Beyond Sterile Neutrinos at Short Baselines

2nd Short-Baseline Experiment-Theory Workshop
April 3rd 2024

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Short Baseline Neutrino Physics

The LSND, MiniBooNE, Gallium, and reactors puzzles pushed theory and experiment to **new directions**

SBL community and program have become major **players in BSM physics at neutrino experiments** (beyond oscillations)

We are a data-driven and resourceful community

Sterile neutrinos

Theoretically, an extremely **compelling hypothesis.**

Much has been said about **eV-scale** sterile oscillations.
Still relevant (30+ years later!), but not my focus here.

This talks is about what happens when we go **beyond the minimal scenario**

Additional new physics can completely modify
the phenomenology of sterile neutrinos.

Heavy Neutral Leptons

E. Fernández-Martínez, M.González-López, J. Hernández-García, **MH**, J. Lópes-Pavón, 10.1007/JHEP09(2023)001

Heavy Neutral Leptons

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Sterile neutrinos beyond oscillations at SBL

A MiniBooNE focused list…

1) Decays to electromagnetic final states γ and $e^{+/-}$:

   a) beam production

   b) neutrino upscattering

2) Decays to neutrinos: $\nu_\mu \to \nu_e$ conversion from decay

3) Sterile-induced matter potential: resonant $\nu_\mu \to \nu_e$ conversion

Sterile neutrinos beyond oscillations at SBL

1) **Decays to electromagnetic final states γ and $e^{+/-}$:**

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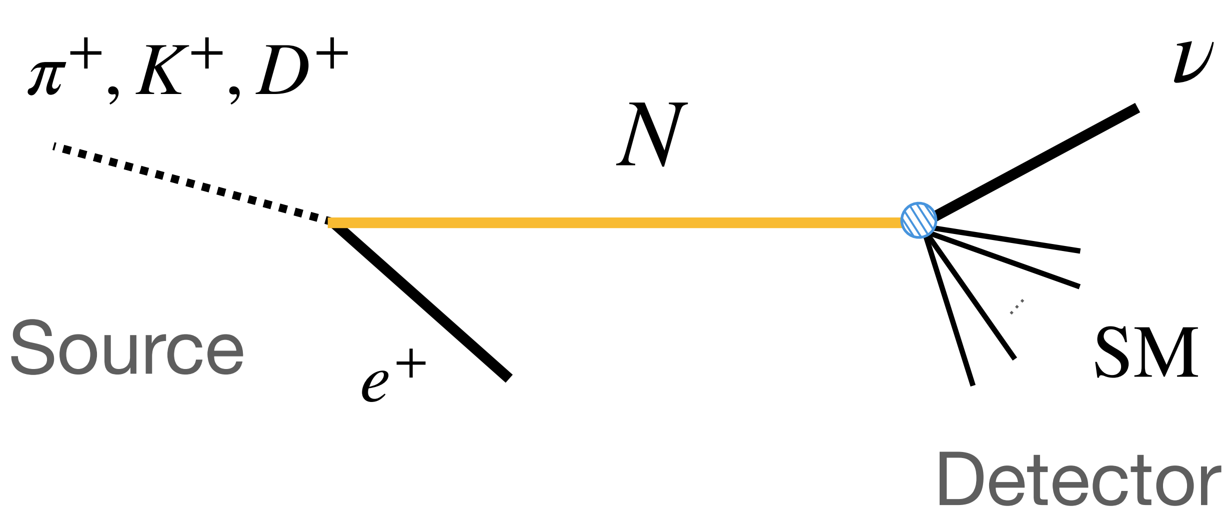
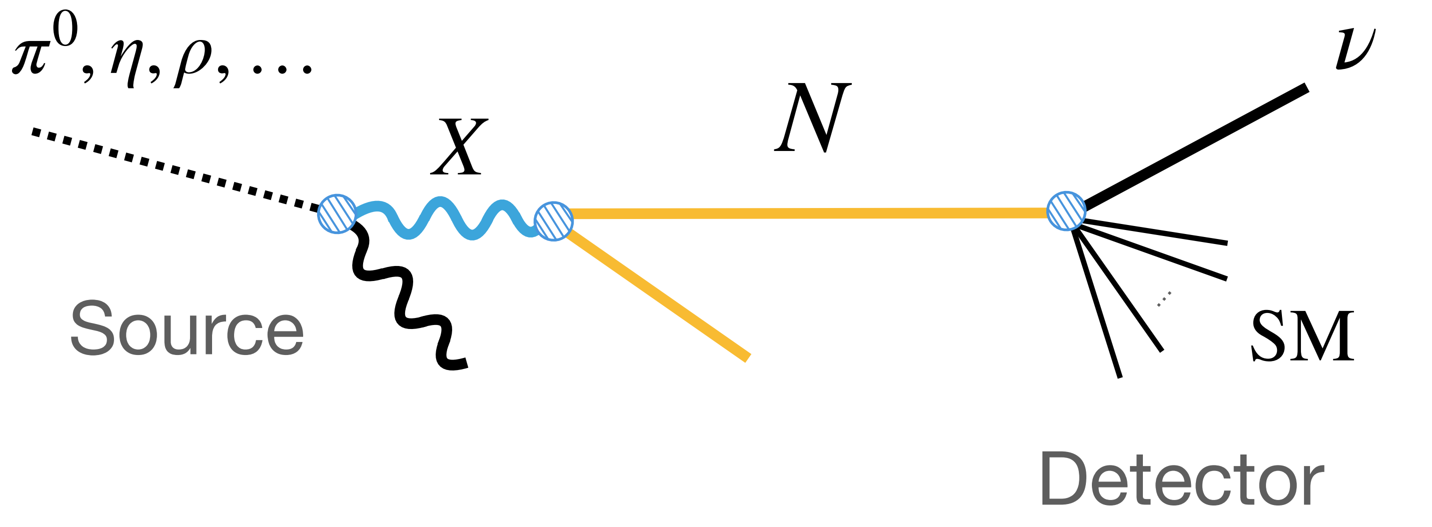
Influence of dark forces on heavy neutrinos

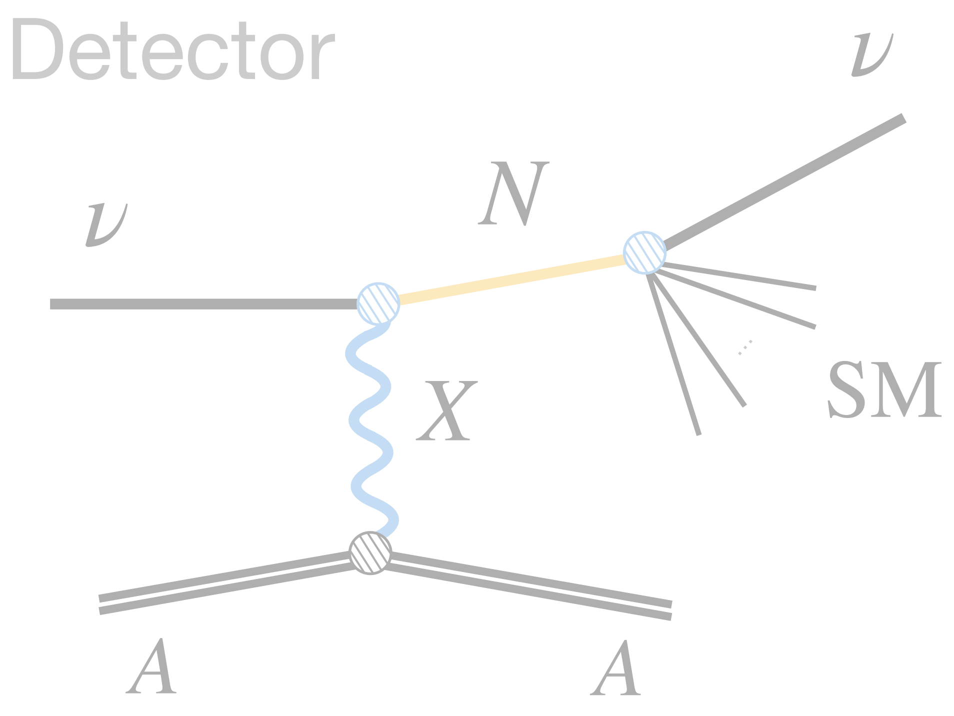
← Longer lifetime **Shorter lifetime →**

Decay in flight



New production modes and decays

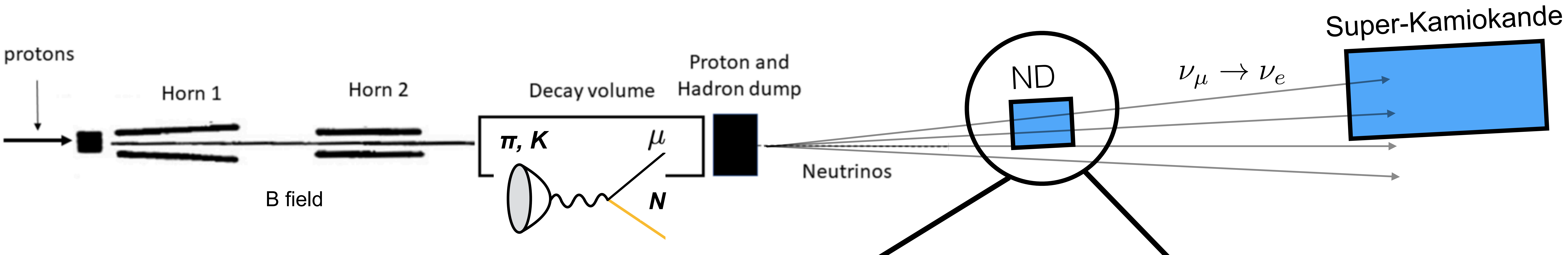




No dark forces **Stronger dark forces →**

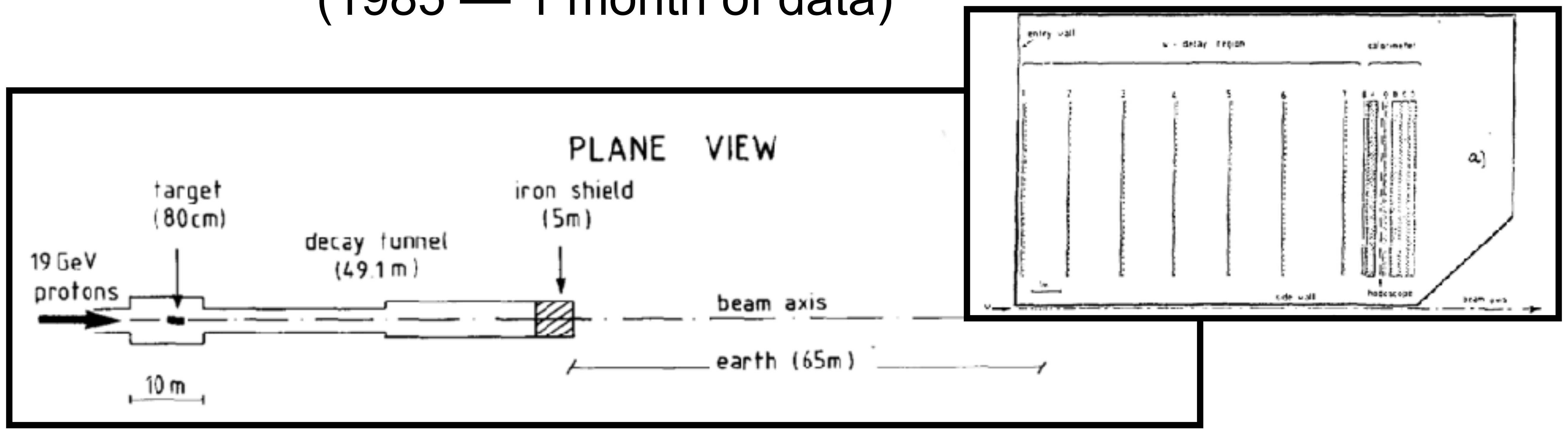
Long-lived Heavy Neutrinos
Hodoscopic detectors

C. Argüelles, N. Foppiani, MH arxiv:2109.03831



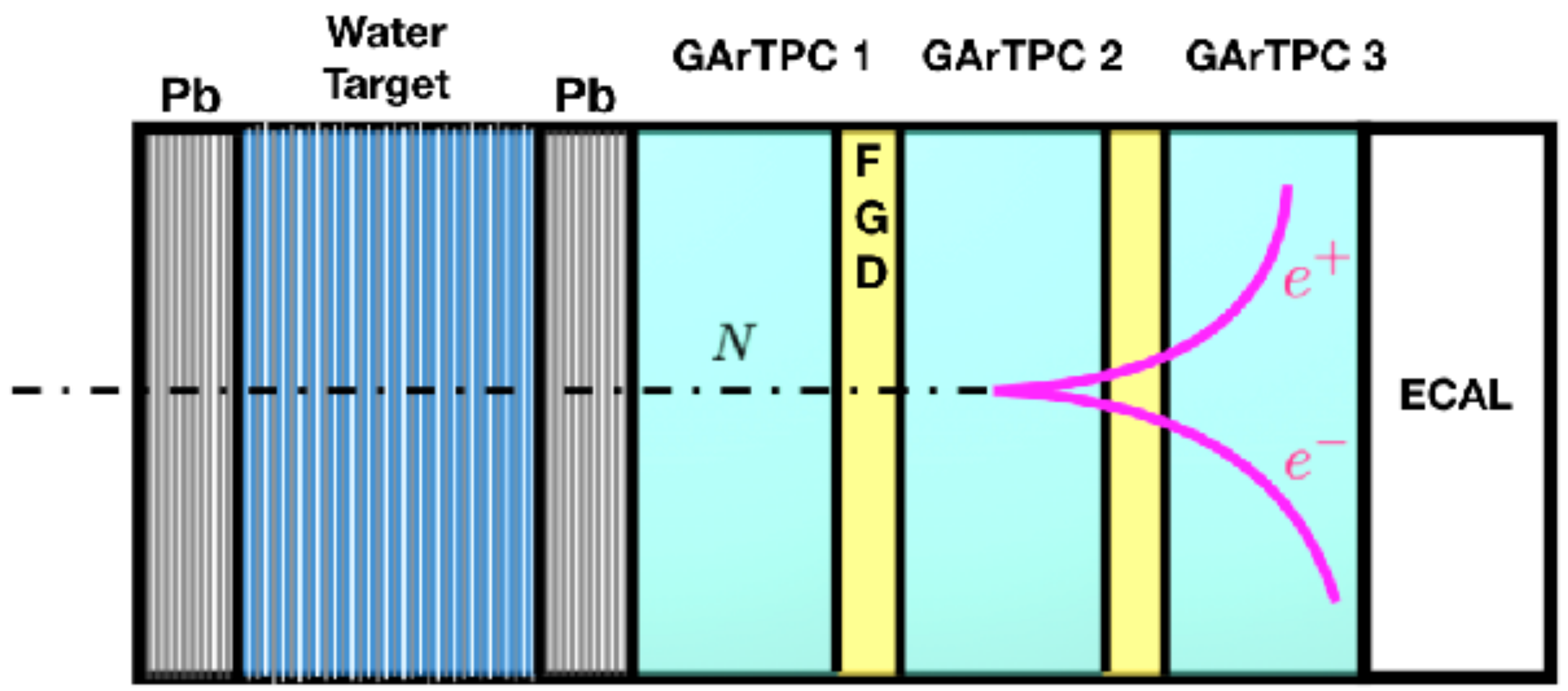
Most sensitive searches below the kaon mass:

PS191 (low-density Helium bags)
(1985 — 1 month of data)



G. Bernardi et al, Phys. Lett. 166B (1986) 479–483

ND280 @ T2K (low-density GAr TPCs)



T2K collaboration, *PRD* 100 (2019) 5, 052006

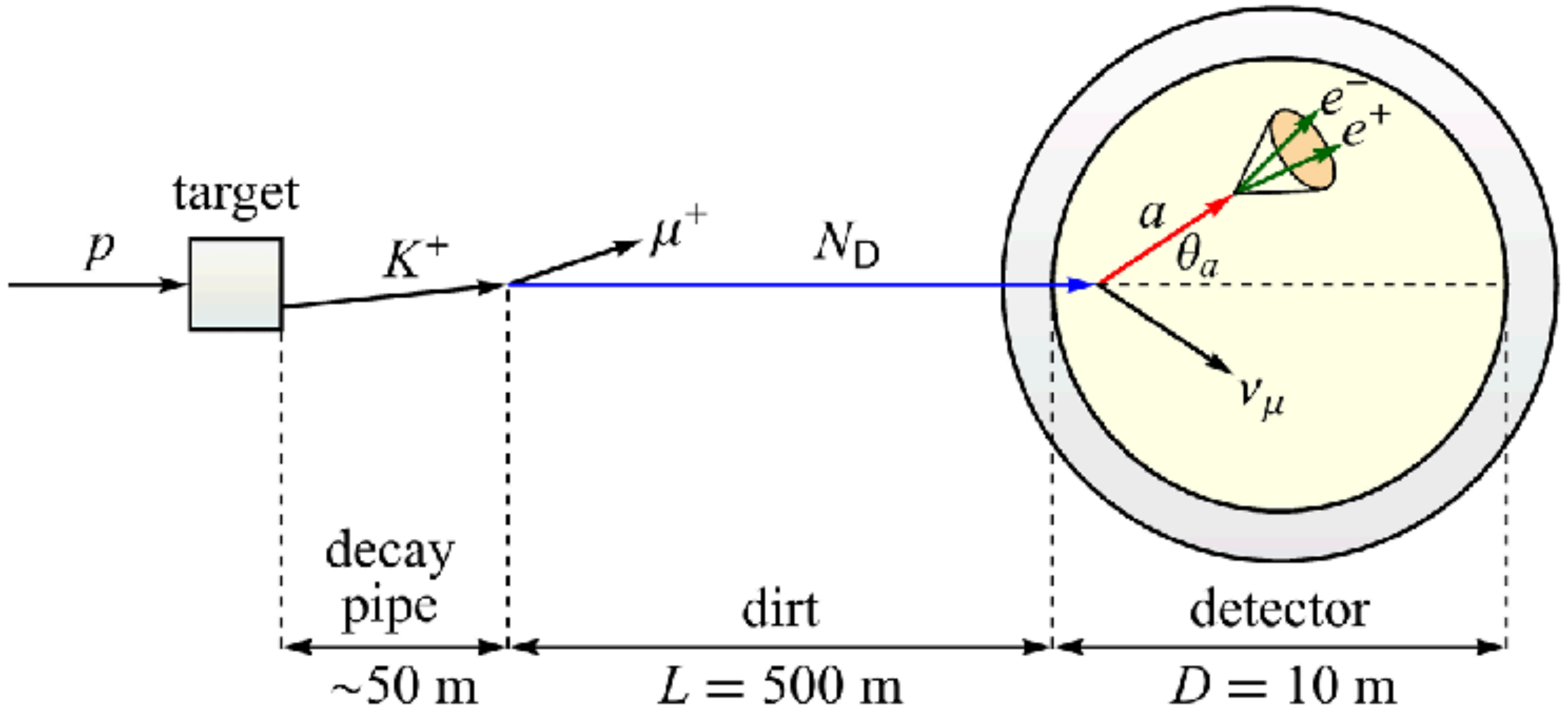
Long-lived Heavy Neutrinos at MiniBooNE
Constraints from other neutrino experiments

C. Argüelles, N. Foppiani, MH arxiv:2109.03831

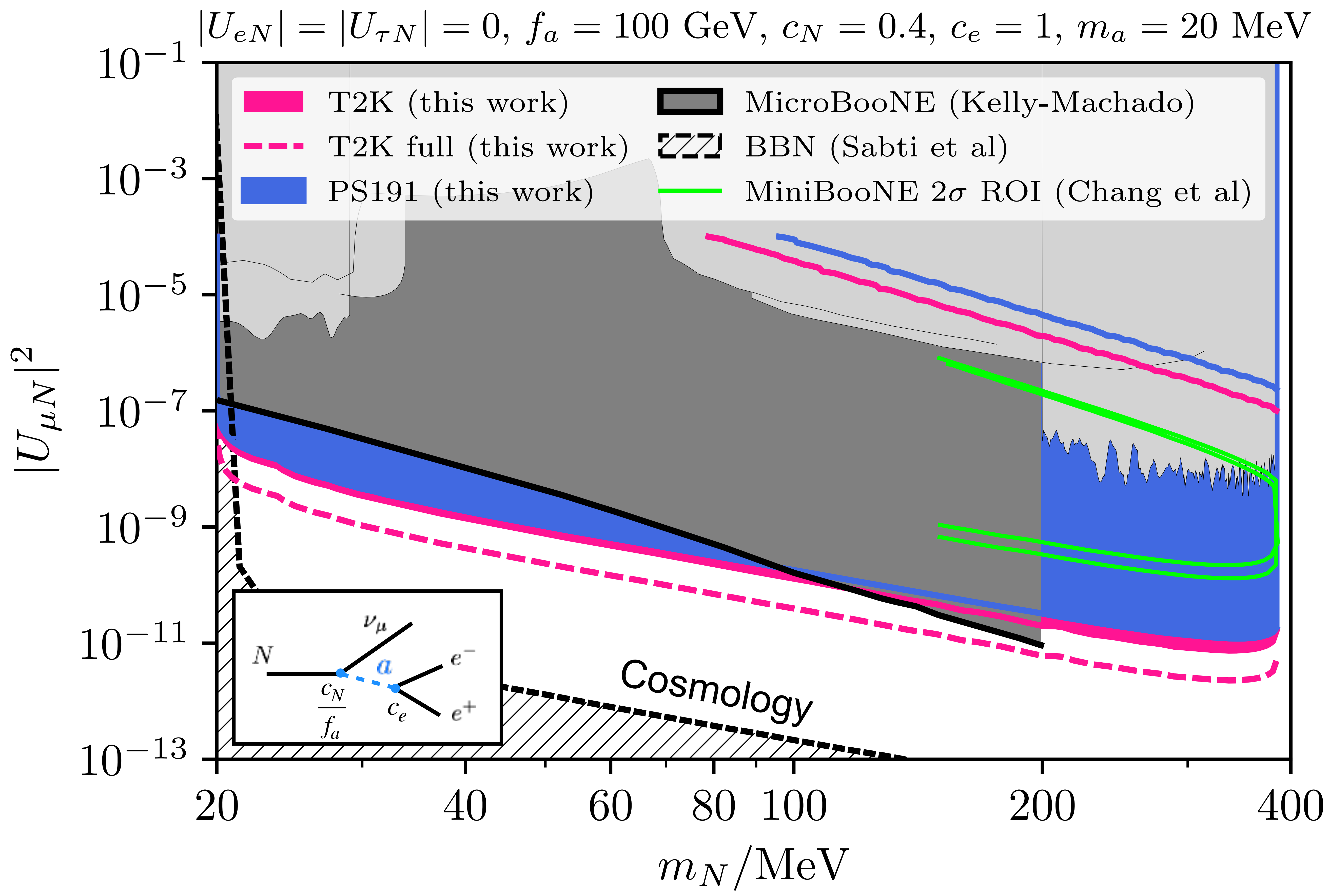
Axion-like-particle in $N \to \nu(a \to e + e^-)$ decays:

C. V. Chang, C. Chen, S. Ho, S. Tseng, PhysRevD.104.015030

$$-\mathcal{L} \supset \frac{\partial_\mu a}{2 f_a} \left(c_N \overline{N} \gamma^\mu \gamma^5 N + c_e \bar{e} \gamma^\mu \gamma^5 e \right)$$



Timing is also an important issue!



T2K and PS191 already placed strong limits on long-lived particle scenarios with e^+e^- decays

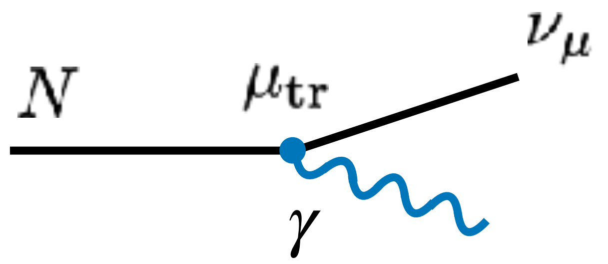
Long-lived Heavy Neutrinos at MiniBooNE
Constraints from other neutrino experiments

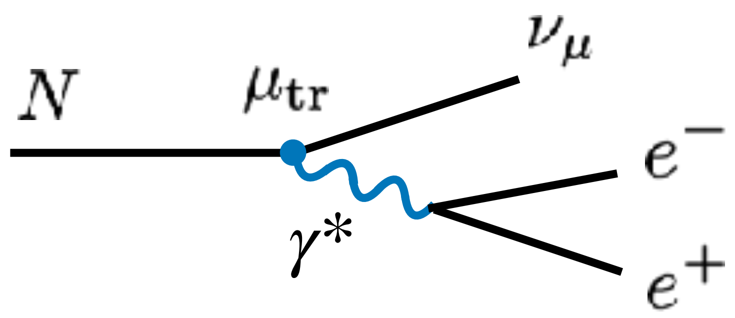
C. Argüelles, N. Foppiani, MH arxiv:2109.03831

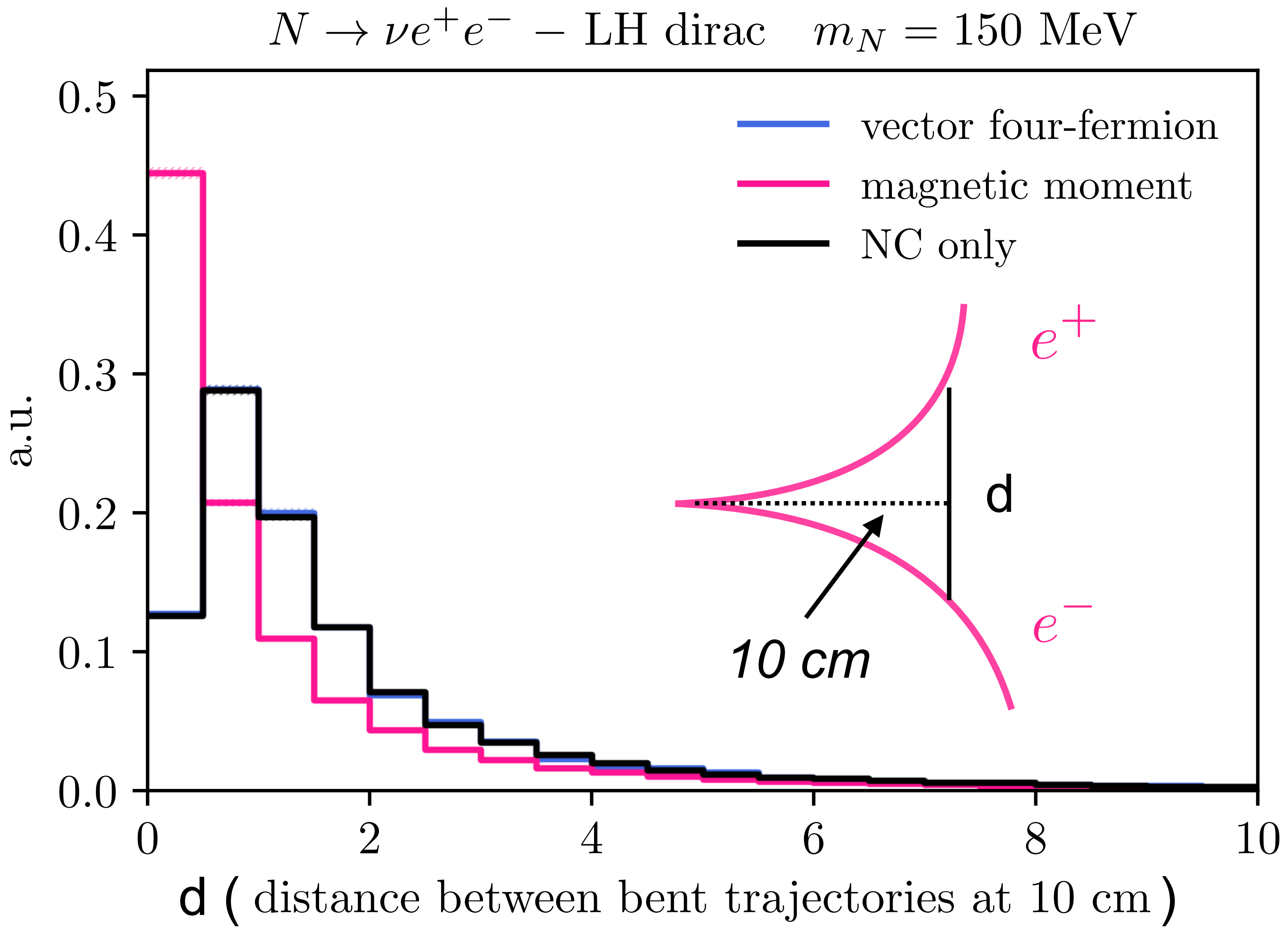
Mixing + dipole portals to heavy neutrinos ($N \to \nu\gamma$ decays):

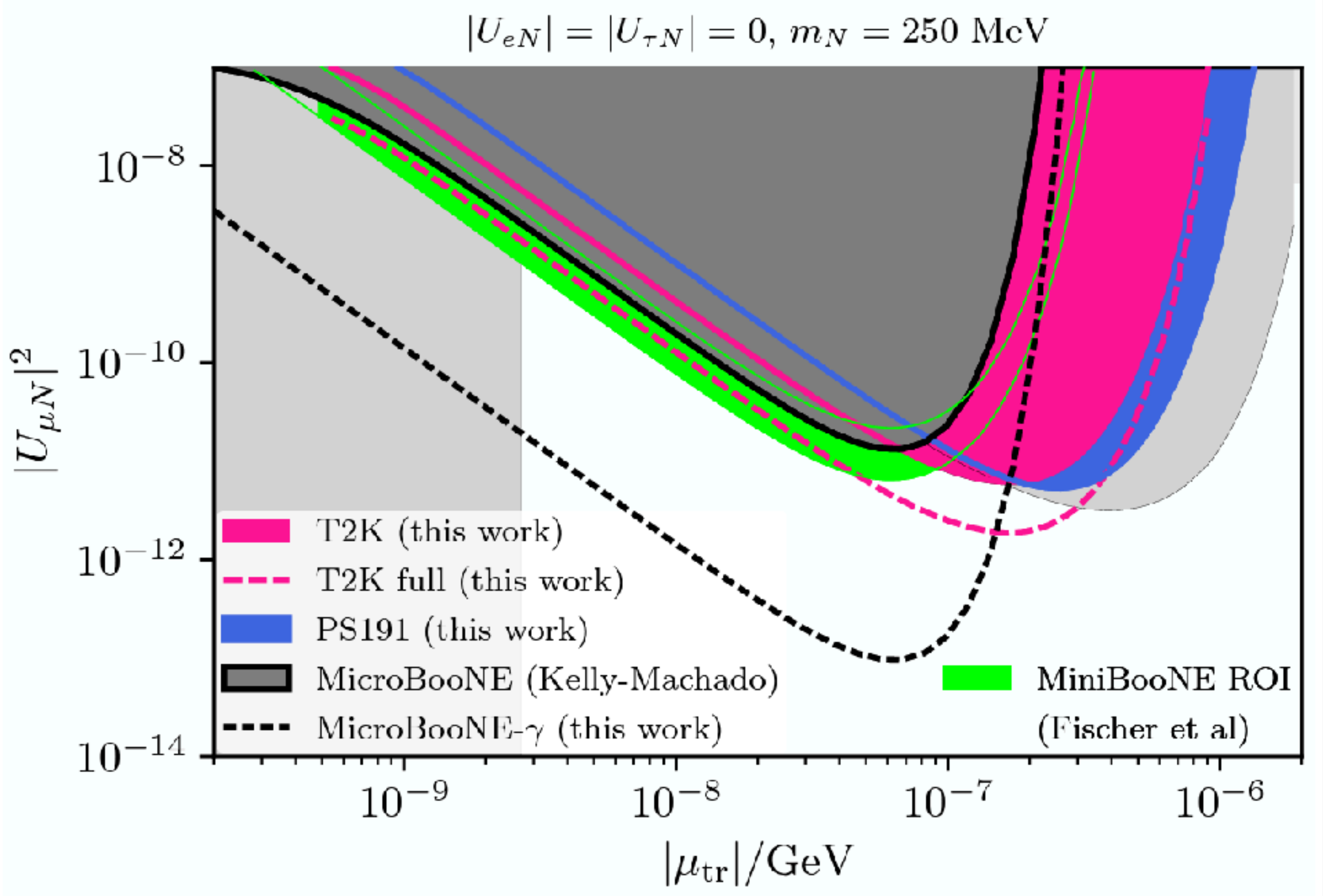
O. Fischer, A. Hernández-Cabezudo, and T. Schwetz,
Phys. Rev. D 101, 075045 (2020),

$$\mathcal{L} \supset \frac{\mu_{tr}}{2} \overline{\nu_\alpha} \sigma^{\mu\nu} N F_{\mu\nu}$$









Single photons decay less constrained, as ND280 relies on off-shell photon:

$$N \to \nu(\gamma^* \to e^+e^-)$$

Long-lived Heavy Neutrinos at MiniBooNE
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C. Argüelles, N. Foppiani, MH arxiv:2109.03831

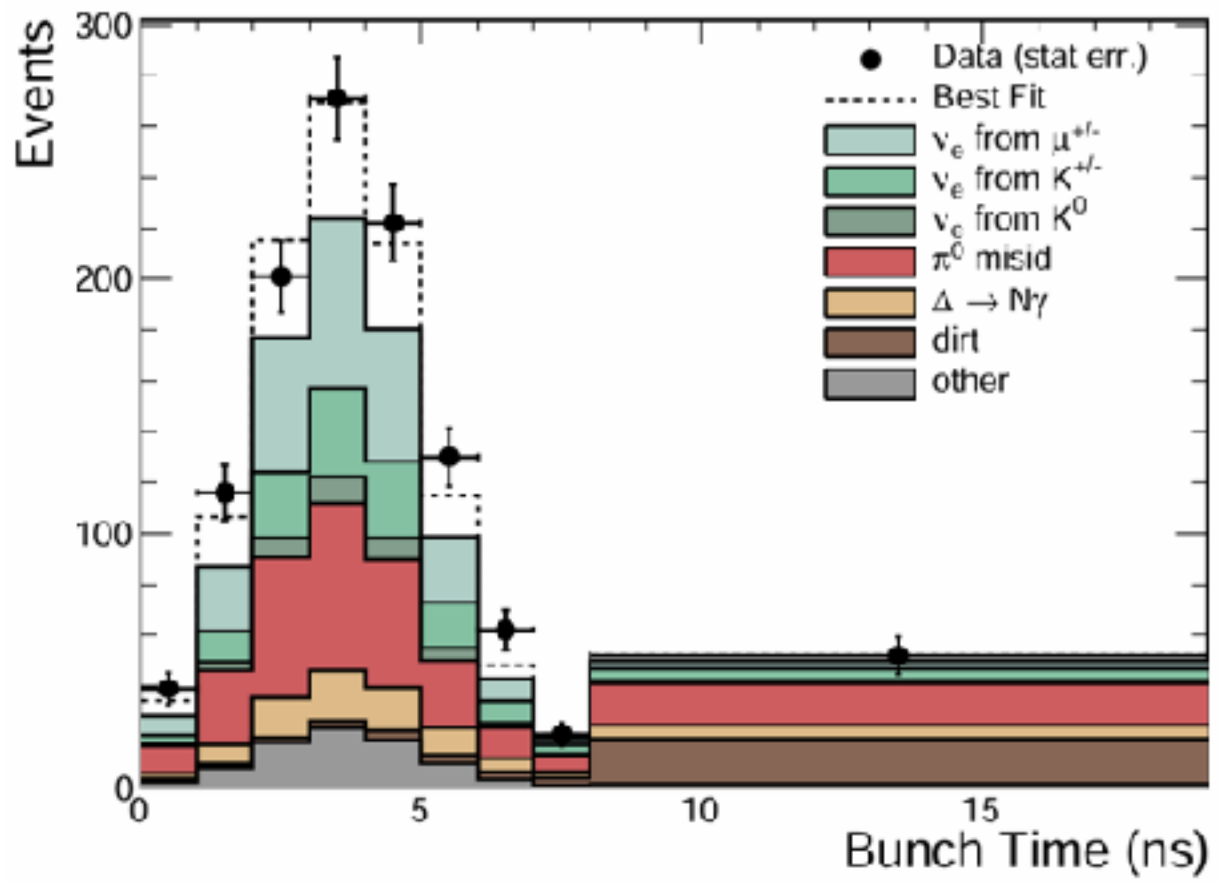
$|U_{eN}| = |U_{\tau N}| = 0,\ m_N = 250$ MeV

Mixing + dipole portals to heavy neutrinos ($N \to \nu\gamma$ decays):

O. Fi…
Phys…

Decays of long-lived particles as explanations of MiniBooNE:

- Timing at MiniBooNE is measured, consistent with a 10 ns spread, so $M_X \lesssim$ 30 MeV
- Either production mechanism is very different at BNB compared to J-PARC
- Or new particle decays to photons only (photons do not convert in T2K ND280)



Scattering of light particles still okay (see Doojin's and Adrien's talks)

N

0.0
0 2 4 6 8 10
d (distance between bent trajectories at 10 cm)

as ND280 relies on off-shell photon:

$N \to \nu(\gamma^* \to e^+e^-)$

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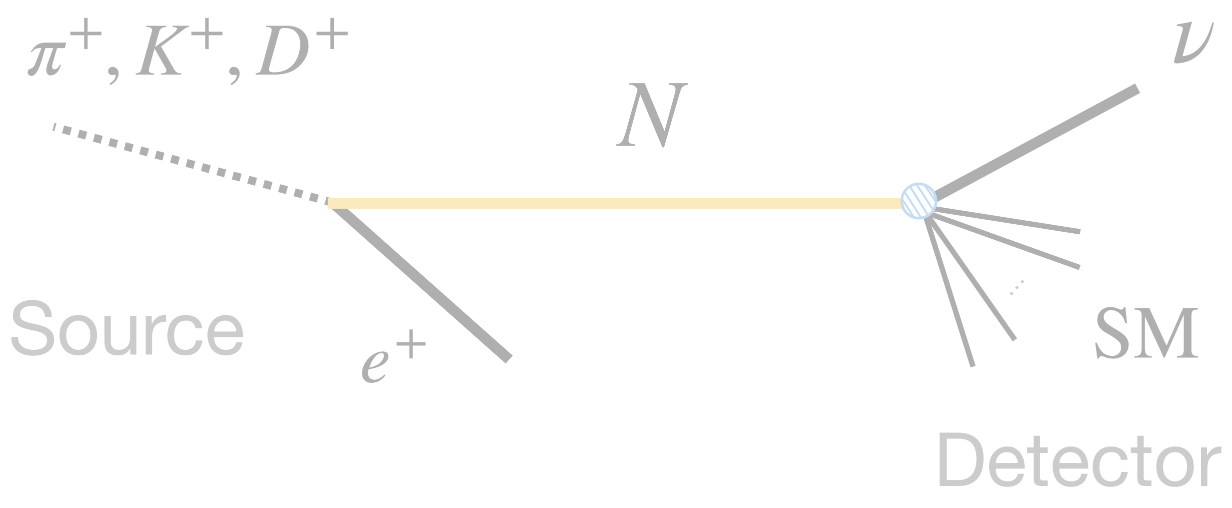
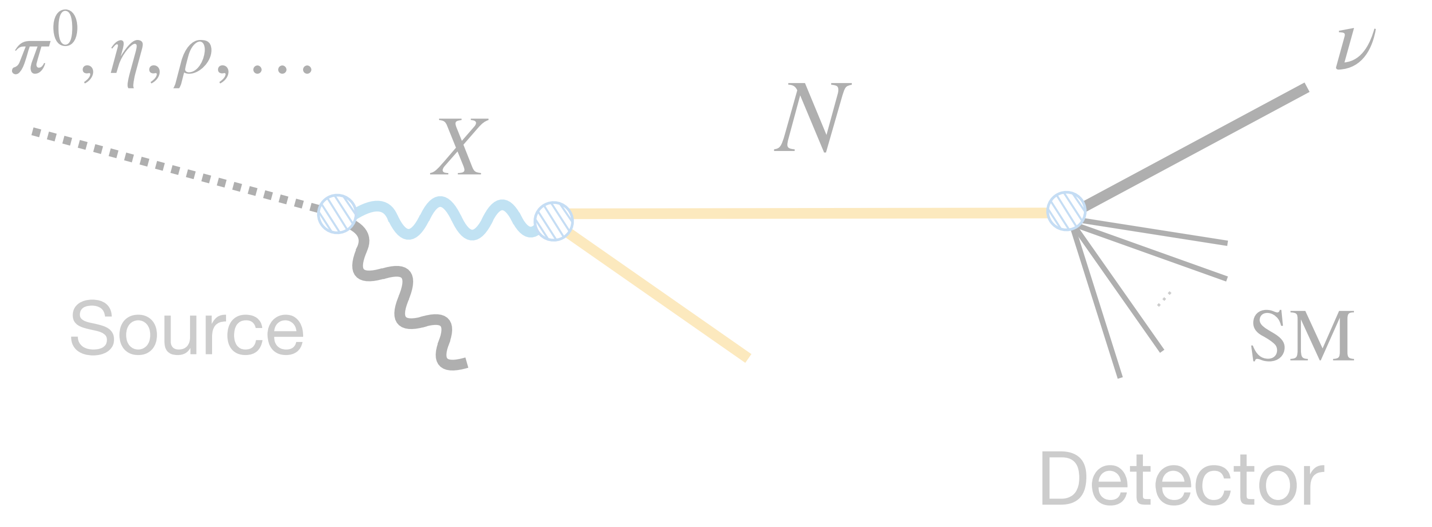
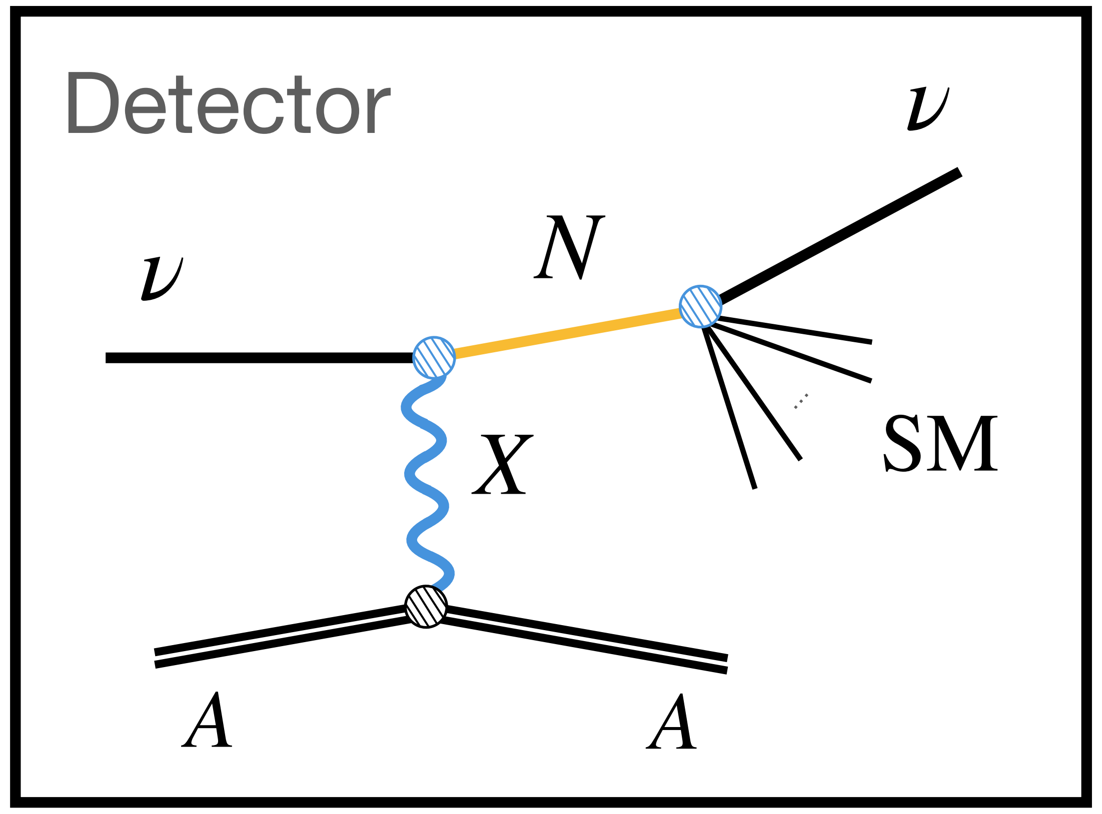


New production modes and decays

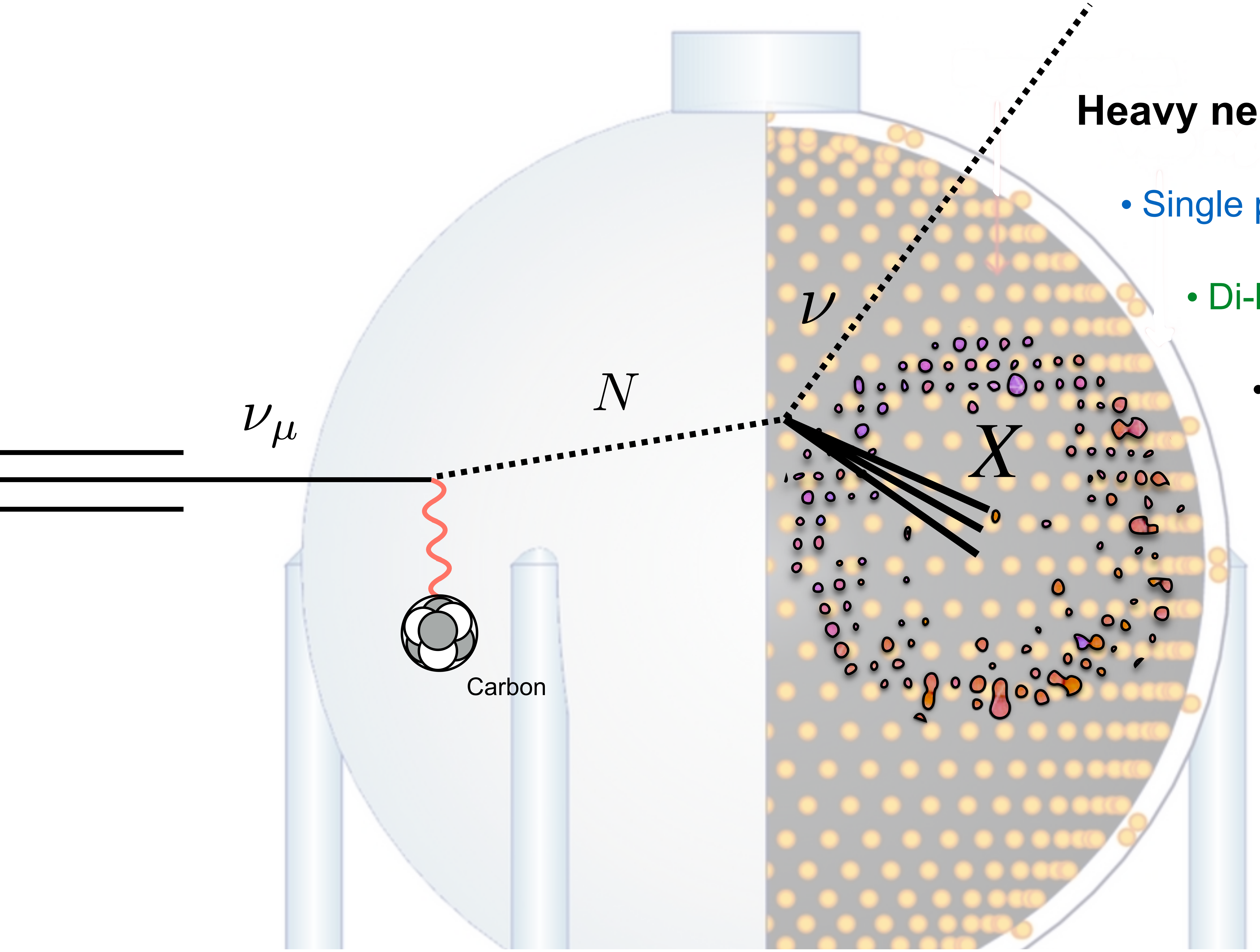




No dark forces **Stronger dark forces →**

Dark Sectors in the MiniBooNE Low-Energy Excess

Particle production inside the detector



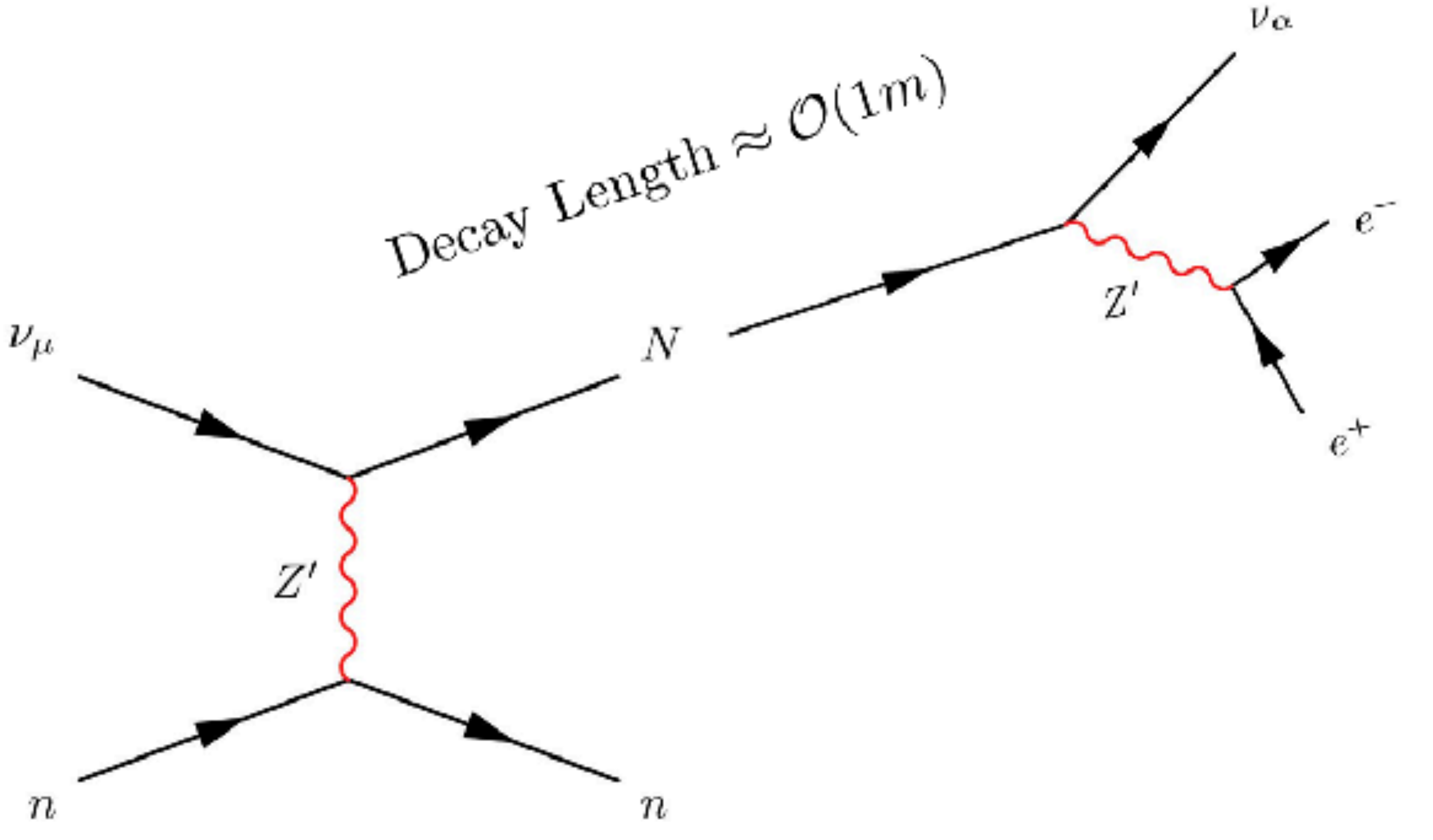
Heavy neutrino decays:

- Single photons via transition magnetic moment ($X = \gamma$)
- Di-leptons from dark photons or scalars ($X = e^+e^-$)
- Di-photons from dark scalars ($X = \gamma\gamma$)

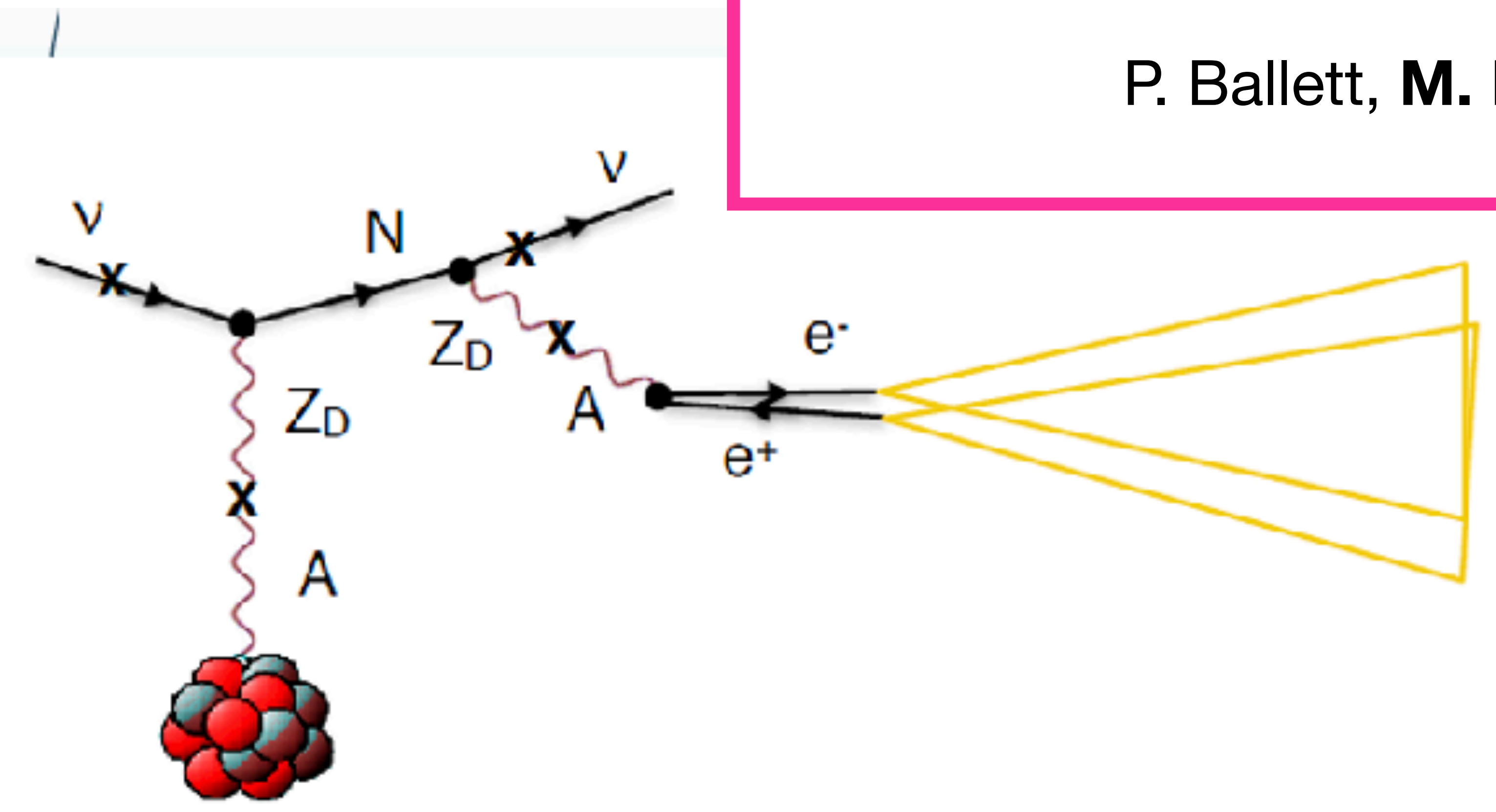
Non-exhaustive list:

E. Bertuzzo et al, [arXiv:1807.09877]
P. Ballett et al, [arxiv:1808.02915]
C. Argüelles, **MH**, Y. Tsai, [arXiv:1812.08768]
P. Ballett, **MH**, S. Pascoli, [arxiv:1903.07589]
A. Abdullahi, **MH**, S. Pascoli, [arXiv:2007.11813]
J. Liu et al, [arXiv:2001.06522]
W. Abdallah et al, [arXiv:2202.09373]
B. Dutta et al, [arxiv:2006.01319]
A. Datta et al, [arXiv:2005.08920]
B. Dutta et al, [arxiv:2006.01319]
S. Bansal et al, [arXiv:2210.05706]
W. Abdallah, et al, [arxiv:2202.09373]
...

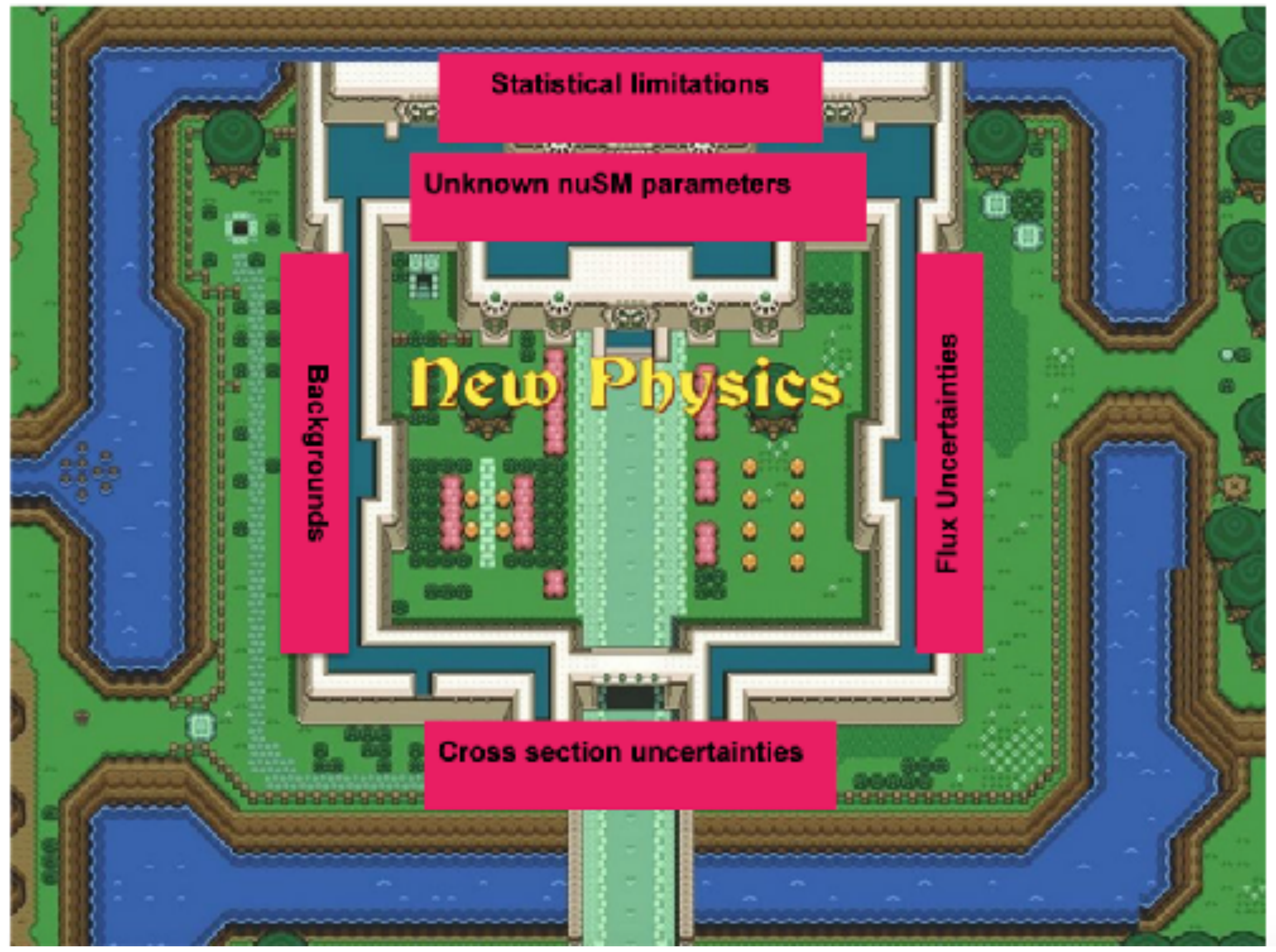
The year was 2018… and we were excited



P. Ballett, **M. Ross-Lonergan**, S. Pascoli, PRD 99, 071701 (2019)



E. Bertuzzo, **S. Jana**, P. A. N. Machado, R. Z. Funchal, PRL. 121, 241801 (2018)



C. Argüelles, MH, Y. Tsai, PRL. 123, 261801 (2019)

Neutrino upscattering explanations of MiniBooNE within new light of dark sectors:

Strong synergy with light dark sector program

Connection to neutrino mass models at low-scales

Lots of attention due to new MiniBooNE 2018 results

Then 2021 came… and were still excited. Perhaps too excited?

Mini SBN-Theory workshop

15:30 → 16:30 **Alternative models for the MiniBooNE LEE** 1h

Speakers: Asli Abdullahi (Durham U.), Carlos Arguelles (Harvard), Doojin Kim (Texas A&M), Ivan Martinez-Soler (Harvard), Matheus Hostert (Perimeter)

SBN workshop slide...

Model	U. Signature	LSND	MB	Reactors	Cosmology	Issues	Score
3+1	Oscillations					Appearance-disappearance tension.	6
(3+1) + inv-ν decay	Damped oscillations					Large couplings. UV model?	4
(3+1) + NSI	Modified matter effects					Large NSI couplings. DeepCore tension.	11
Anomalous matter	Resonant appearance				unknown	Tension with T2K if resonance in E.	9
Large extra dim	Osc with related freqs.				unknown	Same issues as 3+1 or worse.	12
LNV in μ decays	$\mu^+ \to$ anti-ν_e					Michel params in tension w/ TRIUMF.	8
Lorentz violation	Sidereal time variation				unknown	HE IceCube tension.	10
Dark neutrinos	Upscattering to $N \to \nu e^+e^-$					MINERvA/CHARM-II/ND280 tension?	2
Dipole portal	Upscattering to $N \to \nu \gamma$					MINERvA/CHARM-II/ND280 tension?	3
(3+1) + vis-ν decay	DIF of $\nu_s \to \nu_e$					Tension with solar antineutrinos.	5
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Dark sectors: dark matter	Upscattering to $\chi' \to \chi e^+e^-$					MINERvA/CHARM-II/ND280 tension?	5
Dark sectors: (pseudo)-scalar	Forward scattering to γ					MINERvA/CHARM-II/ND280 tension?	1

In a moment of poor judgement,
we made a **ranking of models** for the talk.

Let me right this wrong we caused.

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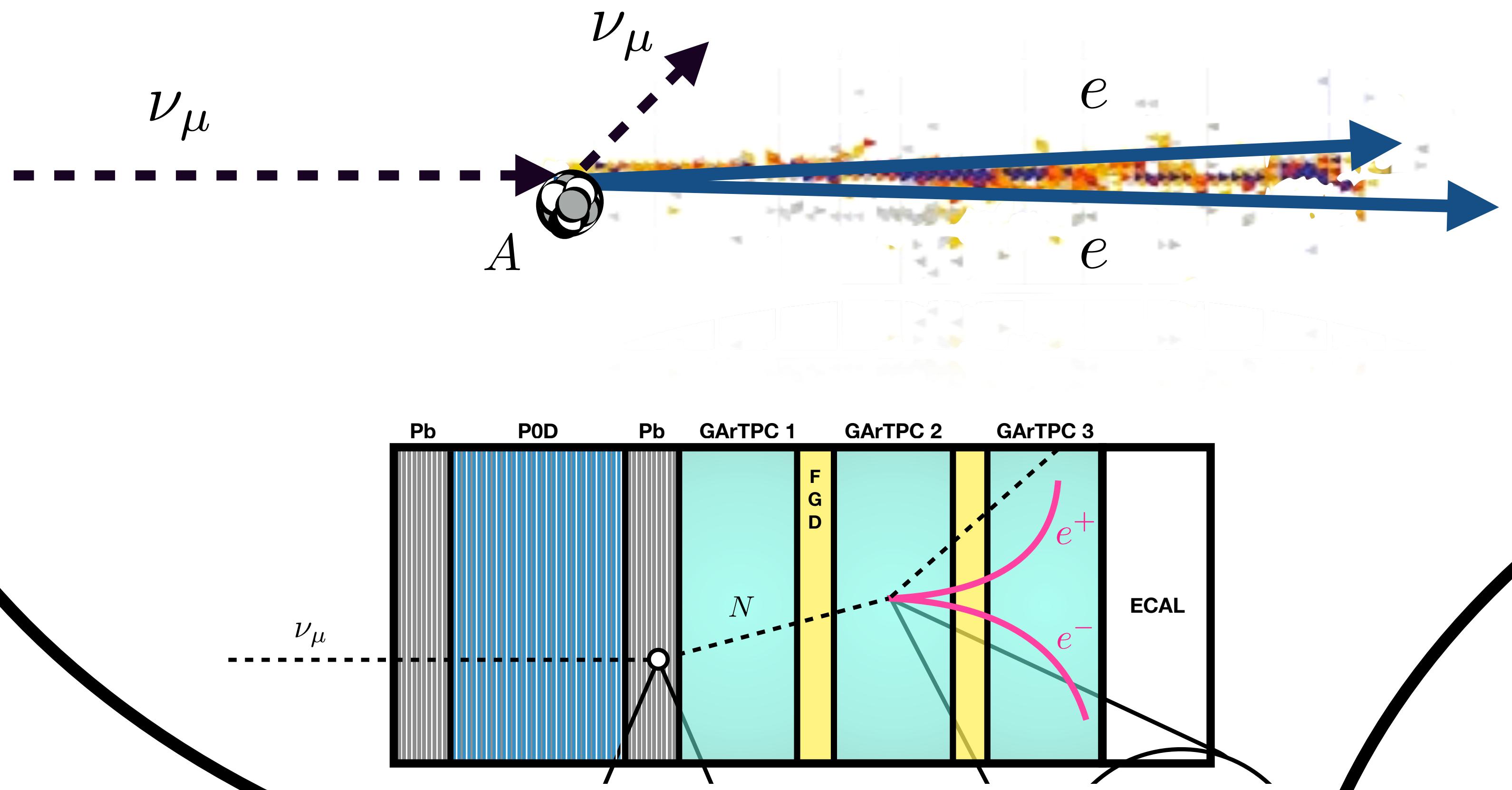
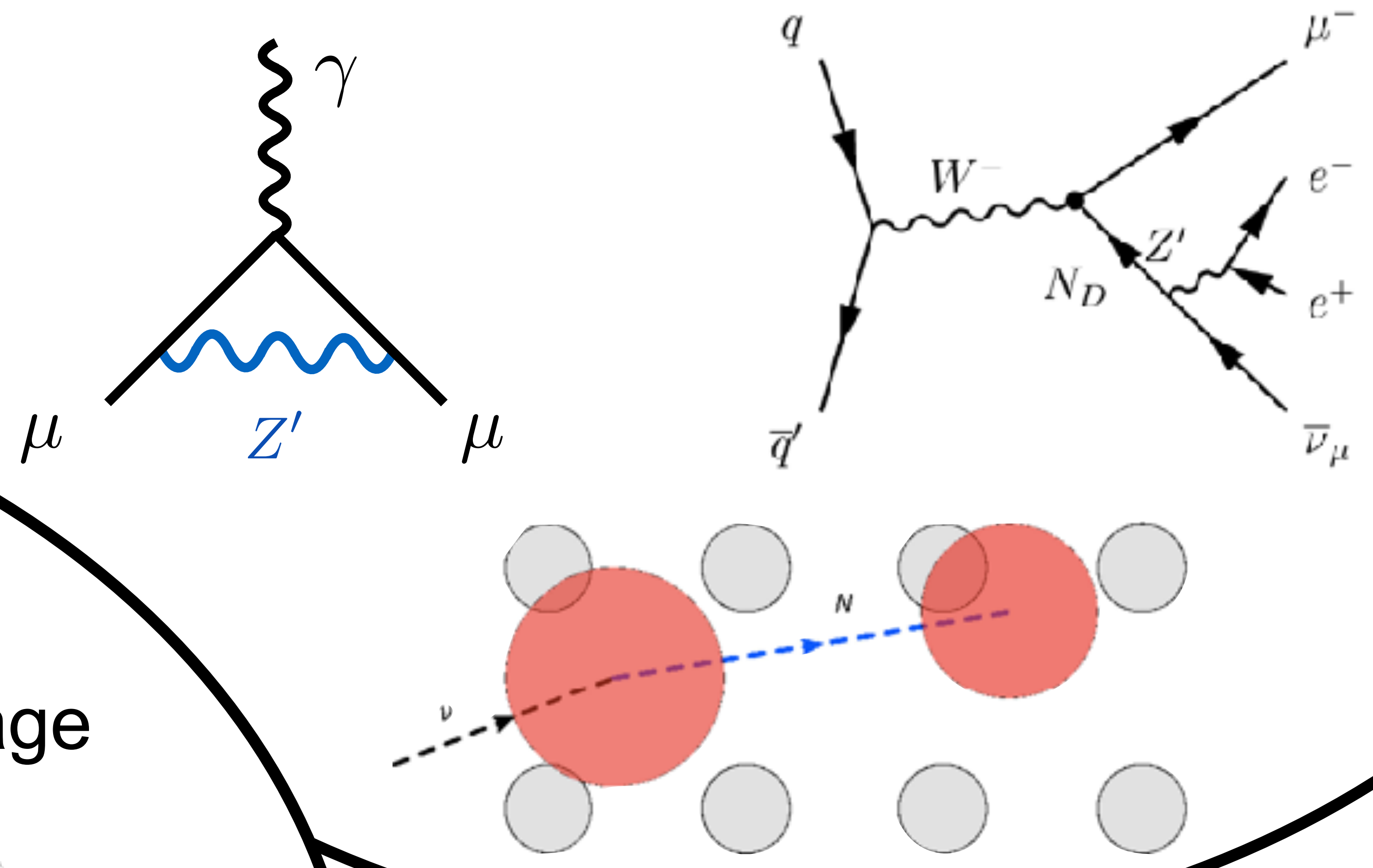
The short-baseline olympics are cancelled. We are all winners.

Jokes aside, we are now in 2024: what have we learned?

Novel uses of existing neutrino data by pheno community

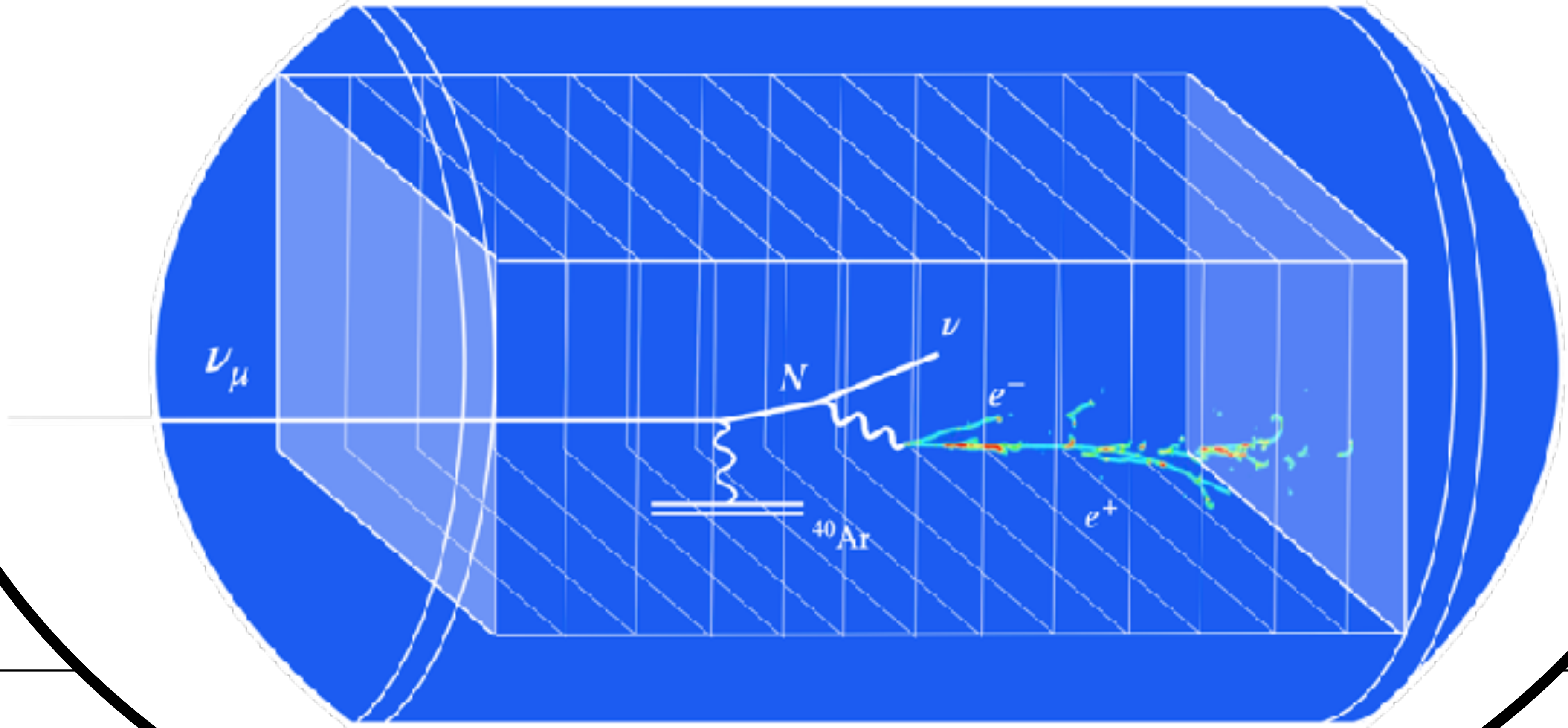


Numerous connections to other experimental programs

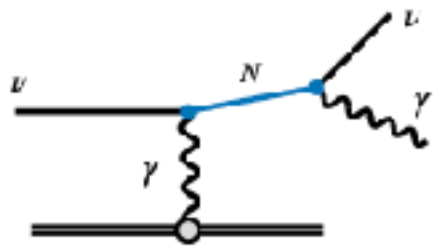
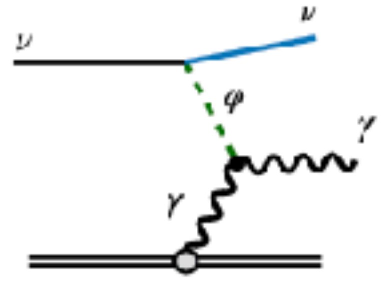
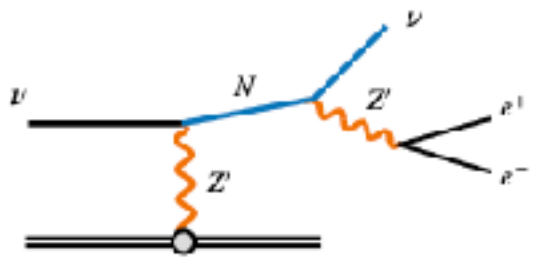
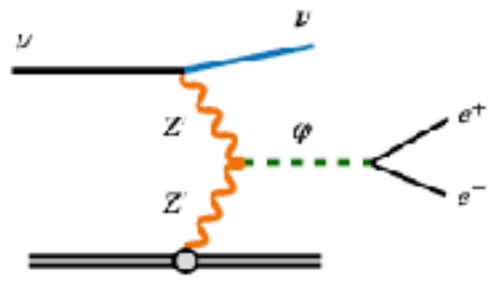
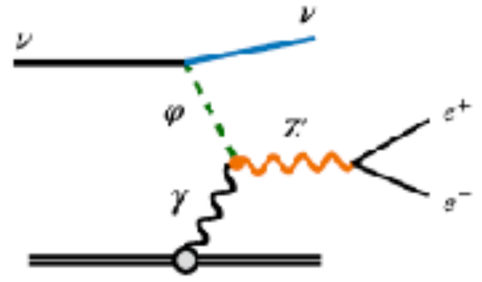
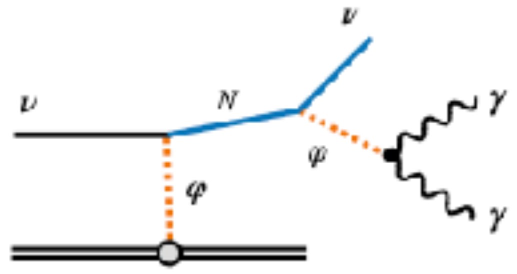
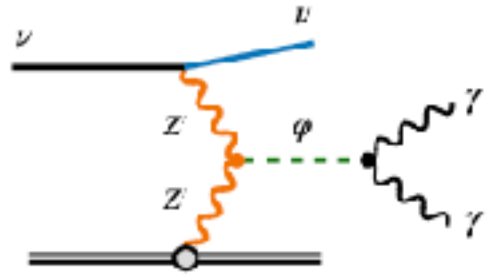


MicroBooNE e^+e^- and γ searches

Experimental analysis in advanced stage



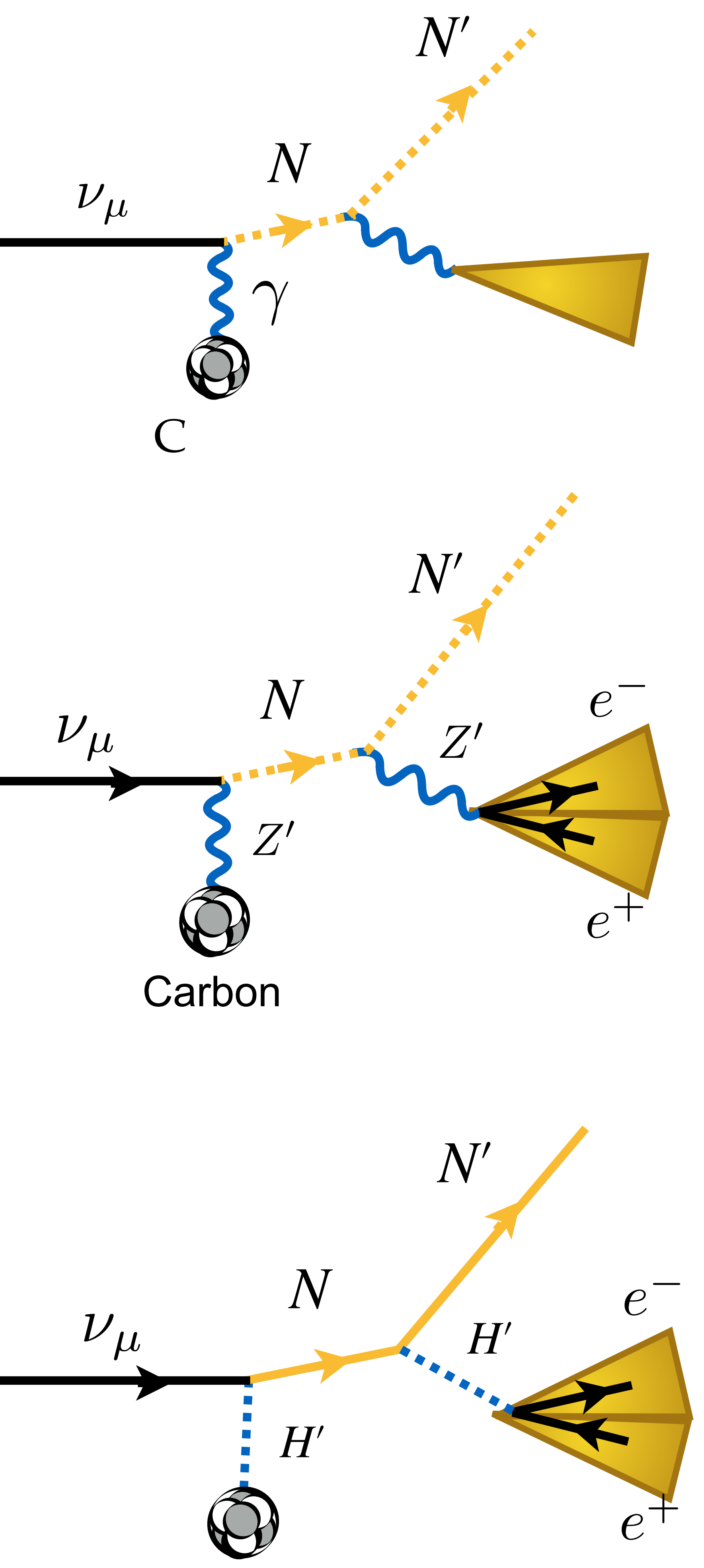
Variations on upscattering

New physics in scattering				
Topology	Model	Diagram	Signal	References
single γ	neutrino upscattering		$N \to \nu\gamma$	[74–84]
	neutrino-induced inverse-Primakoff scattering		$\varphi^* A \to \gamma A$	[84]
e^+e^-	neutrino upscattering		$N \to \nu e^+ e^-$ on-shell N	[36–41, 71–73] Section IV
	neutrino-induced bremsstrahlung		$Z' \to e^+e^-$ off-shell N	not studied
	neutrino-induced Primakoff scattering		$\varphi \to e^+e^-$	[40]
	neutrino-induced inverse-Primakoff scattering		$Z' \to e^+e^-$	not studied
$\gamma\gamma$	neutrino upscattering		$N \to \nu\gamma\gamma$	[39]
	neutrino-induced Primakoff scattering		$\varphi \to \gamma\gamma$	not studied

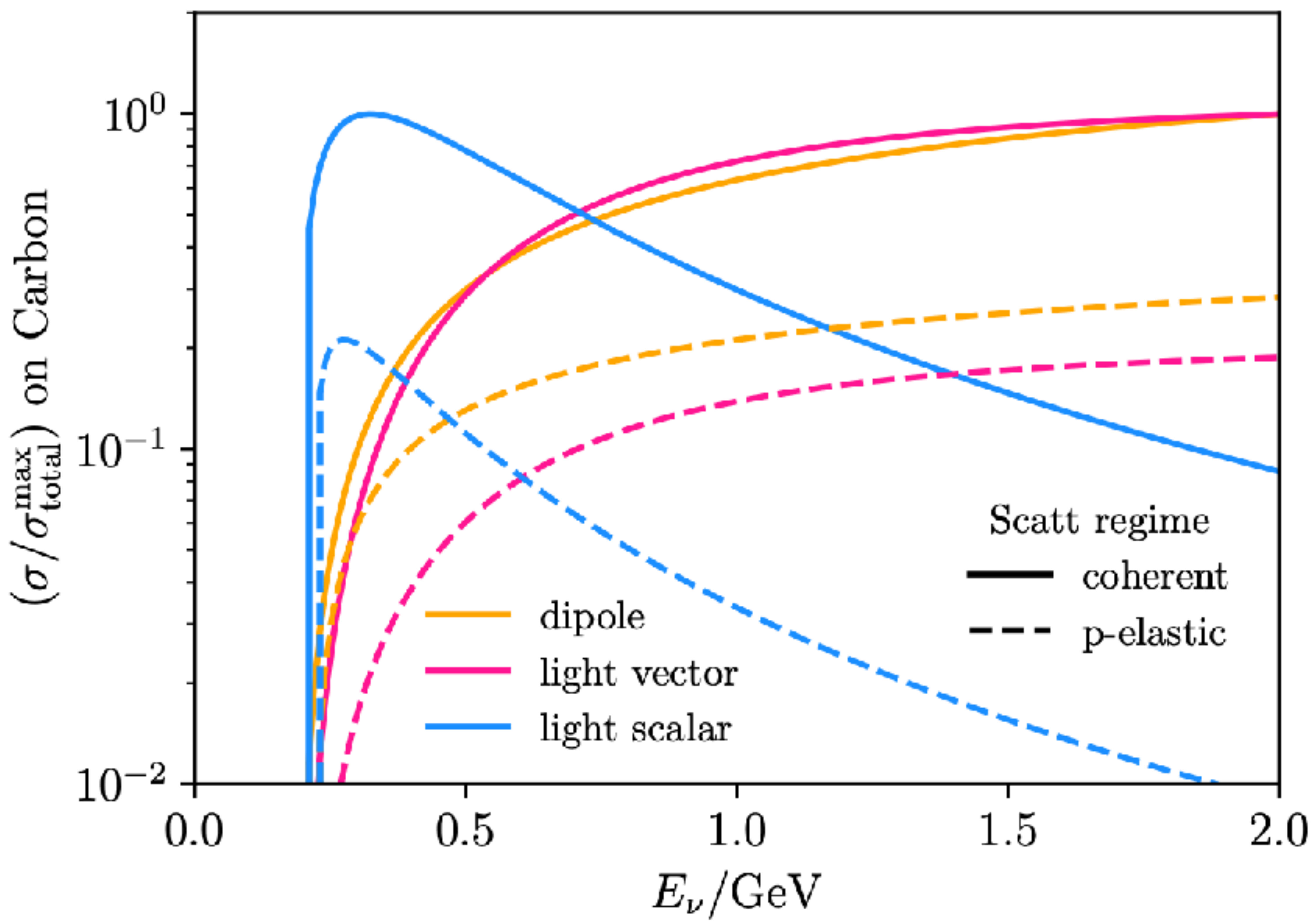
For a review see:

A. M. Abdullahi, J. Hoefken Zink, M. Hostert, D. Massaro, S. Pascoli
arXiv:2308.02543

Dark neutrino sectors at MiniBooNE
The nature of the mediator matters



Normalized upscattering cross sections in different models:



Not all neutrino experiments would see the same physics.
Importance of complementarity.

Dark neutrino sectors at MiniBooNE
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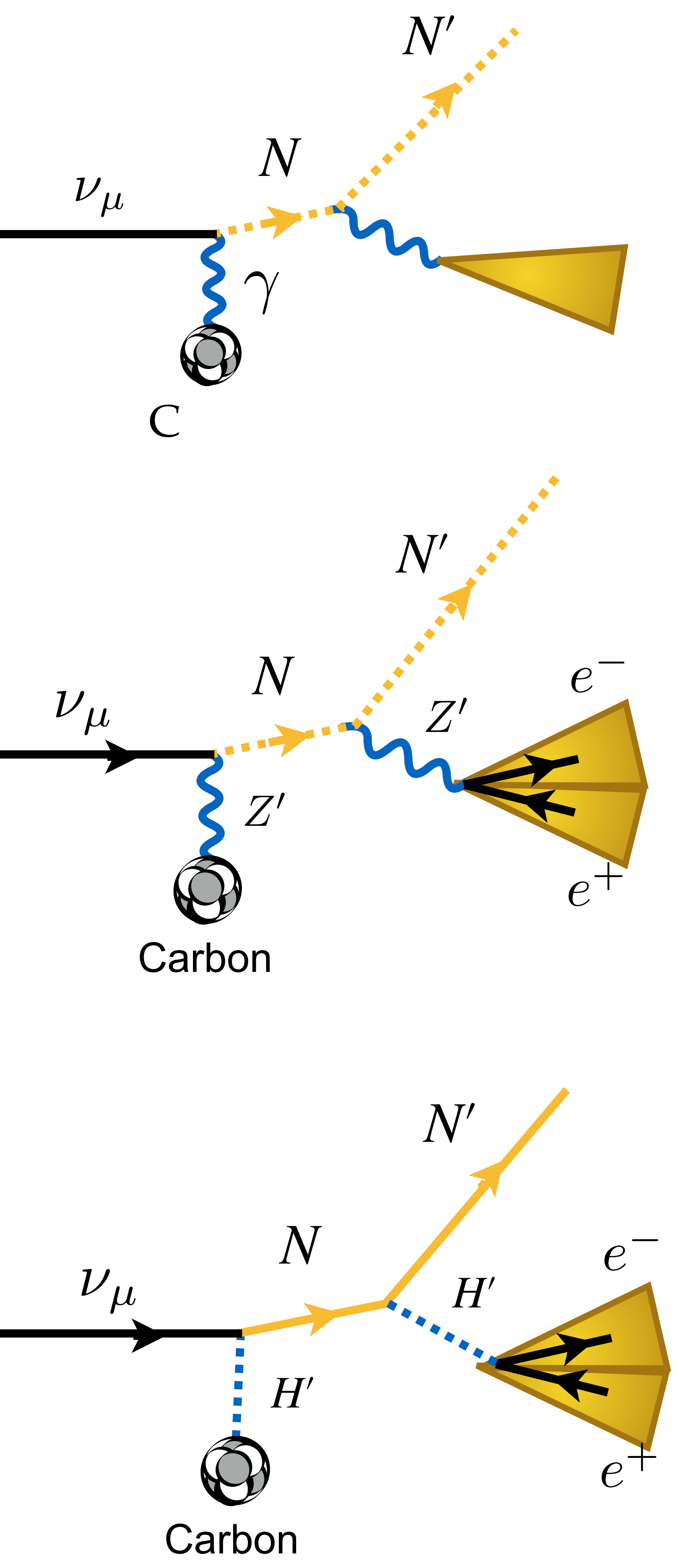
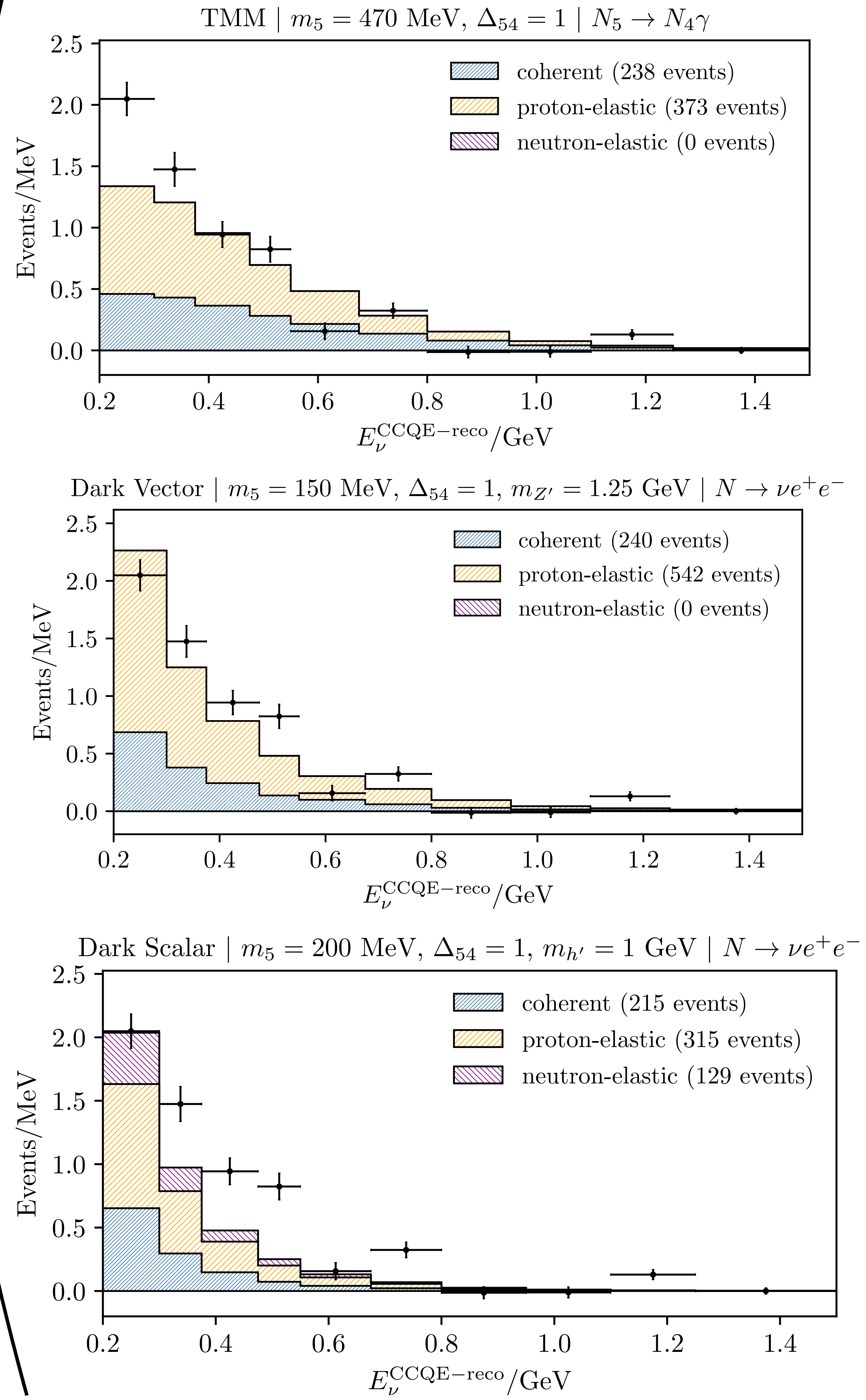
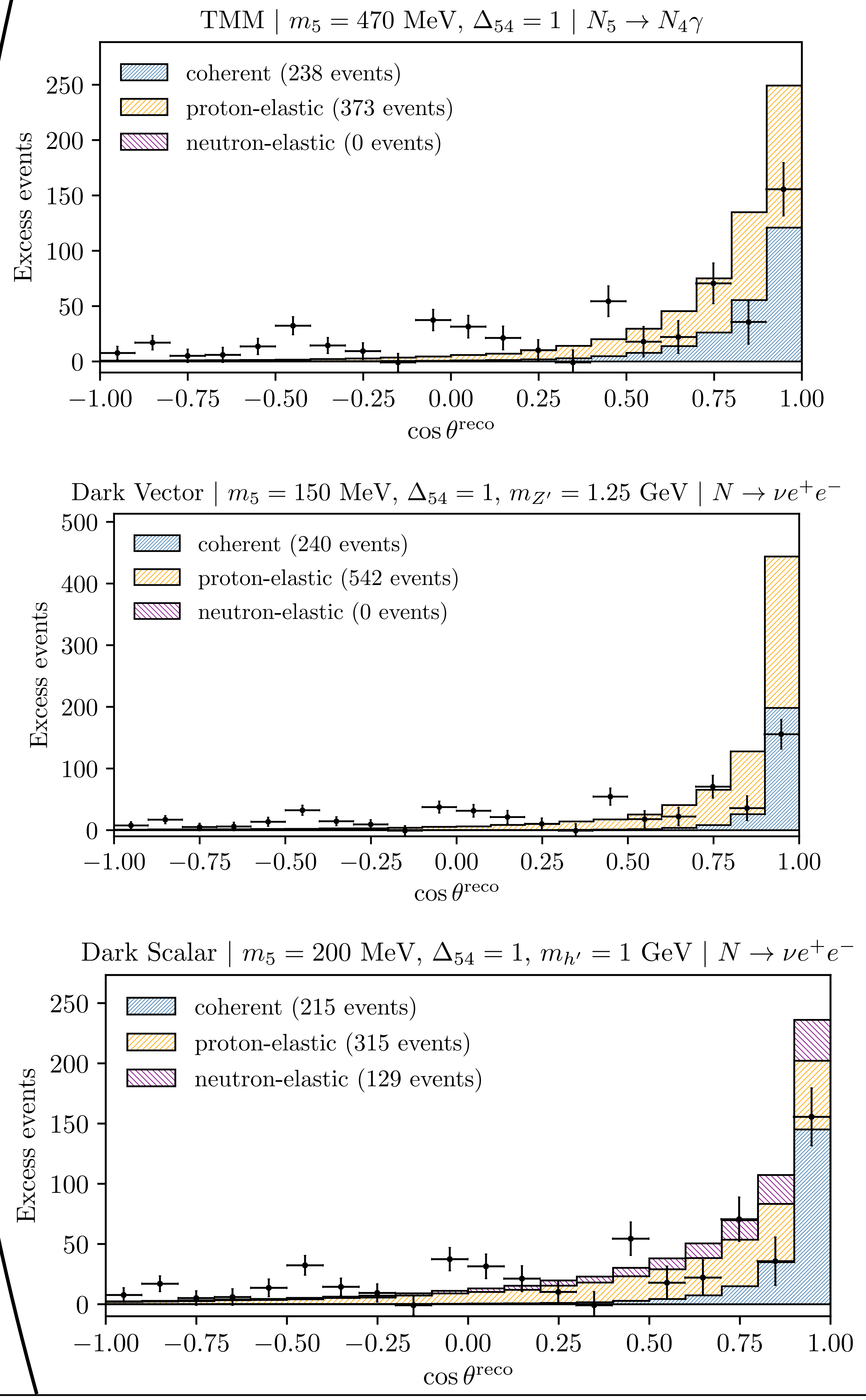
A. M. Abdullahi, J. Hoefken Zink, M. Hostert, D. Massaro, S. Pascoli arXiv:2308.02543



$E_\nu^{\rm CCQE}$



$\cos\theta$

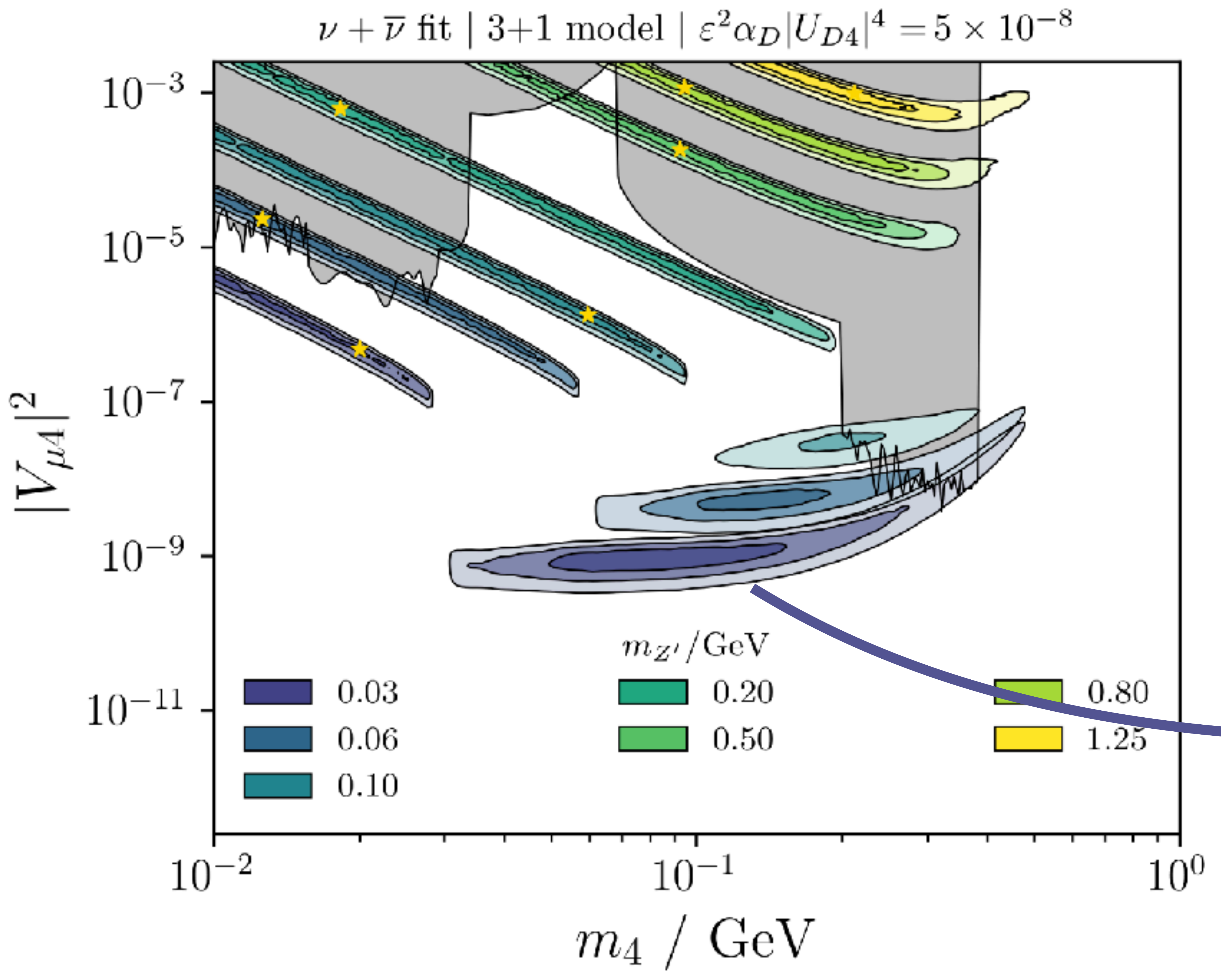


Dark neutrino sectors at MiniBooNE

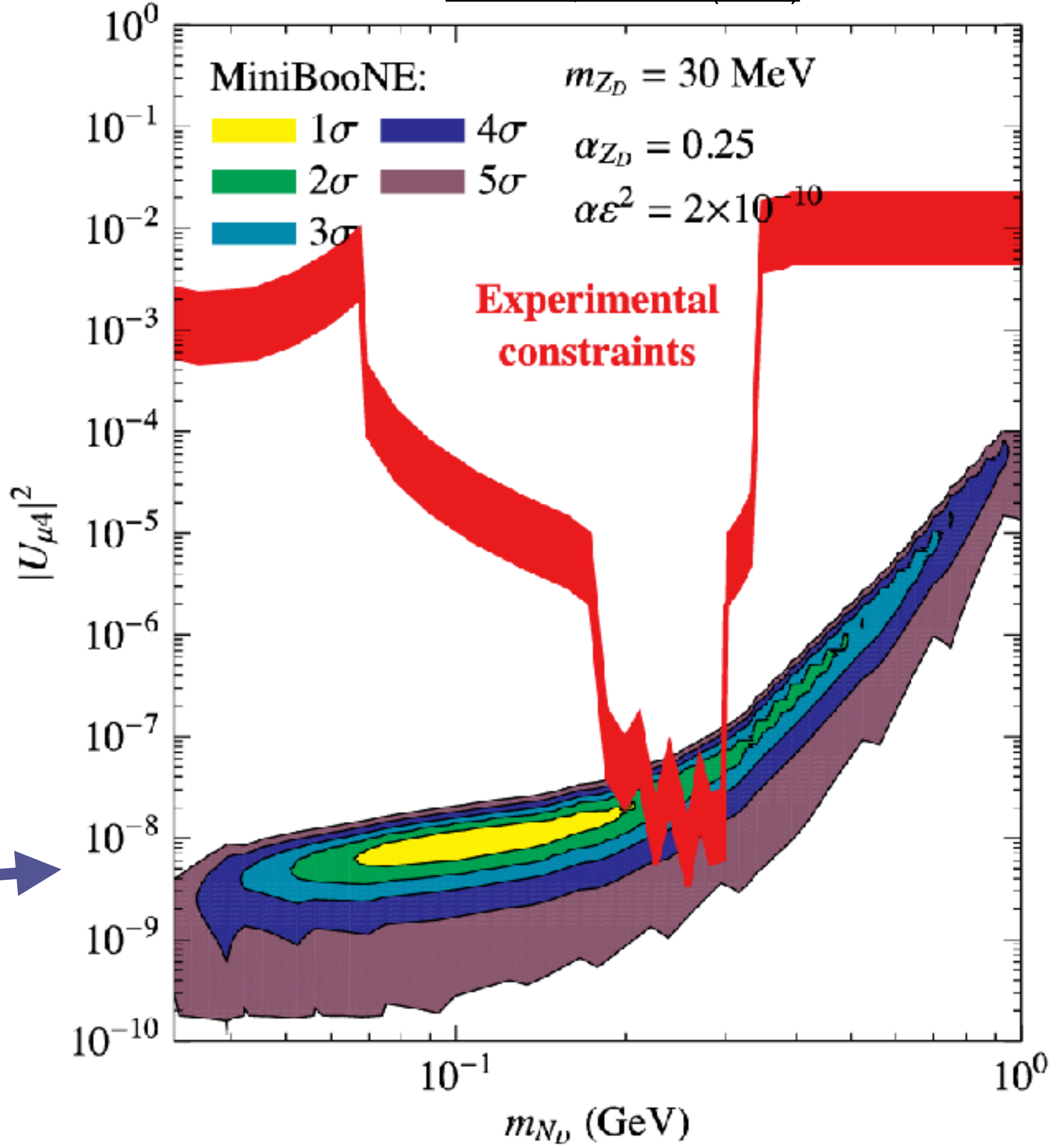
A comprehensive fit to dark photon models

A. M. Abdullahi, J. Hoefken Zink, M. Hostert, D. Massaro, S. Pascoli

arXiv:2308.02543



E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Z. Funchal, PRL 121, 241801 (2018)



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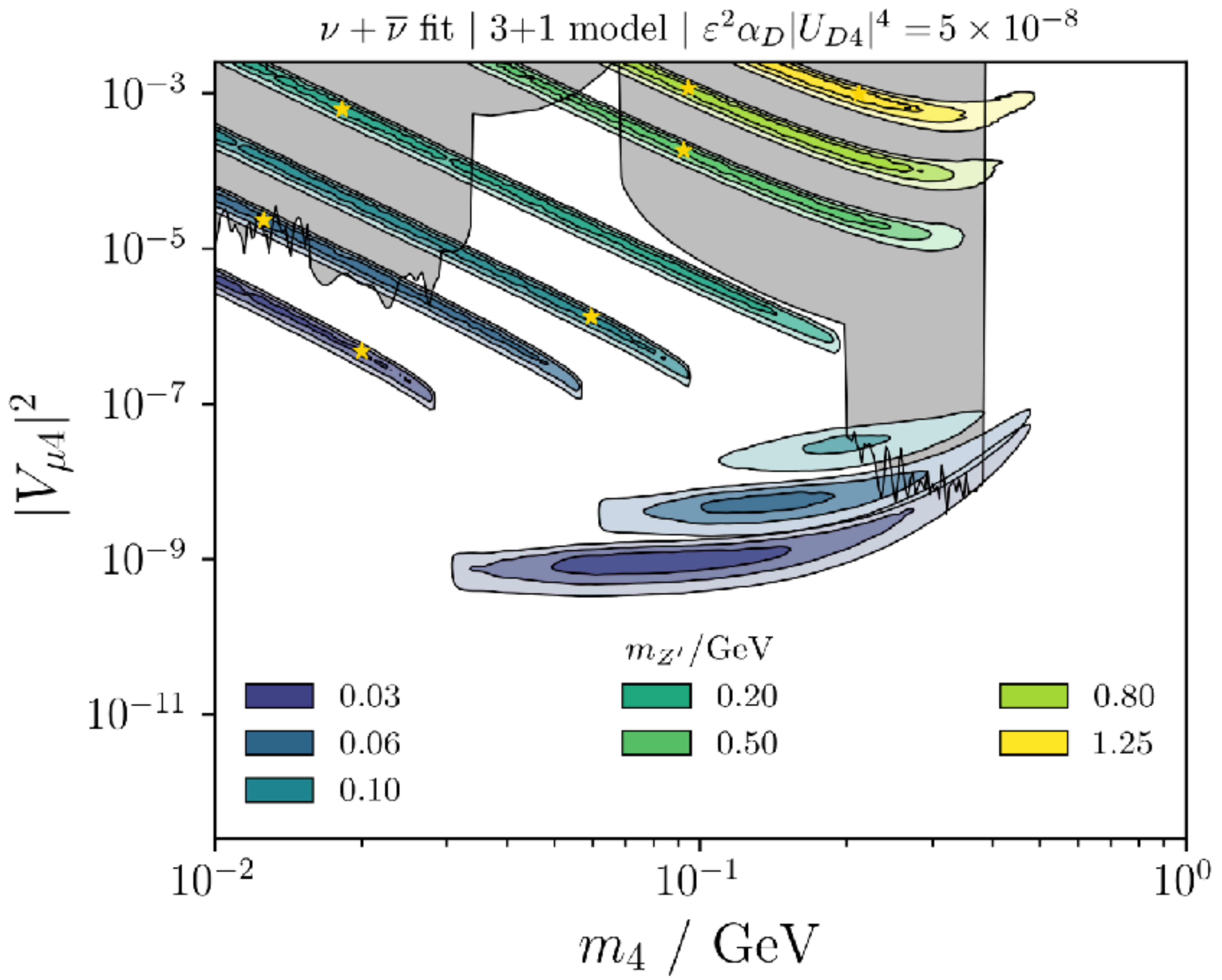
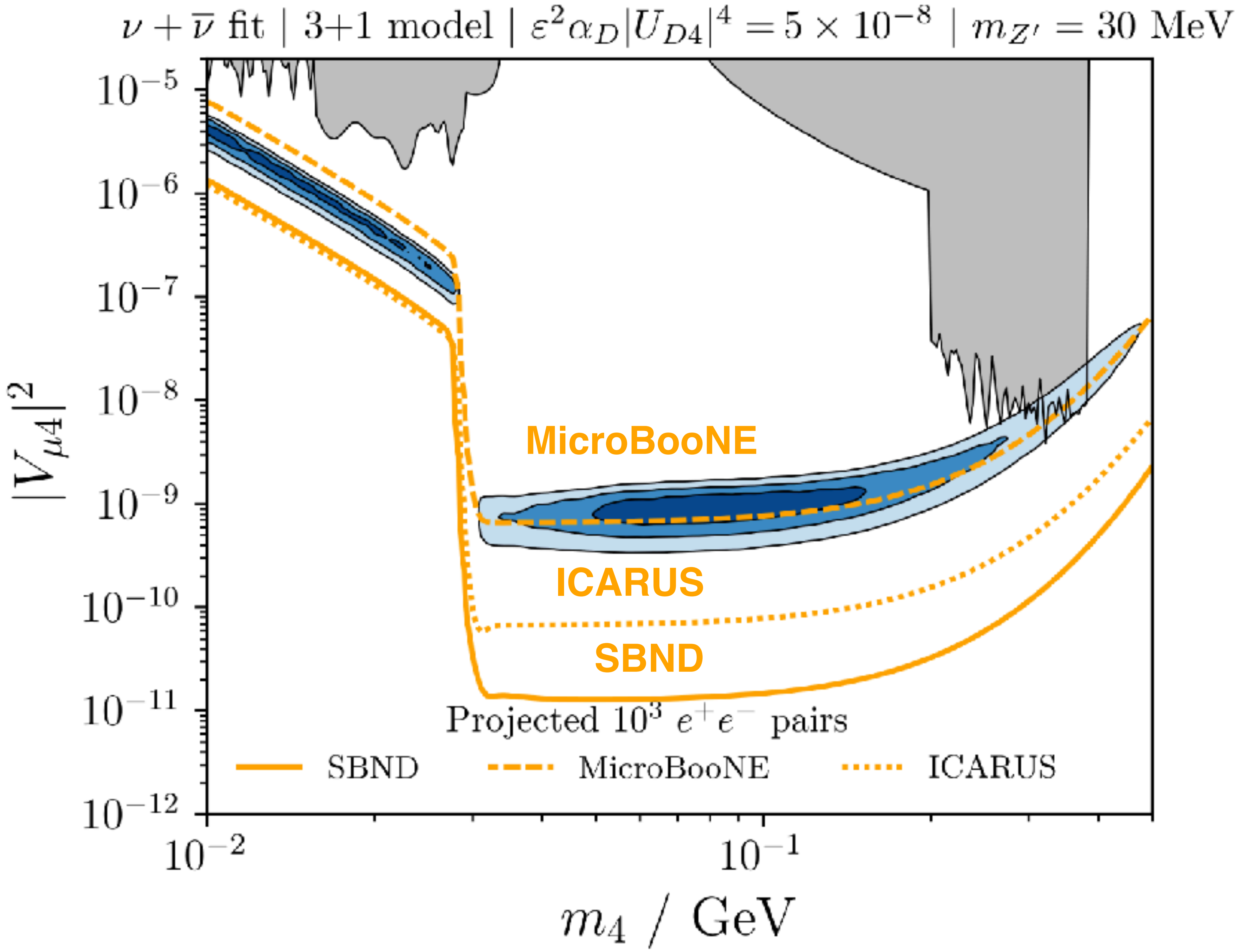
arXiv:2308.02543

Not a sensitivity plot! Just benchmarking the rate.



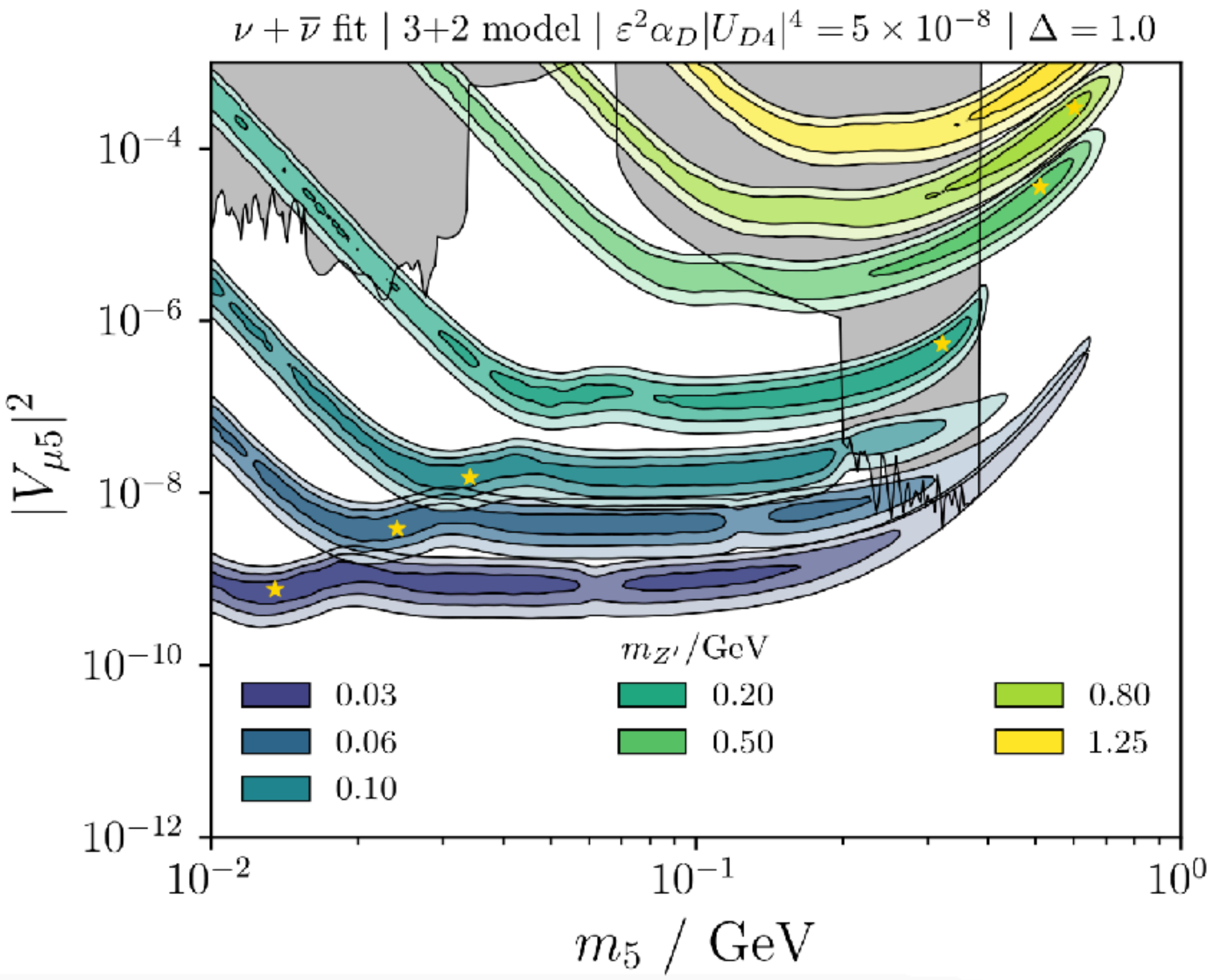


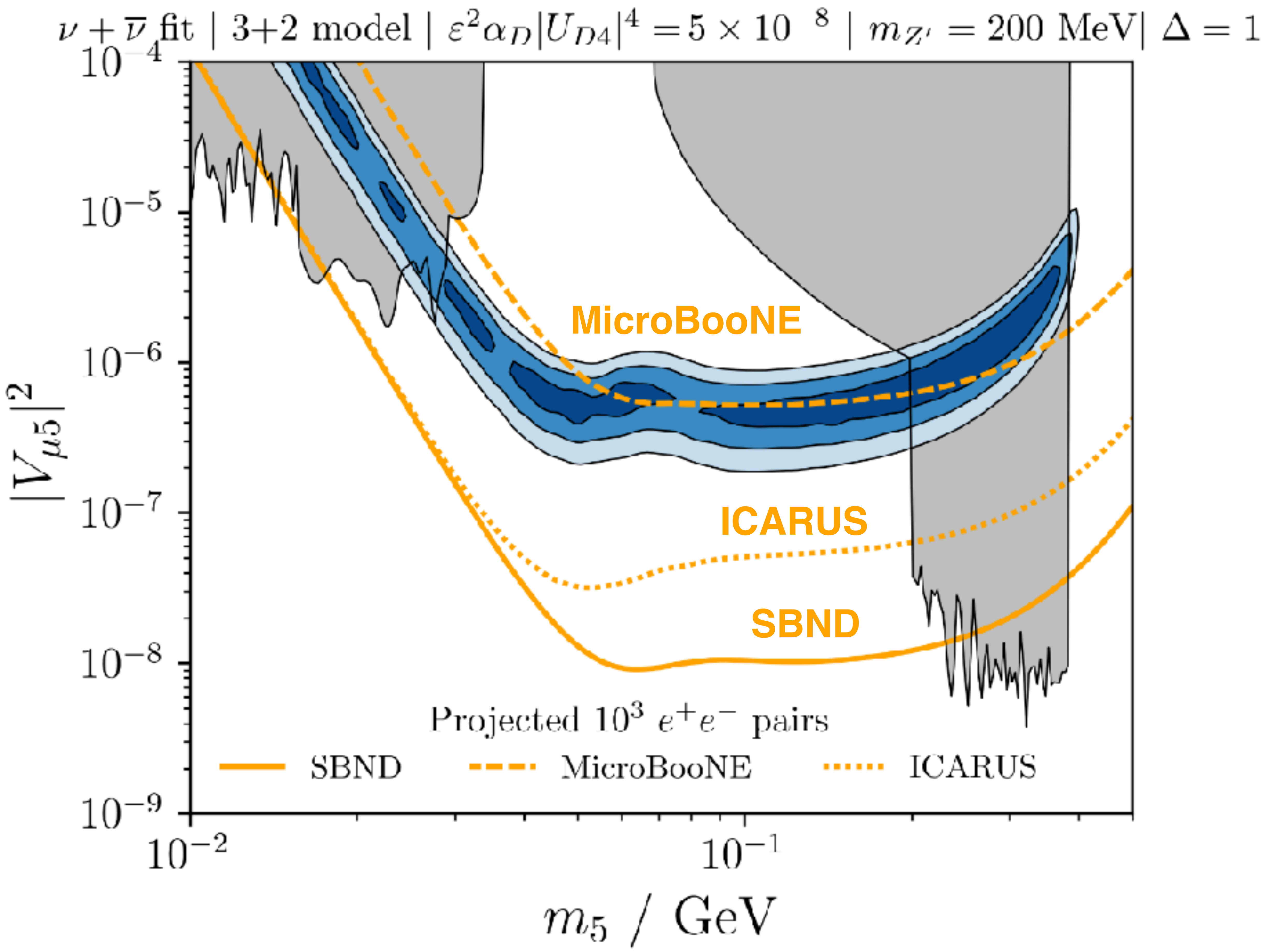
Dark neutrino sectors at MiniBooNE

A comprehensive fit to dark photon models

A. M. Abdullahi, J. Hoefken Zink, M. Hostert, D. Massaro, S. Pascoli
arXiv:2308.02543

Not a sensitivity plot! Just benchmarking the rate.





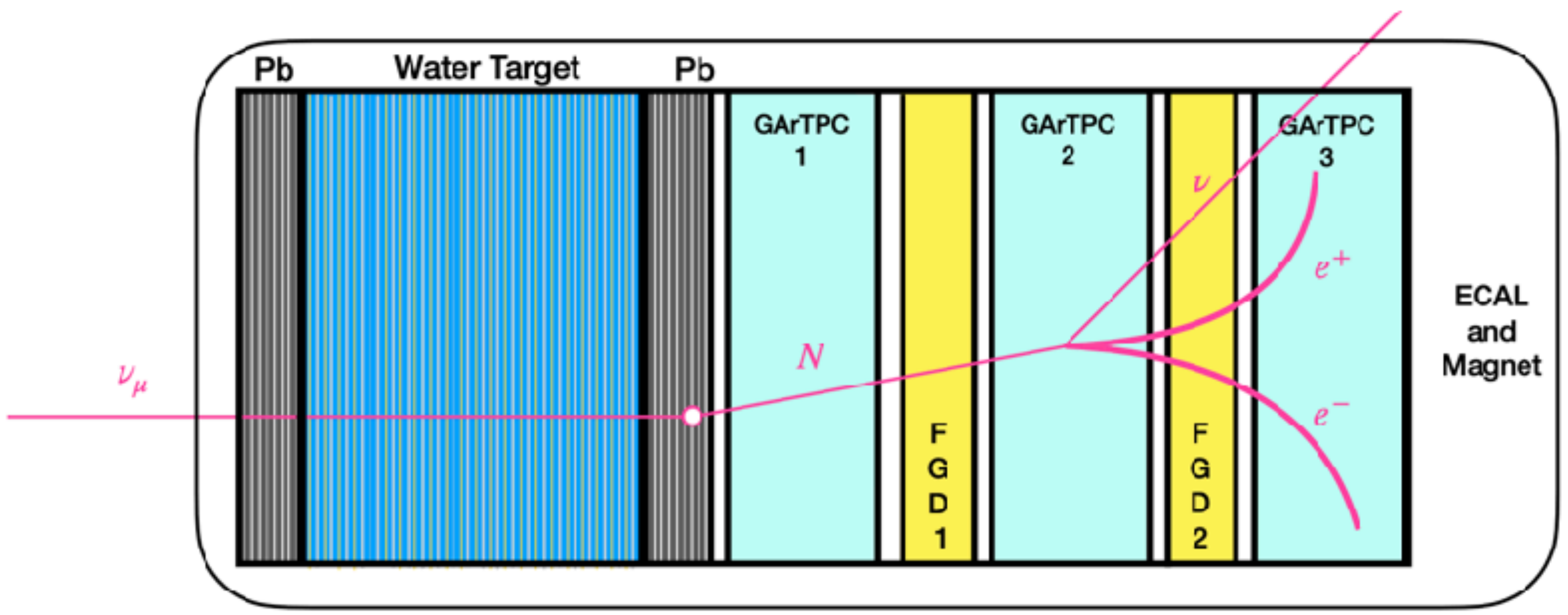
Dark neutrino sectors at the T2K near detector

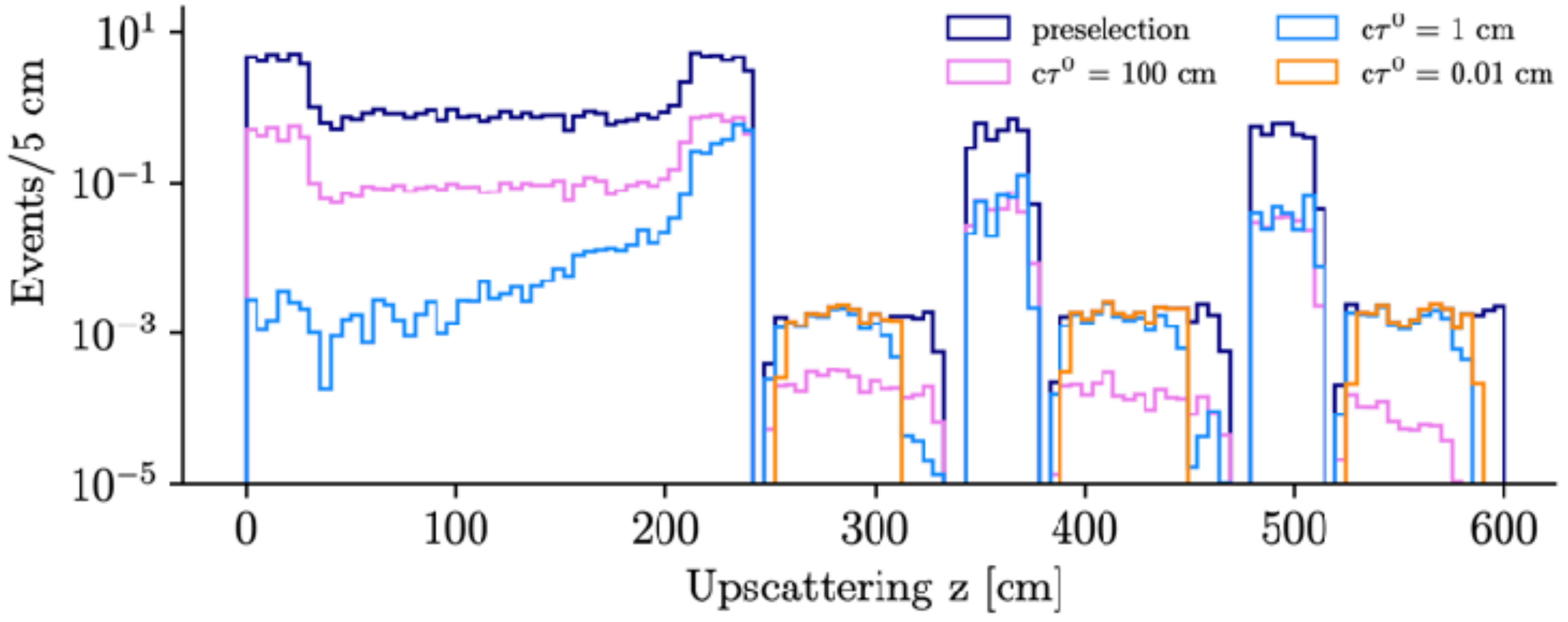
Multi-purpose detector — advantageous for this signature

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)
See also, Vedran Brdar et al, 10.1103/PhysRevD.103.075008

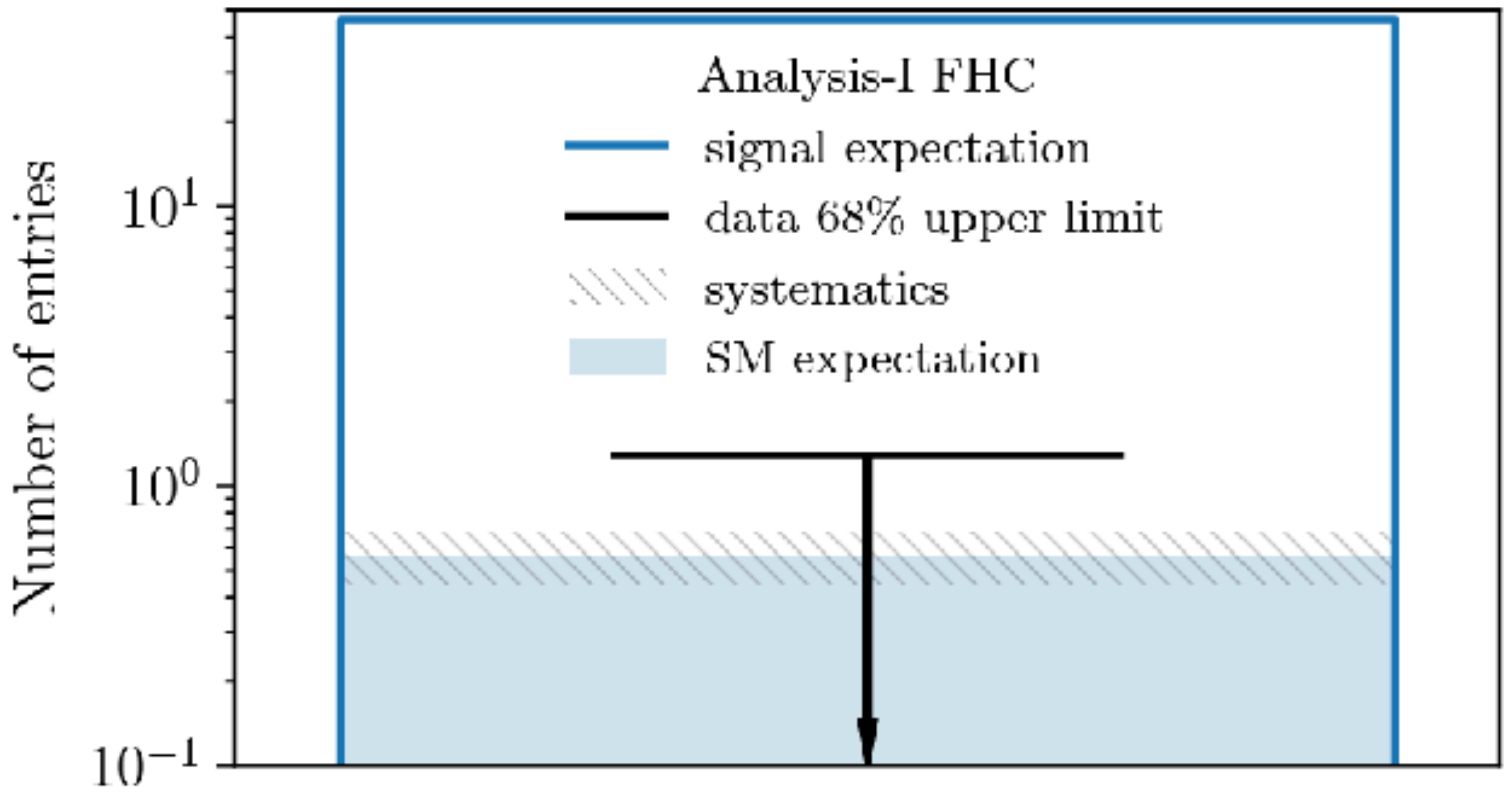
C. Arguelles, MH, N. Foppiani, 10.1103/PhysRevD.107.035027

ND280

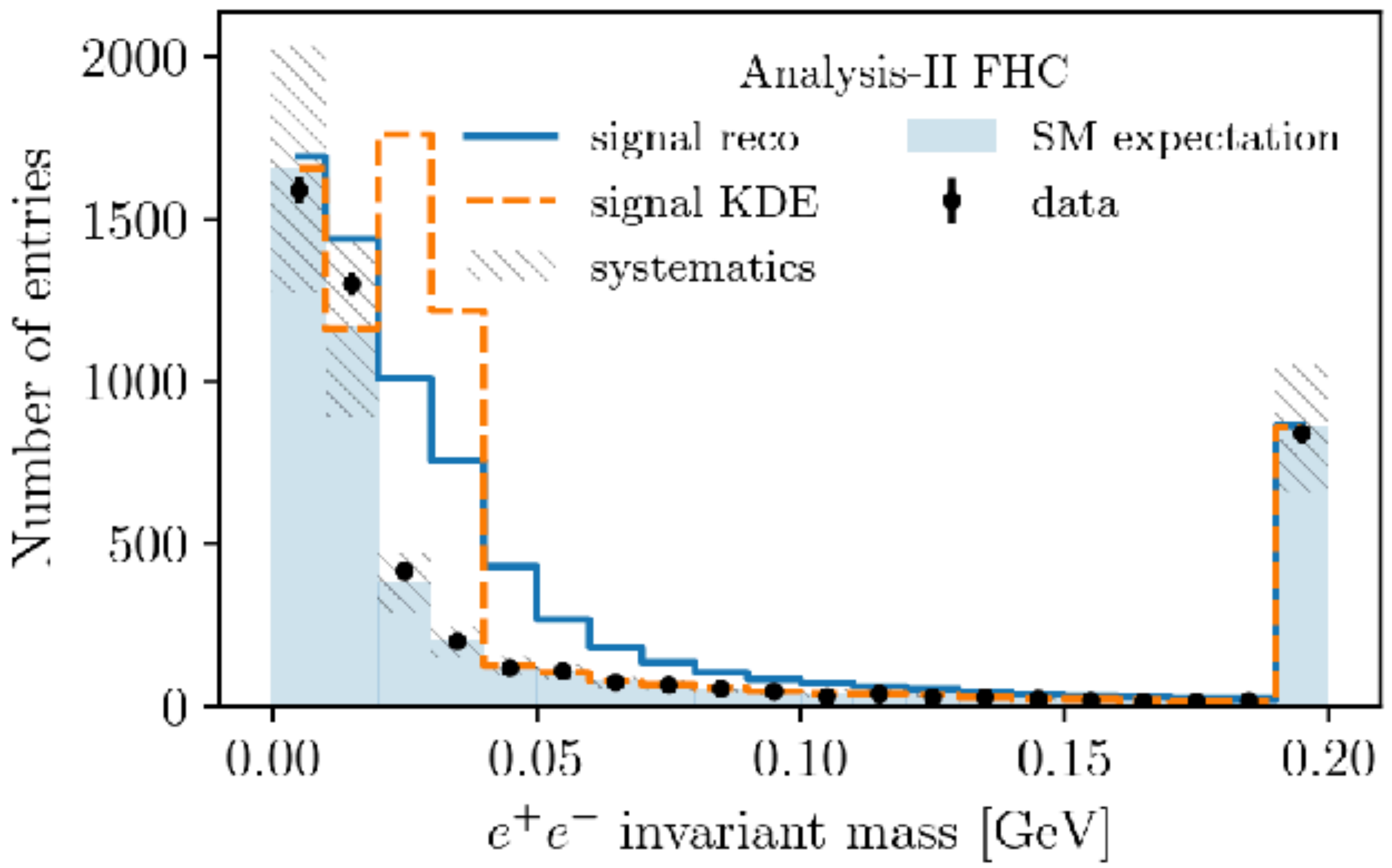




Upstream **lead** plates and magnetized gaseous argon TPCs



Events in GArTPCs
Just event counting,
none observed.



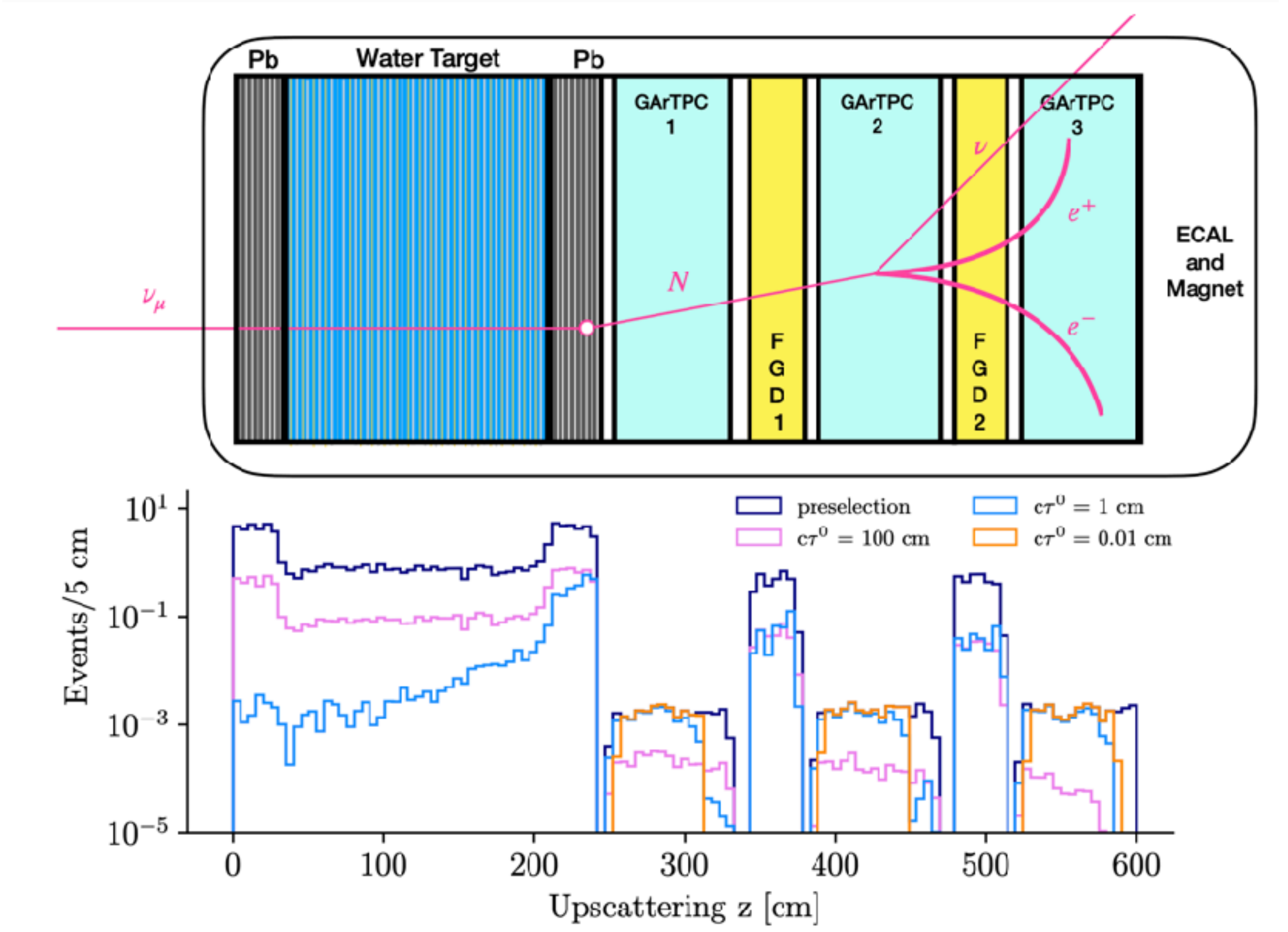
Events in FGDs
(Using Z'
invariant mass)

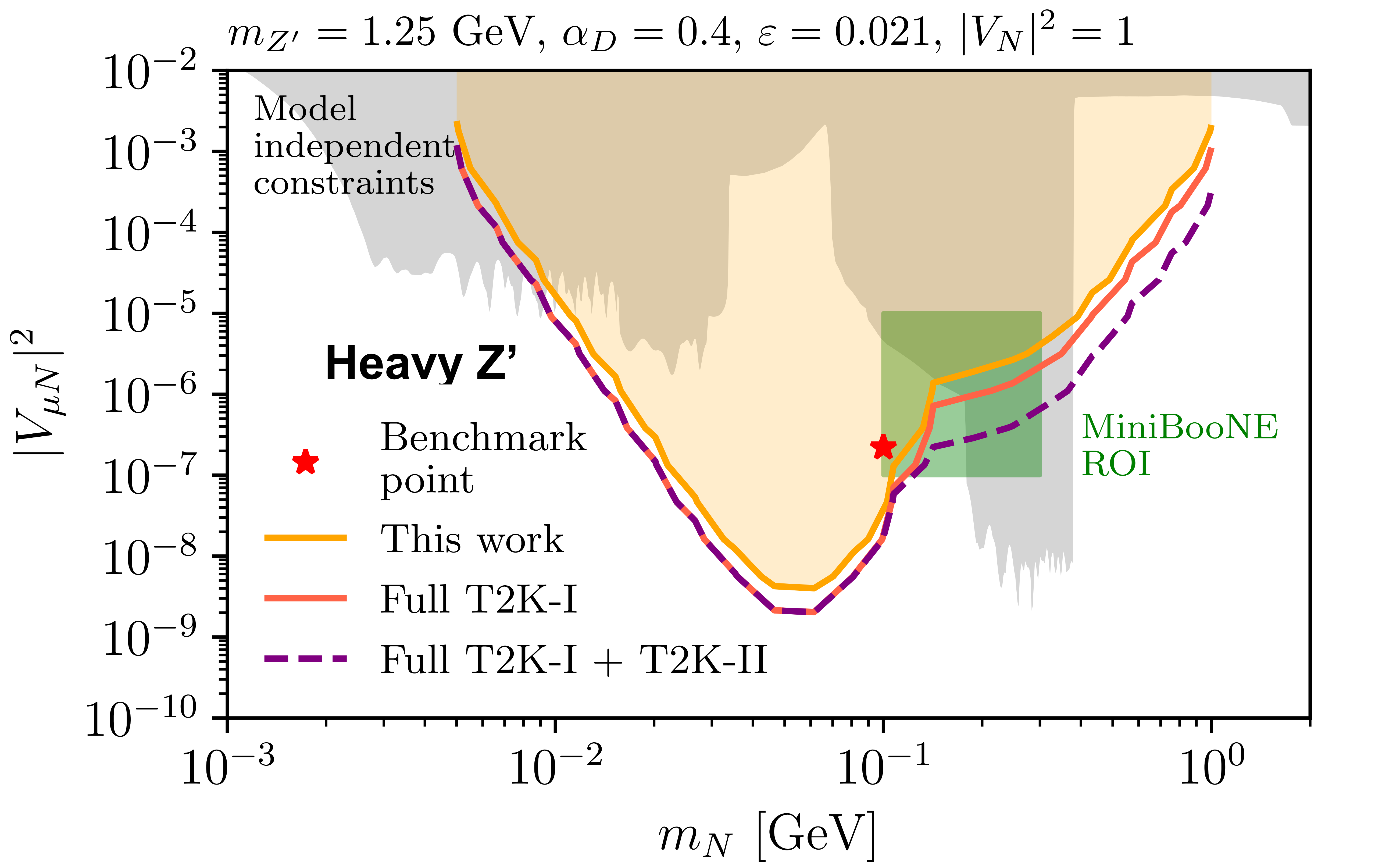
Dark neutrino sectors at the T2K near detector
Multi-purpose detector — advantageous for this signature

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)
See also, Vedran Brdar et al, 10.1103/PhysRevD.103.075008

C. Arguelles, MH, N. Foppiani, 10.1103/PhysRevD.107.035027

ND280

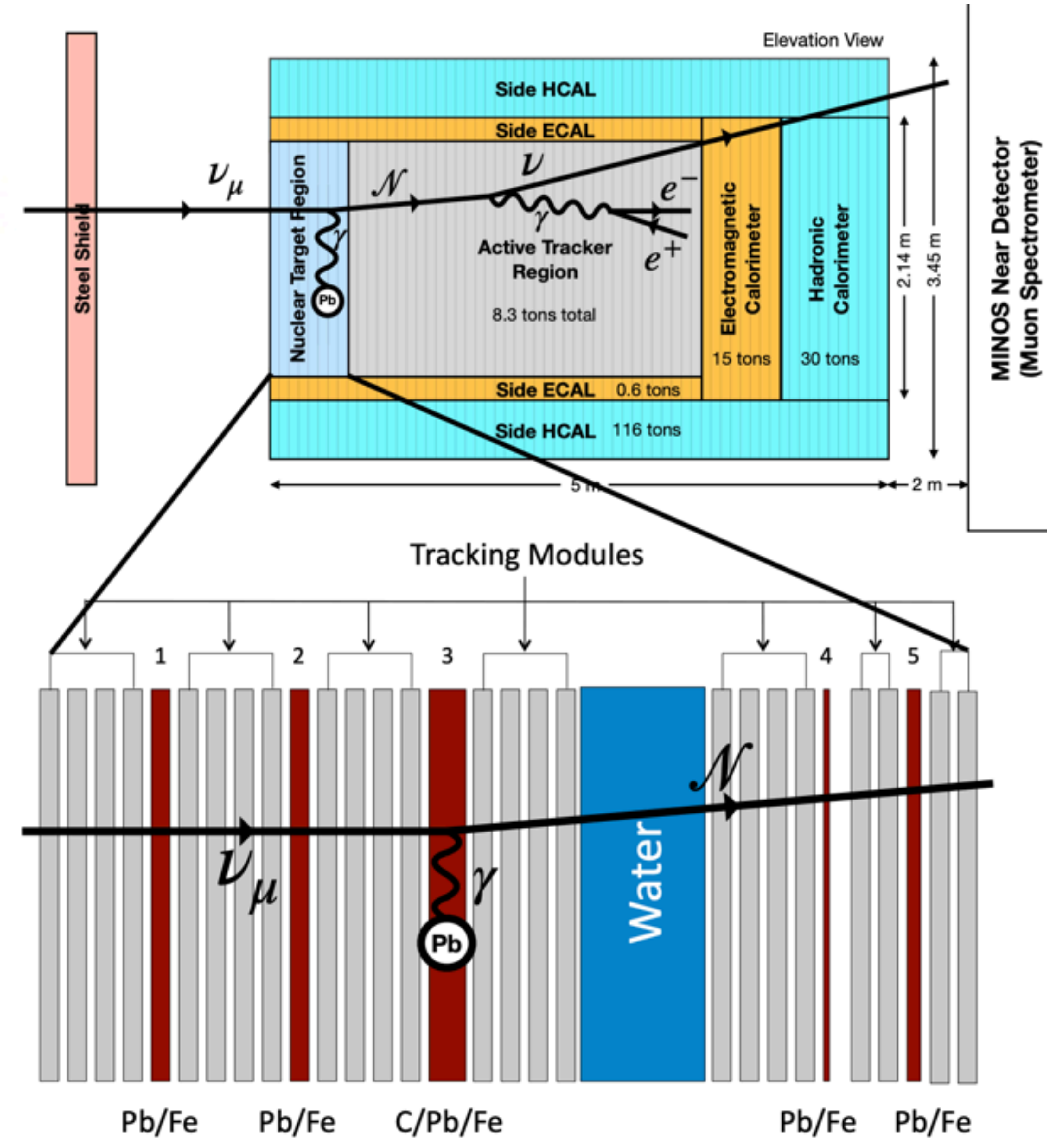




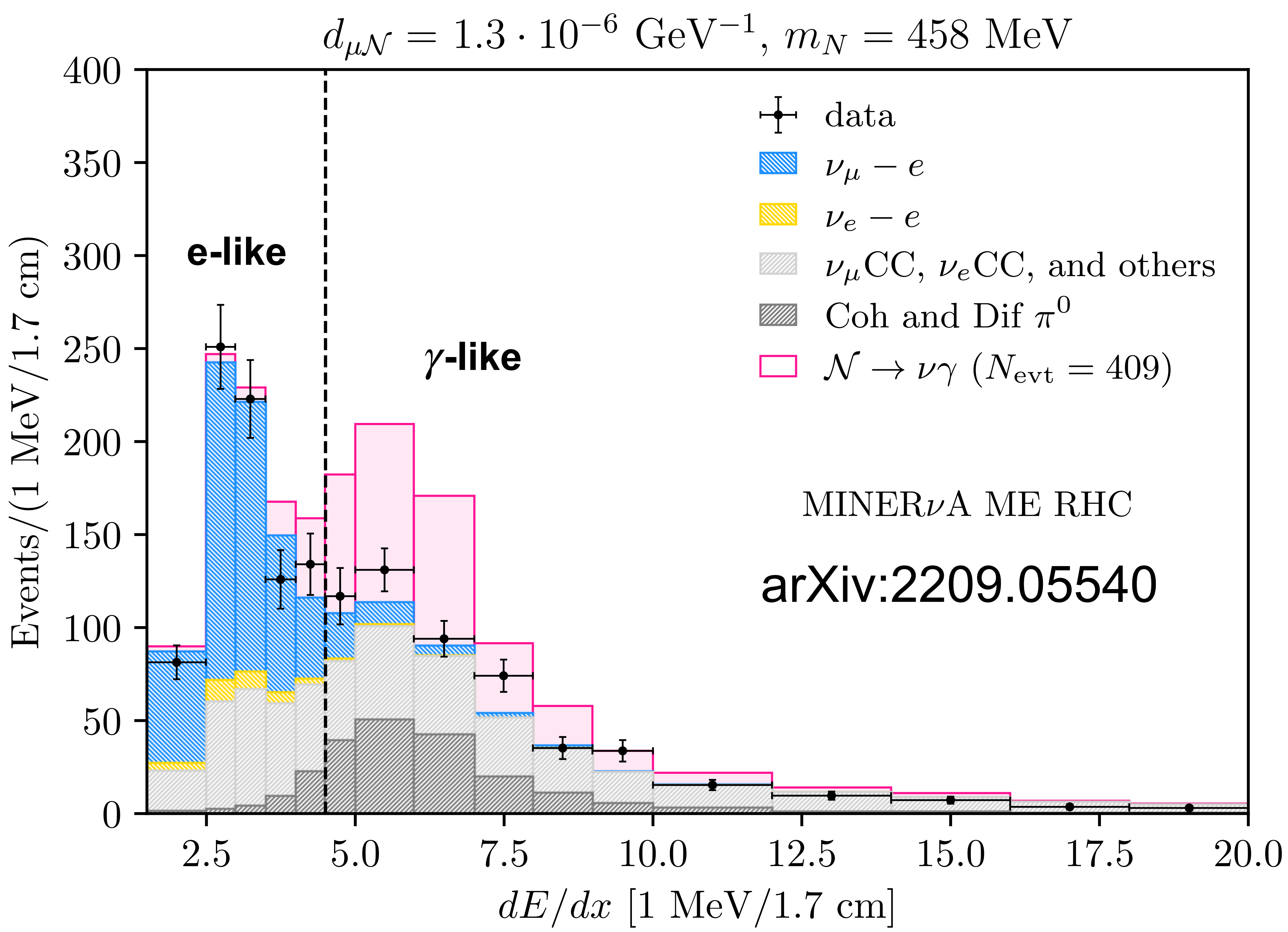
e^+e^- models with $c\tau_N^0/m_N \gtrsim 3\,\mathrm{cm/GeV}$ are in tension with T2K data.

Dark neutrino sectors at MINERvA
The dipole portal to heavy neutral leptons

N. Kamp, **MH**, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida Phys.Rev.D 107 (2023) 5, 055009



Antineutrino-electron scattering

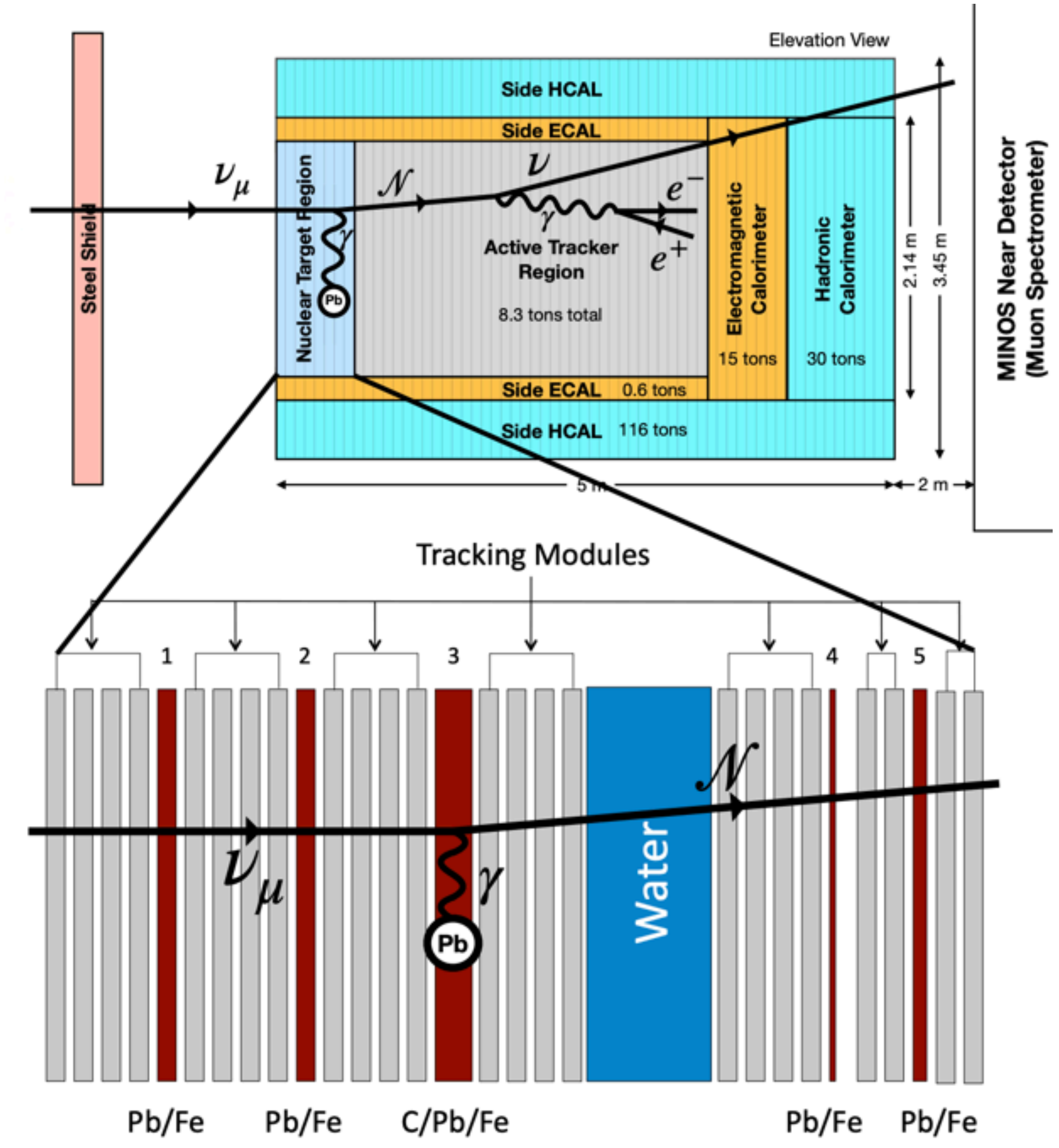


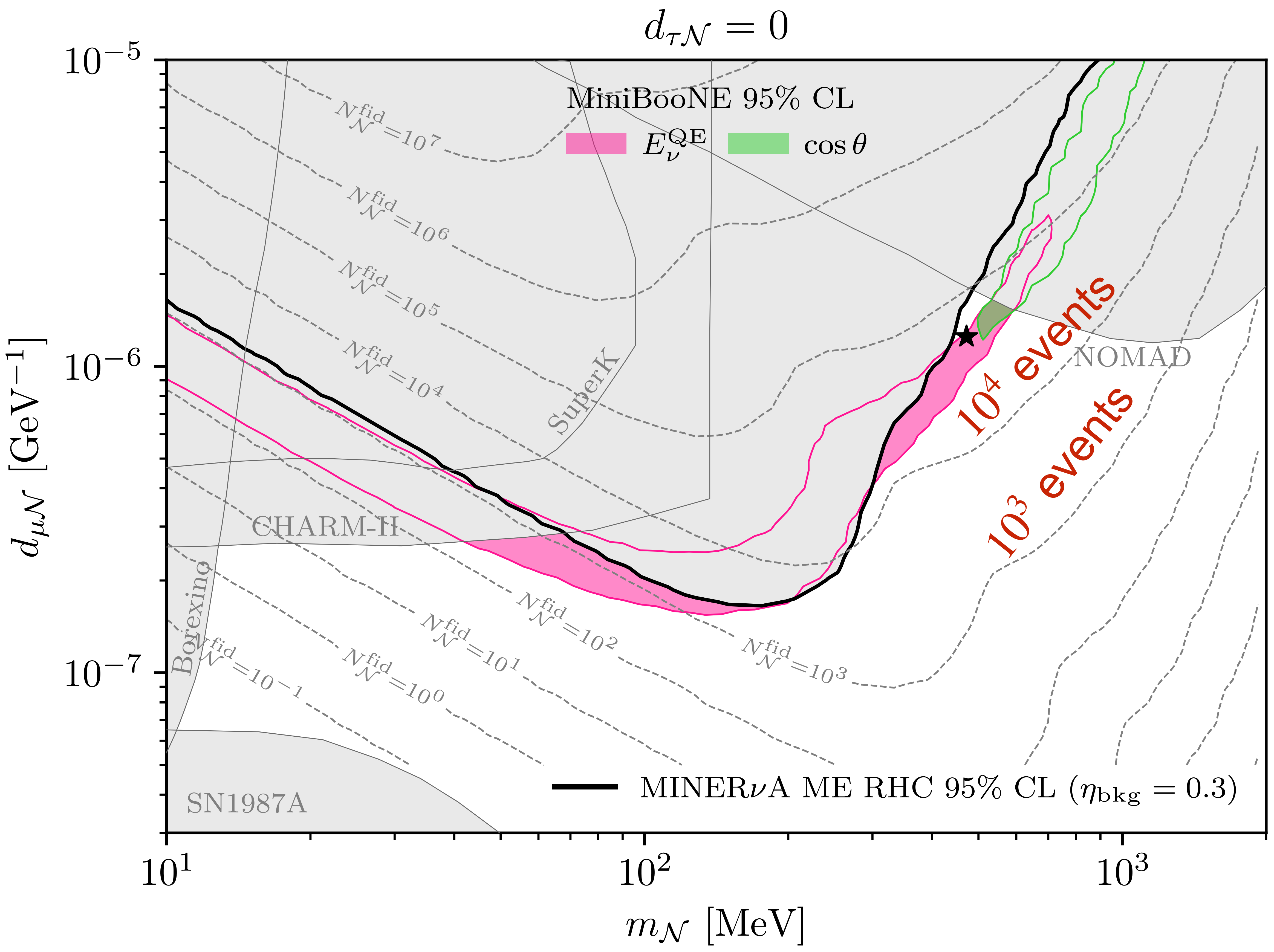
Post-tuning of backgrounds.
Assign 30% and 100% uncertainty to cover it.

Dark neutrino sectors at MINERvA

The dipole portal to heavy neutral leptons

N. Kamp, **MH**, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida Phys.Rev.D 107 (2023) 5, 055009

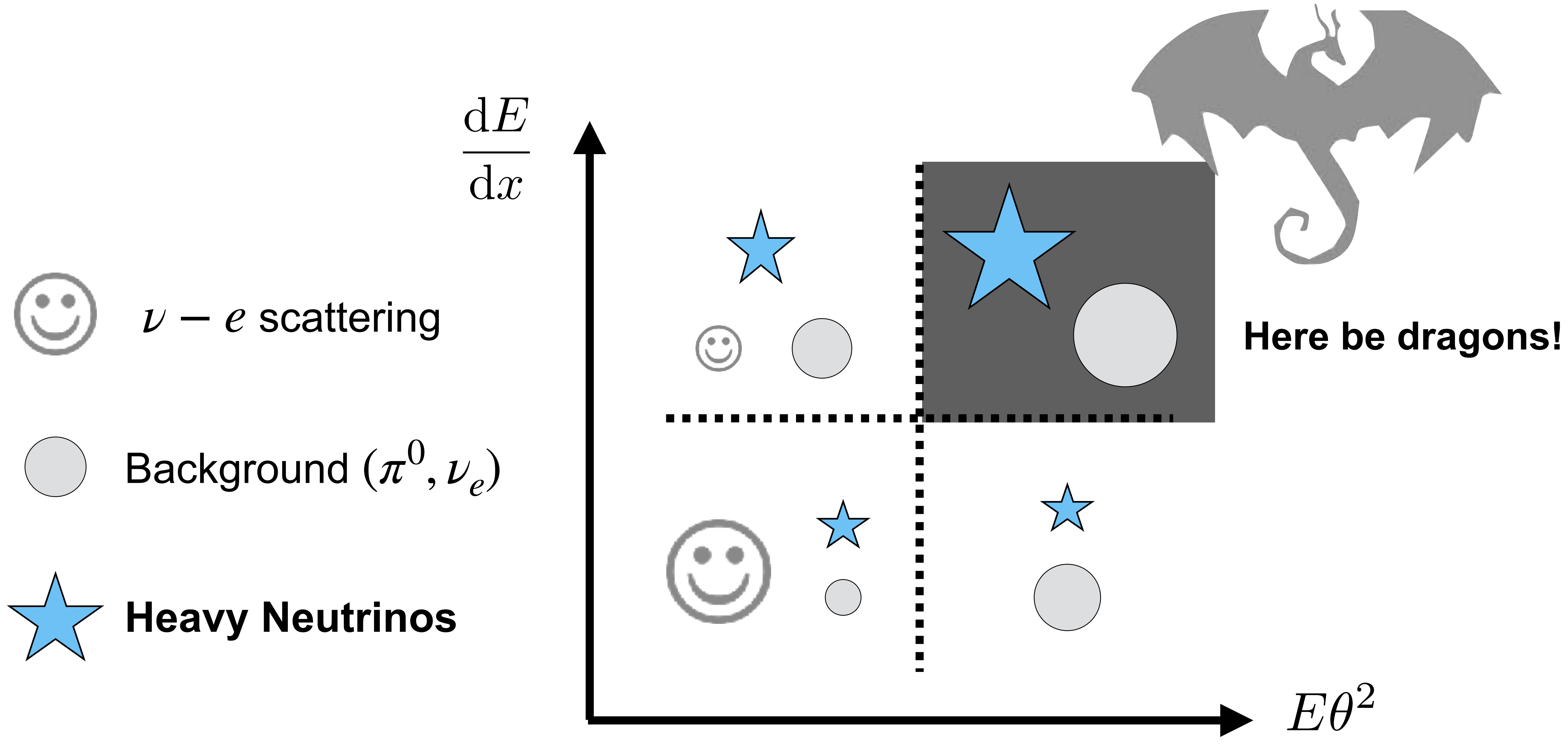




There are a huge number of N that decay inside the fiducial volume of the analysis.

Dark neutrino sectors at MINERvA
Limits, dragons, and opportunity

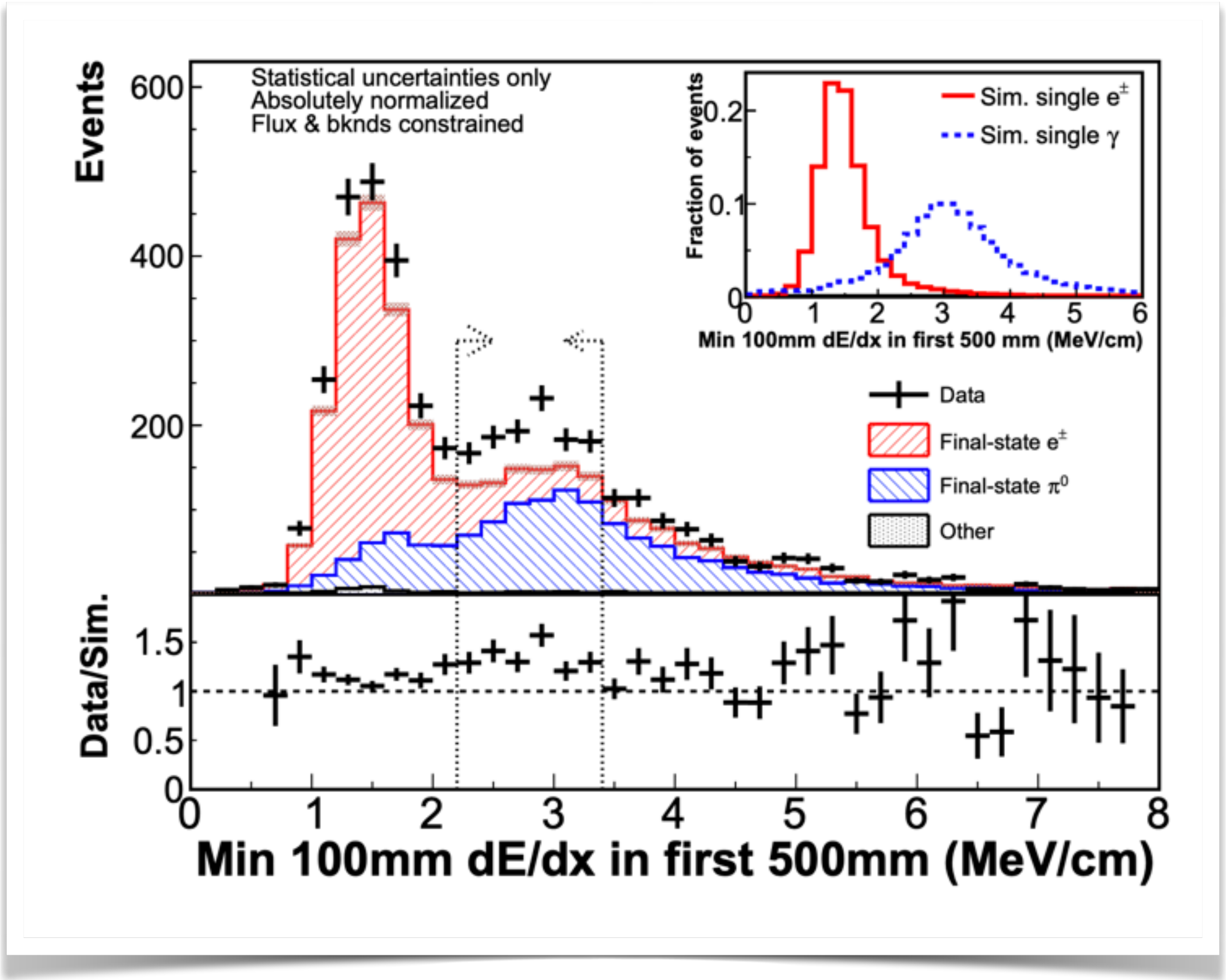
N. Kamp, **MH**, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida Phys.Rev.D 107 (2023) 5, 055009



C. Arguelles, MH, Y. Tsai, PRL123.261801

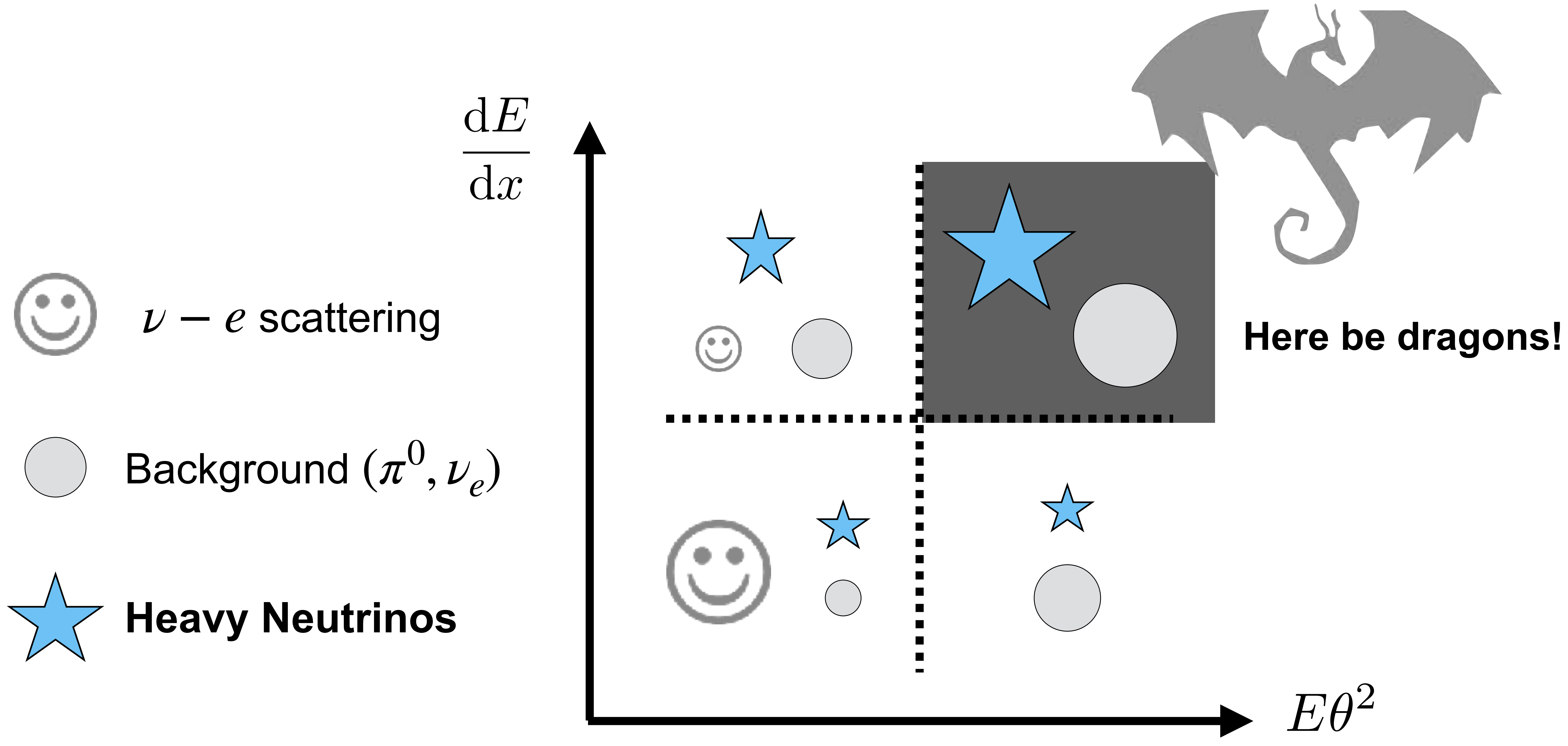
MINERvA coll. PRL117, 111801 (2016) arXiv:1604.01728

* **Excess of events attributed to diffractive π^0 production ($\nu p^+ \to \nu p^+ \pi^0$)**



Dark neutrino sectors at MINERvA
Limits, dragons, and opportunity

N. Kamp, **MH**, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida Phys.Rev.D 107 (2023) 5, 055009



C. Arguelles, MH, Y. Tsai, PRL123.261801

MINERvA coll., arXiv:2312.16631

Excess of events shows up again low-$|t|$ ν_e study.

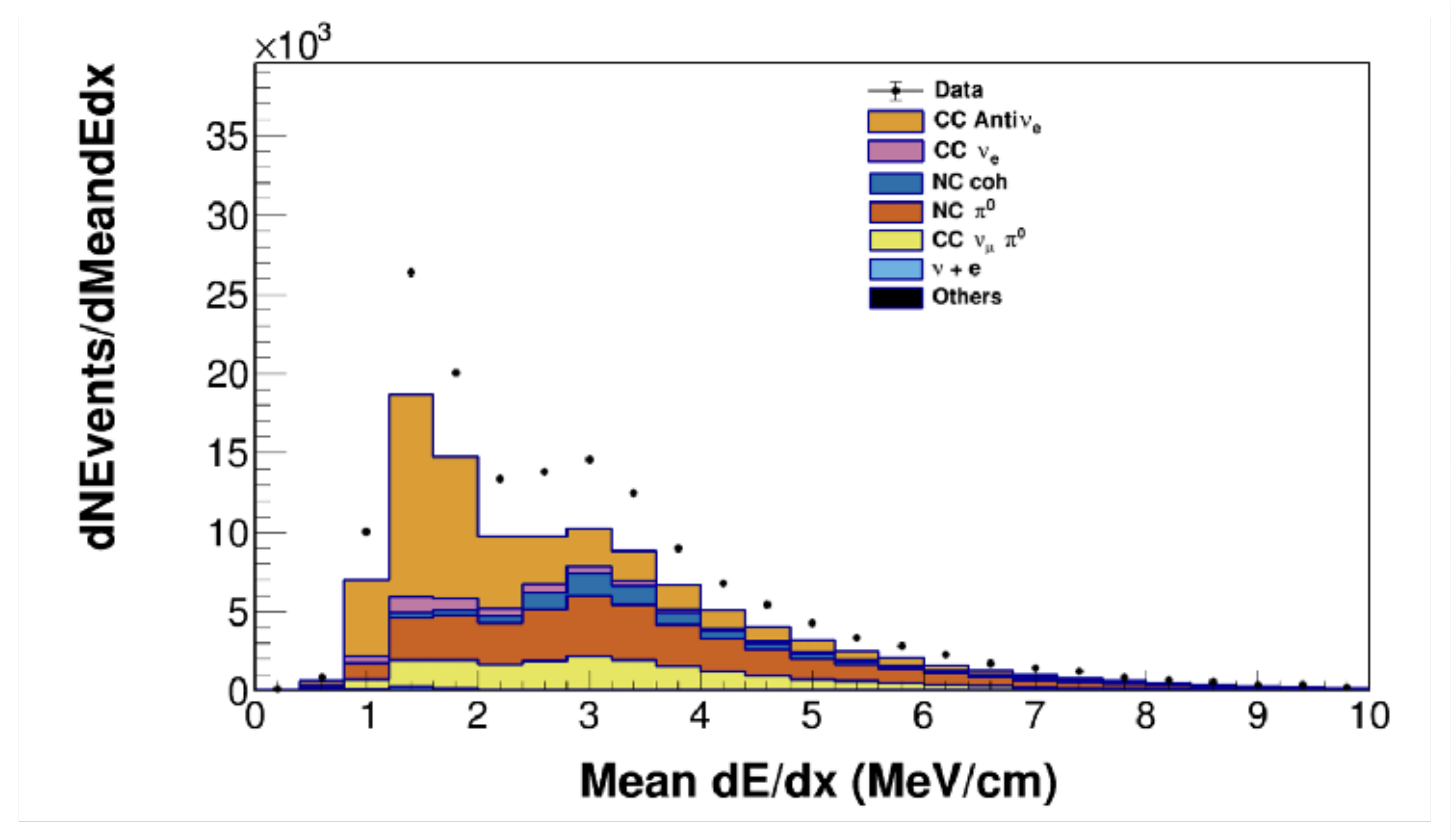


Figure 2 shows the distribution of the mean dE/dx quantity described above for both data and simulation. There is a large excess of data events in the background dominated region with mean $dE/dx > 2.4$ MeV/cm.

This excess is similar to what was reported in MINERvA's LE data[23] and with the conclusion that it may be explained through diffractive pion production. NC

DarkNews Generator

A. Abdullahi, J. Hoefken, **MH**, D. Massaro, S. Pascoli, Comput.Phys.Commun. 297 (2024) 109075

`DarkNews` is a lightweight MC generator for new physics in neutrino-nucleus scattering.

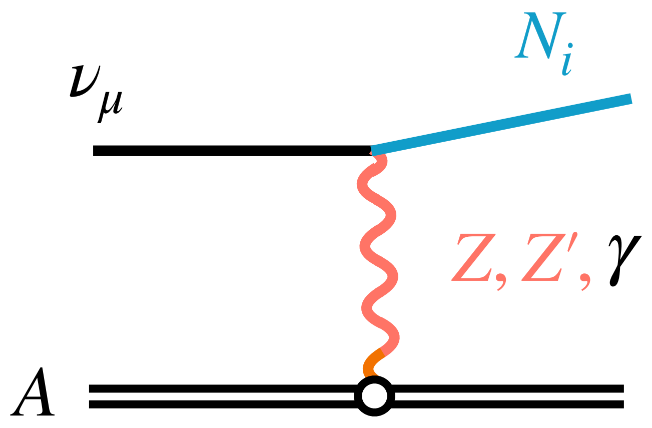
To bridge theory and experiment, we require simulation tools.

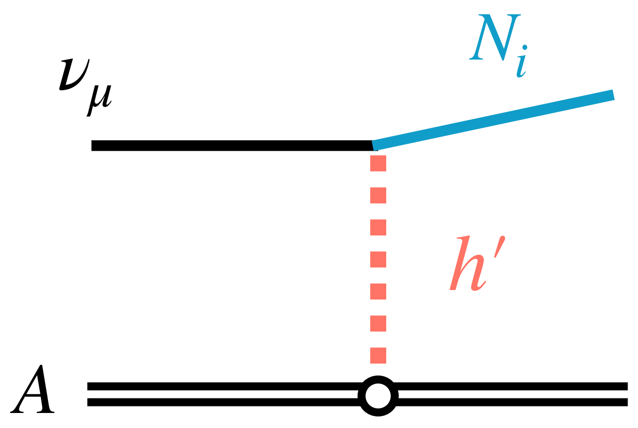
pip install DarkNews

github.com/mhostert/DarkNews-generator

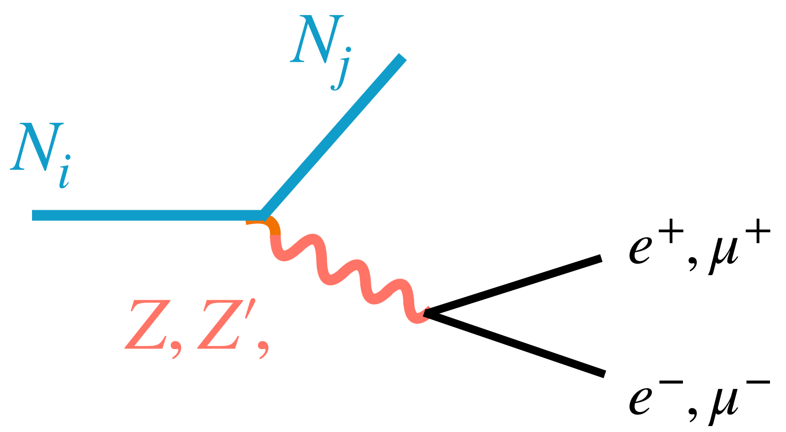
Modeling several processes for GeV-scale accelerator experiments:

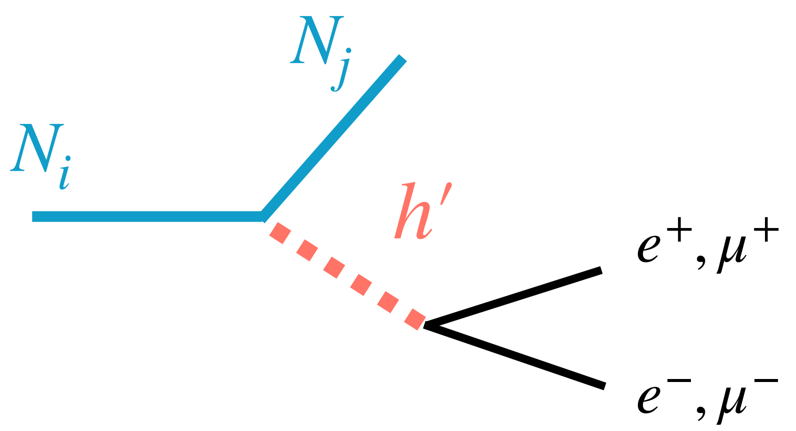
Particle production:
$\nu A \to N A$
(Coherent & QE peak)

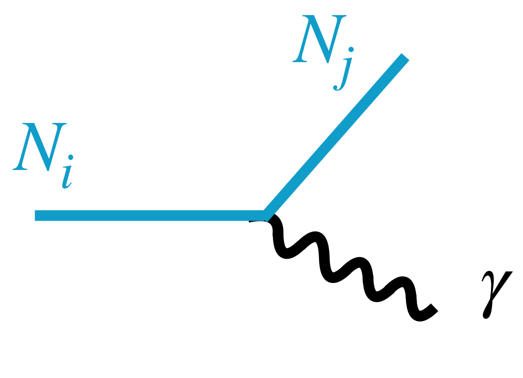




Particle decay:







SIREN

Sampling Injected Rare Events in ExperimeNts

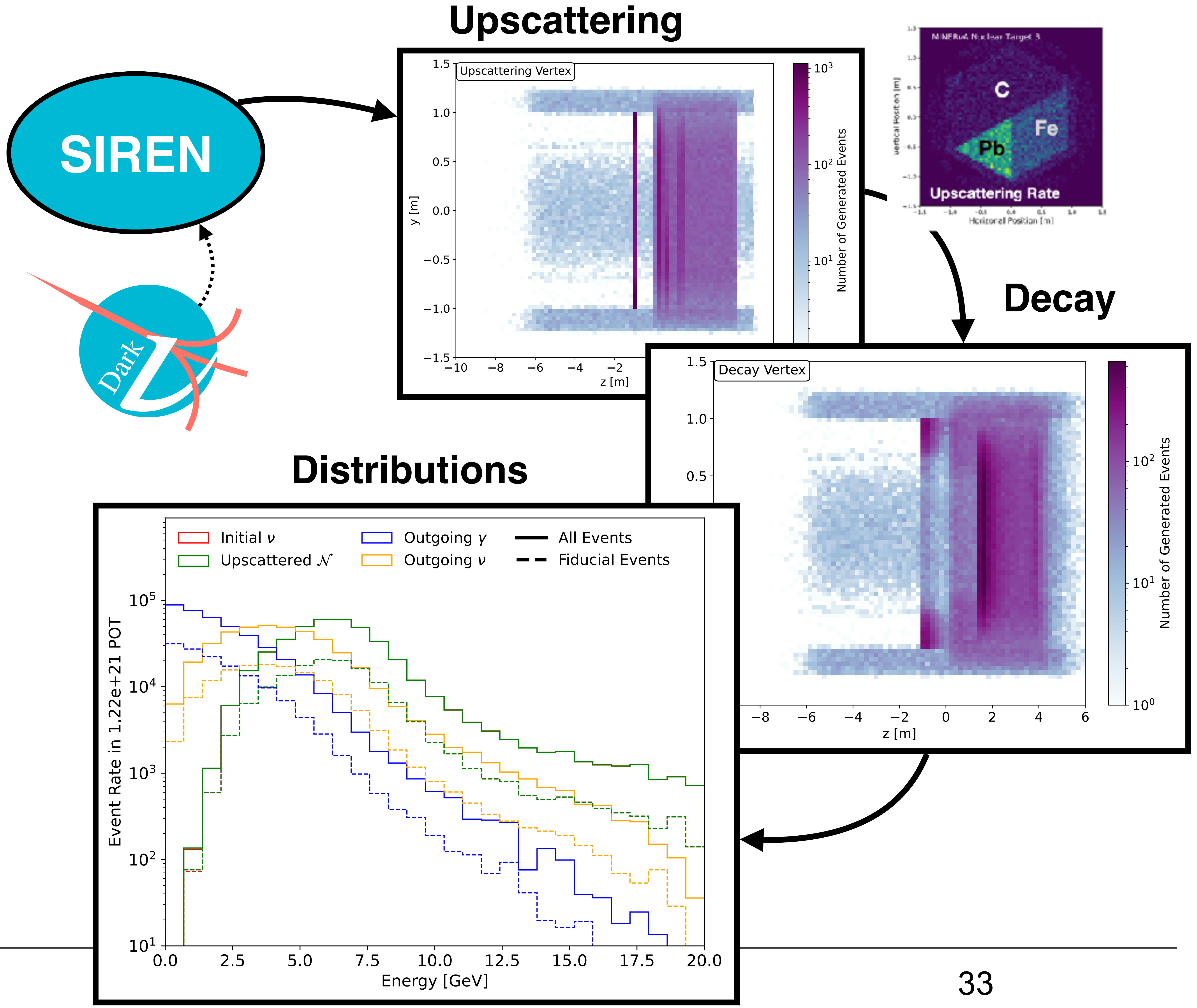
A. Schneider, N. Kamp, A. Wen, *in progress*

Reimagined ***LeptonInjector*** for BSM studies.

Efficient sampling of interactions and decay locations given a detector geometry.

Already used for MINERvA, CCM, and MiniBooNE studies.

Now integrated with DarkNews, so has access to cross section and decay rates in dark sector models.



Sterile neutrinos beyond oscillations at SBL

1) Decays to electromagnetic final states γ and $e^{+/-}$:

a) beam production

b) neutrino upscattering

2) Decays to neutrinos: $\nu_\mu \to \nu_e$ conversion from decay

3) Sterile-induced matter potential: resonant $\nu_\mu \to \nu_e$ conversion

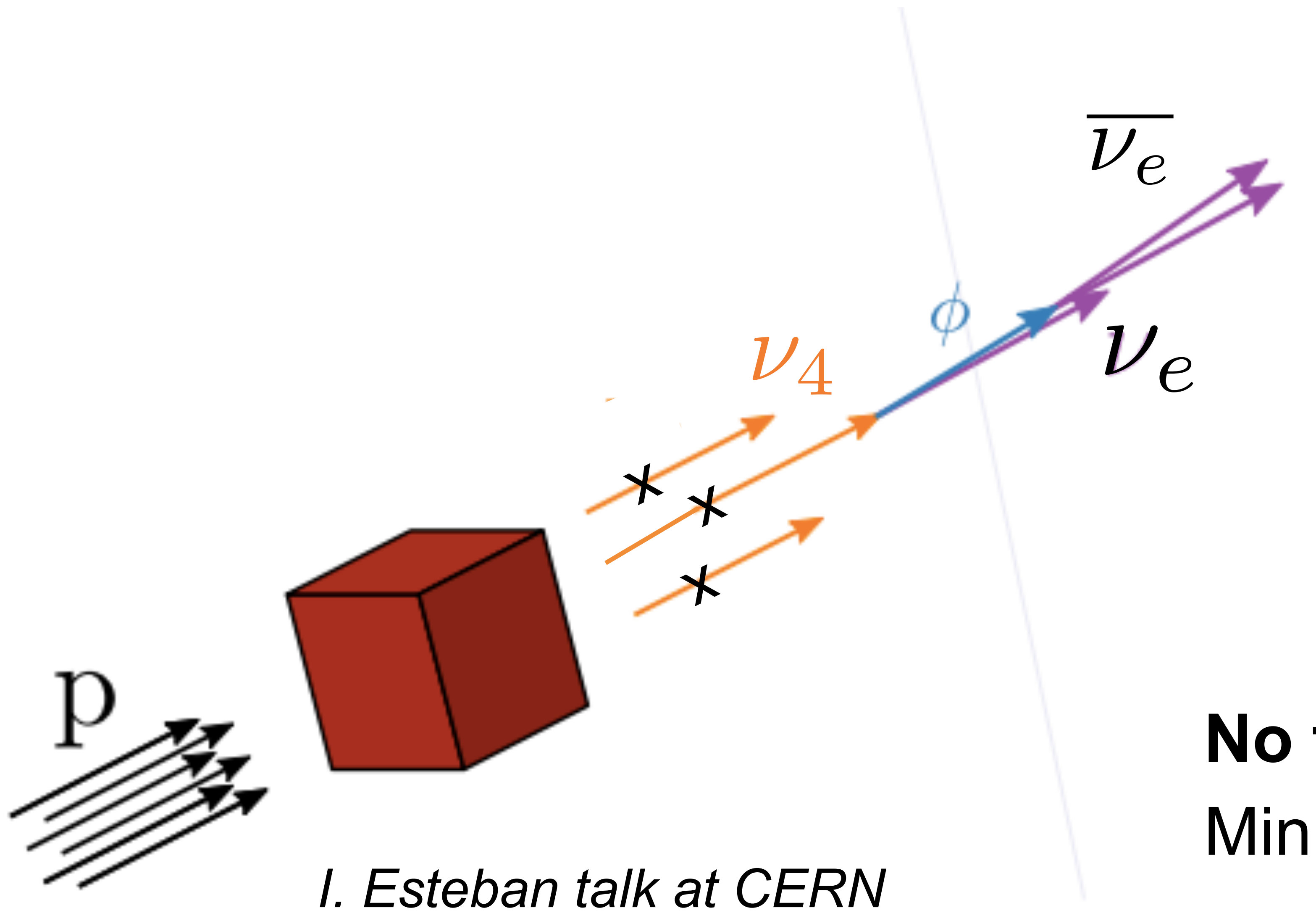
Decaying sterile neutrinos

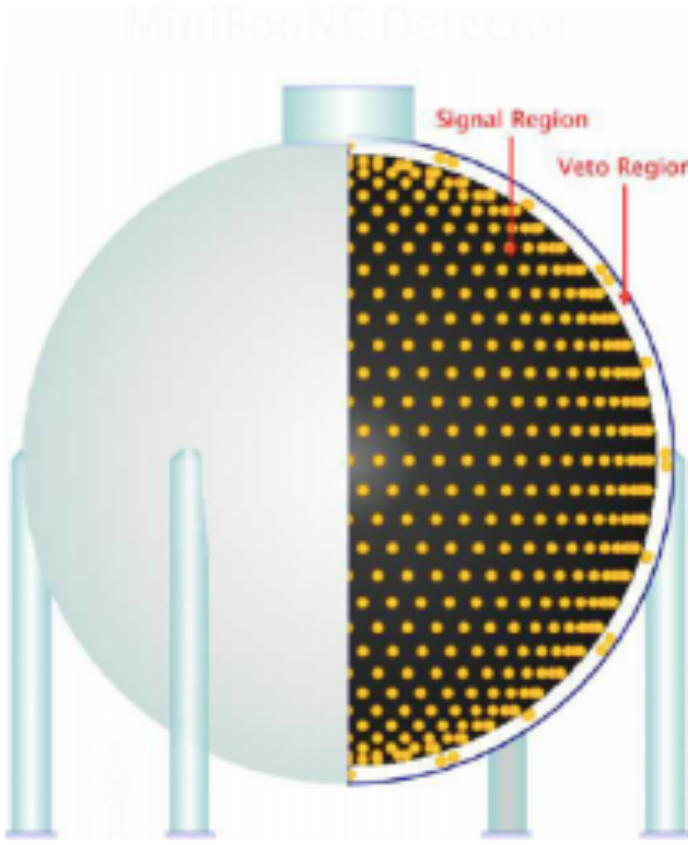
Effective $\nu_\mu \to \nu_e$ appearance with small ν_μ disappearance

S. Palomares-Ruiz *et al*, JHEP09(2005)048
Z. Moss *et al* , PRD 97, 055017 (2018)
M. Dentler *et al*, PRD101(2020) 115013.
A. deGouvea *et al*, JHEP07(2020)141

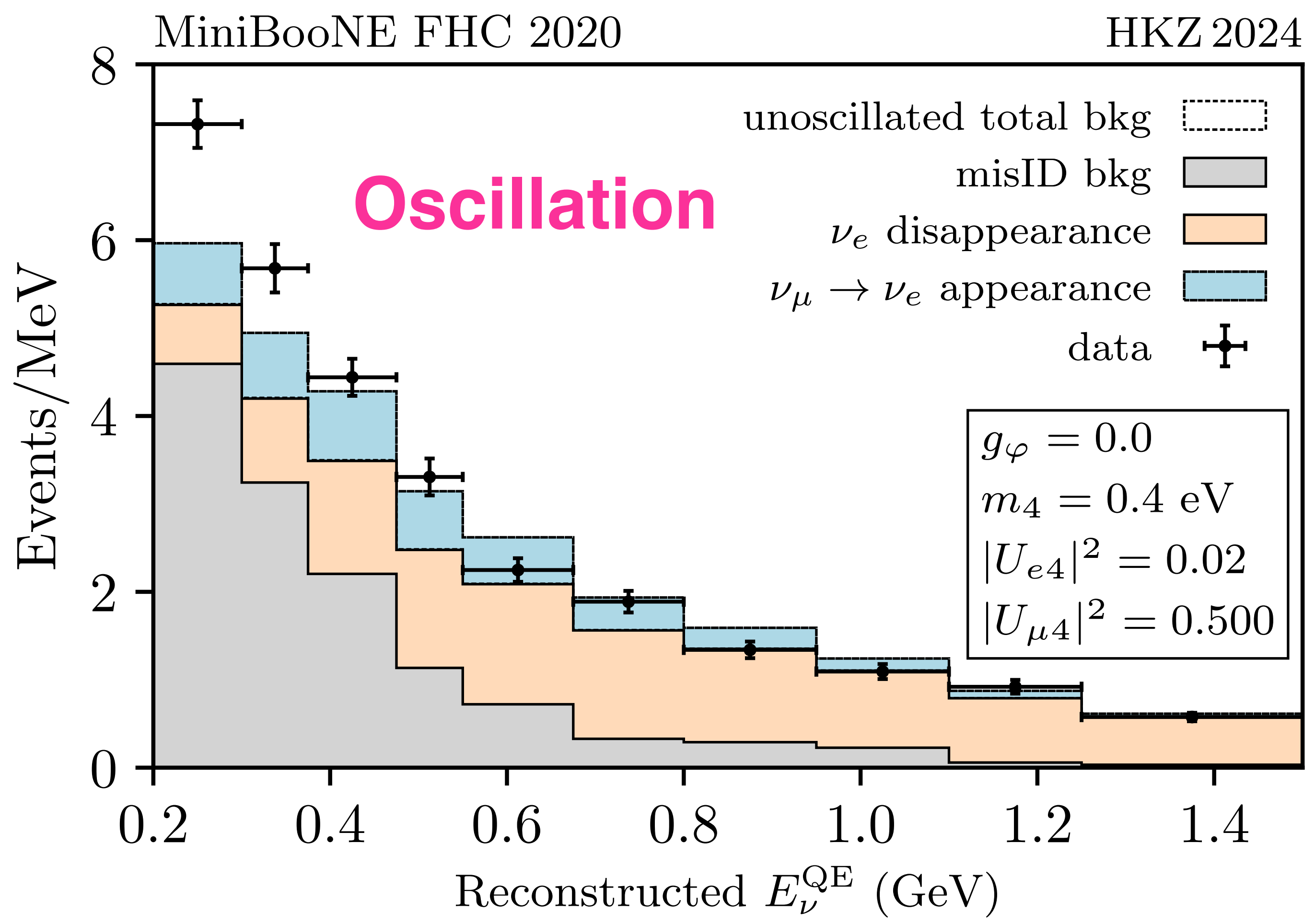
Light sterile and a new scalar particle φ:

$$-\mathscr{L} \supset g_\varphi \overline{\nu_s} \nu_s \varphi + \sum_{\alpha,\beta} m_{\alpha\beta} \overline{\nu}_\alpha \nu_\beta,$$

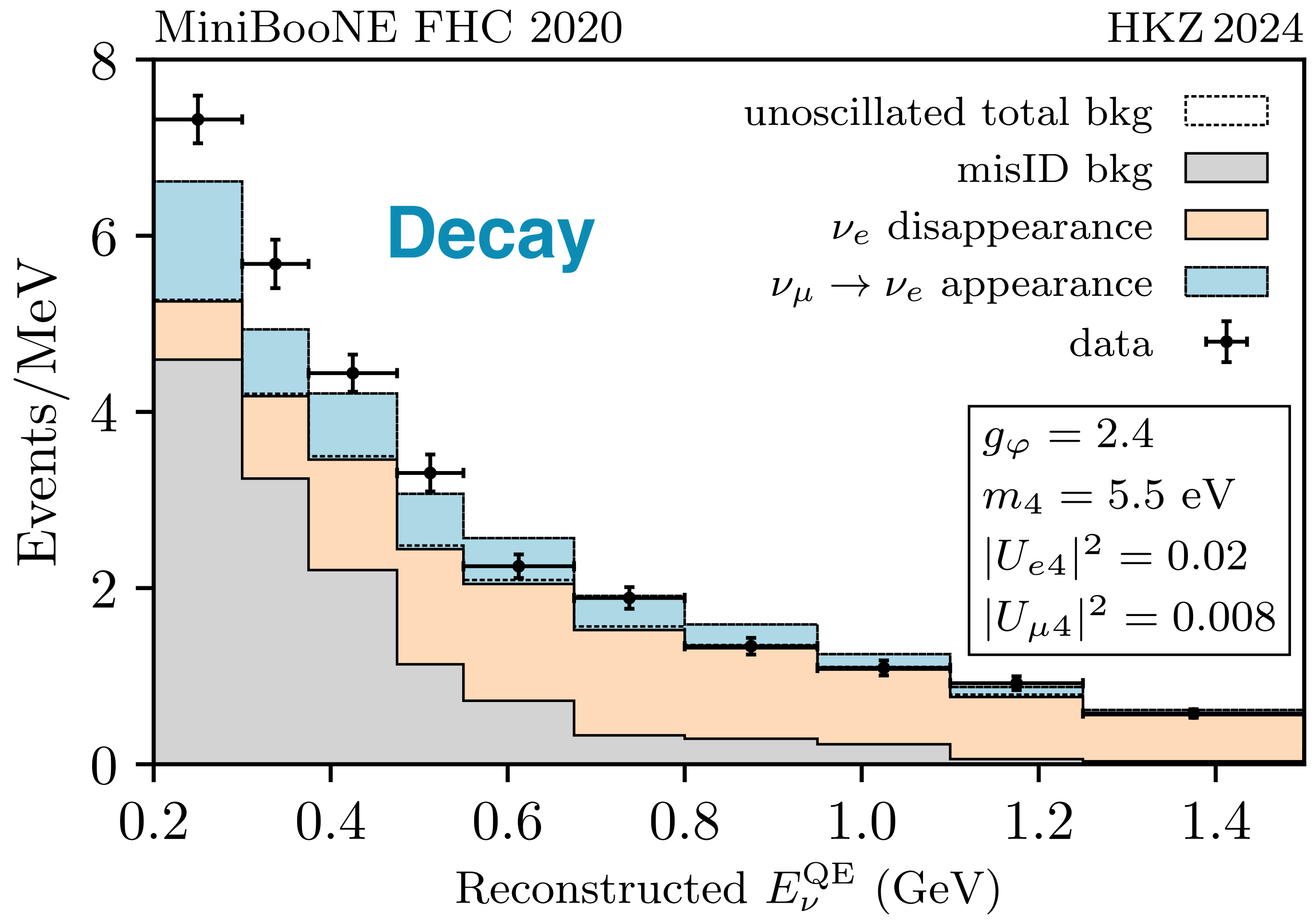




I. Esteban talk at CERN 10.5281/zenodo.3509890.



MH, K. Kelly, T. Zhou, in preparation



No tension with disappearance:

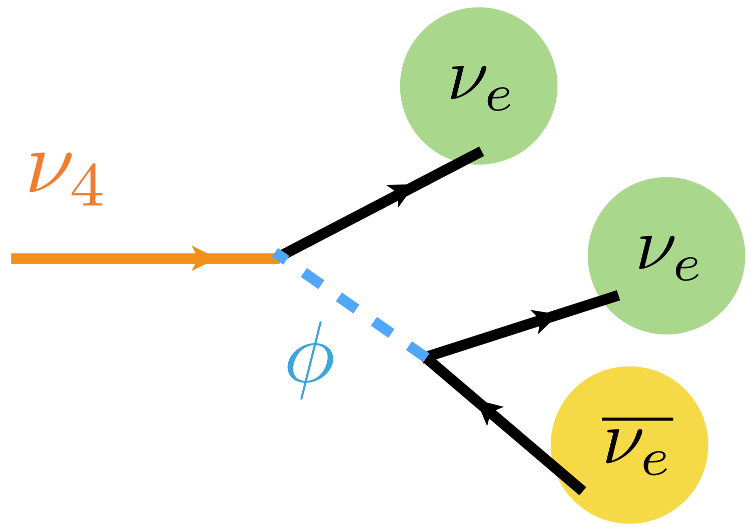
MiniBooNE signal: $|U_{\mu 4}|^2$

ν_μ disappearance: $|U_{\mu 4}|^2$

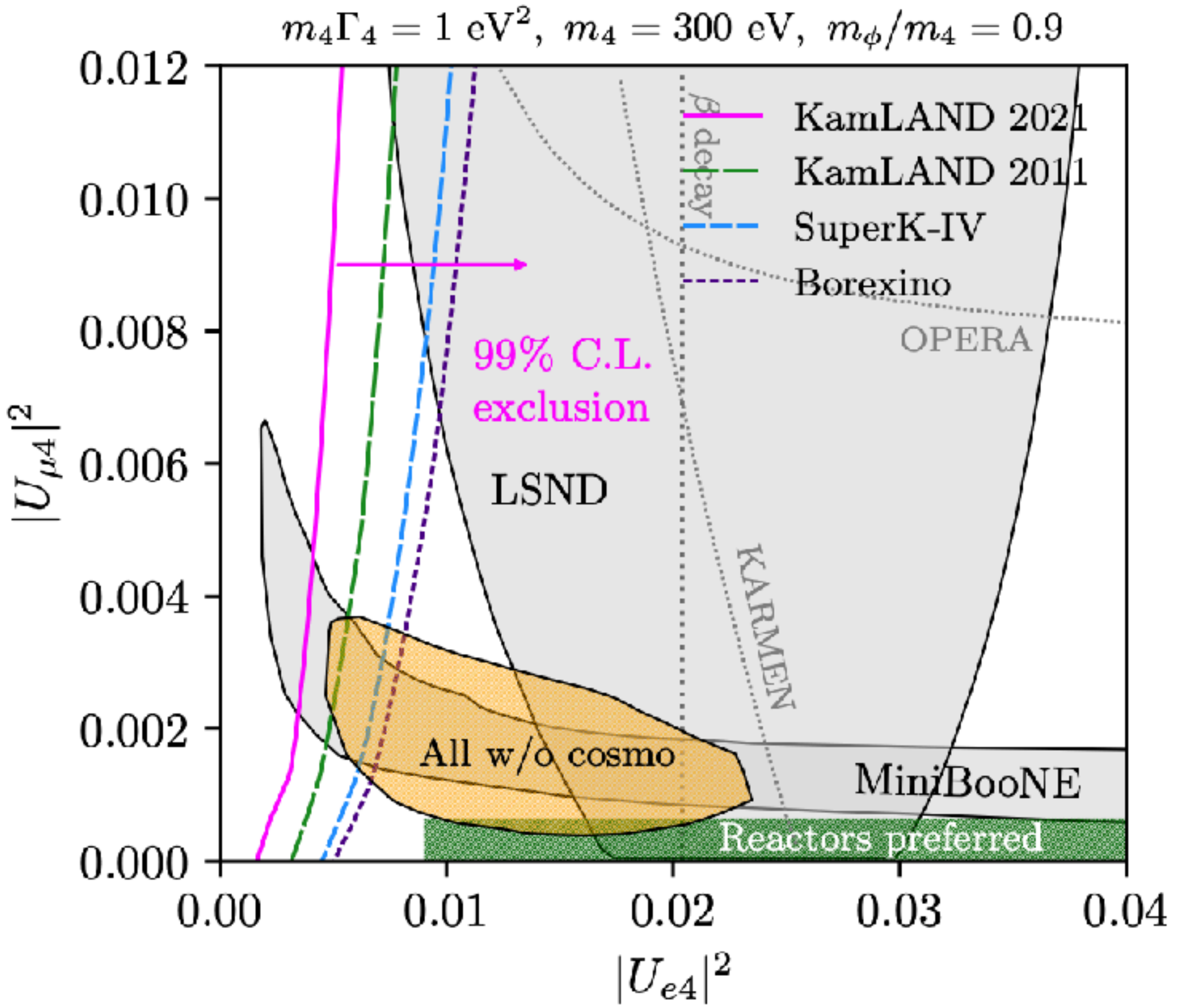
"Visible" sterile neutrino decay

1) ν_4 decays to $\nu_e \nu_e \overline{\nu_e}$ and $|U_{e4}| \neq 0$

M. Dentler *et al*, PRD101(2020) 115013

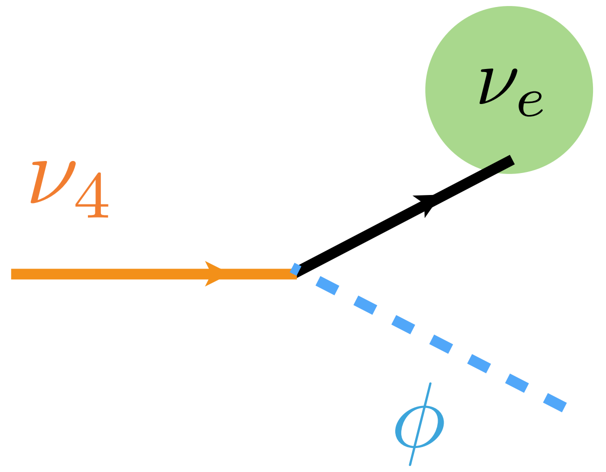


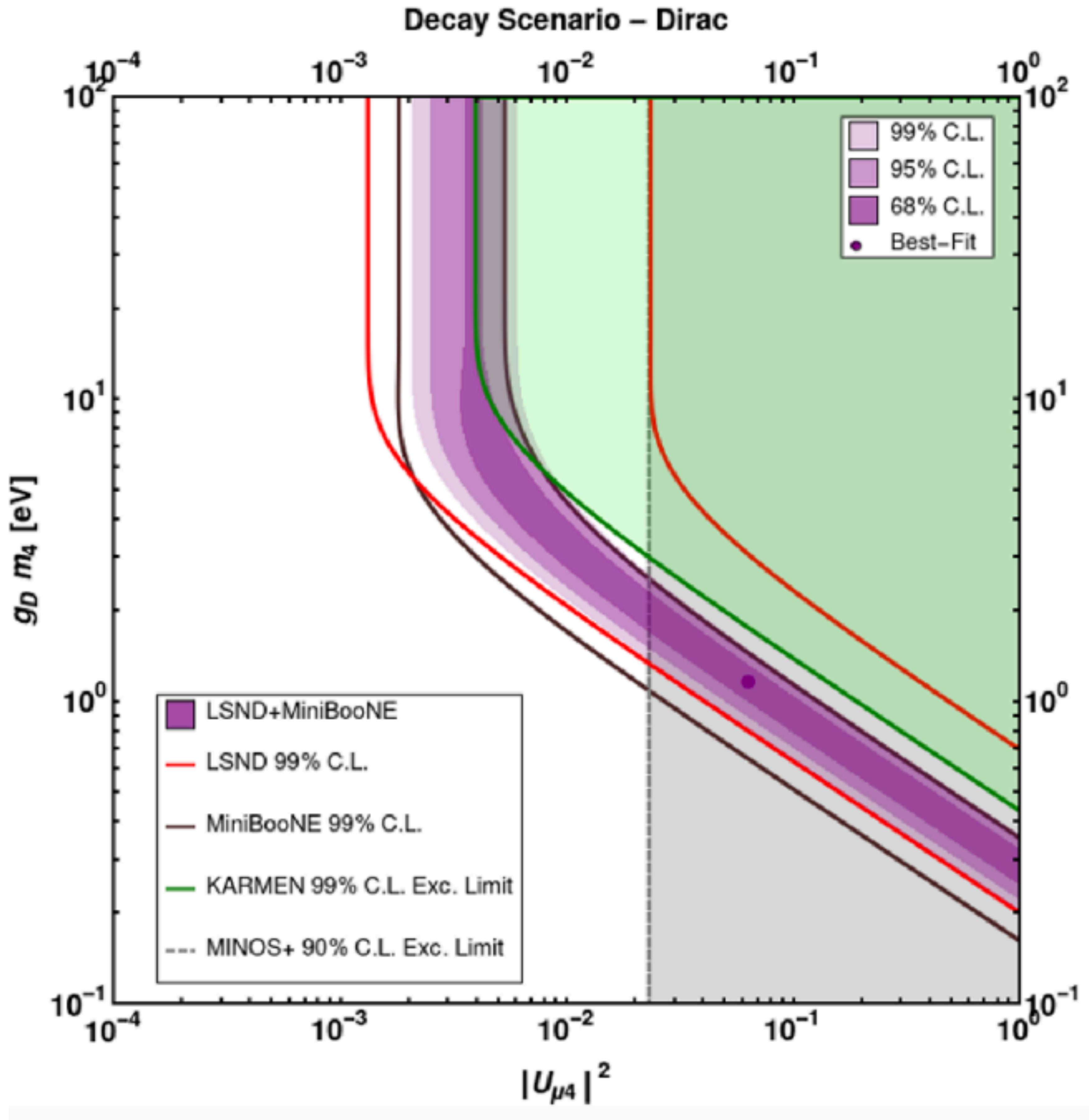
MH, M. Pospelov, PhysRevD.104.055031



2) ν_4 decays to ν_e only and $|U_{e4}| = 0$

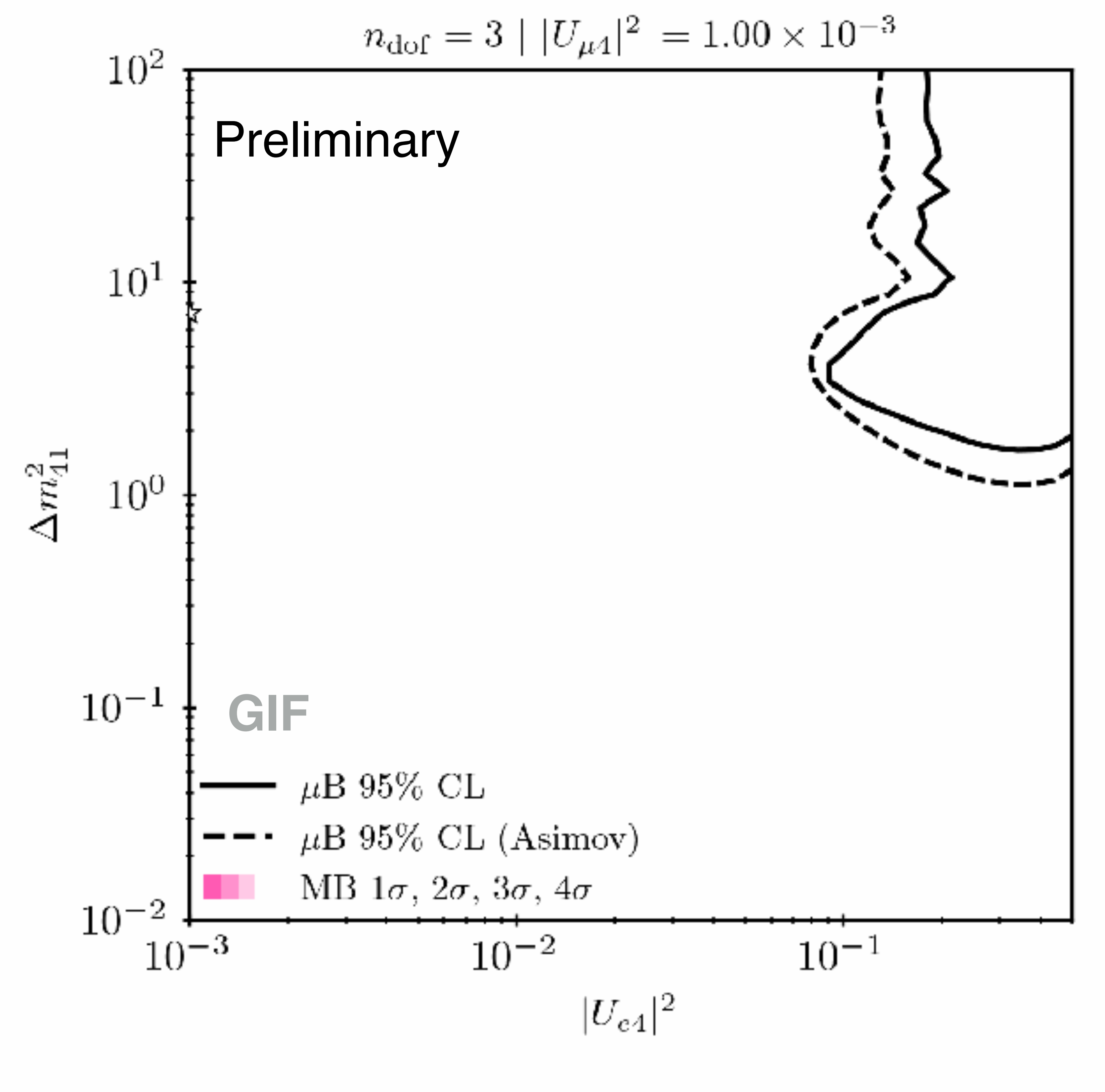
S. Palomares-Ruiz *et al*, JHEP09(2005)048
A. deGouvea *et al*, JHEP07(2020)141

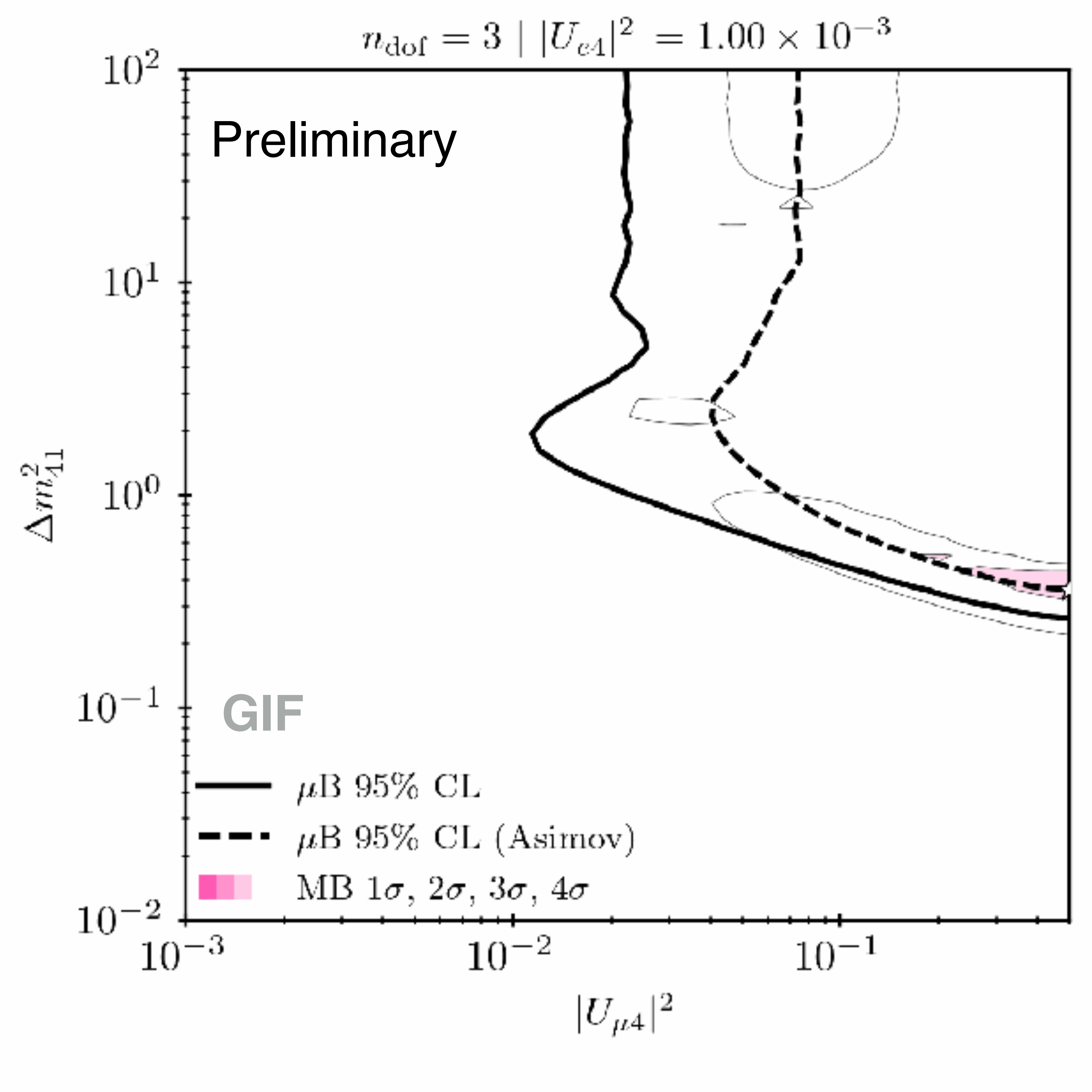




Full 3+1 oscillation with no decay
MiniBooNE vs MicroBooNE in slices in parameter space

MH, K. Kelly, T.Zhou, in preparation

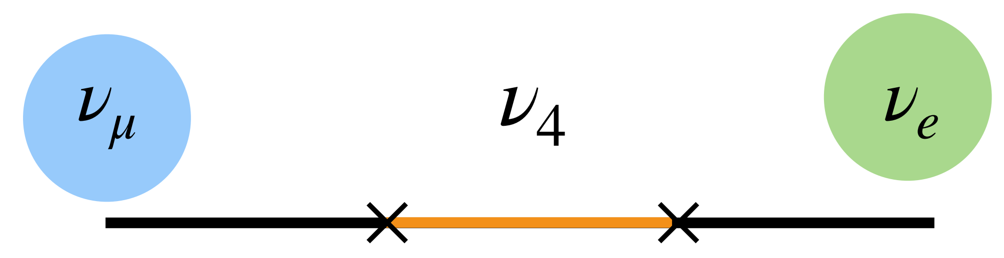




Combined fit to $\nu + \overline{\nu}$ modes:

$\nu_\mu \to \nu_e$ appearance

ν_e and ν_μ disappearance



Expanding on previous work:

C. A. Argüelles, I. Esteban, **MH**, K. J. Kelly, J. Kopp, P. A. N. Machado, I. Martinez-Soler, and Y. F. Perez-Gonzalez

PRL 128, 241802.

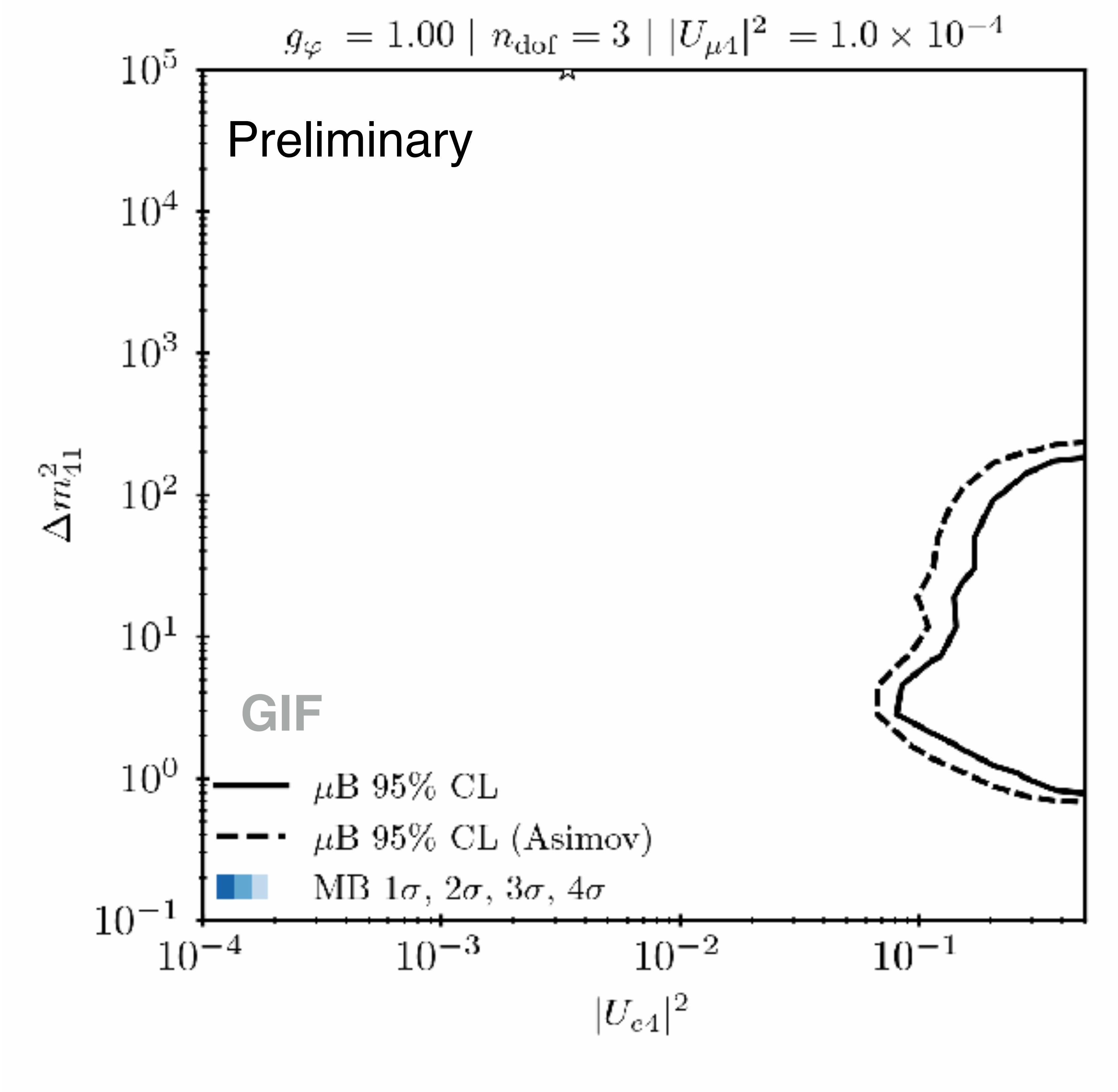
MiniBooNE coll.,
PRL 129 (2022) 20, 201801

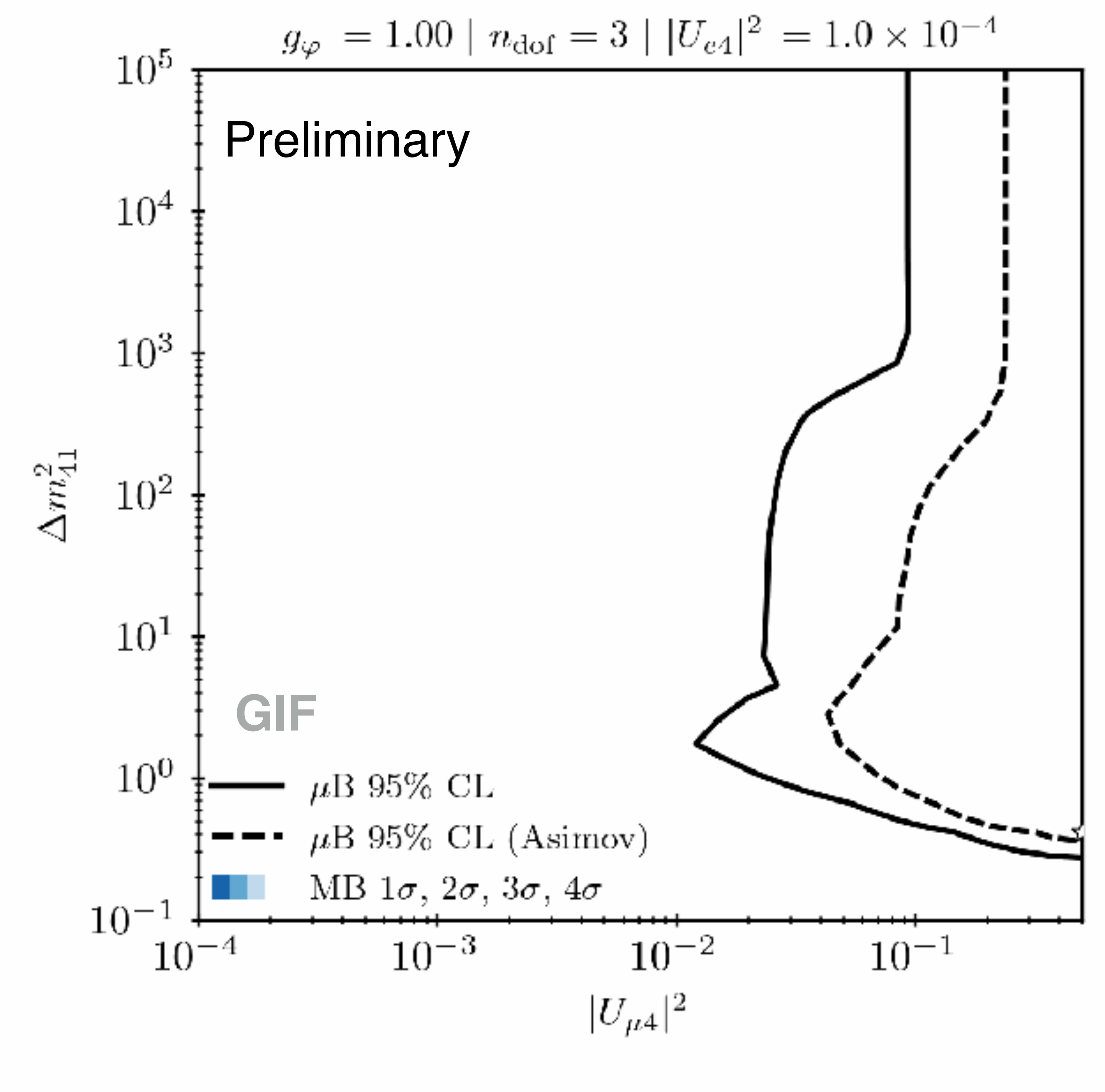
MicroBooNE coll.,
PRL 130 (2023) 1, 011801

*** Other limits not show: ν_e and ν_μ disappearance and cosmology.**

Full 3+1 oscillation with decay
MiniBooNE vs MicroBooNE in slices in parameter space

MH, K. Kelly, T.Zhou, in preparation

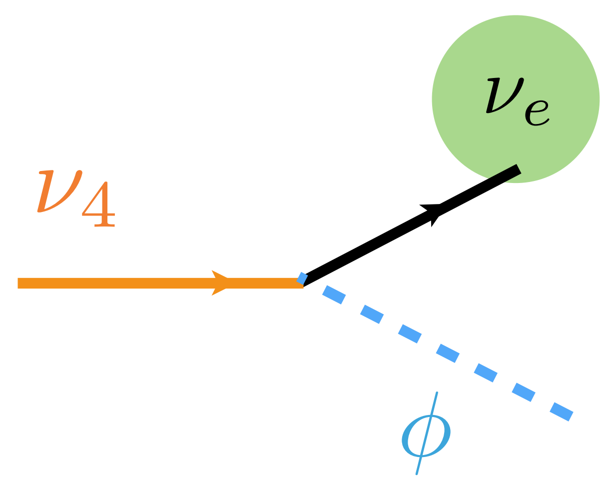




Combined fit to $\nu + \overline{\nu}$ modes:

$\nu_\mu \to \nu_e$ appearance

ν_e and ν_μ disappearance



Overall conclusion is similar, Constraints somewhat stronger due to the energy degradation of signal ν_e

*** Other limits not show: ν_e and ν_μ disappearance, cosmology, and supernovae neutrinos.**

Sterile neutrinos beyond oscillations at SBL

1) Decays to electromagnetic final states γ and $e^{+/-}$:

a) beam production

b) neutrino upscattering

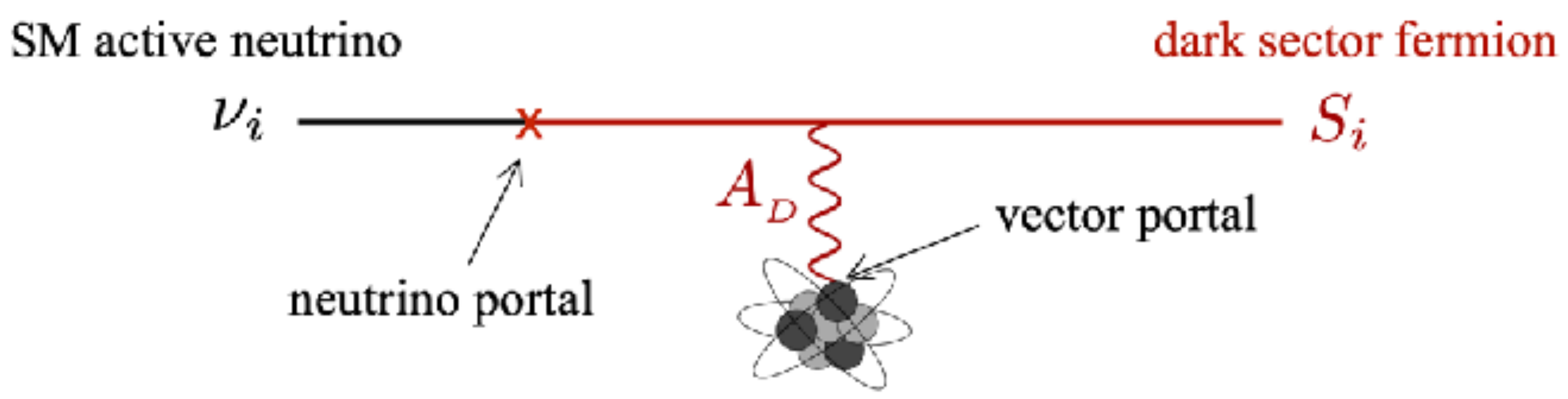
2) Decays to neutrinos: $\nu_\mu \rightarrow \nu_e$ conversion from decay

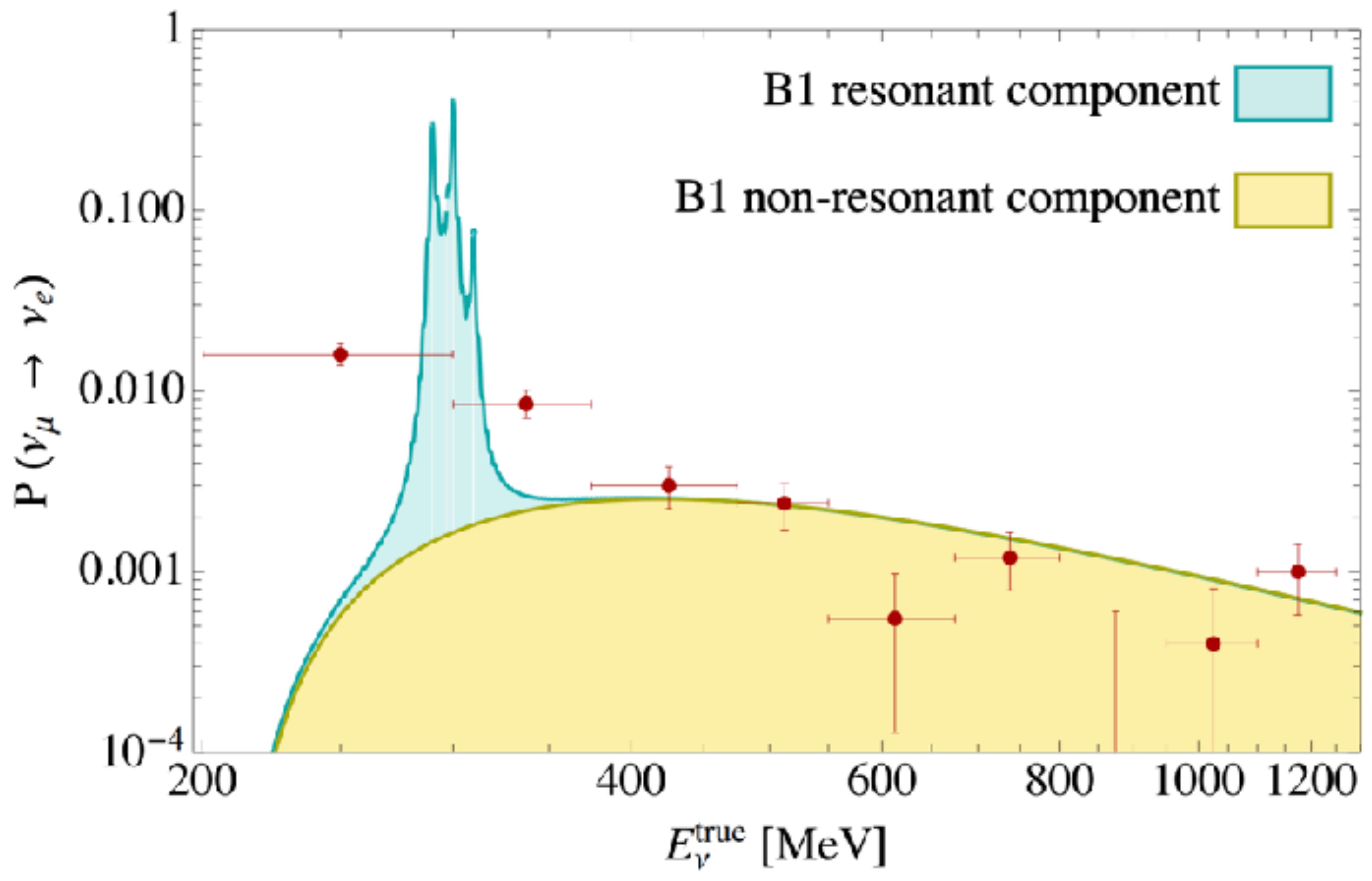
3) Sterile-induced matter potential: resonant $\nu_\mu \rightarrow \nu_e$ conversion

Resonant flavor transitions

Quasi-sterile neutrinos

D. S. M. Alves, W. C. Louis, P. G. deNiverville, JHEP 08 (2022) 034





Quasi-sterile neutrinos with large interactions with matter:

$$\Delta V\big|_{\rm matter} = (V_{S_3} - V_{\nu_i})\big|_{\rm matter}$$

$$E^{\rm res}_{\nu_3} = \frac{\delta M_3^2 \, \cos 2\theta_{S_3}}{2\,|\Delta V|}$$

Challenging to find a UV model with such large potentials, but the potential may come from:

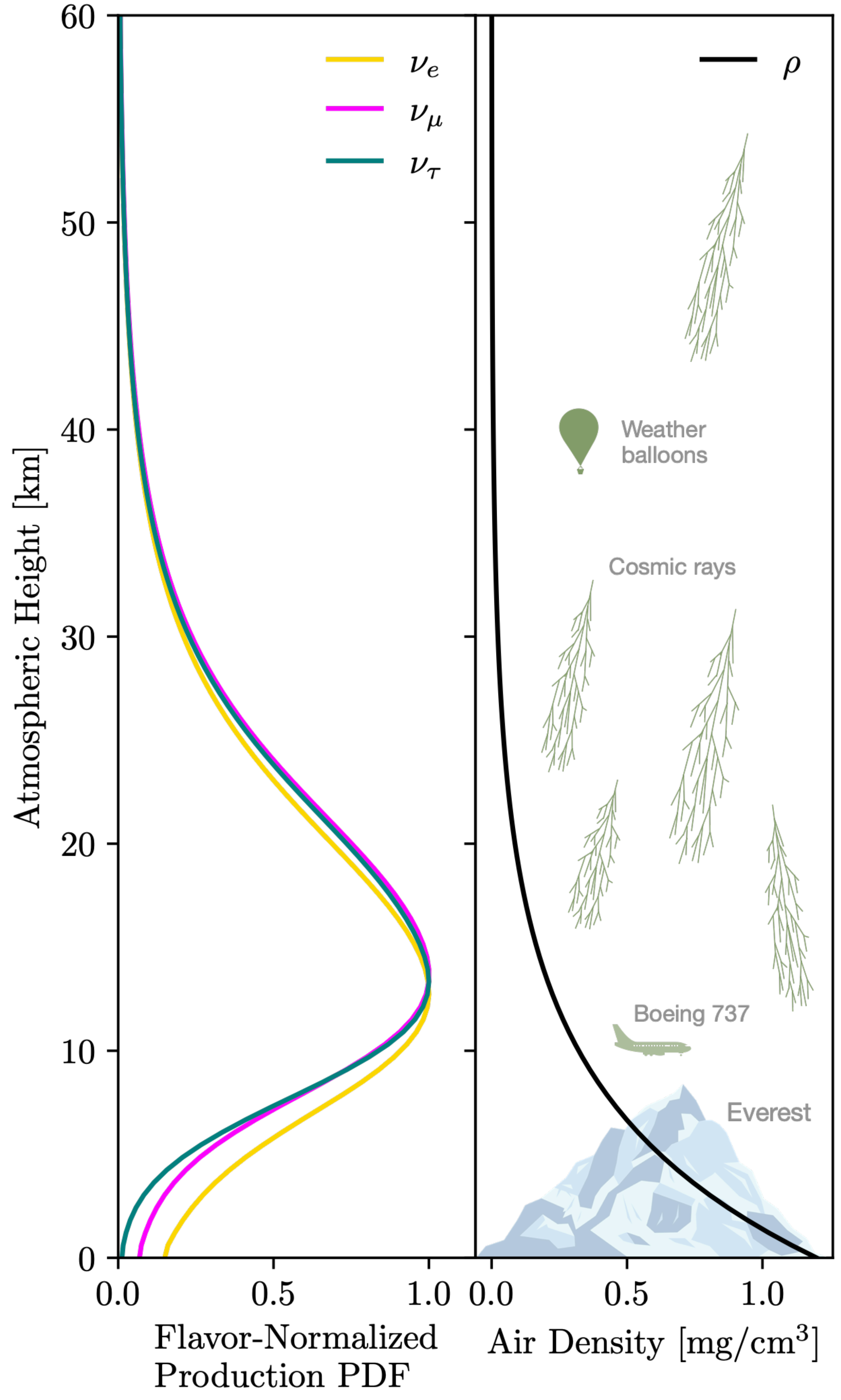
- Ordinary matter (p^+, e^-, n)
- Ultra-light dark matter background
- Modified dispersion relations (e.g., large extra-dimensions)

* Strong limits from T2K as well, but not proven that this doesn't work. $\mathcal{O}(50\%)$ density differences matter.

Resonant flavor transitions
Neutrino telescopes weigh in

C. Sponsler*, MH, I. Martinez-Soler, C. Argüelles, in preparation

* Harvard undergrad student



Neutrinos are produced throughout the atmosphere, transversing varying **air density**

Resonance moves to higher energies:

$$\frac{E_{\rm res}}{200\text{ MeV}} \sim |Q| \left(\frac{3\text{ MeV}}{m_{A'}/g_X}\right)^2 \left(\frac{\rho}{1\text{g/cm}^3}\right)\left(\frac{\delta m^2}{10^4\text{ eV}^2}\right),$$

$$\downarrow$$

$E_{\rm res} \sim \mathcal{O}(500)$ **GeV in atmosphere**

If the quasi-sterile potential is sourced by SM matter (e^-, p^+, n), this resonance must be there.

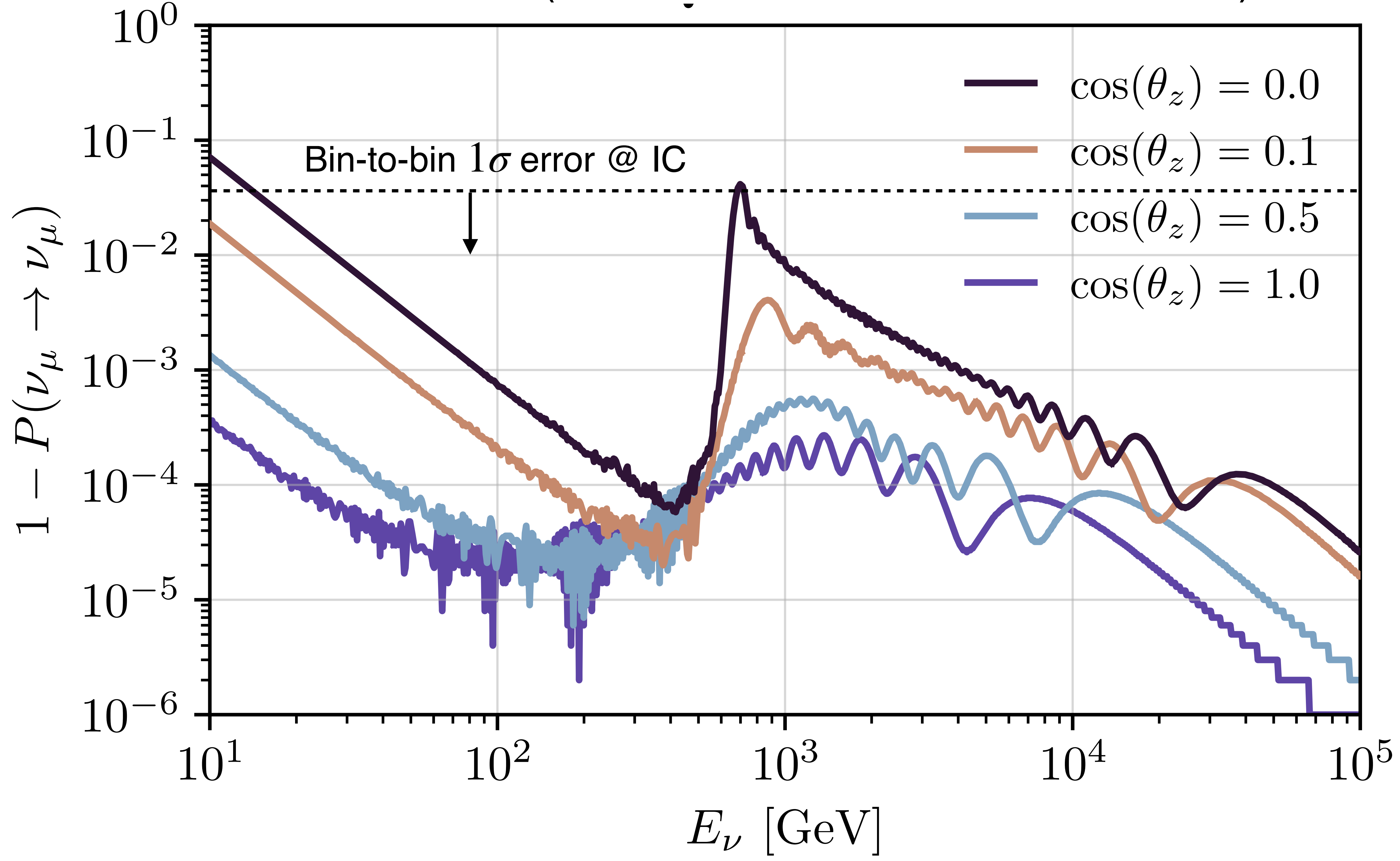
* First implementation of MCEq neutrino production height in the neutrino flavor evolution (in nuSQUIDS).

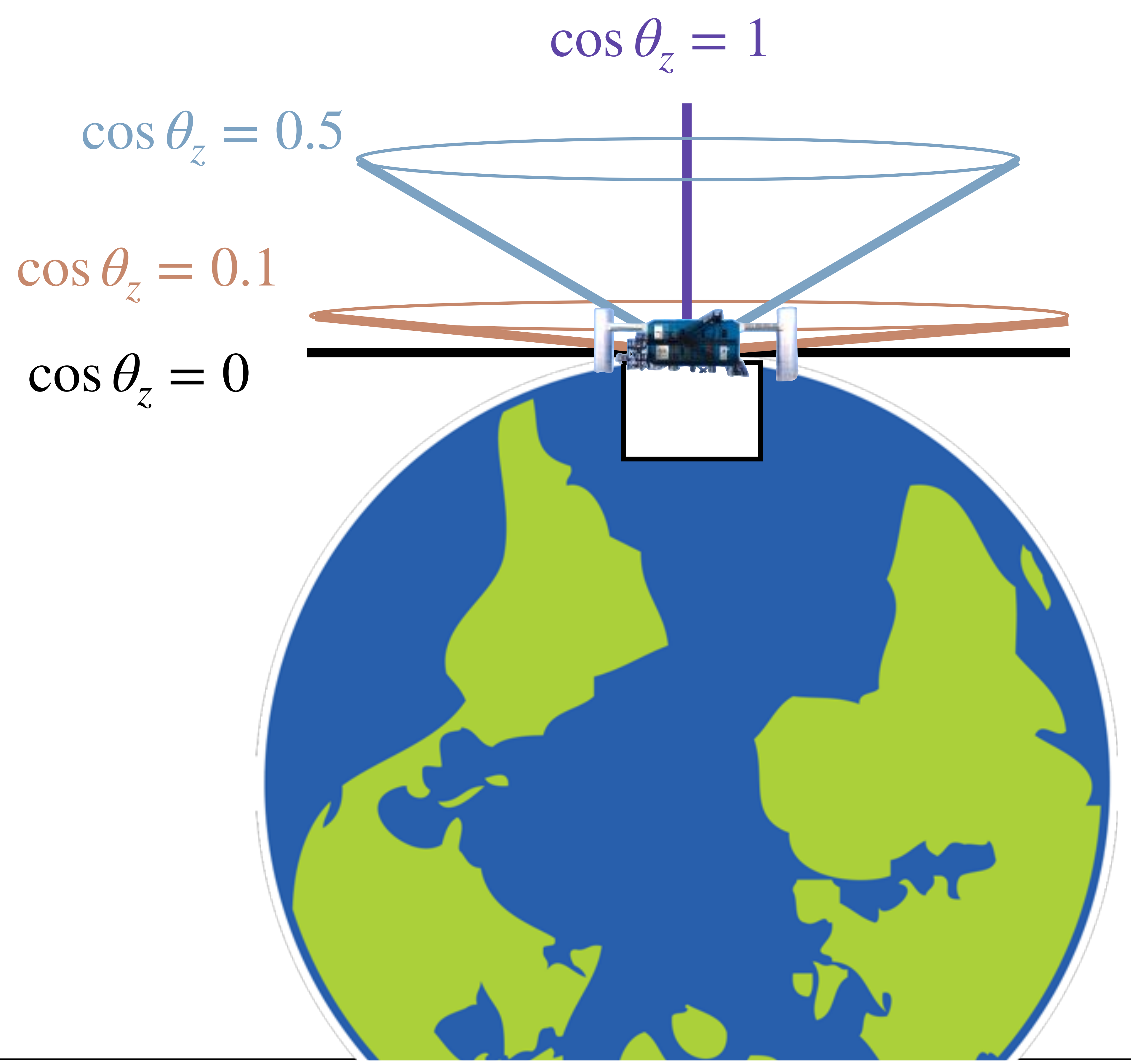
Resonant flavor transitions
Neutrino telescopes weigh in

C. Sponsler*, MH, I. Martinez-Soler, C. Argüelles, in preparation

* Harvard undergrad student

3 Quasi-steriles (MiniBooNE benchmark Alves et al)





Same IceCube sample as eV sterile neutrino search, but in different direction!

Sterile neutrinos beyond oscillations at SBL

1) Decays to electromagnetic final states γ and $e^{+/-}$:

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   b) neutrino upscattering

2) Decays to neutrinos: $\nu_\mu \to \nu_e$ conversion from decay

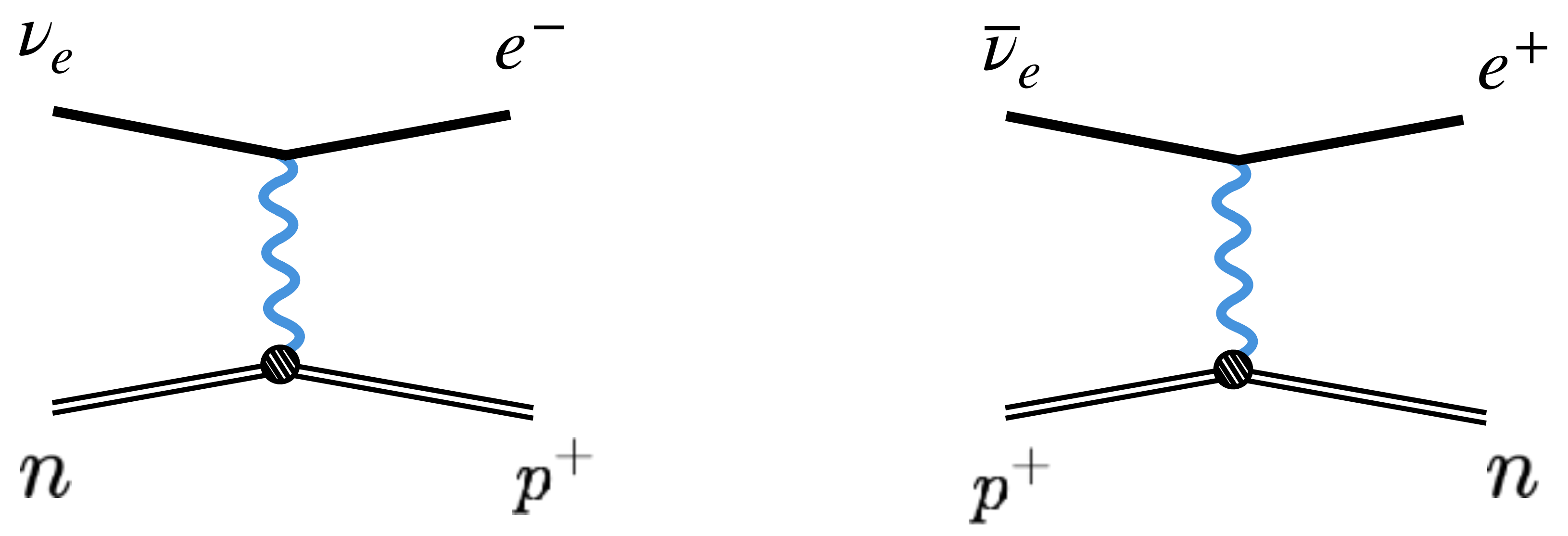
3) Sterile-induced matter potential: resonant $\nu_\mu \to \nu_e$ conversion

Bonus thoughts...

Antineutrino hypothesis of MiniBooNE

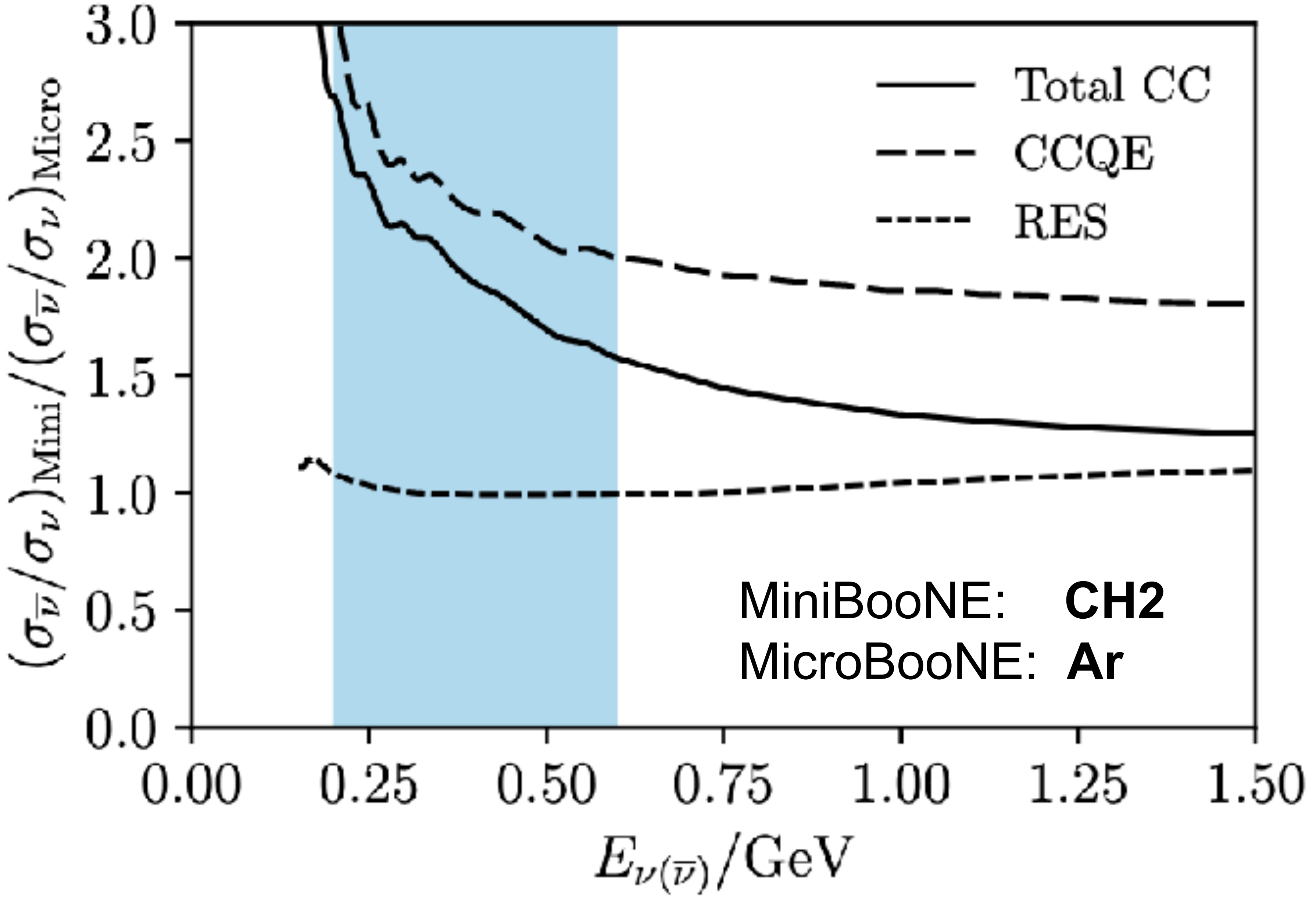
Are we looking at the wrong sign?

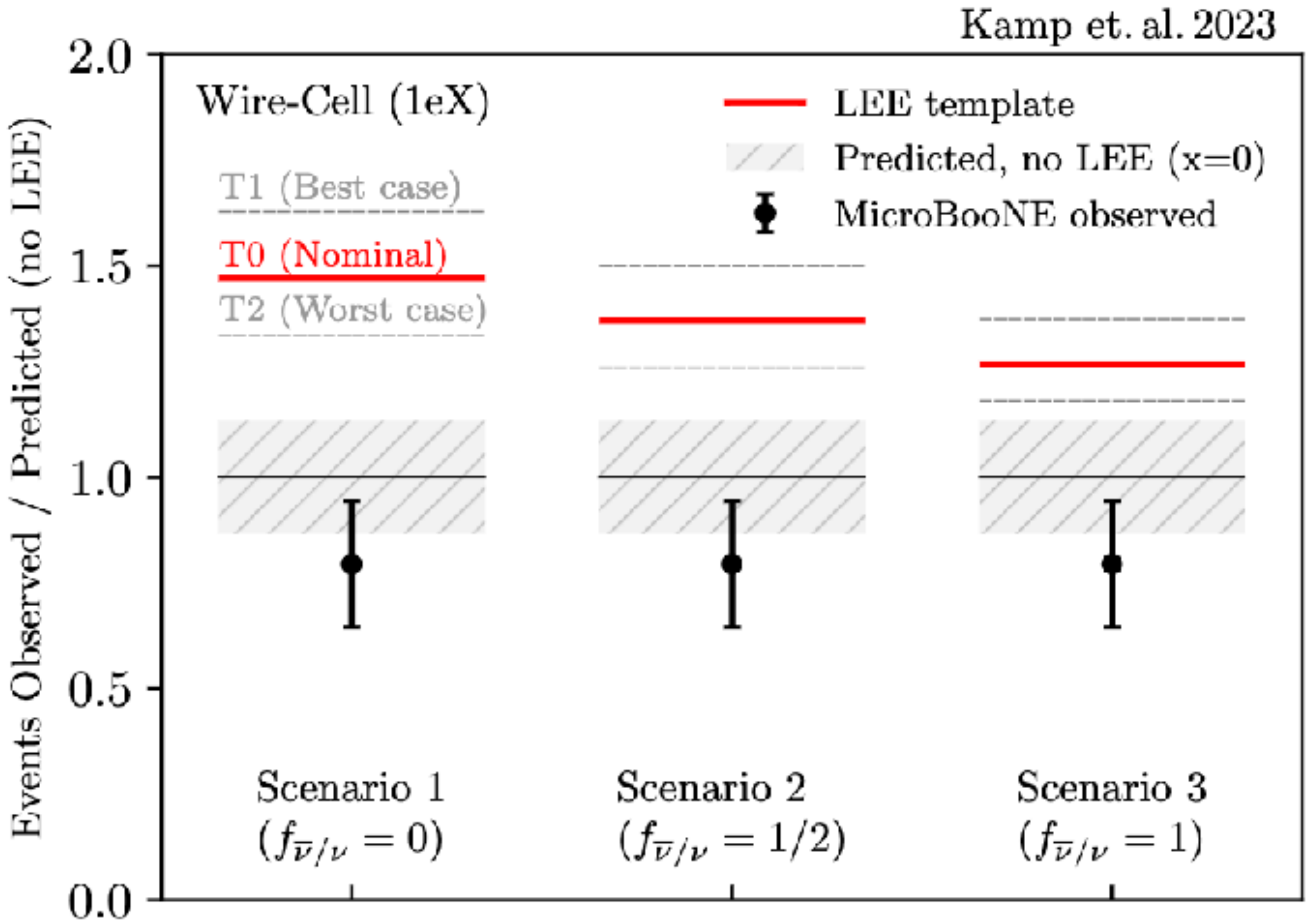
N. Kamp, **MH**, C. Argüelles, J. Conrad, M. Shaevitz
PRD107, 092002 (2023)



Knocking out neutrons from Ar harder than on CH_2:

1) Protons are more tightly bound in Ar.
2) More neutrons, so more Pauli blocking for $p^+ \to n$ transitions.
3) Antineutrinos lead to **higher-energy leptons**.





Complementarity beyond GeV-neutrino beams

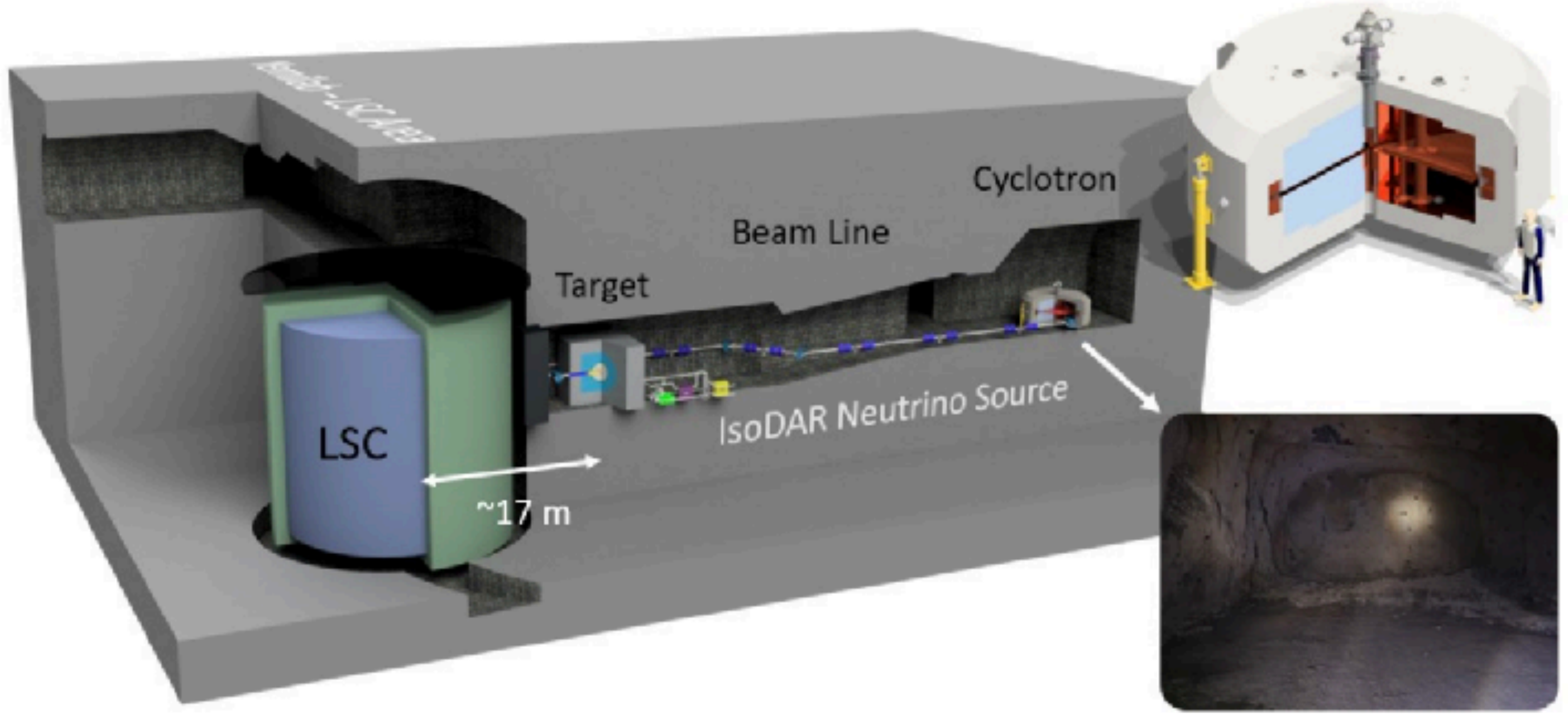
Higher intensities

IsoDAR:

Definitive $\nu_e \to \nu_e$ disappearance test.

Most intense neutrino source deep underground?

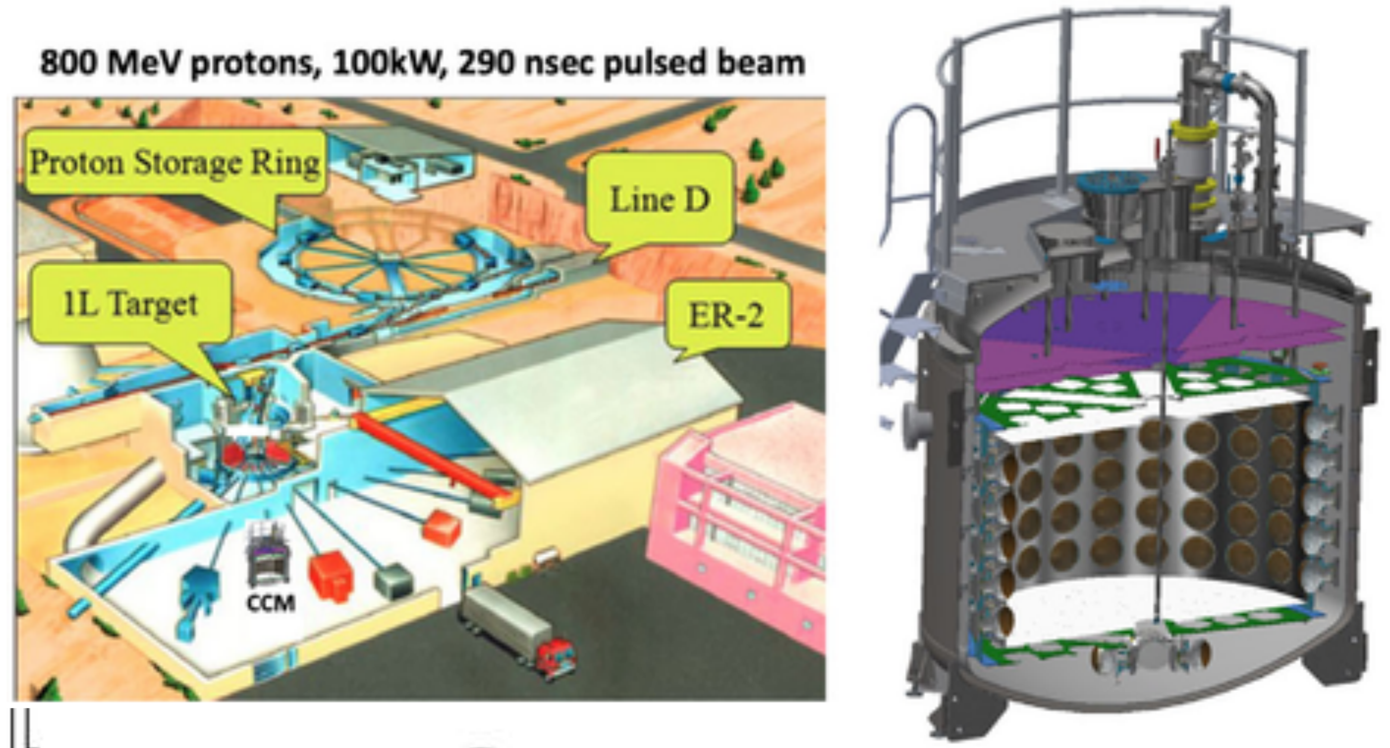
Dark sector searches (ALPs and dark bosons, ideal for $n \to n'$ searches, …)

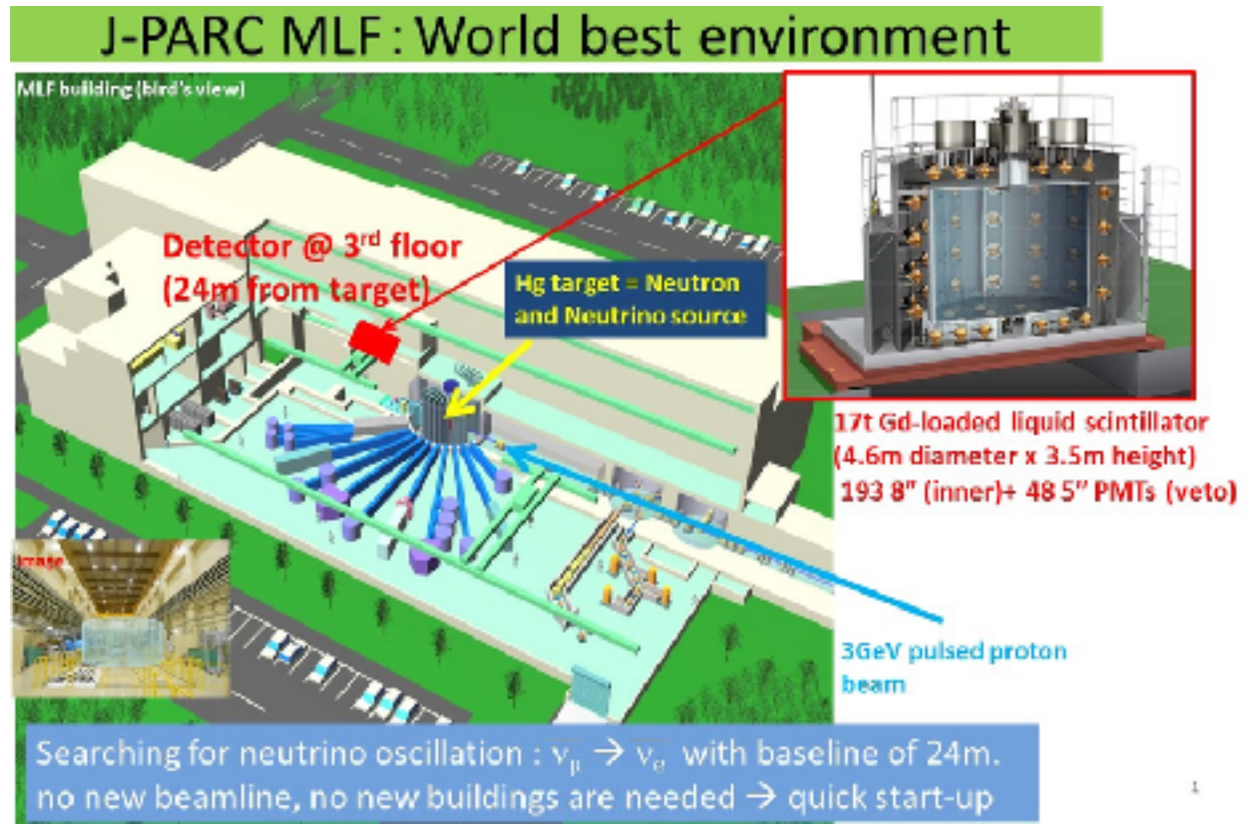


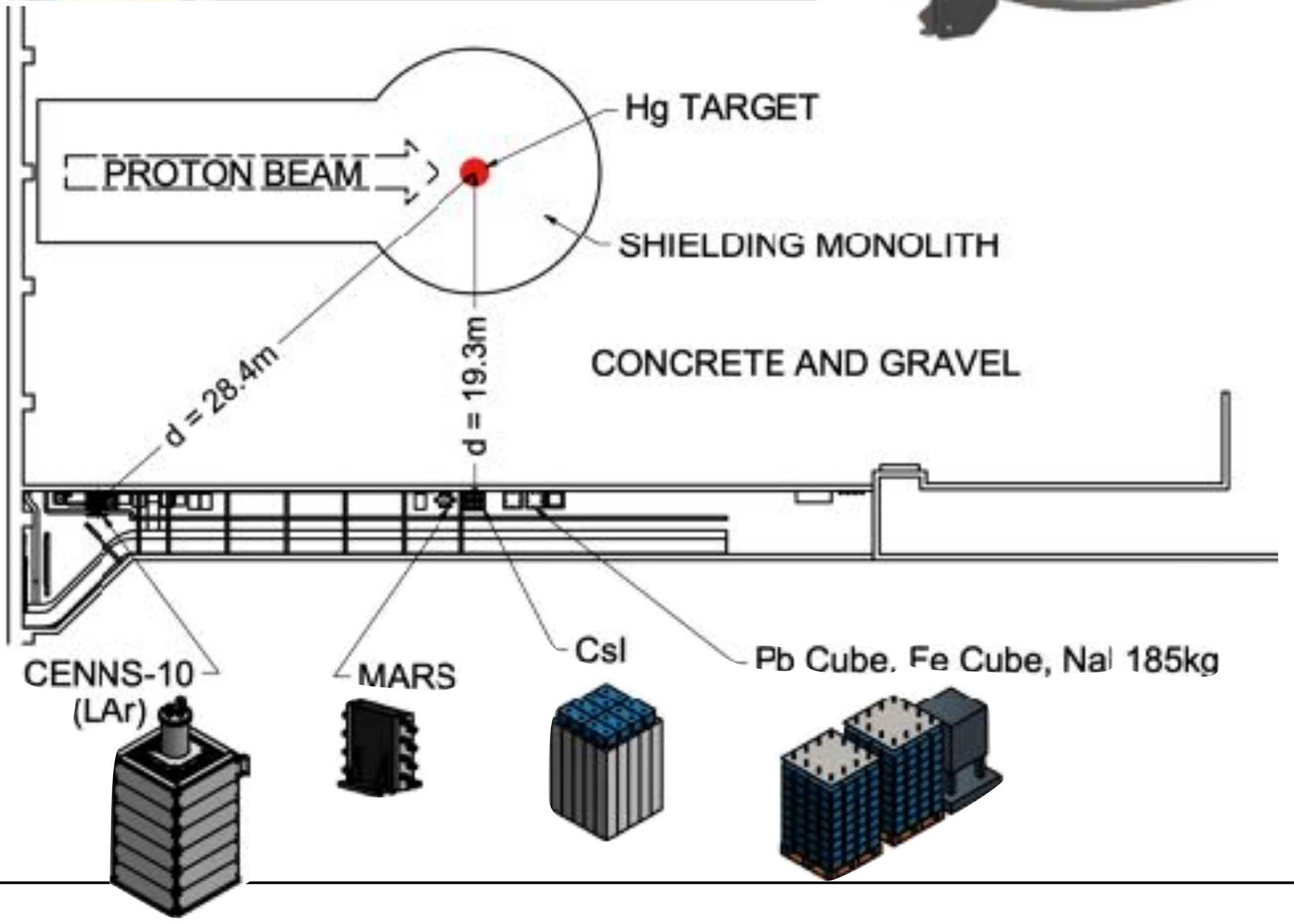
Modern spallation sources:

Great complementarity between LANL, SNS, and JSNS projects:

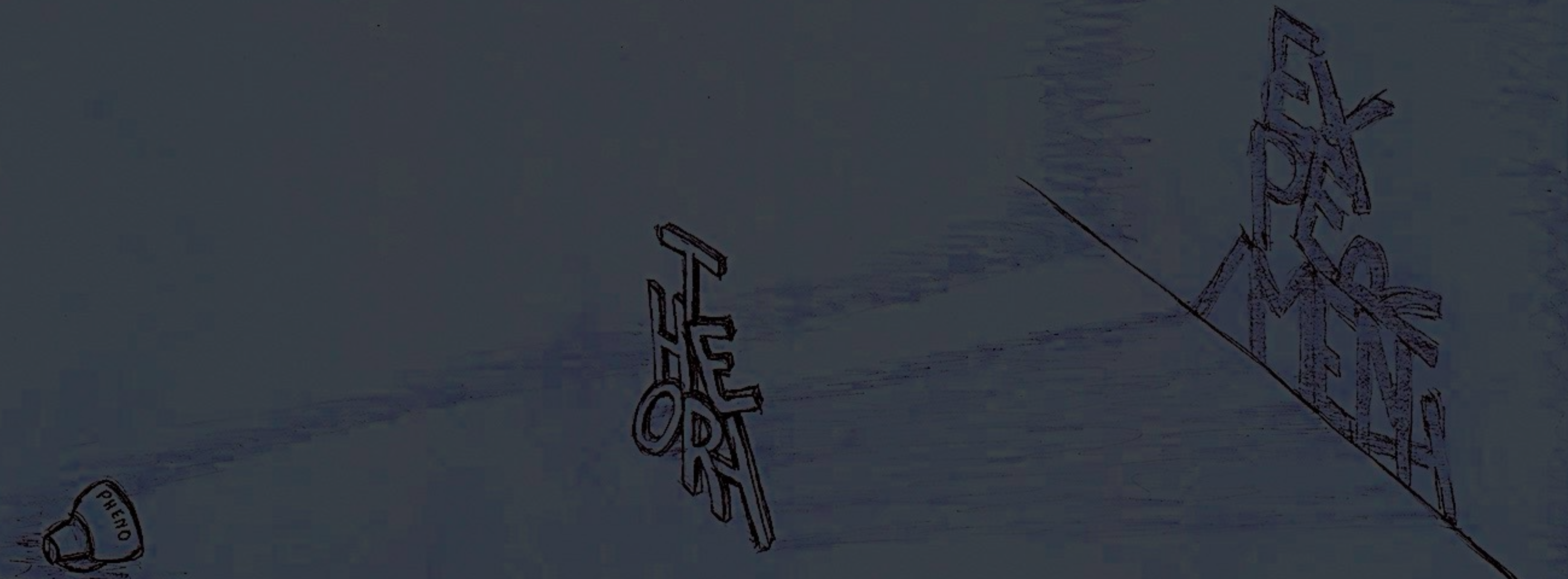
- **Coherent-Captain Mills**
- **COHERENT**
- **JSNS^2** (+ ND280)







Discussion session



NF02 White Paper: arXiv:2203.07323.

SBL anomaly interpretations

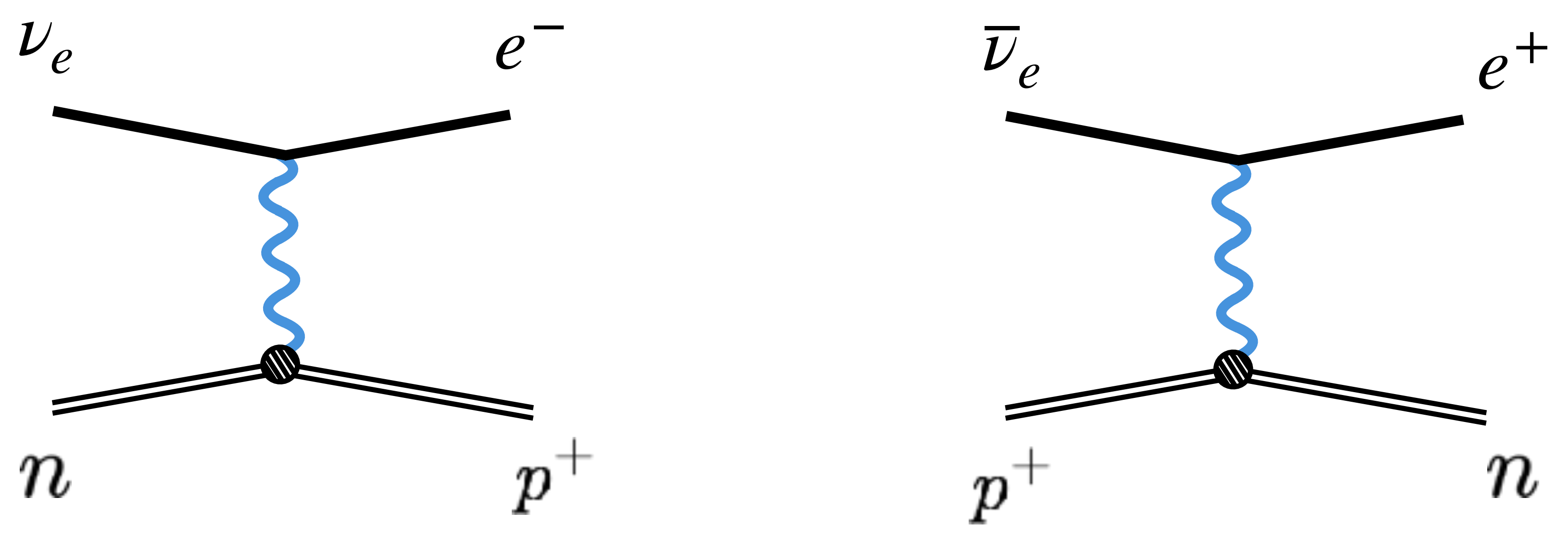
Category	Model	Signature	Anomalies: LSND	MiniBooNE	Reactors	Sources	References
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to NA$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

Model landscape evolved significantly over the years.

Antineutrino hypothesis of MiniBooNE

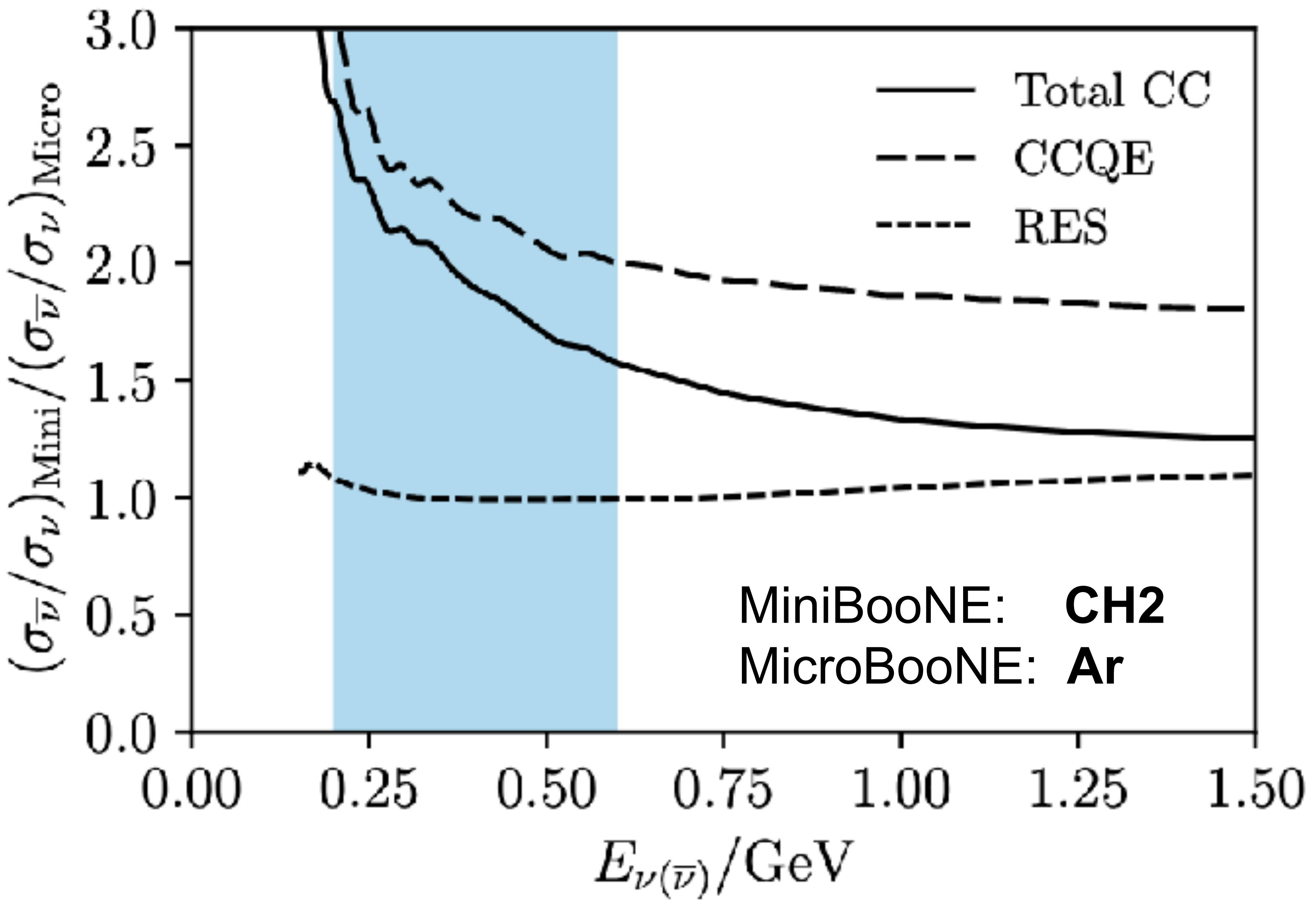
Are we looking at the wrong sign?

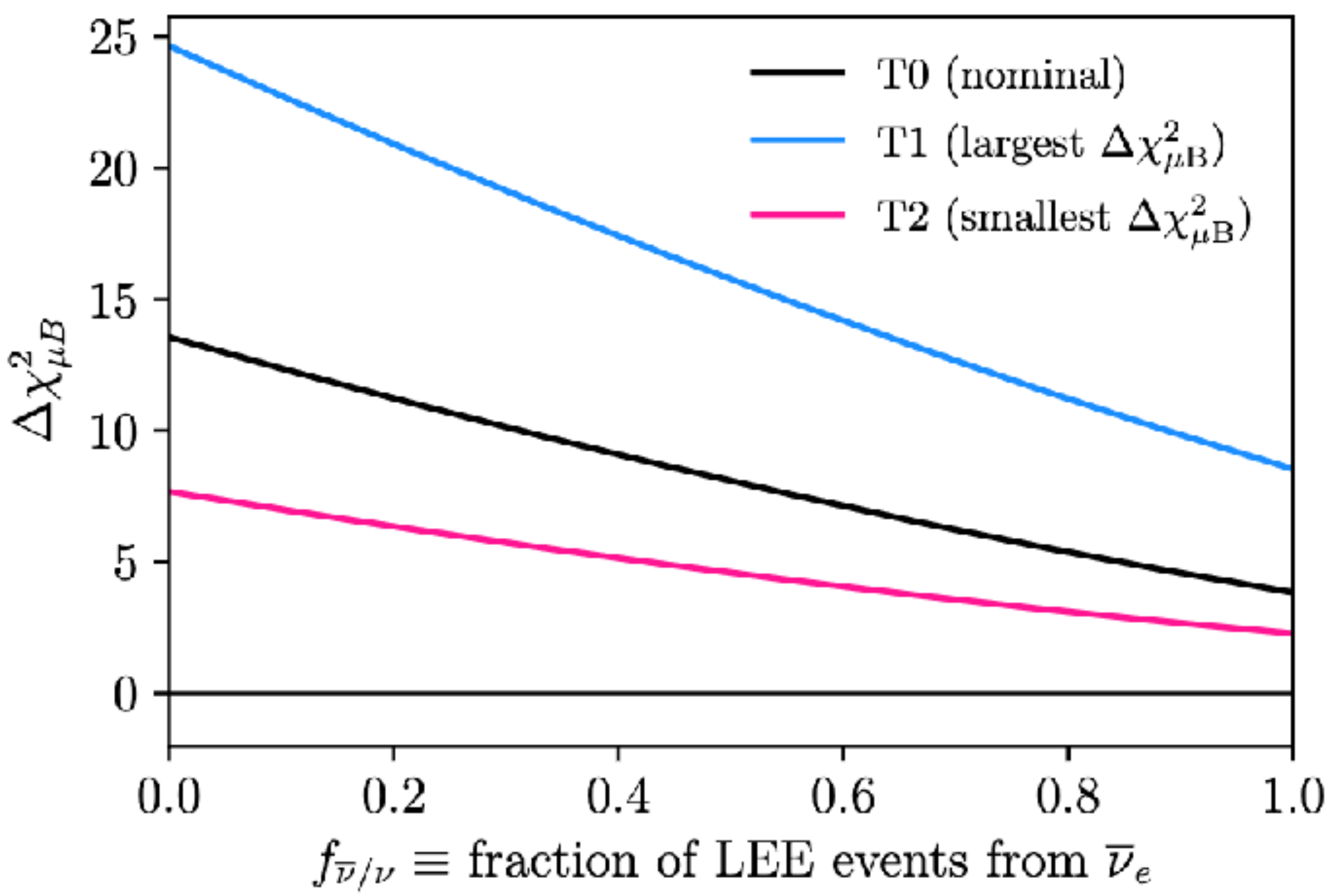
N. Kamp, **MH**, C. Argüelles, J. Conrad, M. Shaevitz
PRD107, 092002 (2023)



Knocking out neutrons from Ar harder than on CH_2:

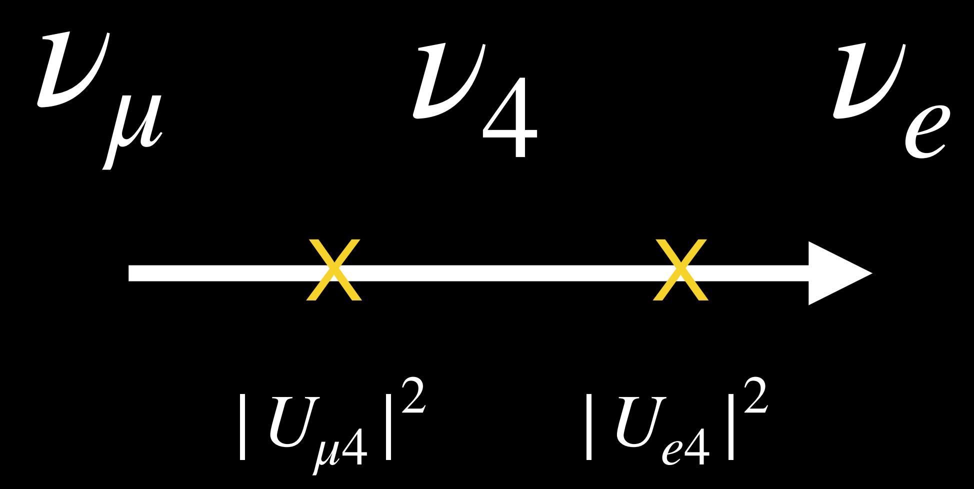
1) Protons are more tightly bound in Ar.
2) More neutrons, so more Pauli blocking for $p^+ \to n$ transitions.
3) Antineutrinos lead to **higher-energy leptons**.

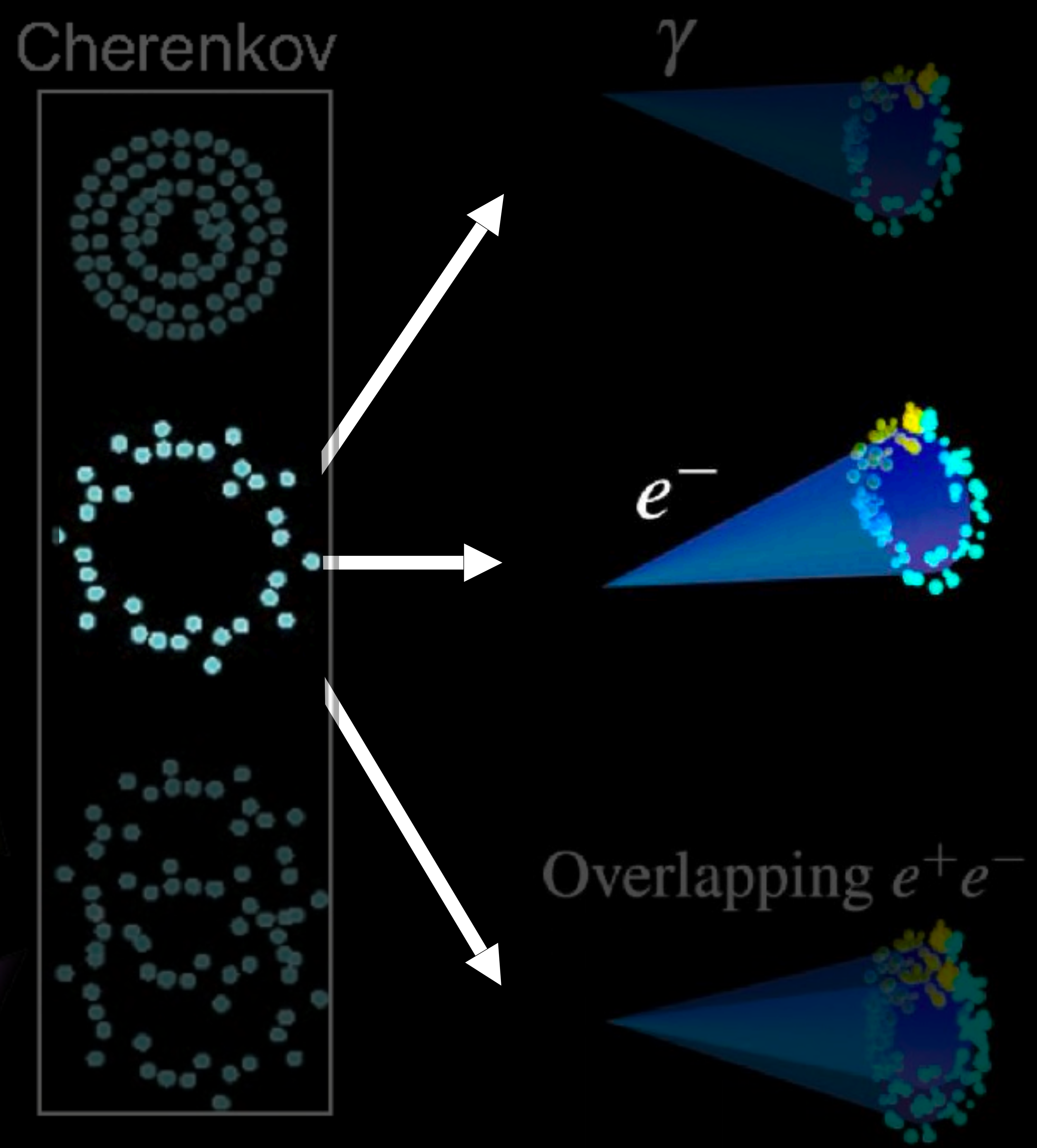


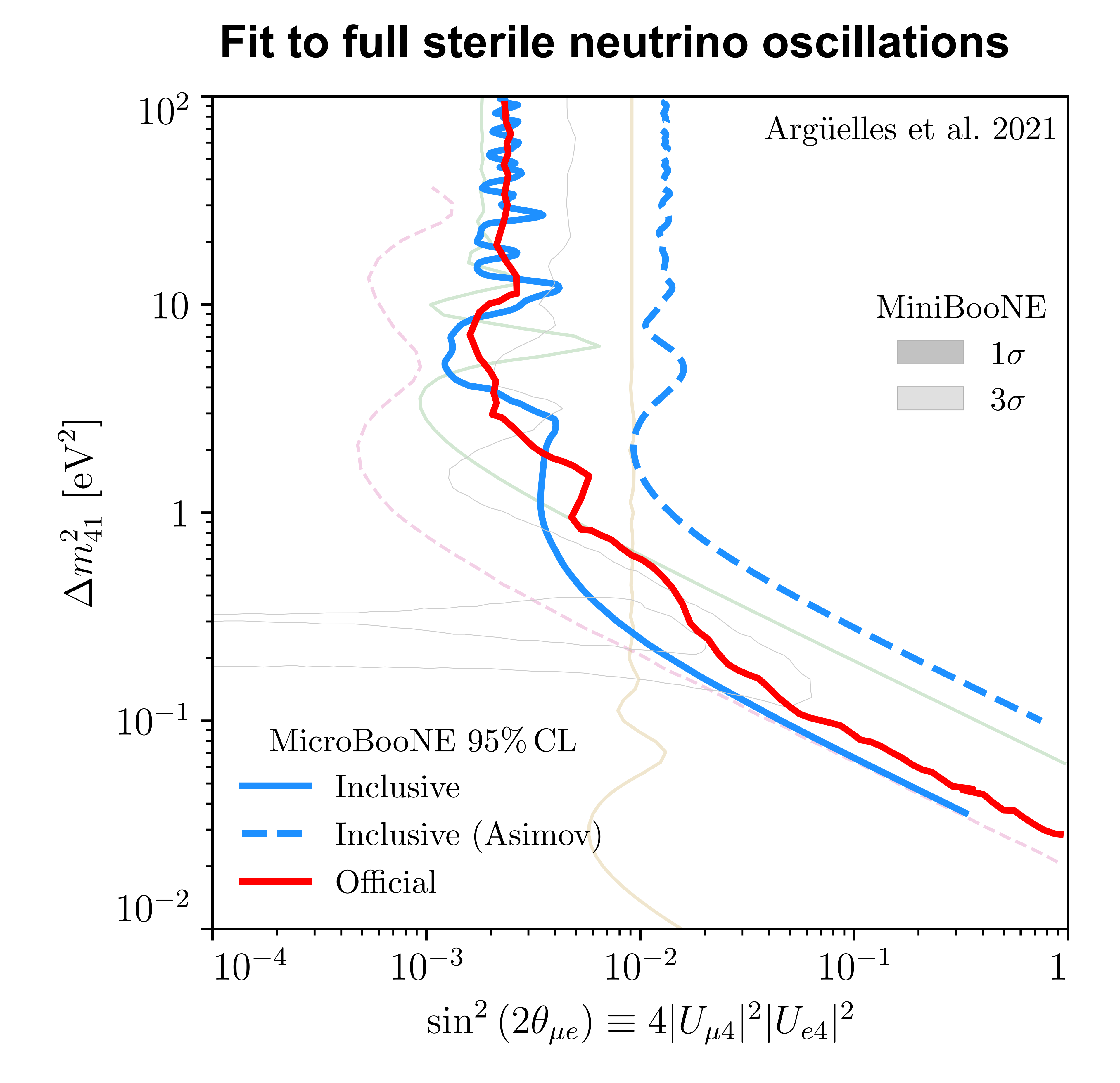


Zooming in on the low-energy excess with MicroBooNE

The ν_e hypothesis (sterile neutrino oscillations)







C. A. Argüelles, I. Esteban, **MH**, K. J. Kelly, J. Kopp, P. A. N. Machado, I. Martinez-Soler, and Y. F. Perez-Gonzalez

PRL 128, 241802.

MicroBooNE coll.,
PRL. 130 (2023) 1, 011801

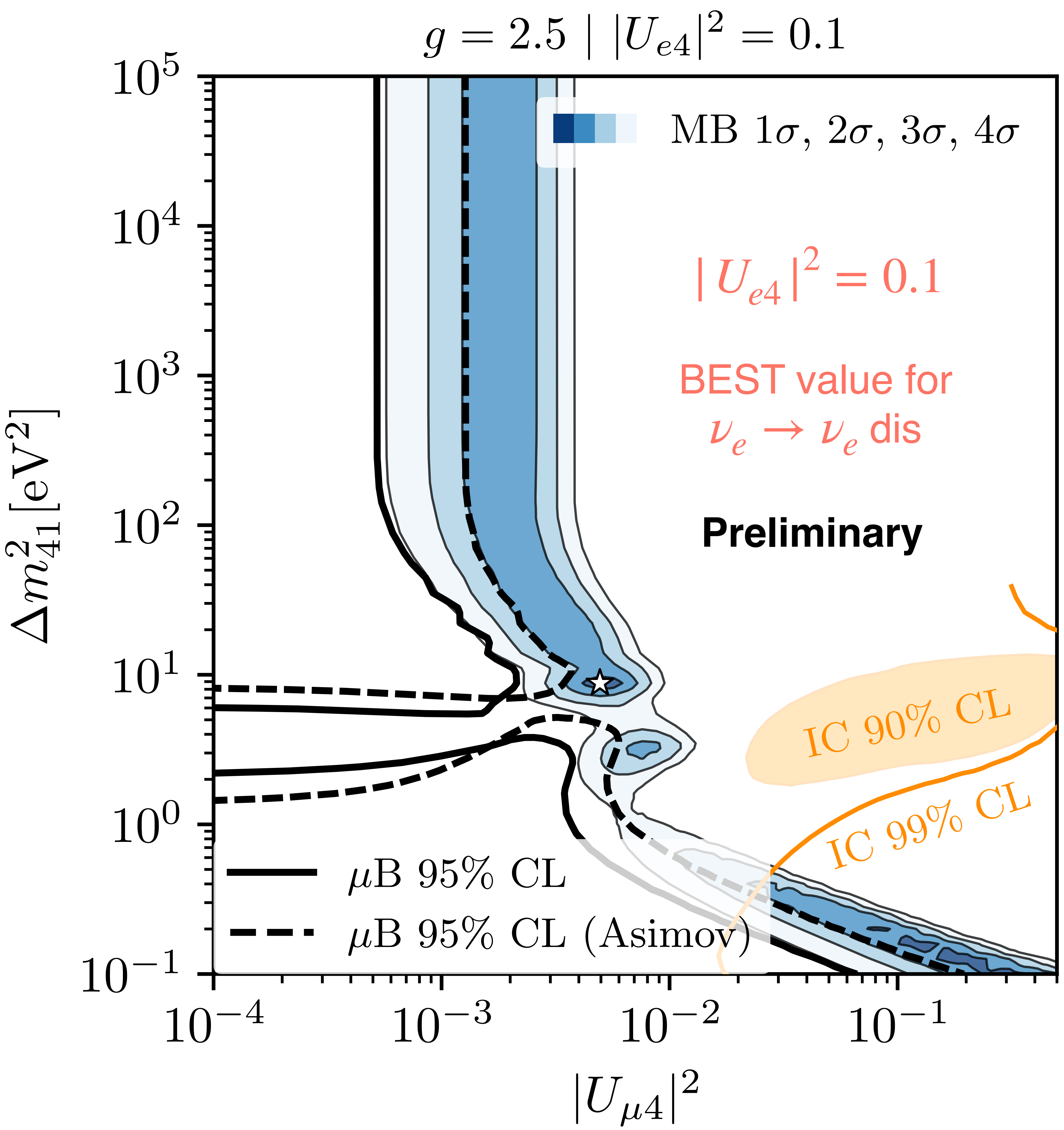
Physics

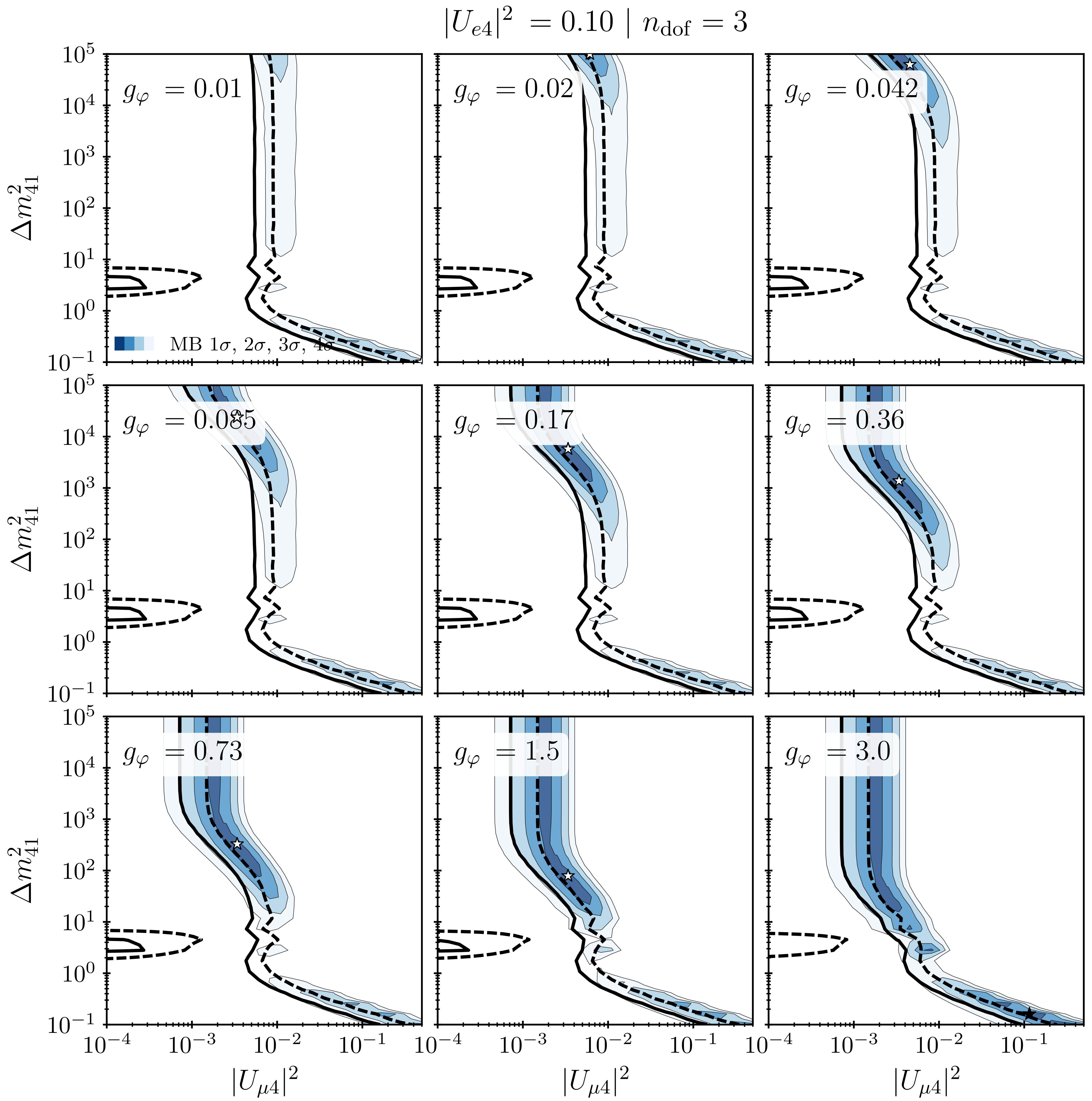
APS Viewpoint:

Neutrino Mystery Endures

Decaying sterile prediction

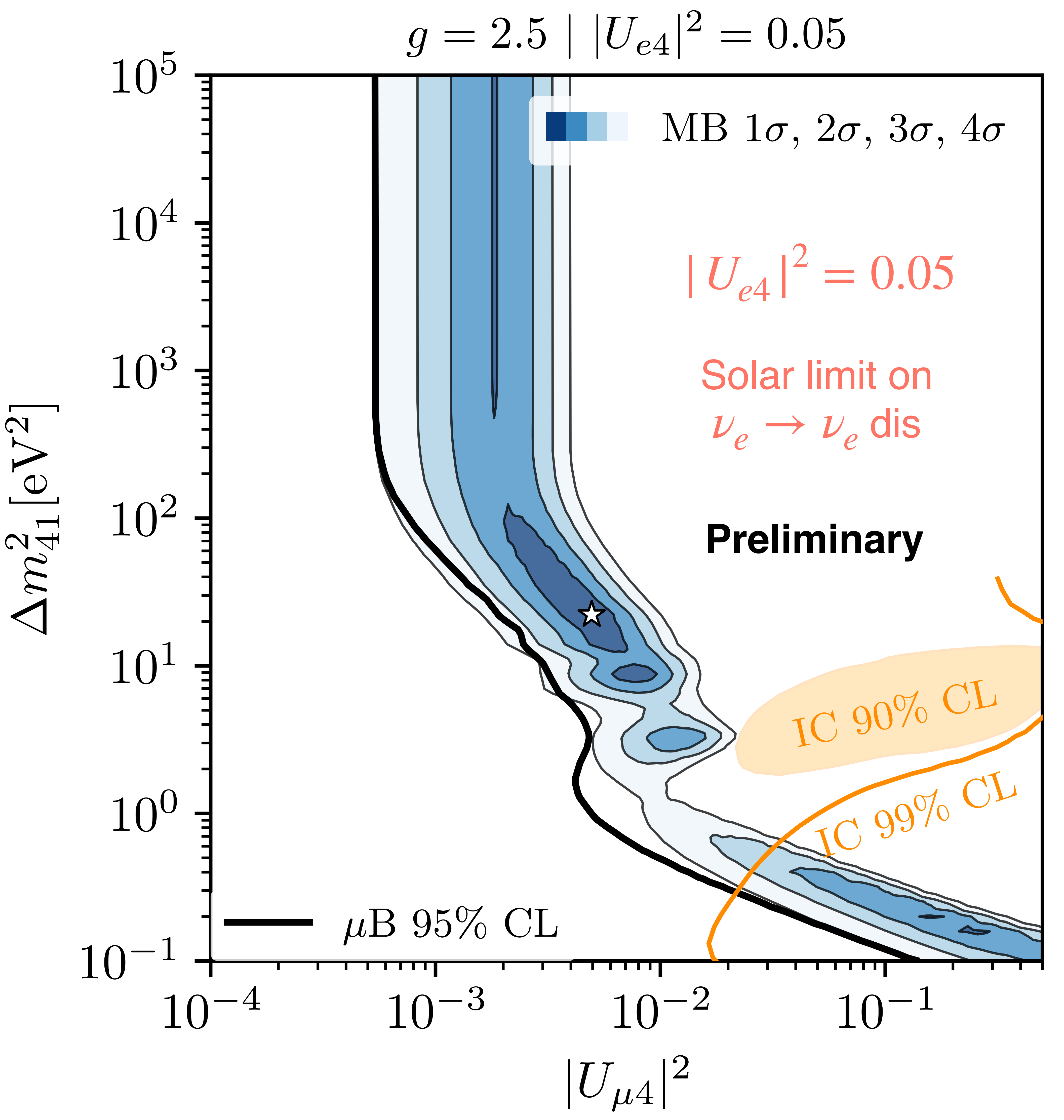
K. Kelly, MH, T. Zhou, *in preparation.*

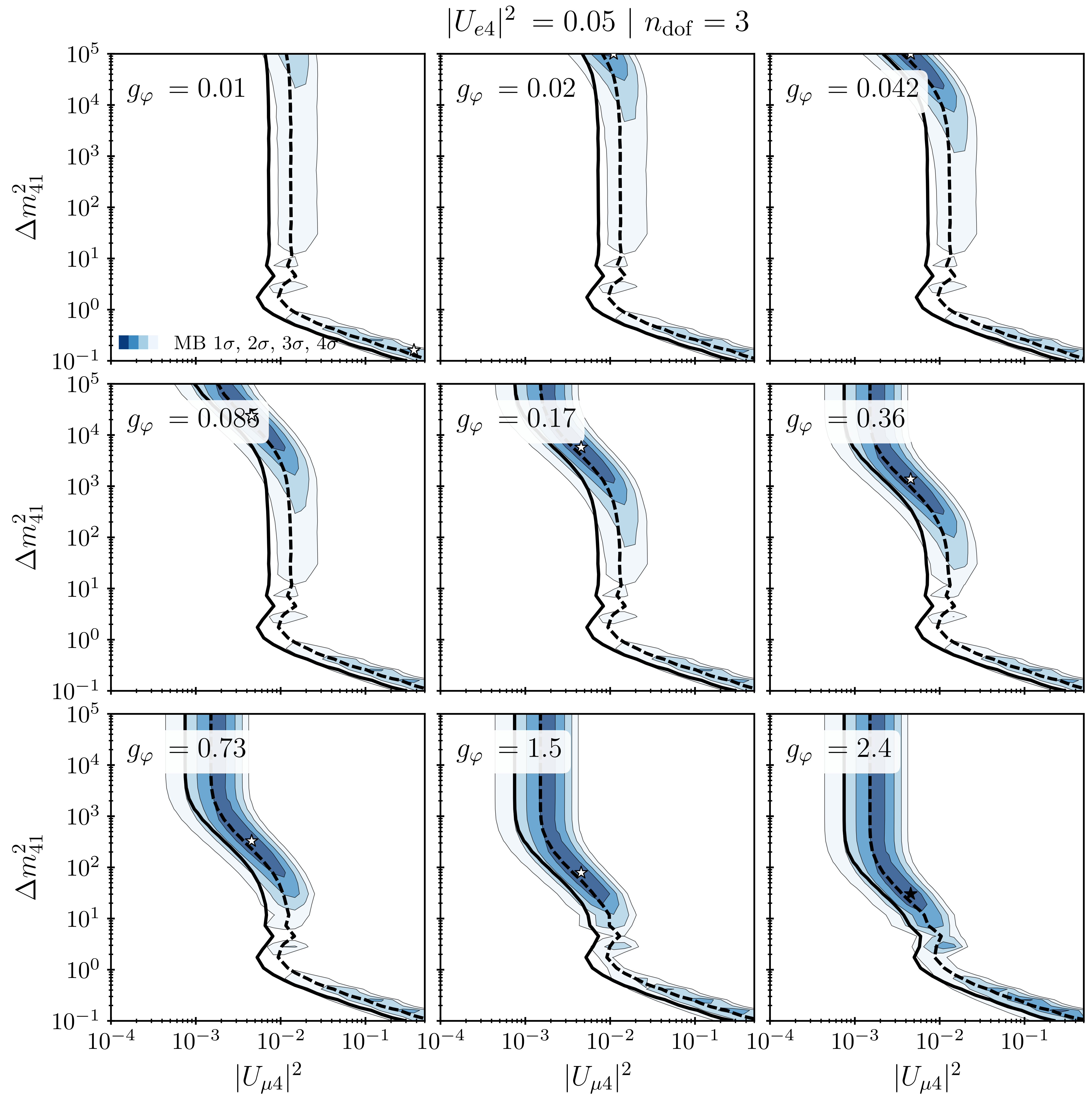


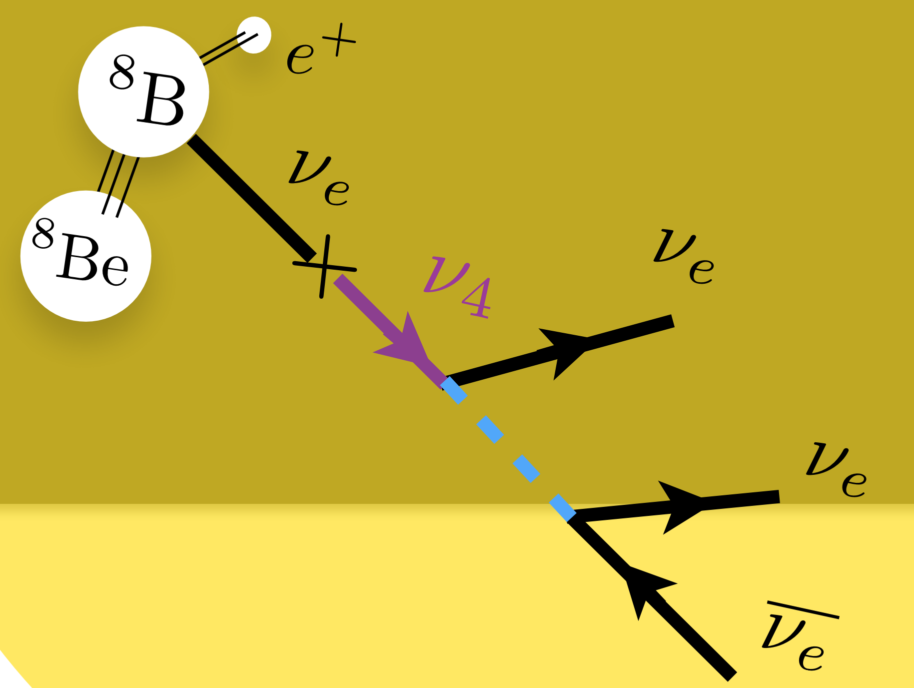


Decaying sterile prediction

K. Kelly, MH, T. Zhou, *in preparation.*







Solar antineutrinos

IBD searches for $\overline{\nu}_e$ from ^8B decay and matter suppressed oscillations