ν_e ν_μ ν_τ

Phenomenology of 3ν oscillations

Eligio Lisi (INFN Bari)

ν_1 ν_2 ν_3

Vulcano Workshop 2022 – Elba Island – September 29th, 2022

Outline:

- The standard 3ν framework
- Oscillation knowns and unknowns
- Impact of non-oscillation physics
- Conclusions

The standard 3ν framework

Mixing 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

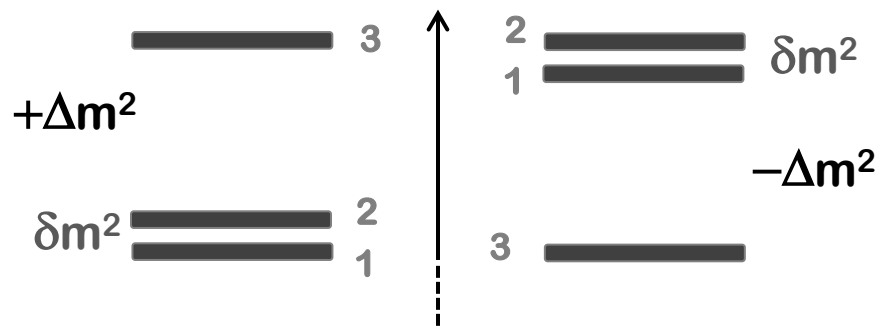
1-3 rotation
+ CPV "Dirac" phase
U(ν) → U*($\overline{\nu}$)

1-2 rotation

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

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

"Normal" Ordering
N.O.



"Inverted" Ordering
I.O.

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

+ interaction energy in matter → ~ $G_F \cdot E \cdot$ density
+ absolute ν mass scale (not tested in oscillations)

Sketchy 3ν overview

5 knowns:

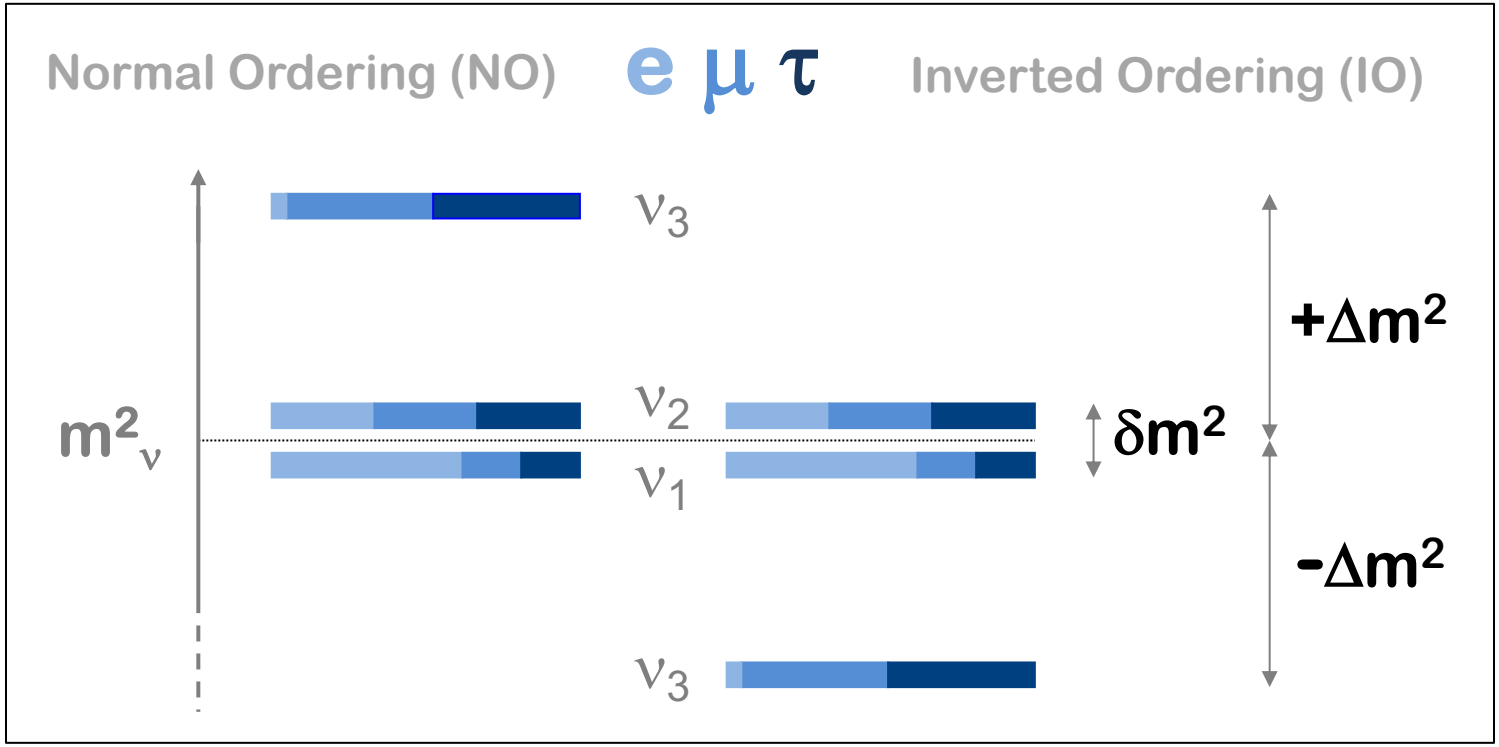
δm^2	~ 8 x 10^{-5} eV^2
Δm^2	~ 2 x 10^{-3} eV^2
$\sin^2\theta_{12}$	~ 0.3
$\sin^2\theta_{23}$	~ 0.5
$\sin^2\theta_{13}$	~ 0.02

Oscillations

Non-oscillat.

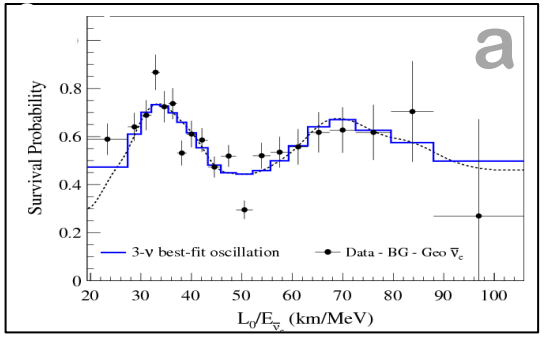
5 unknowns:

- **δ CPV** Dirac phase
- **sign(Δm^2)** → NO/IO
- θ_{23} **octant** degeneracy
- **absolute mass** scale
- **Dirac/Majorana** nature

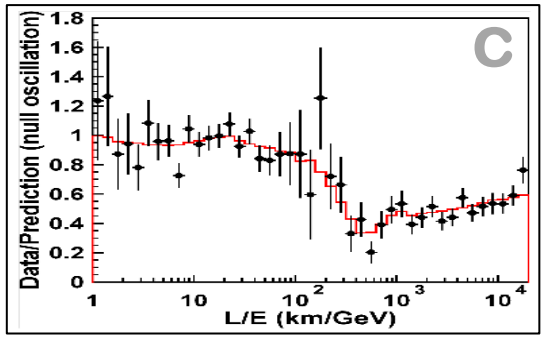


3ν oscillations probed by different experiments in different channels…

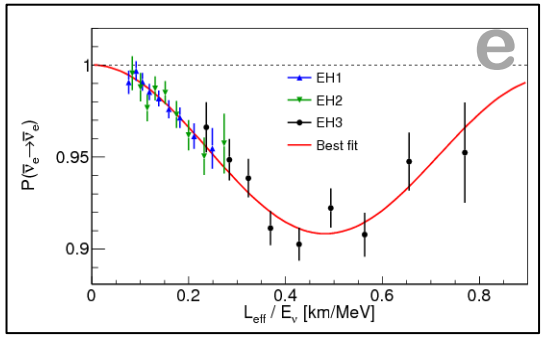
e→e (KamLAND, KL)



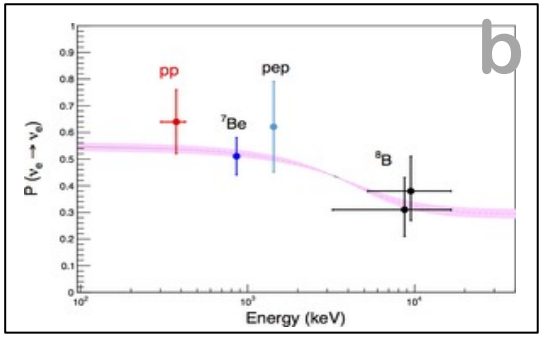
μ→μ (Atmospheric)



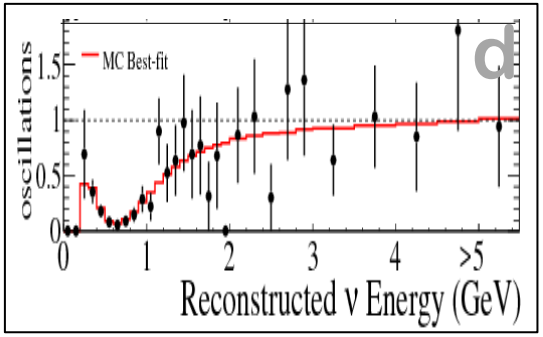
e→e (SBL Reac.)



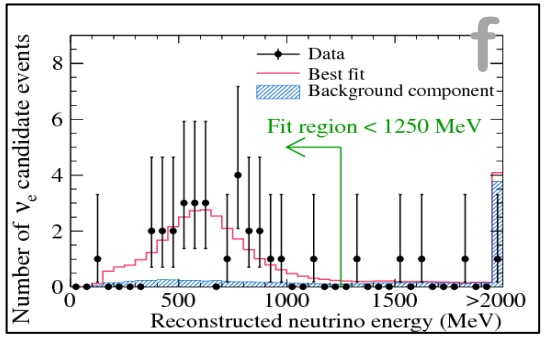
e→e (Solar)



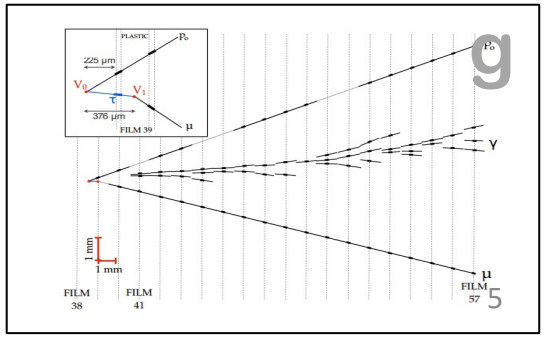
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

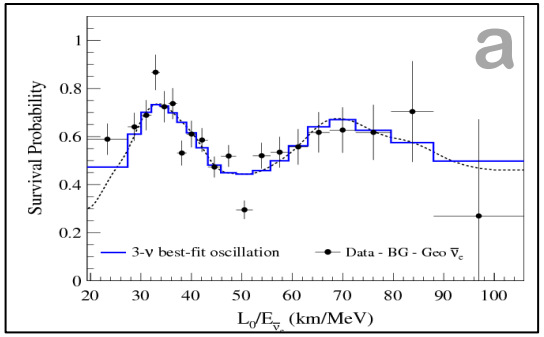


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

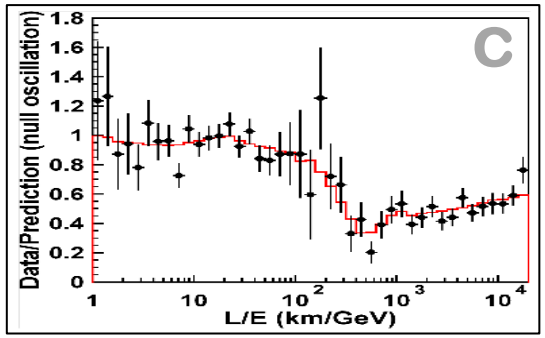
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot]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

… with amplitude and frequency governed by 2 (or 3) leading parameters

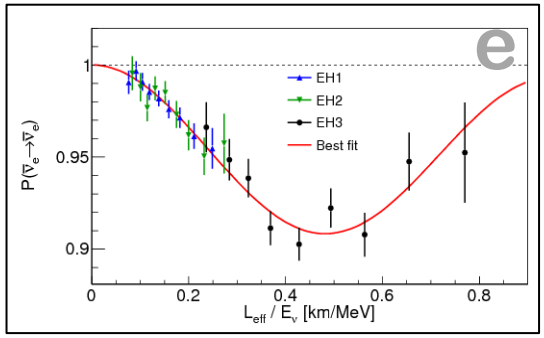
$e \to e$ (δm^2 , θ_{12})



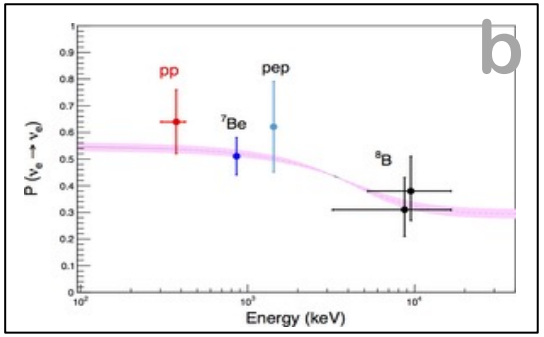
$\mu \to \mu$ (Δm^2 , θ_{23})



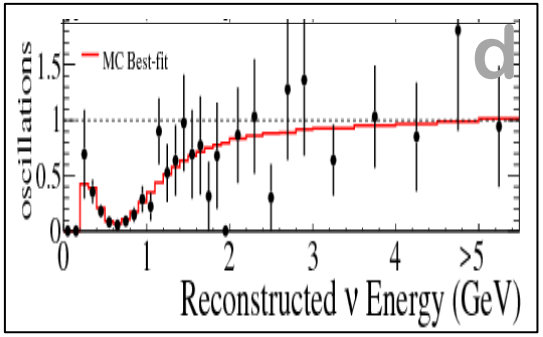
$e \to e$ (Δm^2 , θ_{13})



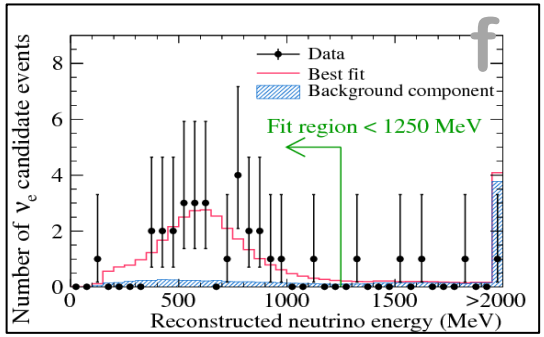
$e \to e$ (δm^2 , θ_{12})



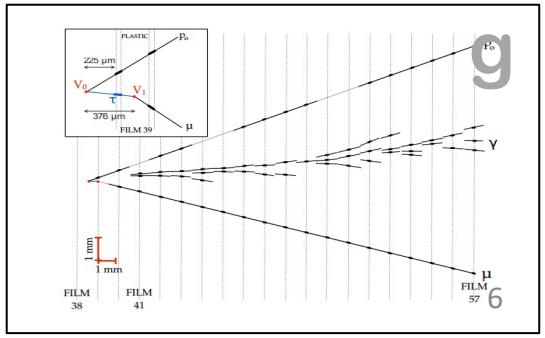
$\mu \to \mu$ (Δm^2 , θ_{23})



$\mu \to e$ (Δm^2 , θ_{13} , θ_{23})



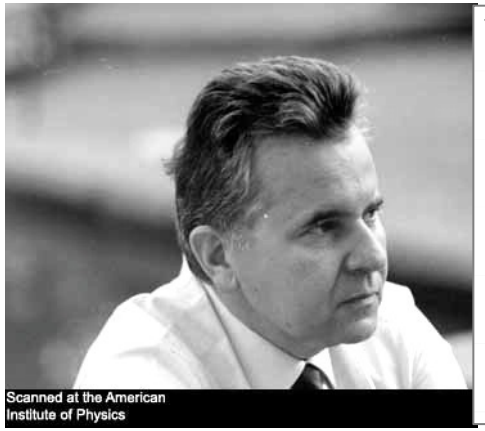
$\mu \to \tau$ (Δm^2 , θ_{23})



5 param.'s known & (over)constrained → consistency

Currently: focus on unknown par. & subleading effects, especially CPV via $\nu_\mu \to \nu_e$ in LBL accel. and atmos. expts and NO/IO mass spectrum via reactor expts + others

How do $\nu_\mu \rightarrow \nu_e$ oscillation searches probe CPV?



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TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*
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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

For two neutrinos, no CPV:

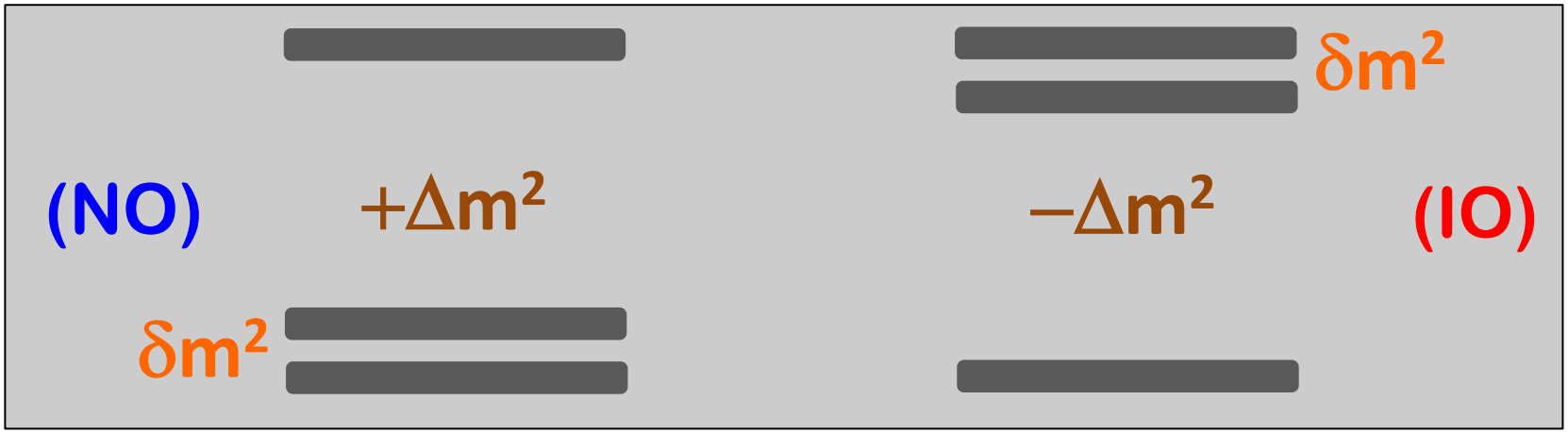
$$\overset{(-)}{\nu}_e = \cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2$$

For three neutrinos: new possible CPV phase δ, tested via ν versus $\bar{\nu}$

$$\overset{(-)}{\nu}_e = \cos\theta_{13}\, (\cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2) + e^{\pm i\delta} \sin\theta_{13}\, \nu_3$$

CPV is a genuine 3ν effect →
all oscillation parameters (known & unknown) are involved/entangled

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 <u>known sign</u>. Options:

$Q \sim \delta m^2$	medium-baseline reactors → JUNO
$Q \sim G_F N_e E$	ν–matter effects → atm & LBL accel. expt.
[$Q \sim G_F N_\nu E$	ν–ν collective effects → core-collapse SN]

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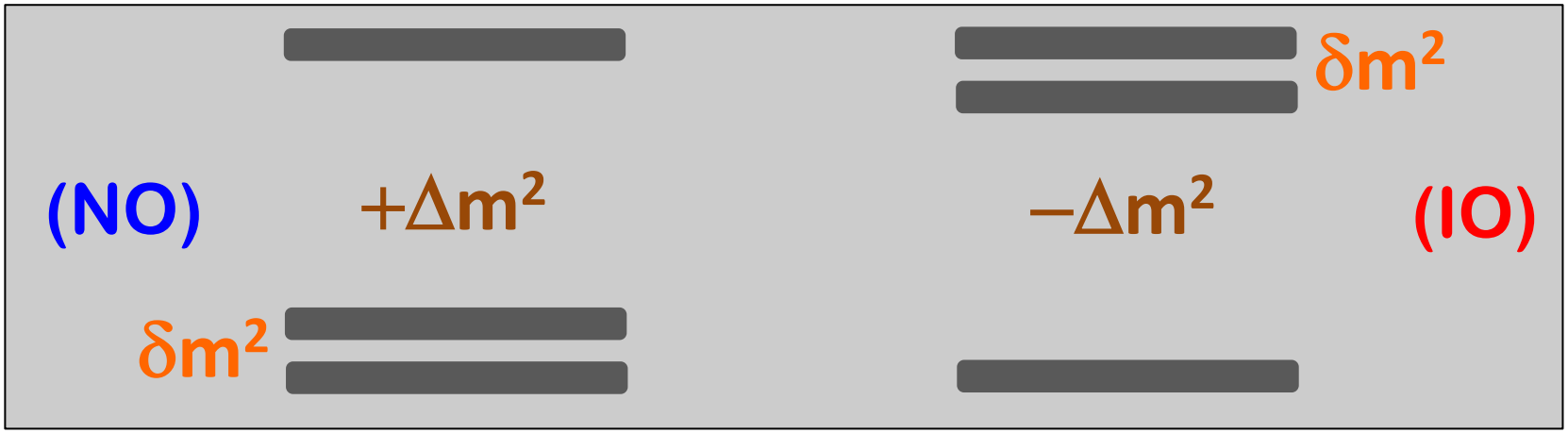

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$Q \sim G_F N_e E$	ν–matter effects → atm & LBL accel. expt.
[$Q \sim G_F N_\nu E$	ν–ν collective effects → core-collapse SN]

Additional tool: synergy of $|\Delta m^2|$ data from different experiments, e.g. two or more data from reactor + accelerator + atmospheric (should converge better in the true ordering than in the wrong one)

→ It makes sense to perform global analyses of all neutrino oscillation data, to squeeze information on subleading 3ν effects and to exploit correlations

Useful analysis 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

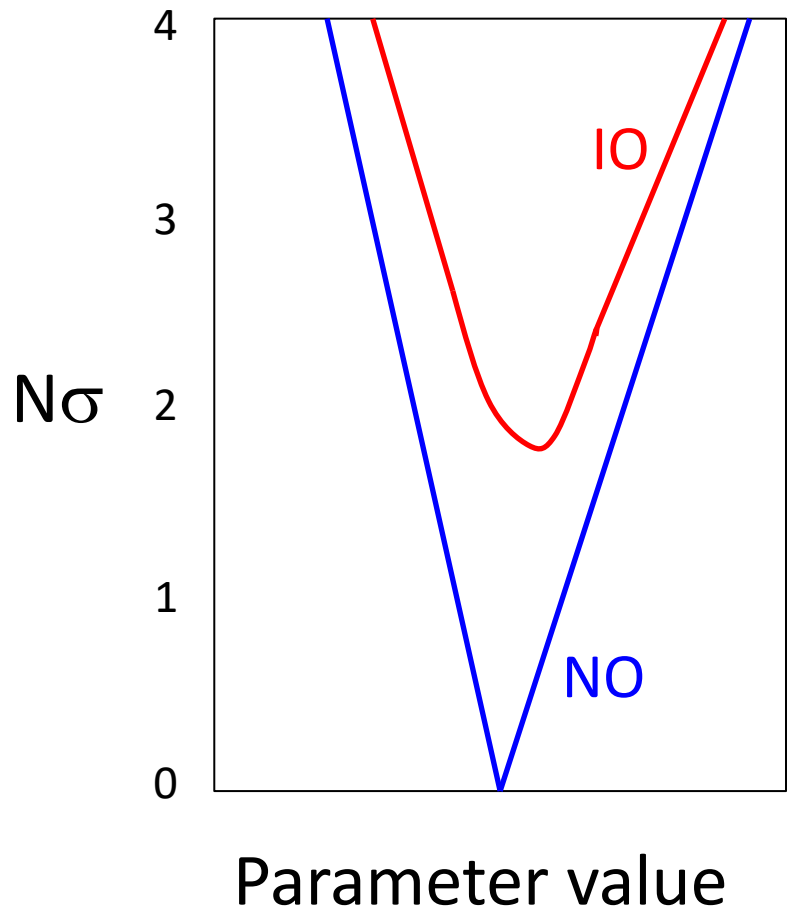
add sensitivity to Δm^2, θ_{13} and affect other parameters via correlations

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

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

$\Delta\chi^2$ statistics adopted for all datasets: $N\sigma = \sqrt{\Delta\chi^2}$ →

E.g.,



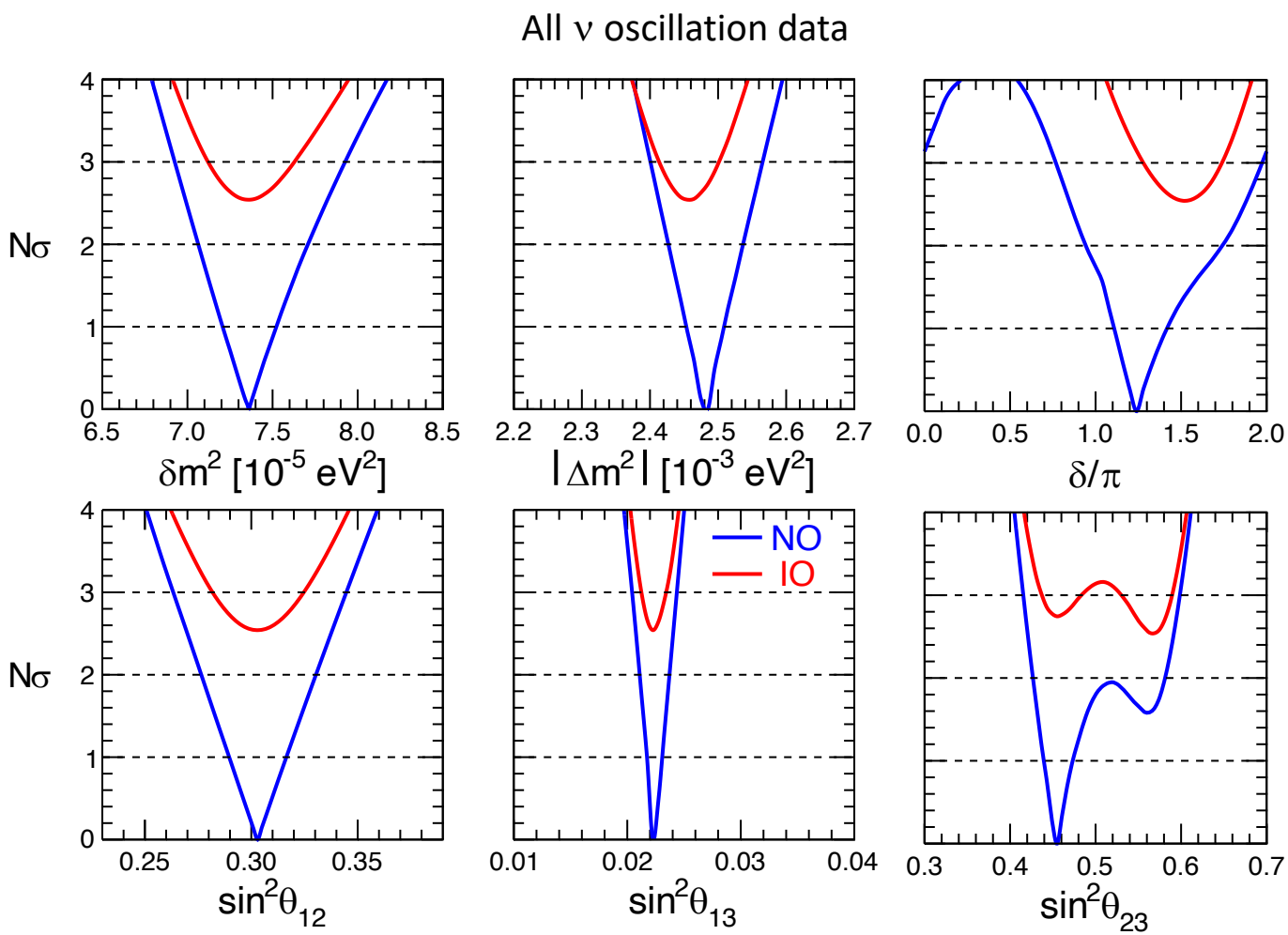
In the following: results from the 2021 global data analysis:
"Unfinished fabric of the three neutrino paradigm", Capozzi et al., hep-ph 2107.00532
(similar results from NuFit and Valencia groups in 2021)

+ educated guesses about the impact of unpublished data presented at Neutrino 2022
→ need to be checked by future global analyses (work in progress)

Status of known and unknown 3ν oscillation parameters, circa 2021

1σ error of **known** parameters

$\lvert\Delta m^2\rvert$	1.1%
δm^2	2.3%
θ_{13}	3.0%
θ_{12}	4.5%
θ_{23}	~ 6%



Hints on oscillation **unknowns (2021)**

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

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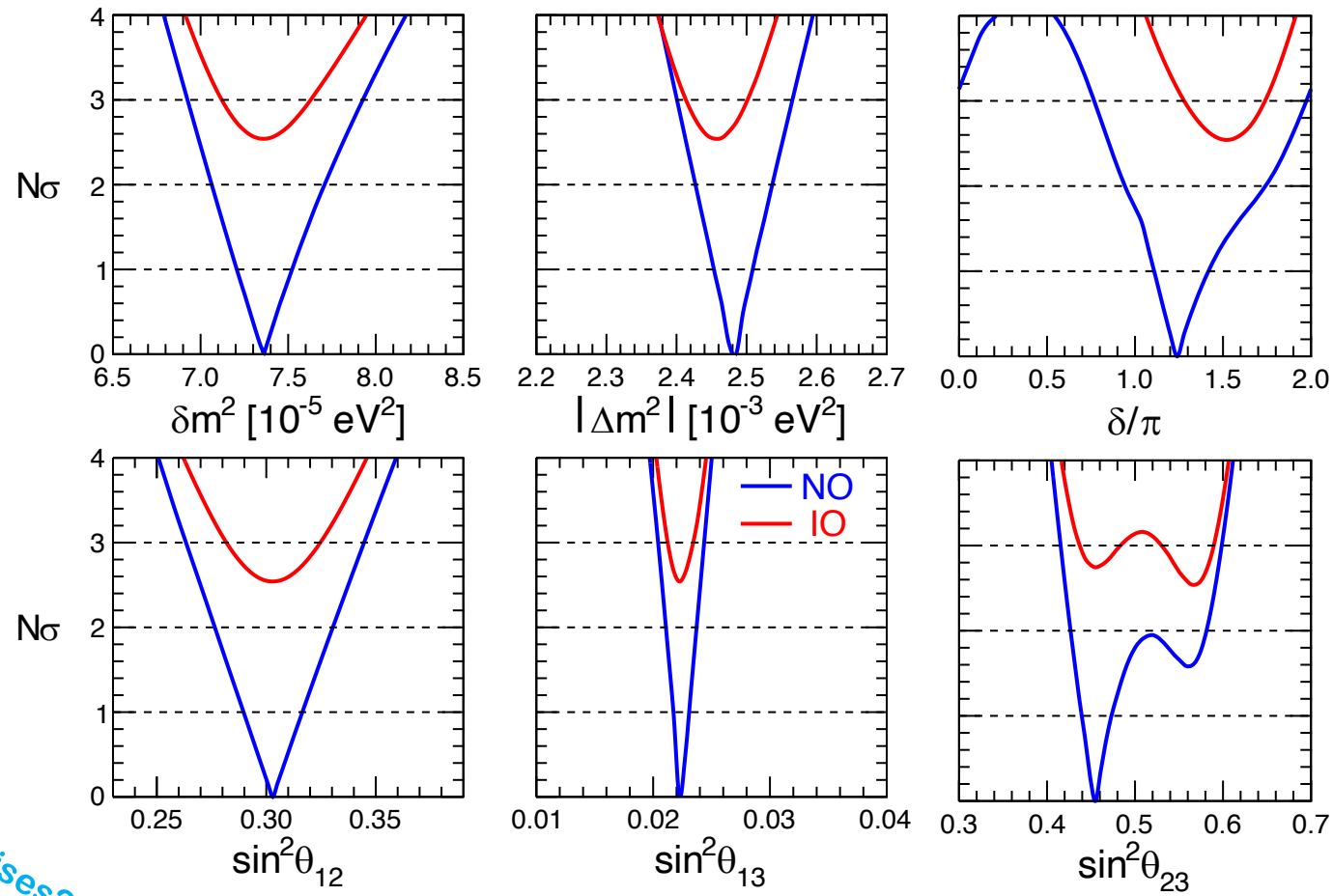
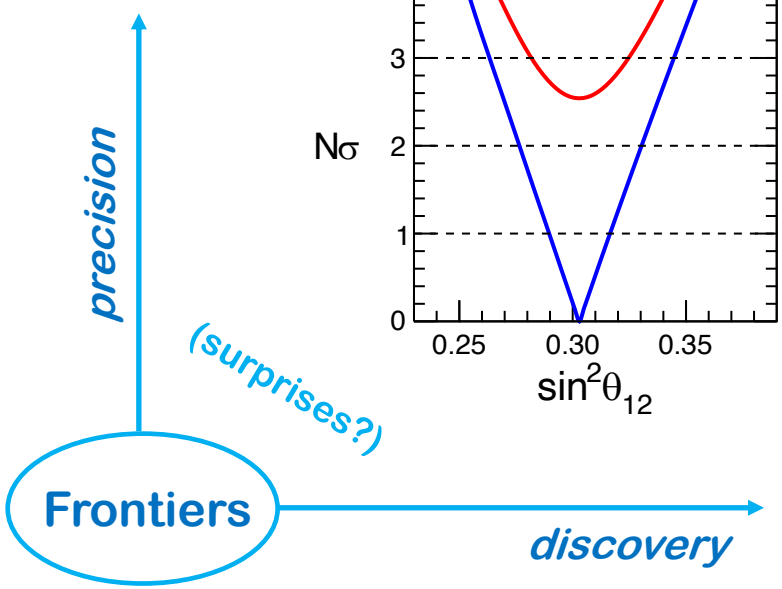
All ν oscillation data





Hints on oscillation **unknowns (2021)**

NO	~99% CL
sinδ < 0	~90% CL
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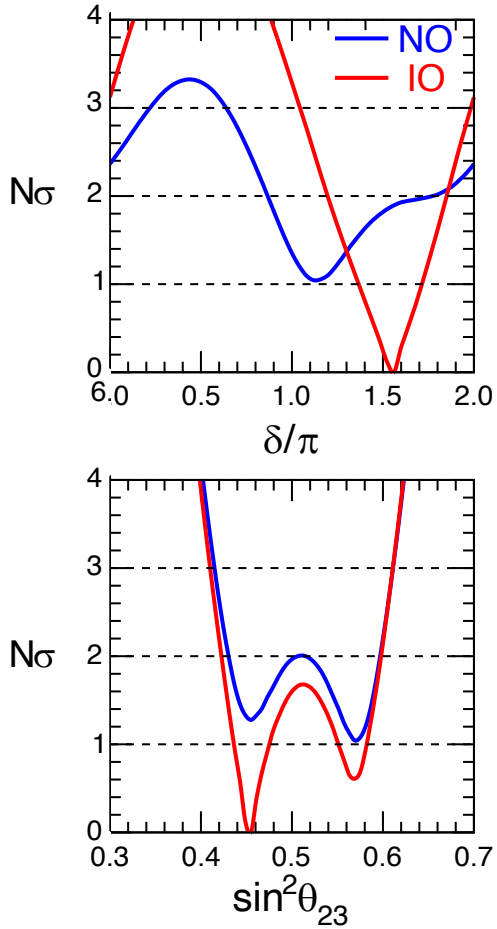
Focus on the three oscillation unknowns: NO/IO, δ, θ_{23} octant degen.

LBL Acc + Solar + KamLAND



IO favored (~1σ)

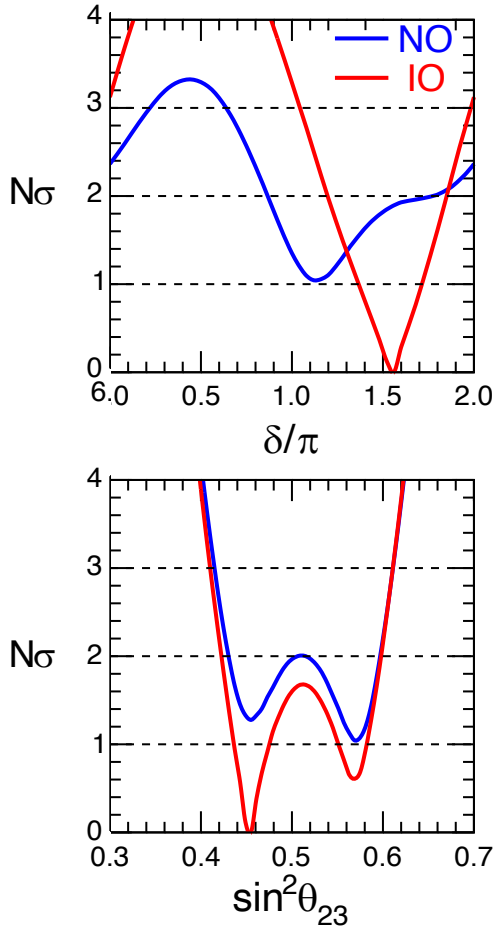
$\delta \sim 1.5\pi$ (IO), $\sim\pi$ (NO)

θ_{23} octants ~degenerate

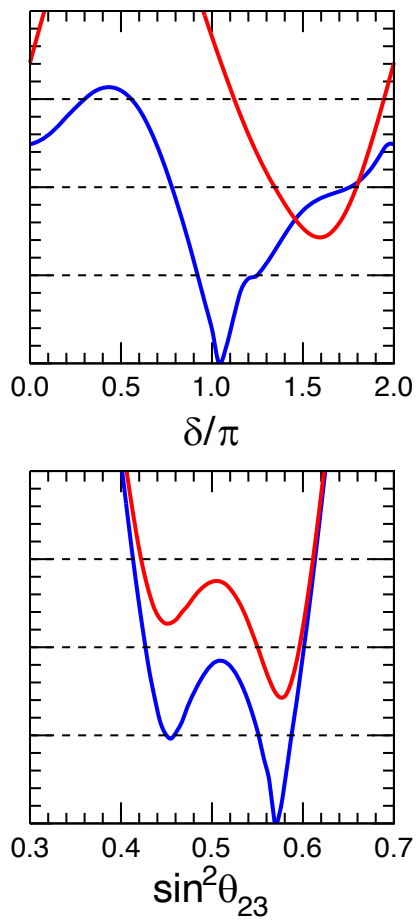
[confusing T2K-NOvA tension]

Focus on the three oscillation unknowns: NO/IO, δ, θ_{23} octant degen.

LBL Acc + Solar + KamLAND



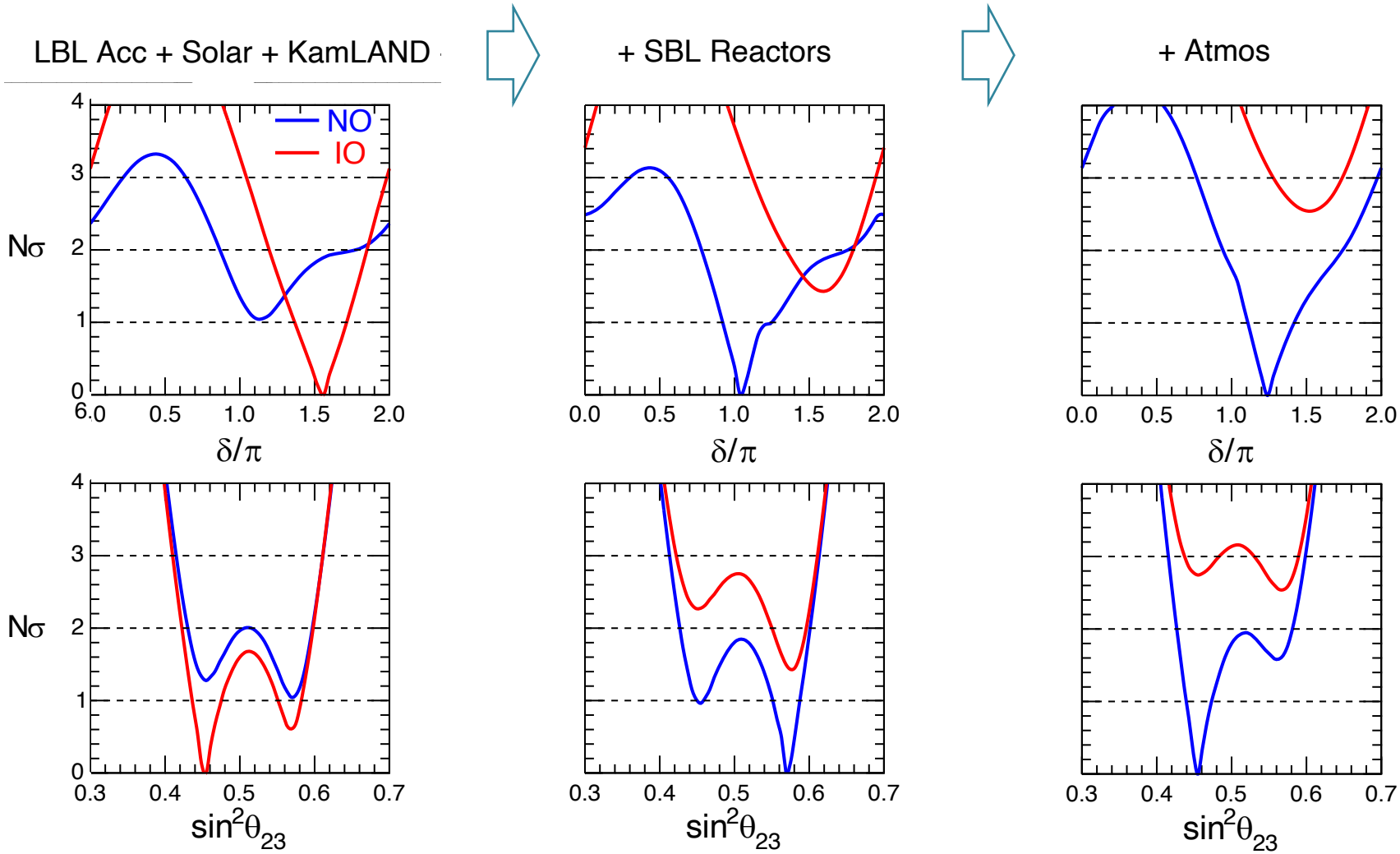
+ SBL Reactors



IO favored (~1σ)
δ~1.5π (IO), ~π (NO)
θ_{23} octants ~degenerate

NO favored (~1.5σ)
δ~π (NO), ~1.5π (IO)
θ_{23}~0.57 favored (~1σ)

Focus on the three oscillation unknowns: NO/IO, δ, θ_{23} octant degen.



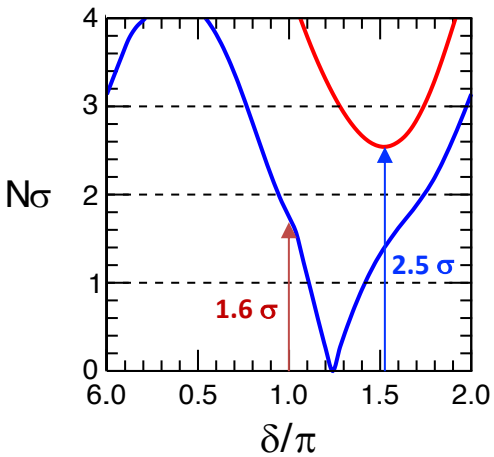
IO favored (~1σ)
δ~1.5π (IO), ~π (NO)
θ_{23} octants ~degenerate

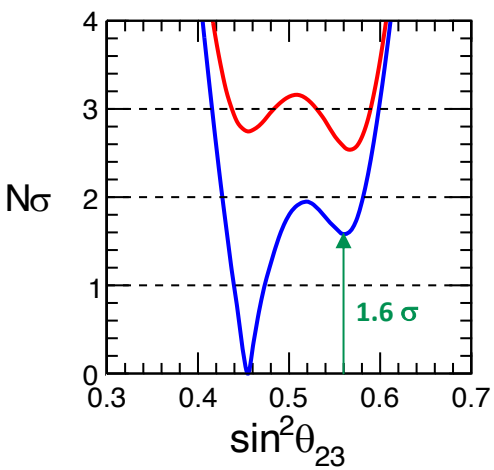
NO favored (~1.5σ)
δ~π (NO), ~1.5π (IO)
θ_{23}~0.57 favored (~1σ)

NO favored (~2.5σ)
δ~1.2π (NO) fav. (~1.6σ)
θ_{23}~0.46 favored (~1.6σ)

Hints on oscillation **unknowns, 2021…**

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





Hints on oscillation
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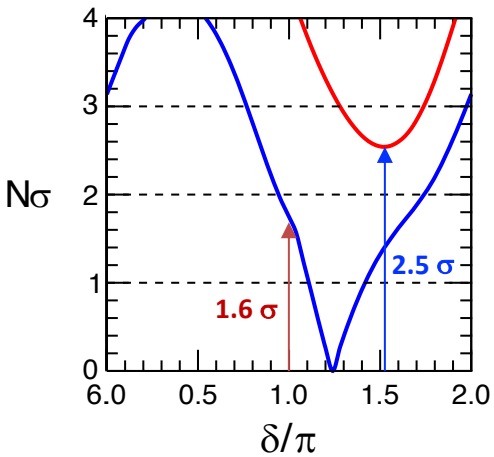
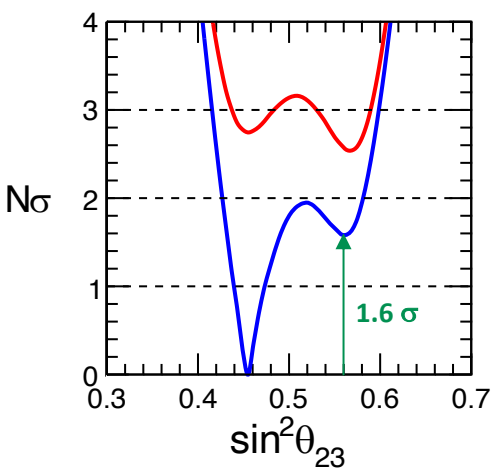




…Educated guess on
unknowns,
after Neutrino 2022

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

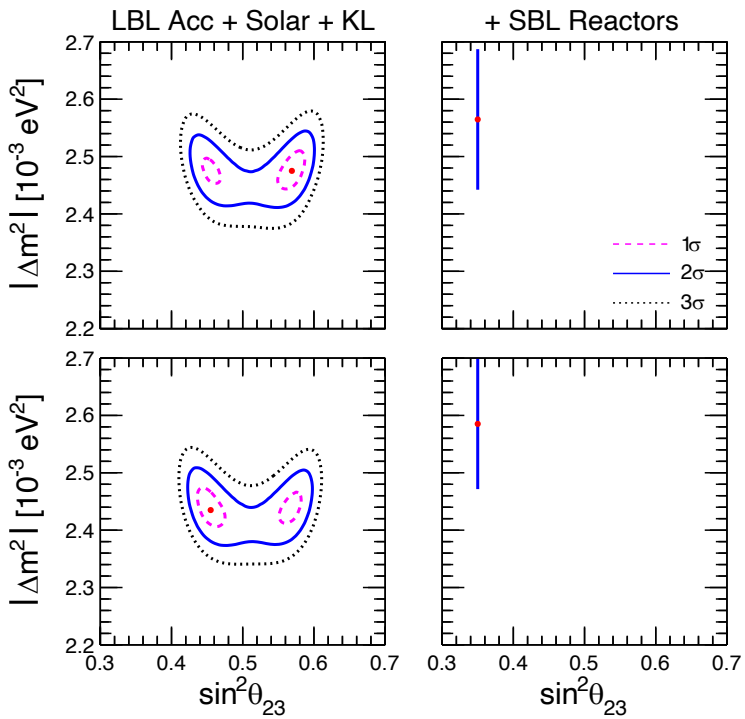
*Main impact expected from **new SK atm. data in combination with T2K**, which may win over the T2K-NOvA tension and other small changes [see extra slides]*

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

Watch for synergy of various $|\Delta m^2|$ measurements:
convergence / divergence in true / wrong mass ordering

($\pm\Delta m^2$, θ_{23}) pair: 2021 data synergy

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

($\pm\Delta m^2$, θ_{23}) pair: 2021 data synergy

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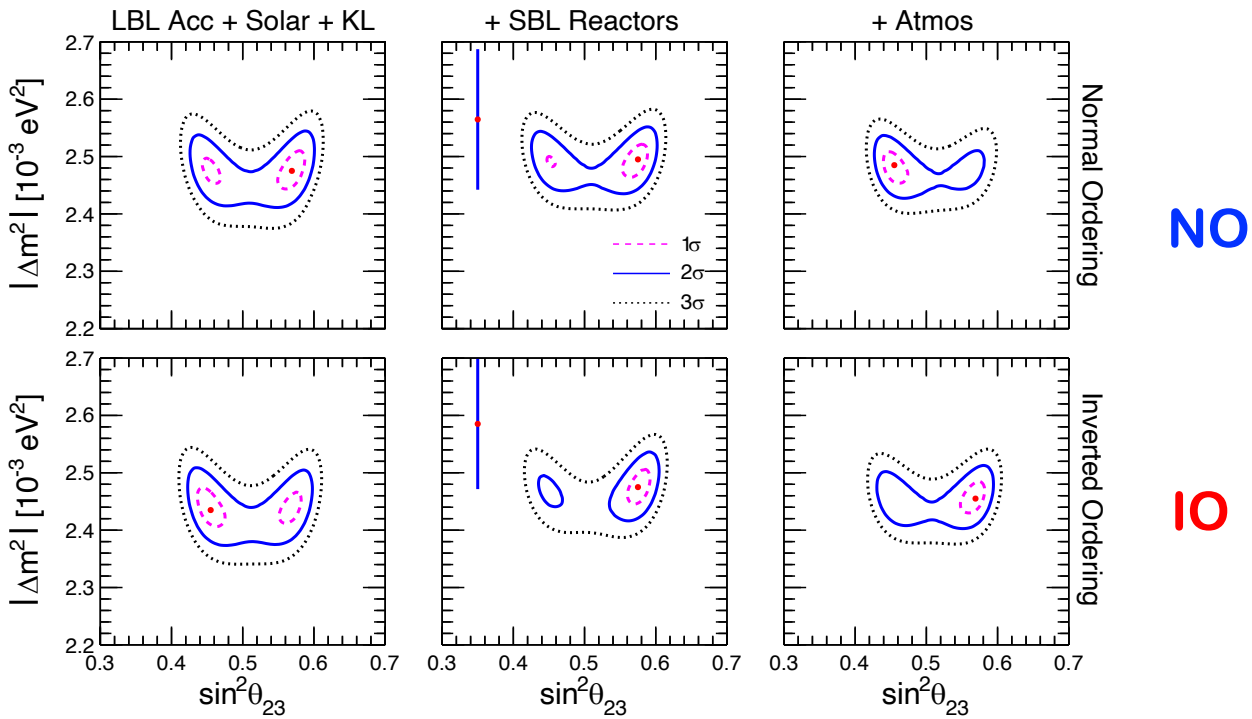

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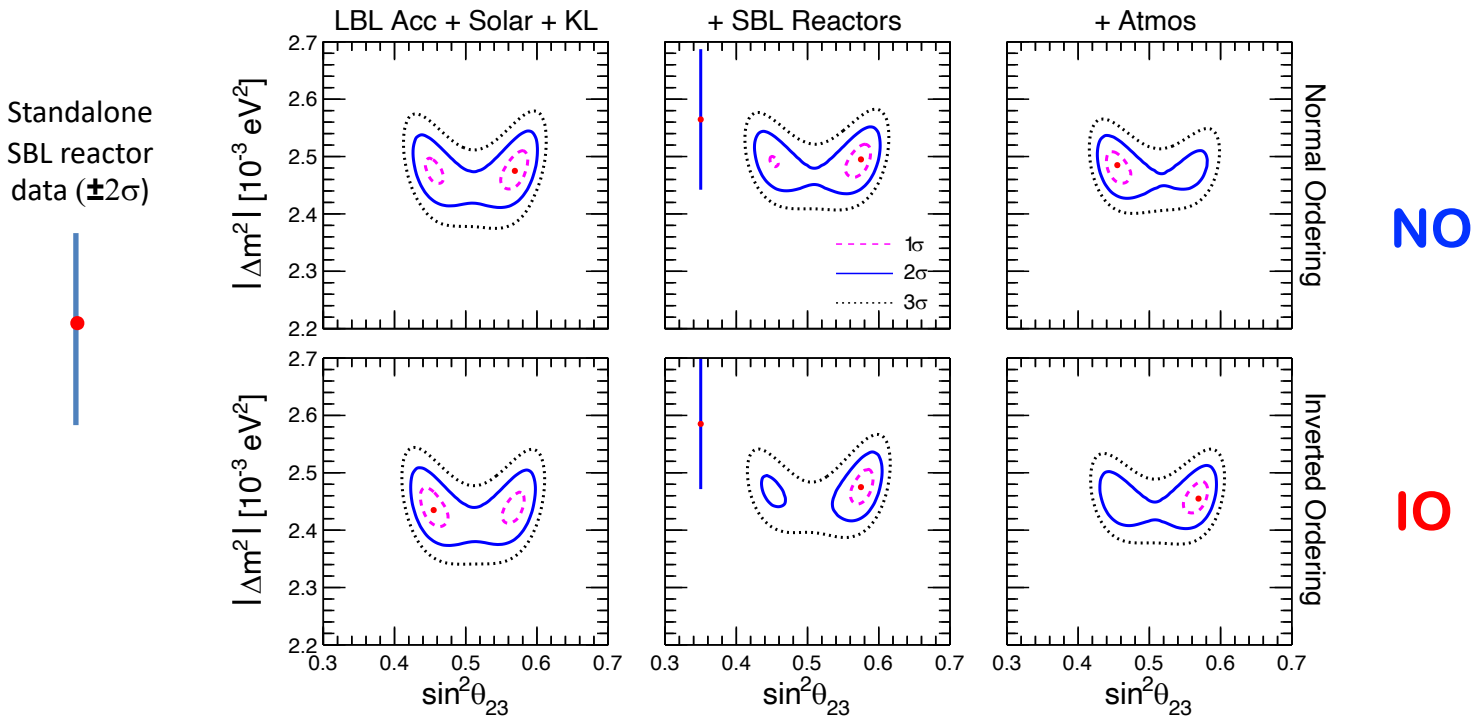
Relative difference is **smaller** for **NO** and for non-maximal θ_{23} mixing

→ 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!

($\pm\Delta m^2$, θ_{23}) pair: 2021 data synergy



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

Near Future: incremental progress from Daya Bay + T2K + NOvA + SK + IC-DC…
Farther Future: decisive progress with JUNO + DUNE + HK + IC + KM3…

Outline:

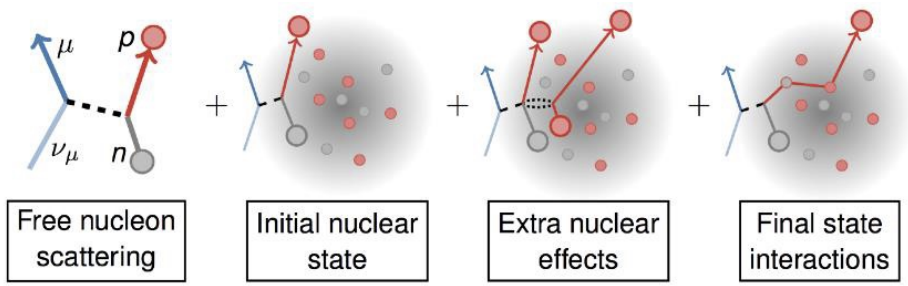
- The standard 3ν framework
- Oscillation knowns and unknowns
- **Impact of non-oscillation physics**
- Conclusions

Neutrino Interaction Physics

Oscillation phase ∝ $\Delta m^2/E$ → E-reconstruction uncertainties may bias Δm^2

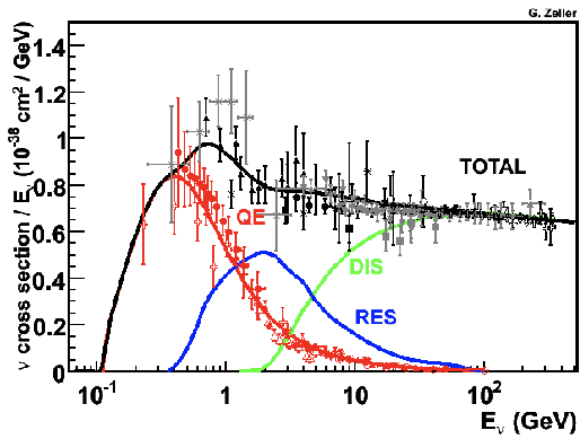
… and may affect central values and errors of other parameters via correlations

Theory: complex nuclear effects



Kajetan Niewczas @ NuFact2018

Experiment: relatively few data



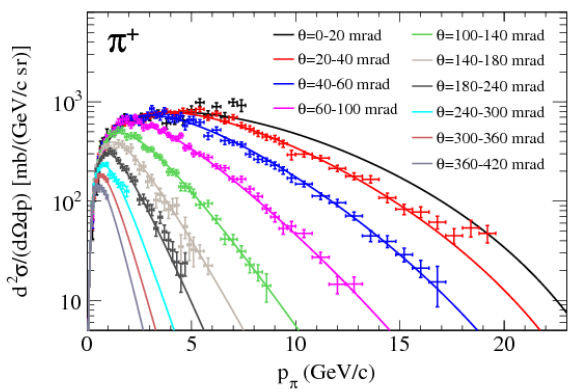
Great effort to improve the situation through dedicated measurements and improved nuclear models, but non-negligible uncertainties remain

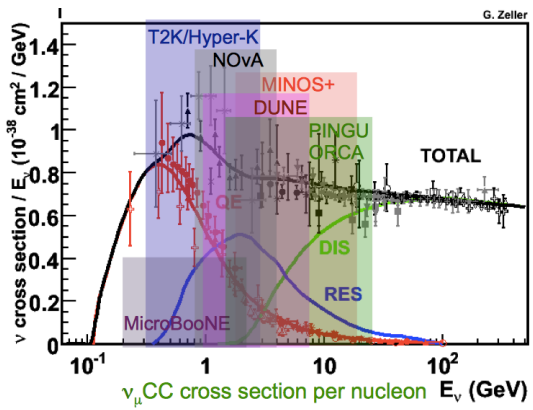
"Strong interaction" effects on "weak interaction" physics are ubiquitous…

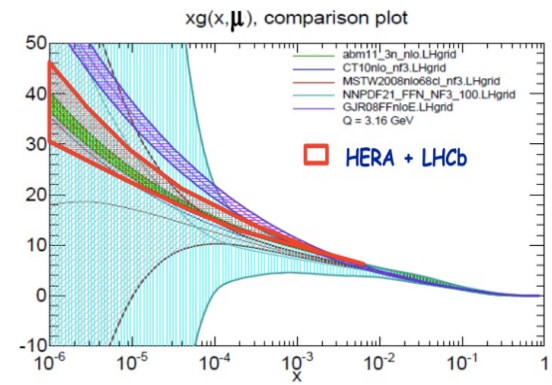
Need hadron production data, e.g. pA → πX, +theory models to improve estimates of atmos. and acceler. ν fluxes and errors

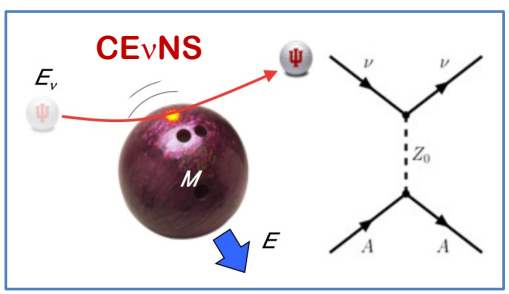
Current understanding of ν cross sections at O(GeV) does not match the needs of (next-generation) ν expts

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



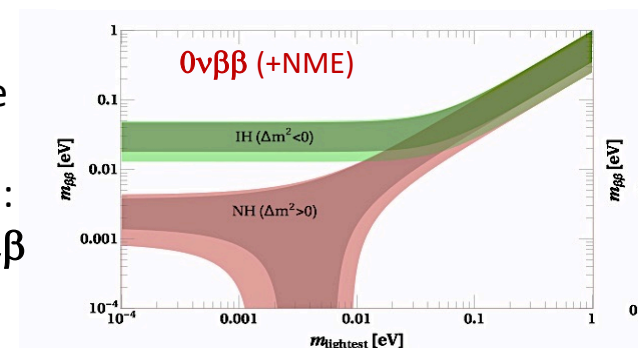






Control of nuclear EW response (e.g., form factors) relevant to interpret many low-energy data: coherent scatt., reactor spect., 2β

…



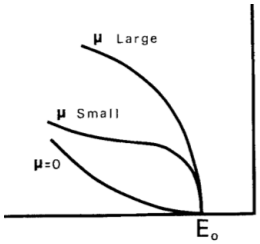
Progress requires further integration of different Expt+Theo communities:

→ (re)emerging field of "Electroweak Nuclear Physics"

Non-oscillation neutrino mass observables: (m_β , $m_{\beta\beta}$, Σ)

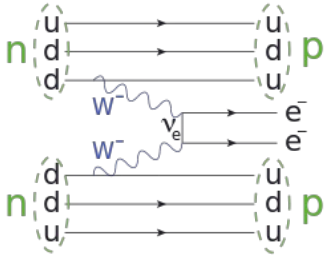
β decay, sensitive to the "effective electron neutrino mass":

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



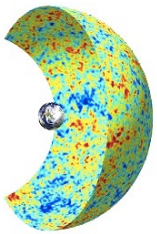
0νββ decay: only if Majorana. "Effective Majorana mass":

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



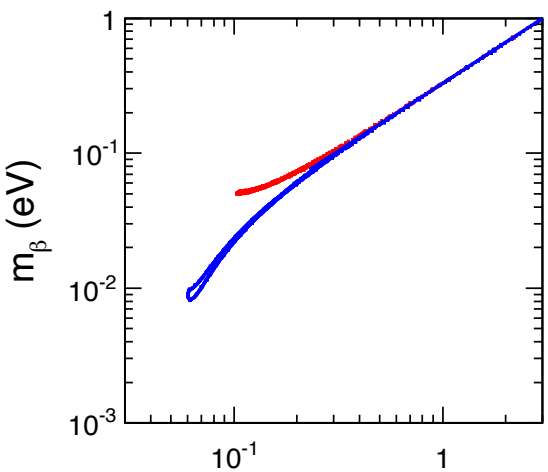
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



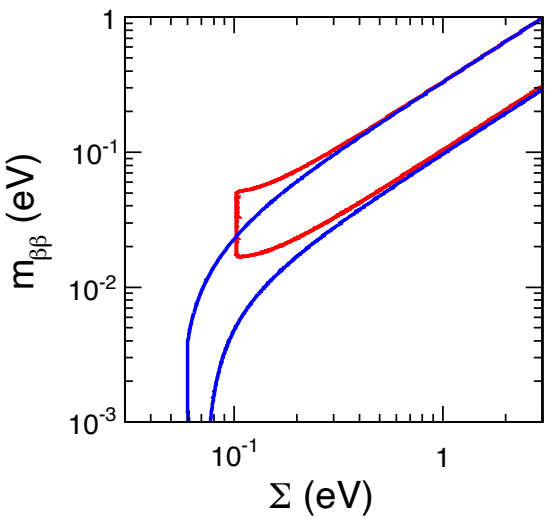
May provide additional handles to distinguish NO/IO!

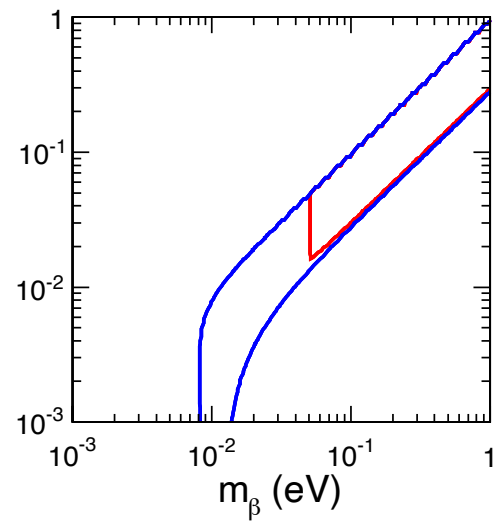
Non-oscillation parameter space (2σ) constrained by oscillations:



NO

IO

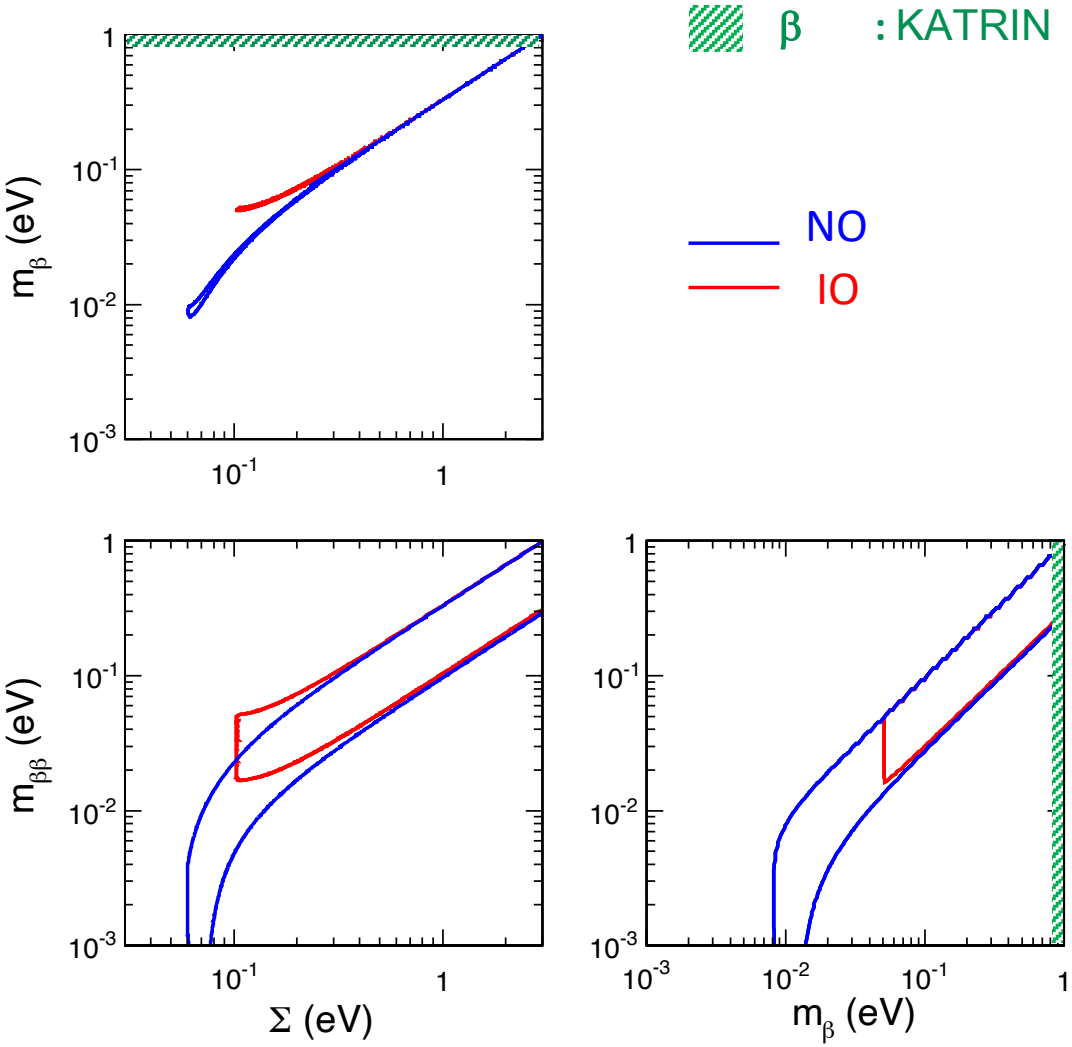




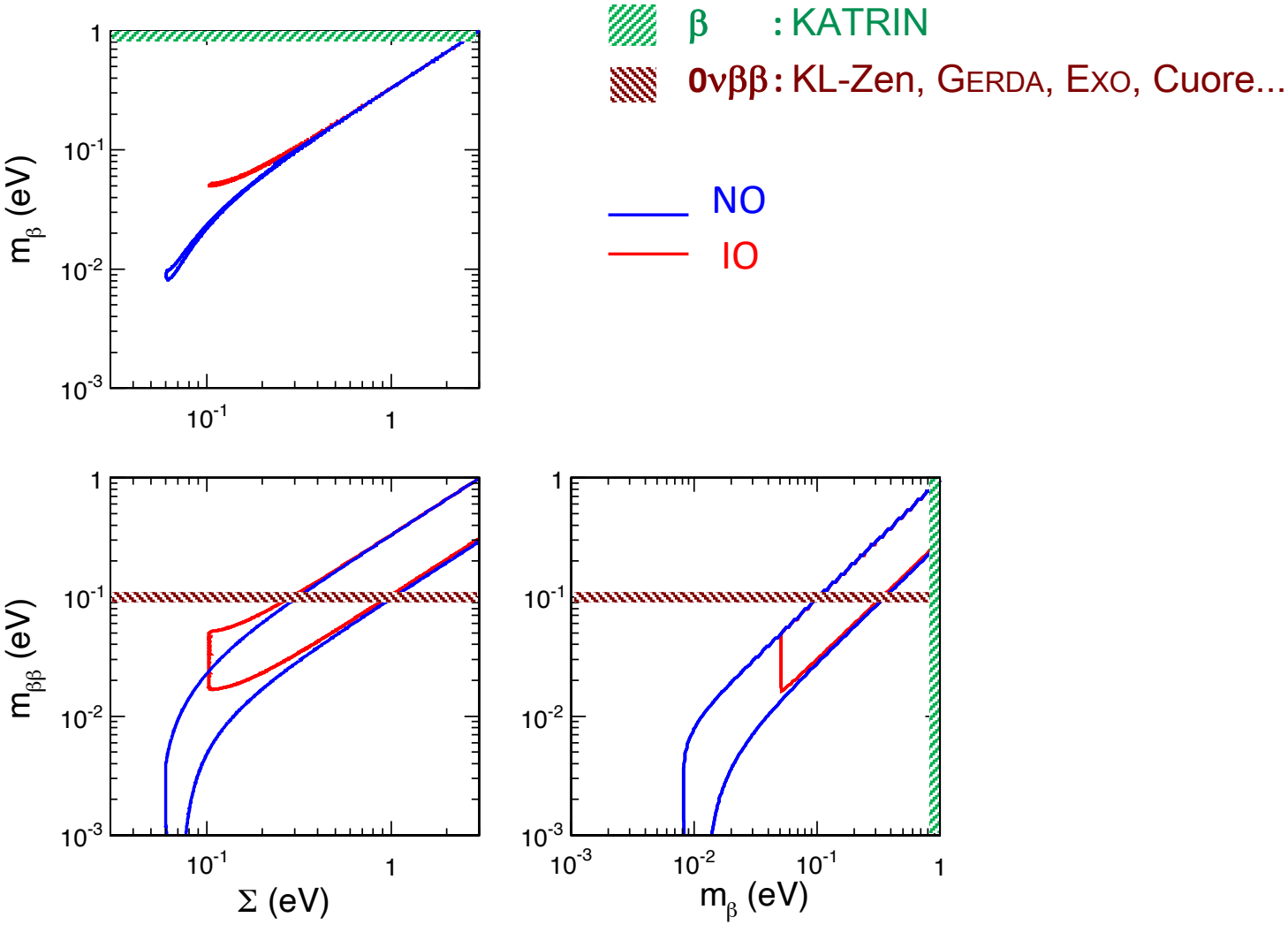
$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

(but: no NME errors included here!)

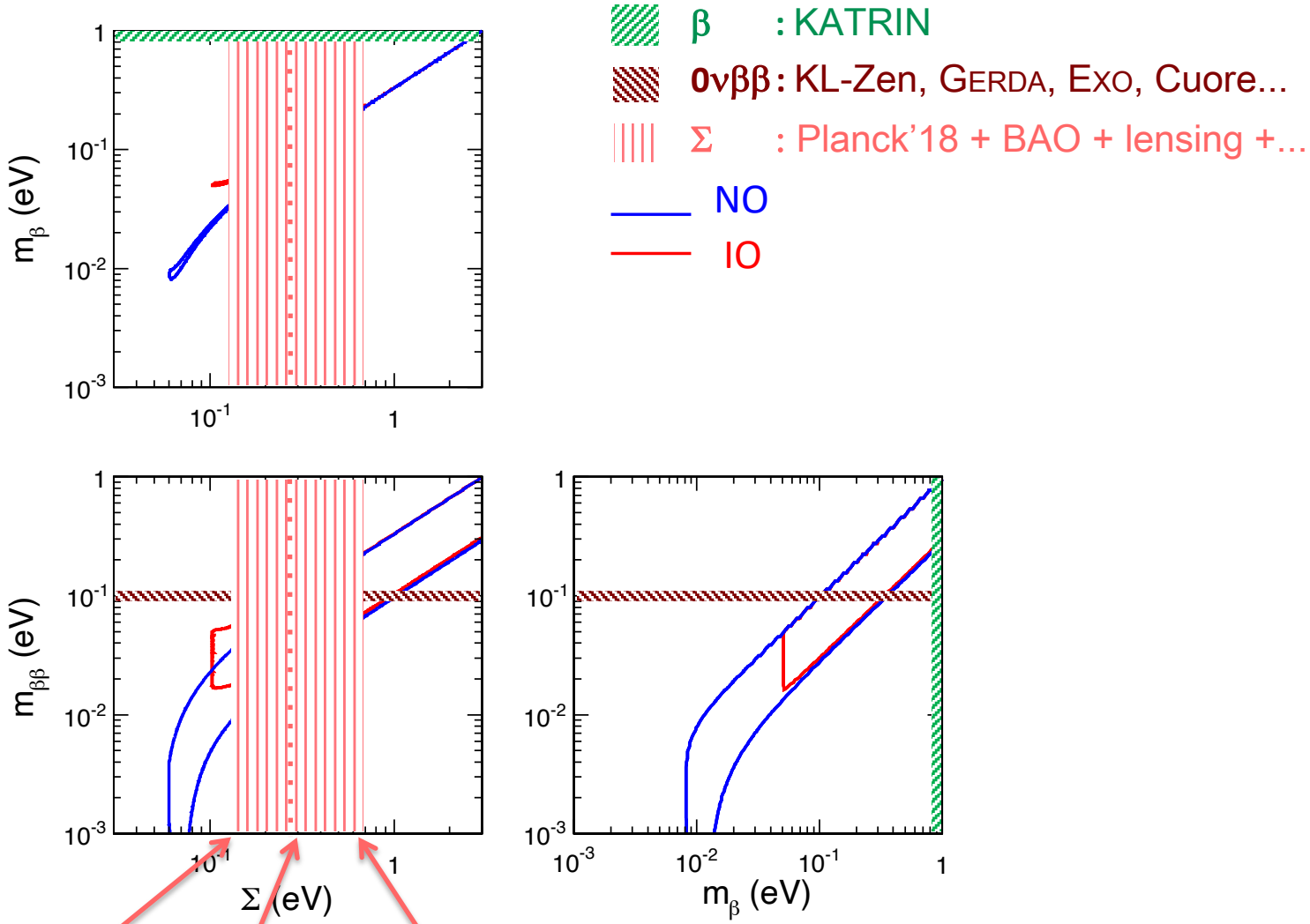
No signal (yet), but upper limits on m_β



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



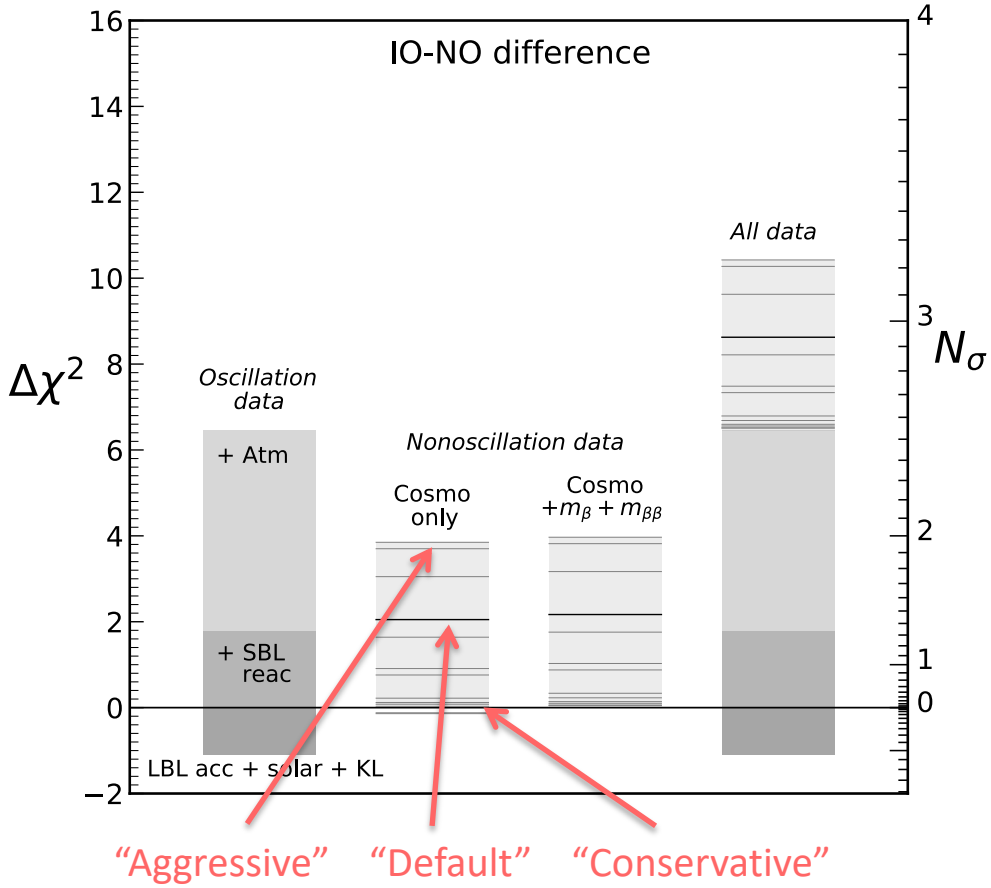
… and on Σ, from a variety of cosmo bounds, with IO "under pressure"



"Aggressive" "Default" "Conservative" cosmological limits

Grand total (oscillations + nonoscillations) for the IO-NO difference

[envelope of conservative, default, aggressive cosmological fits = horizontal lines]

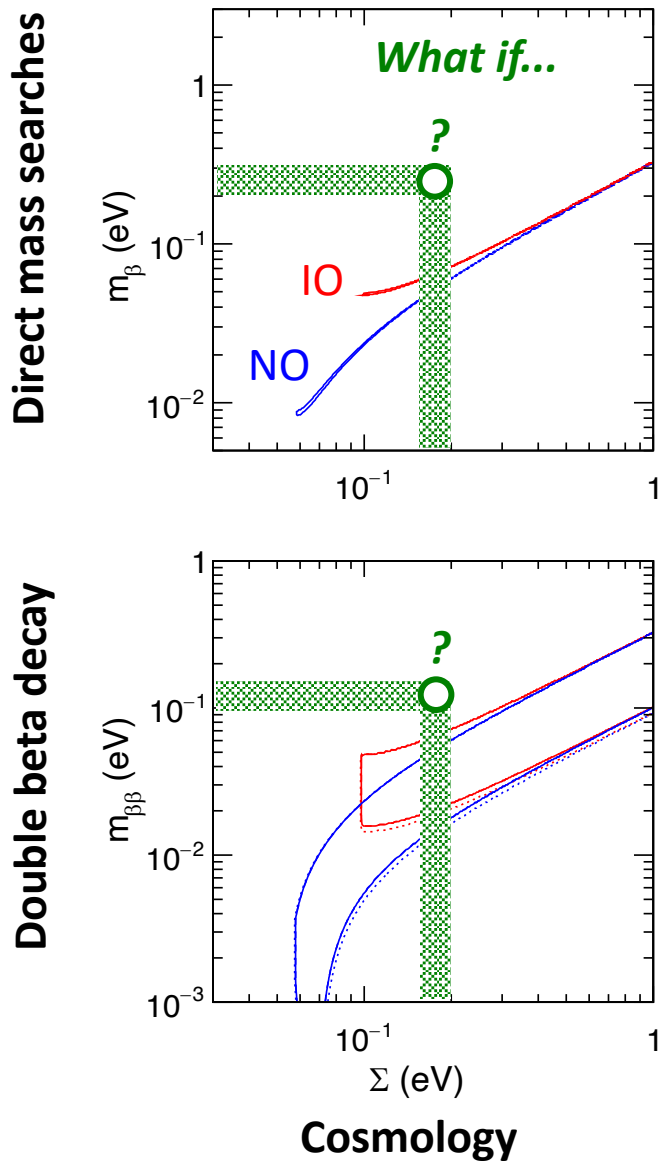


2.5σ (osc) $\oplus$ up to 0.7σ (nonosc) =

$2.5\sigma - 3.2\sigma$ in favor of NO (all 2021 ν data)

Presumably stronger with 2022 oscill. data. Progress expected on all fronts!

Future data might also bring us beyond 3ν and re-shape the field…



Disagreement among future data (barring expt mistakes) **might point towards new possibilities:**

- *Cosmology beyond ΛCDM*
- *Alternative DBD mechanisms*
- *New interactions (NSI)*
- *New neutrino states …*

Main contender in current ν physics:
Light sterile ν at O(1 eV) scale
but… confusing/unconfirmed hints

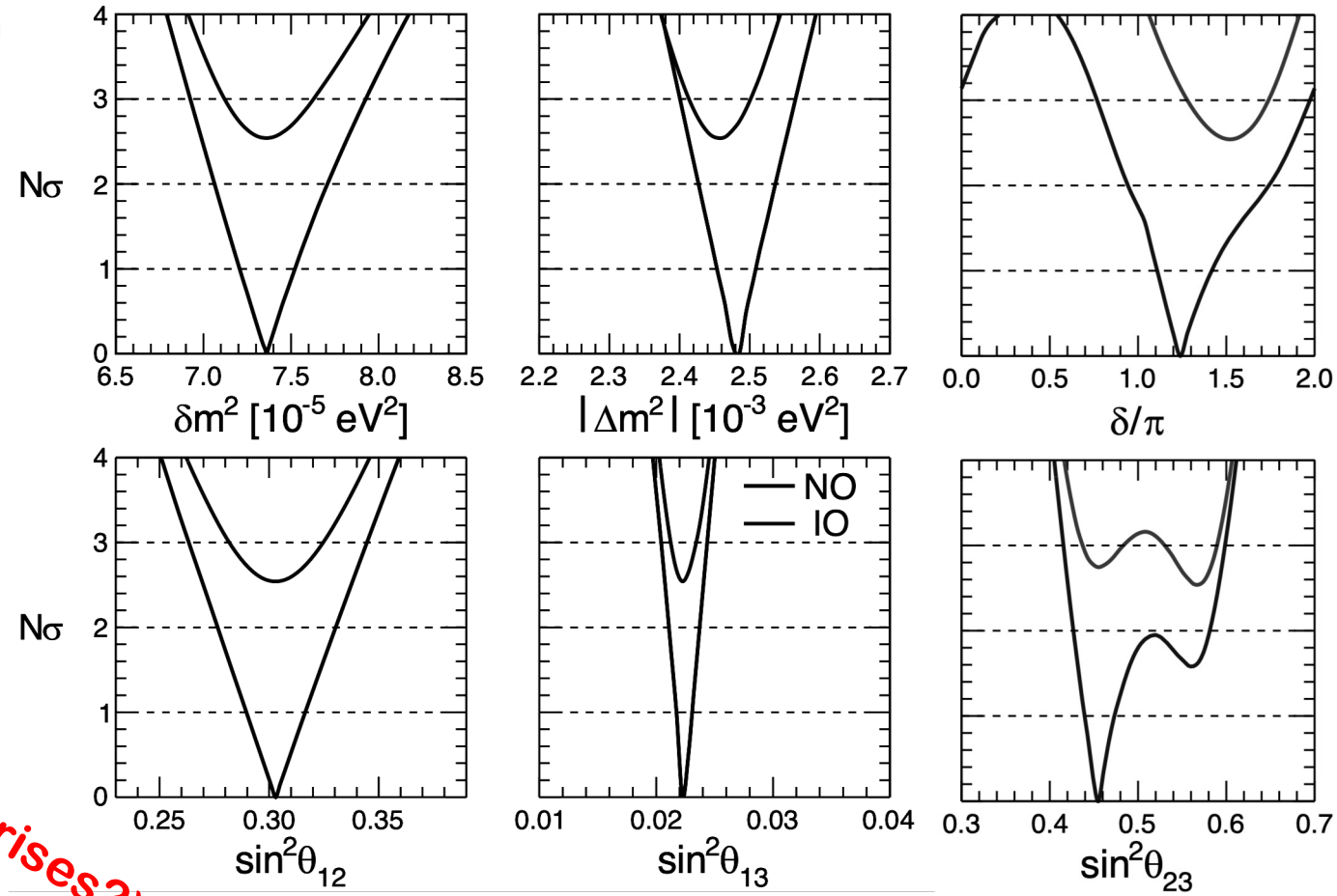
In any case: generic expectations **for new possible ν mass state(s)**

CONCLUSIONS

All ν oscillation data

1σ error of **known** parameters

$\lvert\Delta m^2\rvert$	1.1%
δm^2	2.3%
θ_{13}	3.0%
θ_{12}	4.5%
θ_{23}	~ 6%



precision

(surprises?)

Frontiers

discovery

Hints on oscillation **unknowns (2021)**

NO	~99% CL
sinδ < 0	~90% CL
$\theta_{23} < \pi/4$	~90% CL


ν_e ν_μ ν_τ
Thank you for your attention!
ν_1 ν_2 ν_3

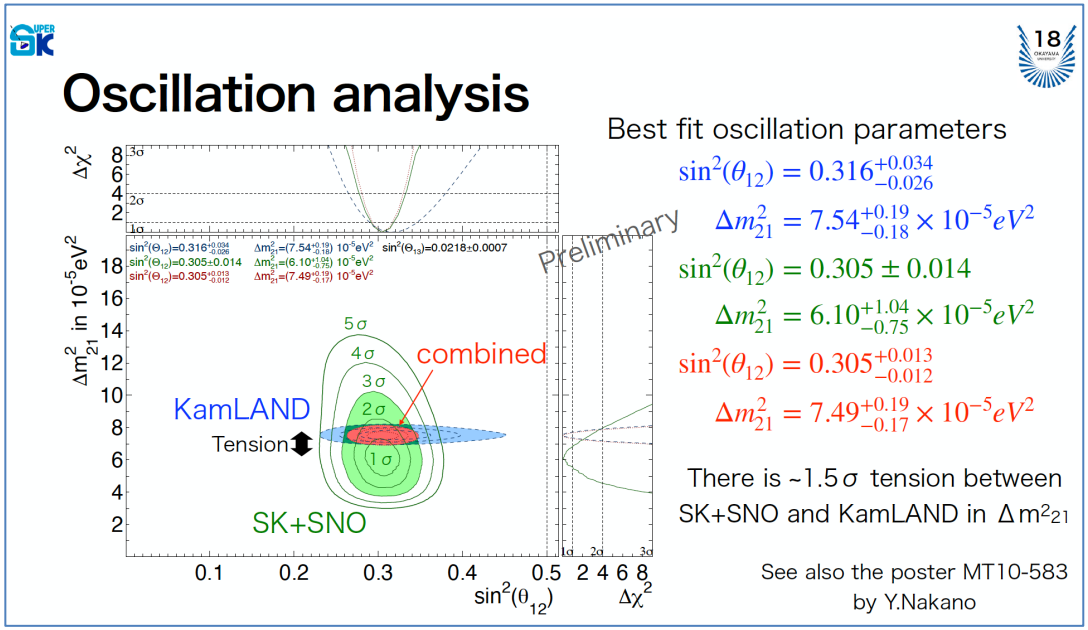
Extra slides:

Selected new oscillation results shown at Neutrino 2022

+ personal comments

(δm^2, θ_{12}) pair from solar experiments

B. Caccianiga	→ BOREXINO + [revised O, N abundances] independently favor high-Z/X SSM
Y. Koshio	→ SK energy spectrum consistent with low-energy upturn
Y. Koshio	→ SK D/N asymmetry drives again solar δm^2 below the KamLAND one, by 1.5σ



Comment #1: Seems an acceptable fluctuation in an overall consistent scenario
Comment #2: Minor impact expected on previous estimates for this oscill. parameter pair

(Δm^2, θ_{13}) pair from reactor experiments

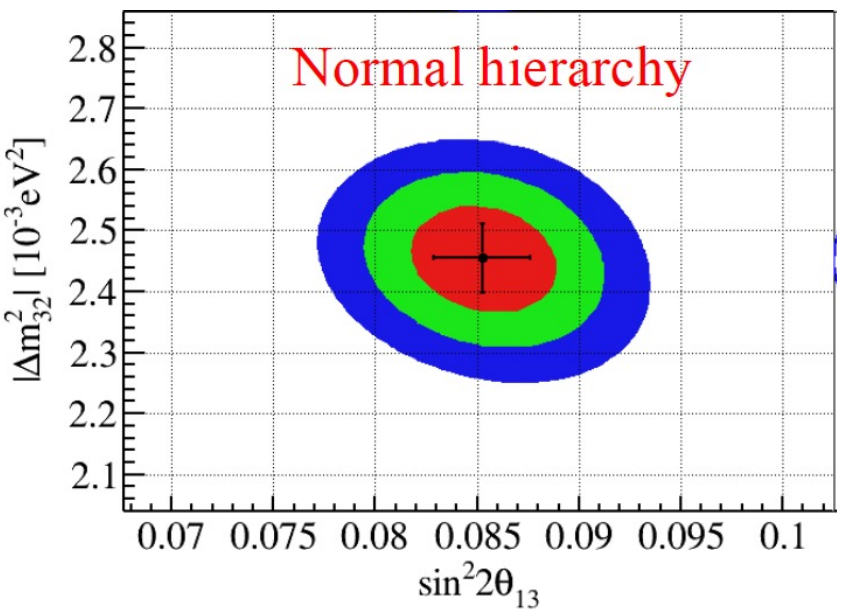
K.B. Luk → Daya Bay improved determinations of both mass-mixing parameters

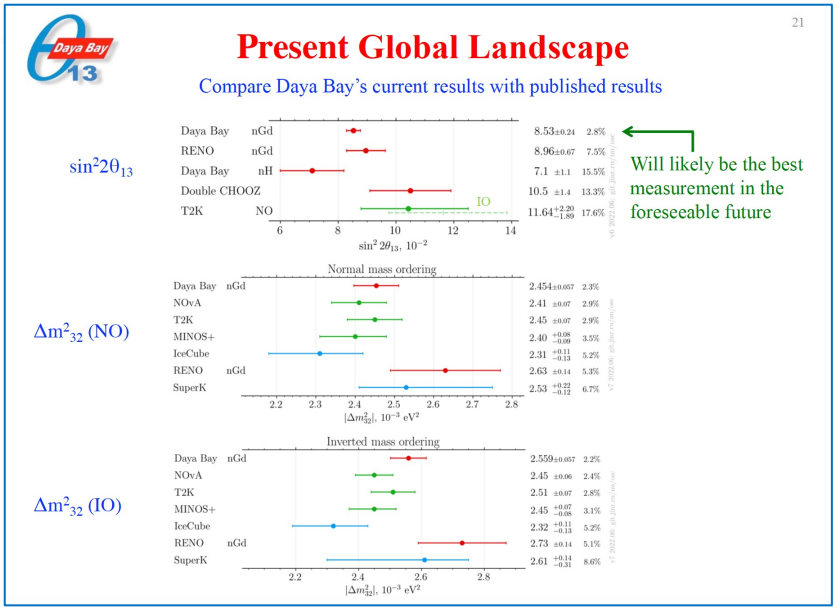
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \quad \text{(2.8\% precision)}$$

Normal hierarchy: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

Inverted hierarchy: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$

(2.3% precision)





Comment #1: W.r.t. previous official release: errors reduced by 20% on both parameters

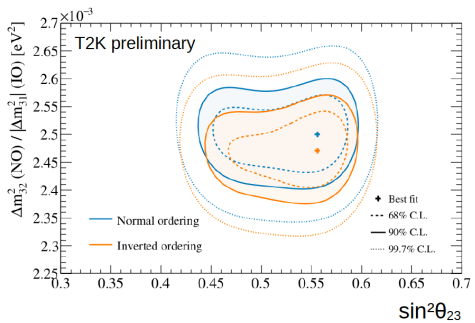
Comment #2: DYB best fits shifted by less than 0.3σ wrt previous release → robust results

Comment #3: Overall $|\Delta m^2|$ value from reactors a bit lower, but still on the "high" side

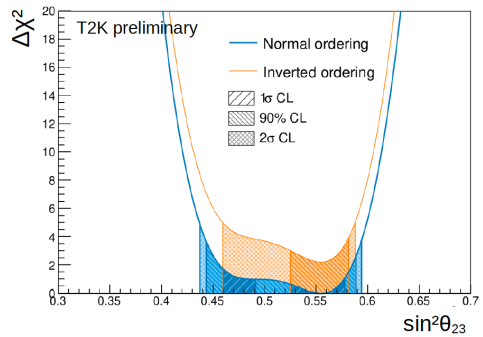
(Δm^2, θ_{23}) pair from LBL experiments (mainly from improved analyses rather than new data)

Bronner → T2K results with revised cross sections, fluxes, systematics

2D constant $\Delta\chi^2$ regions

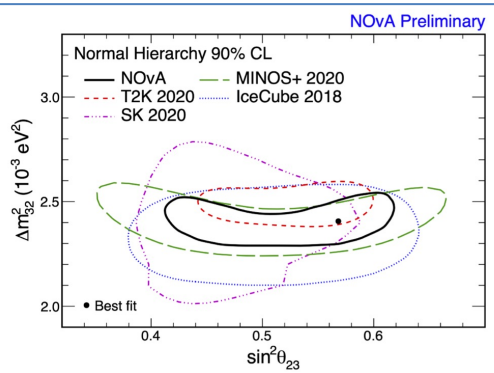


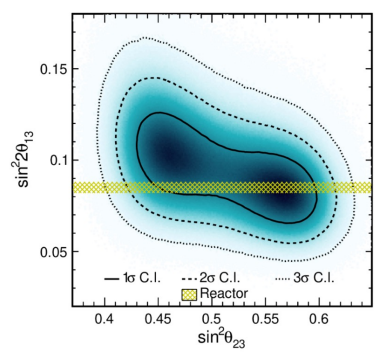
1D frequentist intervals for $\sin^2\theta_{23}$
(Feldman-Cousins method)



Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

Hartnell + posters → NOvA results with revised cross sections, interaction models



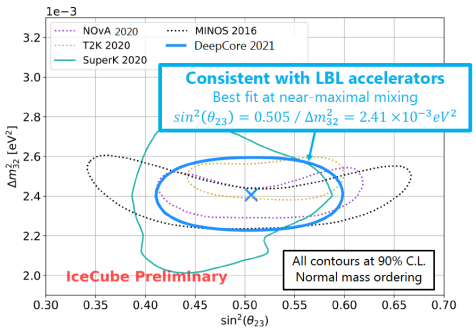


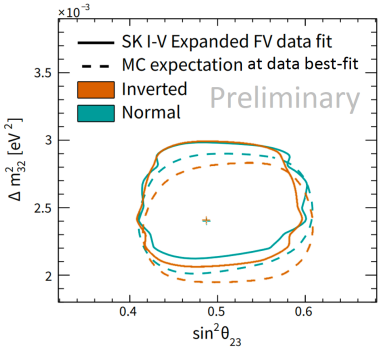
Comment #1: NOvA constraints basically unchanged; slight increase of $|\Delta m^2|$ in T2K
Comment #2: Both T2K and NOvA prefer 2nd octant of θ_{23} (at reactors' θ_{13} value)
Comment #3: T2K and NOvA cross-sections: revised separately (not jointly yet)

(Δm^2, θ_{23}) pair from atmospheric experiments

Stuttard (IC-DC), Wan (SK) → new atmospheric neutrino data

IC-DC

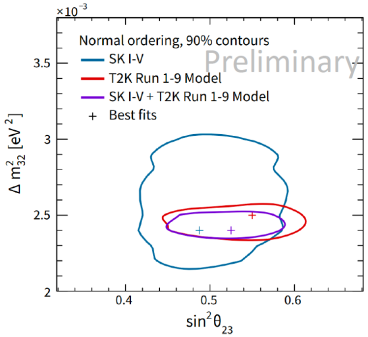




SK

Wan (SK) → Joint analysis of SK+T2K (including, e.g., common x-sec systematics)

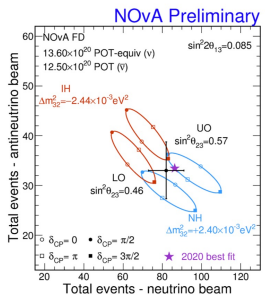
SK+T2K

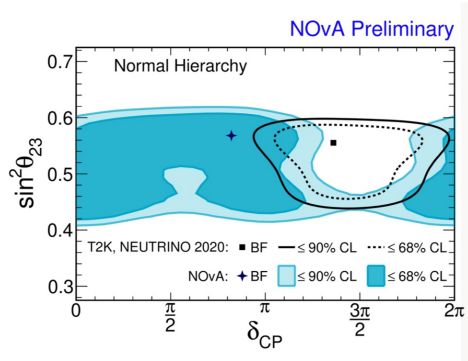


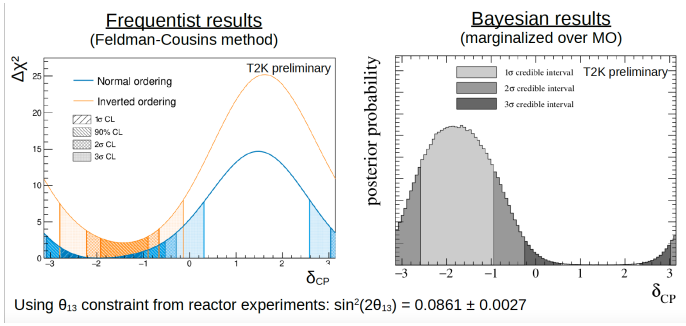
Comment #1: Both IC-DC and SK atmospheric consistent with nearly maximal θ_{23}
Comment #2: Combination of SK atmos. + T2K LBL data brings θ_{23} in 2nd octant
Comment #3: Both IC-DC and SK prefer the "low" side of $|\Delta m^2|$
Comment #4: Scatter of $|\Delta m^2|$ best fits in react/LBL/atm → some impact on NO/IO separation

NO/IO and δ_{CP} overview

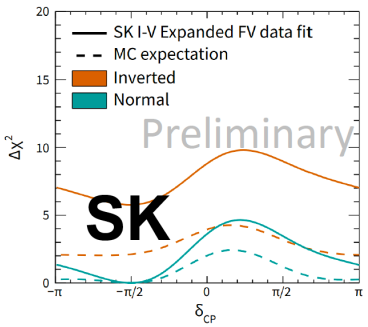
T2K and NOvA: still in tension; but no joint analysis yet. IC-DC: IO and δ not discussed yet.

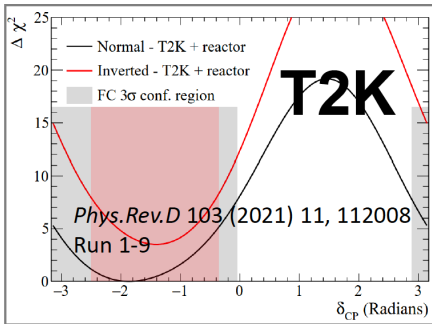




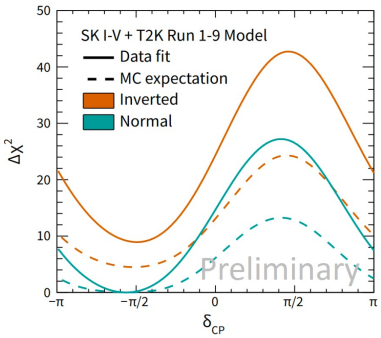


But SK atm. alone, and SK atm. +T2K → Increased preference for NO and for sinδ < 0





→ **SK+T2K**



Comment #1: Seperately revised cross sections have not shed light on T2K vs NOvA tension
Comment #2: … but joint T2K+NOvA analysis with common interaction model still lacking
Comment #3: SK and T2K synergy strengthens current hints on NO/IO and δ_{CP}
Comment #4: … but SK speaker admits that *"Results from both experiments exceed sensitivity"*