Searching for ν-Physics: Overview of Experimental Neutrino Physics

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Workshop on Higgs and Cosmology Connection

Brookhaven National Laboratory

Caveats

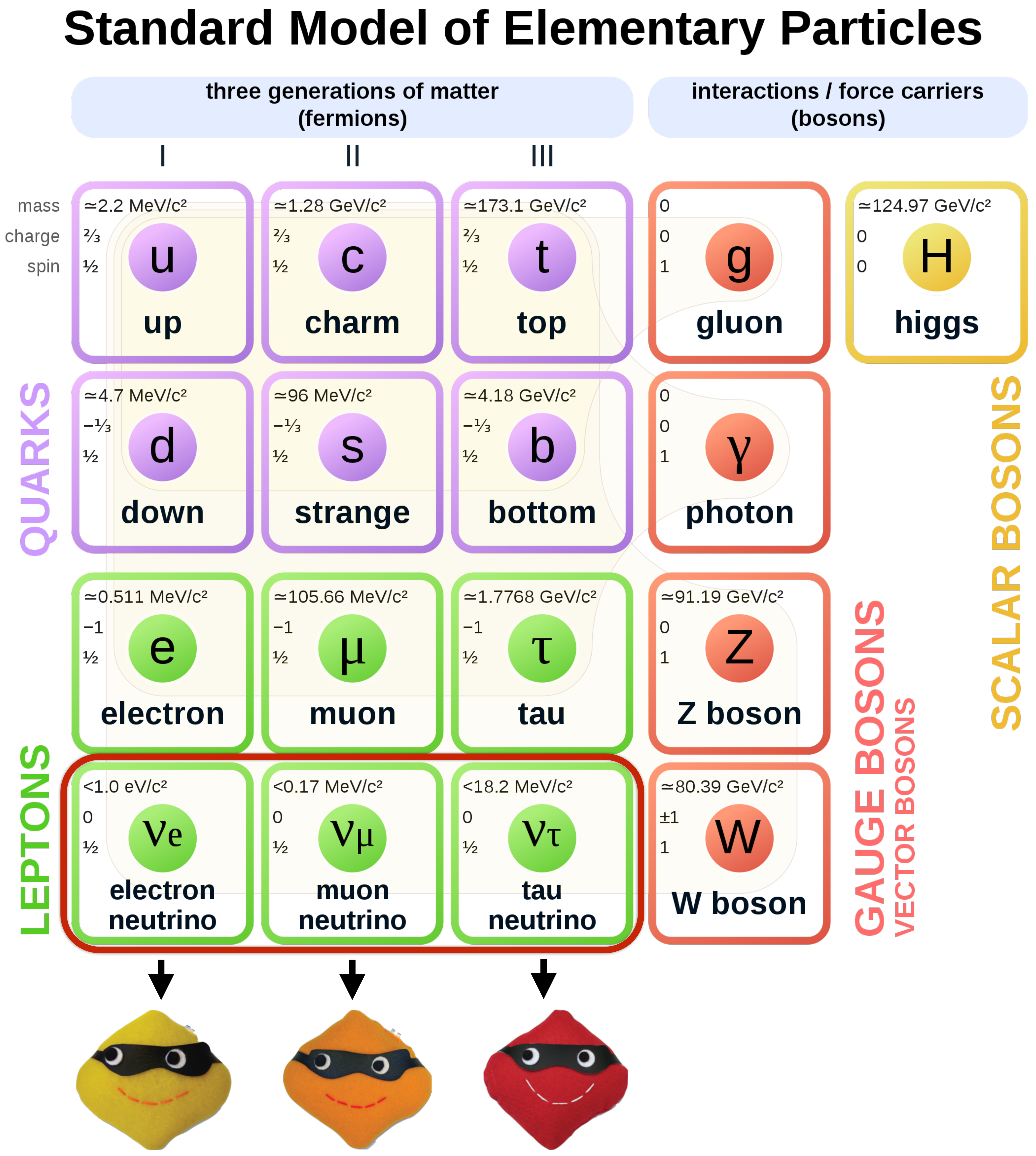
- I'm just a mere experimental neutrino physicist…
- my main experience covers neutrino oscillation, sterile neutrino search, and neutrino cross-section
  - I did touch on direct dark matter detection in the past, but maybe that's for another time
- I will try my best to cover (very) wide field of exp. neutrino physics, but I may/will be biased and won't be able to cover everything; my apologies in advance
- this talk will consists of full of experimentalist's point of views, and high-level ones; if you would have any detailed questions, please feel free to grab me during the workshop!

Contents

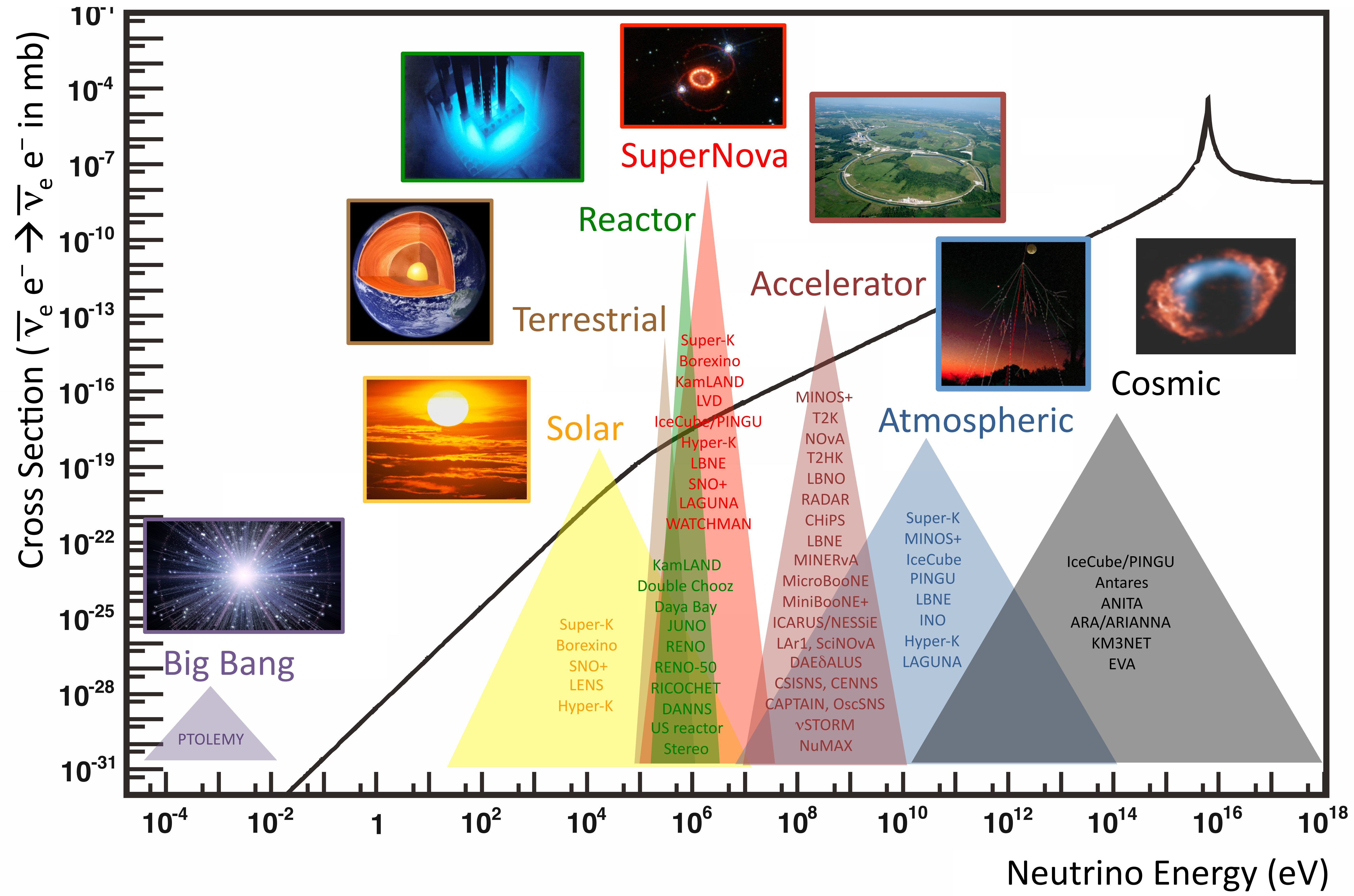
- intro: neutrinos in Standard Model and Beyond Standard Model
- current status and prospect of neutrino experiments
  - long-baseline neutrino exp.
  - short-baseline neutrino exp. (acc. & reactor-based)
  - neutrino mass measurements (β-decay & $0\nu\beta\beta$ exp.)
  - others
- summary

Standard Model of particle physics

- standard model (SM) that describes the elementary particles has been very successful so far
- however, there are still unsolved questions in SM, especially in neutrino sector
  - neutrino oscillation observation implies neutrino has non-zero mass
  - but we still do not know neutrino masses, mass ordering, precise value of δ_{CP} values, …



Neutrinos are everywhere



Translation of the open letter sent by Wolfgang Pauli to Lise Meitner and Hans Geiger and a group of radioactive people at the Gauverein meeting in Tübingen.

Zürich, Dec. 4, 1930

Physics Institute of the ETH
Gloriastrasse

Zürich

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than e • (10 -13cm).

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I amindispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

W. Pauli

- many neutrinos and neutrino experiments over many different energies!
- far cry from Pauli's worry that he had postulated a particle that could never be experimentally detected

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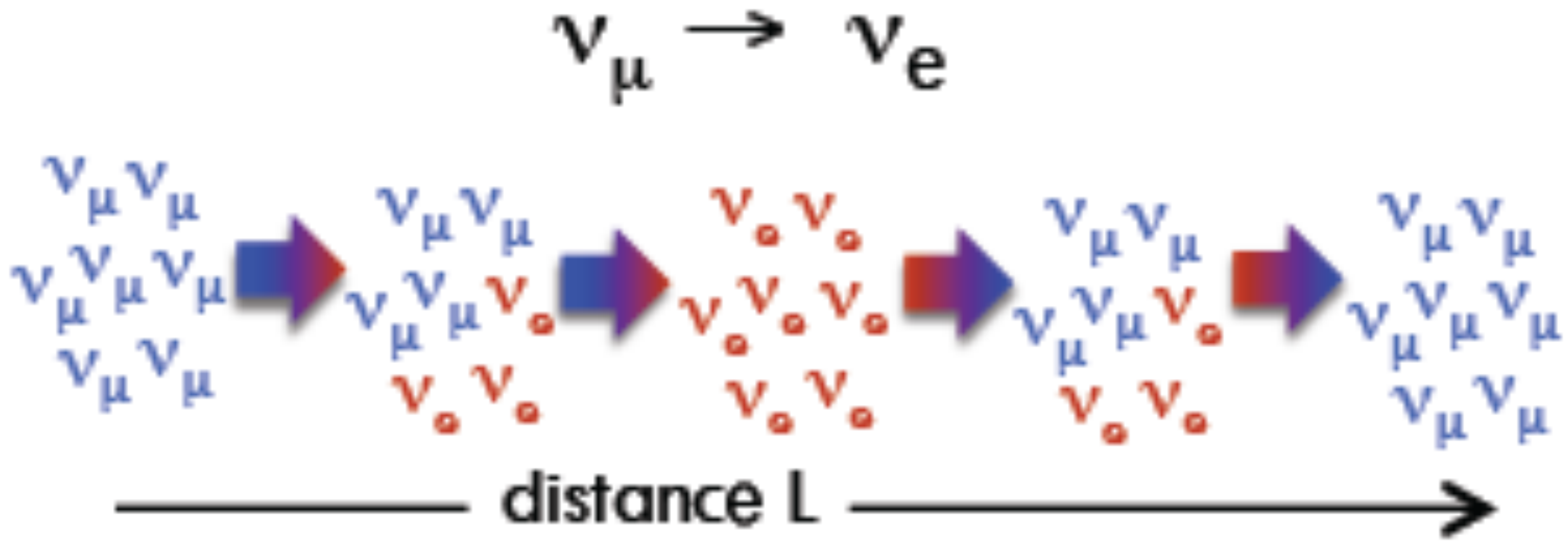
W. Pauli

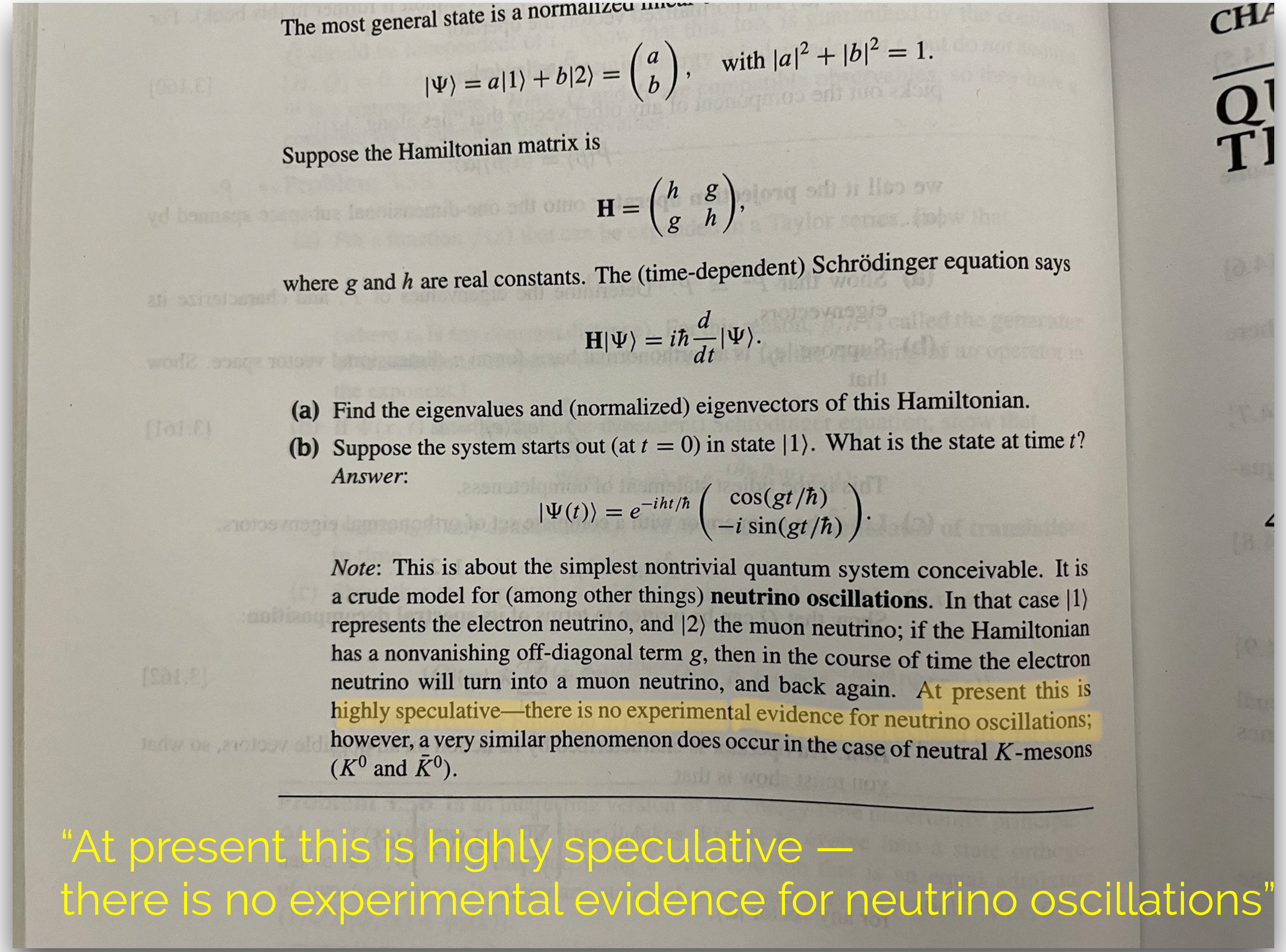
Crack in the Standard Model: Massive neutrinos

- the Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which showed that **neutrinos have mass**"



- neutrino morph into another kind & back again: quantum mechanical effect
  - if neutrinos oscillate, they must have mass
  - depend on neutrino flavor and neutrino energy

Crack in the Standard Model: Massive neutrinos



The most general state is a normalized

$$|\Psi\rangle = a|1\rangle + b|2\rangle = \begin{pmatrix} a \\ b \end{pmatrix}, \quad \text{with } |a|^2 + |b|^2 = 1.$$

Suppose the Hamiltonian matrix is

$$\mathbf{H} = \begin{pmatrix} h & g \\ g & h \end{pmatrix},$$

where g and h are real constants. The (time-dependent) Schrödinger equation says

$$\mathbf{H}|\Psi\rangle = i\hbar \frac{d}{dt}|\Psi\rangle.$$

(a) Find the eigenvalues and (normalized) eigenvectors of this Hamiltonian.

(b) Suppose the system starts out (at $t = 0$) in state $|1\rangle$. What is the state at time t?

Answer:

$$|\Psi(t)\rangle = e^{-iht/\hbar} \begin{pmatrix} \cos(gt/\hbar) \\ -i\sin(gt/\hbar) \end{pmatrix}.$$

Note: This is about the simplest nontrivial quantum system conceivable. It is a crude model for (among other things) **neutrino oscillations**. In that case $|1\rangle$ represents the electron neutrino, and $|2\rangle$ the muon neutrino; if the Hamiltonian has a nonvanishing off-diagonal term g, then in the course of time the electron neutrino will turn into a muon neutrino, and back again. At present this is highly speculative—there is no experimental evidence for neutrino oscillations; however, a very similar phenomenon does occur in the case of neutral K-mesons (K^0 and $\bar{K}^0$).

"At present this is highly speculative —
there is no experimental evidence for neutrino oscillations"

D. J. Griffith, *Introduction to Quantum Mechanics* (p.120, 1995)

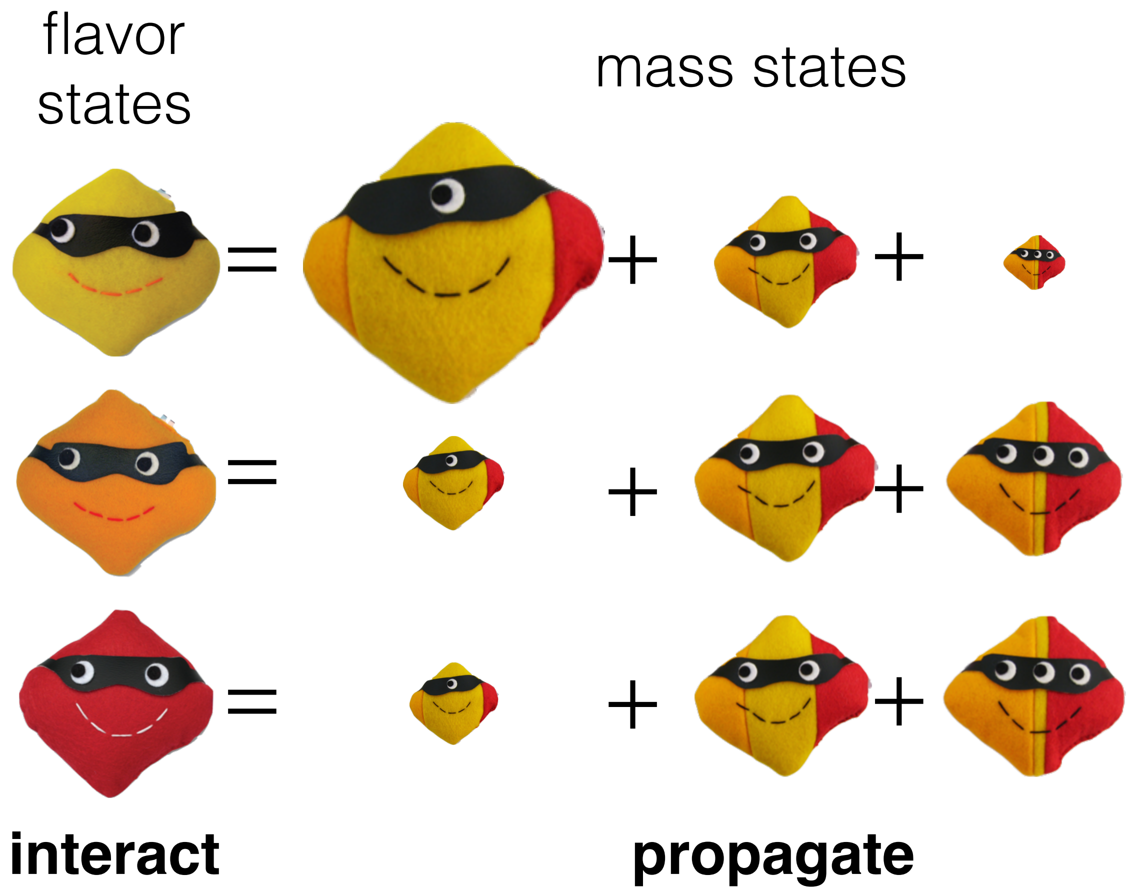
Neutrino oscillation

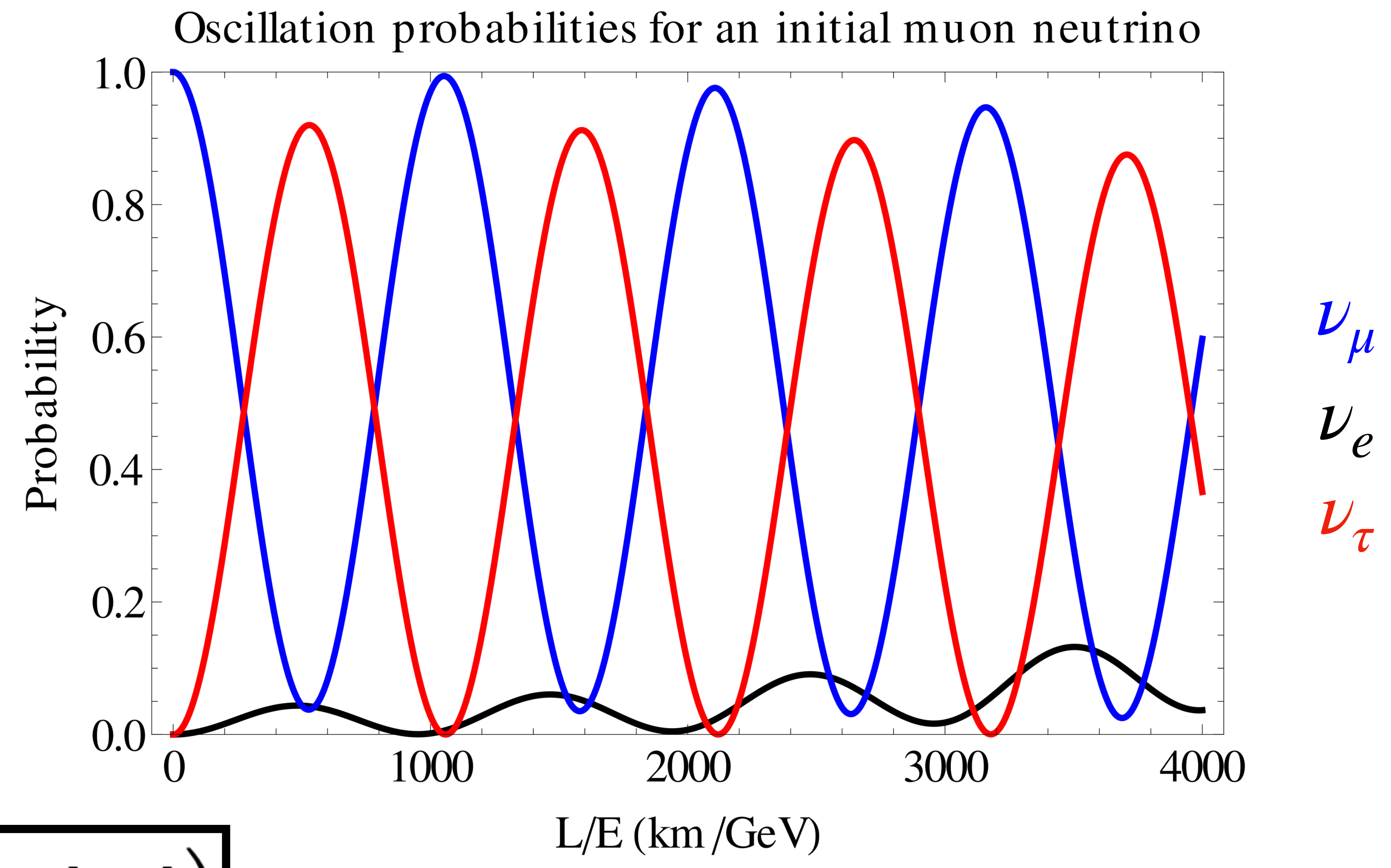
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Mixing matrix

Flavor eigenstates participating in weak interactions

Mass eigenstates ν_1, ν_2, ν_3



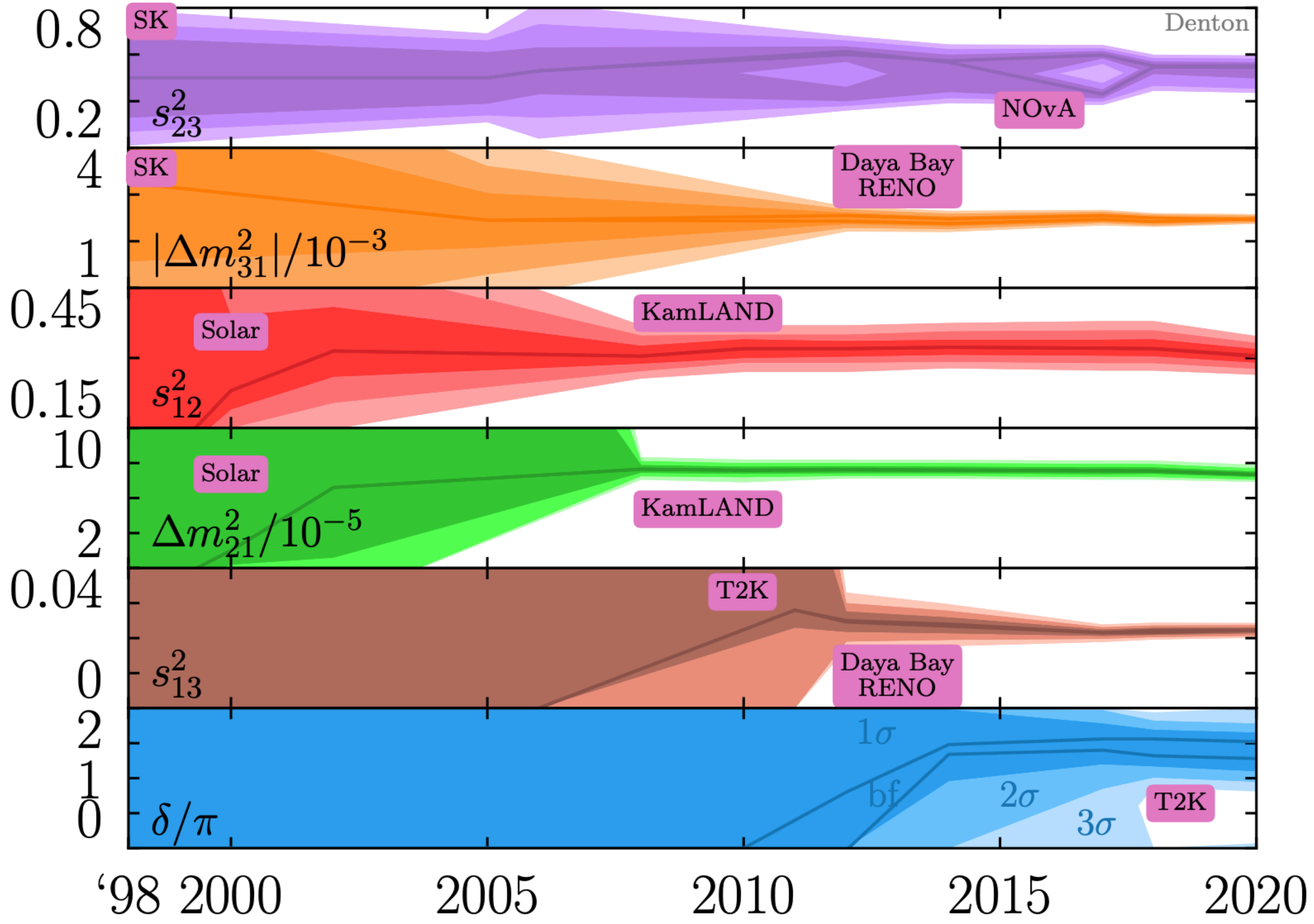


two-neutrino model

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2\ [\mathrm{eV}]^2 \cdot L\ [\mathrm{km}]}{E_\nu\ [\mathrm{GeV}]}\right)$$

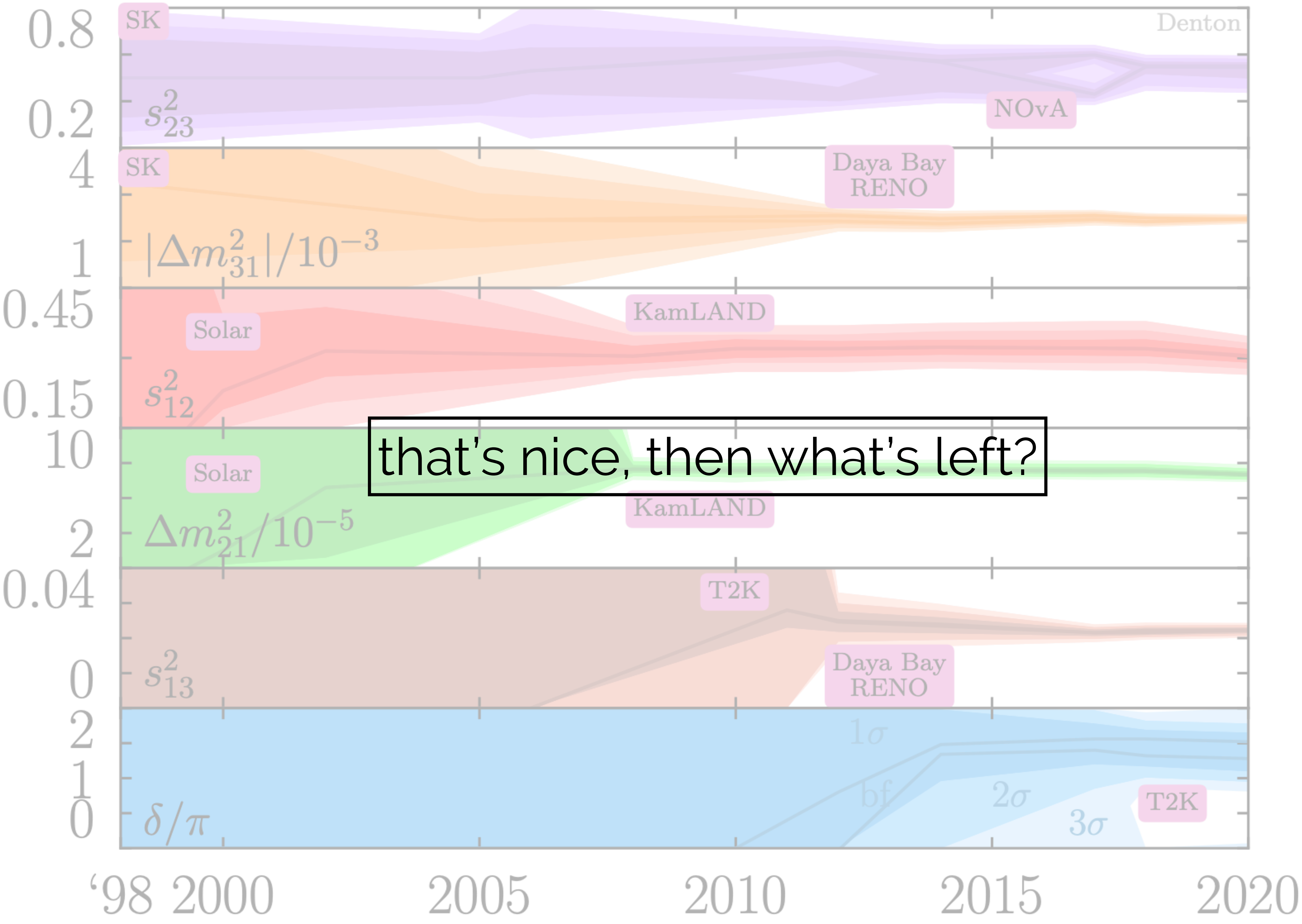
- neutrino flavor eigenstates are not the same as the mass eigenstates
- neutrino generally are produced in a *flavor* eigenstate, which is superposition of three *mass* eigenstates
- these mass eigenstates change phase over time at different rates, leads to **neutrino oscillation** when viewed in the flavor basis

Incredible progress in our knowledge in neutrino oscillation



plot by: Peter Denton

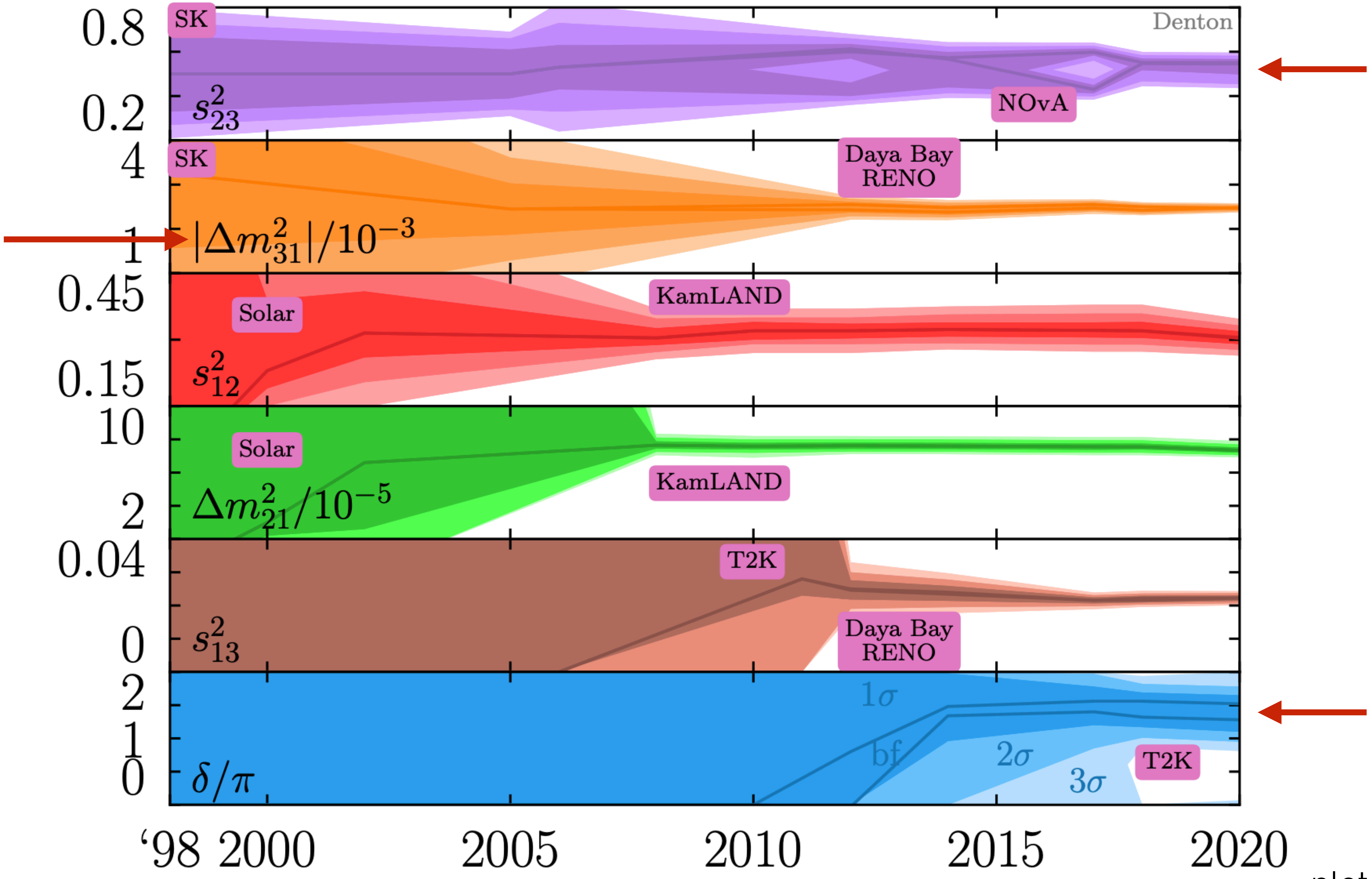
Incredible progress in our knowledge in neutrino oscillation



that's nice, then what's left?

plot by: Peter Denton

Incredible progress in our knowledge in neutrino oscillation



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Remaining questions in ν physics

standard model

could **CP violation** in neutrino interactions explain the matter/antimatter asymmetry?

what is the **ordering of the neutrino mass**?

beyond the standard model

are there **new interactions** we could discover via neutrino?

are there **additional neutrinos** beyond known three types?

what is neutrino mass?

is the neutrino its own anti particle?

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Long-baseline neutrino experiments

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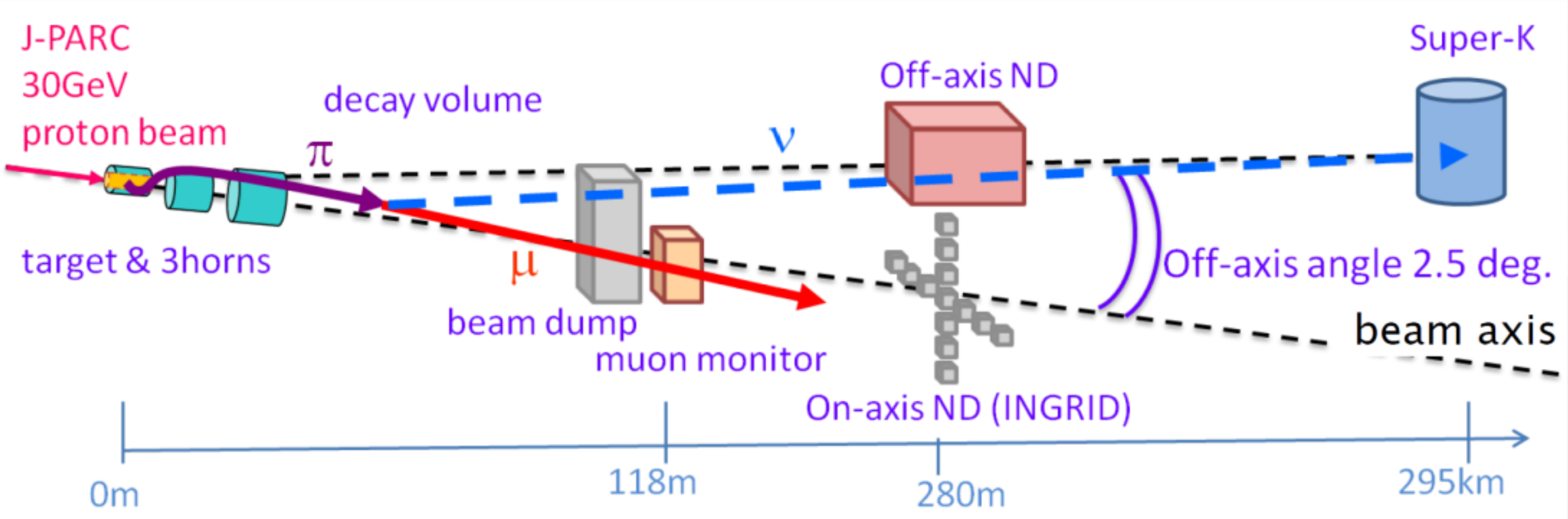
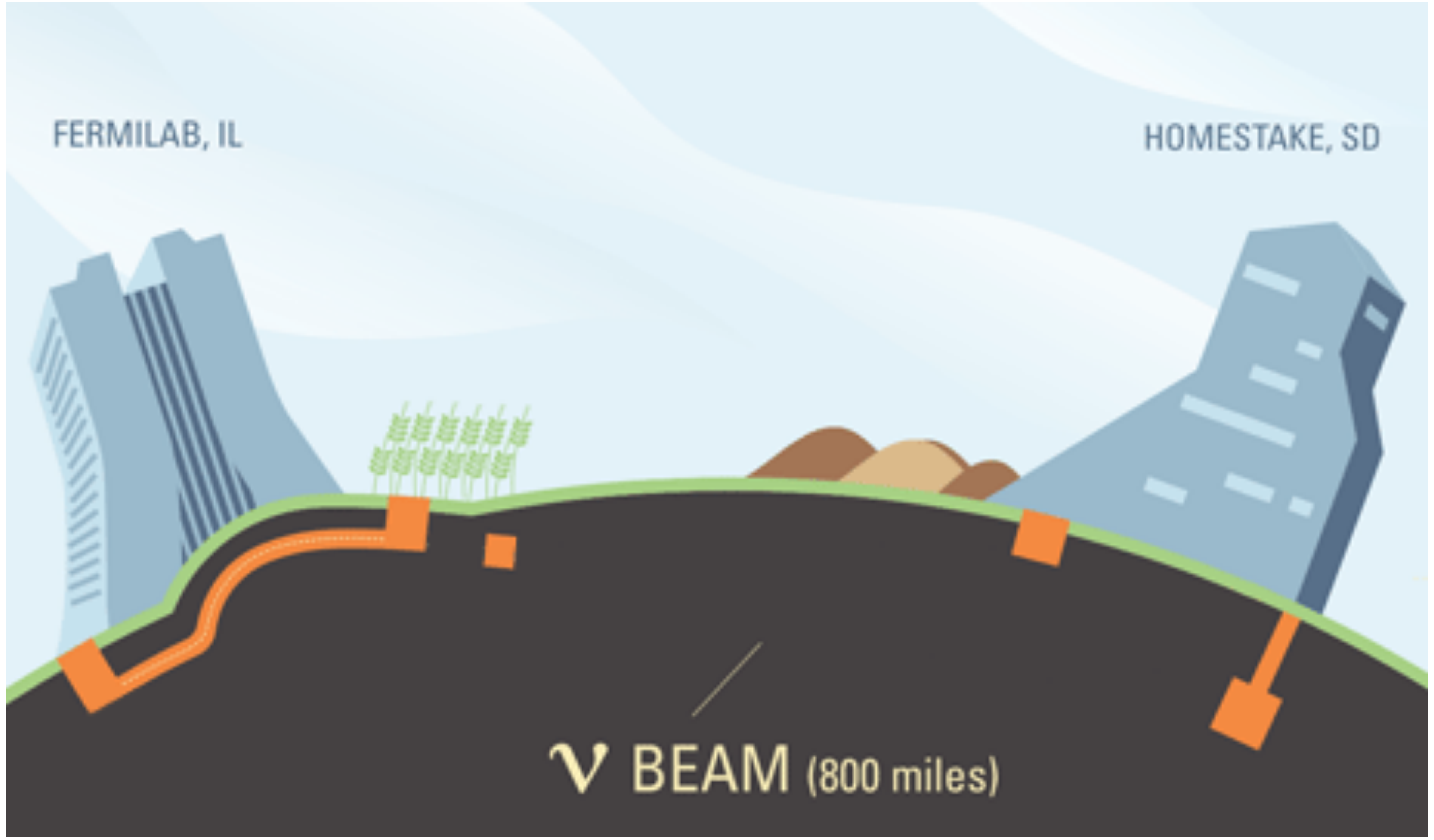
Long-baseline neutrino experiments: principle

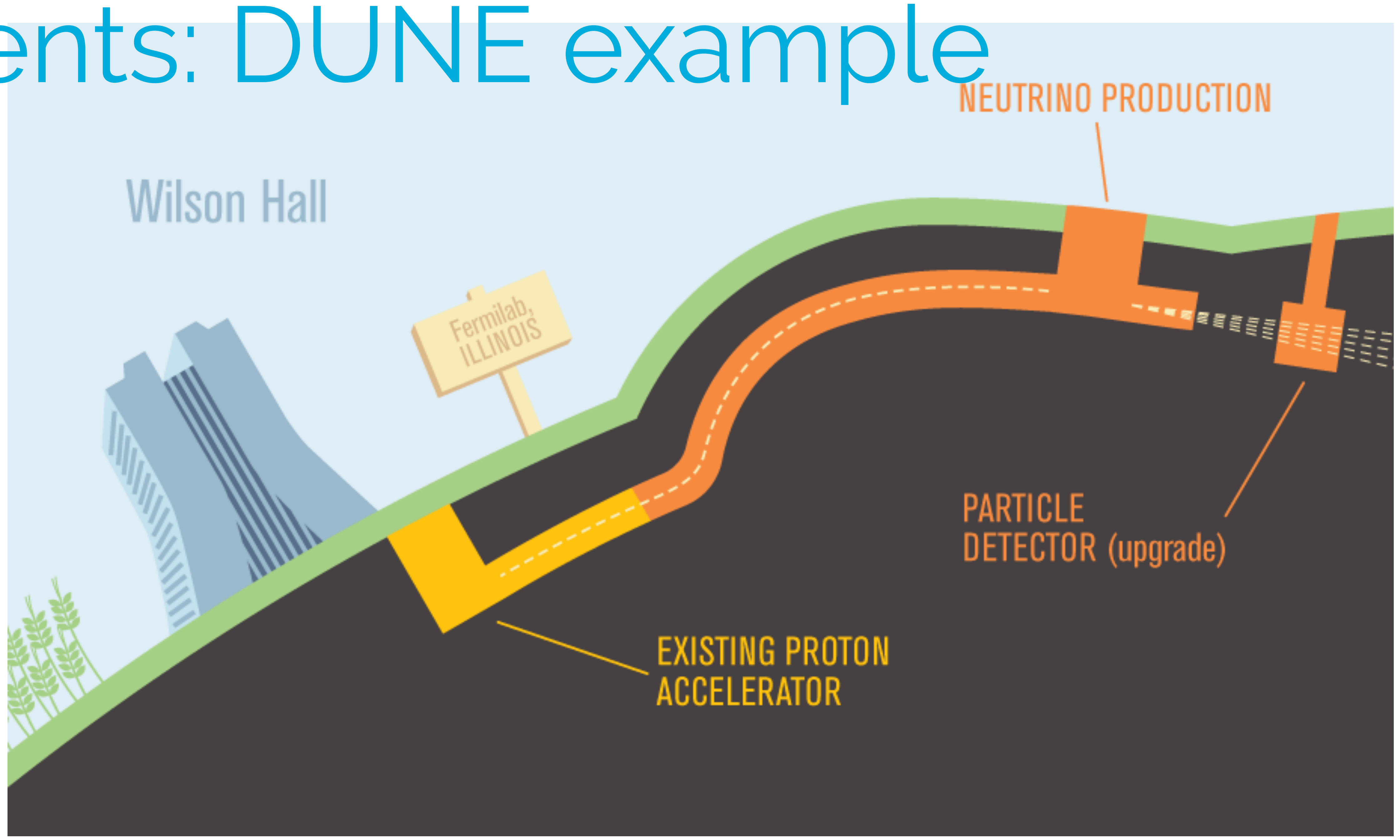
T2K example

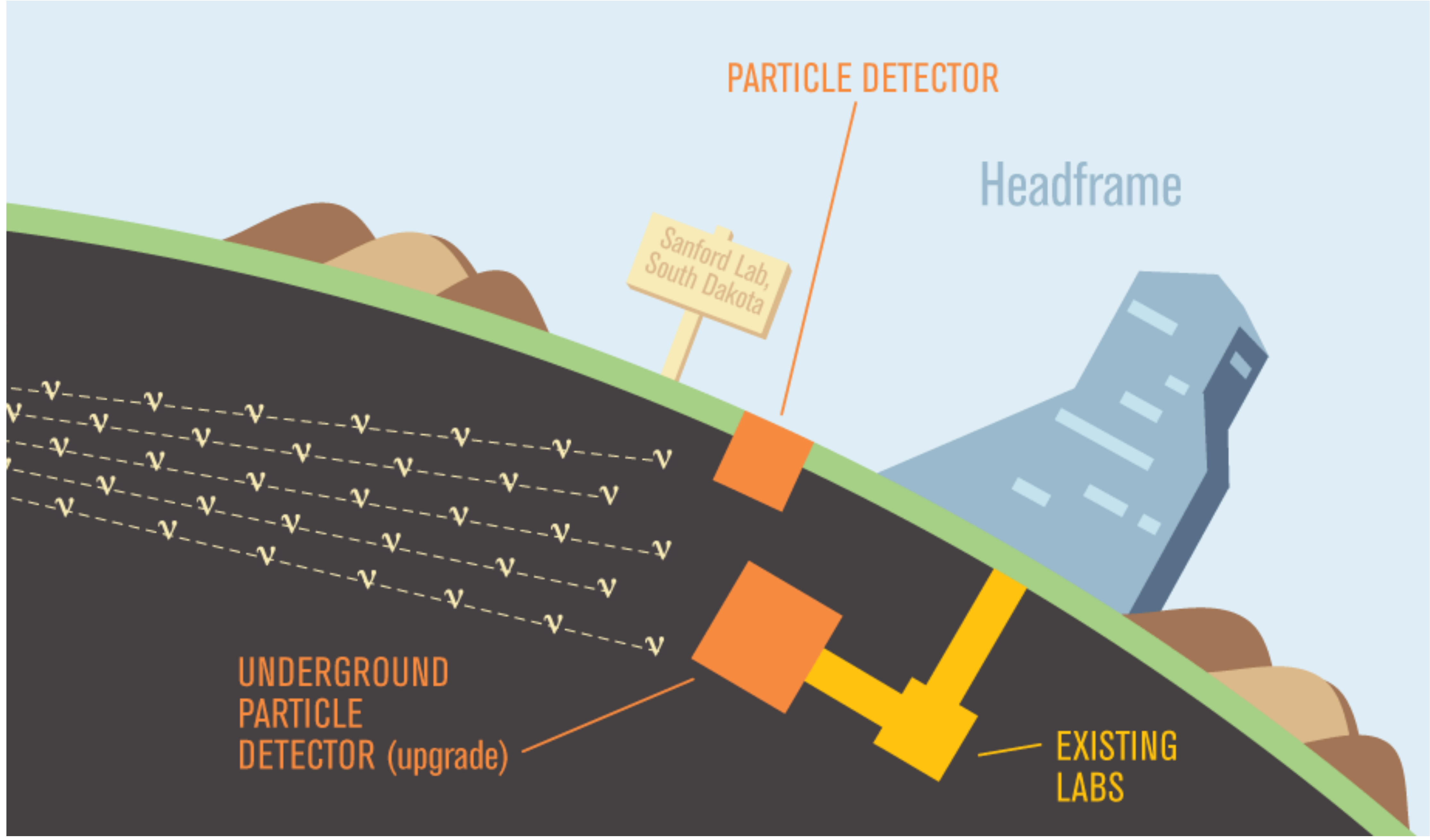


- proton beam hits target, produce pions → pions decay to muons and neutrinos → neutrino travels far in distance
  - measure neutrinos in near detector for systematics control
  - measure neutrinos in far detector to measure *oscillated* neutrinos
- switching polarity of horn current will change neutrino to antineutrino beam
- usually put detectors in "off-axis" to get narrower neutrino energy spectrum

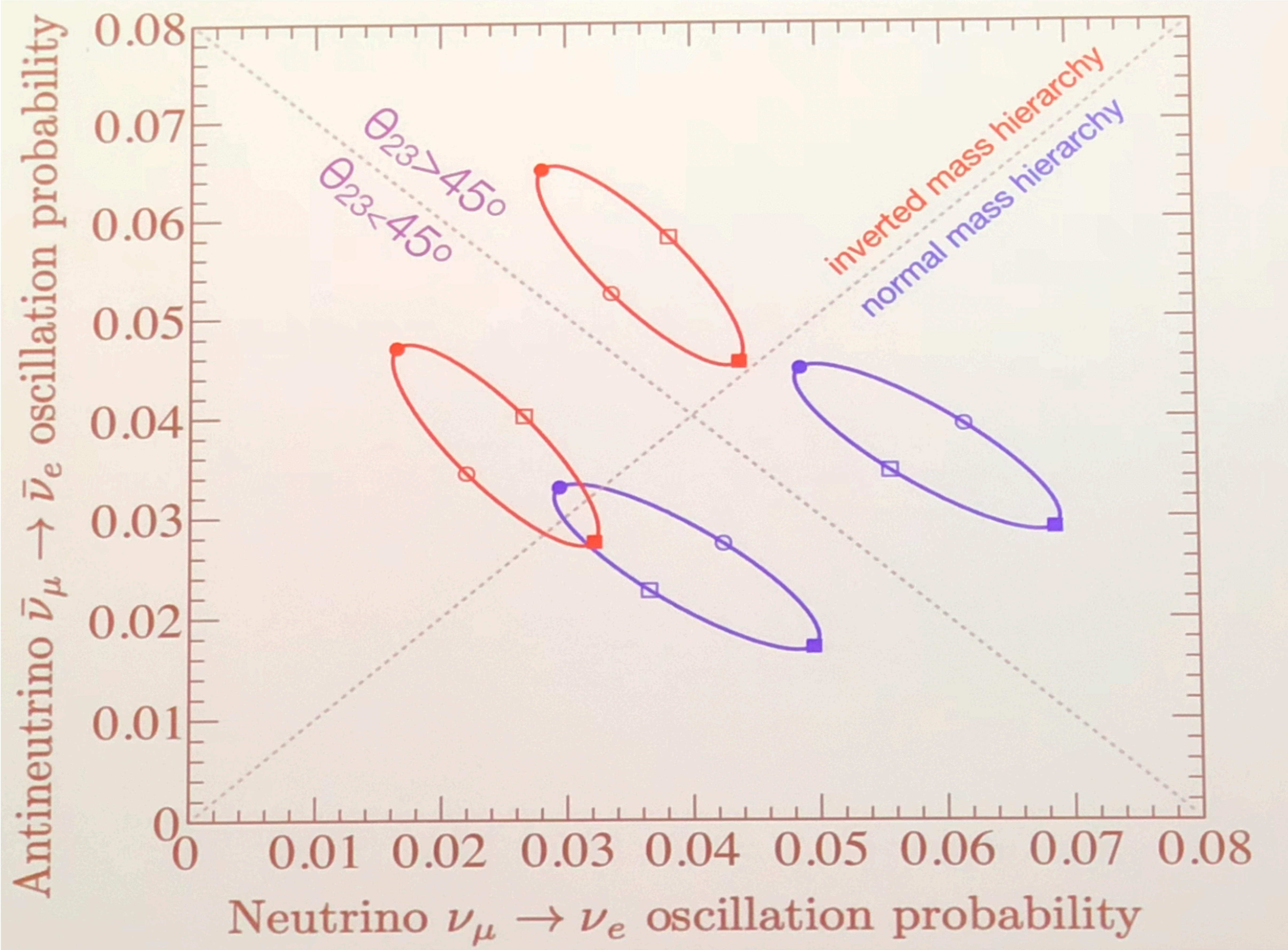
Long-baseline neutrino experiments: DUNE example







Long-baseline neutrino experiments: What can we measure with this?



credit: Mark Messier
from NOvA's example

- with right experimental setting (baseline L, neutrino energy E) and already-measured parameters
- one can measure deltaCP, mass ordering, theta23 octant
- but uncertainty needs to be small enough…

Long-baseline neutrino experiments: What can we measure with this?

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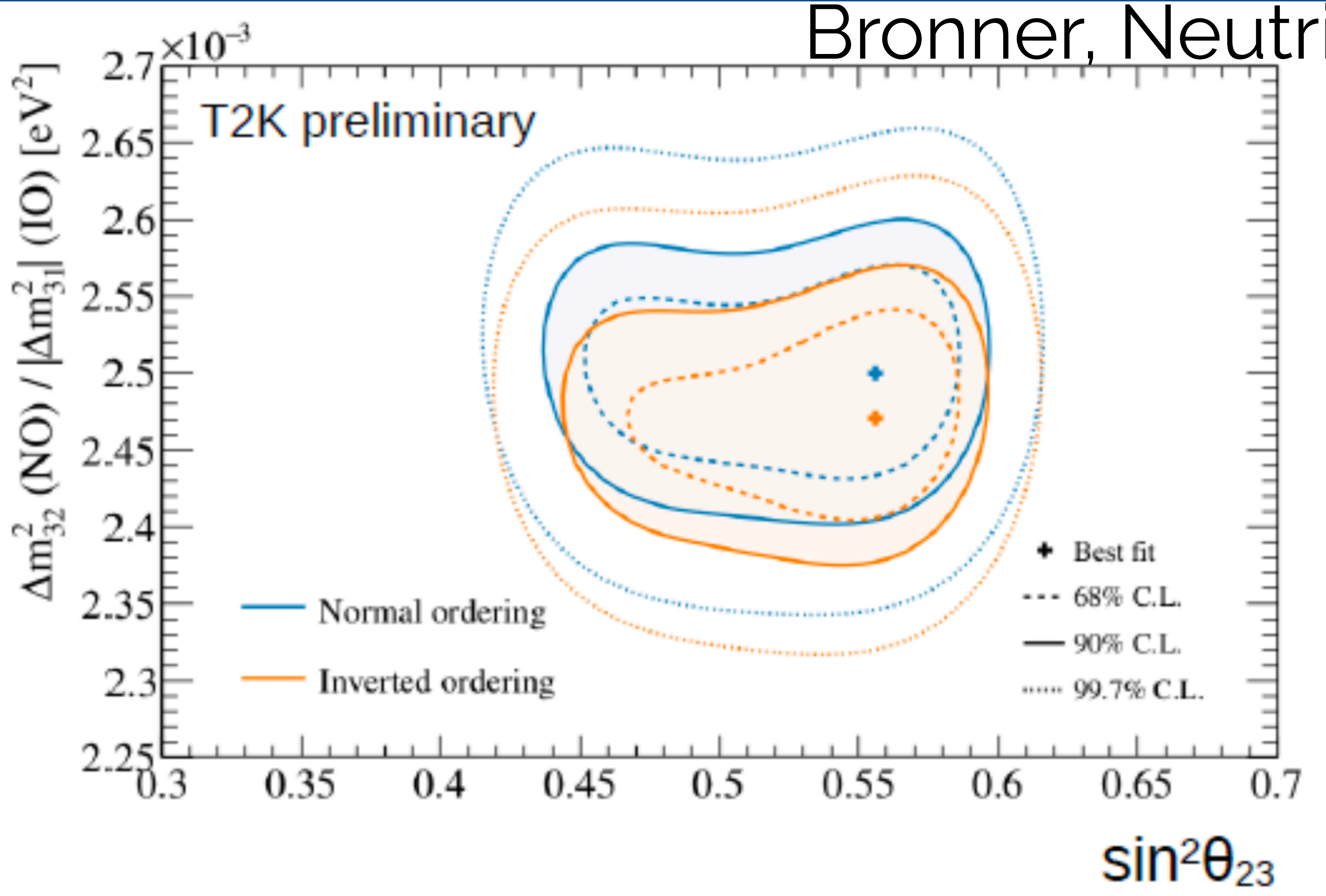
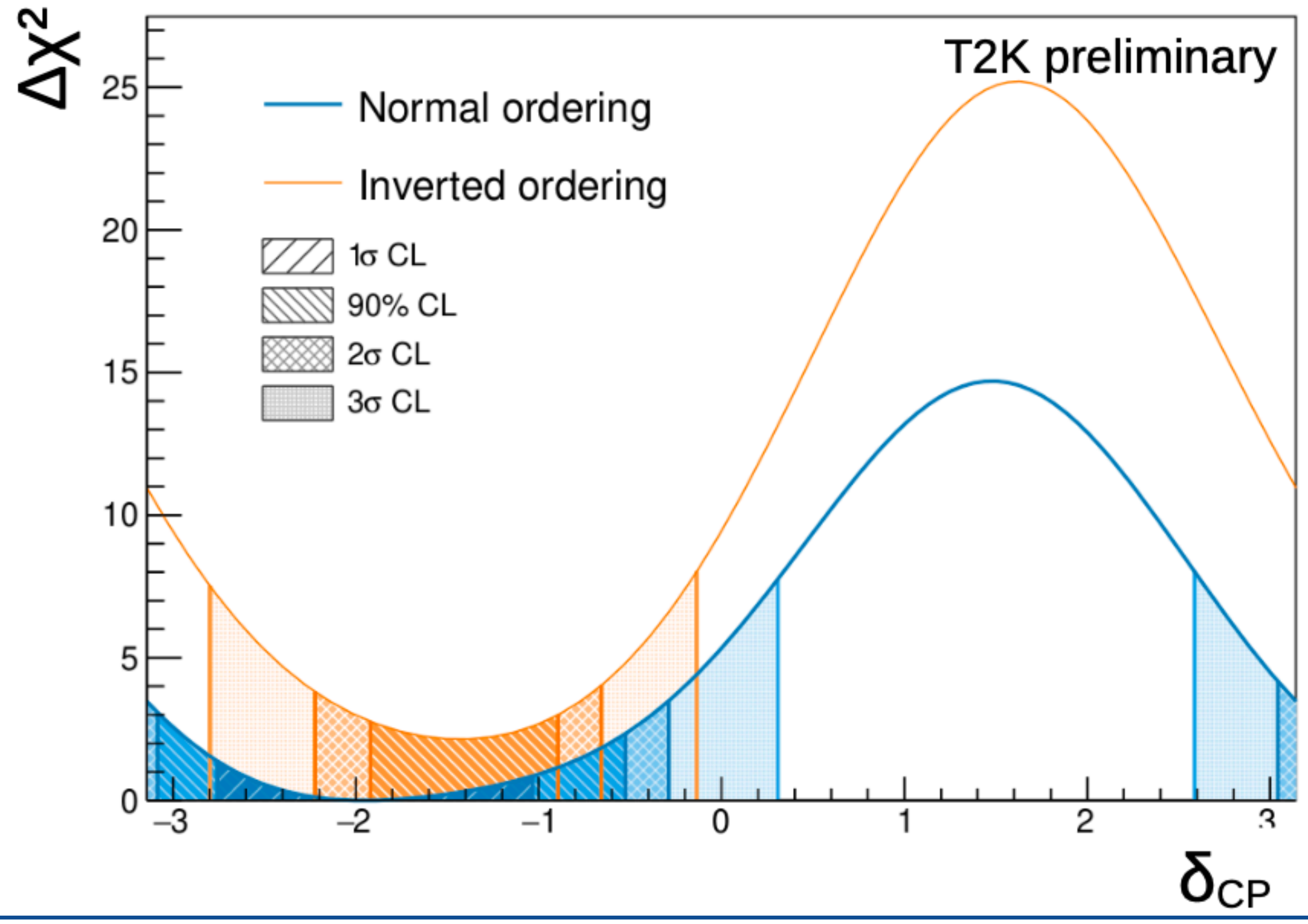
Patterson, Annu. Rev. Nucl. Part. Sci. 2015. 65:117-92

Long-baseline neutrino experiments: Recent results

- **T2K experiment**
  - Tokai-2-Kamioka
  - 295km baseline, neutrino energy peak at ~0.6 GeV
  - more sensitive to deltaCP, but not as much to mass hierarchy (compared to NOvA)
- best fit in the upper octant, but lower octant still allowed at the 68% CL
- mild preference for normal ordering
- CP-conserving values of delta=0/pi outside 90% CL

Bronner, Neutrino2022

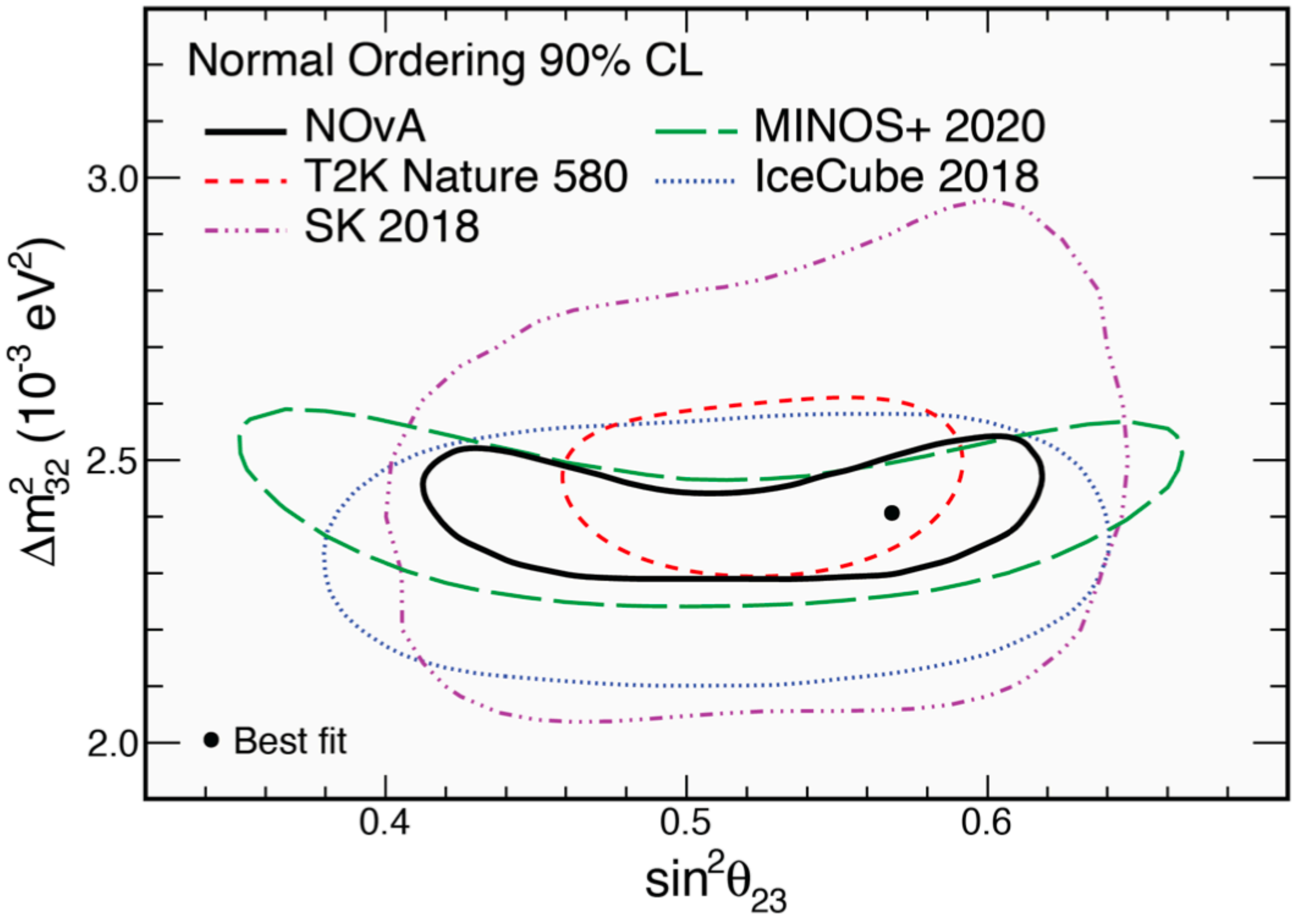


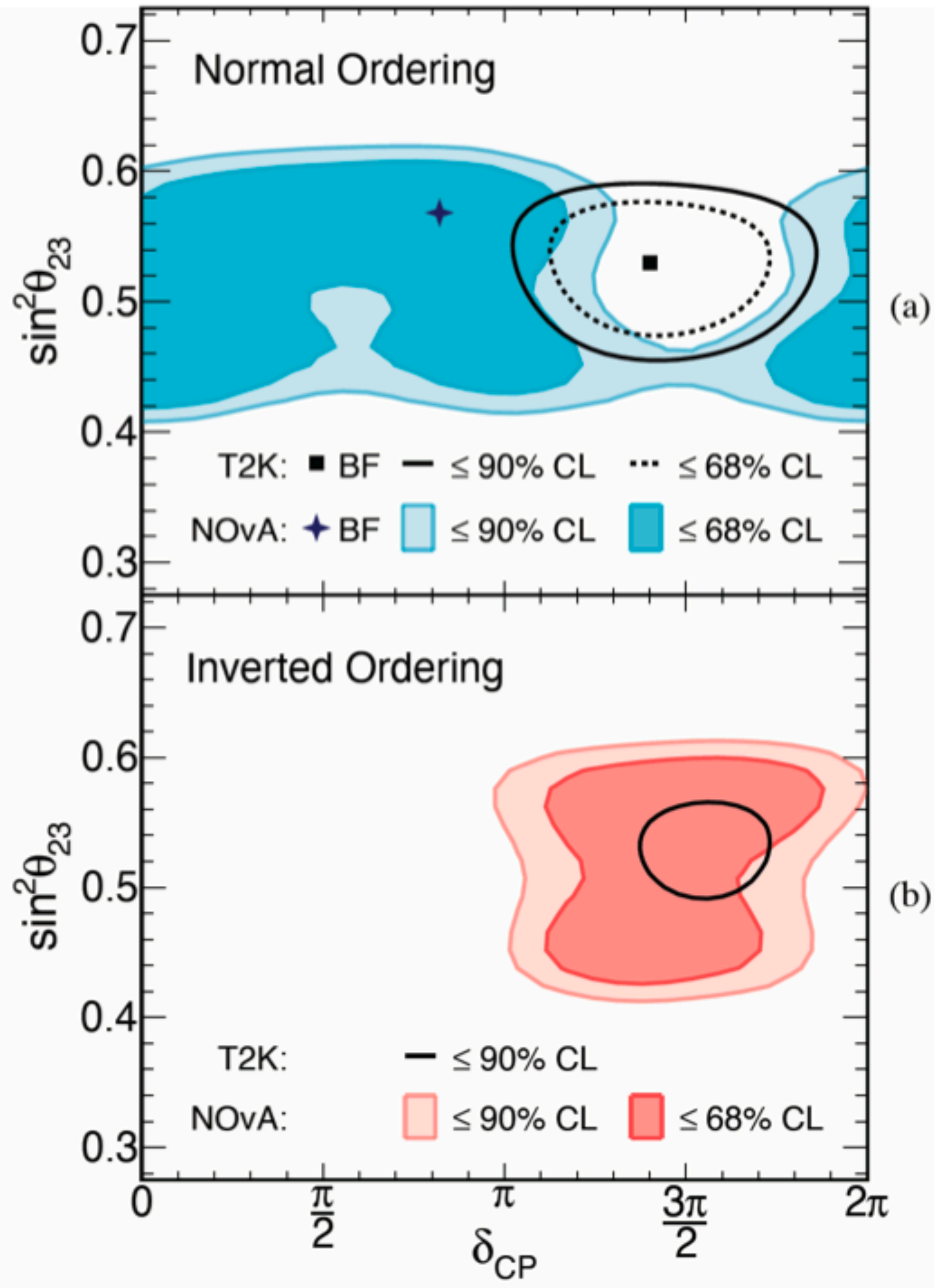


Long-baseline neutrino experiments: Recent results

Hartnell, Neutrino2022

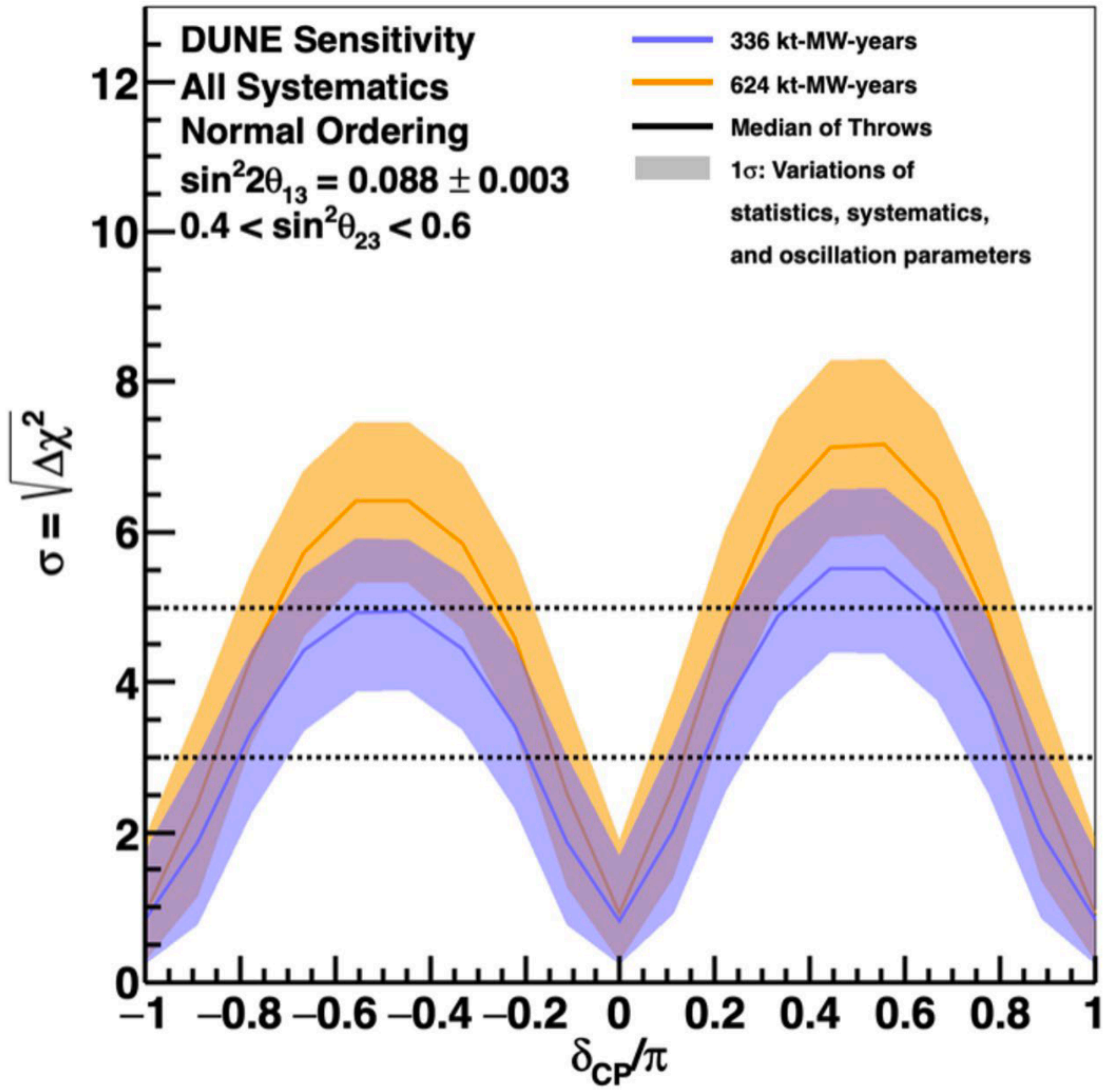
- **NOvA experiment**
  - Fermilab to Ash River, MN
  - 810km baseline, neutrino energy peak at ~2GeV
  - more sensitive to mass hierarchy, but not as much to delta CP (compared to T2K)
- best fit in normal ordering and upper octant
- best fit delta CP in slight tension with T2K





Long-baseline neutrino experiments: Future experiments

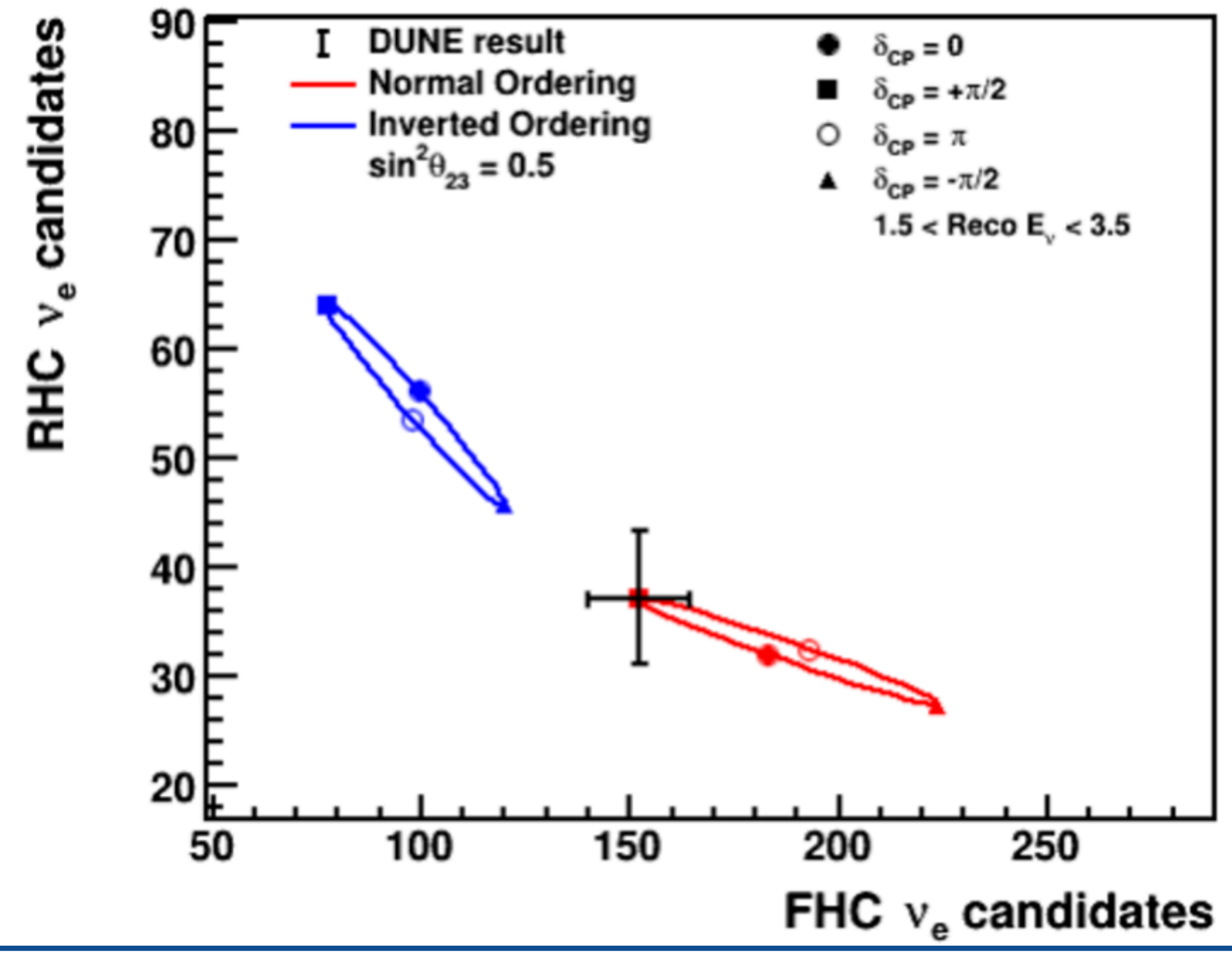
- for definitive measurement of the parameters, one needs more powerful & precise experiments
- **DUNE**
  - baseline 1300km, broad neutrino energy up to 10 GeV
  - new LArTPC technology
  - 2-phase program (20 kton + 20 kton far detector volume)
  - plan to operate in 2029 (phase1)
- **Hyper-Kamiokande**
  - baseline 295 km, nu energy 0.6 GeV
  - conventional water cherenkov technology
  - 260 kton far detector volume
  - plan to operate in 2027



Muether, Neutrino2022

DUNE 10 years:
5σ discovery potential
for CP violation over >50% of
δ_{CP} values

4 years with 20 kt



4 years of running
with even conservative
configuration provides
clear discovery potential

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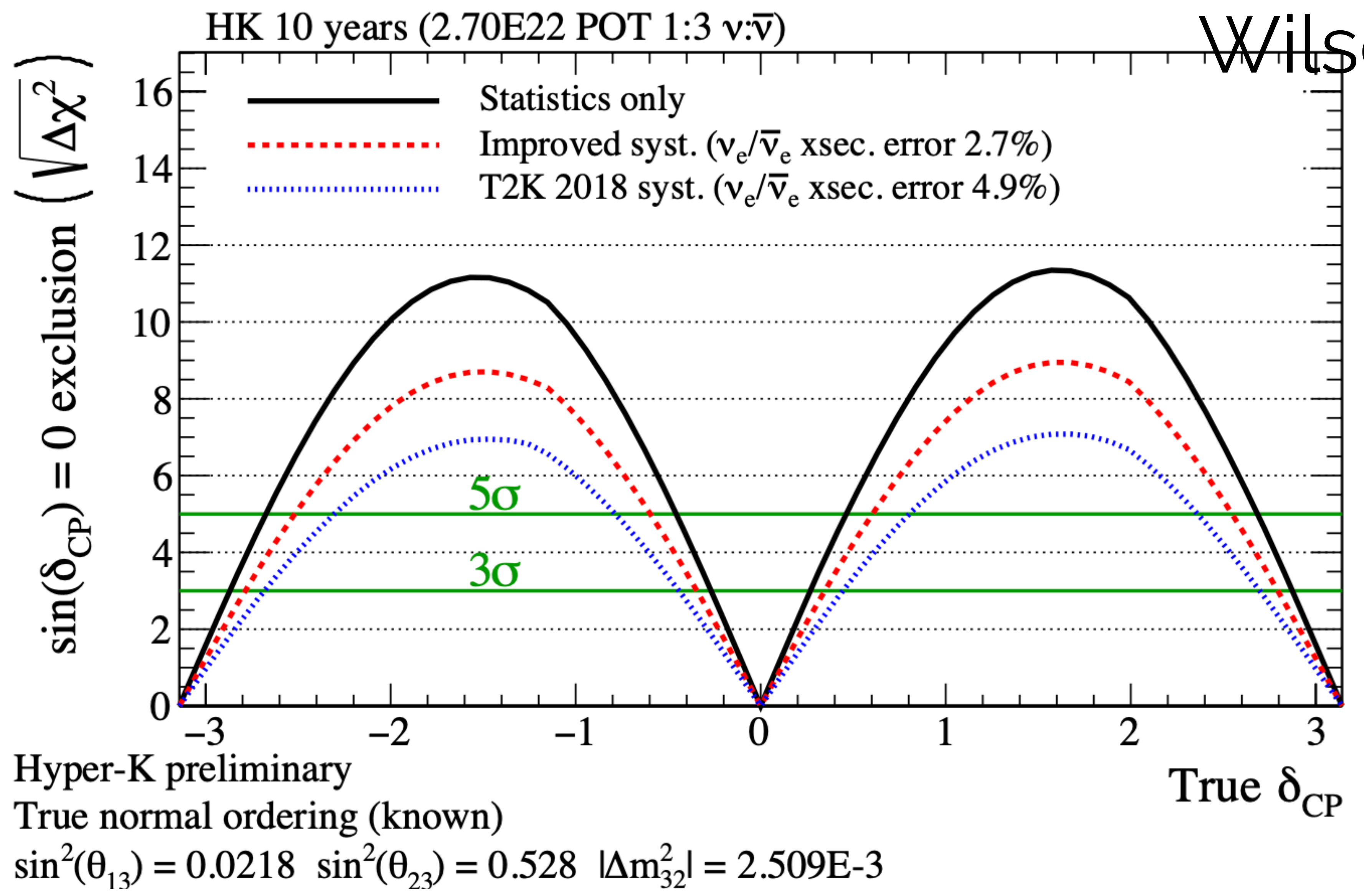
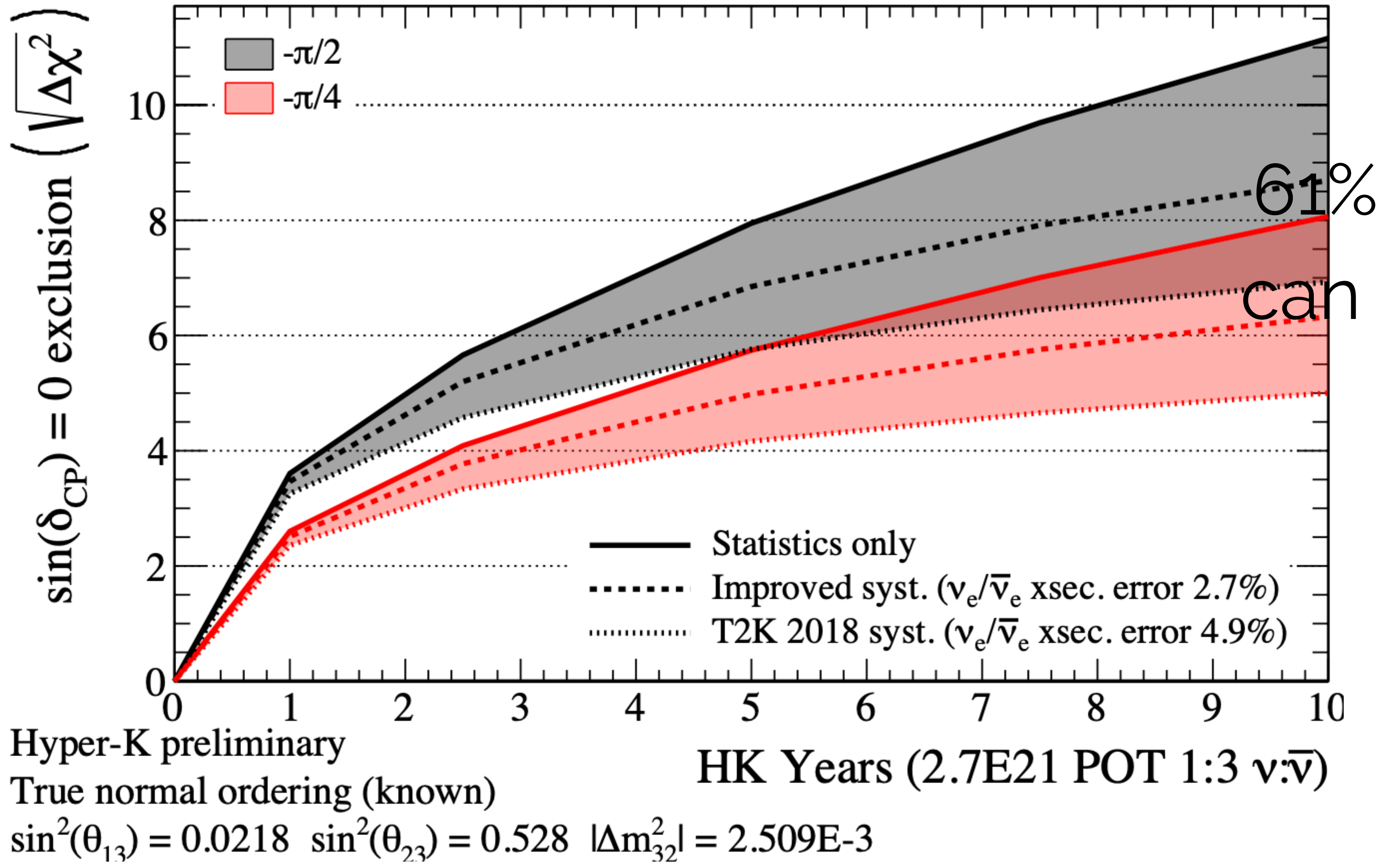
Wilson, Neutrino2022





10 HK-years:
61% of true δ_{CP} values can be excluded at 5σ

Remaining questions in ν physics

standard model

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what is the **ordering of the neutrino mass**?

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is the neutrino its own anti particle?

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Short-baseline neutrino experiment

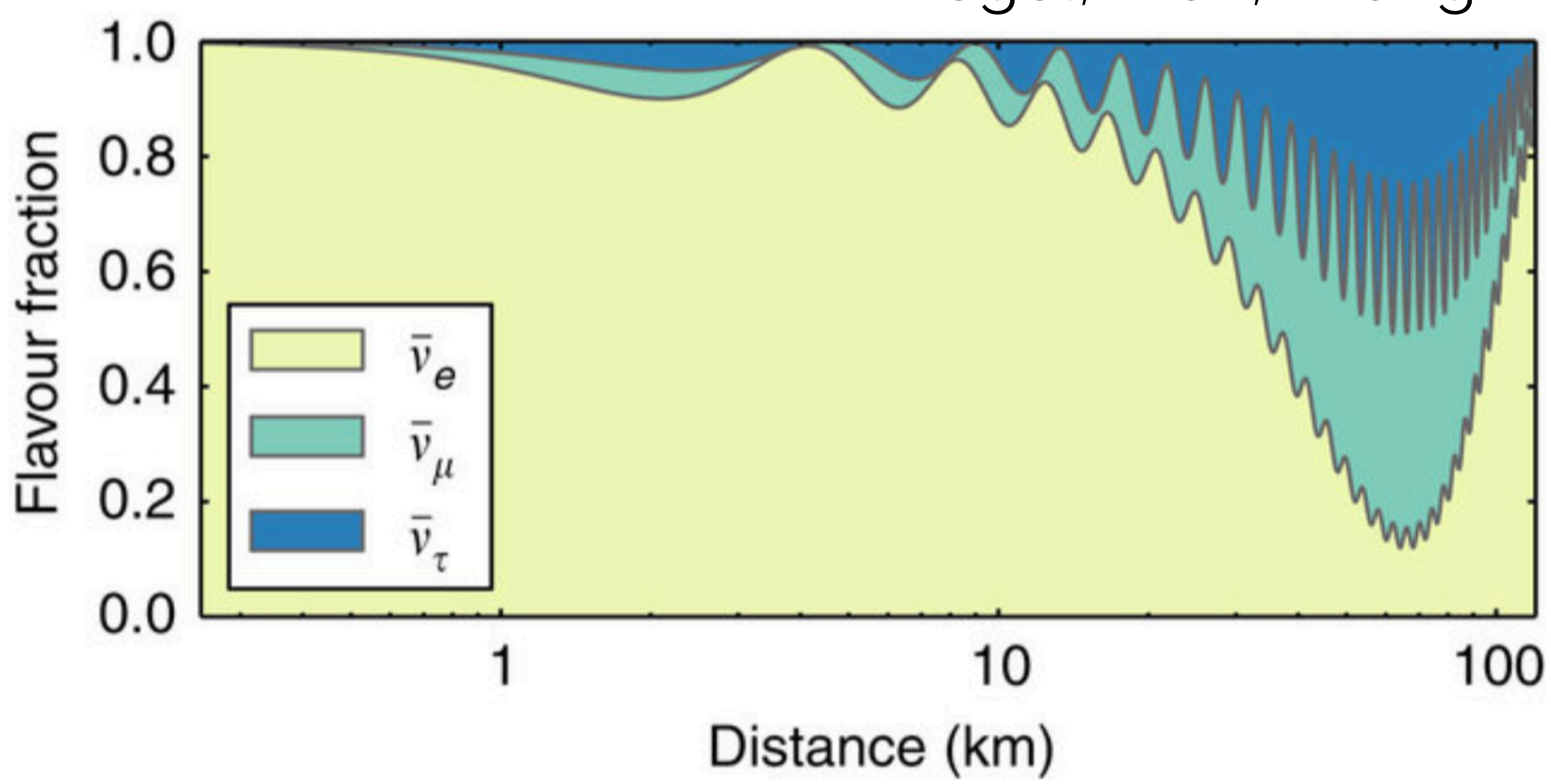
Short-baseline neutrino experiments: general principle

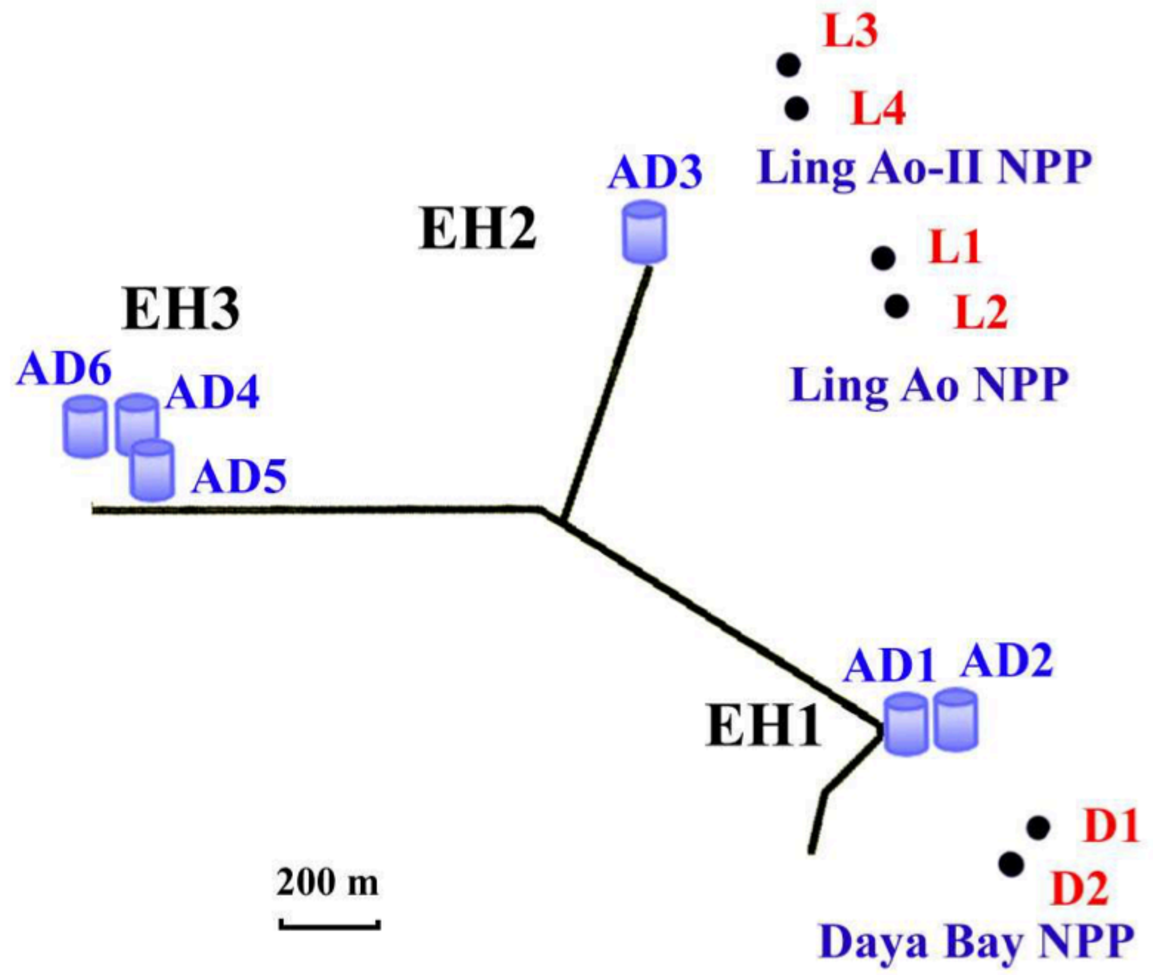
- naively speaking, the shorter the travel distance, the lesser neutrinos oscillate

- but one can still measure the oscillation, with big advantage: huge neutrino flux/statistics

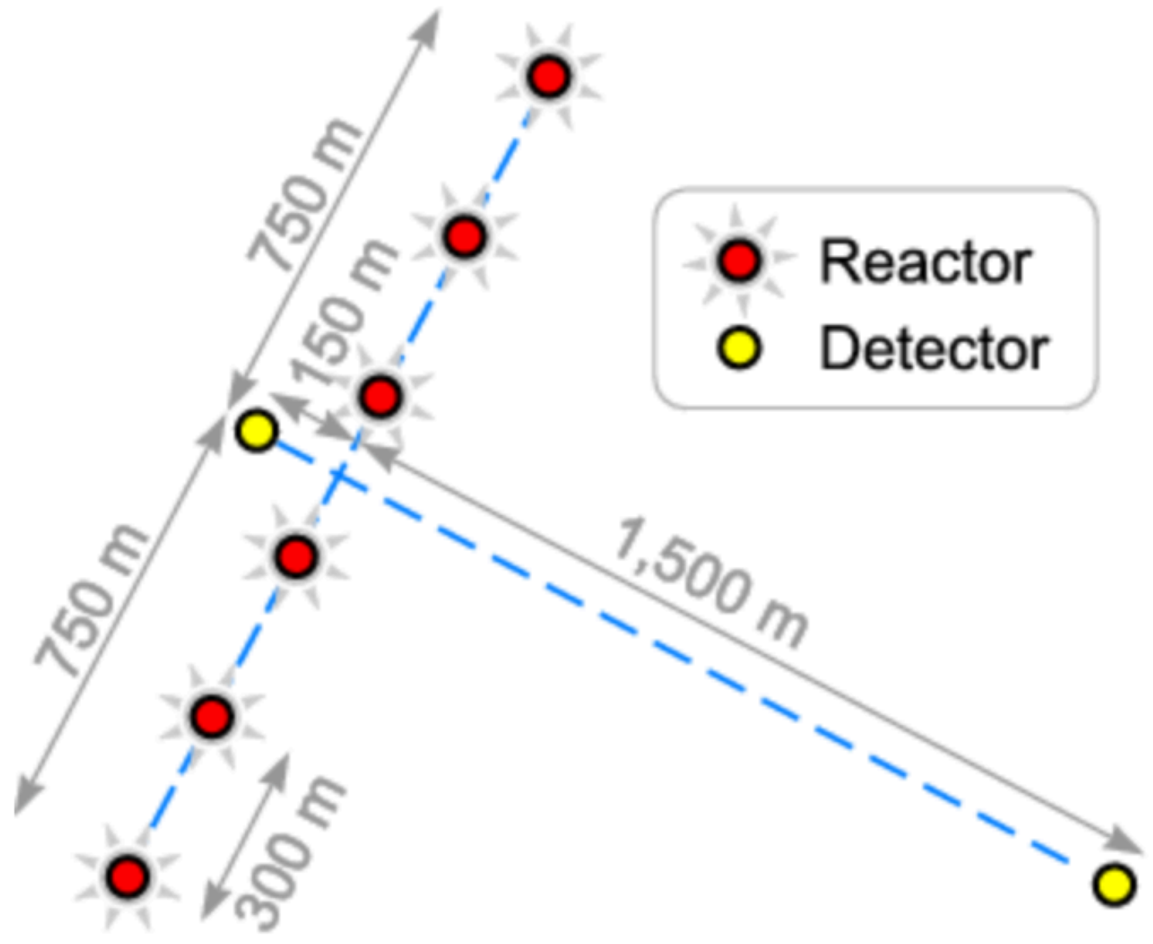
- (anti) neutrinos are generated either from accelerators or nuclear reactors

Vogel, Wen, Zhang





Daya Bay experiment



RENO experiment

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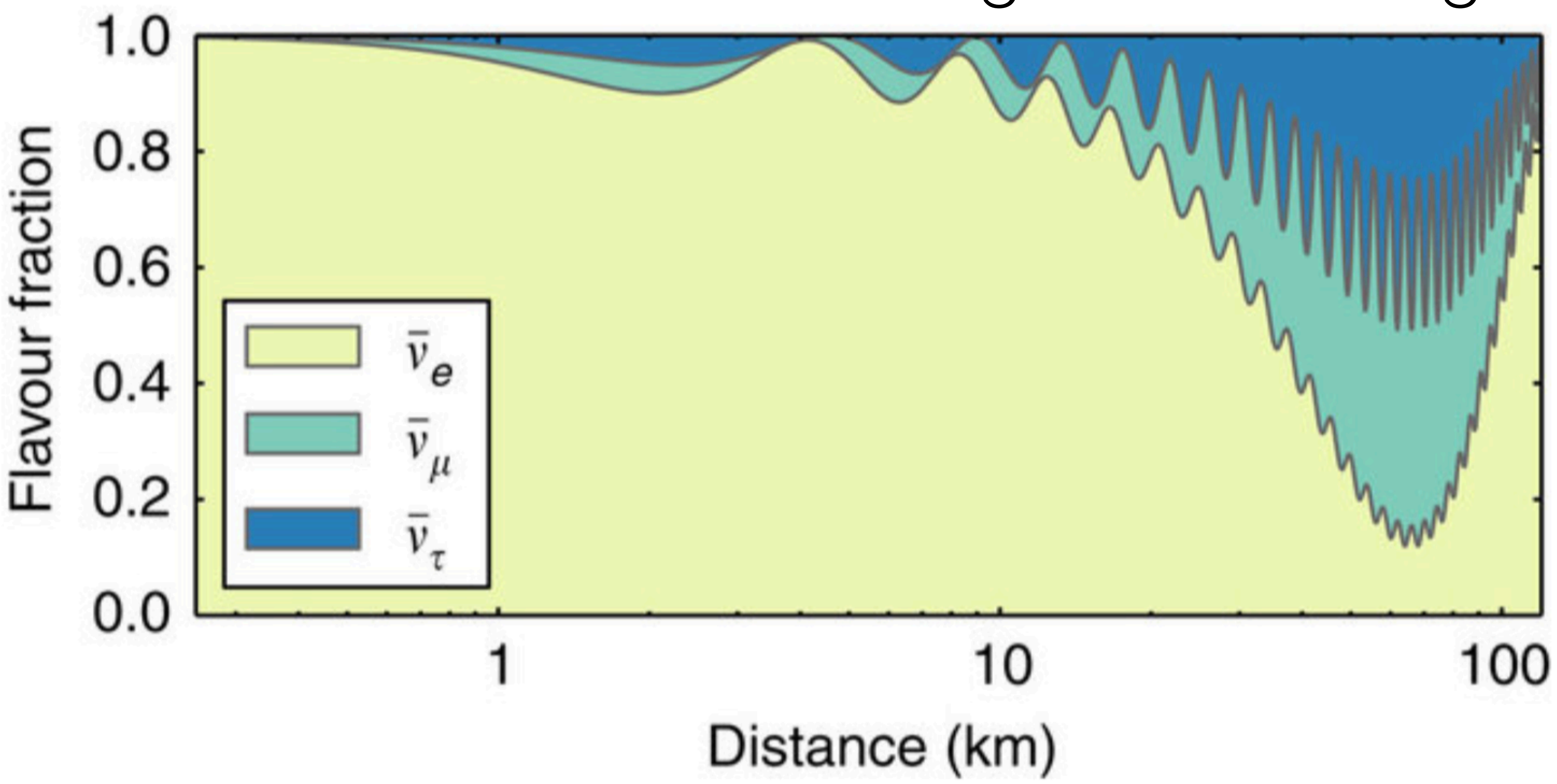
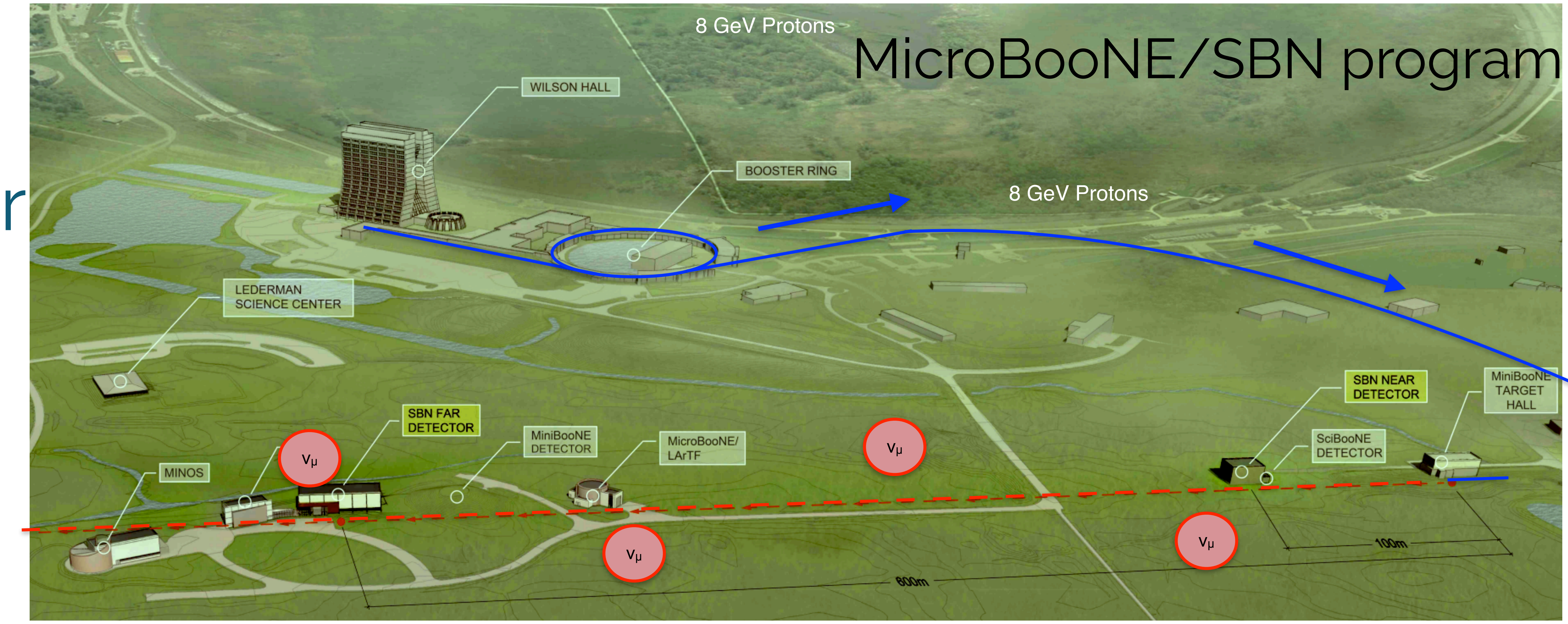


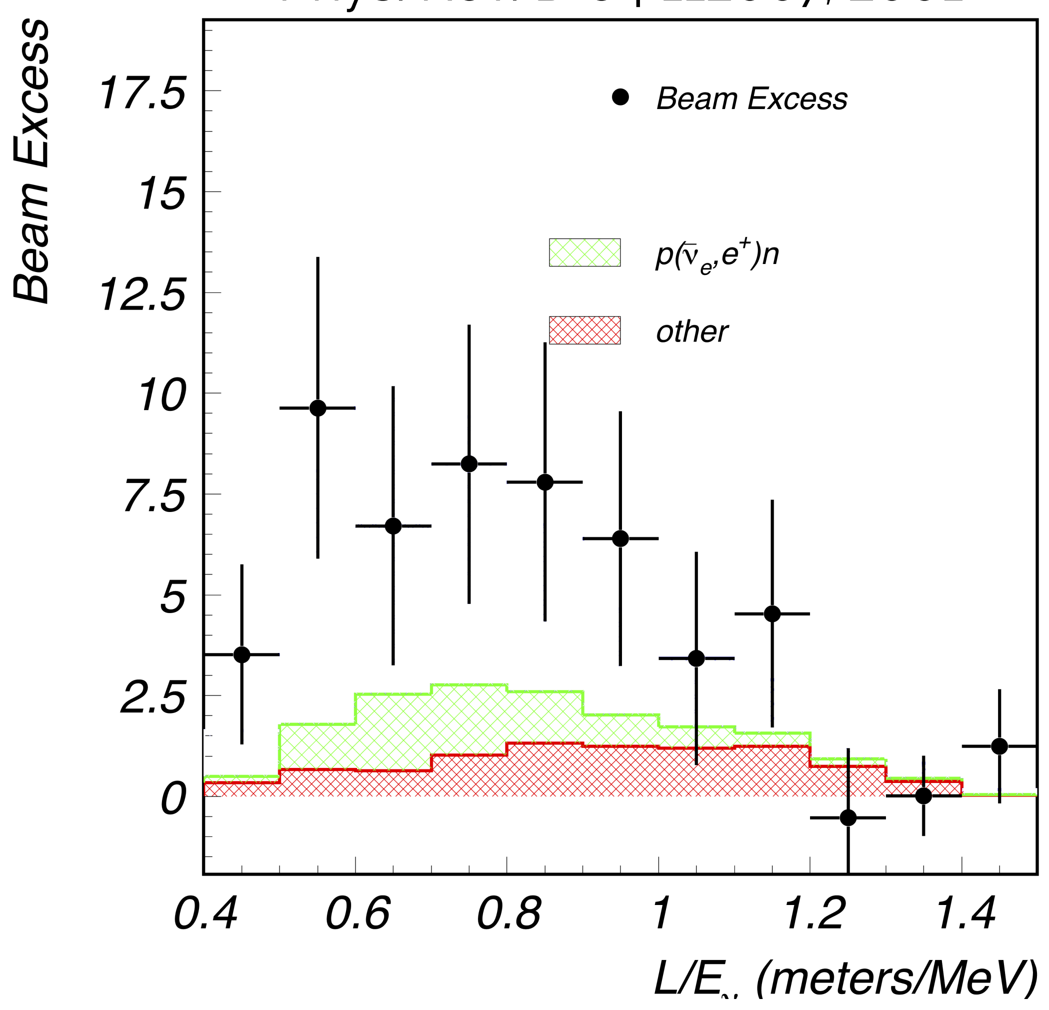


MicroBooNE/SBN program

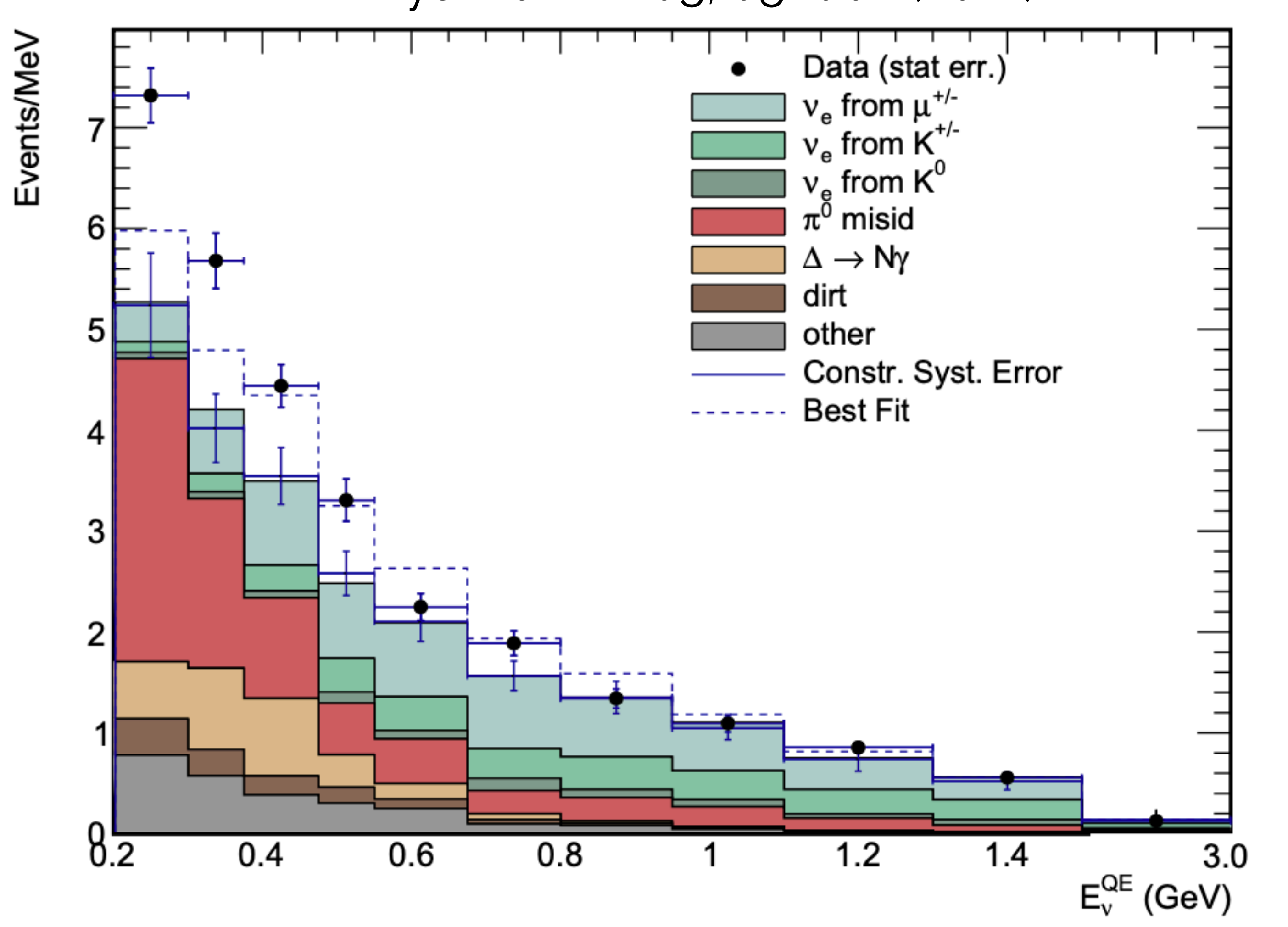
Short-baseline neutrino experiments: anomalies

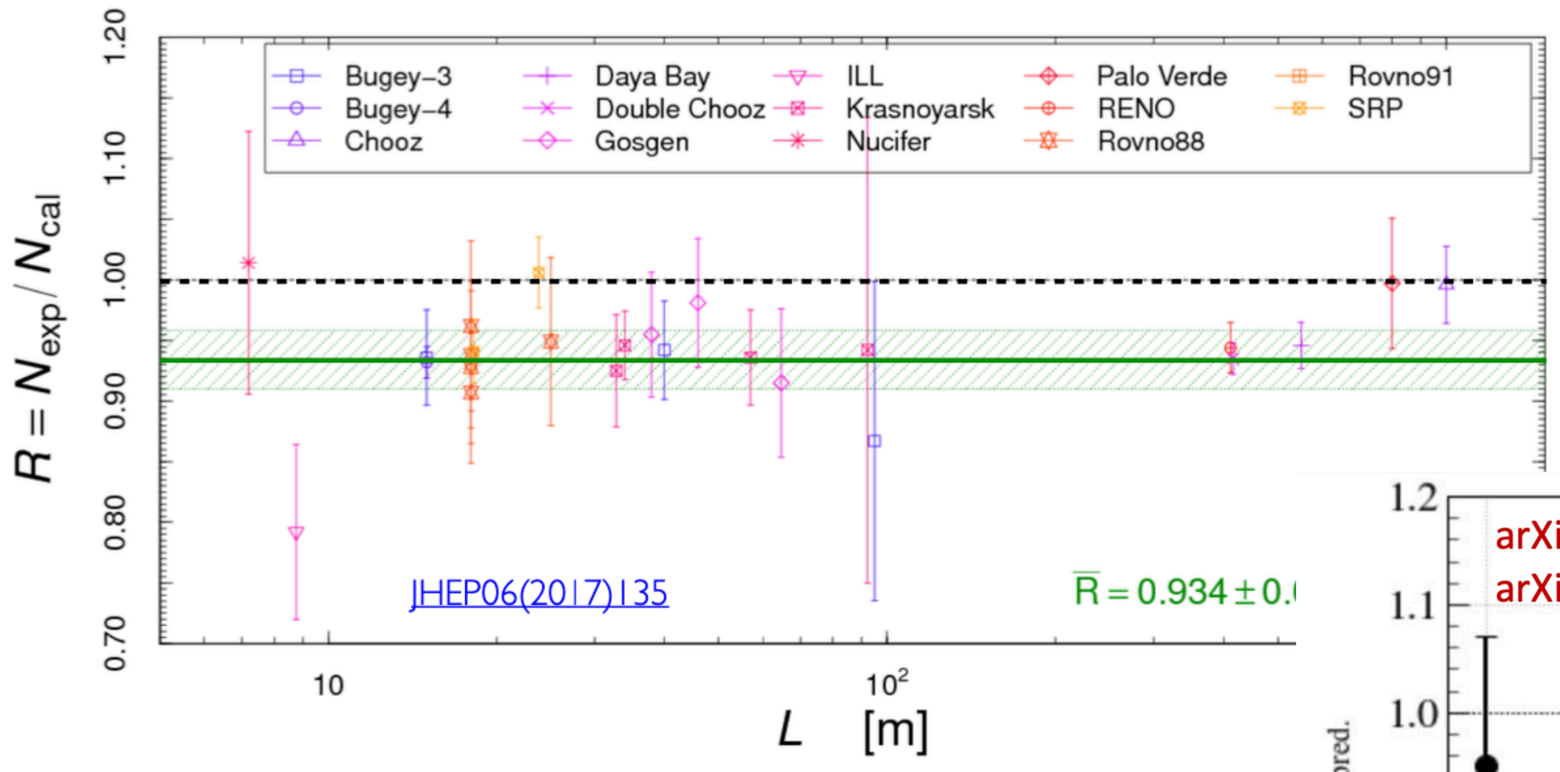
- series of anomalous results seen at short-baseline using a variety of neutrino sources
  - LSND ν_e excess
  - MiniBooNE $\nu_e/\overline{\nu}_e$ excess
  - GALLEX/SAGE/BEST ν_e deficit (Gallium Anomaly)
  - reactor $\overline{\nu}_e$ deficit (Reactor Antineutrino Anomaly)
- taken individually, each anomaly is not significant enough to be convincing: but they all seem to be pointing toward the same thing…
- most commonly interpreted as hint for one or more new "**sterile**" neutrino (oscillates but does not interact weakly) at large Δm^2_{new} (~1eV²) and small mixing

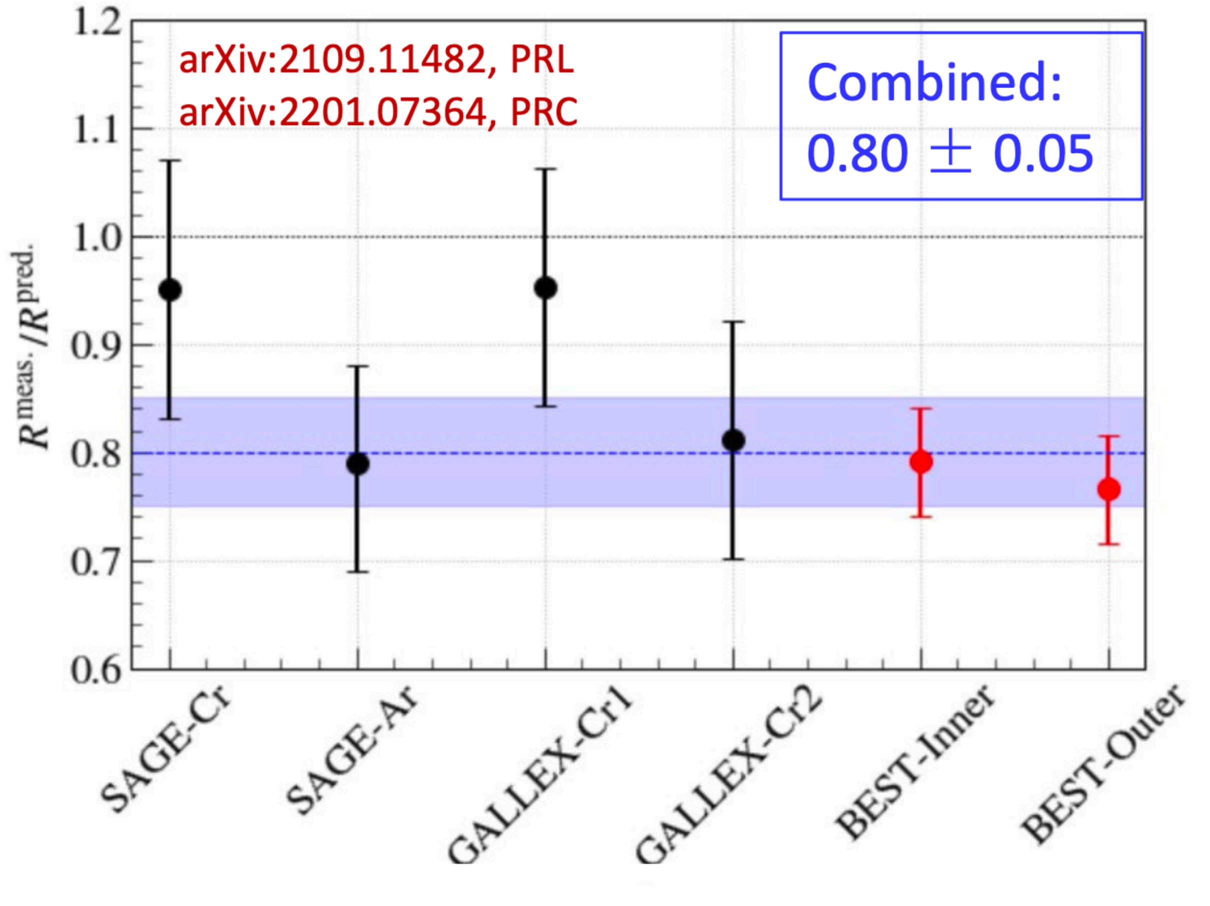
Phys. Rev. D 64 112007, 2001



Phys. Rev. D 103, 052002 (2021)







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K. N. Abazajian et al. arxiv:1204.5379

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

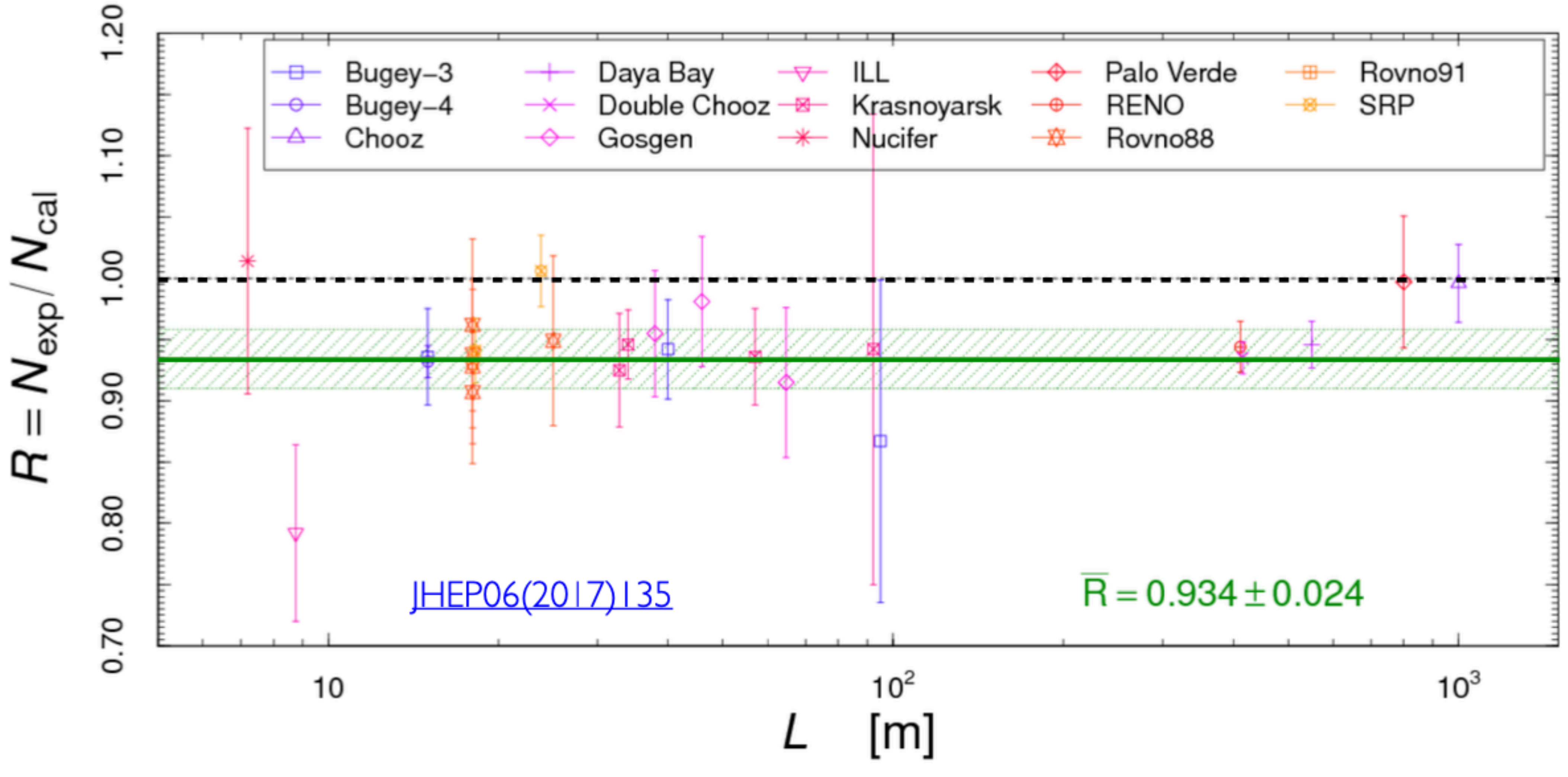
Short-baseline neutrino experiments: reactor-based

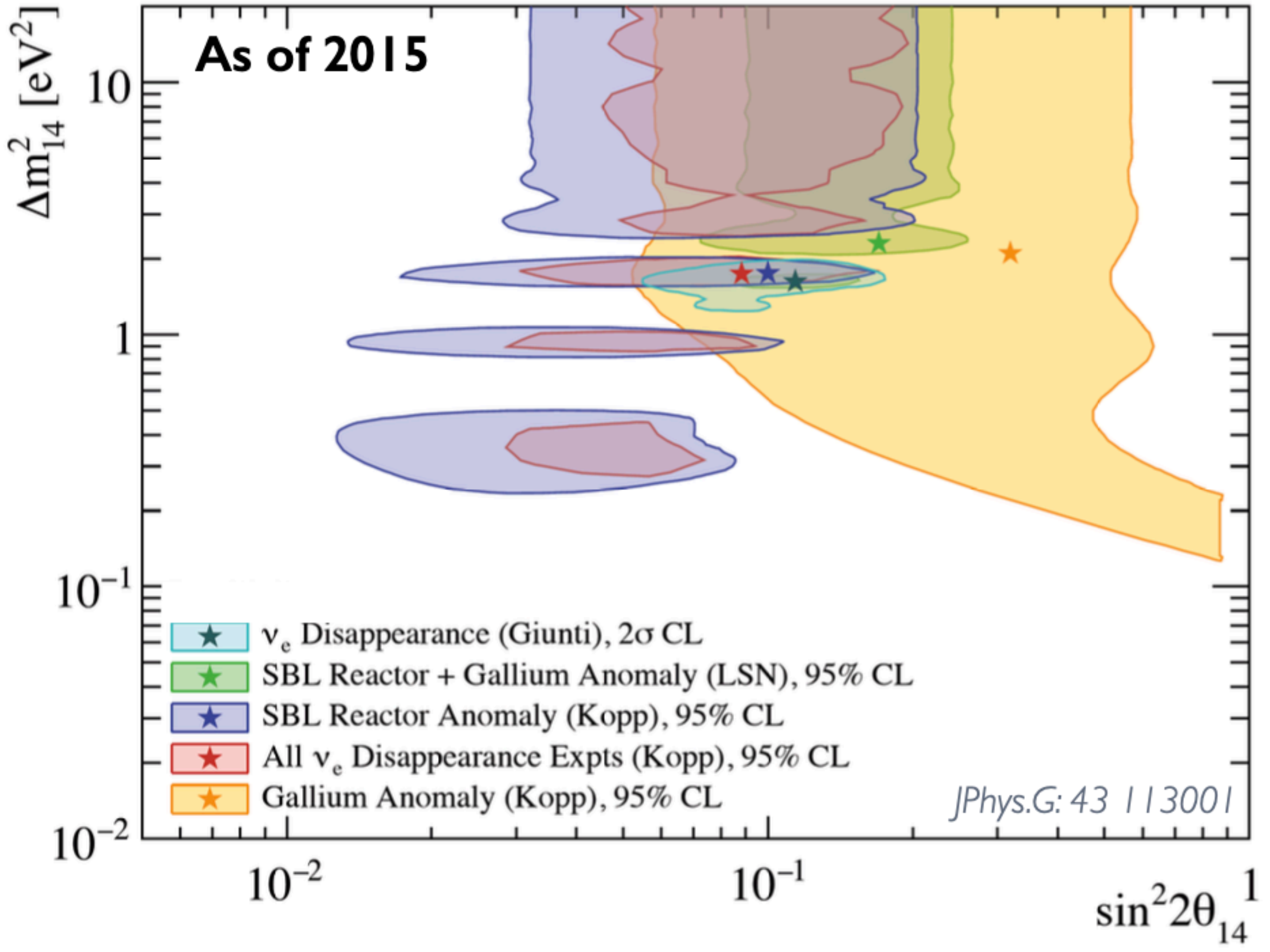
- reactor antineutrino anomaly (RAA): measured data show ~6% deficit w.r.t. updated reactor models

- it could be explained by eV-scale sterile neutrinos

- recent Daya Bay study shows that 235U mismodeling seem to be the source of RAA

- but reactor mismodeling and sterile neutrinos not mutually exclusive, yet





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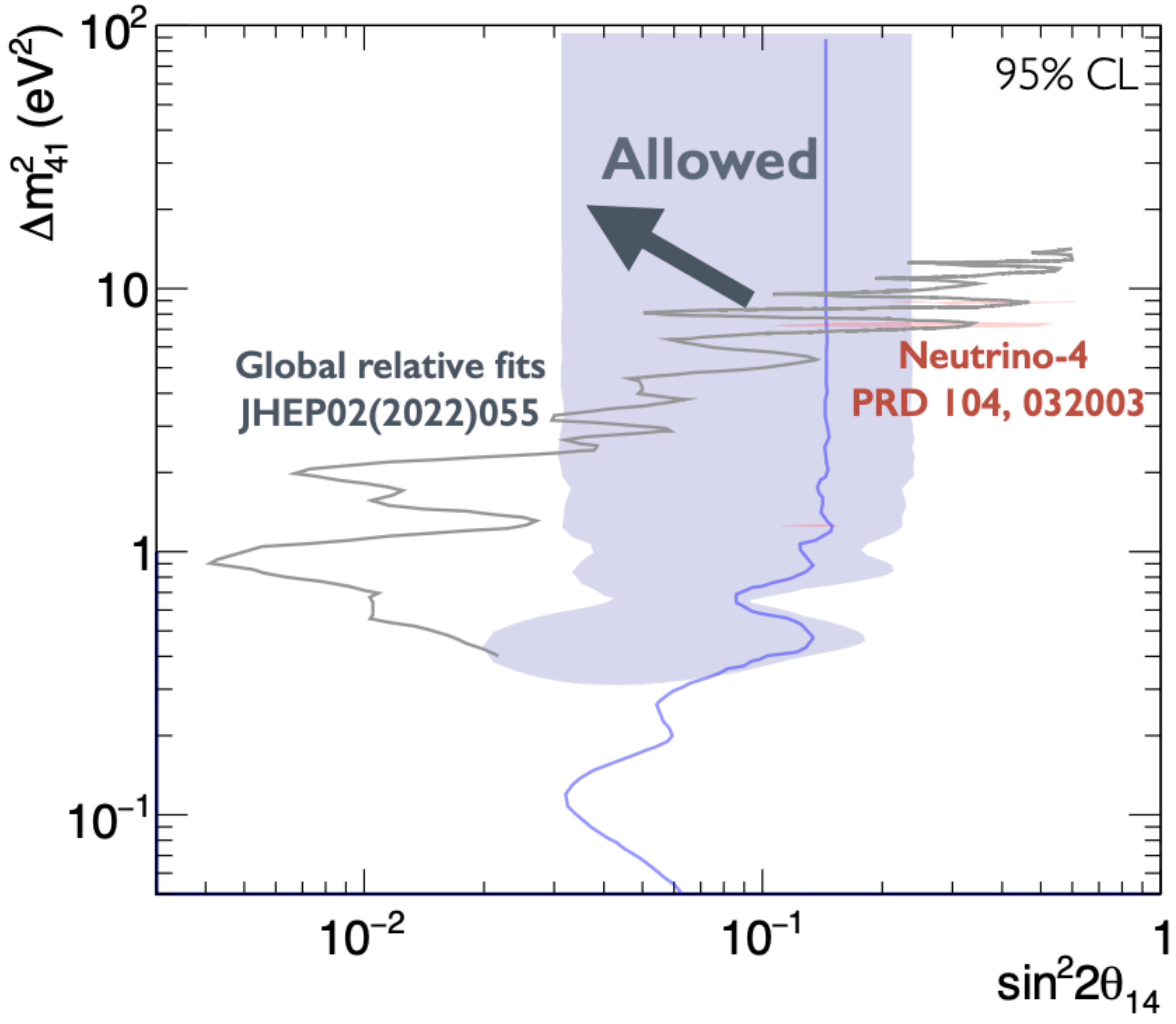

Short-baseline neutrino experiments: accelerator-based

- LSND & MiniBooNE (MB) anomaly recap: (anti) electron neutrino excess observed
- it could (again) be explained by eV-scale sterile neutrinos
- recent MicroBooNE result showed the MB excess is not from electron neutrinos
- but it still does not exclude entire sterile neutrino allowed phase space

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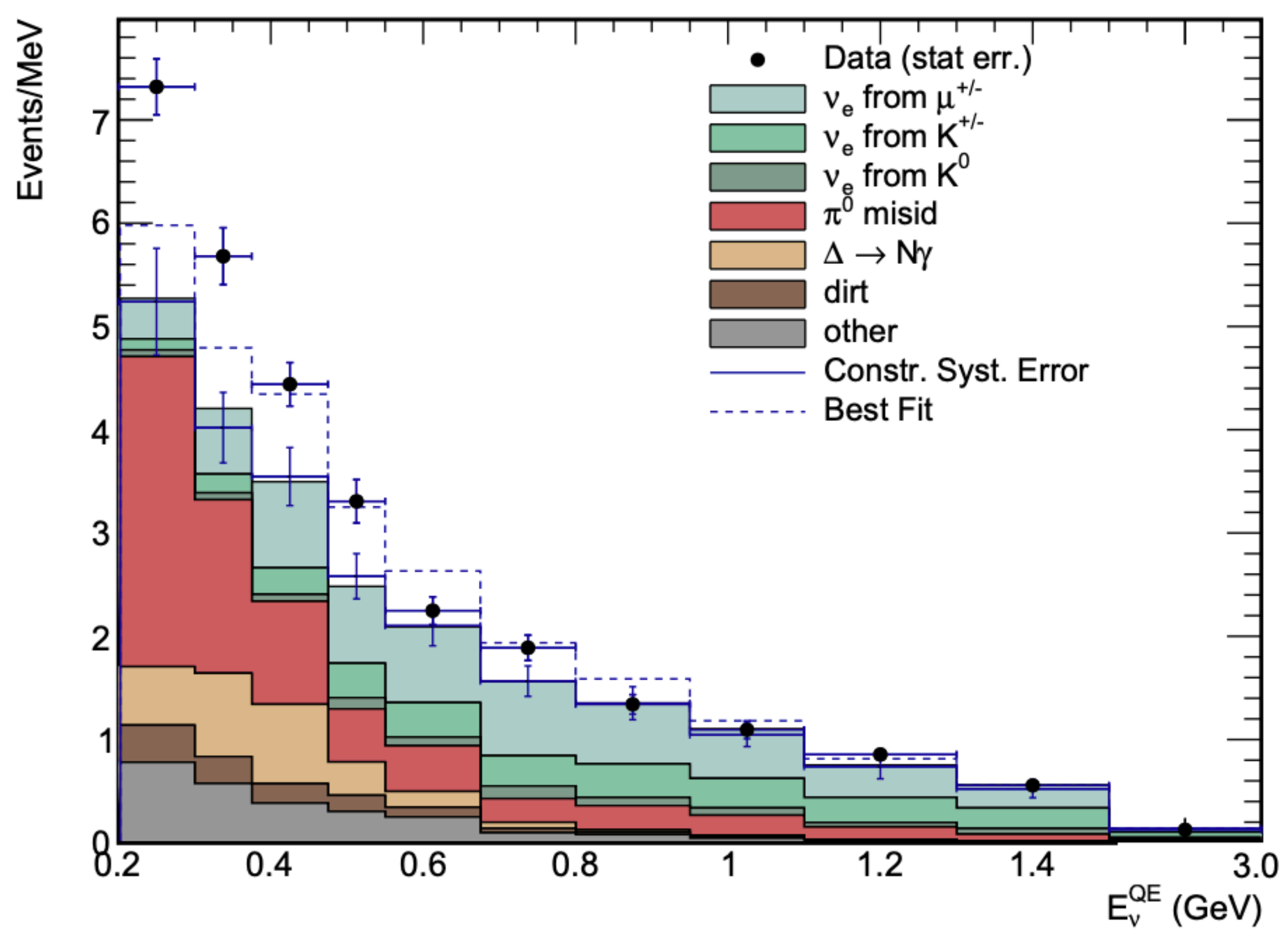
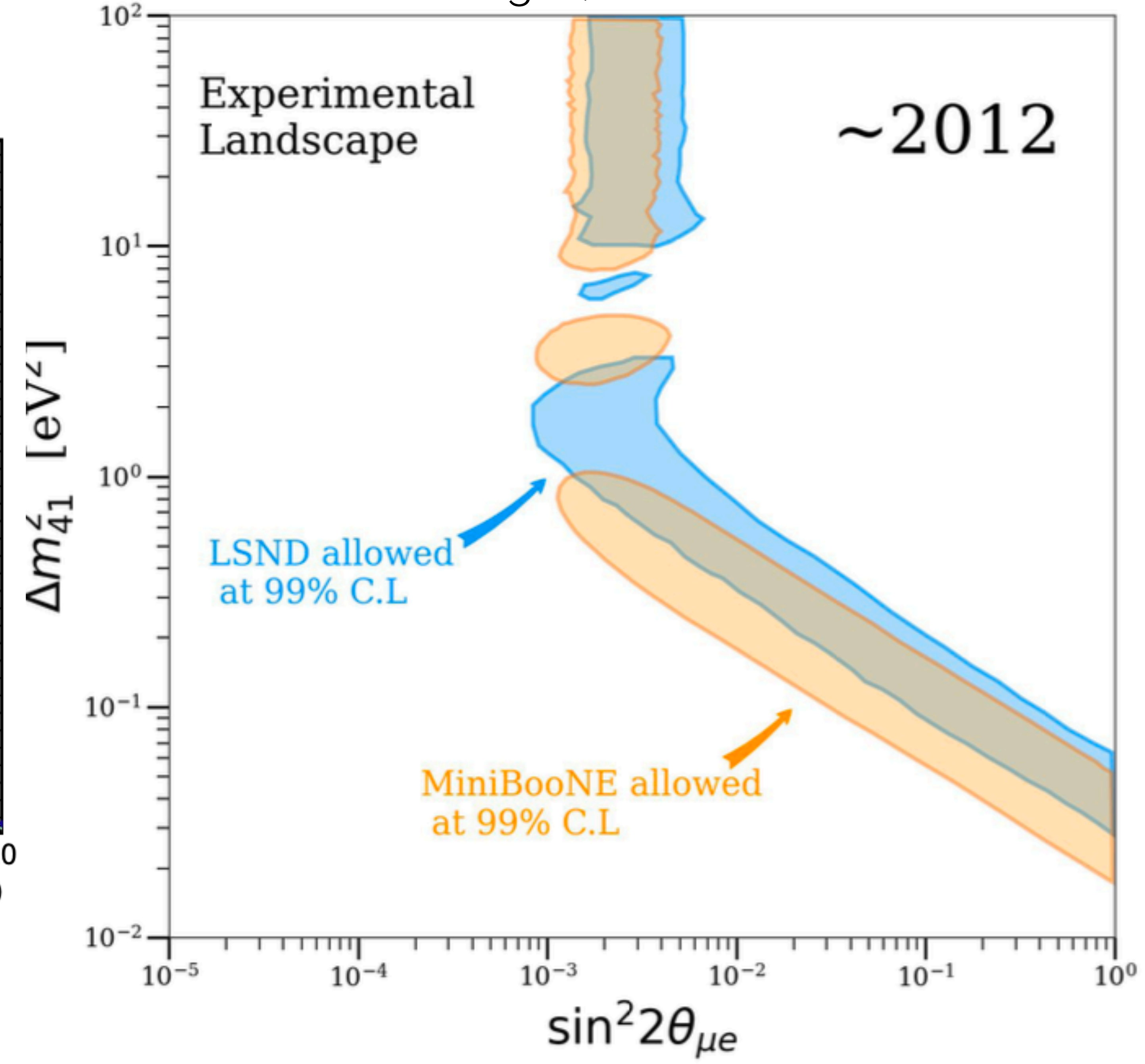
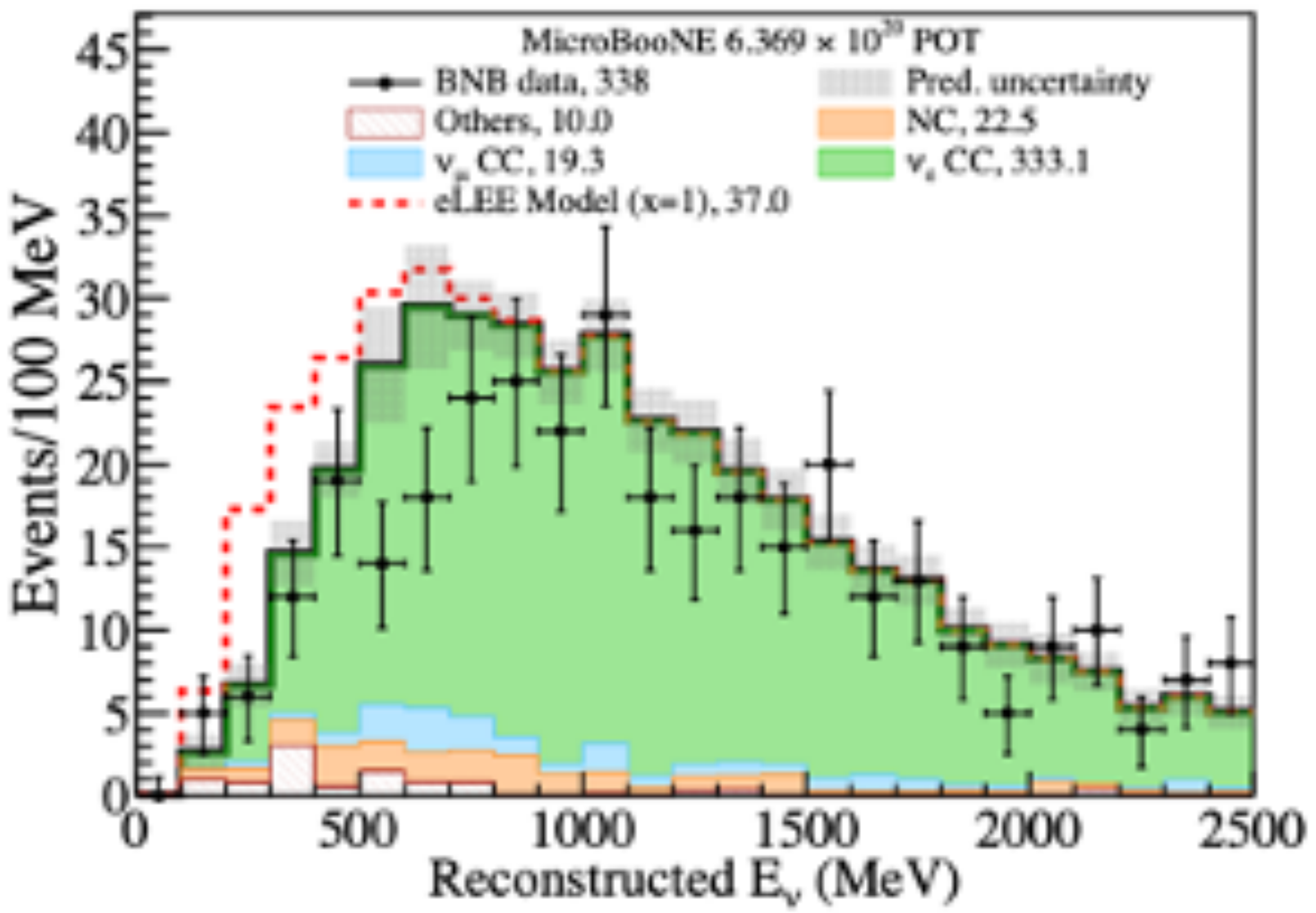


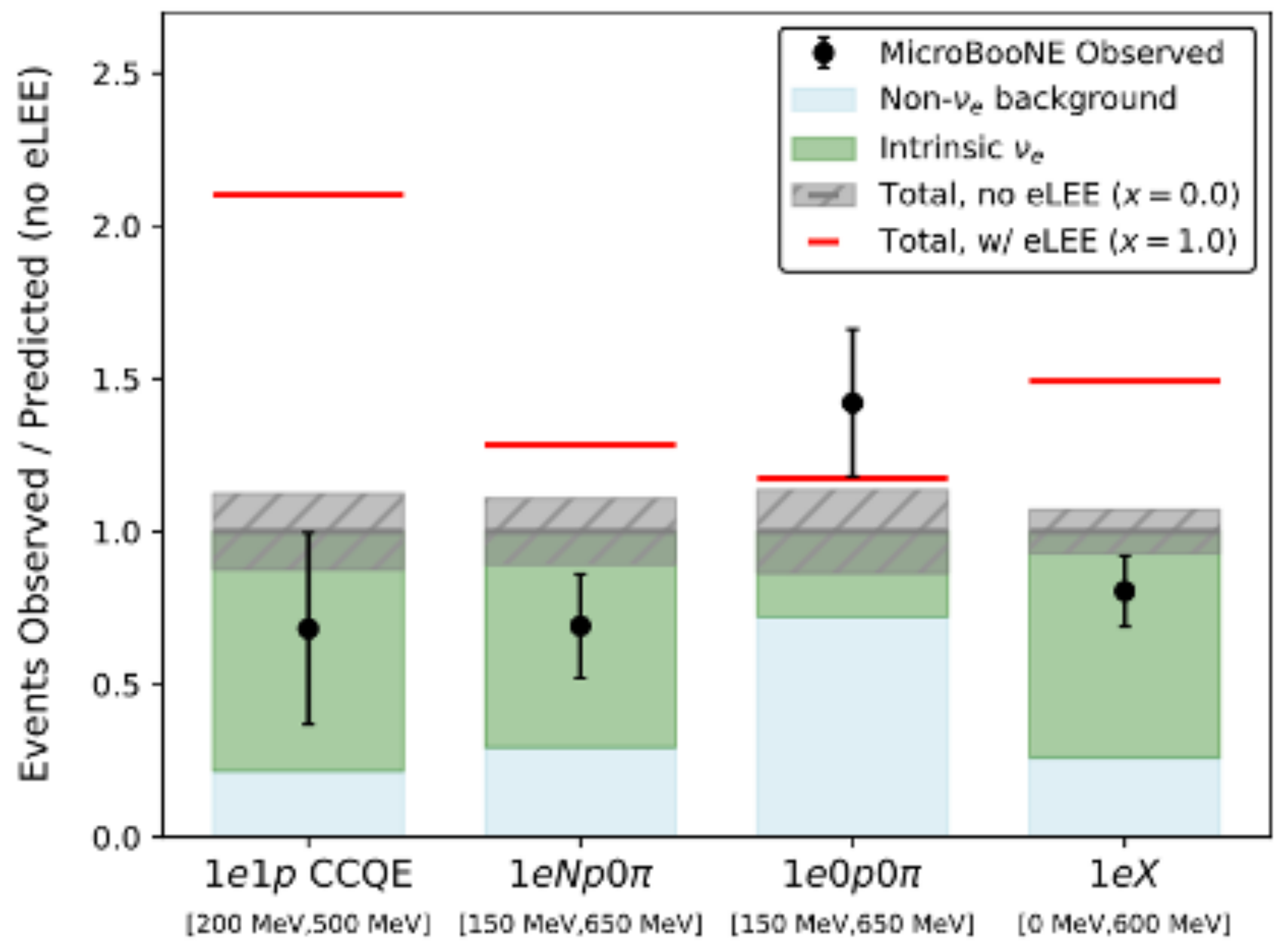
Ross-Lonergan, Snowmass2021 CSS



Phys. Rev. Lett. 128, 241801 (2022)



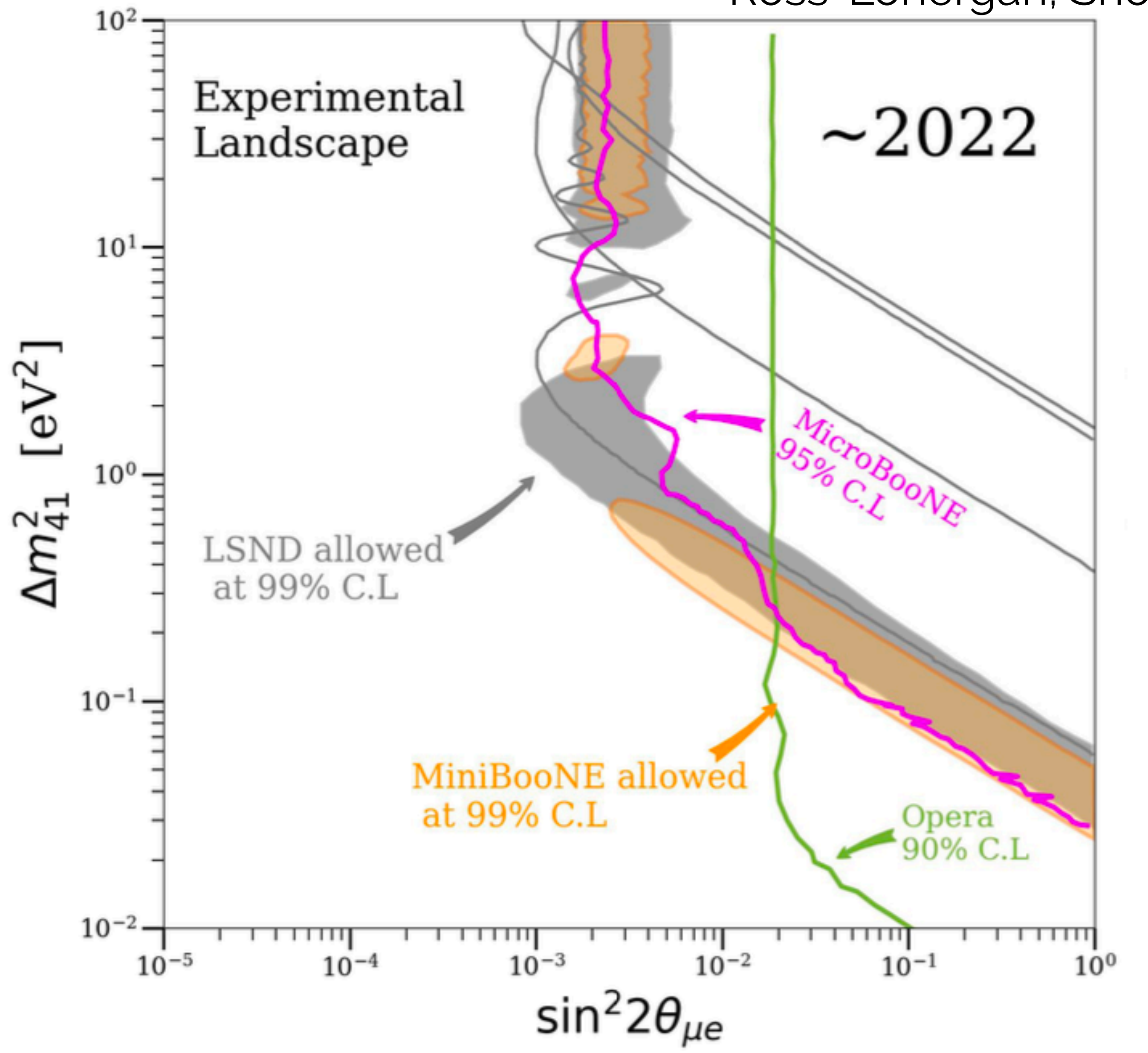
Phys. Rev. Lett. 128, 241801 (2022)

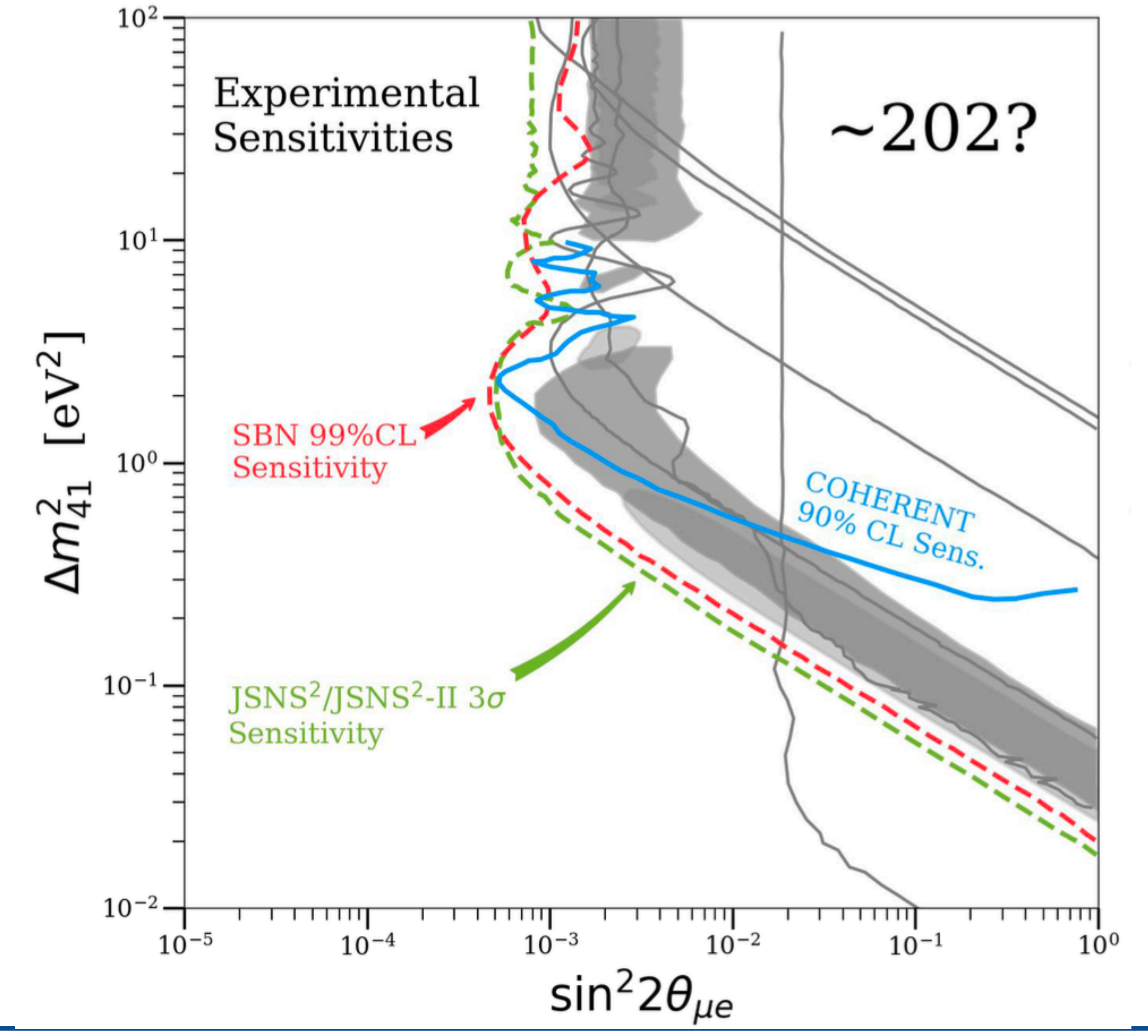


Short-baseline neutrino experiments: accelerator-based

- LSND & MiniBooNE (MB) anomaly recap: (anti) electron neutrino excess observed
- it could (again) be explained by eV-scale sterile neutrinos
- recent MicroBooNE result showed the MB excess is not from electron neutrinos
- but it still does not exclude entire sterile neutrino allowed phase space

Ross-Lonergan, Snowmass2021 CSS





Remaining questions in ν physics

standard model

could **CP violation** in neutrino interactions explain the matter/antimatter asymmetry?

what is the **ordering of the neutrino mass**?

beyond the standard model

are there **new interactions** we could discover via neutrino?

are there **additional neutrinos** beyond known three types?

what is neutrino mass?

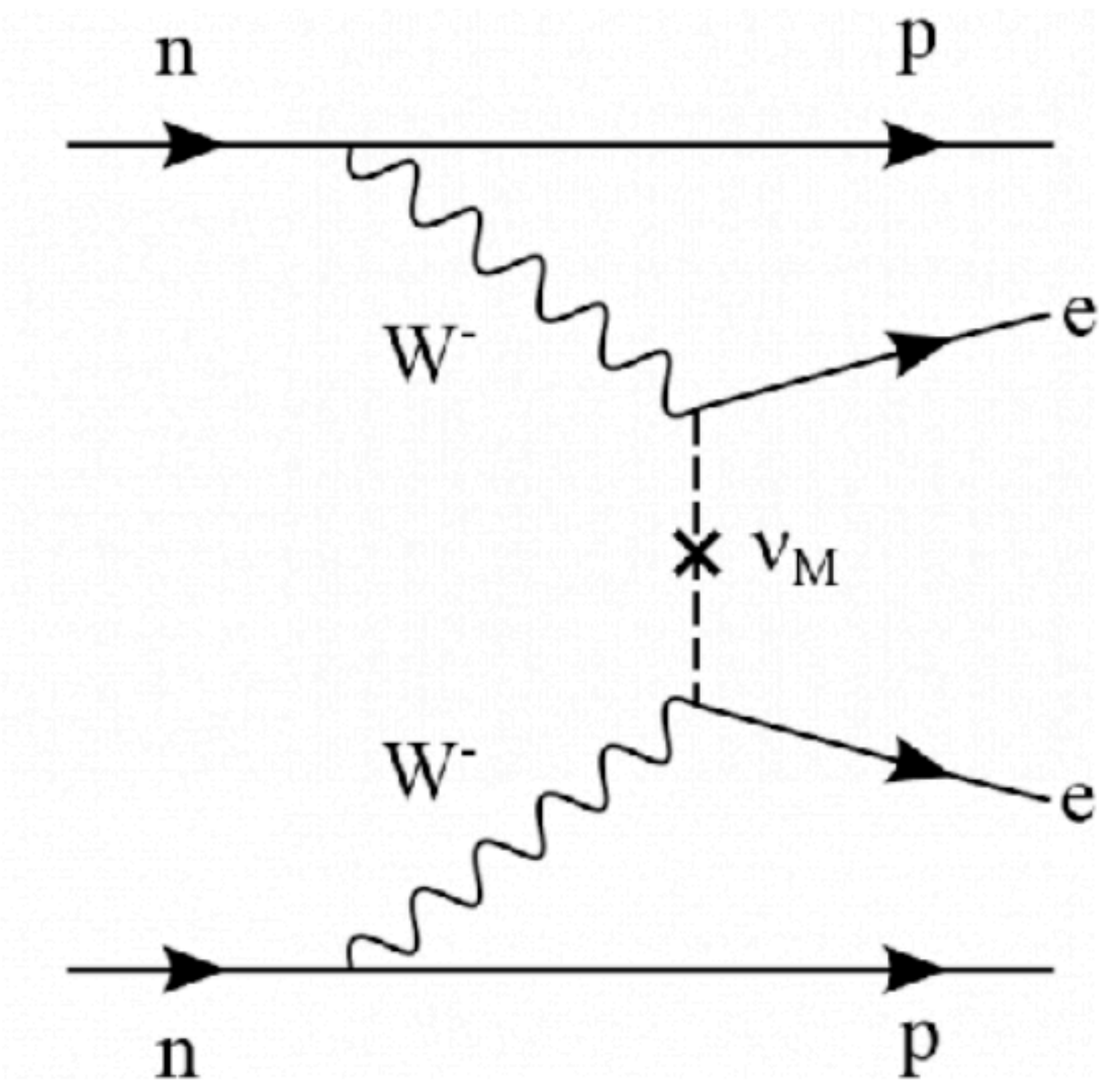
is the neutrino its own anti particle?

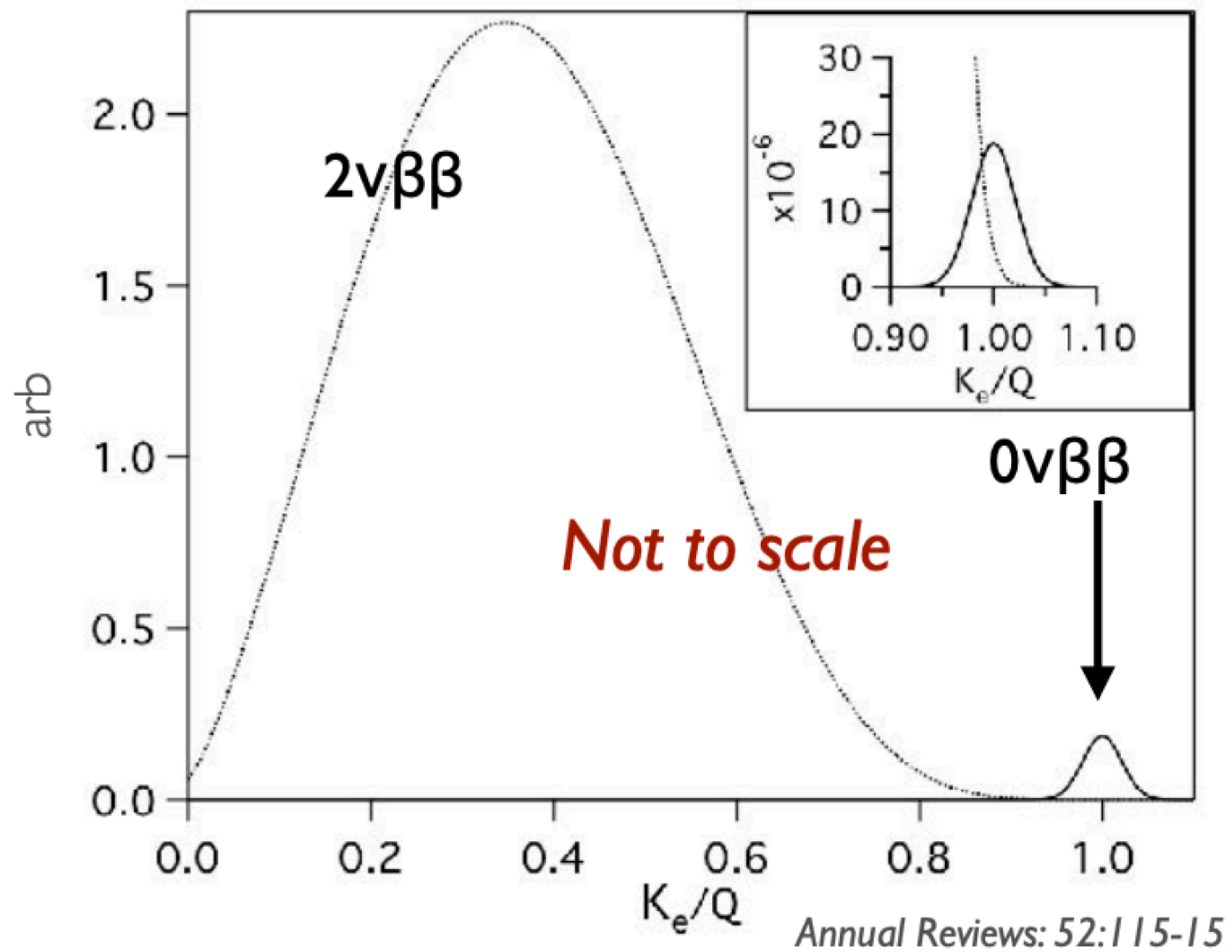
0νββ decay & β-decay experiments

Absolute neutrino mass measurements: 0νββ experiments

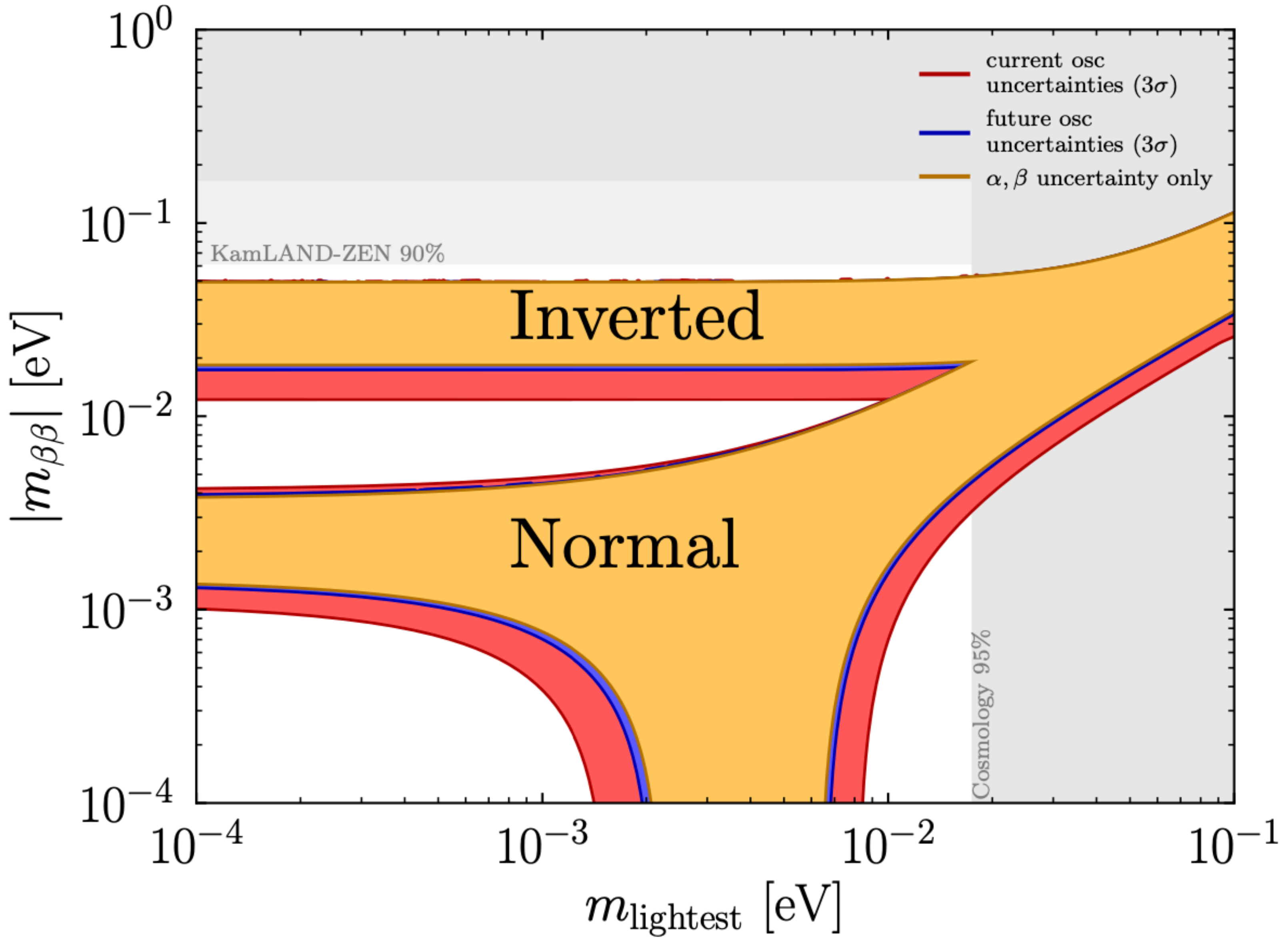
- 0νββ experiments' main goal is to find if neutrinos are Majorana type
  - if so, neutrinos are their own anti particle
  - result in 0 neutrinos in final state of conventional 2νββ decay process
- look for a (tiny) peak at the end of the spectrum
- effective Majorana mass can be infer from the rate of the decay:

$$< m_{\beta\beta} > = | \sum_j m_j U_{ej}^2 |$$





Annual Reviews: 52:115-151



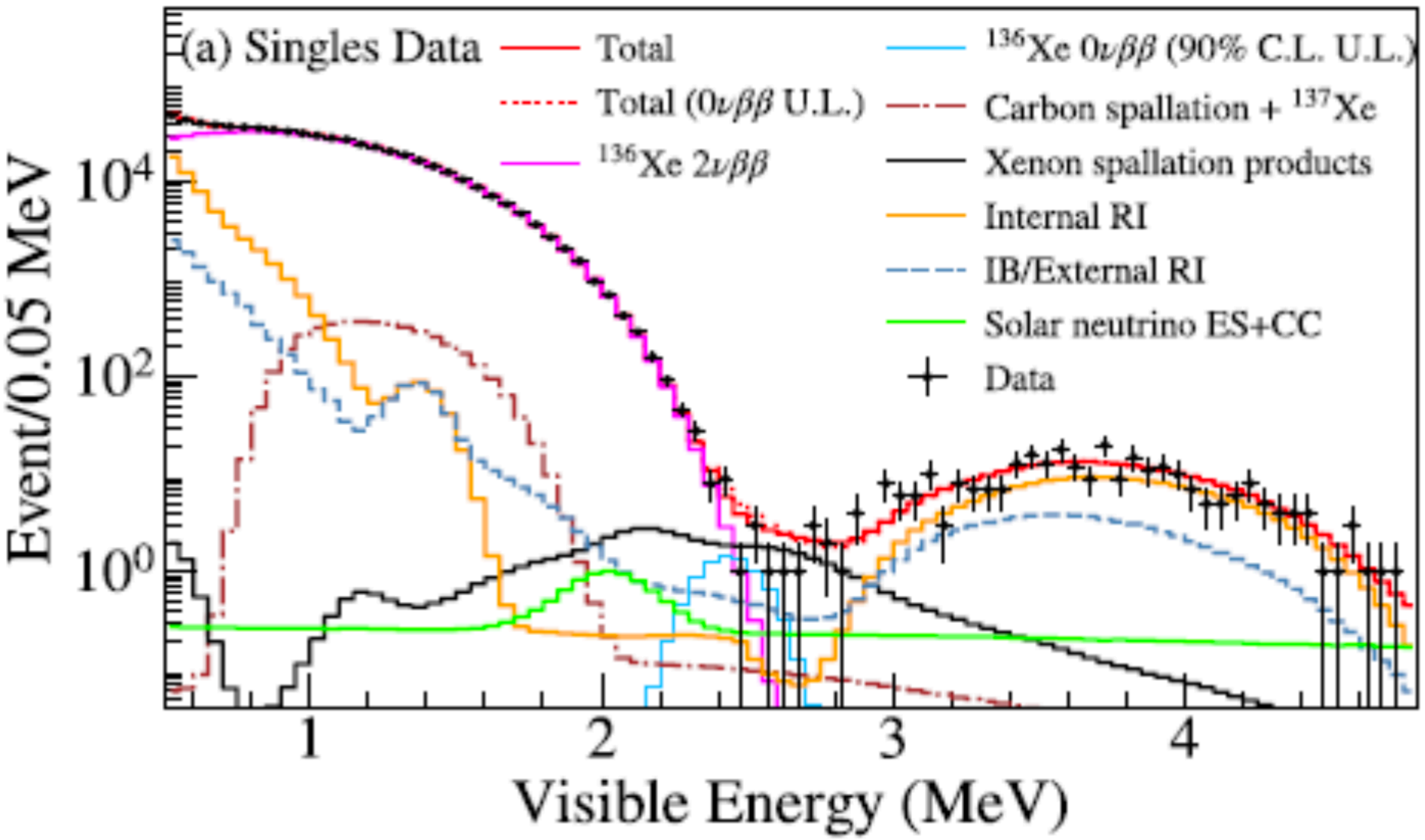
Absolute neutrino mass measurements: $0\nu\beta\beta$ experiments

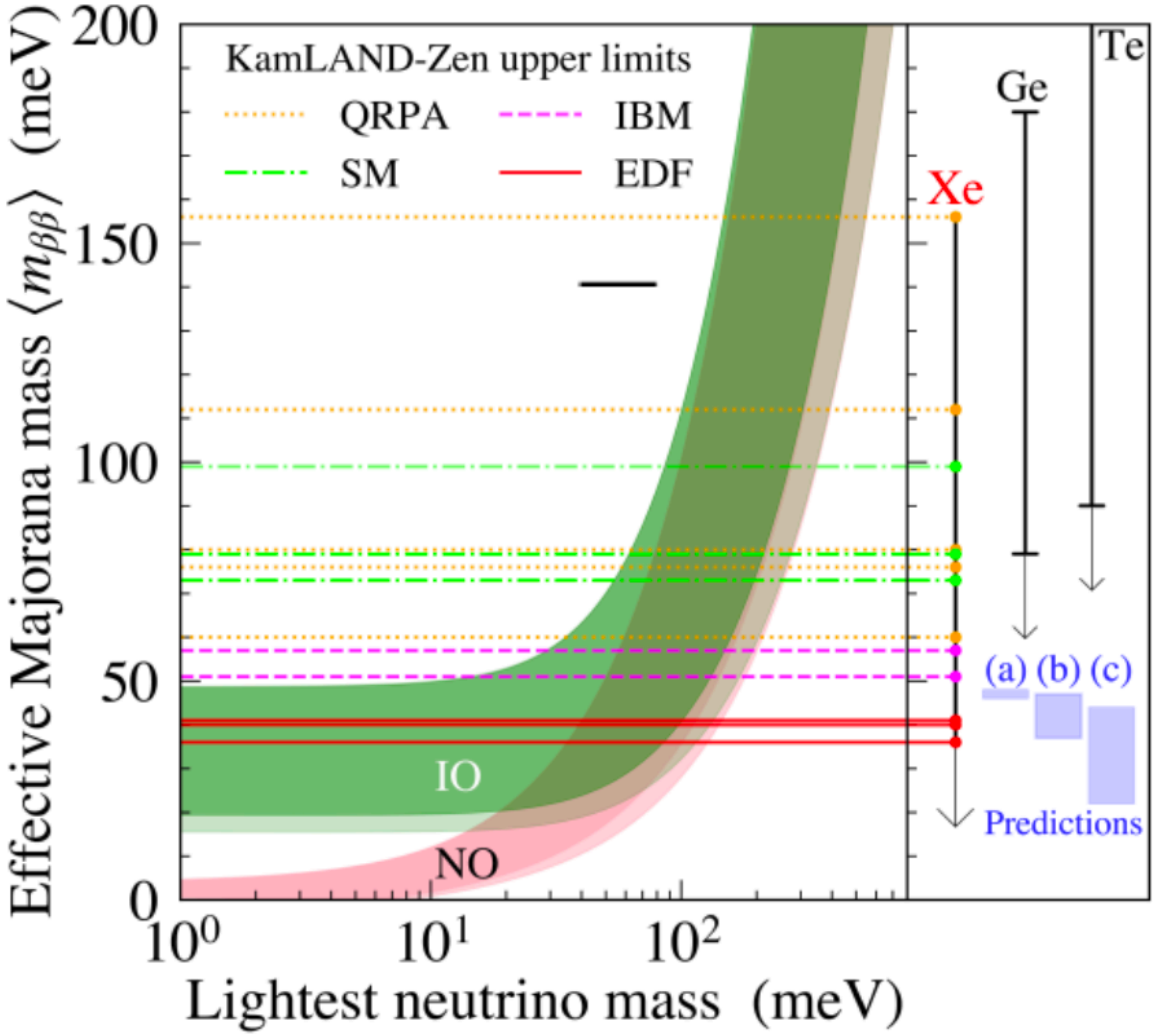
Wang, Neutrino 2022

Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

Absolute neutrino mass measurements: 0νββ experiments

KamLAND-Zen, arXiv:2203.02139

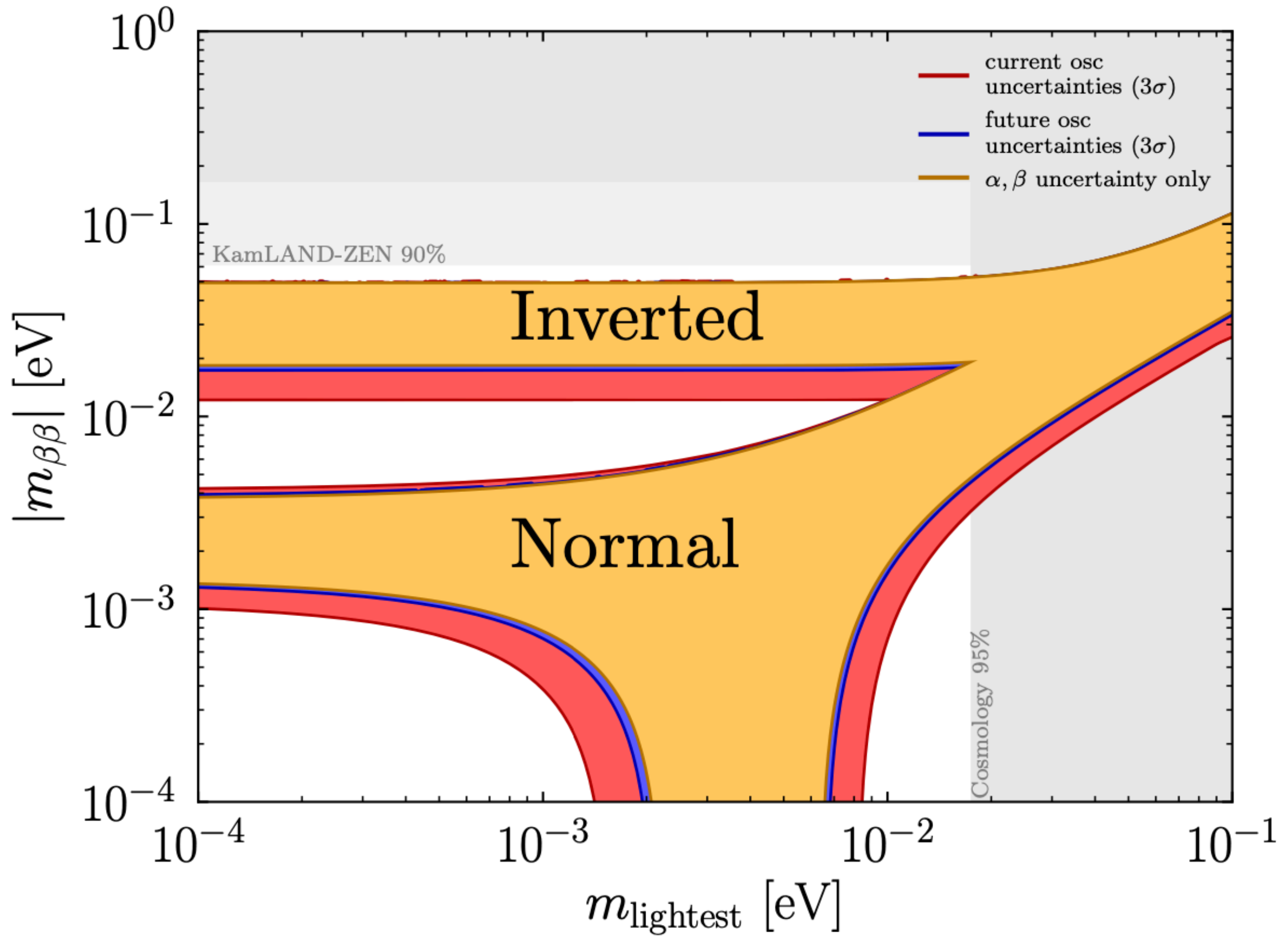




finally starting to reach IO region

Absolute neutrino mass measurements: 0νββ experiments

Wang, Neutrino 2022



- many ton-scale experiments underway with different isotopes
- aim to cover IO region completely, and further reach into NO region

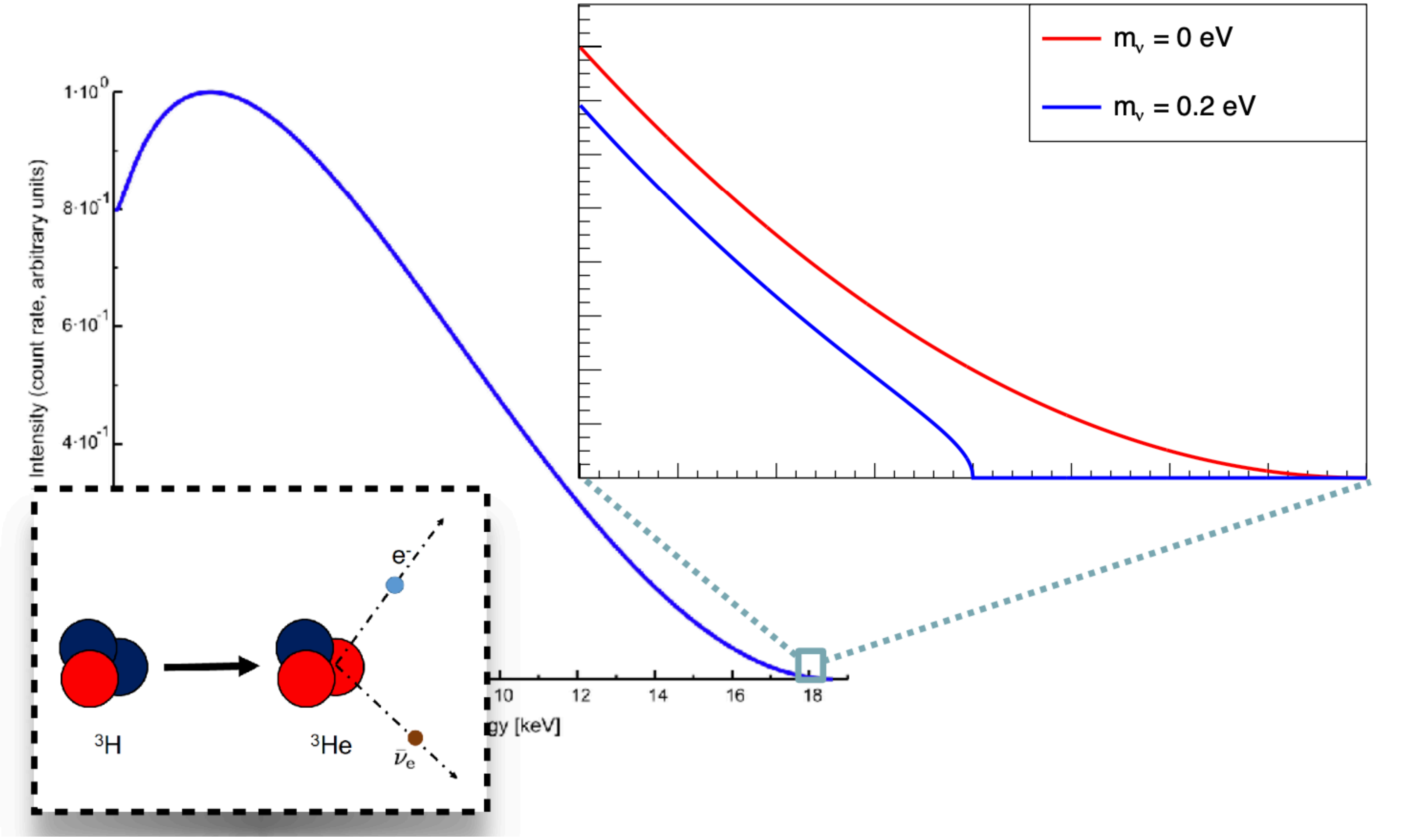
	Isotope	Mass(t)	<$m_{\beta\beta}$>,meV
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
LEGEND-1000	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO-ββ	^{136}Xe	50	4-10
	^{130}Te	100	3-14

Absolute neutrino mass measurements: β-decay experiments

- the shape near the end point can be used to infer neutrino mass:

$$m_\beta^2 = \sum_{i=1,3} |U_{ei}|^2 m_i^2$$

- purely kinematic measurement
- model-independent
- quite challenging to measure, as small portion (~10^{-13}) of decays in the last 1 eV

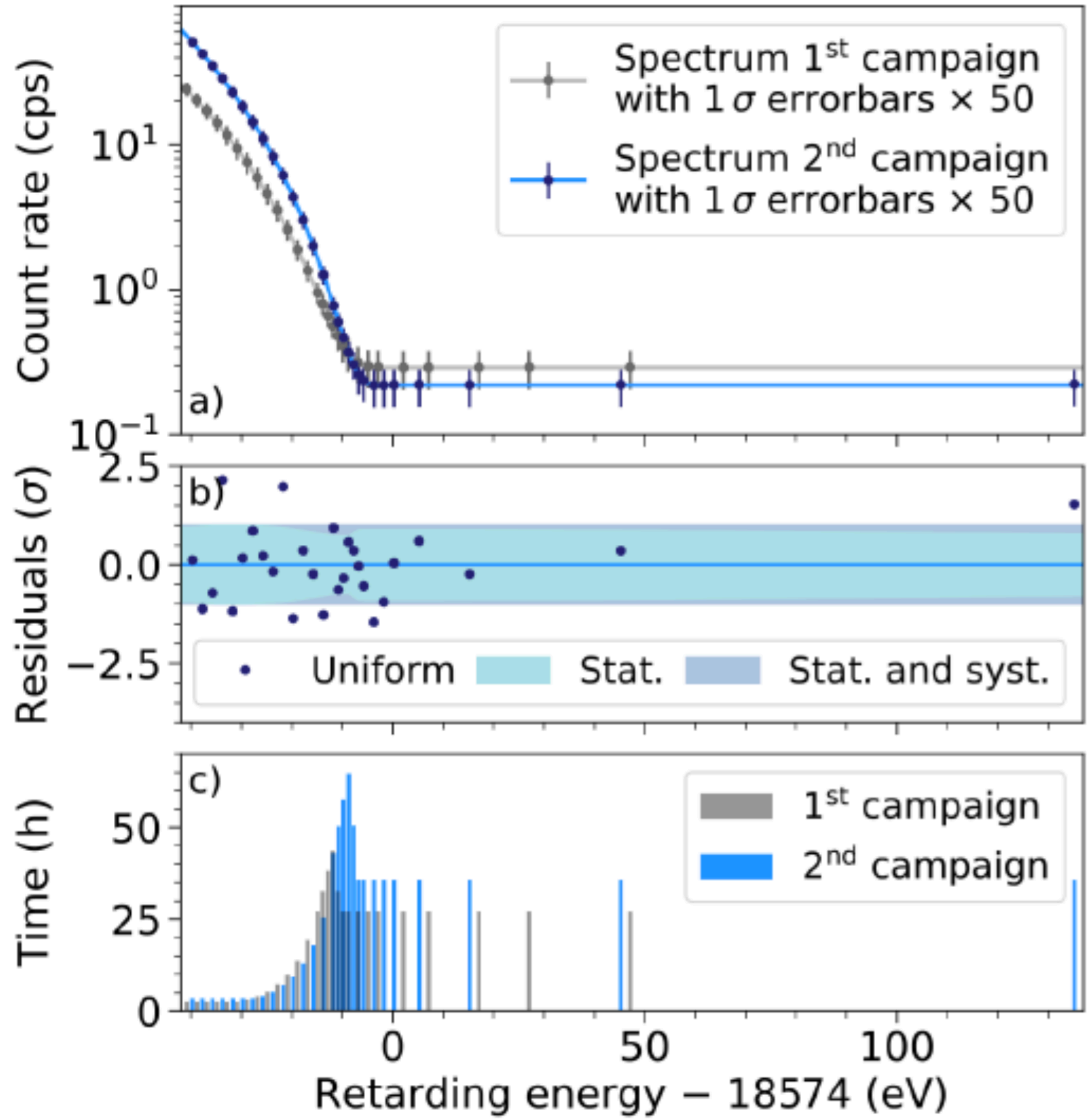


plot by: Pranava Teja Surukuchi

Absolute neutrino mass measurements: β-decay experiments

Nature Phys. 18 (2022) 2, 160-166

- KATRIN experiment
  - beta decay technique: Magnetic Adiabatic Collimation combined with Electrostatic Filter
  - beta decay electrons guided towards the center of the spectrometer
  - best neutrino mass limits we have so far
- 53 days of data, upper limit 0.8 eV/c² (90% CL)



Absolute neutrino mass measurements: β-decay experiments

Wang, Neutrino 2022

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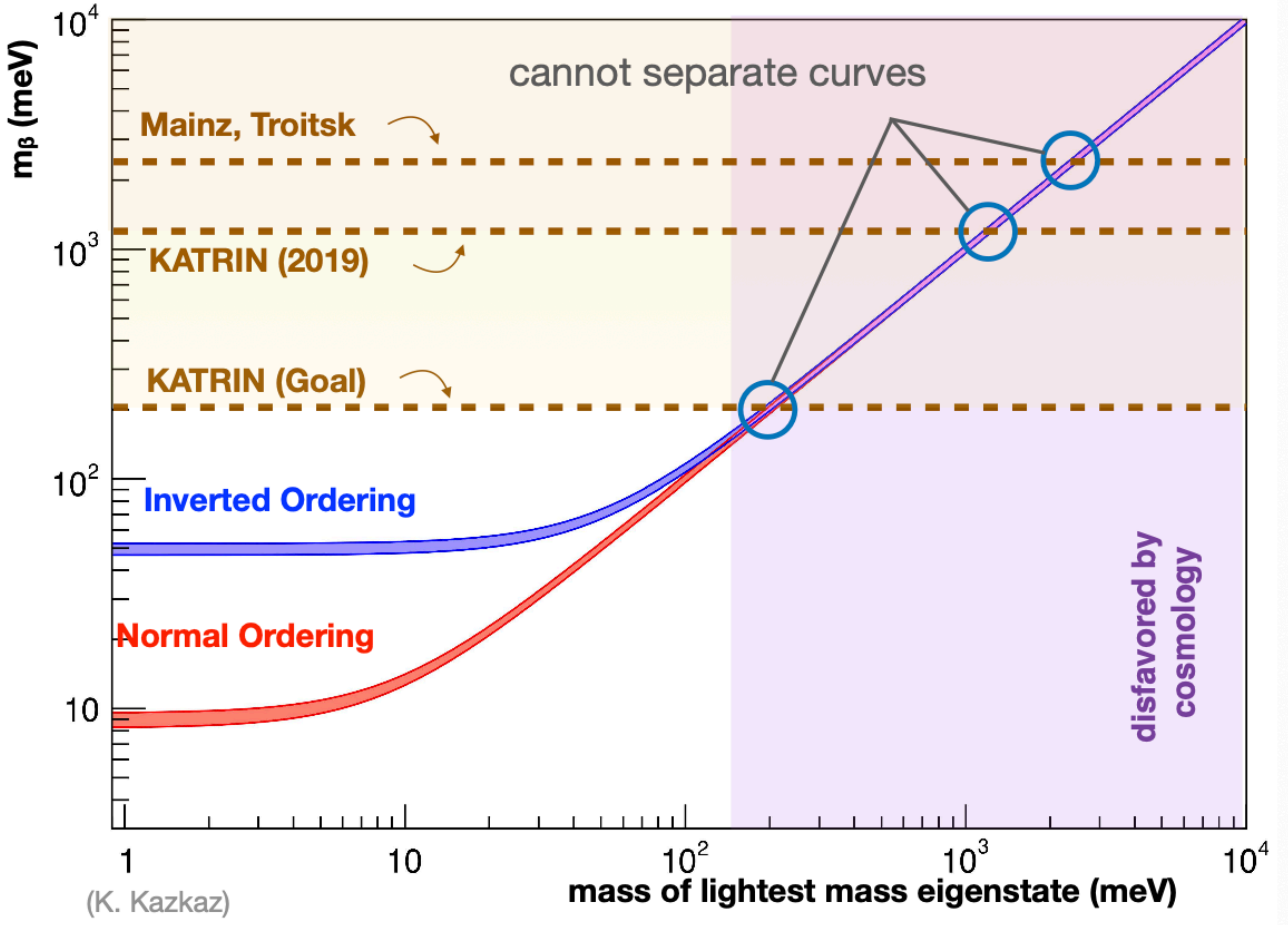
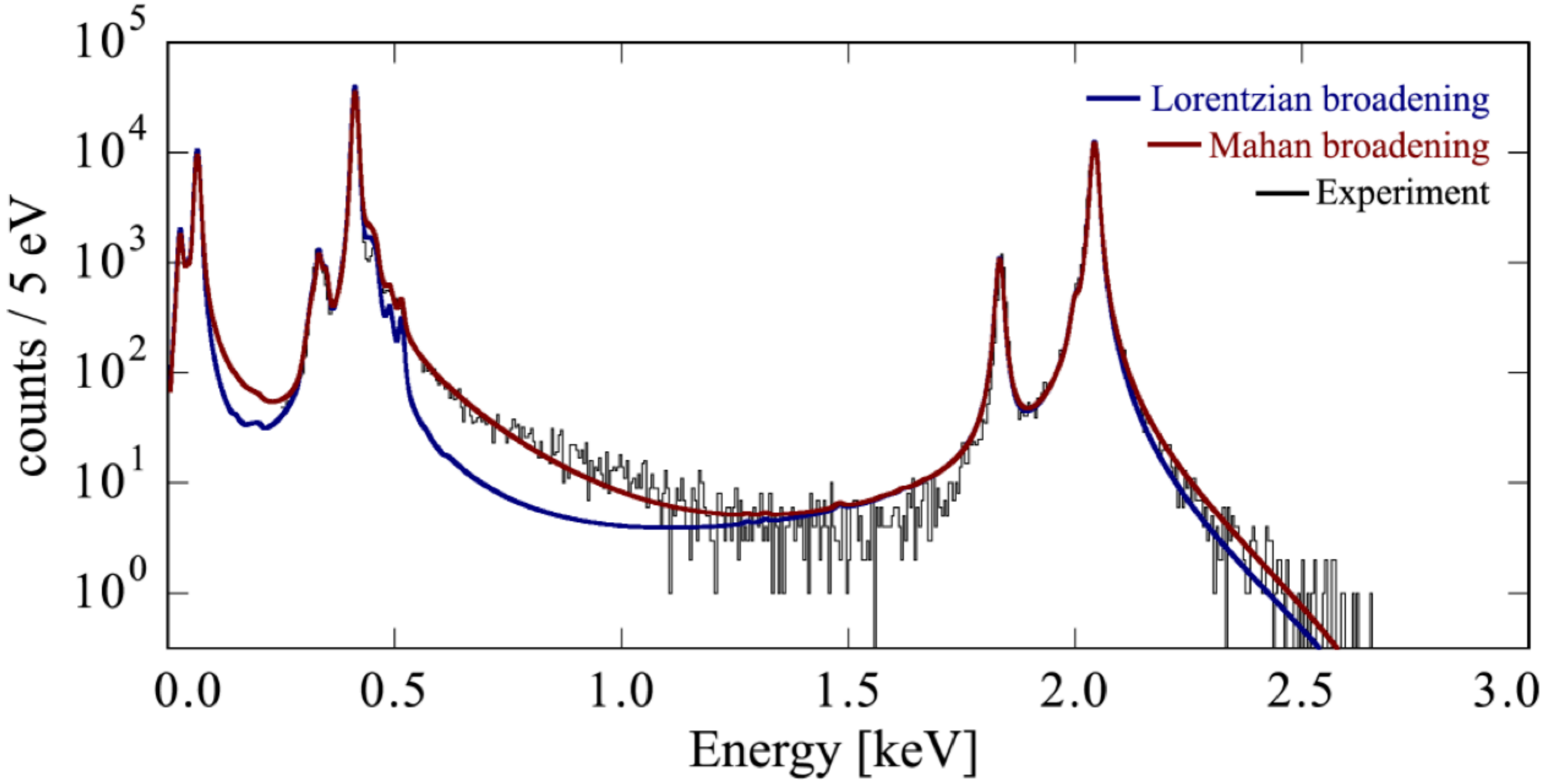
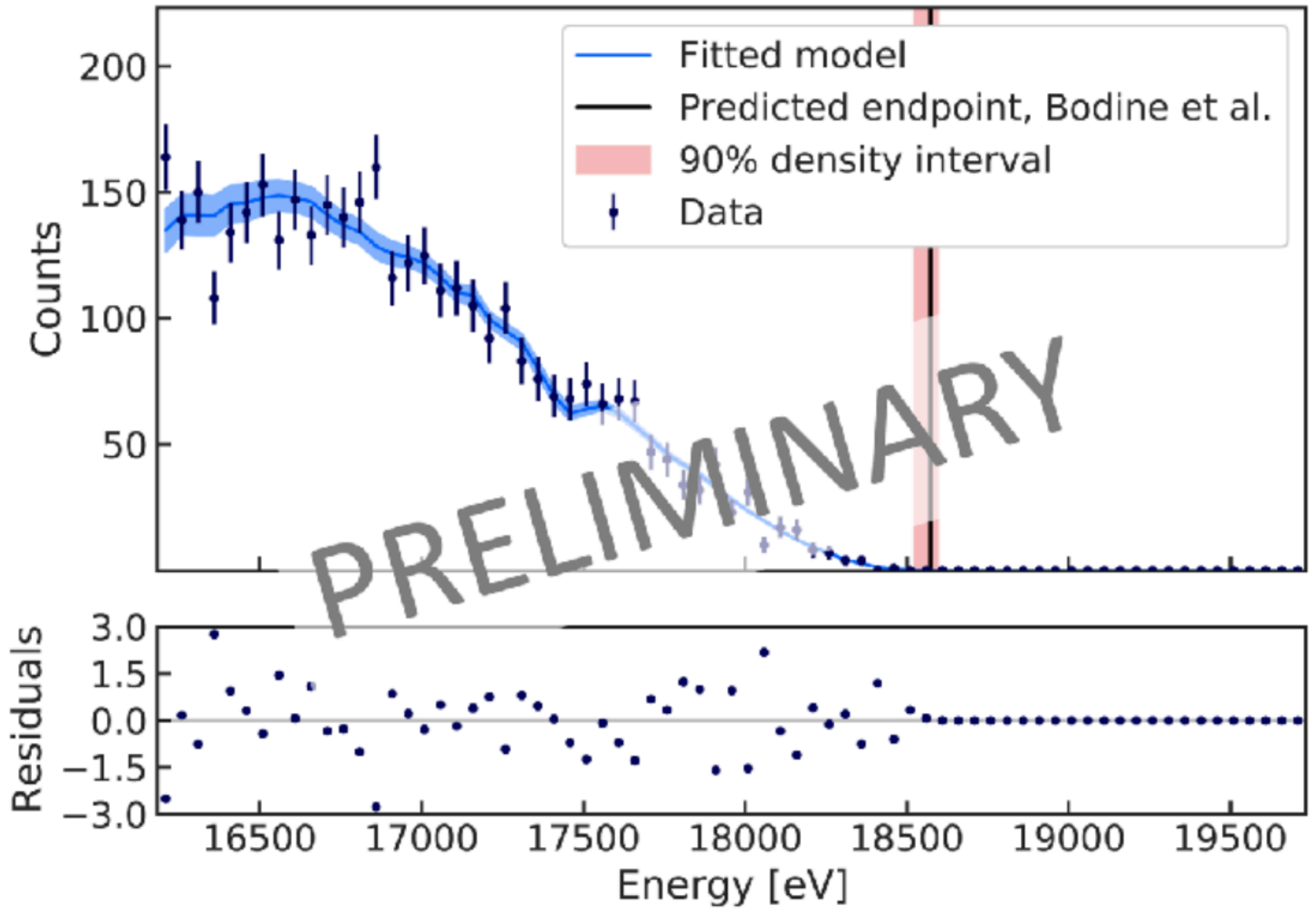


Absolute neutrino mass measurements: β-decay experiments

- new projects are underway
  - ECHO & HOLMS: calorimetric sensors coupled to ^{163}Ho implanted sources
    - obtained neutrino mass limit ~150 eV, with a goal to ~1eV
  - Project8: Cyclotron Radiation Emission Spectroscopy (CRES)
    - phased program, phase 2 obtained mass limit 178 eV, goal is to reach 0.04 eV



C. Velte et al., EPJC **79** (2019) 1026



there are so many other exciting topics I didn't get to cover…

- **solar neutrino**: Borexino result with CNO neutrino observation
- **atmospheric neutrino**: SuperK with precise measurements of theta23 and |delta_m2_32|
- **relic neutrino/diffused supernova neutrino:** Ptolemy, SupwerK-Gd, …
- **astrophysical neutrinos**: IceCube, in association with multi-messaengers
- **neutrino flux & cross section**: dedicated experiments and many other measurements
- along with many novel **detector technology**: LArTPC, emulsion detector, WbLS, …

Summary

- neutrino oscillation showed that the neutrinos have mass, which is the only "palpable" evidence of physics beyond the Standard Model

- field of neutrino physics has been flourishing last few decades: so much advancement, but still so much more to understand

- many experiments operating/planned to look for such well-defined experimental questions (paraphrasing Yifang Wang (IHEP) at Neutrino2022)

  - in 10 years, we will/hope to understand mass hierarchy and CP phase

  - in 20 years, we will/hope to measure absolute mass of neutrinos

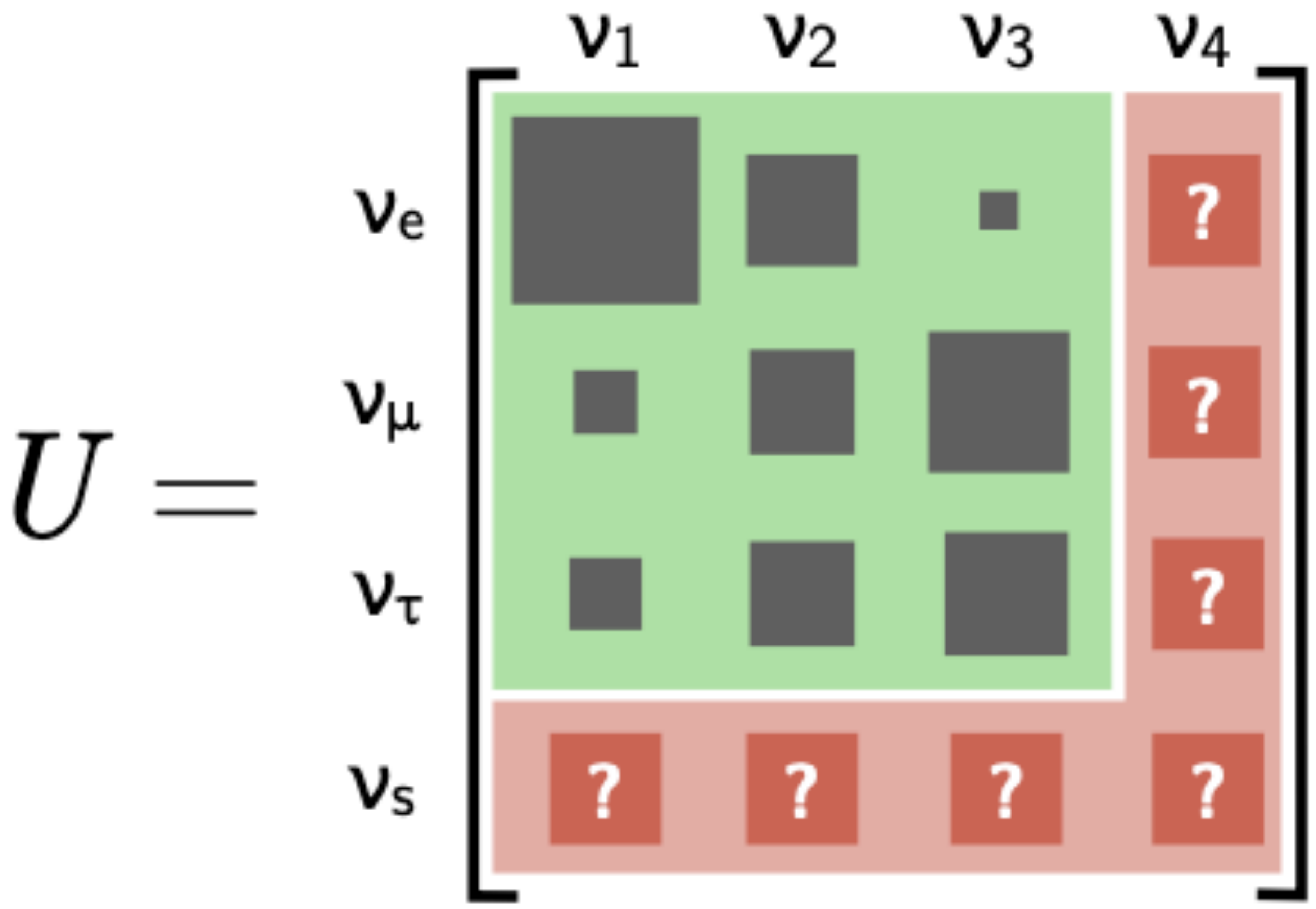
  - in 30 years, we will/hope to determine Majorana nature of neutrinos

- but I'm pretty sure there will be few surprises on the way

Backup slides

extra neutrinos?

- the number of *weakly interacting* "**active**" neutrino flavors is fixed to three, by the *Z* width measurements (LEP)
- but additional, *non-interacting* "**sterile**" neutrino states could still exist
- potentially detectable through impact on neutrino oscillations
- *Q: can this new type of neutrino be solution to these anomalies?*
- *A: unfortunately, it's not so simple… there are severe tension between different measurements & channels*

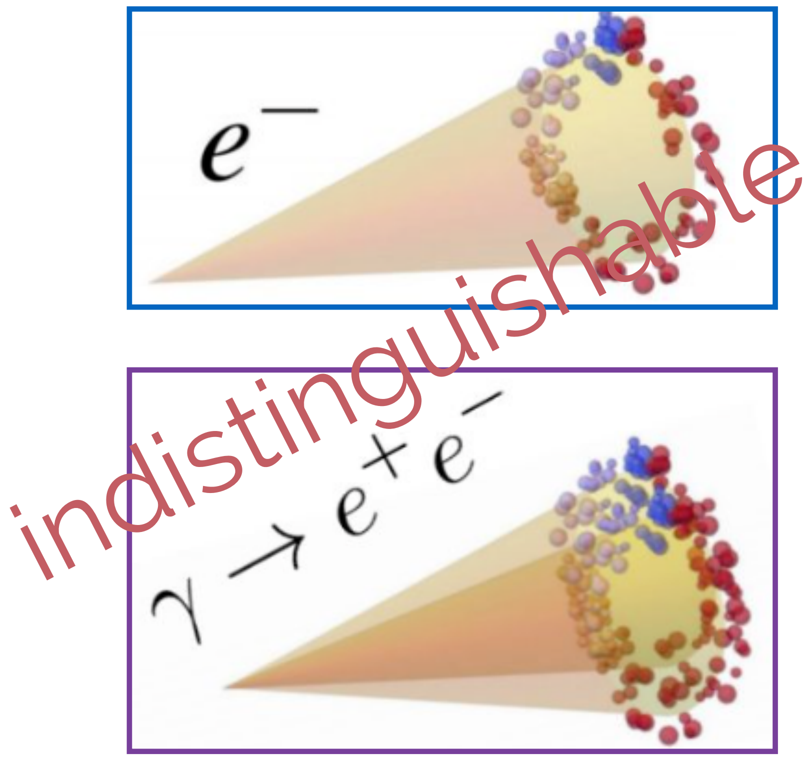


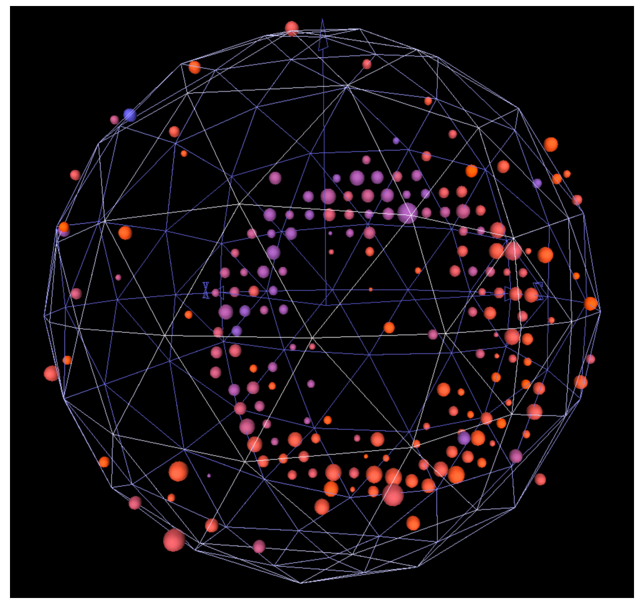
Flavor transitions via this new mixing:

$$P_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(1.27\frac{\Delta m^2_{41} L}{E}\right)$$

MiniBooNE low energy excess

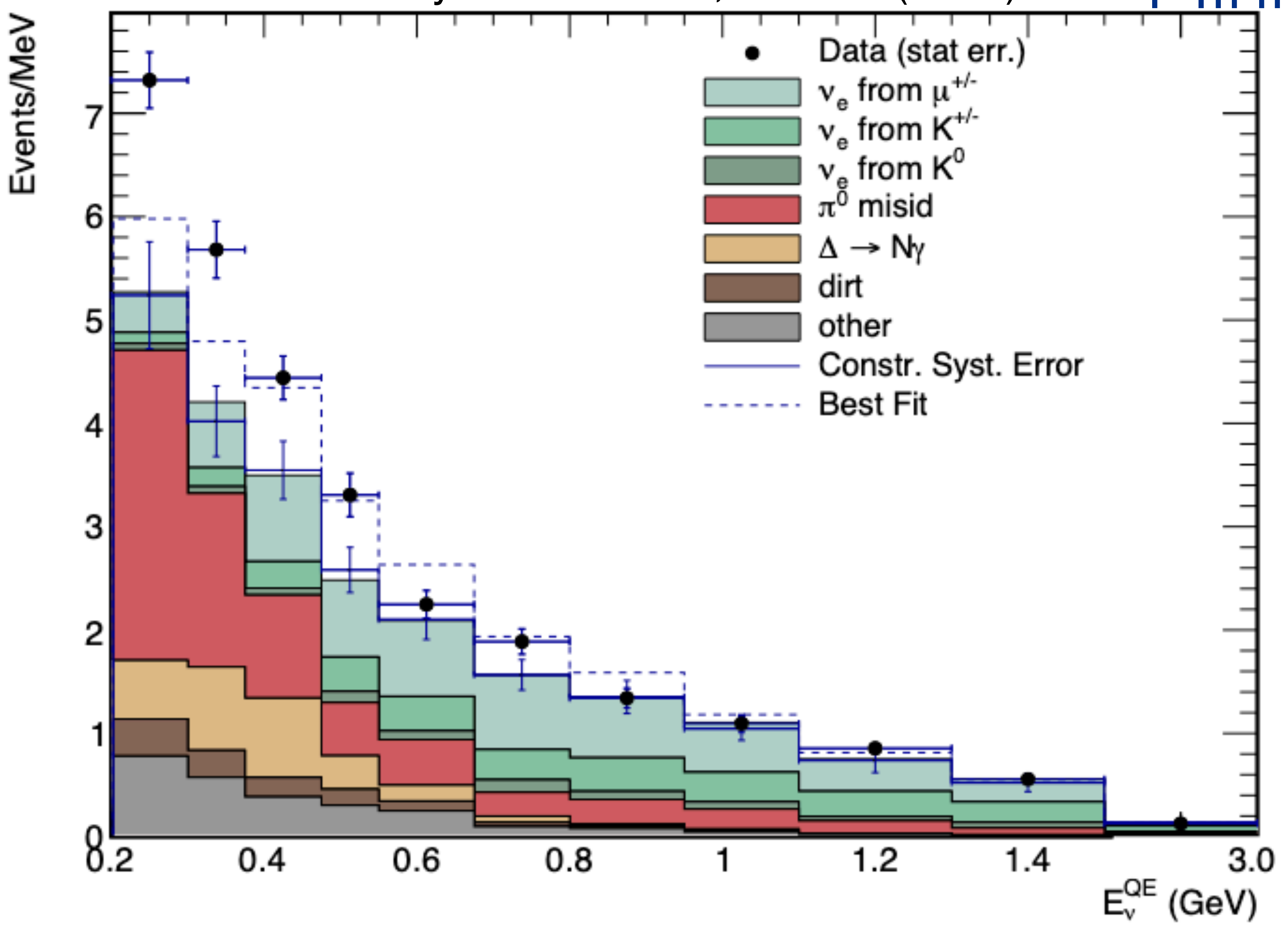
- nature of the excess could be "electron-like" (eLEE) or "photon-like" (γLEE)
  - MiniBooNE could not distinguish between electrons and photons, also did not have hadron information
- *can we separate electrons and photons?*
- *can we understand the excess with enough event topology information such as hadronic activities?*

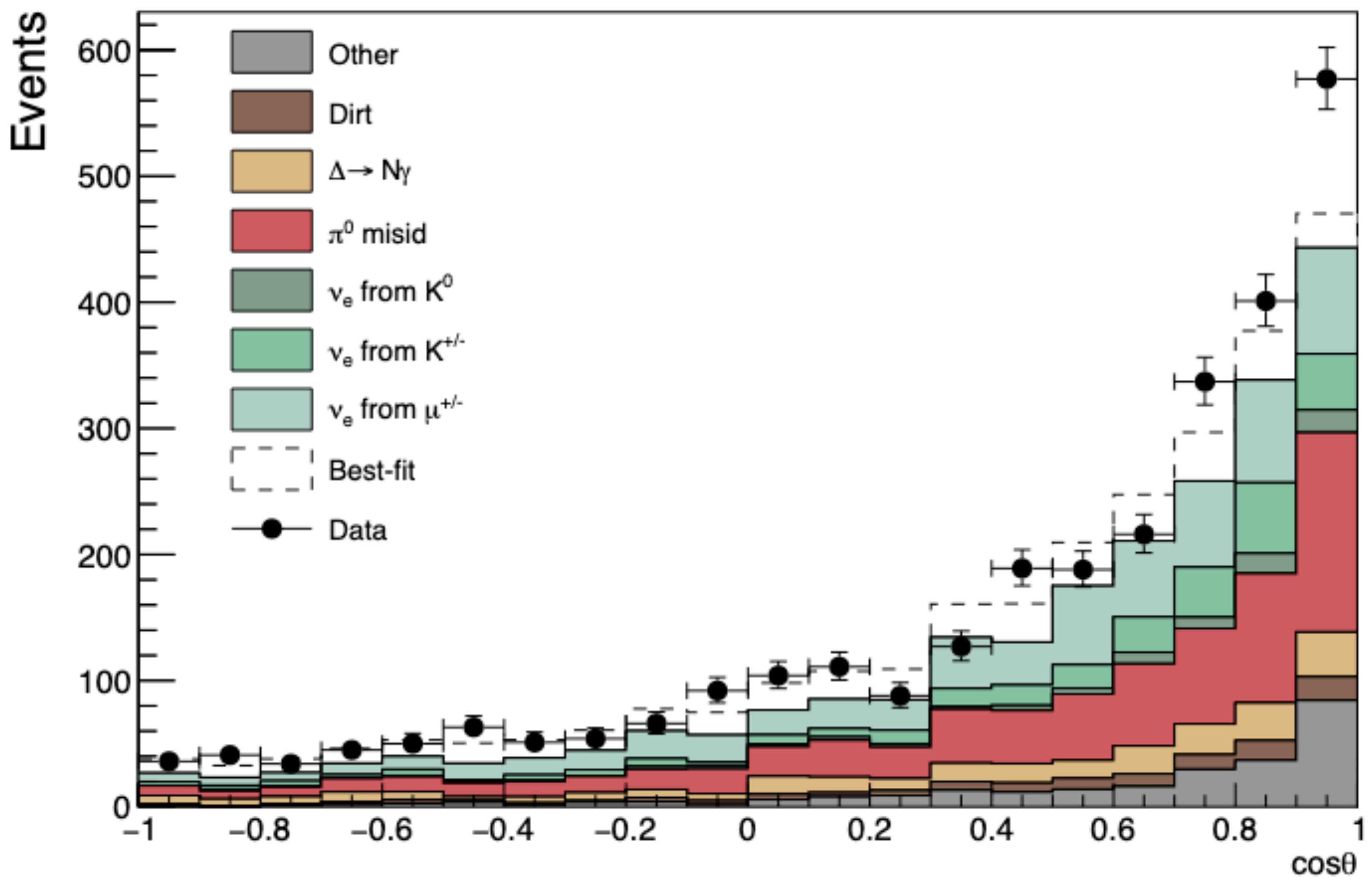




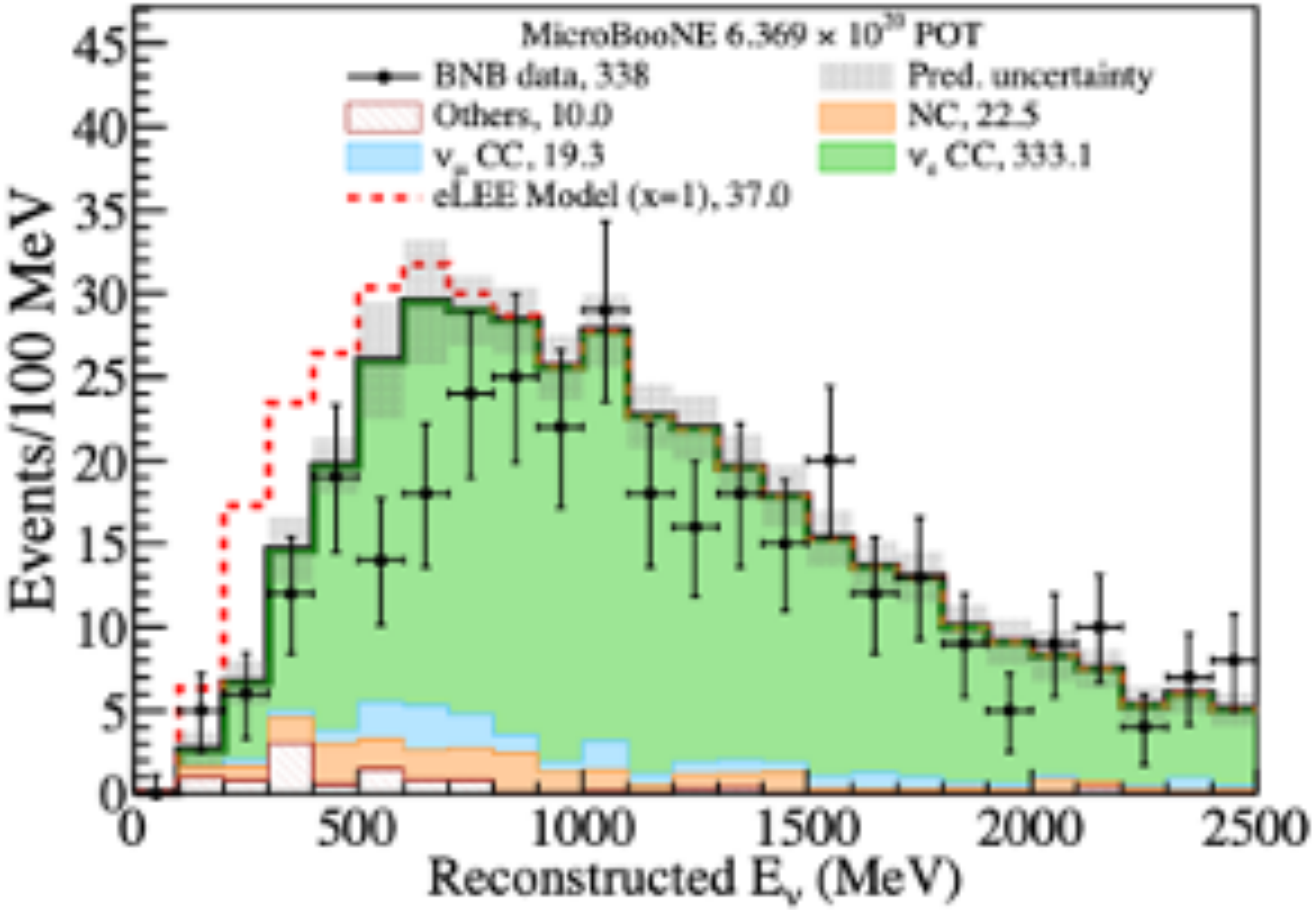
Phys. Rev. D 103, 052002 (2021)

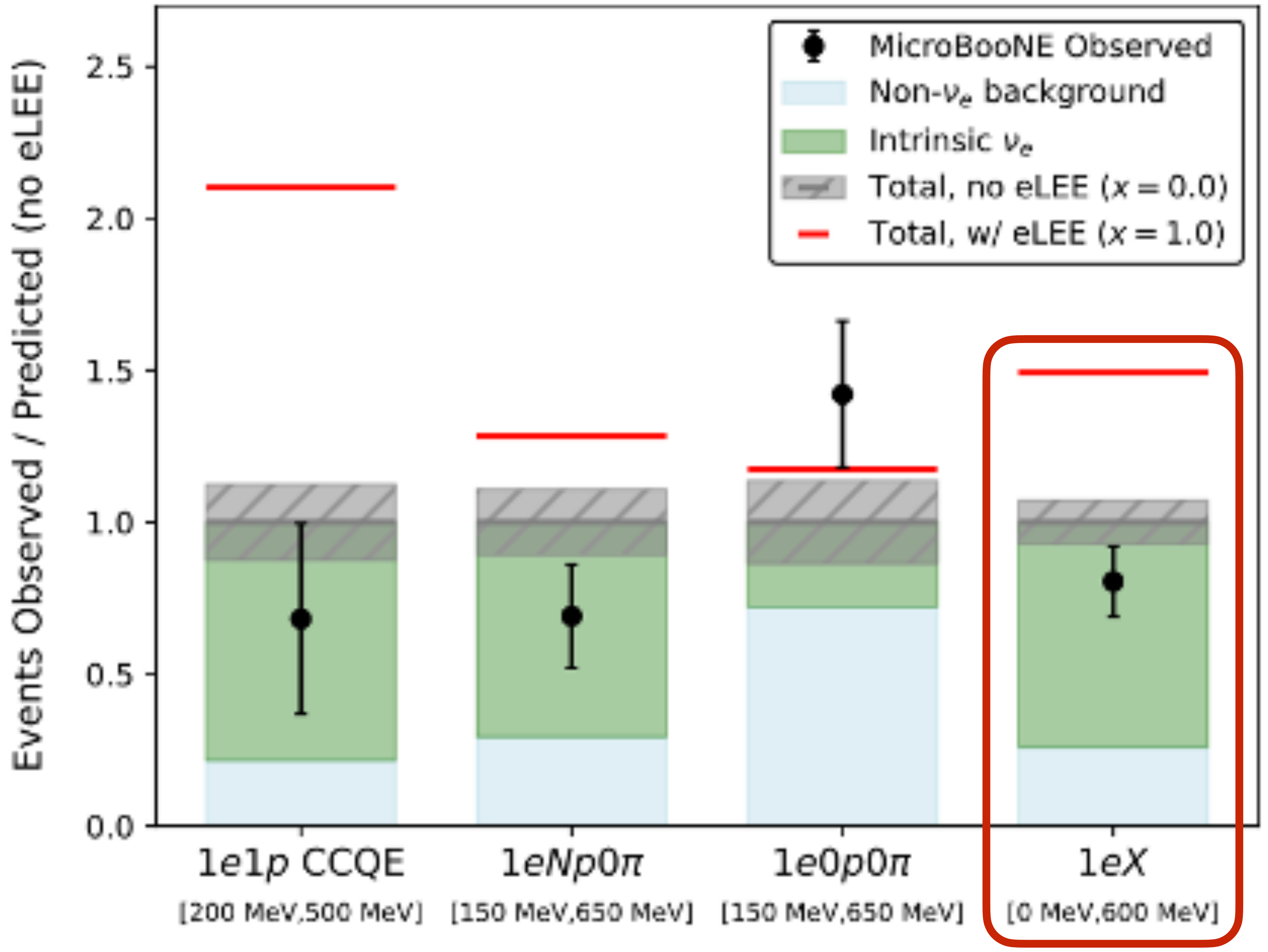
MiniBooNE

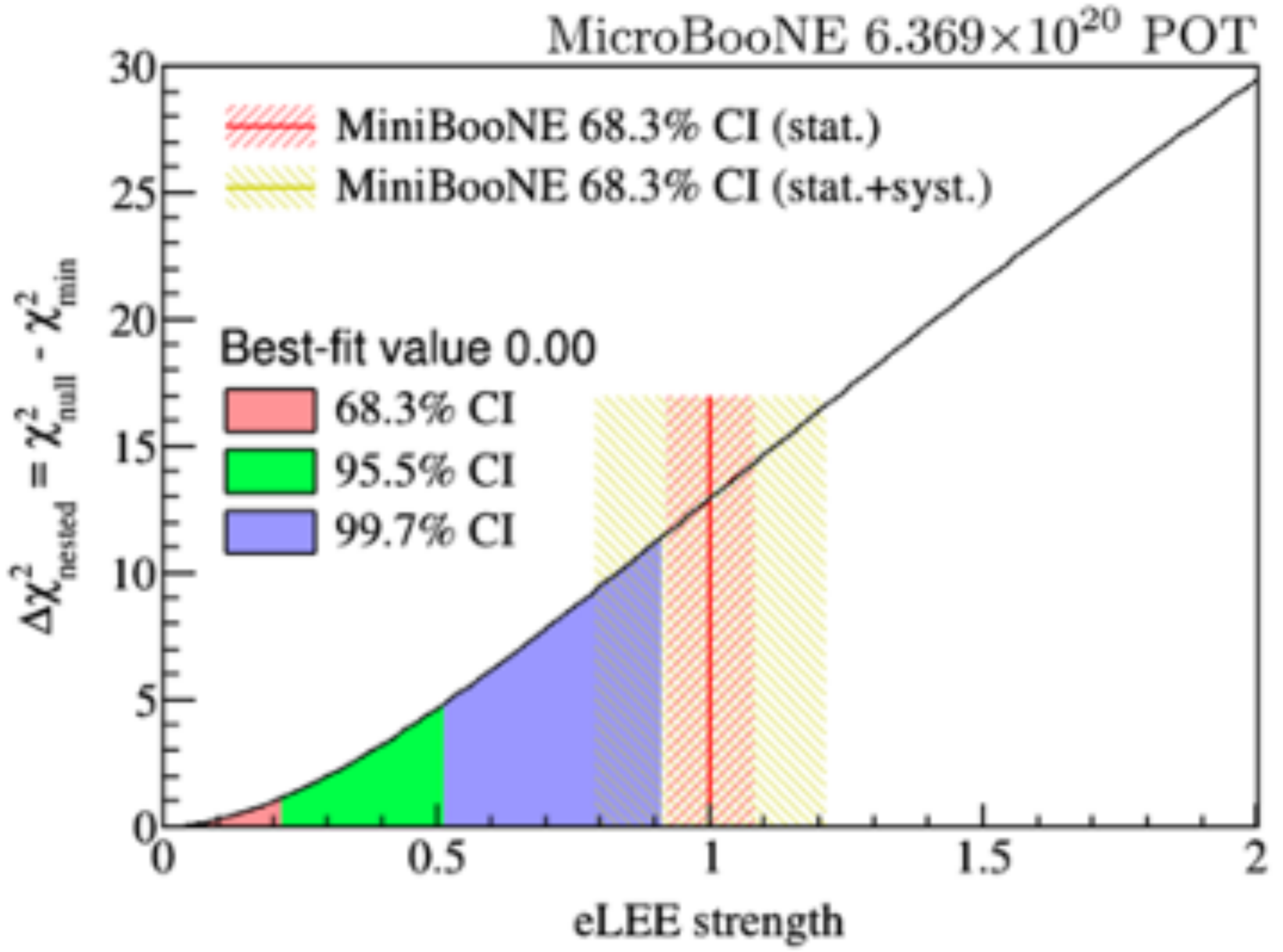




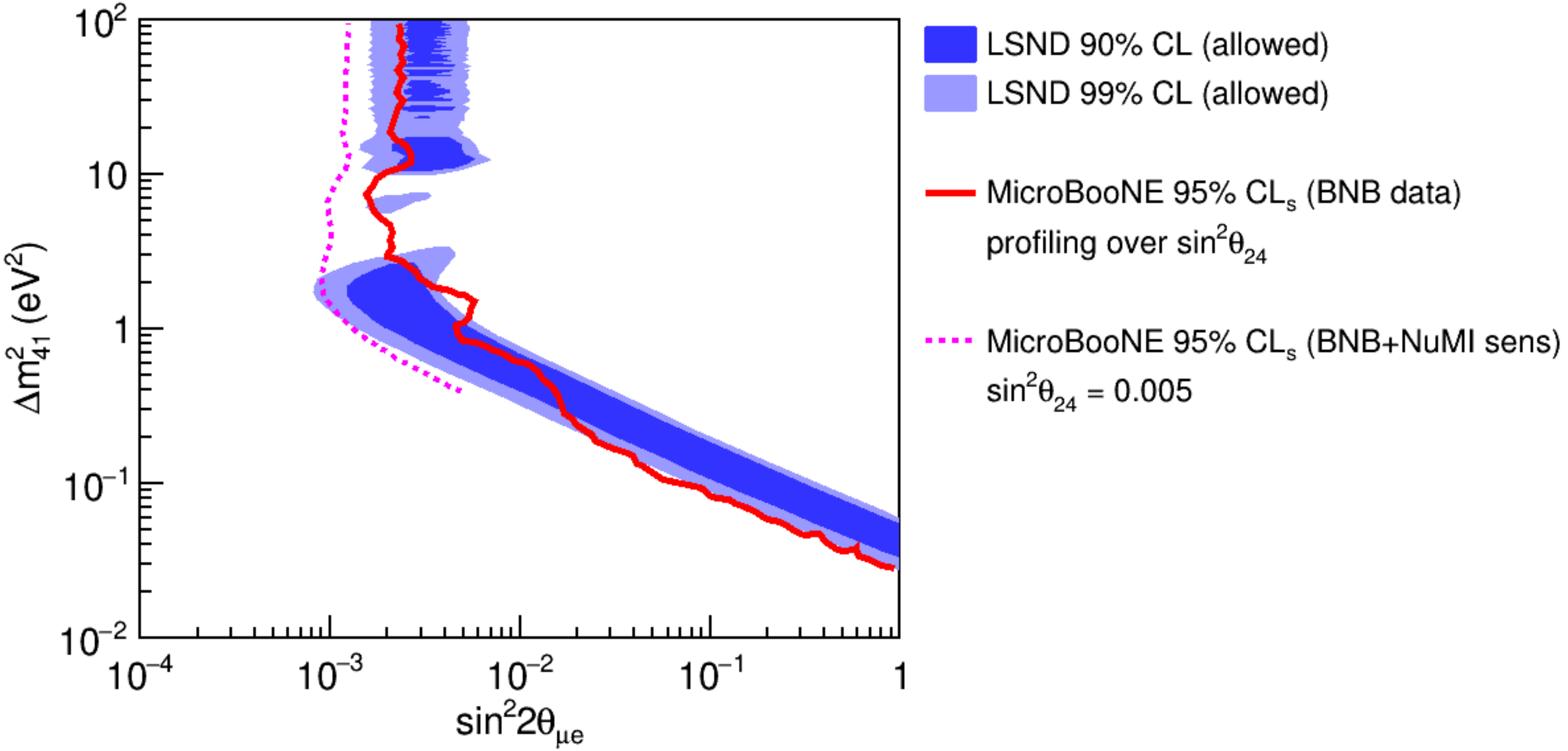
MicroBooNE results







MicroBooNE results



MicroBooNE's exploration of the MiniBooNE excess

First series of results (1/2 the MicroBooNE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma0p$	$1\gamma1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

* Requires heavy sterile/other new particles also

Evolving theory landscape

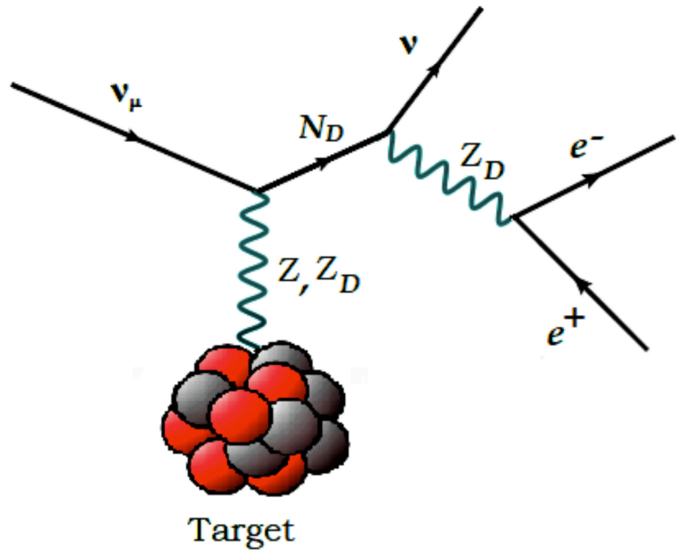
motivated by attempts to explain the new MiniBooNE results as well as other experimental data; eg., ν_e appearance but no ν_μ disappearance *(caution: not an exhaustive list!)*

- 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



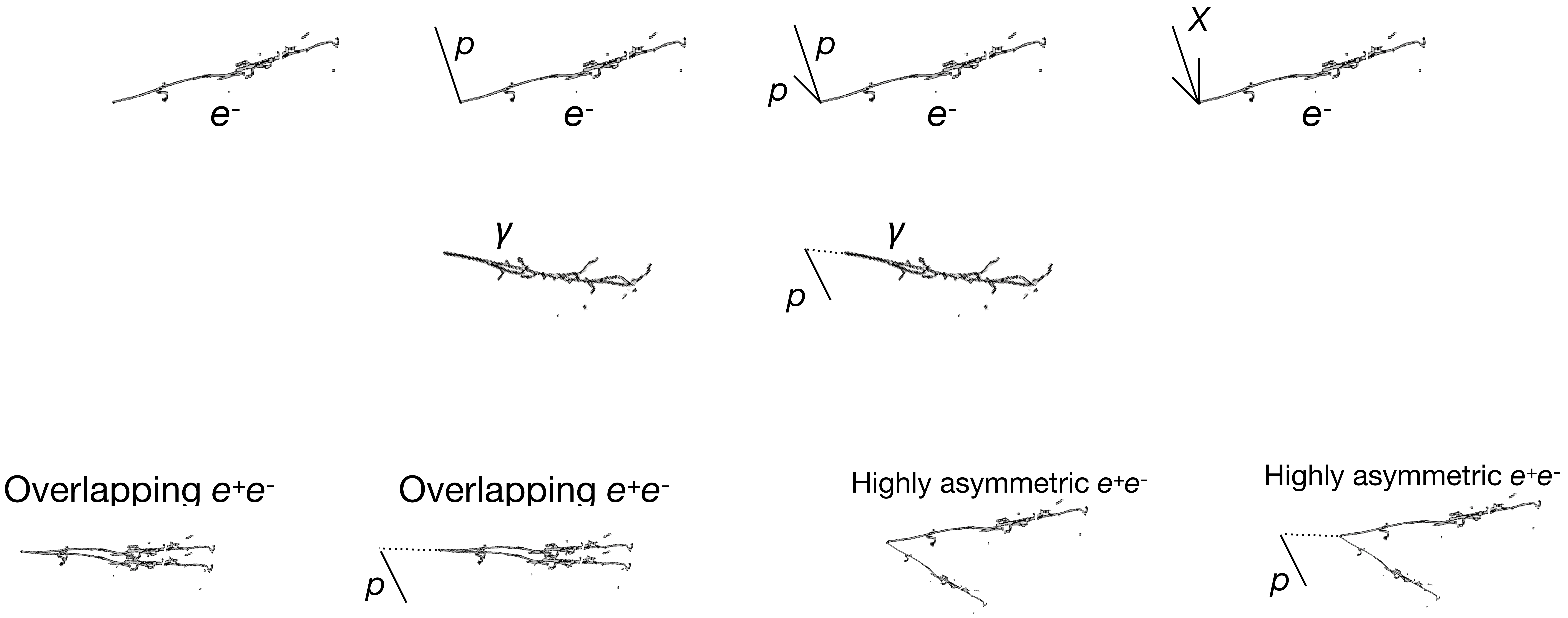
PRL 121, 241801 (2018)

- many of these models predict more complex final states (e^+e^-) and/or differing levels of hadronic activity

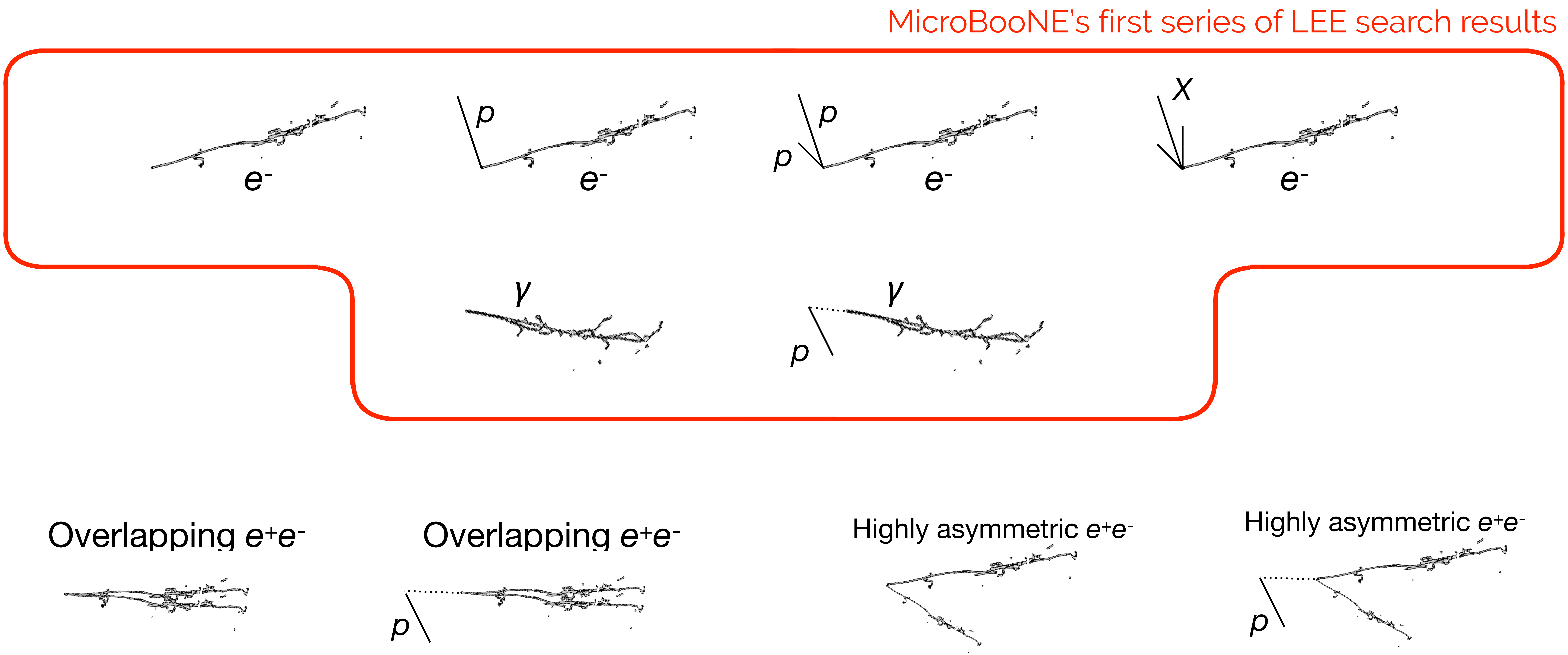
→ *the **hadronic state** is becoming increasingly more important as a model discriminator*

- we are fortunate that LArTPCs are sensitive to these possibilities

Landscape of possible MiniBooNE LEE final state topologies



Landscape of possible MiniBooNE LEE final state topologies



Landscape of possible MiniBooNE LEE final state topologies