Update on Short-Baseline Neutrino Anomalies

June 10, 2025

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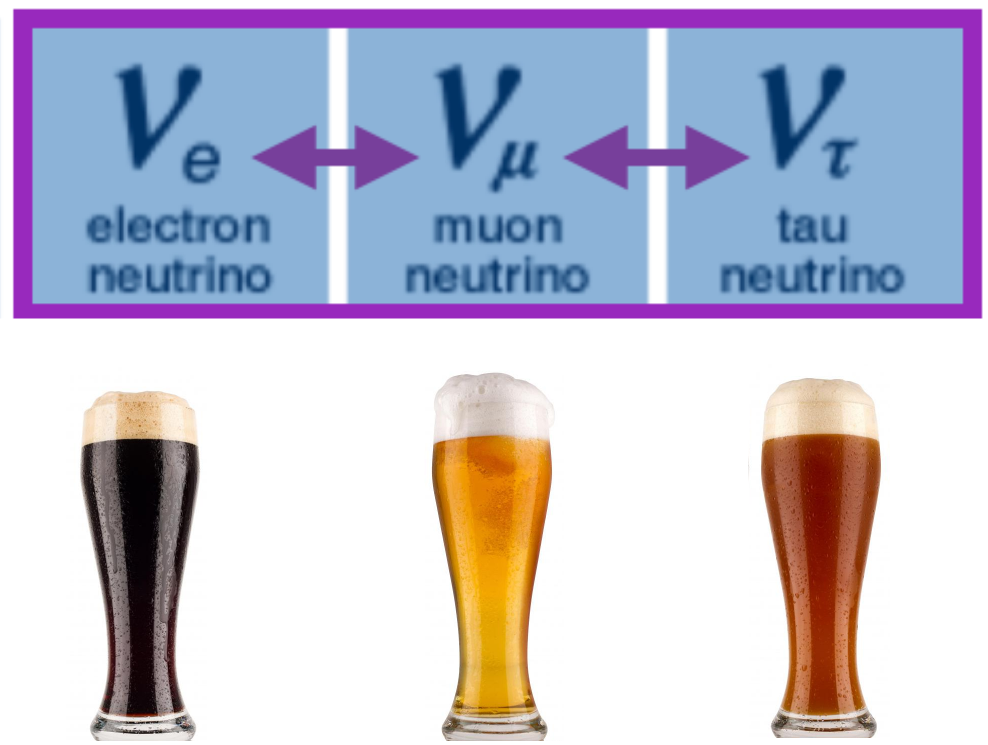
Illinois Institute of Technology



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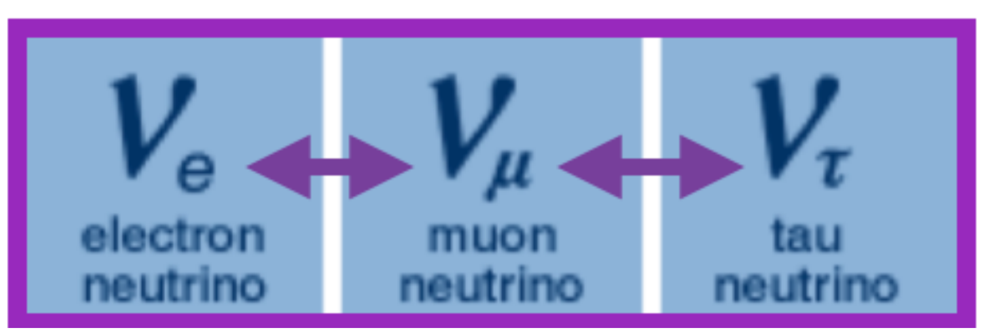
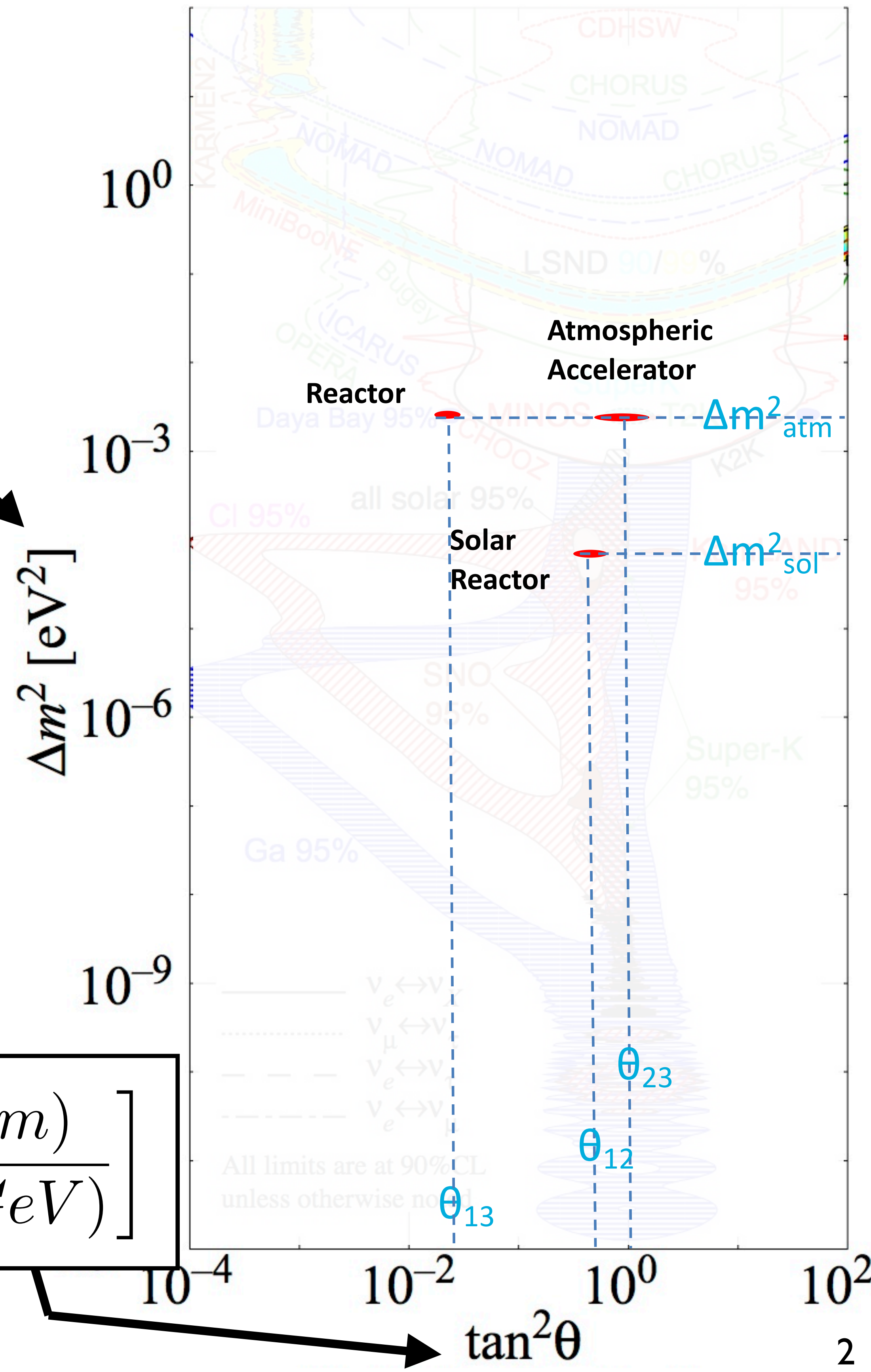
Standard Model Neutrino Oscillations

- Have a beautiful picture of 3 oscillating Standard Model neutrinos coming into focus
  - Three mass differences Δm² define the relative weights of the different neutrinos
    - Also defines the travel distance required for flavor change to occur
  - Three angles θ define which flavors are in each mass state
    - Also defines magnitude of flavor changing



$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left[1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)}\right]$$



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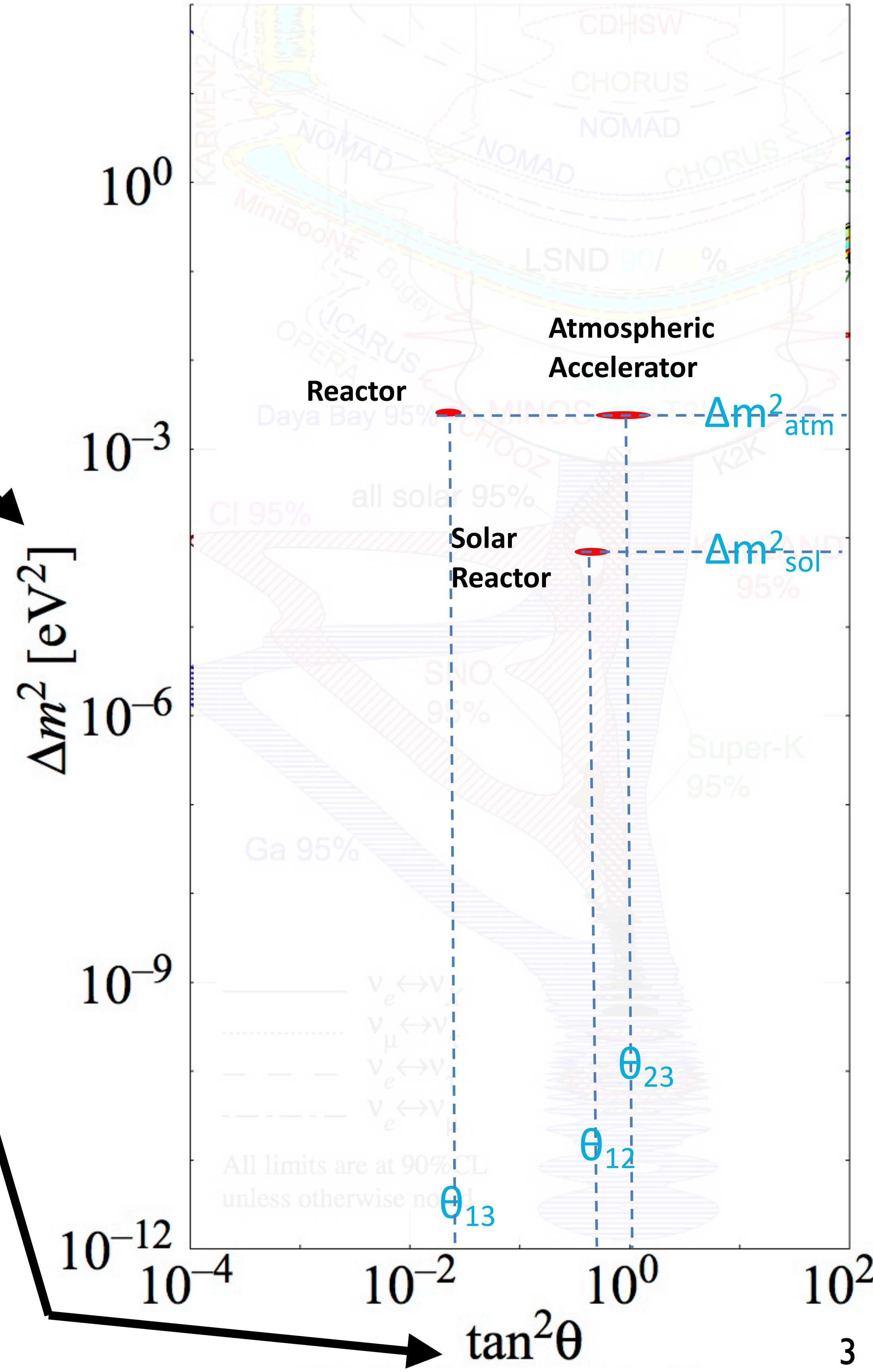
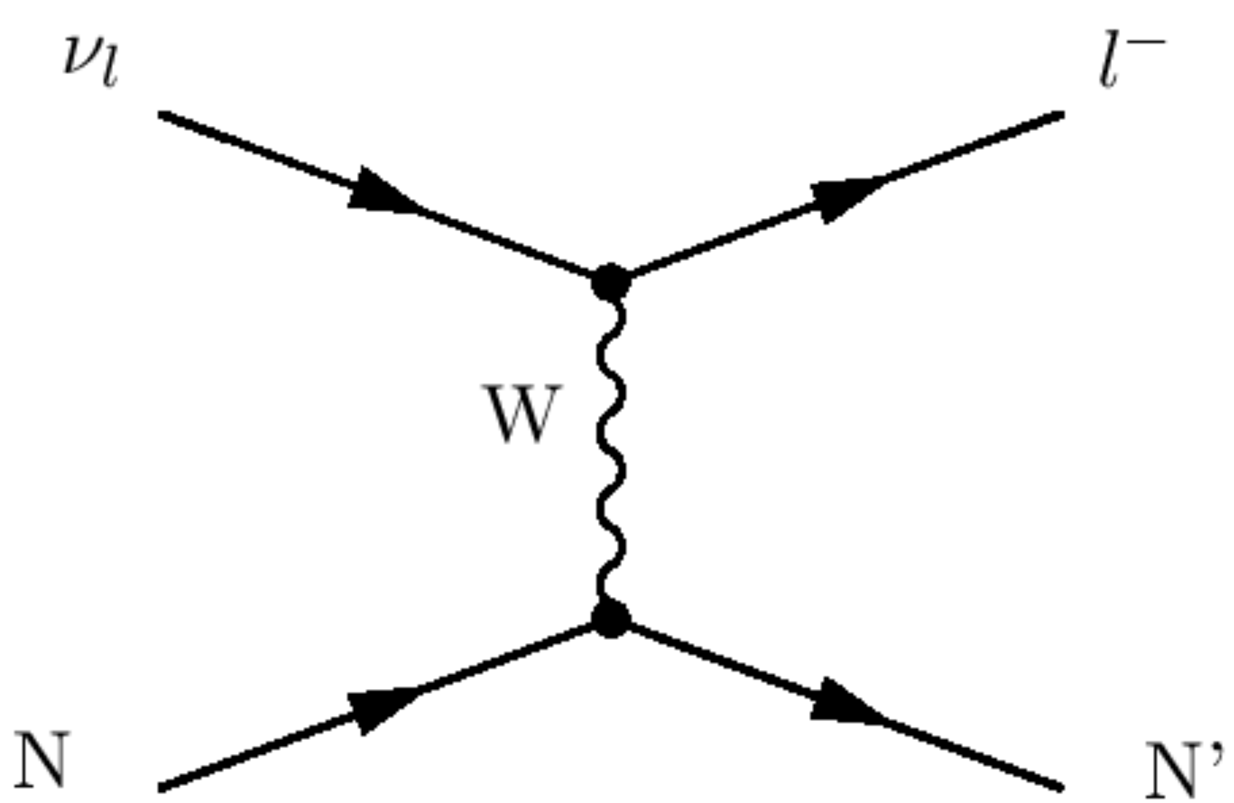


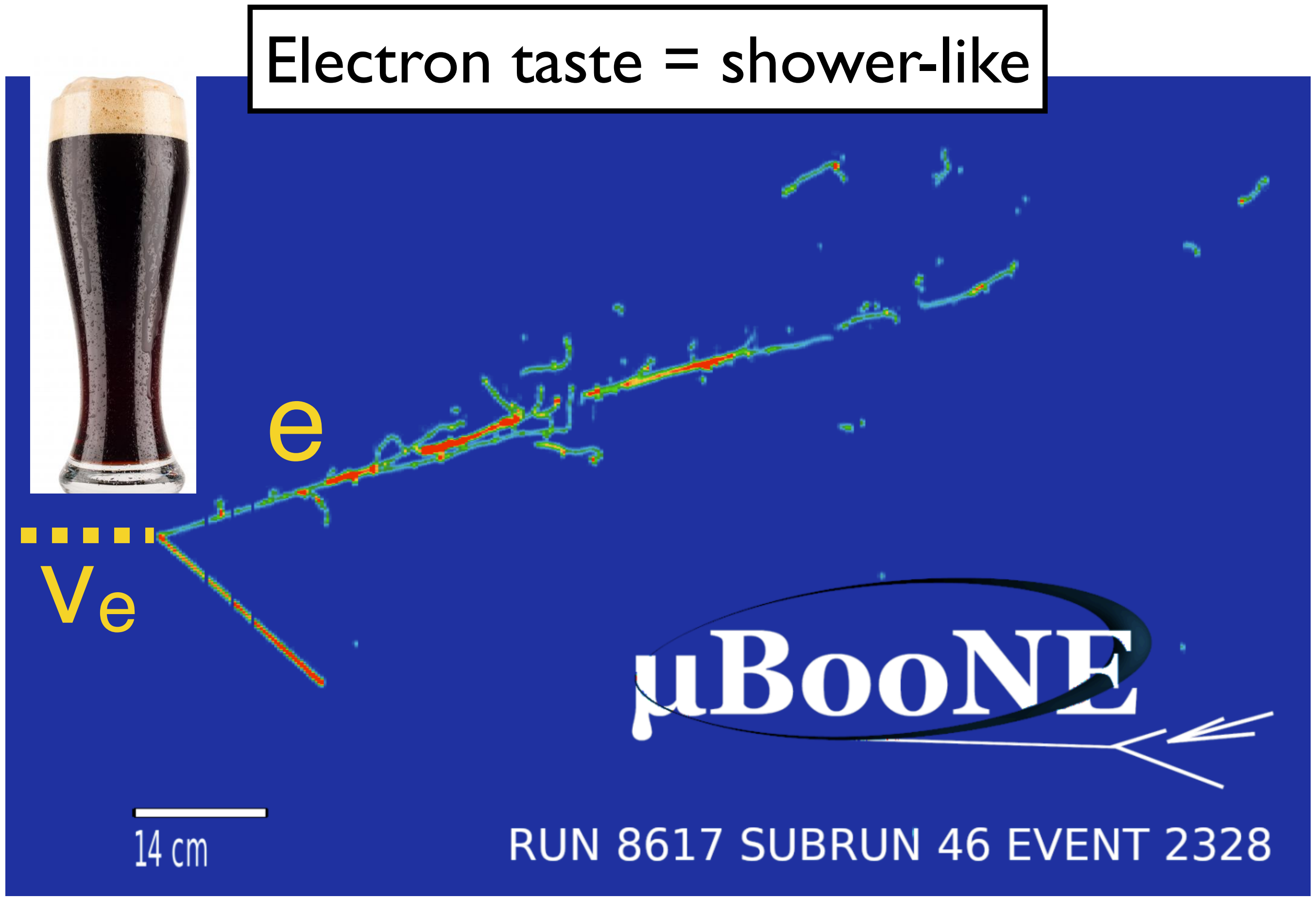
Sampling Neutrino Flavors

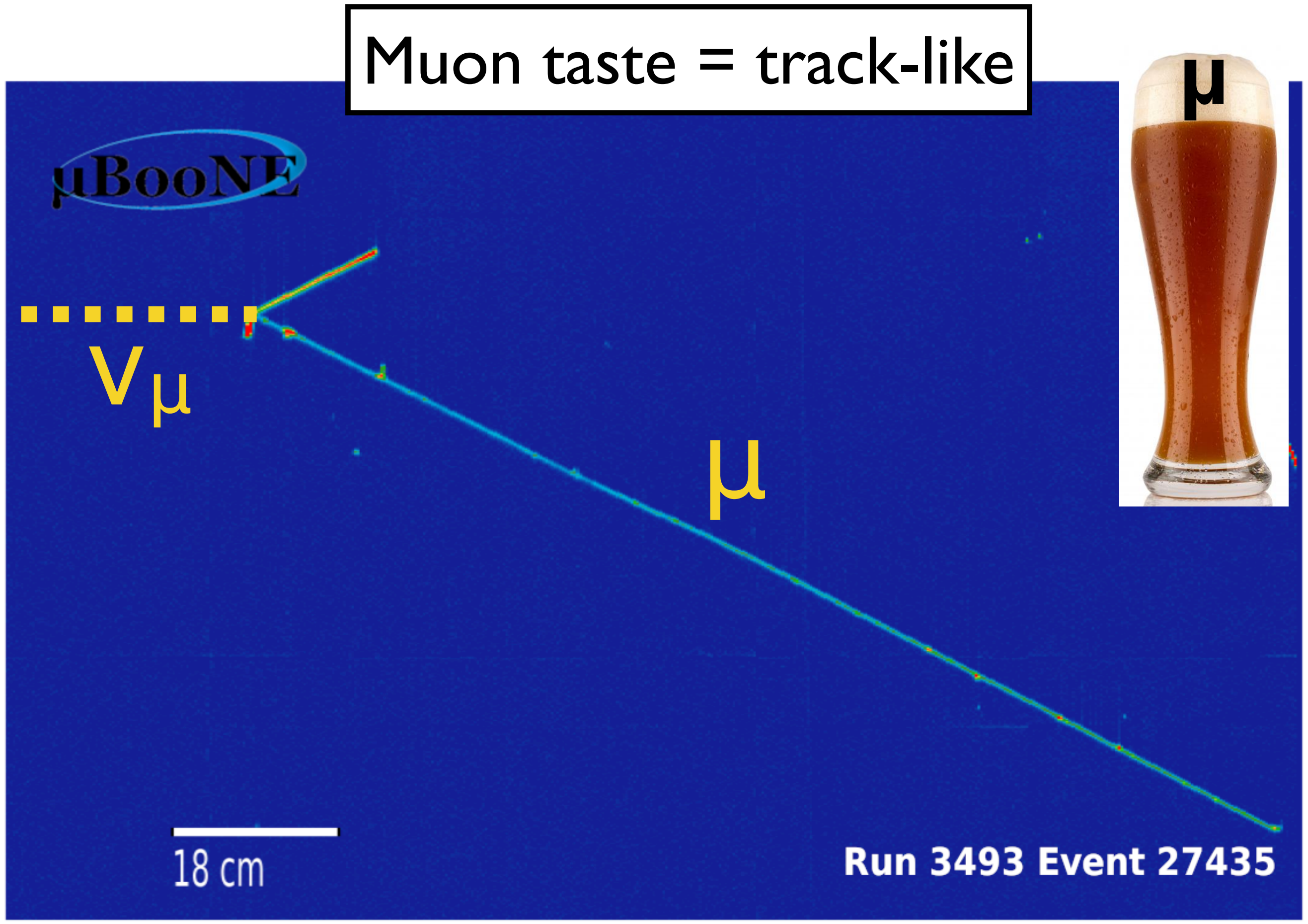
- We got here by sampling neutrino flavors
  - Want to make sure I <u>taste</u> the flavor that was produced: stout, amber, pilsner?
- For neutrinos, charged current interactions enable 'tasting' flavor
  - Want to make sure I <u>detect</u> the flavor that was produced: e, μ, or τ ?



Sampling Neutrino Flavors

- Many detector technologies can help us taste that flavor:



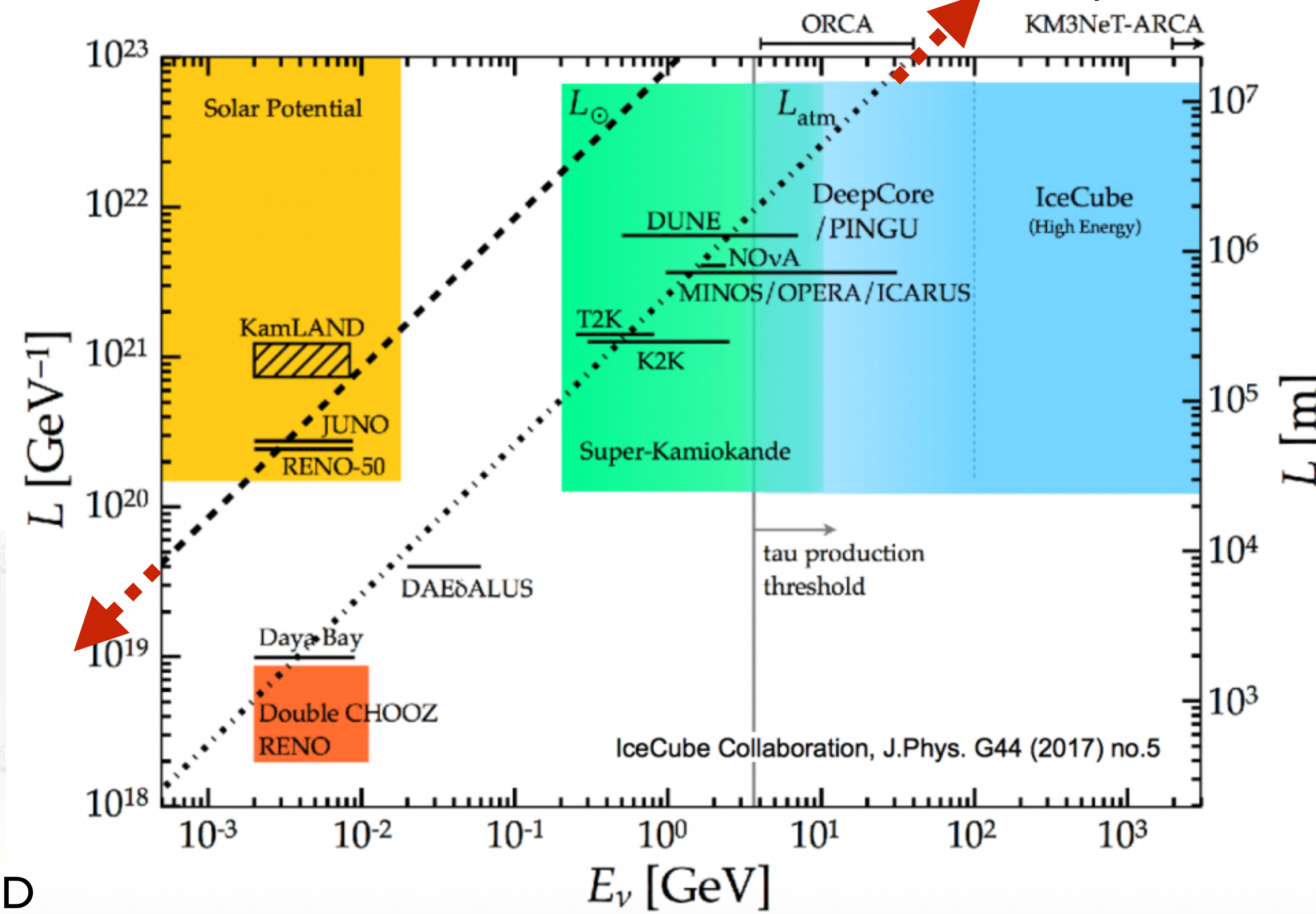


MicroBooNE: a liquid argon TPC in a ν_μ beamline

Neutrino Oscillations: L and E

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Took many experiments to get us here!
- Baselines (L): >km-scale
- Energies (E): MeV to GeV++!

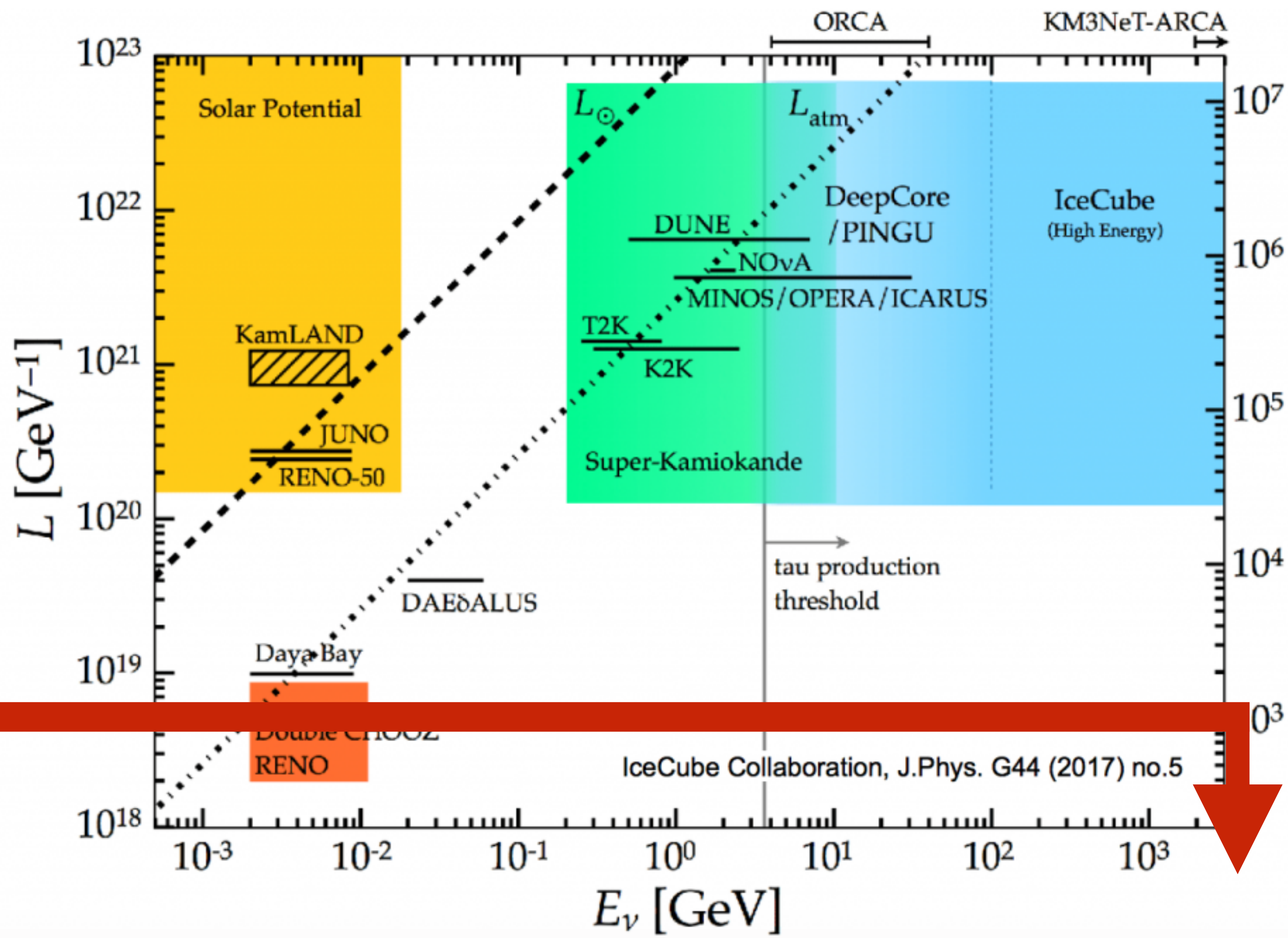
Example: OPERA



Example: KamLAND

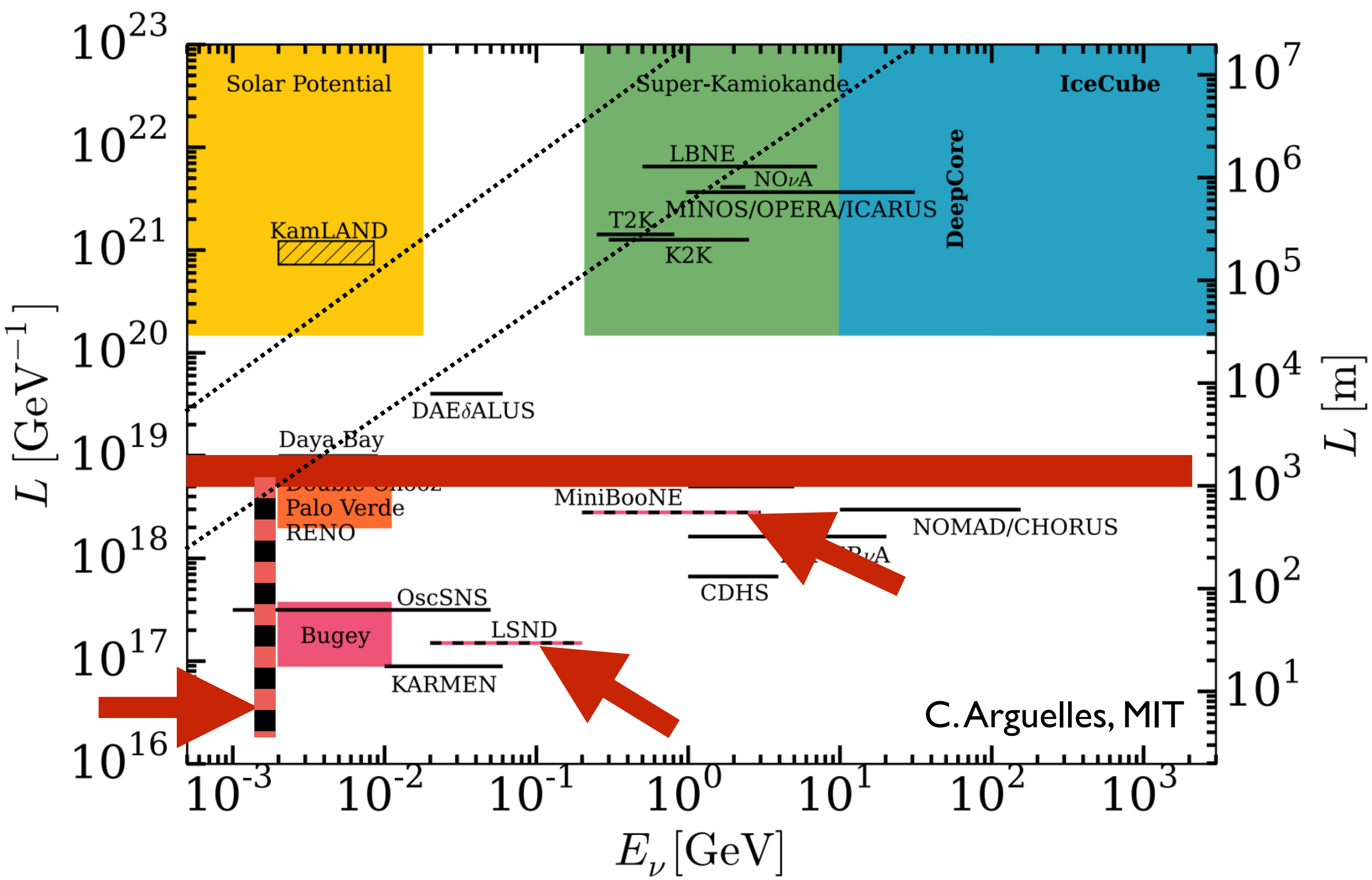
Neutrino Oscillations: L and E

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Took many experiments to get us here!
- Baselines (L): >km-scale
- Let's go HERE!
- WHY go here?



Neutrino Anomalies

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Indications of flavor changing beyond 'SM oscillations'?!



New Neutrino Mass States?

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Indications of flavor changing beyond ‘SM oscillations’?!
  - Another ~eV - keV neutrino mass state: **<u>‘3+1’ sterile neutrinos?</u>**

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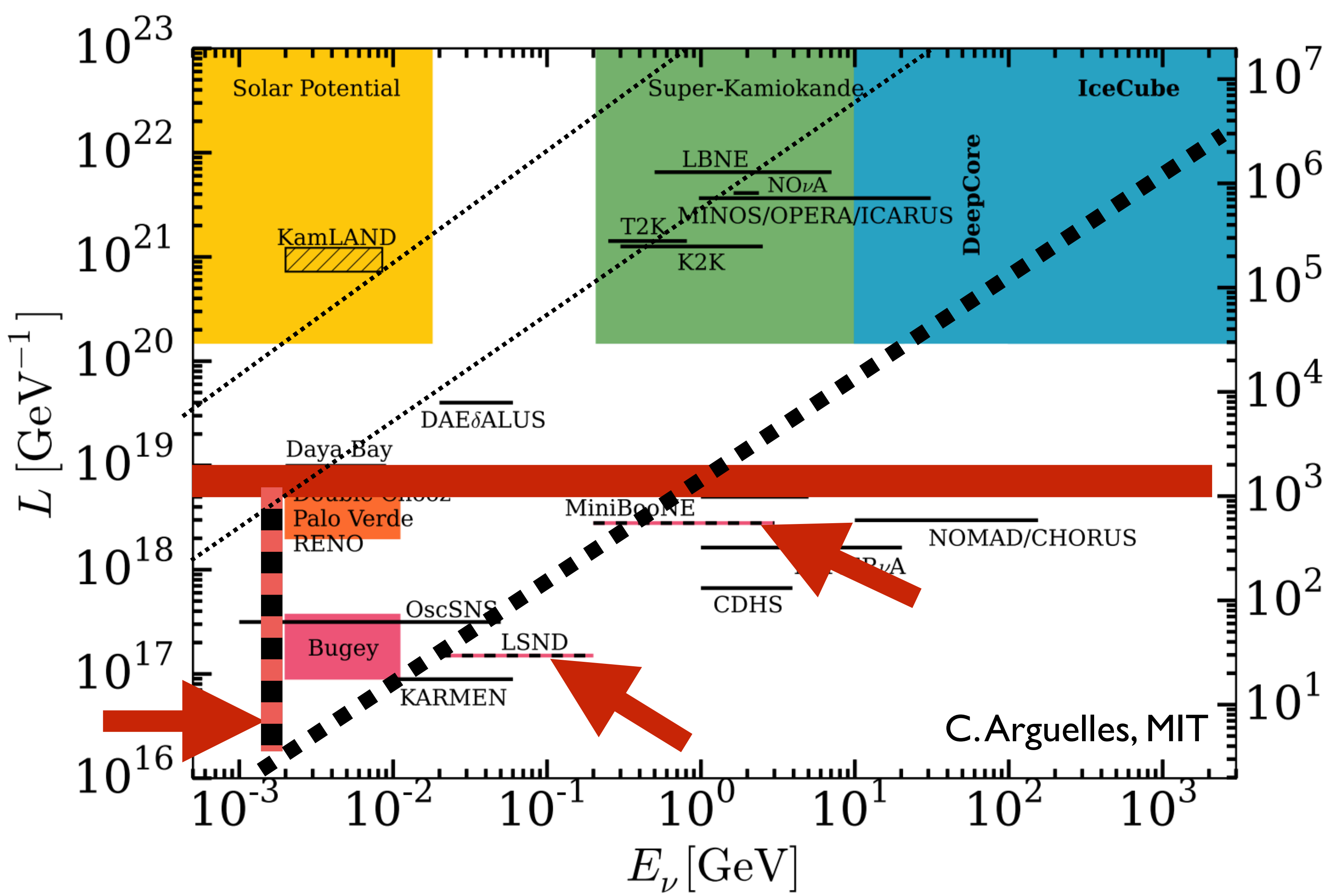


Recent Theory Progress: More New Physics

- Once you've made new mass states, how do they behave?
  - Do they decay (3+1+dk)? [Palomares-Ruiz et al, JHEP 09 (2005)] [DeGouvea, et al, JHEP 2019:141] [Dentler, et al, PRD 101 (2020)] [Balantekin et al, PLB 789 (2019)]
  - Do they have couplings to larger hidden sector? [Magill, et al, PRD 98 (2018)] [Ballett, et al, PRD 99 (2019)]
- Why neutrinos at all? Other BSM? [M.Acero, et al, J. Phys. G 51 (2024)] [S. Gori, et al, Snowmass RF06 Report]
- If we crack open a hidden sector, who knows what we'll find!?

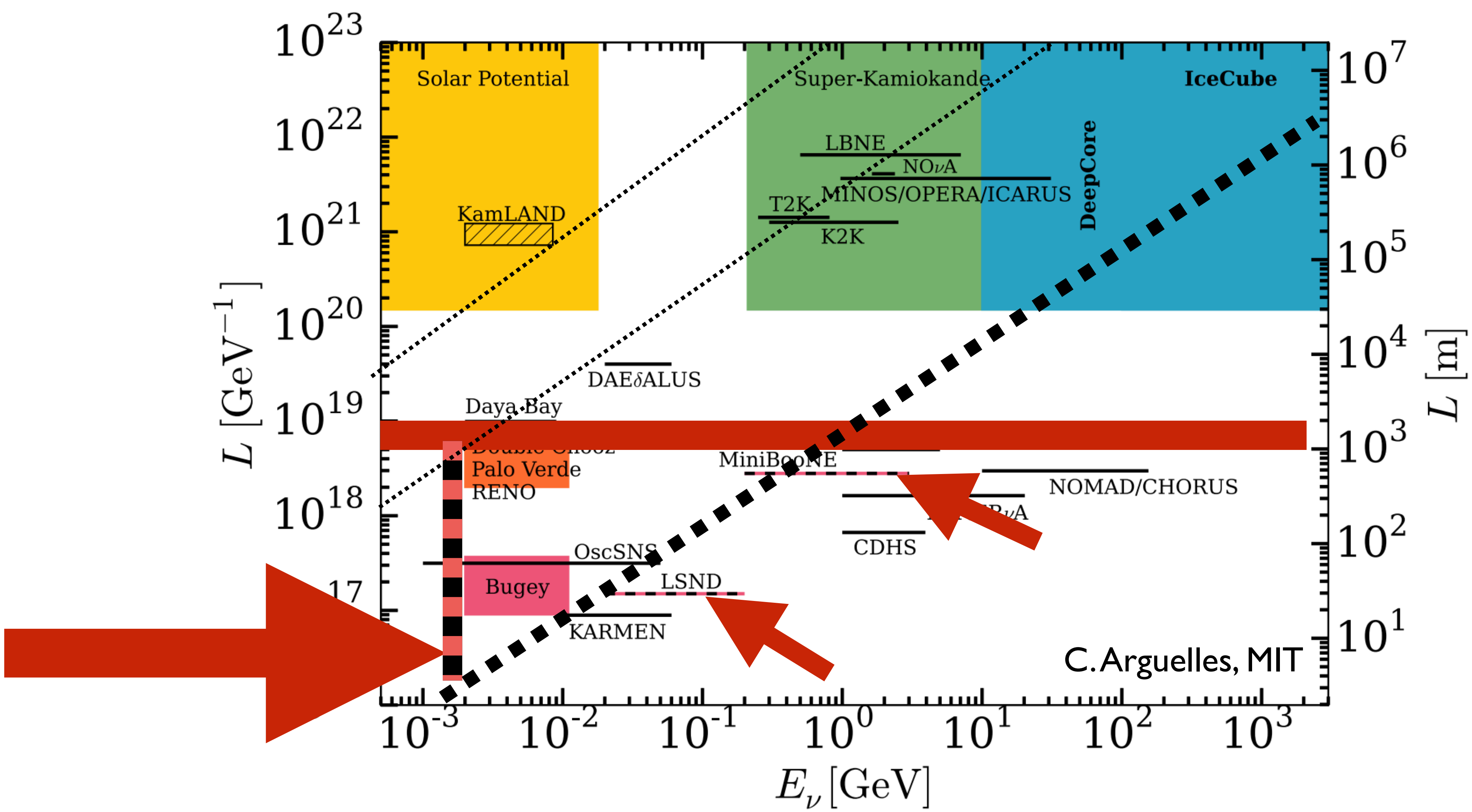
Double Fruit Smoothie

and/
or:

Pastry Stout?!

Imperial Seltzer!?

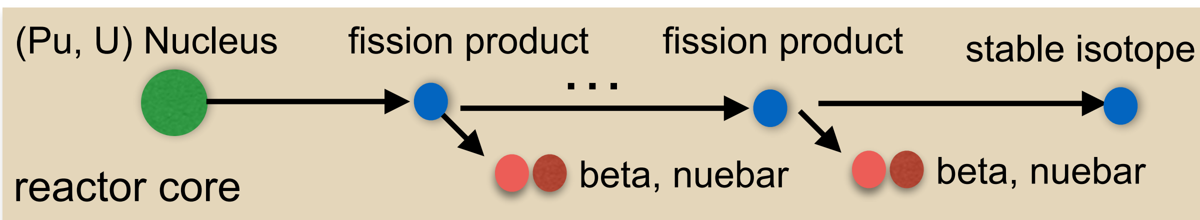
A Low-Energy Neutrino Anomaly

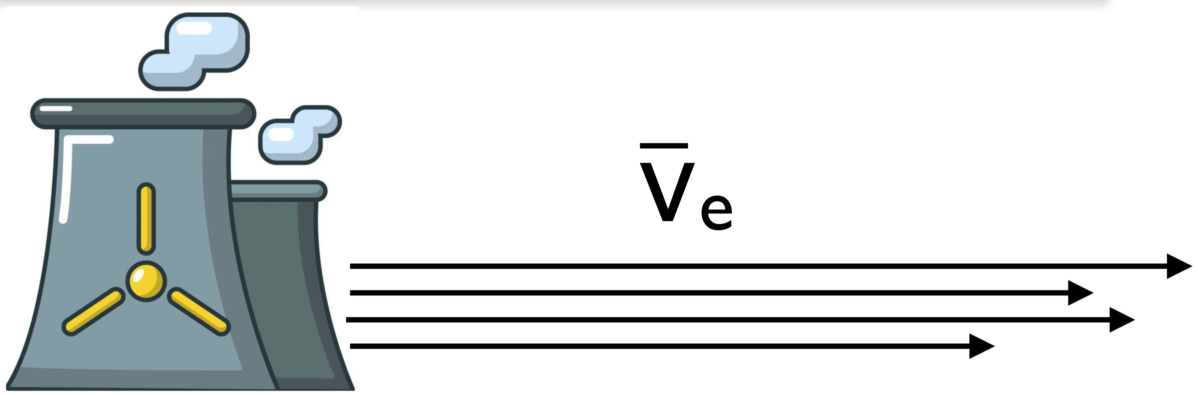


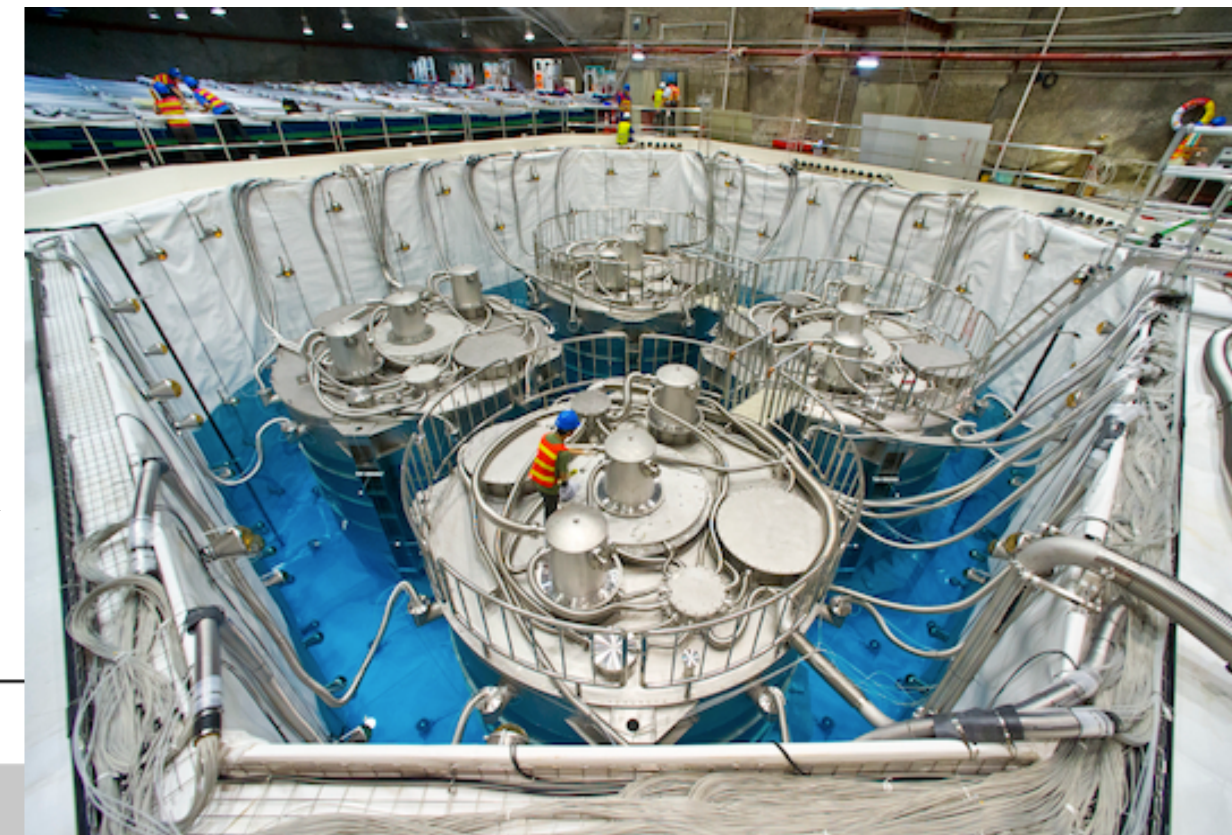
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \left[1.27 \Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)}\right]$$

Reactor and Gallium Anomalies

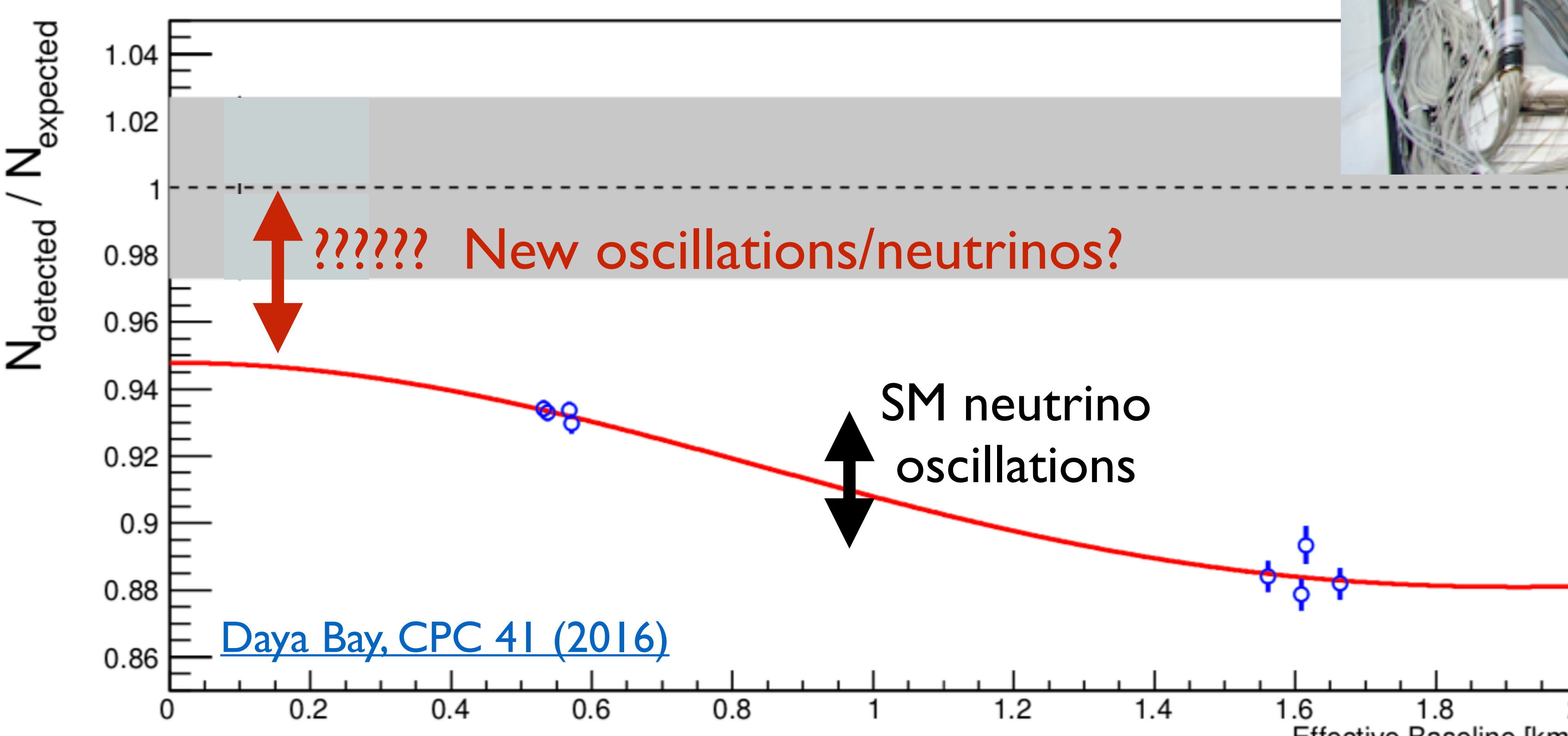
- Deficits in neutrino detection rates at electron-flavor sources
- Sources host only lower-energy (~MeVs) processes (β^-, EC)







Daya Bay: liquid scintillator inverse beta decay detectors



Probing Reactor E-Flavor Disappearance

- In ton-scale scintillator detectors, look for variations between ν_e energy spectra of full detector versus individual baselines

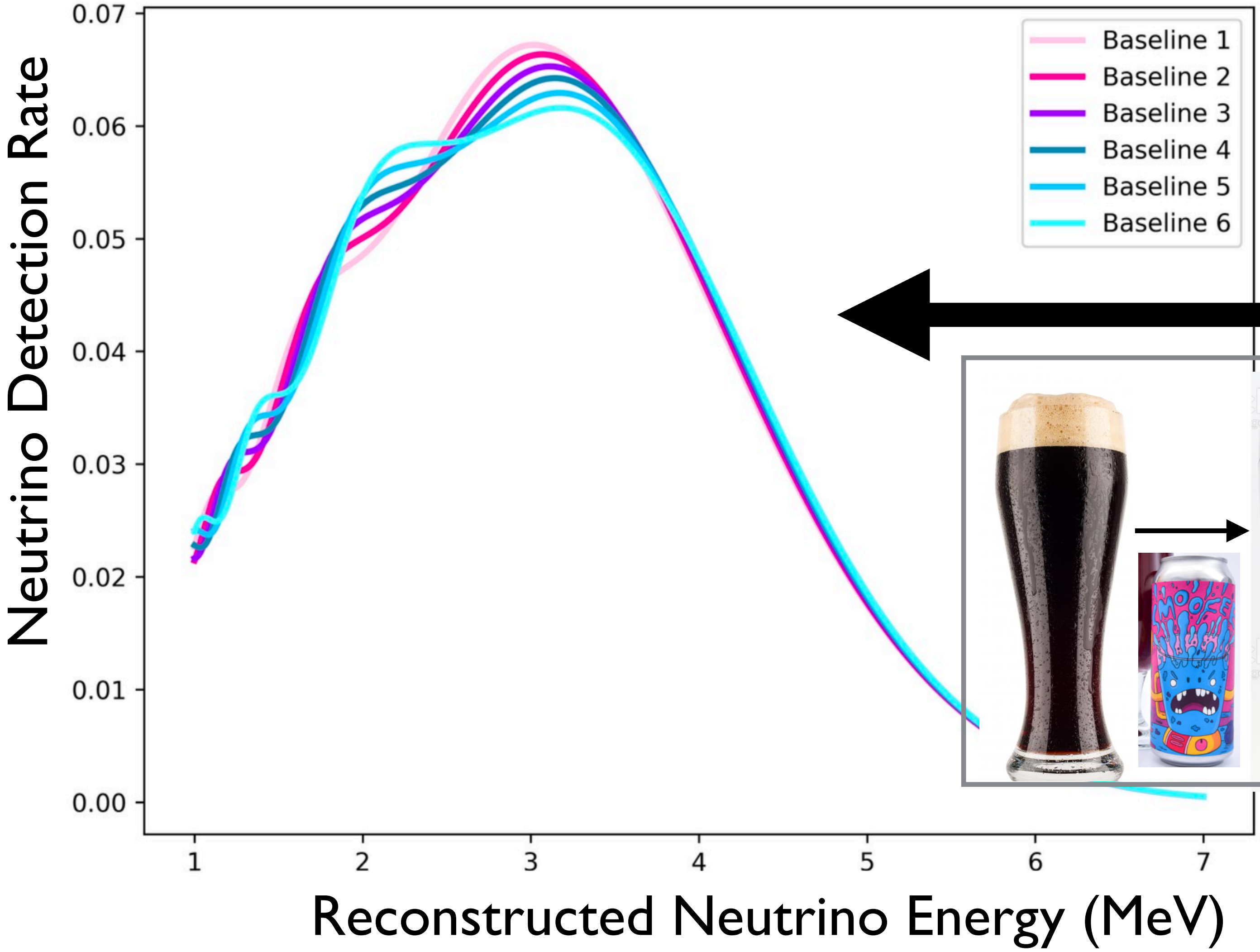
Ouside the PROSPECT detector

Inside: different segments, different baselines

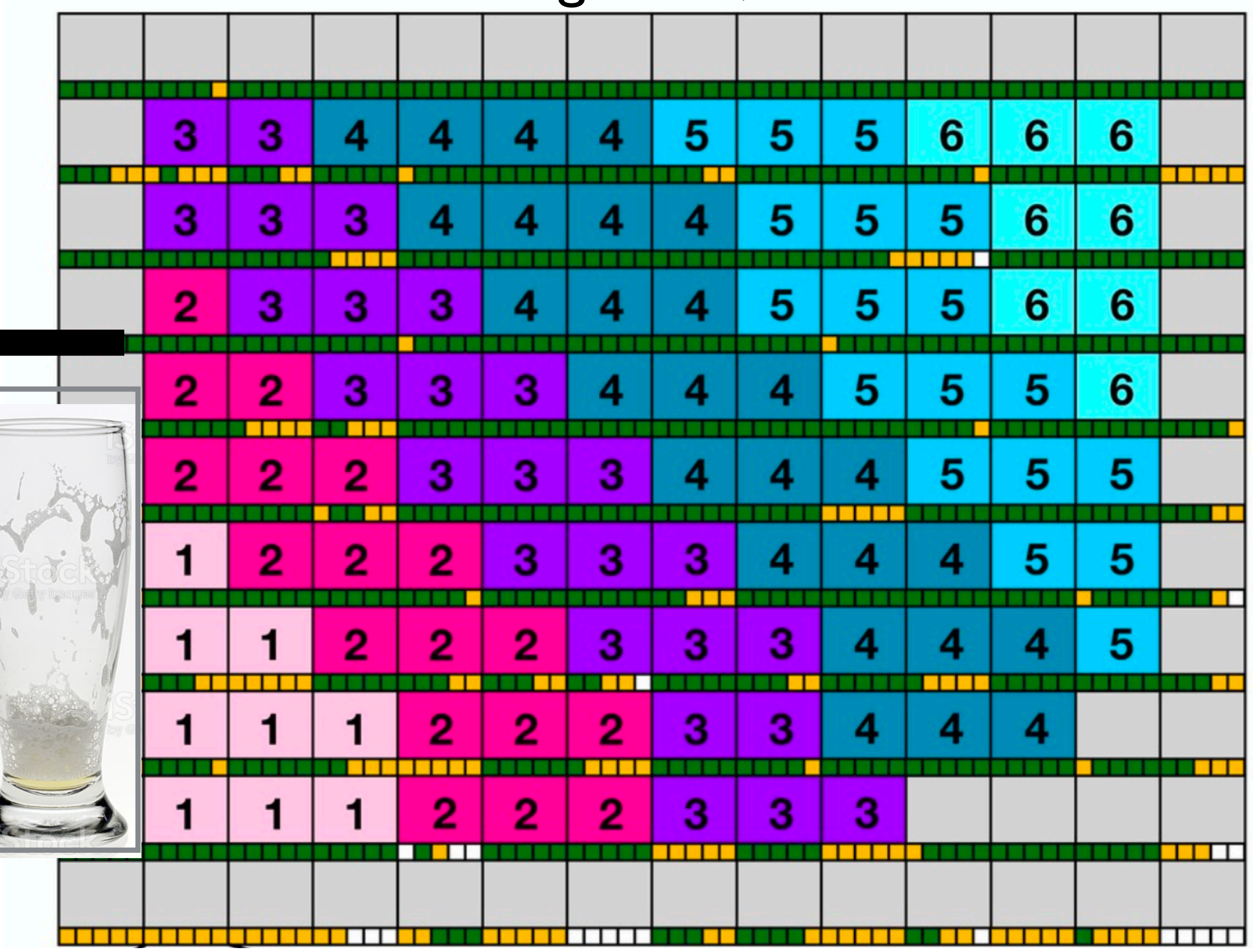
Probing Reactor E-Flavor Disappearance

- In ton-scale scintillator detectors, look for variations between ν_e energy spectra of full detector versus individual baselines
  - Any wiggles in ratio is evidence of L/E nature of '3+1' sterile neutrino picture

Different baselines, different oscillations

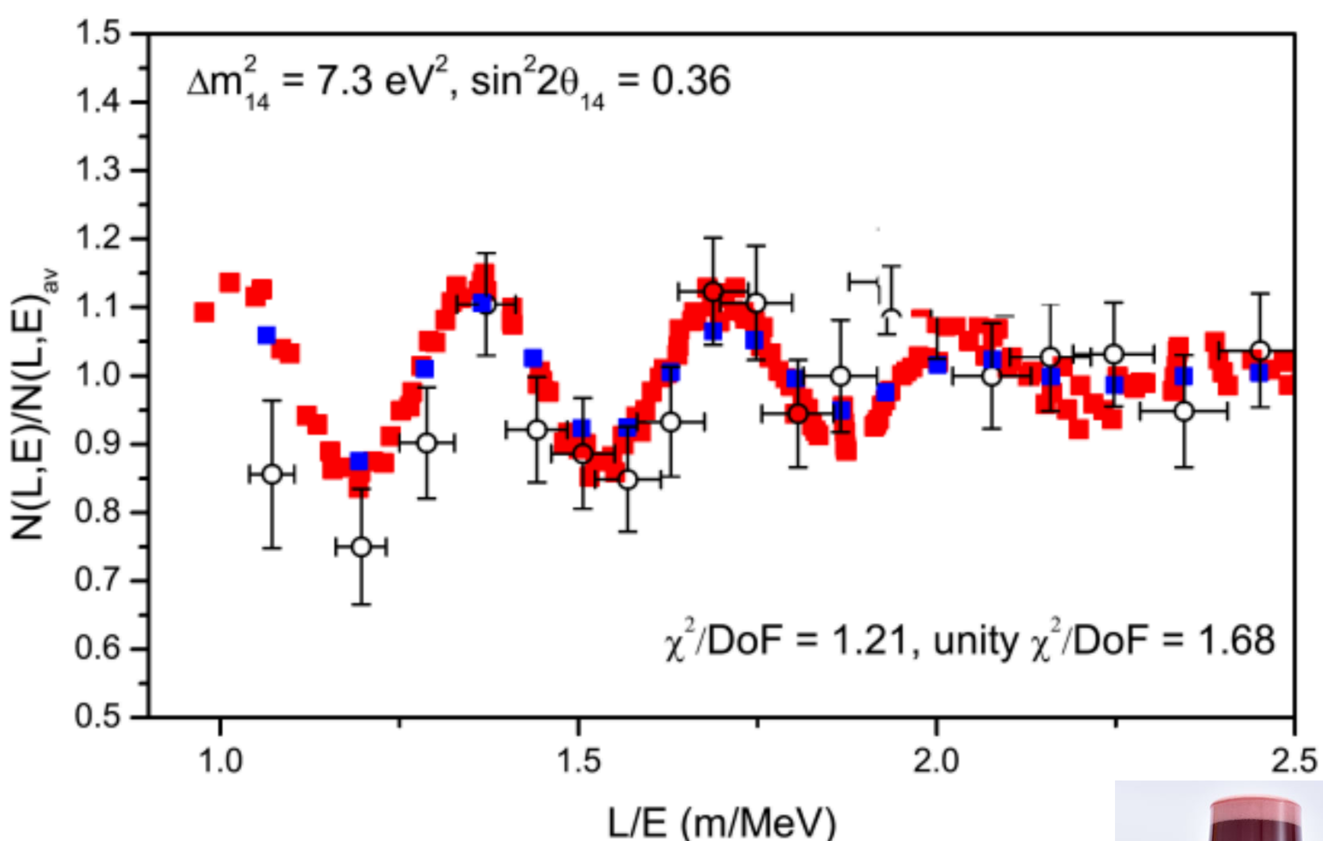


Inside: different segments, different baselines



Positive Hints: Neutrino-4

- In ton-scale scintillator detectors, look for variations between ν_e energy spectra of full detector versus individual baselines
- In 2020: the Russian Neutrino-4 experiment claims 2-3σ observation of these '3+1' wiggles



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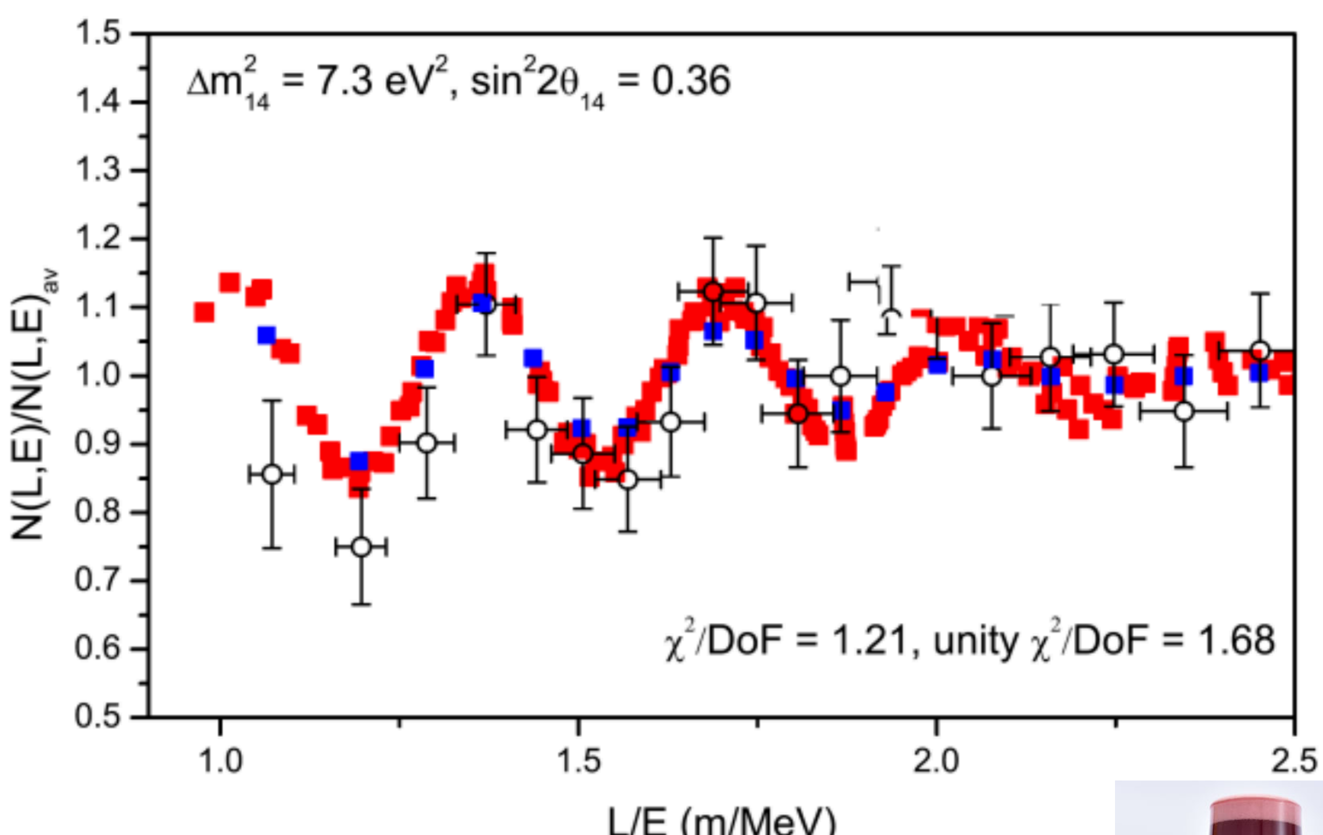
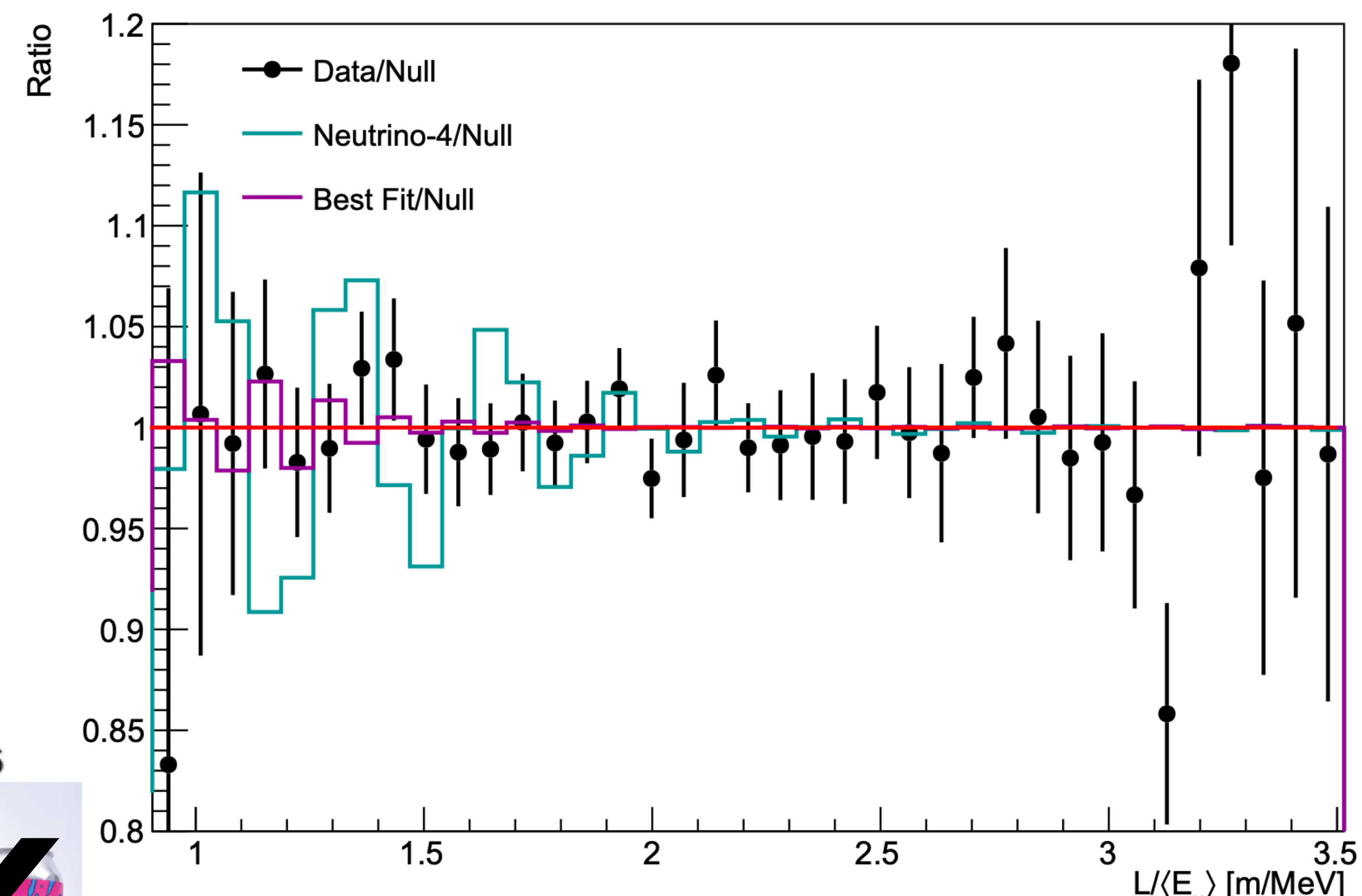
Null Results: PROSPECT

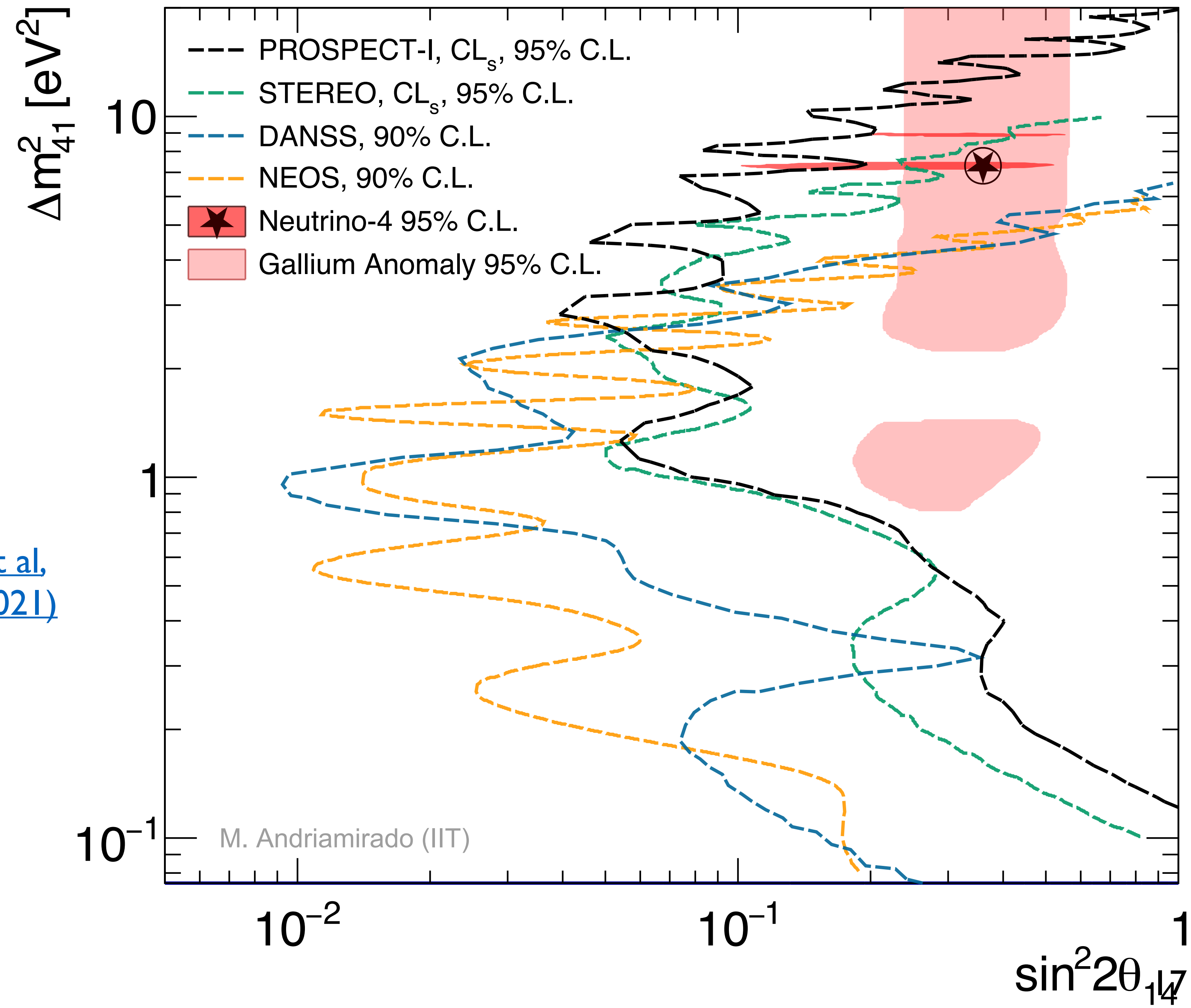
- In ton-scale scintillator detectors, look for variations between ν_e energy spectra of full detector versus individual baselines
- In 2024: the PROSPECT experiment strongly disfavors this claim with a lower-background measurement





Global Short-Baseline Reactor Picture

- Recent short-baseline reactor measurements have collectively dampened reactor-sector anomaly / Neutrino-4 excitement
  - PROSPECT's final 3+1 oscillation result rules out the most-favored Neutrino-4 phase space point at more than 5σ CL.
  - More room to push harder with next gen: PROSPECT-II

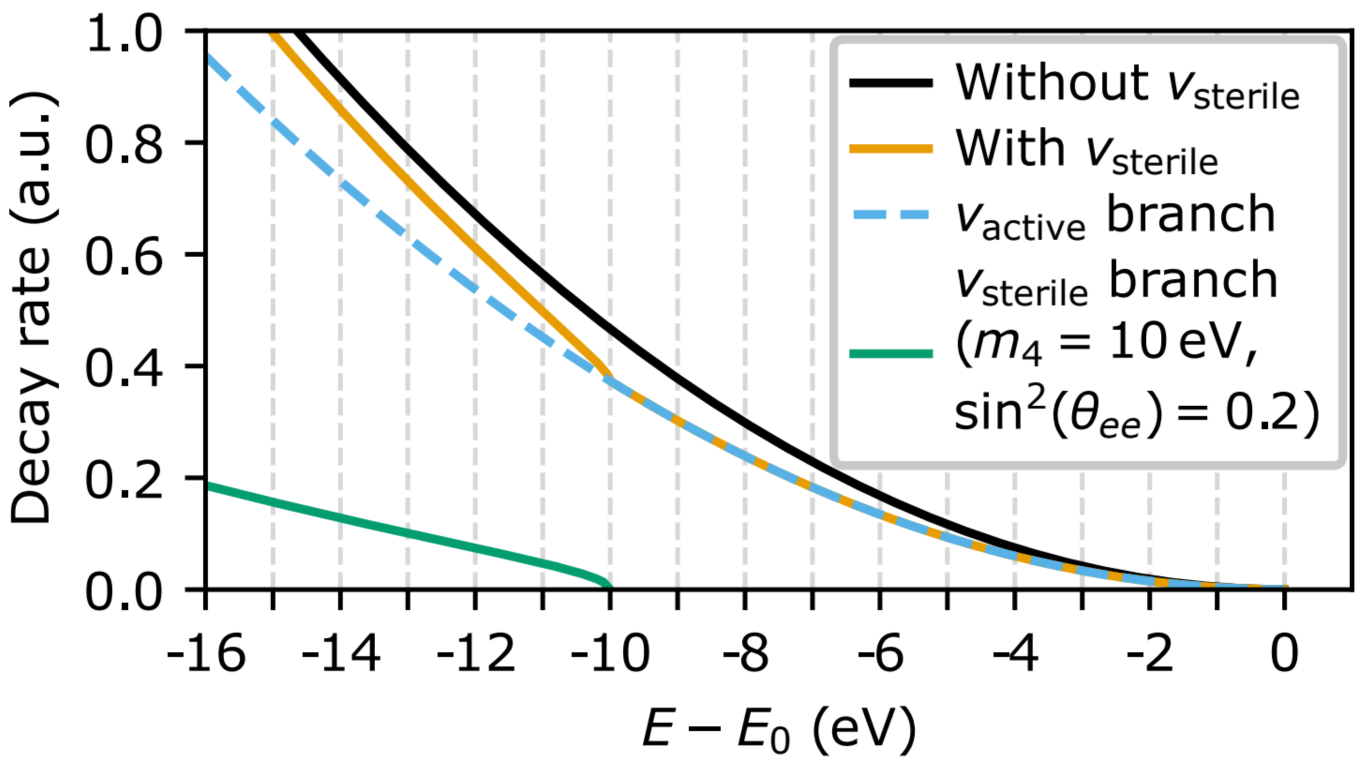


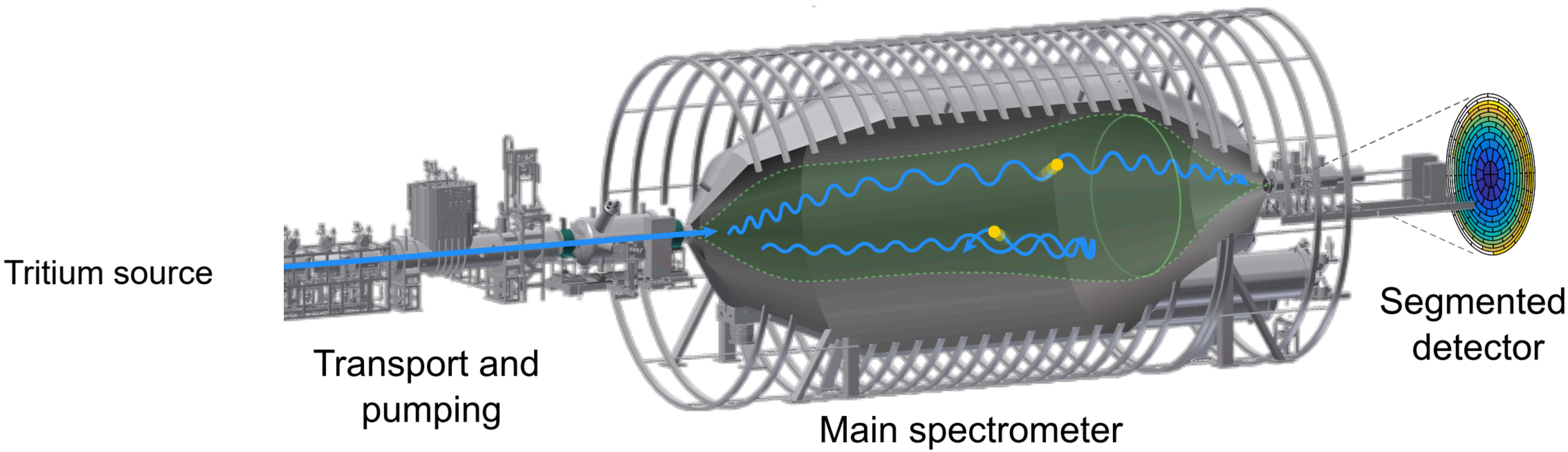
- Recent nuclear theory and experiment point to another anomaly cause: incorrect reactor flux predictions

[Daya Bay PRL 118 (2017)](#) [Estienne, et al, PRL 123 (2019)](#) [Kopeikin, et al, PRD 104 (2021)](#)

KATRIN Sterile Neutrino Searches

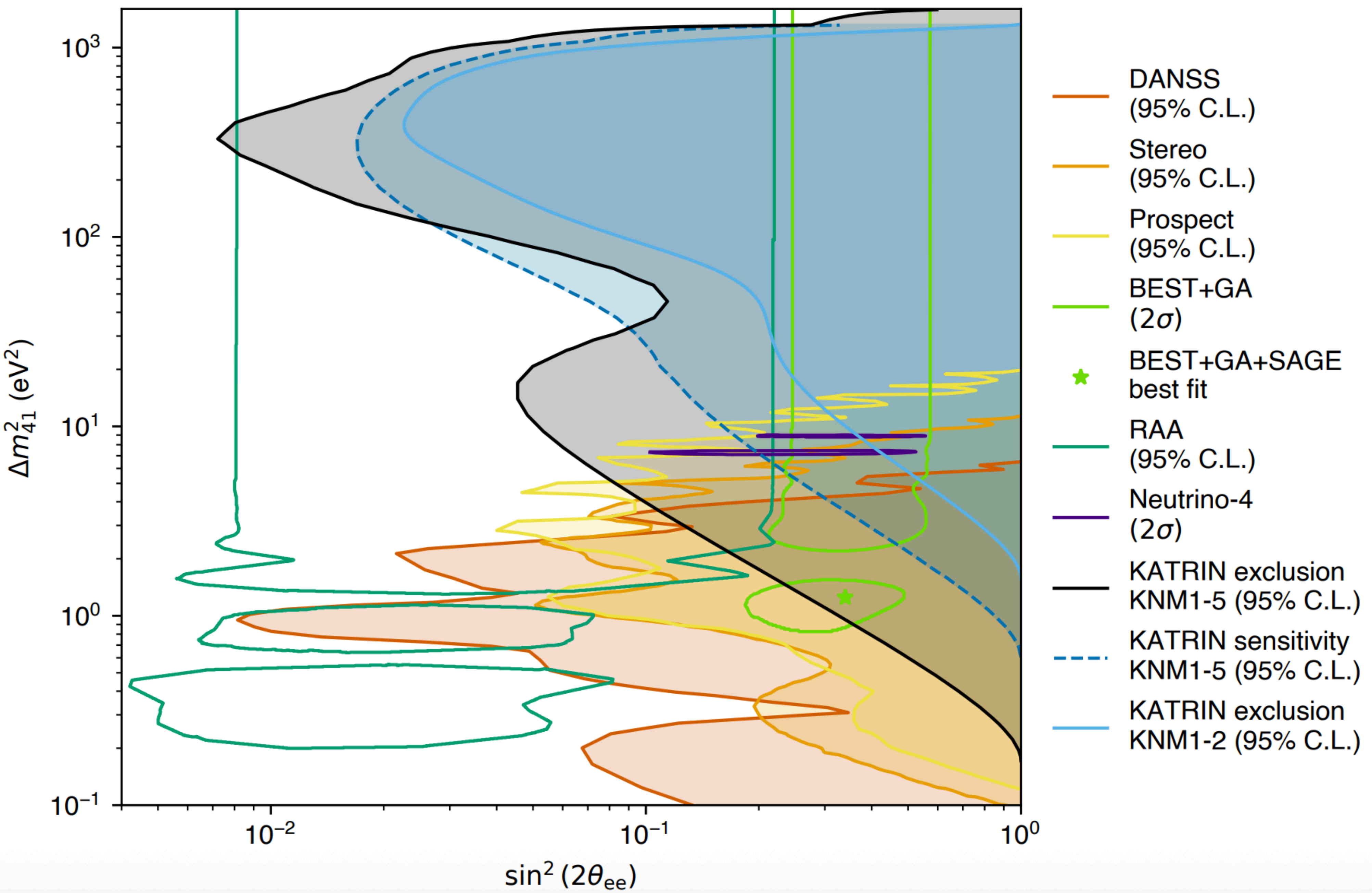
- KATRIN: push harder at higher Δm^2 by looking for kinks in its tritium beta spectrum endpoint measurement





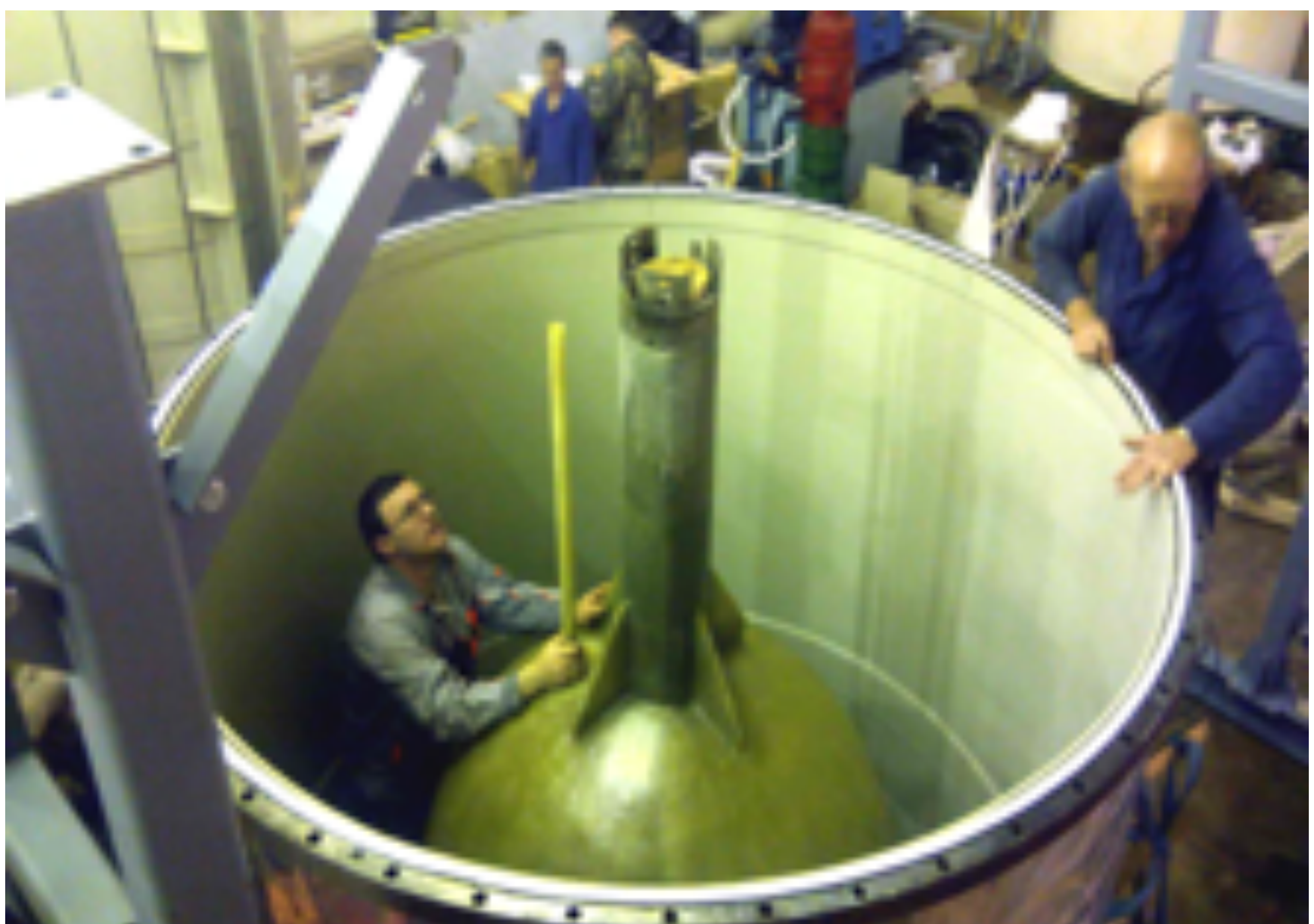
θ_{ee} Limits in KATRIN

- KATRIN: push harder at high Δm^2 by looking for kinks in its tritium beta spectrum endpoint measurement
  - Both tritium measurements AND most short-baseline reactor measurements seem to be closing the door on the reactor-sector 3+1 oscillation picture.



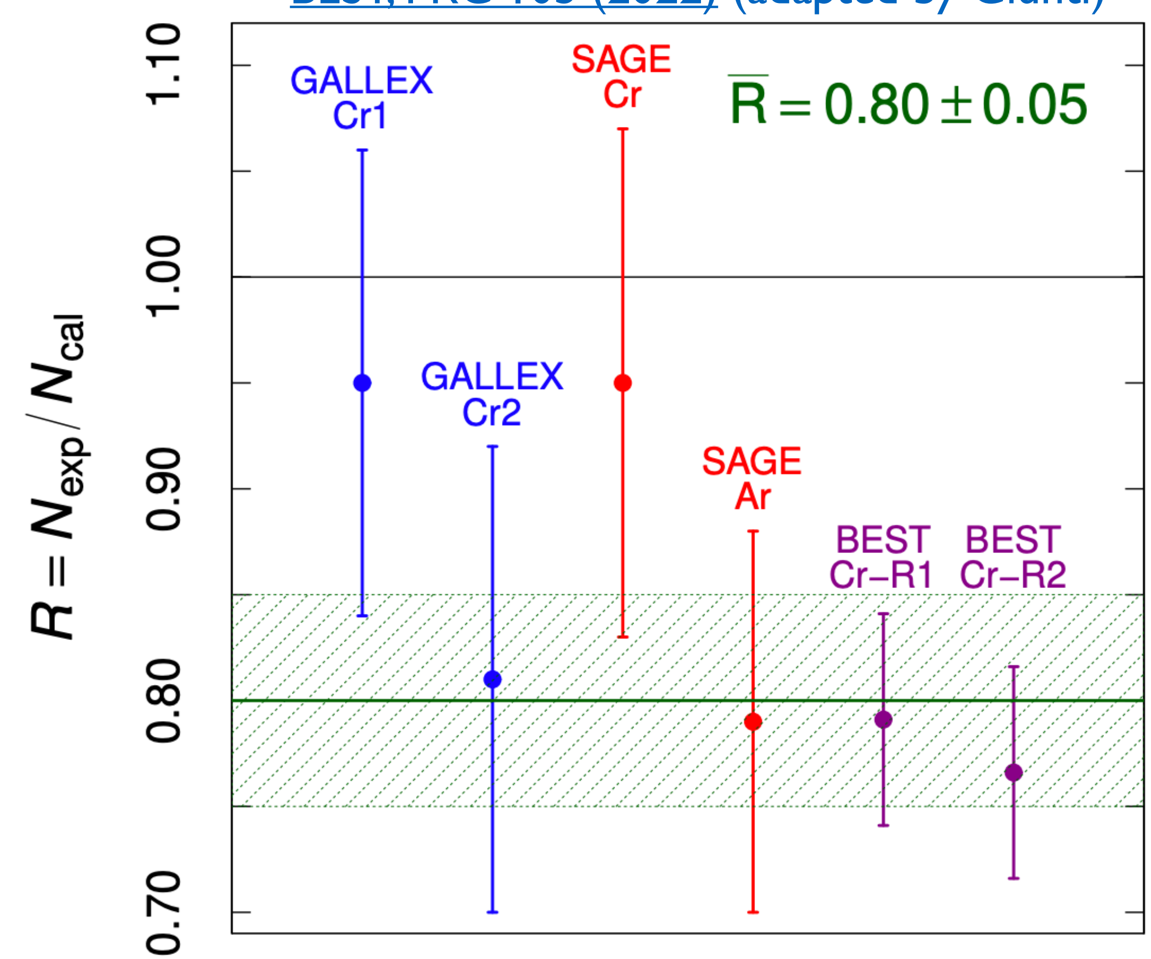
The Enduring Gallium Anomaly

- On the other hand, electron-flavor deficits remain in intense ν_e radioactive source experiments: GALLEX, SAGE, and BEST
  - BEST's two-zone gallium detector shows no signs of baseline (L/E) dependence
  - 'Reactor-gallium tension:' why a deficit in one MeV e-source, but not another???
  - BEST-2: 3-zone detector with new Co-58 source (E_{nu} = 1.5 MeV) V. Gavrin et al, 2501.08127

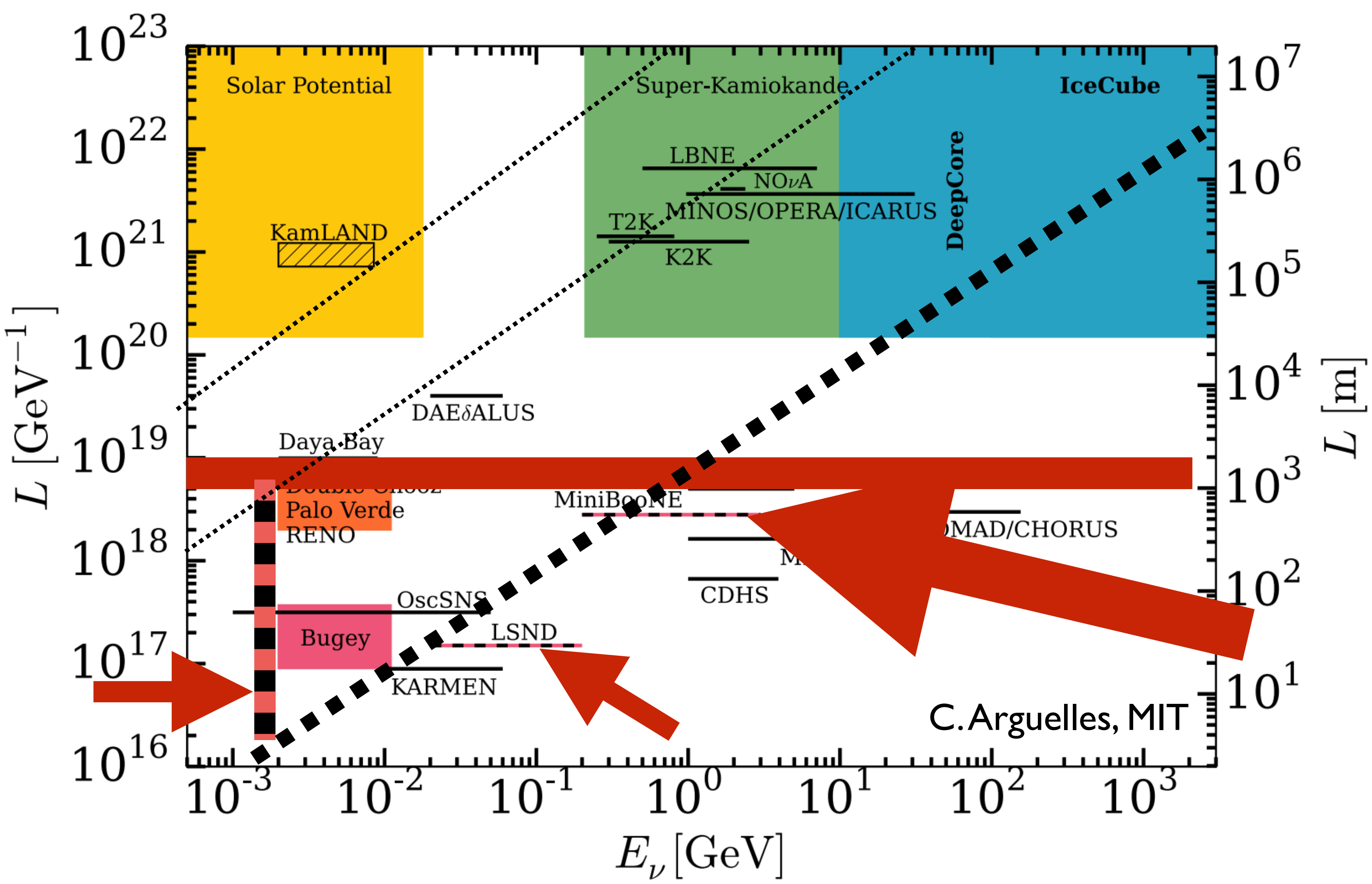


BEST: ^{51}Cr source inside a 2-zone Ga neutrino target

BEST, PRC 105 (2022) (adapted by Giunti)



A High-Energy Neutrino Anomaly



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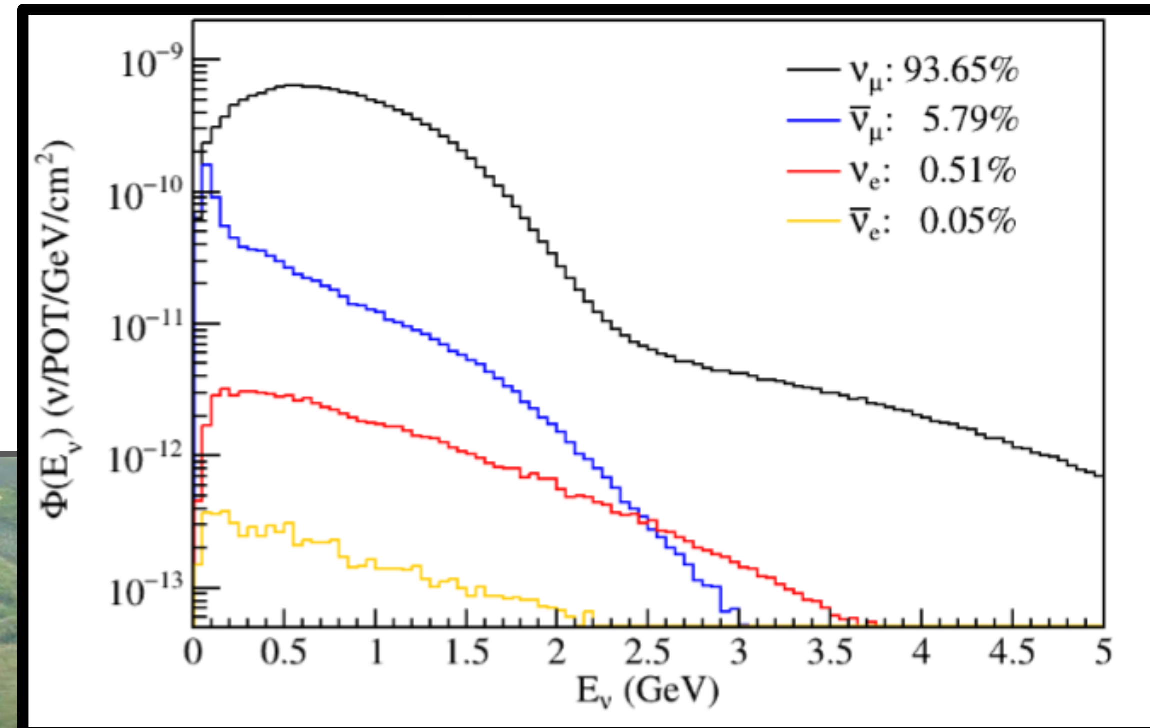
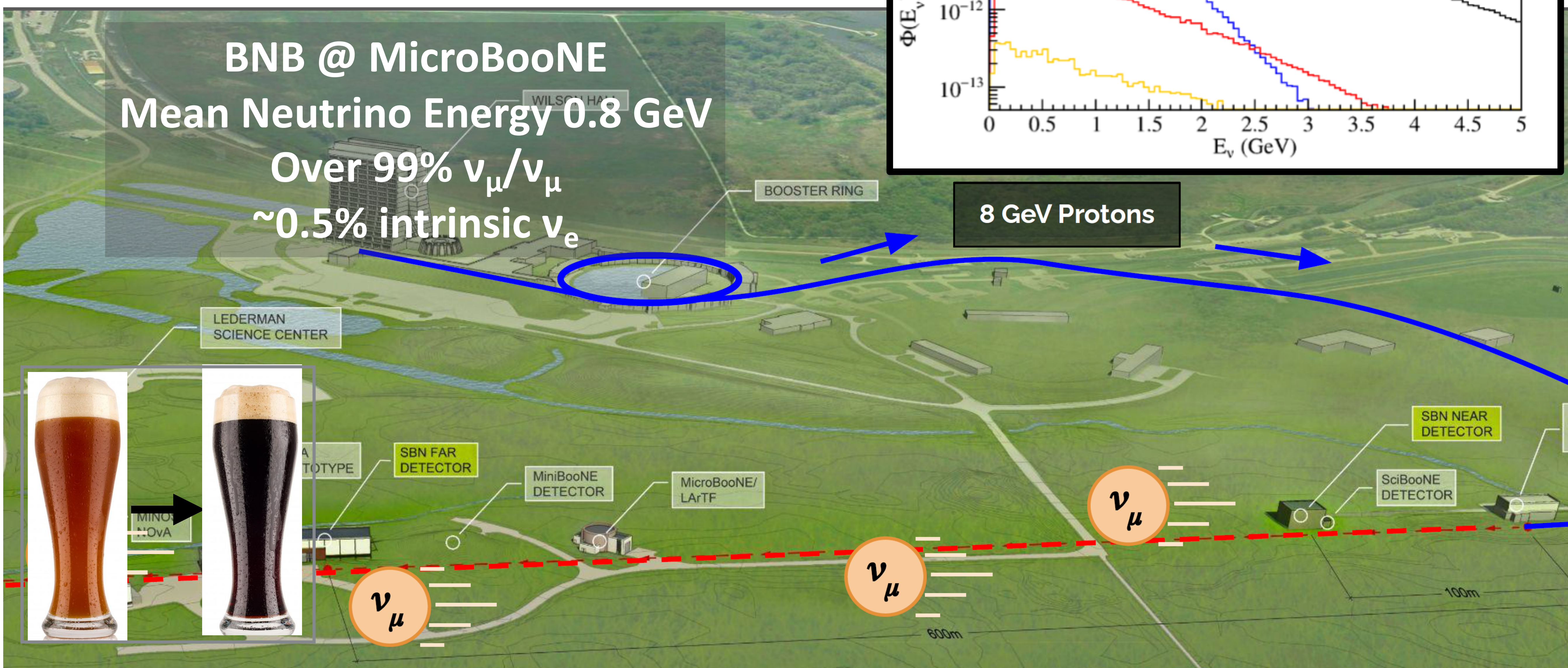
A High-Energy Neutrino Anomaly

- Anomalous results seen along the ~muon-flavored Booster Neutrino Beamline at Fermilab: MiniBooNE (2002-2019)





MiniBooNE Anomaly: Electron or Gamma

- Anomalous results seen along Booster Neutrino Beamline at Fermilab: MiniBooNE (2002-2019)

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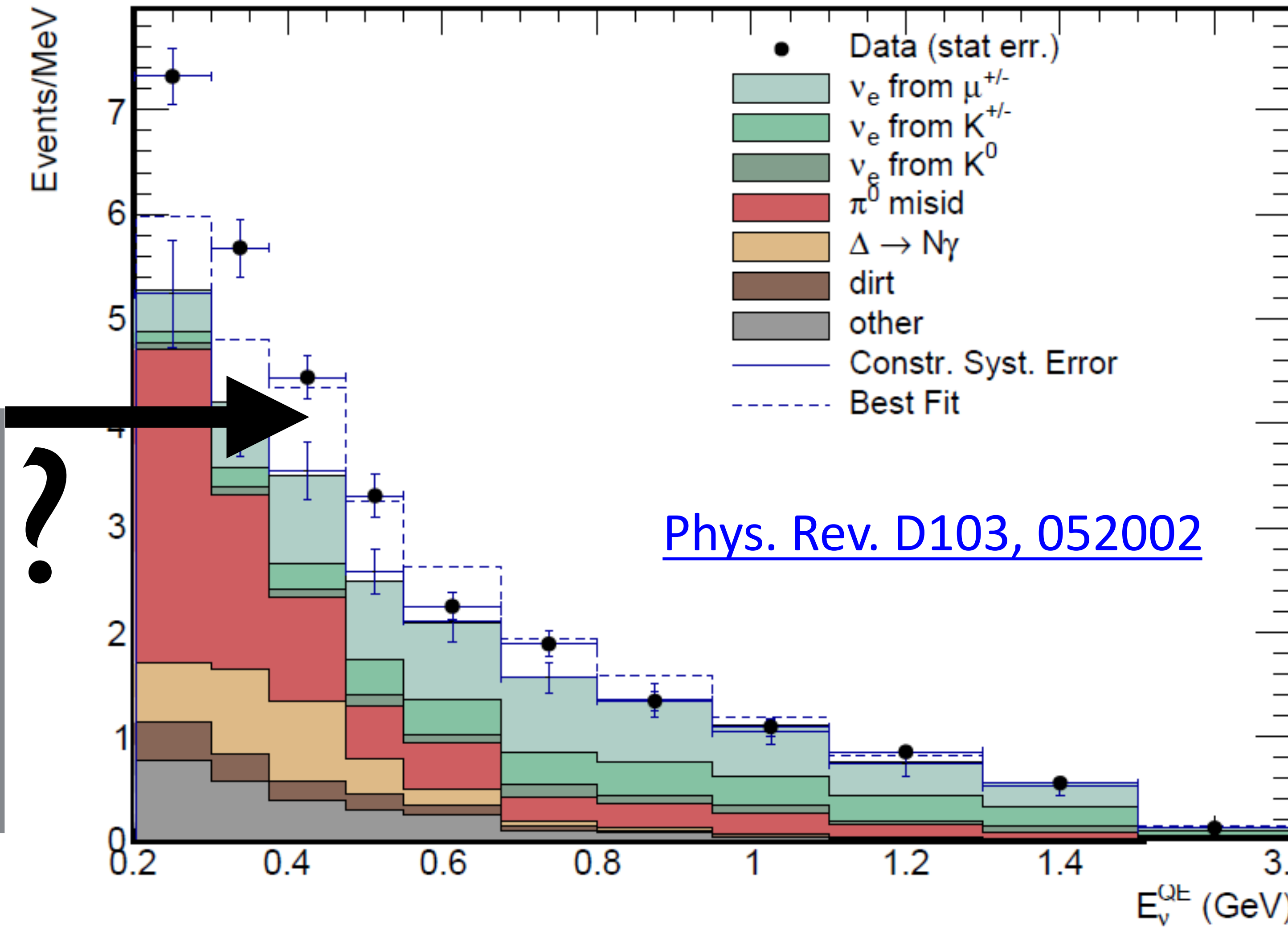
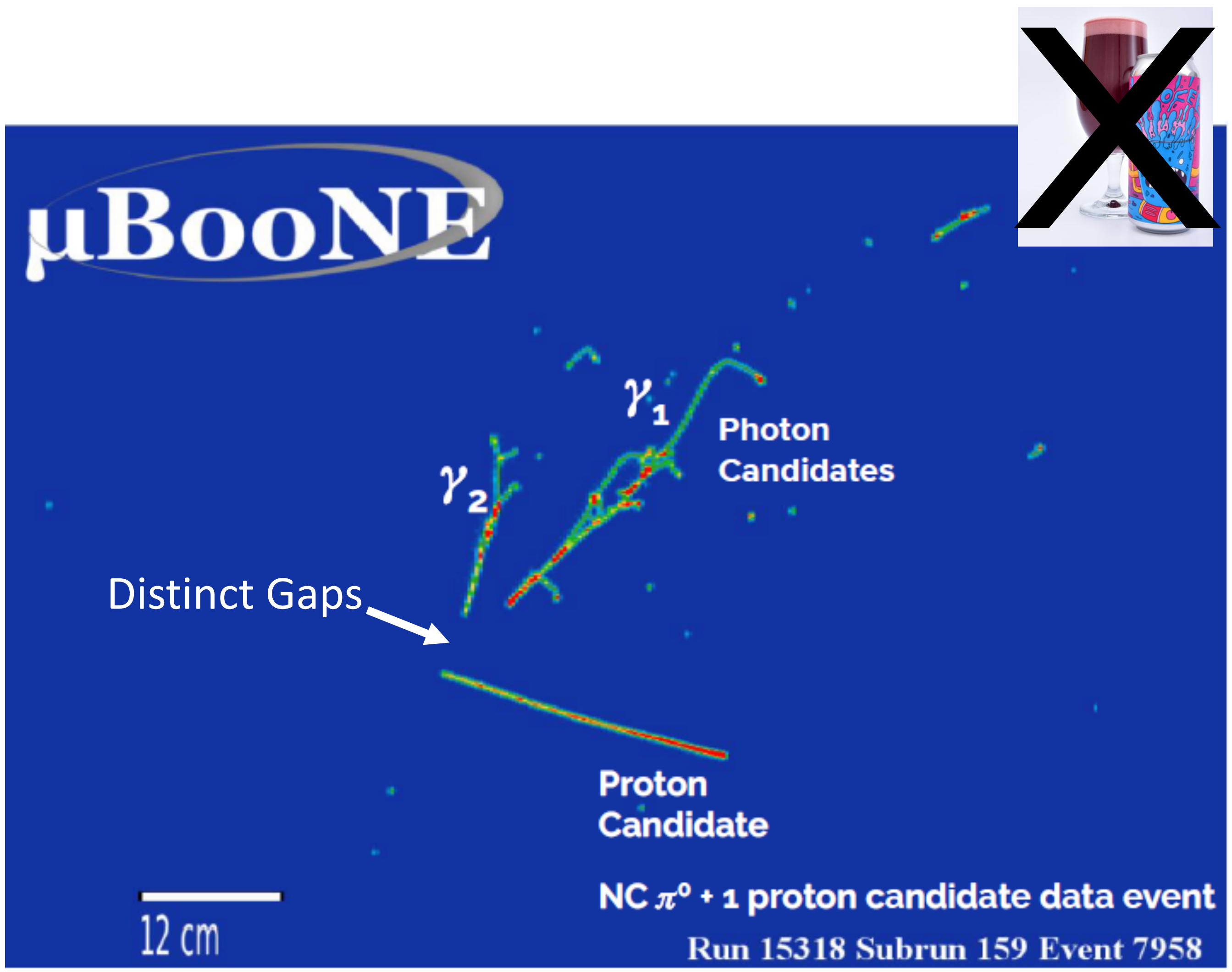


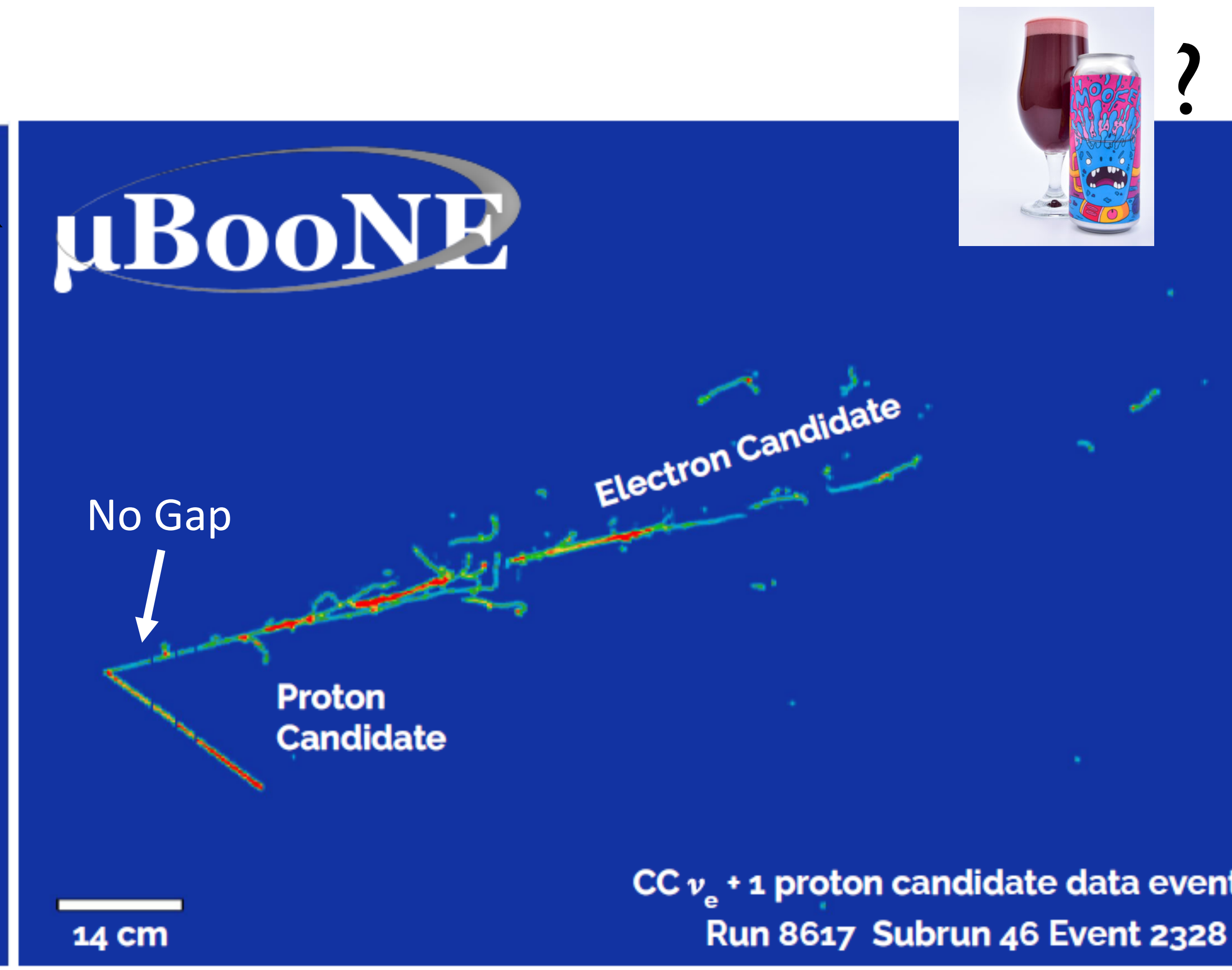
Phys. Rev. D103, 052002

- To learn more about MiniBooNE's anomaly, we need a measurement with better electron - gamma separation
- Enter: LArTPC experiments of the SBN Program at FNAL

MicroBooNE: Electron or Gamma

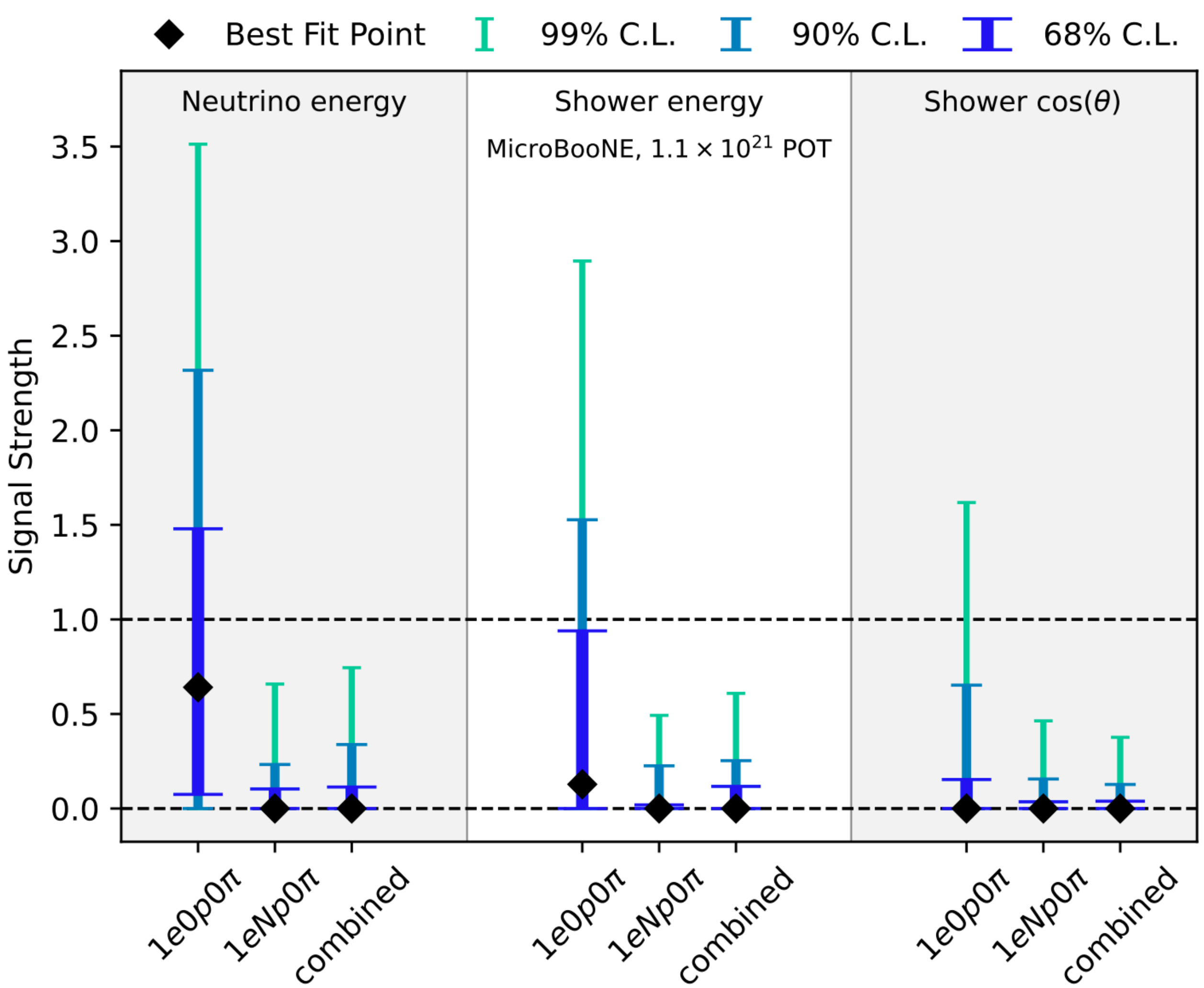
- Event topology separates showers (e/ɣ) and tracks (μ/p/pi)
- Separate e and ɣ using spatial gaps and shower dE/dx profiles

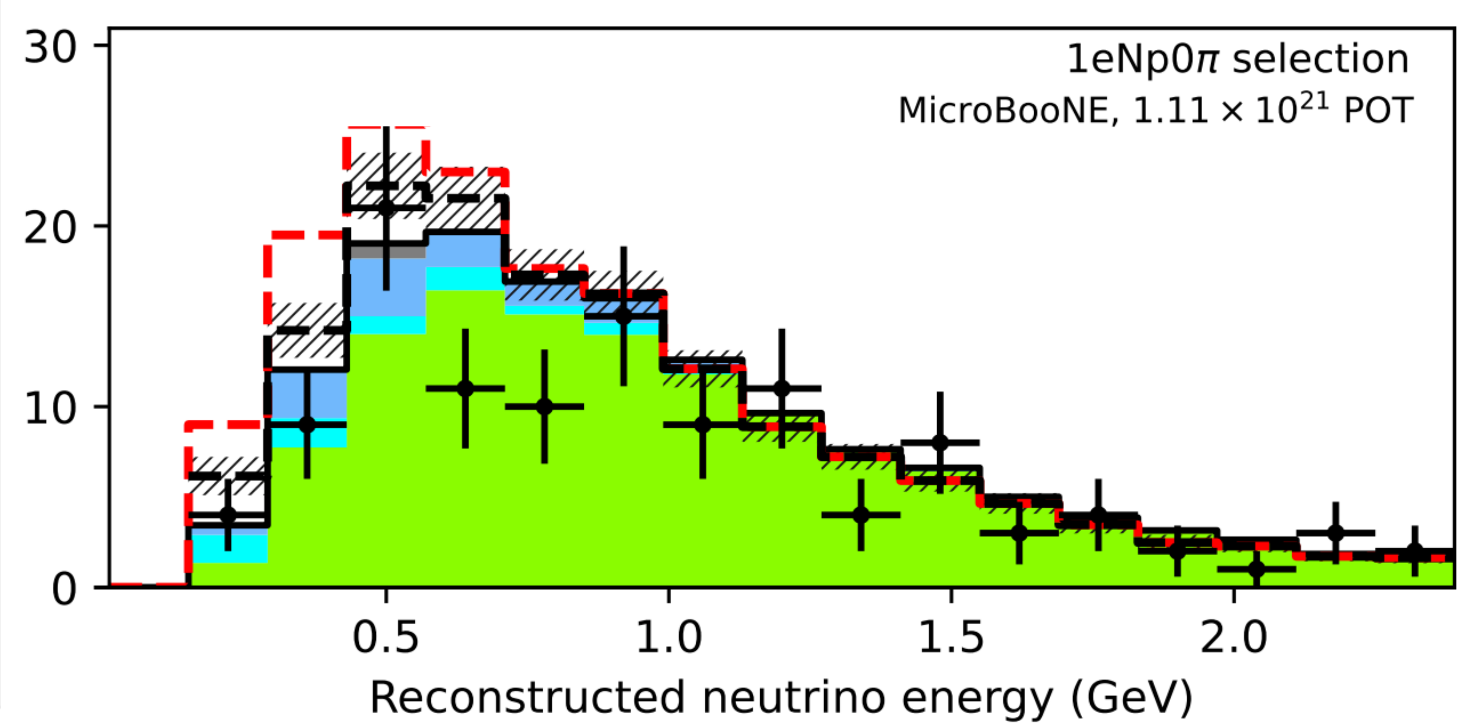




MicroBooNE Electron Searches

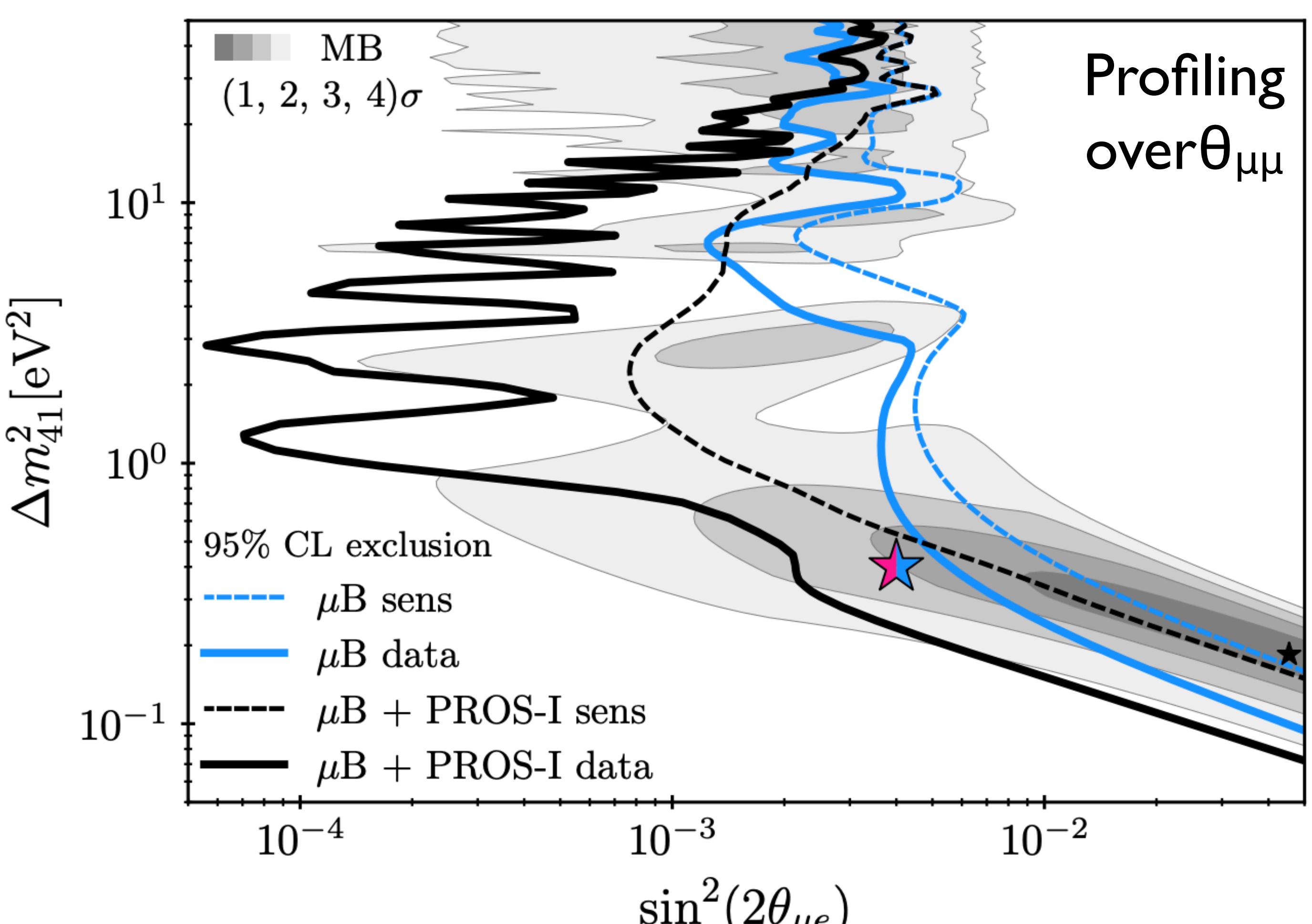
- **MicroBooNE data now excludes the possibility of a pure electron-like MiniBooNE excess at >99% CL**
  - Consistent across multiple event topologies (1e1p, 1eX), kinematic variables
  - If anything, a (low-CL) deficit, not an excess, is observed
- **Sterile neutrino oscillation hints from multiple experimental sectors appear to be weakening**





LArTPC 3+1 Oscillation Limits

- MicroBooNE's 3+1 osc parameter exclusion is complicated by competing BNB appearance and disappearance effects
  - Fix: fit MicroBooNE results from both 'purer' BNB and 'mixed' NuMI beams: this completed analysis is currently under peer review [MicroBooNE: Neutrino 2024]
  - Fix: fit MicroBooNE while constraining disappearance with PROSPECT
  - 'Fix:' Stop fit profiling: in a full 3D scan of 3+1 space, all 95% preferred MiniBooNE phase space is ruled out at >95% CL by MicroBooNE BNB data!

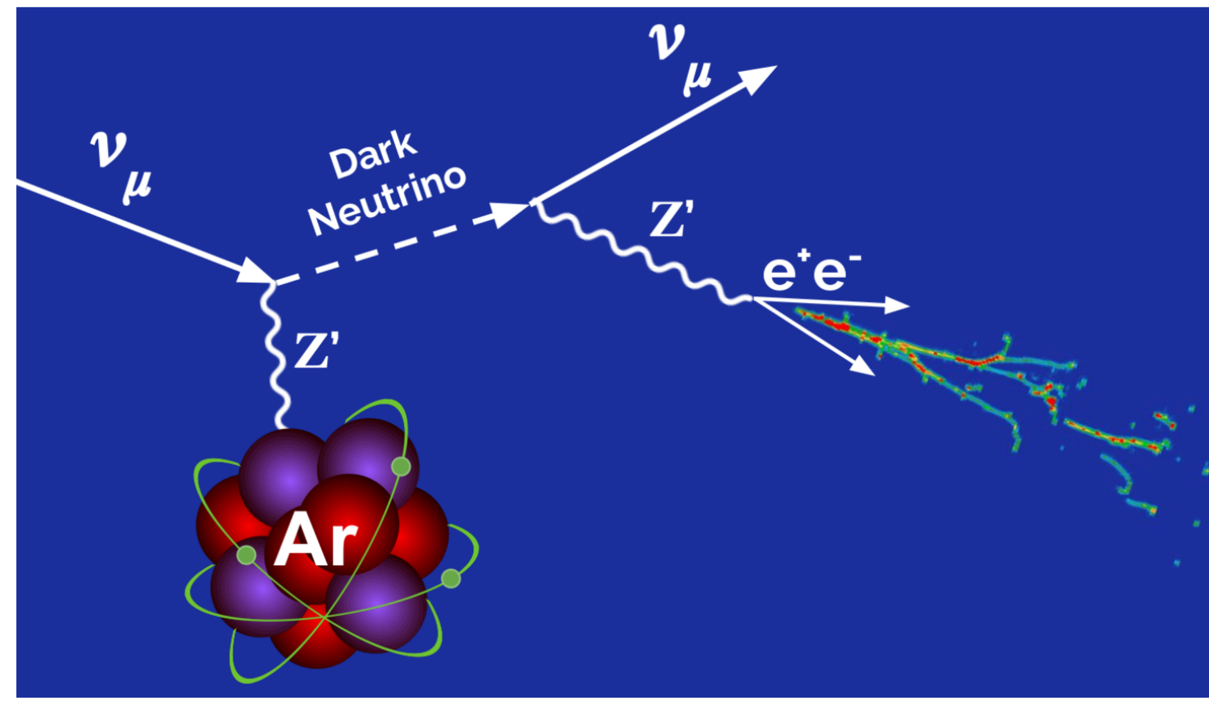


[O.B. Rodrigues, et al, 2503.13594]

MicroBooNE Photon Searches

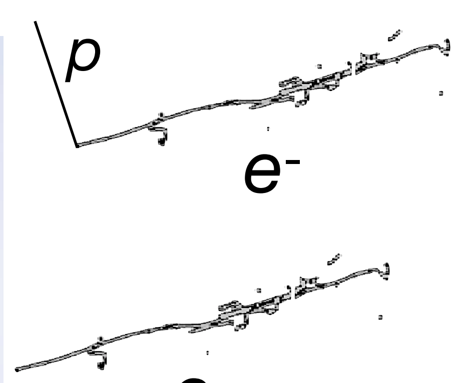
- So if MicroBooNE doesn't see an electron-like excess, does it see a photon-like excess?
    - Both options seem to be attracting equal community attention lately
- **Exclusive MicroBooNE results have turned up 'null' results**
    - Cross-section scenarios: NCΔ 1g decay, NC coh 1g   [MicroBooNE, PRL 128 (2022)](#) [2502.06091](#) [2502.05750](#)
    - BSM scenarios: e+e- pairs from heavy-neutrino-induced up-scattering

[MicroBooNE, 2502.10900](#)



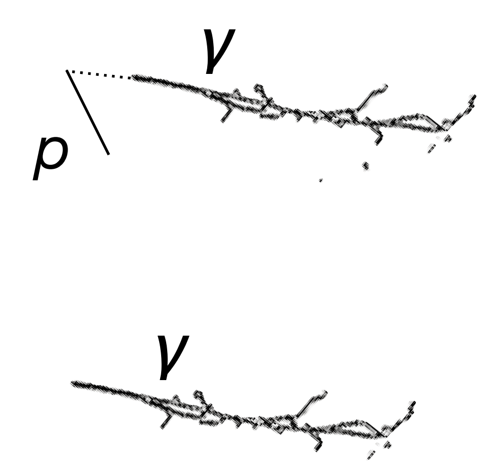
Maybe not

Smoothie Beer



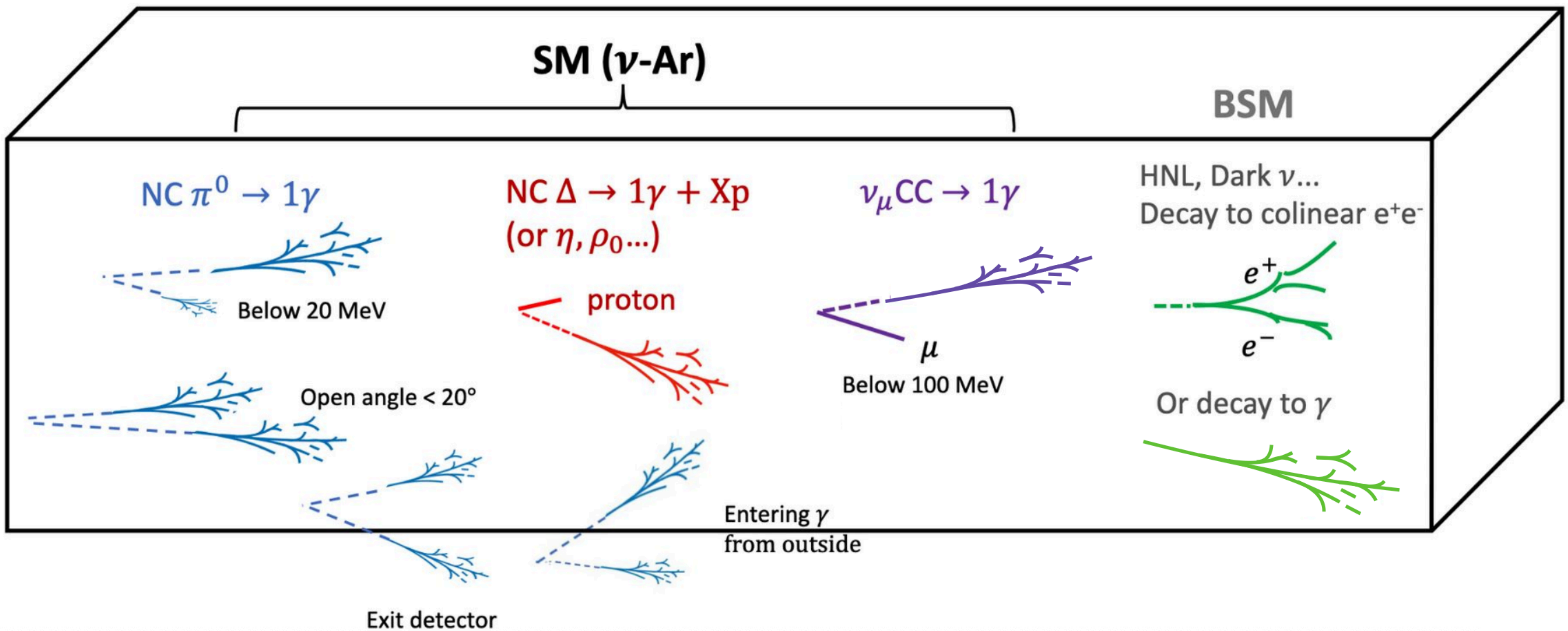
but instead:

Imperial Seltzer!



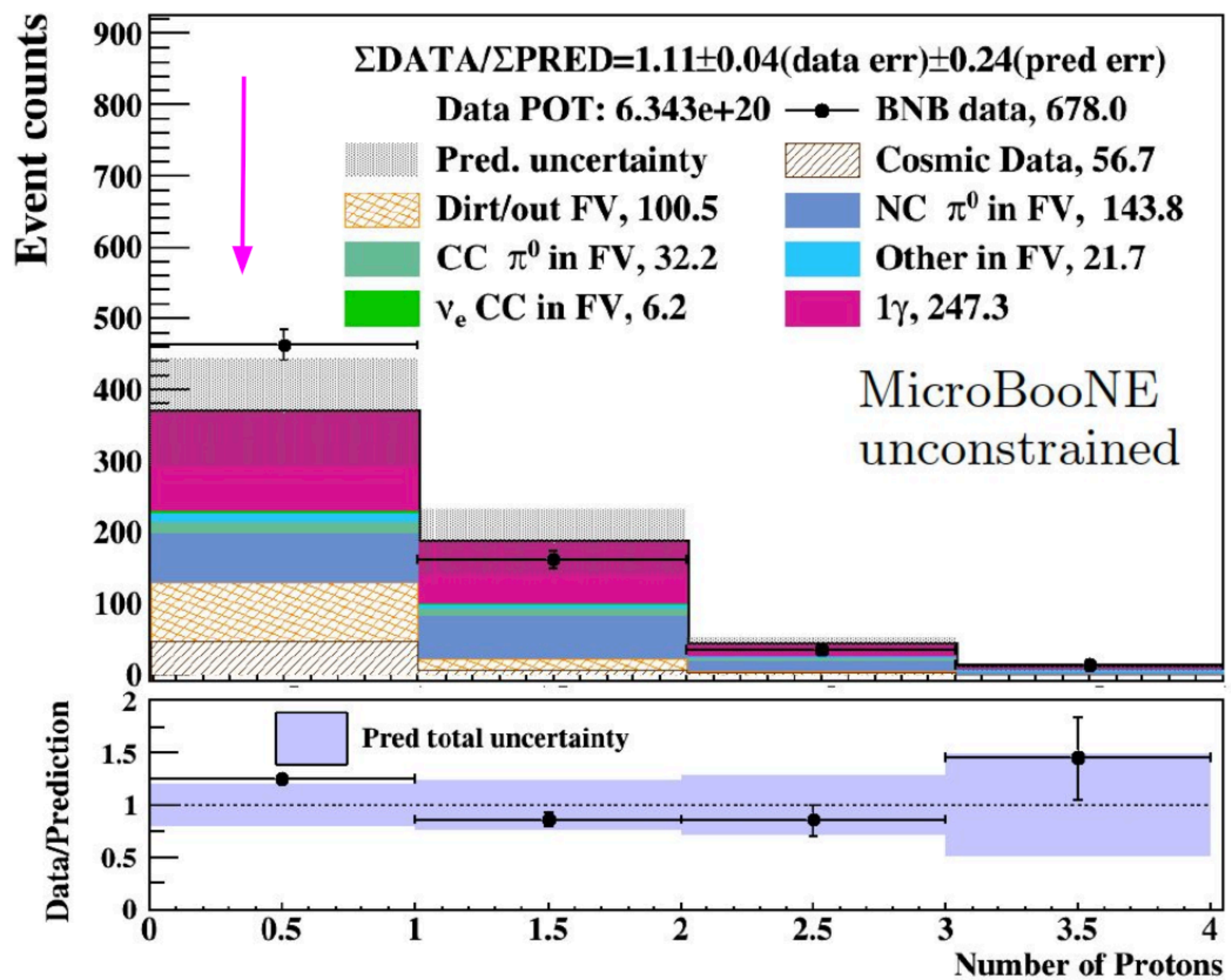
MicroBooNE Inclusive Photon Search

- So if MicroBooNE doesn't see an electron-like excess, does it see a photon-like excess?
- New approach: a model-agnostic inclusive search
  - Let's just look for isolated photons without conjecturing about origins



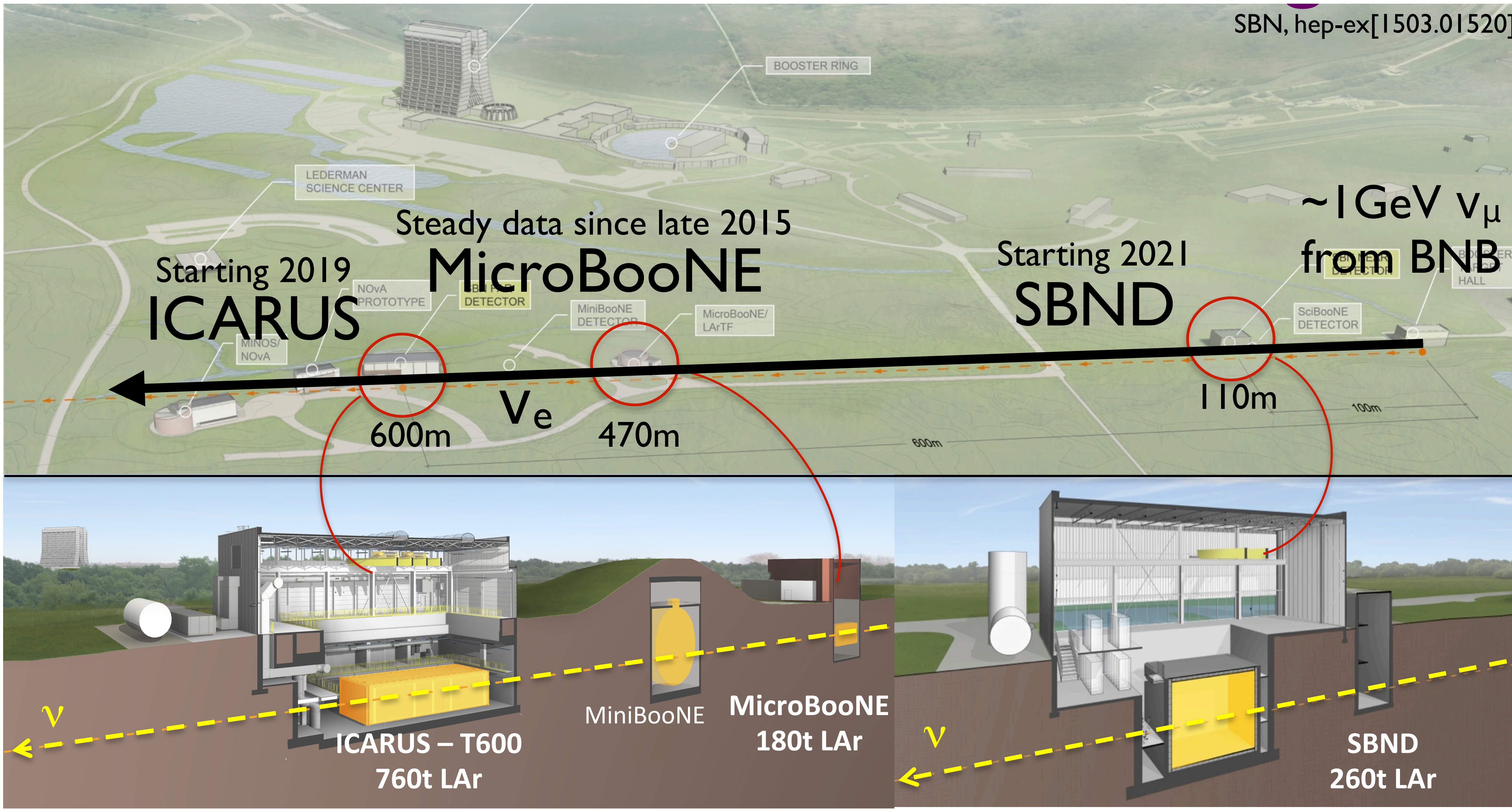
MicroBooNE Photon Searches

- So if MicroBooNE doesn't see an electron-like excess, does it see a photon-like excess?
- New approach: a model-agnostic inclusive search
  - The sample of <600 MeV photon showers accompanied by no other protons, shows a 2.2σ statistically significant deviation from GENIE-derived predictions
  - A follow-up investigation will:
    - Use all MicroBooNE data, doubling available stats
    - Combine stats from different reconstruction pathways
    - Explore details of selected 1g0p: proton proximity, edge location
    - Incorporate low-energy 'blip' reconstruction, and new sensitivity to final-state neutrons and lower-energy protons



Looking Forward: Fermilab SBN

- FNAL SBN will test a vast array of MiniBooNE explanations: flavor transformations, BSM particle production, and more.
- 3 of 3 detectors have physics quality data. Stay tuned!



Conclusions

- The experimental case for a 'vanilla' 3+1 sterile neutrino is in retreat after new results from multiple experiment sectors
  - New results in the past year from PROSPECT and KATRIN leave little space for an observed reactor flux deficit, Neutrino-4, or the Gallium Anomaly to be explained by oscillations from a single sterile neutrino state.
  - MicroBooNE's existing BNB electron-neutrino results disfavor the entire MiniBooNE 95% CL 3+1 allowed region at >95% CL
- These developments must <u>shift</u> (<u>not</u> end) the community's pursuit of new physics in the short-baseline neutrino space
  - MicroBooNE, in its inclusive single-photon analysis, has seen a first hint that MiniBooNE's excess may in fact be photon-like in nature.
  - The reactor-gallium tension exists! WHY/HOW?
  - Phenomenologists have sketched a colorful, multifaceted 'anomaly landscape' of individual or multiple competing BSM effects that experiments should explore!

Conclusions

- Many experiment sectors have a role to play in contributing to the resolution of the neutrino anomalies:

1 - Short-Baseline Neutrino

- Direct MiniBooNE test.
- Access to rich hidden sector in $>$ GeV beam.
- Two-beam osc capabilities.

2 - DUNE

- Highest ν/BSM flux.
- High beam energy.
- PRISM ND concept.

3 - IceCube

- Probe non-standard matter effects.
- Very high energy ν's also accessible

6 - JSNS^2

- Direct LSND test.
- Access to rich 'lowmass' hidden sector.
- Probe LFV models.

5 - Reactor

- Pure e-flavor.
- Low (MeV) ν energies.
- Pure probe of vacuum oscillations.

4 - Sources

- Direct Gallium Anomaly Test.
- Pure e-flavor.
- Lowest ν energy.

Thanks for Listening!

Thanks!

Neutrinos!

+

Sconnie Brews!

New Glarus Brewing Co. · Only in Wisconsin ·

Great Dane Pub & Brewing Est. 1994

Young Blood Beer Co.

Working Draft Beer Company

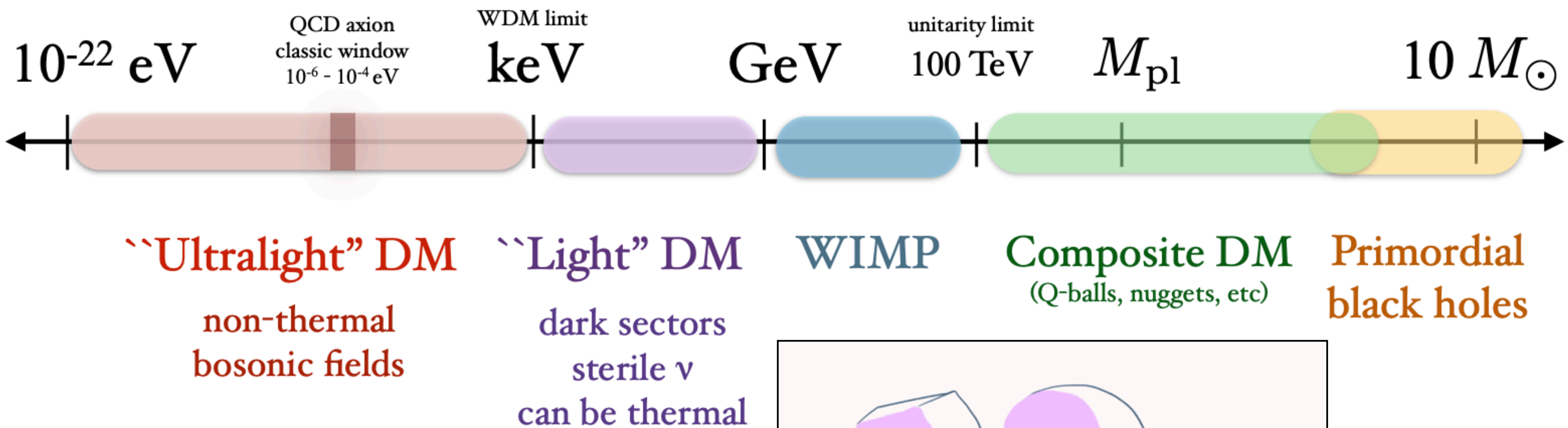
The Brewing Projekt

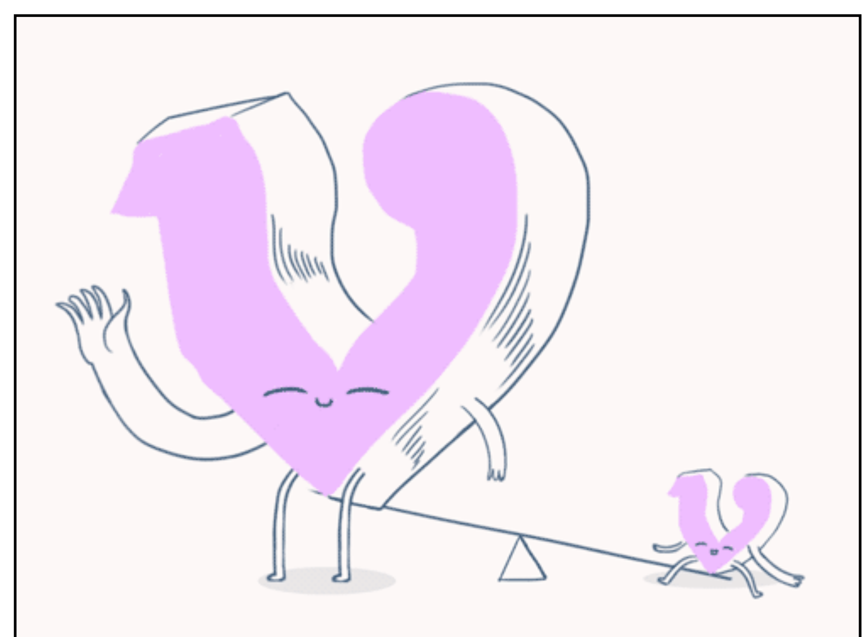
Untitled Art.

Backup

New Neutrino Mass States?

- Other good reasons to look for new mass states:
  - Cosmic dark matter: could heavy neutral leptons be a candidate?
  - See-saw mechanism: heavier neutral leptons help explain why SM neutrinos are so light?





PROSPECT-II

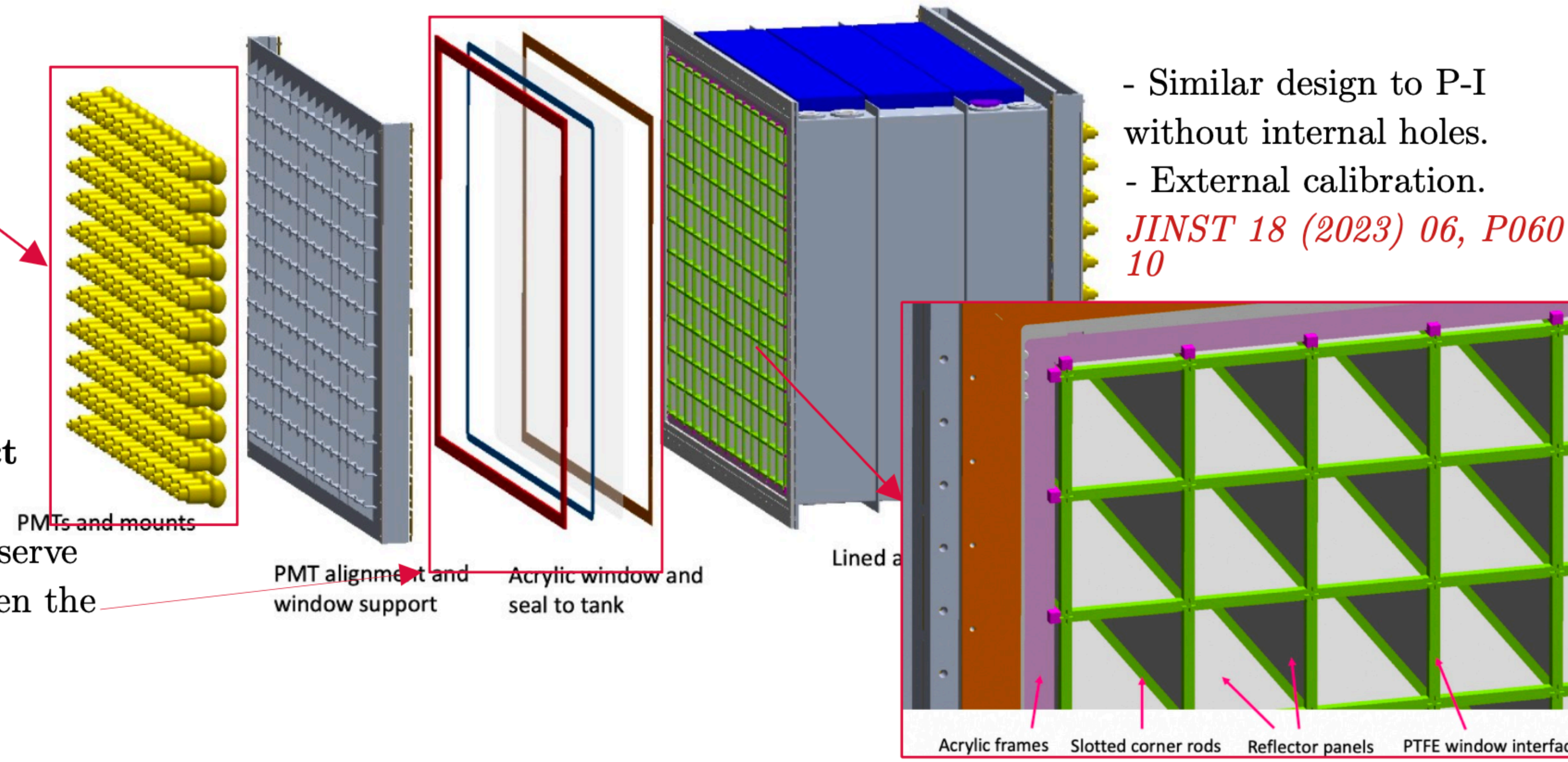
PROSPECT-II Detector

Improving stability and performance of the detector to achieve these goals.

Avoid PMT exposure to the liquid scintillator:
- Separate PMTs from LiLS.

- Similar design to P-I without internal holes.
- External calibration.

JINST 18 (2023) 06, P06010



Minimize the LiLS contact with other materials:
- Thin UVT acrylic windows serve as the optical interface between the PMTs and LiLS.
- Double-layer seal design.

PROSPECT-II

PROSPECT

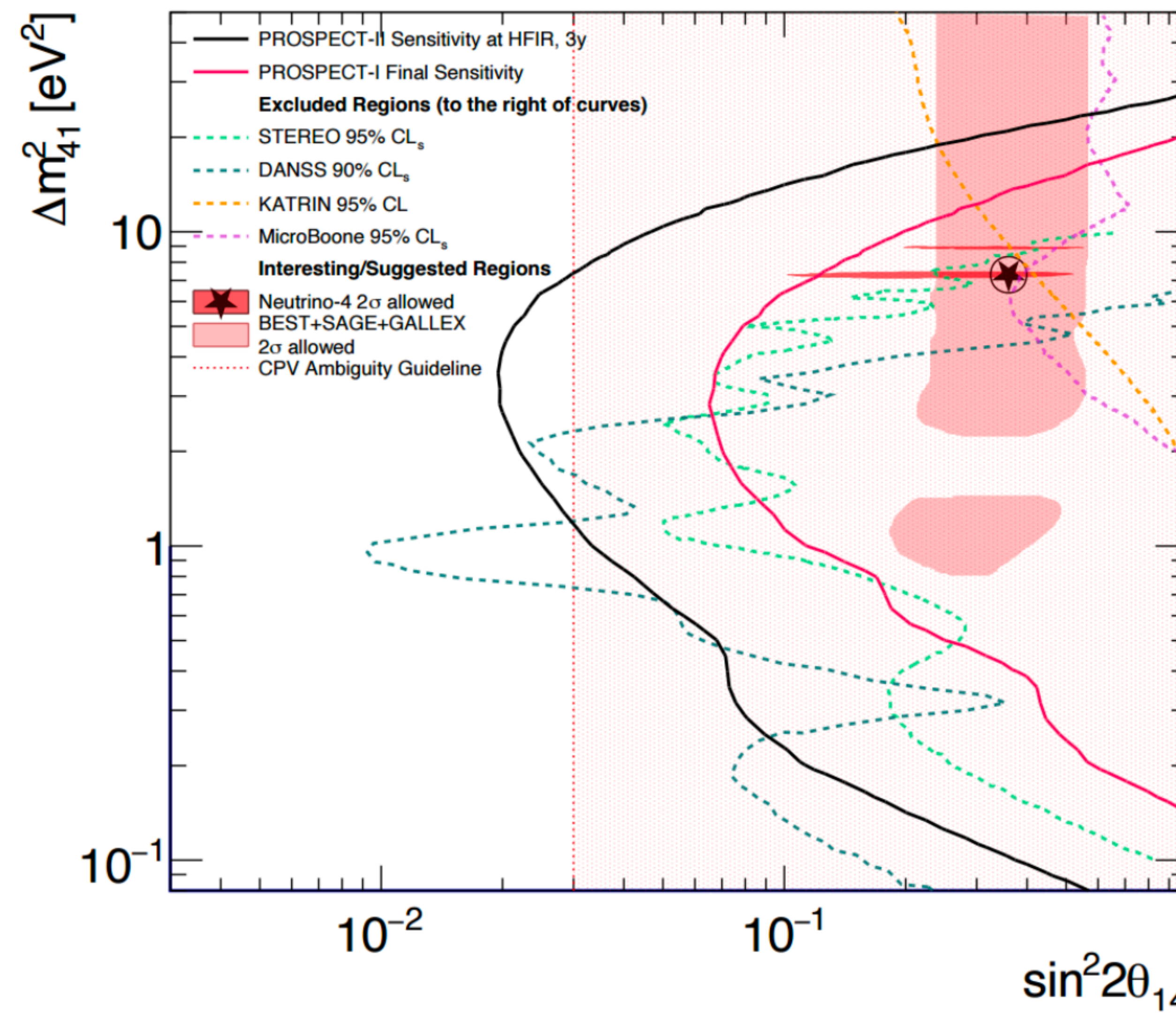
ILLINOIS INSTITUTE OF TECHNOLOGY

PROSPECT-II Projected Sensitivity

F. Machado - IIT

Deployment at HFIR will address the remaining interesting oscillation phase space.

- Address Neutrino-4 allowed sterile neutrino observation at high mass splitting.
- Cover the Gallium Anomaly below ~15 eV^2.
- Constraint the mixing angle Θ_{14} in between 1-10 eV^2 for the long baseline CP violation interpretation.
- Unmatched performance below 20 eV^2 compared to accelerator based experiment.
- P-II exceed P-I sensitivity by a factor of 3-5.



BEST-2

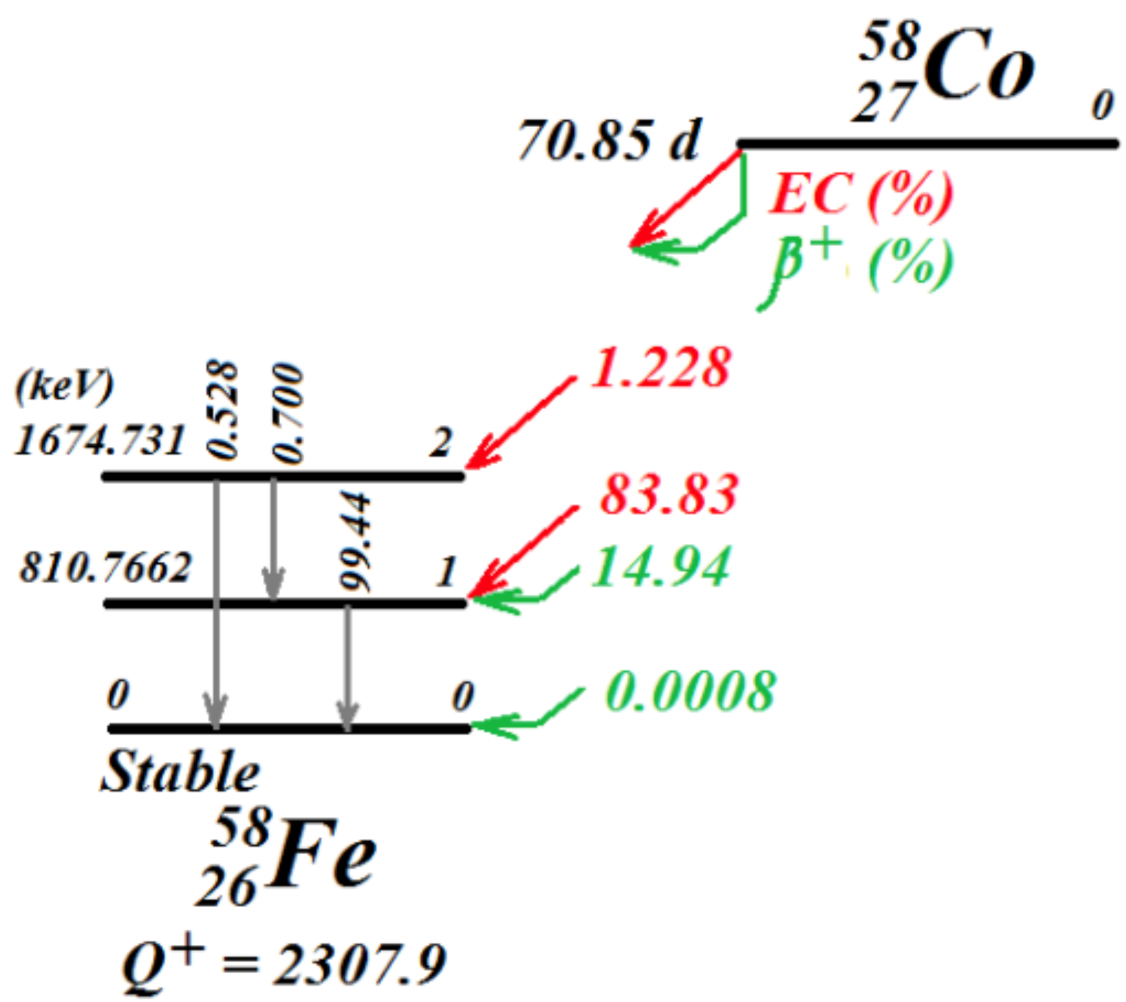
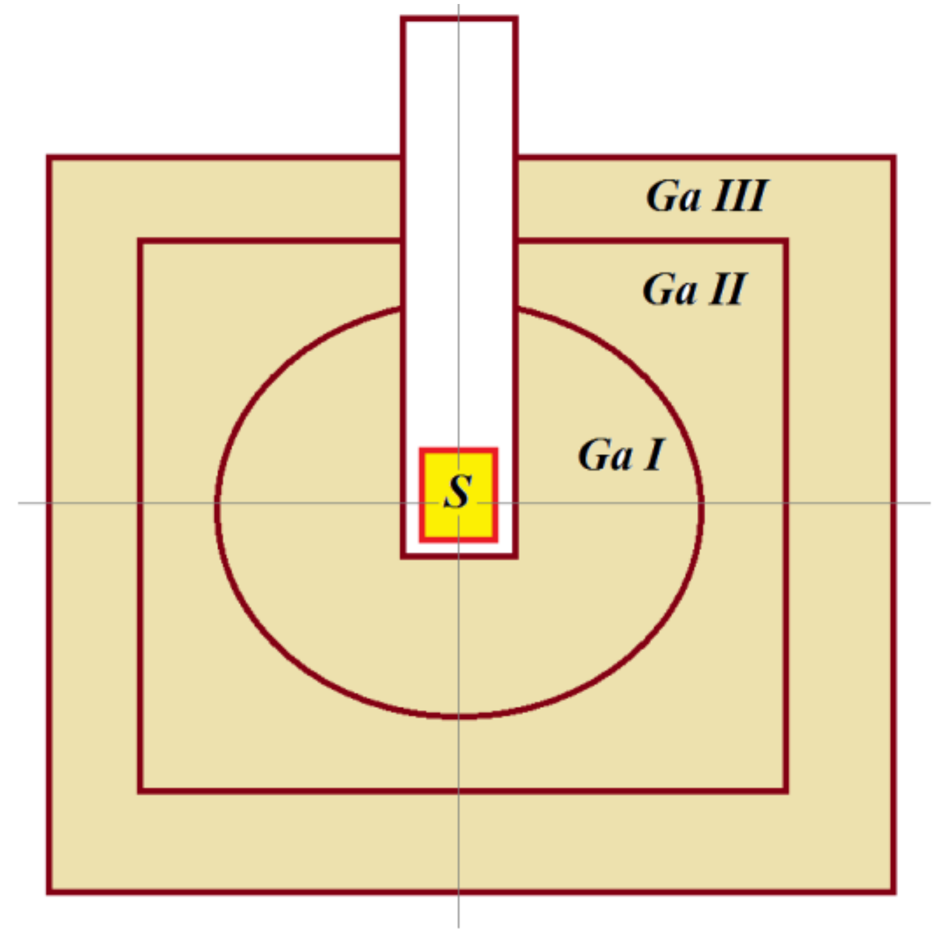
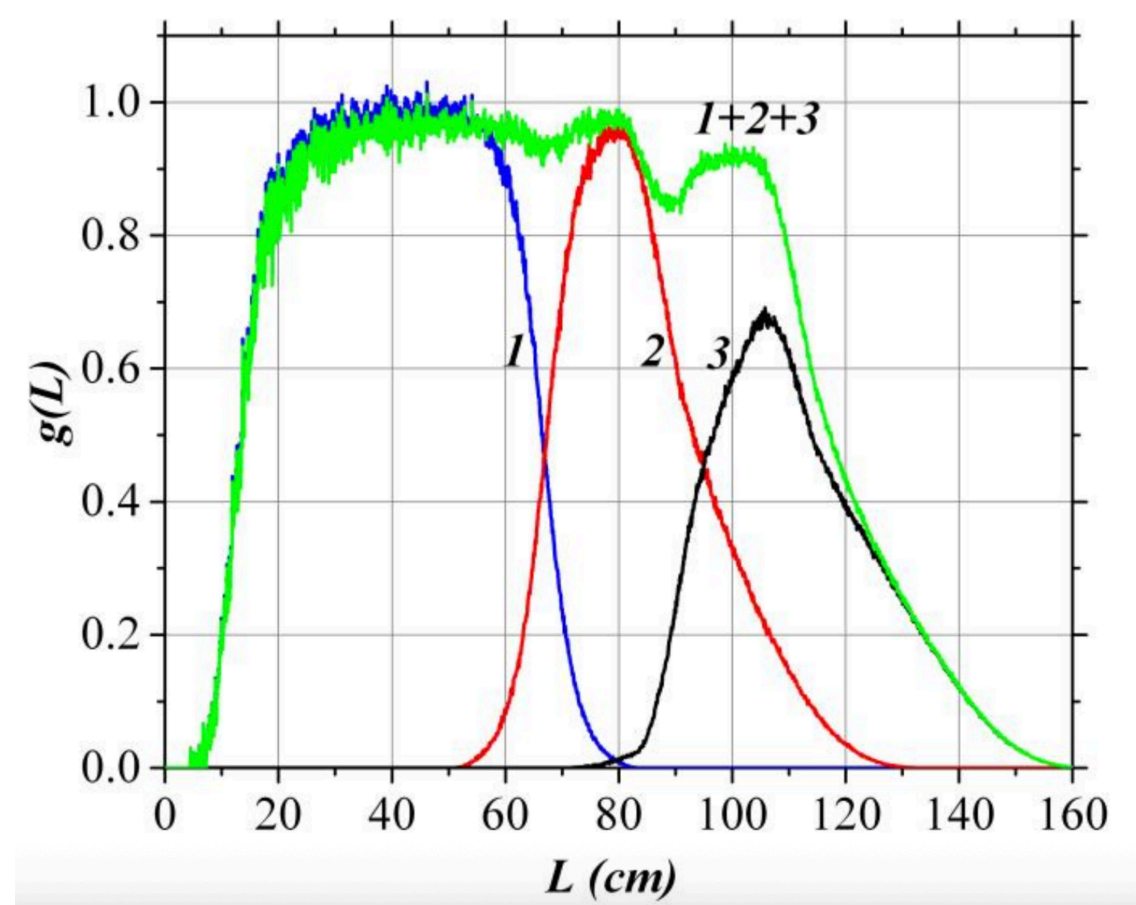
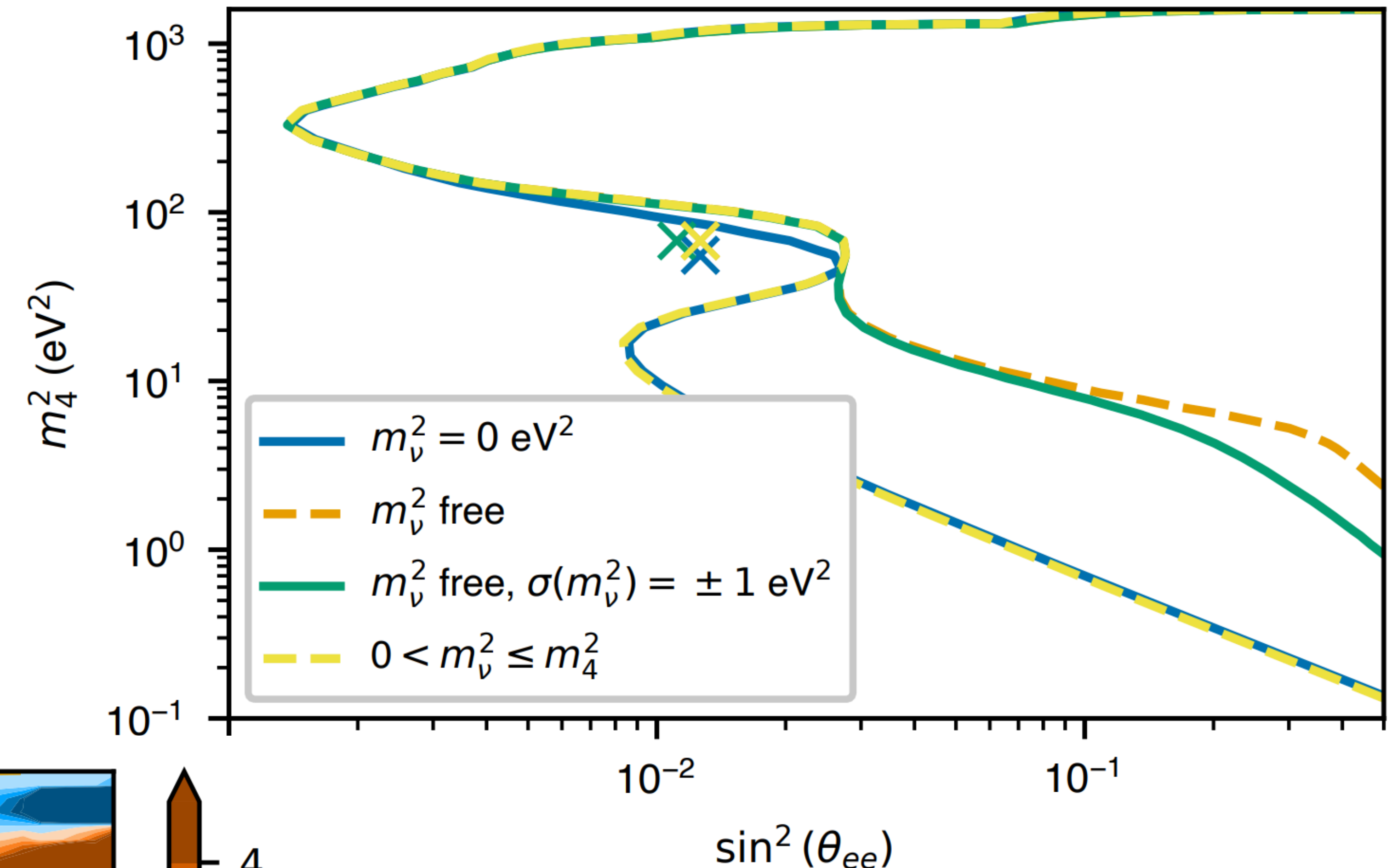


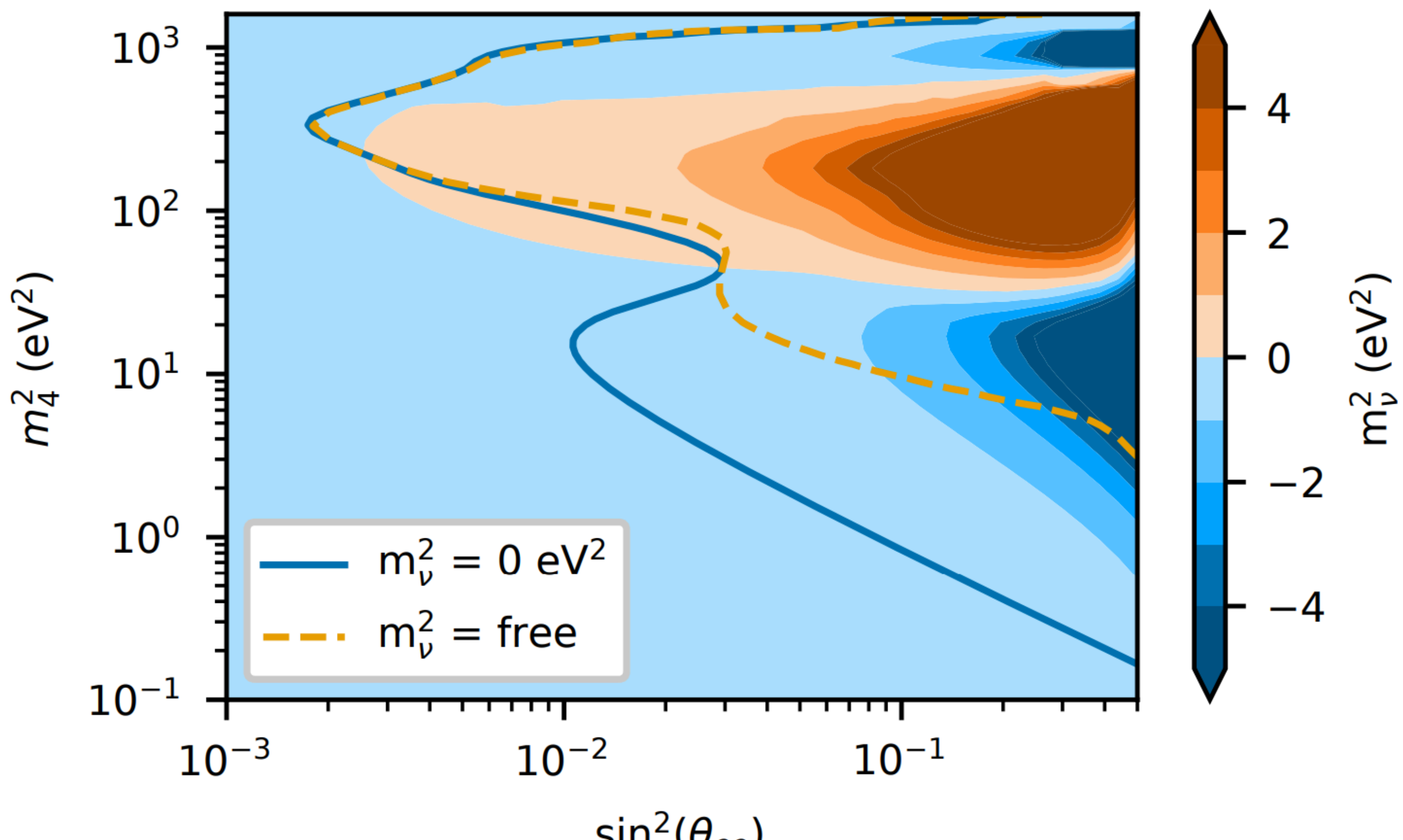
Fig.2. Decay scheme of ^{58}Co.





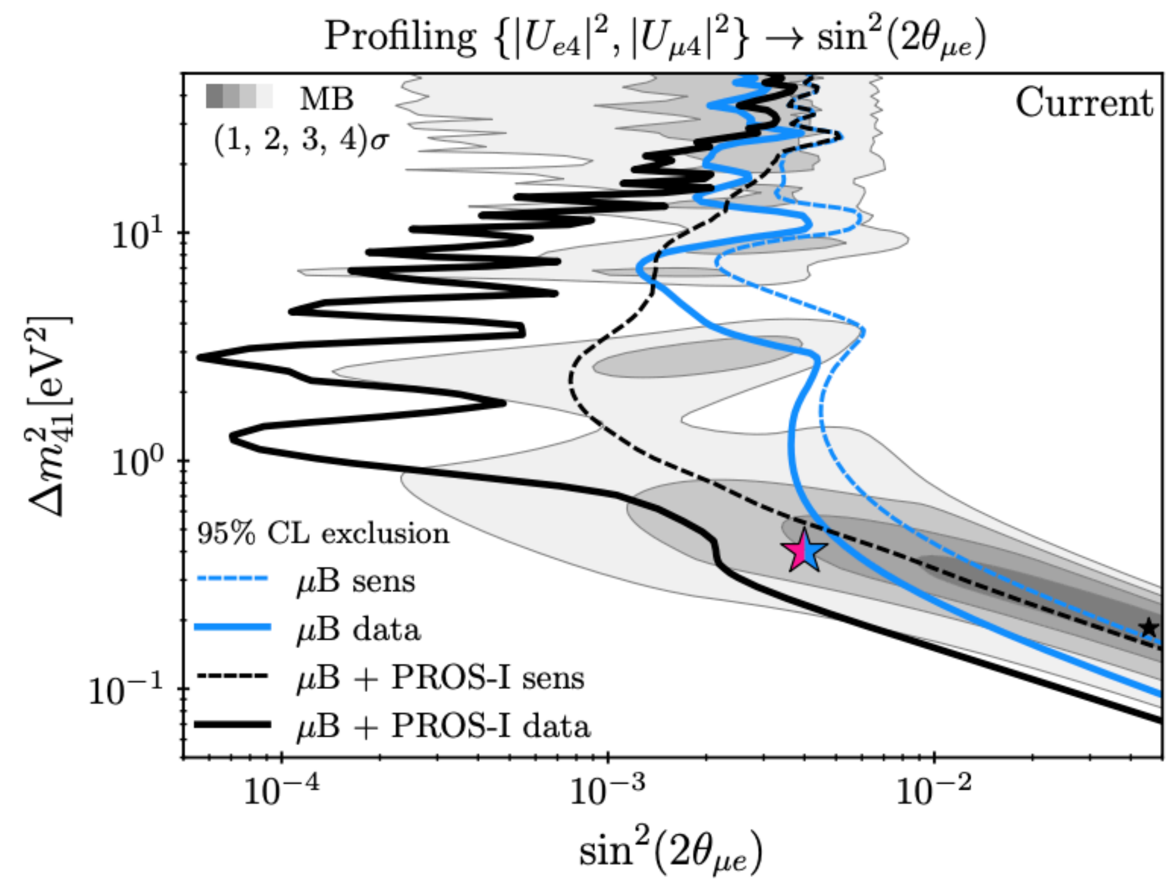
KATRIN: Free m_nu Fits

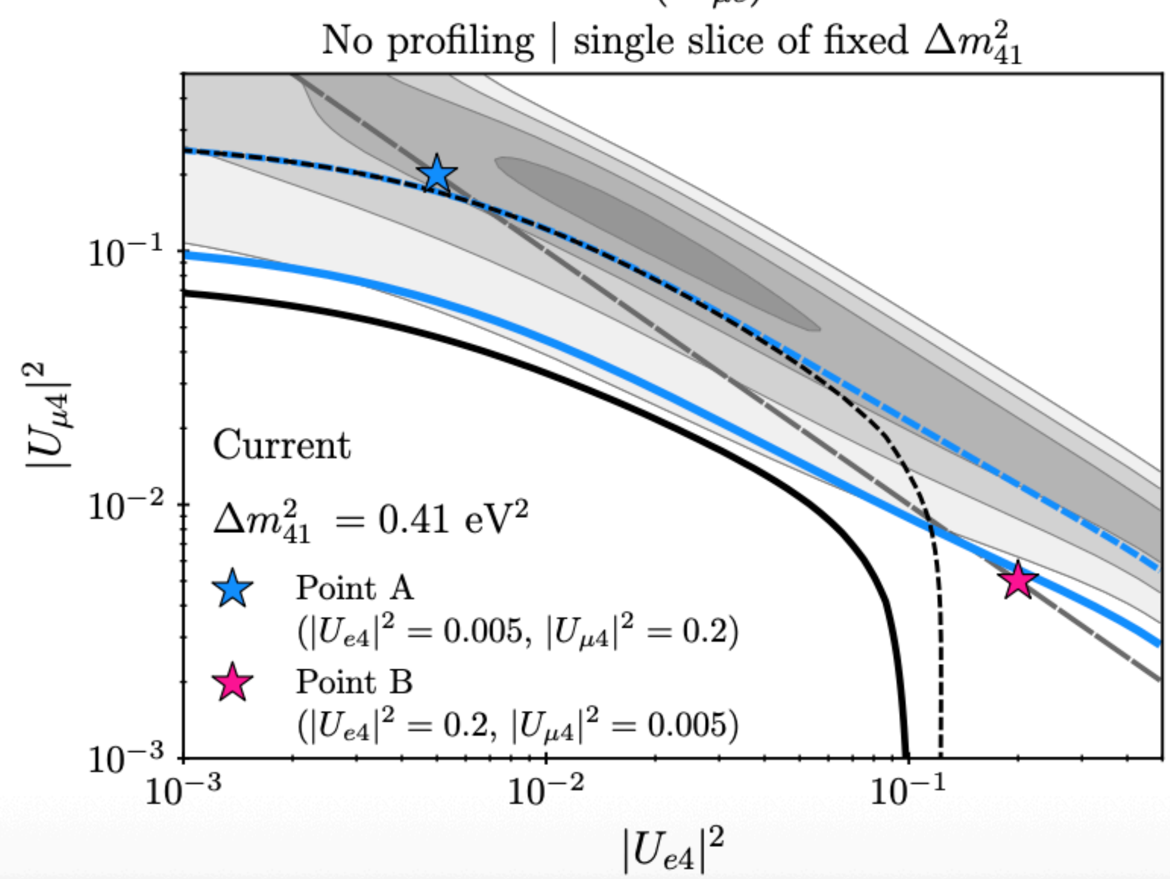


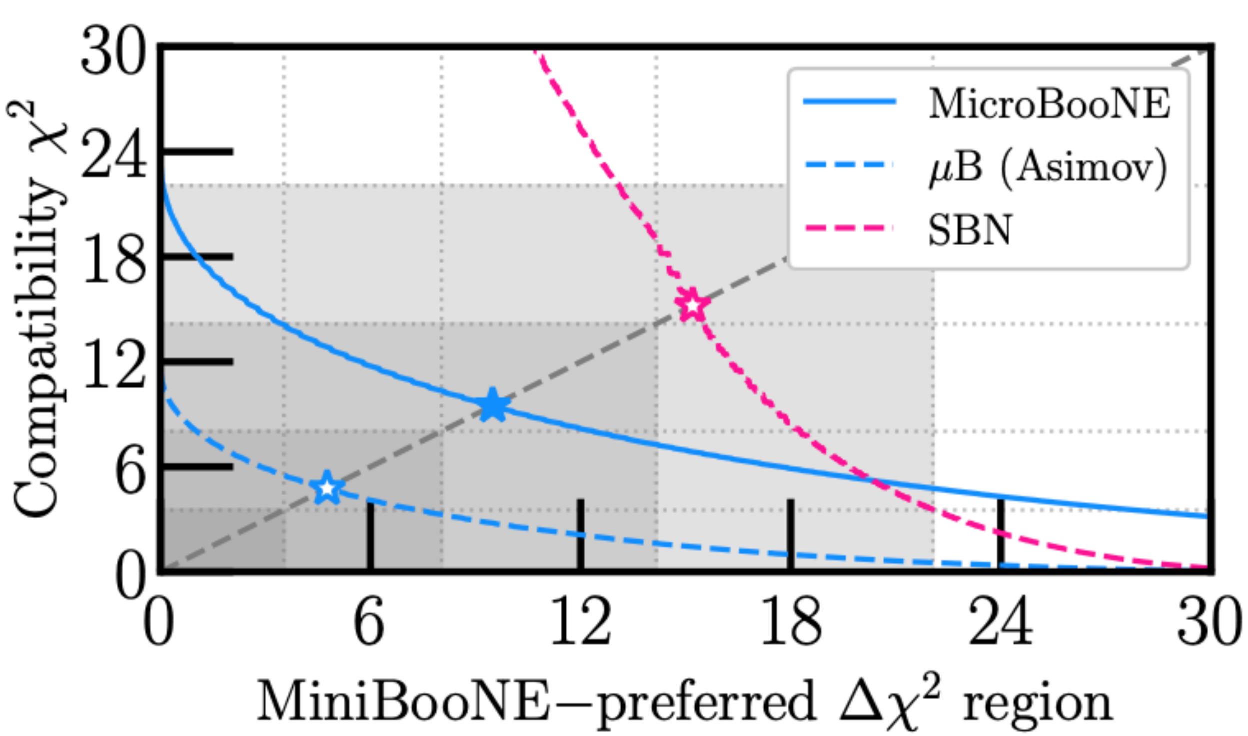


3D Oscillation Space Slices

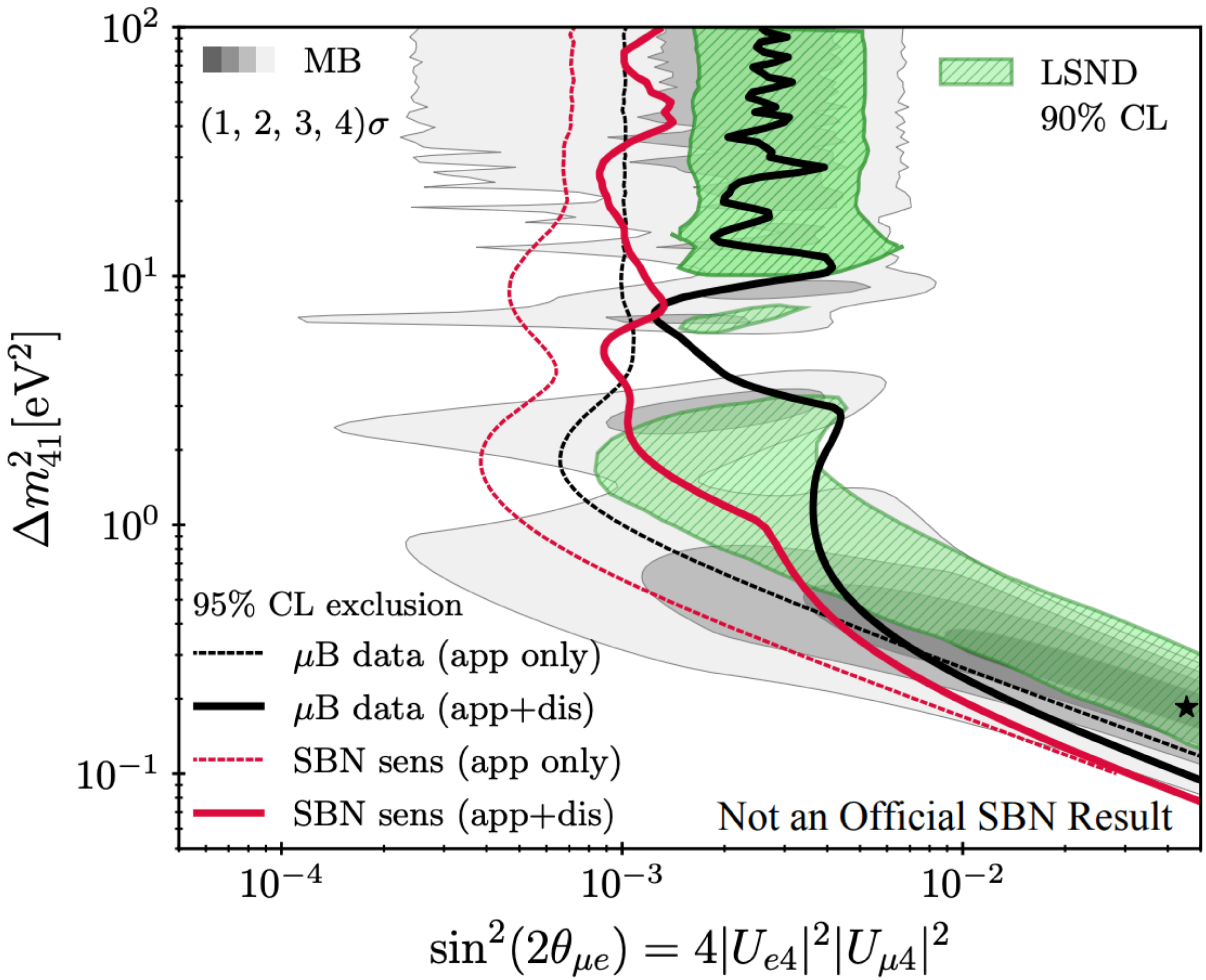
- 2D profiling gives some incorrect indications
- Zooming out to 3D space corrects this confusion



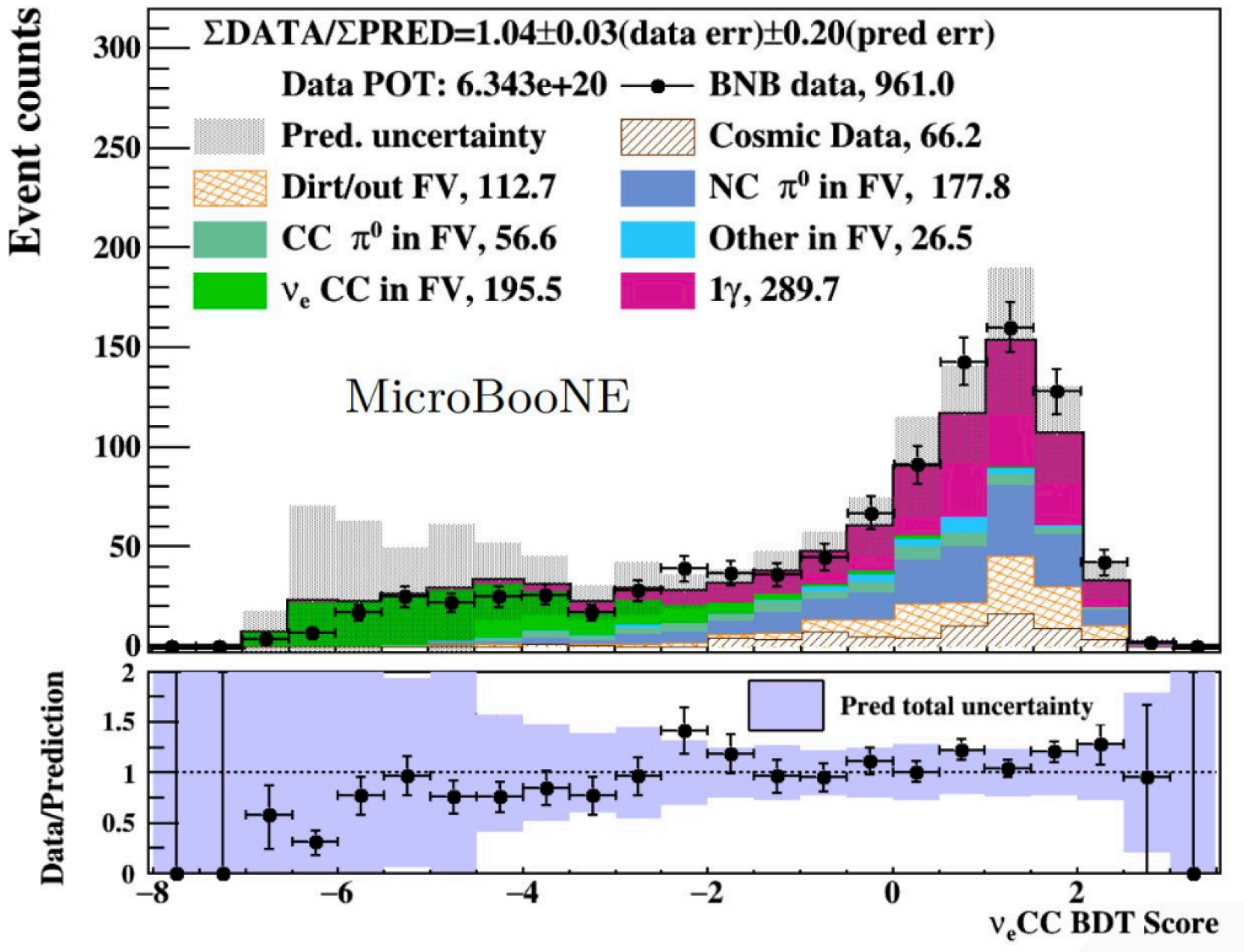




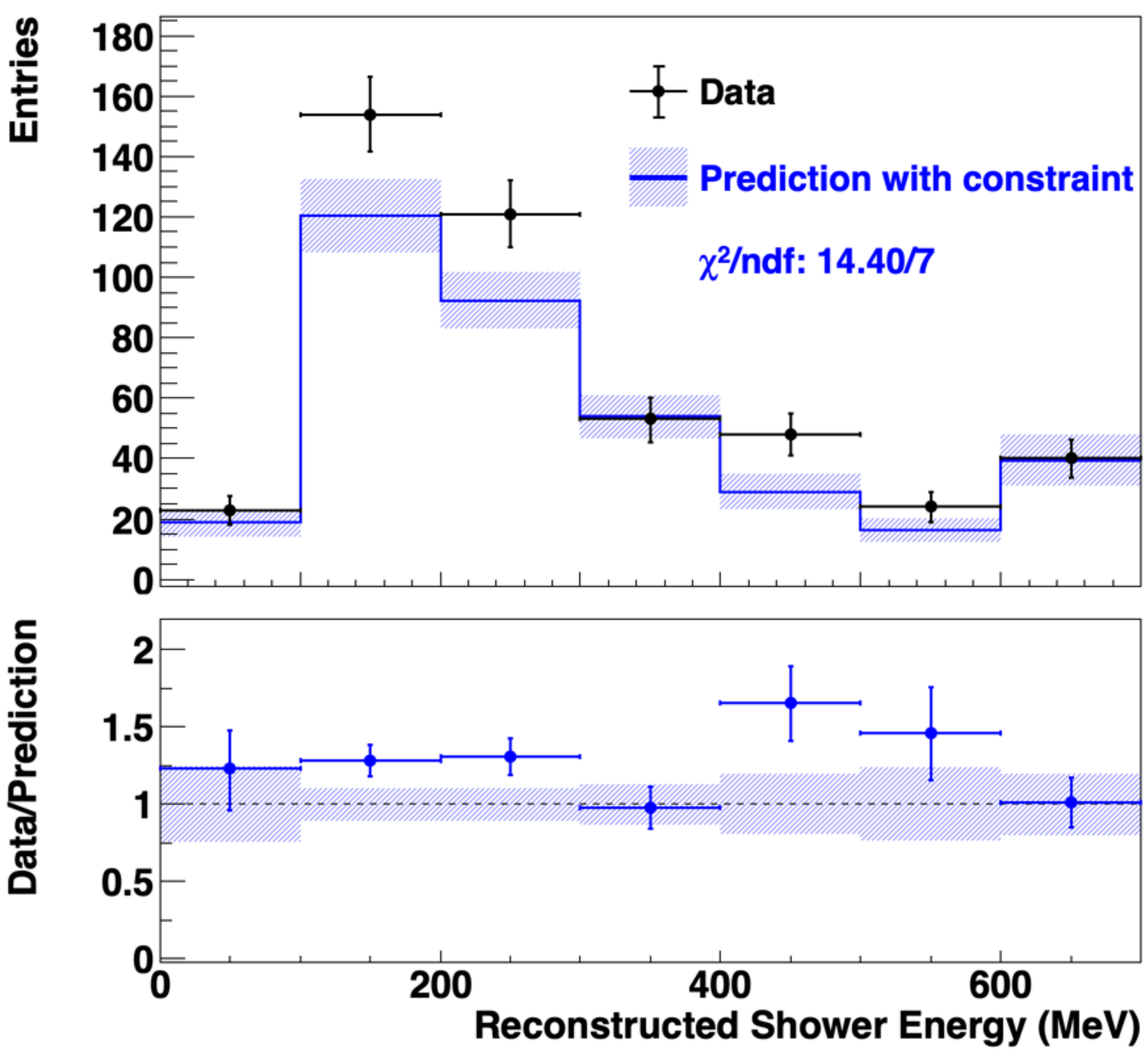
Fake ‘Bad’ Profiled Sensitivities

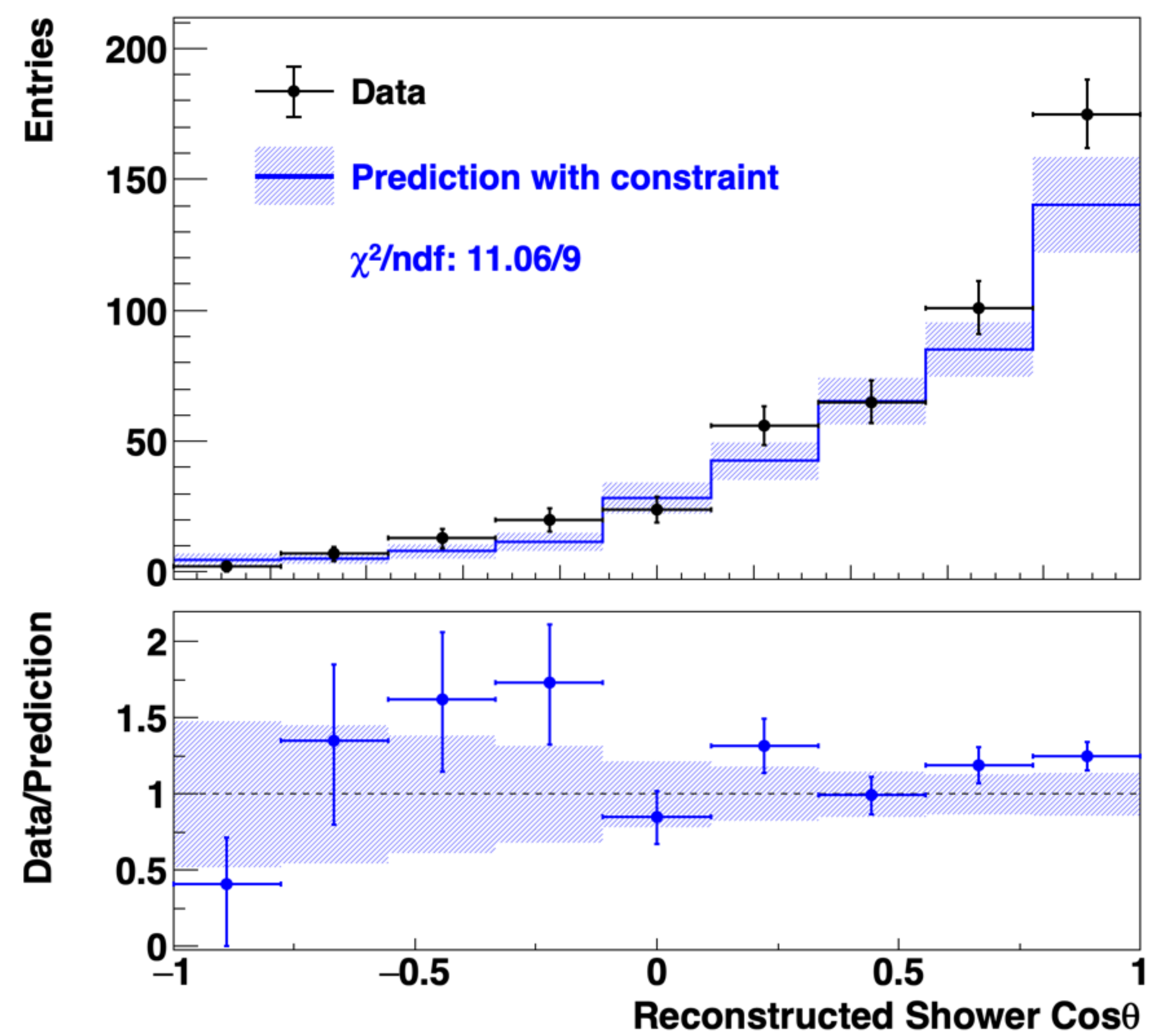


Shower Excess: Full BDT Spectrum

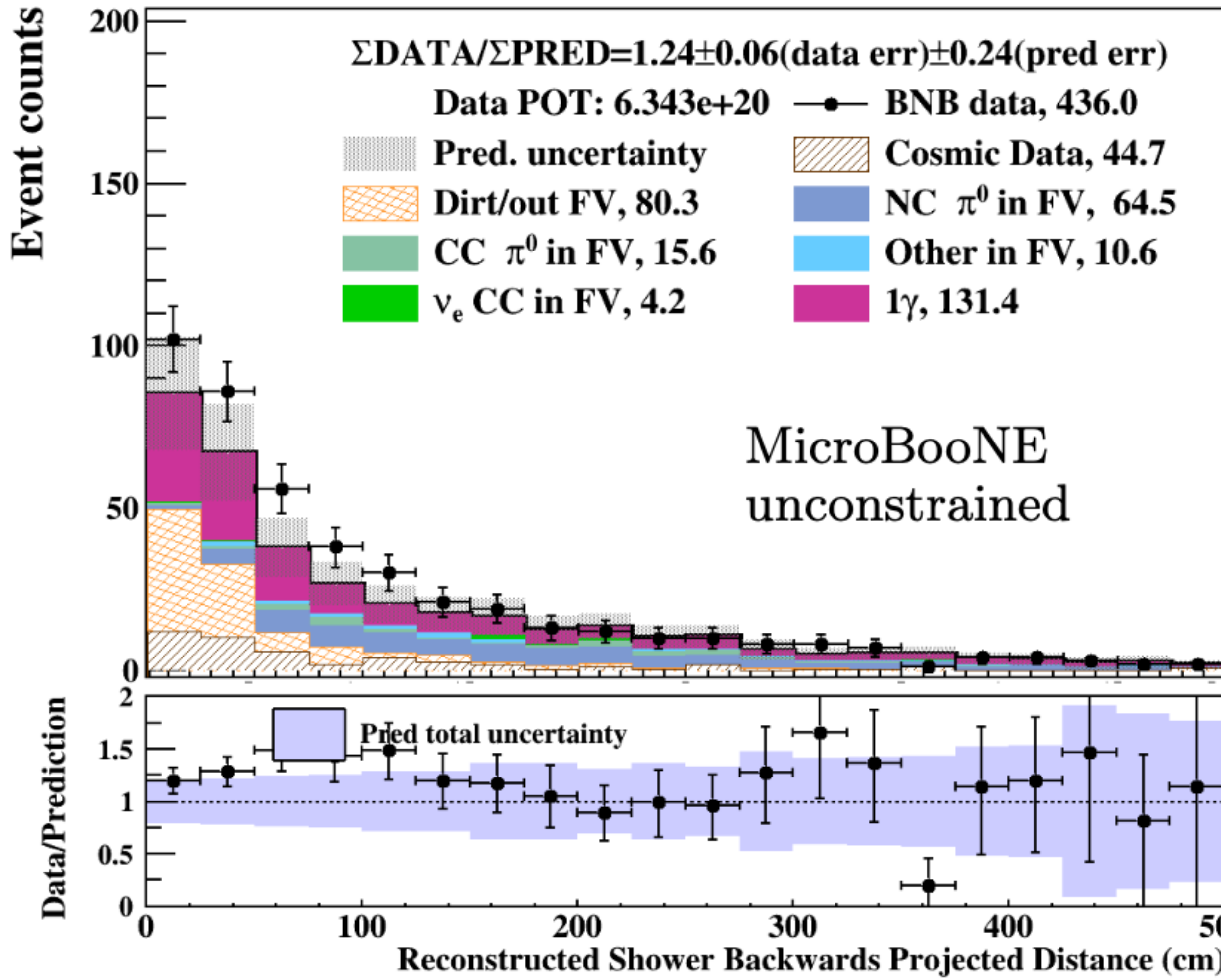


0p Excess: Digging into the Cross-Tabs





0p Excess: Digging into the Cross-Tabs

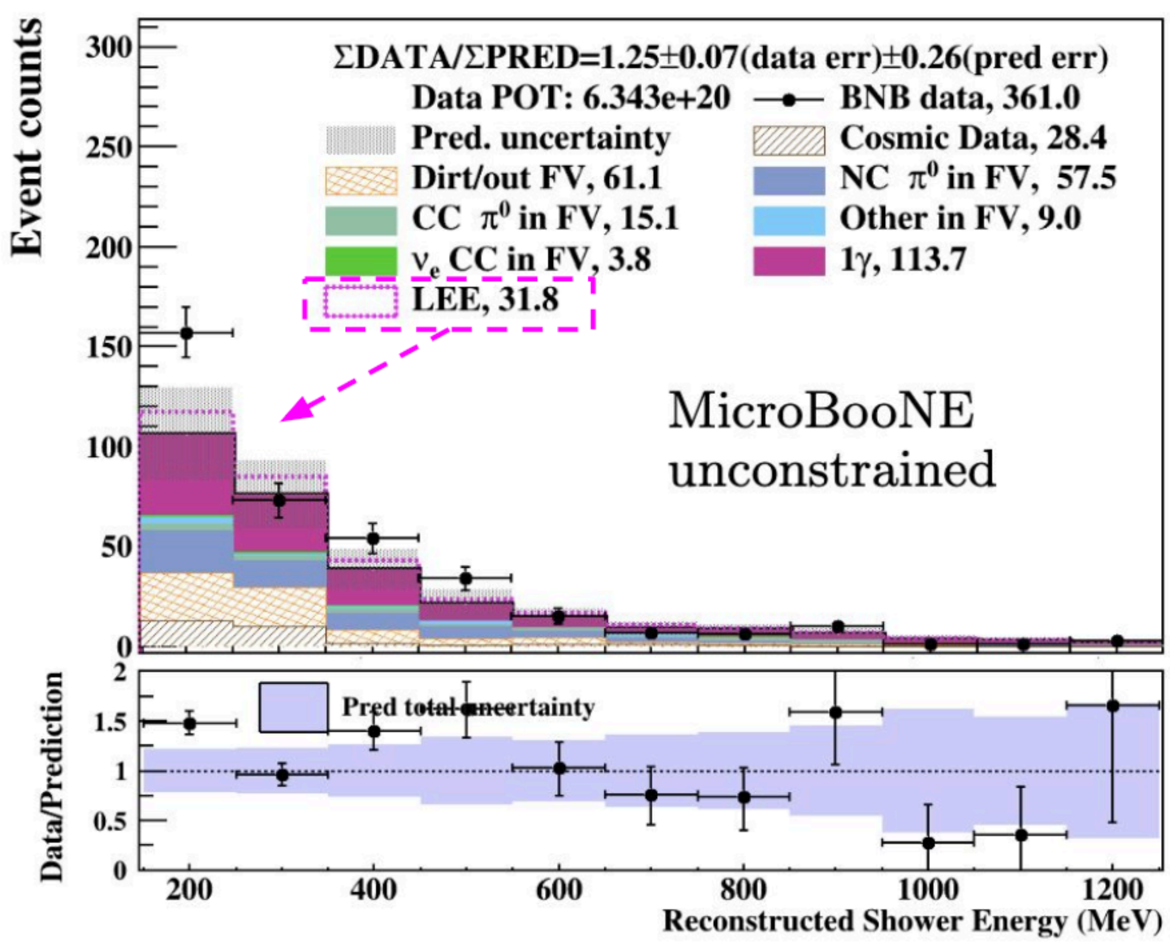


A MiniBooNE Excess Toy Model

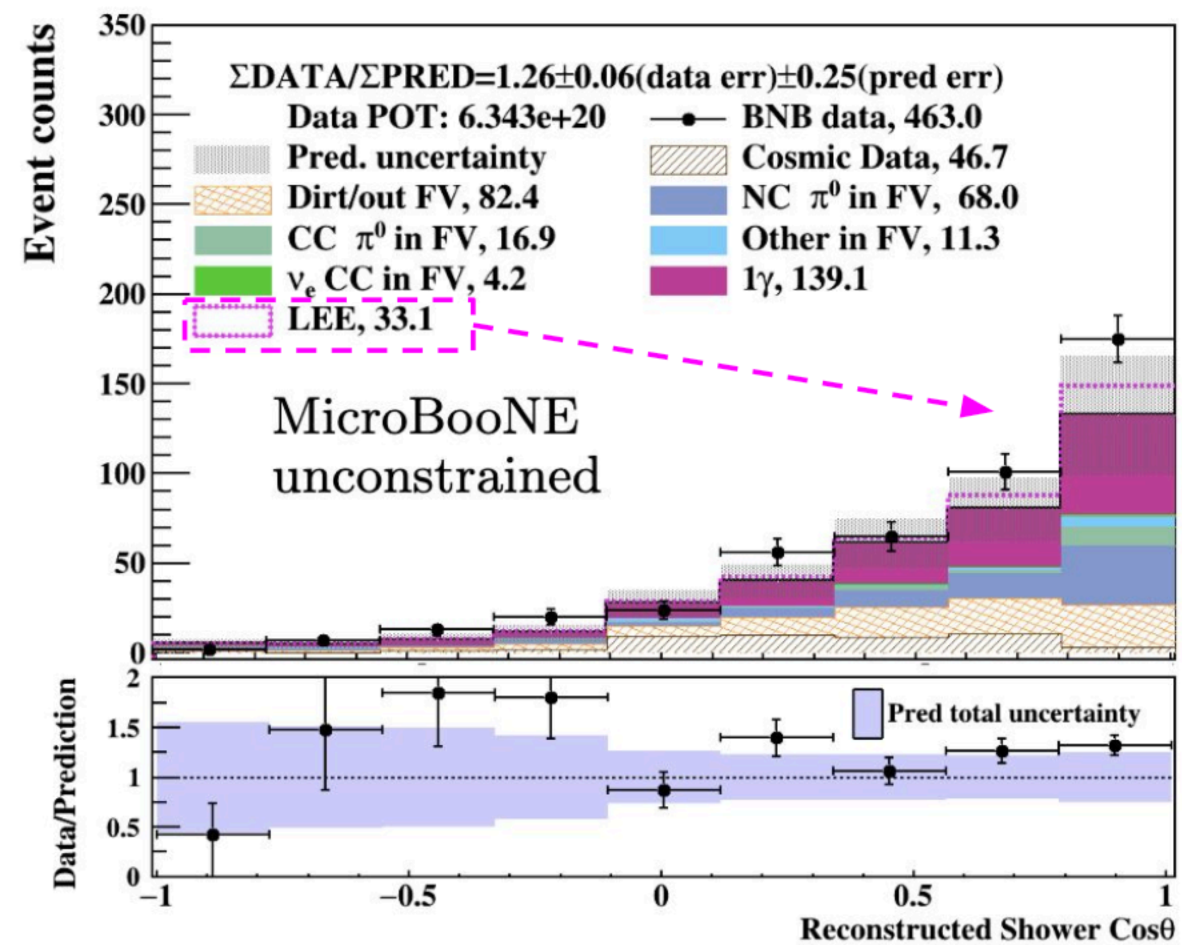
1. A neutrino interaction with target nucleons: Scale by mass (number of nucleons)

Observed excess of 93 events > 33 event excess predicted using this scaling assumption

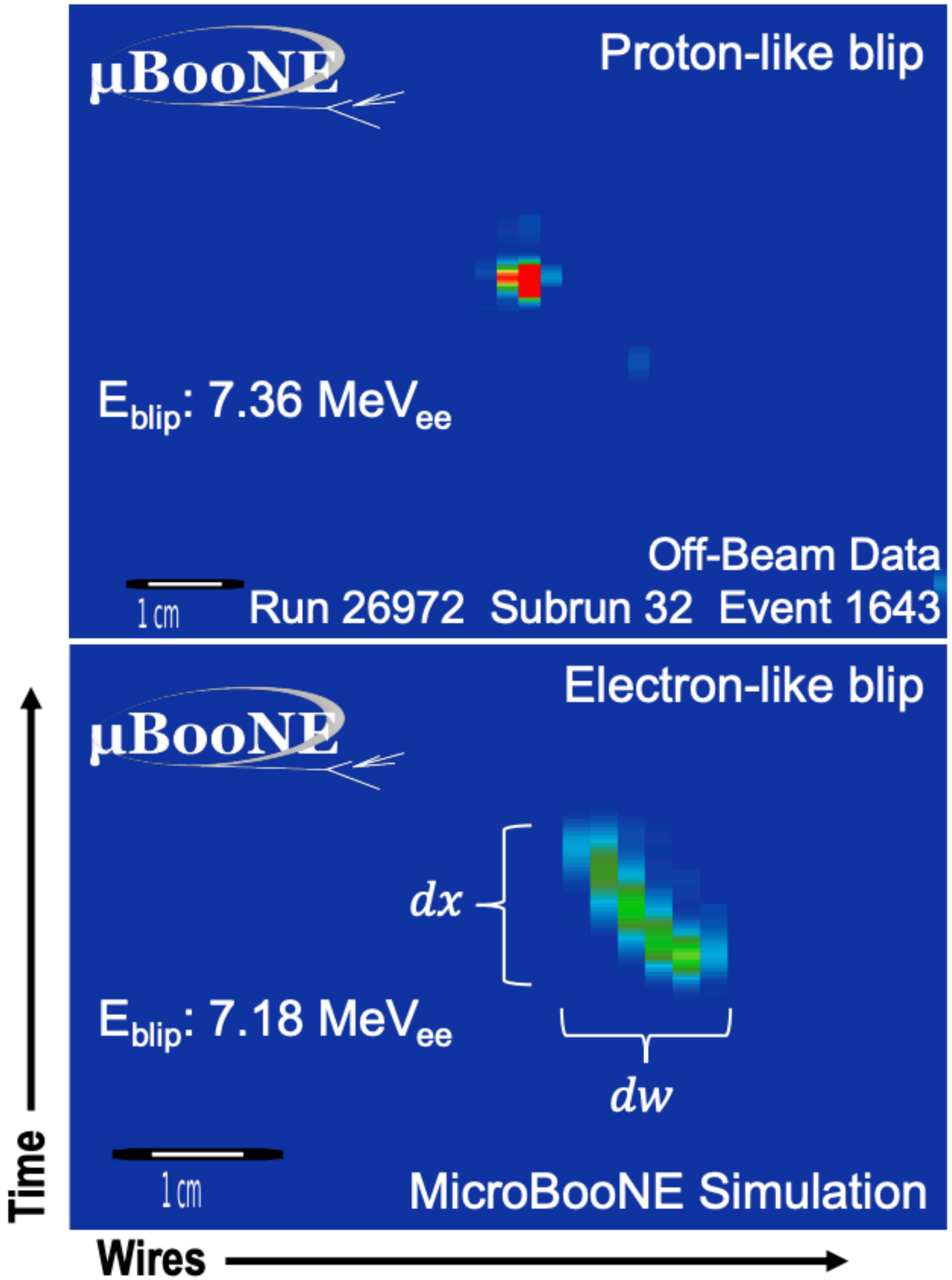
Shower Energy



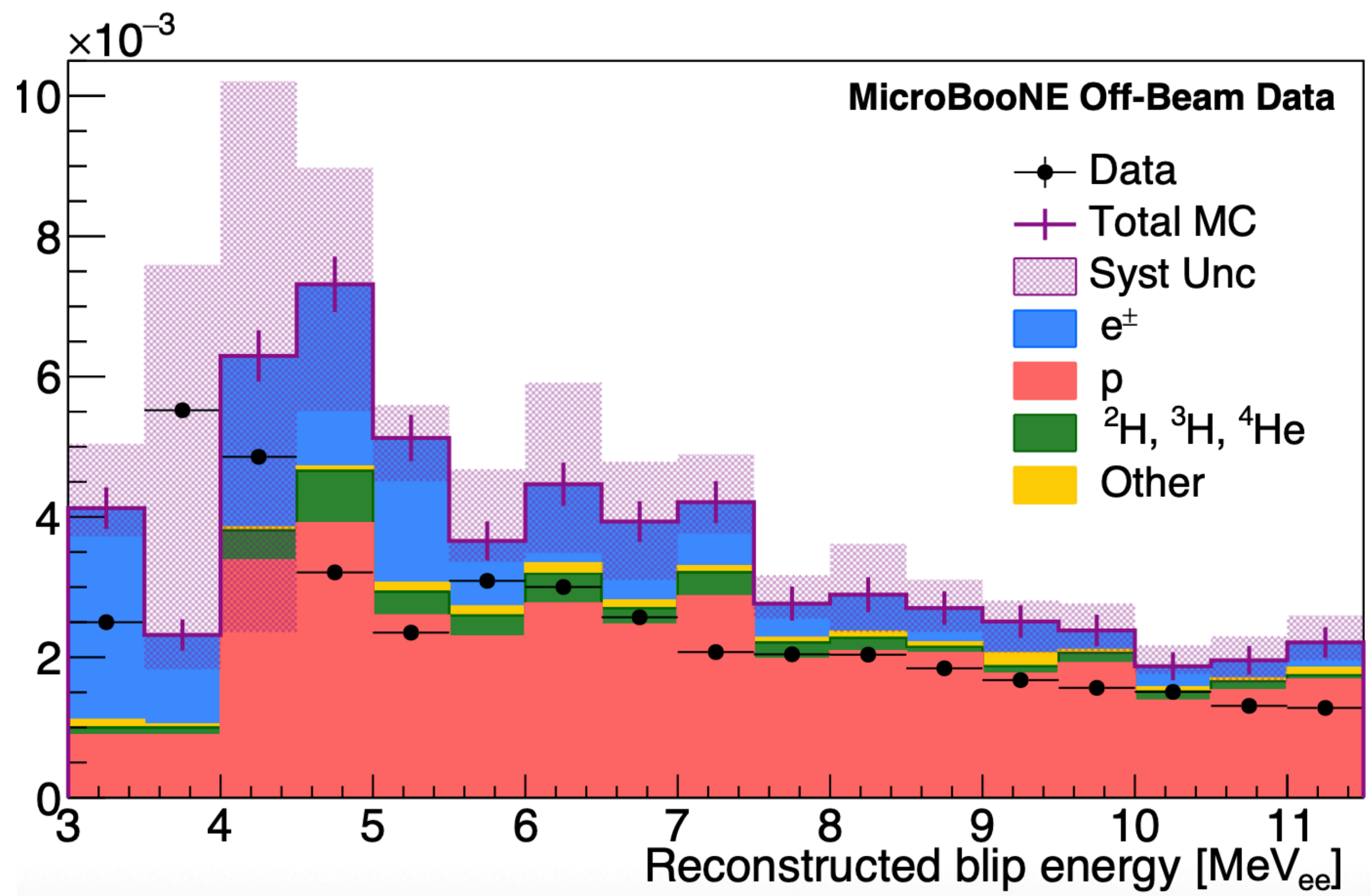
Shower Angle



Blips



MicroBooNE: Cosmic Data

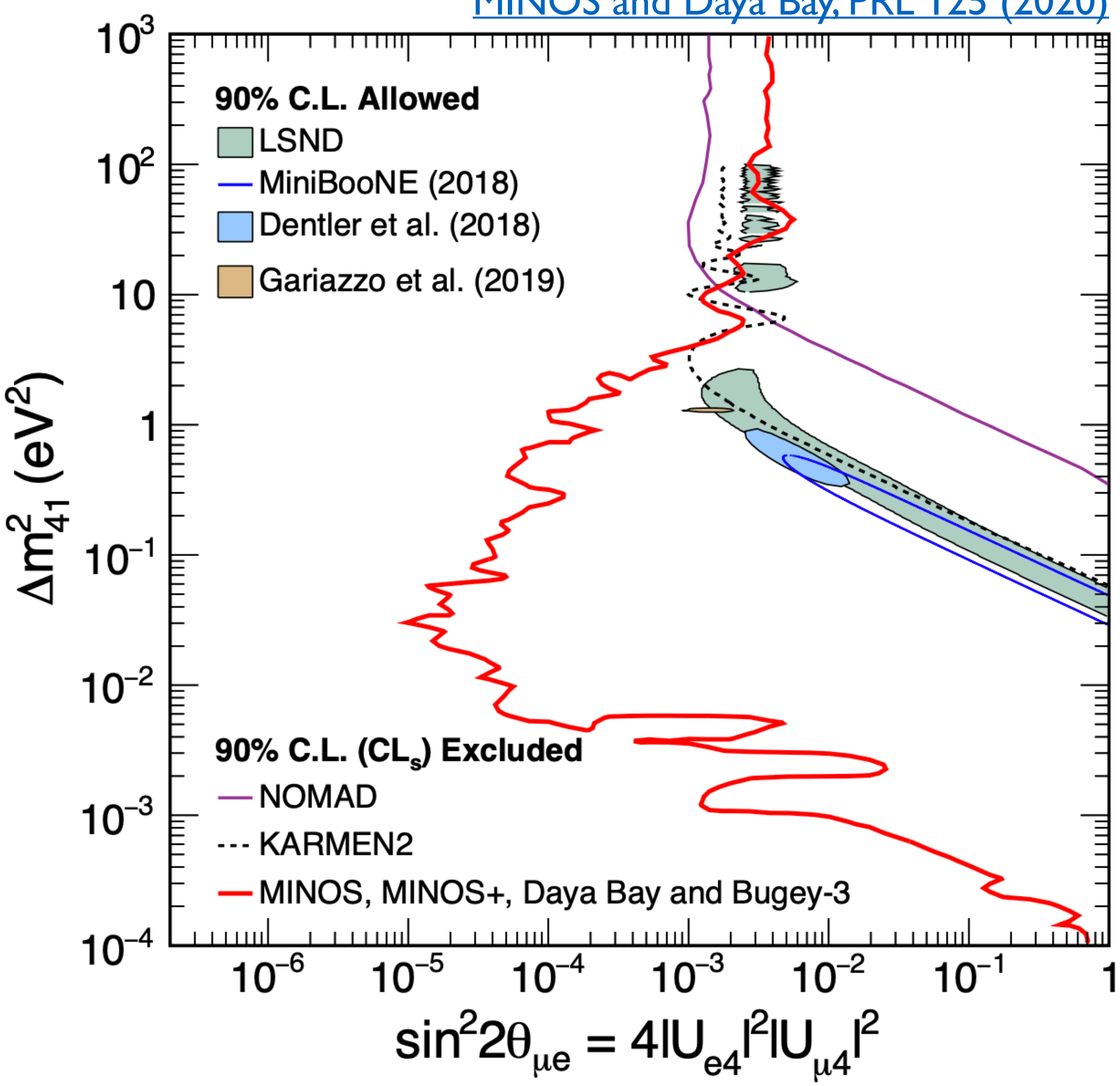


https://arxiv.org/pdf/2410.18419

Recent Progress: Global Data Combos

- Major progress made disfavoring miniBooNE, LSND oscillation space
  - MINOS beam neutrino experiment sees no muon-flavor disappearance; Daya Bay and others see no electron-flavor disappearance
  - If only one sterile state exists (‘3+1’) this combined observations rule out most suggested oscillation space

MINOS and Daya Bay, PRL 125 (2020)



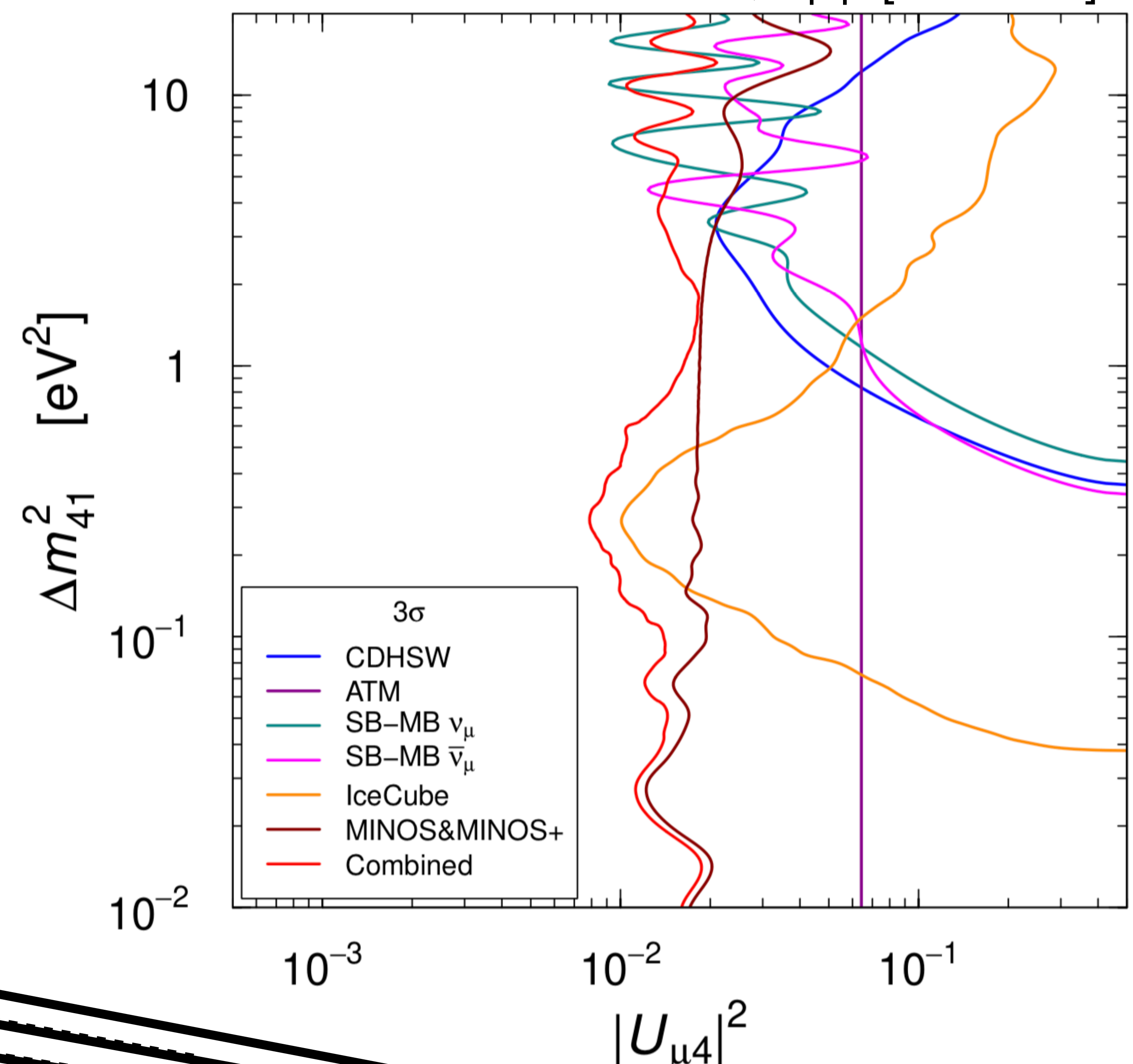
Other Disappearance Channels

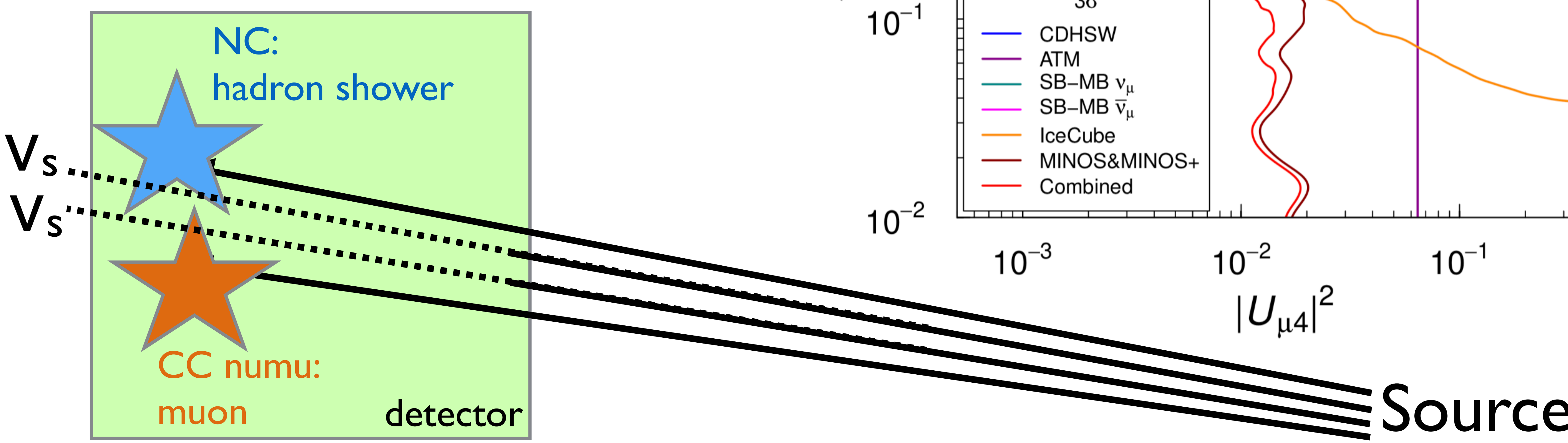
- Other experiments forego direct checks of 'anomalies' in favor of directly assessing sterile neutrino oscillations
  - NC: active neutrino disappearance (MINOS+, NoVA)

    MINOS(+), PRL 122 (2019) NoVA, PRD 96 (2017)
  - CC: muon neutrino disappearance (MINOS+, IceCube)

    MINOS(+), PRL 122 (2018) IceCube, PRL 117 (2016)
  - New analyses of these types are expected in the near future with existing experiments.

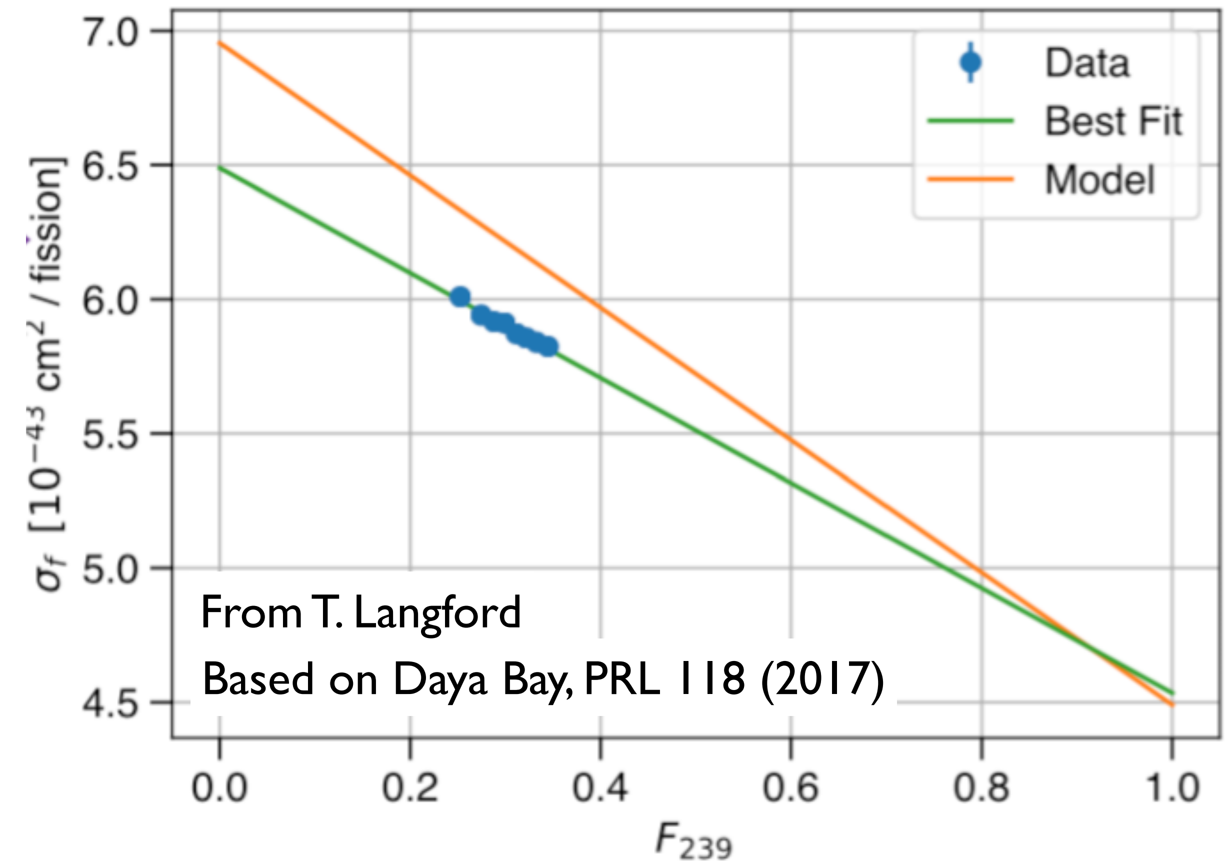
Giunti and Lasserre, hep-ph[1901.08330]

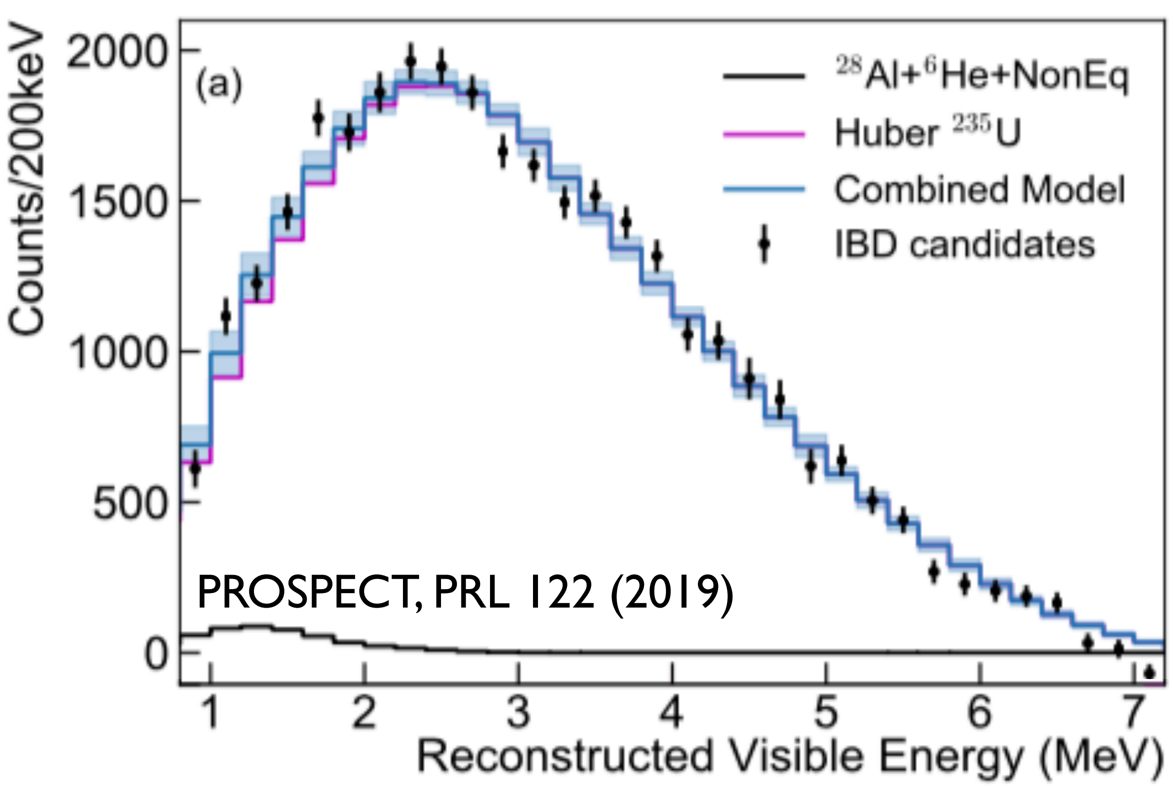


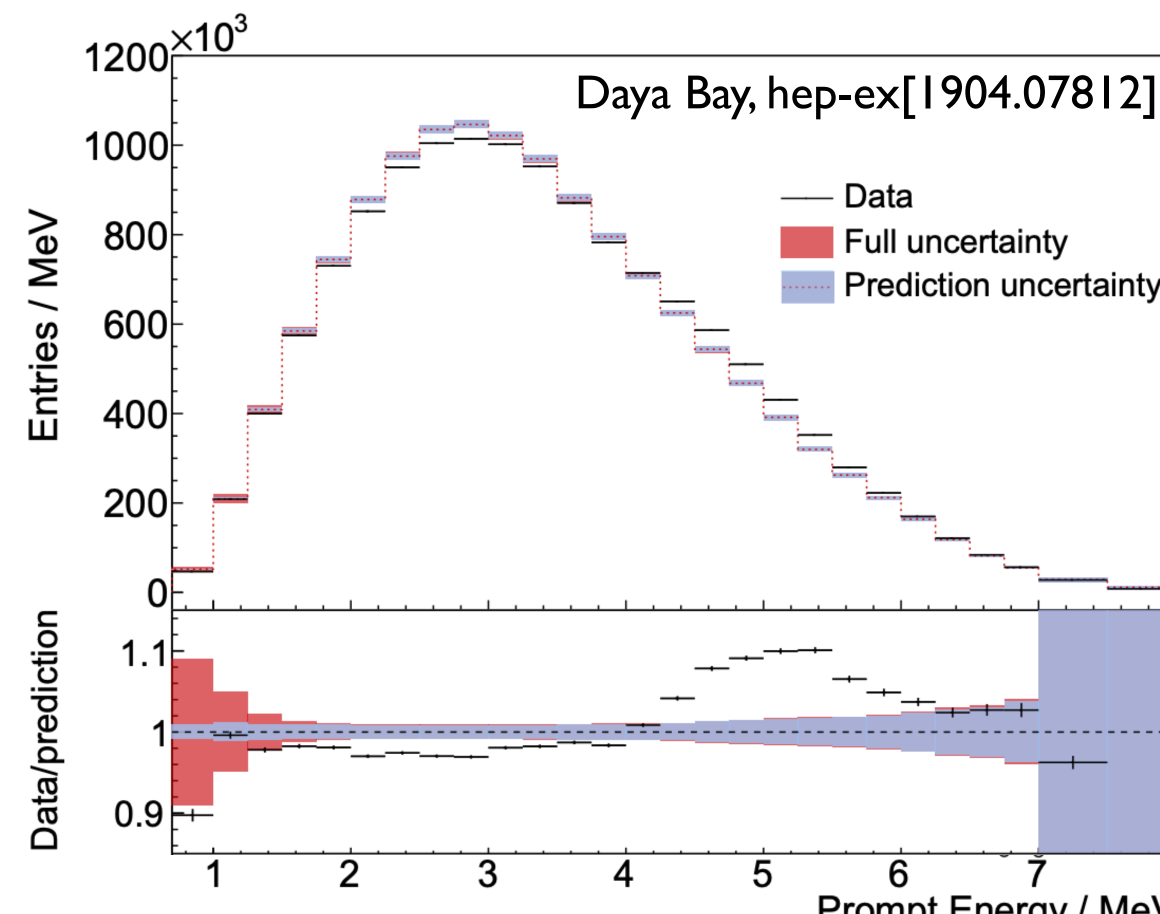


Ample 'Bad Model' Evidence

- Flux evolution looks wrong.
- Spectrum looks wrong.
- Further insight into both can come from ^{235}U exps (PROSPECT, STEREO)
  - Also from detailed comparison of LEU exps to these HEU exps
  - Valuable for testing BSM physics, CEvENS, JUNO, nuclear applications







Note: LBL CP-Violation

- If bounds on sterile mixing angles are too loose, LBL bar(nu$_e$), nu$_e$ appearance signals can vary a TON.
- Once you get θ_{14} and θ_{24} below the 5 degree level ($\sin^2 2\theta_{14} \sim 0.035$), the 3+1 effects start becoming more close to negligible.
  - https://arxiv.org/pdf/1607.02152.pdf
  - https://arxiv.org/pdf/1508.06275.pdf