Tau Neutrinos and what lies beyond …

Carlos Argüelles
HARVARD UNIVERSITY

NuTau2021
September, 2021
Online

Outline

- The odyssey of HNL tau searches
- Three, four, or more neutrinos
- A search for misbehaving neutrinos

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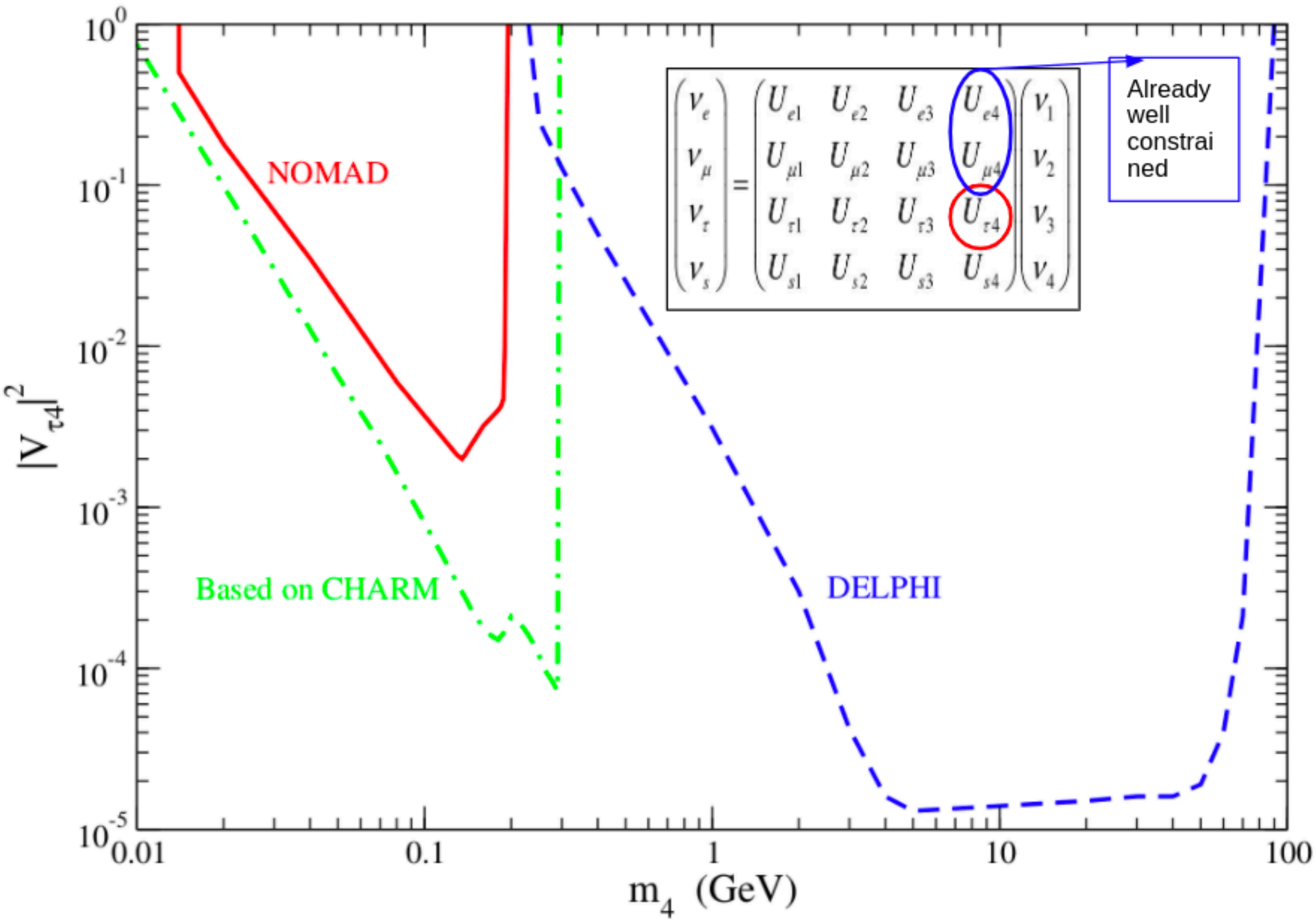
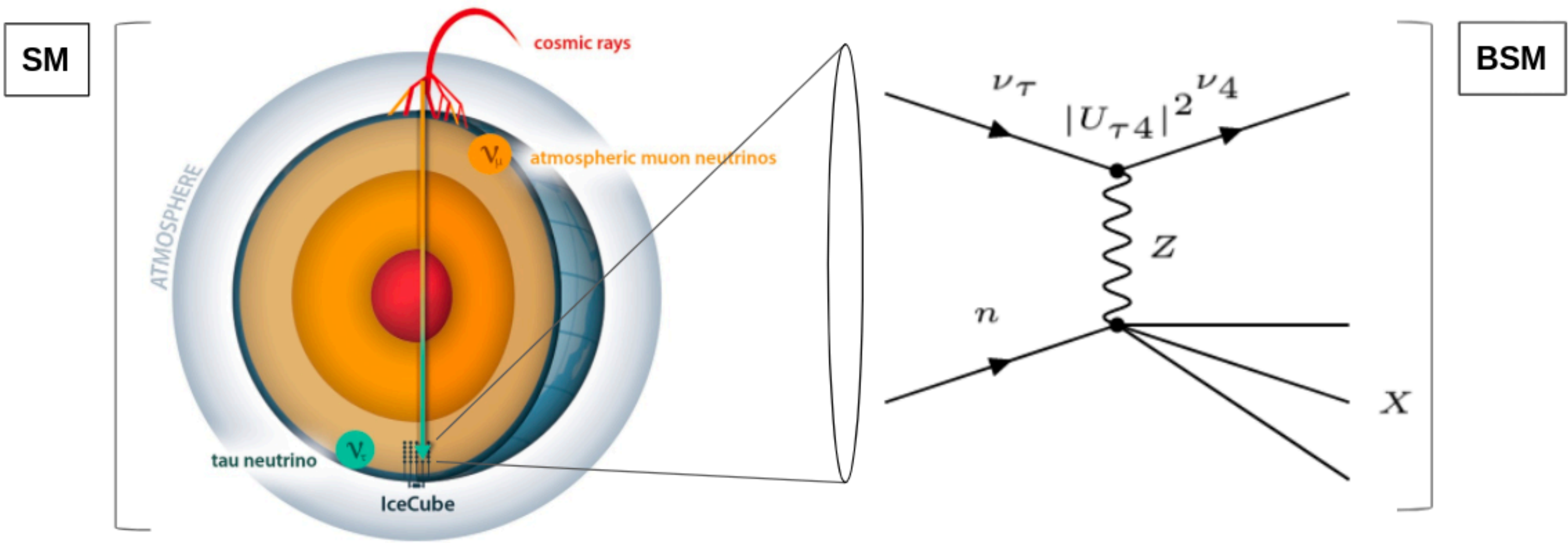
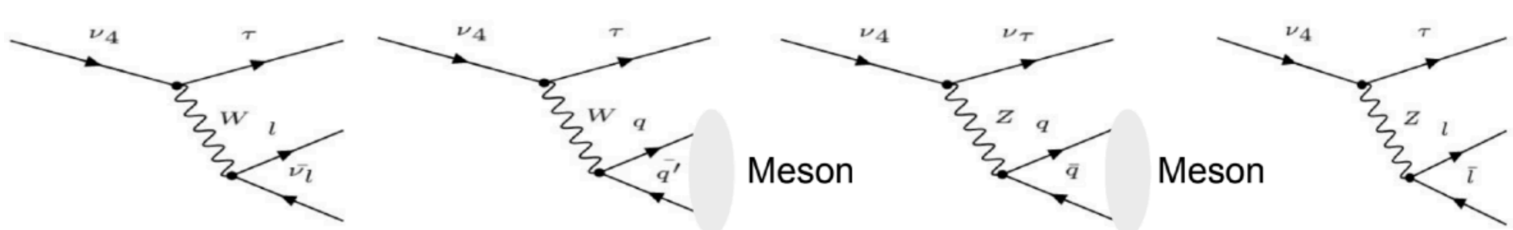
A triangle of opportunity



Search using atmospheric neutrinos

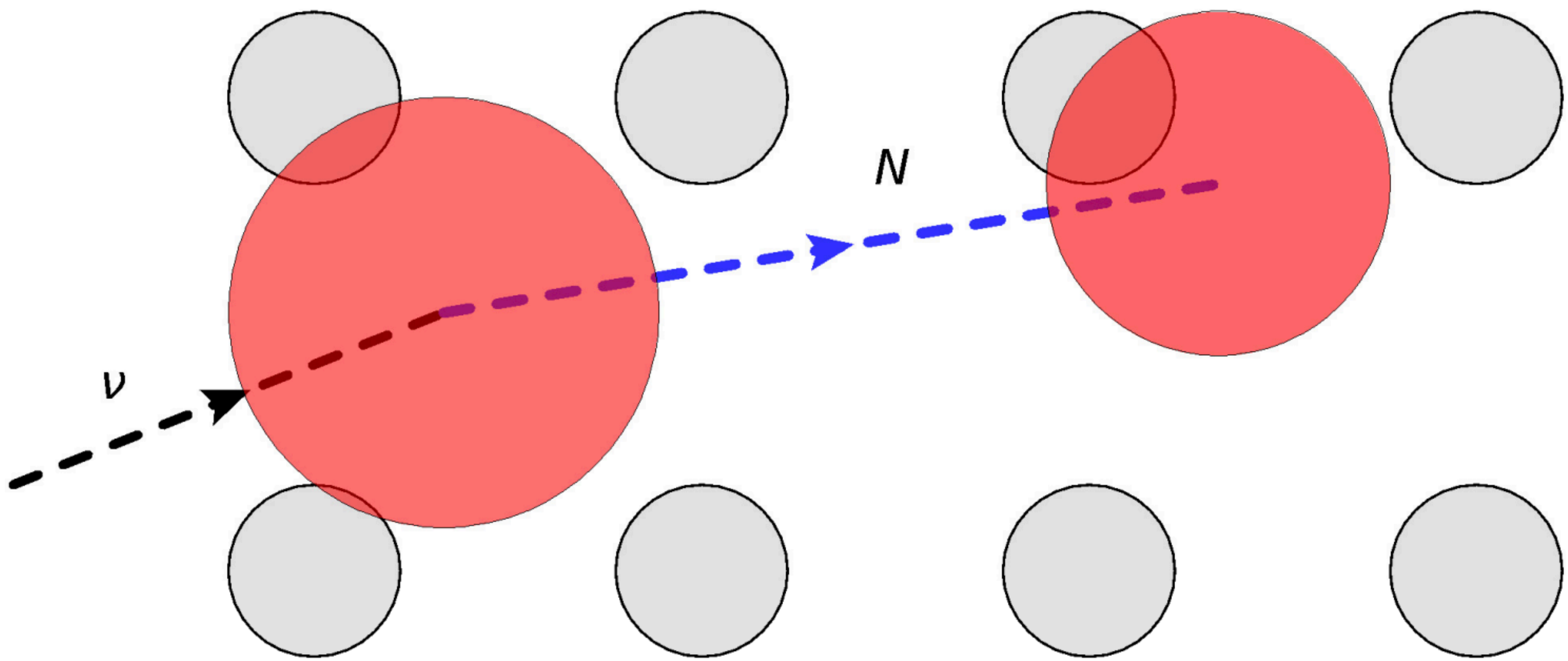


And **decays**:



Coloma, Machado, Martinez-Soler & Shoemaker Phys. Rev. Lett. 119, 201804 (2017)

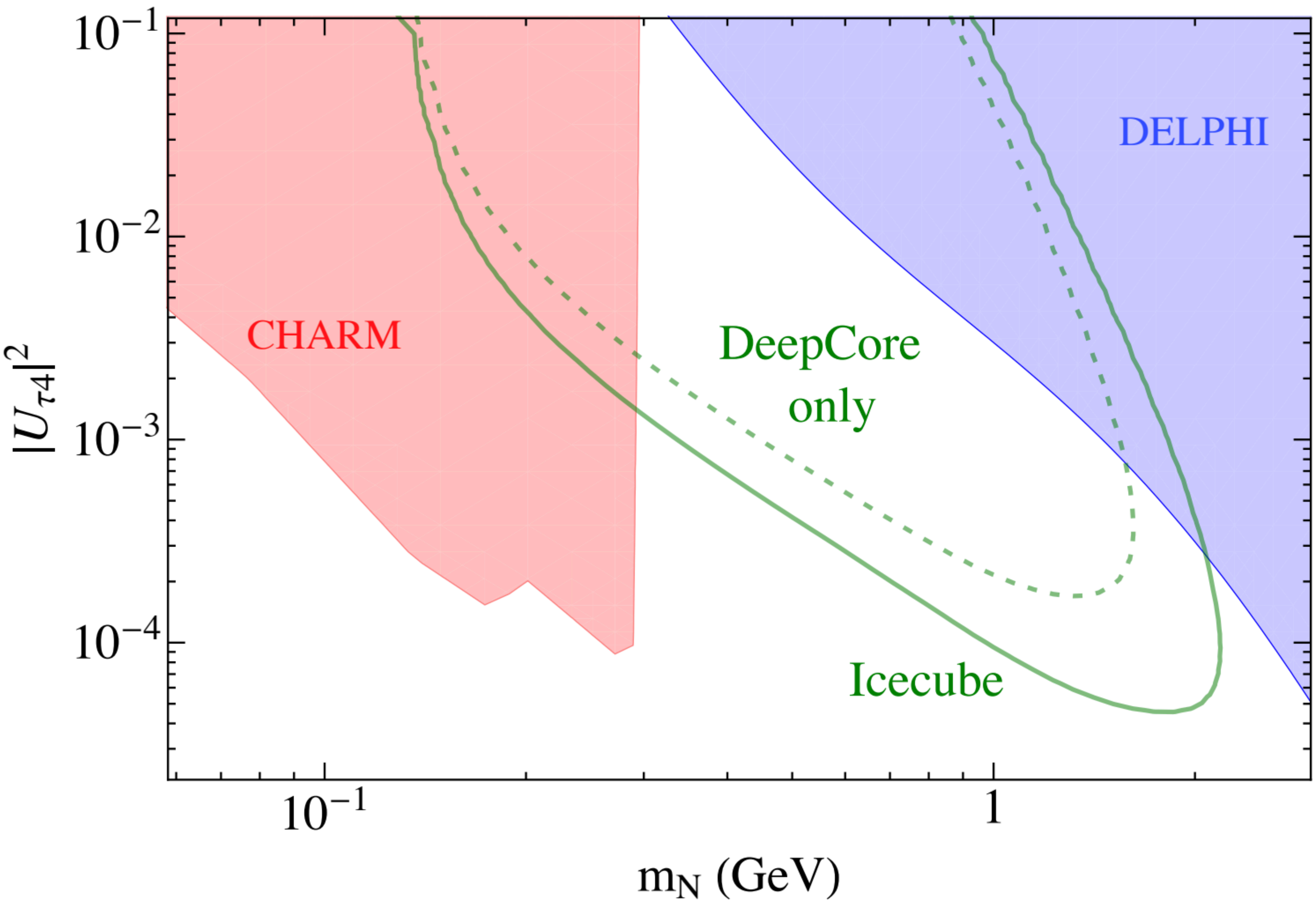
Signature is like a low-energy *double bang*



Coloma, Machado, Martinez-Soler & Shoemaker Phys. Rev. Lett. 119, 201804 (2017)

Signature also produced by TMM. See ref. above and Magill (1803.03262), Brdar (2007.15563), Vergani (2105.06470), …

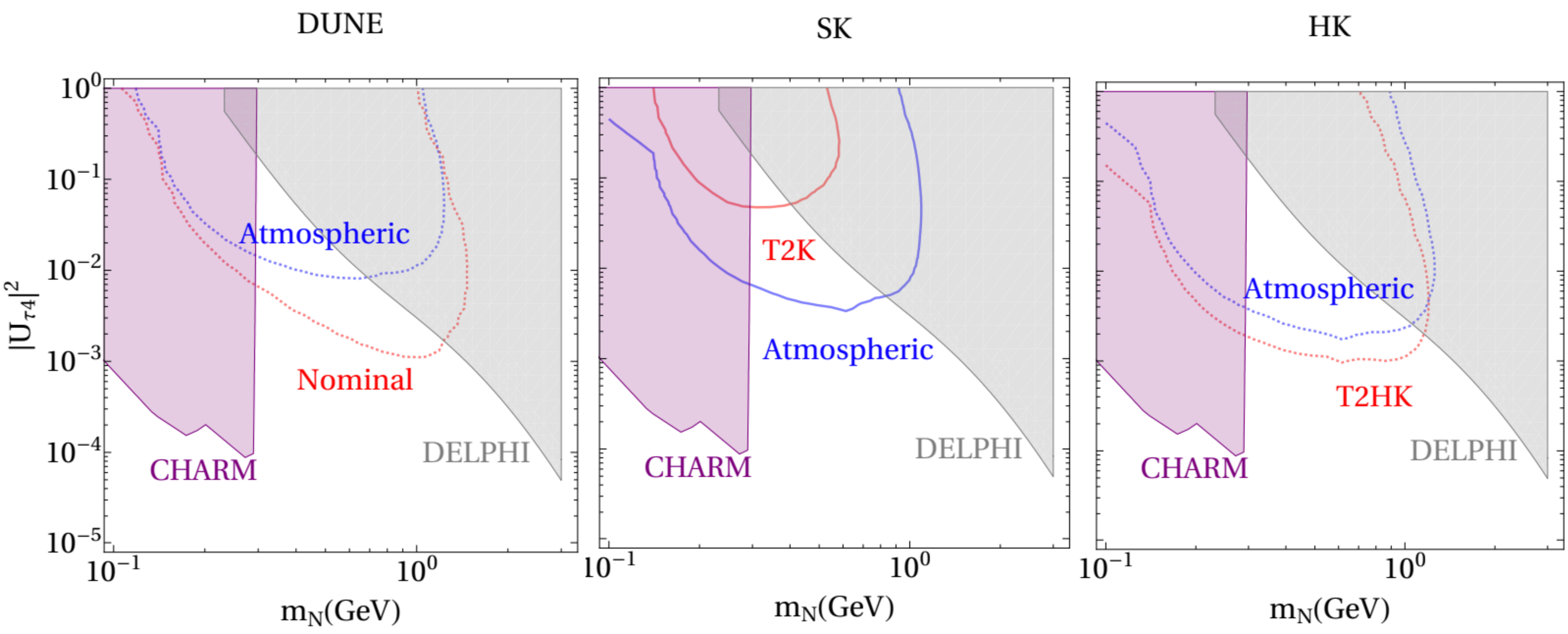
Search for HNLs



Coloma et al Phys. Rev. Lett. 119, 201804 (2017)

Prospects in other experiments

Nice complementarity between natural and anthropogenic neutrino sources!



*Contours represent one HNL event

Atkinson et al arXiv:2105.09357
see also Coloma et al 2007.03701 for non-double-bang event estimations

Prospects in other experiments

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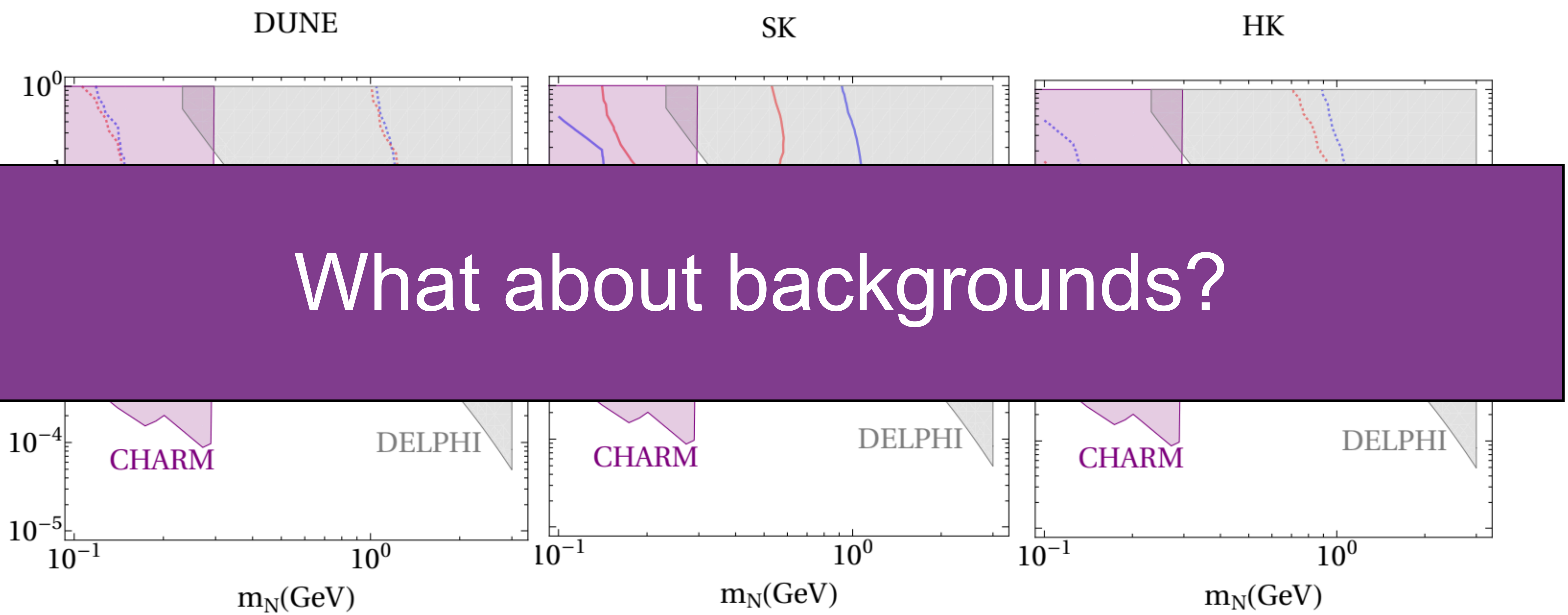
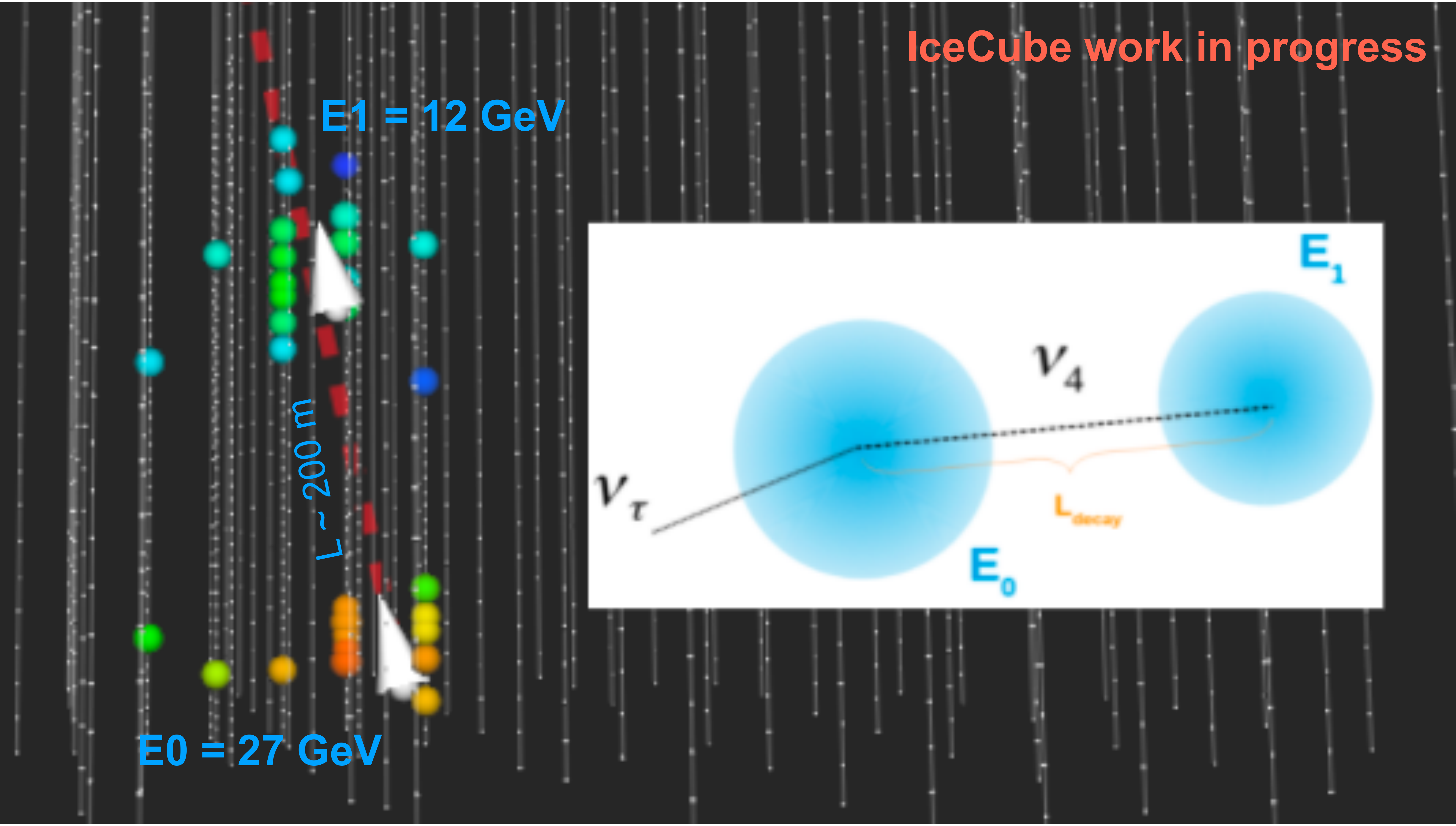


What about backgrounds?

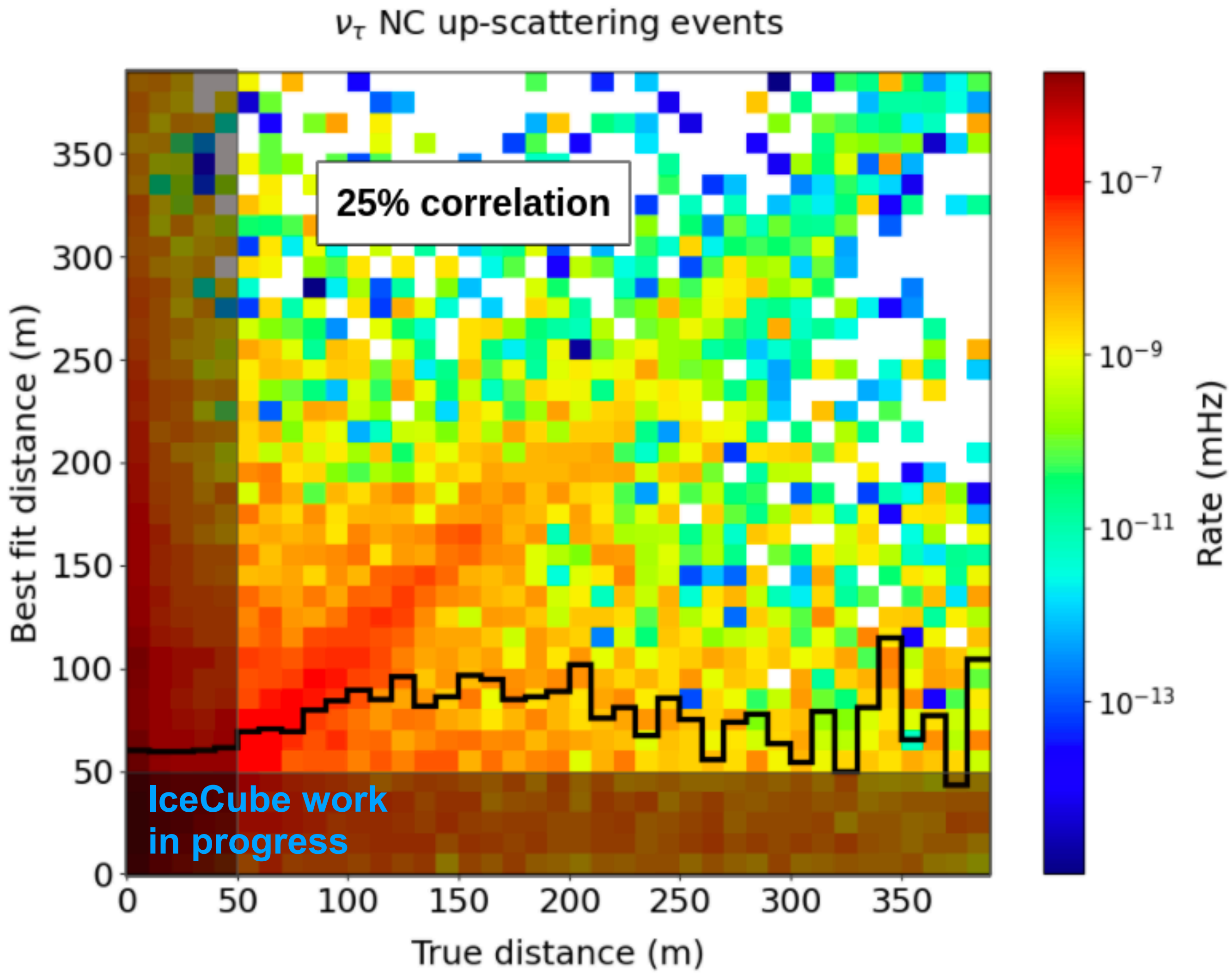
*Contours represent one HNL event

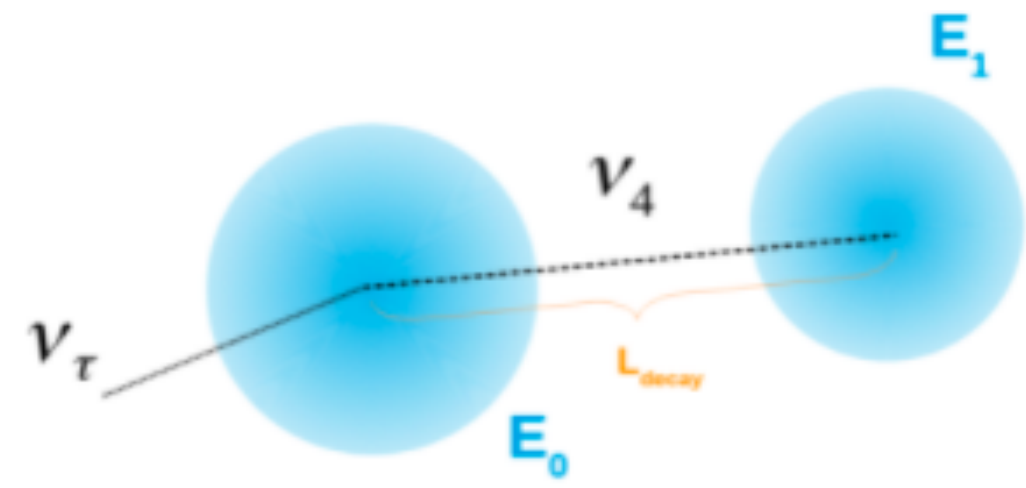
Atkinson et al arXiv:2105.09357
see also Coloma et al 2007.03701 for non-double-bang event estimations

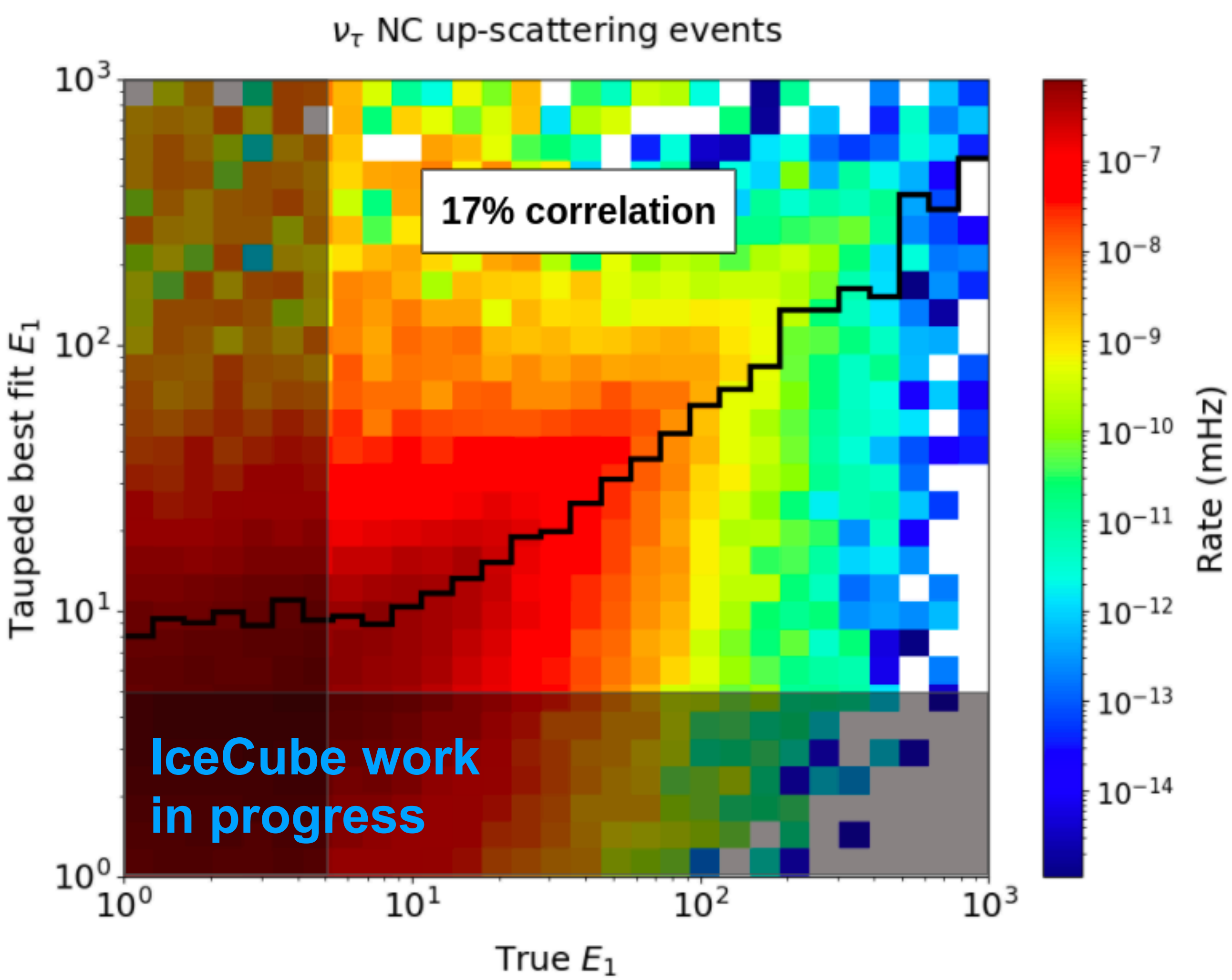
Signature in IceCube



Reconstruction Performance





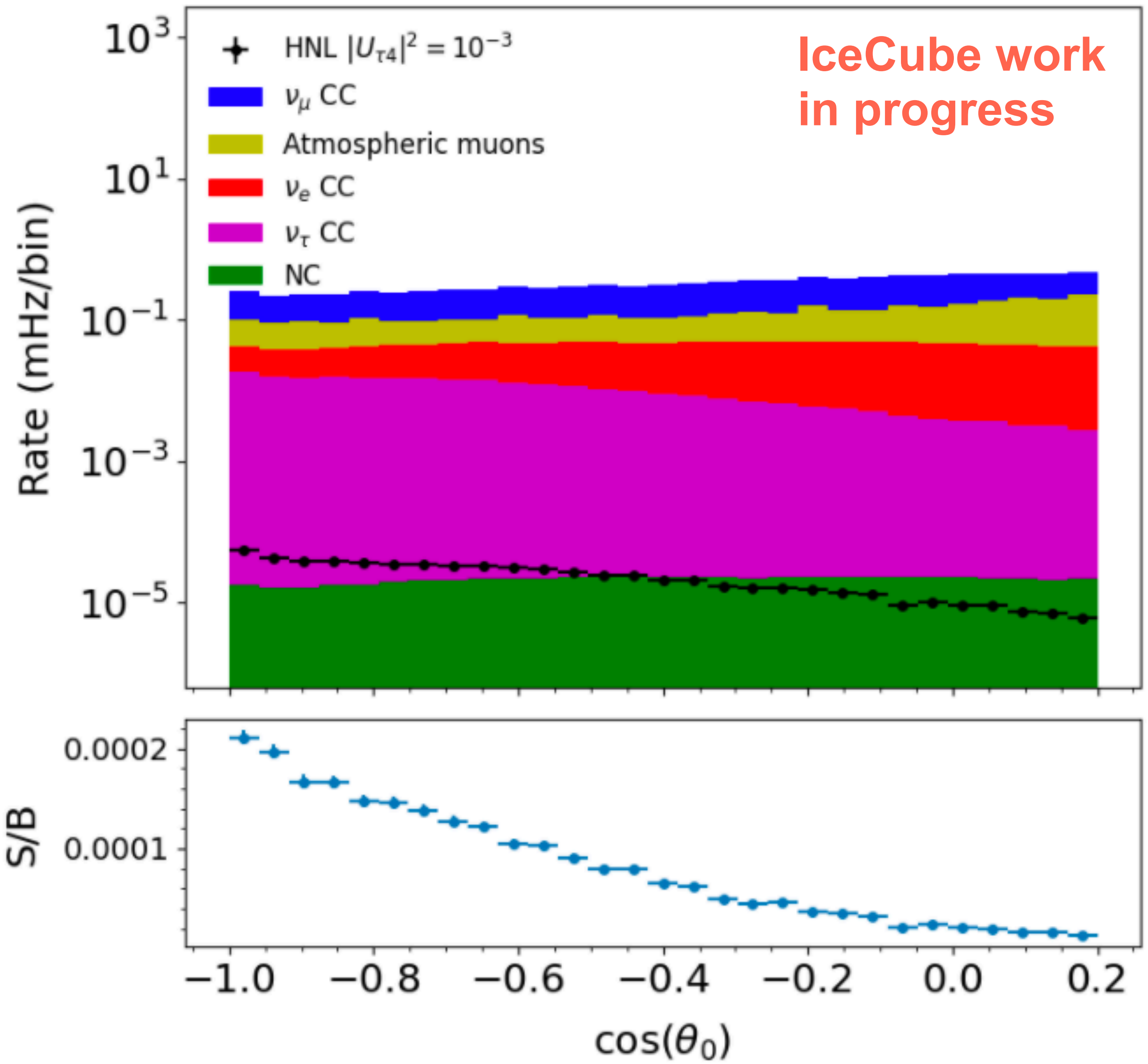


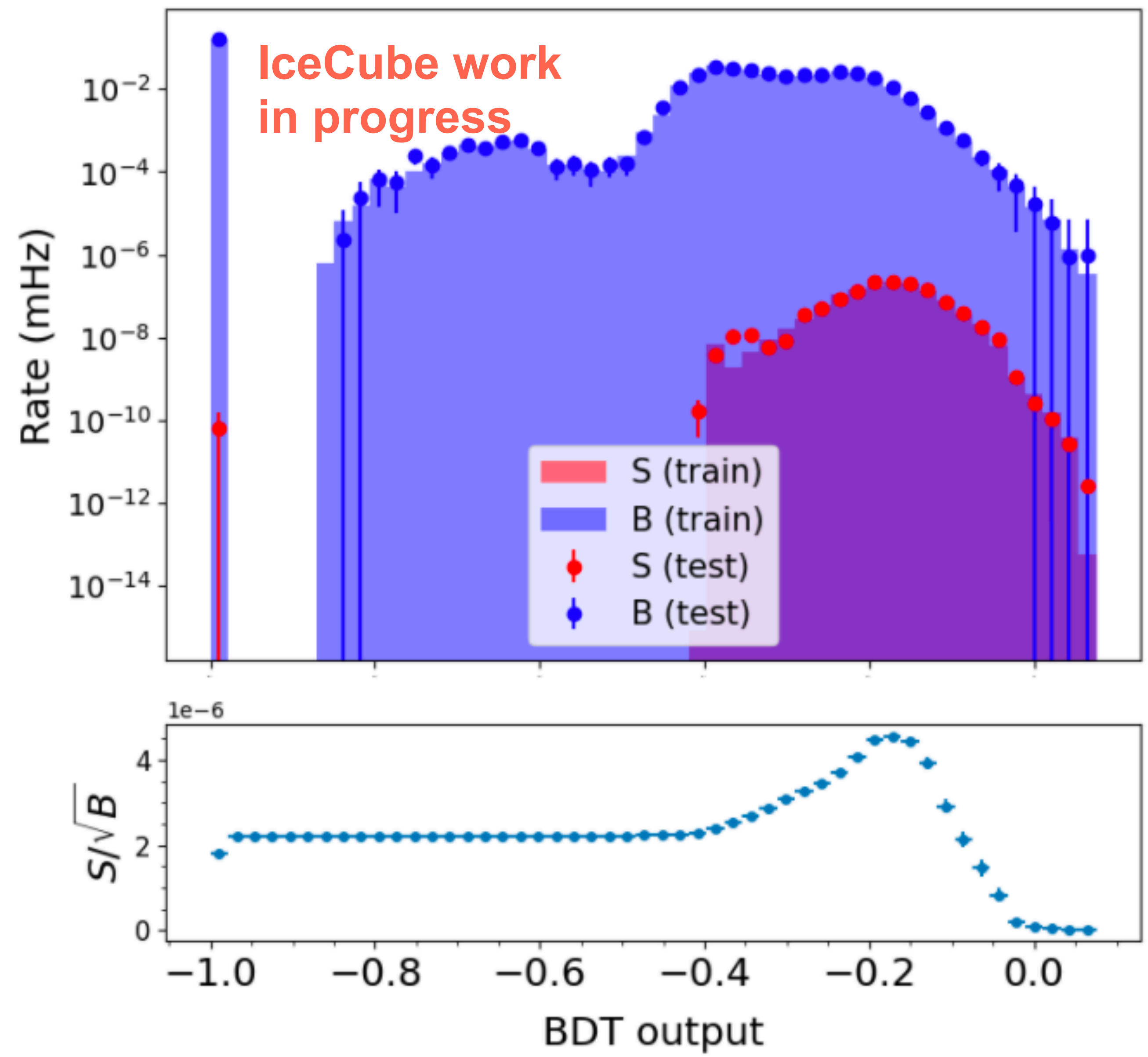
Reconstruction of low-energy double cascades is challenging.

Distance resolution is poor due to two scenarios: contained and unconfined double cascades.

D. Vannerom PANIC2021

Signal vs background

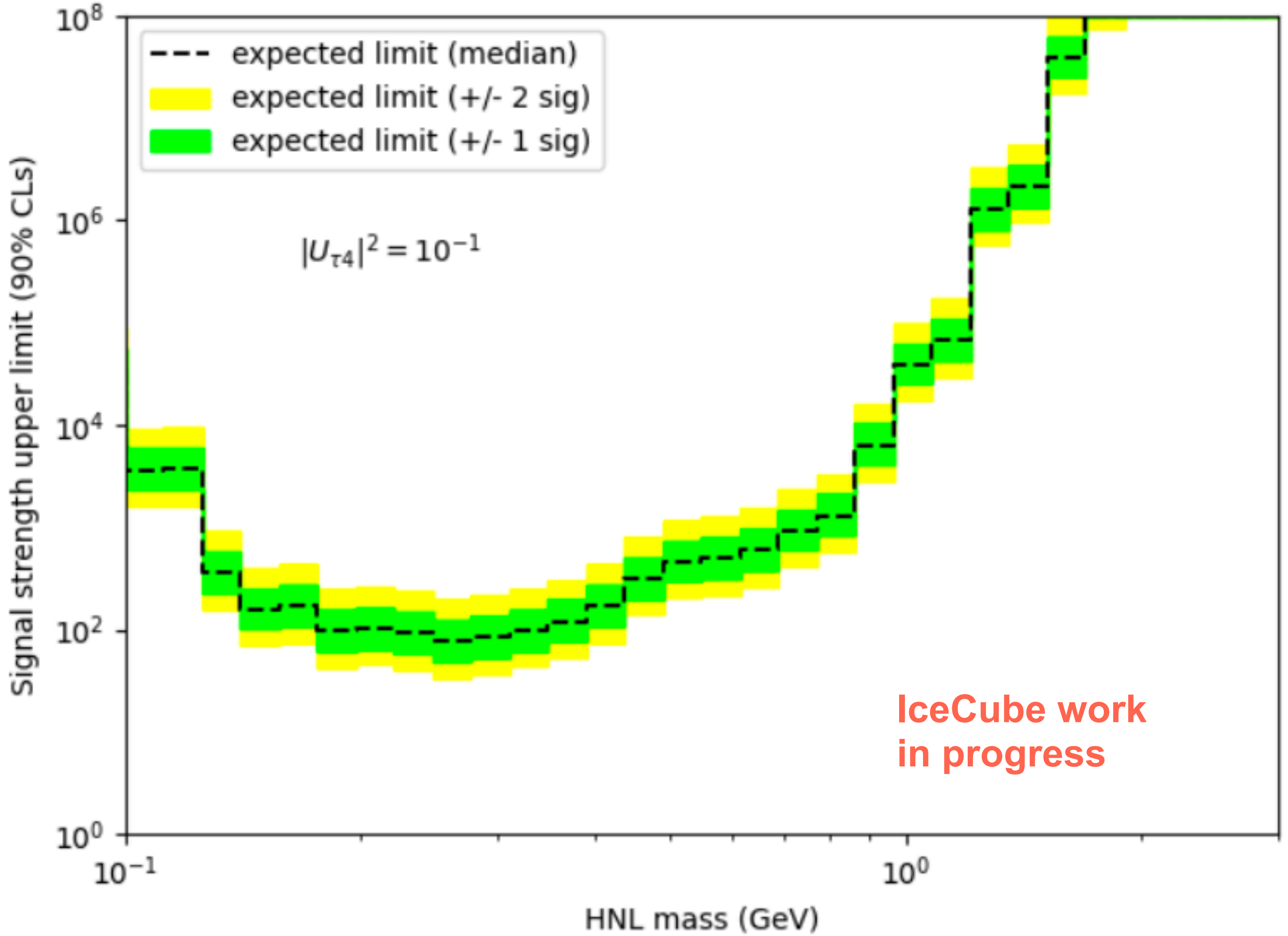




For $|U_{\tau 4}| = 10^{-1}$: $S/\sqrt{B} \sim 5 \times 10^{-6}$ at BDT = -0.2

D. Vannerom PANIC2021

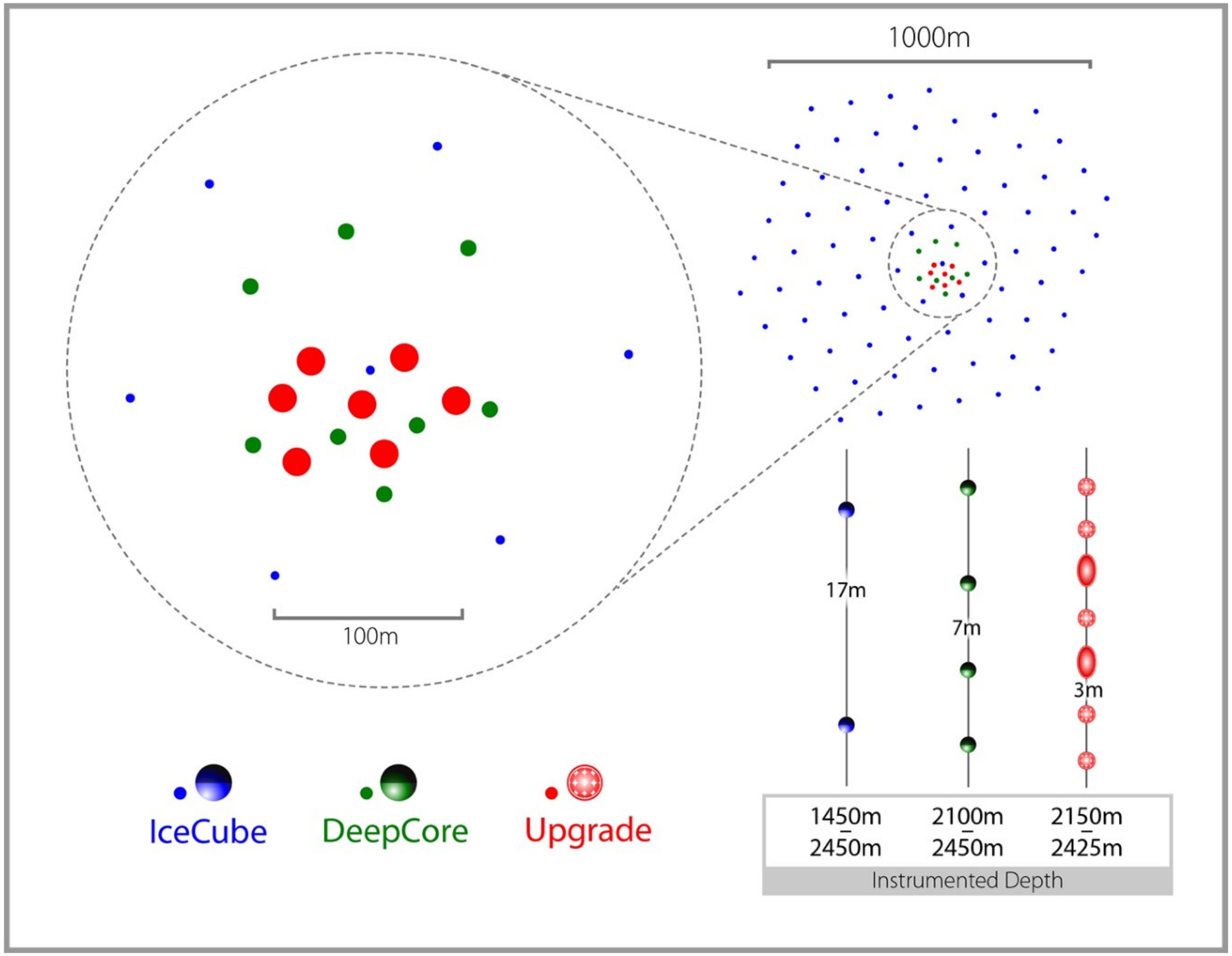
Estimated Sensitivity



Current sensitivity is not as good as expected due to large backgrounds.

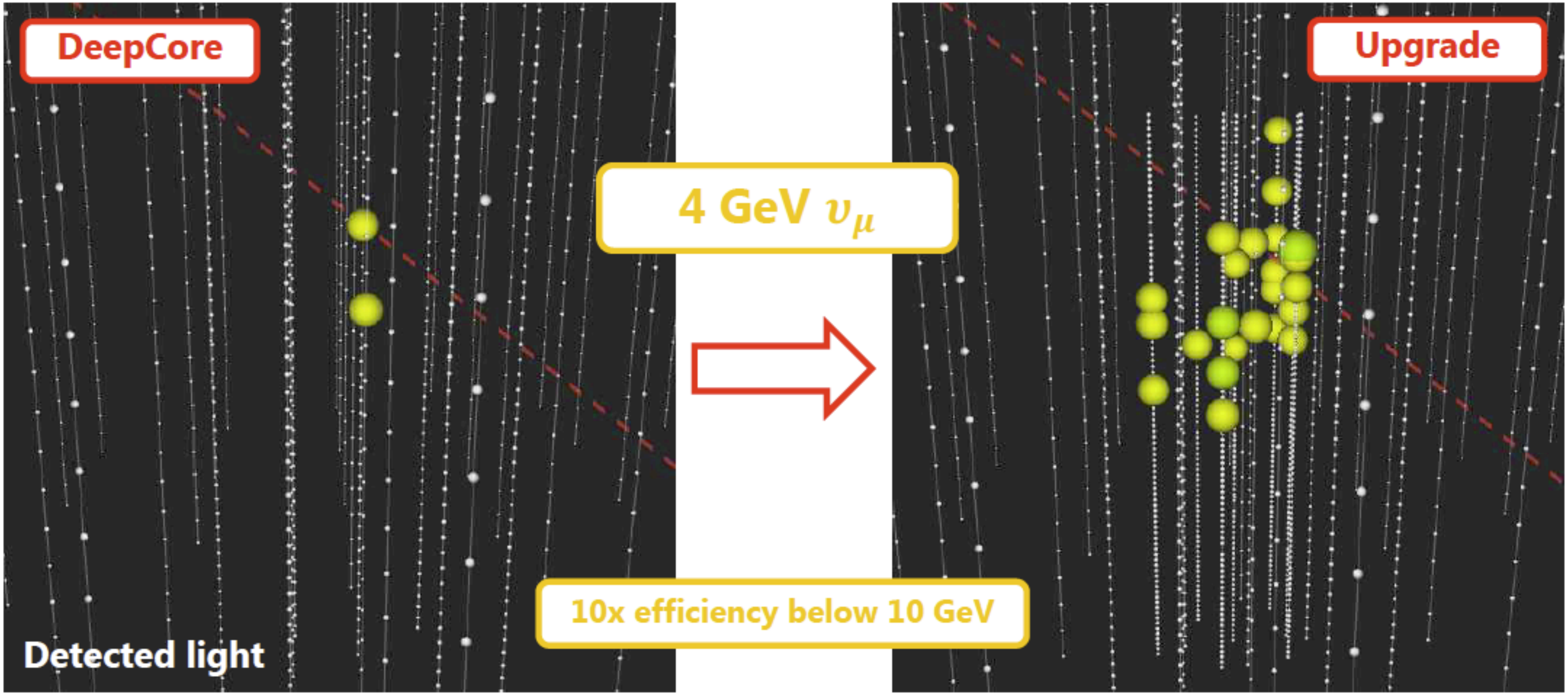
But, there is hope!

The IceCube-Upgrade



Improved sensitivity to low-energy neutrinos and ice characterization.

Improved light-collection for low-energy events

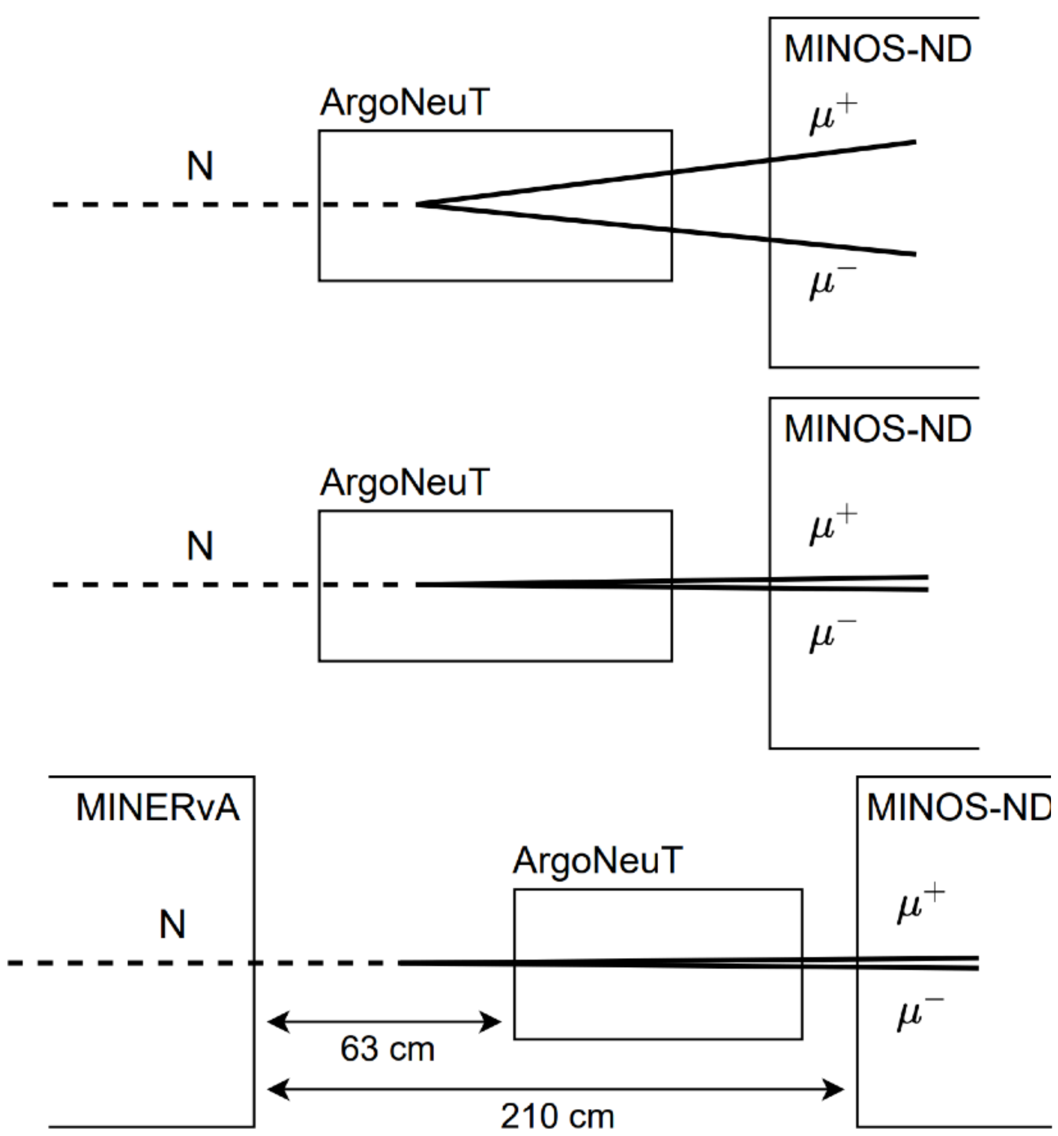


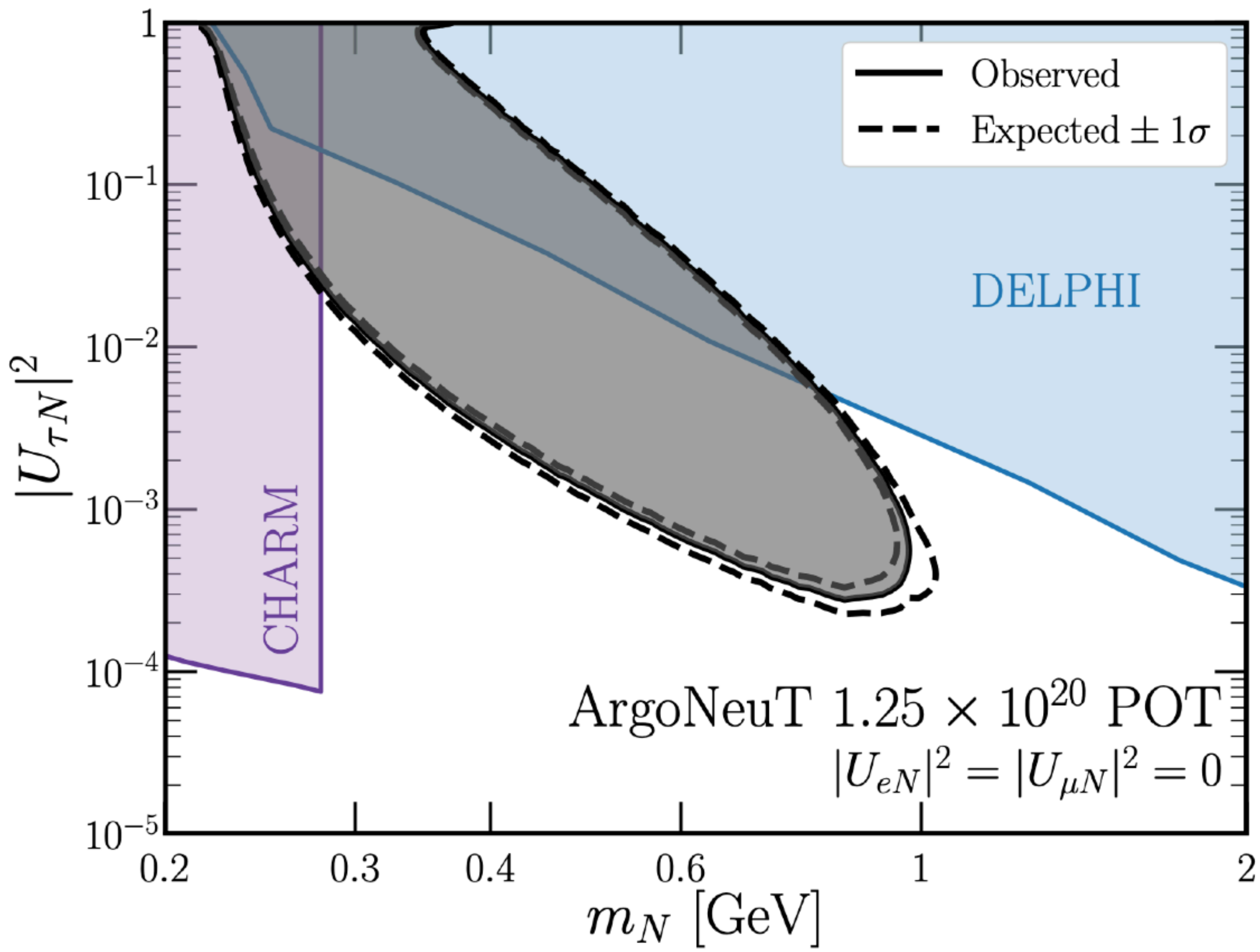
Summer Blot Neutrino2020

*DeepCore (shown on the left) is the current low-energy extension of IceCube

Recent constraints from ArgoNeuT

*Diagrams not to scale

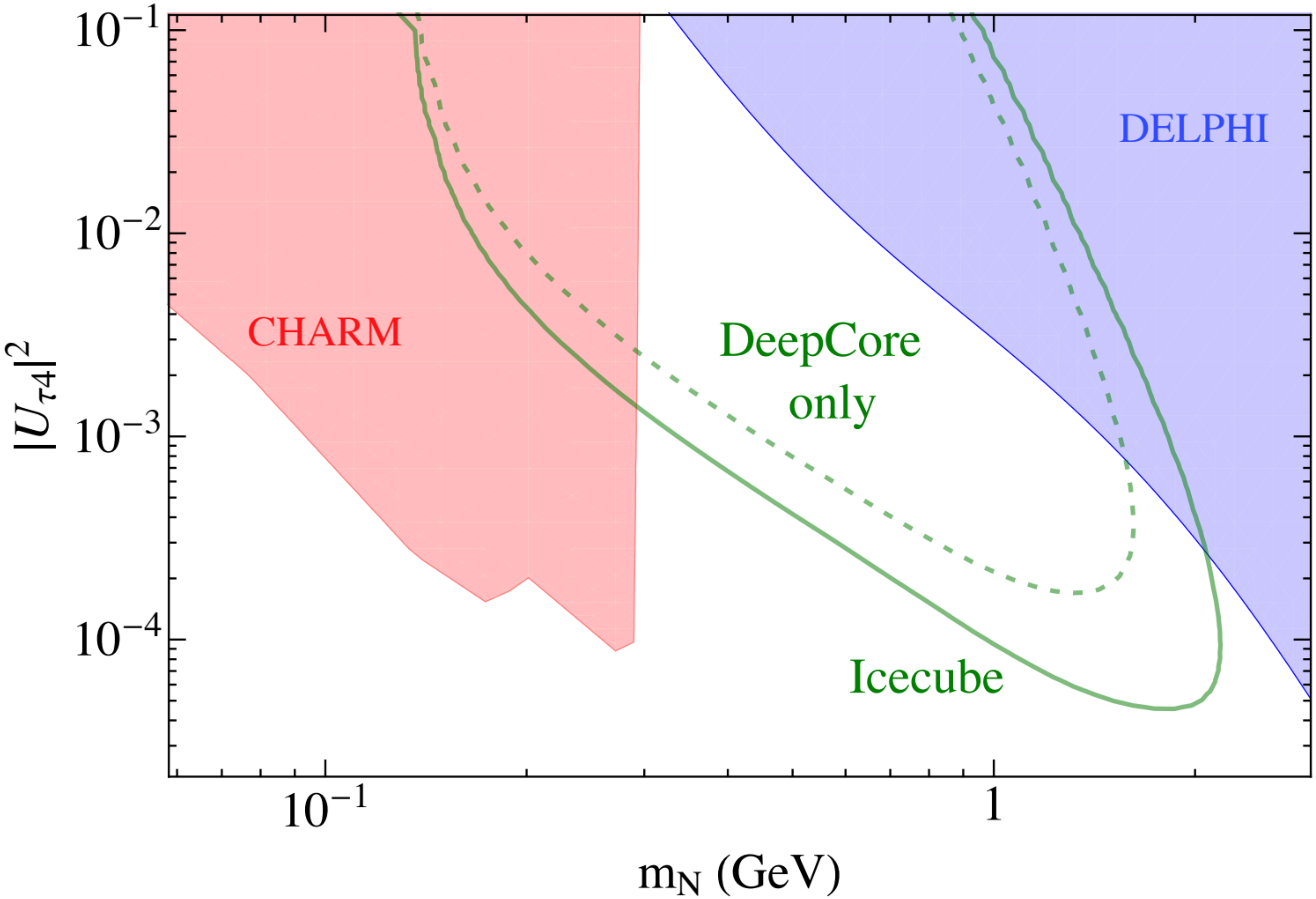




- HNLs are produced in the NuMI target.
- 120 GeV protons producing D/Ds, which can decay to taus subsequently producing HNLs
- Search focused on $N \to \nu\mu^+\mu^-$

ArgoNeuT Collaboration arXiv:2106.13684

Why does the CHARM bound stop abruptly?



Adapted from Coloma et al Phys. Rev. Lett. 119, 201804 (2017)

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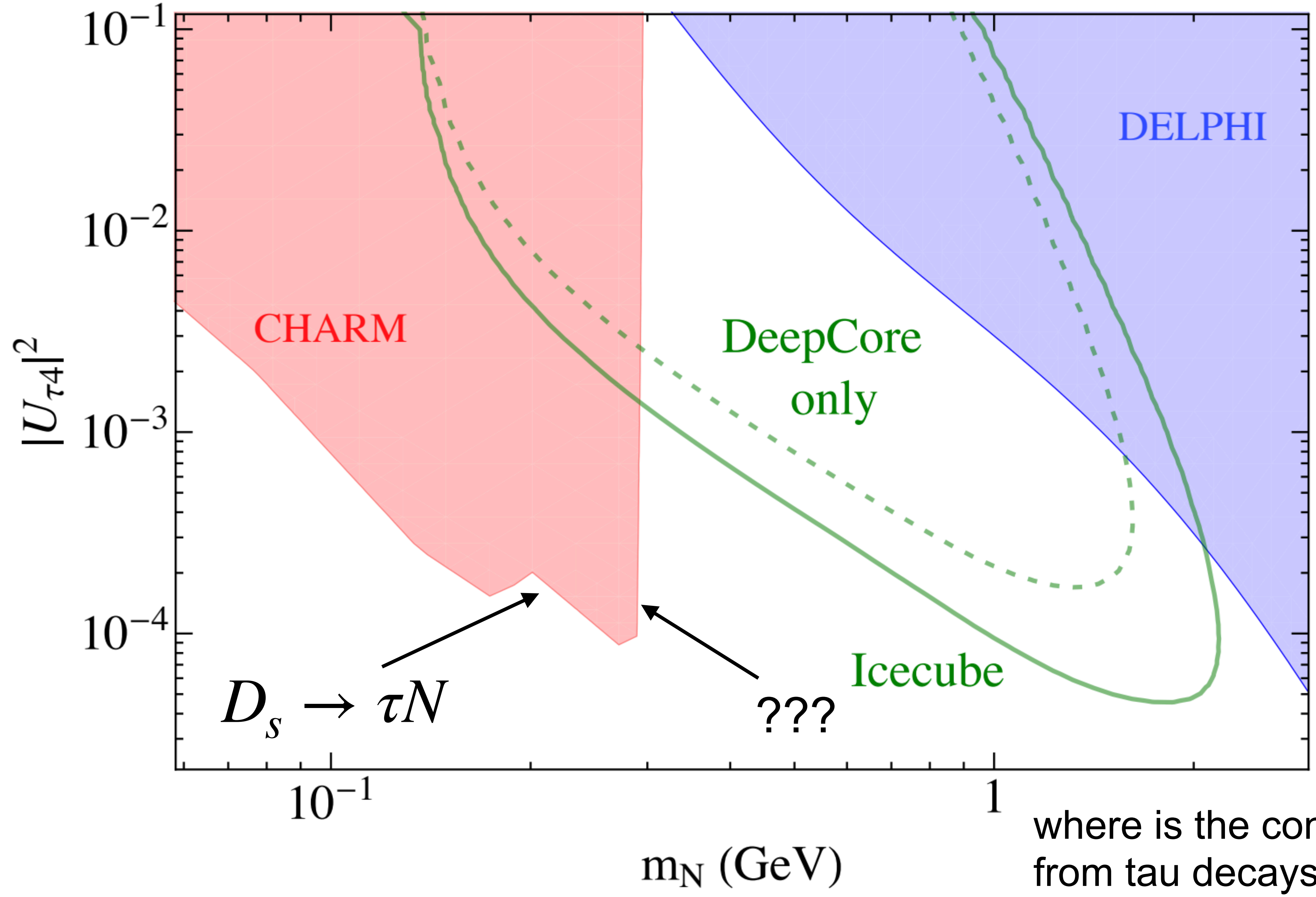
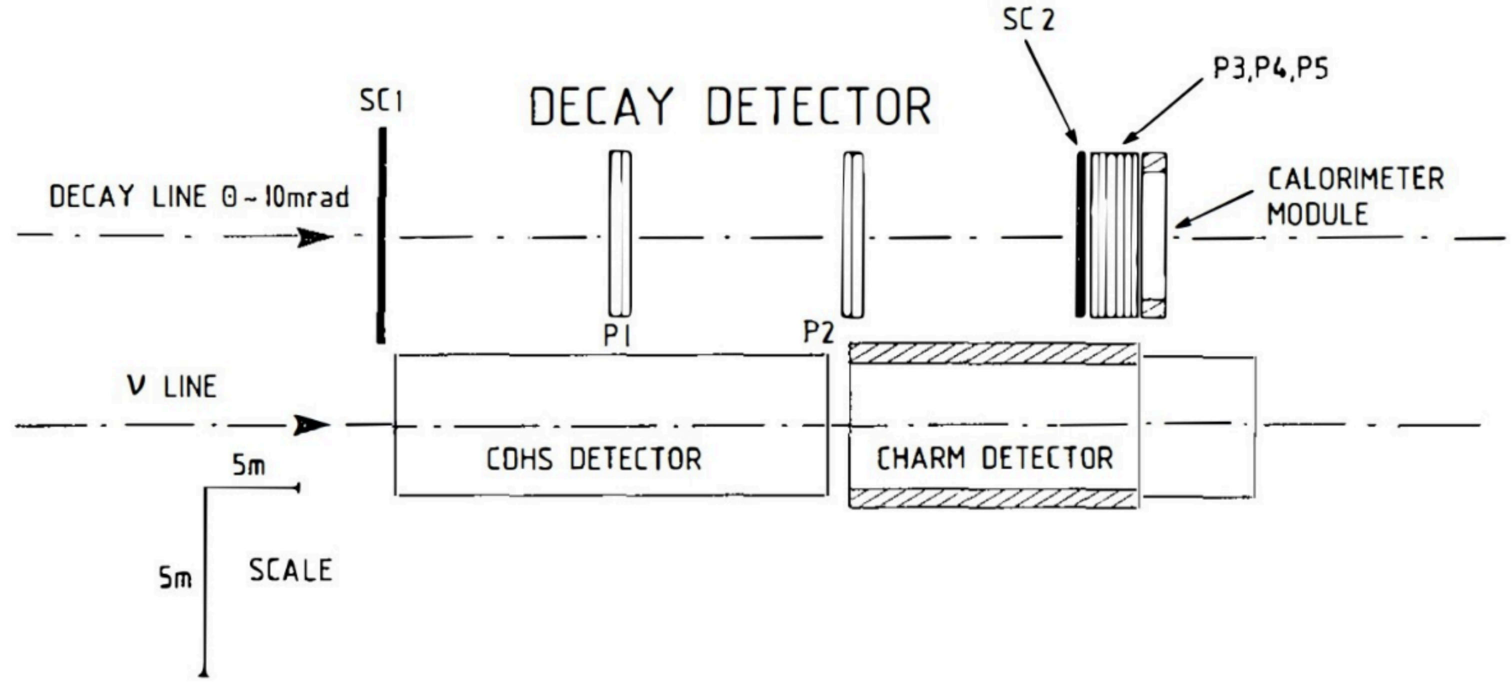
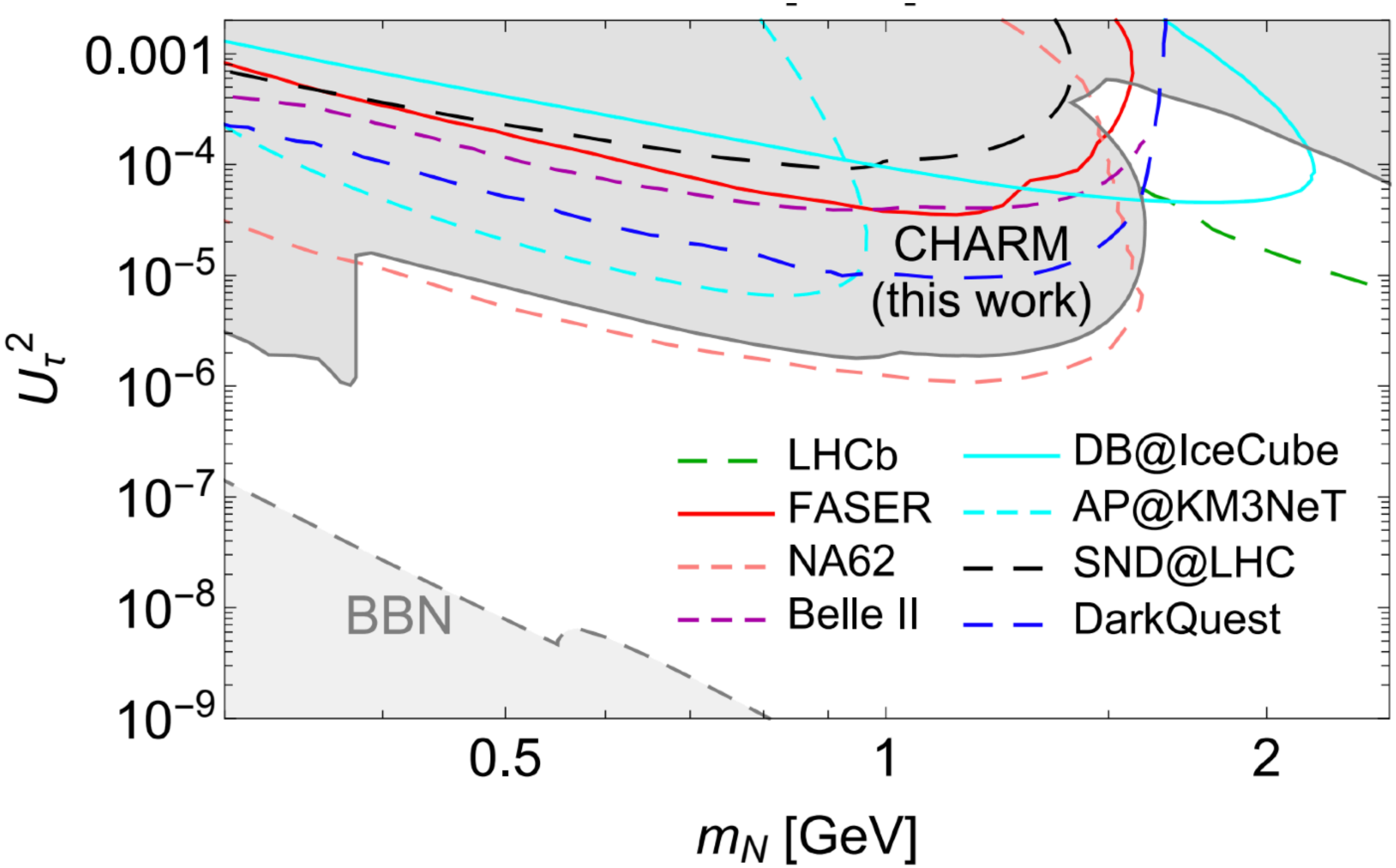


where is the contribution from tau decays?

Adapted from Coloma et al Phys. Rev. Lett. 119, 201804 (2017)

A blast from the past!

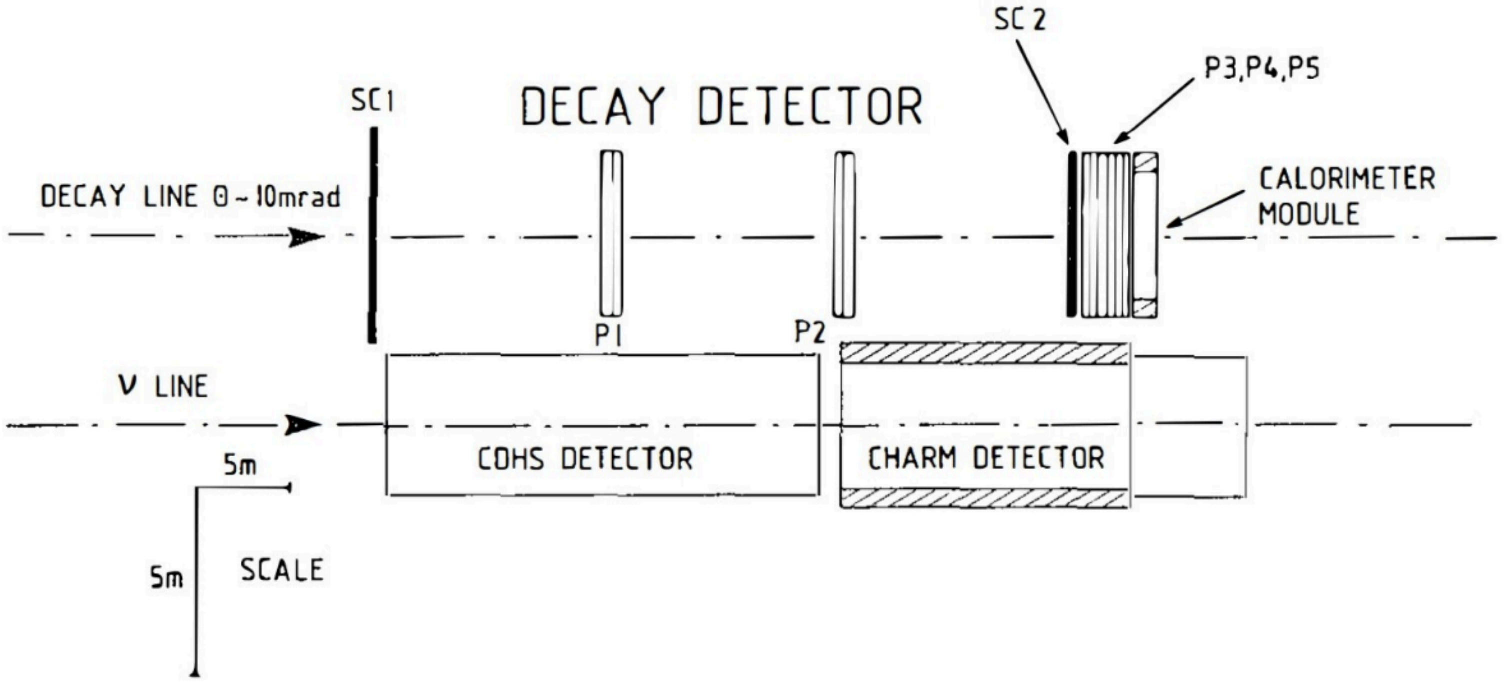


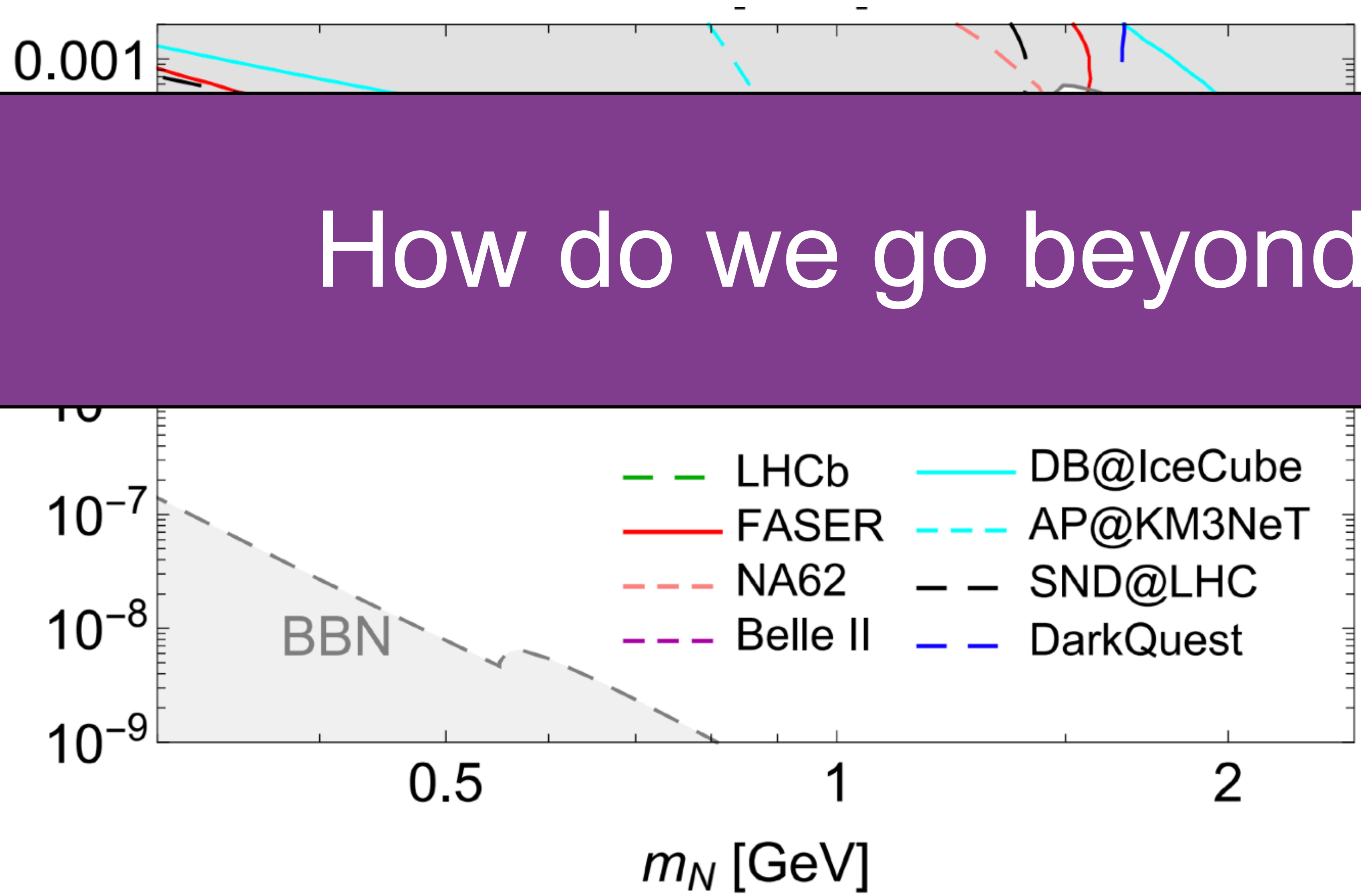


- Authors revisited the HNL flux prediction
- Added contribution from tau decay.
- <u>Opportunity triangle gone.</u>

Boiarska et al arXiv:2107.14685

A blast from the past!





How do we go beyond this?

- Added contribution from tau decay.
- <u>Opportunity triangle gone.</u>

Boiarska et al arXiv:2107.14685

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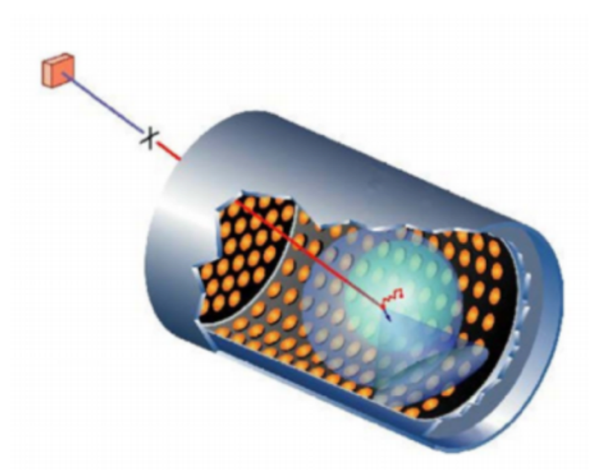
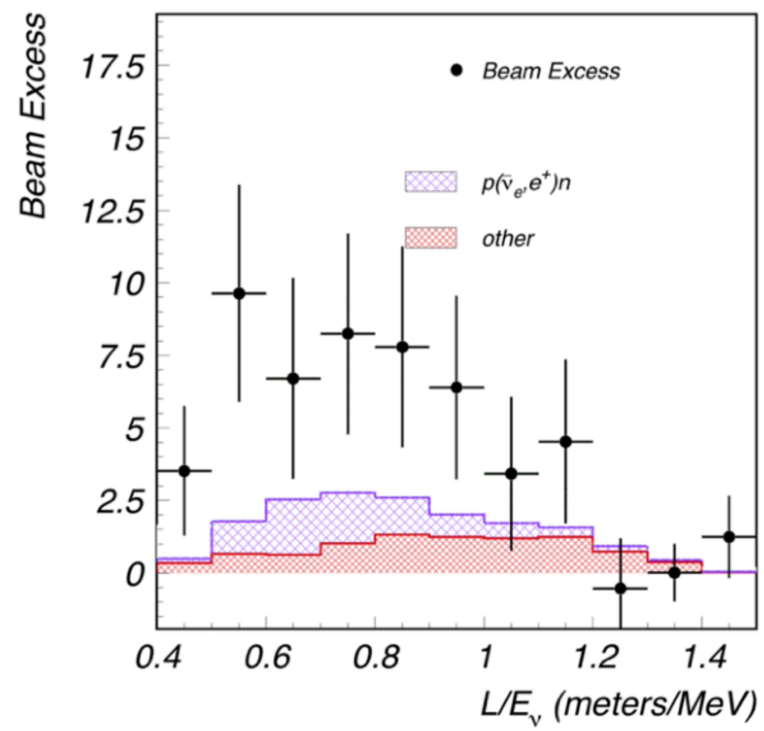
- The odyssey of HNL tau searches
- Three, four, or more neutrinos
- A search for misbehaving neutrinos

The short-baseline anomalies have motivated searches for more neutrinos

LSND

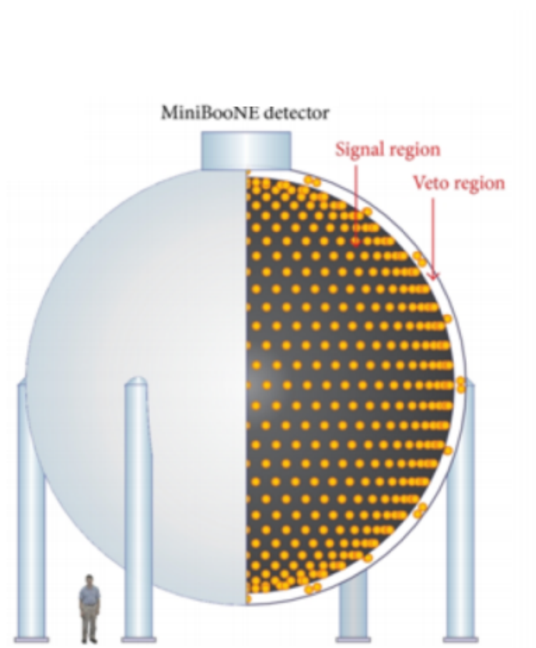


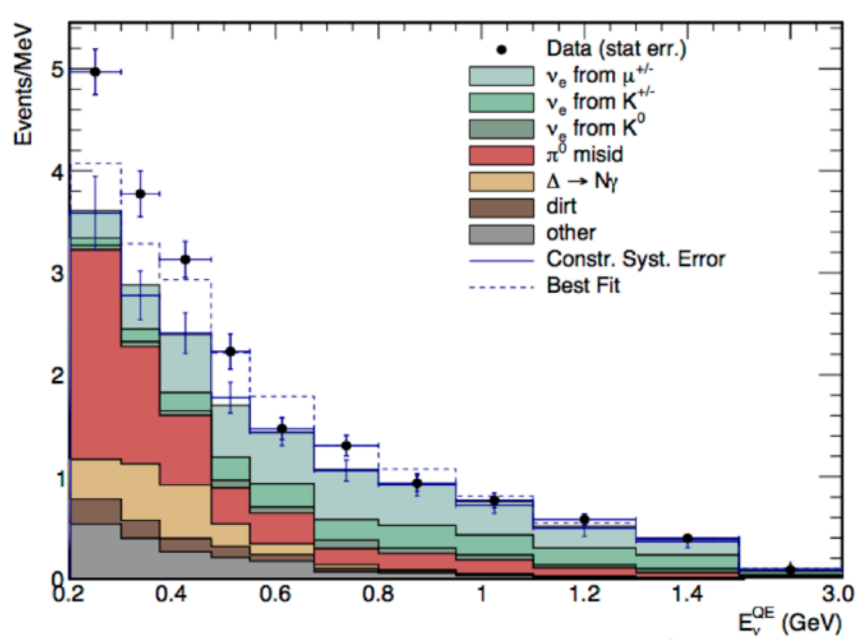


These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

This points to $\Delta m^2 \sim 1 eV^2$

MiniBooNE

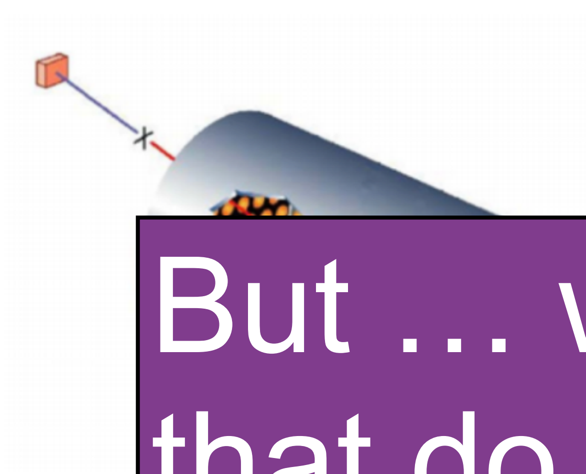


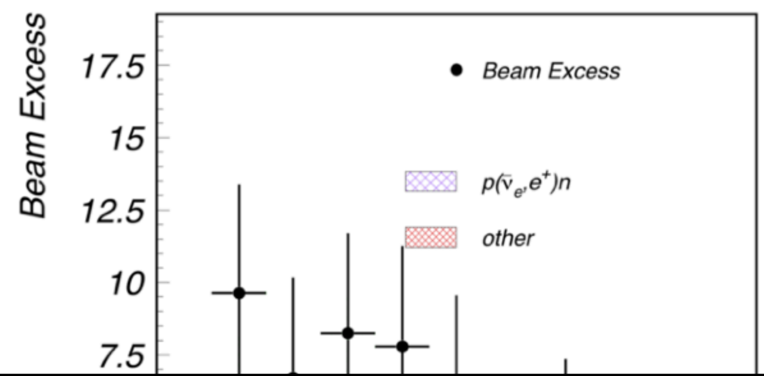


We will hear exciting news about this later today at the FNAL Wine & Cheese!!!

The short-baseline anomalies have motivated searches for more neutrinos

LSND

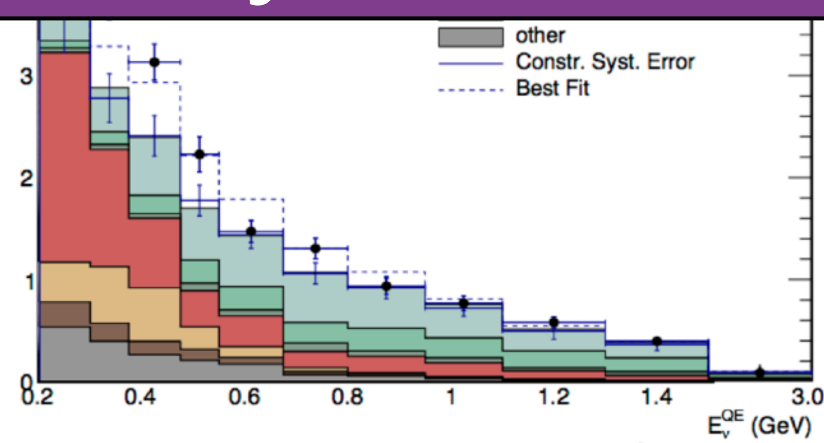




These experiments observe ν_e appearance at L/E ~ 1 km/GeV!

But … what about heavier neutrinos that do not appear through oscillations, but can be produced kinematically …

Min

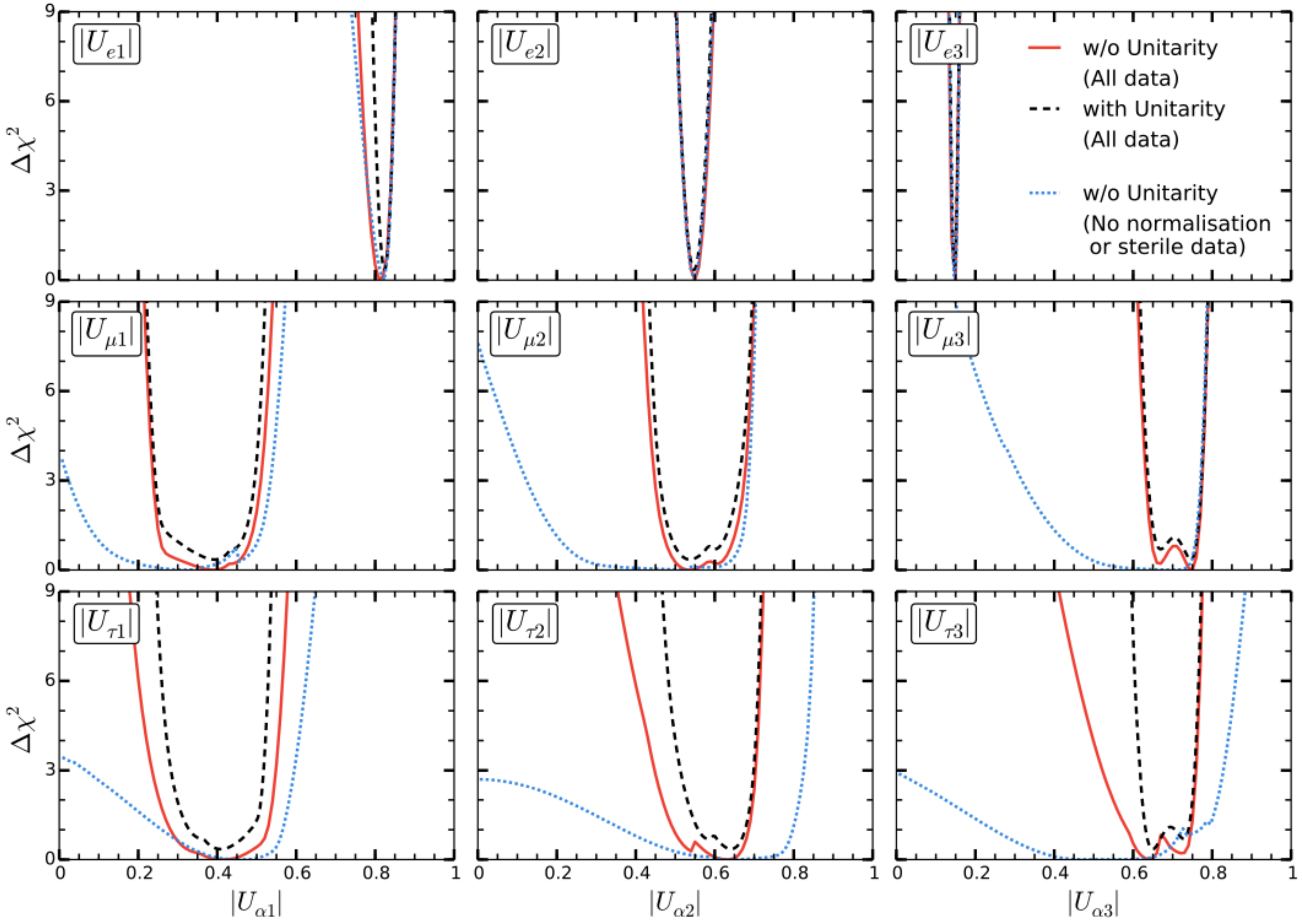


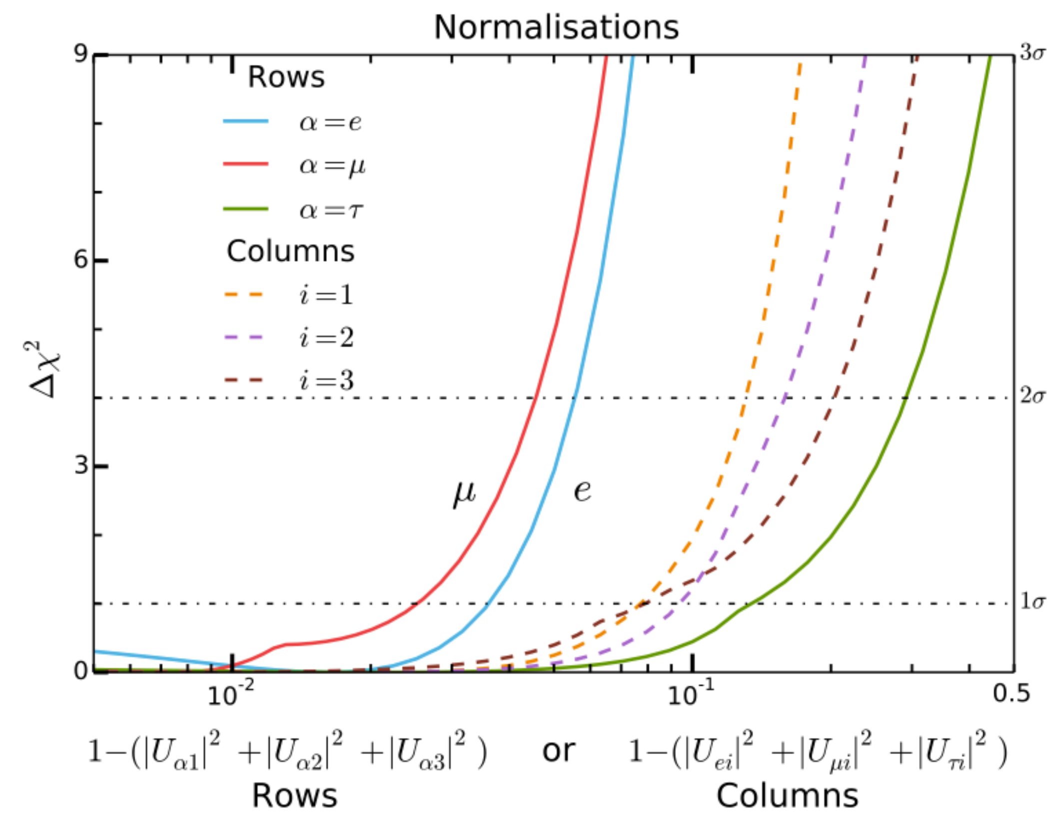
g
news about this later today at the FNAL Wine & Cheese!!!

A broad net: testing unitarity

Parke & Ross-Lonergan arXiv:1508.05095
See talk by S. Parke earlier this week!

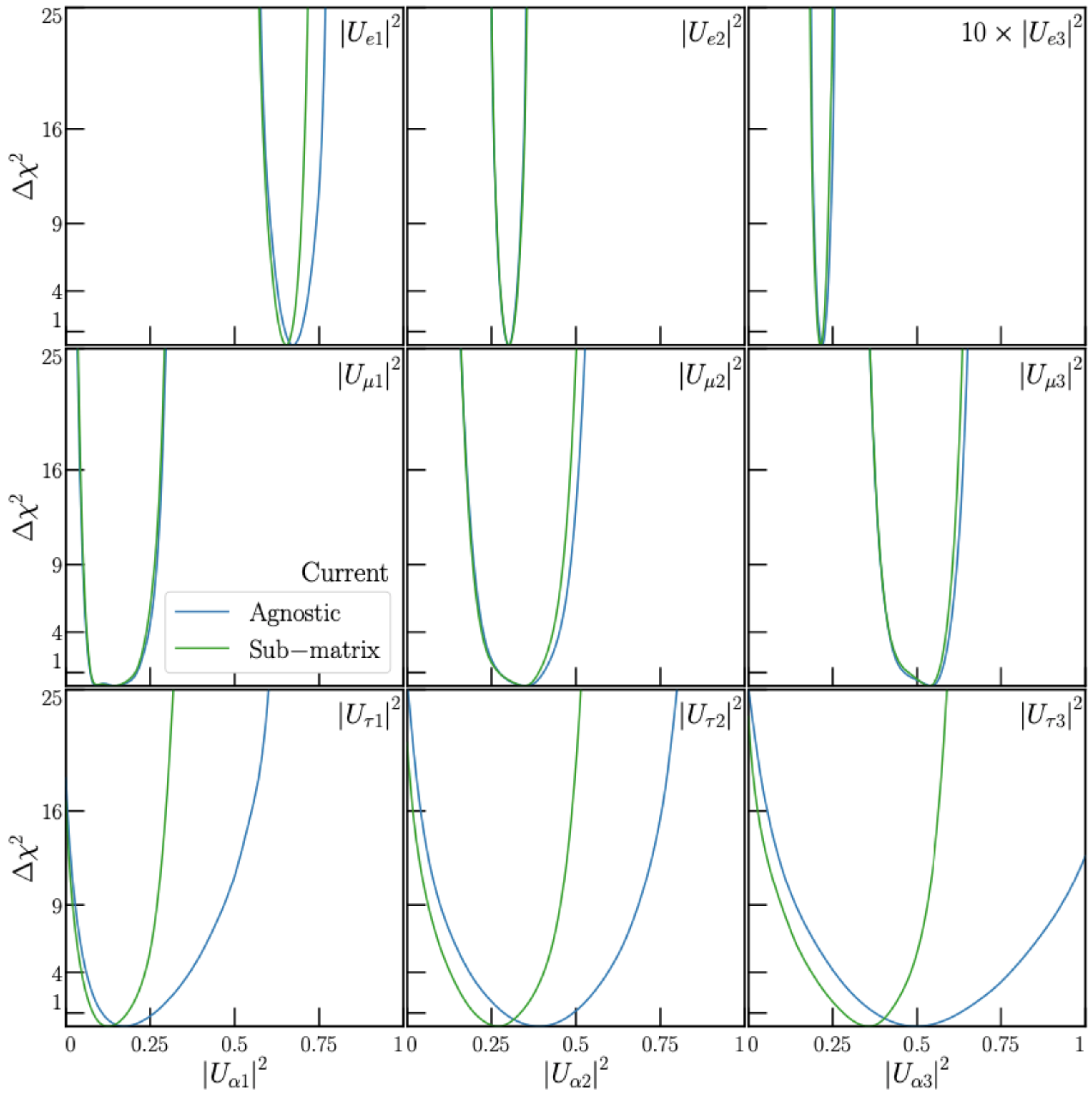
2015





Conclusion: we need to study the tau row!

A broad net: testing unitarity



Ellis et al 2008.01088

2020!

Conclusion remains the same: <u>we need to study the tau row</u>

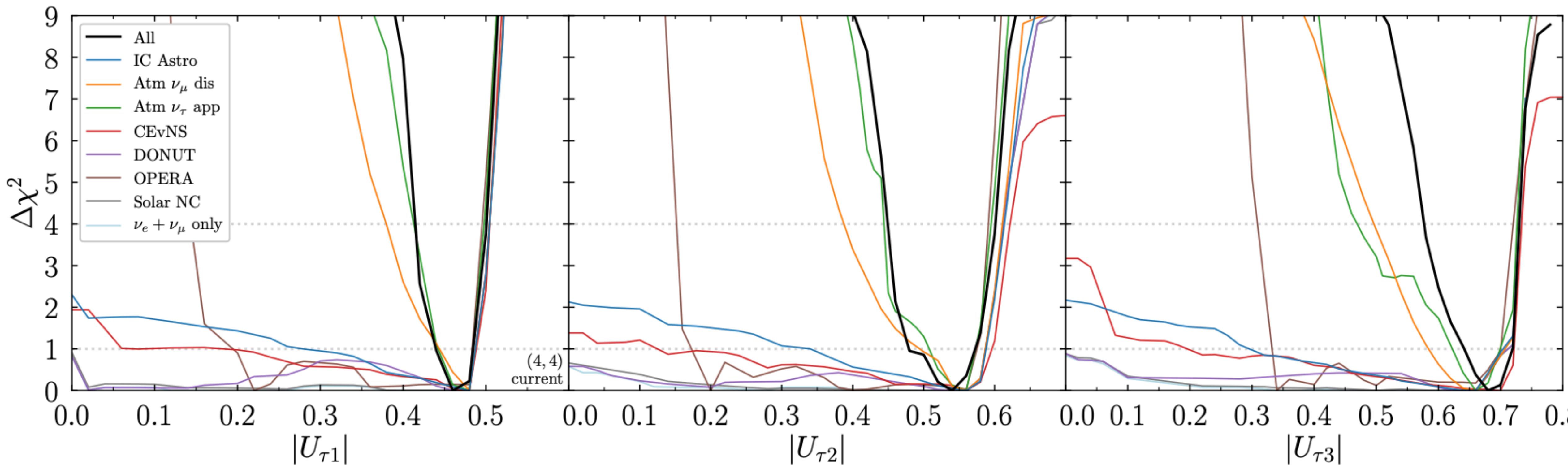
See also Gouvêa et al 1904.07265 for DUNE insight

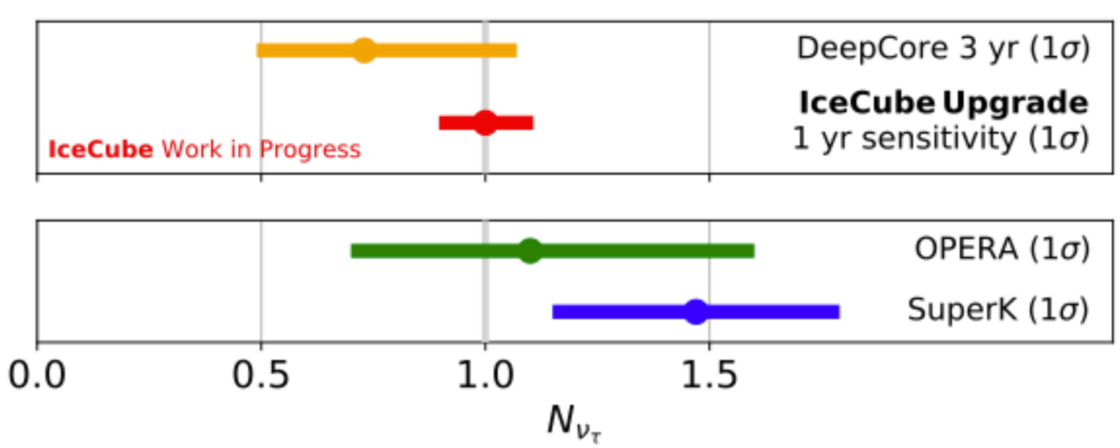
A broad net: testing unitarity

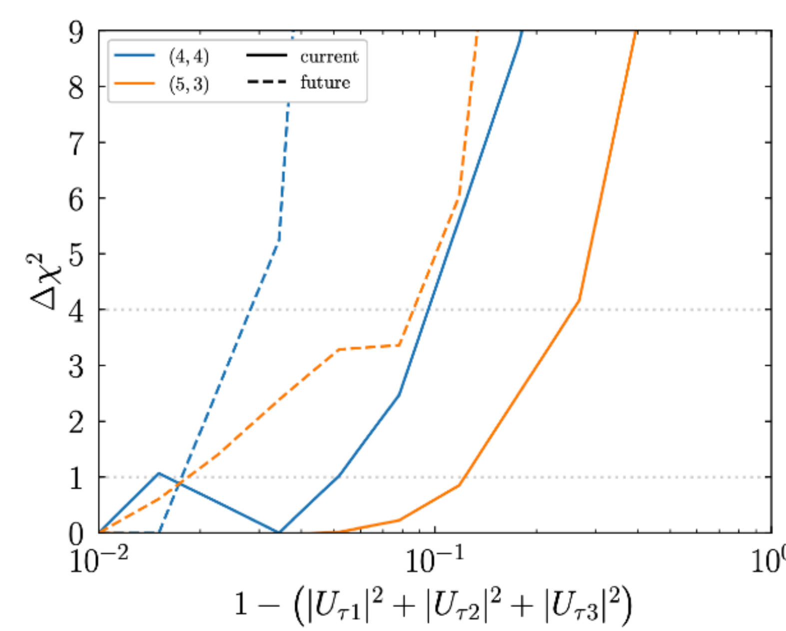
2021!!

Addition of tau appearance measurements with atmospheric neutrinos has a significant impact!

Denton & Gehrlein arXiv:2109.14575







A. Ishihara for IceCube 1908.09441
See talk by Jason Koskinen

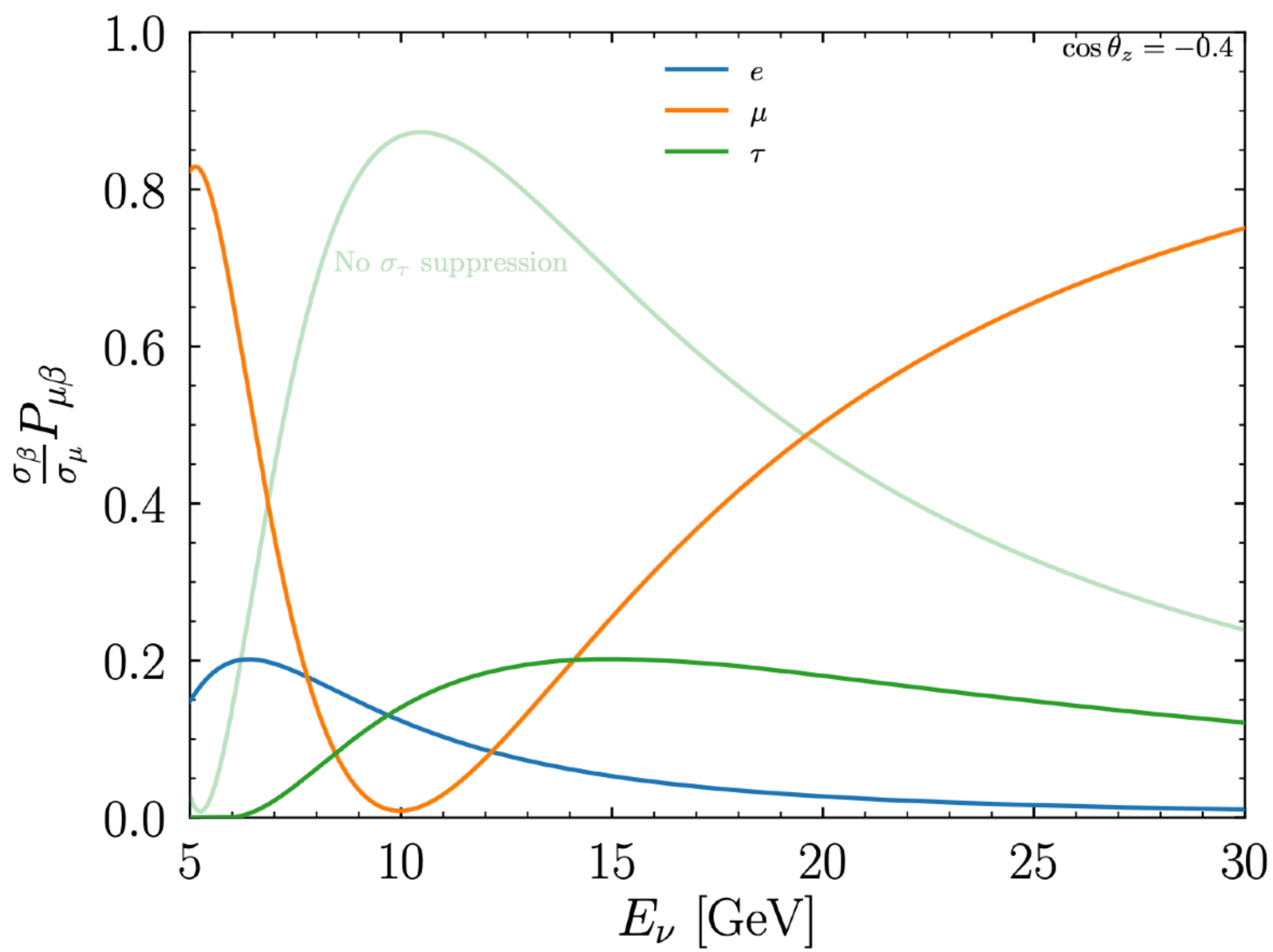
How can IceCube tau appearance test unitarity?

Naïvely low-energy electron- and tau-neutrinos are morphologically indistinguishable

Denton & Gehrlein arXiv:2109.14575

Three important elements:

- Well-known cross sections for all neutrino flavors (DIS dominated, see Jason Koskinen back-up slides!)
- Energy distribution of cascades produced by taus is shifted to lower energies.
- Tau-induced event rate are affected by well-defined cross-section threshold



T. Stanev PRL (1999)
P. Denton arXiv:2109.14576

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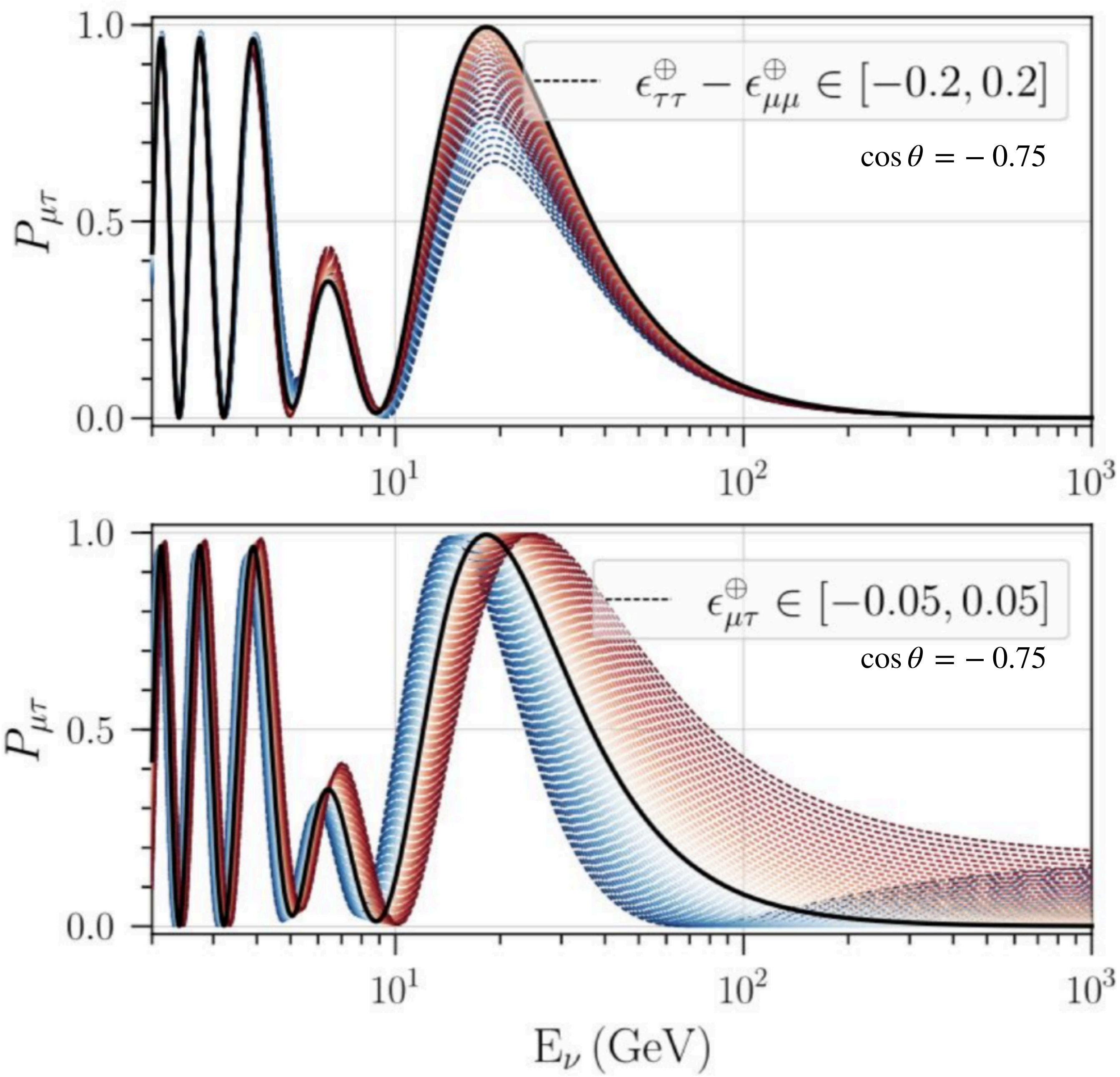
Are there new neutrino interactions?

Non-standard neutrino interactions

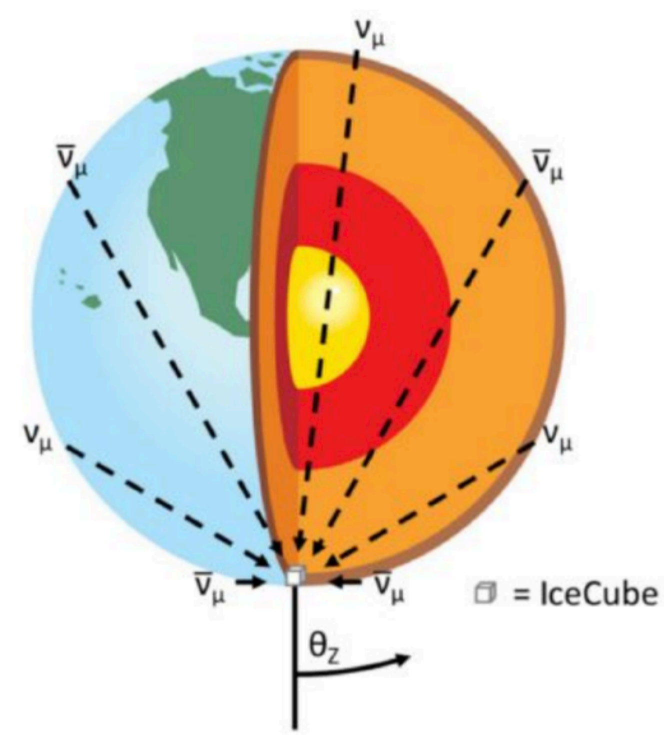
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)(\bar f\gamma_\mu P f)$$

IceCube arXiv:2106.07755



$$\varepsilon_{\alpha\beta} = \sum_{f,P} \varepsilon^{fP}_{\alpha\beta}\frac{N_f}{N_e}$$

$$H_{\rm mat} = \sqrt{2}G_F N_e(x)\begin{pmatrix} 1+\varepsilon_{ee}(x) & \varepsilon_{e\mu}(x) & \varepsilon_{e\tau}(x) \\ \varepsilon^*_{e\mu}(x) & \varepsilon_{\mu\mu}(x) & \varepsilon_{\mu\tau}(x) \\ \varepsilon^*_{e\tau}(x) & \varepsilon^*_{\mu\tau}(x) & \varepsilon_{\tau\tau}(x)\end{pmatrix}$$



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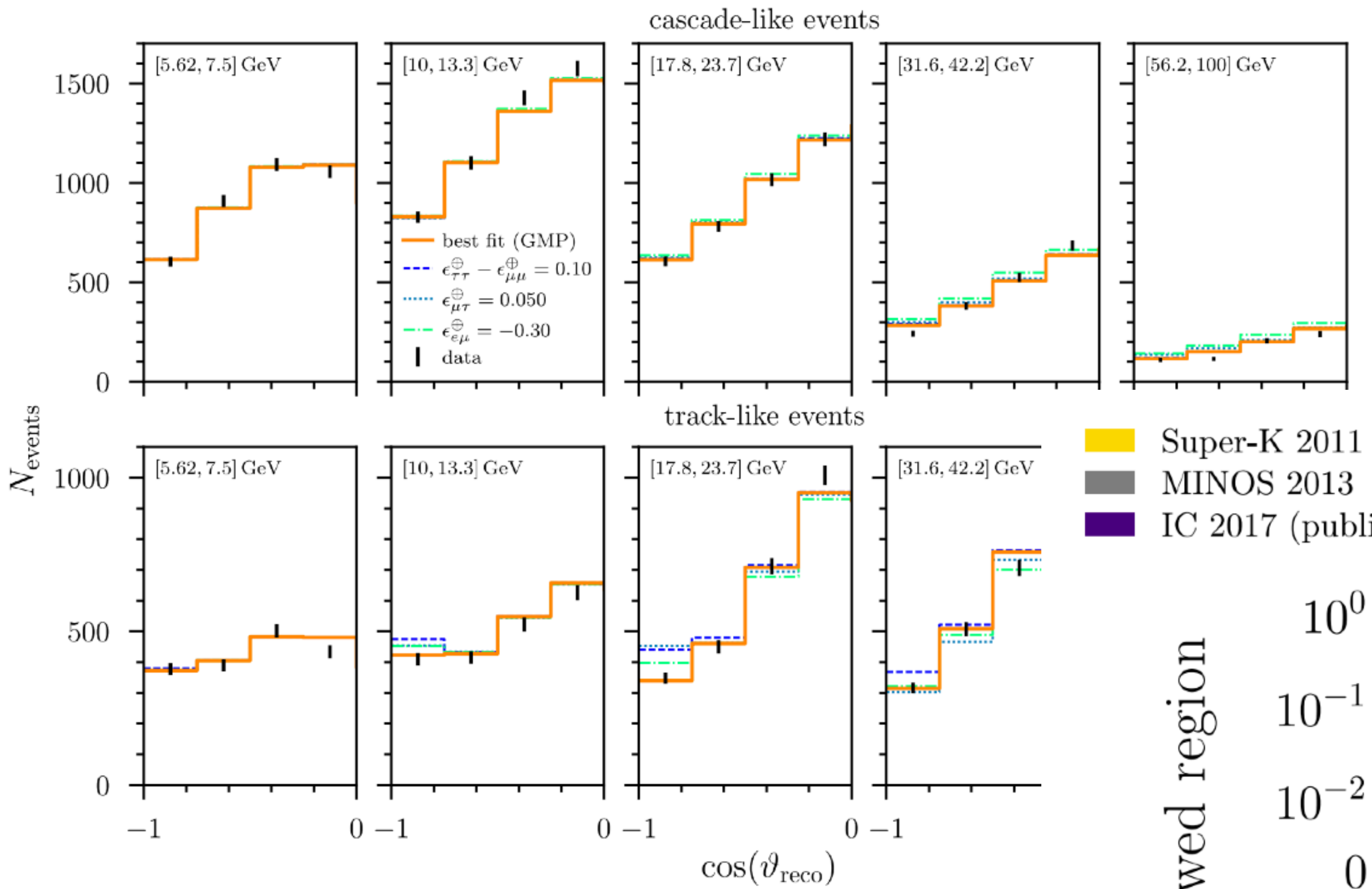
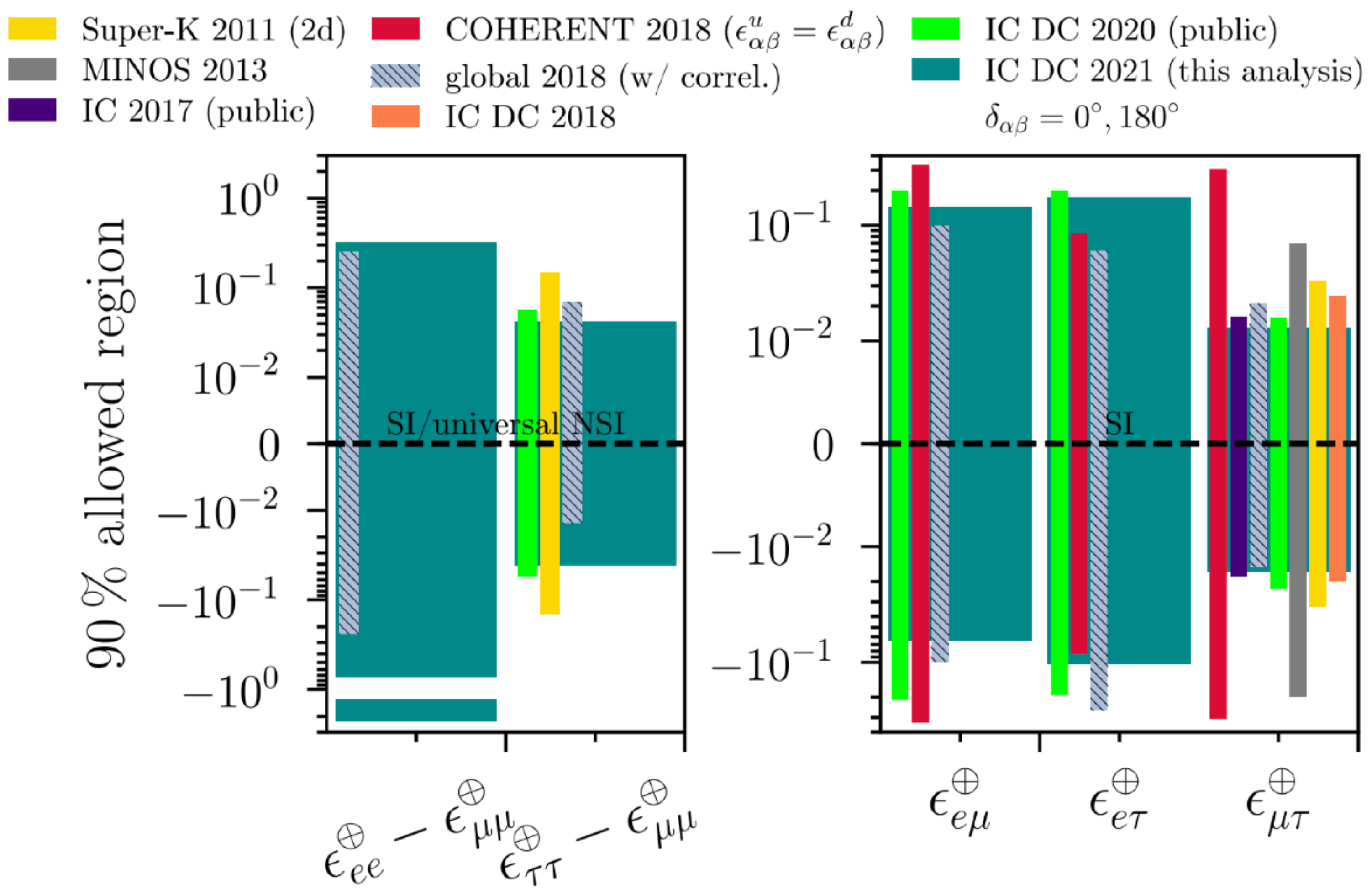
Measurements using IceCube-DeepCore

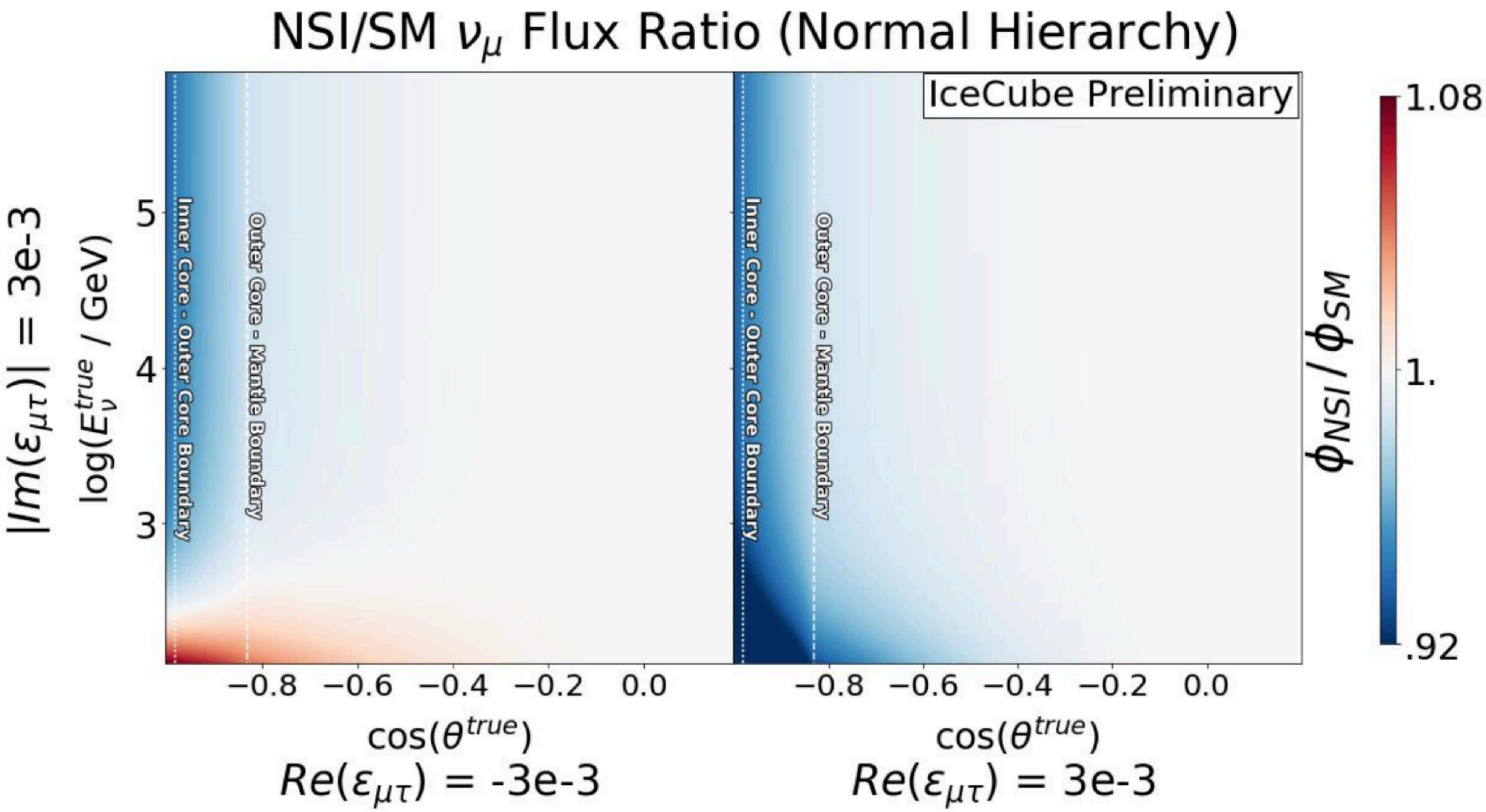
IceCube arXiv:2106.07755





- Three years of IceCube-DeepCore data were analyzed.
- No significant evidence for NSI.
- Constraints dominate over many of the NSI parameters.

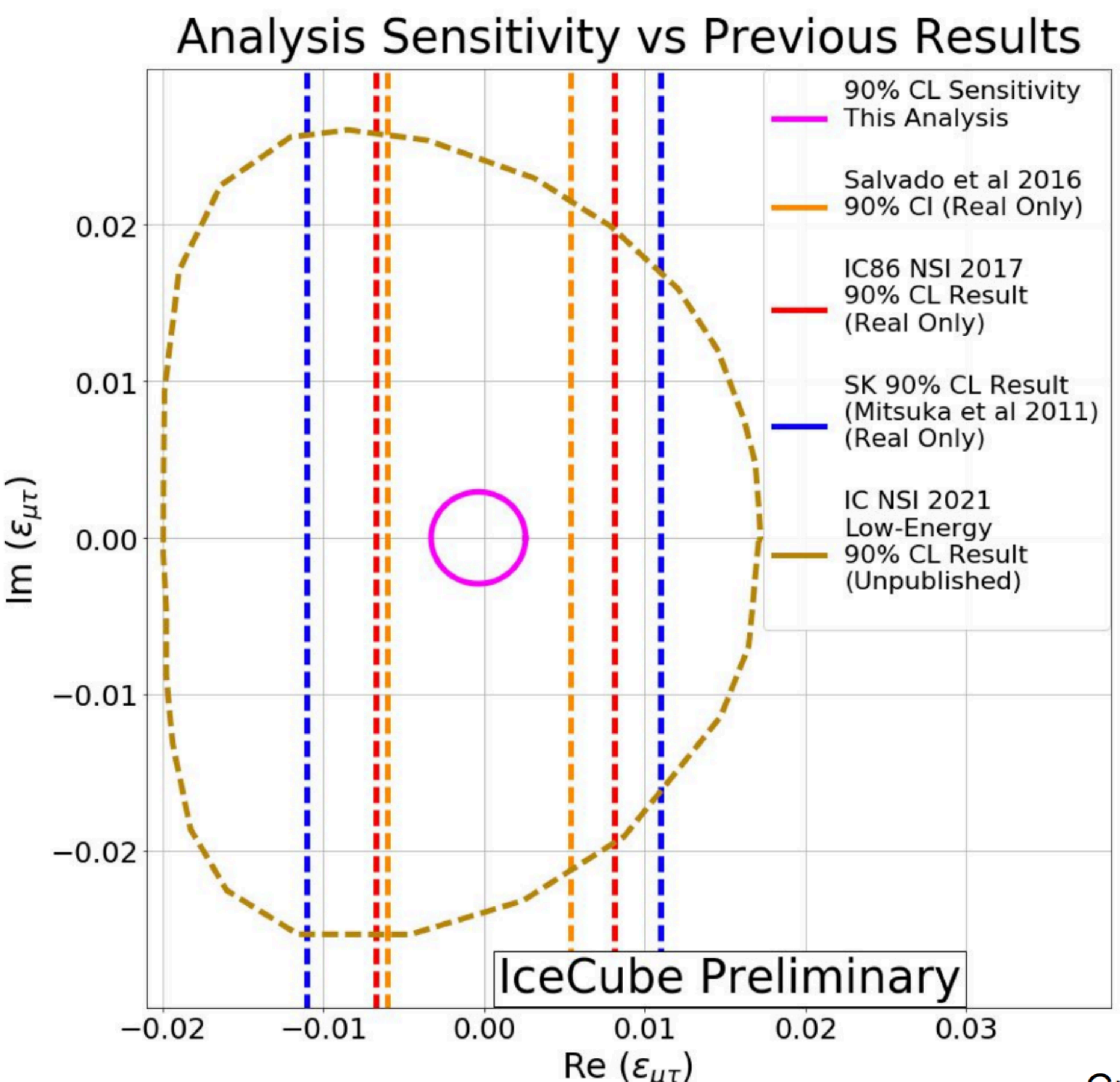
What about IceCube high-energy NSI searches?



At high-energies signature predominantly a change in the zenith distribution.

No interference/ dependence on standard oscillation parameters.

What about IceCube high-energy NSI searches?



- Use same event selection as recent eight year sterile neutrino search.
- Significant improvement in sensitivity!
- Stay tuned for results!

G. Parker NuFACT2021

Take home message

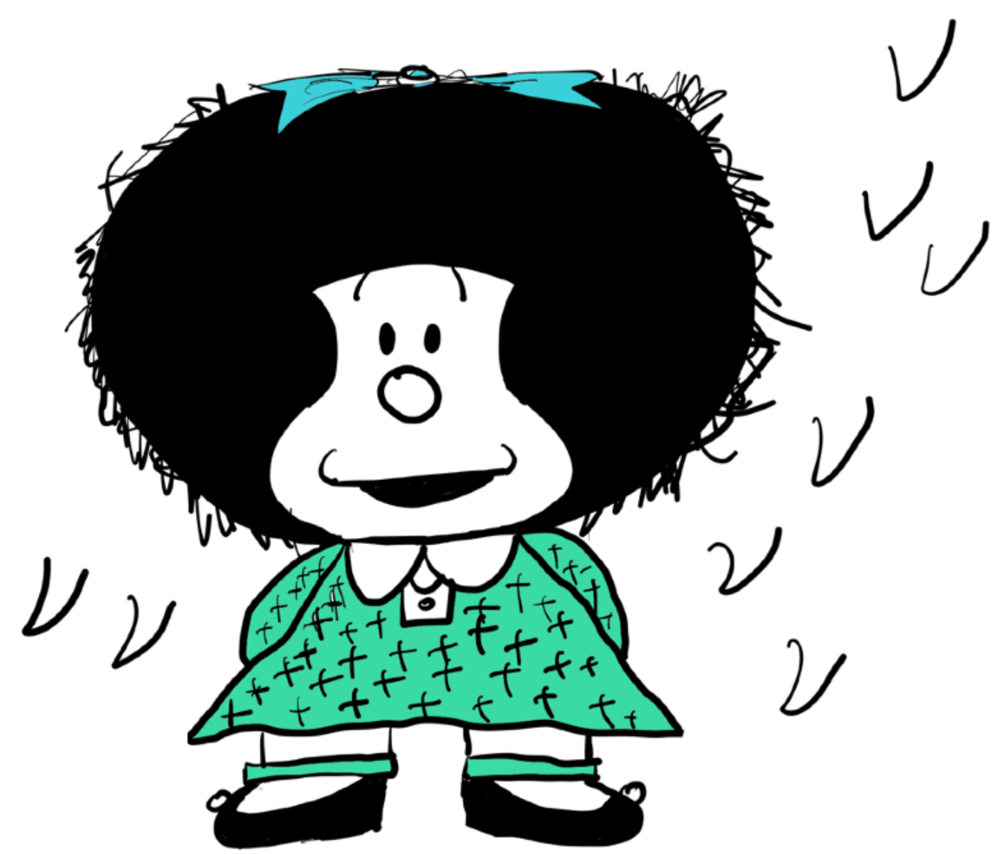
❖Searching for new physics with tau neutrinos is challenging, but exciting.

❖Recent constraints on HNLs mixing with taus close the “opportunity triangle.” Background estimations critical for these searches.

❖Tau appearance measurements with atmospheric and astrophysical neutrinos significantly improve constraints on tau row unitarity tests.

❖Searches for NSI with mu-tau element among the strongest. New results soon!

Thank you!



Bonus slides

Menu of other explanations

New signatures

Gninenko 1107.0279
Magill et al 1803.03262
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916,
CA, Hostert, Tsai et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay

Heavy Neutrino Decay

Bai et al 1512.05357

Dentler et al 1911.01427,
de Gouvea et al 1911.01447,
Hostert & Pospelov 2008.11851

Heavy O(100MeV) decay to ν_e

Fisher et al 1909.0956,
CA, Foppiani, Hostert 2109.03831

Heavy O(100MeV) decay to photon

Oscillations+X

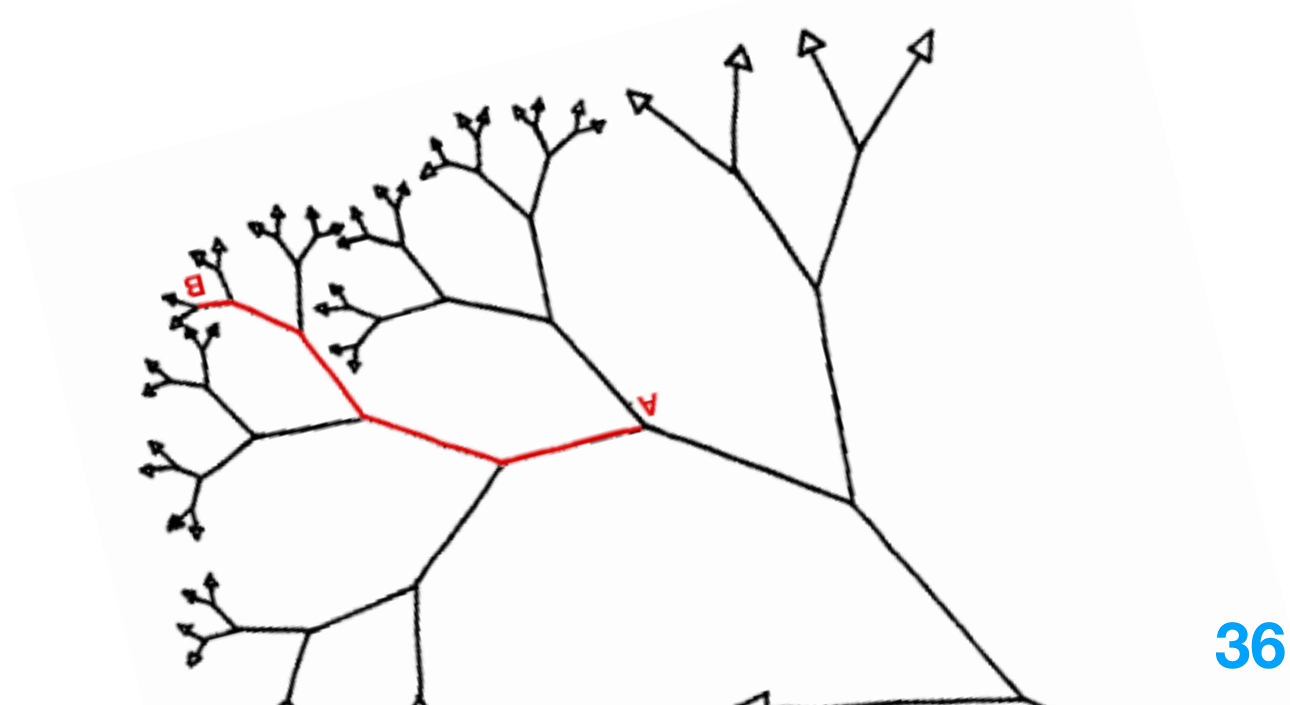
Assadi et al 1712.08019
Resonant matter effect

Moss et al 1711.05921, Moulai et al 1910.13456
Steriles +decay

Liao et al 1810.01000
Steriles + NCNSI + CCNSI

More than one at a time

S. Vergani et al arXiv:2105.06470
Light Sterile + Heavy neutrino O(100MeV),
magnetic moment

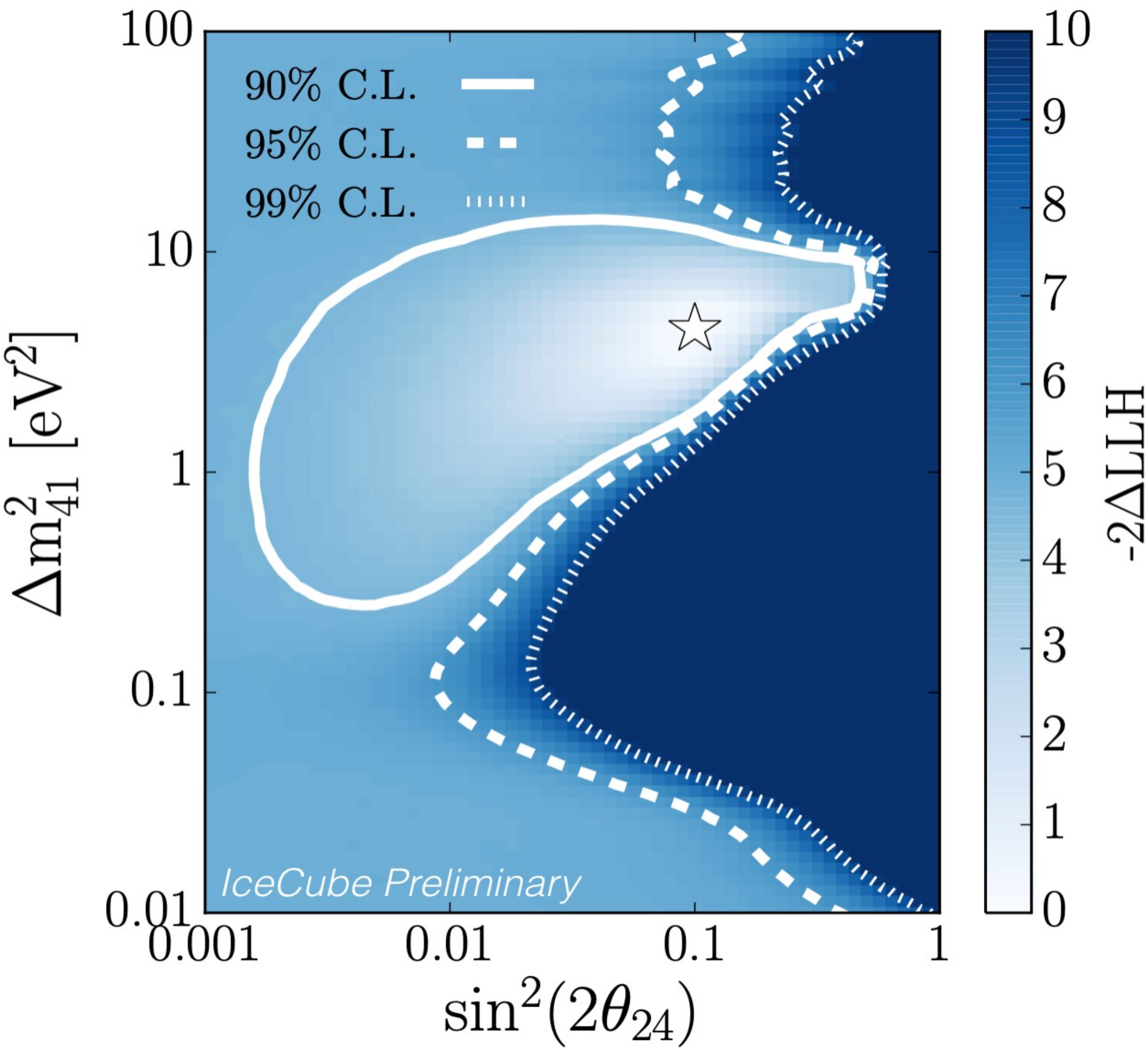


IceCube Hints

- Best fit:

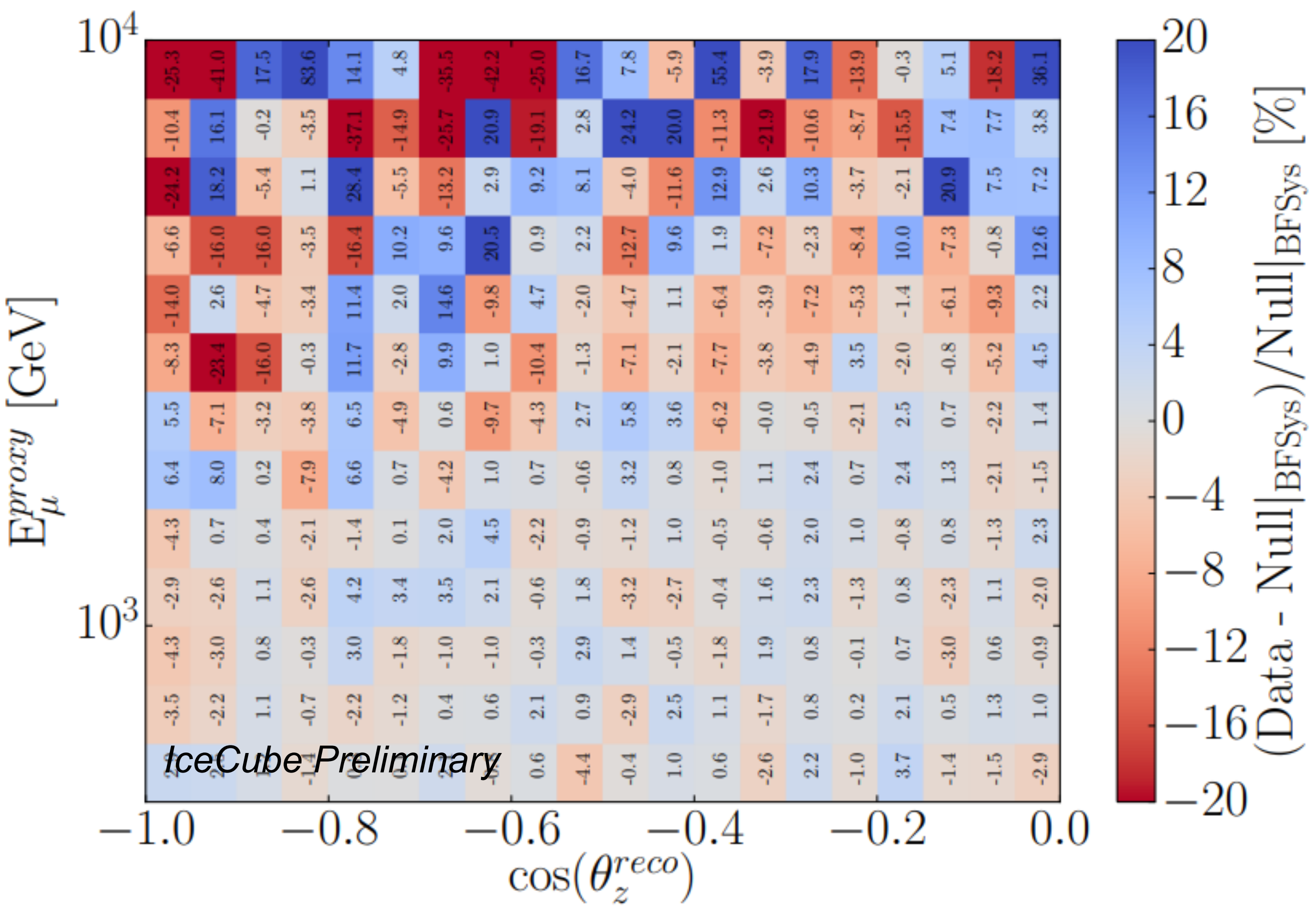
$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08}\,\mathrm{eV}^2$$
$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$

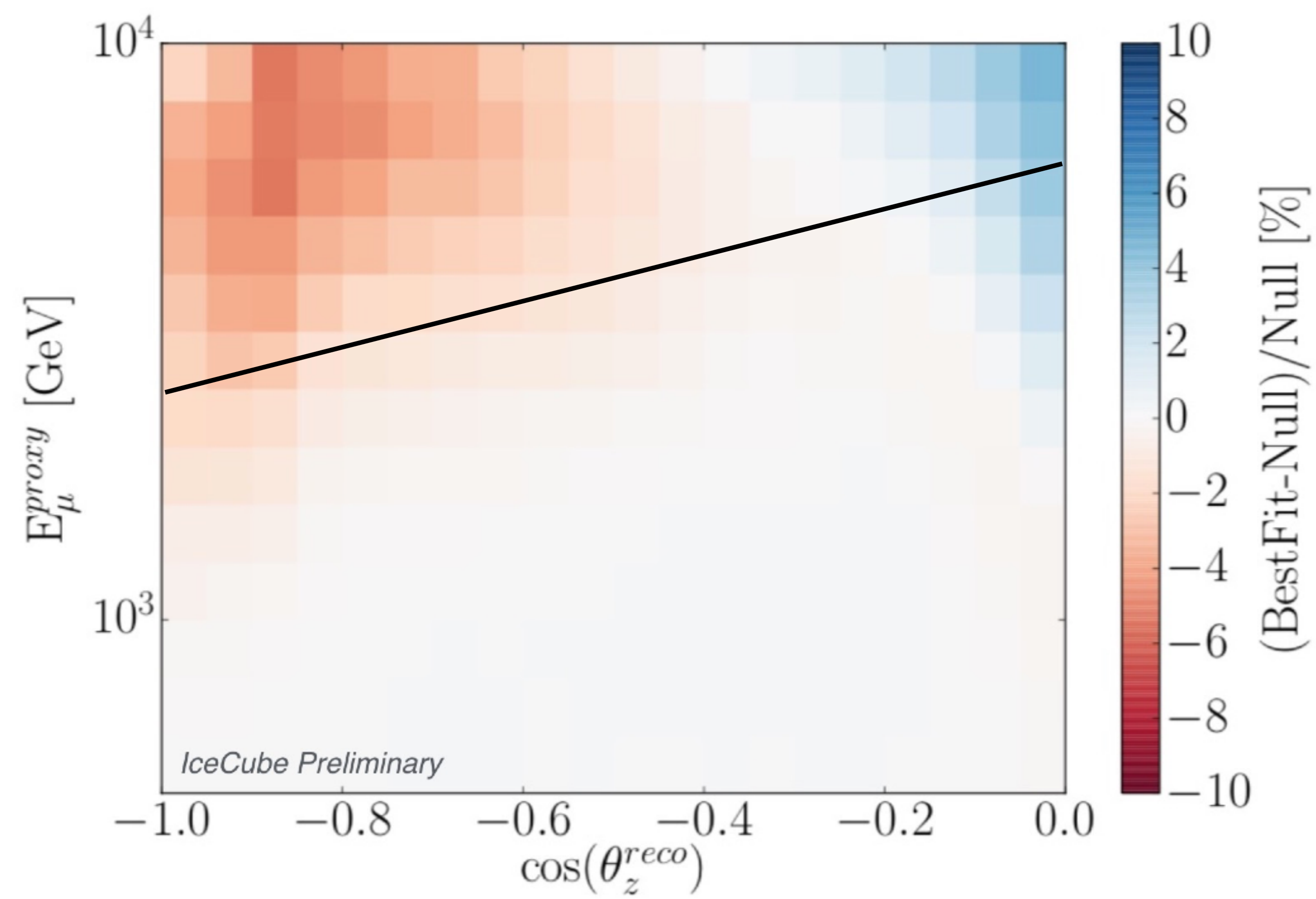
- Sterile neutrino hypothesis is preferred to null
- Null is rejected at 8% p-value



Event distribution (data) and best-fit shape (Monte Carlo)

- Best-fit shape effect is in a low-statistics regime
  - Hard to see by eye in the data
- But the result does not seem to be a statistical fluctuation
  - Consistent year-to-year

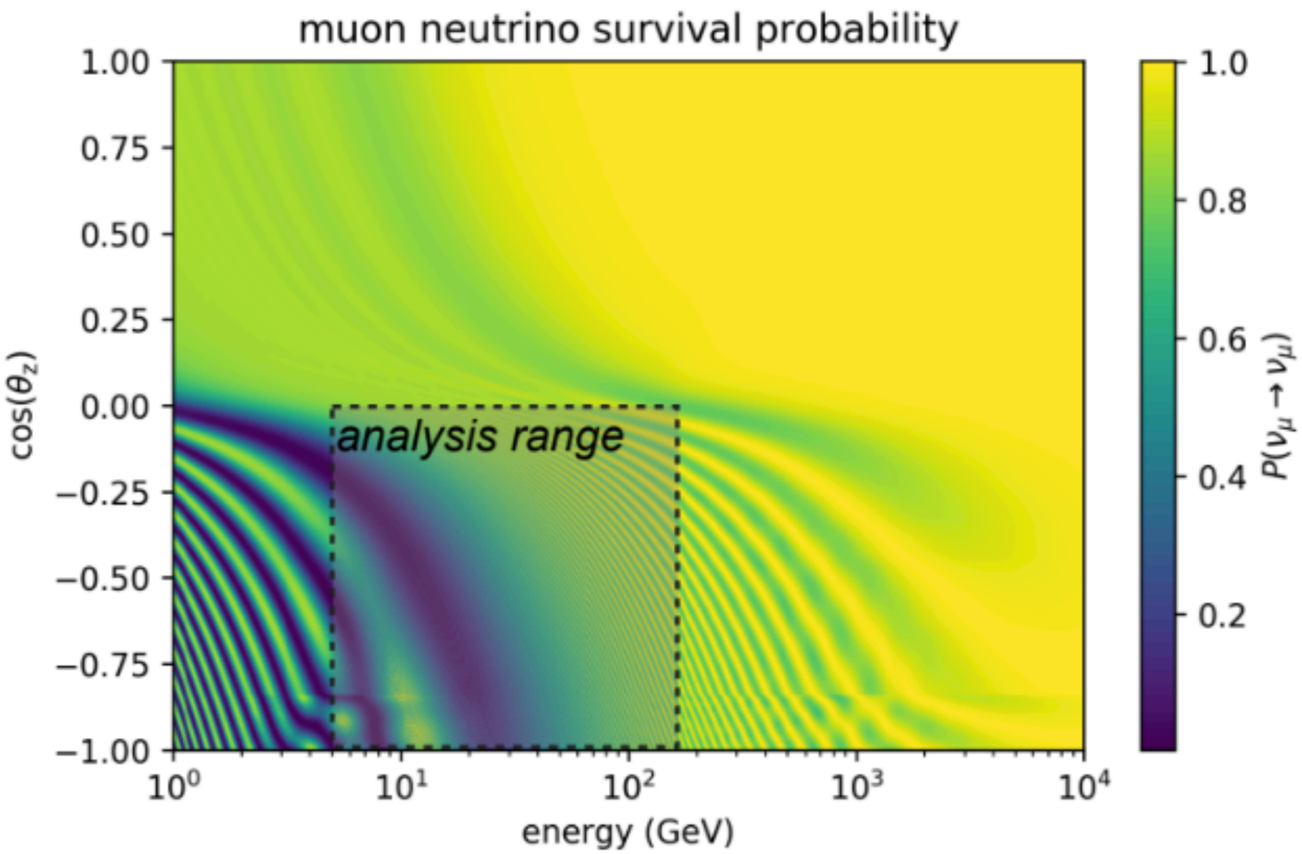


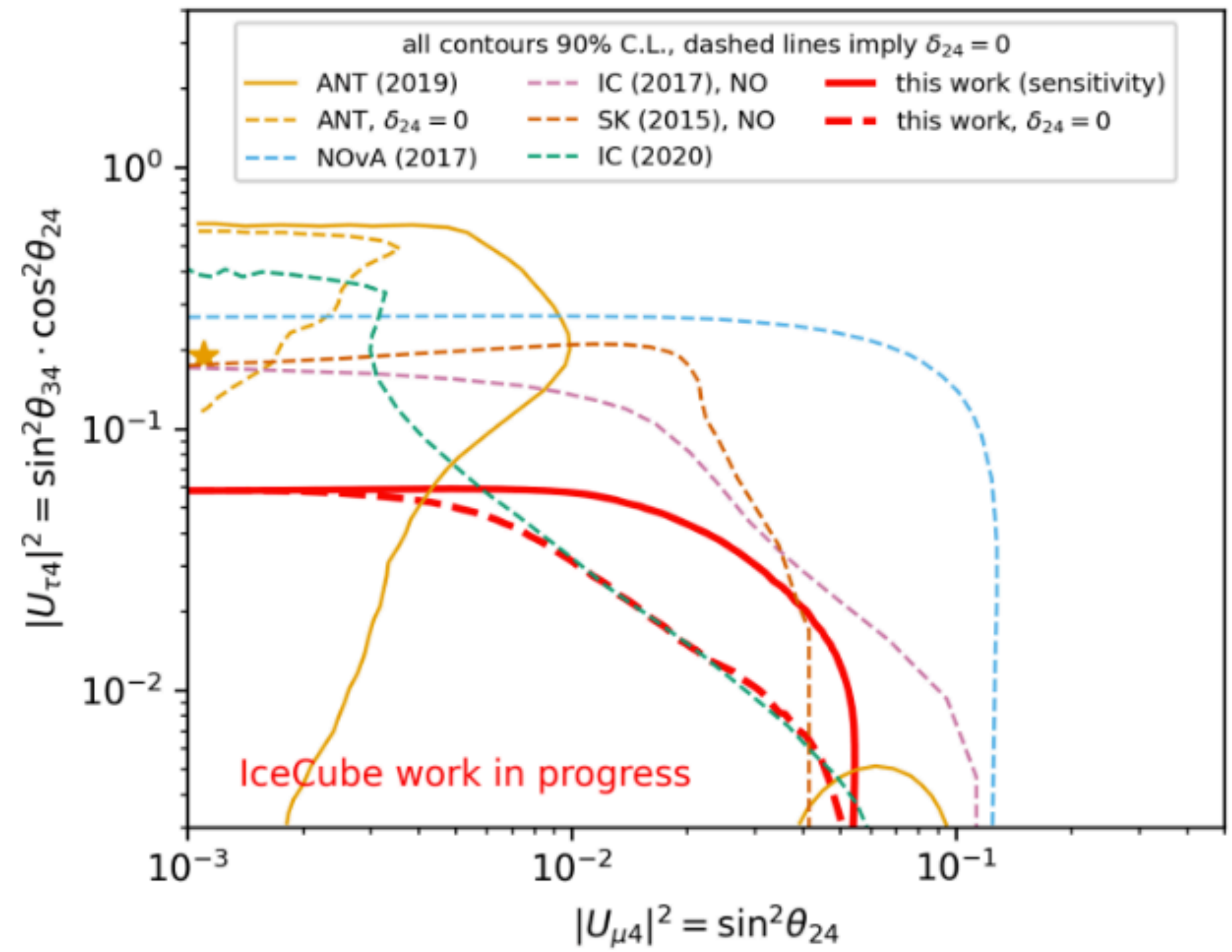


IceCube@Antartica

Talk by A. Trettin@PANIC2021

"Low" energies: 5 - 150 GeV





Projected sensitivity of sterile search with 8 years of DeepCore data

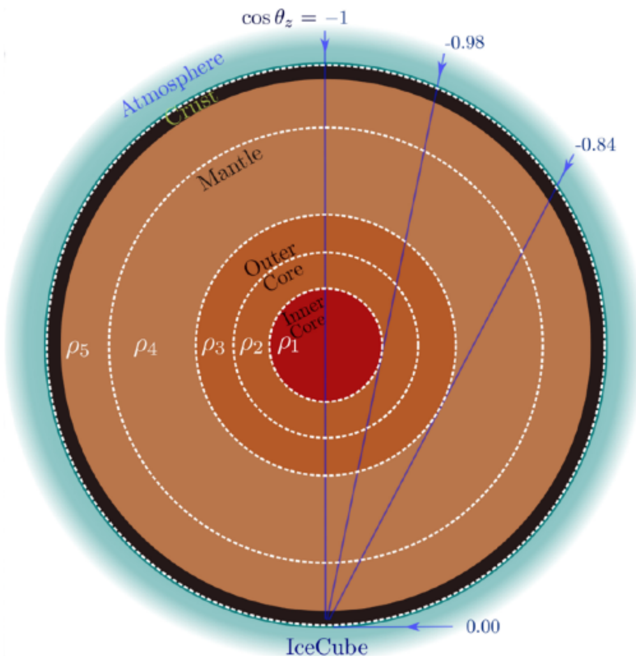
> very fast, unresolvable oscillations + distortion

> IceCube: World-leading limits on $|U_{\tau 4}|^2$ and $|U_{\mu 4}|^2$!

IceCube will continue improving muon neutrino disappearance searches.
"Low energy" sample (<100 GeV) still not studied.

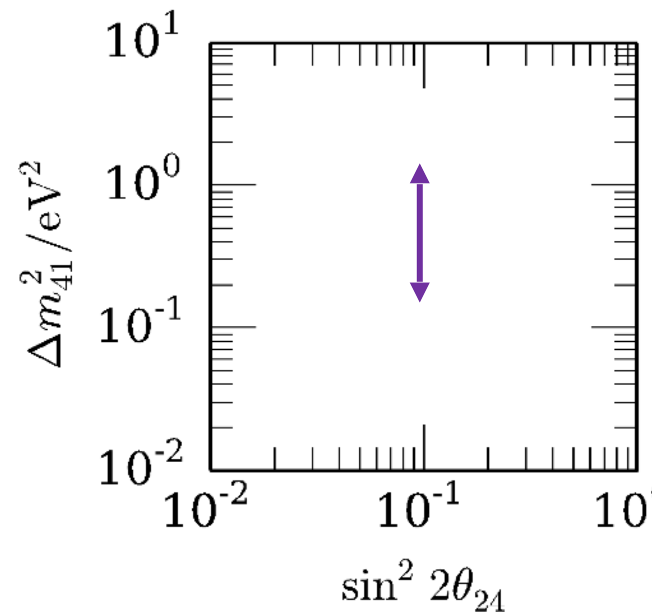
See talk by K. Leonard DeHolton@nuFACT for more details

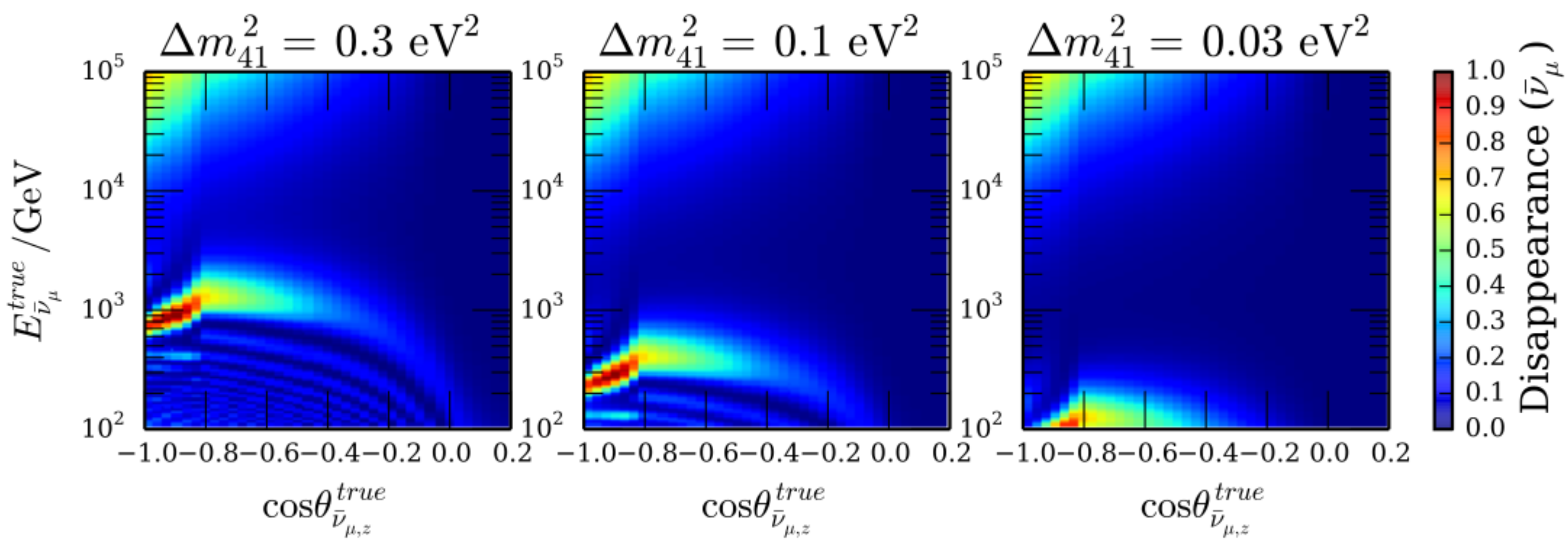
How does the IceCube analysis work?



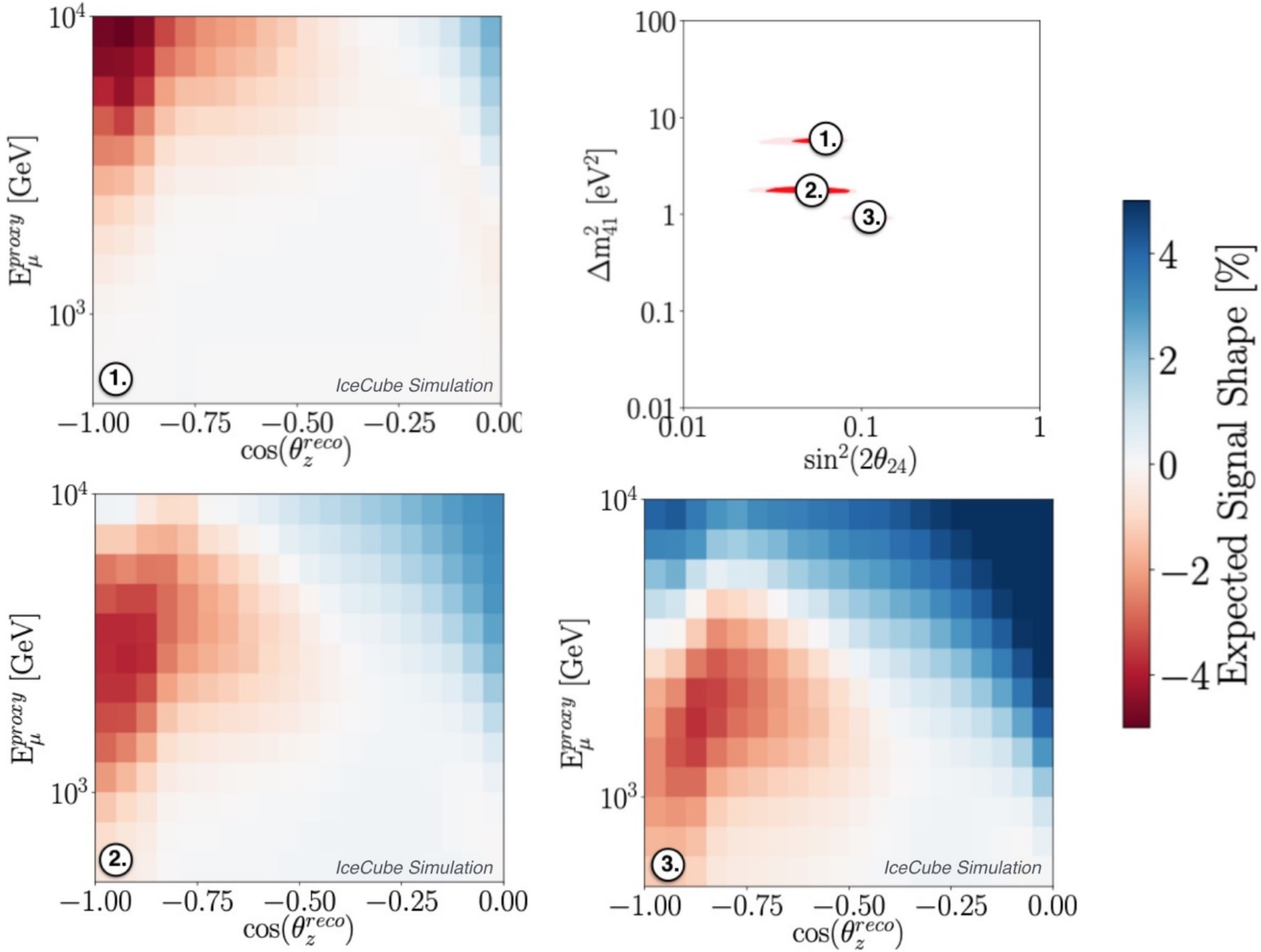
We measure two things:
- length (direction)
- energy

We extract two parameters:
- squared mass difference
- mixing angle





Example signatures in analysis observables

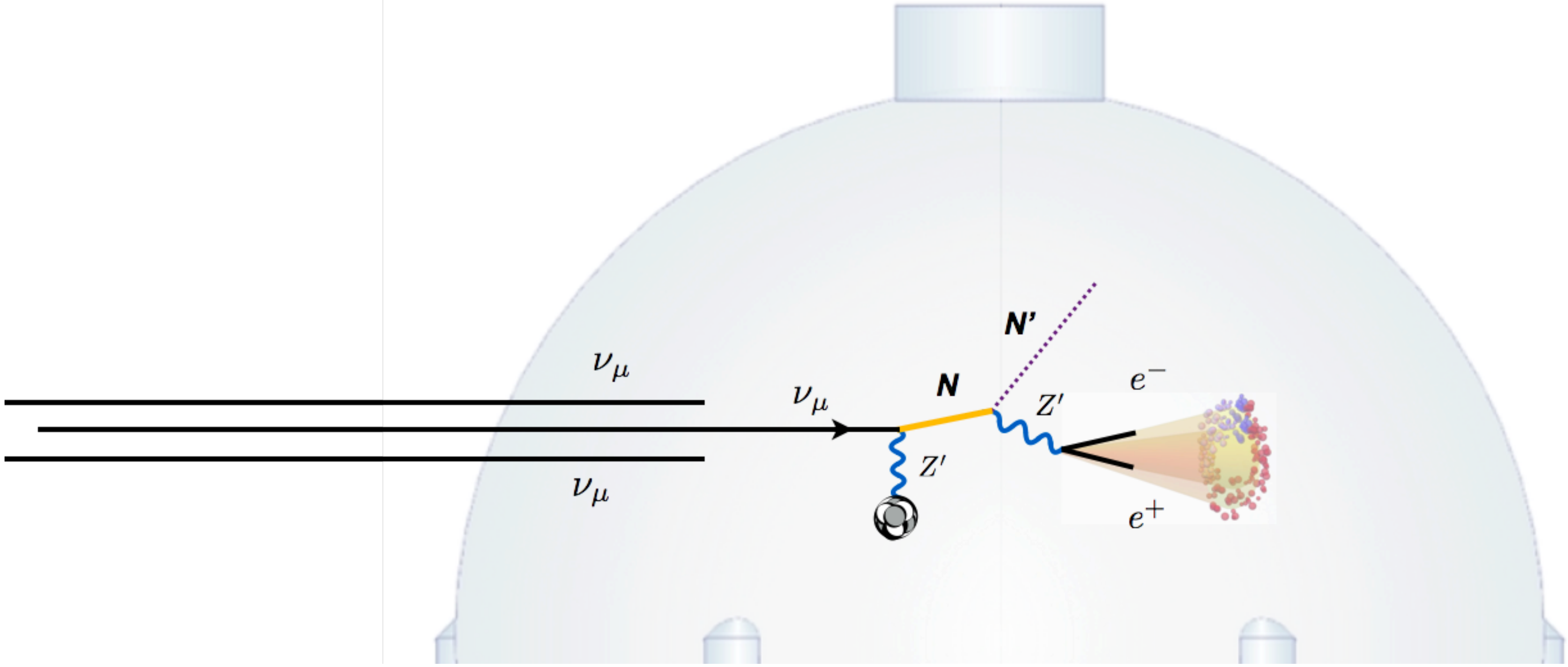


Non-Minimal HNL: di-electron scenario

E. Bertuzzo et al., PhysRevLett.121.241801

P. Ballett, M. Ross-Lonergan, S. Pascoli, PhysRevD.99.071701

A. Abdullahi, M. Hostert, S. Pascoli, arXiv:2007.11813



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E. Bertuzzo et al., PhysRevLett.121.241801

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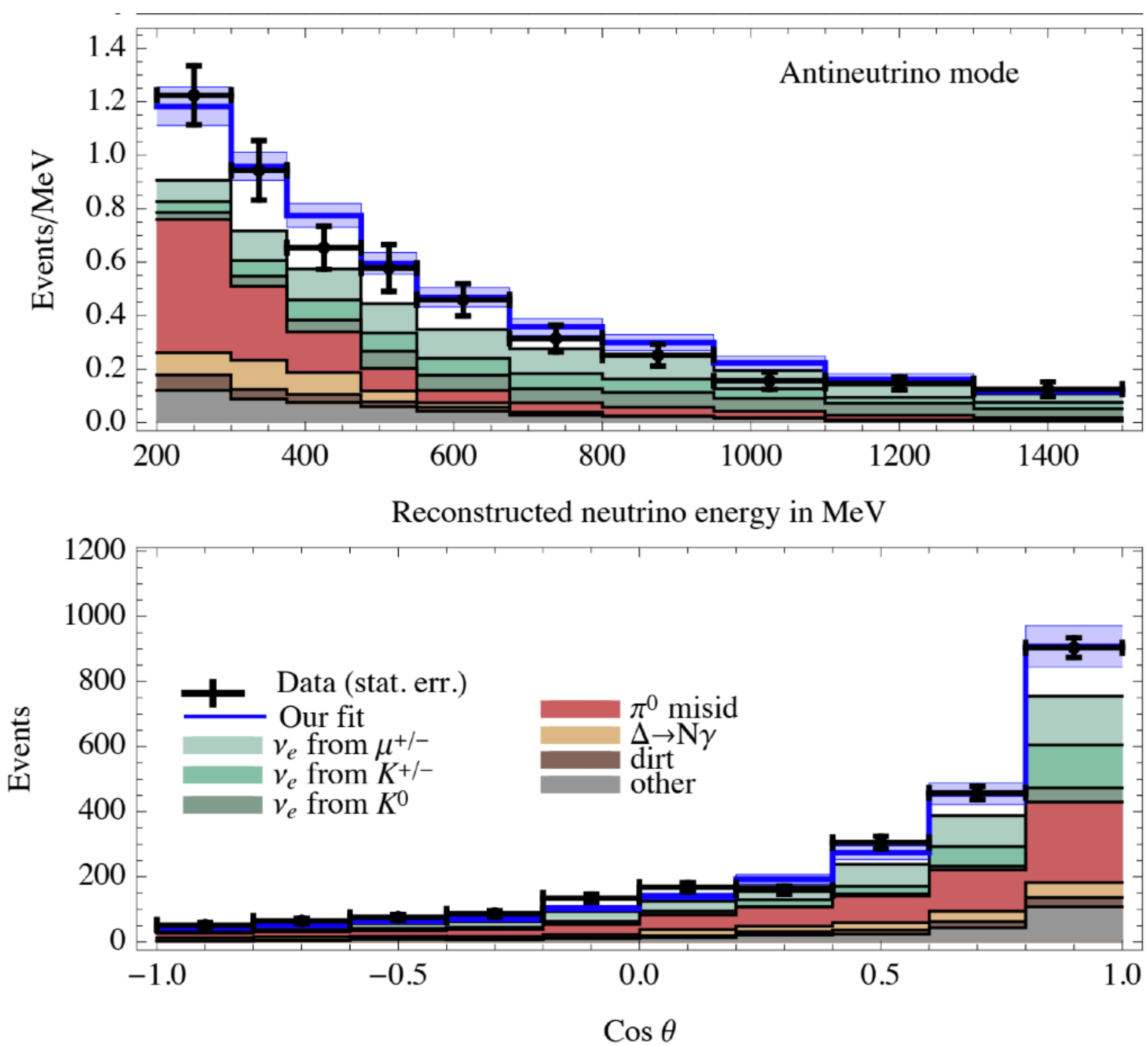
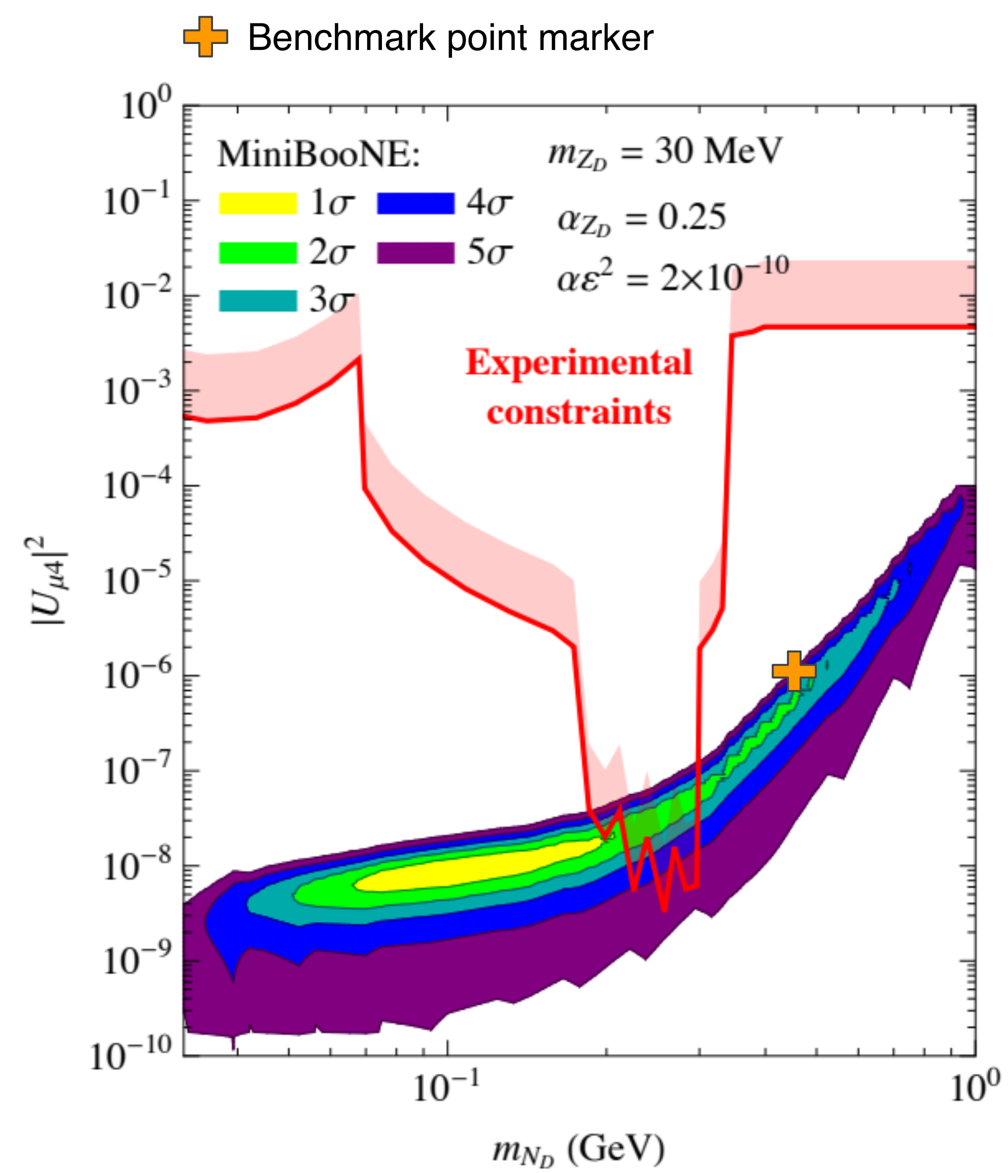
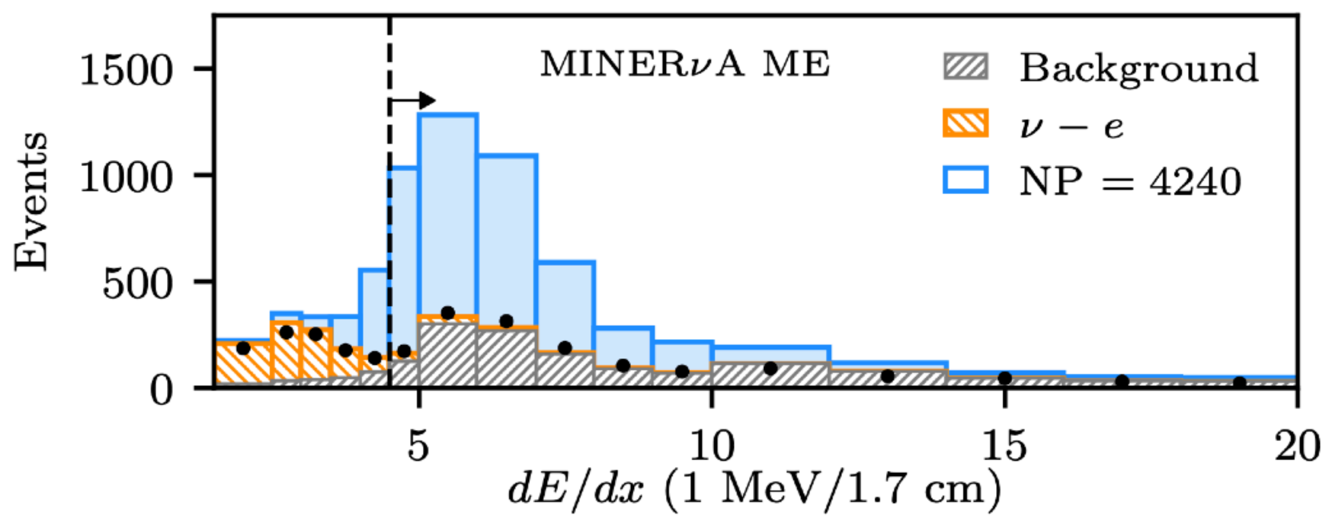
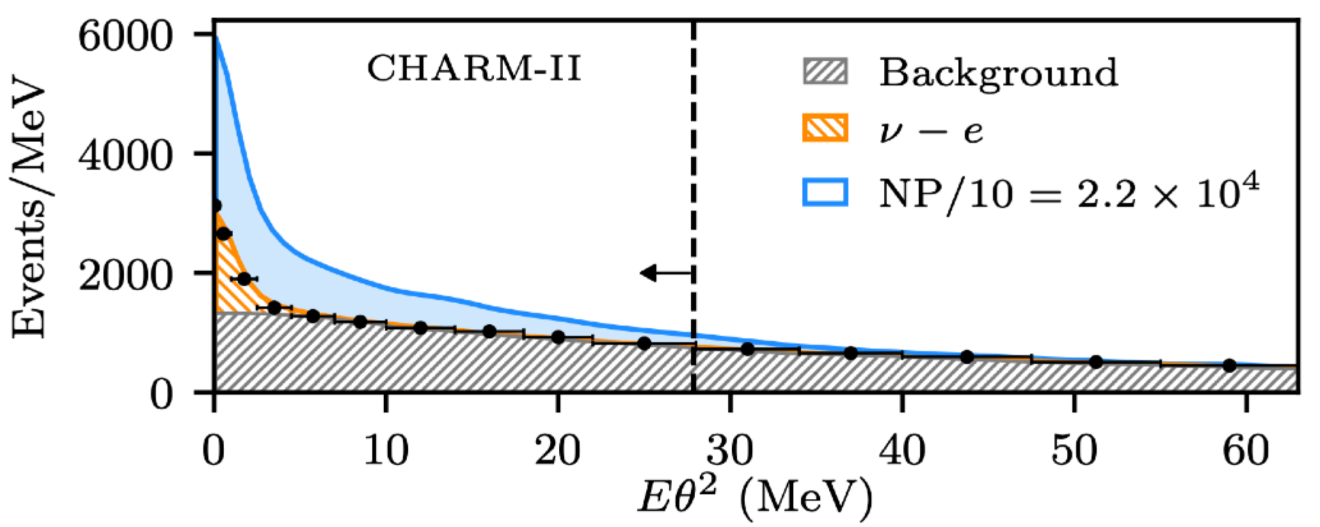




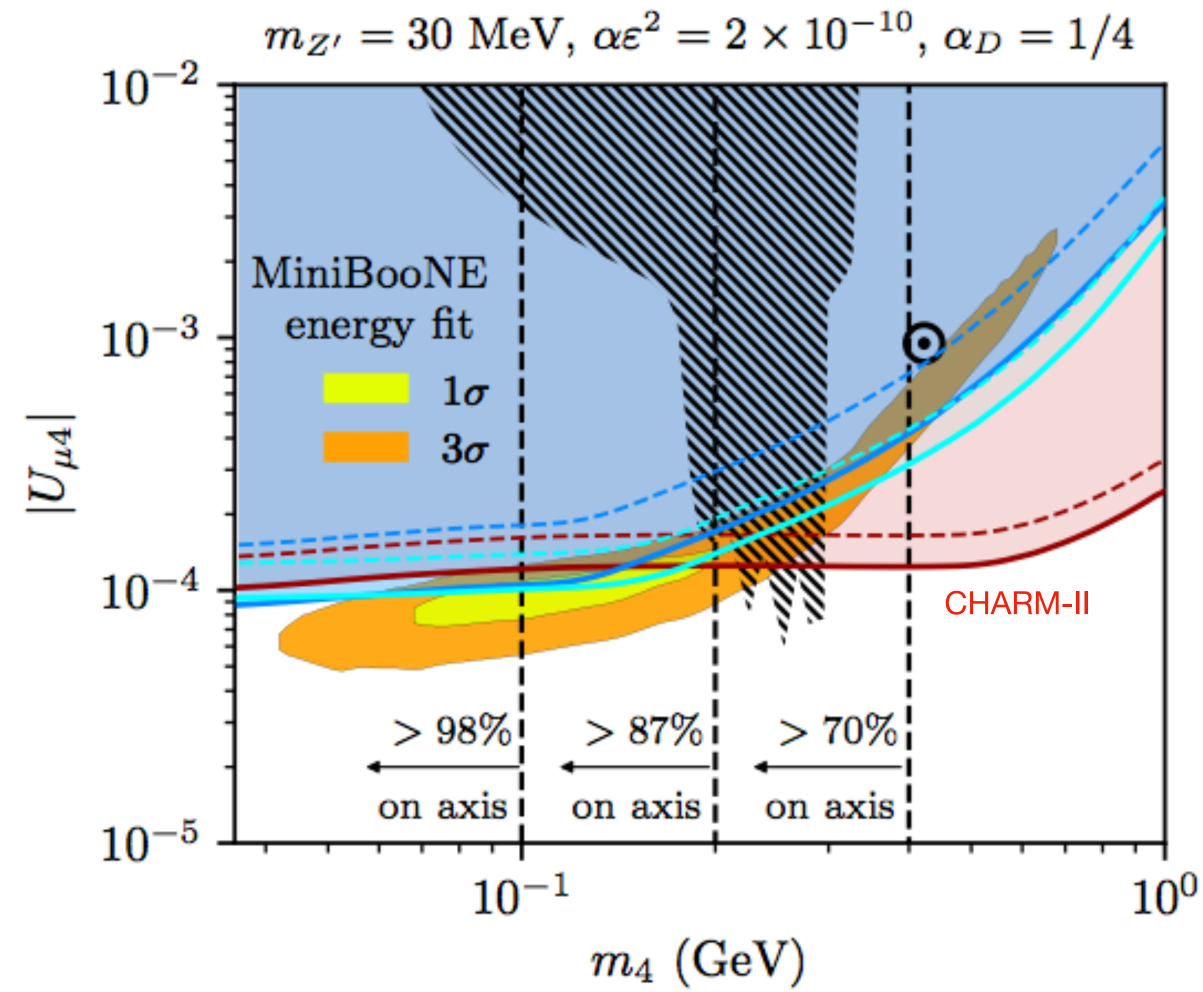
Good fit to the energy and angular distribution.

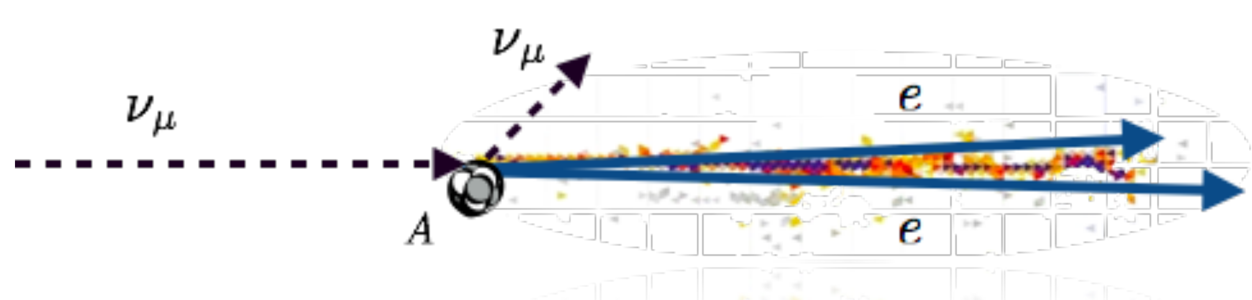
Non-Minimal HNL: di-electron scenario





CA, M. Hostert, Y. Tsai, PhysRevLett. 123, 261801 (2019)



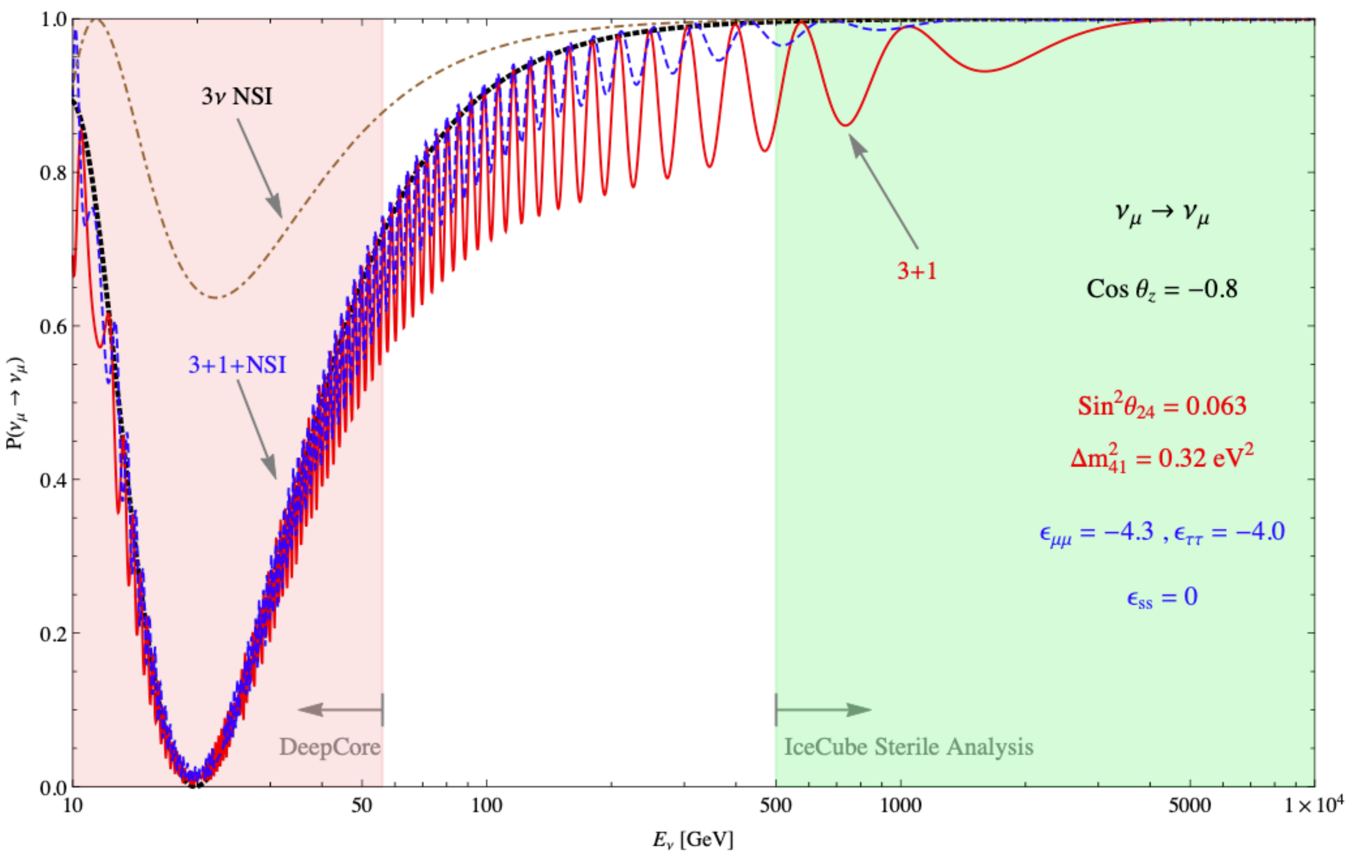


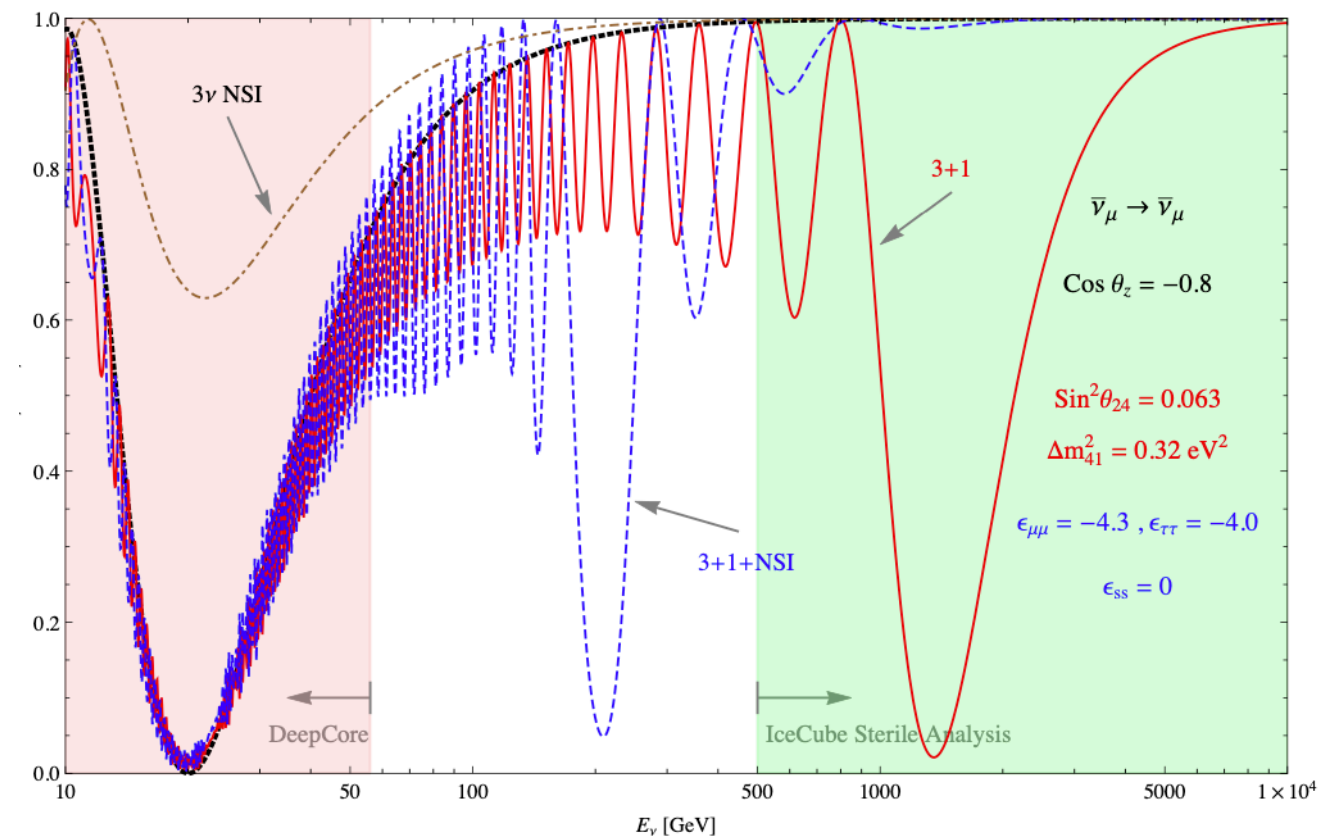
In tension with measurements of electron-neutrino scattering

Non-Standard Matter Effects (3+1+NSI)

J. Liao et al

A. Esmaili et al https://arxiv.org/abs/1810.11940





See also Denton et al
Bhupal Dev et al

Direct Probes of Matter Effects In Neutrino Oscillations
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF3-TF0_TF0_Peter_Denton-010.pdf)

Neutrino NonStandard Interactions

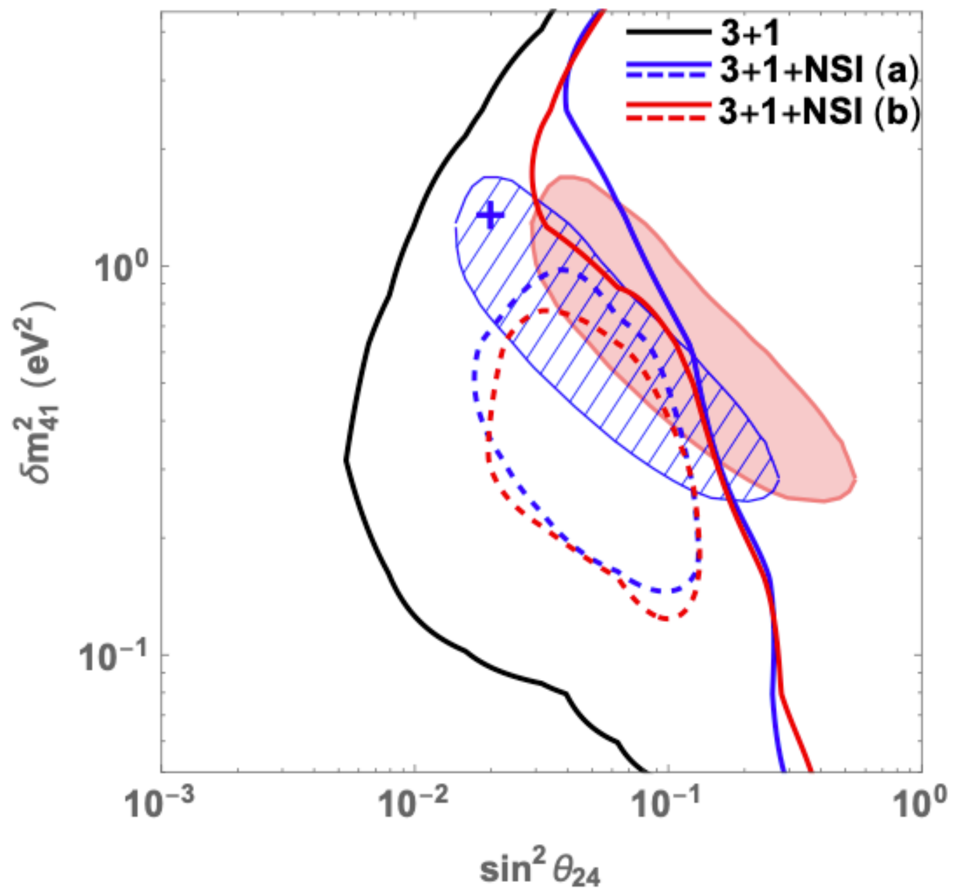
( )

Non-Standard Matter Effects
(3+1+NSI)

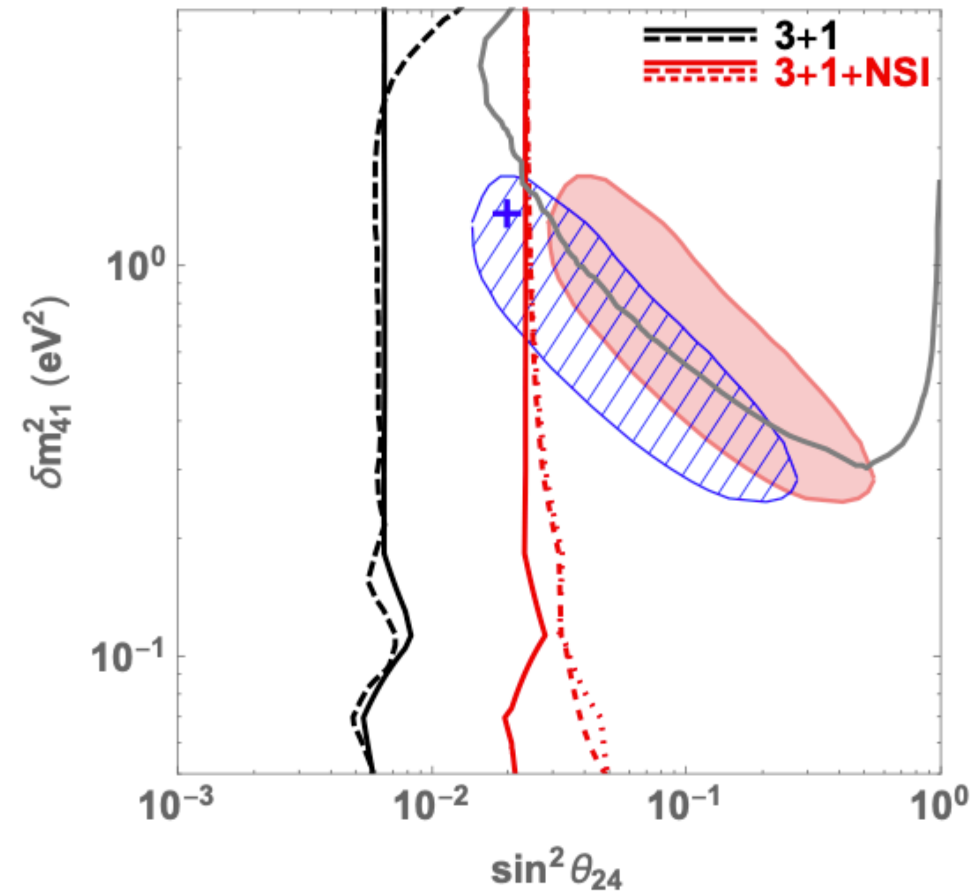
J. Liao et al

A. Esmaili et al https://arxiv.org/abs/1810.11940

IceCube modified by NSI



MINOS modified by NSI



See also Denton et al
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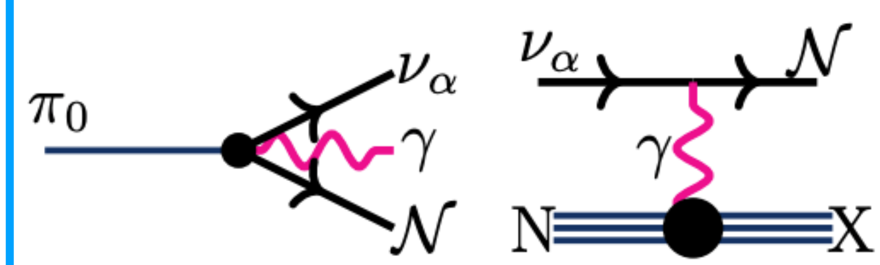
Direct Probes of Matter Effects In Neutrino Oscillations
(https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF1_NF3-TF0_TF0_Peter_Denton-010.pdf)

Non-Minimal HNL: photon scenario

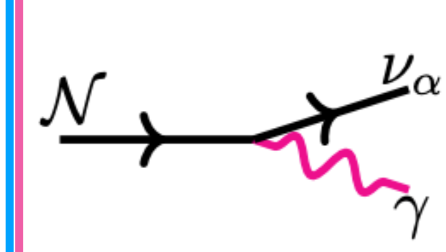
$$\sum_{j=1}^{3} \bar{\mathcal{N}}_j (i\partial\!\!\!/ - M_j)\mathcal{N}_j + \sum_{i=1}^{3} (d_{i,j}\bar{\nu}_i \sigma_{\mu\nu} F^{\mu\nu} \mathcal{N}_j + h.c.)$$

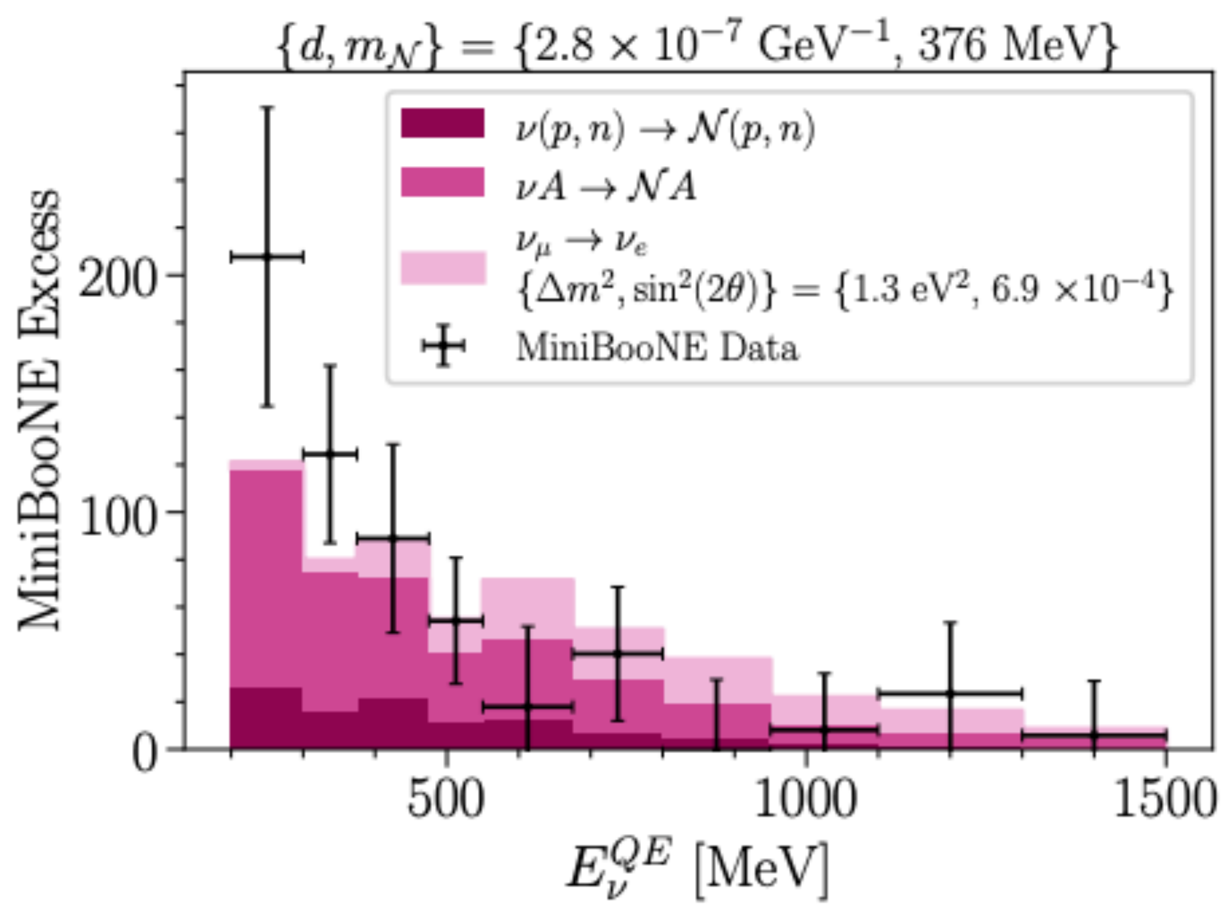
Parameters	χ^2/dof			
$(\sin^2 2\theta, d, m_{\mathcal{N}})$	$3+1+\mathcal{N}$		$3+1$	
	E_ν^{QE}	$\cos\theta$	E_ν^{QE}	$\cos\theta$
(0.30, 3.1, 376)	5.7/8	32.1/18	30.5/10	86.4/20
(0.69, 2.8, 376)	7.9/8	31.4/18	27.3/10	71.8/20
(2.00, 5.6, 35)	20.2/8	36.7/18	27.6/10	40.8/20
(0, 0, 0)	34.1/10	99.4/20	same	same

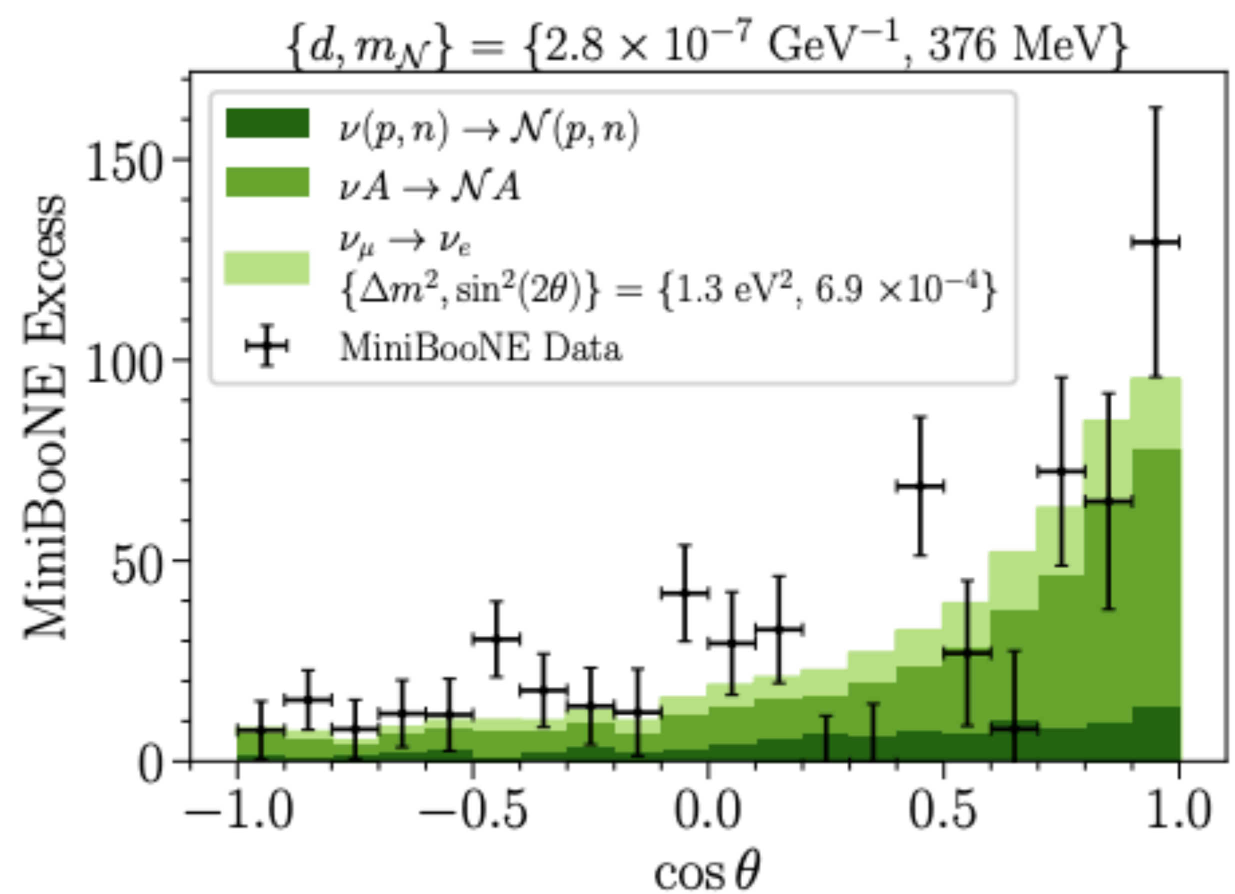
PRODUCTION



SIGNAL







S. Vergani, N. Kamp, Diaz, CA, J. M. Conrad, M. H. Shaevitz, M. A. Uchida, arXiv:2105.06470

Non-Minimal HNL: photon scenario

Used to Test	References (Flux Type)	Type of Fit
$\bar{\nu}_e$ disappearance	[39–43] (Reactor)	↑
ν_e disappearance	[44–46] (Source)	
$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance	[47, 48](π/μ DAR)	
$\nu_\mu \to \nu_e$ appearance	[49](π/μ DIF)	3+1-only
$\bar{\nu}_\mu$ disappearance	[50–53] (π/μ DIF)	
ν_μ disappearance	[51, 54–56] (π/μ DIF)	↓
$3+1+\mathcal{N}$	[8] (MiniBooNE BNB ν)	$\mathcal{N}$

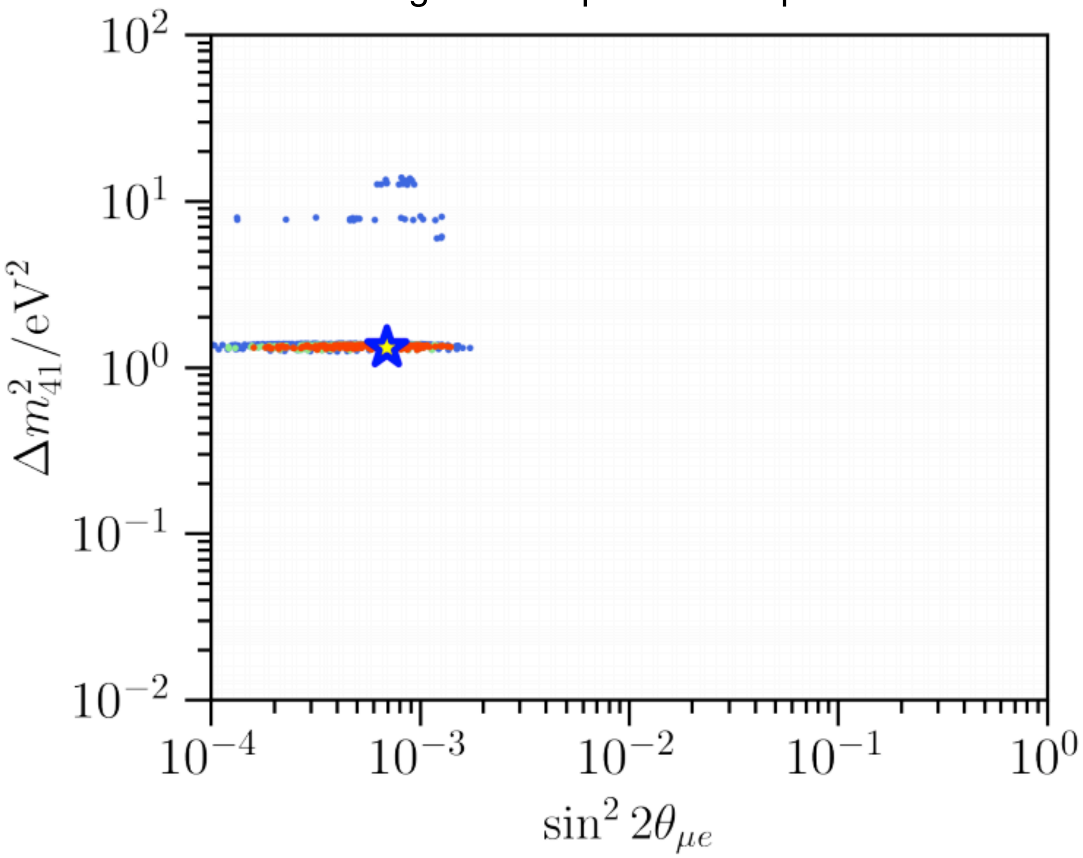
Explained by eV-sterile

Explained by MeV-HNL

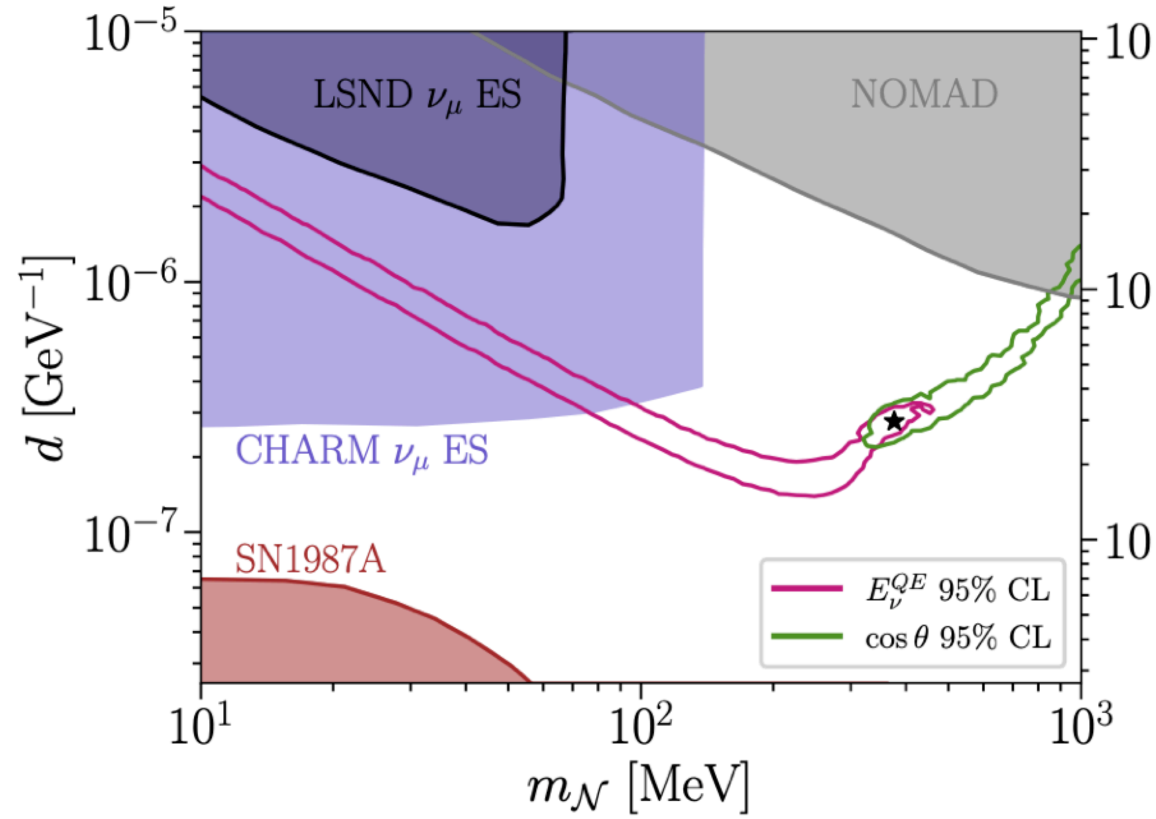
Fit type:	3+1-only	3+1-complete
χ^2_{app}	48	79
N_{app}	2	2
χ^2_{dis}	557	557
N_{dis}	3	3
χ^2_{glob}	615	664
N_{glob}	3	3
χ^2_{PG}	10	28
N_{PG}	2	2
p-value	7E-03	8E-07
$N\sigma$	2.7σ	4.8σ

Tension

Light sterile parameter space



Heavy "sterile" parameter space



S. Vergani, N. Kamp, Diaz, CA, J. M. Conrad, M. H. Shaevitz, M. A. Uchida, arXiv:2105.06470