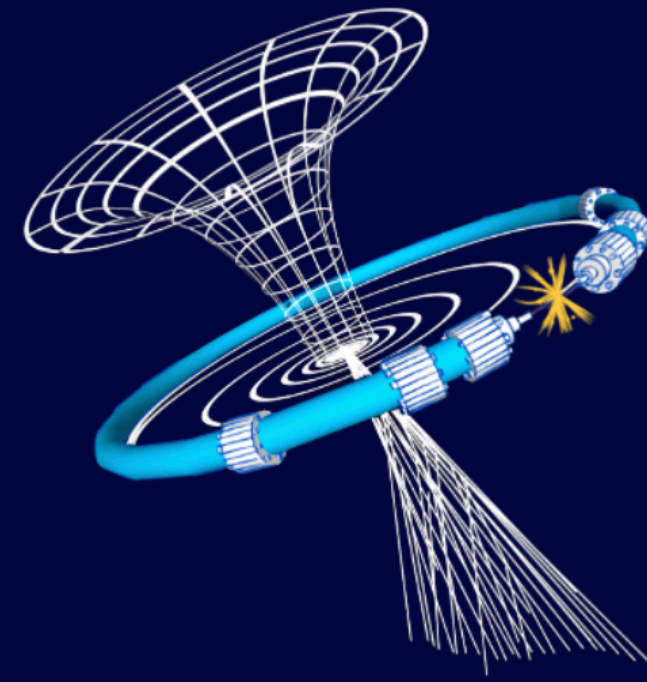


15th IDPASC Summer School

20 - 29 July 2026

Natal, Brazil



Neutrino Physics

Renata Zukanovich Funchal

Instituto de Física, Universidade de São Paulo

Lecture II:

Recent Measurements & Perspectives

"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy."

W. Shakespeare (Hamlet)

**WHAT HAVE WE ALREADY
LEARNED FROM
OSCILLATION EXPERIMENTS ?**

HOW DO WE CLASSIFY OSCILLATION EXPERIMENTS?

Four Basic Types

$$\nu_{\alpha} \rightarrow \nu_{\alpha}$$

$$\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_{\alpha}$$

disappearance experiments

we talk about survival probability

$$\nu_{\alpha} \rightarrow \nu_{\beta}$$

$$\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_{\beta}$$

appearance experiments

we talk about oscillation probability

HOW DO WE COMPARE DATA WITH THEORY?

WHAT DO EXPERIMENTS MEASURE?

The diagram illustrates the equation for the number of neutrinos detected, $N_\alpha(L)$, and maps its components to experimental measurements or theoretical predictions. The equation is presented in a red box with yellow text. Annotations with arrows point to specific parts of the equation:

- [Experiment]** # of neutrinos: Points to the left side of the equation, $N_\alpha(L)$.
- [Type of Source]** ν Flux: Points to $\Phi_\alpha(E)$.
- [Theory]** survival probability: Points to $P(\nu_\alpha \rightarrow \nu_\alpha; E, L)$.
- number of targets x time** [Experiment]: Points to A .
- x-section** [Theory]: Points to $\sigma(E)$.
- detector efficiency** [Experiment]: Points to $\epsilon(E)$.

$$N_\alpha(L) = A \int \Phi_\alpha(E) \sigma(E) P(\nu_\alpha \rightarrow \nu_\alpha; E, L) \epsilon(E) dE$$

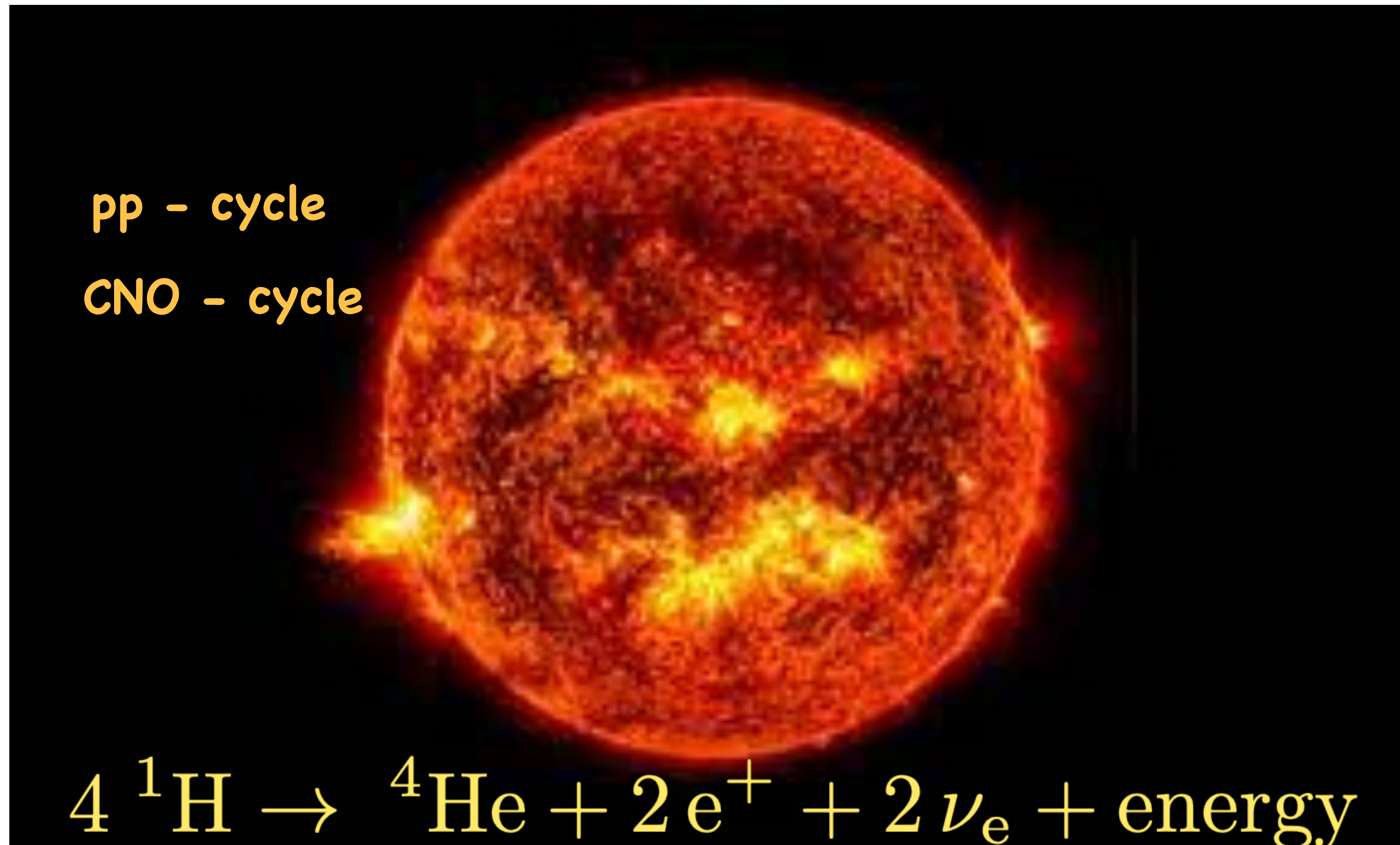
Solar Neutrinos

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{matrix} \Delta m_{21}^2 \\ \Delta m_{31}^2, \Delta m_{32}^2 \end{matrix}$$

Solar Neutrinos

Standard Solar Model

[H. A. Bethe, “Energy production in stars” (1939)]



[J. Bahcall et al. (2001)]

[Vinyoles et al. (2017)]

[@NASA]

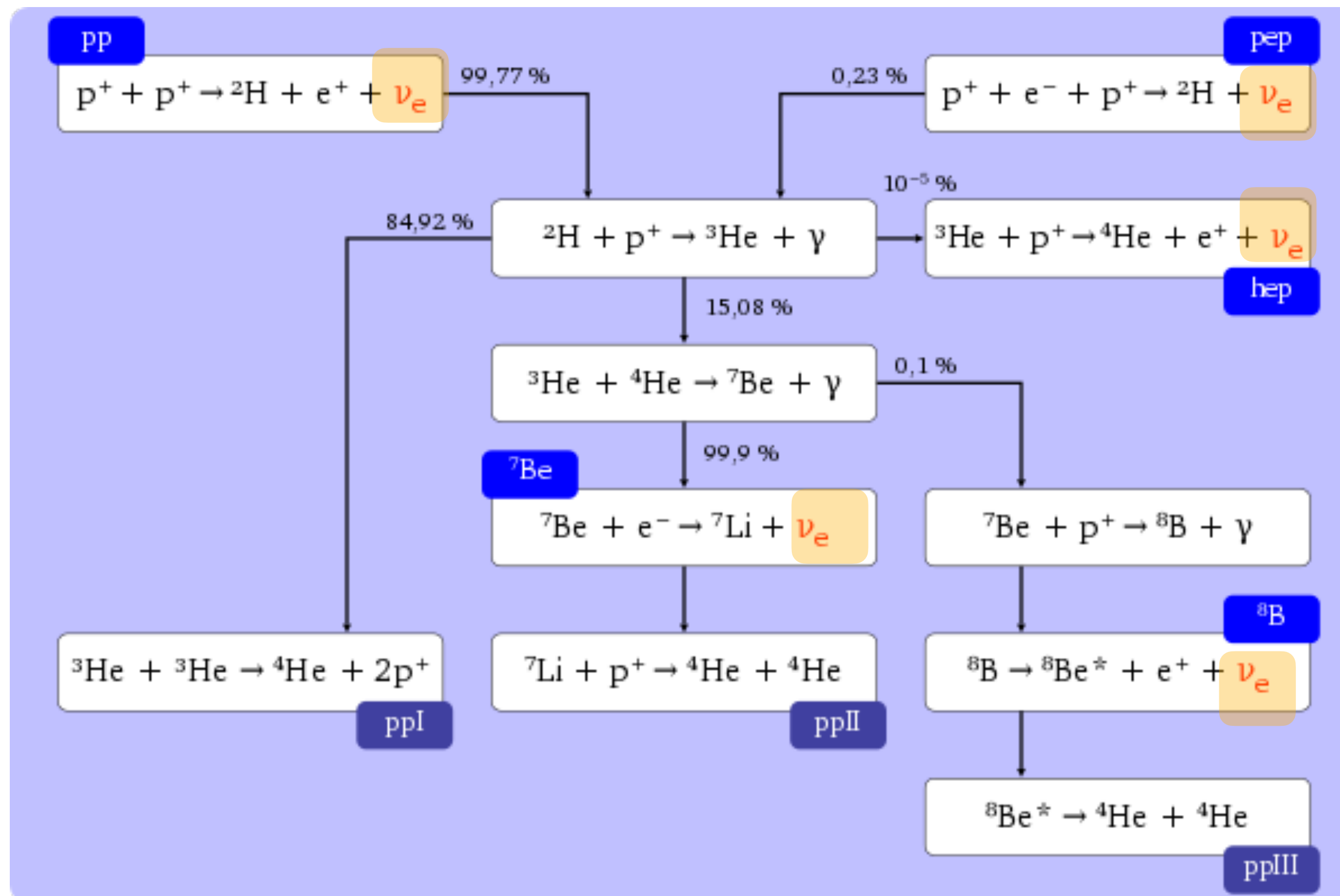
only electron neutrinos are produced in the Sun

Solar Neutrinos

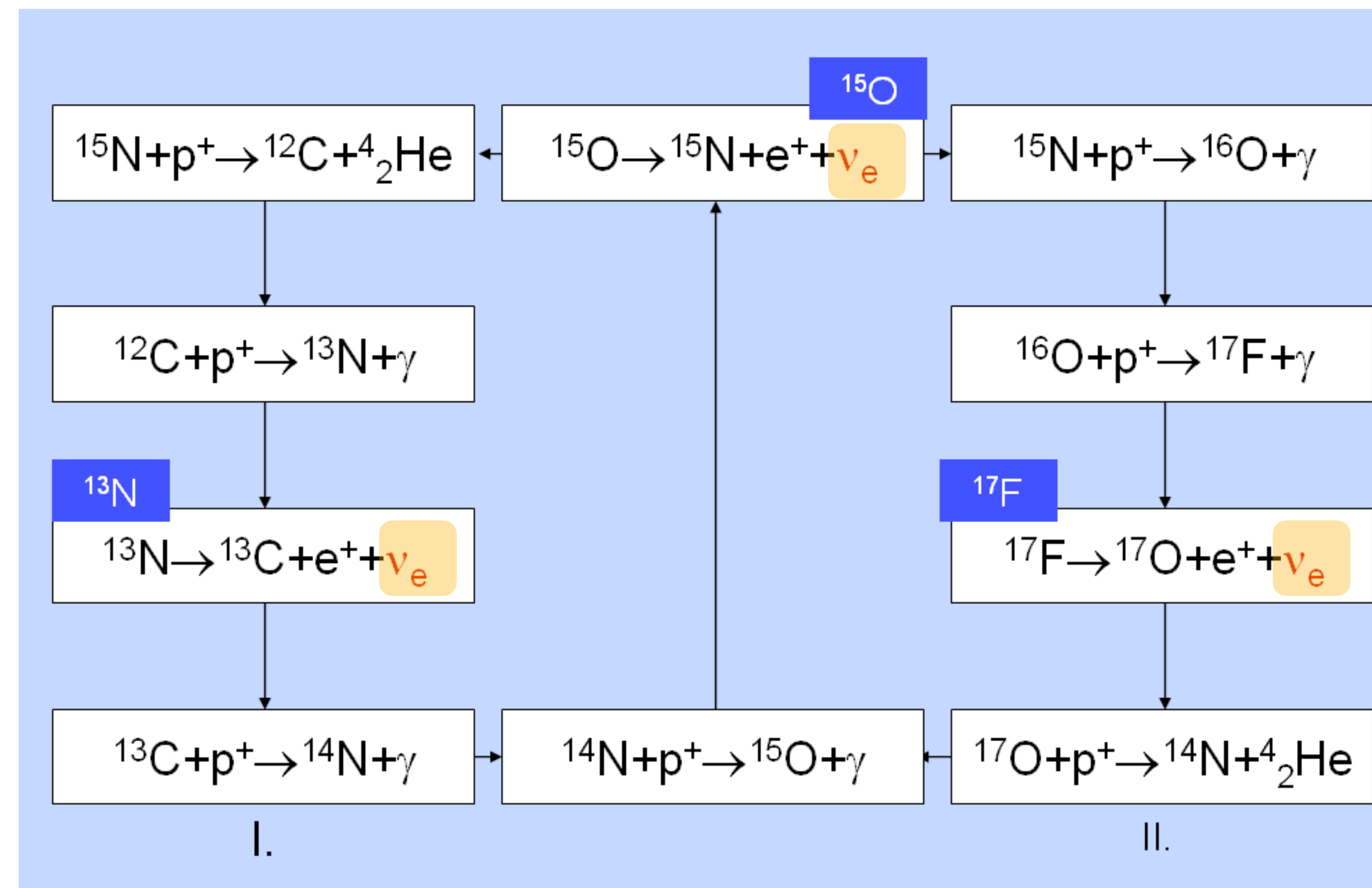
Standard Solar Model

chains of thermonuclear reactions

pp-cycle (99% of energy output of the Sun)

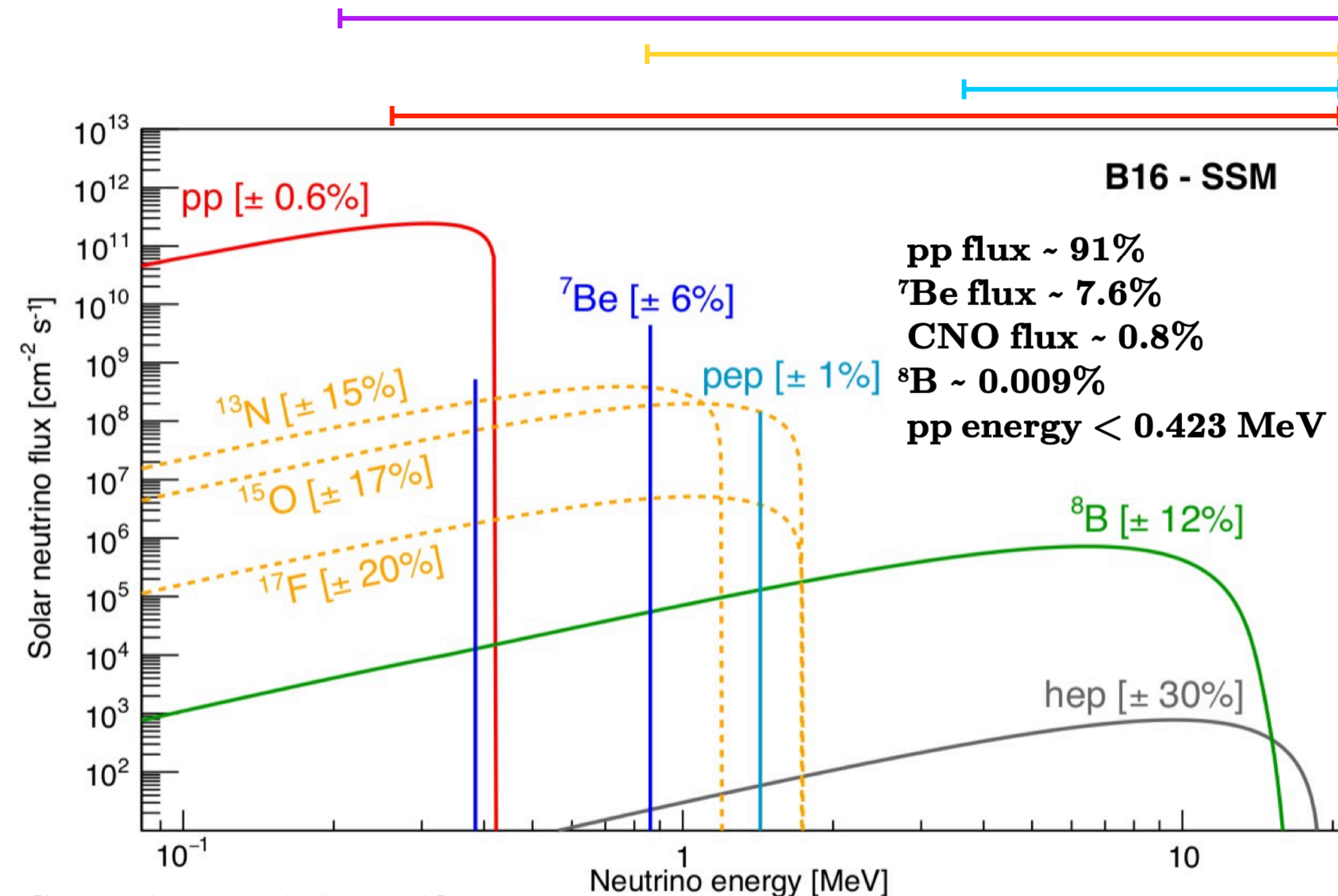


CNO-cycle



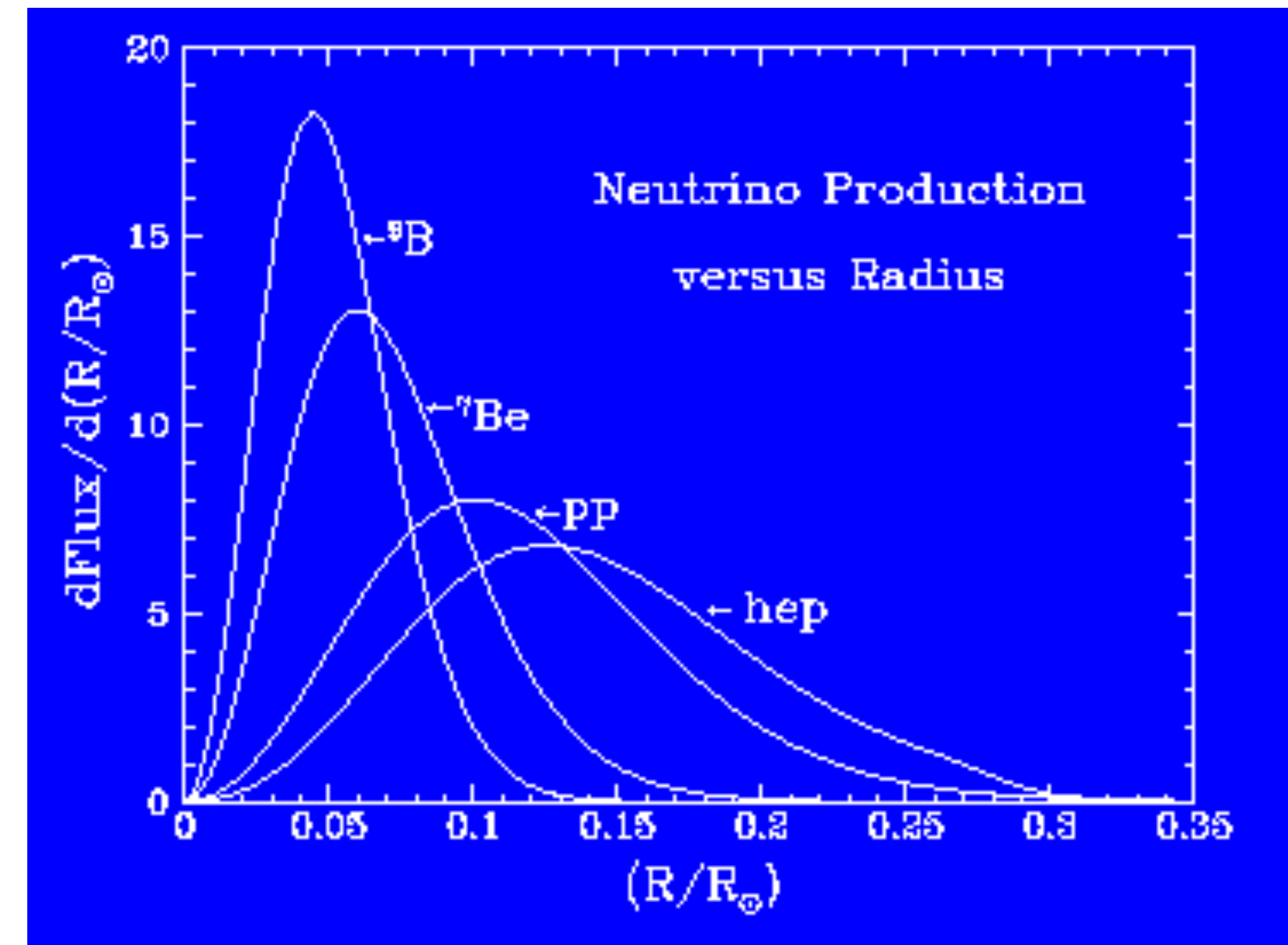
Solar Neutrino Flux

Standard Solar Model



GALLIUM
CHLORINE
WATER
LIQUID SCINTILLATOR

GALLEX/GNO/SAGE
HOMESTAKE
KAMIOKANE/SuperK/SNO
BOREXINO



Production Point Distribution

[@J.Bahcall]

[Vinyoles et al. (2017)]

Energy Distribution

Solar Neutrinos

ν_e Survival Probability

Solar neutrinos undergo matter effects inside the Sun and also when they travel through the Earth (ignored here)
In the Sun the problem reduces to an effective 2 flavor problem

$$P_{3\nu}(\nu_e \rightarrow \nu_e) = s_{13}^4 + c_{13}^4 P_{2\nu}(\nu_e \rightarrow \nu_e; V_{CC} \rightarrow c_{13}^2 V_{CC})$$

$$P_{2\nu}(\nu_e \rightarrow \nu_e; V_{CC} \rightarrow c_{13}^2 V_{CC}) = |\mathcal{A}_{ee}(R_\odot)|^2$$

Survival Probability at the surface

Solar Neutrinos

ν_e Survival Probability

Sensitivity to the 12-sector

Solar neutrinos undergo matter effects inside the Sun and also when they travel through the Earth (ignored here)
In the Sun the problem reduces to an effective 2 flavor problem

$$P_{3\nu}(\nu_e \rightarrow \nu_e) = s_{13}^4 + c_{13}^4 P_{2\nu}(\nu_e \rightarrow \nu_e; V_{CC} \rightarrow c_{13}^2 V_{CC})$$

$$P_{2\nu}(\nu_e \rightarrow \nu_e; V_{CC} \rightarrow c_{13}^2 V_{CC}) = |\mathcal{A}_{ee}(R_\odot)|^2$$

Survival Probability at the surface

finally we have to take into account the energy distribution and the distribution of the production point

$$P_{2\nu}^X = \overline{\cos^2 \theta_m} \cos^2 \theta_{12} + \overline{\sin^2 \theta_m} \sin^2 \theta_{12} \quad X = \text{pp}, {}^7\text{Be}, {}^8\text{B}, \text{etc.}$$

averaged over production point and energy distribution

Solar Neutrinos

Adiabatic Transition

in our current notation

$$\Delta m_{21}^2 \equiv \delta m_{\odot}^2$$

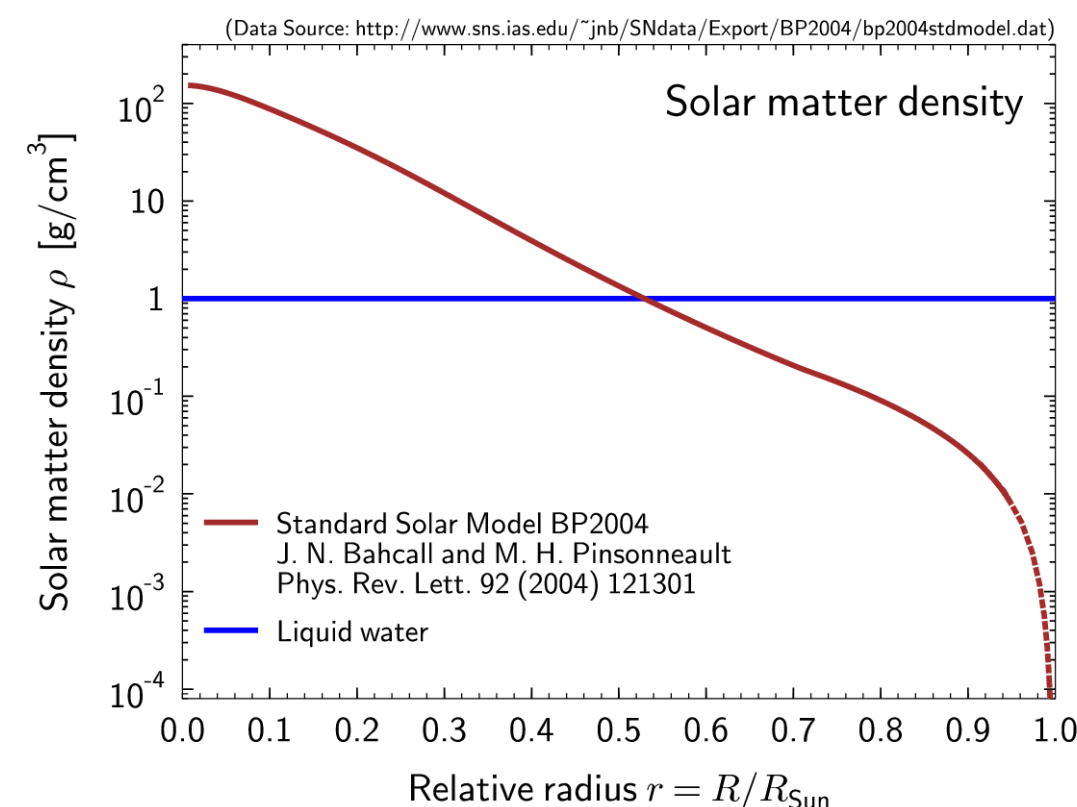
$$\sin^2 \theta_{12} \equiv \sin^2 \theta_{\odot}$$

$$\sin^2 \theta_m \equiv \sin^2 \theta_{\odot}^N$$

Solar neutrinos

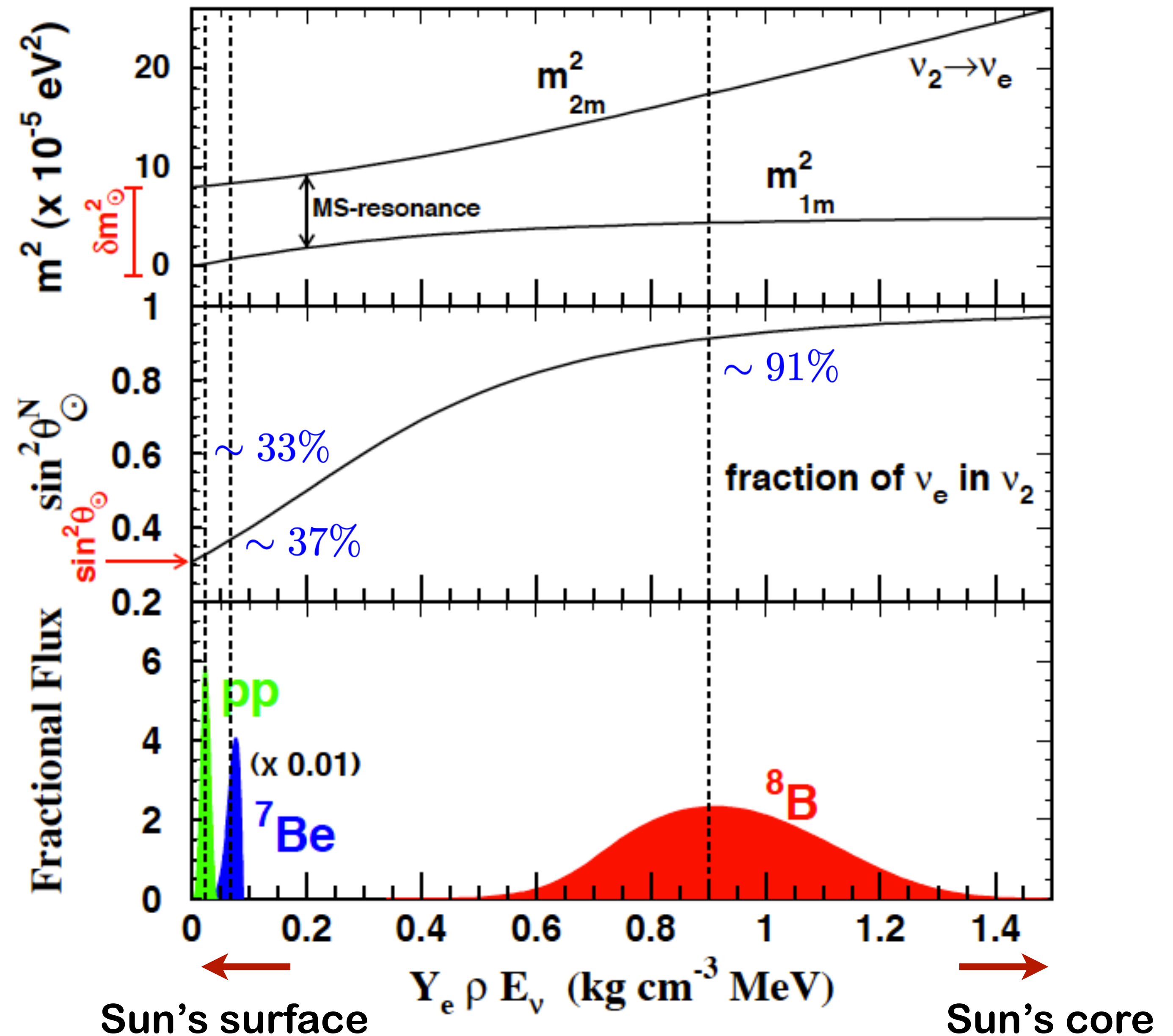
tell us that

$$\Delta m_{21}^2 > 0$$



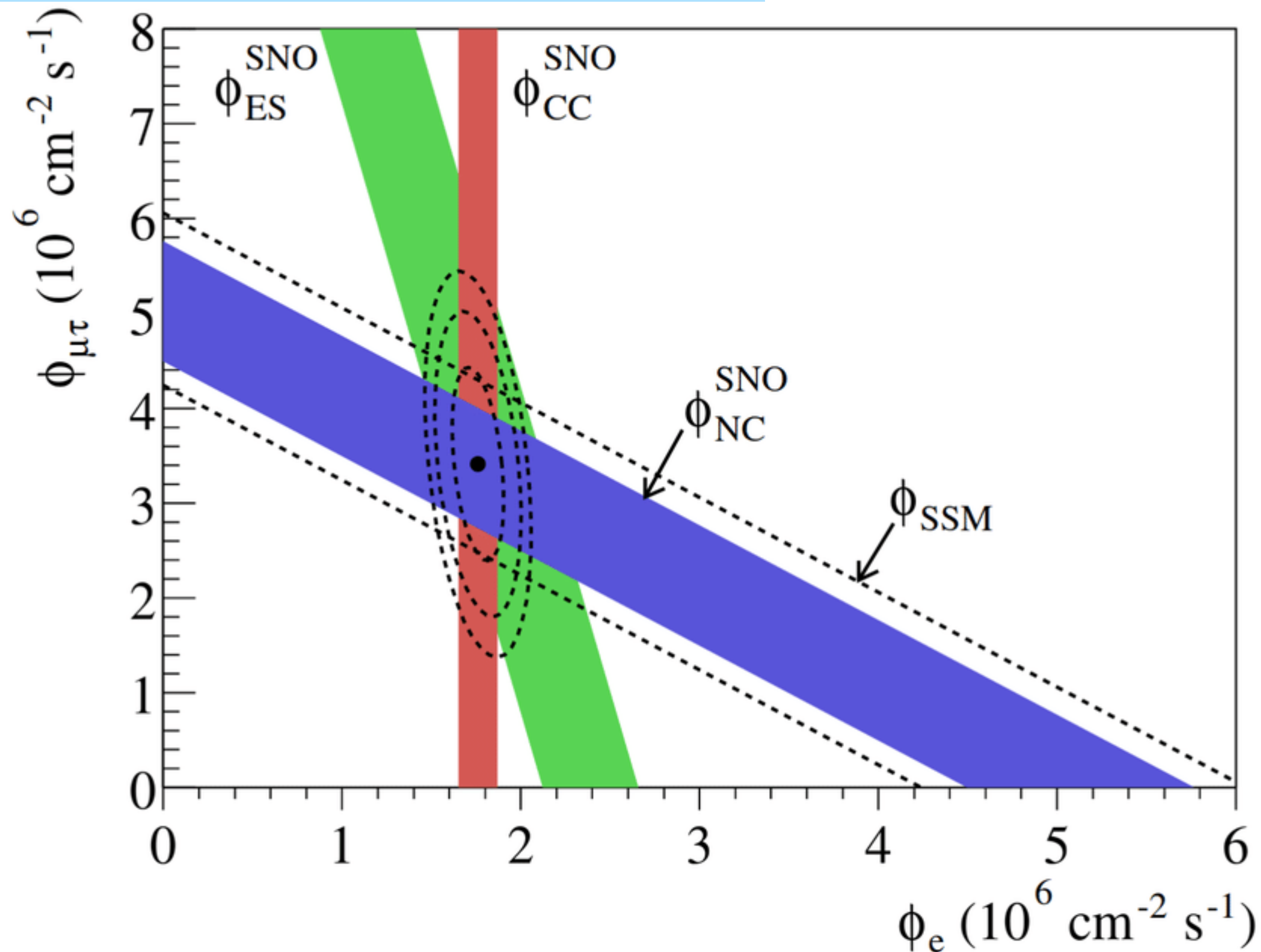
$$\nu_e \equiv \nu_2$$

Sun's core

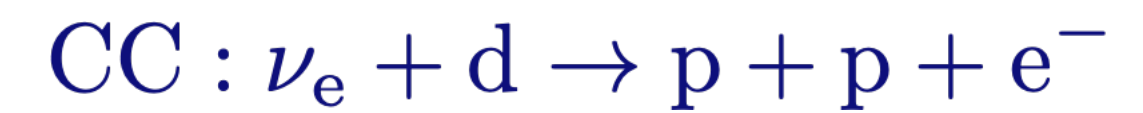


Solar Neutrinos

SNO Historical Results



[Taken from SNO Collab. (2003)]



$$E_{\text{threshold}} = 1.4 \text{ MeV}$$



$$E_{\text{threshold}} = 2.2 \text{ MeV}$$



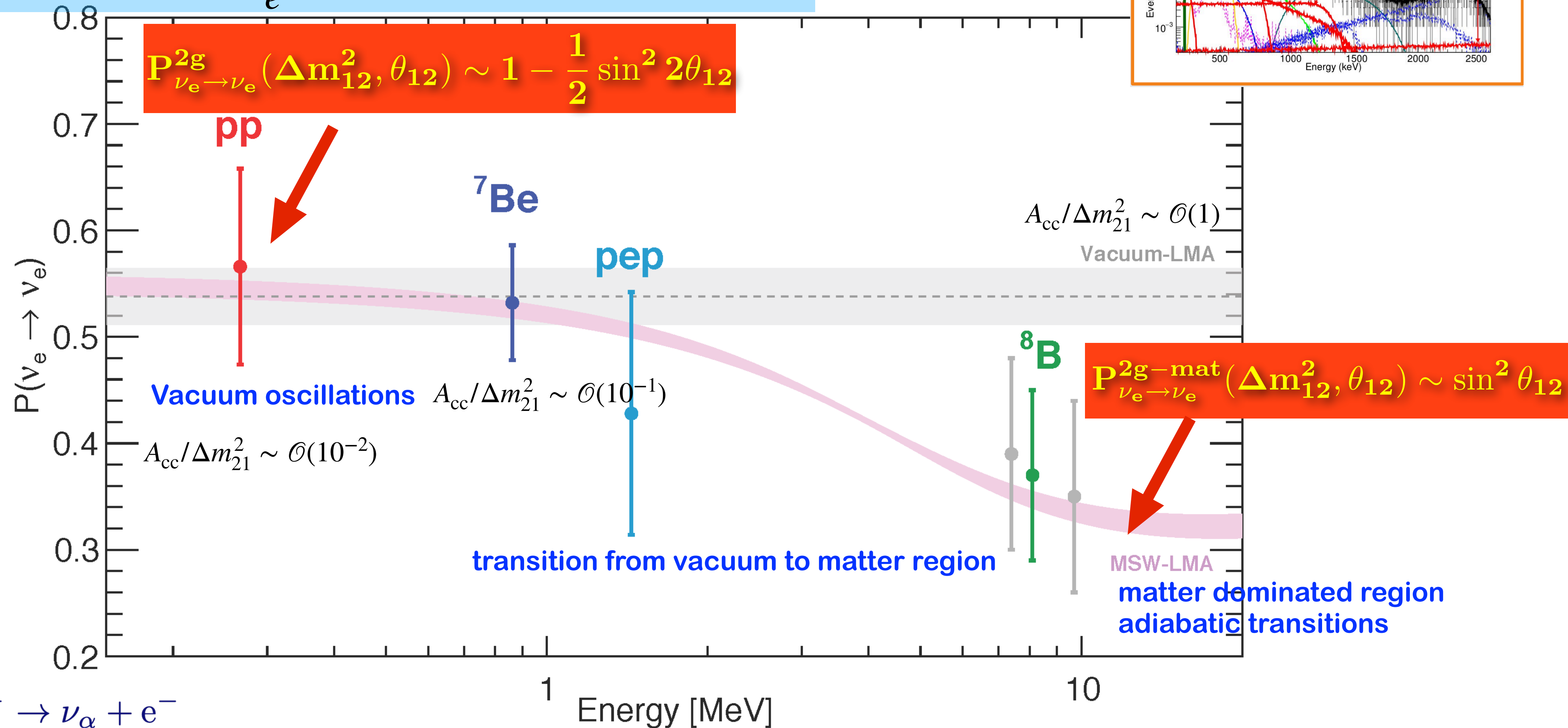
$$E_{\text{threshold}} = 0$$



Solar Neutrinos

General Picture of ν_e transitions in the Sun

$$A_{cc} = 2EV_{cc}$$



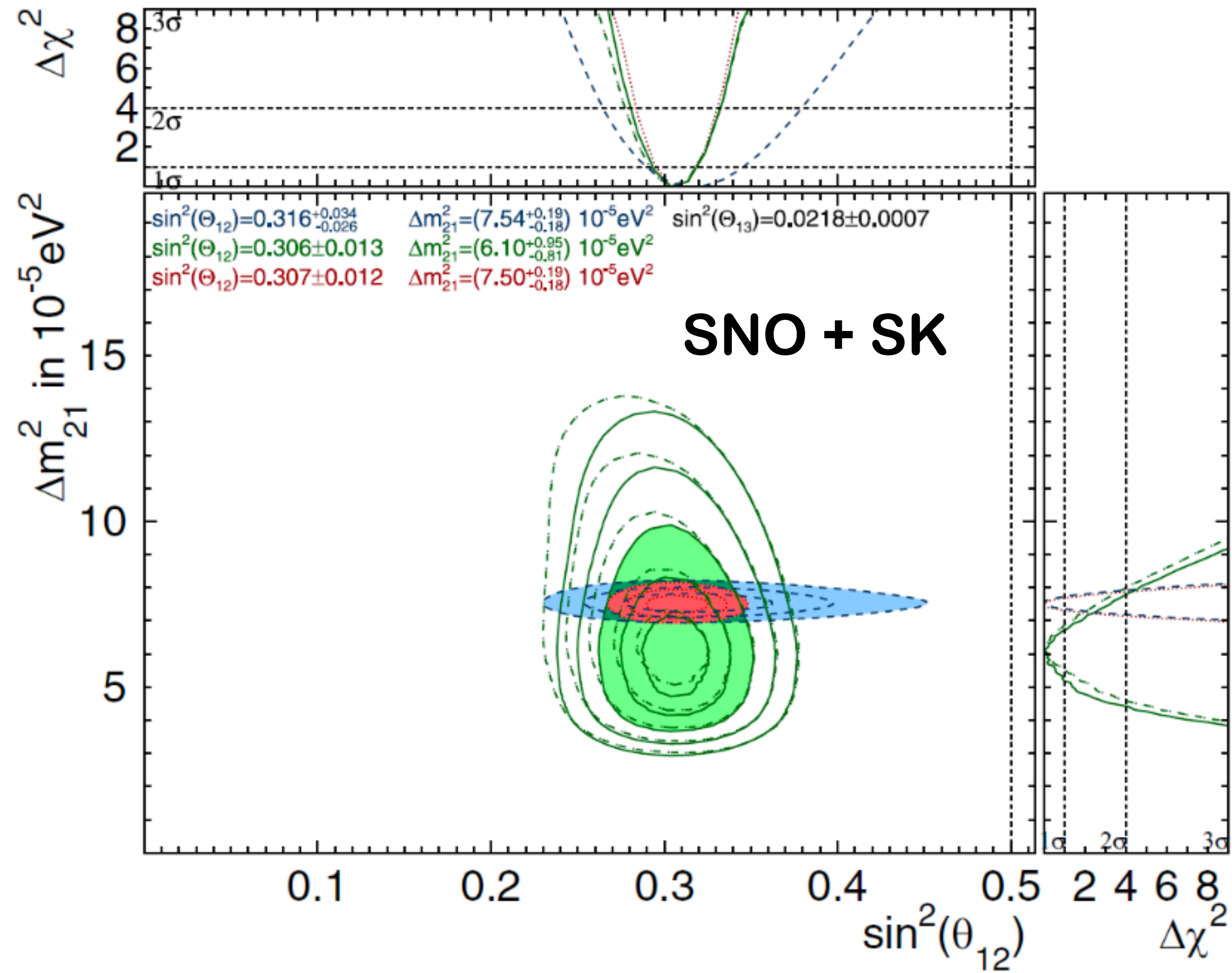
$$ES : \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

[Taken from Borexino Collab. (2018)]

$$P_{\nu_e \rightarrow \nu_e}^{3g} = \sin^4 \theta_{13} + \cos^4 \theta_{13} P_{\nu_e \rightarrow \nu_e}^{2g-mat}(\Delta m_{12}^2, \theta_{12})$$

$\Delta m_{21}^2, \sin^2 \theta_{12}$

SK I-IV PRD 109 (9), 092001 (2024)



Atmospheric Neutrinos

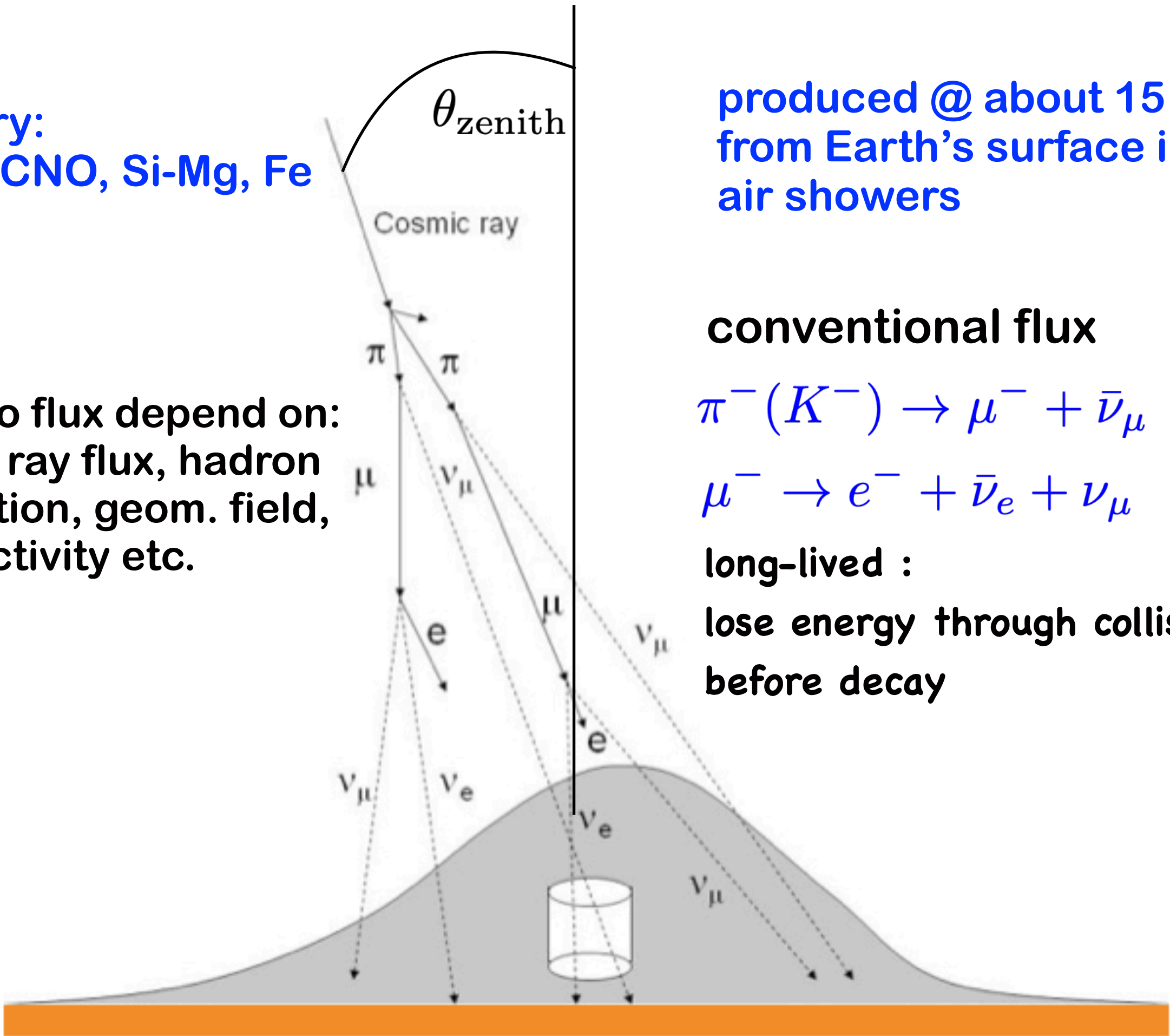
$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{matrix} \Delta m_{21}^2 \\ \Delta m_{31}^2, \Delta m_{32}^2 \end{matrix}$$

Atmospheric Neutrinos

Sources of the Flux

primary:
p, He, CNO, Si-Mg, Fe

neutrino flux depend on:
cosmic ray flux, hadron
interaction, geom. field,
solar activity etc.



produced @ about 15 km
from Earth's surface in
air showers

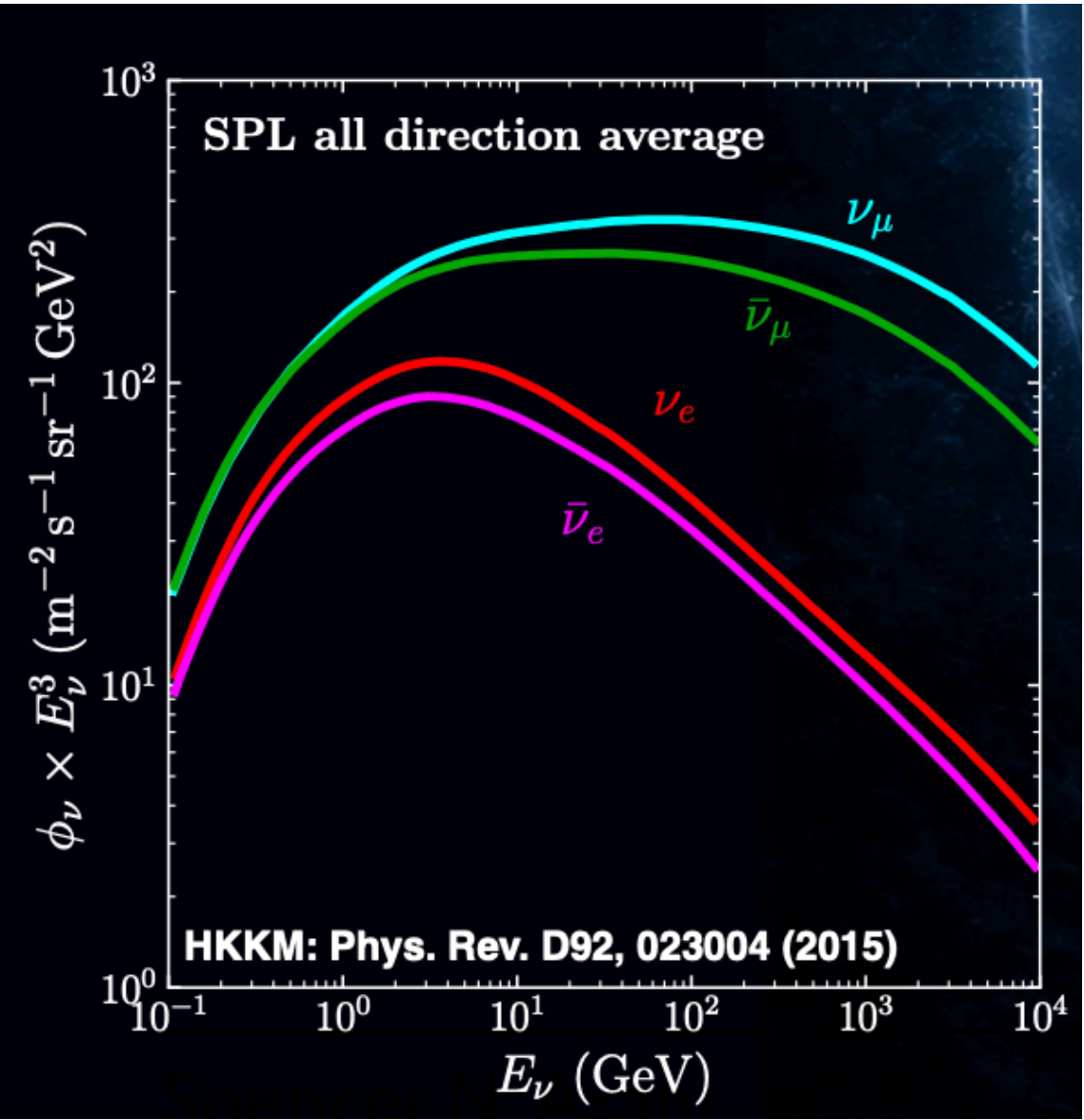
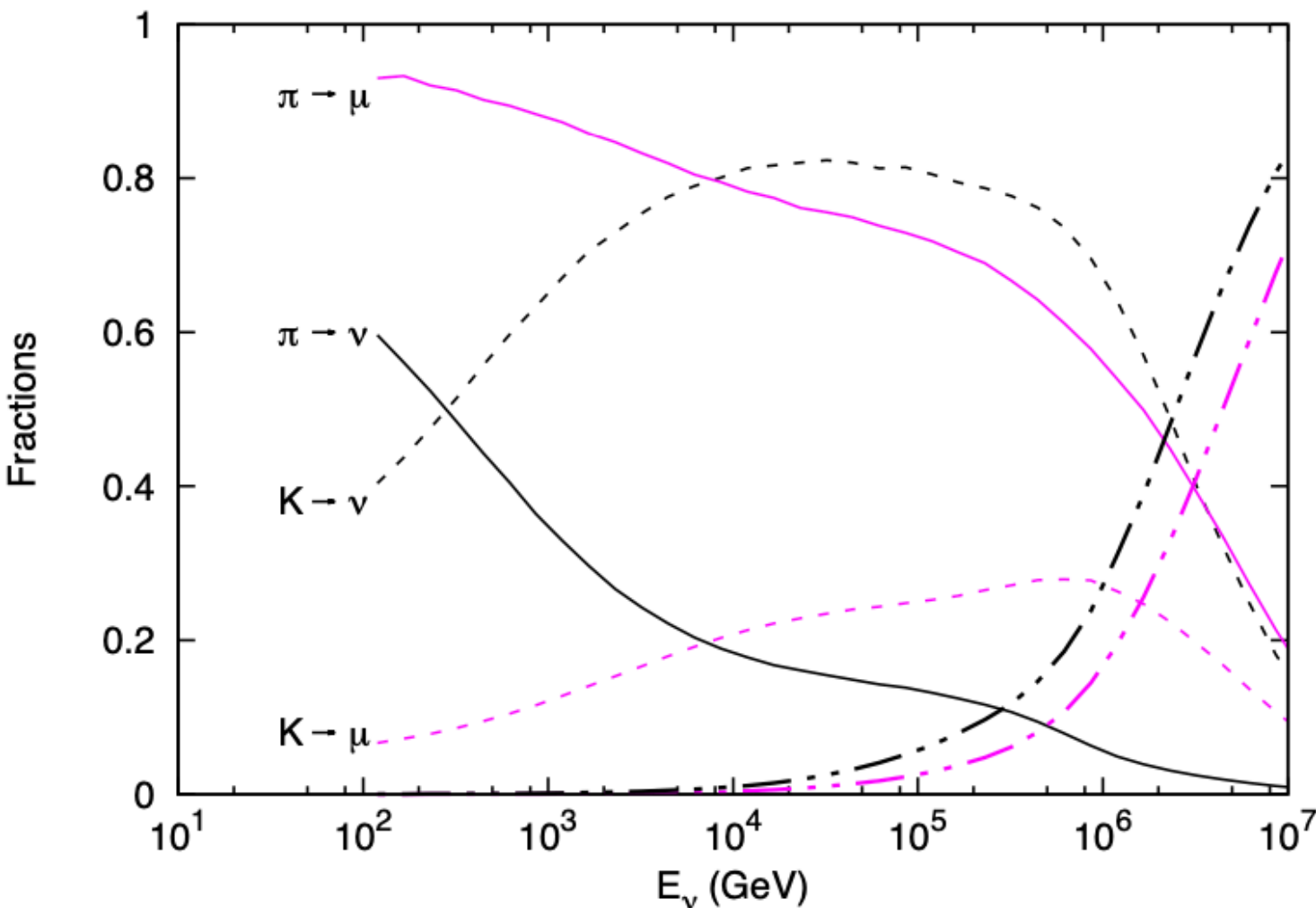
conventional flux

$$\pi^- (K^-) \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

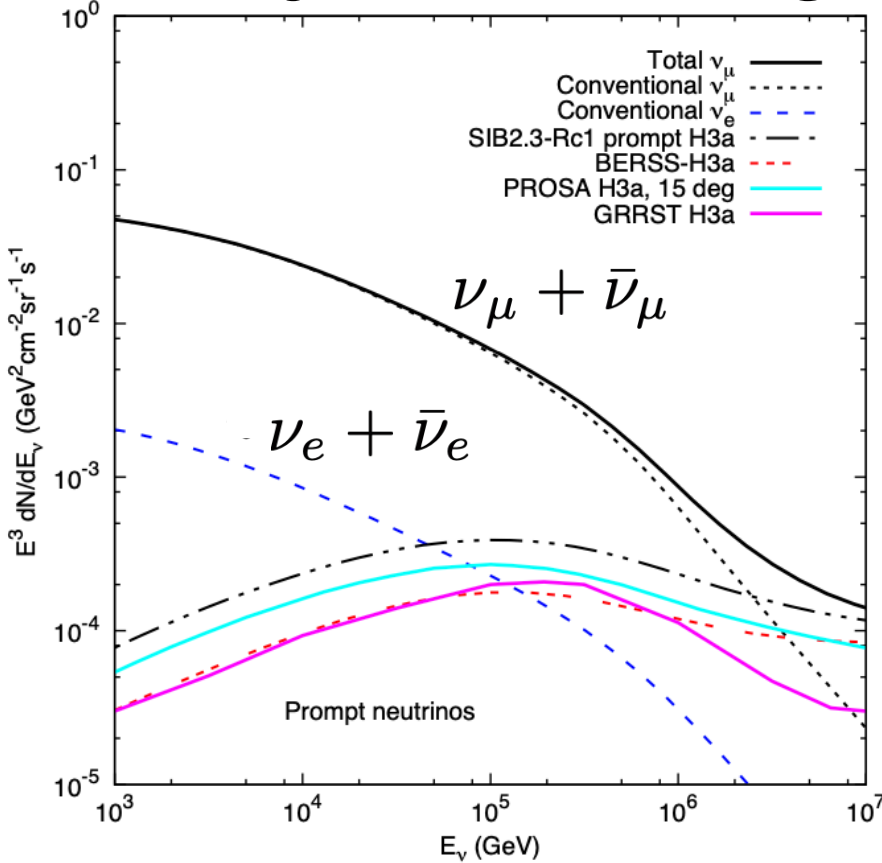
long-lived :
lose energy through collisions
before decay

prompt flux = charm mesons



unoscillated flux
averaged over zenith angle

prompt: mesons
decay before losing energy



Atmospheric Neutrinos

Sensitivity to the 32/31-sectors

Experiments count $N_{\nu_e + \bar{\nu}_e}$ & $N_{\nu_\mu + \bar{\nu}_\mu}$ as a function of the zenith angle

have to take into account matter effect for neutrinos traveling through the Earth

$$P_{\nu_e \rightarrow \nu_e}$$

$$P_{\nu_e \rightarrow \nu_\mu}$$

$$P_{\nu_e \rightarrow \nu_\tau}$$

$$P_{\nu_\mu \rightarrow \nu_\mu}$$

$$P_{\nu_\mu \rightarrow \nu_e}$$

$$P_{\nu_\mu \rightarrow \nu_\tau}$$

Δm_{31}^2 (or Δm_{32}^2)

θ_{32}

+ for antineutrinos

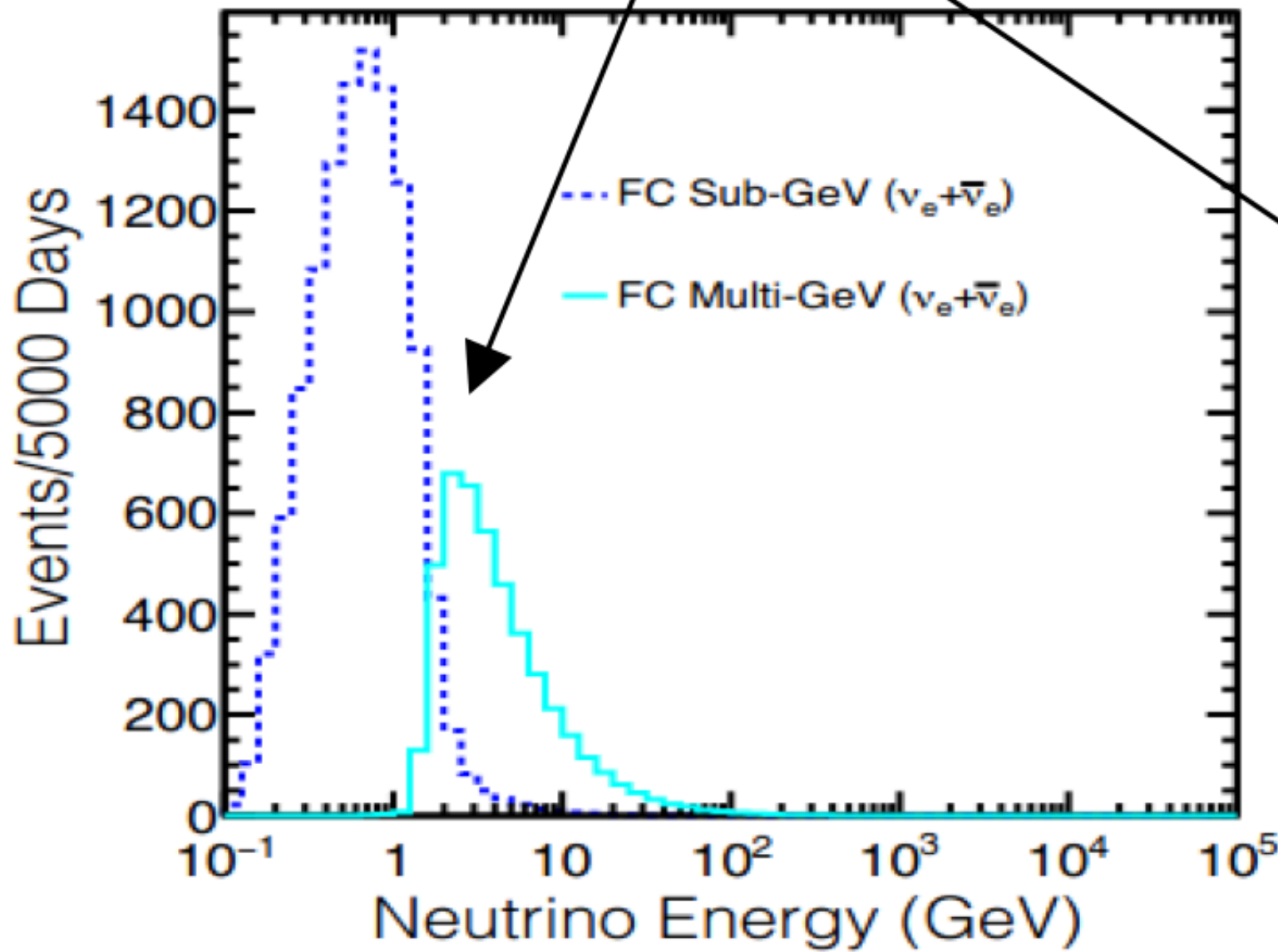
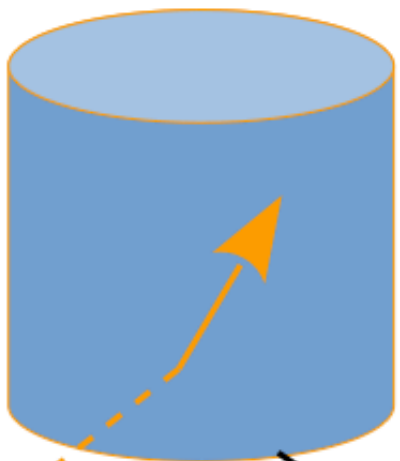
disappear

Atmospheric Neutrinos

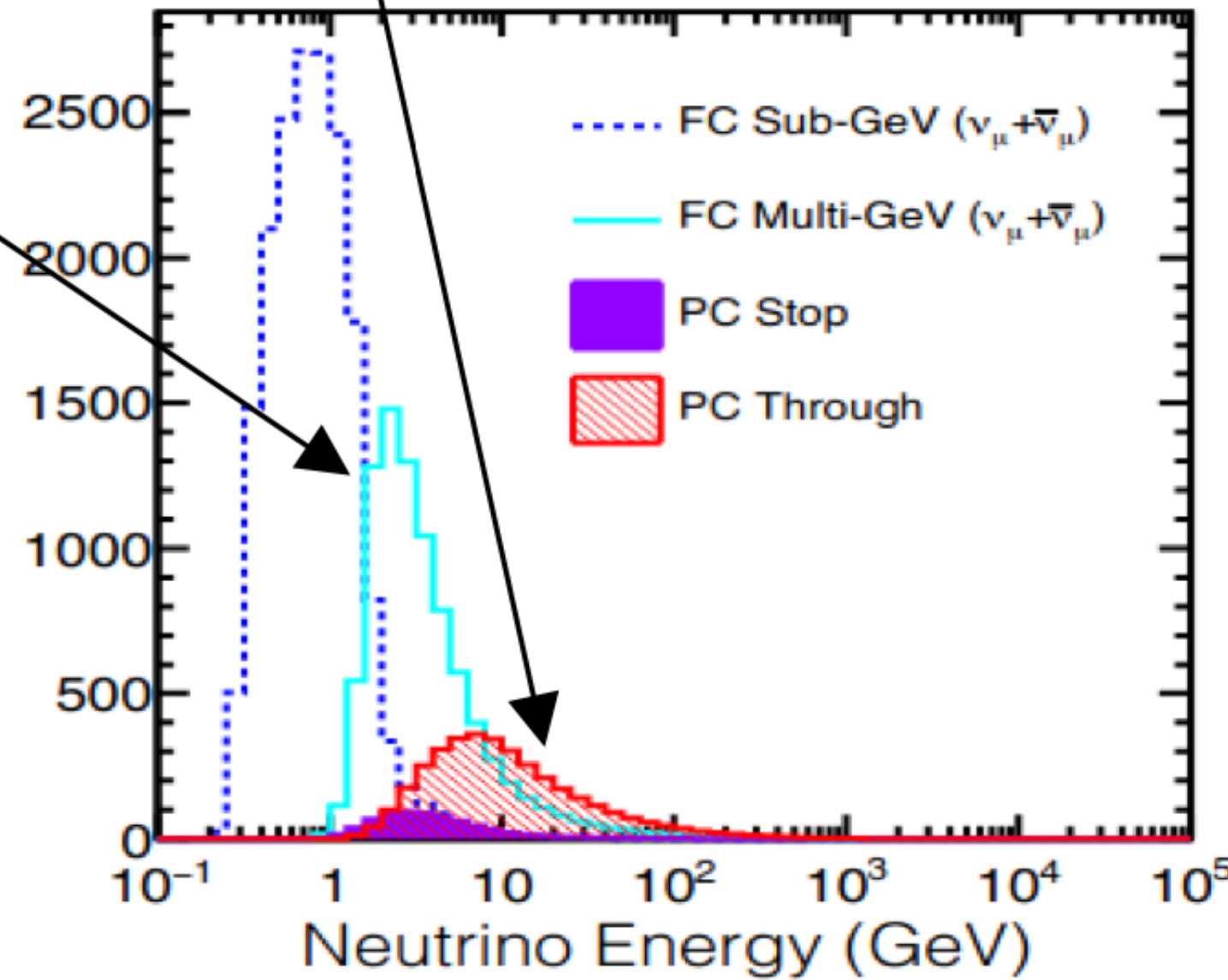
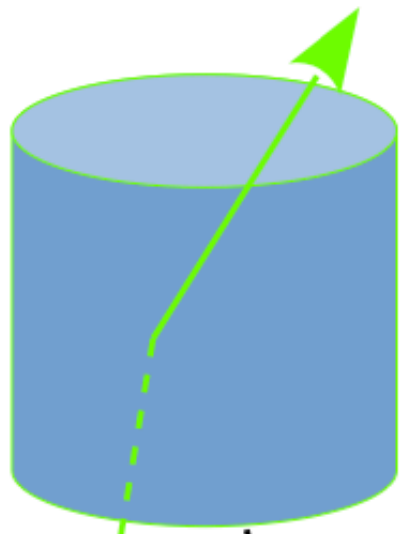
SuperKamikande Event Classification



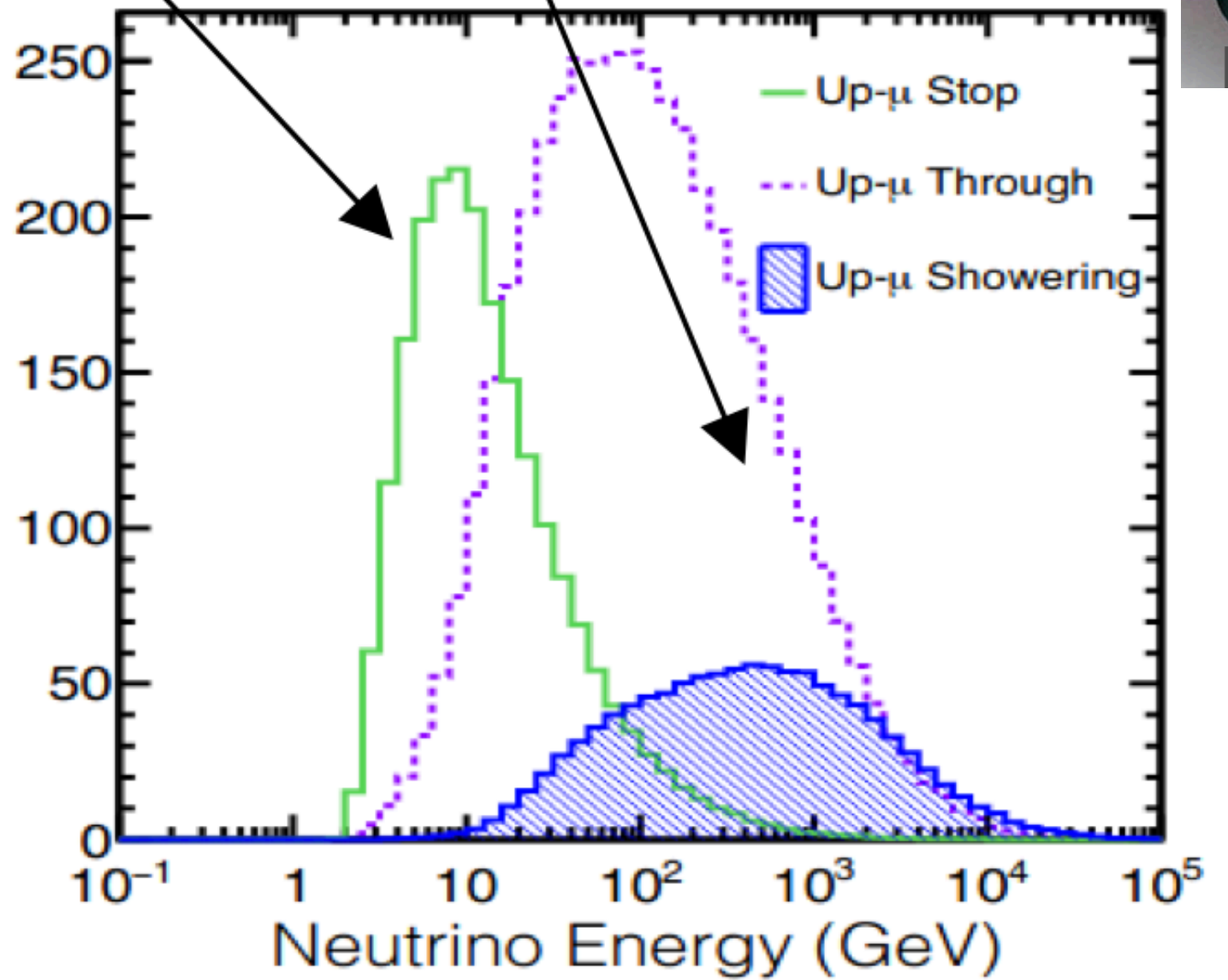
Fully contained



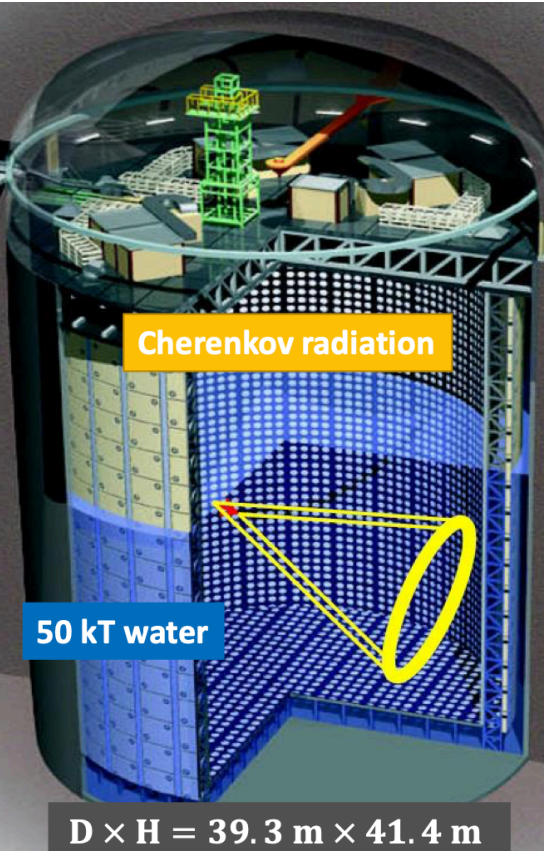
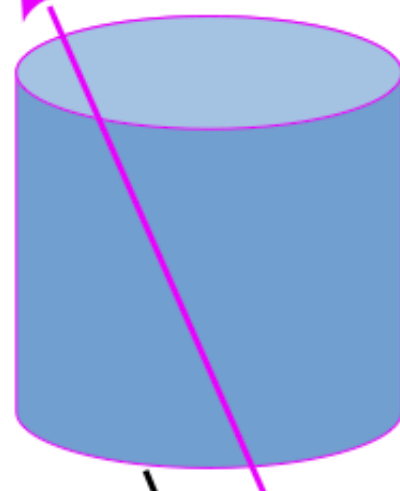
Partially contained



Upward stopping μ

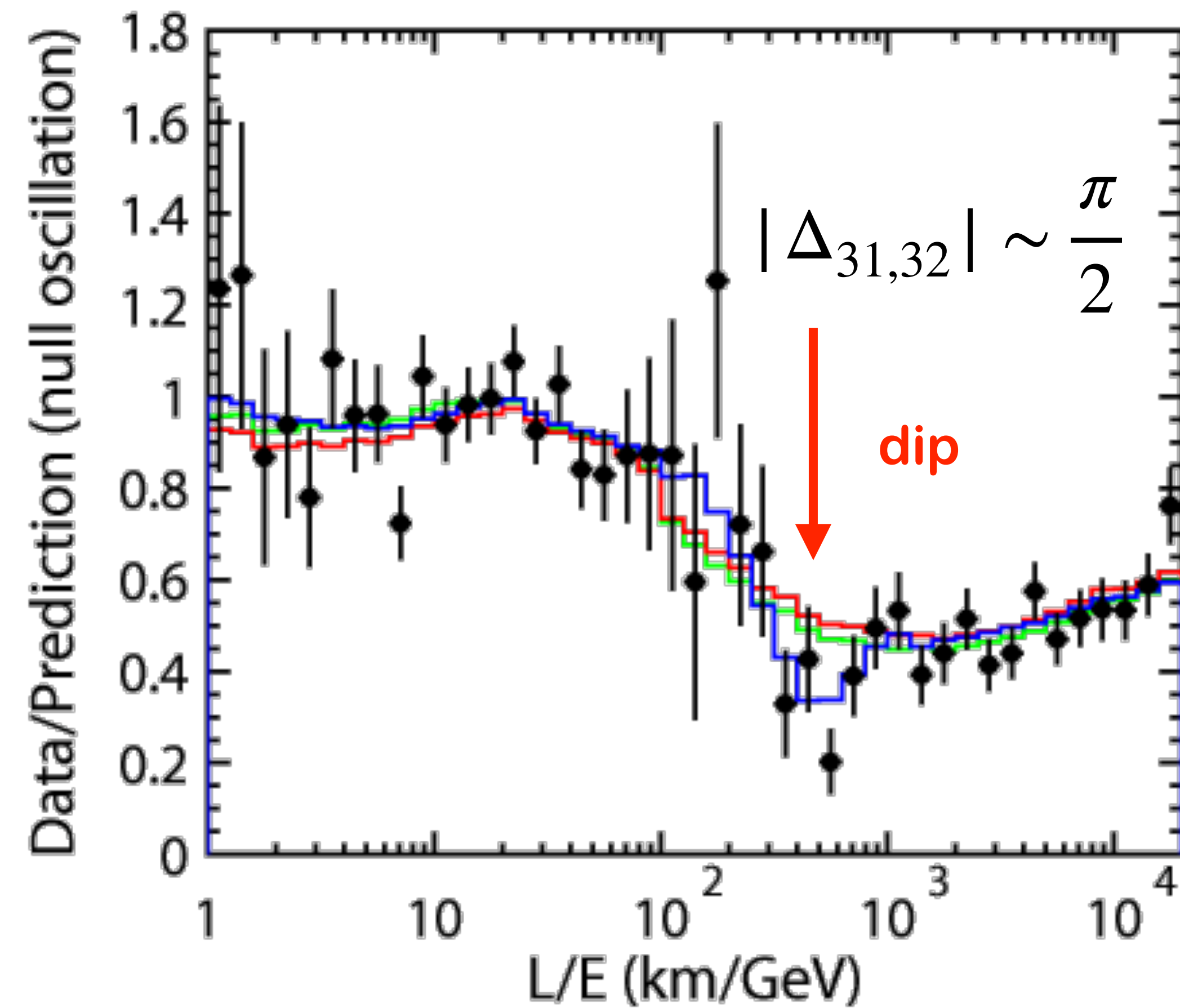


Upward through-going μ

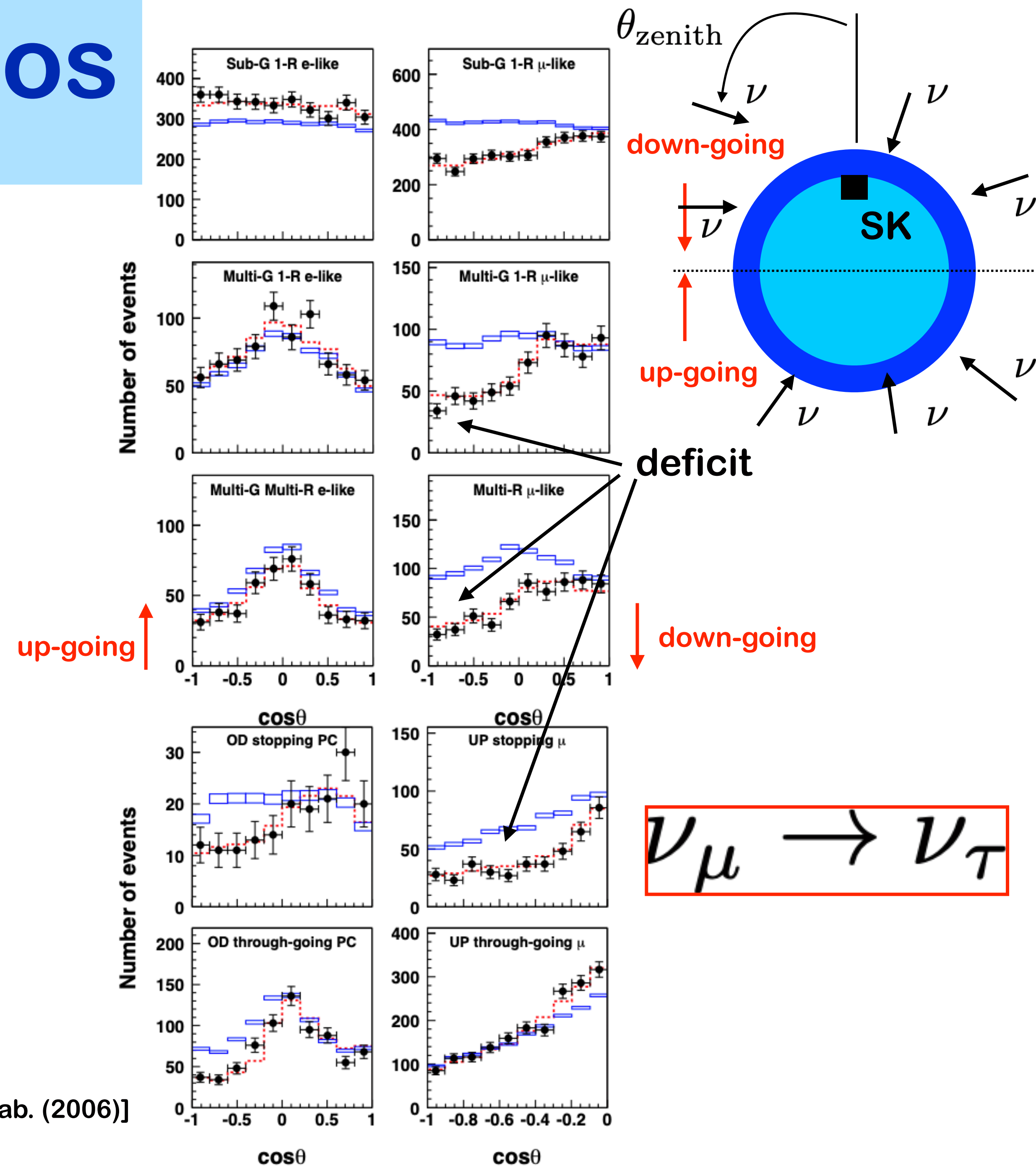


Atmospheric Neutrinos

SuperKamikande Observations



[Super-Kamiokande Collab. (2006)]



Atmospheric Neutrinos

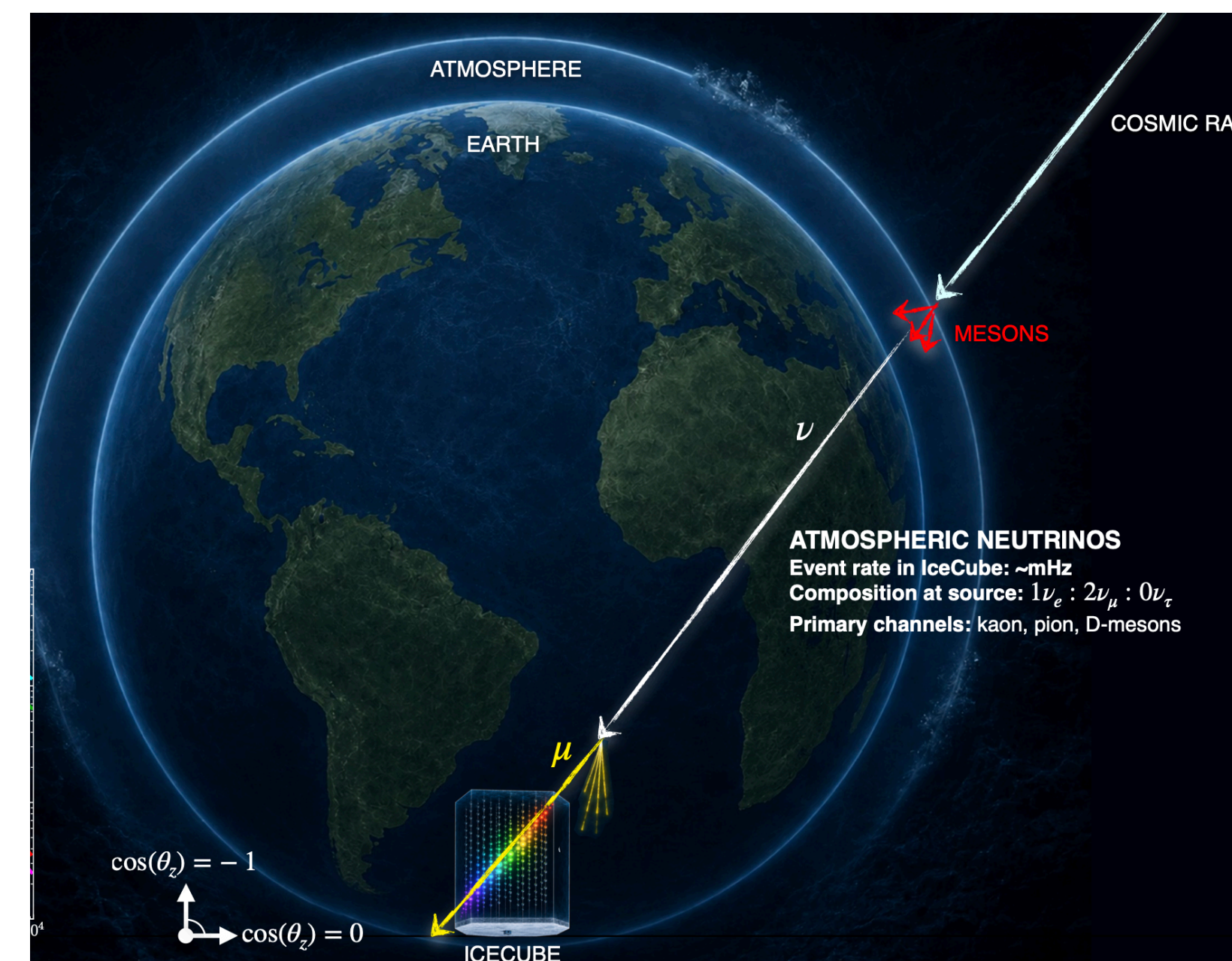
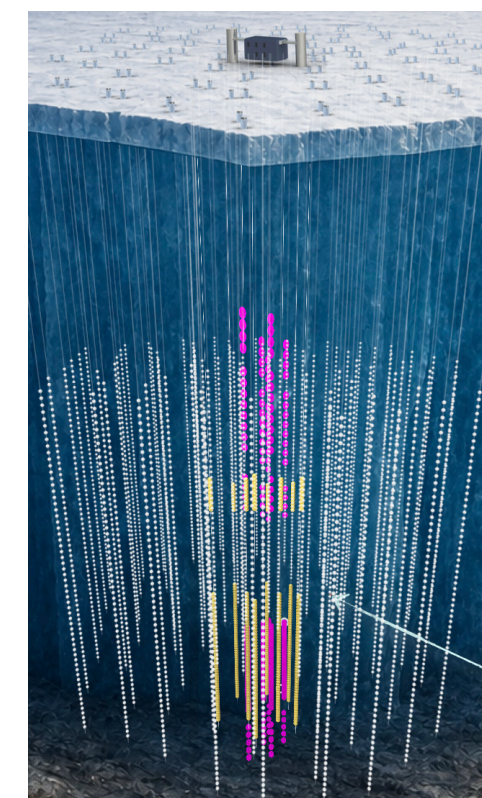
IceCube/DeepCore Observations

Sensitivity from 7 GeV to 300 GeV

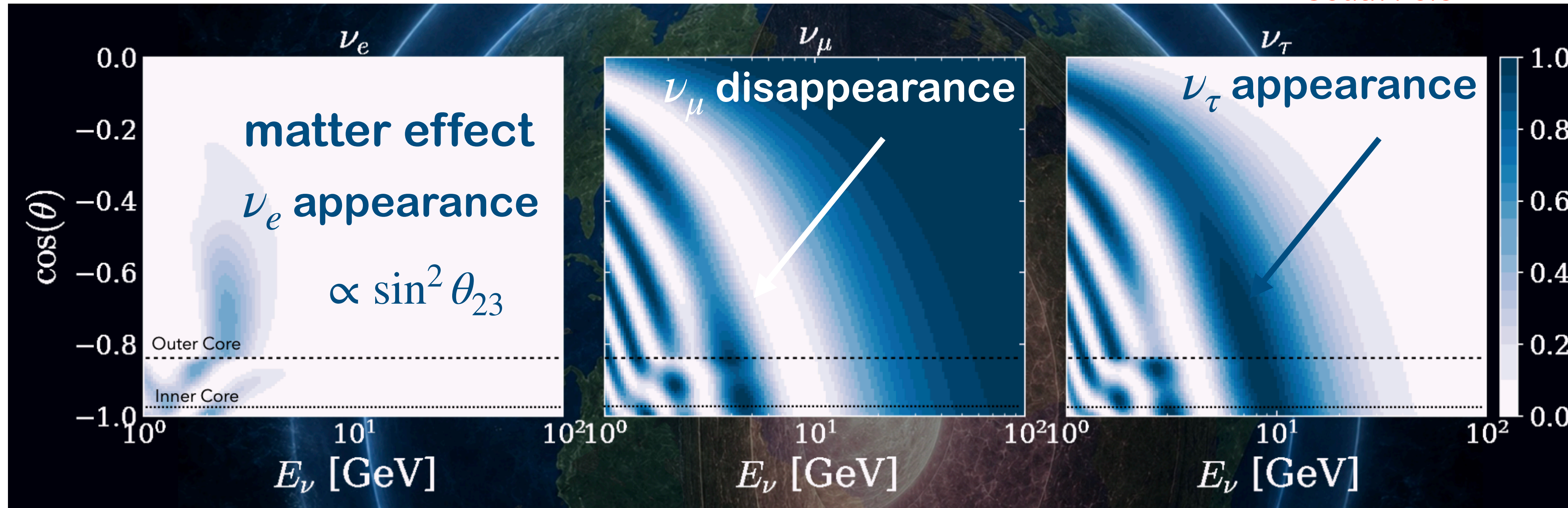
Detection via Cherenkov light emission from secondary particles produced in $\nu - N$ interactions :

tracks : μ
cascades: $e, \tau, \text{hadrons}$

assuming NO



South Pole



$$P(\nu_\mu \rightarrow \nu_\alpha)$$

Atmospheric Neutrinos

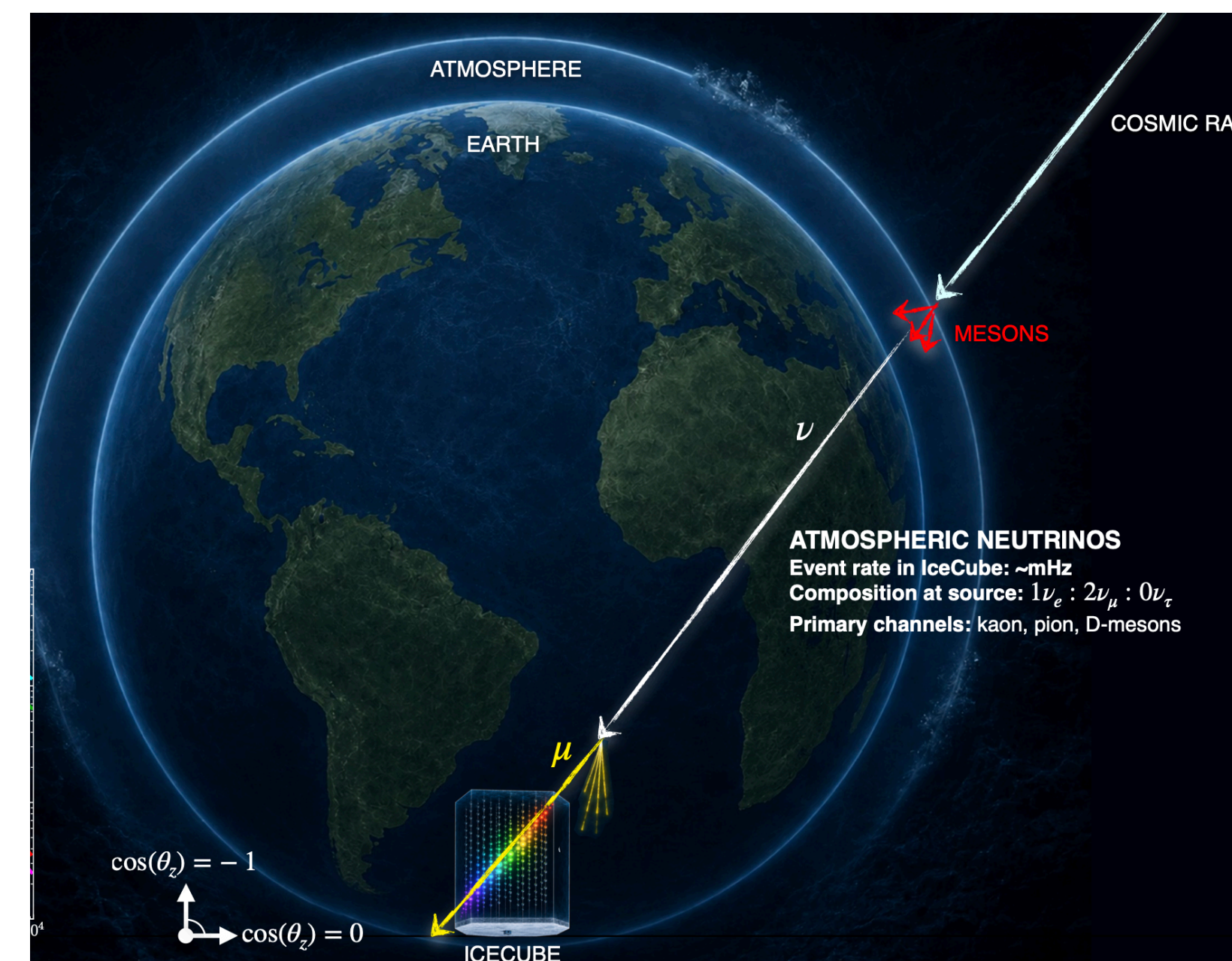
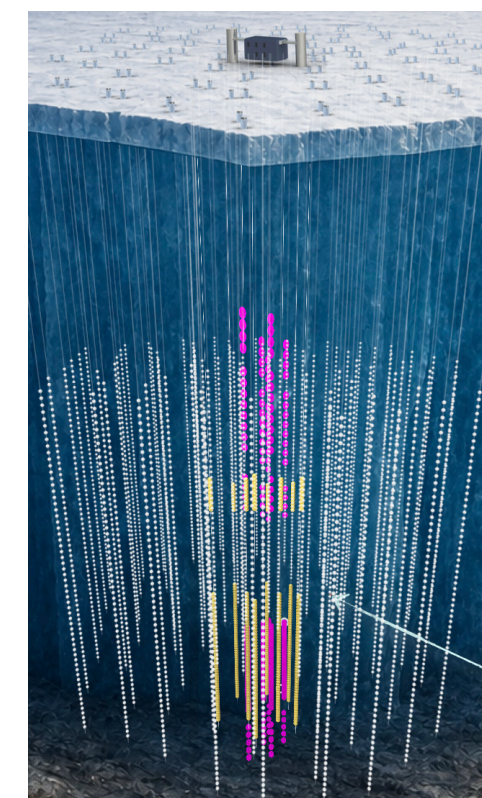
IceCube/DeepCore Observations

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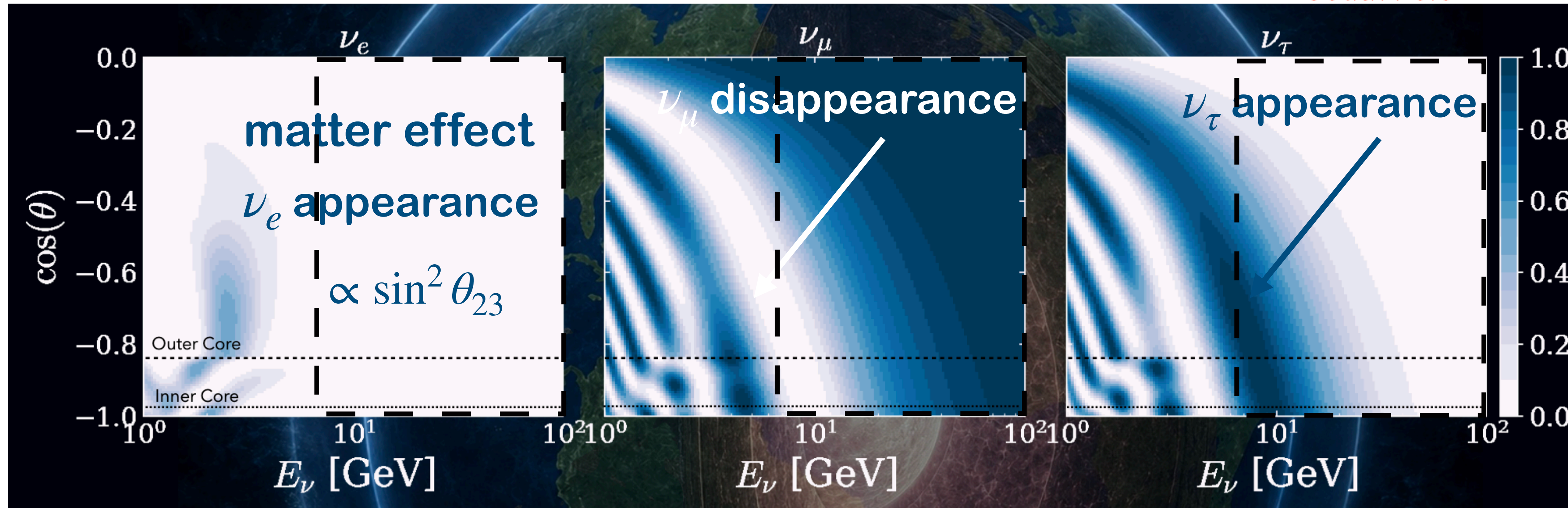
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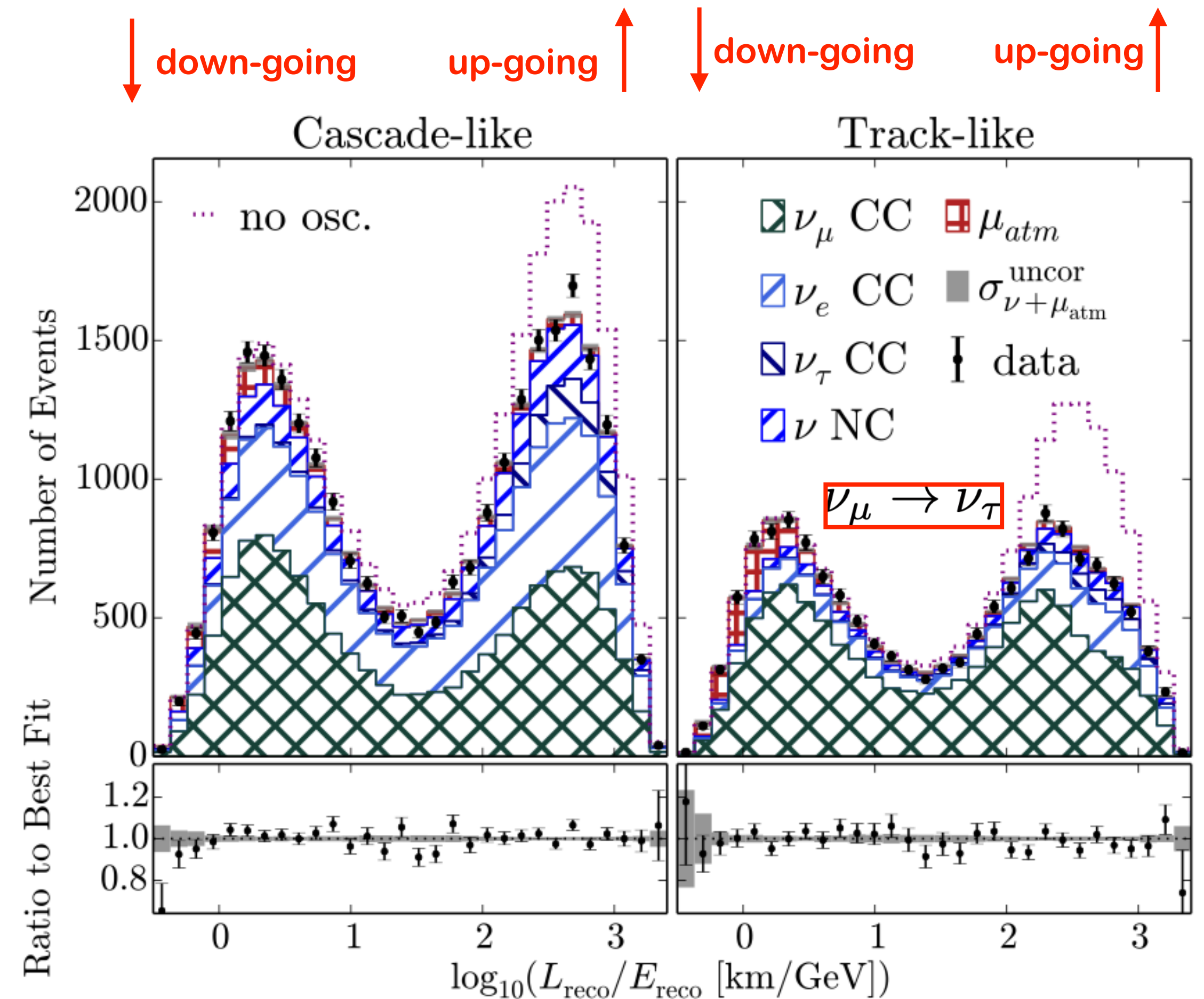
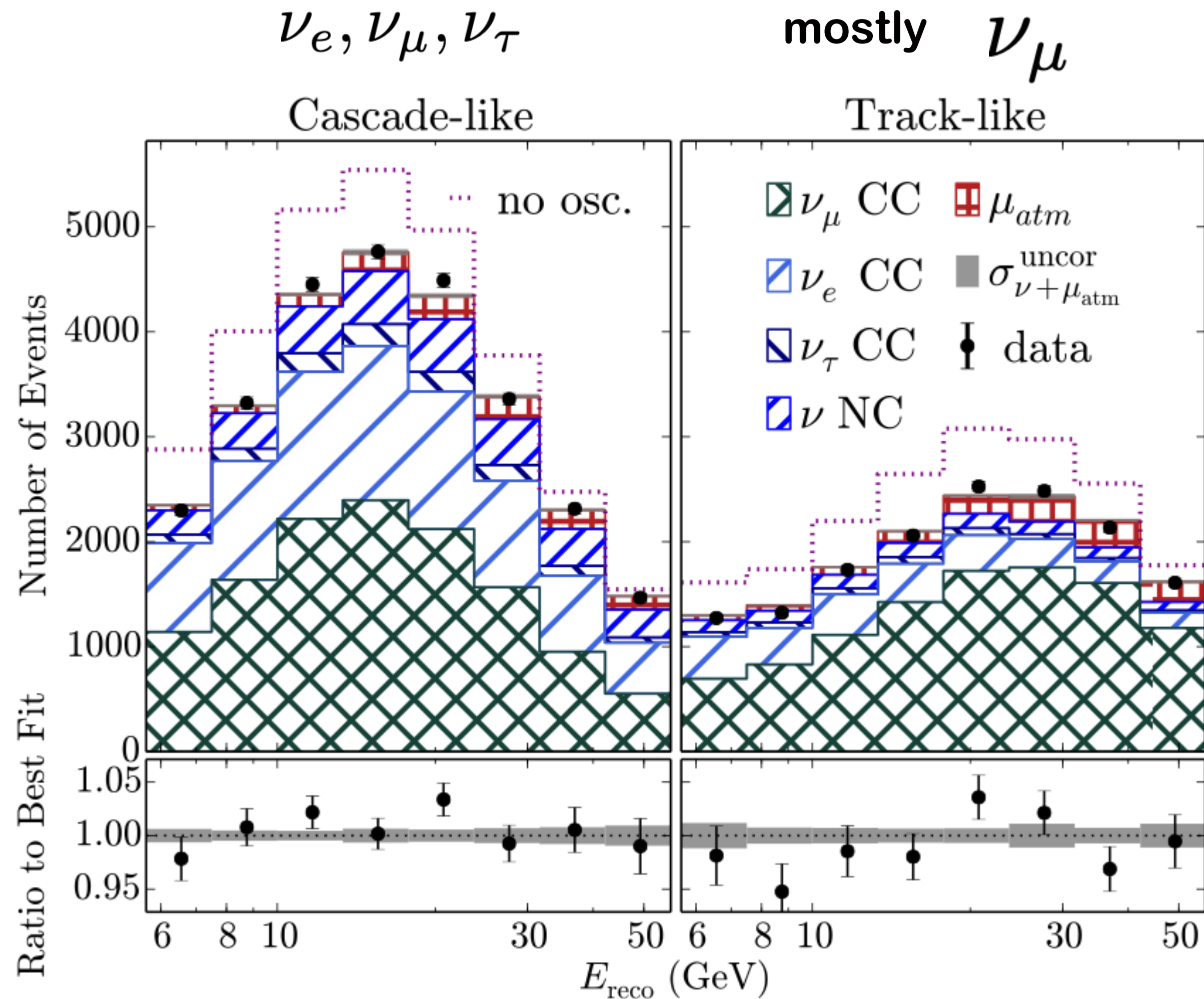
South Pole



$$P(\nu_\mu \rightarrow \nu_\alpha)$$

Atmospheric Neutrinos

IceCube/DeepCore Observations



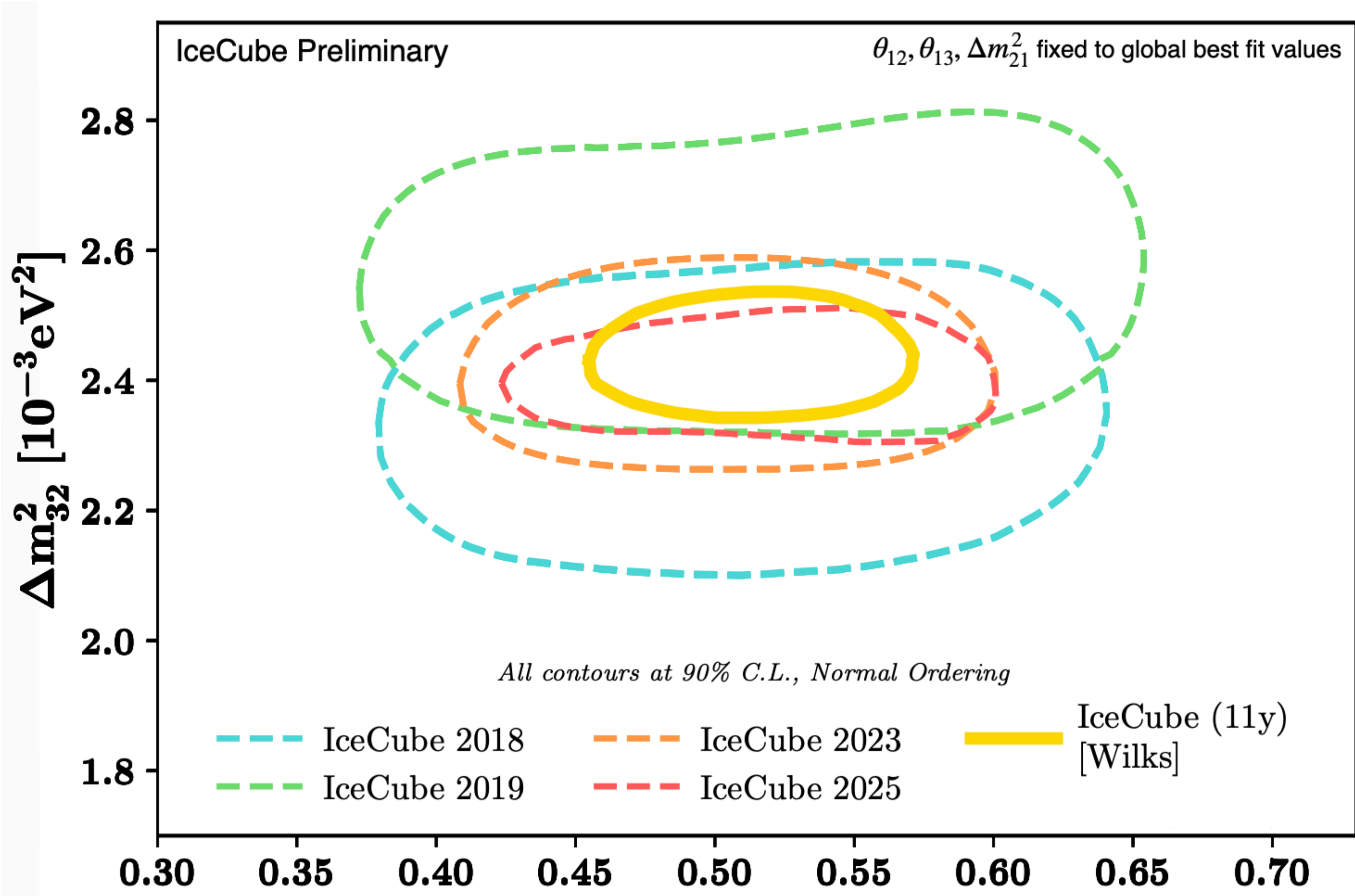
[IceCube/DeepCore Collab. (2017)]

Atmospheric Neutrinos

IceCube/DeepCore Observations

Detection via Cherenkov light emission from secondary particles produced in $\nu - N$ interactions :

tracks : μ
cascades: $e, \tau, \text{hadrons}$



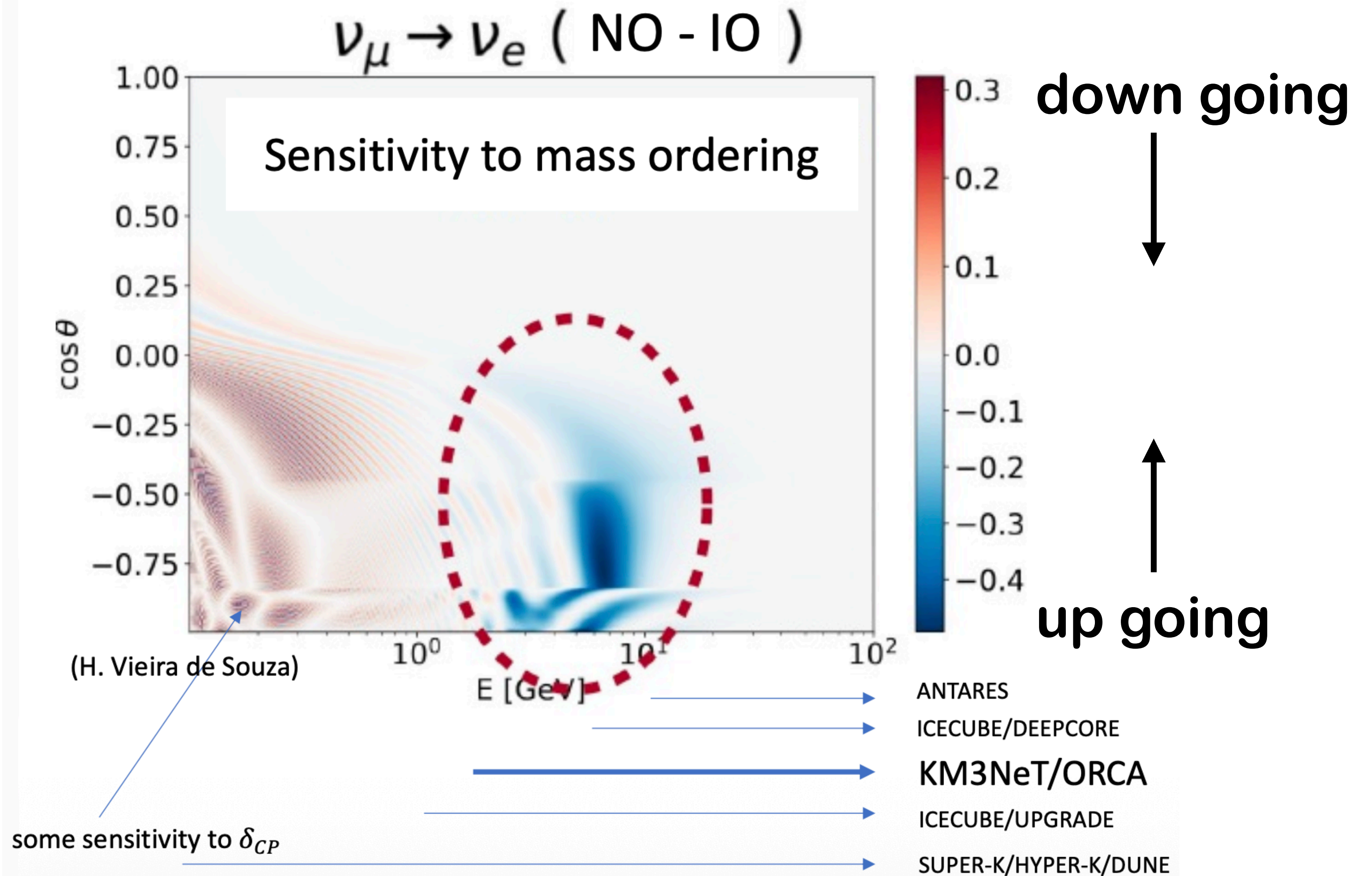
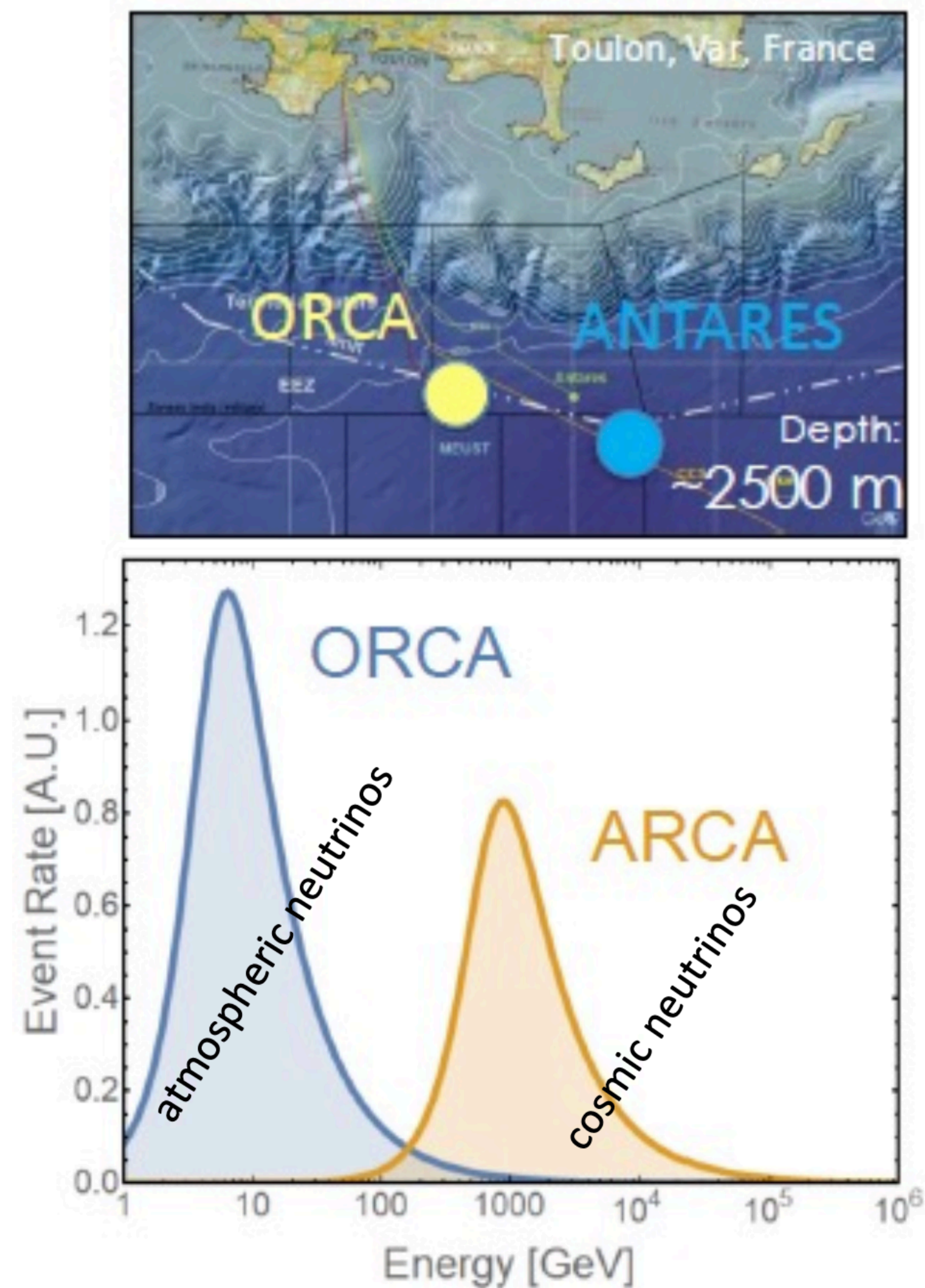
	Rate [μHz]	Num events [11.1 yr]	% of sample
$\nu_e\text{CC}$	71	$24,822 \pm 56$	22.8
$\nu_\mu\text{CC}$	187	$65,665 \pm 97$	60.4
$\nu_\tau\text{CC}$	16	$5,629 \pm 21$	5.2
$\nu\text{ NC}$	34	$11,912 \pm 39$	11.0
μ_{atm}	2	754 ± 46	0.7
Total	311	$108,784 \pm 129$	100

[IceCube - Neutrino 2026]

Best Fit:
 $\Delta m_{32}^2 = 2.437^{+0.043}_{-0.048} \times 10^{-3} \text{ eV}^2$
 $\sin^2(\theta_{23}) = 0.516^{+0.024}_{-0.035}$

Atmospheric Neutrinos

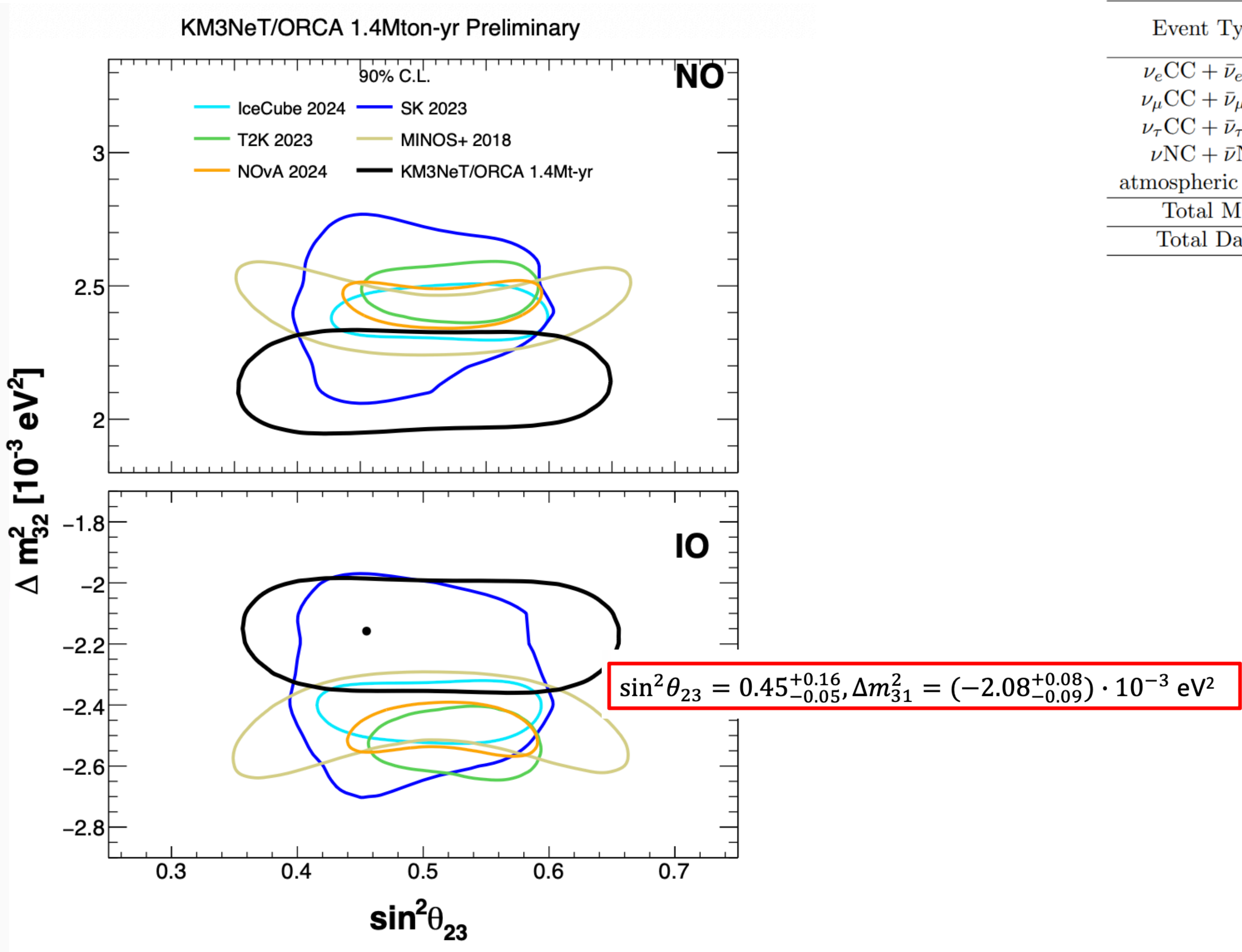
KM3NeT/ORCA



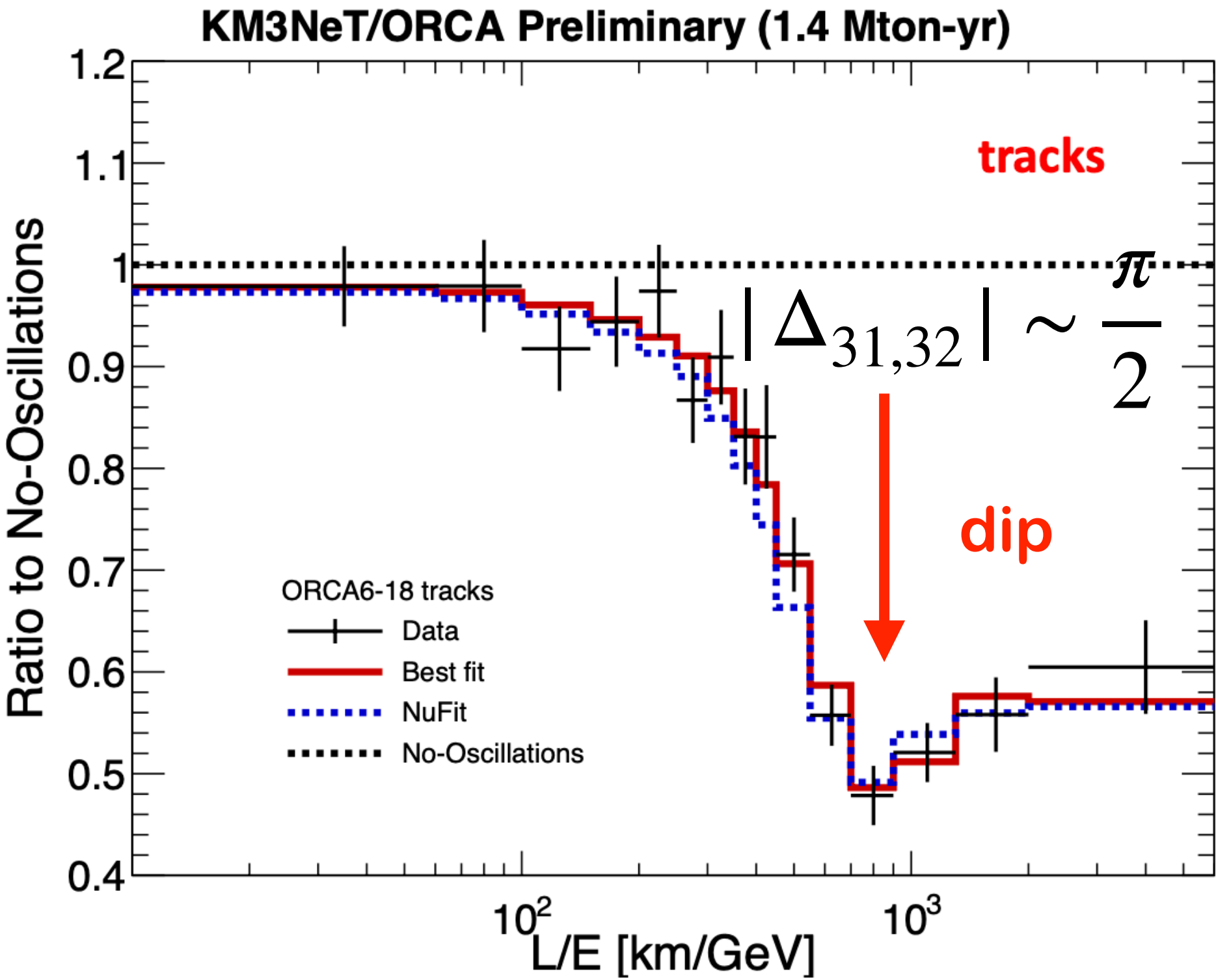
Atmospheric Neutrinos

KM3NeT/ORCA

[KM3NeT - Neutrino 2026]



Event Type	ORCA6/7 tracks	ORCA6/7 interm.	ORCA6/7 showers	ORCA11-18 tracks	ORCA11-18 interm.	ORCA11-18 showers
$\nu_e \text{CC} + \bar{\nu}_e \text{CC}$	50	336	682	87	646	911
$\nu_\mu \text{CC} + \bar{\nu}_\mu \text{CC}$	3869	748	493	5641	1151	557
$\nu_\tau \text{CC} + \bar{\nu}_\tau \text{CC}$	36	80	176	53	141	212
$\nu \text{NC} + \bar{\nu} \text{NC}$	19	112	276	31	219	430
atmospheric $\mu + \bar{\mu}$	29	22	30	31	20	21
Total MC	4003	1298	1657	5843	2176	2131
Total Data	4098	1361	1586	6329	2236	2016

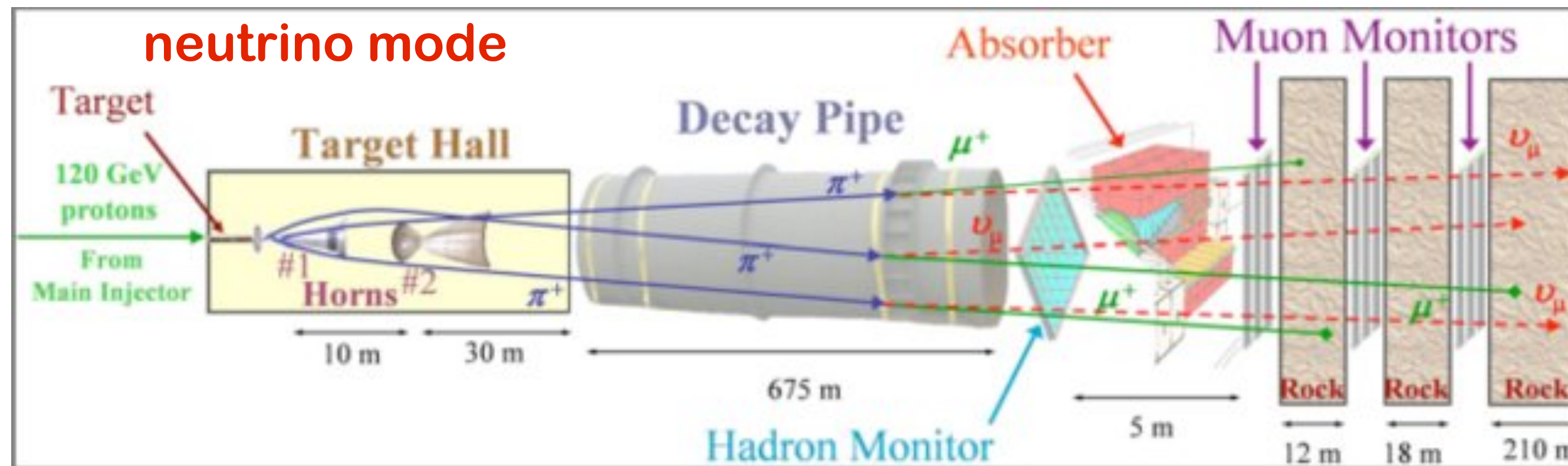


Accelerator Neutrinos

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{matrix} \Delta m_{21}^2 \\ \Delta m_{\mu\mu}^2 \\ \text{mass ordering} \end{matrix}$$

Accelerator Neutrinos

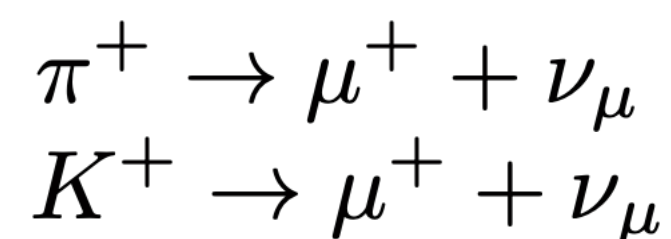
Disappearance and appearance for neutrinos and antineutrinos



NuMI neutrino beam @ FNAL

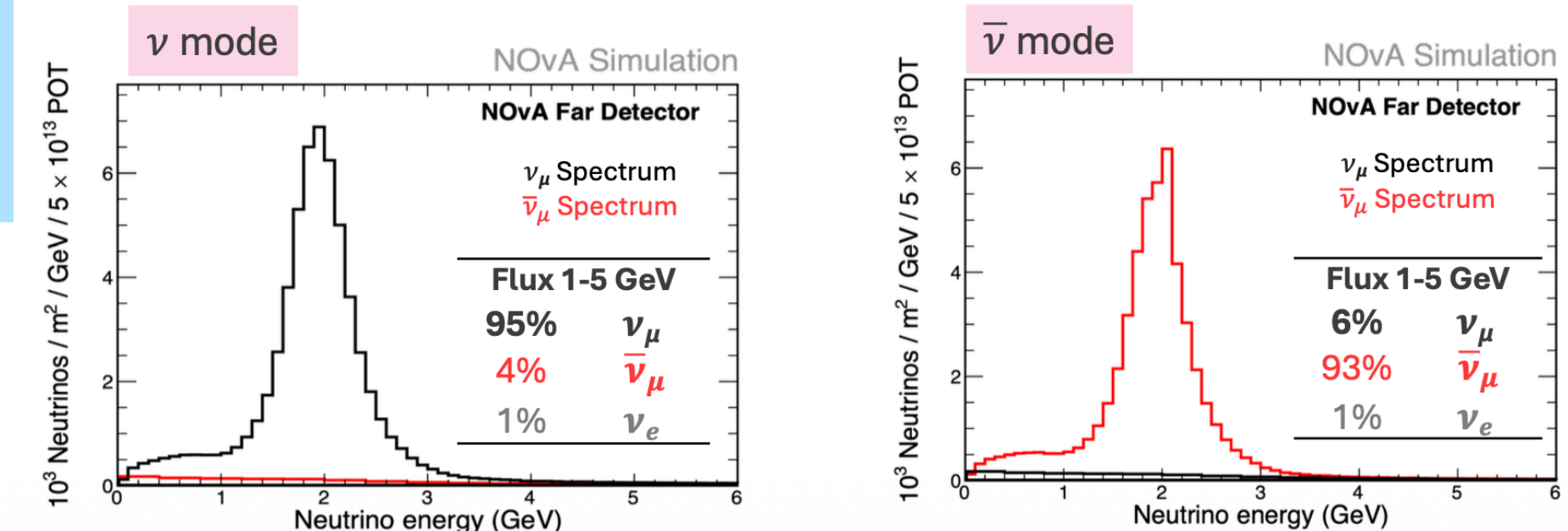
$\nu_\mu \rightarrow \nu_\mu$
 $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ **disappearance modes**

$\nu_\mu \rightarrow \nu_e$
 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **appearance modes**

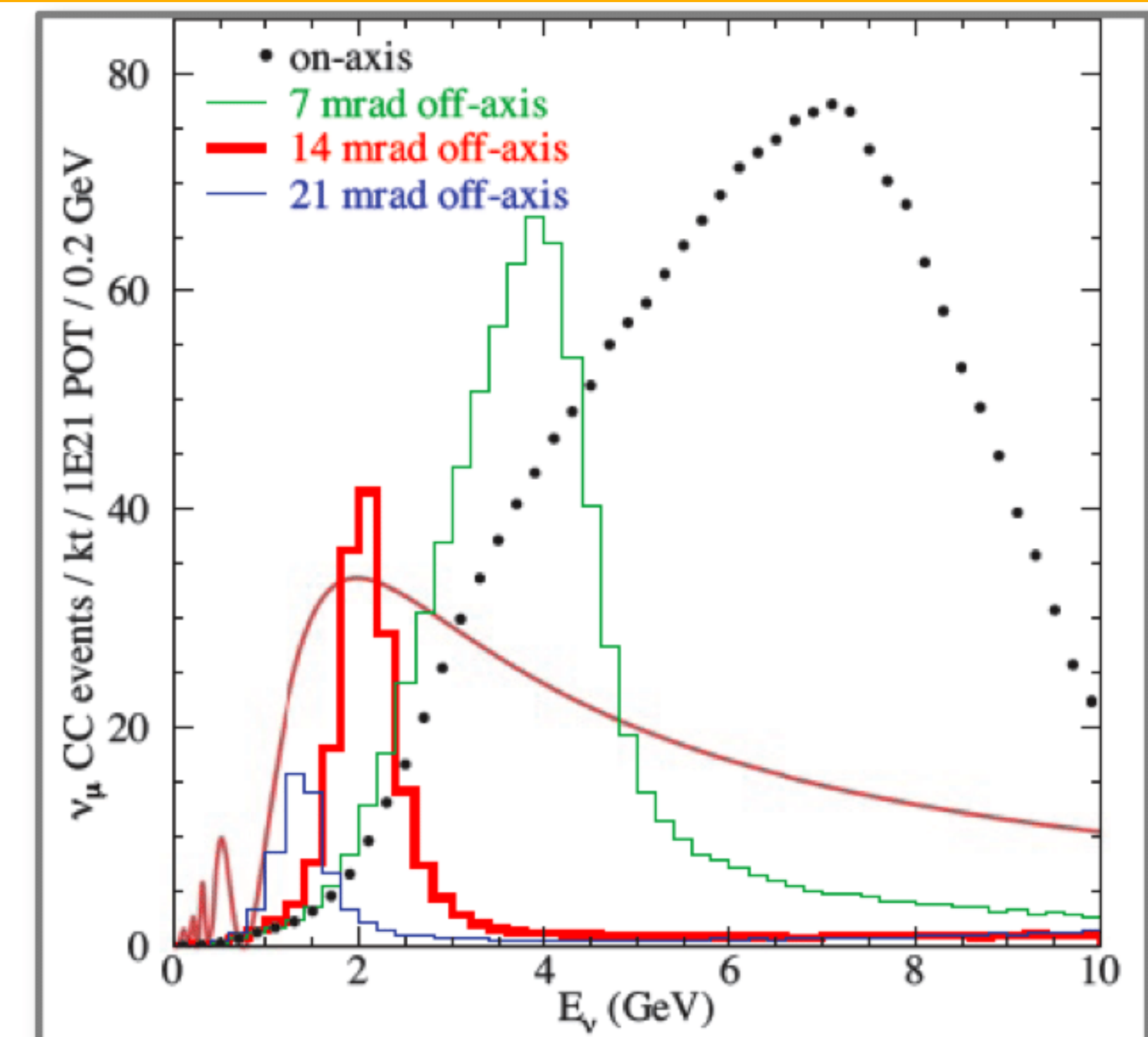


are the main processes for the neutrino flux

[taken from NOvA Collab.]

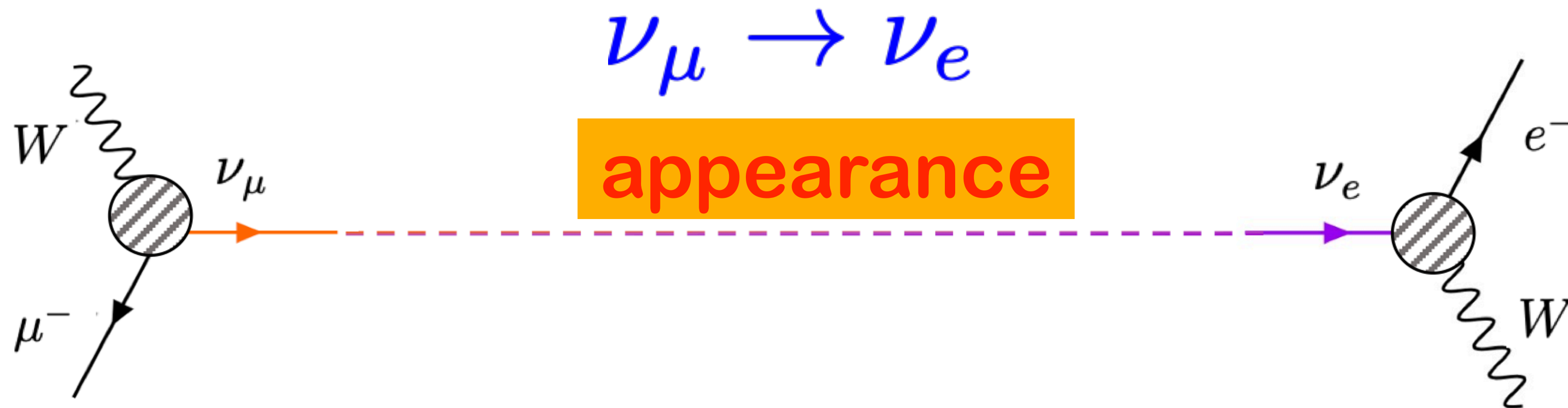
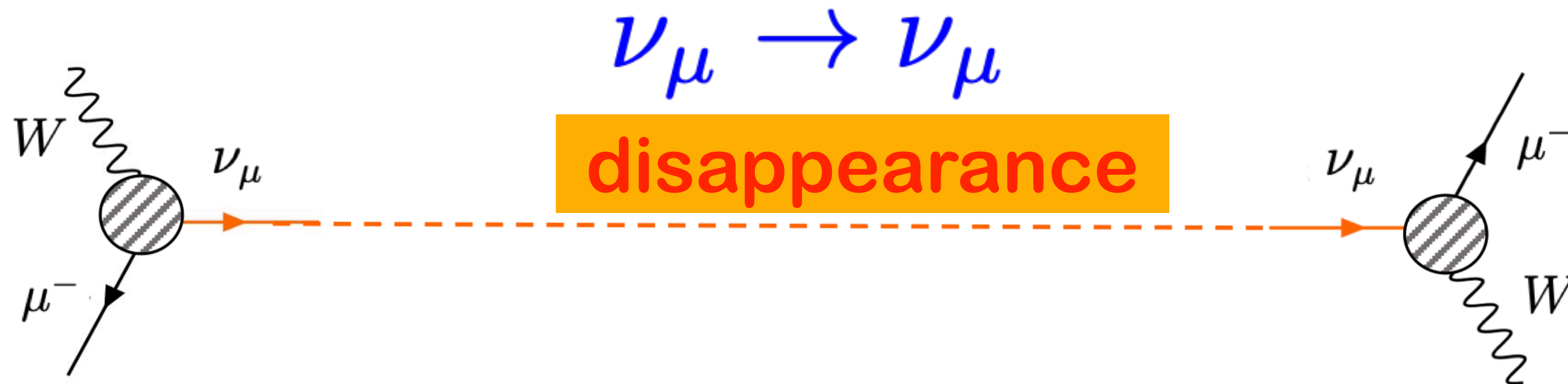
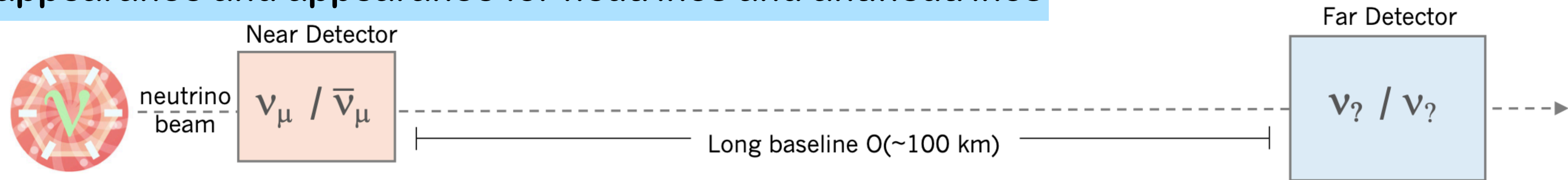


Off-axis : the beam is collimated in energy



Accelerator Neutrinos

Disappearance and appearance for neutrinos and antineutrinos



Accelerator Disappearance Probability

Sensitivity to the 32/31-sectors

$$\nu_\mu \rightarrow \nu_\mu \quad \& \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \sin^2 \Delta_{\mu\mu} + 4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2 \Delta_{21} + \mathcal{O}(\Delta_{21}^2)$$

vacuum

Accelerator Disappearance Probability

Sensitivity to the 32/31-sectors

$$\nu_\mu \rightarrow \nu_\mu \quad \& \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \sin^2 \Delta_{\mu\mu} + 4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2 \Delta_{21} + \mathcal{O}(\Delta_{21}^2)$$

effective atmospheric

$$\Delta m_{\text{atm}}^2$$

for accelerator experiments

negligible

vacuum

$$\Delta m_{\mu\mu}^2 = s_{12}^2 \Delta m_{31}^2 + c_{12}^2 \Delta m_{32}^2 + s_{13} \Delta m_{21}^2 \sin 2\theta_{12} \tan \theta_{23} \cos \delta \approx s_{12}^2 \Delta m_{31}^2 + c_{12}^2 \Delta m_{32}^2$$

MINOS baseline $L = 735$ km

$$\langle E \rangle \sim 3 \text{ GeV}$$

$$\Delta_{21} \sim 0.02$$

T2K baseline $L = 295$ km

$$\langle E \rangle \sim 0.6 \text{ GeV}$$

$$\Delta_{21} \sim 0.05$$

NOvA baseline $L = 810$ km

$$\langle E \rangle \sim 2 \text{ GeV}$$

$$\Delta_{21} \sim 0.04$$

Accelerator Disappearance Probability

Sensitivity to the 32/31-sector

$$\nu_\mu \rightarrow \nu_\mu \quad \& \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \sin^2 \Delta_{\mu\mu} + 4|U_{\mu 2}|^2|U_{\mu 1}|^2 \sin^2 \Delta_{21} + \mathcal{O}(\Delta_{21}^2)$$

vacuum

effective atmospheric Δm_{atm}^2 for accelerator experiments

$$\Delta m_{\mu\mu}^2 = s_{12}^2 \Delta m_{31}^2 + c_{12}^2 \Delta m_{32}^2 + s_{13} \Delta m_{21}^2 \sin 2\theta_{12} \tan \theta_{23} \cos \delta \approx s_{12}^2 \Delta m_{31}^2 + c_{12}^2 \Delta m_{32}^2$$

so for these experiments to very good approximation we can write

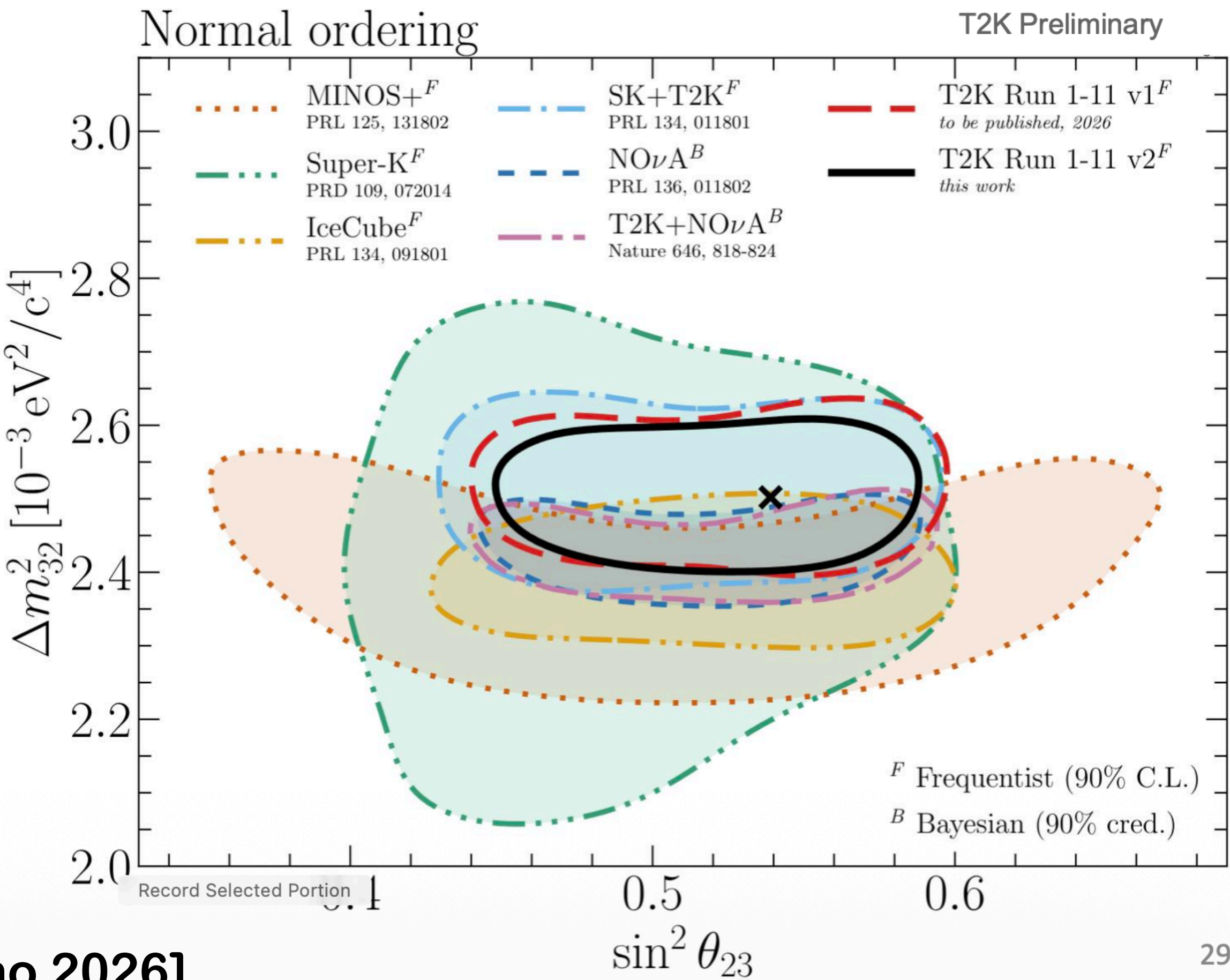
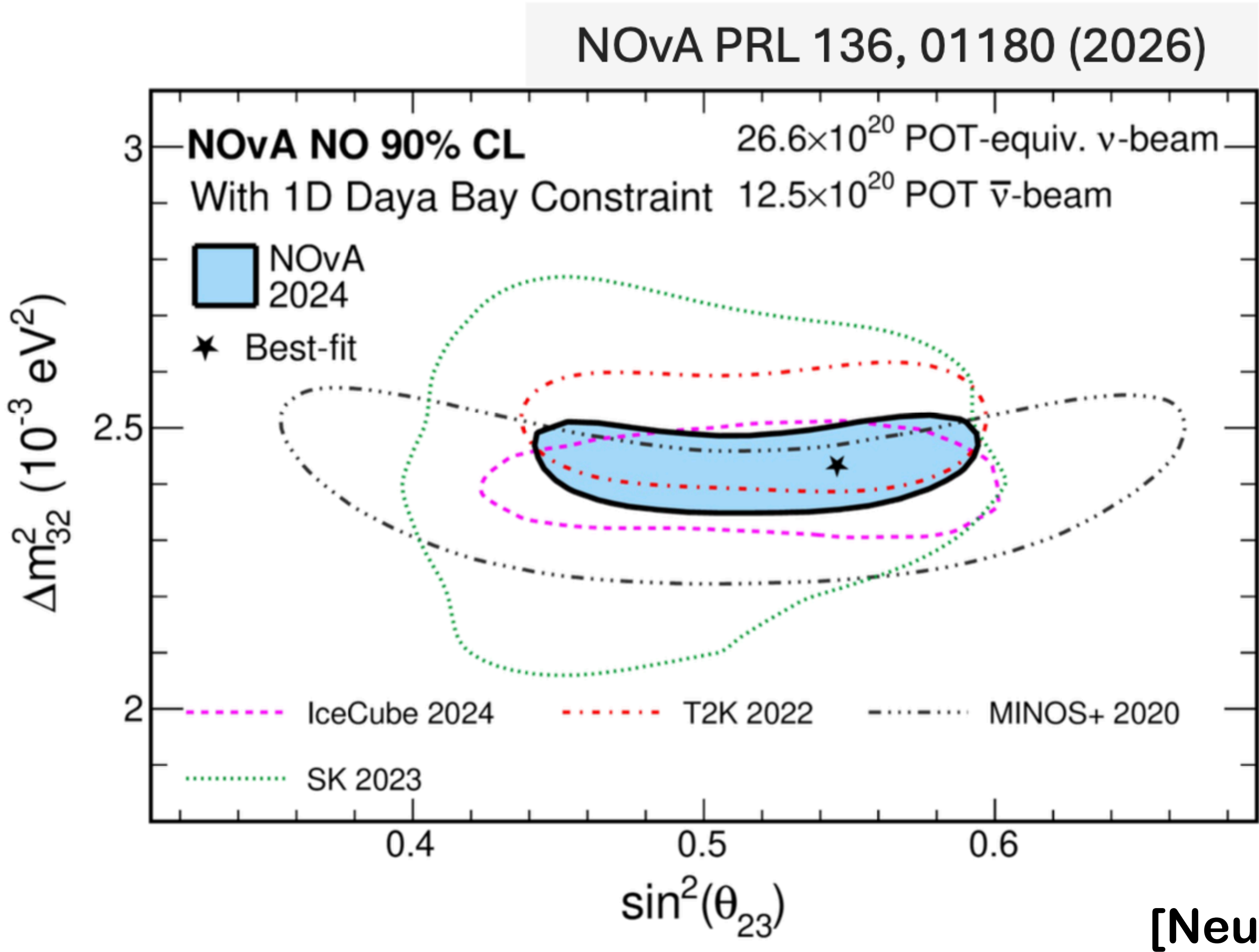
$$P_{\nu_\mu \rightarrow \nu_\mu} \approx 1 - 4s_{23}^2 c_{13}^2 (1 - s_{23}^2 c_{13}^2) \sin^2 \Delta_{\mu\mu} = 1 - \sin^2 2\theta_{\text{eff}} \sin^2 \Delta_{\mu\mu}$$

+ matter effects are negligible

Accelerator Neutrinos

Disappearance Results

T2K $\nu - 21 \times 10^{20}$ POT
 $\bar{\nu} - 16 \times 10^{20}$ POT



[Neutrino 2026]

Accelerator Appearance Probability

Sensitivity to the 32/31-sector: exploring matter effects

$$\nu_\mu \rightarrow \nu_e \text{ \& \; } \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$P_{\nu_\mu \rightarrow \nu_e} \approx P_{\text{atm}} + 2\sqrt{P_{\text{atm}}}\sqrt{P_{\text{sol}}}\cos(\Delta_{32} + \delta) + P_{\text{sol}}$$

in vacuum

$$\sqrt{P_{\text{sol}}} \equiv c_{23}c_{13}\sin 2\theta_{12}\sin \Delta_{21}$$

sensitive to δ

$$\sqrt{P_{\text{atm}}} \equiv s_{23}\sin 2\theta_{13}\sin \Delta_{31}$$

matter effects are important because they increase the difference between neutrino & antineutrinos

Accelerator Appearance Probability

Sensitivity to the 32/31-sector: exploring matter effects

$\nu_\mu \rightarrow \nu_e$

atmospheric term

solar term

octant

$$P_{\nu_\mu \rightarrow \nu_e} \approx 4s_{23}^2 s_{13}^2 c_{13}^2 \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + 4s_{12}^2 c_{12}^2 c_{13}^2 c_{23}^2 \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2$$

mass ordering

interference term

$$+ 8 \frac{J}{\sin \delta} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta)$$

CP phase

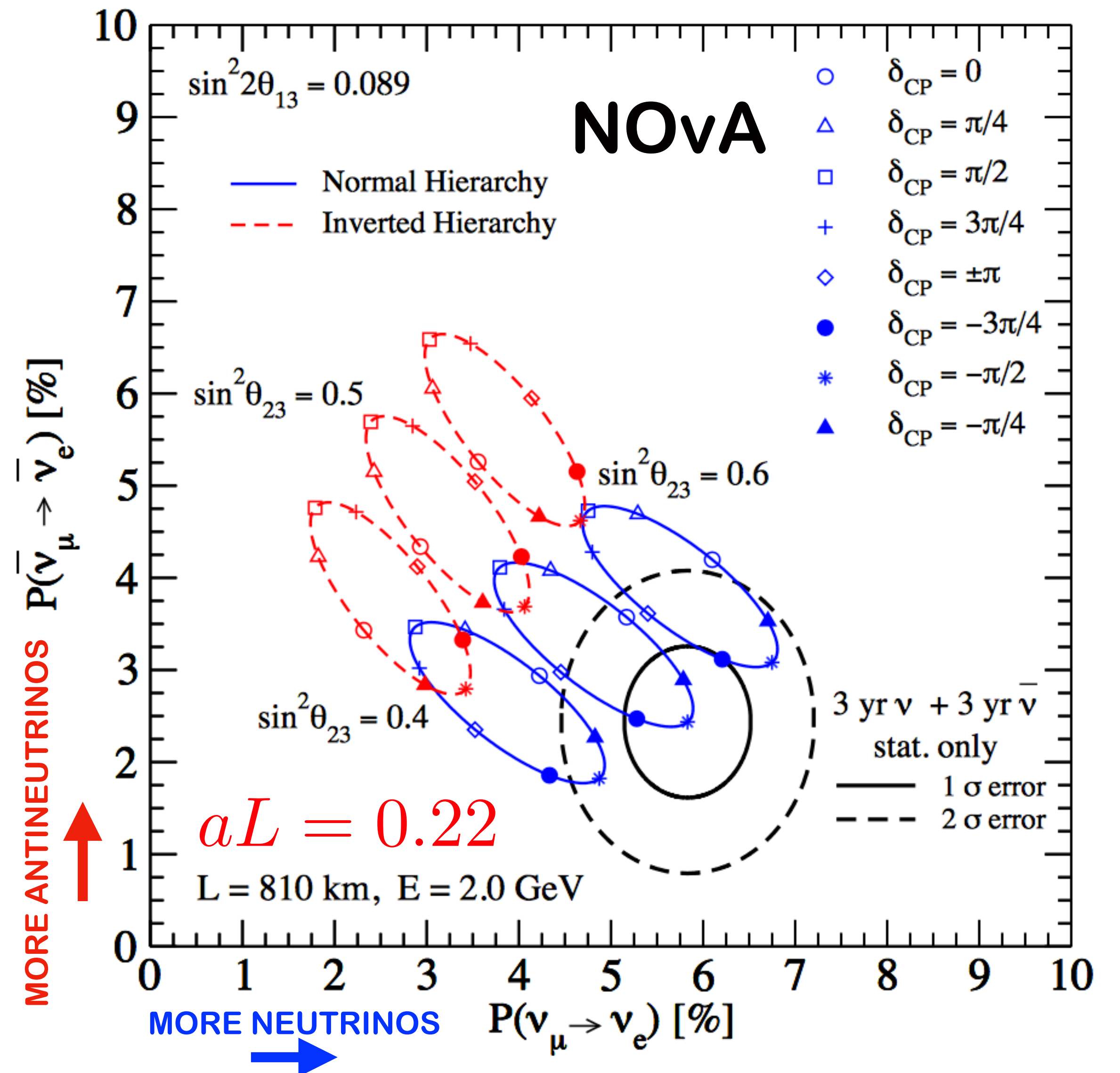
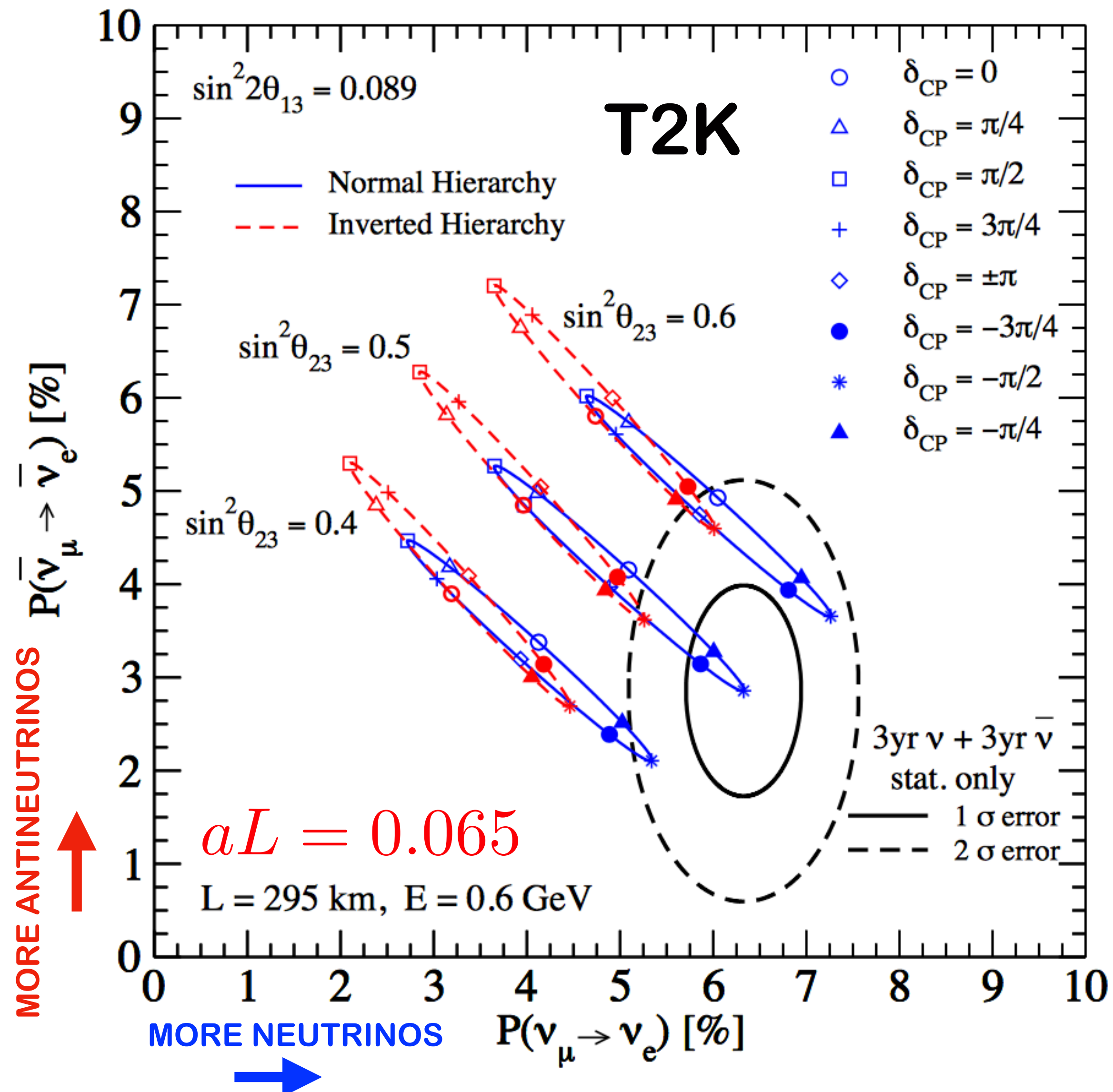
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} = P_{\nu_\mu \rightarrow \nu_e}(\delta \rightarrow -\delta, aL \rightarrow -aL)$$

effect of the matter potential

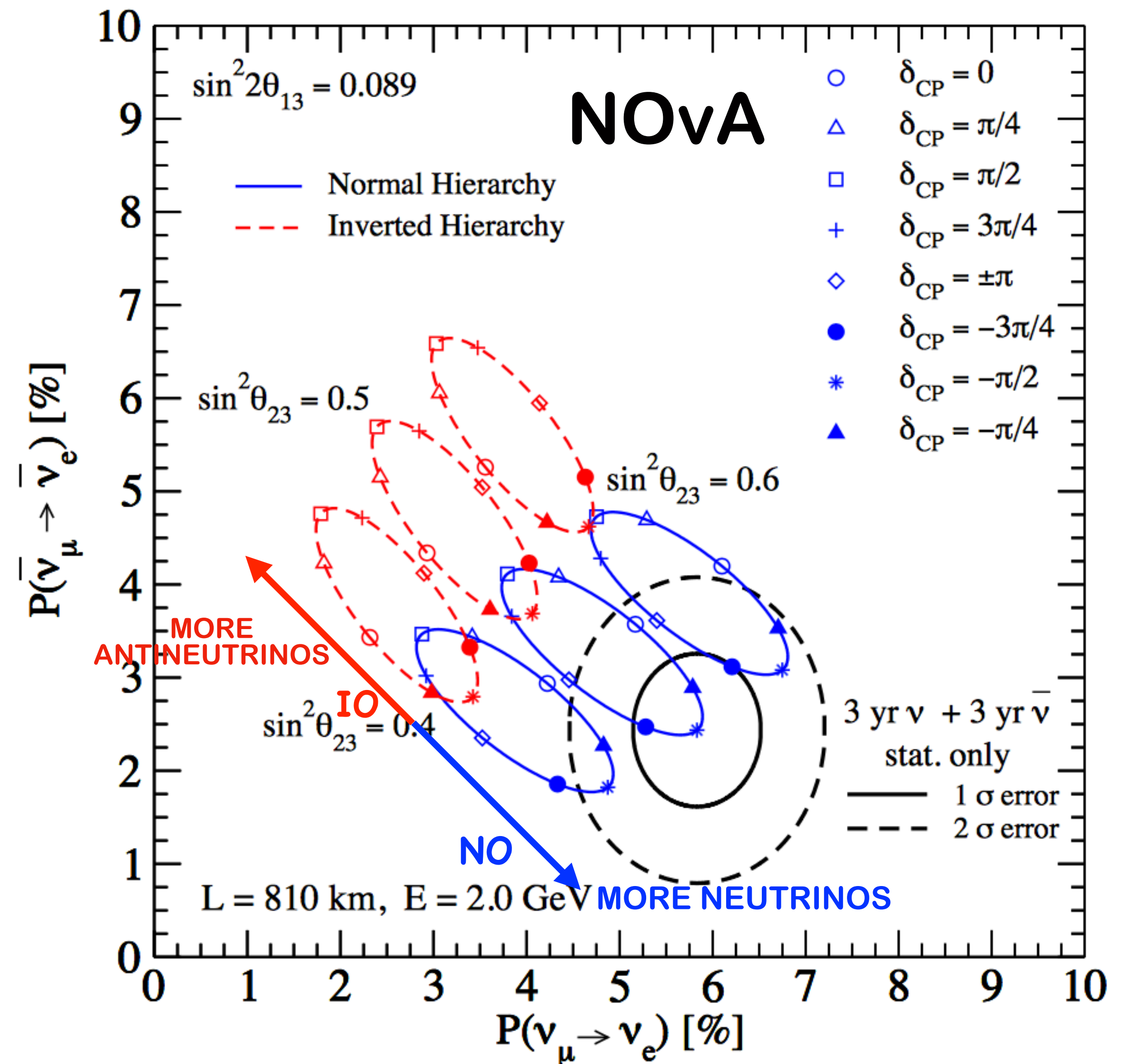
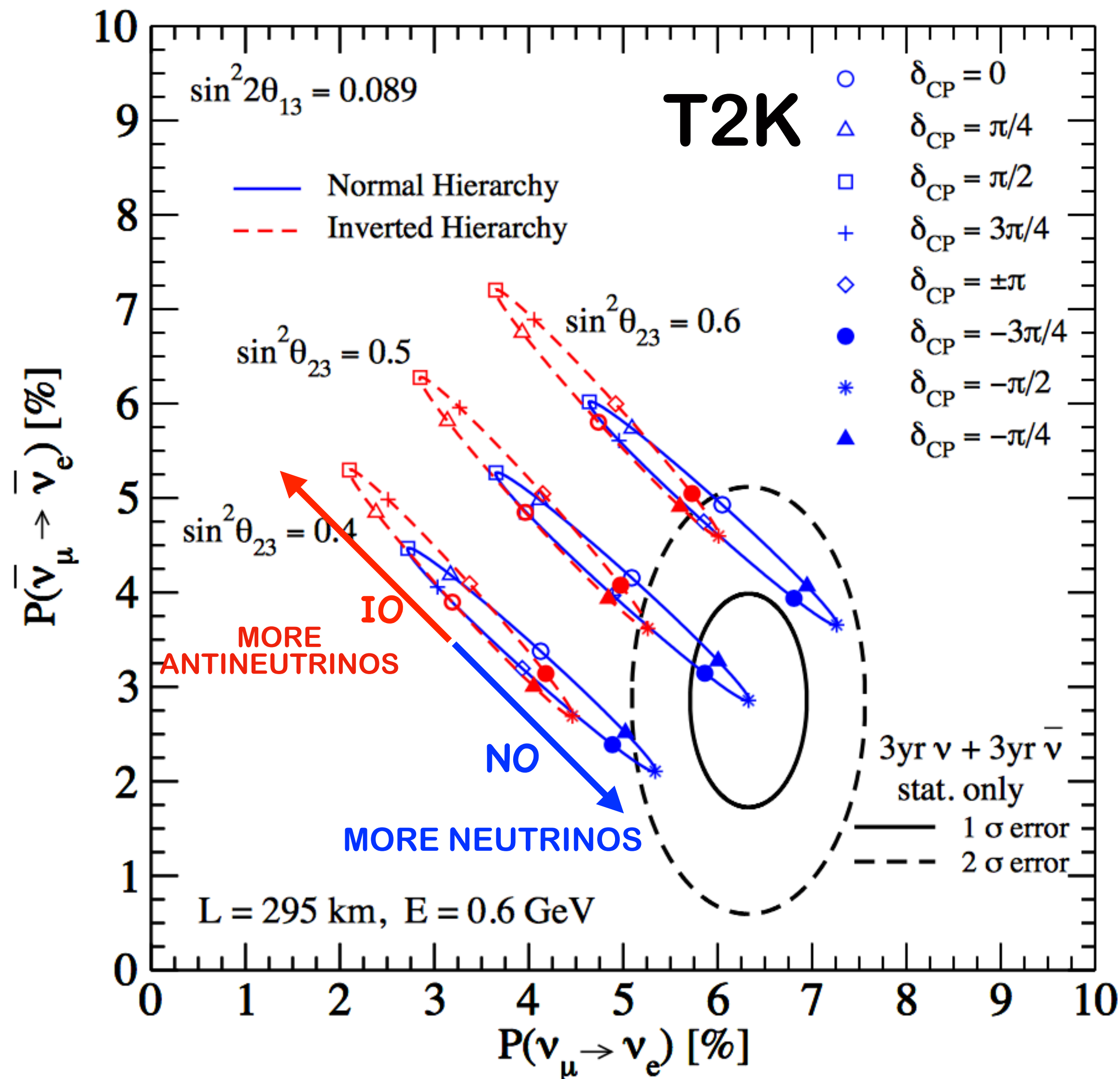
$$a \equiv \frac{G_F n_e}{\sqrt{2}} \approx \frac{1}{3500 \text{ km}} \left(\frac{\rho}{3 \text{ g/cm}^3} \right)$$

Bi-probability plots



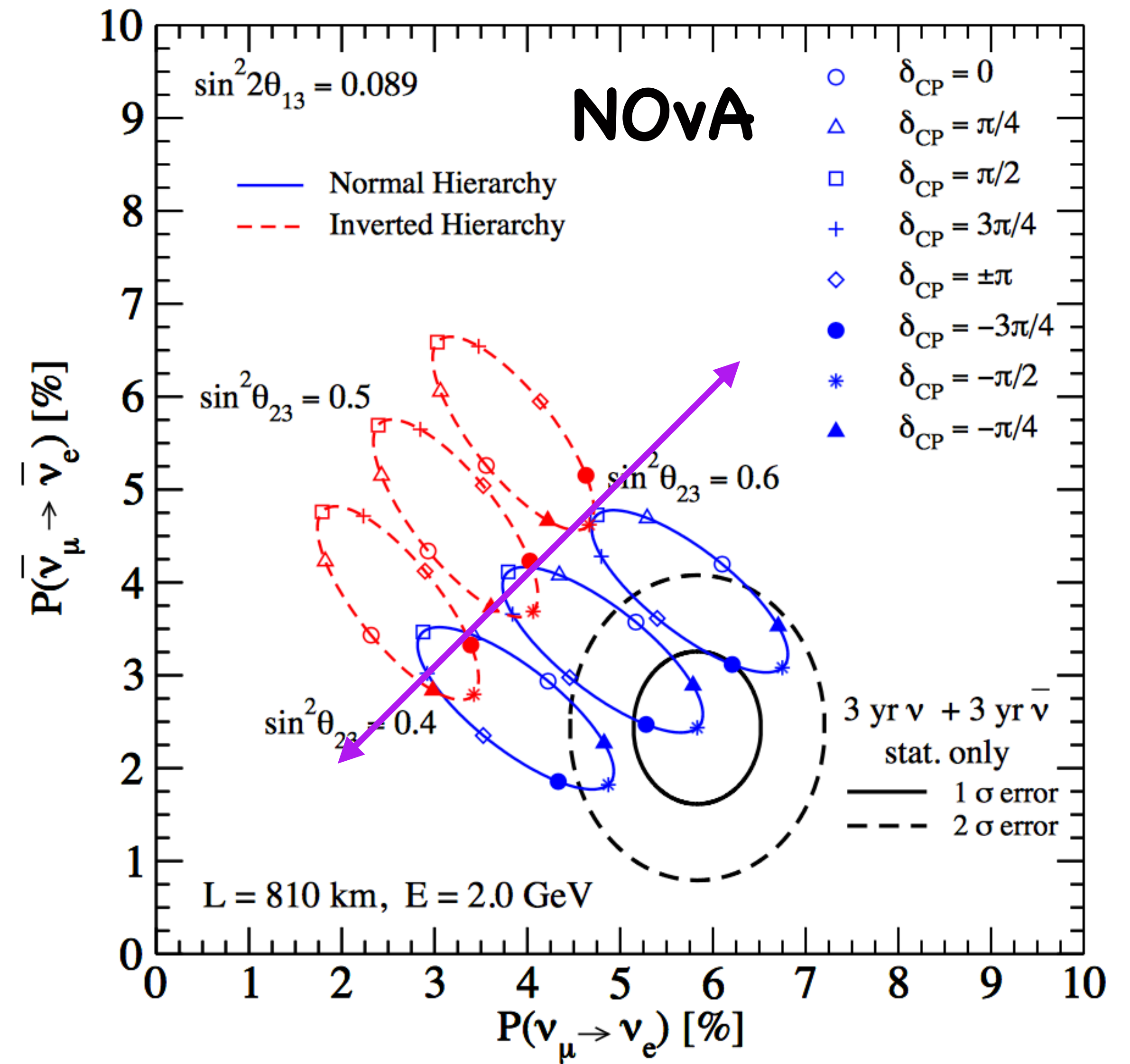
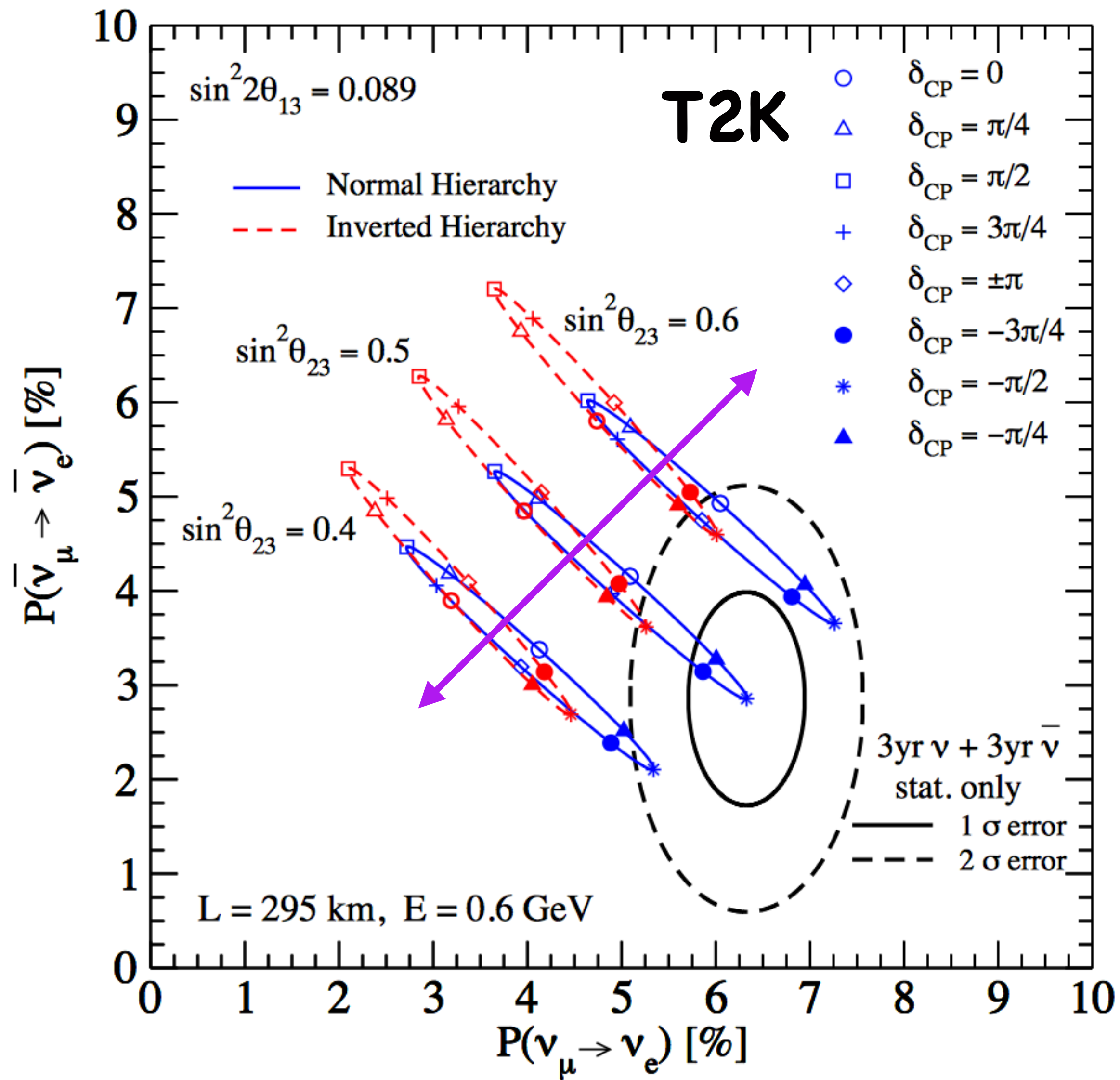
Bi-probability plots

Mass Ordering



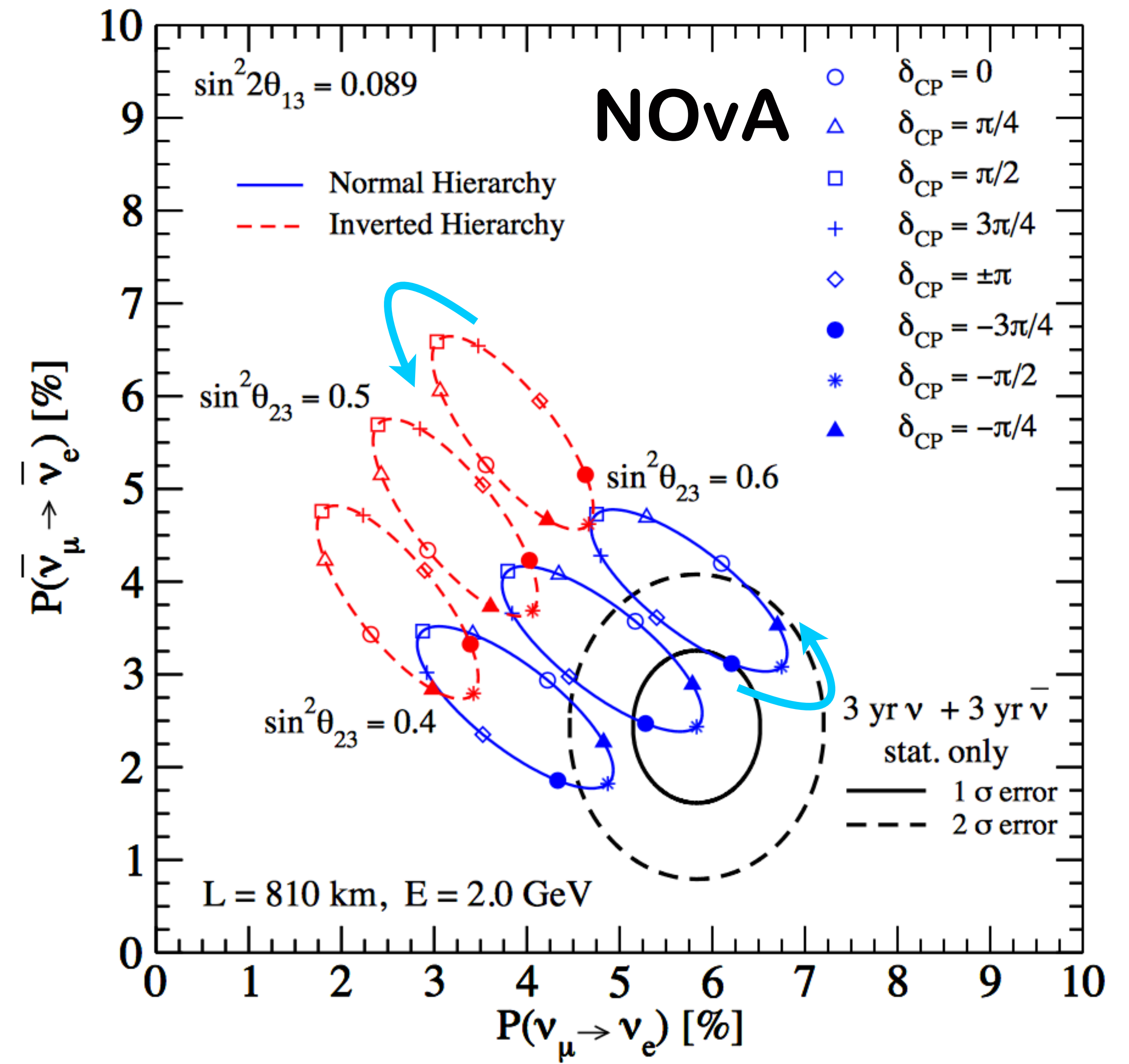
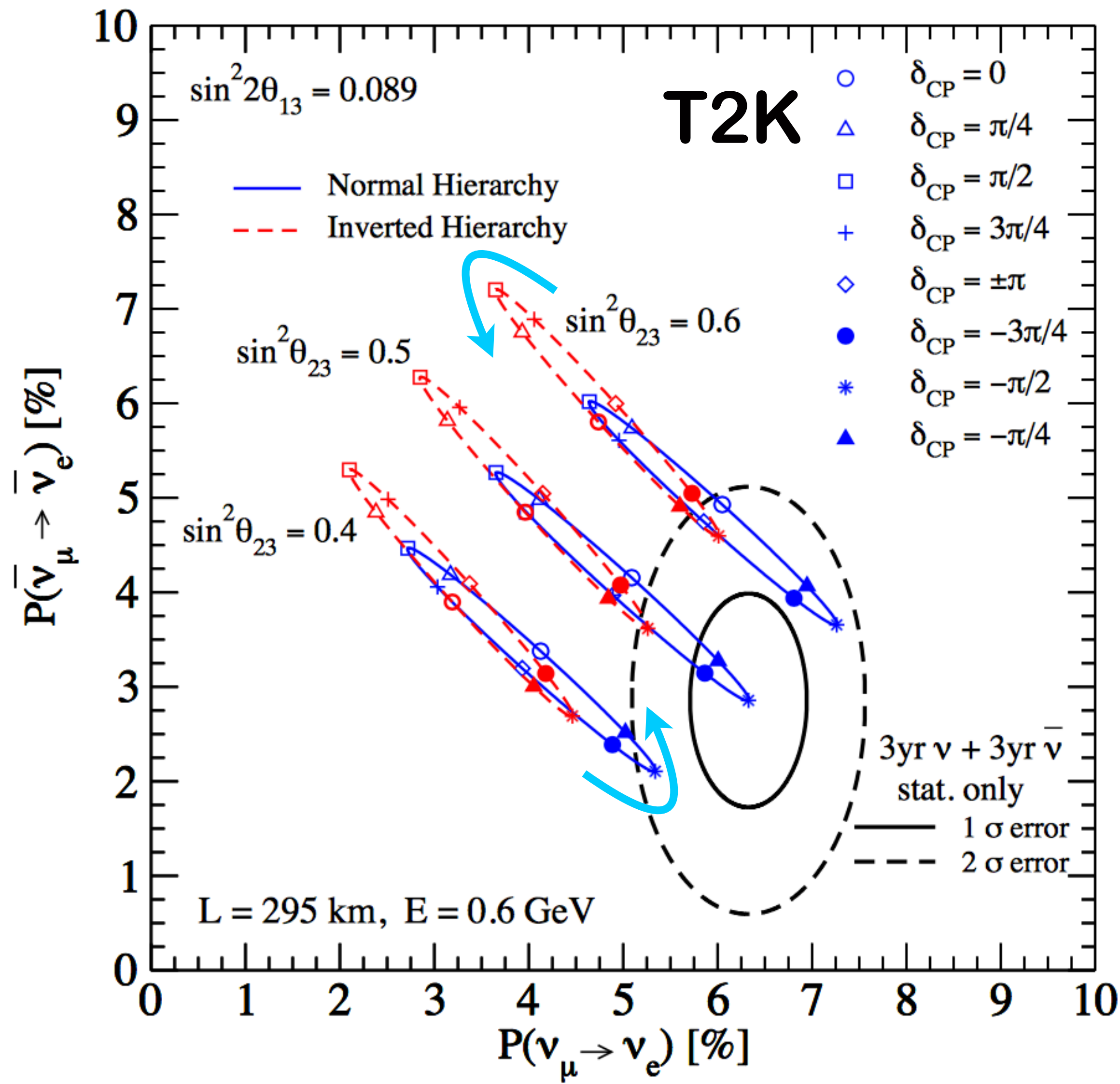
Bi-probability plots

octant θ_{23}



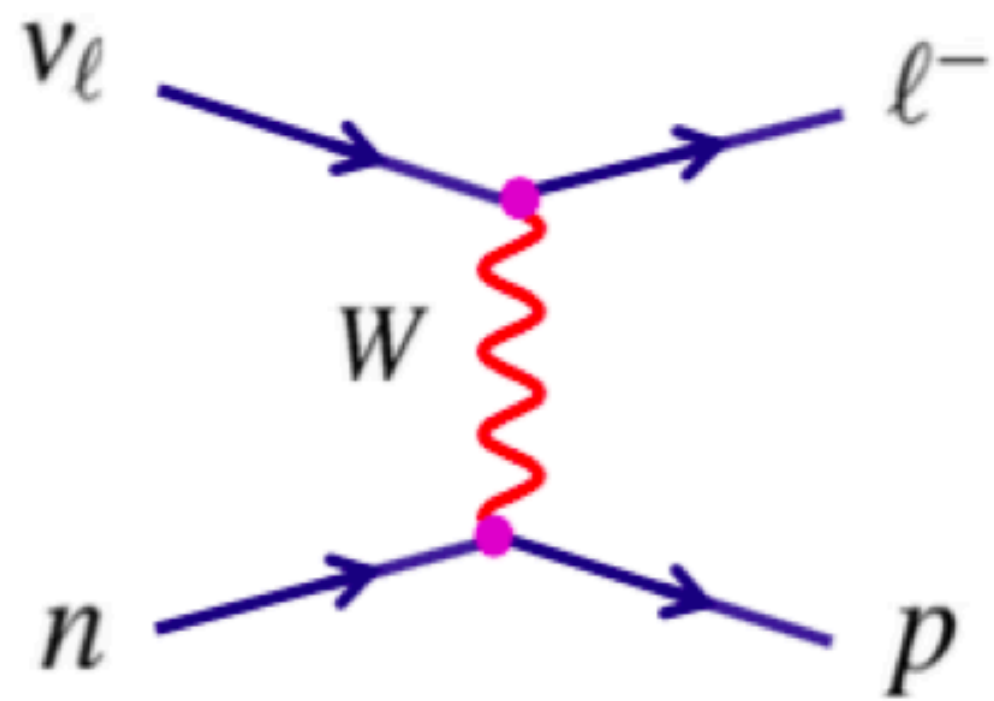
Bi-probability plots

CP Phase

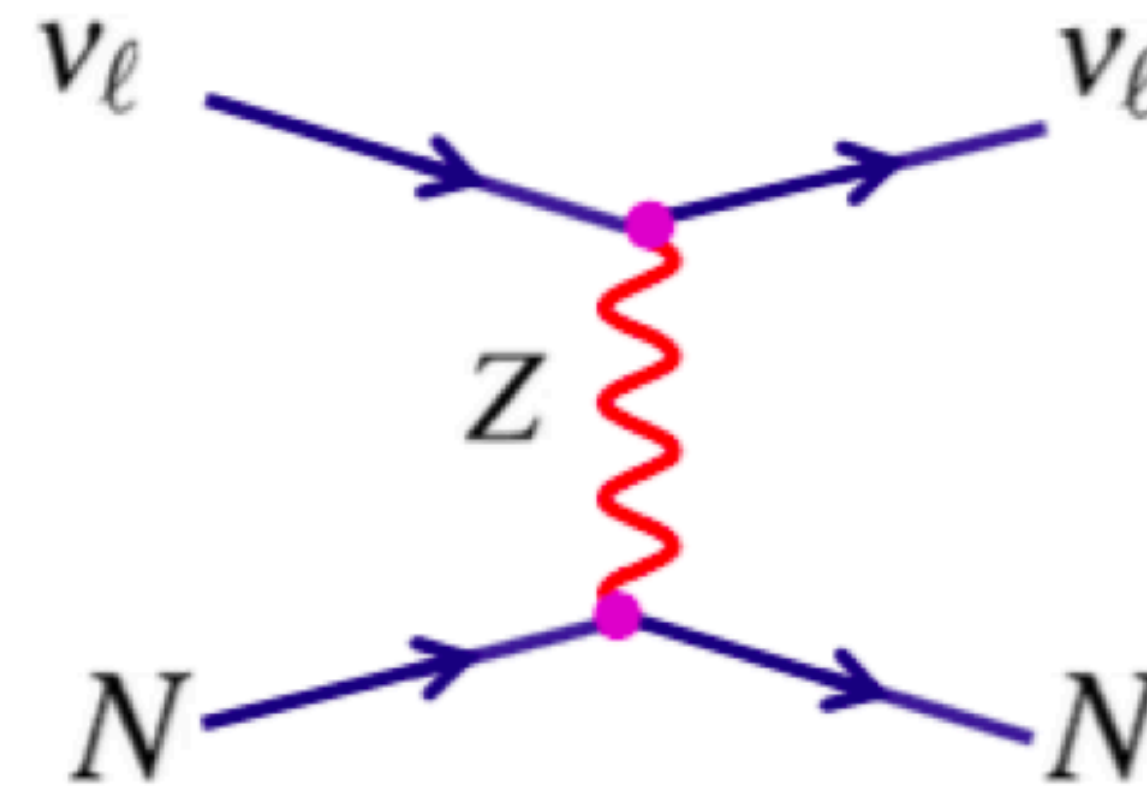


Accelerator (& Atmospheric) Neutrinos

How neutrinos are measured?

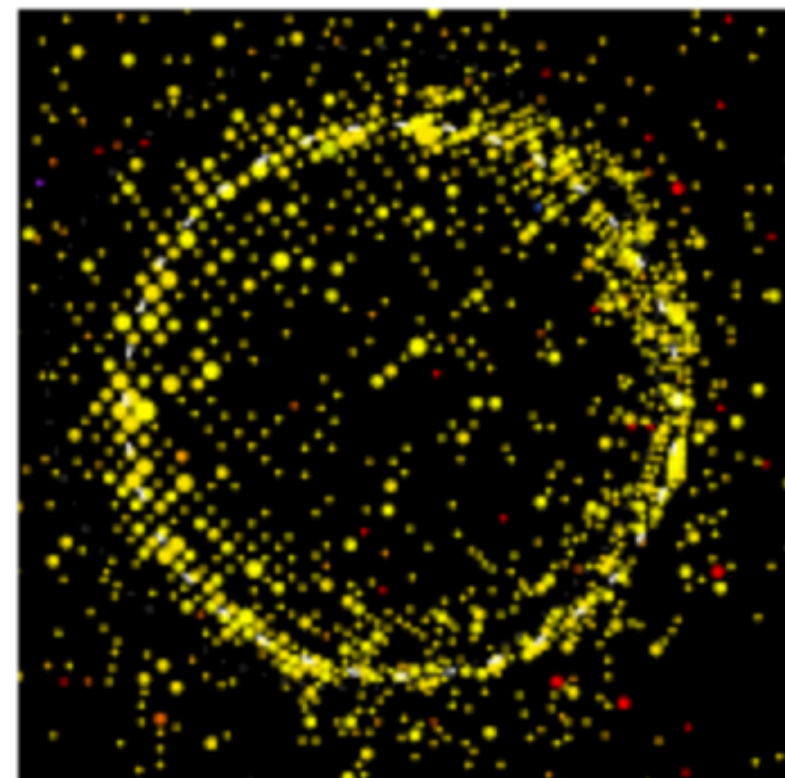


Charged Current (CC)
interaction reveals the
flavor from the outgoing
charged lepton

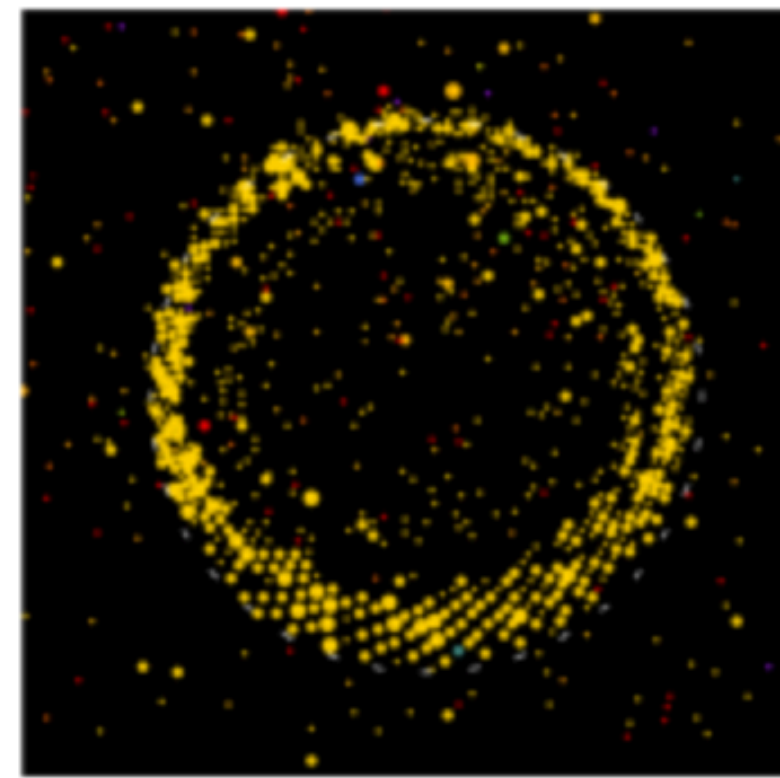


Neutral Current (NC)
interactions mediated
by Z boson is
indistinguishable for
the the 3 flavors

NOvA

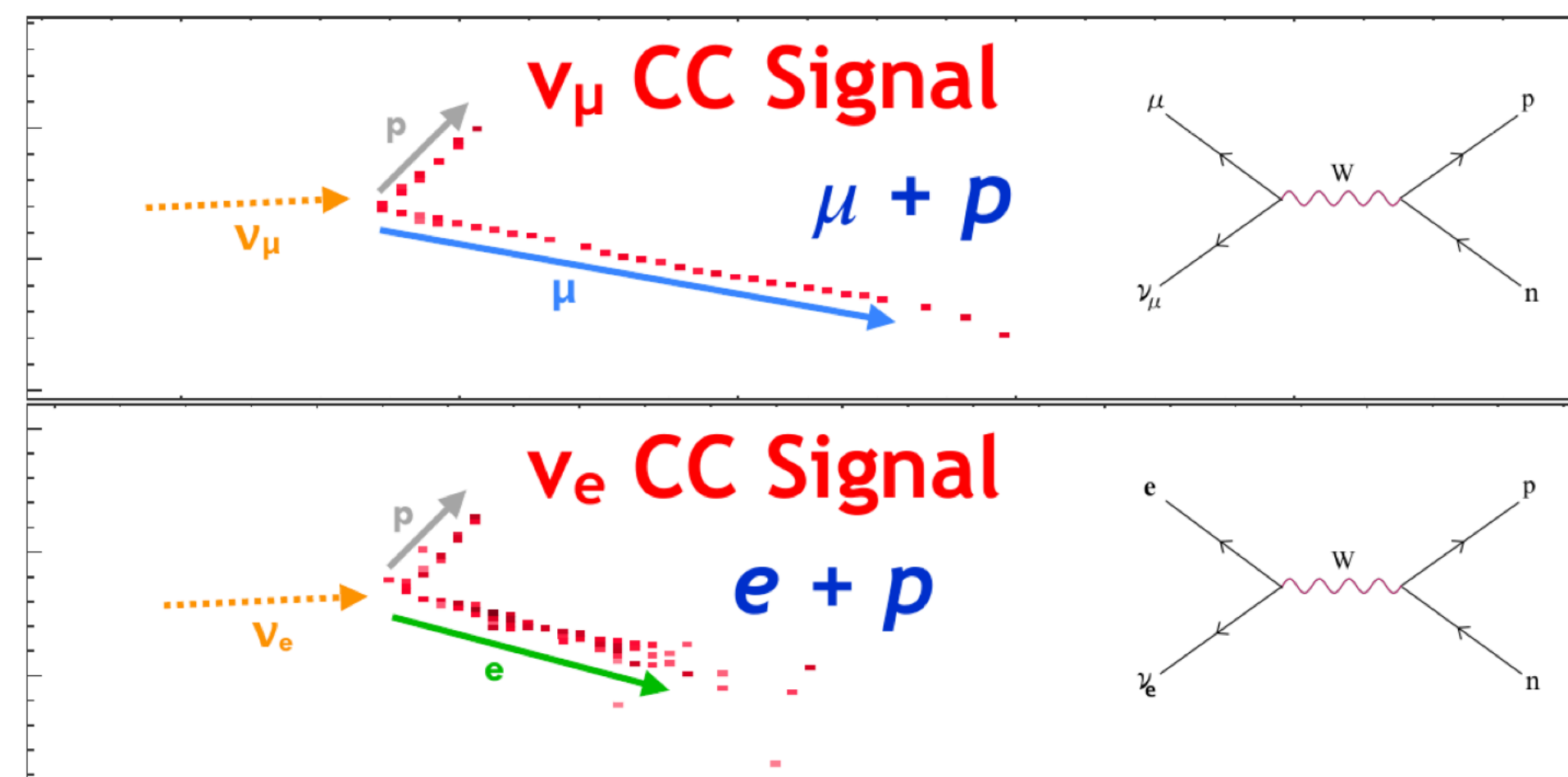


ν_e -like



ν_μ -like

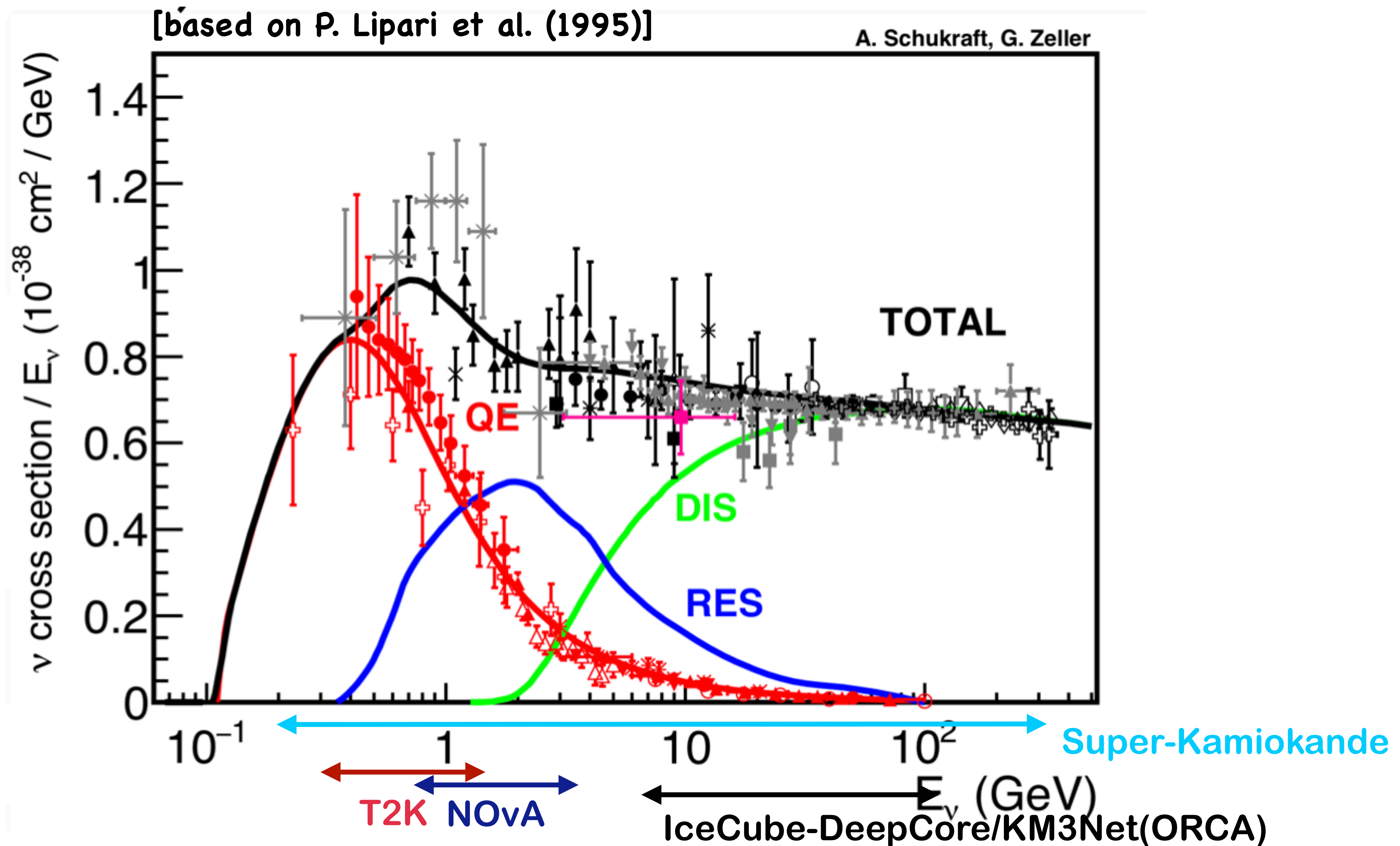
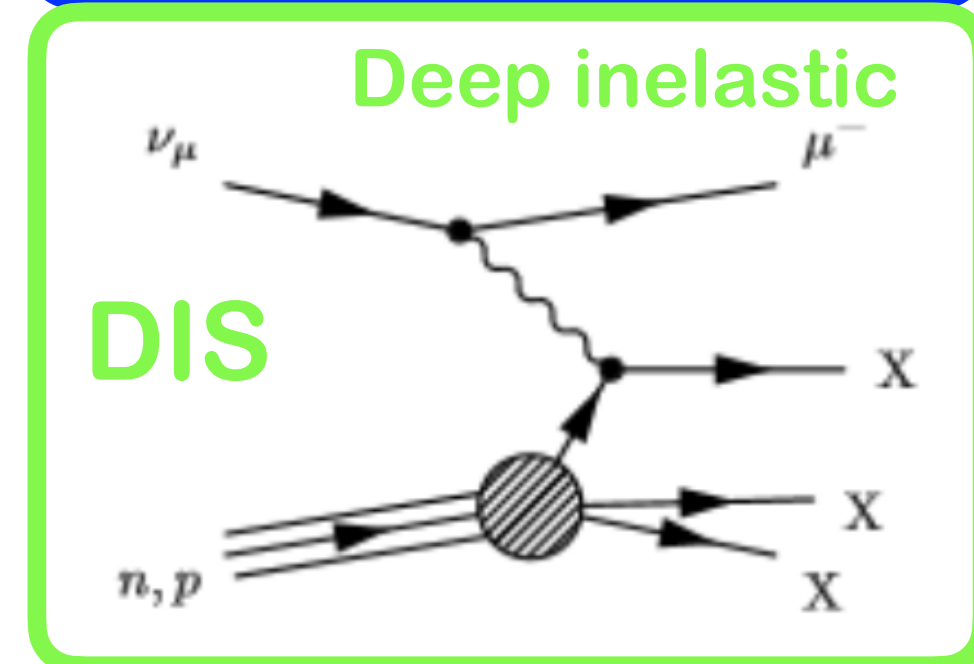
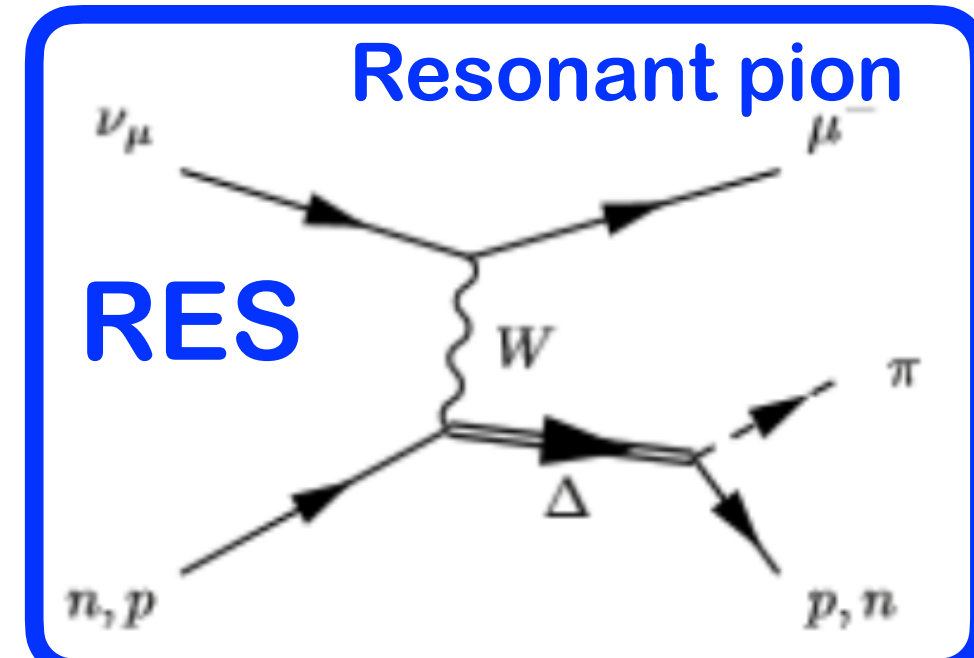
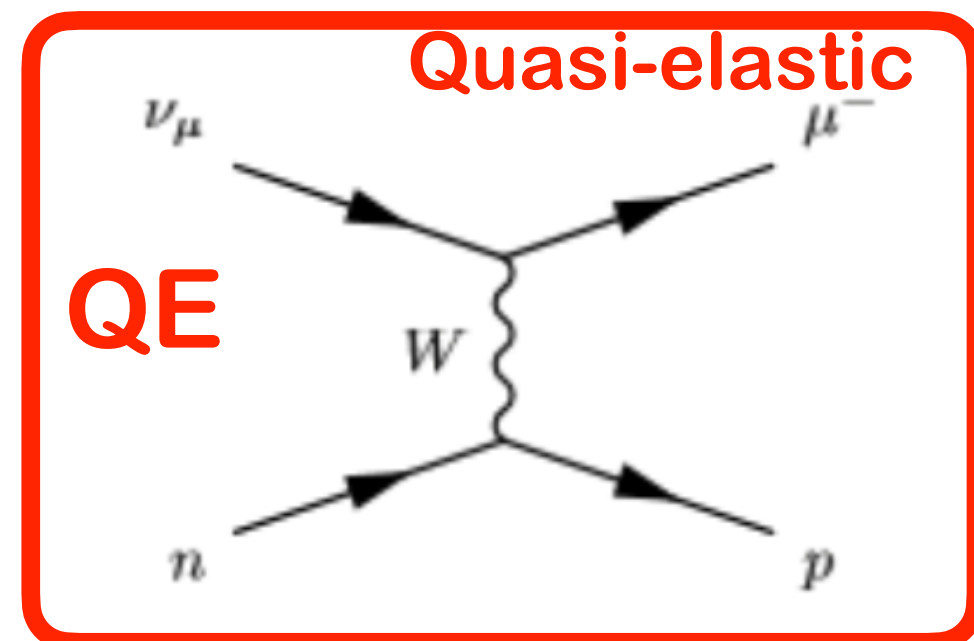
T2K/Super-Kamiokande



Accelerator (& Atmospheric) Neutrinos

x-sections

CC-interaction



Accelerator Neutrinos

Results from NOvA

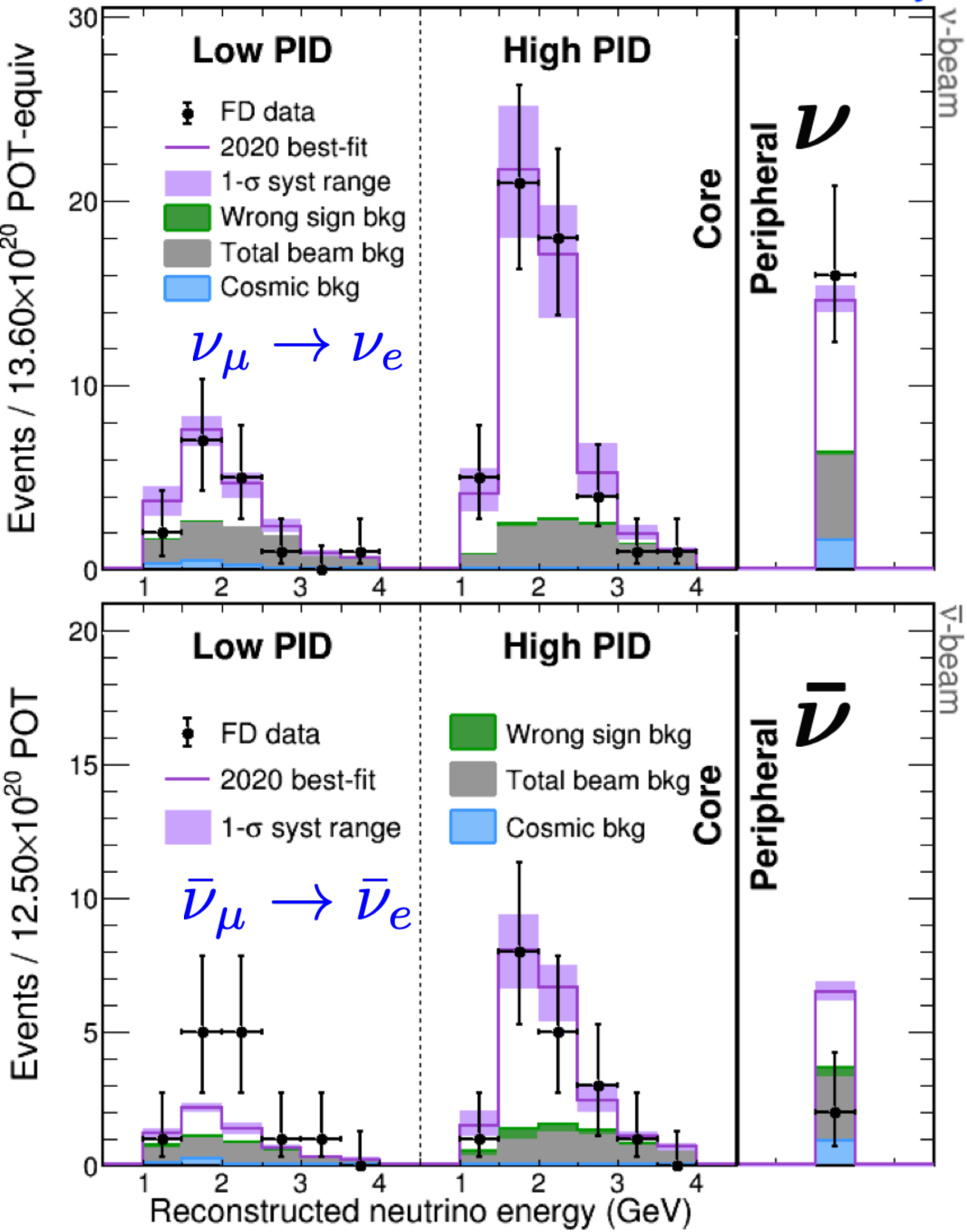
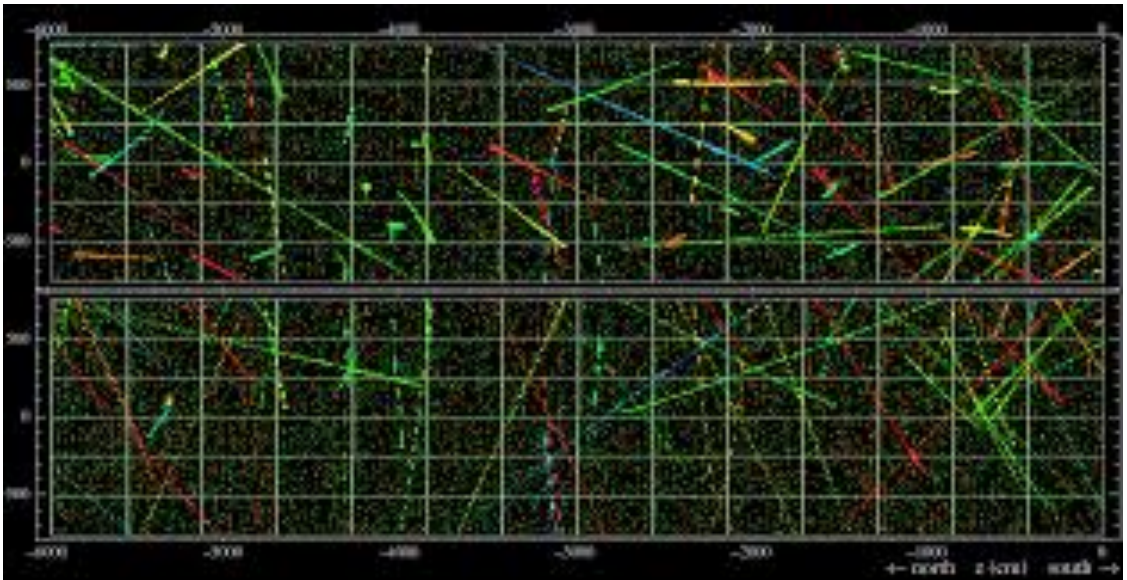
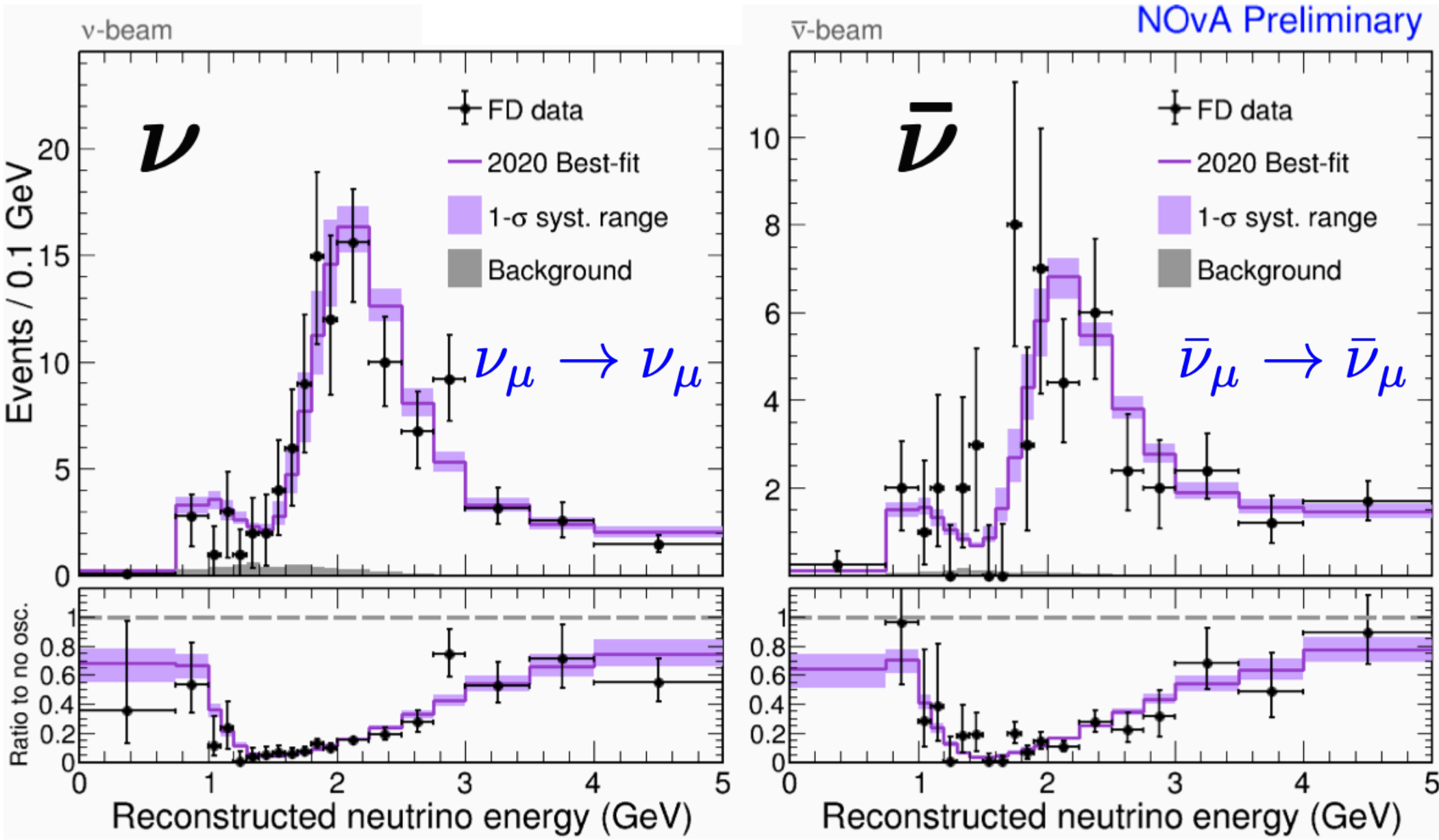
211 ν_μ CC candidates observed			
$\nu_\mu \rightarrow \nu_\mu$ 201.1		$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ 12.6	
NC	cosmic	other	total
2.6	5.0	1.0	$222.3^{+16.3}_{-15.7}$

105 $\bar{\nu}_\mu$ CC candidates observed			
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ 77.2		$\nu_\mu \rightarrow \nu_\mu$ 26.0	
NC	cosmic	other	total
0.8	0.9	0.4	$105.4^{+7.8}_{-7.7}$

82 ν_e CC candidates observed					
Signal $\nu_\mu \rightarrow \nu_e$					59.0
$\bar{\nu}_e$	beam ν_e	ν_μ	NC	cos.	other
1.0	14.1	1.7	6.3	3.1	0.5
total					$85.8^{+4.1}_{-4.2}$ (background 26.8)

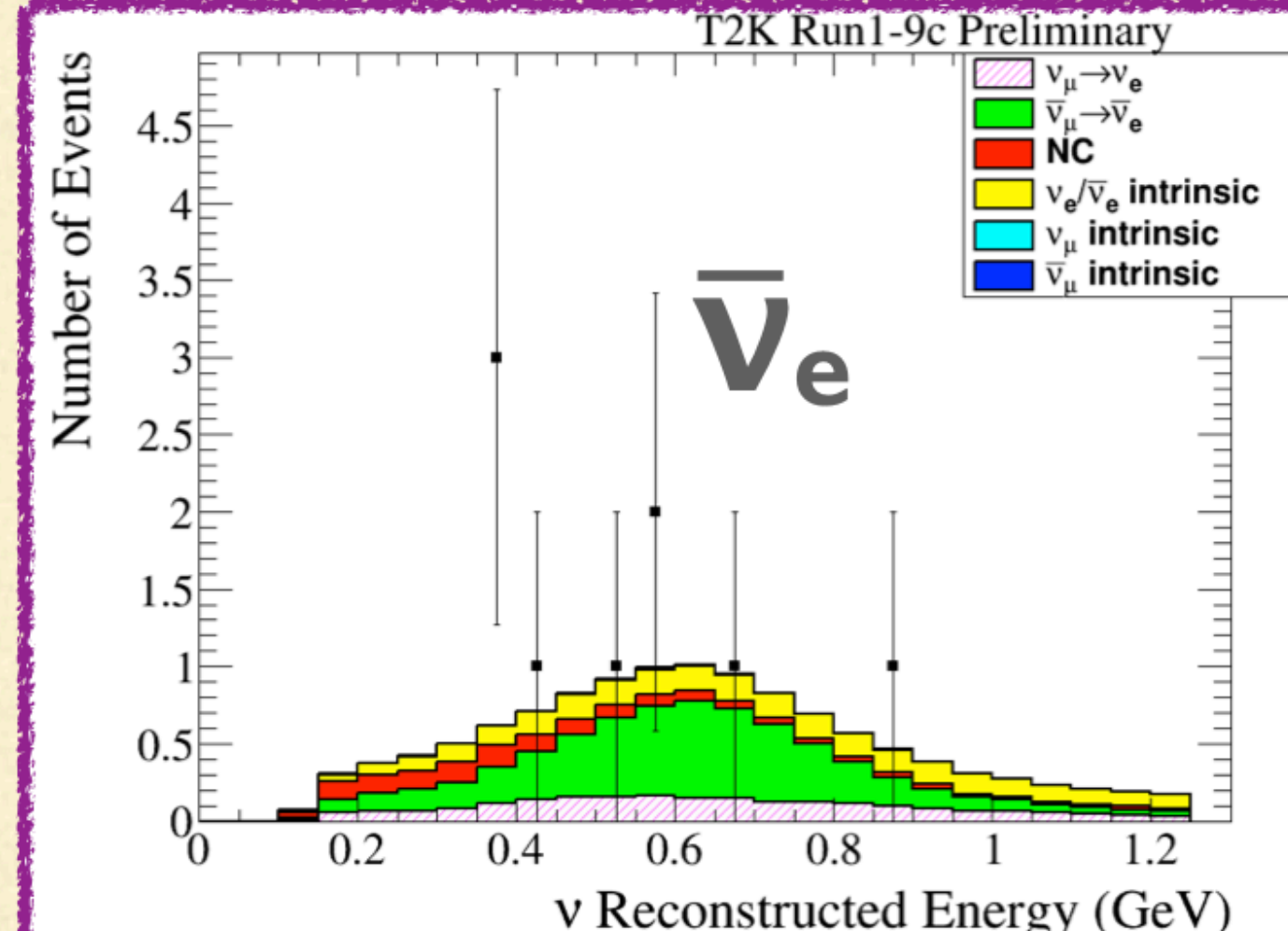
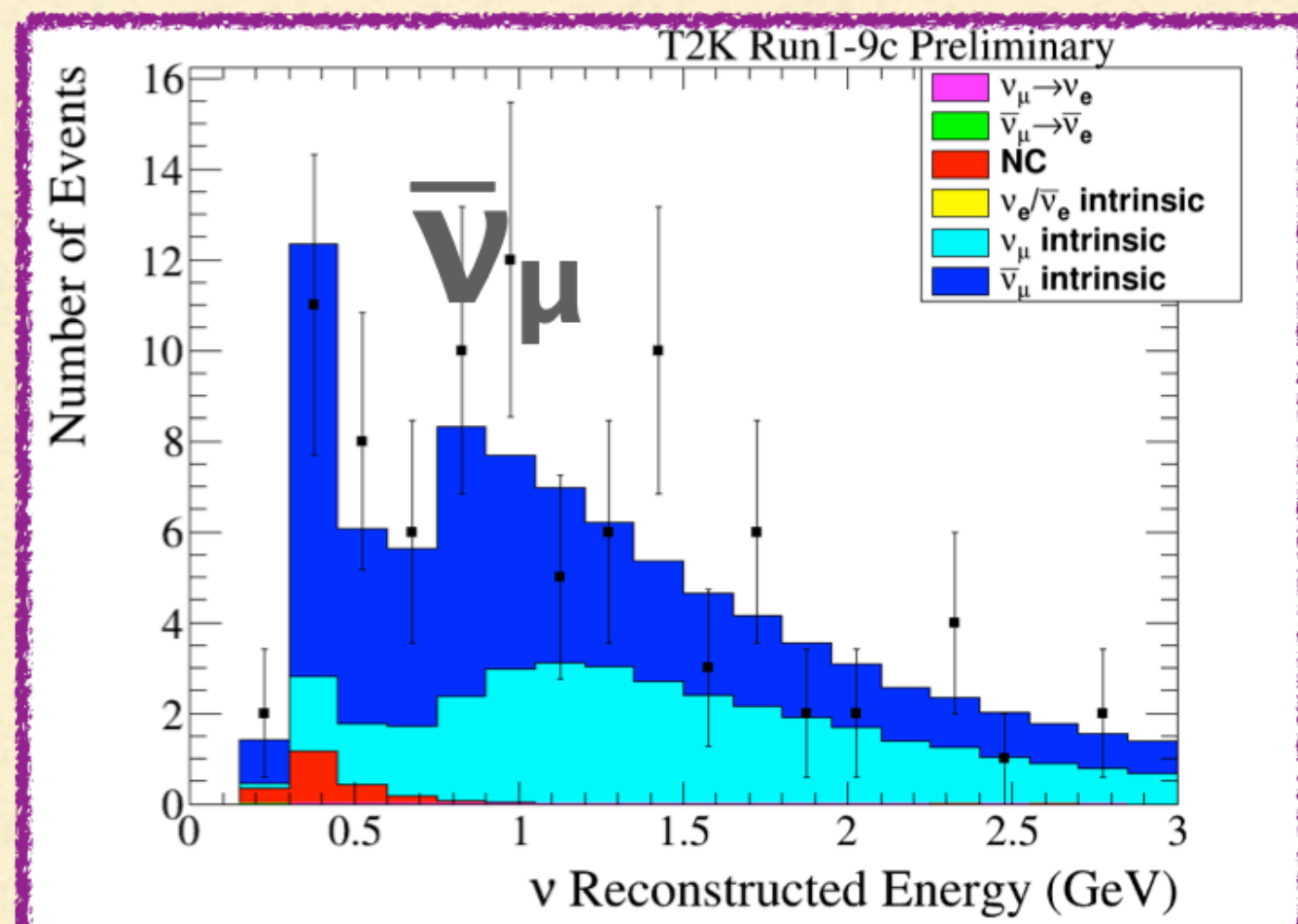
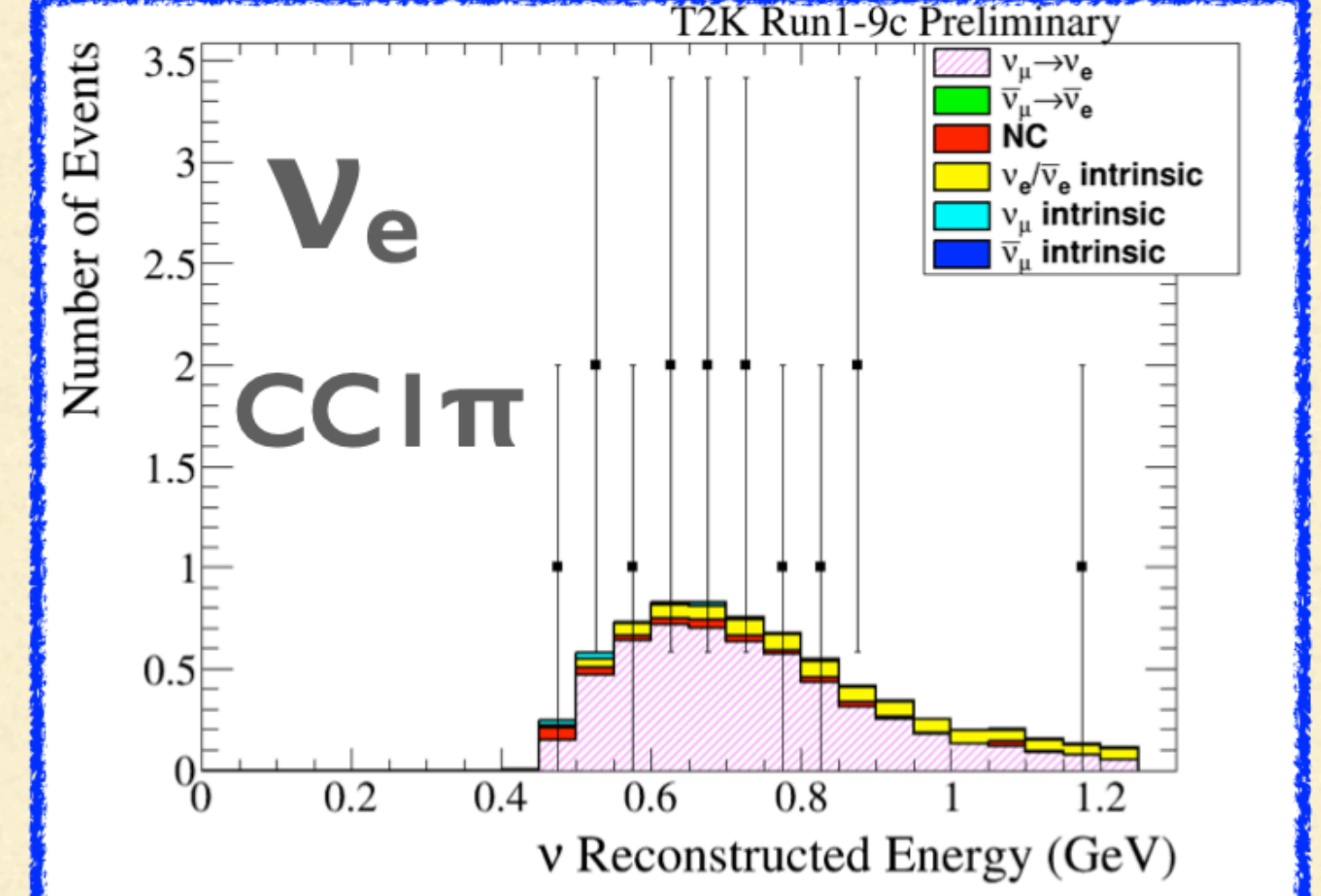
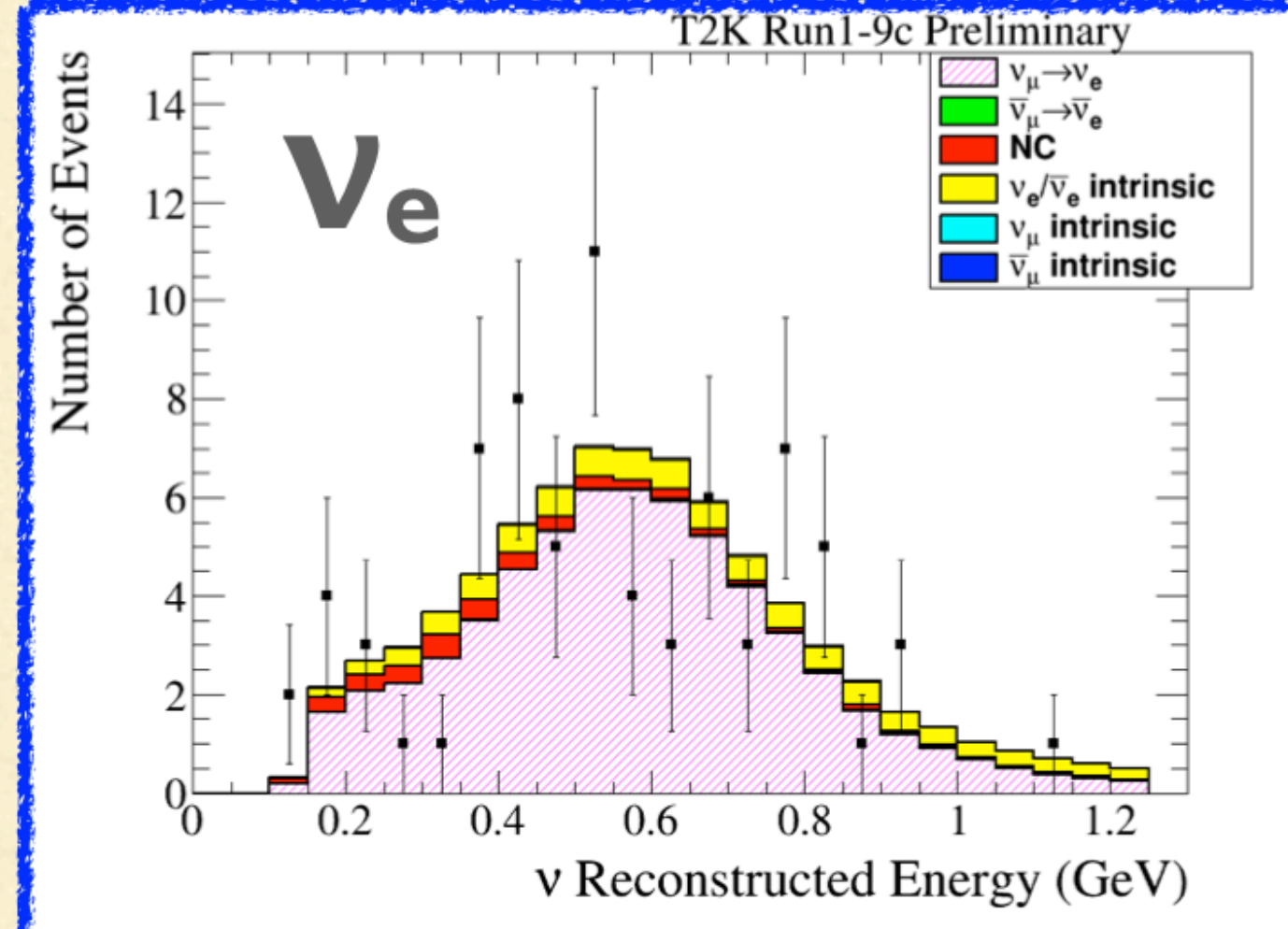
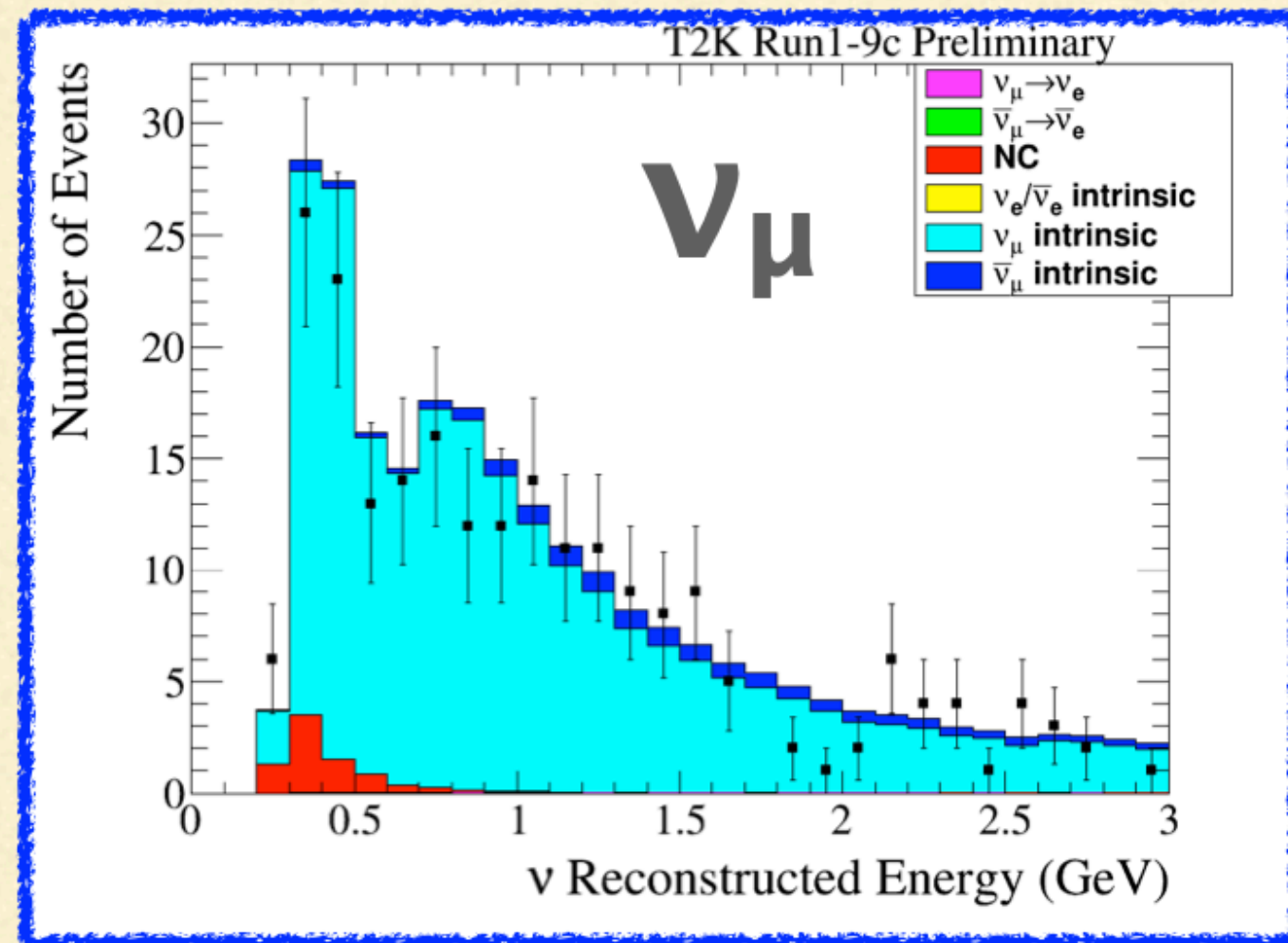
33 $\bar{\nu}_e$ CC candidates observed					
Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$					19.2
ν_e	beam ν_e	ν_μ	NC	cos.	other
2.3	7.3	0.4	2.2	1.6	0.3
total					$33.2^{+1.5}_{-1.7}$ (background 14.0)

[Taken from NOvA Collab. (2022)]



Accelerator Neutrinos

Results from T2K



[Taken from T2K Collab. (2020)]

Energy distribution

ν -mode

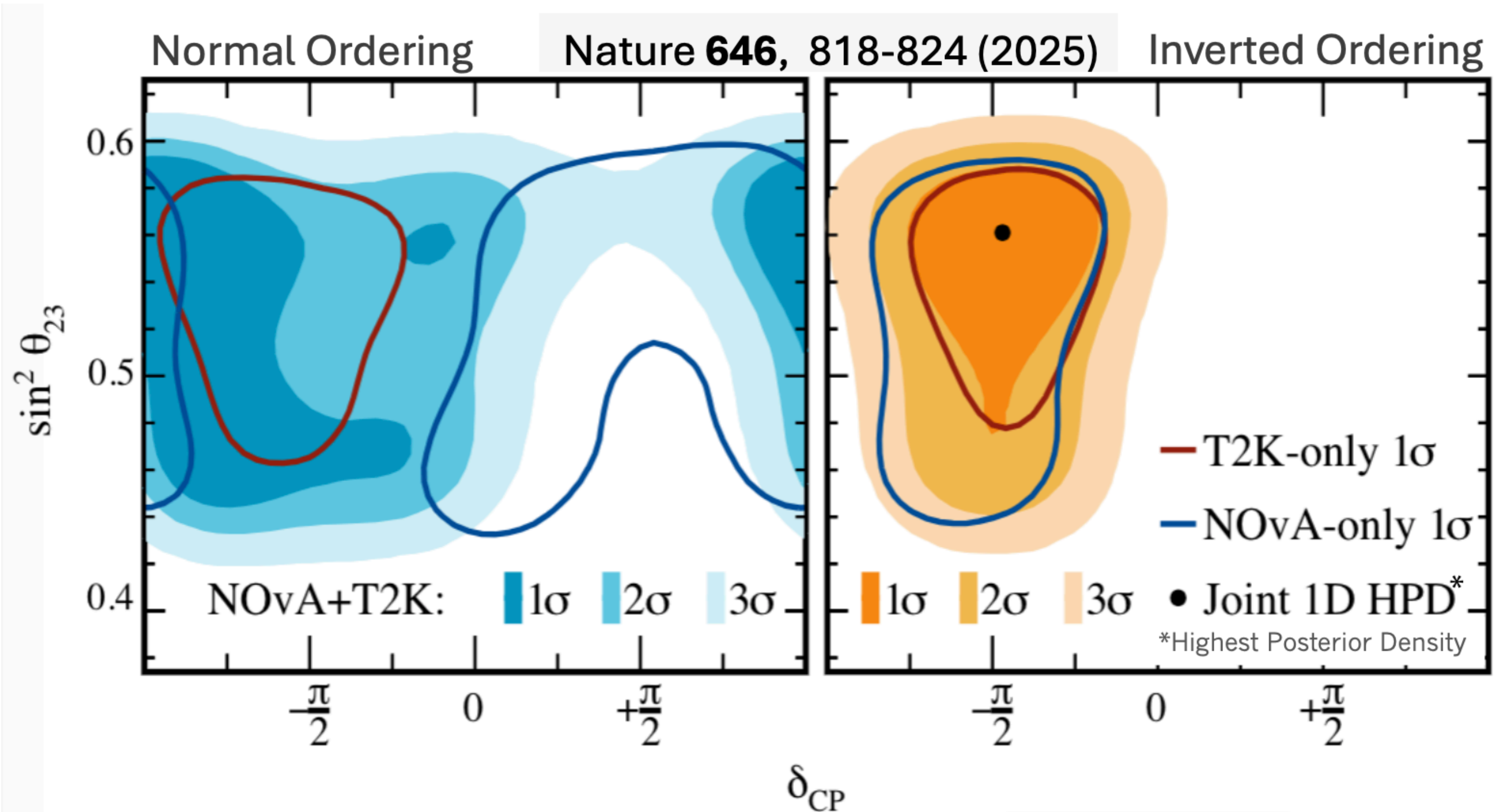
anti- ν -mode

* T2K Preliminary



Accelerator Neutrinos

Appearance Results



Reactor Neutrinos

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{matrix} \Delta m_{21}^2 \\ \Delta m_{ee}^2 \end{matrix}$$

Reactor Neutrinos

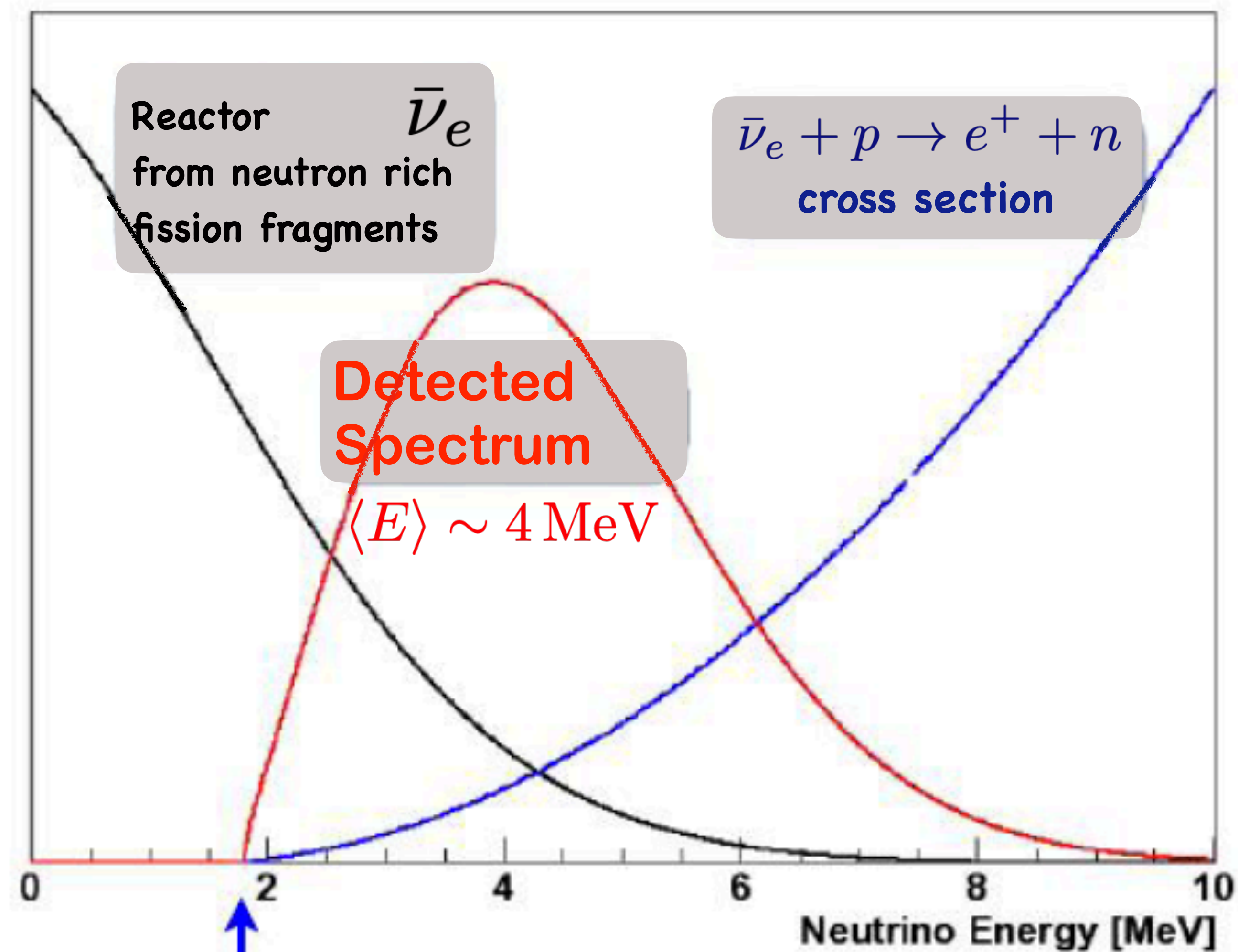
Disappearance of antineutrinos

commercial reactors fuel

$^{235}\text{U}(\sim 50 - 60\%), ^{239}\text{Pu}(\sim 25 - 35\%), ^{238}\text{U}(\lesssim 8\%), ^{241}\text{Pu}(\lesssim 6\%)$

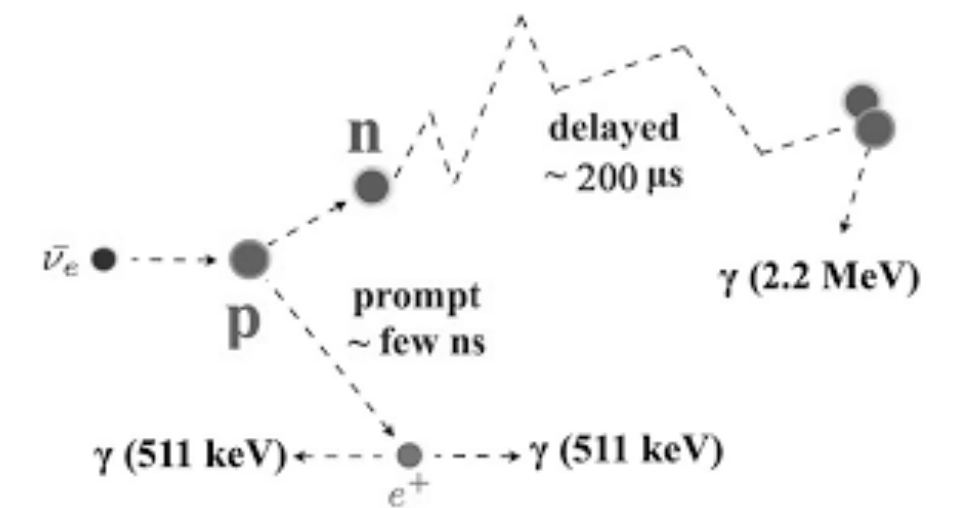
Neutrino Flux from commercial nuclear reactors

$$2 \times 10^{20} \quad \bar{\nu}_e / \text{GW}_{\text{th}}$$



1.8MeV threshold in Inverse Beta Decay

Liquid Scintillator Detectors



Reactor Neutrino Oscillations

Disappearance of antineutrinos

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \Phi_{\odot}) \right] - P_{\odot}$$

[H. Minakata, H. Nunokawa, S. J. Parke, RZF (2007)]

in vacuum

$$P_{\odot} = \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21}$$

solar term

effective atmospheric Δm_{atm}^2 for reactor experiments

$$\Delta_{ee} \equiv \frac{\Delta m_{ee}^2 L}{4E}$$

$$\Delta m_{ee}^2 \equiv \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$$

+NO | -IO

retardation/advancement of the phase

$$\Phi_{\odot} = \arctan(\cos 2\theta_{12} \tan \Delta_{21}) - \Delta_{21} \cos 2\theta_{12}$$

Very useful for JUNO

Reactor Neutrino Oscillations

Disappearance of antineutrinos

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \Phi_{\odot}) \right] - P_{\odot}$$

in vacuum

since we know

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

$$L_{\odot}^{ee} \sim 3 \text{ km}$$

$$\Delta m_{21}^2 \sim 7 \times 10^{-5} \text{ eV}^2$$

$$L_{\odot}^{12} \sim 140 \text{ km}$$

$$\langle E \rangle \sim 4 \text{ MeV}$$

Reactor Neutrino Oscillations

Disappearance of antineutrinos

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$$L_{\odot}^{12} \sim 140 \text{ km}$$

averaged out

$$\langle E \rangle \sim 4 \text{ MeV}$$

in vacuum

KamLAND has a baseline about 180 km

SNO+ has a baseline > 240 km

$$L \approx L_{\odot}^{12} \gg L_{\odot}^{ee}$$

Reactor Neutrino Oscillations

Disappearance of antineutrinos

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \Phi_{\odot}) \right] - P_{\odot}$$

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averaged out

$$\langle E \rangle \sim 4 \text{ MeV}$$

in vacuum

KamLAND has a baseline about 180 km

SNO+ has a baseline > 240 km

$$L \approx L_{\odot}^{12} \gg L_{\odot}^{ee}$$

the formula reduces to

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = s_{13}^4 + c_{13}^4 P_{2\nu}(\bar{\nu}_e \rightarrow \bar{\nu}_e)$$

$$P_{2\nu}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

Reactor Neutrino Oscillations

Disappearance of antineutrinos

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \Phi_{\odot}) \right] - P_{\odot}$$

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$$L_{\odot}^{12} \sim 140 \text{ km}$$

$$\langle E \rangle \sim 4 \text{ MeV}$$

in vacuum

Daya Bay/Reno/Double Chooz have a baseline of 1 km

$$L \approx L_{\odot}^{ee} \ll L_{\odot}^{12}$$

Reactor Neutrino Oscillations

Disappearance of antineutrinos

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

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$$L_{\odot}^{12} \sim 140 \text{ km}$$

$$\langle E \rangle \sim 4 \text{ MeV}$$

$$\Delta m_{ee}^2 \equiv \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2$$

Daya Bay/Reno/Double Chooz have a baseline of 1 km

effective atmospheric scale for ν_e disappearance

$$L \approx L_{\odot}^{ee} \ll L_{\odot}^{12}$$

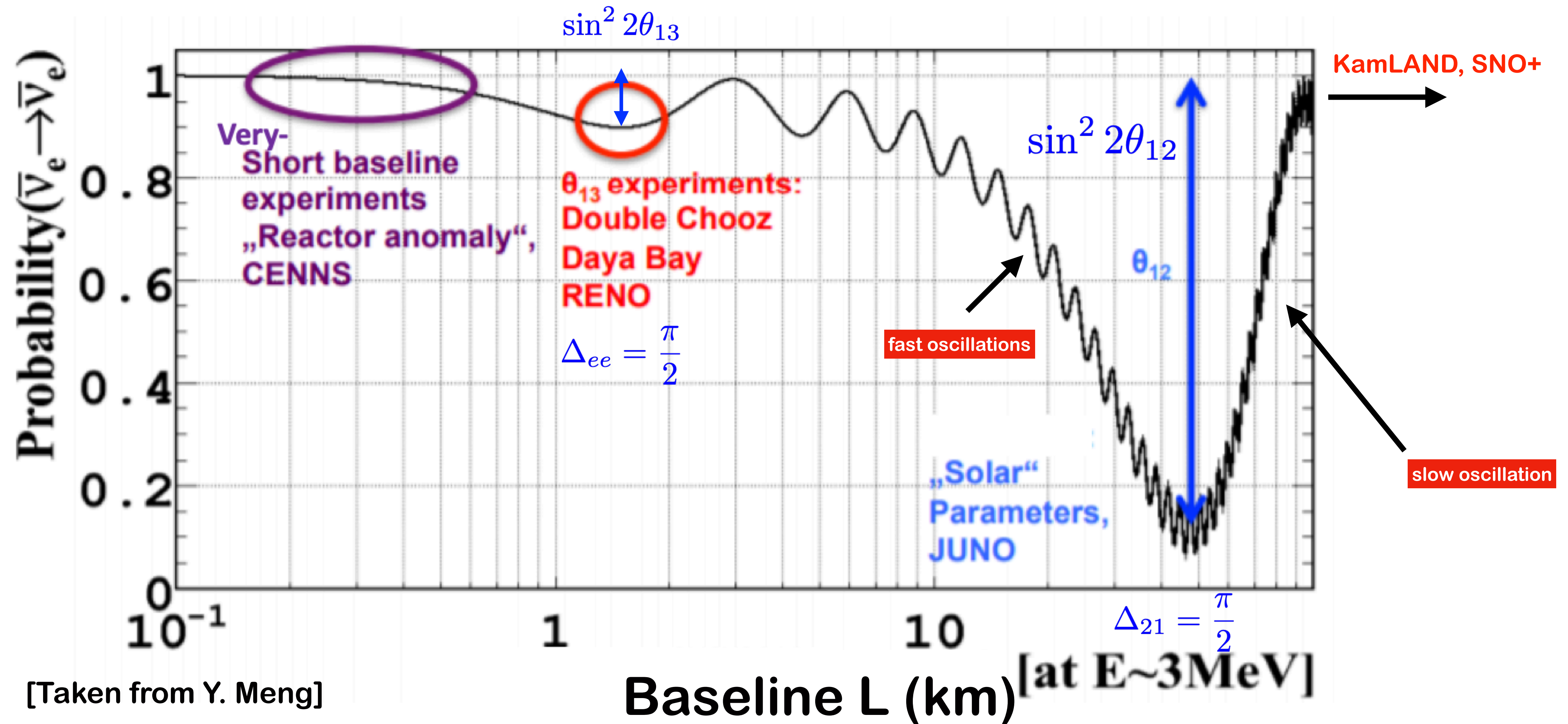
the formula reduces to

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

+ matter effects are negligible

Reactor Neutrino Oscillations

Disappearance of antineutrinos

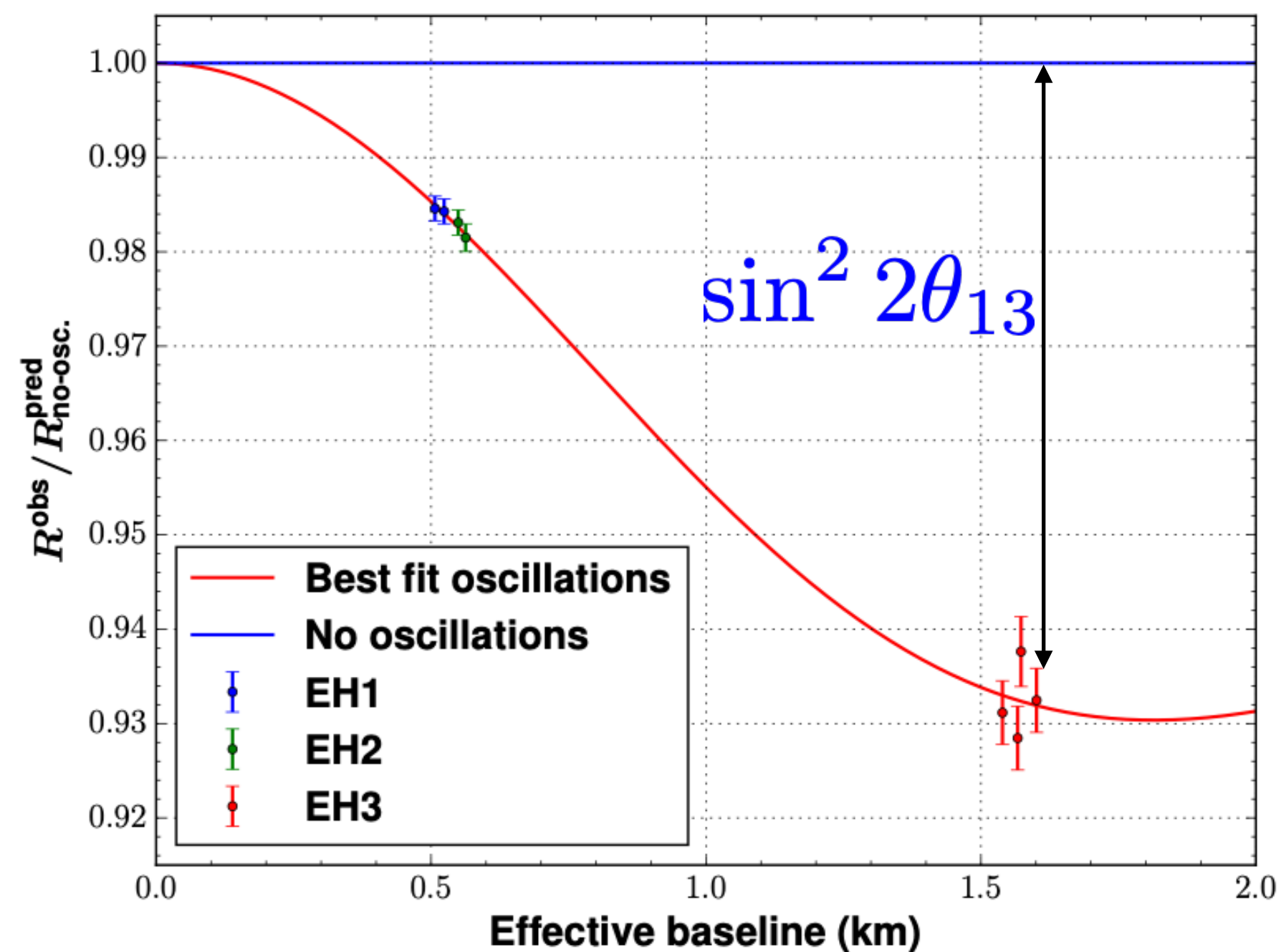


Reactor Neutrinos

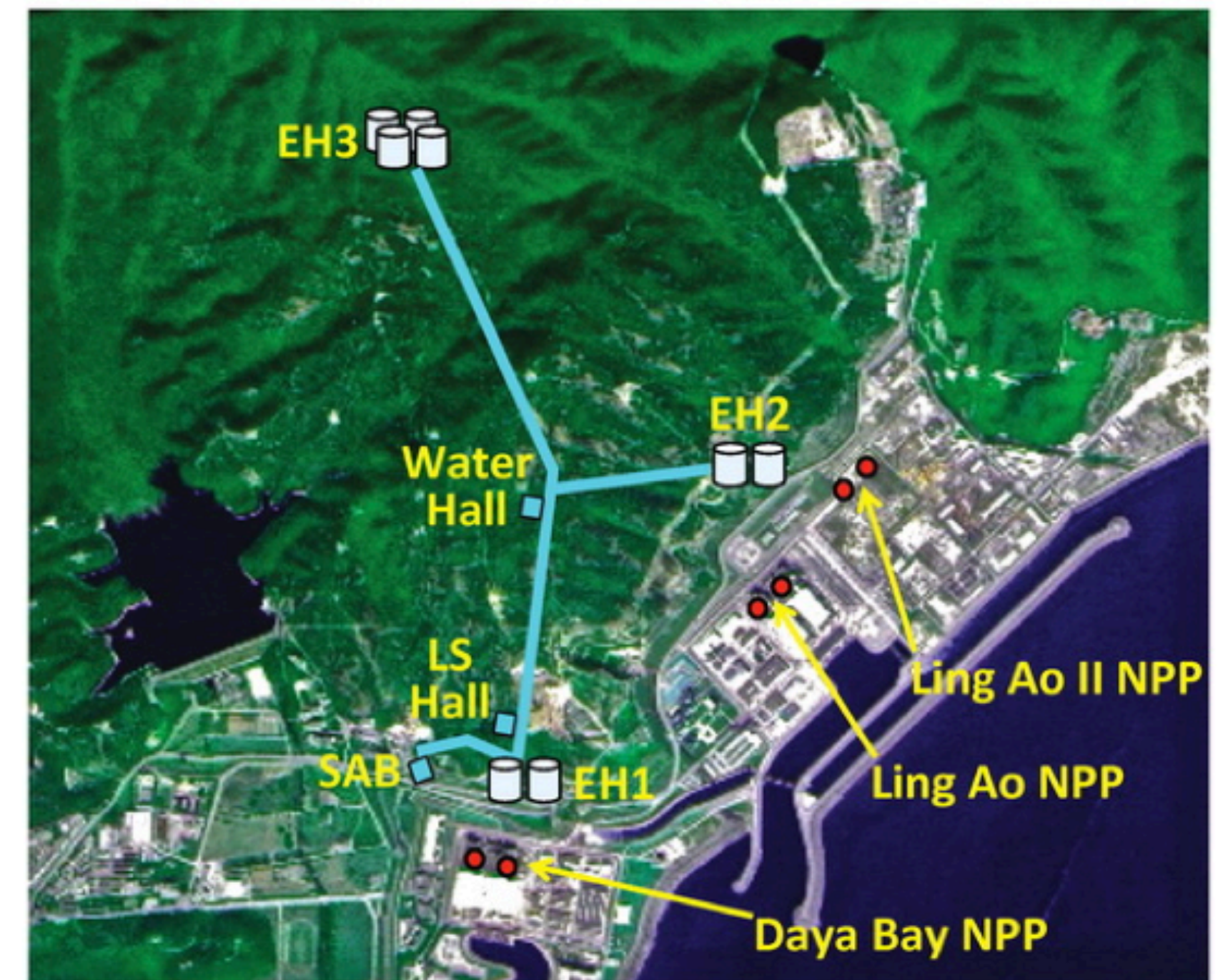
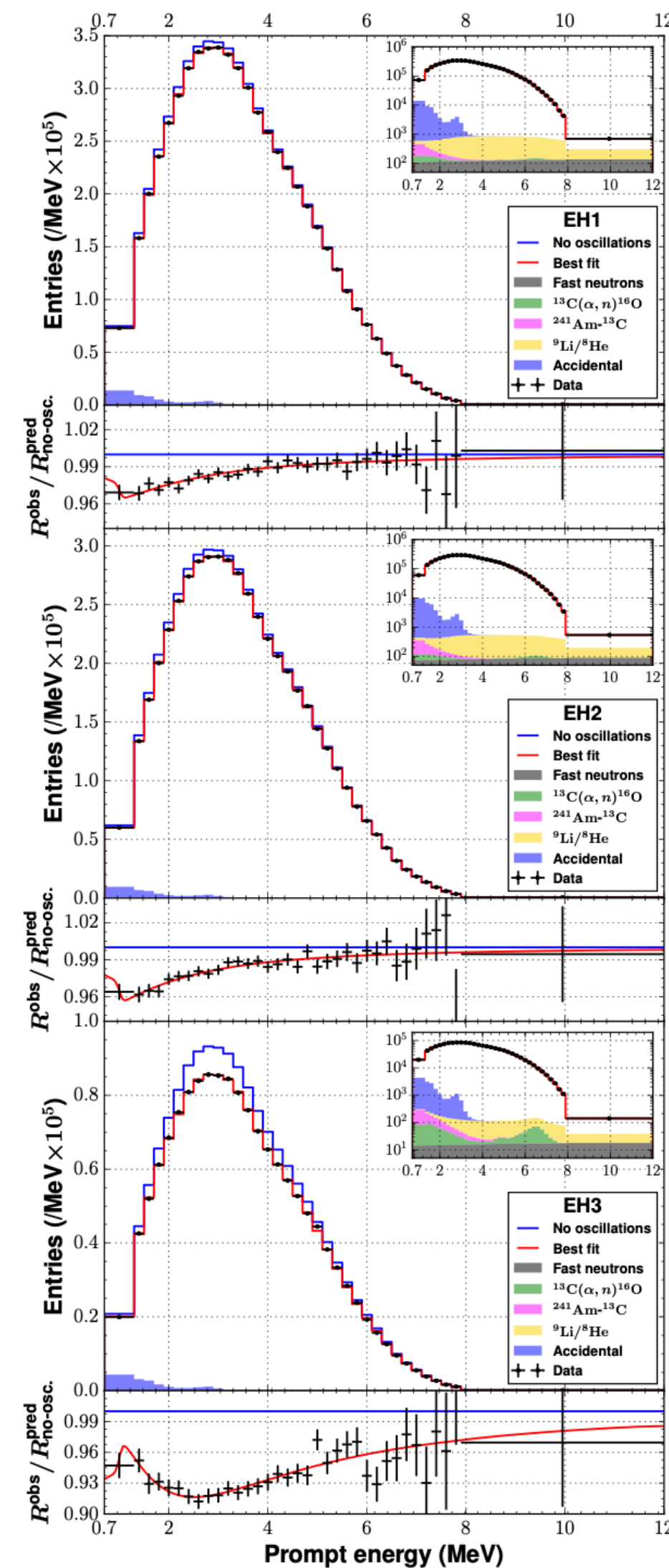
Results from Daya Bay

Dominates the
measurement of $\sin^2 \theta_{13}$

2.5%



[Taken from Daya Bay Collab. (2017)]



Reactor Neutrinos

JUNO's Concept

$$\Delta_{21} \equiv \frac{\Delta m_{21}^2 L}{4E} \sim \frac{\pi}{2}$$

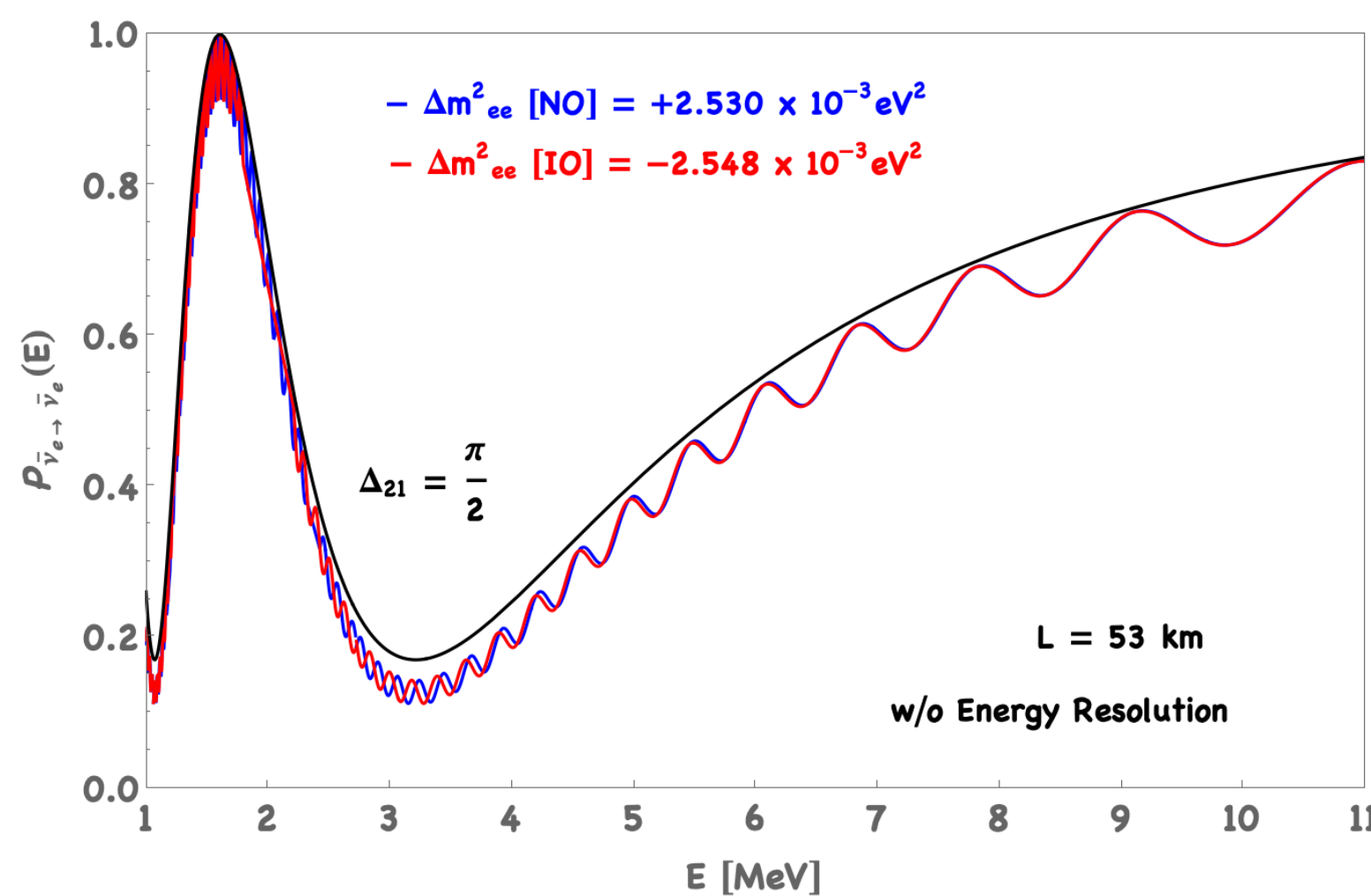
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \Phi_{\odot}) \right] - P_{\odot}$$

[H. Minakata, H. Nunokawa, S. J. Parke, RZF (2007)]

in vacuum

$$P_{\odot} = \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21}$$

$$\Phi_{\odot} = \arctan(\cos 2\theta_{12} \tan \Delta_{21}) - \Delta_{21} \cos 2\theta_{12}$$

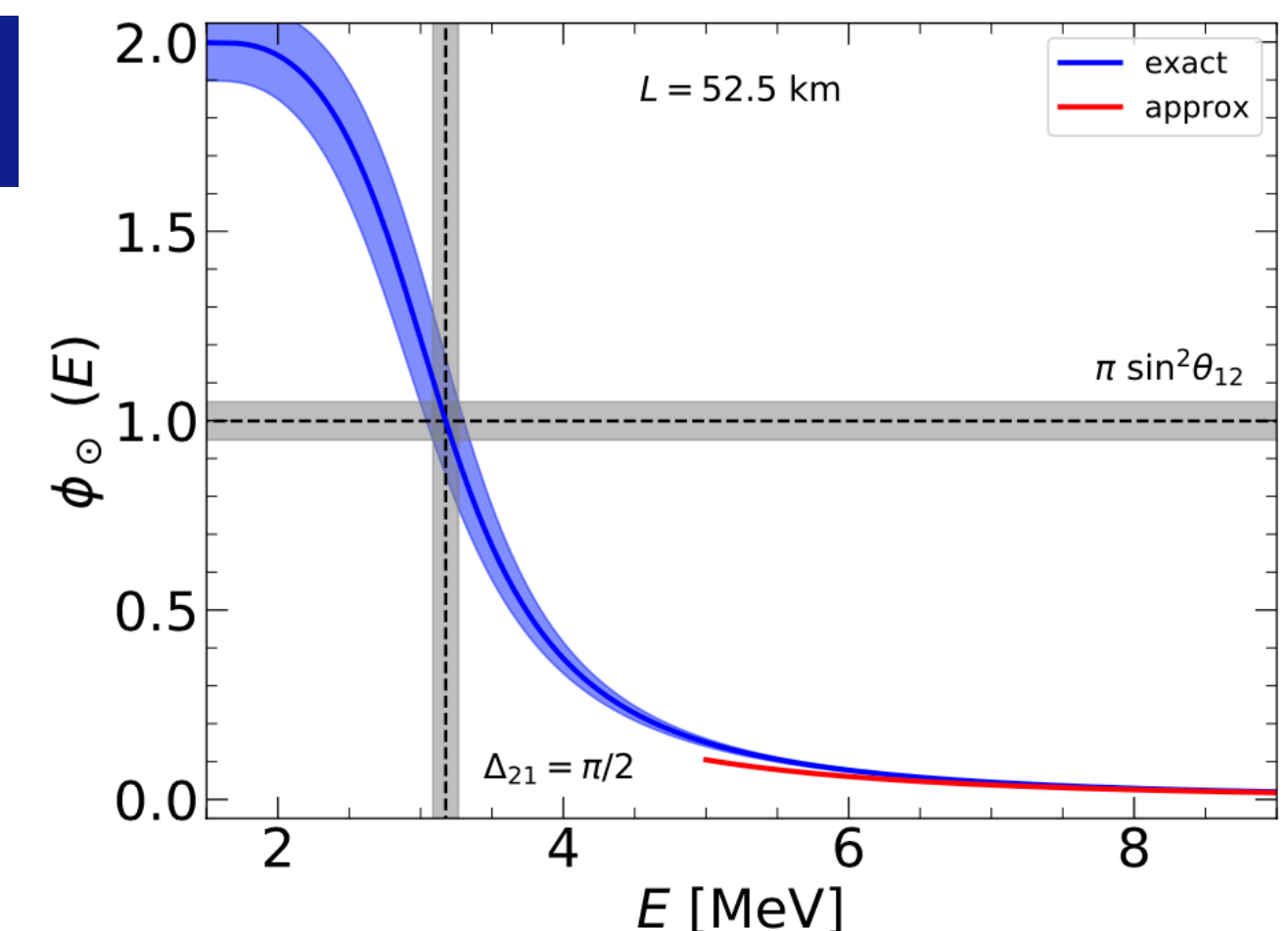


retardation/advancement of the phase result in a change of the "effective fast oscillation scale"

$$|\Delta m_{ee}^2|_{\text{IO}} > |\Delta m_{ee}^2|_{\text{NO}}$$

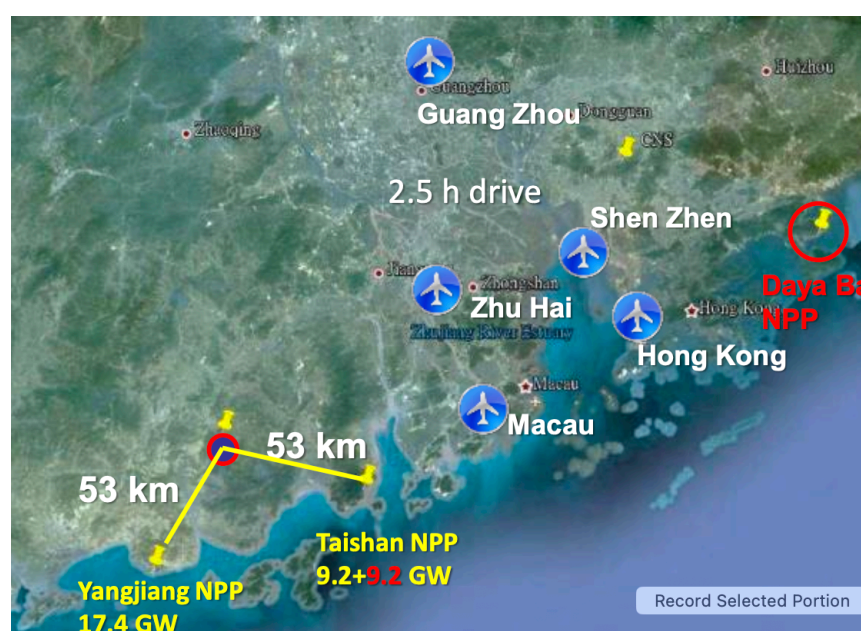
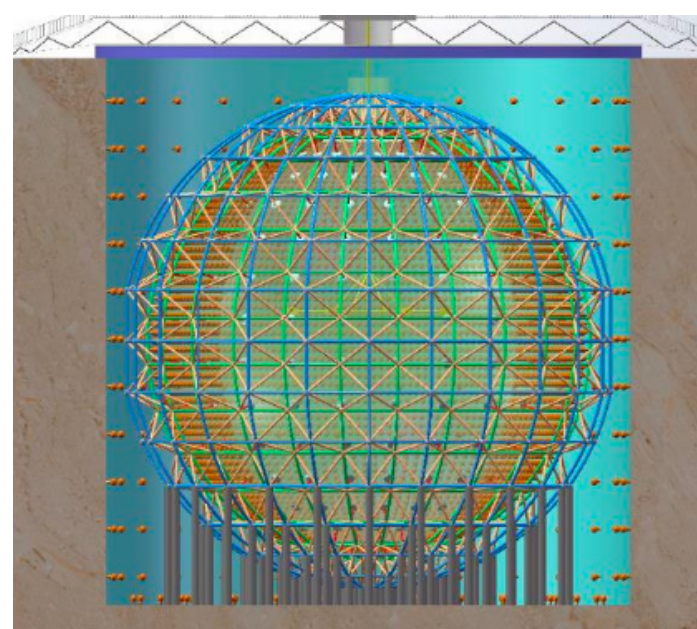
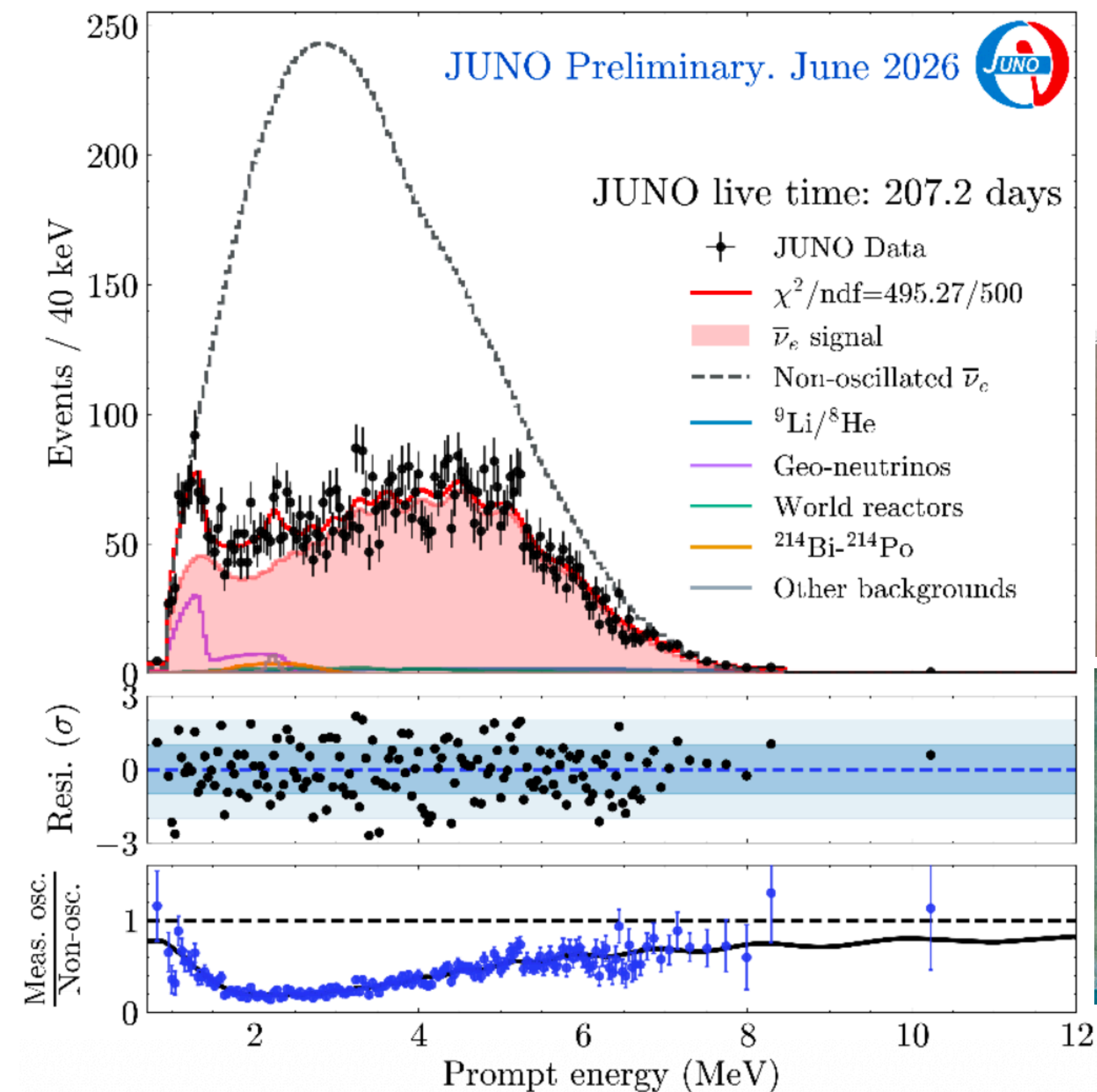
sub-% precision

$$\Delta m_{21}^2, \sin^2 \theta_{12}, |\Delta m_{31}^2| \text{ or } |\Delta m_{32}^2|$$

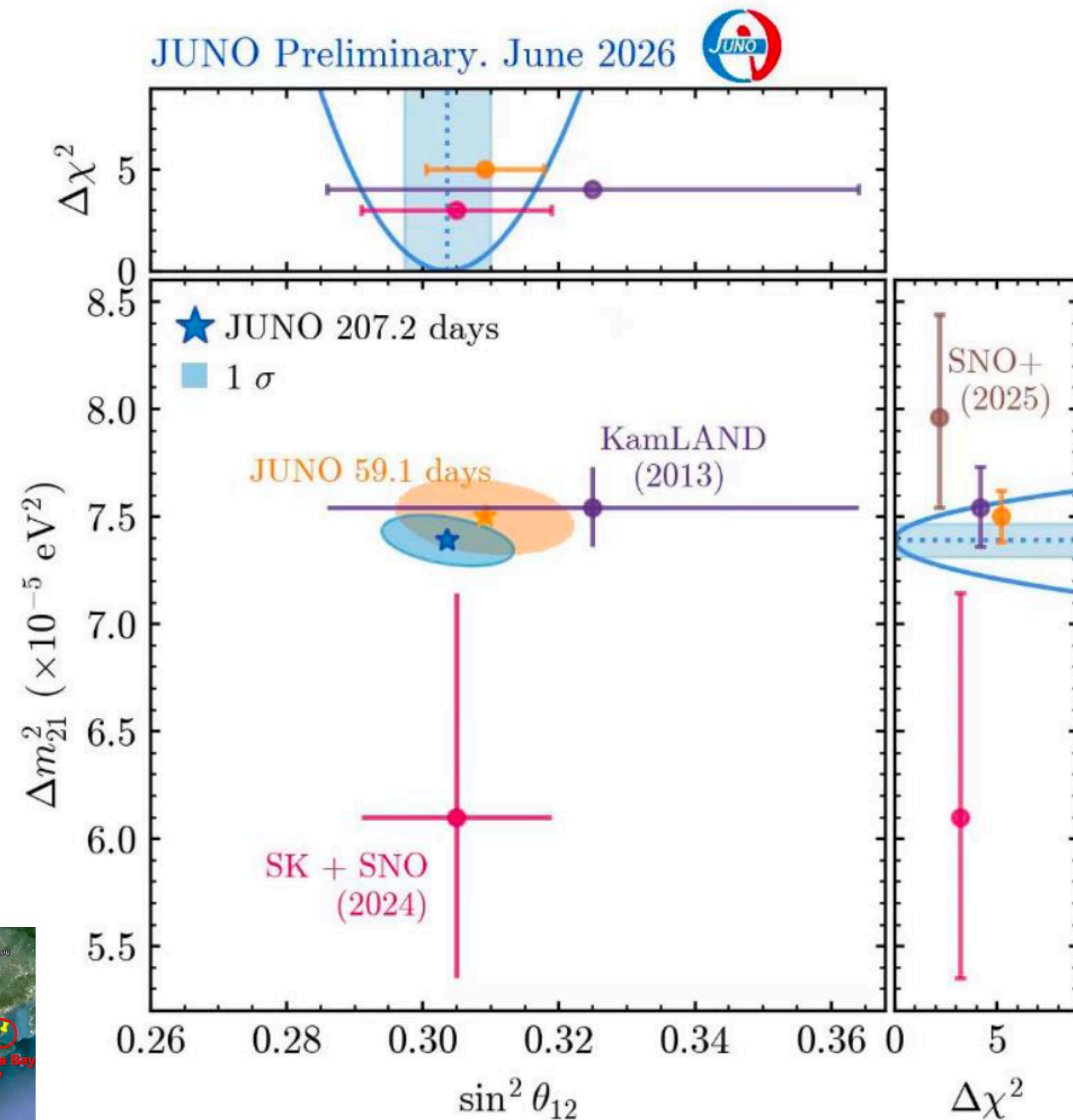


Reactor Neutrinos

Results from JUNO



[Neutrino 2026]

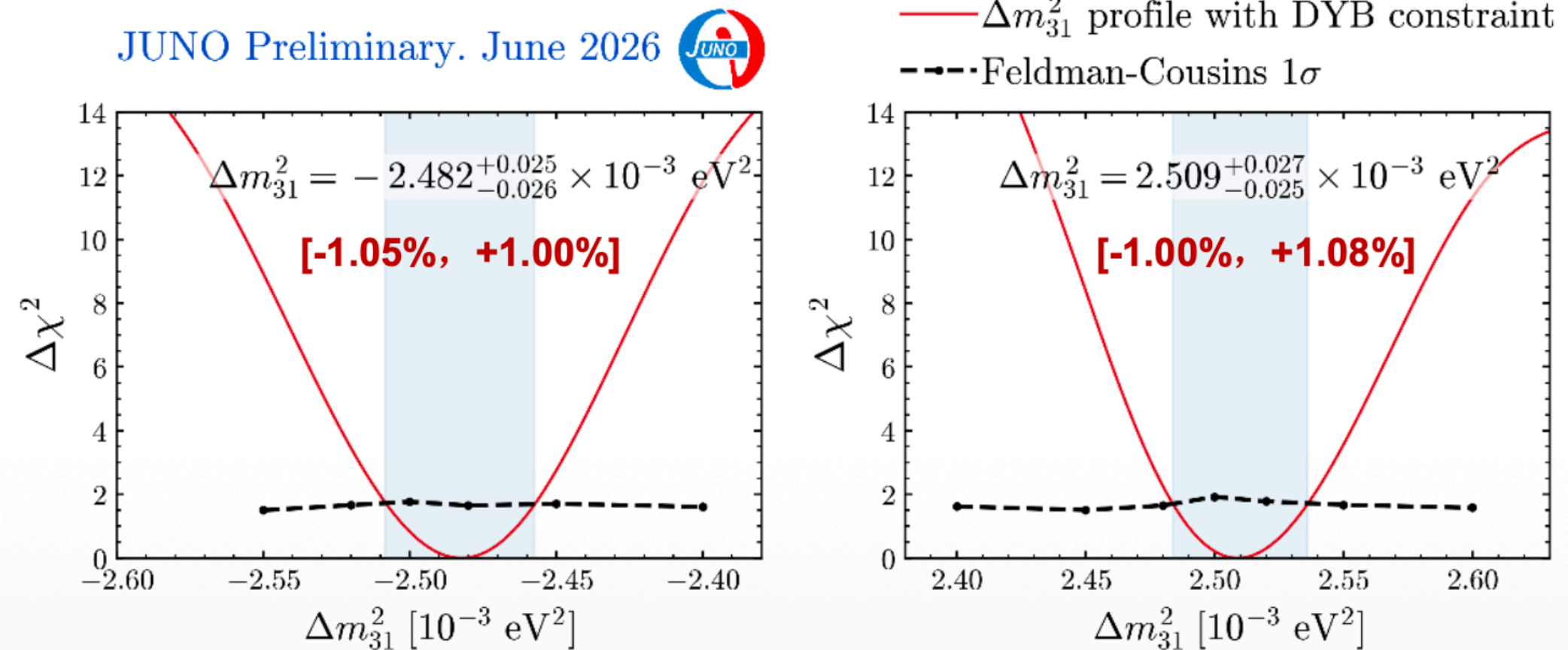
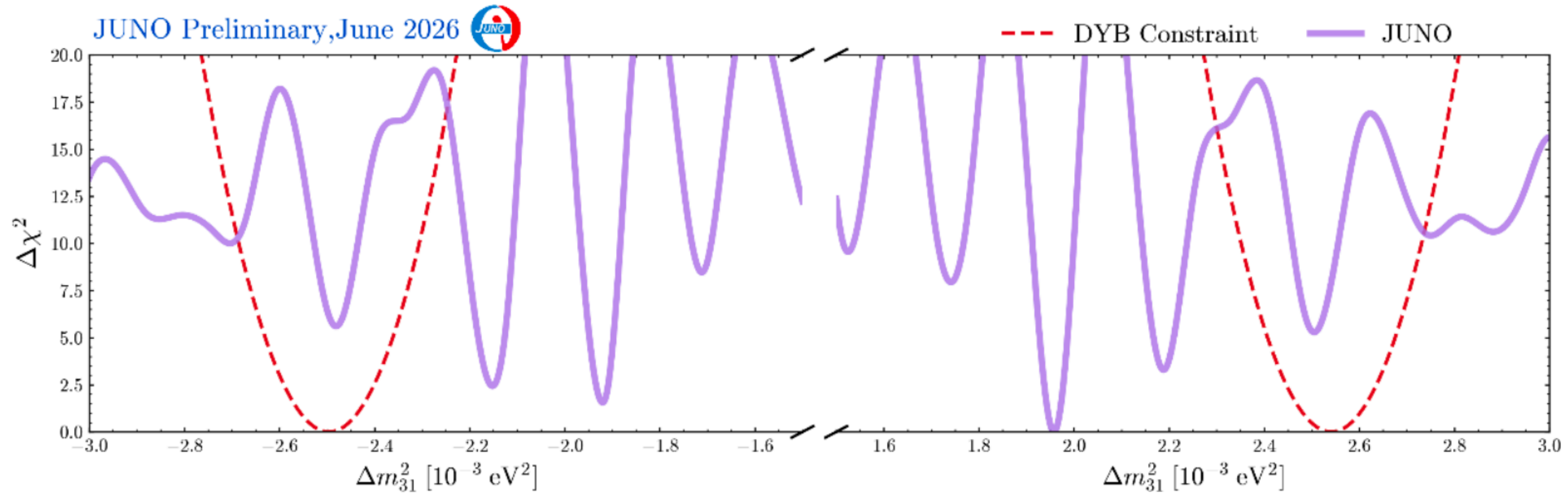


Δm_{21}^2	7.388 ± 0.078 (1.60% $\rightarrow$ 1.06%)
$\sin^2 \theta_{12}$	0.3036 ± 0.0064 (2.8% $\rightarrow$ 2.1%)

Reactor Neutrinos

Results from JUNO

[Neutrino 2026]

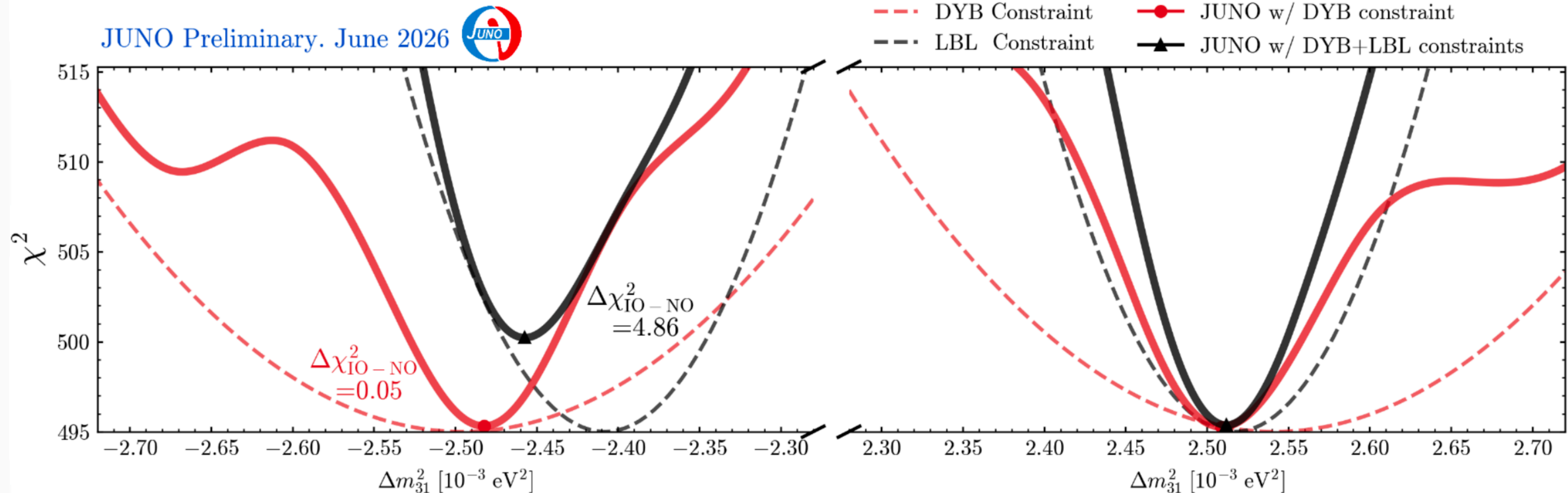


Reactor Neutrinos

Results from JUNO

[Neutrino 2026]

- Normal Ordering is favored at 2.3σ



[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)

[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Reactor Neutrinos

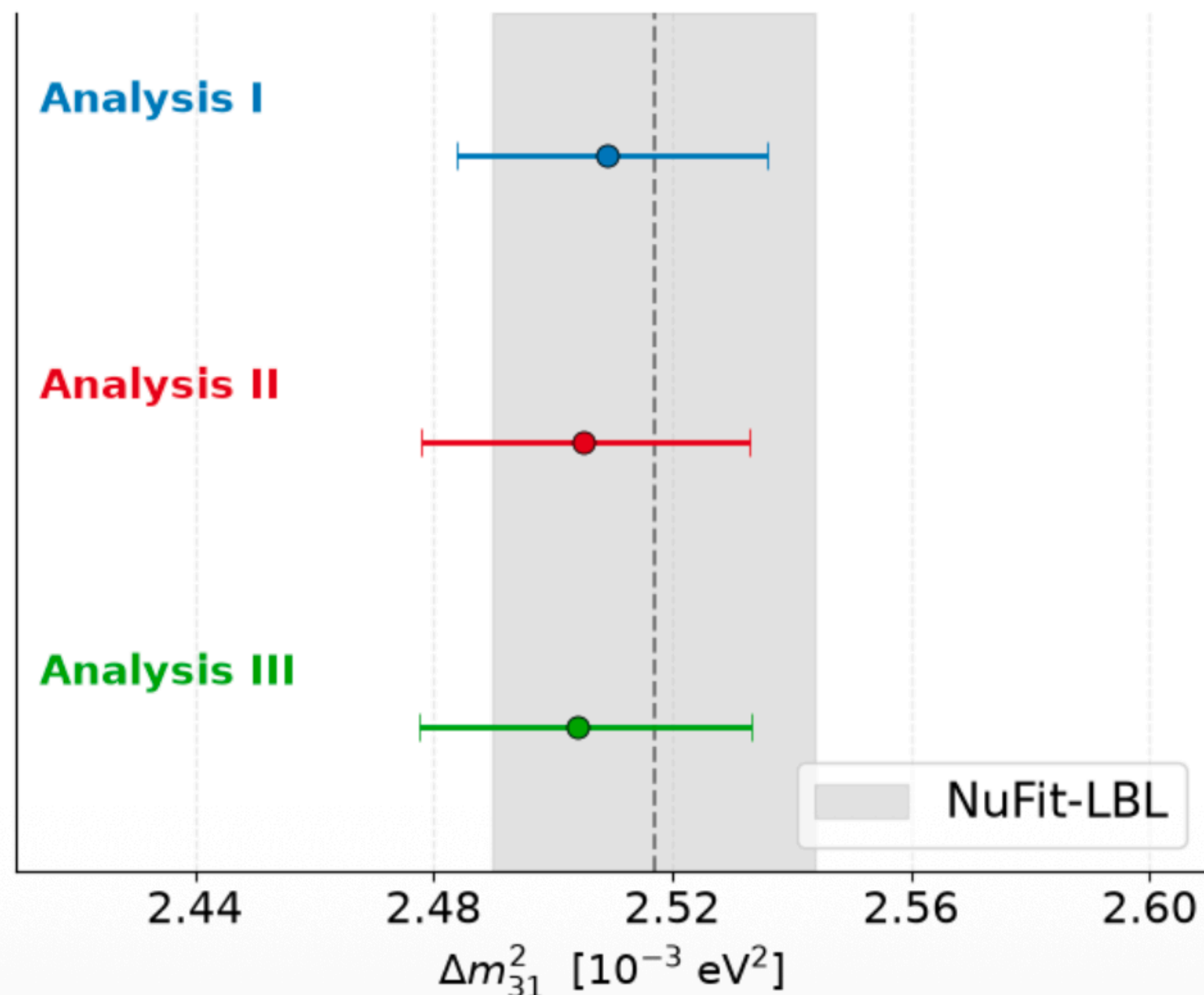
Results from JUNO

[Neutrino 2026]

- Normal Ordering is favored at 2.3σ

JUNO+DYB Feldman-Cousins

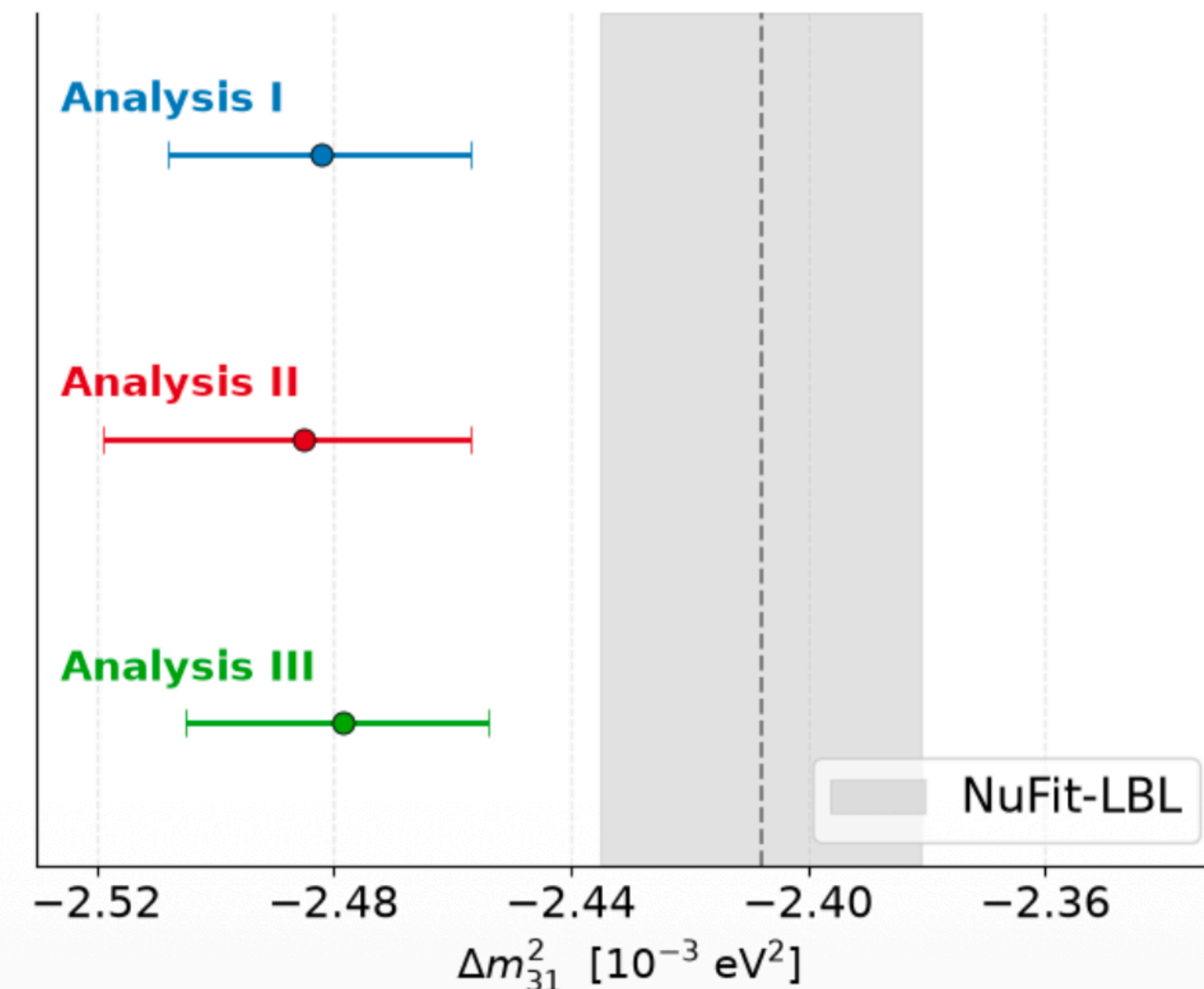
Normal Ordering



JUNO Preliminary. June 2026

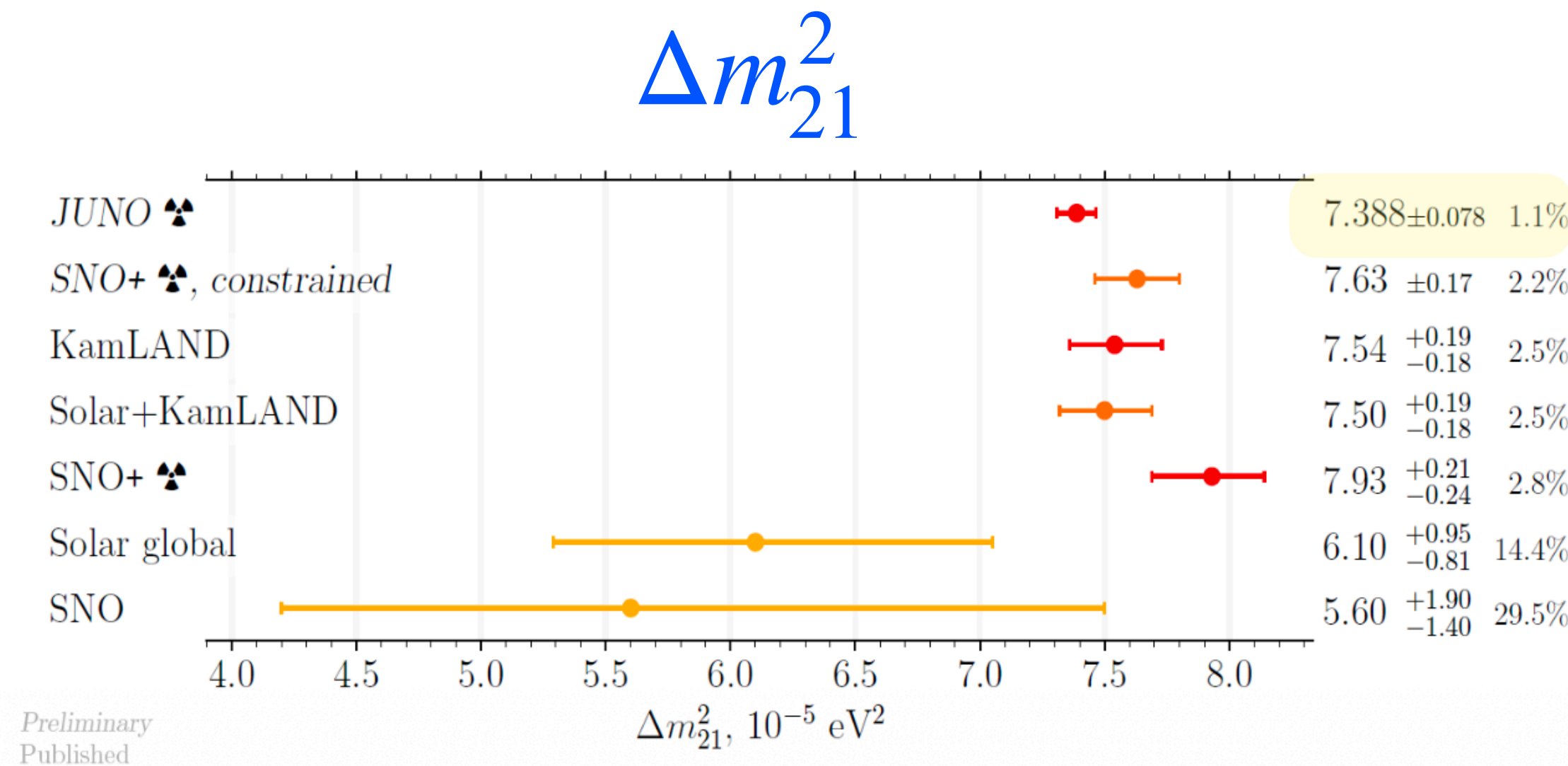
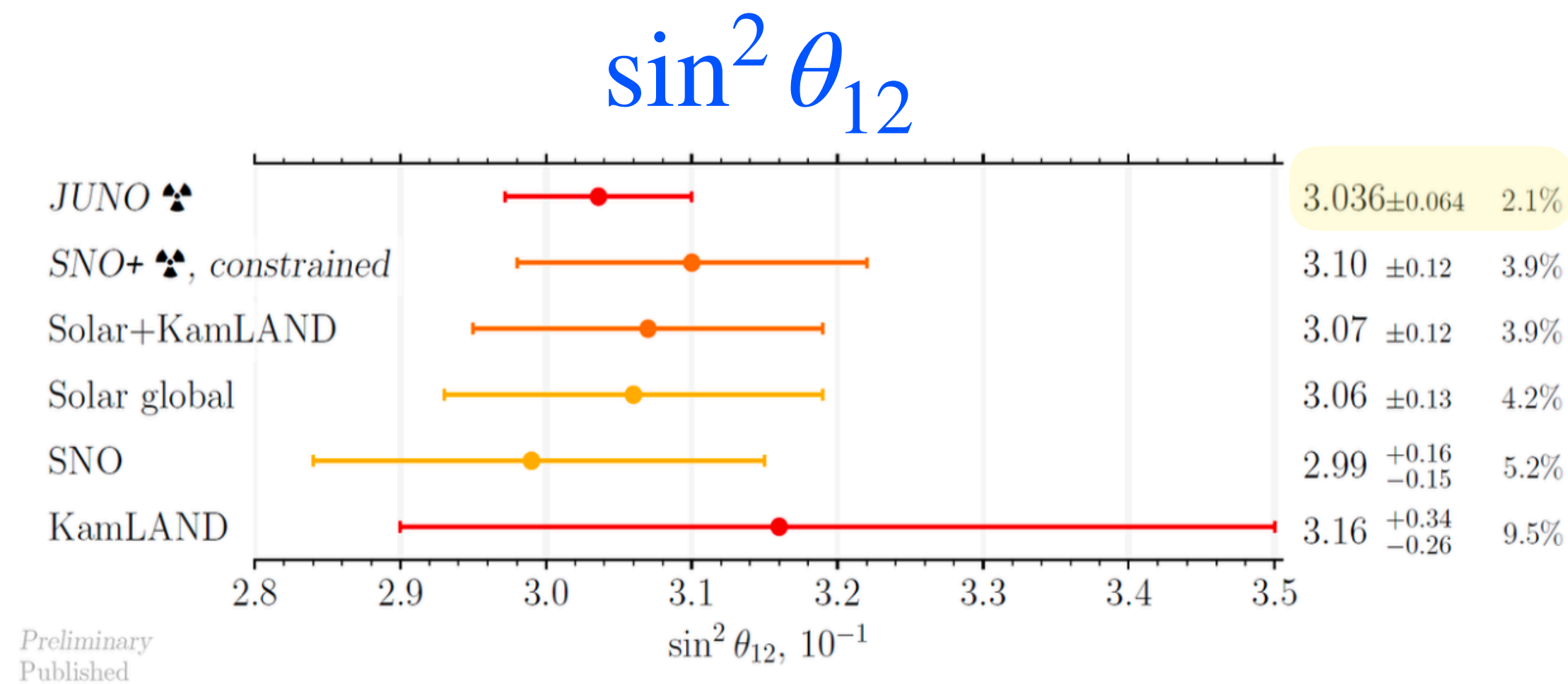


Inverted Ordering



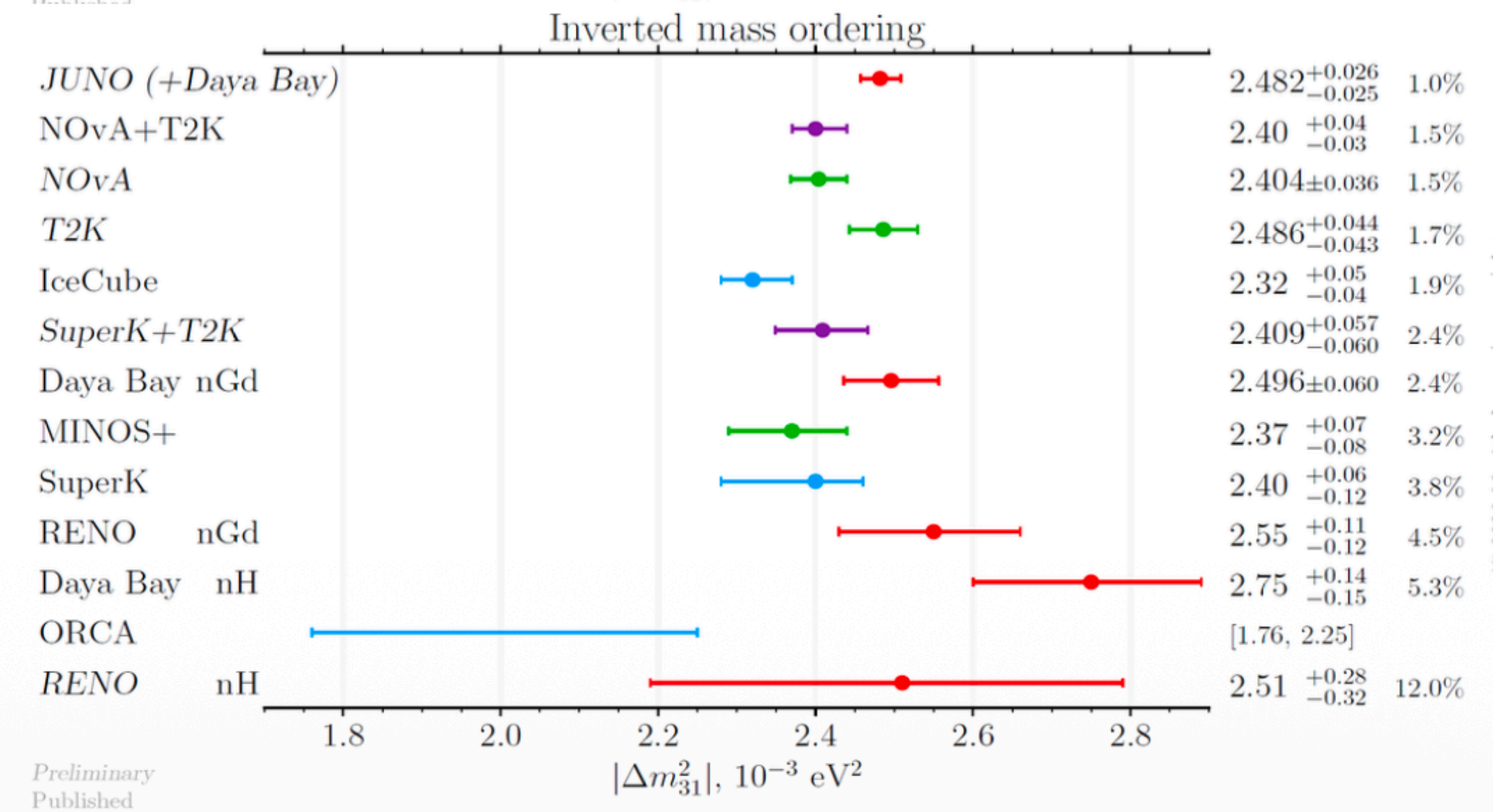
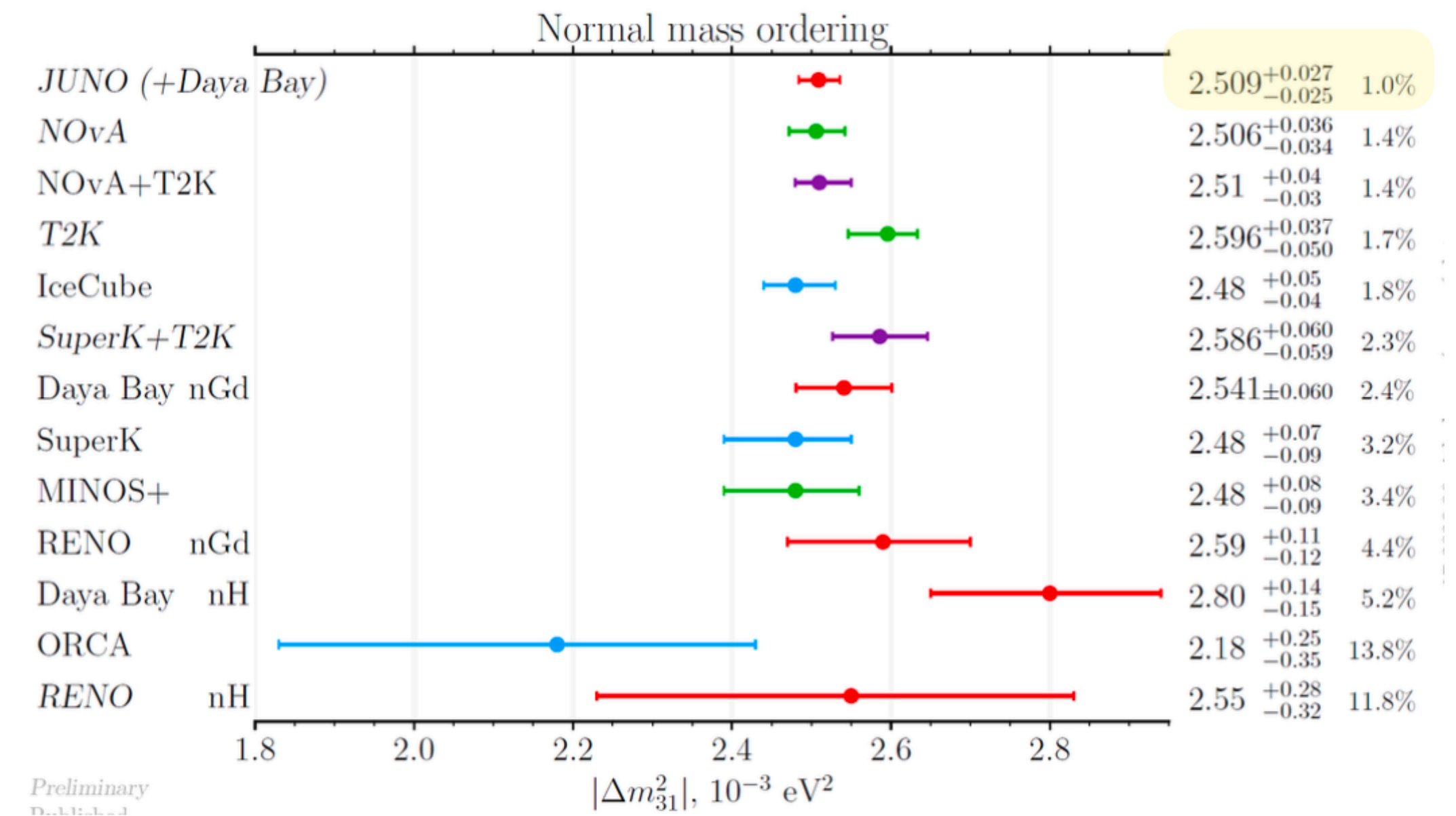
Reactor Neutrinos

Results from JUNO



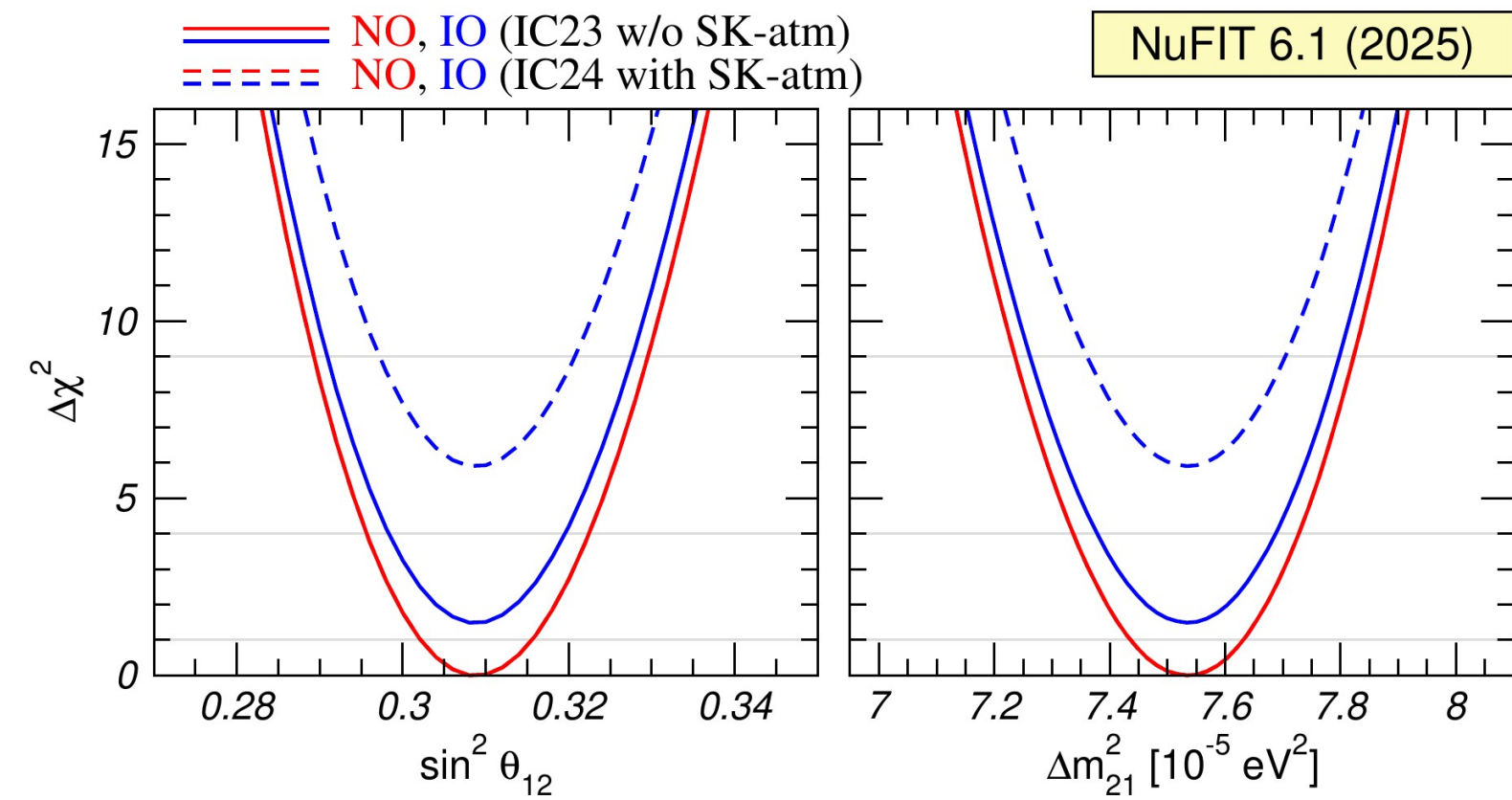
[Neutrino 2026]

$|\Delta m_{31}^2|$



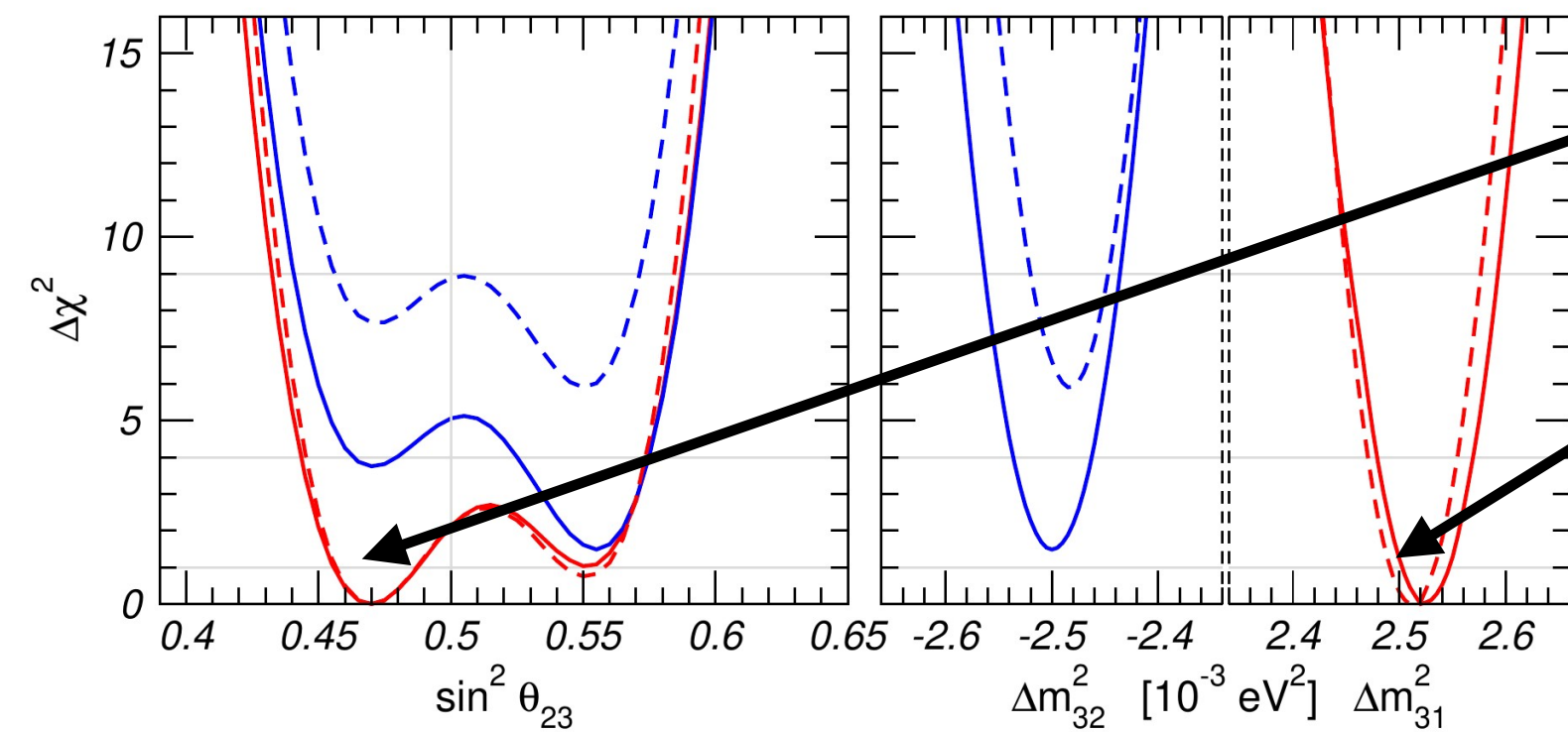
Status of the Standard Paradigm

2.2%



[before Neutrino 2026]

1.3%

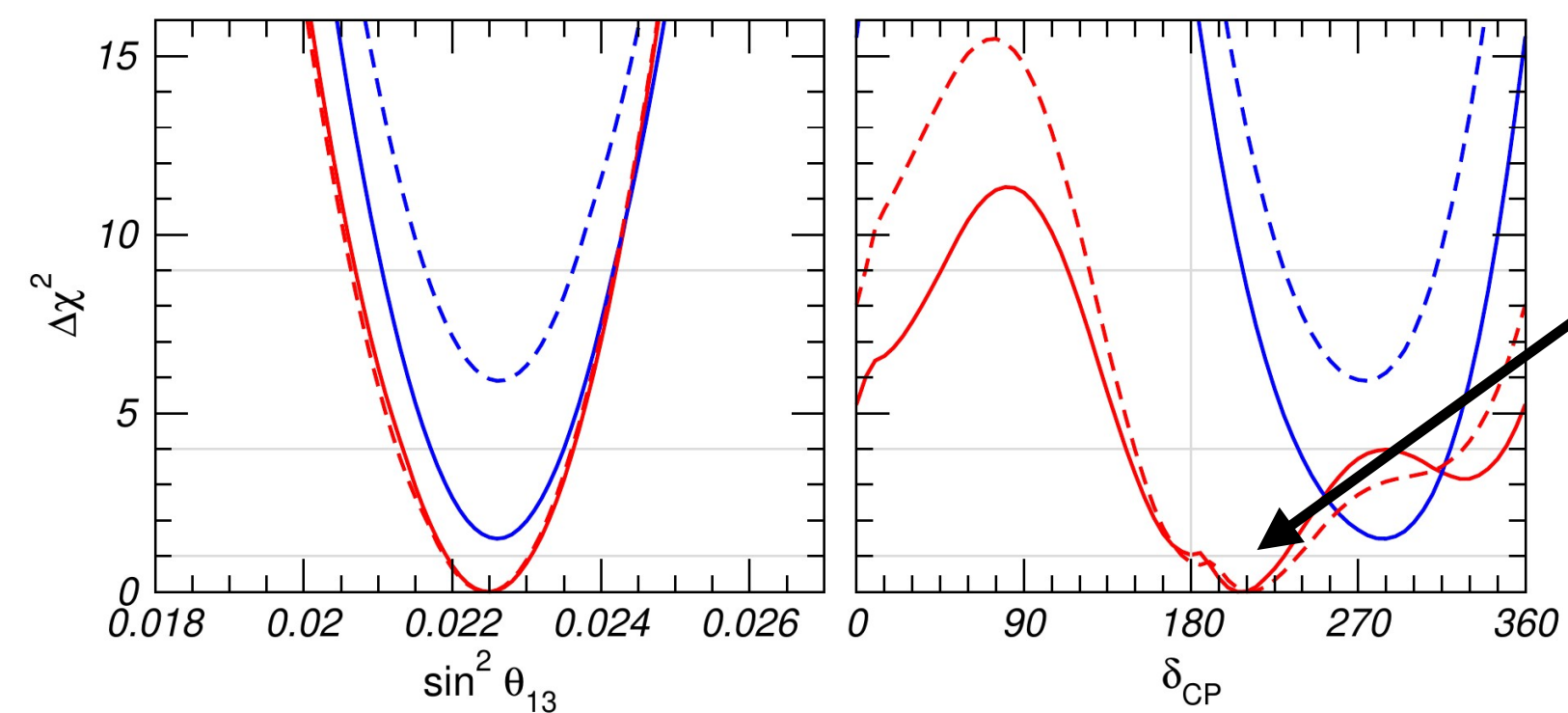


θ_{23}

NO/IO

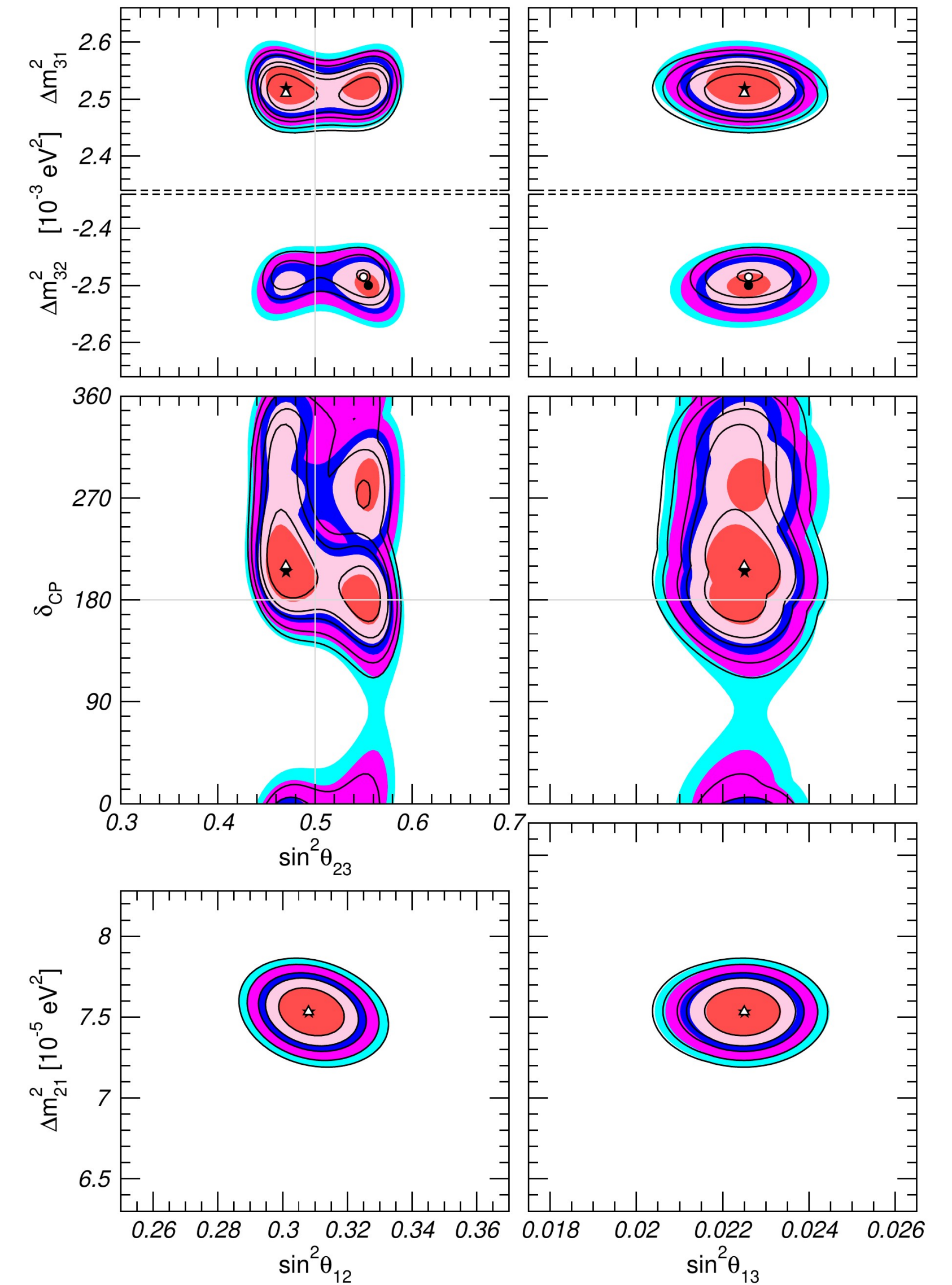
1%

2.5%

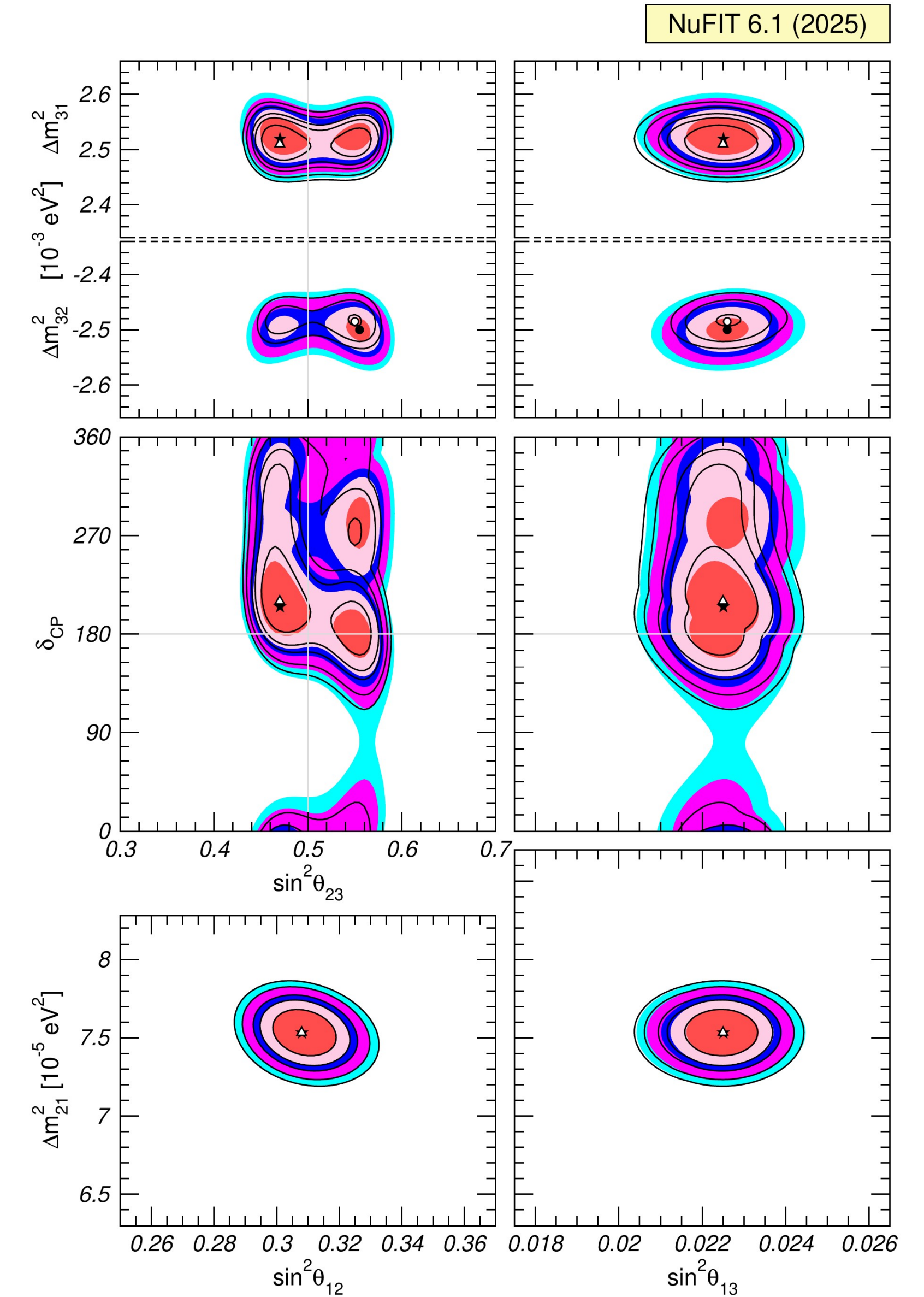
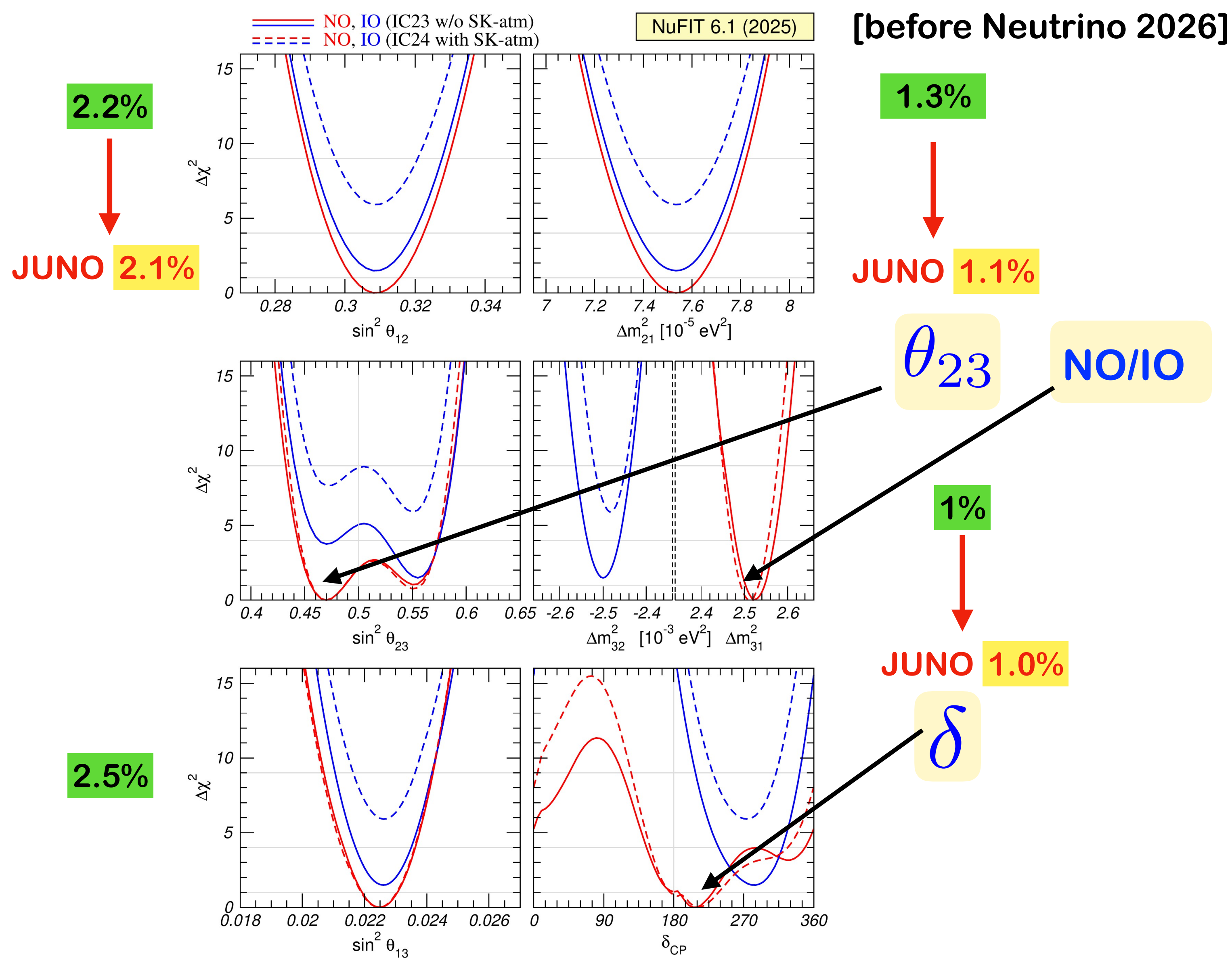


δ

NuFIT 6.1 (2025)



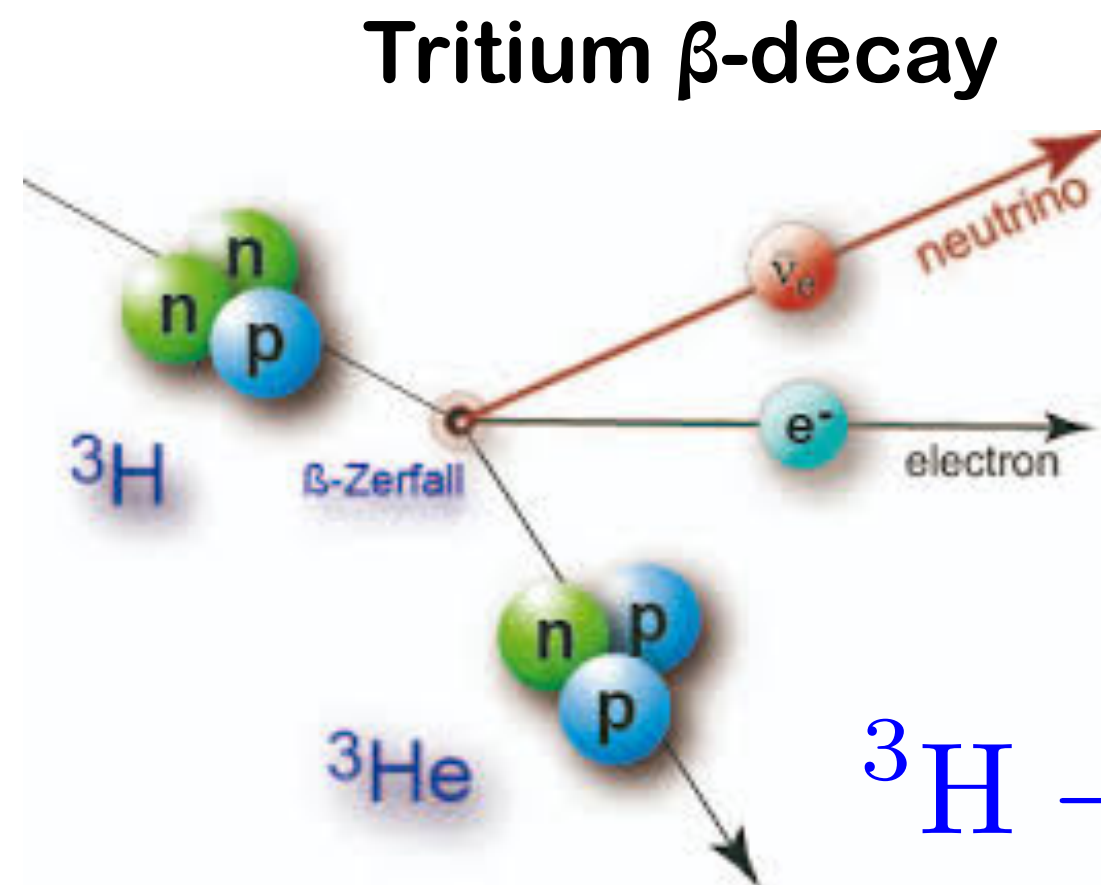
Status of the Standard Paradigm



**WHAT ELSE DO WE KNOW
ABOUT
NEUTRINO MASSES?**

Effective Neutrino Mass

Absolute Neutrino Mass Scale



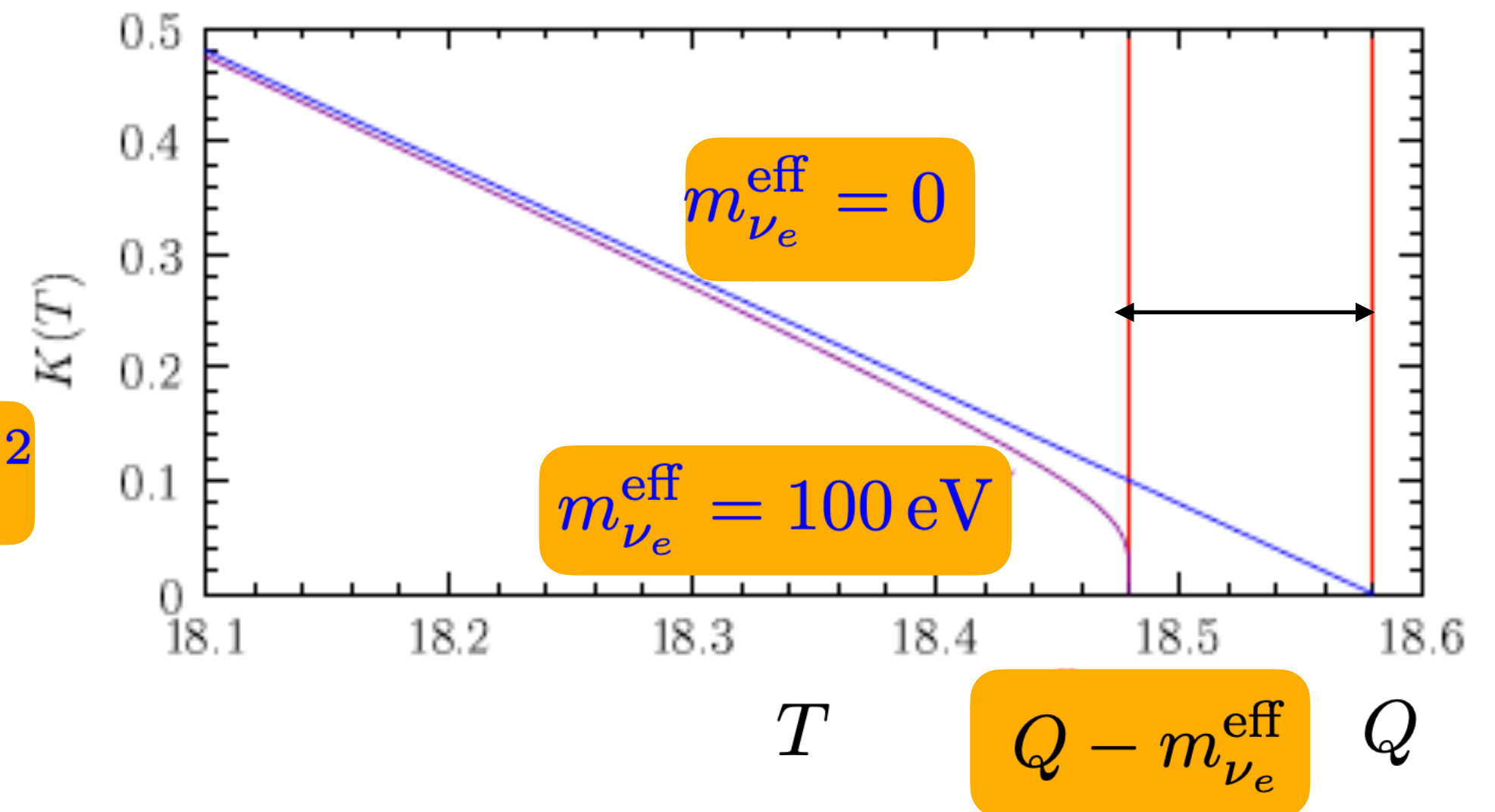
Valid for Dirac or Majorana neutrinos

$$m_{\nu_\alpha}^{\text{eff}} = \sqrt{\sum_i m_i^2 |U_{\alpha i}|^2}$$



pure kinematics
model independent

Kurie plot:



$$\frac{d\Gamma}{dT} \propto |\mathcal{M}|^2 F(E) p E(Q - T) \sqrt{(Q - T)^2 - (m_{\nu_e}^{\text{eff}})^2}$$

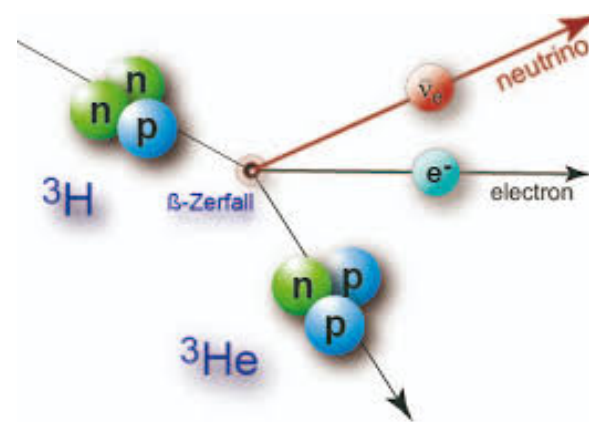
$$K(T) = \sqrt{(Q - T)} \sqrt{(Q - T)^2 - (m_{\nu_e}^{\text{eff}})^2}$$

$$Q = M_{\text{H}} - M_{\text{He}} - m_e = 18.58 \text{ keV}$$

Effective Neutrino Mass

Absolute Neutrino Mass Scale

Tritium β -decay



Valid for Dirac or Majorana neutrinos

pure kinematics
model independent

$$m_{\nu_\alpha}^{\text{eff}} = \sqrt{\sum_i m_i^2 |U_{\alpha i}|^2}$$

neutrino mass scale

$$(m_{\nu_e}^{\text{eff}})^2 = \begin{cases} m_0^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 + \Delta m_{31}^2 s_{13}^2 \\ m_0^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 - \Delta m_{31}^2 c_{13}^2 \end{cases}$$

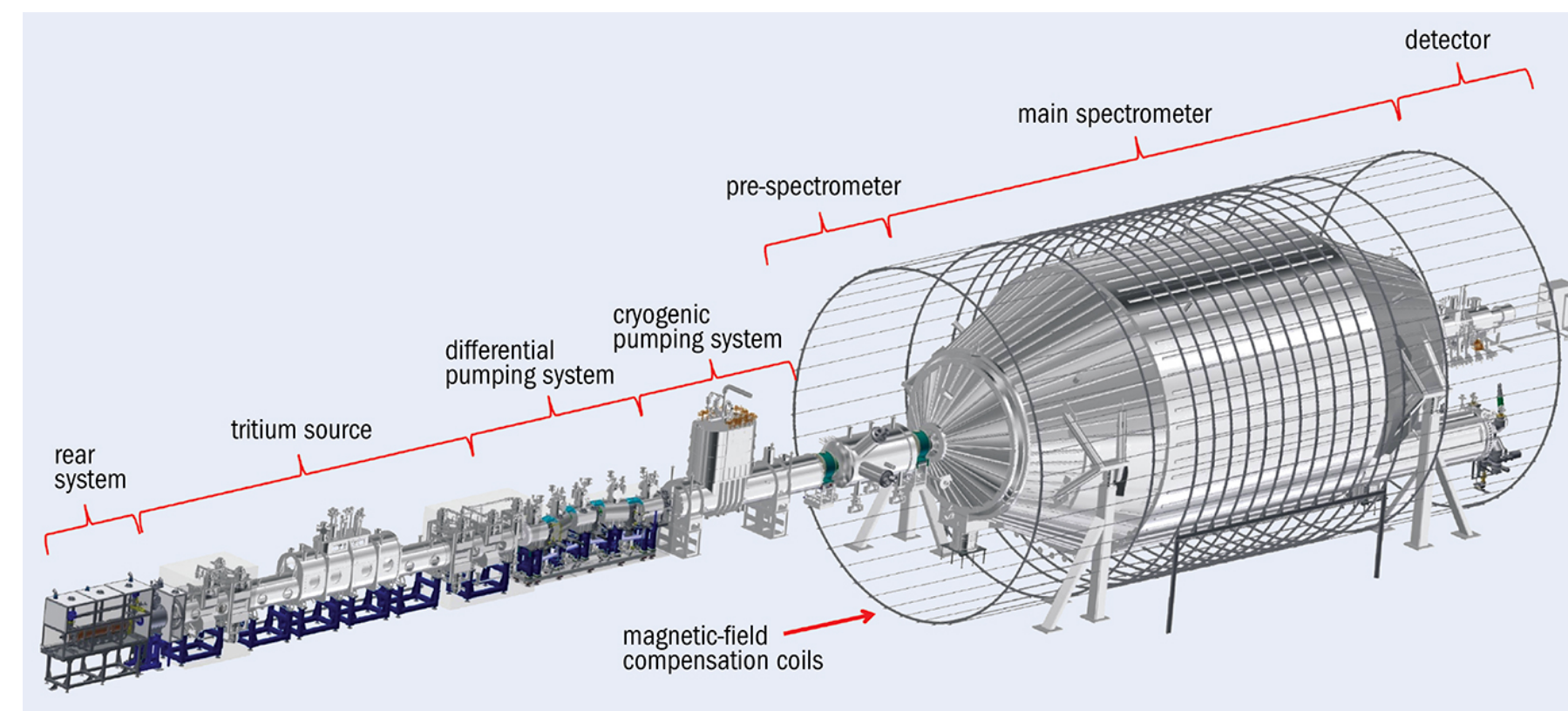
normal ordering

inverted ordering

current bound

$$m_{\nu_e}^{\text{eff}} < 0.45 \text{ @ } 90 \% \text{ CL}$$

[KATRIN Collab., Science 388 (2025) 6743]



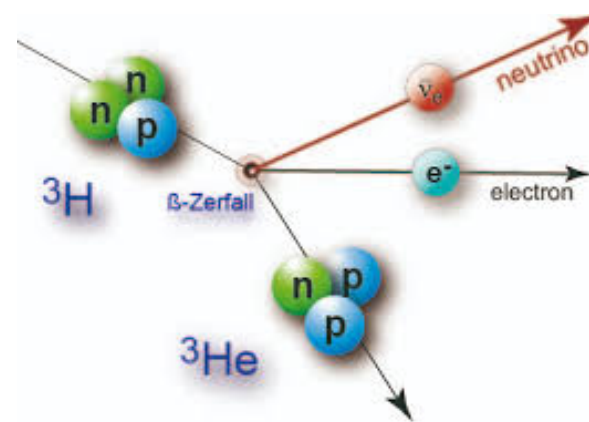
$$m_{\nu_e}^{\text{eff}} \sim (0.2 - 0.3) \text{ eV}$$

KATRIN future sensitivity

Effective Neutrino Mass

Absolute Neutrino Mass Scale

Tritium β -decay



Valid for Dirac or Majorana neutrinos

pure kinematics
model independent

$$m_{\nu_\alpha}^{\text{eff}} = \sqrt{\sum_i m_i^2 |U_{\alpha i}|^2}$$

neutrino mass scale

$$(m_{\nu_e}^{\text{eff}})^2 = \begin{cases} m_0^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 + \Delta m_{31}^2 s_{13}^2 & \text{normal ordering} \\ m_0^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 - \Delta m_{31}^2 c_{13}^2 & \text{inverted ordering} \end{cases}$$

$m_{\nu_e}^{\text{eff}} > 0.0085 \text{ eV (NO)}$
 $m_{\nu_e}^{\text{eff}} > 0.048 \text{ eV (IO)}$

current bound

$$m_{\nu_e}^{\text{eff}} < 0.45 \text{ eV @ 90 \% CL}$$

[KATRIN Collab., Science 388 (2025) 6743]

other limits

$$m_{\nu_\mu}^{\text{eff}} < 190 \text{ keV}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$m_{\nu_\tau}^{\text{eff}} < 18.2 \text{ MeV}$$

$$\tau \rightarrow n\pi + \nu_\tau \quad n \geq 3$$

Effective Majorana Neutrino Mass

$0\nu\beta\beta$ - decay



Majorana Neutrino

$$\nu = \bar{\nu}$$

$\times$

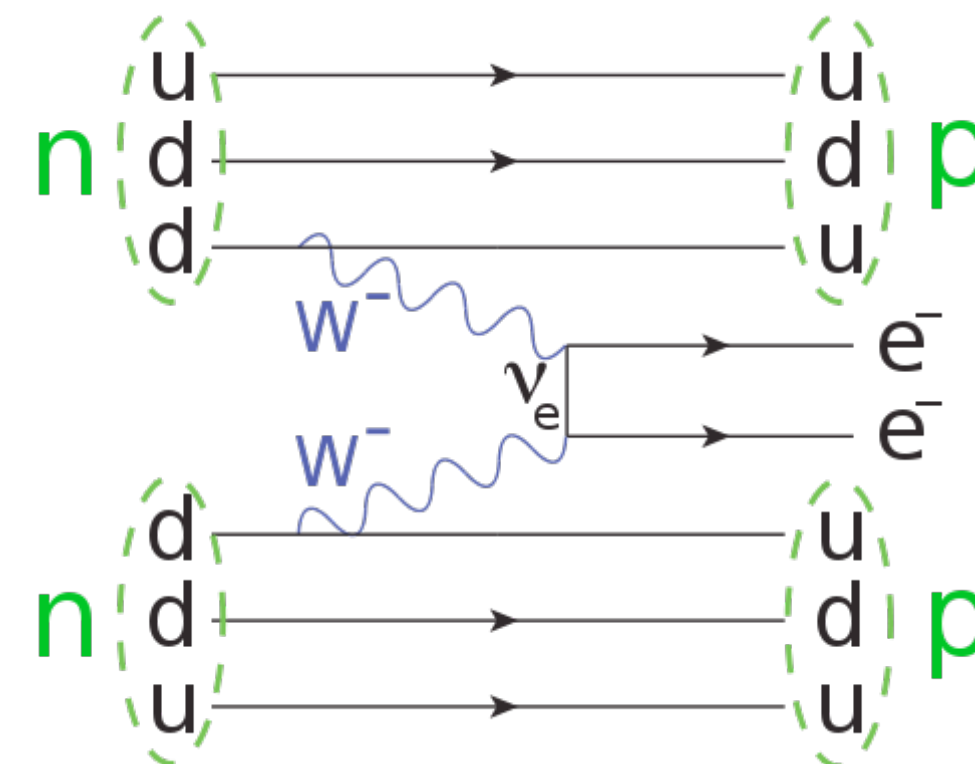
Dirac Neutrino

$$\nu \neq \bar{\nu}$$



Neutrinoless Double
Beta Decay

$$(A, Z) \rightarrow (A, Z + 2) + 2e^{-}$$



$$|\Delta L| = 2$$

Effective Majorana Neutrino Mass

$0\nu\beta\beta$ - decay

Only occurs for Majorana neutrinos

phase space integral

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M_{0\nu}|^2 m_{\beta\beta}^2 \quad \text{if neutrino mass is the only source of } \mathcal{X}$$

half-life of the decay

nuclear matrix element

Normal Ordering

$$m_1 \equiv m_0$$

$$m_2 \equiv \sqrt{m_0^2 + \Delta m_{21}^2}$$

$$m_3 \equiv \sqrt{m_0^2 + \Delta m_{21}^2 + \Delta m_{32}^2}$$

$$m_{\beta\beta} = \sum_i m_i U_{ei}^2$$

Inverted Ordering

$$m_1 \equiv \sqrt{m_0^2 - \Delta m_{21}^2 - \Delta m_{32}^2}$$

$$m_2 \equiv \sqrt{m_0^2 - \Delta m_{32}^2}$$

$$m_3 \equiv m_0$$

$$m_{\beta\beta} = |m_1 c_{12}^2 c_{13}^2 e^{2i\alpha_1} + m_2 s_{12}^2 c_{13}^2 + m_3 s_{13}^2 e^{2i\alpha_3}|$$

Effective Majorana Neutrino Mass

$0\nu\beta\beta$ - decay

Only occurs for Majorana neutrinos

$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M_{0\nu}|^2 m_{\beta\beta}^2$ if neutrino mass is the only source of χ

$m_{\beta\beta} = \sum_i m_i U_{ei}^2$

NO/IO

$m_{\beta\beta} = f(m_0, \text{order, Majorana phases})$

neutrino mass scale

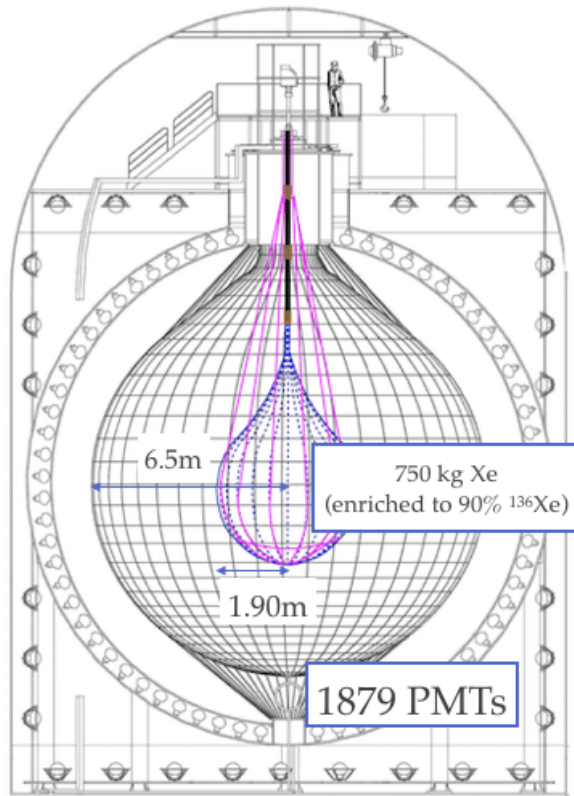
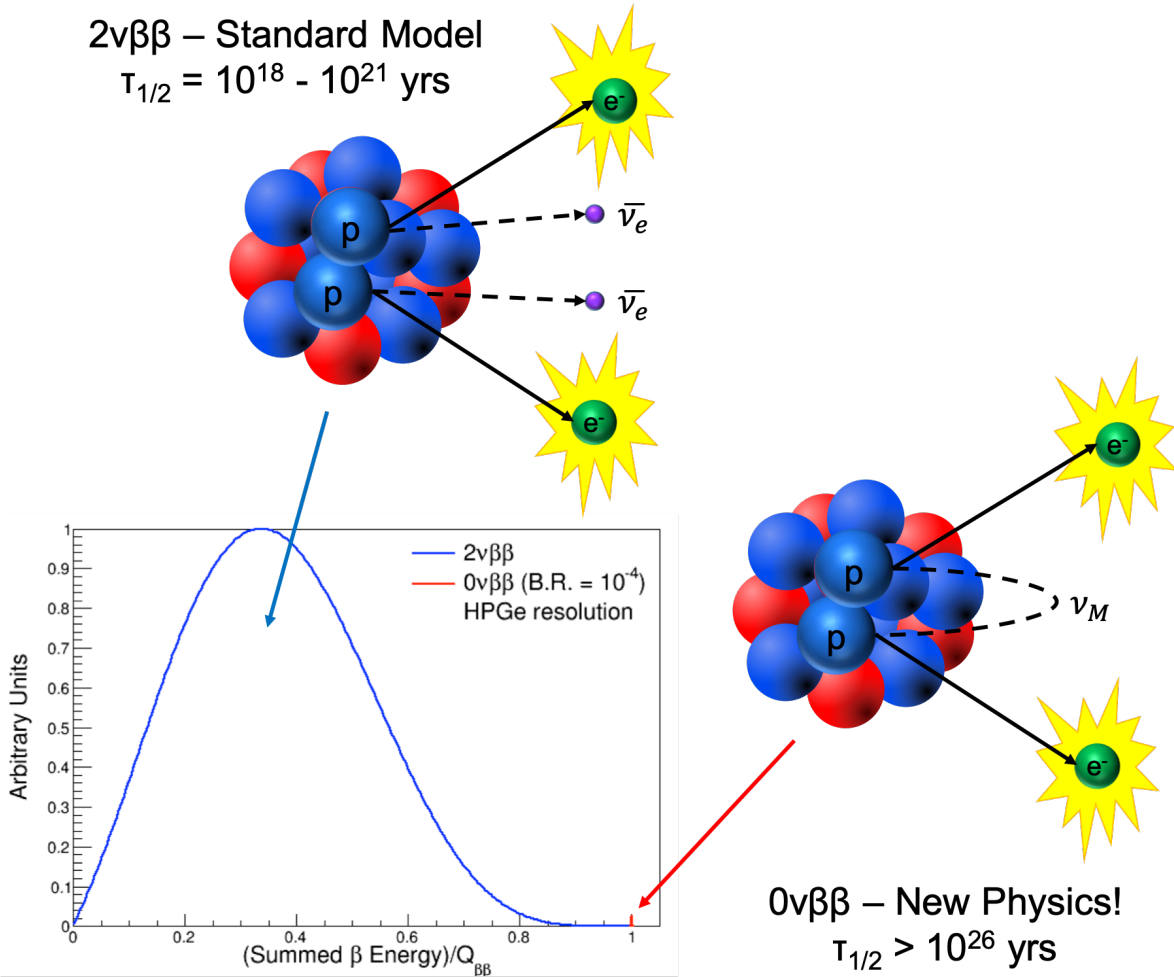
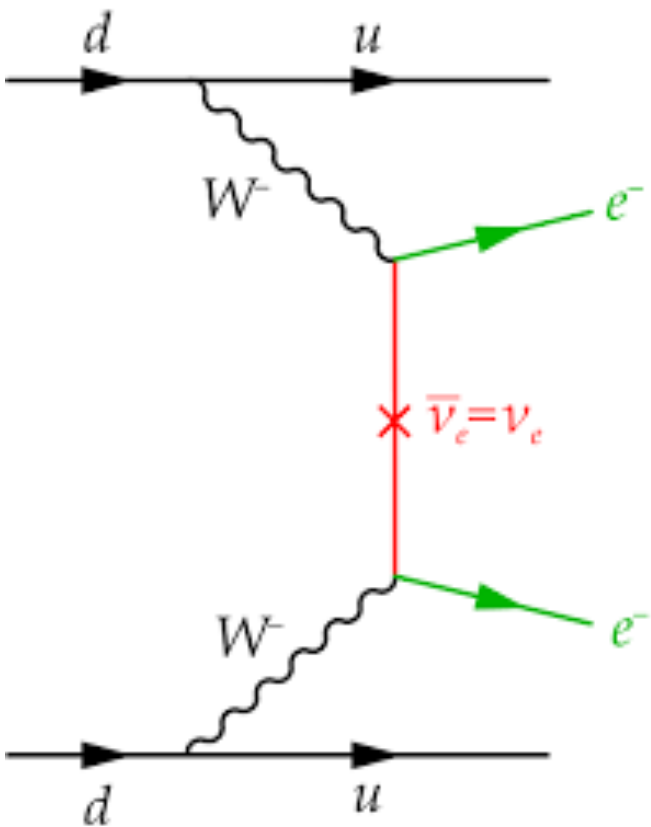
α_1, α_3

current bound

$m_{\beta\beta} < (28 - 122) \text{ meV}$

[KamLAND-Zen Collab., Phys.Rev.Lett. 135 (2025) 26, 262501]

Isotope	Natural abundance (%)	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

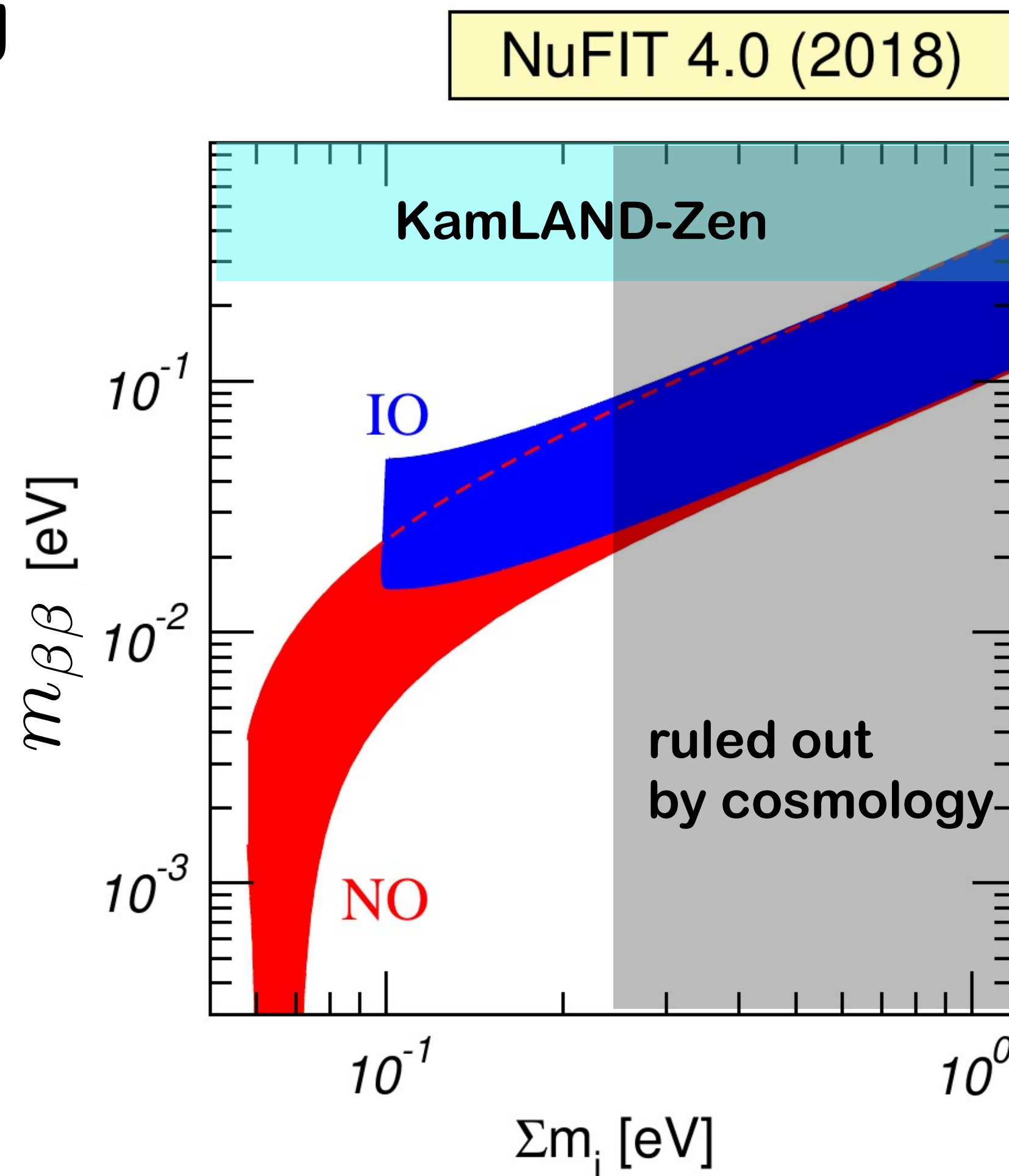
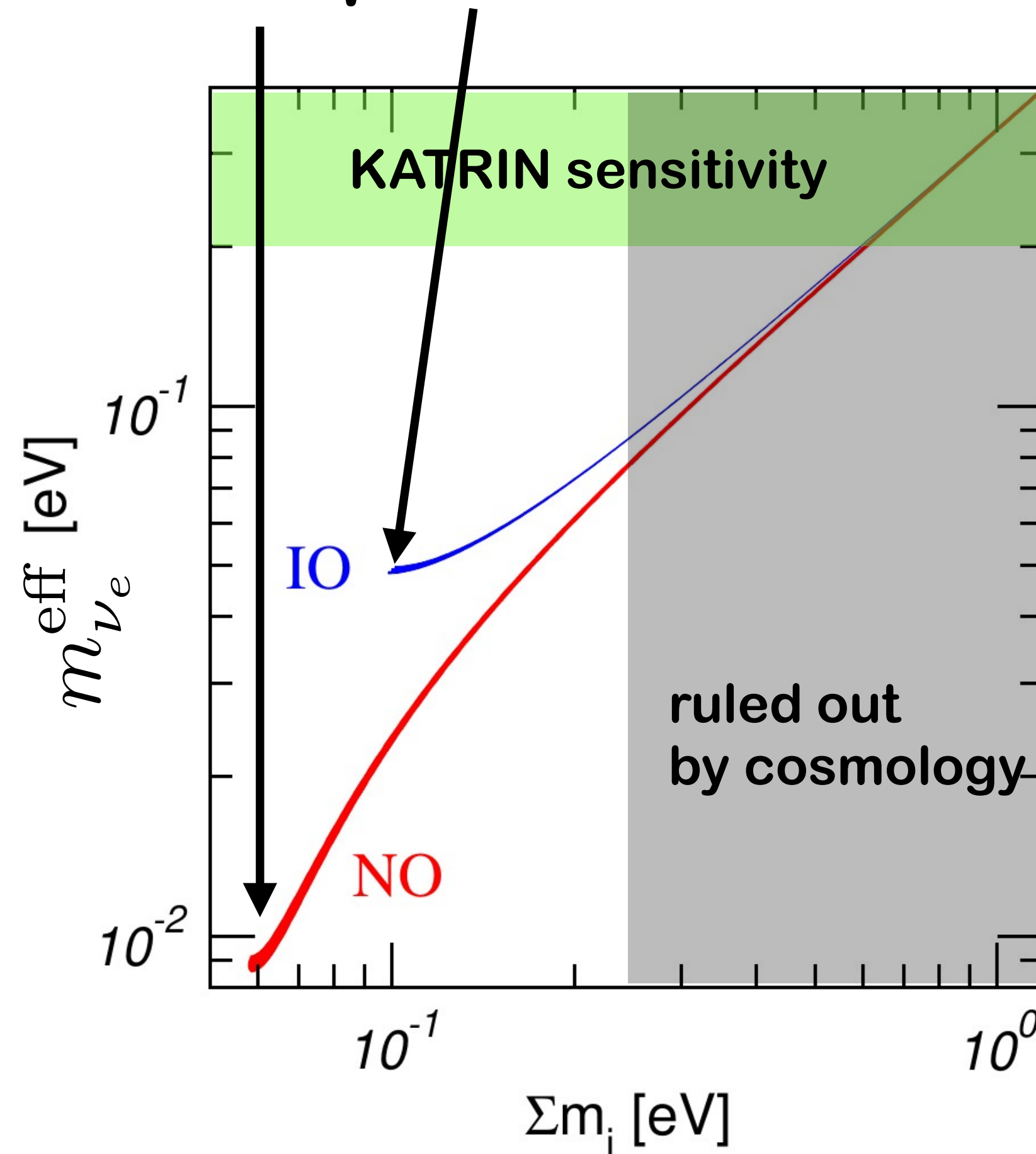


$T_{1/2}^{0\nu} > 3.8 \times 10^{26} \text{ yr}$

Correlation Among Measurements

Absolute Neutrino Mass Scale

lower bound depends on ordering



WHAT COMES NEXT?

JUNO - Precision Experiment

Oscillation Parameters

	200 days	6 years
Δm_{21}^2	$\sim 1.1 \% (2.5\%)$	$\sim 0.3 \%$
$\sin^2 \theta_{12}$	$\sim 2.1 \% (3.9\%)$	$\sim 0.5 \%$
$ \Delta m_{31}^2 $	$\sim 1.0 \% (2.4\%)$	$\sim 0.2 \%$

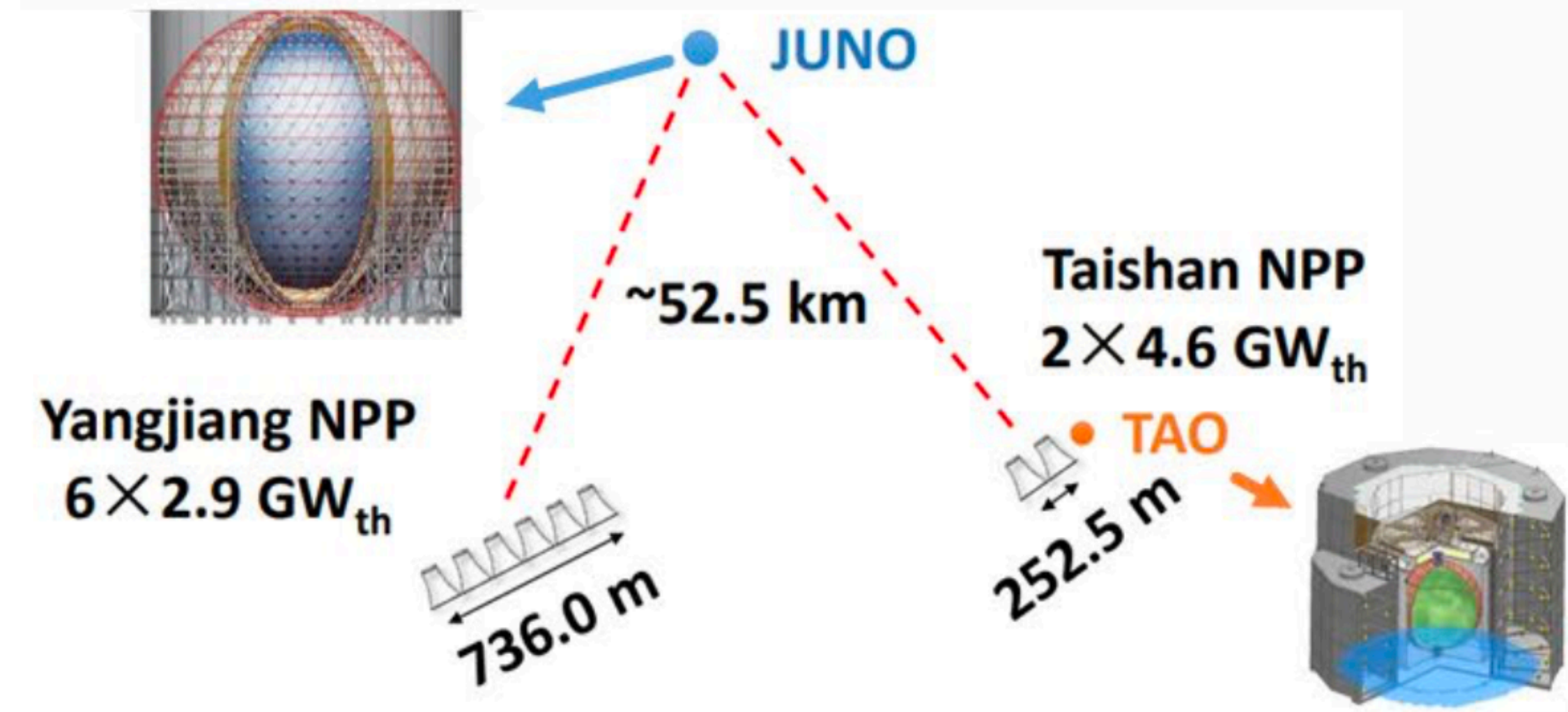
Daya Bay

+ Mass Ordering

+ Atmospheric Neutrinos

+ Solar Neutrinos

+ SN Neutrinos



Sub-percent precision
on

$$\Delta m_{21}^2, \sin^2 \theta_{12}, |\Delta m_{31}^2|$$

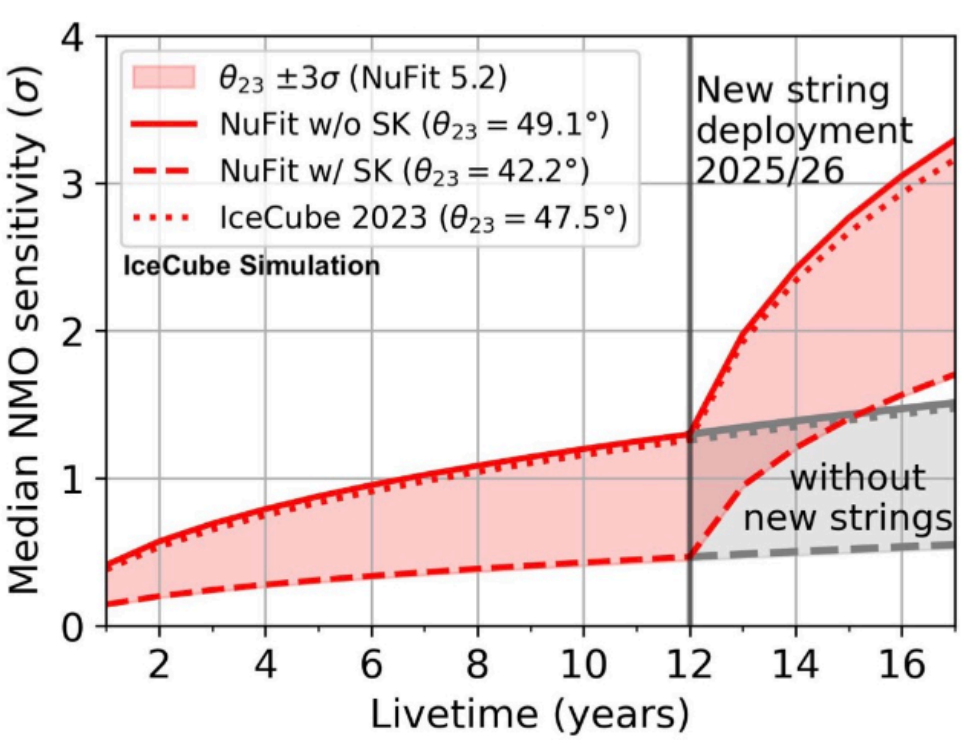
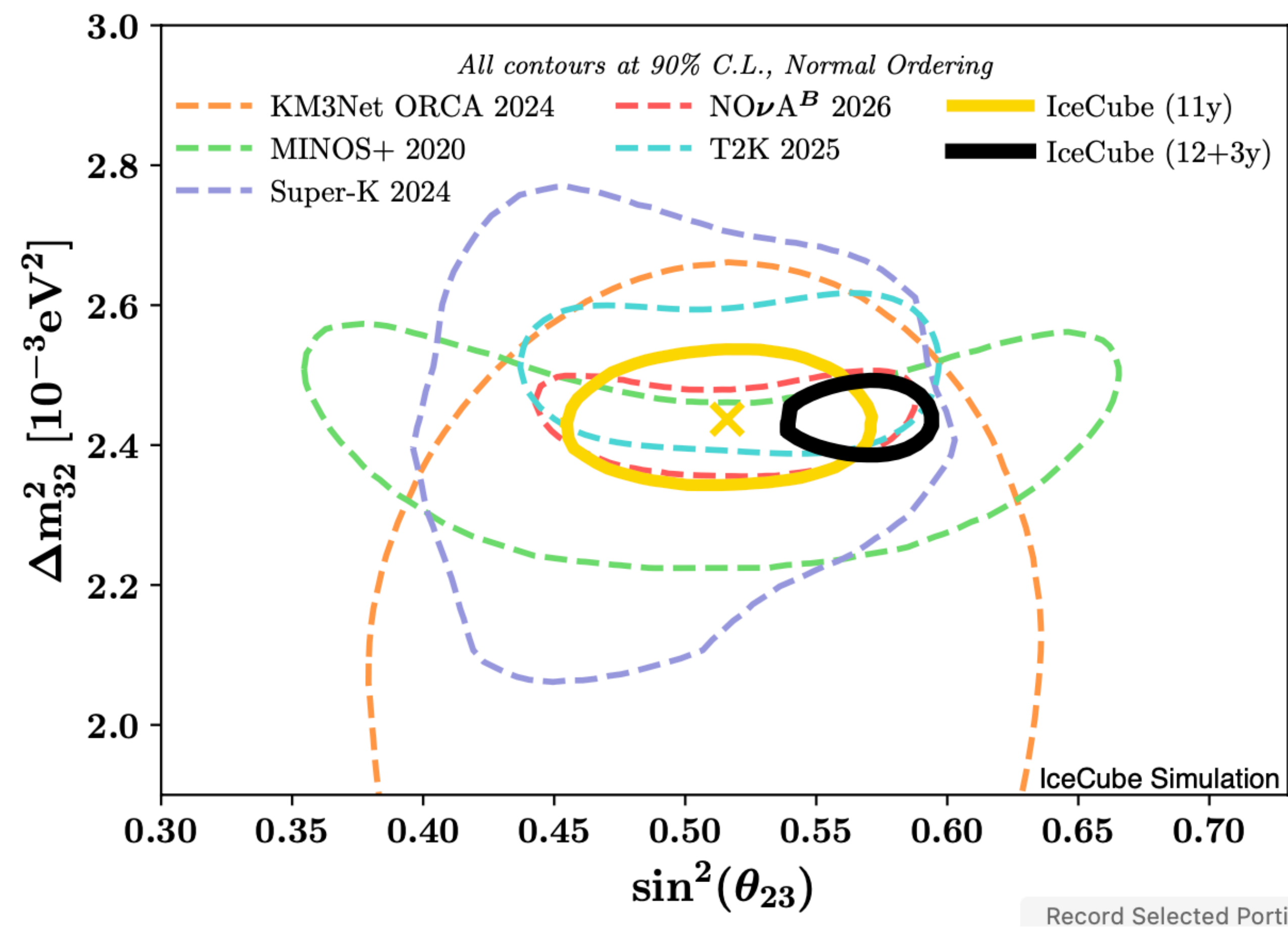
IceCube & KM3NeT/ORCA

Oscillation Parameters

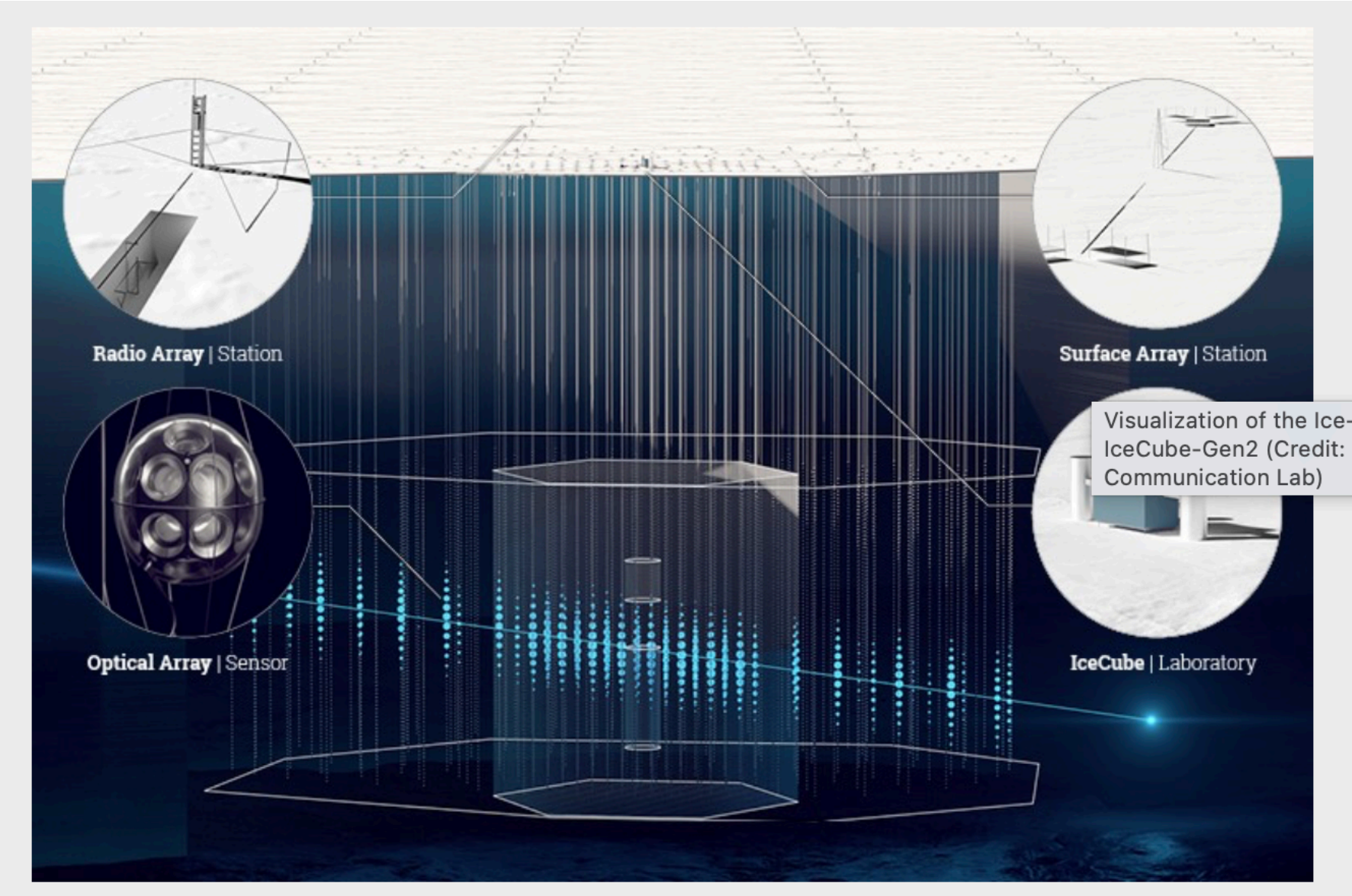
~1.5-2.5 σ sensitivity to neutrino mass ordering after 3 years.

IceCube Upgrade (ICU) new calibration devices

New calibration devices will improve our understanding of the Antarctic ice, **enabling IceCube to reanalyze more than 12 years of data** with enhanced detector modeling, reduced systematic uncertainties, and improved physics sensitivity.



IceCube-Gen2 - 10x IceCube volume



IceCube & KM3NeT/ORCA

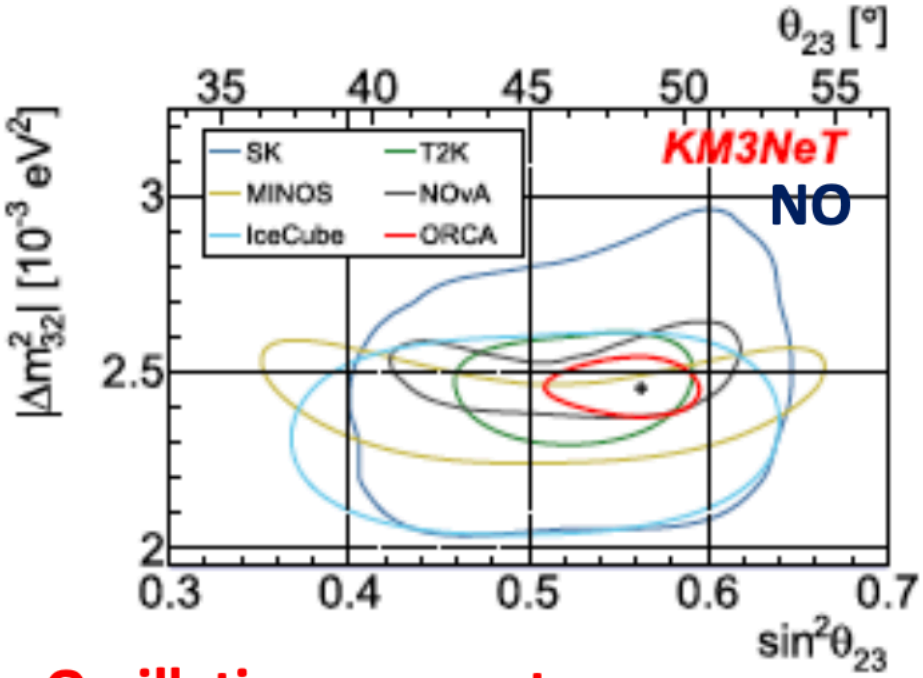
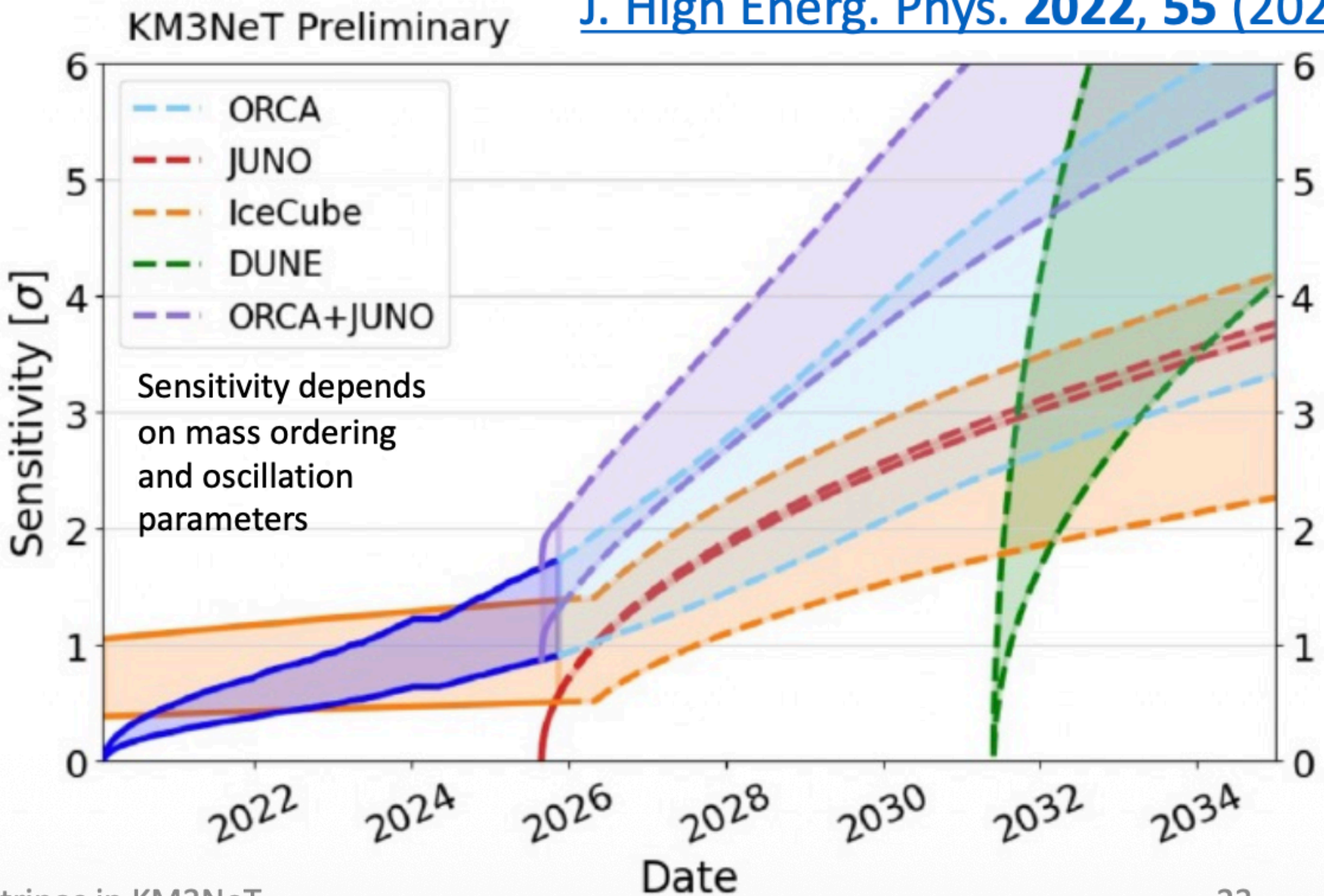
Oscillation Parameters

ORCA: 108 detection units, dense spacing (20m between lines), 6.5 Mton fiducial mass

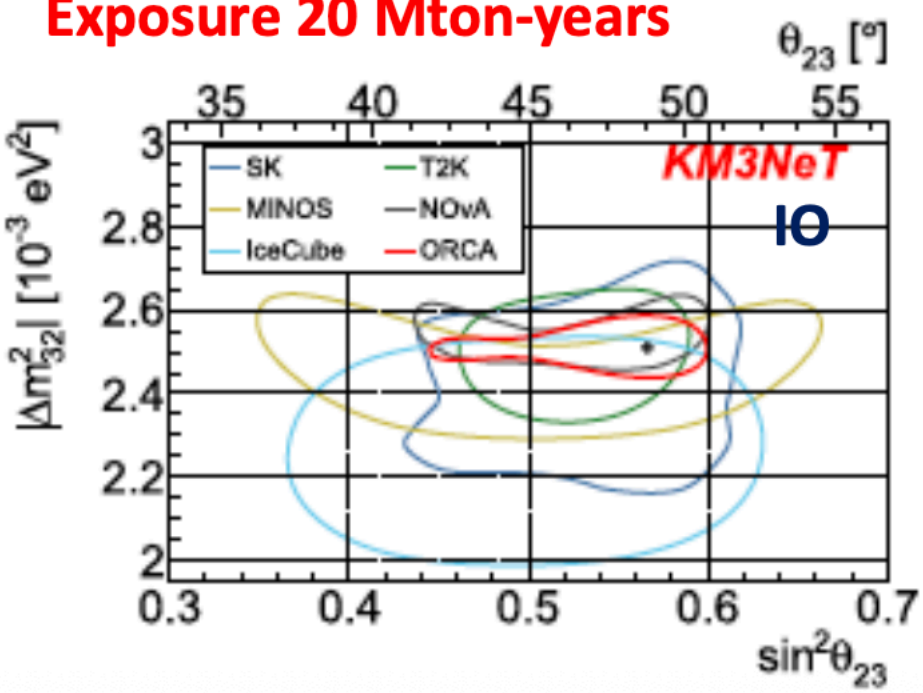
ORCA keeps growing, from 38 DUs now, to 52 DUs (node 2 filled, 2027), to 80 DUs (node 3 filled, 2028/2029), to 108 DUs (node 4 filled, 2030) (roughly: 2.3 Mton $\rightarrow$ 3.1 Mton $\rightarrow$ 4.8 Mton $\rightarrow$ 6.5 Mton)

Sensitivity to mass ordering with realistic detector growth:

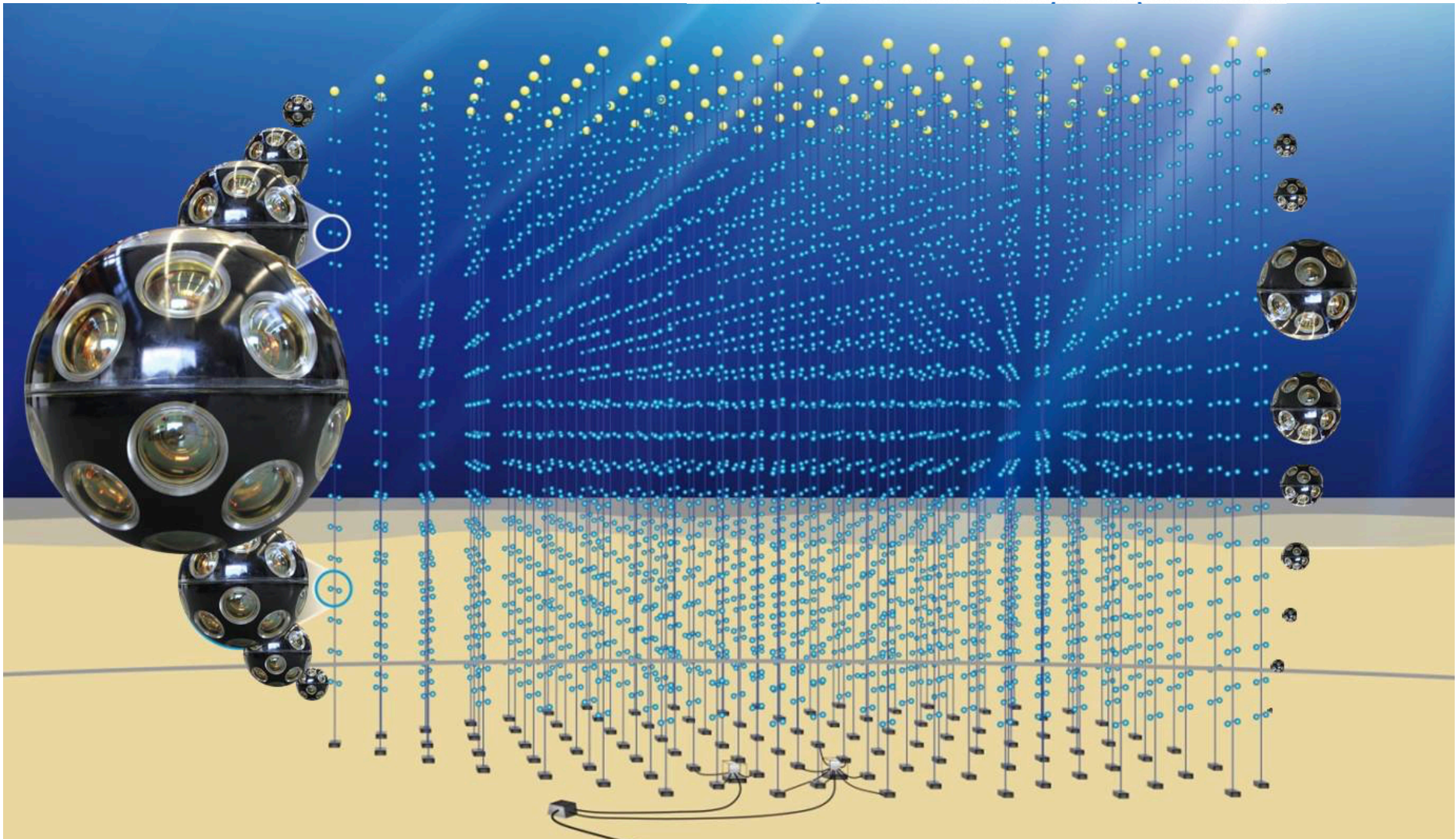
[J. High Energ. Phys. 2022, 55 \(2022\)](#)



Oscillation parameters
Exposure 20 Mton-years

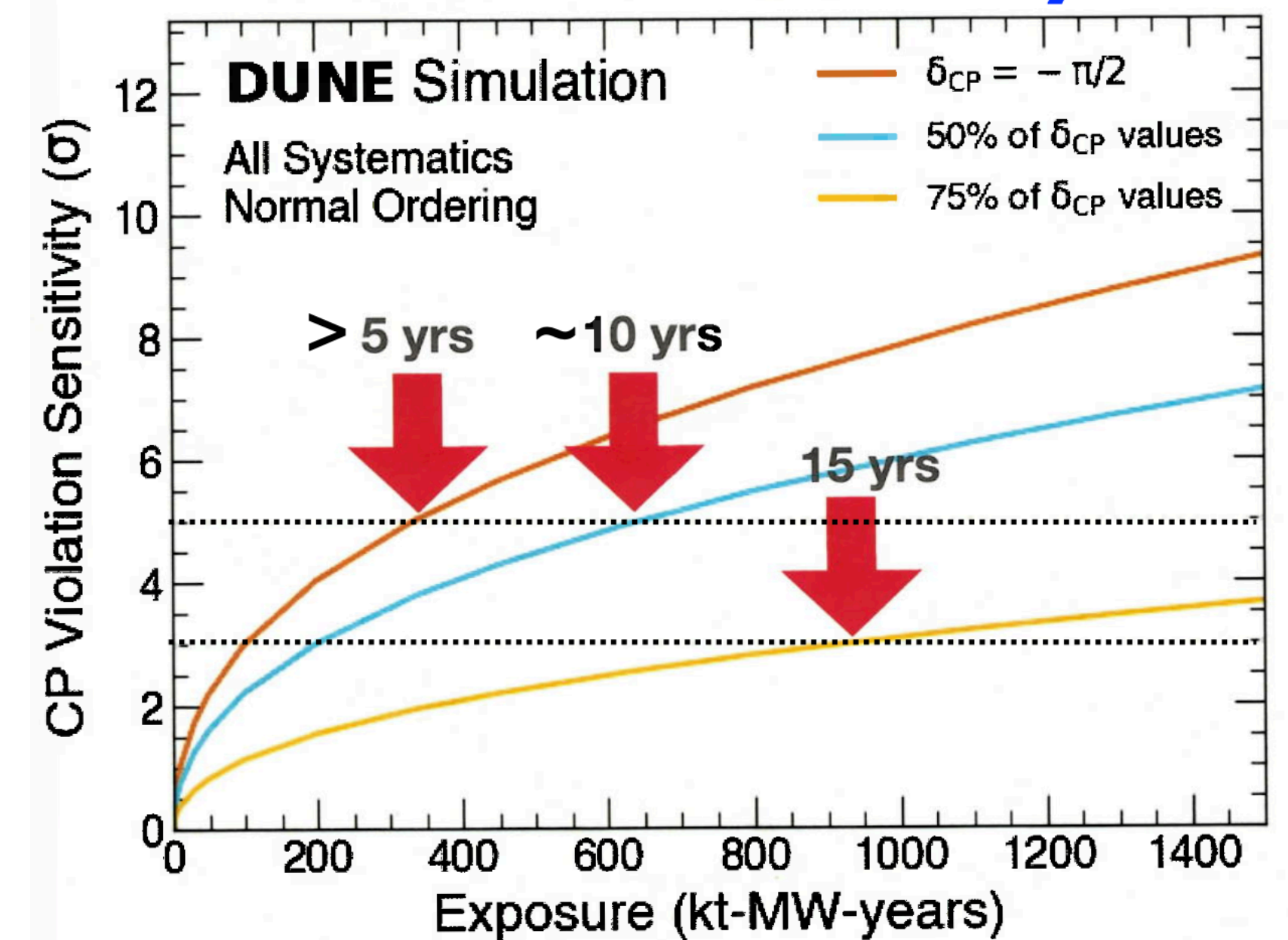
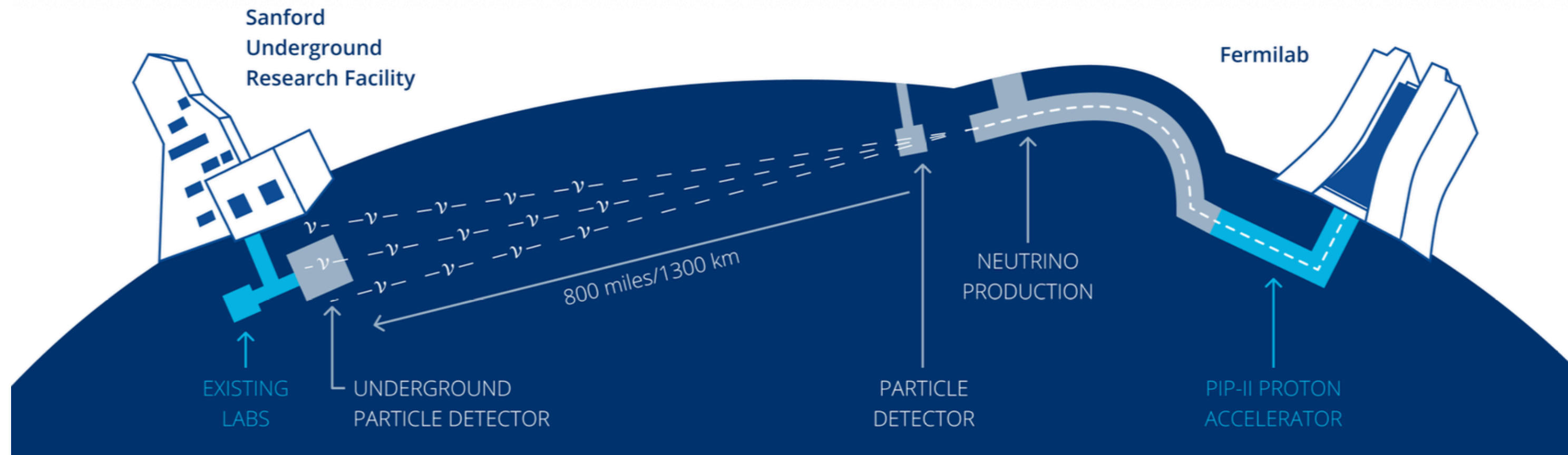


KM3NeT/ORCA



DUNE & HYPER-KAMIOKANDE

Oscillation Parameters



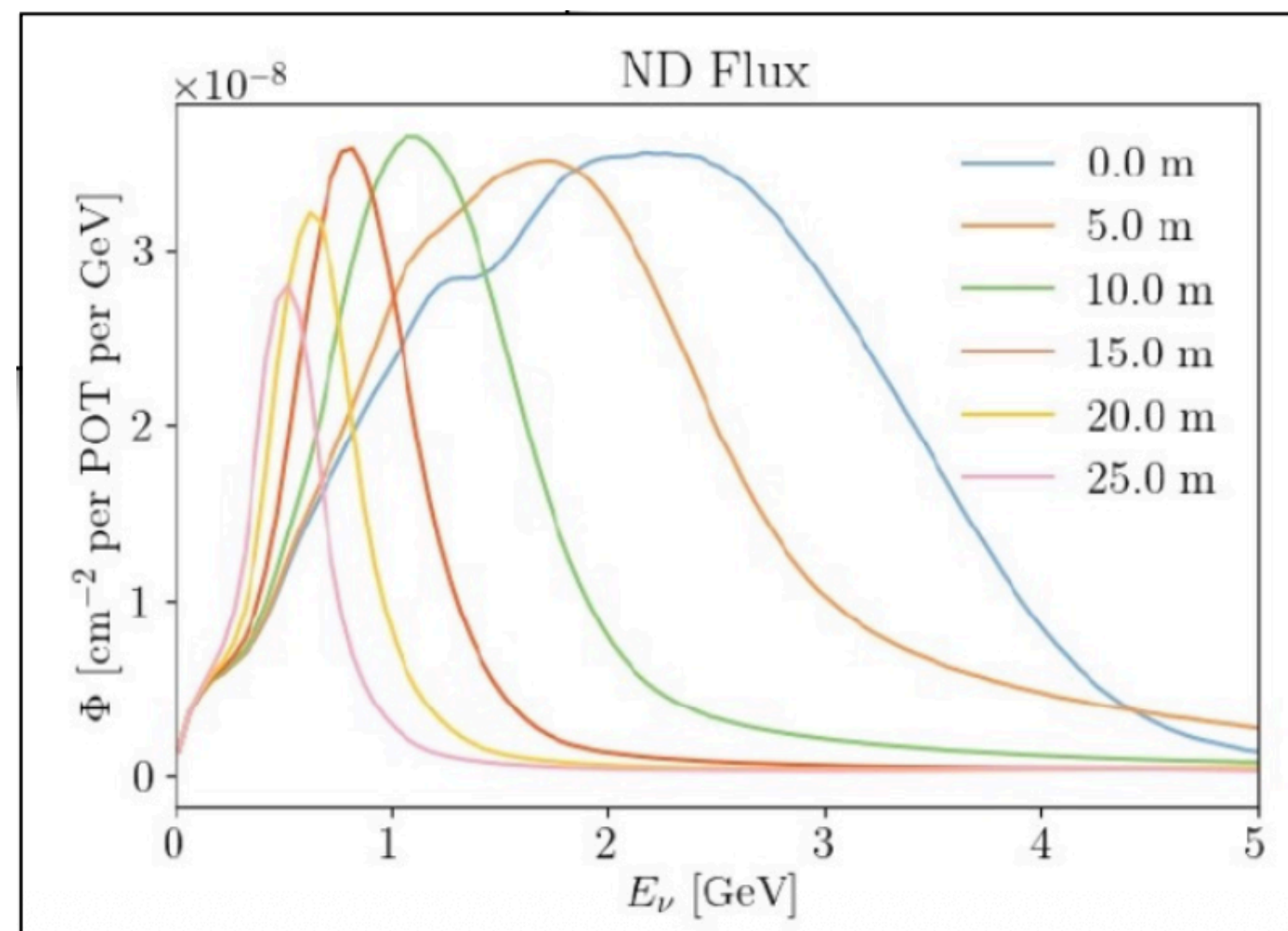
Phase I

Phase II

LBNF: Long Baseline Neutrino Facility

Phase I = 1.1 MW + 2×10 kton
22 kt-MW-year / year

Phase II = 2.1 MW + 4×10 kton
84 kt-MW-year / year



DUNE-PRISM

The Technology (DUNE)

- Four 17 kiloton LAr detectors – largest of its kind!
- A movable near detector

DUNE will be built in two phases

The Facility (LBNF)

- Colossal caverns at 1.5 km underground
- World's most intense neutrino beam (> 2 MW) and wide-band
- longest distance accelerator neutrinos ever traveled

DUNE & HYPER-KAMIOKANDE

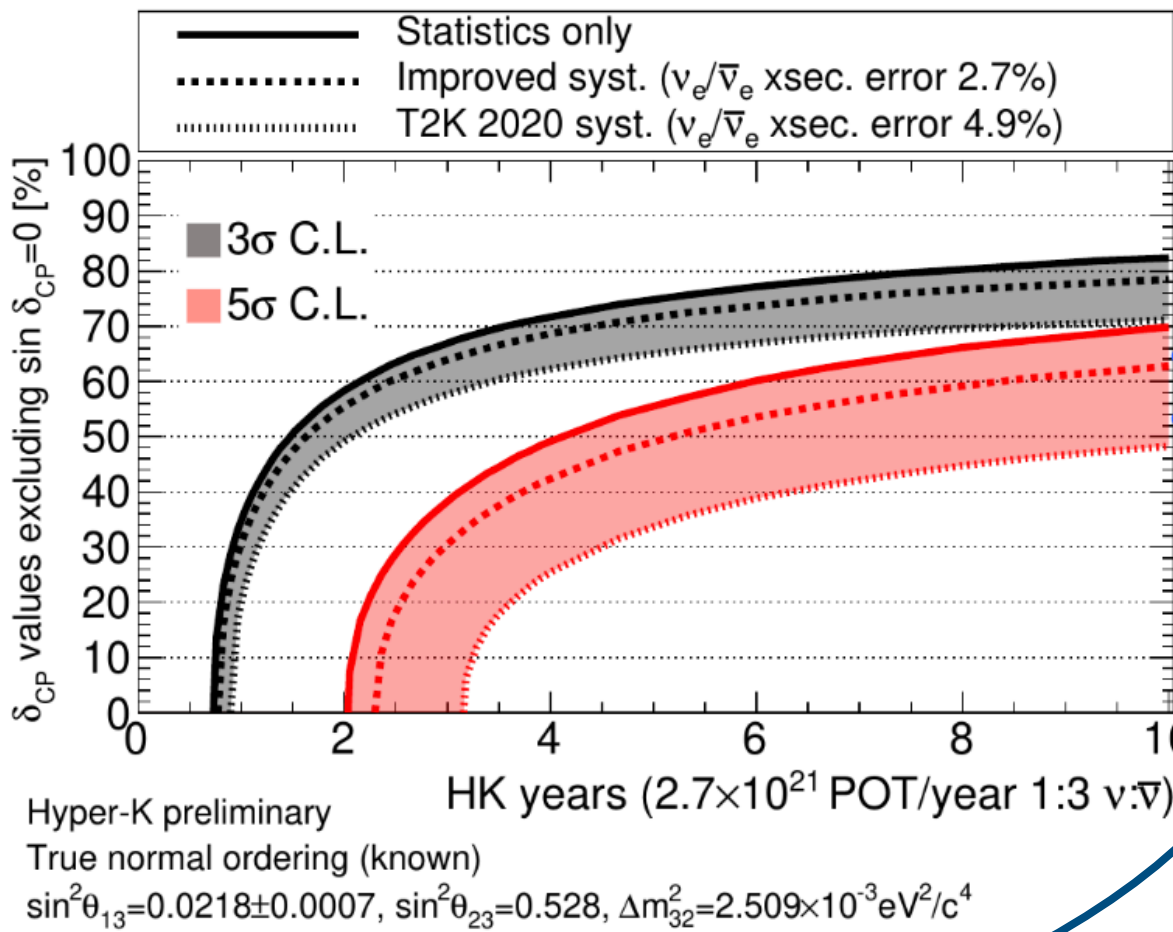
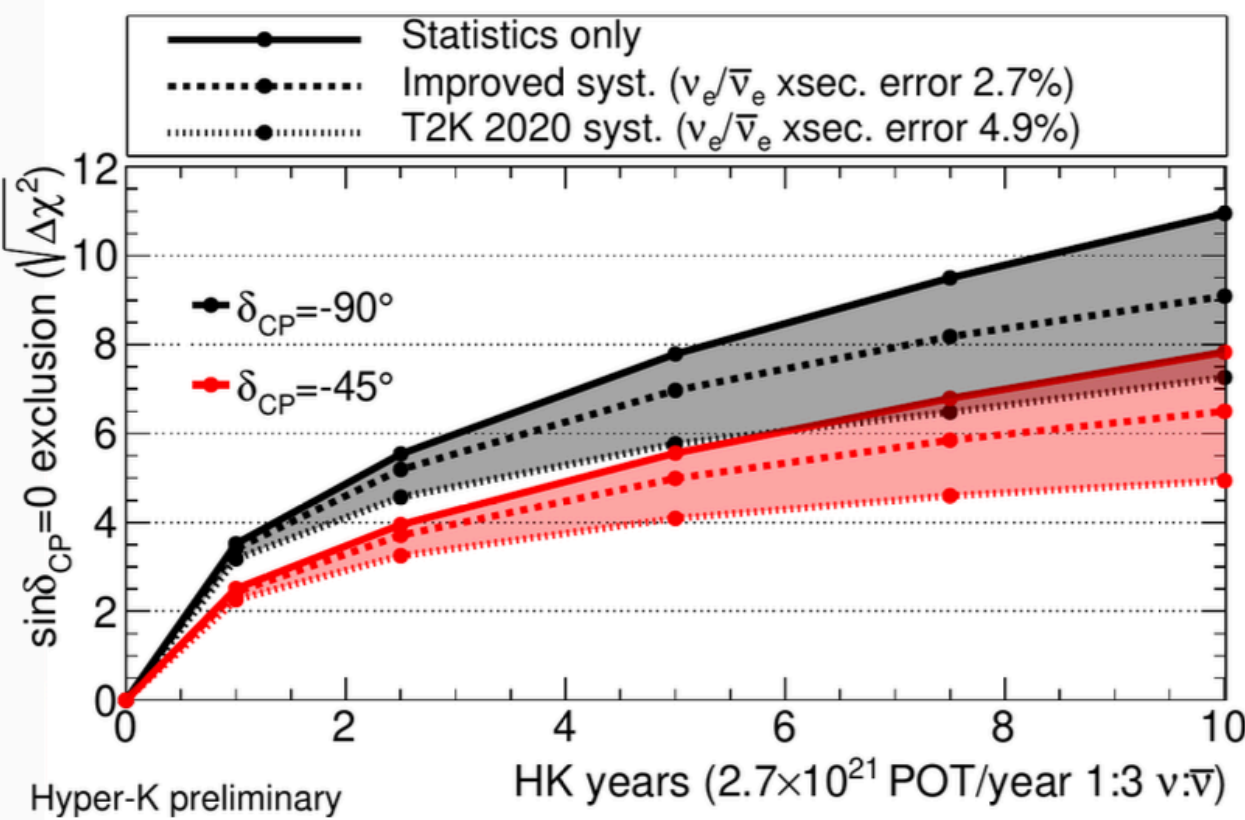
Oscillation Parameters

Generally the same setup as T2K

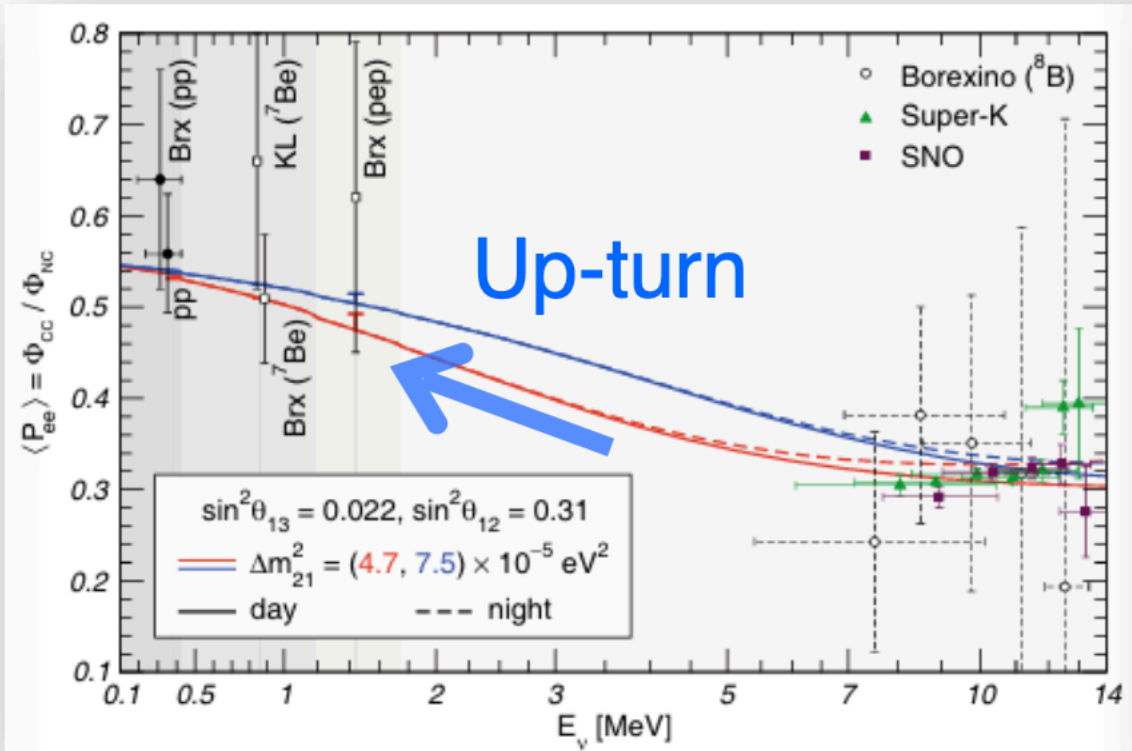
Baseline	295km
Off-axis angle	2.5 degree
Flux peak energy	0.6 GeV
Matter effect	Small

- ~20 times higher event rates than T2K
 - 1.3 MW beam x 187 kton of FD's fiducial mass
- For ν_e appearance, >1k events can be collected for each beam mode

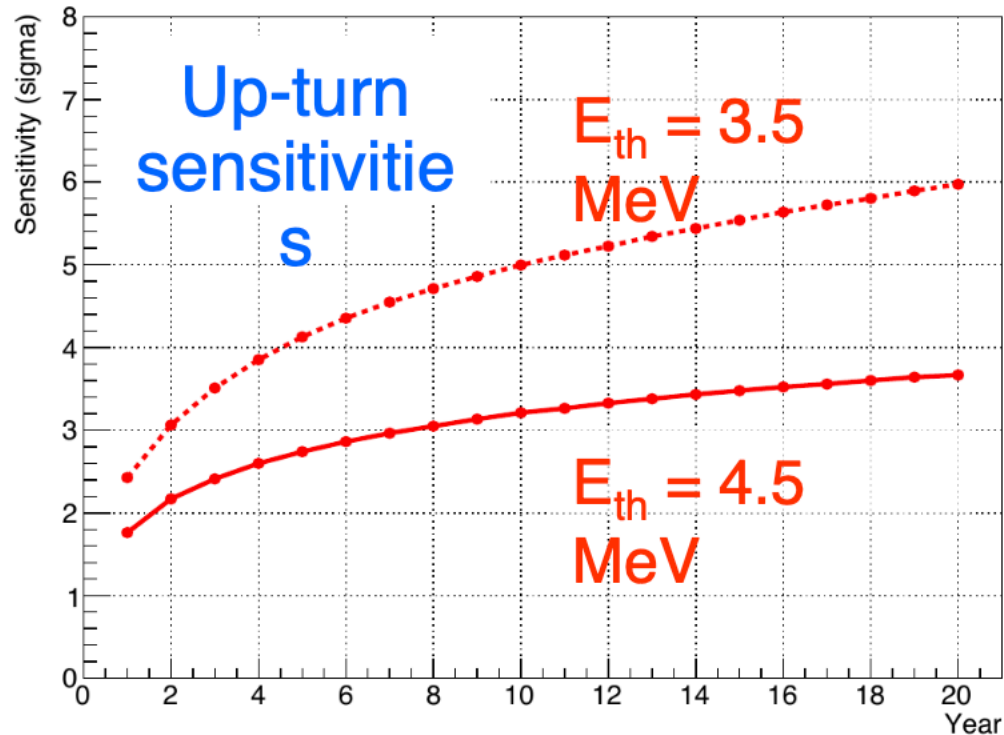
Hyper-Kamiokande



Impact of systematic uncertainty



M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)



- Solar 8B neutrino observation with ~130 events per day
- Confirmation of MSW effects by studying up-turn distortion
 - >3σ sensitivities in 10 years

	True $\sin^2\theta_{23}$	Atmospheric only	Atmospheric + accelerator
Mass ordering	0.40	2.2σ	3.8σ
	0.60	4.9σ	6.2σ
θ_{23} octant	0.45	2.2σ	6.2σ
	0.55	1.6σ	3.6σ

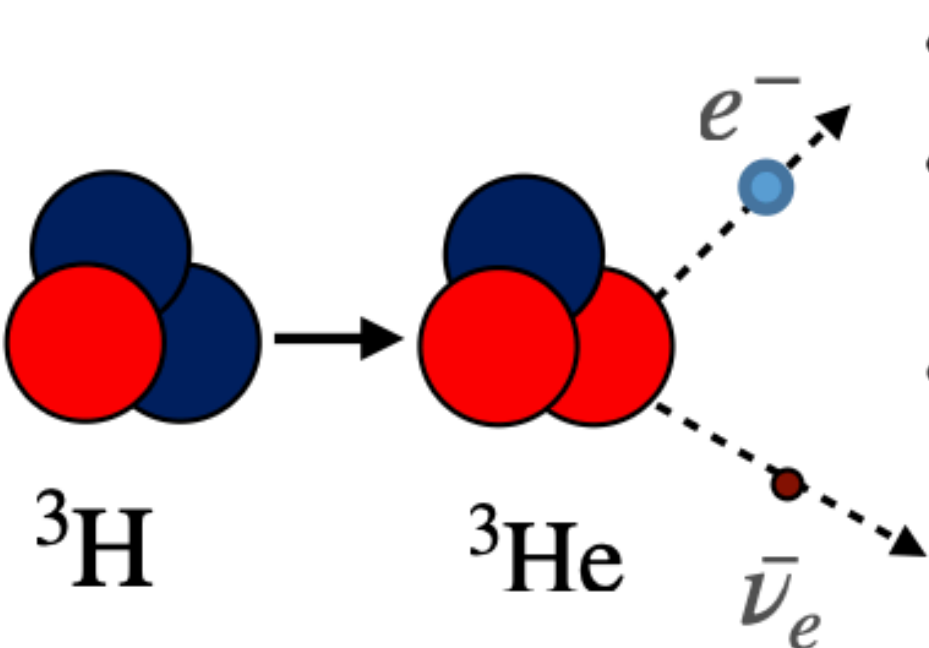
10 years w/ 1.3 MW beam & normal ordering assumed

PROJECT 8, HOLMES, ECHo

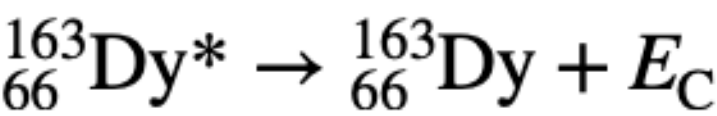
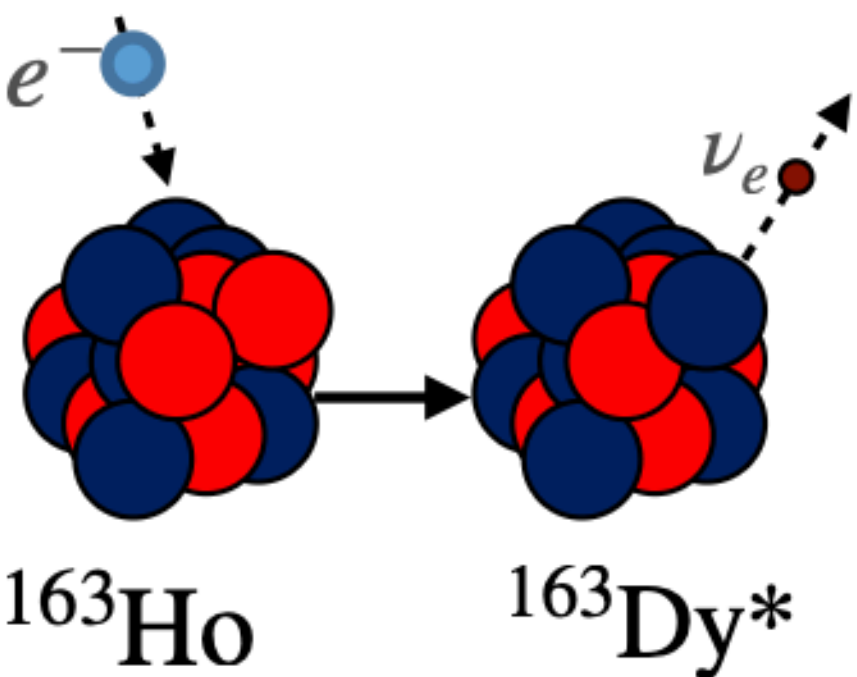
Absolute Neutrino Mass Scale

[Neutrino 2026]

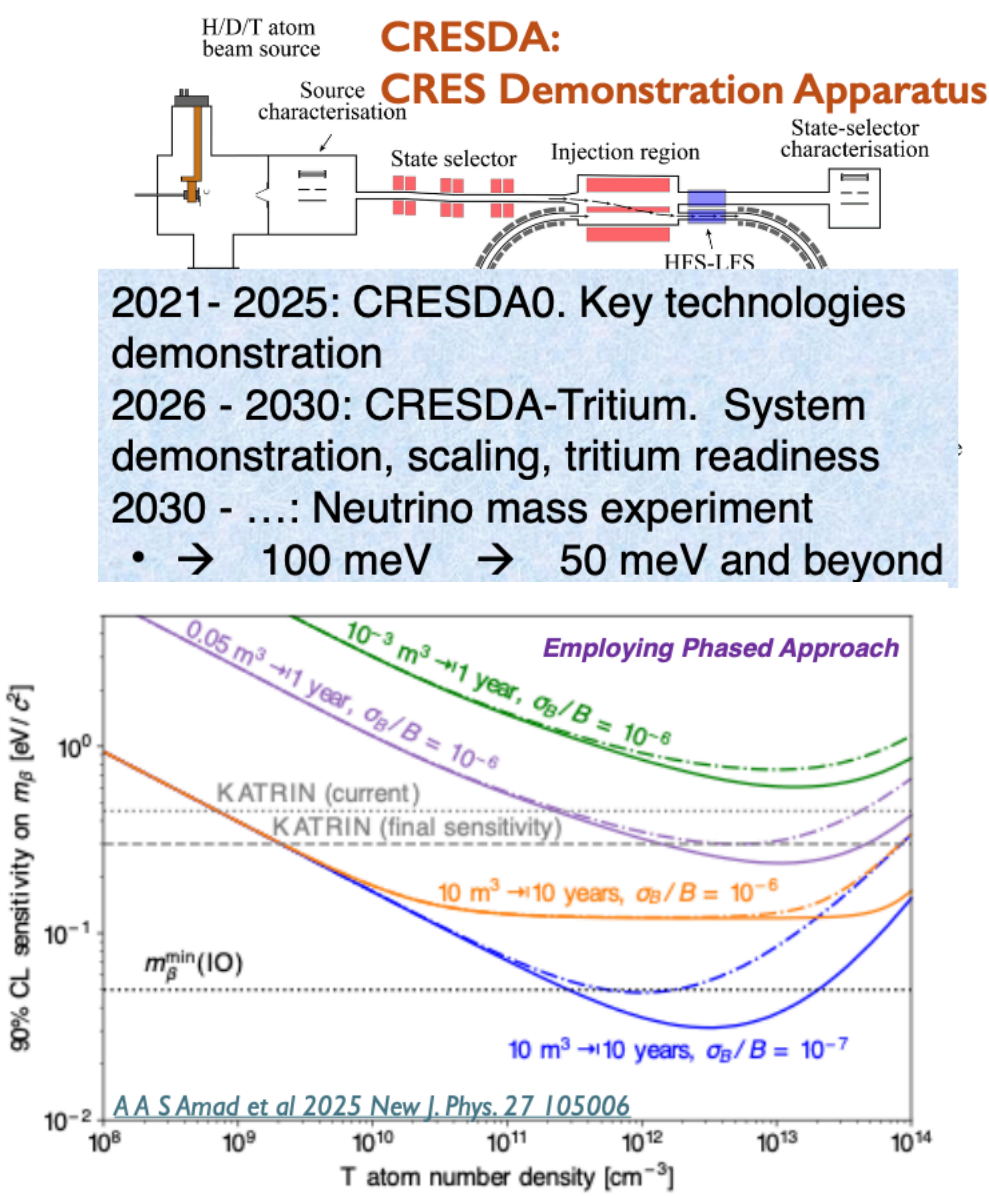
★ New Technologies



- Beta decay of neutron-rich nucleus
- Anti-neutrino escapes; electron's kinetic energy encodes neutrino mass
- Tritium:
 - $\tau_{1/2} = 12.3 \text{ yr}$
 - Fraction in last eV: 2.9×10^{-13}
 - Well-understood final state distribution



- Atomic electron capture by a proton-rich nucleus
- Neutrino escapes; de-excitation energy of the daughter nucleus encodes neutrino mass
- ${}^{163}\text{Ho}$:
 - $\tau_{1/2} = 4570 \text{ yr}$
 - Fraction in last eV: $\sim 10^{-12}$
 - Precise modeling required; significant recent progress

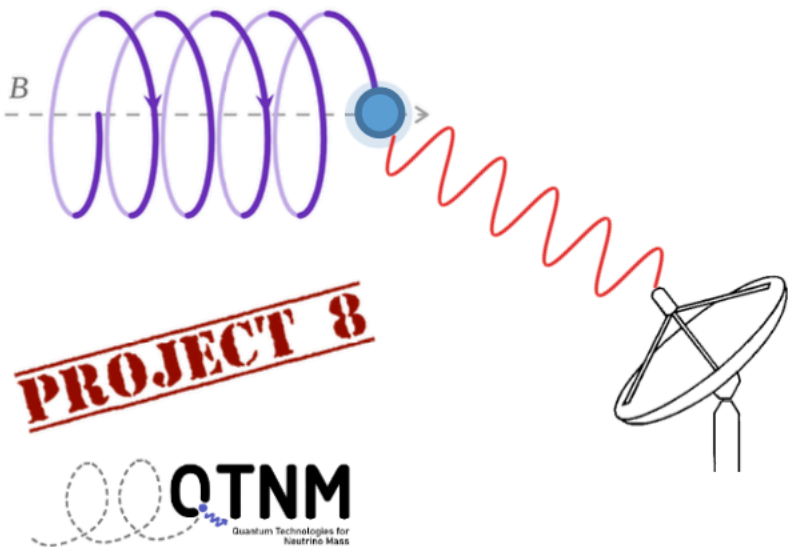


ECHo-LE (2026 - 2030)

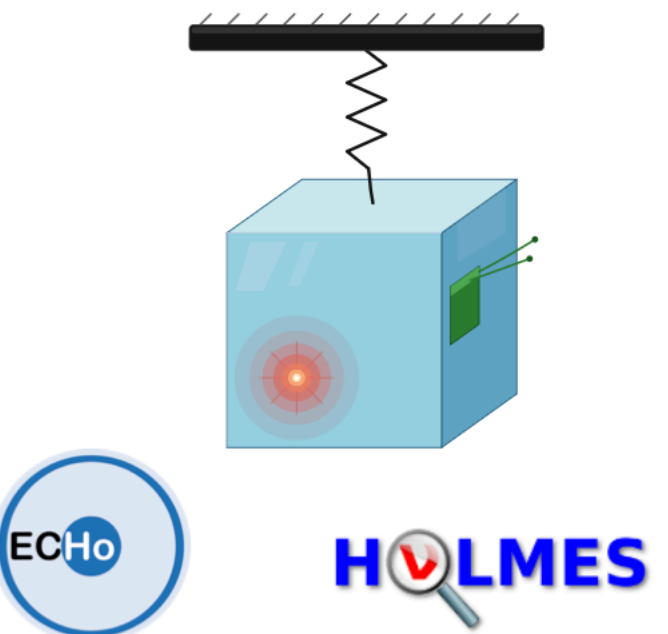
Activity per pixel $\sim 10 \text{ Bq/pixel}$
Number of detectors: 20000 → Multiplexed readout
 $\Delta E_{\text{FWHM}} < 5 \text{ eV}$
 $f_{\text{pu}} < 10^{-6}$
 $b < 10^{-6} \text{ eV/detector/day}$

$m_\beta < 0.8 \text{ eV}/c^2$ (90% C.L.)

Cyclotron Radiation Emission Spectroscopy (CRES)



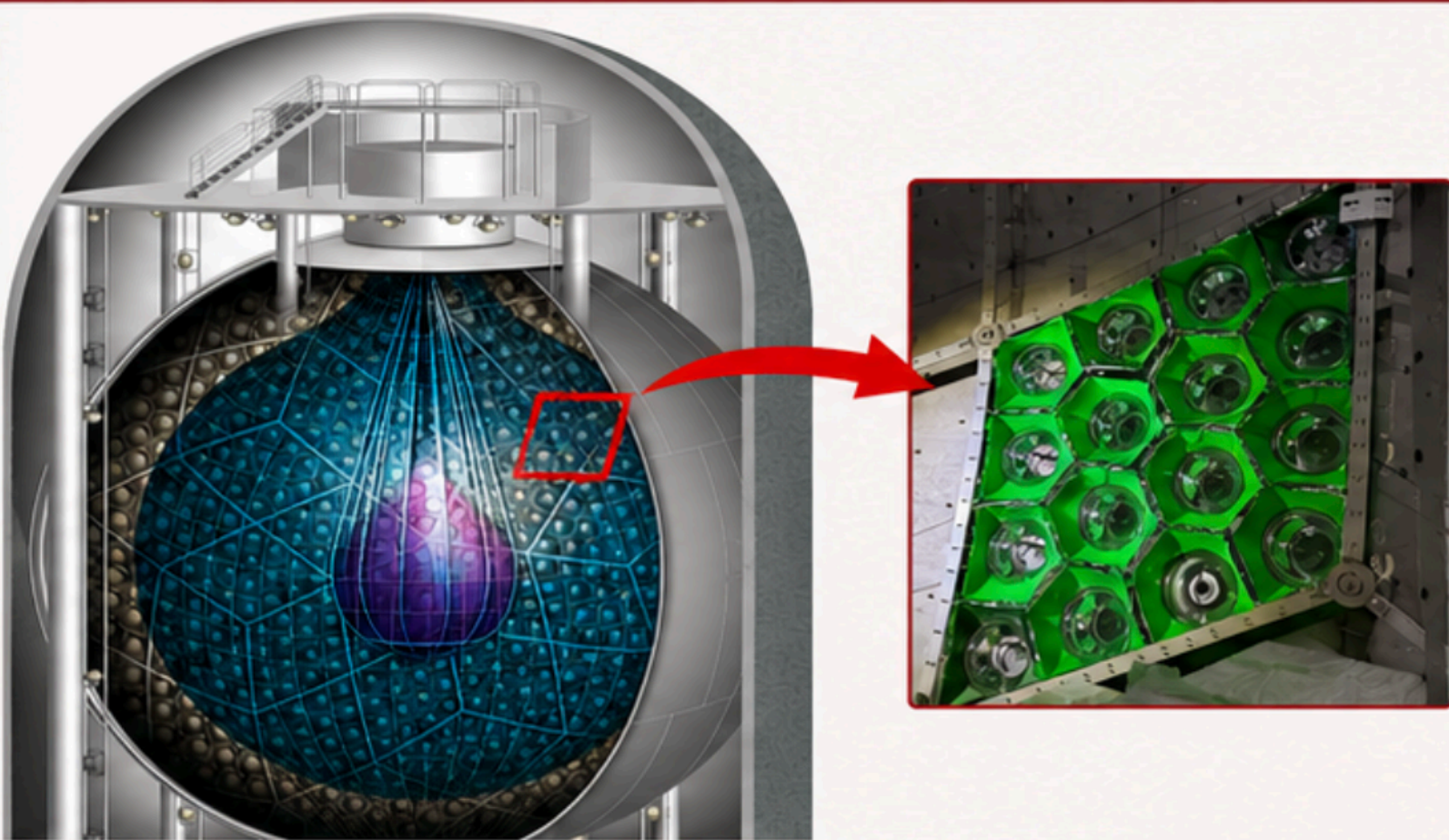
Cryogenic Microcalorimetry



KamLAND2-Zen, nEXO, LEGEND ...

$0\nu\beta\beta$ - decay : Dirac or Majorana?

KamLAND2-Zen



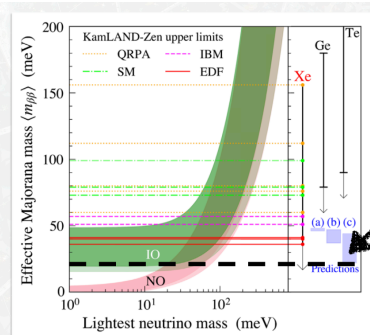
Upgrade an existing observatory

- More light: mirrors + HQE PMTs
- 5x photons / MeV
- ~2% energy resolution at $Q_{\beta\beta}$
- AI-enabled reconstruction and spallation rejection
- More isotope: Xe-loading upgrade → several tonnes of ^{136}Xe

Main DAQ start: 2028

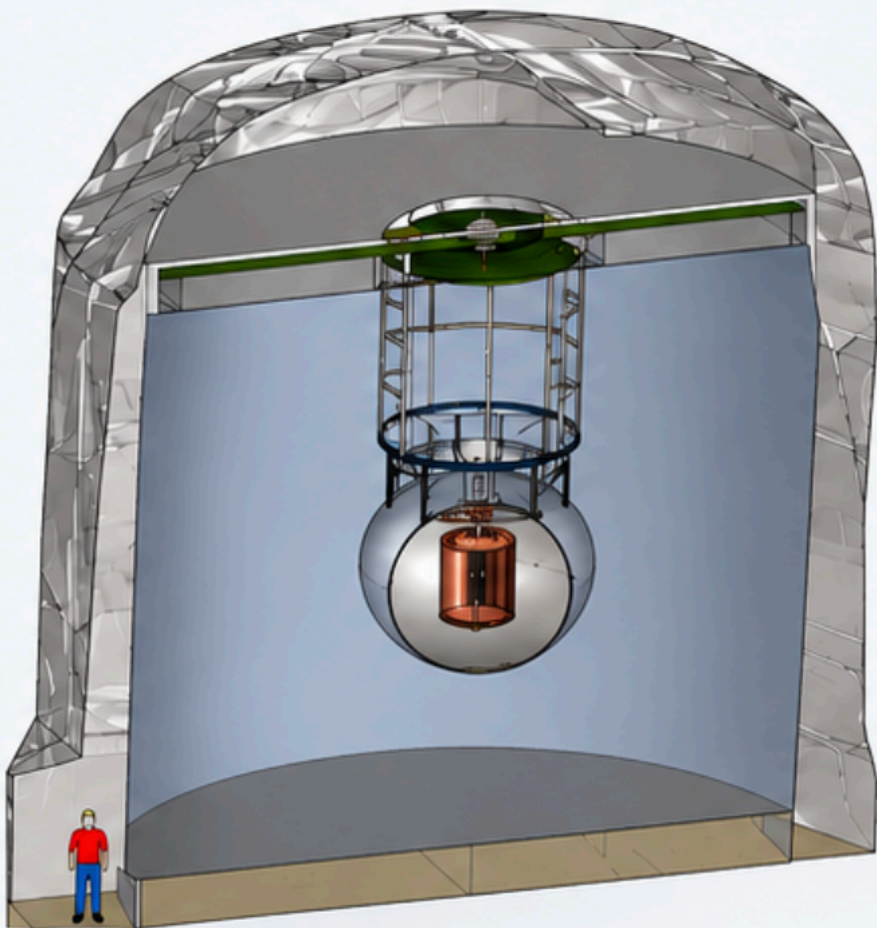
Target sensitivity: $\langle m_{\beta\beta} \rangle \sim 20 \text{ meV}$ (5 years)

Record Sel



- Energy Resolution
4% → 2% @ 2.458 MeV
- Cover IO region almost completely (NME precision)
- Target mass limit
 $\langle m_{\beta\beta} \rangle \sim 20 \text{ meV}$ / 5 Years
- Target half life limit for 5 Years
 $T > 2 \times 10^{27} \text{ years}$ (90% C.L.)

nEXO



Build a dedicated detector from the ground up

Multi-ton enriched xenon (~5 tonnes ^{136}Xe)

Monolithic LXe TPC

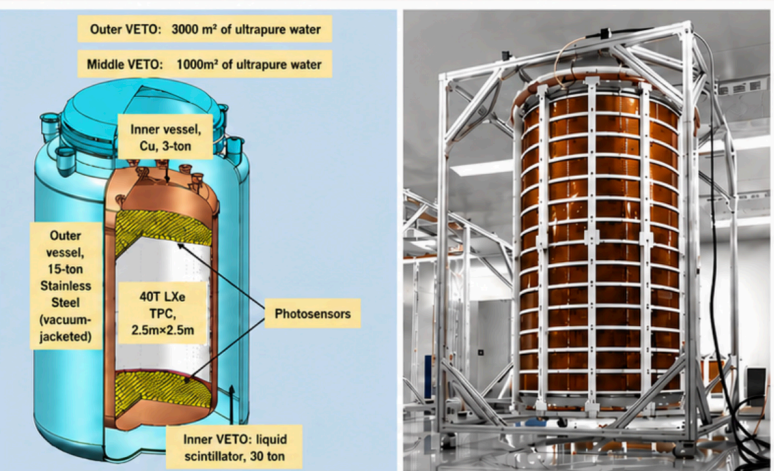
Self-shielding: ultra-low background environment

Topological discrimination: energy, topology & standoff

Design goal: background-free
Sensitivity approaching 10^{28} yr

ected Portion

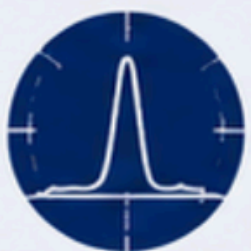
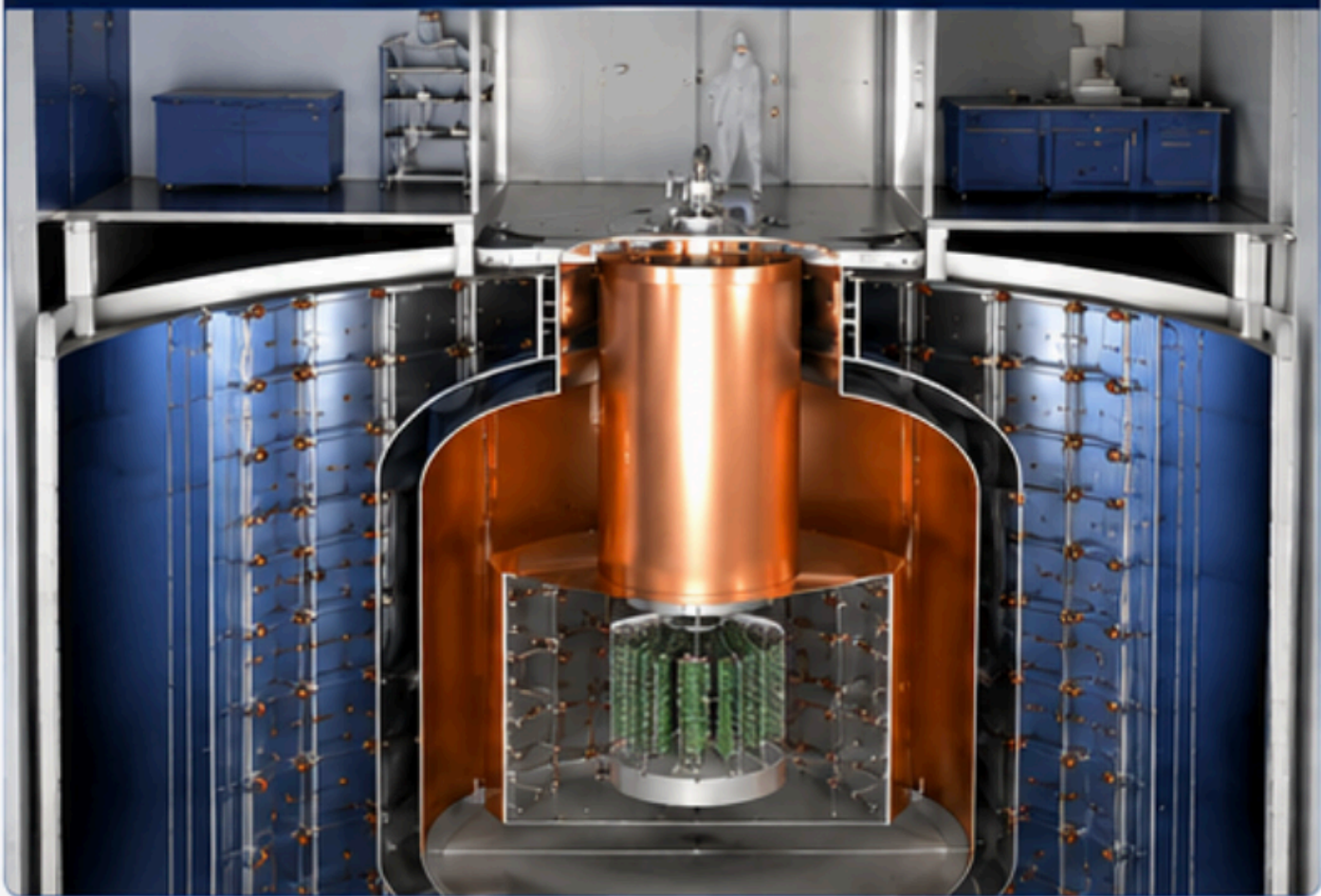
PandaX-xT



Scaling a proven xenon program

- 43 t liquid xenon target
- Dark matter & $0\nu\beta\beta$ flagship
- 20 t first stage fully funded
- Planned operation in 2028

LEGEND LEGEND-6000 (Concept)



Precision Spectroscopy

Ultra-high energy resolution to isolate the signal

- 0.12% FWHM at $Q_{\beta\beta}$ (best resolution at $0\nu\beta\beta$ Q-value)
- Post-LEGEND-1000 concept: LEGEND-6000
- 133 strings of larger detectors: 6 tons Ge
- 15 years livetime / 100 t-yr exposure
- $T_{1/2}$ sensitivity $\sim 10^{29} \text{ yr}$ → $m_{\beta\beta} \approx 3-6 \text{ meV}$

SUMMARY OF THE LECTURES

What have we learned?

- We have a theoretical framework for neutrino flavor oscillations based on masses & mixings in vacuum and in matter
- This framework explains well the available oscillation data
- We still do not know the neutrino mass ordering (some hits now of NO)
- We still do not know if we have CP violation in the leptonic sector
- We still do not know the octant of θ_{23}
- We still do not know the absolute neutrino mass scale
- We still do not know if neutrinos are Dirac or Majorana particles

SUMMARY OF THE LECTURES

What are the future perspectives?

- High precision experiments era started with JUNO in 2025 (sub-%)
- KM3Net/ORCA (not yet complete) + IceCube (11 yrs) → IceCubeGen2
- DUNE & Hyper-Kamiokande (CP-violation)
- KATRIN → PROJECT X, HOLMES, ECHo (towards absolute mass scale)
- KamLAND-ZEN → KamLAND2-ZEN, nEXO, LEGEND, etc.
- Many experiments to come - many possible new discoveries ahead...