of eq. (1):

$$\begin{aligned} &\varepsilon_e \cdot 4\sqrt{2} G_F N_e E/\Delta m^2 && \text{for} \quad \nu_e e \to \nu_\tau e\,, \\ &\varepsilon_u \cdot 4\sqrt{2} G_F (2N_p + N_n) E/\Delta m^2 && \text{for} \quad \nu_e u \to \nu_\tau u\,, \qquad (2) \\ &\varepsilon_d \cdot 4\sqrt{2} G_F (N_p + 2N_n) E/\Delta m^2 && \text{for} \quad \nu_e d \to \nu_\tau d\,, \end{aligned}$$



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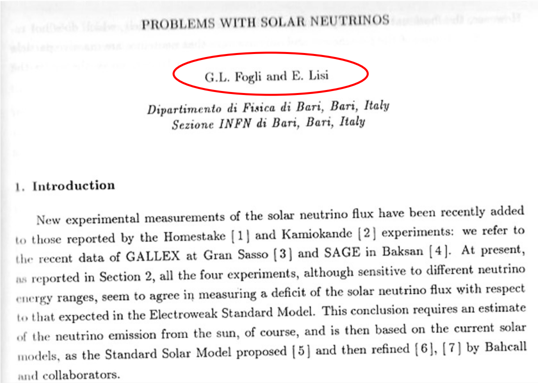
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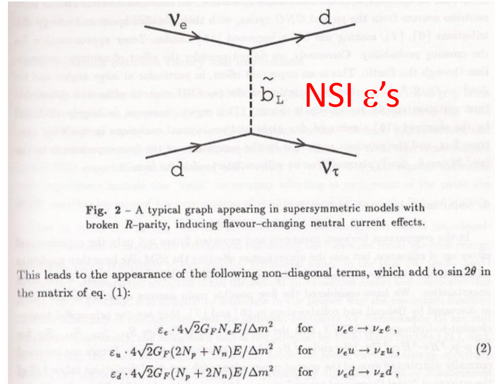

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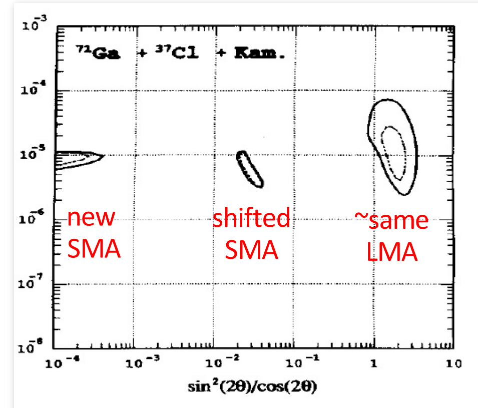
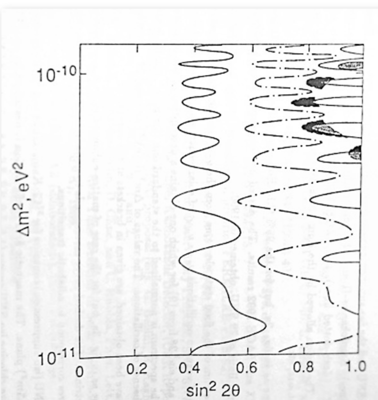
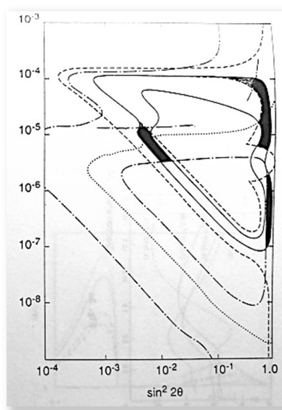
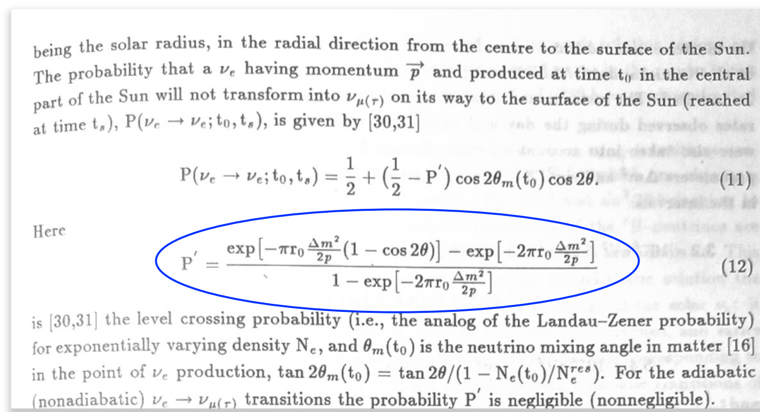


At the same conference, Serguey reviewed solutions to the solar ν problem, including:






being the solar radius, in the radial direction from the centre to the surface of the Sun. The probability that a ν_e having momentum $\vec{p}$ and produced at time t_0 in the central part of the Sun will not transform into $\nu_{\mu(\tau)}$ on its way to the surface of the Sun (reached at time t_s), $P(\nu_e \to \nu_e; t_0, t_s)$, is given by [30,31]

$$P(\nu_e \to \nu_e; t_0, t_s) = \frac{1}{2} + \left(\frac{1}{2} - P'\right)\cos 2\theta_m(t_0)\cos 2\theta. \qquad (11)$$

Here

$$P' = \frac{\exp\left[-\pi r_0 \frac{\Delta m^2}{2p}(1-\cos 2\theta)\right] - \exp\left[-2\pi r_0 \frac{\Delta m^2}{2p}\right]}{1 - \exp\left[-2\pi r_0 \frac{\Delta m^2}{2p}\right]} \qquad (12)$$

is [30,31] the level crossing probability (i.e., the analog of the Landau–Zener probability) for exponentially varying density N_e, and $\theta_m(t_0)$ is the neutrino mixing angle in matter [16] in the point of ν_e production, $\tan 2\theta_m(t_0) = \tan 2\theta/(1 - N_e(t_0)/N_e^{res})$. For the adiabatic (nonadiabatic) $\nu_e \to \nu_{\mu(\tau)}$ transitions the probability P' is negligible (nonnegligible).

Vacuum solutions

Matter (MSW) solutions

Serguey's double-exponential generalization of Landau-Zener (single-exp.) crossing probability P_c

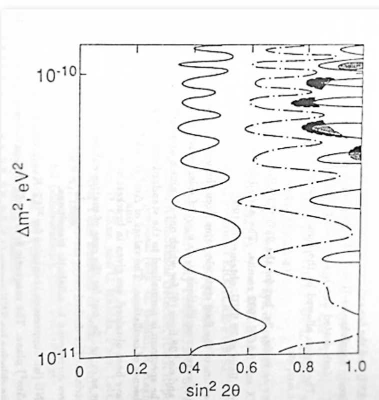
In 2001 we worked together to bridge the gap between vacuum and matter solutions via P_C , after extended visits in Trieste by Daniele Montanino and Antonio Marrone

Analytical description of quasivacuum oscillations of solar neutrinos

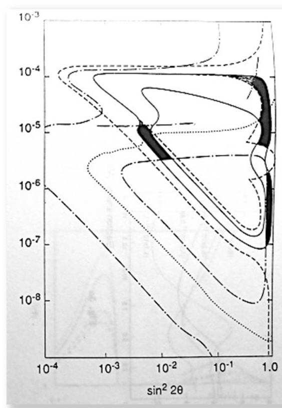
E. Lisi,[1] A. Marrone,[1] D. Montanino,[2] A. Palazzo,[1] and S. T. Petcov[3,4,*]

(Supporting and encouraging young fellows is a distinctive aspect of Serguey character)

I'll come back to Serguey's 2-level crossing (or "jump") probability P_C in the end !



Vacuum solutions



Matter (MSW) solutions

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Serguey's double-exponential generalization of Landau-Zener (single-exp.) crossing probability P_C

Many occasions to interact with Serguey and to witness his passion for physics, e.g.:

- In astroparticle theory networks within Italian INFN (FA51, TAsP) and MUR (PRINs)
- at Neutrino Oscillation Workshop in Apulia (in 2004, 2006, 2008, 2010, 2012, and 2022) with his great presentations on ν theory/pheno/history and lively questions/discussions!

Dirac and Majorana CP violation…

Tribute to Pontecorvo & Bilenky…

Neutrino Mass Spectrum and Leptogenesis…

Serguey's contributions to neutrino phenomenology are both deep and wide-ranging, covering essentially all aspects of interest, within and beyond the standard framework!

I'll survey very briefly just one of his favorite topics – ν mass ordering – that, in my opinion, will show a relatively rapid progress in the next future w.r.t. other ν unknowns

Serguey's contributions to mass ordering probes are both deep and wide-ranging:

How do we get sign($\pm\Delta m^2$)? (+1 normal NO, -1 = inverted IO)

Flavor oscillations:

$\pm\Delta m^2$ interfering with…

δm^2 (vacuum)

$G_F E N_e$ (matter bkgd)

$G_F E N_\nu$ (dense ν gas)

← **Medium baseline reactors (~2001-2003)!**

← **In matter (Earth):**
atmospheric ν through mantle-core layers,
appearance searches with LBL accelerators

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How do we get sign($\pm\Delta m^2$)?

(+1 normal NO, -1 = inverted IO)

Absolute mass observables:

$\pm\Delta m^2$ adding to m^2 in…

$m_{\beta\beta}$ (neutrinoless DBD)

m_{β} (beta decay)

Σ (cosmology)

Influential work on Majorana ν masses/phases and 0νββ mechanisms, supporting ton-scales →

Connections with β-decay (and cosmology) →

Where are we (going) with sign($\pm\Delta m^2$)?

Flavor oscillations:

$\pm\Delta m^2$ interfering with…

δm^2	(vacuum)
$G_F\, E\, N_e$	(matter bkgd)
$G_F\, E\, N_\nu$	(dense ν gas)

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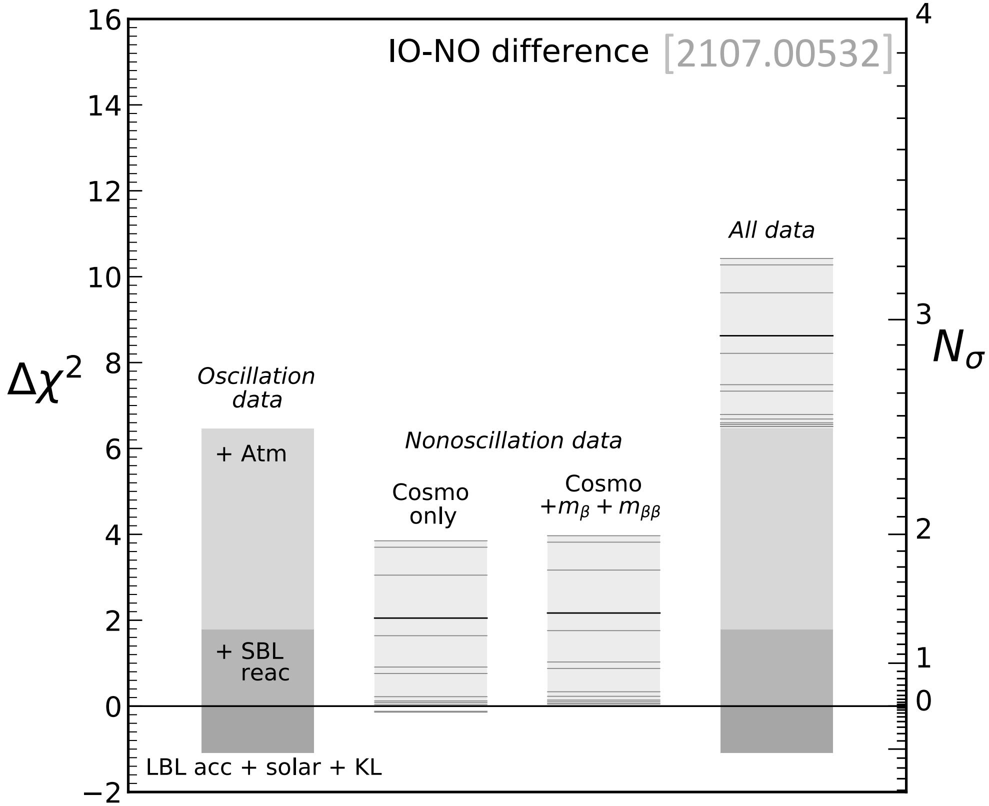
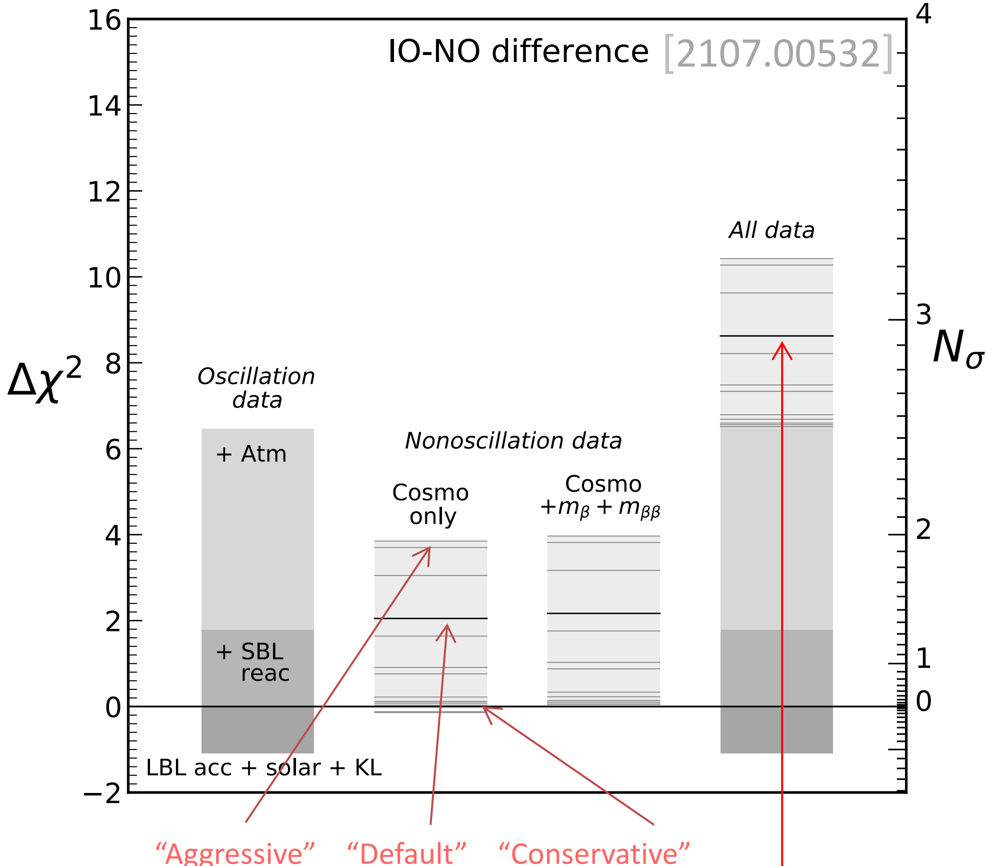
Statistical significance of IO-NO difference



2.5σ (osc)

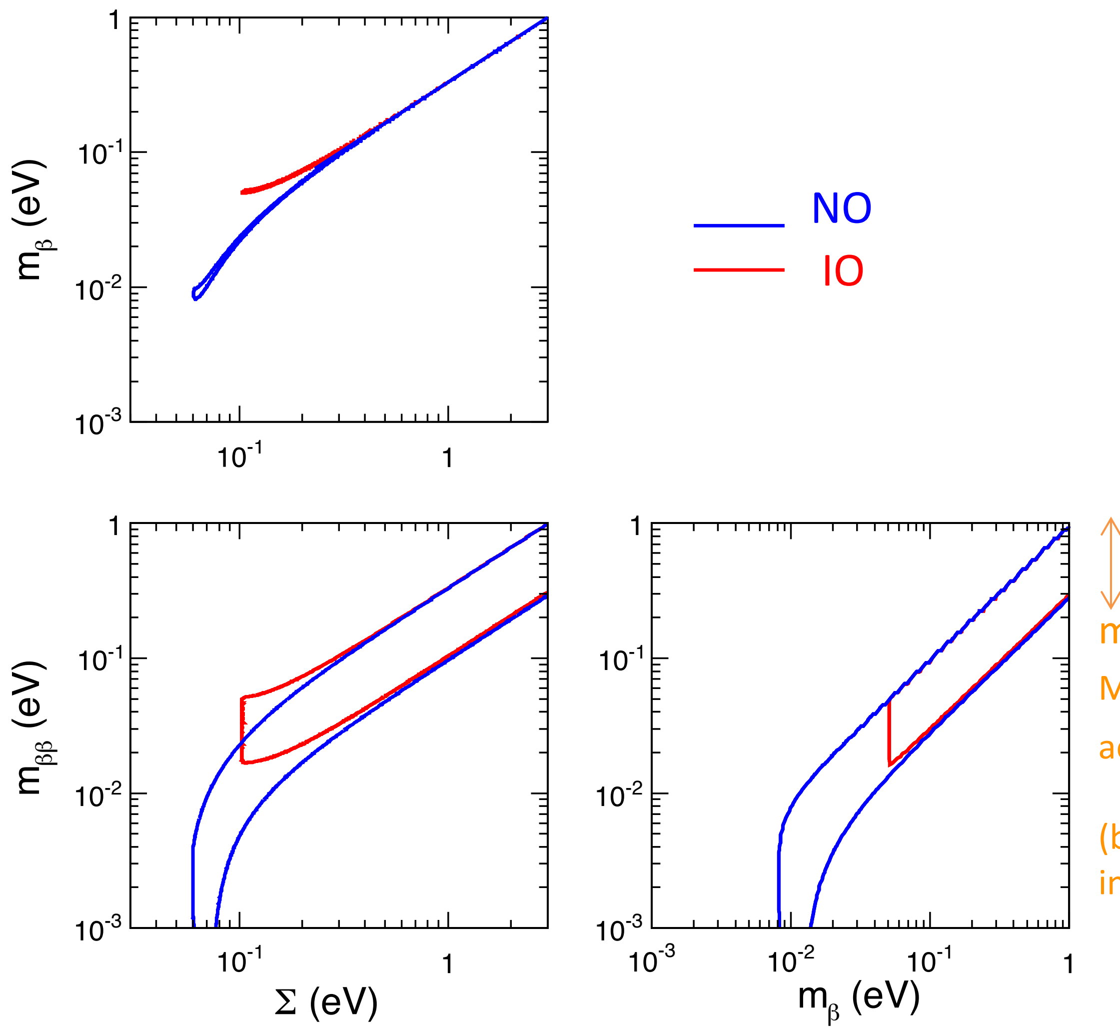
Statistical significance of IO-NO difference



2.5σ (osc) ⊕ up to 2.0σ (nonosc) =

2.5σ – 3.2σ in favor of NO

Non-oscillation parameter space (2σ) constrained by oscillations:



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

(but: no NME uncertainties included here!)

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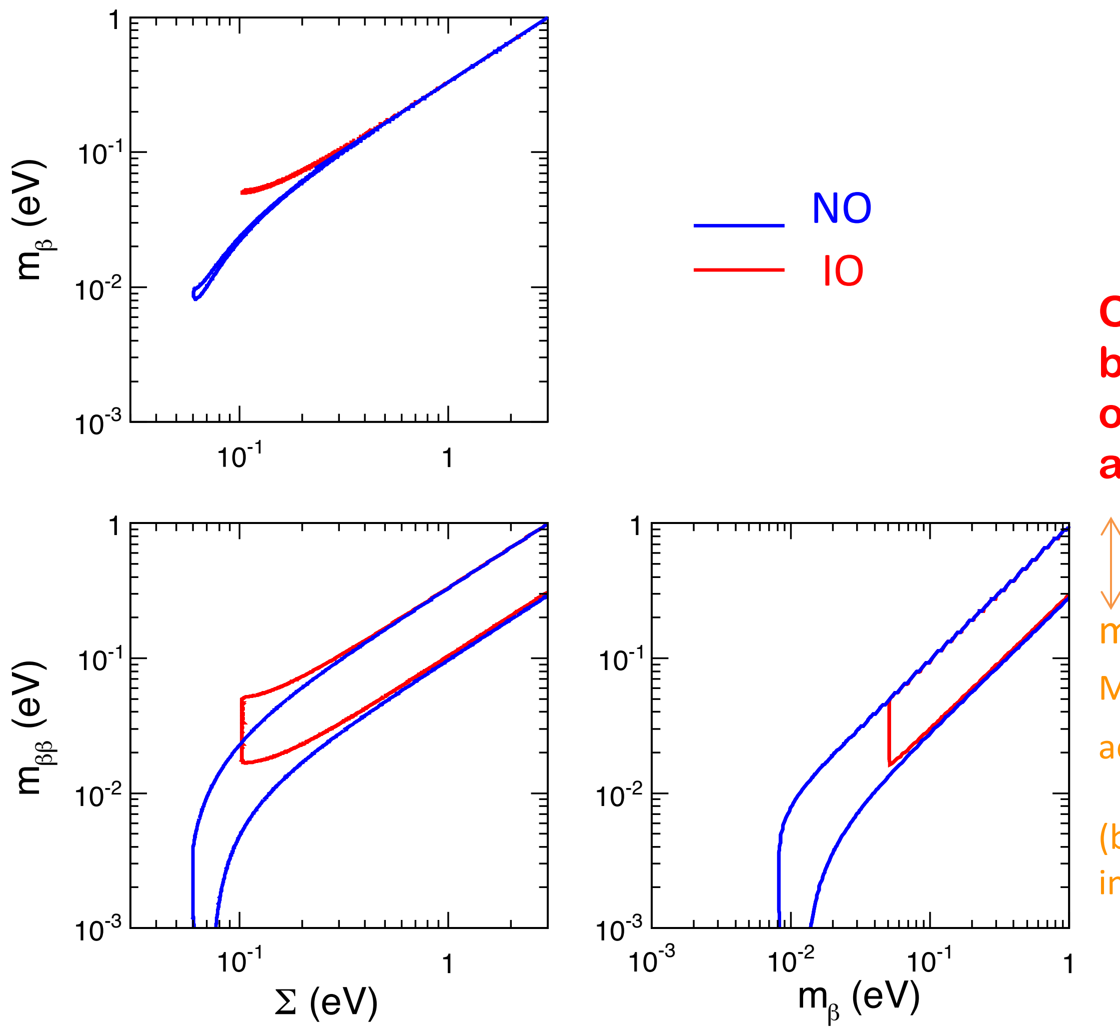
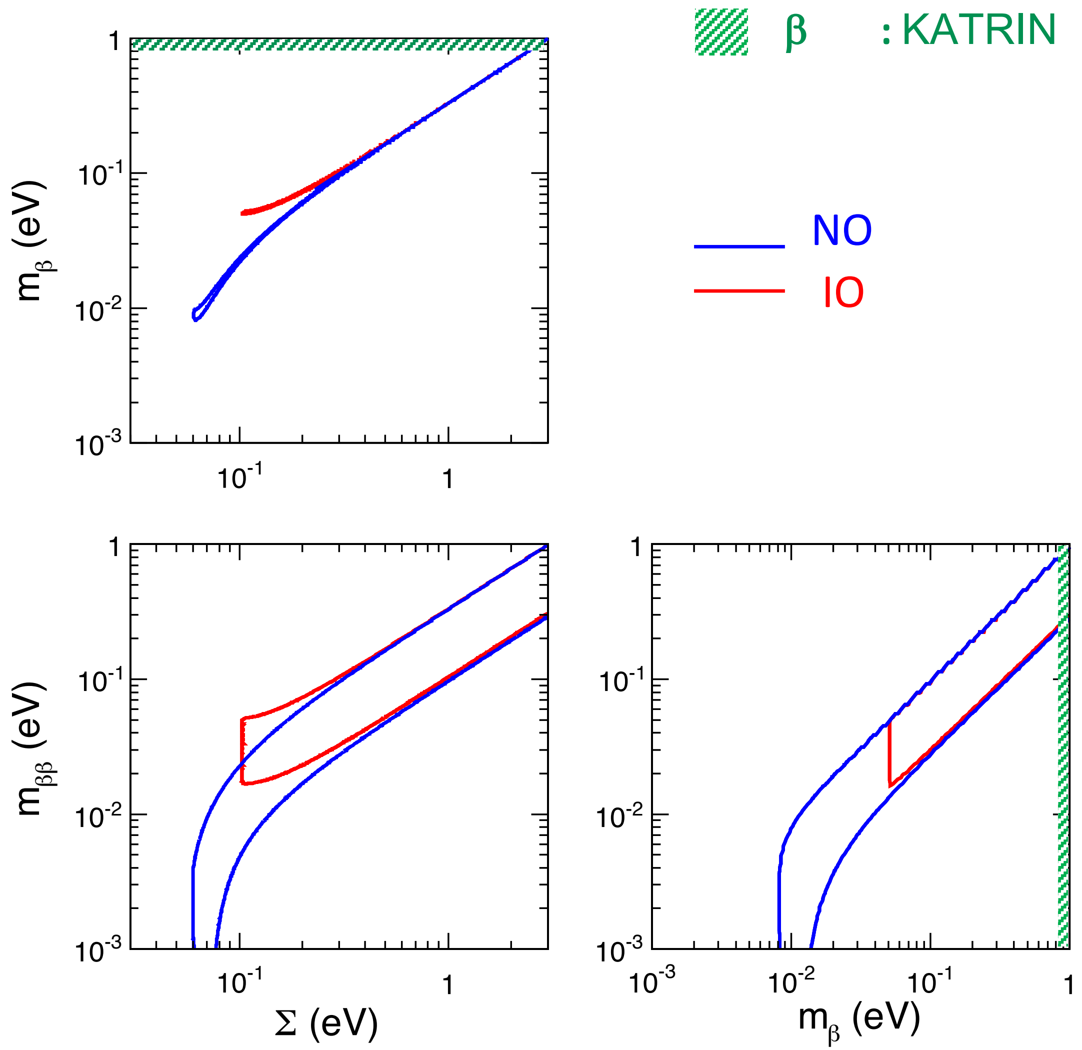


Outstanding work by Serguey et al. on $0\nu\beta\beta$ physics and param. space

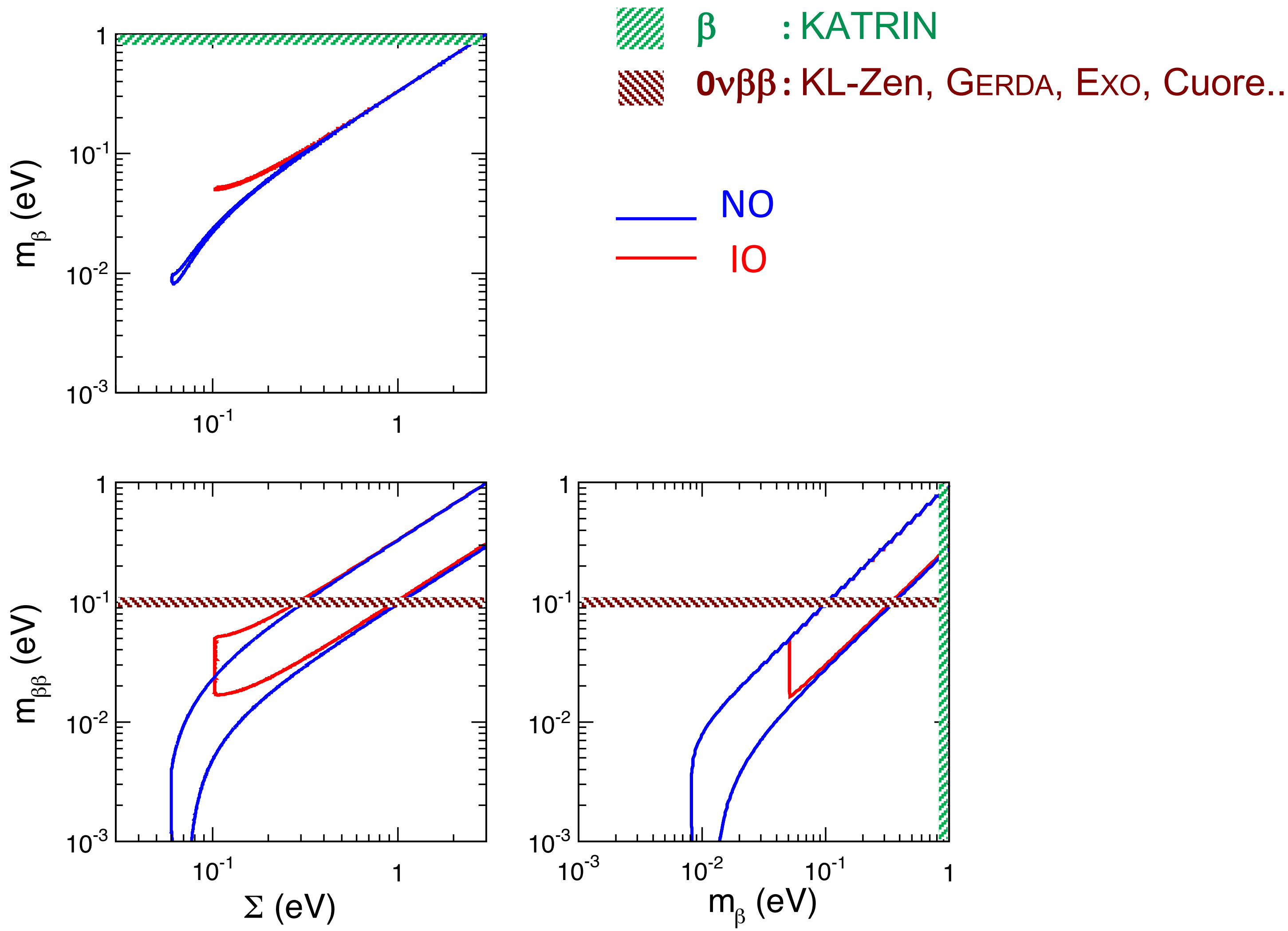
$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

(but: no NME uncertainties included here!)

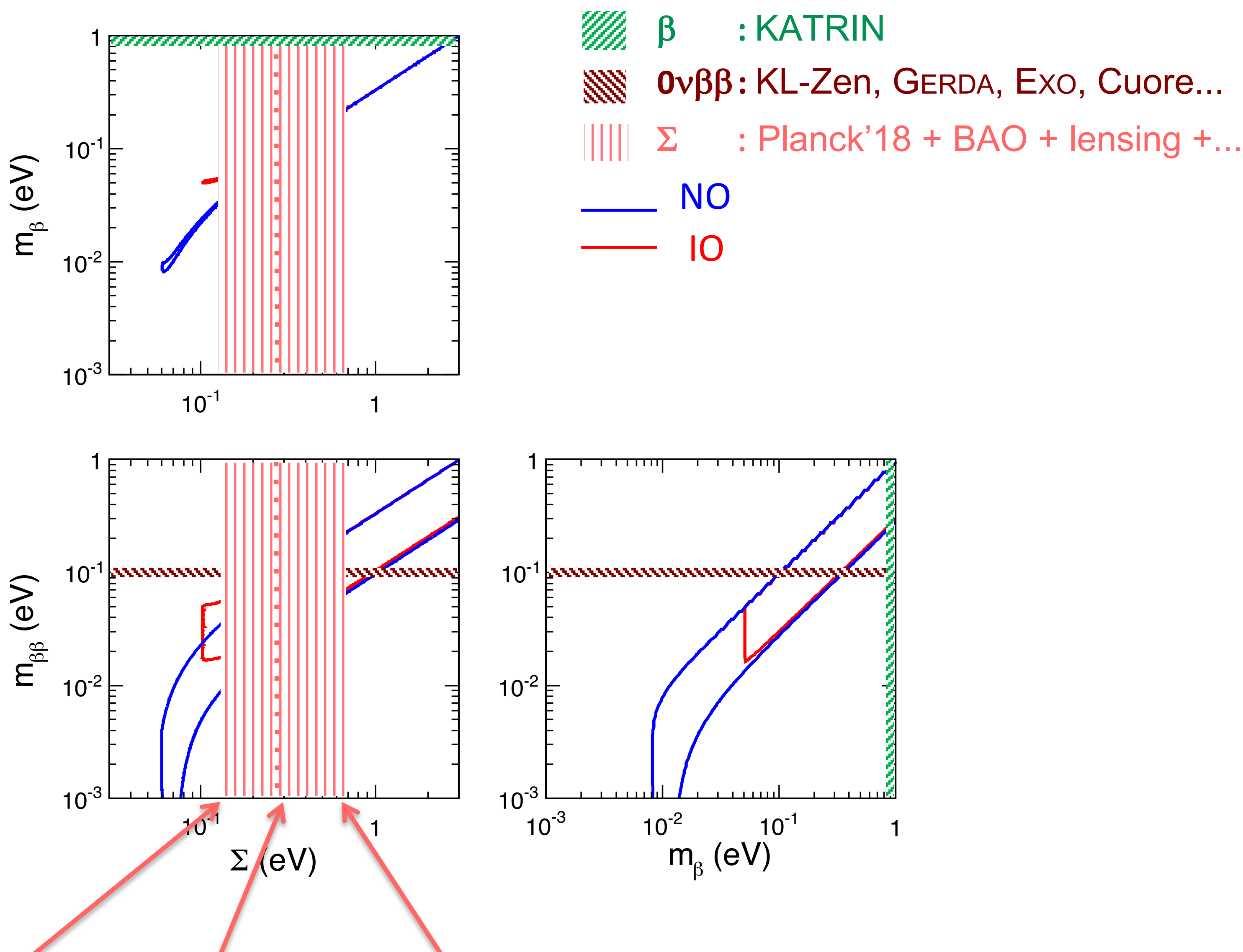
No signal (yet) in these planes, but… upper limits on m_β …



… on $m_{\beta\beta}$, starting to cover non-degenerate mass regions …

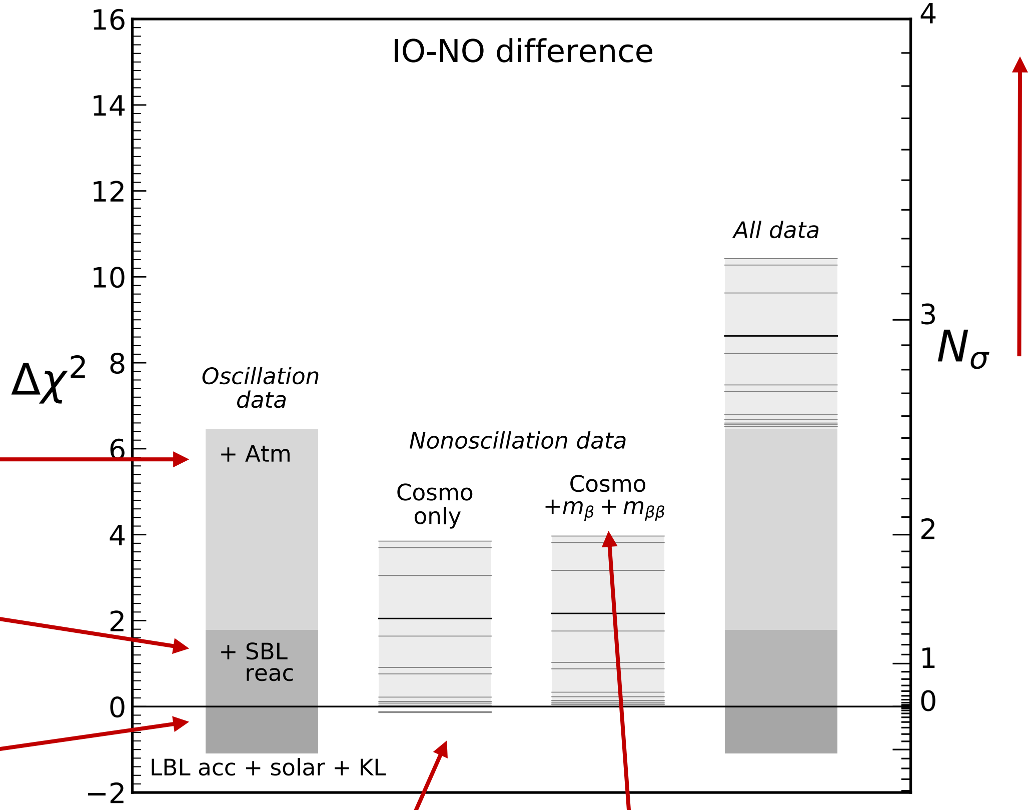


… and on Σ, from a variety of cosmo bounds, with IO "under pressure"



"Aggressive" "Default" "Conservative" cosmological limits

Prospects



SK, IC-CD
+new atm

JUNO

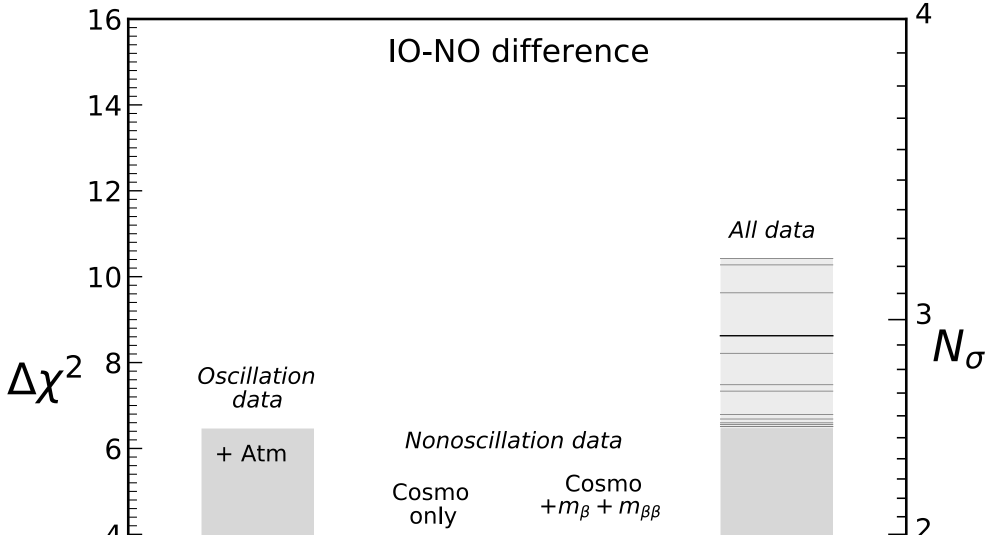
T2K, NOvA
+new LBL

Upcoming
cosmo
surveys

Beyond
current β, ββ
generation?

We may expect
a growing
significance
(if data converge)
…or surprises,
(if data diverge)

Prospects



We may expect a growing significance *(if data converge)* …or surprises, *(if data diverge)*

…Also hope that Serguey and all of us can see the next SN explosion, with NO/IO signatures via ν collective or nonadiabatic effects!

Back to double-exponential crossing probability…
…to give Serguey further work to do on this topic!

$$P' = \frac{\exp\left[-\pi r_0 \frac{\Delta m^2}{2p}(1-\cos 2\theta)\right] - \exp\left[-2\pi r_0 \frac{\Delta m^2}{2p}\right]}{1-\exp\left[-2\pi r_0 \frac{\Delta m^2}{2p}\right]}$$

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Well-known aspects of a 2ν system with hamiltonian H(t)

H = constant	← vacuum (reactors), constant-density matter (accelerators)
H = slowly changing	← adiabatic evolution in matter (solar LMA solution)
H = changing in time	← nonadiabatic evolution (Earth layers, SN shock front)

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Nonadiabatic level crossing ("two-level tunnelling") for H linear in time (dH/dt ≠ 0)

Solved by **Landau, Zener** (& Stueckelberg) in 1932: **LZ** or **LZS** single-exponential formula.
But actually solved first by **Majorana** (same year!) for spin flip in a magnetic field:
Majorana, E., 1932. Atomi orientati in campo magnetico variabile. Il Nuovo Cimento 9 (2), 43–50.
It should be called MLZS or LSZM formula! See quant-ph/2203.16348 (Phys. Rept.) →

quant-ph/2203.16348

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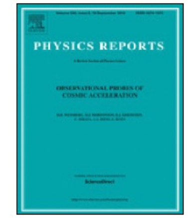

Nonadiabatic Landau–Zener–Stückelberg–Majorana transitions, dynamics, and interference

Oleh V. Ivakhnenko [a,b], Sergey N. Shevchenko [a,c,b,*], Franco Nori [b,d]

[a] *B. Verkin Institute for Low Temperature Physics and Engineering, Kharkiv 61103, Ukraine*
[b] *Center for Quantum Computing, Cluster for Pioneering Research, RIKEN, Wako-shi, Saitama 351-0198, Japan*
[c] *V. N. Karazin Kharkiv National University, Kharkiv 61022, Ukraine*
[d] *Physics Department, University of Michigan, Ann Arbor, MI 48109-1040, USA*

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Coherent destruction of tunneling
Kibble–Zurek mechanism
Photon-assisted tunneling
Rapid adiabatic passage
Quantum control
Classical coherent phenomena

ABSTRACT

Since the pioneering works by Landau, Zener, Stückelberg, and Majorana (LZSM), it has been known that driving a quantum two-level system results in tunneling between its states. Even though the interference between these transitions is known to be important, it is only recently that it became both accessible, controllable, and useful for manipulating a growing number of quantum systems. Here, we systematically study various aspects of LZSM physics and review the relevant literature, significantly expanding the review article in Ref. Shevchenko et al. (2010).

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$$P' = \frac{\exp\left[-\pi r_0 \frac{\Delta m^2}{2p}(1-\cos 2\theta)\right] - \exp\left[-2\pi r_0 \frac{\Delta m^2}{2p}\right]}{1-\exp\left[-2\pi r_0 \frac{\Delta m^2}{2p}\right]}$$

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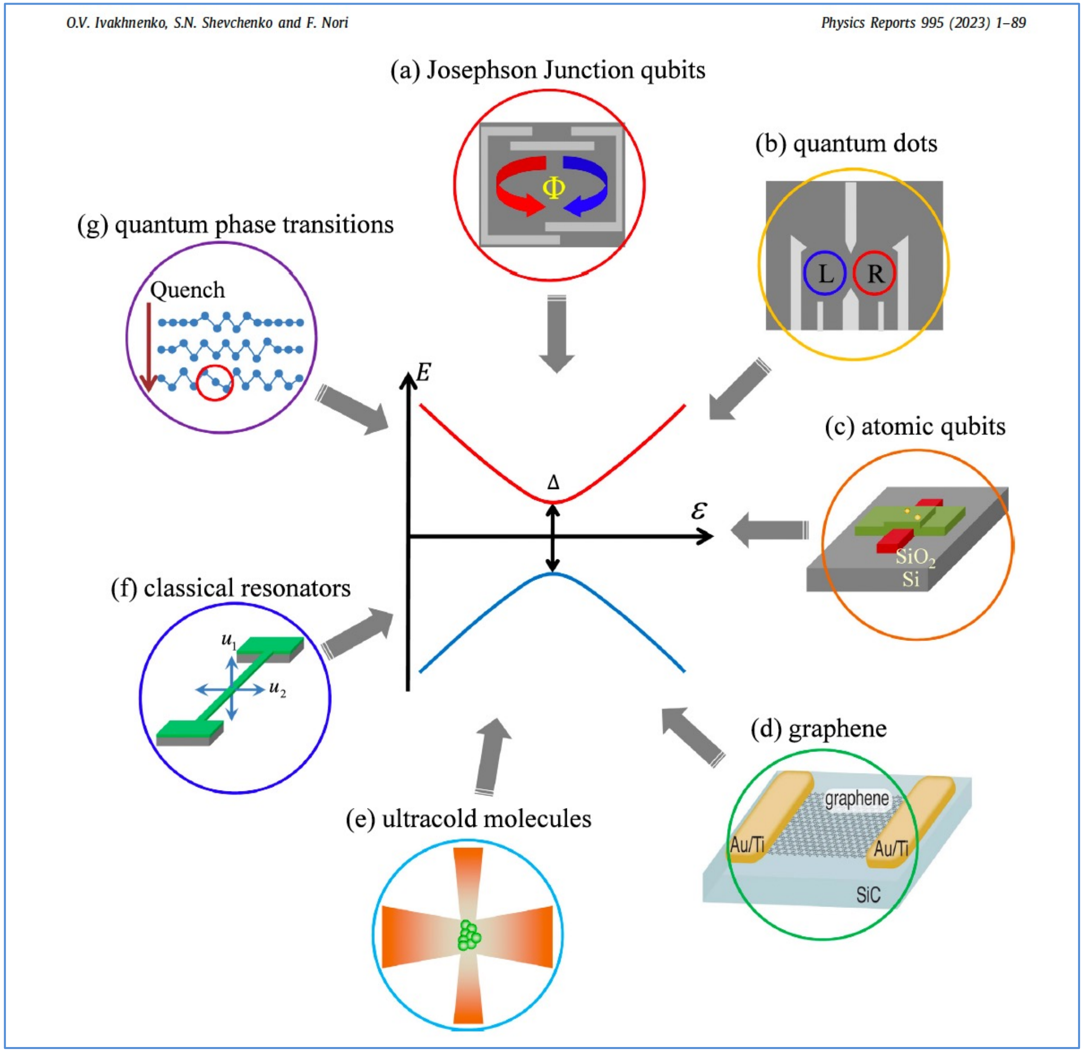
It should be called MLZS or LSZM formula! See quant-ph/2203.16348 (Phys. Rept.) →

Nonadiabatic level crossing for nonlinear H: infinite possibilities, huge literature!

For solar **ν** with exponentially decreasing H: solved by Serguey (1988, above form of P_c)
"Double exponential" form satisfies well all symmetries and limits, and largely applies
to other H=H(t) profiles, e.g., power laws (Kuo & Pantaleone + others) with modifications

Nonadiabatic level crossing: an interdisciplinary topic of increasing interest!

... especially in the era of qbit manipulation ...



In this recent 89-page review:

- emphasis on Majorana primacy for (elegant) solution with linear H

- discussion of known solutions for nonlinear H (including ~periodic, akin to Serguey's mantle-core-mantle ...)

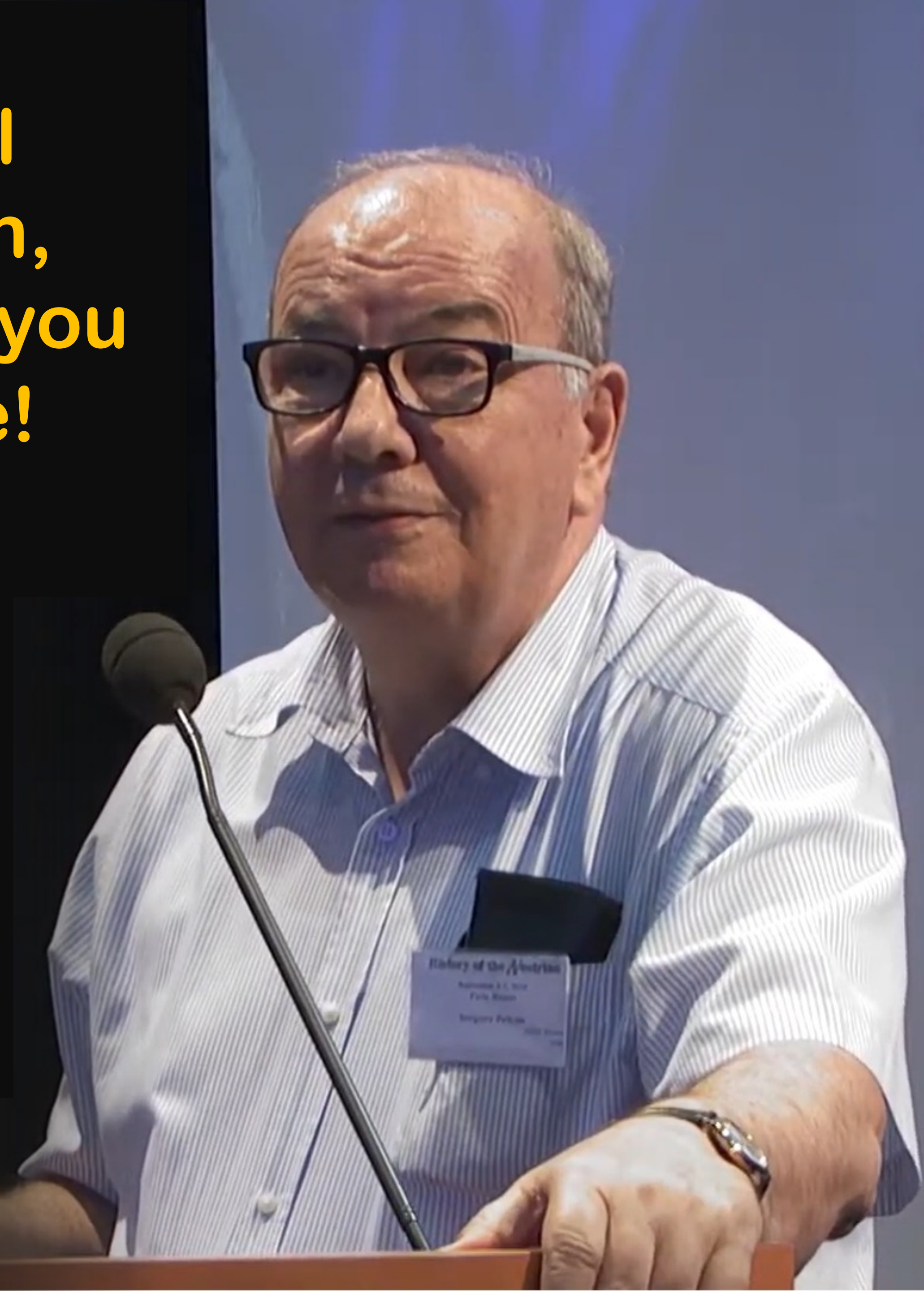
- N-level factorization of crossings

... but no intersection with ν literature on nonadiabatic / N-level evolution!

... and (at first sight) no equivalent of a "double-exponential" formula of general applicability to crossings

Might be a nice read – and inspire further work on Pc, Serguey!

Whatever you will choose to work on, we shall learn from you excellent science!



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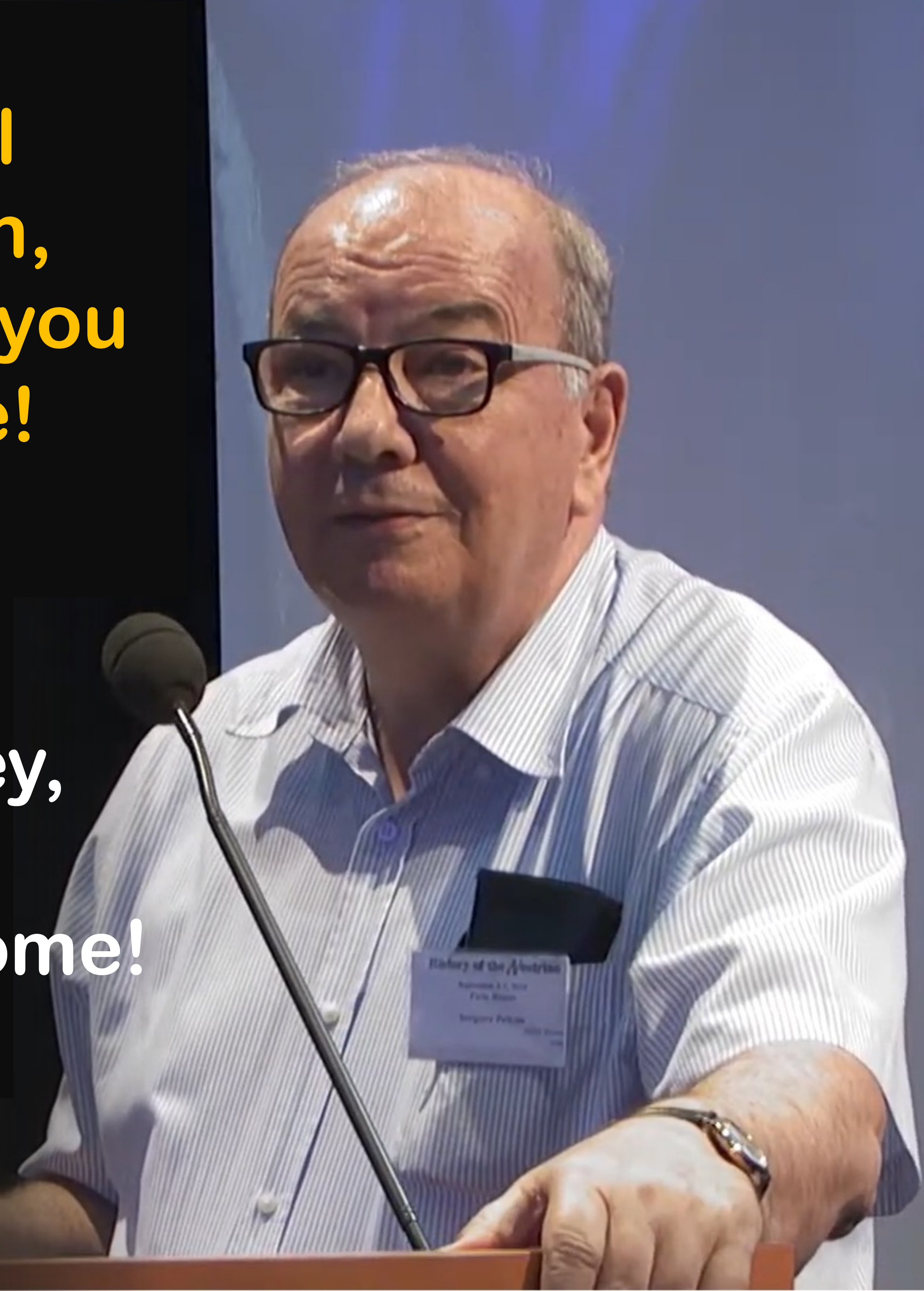
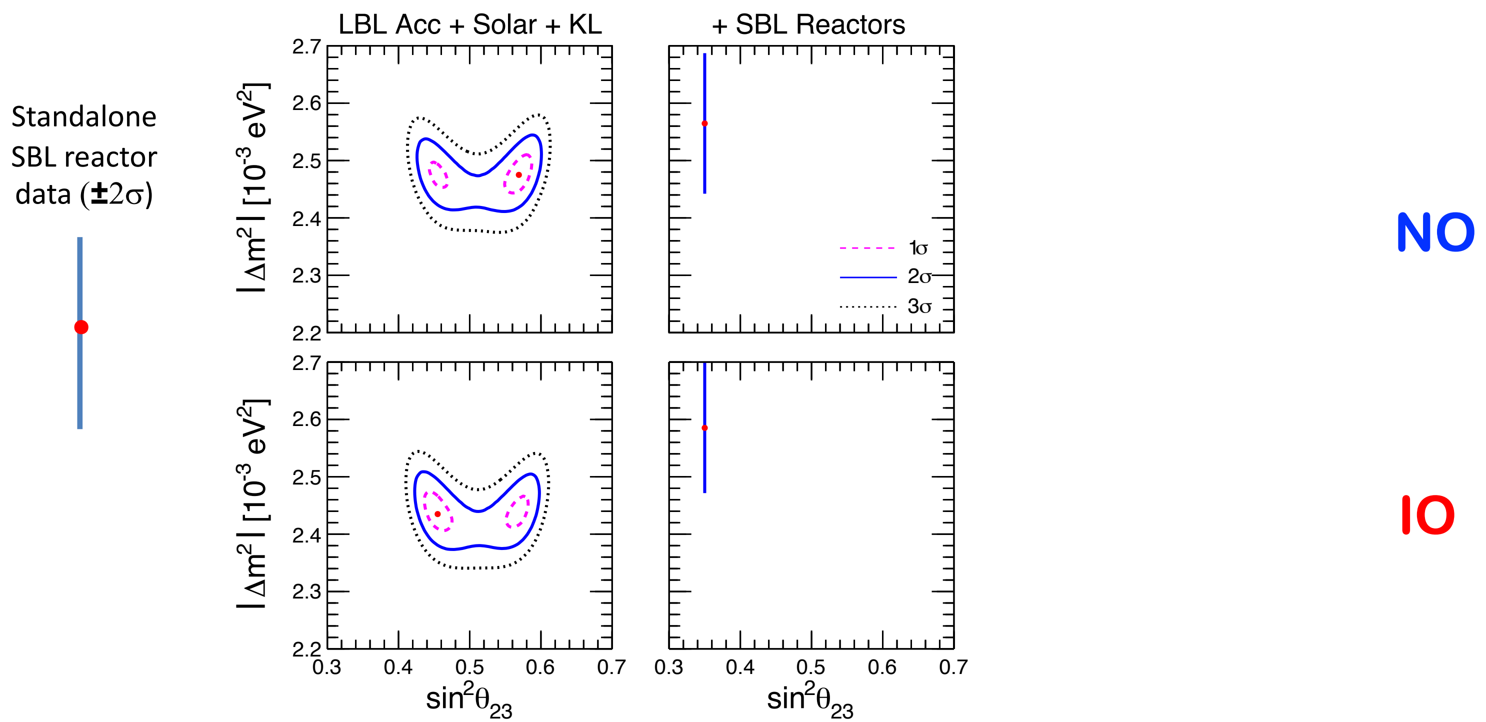
Thank you Serguey, and best wishes for many years to come!



Extra slides on mass ordering, mainly based on [2107.00532]

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

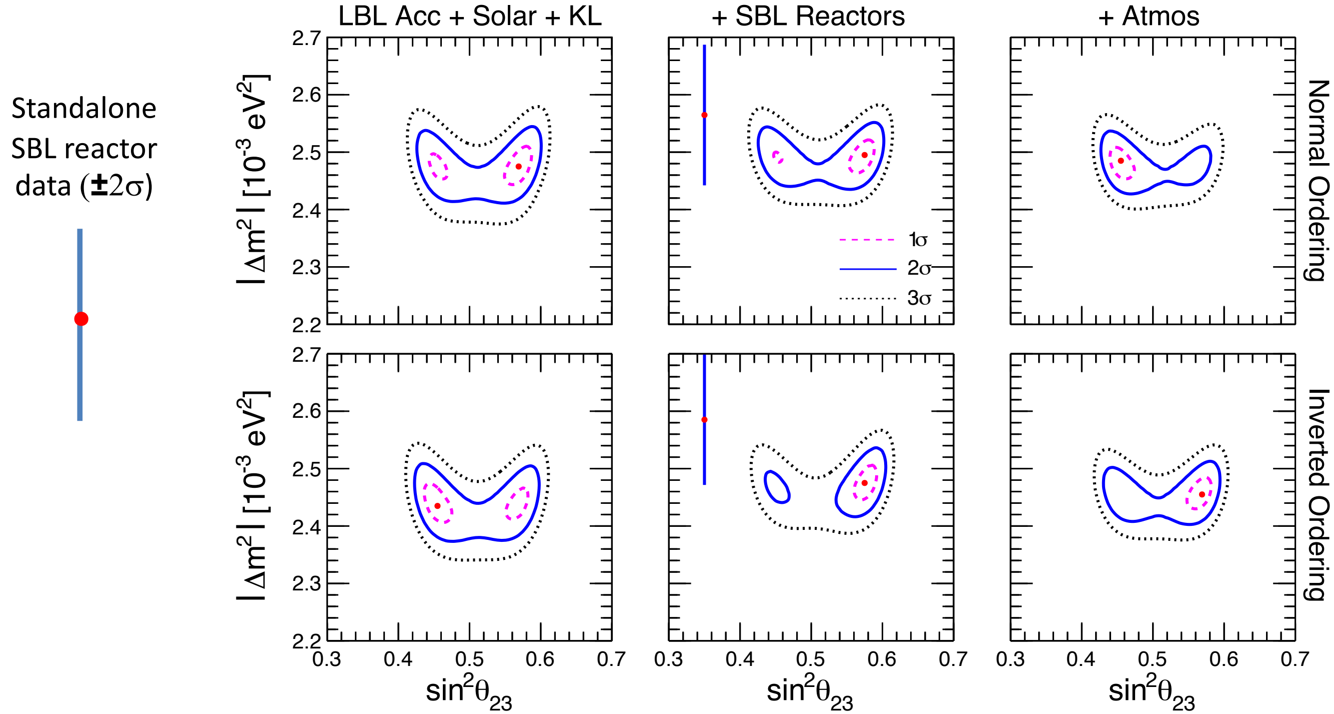


SBL reactors prefer **higher** Δm^2 than LBL accel. (and atmos.) expts.

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

($\pm\Delta m^2$, θ_{23}) pair

Standalone SBL reactor data ($\pm 2\sigma$)



NO

IO

SBL reactors prefer **higher** Δm^2 than LBL accel. (and atmos.) expts.

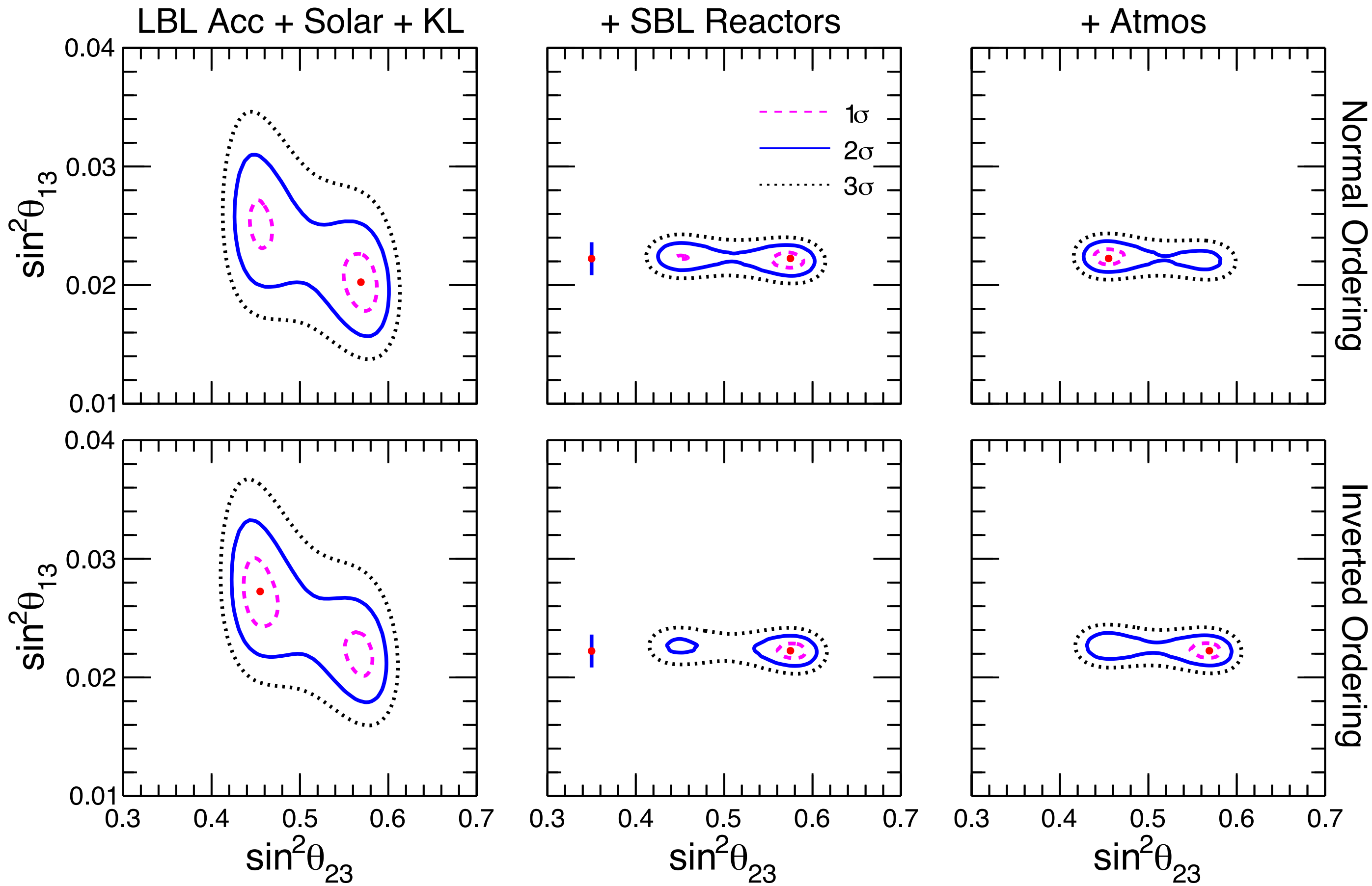
Relative difference is **smaller** for **NO** and for non-maximal θ_{23} mixing

→ Better agreement reached for **NO** & **nonmax θ_{23} at intermediate Δm^2**

→ SBL reactor data not sensitive to sign(Δm^2) and θ_{23}, but affect their likelihood

Future: handle on NO/IO from complementary Δm^2 data (JUNO+Acc/Atm)

Another pair: (θ_{13} , θ_{23})

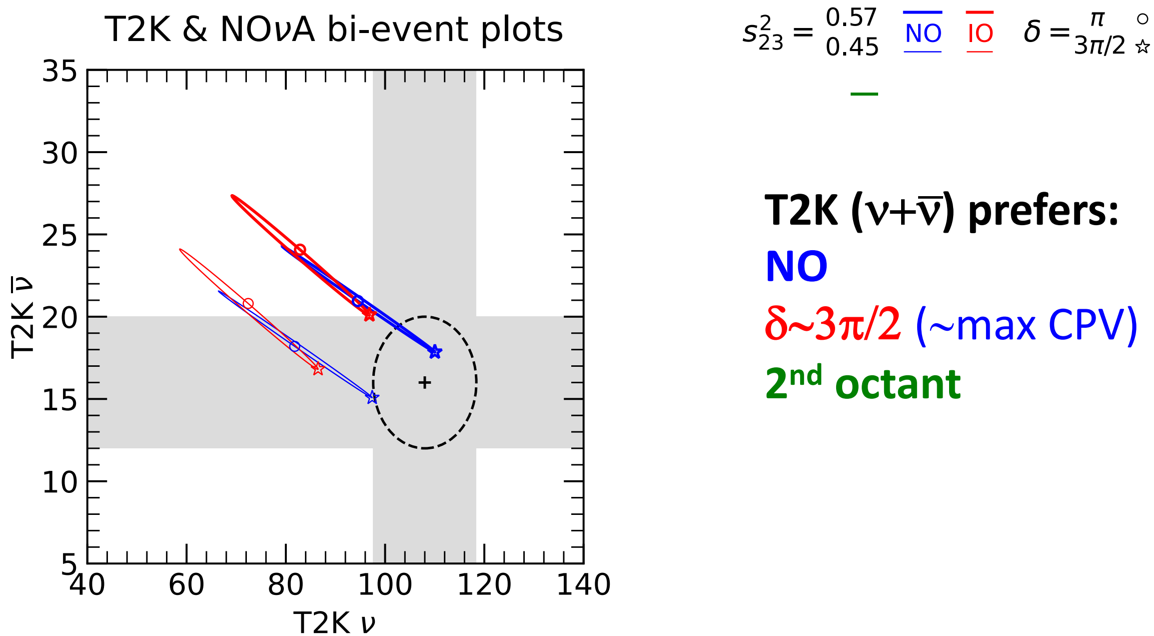


Anticorrelation due to leading $\nu_\mu \rightarrow \nu_e$ term $\sim \sin^2\theta_{23}\ \sin^2 2\theta_{13}$

Narrow and "low" θ_{13} reactor angle selects 2nd octant [especially in IO]

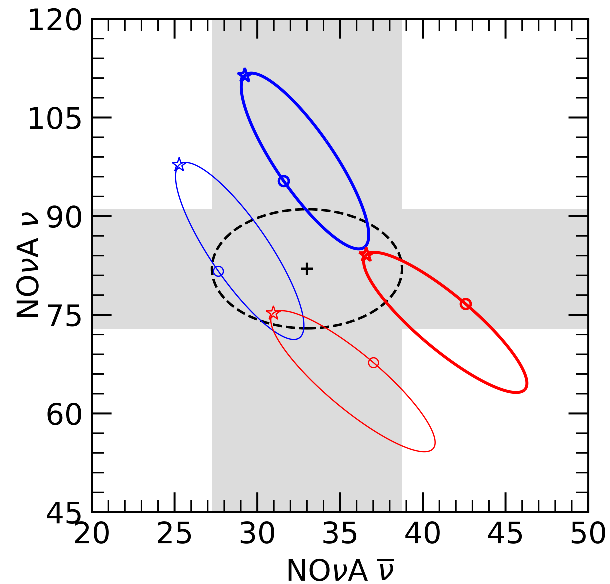
1st octant preferred by atmospheric data in NO (not in IO) → fragile!

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



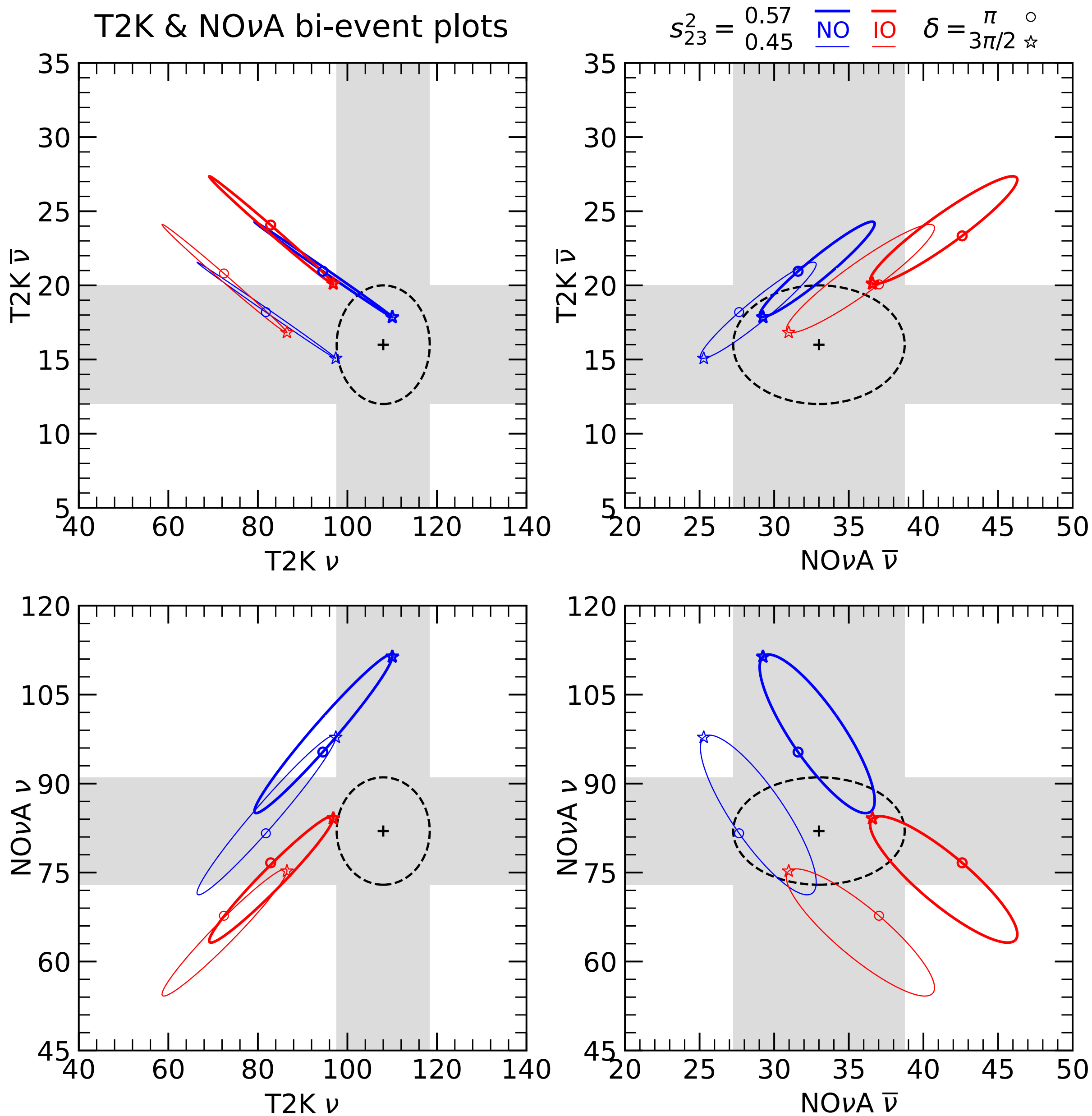
T2K (ν+$\overline{\nu}$) prefers:
NO
δ~3π/2 (~max CPV)
2nd octant

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

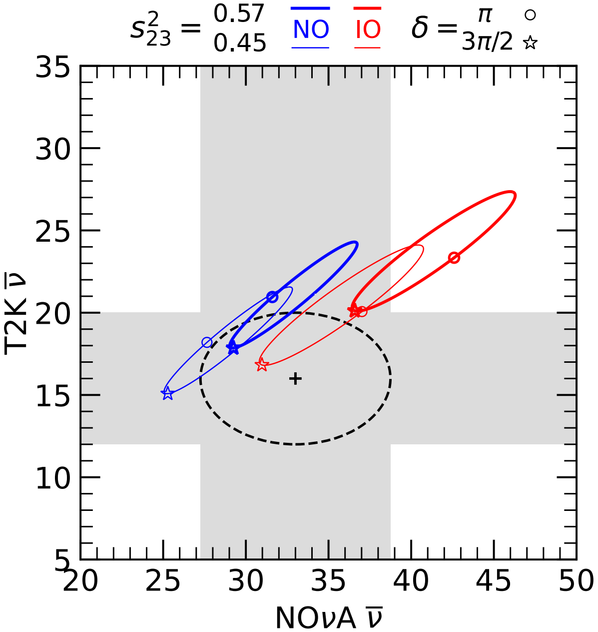


→ **T2K and NOVA, separately: NO preferred; CP and octant ambiguous**

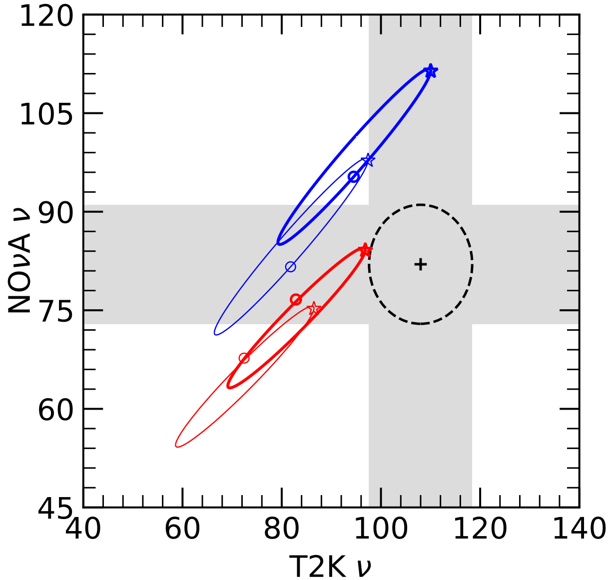
The same info can be reorganized in terms of T2K vs NOvA:



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

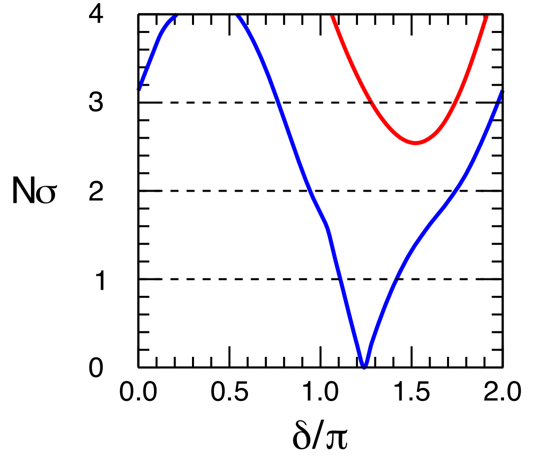
→ T2K and NOVA, jointly: IO and CPV preferred; octant ambiguous

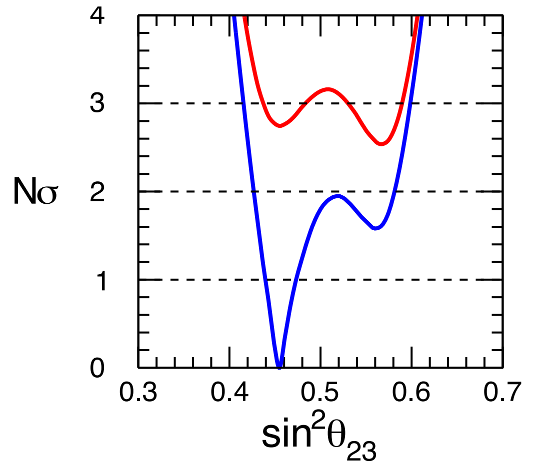
...In the T2K+NOvA combination, still unstable results on three unknowns:

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

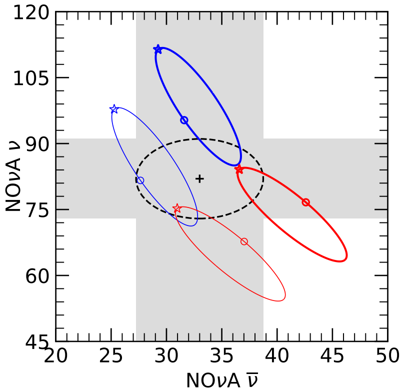
Further data may tilt the current balance, or even point to new physics (NSI?)

LBL Acc + Solar + KamLAND (current)

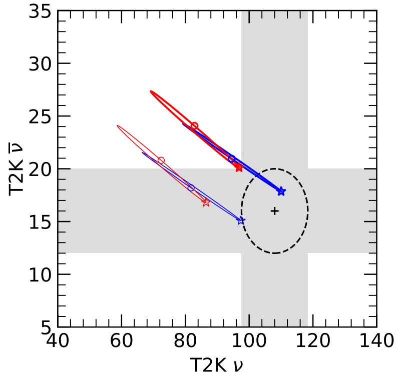




NOvA close to different options within 1σ...



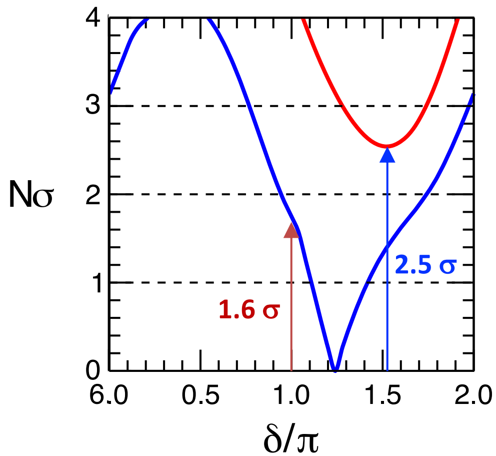
T2K close to the edge of its expected sensitivity...

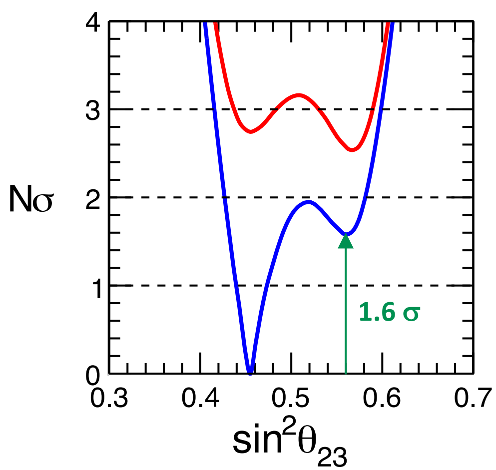


T2K + NOvA joint analysis?

Hints on oscillation
unknowns,
2021...

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





...Educated guess on
unknowns,
after Neutrino 2022

→ presumably >99% CL
→ presumably >90% CL
→ presumably flipped to > $\pi/4$

*Main impact expected from **new SK atm. data in combination with T2K**, which may win over the T2K-NOvA tension and other small changes*

Wait for IC-DC atm. data and T2K+NOvA joint fit!

Watch for synergy of various |Δm²| measurements: *convergence / divergence in true / wrong mass ordering*