COMBINING STERILE NEUTRINO FITS TO SHORT BASELINE DATA WITH ICECUBE DATA

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In collaboration with:

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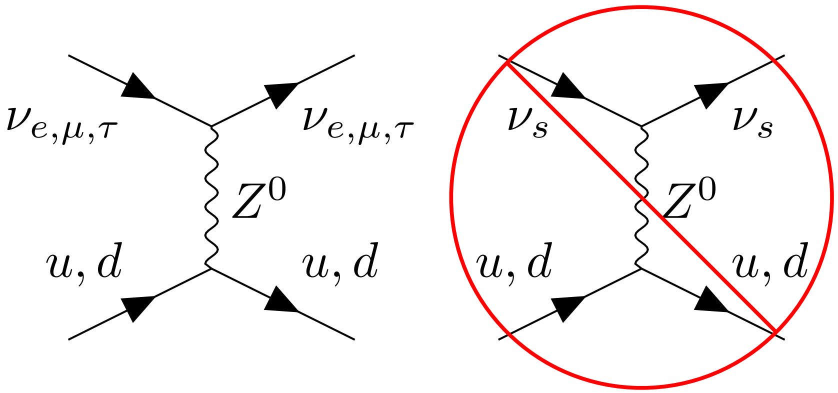
Outline

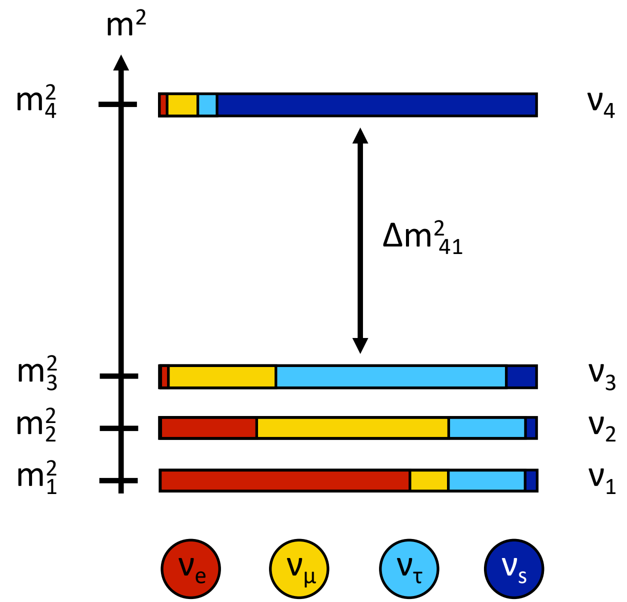
- Introduction
  - Sterile neutrinos
  - What makes IceCube unique
- Fit results for a 3+1 model New!
- Fit results for a 3+1+decay model New!
- Conclusion

Anomalies have been observed

- And seem to fit a 3+1 sterile neutrino model at some level
- Can parameterize a 3+1 model with Δm^2_{41} and $\theta_{\mu e}$ (simplification)



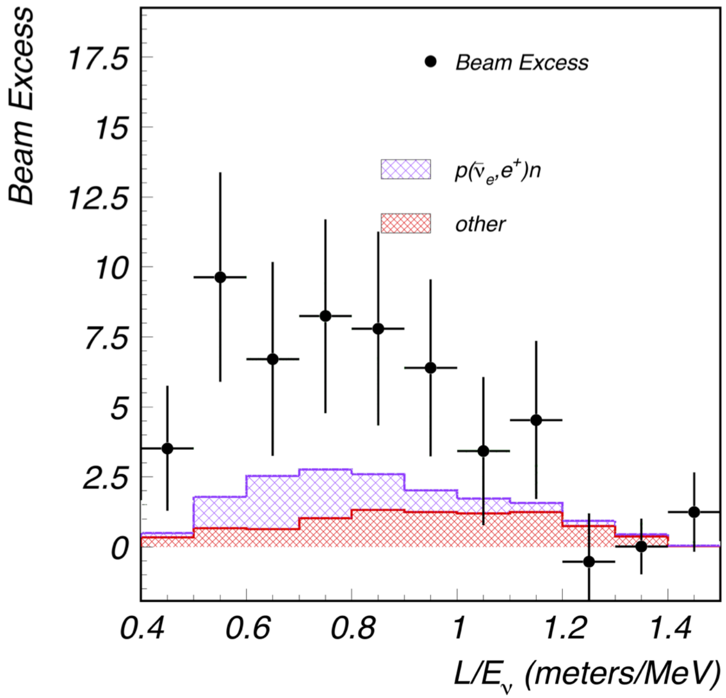
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



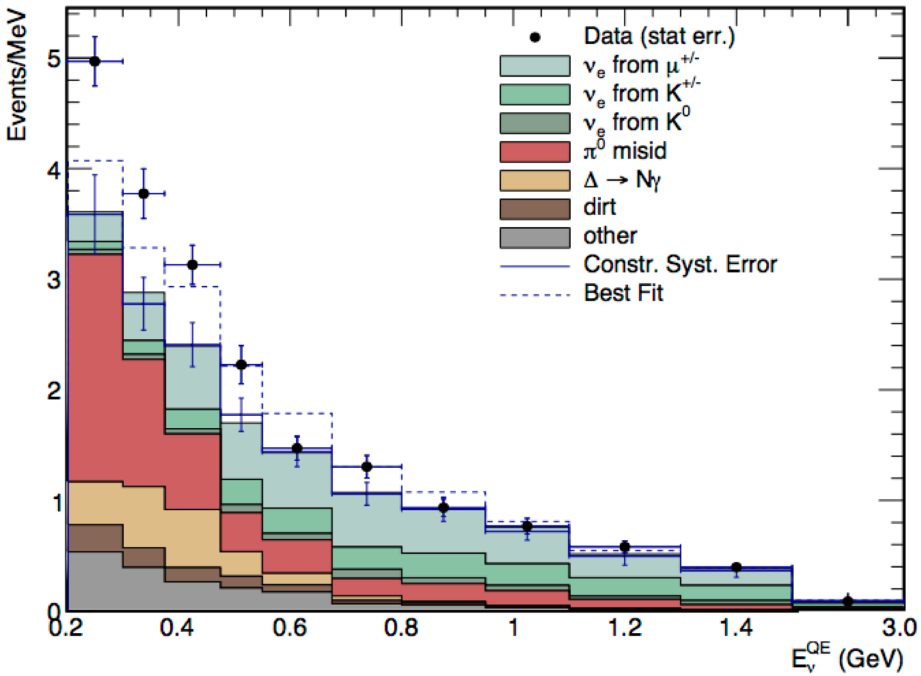
Assuming Normal Ordering

$\nu_\mu \longrightarrow \nu_e$ Anomalies

LSND : 3.8σ



MiniBooNE (2018) : 4.7σ



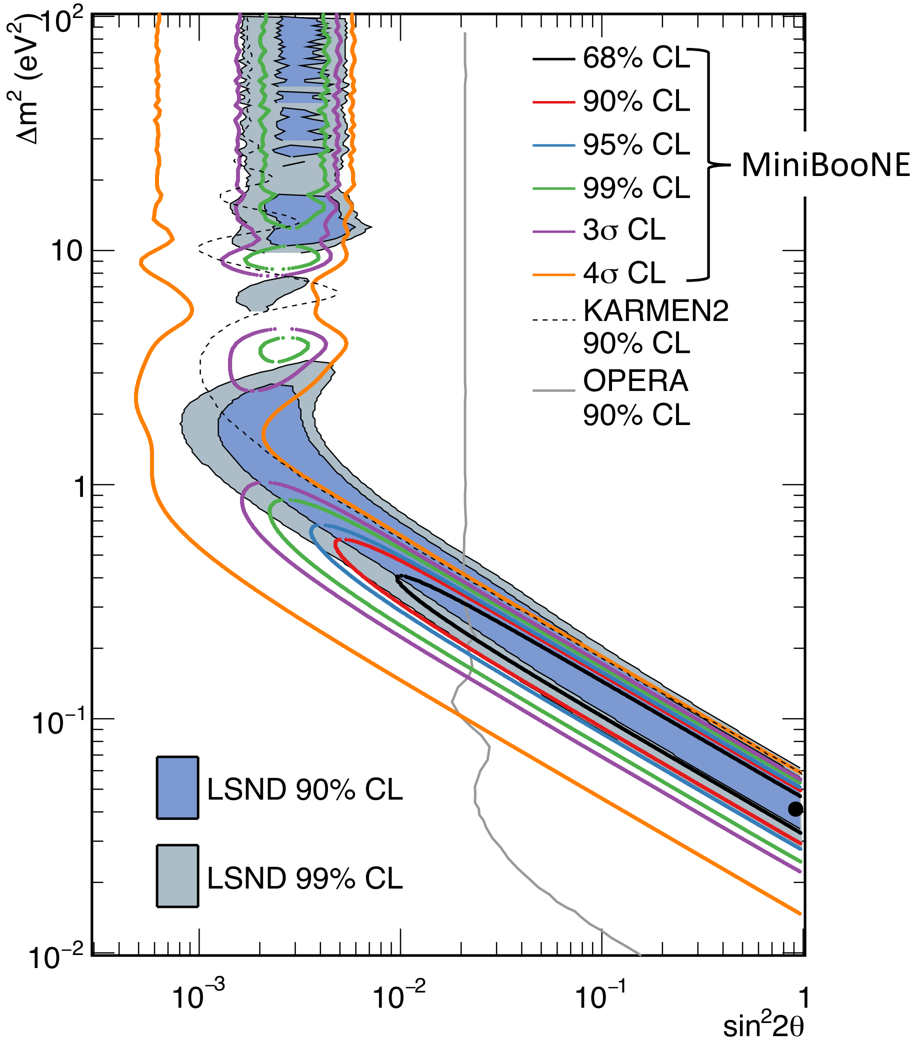
arXiv:hep-ex/0104049
arXiv:1805.12028

LSND and MiniBooNE Fits to 3+1 model

LSND ($\bar{\nu}$) and MiniBooNE (ν and $\bar{\nu}$) combined best fit:

- $(\Delta m^2, \sin^2 2\theta) = (0.04\ \text{eV}^2, 0.96)$
- $\chi^2/\text{dof} = 22.4/22.4$
- p-value for the χ^2 = 42.5%

- Significance of combined excesses: 6.0σ

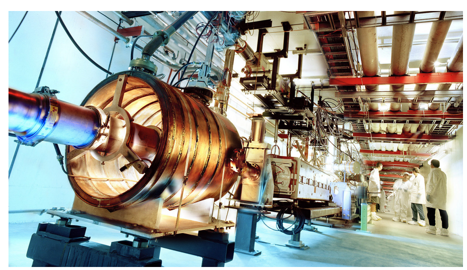


arXiv:1805.12028

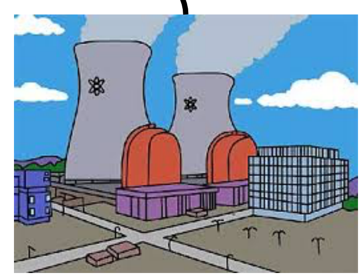
Short-Baseline (SBL) Experiments Included in Fits

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) *	SciBooNE/MiniBooNE	KARMEN/LSND Cross Section
	MiniBooNE(NuMI)	CCFR	Gallium *
	NOMAD	CDHS	
		MINOS	
Antineutrino	LSND *	SciBooNE/MiniBooNE	Bugey
	KARMEN	CCFR	NEOS
	MiniBooNE (BNB) *	MINOS	DANSS *
			PROSPECT

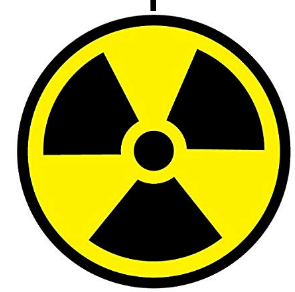
* (highlighted box) $\Longrightarrow$ >2.5σ "signal"



Accelerator



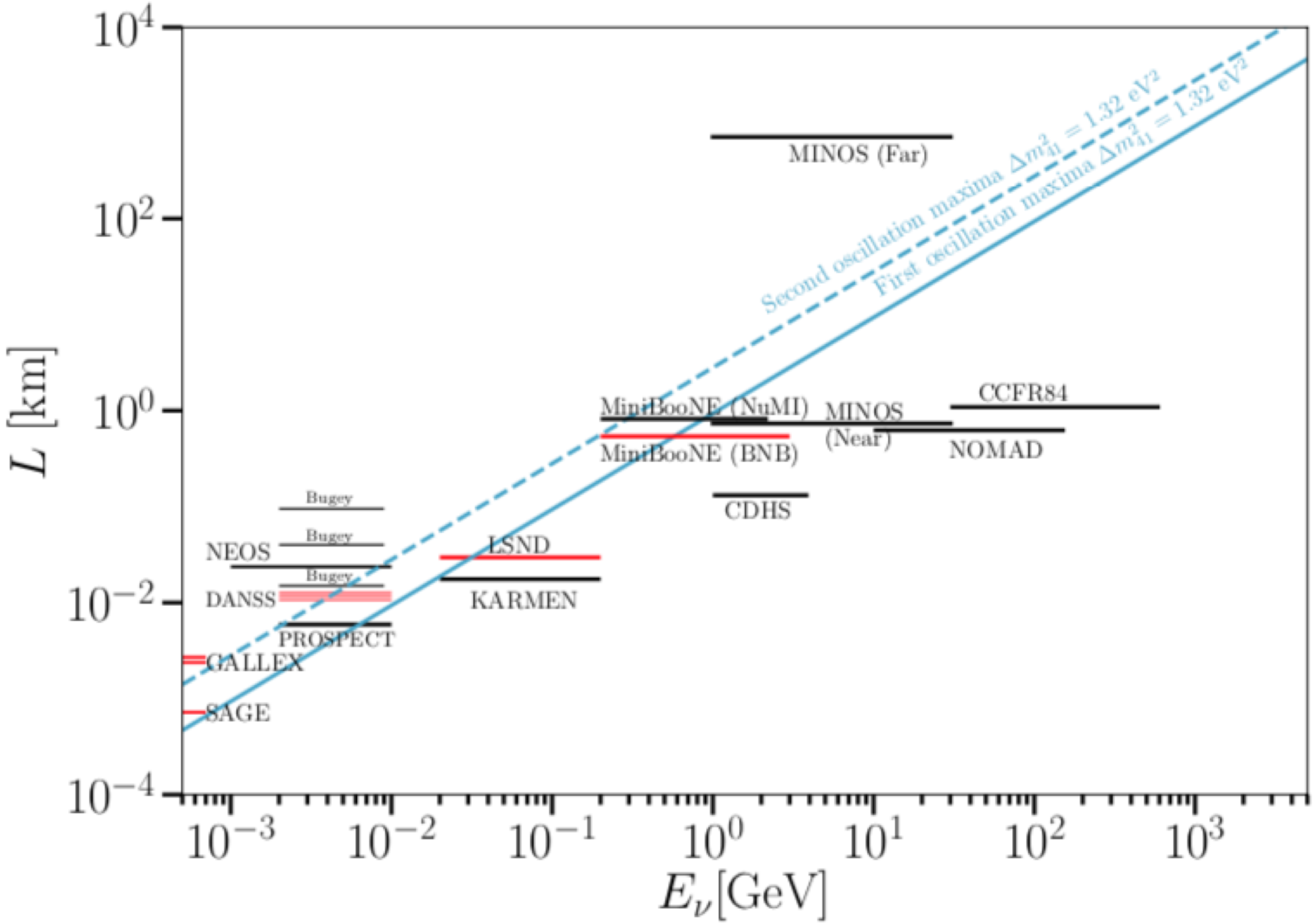
Reactor



Radioactive Source

For an overview of these experiments & recent SBL fits, see: [arXiv: 1906.00045]

Short-Baseline (SBL) Experiments Included in Fits



❖ Baselines are short ⟶ Negligible matter effects ⟶ Vacuum oscillations

SBL Only Global Fit to 3+1

[arXiv:1906.00045]

$$P_{\nu_e \to \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

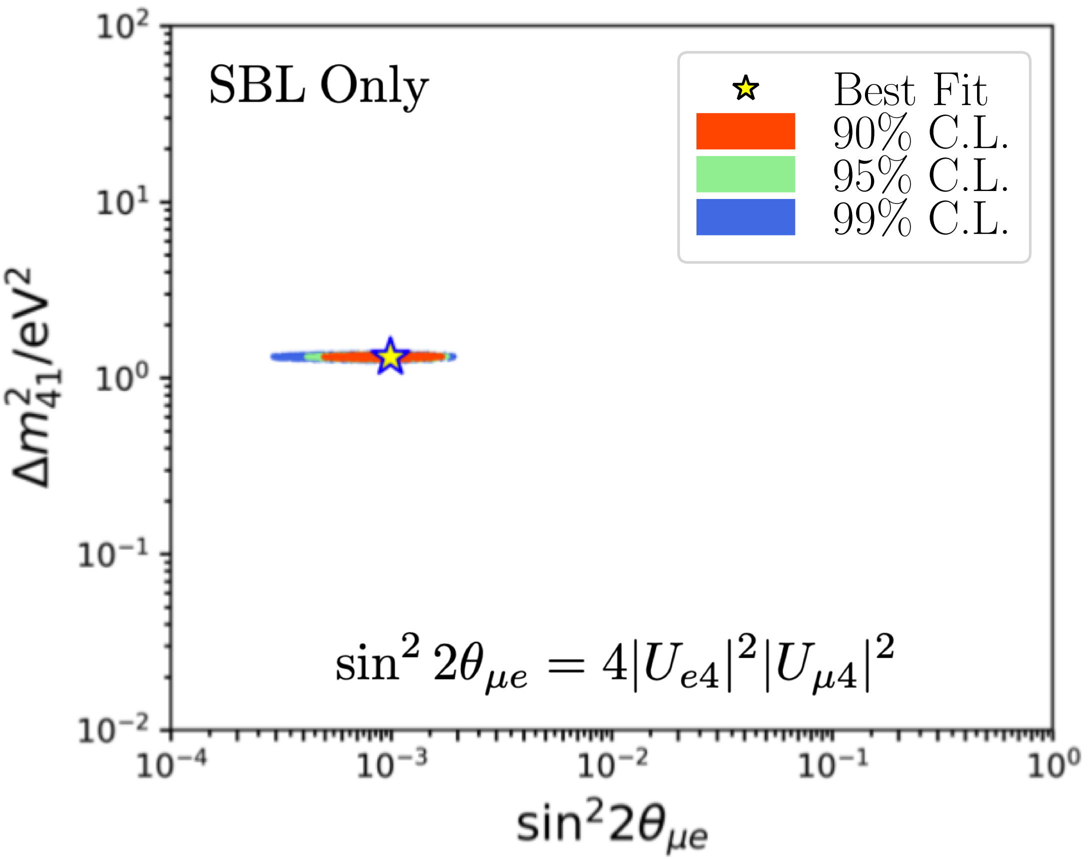
$$P_{\nu_\mu \to \nu_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$

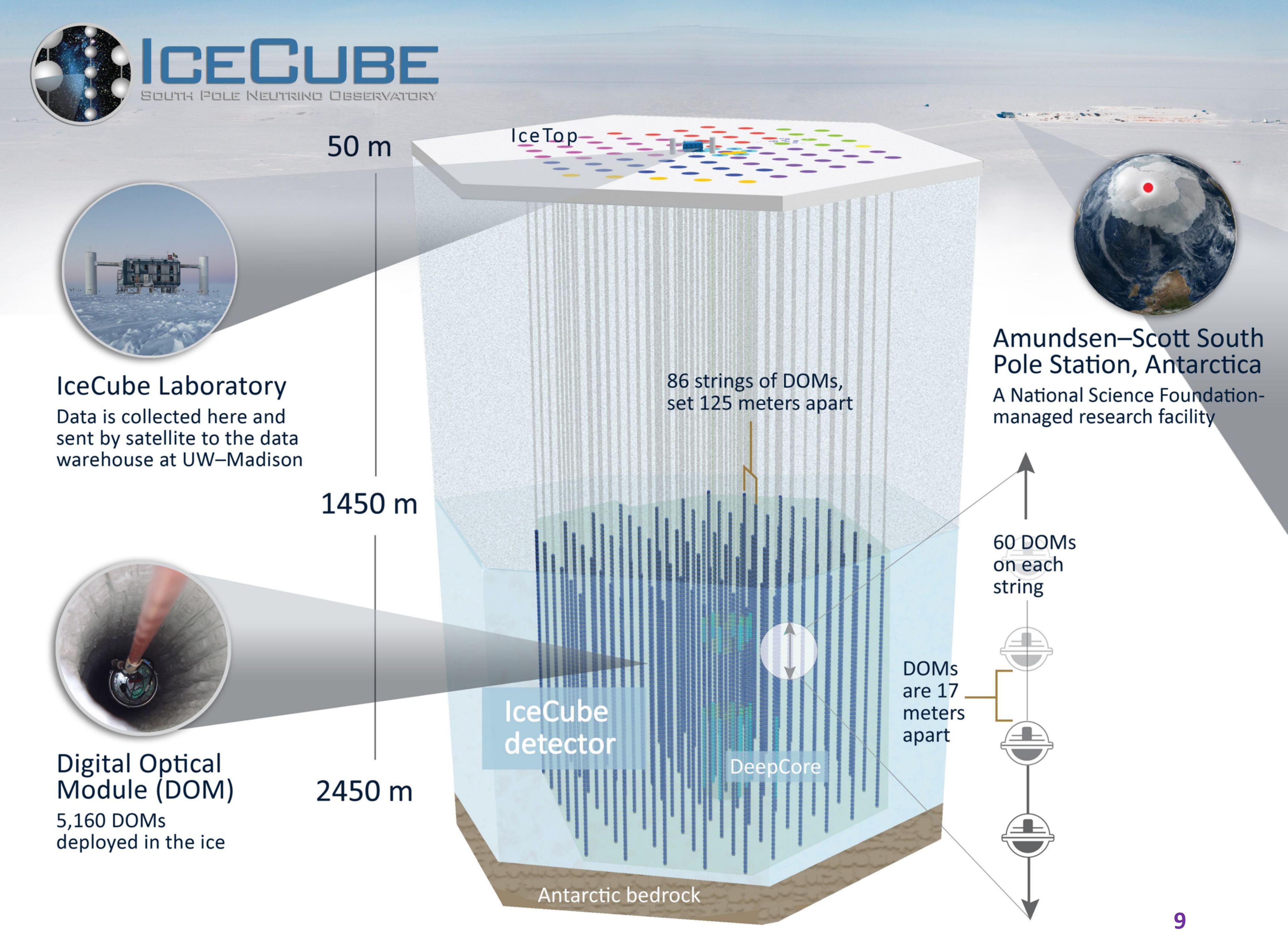
Best-Fit Point:

$$\Delta m^2_{41} = 1.3\,\mathrm{eV}^2$$

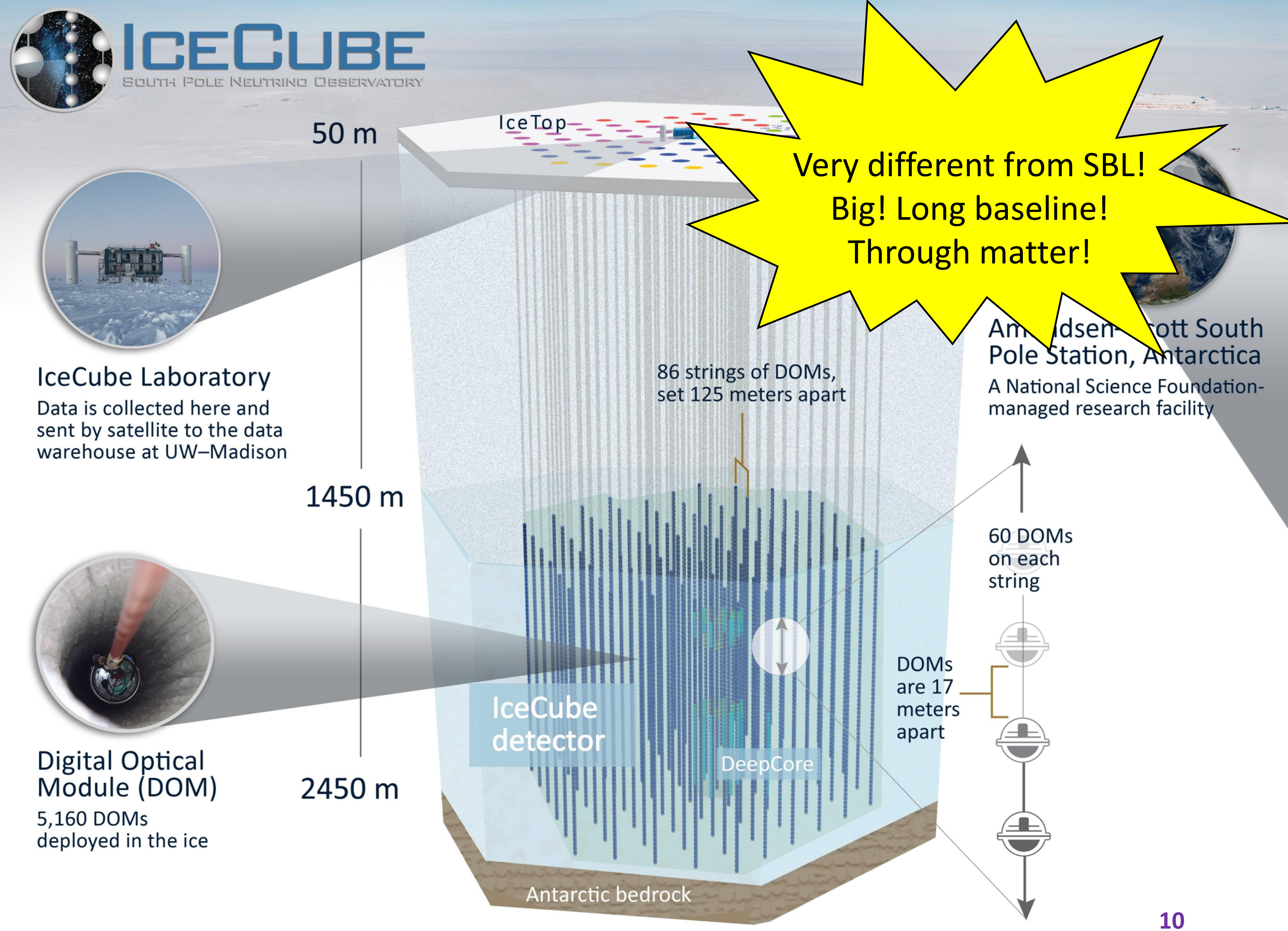
$$\sin^2 2\theta_{\mu e} = 0.00098$$

- 5.2σ for sterile neutrino vs. Standard Model
- **Why isn't this a discovery?** Tension…more on this later



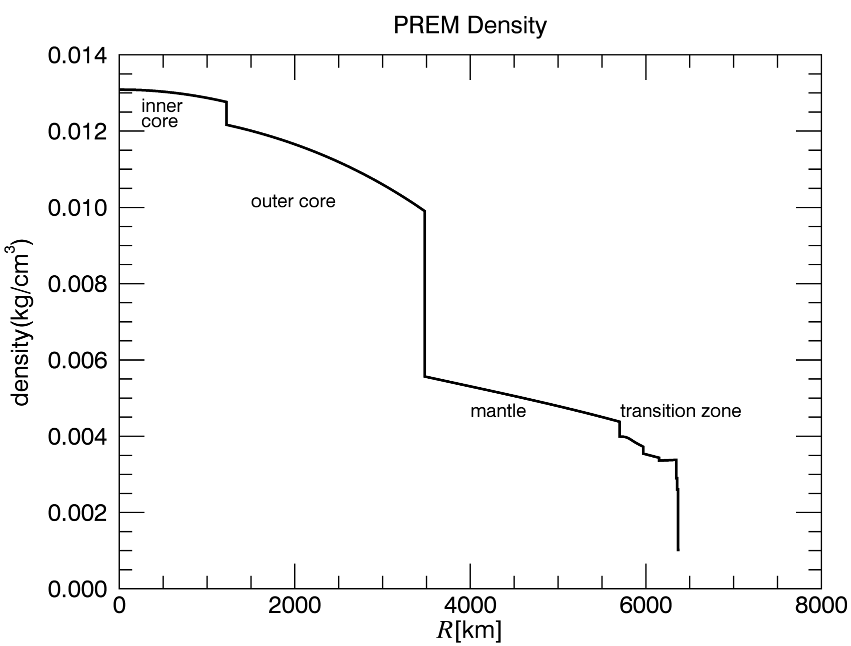

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

Very different from SBL!
Big! Long baseline!
Through matter!

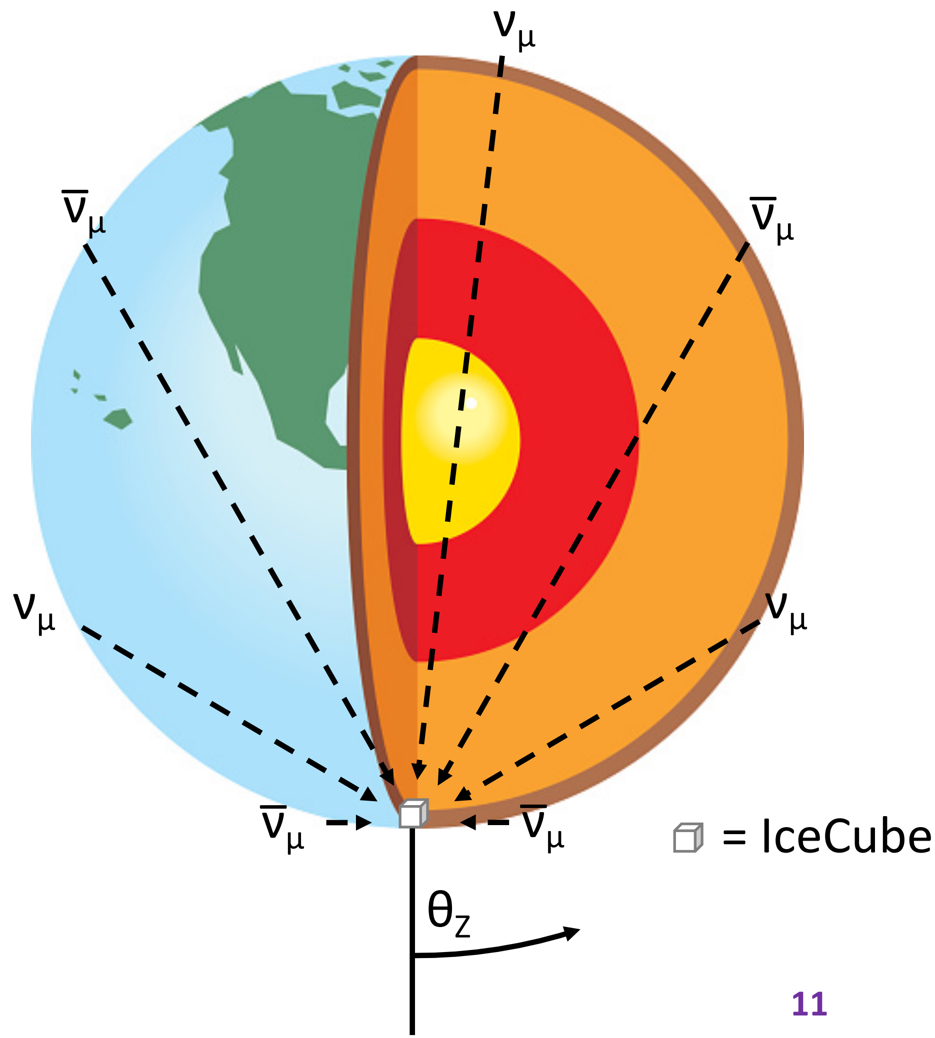


IceCube has a unique method for sterile searches

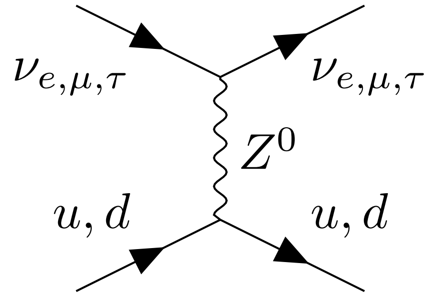
- Takes advantage of a matter resonance occurring in the Earth

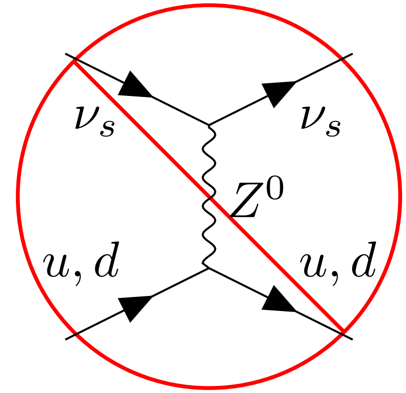


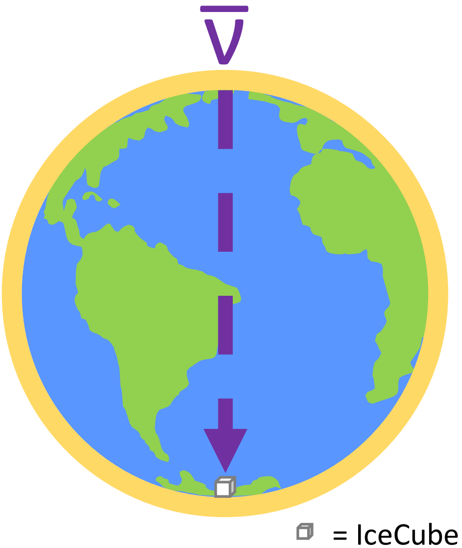
Plot from 1507.07009

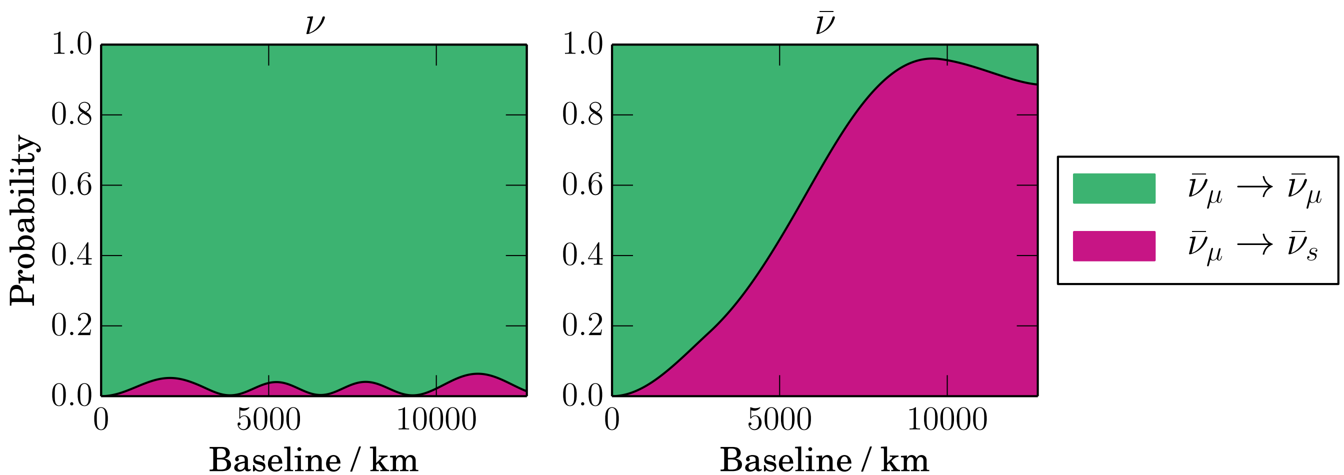


Matter Resonance





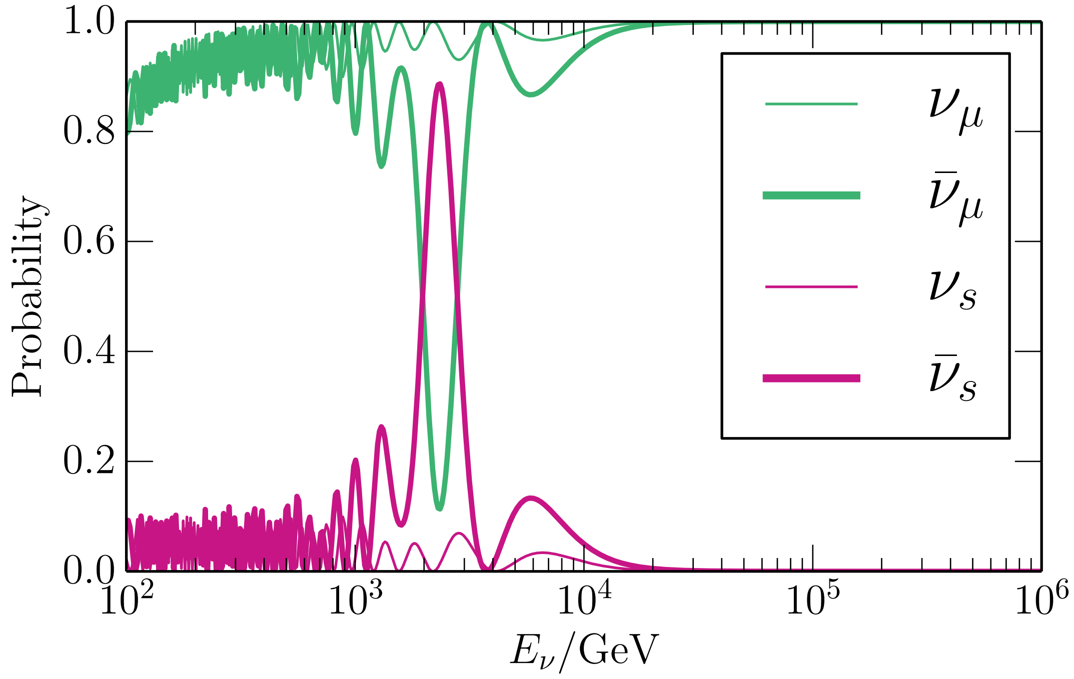


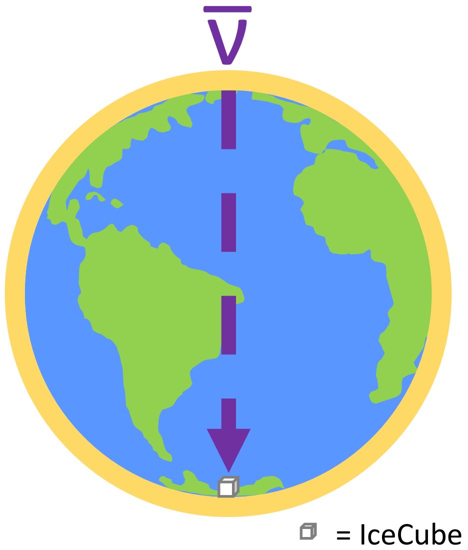


Plotted for:

- 2.3 TeV
- Δm^2_{41} = 1 eV^2, $\sin^2 2\theta_{24}$ = 0.1 (compatible with best fit)

Matter Resonance

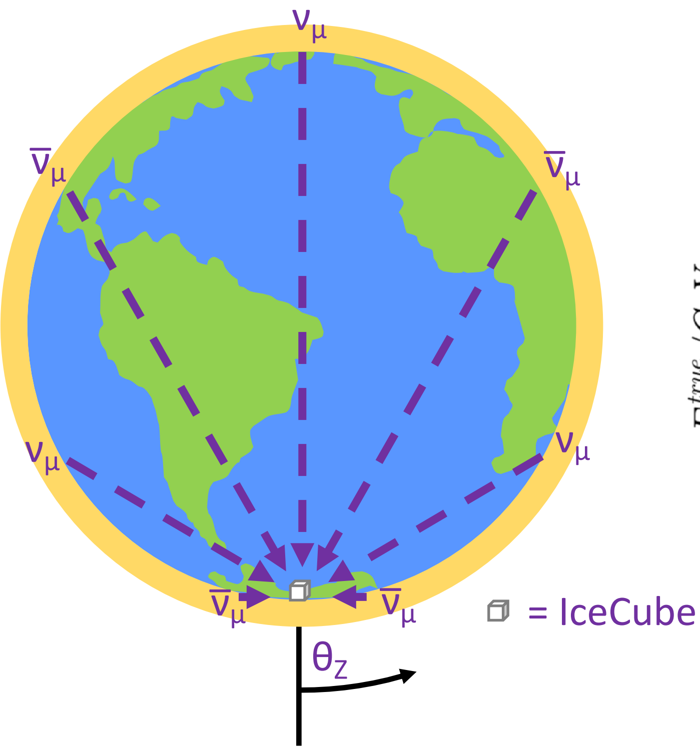




Plotted for:

- ❖ $\Delta m^2_{41} = 1$ eV^2, $\sin^2 2\theta_{24} = 0.1$ (compatible with best fit)

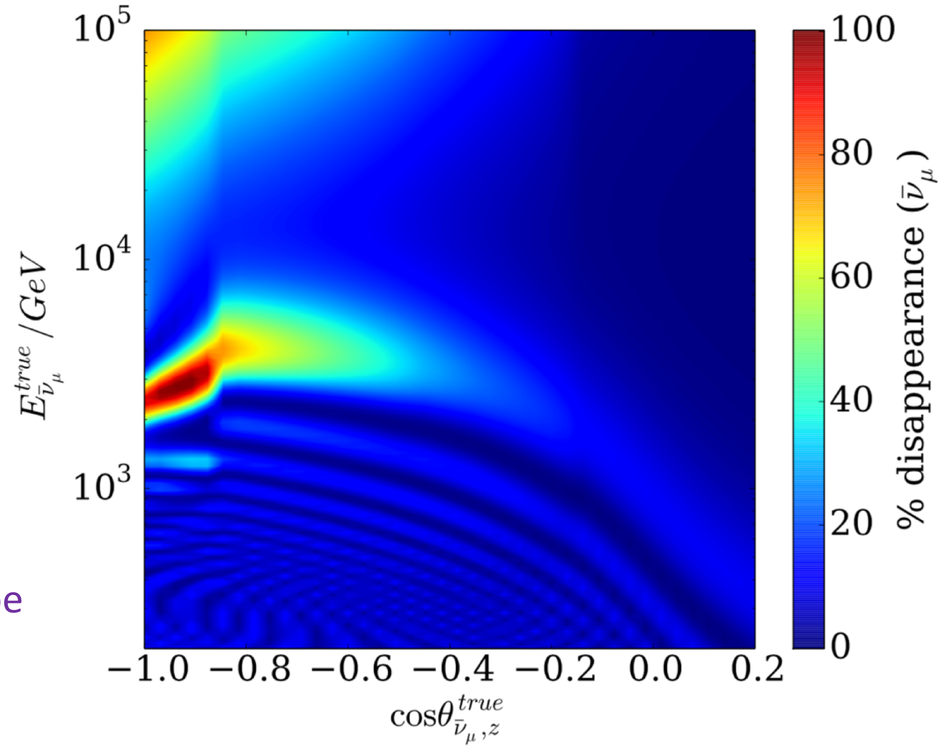
IceCube Oscillogram



For point:

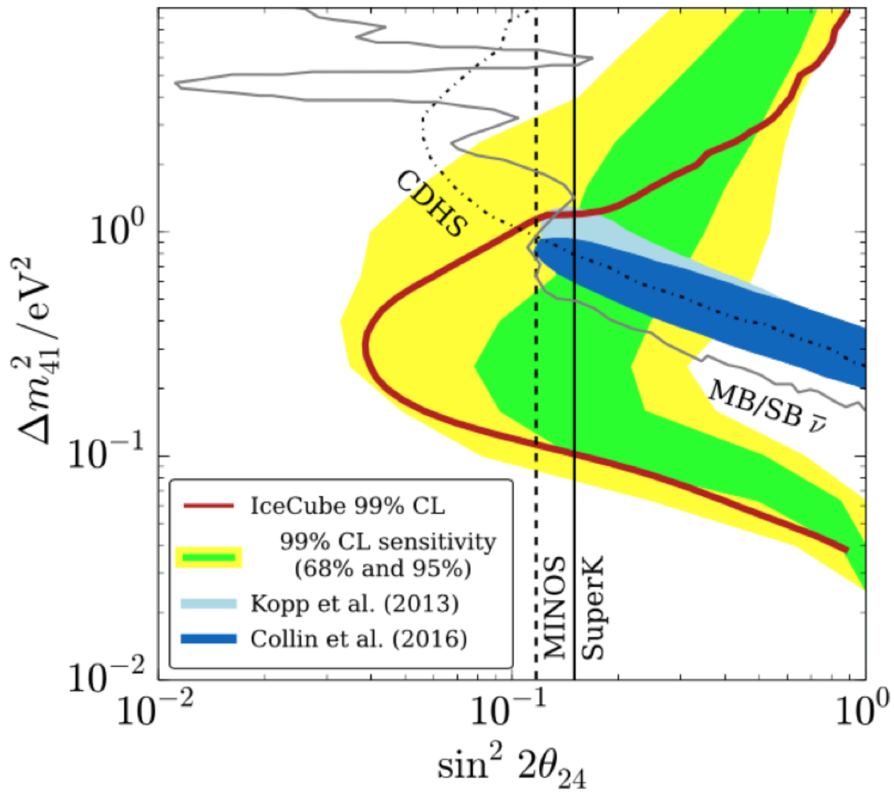
$\Delta m^2_{41} = 1\ eV^2$, $\sin^2 2\theta_{24} = 0.1$

(compatible with SBL best fit)



1-year High Energy Search for Sterile Neutrinos in IceCube

- 20,145 events : 1 year
- 400-GeV – 20-TeV
- Data binned in (anti)neutrino reconstructed [$\cos\theta_{zenith}$, E]

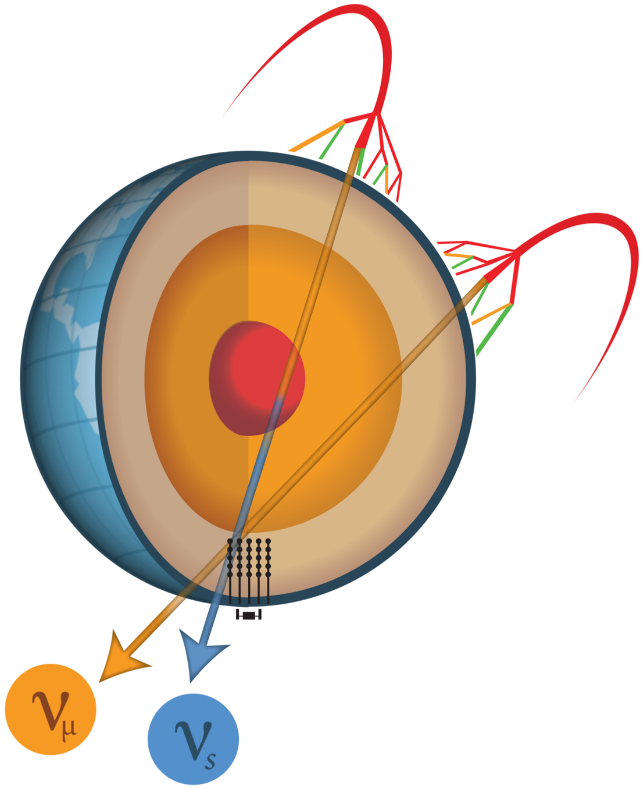


IceCube found no evidence for ~1-eV sterile neutrino.

IceCube, 2016
arXiv : 1605.01990

Upcoming Results from IceCube

- Expanding 1-year search to 8 years
- See PPNT19 talk by Carlos Argüelles



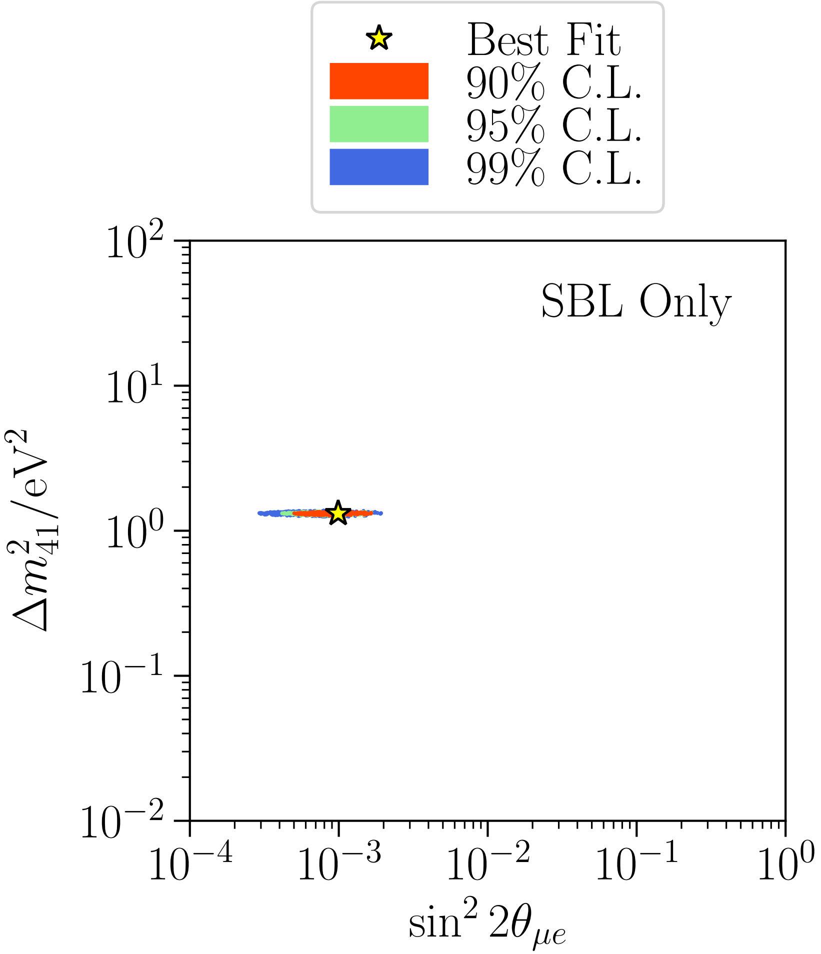
Fitting a 3+1 Model

[arXiv:1906.00045]

Incorporating IceCube data into 3+1 fit

- IceCube sterile analysis is very computationally intensive
- Cannot be directly incorporated into fit
- Compute IceCube likelihood for a random down-sample of points from the SBL global fit
- Convert IceCube likelihood into χ^2_{IceCube} and add to χ^2_{SBL}

$$\chi^2_{\text{SBL+IC}} = \chi^2_{\text{SBL}} + \chi^2_{\text{IceCube}}$$



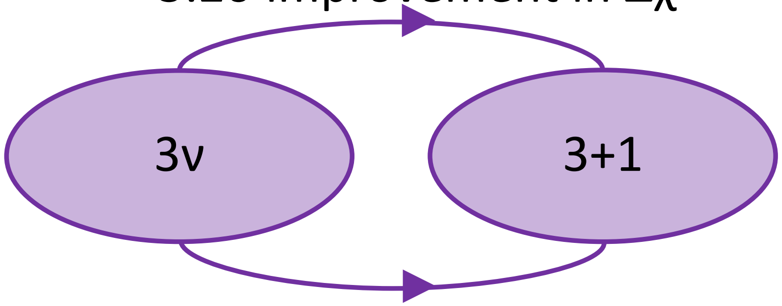
arXiv:1906.00045

New!

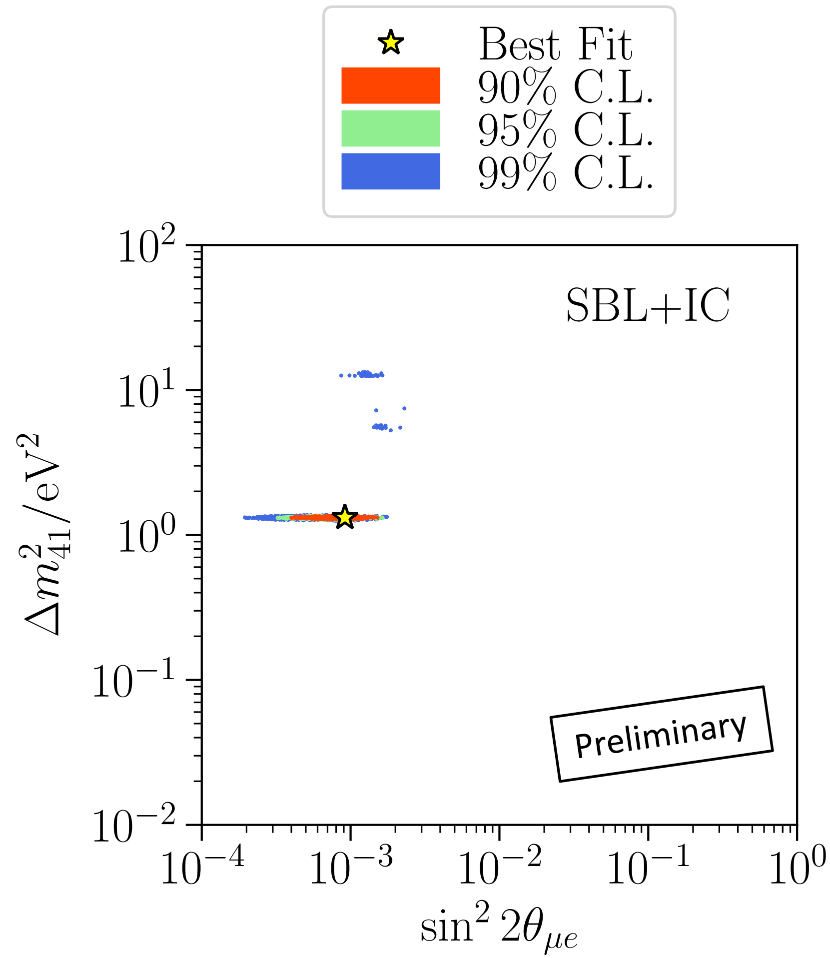
Incorporating IceCube data into 3+1 fit

- Higher-mass islands at 99% C.L.
- Slight push to smaller mixings

SBL only:
5.2σ improvement in $\Delta\chi^2$



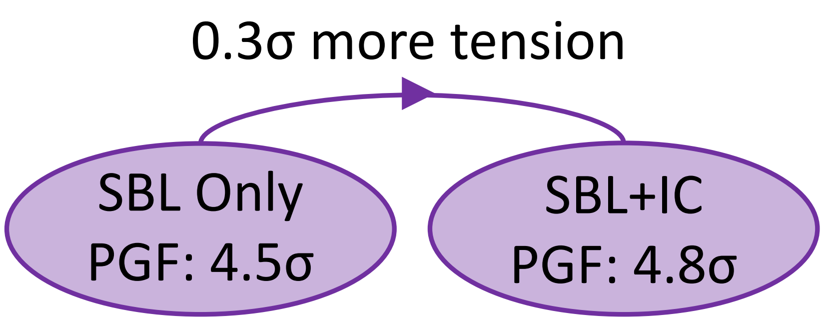
SBL+IC:
4.9σ improvement in $\Delta\chi^2$



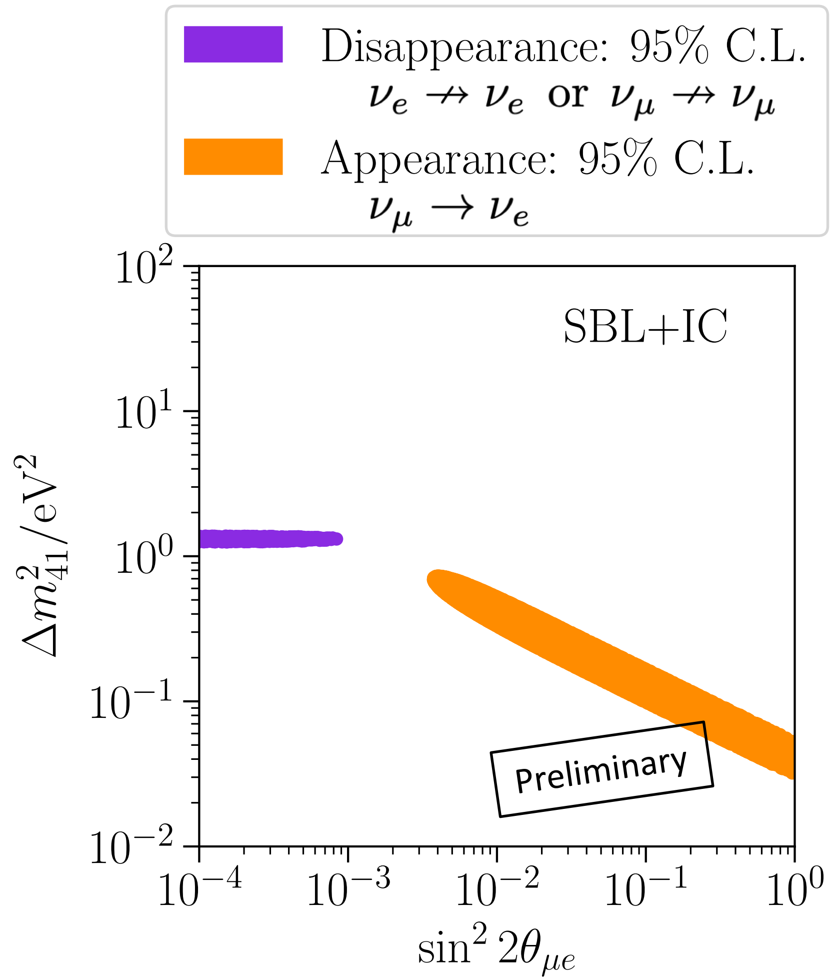
New!

Significant Tension Remains in the Fits

- Tension quantified with Parameter-Goodness-of-Fit (PGF)



- Can a more complex scenario reduce this tension?

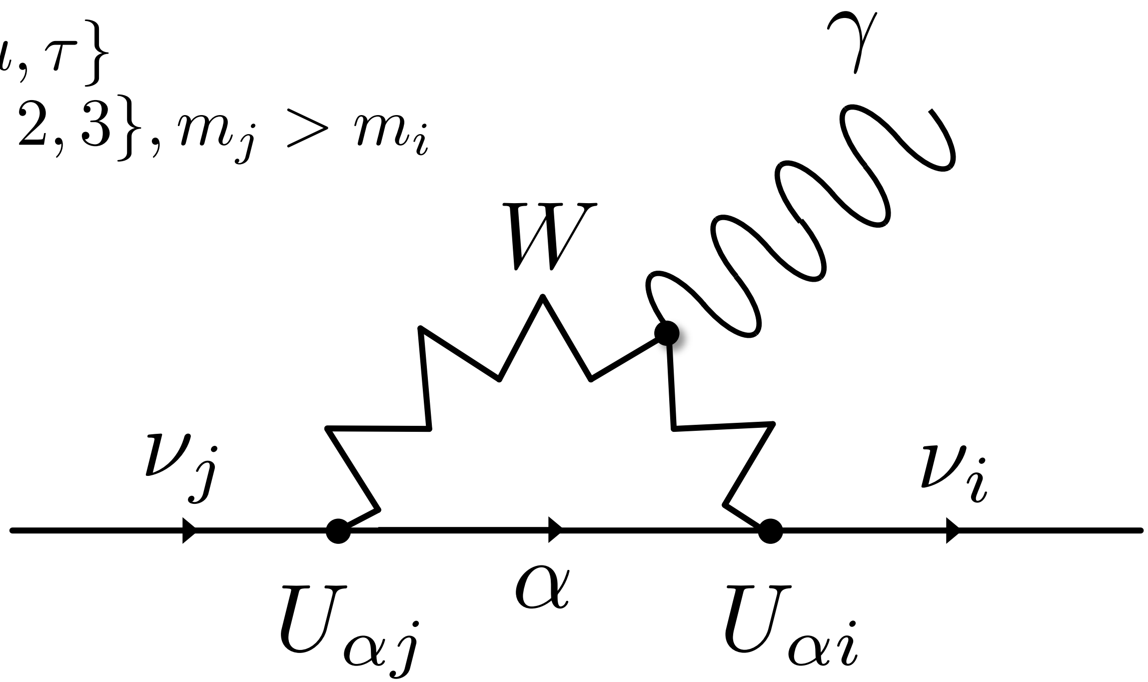


3+1+Decay Model

In the Standard Model, stable particles are those protected by a symmetry.

Standard Model Neutrino Decay

$\alpha \in \{e, \mu, \tau\}$
$i, j \in \{1, 2, 3\}, m_j > m_i$

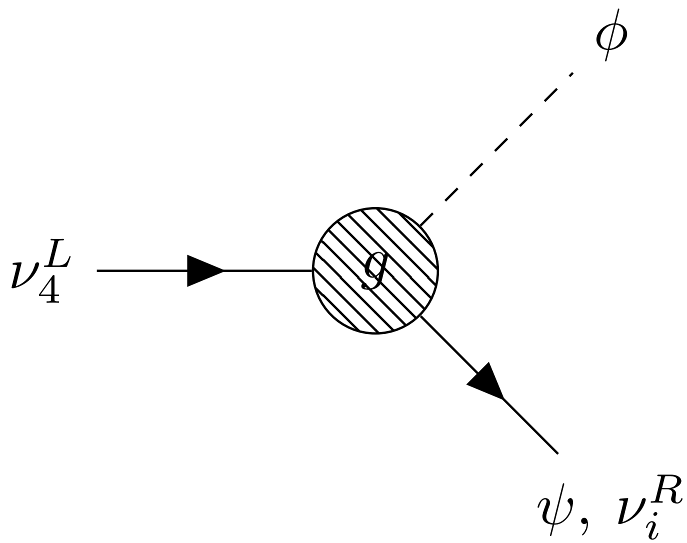


$$\nu_j \to \nu_i + \gamma \quad \Rightarrow \quad \tau \simeq 10^{36} (m_i/\mathrm{eV})^{-5} \mathrm{yr}$$

$$\nu_j \to \nu_i + \gamma + \gamma \quad \Rightarrow \quad \tau \simeq 10^{67} (m_i/\mathrm{eV})^{-9} \mathrm{yr}$$

Pal & Wolfenstein, PRD 25:766-773, Feb. 1982
Nieves, PRD, 28:1664-1670, Oct 1983

3+1 with Invisible ν_4 Decay

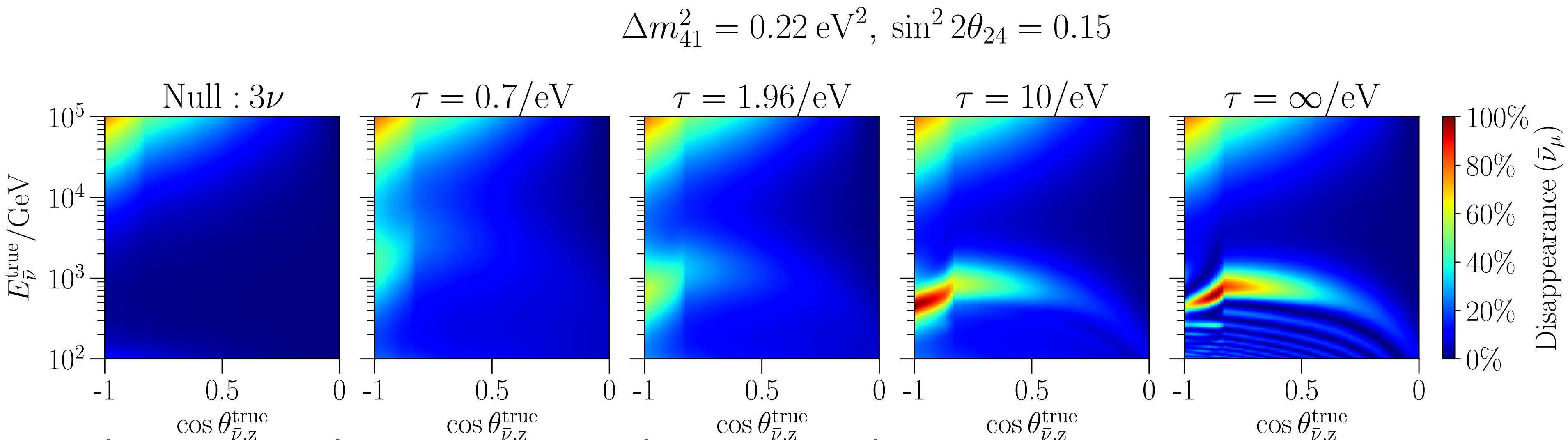


$$\frac{1}{\tau_4} = \Gamma = \frac{g^2 \cdot m_4}{16\pi}$$

- ϕ and ψ are BSM particles that are invisible to the detector
- Assume neutrinos are Dirac

What does 3+1+decay look like in IceCube?

IceCube Oscillograms: $\bar{\nu}_\mu$



Null (3ν)

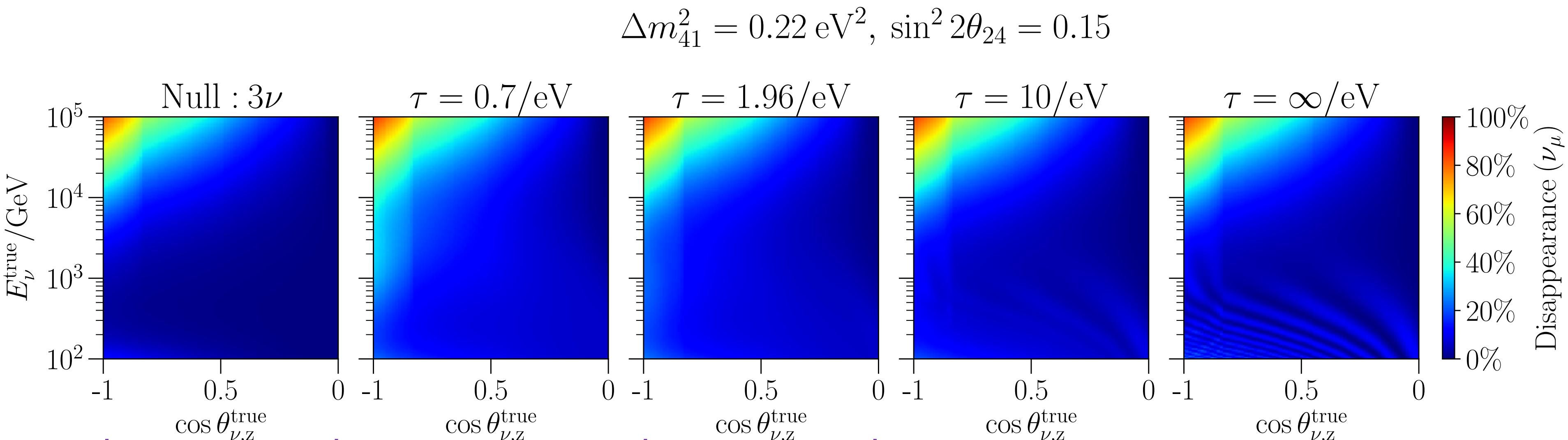
SBL-Only Best-Fit Parameters

Increasing lifetime

For $\tau = 1/\mathrm{eV}$:

$\hbar c\tau \approx 1\,\mu\mathrm{m}$

IceCube Oscillograms: ν_μ



Null (3ν)

SBL-Only Best-Fit Parameters

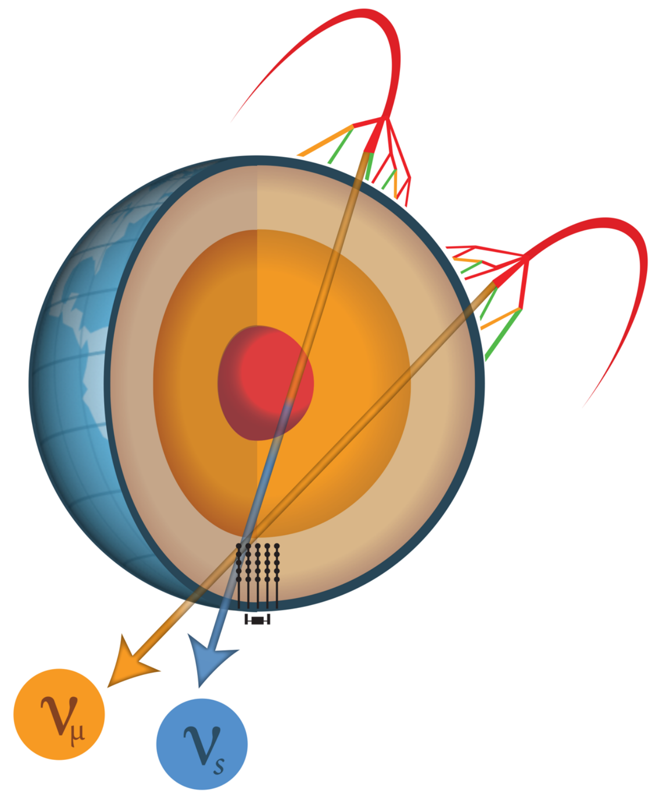
Increasing lifetime

For $\tau = 1/\mathrm{eV}$:

$\hbar c \tau \approx 1\,\mu\mathrm{m}$

Future 3+1+Decay Search in IceCube

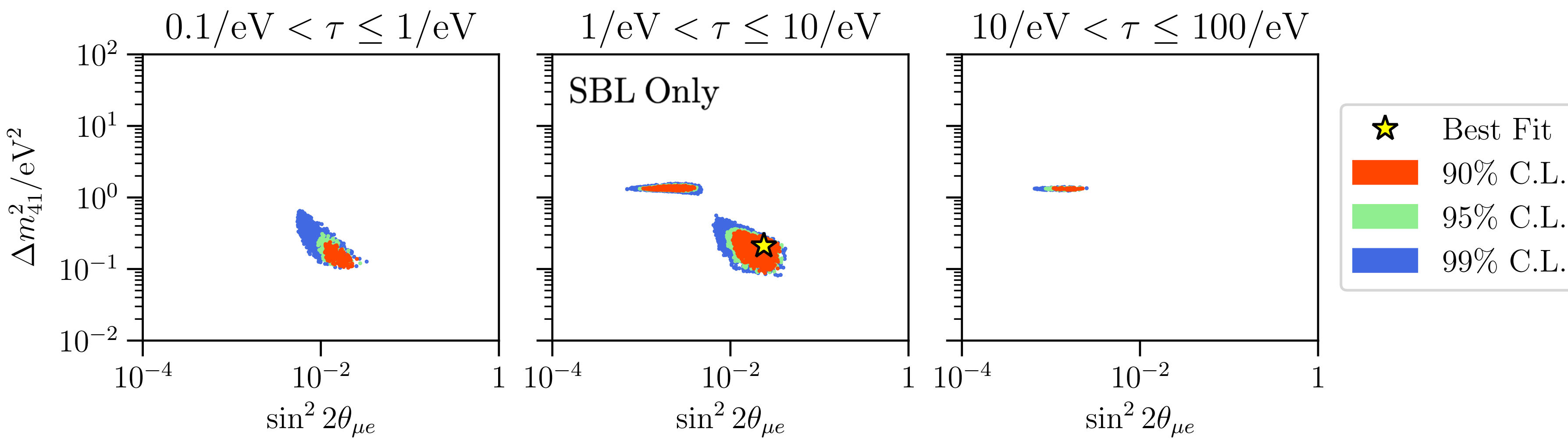
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

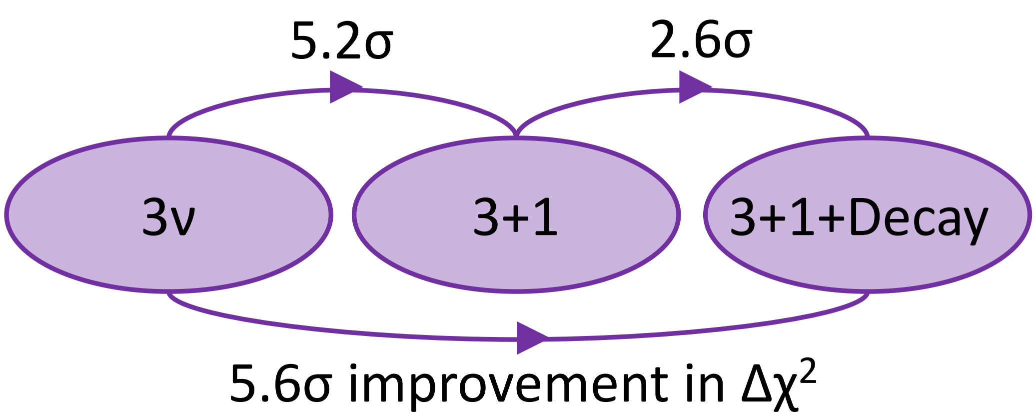


3+1+Decay Fit Results

[arXiv:1906.00045]

SBL only fits to 3+1+decay



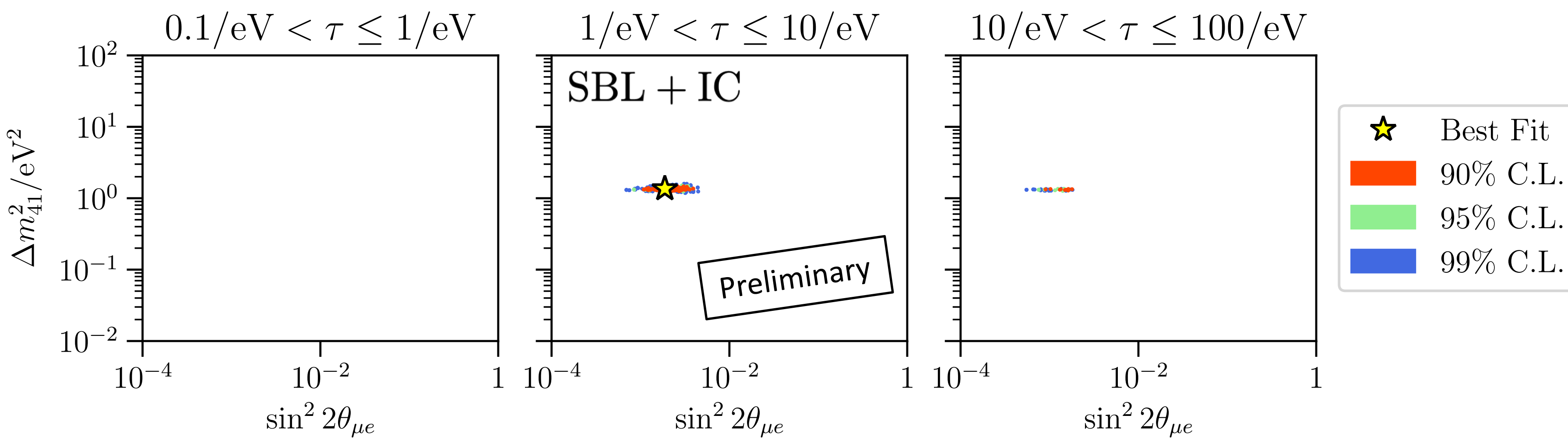


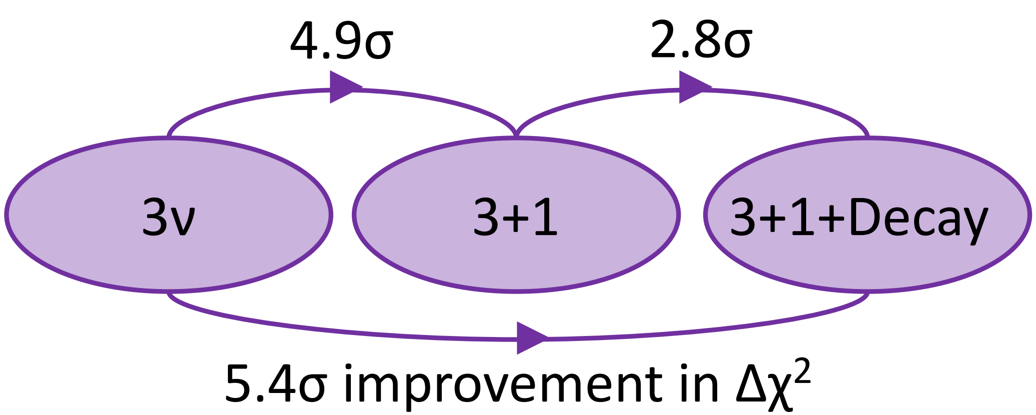
Best-Fit Point:

$$\Delta m^2_{41} = 0.23\,\text{eV}^2$$
$$\sin^2 2\theta_{\mu e} = 0.022$$
$$\tau = 1.8/\text{eV}$$

New!

IceCube added to 3+1+Decay fits

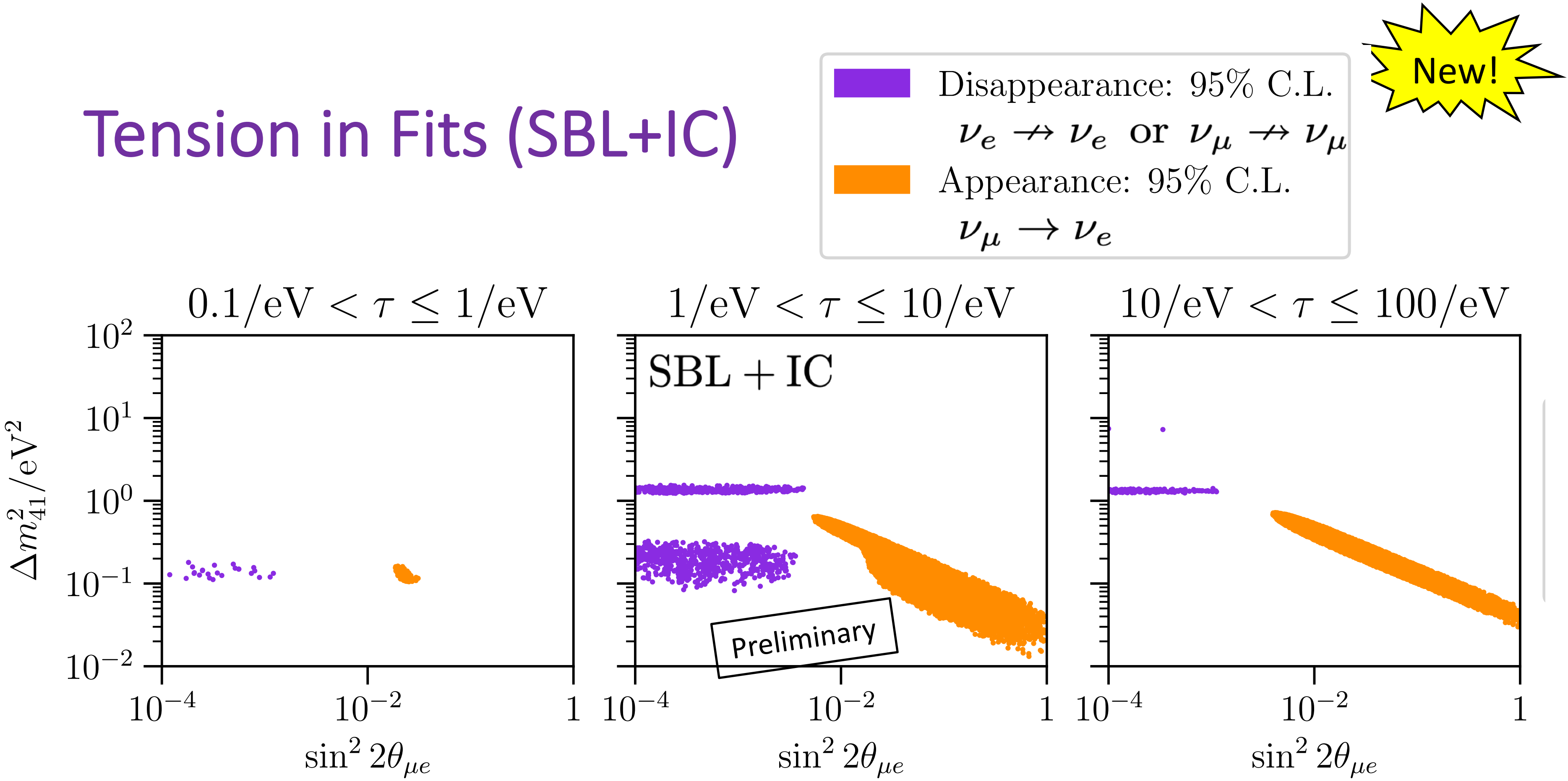




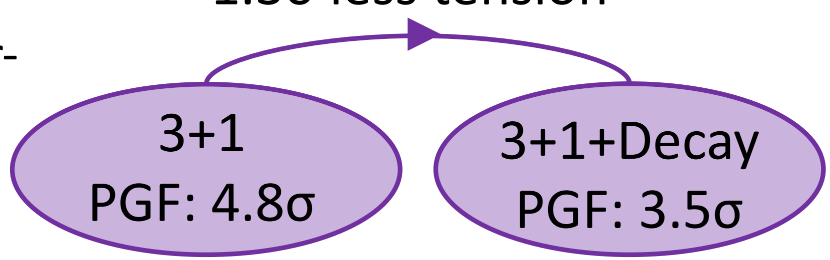
Best-Fit Point:

$$\Delta m^2_{41} = 1.4\,\mathrm{eV}^2$$
$$\sin^2 2\theta_{\mu e} = 0.0019$$
$$\tau = 4.5/\mathrm{eV}$$

Tension in Fits (SBL+IC)

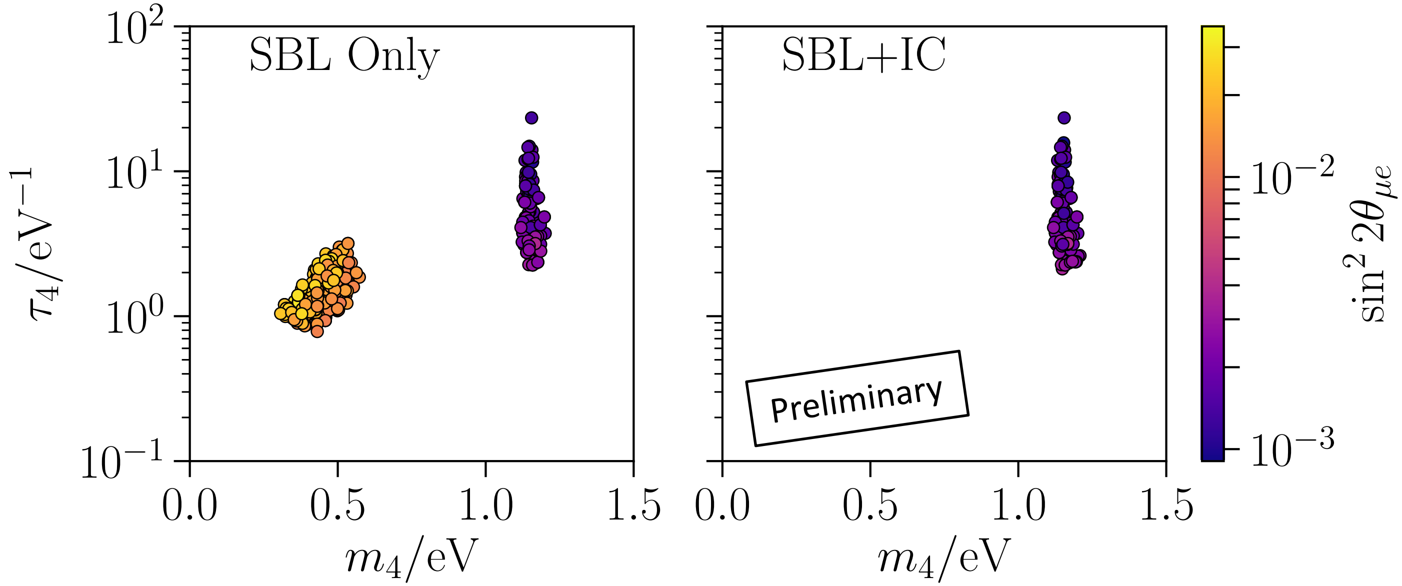


- Tension in fits is reduced
  - Quantified with Parameter-Goodness-of-Fit (PGF)



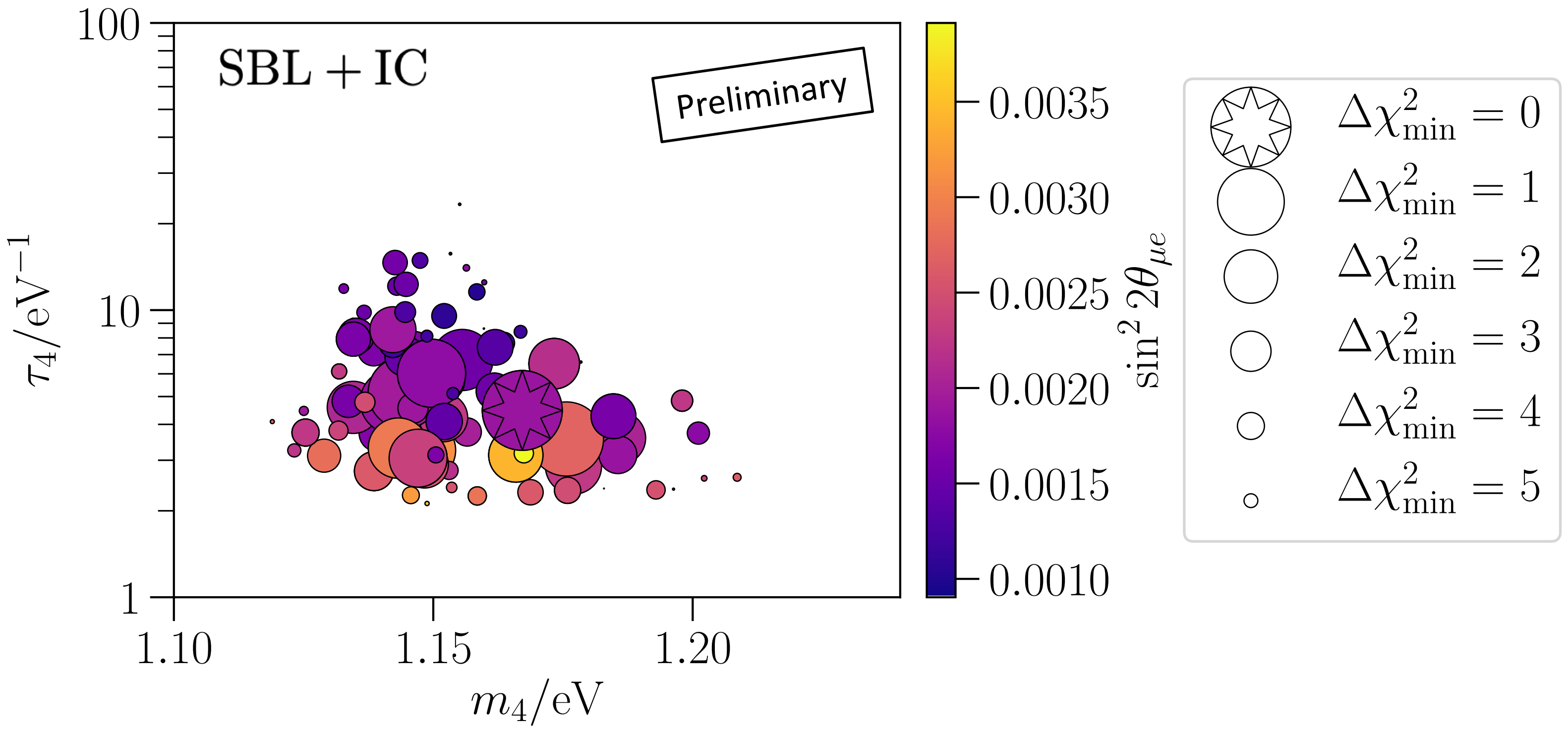
arXiv:1906.00045

Allowed regions at 95% C.L.



- IceCube eliminates the island around 0.5 eV^2

Zooming in on allowed region at 95% C.L.



Conclusions

- Sterile neutrinos could explain some anomalies we've seen
- IceCube sees a unique signature of sterile neutrinos
- Added 1-year of IceCube data to SBL fits of 3+1 and 3+1+decay
- Both 3+1 and 3+1+decay models improve over the Standard Model
- Yet tension remains, although reduced in 3+1+decay

Combined Short Baseline + IceCube Fit Results

Model	Improvement over 3ν (Significance of $\Delta\chi^2_{3\nu}$)	Improvement over 3+1 (Significance of $\Delta\chi^2_{3+1}$)	Tension (Parameter-Goodness-of-Fit)
3+1	5.2σ ⟶ 4.9σ	—	4.5σ ⟶ 4.8σ
3+1+Decay	5.6σ ⟶ 5.4σ	2.6σ ⟶ 2.8σ	3.2σ ⟶ 3.5σ

Preliminary

SBL ⟶ SBL+IC

Thank you! Questions?

Back-Up

Parameter Goodness of Fit (PGF)

- Perform three separate fits:
  - Appearance-only experiments (app)
  - Disappearance-only experiments (dis)
  - All experiments (glob)
- Effective χ^2:

$$\chi^2_{\mathrm{PGF}} = \chi^2_{\mathrm{glob}} - \left(\chi^2_{\mathrm{app}} + \chi^2_{\mathrm{dis}}\right)$$

- Effective degrees of freedom:

$$N_{\mathrm{PGF}} = N_{\mathrm{glob}} - \left(N_{\mathrm{app}} + N_{\mathrm{dis}}\right)$$

Neutrino Decay Equations

Hamiltonian for standard oscillations in matter

Decay operator

Hamiltonian, where $\Gamma = 1/\tau$:

$$H = H_0 - i\frac{1}{2}\Gamma \quad (1)$$

Density matrix formalism:

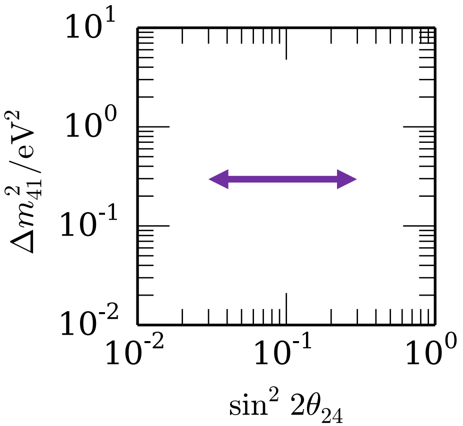
$$\frac{\partial \rho(E,x)}{\partial x} = -i[H_0, \rho] - \frac{1}{2}\{\Gamma, \rho\} \quad (2)$$

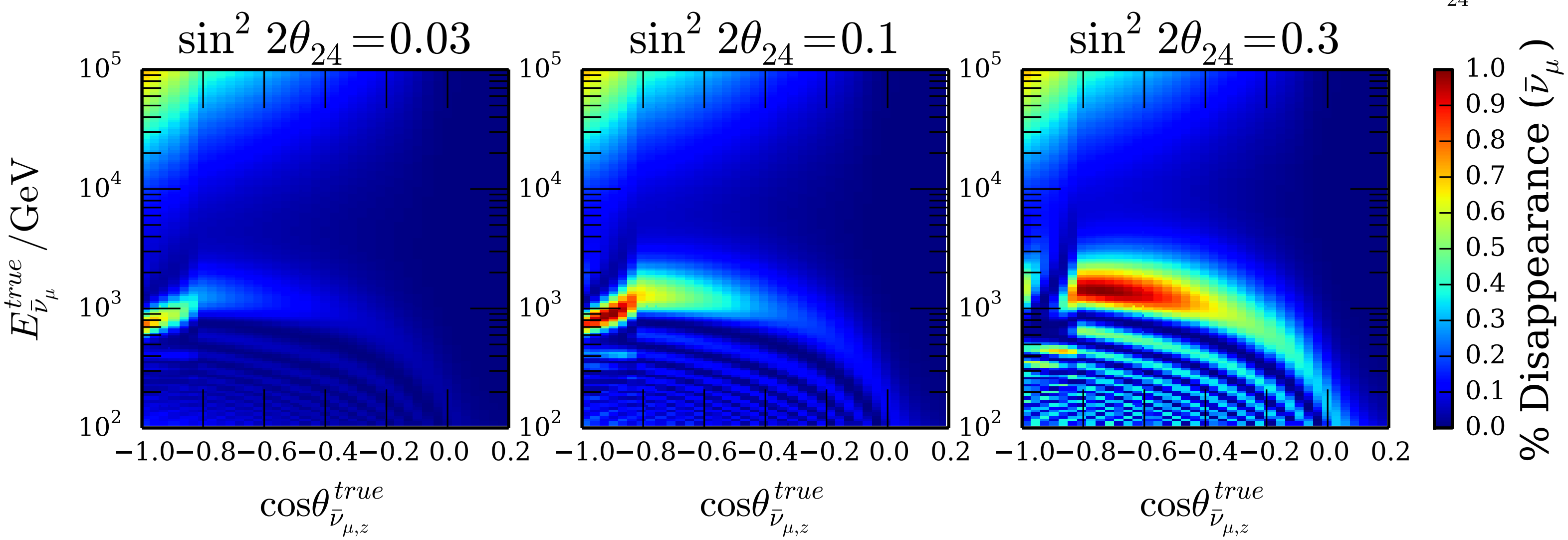
Neutrino ensemble

Calculate with nuSQuIDS

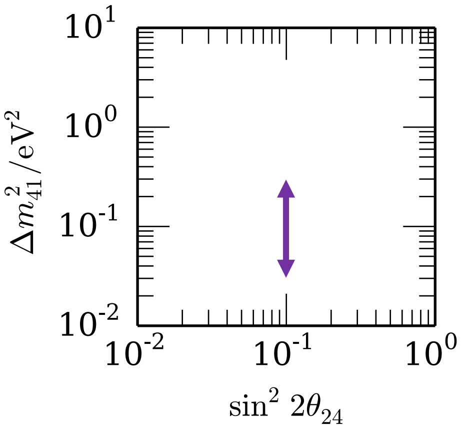
Position of resonance maps onto sterile parameter space

- Important to know backgrounds that can mimic these shapes





Position of resonance maps onto sterile parameter space



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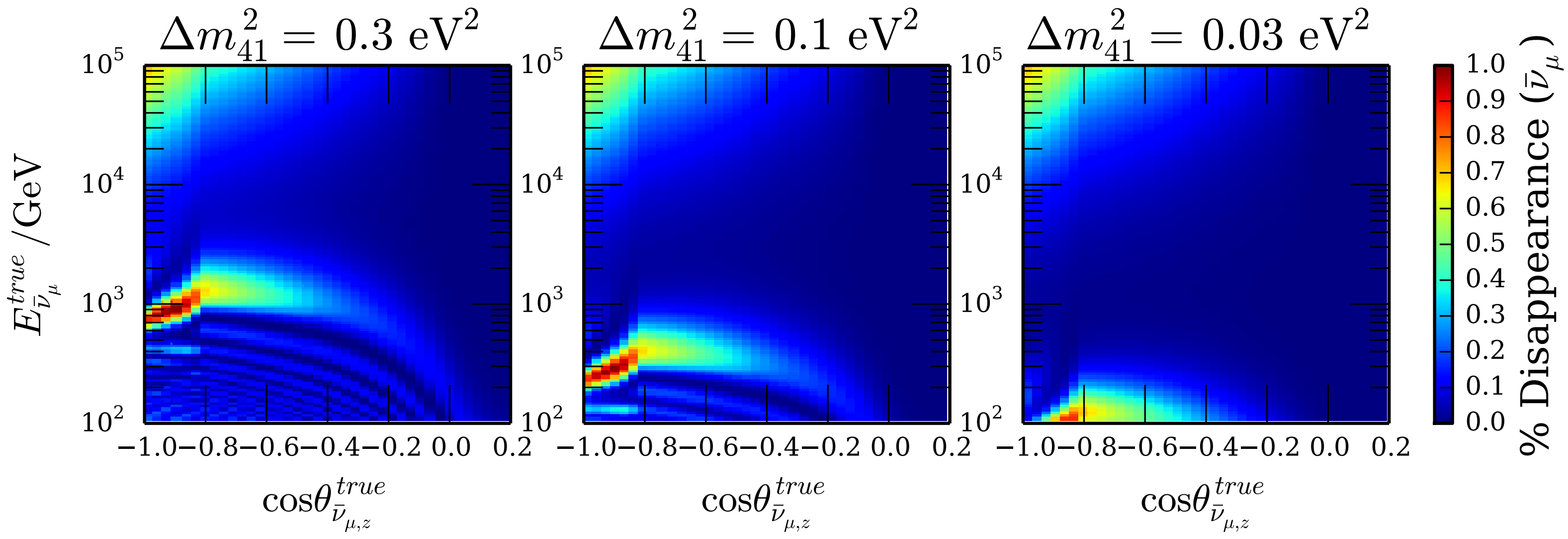
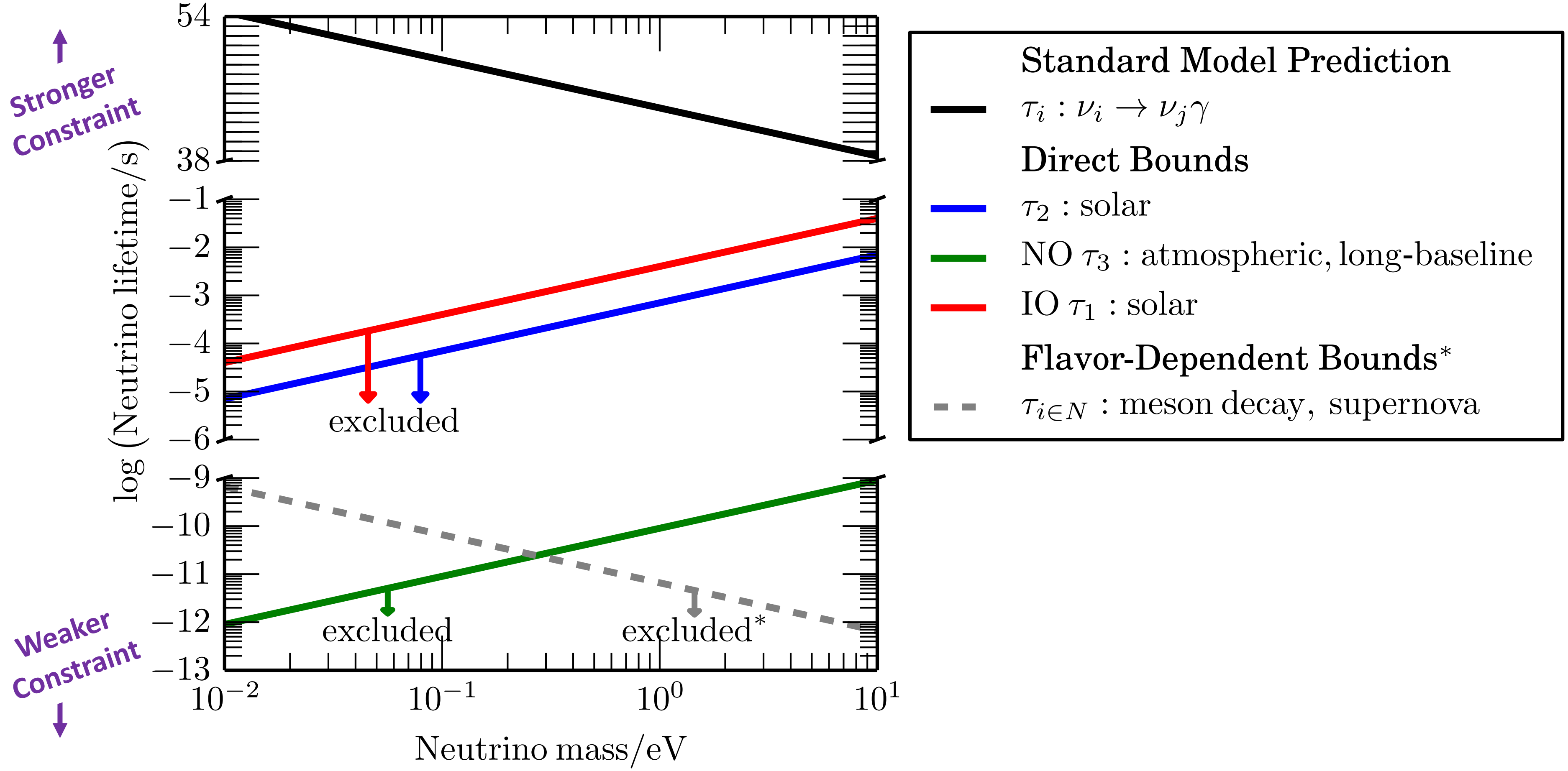


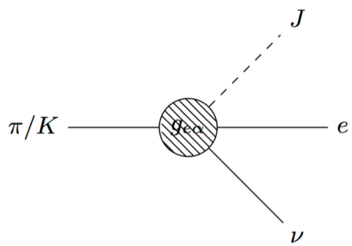
Constraints on Neutrino Decay



Flavor-dependent bounds

Bound from meson decays:

$$\sum_\alpha |g_{e\alpha}|^2 < 3 \times 10^{-5}$$



$$g_{\alpha\beta} = \sum_{i,j} g_{ij} U_{\alpha i} U^*_{j\beta}$$

Assume only one g_{4j} is non-zero:

$$g_{\alpha\beta} = g_{4j} U_{\alpha 4} U^*_{j\beta}$$

From SBL fits:

$$U_{\alpha 4} \sim \mathcal{O}(0.1)$$

From standard measurements:

$$U_{j\beta} \sim \mathcal{O}(0.1)$$

$$\Rightarrow g_{4j} < \mathcal{O}(0.1)$$

$$\Gamma_{ij} = g_{ij}^2 m_i / 32\pi$$

$$\tau_{ij} > 10^4 / m_i$$

But if more than one g_{4j} is non-zero, cancellations may occur, decreasing the constraint on decay rate.

Sterile Neutrinos and Cosmological Bounds

- Active area of research
- Bounds from cosmology are model-dependent
- Hubble Tension (4 σ)
  - Planck CMB + LCDM: [arXiv:1807.06209] — $H_0 = 67.4 \pm 0.5$ km/s/Mpc ↳ $N_{eff} = 2.99 \pm 0.17$
  - Hubble Space Telescope, local measurement: [arXiv:1903.07603] — $H_0 = 74.03 \pm 1.42$ km/s/Mpc
  - Relaxing H_0 could accommodate higher N_{eff}
- "Secret interactions" could prevent/delay sterile neutrino thermalization
  - [arXiv:1902.00534]
    - "Strongly interacting" neutrino cosmology fits:
      - $N_{eff} = 4.02 \pm 0.02$
      - $H_0 = 72.3 \pm 1.4$ km/s/Mpc
  - [arXiv:1806.10629]
    - Secret interactions that may evade bounds from CMB, LSS, & BBN
    - Prompt invisible decay may help
- Ultra-light scalar with Yukawa coupling to sterile neutrino [arXiv:1907.04271]
- Cosmological implications of 3+1+decay needs to be studied