µBooNE

UNIVERSITY OF
OXFORD

NEUTRINO PHYSICS, (SOME) ANOMALIES, AND INVESTIGATIONS

Kirsty Duffy
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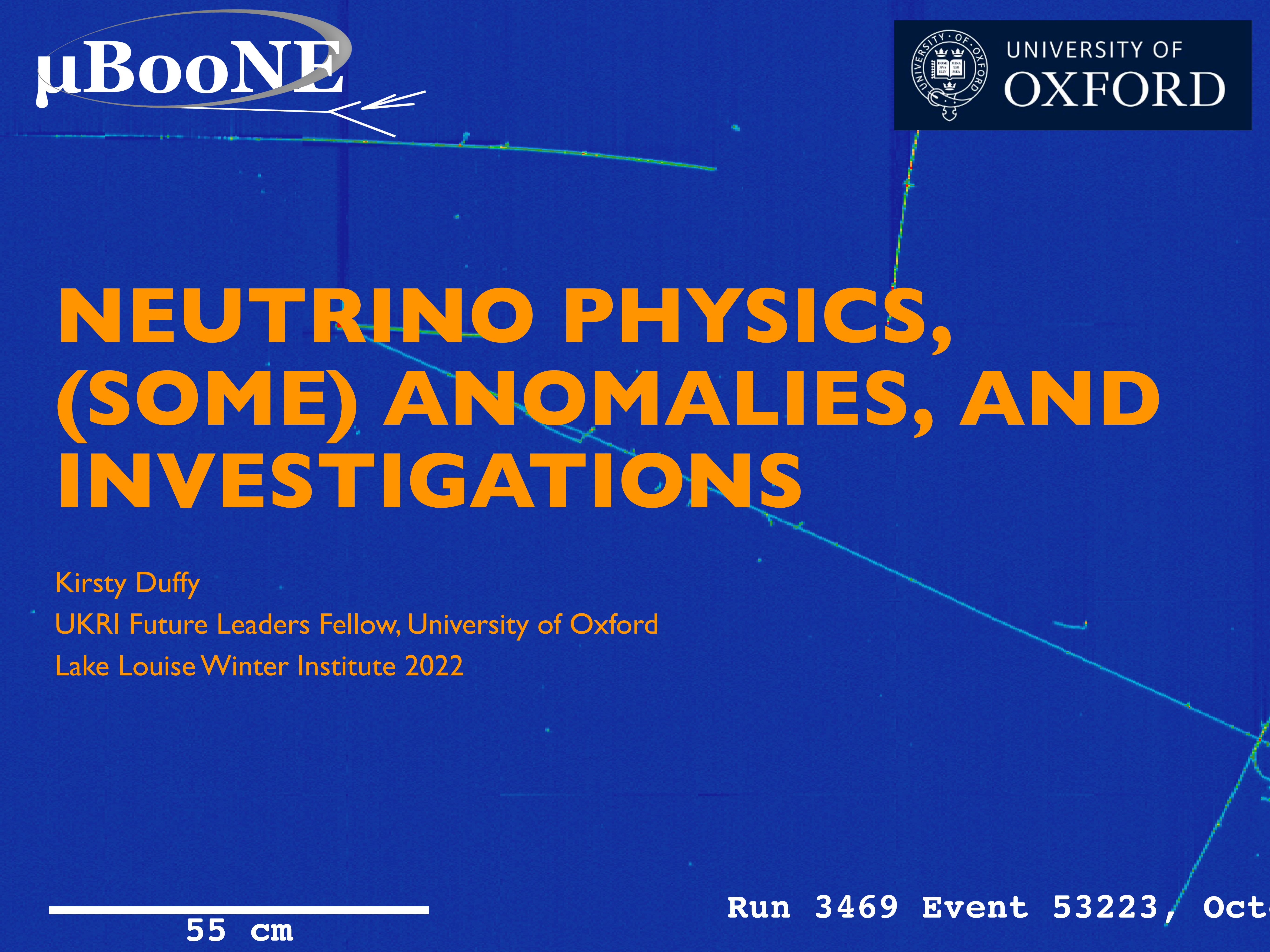
Lake Louise Winter Institute 2022



- Neutrinos are one of the **least-well-understood particles** in the Standard Model

- Neutrino oscillation is **beyond the Standard Model**, and opens the door to **exciting new possibilites**

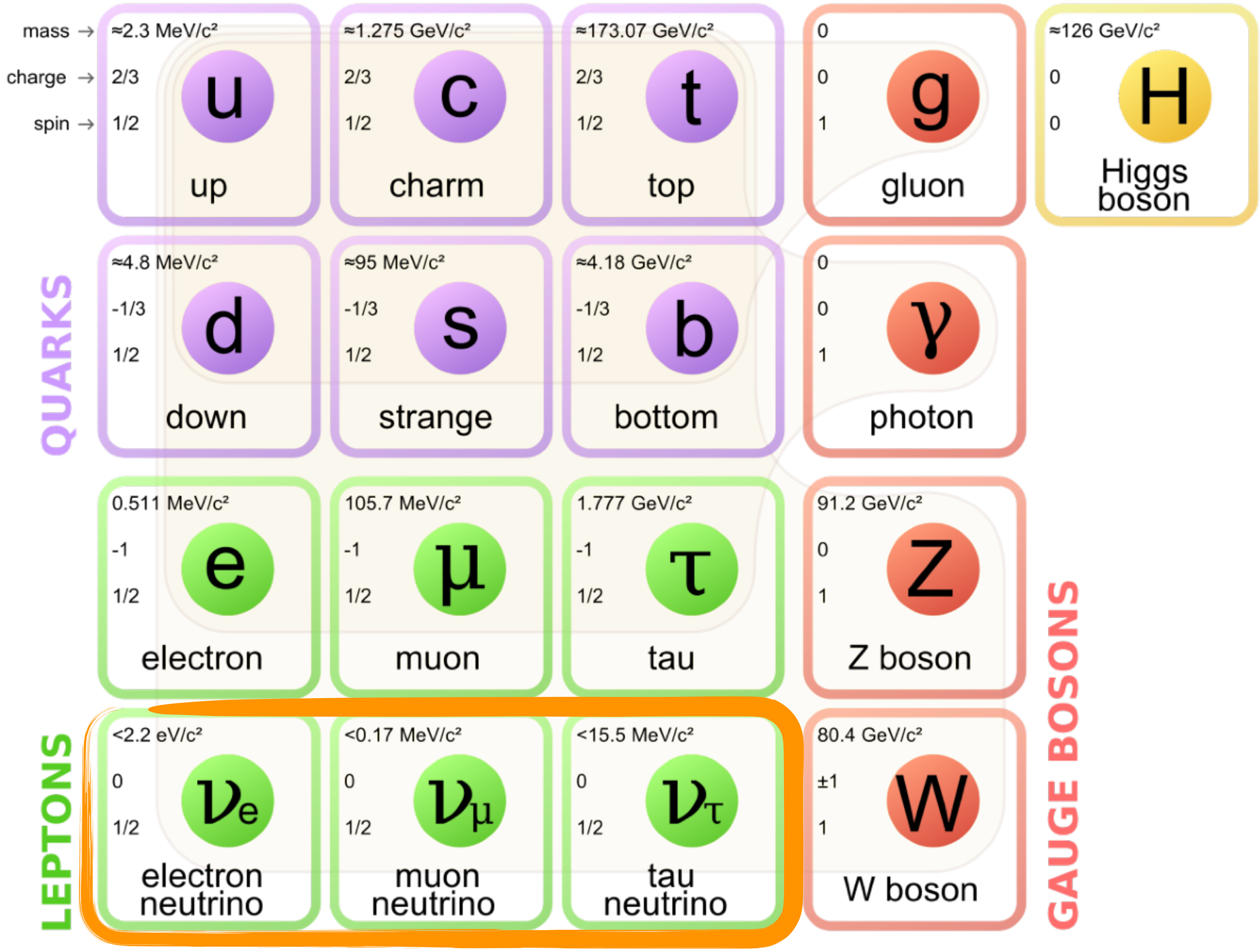
- However, a lot remains that we **don't understand** (both within the 3-flavour oscillation picture and outside it)

- **New data** from current and future **precision experiments** will shed light on this

MY PERSONAL BIAS

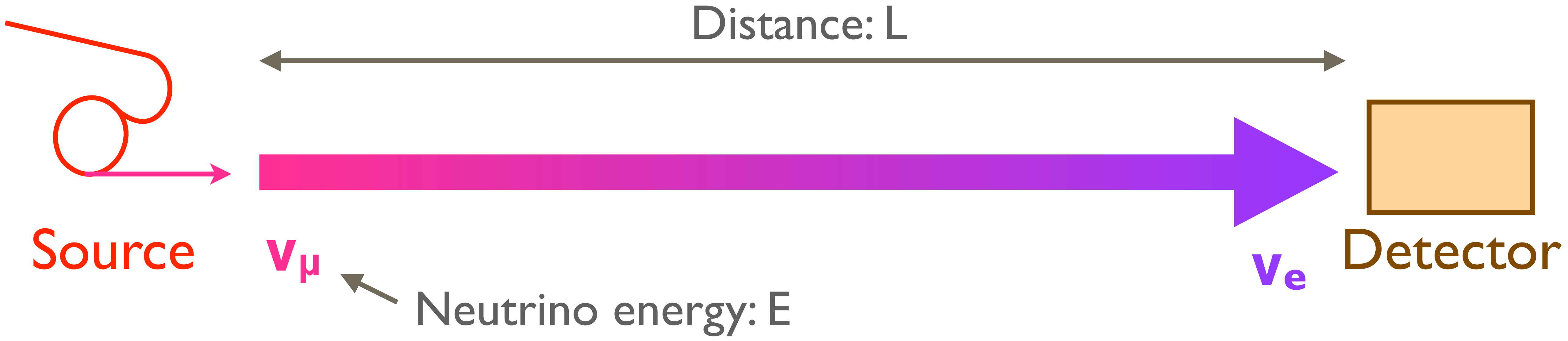
- Overview of (experimental) neutrino physics
- MiniBooNE anomaly
- MicroBooNE recent results

NEUTRINOS: WHAT WE KNOW



- Fundamental particles in the Standard Model
- Interact via weak force
- "Paired" with charged leptons

NEUTRINO OSCILLATION

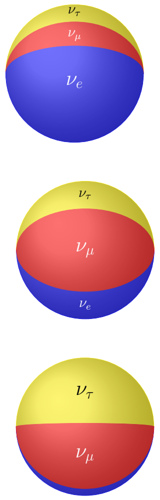


Muon neutrino disappearance

Electron neutrino appearance

TWO SETS OF EIGENSTATES

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



flavour

Interaction

mass

Propagation

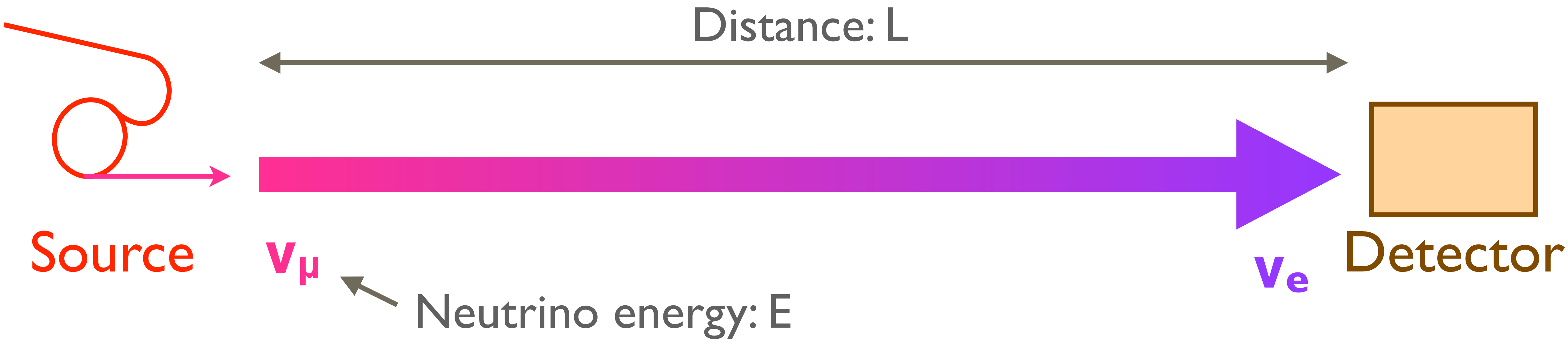
PMNS matrix

named after Pontecorvo, Maki, Nakagawa, and Sakata

Four free parameters:

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

One phase **δ_{CP}**



Distance: L

Source

ν_μ

Neutrino energy: E

ν_e

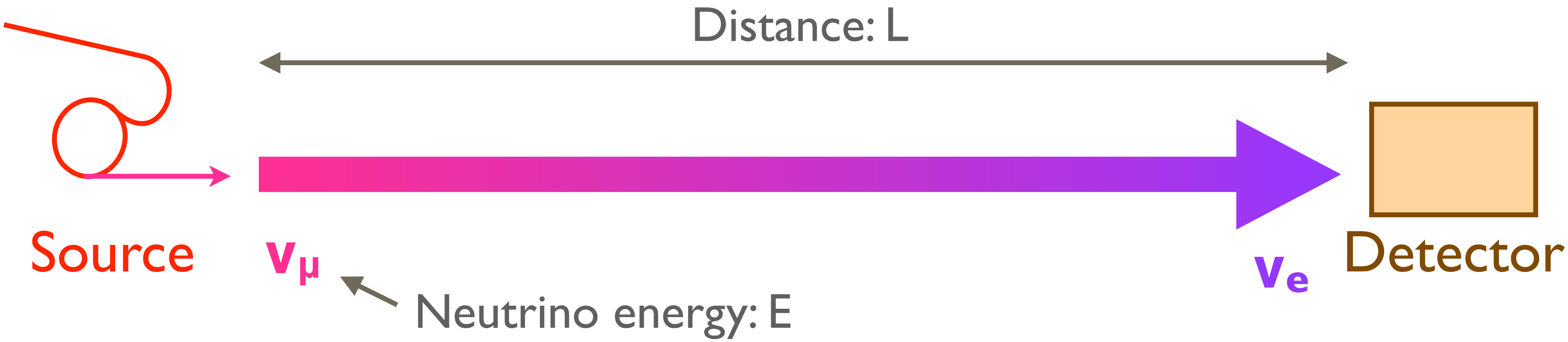
Detector

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

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

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

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



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

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Neutrino oscillation

→ Neutrinos have mass

→ Physics **beyond the Standard Model!**

How many neutrinos are there?

How do neutrinos interact in the nuclear medium?

Which neutrino is heaviest? Which is lightest?

Why is neutrino mixing so large?

Is neutrino oscillation different for neutrinos and antineutrinos?

How much do neutrinos weigh?

Are neutrinos their own antiparticles?

Why are neutrino masses so much smaller than all other particles?

What else can neutrinos teach us?

Which neutrino is heaviest? Which is lightest?

THE MASS HIERARCHY

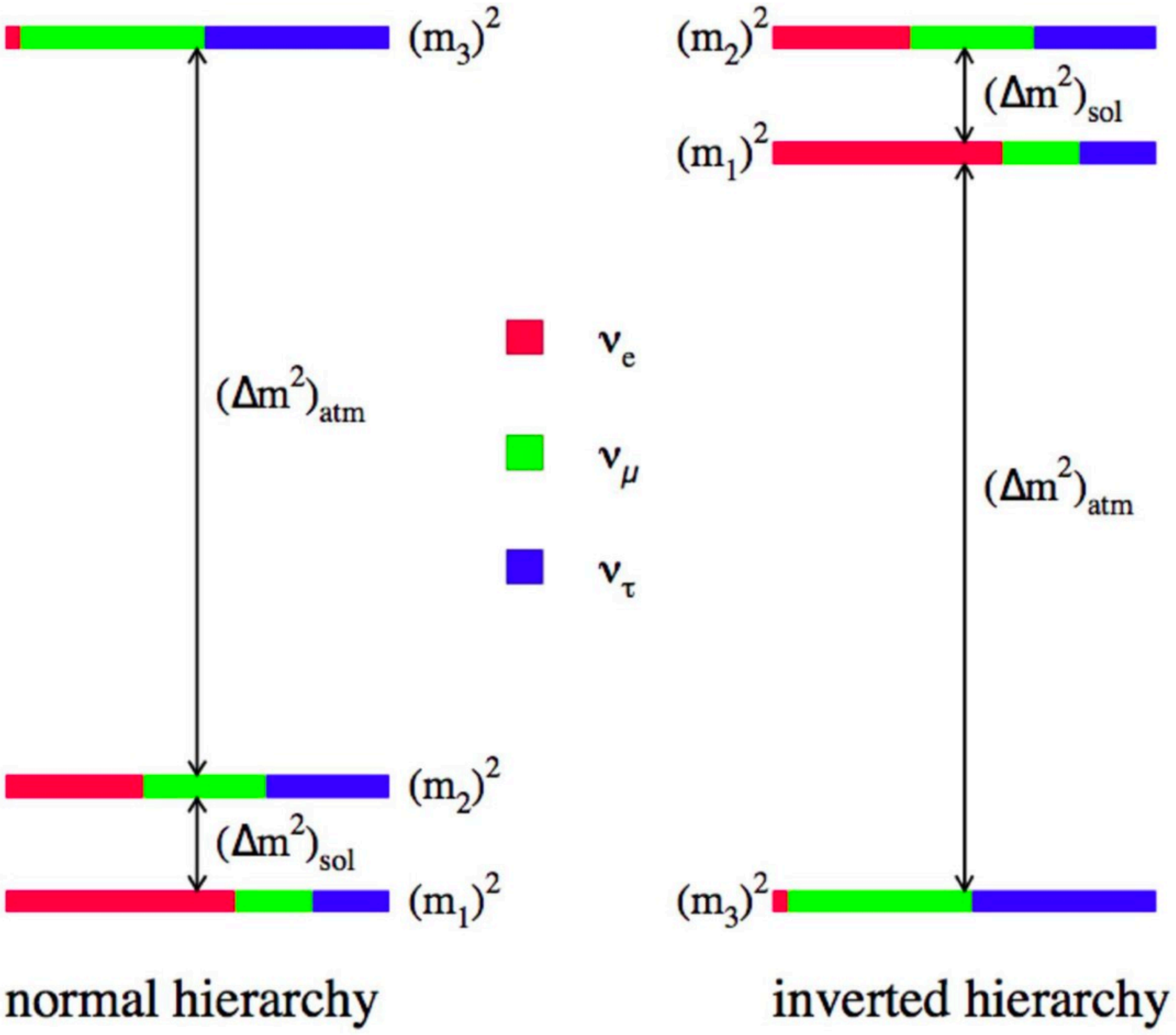
$$\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

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

Oscillation is only sensitive to the **size** of Δm², not the **sign**

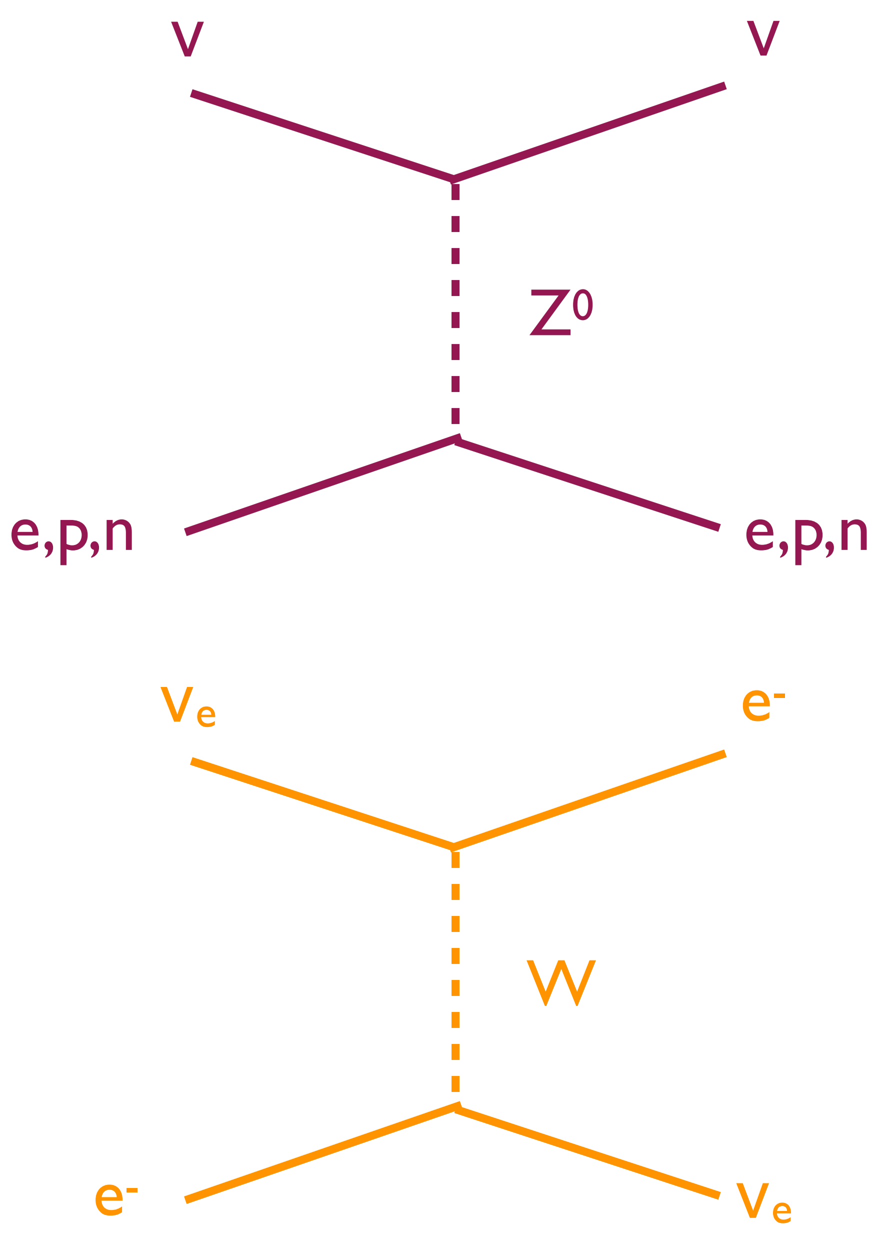
→ We **know the sign of Δm^2_{21}** from solar neutrino measurements

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



MEASURING THE MASS HIERARCHY: MATTER EFFECTS

- Long-baseline experiments are **sensitive to the mass hierarchy via matter effects**
- Additional charged-current interactions in matter for ν_e, not available to ν_μ, ν_τ
- → **"extra potential"** for ν_e breaks mass-hierarchy symmetry (depending on which mass state contains the most ν_e)

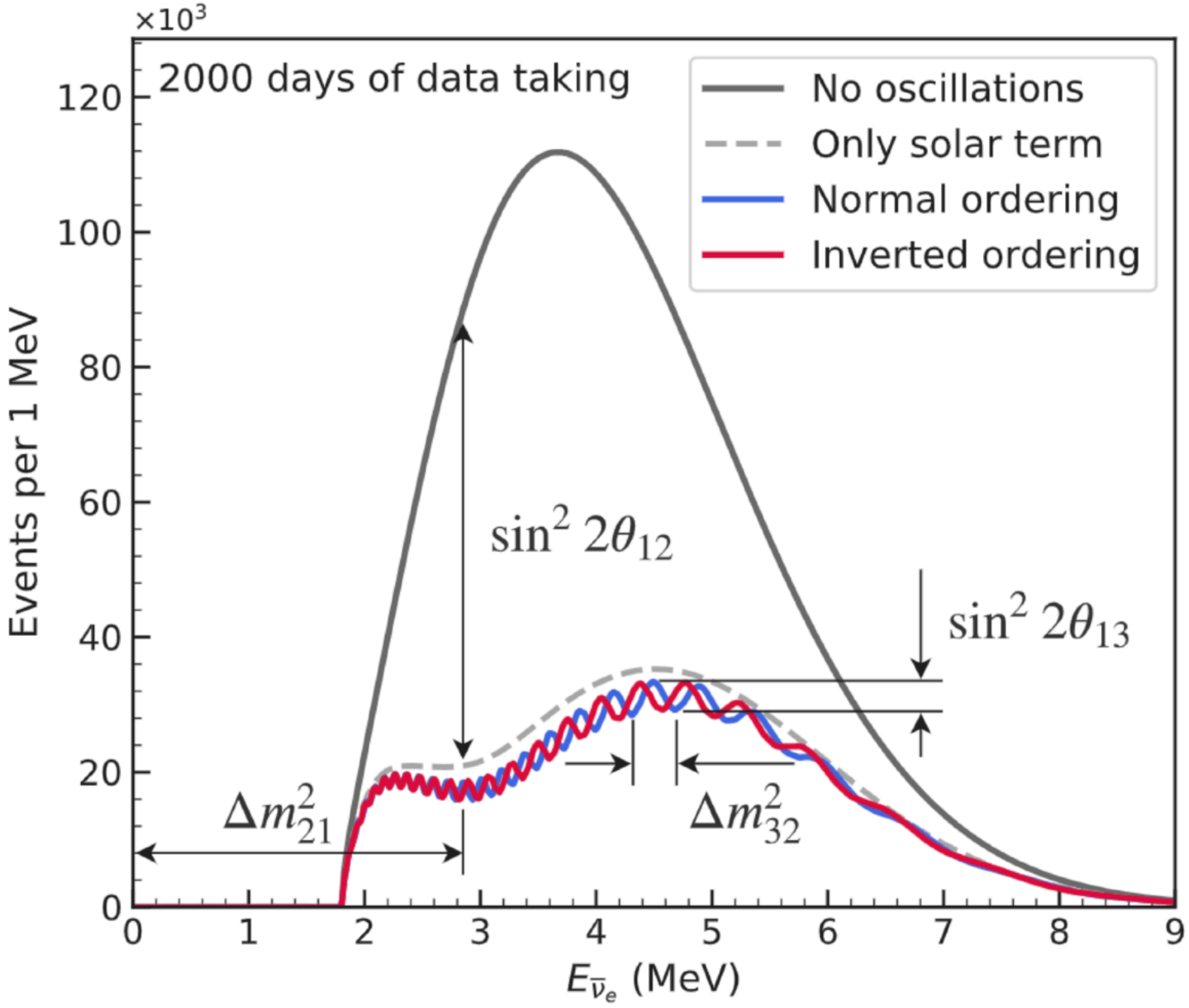


MEASURING THE MASS HIERARCHY: JUNO

Phys.Lett. B533 (2002) 94-106

Prog.Part.Nucl.Phys. 123 (2022) 103927

- Reactor neutrino experiment: $\bar{\nu}_e$ disappearance at baseline ~50 km
- Sensitive to both oscillations according to Δm^2_{21} and Δm^2_{32} → **interplay of both** gives sensitivity to mass hierarchy
- Extremely precise energy resolution → **determine mass hierarchy at 3σ in 6 years**



PROJECT 8

How much do neutrinos weigh?

KATRIN

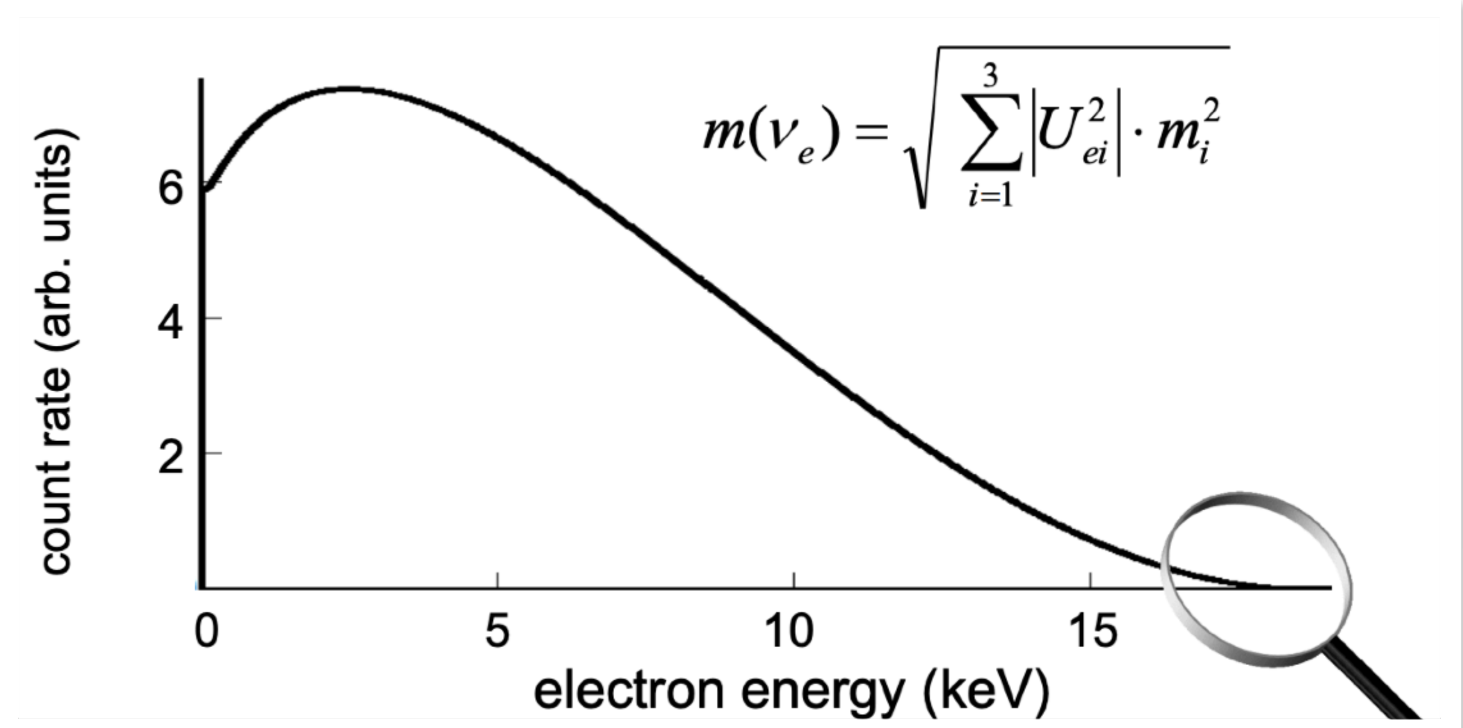
KARLSRUHE TRITIUM NEUTRINO EXPERIMENT

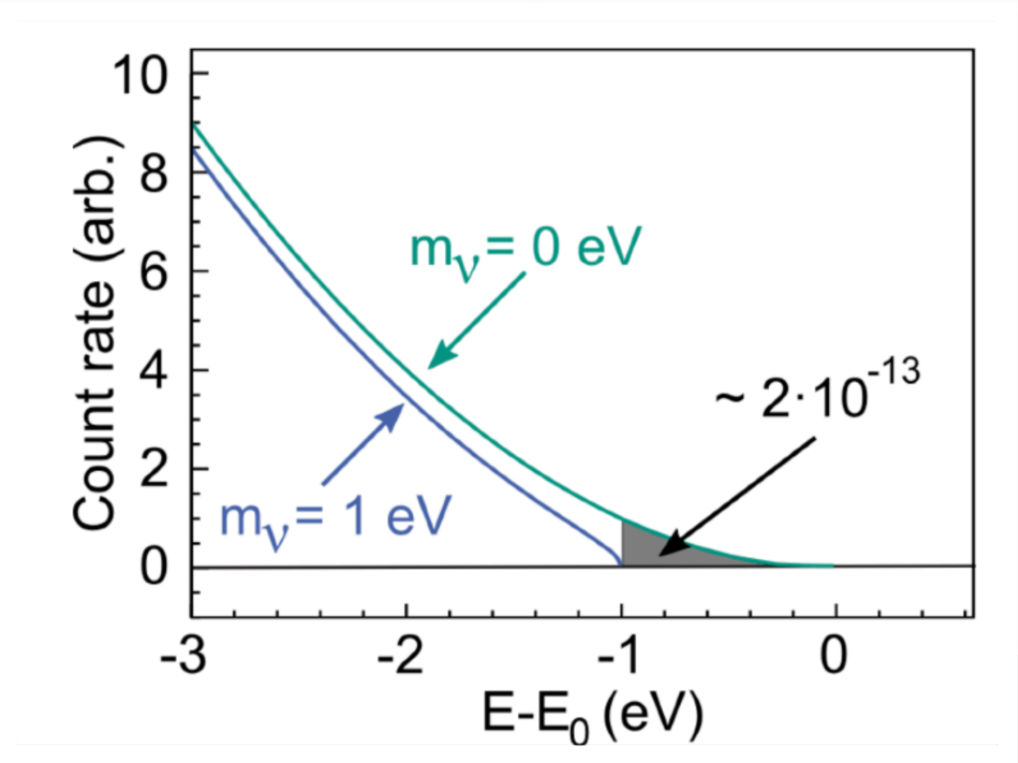
MEASURING THE NEUTRINO MASS

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

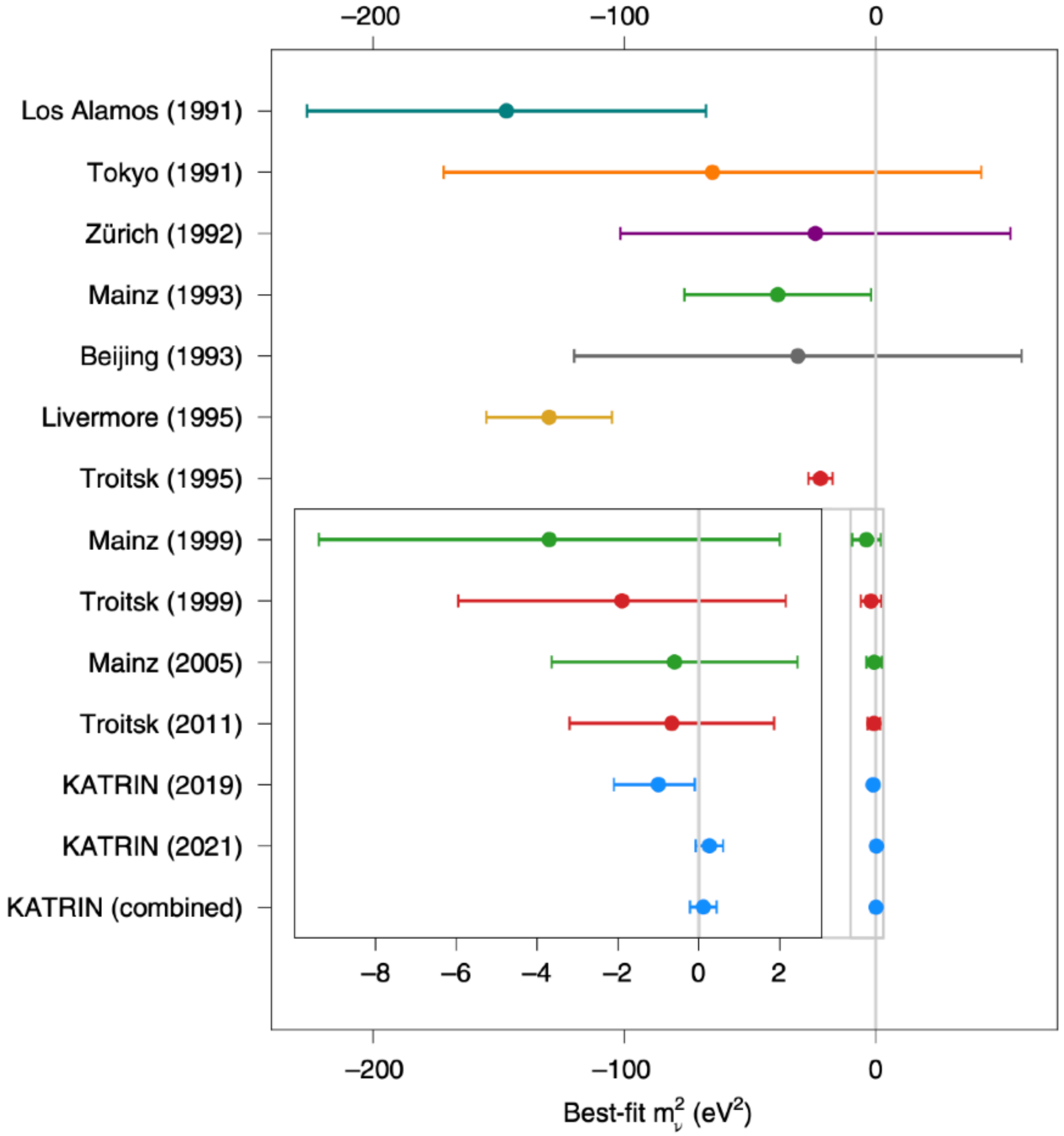
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

- Neutrino oscillation tells us that neutrinos have mass
- But not the absolute mass (only the Δm^2 differences)



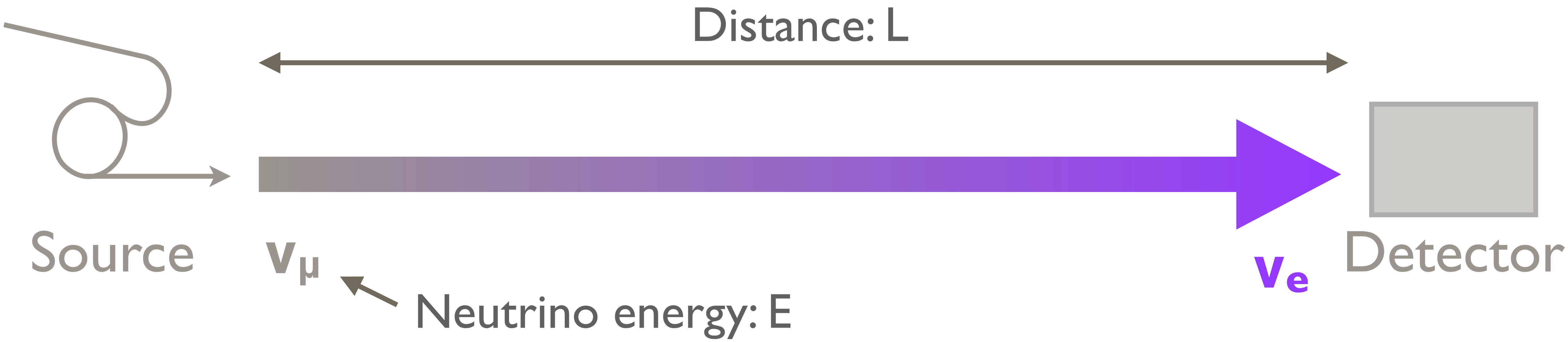


MEASURING THE NEUTRINO MASS



- New KATRIN result: Nature Physics volume 18, pages 160–166, 14th February 2022
- **World's best constraint on neutrino mass**
- Best fit: $m_\nu = 0.26 \pm 0.34$ eV^{2}c^{-4}
- Upper limit of $m_\nu < 0.8$ eVc^{-2} at 90% confidence level

Is neutrino oscillation different for neutrinos and antineutrinos?



Distance: L

Source

ν_μ

Neutrino energy: E

ν_e

Detector

Muon neutrino disappearance

Electron neutrino appearance

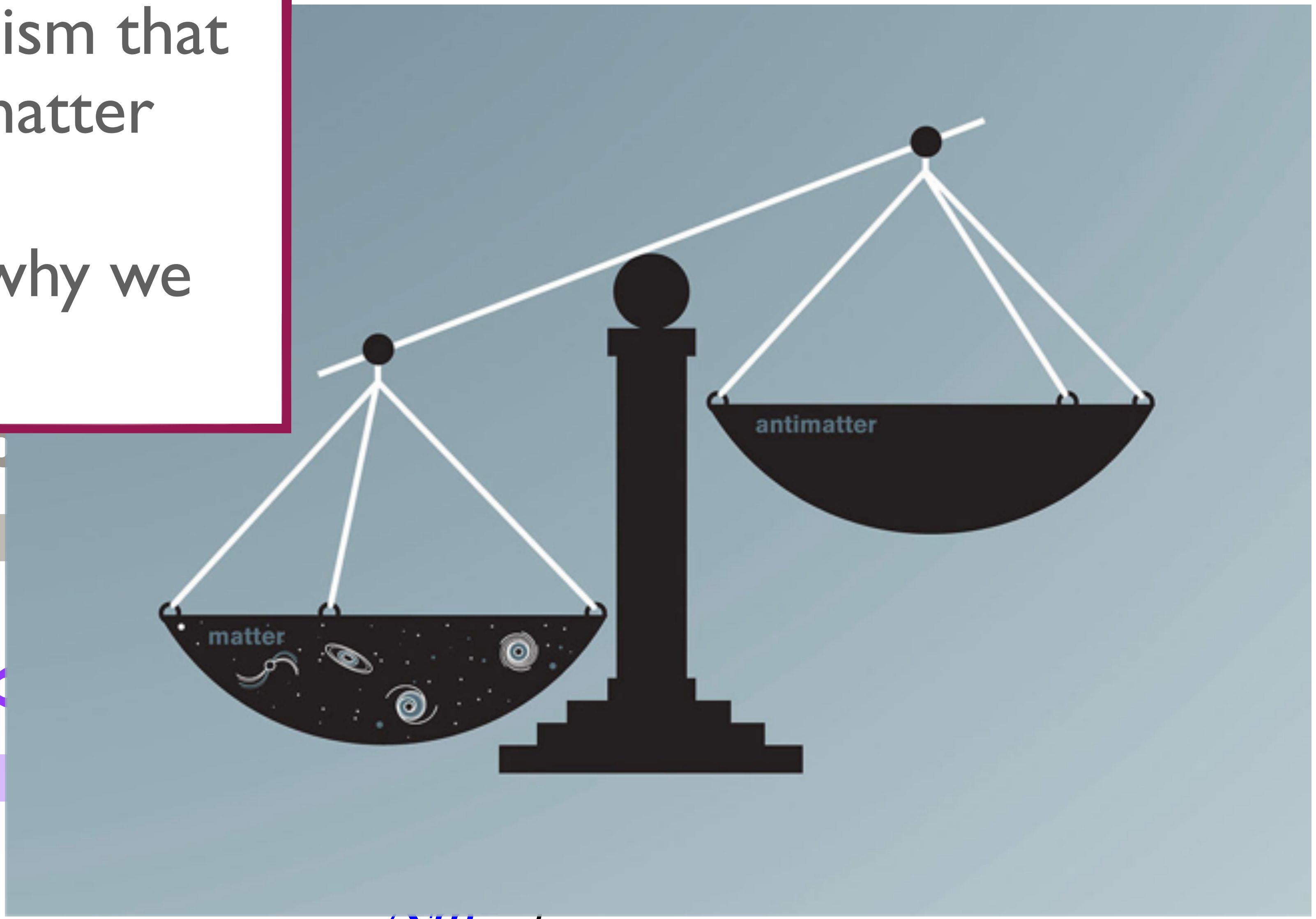
$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E} \\
& (+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13} \\
& \times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big] \\
& + (\text{CP-even, solar, matter effect terms})
\end{aligned}
$$

CP violation in neutrinos could provide insight into a mechanism that could provide matter-antimatter asymmetry
→ could neutrinos explain why we exist?

: L

Muon neutrino disapp

Electron neutrino app



$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$

$$(+)-\Big[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}$$

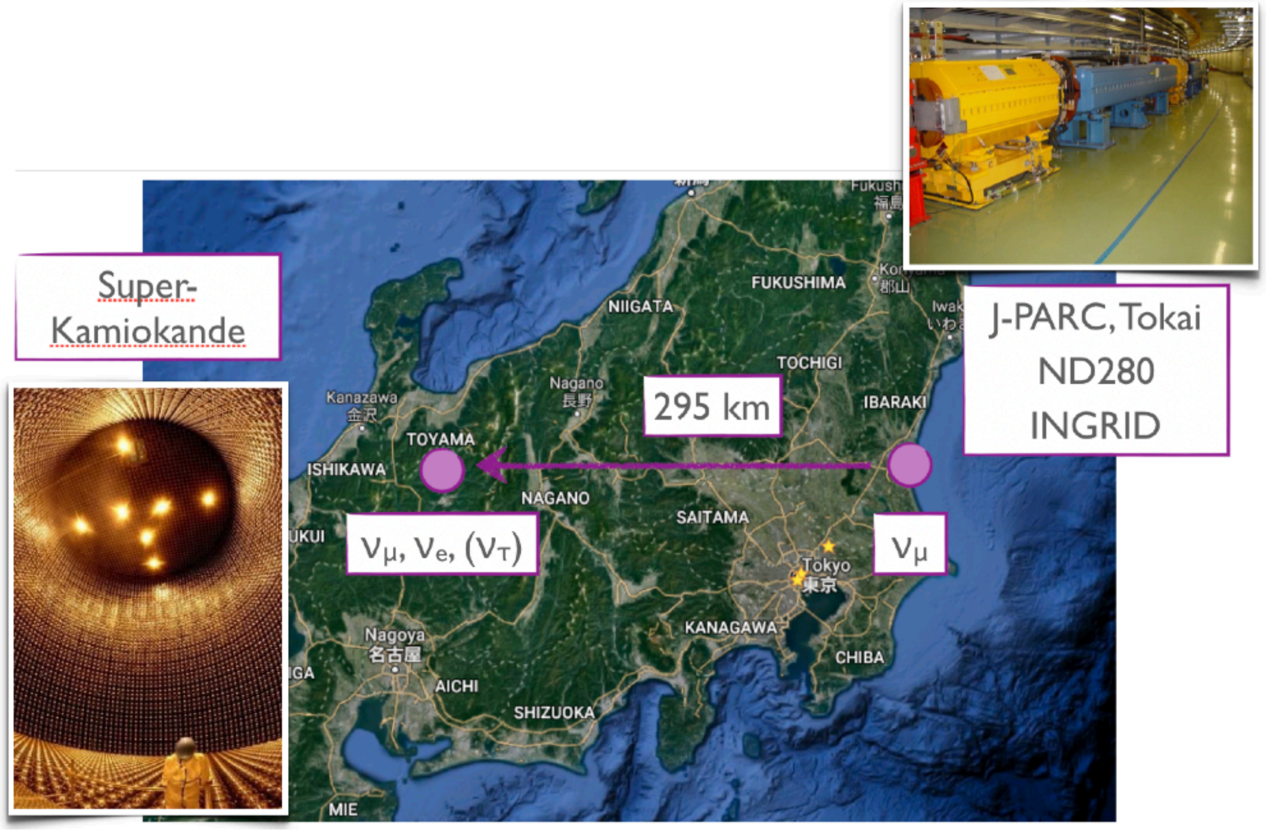
$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\Big]$$

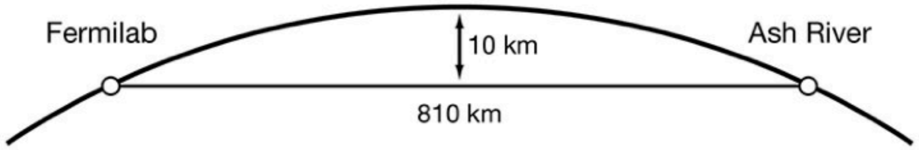
$$+\ (\text{CP-even, solar, matter effect terms})$$

(TRYING TO) MEASURE CP VIOLATION

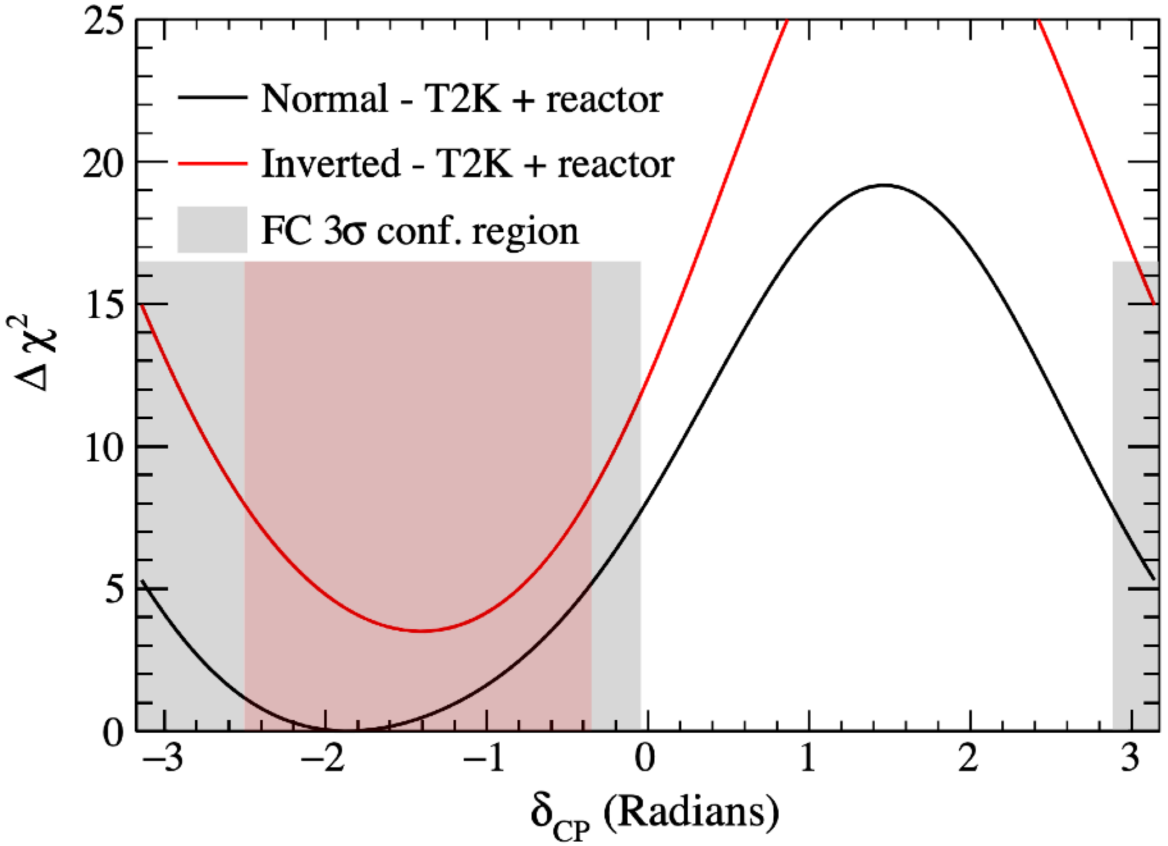
T2K
(Tokai to Kamioka)

NOvA
(NuMI Off-axis ν_e Appearance)



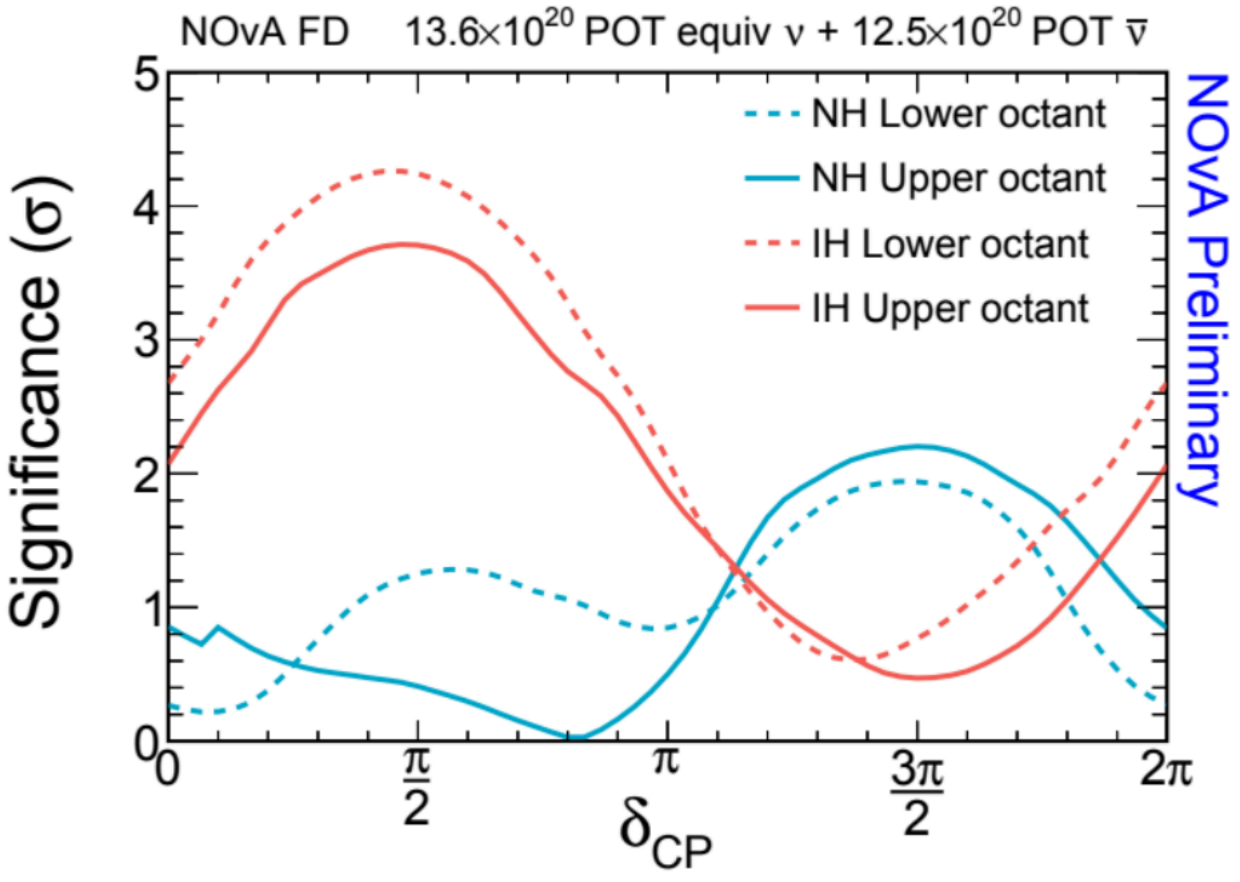


(TRYING TO) MEASURE CP VIOLATION



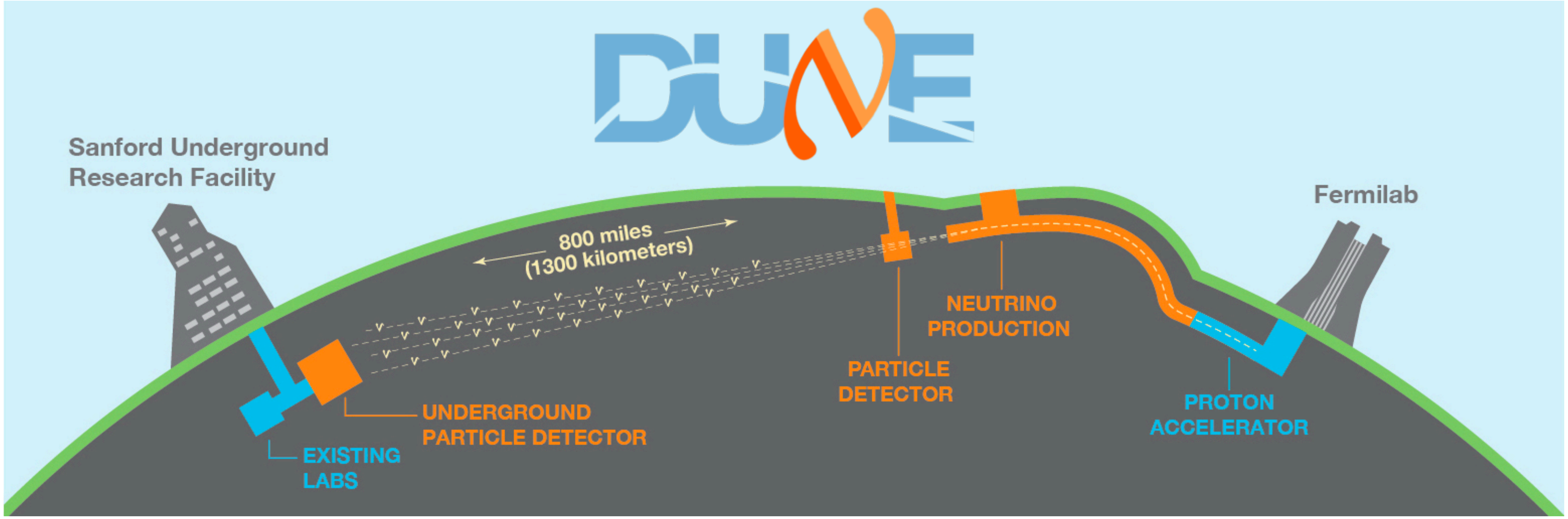
T2K

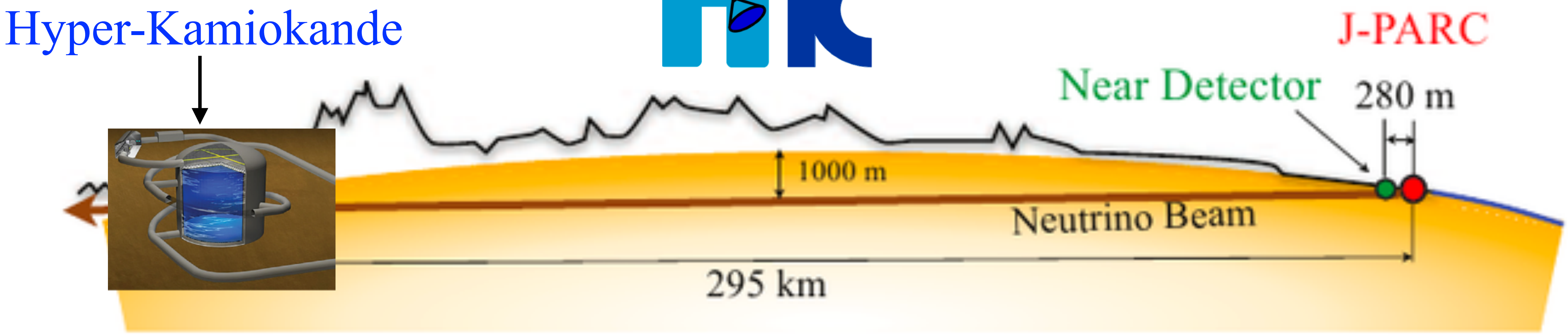
Favours $\delta_{CP}=-\pi/2$ in both normal and inverted hierarchy



NOvA

Favours $\delta_{CP}=-\pi/2$ in inverted hierarchy; $\delta_{CP}=\pi/2$ in normal


DUNE
Sanford Underground Research Facility
800 miles (1300 kilometers)
Fermilab
NEUTRINO PRODUCTION
PARTICLE DETECTOR
PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS


Hyper-Kamiokande
J-PARC
Near Detector
280 m
1000 m
Neutrino Beam
295 km

NOvA

T2K

annie

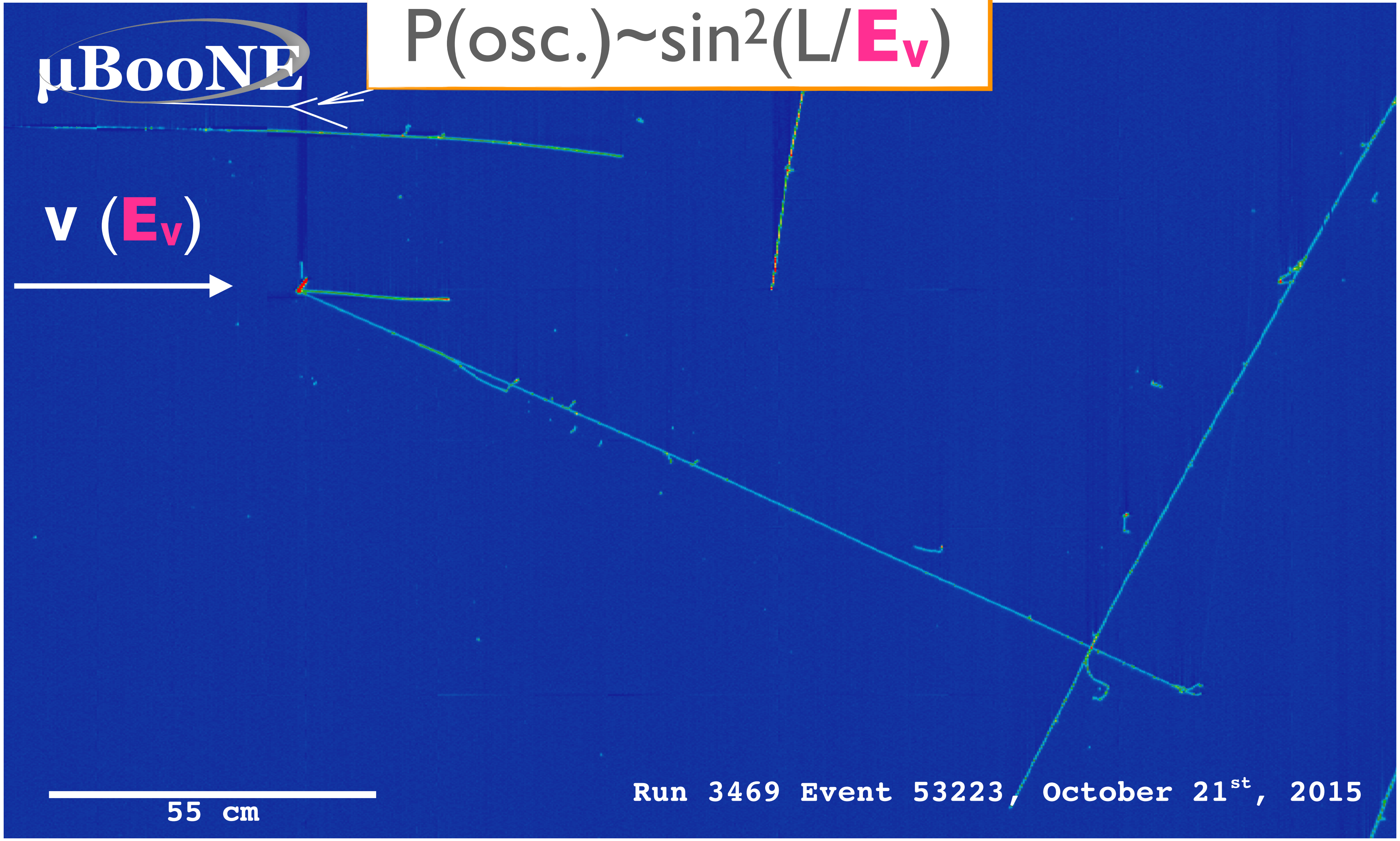
How do neutrinos interact in the nuclear medium?

MINERvA

μBooNE

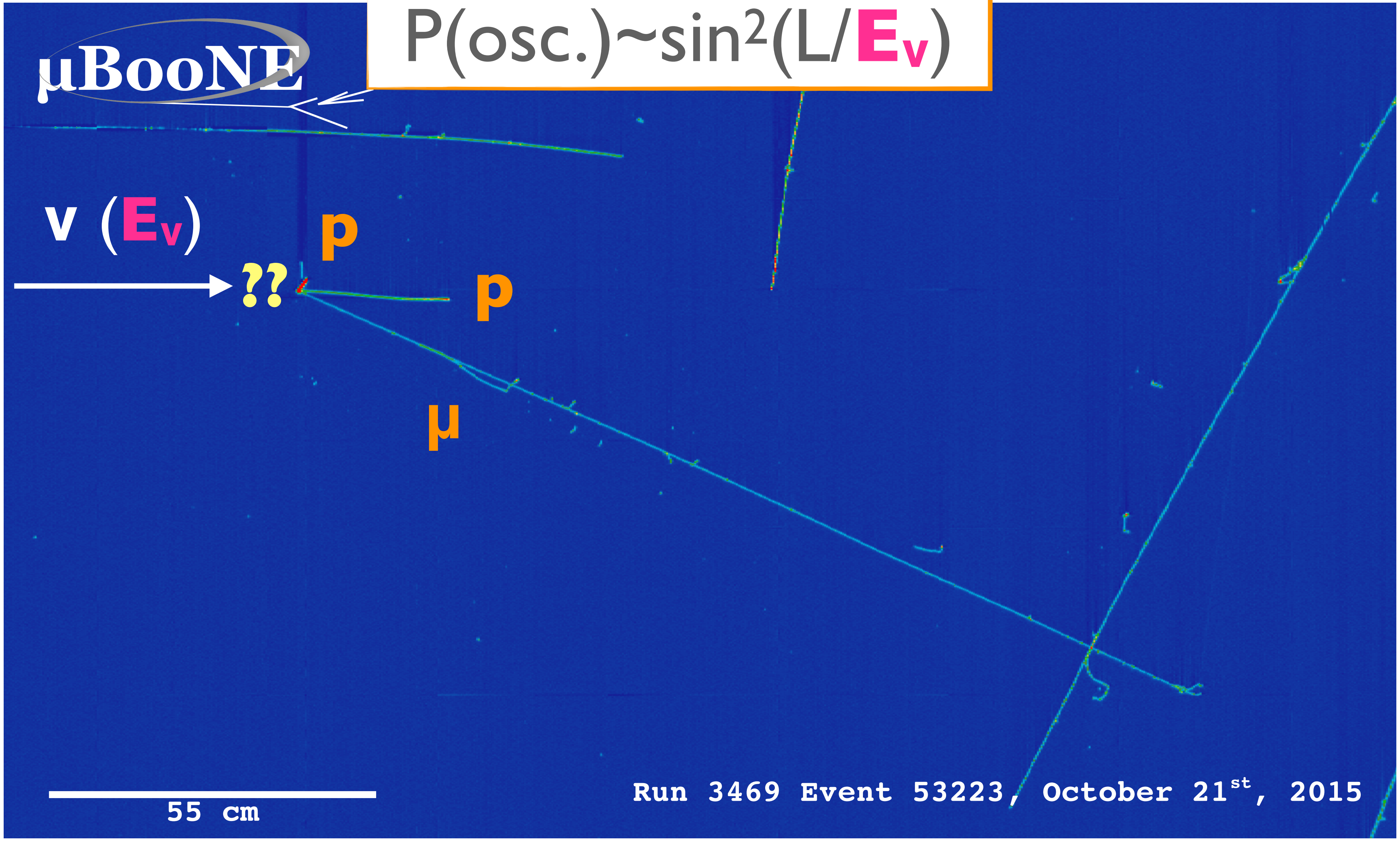
NEUTRINO INTERACTIONS

$P(\text{osc.}) \sim \sin^2(L/E_\nu)$



NEUTRINO INTERACTIONS

P(osc.)~$\sin^2(L/E_\nu)$



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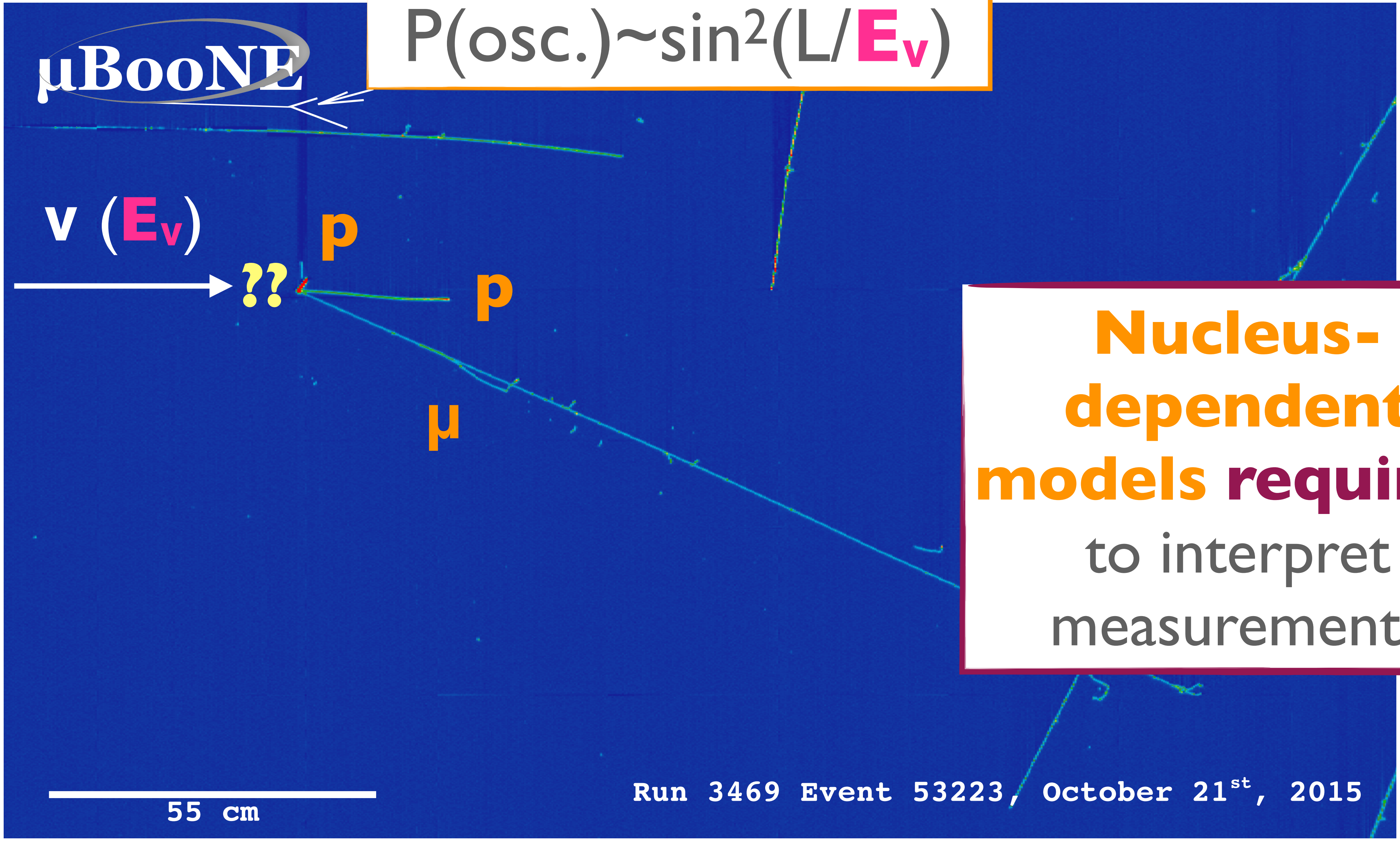
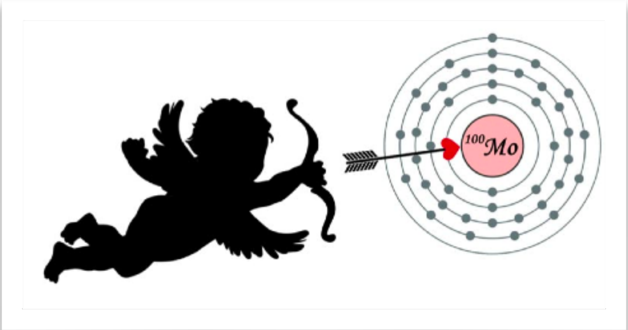


$P(\text{osc.}) \sim \sin^2(L/E_\nu)$

Nucleus-dependent models required to interpret measurements

CUORE

LEGEND



Are neutrinos their own antiparticles?

SNO+

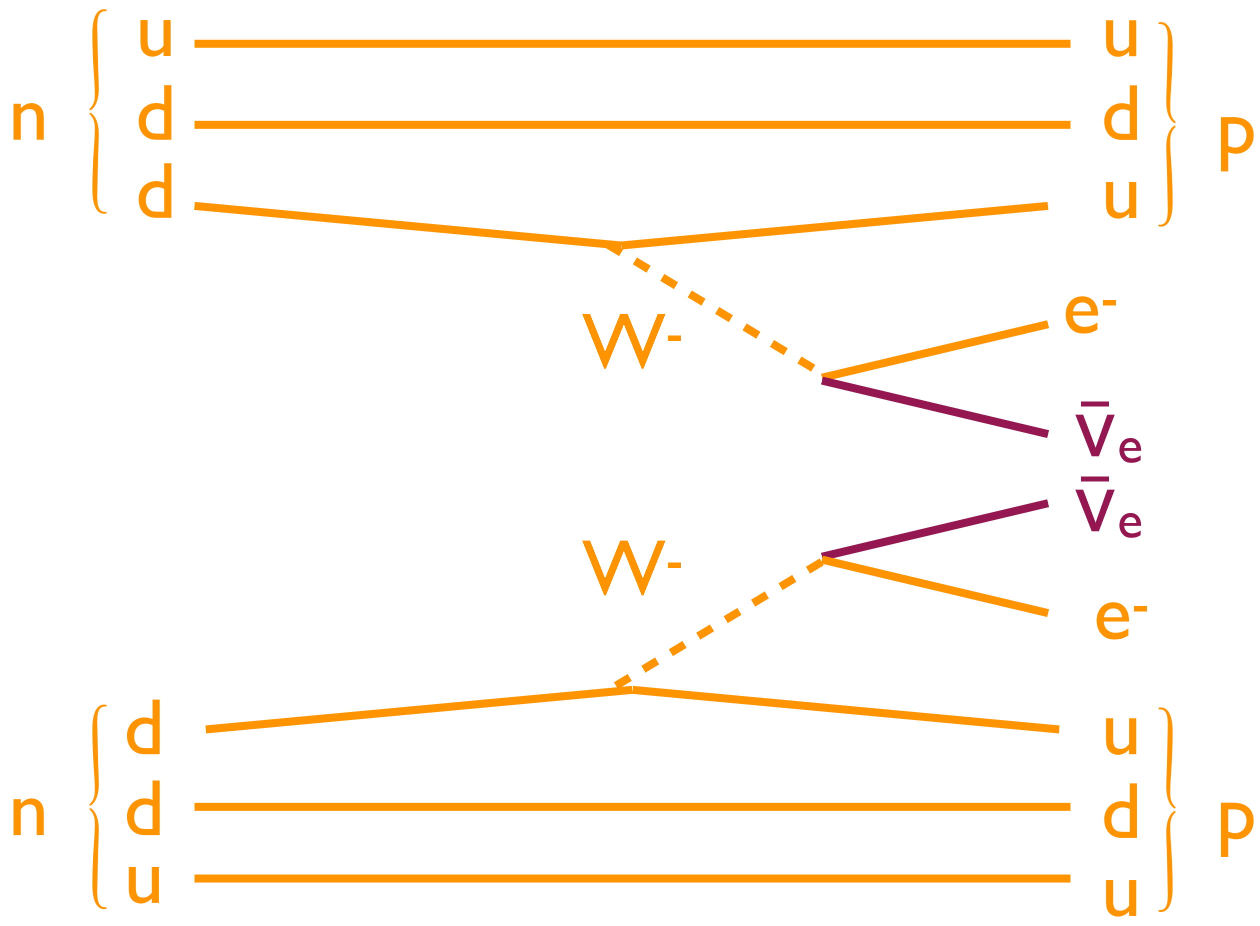
nEXO

ARE NEUTRINOS THEIR OWN ANTIPARTICLES?

- Uniquely in the Standard Model, neutrinos could be their own particles → Majorana fermions

- Could explain small neutrino mass

- Most promising way to search: neutrinoless double beta decay



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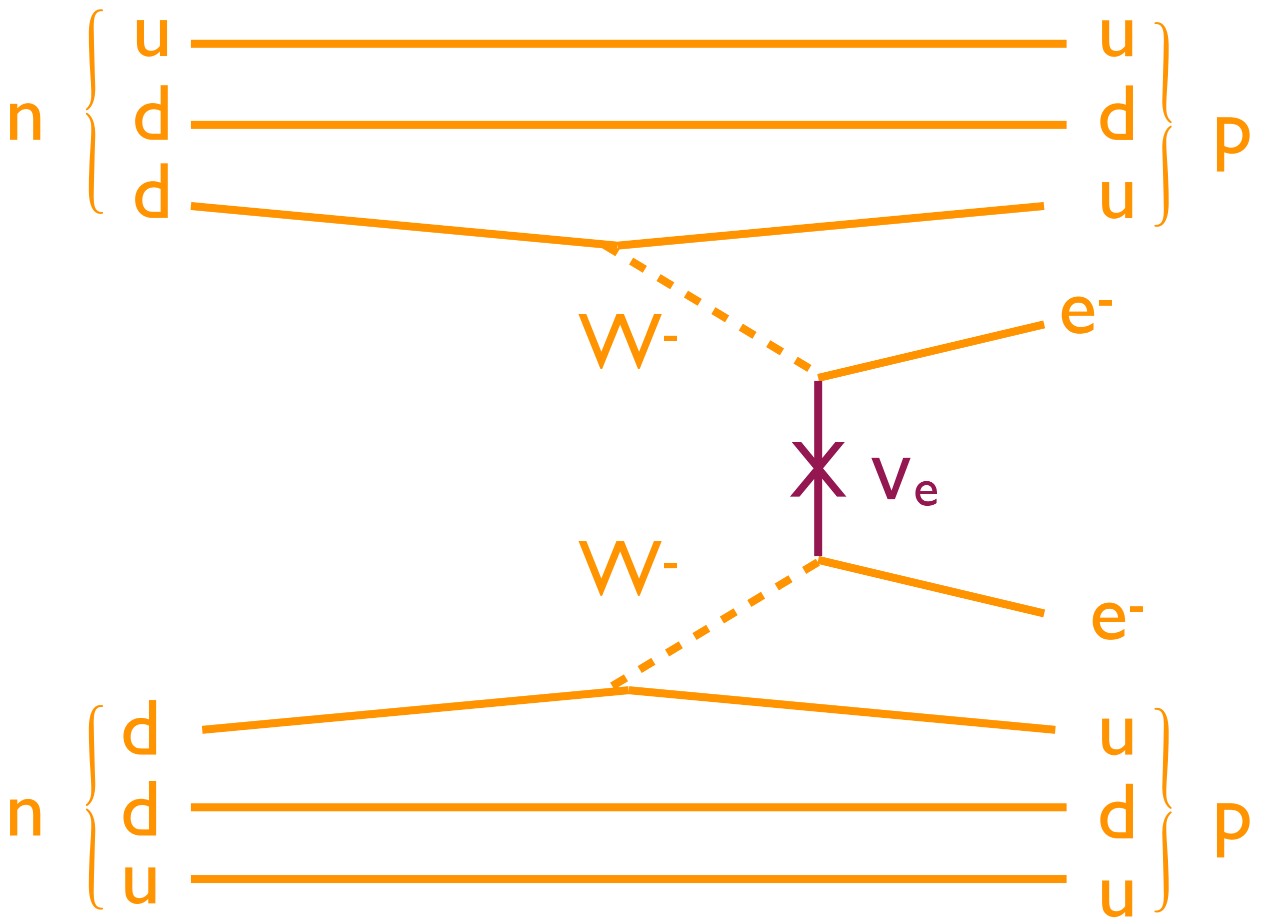

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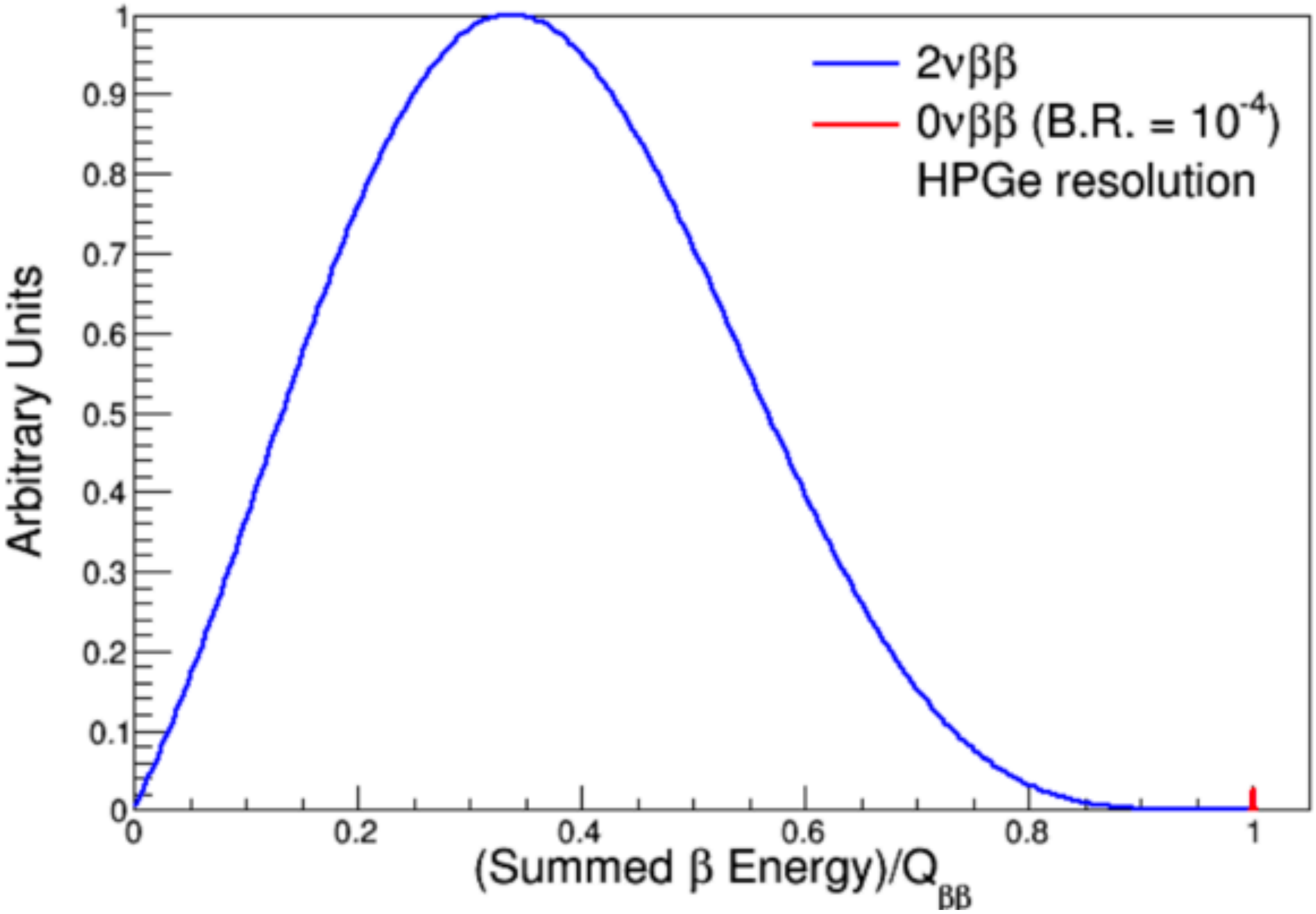


ICECUBE
NEUTRINO OBSERVATORY

BOREXINO
ν_e ν_x
GRAN SASSO

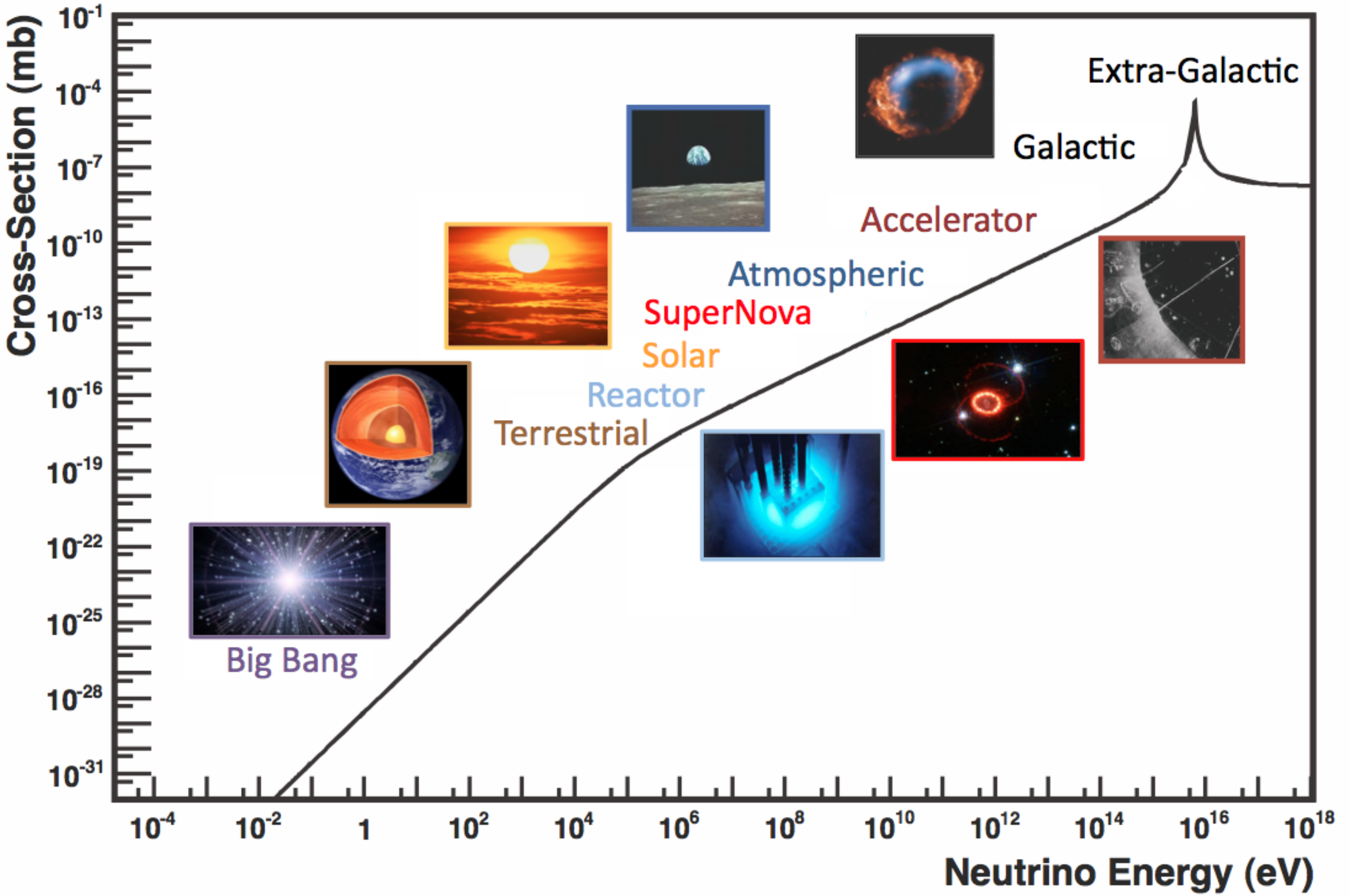
FASER

What else can neutrinos teach us?

PIERRE AUGER
OBSERVATORY

P-ONE

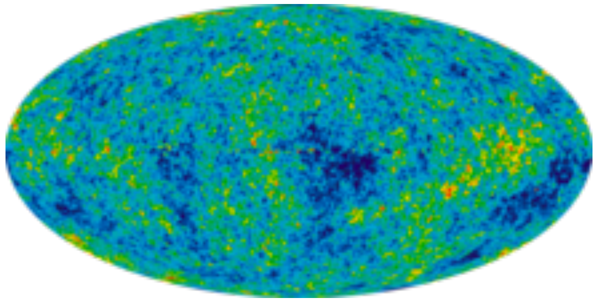
KM3NeT

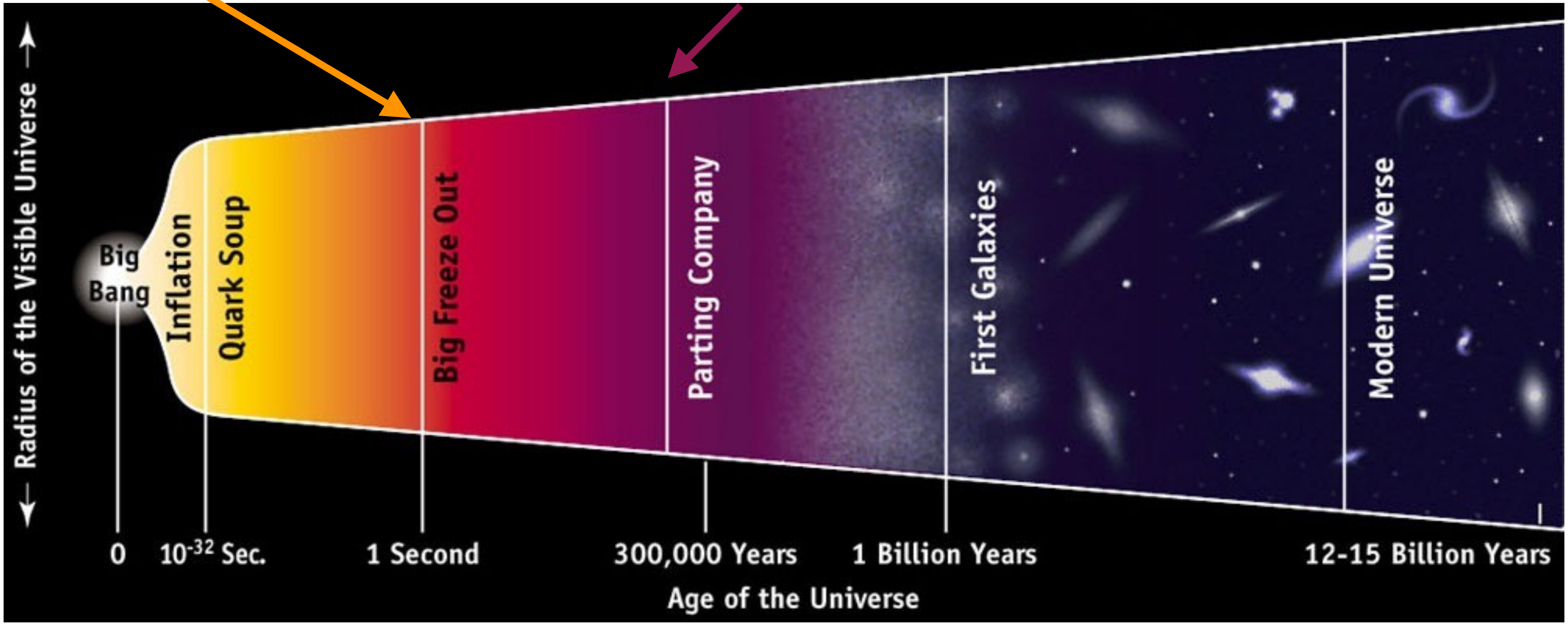

Cross-Section (mb)
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Neutrino Energy (eV)
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang

COSMIC NEUTRINO BACKGROUND

Big-Bang Relic Neutrinos:
1 second old

Cosmic Microwave Background:
~300,000 years old



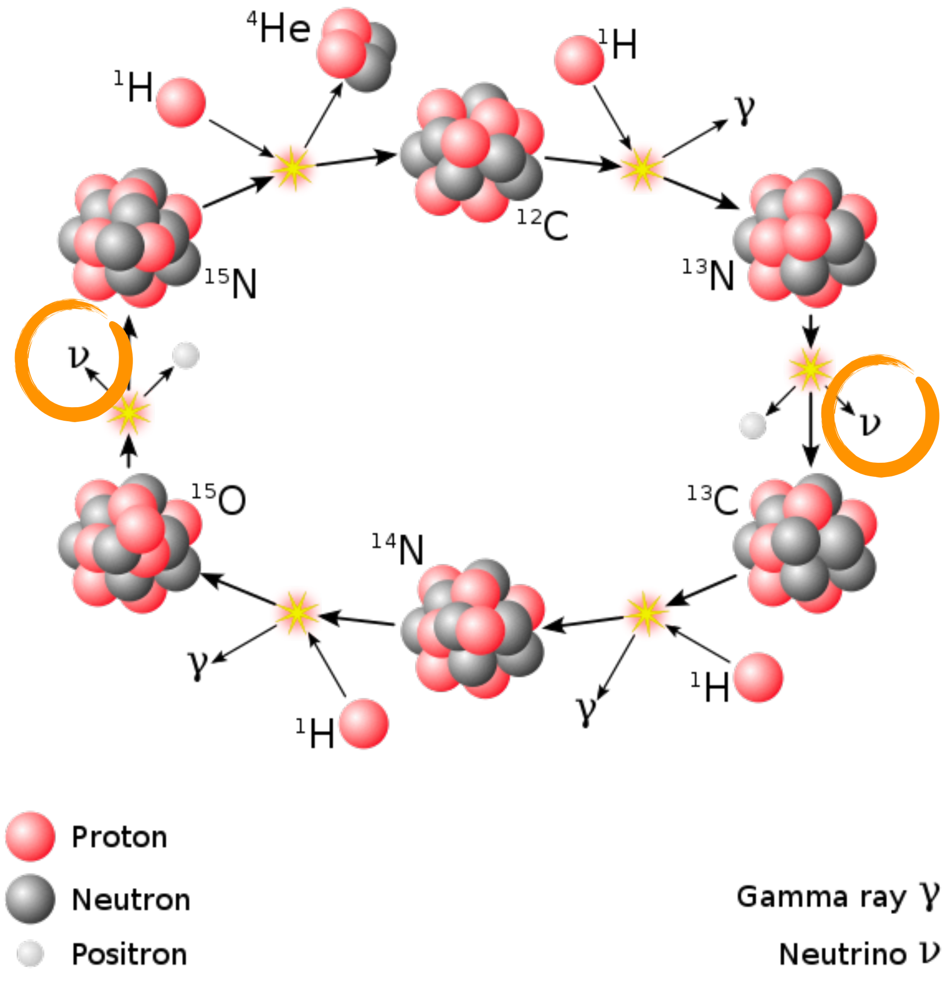


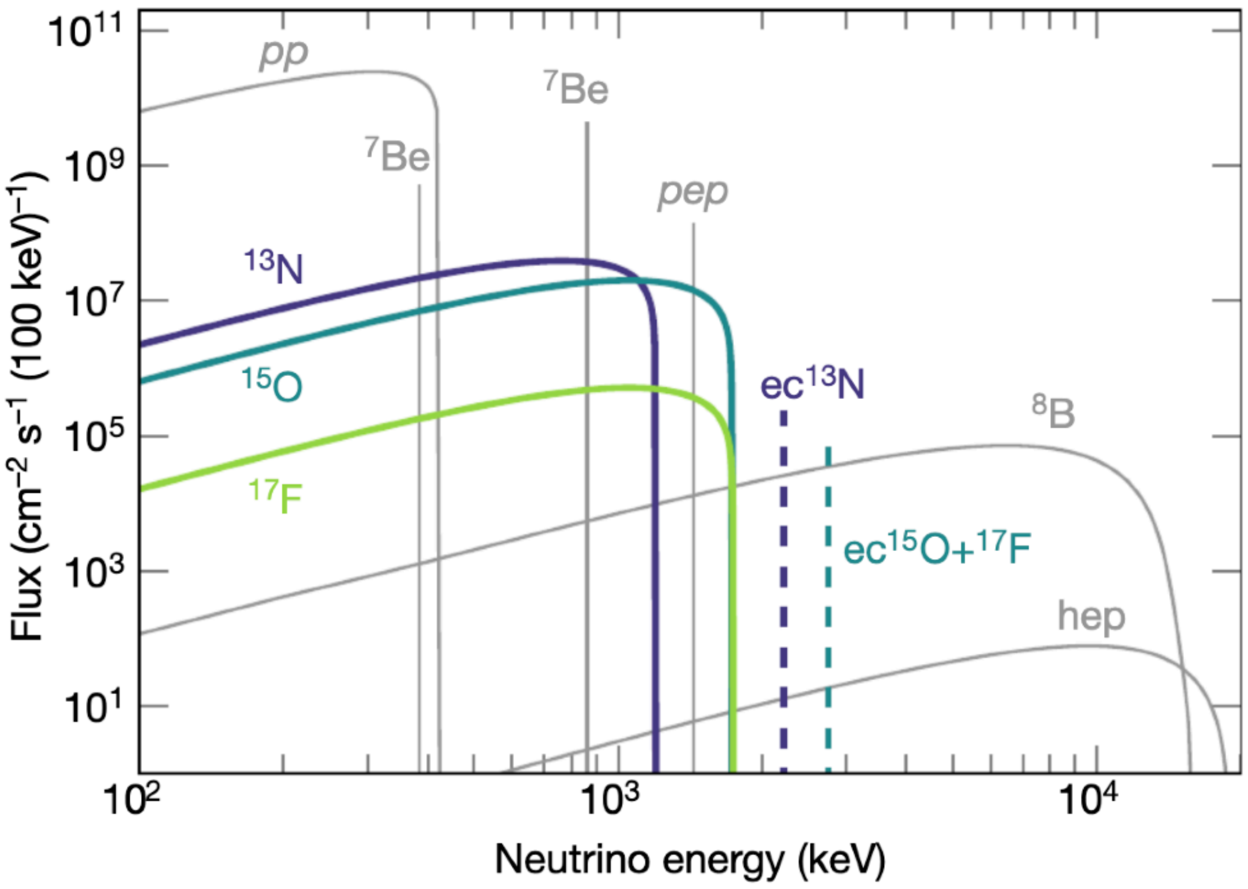
SOLAR NEUTRINOS

nature

CATCHING THE RAYS

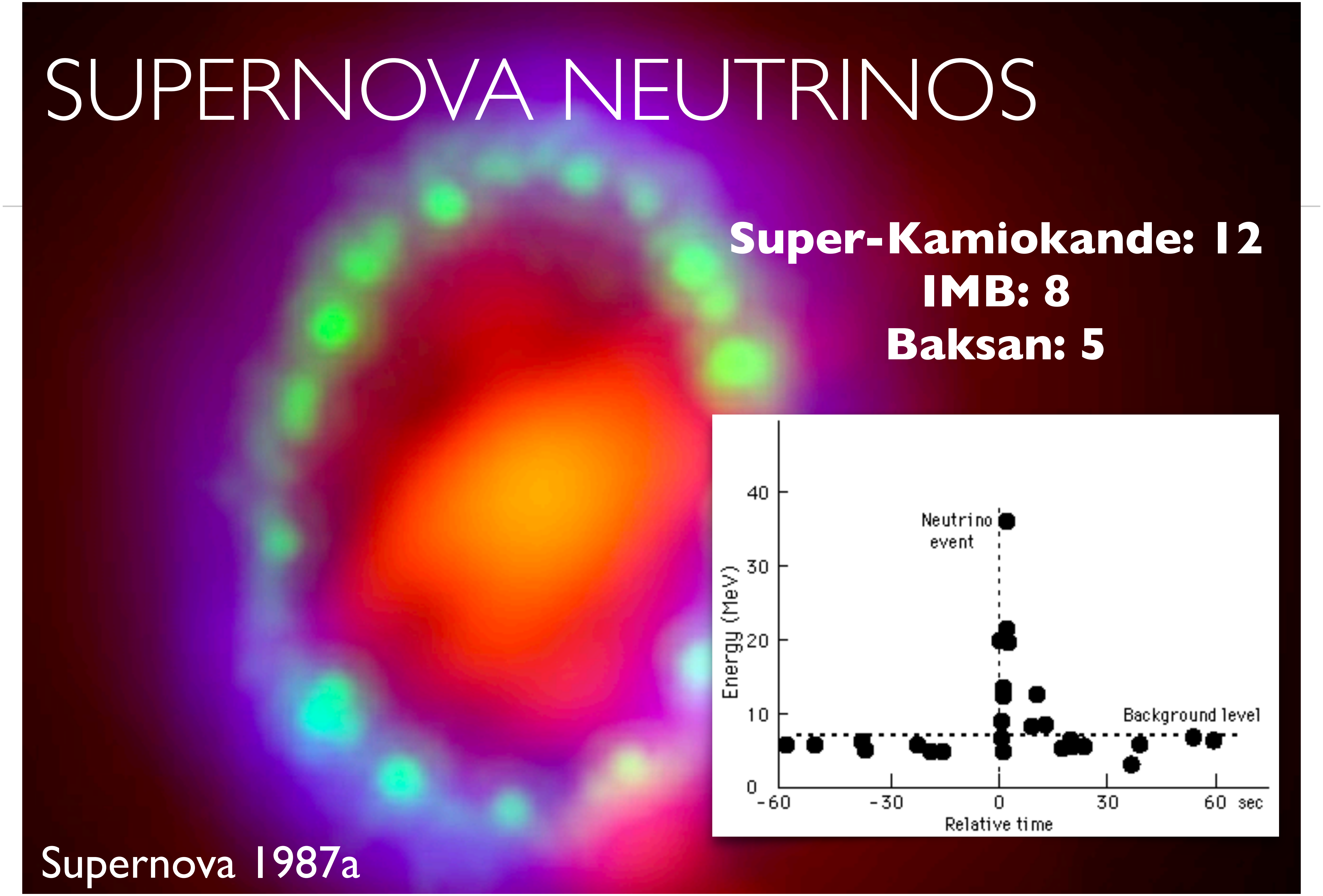
Neutrino detector secures evidence of the Sun's secondary fusion cycle





Nature volume 587, pages 577–582 (2020)

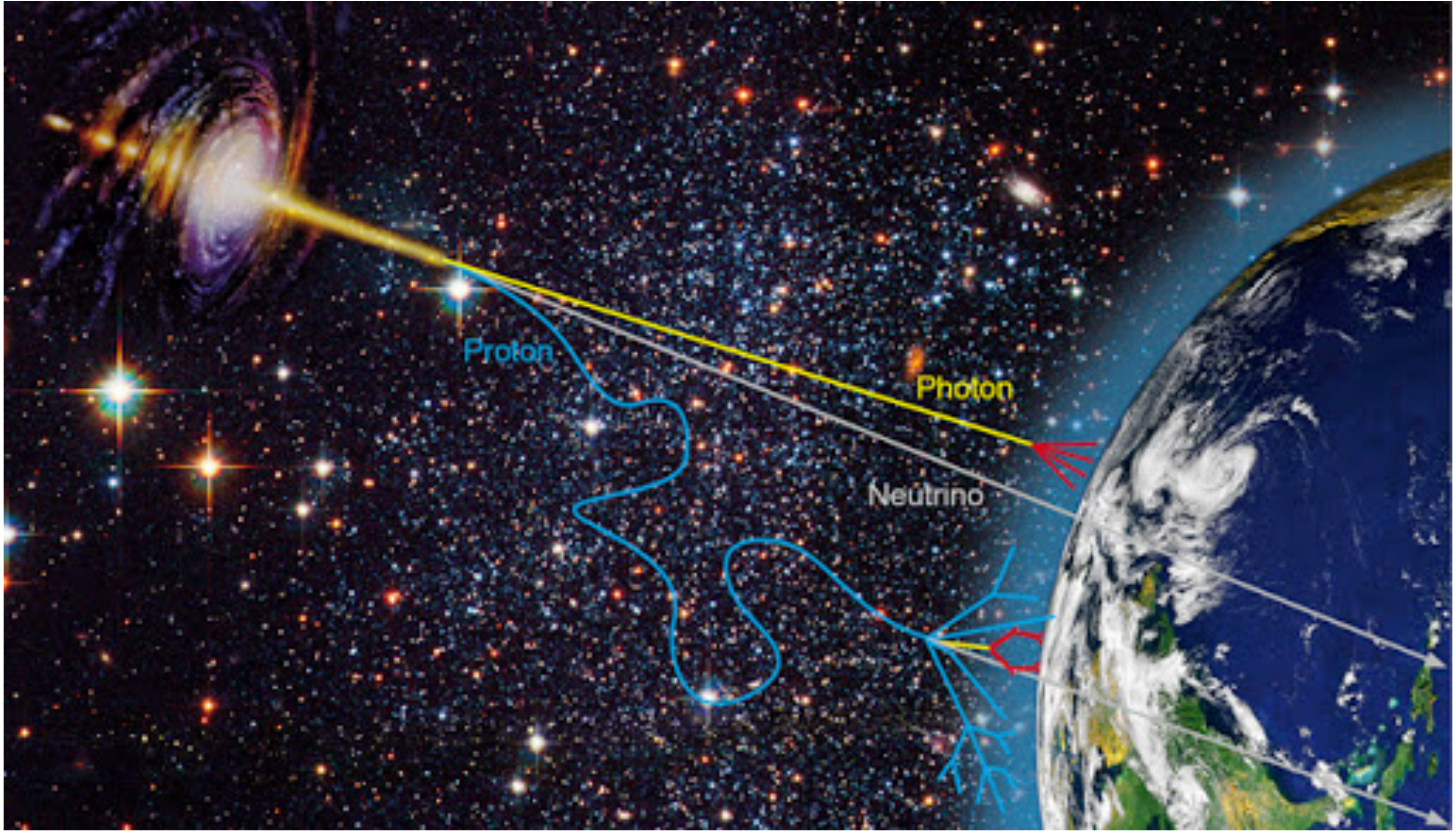
SUPERNOVA NEUTRINOS



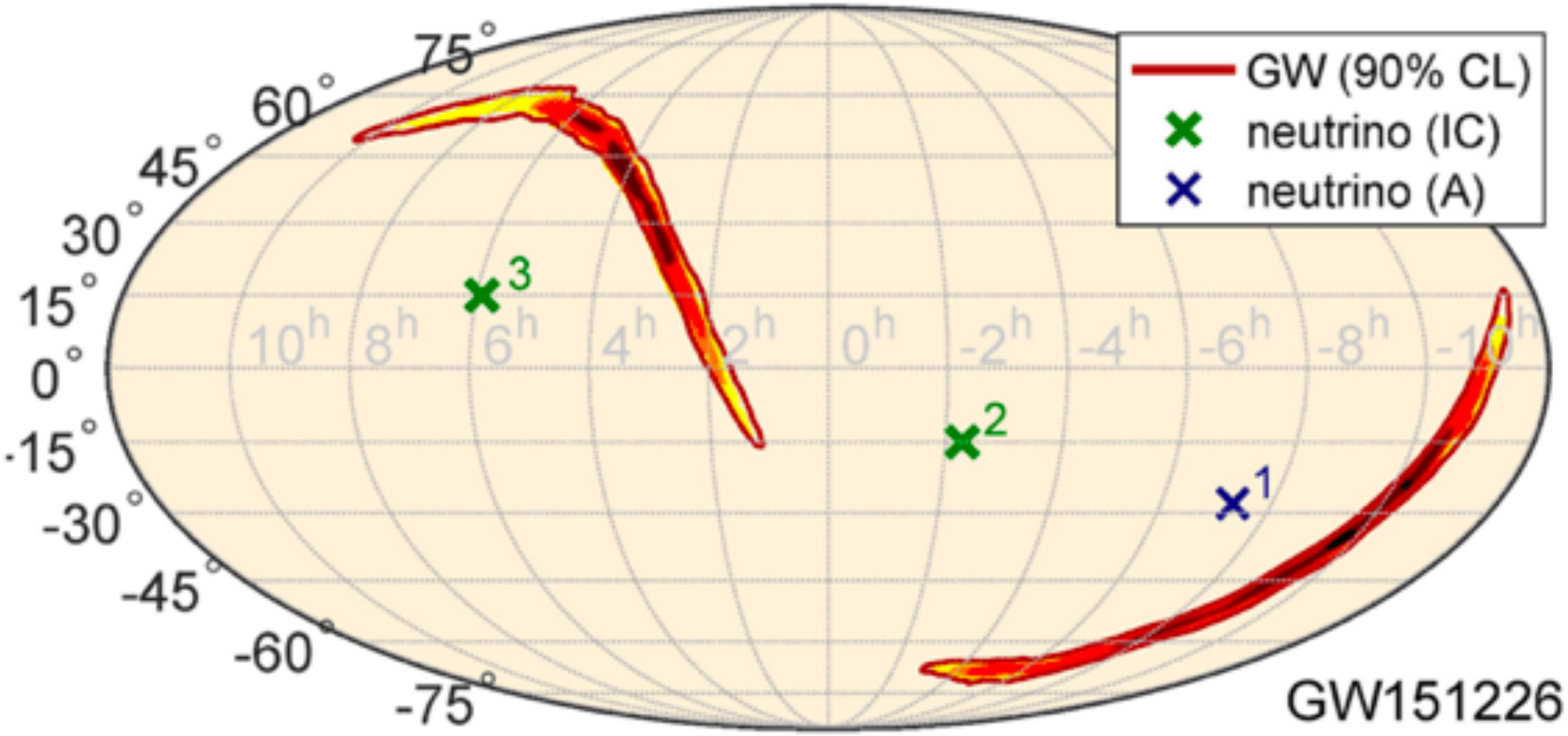
Super-Kamiokande: 12
IMB: 8
Baksan: 5

Supernova 1987a

GALACTIC NEUTRINOS



GALACTIC NEUTRINOS



How many neutrinos are there?

(A SMALL SELECTION OF) NEUTRINO ANOMALIES

There have been a number of anomalies observed in the past 20-odd 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
ANITA	High energy	High-energy events

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

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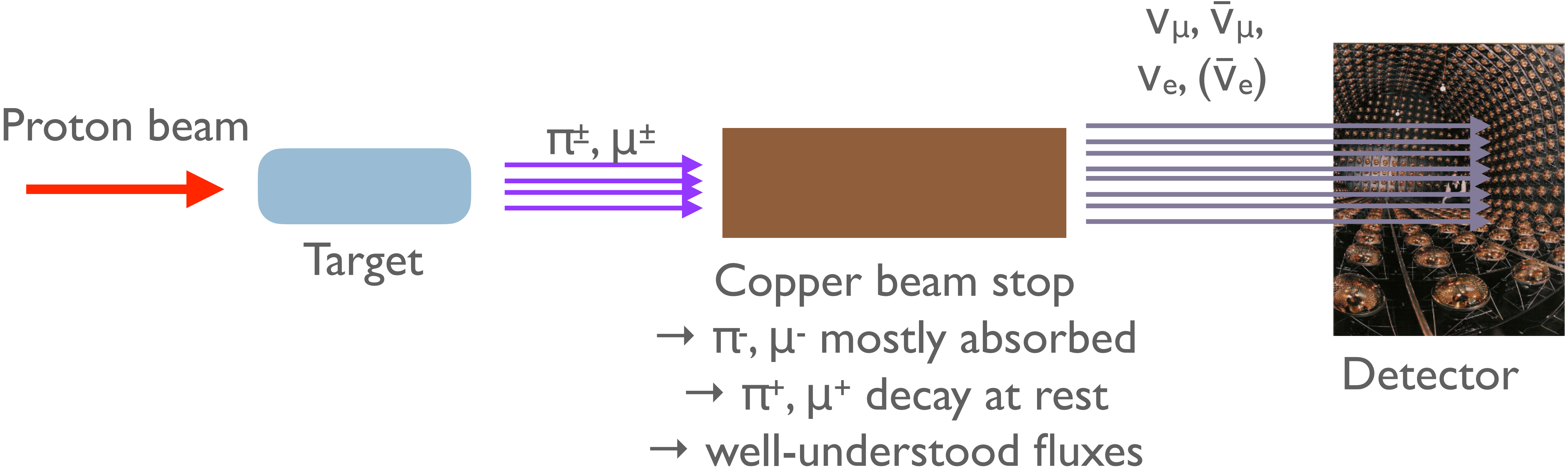
ANOMALIES: LSND

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

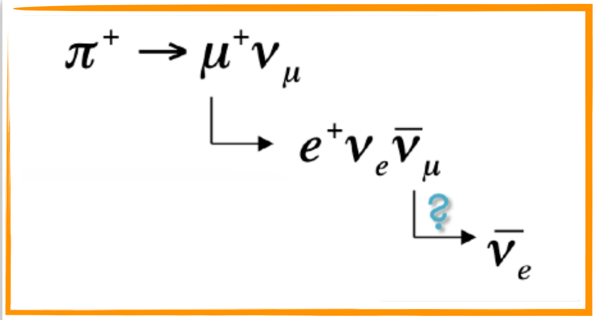


Copper beam stop
→ π^-, μ^- mostly absorbed
→ π^+, μ^+ decay at rest
→ well-understood fluxes

$$\begin{tikzcd}[row sep=small] \pi^+ \arrow[r] & \mu^+\nu_\mu \arrow[d, phantom] \\ & \hookrightarrow e^+\nu_e\bar{\nu}_\mu \end{tikzcd}$$

Phys. Rev. D 64, 112007

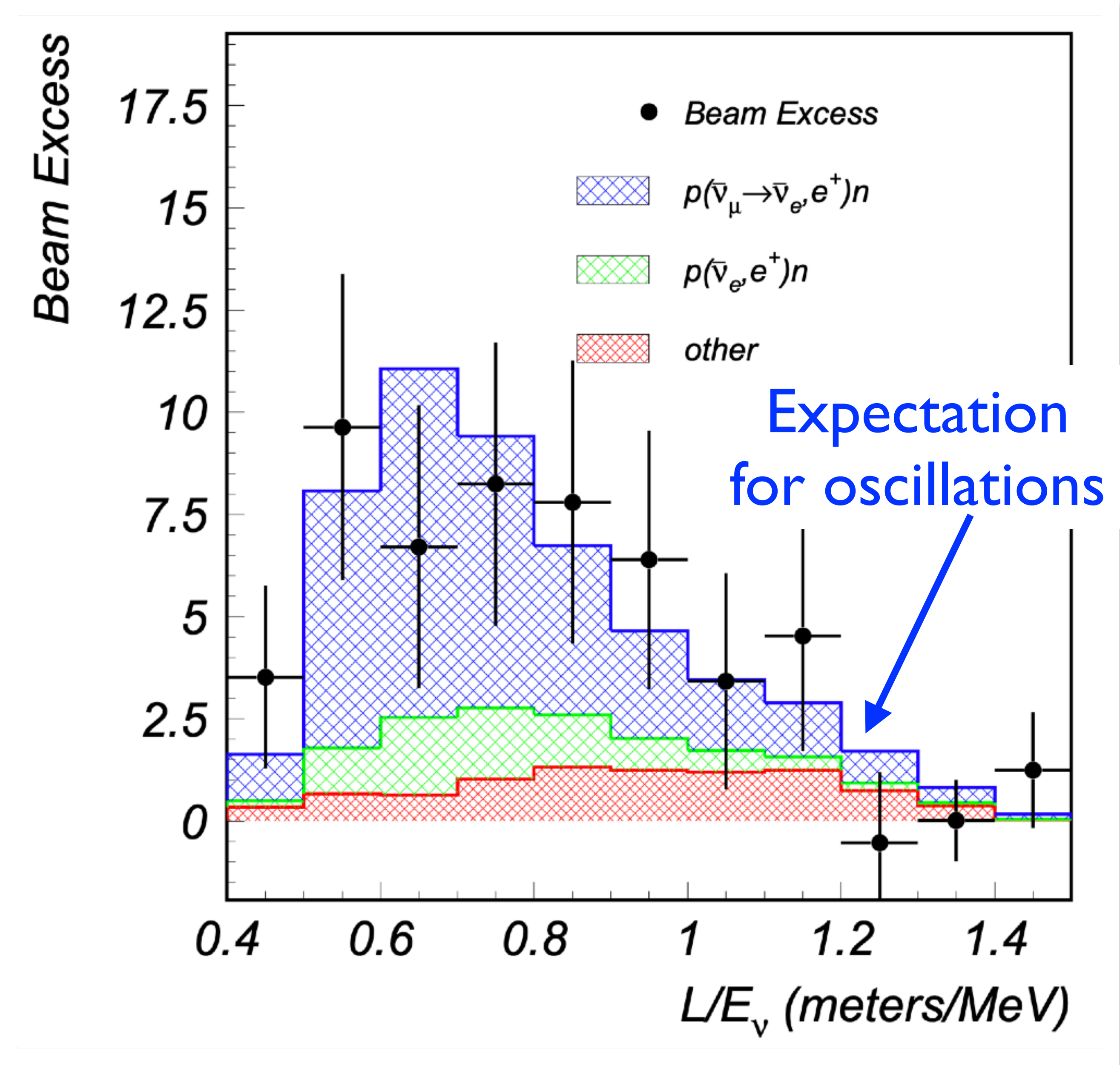
ANOMALIES: LSND



$\pi^+ \rightarrow \mu^+\nu_\mu$

$\hookrightarrow e^+\nu_e\bar{\nu}_\mu$

$\overset{?}{\hookrightarrow} \bar{\nu}_e$

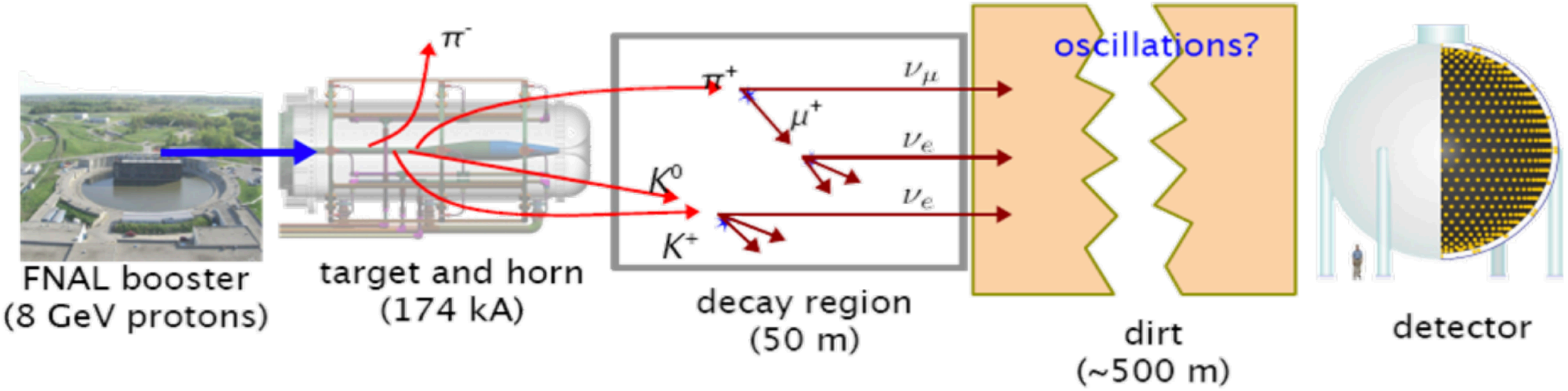


Expectation for oscillations

Phys. Rev. D 64, 112007

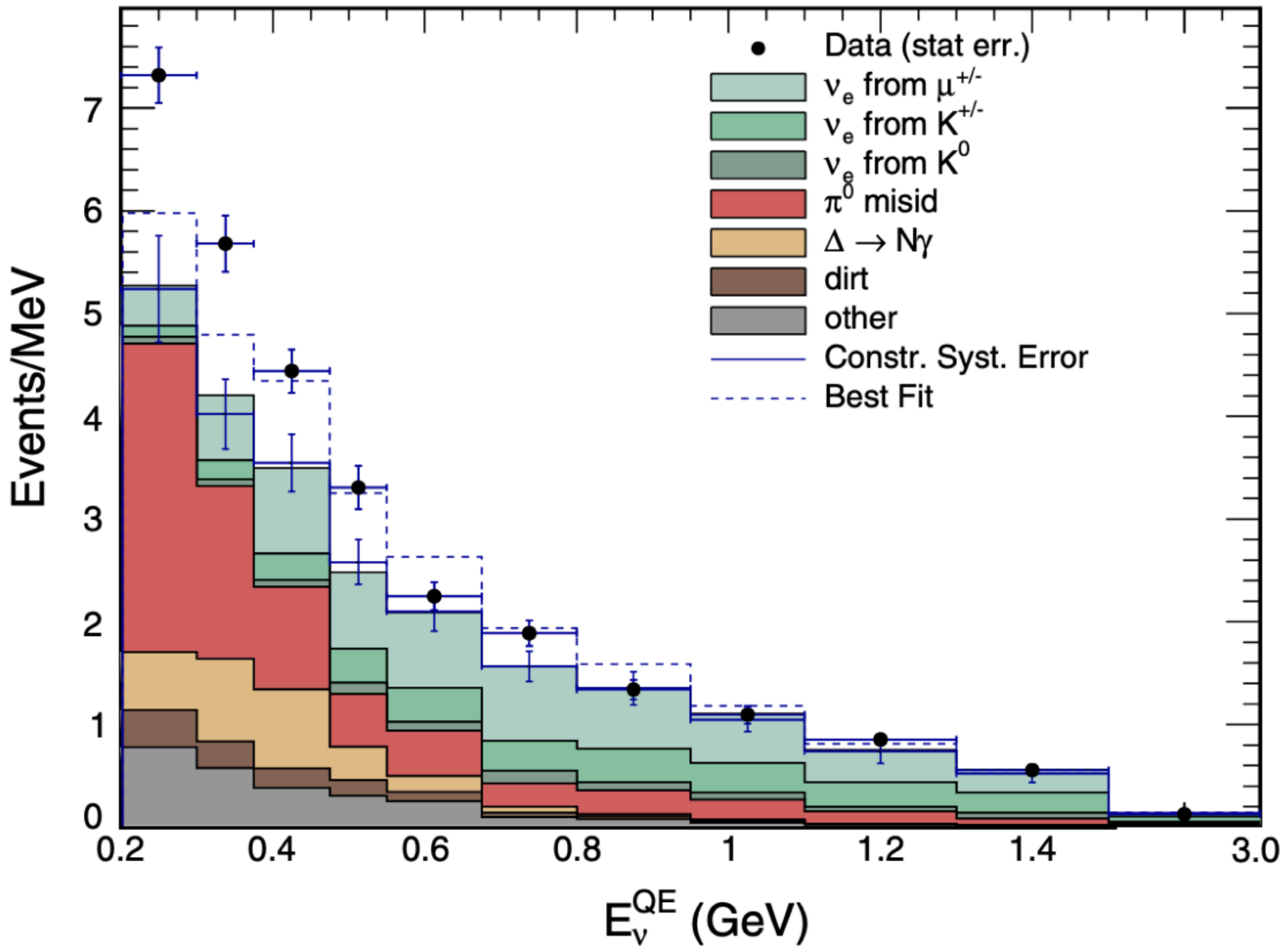
- Observed excess of $\bar{\nu}_e$ at 3.8σ
- If interpreted as two-flavour neutrino oscillation, requires **$\Delta m^2 \sim 0.2\text{-}10\,\mathrm{eV}^2$**
- **Not consistent with any known 3-flavour oscillation**

ANOMALIES: MINIBOONE



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

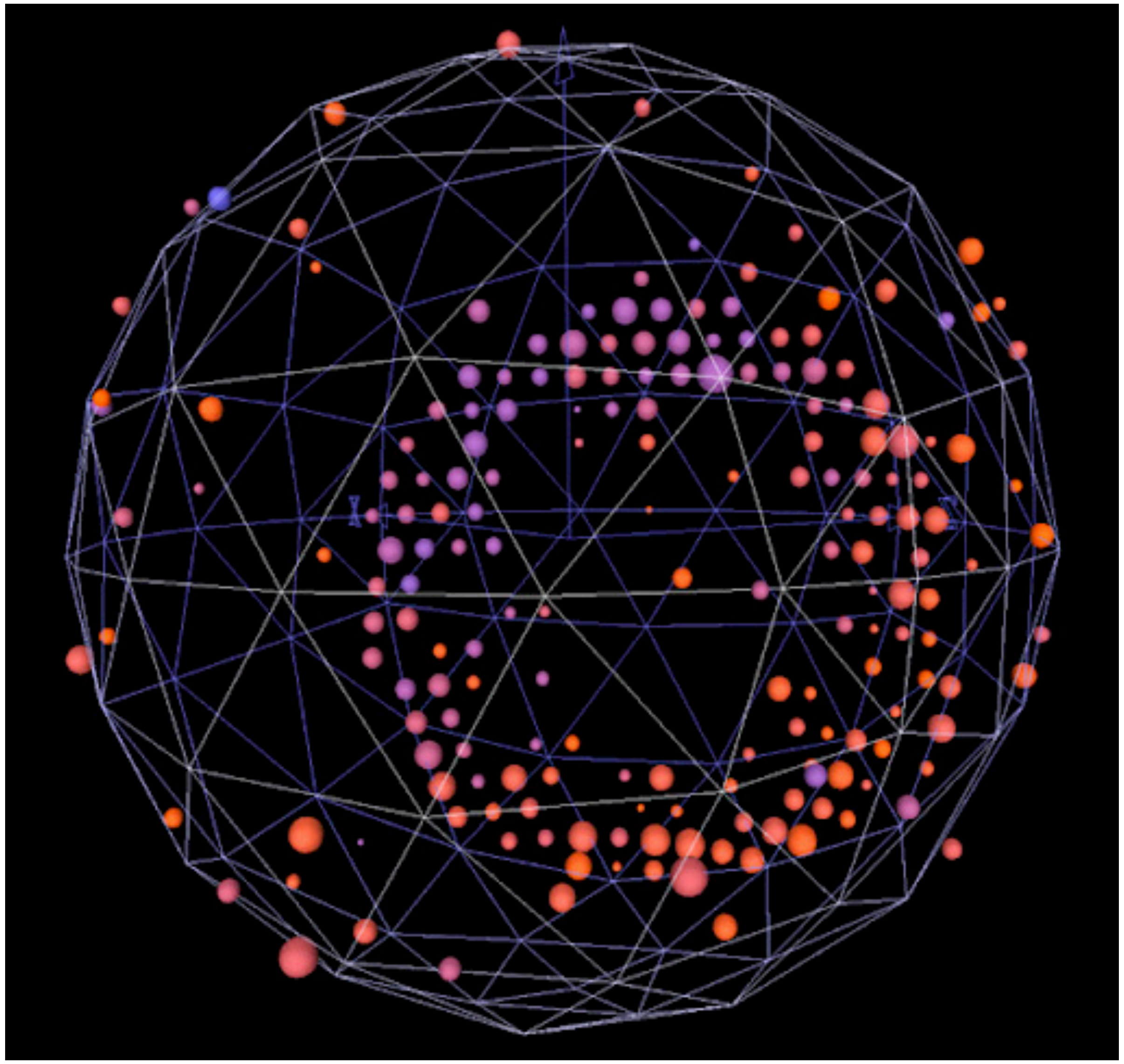
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



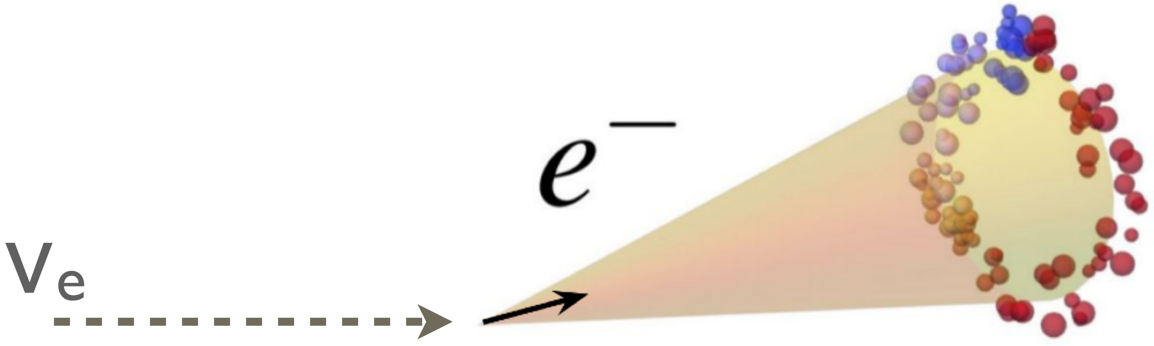
- Recently released updated results (2021) with x2 more data than original anomaly (2009)
- 4.8σ excess of measured ν_e and $\bar{\nu}_e$ over prediction, focused at low energy
- Consistent with LSND results: combined significance of 6.1σ
- Best fit for neutrino oscillation hypothesis: $\Delta m^2 =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

Phys. Rev. D 103, 052002

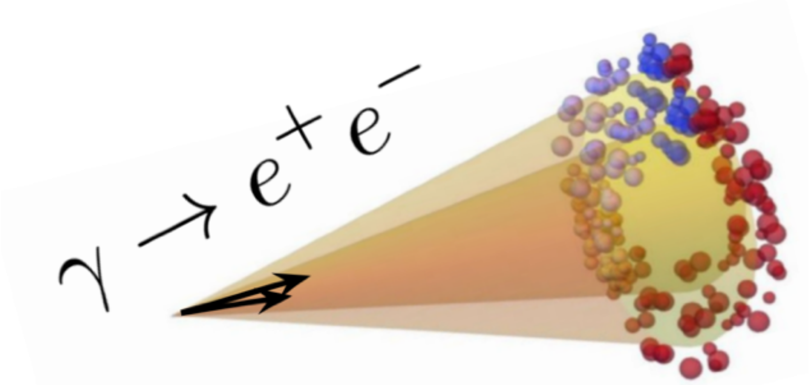
MINIBOONE



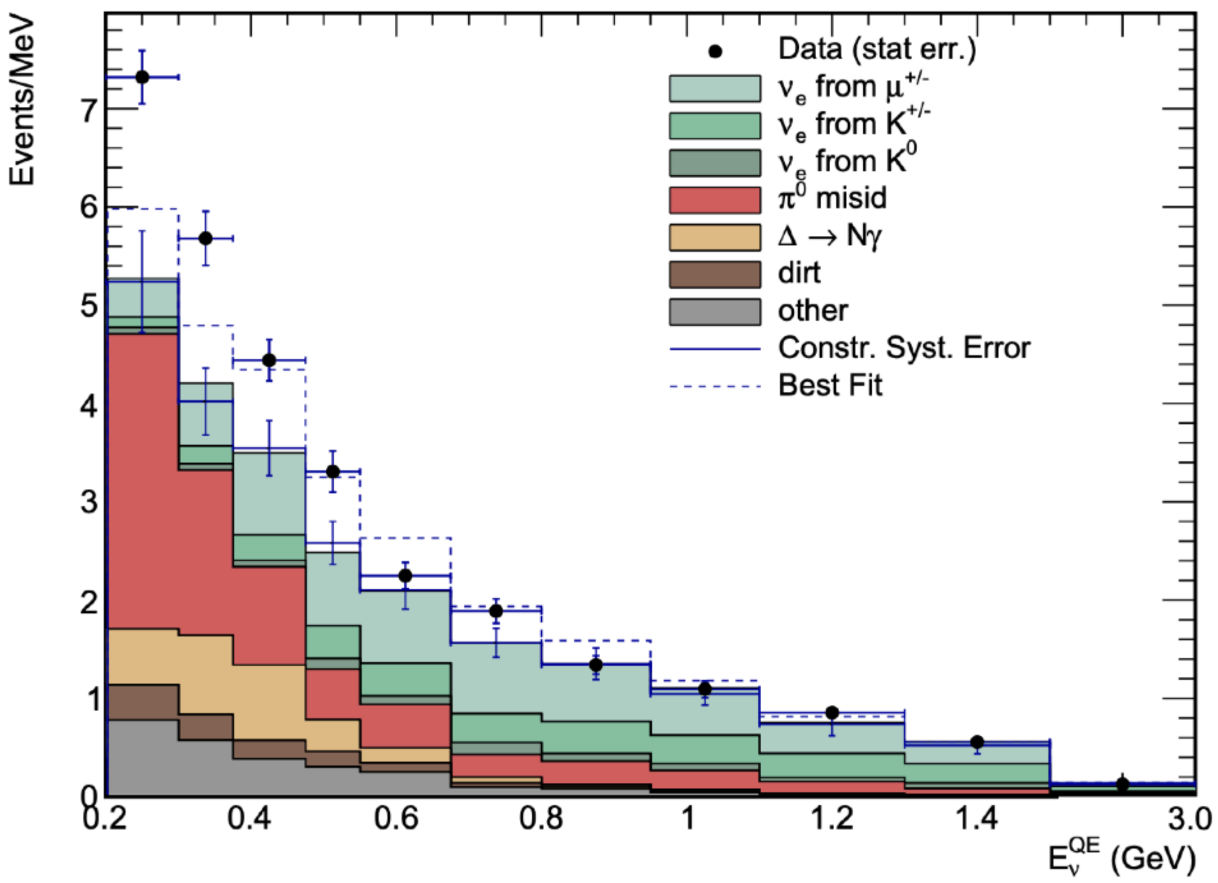
- 800-ton mineral oil (CH_2) Cherenkov detector
- Detect Cherenkov ring from **electrons** produced in **ν_e CC scattering** interactions



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



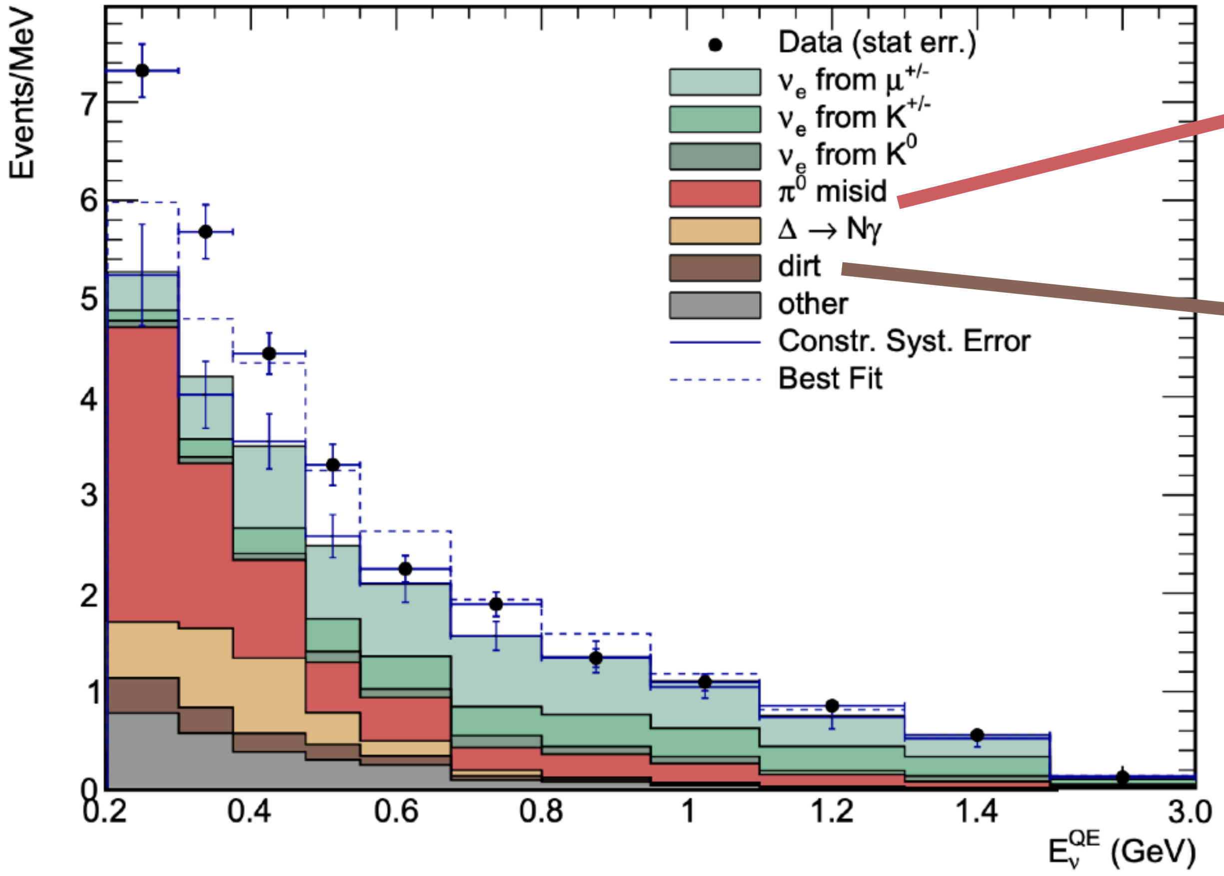
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



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!

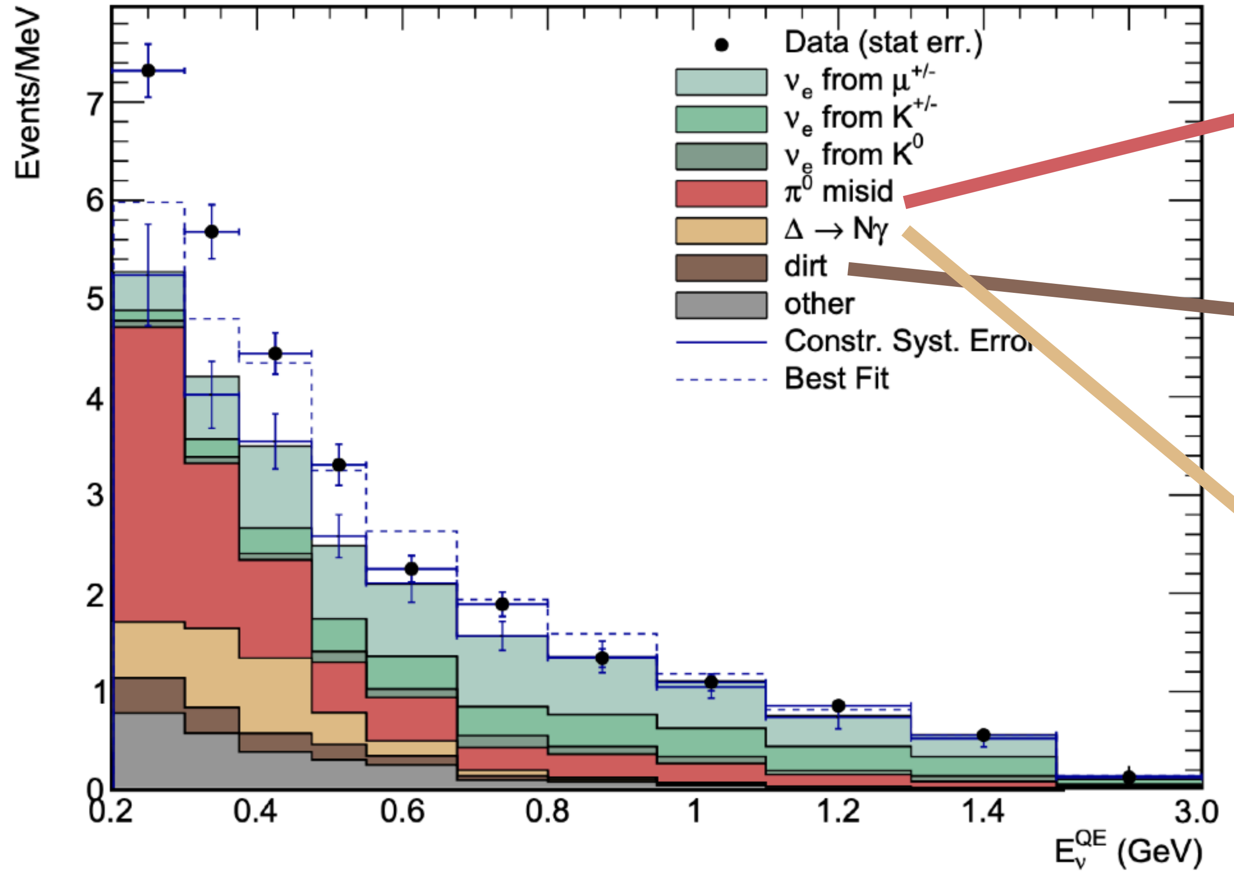
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



Is the excess photons?

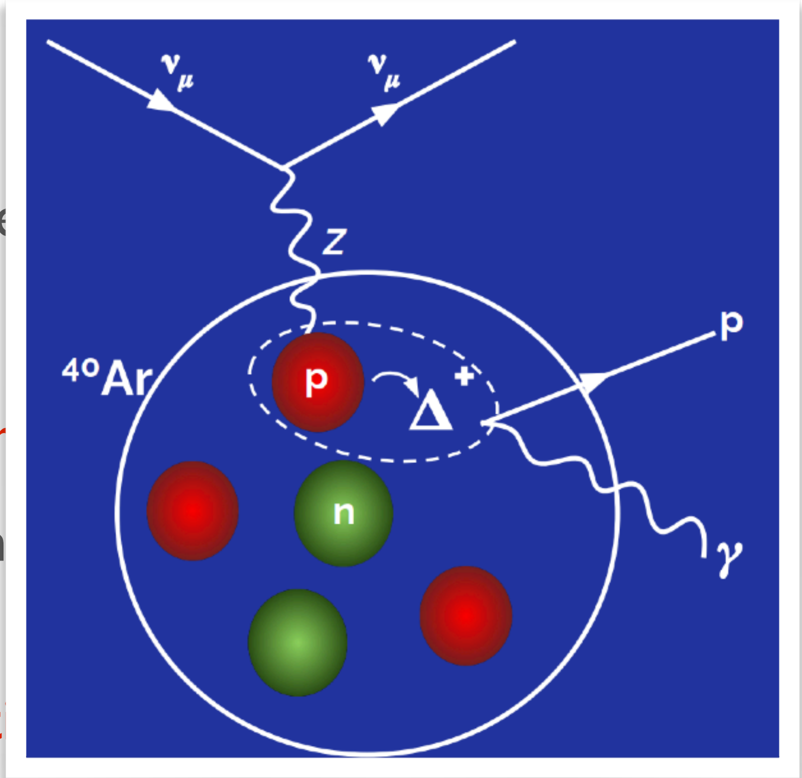
- Several sources of photon backgrounds:
- **NCπ⁰ mis-ID**
  - → measured in-situ
- **Dirt** (neutrino interactions outside the detector)
  - → beam timing

THE MINIBOONE LOW-ENERGY EXCESS (LEE)

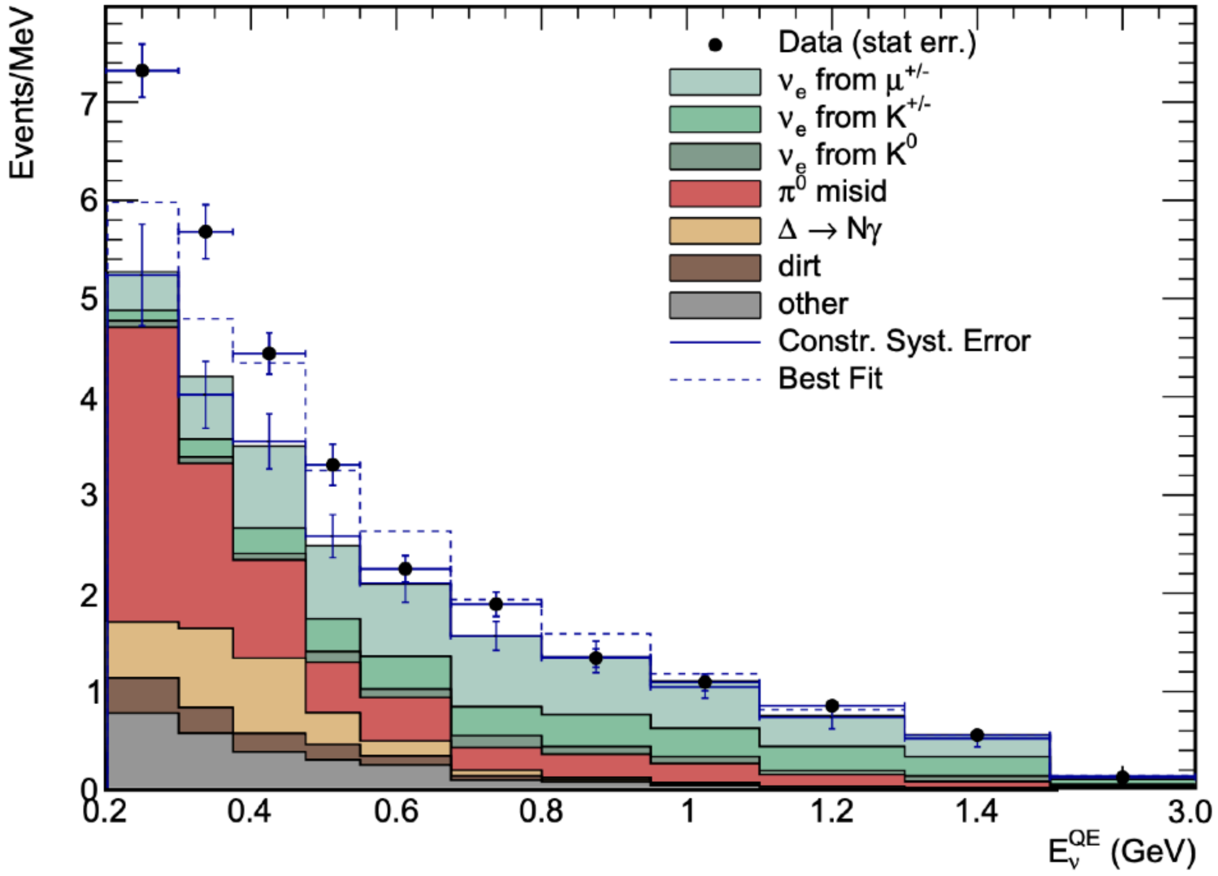


Is the excess

- Several source
- **NCπ^0 mis-I**
  - → measur
- **Dirt** (neutrin
  detector)
  - → beam t
- **NC Δ→Nɣ**
  - → not constrained directly - predicted from NCπ^0 rate and theoretical branching fraction
  - Need x3.18 increase to explain excess
  - → to be investigated…



THE MINIBOONE LOW-ENERGY EXCESS (LEE)



Or neither?

- Rich phenomenology developed in recent years
- I'll come back to this!

For now, it's clear that we need more information…

MICROBOONE

MicroBooNE: 170 ton Liquid Argon Time Projection Chamber (LArTPC)

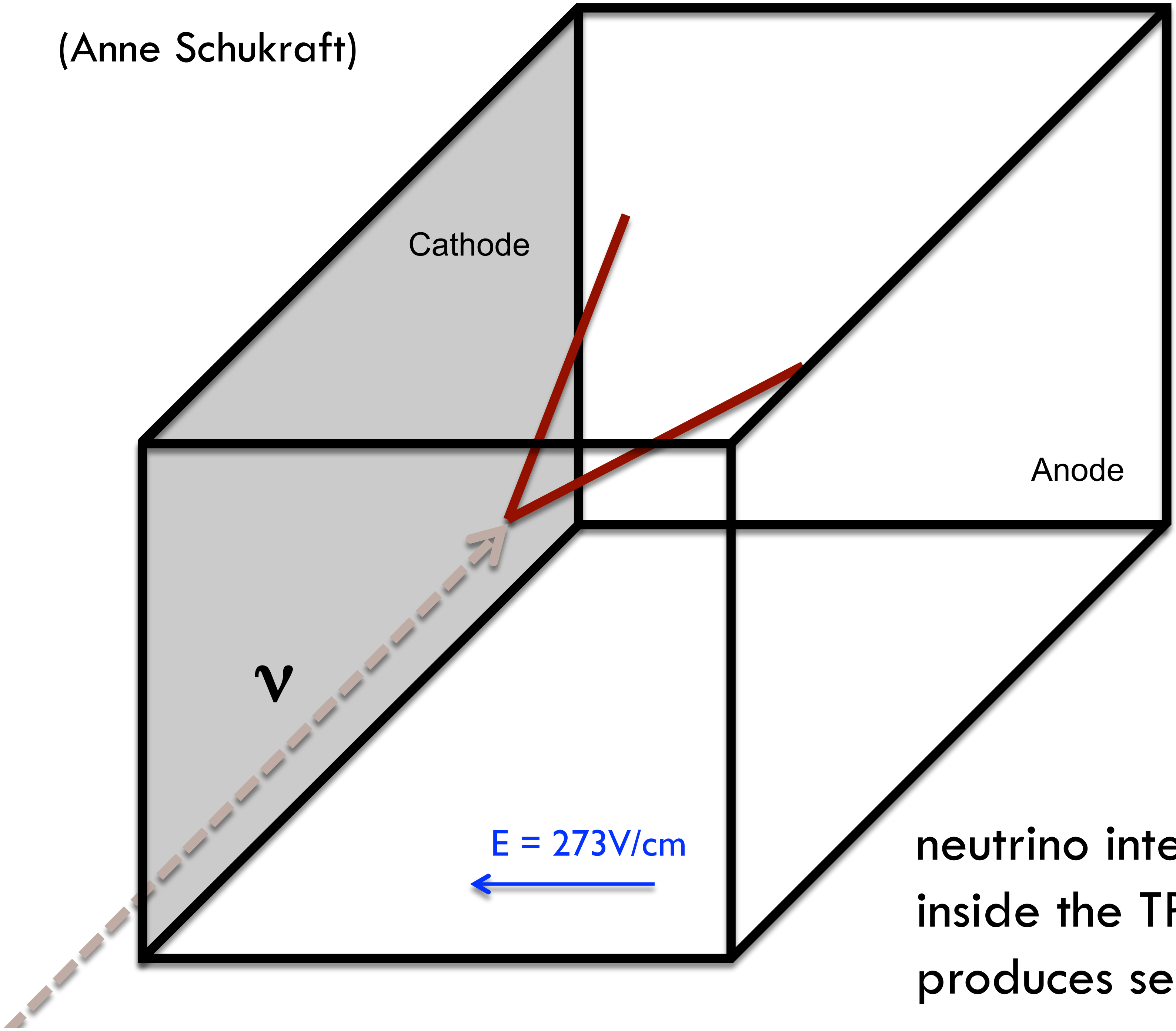
- Stable detector operation since 2015: **longest-running LArTPC to date**
  - >95% DAQ uptime
  - 1.52×10^{21} POT collected in total (analyses shown here use subsets, not full POT)

Grateful to Fermilab Accelerator Division, Cryogenics team, Operations team, and Scientific Computing Division!


MicroBooNE - Driving Nu Physics
Fermilab
ENERGY

LIQUID ARGON TPC

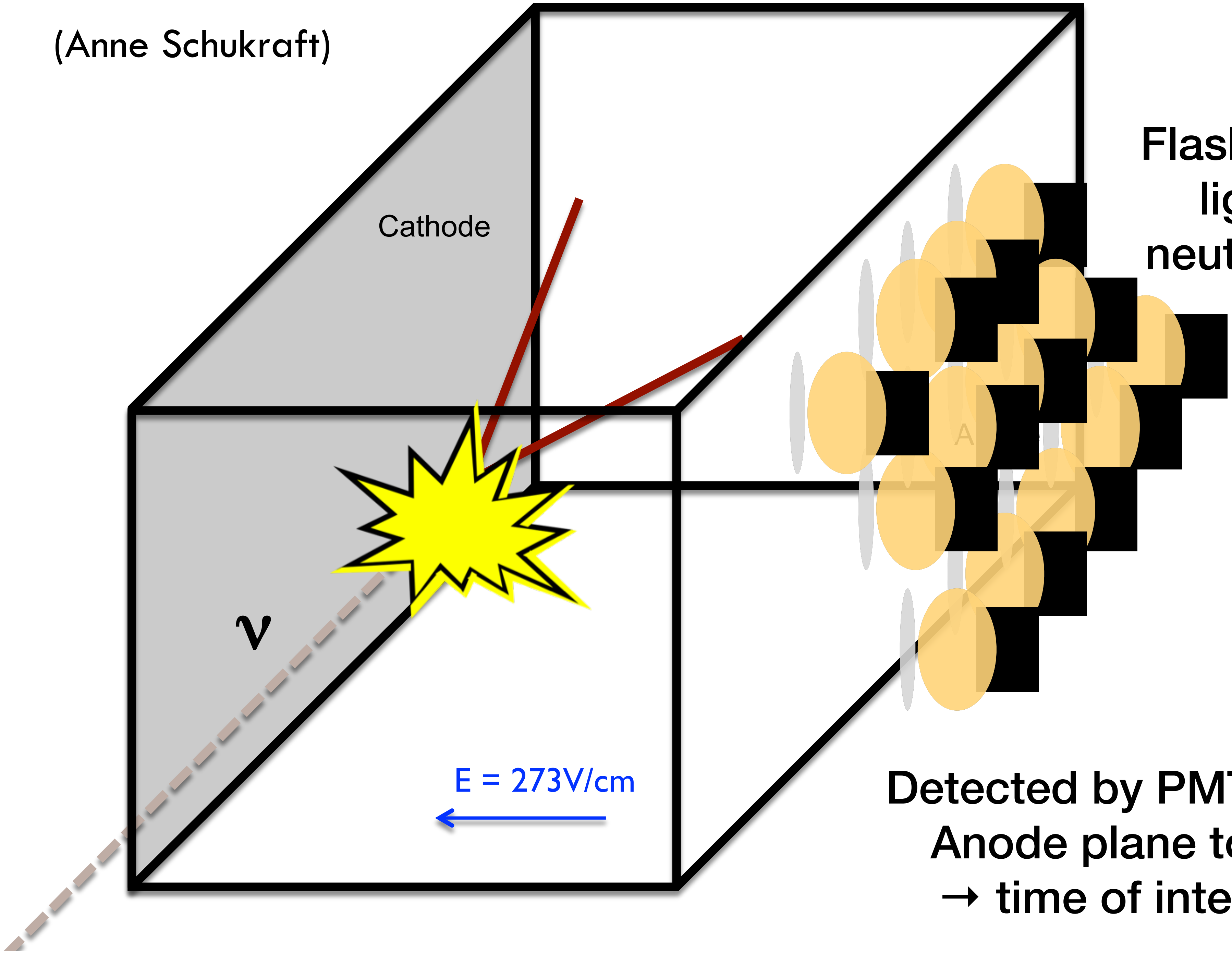
(Anne Schukraft)



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

LIQUID ARGON TPC

(Anne Schukraft)

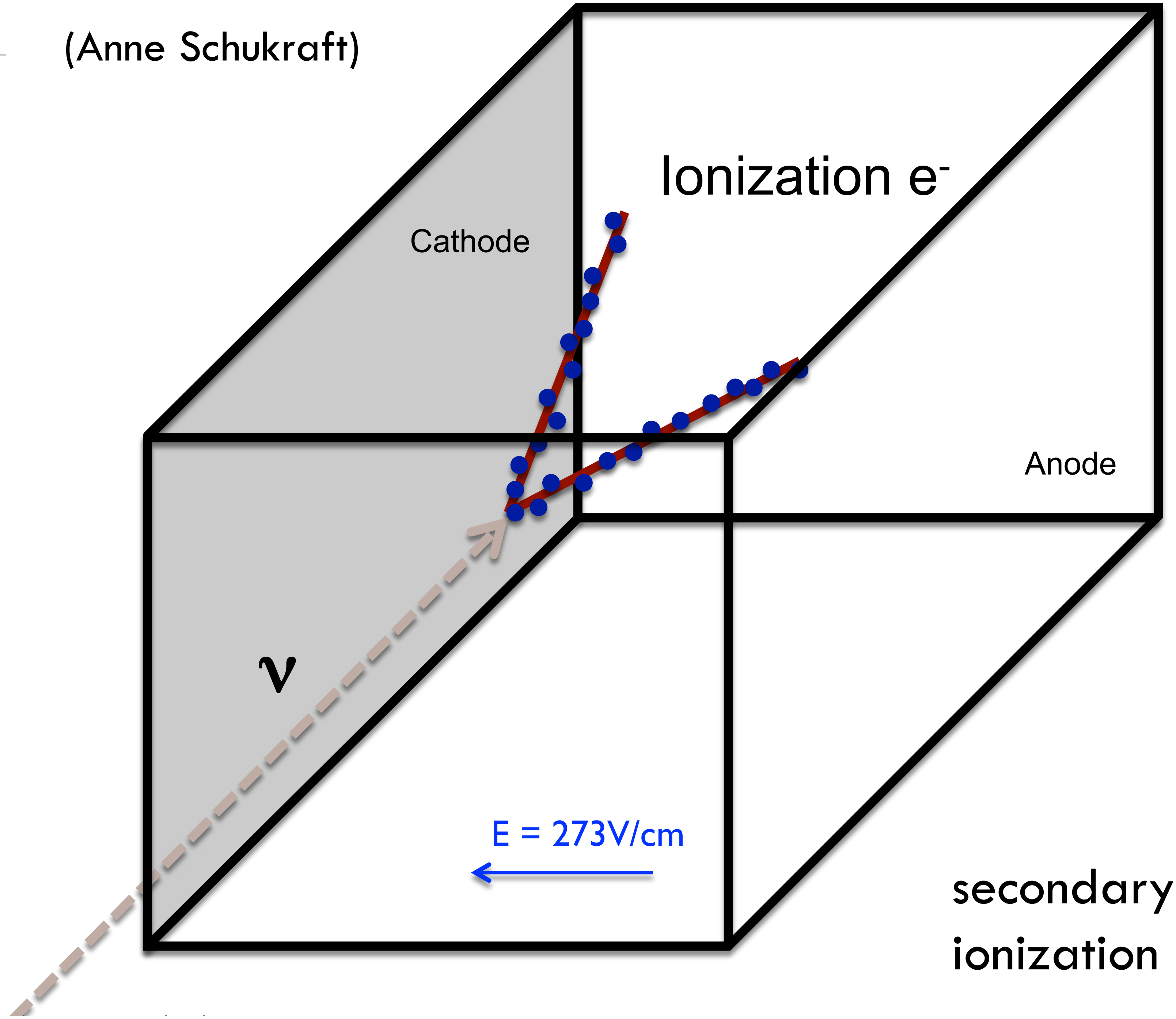


Flash of scintillation light at time of neutrino interaction

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

LIQUID ARGON TPC

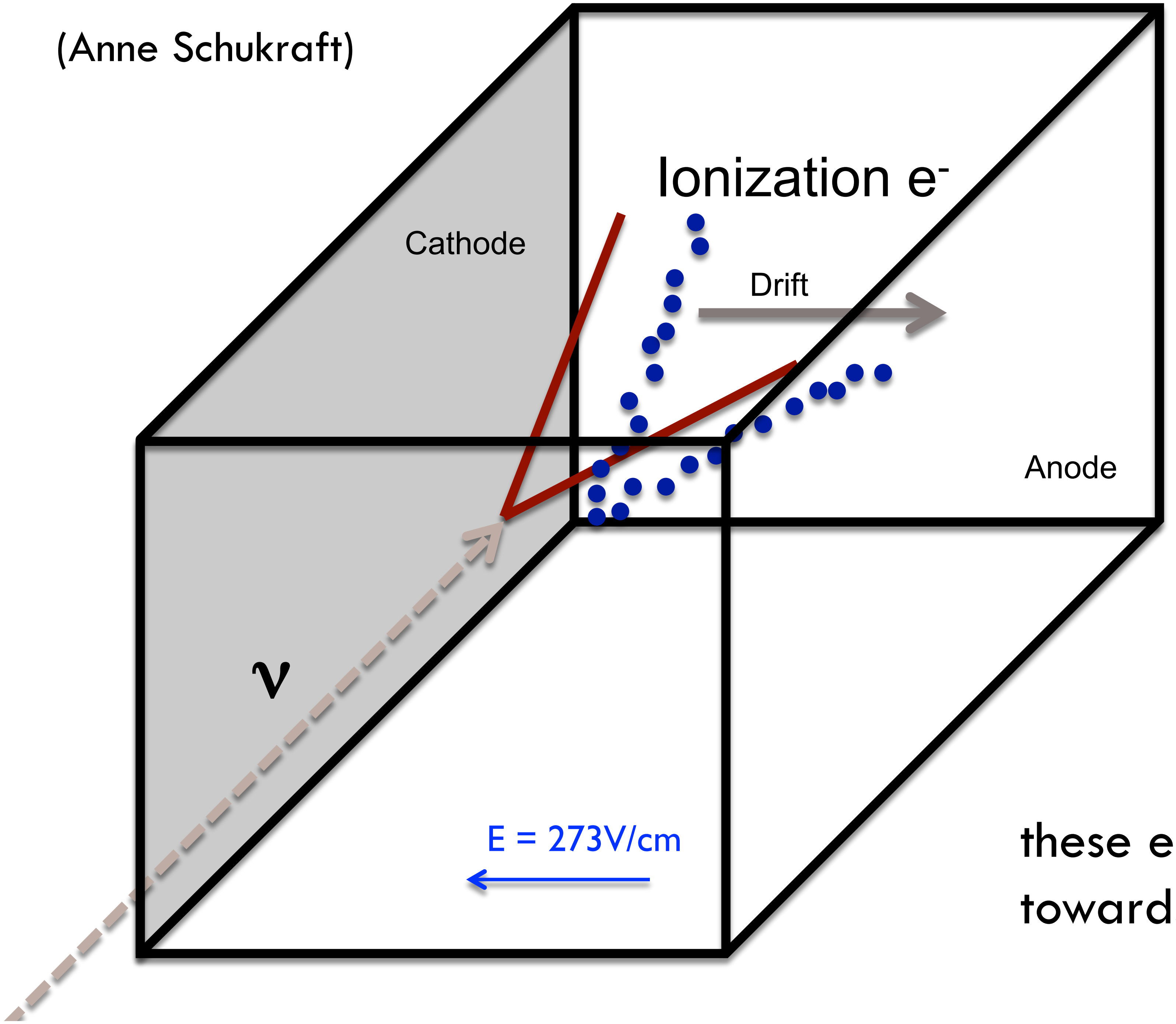
(Anne Schukraft)



secondary particles produce ionization electrons

LIQUID ARGON TPC

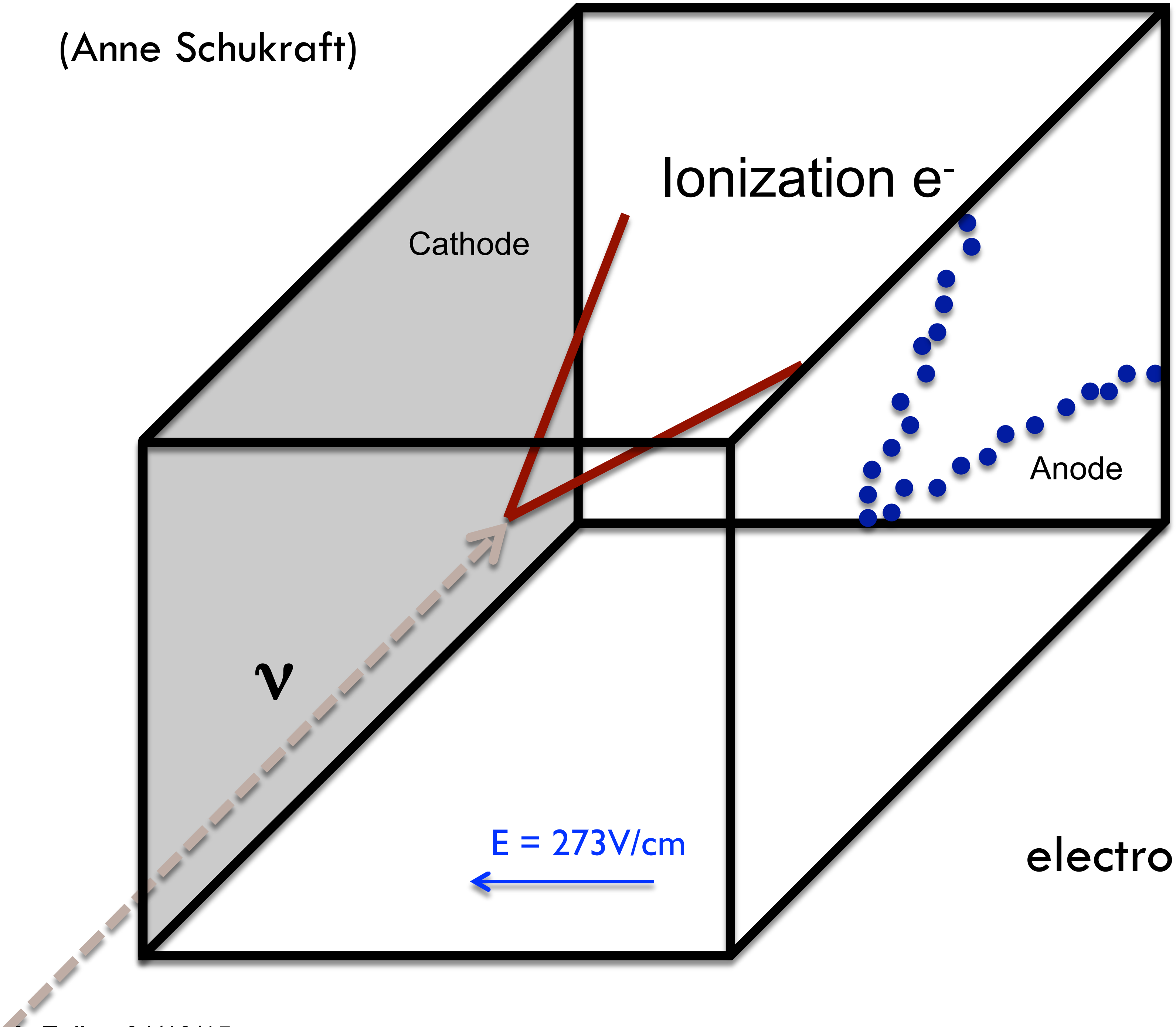
(Anne Schukraft)



these electrons drift towards the anode

LIQUID ARGON TPC

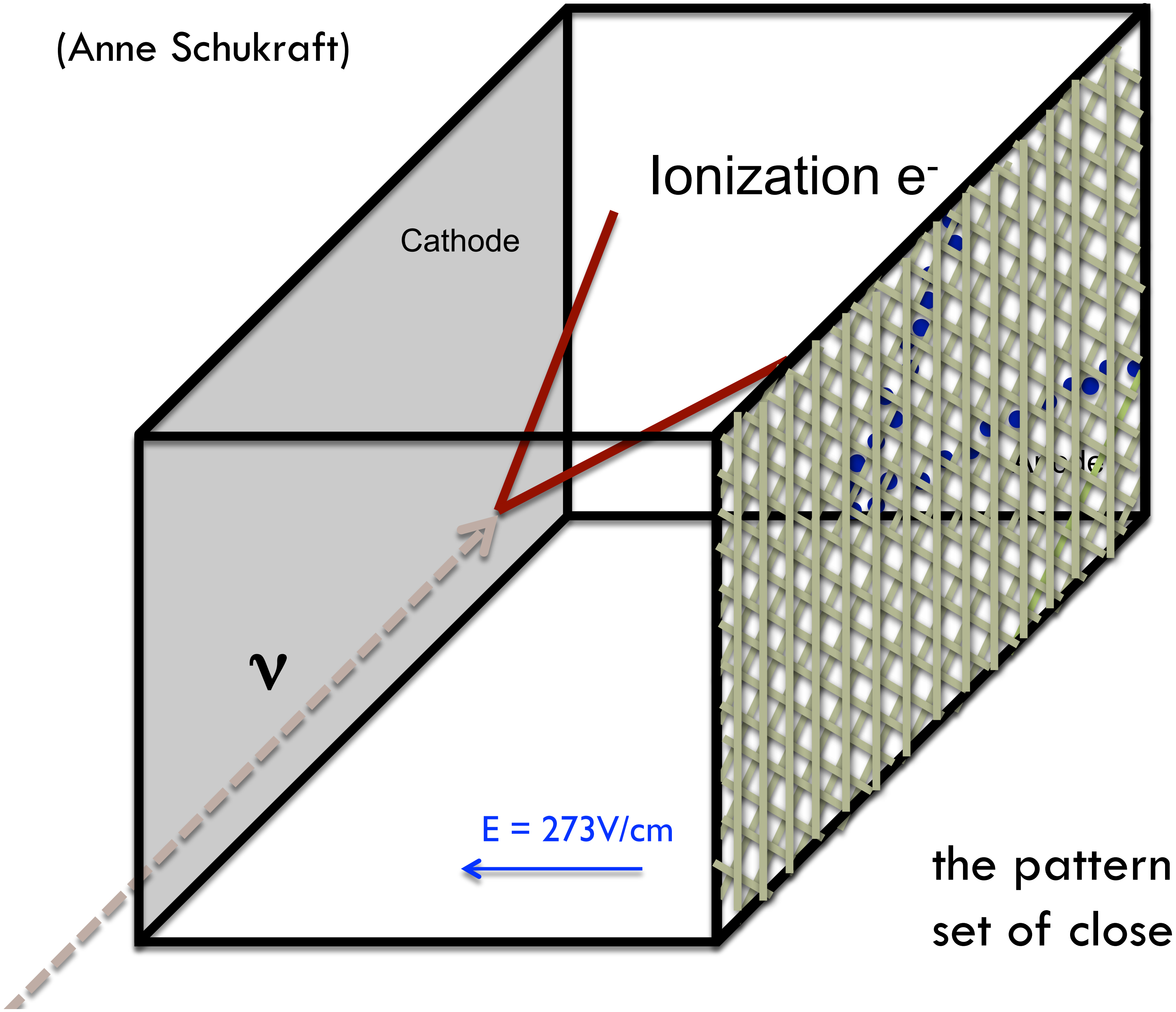
(Anne Schukraft)



electrons arrive at anode

LIQUID ARGON TPC

(Anne Schukraft)



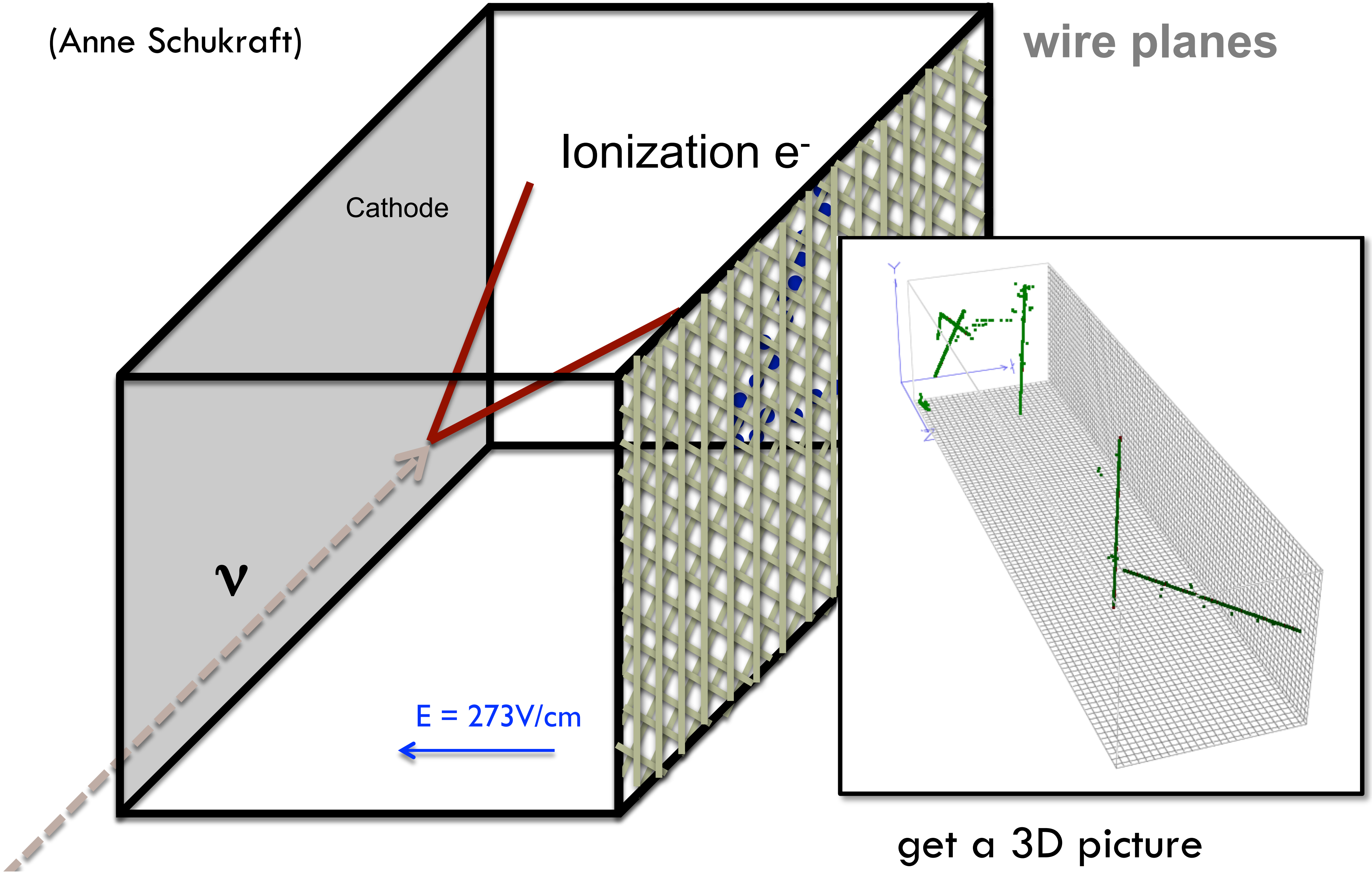
wire planes

the pattern is recorded on a set of closely spaced wires

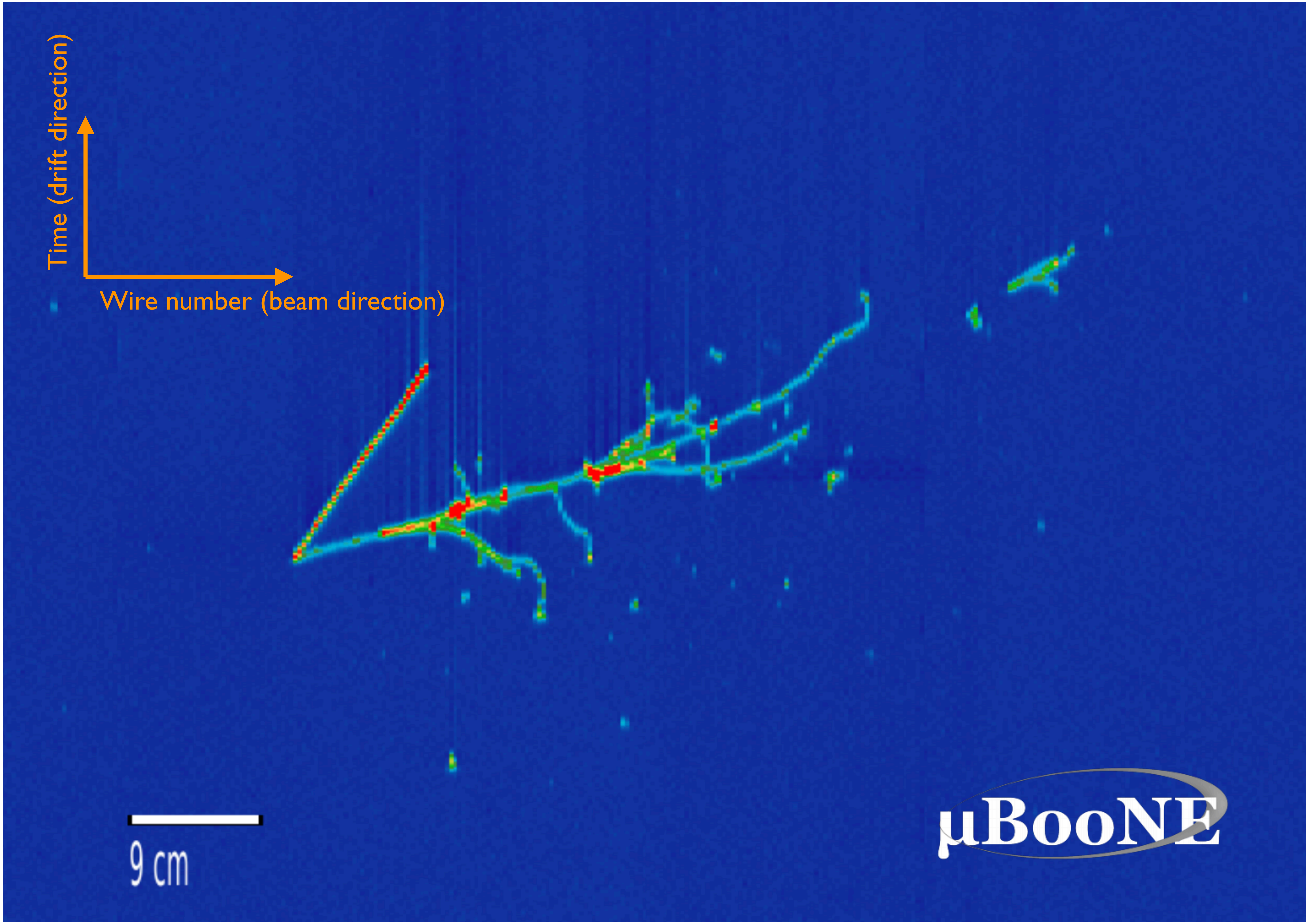
LIQUID ARGON TPC

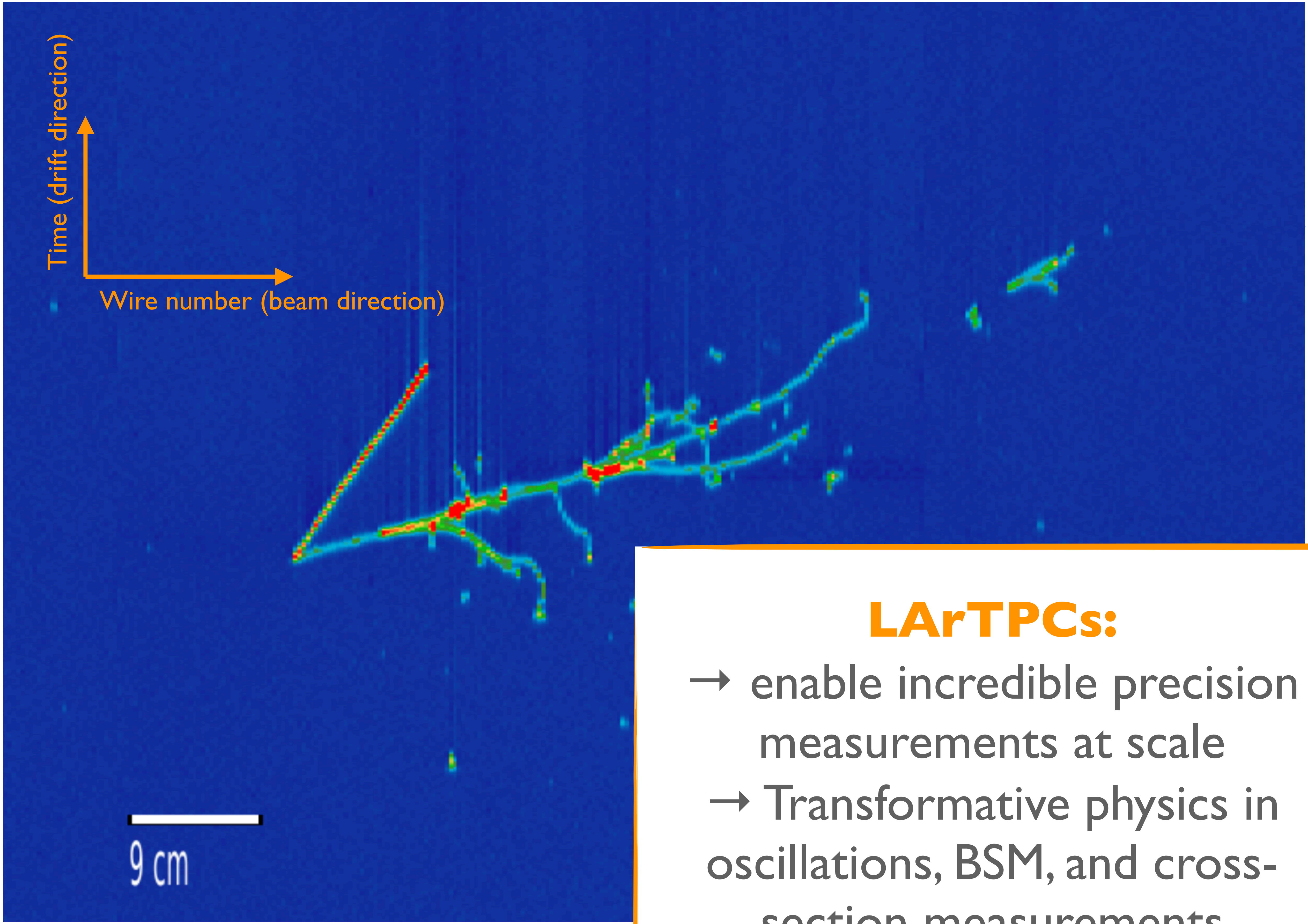
(Anne Schukraft)

wire planes



get a 3D picture


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



LArTPCs:

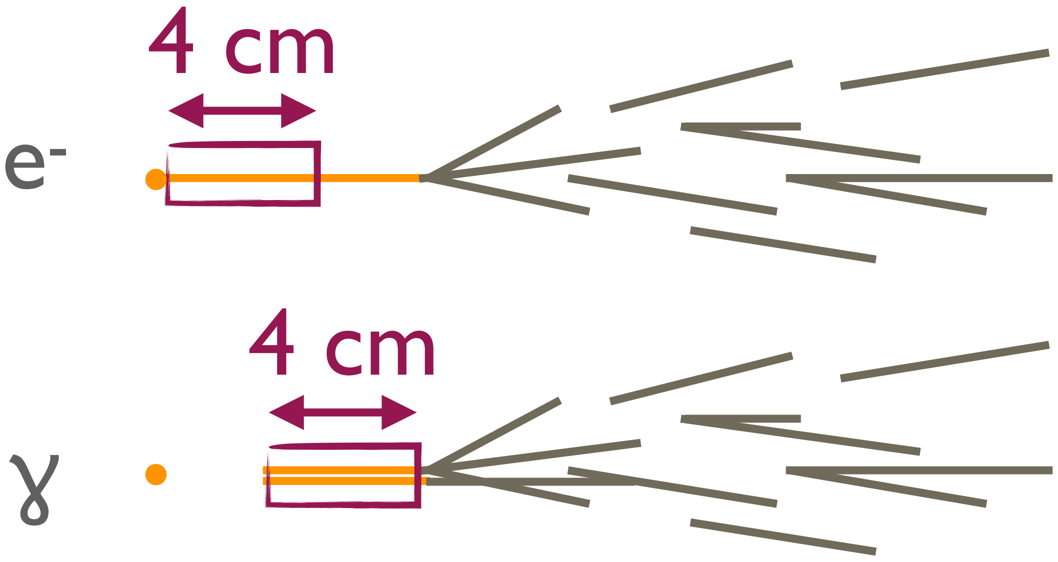
→ enable incredible precision measurements at scale

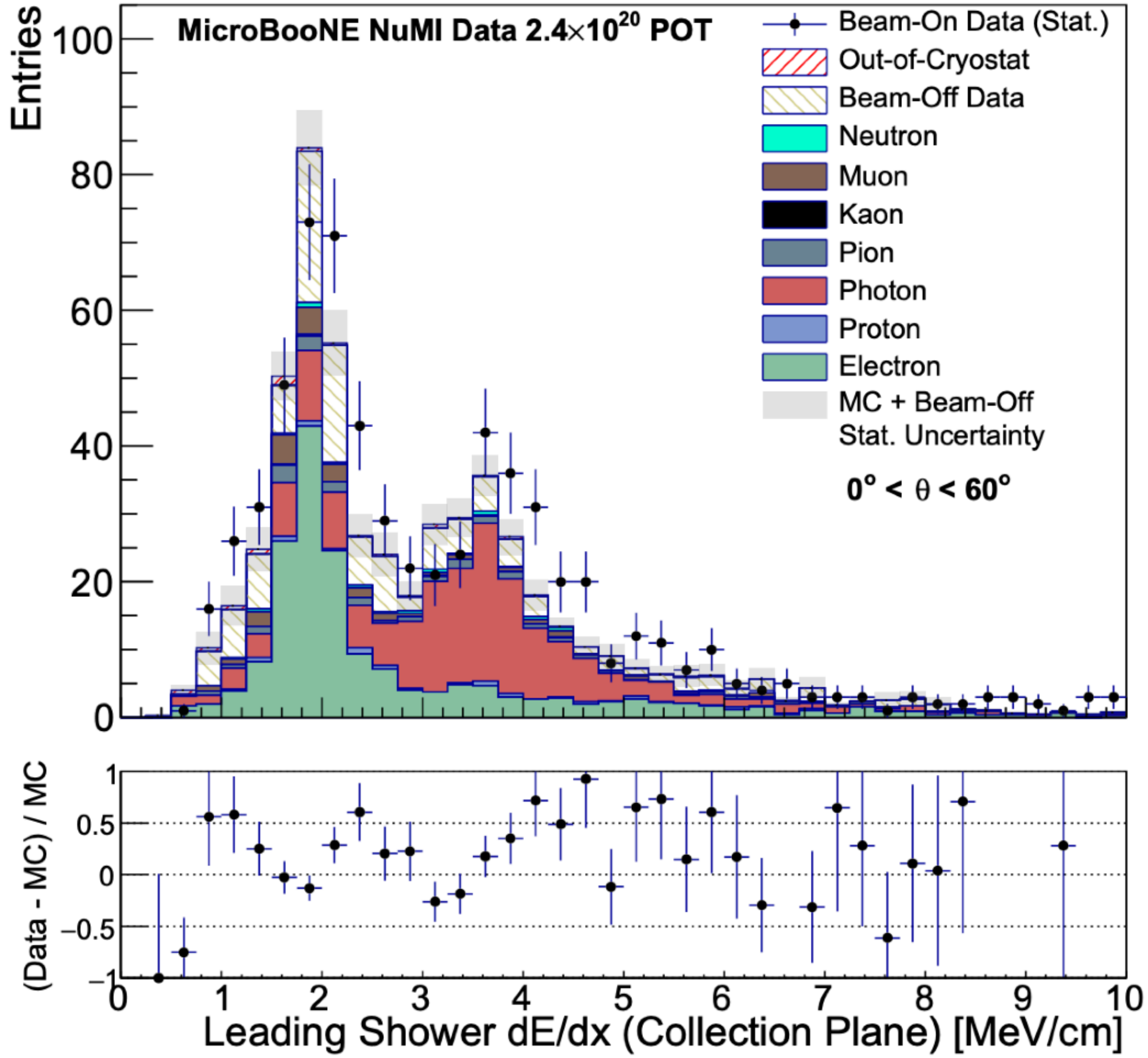
→ Transformative physics in oscillations, BSM, and cross-section measurements

LARTPC STRENGTH: ELECTRONS AND PHOTONS

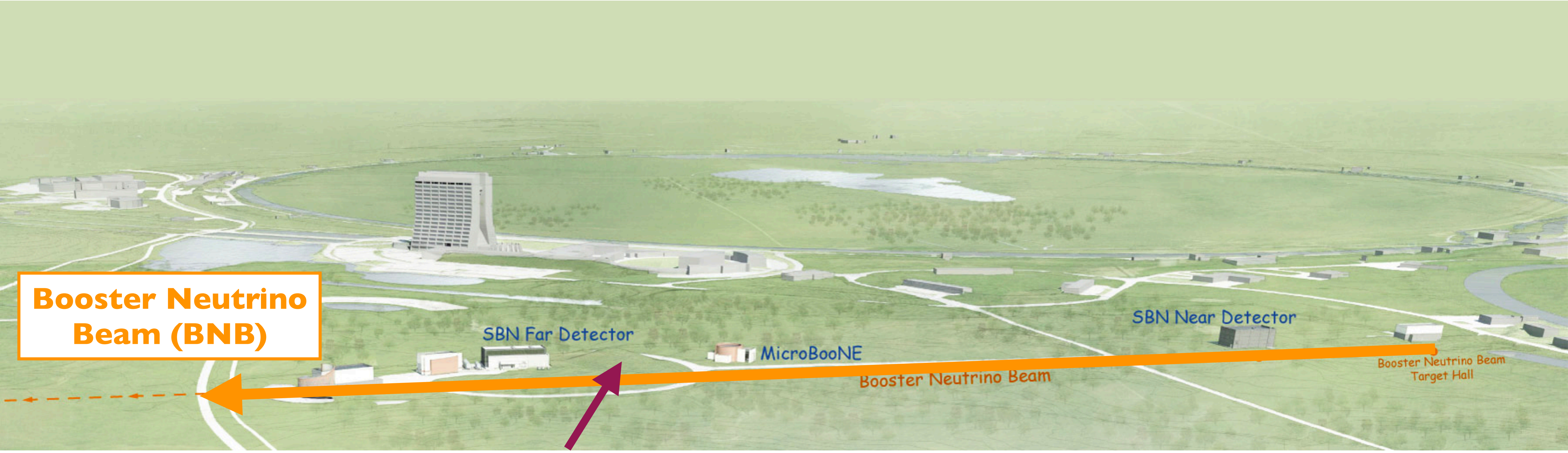
Phys. Rev. D 104, 052002 (2021)

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

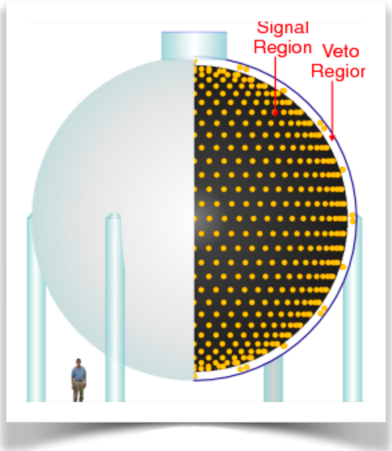




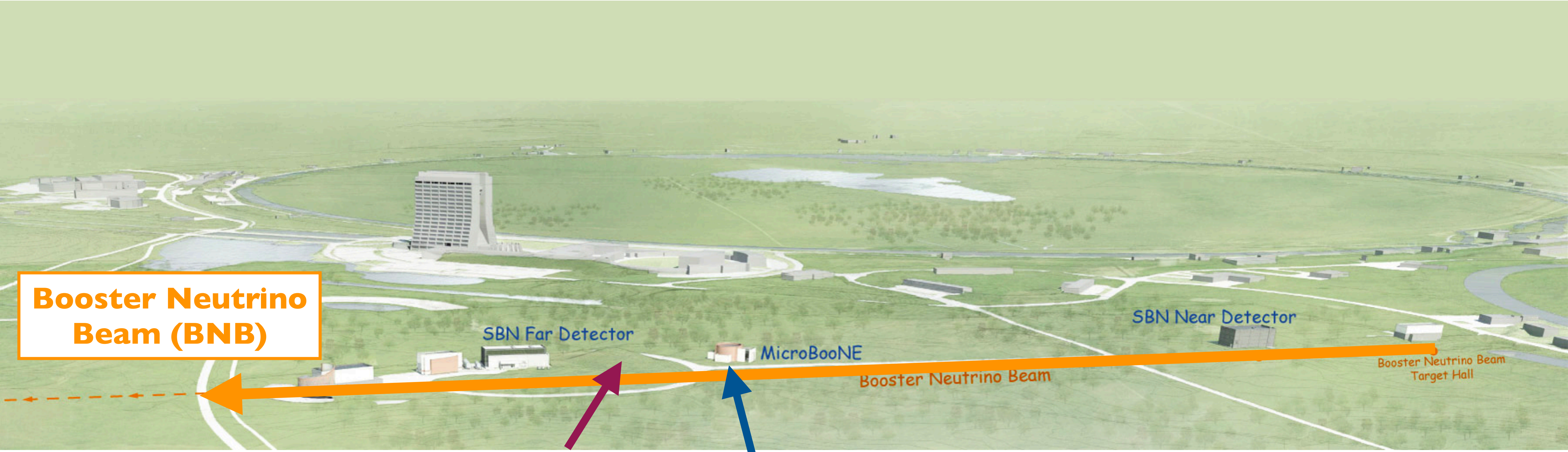
SHORT-BASELINE NEUTRINOS AT FERMILAB



MiniBooNE

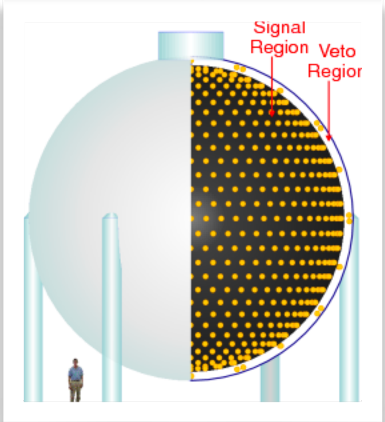


SHORT-BASELINE NEUTRINOS AT FERMILAB



MiniBooNE

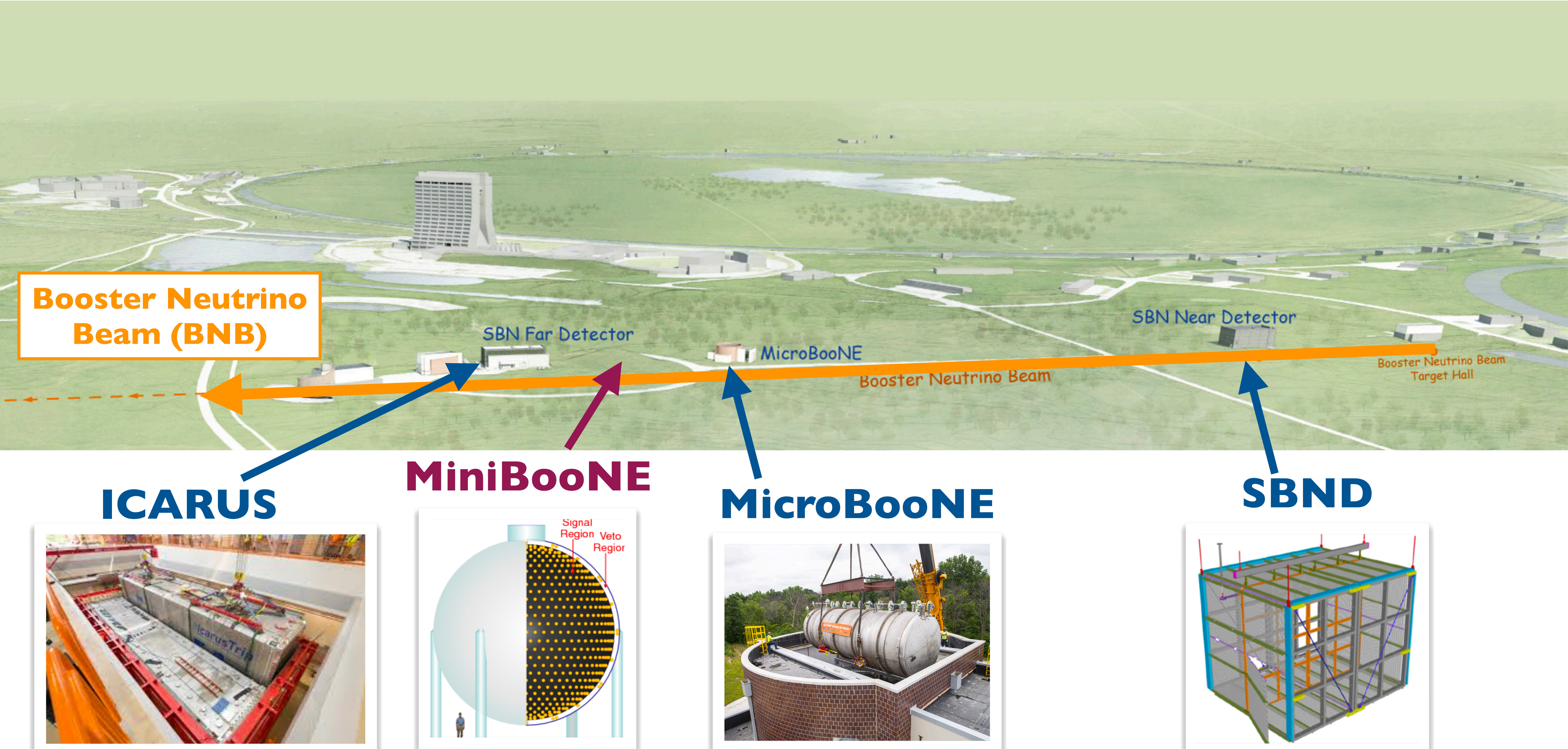
500m



MicroBooNE

470m

SHORT-BASELINE NEUTRINOS AT FERMILAB



Booster Neutrino Beam (BNB)

ICARUS

MiniBooNE

MicroBooNE

SBND

INVESTIGATING THE MINIBOONE LOW-ENERGY EXCESS

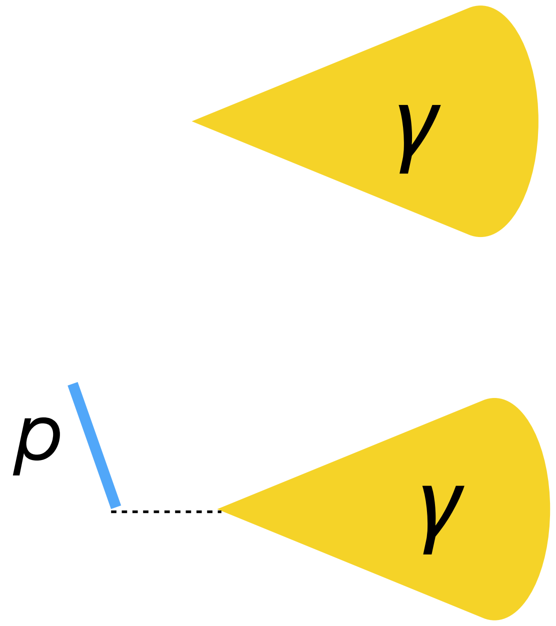
I will give only a brief overview of the headline results from MicroBooNE

For more details and information, please see the following talk by N. Foppiani

MICROBOONE SELECTIONS

Photon search

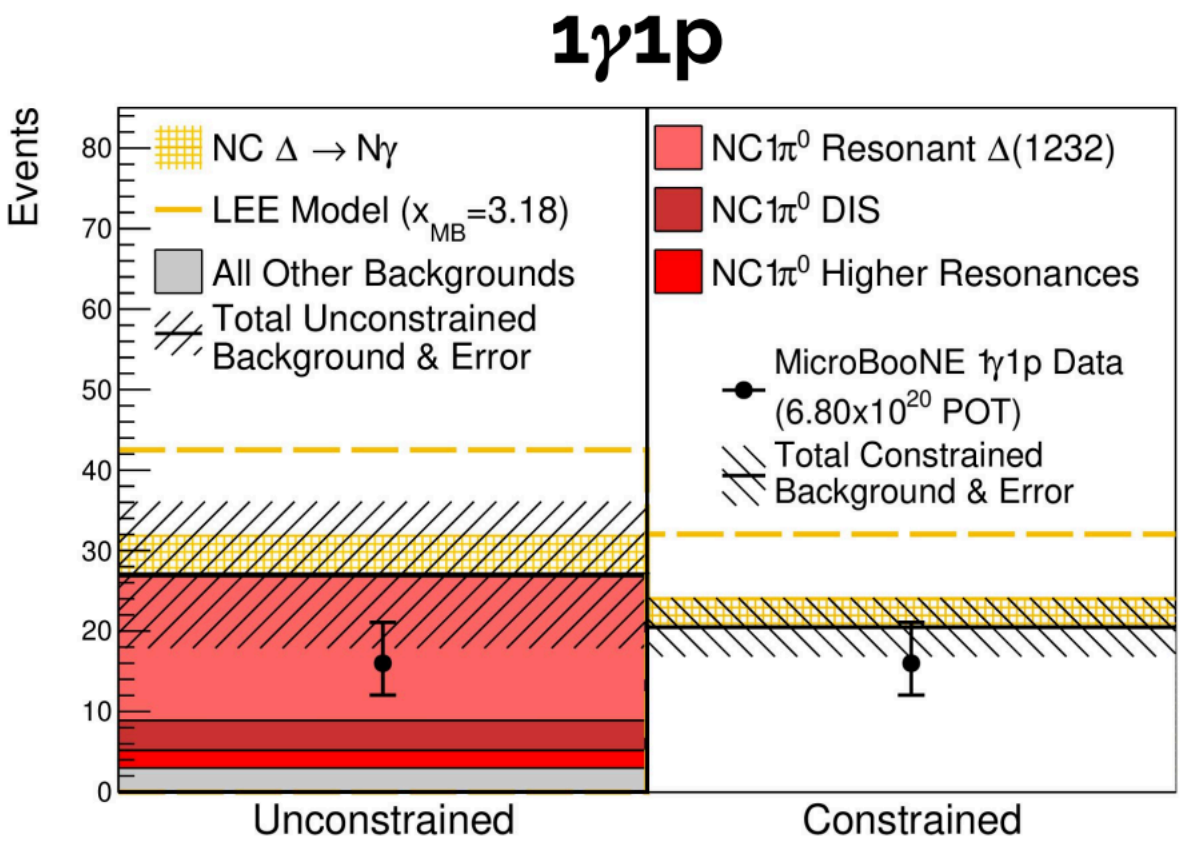
Target Δ→Nγ:
1γ0p and 1γ1p



arXiv:2110.00409 [hep-ex]

SINGLE PHOTON SEARCH

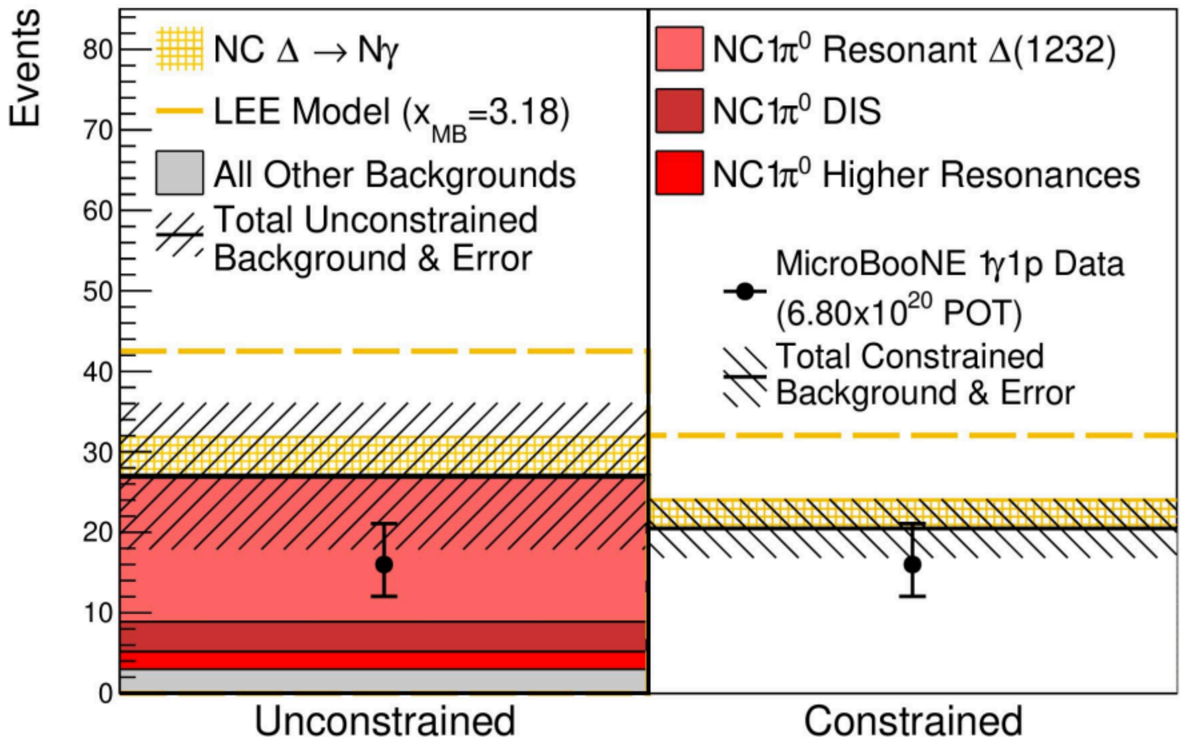
arXiv:2110.00409 [hep-ex]



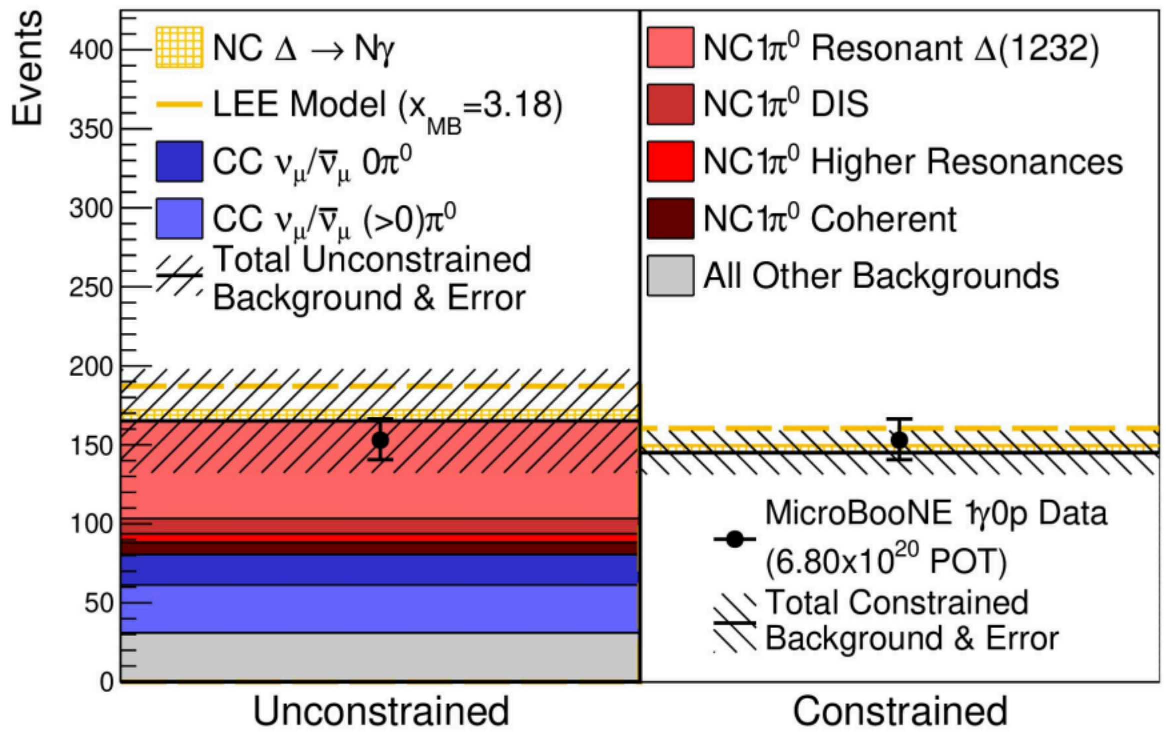
SINGLE PHOTON SEARCH

arXiv:2110.00409 [hep-ex]

$1\gamma1p$



$1\gamma0p$

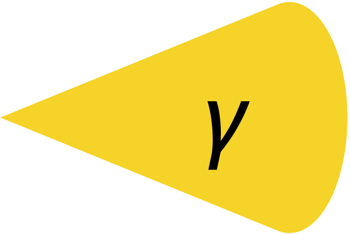


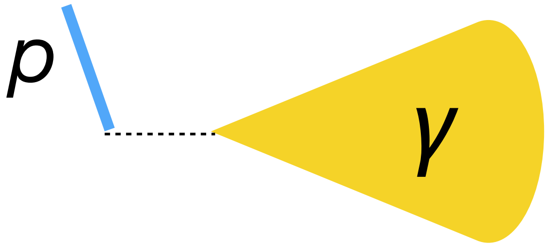
No evidence of an excess in either sample

OUR SELECTIONS

Photon search

Target Δ→Nɣ:
1ɣ0p and 1ɣ1p



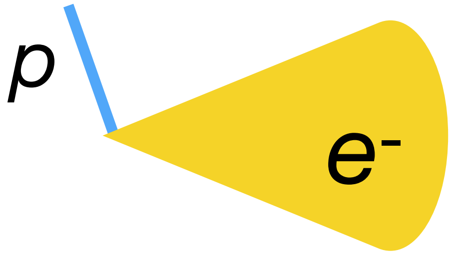


arXiv:2110.00409 [hep-ex]

Electron searches

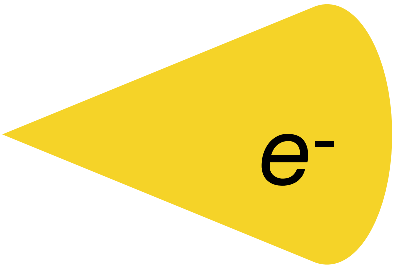
arXiv:2110.14080 [hep-ex]

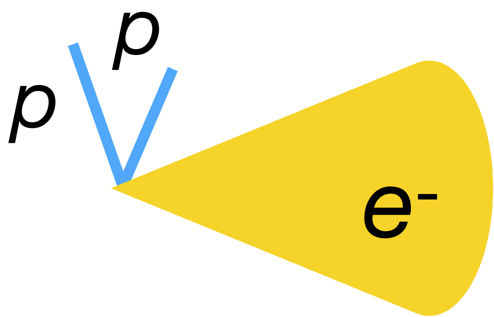
CCQE-like:
1e1p



arXiv:2110.14065 [hep-ex]

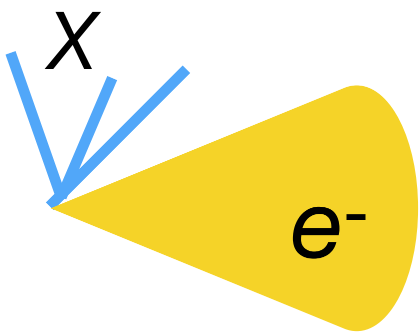
CC0π: 1e0p
and 1eNp





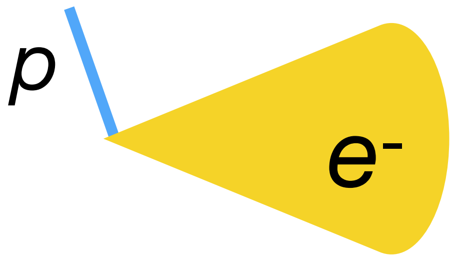
arXiv:2110.13978 [hep-ex]

Inclusive:
1eX



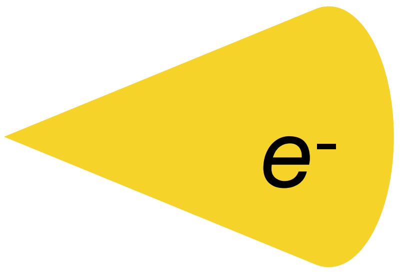
ν_e SEARCH

1e1p



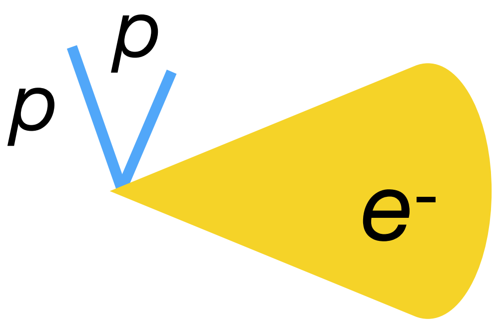
arXiv:2110.14080 [hep-ex]

1e0p



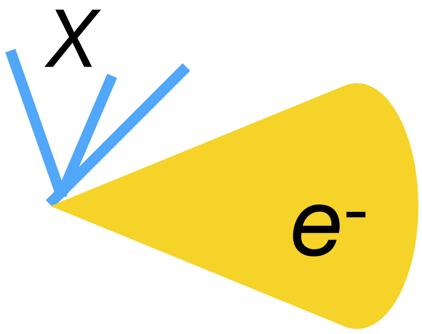
arXiv:2110.14065 [hep-ex]

1eNp



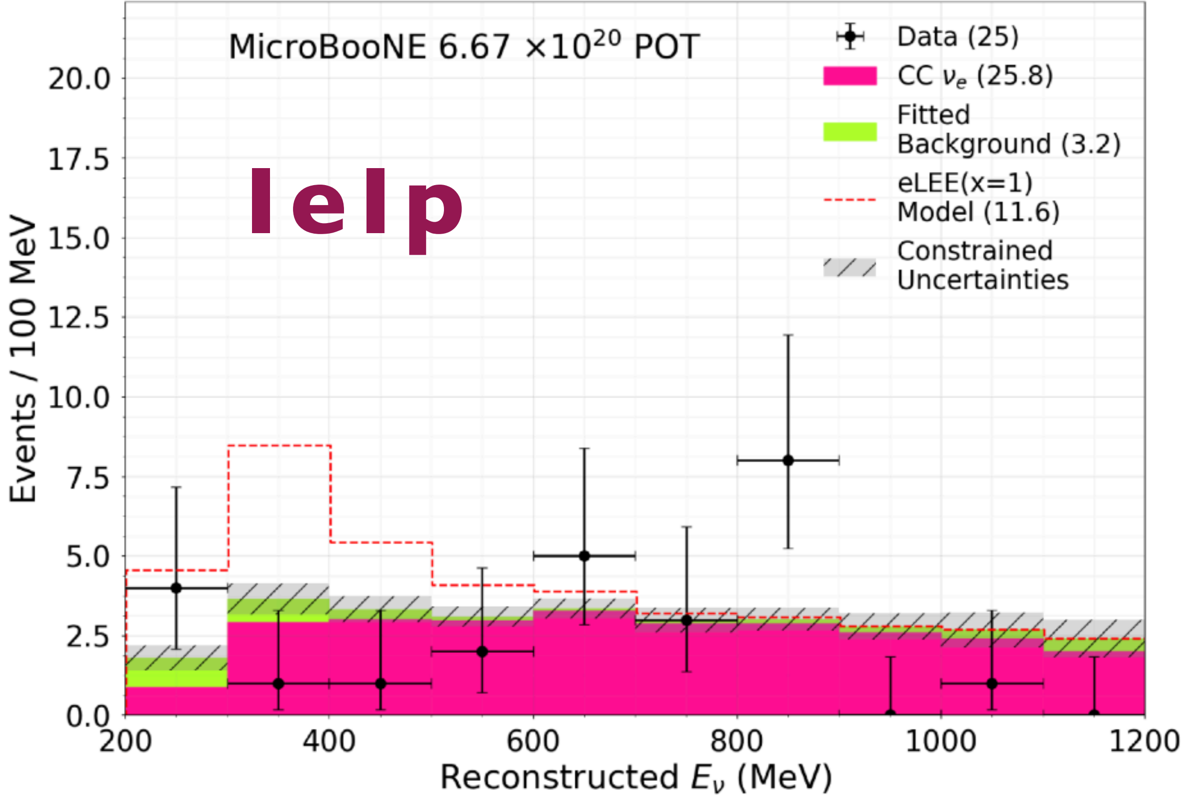
arXiv:2110.14065 [hep-ex]

1eX



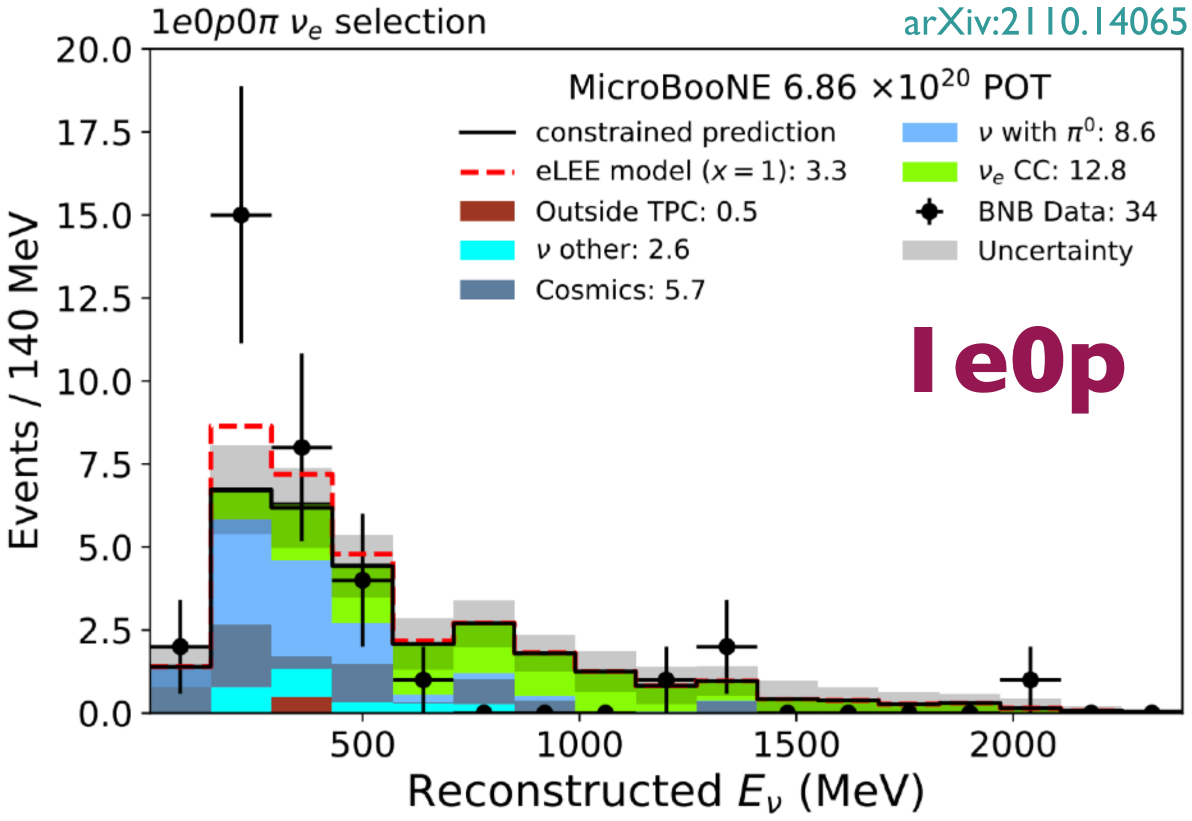
arXiv:2110.13978 [hep-ex]

arXiv:2110.14080 [hep-ex]

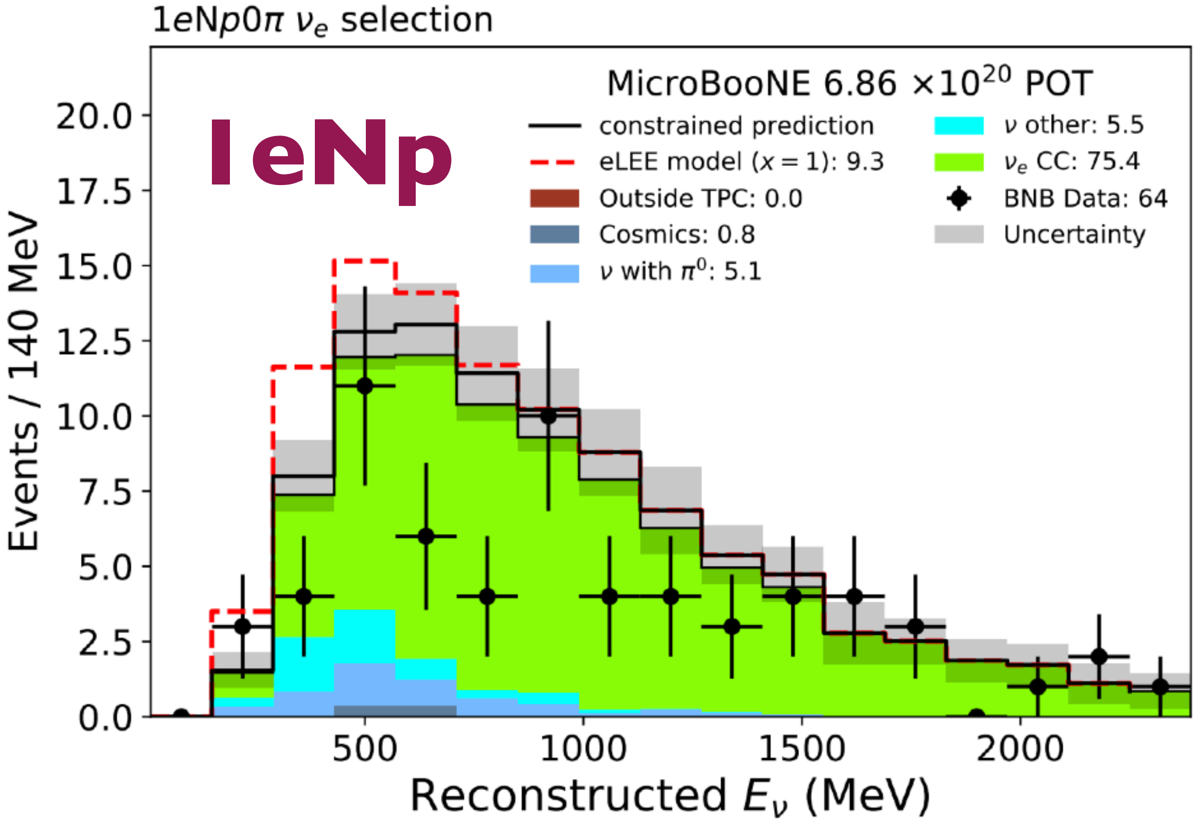


1e1p

arXiv:2110.14065 [hep-ex]

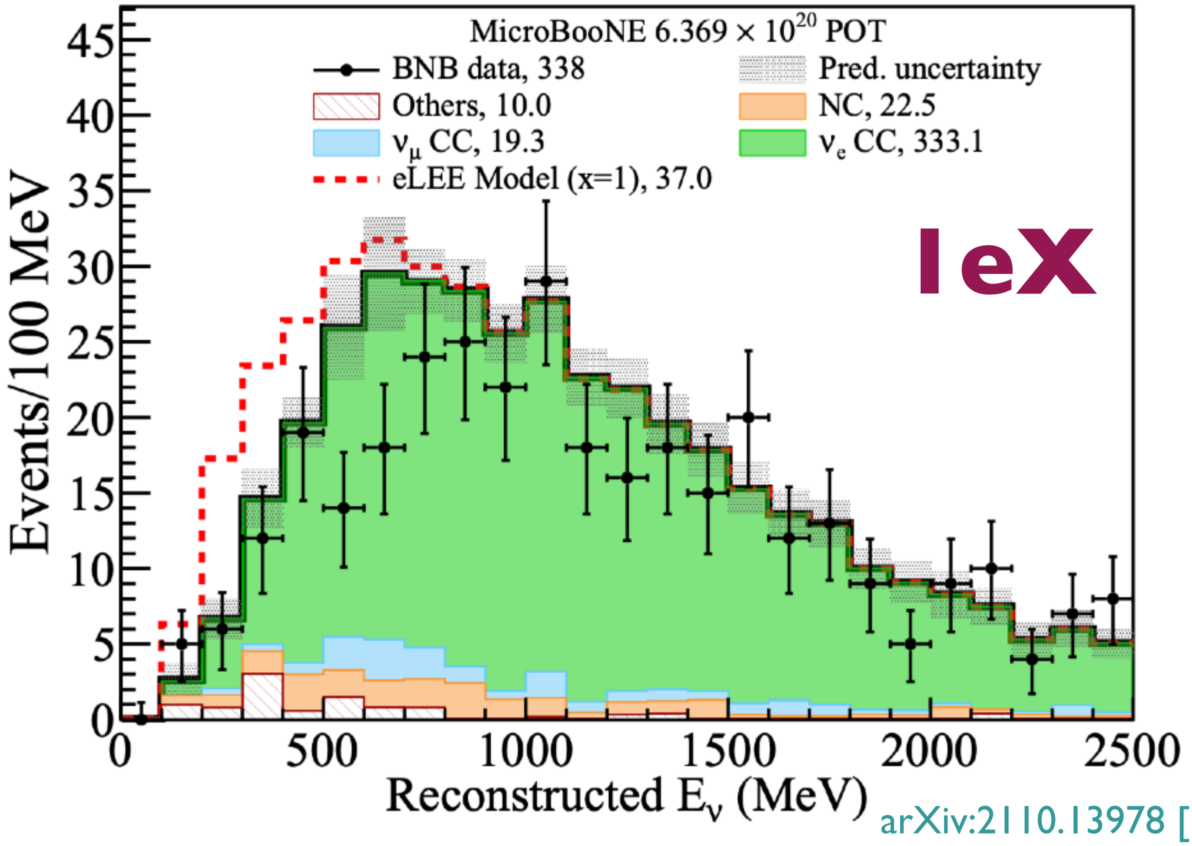


1e0p



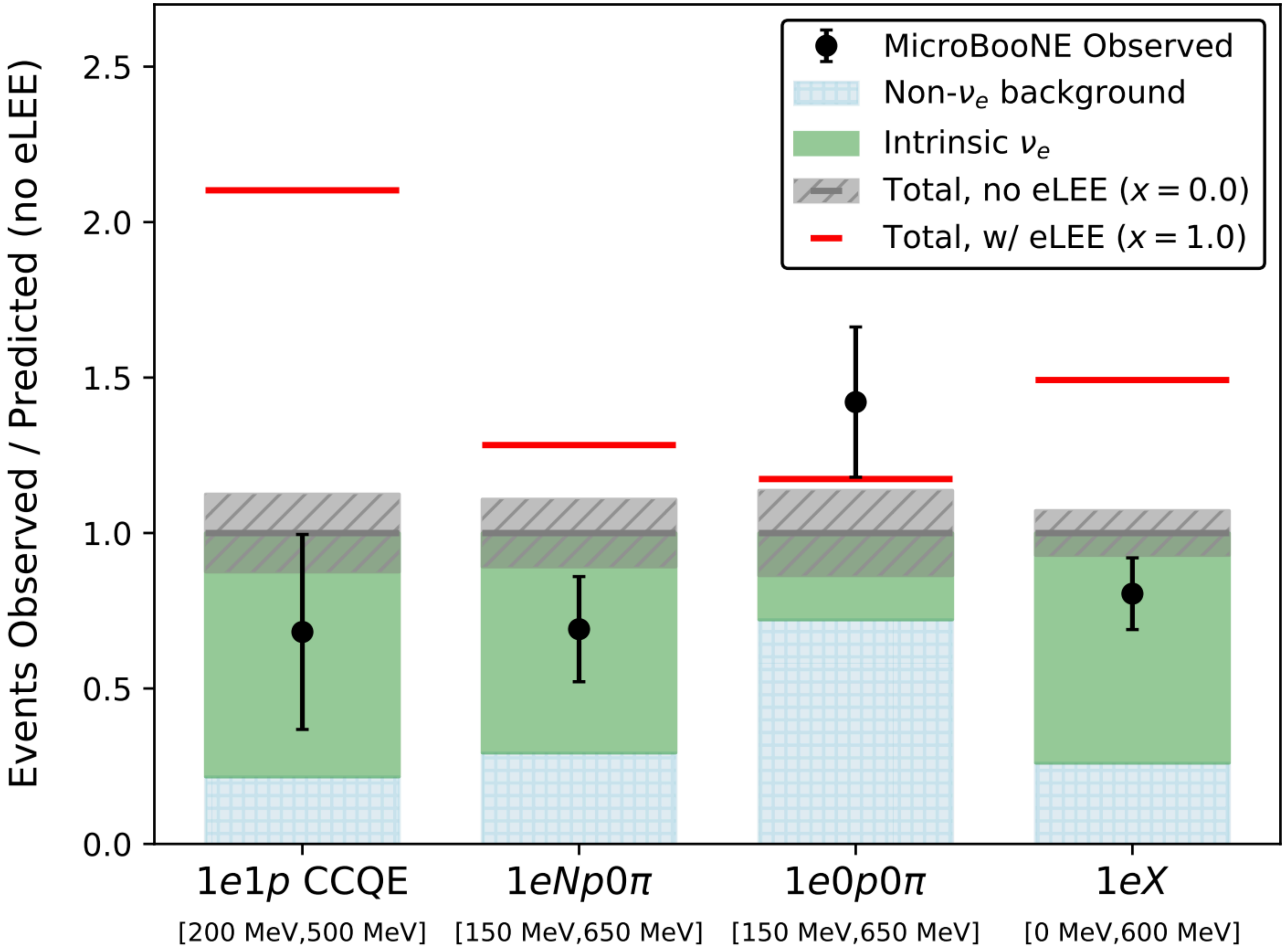
1eNp

arXiv:2110.14065 [hep-ex]



1eX

arXiv:2110.13978 [hep-ex]



More details: N. Foppiani talk

arXiv:2110.14054 [hep-ex]

WHAT DOES THIS MEAN?

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7]Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

Produces True Electrons

Produces True Photons

Produces e^+e^- pairs

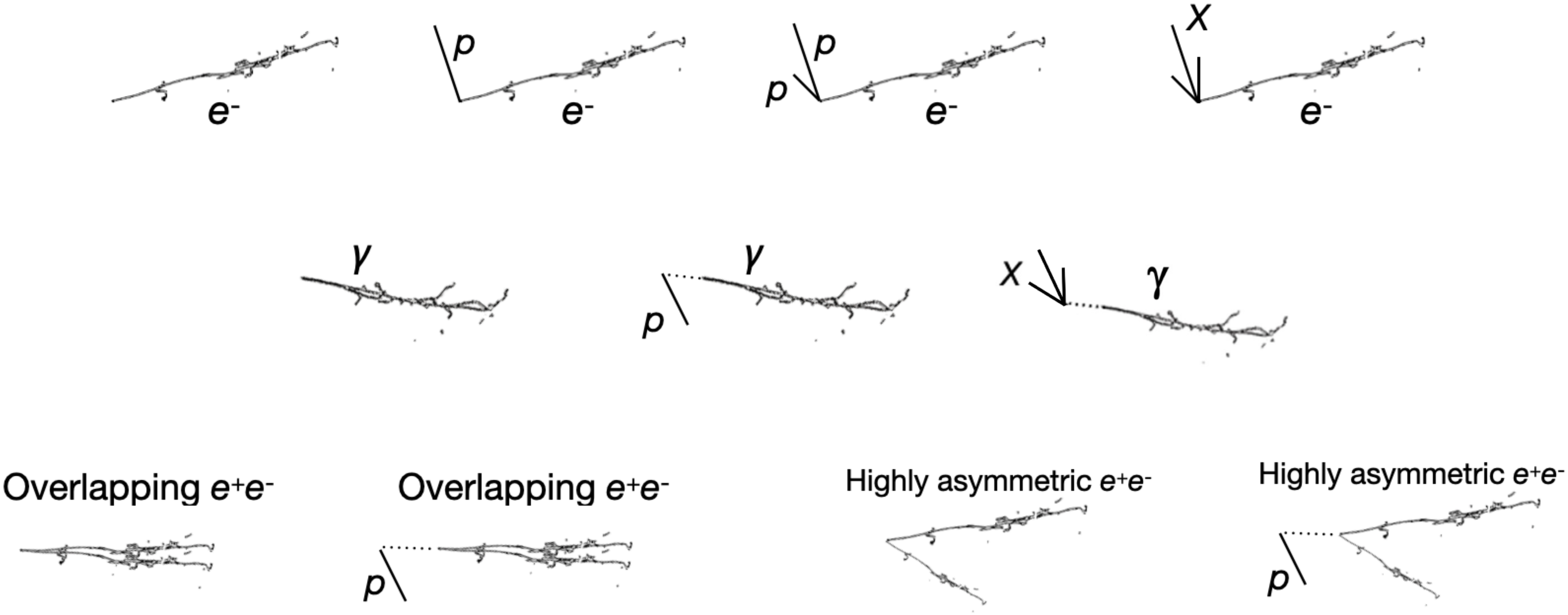
Caution: not an exhaustive list!

This is meant to be representative only

More information: see

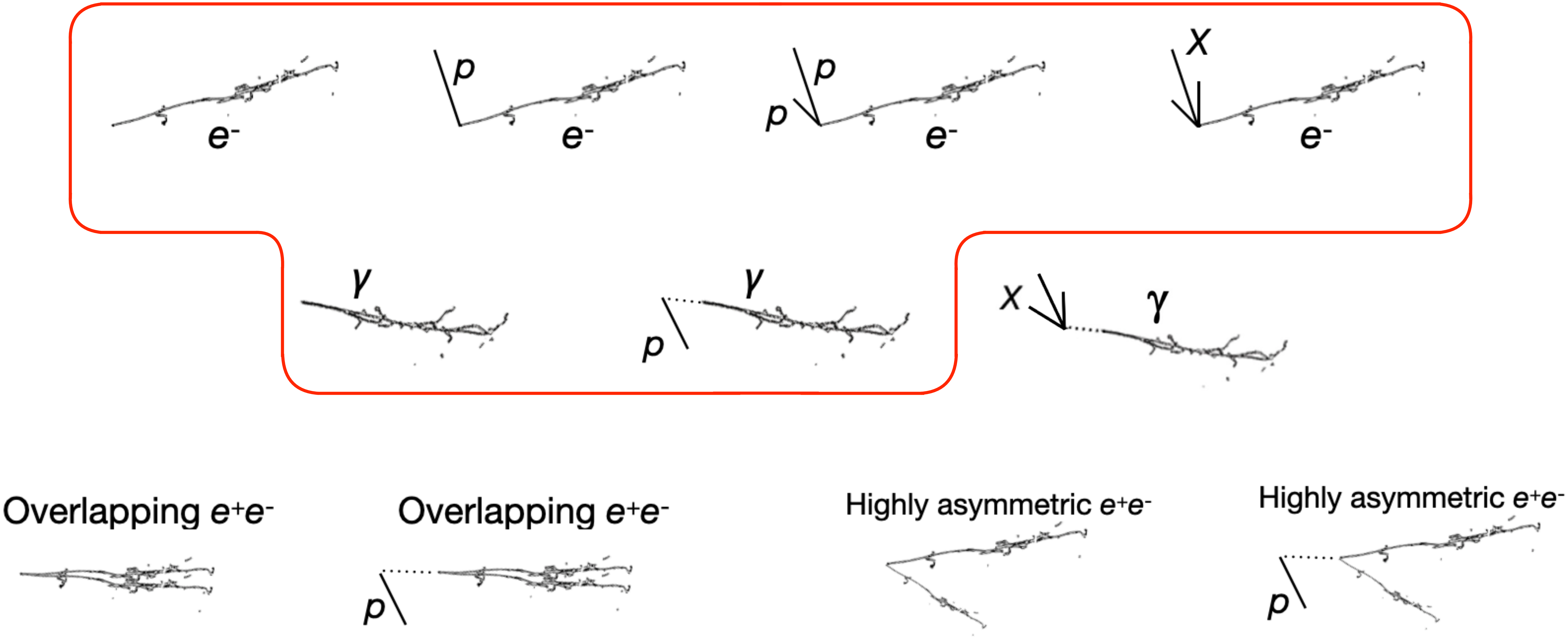
P. Machado, Fermilab PAC, November 2021

WHAT DOES THIS MEAN?



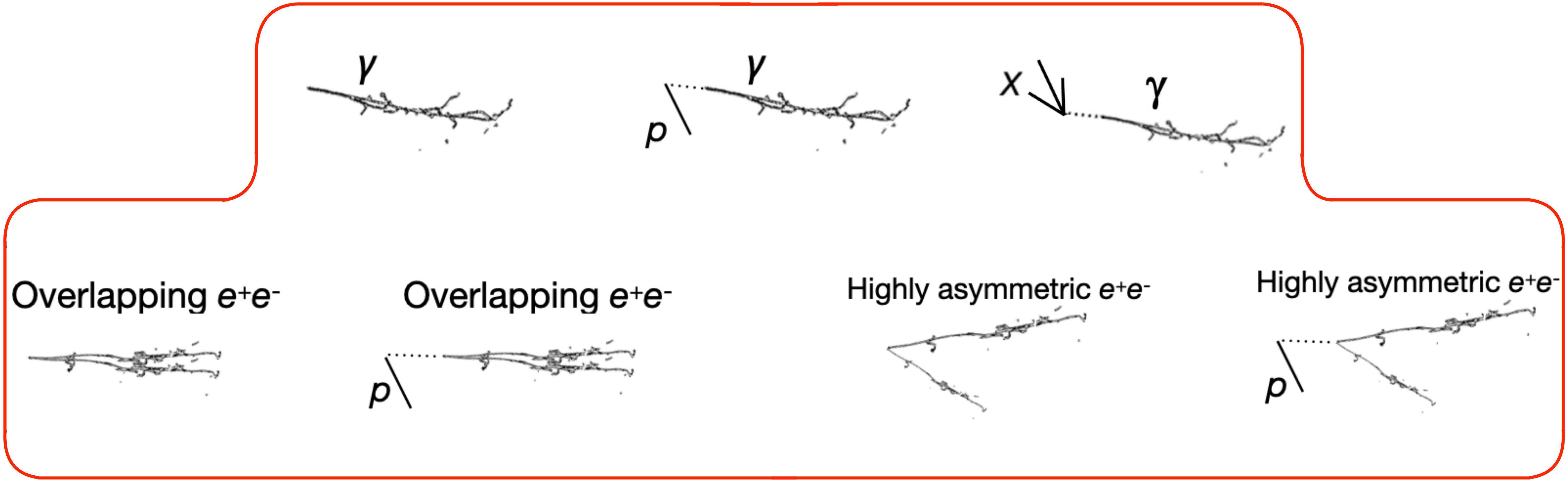
WHAT DOES THIS MEAN?

MicroBooNE's first LEE results



WHAT DOES THIS MEAN?

Future investigations



μBooNE

How many neutrinos are there?

SBN
Program

How many neutrinos are there?

SBN Program µBooNE

T2K NOvA annie

How do neutrinos interact in the nuclear medium?

MINERvA µBooNE

KM3NeT P-ONE

T2K NOvA IceCube Neutrino Observatory

Which neutrino is heaviest? Which is lightest?

JUNO Borexino Gran Sasso

ESSnuSB Hyper-K DUNE

T2K NOvA DUNE JUNO

Is neutrino oscillation different for neutrinos and antineutrinos?

Hyper-K ESSnuSB

Why is neutrino mixing so large?

KATRIN

How much do neutrinos weigh?

Project 8

CUORE LEGEND

Are neutrinos their own antiparticles?

SNO+ nEXO

Why are neutrino masses so much smaller than all other particles?

Pierre Auger Observatory P-ONE Borexino Gran Sasso IceCube Neutrino Observatory

What else can neutrinos teach us?

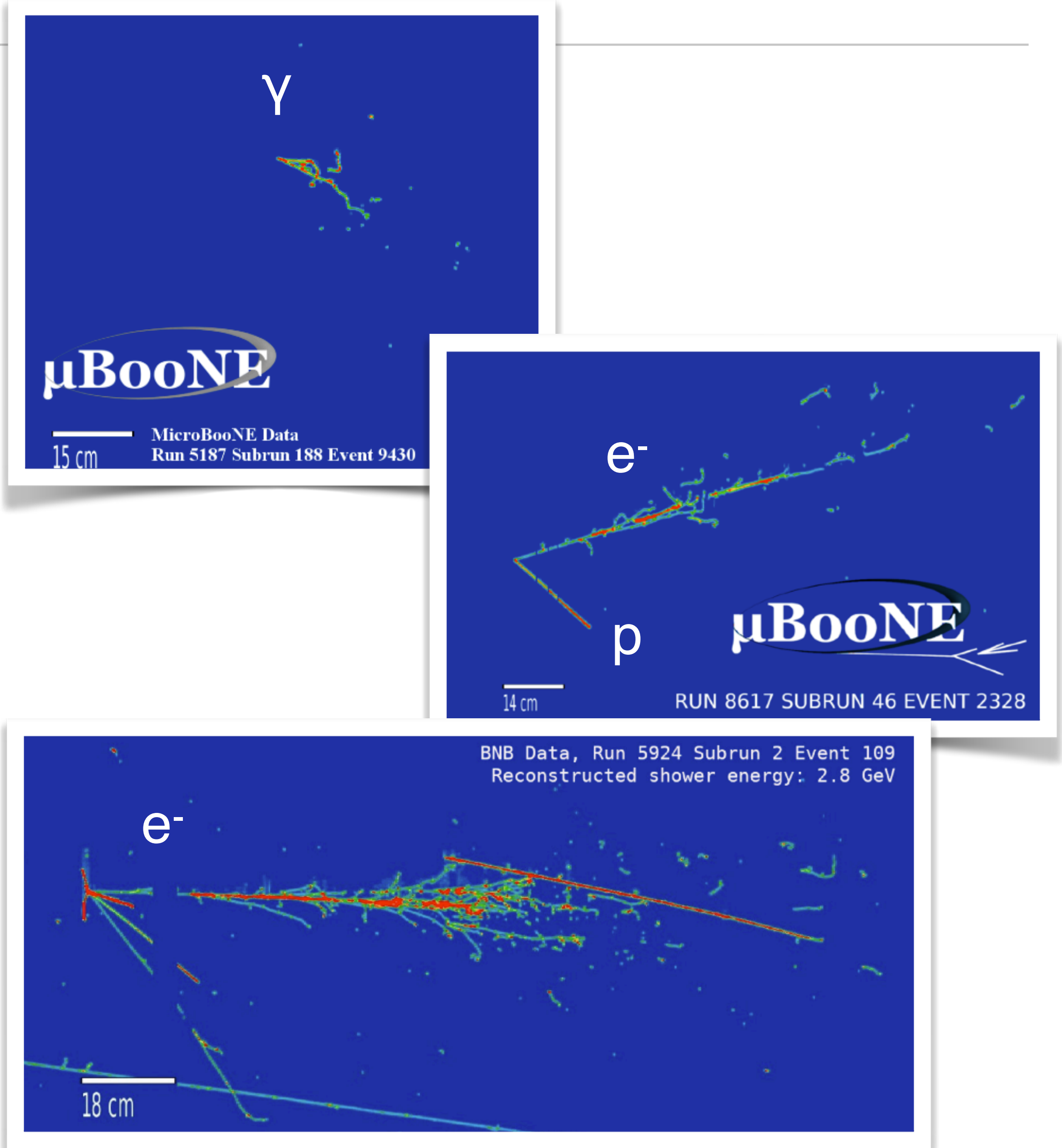
FASER KM3NeT

- Neutrinos are one of the **least-well-understood particles** in the Standard Model
- Neutrino oscillation is **beyond the Standard Model**, and opens the door to **exciting new possibilites**
- However, a lot remains that we **don't understand** (both within the 3-flavour oscillation picture and outside it)
- **New data** from current and future **precision experiments** will shed light on this

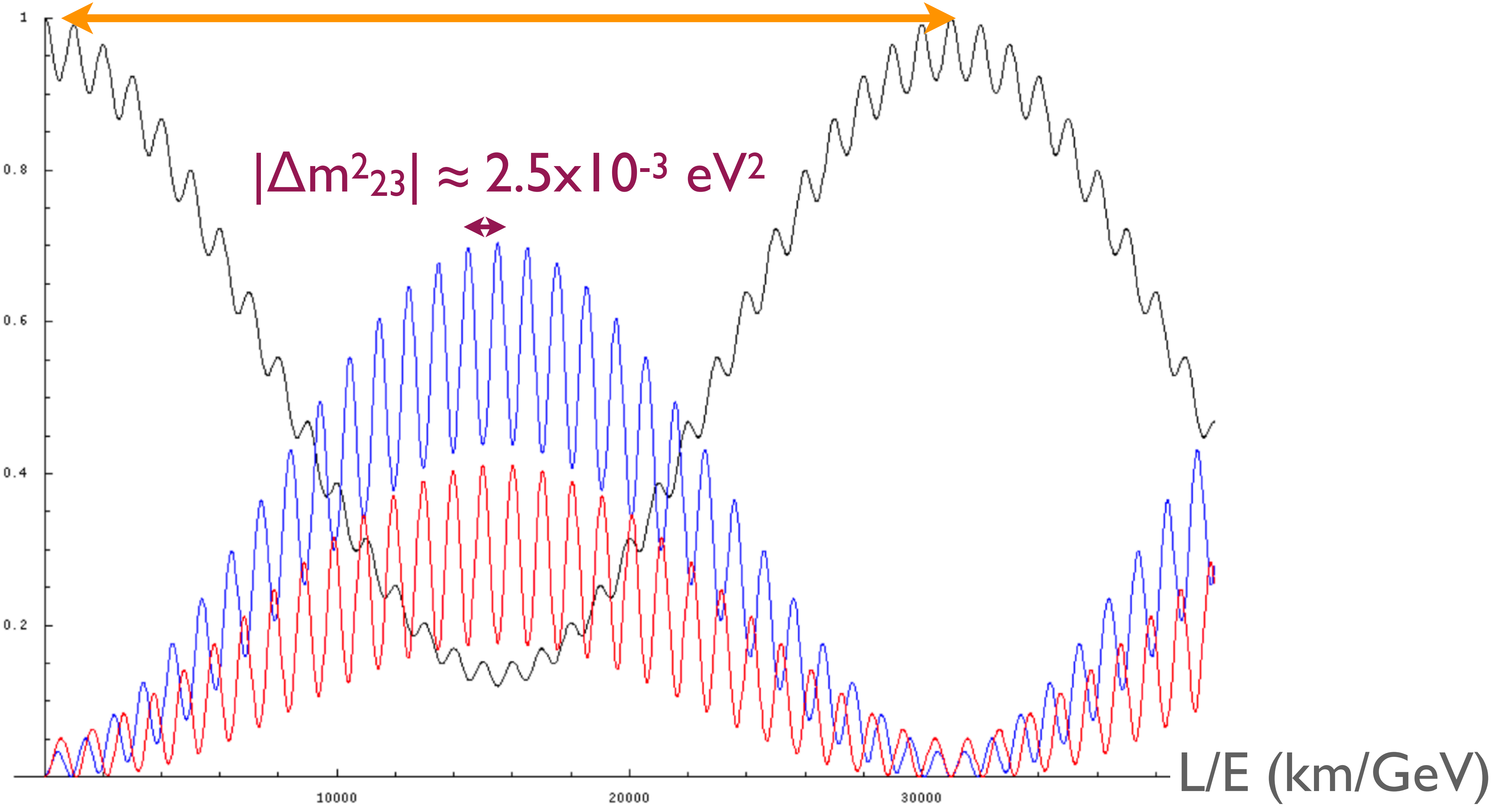
Thank you for listening!

A NOTE ON NEUTRINO ENERGY

- Each analysis selects **different combinations of particles**
- Each analysis uses a **different reconstruction paradigm**
- Electron-search results presented as a function of reconstructed neutrino energy
  - Remember we have to estimate neutrino energy from the particles we measure
  - → reconstructed neutrino energy != true neutrino energy
  - → AND **reco→true mapping is different between analyses**



$\Delta m^2_{21} \approx 7.5\text{x}10^{-5}\ \text{eV}^2$



$|\Delta m^2_{23}| \approx 2.5\text{x}10^{-3}\ \text{eV}^2$

Figure from https://arxiv.org/abs/0905.1793

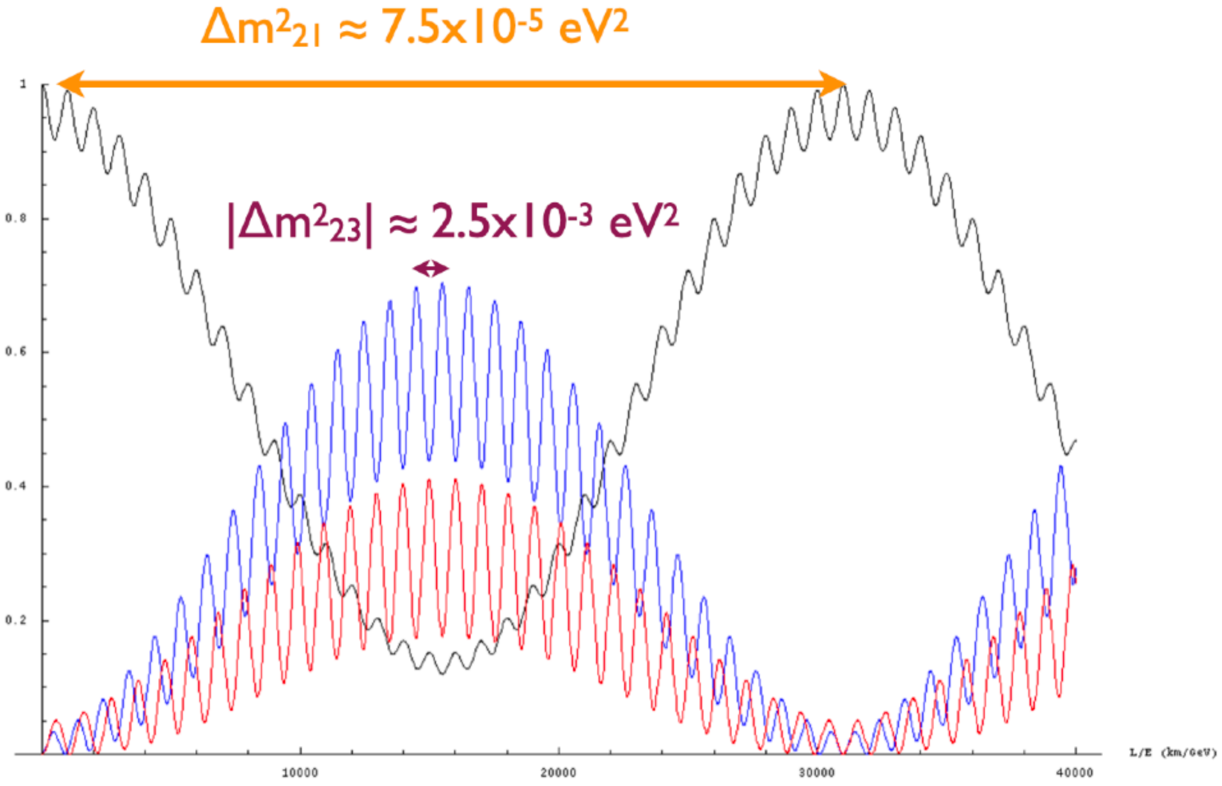


Figure from https://arxiv.org/abs/0905.1793

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

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

Experimental data from PDG review of neutrino mixing

Solar neutrino experiments:

L = 10^{10} m
E = 1 MeV
→ $\Delta m^2 = 10^{-10}$ eV^2

Atmospheric neutrino experiments:

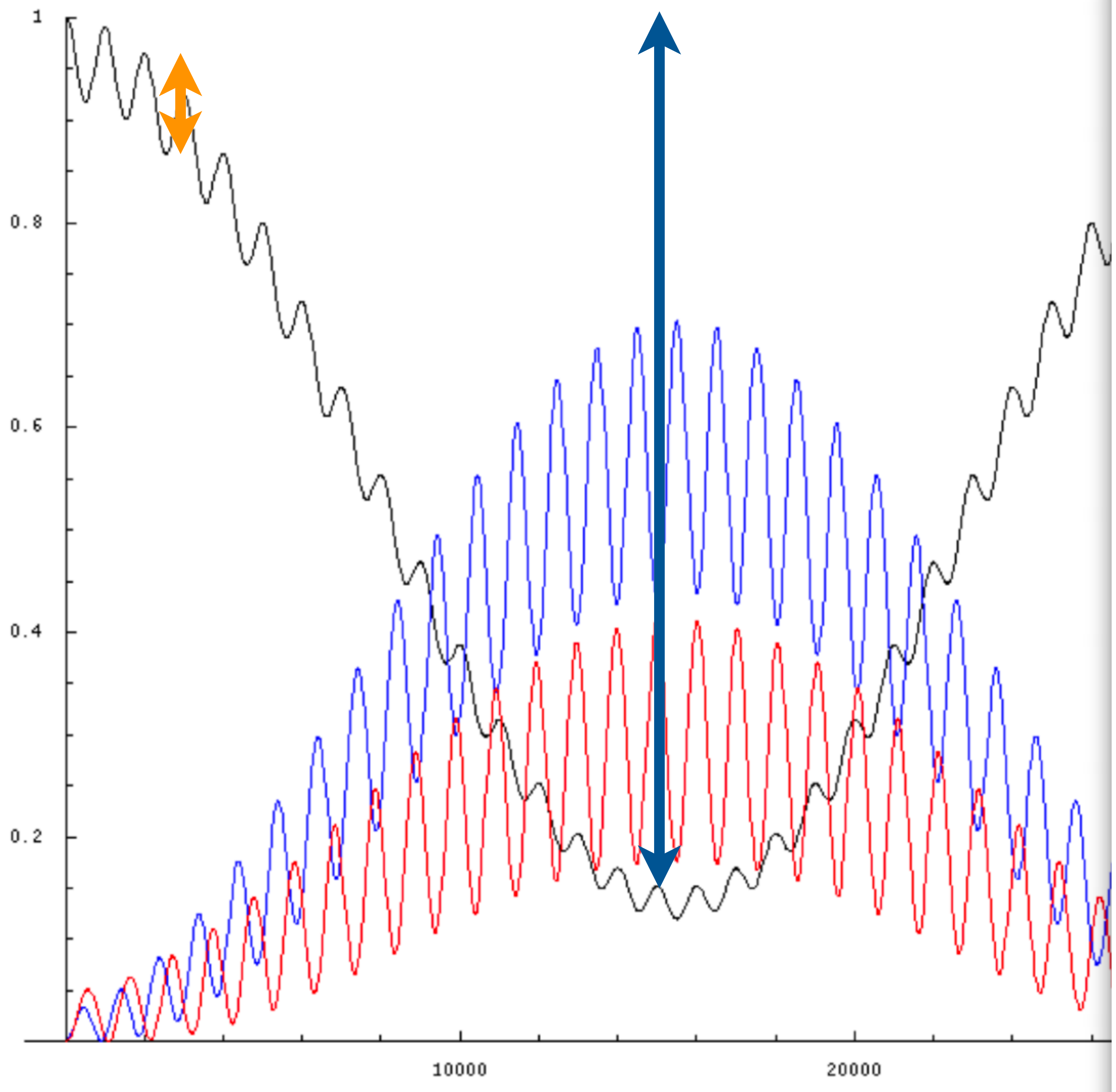
L = 10^4-10^7 m
E = 10^2-10^5 MeV
→ $\Delta m^2 = 10^{-1}$-10^{-4} eV^2

Accelerator neutrino experiments (long-baseline):

L = 10^5-10^6 m
E = 10^3-10^4 MeV
→ $\Delta m^2 = 10^{-2}$-10^{-3} eV^2

Reactor neutrino experiments (medium-baseline):

L = 10^4-10^5 m
E = 1 MeV
→ $\Delta m^2 = 10^{-4}$-10^{-5} eV^2



Heights of oscillation peaks/dips determined by mixing angles

Solar neutrino experiments:

θ_{12}, θ_{13}

Atmospheric neutrino experiments:

θ_{23}

Reactor neutrino experiments (medium-baseline):

θ_{13}

Accelerator neutrino experiments (long-baseline):

θ_{23}, θ_{13}

Figure from https://arxiv.org/abs/0905.1793

THE PMNS MATRIX

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

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

flavour

Interaction

mass

Propagation

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)

I'll come back to what this parameter does…

THE PMNS MATRIX

$c_{ij} = \cos\theta_{ij}$
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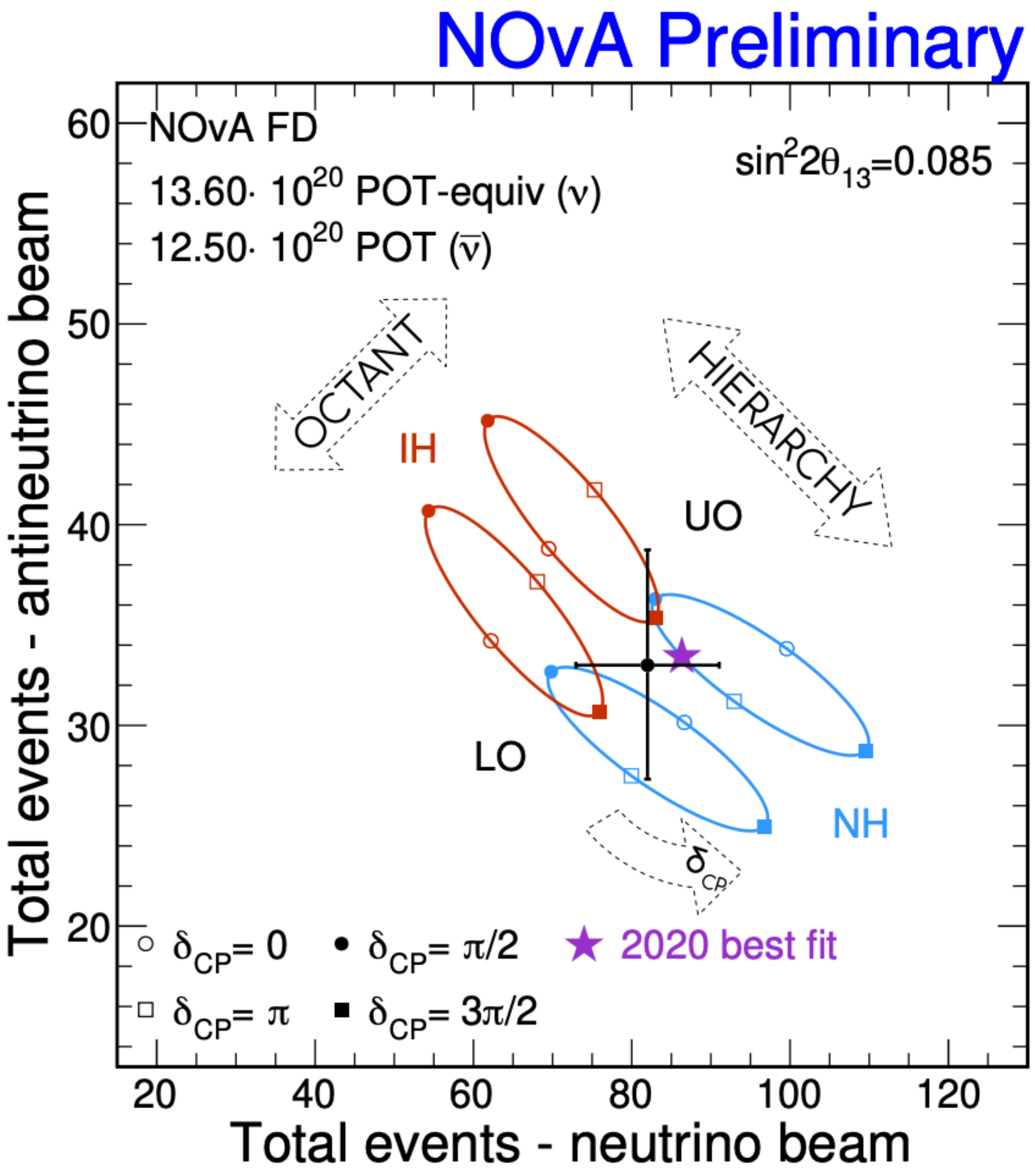
Atmospheric **Reactor** **Solar**

MEASURING THE MASS HIERARCHY: NOVA

- Long-baseline experiments are **sensitive to the mass hierarchy via matter effects**
- Additional charged-current interactions in matter for ν_e, not available to ν_μ, ν_τ
- → **"extra potential"** for ν_e breaks mass-hierarchy symmetry (depending on which mass state contains the most ν_e)



THE MASS HIERARCHY

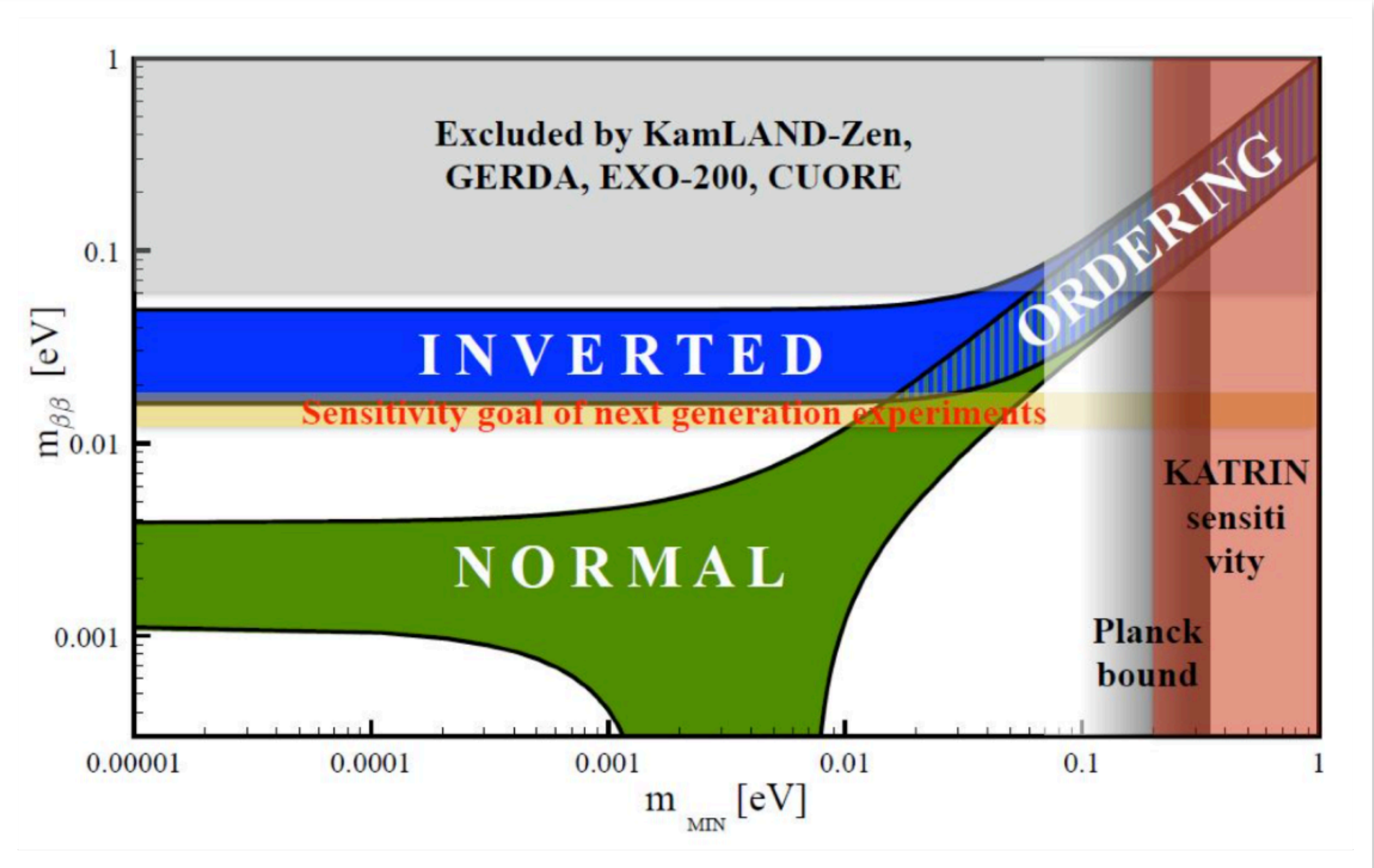
Some interesting motivation:

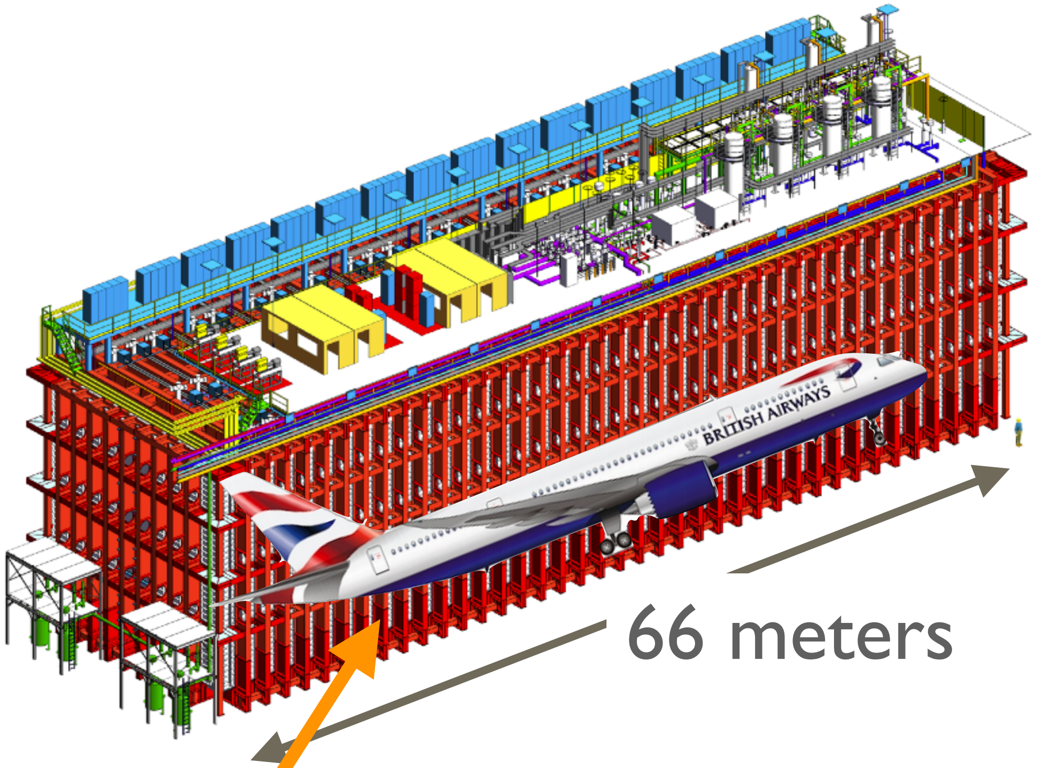
If the hierarchy turns out to be inverted →
neutrinoless double beta decay experiments may have sensitivity to rule in/out Majorana neutrinos in the next few years

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 $|\Delta m^2_{32}|$**

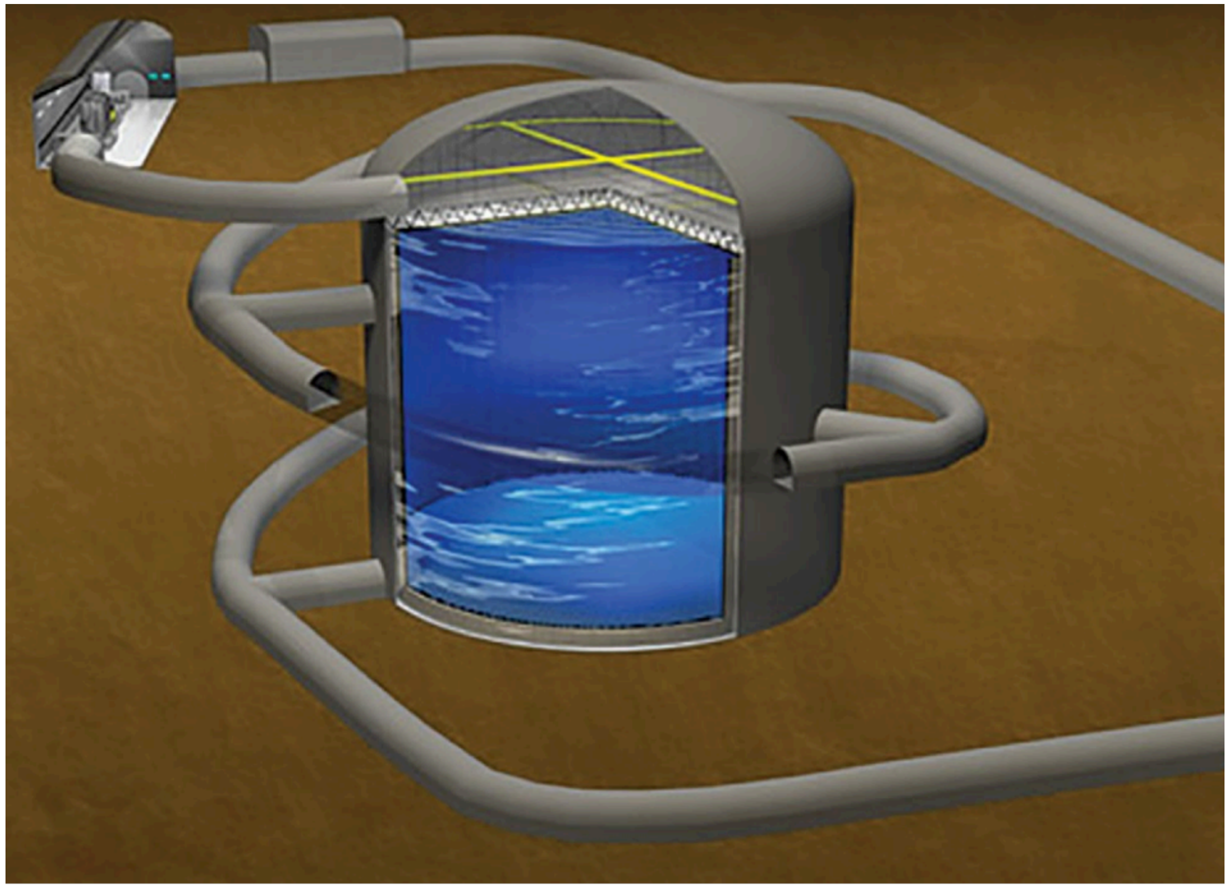


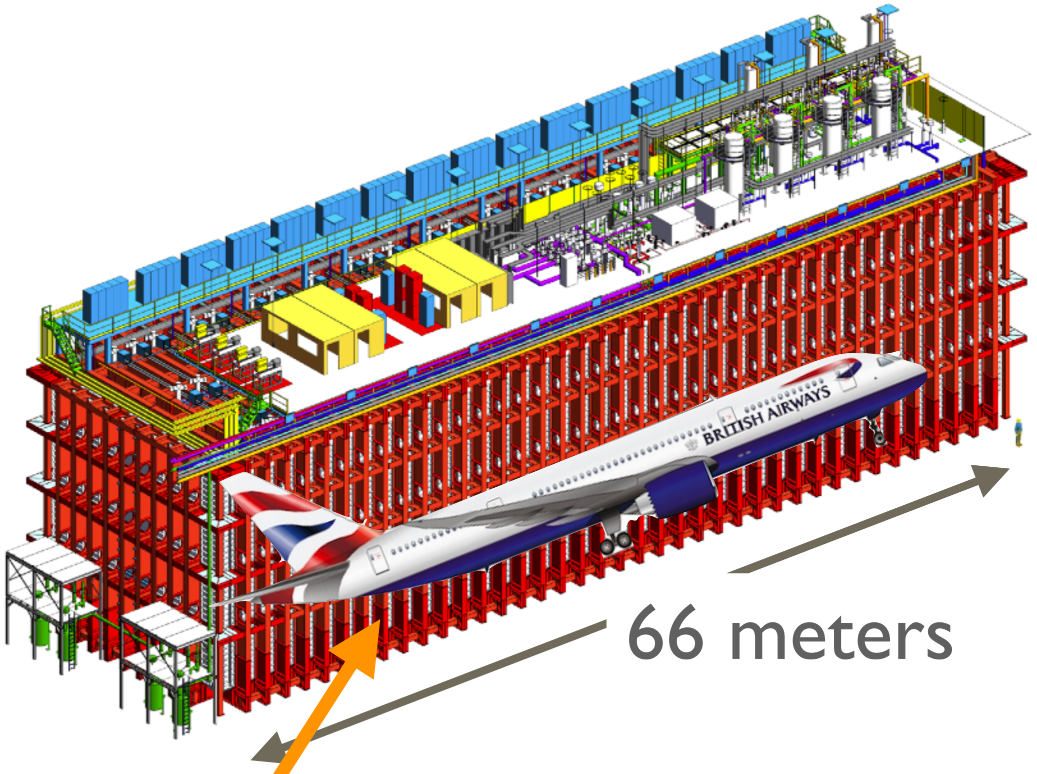


787 Dreamliner:
56.7m

4 x 10kt fiducial volume liquid argon TPC detectors

One 190kt fiducial volume water Cherenkov detector
8 x Super-K FV





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volume liquid argon
TPC detectors

One 190kt fiducial volume
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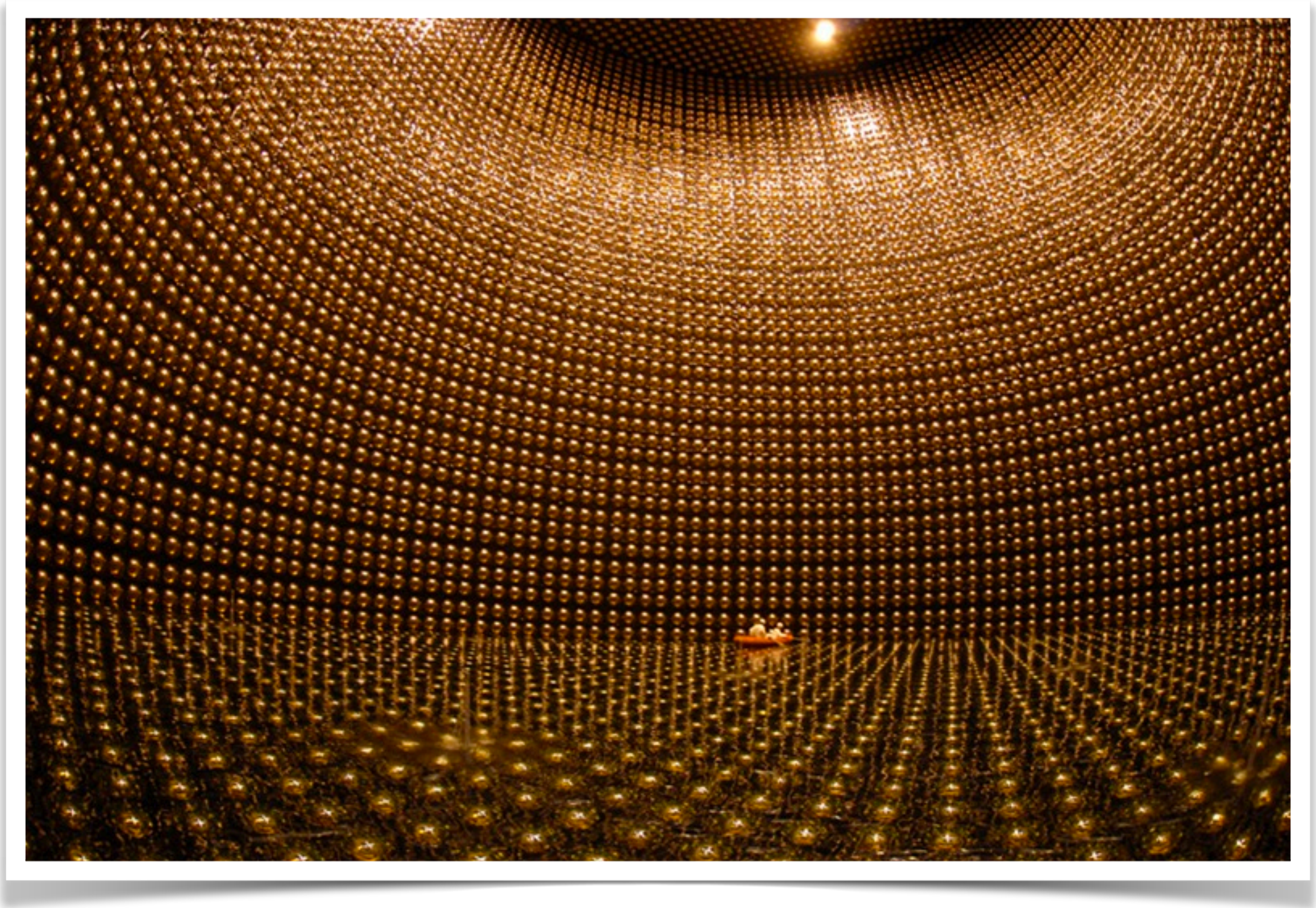

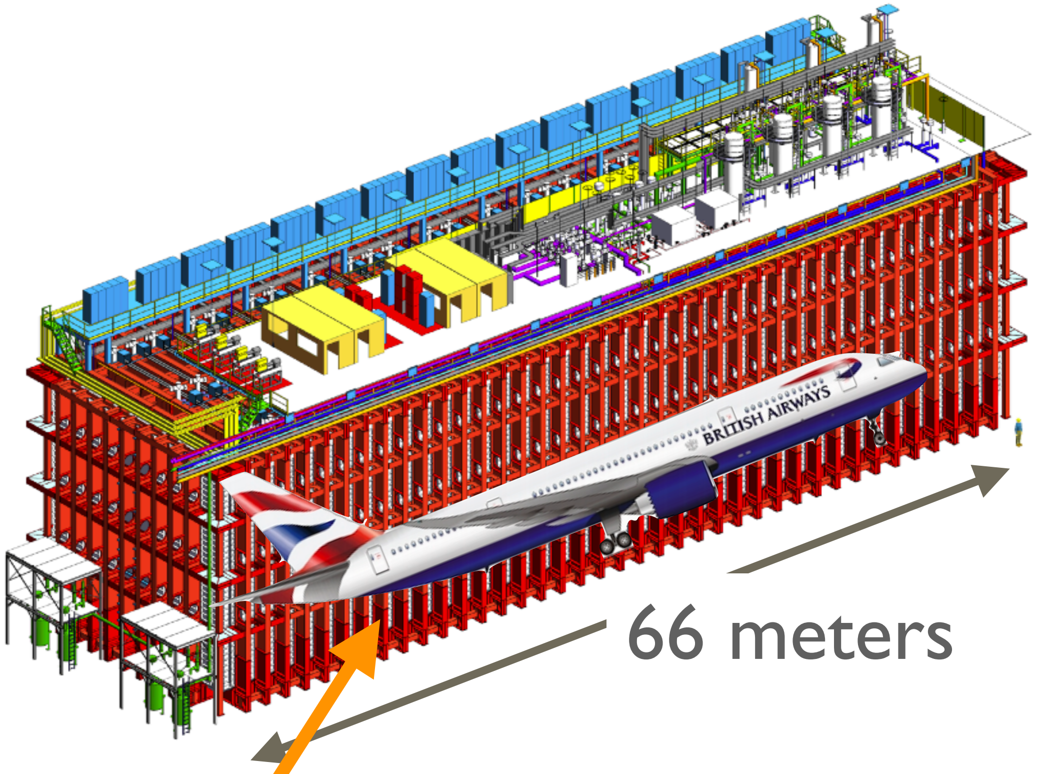

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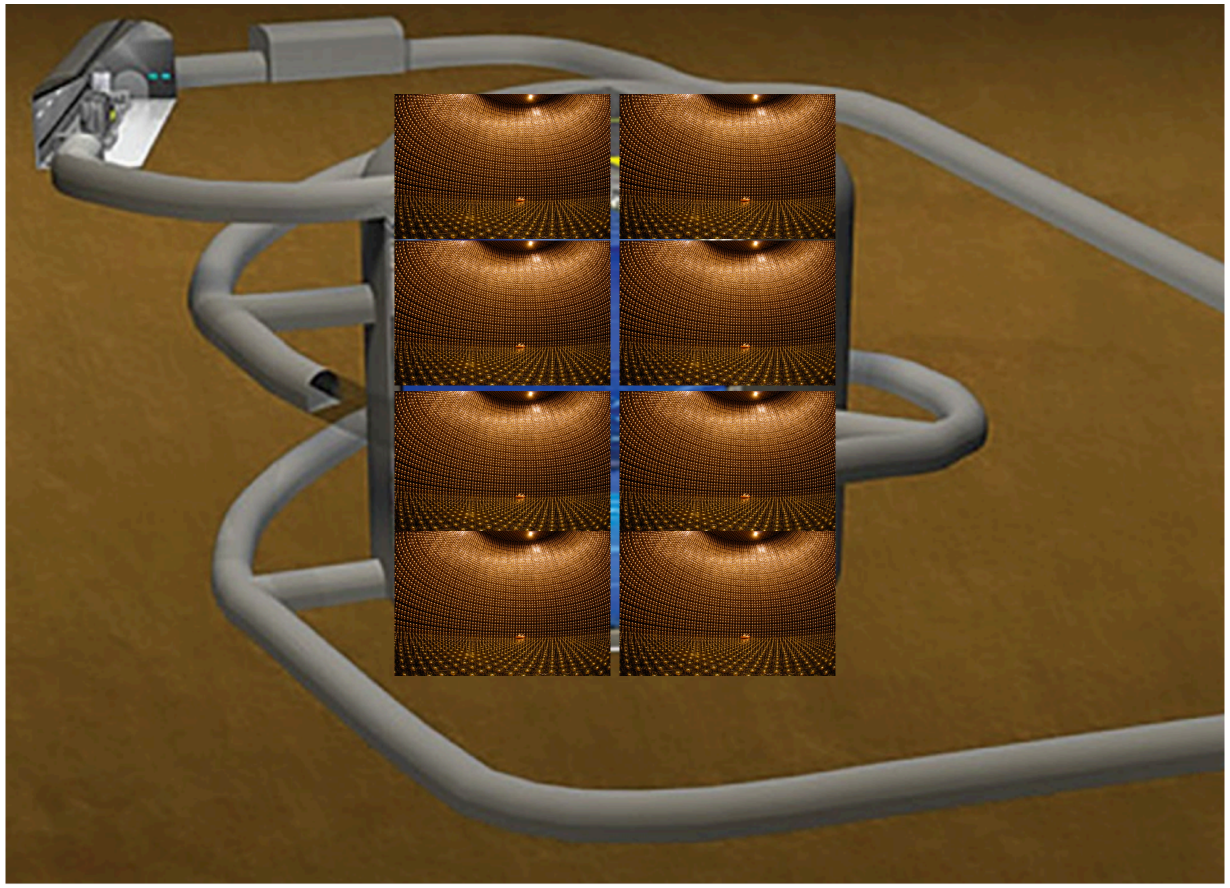


LArTPC STRENGTH: LOW DETECTION THRESHOLDS

Phys. Rev. Lett. 125, 201803 (2020)
Phys. Rev. D 102, 112013 (2020)
JINST 15, P03022 (2020)
arXiv:2110.14065 [hep-ex]
arXiv:2110.13978 [hep-ex]
arXiv:2110.14080 [hep-ex]

- **Low thresholds** → access to new information about nuclear effects, neutrino interactions
- Example: proton detection thresholds

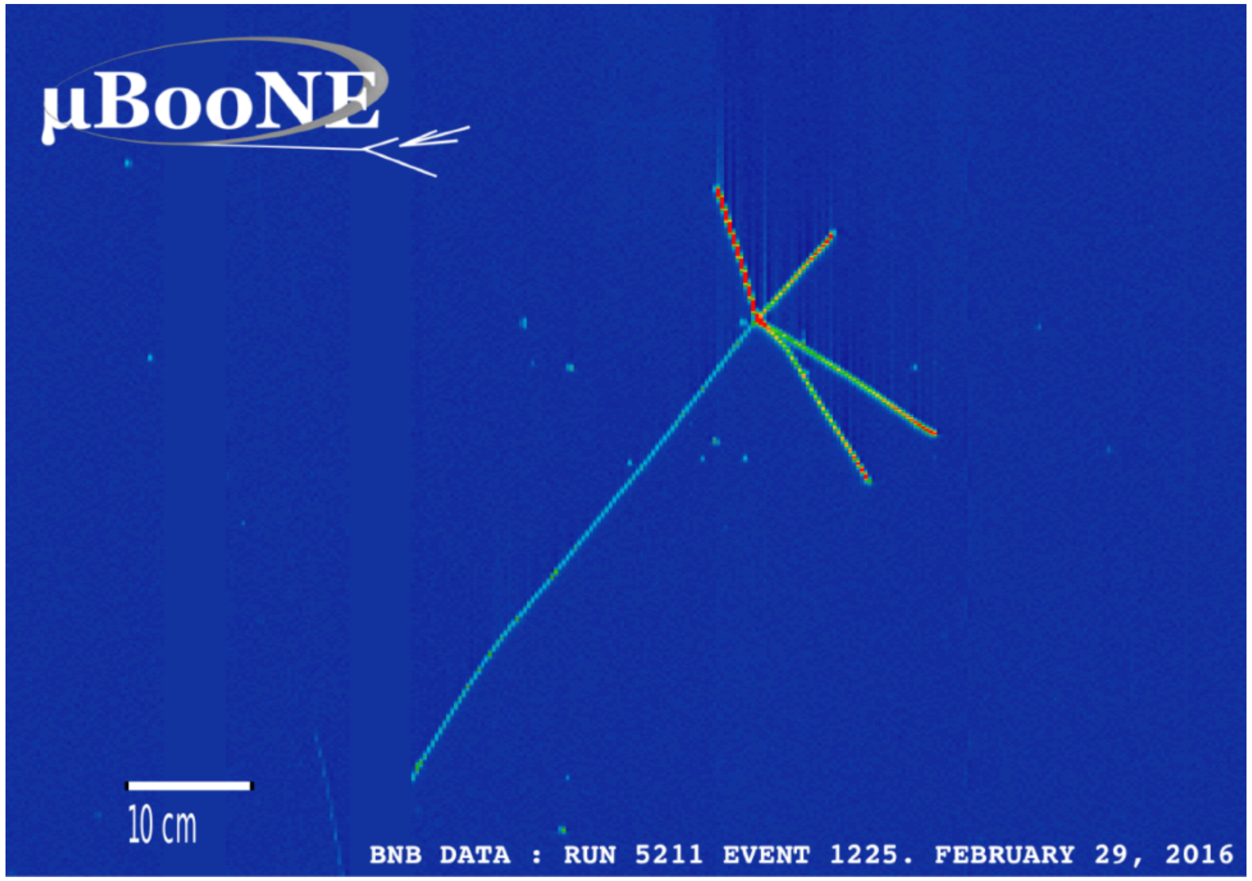
Phys. Rev. D 98, 032003 (2018)

- MicroBooNE: **250 MeV/c**
- ArgoNeuT: **200 MeV/c**

Phys. Rev. D 90, 012008 (2014)

- T2K: 500 MeV/c
- MINERvA: 450 MeV/c

Phys. Rev. D 99, 012004 (2019)

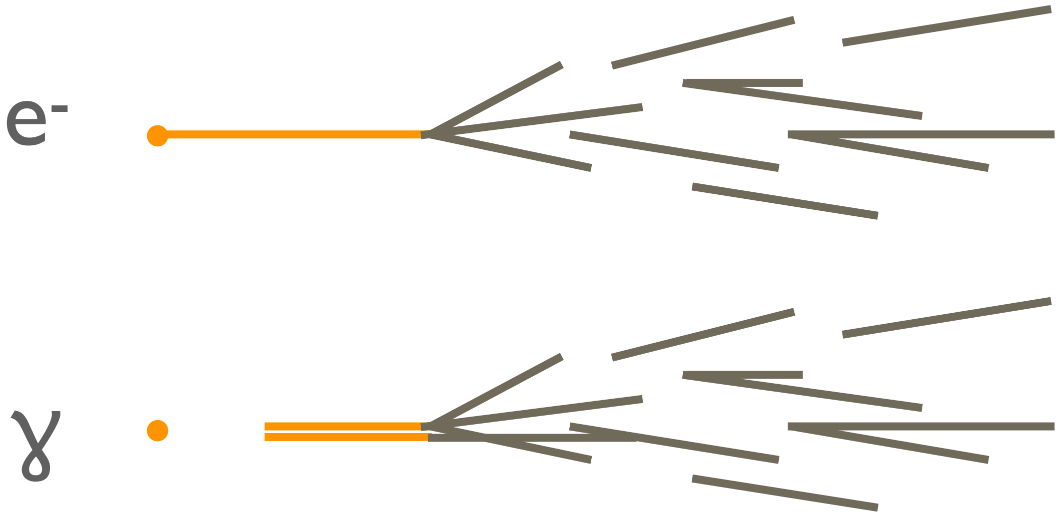


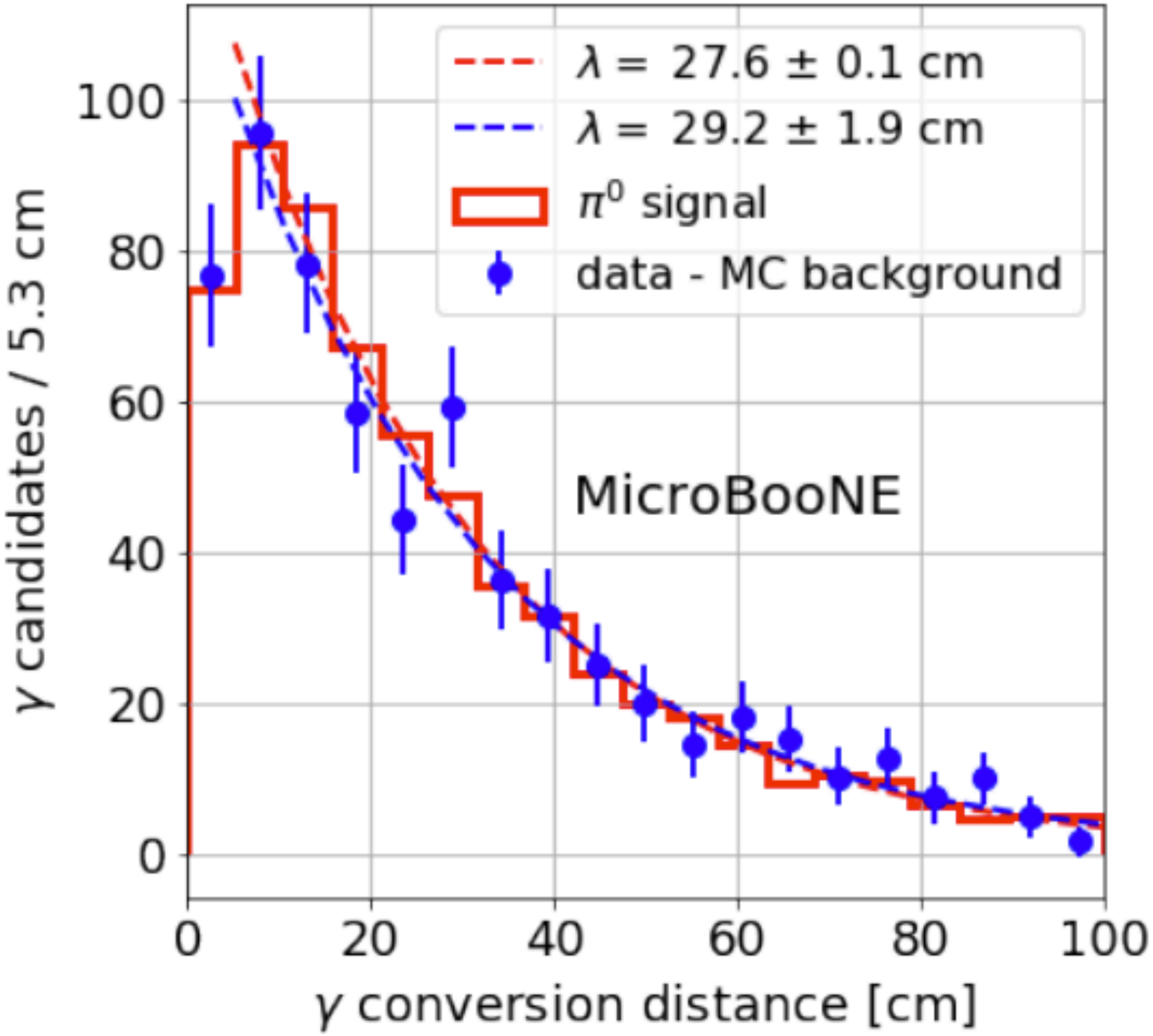
LARTPC STRENGTH: ELECTRONS AND PHOTONS

Phys. Rev. D 104, 052002 (2021)

- **Electrons and photons produce showers in LArTPCs**

- Distinguish using dE/dx at start of shower and start point





SINGLE PHOTON SEARCH

arXiv:2110.00409 [hep-ex]

- Simple hypothesis test: use combined Neyman-Pearson χ^2 as test statistic

Nucl. Inst. Meth. A 961 (2020) 163677

- Data consistent with nominal $\Delta \rightarrow N\gamma$ prediction

- Data **rejects LEE model hypothesis** in favour of nominal prediction at **94.8% CL**