Introduction to Short-Baseline Oscillations & Historical Anomalies

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17th International Neutrino Summer School — UC Santa Barbara

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About Me

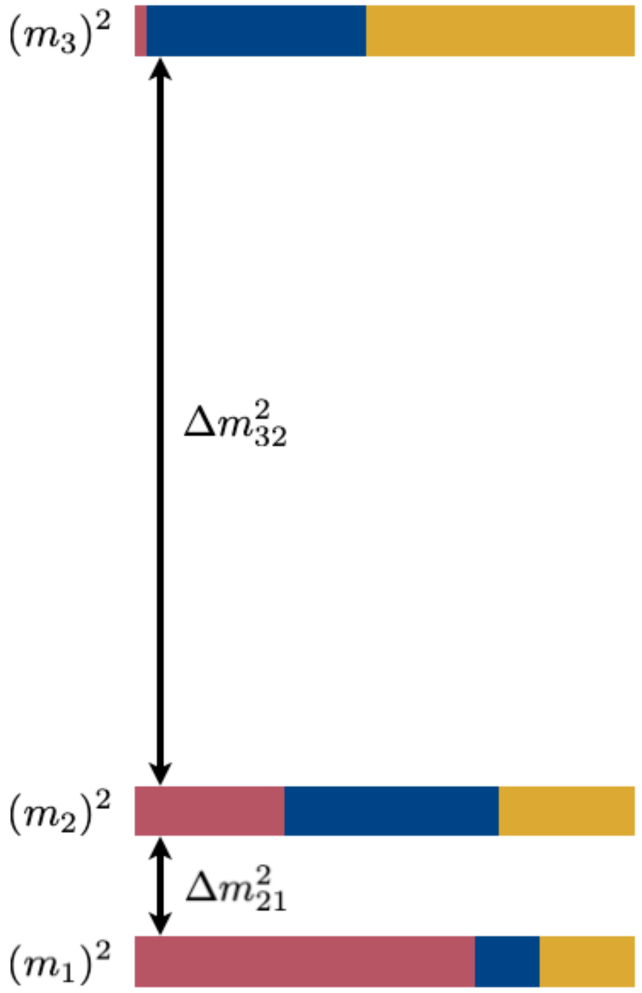
- Grew up in Massachusetts
- Undergraduate degree at Rice University, major in physics and minor in math, 2016
- PhD from MIT, 2022
- Postdoc at Fermilab, 2022 to 2025
- Faculty at University of Notre Dame since last summer

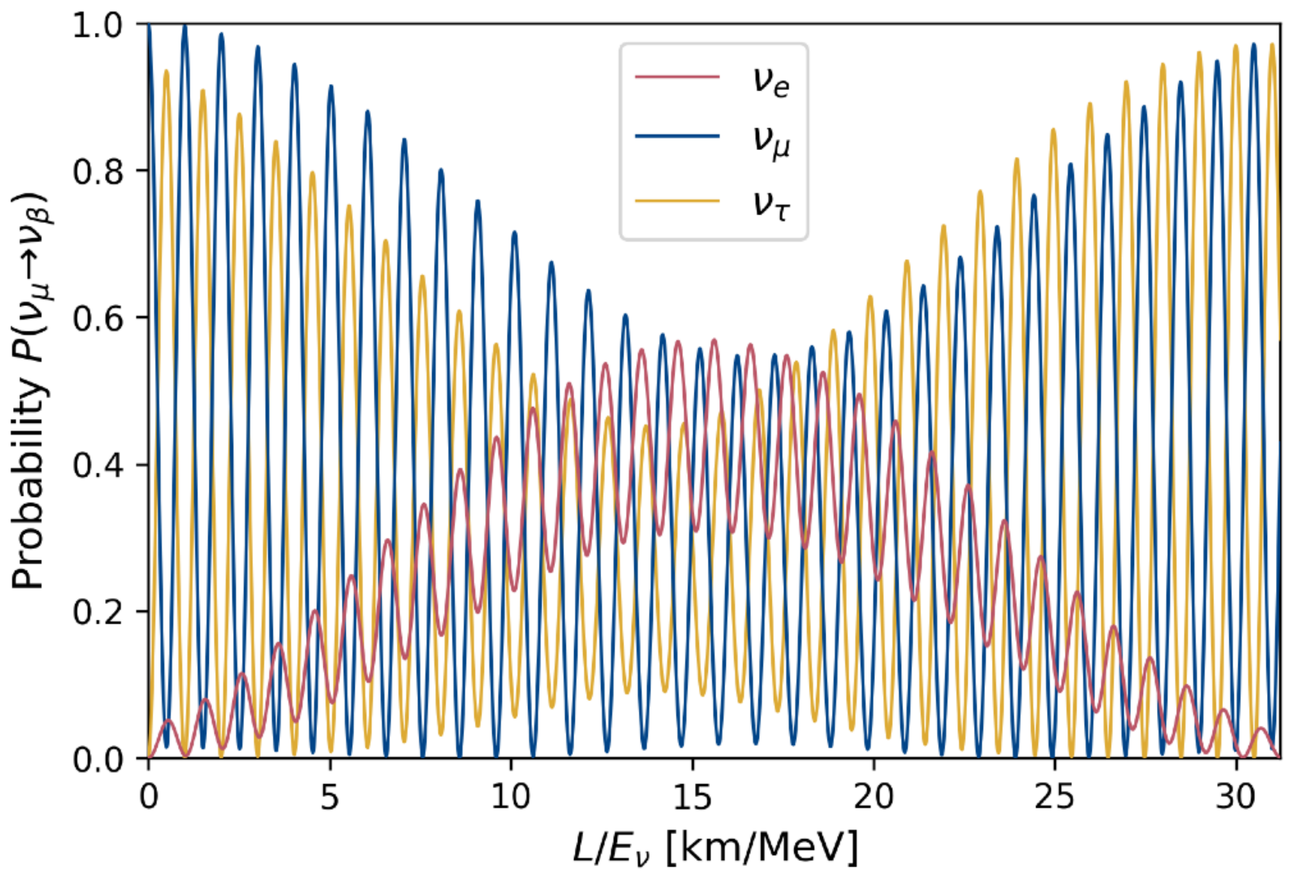
- PhD on MicroBooNE experiment
- Postdoc on Short-Baseline Near Detector (SBND) experiment
- Currently convening short-baseline oscillation physics group on SBND, as part of the Short-Baseline Neutrino (SBN) Program at Fermilab
- Also interested in future work on DUNE

What is Short Baseline?

Reminder: Three-Flavor Neutrino Oscillations

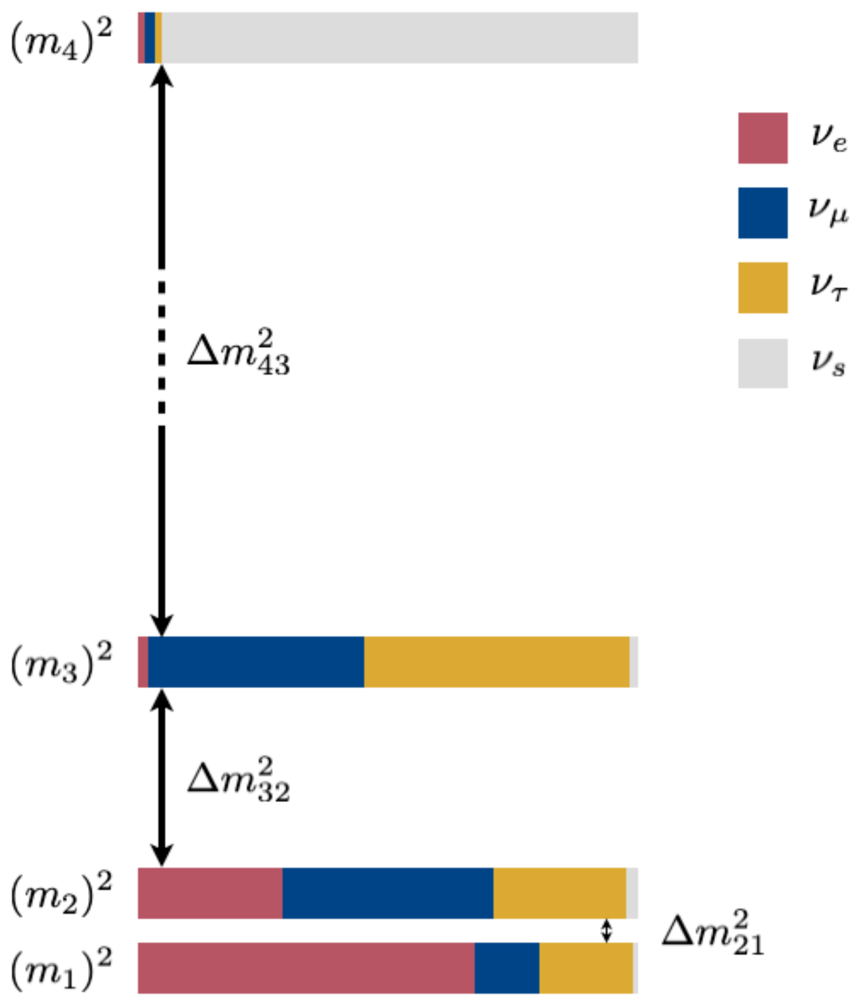
- We now understand that the three flavors of neutrinos in the Standard Model oscillate, because they have non-zero masses and have mixing between mass and flavor eigenstates
- Oscillation probabilities generally involve oscillatory terms with an L/E dependence
- In the simplified two-neutrino case, $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$

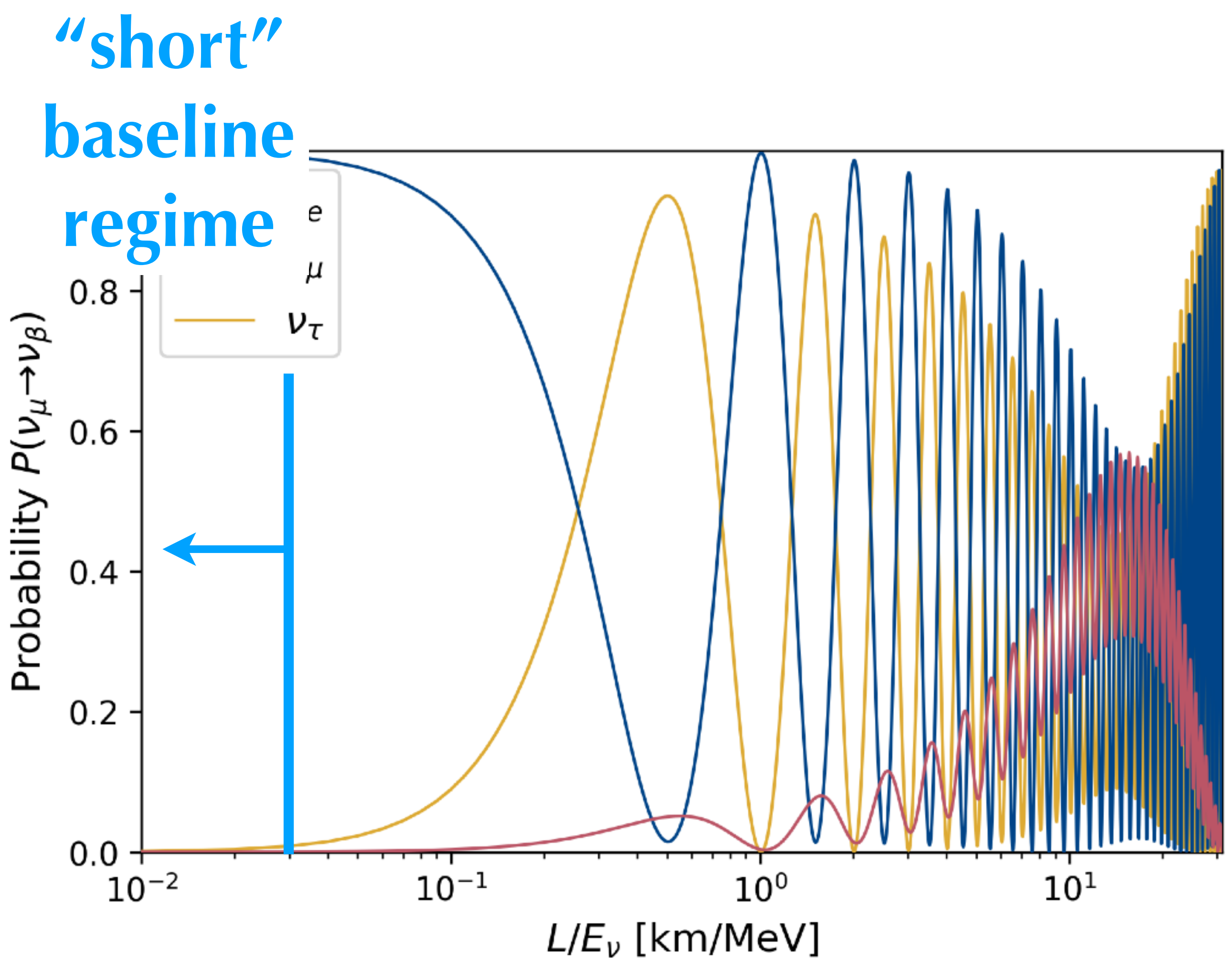




“Short” Baseline

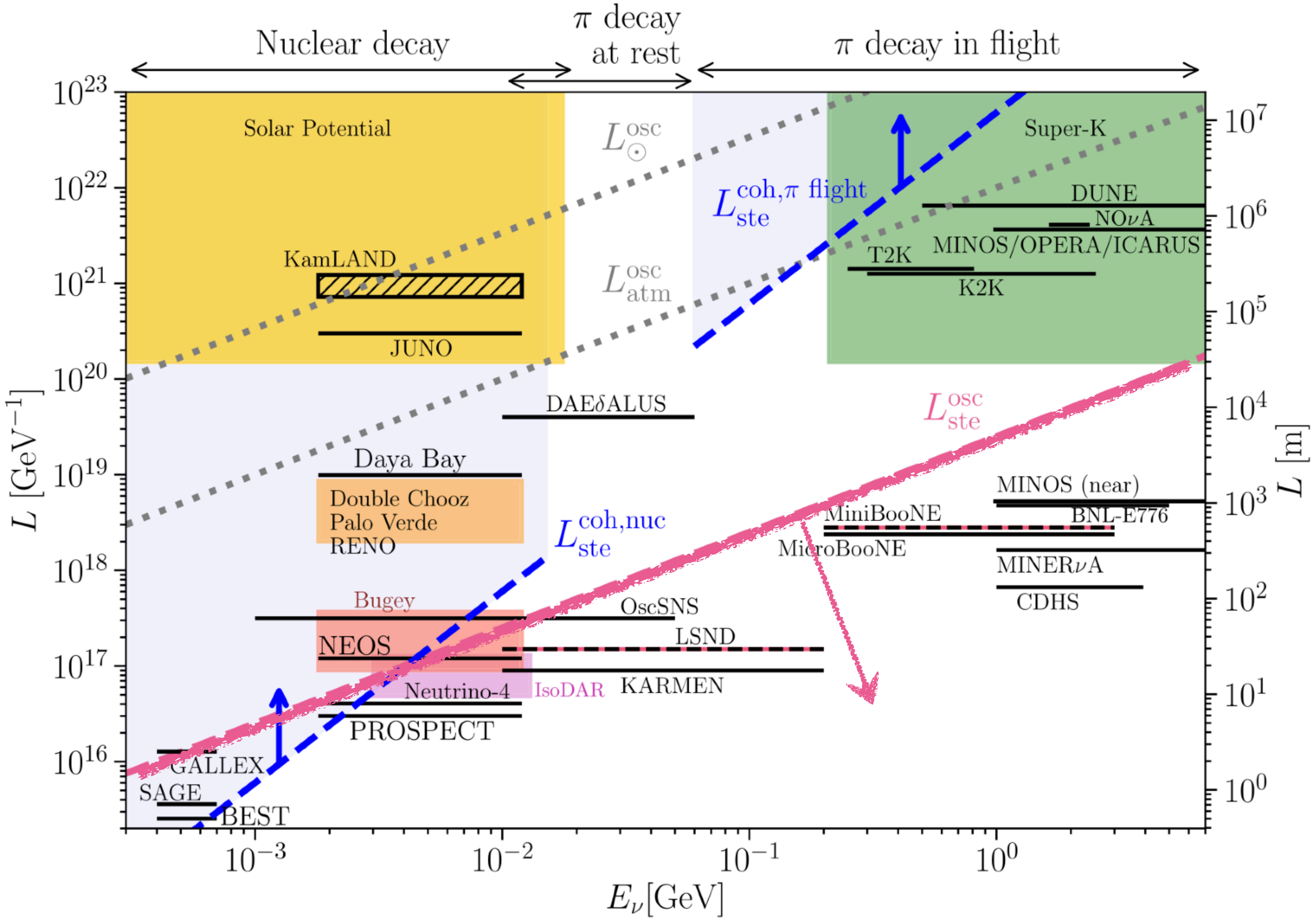
- Short-baseline experiments are ones where the L/E is sufficiently small such that standard neutrino oscillations do not yet have a significant effect
- If we observe oscillations at short baselines, it implies there exists an additional *sterile* neutrino state that mix with the active neutrino states with a large Δm^2





“Short” Baseline

- Many experiments over the years have studied neutrinos in this regime, with varying results



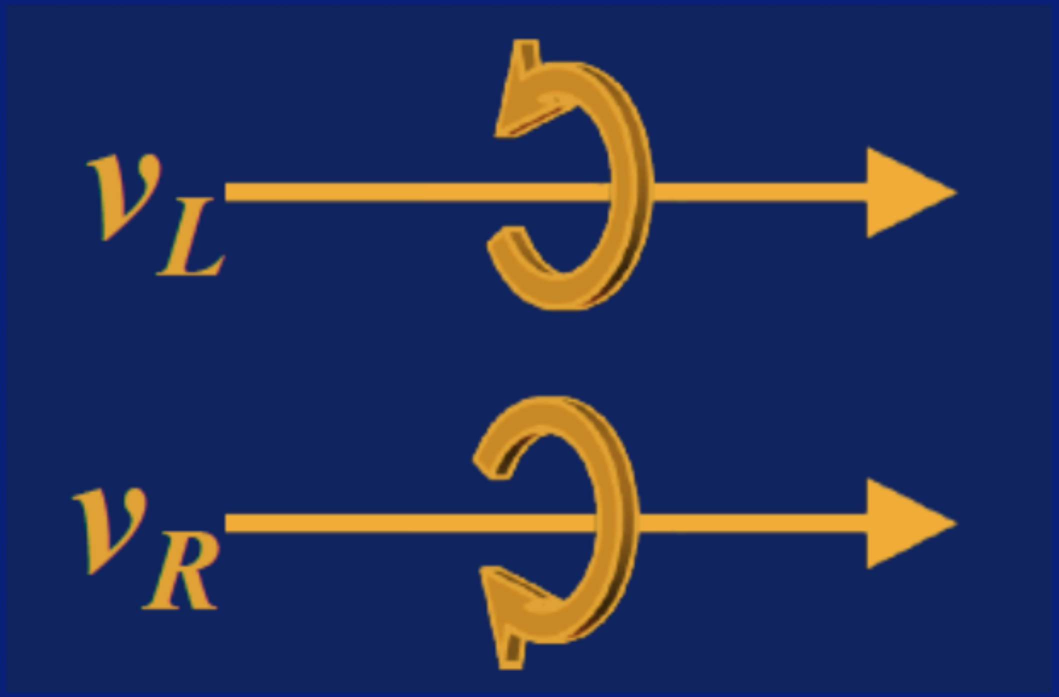
PhysRevD.107.036004

Why Short-Baseline?

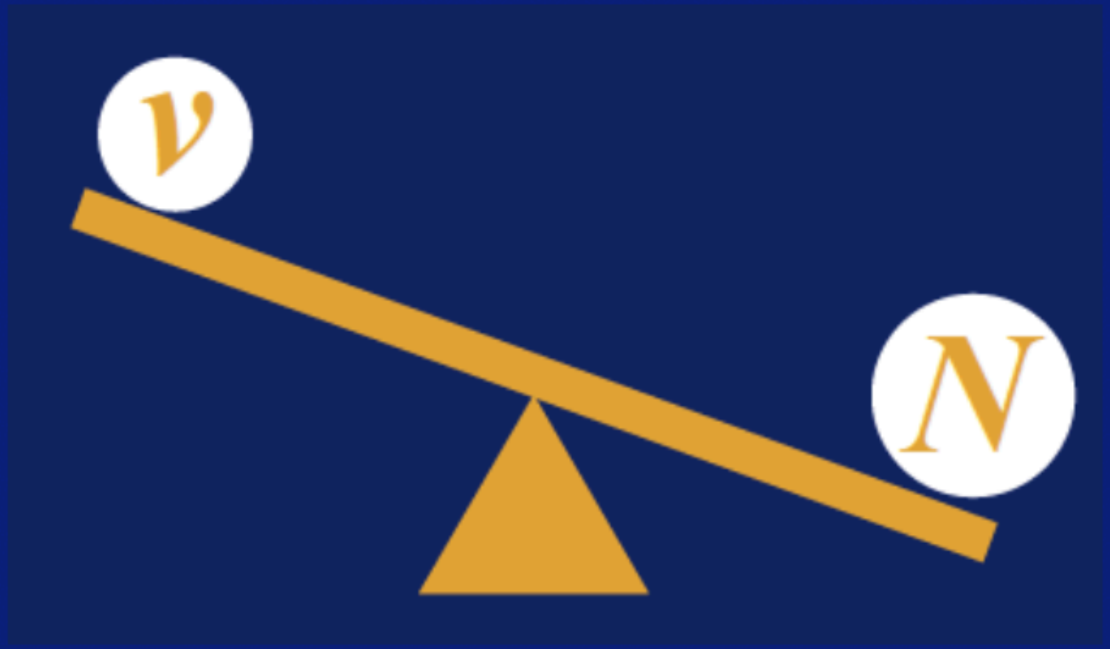
The Puzzle of Neutrino Mass

- Neutrino masses have a number of mysteries that short-baseline experiments can probe by searching for new neutrino states at different oscillation parameters

For neutrinos to gain mass from the same mechanism as all other particles they must have currently-unseen right-handed states

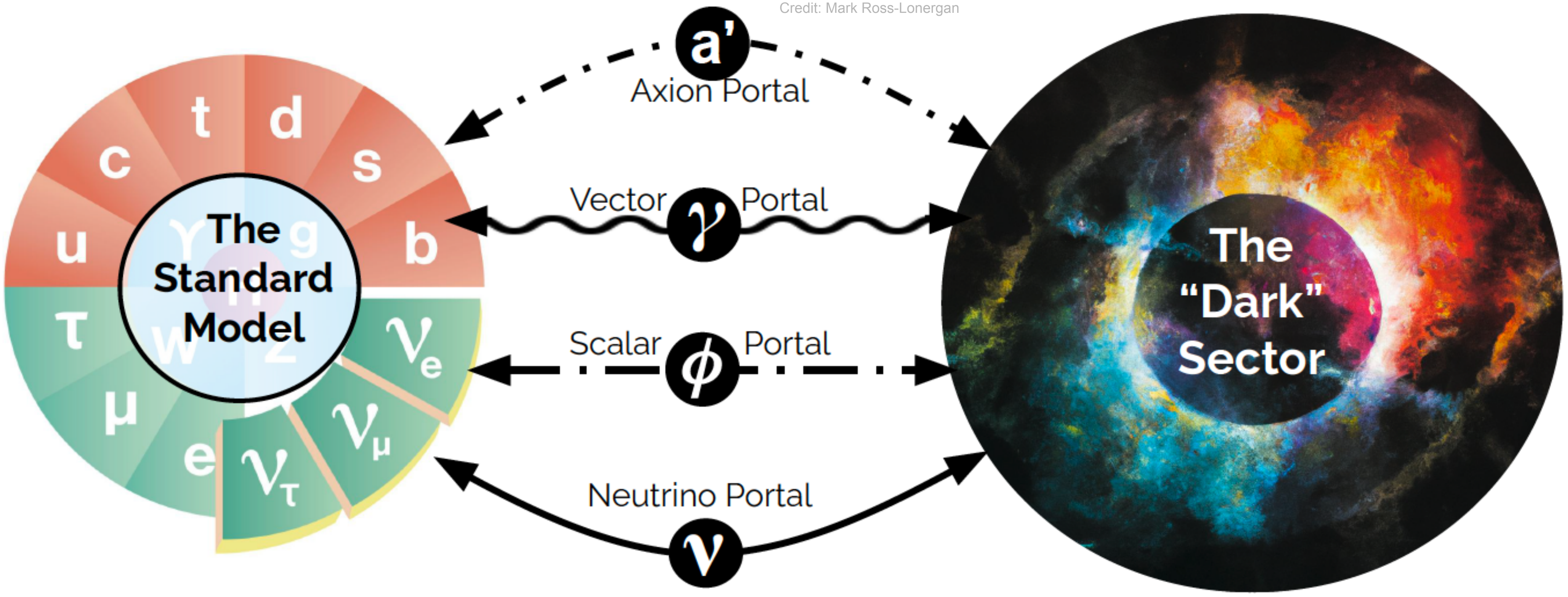


Neutrinos are unnaturally light. Implies they gain mass from an alternative system such as the proposed "see-saw" with currently-unseen large mass states



Portals to Dark Sectors

- Neutrinos can "mix" with dark matter through a number of "portals" that can be probed at short baselines



Neutrino Portal $\mathcal{L} \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.}$

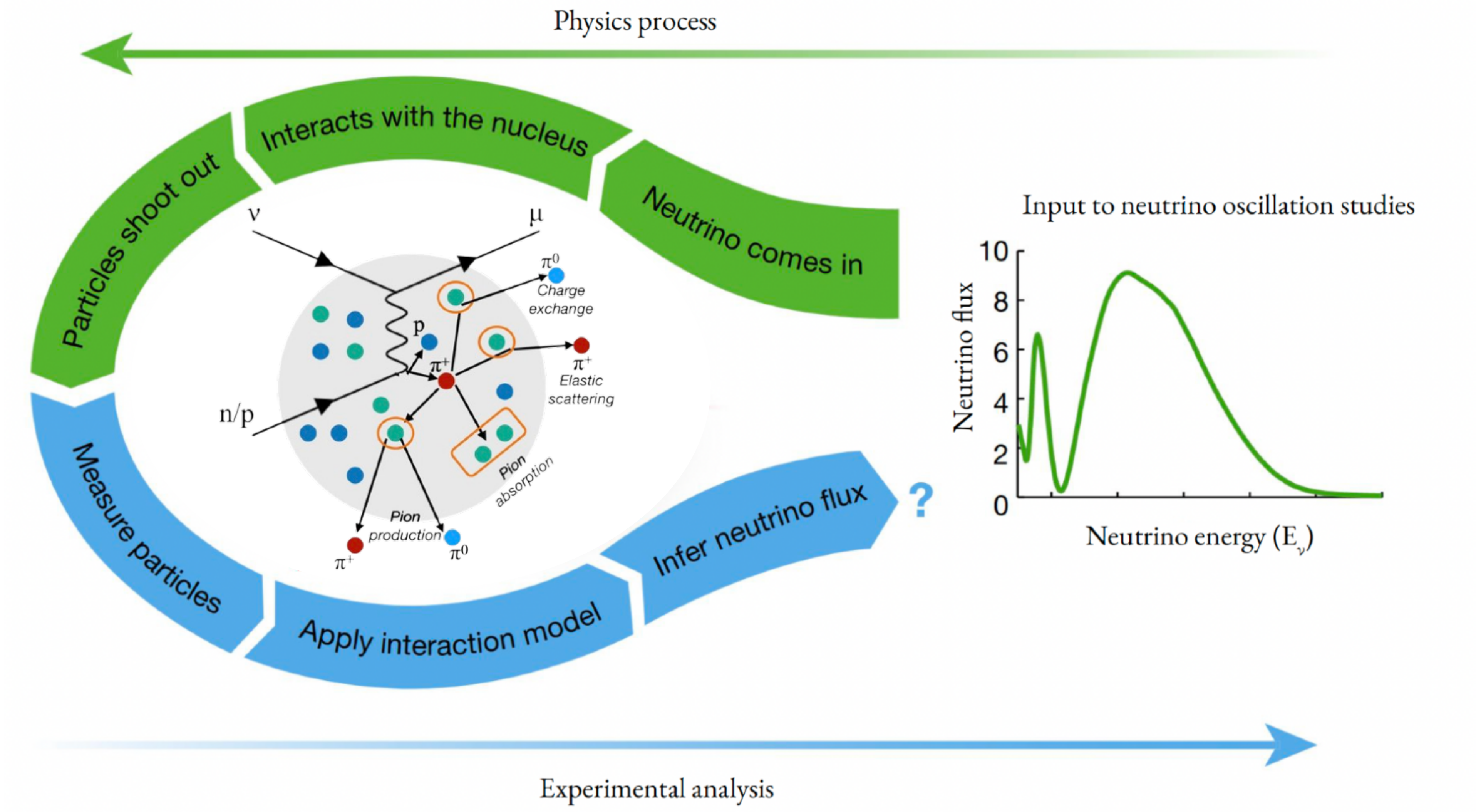
Scalar Portal $\mathcal{L} \supset (A\,S + \lambda\,S^2)\,H^{\dagger}H$

Vector Portal $\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$

Axion Portal $\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^{a}_{\mu\nu} \widetilde{G}^{a,\mu\nu}$

Neutrino–Nucleus Interactions

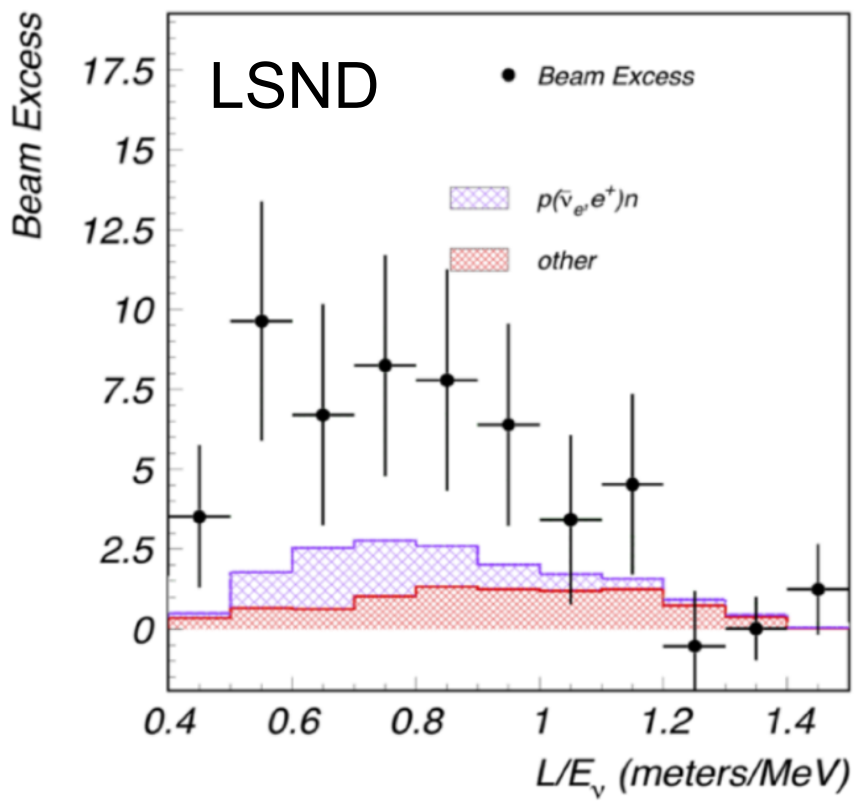
- Current and next-generation experiments require increasingly precise understanding of neutrino–nucleus interactions in order to be successful
- Many experiments designed to measure interactions are also sensitive to short-baseline oscillations, which could bias their results



Nature 599, 565–570 (2021)

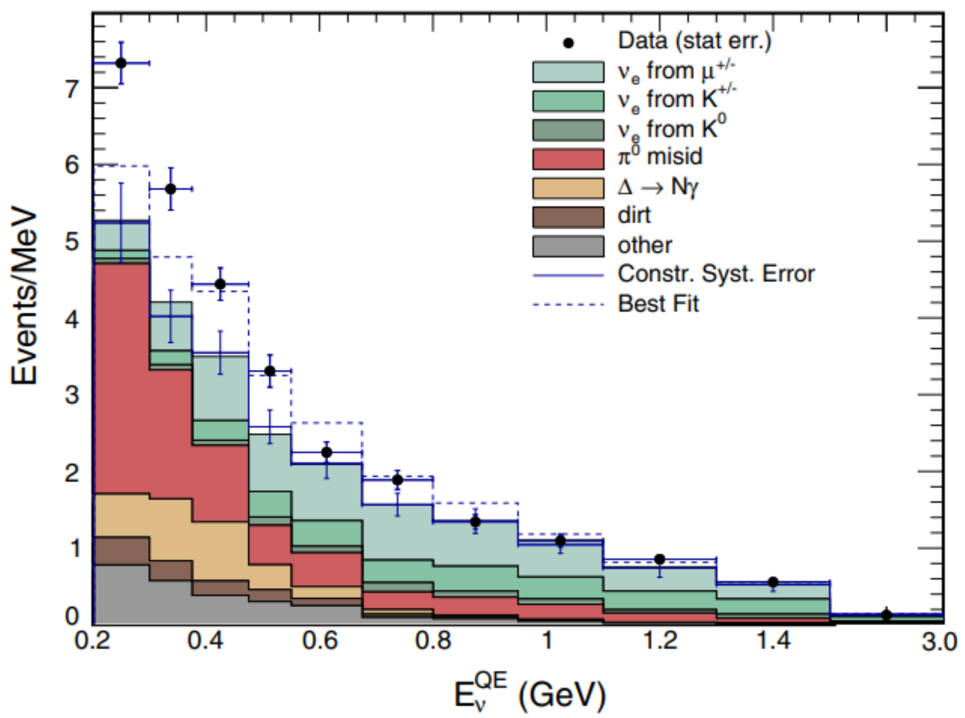
Anomalies

- Historically, we've seen a number of anomalies in short-baseline neutrino experiments, and we would like to understand their source — sterile neutrinos or otherwise



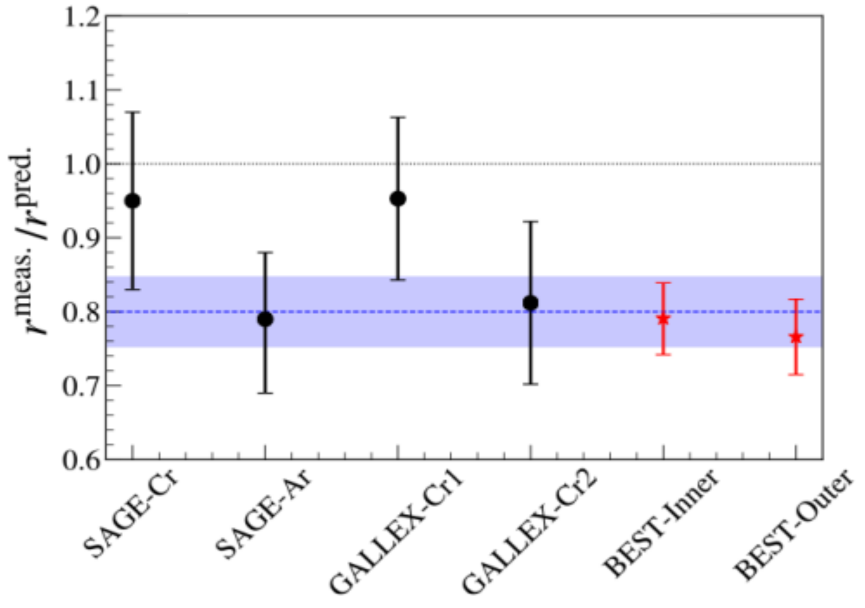
[Phys. Rev. Lett. 75, 2650 (1995)]

MiniBooNE



[Phys. Rev. D 103, 052002 (2021)]

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$



BEST

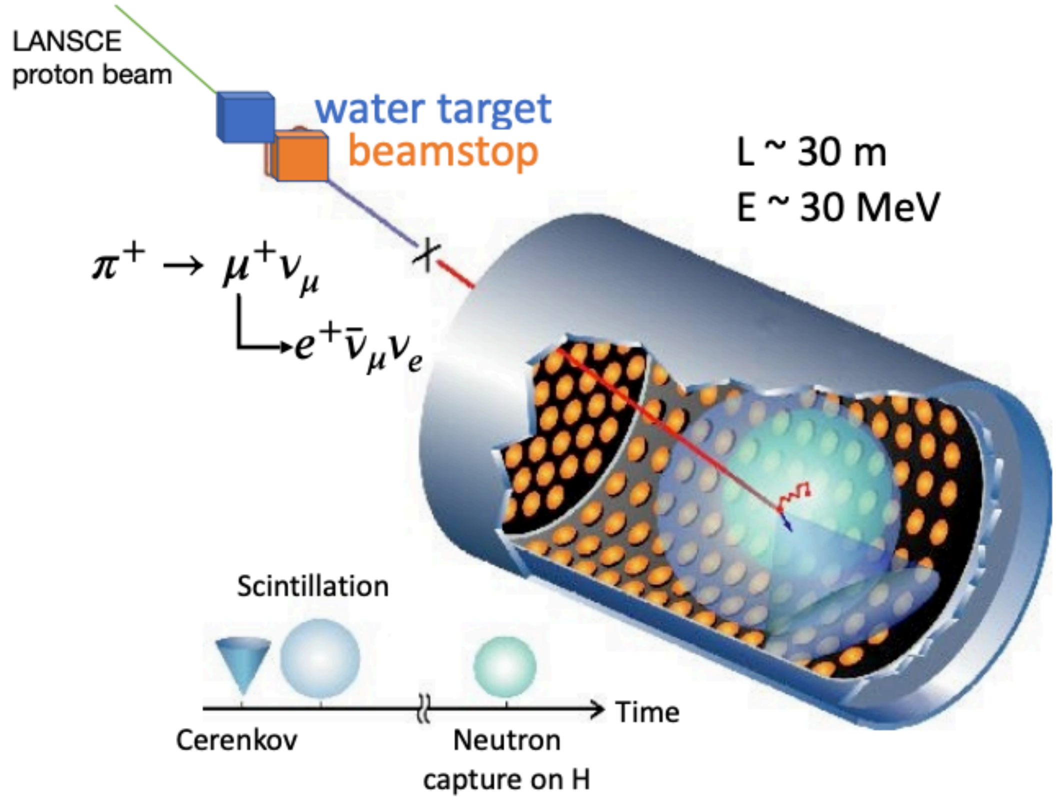
[Phys. Rev. C 105, 065502 (2022)]

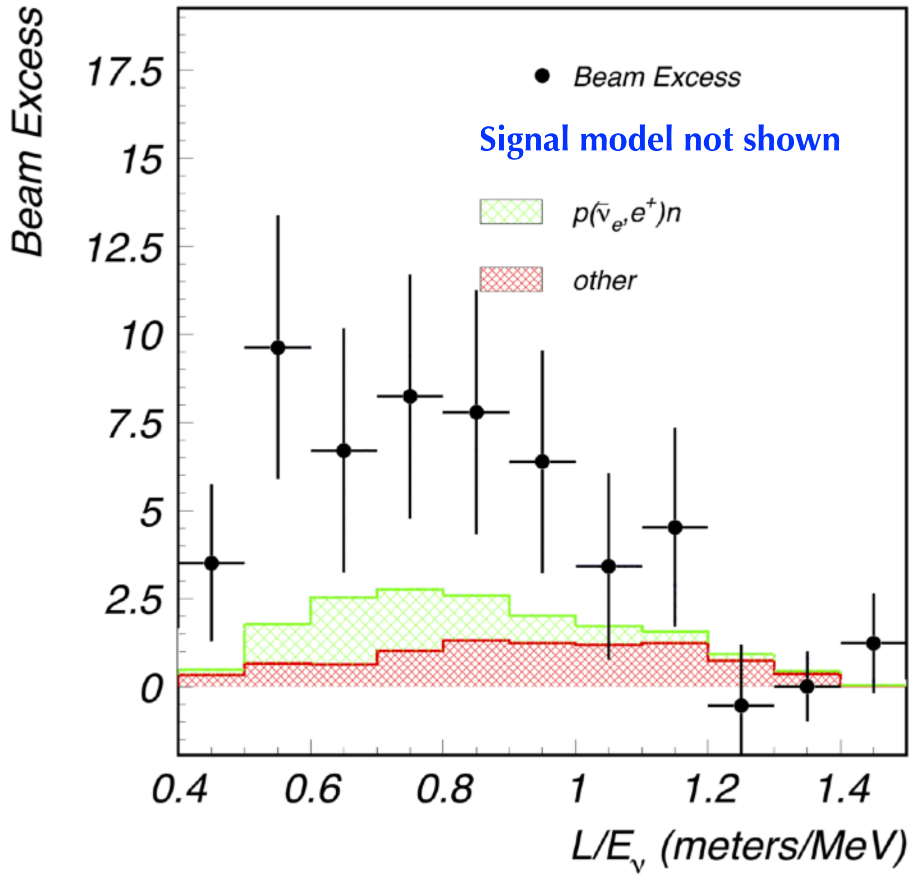
Short-Baseline Anomalies

LSND Anomaly

- The Liquid Scintillator Neutrino Detector (LSND) experiment ran at the Los Alamos Neutron Science Center between 1995 and 2001
- LSND studied $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, using $\bar{\nu}_\mu$ from μ^+ decay at rest
- Typical neutrino energy of about 30 MeV, and distance between the beamstop and detector of about 30m, for a $L/E \sim 1$ MeV/m

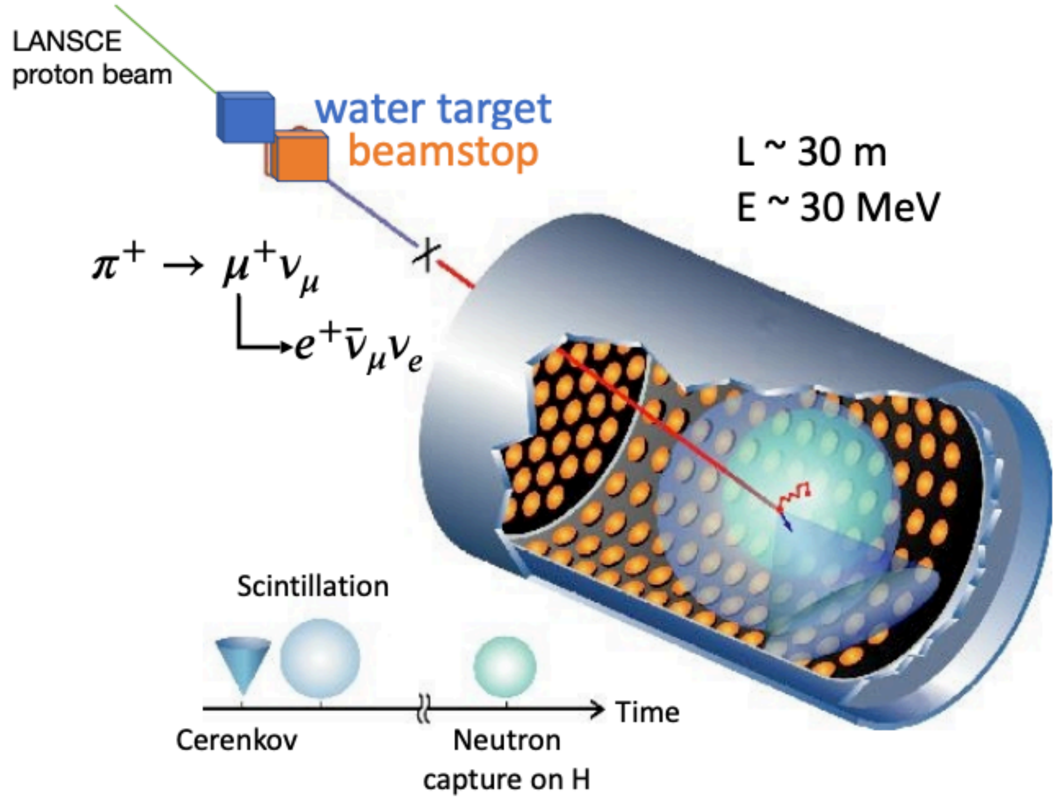
PRD 64, 112007 (2001)





LSND Anomaly

- Detection mechanism: $\bar{\nu}_e + p \rightarrow e^+ + n$, then $n + p \rightarrow d + \gamma$ (2.2 MeV)
- Observe Cherenkov and scintillation light from the positron, then delayed light from subsequent neutron capture — coincidence reduces backgrounds
- Observed a 3.8σ excess of $\bar{\nu}_e$-like events, which can be interpreted as some probability of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations due to a sterile neutrino — $P_{\text{osc}} \sim 0.26\%$



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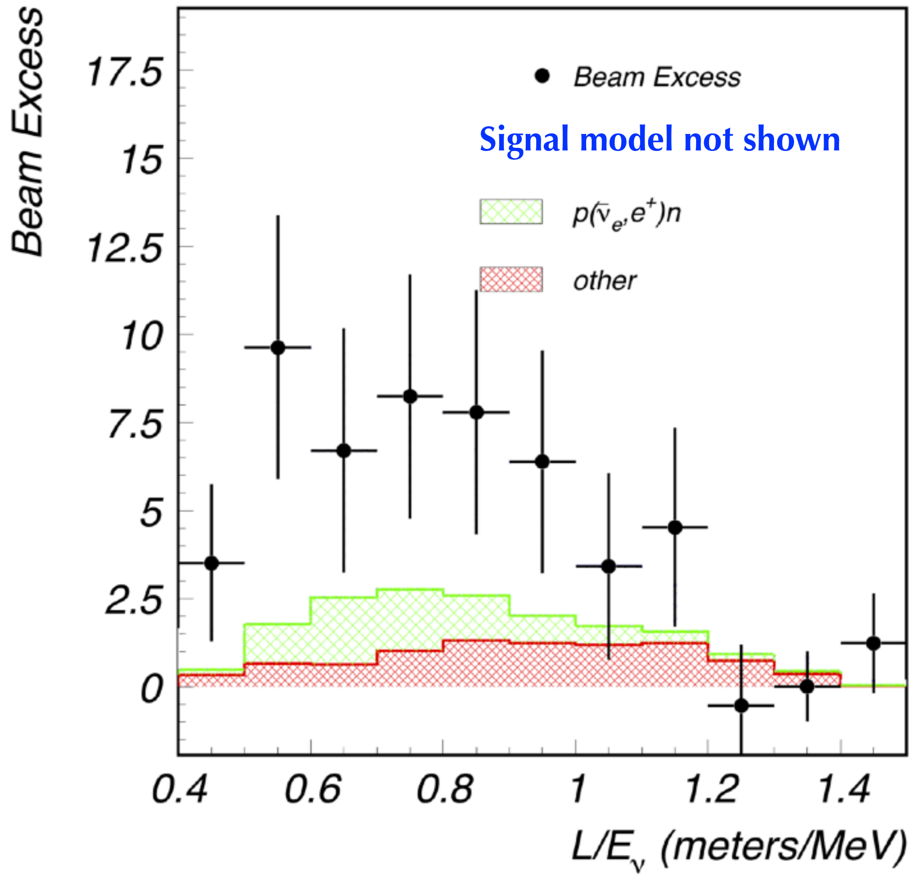
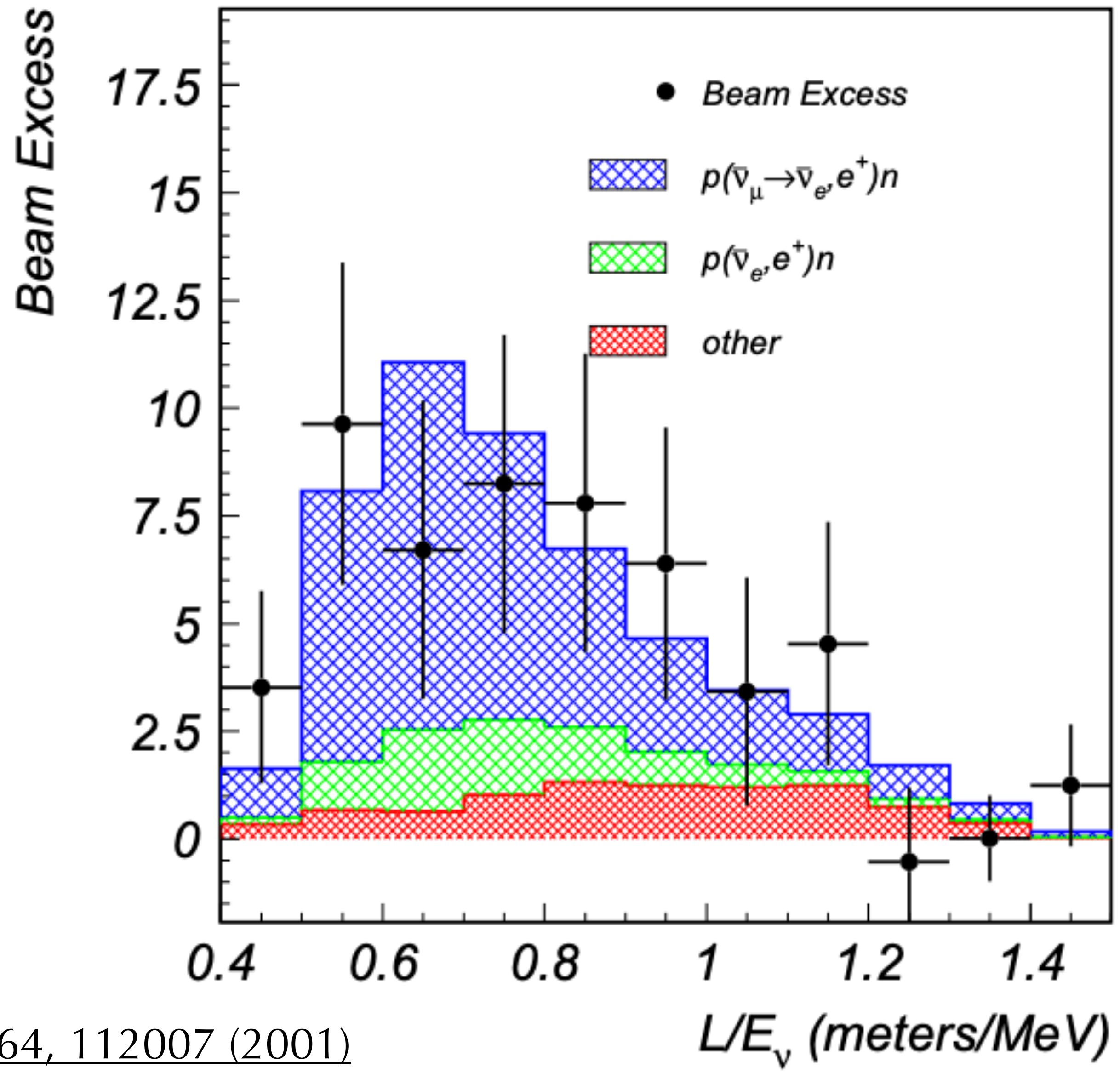


LSND Anomaly

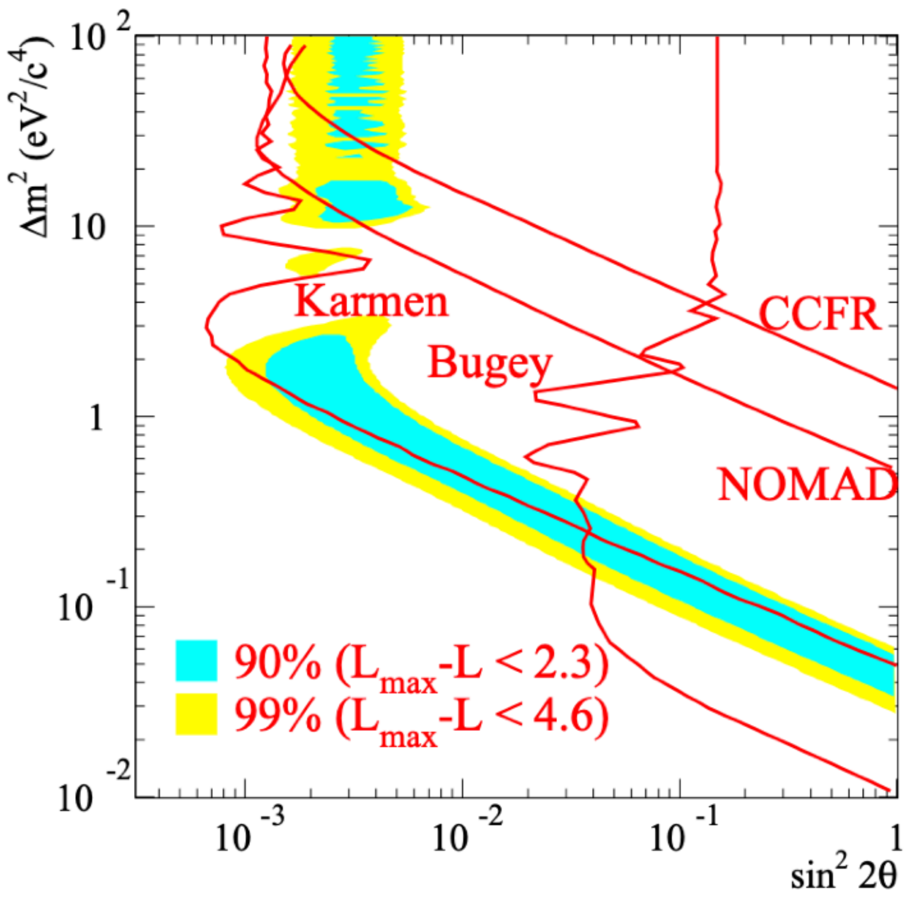
- When excess is plotted as a function of L/E, can use this to determine allowed regions in Δm^2 and $\sin^2(2\theta)$ for a new neutrino state
- This is how the short baseline neutrino anomalies are often plotted



PRD 64, 112007 (2001)

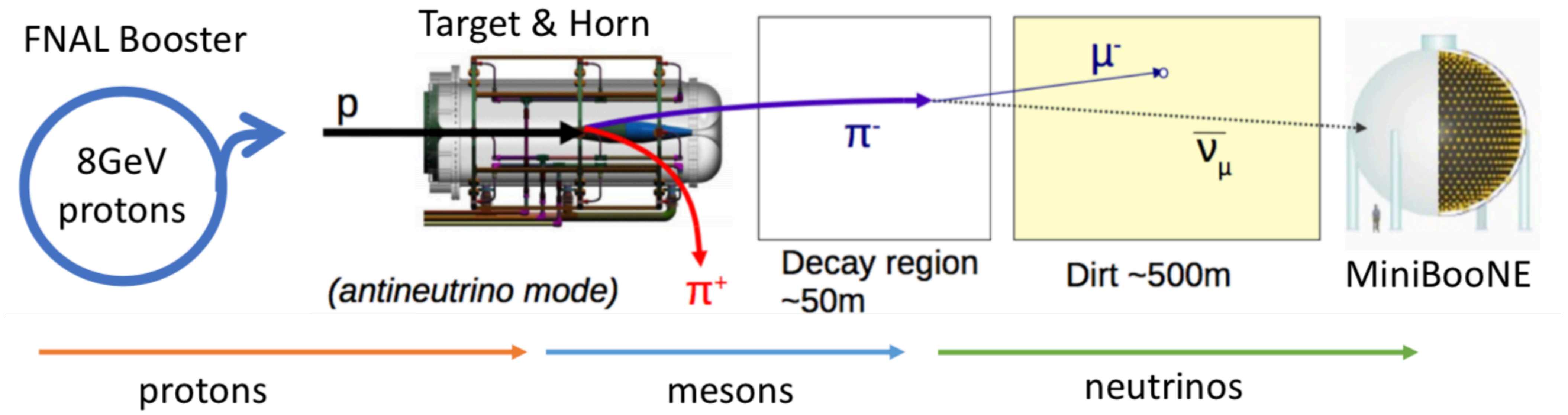
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$



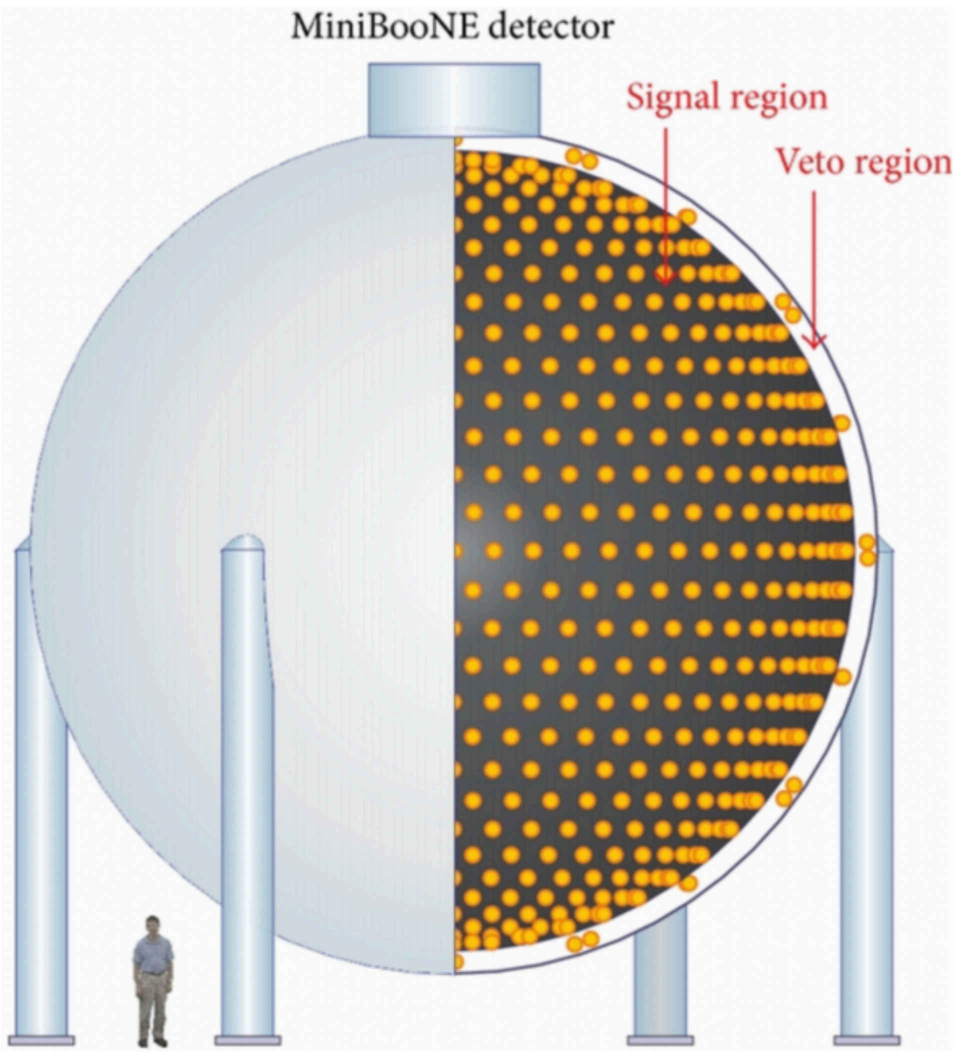
MiniBooNE Anomaly

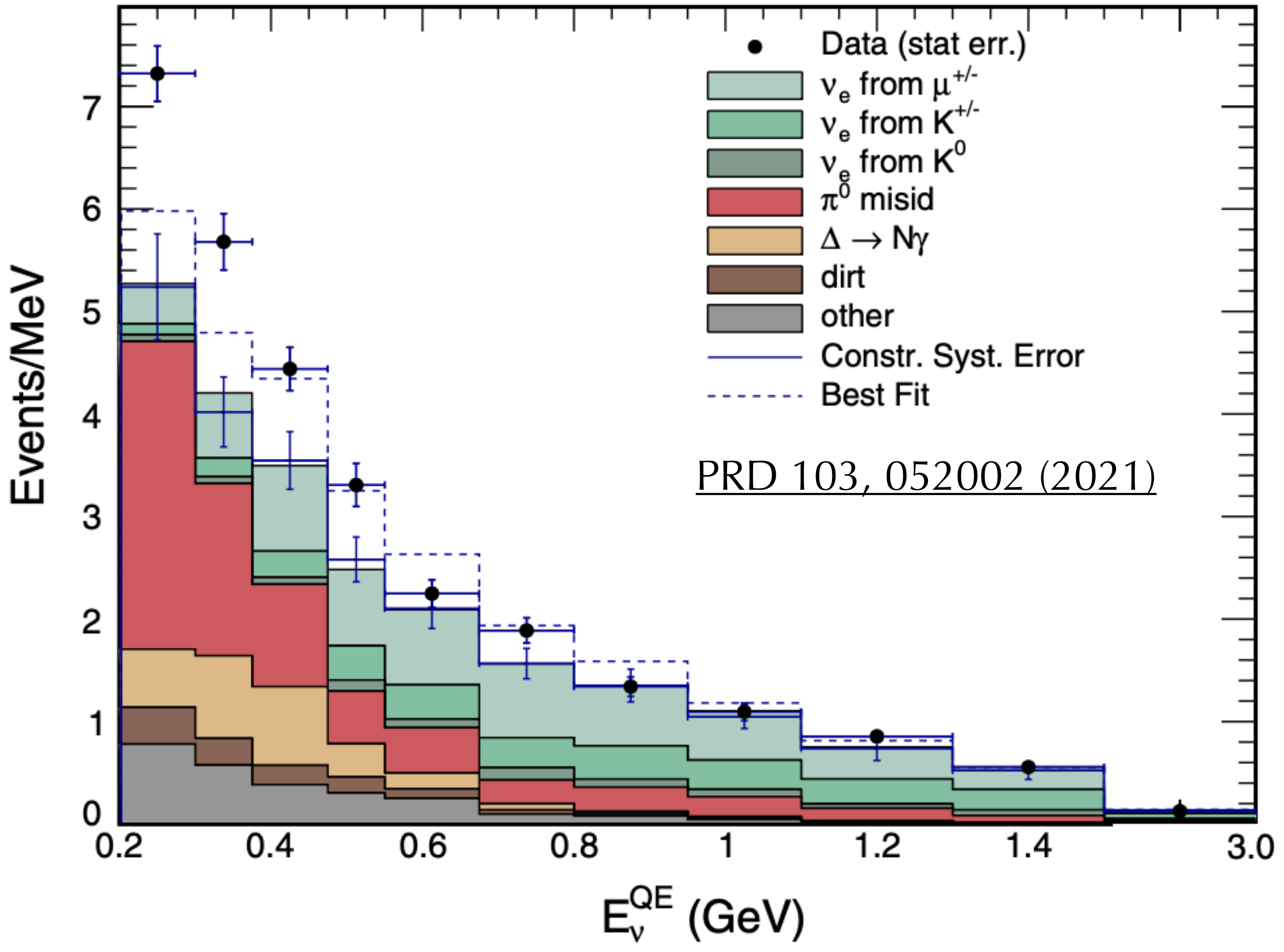
- The MiniBooNE experiment used a mineral oil Cherenkov detector located in the Booster Neutrino Beam (BNB) at Fermilab
- Proposed to search for sterile neutrino oscillations suggested by LSND
- Located at a similar L/E as LSND — tests the oscillation hypothesis
  - MiniBooNE at ~500m/500MeV
  - LSND at ~30m/30MeV
- Experiments have different systematic uncertainties due to different fluxes, event signatures, and backgrounds



MiniBooNE Anomaly

- MiniBooNE tudied $\nu_\mu \rightarrow \nu_e$ appearance using ν_μ from the BNB from 2002 to 2021
- Final oscillation results give a combined 4.8σ excess of ν_e-like events from neutrino and antineutrino mode running

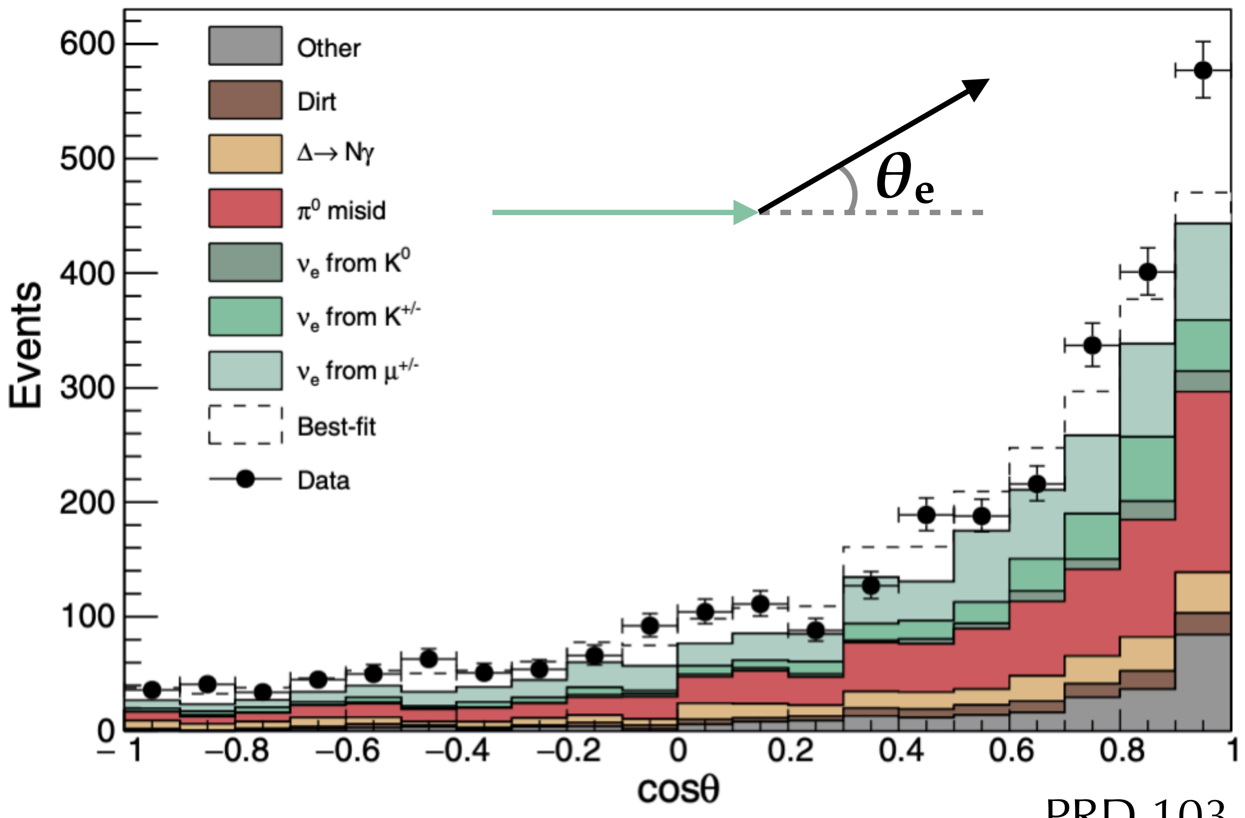


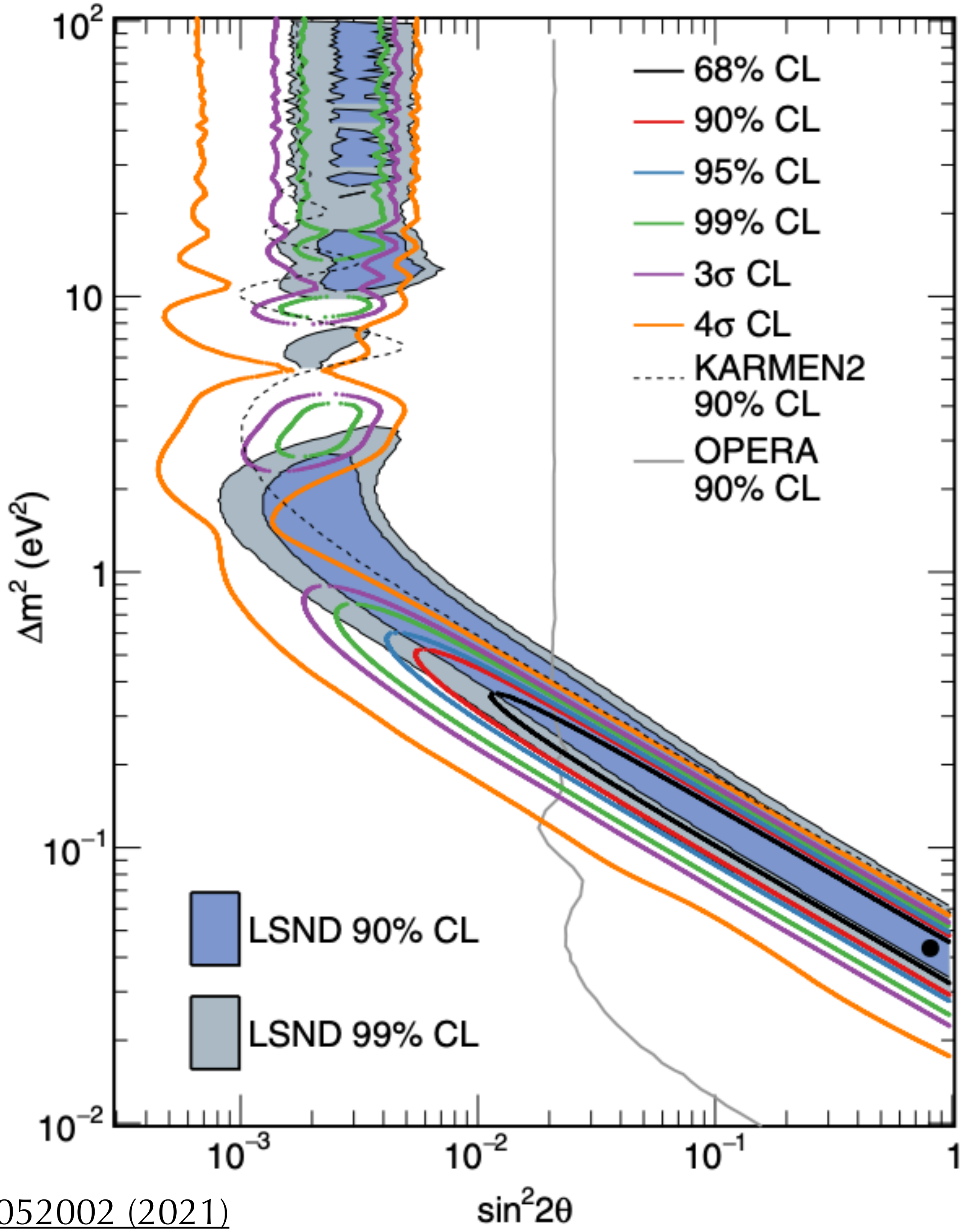


PRD 103, 052002 (2021)

MiniBooNE Anomaly

- The oscillation parameters favored by MiniBooNE overlap with LSND
- However, MiniBooNE results are not completely consistent with this model
  - Excess doesn't look like best fit, more concentrated in forward angles



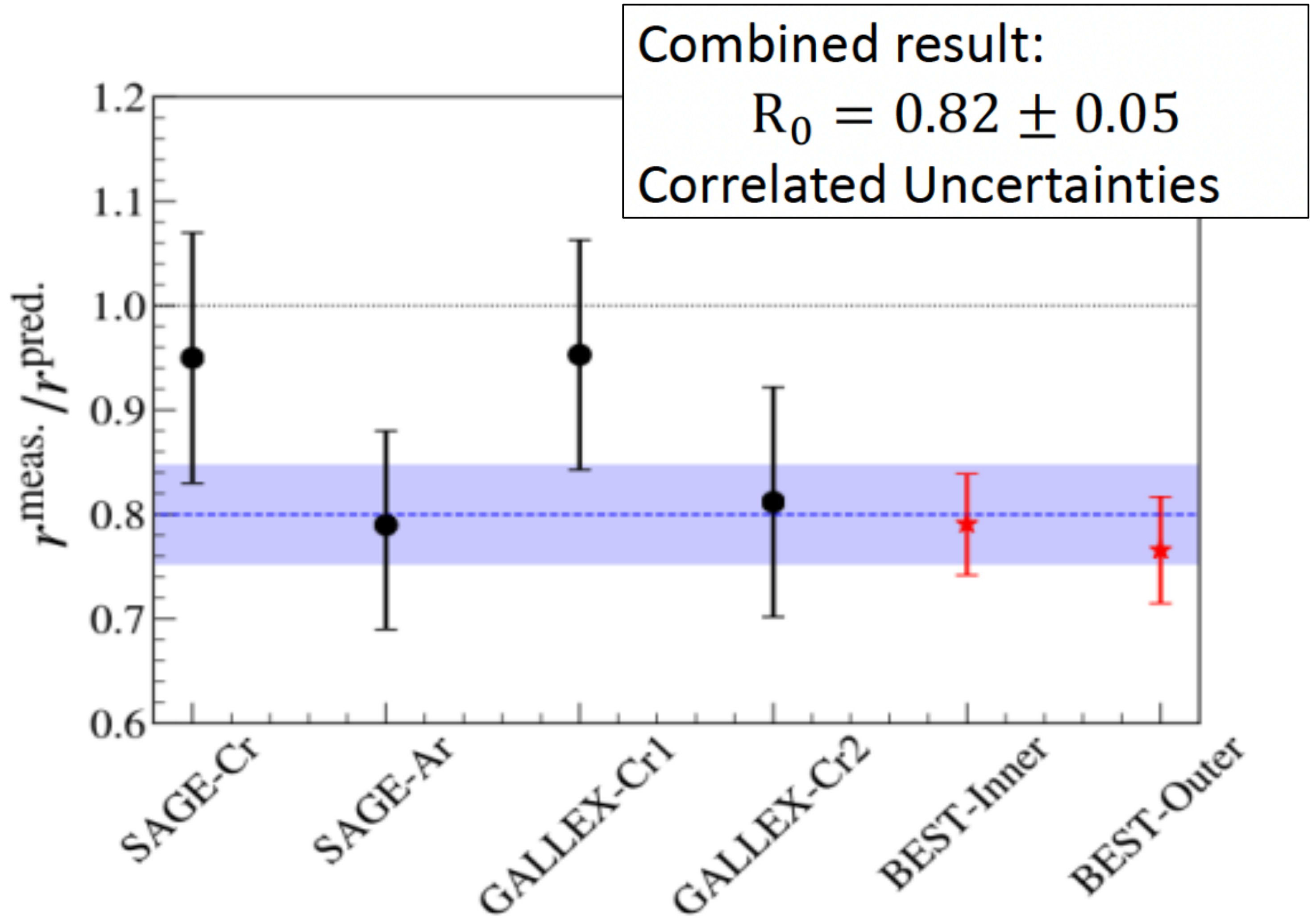


PRD 103, 052002 (2021)

Gallium Anomalies

- Three gallium experiments see a ~20% deficit of ^{71}Ge from ν_e — SAGE, GALLEX, and most recently BEST

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

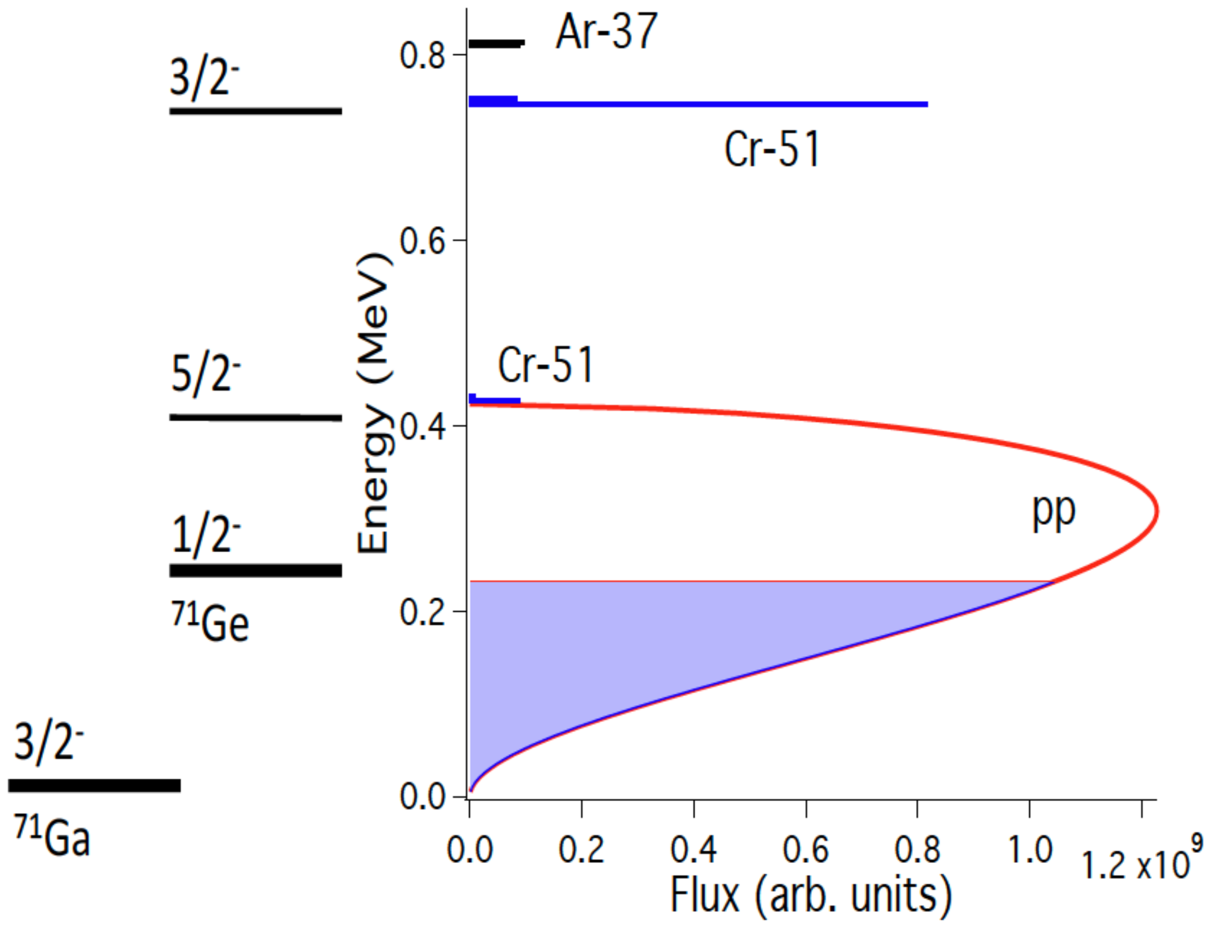


BEST

[Phys. Rev. C 105, 065502 (2022)]

Gallium Anomalies

- Three gallium experiments see a ~20% deficit of ^{71}Ge from ν_e — SAGE, GALLEX, and most recently BEST
- SAGE and GALLEX ran between the mid-1980s and the early 2000s
    - Soviet–American Gallium Experiment (SAGE)
    - The Gallium Experiment (GALLEX)
- Both measured low-energy neutrinos from proton-proton fusion within the Sun using gallium as a target
- Well-predicted flux from the known solar luminosity
- Used a radioactive source of ν_e for calibration



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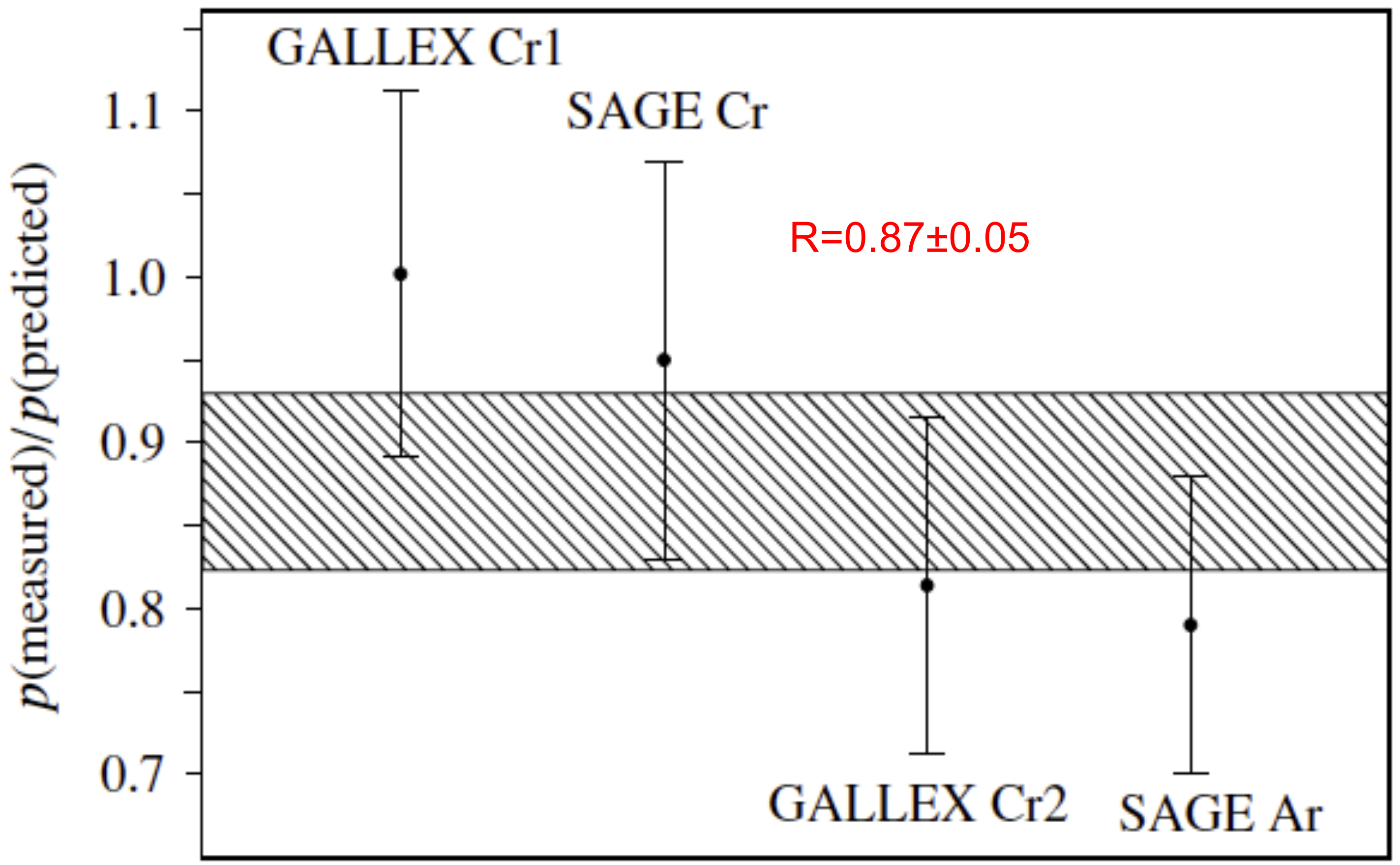
  - The Gallium Experiment (GALLEX)
- Both see a ~8–18% deficit of neutrinos
- Statistics are limited and so results are somewhat inconclusive

PRC 73 (2006) 045805, PRC 80 (2009) 015807

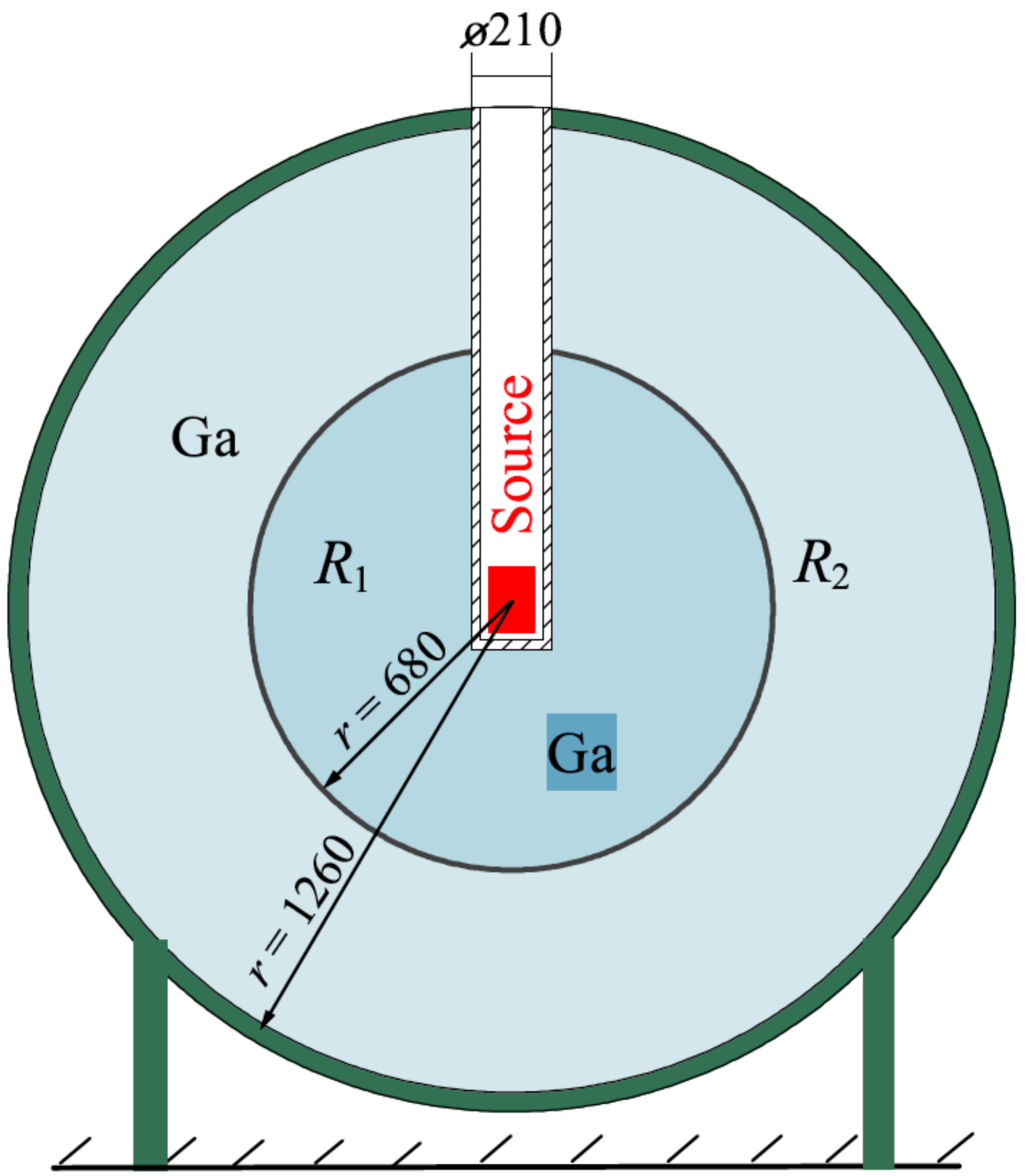


Gallium Anomalies

- Three gallium experiments see a ~20% deficit of ^{71}Ge from ν_e — SAGE, GALLEX, and most recently BEST
- Baksan Experiment on Sterile Transitions (BEST) experiment was as as a high-sensitivity test of the gallium anomaly and started in 2011
- Used a radioactive chromium neutrino source in center of gallium volume

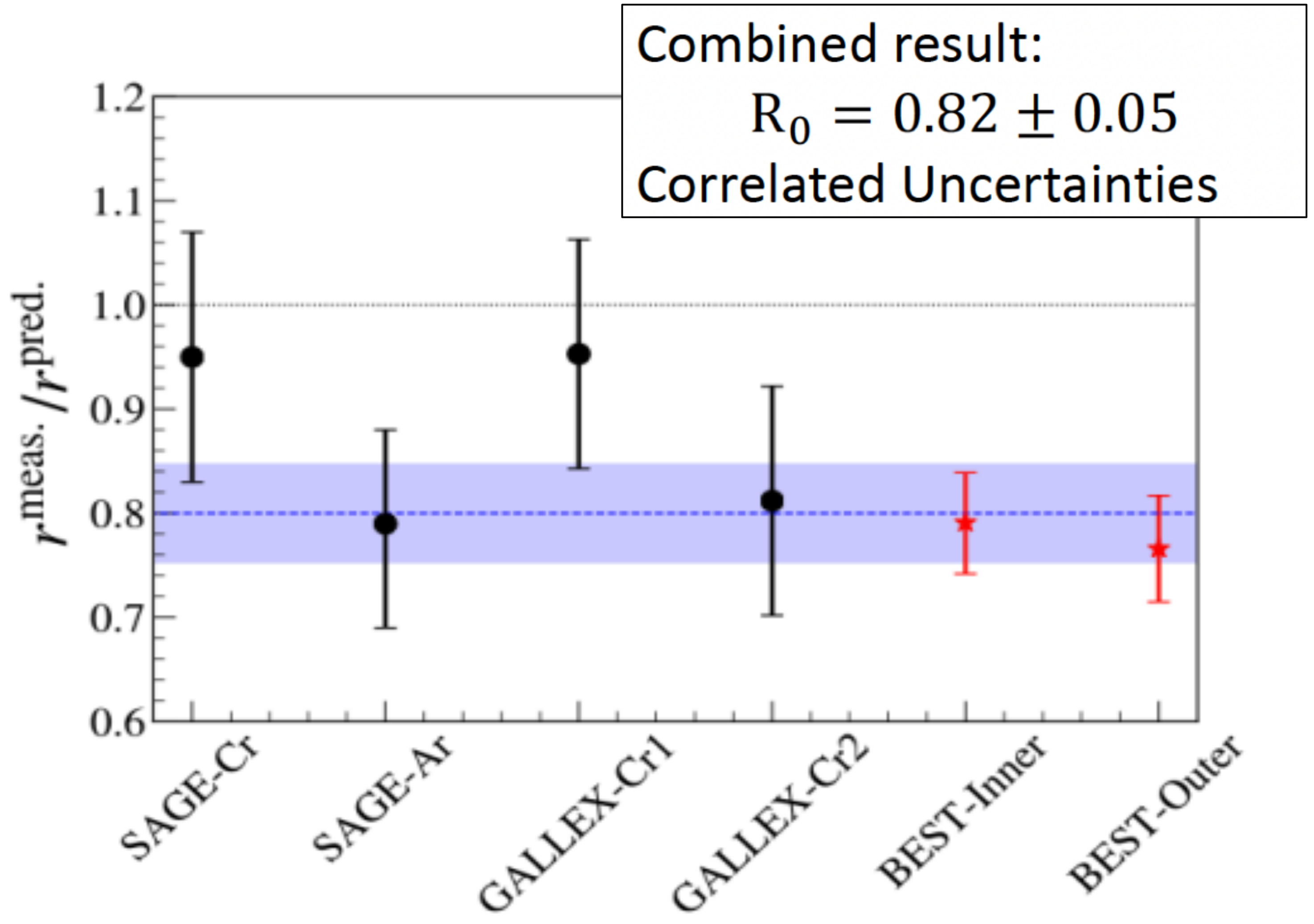
$$^{51}\mathrm{Cr} + e^- \rightarrow {}^{51}\mathrm{V} + \nu_e$$

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$



Gallium Anomalies

- Three gallium experiments see a ~20% deficit of ^{71}Ge from ν_e — SAGE, GALLEX, and most recently BEST
- Baksan Experiment on Sterile Transitions (BEST) experiment was as as a high-sensitivity test of the gallium anomaly and started in 2011
- BEST results see ~20% deficit
- Higher statistical precision
- Reaffirm gallium anomaly is real
- Number of potential explanations but does not provide strong evidence for any one



BEST

Phys. Rev. C 105, 065502 (2022)

Sterile Neutrinos

Sterile Neutrinos?

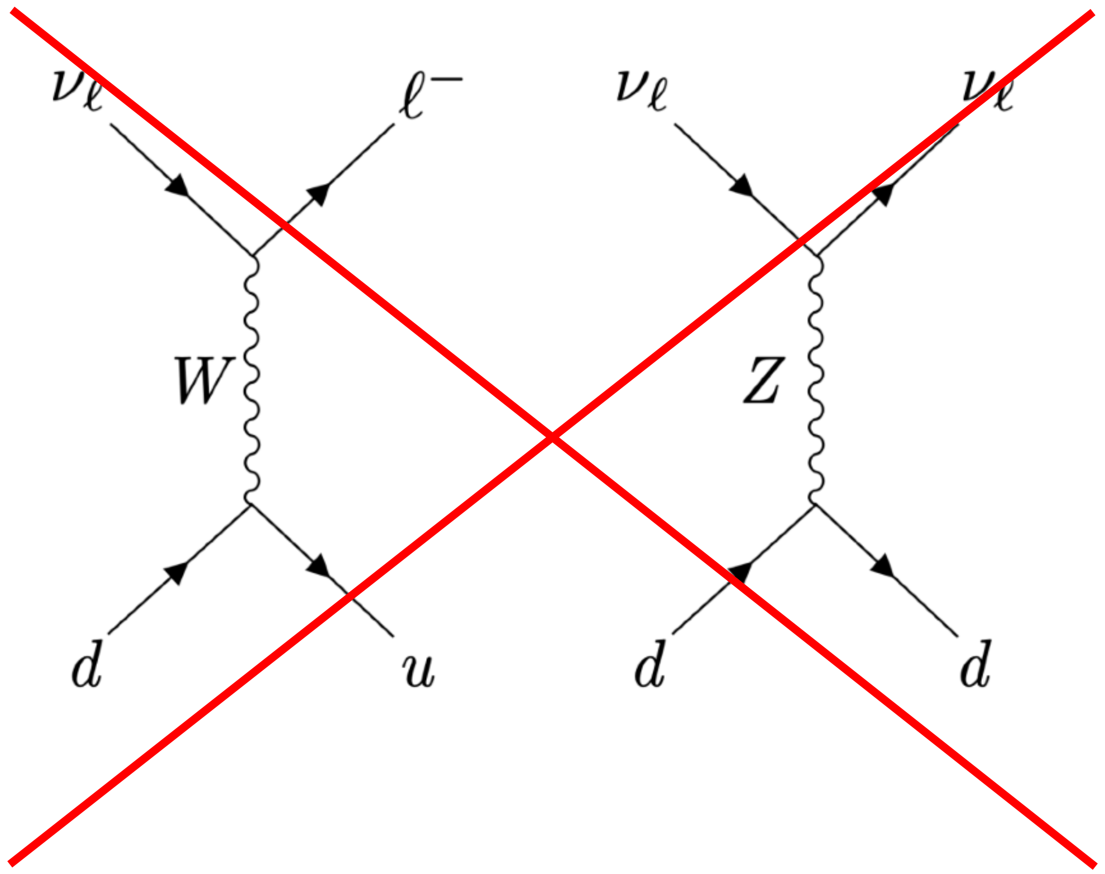
- What if these anomalies truly came from oscillations?

- But it's short-baseline so can't be *standard* oscillations!
- Requires the existence of a 4th neutrino

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

Sterile Neutrino Model

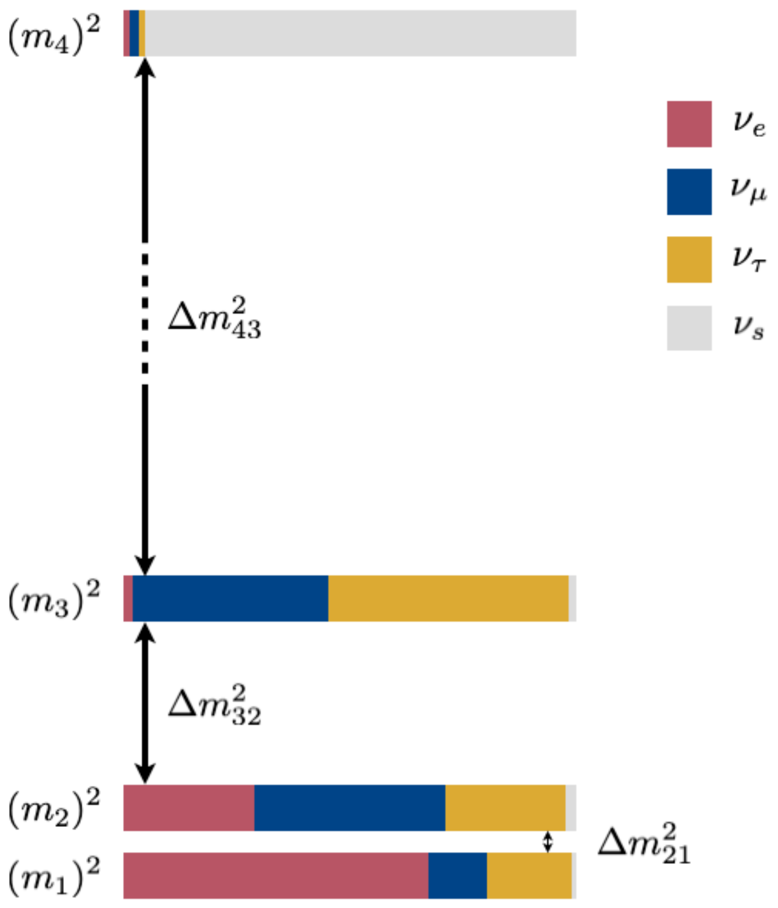
- New neutrino means never detected before
- We detect neutrinos through their weak interactions
- New neutrino must be sterile
- Sterile: No electric charge, no color charge, no weak interactions
- Only detection possible is through oscillation to one of the 3 known flavors

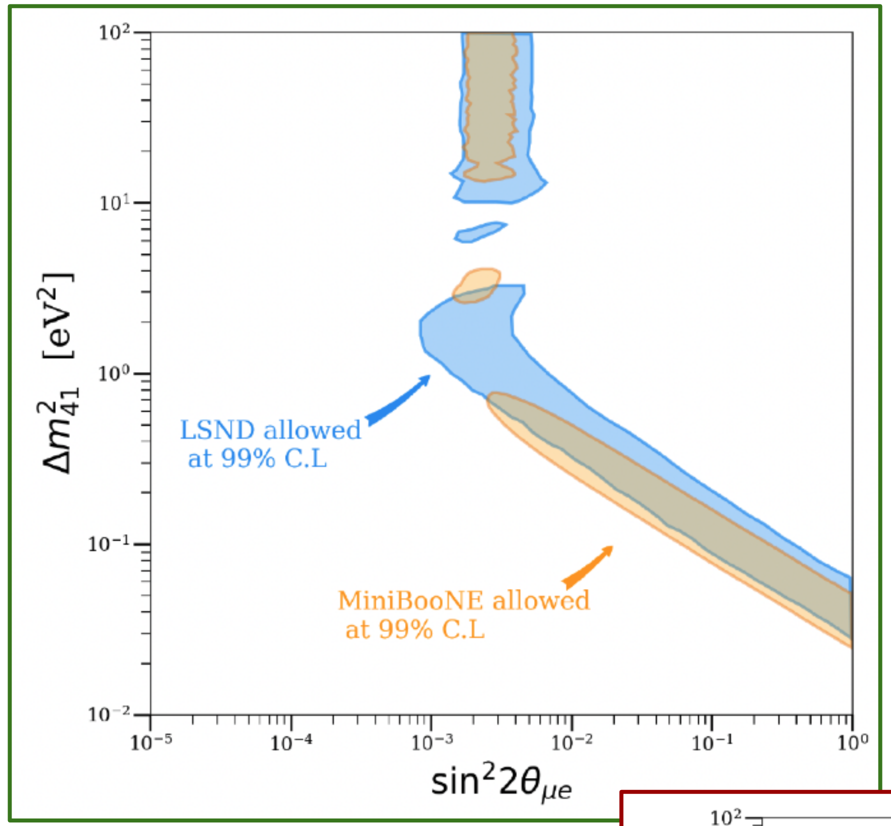


Sterile Neutrino Model

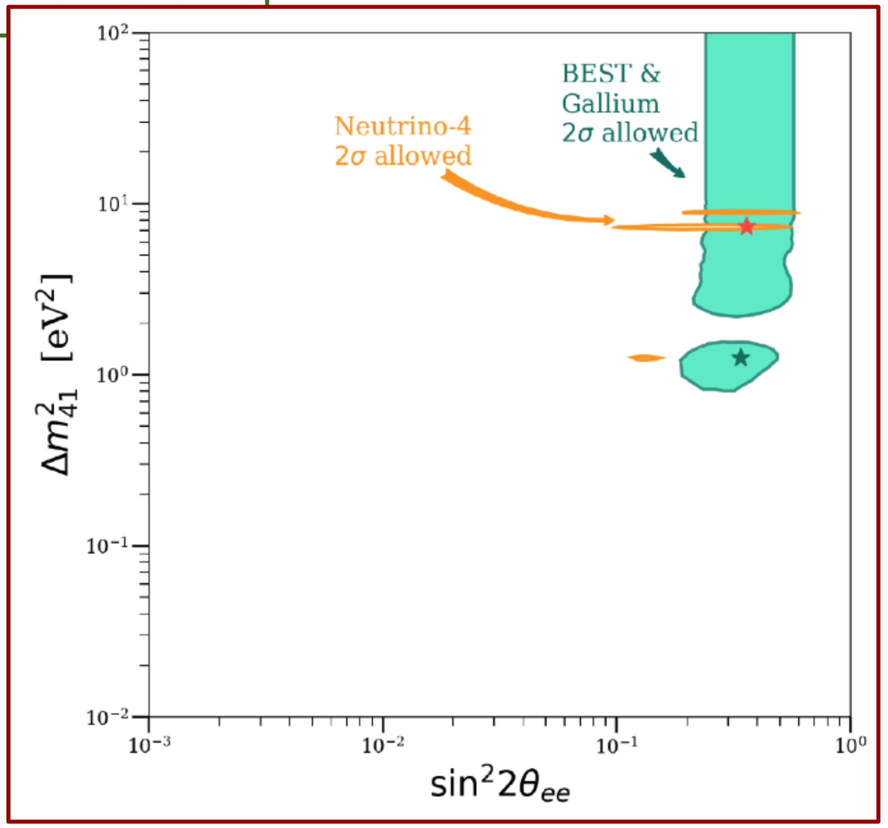
- Evaluate anomalies under the sterile neutrino hypothesis
- All give $\Delta m^2 \sim \mathcal{O}(1\ \mathrm{eV}^2)$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$





ν_e appearance



ν_e disappearance

Sterile Neutrinos?

- All anomalies are consistent with a sterile neutrino hypothesis but none provide a "smoking gun" result
- Other experiments that might expect to see sterile oscillations have null results

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) * MiniBooNE (NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND cross section SAGE/GALLEX *
Antineutrino	LSND * KARMEN MiniBooNE (BNB) *	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS * PROSPECT STEREO Neutrino-4 *

Experiments denoted with * have a >2σ signal

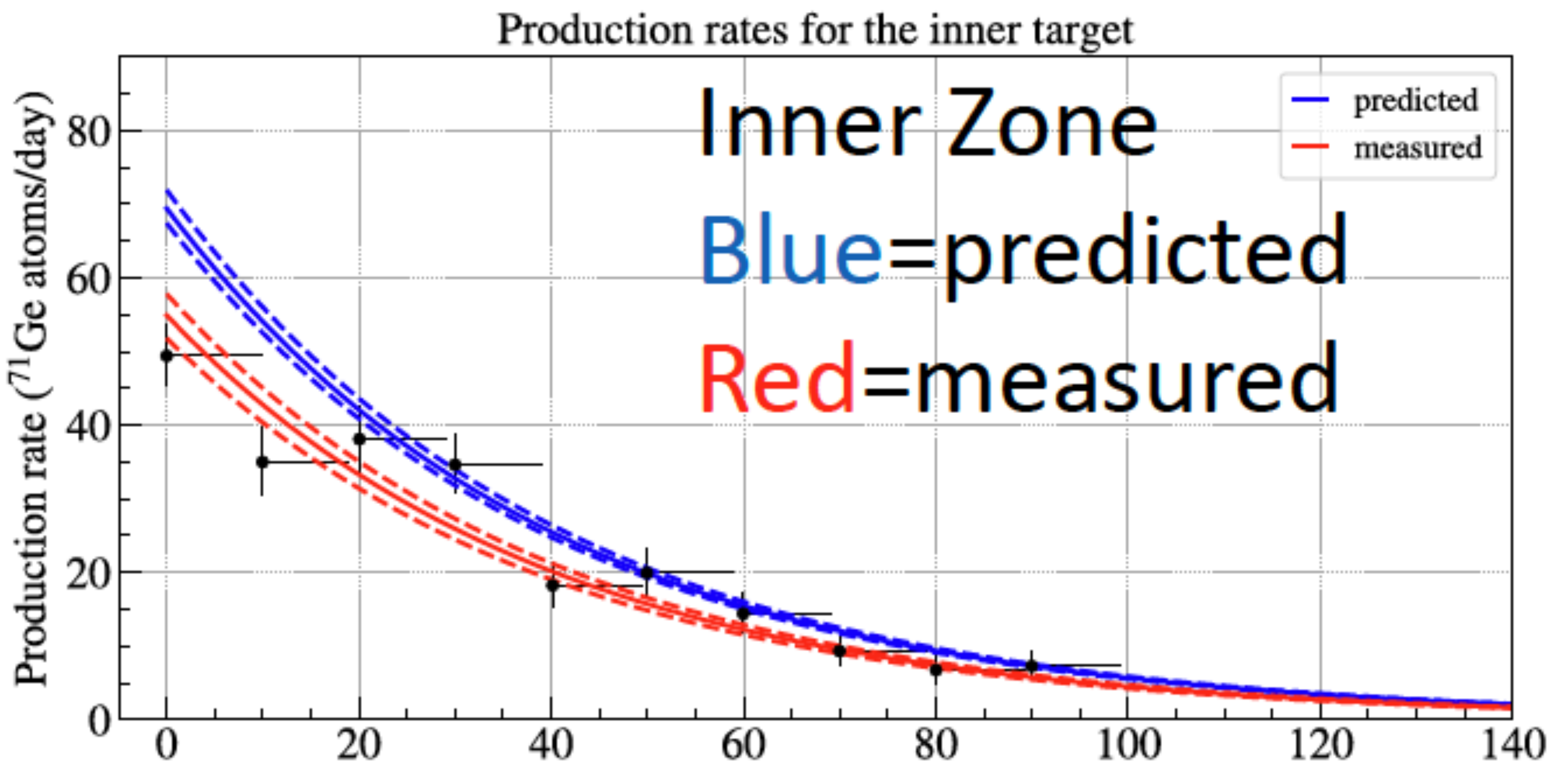
Sterile Neutrinos?

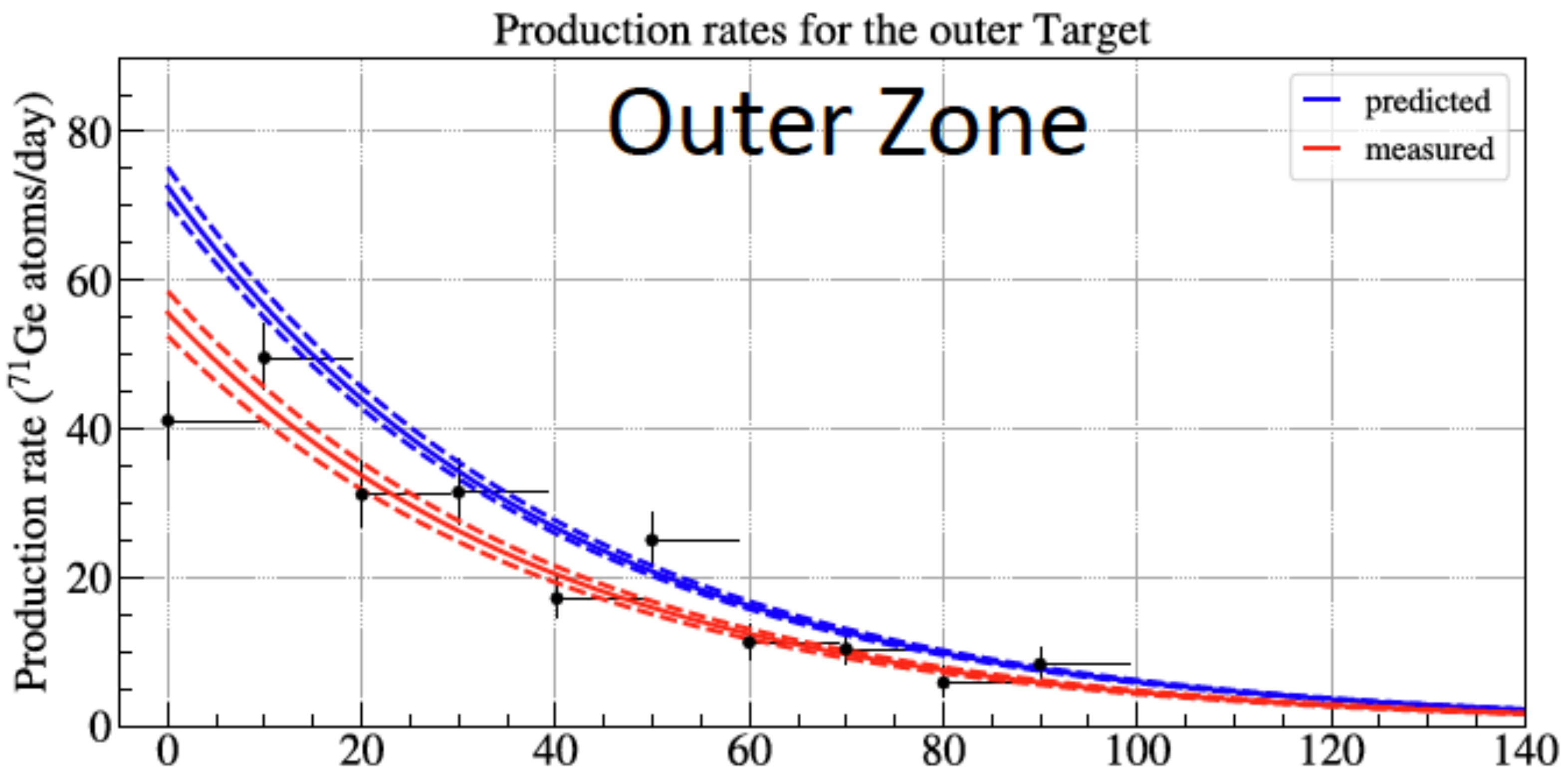
- BEST does not see any dependence on oscillation length

$$\text{Note: } \frac{0.77 \pm 0.05}{0.79 \pm 0.05} = 0.97 \pm 0.07$$

Similar deficits observed in both zones

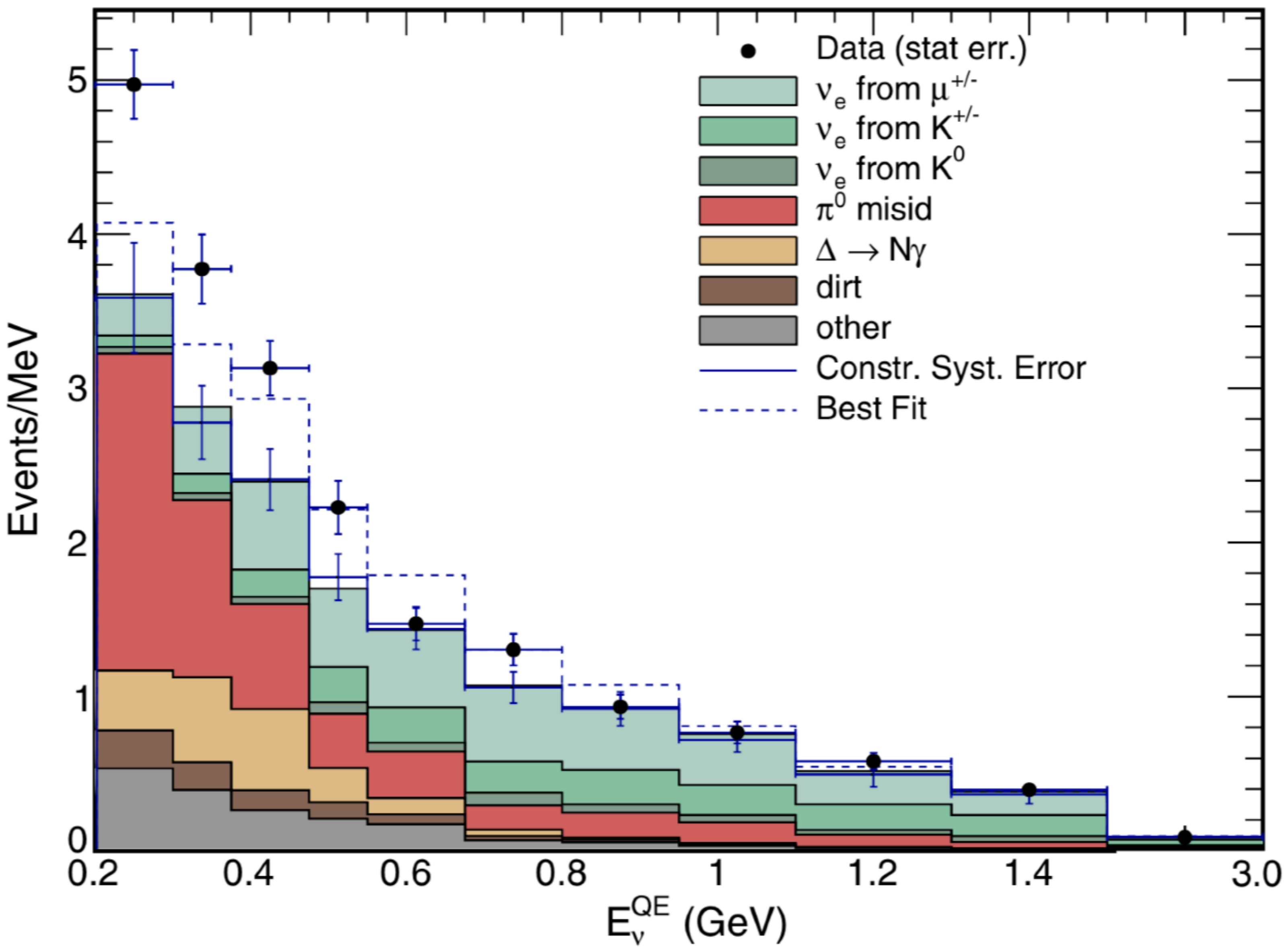
Phys. Rev. C 105, 065502 (2022)

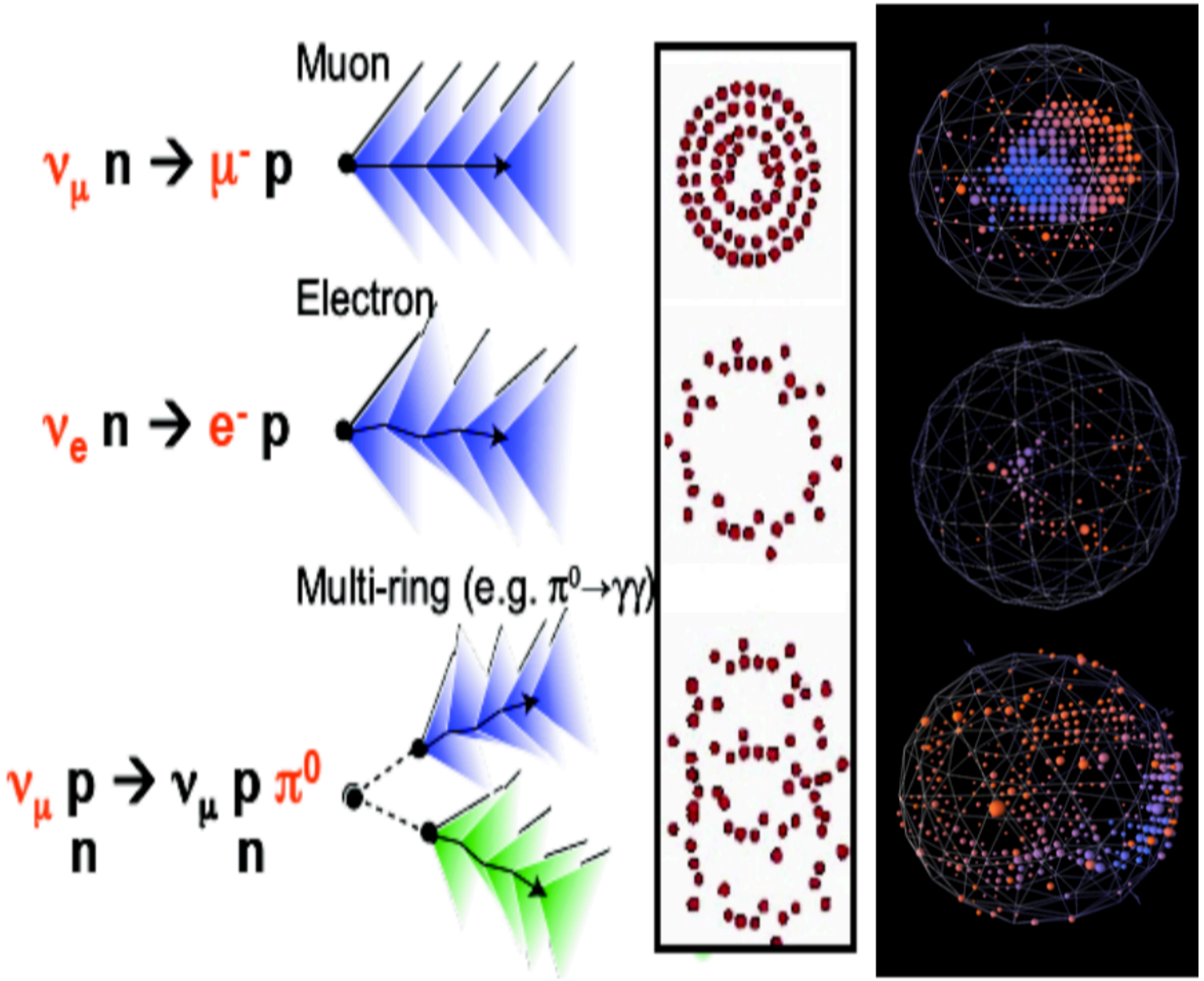




Sterile Neutrinos

- MiniBooNE's signal has ambiguity in its source between electrons and photons





So What's Happening?

- Backgrounds could be modeled incorrectly
  - Data has no new physics, we just predicted incorrectly
- Input could be wrong
  - Predicted neutrino flux could be off from real source
- Methodology could be flawed
  - Efficiencies miscalculated
  - Incorrect statistical treatment of data
  - Detector effects not accounted for
- All experiments claim to have corrected or checked for these. And many do new studies when a concern is raised. But something could always slip past.

So What's Happening?

- New models come out to explain one or more of these anomalies all the time

Snowmass White Paper on Light Sterile Neutrinos
J. Phys. G: Nucl. Part. Phys. 51 120501 (2024)

Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to N A$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to N A$, $N \to \nu\gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

New Physics Explanations of the MiniBooNE Excess

Category	Model	Final state	LEE signal properties			LSND	References
			energy dist.	angular dist.	timing		
Flavor transitions	SBL oscillations	e^-	✓	✓	✓	✓	Reviews and global fits [22–24, 56, 57]
	SBL oscillations with invisible sterile decay	e^-	✓	✓	✓	✓	[58, 59]
	SBL oscillations with anomalous matter effects	e^-	✓	✓	✓	✓	[60–65]
	neutrino-flavor-changing bremsstrahlung	e^-	✓	–	✓	✓	[66]
Decays in flight	SBL oscillations with visible sterile decay	e^-	✓	✓	✓	✓	[67–71]
	heavy neutrino decay	γ, $\gamma\gamma$ e^+e^-	✓	✗	✗	✗	[72, 73]
Scattering	neutrino-induced upscattering	γ, $\gamma\gamma$ e^+e^-	✓	✗ (vector) ✓ (scalar) ✓ (TMM)	✓	✗ (vector) ✓ (scalar) ✓ (TMM)	vector [36–41] scalar [42–44] TMM [74–84]
	dark particle-induced upscattering	γ, $\gamma\gamma$ e^+e^-	✓	model dependent	✓	✗	[85]

arXiv:2308.02543

Variations on Sterile Neutrinos

- “Vanilla” 3+1 model not the only version of a sterile neutrino possible

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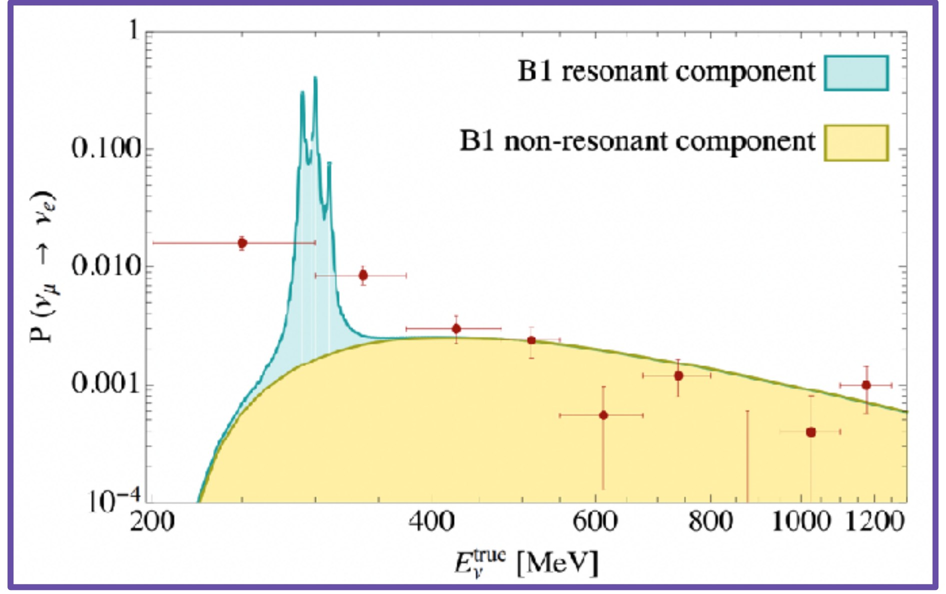
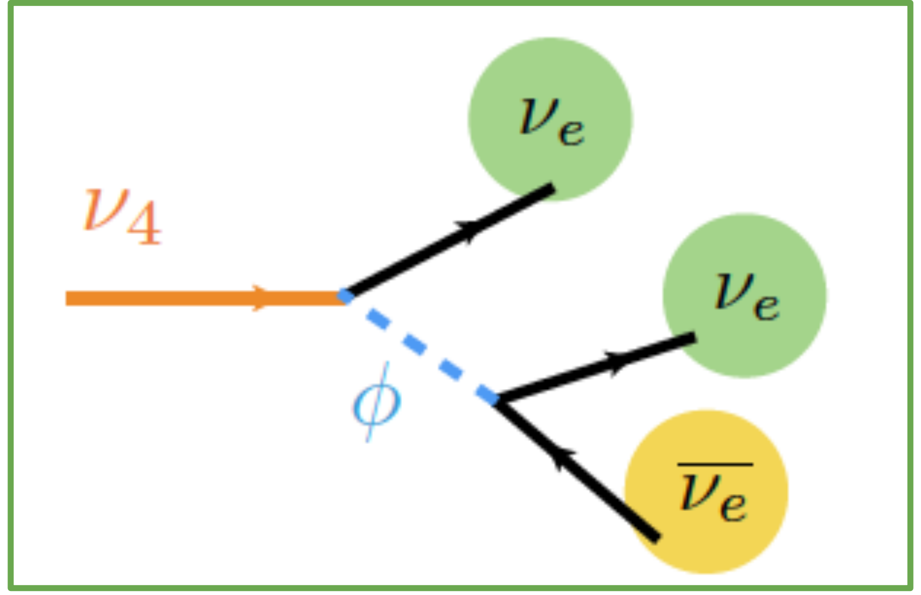
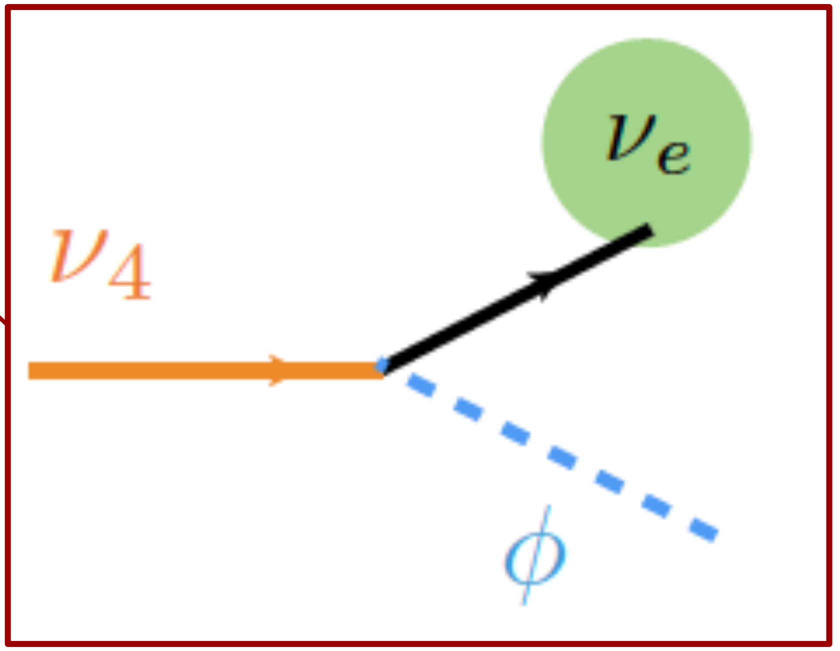
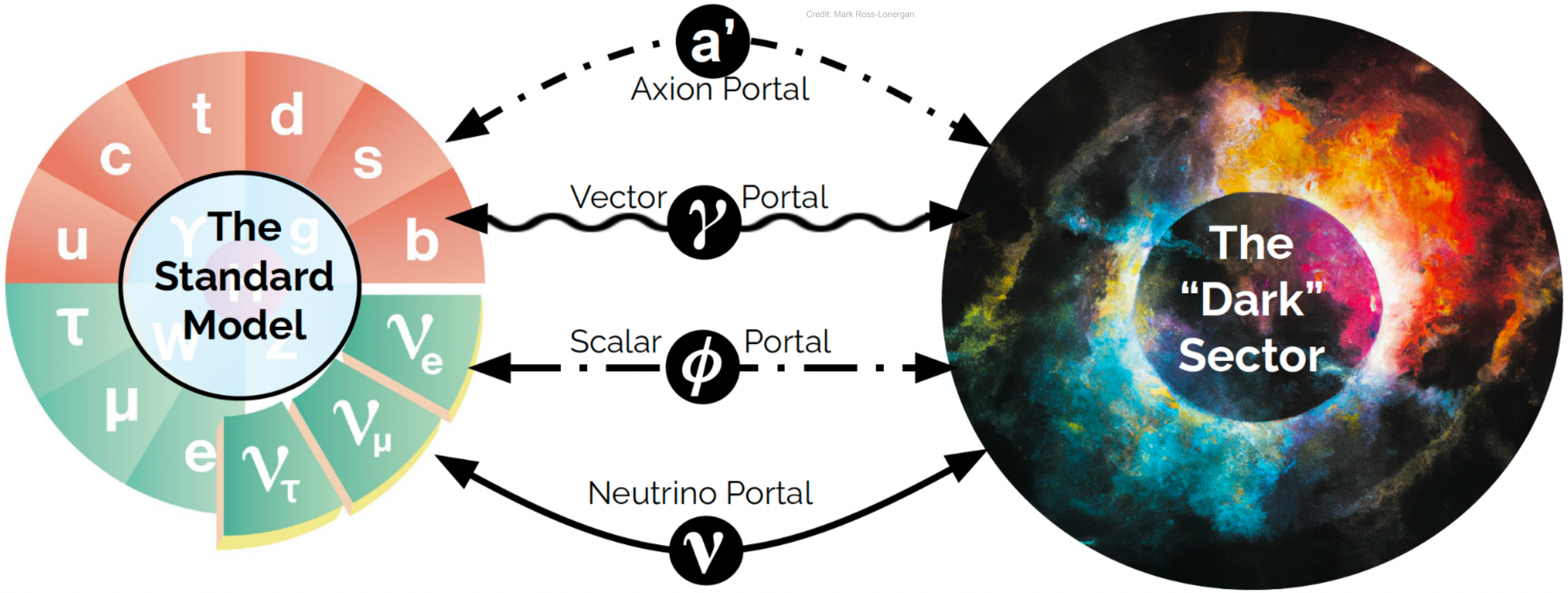
Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]







Dark Sector Portals



Neutrino Portal

$$\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.}$$

- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

Scalar Portal

$$\mathcal{L} \supset (A\,S + \lambda\,S^2)\,H^\dagger H$$

- Higgs Portal Scalars

Vector Portal

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$$

- Light Dark Matter
- Millicharged Particles

Axion Portal

$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$$

- Heavy QCD Axions

Combined and Non-Minimal Portals

Just a few examples. Many more models to investigate!

So Now What?

Preview

- Tomorrow, will discuss more about some of the current and (more) recent experiments working to address short-baseline anomalies
  - JSNS-II — proposed as a follow-up to LSND
  - MicroBooNE — proposed as a follow-up to MiniBooNE
  - SBN Program — enables short-baseline searches with dedicated near and far detectors
  - PROSPECT & other reactor experiments

- While the simple 3+1 sterile neutrino model is disfavored, these anomalies remain and we'd like to know what they are!