Super-Kamiokande Status and Prospects

Vietnam Flavour Physics 2025

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The Super-Kamiokande collaboration

~240 collaborators
from 55 institutes, 11 countries

Contents

Super-Kamiokande: Detector & Physics

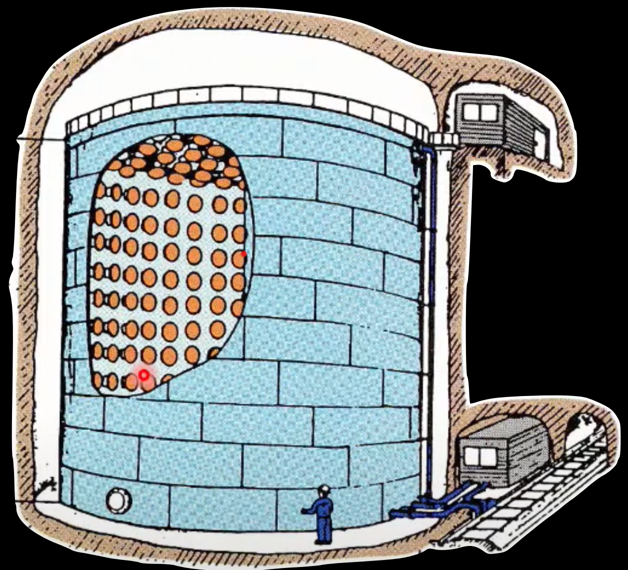
Status: PMNS mixing & BNV search

Recent Gd dissolution for neutron detection

The “Kamiokande” series (1983-)

Started as *Kamioka **N**ucleon **D**ecay **E**xperiment*
to test GUT predictions on proton lifetime (minimal SU(5): ~10^{31} years)

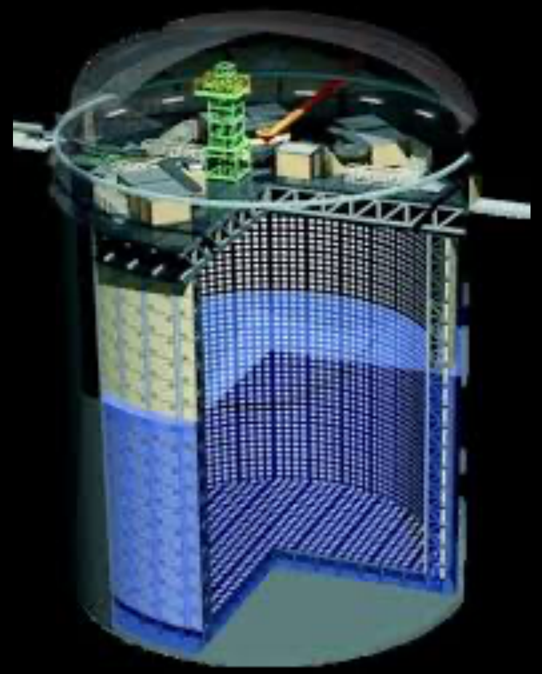
KamiokaNDE
1983-1996



3 kton water
(~10^{33} protons)

Discovery of
Supernova ν
(1987)

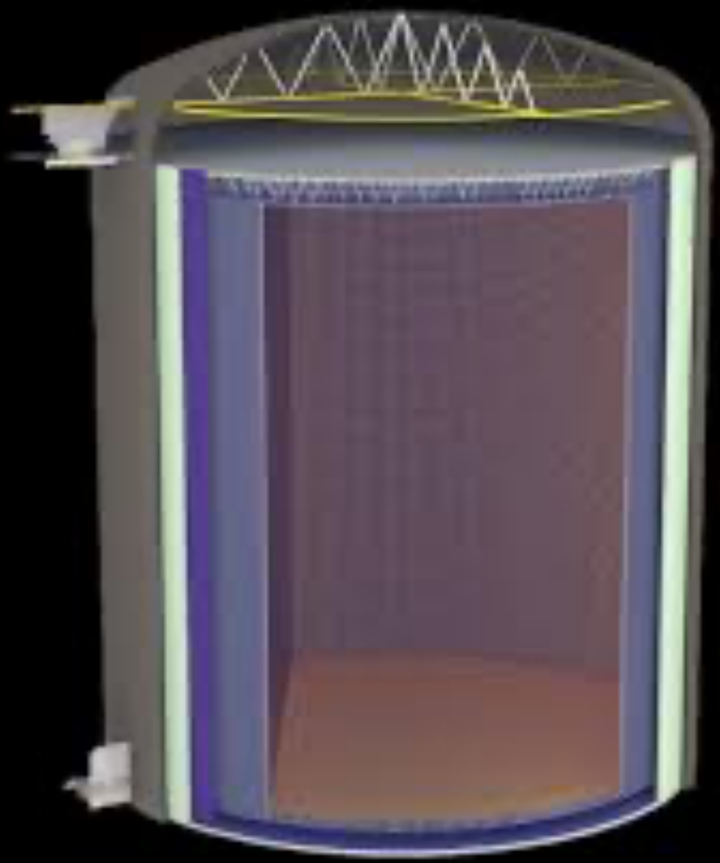
Super-Kamiokande
1996-present



50 kton

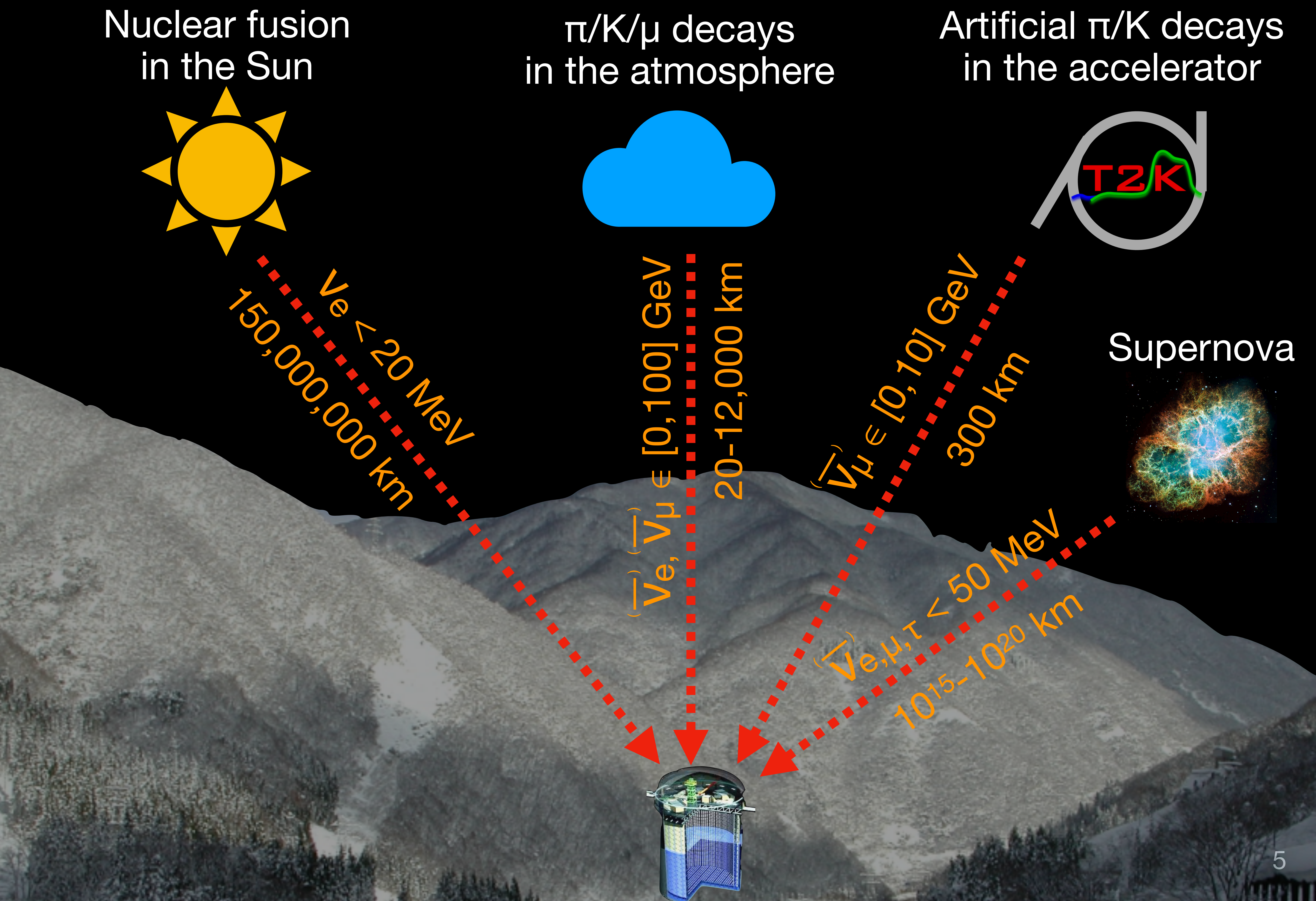
First evidence of
ν mixing (1998)

Hyper-Kamiokande
2028?-

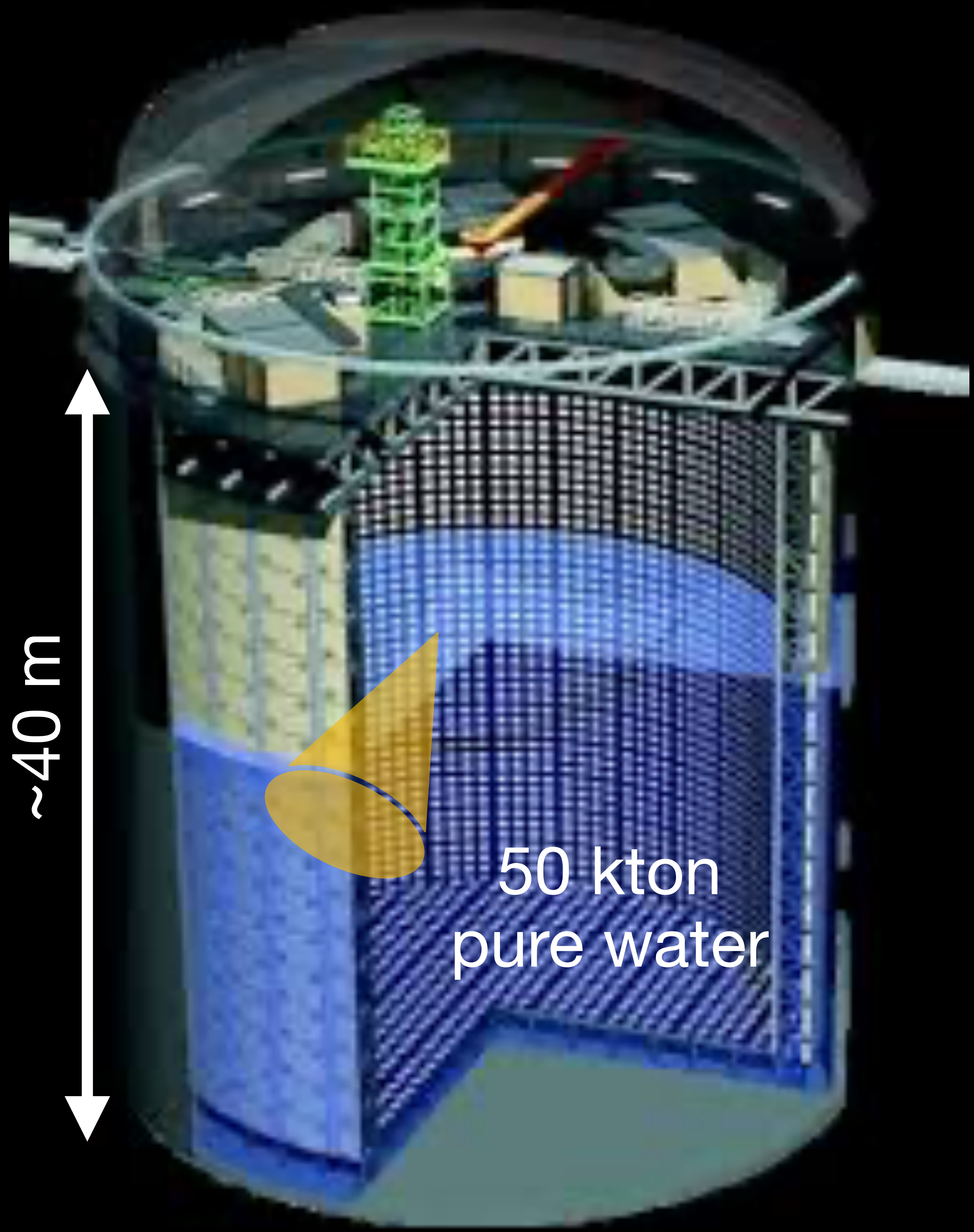


260 kton

?


Nuclear fusion in the Sun
π/K/μ decays in the atmosphere
Artificial π/K decays in the accelerator
T2K
Supernova
ν_e < 20 MeV
150,000,000 km
$\overset{(-)}{\nu}_e$, $\overset{(-)}{\nu}_\mu \in$ [0,100] GeV
20-12,000 km
$\overset{(-)}{\nu}_\mu \in$ [0,10] GeV
300 km
$\overset{(-)}{\nu}_{e,\mu,\tau}$ < 50 MeV
10^{15}-10^{20} km

Super-Kamiokande detector



~11,000 inward PMTs on tank wall

Outward PMTs for cosmic μ veto

Signals : **ν CC events**, p decay, etc.

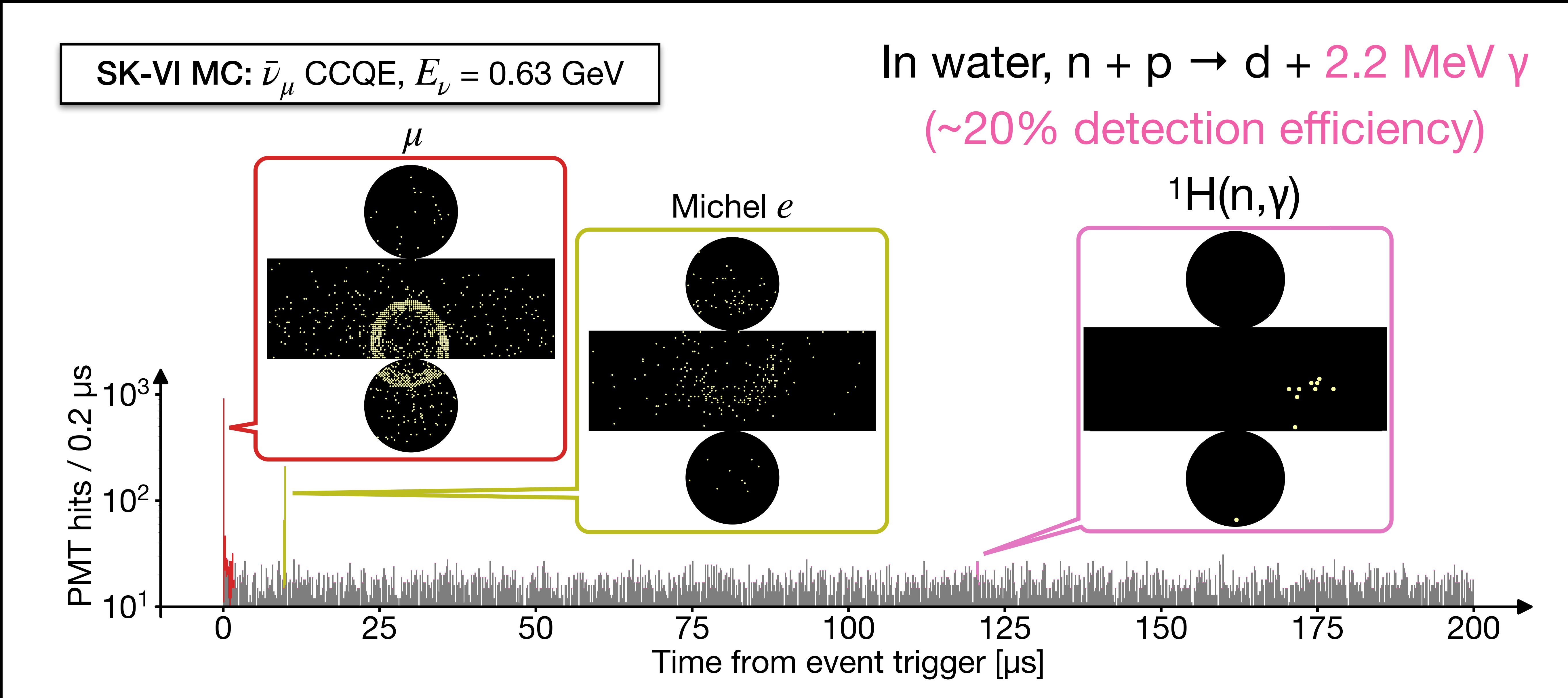
↪ Mainly Cherenkov ring(s) from e/μ

Typical ν event

$0.6\ \text{GeV}\ \bar{\nu}_\mu + p \rightarrow \mu + n$

Good flavor ID (e/μ)
via Cherenkov ring fuzziness

ν vs. ν̄ ID
via n final state in ν̄ CC



+ Good energy reconstruction precision
over O(1) MeV - O(10) GeV range

PMT noise

Neutrino mixing studies @ SK

Standard 3-flavor mixing framework

Mixing angles: θ_{12}, θ_{23}

Neutrino mass splittings: Δm_{12}^2, $|\Delta m_{23}^2|$

CP violation: $\sin \delta_{CP} \neq 0$?

Neutrino mass ordering: $m_1 < m_2 \ll m_3$ (normal)

or $m_3 \ll m_1 < m_2$ (inverted)

Solar

Atmospheric + Accelerator (T2K)

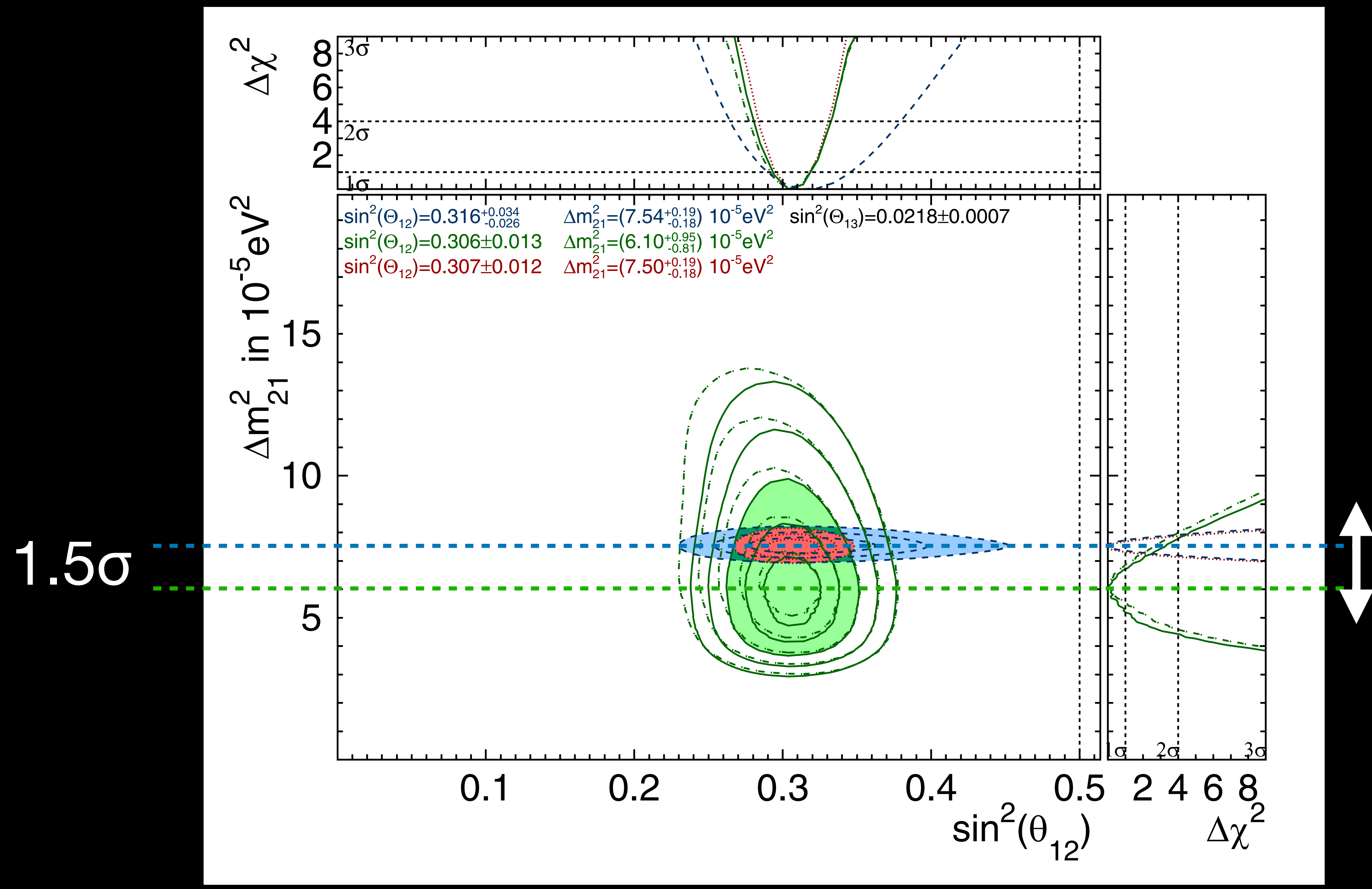
Test of the Standard Framework

Non-standard interactions, Non-unitarity, Lorentz violation, etc.

Solar ν mixing (ν_e,ν_μ) - (ν_1,ν_2)

$\sin^2\theta_{12} = 0.307 \pm 0.012$ ($\theta_{12} = 33.4° \pm 0.7°$)

$\Delta m_{21}^2 = 7.50^{+0.19}_{-0.18}\ 10^{-5}\ \mathrm{eV}^2$



PRD 109, 092001 (2024)

Solar
(SK + Global data)

Reactor
(KamLAND)

Combined

θ_{13} constrained by shorter baseline reactor ν data (PDG 2020)

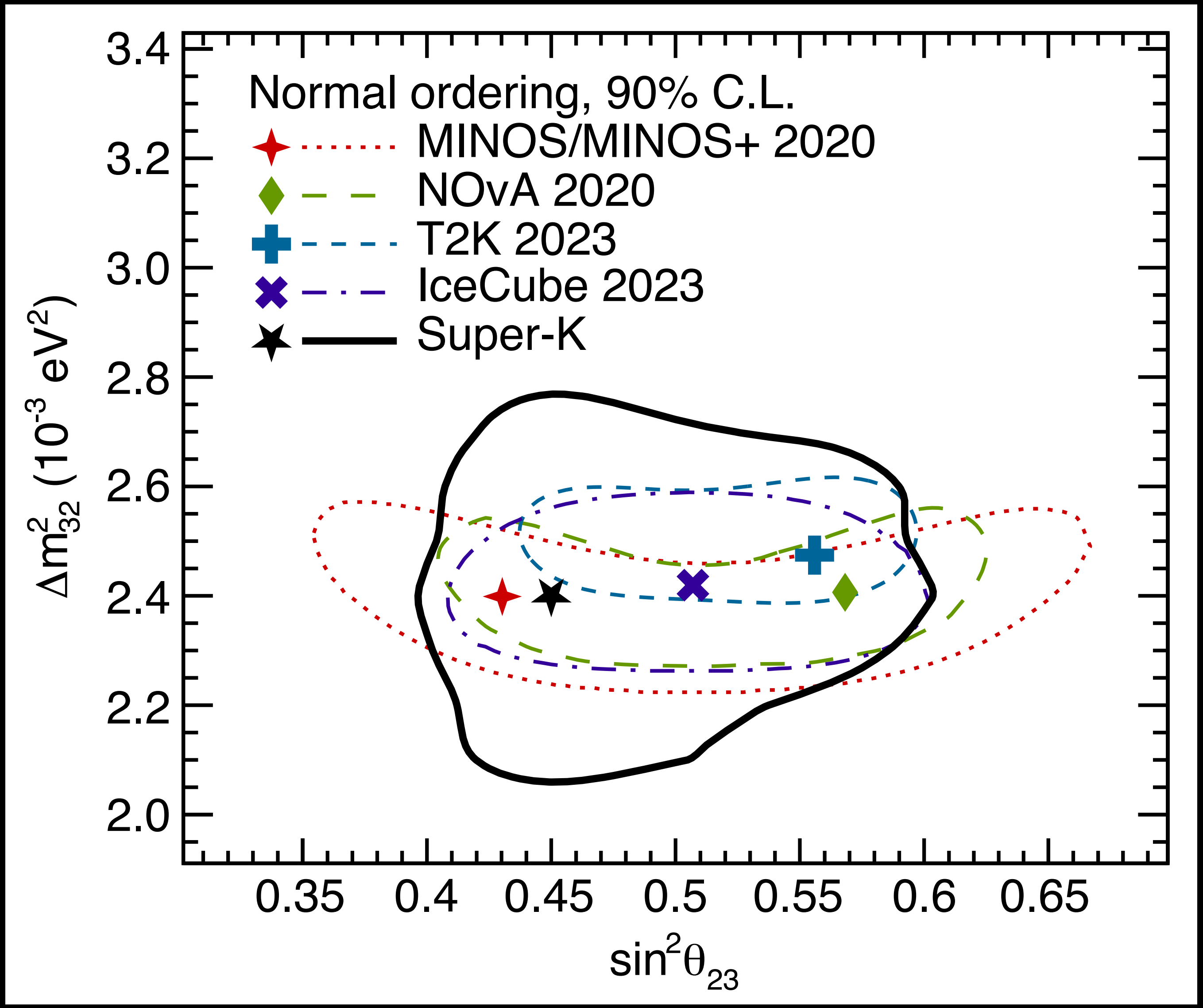
Atm. ν mixing (ν_μ,ν_τ) - (ν_2,ν_3)

$\sin^2\theta_{23} = 0.45^{+0.06}_{-0.03}$ ($\theta_{23} = 42.2°^{+3.3°}_{-1.7°}$)

$|\Delta m_{32}^2| = 2.40^{+0.07}_{-0.09}\ 10^{-3}\ eV^2$

Assuming Normal MO
with θ_{13} constraint

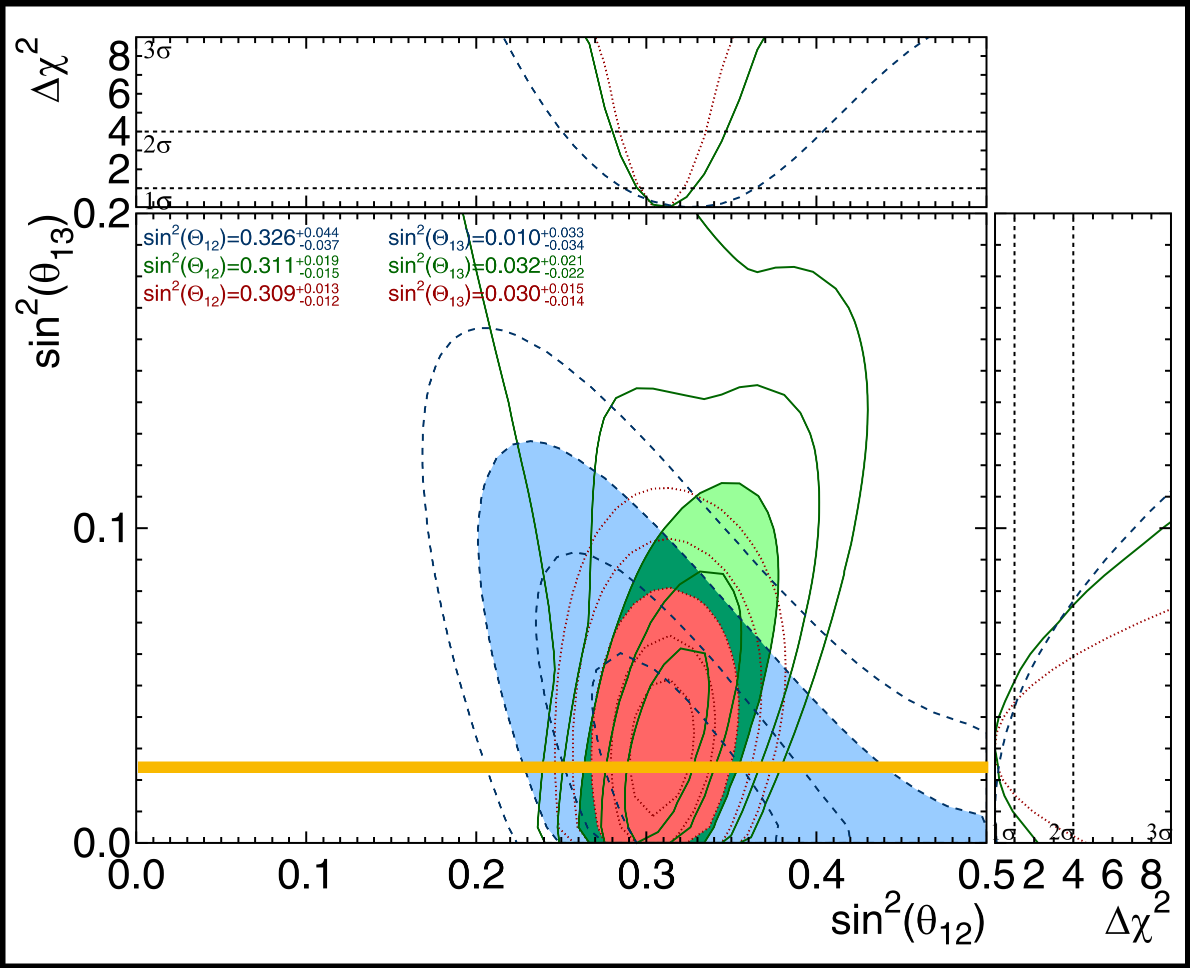
No conclusion on whether $\theta_{23} \neq \pi/4$



PRD 109, 072014 (2024)

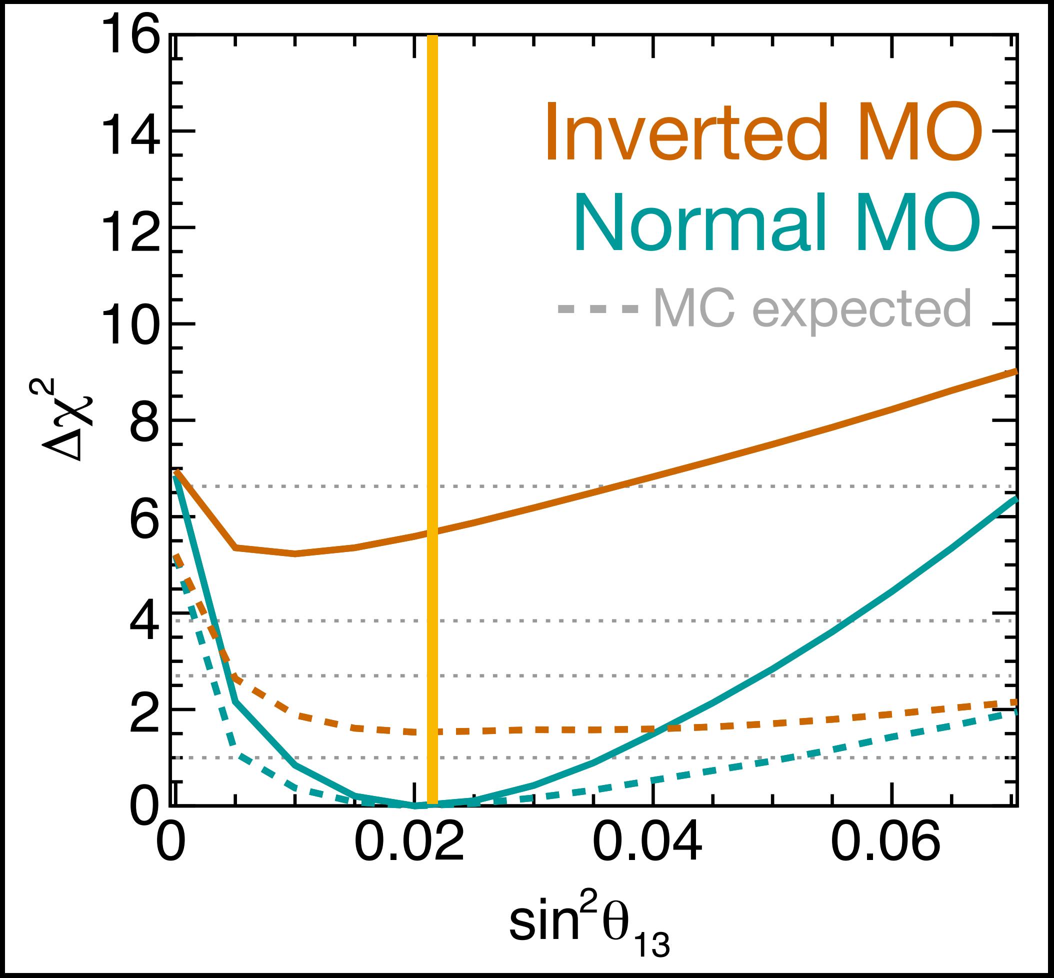
Solar/atm. ν also prefers $\theta_{13} \neq 0$

Solar



PRD 109, 092001 (2024)

Atmospheric



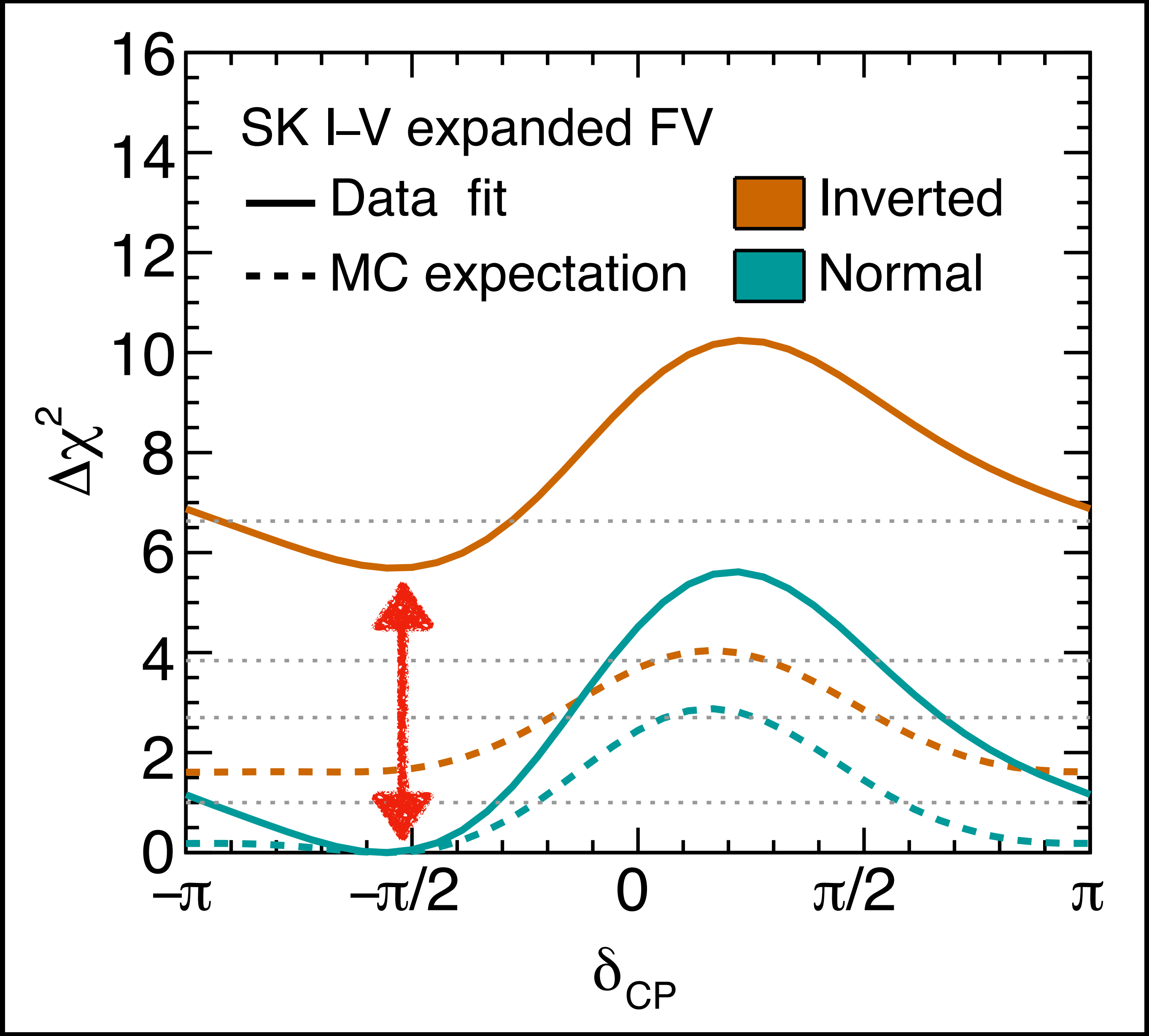
PRD 109, 072014 (2024)

Without shorter baseline reactor data constraint

Neutrino MO and CP phase δ

Normal MO favored at 92.3% CL

$\delta_{CP} = -1.75^{+0.76}_{-1.25}$ $(-0.56^{+0.24}_{-0.40}\pi)$ (assuming Normal MO)



PRD 109, 072014 (2024)

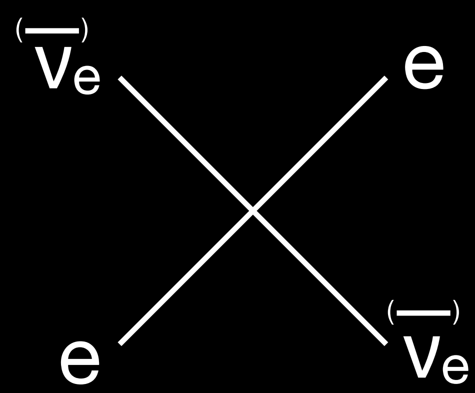
SK sensitivity to neutrino MO (pure water)

ν vs. $\bar{\nu}$ ID based on #e and #n

Effective mixing in matter

a.k.a Mikheyev-Smirnov-Wolfenstein (MSW) effect

CC coherent scattering with electrons in matter induces effective potential ∝ electron density n_e, for $\overset{(-)}{\nu}_e$ only



$E_\nu \ll M_W$

$$V_{CC} = \pm\sqrt{2}G_F n_e$$

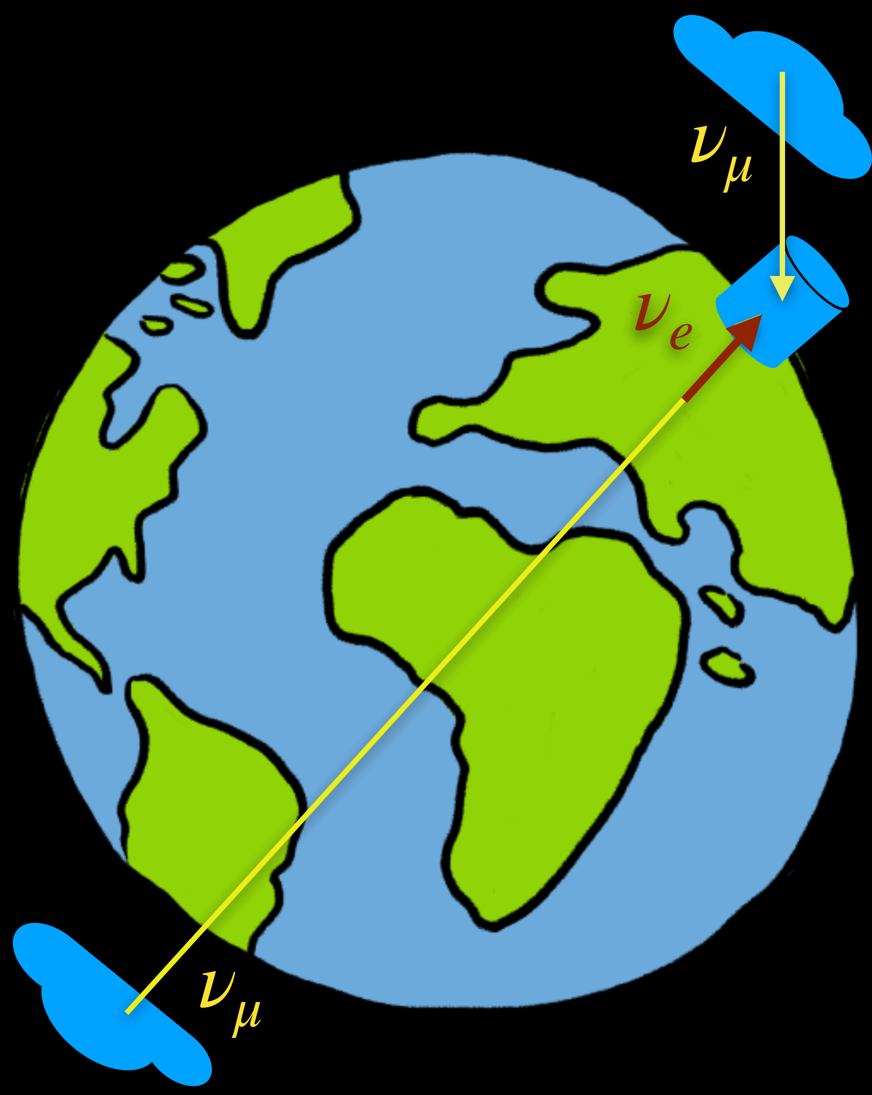
$$V_{NC} = -\frac{\sqrt{2}}{2}G_F n_n$$

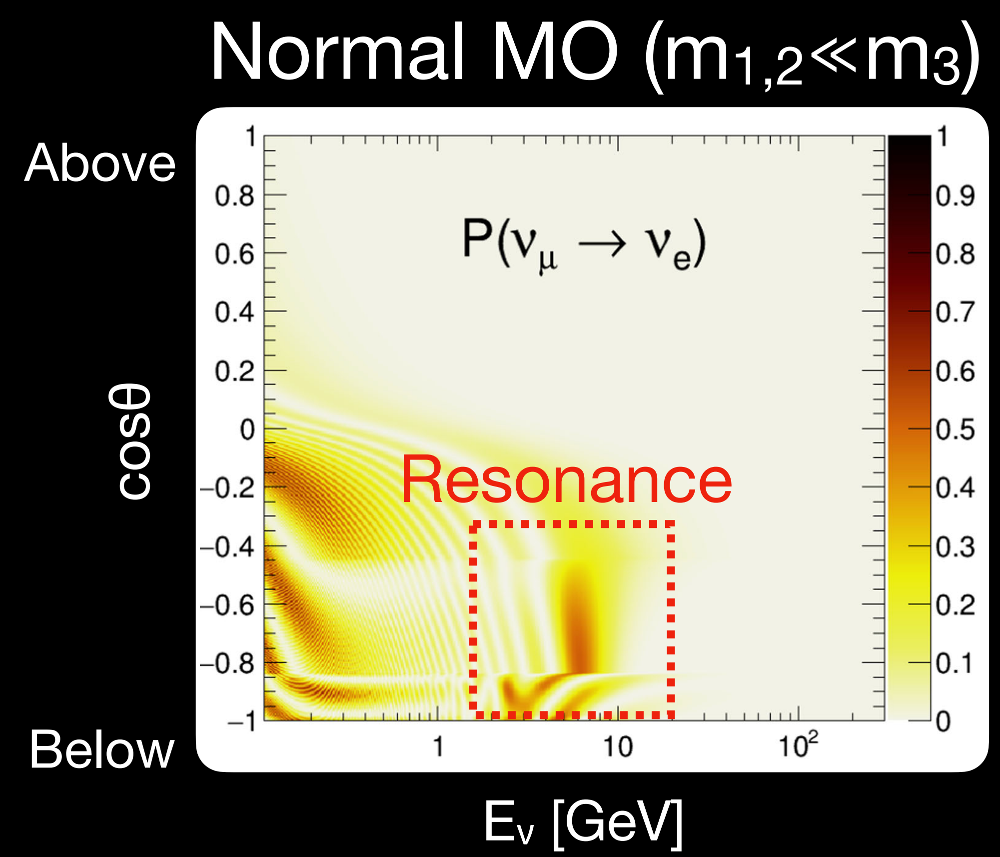
$$H_{flavor} = U\frac{1}{2E}\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}U^\dagger \underset{(-)}{+} \begin{pmatrix} \sqrt{2}G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

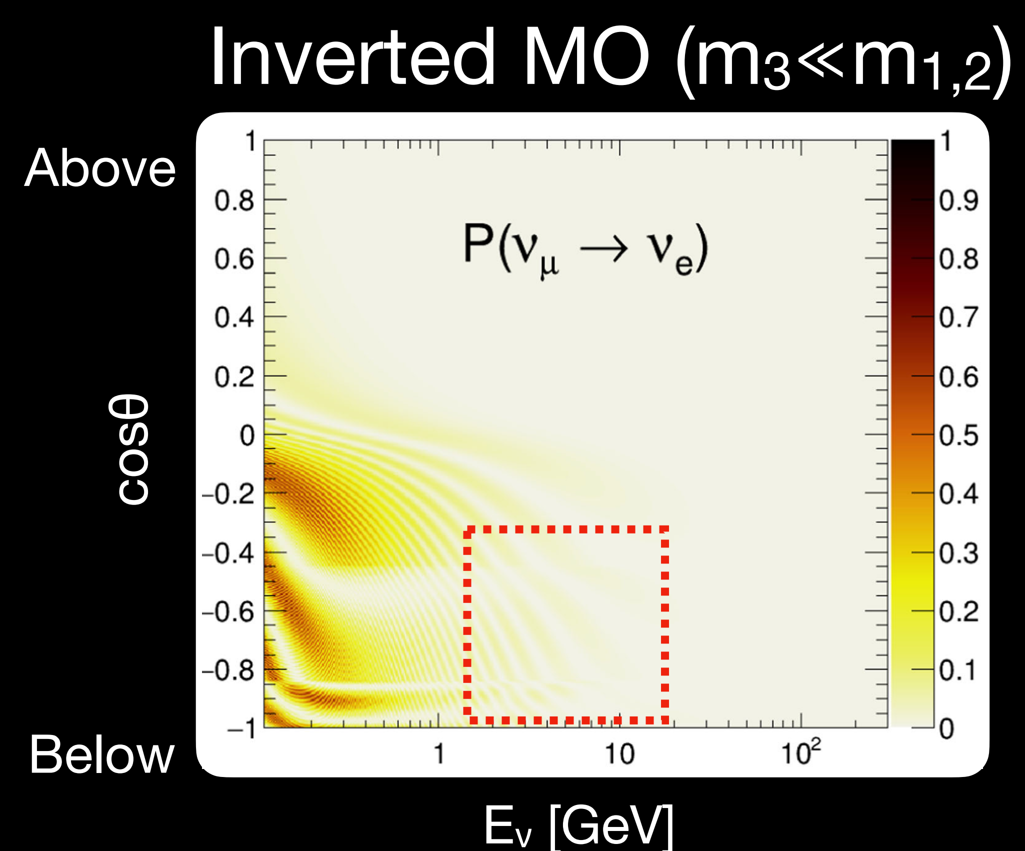
$$= \tilde{U}\frac{1}{2E}\mathrm{diag}(\tilde{m}_1^2, \tilde{m}_3^2, \tilde{m}_3^2)\tilde{U}^\dagger$$

Can mimic CPV
Add sensitivity to νMO

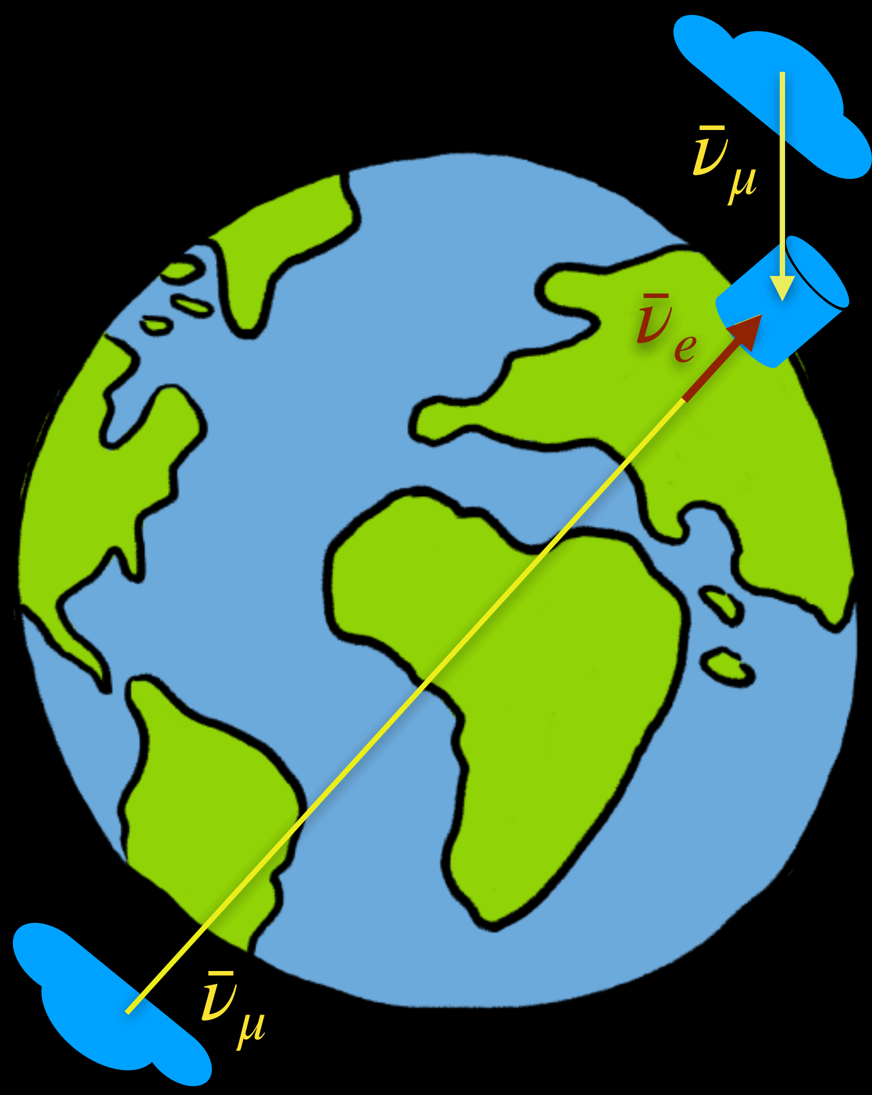
Atmospheric Neutrinos



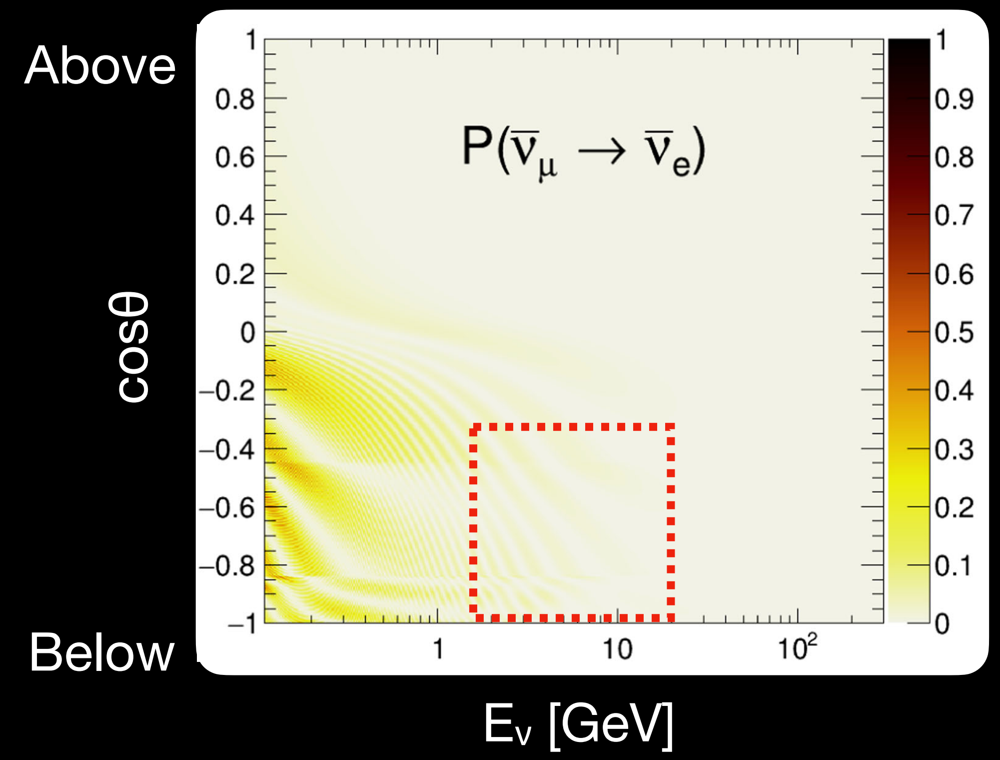




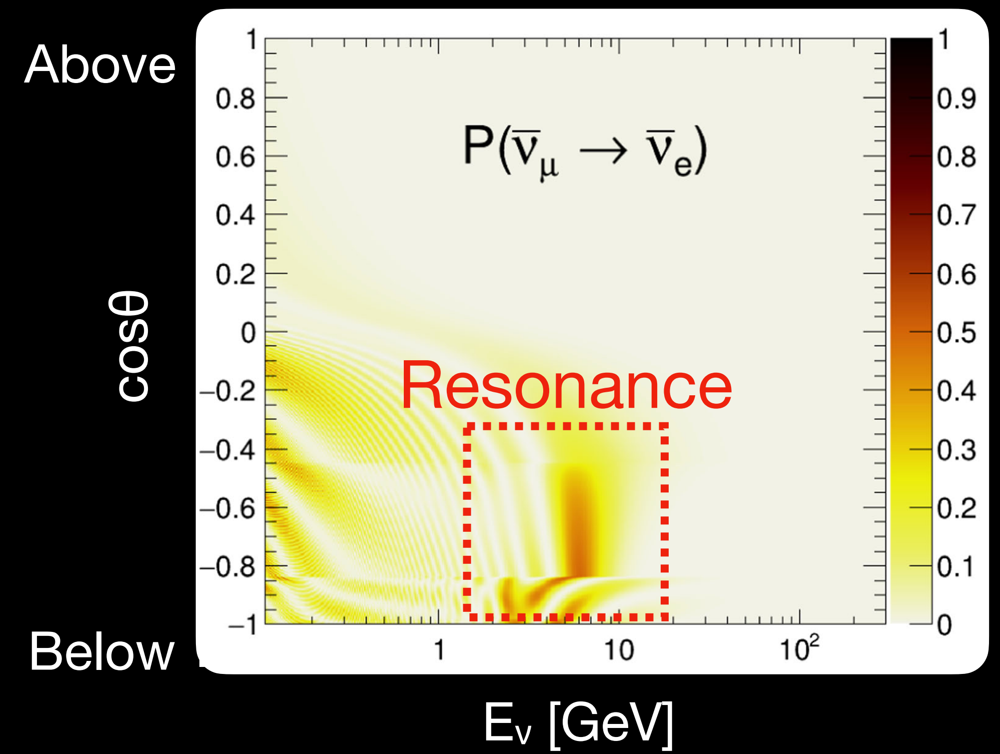
Atmospheric Antineutrinos



Normal MO ($m_{1,2} \ll m_3$)



Inverted MO ($m_3 \ll m_{1,2}$)

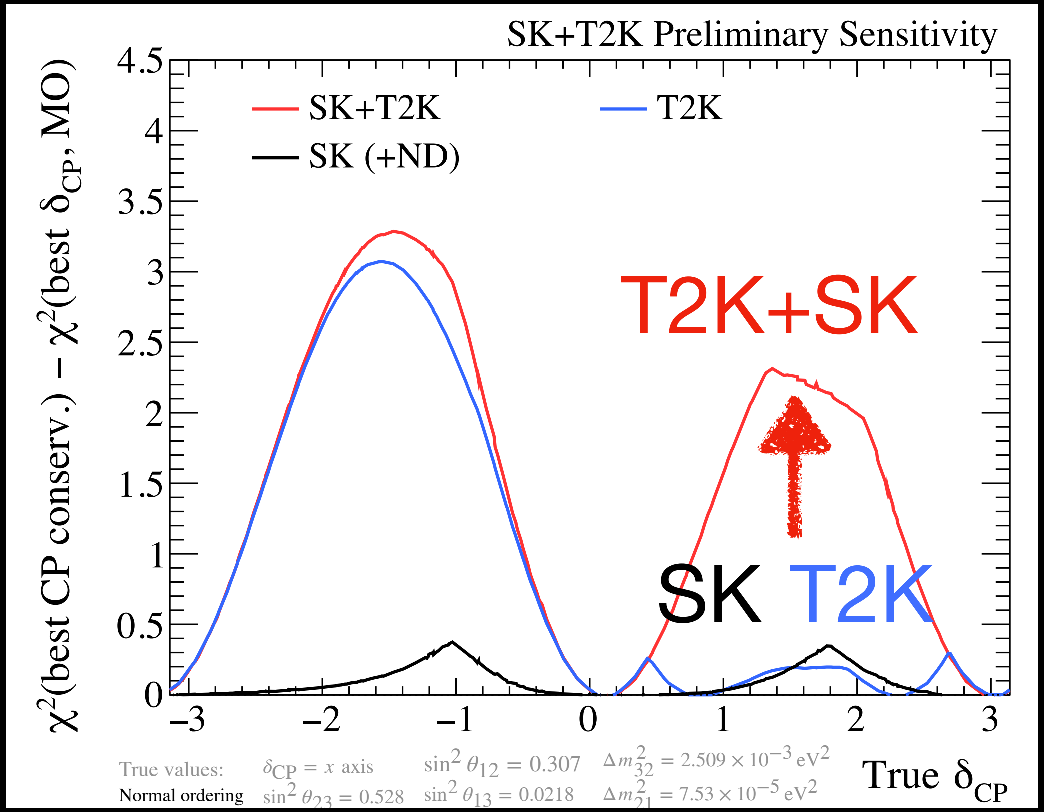


Resolving the degeneracy

	Pros	Cons
Atm. ν	Sensitive to νMO	ν and $\bar{\nu}$ mixed
Acc. ν	ν and $\bar{\nu}$ separated	CPV-νMO degeneracy

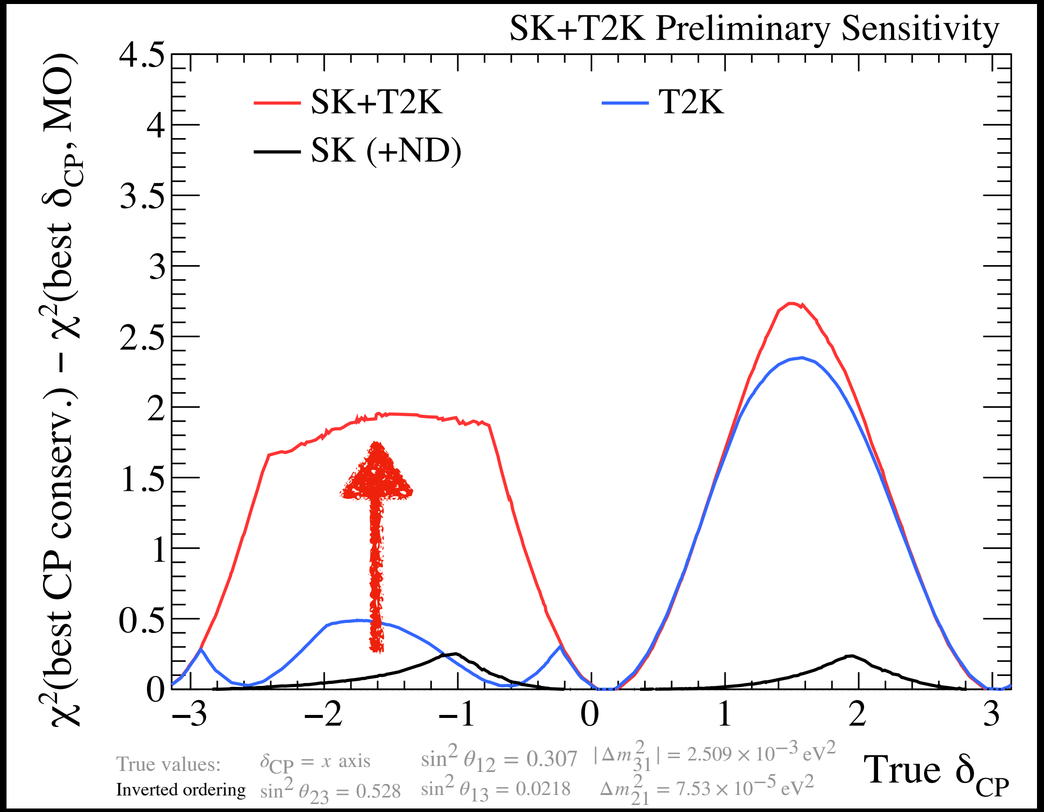
CPC rejection power

True Normal MO



True δ_{CP}

True Inverted MO



True δ_{CP}

T2K+SK joint fit

Joint framework of interaction model, systematics, analysis

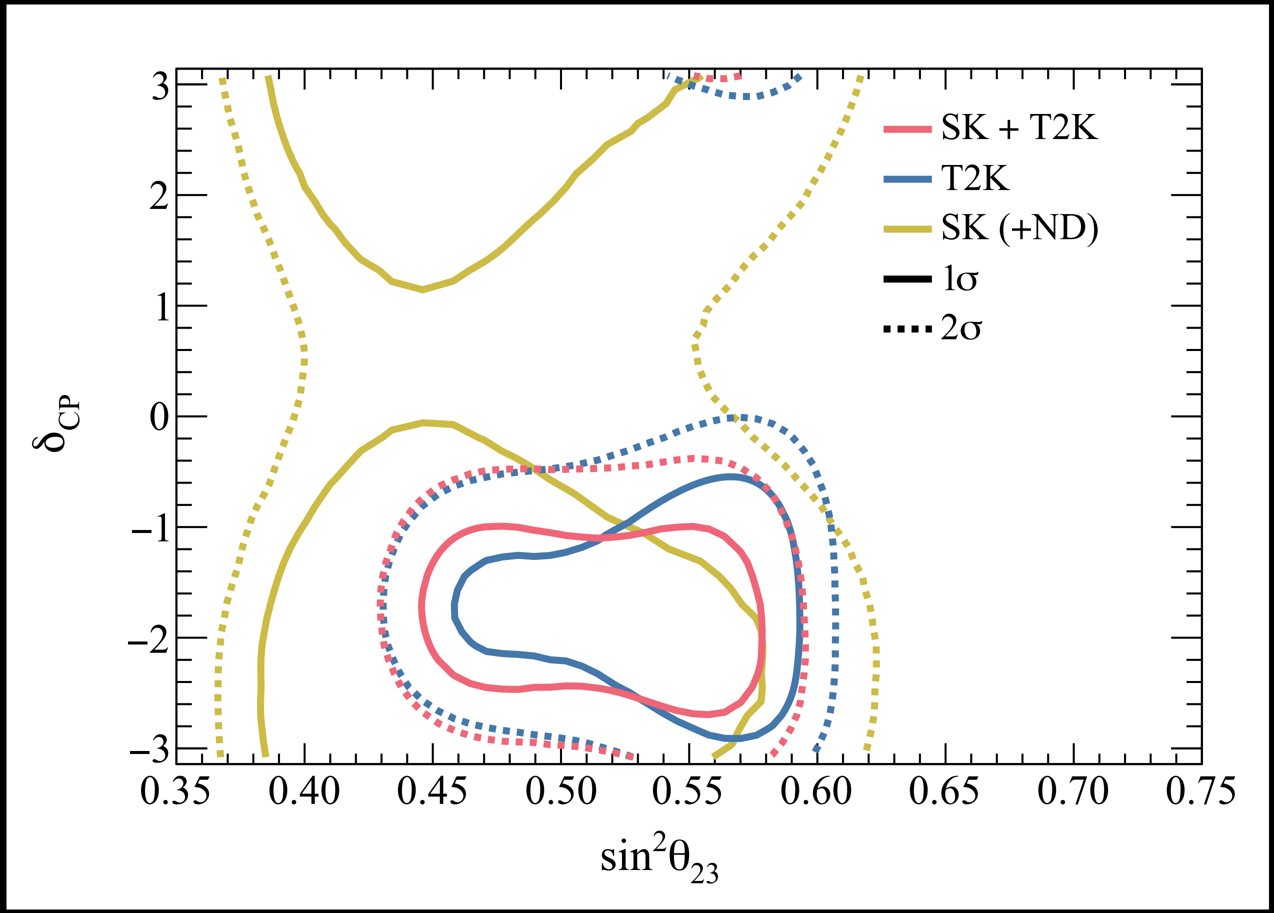
SK atm. ν final state predictions constrained by T2K near detector data

$\sin^2\theta_{23} = 0.468^{+0.106}_{-0.025}$ ($\theta_{23} = 43.2°^{+6.2°}_{-1.3°}$)

$|\Delta m_{32}^2| = 2.52^{+0.048}_{-0.058}\ 10^{-3}\ \text{eV}^2$

CPC disfavored by ~2σ

PRL 134, 011801 (2025)



Baryon number violation

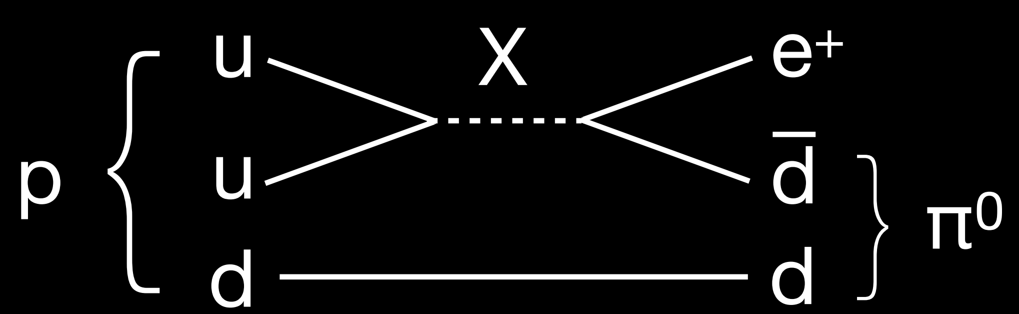
Baryon number is an accidental global symmetry in SM

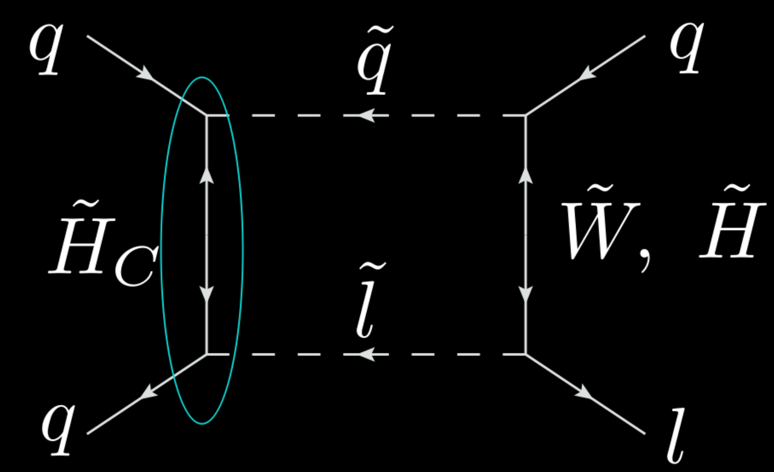
GUTs predict B-violating processes, e.g.

Non-SUSY GUT

SUSY GUT

ΔB=1





$\tau \sim M_X^4$

$\tau \sim M_H^2 M_{SUSY}^2$

|ΔB|=2

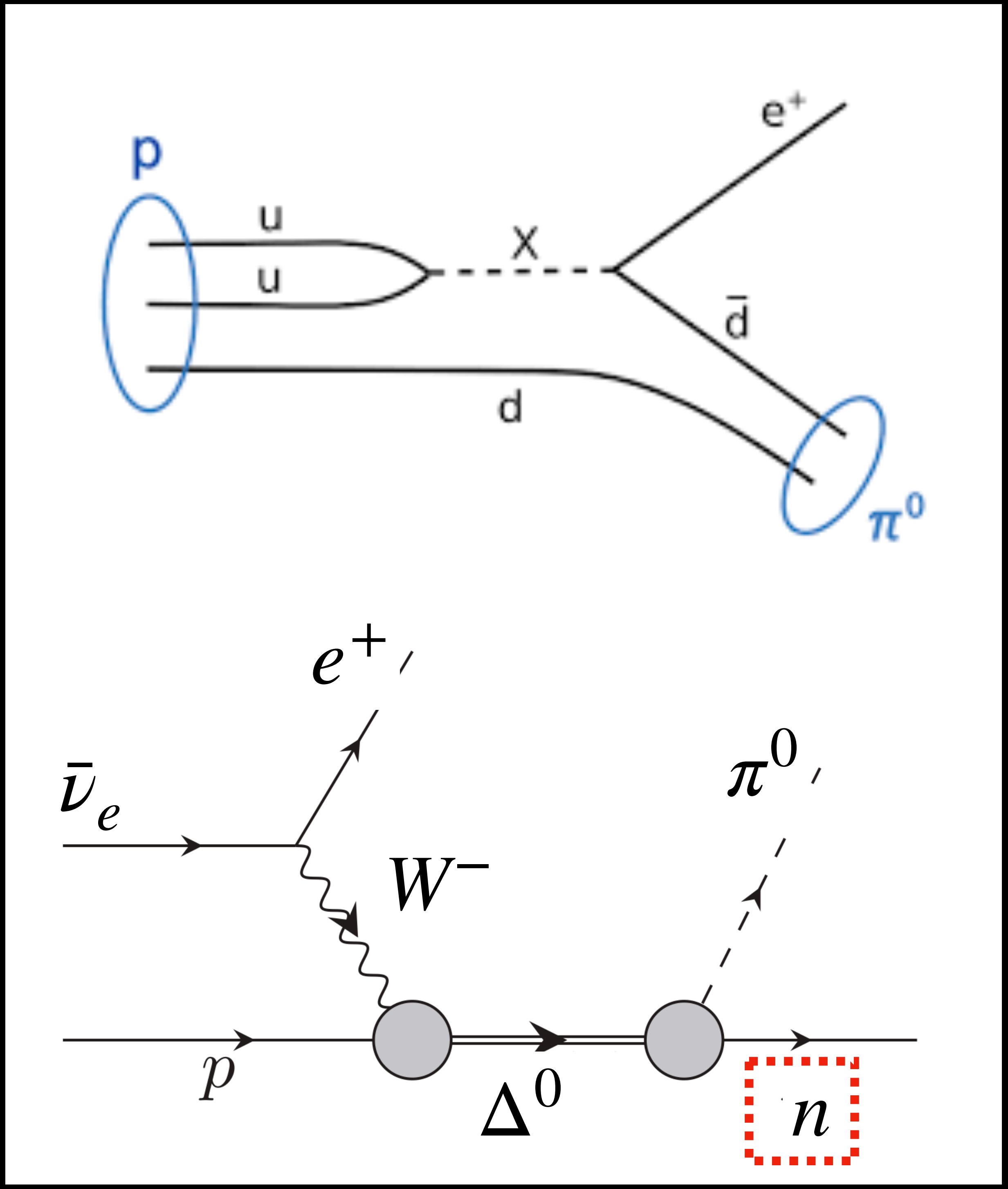
Dinucleon decays

$n \rightleftarrows \bar{n}$ oscillation

Atmospheric ν BG

Signal
(e.g., p→e⁺π⁰)

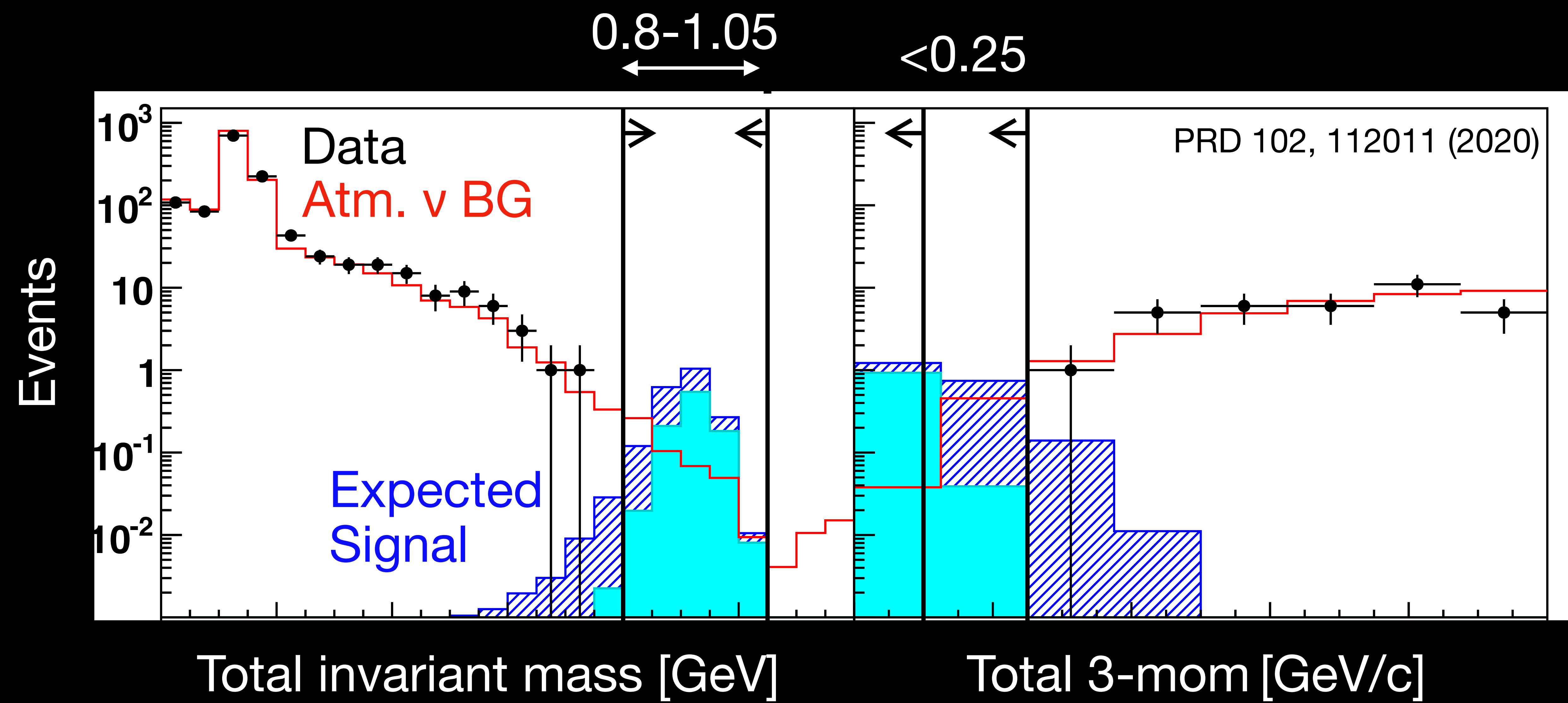
Atm ν BG
(e.g., π production
via nucleon Δ resonance
w/wo π± charge exchange
within nucleus)



Neutron ID can significantly reduce BG

Example: Search for p→$e^+\pi^0$ (eγγ)

Events with two/three e-like rings; if three rings, two should form π^0 mass + no detected neutron



No event found; Set τ/B>2.4×10^{34} years (90% CL)

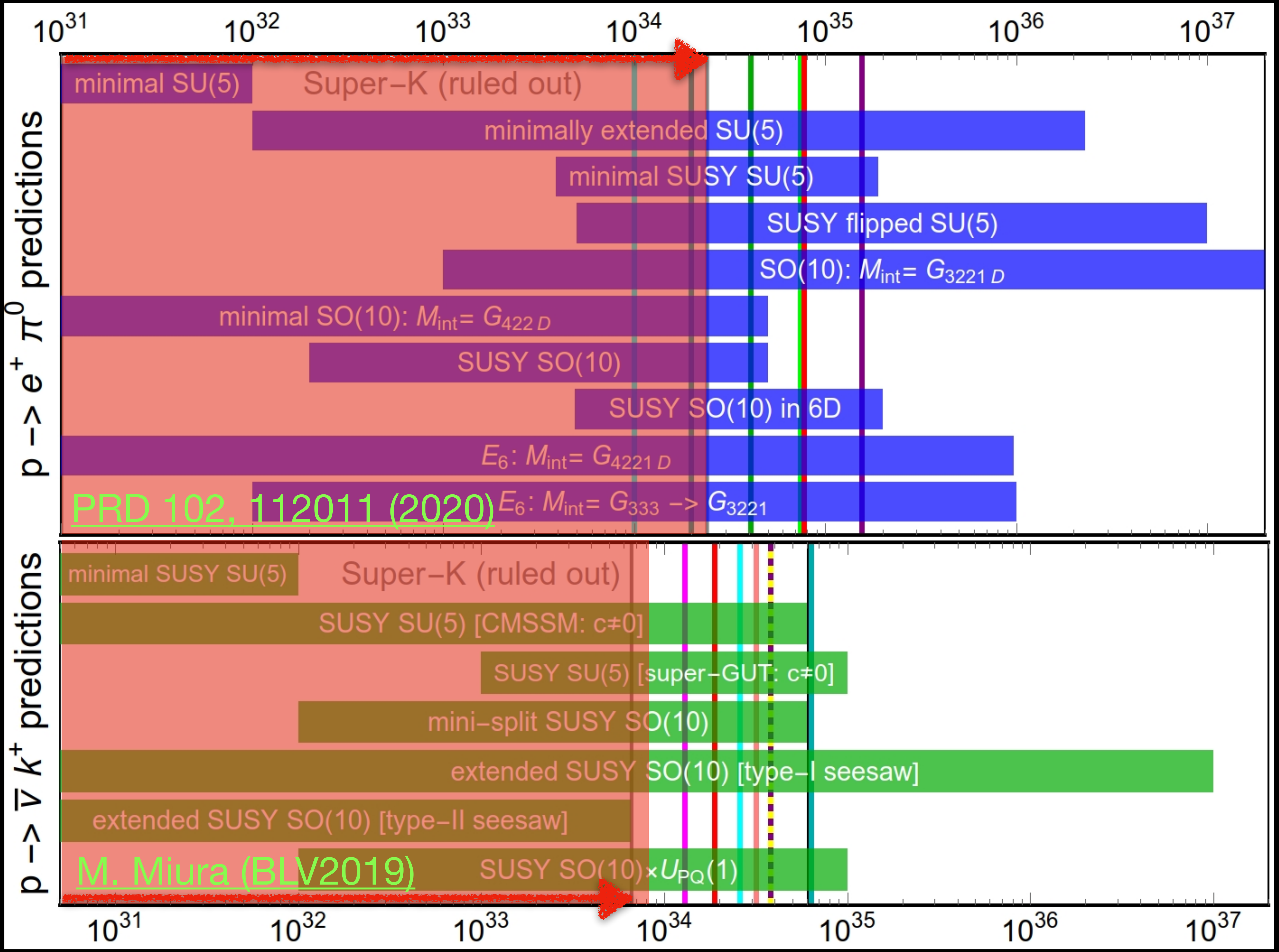
For other modes as well, we have not found excess over BG yet

SK (90% CL)

See this article for summary of SK BNV searches
P S B Dev *et al., J. Phys. G: Nucl. Part. Phys.* **51** 033001 (2024)

$p \to e^+\pi^0$

$p \to \bar{\nu}K^+$



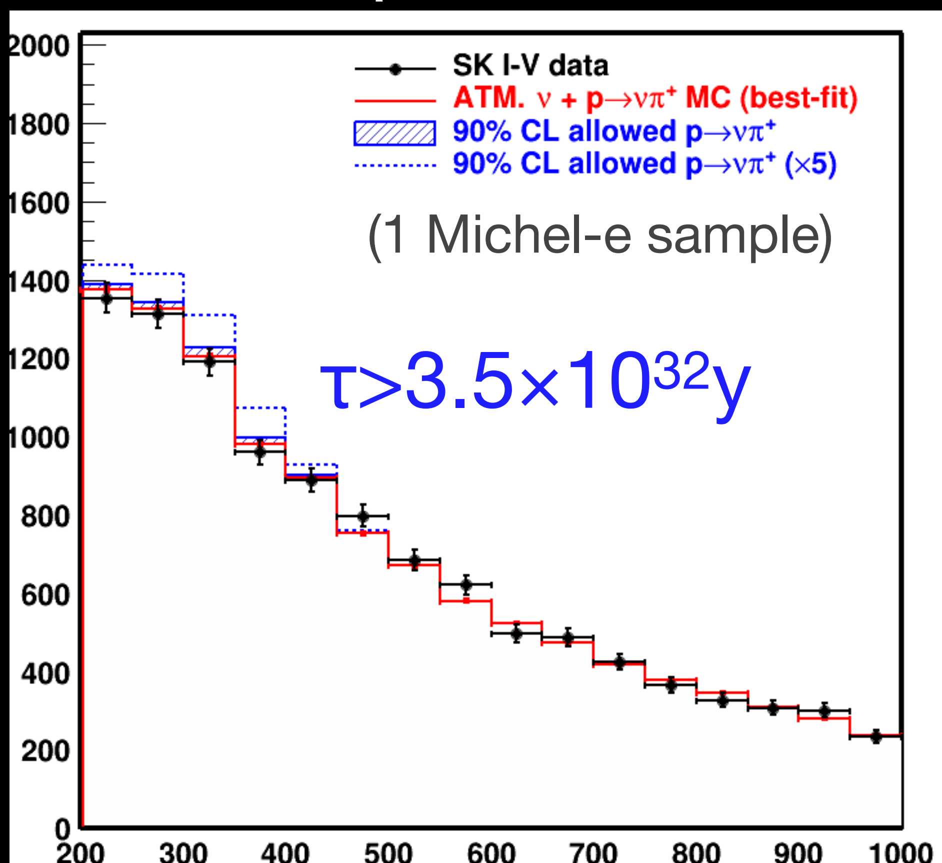
Predicted lifetime [years]

Search for $p \to \nu\pi^+$ and $n \to \nu\pi^0$

One μ-like ring — Two e-like rings with m_π

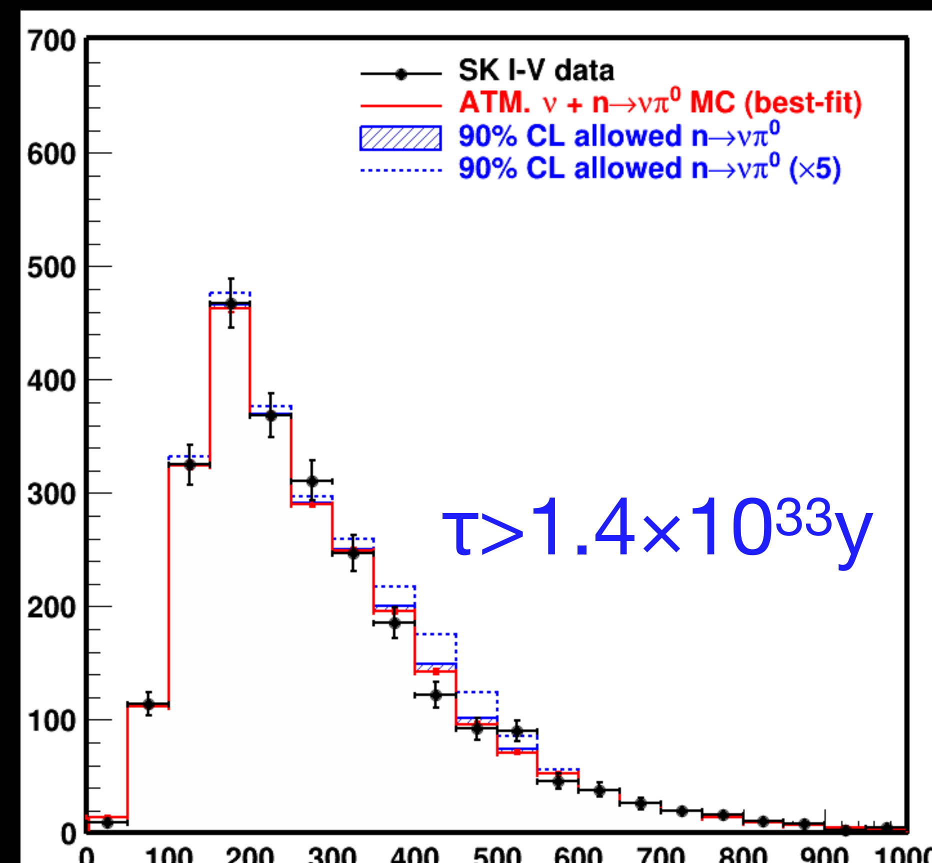
Large atm ν BG, bump search based on p_π ~460 MeV/c

$p \to \nu\pi^+$



Reconstructed p_μ [MeV/c]

$n \to \nu\pi^0$



Reconstructed $p_{\pi 0}$ [MeV/c]

No excess over atm ν BG found

Paper in preparation

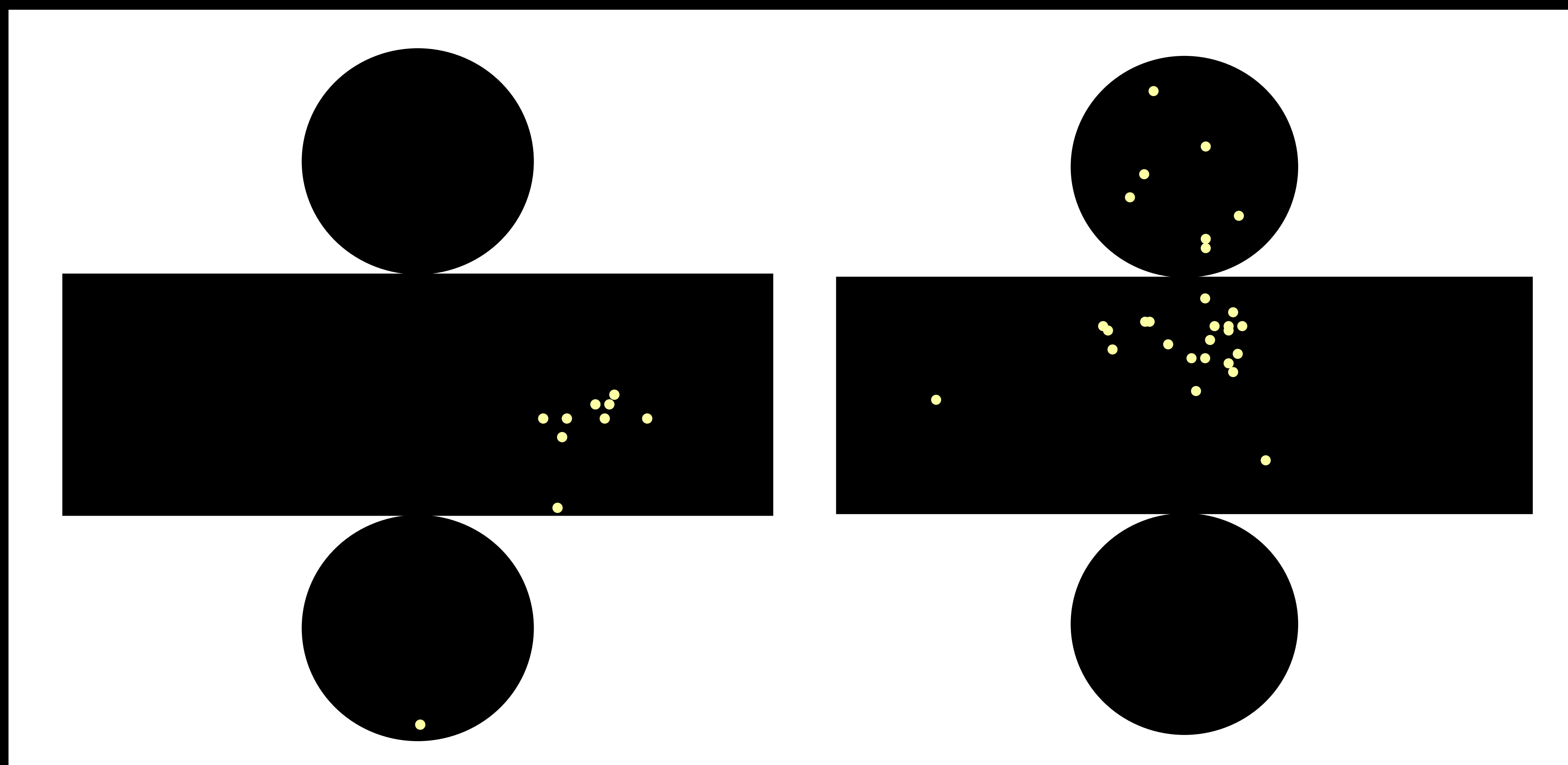
Recent Gd loading for neutron detection

Gadolinium to water

Gadolinium has the highest thermal neutron capture efficiency, with 8 MeV γ-radiated energy per capture (~90% are detectable)

^{1}**H(n,γ)**: 2.2 MeV

$^{155/157}$**Gd(n,γ)**: ~8 MeV



~8 PMT hits

~30 PMT hits

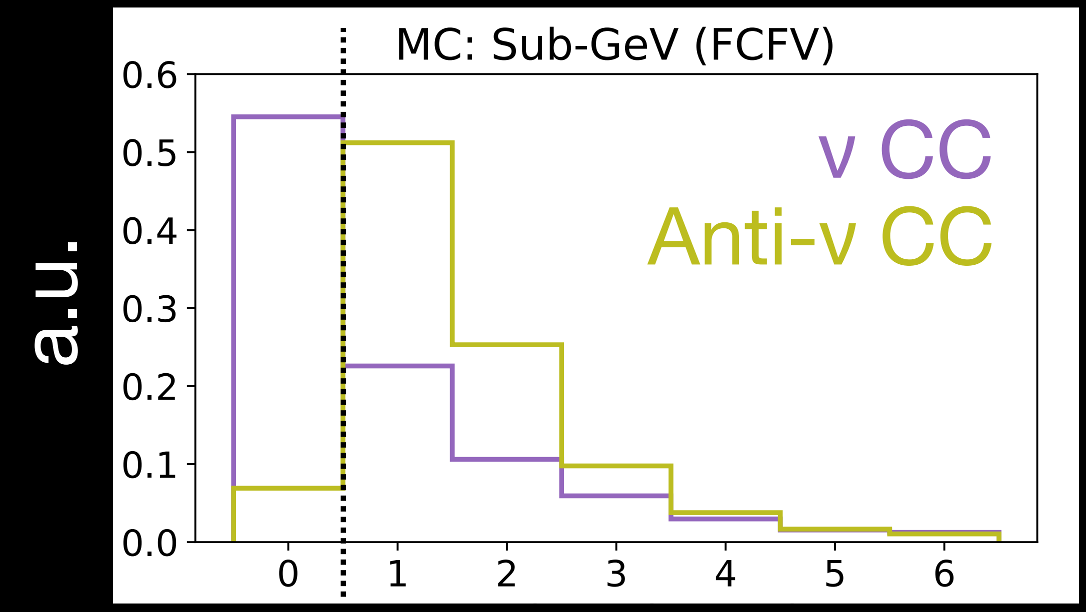
		Gd conc.	H(n,γ)	Gd(n,γ)	n efficiency
1996-2008	12 yrs	-	~100%	-	No data
2008-2020	12 yrs				~20%
2020-2022	2 yrs	0.01w%	55%	45%	~50%
2022-present	3+ yrs	0.03w%	30%	70%	~75%

If SK operates until 2028, we will have 8 years of Gd data
(1/3 of 24-year pure water data)

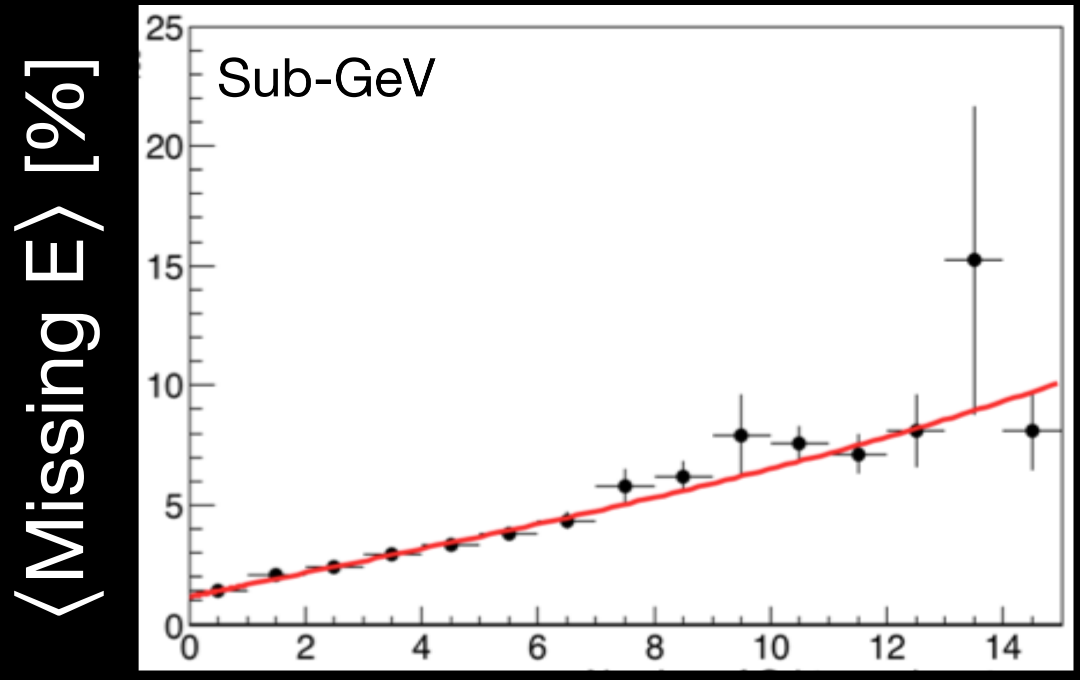
Neutrons for ν MO and CPV test

All plots work in progress with SK simulation

ν/ν̄ ID

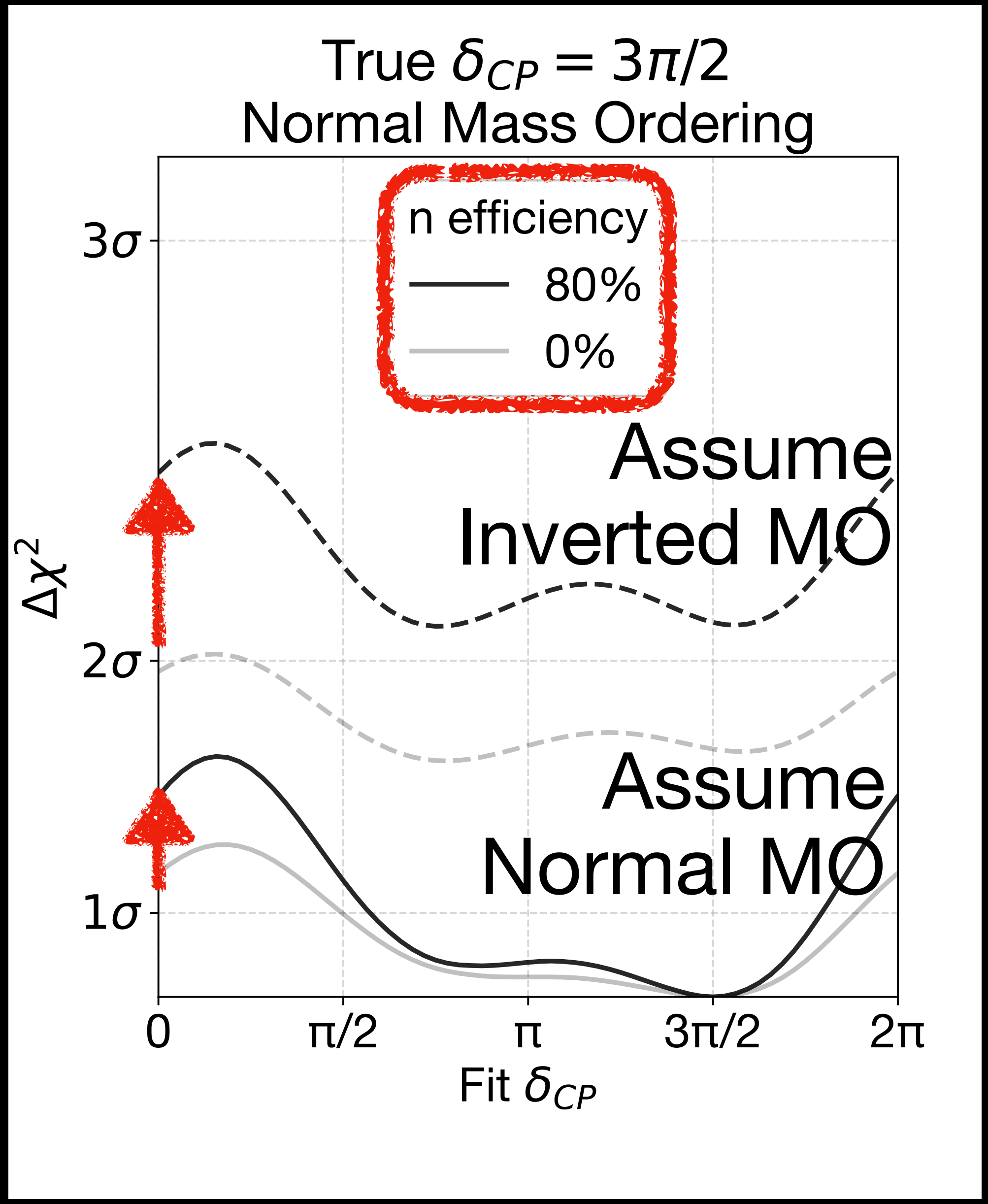


Hadron calorimetry



Neutron counts

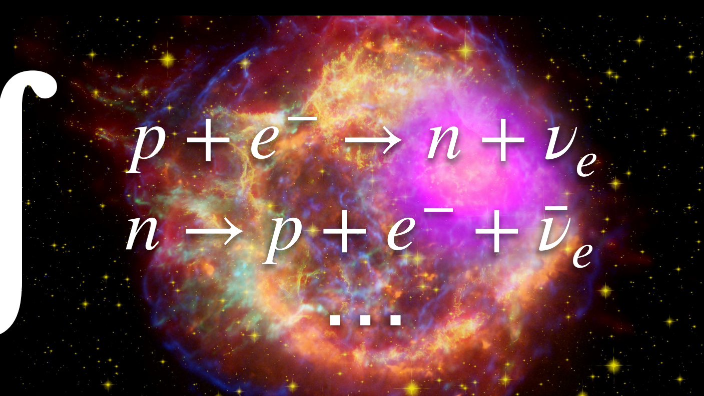
Sensitivity



+10 years of operation (without n calorimetry)

Neutrons for diffuse supernova ν

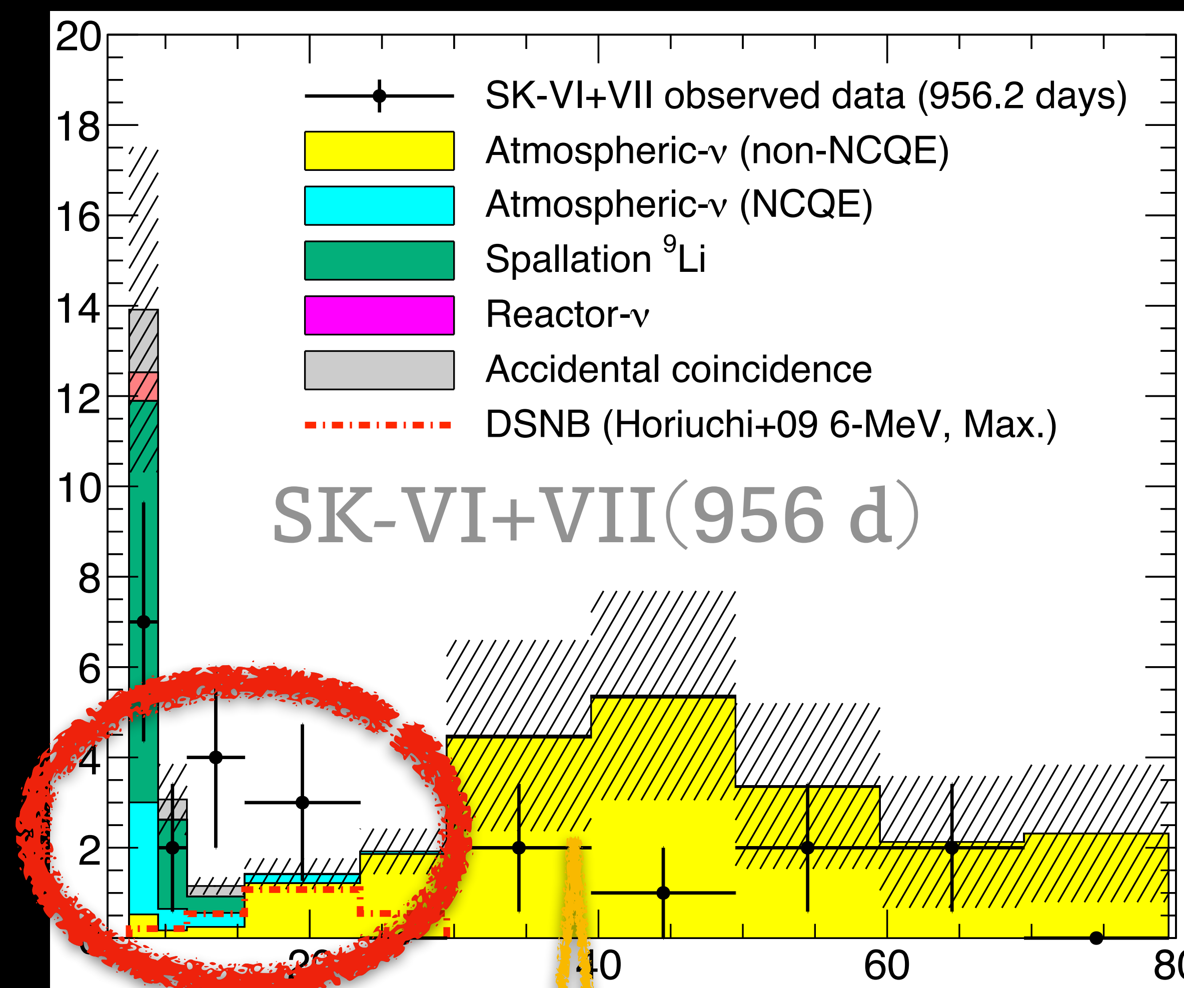
Diffuse Supernova ν Background (DSNB)



$$\int \quad \begin{array}{l} p + e^- \rightarrow n + \nu_e \\ n \rightarrow p + e^- + \bar{\nu}_e \\ \quad \cdots \end{array}$$

- SN formation rate
- ν emission in SN
- Cosmic expansion

$\bar{\nu}_e p \rightarrow e^+ n$ -like events



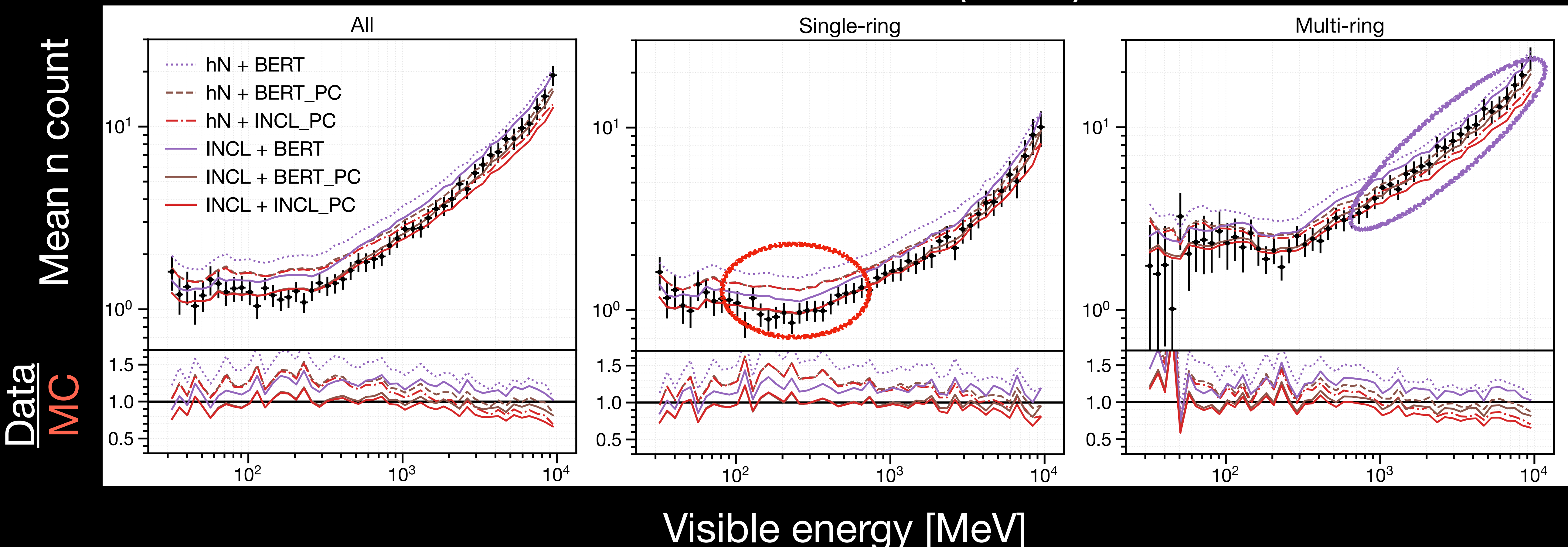
M. Harada, Neutrino 2024

Reconstructed e⁺ energy [MeV]

Requires accurate estimation of secondary n production in atm ν CC/NC events

Measured neutrons in atm. ν events

PRD 112, 012004 (2025)



Cascade + Evaporation models' variability large, up to ~60%

Data prefers models with cascade step correlations + smaller n evap.

+ larger π production

Best model* (INCL+BERT_PC) agrees with data within ~10%

* GENIE 3.4.0 G_18a_10c_02_11b (INCL) for ν-nucleus interaction
Geant4 Bertini cascade (BERT) + Precompound (PC) for secondary hadron inelastic interaction

Super-K Status and Prospects

Super-Kamiokande during its ~30 years journey
has contributed to providing world-leading constraints
e.g., large θ_{12}, θ_{23}, mass gaps $\Delta m_{21}^2 \sim 10^{-5}$, $\Delta m_{32}^2 \sim 10^{-3}$ eV^2,

Latest results prefer Normal νMO and CPV at 1-2σ level;
Plus, SK has set most stringent limits on many BNV modes
(flagship $p \to e^+\pi^0$ mode 90% lifetime limit $\tau/B \sim 10^{34}$ years)

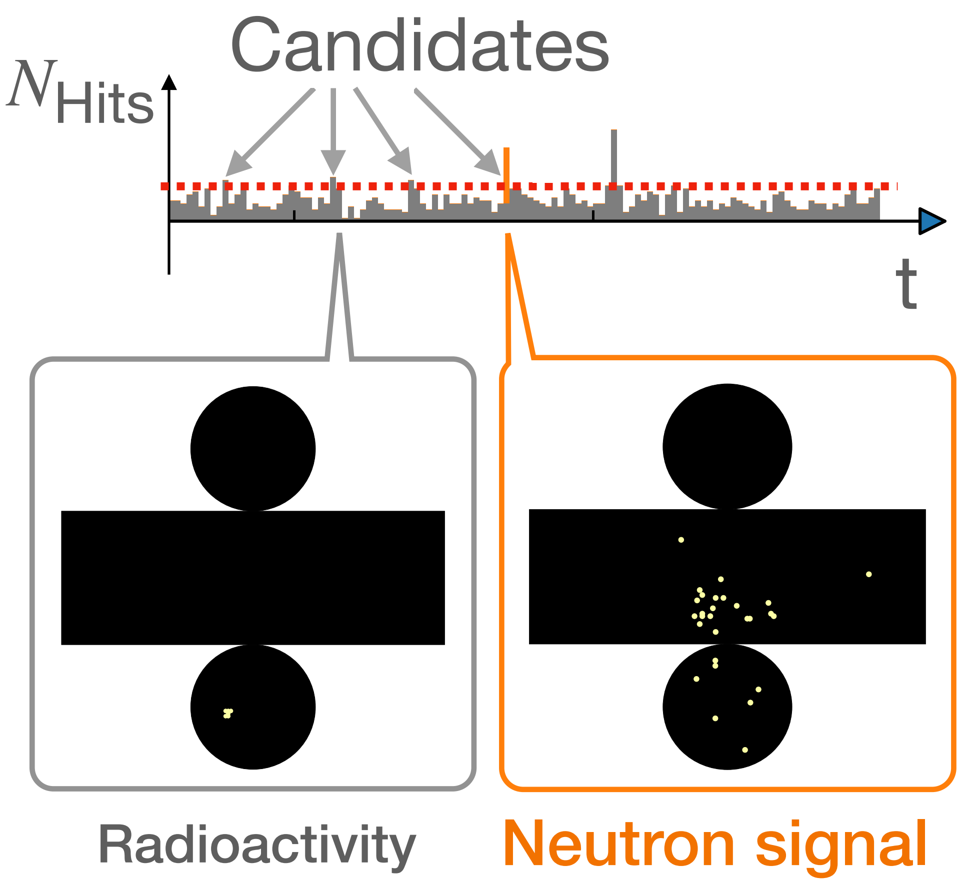
Since 2020, SK has loaded Gd to enhance "neutron tagging"
that is important for ν reconstruction and atm ν BG reduction.
Neutron simulation in SK is getting more accurate than ever.

Stay tuned to SK ν oscillation and astrophysics results with Gd!

Backup

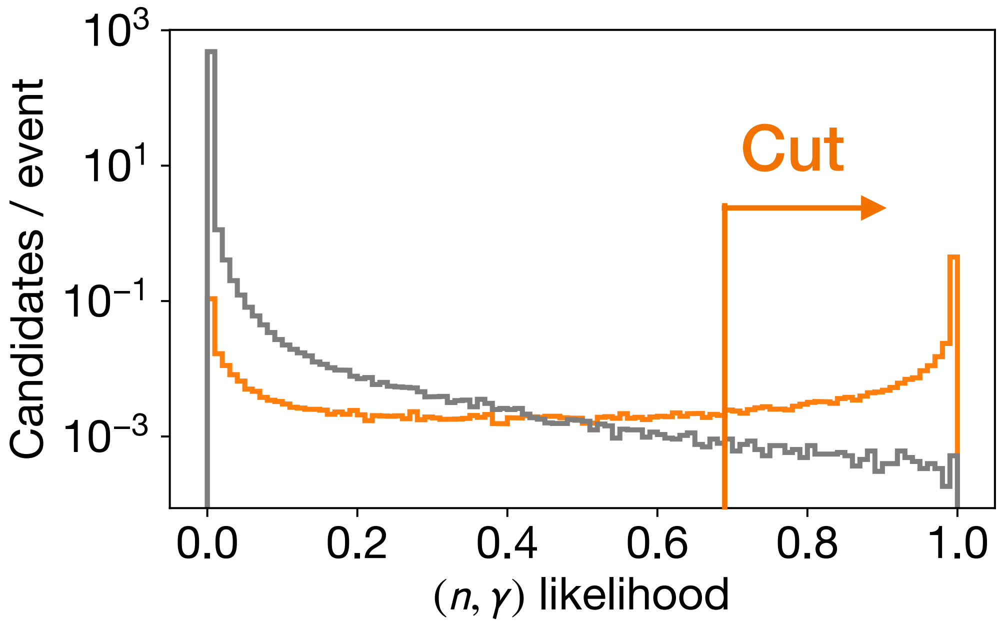
Neutron signal ID

(Step 1) PMT trigger



(Step 2) Neural network

Noise vs. Signal binary classifier based on PMT hits and their corr.



Standard 3-flavor neutrino mixing

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

$$s_{ij} \equiv \sin\theta_{ij}$$
$$c_{ij} \equiv \cos\theta_{ij}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\eta_1} & 0 \\ 0 & 0 & e^{i\eta_2} \end{pmatrix}$$

Majorana phases

3 mixing angles θ_{12}, θ_{13}, θ_{23}

1 phase δ

2 diagonal phases η

ν flavor transition probability in vacuum (Energy E, Path length L)

$$P(\overset{(-)}{\nu_\alpha} \to \overset{(-)}{\nu_\beta}) = \Big|\sum_j U_{\alpha j} U^*_{\beta j} e^{-i\phi_j}\Big|^2 \qquad \phi_i \equiv m_i^2 L/2E \qquad \Omega_{ij}^{\alpha\beta} \equiv U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}$$

$$= \boxed{\delta_{\alpha\beta}} \boxed{- 4 \sum_{i>j} \mathrm{Re}(\Omega_{ij}^{\alpha\beta}) \sin^2 \frac{\Delta m_{ij}^2 L}{4E}} \boxed{\overset{+}{\scriptstyle(-)} 2 \sum_{i>j} \mathrm{Im}(\Omega_{ij}^{\alpha\beta}) \sin \frac{\Delta m_{ij}^2 L}{2E}}$$

Unitarity

Dominant oscillation

Imaginary U ⇄ CPV

$|\Delta m_{12}^2|$, $|\Delta m_{23}^2|$ ~ $|\Delta m_{13}^2|$
sensitive to distinct L/E
(solar, reactor, atm/acc., etc.)

$$\overset{+}{\scriptstyle(-)} 2 J_{CP} \sum_{i>j} \sin \frac{\Delta m_{ij}^2 L}{2E}$$

$$J_{CP} \equiv c_{12} s_{12} c_{23} s_{23} c_{13}^2 s_{13} \sin\delta$$

2-flavor approx.

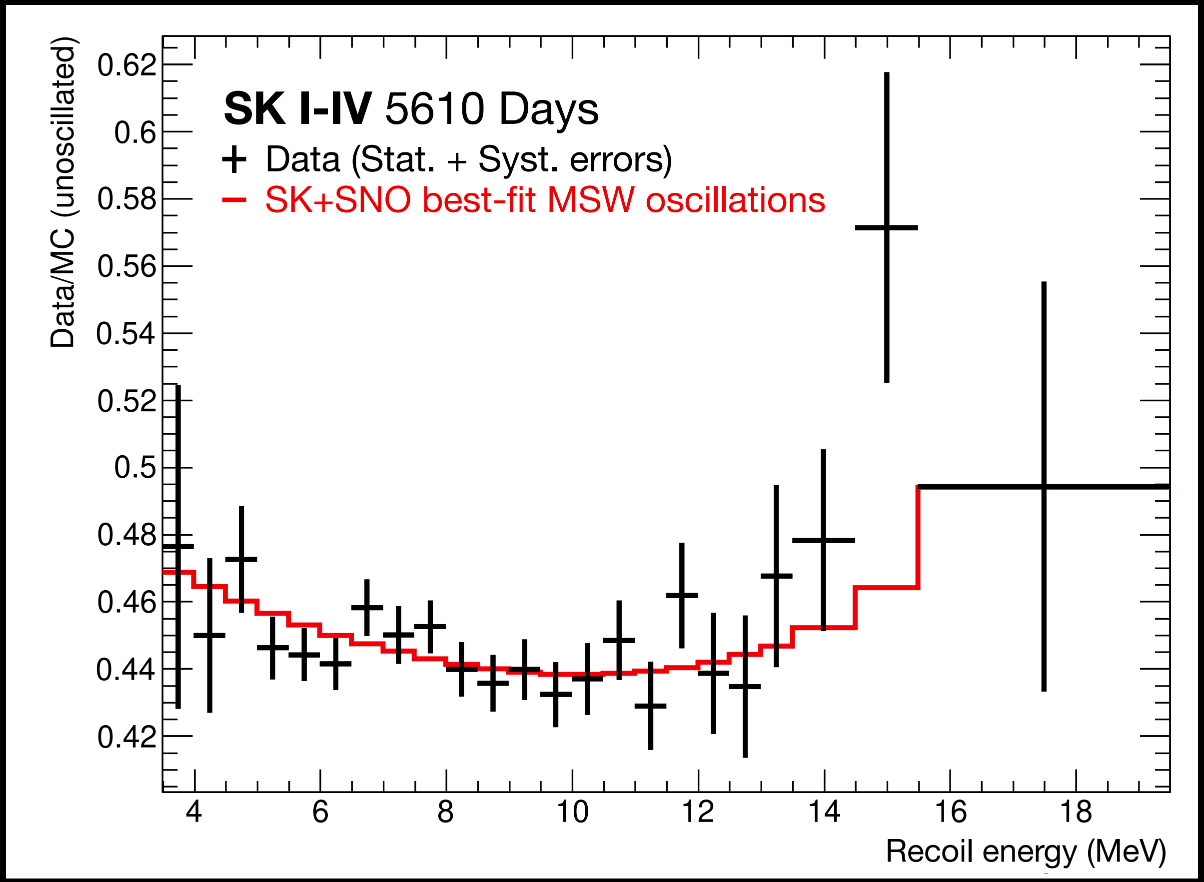
$$P(\nu_\alpha \to \nu_\beta) \approx \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

Insensitive to the sign of Δm^2
(e.g., $m_i > m_j$ or $m_i < m_j$)

We find parameters that best fit the observed oscillatory signatures

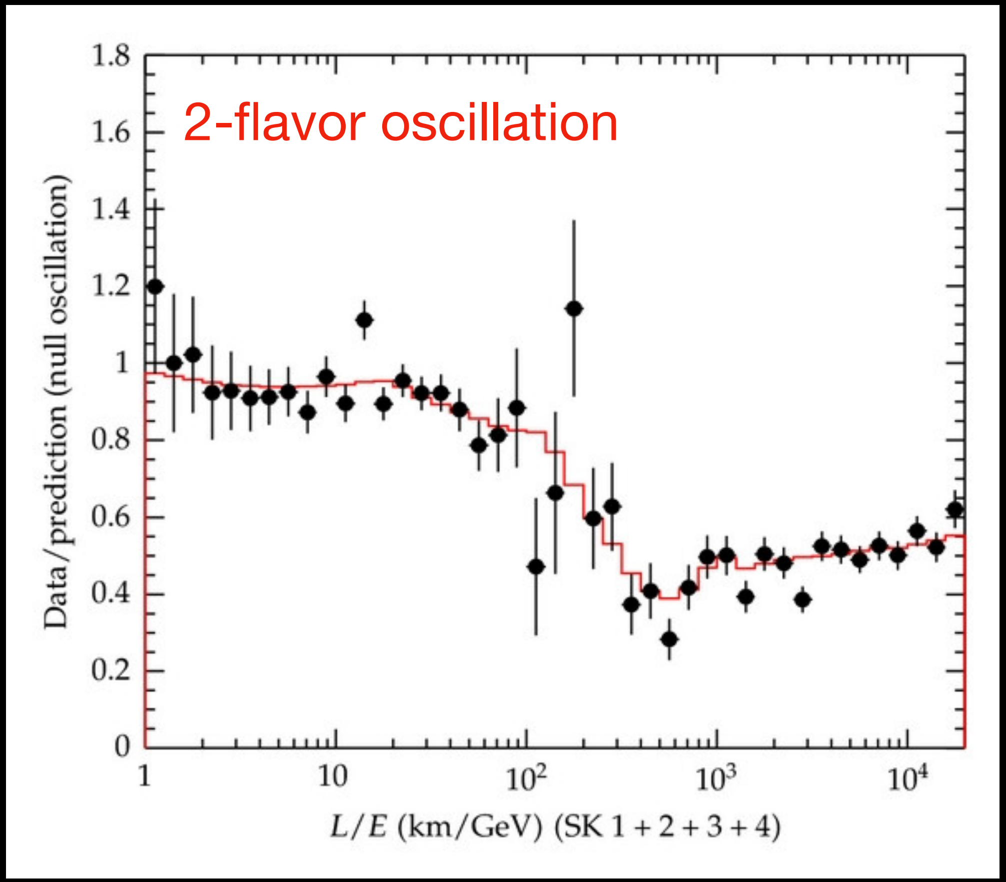
Solar ν
(small variation in L, E)

Charged lepton energy
as a proxy for neutrino E



Atmospheric ν
(large variation in L, E)

Charged lepton energy,
Zenith angle, or BOTH



Resonance in matter

In 2-flavor case,

$$H_{\text{flavor}} = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta \pm \epsilon & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \qquad \epsilon \equiv \frac{4E}{\Delta m^2}\sqrt{2}G_F n_e$$

$$= \tilde{U}\frac{1}{2E}\text{diag}(-\frac{1}{2}\Delta\tilde{m}^2, \frac{1}{2}\Delta\tilde{m}^2)\tilde{U}^\dagger$$

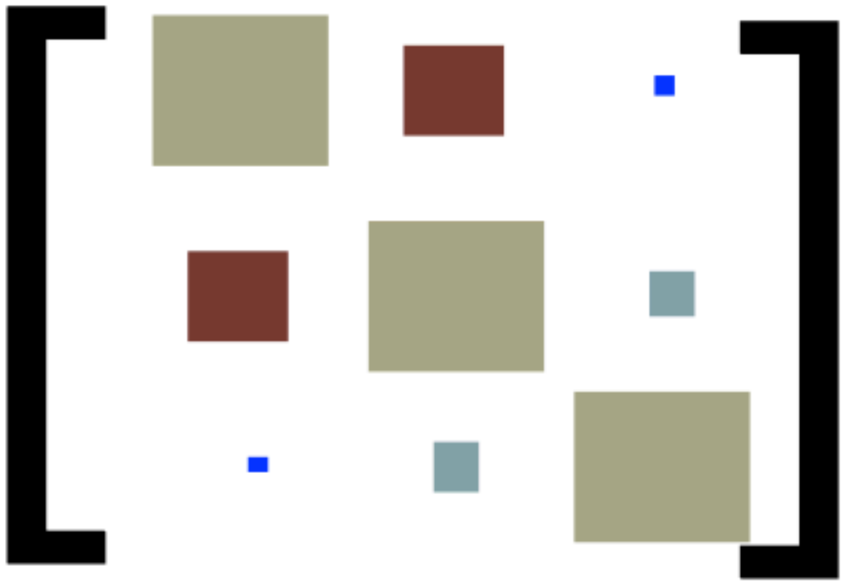
Effective mixing angle $\tan 2\tilde{\theta} = \dfrac{\sin 2\theta}{\cos 2\theta \mp \epsilon}$

Effective mass splitting $\Delta\tilde{m}^2 = \Delta m^2\sqrt{(\cos 2\theta \mp \epsilon)^2 + \sin^2\theta}$

Maximal mixing ($\tilde{\theta} = \pi/4$) occurs when $\epsilon(n_e, E) = \cos 2\theta$

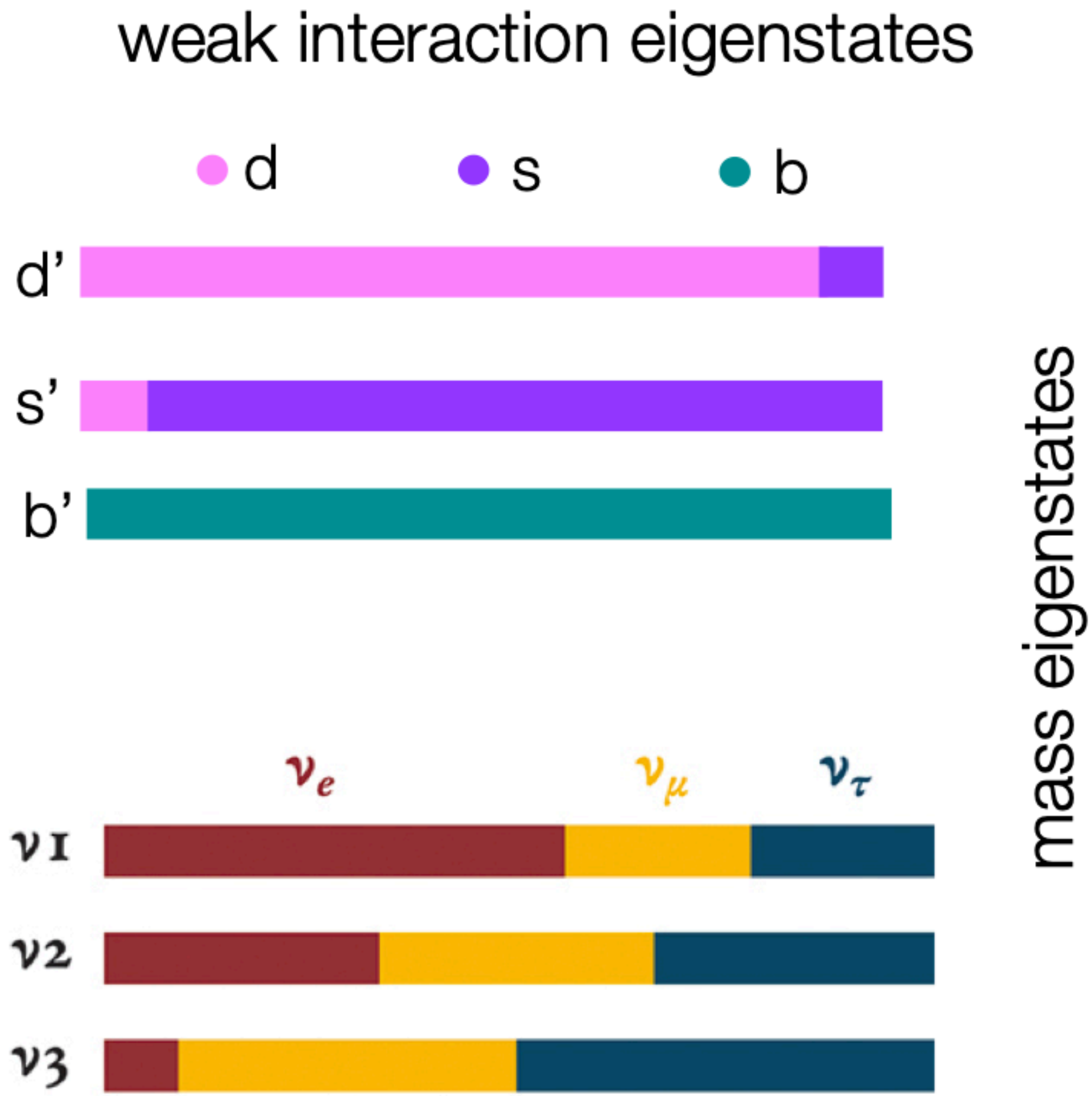
for ν with normal MO ($\Delta m^2>0$) and $\overline{\nu}$ with inverted MO ($\Delta m^2<0$)

☞ Flavor structure:

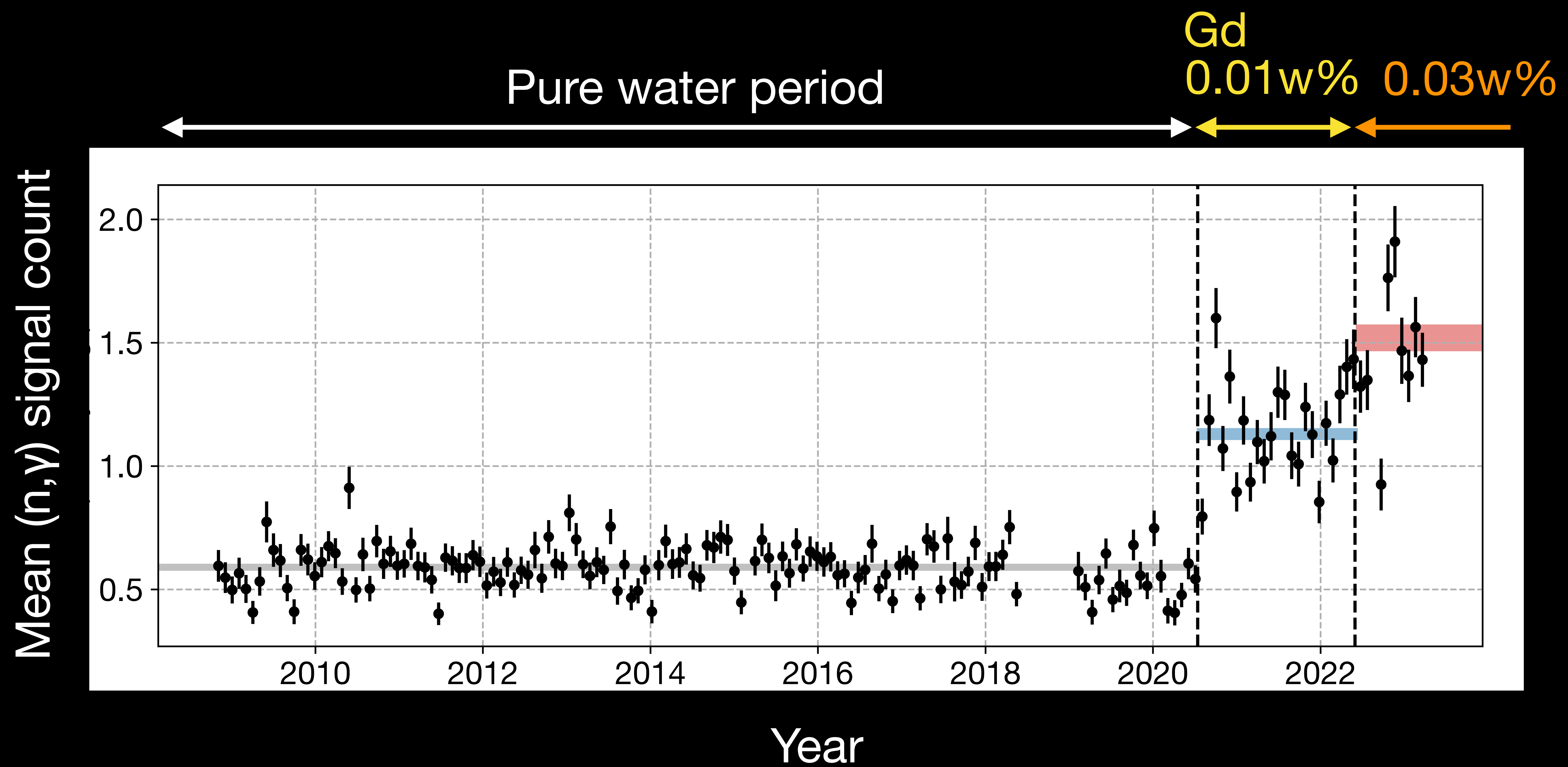


quark mixing

leptonic mixing

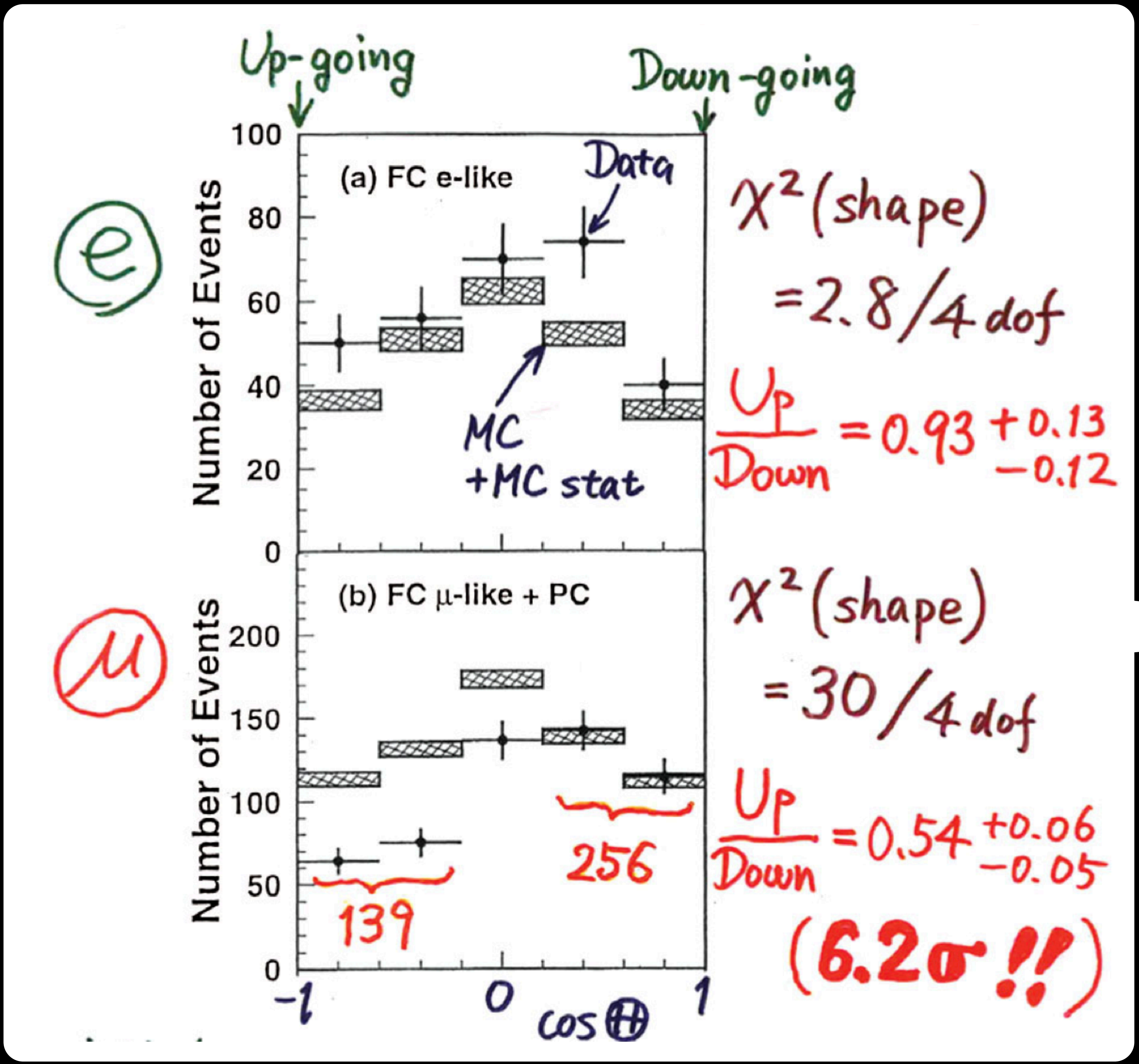


n efficiency increase with more Gd



Mean (n,γ) counts per fully-contained atmospheric ν event is monitored

Our first ν mixing result (1998)



Vacuum 2-flavor model

$\theta \sim 33\text{-}58°$

$\Delta m^2 \sim 10^{-4}\text{-}10^{-3}\ eV^2$

T. Kajita @ Neutrino '98