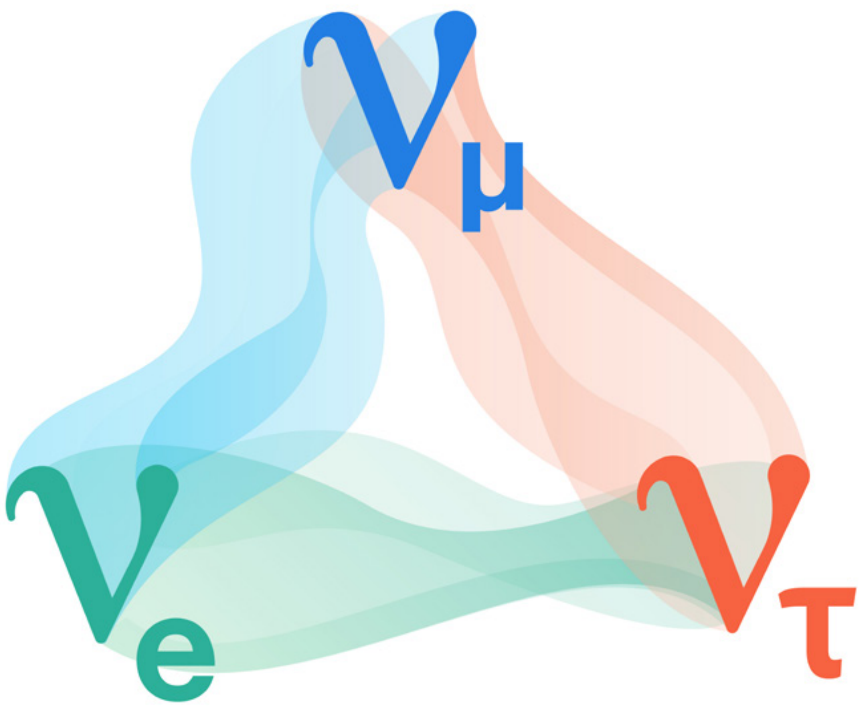
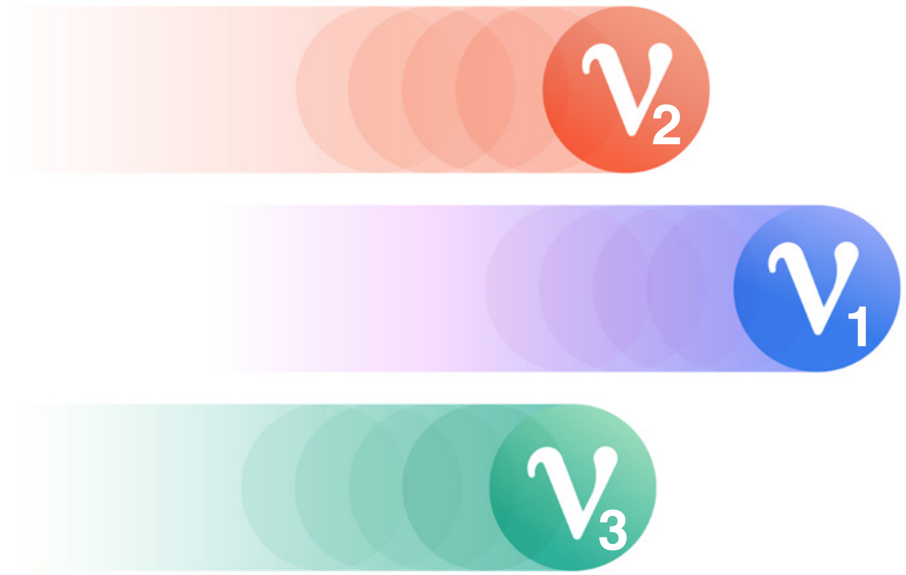
History and present state of neutrino oscillation measurements

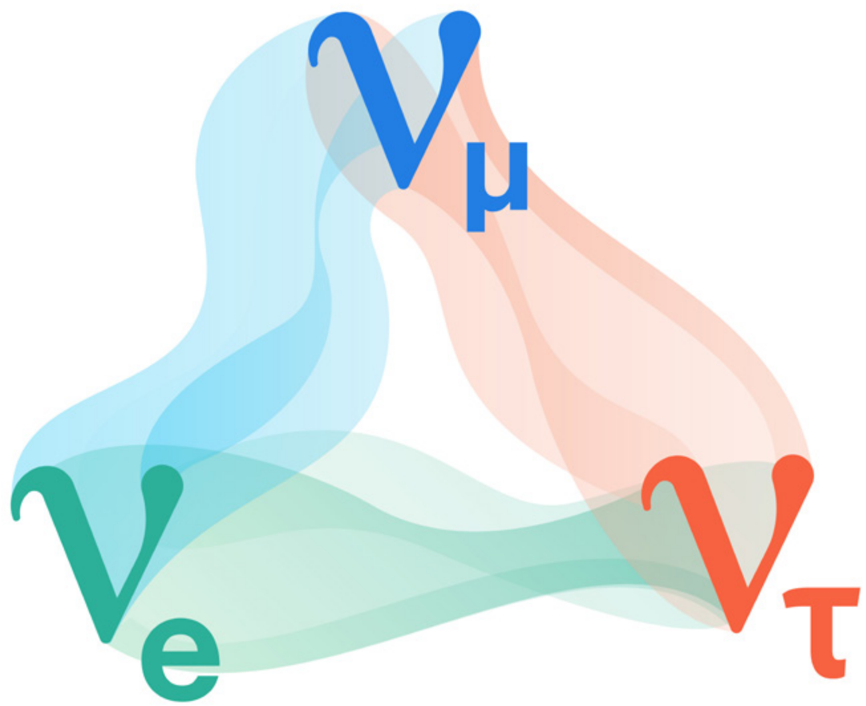
Stephen Parke
Theory

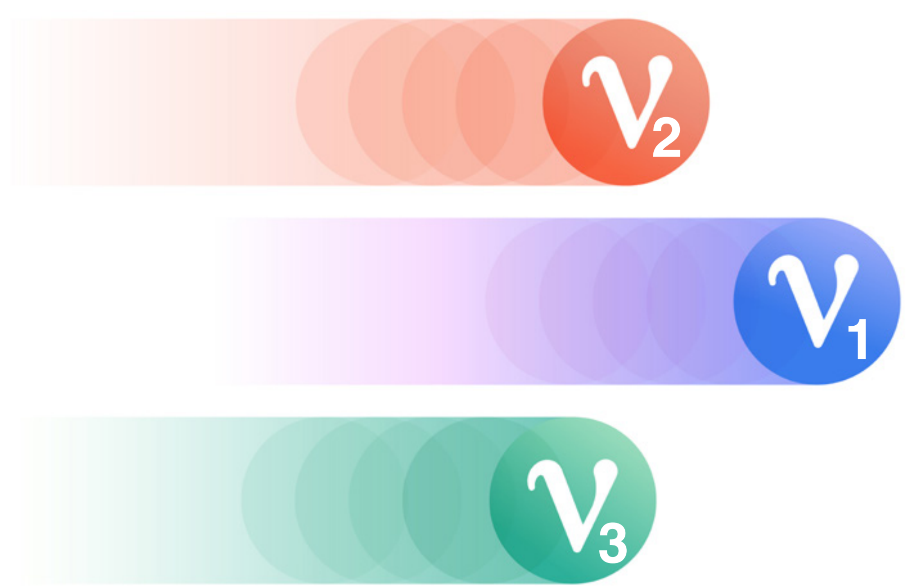




History and present state of neutrino oscillation measurements

Stephen Parke
Theory

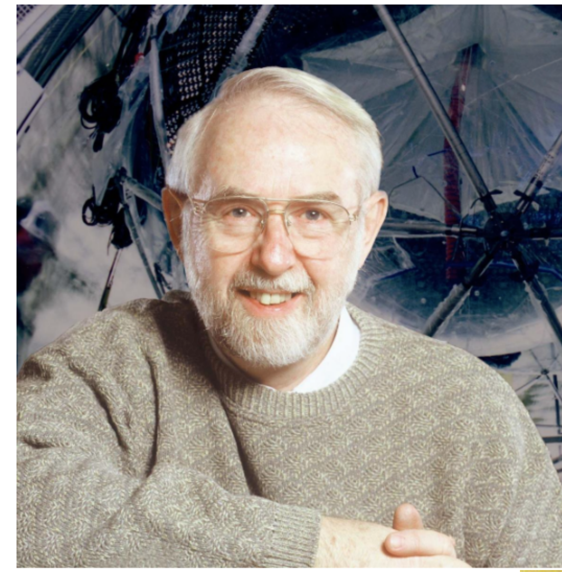




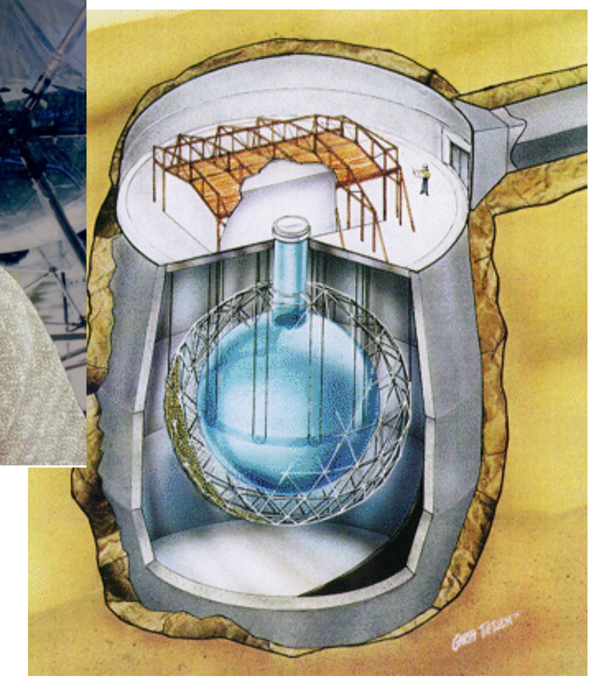
NOBEL 2015

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Takaaki Kajita
SuperKamiokaNDE



Art McDonald
SNO



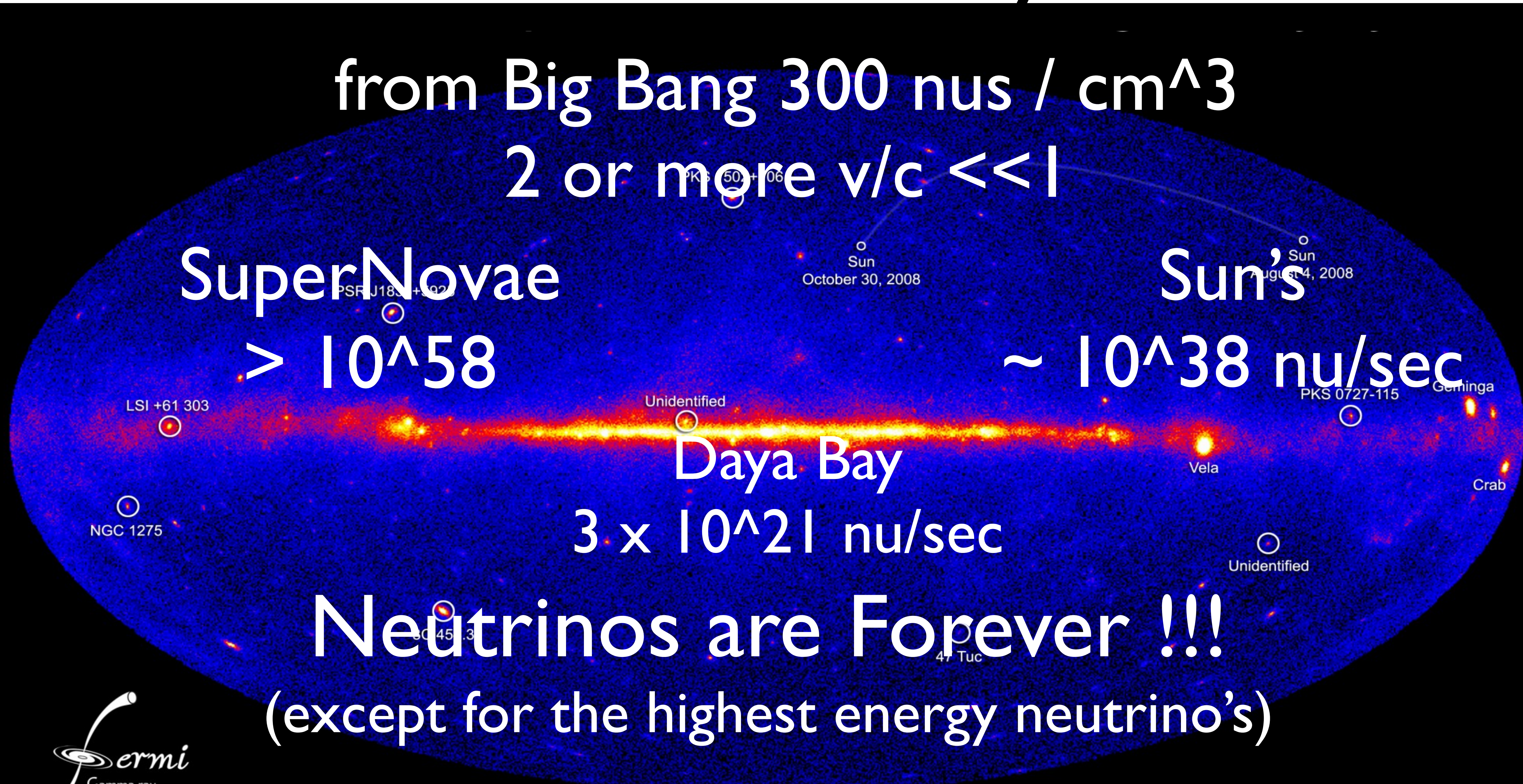
"for the discovery of neutrino flavor transformations, which shows that neutrinos have mass"

~ vacuum oscillations

Wolfenstein matter effects dominant flavor transformations

See Smirnov arXiv:1609.02386

Neutrinos are Everywhere !



from Big Bang 300 nus / cm^3

2 or more v/c <<1

SuperNovae

> 10^58

Sun's

~ 10^38 nu/sec

Daya Bay

3 x 10^21 nu/sec

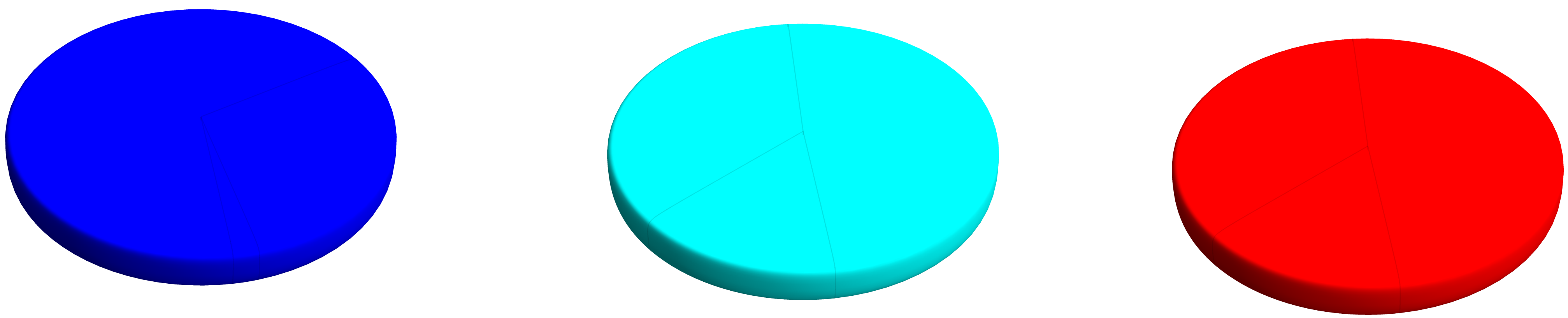
Neutrinos are Forever !!!

(except for the highest energy neutrino's)

therefore in the Universe: $\frac{\partial N_\nu}{\partial t} > 0$

Neutrino Flavor or Interaction States:

$W^+ \to e^+\nu_e$ $W^+ \to \mu^+\nu_\mu$ $W^+ \to \tau^+\nu_\tau$



ν_e ν_μ ν_τ

provided $L/E \ll \mathbf{0.5}$ km/MeV $=$ $\mathbf{500}$ km/GeV !!!

$\sim$ 1 picosecond in Neutrino rest frame !!!

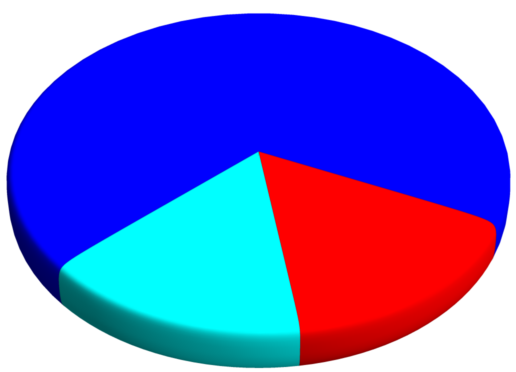
$\approx$ Age of Universe / 10^{26}

Neutrino Mass EigenStates or Propagation States:

$$\text{Propagator } \nu_j \to \nu_k \;=\; \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$$

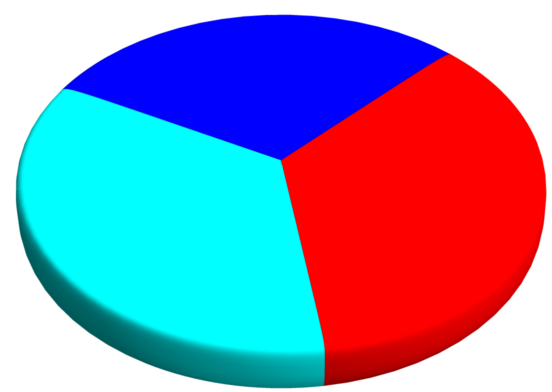
ν_1

most ν_e



δ, θ_{23}

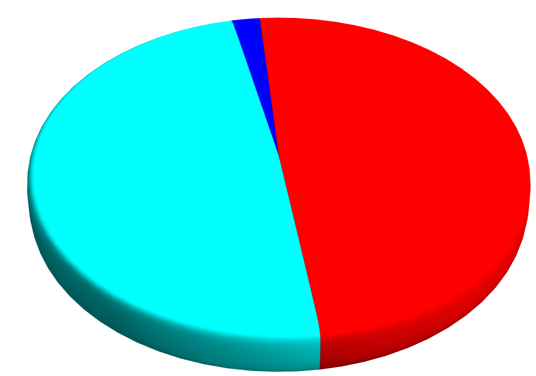
ν_2



δ, θ_{23}

ν_3

least ν_e



θ_{23}

$\nu_e =$

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

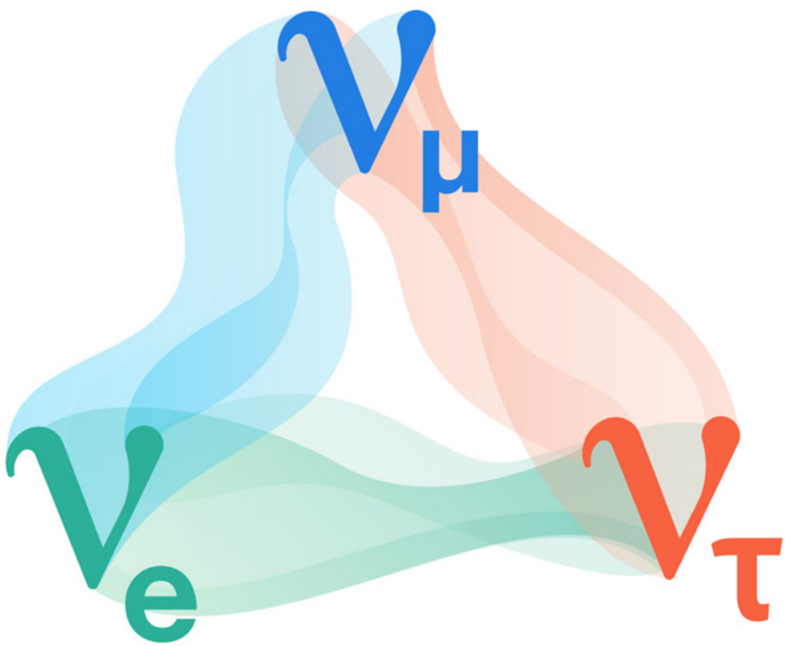
$\nu_\tau =$

Unitarity
SK, Opera
ICECUBE ?

Interactions:

simple

complicated



=U

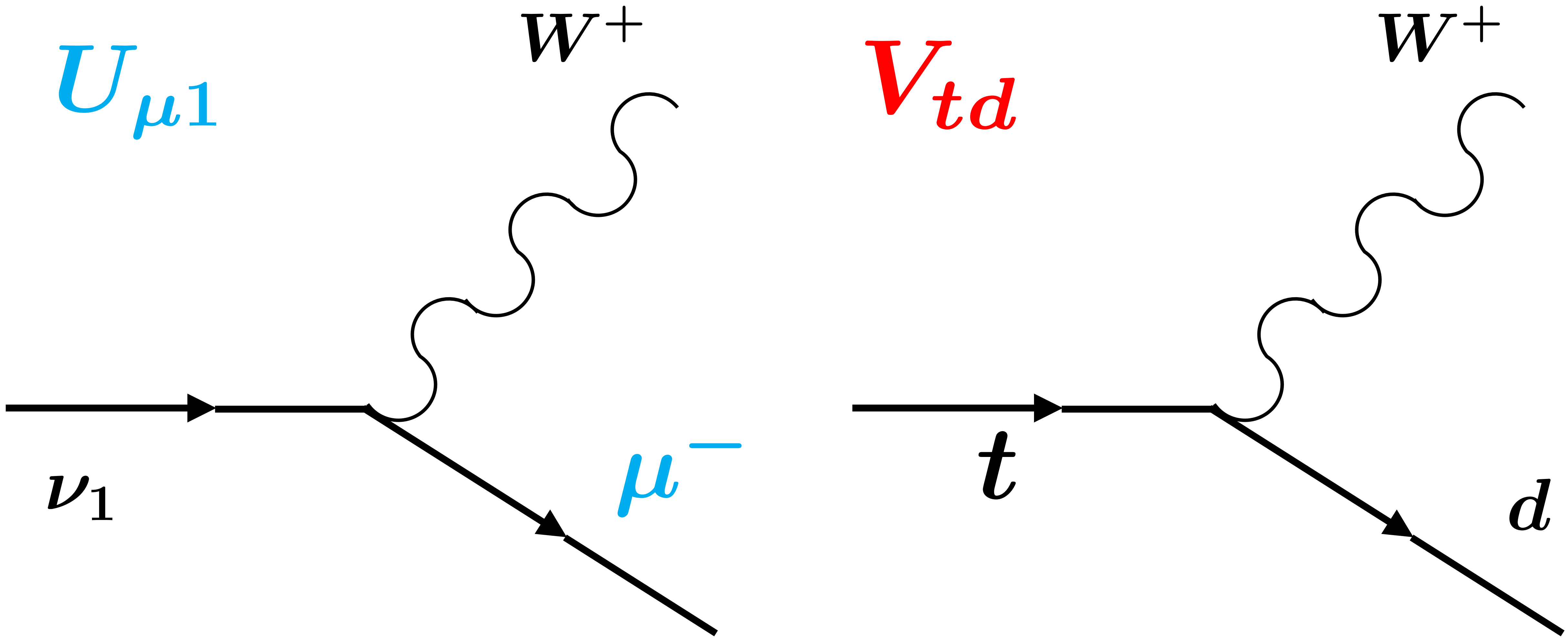
unitary matrix ?

complicated

simple

masses

Propagation:



Rates: $|U_{\mu 1}|^2$ & $|V_{td}|^2$

unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

by defn $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$$U_{PMNS} = U_{23}(\theta_{23}, 0)\, U_{13}(\theta_{13}, \delta)\, U_{12}(\theta_{12}, 0)$$

Why this order ???

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{+i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$

$$\times\, \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})$$

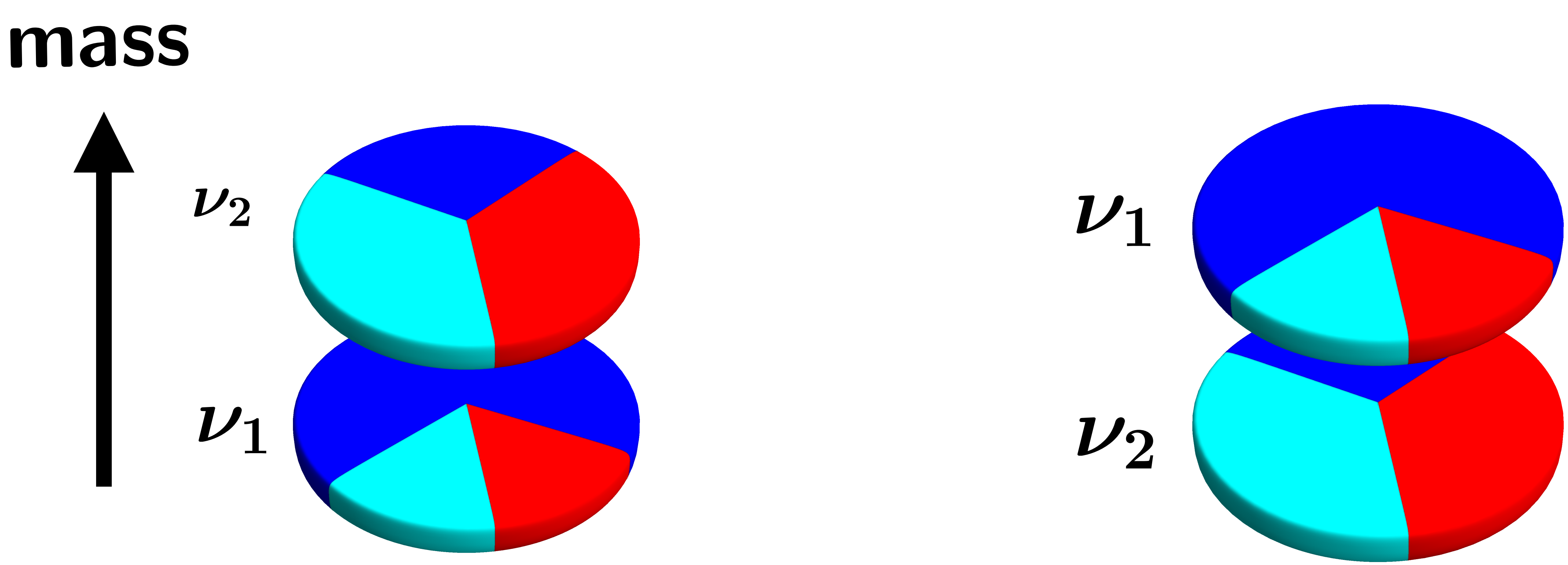
$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

NuFIT 5.1 (2021)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$\nu_1, \ \nu_2$ Mass Ordering:

–solar mass ordering



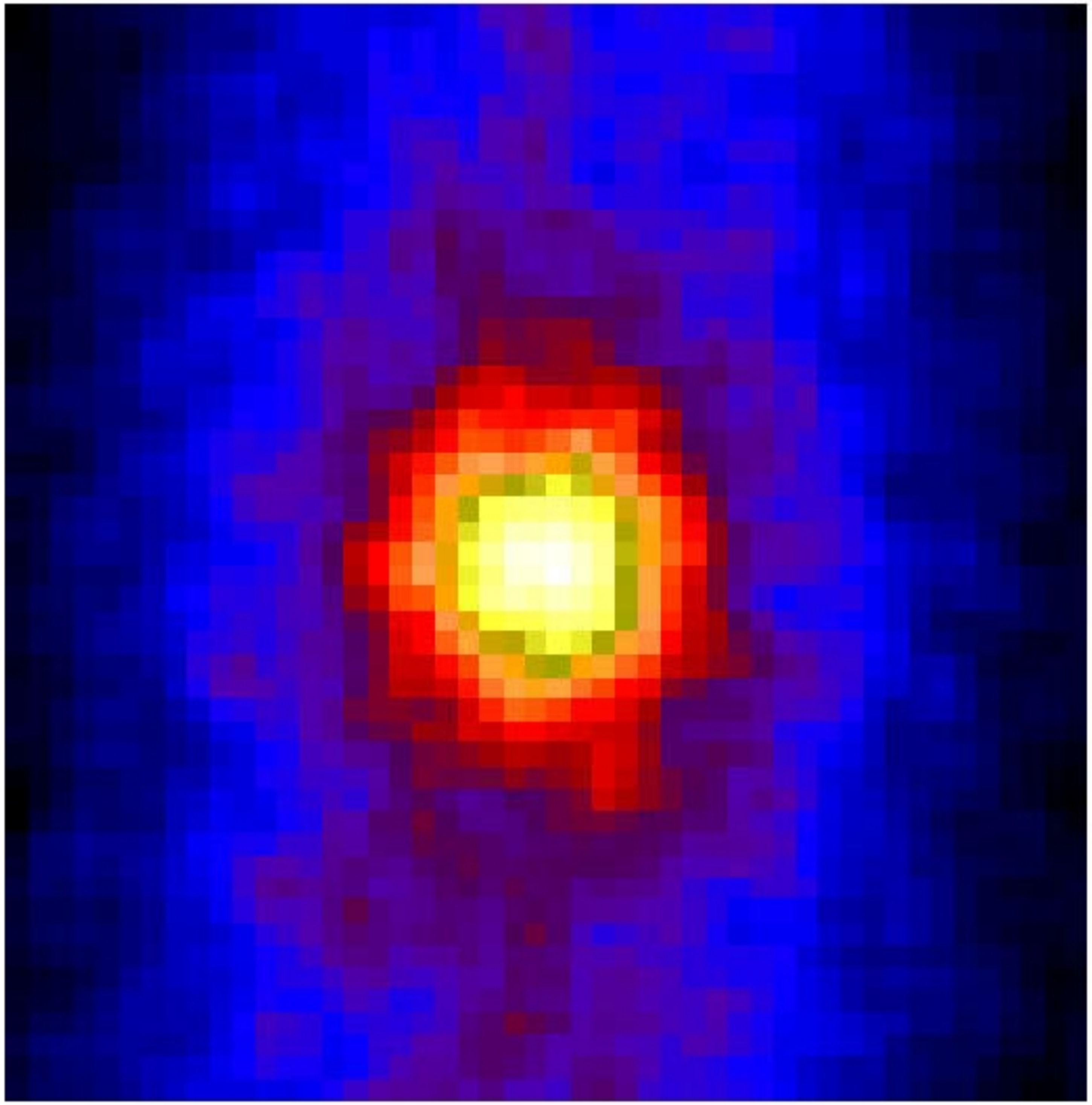
$$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5} \ \mathrm{eV}^2$$

$$L/E = 15 \ \mathrm{km/MeV} = 15,000 \ \mathrm{km/GeV}$$

SNO $\quad m_2 > m_1$

$\nu_e =$ $\qquad \nu_\mu =$ $\qquad \nu_\tau =$

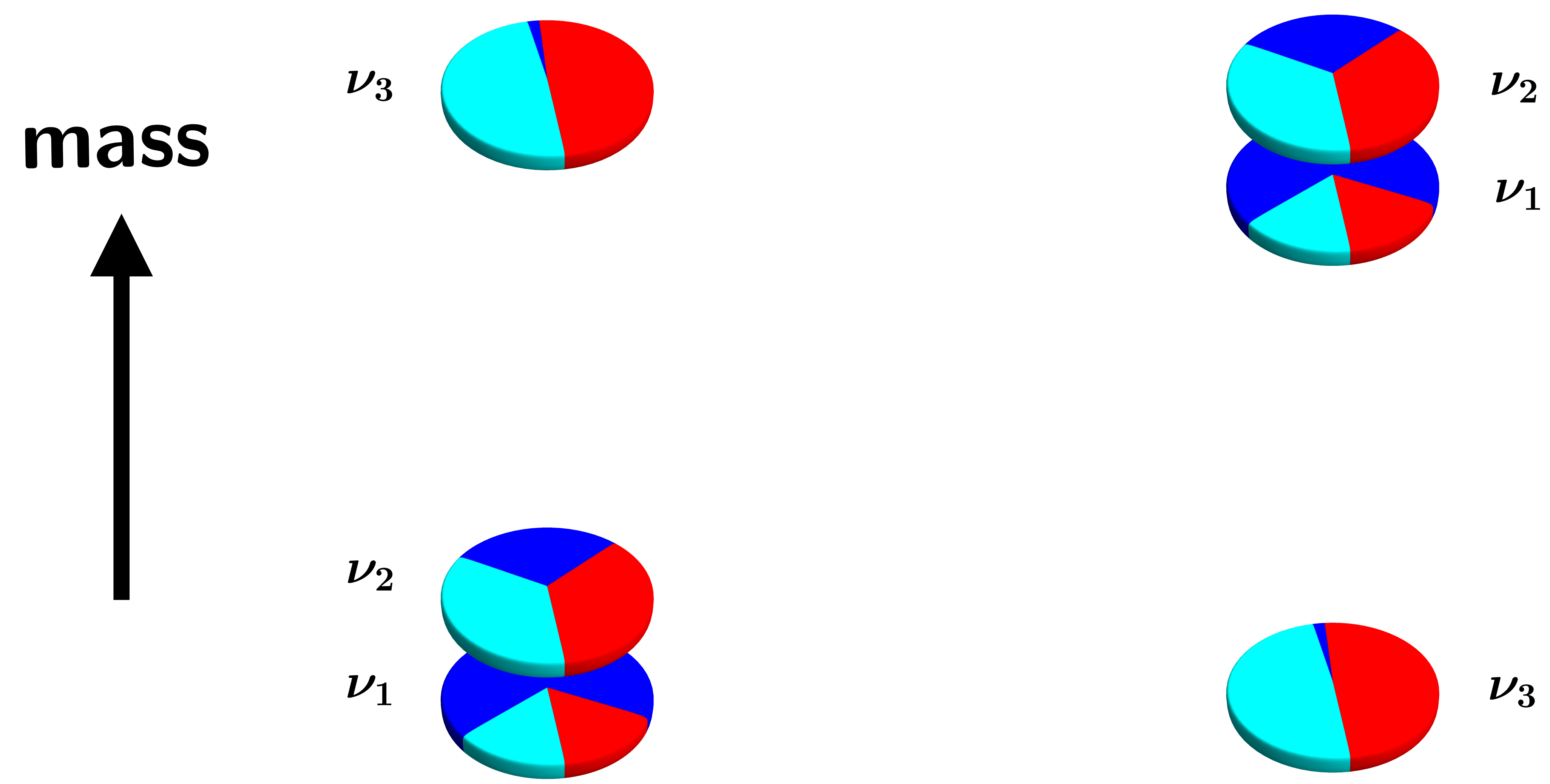
Neutrino Picture of the Sun



ν_e, ν_μ,ν_τ, ν_1, ν_2, ν_3 which dominates ?

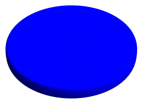
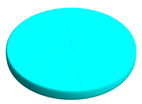
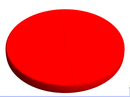
ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering

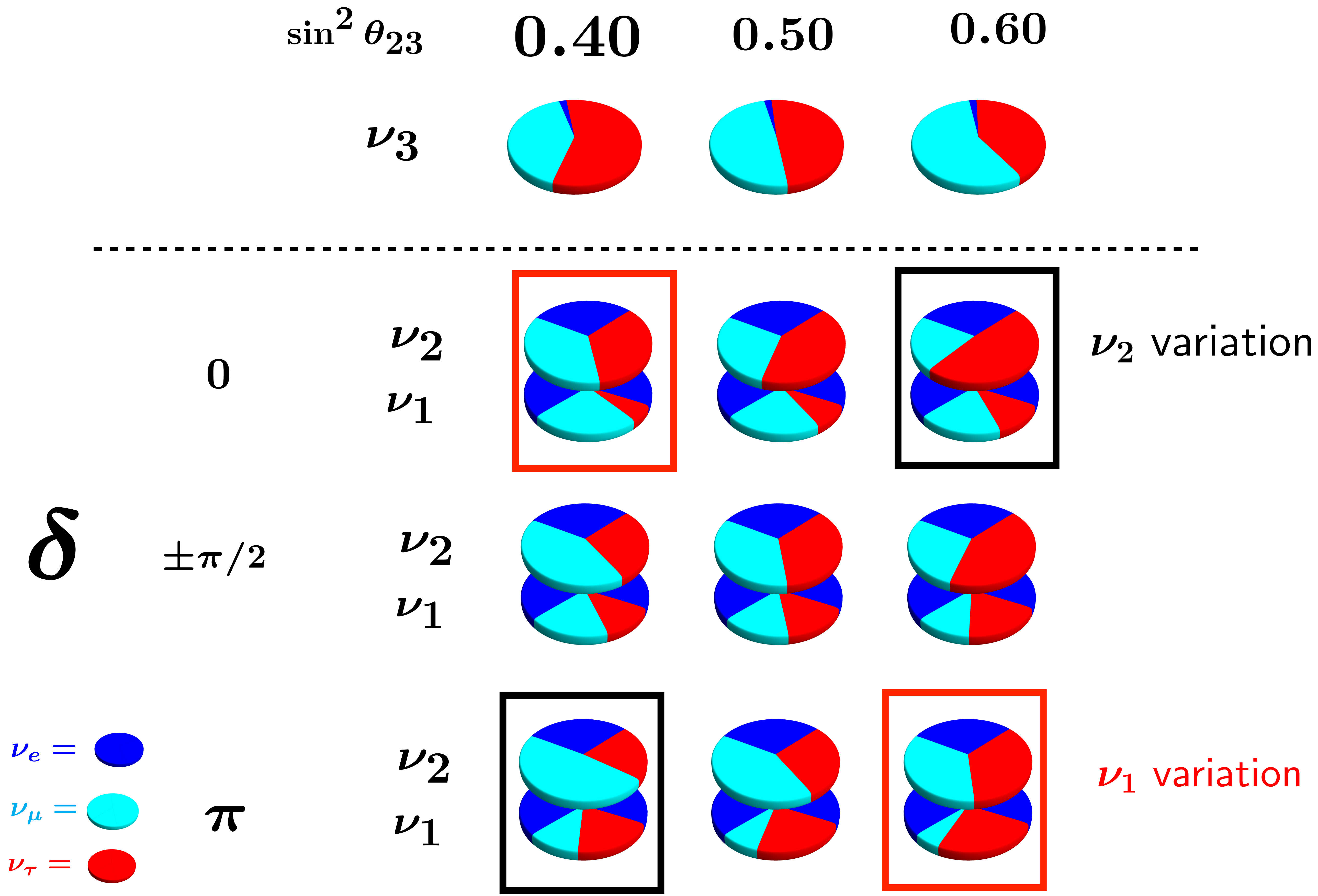


$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \mathrm{eV}^2$ $\quad$ $L/E = 0.5\ \mathrm{km/MeV} = 500\ \mathrm{km/GeV}$

Unknown: NOνA, JUNO, ICECUBE, DUNE, T2HKK....

$\nu_e =$  $\nu_\mu =$  $\nu_\tau =$ 

Summary: Octant of θ_{23}



Neutrino Oscillation Amplitudes in vacuum:

"the billion $ process"

$$P(\nu_\mu \to \nu_e) \quad = \quad |\mathcal{A}_{\mu e}|^2$$

$$\mathcal{A}_{\mu e} \quad = \quad (2i)\ [\ (s_{23}s_{13}c_{13})\ [\ c_{12}^2 e^{-i\Delta_{32}} \sin\Delta_{31} + s_{12}^2 e^{-i\Delta_{31}} \sin\Delta_{32}\ ]$$

$$+\ (c_{23}c_{13}s_{12}c_{12})\ e^{i\delta}\ \sin\Delta_{21}\ ]$$

maintain the symmetry: $m_1^2 \leftrightarrow m_2^2$ with $\theta_{12} \to \theta_{12} \pm \pi/2$

Denton, Minakata, SP arXiv:1604.08167

$$\Delta P_{CP} = 8\ (s_{23}s_{13}c_{13})\ (c_{23}c_{13}s_{12}c_{12})\ \sin\delta\ \sin\Delta_{21}\ \sin\Delta_{31}\ \sin\Delta_{32}$$

J

$$\Delta_{32} \approx \Delta_{31}$$

$$\mathcal{A}_{\mu e} \quad \approx \quad (2i)\ [\ (s_{23}s_{13}c_{13})\ \sin\Delta_{31} + (c_{23}c_{13}s_{12}c_{12})\ e^{i(\delta+\Delta_{31})}\ \sin\Delta_{21}\ ]$$

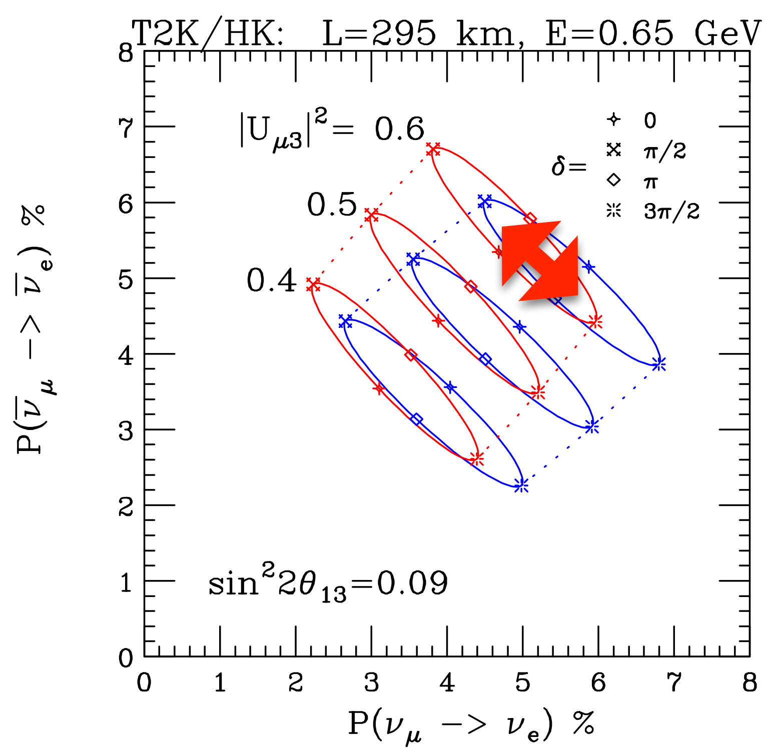
Correlations between $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$

Normal Ordering — Inverted Ordering

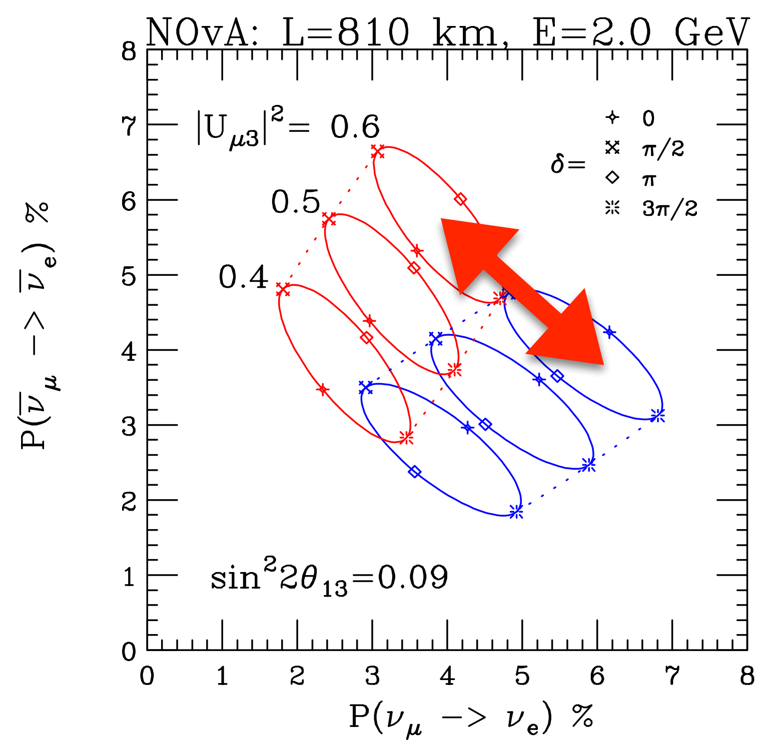
$\nu_\mu \to \nu_\mu$ gives: $\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) = 0.96 \;-\; 1.00$

$|U_{\mu 3}|^2 \leftrightarrow (1-|U_{\mu 3}|^2)$ degeneracy !

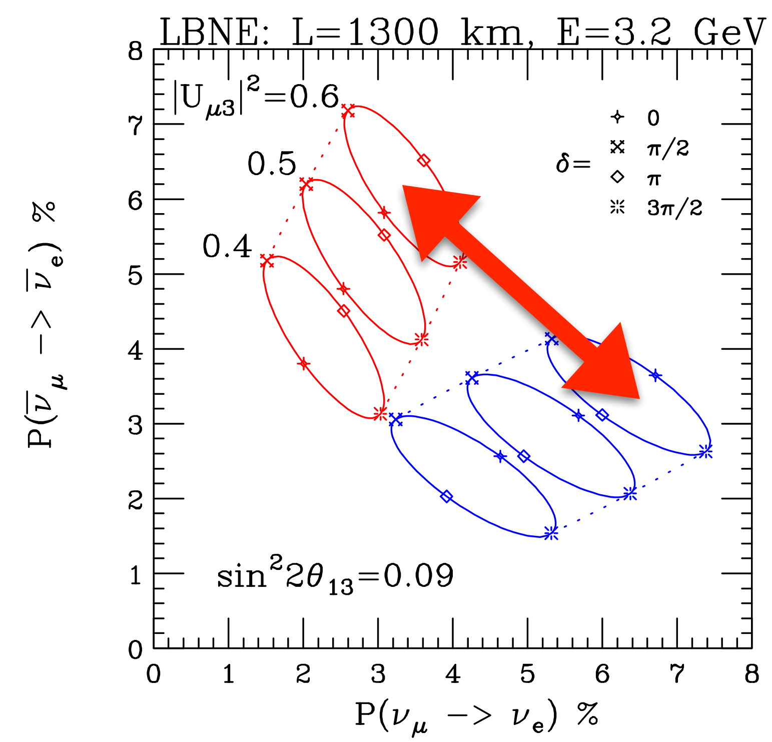
T2K/HK



NOvA



DUNE Same L/E as NOνA



$\propto \rho L \; \sin^2 \theta_{23}$

$$\sin\delta_{NO} - \sin\delta_{IO} = \tan\theta_{23} \times \begin{cases} 0.48 & \text{T2K} \\ 1.62 & \text{NO}\nu\text{A} \\ 2.60 & \text{DUNE} \end{cases}$$

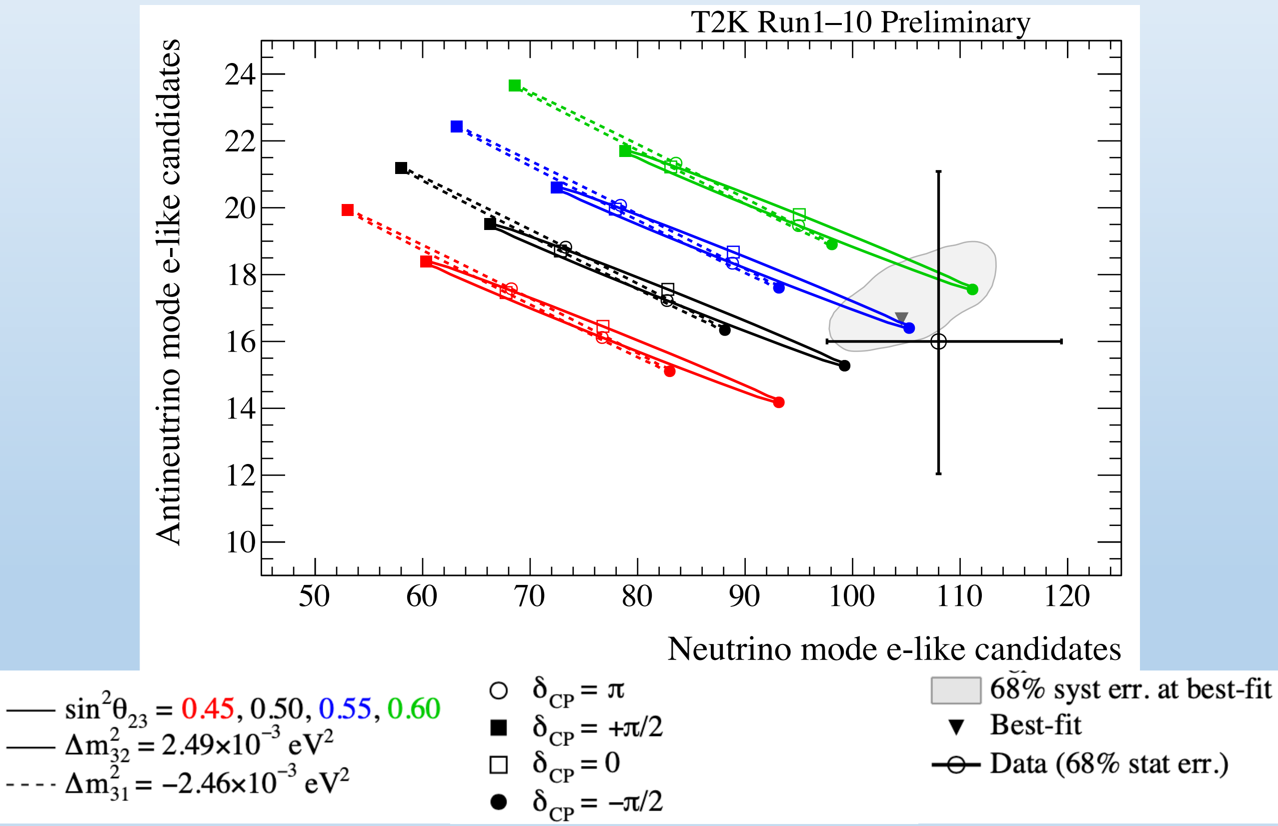
O. Mena & SP hep-ph/0408070

T2K & NOvA

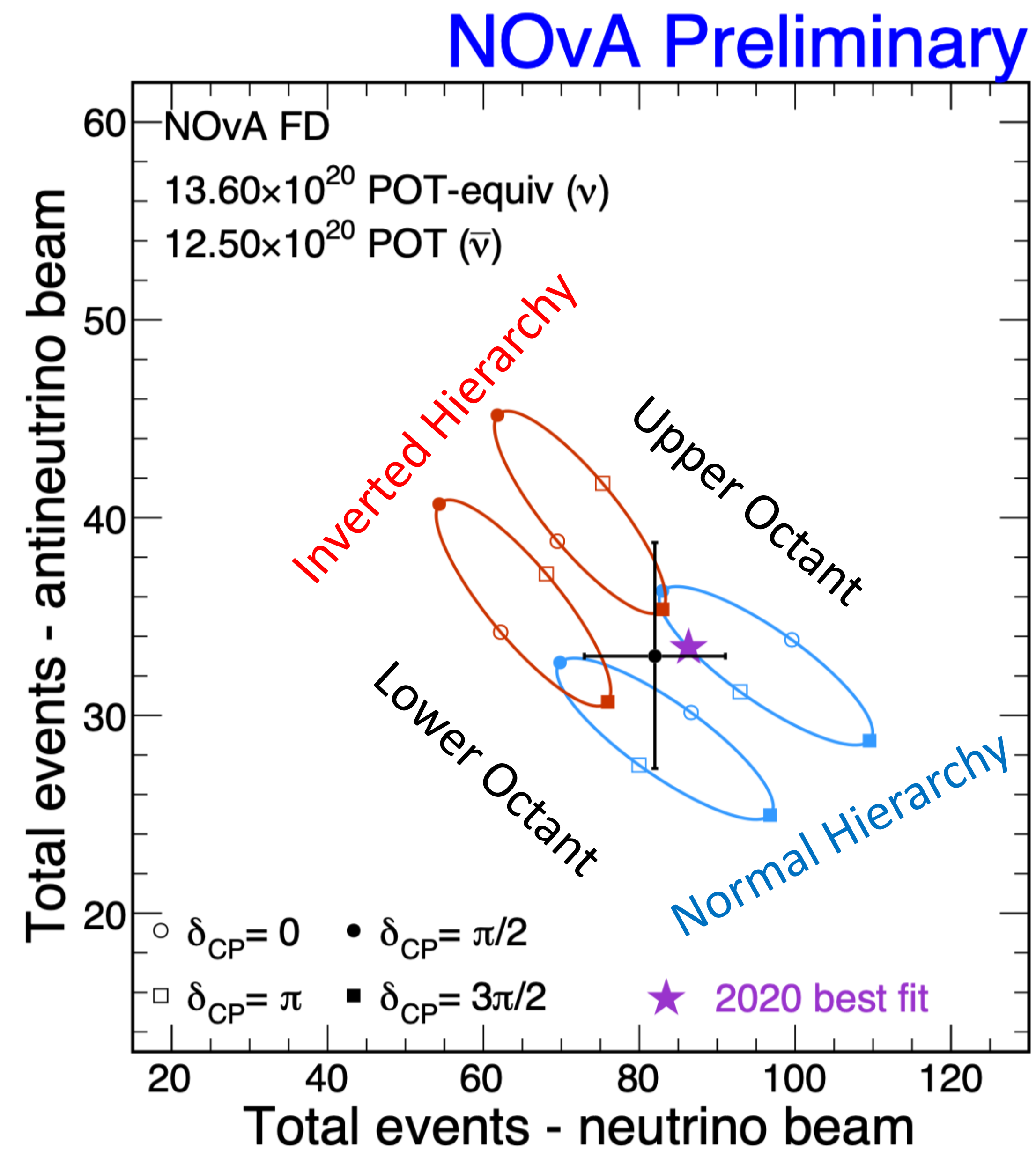
Number of Events proportional to Oscillation Probability

SK event samples

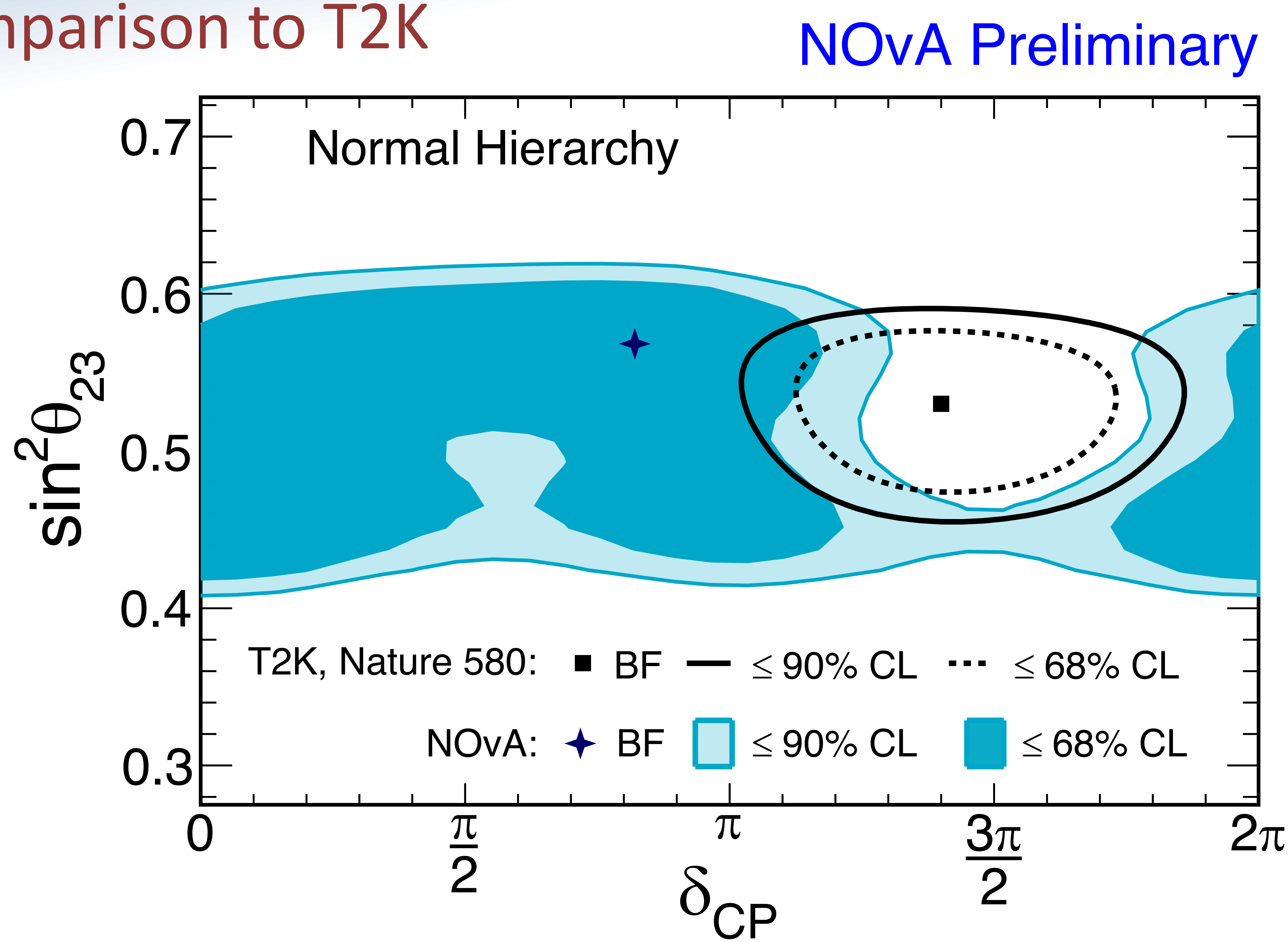
- O(45%) change in electron-like event rate between $\delta_{CP}=+\pi/2$ and $\delta_{CP}=-\pi/2$



Patrick Dunne (p.dunne12@imperial.ac.uk) 23



Comparison to T2K



- Clear tension with T2K's preferred region.

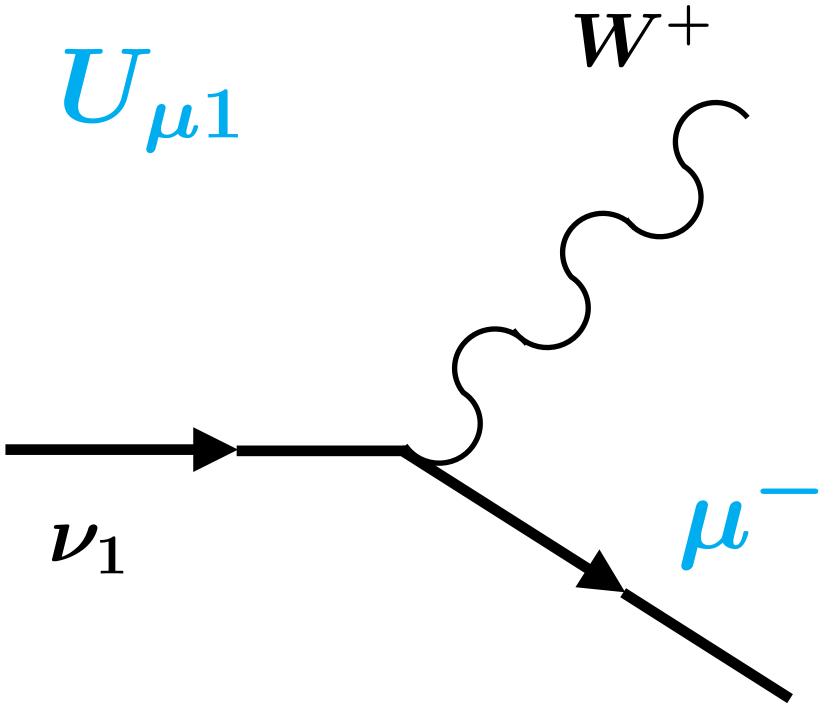
—> bsm papers

Leptons:

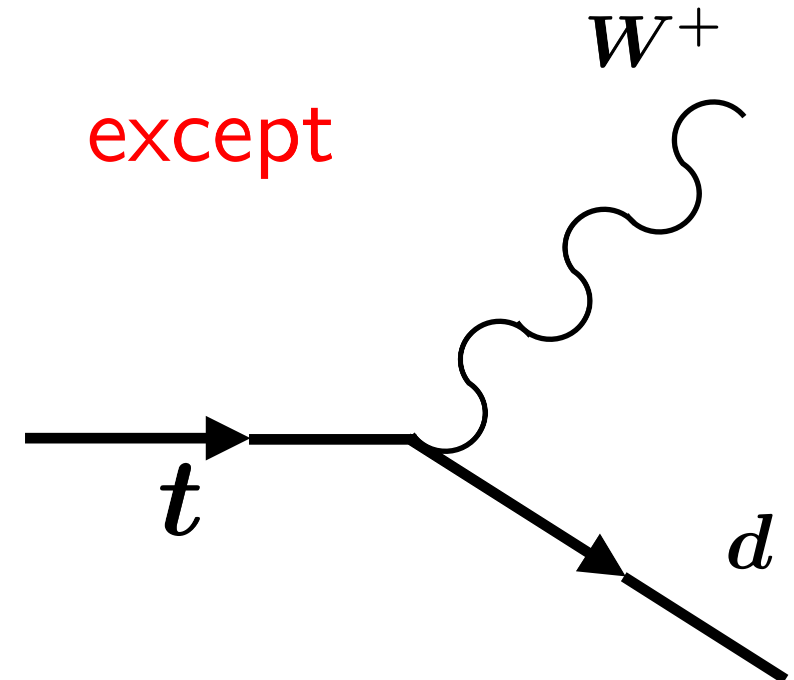
Quarks:

$|V_{ij}|^2$ essentially independent of δ_q !

$U_{\mu 1}$



except



$$0.08 < |U_{\mu 1}|^2 < 0.24$$

variation in δ only !

$$V_{td} \approx A\lambda^3(1 - 0.37e^{i\delta_q})$$

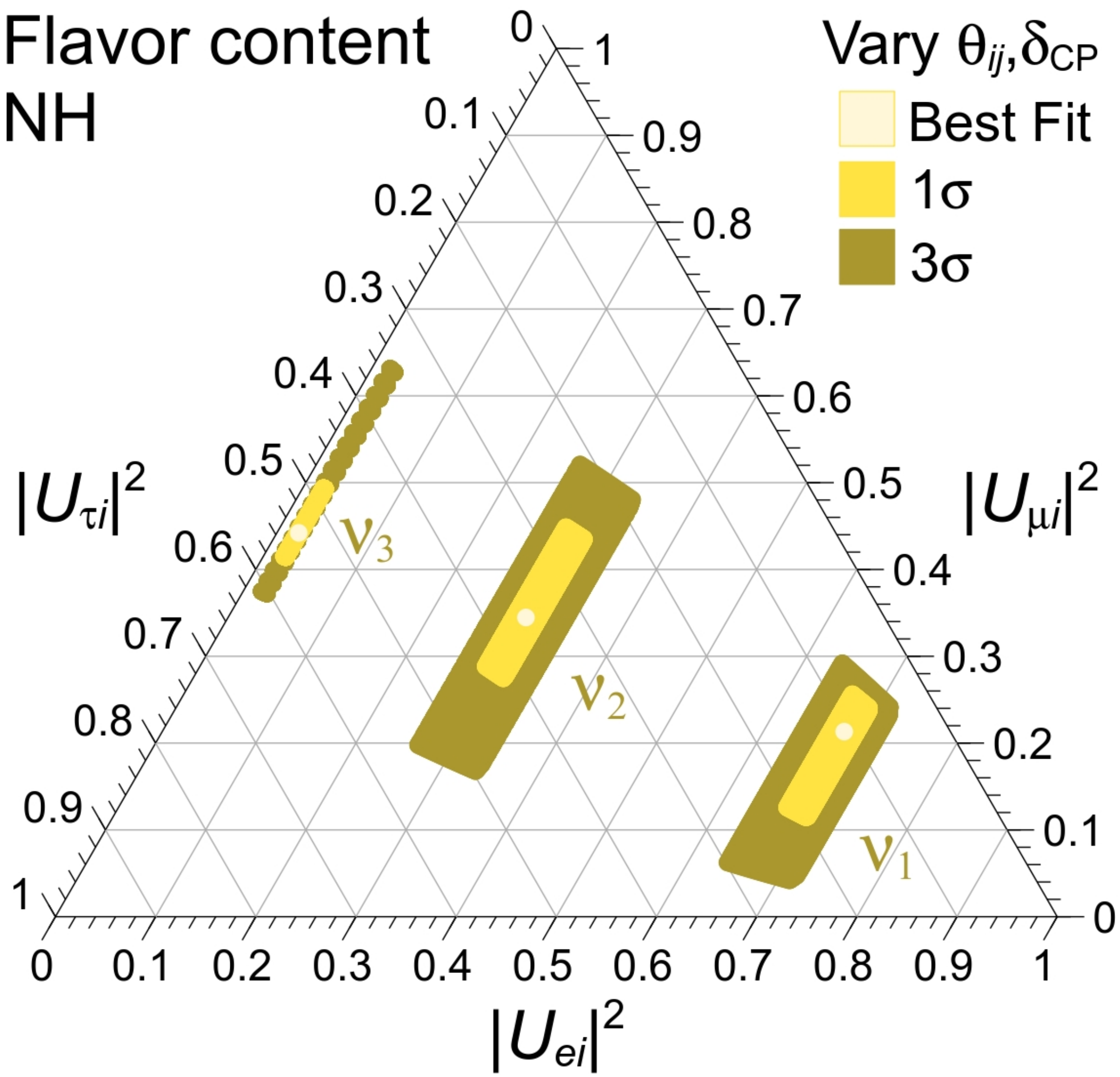
$$|V_{td}|^2 \approx 10^{-4}$$

factor of 3 diff.

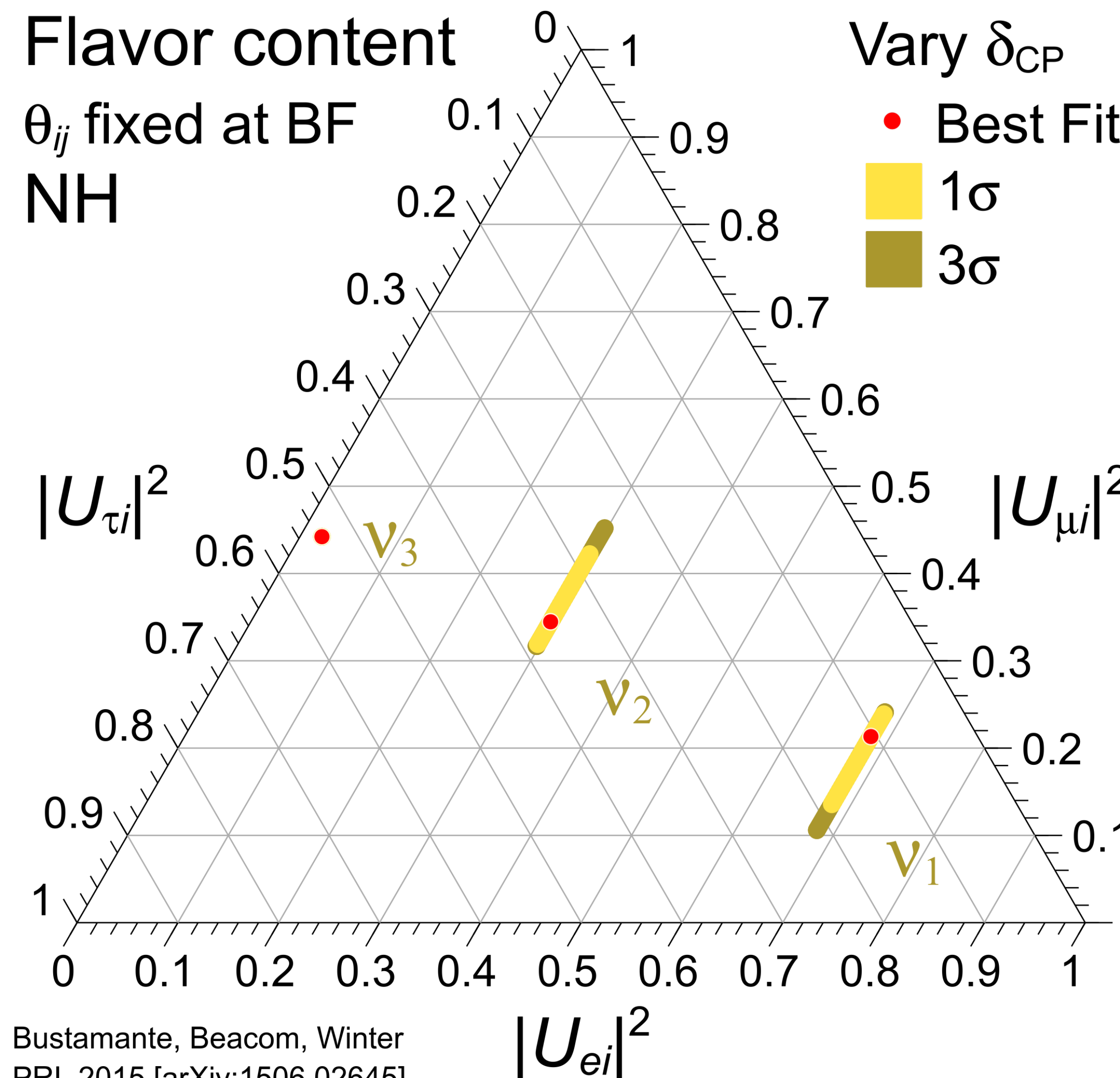
$$|U_{\mu 3}|^2 = 0.4 - 0.6$$
$$|U_{\mu 2}|^2 = 0.26 - 0.41$$
$$|U_{\mu 1}|^2 = 0.08 - 0.24$$

$$|V_{tb}|^2 \approx 1$$
$$|V_{ts}|^2 \sim \lambda^4 \approx 2 \times 10^{-3}$$

δ_q → $|V_{td}|^2 \sim \lambda^6 \approx 8 \times 10^{-5}$



δ & θ_{23} uncertainty



Bustamante, Beacom, Winter
PRL 2015 [arXiv:1506.02645]

no θ_{23} uncertainty

Determine flavor fractions of neutrino mass states

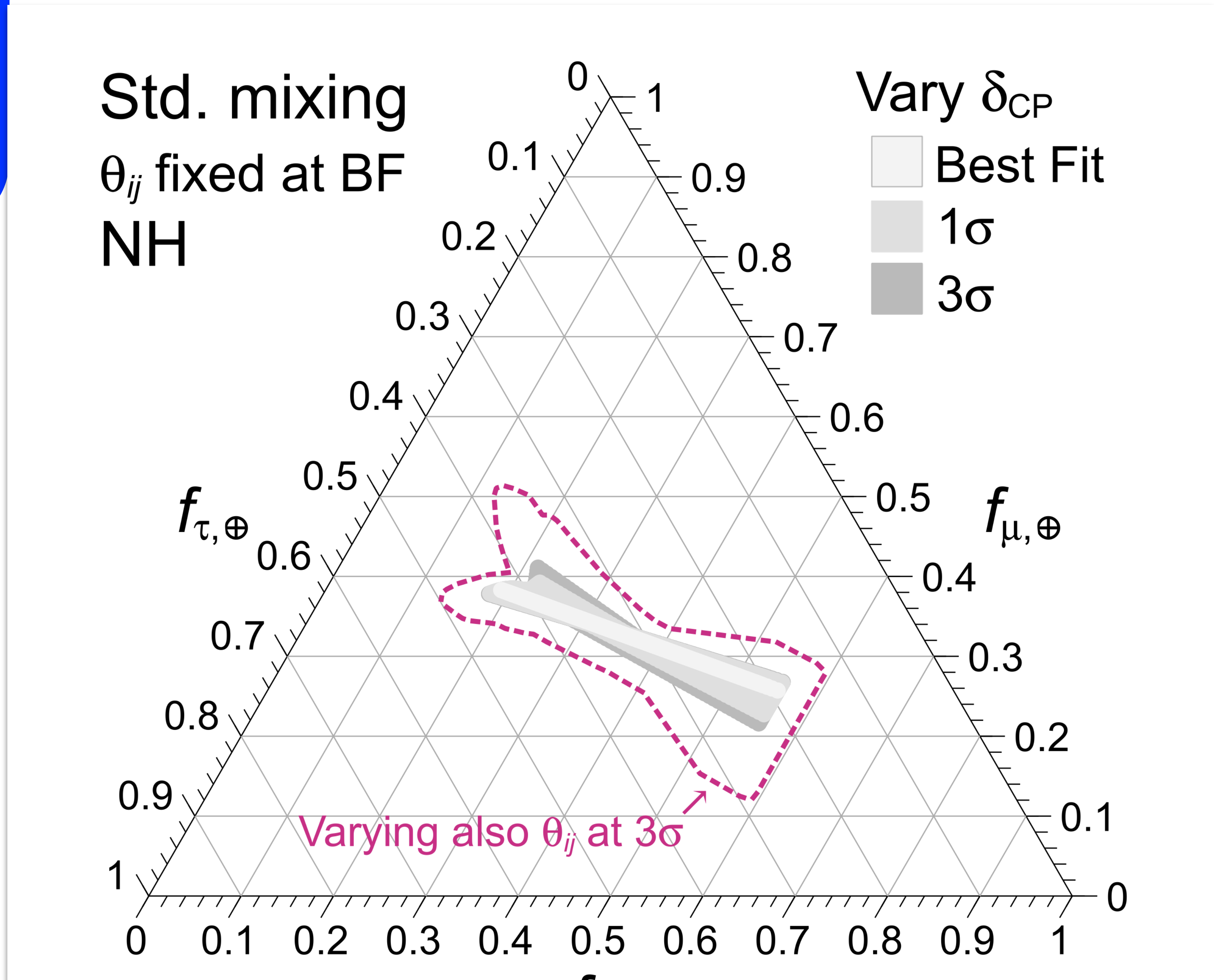
WHY?

Precision Neutrino Measurements:

To discover neutrino BSM,
one needs precision predictions for nuSM

Determine flavor fractions of neutrino mass states

Precision Predictions for flavor ratios at ICECUBE.



Bustamante, Beacom, Winter
PRL 2015 [arXiv:1506.02645]

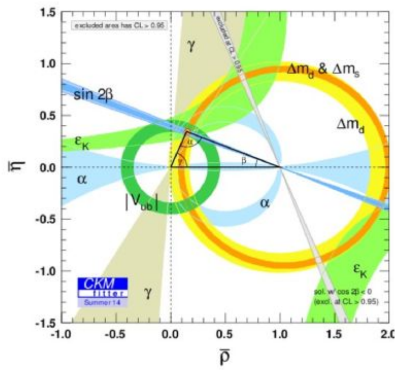
WHY?

Determine flavor fractions of neutrino mass states

Stress Test Neutrino paradigm search for new physics

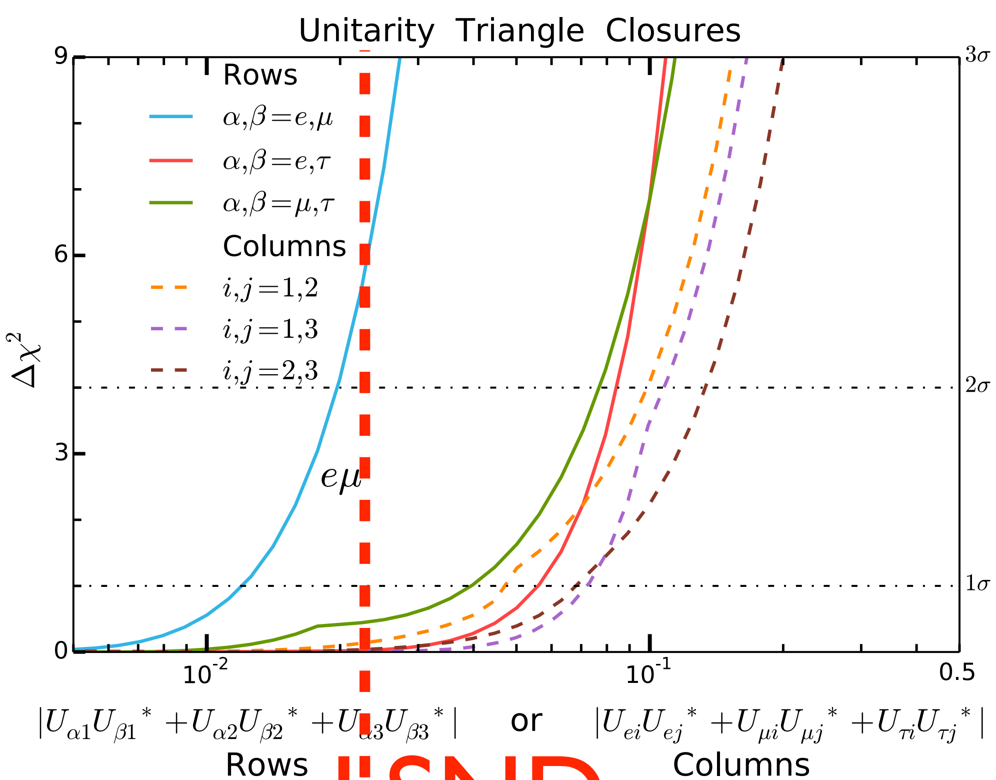
Precision Neutrino Measurements:

Quark



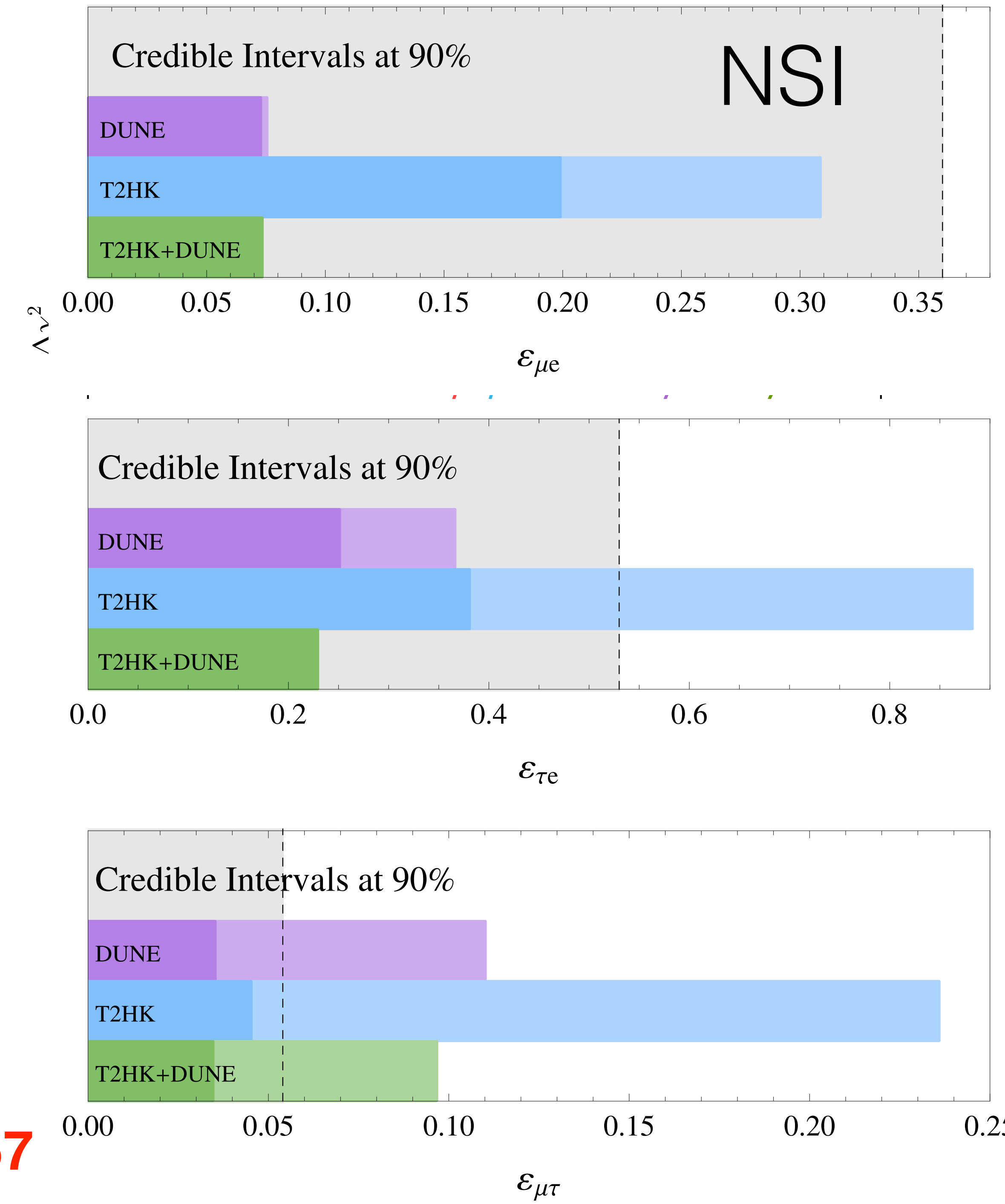
$A\lambda^3$

Stress Test
Neutrino paradigm
search for new physics



LSND

M. Ross-Lonergan + SP
arXiv:1508.05095



P.Coloma
arXiv:1511.06357

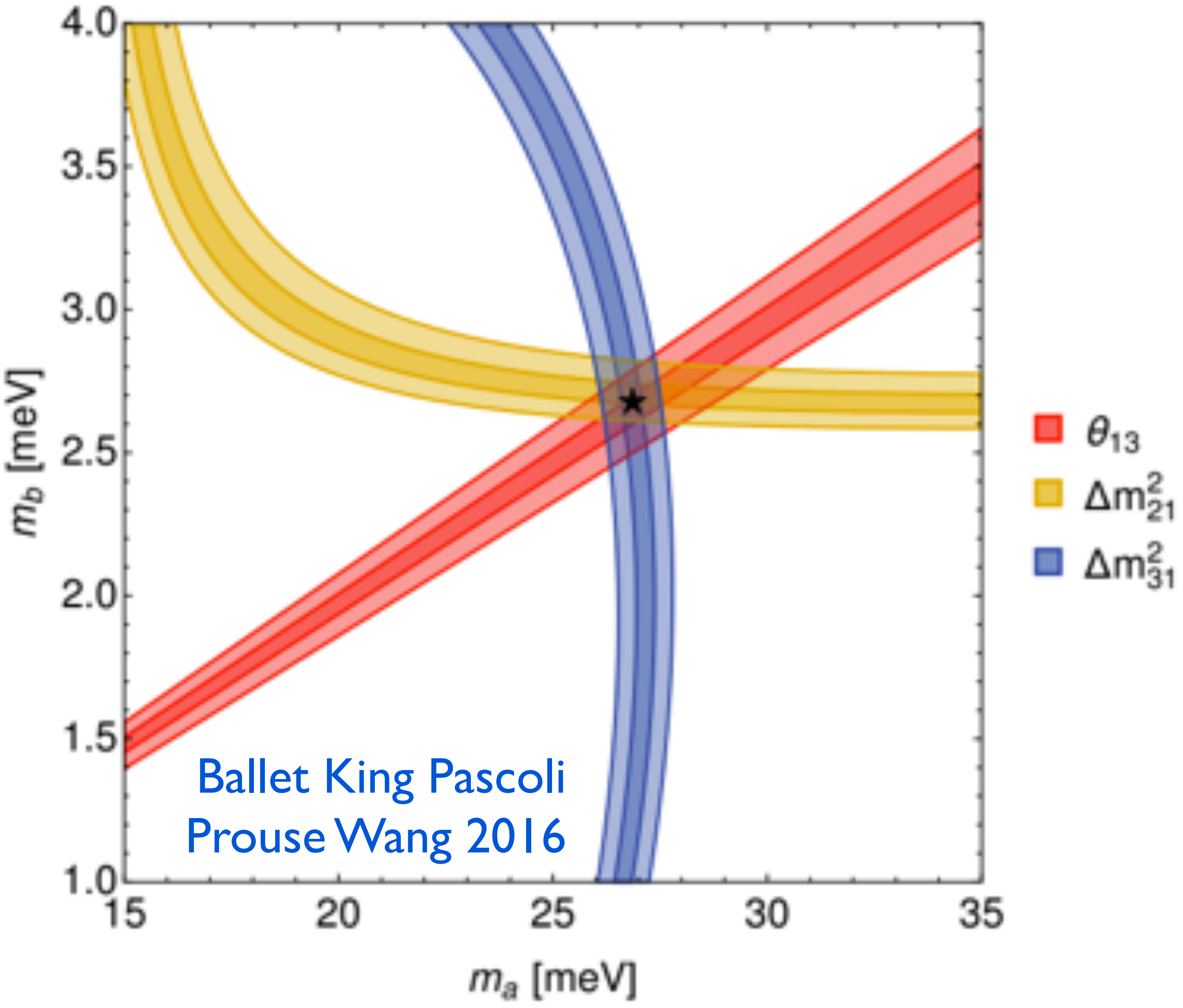
WHY?

Determine flavor fractions of neutrino mass states

Stress Test Neutrino paradigm search for new physics

Precision Neutrino Measurements:

Connection to Leptogenesis Understanding Universe



Connection to Leptogenesis
Understanding Universe

WHY?

Determine flavor fractions of neutrino mass states

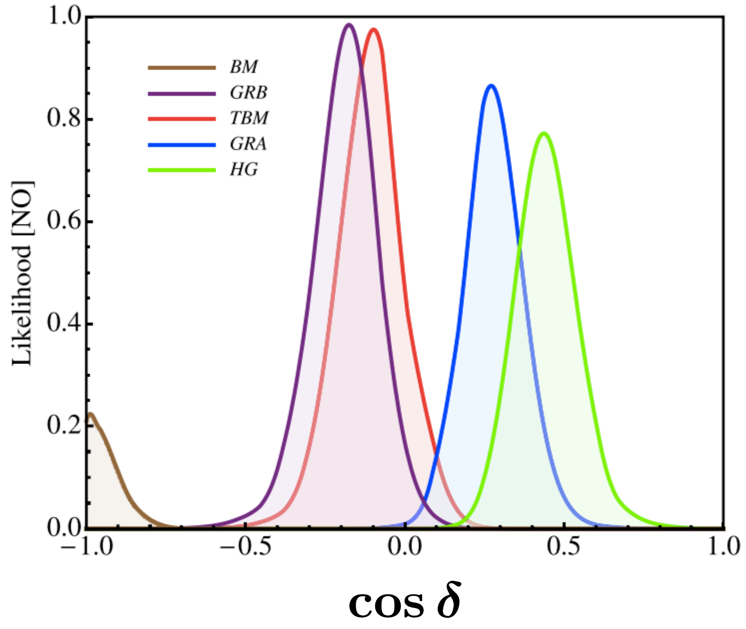
Stress Test Neutrino paradigm search for new physics

Precision Neutrino Measurements:

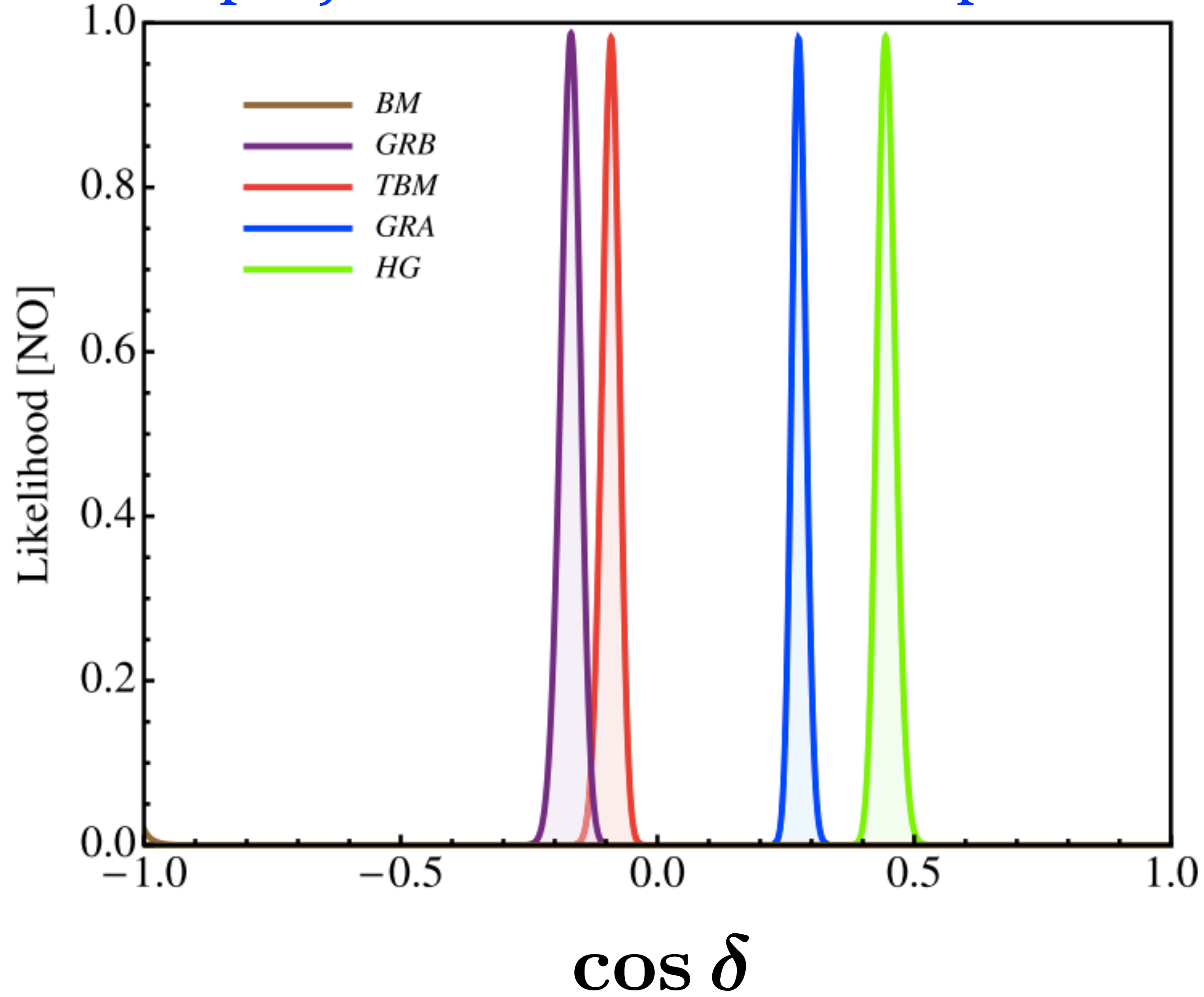
Test Theoretical Neutrino Models

Connection to Leptogenesis Understanding Universe

Predictions from flavor symmetry forms
with current measurement precision



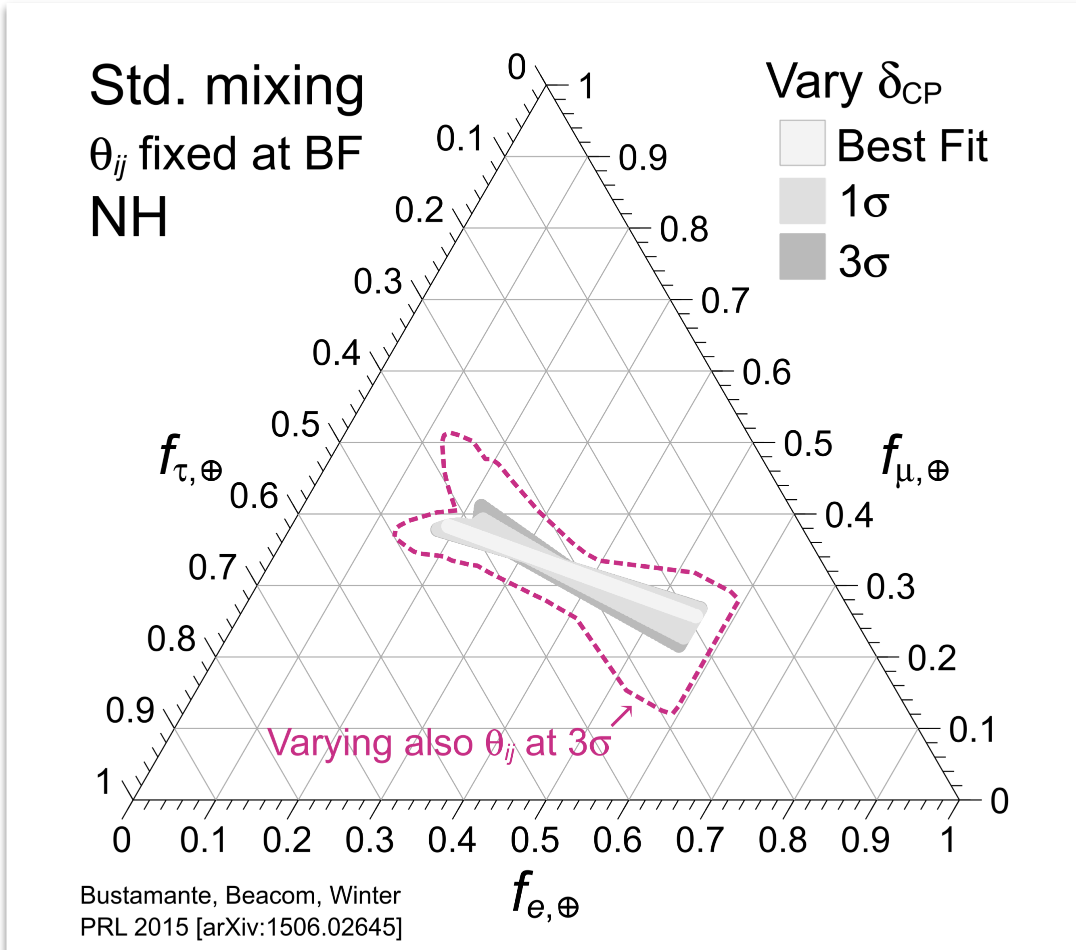
Predictions of flavor symmetry forms
with projected measurement precision

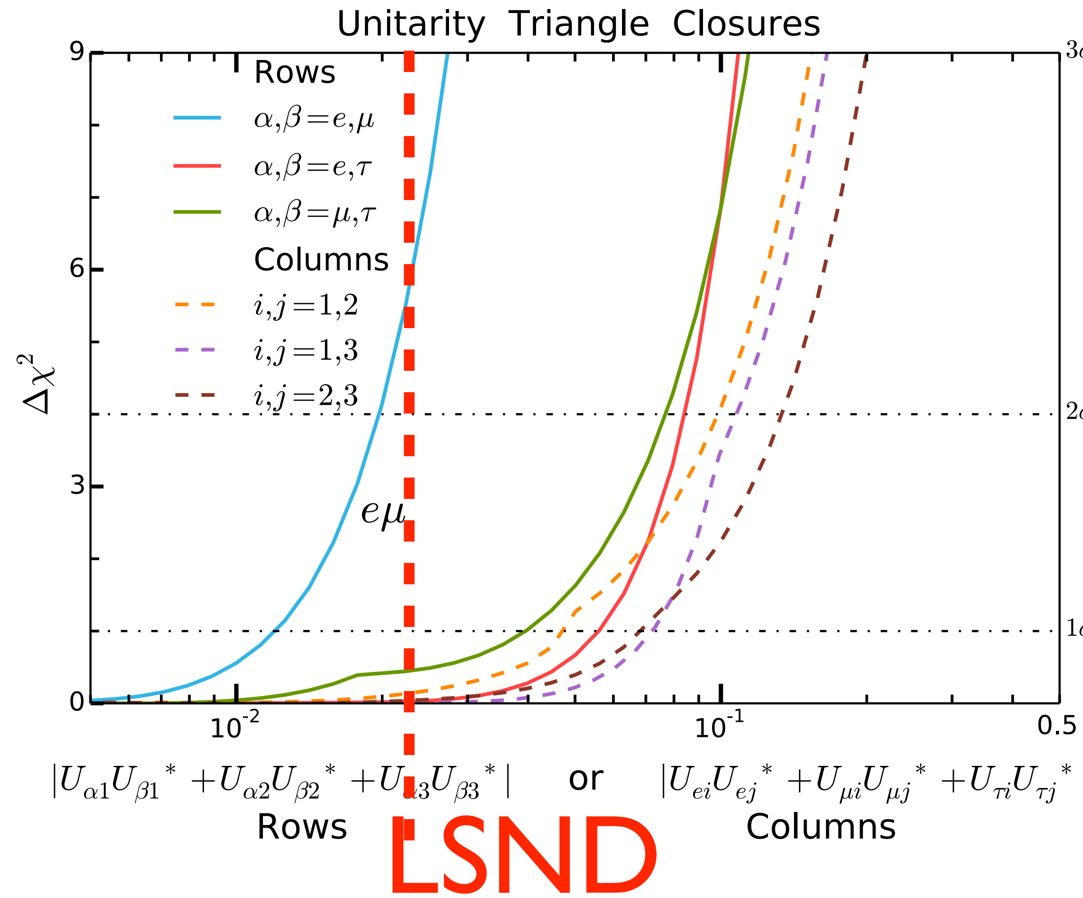


Test Theoretical Neutrino Models

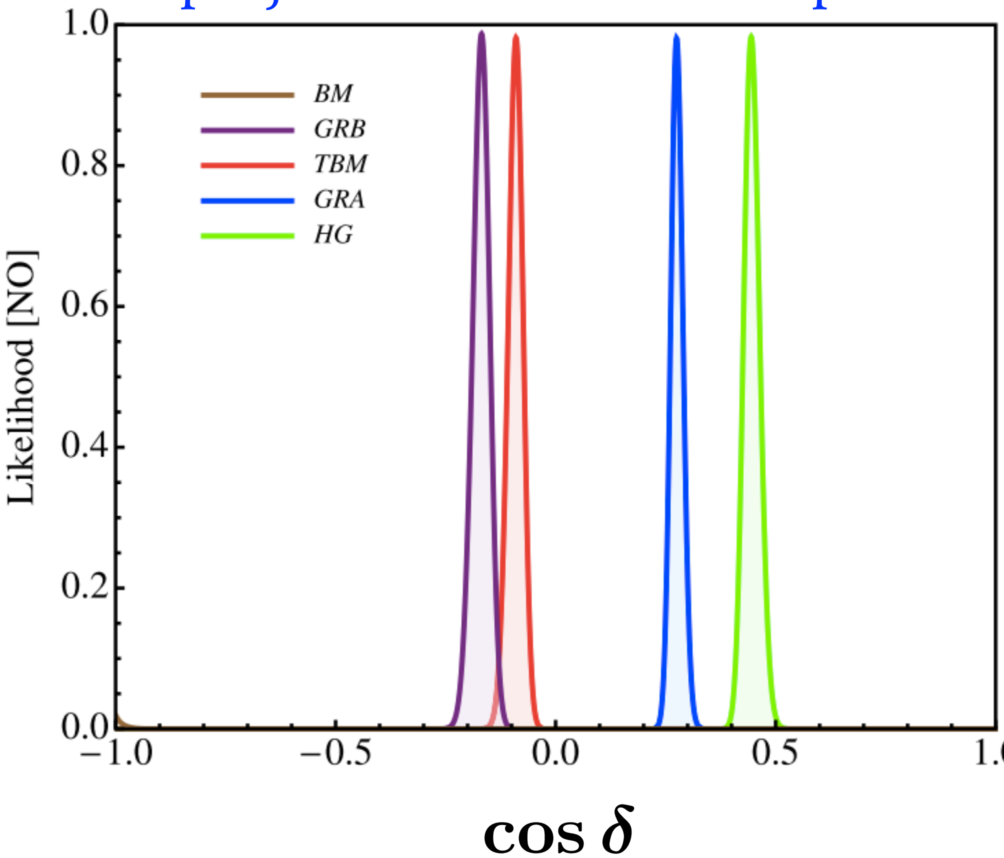
Girardi, Petcov, Titov, arXiv:1410.8056

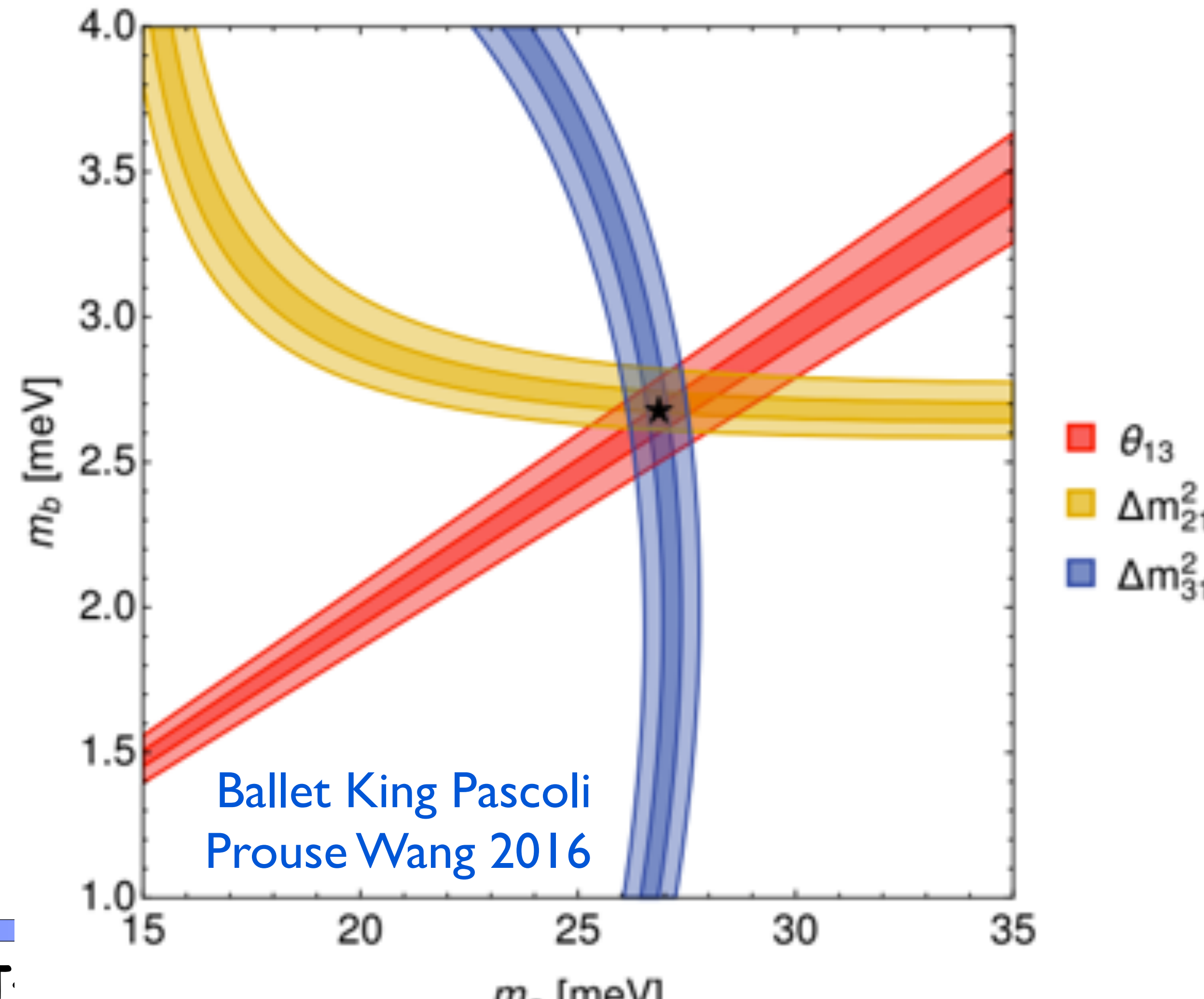
Nucl. Phys. B, Vol. 894, 733-768 (2015)





Predictions of flavor symmetry forms with projected measurement precision





$$\Delta m^2_{31} \;\&\; \Delta m^2_{32}$$

v

$$\Delta m^2_{ee} \;\&\; \Delta m^2_{\mu\mu}$$

Effective Δm^2_{eff} for Δm^2_{31} & Δm^2_{32} at L/E $\sim$ 500 km/GeV = 0.5 km/MeV:

Channel Dependent:

(...) is ν_e average of 1 & 2

$$\begin{aligned}\Delta m^2_{ee} &\equiv m^2_3 - (c^2_{12} m^2_1 + s^2_{12} m^2_2) \\ &= c^2_{12} \Delta m^2_{31} + s^2_{12} \Delta m^2_{32}\end{aligned}$$

$$1 - P(\nu_e \to \nu_e) \approx 4\,|U_{e3}|^2\,(\,1 - |U_{e3}|^2\,)\;\sin^2 \Delta_{ee}$$

Daya Bay and RENO.

(...) is ν_μ average of 1 & 2

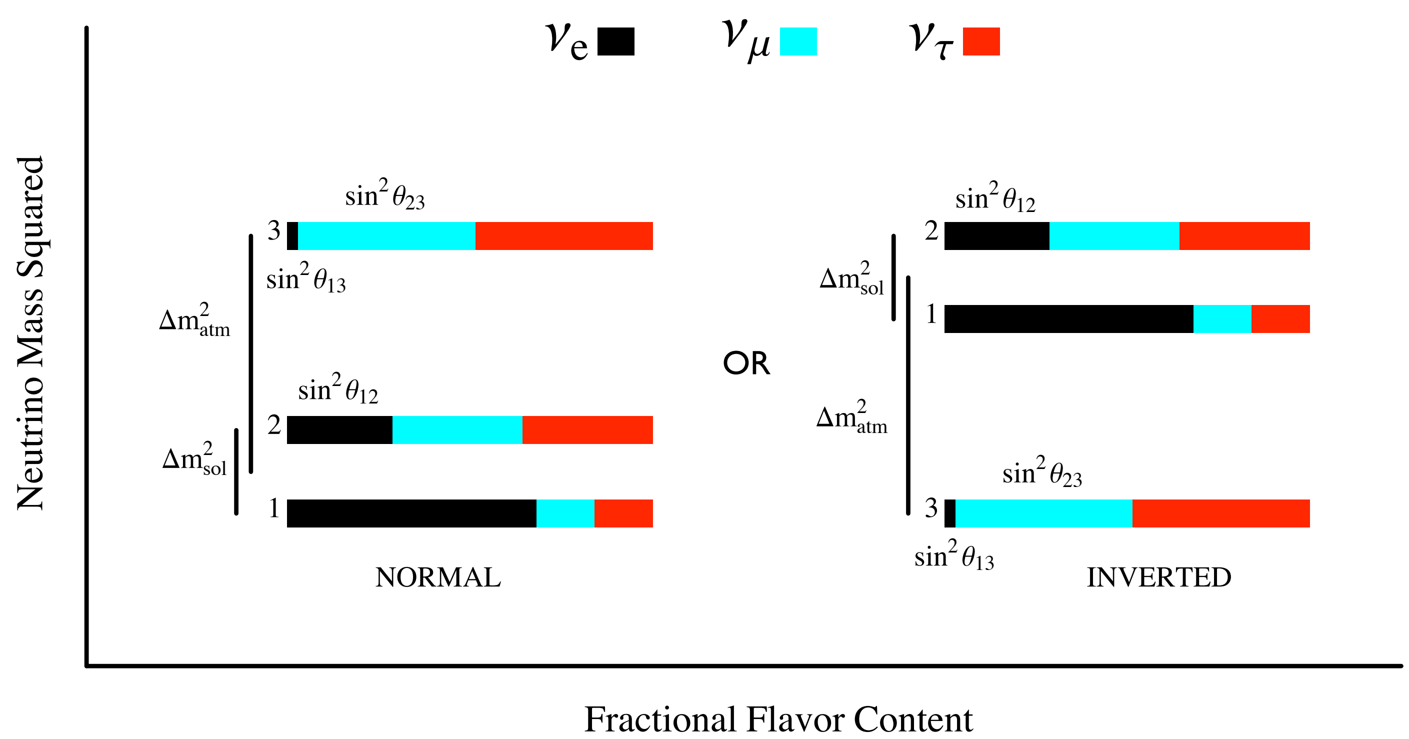
$$\begin{aligned}\Delta m^2_{\mu\mu} &\equiv m^2_3 - (s^2_{12} m^2_1 + c^2_{12} m^2_2) \\ &= s^2_{12} \Delta m^2_{31} + c^2_{12} \Delta m^2_{32}\end{aligned}$$

$$1 - P(\nu_\mu \to \nu_\mu) \approx 4\,|U_{\mu 3}|^2\,(\,1 - |U_{\mu 3}|^2\,)\;\sin^2 \Delta_{\mu\mu}$$

T2K, NOvA, ...

Nunokawa, SP, Zukanovich hep/0503283

Mass Ordering:



Normal Ordering: $|\Delta m^2_{ee}(NO)| > |\Delta m^2_{\mu\mu}(NO)|$

Inverted Ordering: $|\Delta m^2_{ee}(IO)| < |\Delta m^2_{\mu\mu}(IO)|$

Difference is $\cos 2\theta_{12} \Delta m^2_{21} \approx 1.2\%$

How does this come about ?

Hamiltonian in flavor basis $= \frac{1}{2E} U_{23} U_{13} U_{12} \; M^2 \; U_{12}^\dagger U_{13}^\dagger U_{23}^\dagger$

$$U_{12} \; \mathrm{diag}(m_1^2, m_2^2, m_3^2) \; U_{12}^\dagger = \begin{pmatrix} c_{12}^2 m_1^2 + s_{12}^2 m_2^2 & s_{12} c_{12} \Delta m_{21}^2 & \\ s_{12} c_{12} \Delta m_{21}^2 & s_{12}^2 m_1^2 + c_{12}^2 m_2^2 & \\ & & m_3^2 \end{pmatrix}$$

For ν_e disappearance U_{13} is most important:

$$m_3^2 - (c_{12}^2 m_1^2 + s_{12}^2 m_2^2) \equiv \Delta m_{ee}^2$$

For ν_μ disappearance U_{23} is most important:

$$m_3^2 - (s_{12}^2 m_1^2 + c_{12}^2 m_2^2) \equiv \Delta m_{\mu\mu}^2$$

Even in Matter Δm^2_{ee} is useful:

Defn $a \equiv 2\sqrt{2} G_F N_e E_\nu$, the Wolfenstein Matter Potential

Solar Resonance:

$$a_R^{\odot} \approx \Delta m^2_{21} \cos 2\theta_{12}/c^2_{13}$$

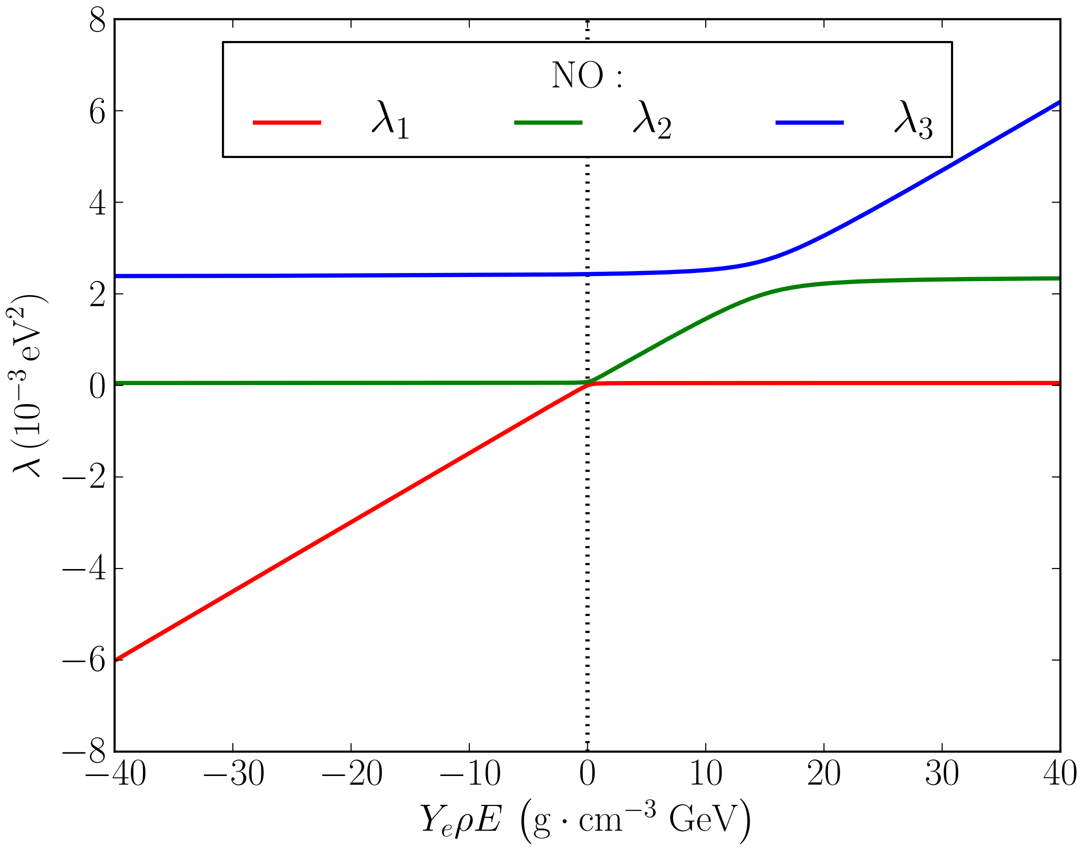
$$\text{Min } \widehat{\Delta m^2}_{21} \approx \Delta m^2_{21} \sin 2\theta_{12}$$

accuracy: $\mathcal{O}(10^{-4})$

Atmospheric Resonance:

$$a_R^{\oplus} \approx \Delta m^2_{??} \cos 2\theta_{13}$$

$$\text{Min } \widehat{\Delta m^2}_{32} \approx \Delta m^2_{??} \sin 2\theta_{13}$$



Δm^2_{32} gives 2% accuracy

Δm^2_{31} gives 1% accuracy

Δm^2_{ee} gives $\mathcal{O}(10^{-4})$ accuracy

SP 2012.07186 (hep-ph)

CP Violation

At oscillation maximum in vacuum:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) - P(\nu_\mu \to \nu_e) = \pi J_0 \left(\frac{\Delta m^2_{21}}{\Delta m^2_{ee}}\right)$$

where J_0 is Jarlskog Invariant (1986):

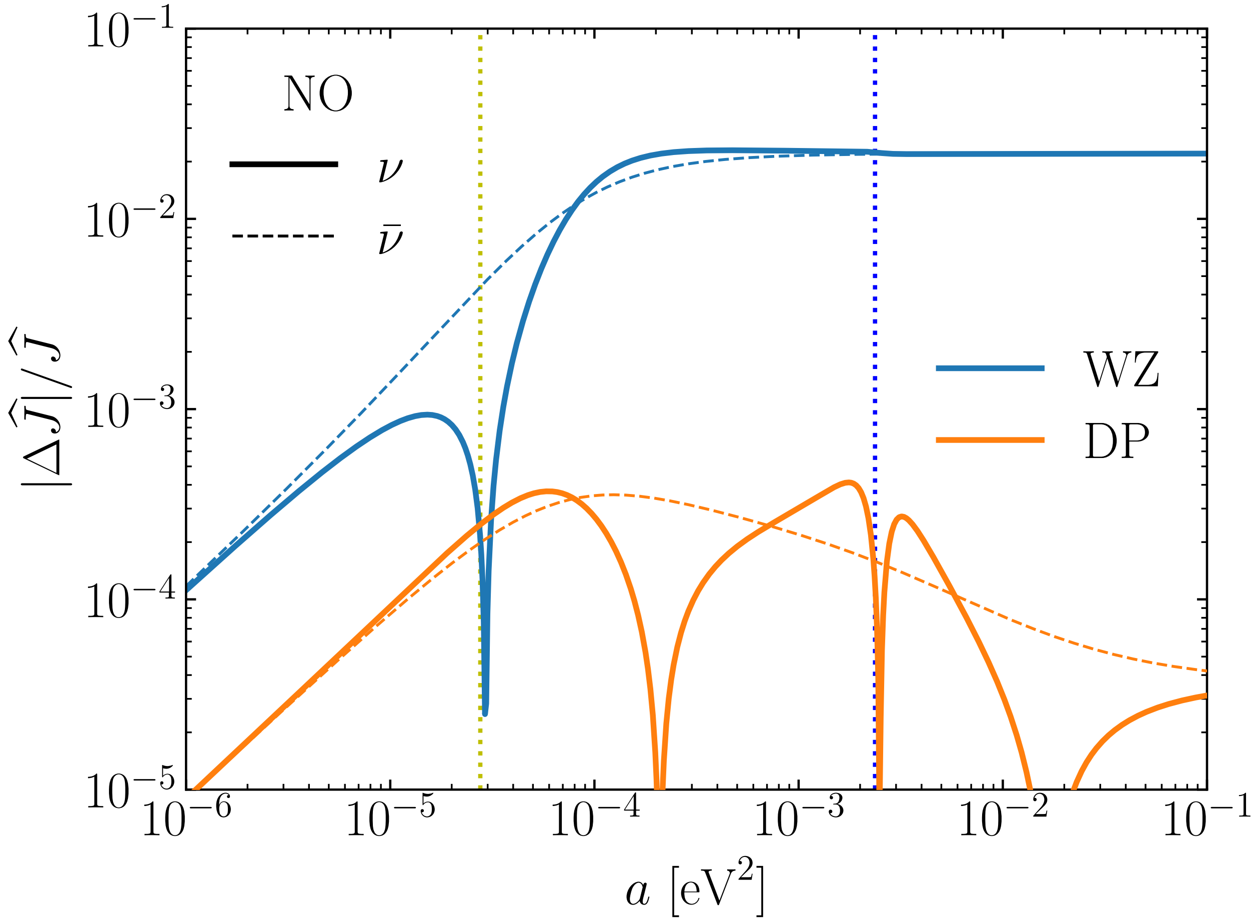
$$J = \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin\delta \approx 0.3 \sin\delta$$

Jarlskog Invariant in Matter

$$\widehat{J} = J_0 \frac{\Pi \Delta m^2_{ij}}{\Pi \widehat{m^2}_{ij}} \approx \frac{J_0}{R_\odot R_\oplus}$$

$$R_\odot = \sqrt{(\cos 2\theta_{12} - a c^2_{12}/\Delta m^2_{21})^2 + \sin^2 2\theta_{12}}$$

$$R_\oplus = \sqrt{(\cos 2\theta_{13} - a/\Delta m^2_{ee})^2 + \sin^2 2\theta_{13}}$$



$\mathcal{O}(10^{-3})$ accuracy !

Denton, SP 1902.07185 (hep-ph)

JUNO by Nu2024 or Nu2026

Best measurements of Δm^2_{21}, $\sin^2\theta_{12}$ and Δm^2_{ee}: accuracy $\Rightarrow\sim$ 0.5%

(JUNO value of $\sin^2\theta_{13}$ will not be more accurate than Daya Bay)

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = 4c^4_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21} + 2s^2_{13}c^2_{13}\left(1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos\left[2|\Delta_{ee}| \pm \Phi(\Delta_{21})\right]\right)$$

Amplitude modulation

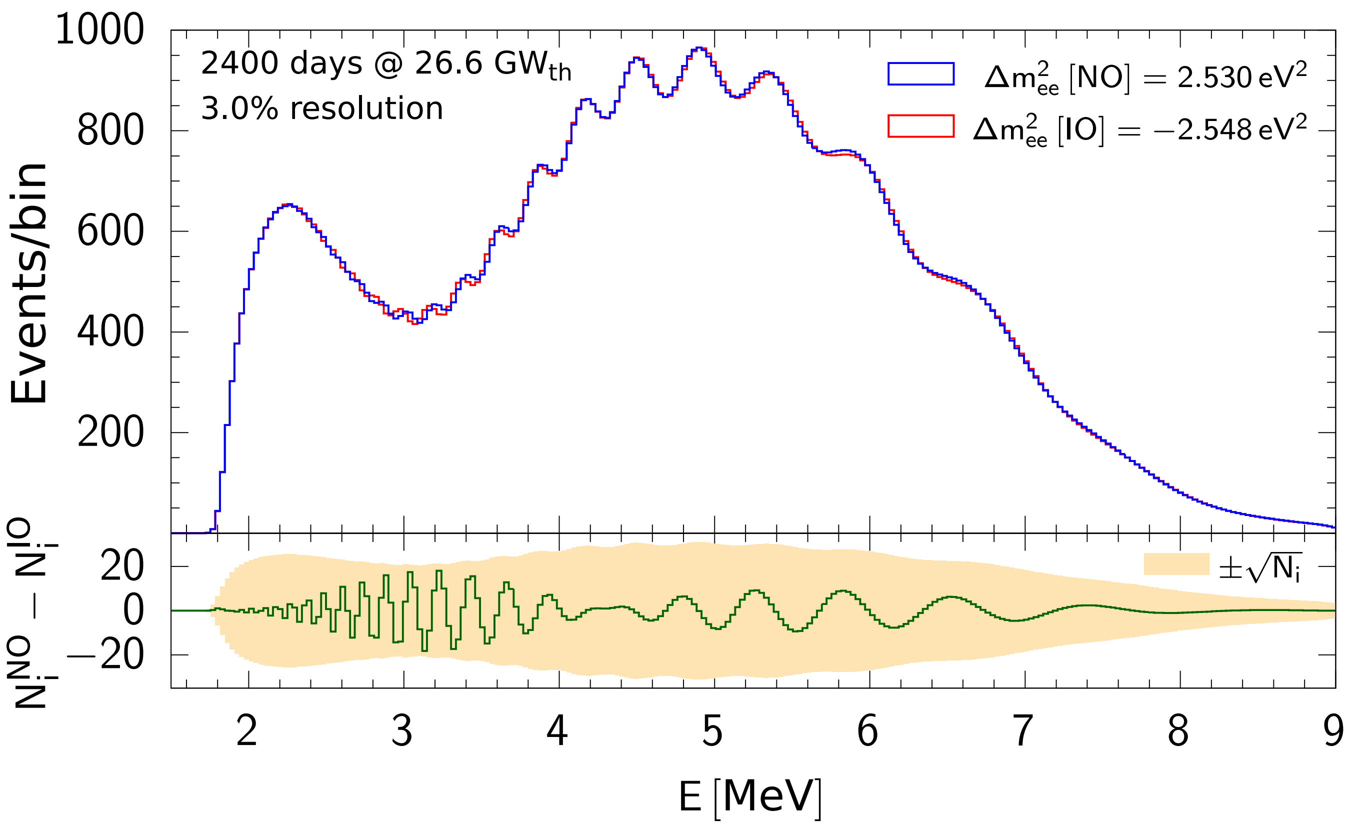
Phase advance(NO)/retardation(IO)

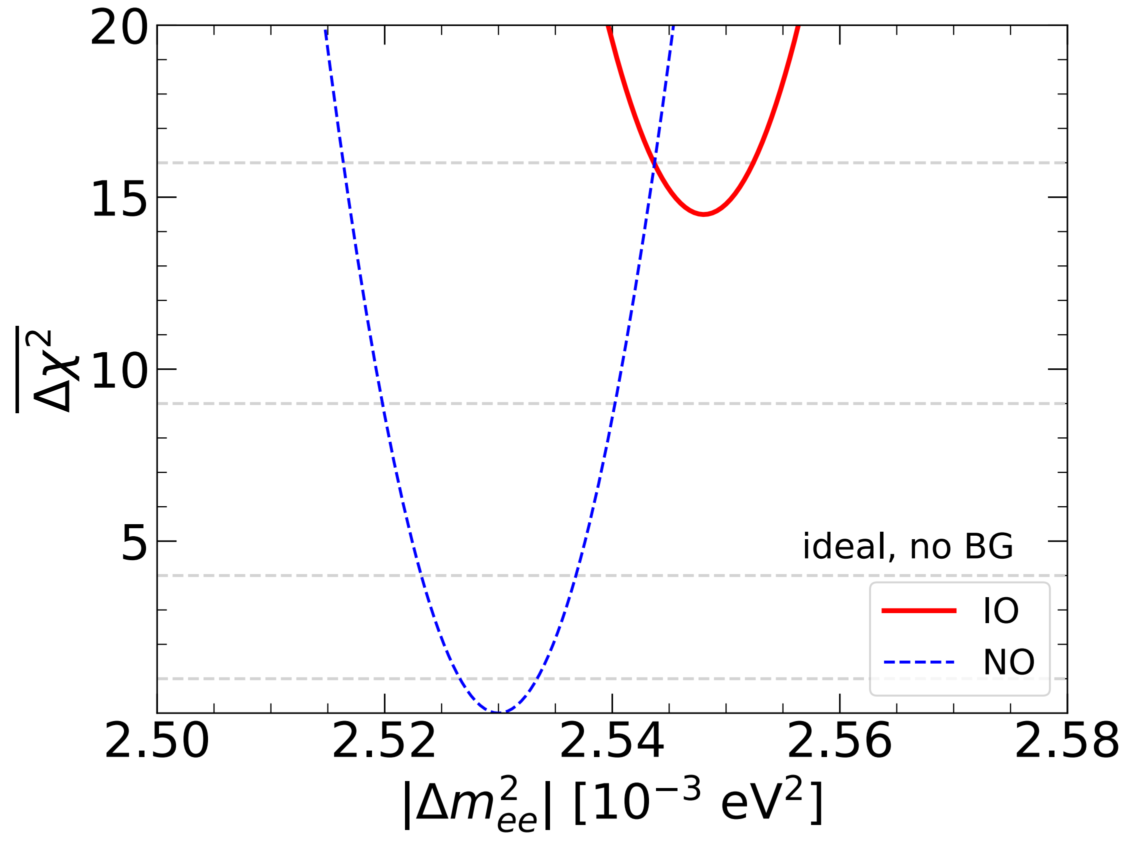
$$\Phi(\Delta_{21}) = \arctan(\cos 2\theta_{12}\tan\Delta_{21}) - \cos 2\theta_{12}\Delta_{21} = \mathcal{O}(\Delta^3_{21})$$

$$\Phi(\Delta_{21} = \pi/2) = \pi\sin^2\theta_{12}$$

Minakata, Nunokawa, SP, Zukanovich hep/0701151

JUNO Events Spectra



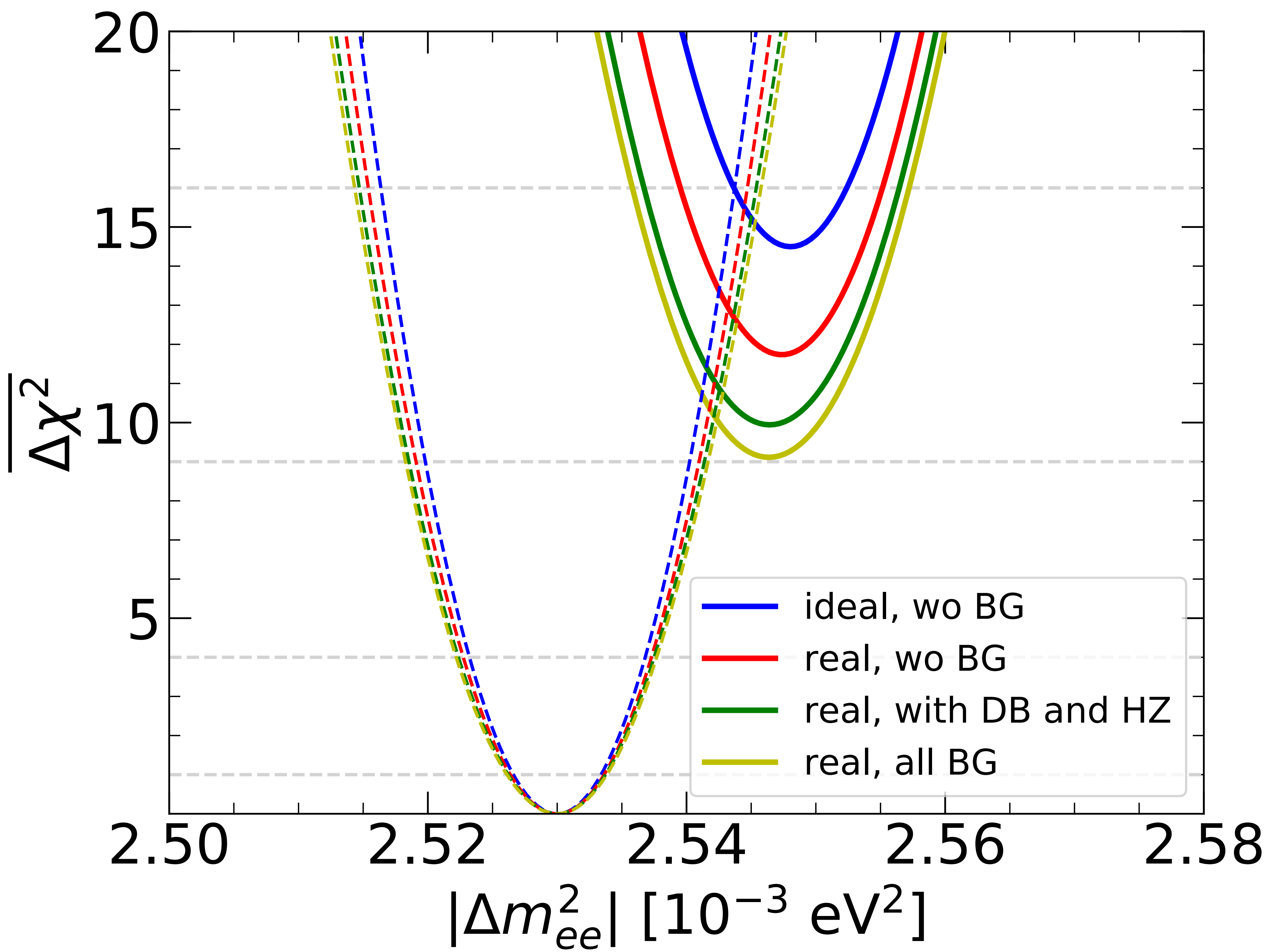


8 years,
26.6 GW_th
52.5 km, baseline
3% resolution

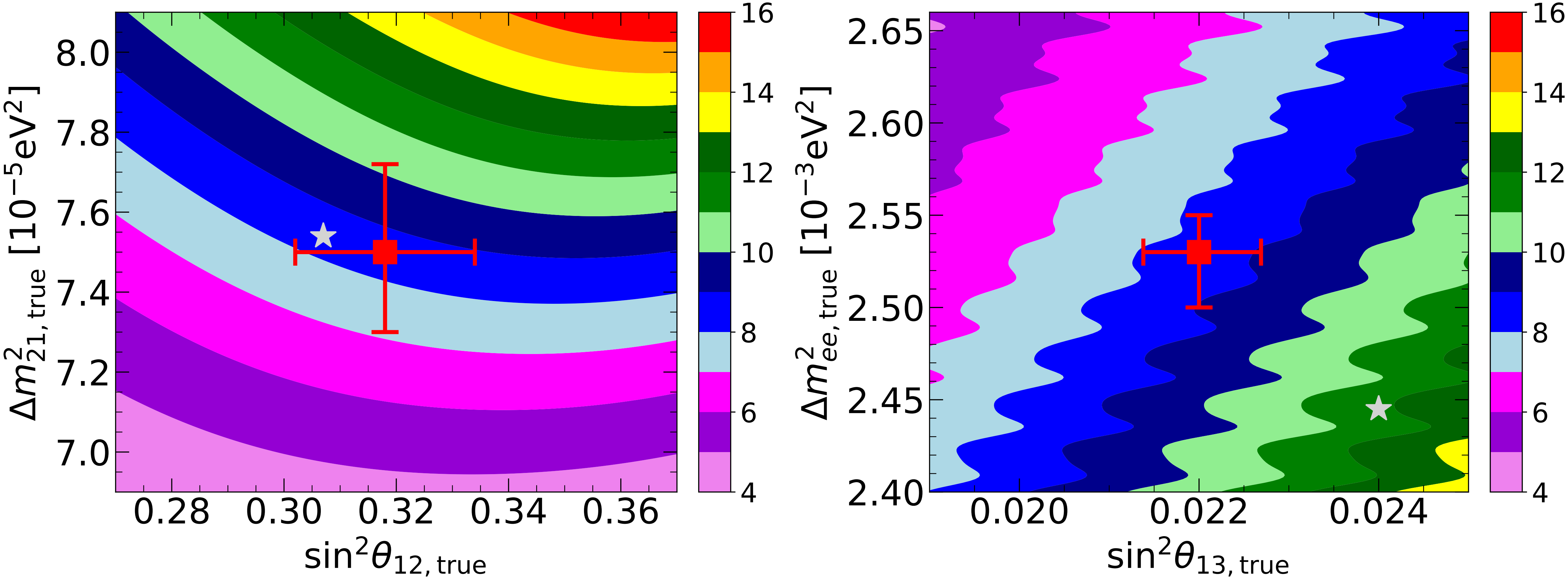
No backgrounds
No Systematics

Forero, SP, Ternes, Zukanovich 2107.12410

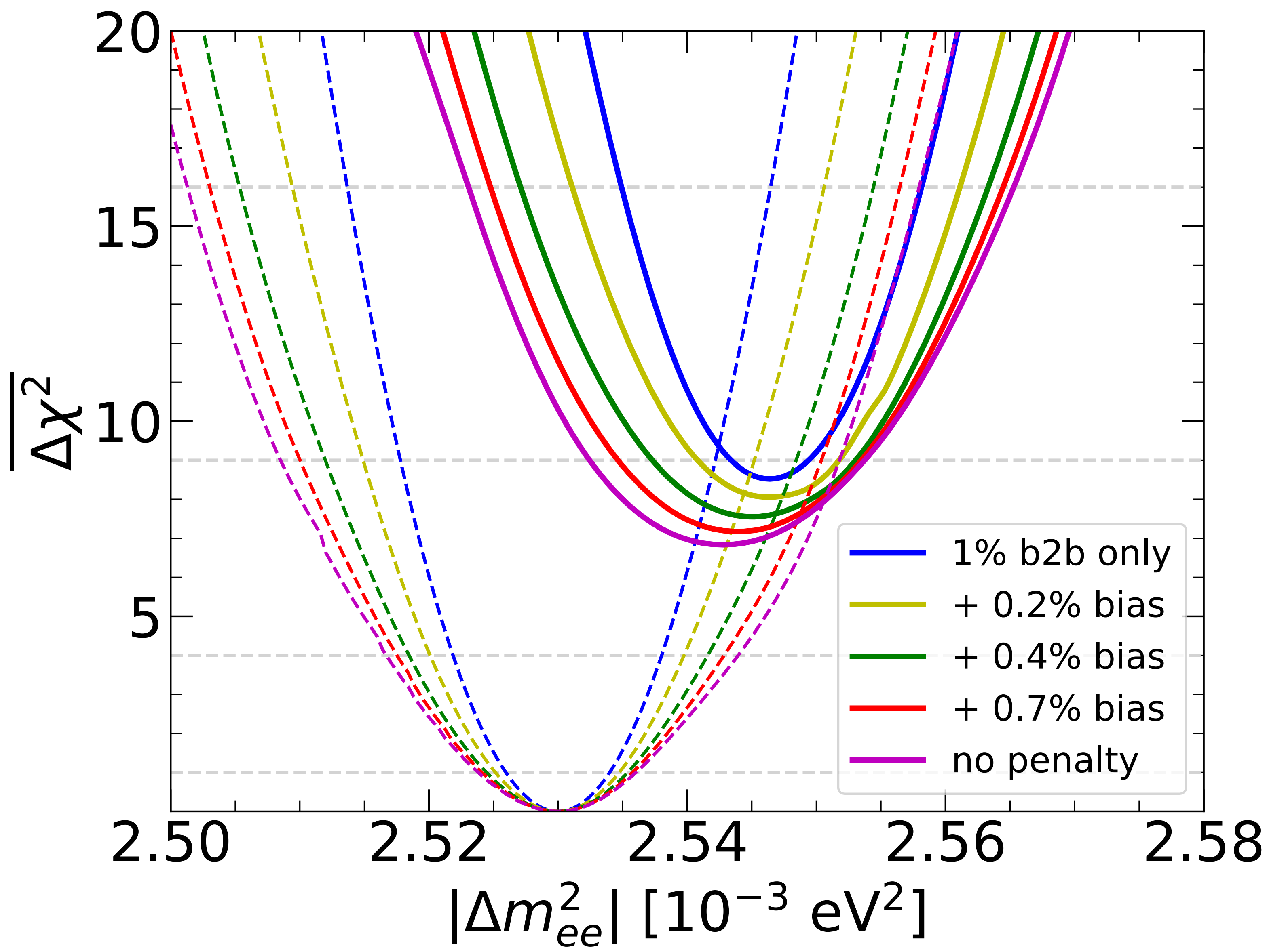
Real Baseline Distribution + Backgrounds



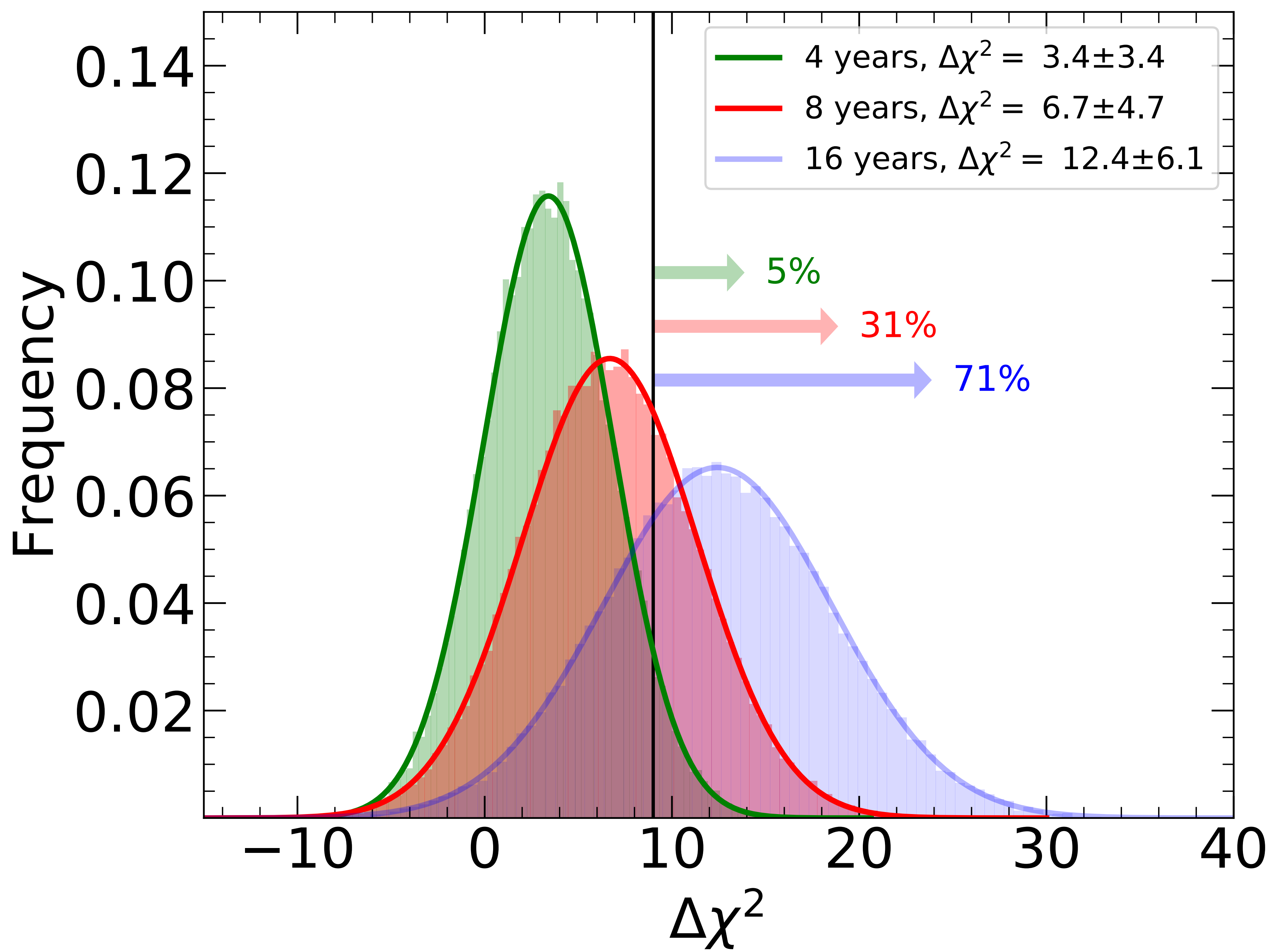
Parameter Sensitivity:



Non-linear Energy Response

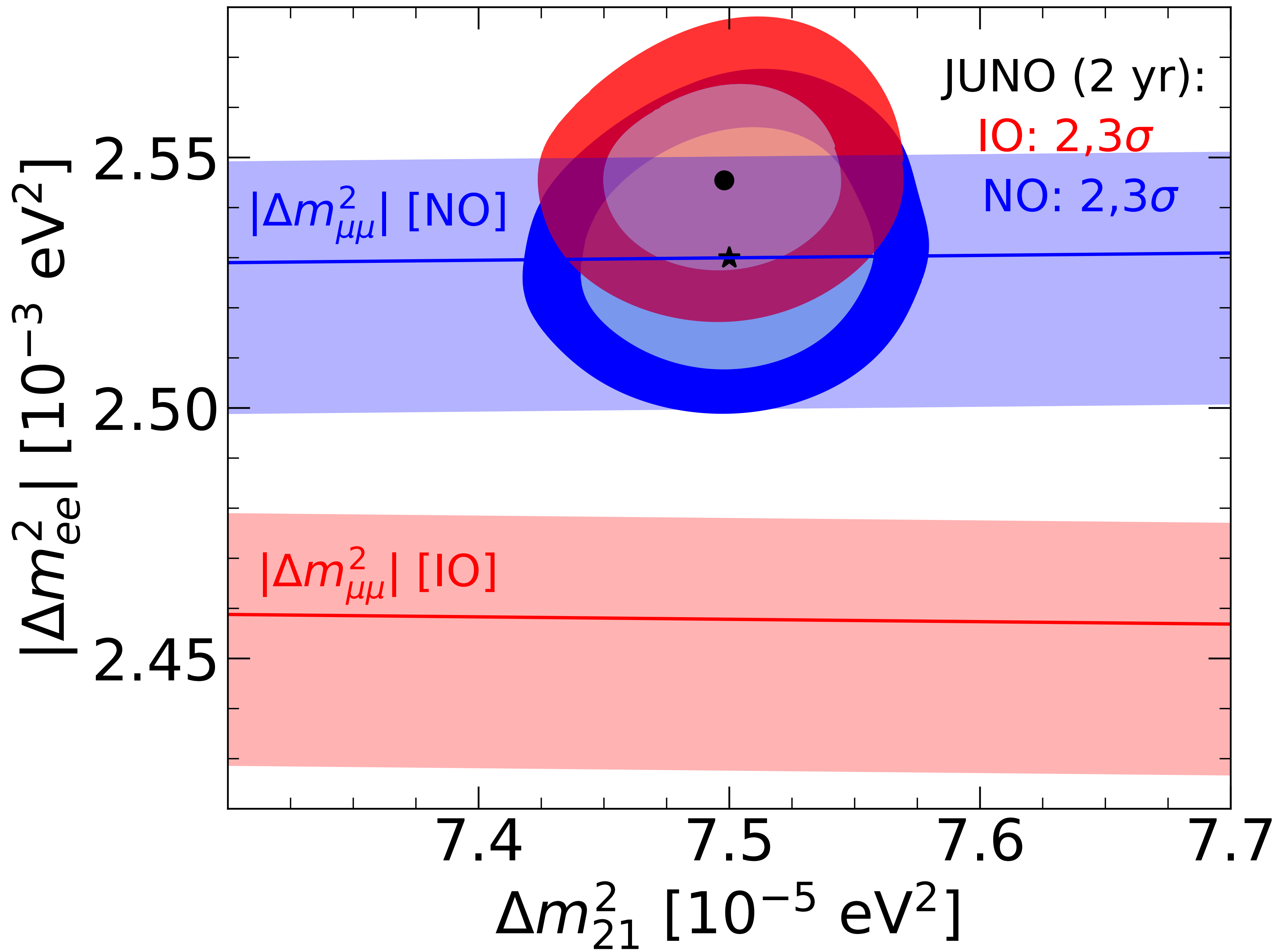


JUNO probability of determining Mass Ordering



GLOBAL DATA:

GLOBAL FIT: with 2 years of JUNO data



Summary:

- from Nu1998 to now, tremendous exp. progress on Neutrino SM: more at Nu2022. May 31-June 4, 2022
- LSND Sterile Nu's neither confirmed or ruled out at acceptable CL: - ultra short baseline reactor exp. —microBooNE
- Great Theoretical progress on understand many aspects of Quantum Neutrino Physics: - Oscillations, Decoherence, Osc. Probabilities in Matter, Leptogenesis, ...
- Still searching for convincing model of Neutrino masses and mixings: with testable and confirmed predictions !