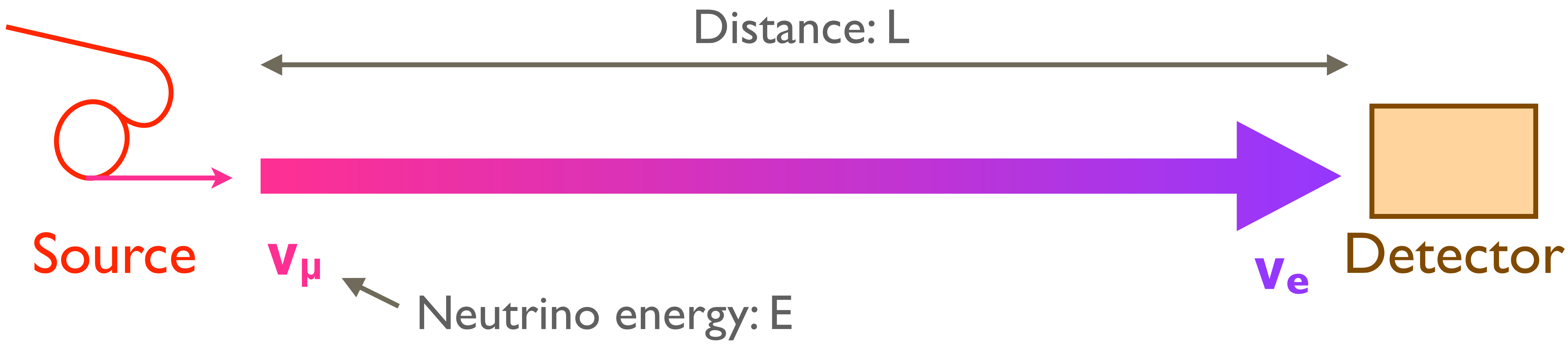
STERILE NEUTRINOS

Kirsty Duffy
UKRI Future Leaders Fellow, University of Oxford
Vietnam School of Neutrinos 2022

- Neutrino oscillation is a **well-understood theory**, and almost all oscillation parameters have now been measured
- However, a lot remains that we **don't understand**: anomalous experimental results in many different channels
- **Sterile neutrinos** have been proposed as a solution to many of these anomalies
- But the picture isn't clear: **can they really explain** all the experimental data?

RECAP: NEUTRINO OSCILLATION

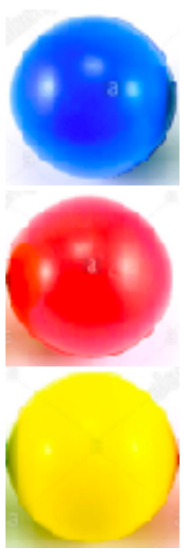
RECAP: NEUTRINO OSCILLATION



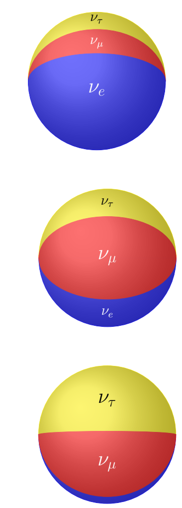
Muon neutrino disappearance

Electron neutrino appearance

RECAP: NEUTRINO OSCILLATION



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



flavour

Interaction

mass

Propagation

PMNS matrix

named after Pontecorvo, Maki, Nakagawa, and Sakata

RECAP: NEUTRINO OSCILLATION

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

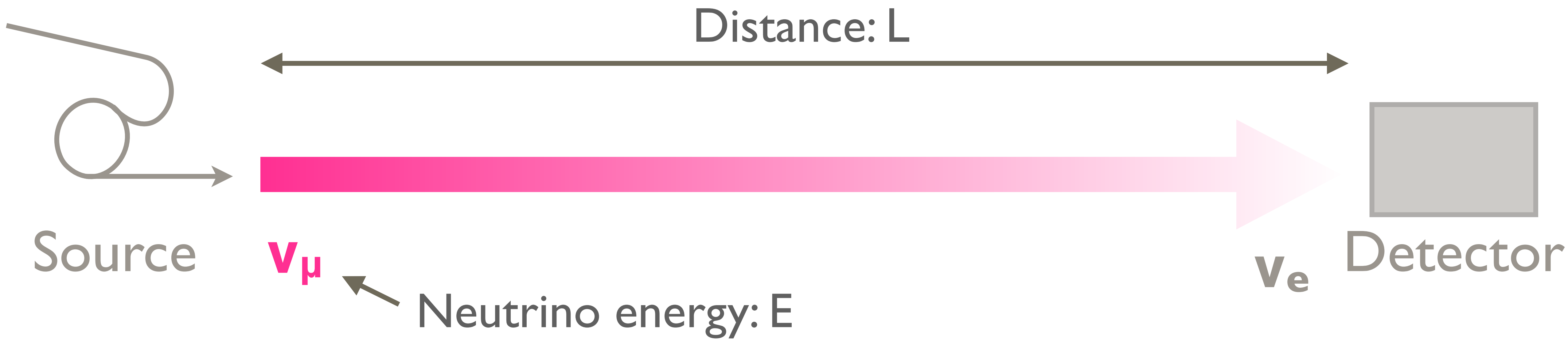
flavour mass

Four free parameters:

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

One phase δ_{CP}

Each mixing angle describes mixing between two mass states (3c2 = 3)



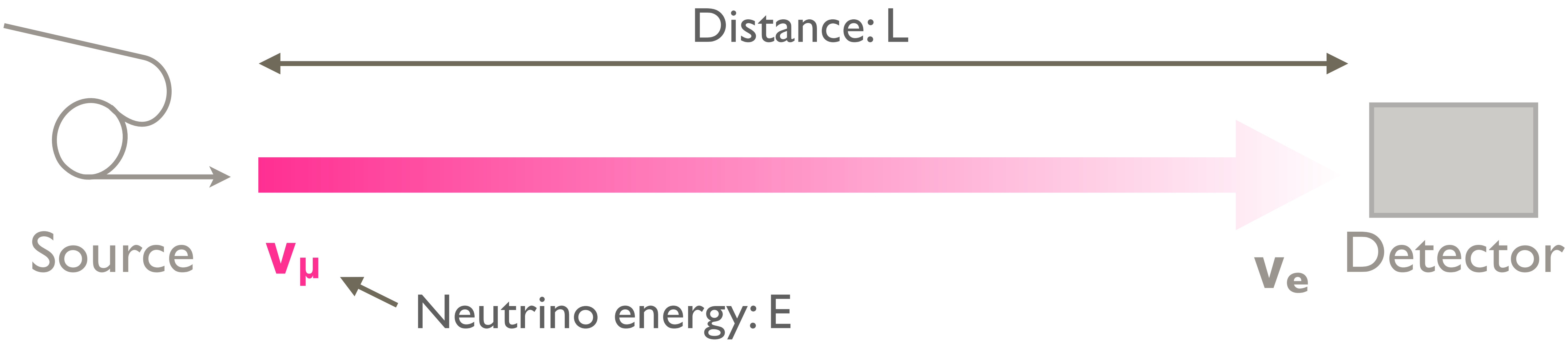
Probability to detect a neutrino of a given flavour **oscillates** as:

$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32} L}{4E} + (\text{solar, matter effect terms})$$

UNIVERSITY OF OXFORD



Depends on **mixing angles** from the PMNS matrix (appearance probability also depends on δ_{CP})

Probability to detect a neutrino of a given flavour **oscillates** as:

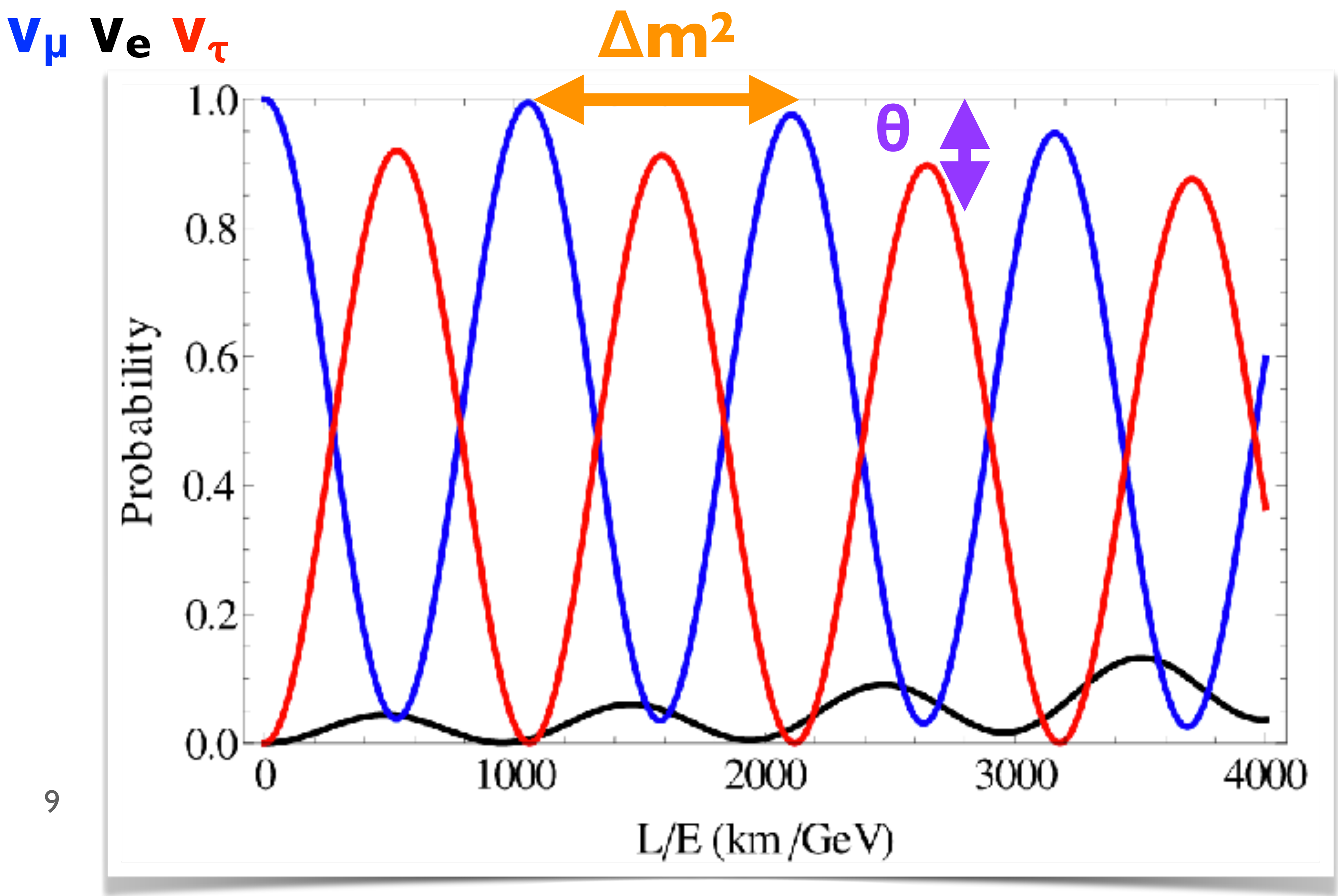
$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32} L}{4E} + (\text{solar, matter effect terms})$$

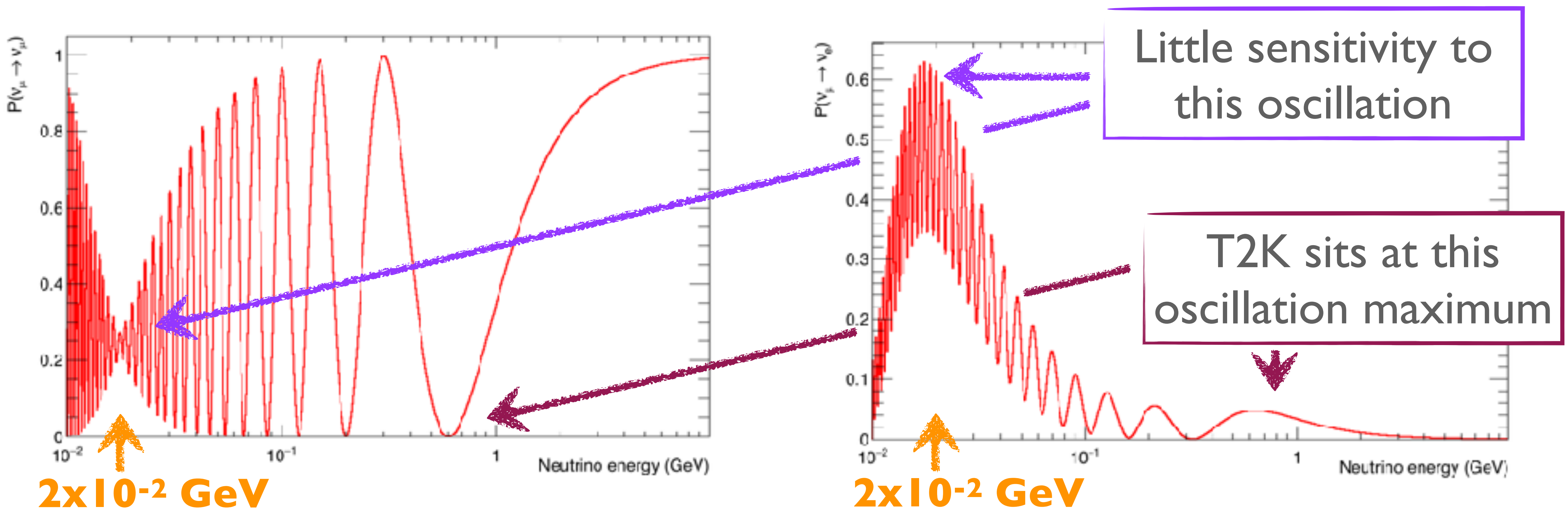
And **mass-squared splittings**

RECAP: NEUTRINO OSCILLATION



RECAP: NEUTRINO OSCILLATION

- Because there are two mass-squared splittings (that we know of!), that gives us **two oscillations**
- BUT many experiments are designed with L/E such that they are mostly sensitive to one
- In some cases we can **approximate as one two-flavour oscillation**



RECAP: NEUTRINO OSCILLATION

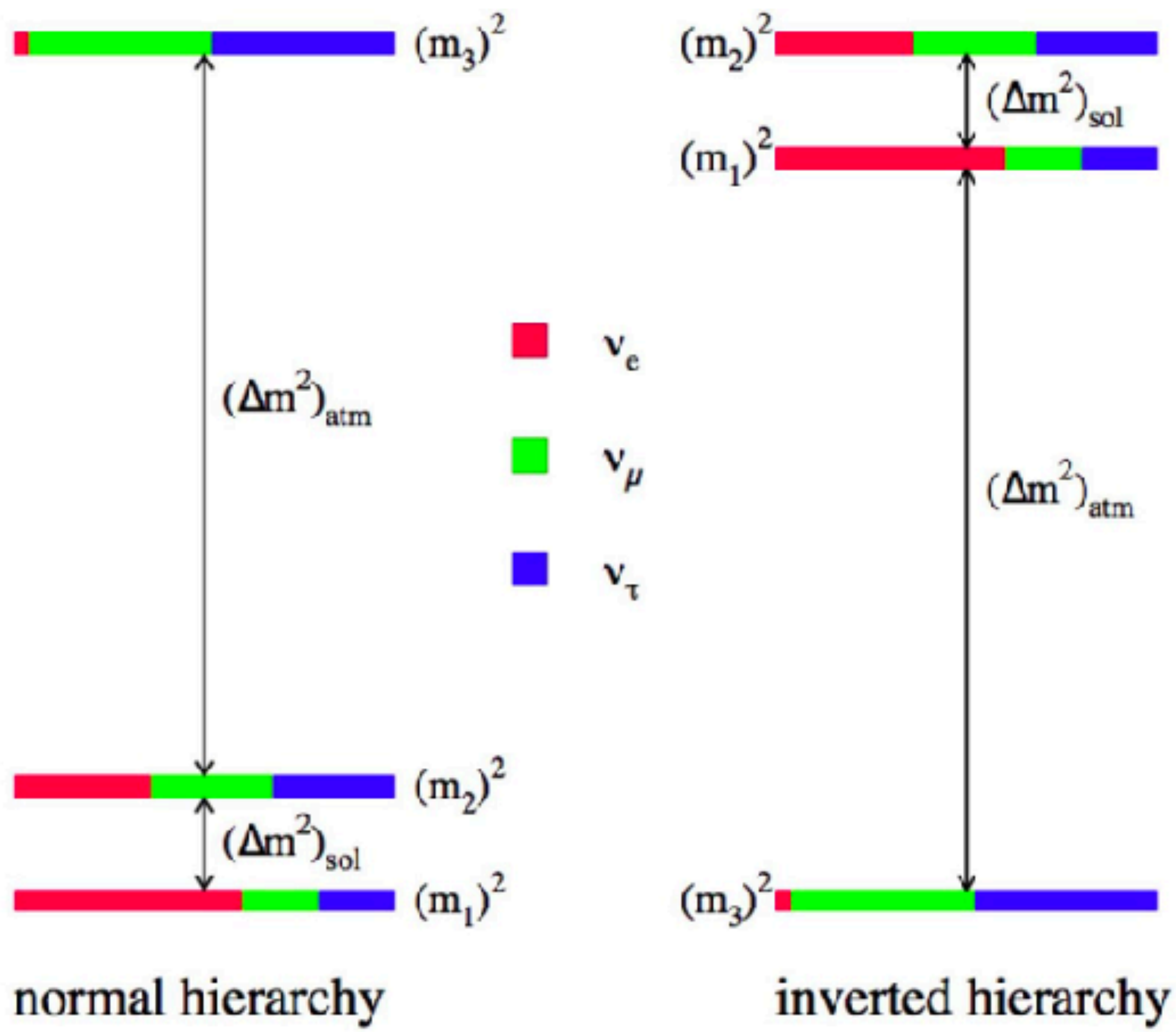
$$\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Oscillation is only sensitive to the **size** of Δm^2, not the **sign**

→ We **know the sign of Δm^2_{21}** from solar neutrino measurements

→ We **do not know the sign of $|\Delta m^2_{32}|$**



HOWEVER…

There have been a number of anomalies observed in the past 20+ years that don't quite fit with the three-neutrino picture we know and love

Experiment	Type	Anomaly
LSND	DAR	$\bar{\nu}_e$ appearance
MiniBooNE	SBL accel.	ν_e appearance
MiniBooNE	SBL accel.	$\bar{\nu}_e$ appearance
GALLEX/SAGE/BEST	Source - e capture	ν_e disappearance
Reactors	Beta decay	$\bar{\nu}_e$ rate
		$\bar{\nu}_e$ shape

Disclaimer: not an exhaustive list!

See also:
R. Guennette, "Short-Baseline Neutrinos", APS-DPF 2019 link
G. Karagiorgi, "Short-baseline neutrino experiments and phenomenology", INSS 2019 link
K. N. Abazajian et. al., Light Sterile Neutrinos: A White Paper, arXiv:1204.5379 [hep-ph] (2012) link

HOWEVER…

There have been a number of anomalies observed in the past 20+ years that don't quite fit with the three-neutrino picture we know and love

Many of these anomalies have motivated people to think about adding one or more **additional neutrinos**

→ **new neutrino oscillations could explain some of these results**

But I should warn you: it's **not a clear picture!**

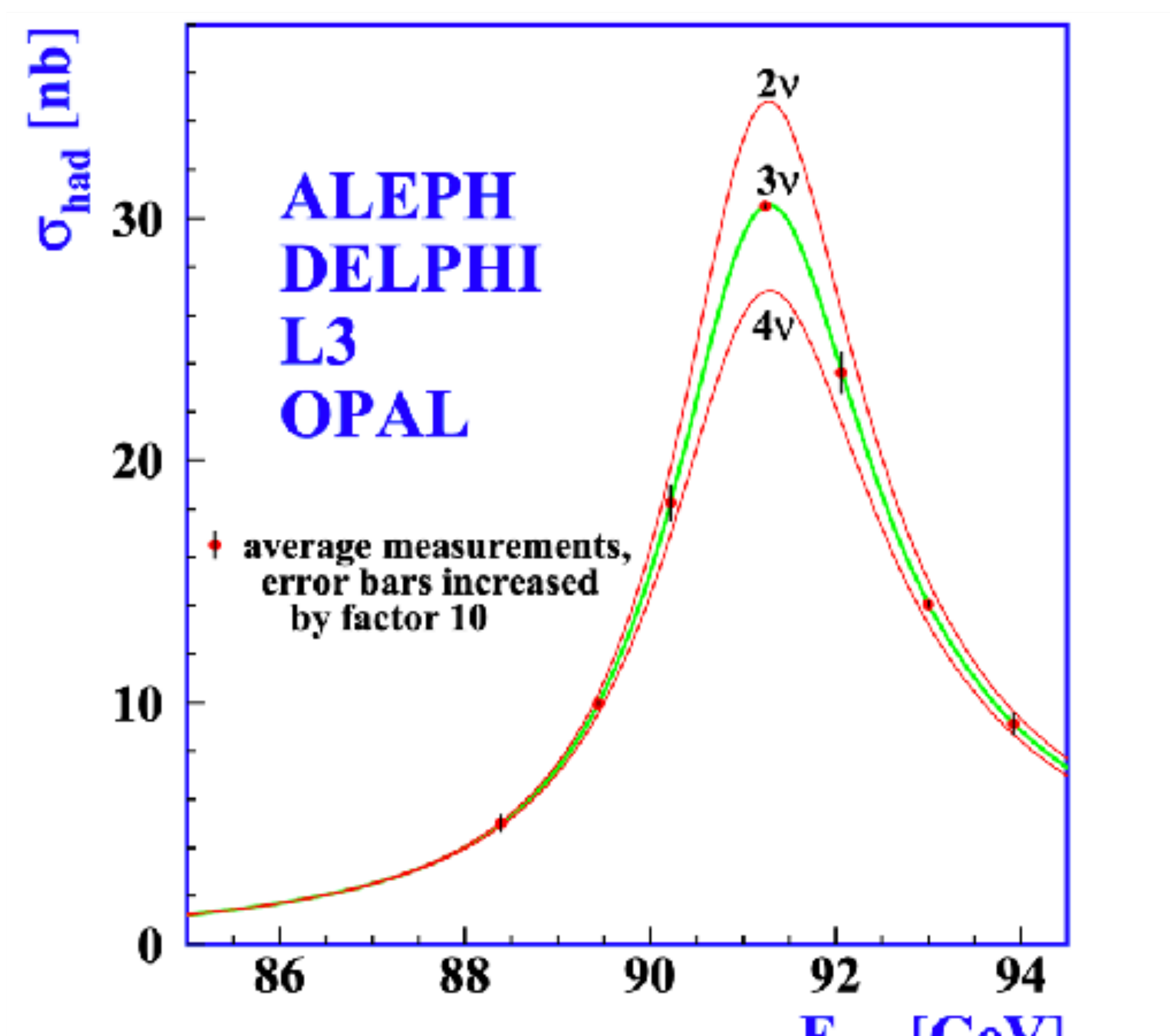
I'm going to talk about the experimental evidence in the second part of this lecture, but first I want to talk about what a **theory of more than 3 neutrinos** might look like

3+1 NEUTRINO OSCILLATION

THE BIGGER PICTURE?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \cdots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$

WHY WE THINK THERE ARE 3 NEUTRINOS



Physics Reports, 427(5-6), 257-454 (2006)

$\sigma(Z\rightarrow had) = \sigma(Z_{total}) - \sigma(Z\rightarrow lep) - \sum_i \sigma(Z\rightarrow \nu_i\bar{\nu}_i)$

- Three flavours that can be produced in decays of Z boson
- → three "active" flavours
- → any new flavours must be **sterile** (not interact with the weak force) or **too heavy** for $Z\rightarrow\nu_i\bar{\nu}_i$ decay!

STERILE NEUTRINOS

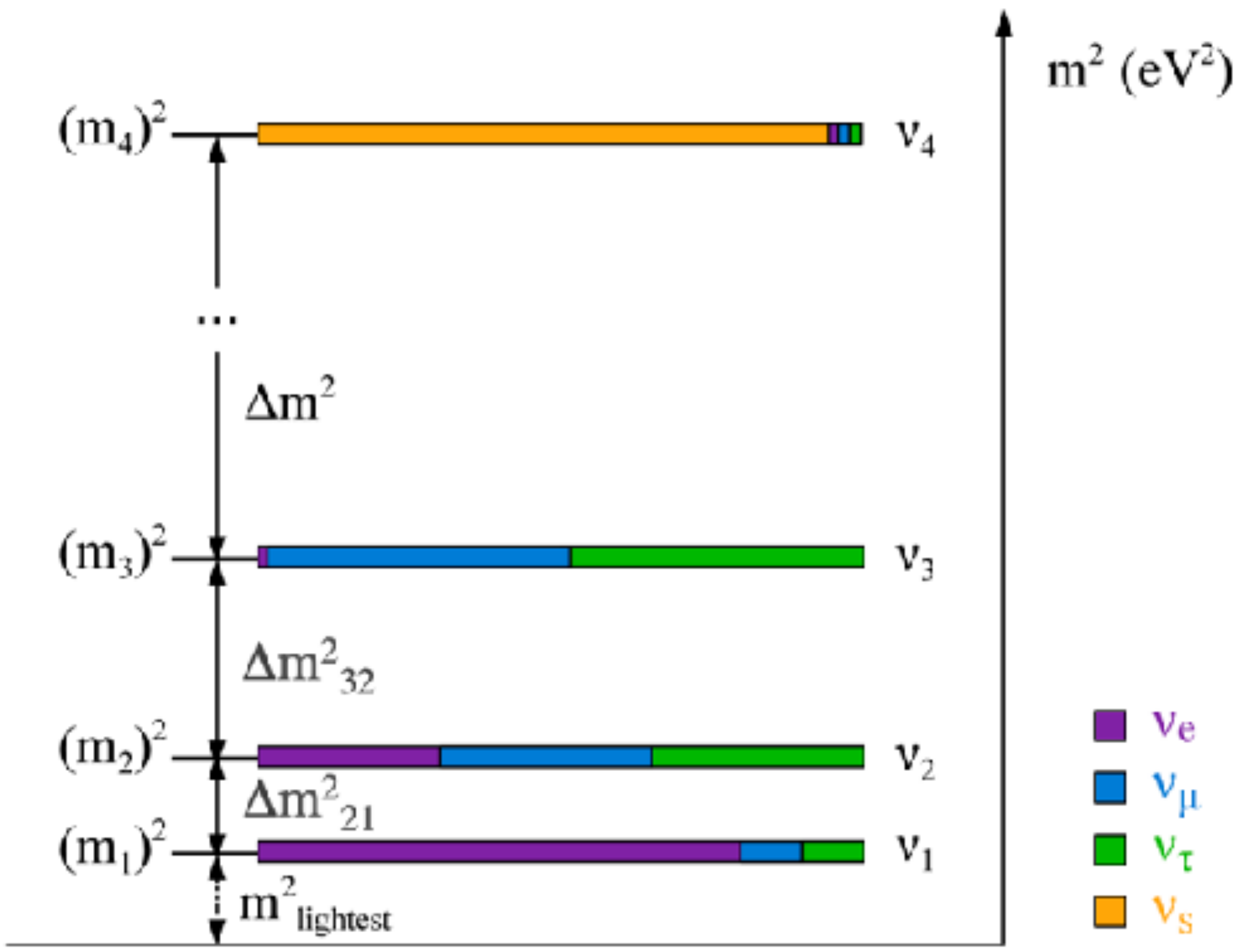
sterile neutrino

/ˈstɛrʌɪl/ /njuːˈtriːnəʊ/

Additional neutrino flavour states which **do not experience weak interactions** (through the standard model W/Z bosons)

The additional mass states associated with them are assumed to be **produced through mixing** with the standard model neutrinos

→ **can affect neutrino oscillation through mixing**



SIMPLEST MODEL: 3+1

Add **one new mass state, ν_4**

We know:

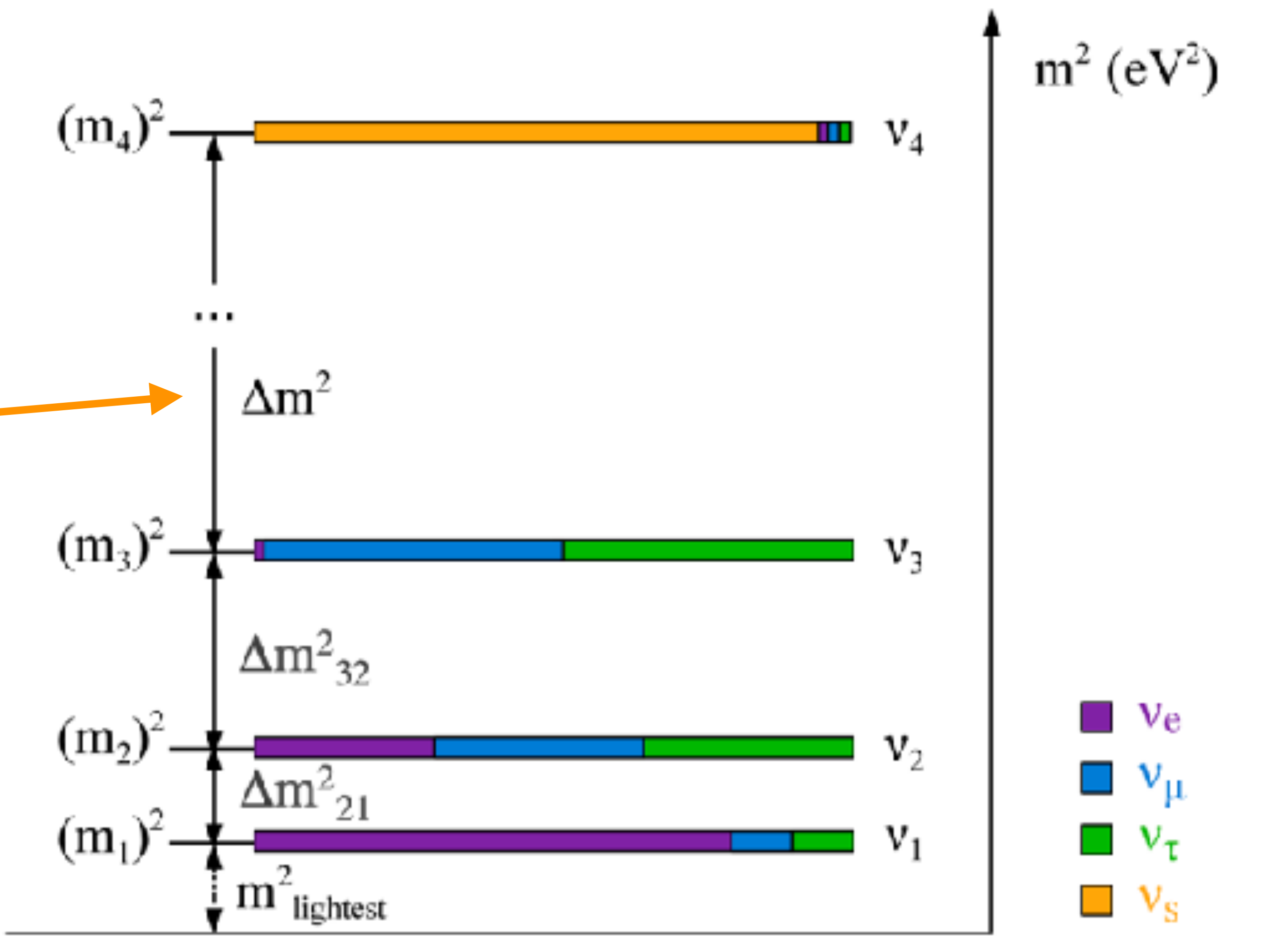
$\Delta m^2_{32} \sim 2.5e^{-3}$ eV^2

$\Delta m^2_{21} \sim 7.5e^{-5}$ eV^2

If our new Δm^2 is large (~ 1eV^2), **we can approximate:**

$\Delta m^2_{43} = \Delta m^2_{42} = \Delta m^2_{41} = \Delta m^2$

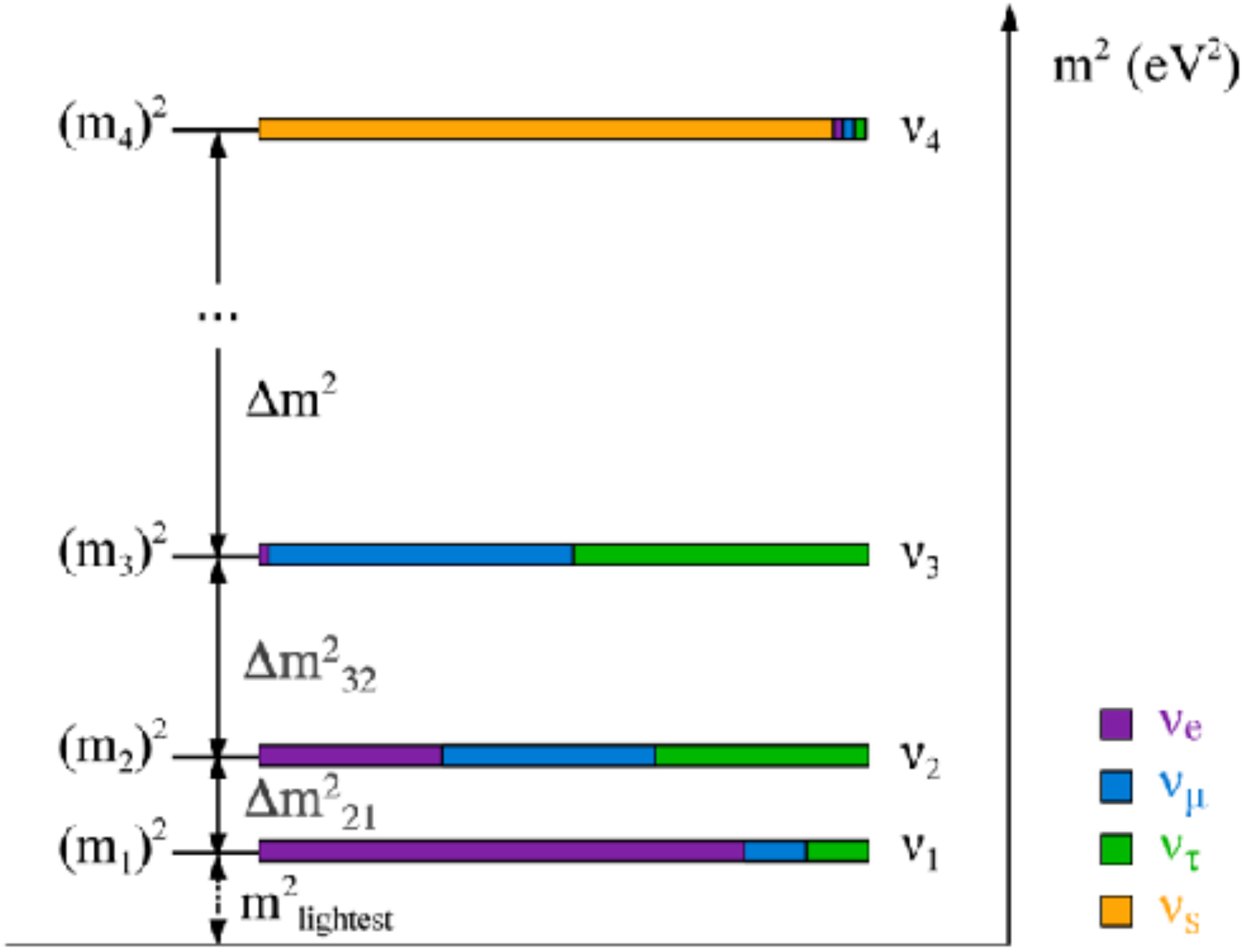
This is basically a **2-flavour approximation**, ignoring the two other oscillations due to the other Δm^2s



SIMPLEST MODEL: 3+1

The PMNS matrix will be expanded with **three new parameters: θ_{14}, θ_{24}, and θ_{34}** (and some new CP-violating phases)

But if we make the 2-flavour approximation, we can define some **new mixing angles** that make the calculations much simpler



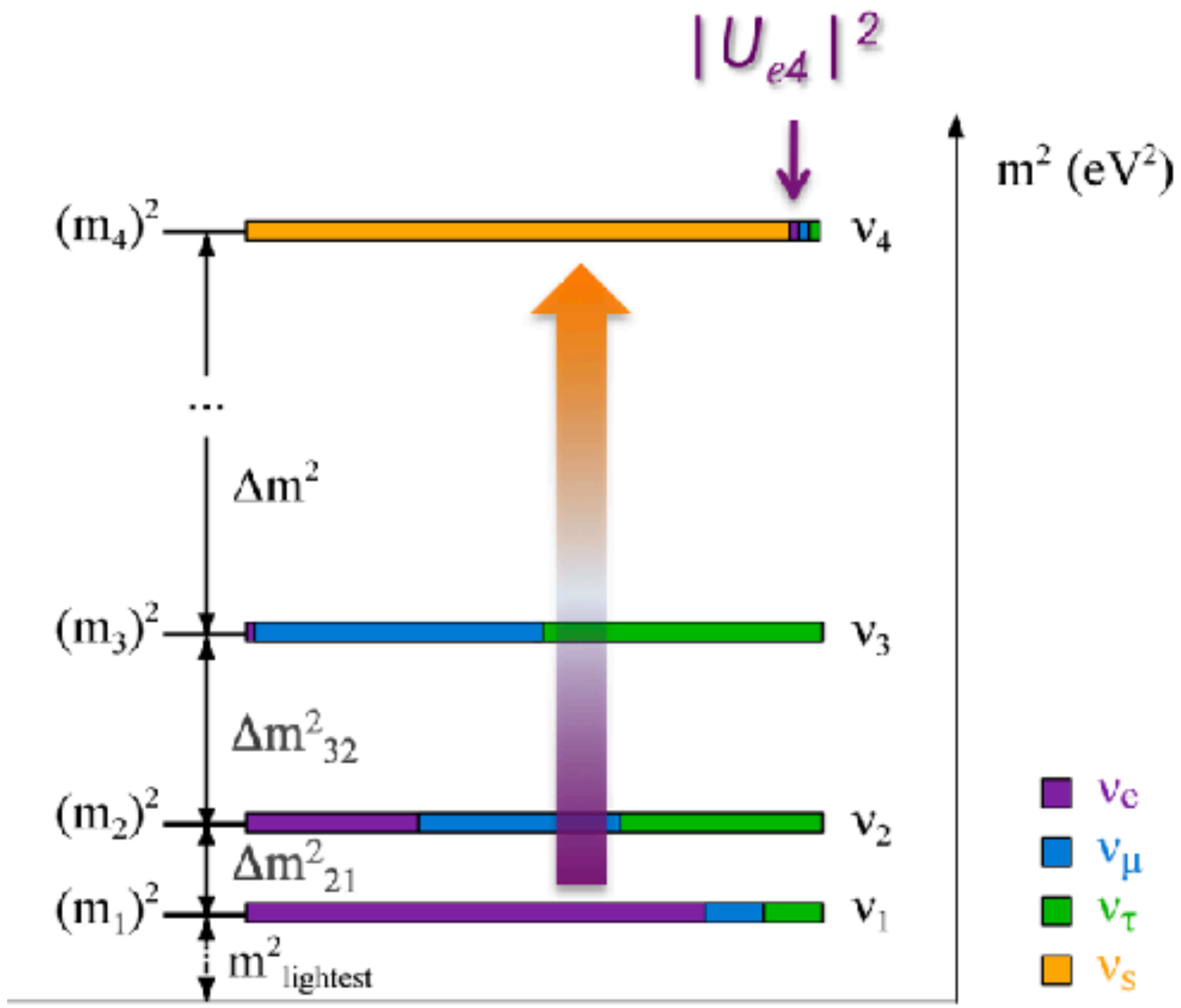
UNIVERSITY OF OXFORD

SIMPLEST MODEL: 3+1

ν_e disappearance probability:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

$$\sin^2 2\vartheta_{ee} \rightarrow 4|U_{e4}|^2(1-|U_{e4}|^2)$$



UNIVERSITY OF OXFORD

SIMPLEST MODEL: 3+1

ν_e disappearance probability:

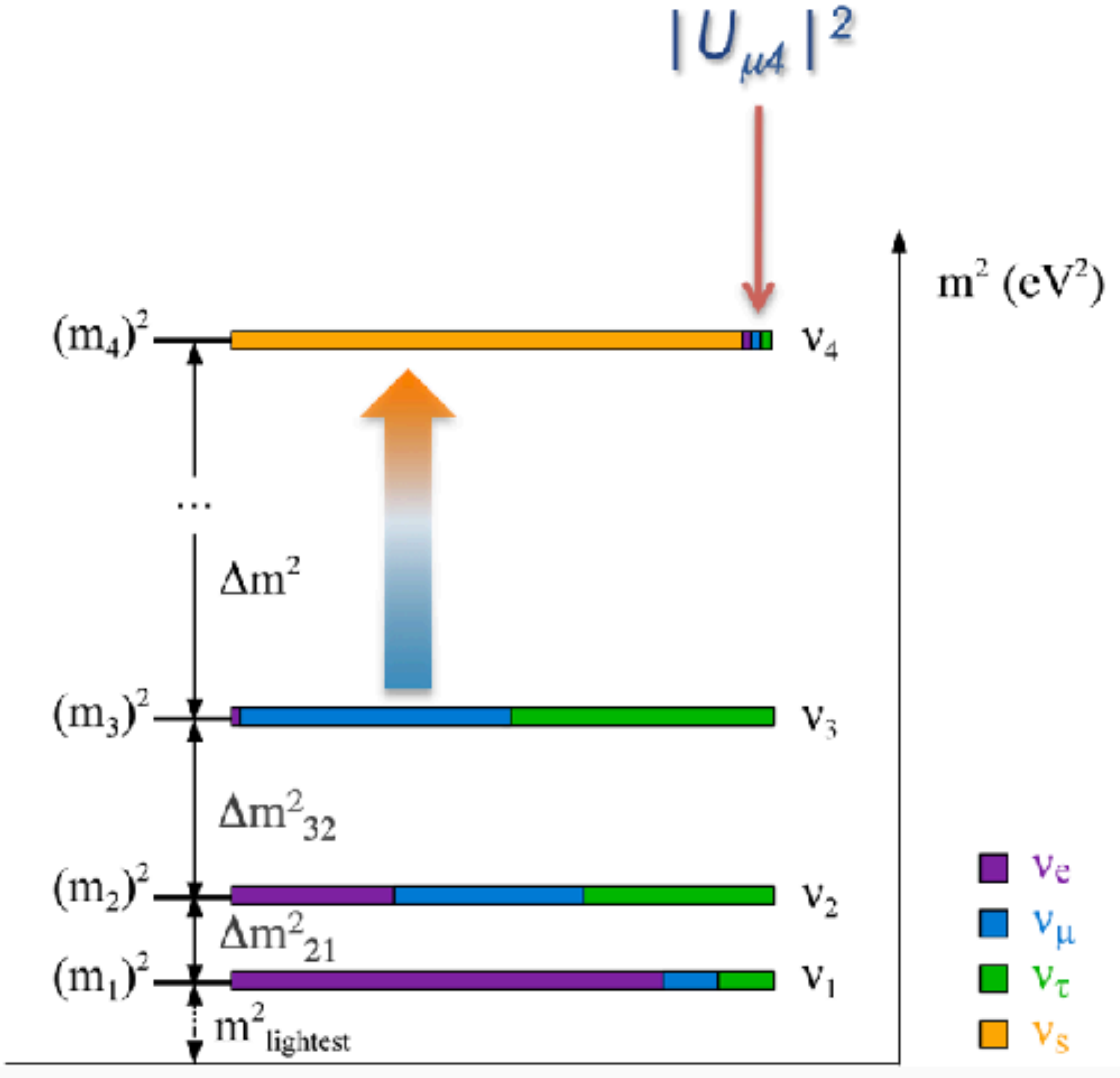
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27 \Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{e4}|^2(1-|U_{e4}|^2)$$

ν_μ disappearance probability:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27 \Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)$$



UNIVERSITY OF OXFORD

SIMPLEST MODEL: 3+1

ν_e disappearance probability:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{e4}|^2(1-|U_{e4}|^2)$$

ν_μ disappearance probability:

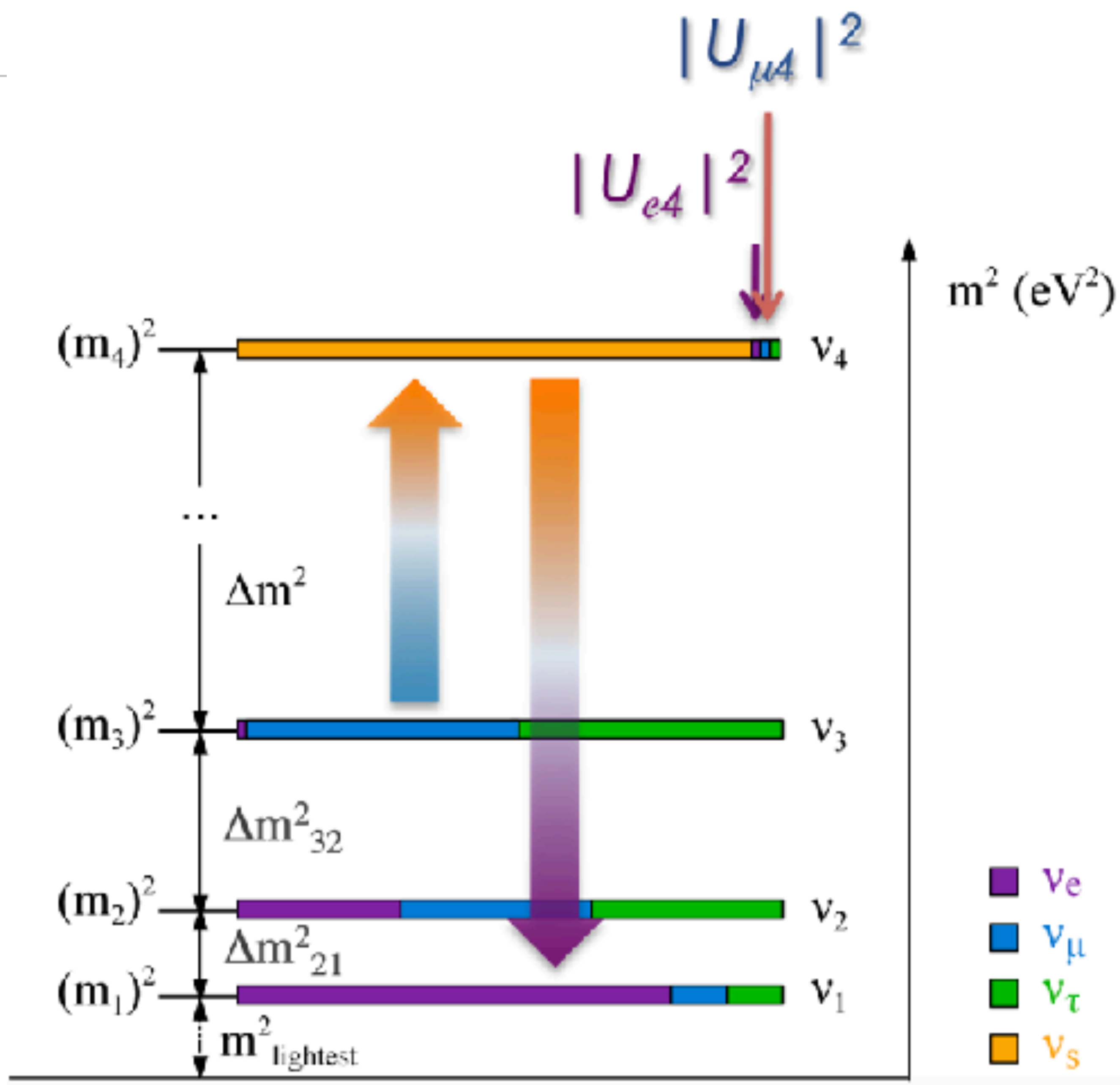
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)$$

$\nu_\mu \rightarrow \nu_e$ "appearance" probability:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{e4}|^2|U_{\mu4}|^2$$



Note: $\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee}$

SIMPLEST MODEL: 3+1

Adding a sterile neutrino gives a **new mechanism for $\nu_\mu \rightarrow \nu_e$ oscillation**

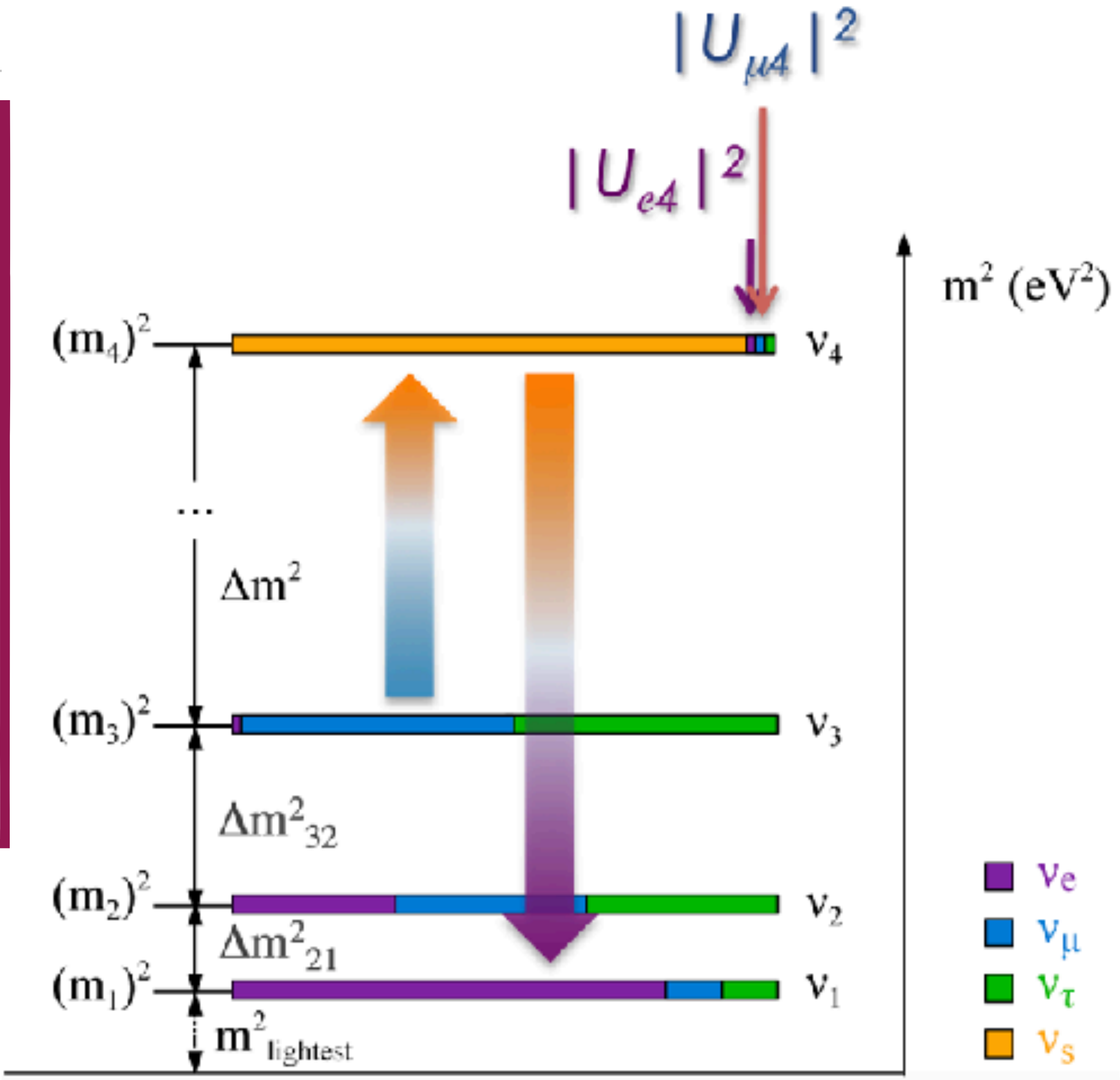
…at a much larger Δm^2 → much shorter L (for fixed E)

We would also expect to see **ν_μ and ν_e disappearance**

$\nu_\mu \rightarrow \nu_e$ "appearance" probability:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

↳ $4|U_{e4}|^2|U_{\mu 4}|^2$



Note: $\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee}$

EXPERIMENTAL ANOMALIES

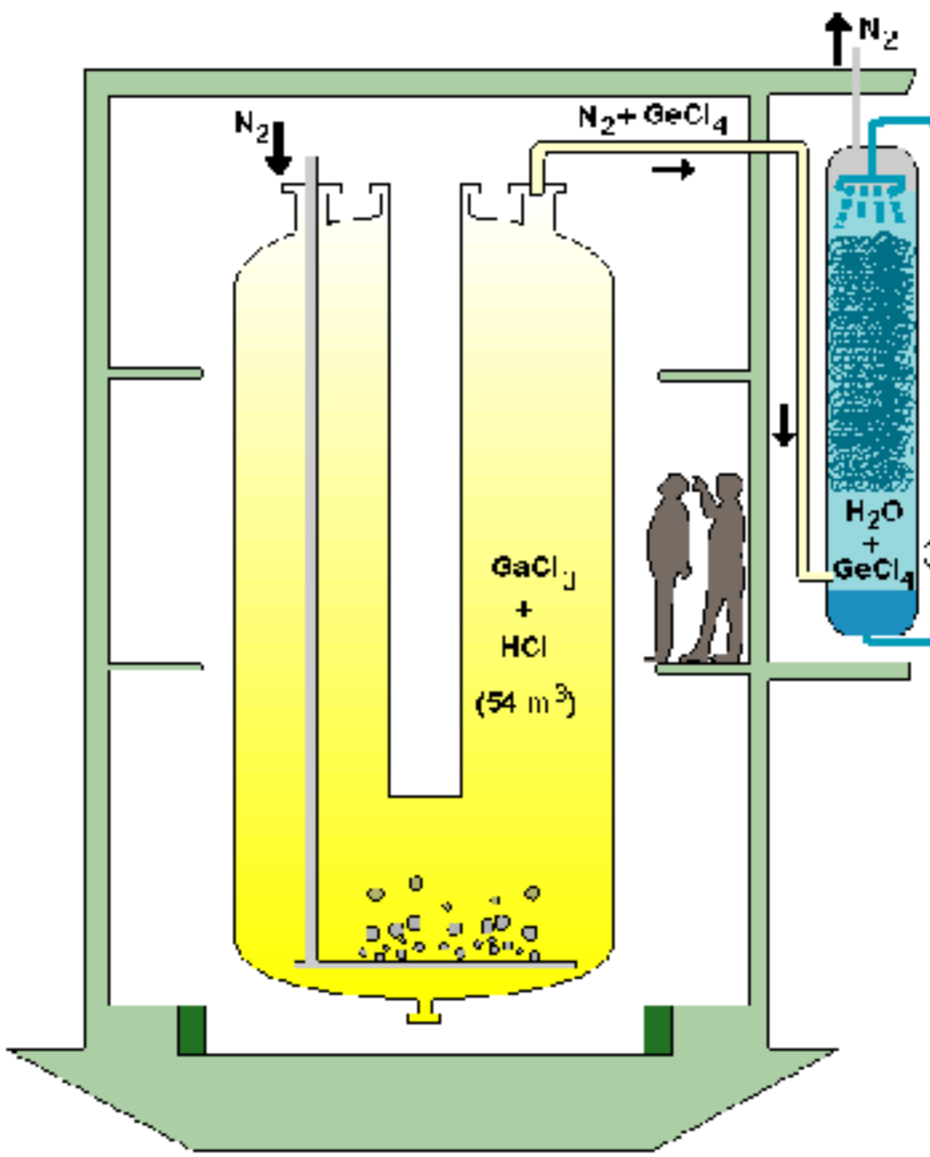
ν_e disappearance

GALLIUM ANOMALY: GALLEX AND SAGE

- Solar neutrino experiments using Gallium for neutrino detection
- Used ^{51}Cr and ^{37}Ar radioactive sources to calibrate ν_e detection efficiency
- Measured 2.8σ deficit of ν_e
- Could be explained by sterile neutrino with $\Delta m^2 > 0.35 eV^2$ (best fit $\Delta m^2 \sim 2 eV^2$)
- SAGE: "A probable explanation for this low result is that the cross section … has been overestimated"

Phys. Rev. C 80, 015807 (2009)

GALLEX experiment

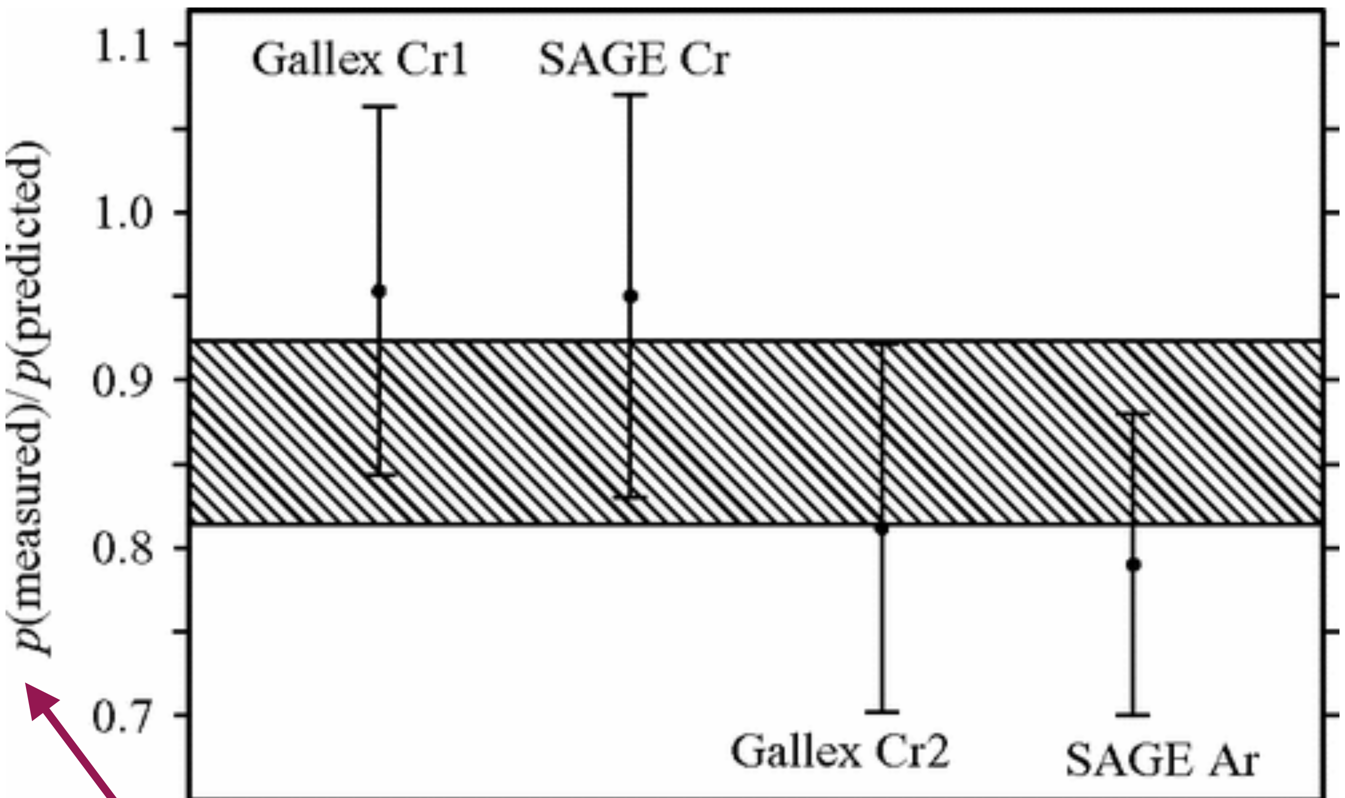


Picture source

GALLIUM ANOMALY: GALLEX AND SAGE

- Solar neutrino experiments using Gallium for neutrino detection
- Used ^{51}Cr and ^{37}Ar radioactive sources to calibrate ν_e detection efficiency
- Measured 2.8σ deficit of ν_e
- Could be explained by sterile neutrino with $\Delta m^2 > 0.35 eV^2$ (best fit $\Delta m^2 \sim 2 eV^2$)
- SAGE: "A probable explanation for this low result is that the cross section … has been overestimated"

Phys. Rev. C 80, 015807 (2009)



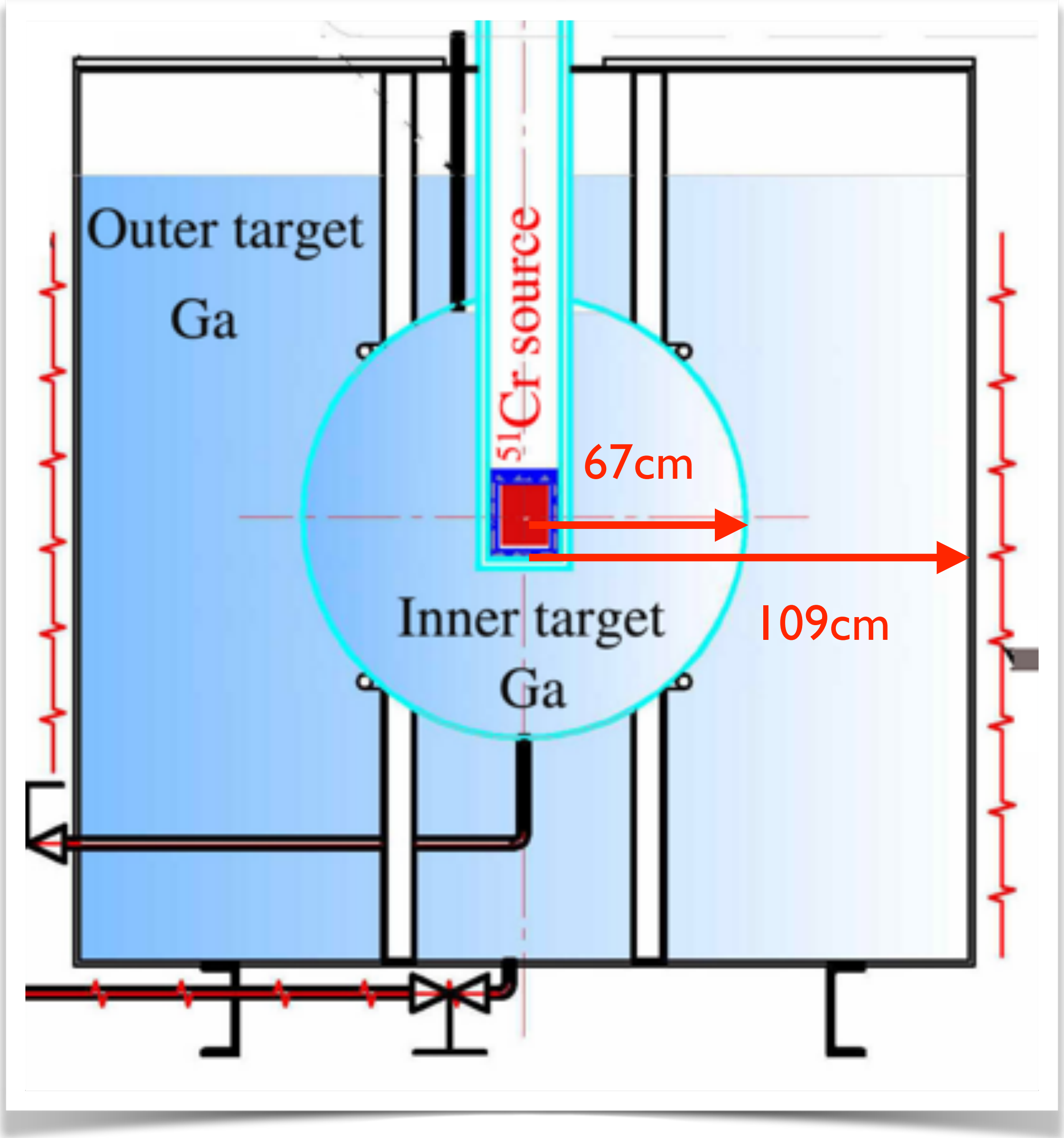
Phys. Rev. C 73, 045805

y-axis: ratio to expectation, R

R=1 → no oscillations

GALLIUM ANOMALY: BEST

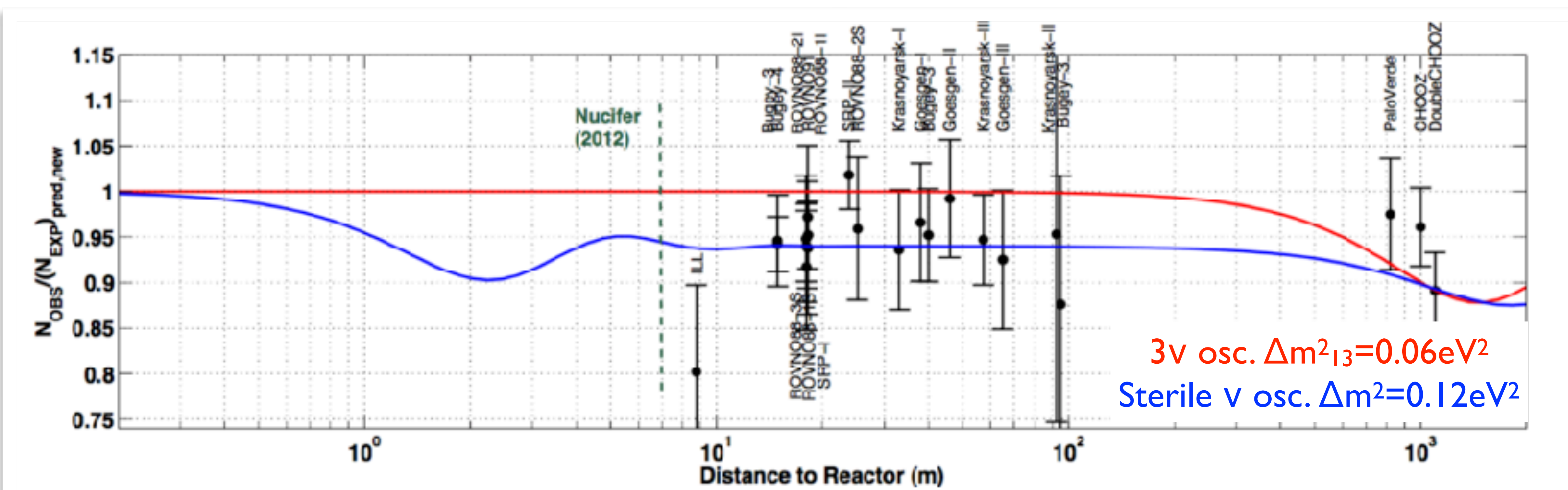
- BEST collaboration recently presented a new result: gallium measurement using a chromium-51 source
- Inner target: R=0.791±0.05 $\langle L_{in} \rangle$ = 52.03±0.18 cm
- Outer target: R=0.766±0.05 $\langle L_{out} \rangle$ = 54.41±0.18 cm
- Gallium anomaly reaffirmed with significantly smaller error bars
- Favours $\Delta m^2 > 1 eV^2$ (best fit: $3.3 eV^2$)



Phys. Rev. Lett. 128, 232501 (2022)

ANOMALIES: REACTOR $\bar{\nu}_e$ RATE

- Recalculation of neutrino flux from nuclear reactors by multiple groups* in 2011: ~3σ (3.5%) deficit in $\bar{\nu}_e$
- Could be explained by neutrino oscillation $\Delta m^2 \sim 0.12 eV^2$
- However…

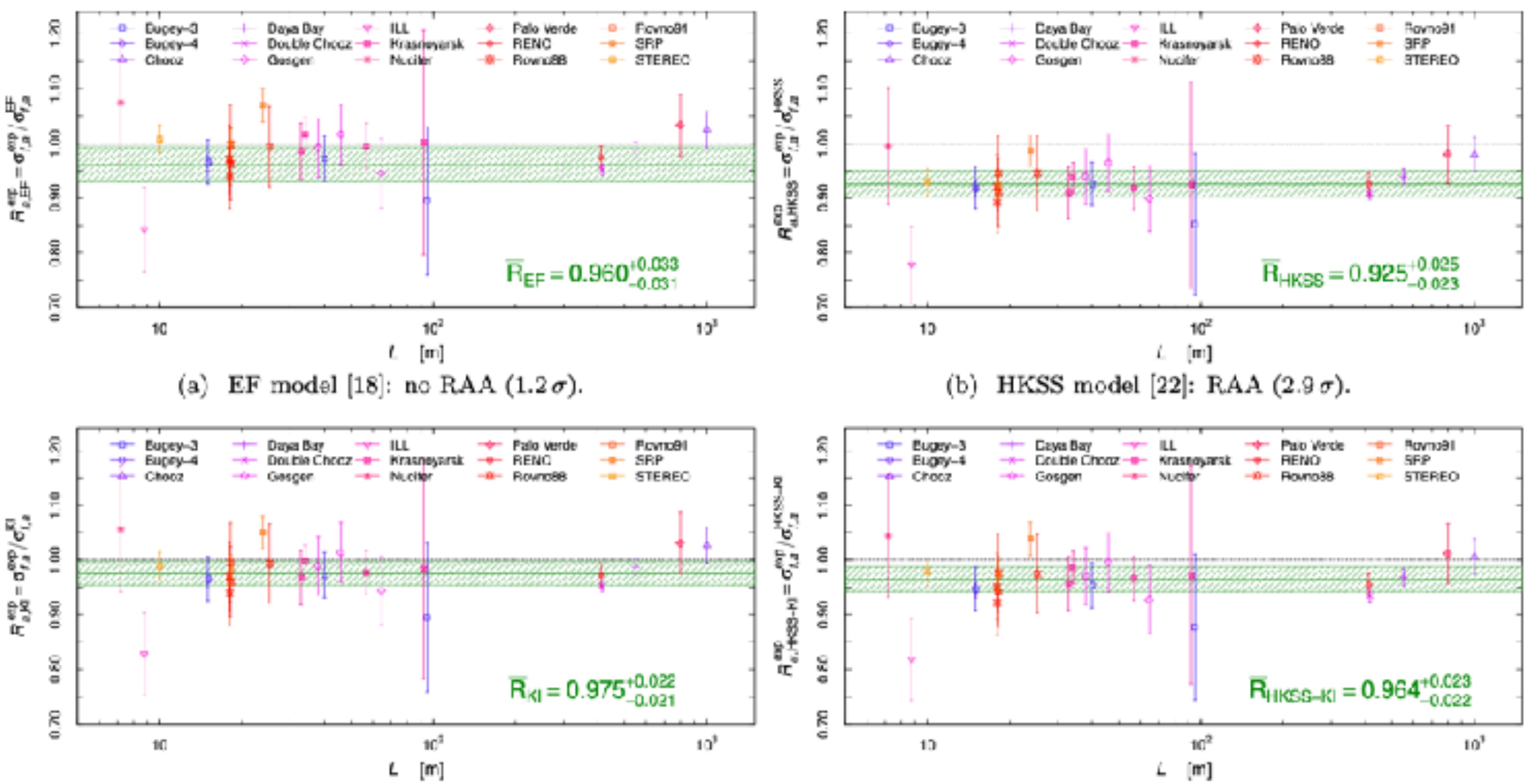


Mention et. al, Phys. Rev. D 83, 073006 (2011)

*Mueller et. al., Phys. Rev. C 83, 054615 (2011), Huber Phys Rev C 84, 024617 (2011)

ANOMALIES: REACTOR $\overline{\nu}e$ RATE

Updated models reduce deficit → tension with Gallium anomaly



(a) EF model [18]: no RAA (1.2 σ).

(b) HKSS model [22]: RAA (2.9 σ).

(c) KI model [24]: no RAA (1.1 σ).

(d) HKSS-KI model: no RAA (1.5 σ).

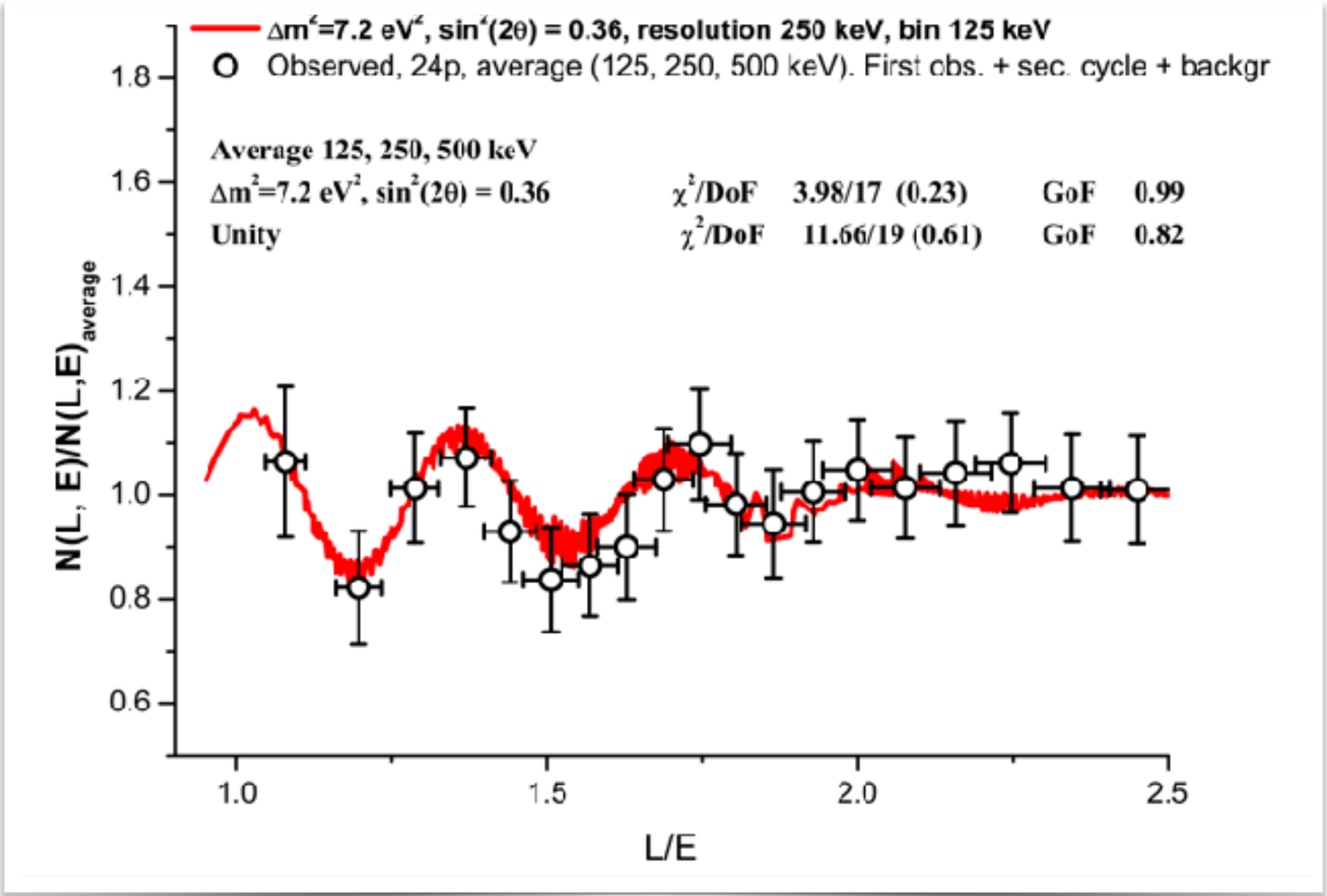
C. Giunti et. al., arXiv:2110.06820 [hep-ph]

ANOMALIES: REACTOR $\bar{\nu}_e$ SHAPE

Neutrino-4

Phys. Rev. D 104, 032003 (2021)

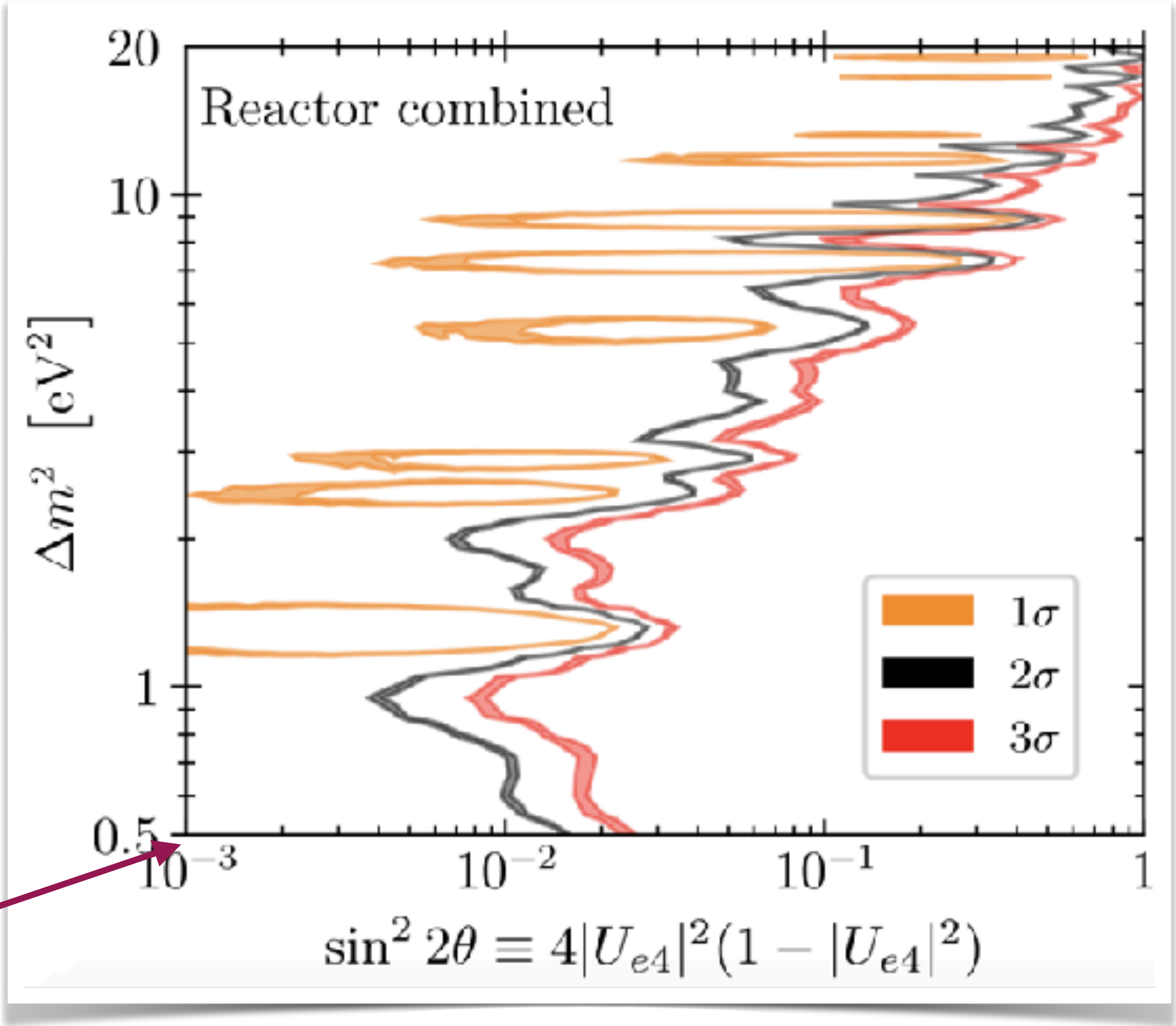
- 6-12m from centre of active zone of the SM-3 reactor
- Spectrum ratio measurement
- Report 2.7σ indication of oscillations with $\Delta m^2 = 7.2 eV^2$



µBooNE

ANOMALIES: REACTOR $\bar{\nu}_e$ SHAPE

PROSPECT
STEREO
DANSS
Neutrino-4
NEOS

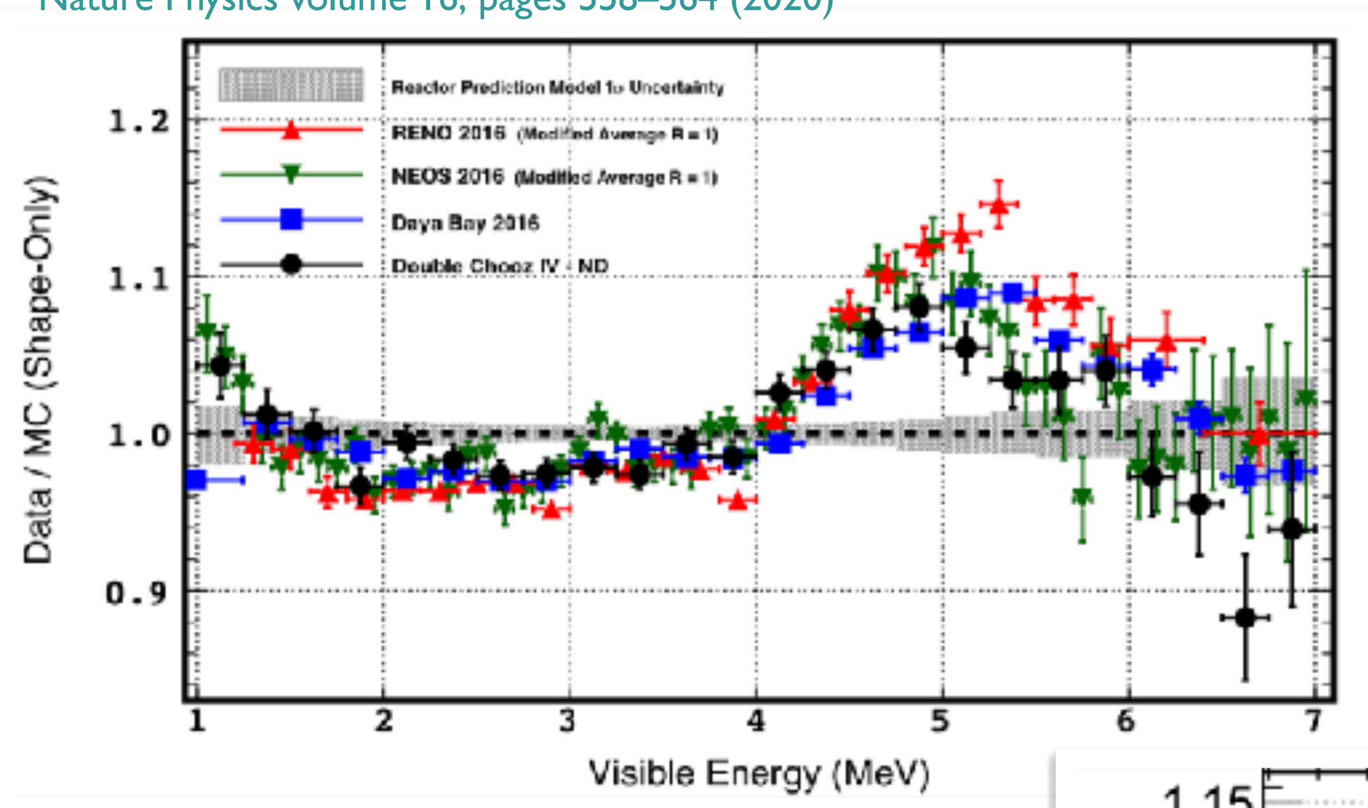


No neutrino oscillation

Berryman et. al., arXiv:2111.12530 [hep-ph]

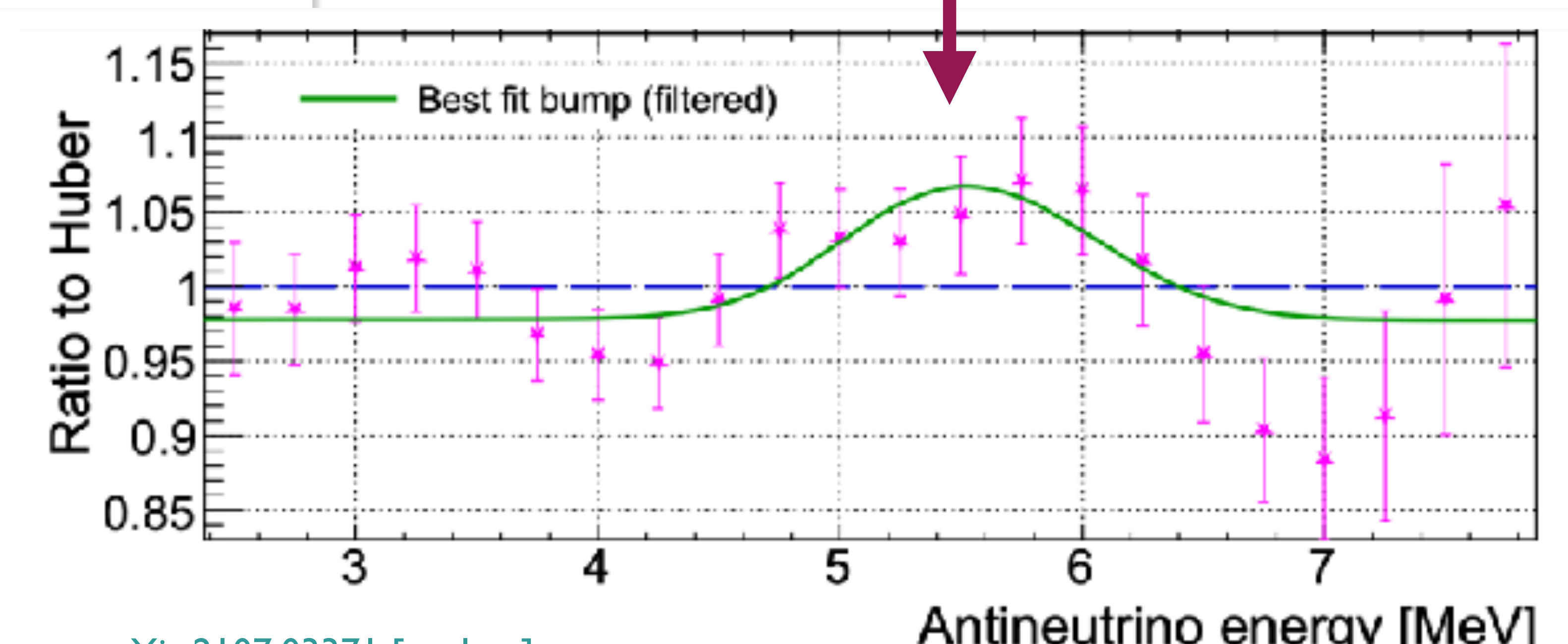
ANOMALIES: THE 5 MEV BUMP

Nature Physics volume 16, pages 558–564 (2020)



RENO
NEOS
Daya Bay
Double Chooz

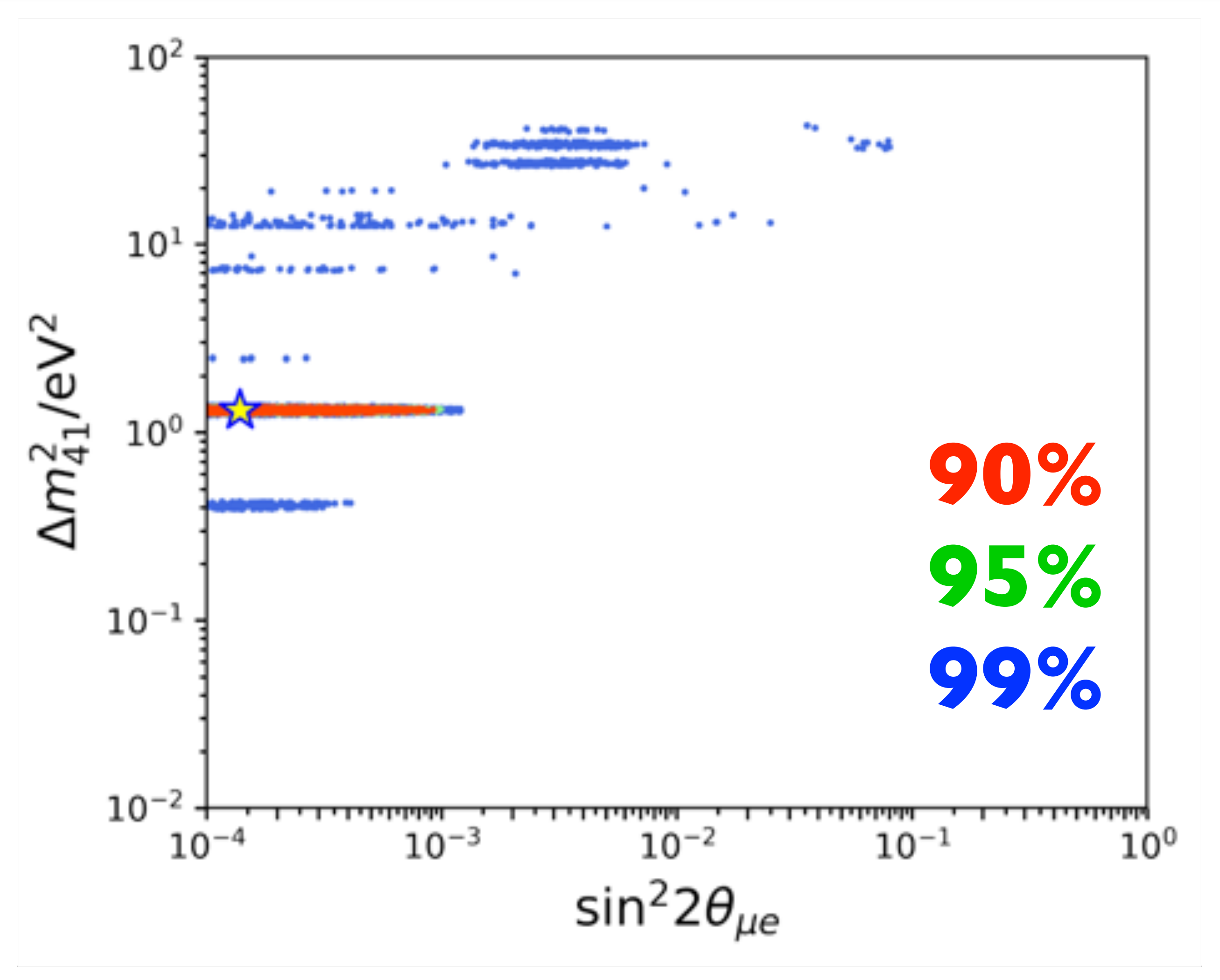
PROSPECT+STEREO



arXiv:2107.03371 [nucl-ex]

PUTTING IT TOGETHER

Diaz et. al., Phys. Rep. 884 (2020) 1-59



Disappearance

Global fit from 2019 combines disappearance data sets

Data used shown below (note: no BEST)

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

* = anomaly at ≥ 2σ

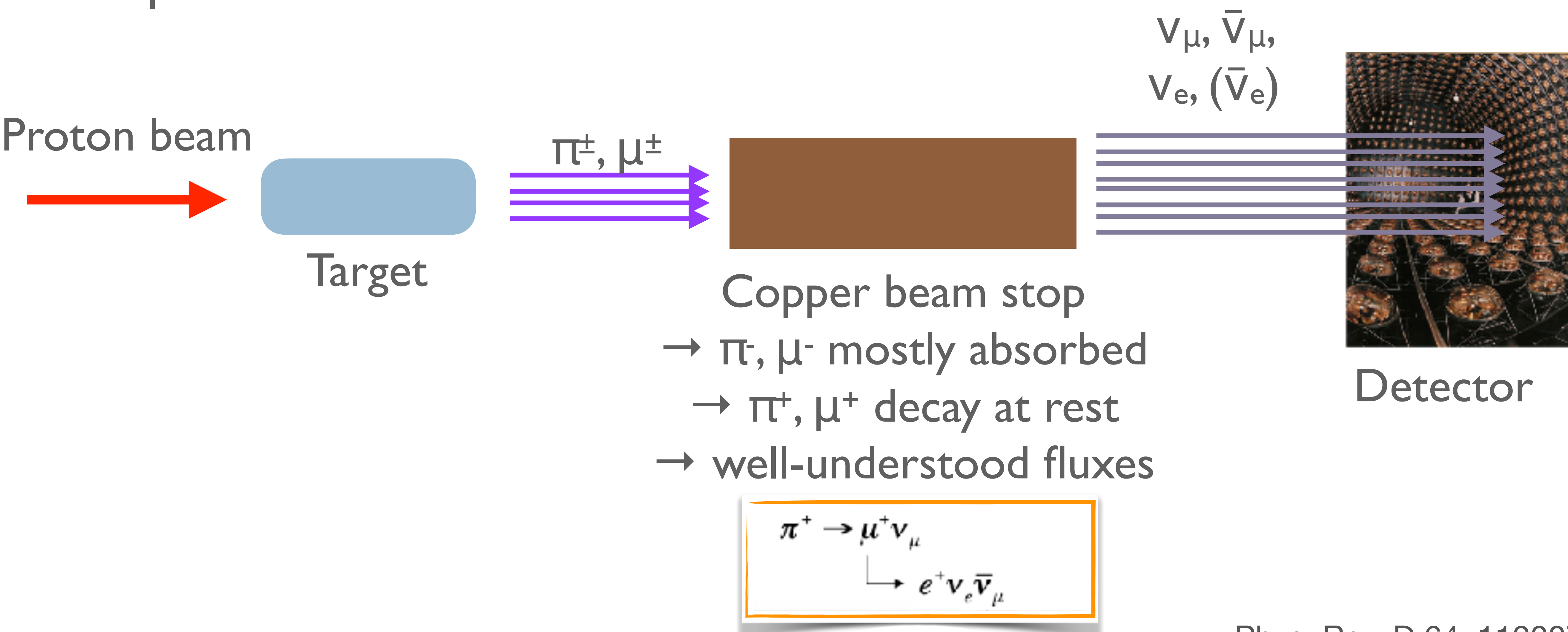
UNIVERSITY OF OXFORD

EXPERIMENTAL ANOMALIES

ν_e appearance

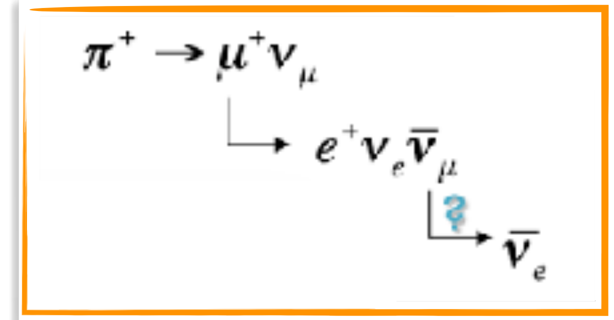
ANOMALIES: LSND

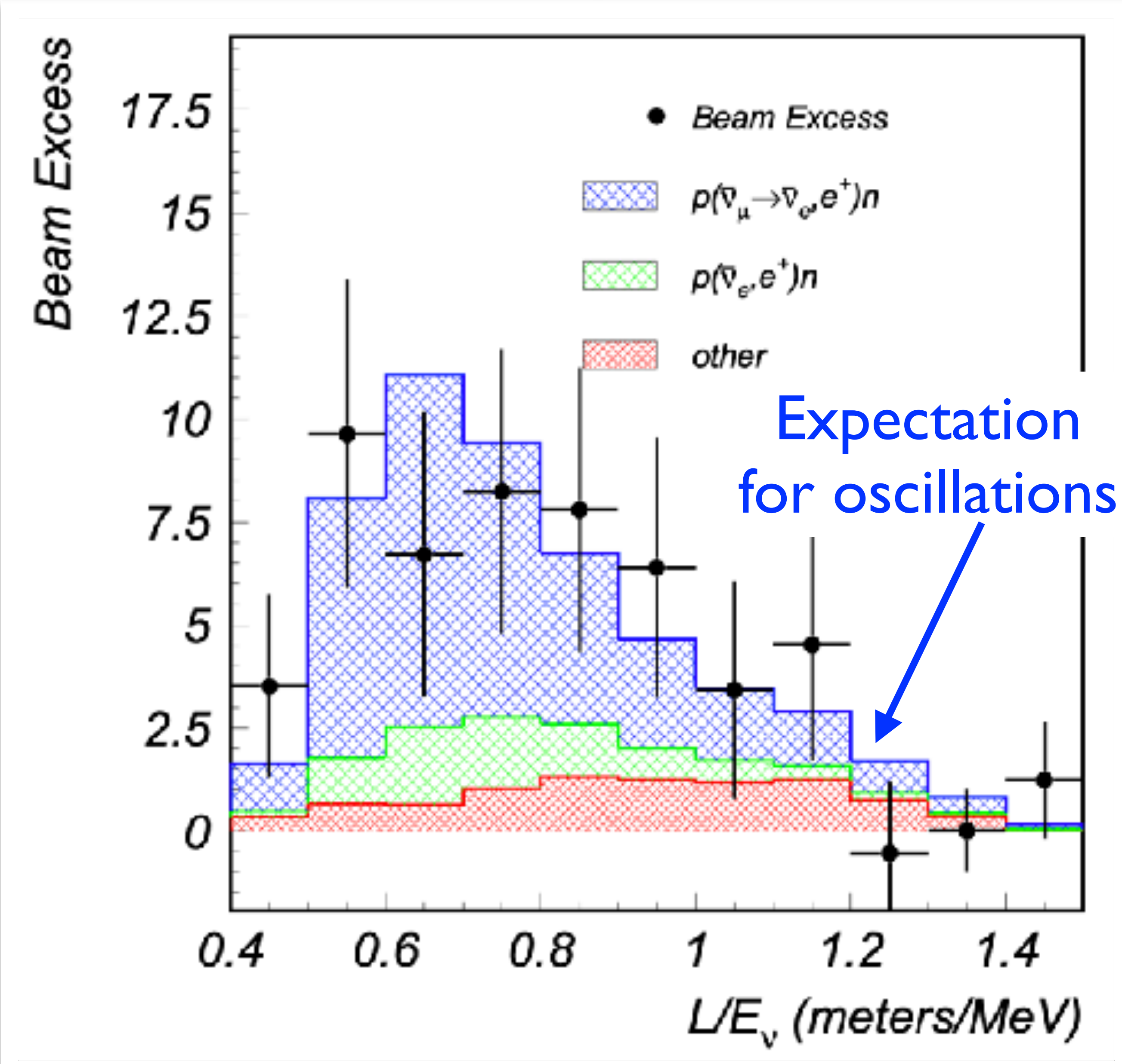
- **L**iquid **S**cintillator **N**eutrino **D**etector: μ^+ decay at rest experiment at Los Alamos National Lab



Phys. Rev. D 64, 112007

ANOMALIES: LSND

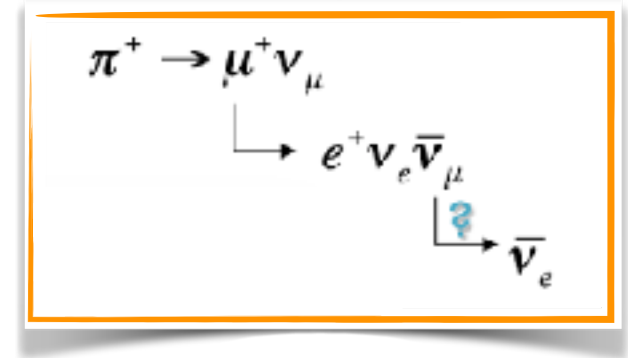


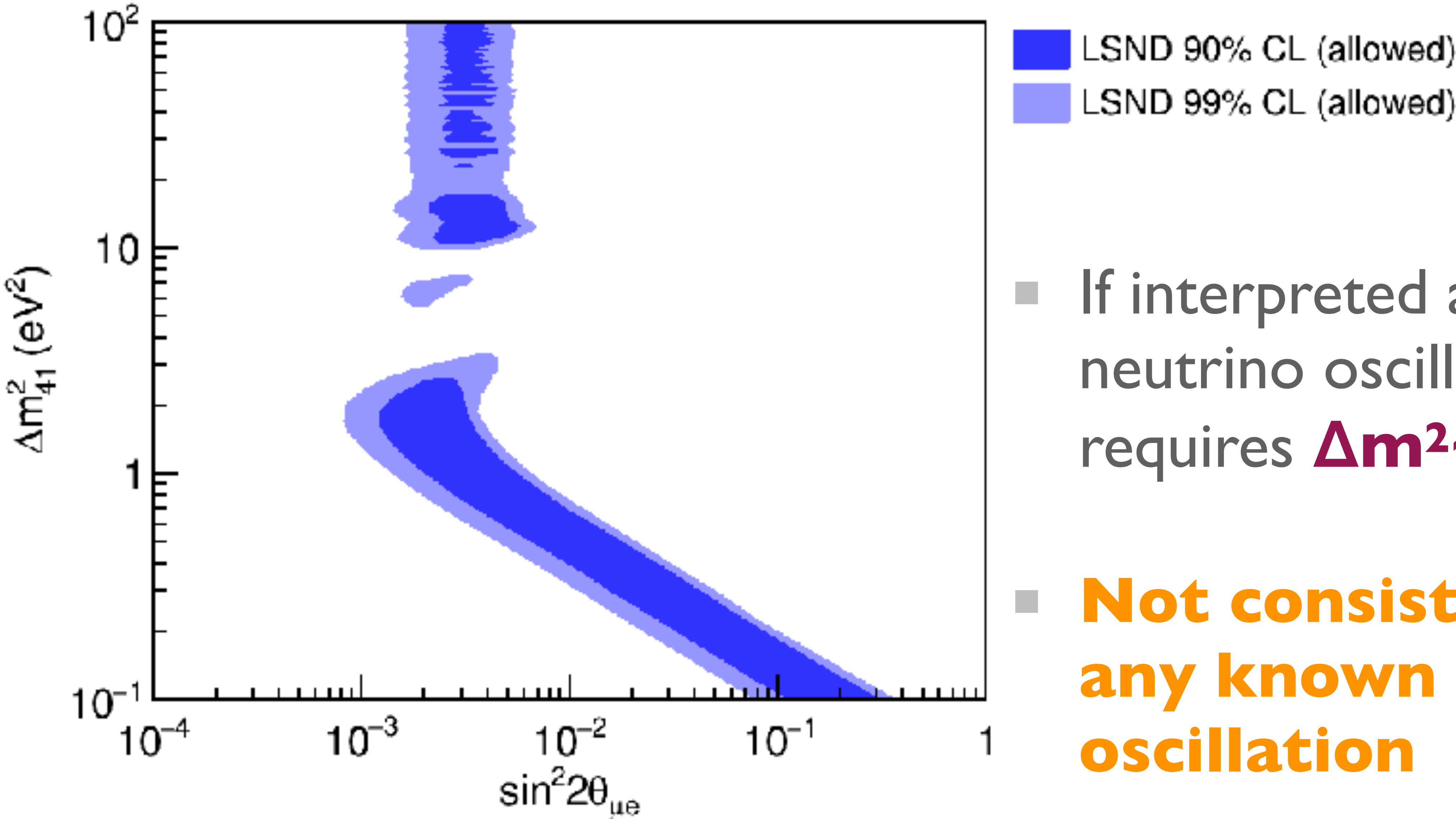


Phys. Rev. D 64, 112007

- Observed excess of $\bar{\nu}_e$ at 3.8σ
- If interpreted as two-flavour neutrino oscillation, requires **$\Delta m^2 \sim 0.2\text{-}10 eV^2$**
- **Not consistent with any known 3-flavour oscillation**

ANOMALIES: LSND

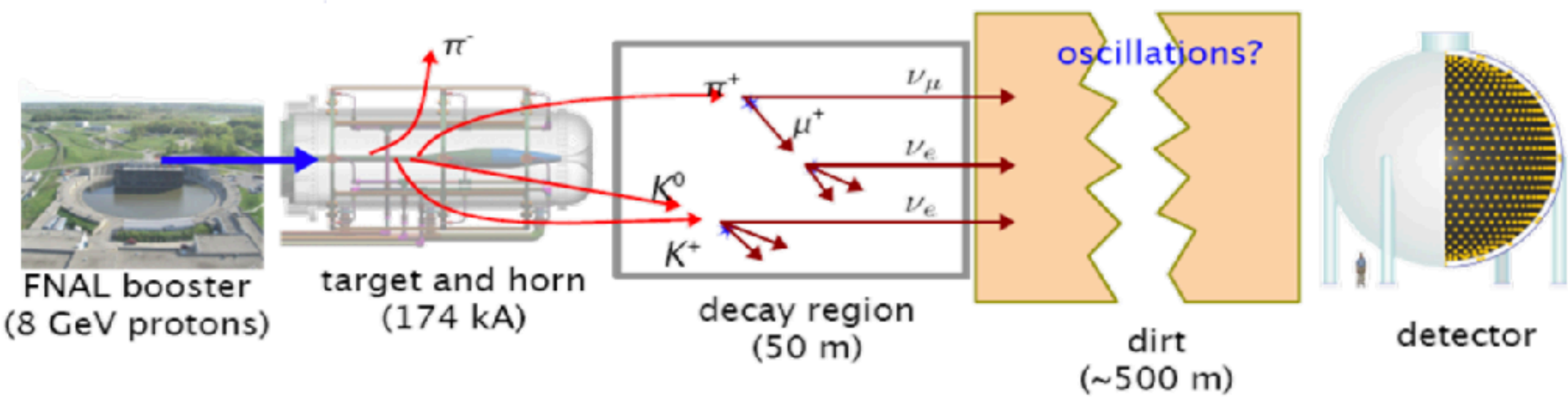




- If interpreted as two-flavour neutrino oscillation, requires **$\Delta m^2 \sim 0.2\text{-}10 eV^2$**
- **Not consistent with any known 3-flavour oscillation**

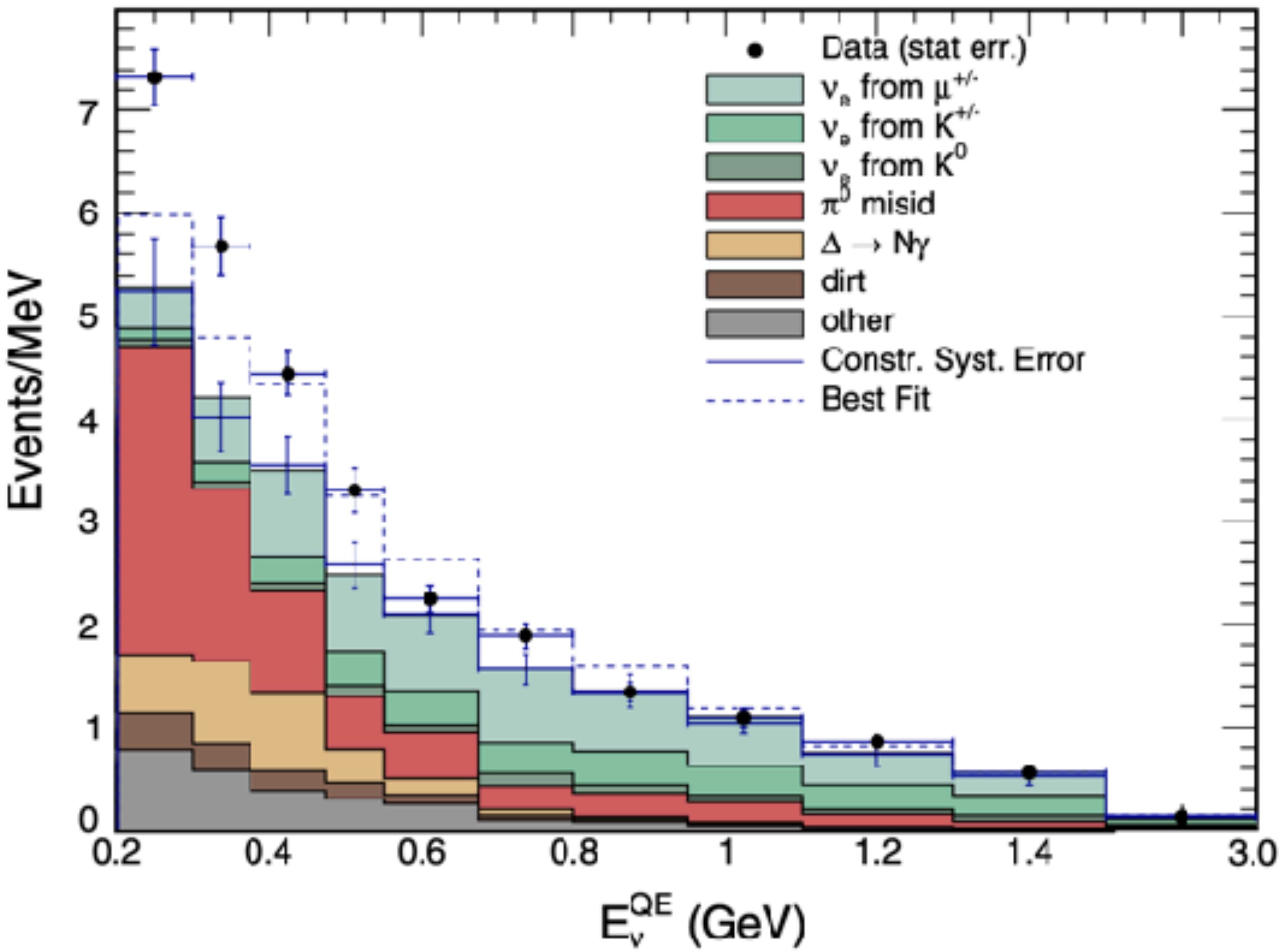
Phys. Rev. D 64, 112007

ANOMALIES: MINIBOONE



- Similar L/E as LSND: if an oscillation really exists, should see it here too
- Different energy, detector, beam, event signatures, backgrounds

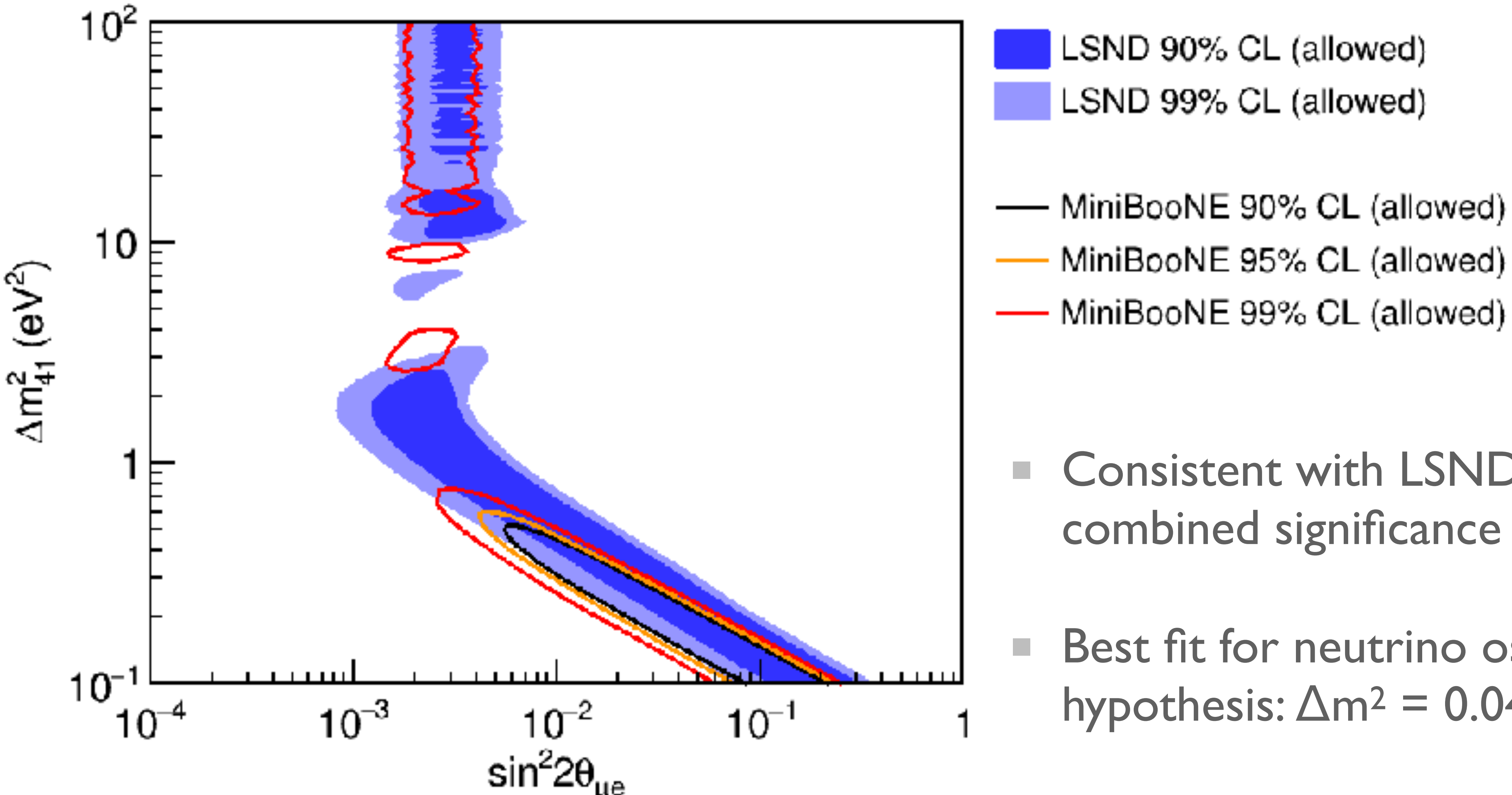
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



- Recently released updated results (2021) with x2 more data than original anomaly (2009)
- 4.8σ excess of measured ν_e and $\bar{\nu}_e$ over prediction, focused at low energy
- Consistent with LSND results: combined significance of 6.1σ
- Best fit for neutrino oscillation hypothesis: $\Delta m^2 = 0.04\ eV^2$

Phys. Rev. D 103, 052002

THE MINIBOONE LOW-ENERGY EXCESS (LEE)

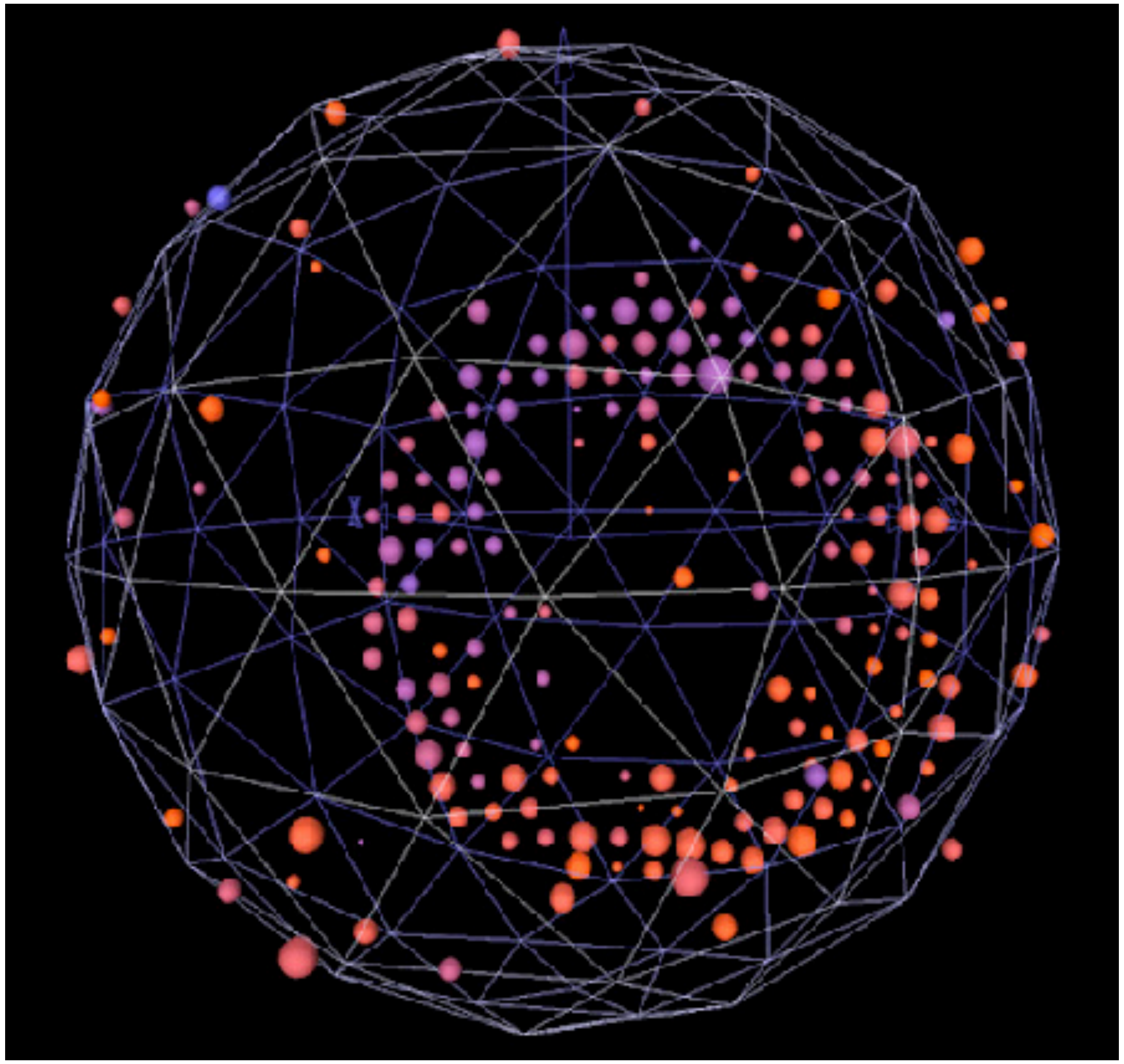


- Consistent with LSND results: combined significance of 6.1σ
- Best fit for neutrino oscillation hypothesis: $\Delta m^2 = 0.04$ eV^2

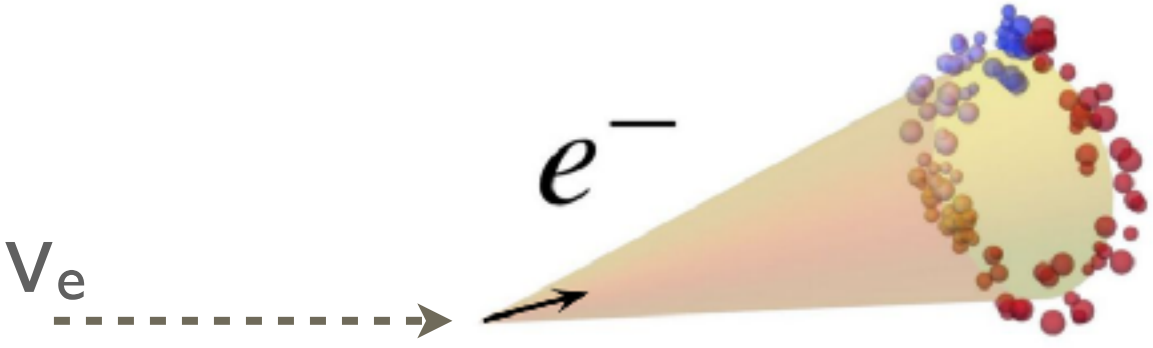
Phys. Rev. D 103, 052002

UNIVERSITY OF OXFORD

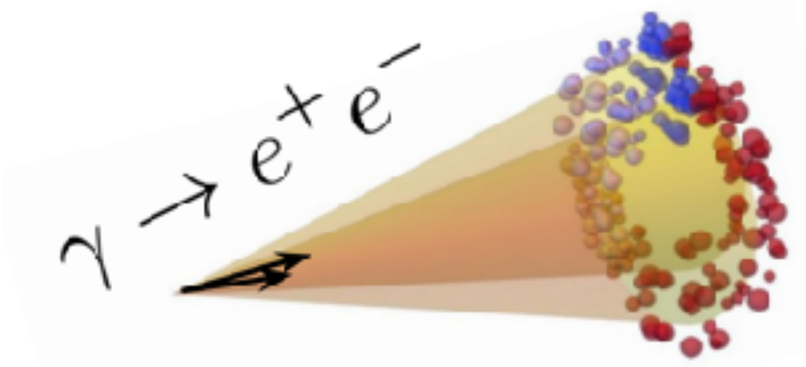
MINIBOONE



- 800-ton mineral oil (CH_2) Cherenkov detector
- Detect Cherenkov ring from **electrons** produced in **ν_e CC scattering** interactions

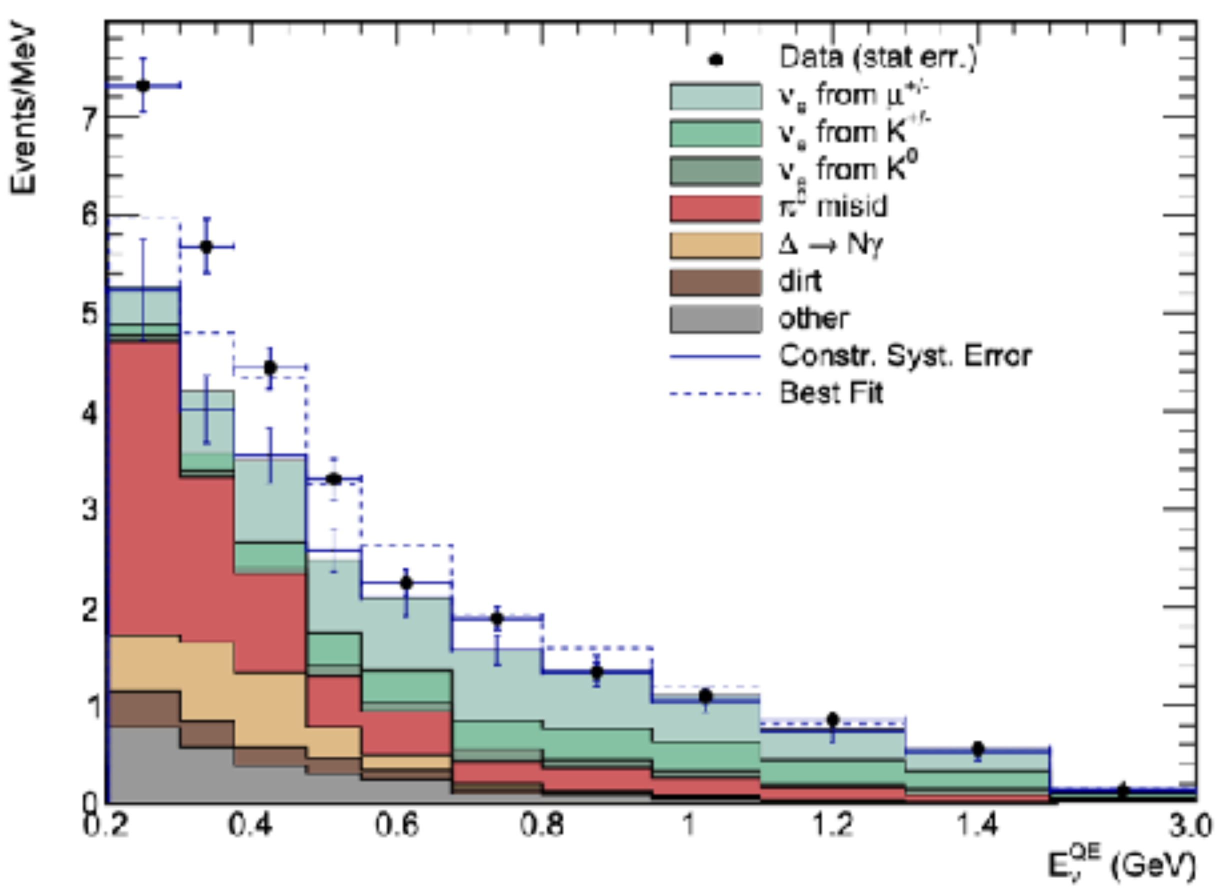


- However, **photons** produce identical Cherenkov rings



UNIVERSITY OF OXFORD

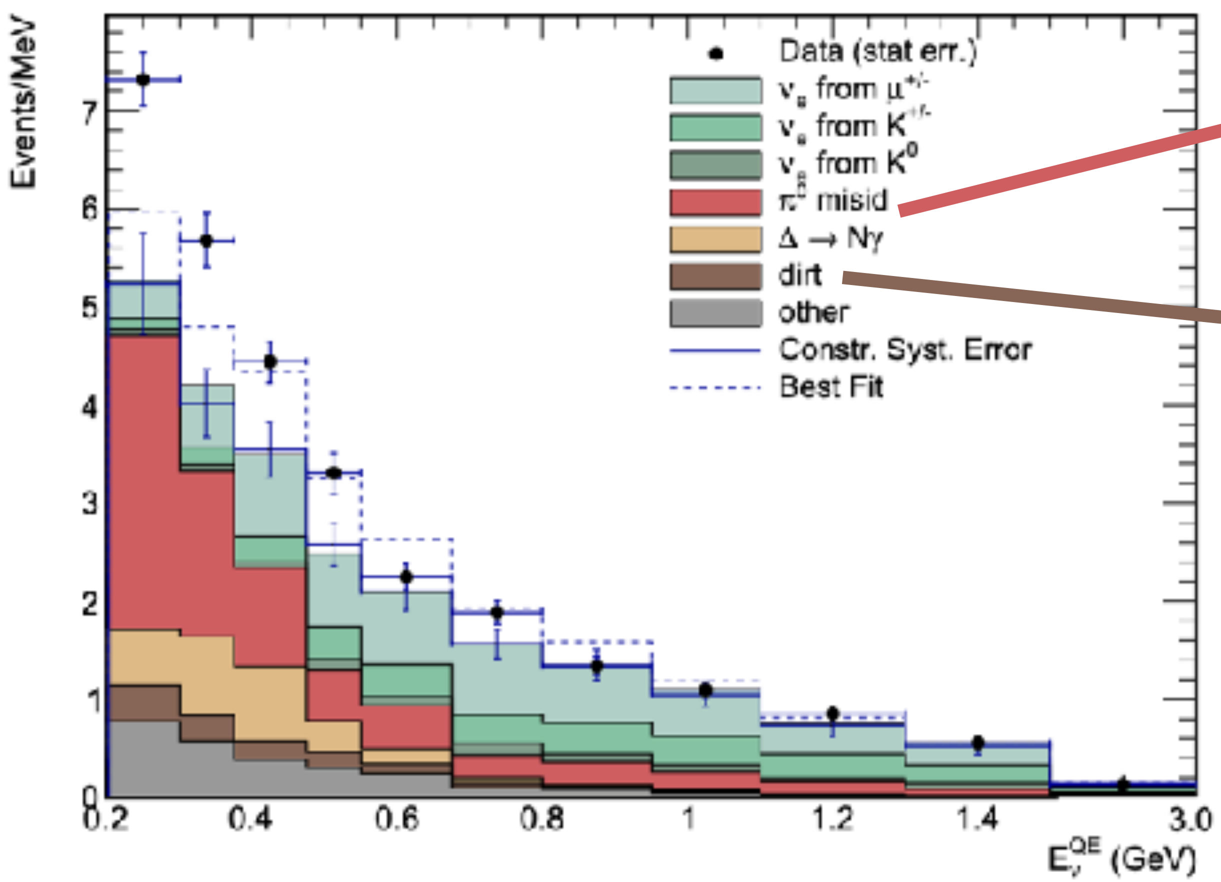
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



Is the excess electrons?

- Sterile neutrino oscillations → difficult to explain MiniBooNE excess and all other global data
- Best-fit 2-neutrino sterile oscillation appearance spectrum does not predict data well at very low energies
- More complex models can help
  - Mixed oscillations and decay
  - Resonance matter effects
  - Additional sterile neutrinos
  - Non-unitary mixing
  - …and many more!

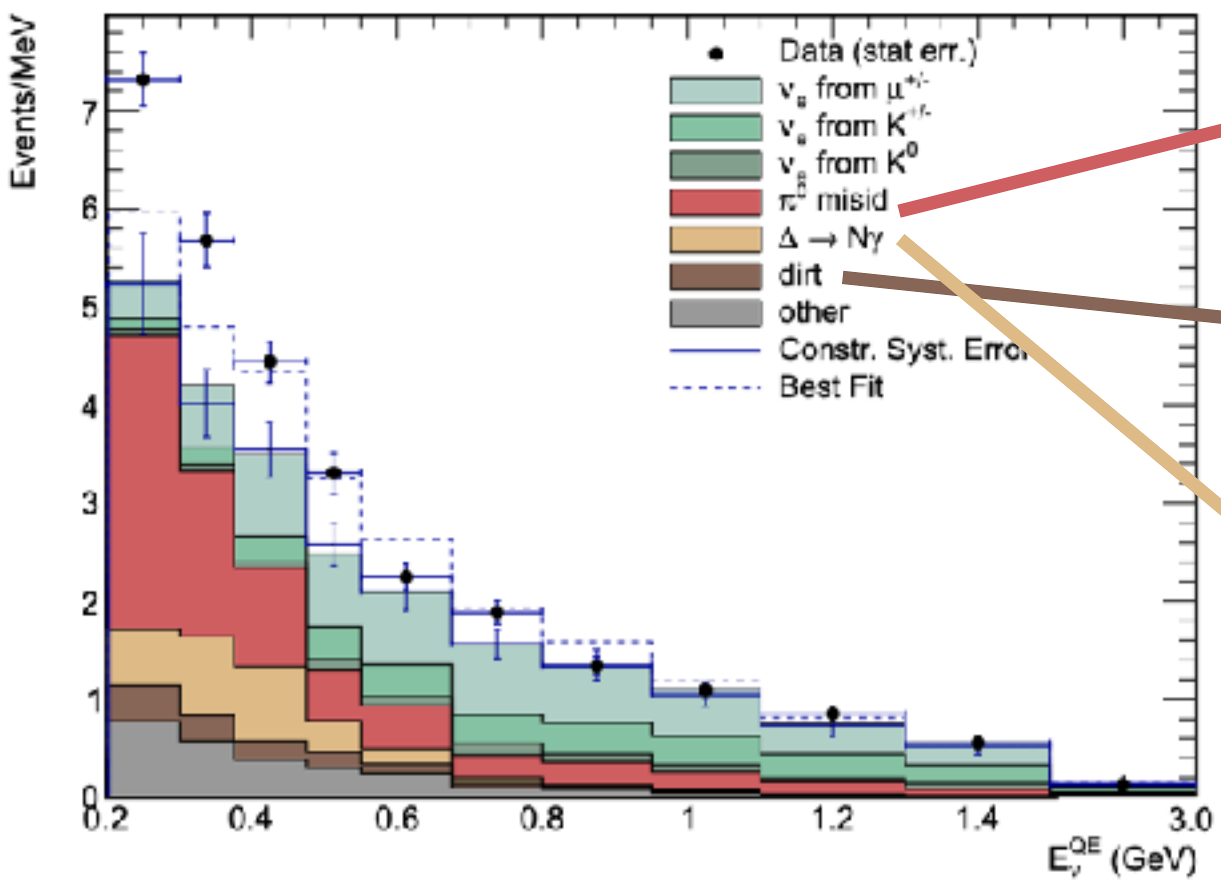
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



Is the excess photons?

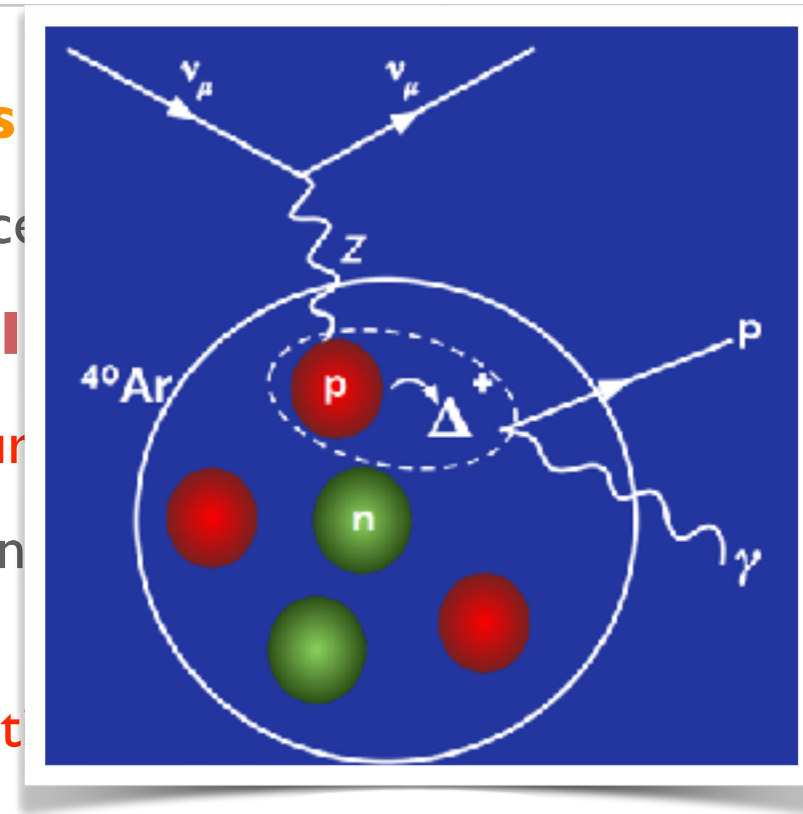
- Several sources of photon backgrounds:
- **NCπ^0 mis-ID**
  - → measured in-situ
- **Dirt** (neutrino interactions outside the detector)
  - → beam timing

THE MINIBOONE LOW-ENERGY EXCESS (LEE)



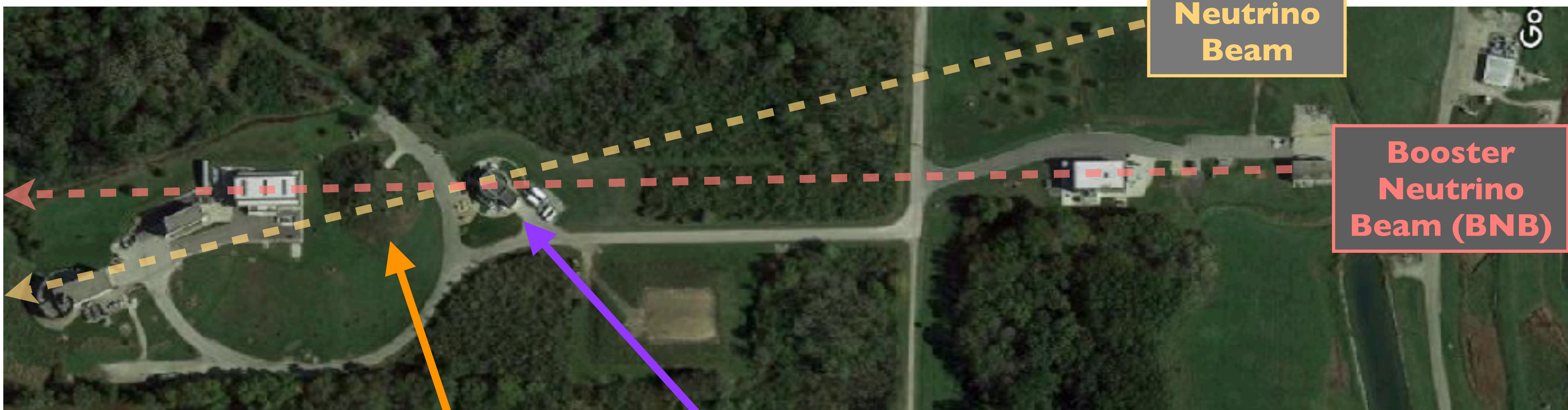
Is the excess

- Several source
- **NCπ⁰ mis-I**
  - → measur
- **Dirt** (neutrin detector)
  - → beam t
- **NC Δ→Nγ**
  - → not constrained directly - predicted from NCπ⁰ rate and theoretical branching fraction
  - Need x3.18 increase to explain excess
  - → to be investigated…



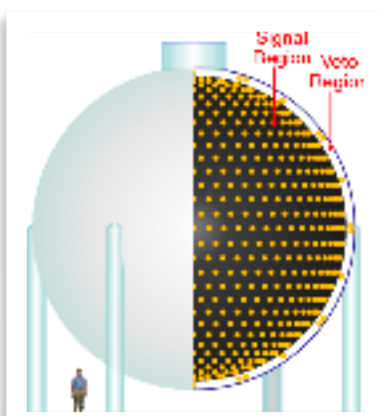
UNIVERSITY OF OXFORD

ENTER MICROBOONE



MiniBooNE

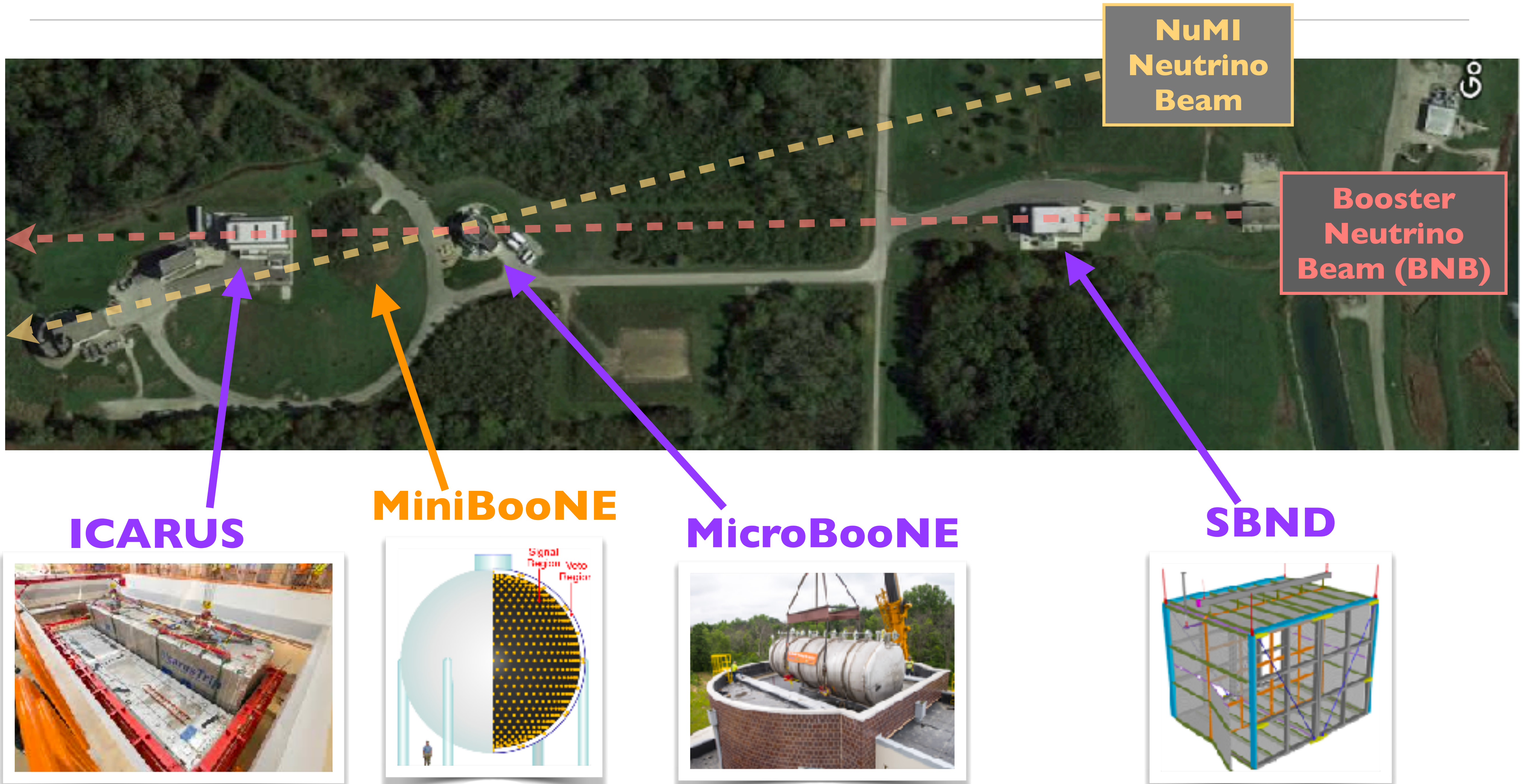
500m



MicroBooNE

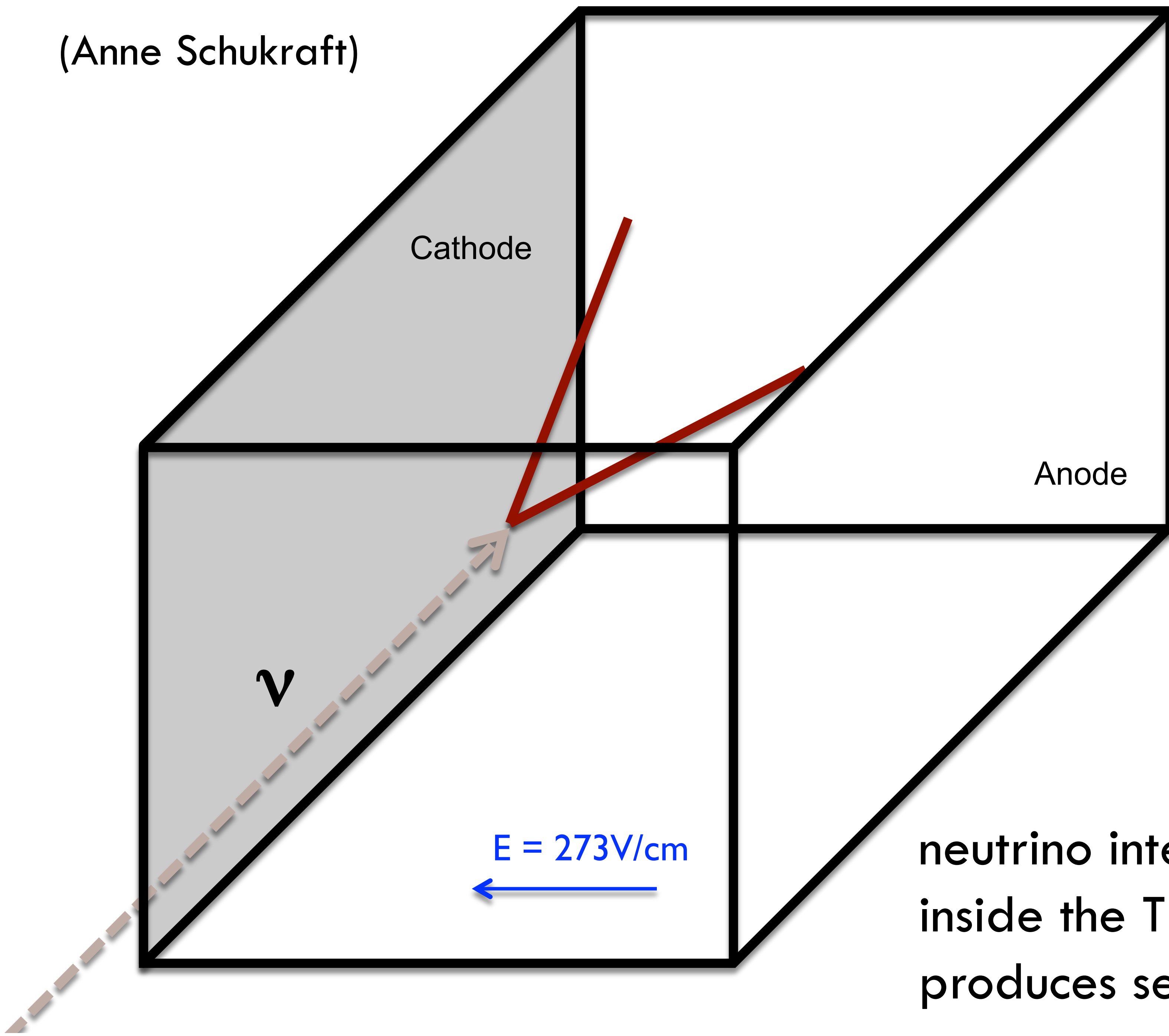
470m

FIRST STEP IN THE FERMILAB SBN PROGRAMME



LIQUID ARGON TPC

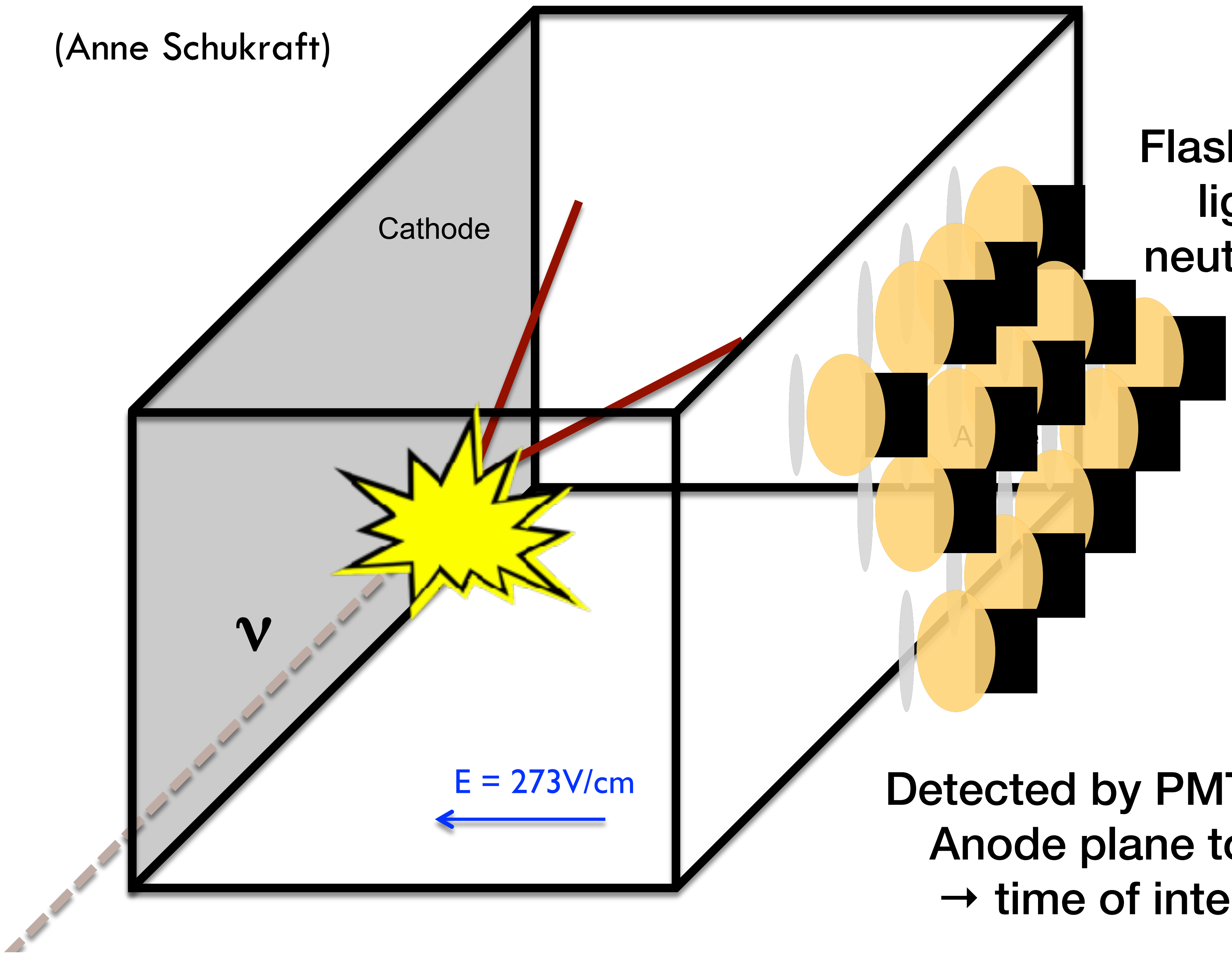
(Anne Schukraft)



neutrino interacts with the argon inside the TPC volume and produces secondary particles

LIQUID ARGON TPC

(Anne Schukraft)



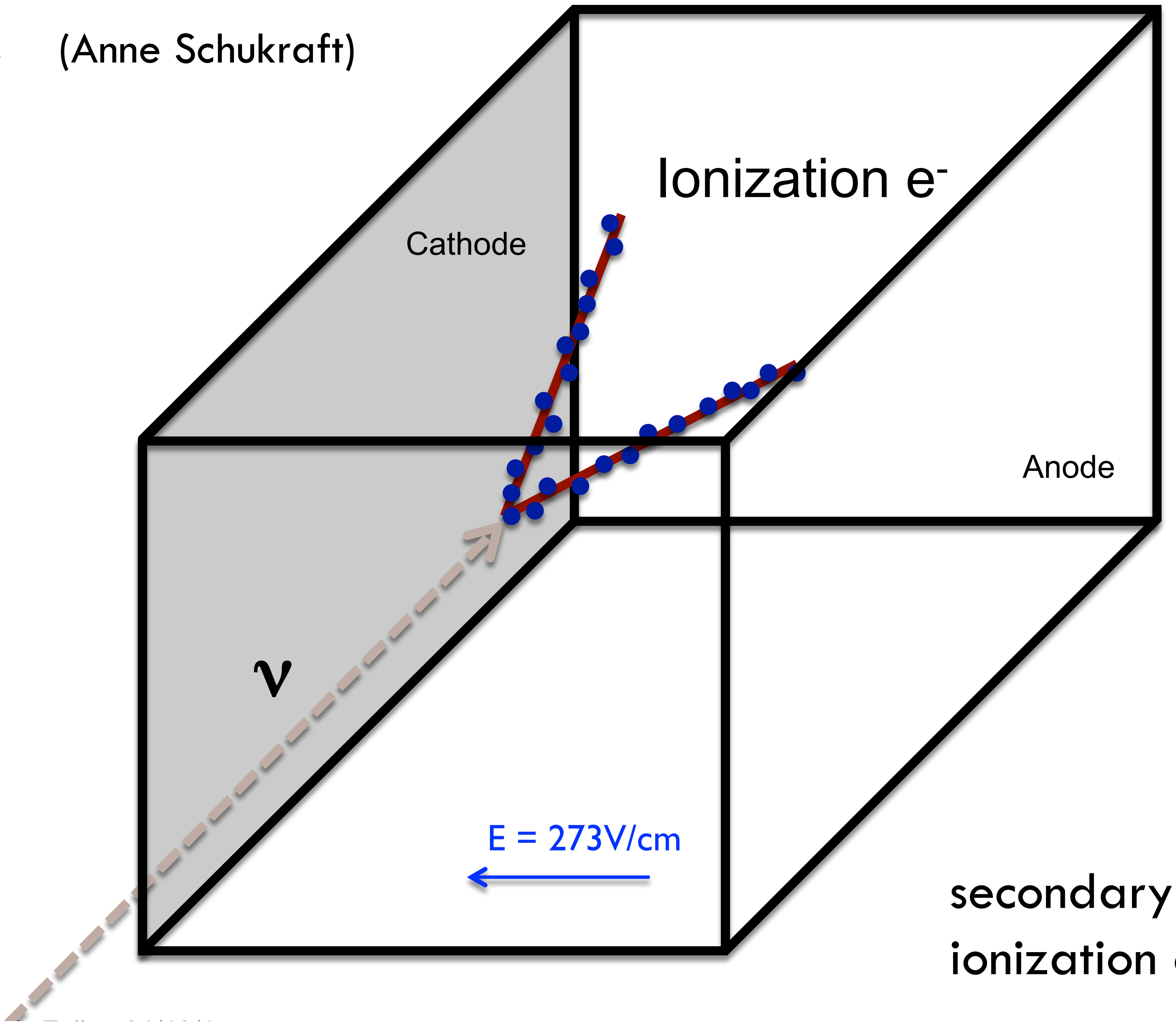
Flash of scintillation light at time of neutrino interaction

Detected by PMTs behind Anode plane to get t0 → time of interaction

UNIVERSITY OF OXFORD

LIQUID ARGON TPC

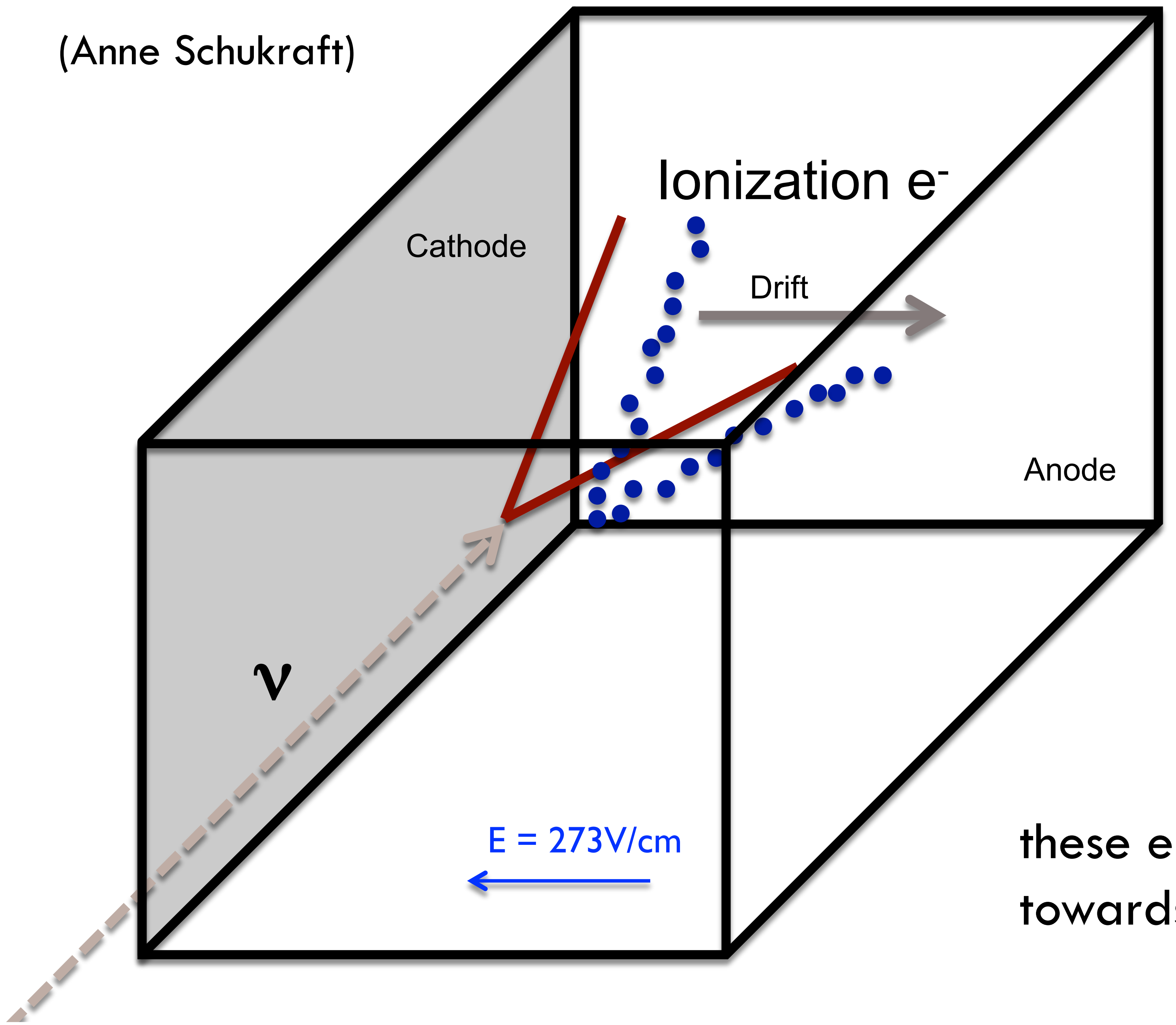
(Anne Schukraft)



secondary particles produce ionization electrons

LIQUID ARGON TPC

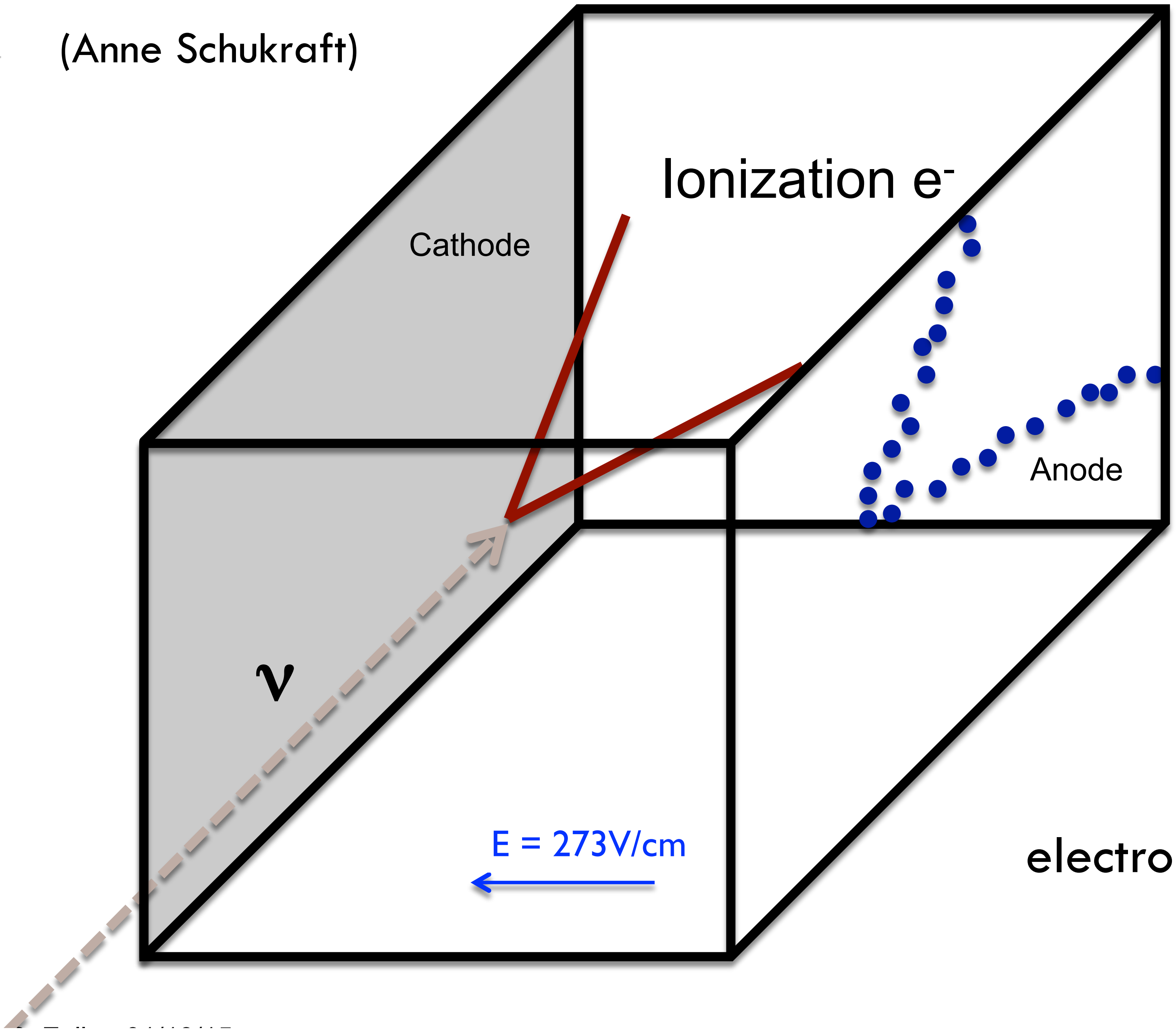
(Anne Schukraft)



these electrons drift towards the anode

LIQUID ARGON TPC

(Anne Schukraft)

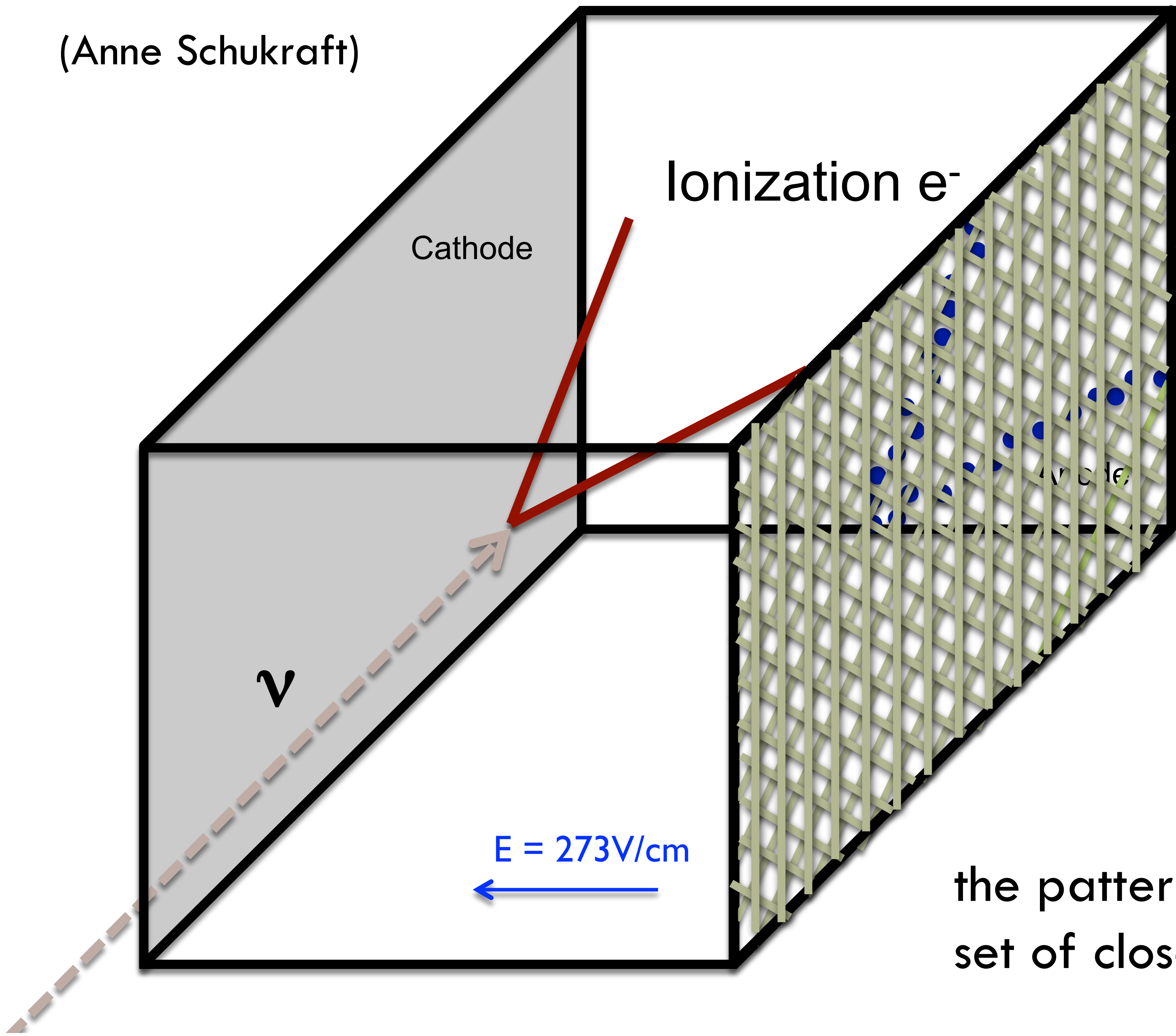


electrons arrive at anode

LIQUID ARGON TPC

(Anne Schukraft)

wire planes

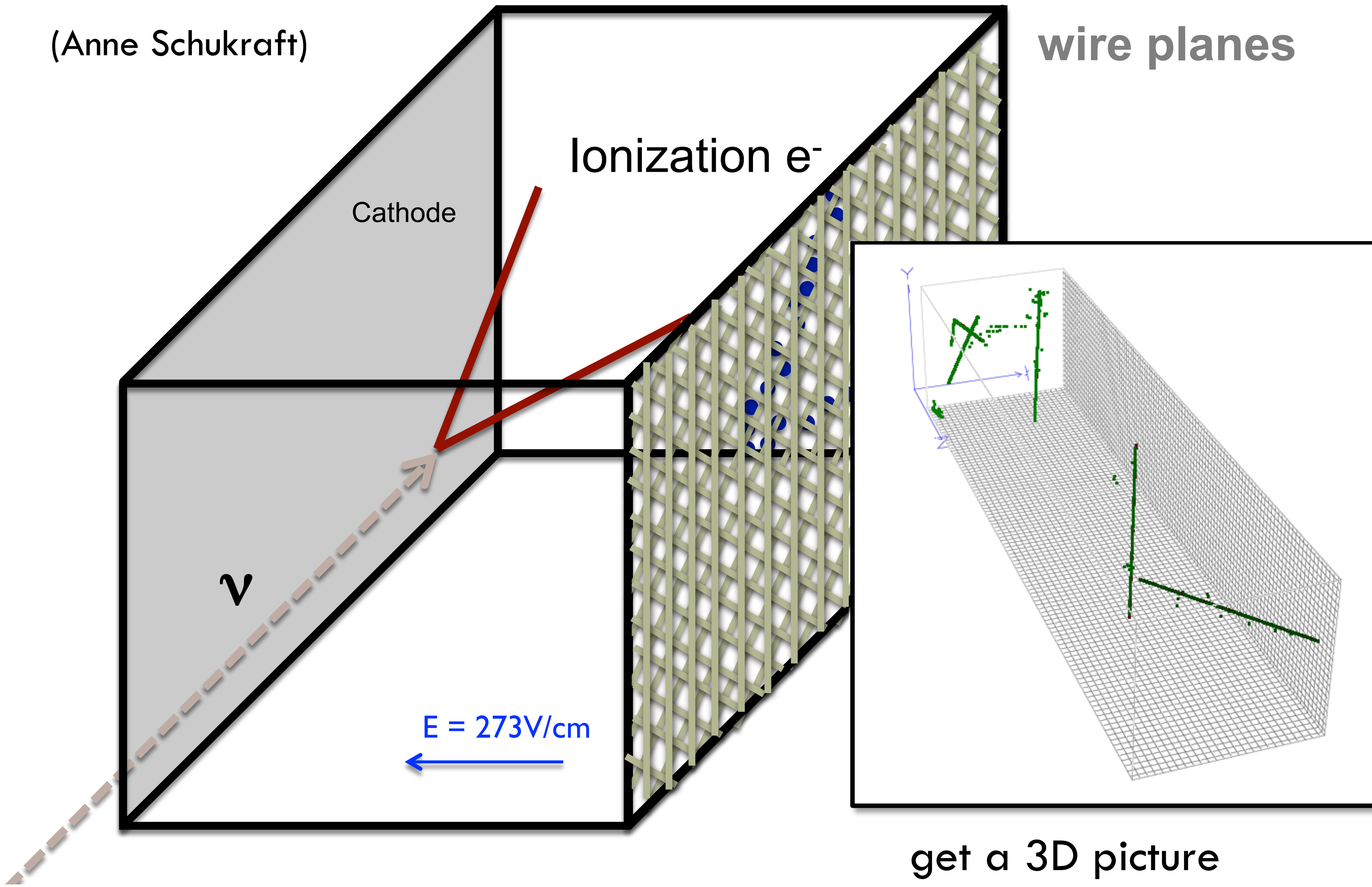


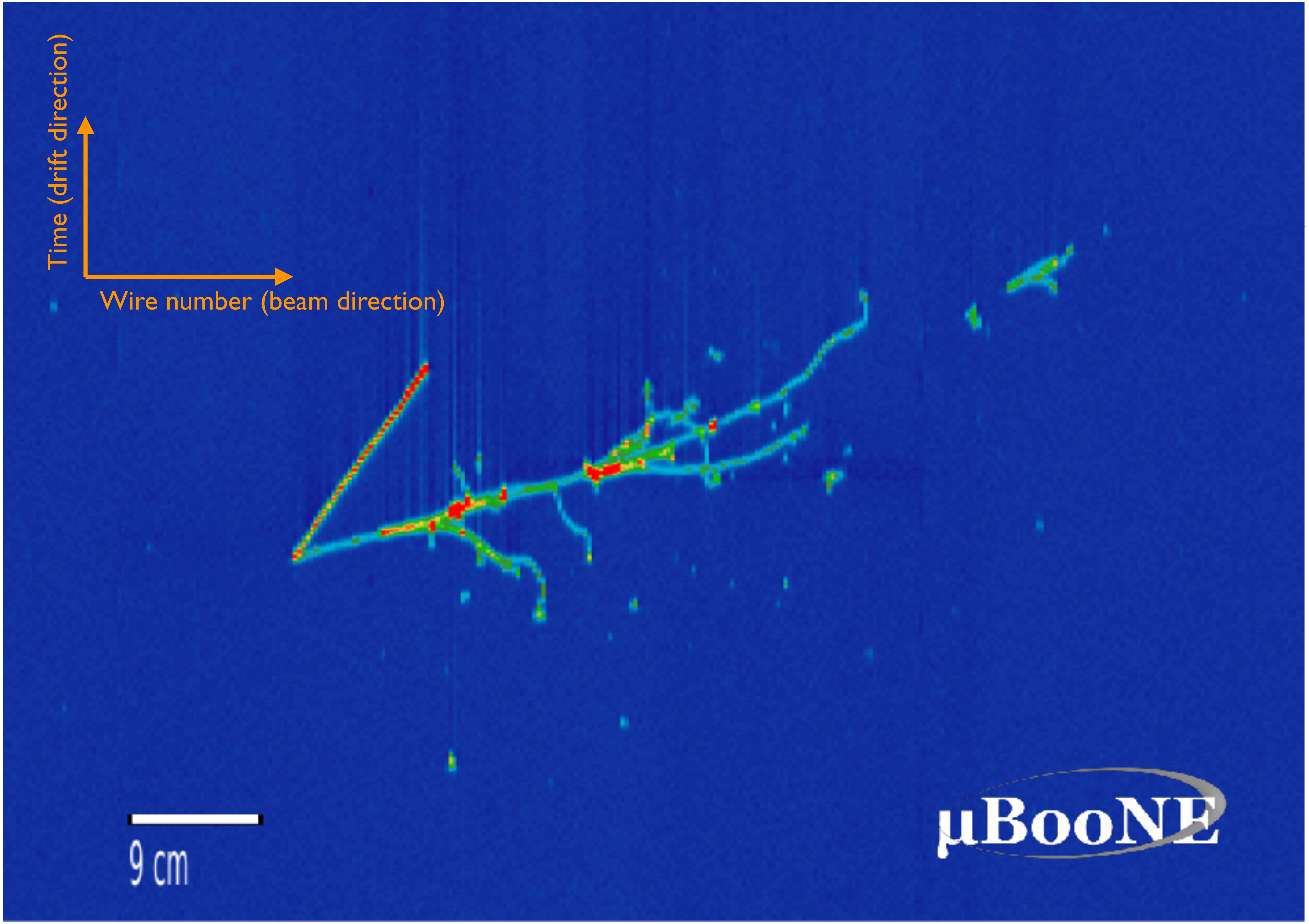
the pattern is recorded on a set of closely spaced wires

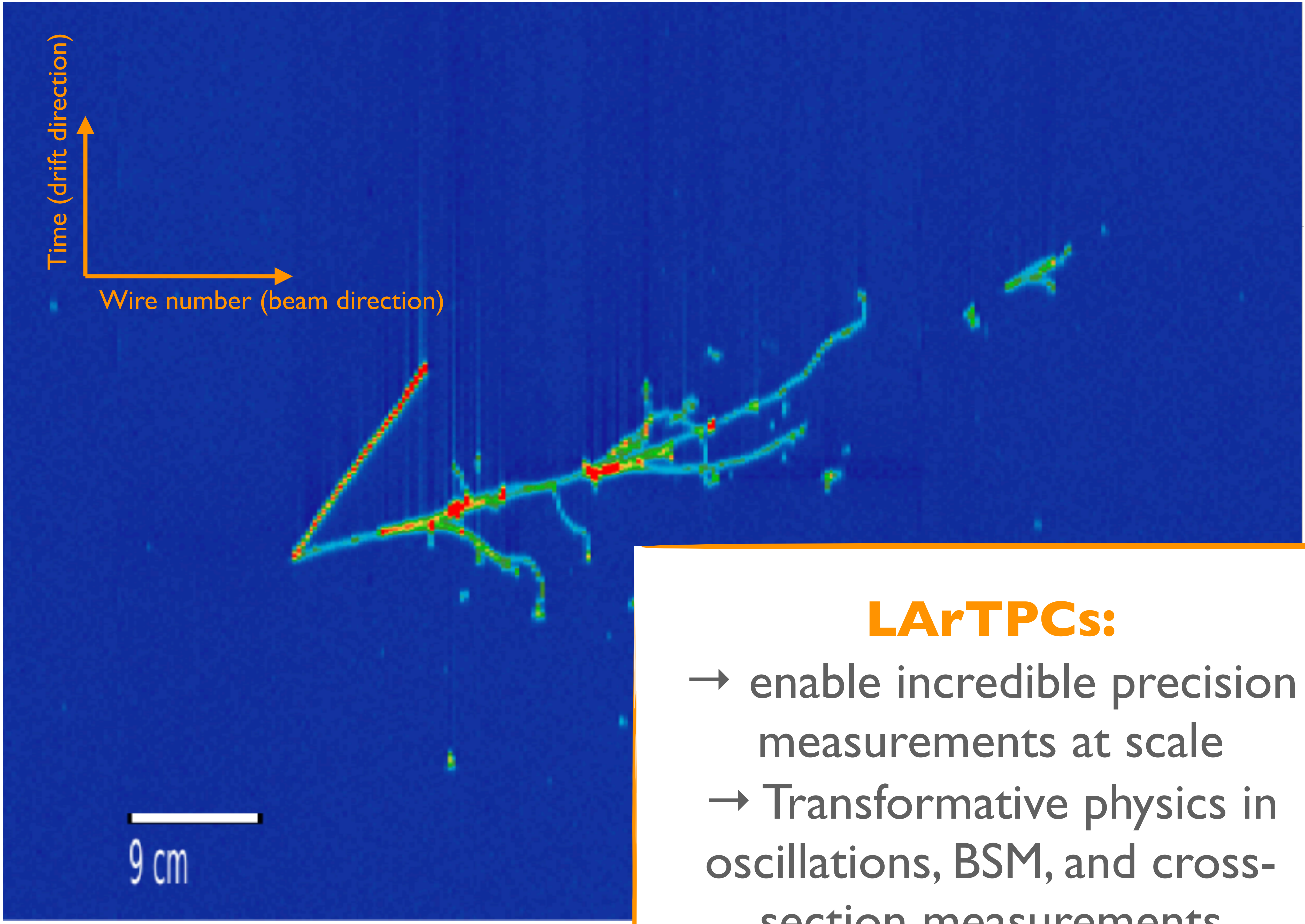
UNIVERSITY OF OXFORD

LIQUID ARGON TPC

(Anne Schukraft)




Time (drift direction)
Wire number (beam direction)
9 cm
μBooNE



LArTPCs:

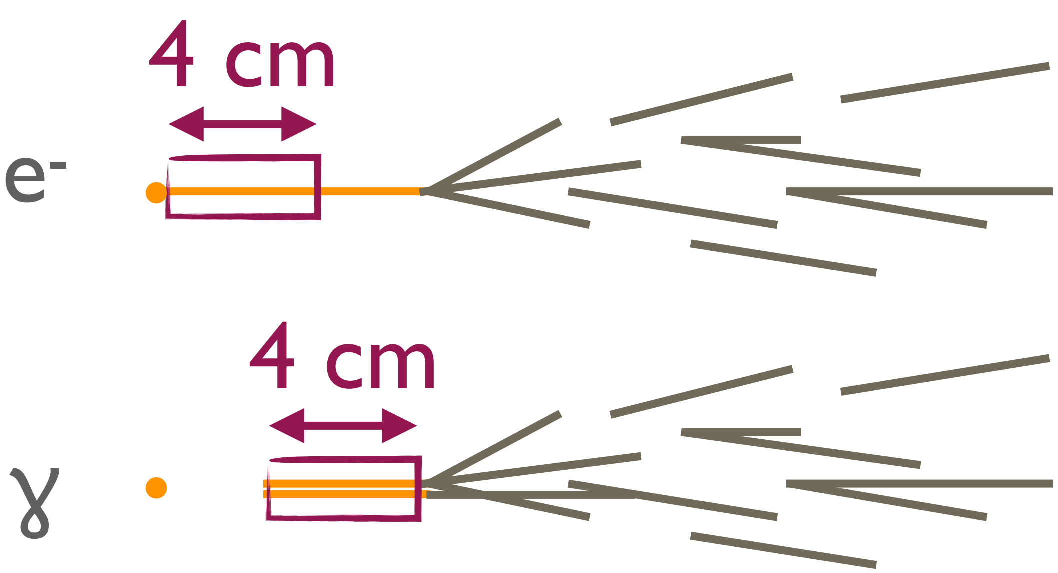
→ enable incredible precision measurements at scale

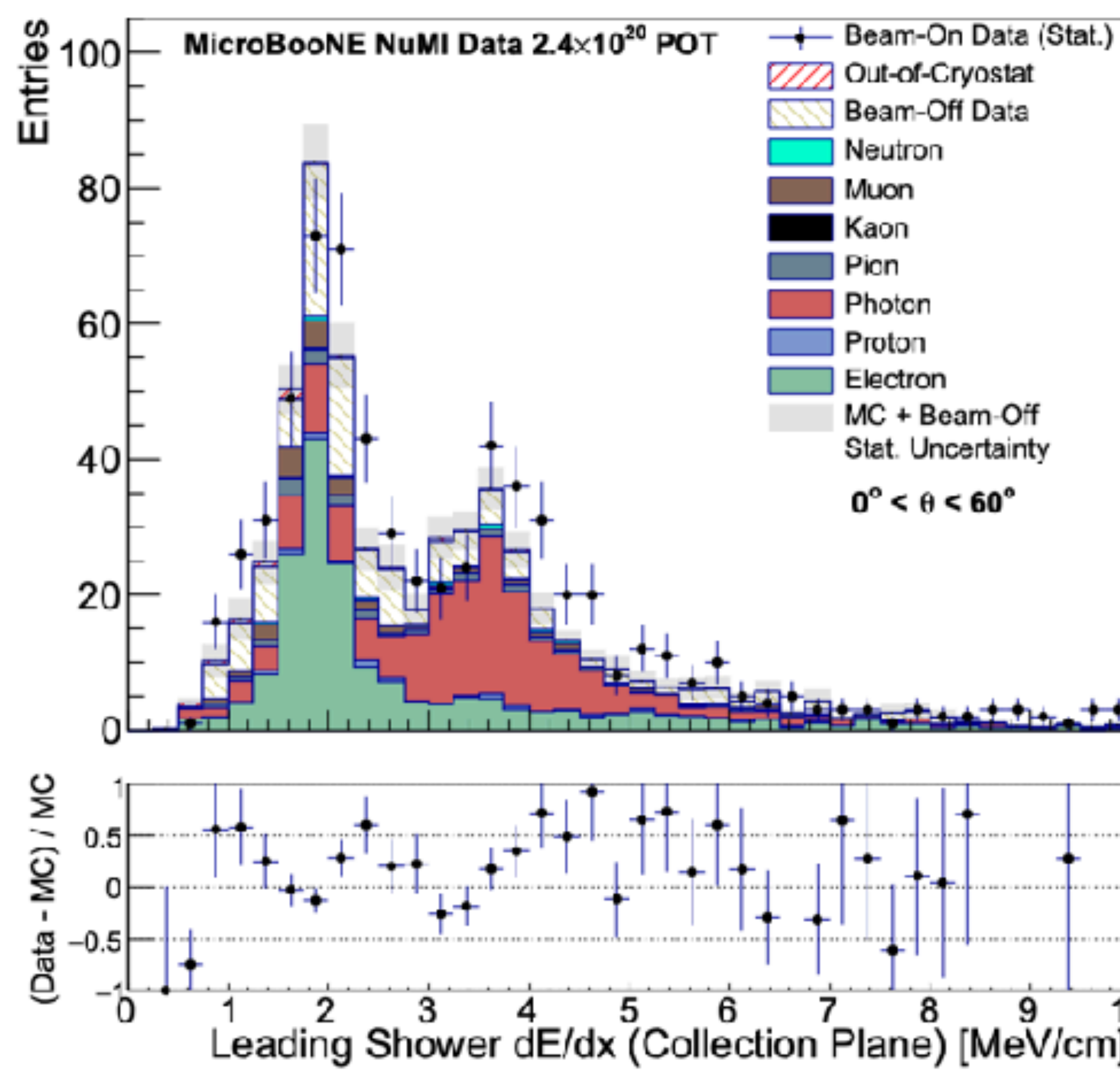
→ Transformative physics in oscillations, BSM, and cross-section measurements

LARTPC STRENGTH: ELECTRONS AND PHOTONS

Phys. Rev. D 104, 052002 (2021)

- **Electrons and photons produce showers in LArTPCs**
- Distinguish using dE/dx at start of shower and start point



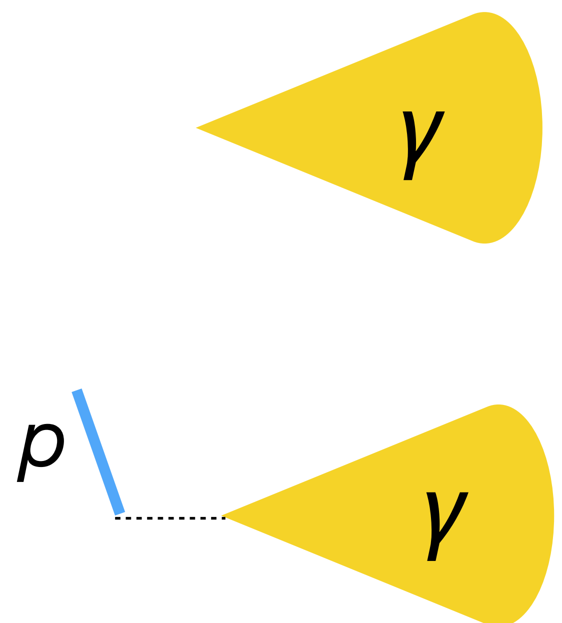


UNIVERSITY OF OXFORD

INVESTIGATING THE MINIBOONE LOW-ENERGY EXCESS

Photon search

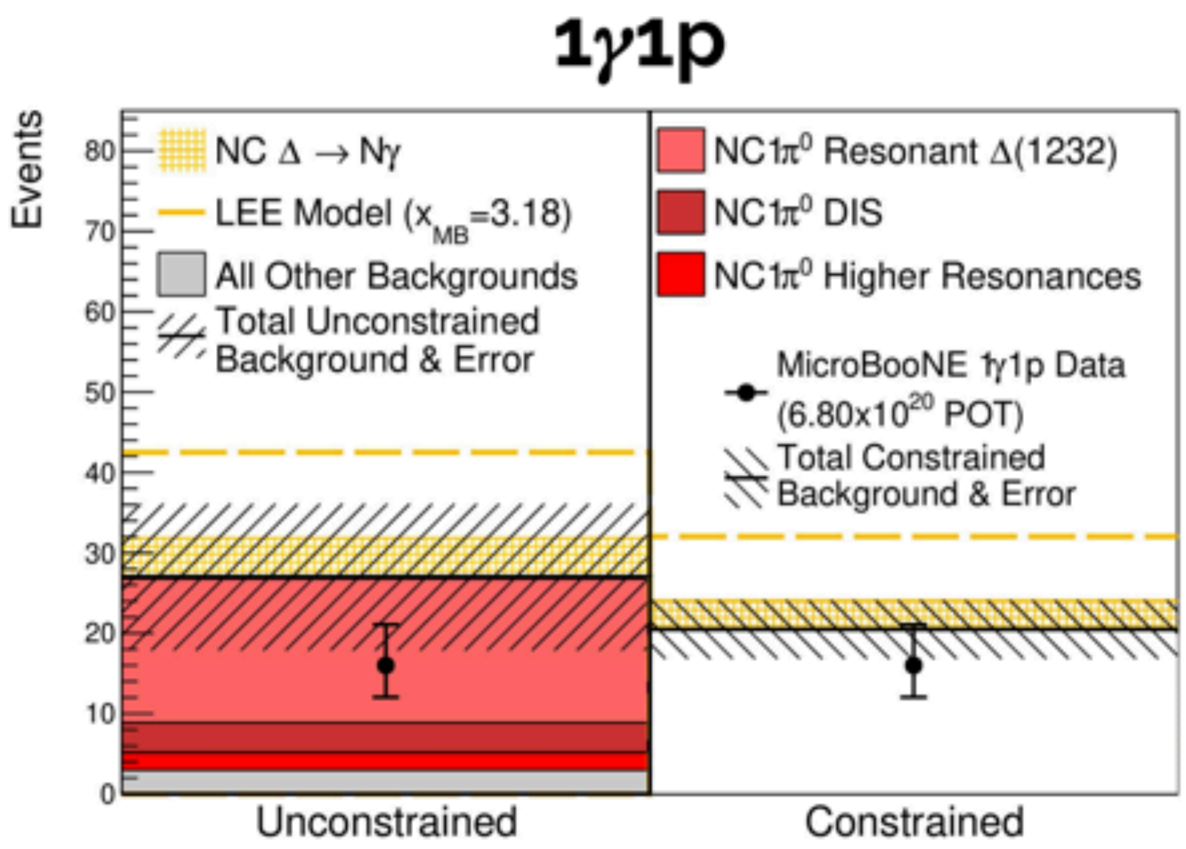
Target $\Delta \rightarrow N\gamma$:
$1\gamma0p$ and $1\gamma1p$



Phys. Rev. Lett. 128, 111801

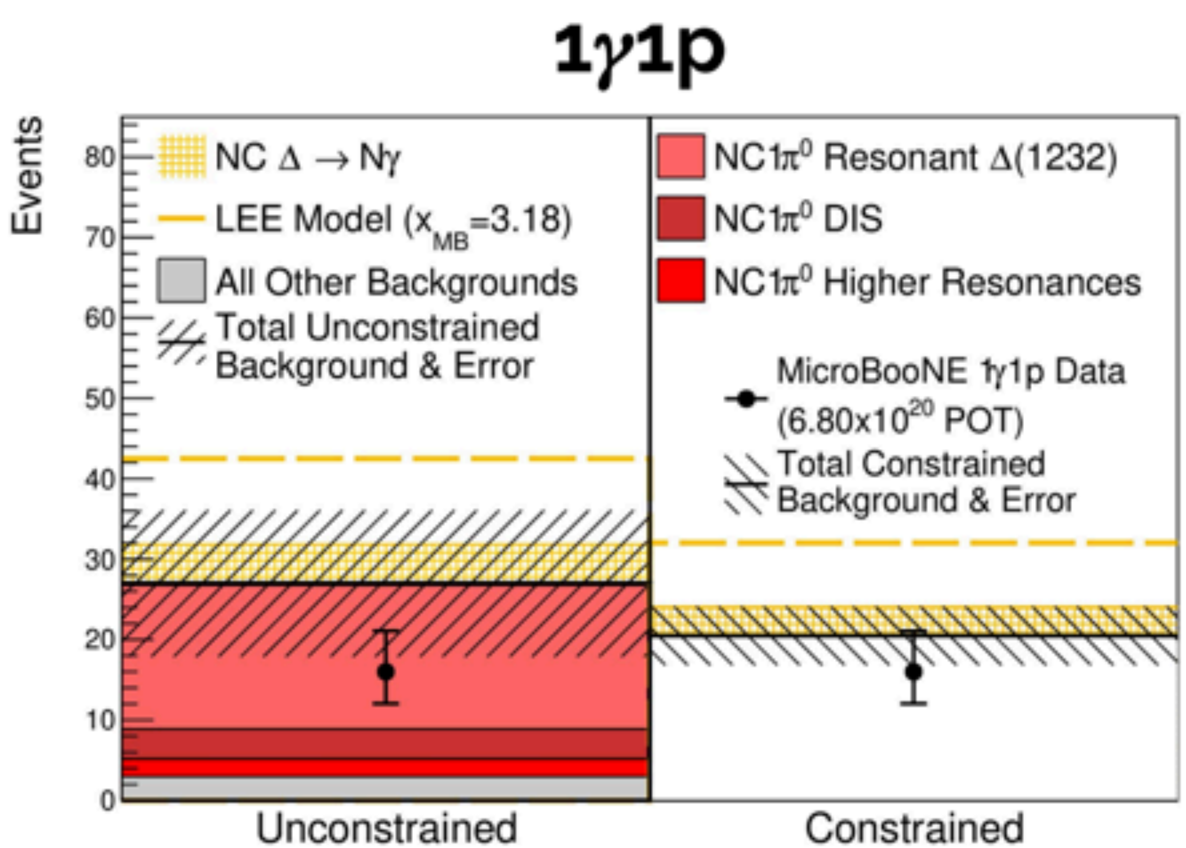
SINGLE PHOTON SEARCH

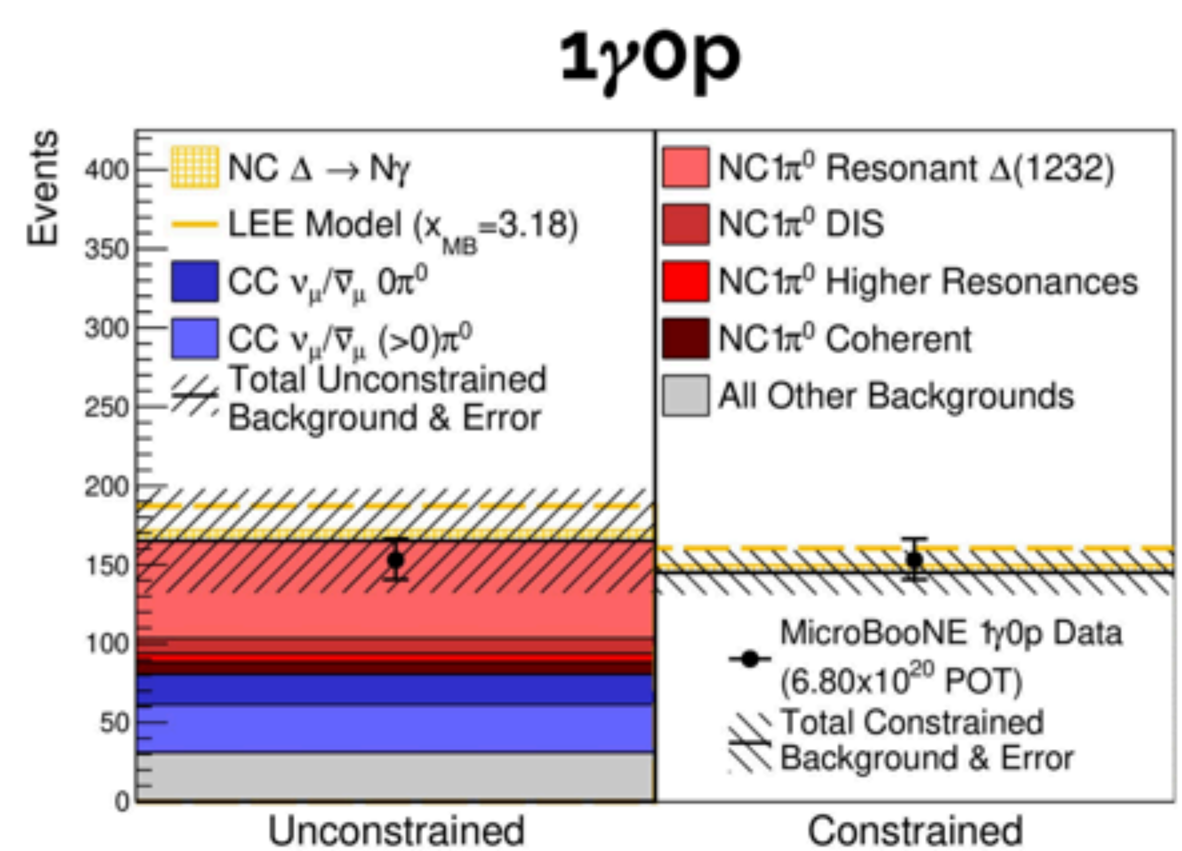
Phys. Rev. Lett. 128, 111801



SINGLE PHOTON SEARCH

Phys. Rev. Lett. 128, 111801



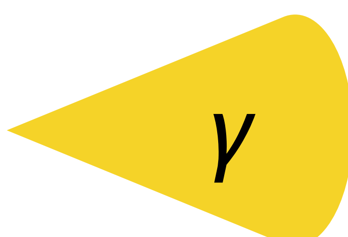


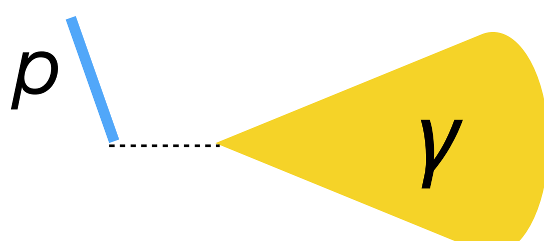
No evidence of an excess in either sample

INVESTIGATING THE MINIBOONE LOW-ENERGY EXCESS

Photon search

Target $\Delta \rightarrow N\gamma$:
$1\gamma0p$ and $1\gamma1p$



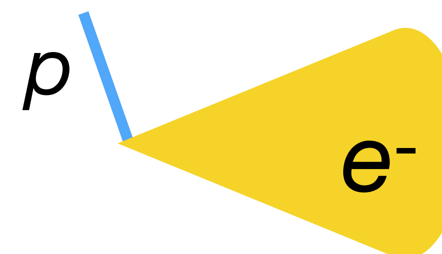


Phys. Rev. Lett. 128, 111801

Electron searches

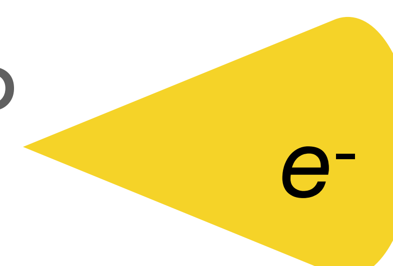
Phys. Rev. D 105, 112003

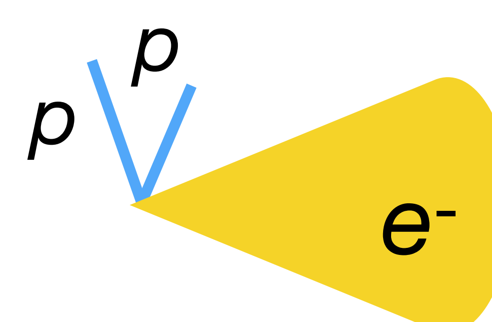
CCQE-like:
1e1p



Phys. Rev. D 105, 112004

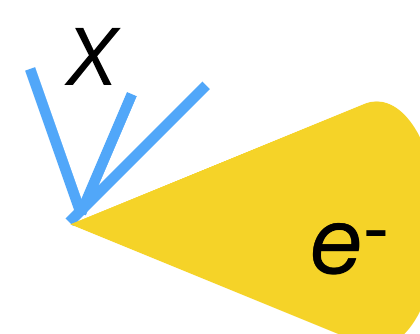
CC0π: 1e0p
and 1eNp





Phys. Rev. D 105, 112005

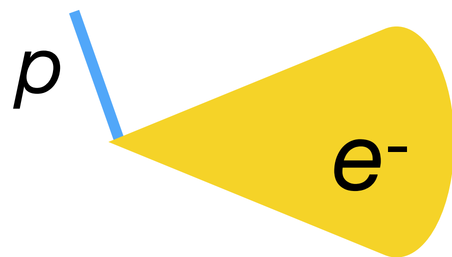
Inclusive:
1eX



UNIVERSITY OF OXFORD

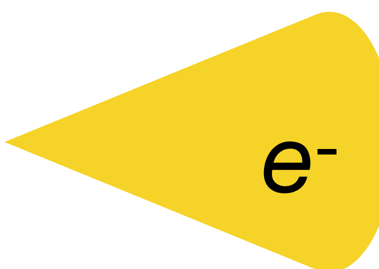
ν_e SEARCH

1e1p



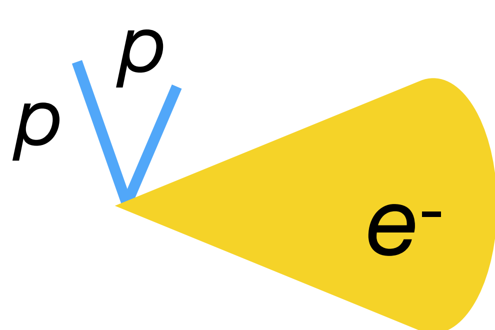
Phys. Rev. D 105, 112003

1e0p



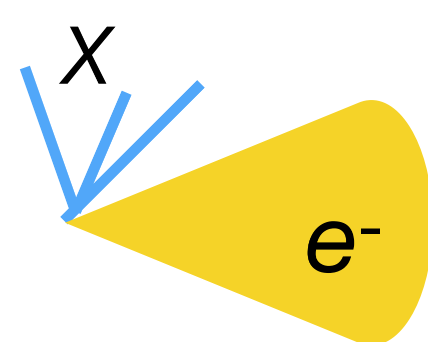
Phys. Rev. D 105, 112004

1eNp



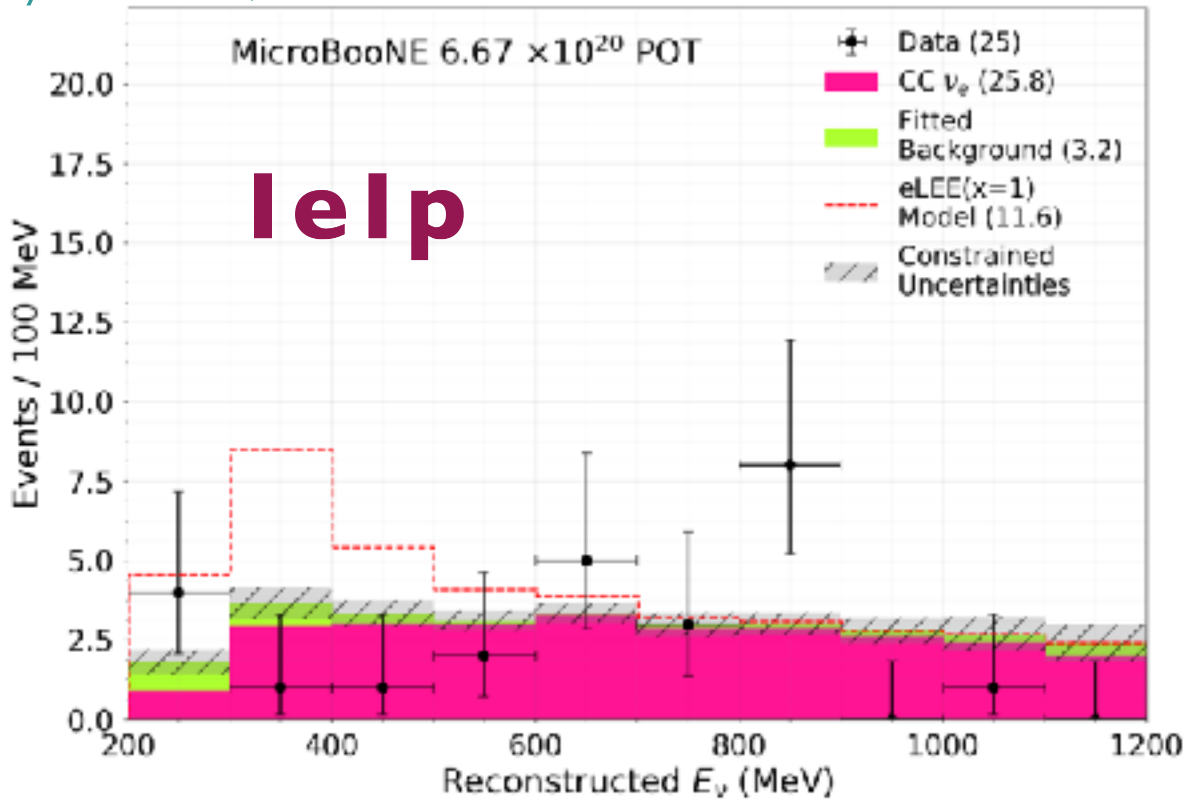
Phys. Rev. D 105, 112004

1eX

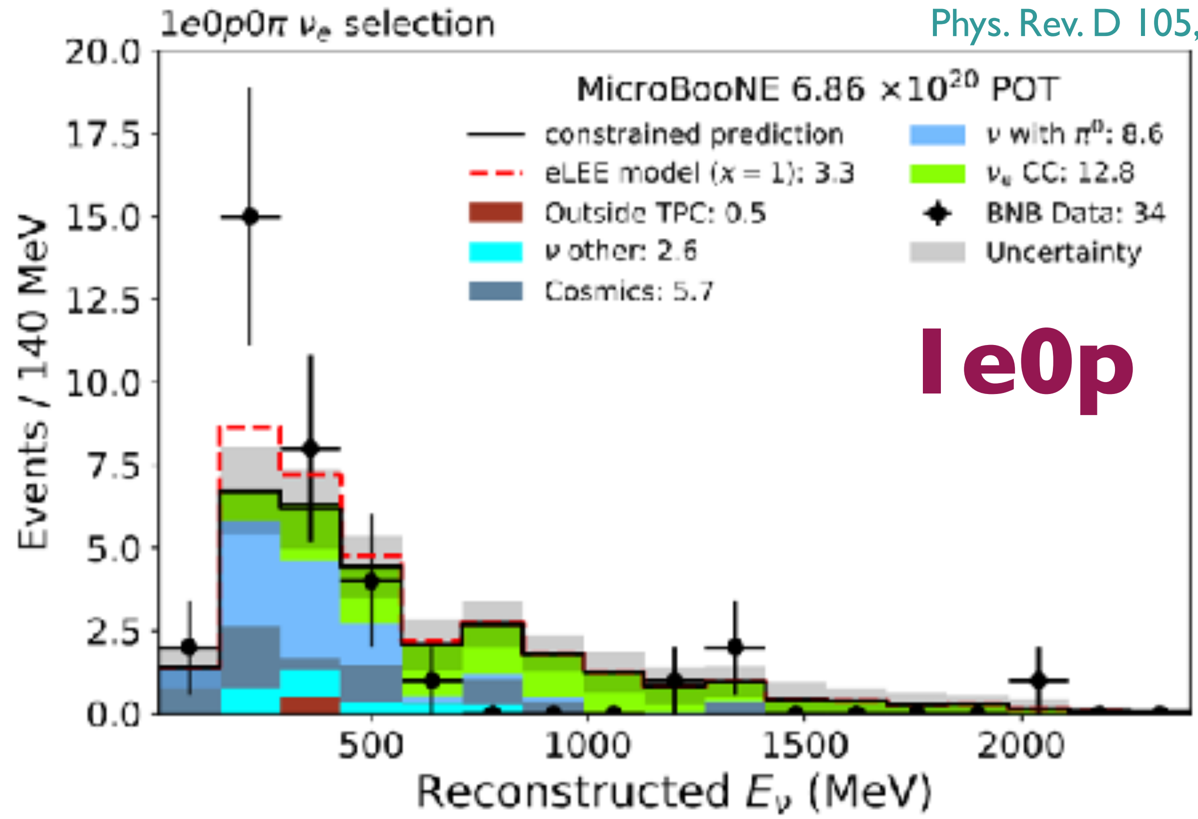


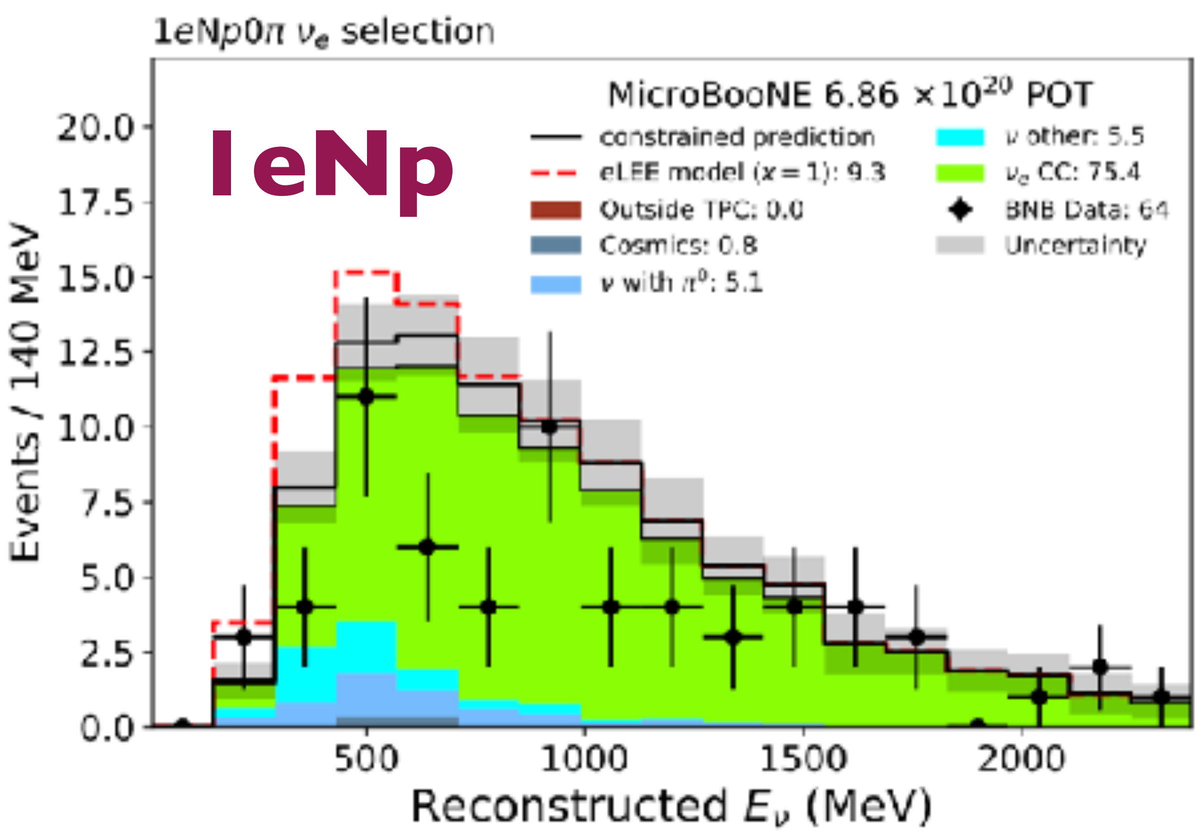
Phys. Rev. D 105, 112005

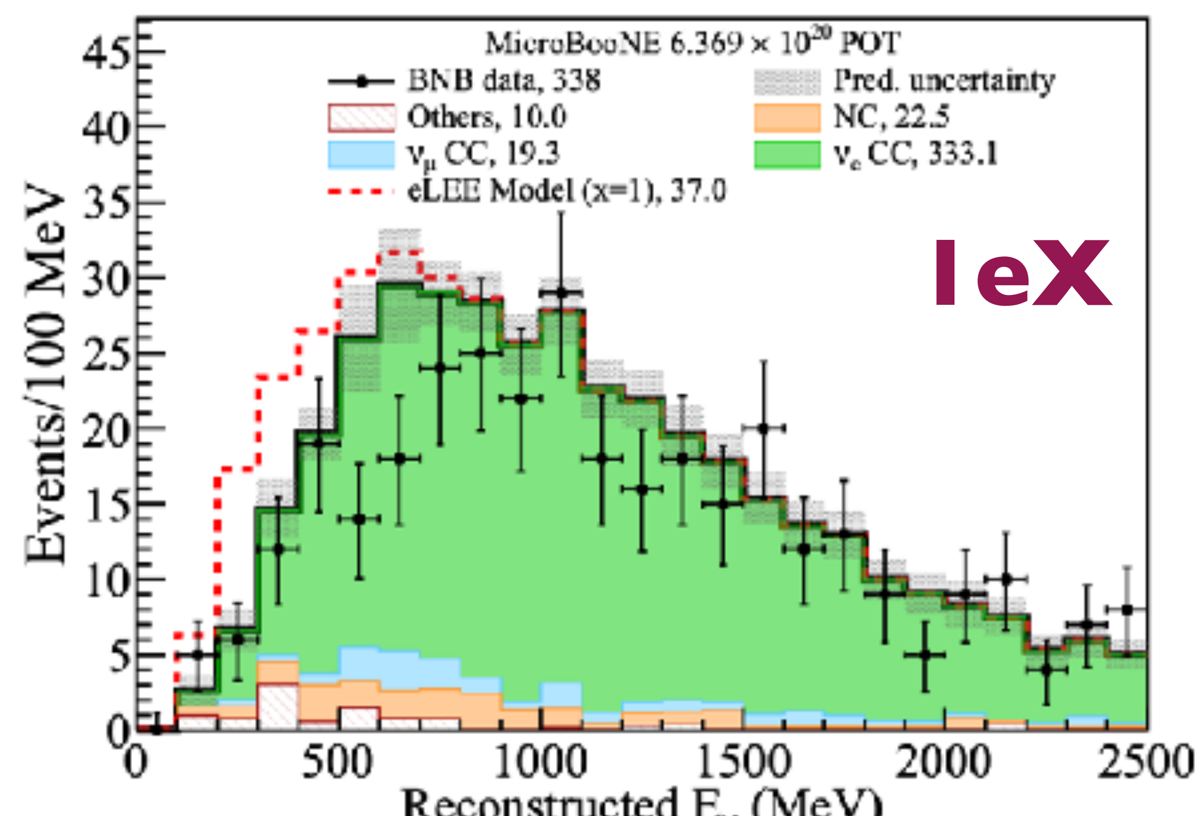
Phys. Rev. D 105, 112003



Phys. Rev. D 105, 112004

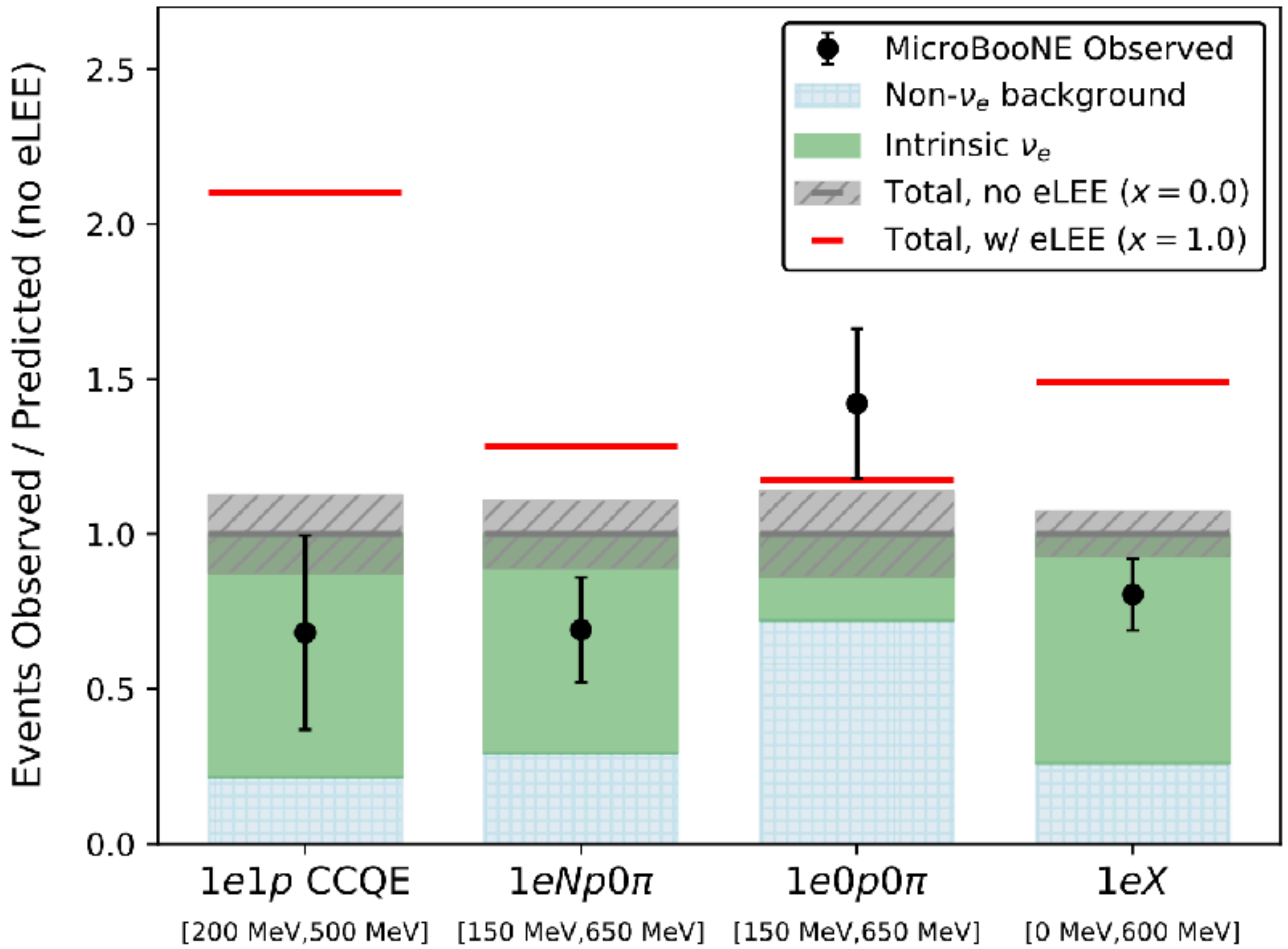






Phys. Rev. D 105, 112004

Phys. Rev. D 105, 112005



Phys. Rev. Lett. 128, 241801

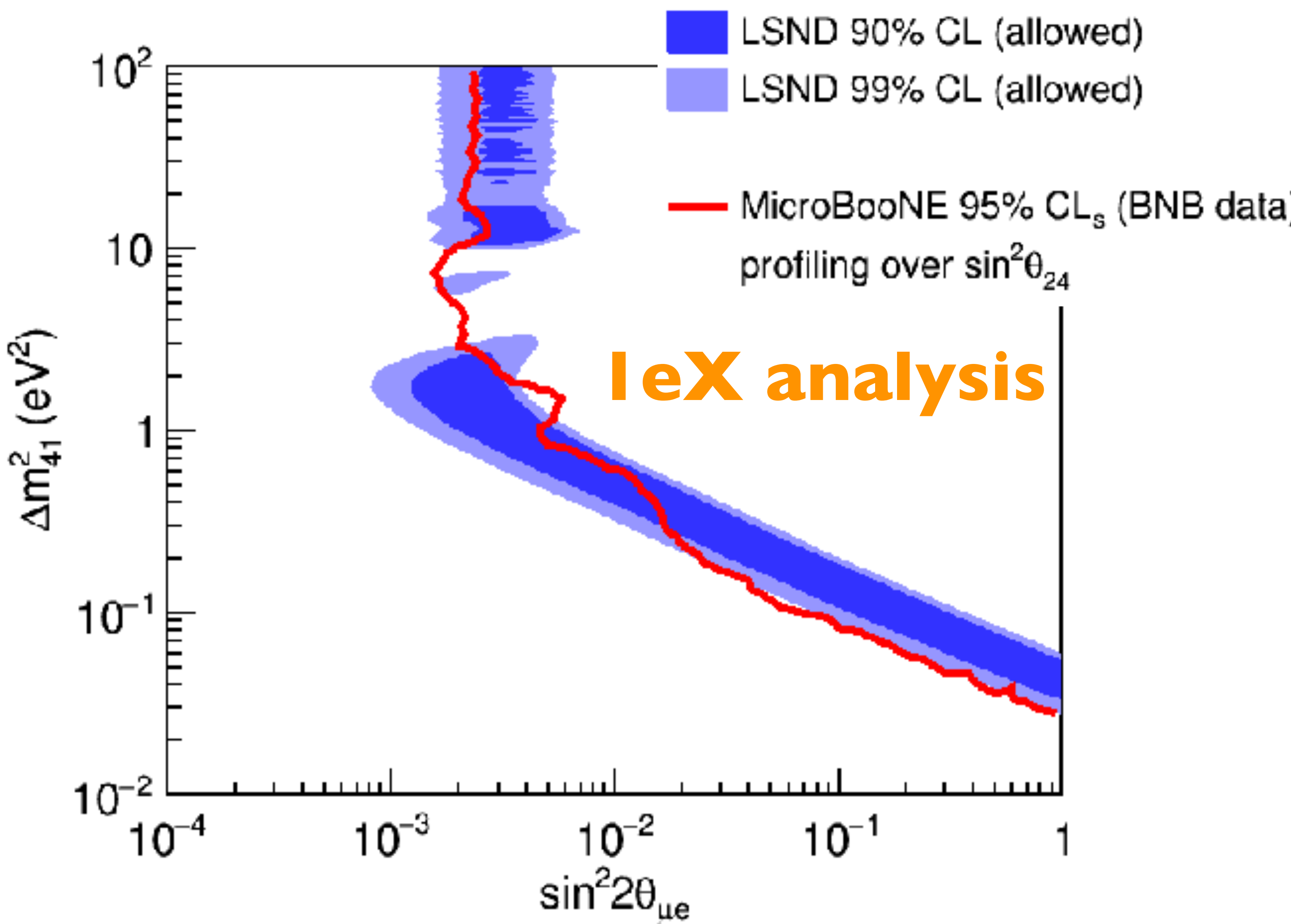
University of Oxford

EXCLUSION CONTOURS

New summer 2022

MICROBOONE-NOTE-1116-PUB

- What does this mean for the sterile neutrino hypothesis?
- MicroBooNE hasn't seen evidence of an excess → place constraints on oscillation phase space for a new neutrino flavour

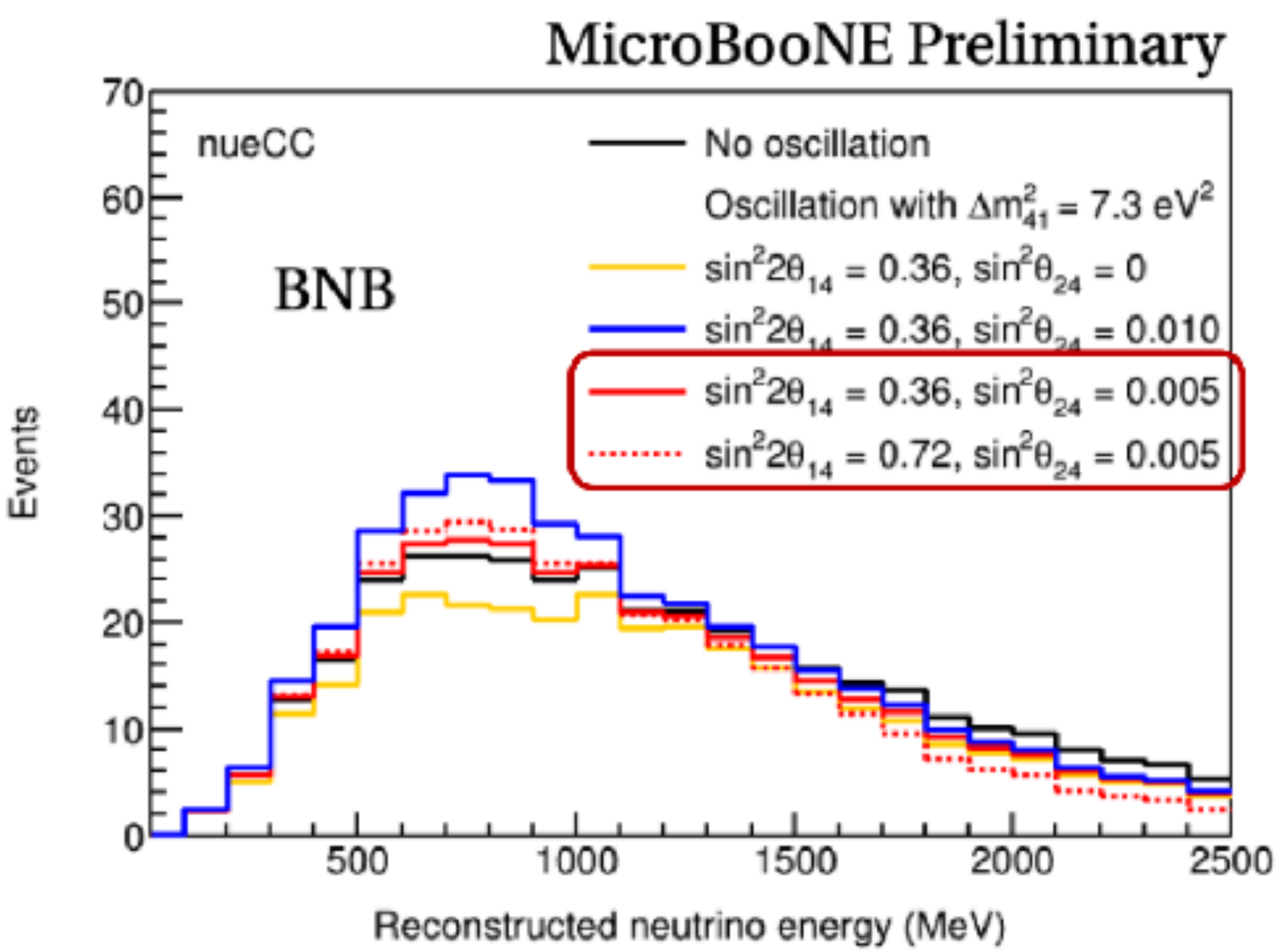


UNIVERSITY OF OXFORD

OSCILLATION PARAMETER DEGENERACY

New summer 2022

MICROBOONE-NOTE-1116-PUB



ν_e disappearance → ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} P_{\nu_\mu \to \nu_e}$$

$$= N_{\text{intrinsic } \nu_e}[1 + (R_{\nu_\mu/\nu_e} \sin^2\theta_{24} - 1)\sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}]$$

Cancellation if $\sin^2\theta_{24} = R_{\nu e/\nu\mu}$

(ratio of ν_e to ν_μ in beam)

→ about 0.005 in BNB

→ about 0.04 in NuMI beam

FUTURE PROSPECTS: BNB+NUMI

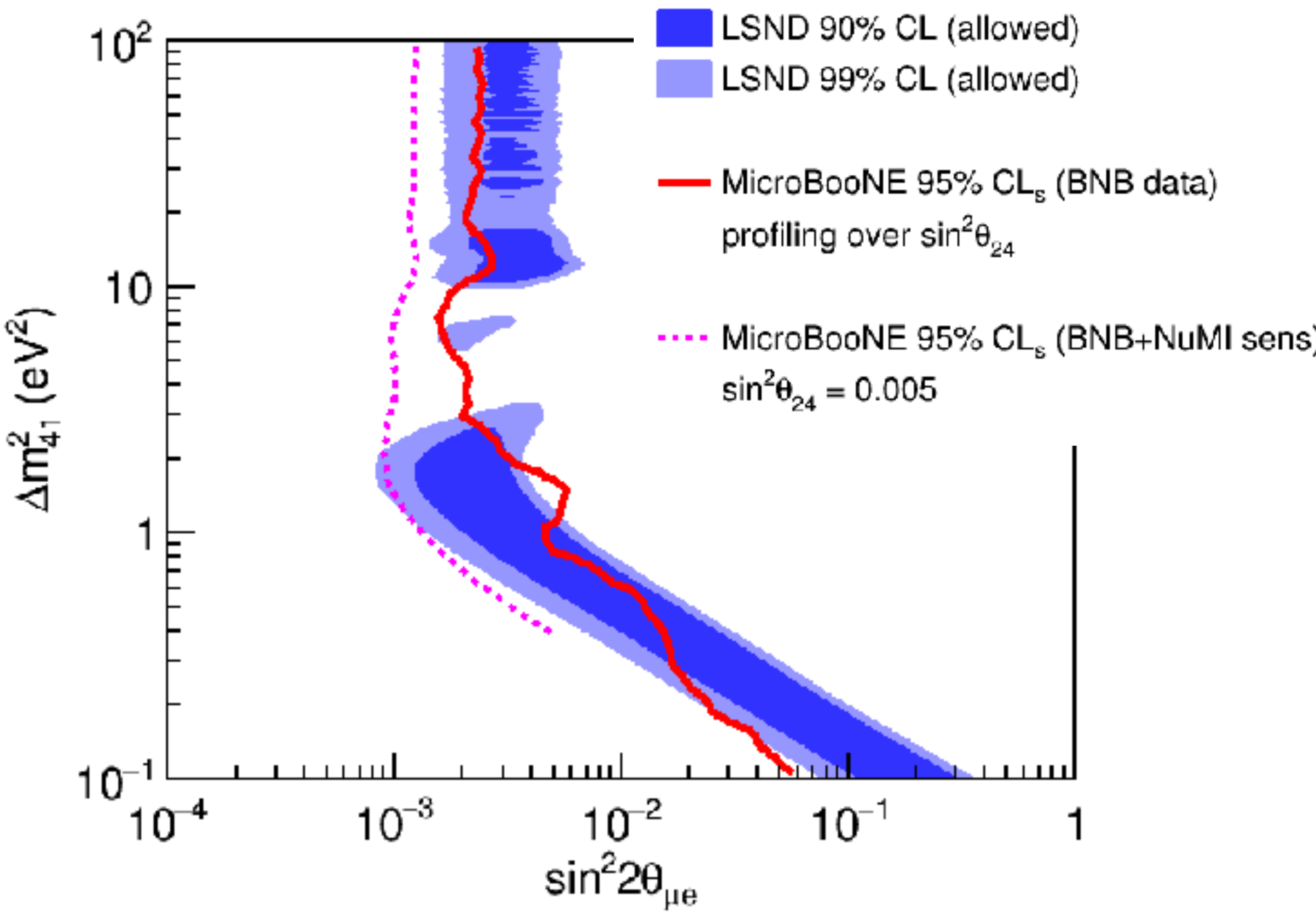
New summer 2022

MICROBOONE-NOTE-1116-PUB

- BNB $R_{\nu e/\nu\mu}$: 0.005
- NuMI $R_{\nu e/\nu\mu}$: 0.04

- Combining both data sets → significantly improved sensitivity

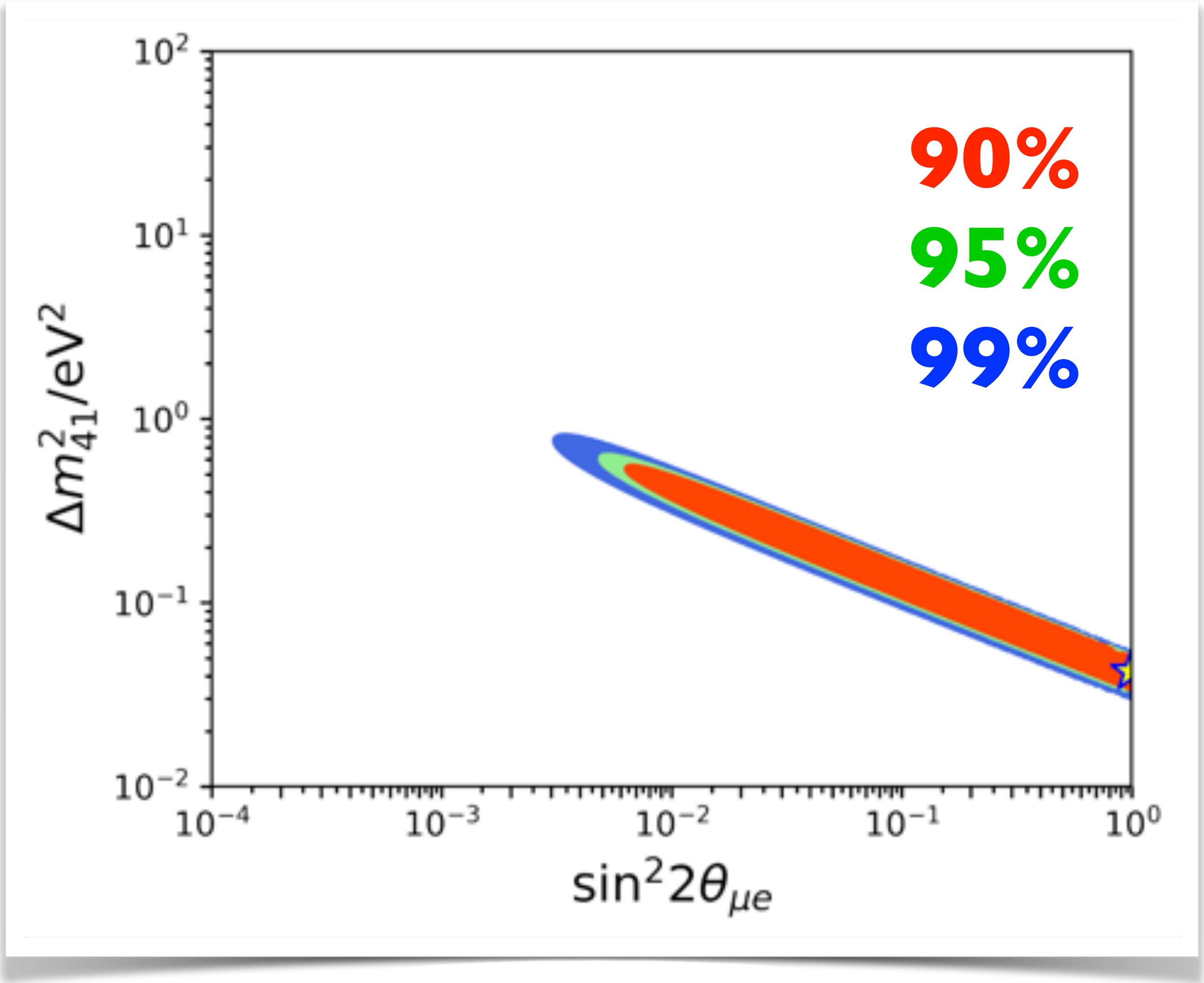
- → Upcoming BNB + NuMI analysis will be sensitive to full LSND allowed regions



UNIVERSITY OF OXFORD

PUTTING IT TOGETHER

Diaz et. al., Phys. Rep. 884 (2020) 1-59



Appearance

We can now also look at global fits using only $\nu_\mu \rightarrow \nu_e$ appearance data

Note: does not include MicroBooNE

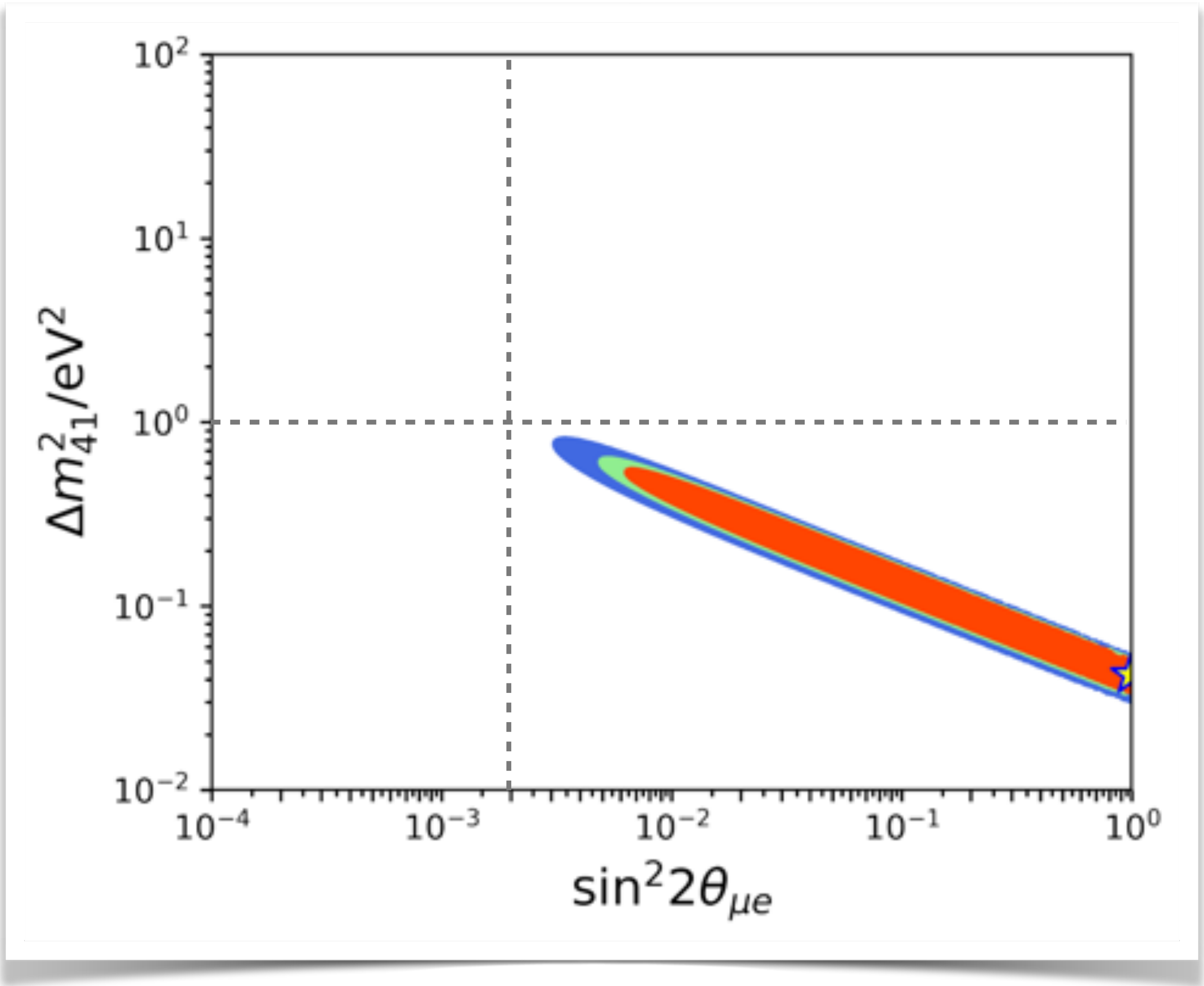
	$\nu_\mu \rightarrow \nu_e$
Neutrino	MiniBooNE (BNB) * MiniBooNE(NuMI) NOMAD
Antineutrino	LSND * KARMEN MiniBooNE (BNB) *

* = anomaly at ≥ 2σ

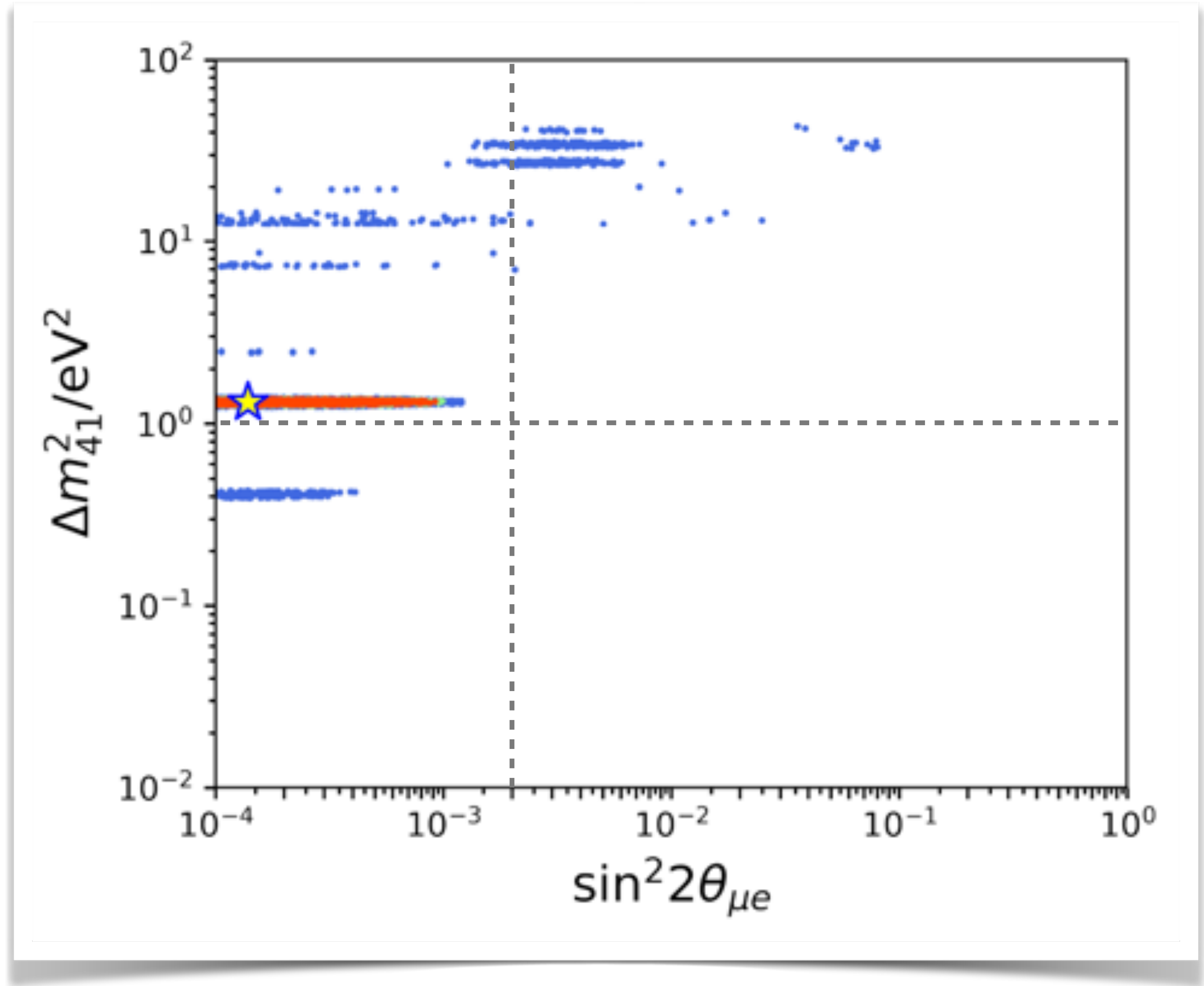
UNIVERSITY OF OXFORD

DOES THE MODEL FIT ALL THE DATA?

Diaz et. al., Phys. Rep. 884 (2020) 1-59



Appearance



Disappearance

SO WHAT DOES THIS MEAN?

SO WHAT DOES THIS MEAN?

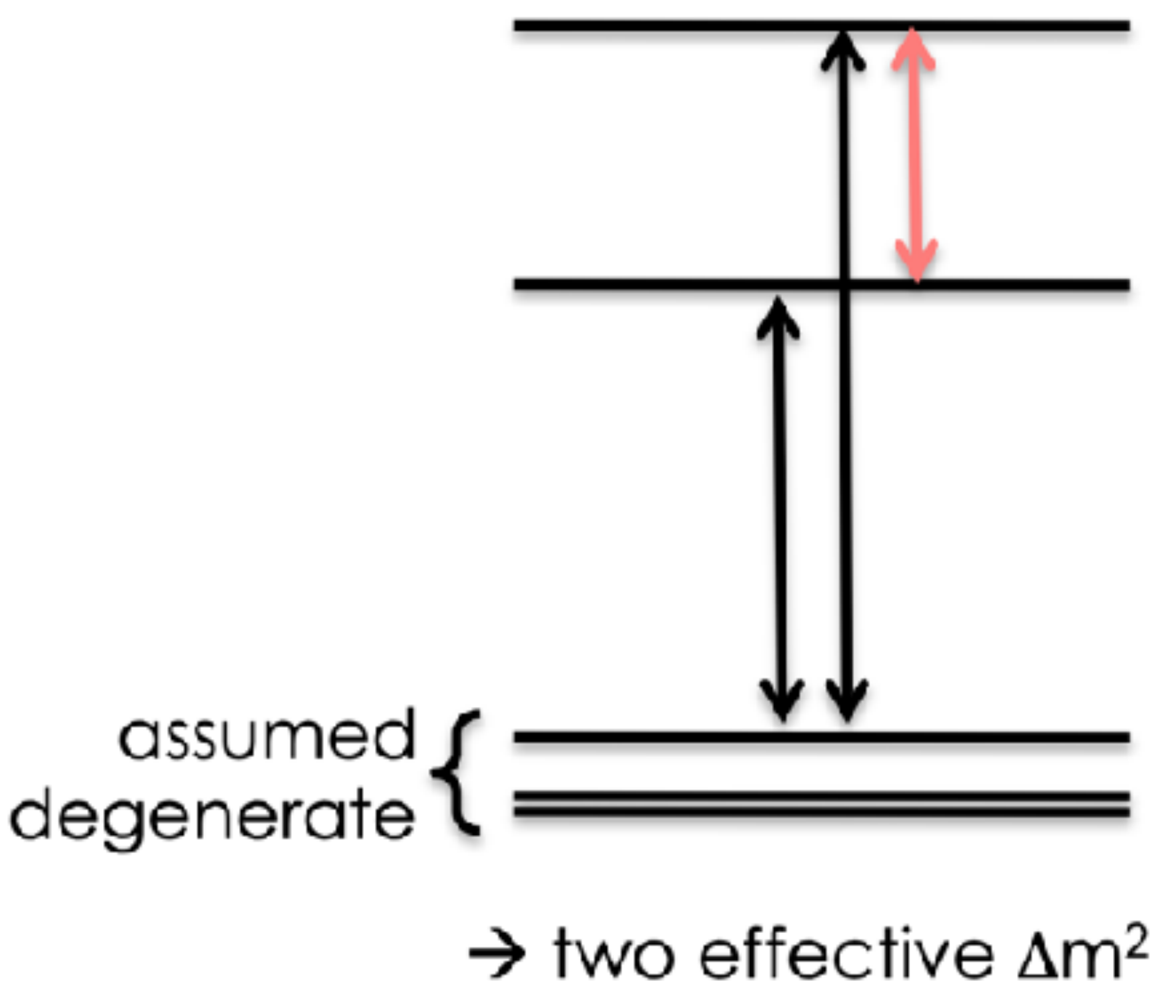
- We have a large number of **anomalous experimental results**
- Note: a lot of these are enduring, but not statistically significant: very few above 2σ
- Many could be explained by the addition of a **sterile neutrino**
- But adding one new neutrino to the model **can't explain all the data**

MORE STERILE NEUTRINOS?

- What about 3+2, 3+3 models?
- Add in a lot of new degrees of freedom (3+2 adds 7dof to the fits!)
- **Helps a little with the tension, but not a lot**

Appearance vs Disappearance tension:
Diaz et. al., Phys. Rep. 884 (2020) 1-59

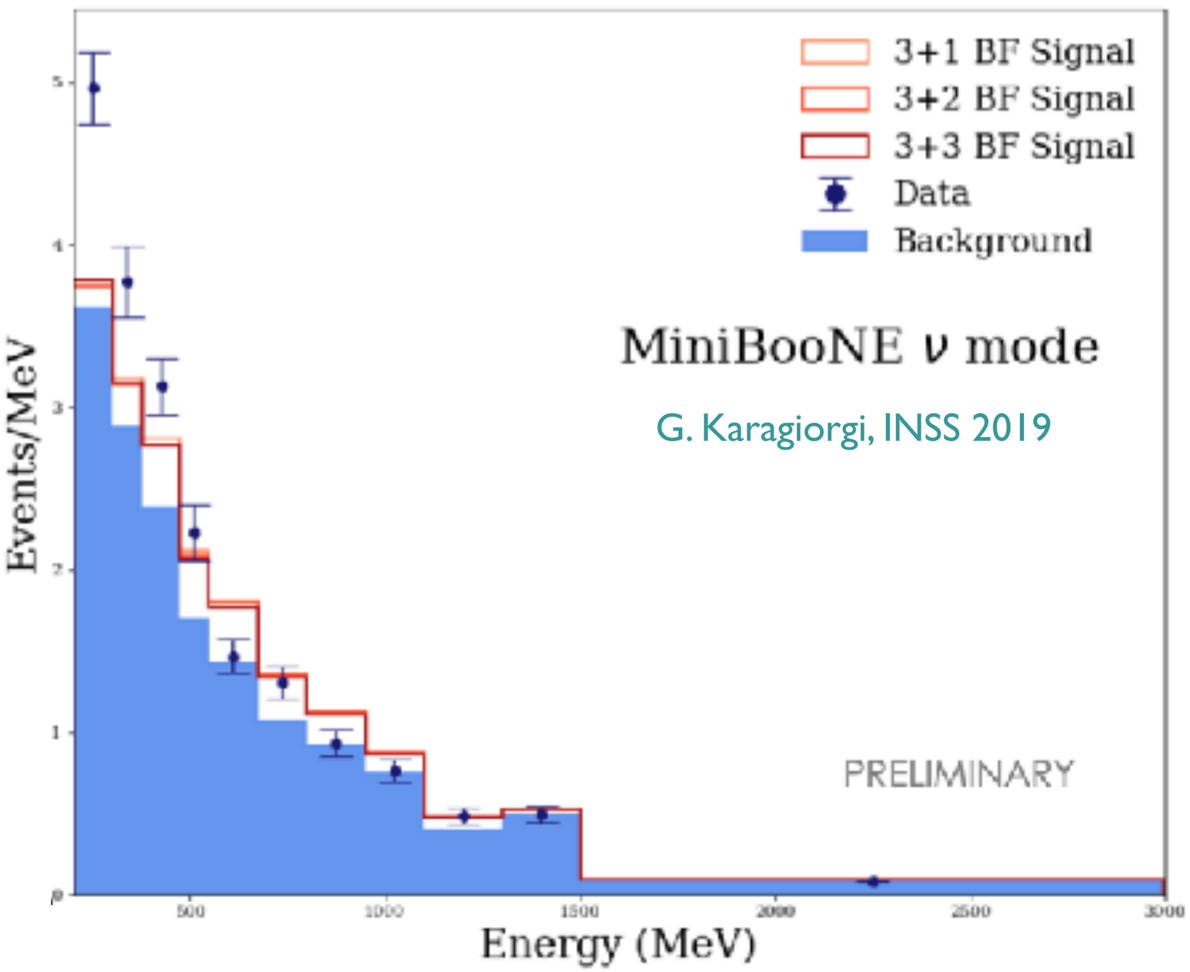
3+1 → 4.5σ
3+2 → 4.4σ



UNIVERSITY OF OXFORD

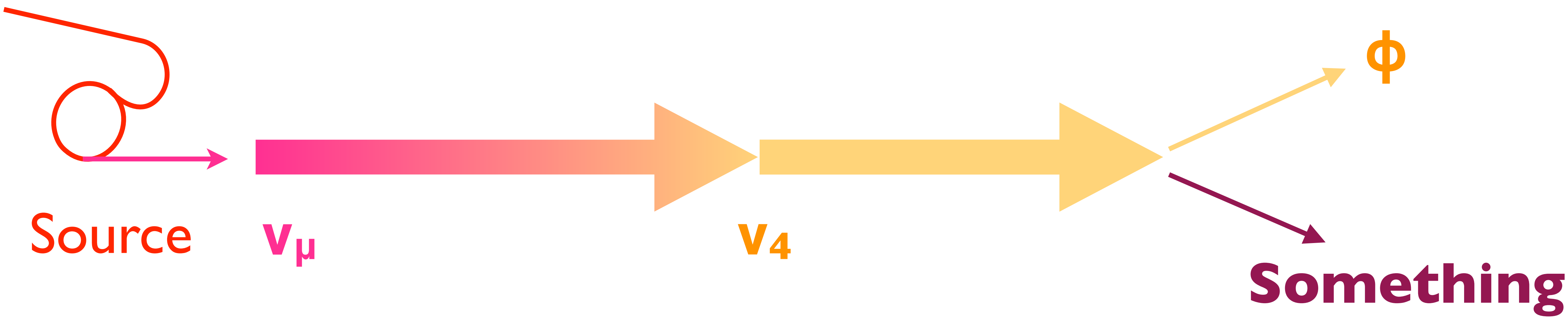
MORE STERILE NEUTRINOS?

- What about 3+2, 3+3 models?
- Add in a lot of new degrees of freedom (3+2 adds 7dof to the fits!)
- Helps a little with the tension, but not a lot
- **Does not improve agreement with MiniBooNE**



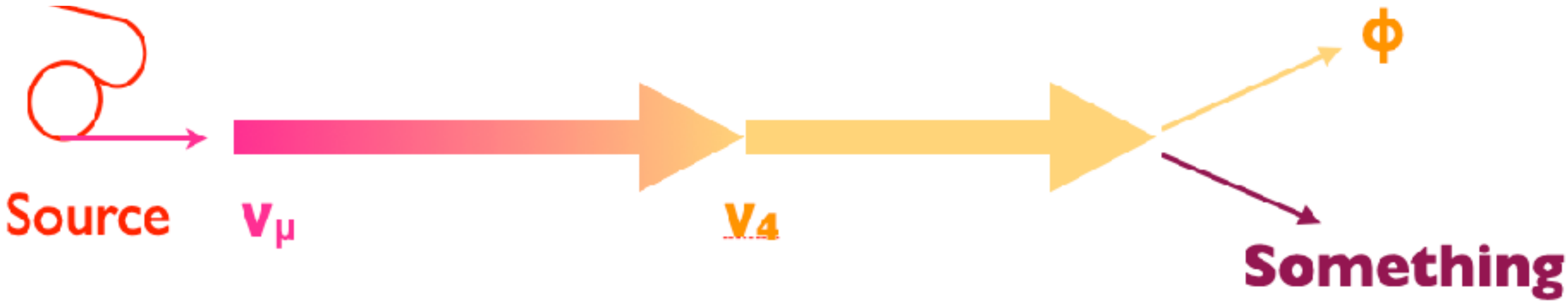
UNIVERSITY OF OXFORD

STERILE NEUTRINOS + DECAY?



Different models have different predictions for the **something**:

- **Something = invisible** (non-interacting)
  - As long as the decay takes place before the detector…
  - …effect is that active neutrino flavour (ν_μ in this diagram) seem to disappear, with no balancing appearance



Something = visible

- Option 1: **active neutrino, ν_e or ν_τ**
  - Effect is of **ν_e/ν_τ appearance** but **not** with L/E dependence we'd expect from oscillation
  - Decay can happen before or in the detector
- Option 2: **active neutrino, ν_μ**
  - High energy $\nu_\mu \rightarrow \nu_4 \rightarrow$ lower-energy $\nu_\mu + \phi$
  - Effect is to **change the energy spectrum** in favour of lower-energy neutrinos
  - Decay can happen before or in the detector
- Option 3: **something else visible e.g. γ, e^+e^-**
  - Perhaps this thing can be **mistaken as the ν_e interaction** (e.g. in MiniBooNE)?
  - Decay needs to happen inside the detector

Some more beyond-the-standard-model models that aren't sterile neutrinos

Mostly motivated by appearance measurements (MiniBooNE) rather than disappearance

These slides heavily inspired by
P. Machado, Fermilab PAC, November 2021

Ballett, Pascoli, Ross-Lonergan PRD 2019

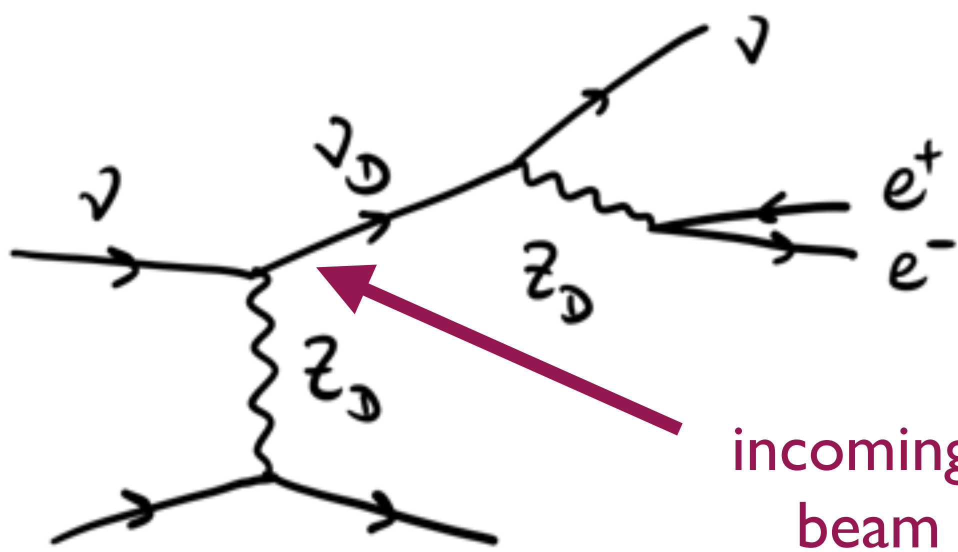
Ballett, Hostert, Pascoli PRD 2020

Bertuzzo, Jana, Machado, Zukanovich PRL 2018

Bertuzzo, Jana, Machado, Zukanovich PLB 2019

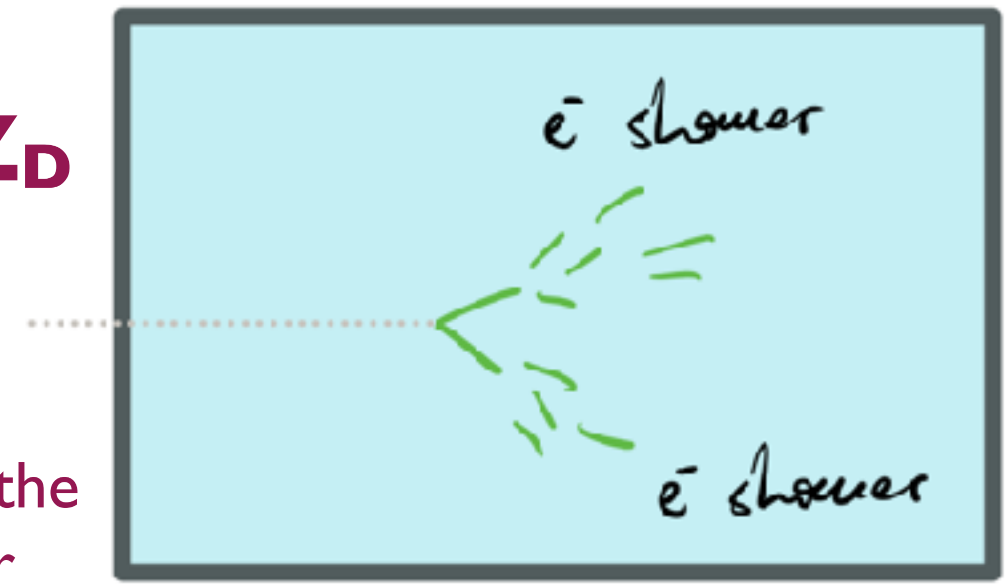
Arguelles, Hostert, Tsai PRL 2019

DARK NEUTRINOS

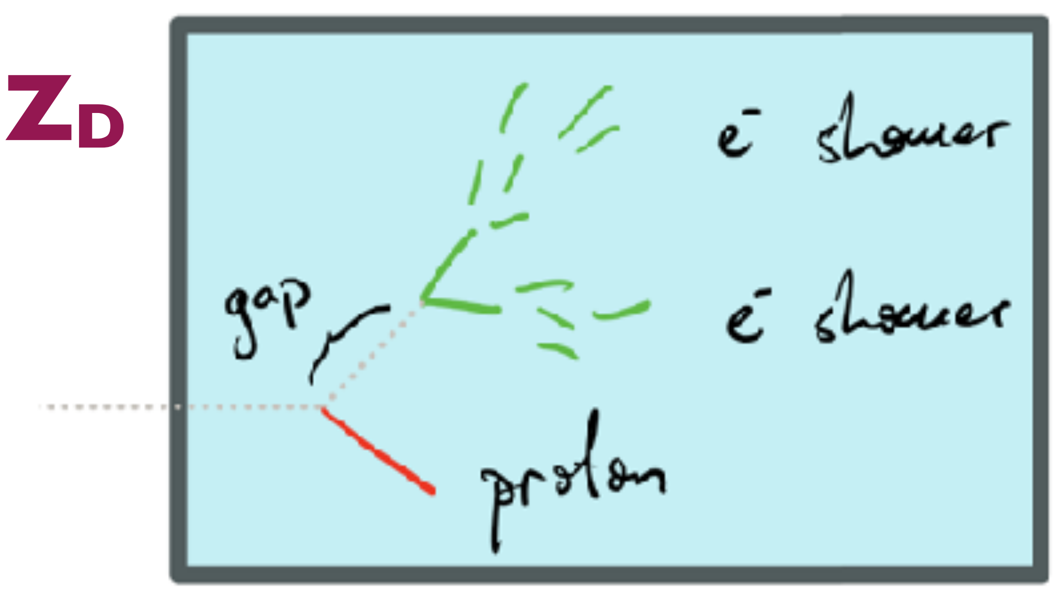


incoming neutrinos from the beam scatter/up-scatter inside the detector

Light Z_D



Heavy Z_D



Motivation:

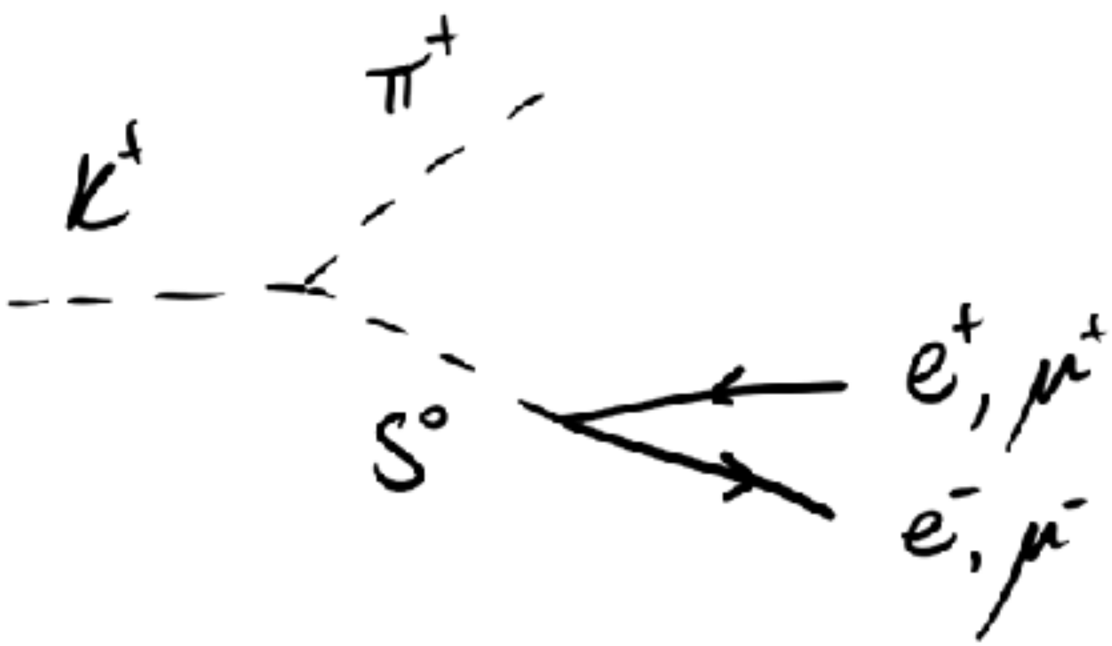
- Origin of neutrino masses
- Dark sector portal
- Fit to MiniBooNE energy and angular spectrum

UNIVERSITY OF OXFORD

HIGGS PORTAL SCALARS

Batell, Berger, Ismail PRD 2019

Patt, Wilczek 2006



Experimental signature:

- No hadronic activity
- e^+e^- or $\mu^+\mu^-$
- Invariant mass

Motivation:

- Portal to dark sector
- Connection to Higgs sector

Too many papers to list, but see

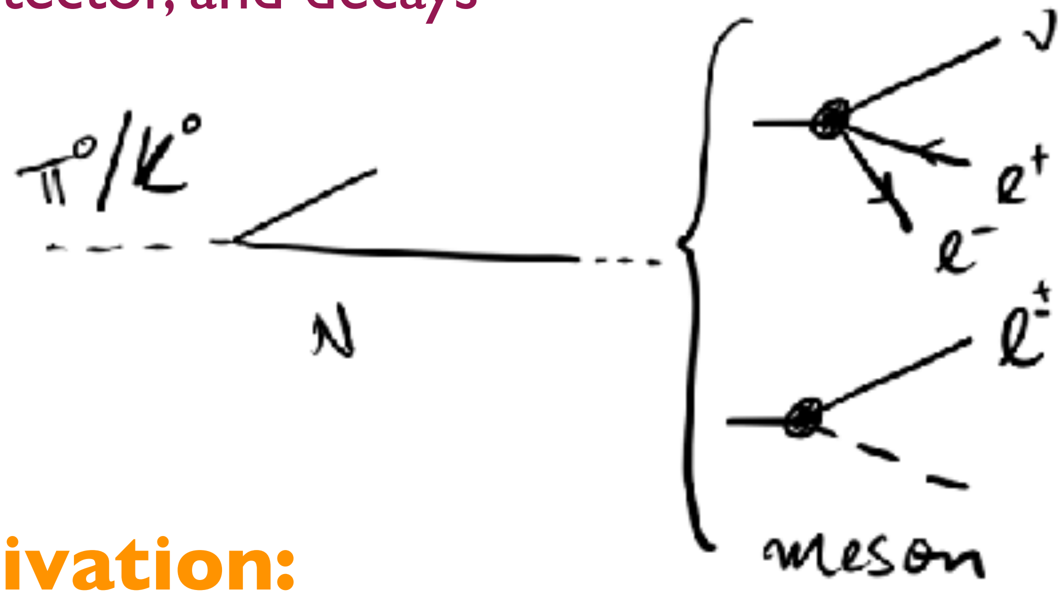
Ballett, Pascoli, Ross-Lonergan PRD 2019

Ballett, Pascoli, Ross-Lonergan JHEP 2017

Kelly, Machado PRD 2021

HEAVY NEUTRAL LEPTONS

HNL produced in beam decay pipe, propagates to detector, and decays



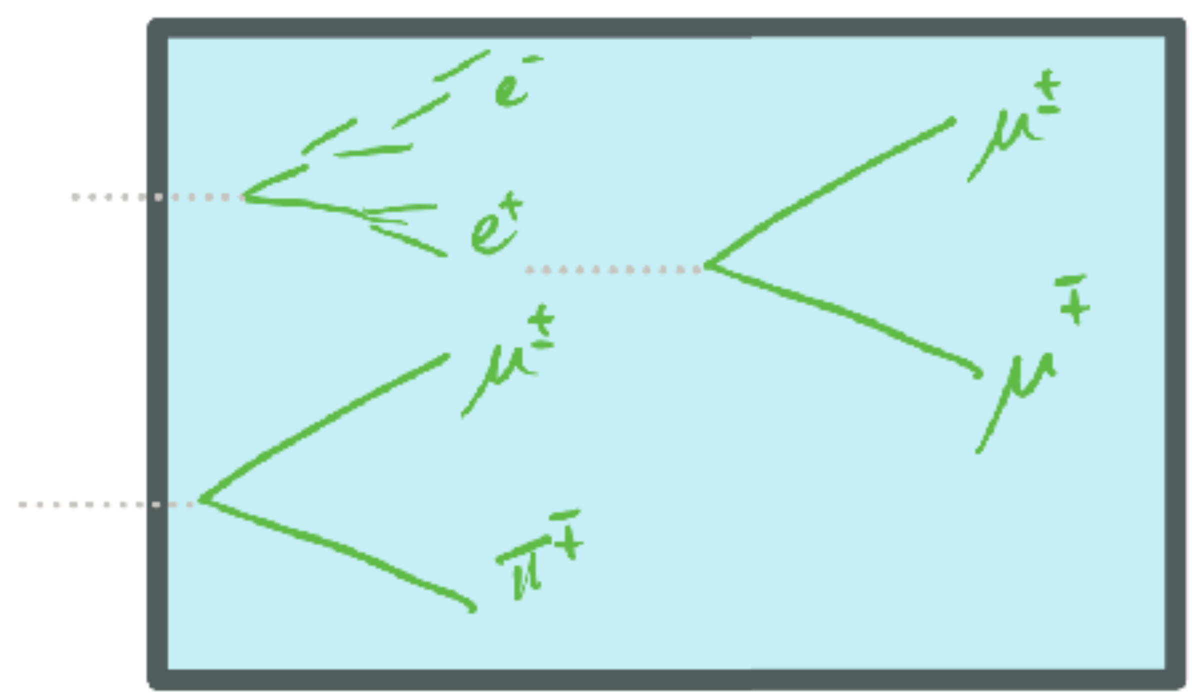
Motivation:

- Possibly related to neutrino mass
- Dirac vs Majorana nature of HNLs can be probed, if discovered

Experimental signature:

- Several possibilities
- Delayed timing w.r.t. beam neutrinos
- Reconstruct invariant mass?

Less likely/ harder to explain anomalies



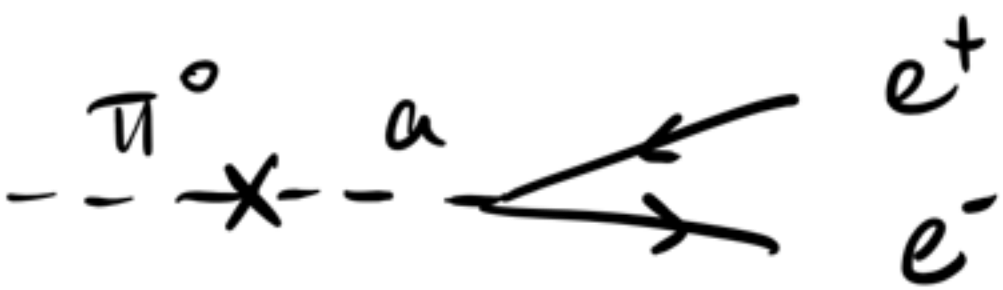
UNIVERSITY OF OXFORD

AXION-LIKE PARTICLES

Kelly Kumar Liu PRD 2021

Brdar et al PRL 2021

Axion produced in beam decay pipe, propagates to detector, and decays

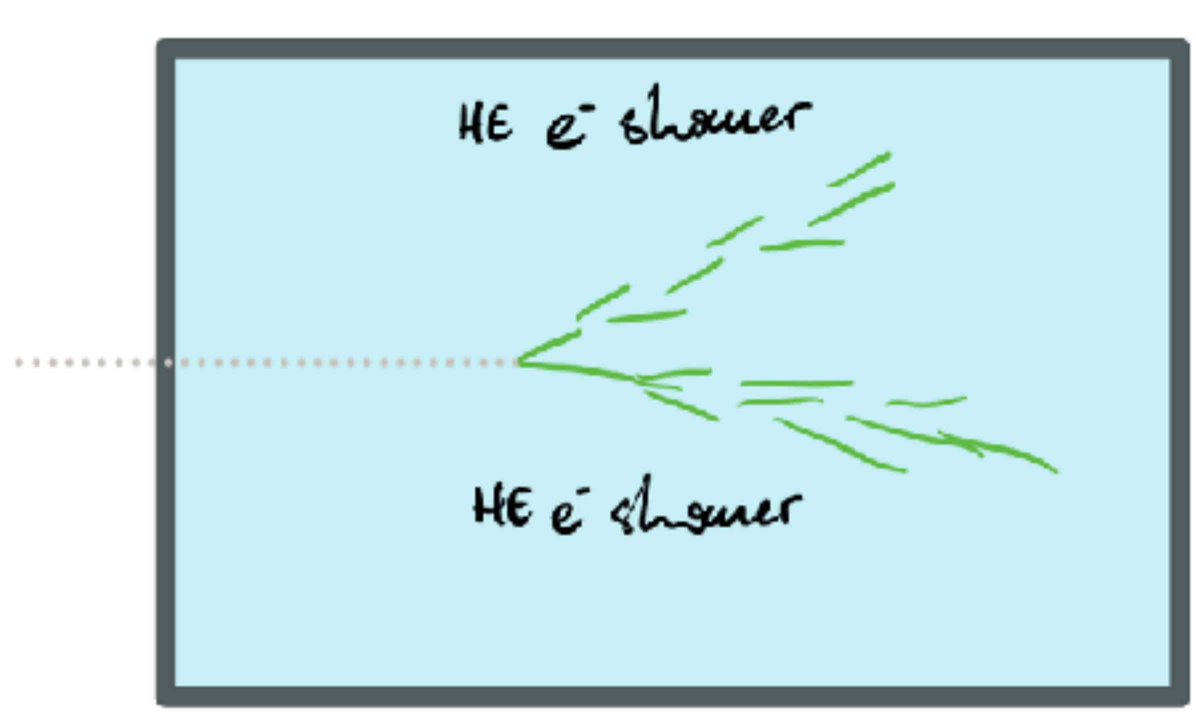


Motivation:

- Axions are well motivated (although this isn't necessarily related to strong CP problem)
- Relatively simple search

Experimental signature:

- Two high-energy electron-like EM showers
- No hadronic activity
- Invariant mass

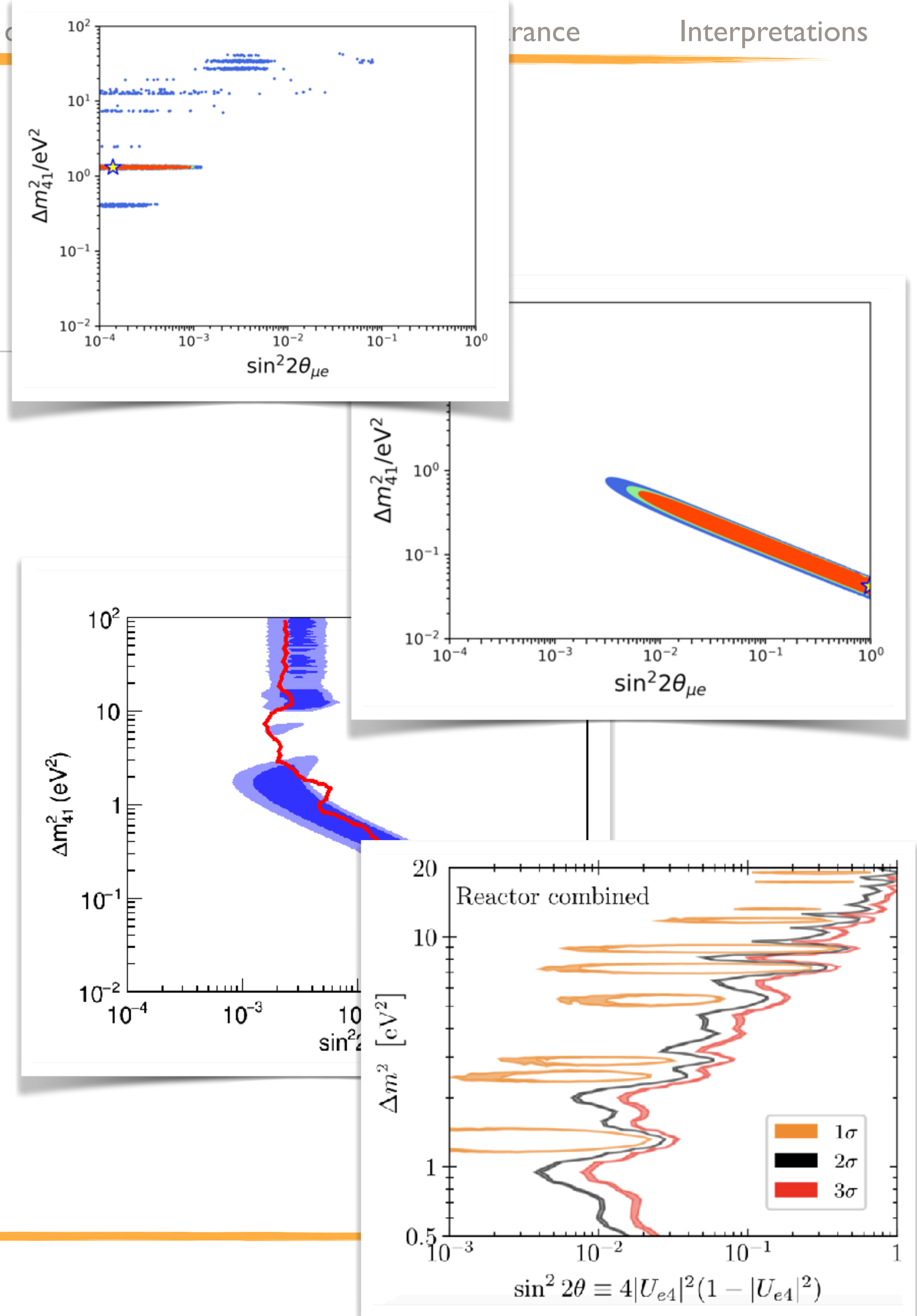


WHAT WE REALLY NEED IS MORE DATA

- Follow-up **high-sensitivity, direct experimental tests** (ongoing, planned, and proposed sterile neutrino oscillation searches):
  - Accelerator-based: **SBN (ICARUS+SBND), IsoDAR**
  - Reactor-based: **SoLiD, Neutrino-4, DANSS, NEOS, STEREO, PROSPECT, CHANDLER, …**
  - Radioactive source: **BEST**
  - Also searches at long-baseline experiments (using near detectors or looking for NC active-flavour disappearance) and at high-energy atmospheric neutrino experiments: **T2K, NOvA, IceCube/DeepCore, Super-K**
  - And neutral-current based searches with coherent scattering: **COHERENT, CEvNS**

SUMMARY

- A number of **anomalies** exist that can't be explained in the 3-neutrino paradigm
- Could hint at interesting **new physics?**
- May be evidence for **sterile neutrinos** but picture is unclear — **tension in 3+1 model**
- **More data** and **more experiments** will soon add to this picture!



TRANSITION MAGNETIC MOMENT

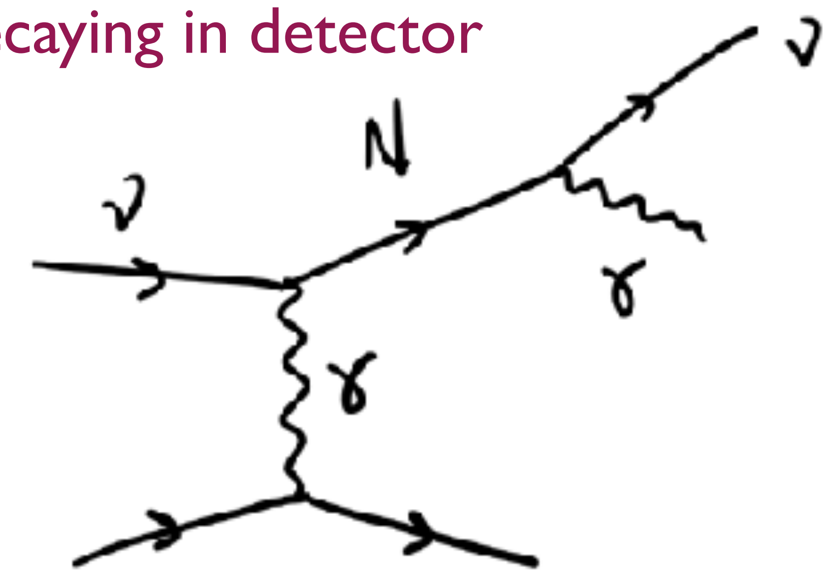
Gninenko PRL 2009

Coloma Machado Soler Shoemaker PRL 2017

Atkinson et al JHEP 2022

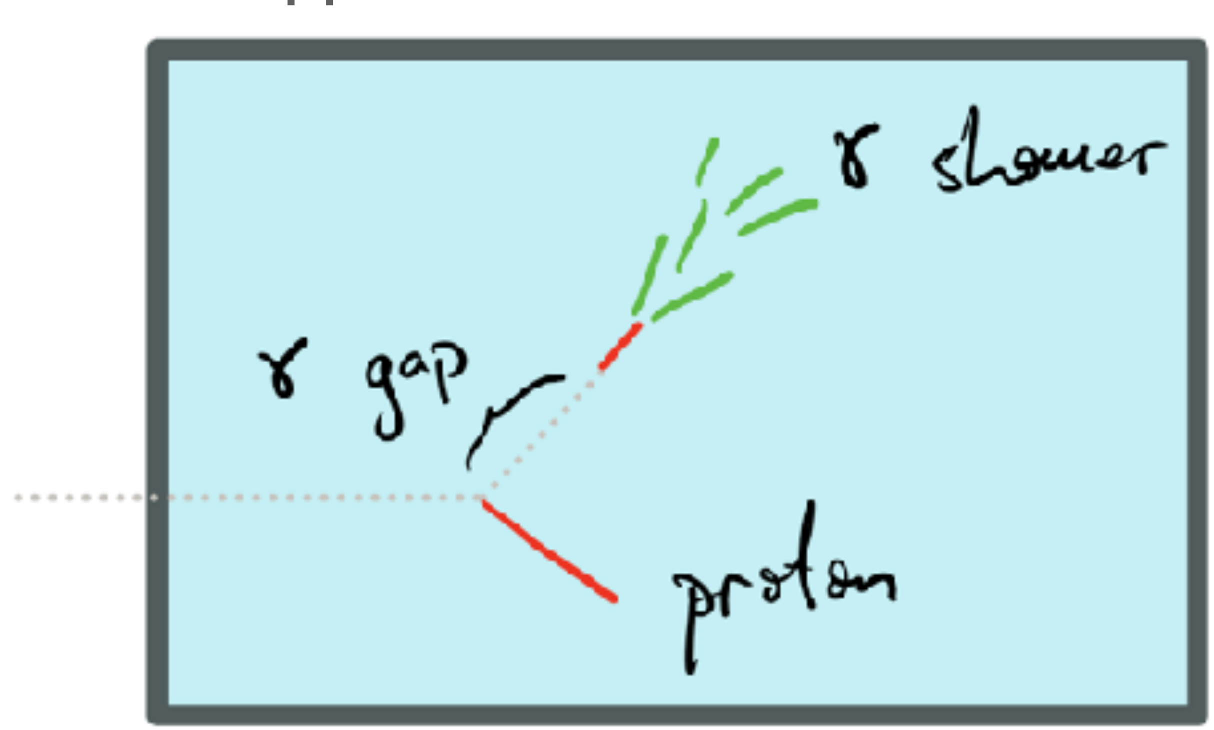
Vergani et al PRD 2021

Neutrino up-scatters to a heavy neutrino - travels some distance before decaying in detector



Experimental signature:

- Photon EM shower
- Some hadronic activity (1γ 1p)
- "Double bang" if both interactions happen within detector



Motivation:

- May be a consequence of the mechanism for neutrino masses
- Excellent fit to MiniBooNE energy spectrum