Beyond the Standard Model Physics with Neutrinos

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Neutrino University, 29th July, 2021

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Outline

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- “SM” vs. “BSM” in Neutrino Physics

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- BSM in studying Neutrino Oscillations

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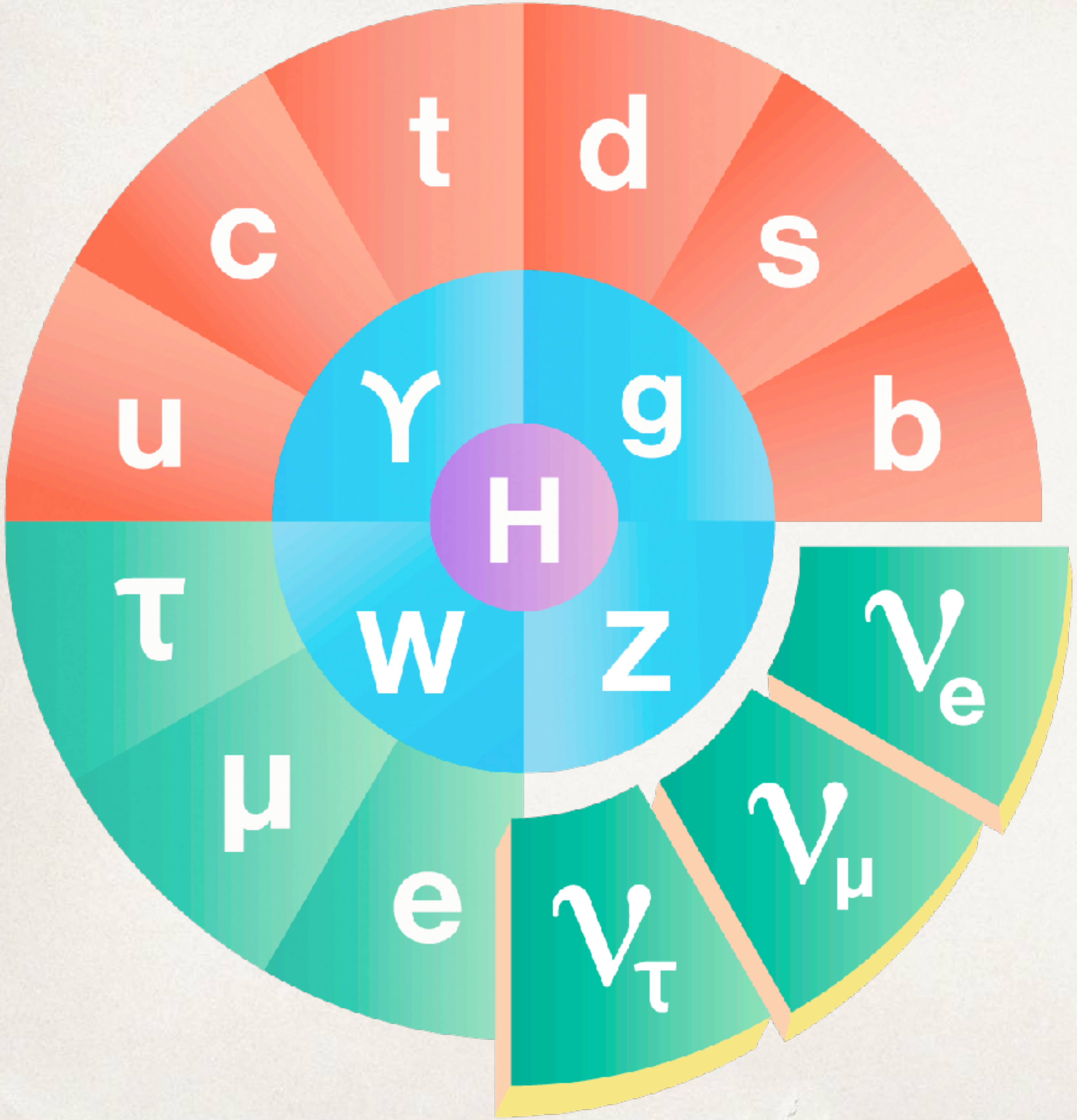
- BSM in studying Neutrino Oscillations
- BSM Searches at Neutrino Experiments

Neutrino Physics requires BSM



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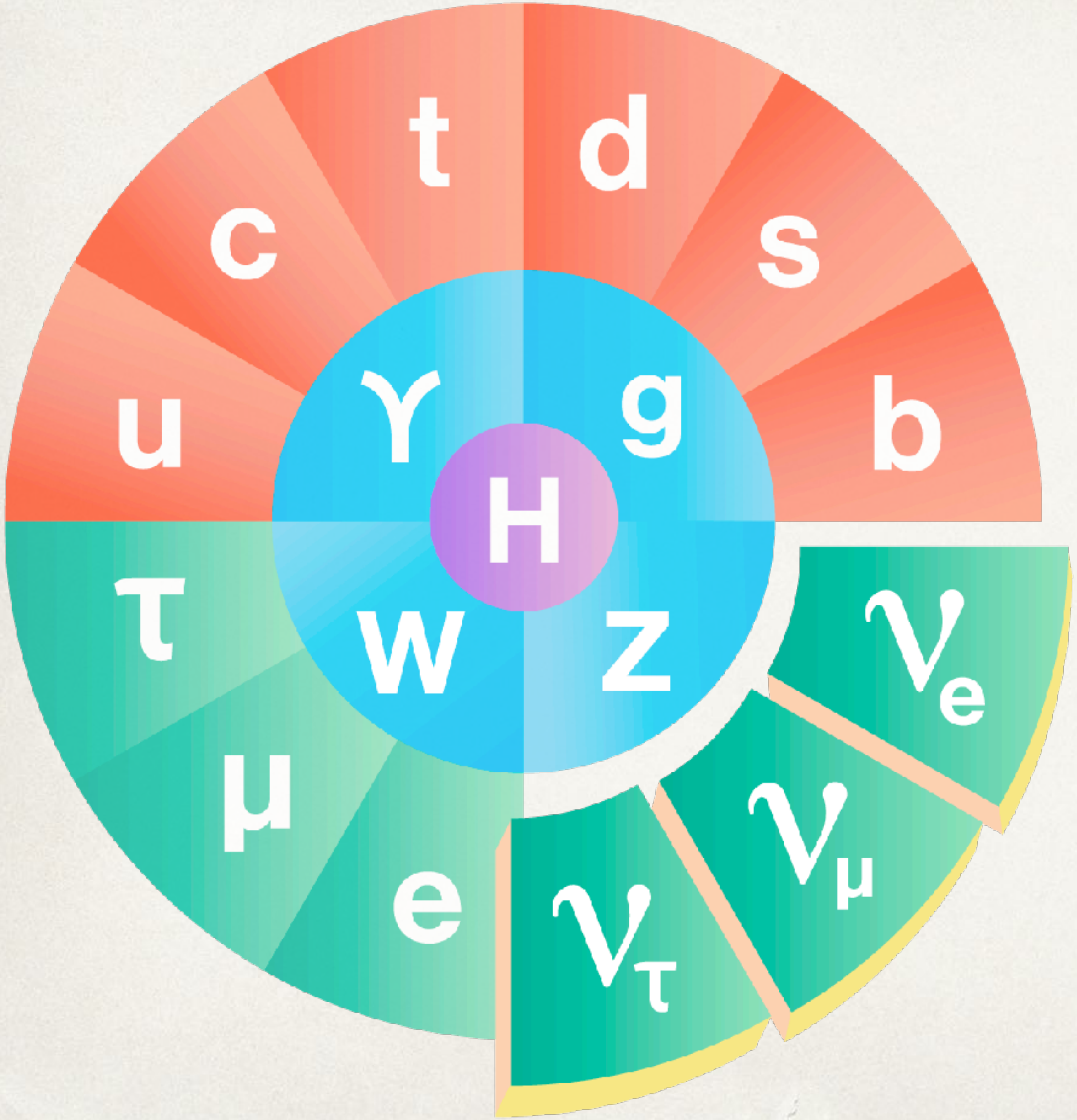

Neutrinos have mass.

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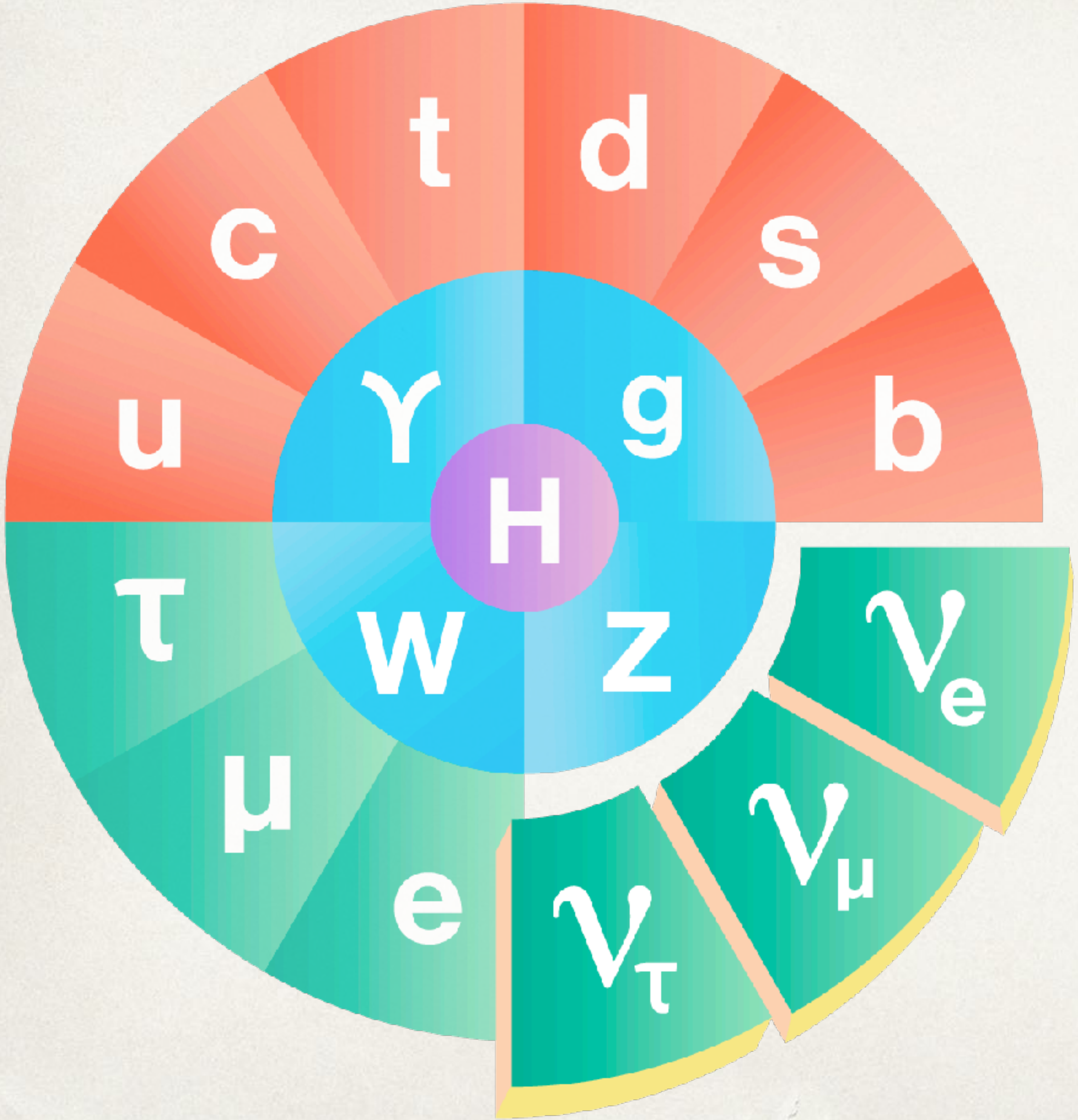

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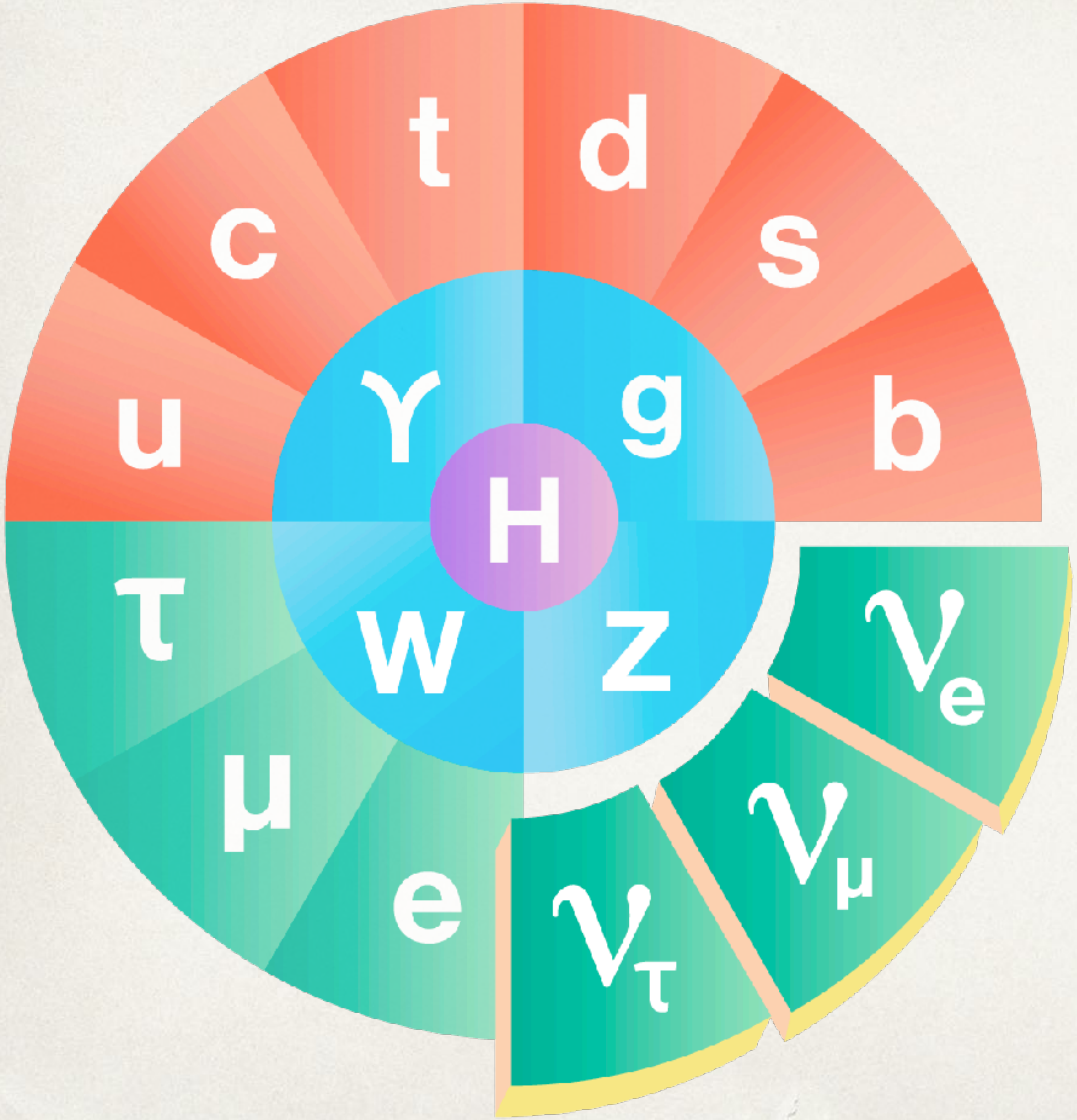

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New physics (fields and/or interactions) are required to explain this.

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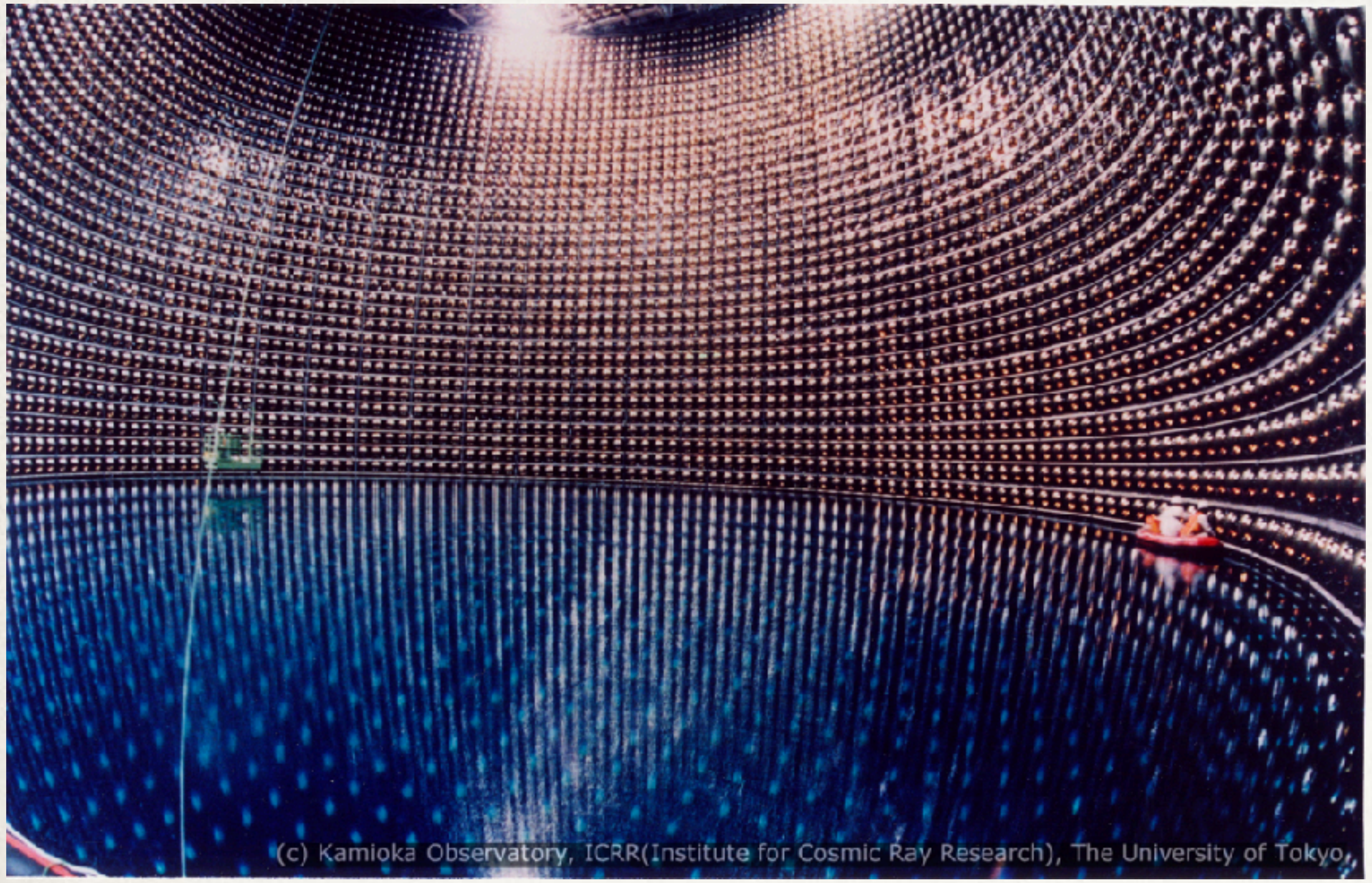

Anomalous neutrino “disappearance” in several sectors: atmospheric, solar, reactor…

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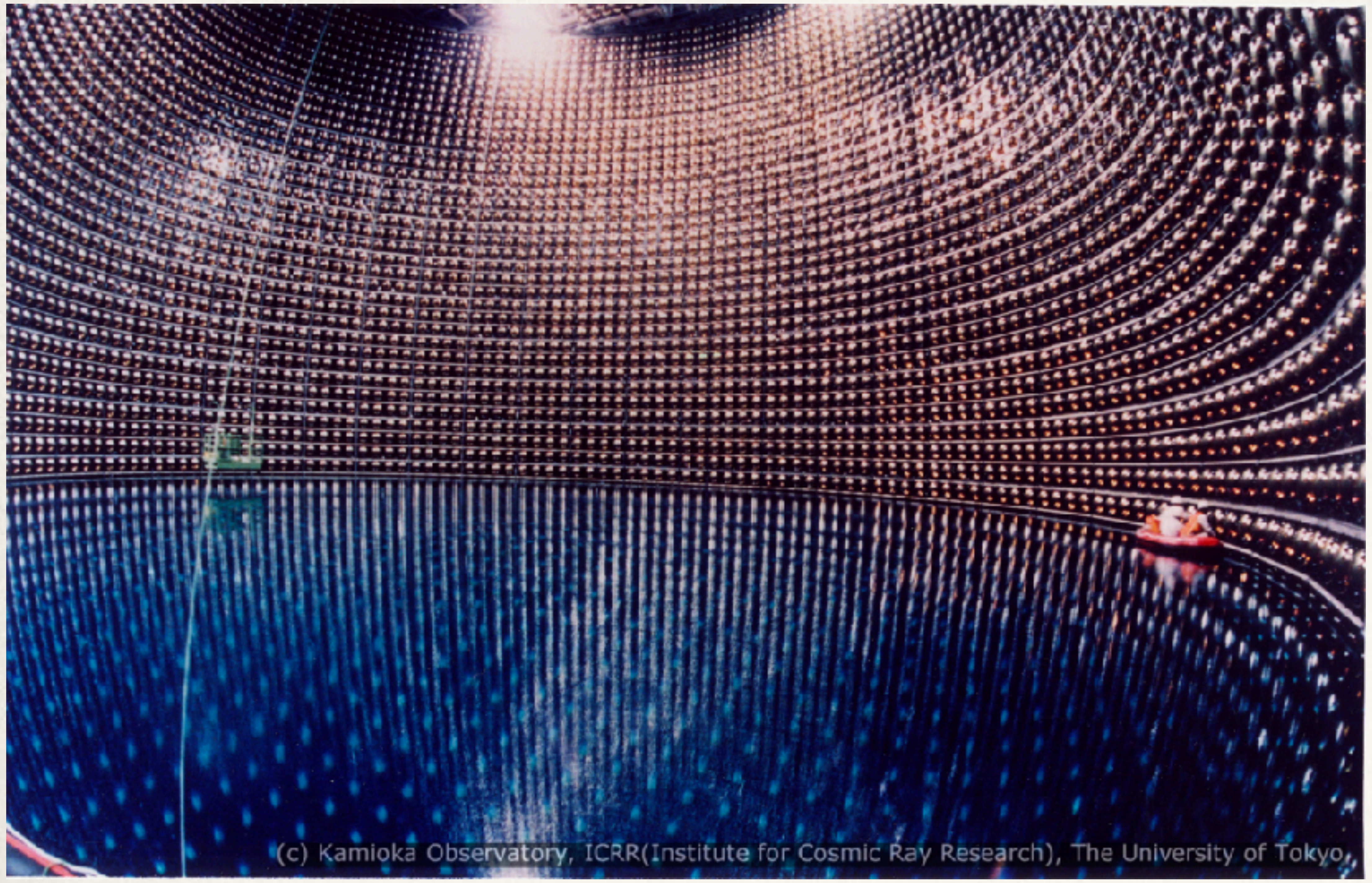

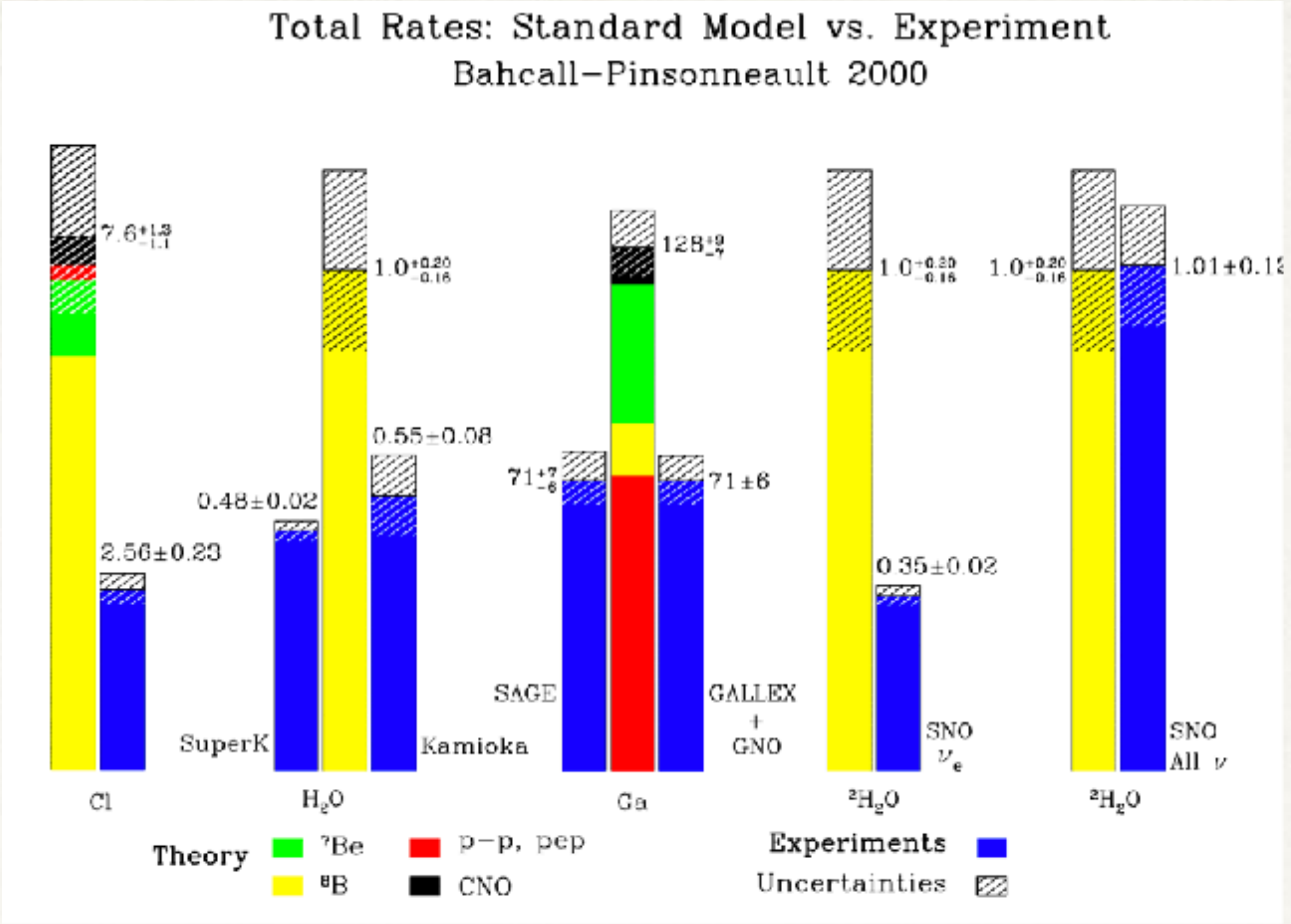

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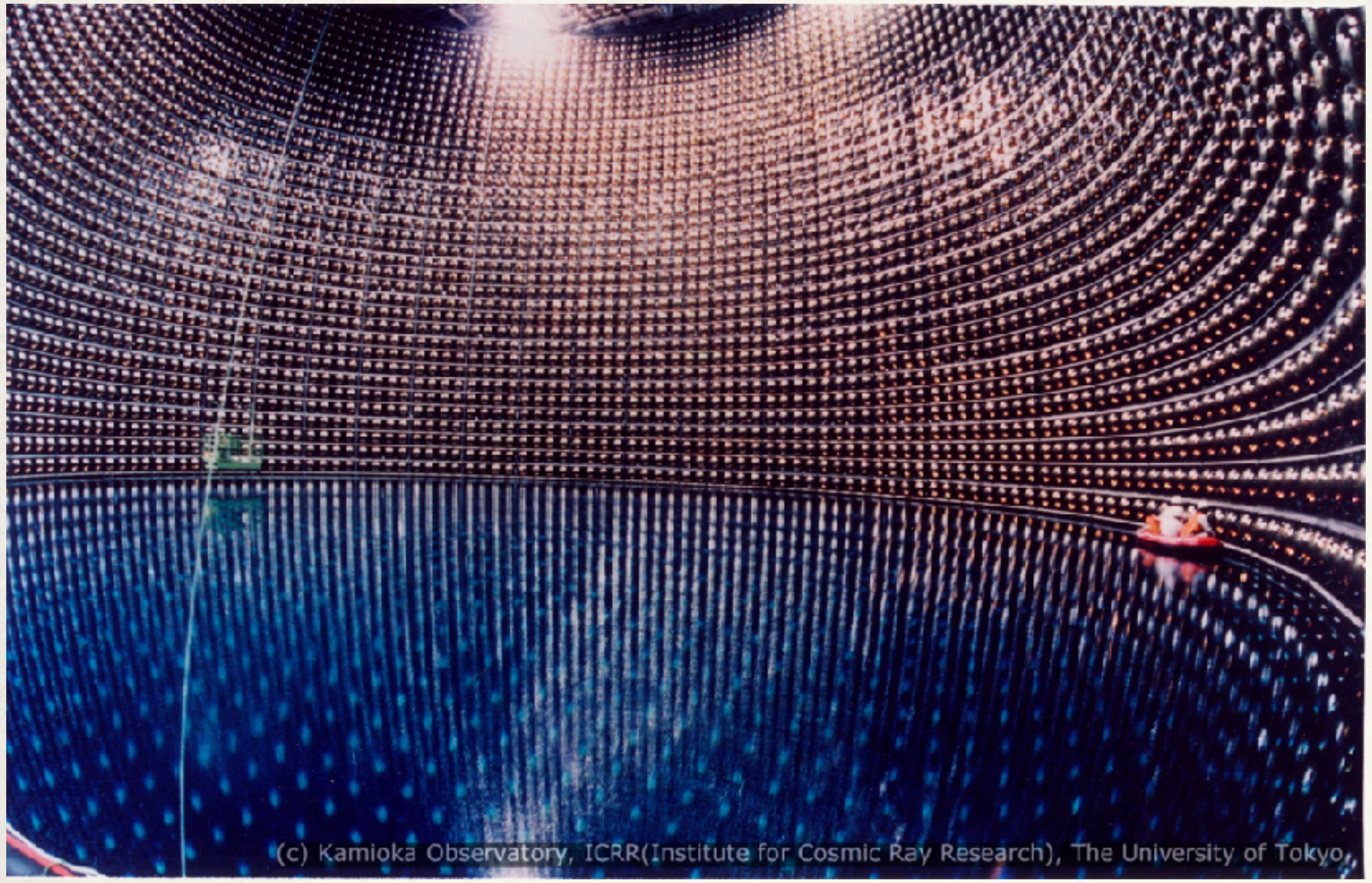

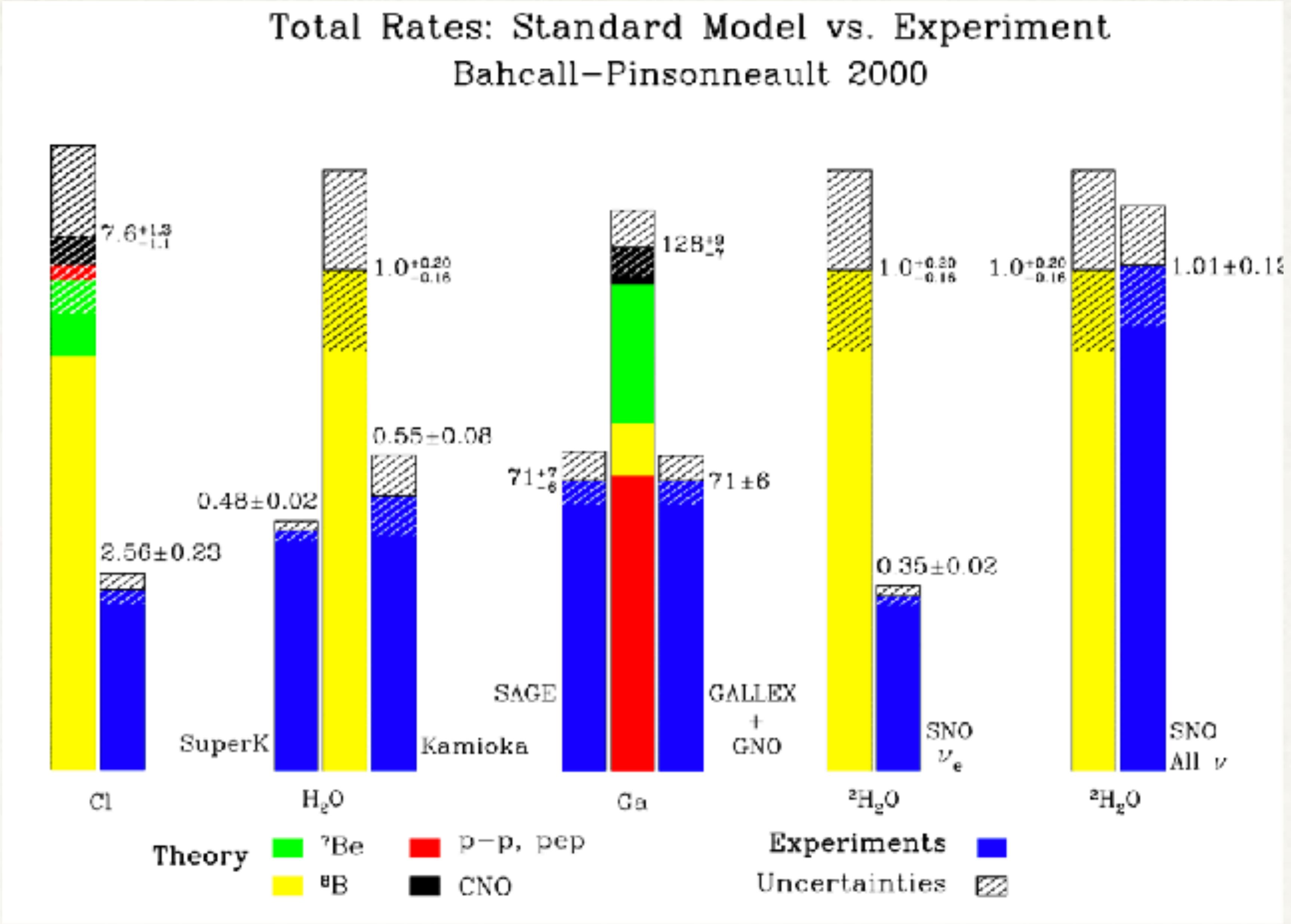

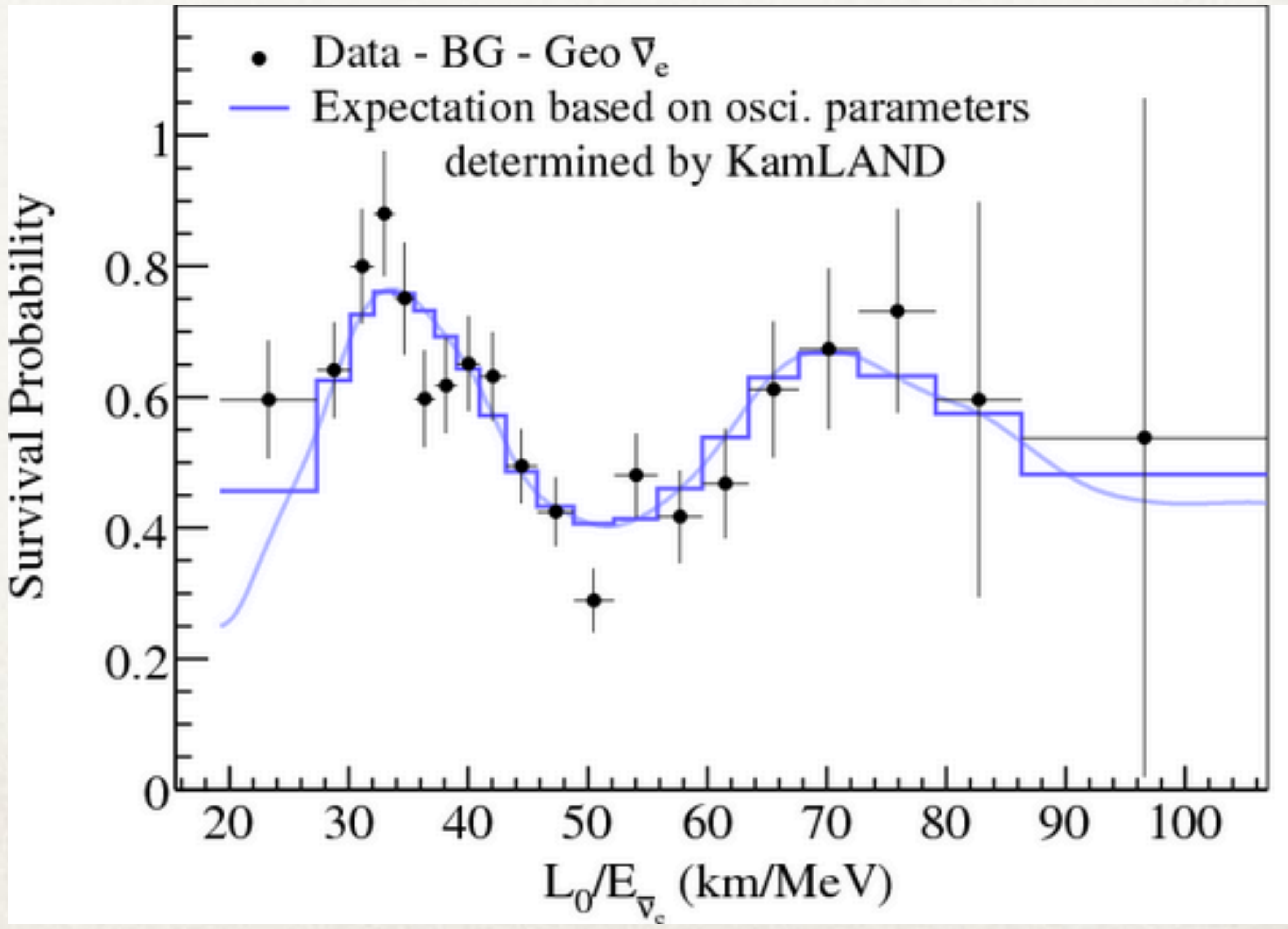

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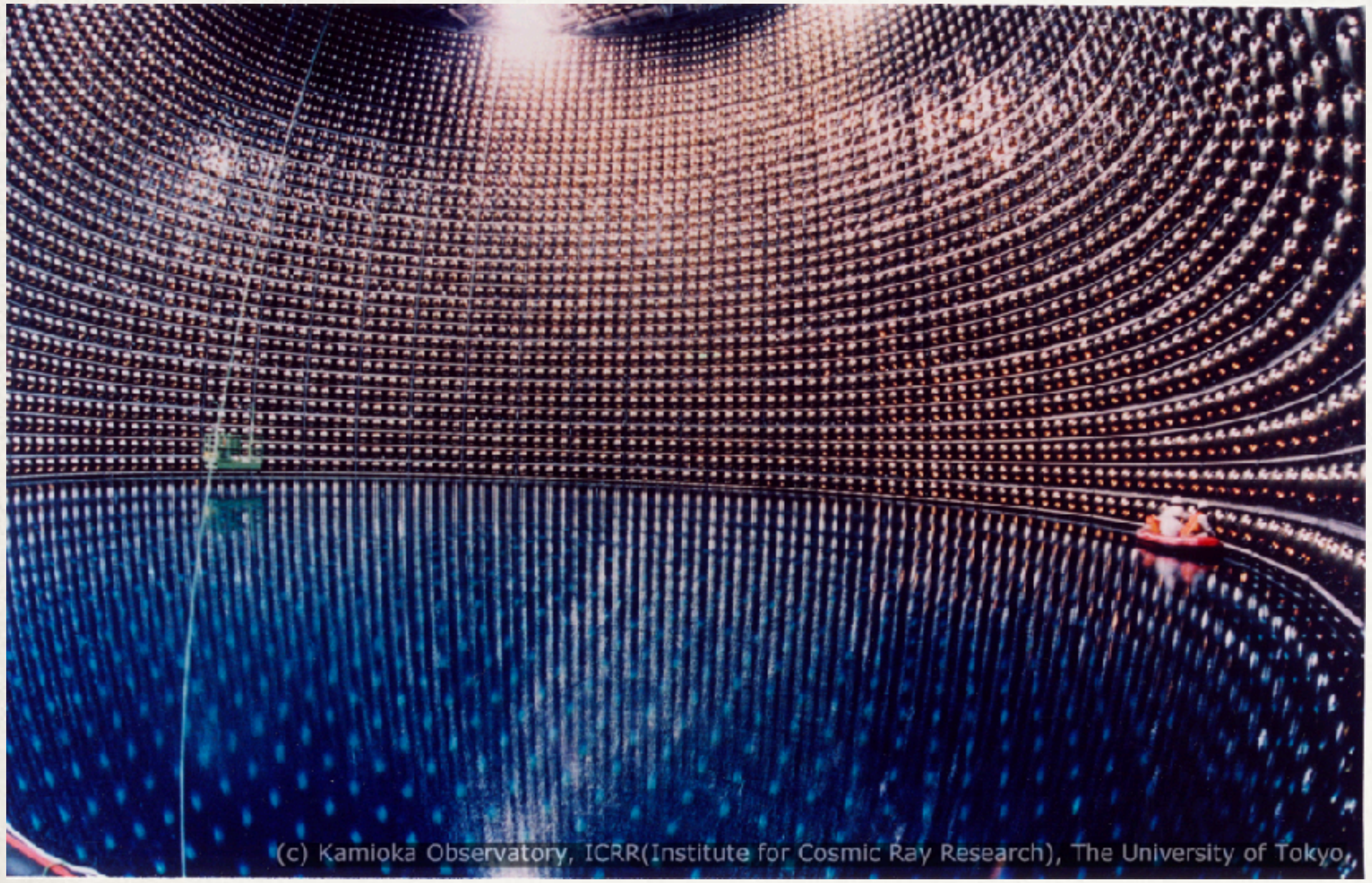

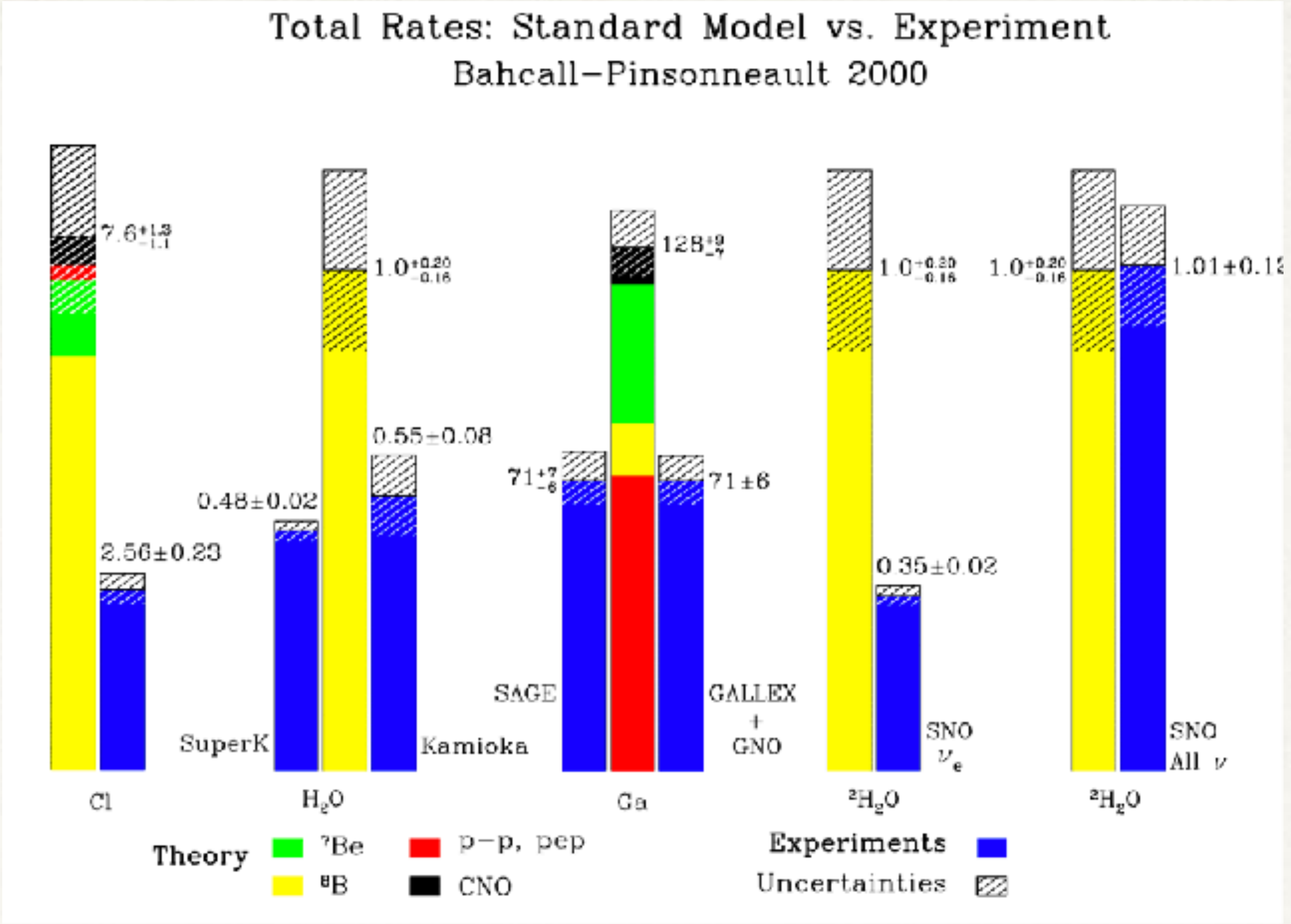

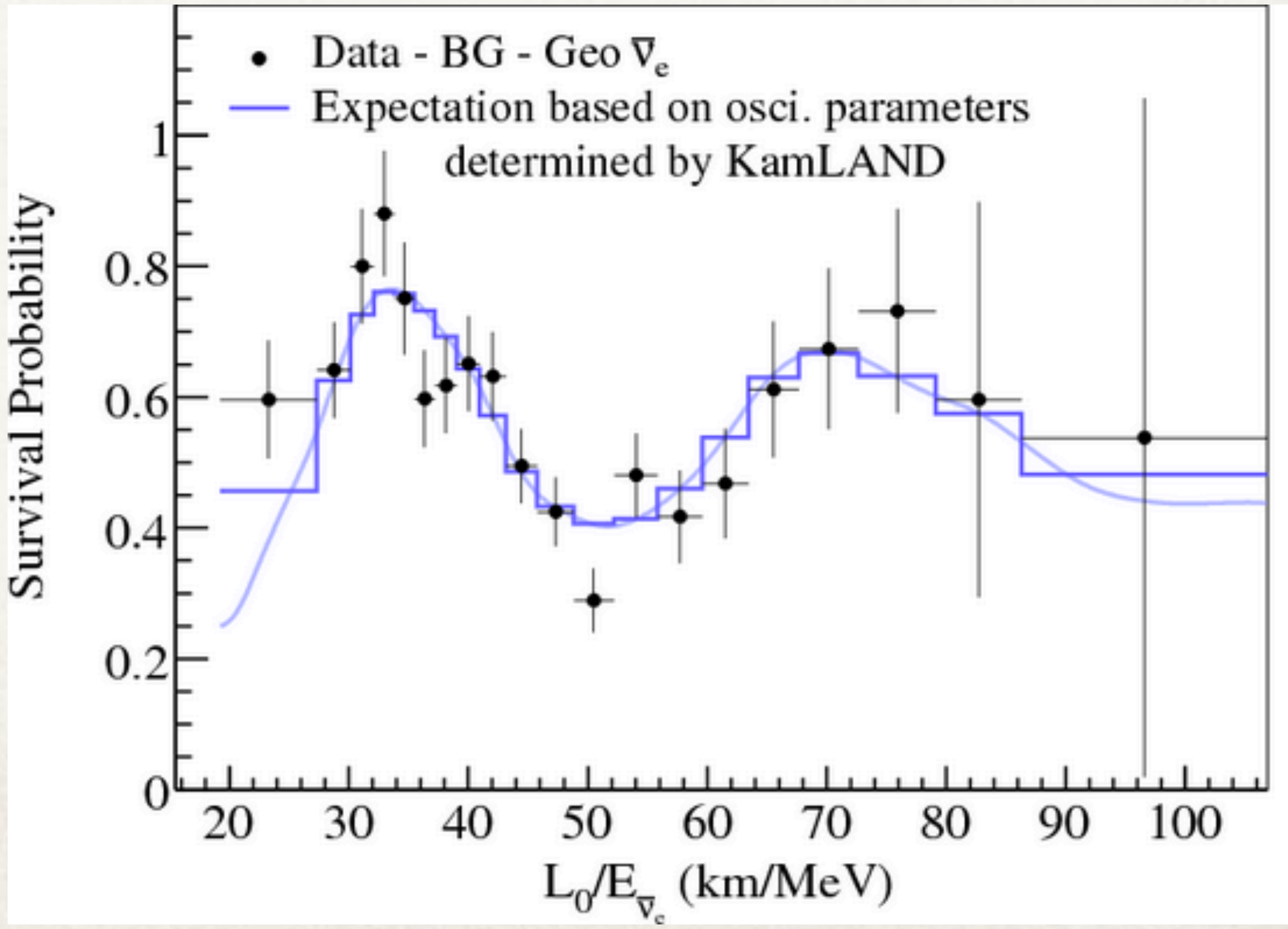

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Only satisfactory explanation of this and other data: neutrinos have (distinct) masses and mix.

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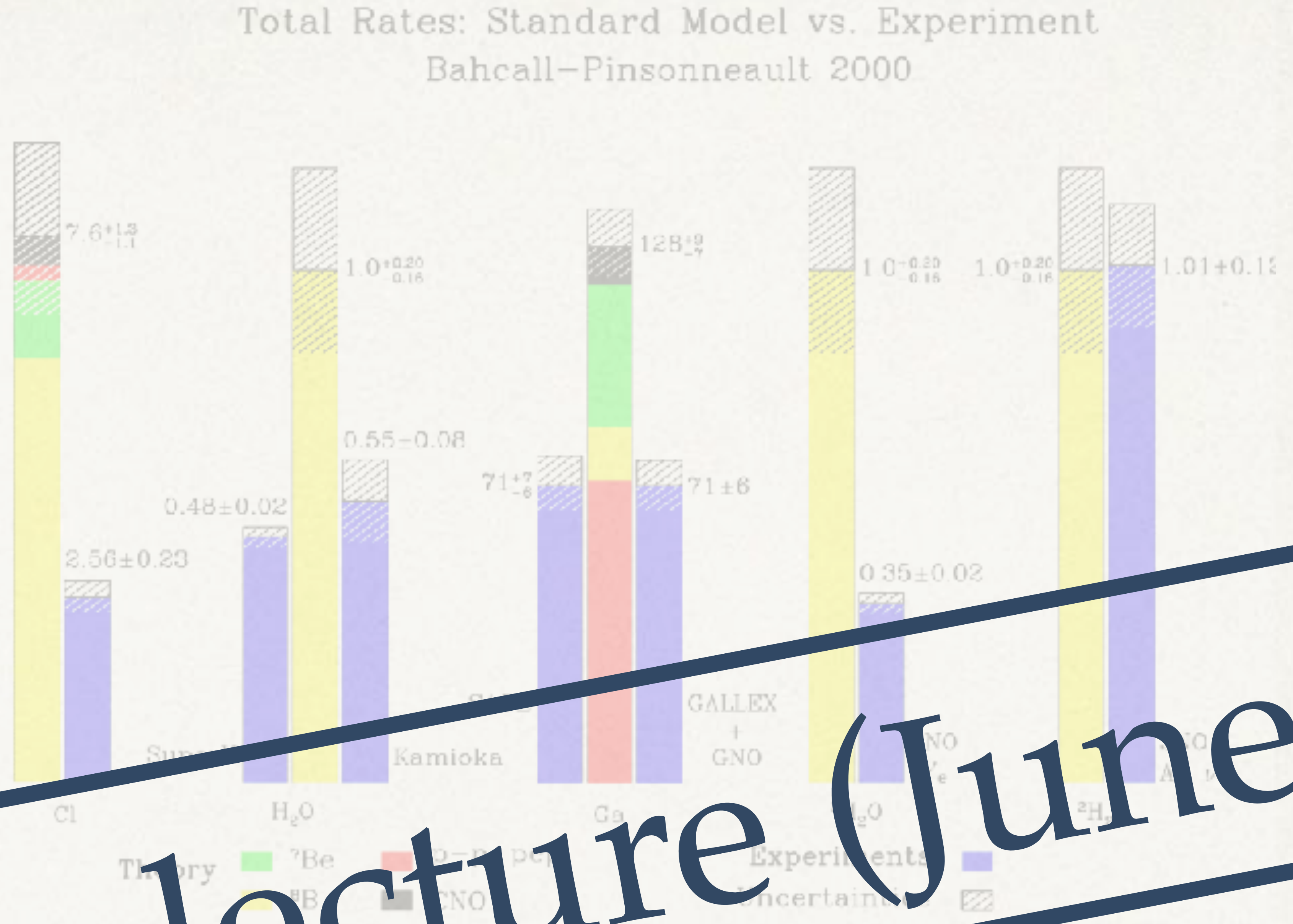

See Prof. Pascoli's lecture (June 3rd)

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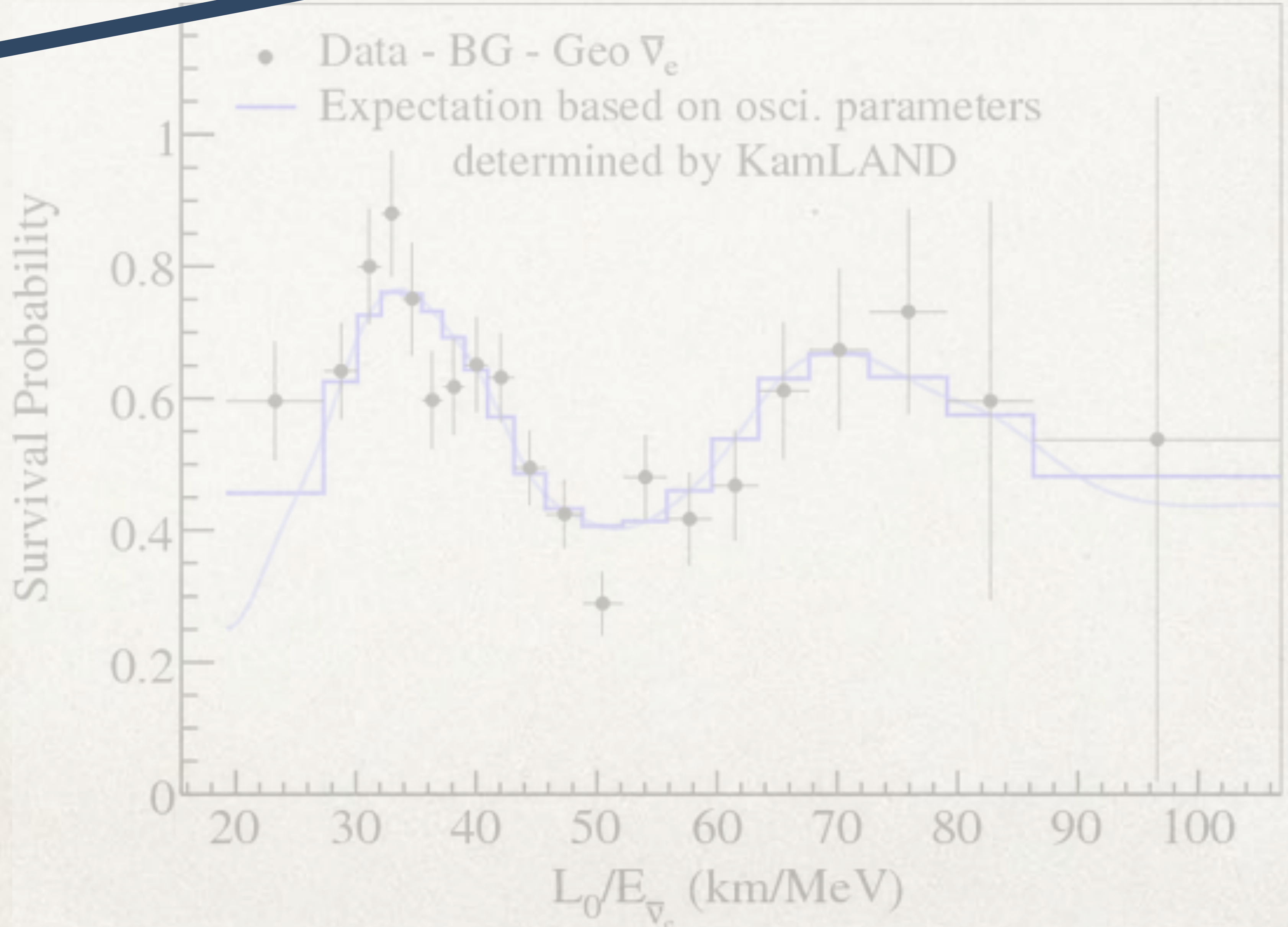

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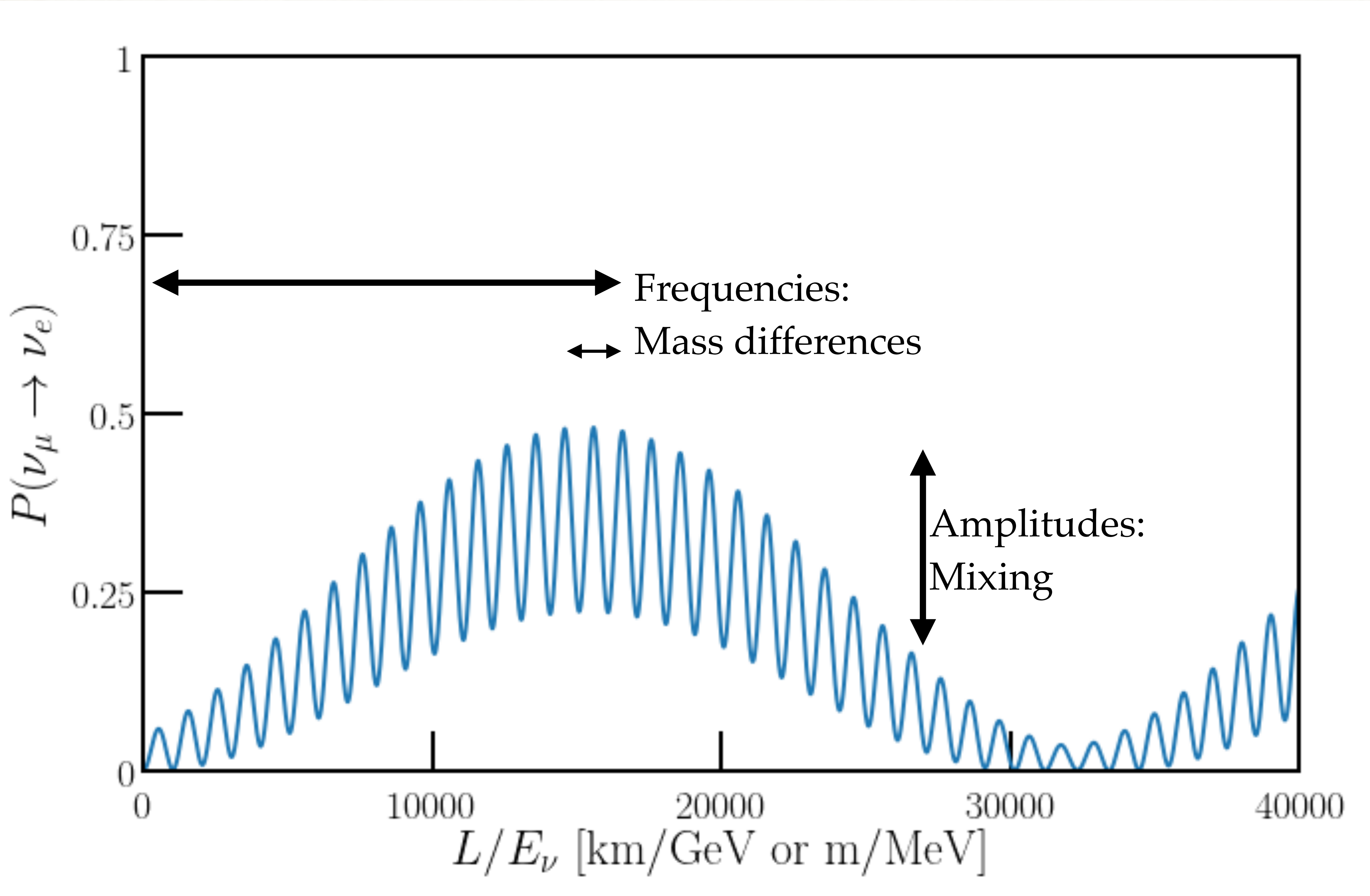
Oscillations Refresher



Oscillation probabilities depend (predominantly) on baseline length divided by neutrino energy.

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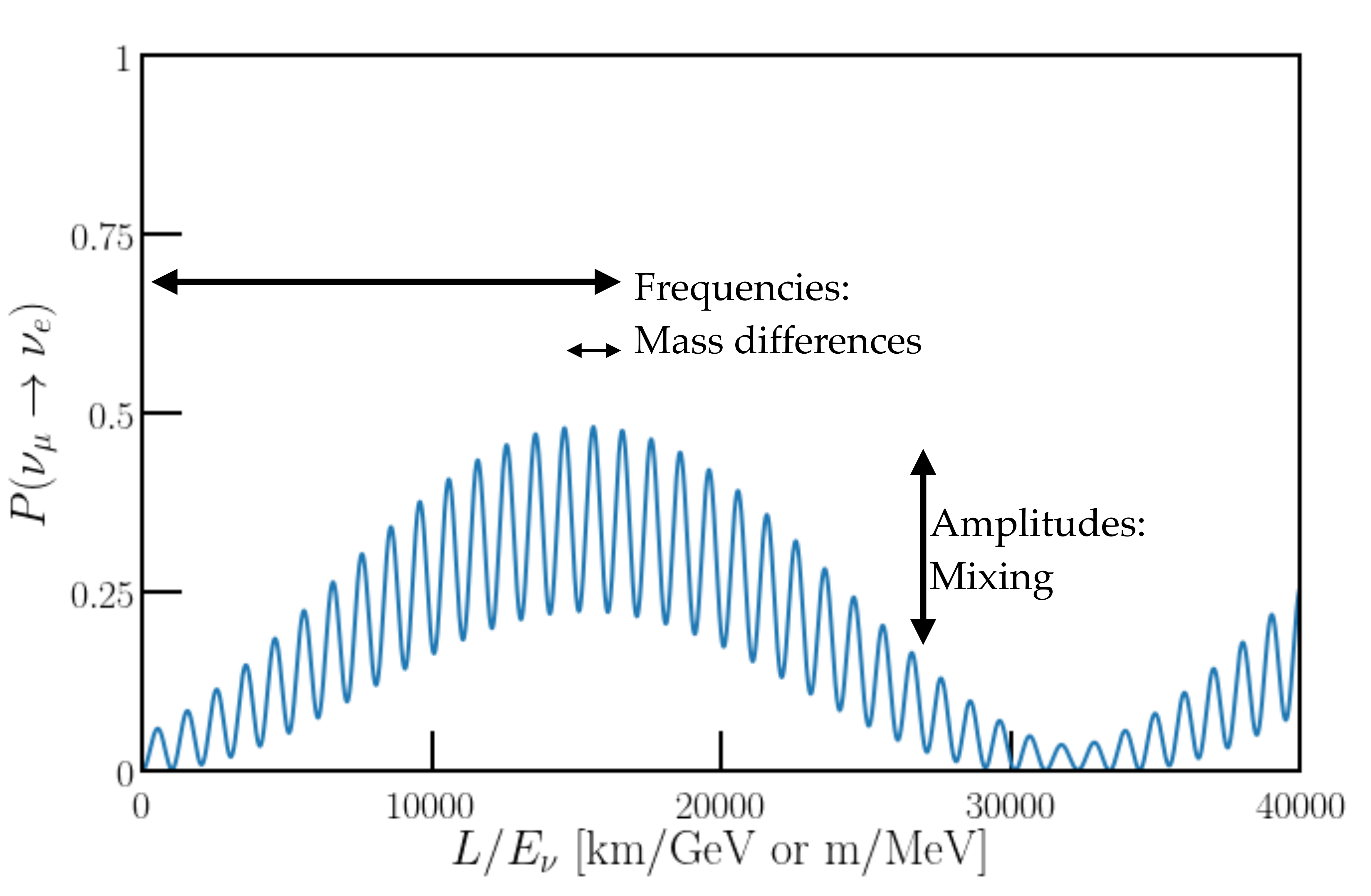

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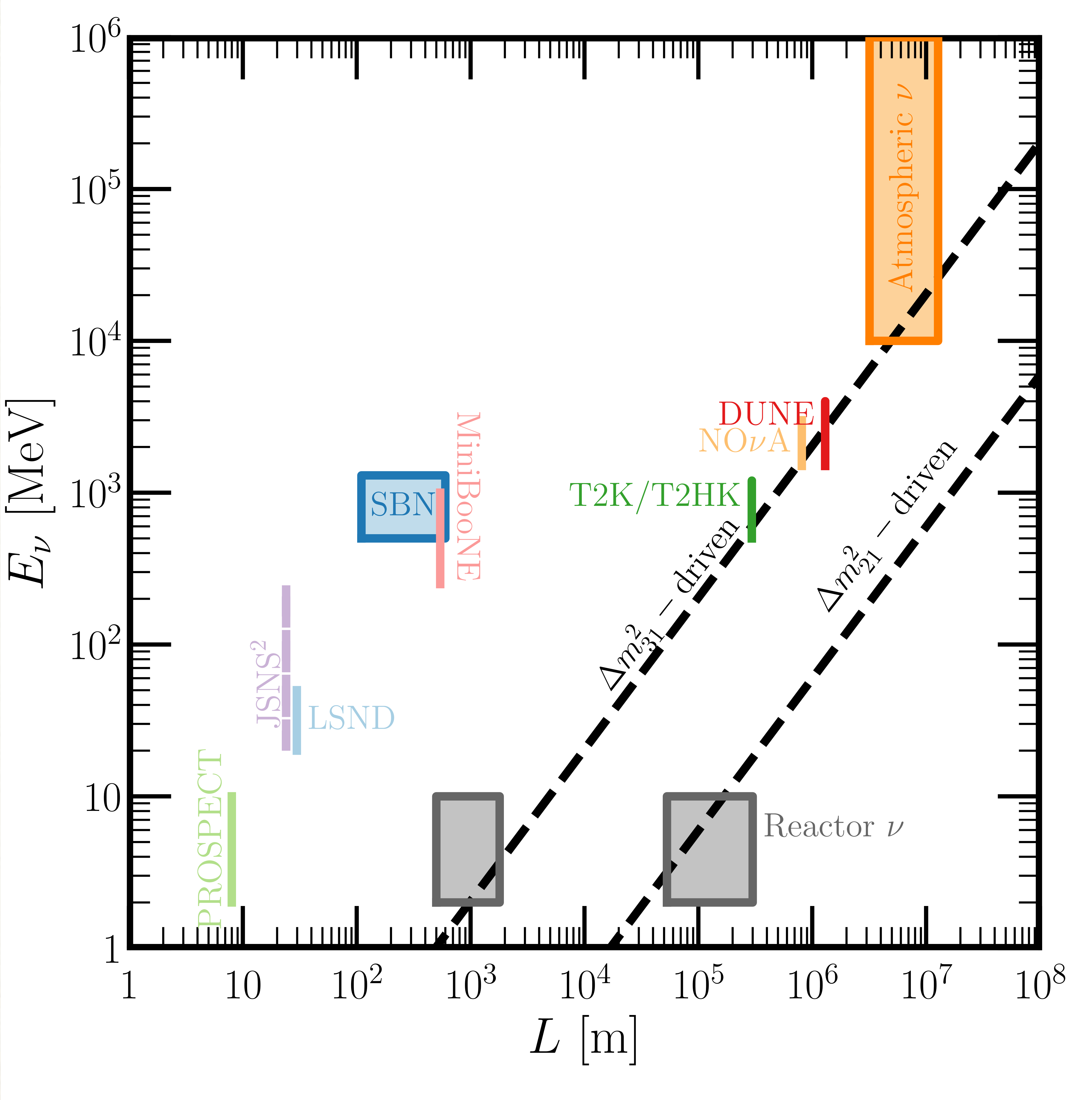

Experiments have been/will be performed for a variety of baselines and energies.

Requirements for Oscillations: Mixing and Mass Differences

Mixing between mass and flavor eigenstates: 3x3 unitary matrix (PMNS Matrix)

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix}$$

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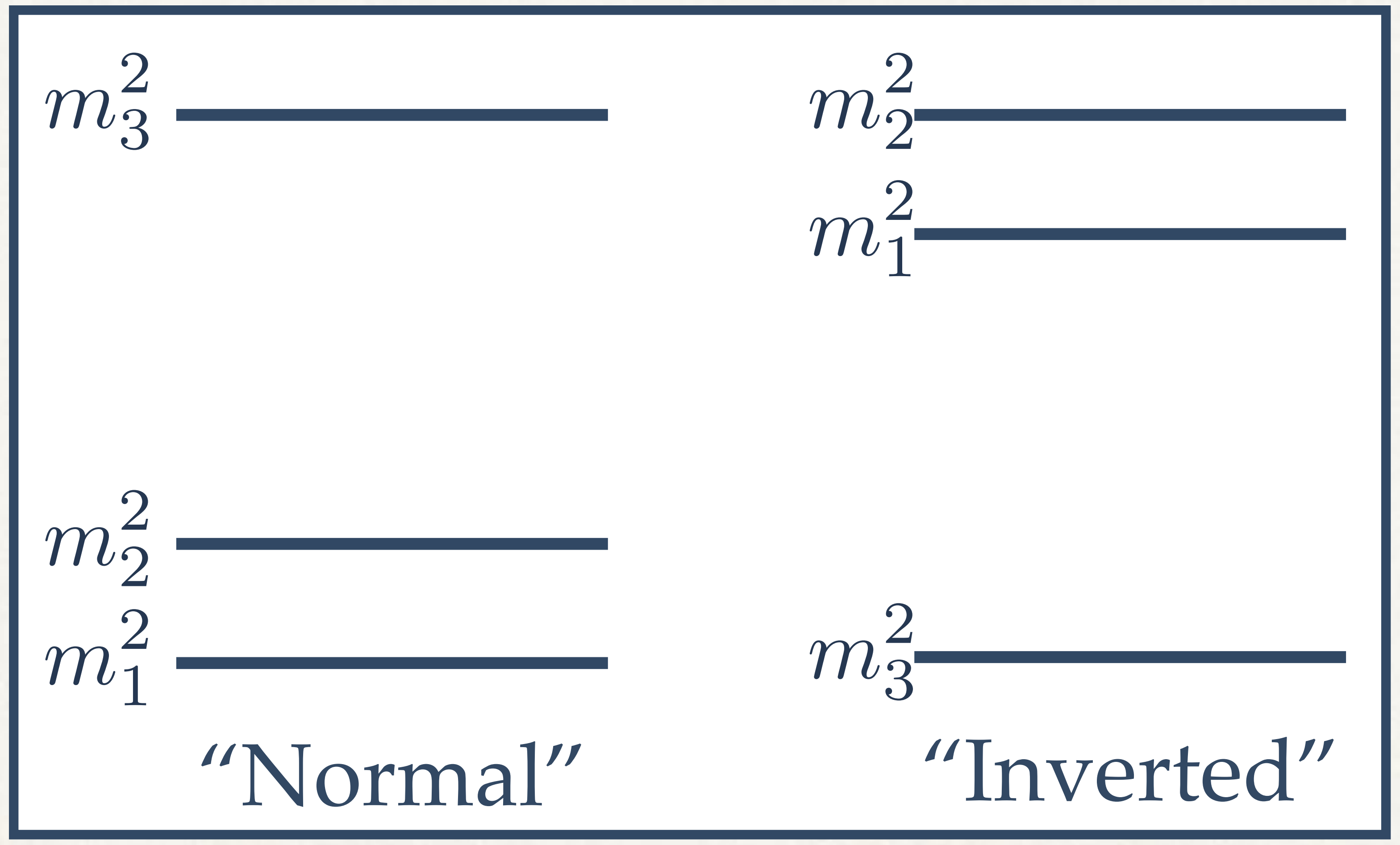
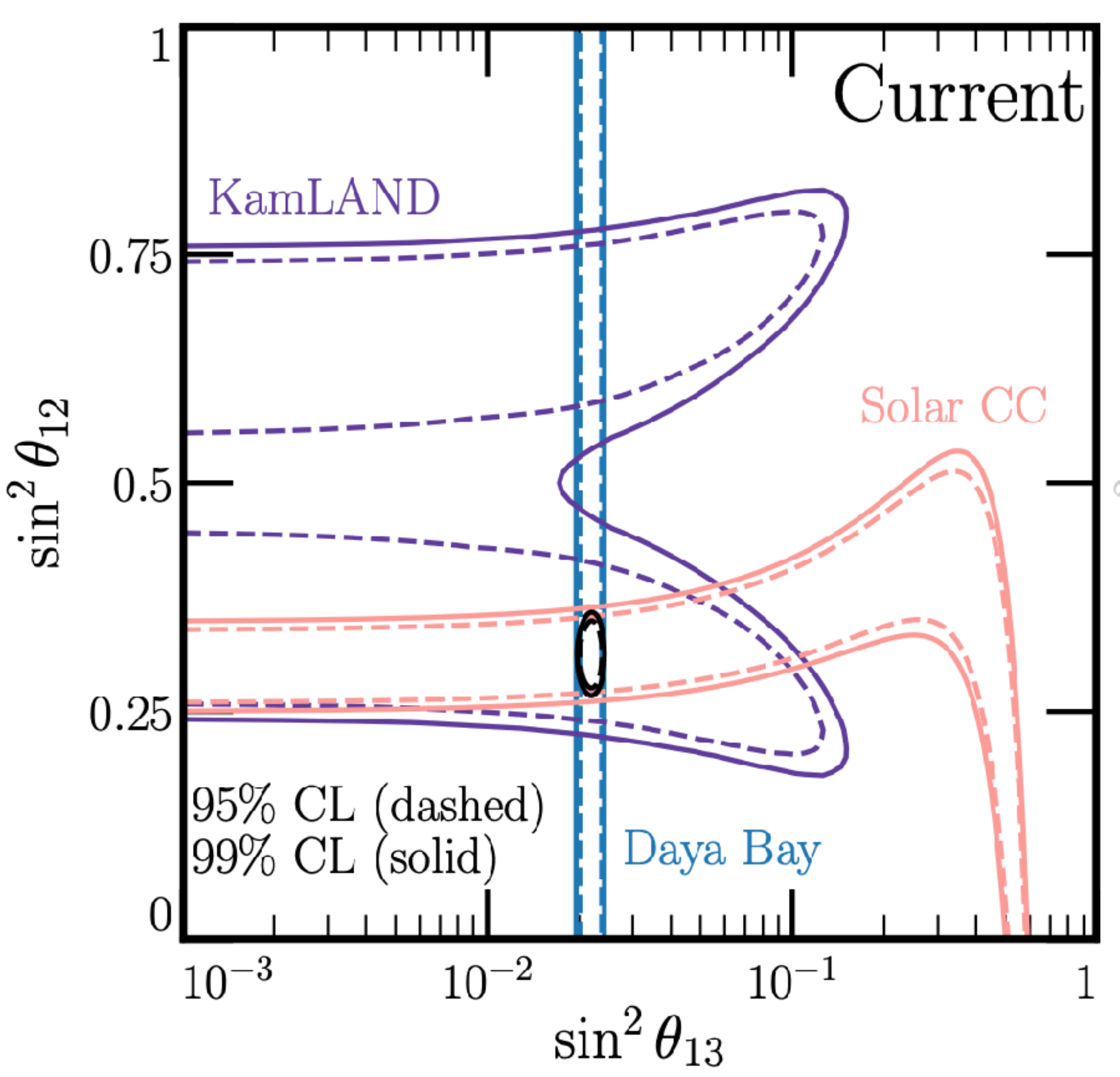
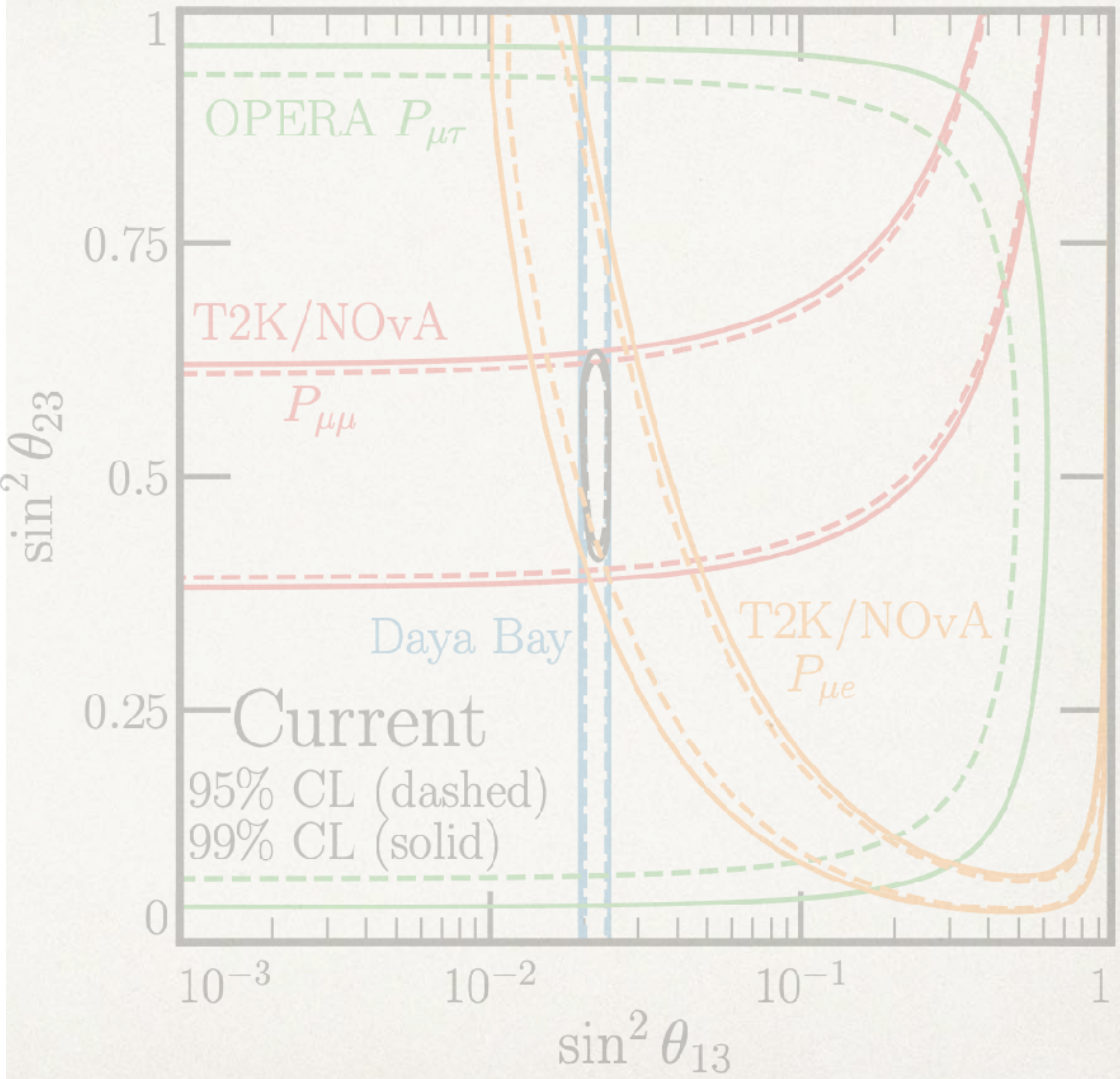
Differences between masses: relative phase acquired between different eigenstates during propagation.



- Because oscillations to date always involve ultrarelativistic neutrinos, we can only access their mass-squared differences.

Current Mixing Angle Knowledge





Black regions: Combined fit of current data.

Ellis, KJK, Li [2008.01088]

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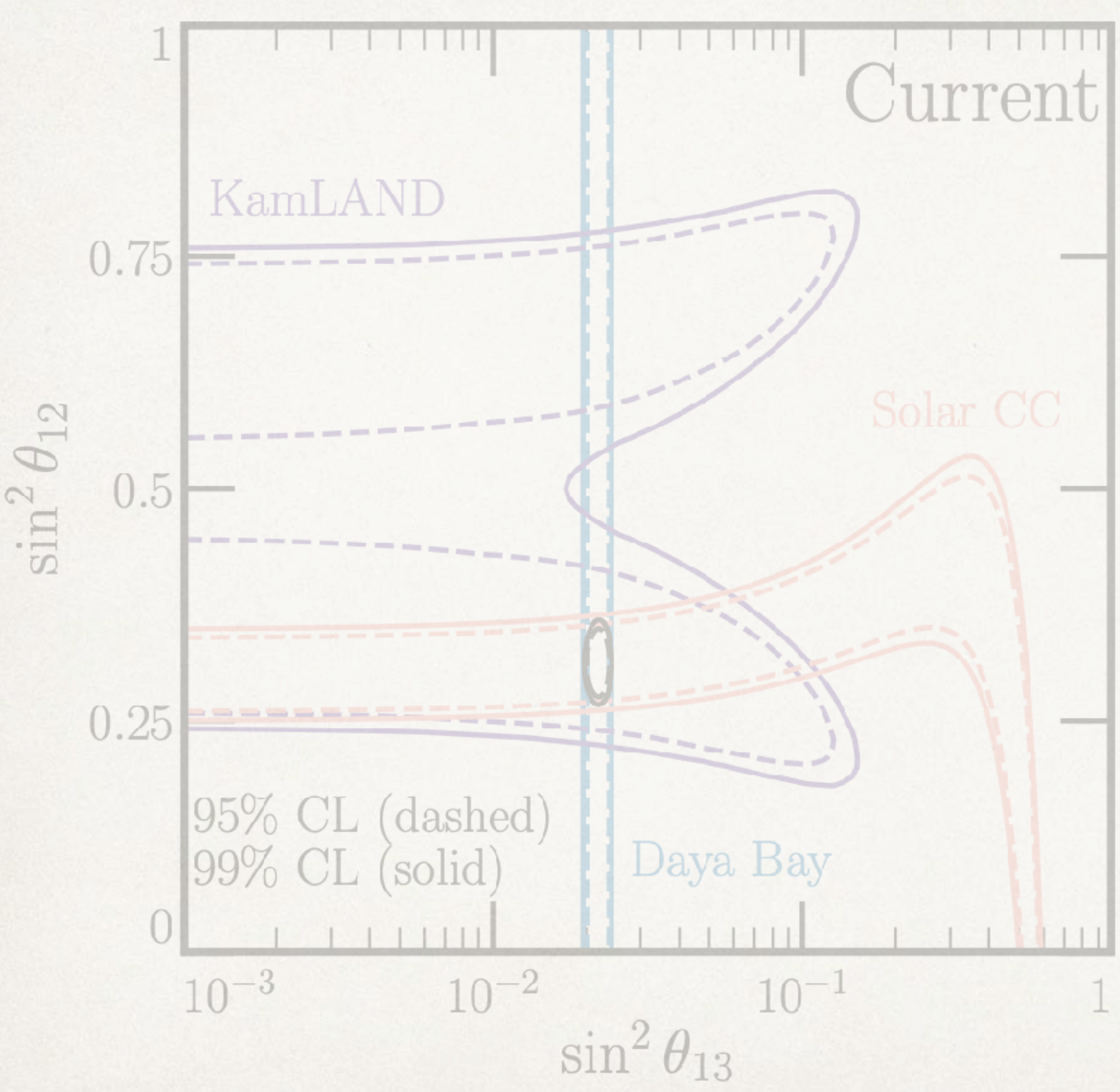

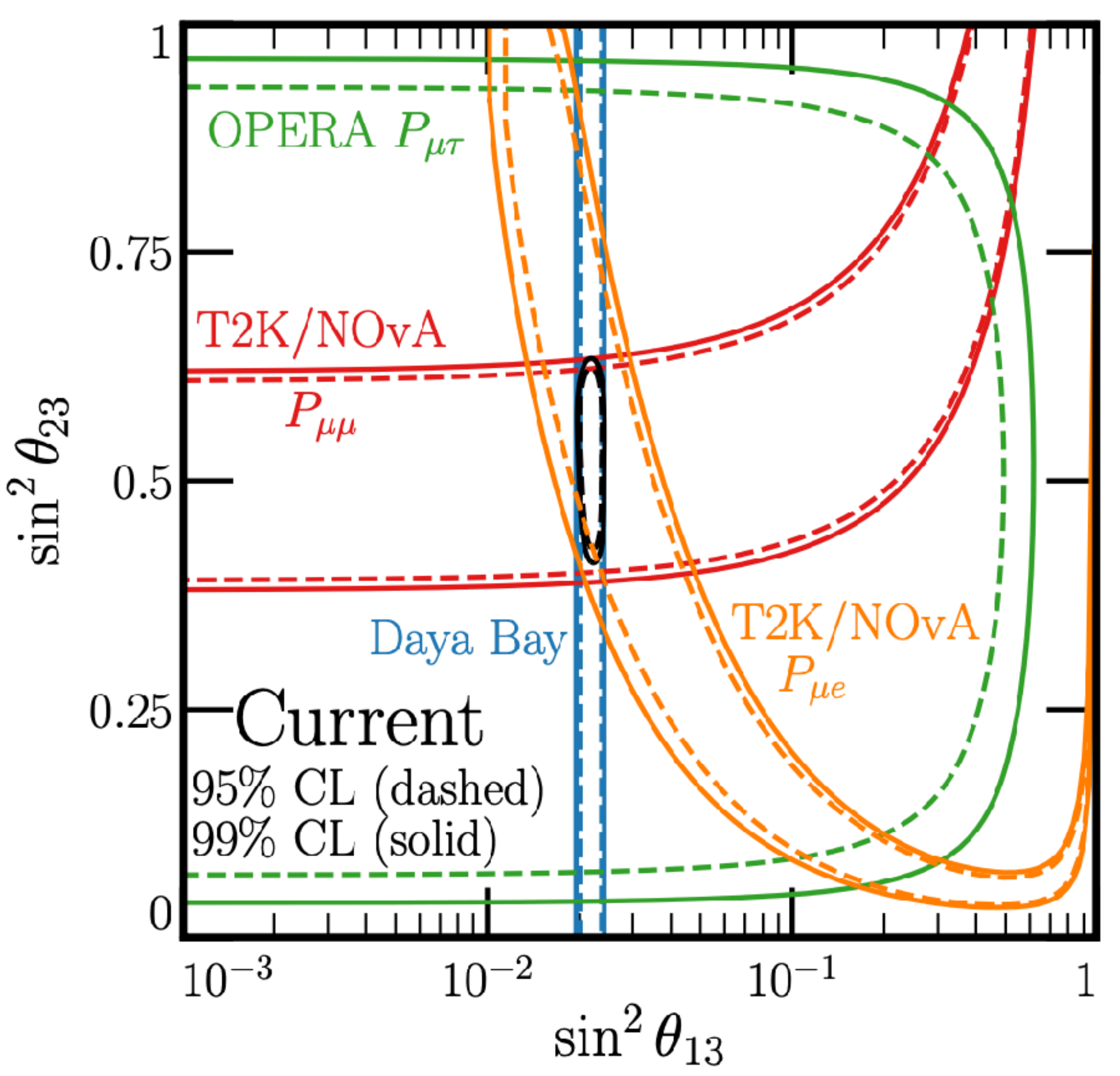

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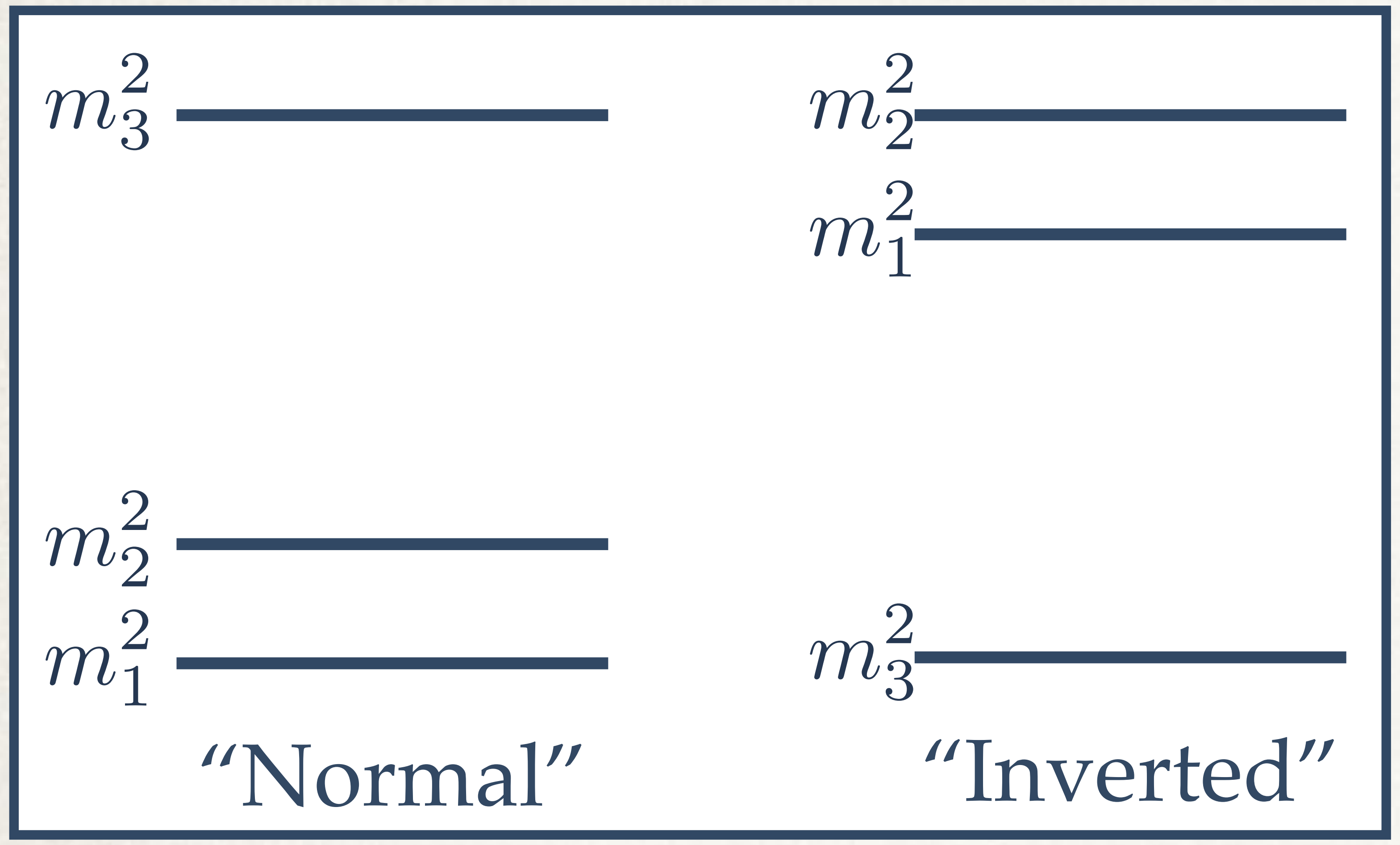
Masses/Mass ordering



- Combination of solar experiments/reactor antineutrino experiments measure $\Delta m_{21}^2 \equiv m_2^2 - m_1^2$
- Atmospheric/long-baseline muon disappearance/short-baseline reactor experiments measure $\Delta m_{31}^2 \equiv \left| m_3^2 - m_1^2 \right|$

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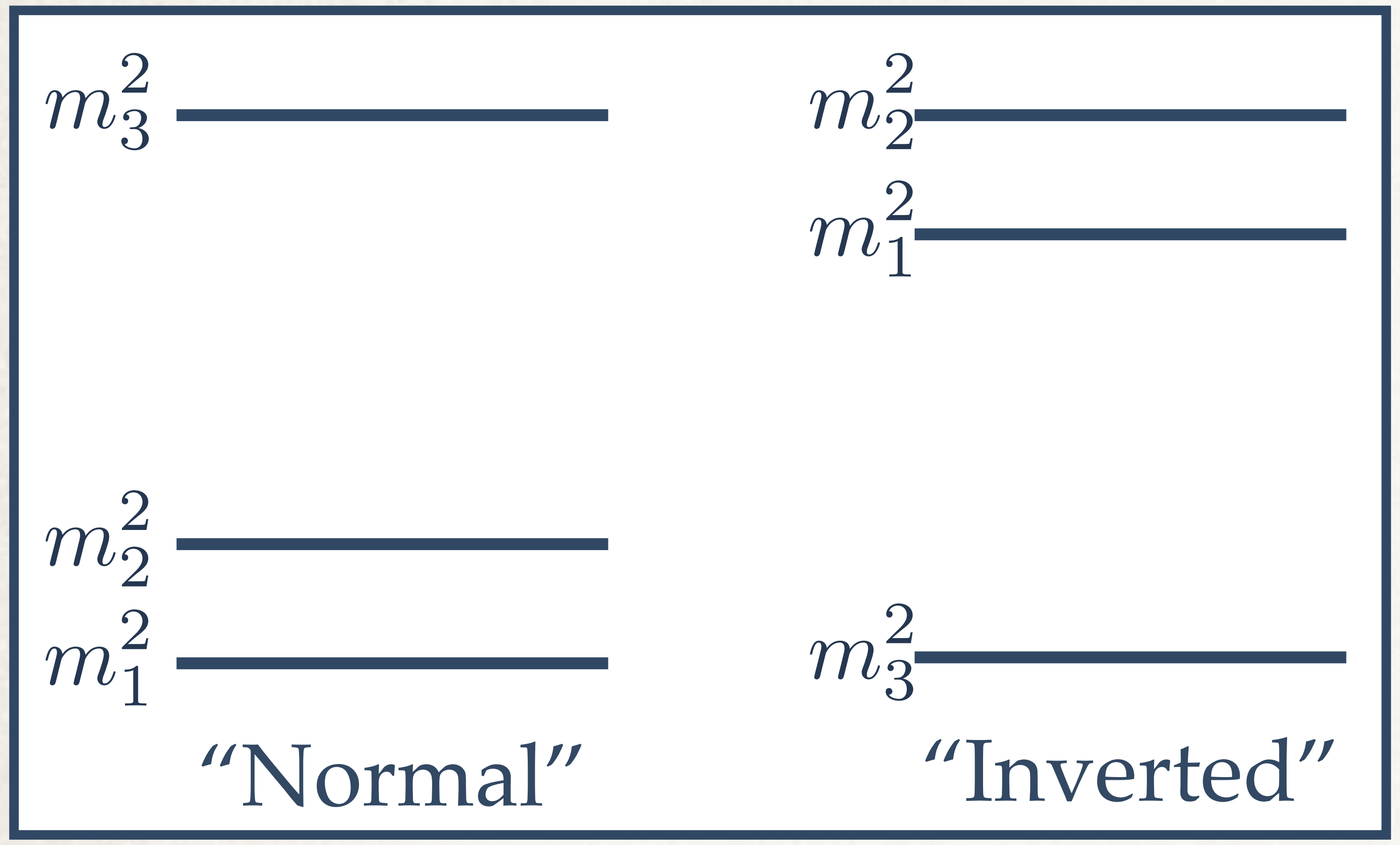

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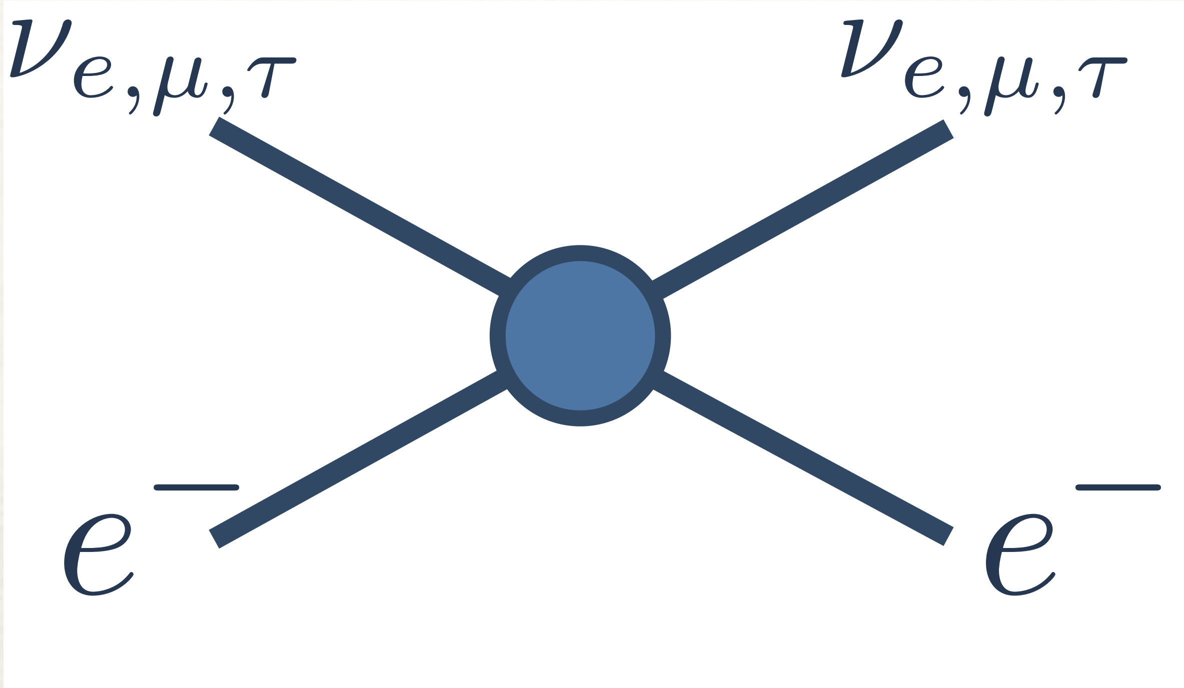
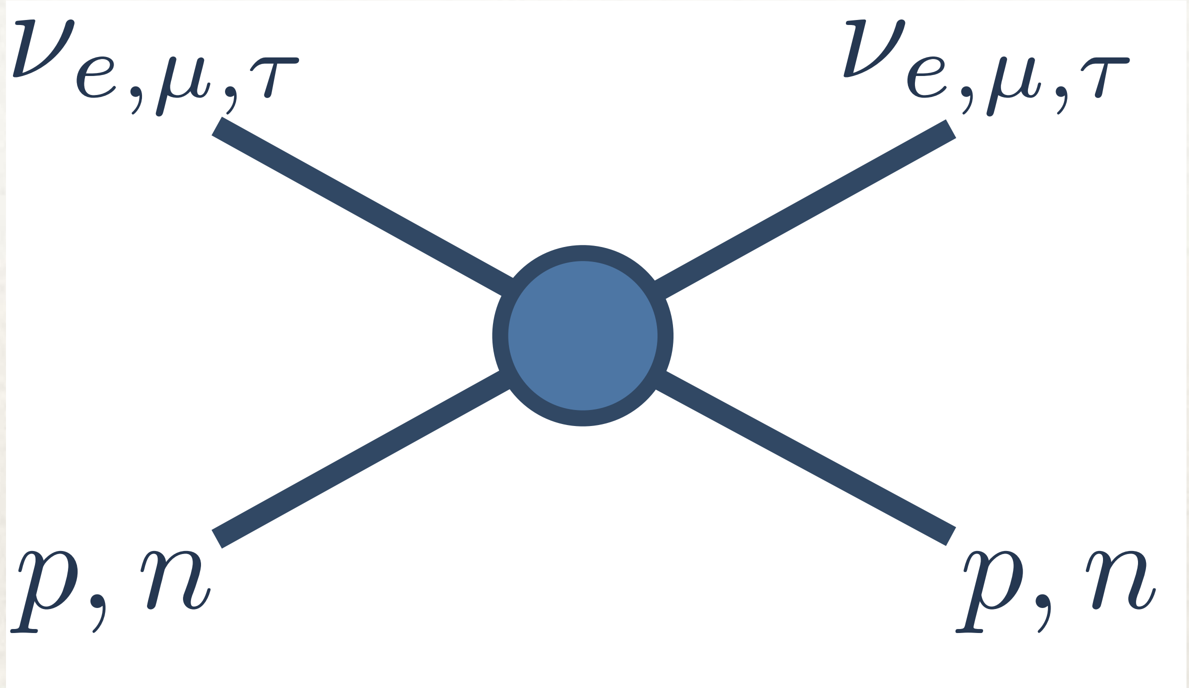
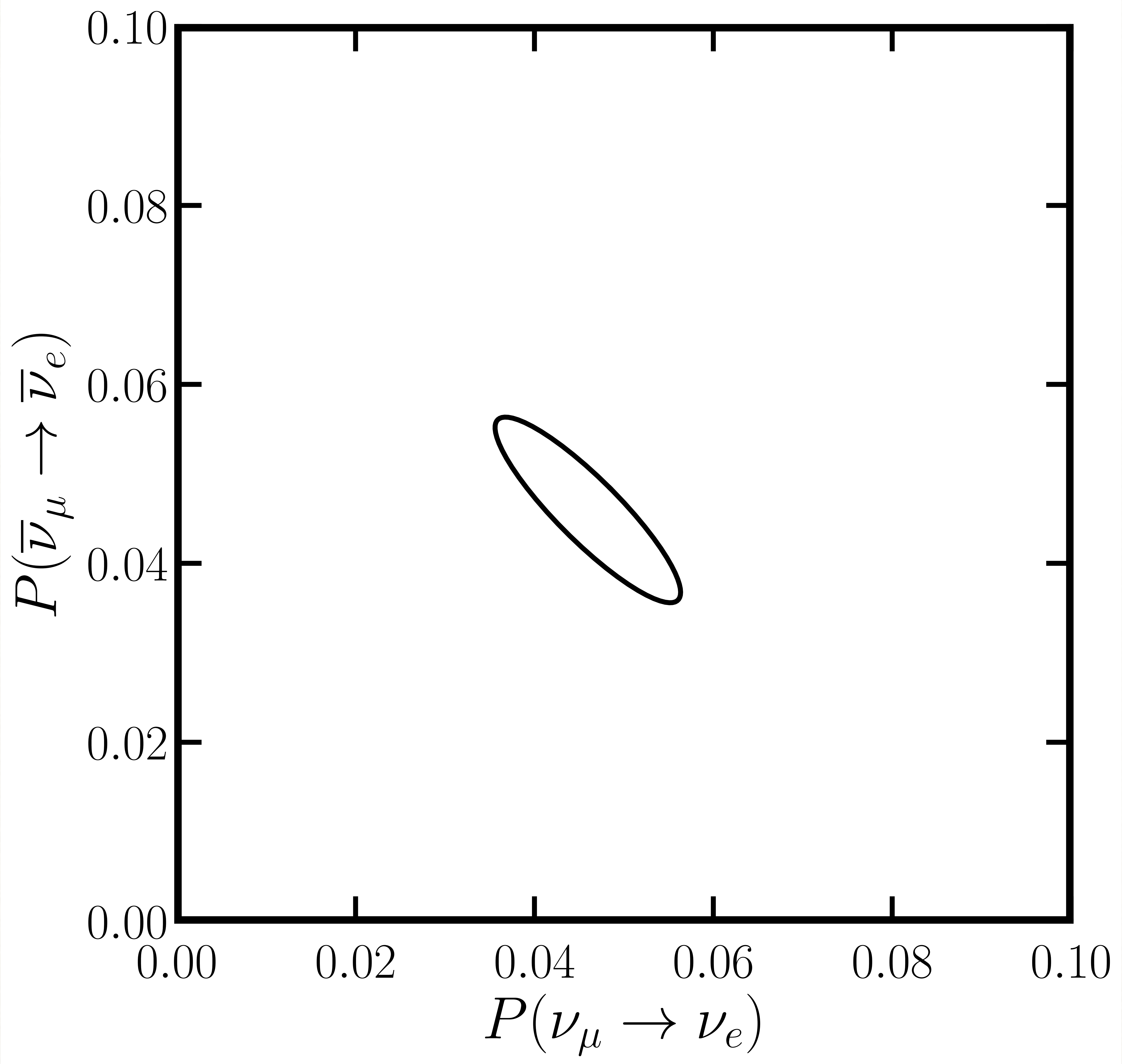
- One way to determine the mass ordering: measure electron neutrino appearance after muon neutrinos propagate through matter





Matter effects in Neutrino Oscillations



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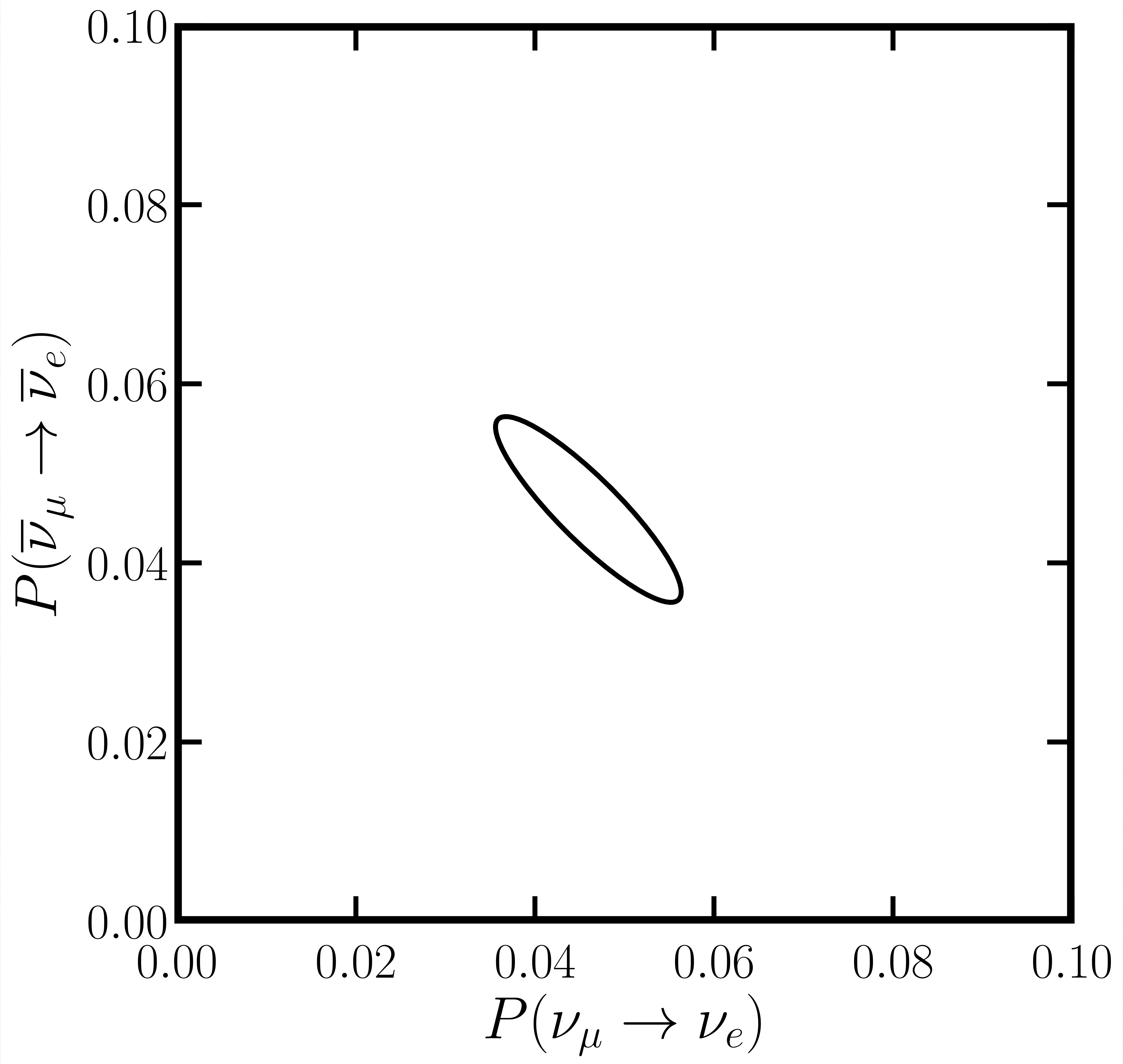

- For a fixed baseline length and neutrino energy, fix the mixing angles and mass-squared splittings to their best-fit values.
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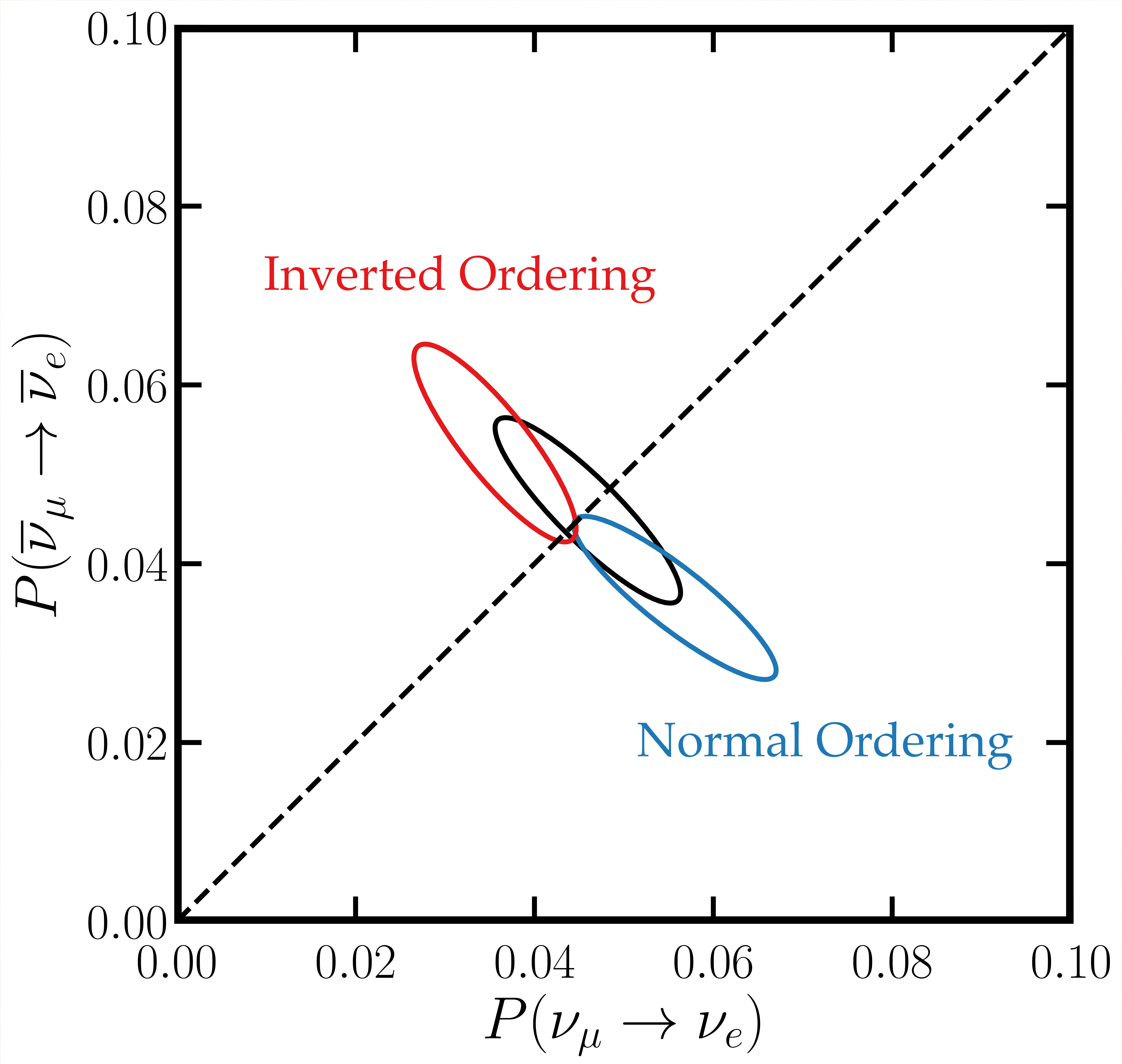


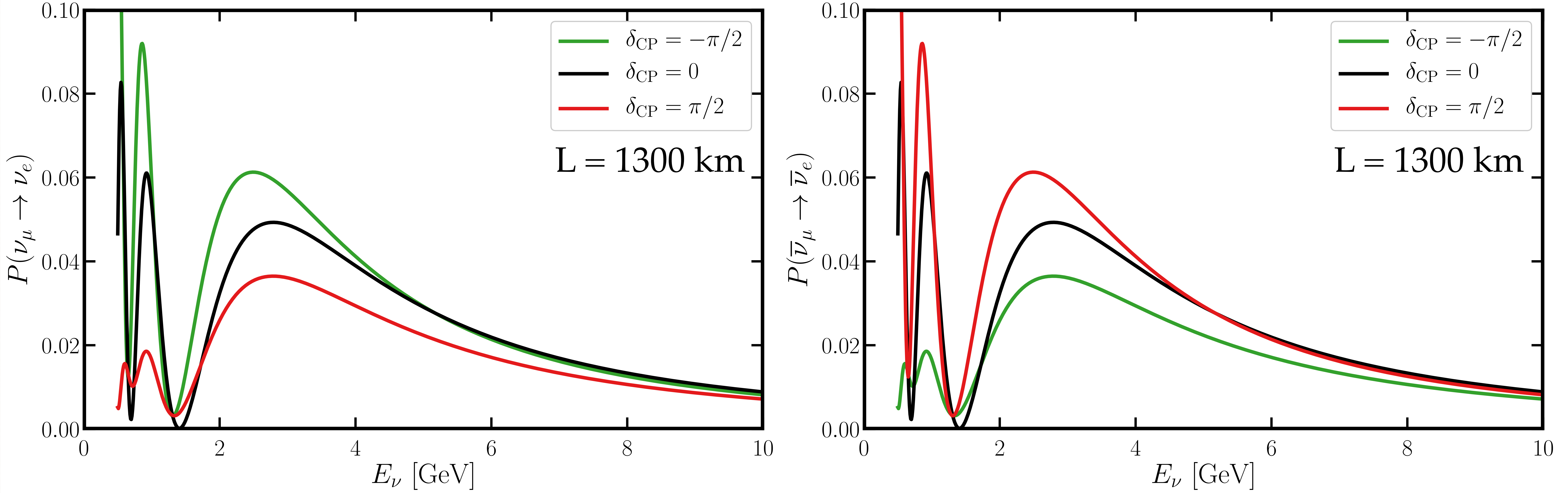
- For a fixed baseline length and neutrino energy, fix the mixing angles and mass-squared splittings to their best-fit values.
- Black line: generated by varying the CP-violating phase for vacuum oscillations.
- Red/blue lines: generated considering oscillations in matter assuming the inverted/normal orderings.
- For similar L/E, this separation increases for larger L and E.

Other Prevailing Unknown: CP Violation

CP Violation causes

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

Vacuum Oscillations



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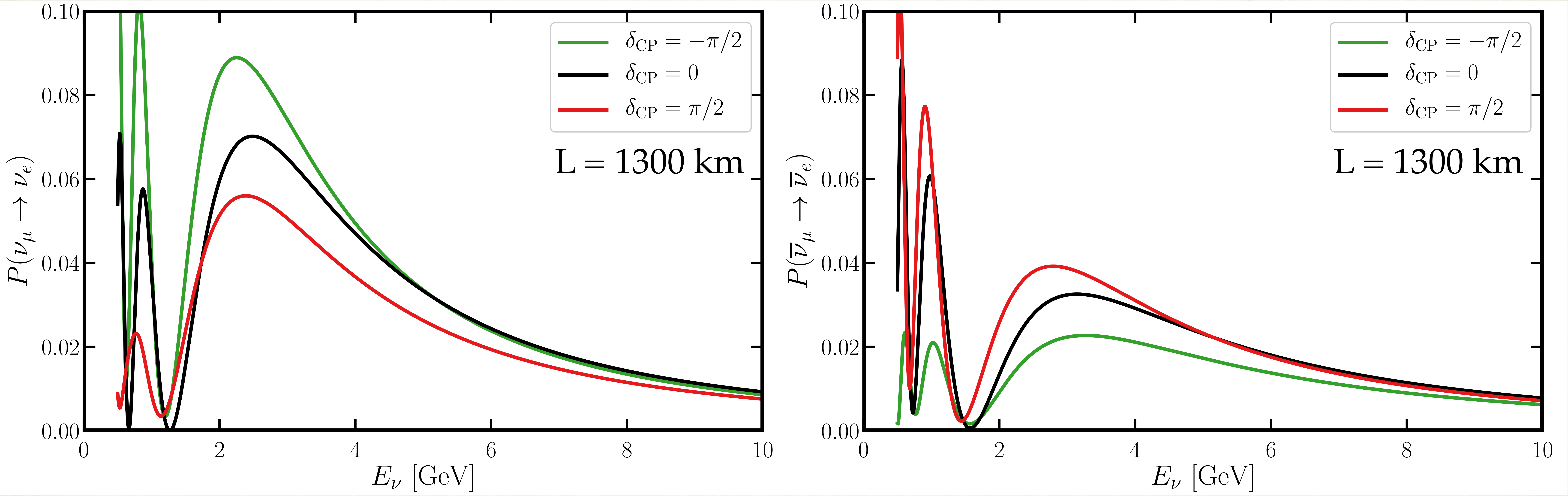

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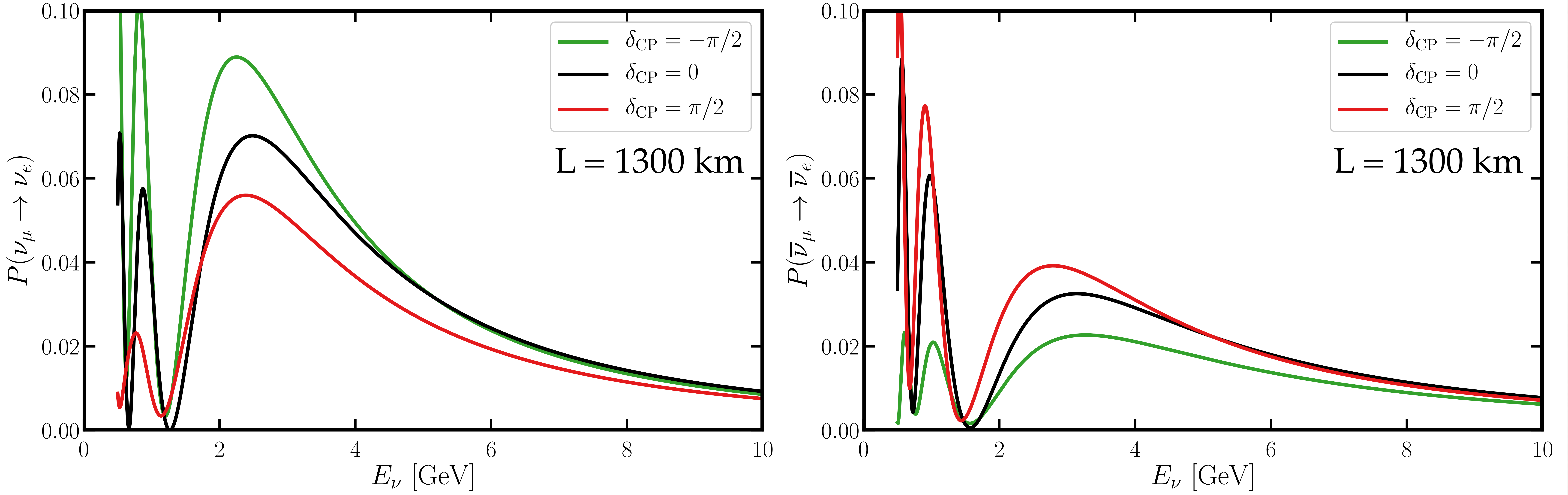
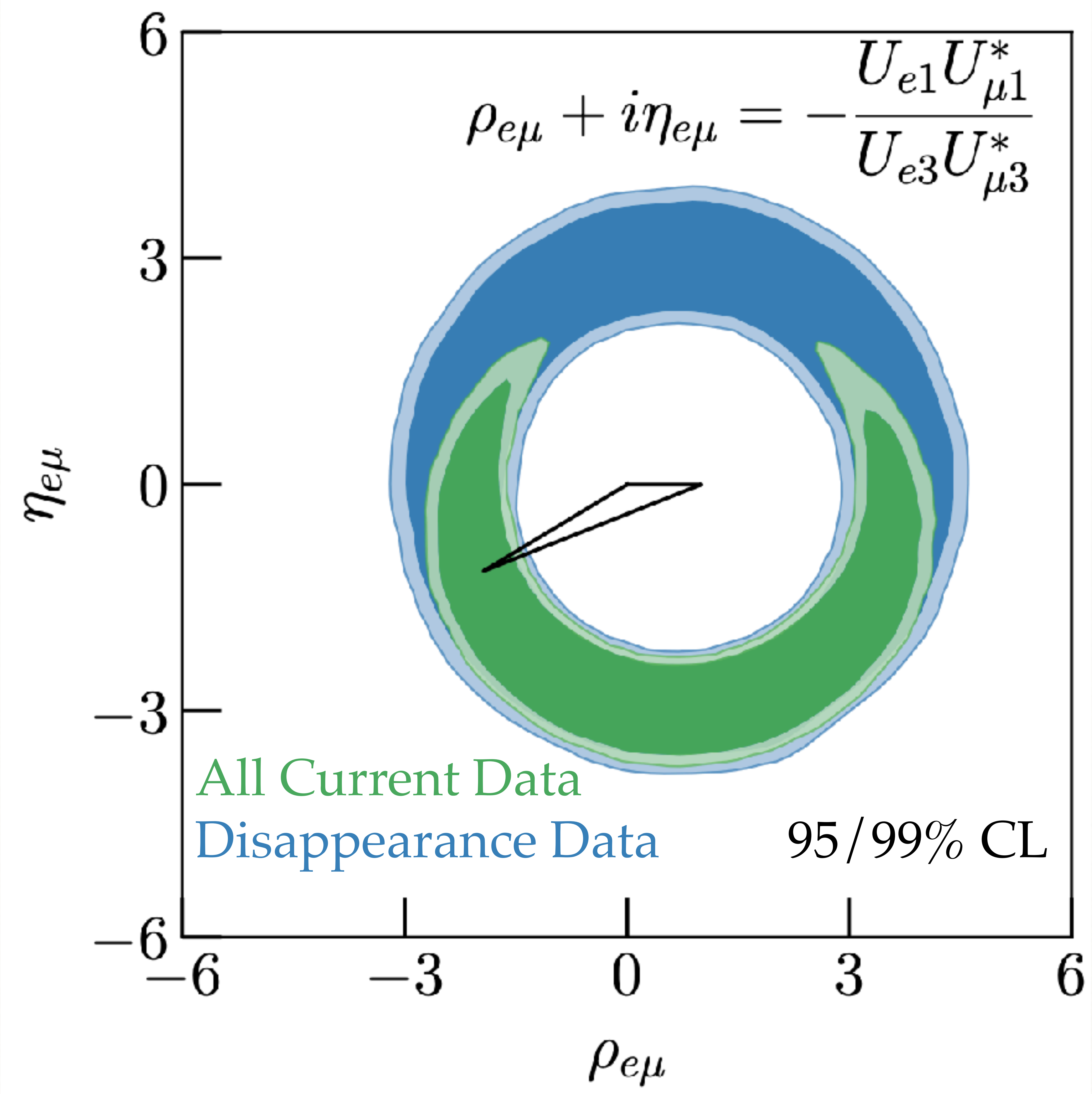
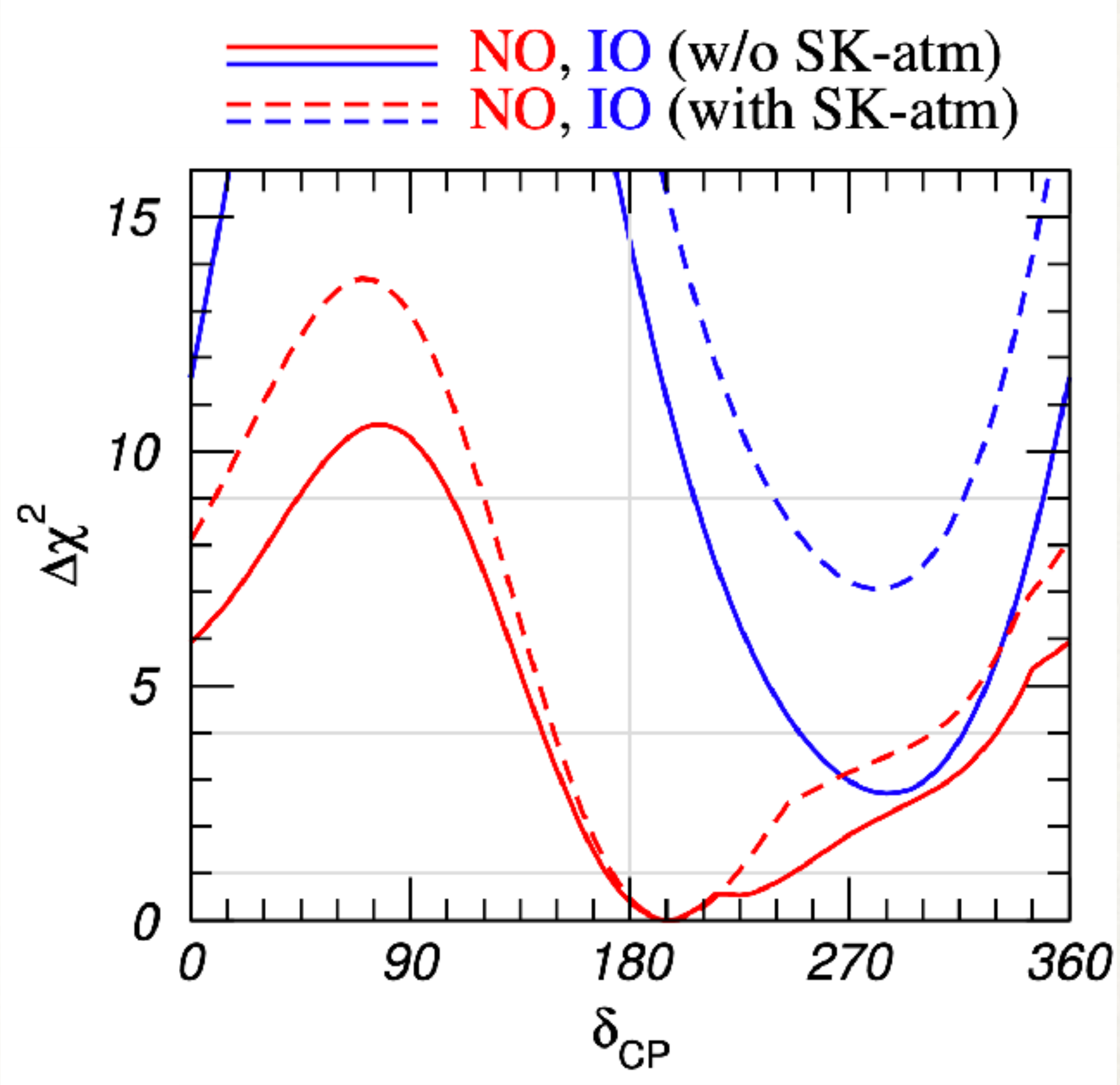


- Matter effects themselves are CP-violating. Because of this and degeneracy with other parameters, CP-violation is better measured with wide-energy beams.

Unitarity Triangles as a Probe of CP Violation

Ellis, KJK, Li [2004.13719]





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See also Capozzi et al [2107.00532]

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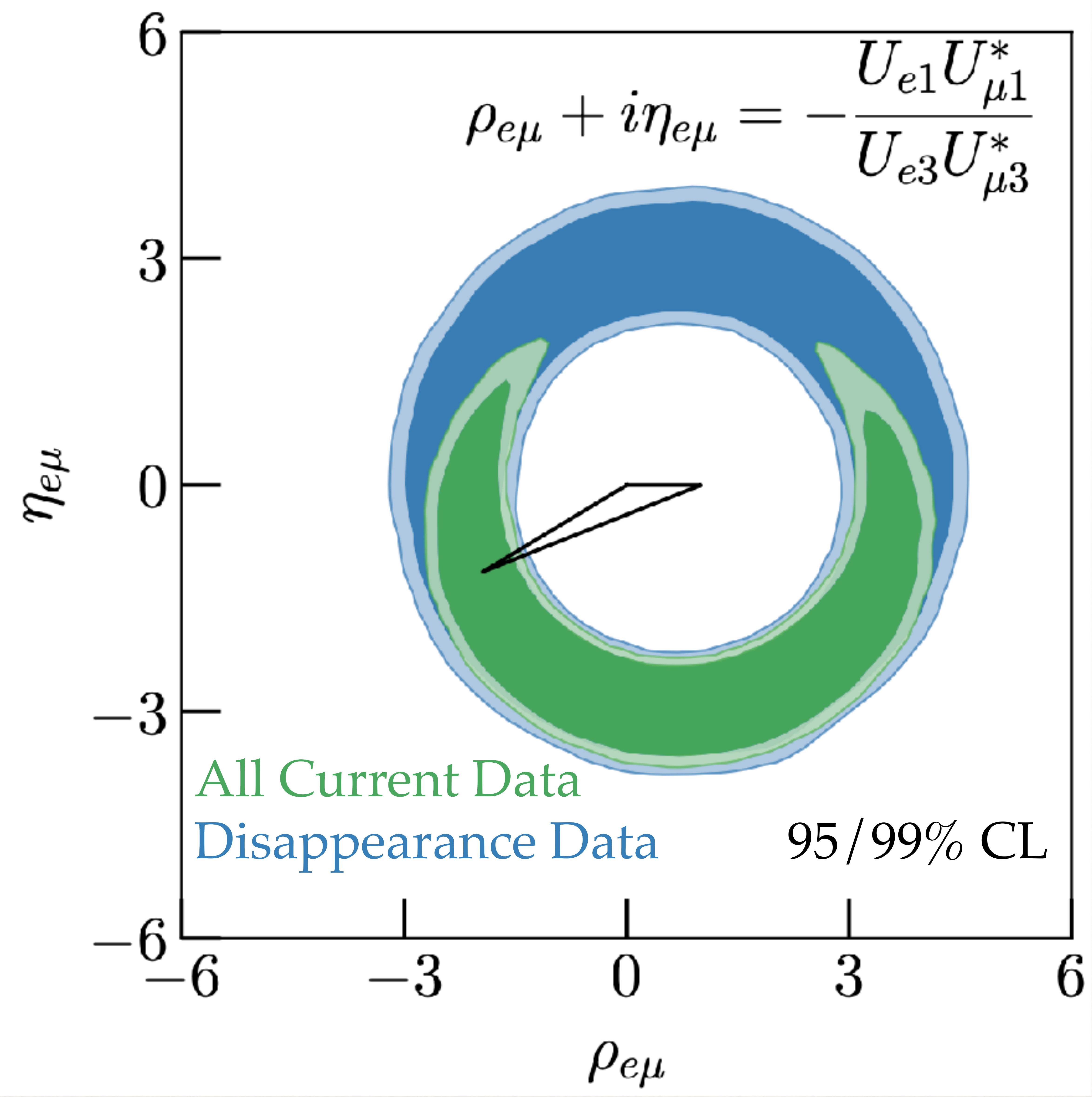
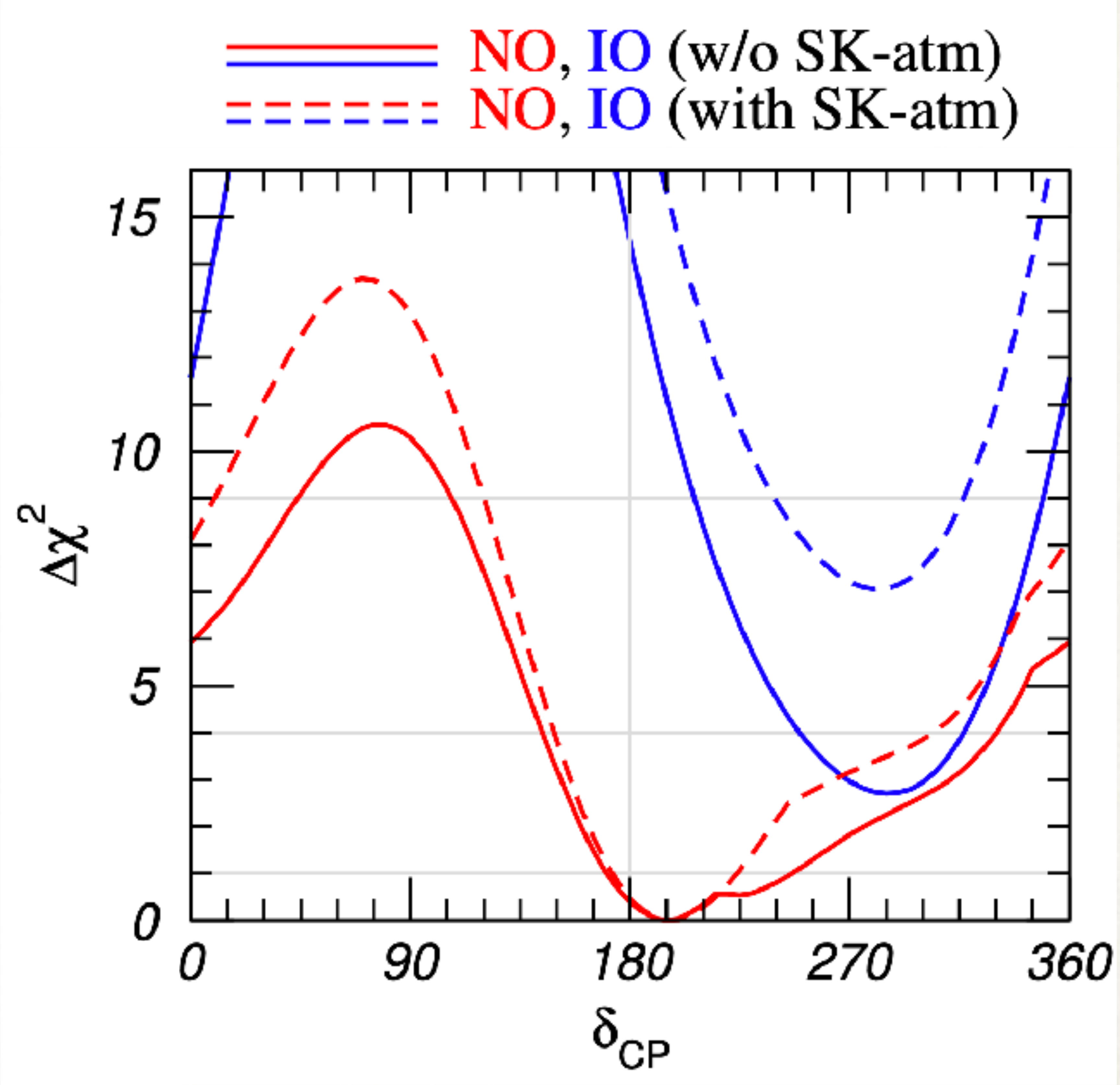


Current data: compatible with no CP violation and maximal CP violation at 95% CL.



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So, what constitutes “SM” and “BSM”?

*Note: this is a subjective distinction!

For neutrino physics, SM includes

- Massive neutrinos (3, with two non-zero mass-squared splittings)
- Mixing (3 well-measured mixing angles, possibility of CP violation)
- Interactions via the SM weak interactions (charged- and neutral-current)
- Oscillations can be calculated exactly (numerically) from the above ingredients

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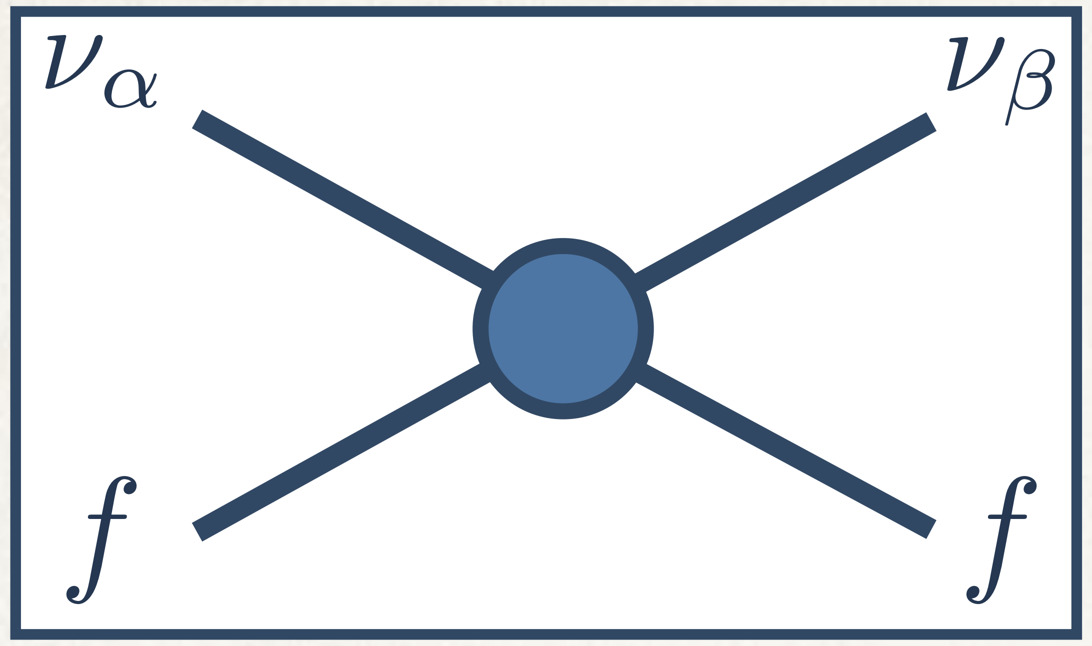
BSM includes any effect beyond this, and how it can impact our measurements from laboratory / cosmological / astrophysical observations.

- Additional light and / or heavy neutrino states
- New interactions among neutrinos or with other particles
- …

BSM with Neutrino Oscillations

What can Oscillations Teach Us?



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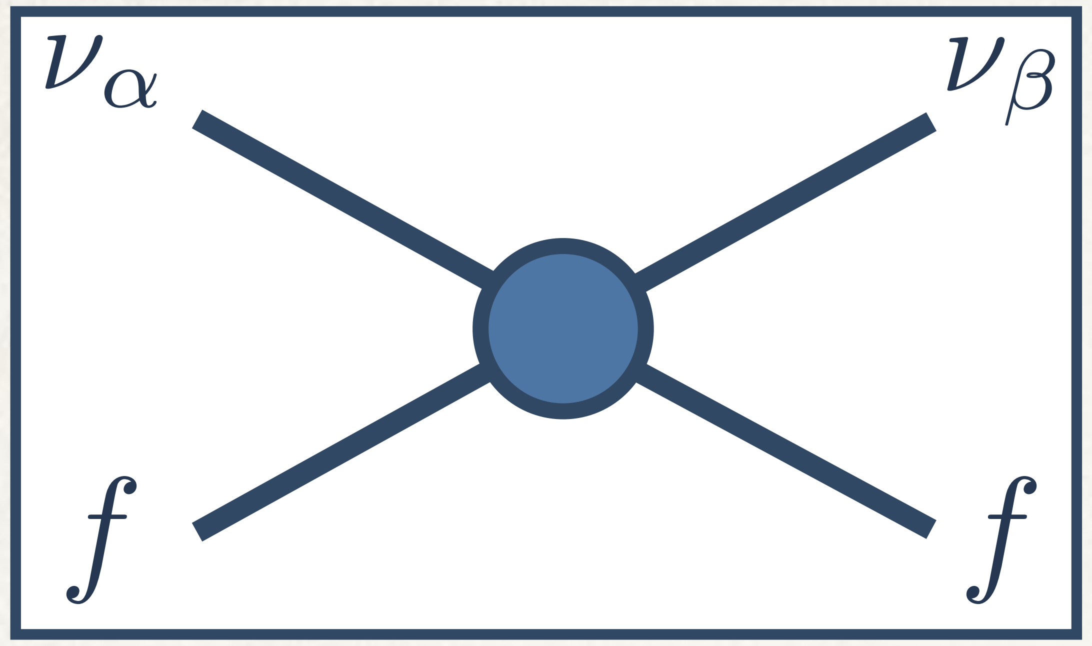

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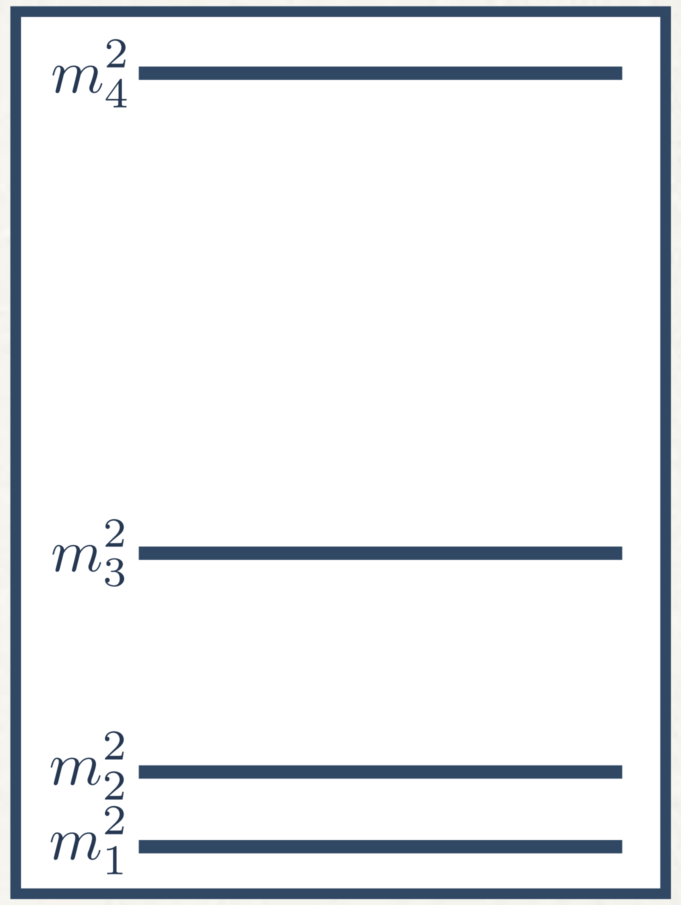

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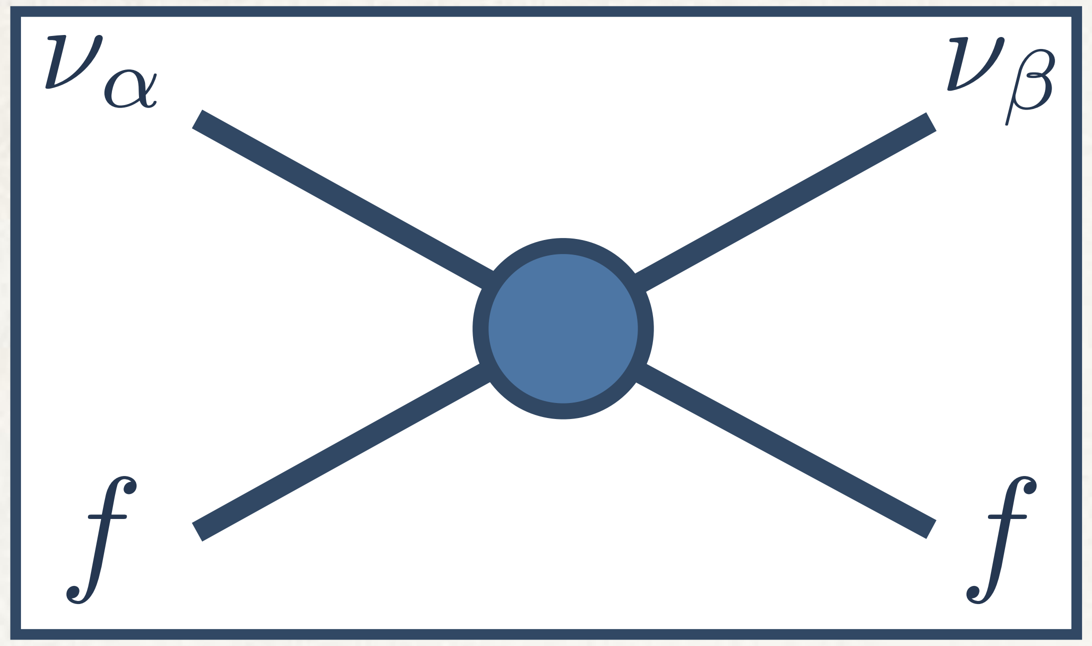

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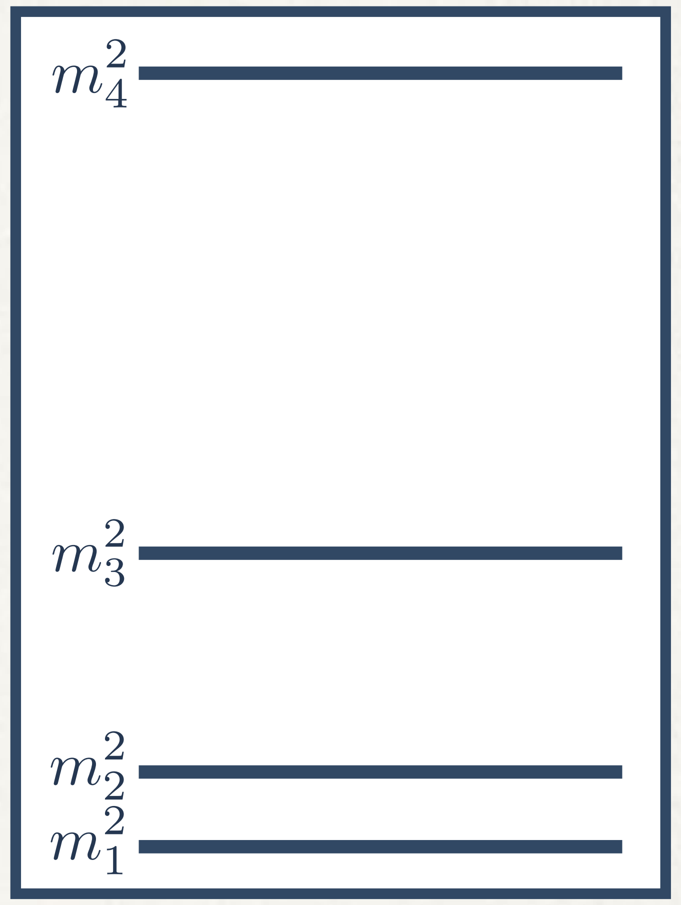

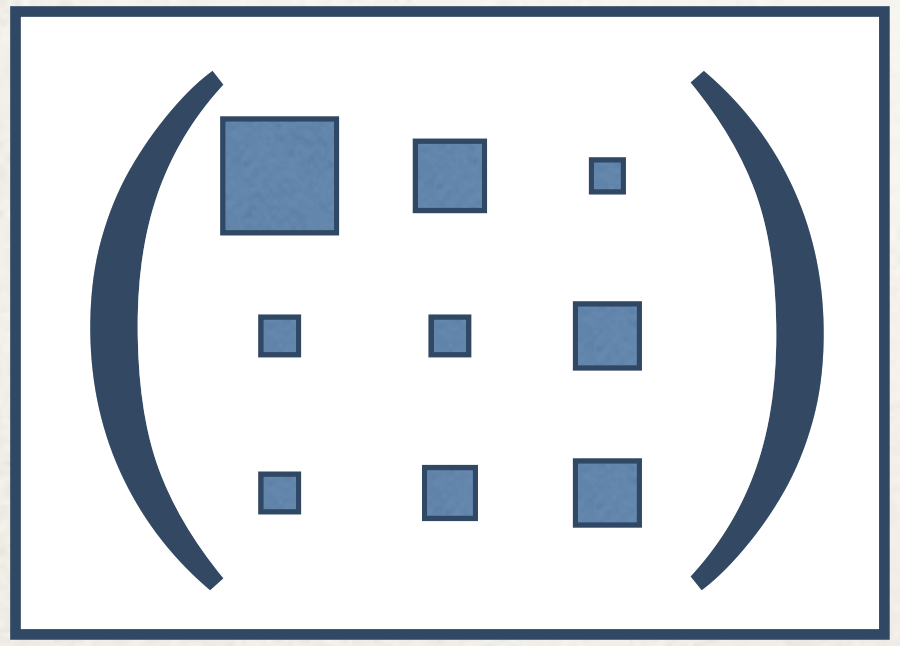

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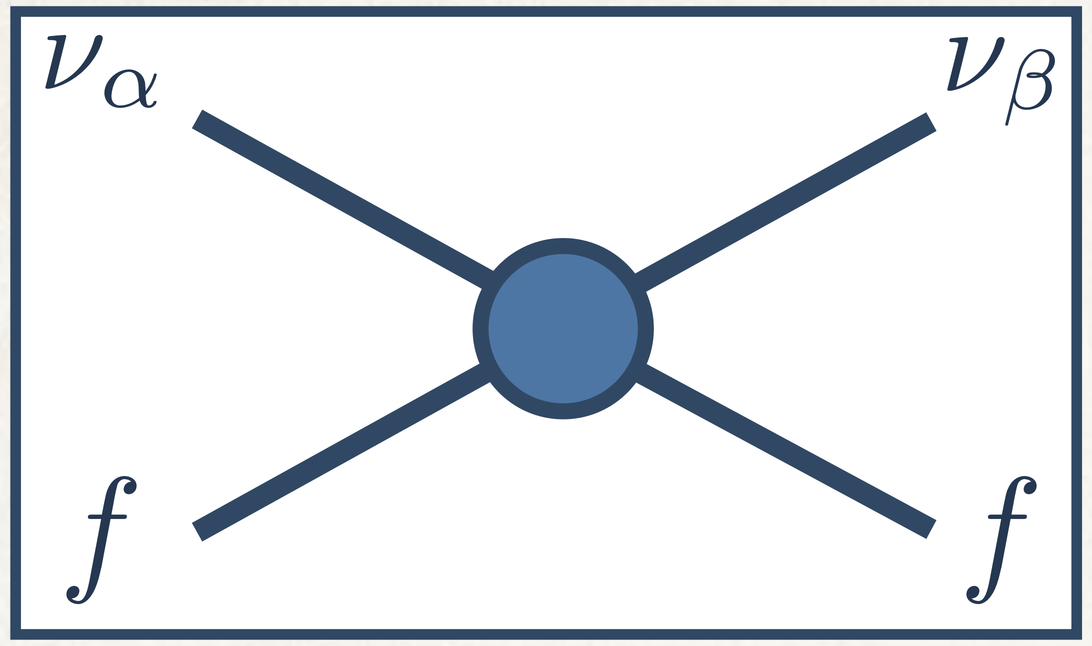

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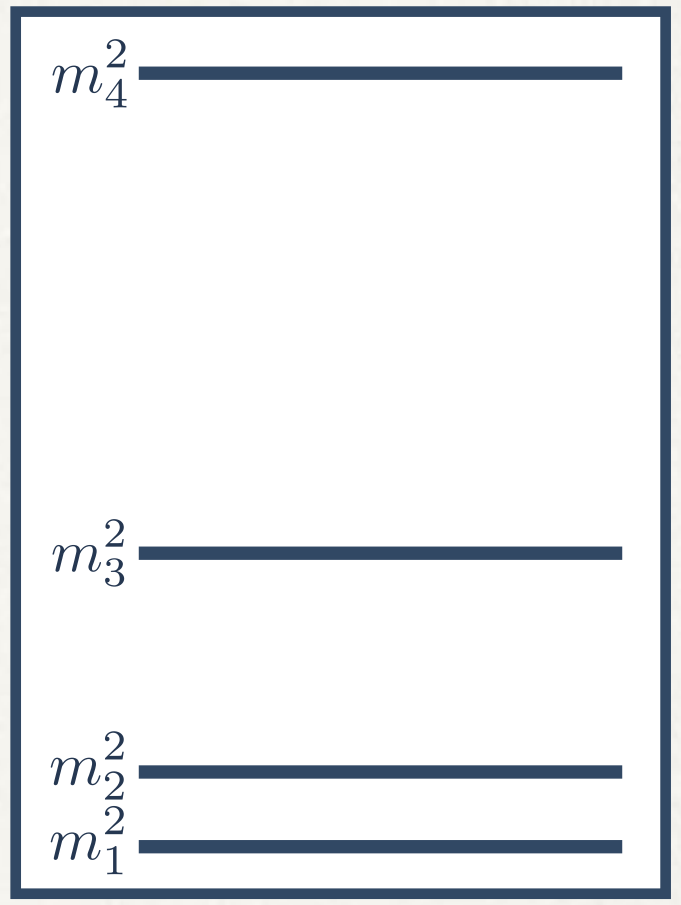

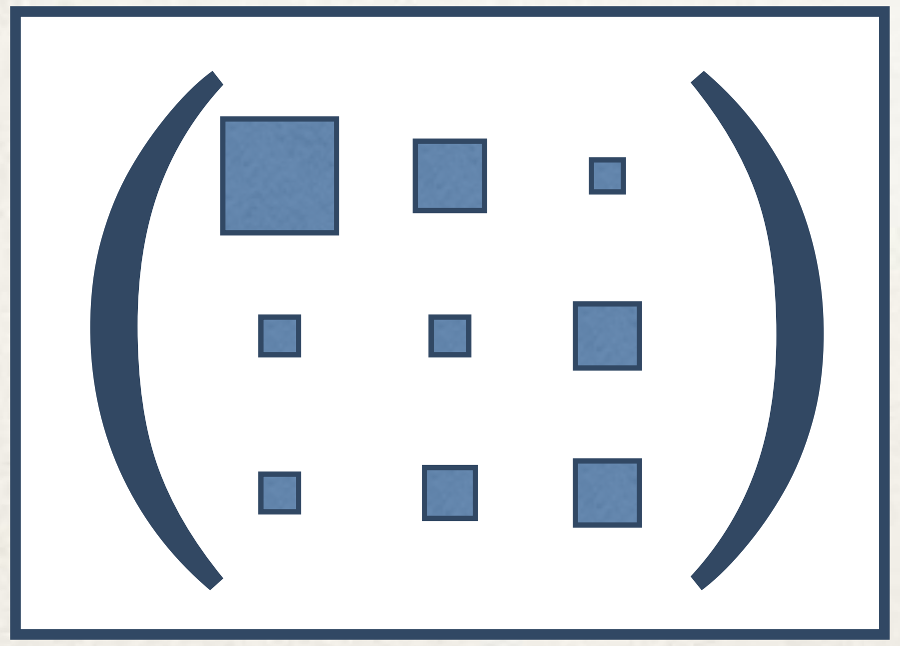

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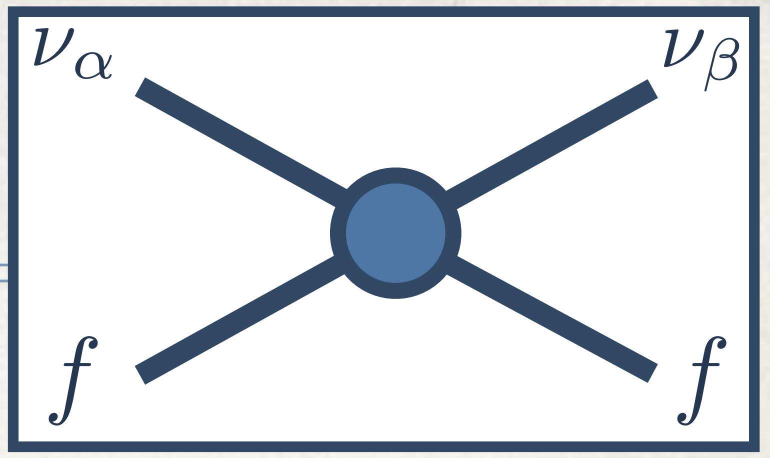

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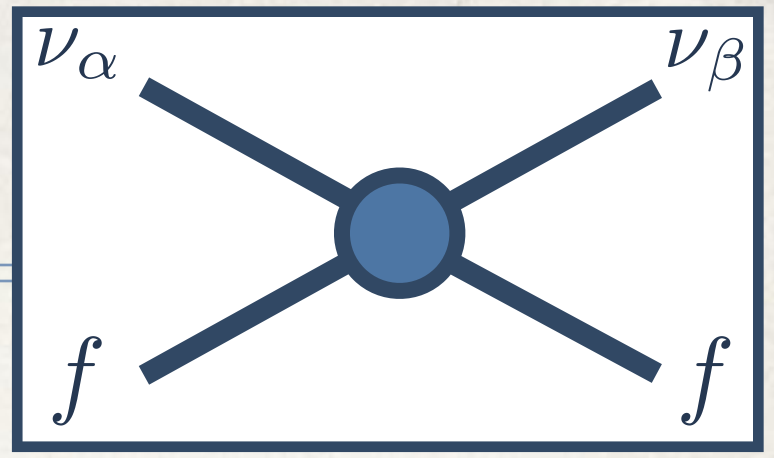

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Impact on Neutrino Oscillations

$$H_{ij} = \frac{1}{2E_\nu}\mathrm{diag}\left\{0, \Delta m^2_{12}, \Delta m^2_{13}\right\} + V_{ij}$$

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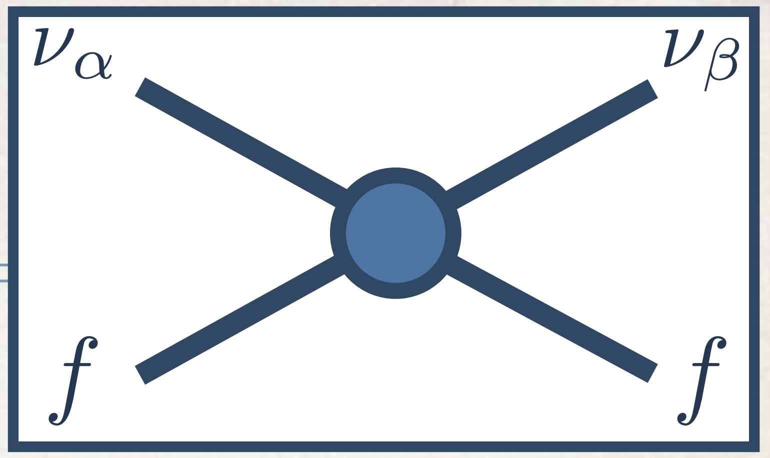

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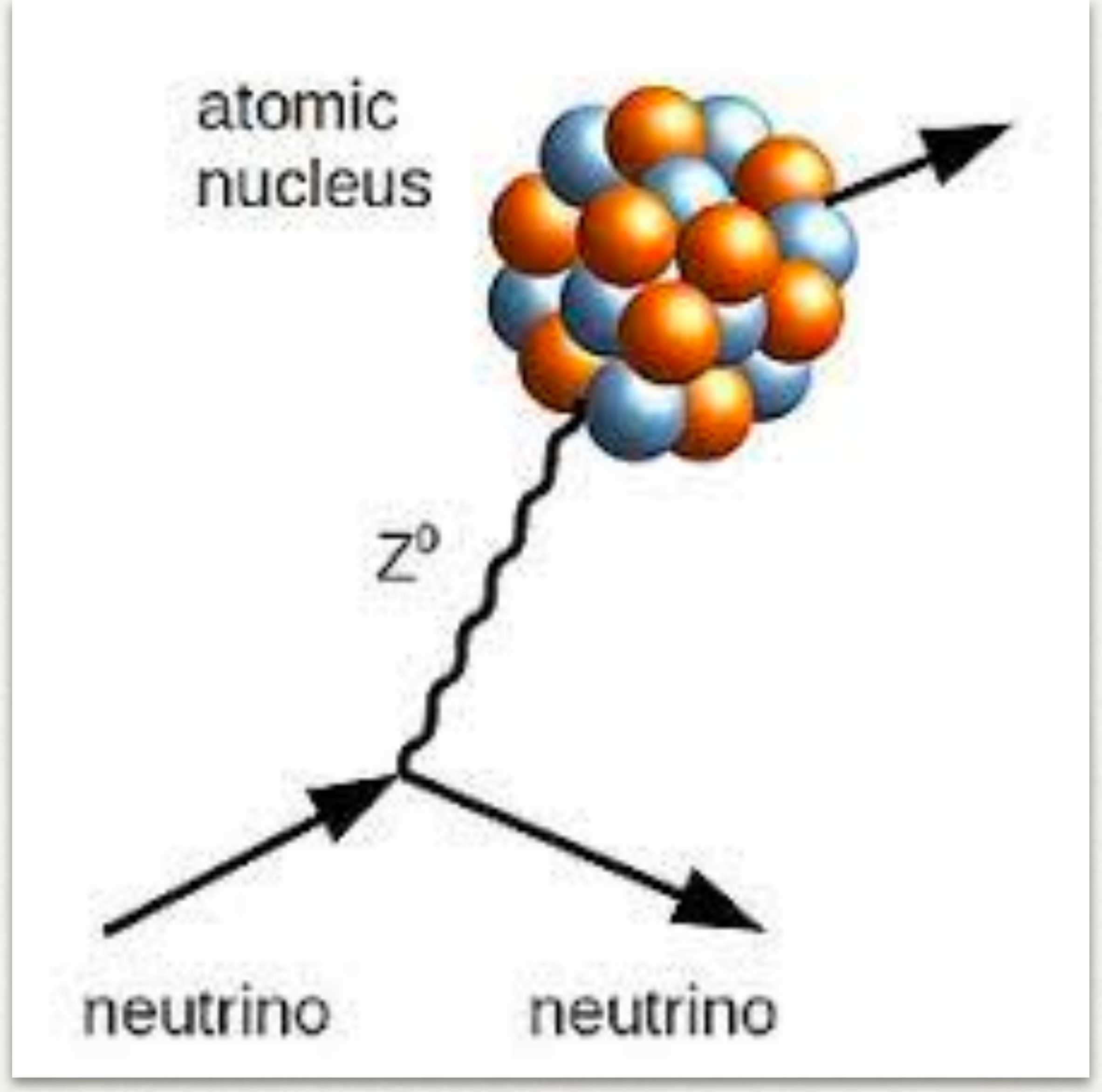
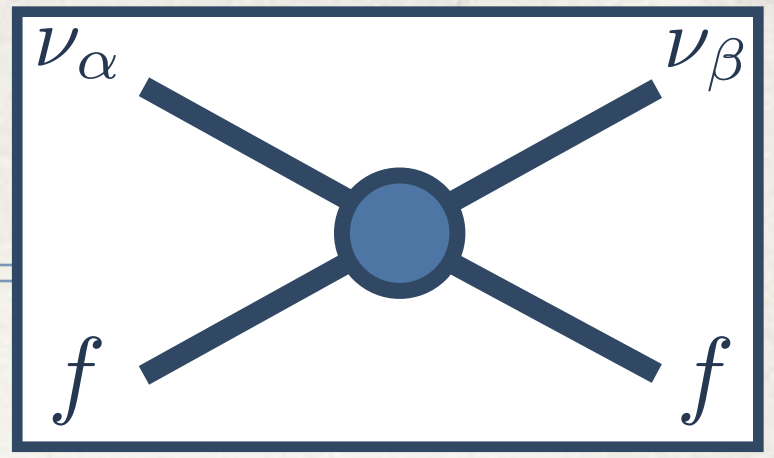
Impact on Neutrino Scattering



Modifies the cross section for coherent elastic neutrino-nucleus scattering

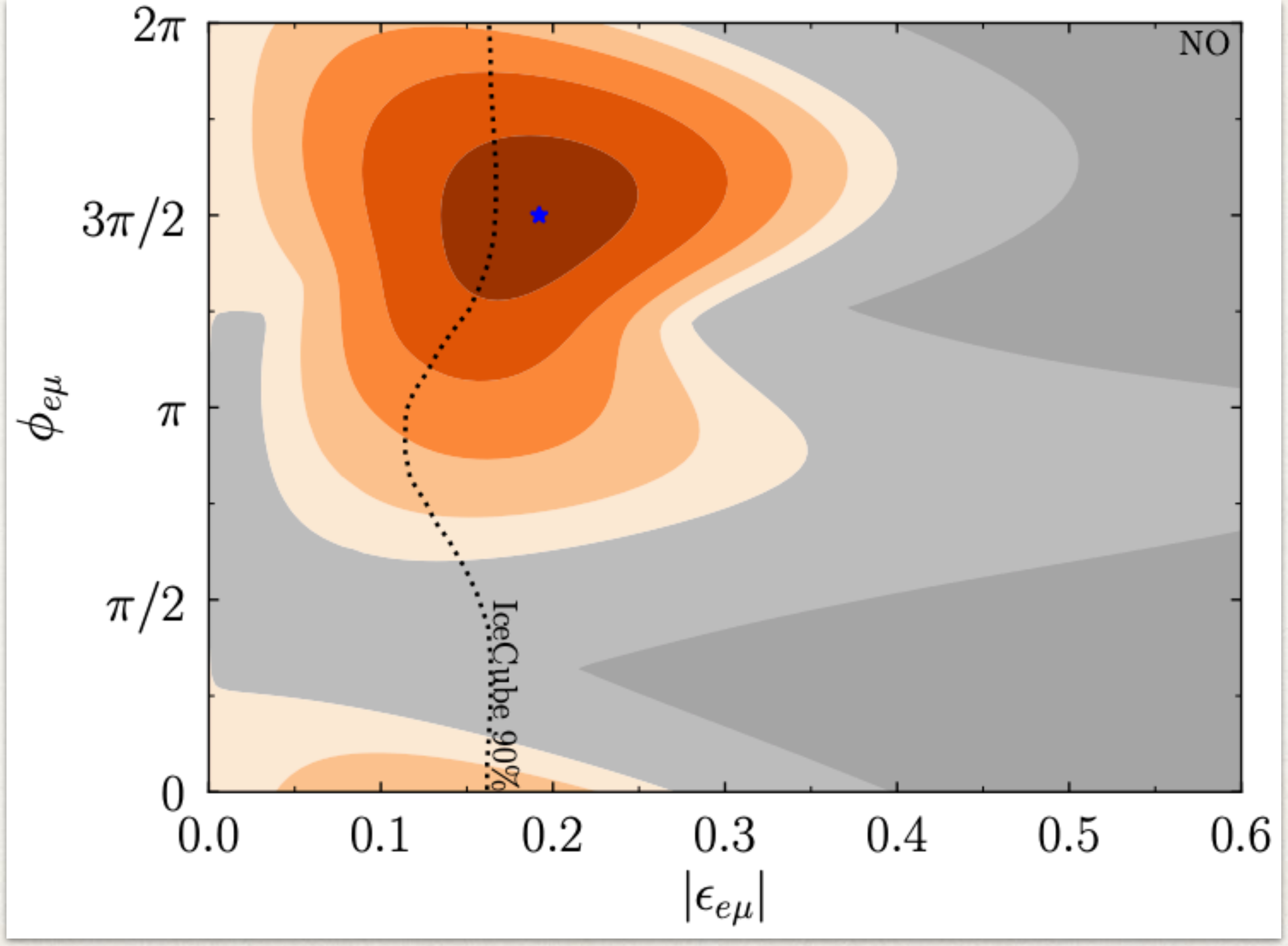
Non-Standard Interactions (NSI)

Recent review: [1907.00991]



Mild preference for new interactions to reduce tension between T2K and NOvA results

Denton et al [2008.01110]



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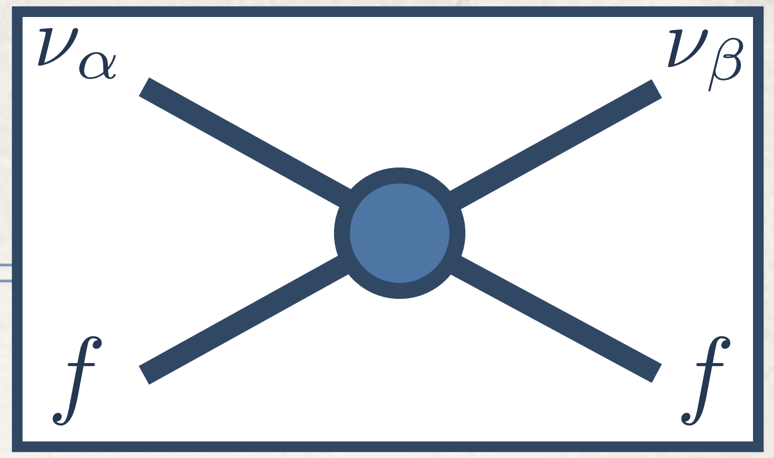

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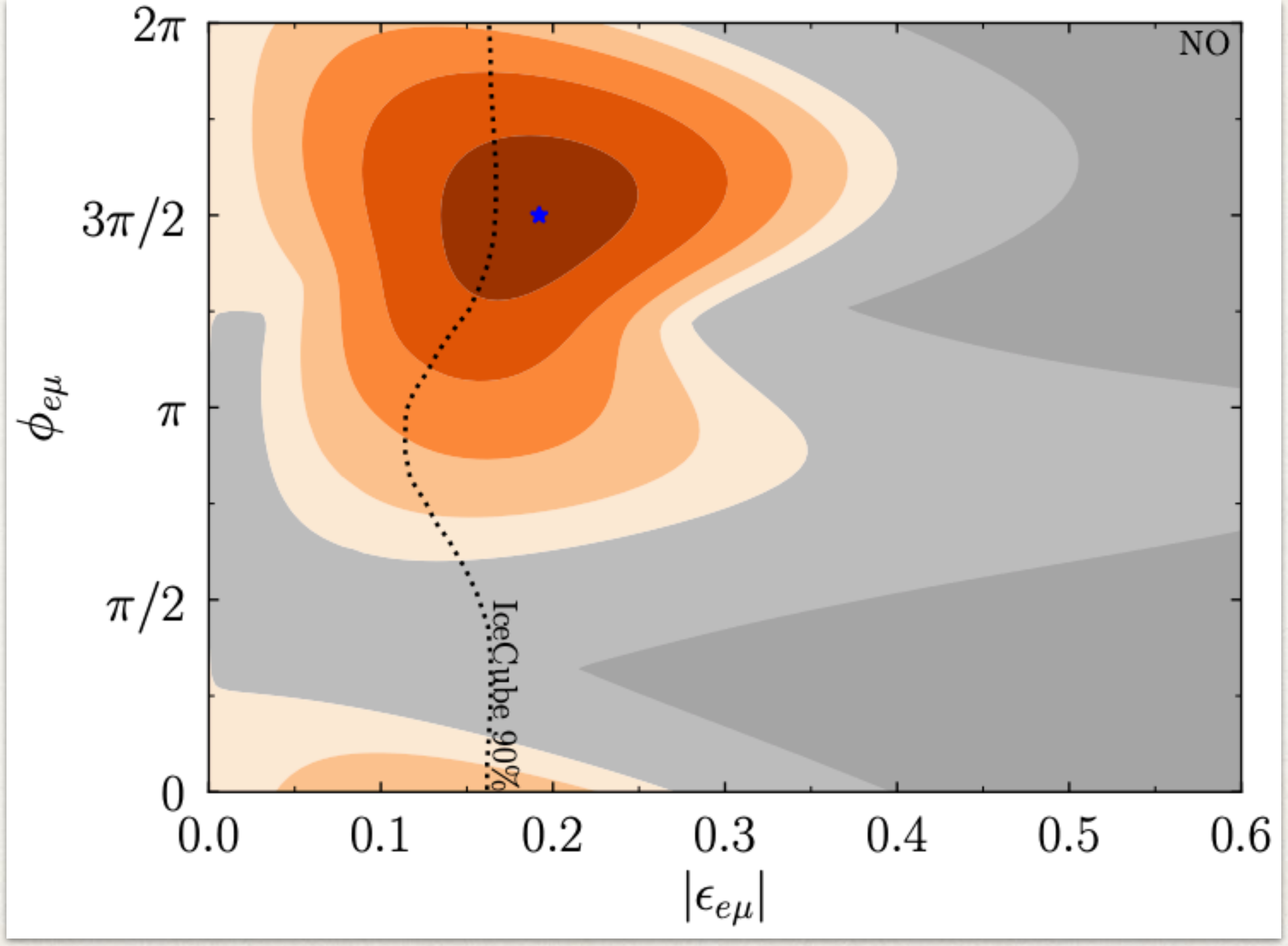

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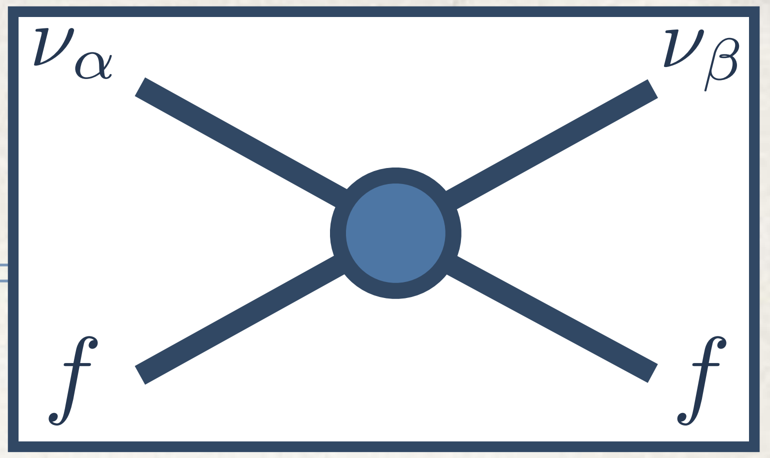

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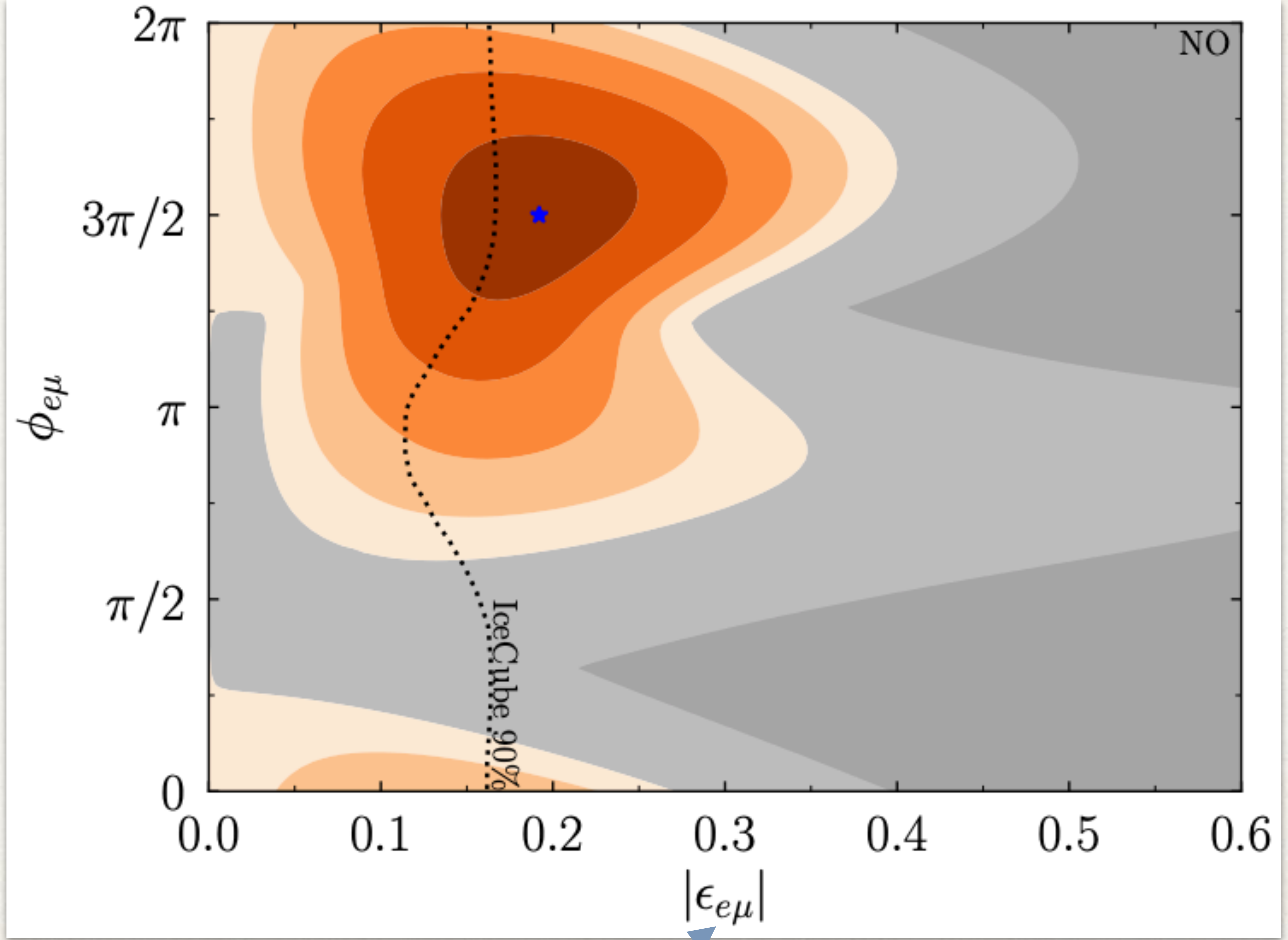

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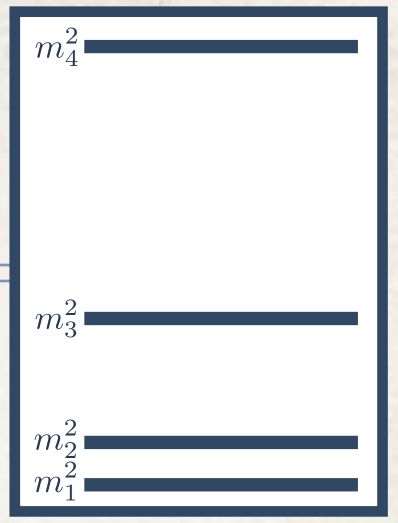
CP-violating!

Flavor-violating!

How many neutrinos are there?



They have charge current (CC) and neutral current (NC) interactions

$$\mathcal{L}_{\rm SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \overline{\nu}_{\alpha L}\gamma^{\mu}\ell_{\alpha L}W_{\mu} - \frac{g}{2\cos\theta_W} \sum_{\alpha=e,\mu,\tau} \overline{\nu}_{\alpha L}\gamma^{\mu}\nu_{\alpha L}Z_{\mu} + \text{h.c.}$$

Number of active neutrinos

The invisible width of the Z (measured precisely at LEP) restricts the number of active neutrinos to

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\bar{\nu}\nu}} = 2.984 \pm 0.008$$

Note: Additional neutrinos can be present but they cannot partake of the SM interactions and are called sterile neutrinos.

8

@Silvia Pascoli

Three neutrinos means two distinct mass-squared splittings — any additional splittings implies the existence of more states!

Enter: LSND (Liquid Scintillator Neutrino Detector)

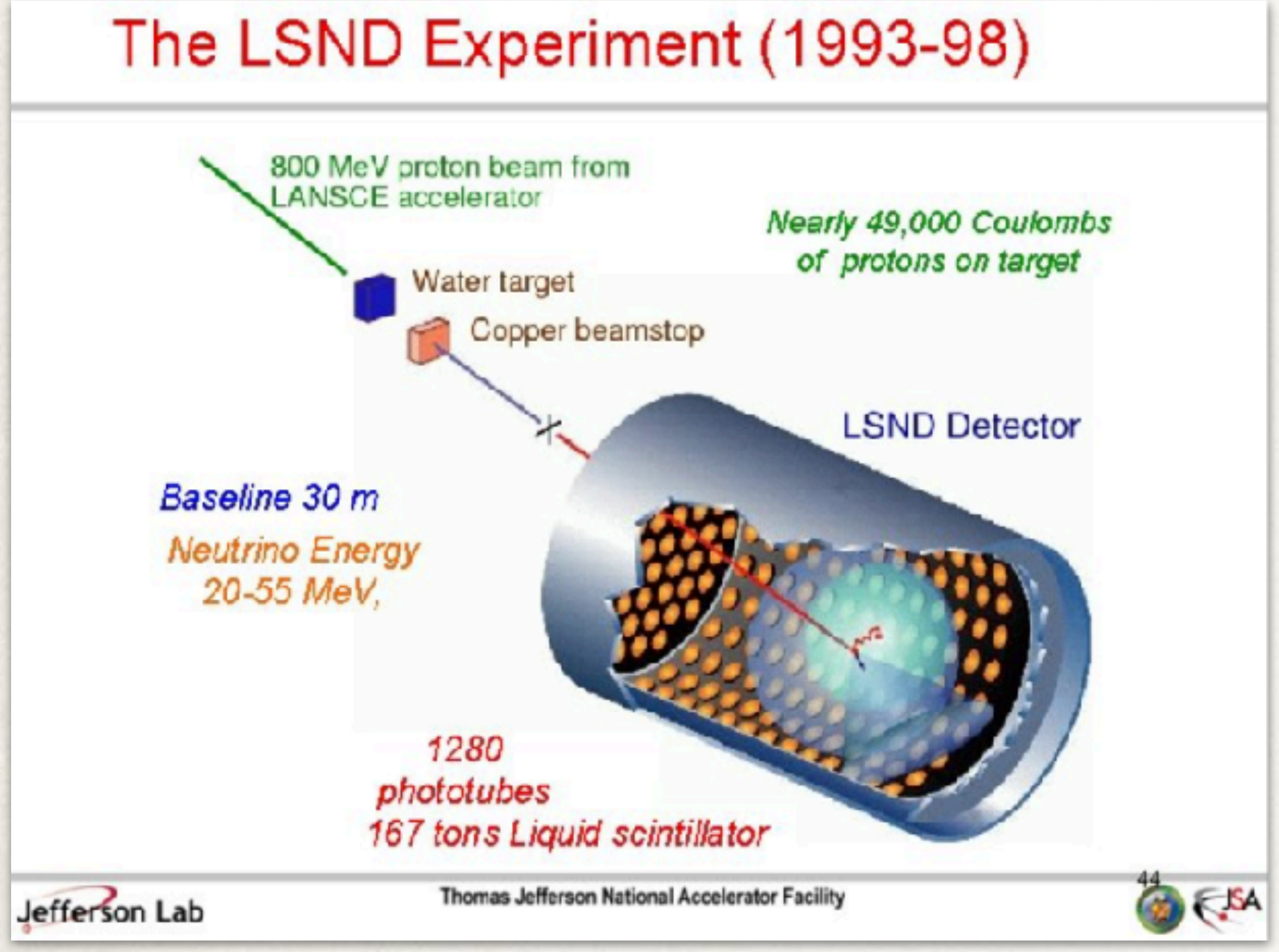
Designed to study the neutrinos that come out of muon decay-at-rest:

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

Note — no electron **anti**neutrinos expected from this chain.

https://slidetodoc.com/lecture-1-history-of-the-neutrino-r-d/



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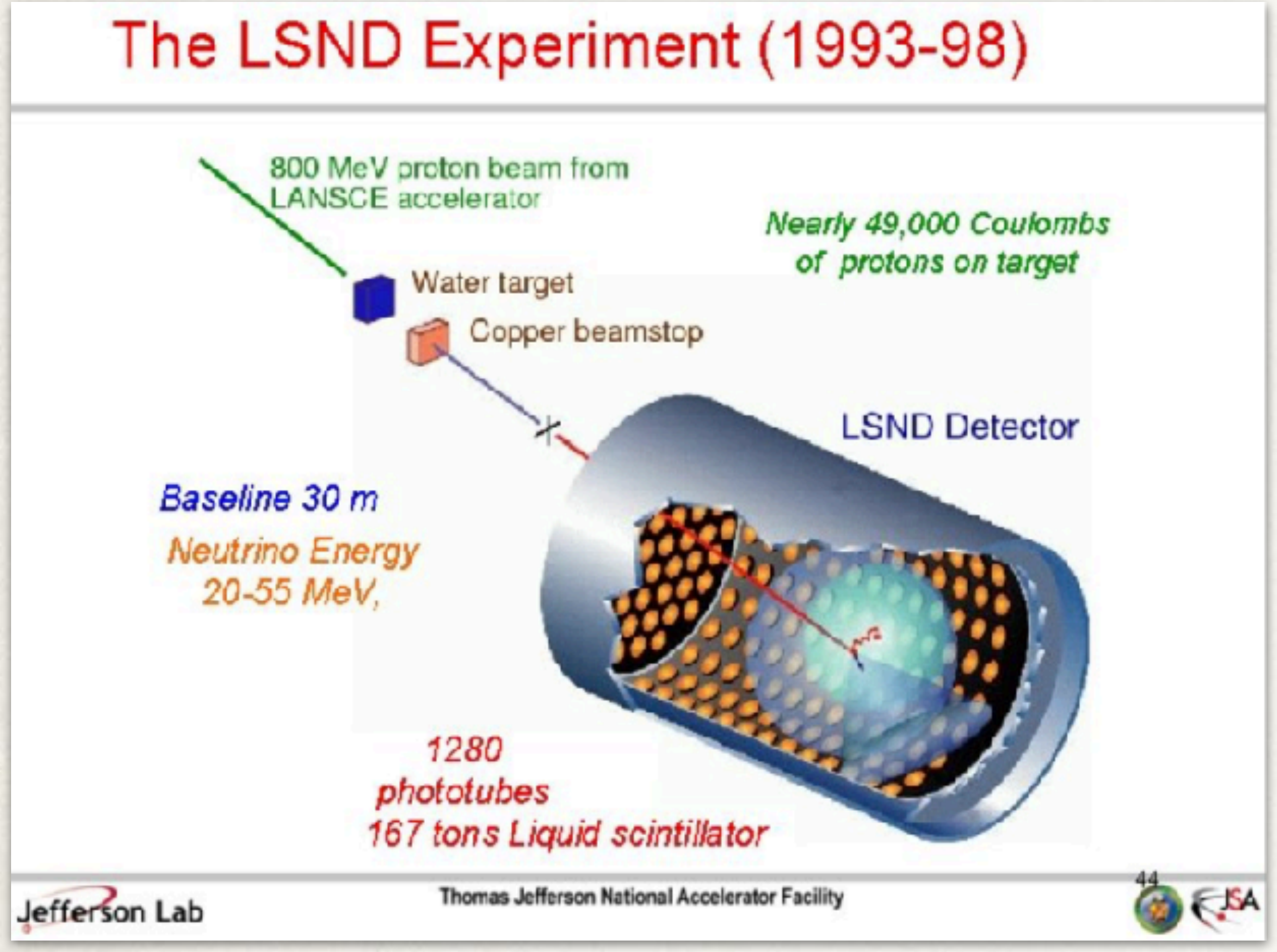

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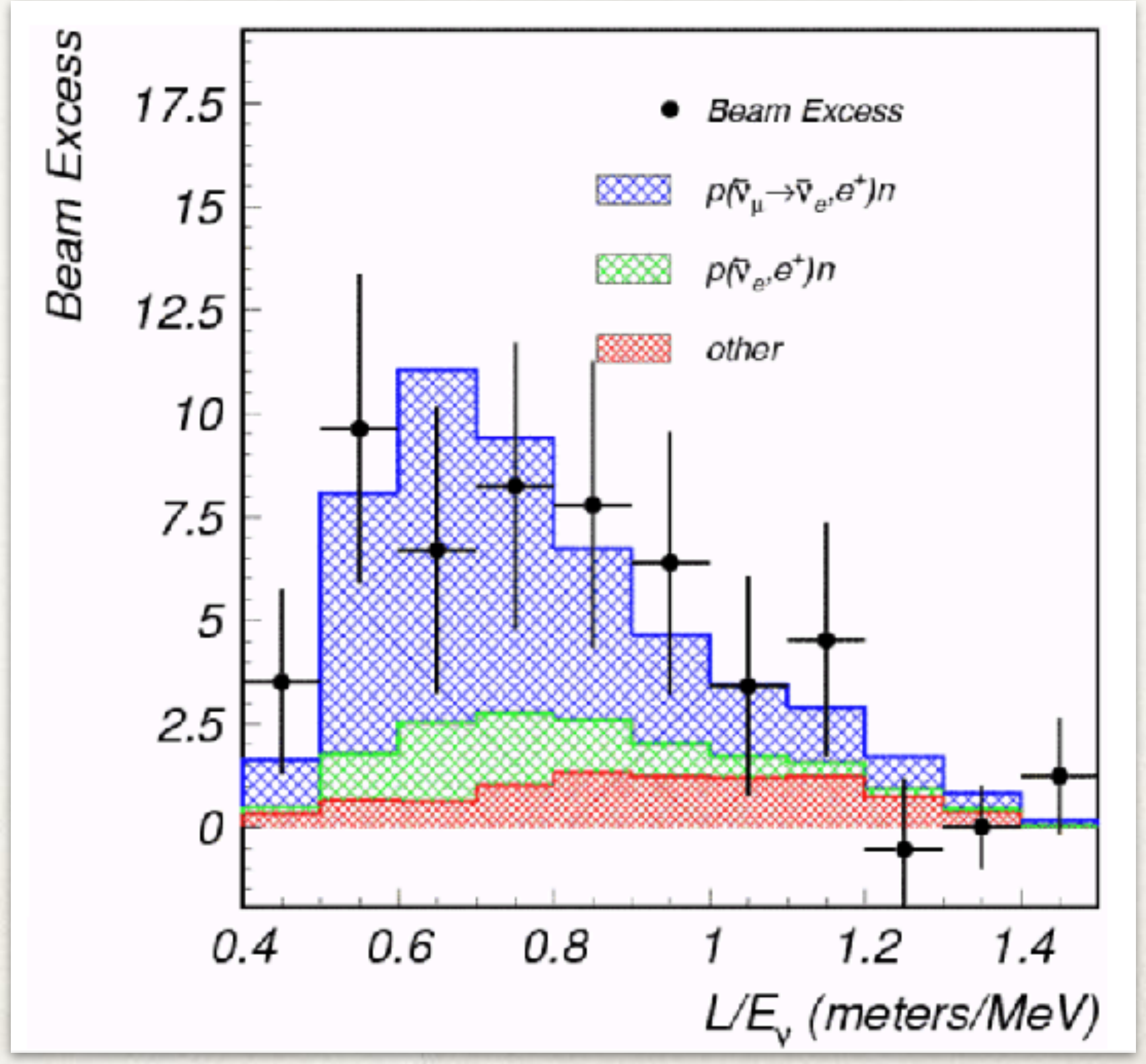

$$\boxed{P(\overline{\nu}_\mu \to \overline{\nu}_e) \approx 0.3\%}$$

A sterile neutrino for LSND (and MiniBooNE)?

Assume only two neutrinos exist, vacuum oscillations:

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

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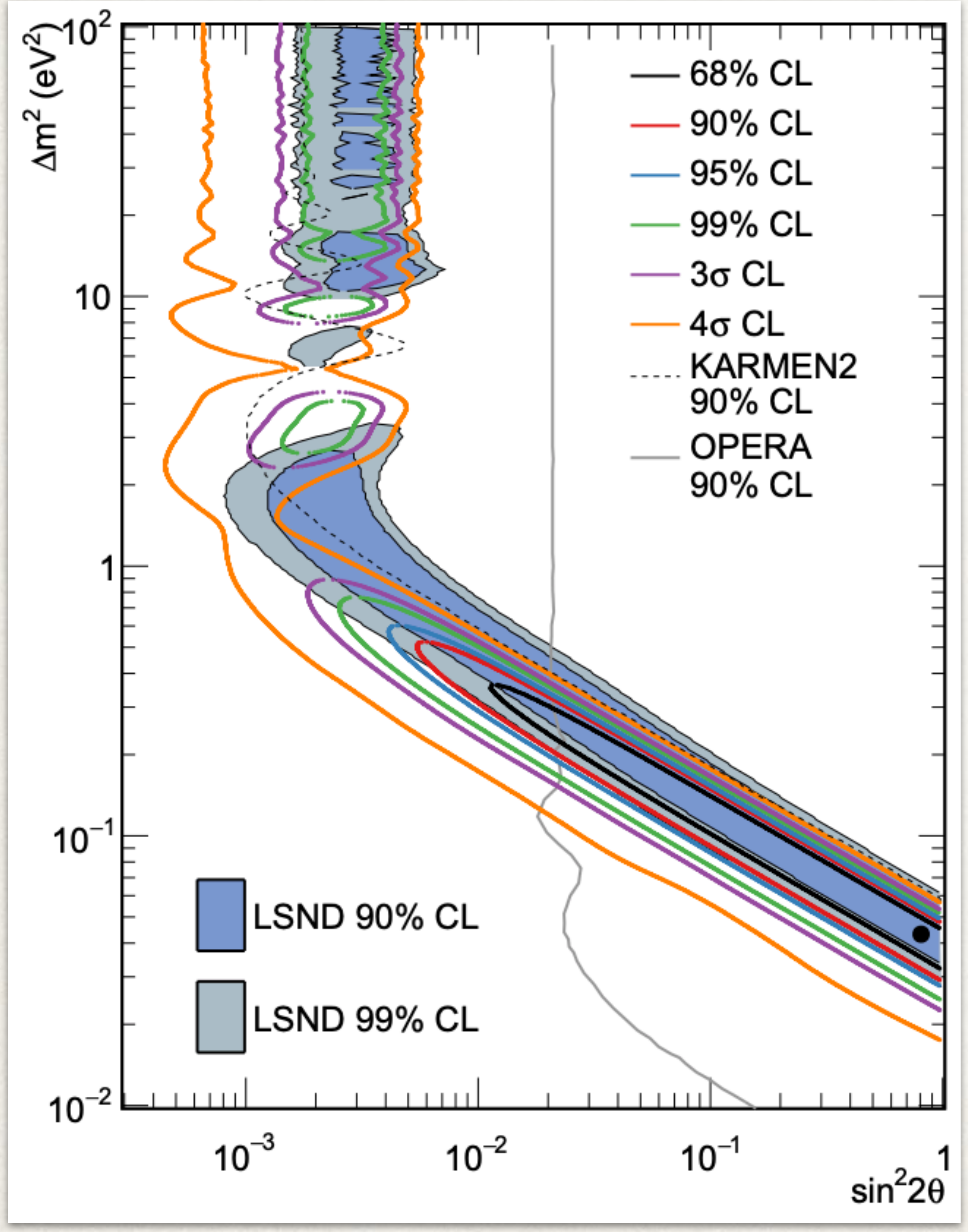
LSND & MiniBooNE had different L, E, but similar L/E — simultaneous explanation with a common mass-squared splitting?

Latest & Greatest Results



MiniBooNE, [2006.16883]

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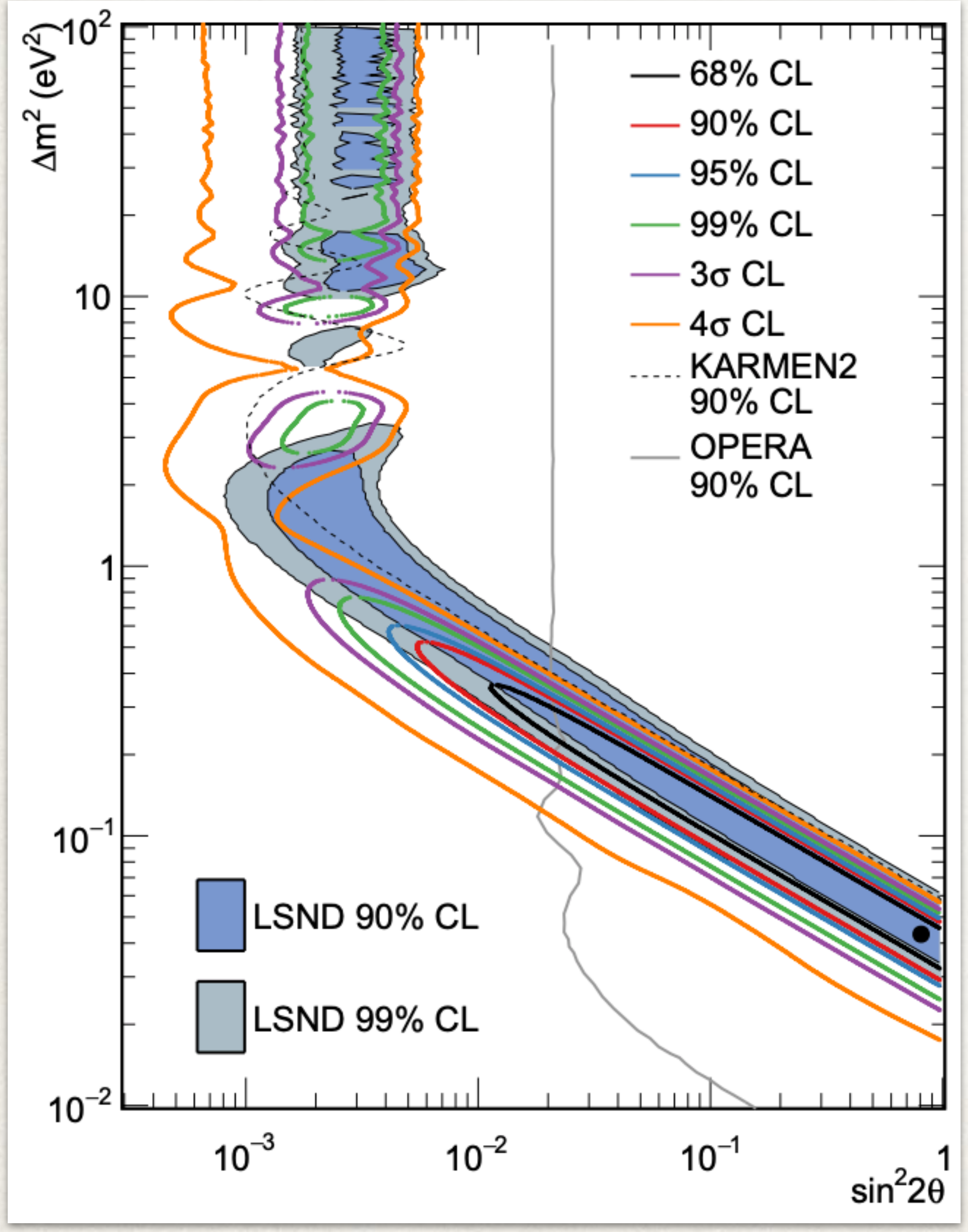

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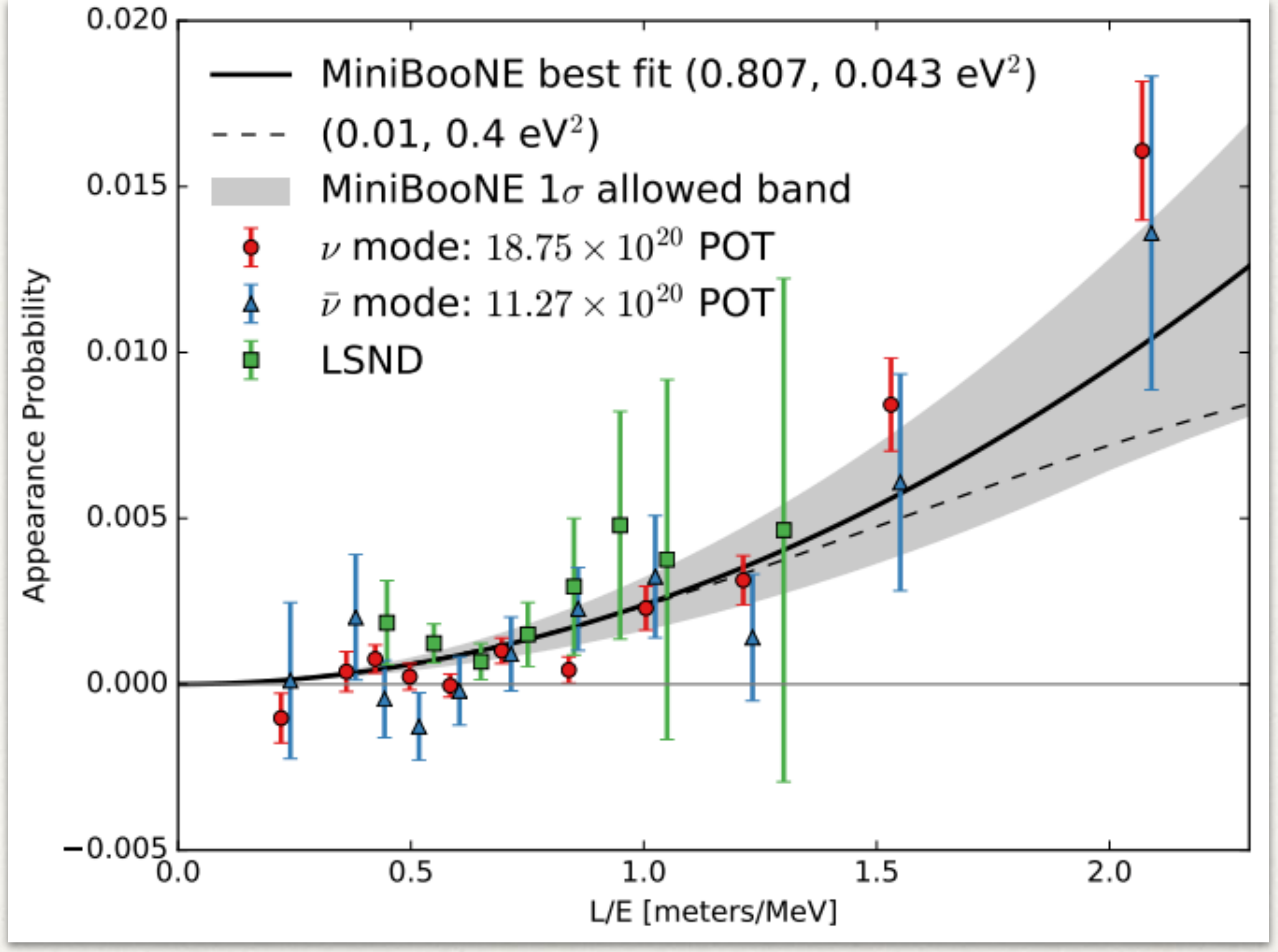

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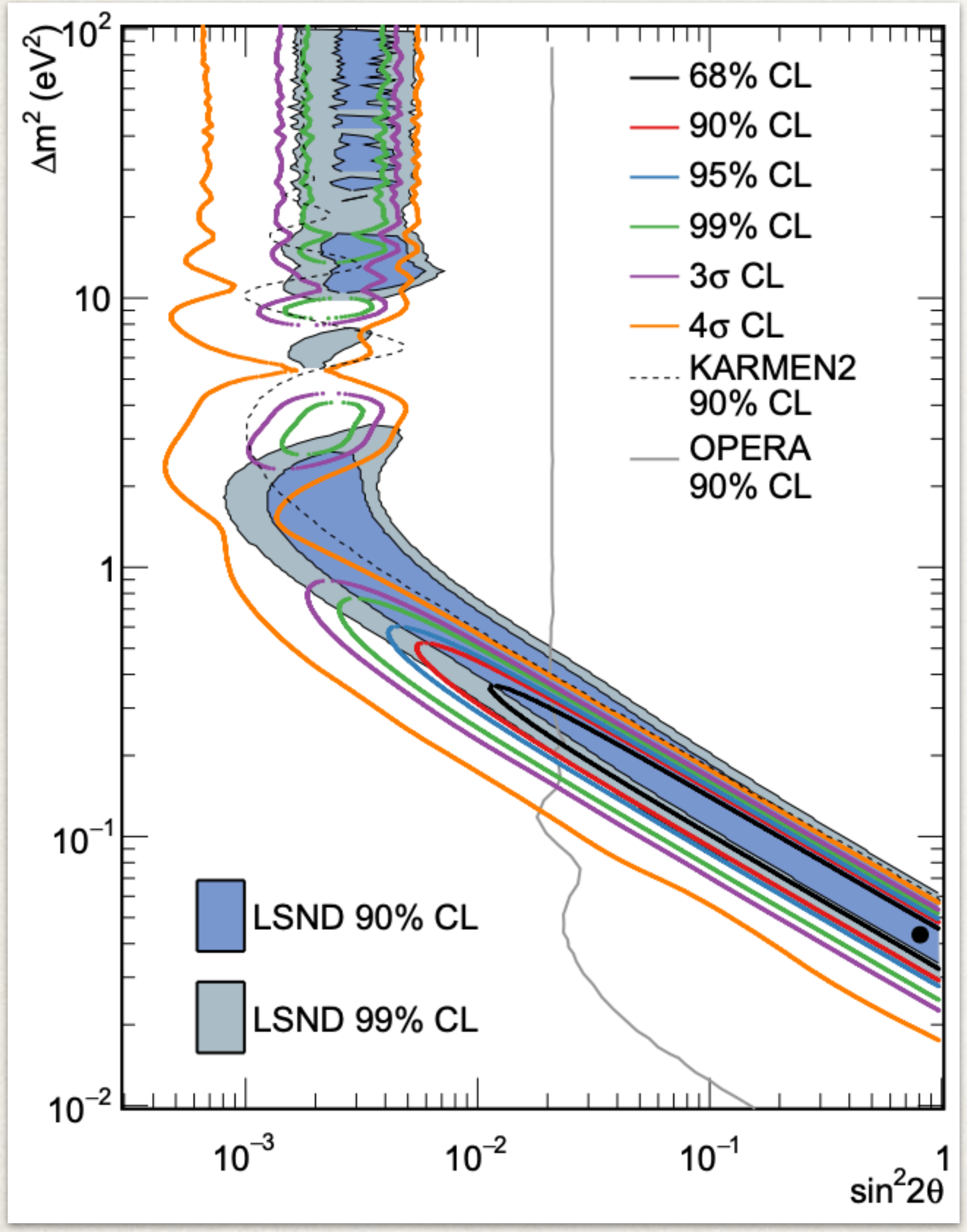

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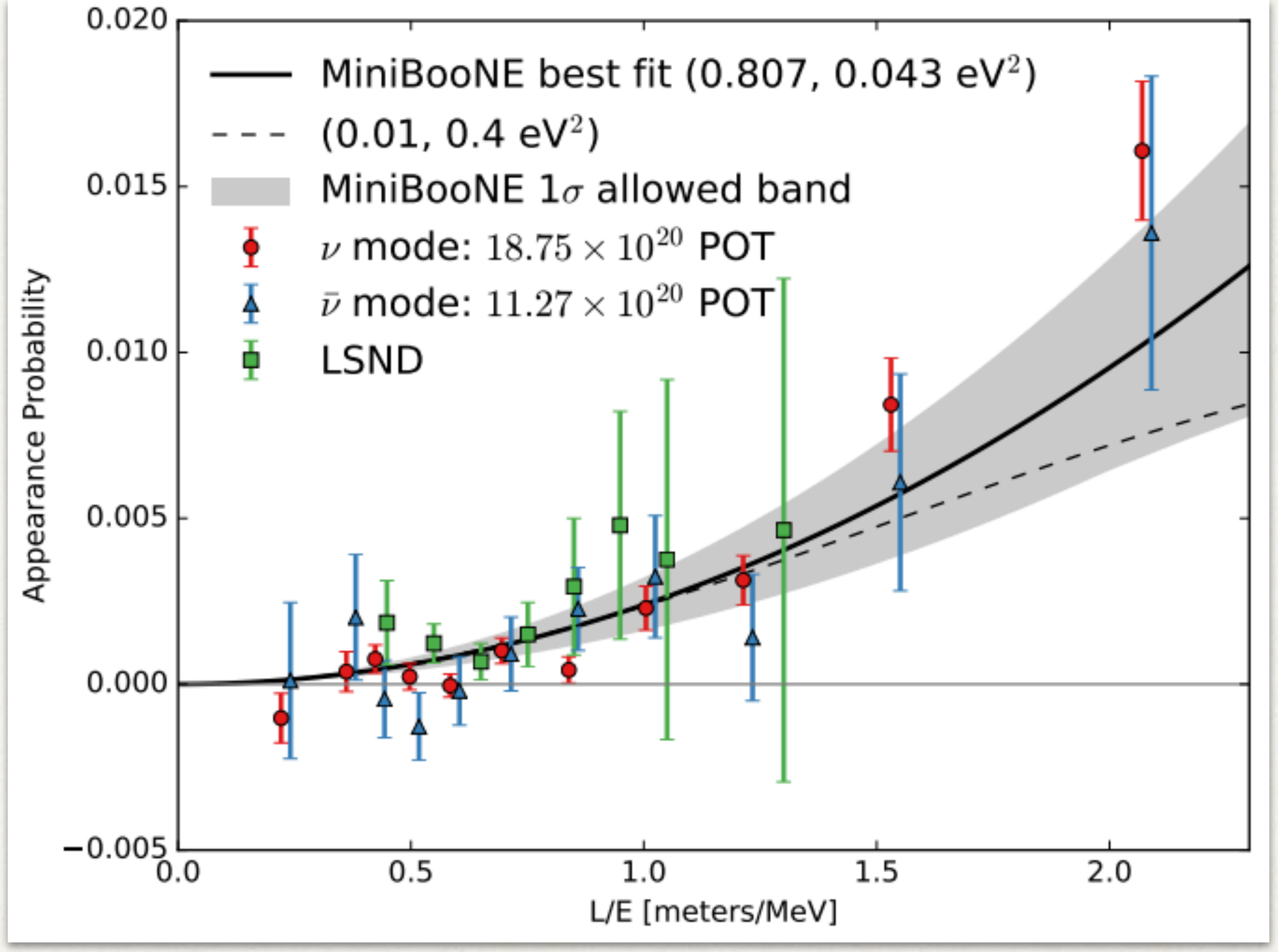
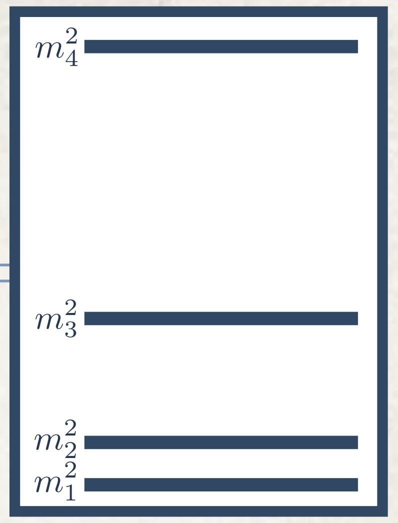


Large mass splitting implies a *new* neutrino state.

New State, Bigger Mixing Matrix



$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\mathrm{CP}}} & c_{13}c_{23} \end{pmatrix}$$

3 mixing angles, 1 CP-violating phase

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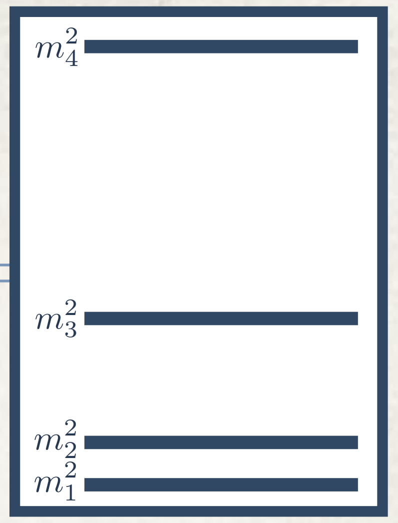

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6 mixing angles, 3 CP-violating phases

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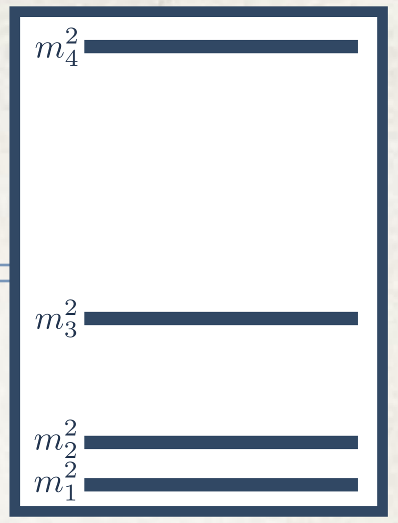

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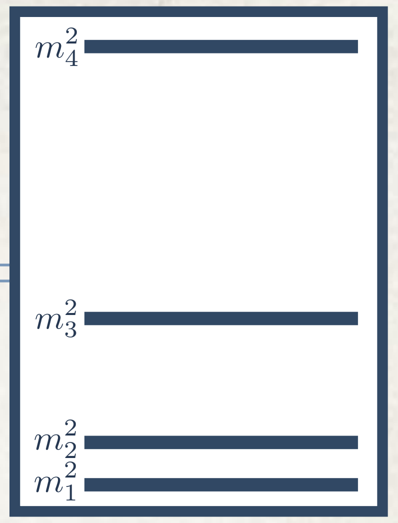

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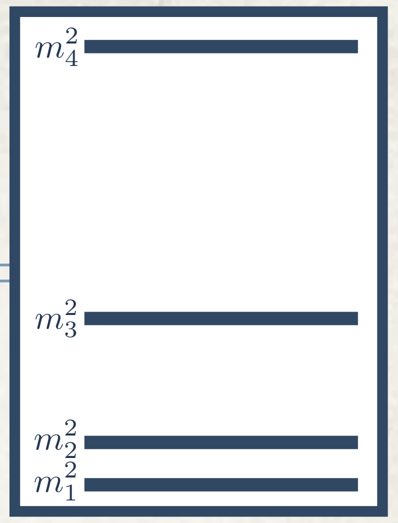

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Appearance (MiniBooNE/LSND) requires *two* new mixing angles to be nonzero.

Appearance *requires* Disappearance

$$\boxed{P(\nu_\mu \to \nu_e) = 4\left|U_{e4}\right|^2\left|U_{\mu 4}\right|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)}$$

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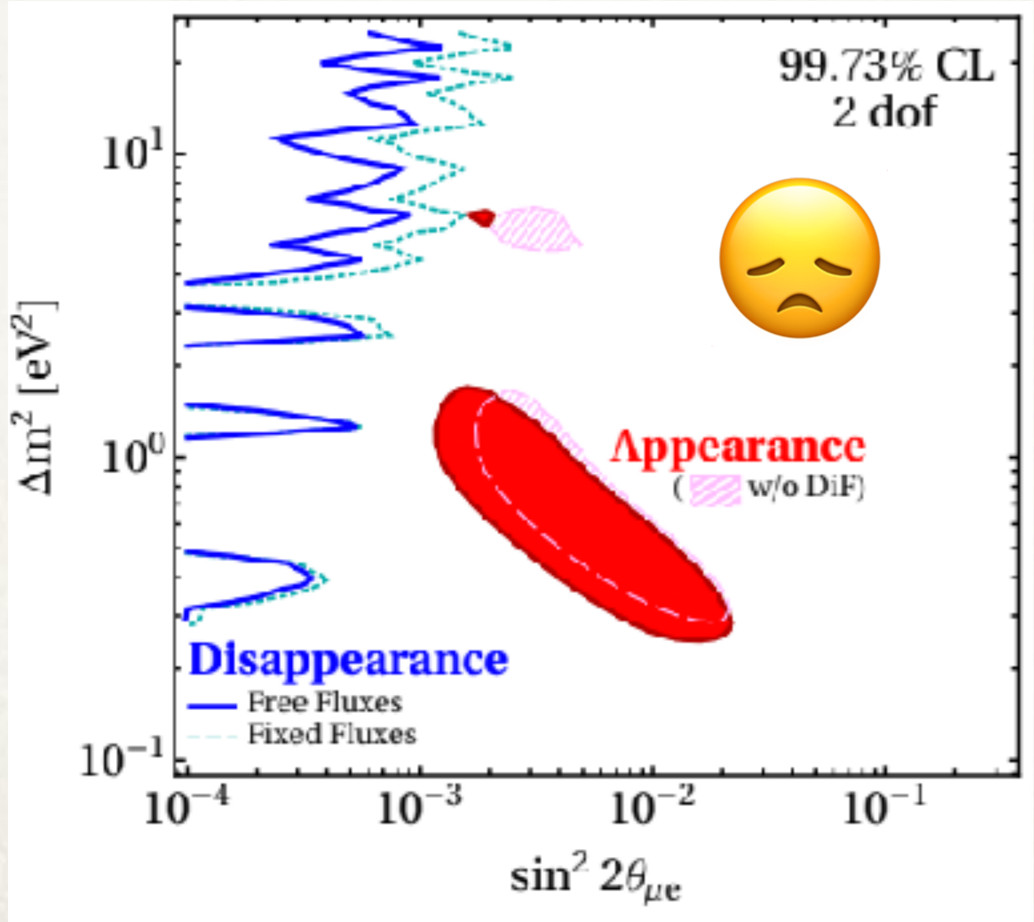
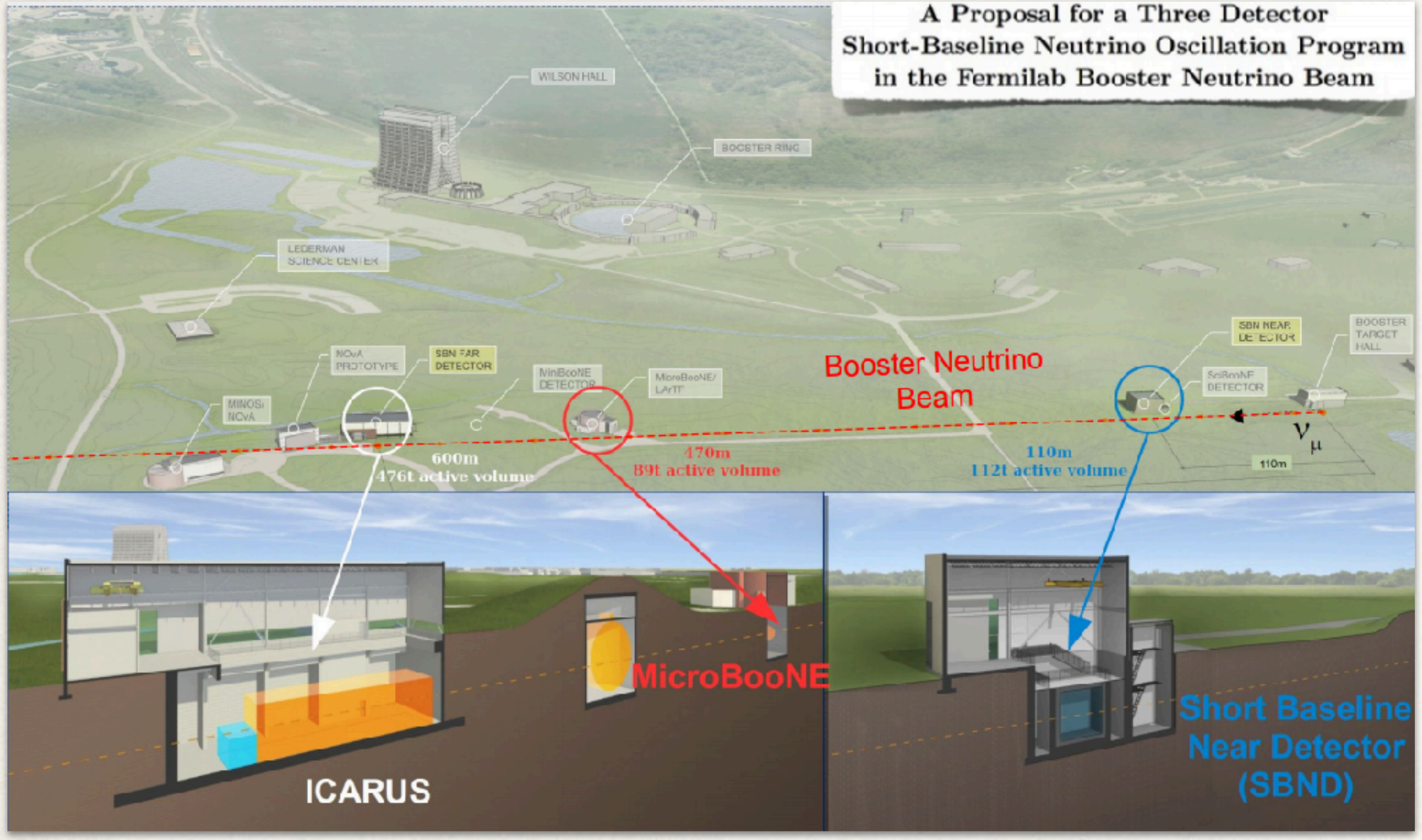


Dentler et al, [1803.10661]

The Final Word? Fermilab SBN



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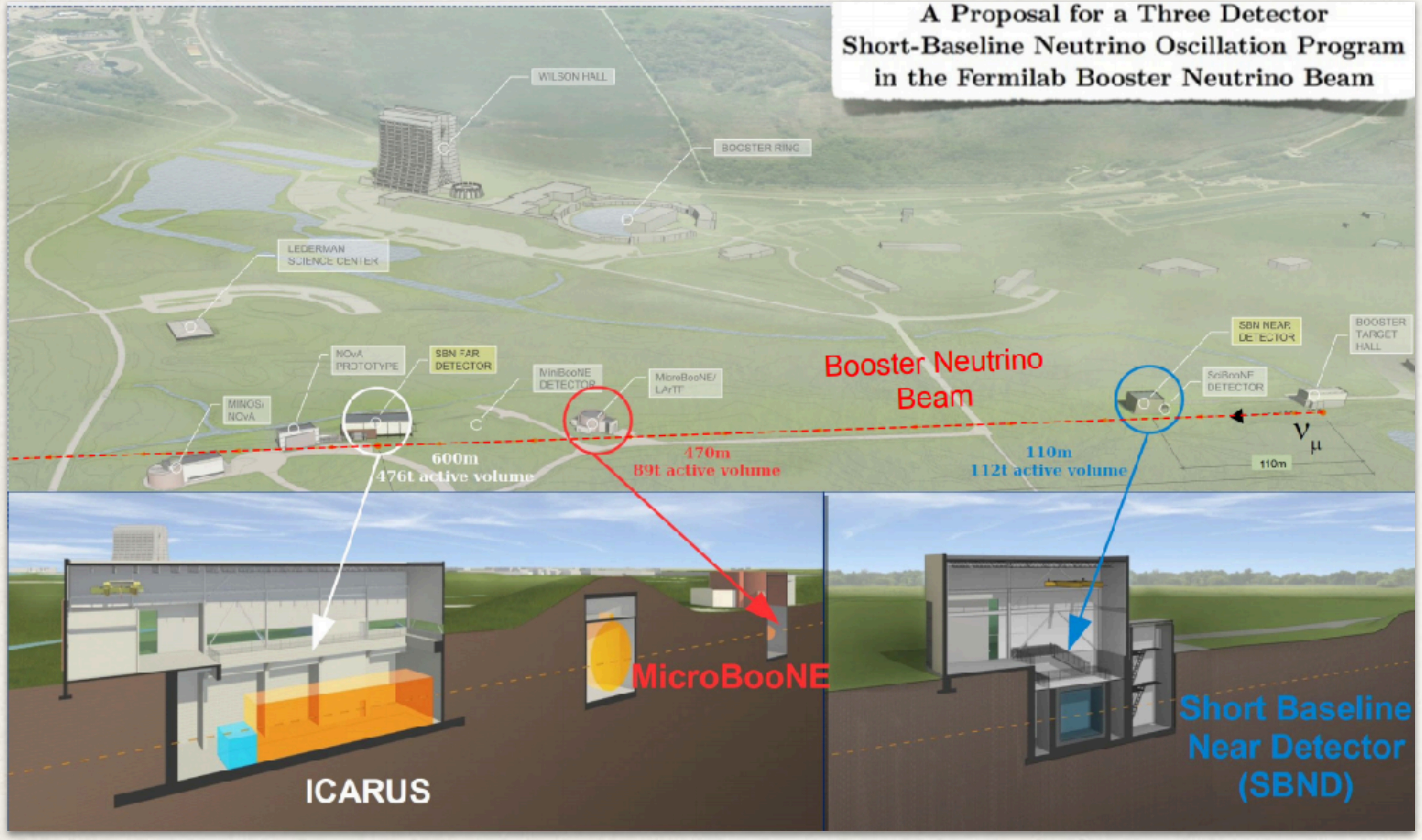

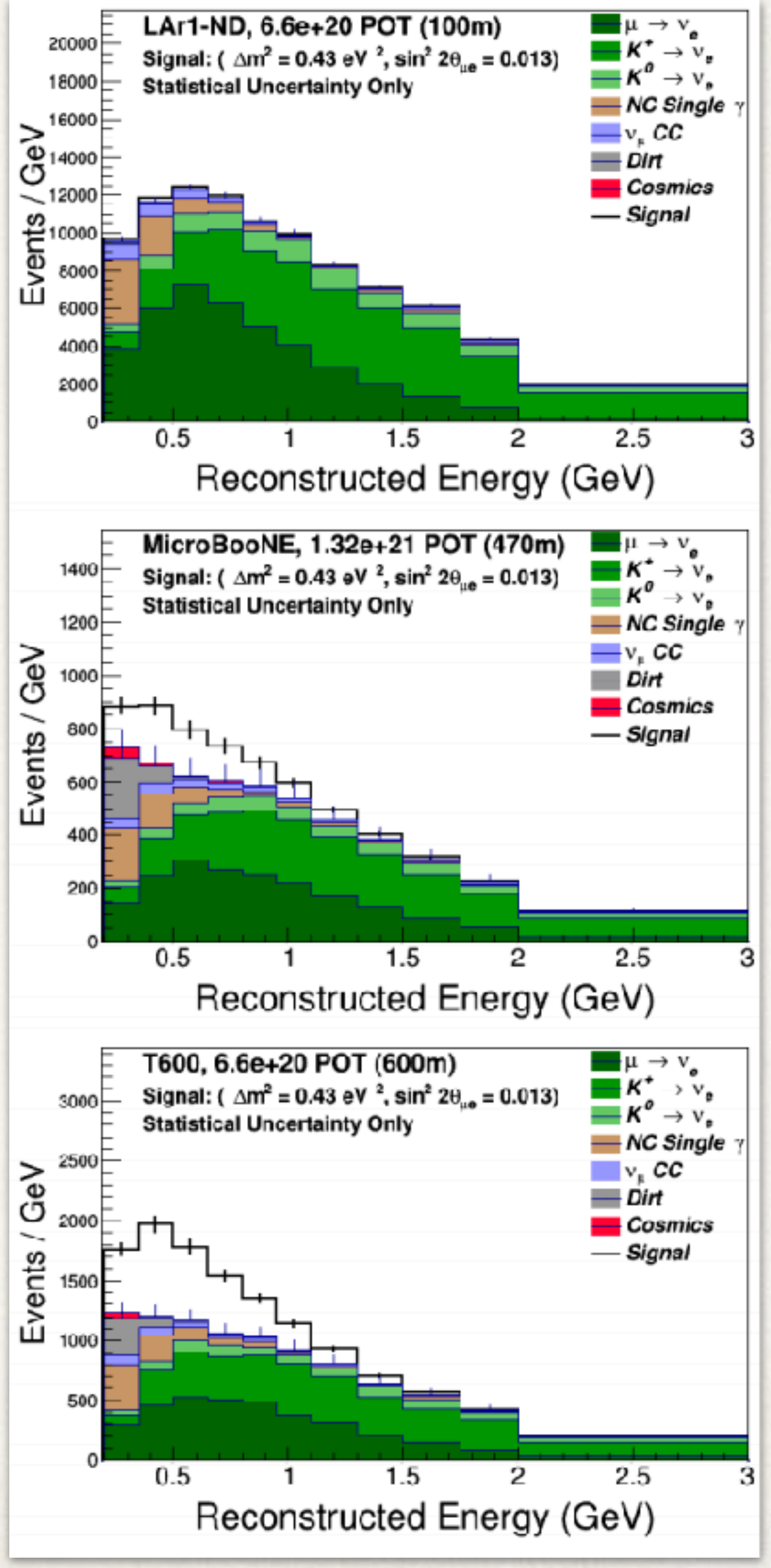

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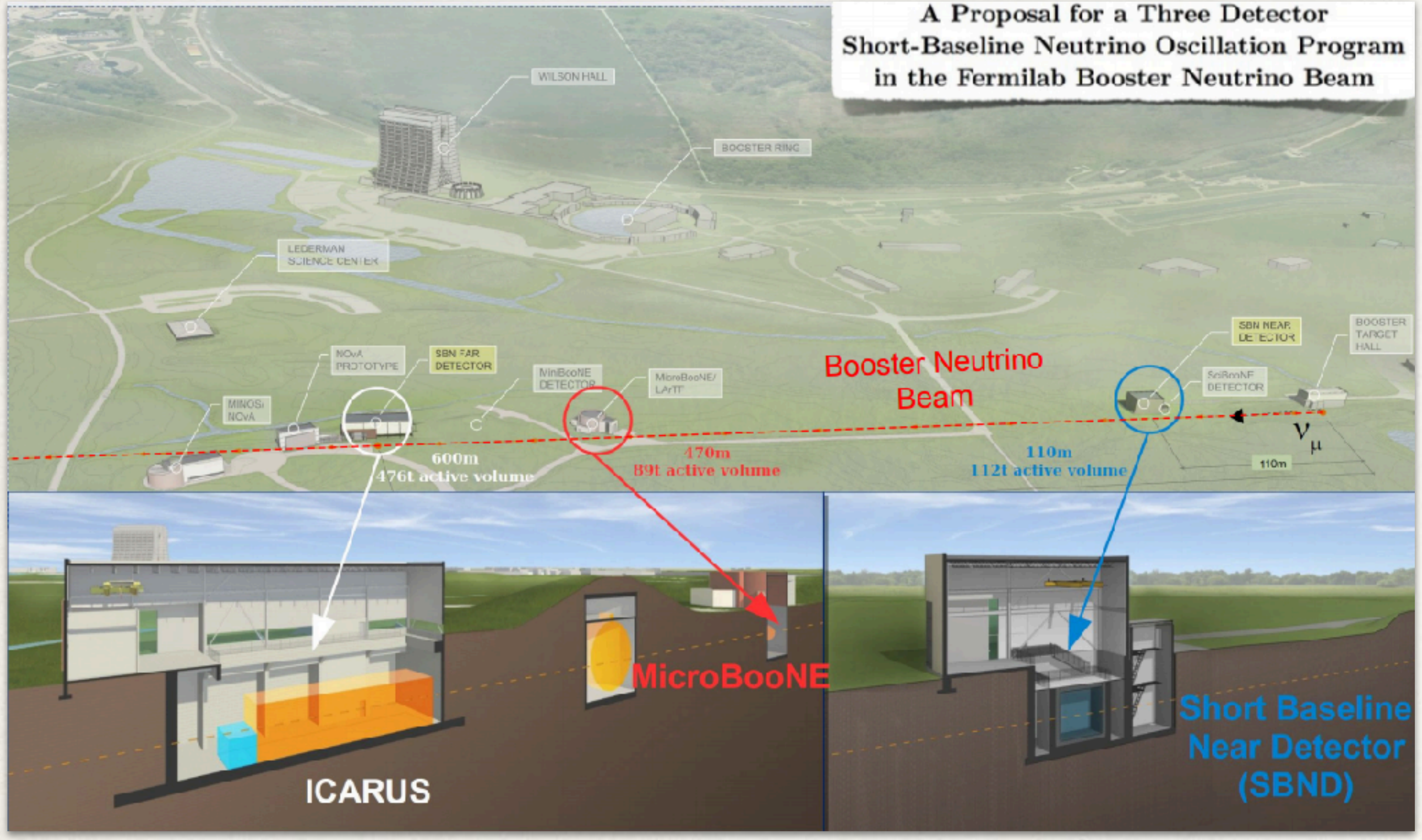
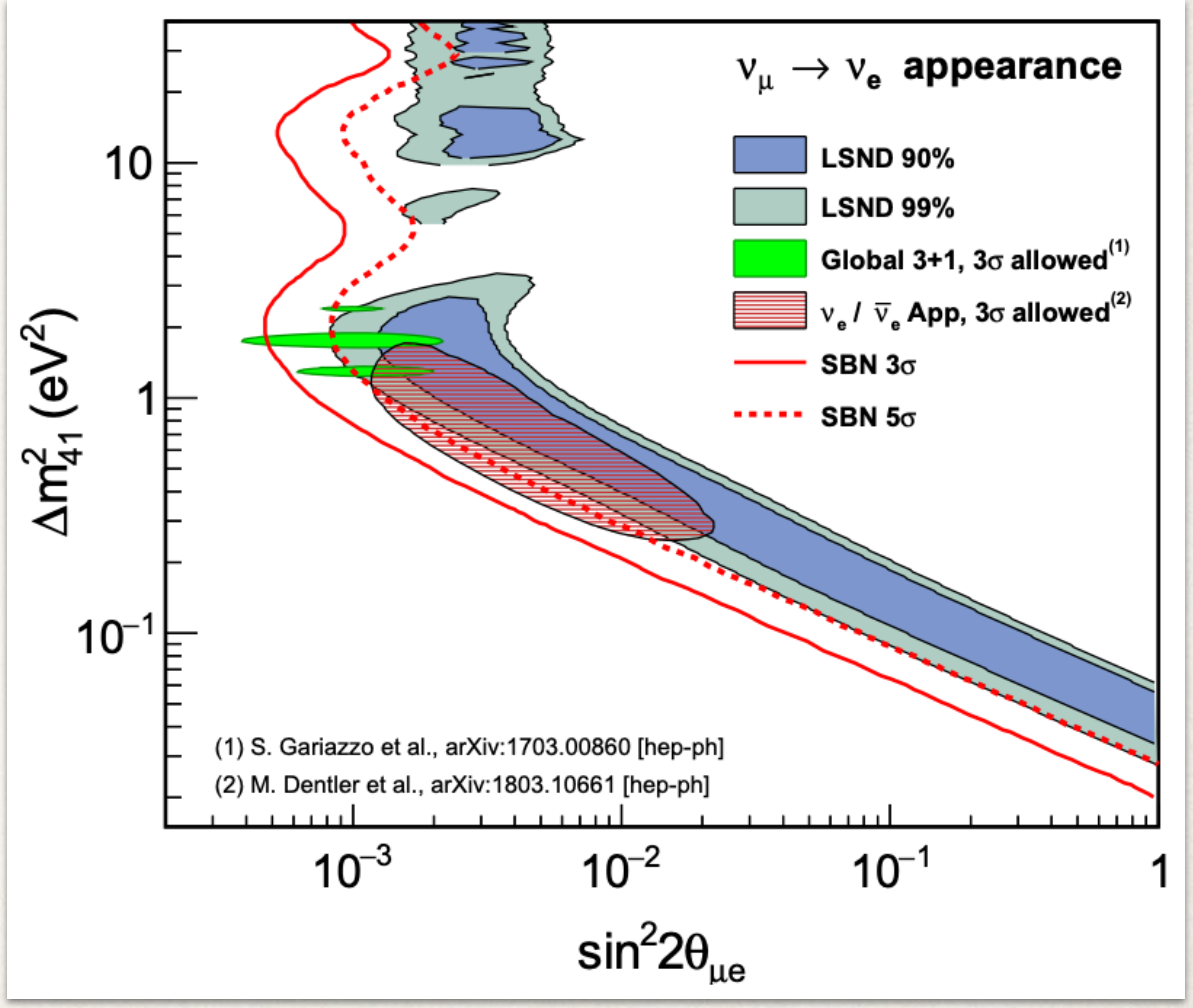
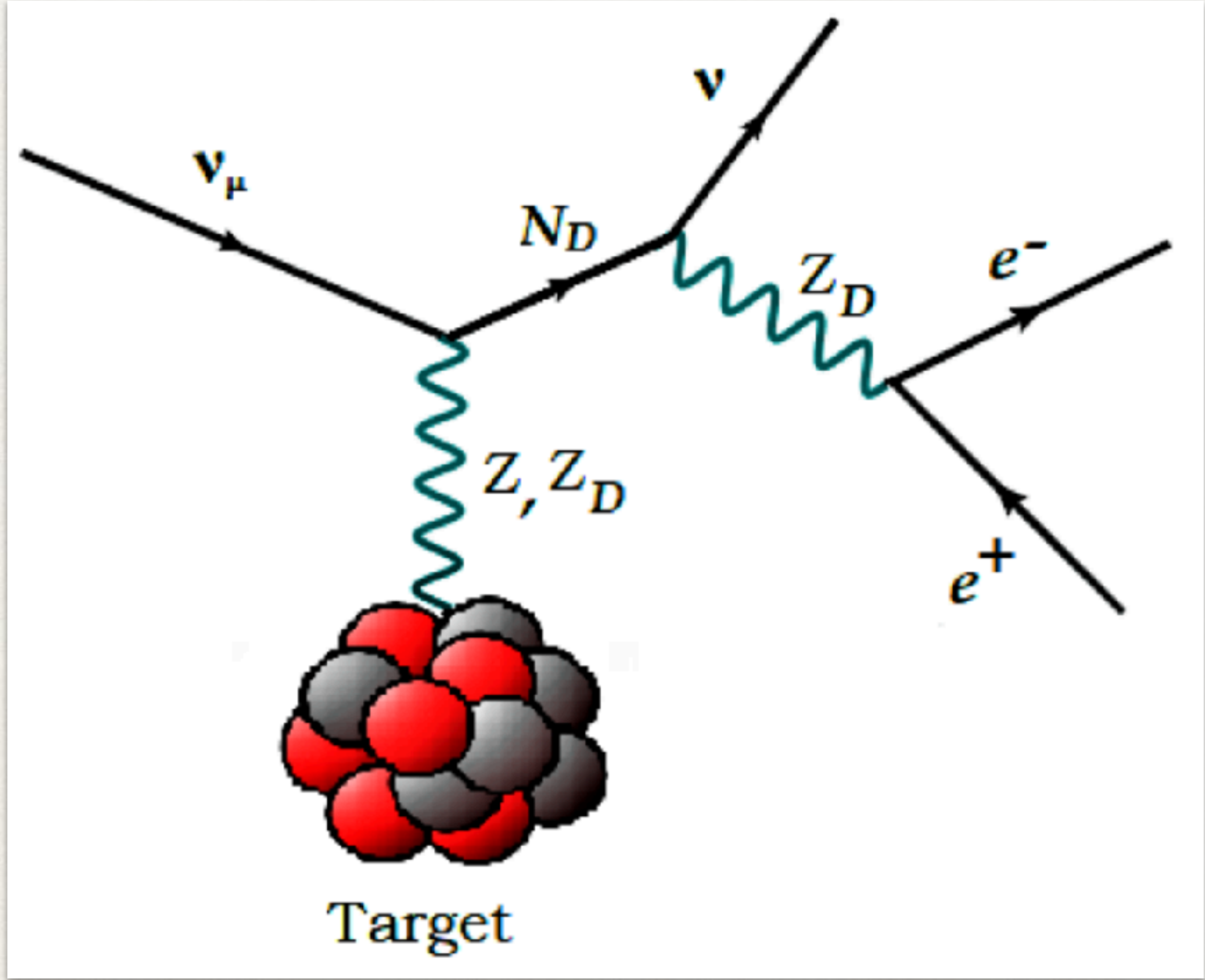




What if it's not a sterile neutrino…?

Given the tension between searches for appearance and null results for disappearance, what if LSND and/or MiniBooNE are seeing some "other" new physics?



Bertuzzo et al [1807.09877]

See also Ballett et al [1808.02915]

Nice overviews of possible types of models that can explain MiniBooNE:
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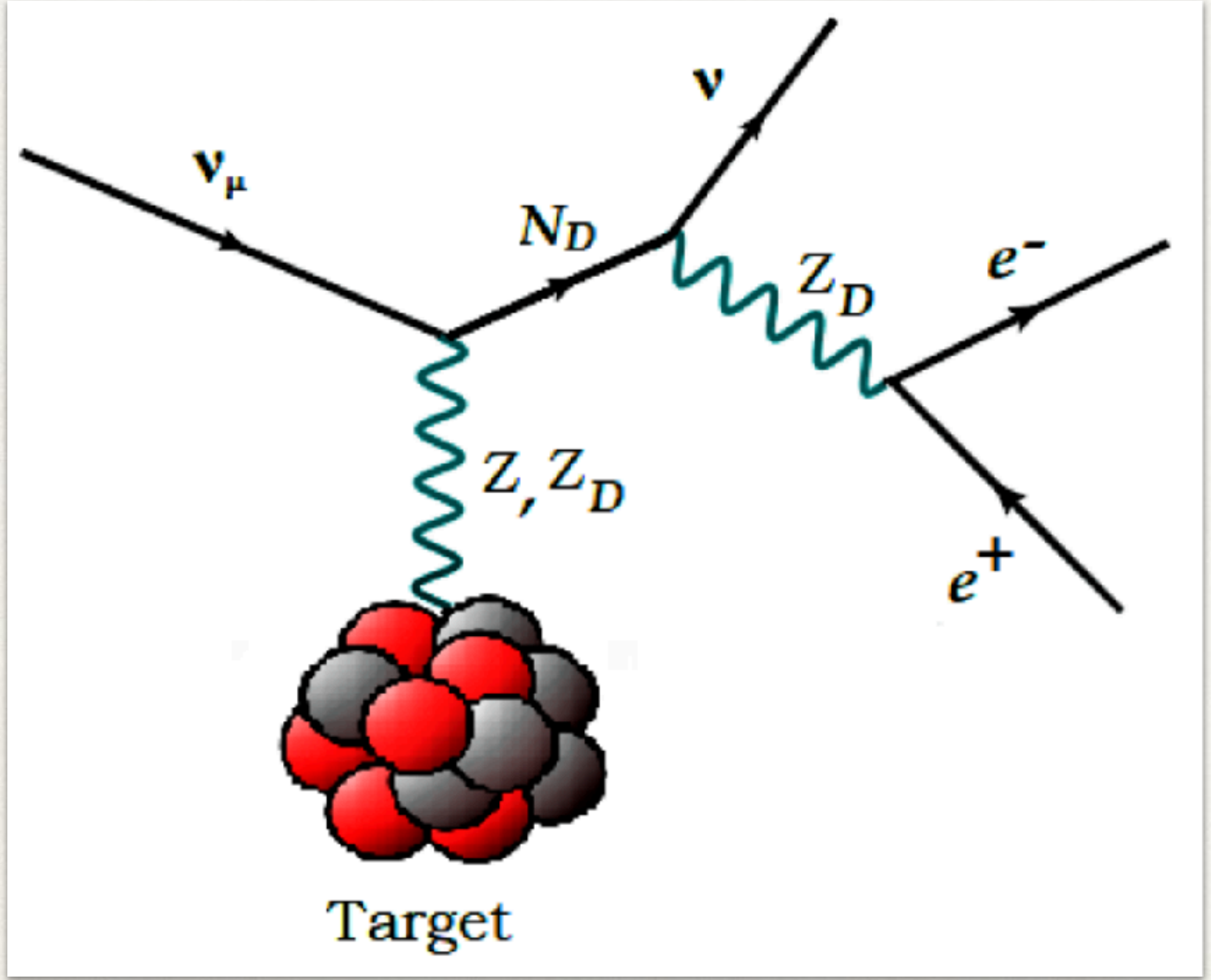

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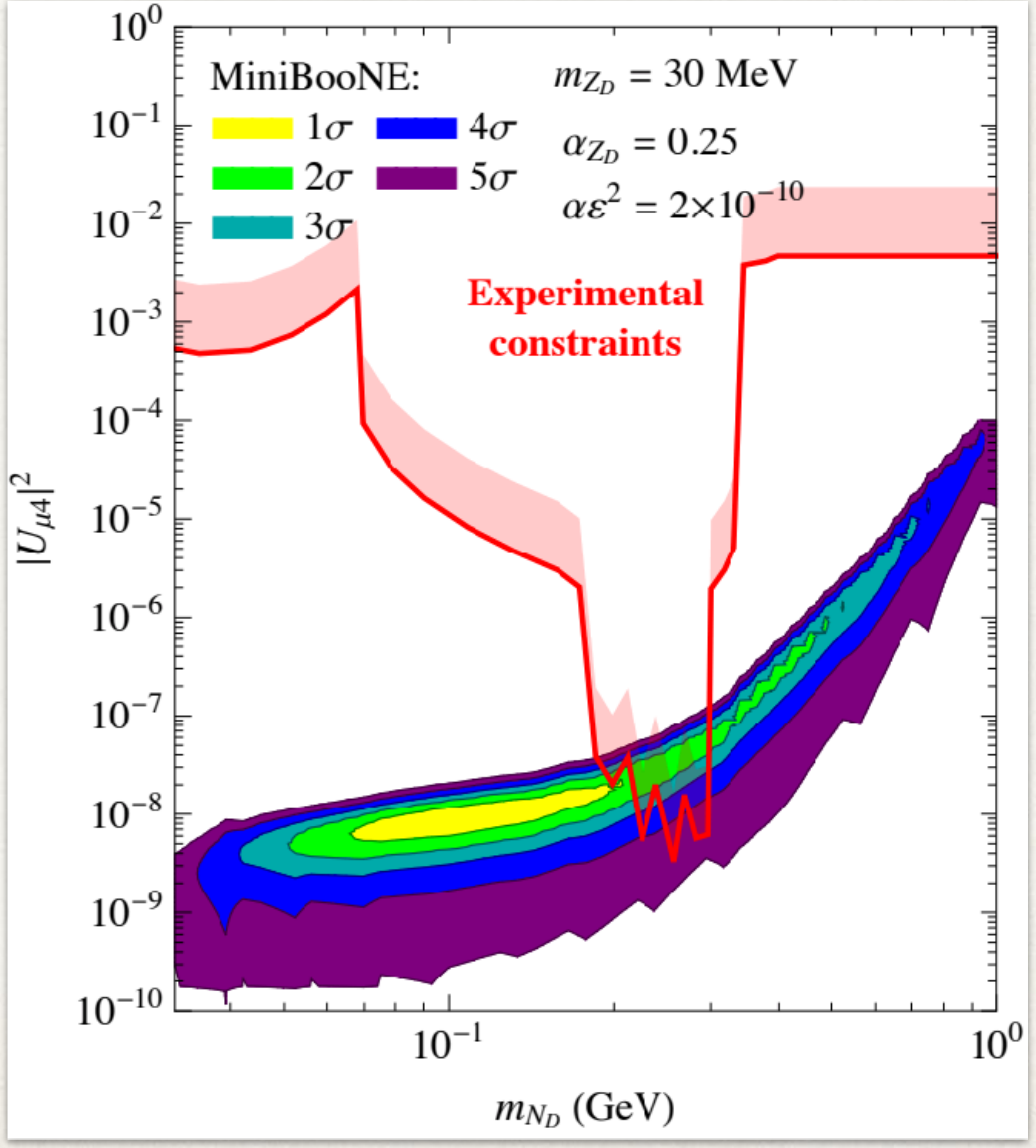

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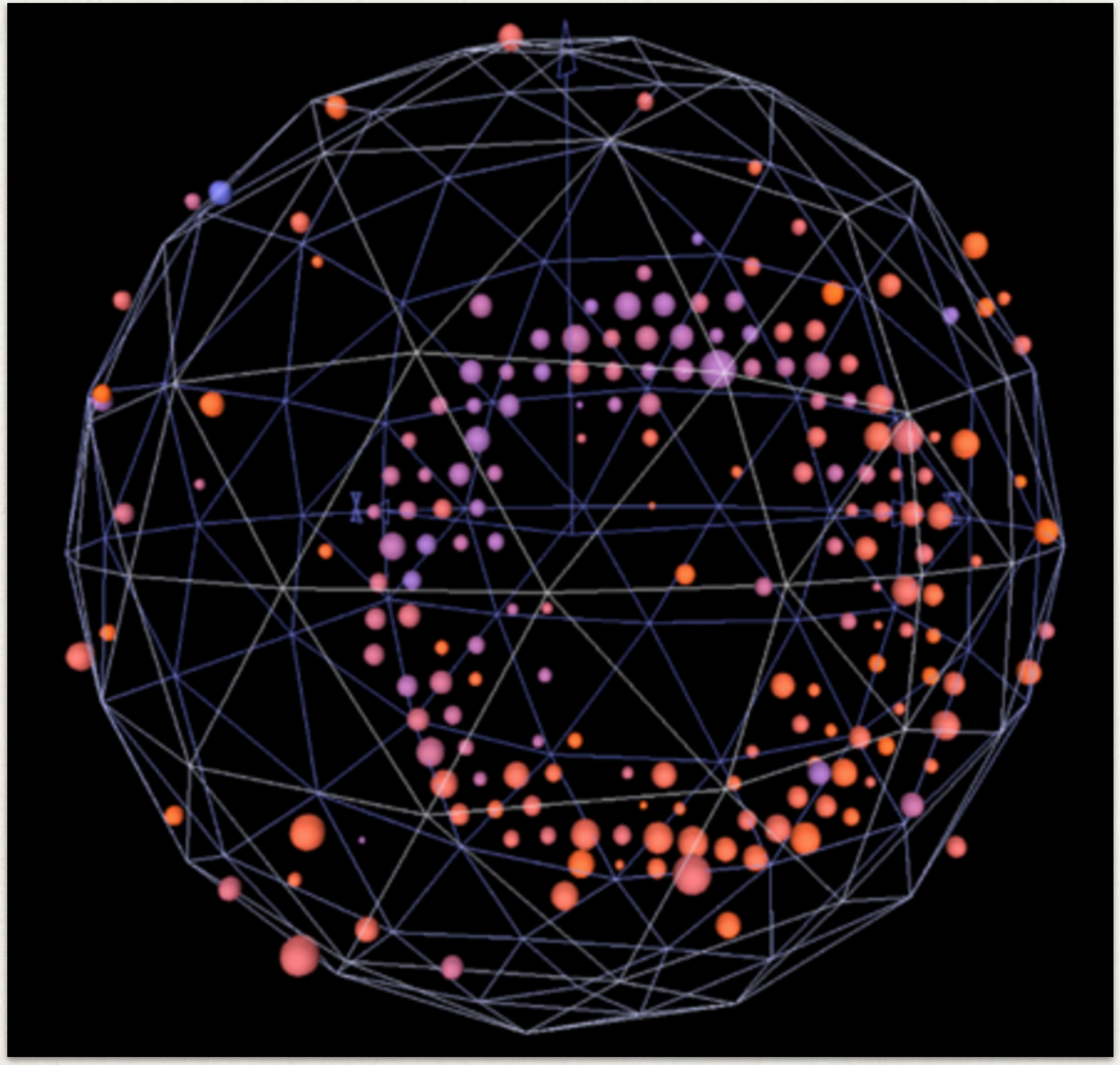
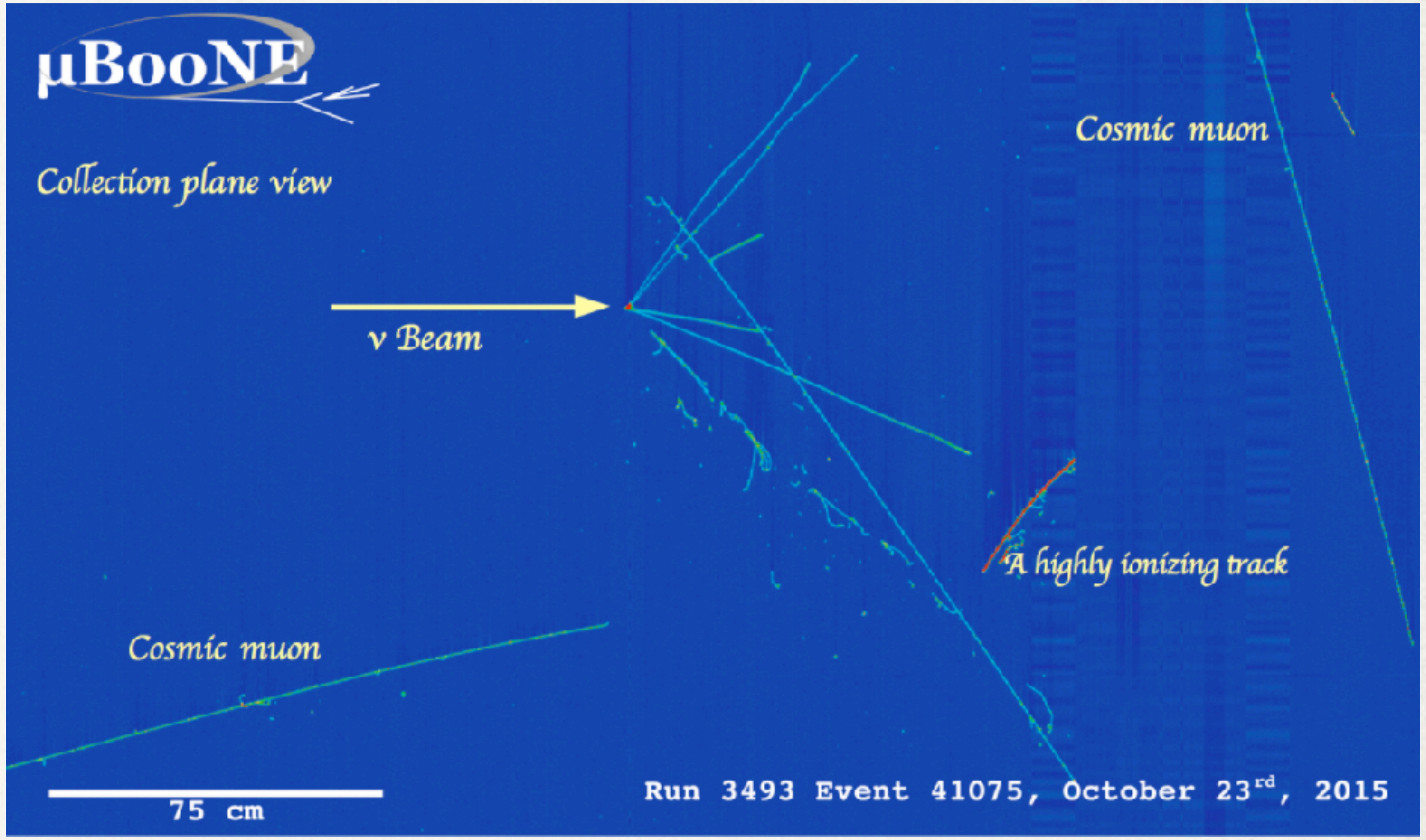
What does the next generation of experiments have to offer?



MiniBooNE



MicroBooNE

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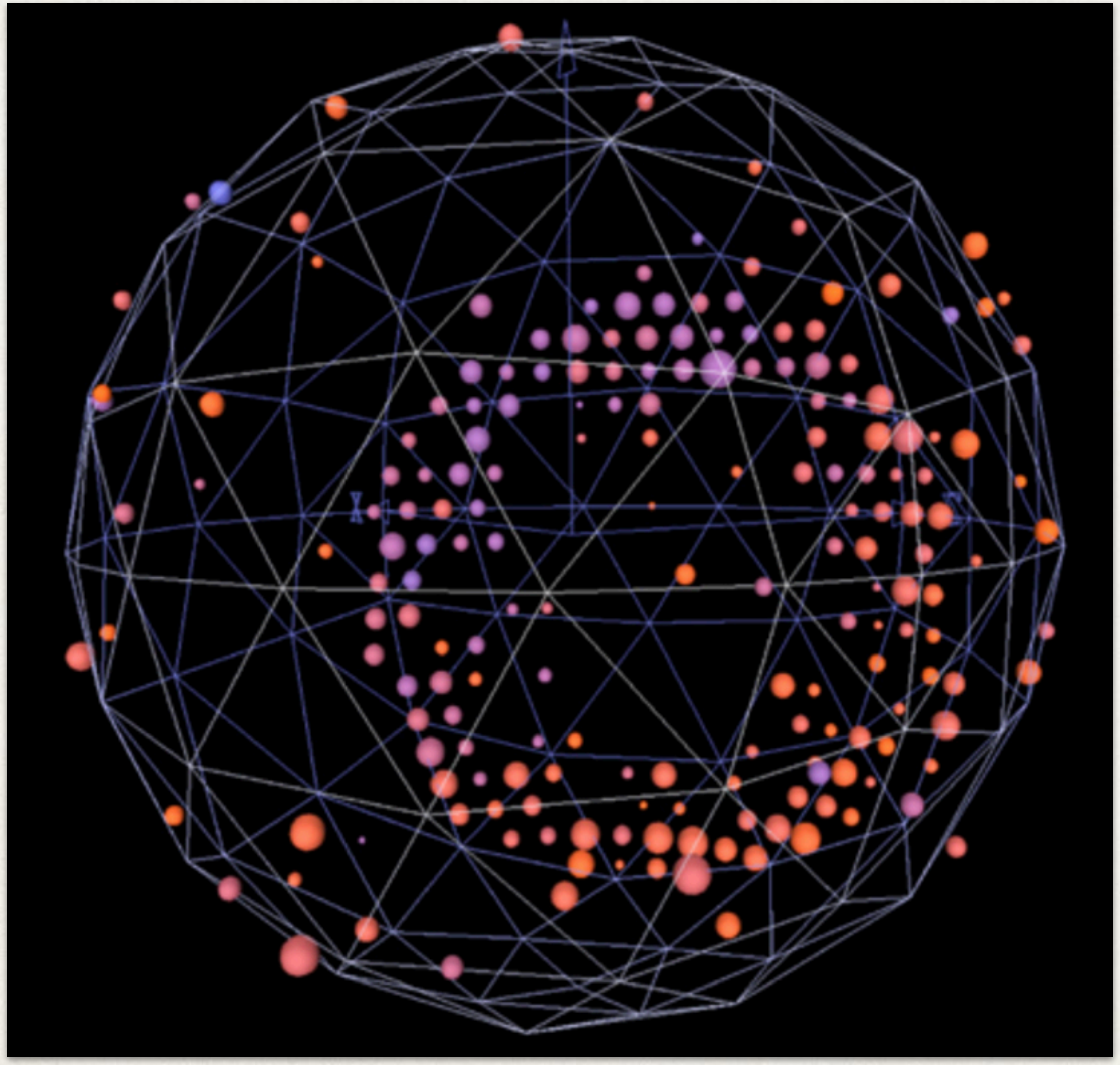

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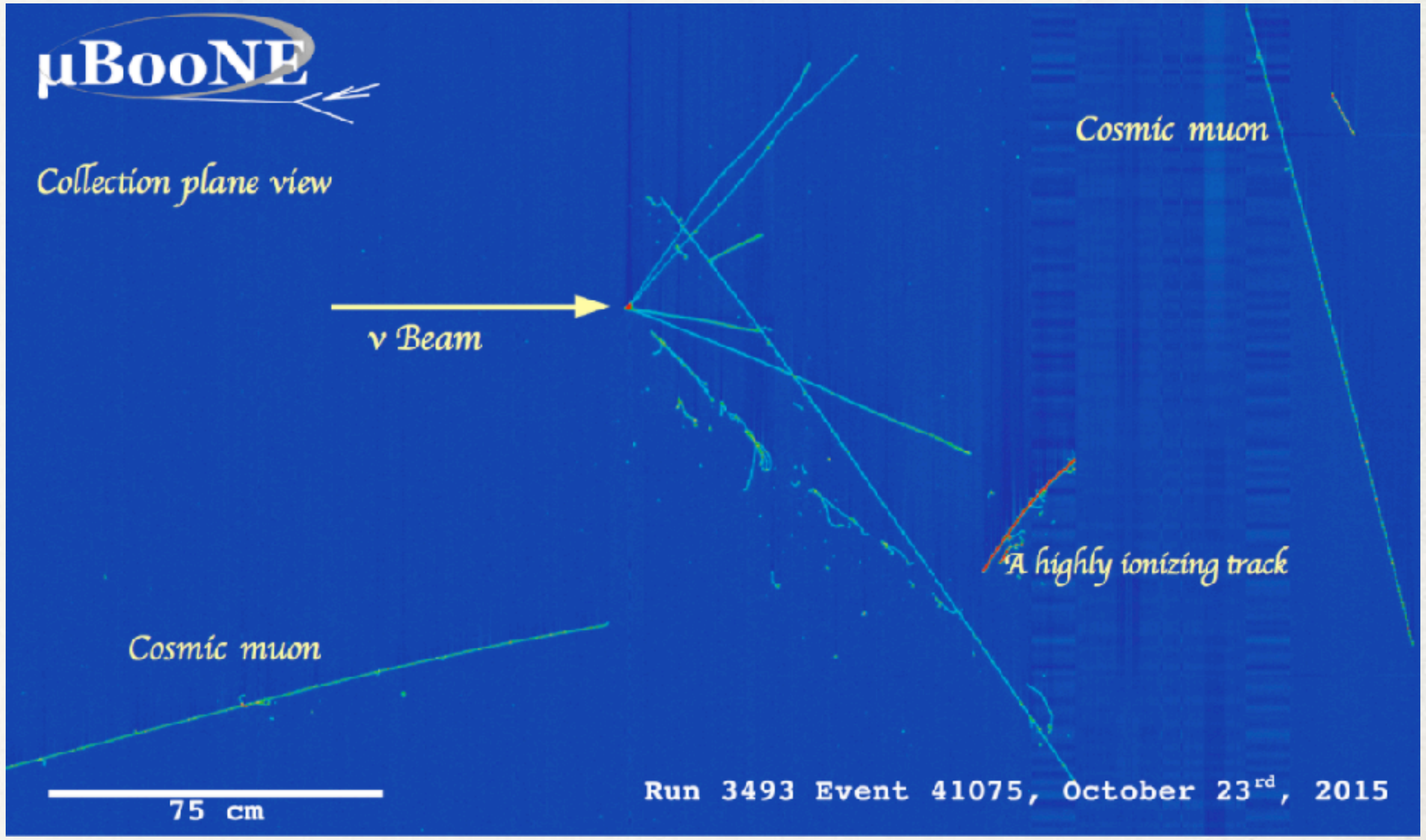
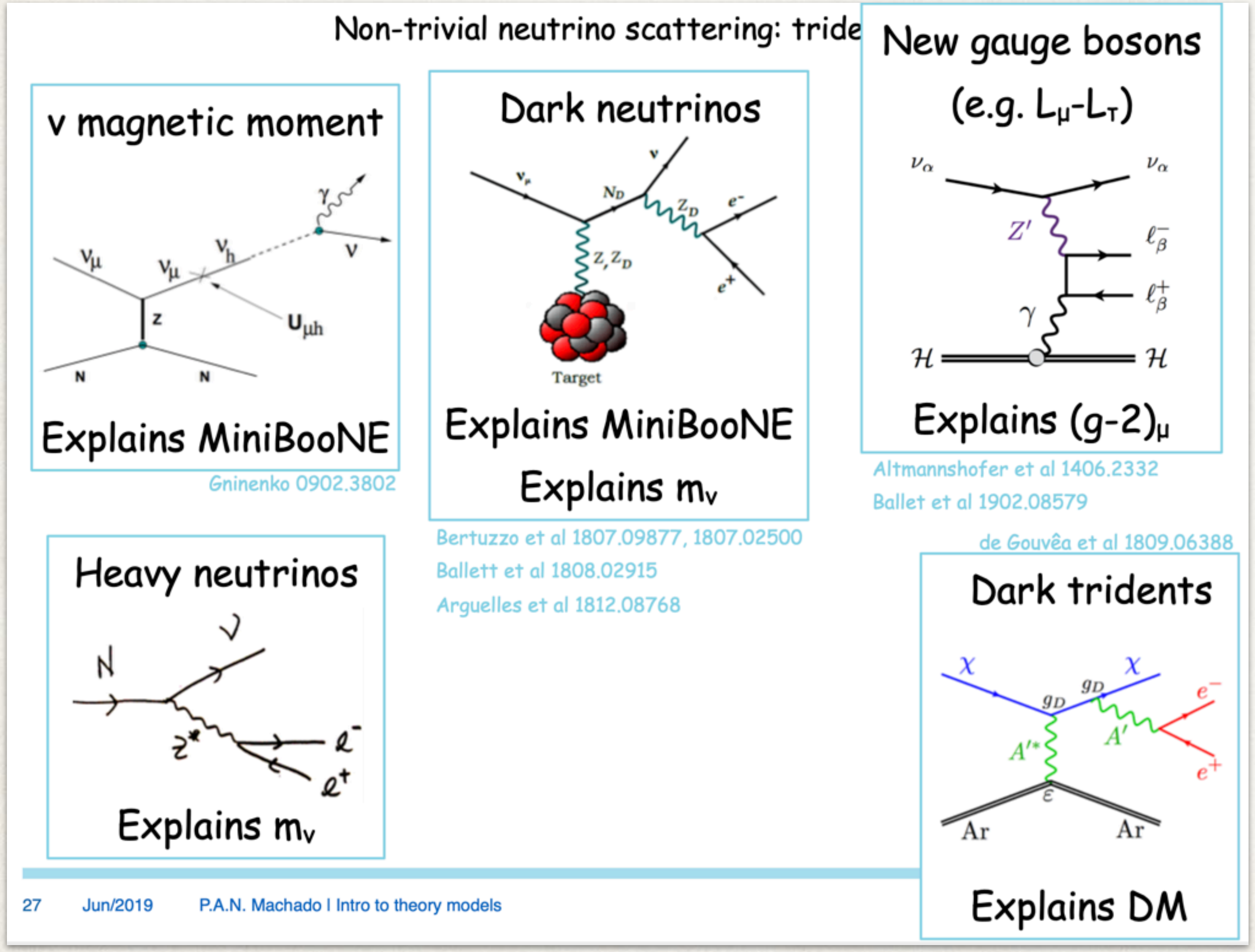


MicroBooNE

Excellent particle ID will allow next-generation experiments to test MiniBooNE anomaly explanations and search for even more new physics!

A sampling of new scattering to be tested…



Courtesy of Pedro Machado

Various new-physics scenarios that give rise to photon or electron/positron pairs in the SBN detectors

BSM with Neutrino Oscillations

BSM with Neutrino ~~Oscillations~~ Experiments

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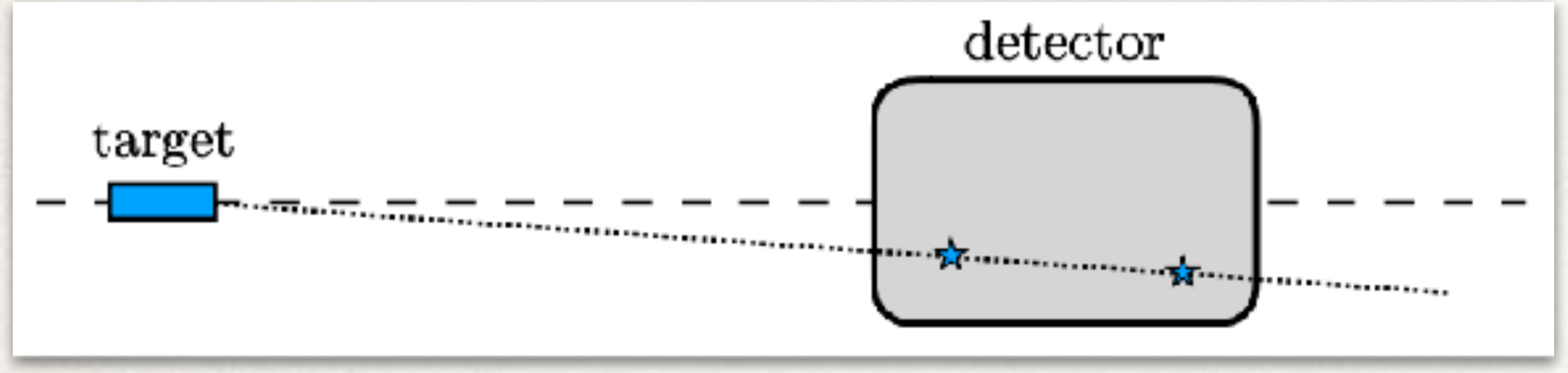
White Paper on New Opportunities at the Next-Generation Neutrino Experiments
(Part 1: BSM Neutrino Physics and Dark Matter)

C.A. Argüelles[1], A.J. Aurisano[2], B. Batell[3], J. Berger[3], M. Bishai[4], T. Boschi[5], N. Byrnes[6], A. Chatterjee[6], A. Chodos[6], T. Coan[7], Y. Cui[8], A. de Gouvêa[* 9], P.B. Denton[4], A. De Roeck[* 10], W. Flanagan[11], D.V. Forero[12], R.P. Gandrajula[13], A. Hatzikoutelis[14], M. Hostert[15], B. Jones[6], B.J. Kayser[16], K.J. Kelly[16], D. Kim[17], J. Kopp[10,18], A. Kubik[19], K. Lang[20], I. Lepetic[21], P.A.N. Machado[16], C.A. Moura[22], F. Olness[6], J.C. Park[23], S. Pascoli[15], S. Prakash[12], L. Rogers[6], I. Safa[24], A. Schneider[24], K. Scholberg[25], S. Shin[26,27], I.M. Shoemaker[28], G. Sinev[25], B. Smithers[6], A. Sousa[* 2], Y. Sui[29], V. Takhistov[30], J. Thomas[31], J. Todd[2], Y.-D. Tsai[16,32], Y.-T. Tsai[33], J. Yu[* 6], and C. Zhang[4]

[1907.08311]

BSM Prospects with Neutrino Experiments

Millicharged Particles



Harnik et al, [1902.03246]
See also Magill et al, [1806.03310]

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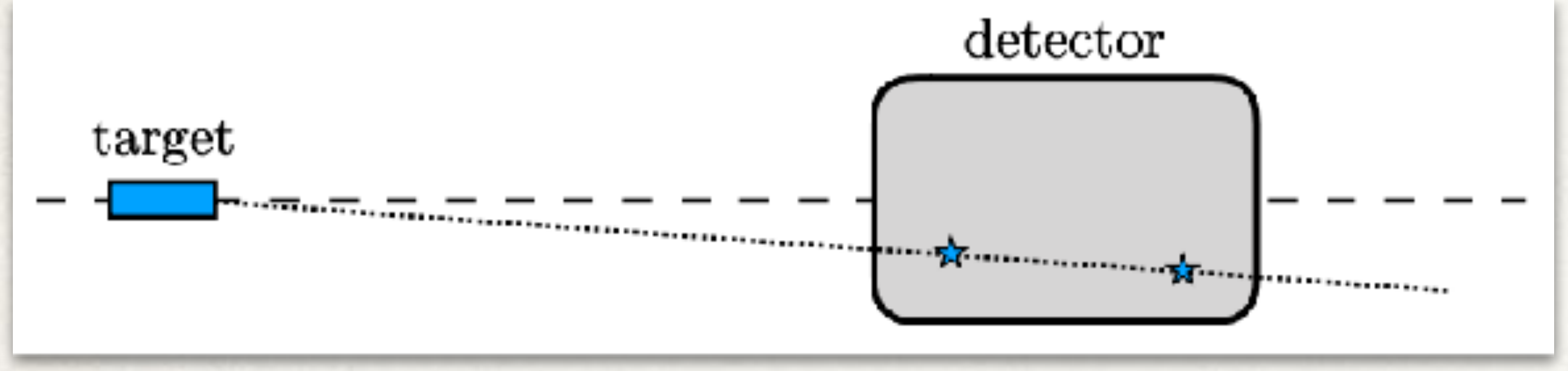

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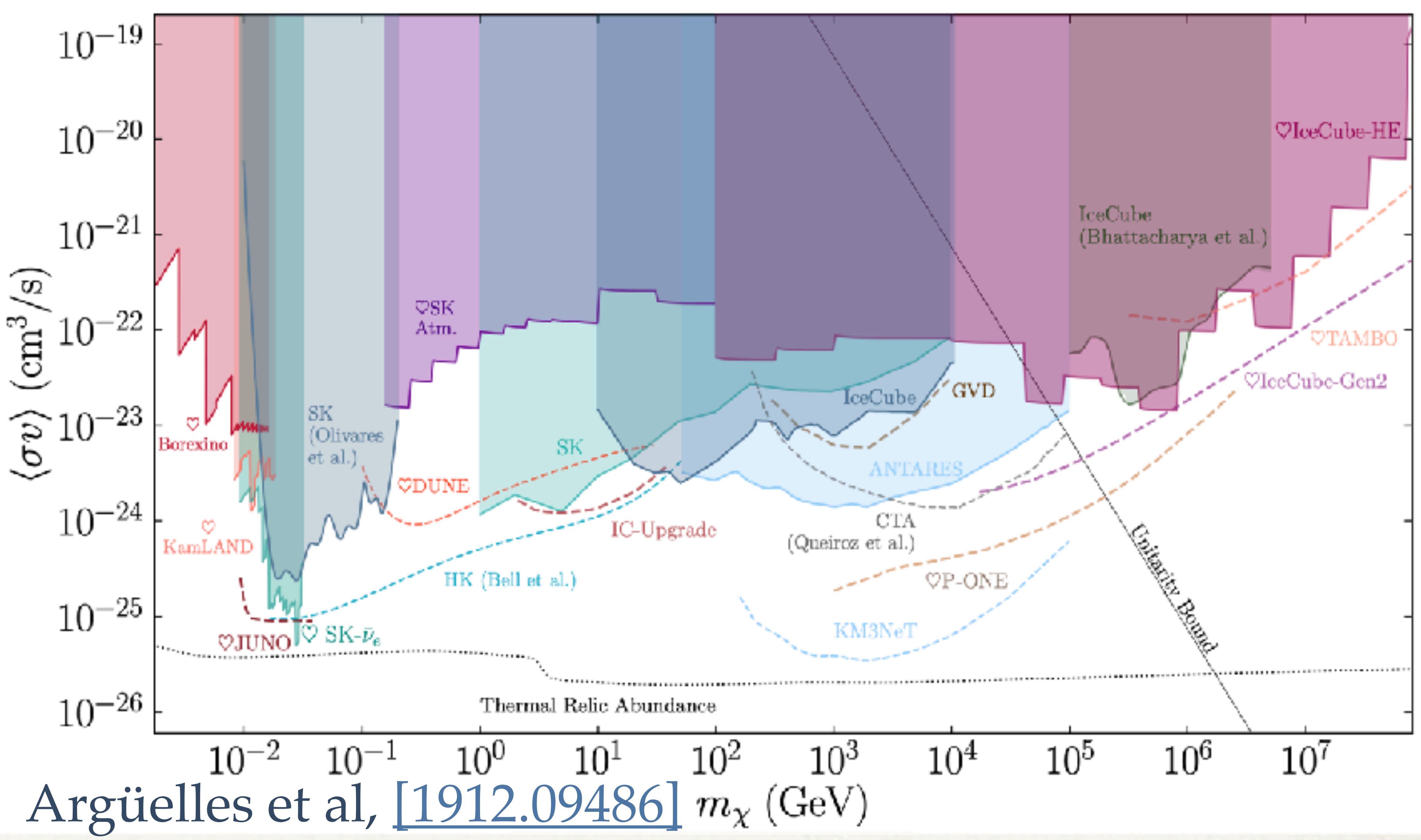
Dark Matter annihilation into Neutrinos



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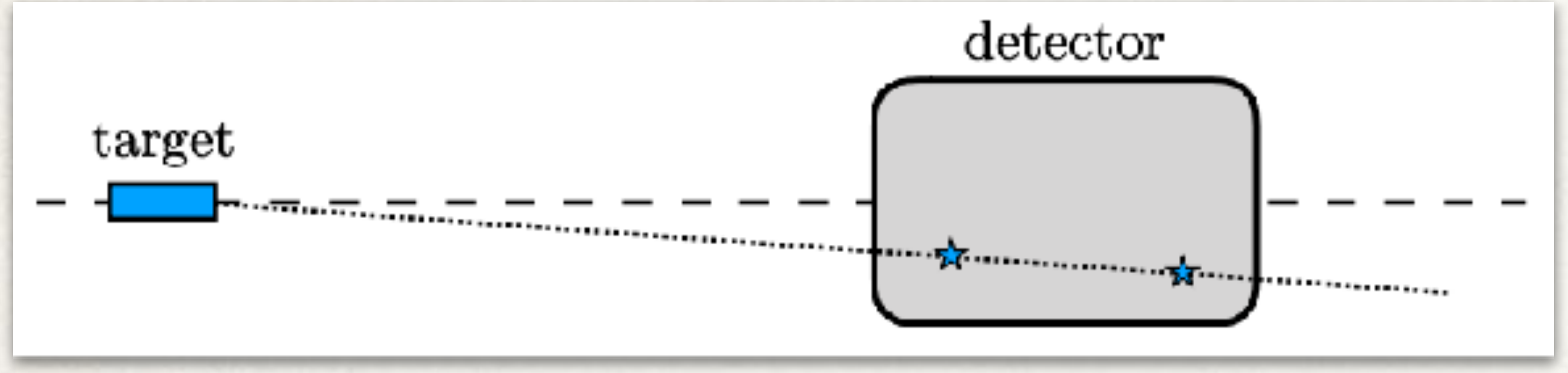

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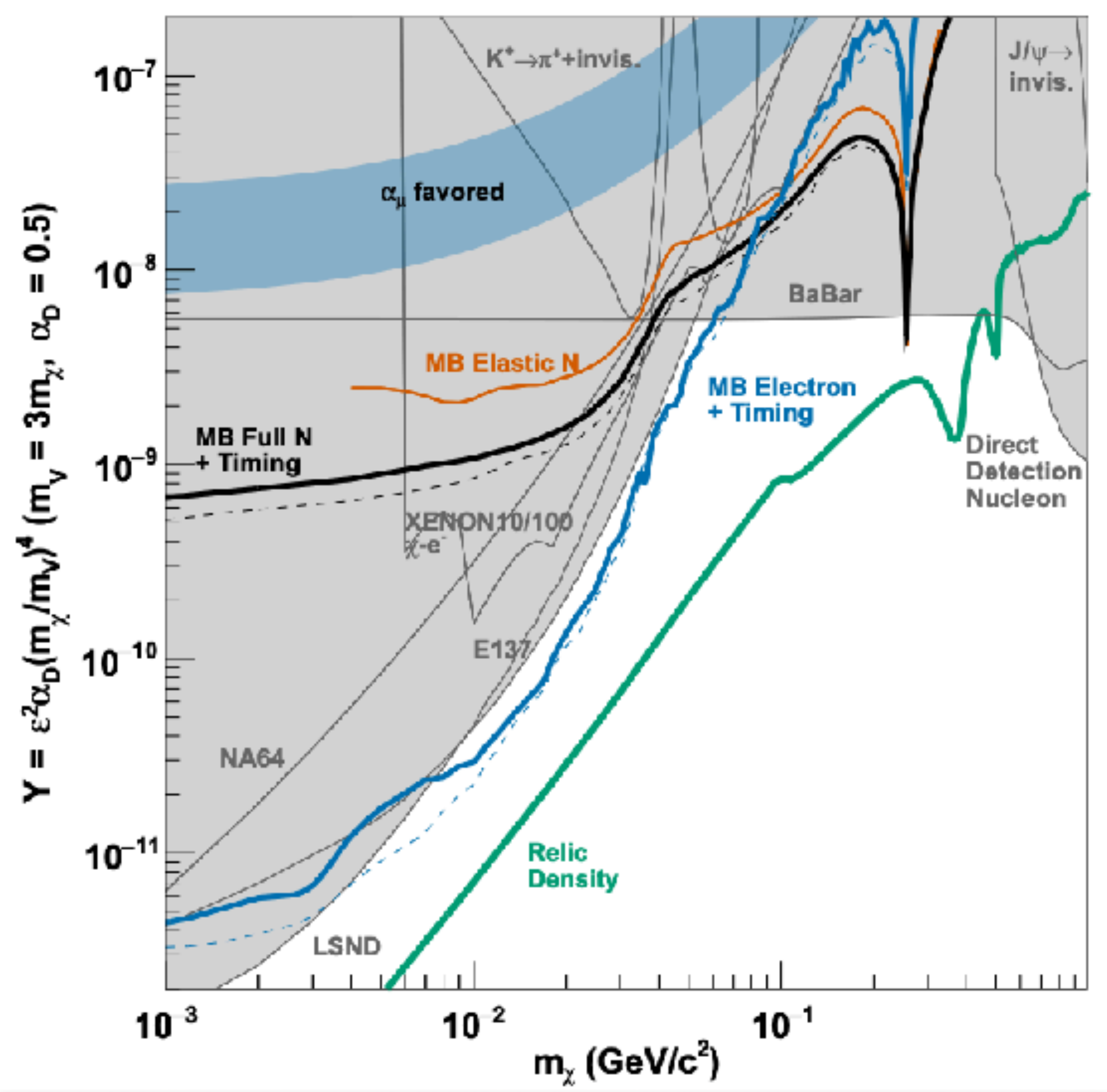
Sub-GeV Dark Matter



MiniBooNE-DM Collaboration, [1807.06137]

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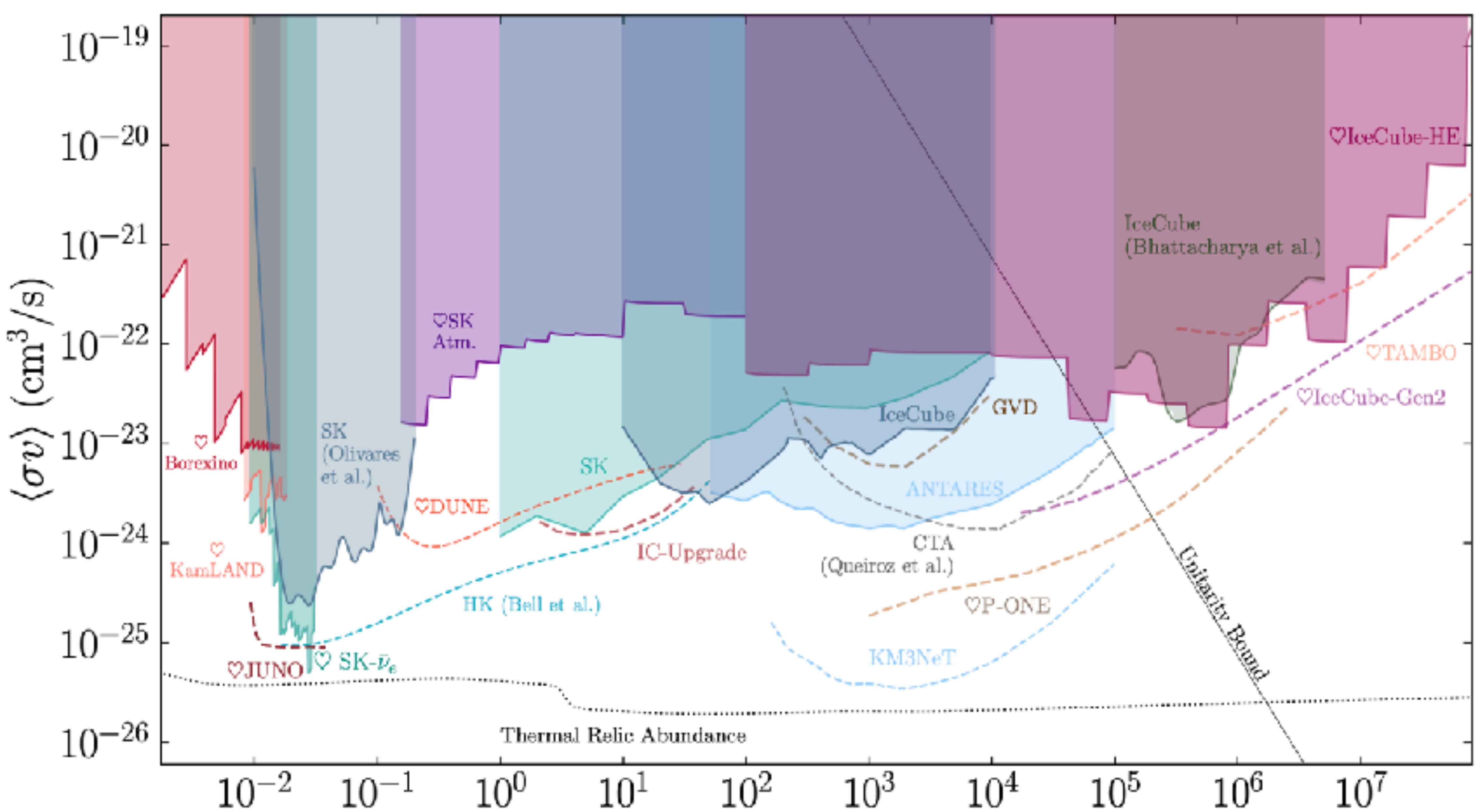

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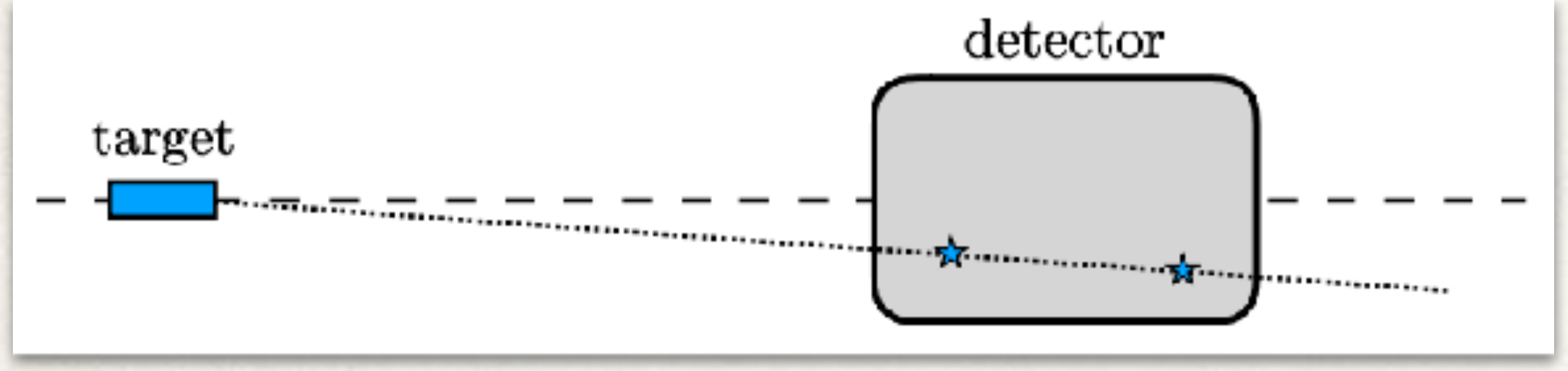

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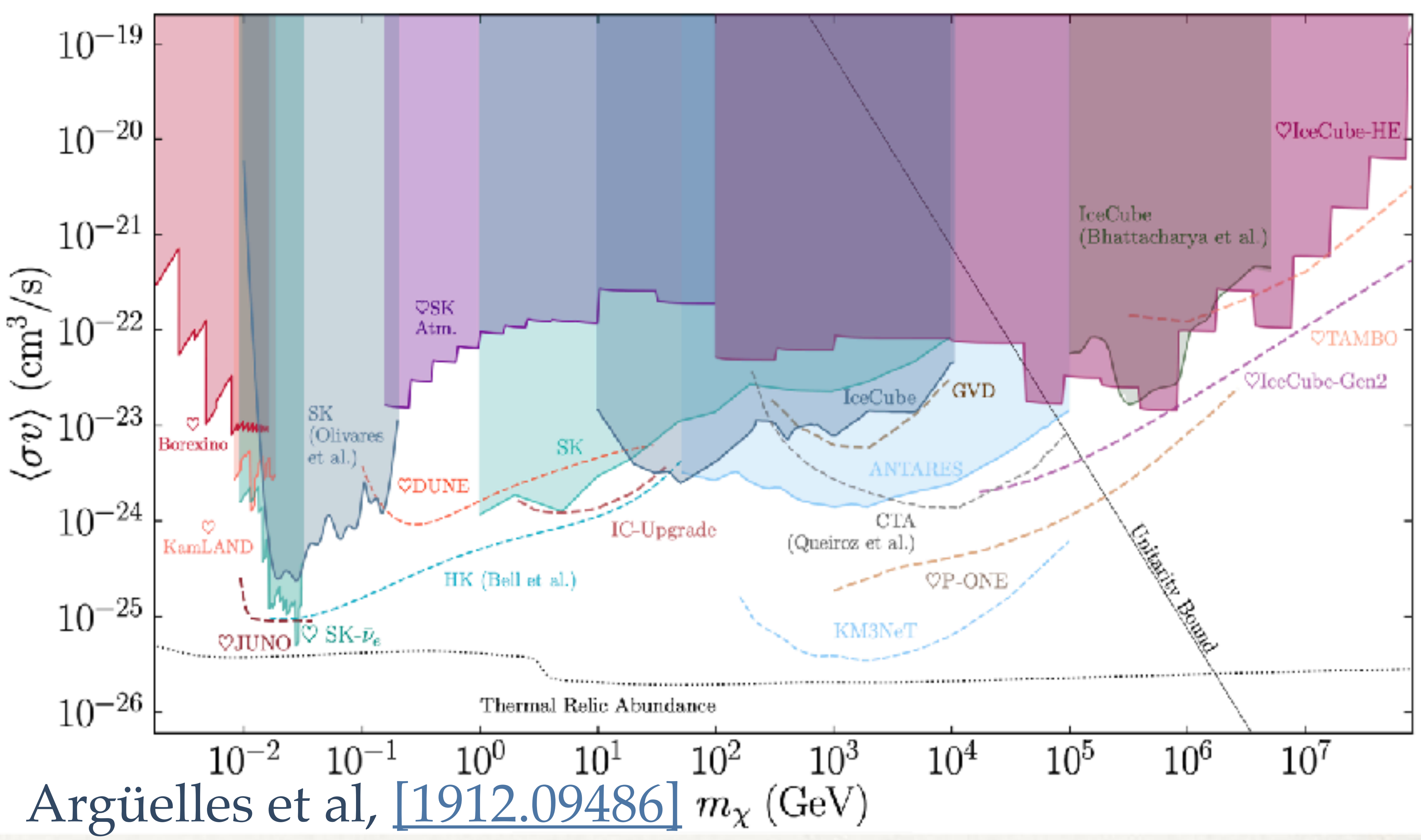

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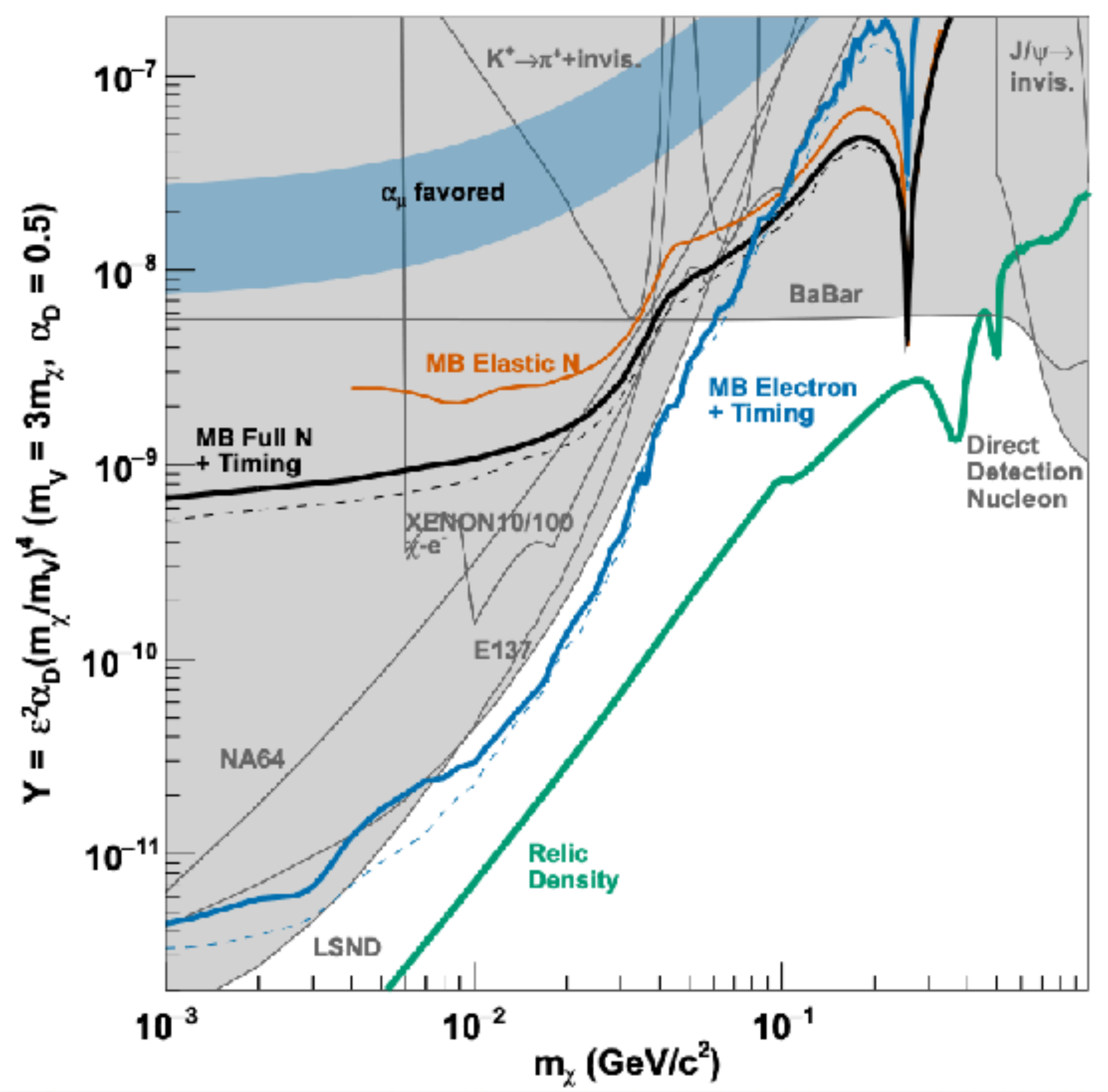

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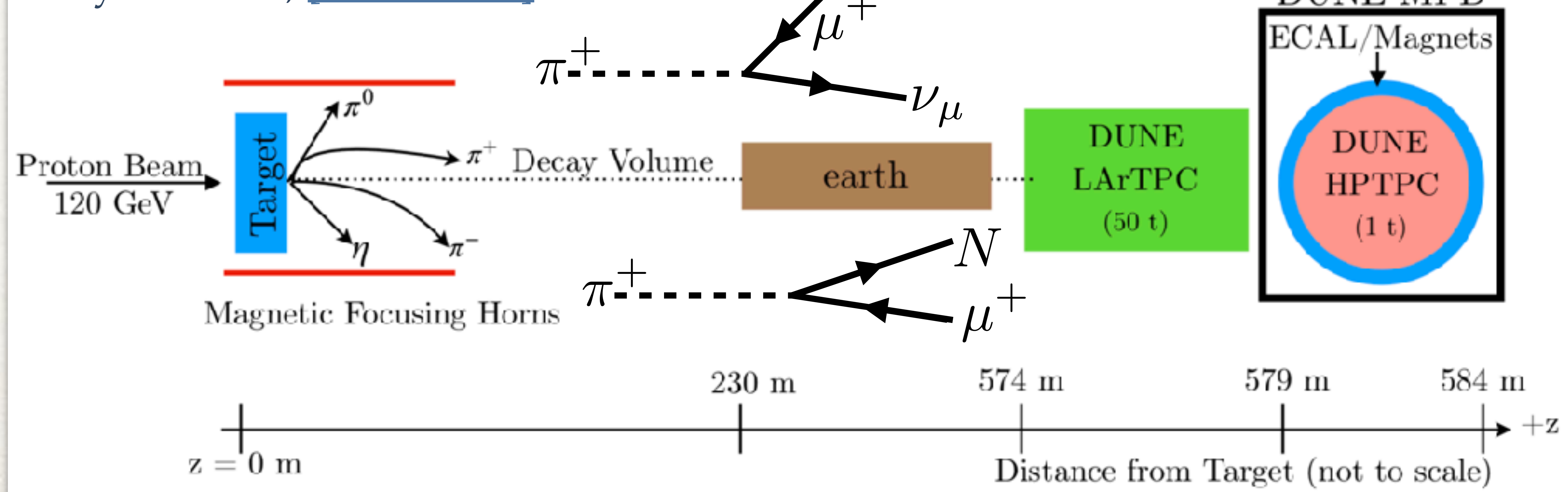
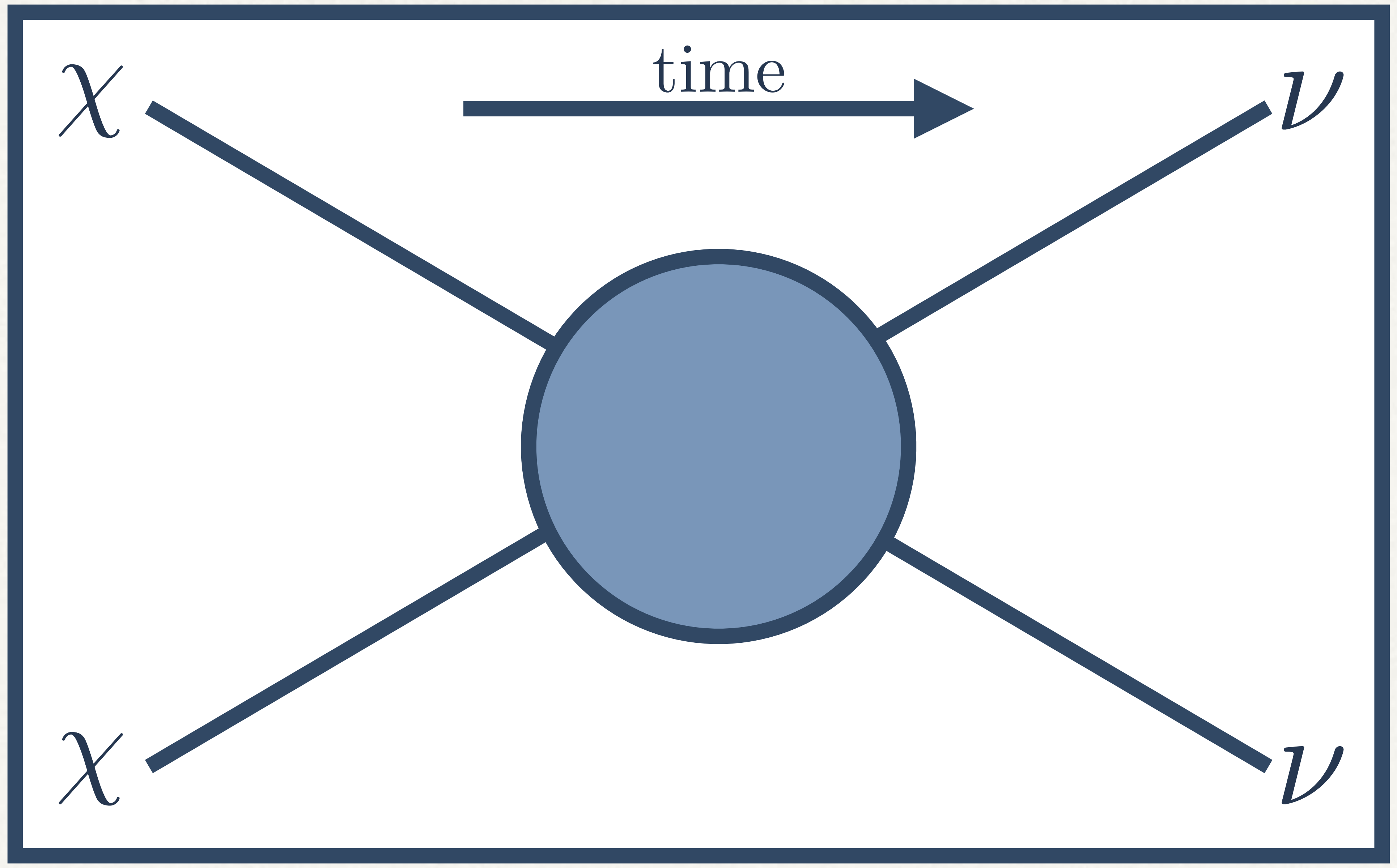
Neutrino Near Detectors as Beam Dump Facilities

Berryman et al, [1912.07622]



Neutrinophilic Dark Matter Annihilation

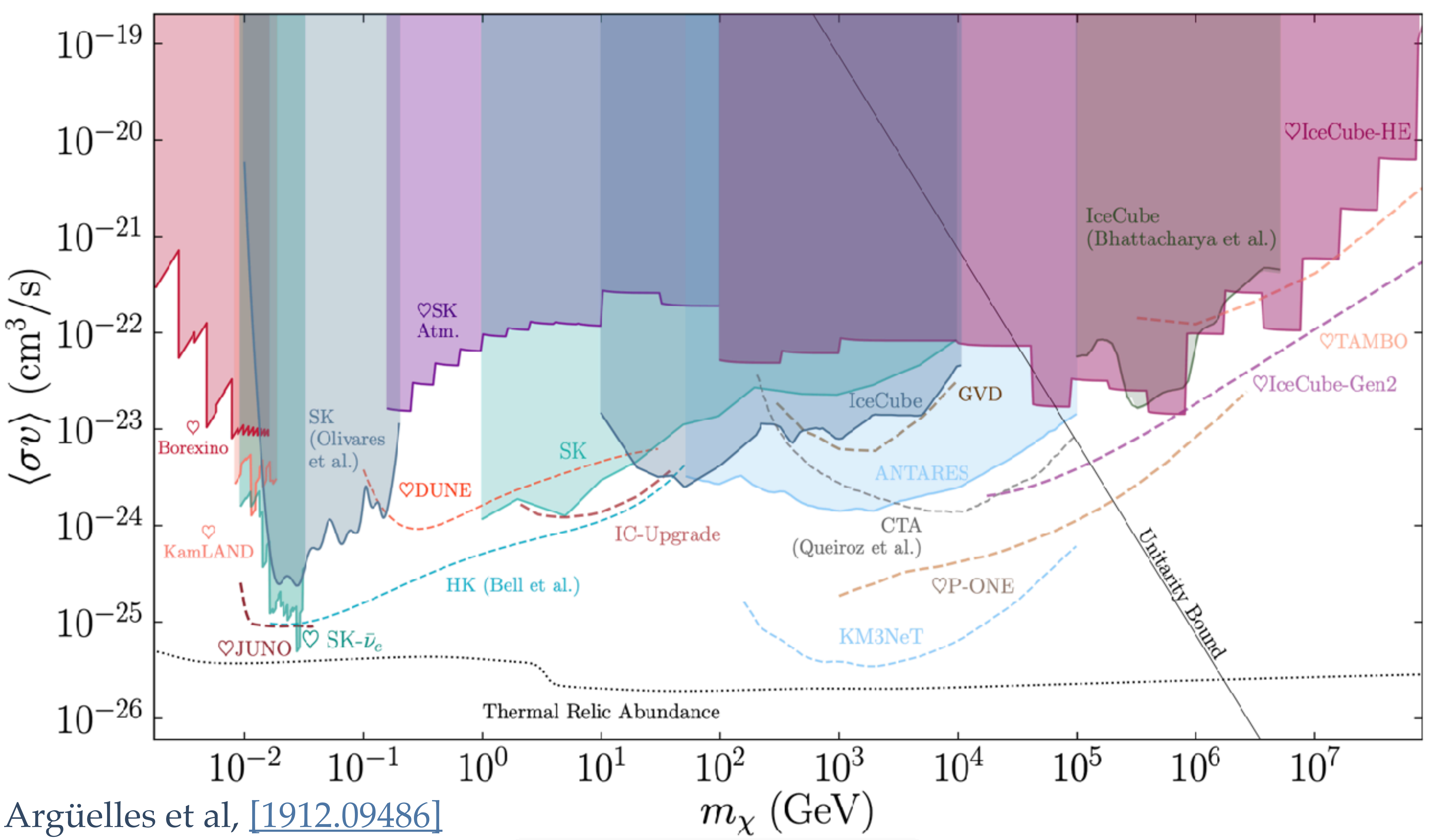


If this is the main interaction between dark matter and the standard model, then

- in the early universe, DM can freeze-out to its present-day abundance (WIMP miracle) via this process.
- in the present day, regions of space that are over-dense with DM can lead to annihilation of DM pairs, generating an over-abundance of neutrinos coming from those regions.

→ Best place to look for this? Large neutrino detectors!

Neutrinophilic Dark Matter Annihilation



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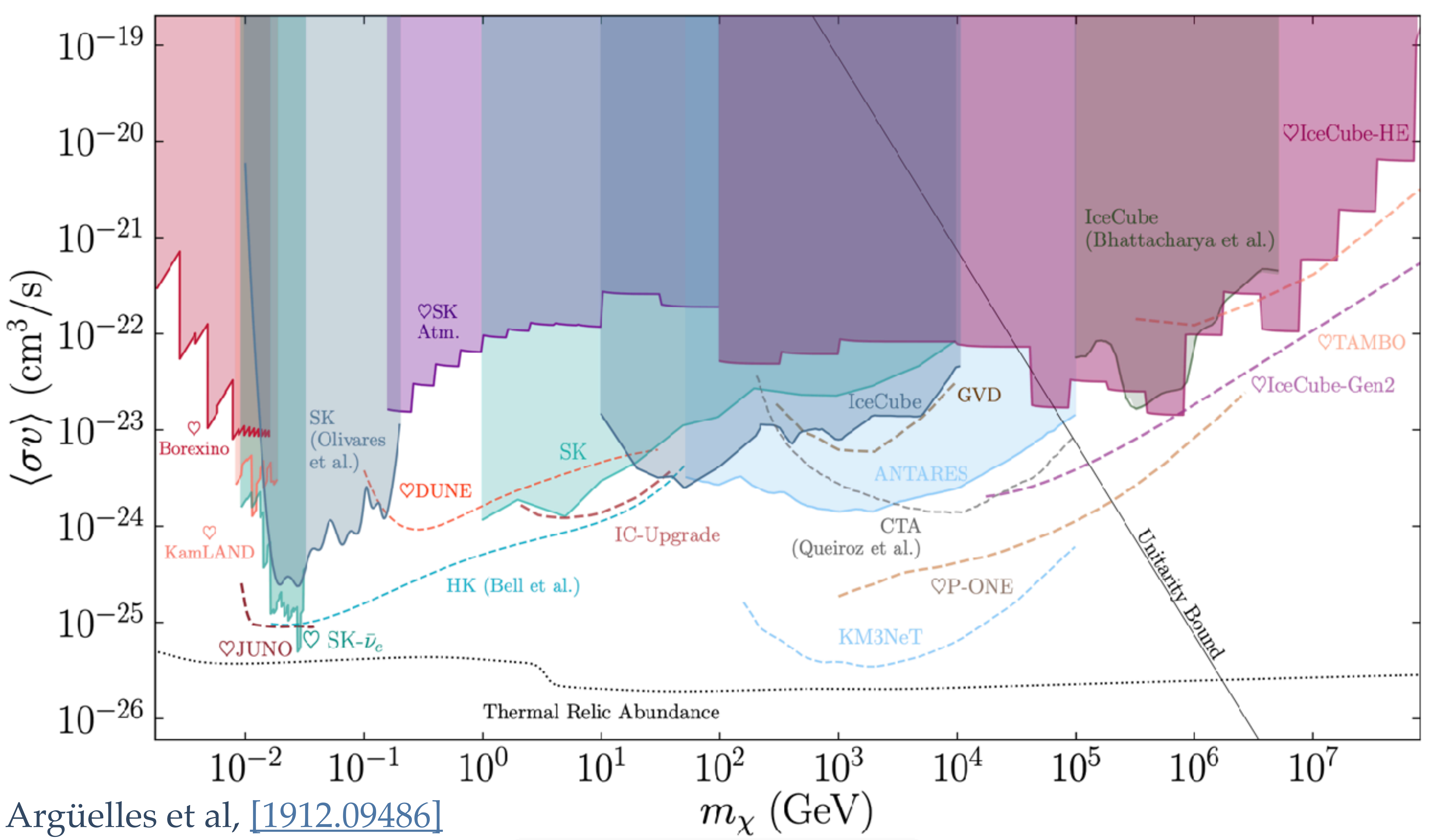

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DM mass

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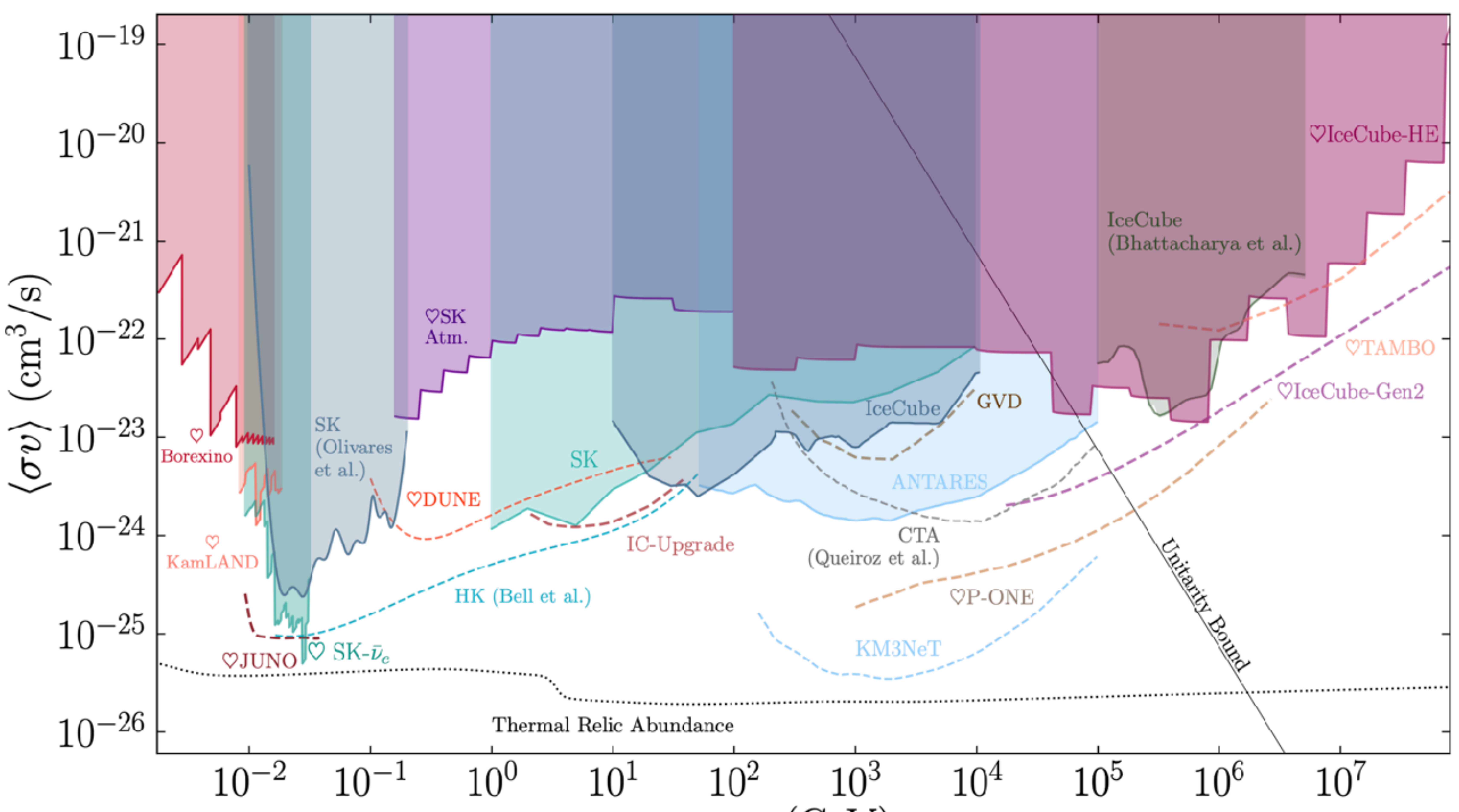

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Strength of neutrino/ DM interaction

DM mass

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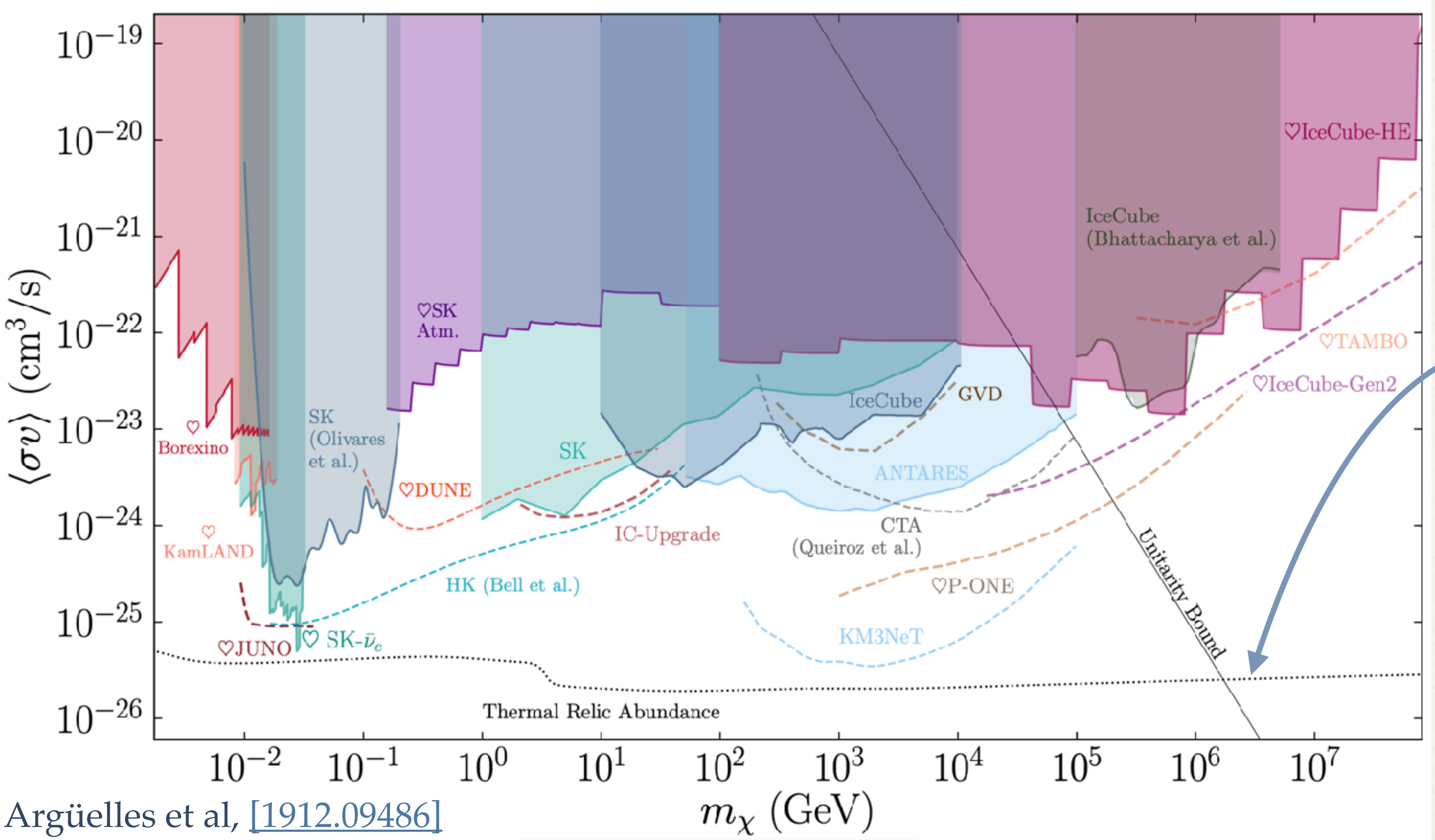

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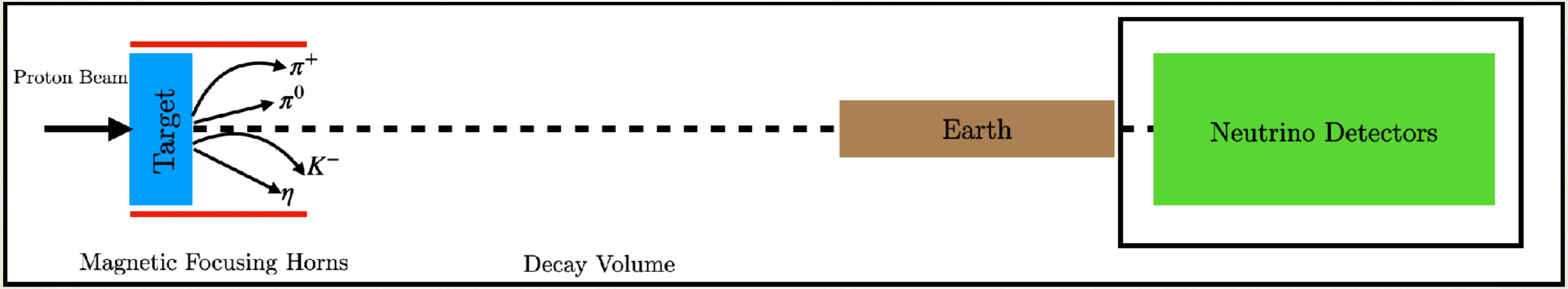
Strength of neutrino / DM interaction

Theoretical target — explains the current density of dark matter via "freeze-out"

DM mass

How can Neutrino Near Detectors be Beam Dumps?



Theorist's view of a neutrino beam & near detector facility

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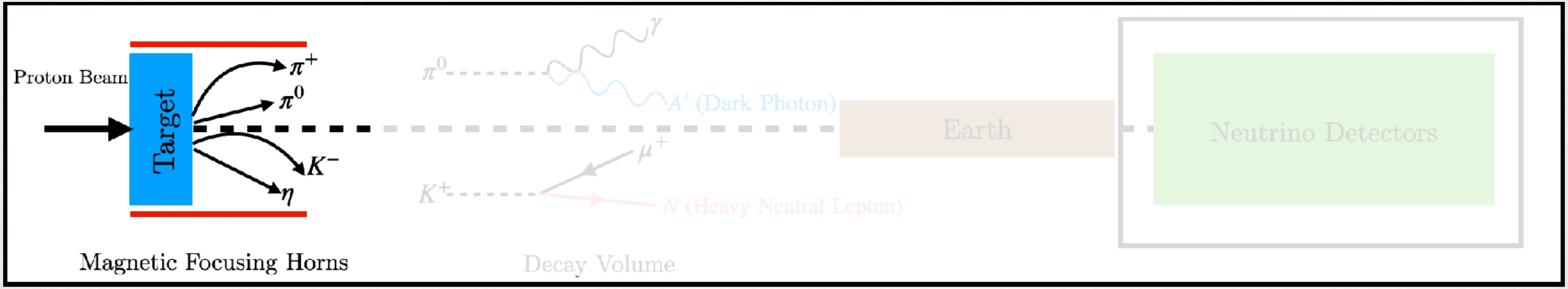

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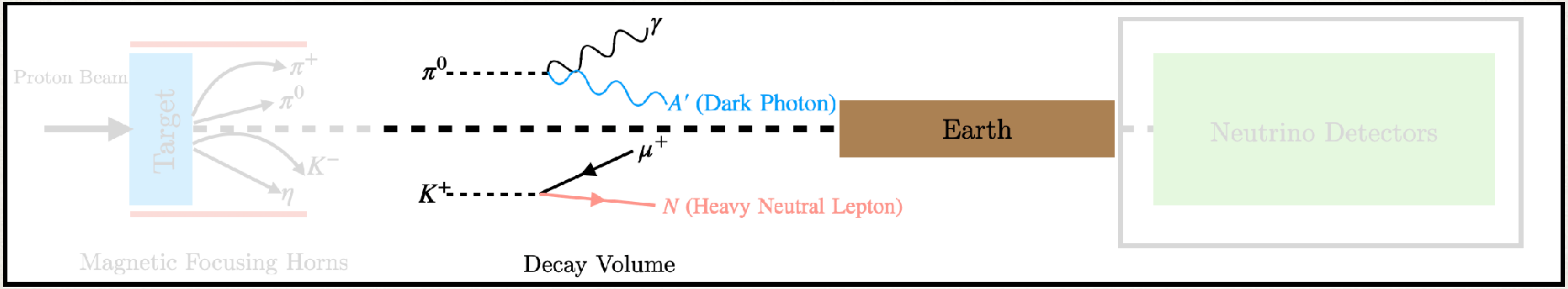

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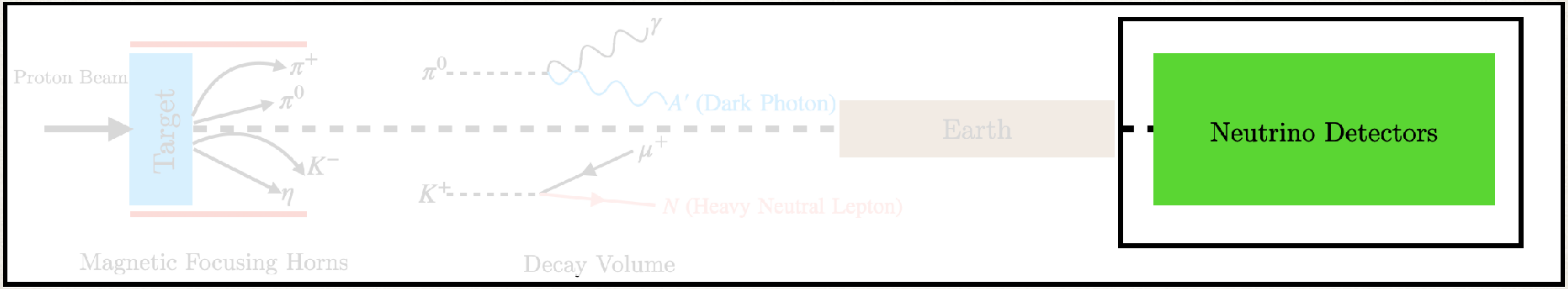

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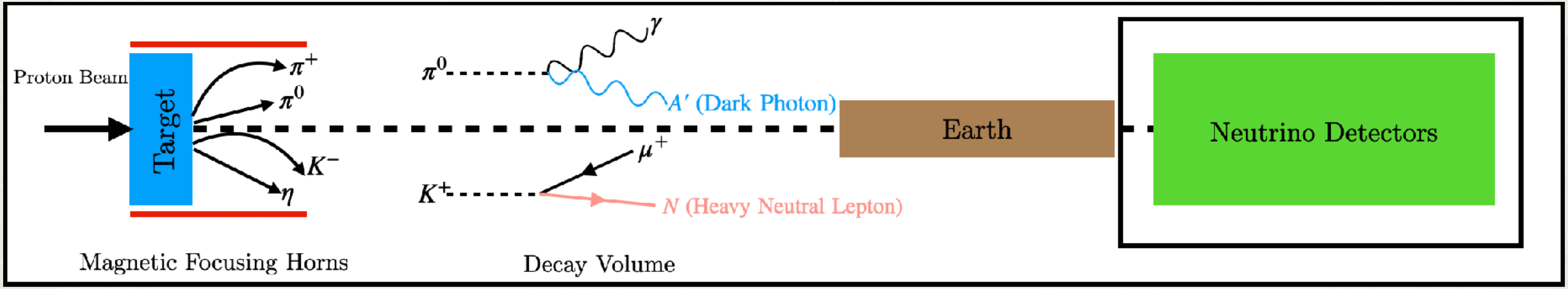

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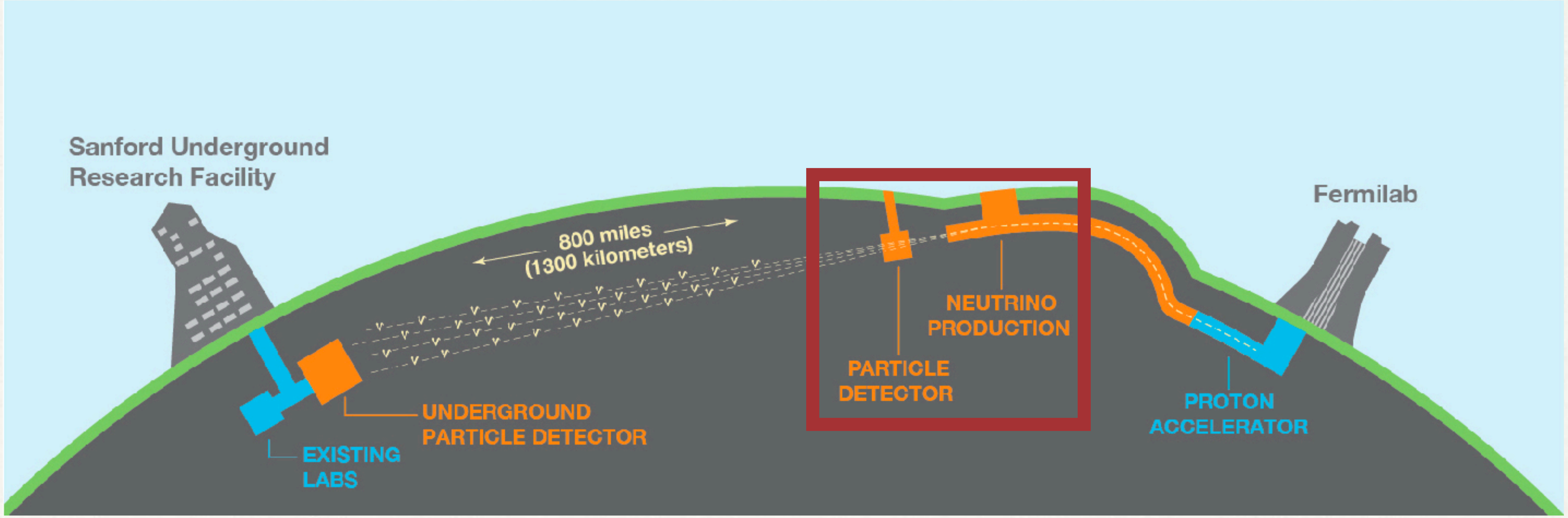
The DUNE Near Detector Complex



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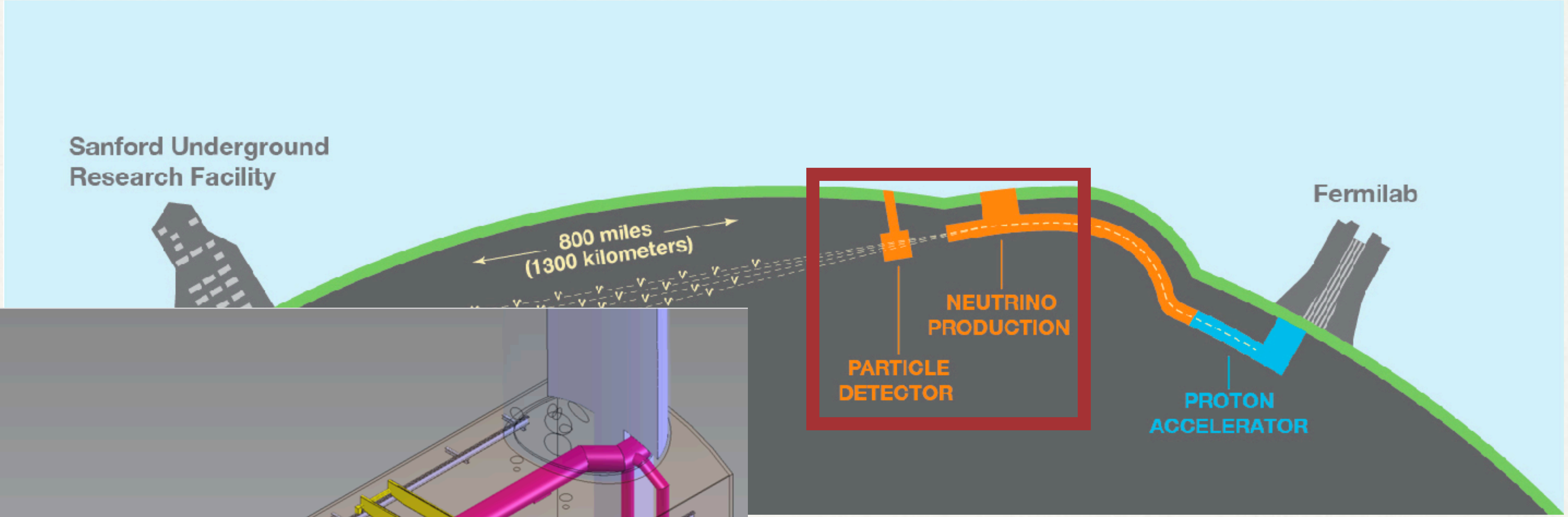

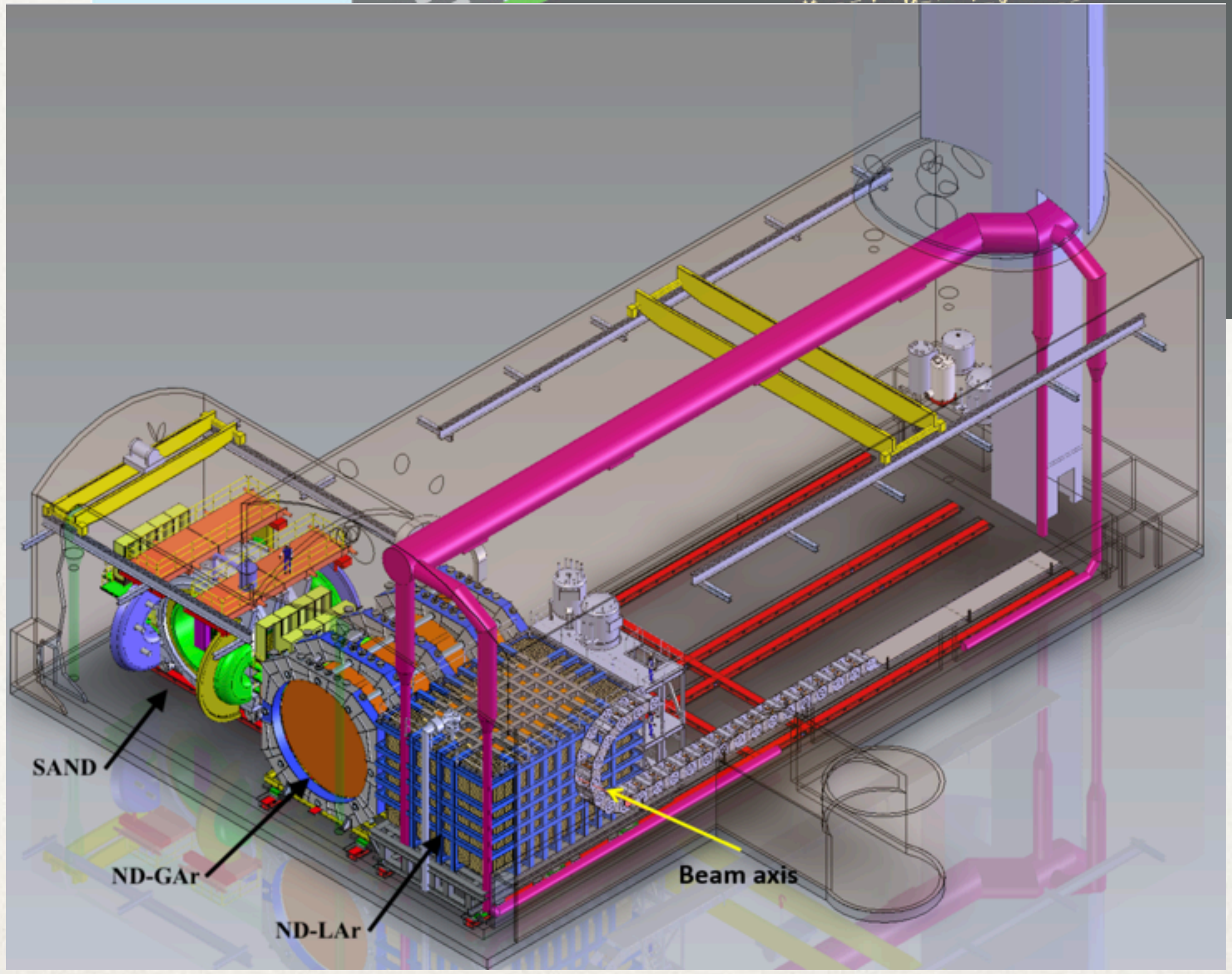

- Near Detector design is to meet neutrino oscillation-based goals.
- Various detector components can also allow for rich new physics searches.

DUNE Collaboration, [2103.13910]

Example: Heavy Neutral Leptons

Production Modes Considered:

$\pi^\pm \to \mu^\pm N$

$K^\pm \to \mu^\pm N$

$K^\pm \to \pi^0 \mu^\pm N$

$D^\pm \to \pi^0 \mu^\pm N$

$D^\pm_{(s)} \to \mu^\pm N$

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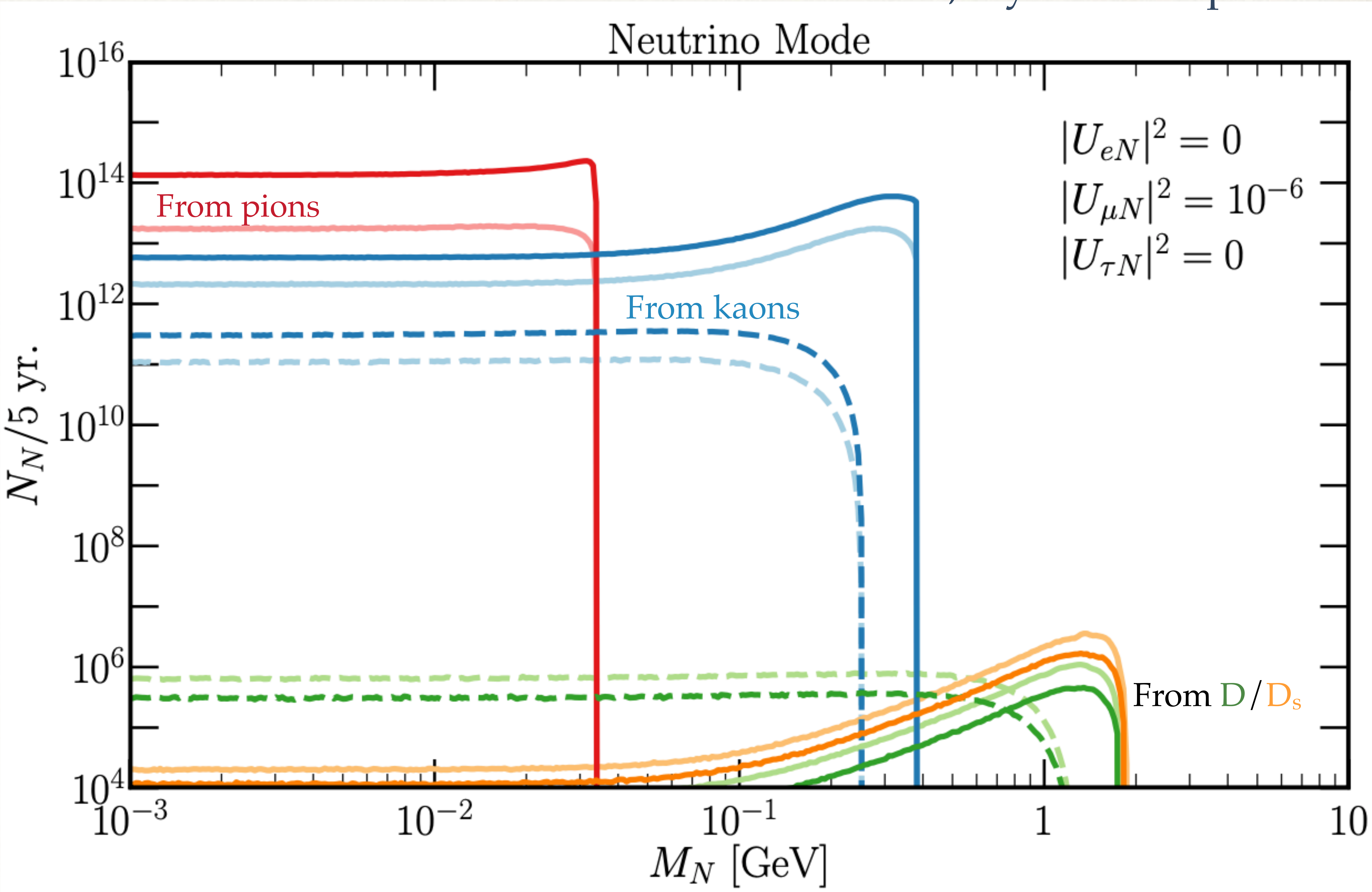
Flux at Near Detector, 5 years of Operation



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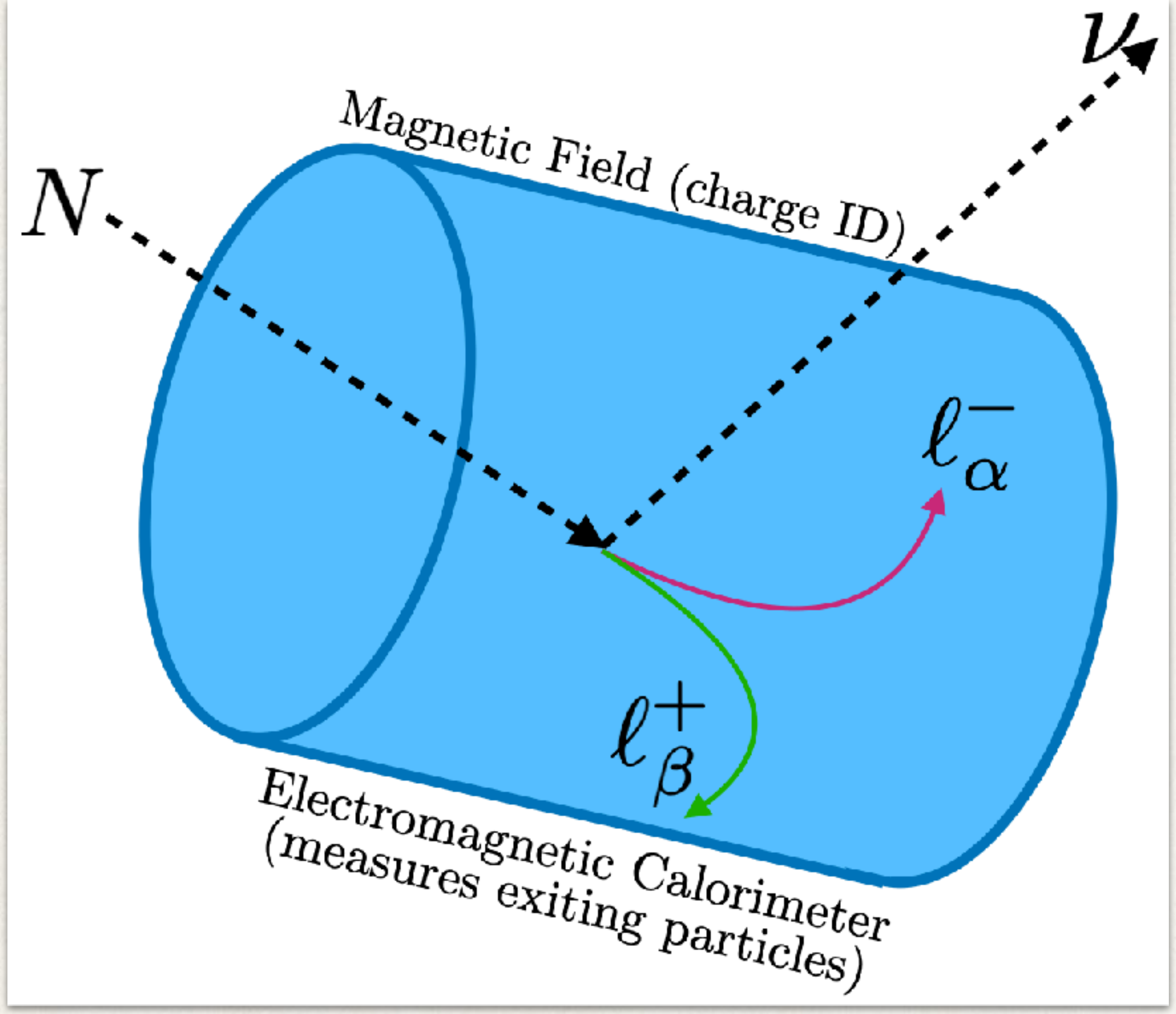
Signals of rare decays

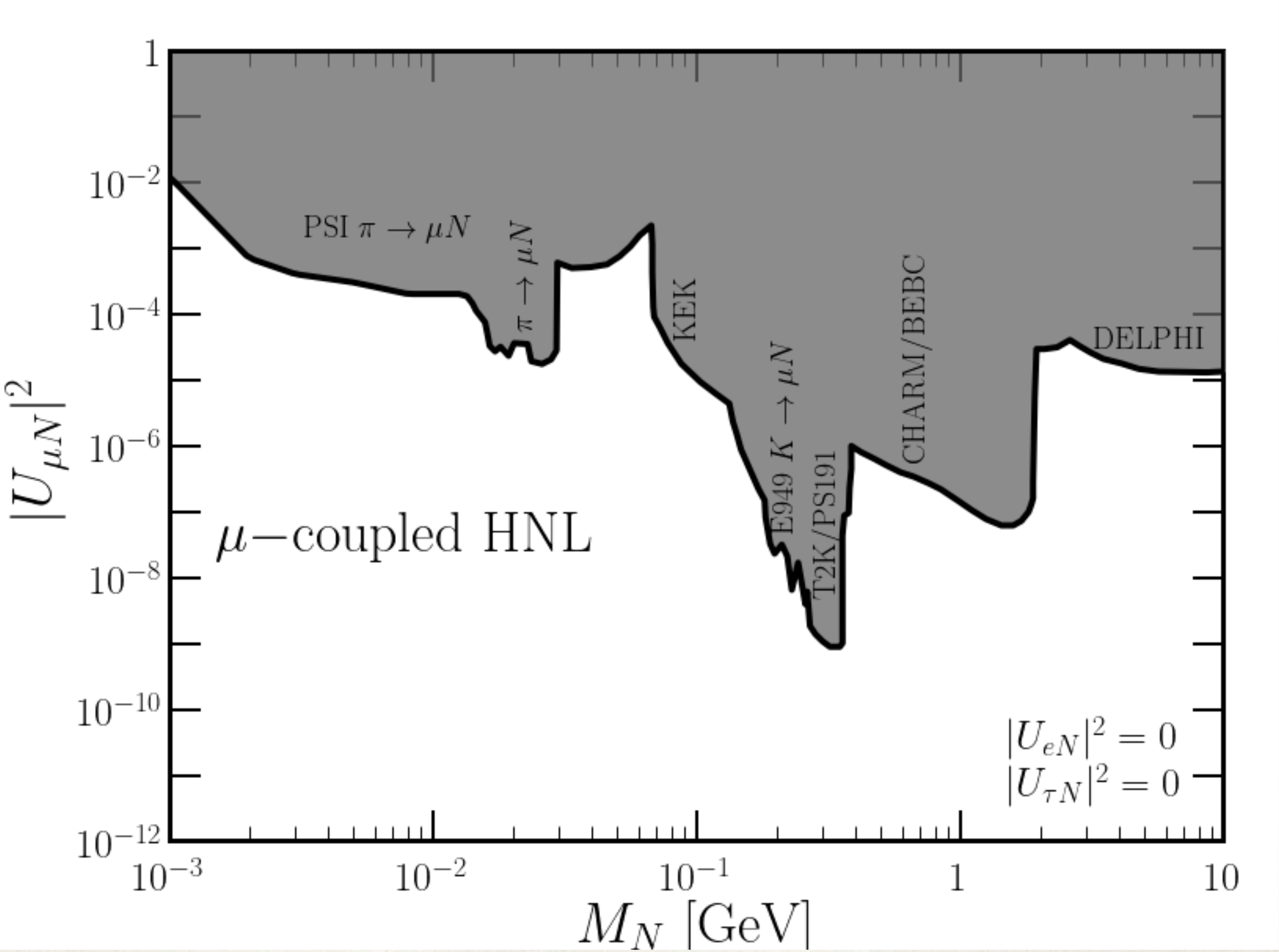


- Portal particles can decay inside of the gaseous argon detector and produce a signal that is difficult for the neutrino source to mimic.
- This includes sets of charged leptons, pions, etc.
- Low backgrounds in gaseous argon provide an ideal site to search for the rare decays.

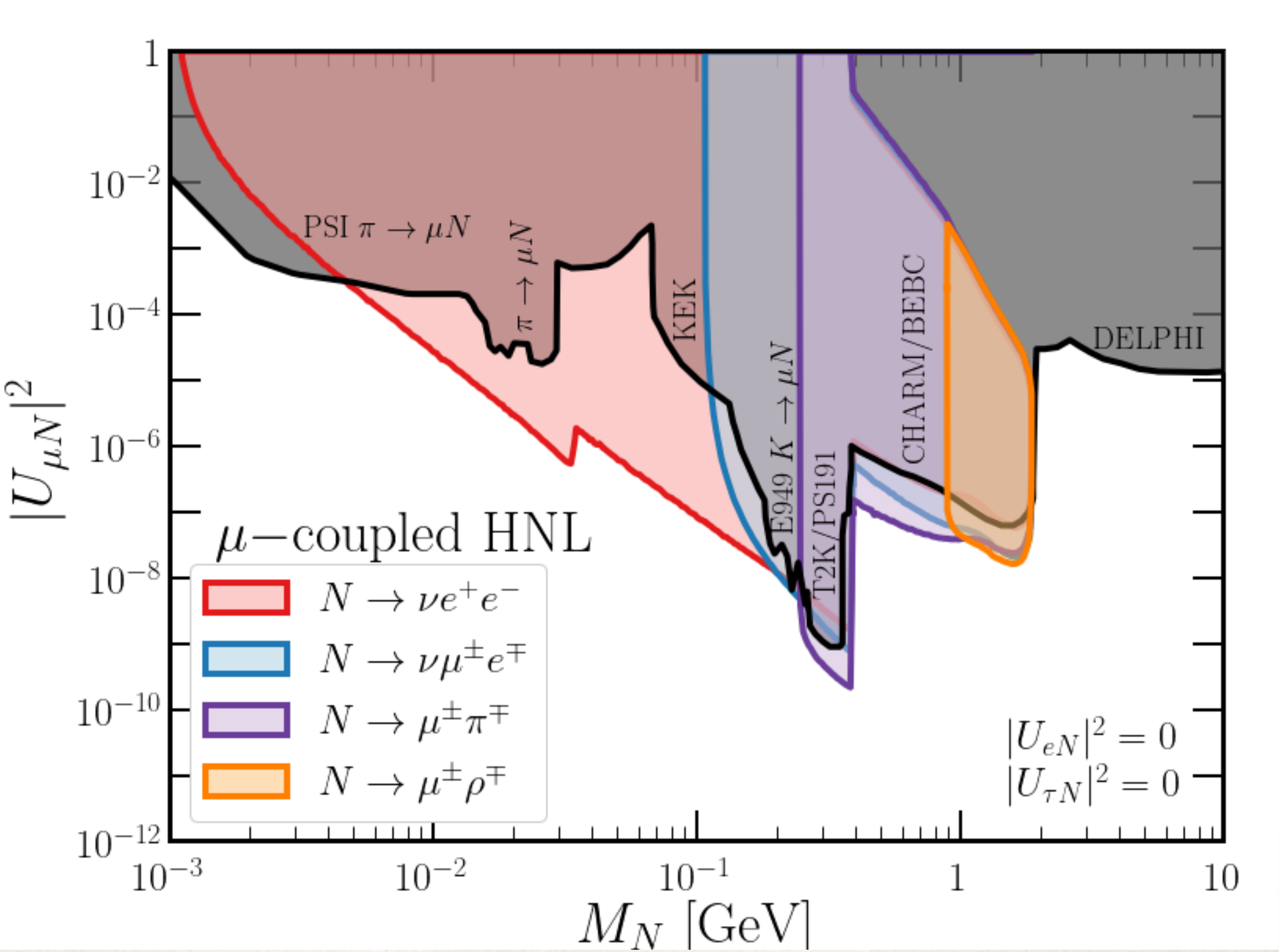
$\boxed{\text{Signal} \propto \text{Volume}}$

$\boxed{\text{Background} \propto \text{Mass}}$

Existing Constraints: Muon-Coupled HNL



DUNE Sensitivity: Muon-Coupled HNL

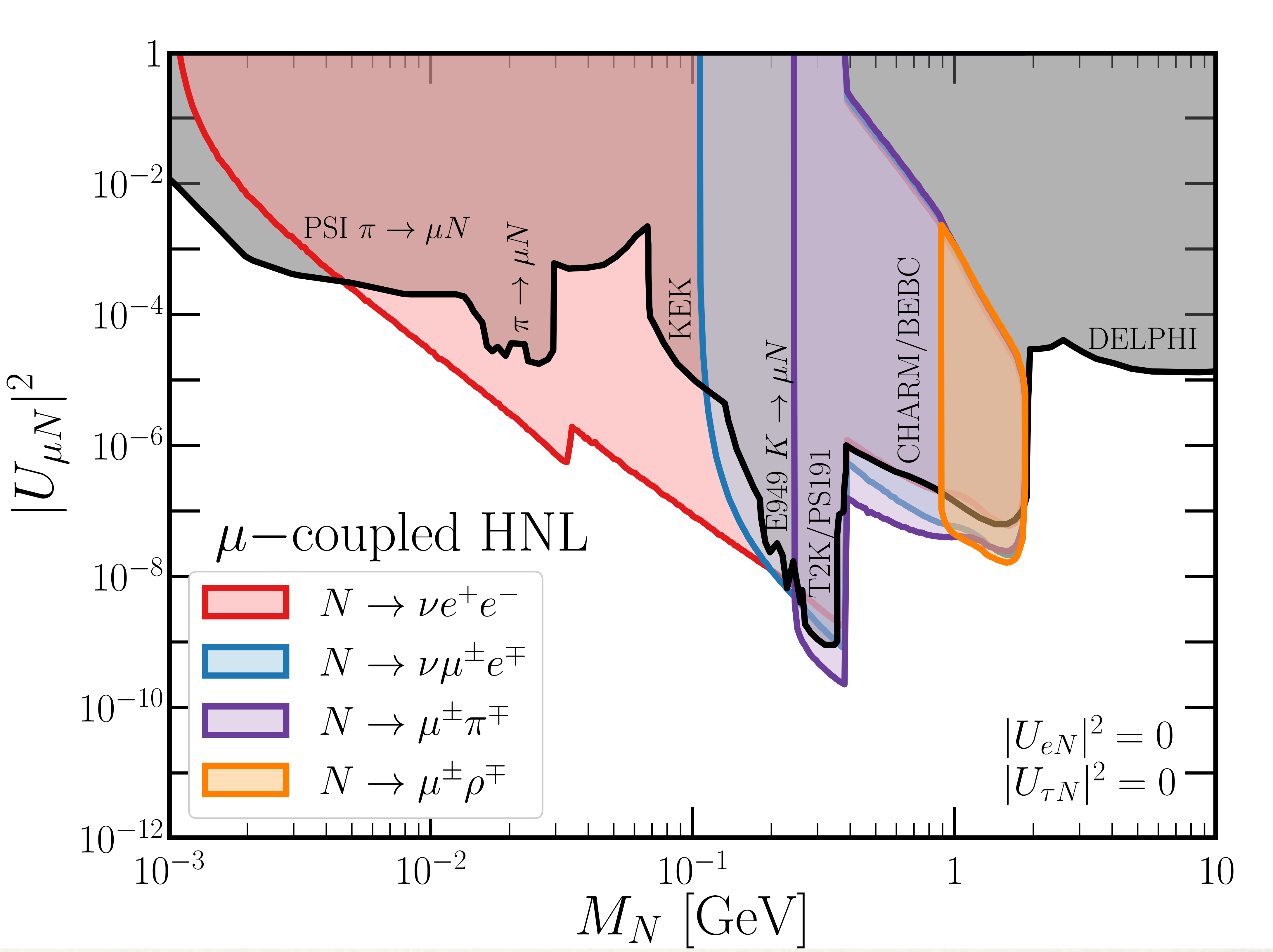


Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf, [1912.07622]

Going Beyond Discovery?

Berryman, **KJK**, et al, [1912.07622]

- Significant parameter space where next-generation experiments can discover these Heavy Neutral Leptons.
- If discovered, then what?
- Search for Lepton Number Violation!



More on HNLs at DUNE? Ballett et al [1905.00284], Coloma et al [2007.03701], Breitbach et al [2102.03383]

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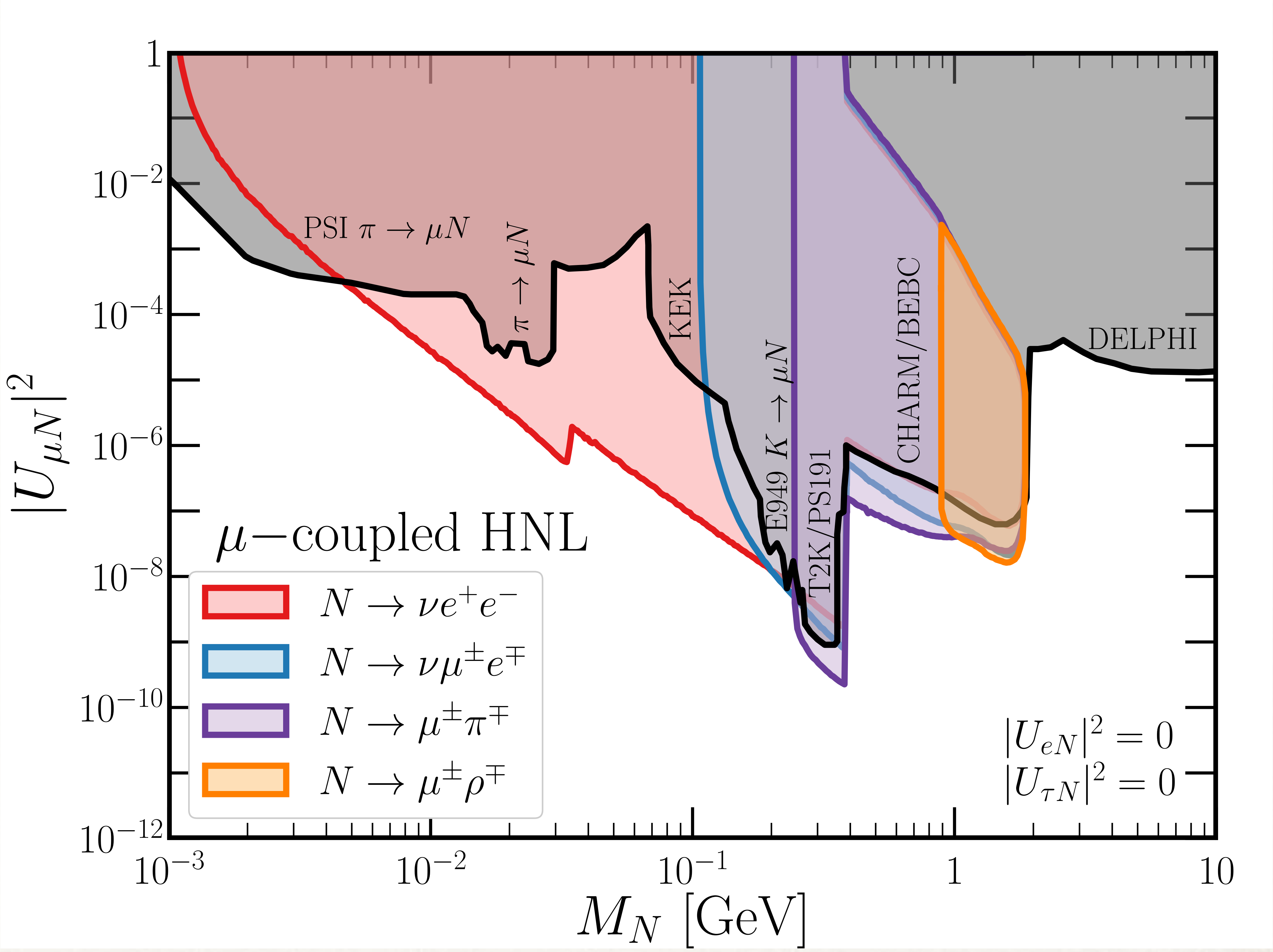


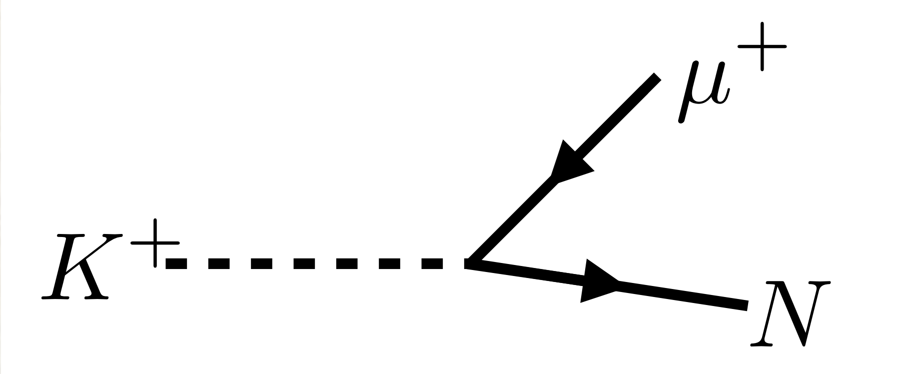
Is Lepton Number Conserved? → Are the HNLs their own antiparticles? → Are the SM Neutrinos *their* own antiparticles?

More on HNLs at DUNE? Ballett et al [1905.00284], Coloma et al [2007.03701], Breitbach et al [2102.03383]

What if We Discover an HNL?

- See if its decays conserve/violate Lepton Number

Assume a "pure" beam:



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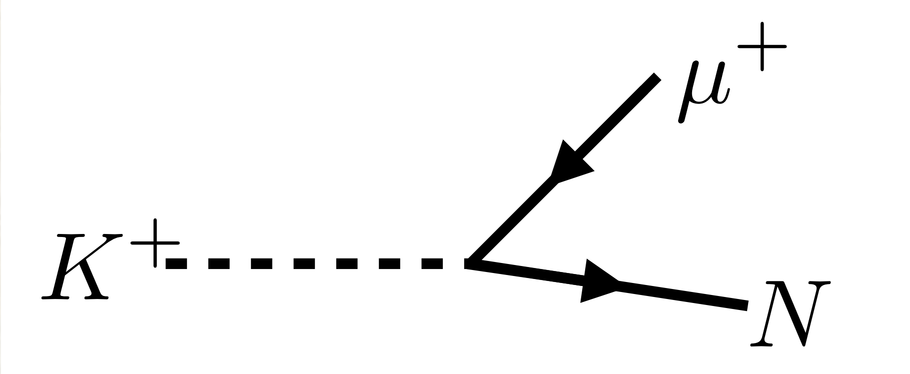

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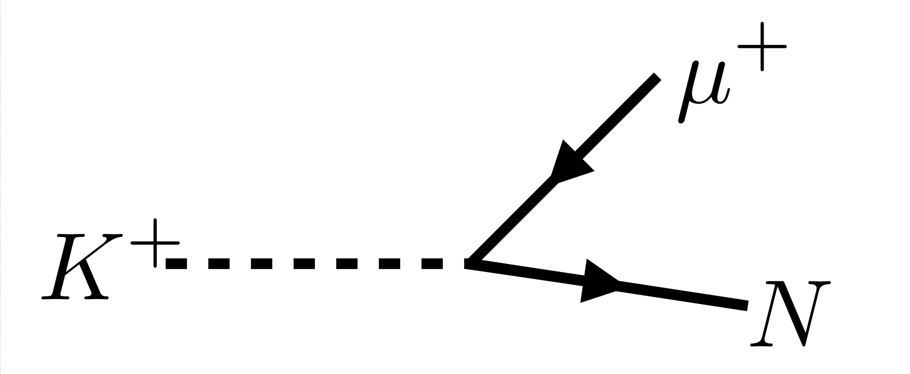

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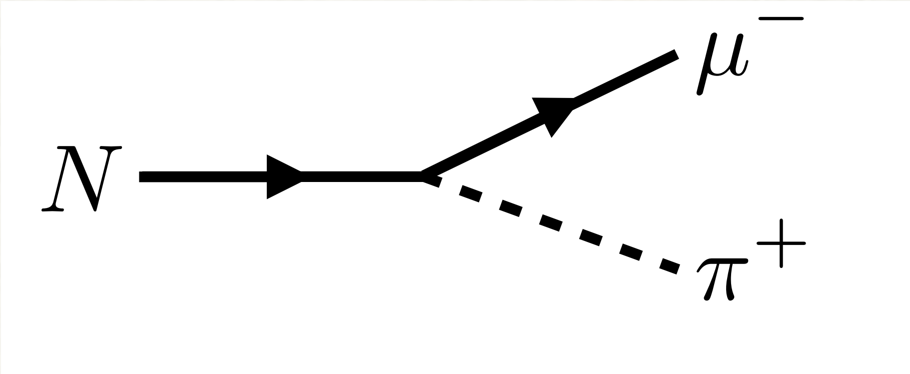

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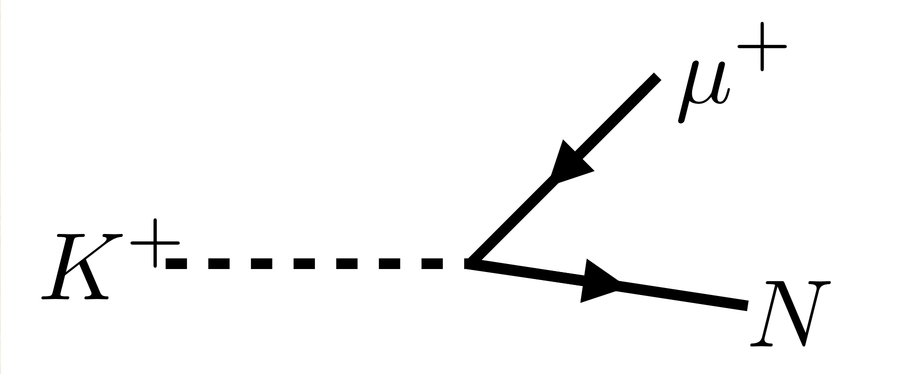

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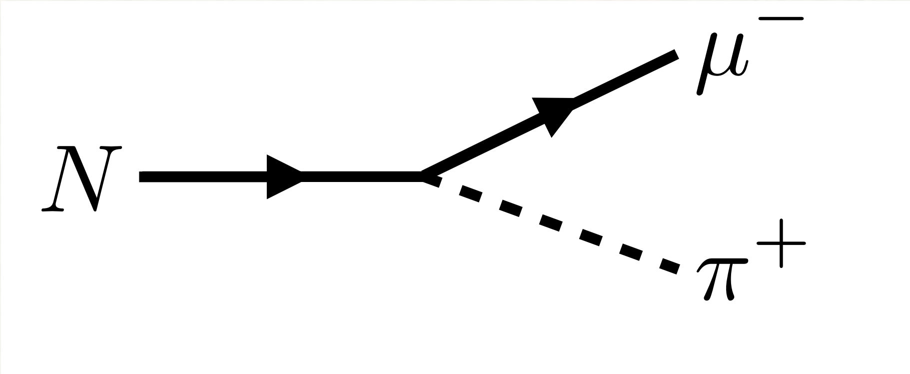

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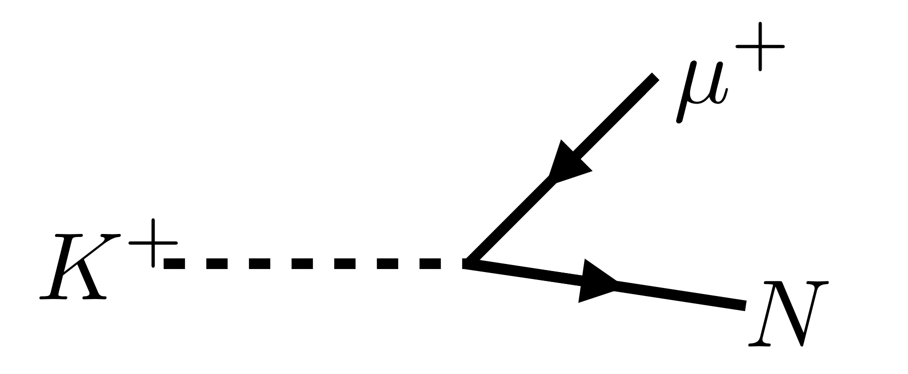

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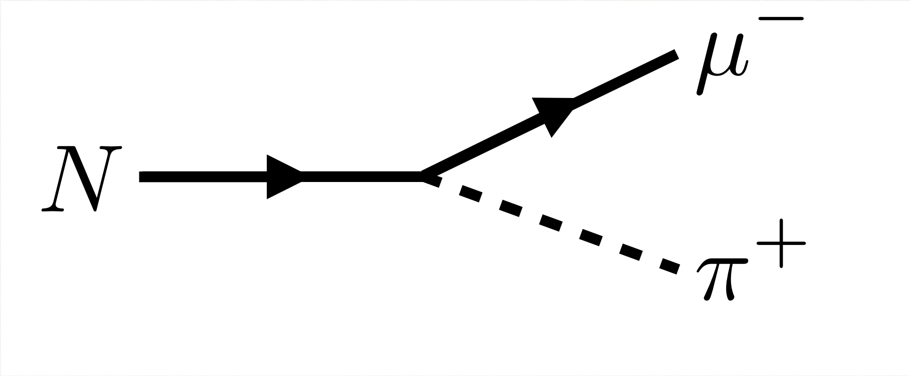

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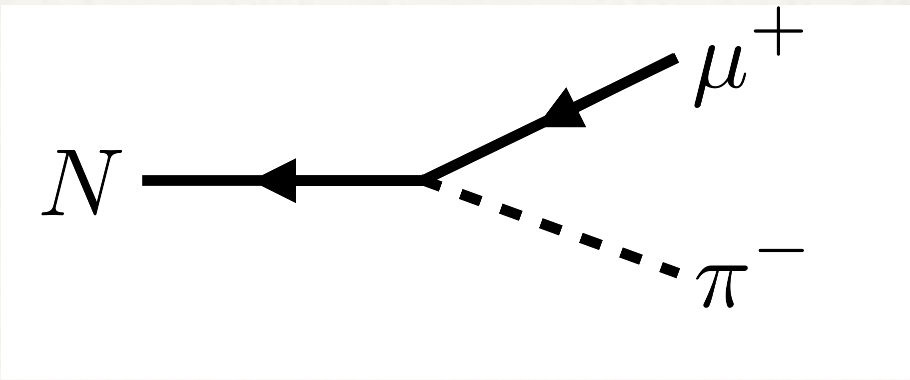

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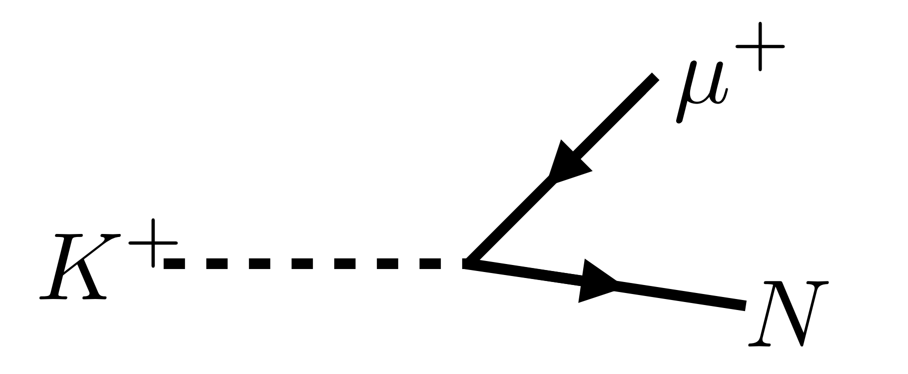

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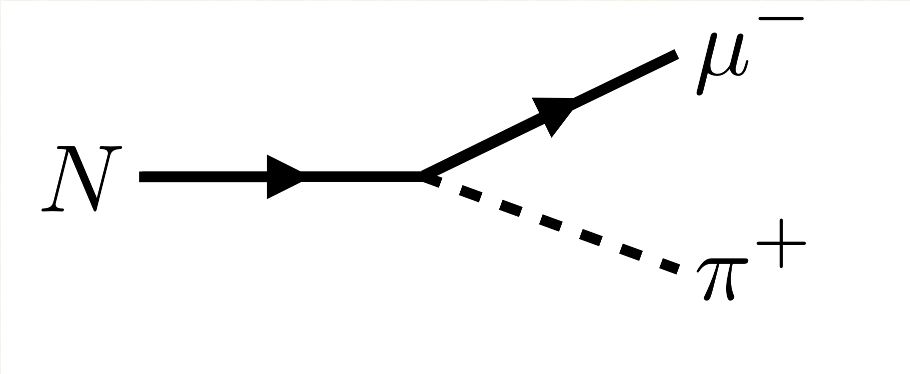

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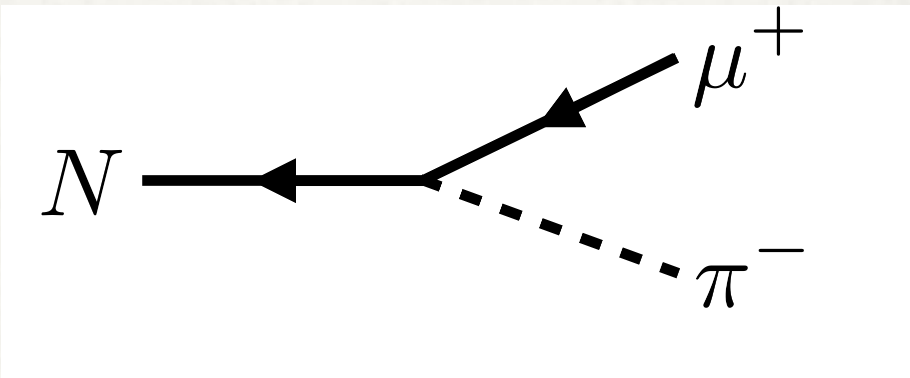

Measure the ratio of these final states in your detector (assuming you can identify the charges/particles on an event-by-event basis)

No Production Source is Perfect

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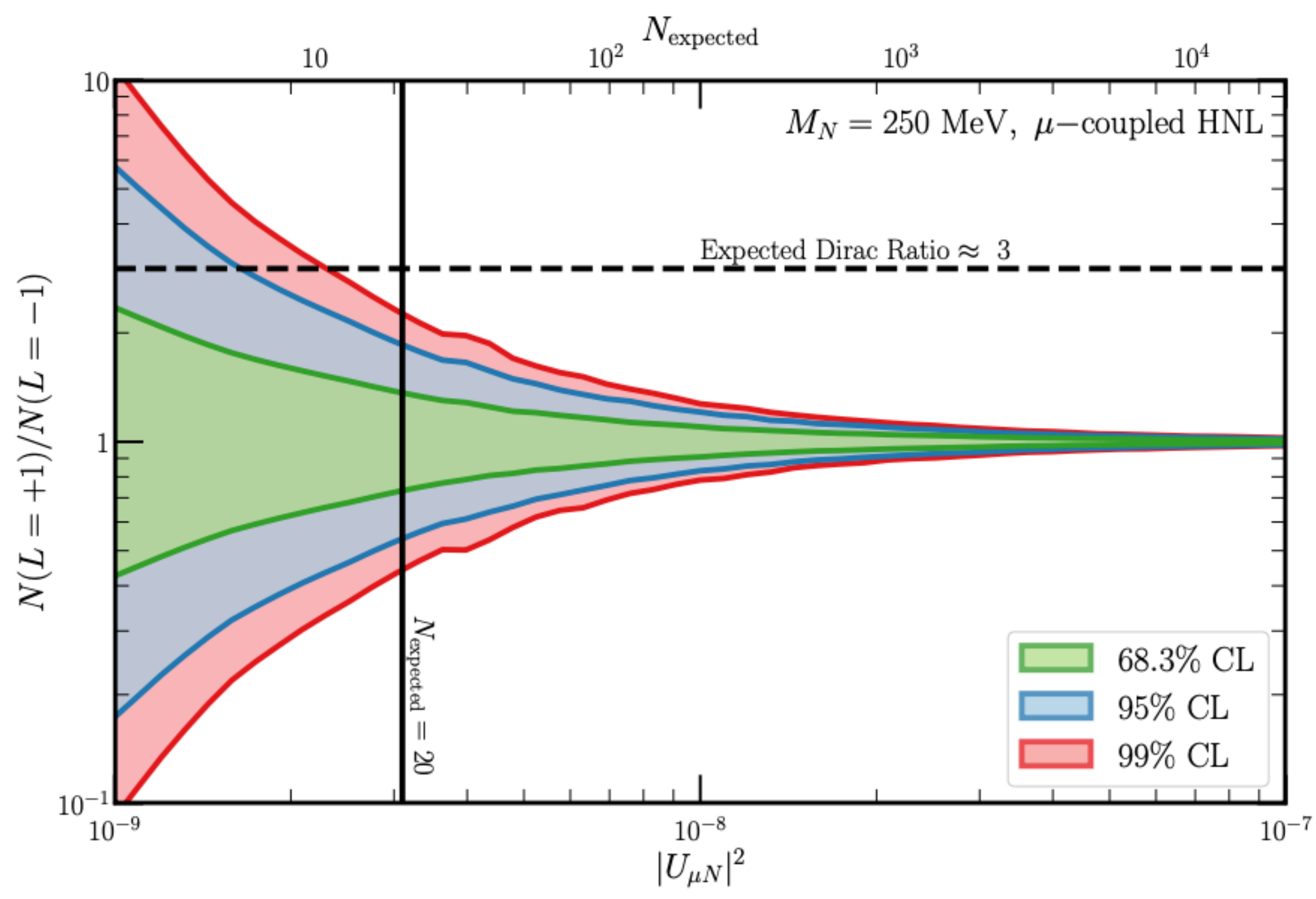
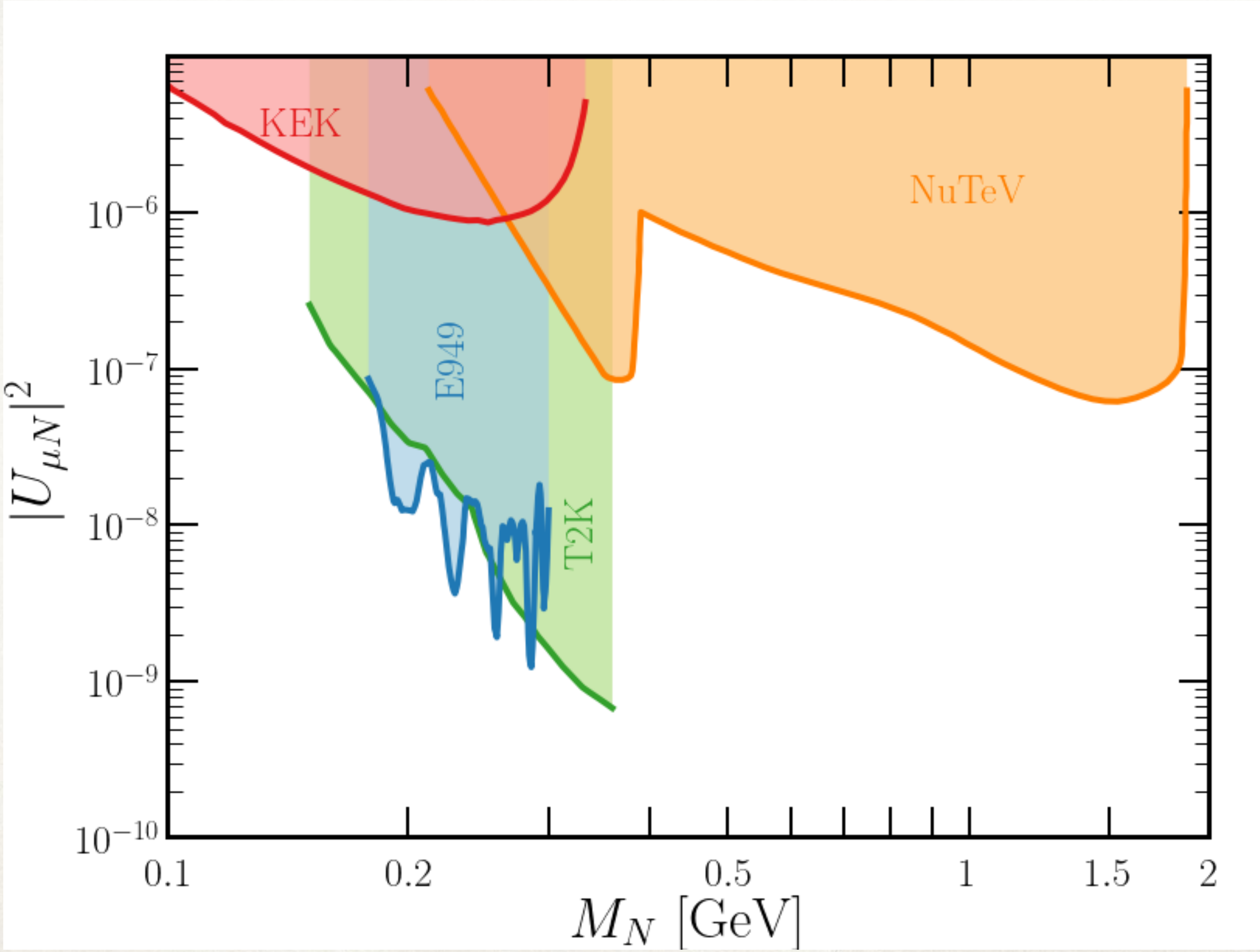
Toy Example: Identify Every Decay Perfectly



Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf, [1912.07622]

Broader Picture: Muon-Coupled HNL



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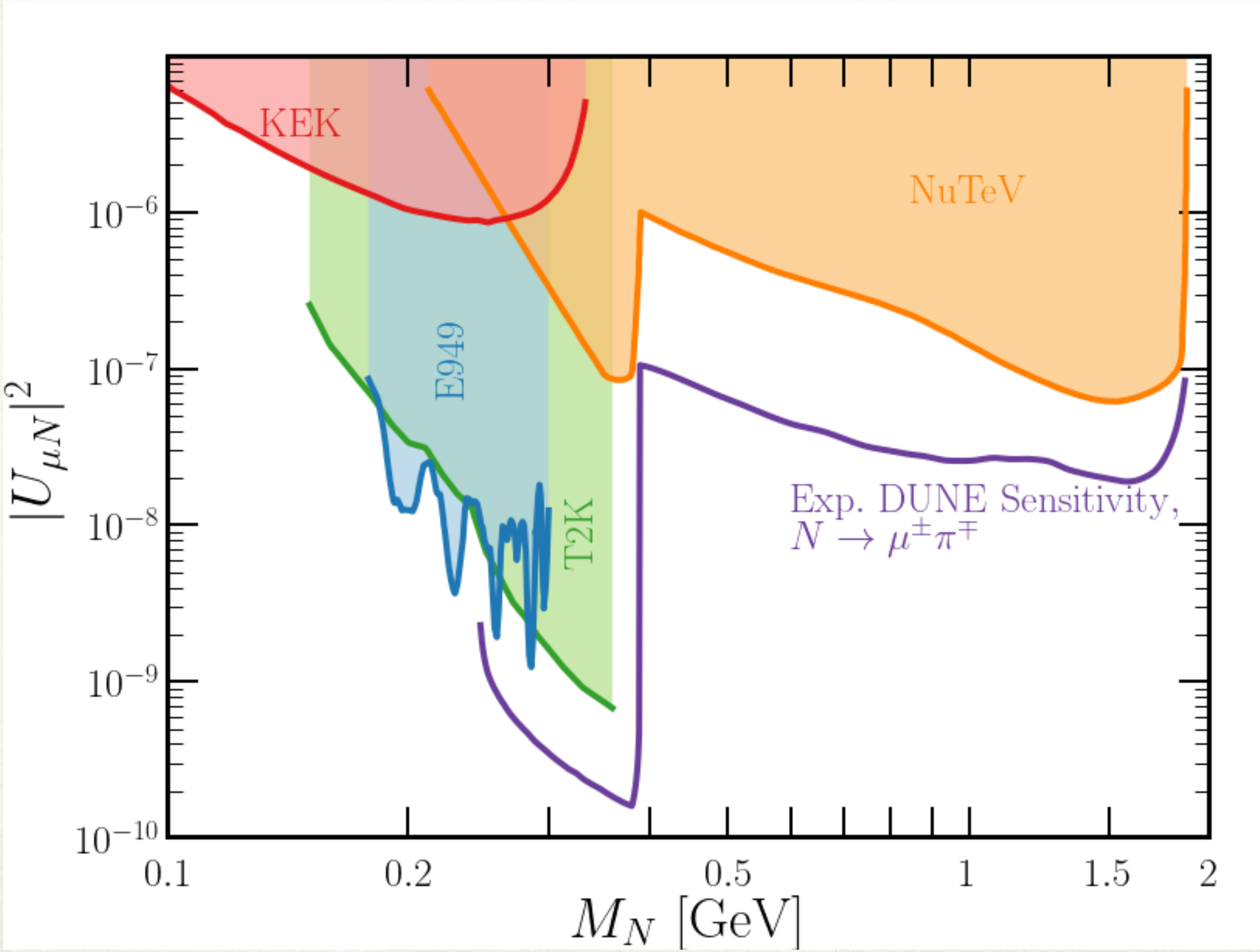

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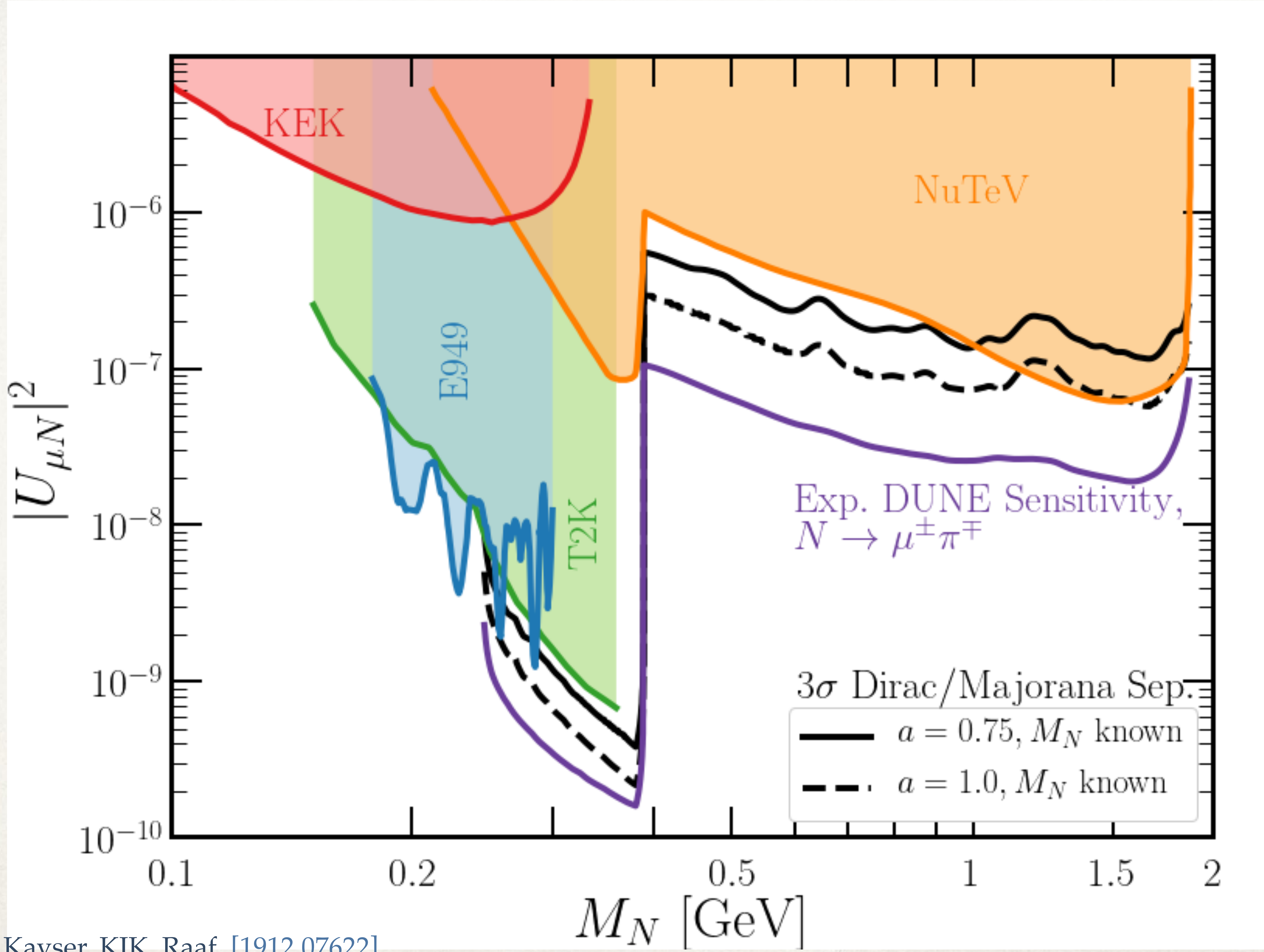

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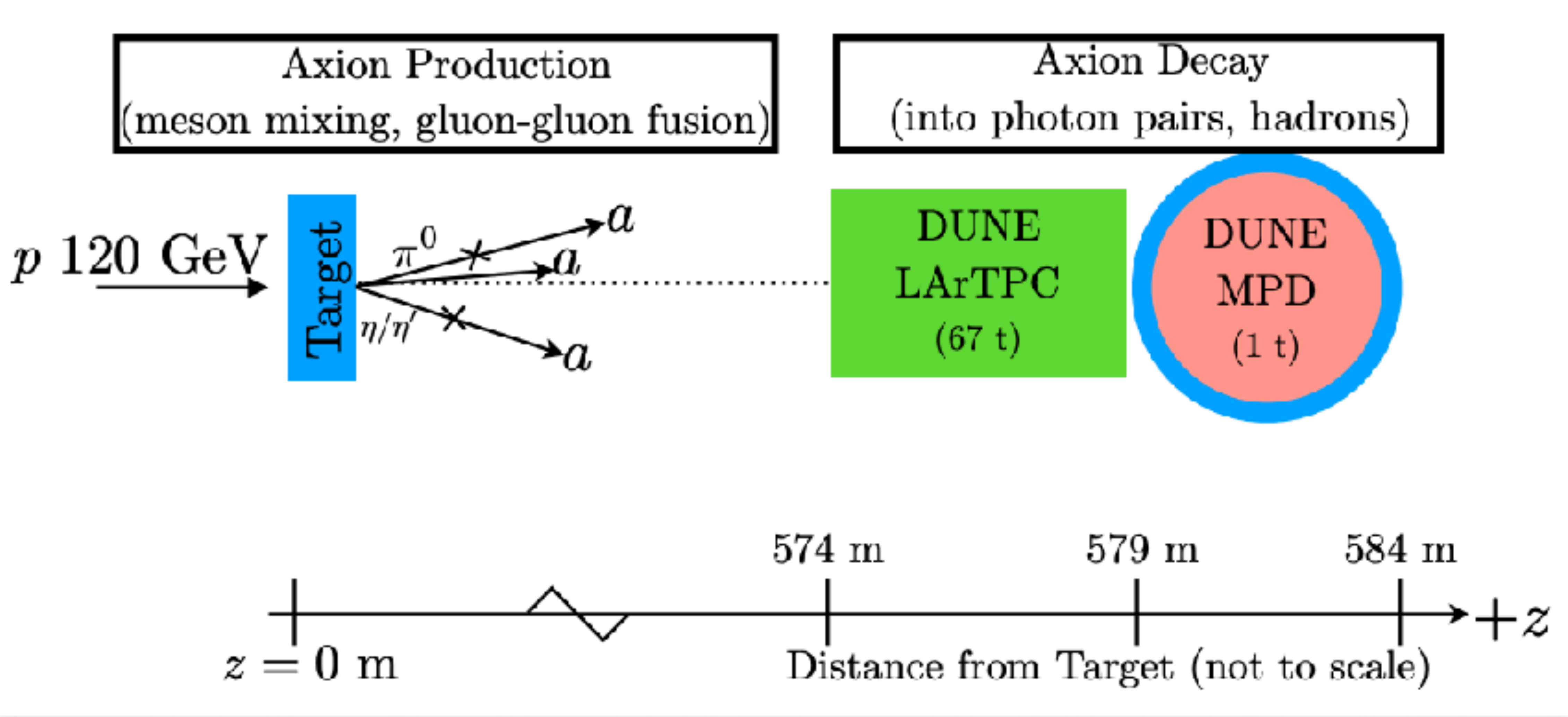
Axions & Axion-Like-Particles: Distinct Phenomenology

KJK, Kumar, and Liu [2011.05995]: "Heavy Axion"



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Decay into pairs of (high energy) photons/hadrons.

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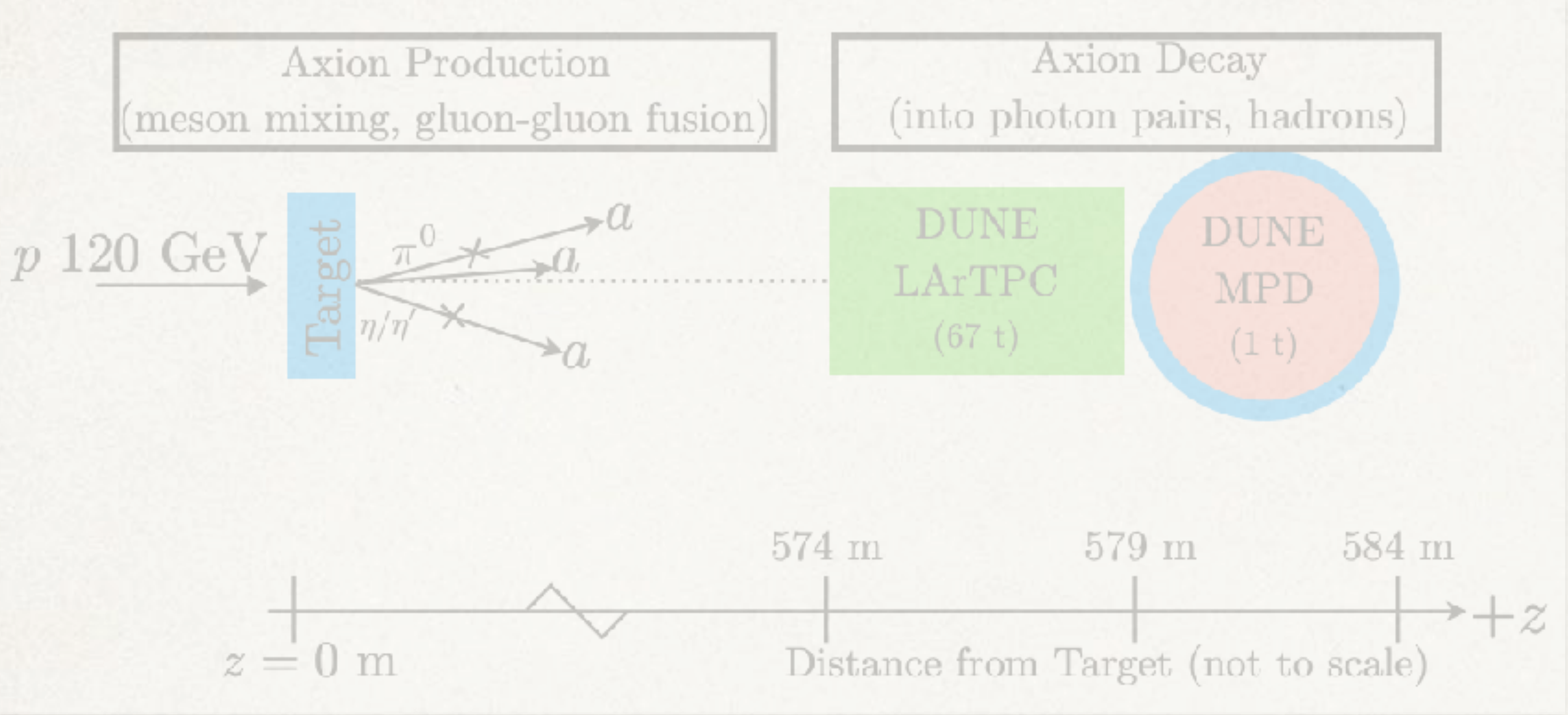

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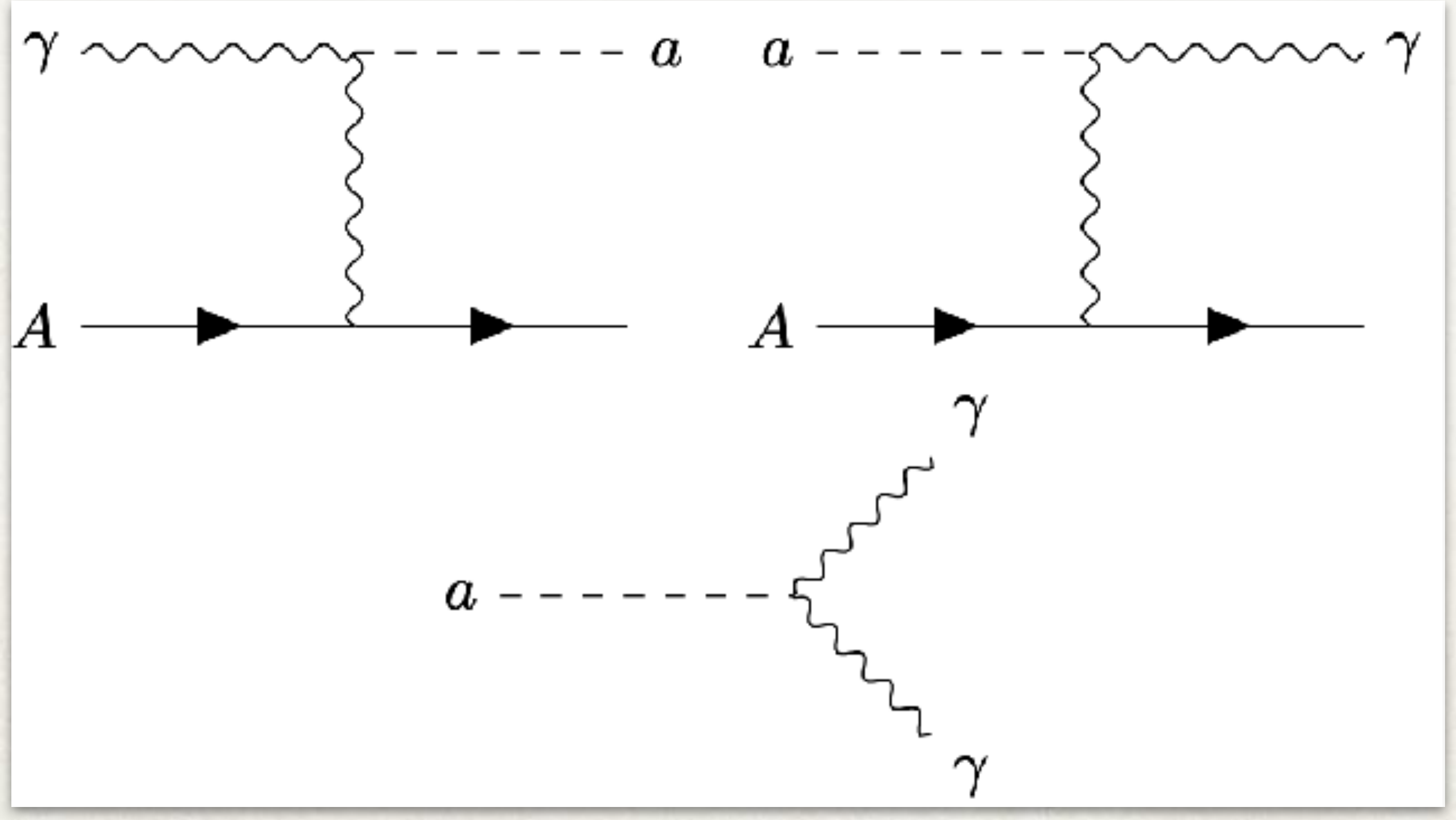
Brdar et al [2011.07054]: "Axion-Like Particle"



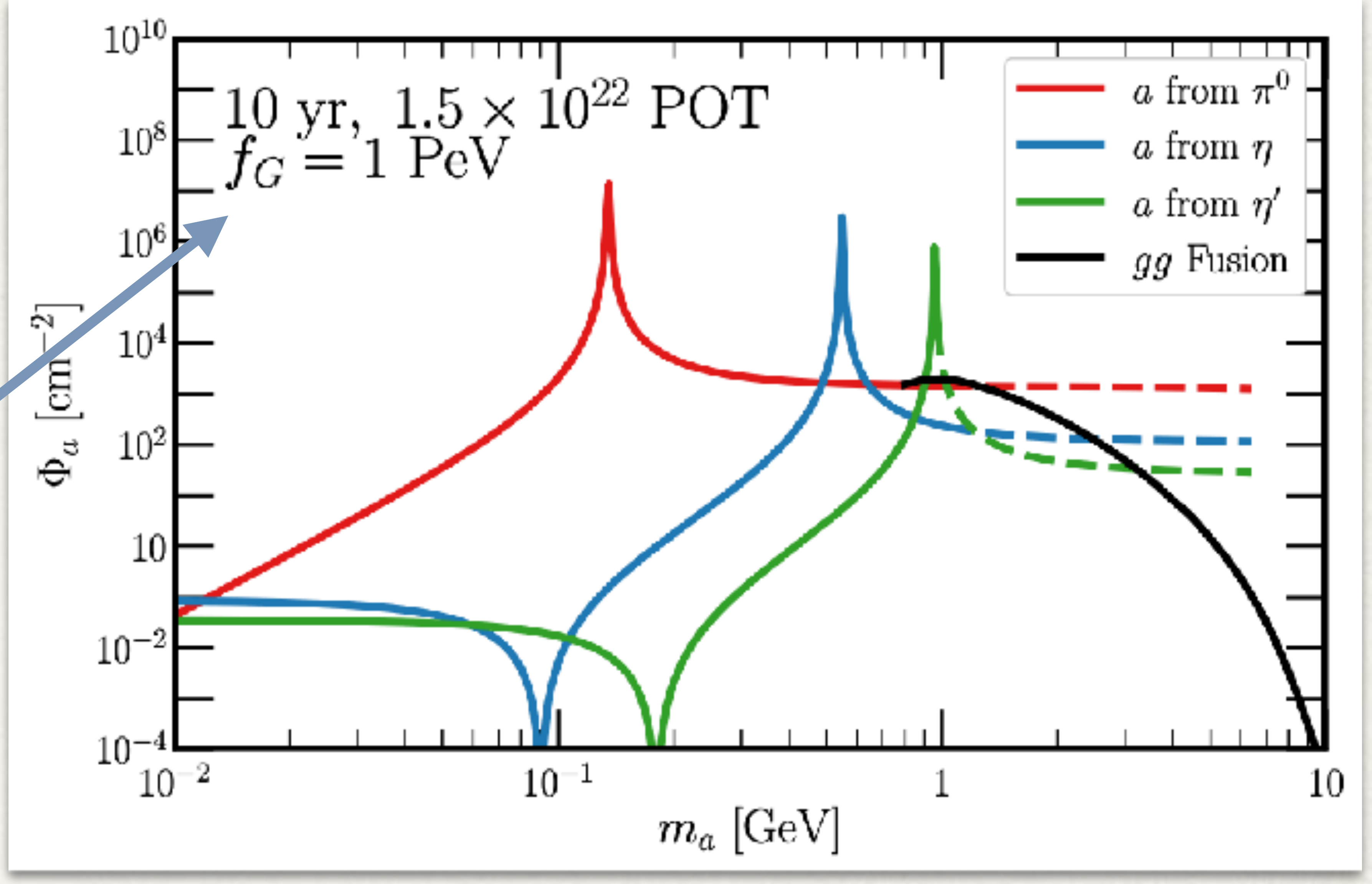
Production via *decays* of SM mesons or Primakoff scattering.

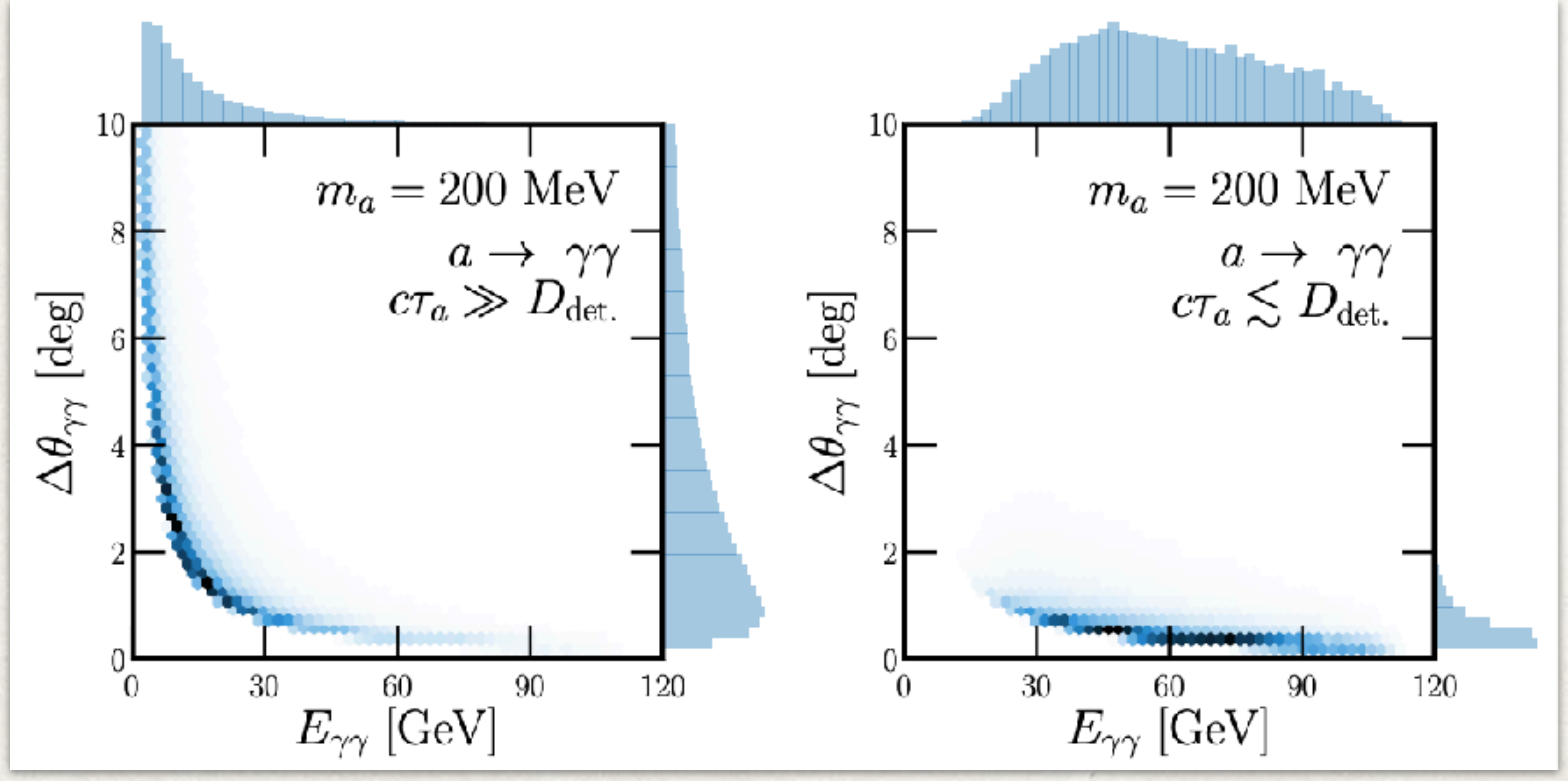
Decay into pairs of photons or Primakoff scattering off targets in detector.

Heavy Axion Search

Production: either via mixing with SM mesons or gluon-gluon fusion. Peaks here are due to resonant mixing.

Axion decay constant

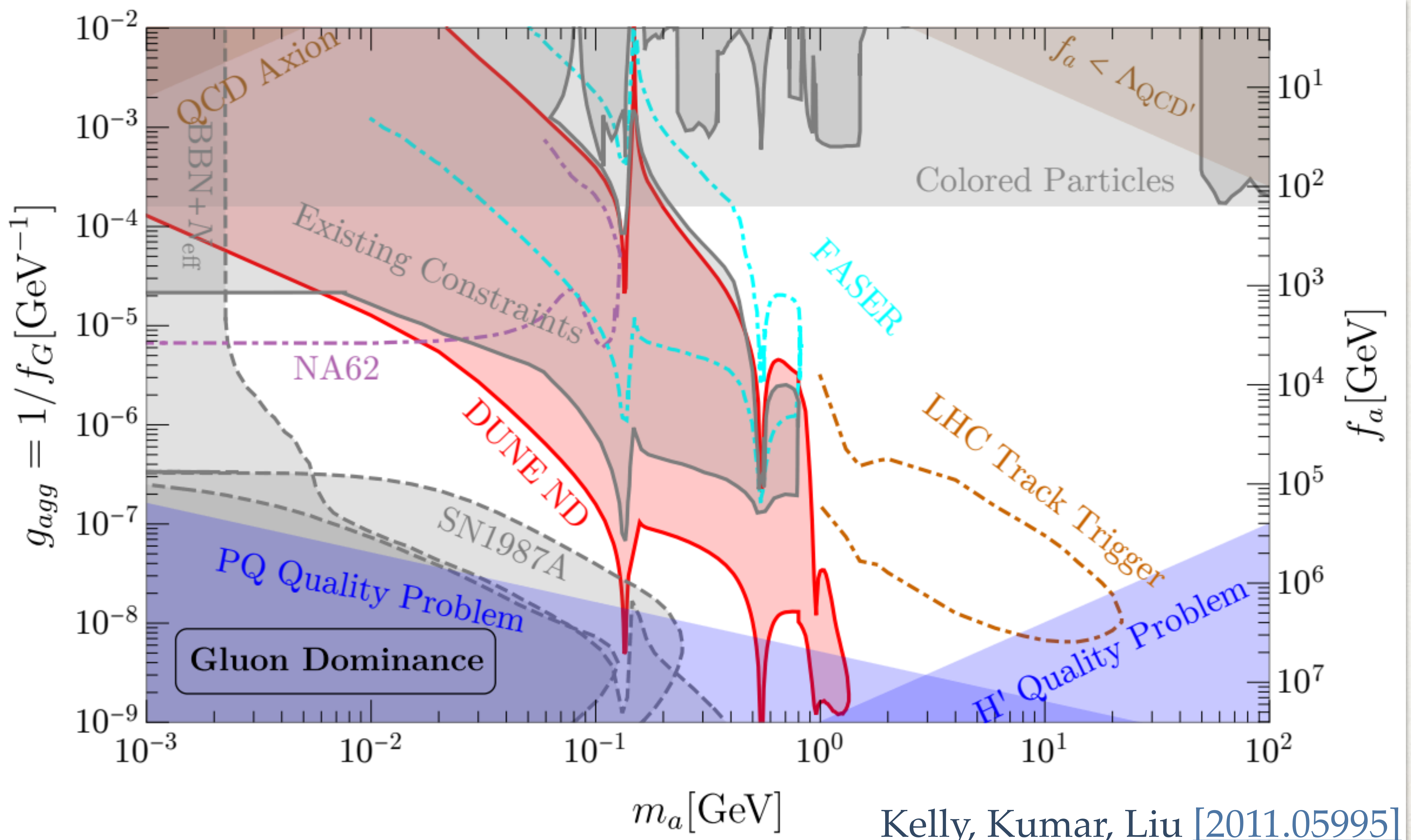




Detector Signature: A pair of high-energy photons or hadrons with a relatively small opening angle.

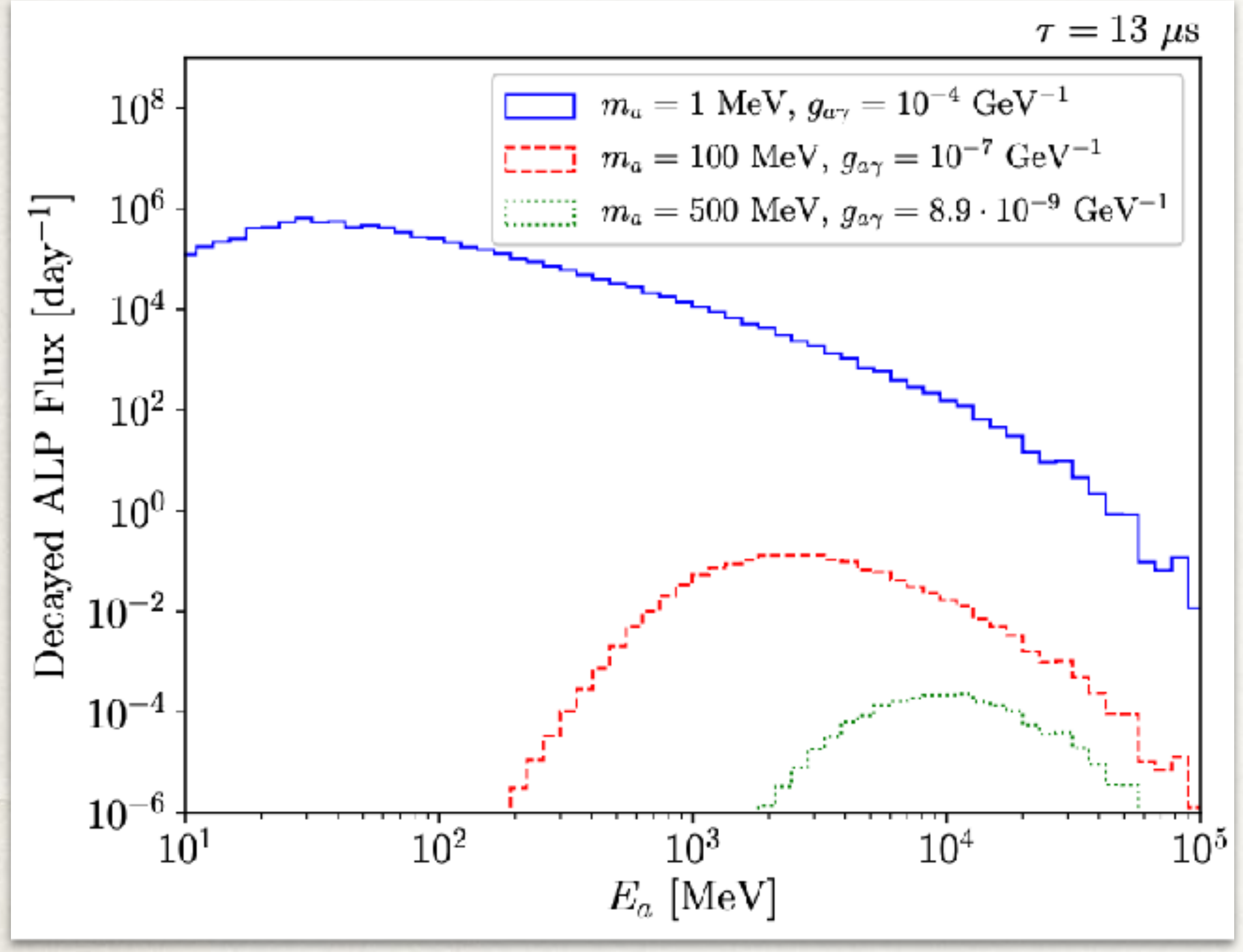
Energy spectrum depends strongly on the lifetime of the Axion.

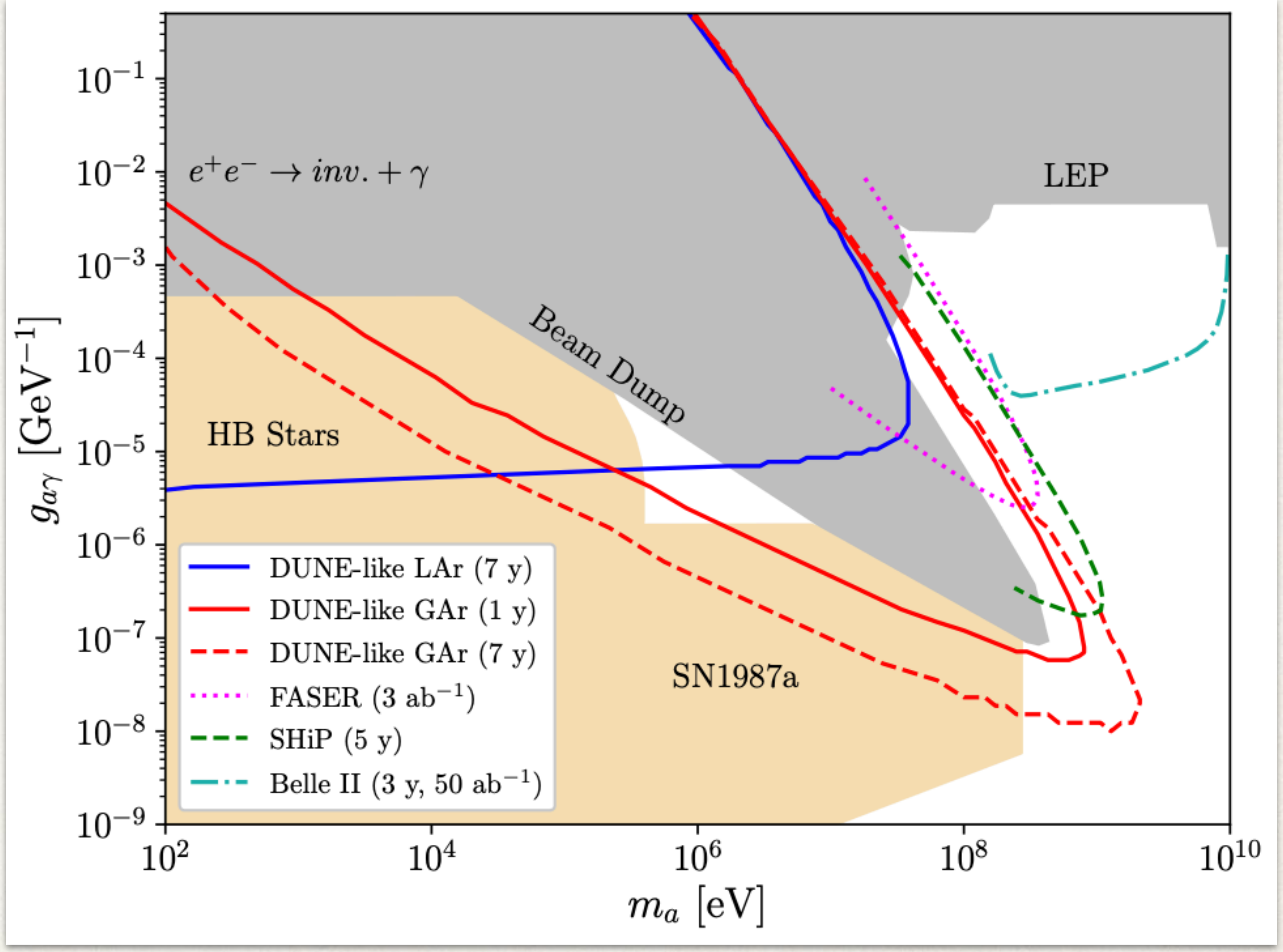
Heavy Axion Sensitivity



Kelly, Kumar, Liu [2011.05995]

ALP Spectra & Sensitivity





Brdar, Dutta, Jang, Kim, Shoemaker, Tabrizi, Thompson, Yu [2011.07054]

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Thank you!