Summary of the NuFact 2024 Working Group 5

Beyond the PMNS matrix

Matheus Hostert **on behalf of the WG 5**

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Koun Choi (최고운)
IBS Daejeon

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JGU Mainz

Matheus Hostert
Harvard U.

Special thanks to Koun for her 3rd and last year!

Working Group 5 Summary

1) **4 WG4 parallel sessions and one WG1+5 joint session:** 23 talks and 2 posters.

2) **Present in several plenaries:**
    1) Peter Denton (Theory Kickoff)
    2) André de Gouvea (Oscillation Theory and Future)
    3) Alexey Boyarsky (CERN activities)
    4) Minerba Betancourt (Short-Baseline Neutrino Experiments)
    5) Nitish Nayak (MicroBooNE Results)
    6) Yuri Efremenko (Coherent Neutrino Experiments)
    7) Shiqi Yu (IceCube and Atmospheric Neutrino Experiments)
    8) Christoph Wiesinger (Beta Decay and Cosmology)

Thank you to all of our session chairs!

Julia Gehrlein
Shiqi Yu
Peter Denton
Minerba Betancourt
Vishvas Pandey

Working Group 5 Summary

Topics:

1) Unlocking the potential of astrophysical neutrinos

2) Towards a resolution of the Short-Baseline puzzle

3) Ultra-rare processes from new physics

4) New matter effects in neutrino oscillations

Caveat: this is only a subset of what "beyond the PMNS" means to our community.

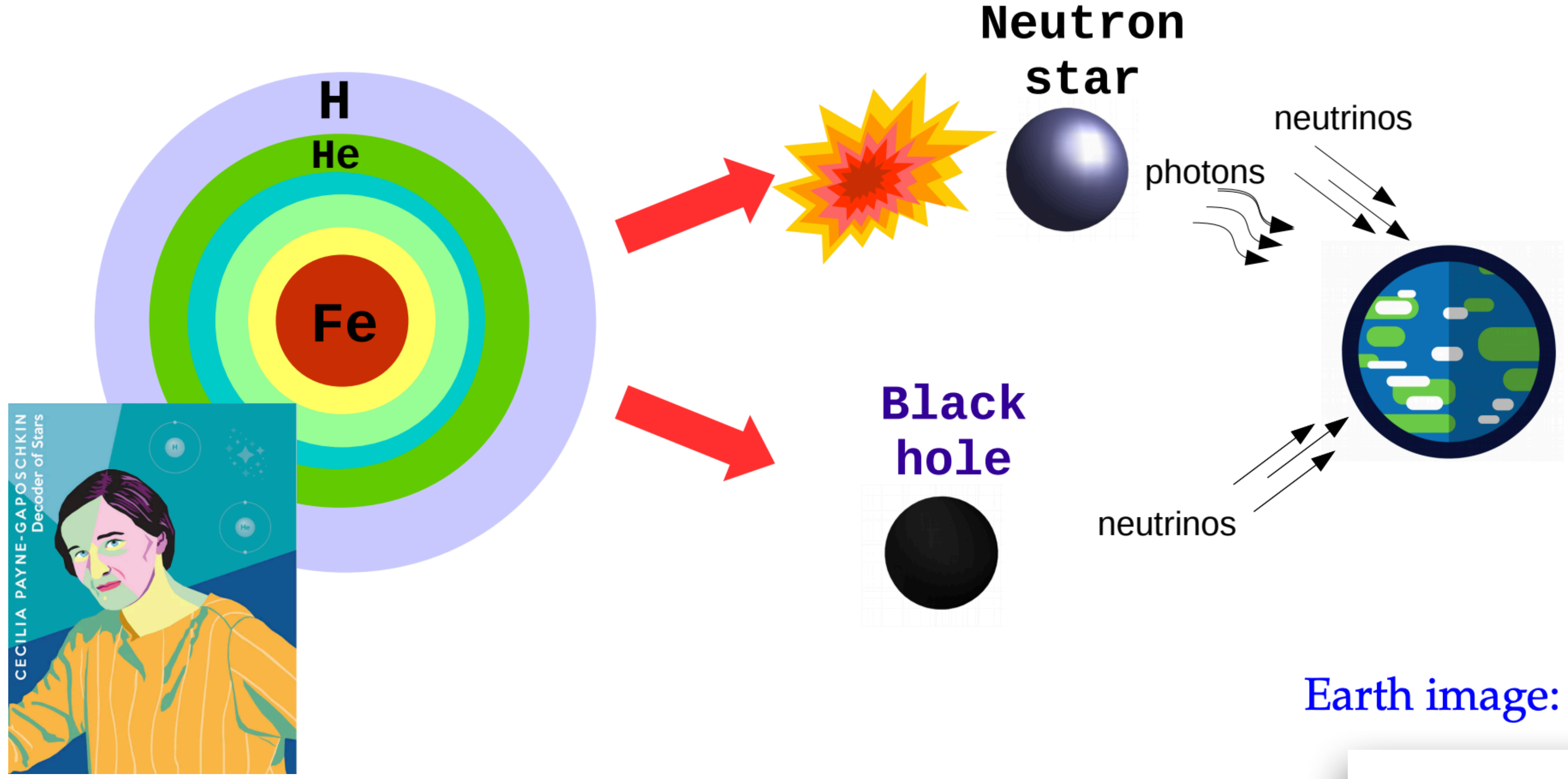
If you have suggestions, feedback, or question, do not hesitate to contact us!
We want to cover more in following years.

Unlocking the potential of astrophysical neutrinos

Neutrino-Sterile Neutrino (Dark Matter) Interactions

Diffuse Supernova Neutrinos

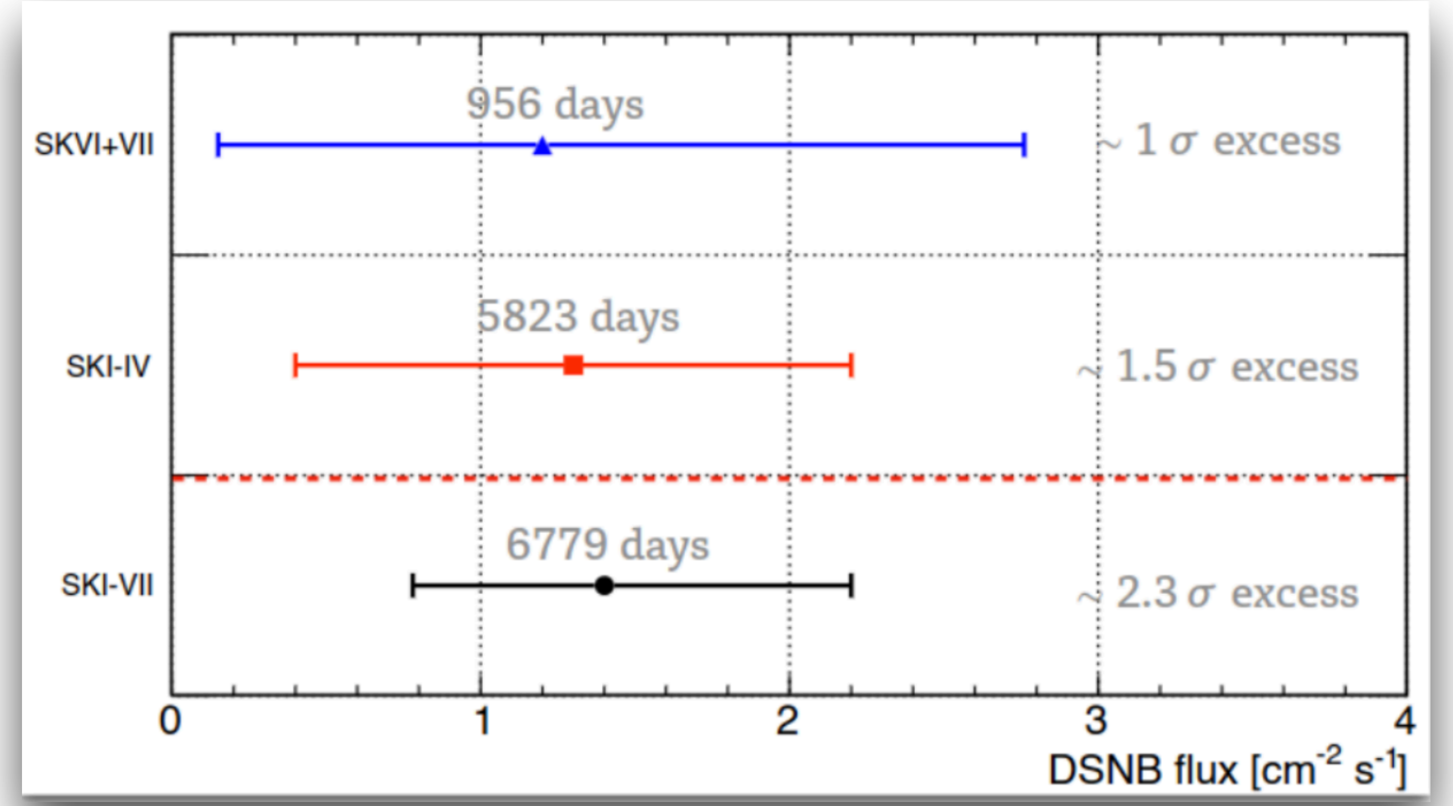
Anna M. Suliga (UC Berkeley/UC San Diego)

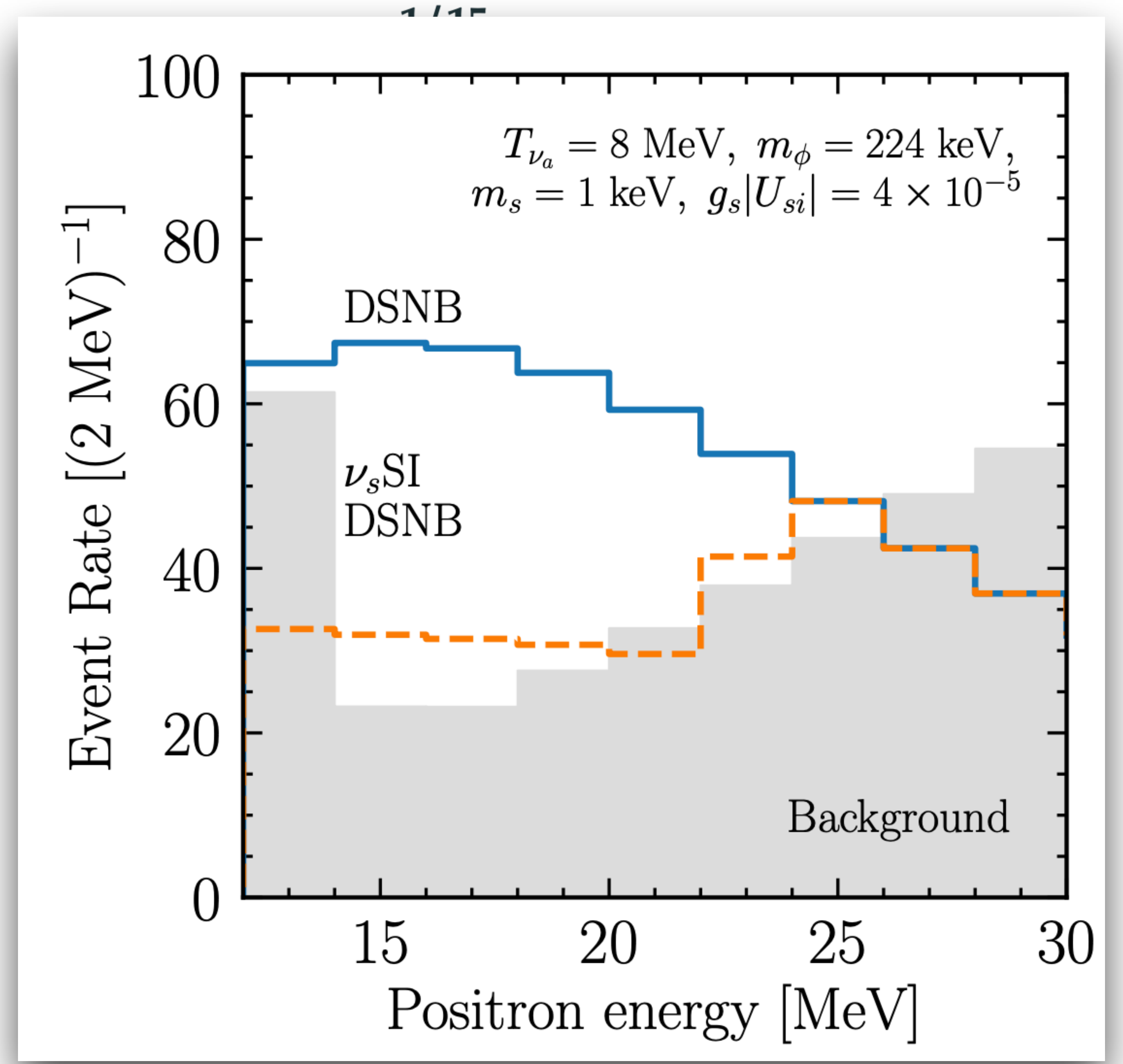


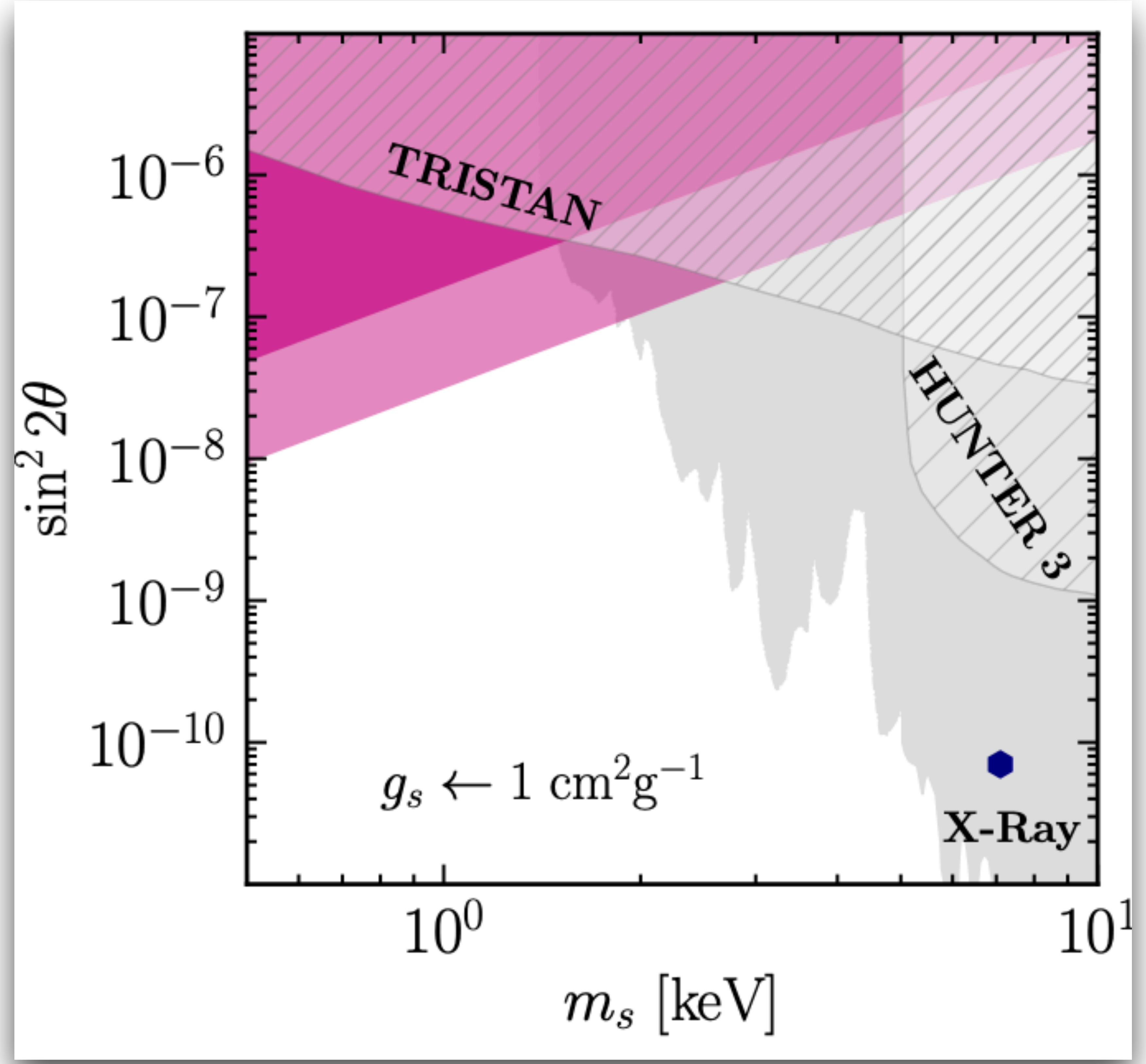
Earth image: Kurzgesagt

Neutrino interactions with dark matter on the way to Earth can modify their energy. Considering **sterile neutrino dark matter.**

DSNB detection can constrain this and **Super-K** is getting there!





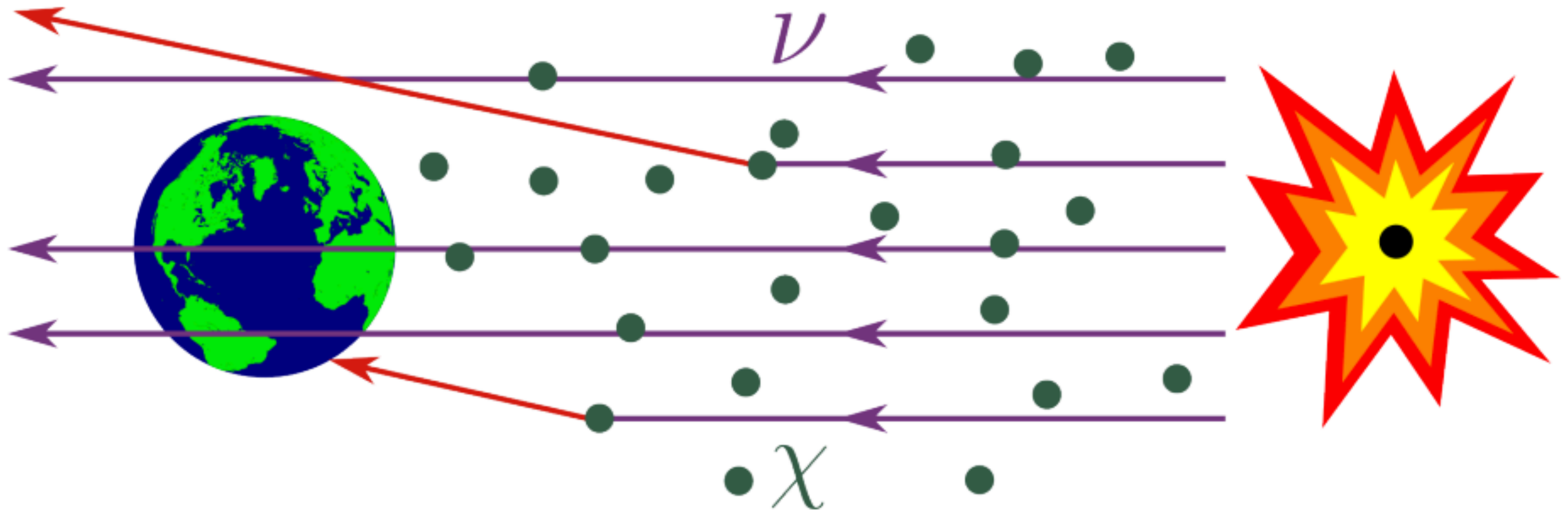


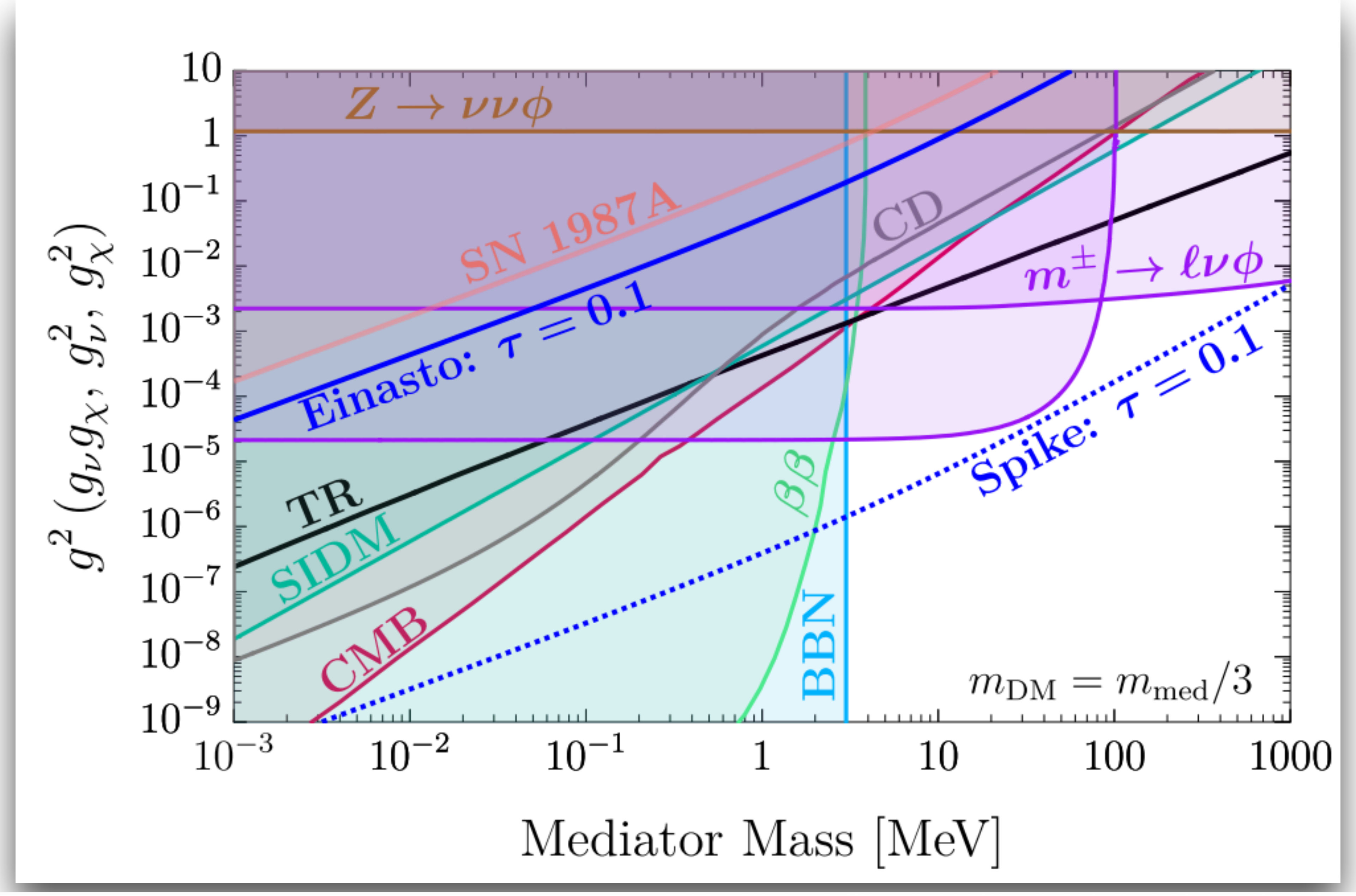
Neutrino Interactions w/ (all types of) Dark Matter
Supernova neutrinos @ DUNE & HK

Deepak Sathyan (Texas A&M)

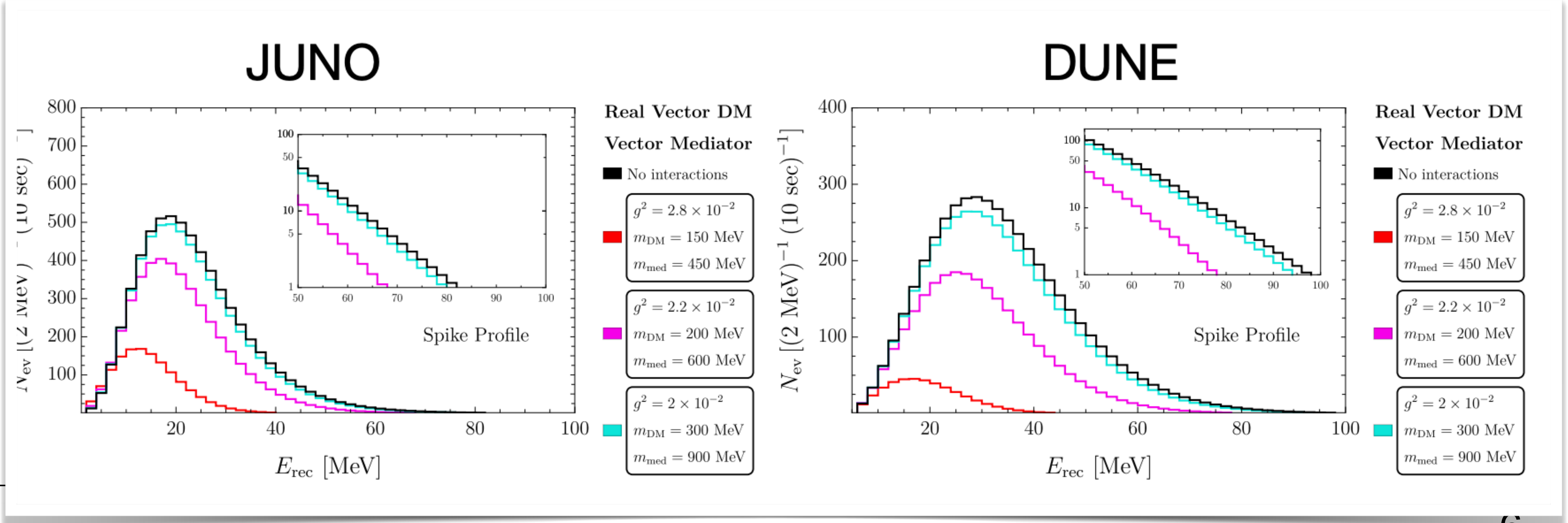
Extremely **comprehensive** study of neutrino-dark matter interactions and their impact on supernova neutrinos at LBL experiments:

Energy degradation and time delay.





scenario	Lagrangian	channels	amp. sq.	[54]	[32]
complex scalar †	(2.7)	t	(2.8)	–	✓
Dirac fermion	(2.9)	DM-ν: u	(2.10)	✓*	–
		DM-$\bar{\nu}$: s	(2.11)	–	–
Majorana fermion	(2.9)	s, u	(2.12)	✗	–
Dirac fermion †	(2.13)	t	(2.14)	–	✓
complex vector †	(2.15)	t	(2.16)	–	–



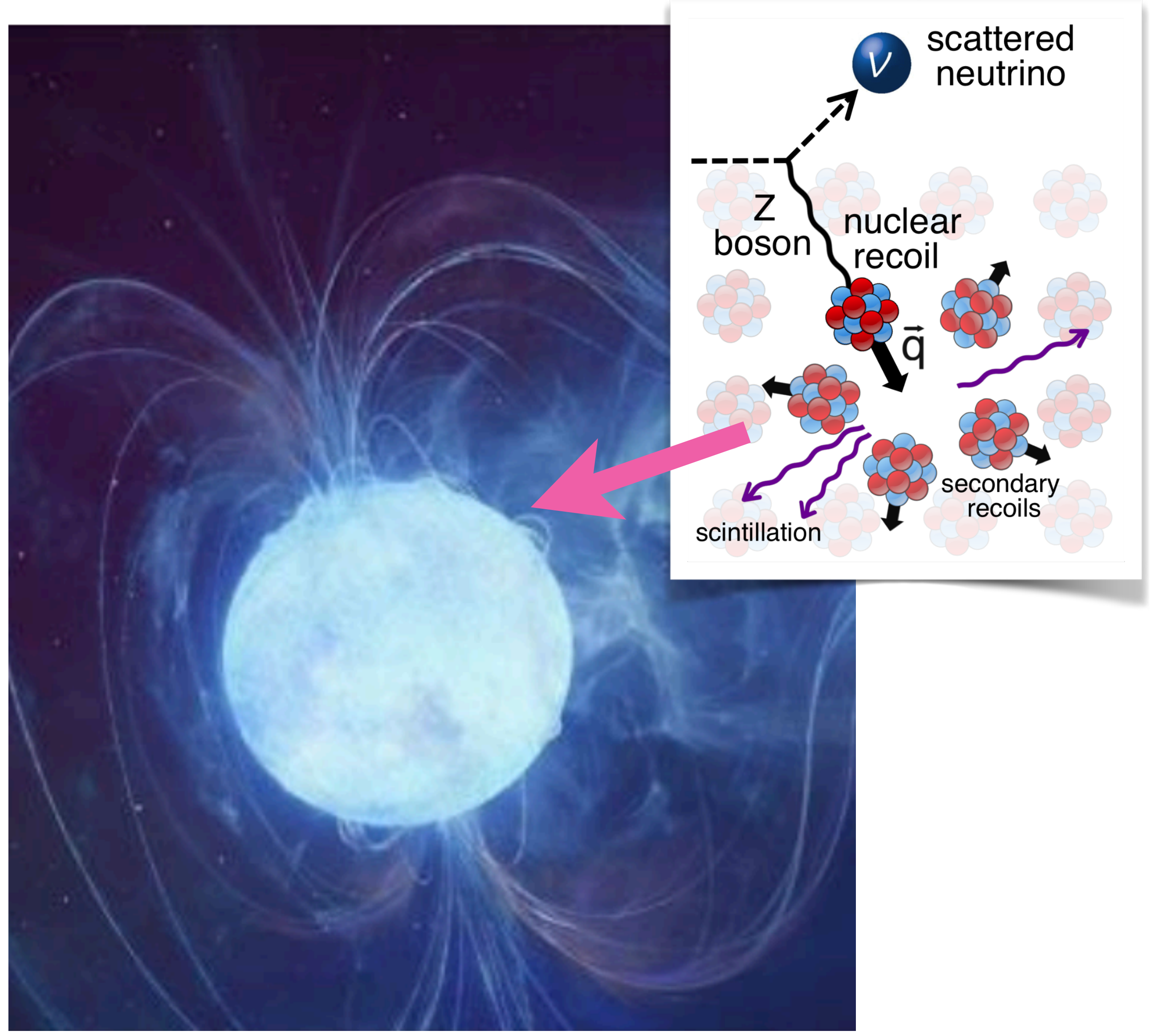
[32] C. Argüelles, A. Kheirandish, A. Vincent [1703.00451]
[54] A. Campo, C. Bœhm, S. Palomares-Ruiz, S. Pascoli [1711.05283]

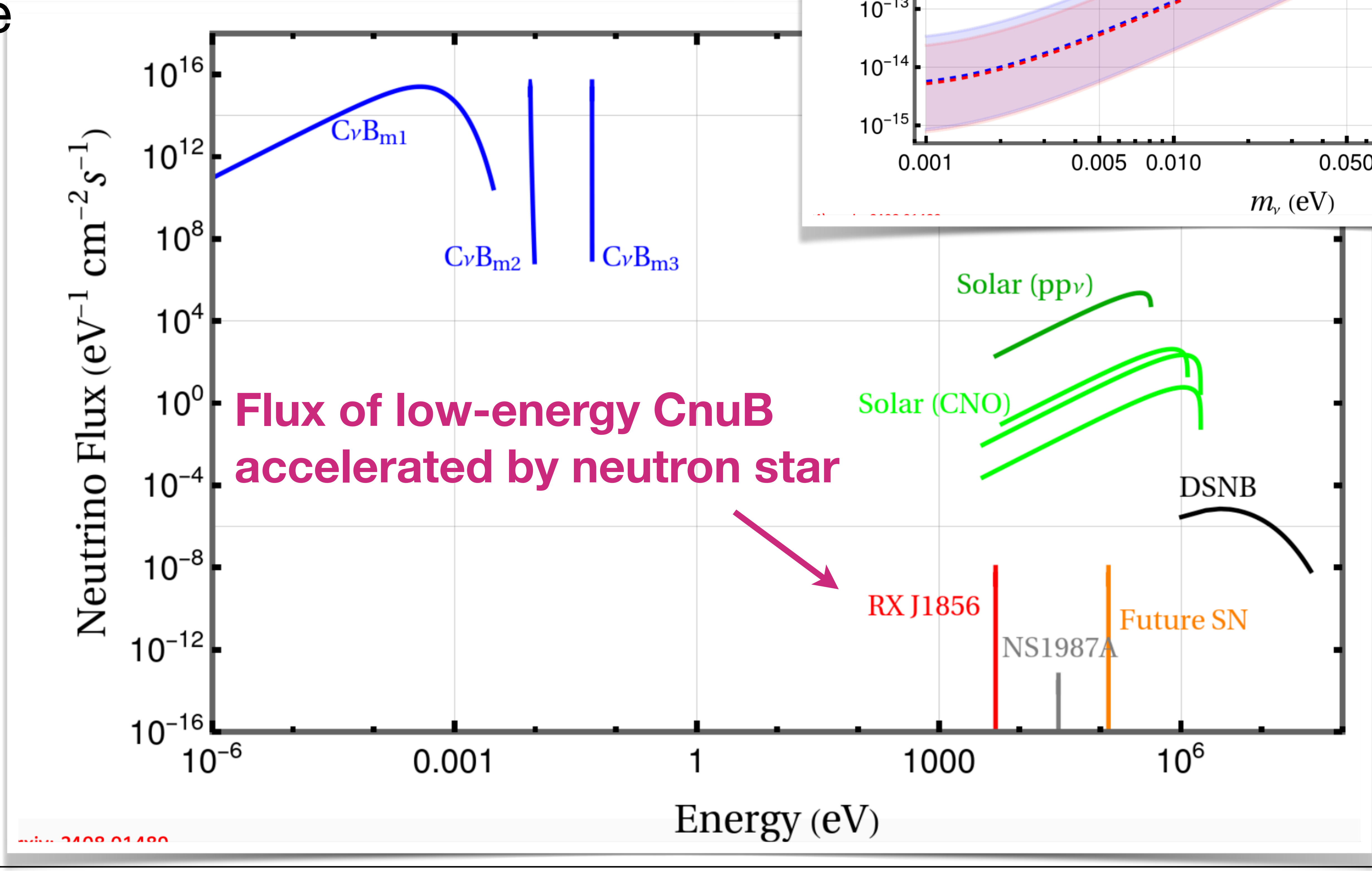
Cooling of neutron stars
A new challenging method for CvB detection

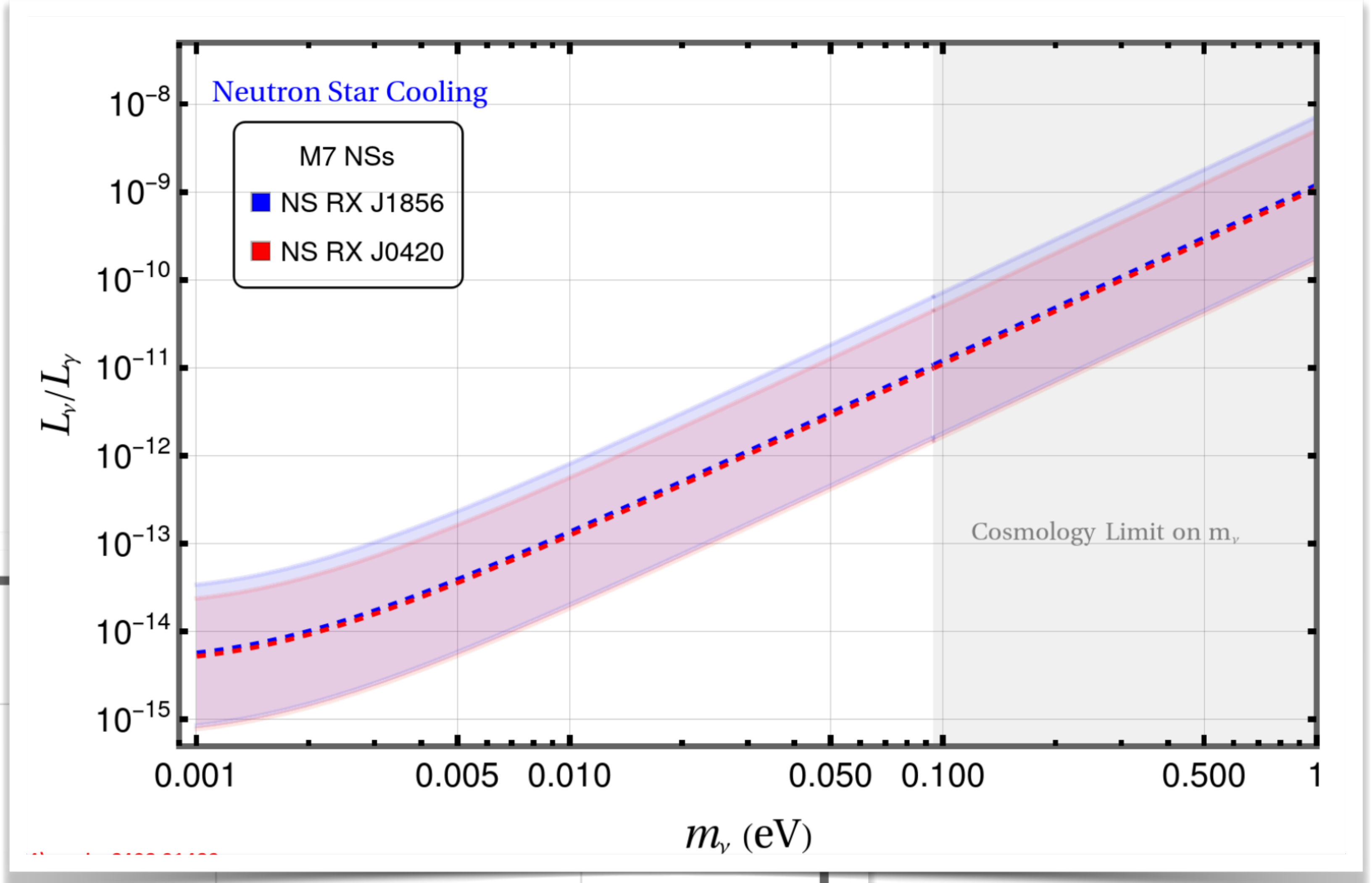
Garv Chauhan (Virginia Tech)

While the internal temperature of newly born NSs is around several MeVs, the oldest observed neutron stars have cooled down to keV.

Coherent scattering of CnuB inside the neutron will cool it further!





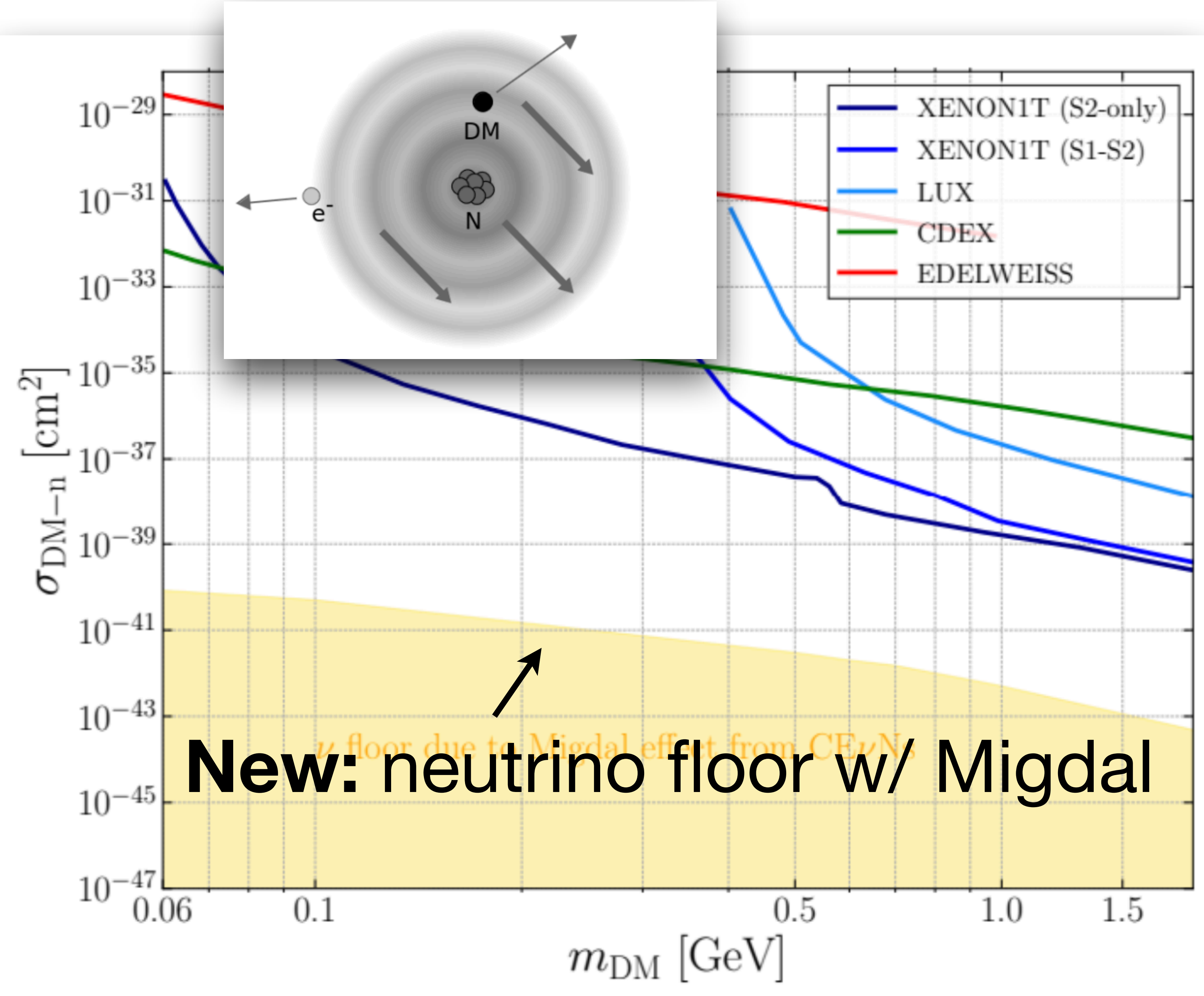


Dark Matter & Neutrino experiment synergies

Gonzalo Herrera (Virginia Tech)

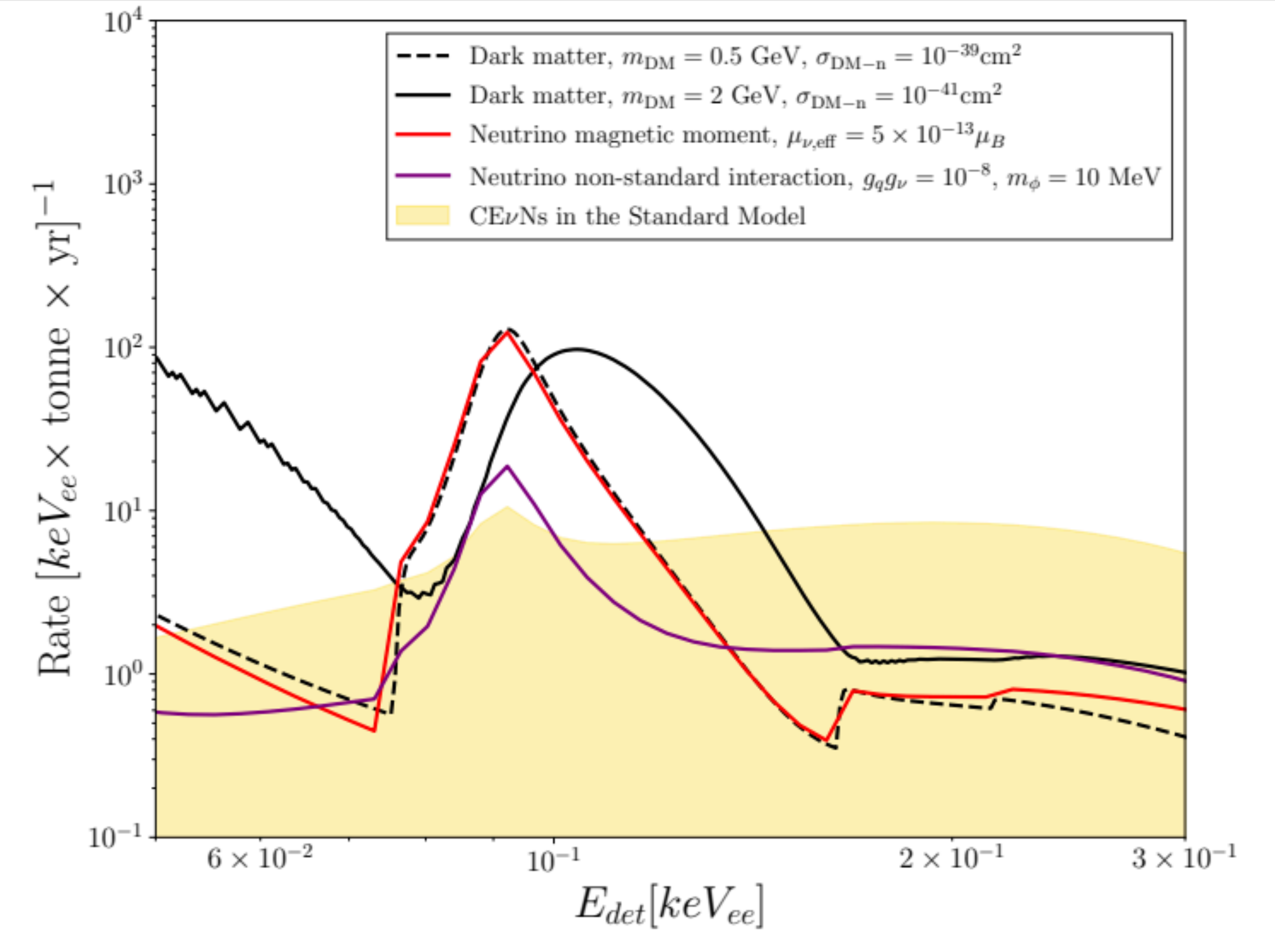
Many new ideas to constrain neutrino properties with dark matter experiments.

One of them was about using the Migdal effect:



- The **neutrino floor** is ~ 4 orders of magnitude away from current sensitivity to the Migdal effect from light dark matter

Neutrino magnetic moments can look very similar to dark matter...



- New physics can induce a **distinct peak** in the ionization spectrum around 0.1 keV, arising from the ionization of $n = 4$ electrons by pp neutrinos, which is absent in the weak interaction spectrum

Could distinguish them by putting radioactive sources close to direct detection experiments?!

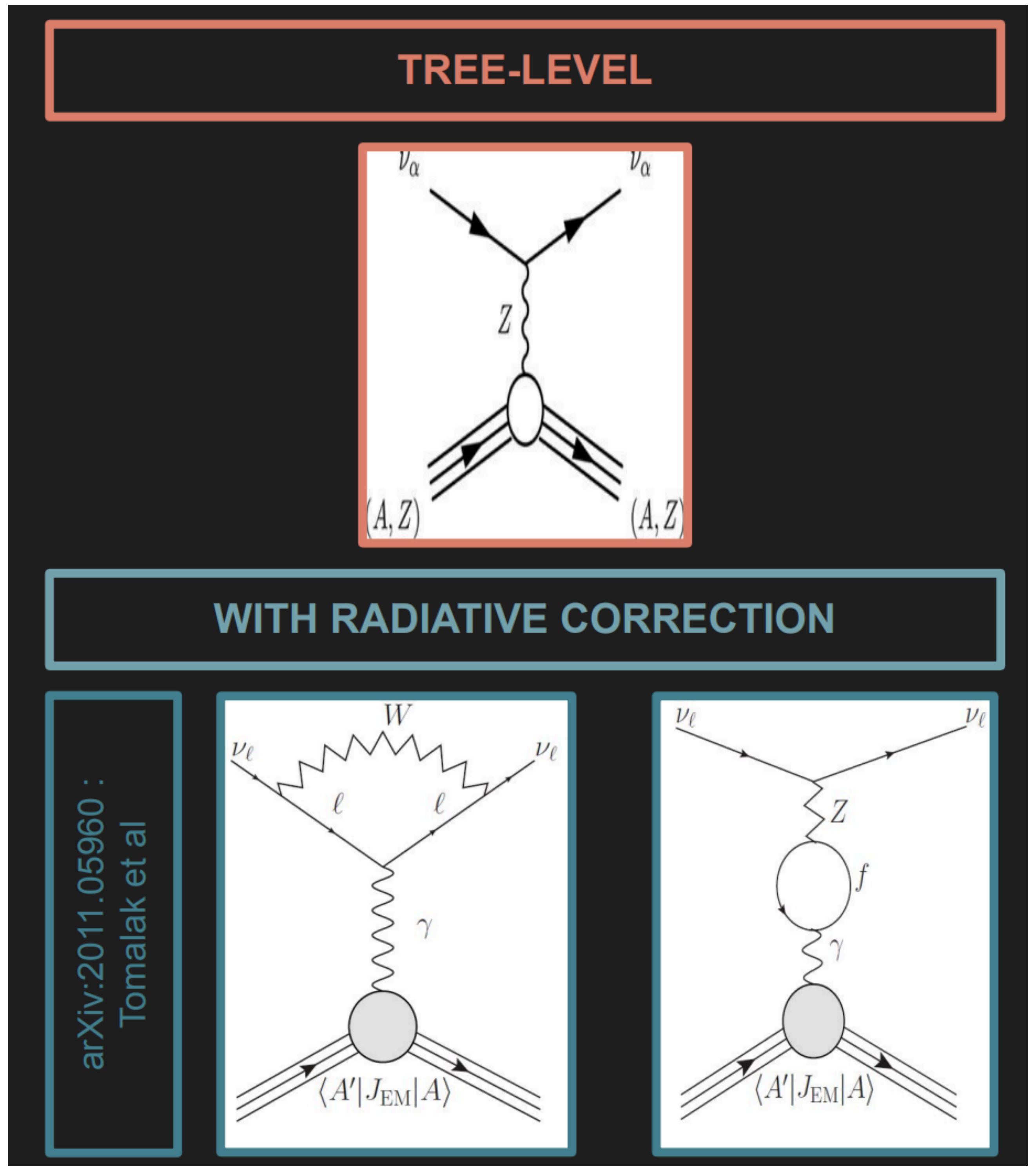
Cr51 source w/ 100x more intense nu flux than solar pp neutrinos.

Coherent elastic neutrino-nucleus scattering in direct detection

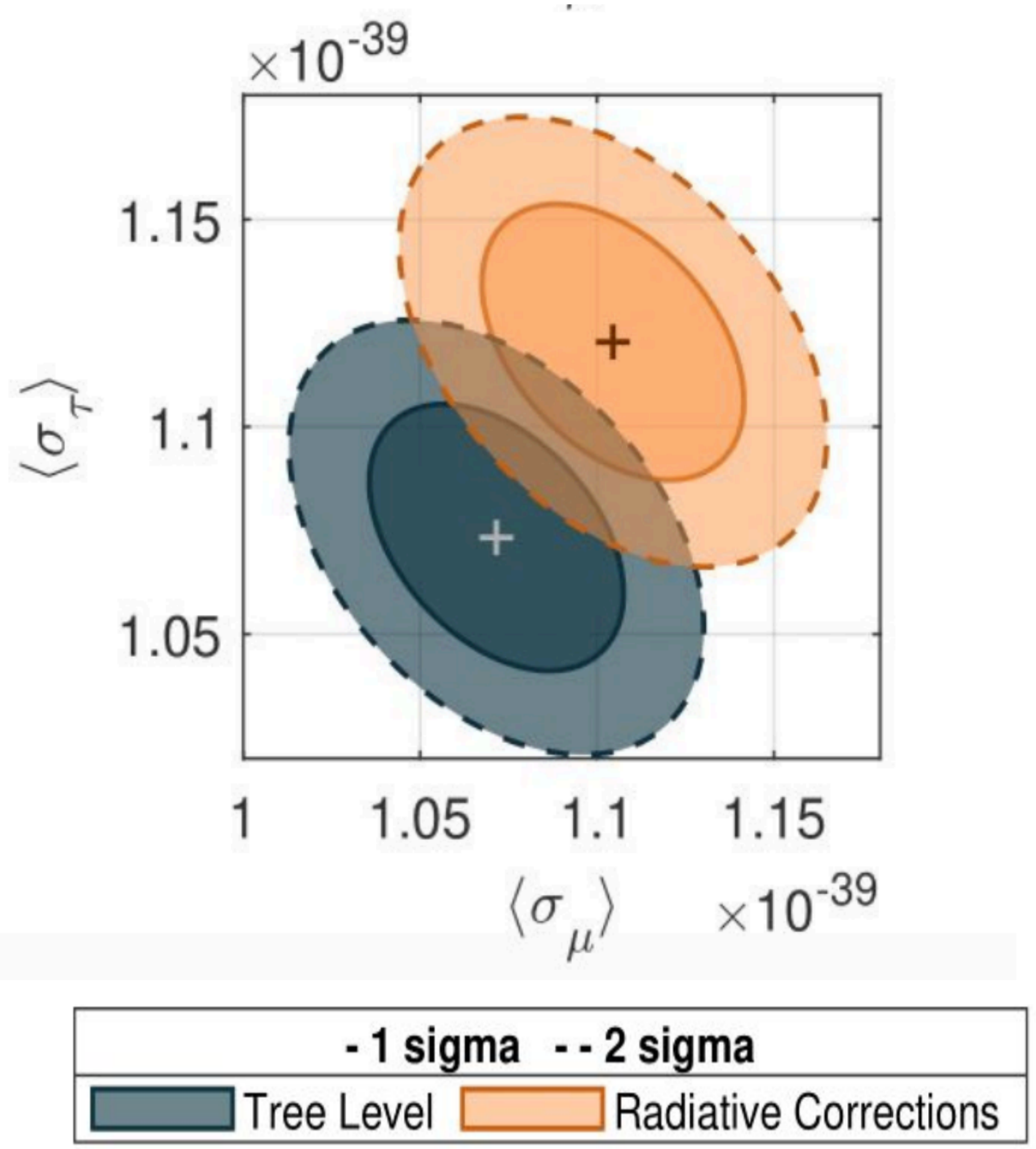
Flavor dependence & new limits

Nityasa Mishra (Texas A&M University)

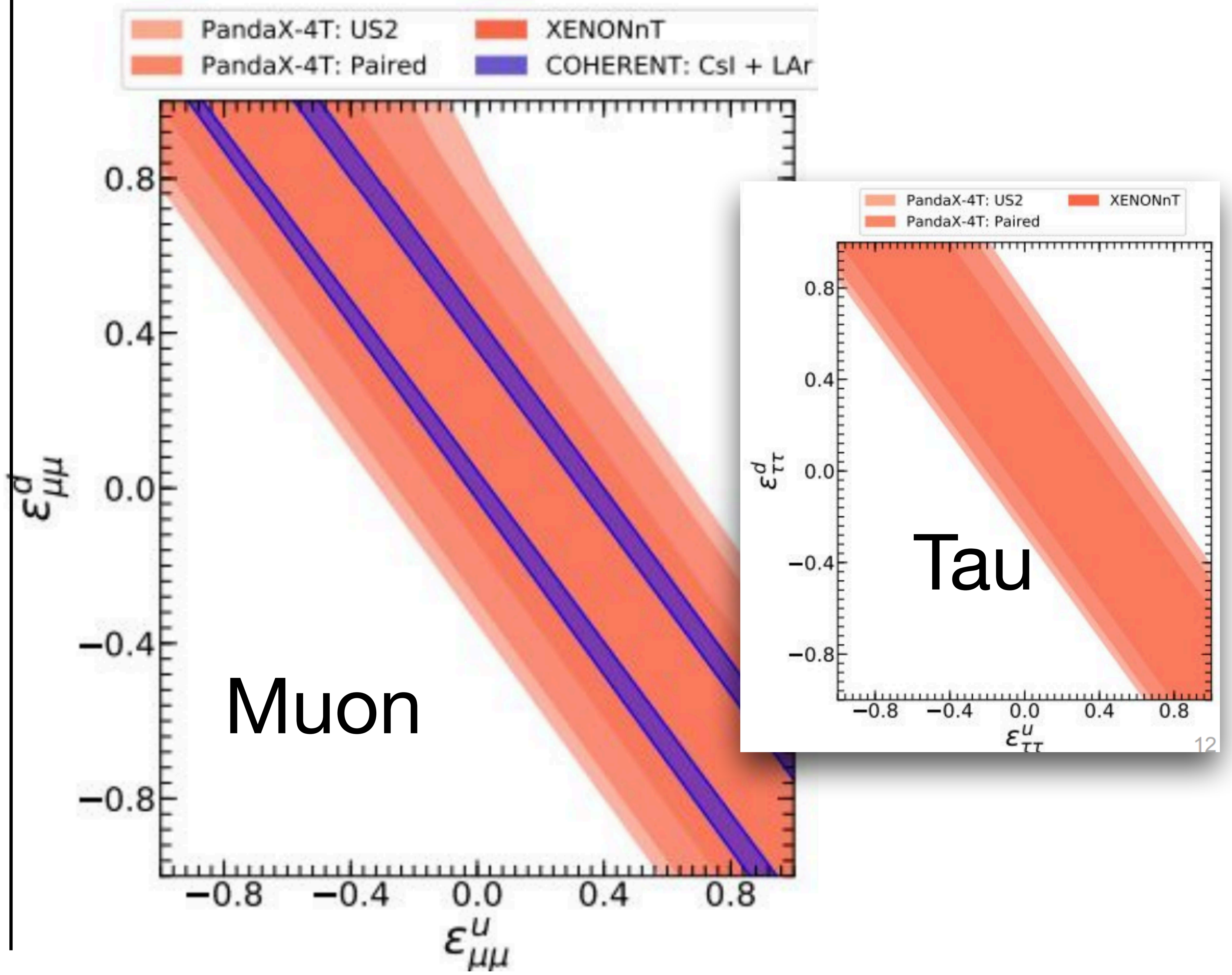
Radiative corrections lead to flavor dependence on CEvNS cross section!
Can affect interpretation depending on **precision** and **thresholds.**



Lepton masses enter in logarithms

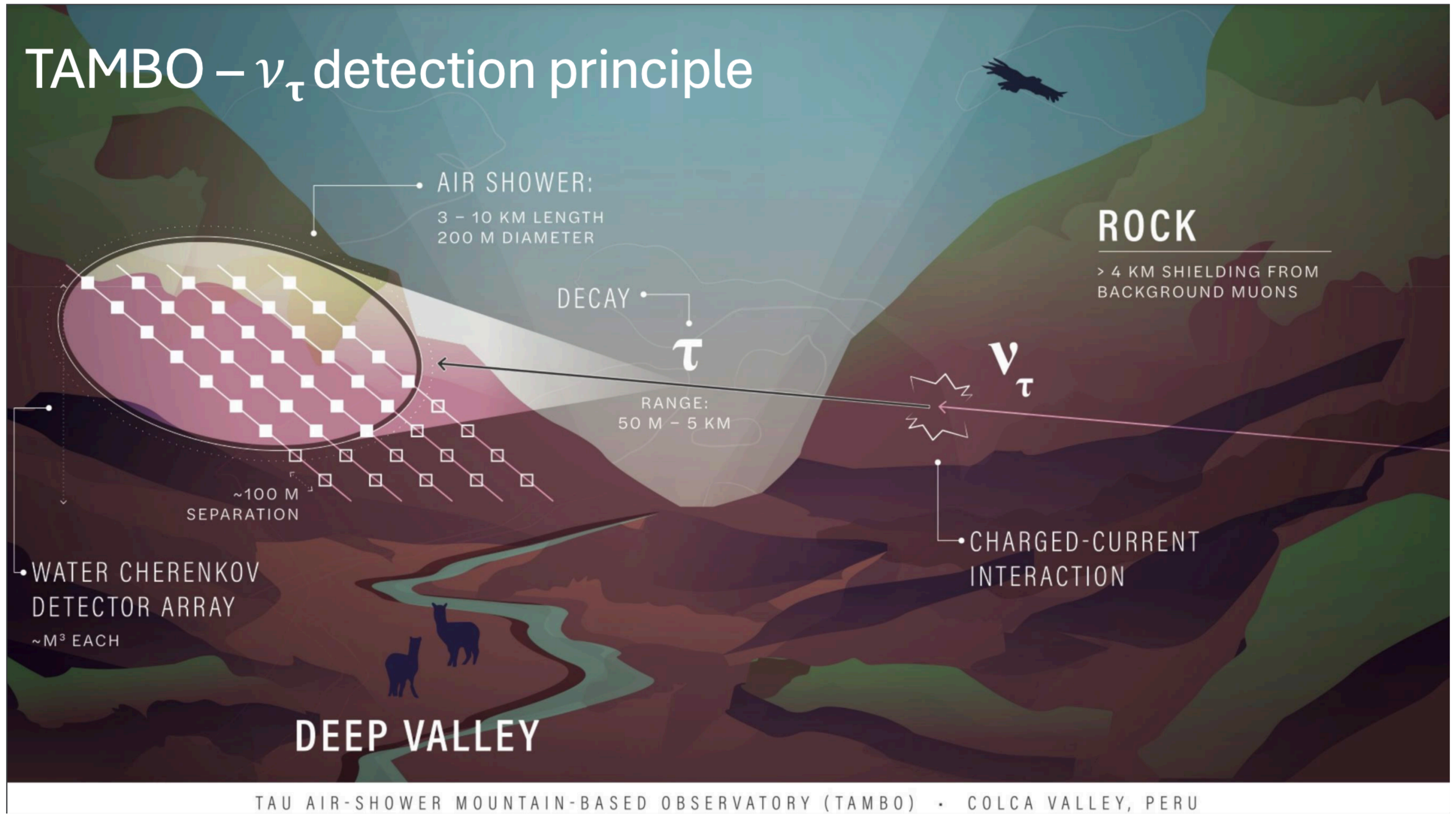


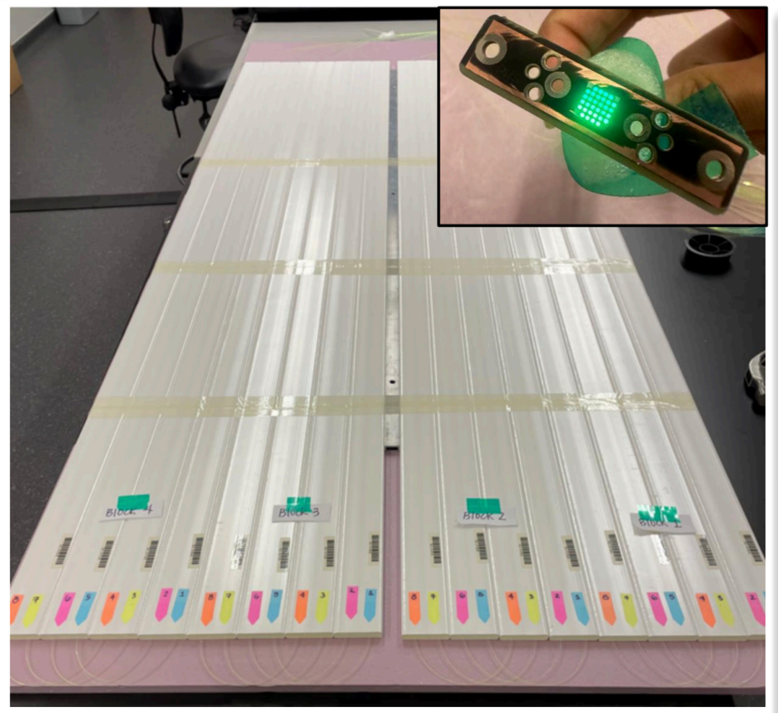
New limits on non-standard interactions from latest XENON and Panda-X solar neutrino CEvNS searches.



Ultra high-energy tau neutrinos
TAMBO

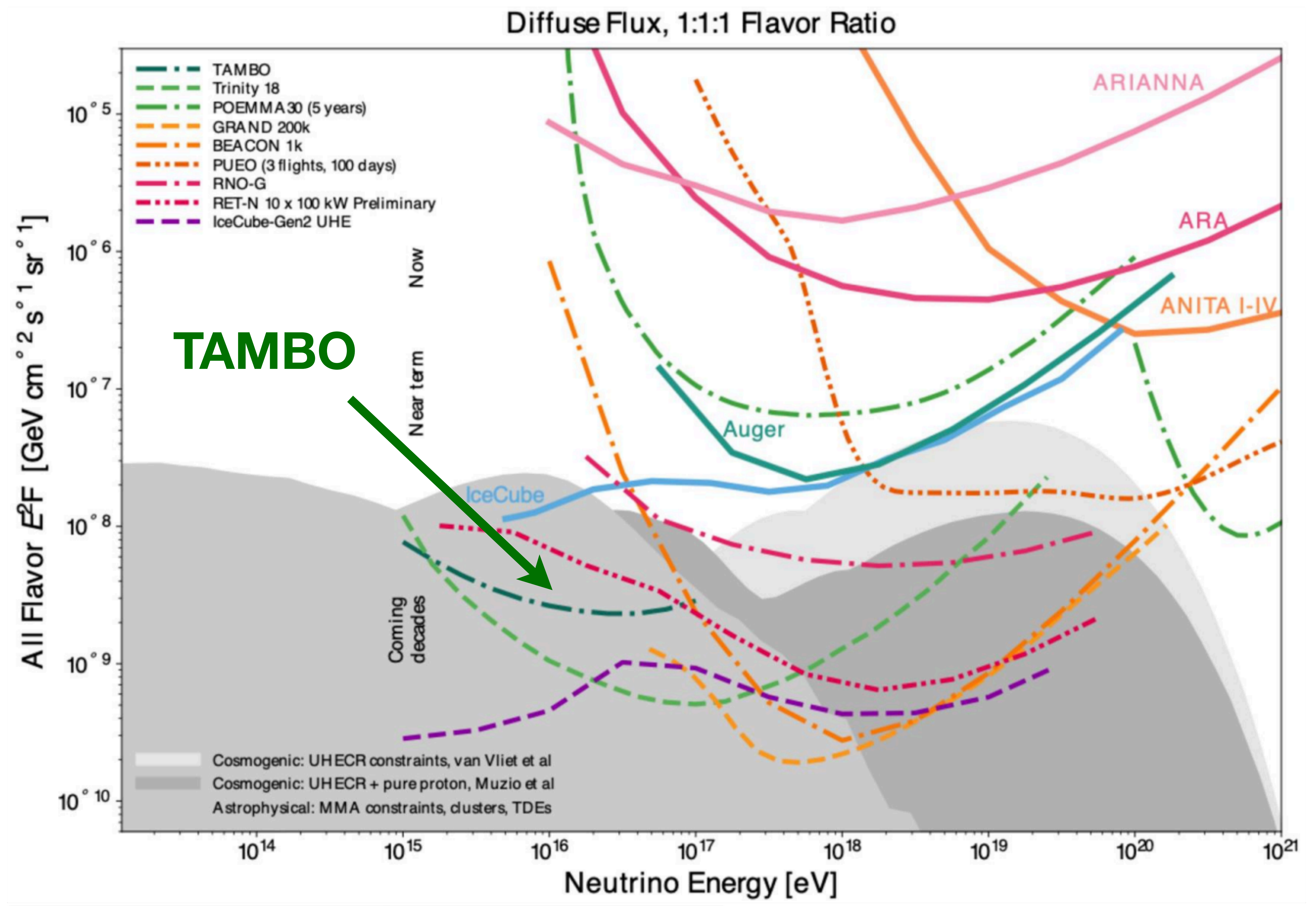
Robert-Mihai Amarinei (University of Geneva)





TAMBO comprises 22000 modules:

- Water Cherenkov vs plastic scintillator
- ~ns time resolution for 1° angular resolution
- No R&D needed to reach goals
- However, needs to be scalable and easy do deploy on a mountain face.



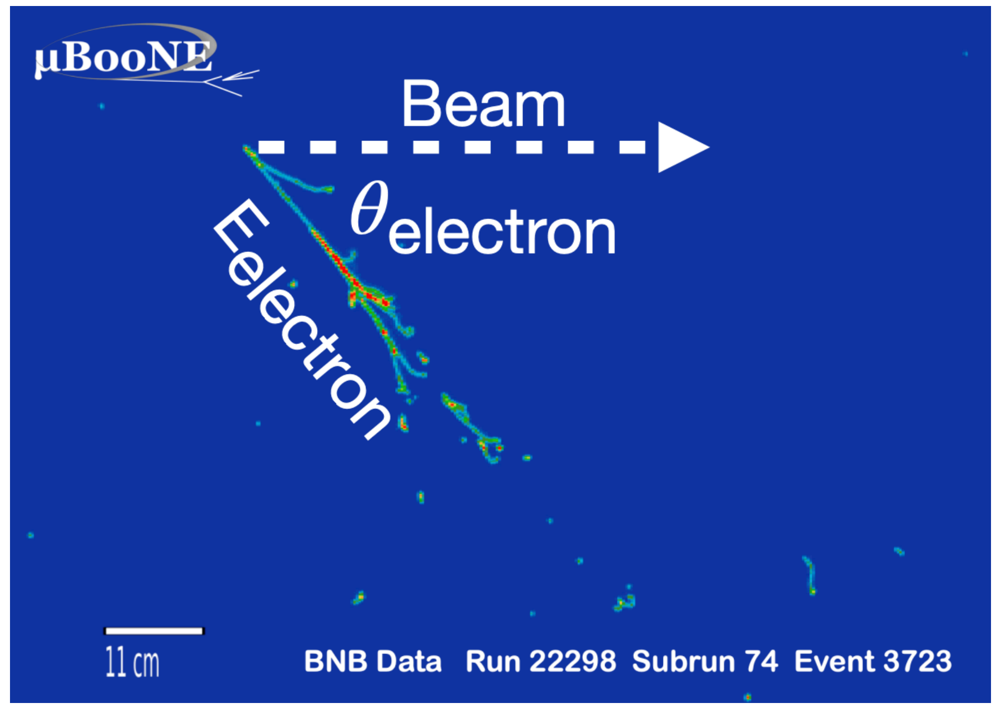
Current prototype:

- Plastic scintillator (1cm thick) with wavelength shifter
- 1.5 m^2 area
- Readout by SiPM array.

Towards a resolution of the Short-Baseline puzzle

MicroBooNE
A new template test of the low-energy excess (ν_e)

Fan Gao (UC Santa Barbara)

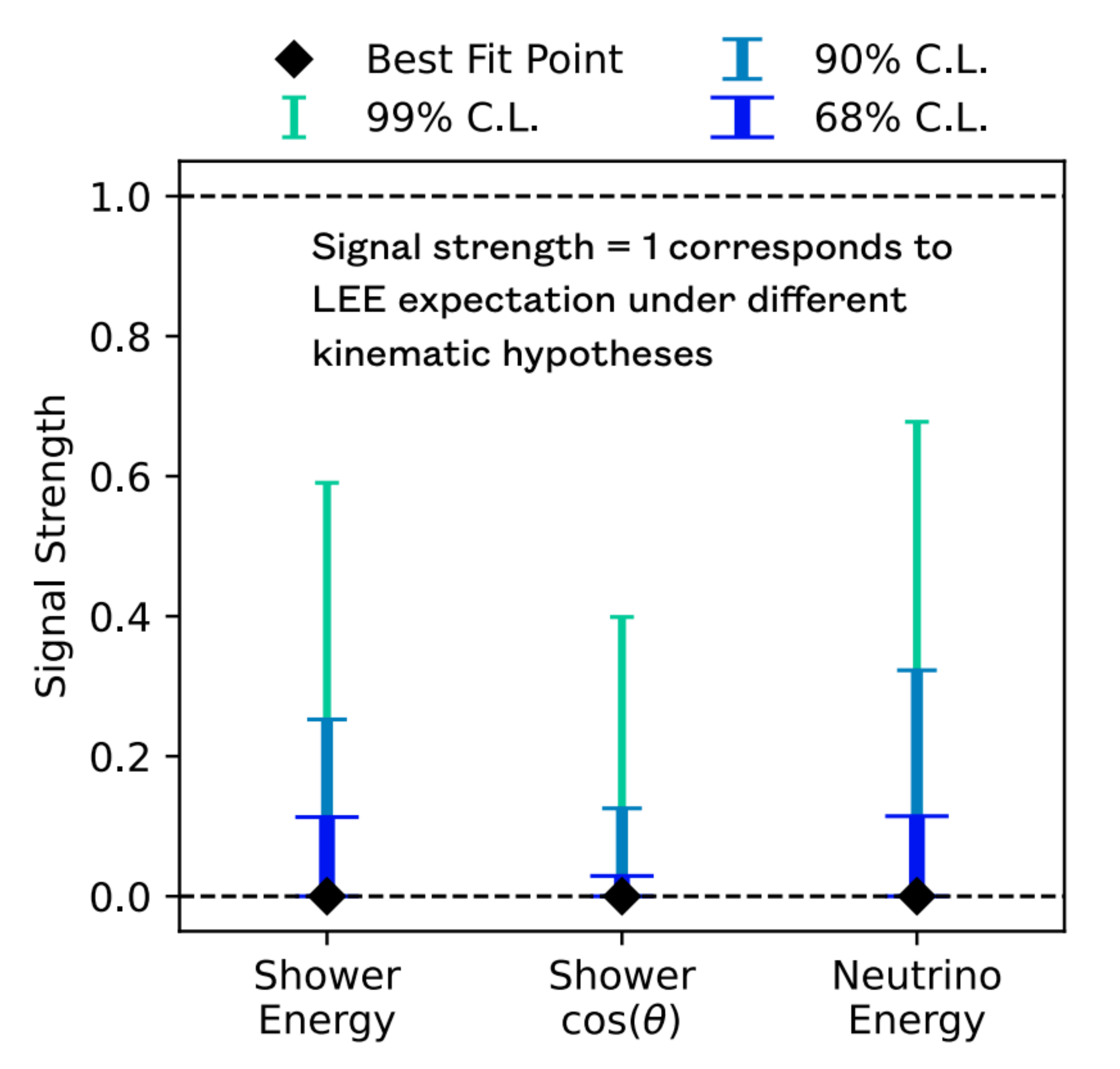


Searches for the template of MiniBooNE excess now in E_ν, $\cos\theta$, and $E_{\rm vis}$.

* First analysis to use all of five runs data from MicroBooNE (2015-2020)

* 11.1×10^{20} POT of BNB data

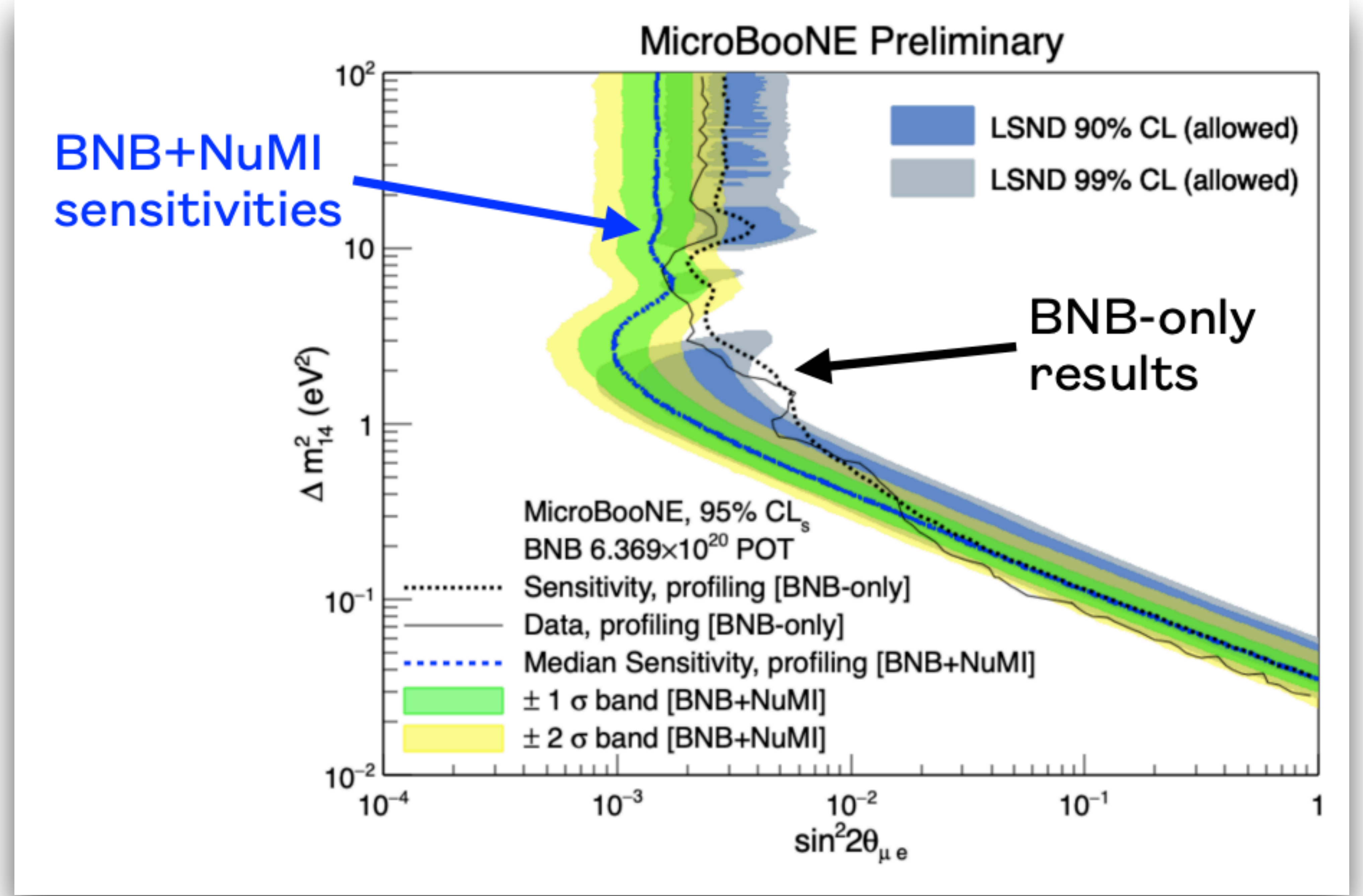
- Test **Signal Model 2 - 2D shower kinematics-based model**:
  - Exclude this excess model @ > 99.9% CL in combined Np & 0p channels.



Plans to update sterile neutrino oscillation search:

Joint NuMI+BNB breaks degeneracy between app and dis for *BEST-motivated* mixing angles.

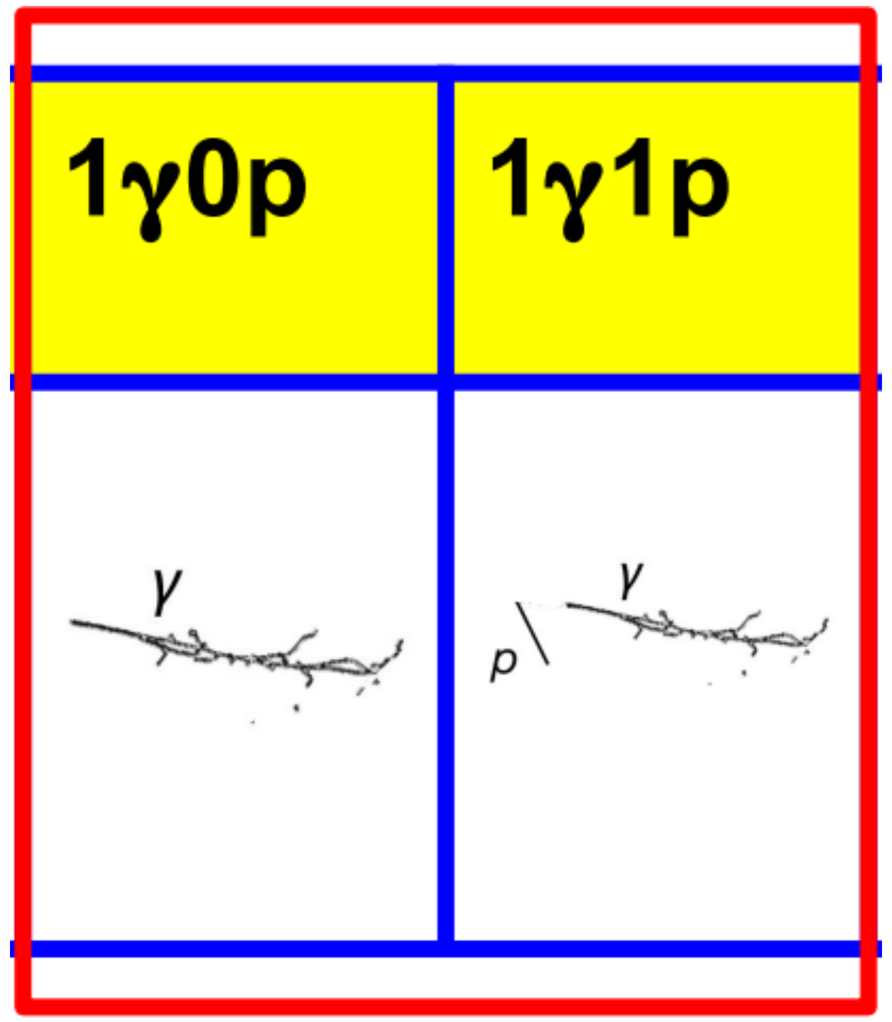
$\nu_\mu \to \nu_e$ **appearance angle.**



MicroBooNE
Plans for updated single photon searches (γ)

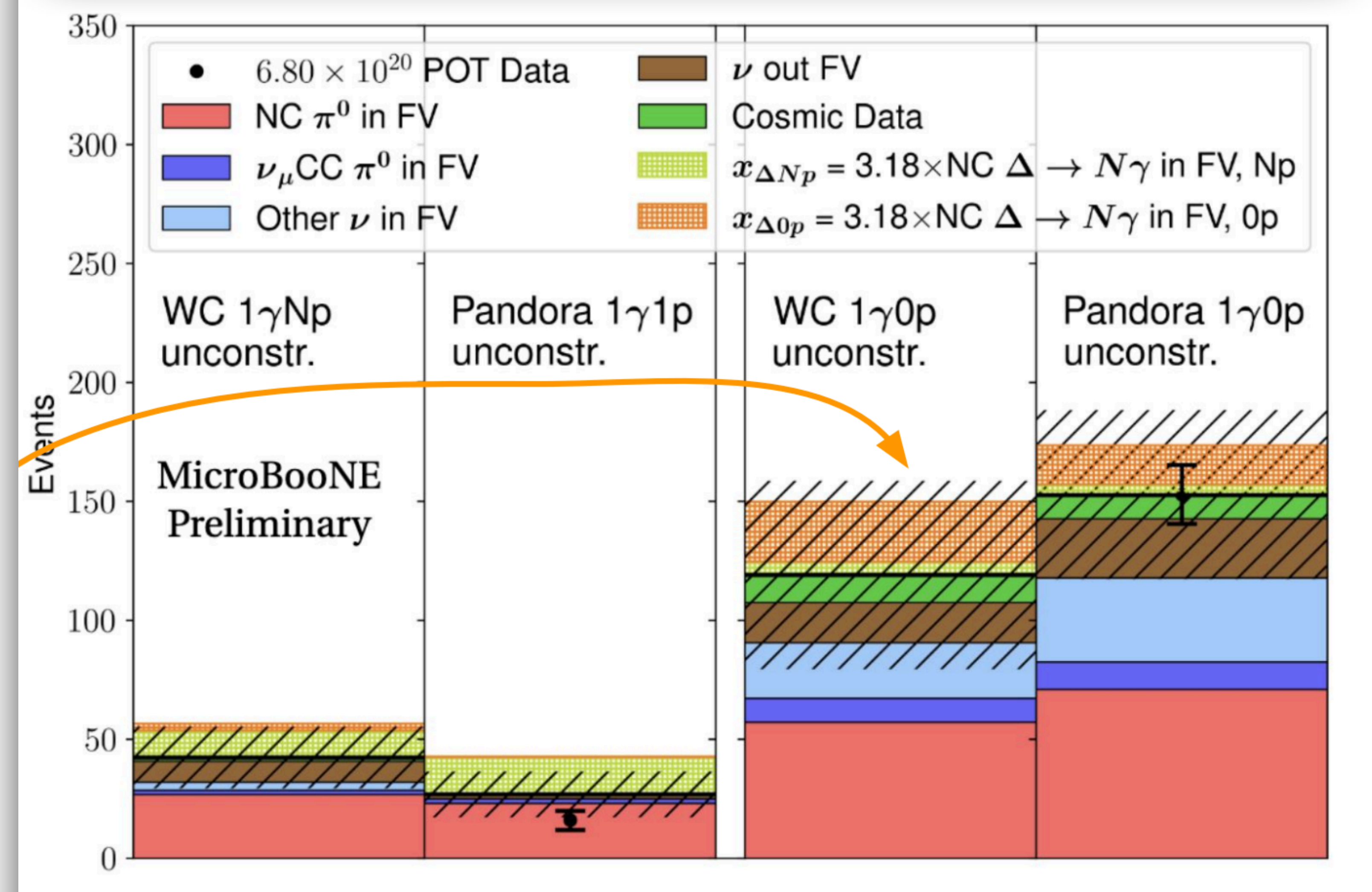
Erin Yandel (UC Santa Barbara)

A new search for a single-photon origin of the MiniBooNE low-energy excess



- Expanded NC $\Delta \to N\gamma$ search
- Incorporates Wire-Cell reconstruction in addition to previous Pandora-based results
  - largely orthogonal -> almost doubles statistics
- In particular, additional 1γ0p selection has more sensitivity

	Wire-Cell $1\gamma Np$	Pandora $1\gamma 1p$	Wire-Cell $1\gamma 0p$	Pandora $1\gamma 0p$
NC $\Delta \to N\gamma$ eff.	4.09%	4.31%	8.78%	5.58%
NC $\Delta \to N\gamma$ pur.	9.95%	15.1%	8.79%	4.35%

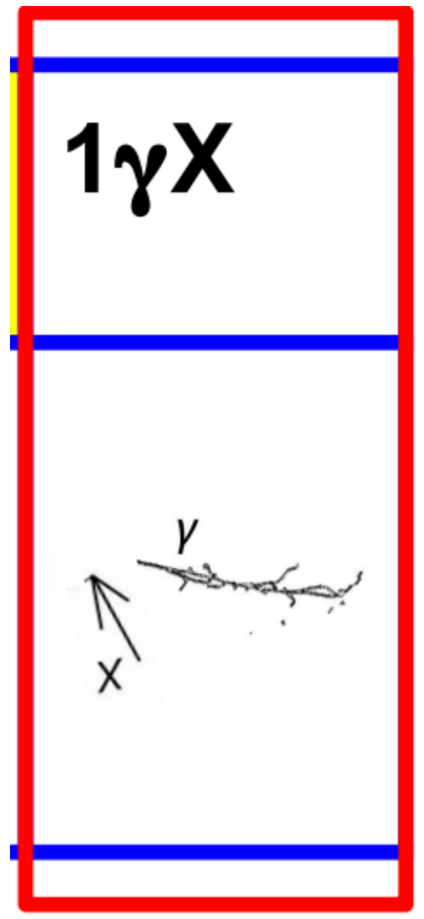


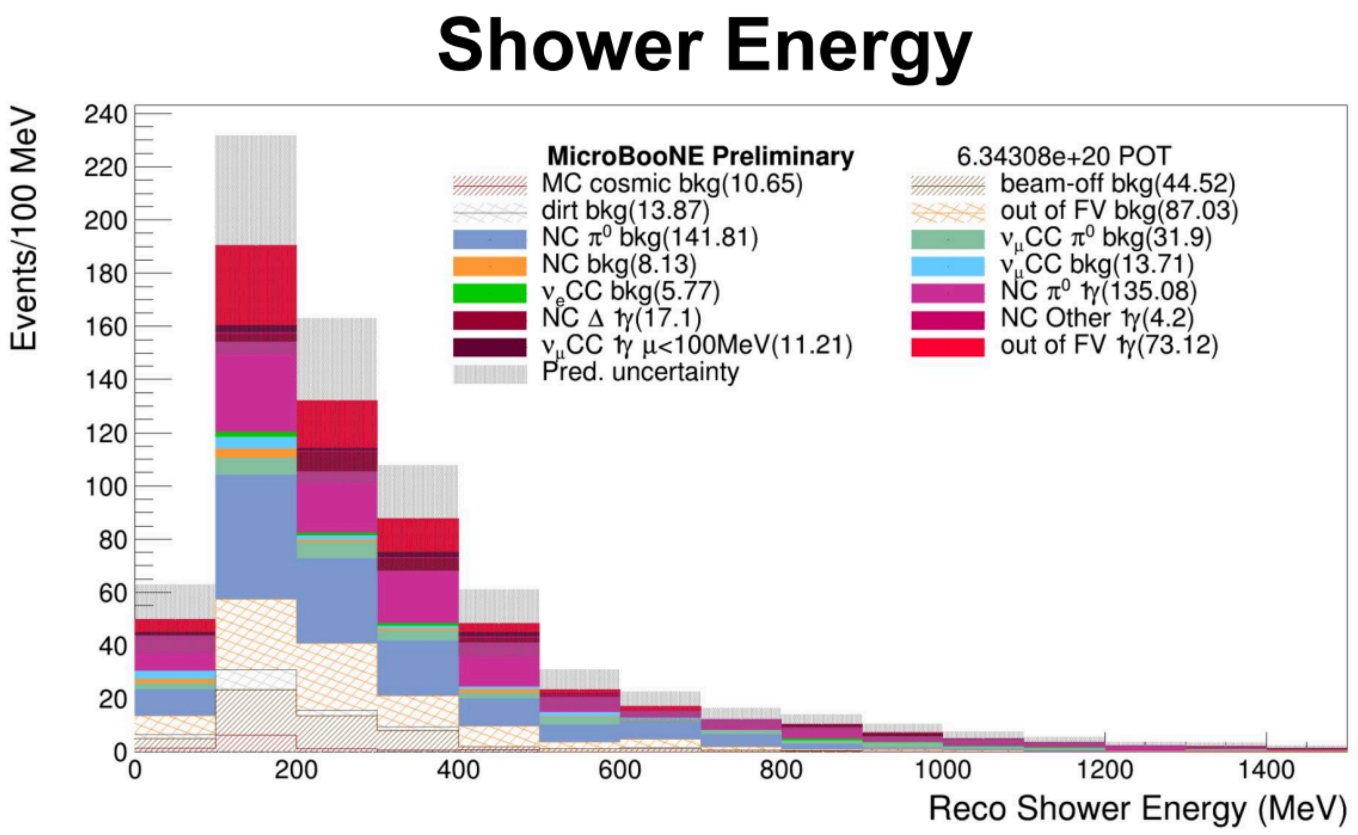
stay tuned for data analysis!

"1γ0p channel" with no visible hadronic activity can be used to search for:
- (neutral-current delta radioactive decay)
- (inelastic coherent scattering)

MicroBooNE
Inclusive gamma and dark neutrinos (γ, e^+e^-)

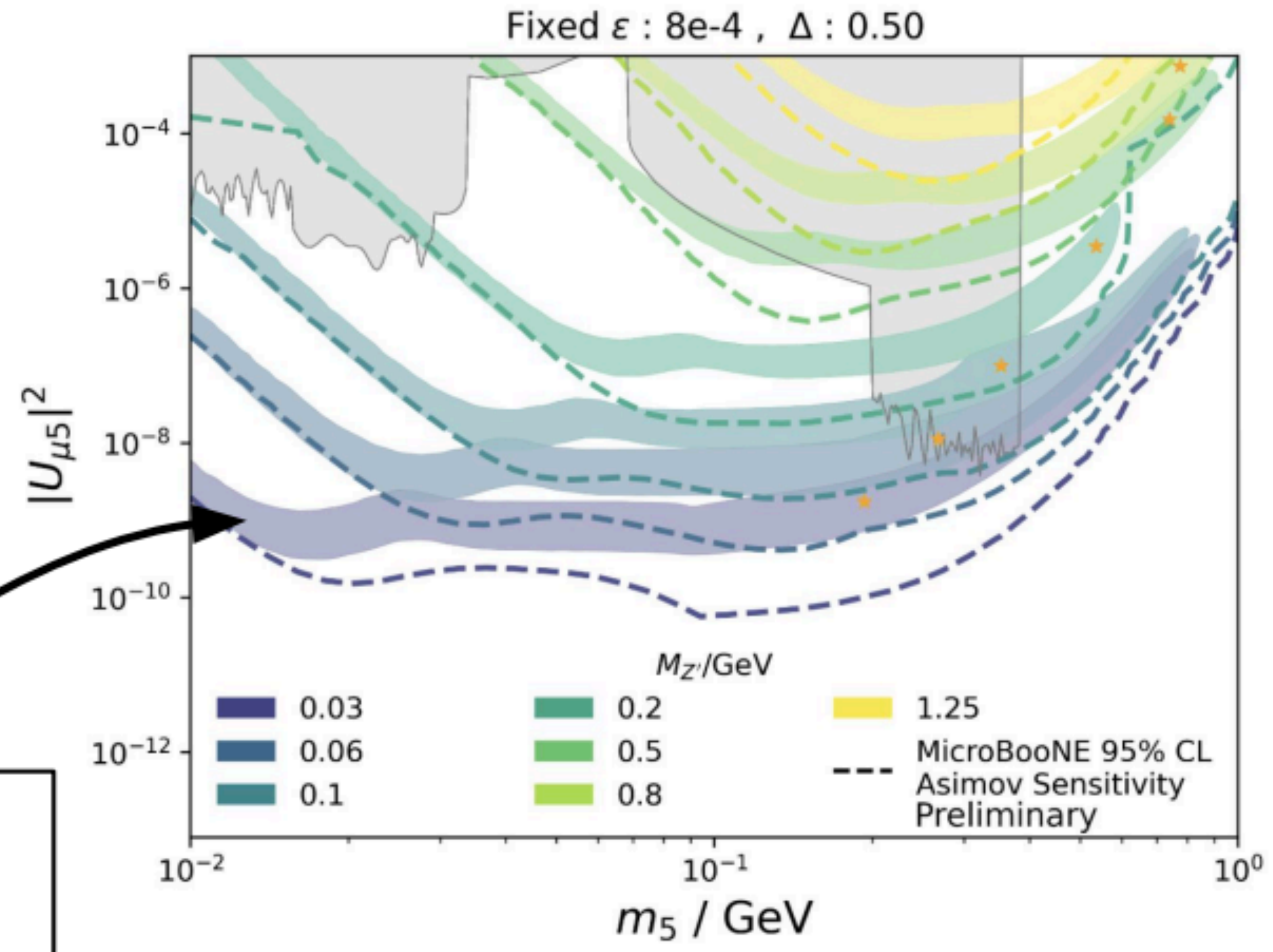
Erin Yandel (UC Santa Barbara)



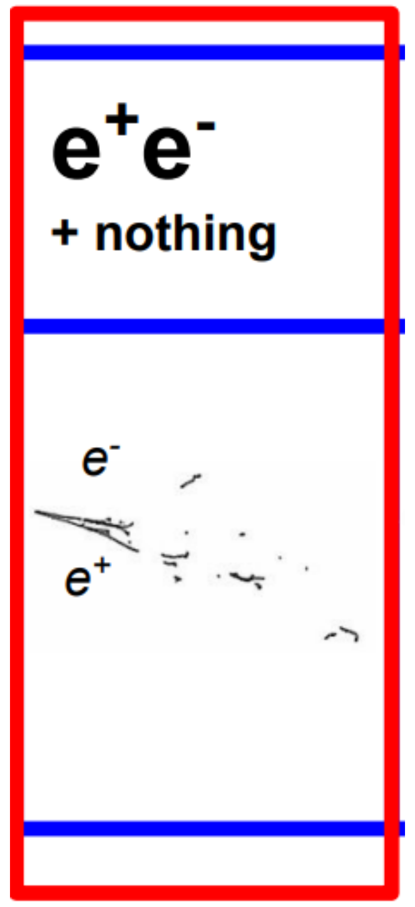


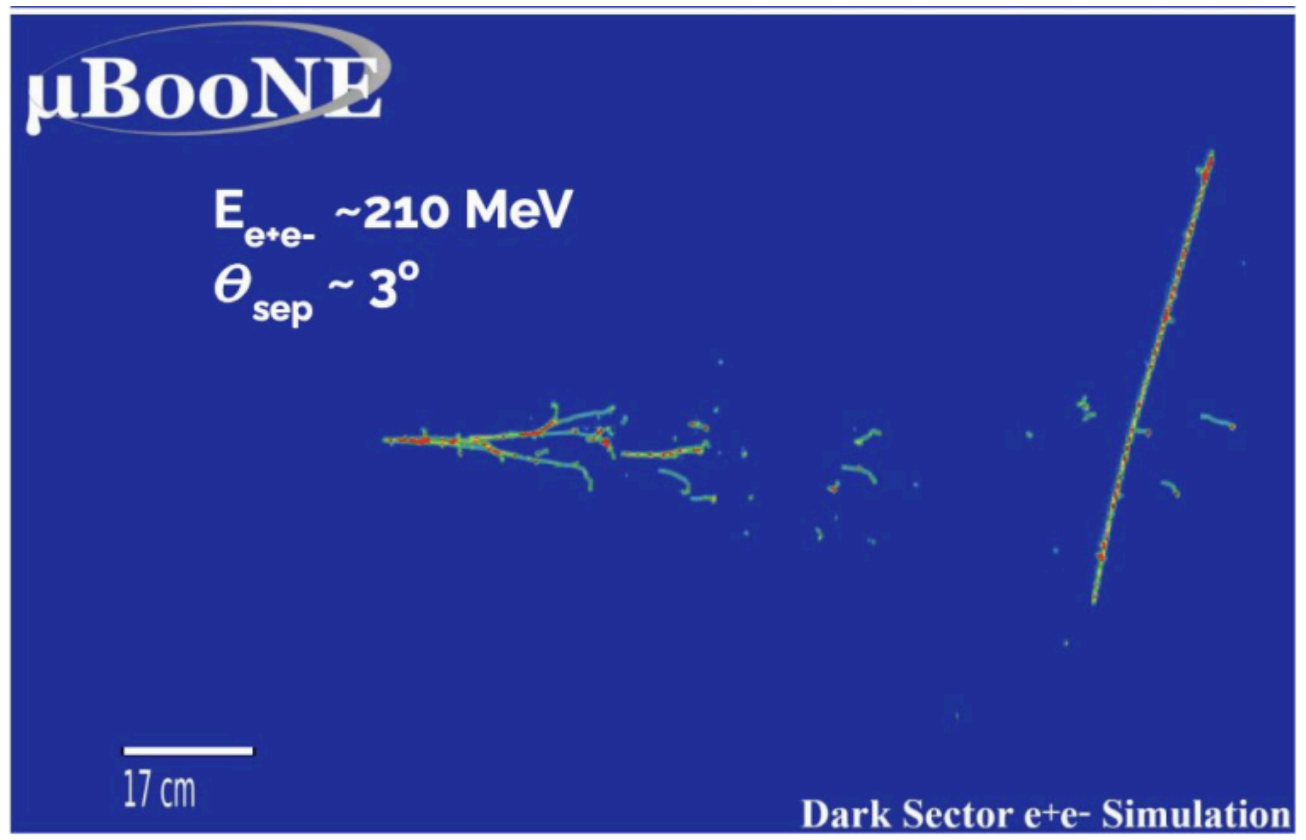
Expect **O(600) events** in final selection, with ~40% purity and 7% efficiency.

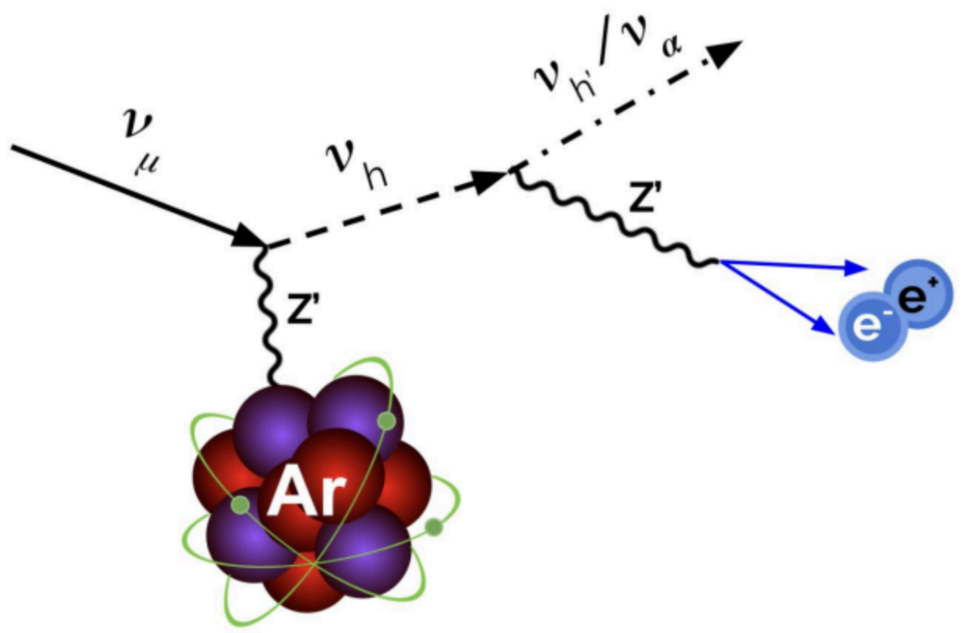
Inclusive test! Broader coverage at the expense of larger backgrounds.



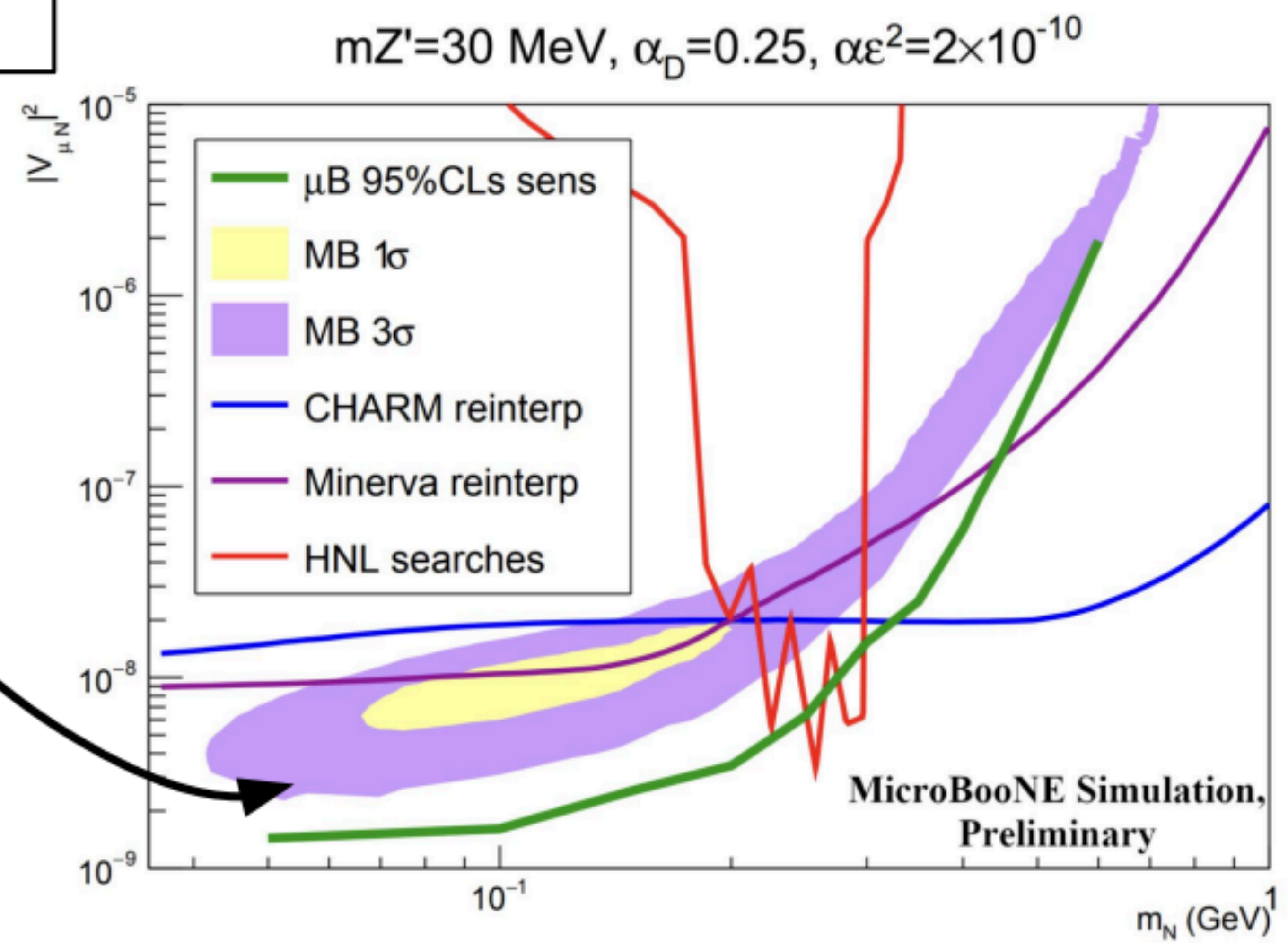
MiniBooNE allowed region







Overlapping e+e - final states will mimic a single shower topology.



The ICARUS detector
Sizeable dataset already colleted

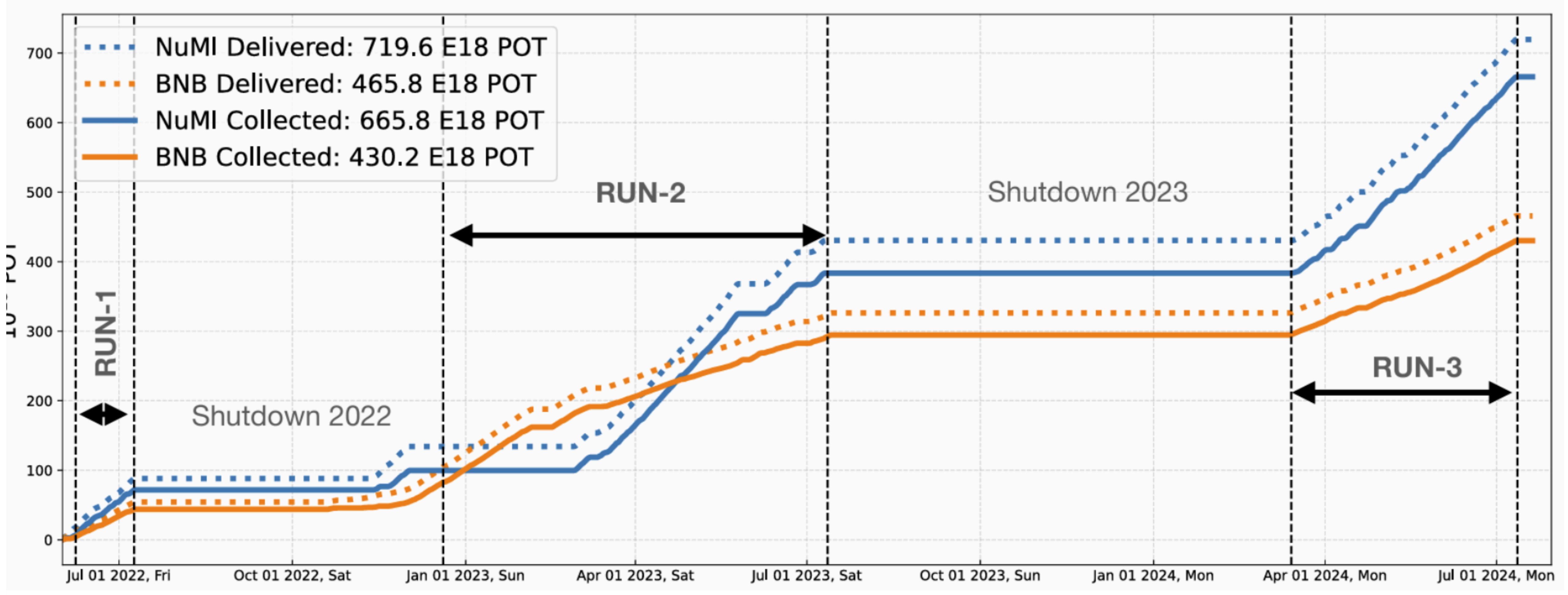
Jacob Zettlemoyer (Fermilab)

ICARUS has a lot of data collected.

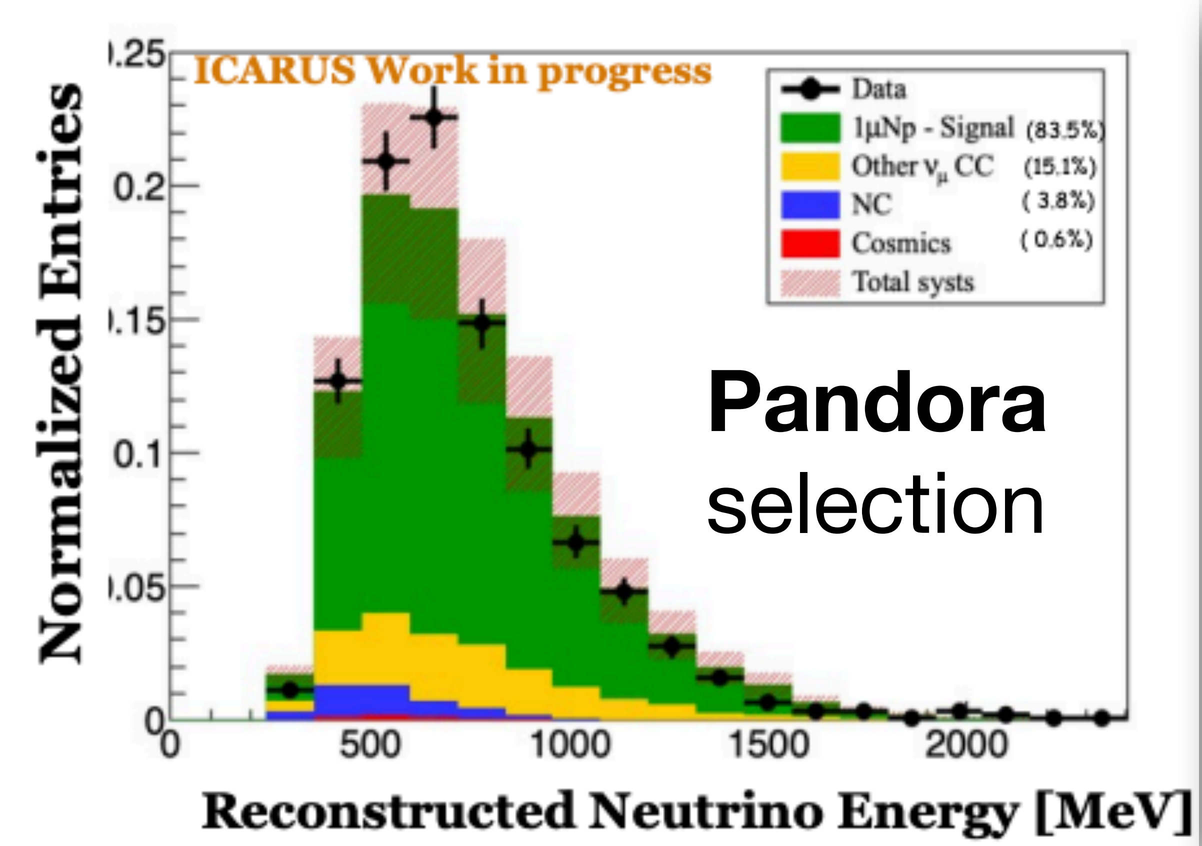
We're now seeing first physics results!

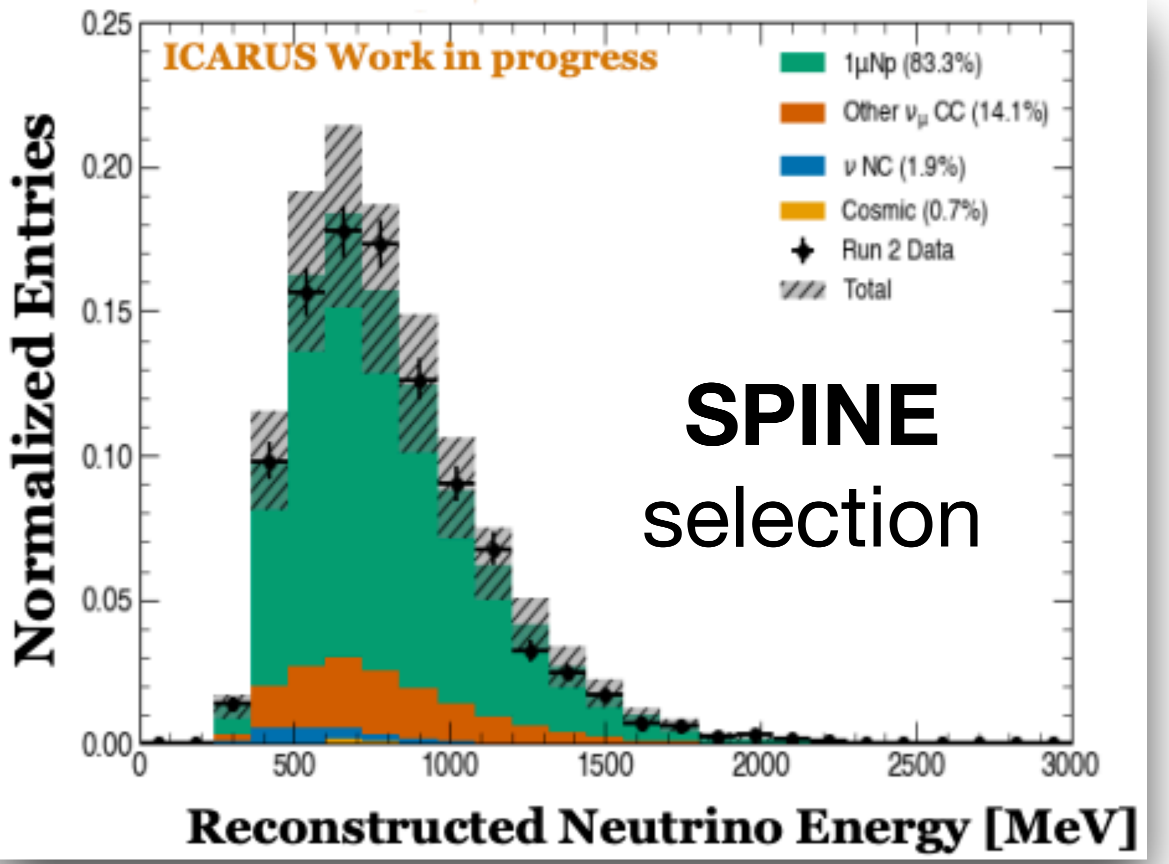
Advanced event selections are in place looking at 1μNp0π final states

Good data/MC agreement seen in 10% subset of the Run 2 (2023) data



- BNB Run1/Run2/Run3: 0.4/2.1/1.4 x 10^{20} POT (total 3.9 x 10^{20} POT)
- NuMI Run1/Run2/Run3: 0.7/2.7/2.8 x 10^{20} POT in FHC/FHC/RHC configuration (total 3.4/2.8 x 10^{20} POT in FHC/RHC configuration)





On the horizon:

Numu disappearance in BNB
Neutrino-Argon cross sections
BSM searches with NuMI (see later)

Later:

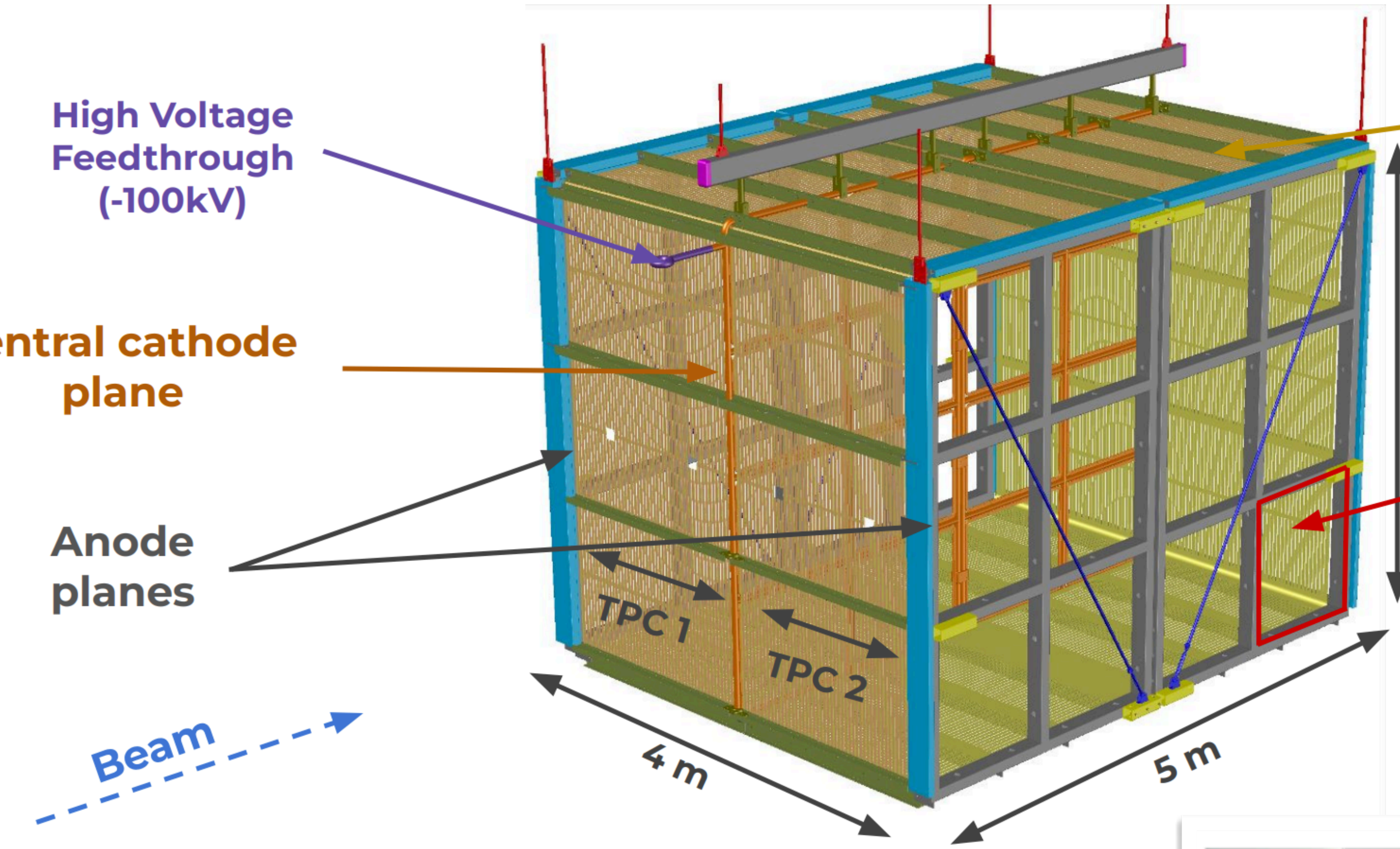
joint oscillation search with SBND.

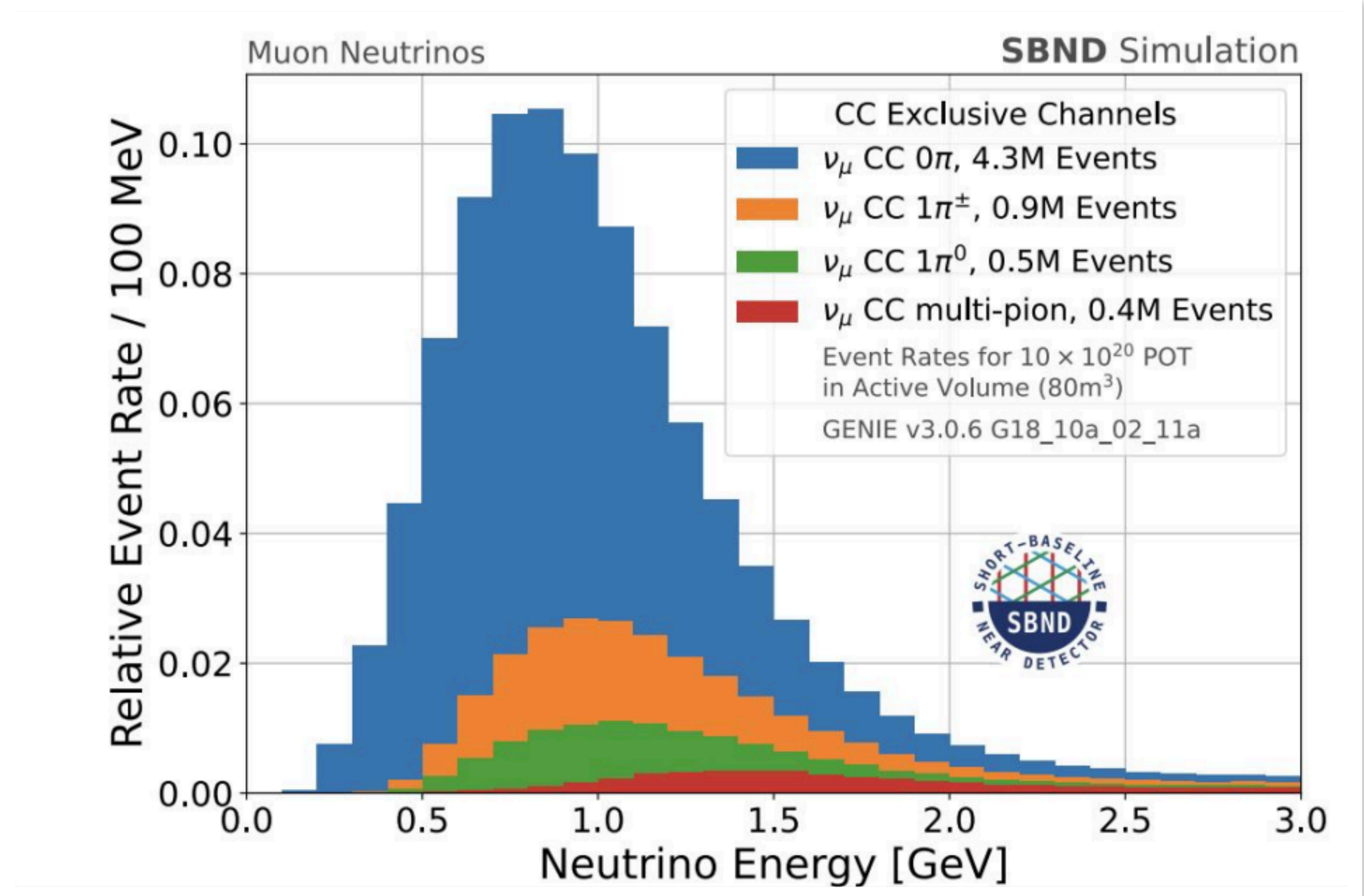
Imaging Cosmic And Rare Underground Signals

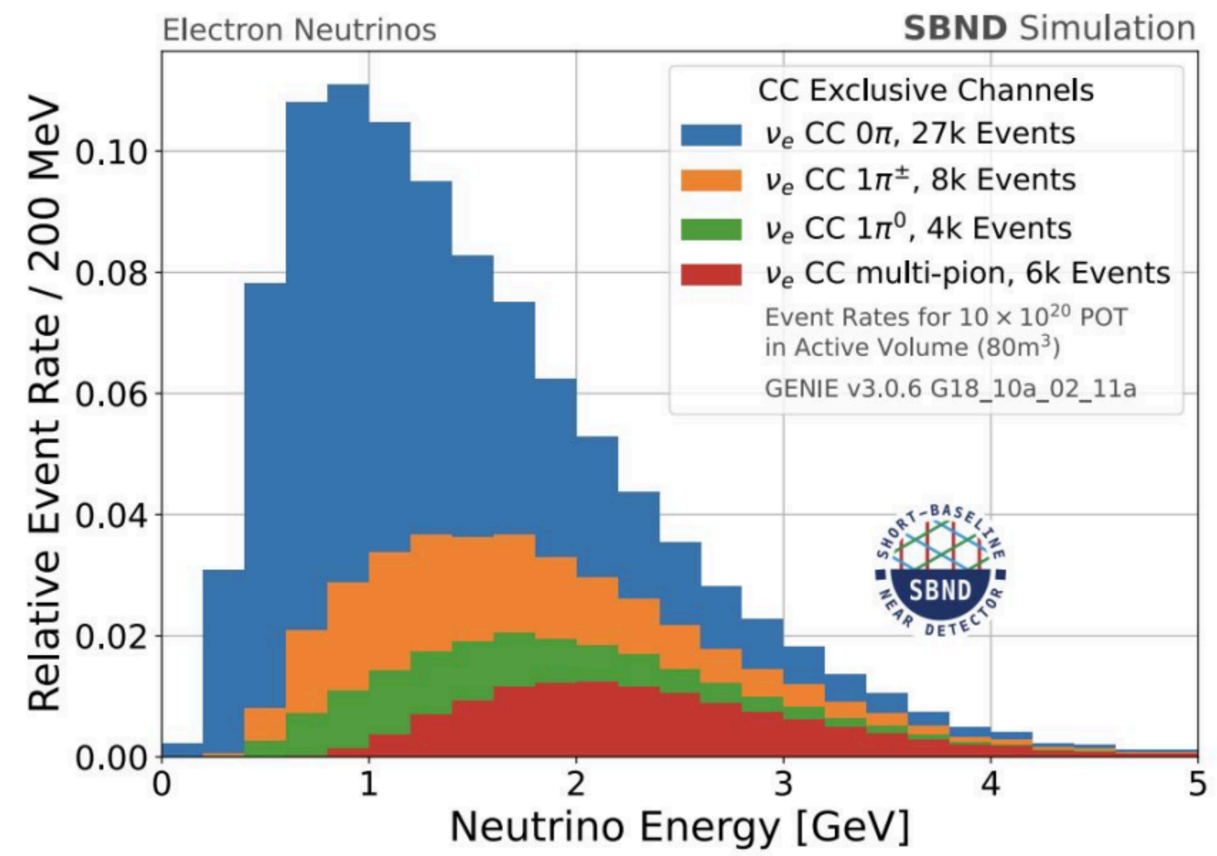
The SBND detector
First glimpse of BNB neutrinos!

Tereza Kroupová (Penn. U.)

112 tons of LAr between two drift volumes separated by central cathode







2M ν_μ CC events

15k ν_e CC events in 1 year

Order of magnitude higher LAr statistics than currently available!

SBND has collected first data and is getting ready for BNB operations in the fall

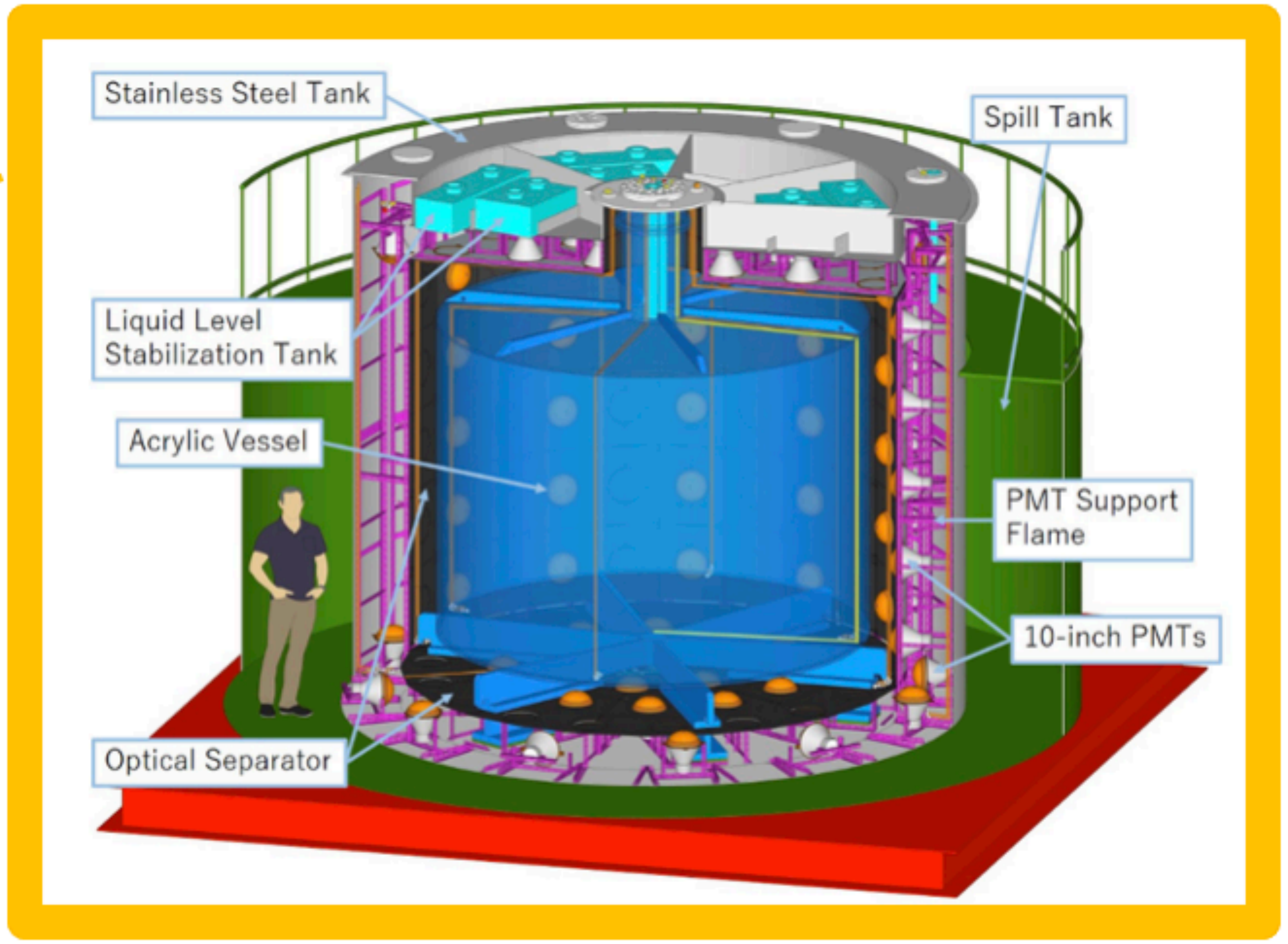
July 2024

TPC high voltage ramped up

JSNS^2
Replicating LSND

(J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

Dongha Lee (KEK)



Test of LSND results with Inverse Beta Decay (IBD) events

4.85x10^{22} POT so far
- 43% of approved POT

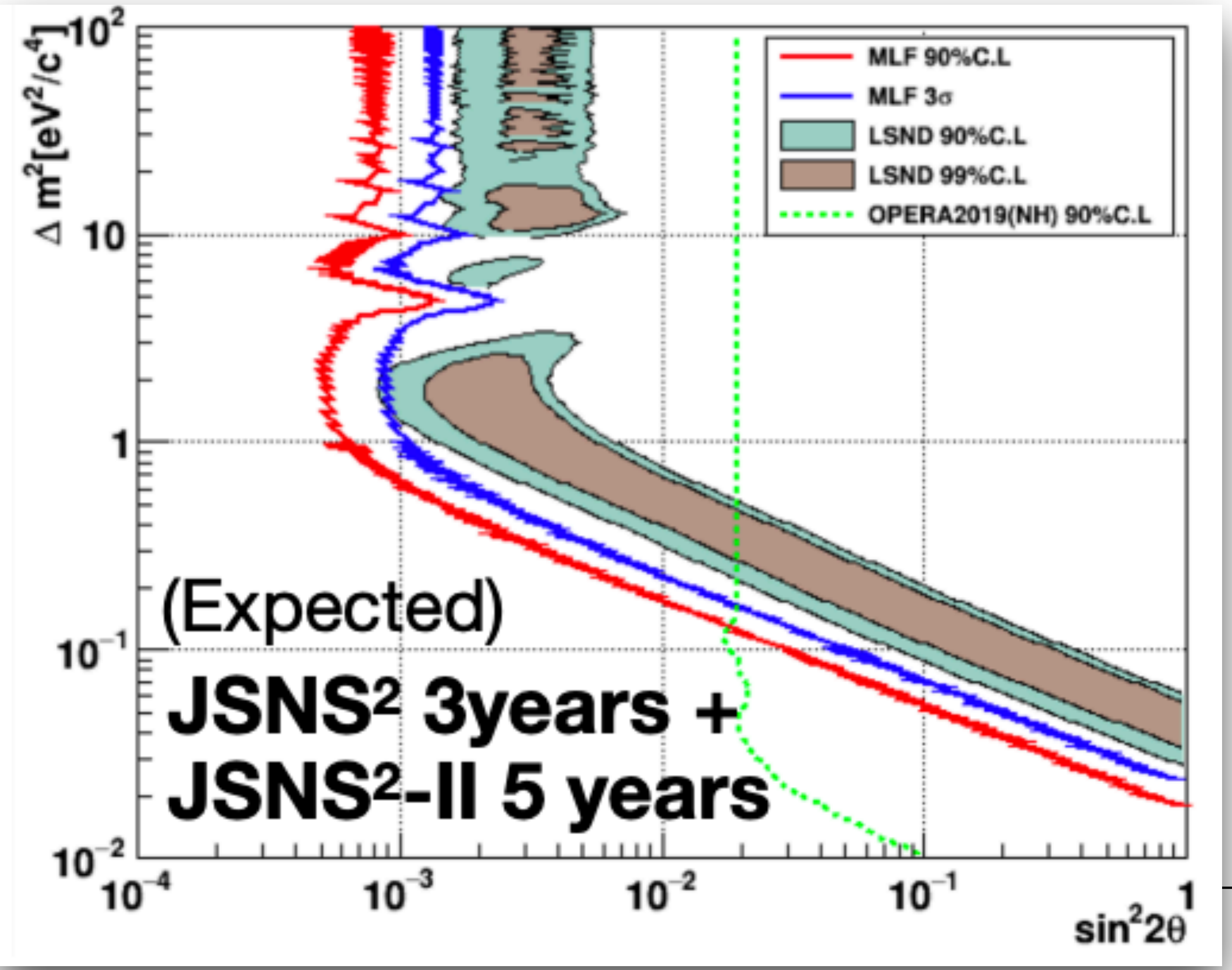
*2022 physics data (0.8x10^{22} POT)

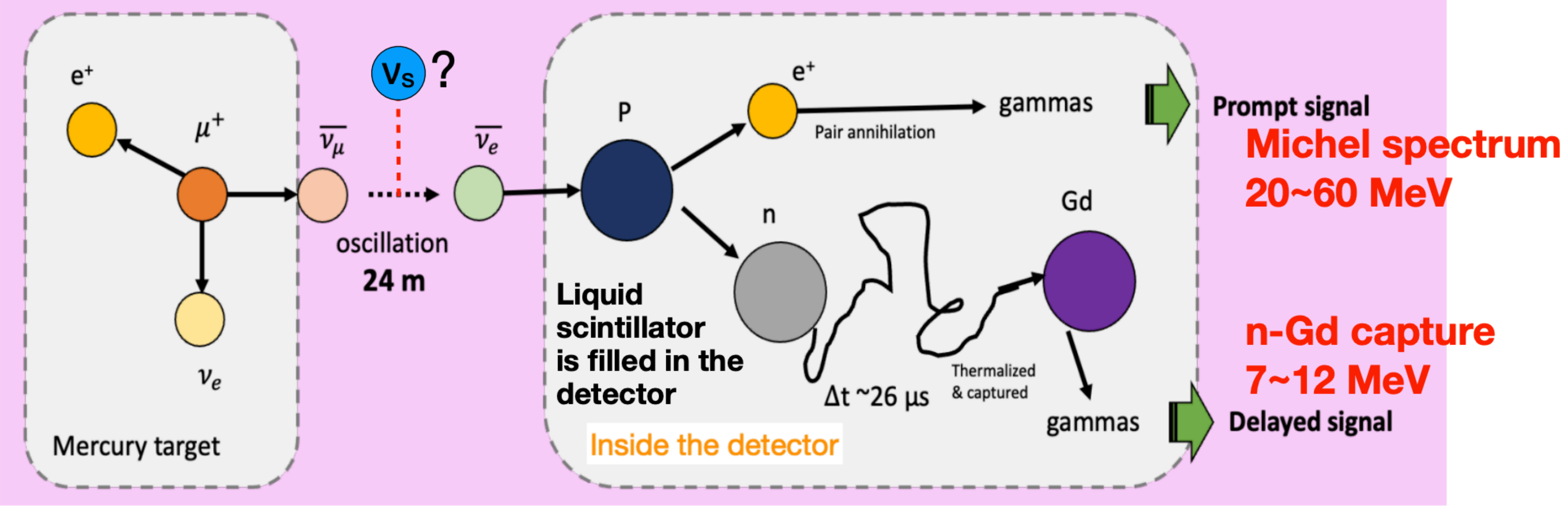
	# of Observation events	# of Expectation events
Total	818 +- 28.6 (stat) + 6.0 (sys)	839.3 +- 3.0 (stat) +- 2.6 (sys)

IBD sideband data
(prompt 60~100MeV)

Second detector being filled w/ LS

Two detector setup to cover LSND sterile neutrino region.





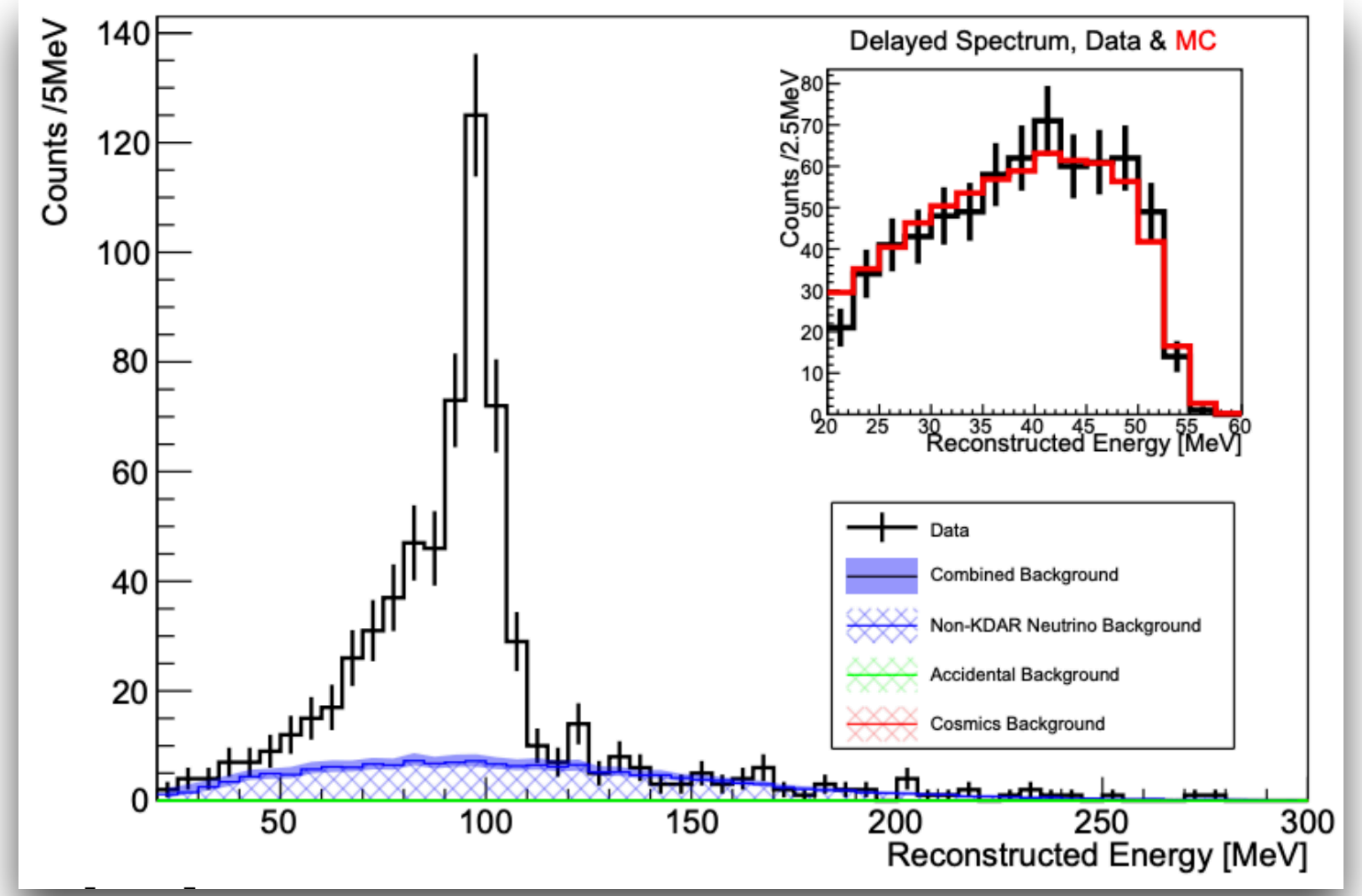
JSNS^2
Replicating LSND

(**J**-PARC **S**terile **N**eutrino **S**earch at **J**-PARC **S**pallation **N**eutron **S**ource)

Dongha Lee (KEK)

Measured monochromatic neutrinos from kaon DAR

Missing energy due to nuclear effects.



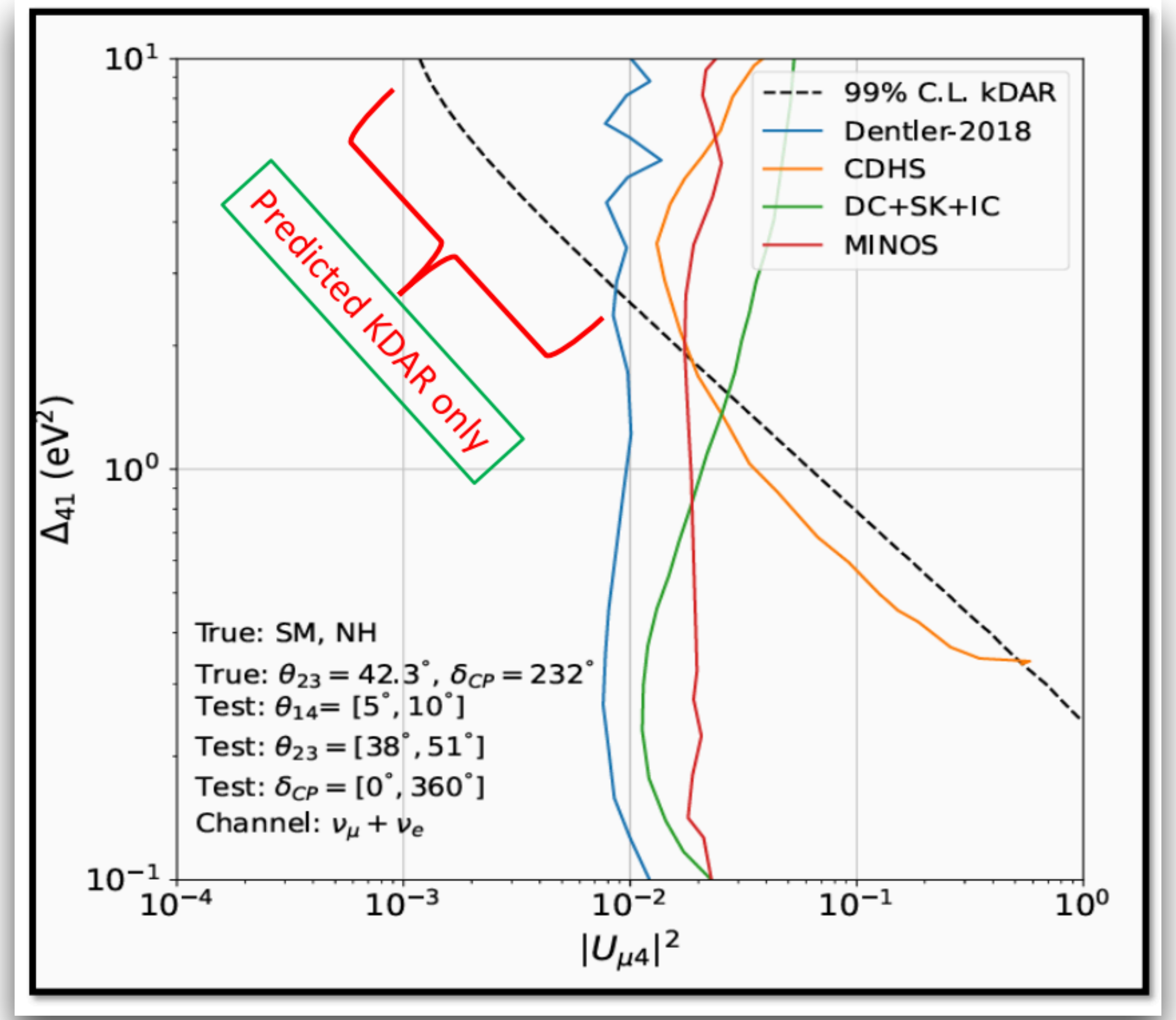
- 2021 physics data is used. (1.4x10[22] POT)
- KDAR candidates : 621 events
- Best Fit Bkg : $144.4^{+21.3}_{-21.1}$ events (πDIF ν dominant)

Aman Gupta (Saha Institute of Nuclear Physics)

KDAR result can also search for new physics.

E.g., sensitive to large-mass sterile oscillations -->

And non-standard interactions:

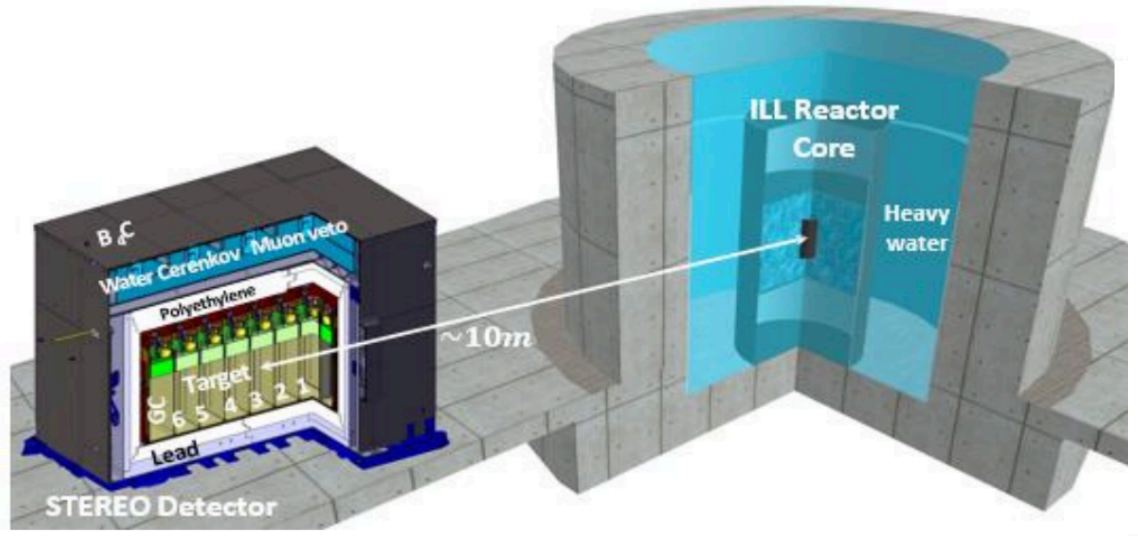


❑ Constraints on the non-standard coupling, for the first time in *us* sector (strange quark) have been obtained:

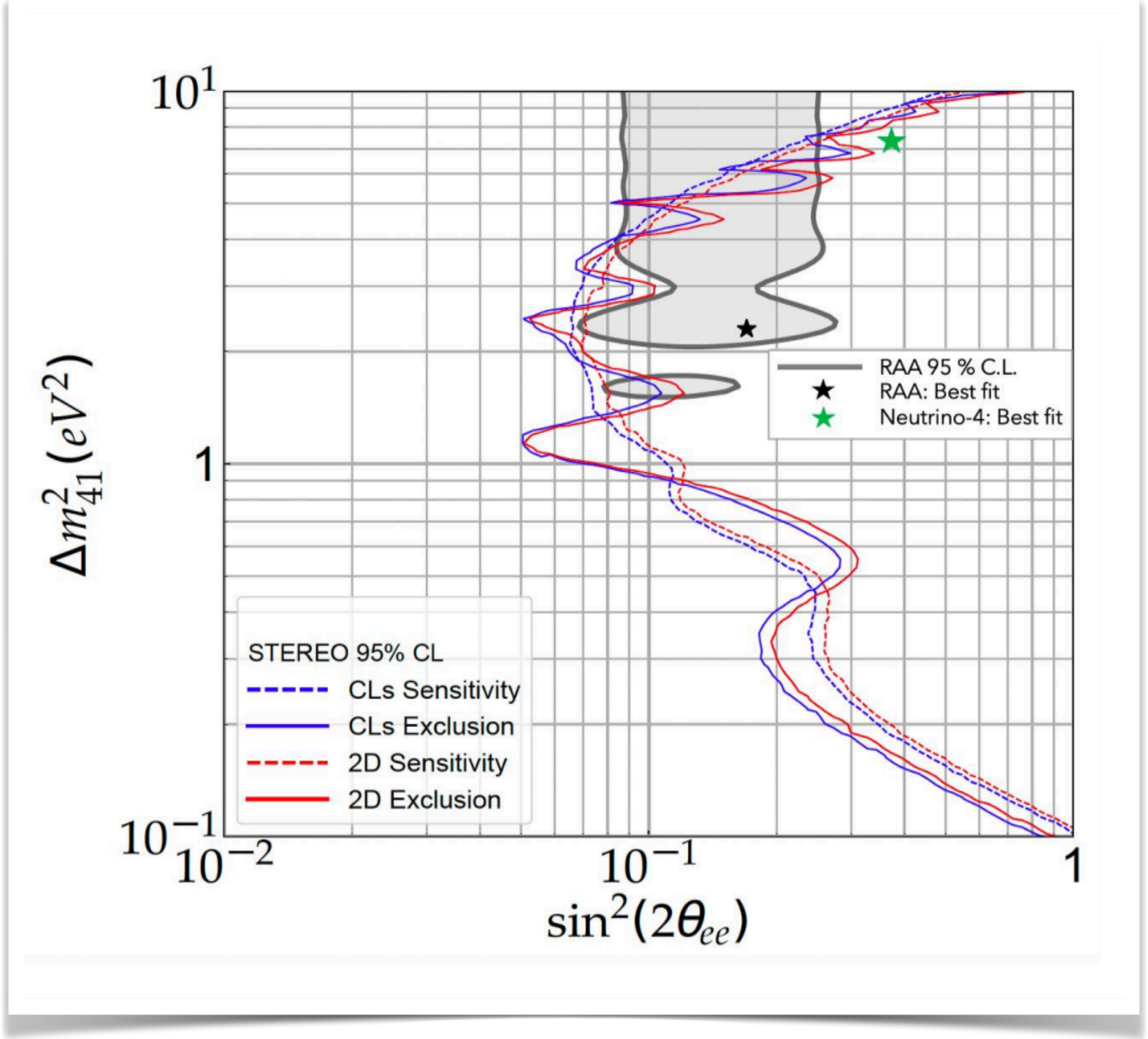
$|\varepsilon^{us}_{\mu e}| < 0.03$ (0.005) at 99% C.L. with current (future) statistics

Reactor neutrinos
STEREO and PROSPECT

Ilham El Atmani
(IRFU, CEA Paris-Saclay)



STEREO final result:



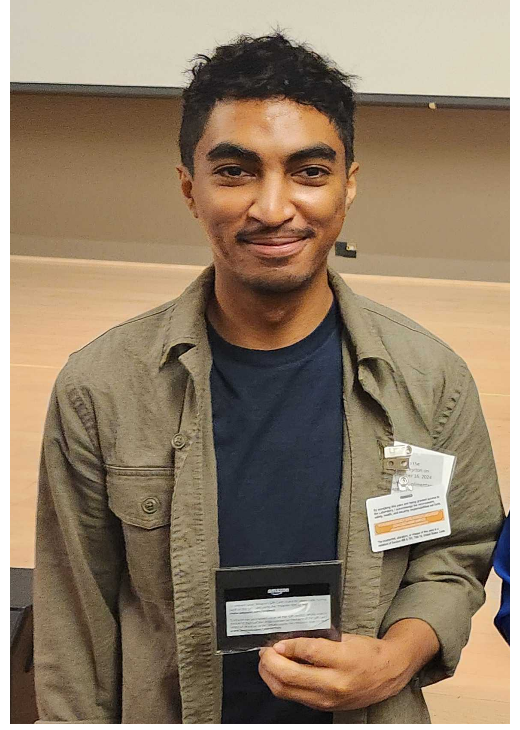
Other searches:

e.g., mirror neutrons

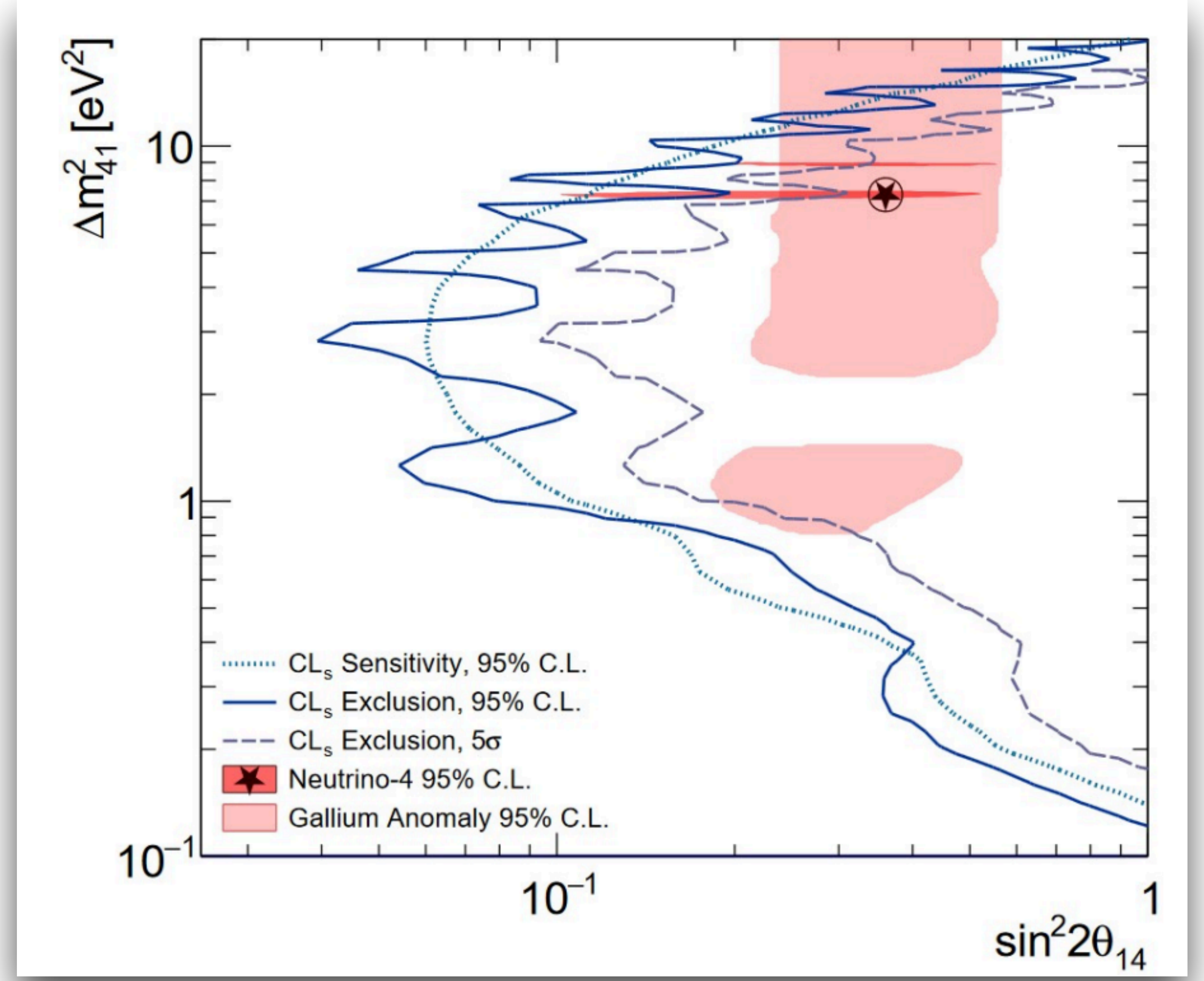
n > n' > n regeneration

Manoa Andriamirado
(Illinois Institute of Technology)

PROSPECT-I final result:



BEST POSTER WINNER!



Observation of short-baseline oscillation from the Neutrino-4 experiment is ruled out at more than 5σ.

Exclusions in all Δm^2 below 10 eV^2 suggested by the (recently strengthened) Gallium Anomaly.

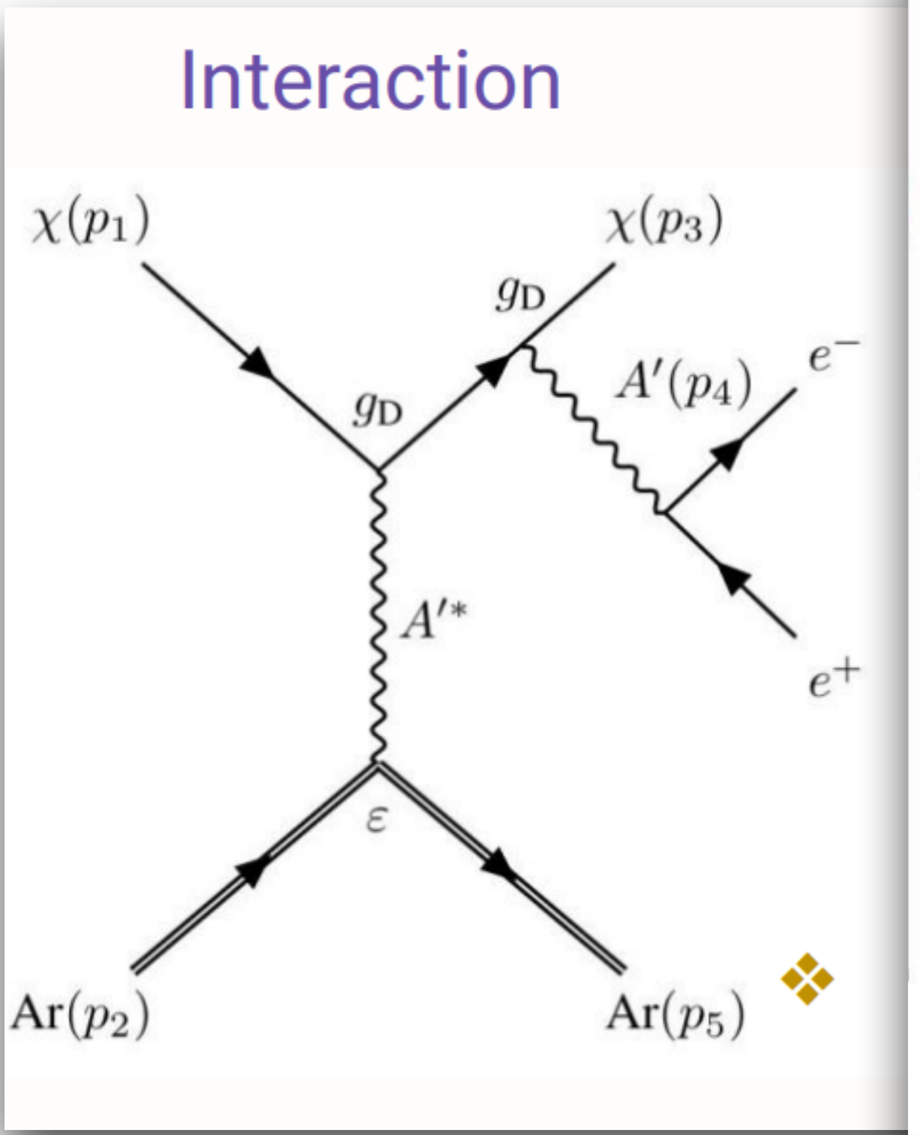
Ultra-rare processes from new physics

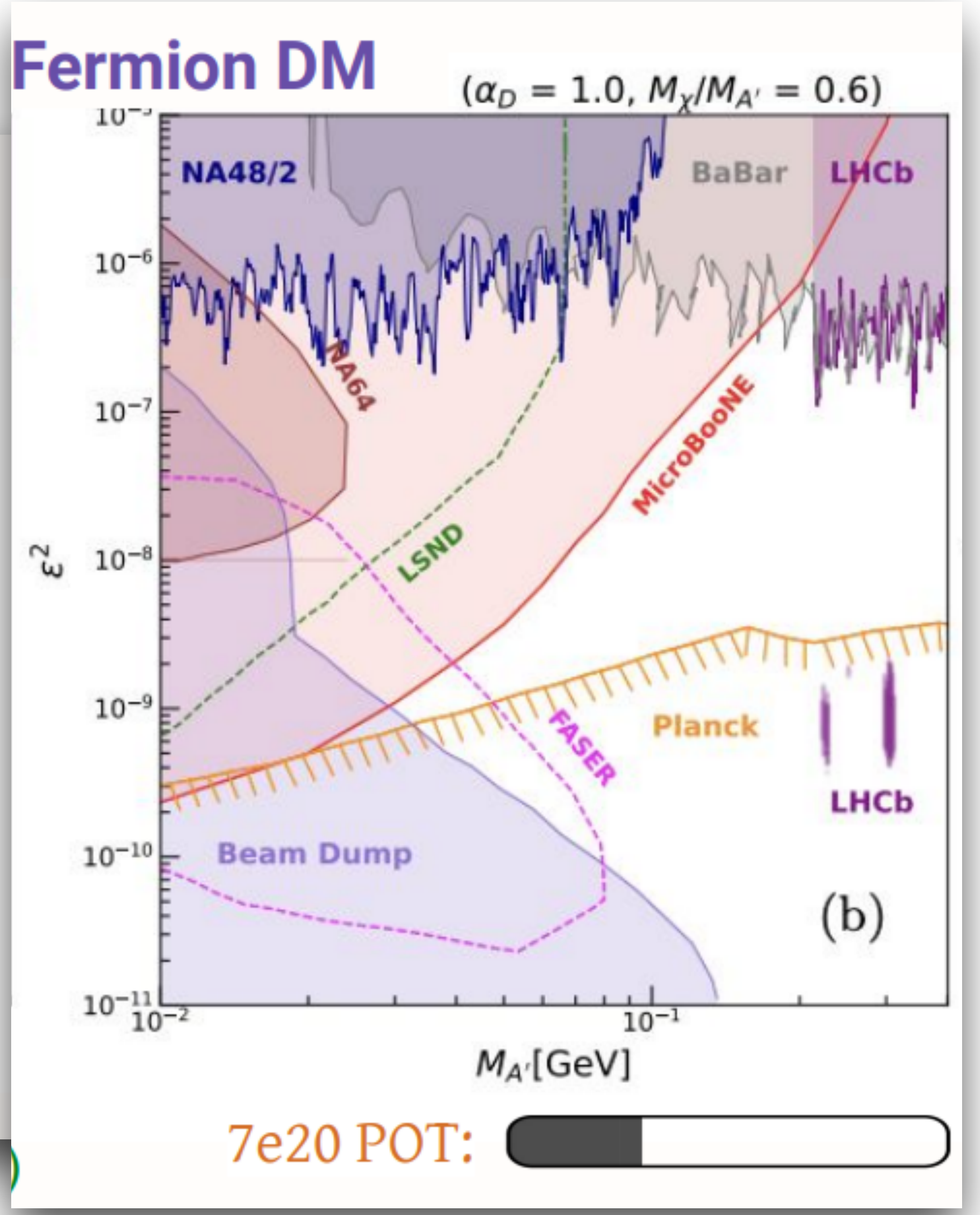
Dark sector searches at MicroBooNE
Light dark matter, heavy neutral leptons, and dark higgs

Keng Lin (Rutgers)

Dark tridents from light dark matter:

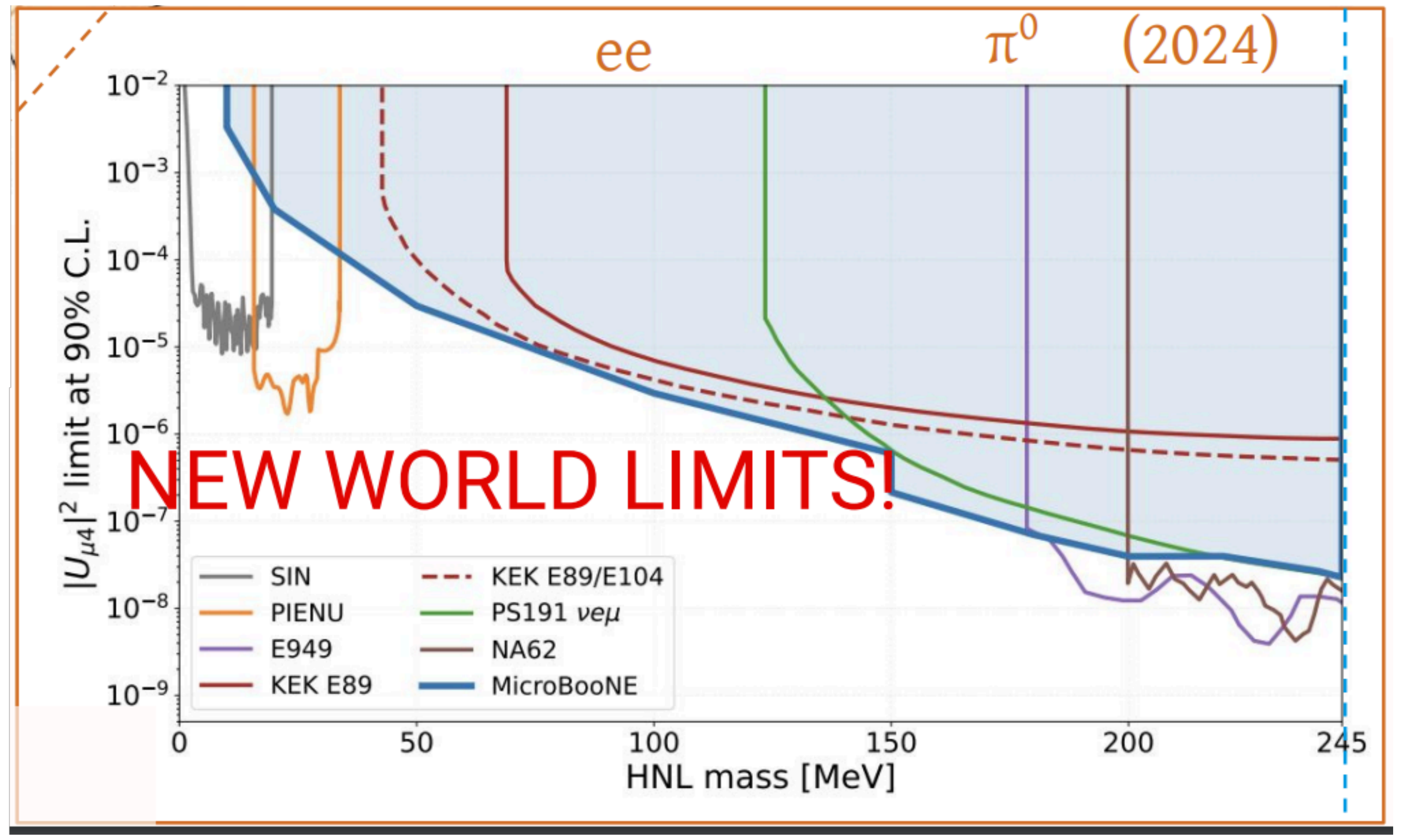
e^+e^- search from light dark matter





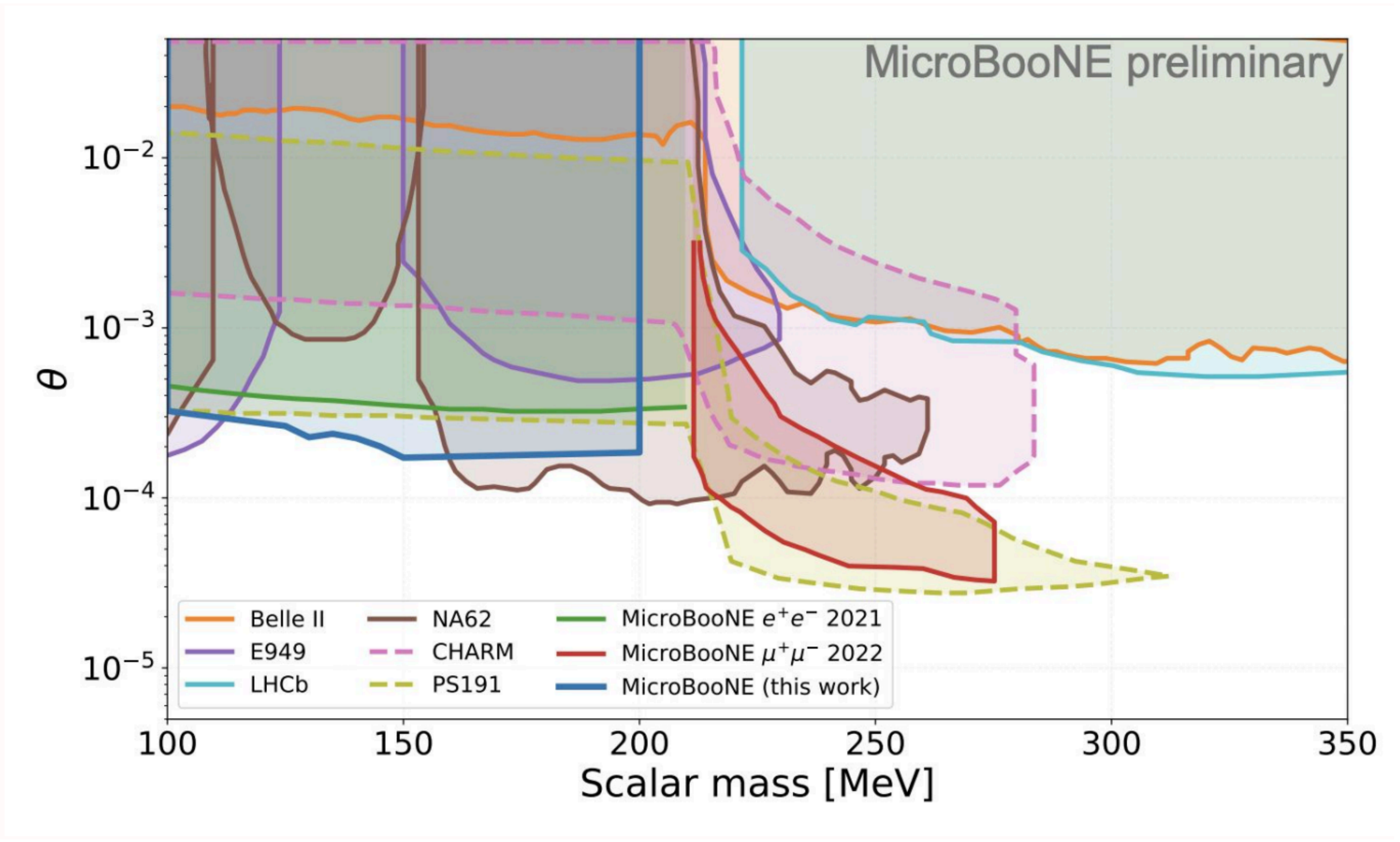
Heavy Neutral Leptons:

Future potential using O(1) ns timing resolution!



Higgs Portal Scalars:

World-leading limits in the "pion gap"

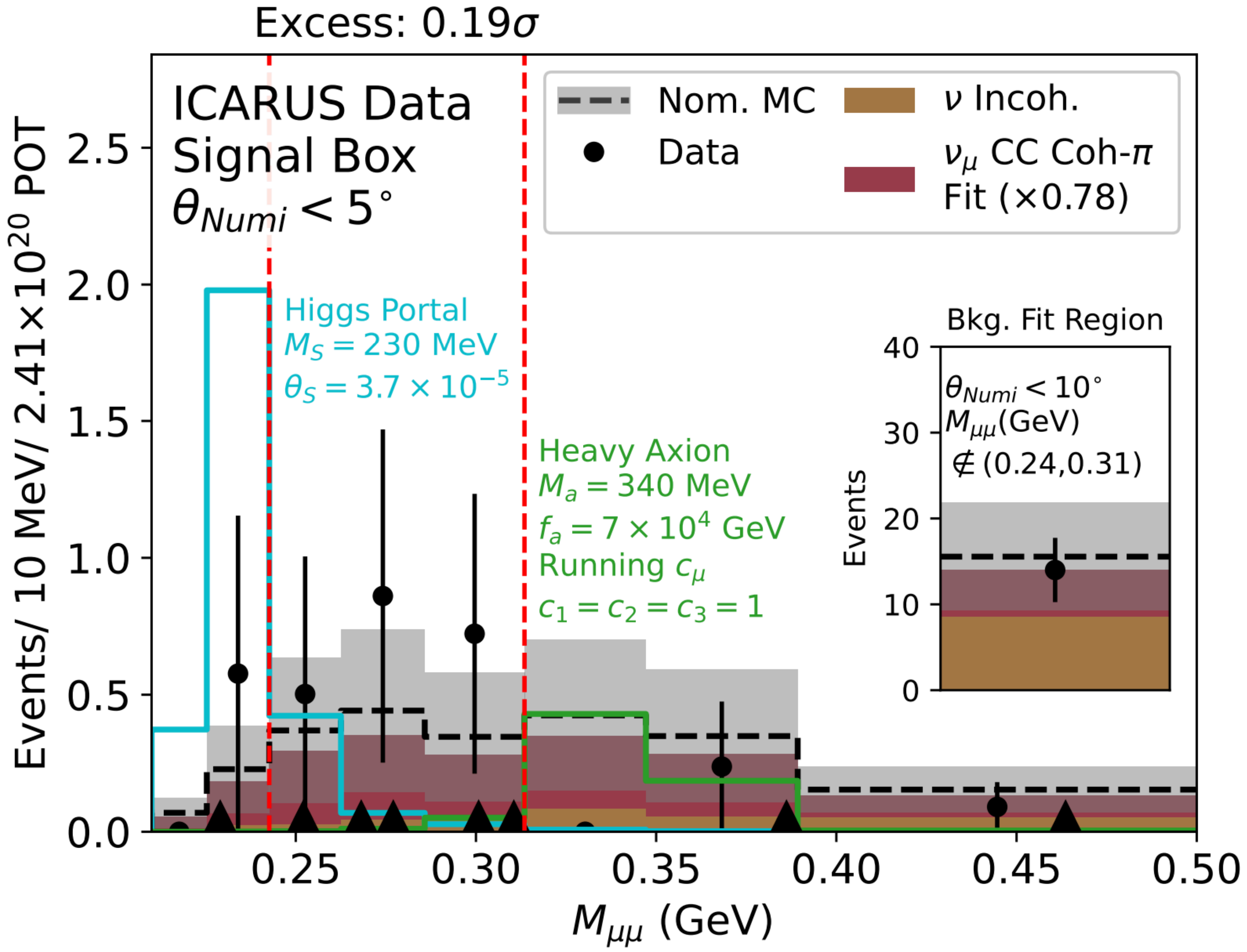


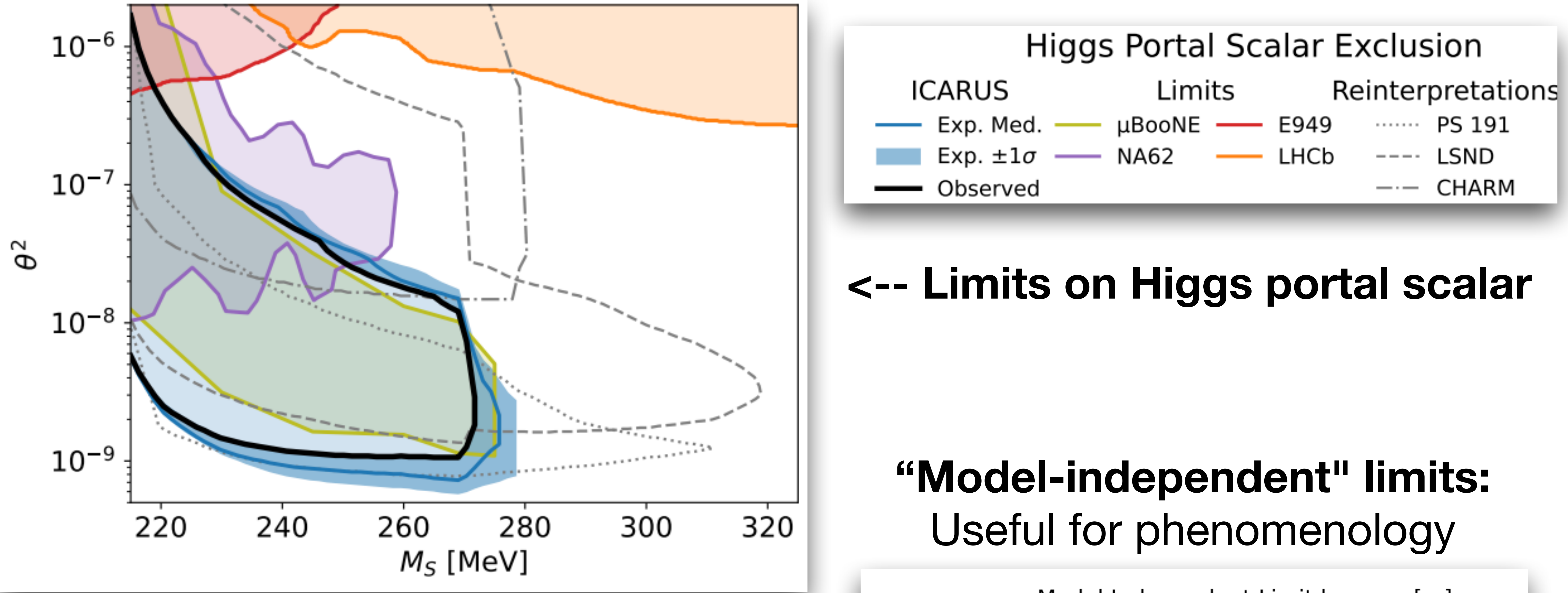
Dark sector searches at ICARUS
Dimuons from dark (pseudo-)scalars

Jacob Zettlemoyer (Fermilab)
Nathaniel Rowe (U. of Chicago)

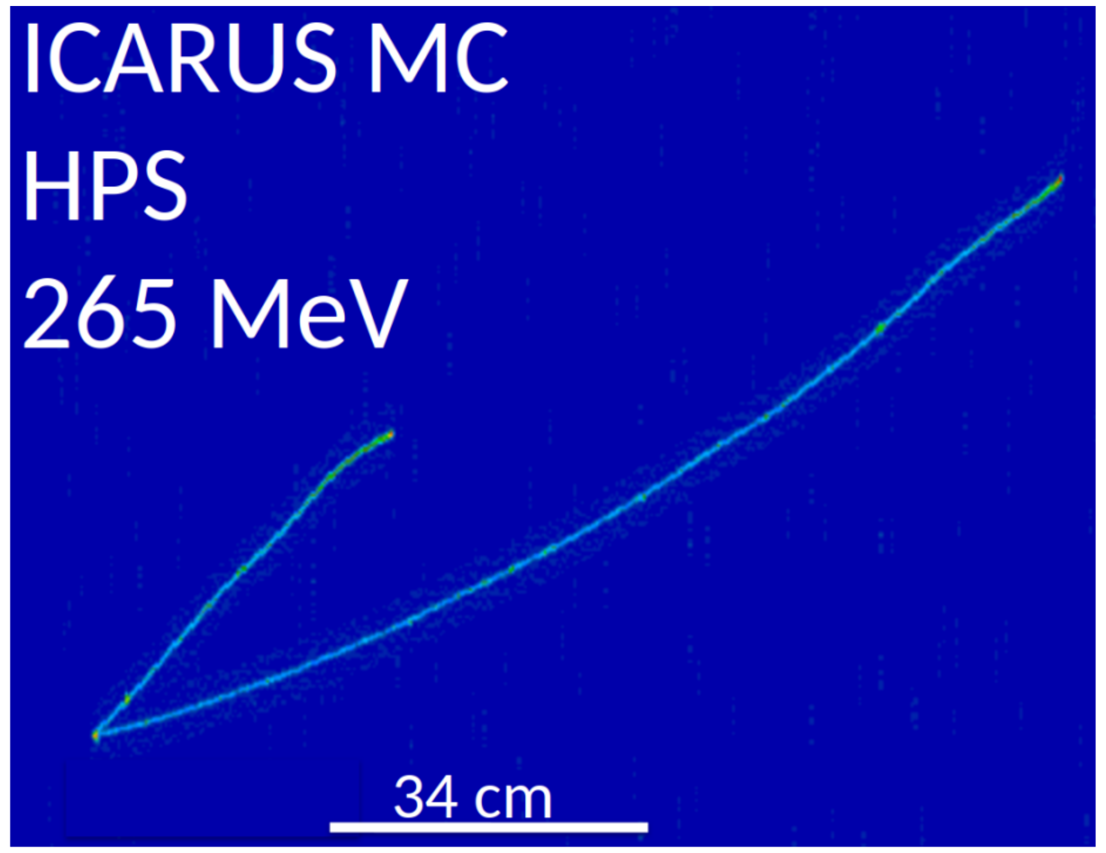
Low background dimuon channel

Run1+Run2 (2022+2023) NuMI data
Final POT: 2.41×1020

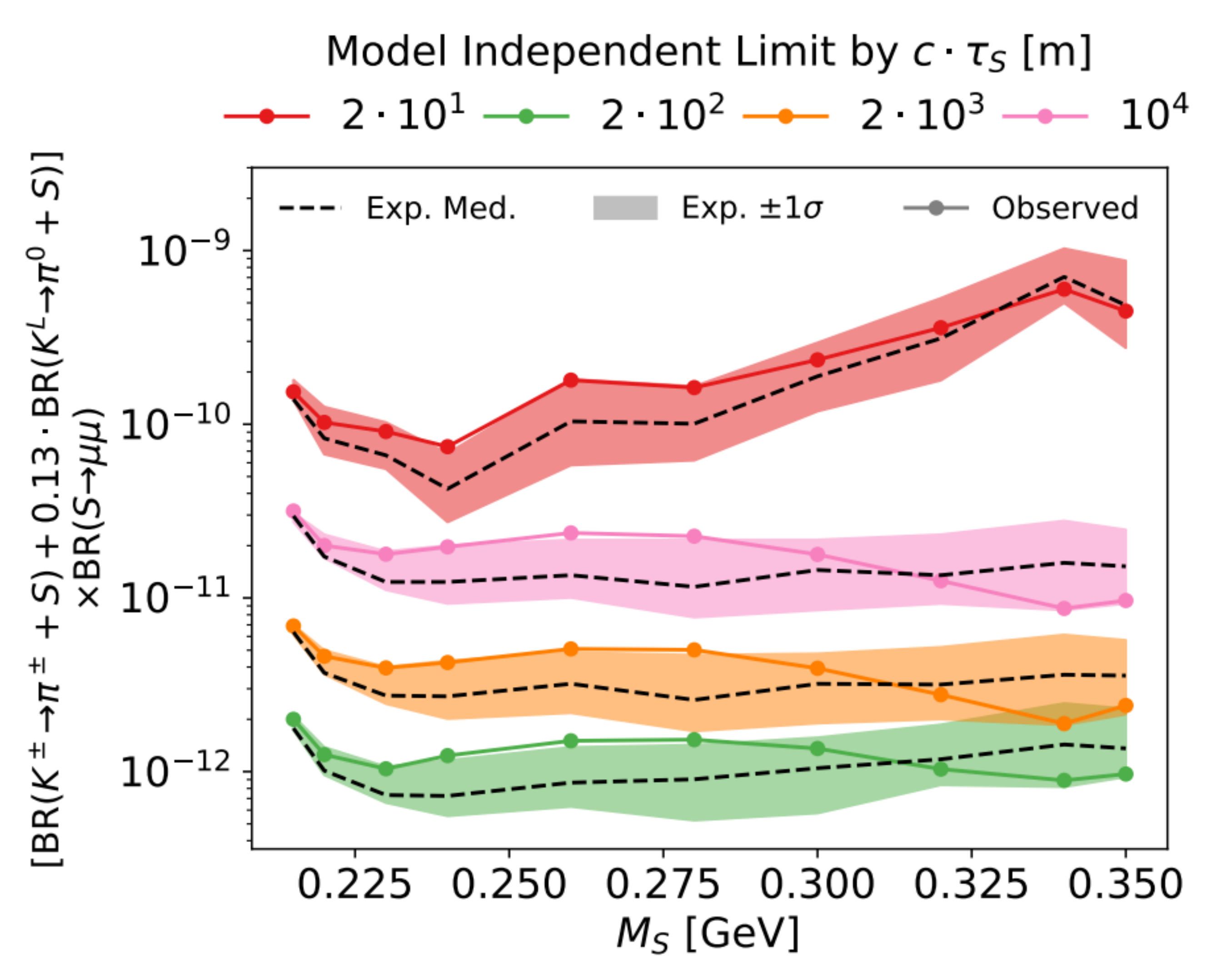




<-- Limits on Higgs portal scalar



“Model-independent" limits:
Useful for phenomenology



Sharpening our tools for BSM
Model-agnostic framework in generators

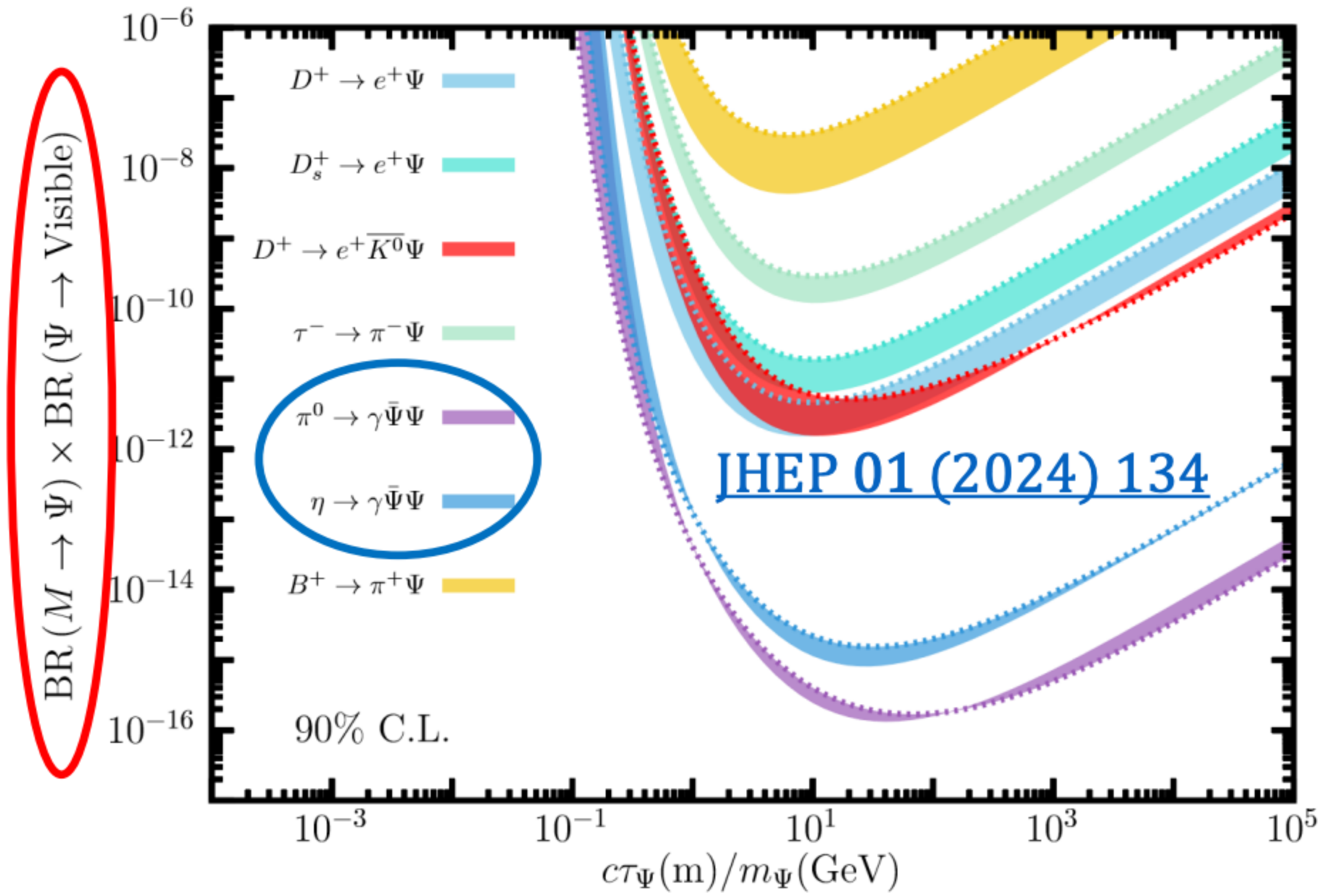
Komninos-John Plows (U. of Liverpool)

1. How can we maximise the potential for BSM searches?
2. What **inputs** do analyses need to search for anomalies?
3. What **outputs** does theory need to constrain BSM landscape?

UNIVERSITY OF LIVERPOOL

John Plows - ExoticLLP

- implement model-agnostic frameworks for event generation to GENIE
- in case of LLP, user passes LLP mass, lifetime, decay probability as config-level & provide user with flexibility to "mix and match" different channels
- a new class, FluxContainer, keeps all the useful output information including full particle stack for LLP production and decay



Leveraging beam intensity differently:
New physics in Weak cross sections

Richard Hill (Kentucky)

Constraints on a general new physics parameterization in Weak interaction --> neutrinos can beat Beta decay observables when new effects are suppressed by the charged lepton mass

Muon mass enhances sensitivity -->

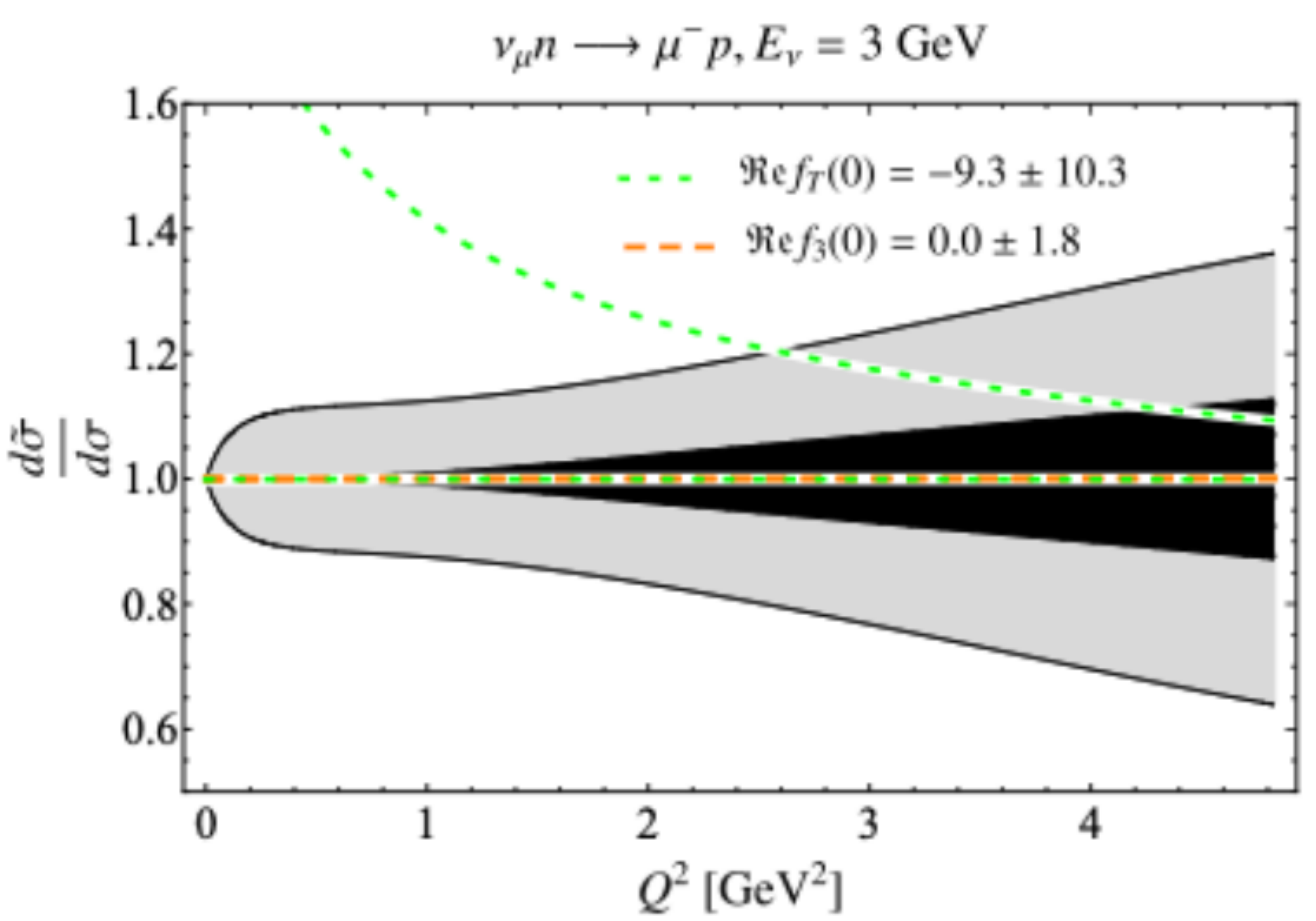
	$\Re e \bar{f}_3$	$\Re e \bar{f}_T$	$\Re e \bar{f}_{A3}$	$\Re e \bar{f}_R$
$\bar{\nu}p$ scattering	$88.4^{+33.5}_{-58.0}$	$-0.5^{+5.0}_{-4.8}$	$-1.0^{+0.4}_{-0.3}$ & $1.0^{+0.3}_{-0.4}$	$-80.1^{+40.6}_{-26.0}$
beta decay	0.0 ± 1.8 [72]	-9.3 ± 10.3 [73]	0.0 ± 0.075 [66]	

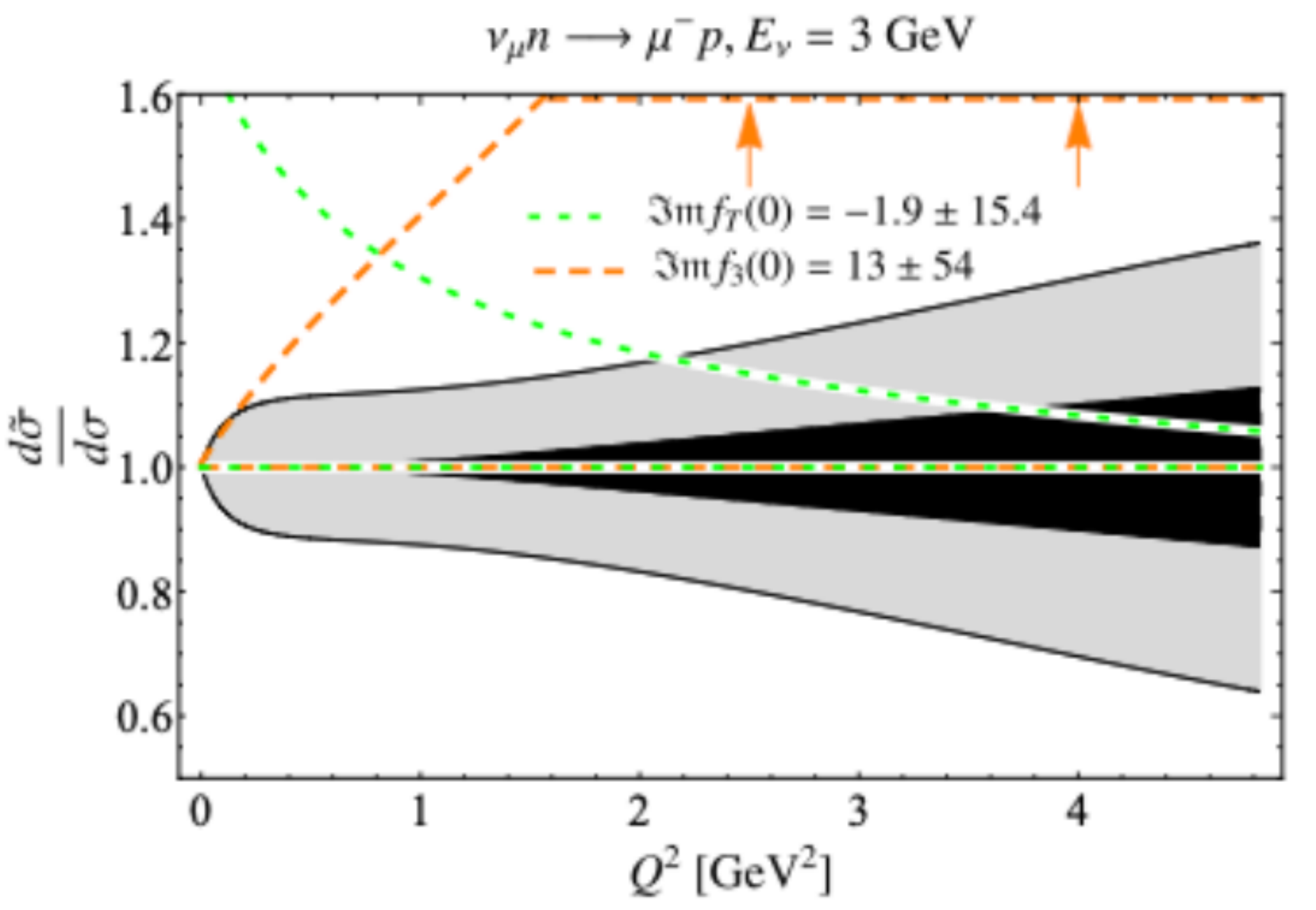
	$\Im m \bar{f}_3$	$\Im m \bar{f}_T$	$\lvert \Im m \bar{f}_{A3} \rvert$	$\lvert \Im m \bar{f}_R \rvert$
$\bar{\nu}p$ scattering	$-82.1^{+34.6}_{-23.8}$ & $82.1^{+23.8}_{-34.6}$	0.0 ± 4.9	$1.00^{+0.29}_{-0.43}$	$69.9^{+20.9}_{-30.9}$
beta decay	13.0 ± 54.0 [73]	-1.9 ± 15.4 [73]		

taus would be even better, but not enough stats.

Using **MINERvA** data to constrain BSM contributions

Constraints on amplitudes stronger than precision beta decay! (x1.2~3 improvements)





Post DUNE/Hyper-K proton decay searches
Paleodetectors on the Moon?

Cassandra Little (U. of Michigan)

Limits on proton lifetime now:

$$\tau_p(p \to \bar{\nu}K^+) > 5.9 \times 10^{33} \text{ yrs}$$

DUNE/Hyper-K will probe 1e34/1e35 years.

But after that, how can we improve on proton decay searches?!

Paleo-detector may be a way out!

Exposure = **time**↑ x mass↓

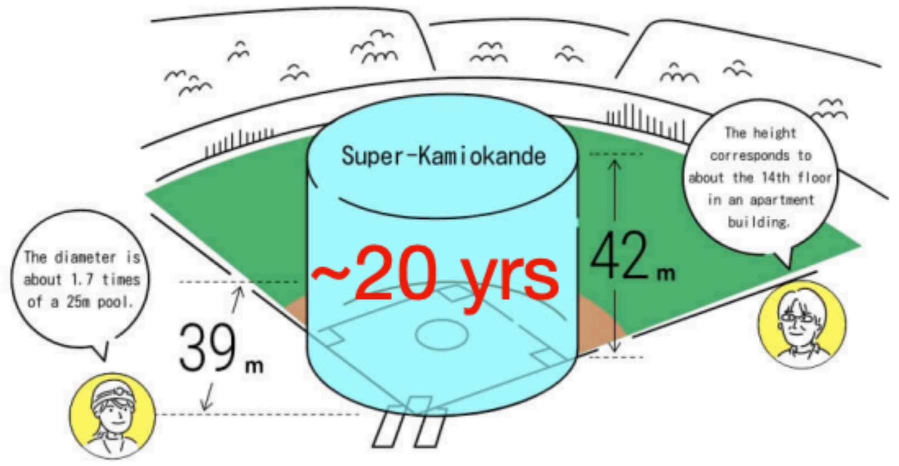
Atmospheric neutrinos are a problem, but...

5 km deep, ~0.1 kaons/100 g/Gyr on the moon!

Paleo-detectors

Mikon Mineralienkontor, mikon-online.com

=



1 kg would match the Mton·yr exposure of Hyper-Kamiokande and DUNE!

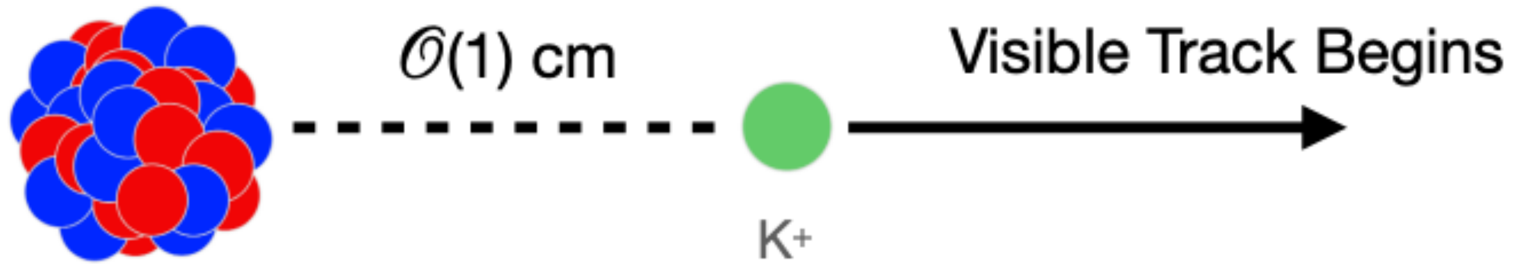
- Can retain tracks for >>10^9 yrs
- Natural minerals can be >10^9 yrs old

} **Paleo-detector exposure**

100 g x 1G yr = 10 kton x 10 yr

- Current microscopy technology has sub-nanometer-scale resolution

$\lesssim$ KeV recoil thresholds in laboratory settings



$$p \to \bar{\nu}K^+$$

New matter effects in neutrino oscillations

Long-range forces @ WG1+WG5
Scalar non-standard interactions

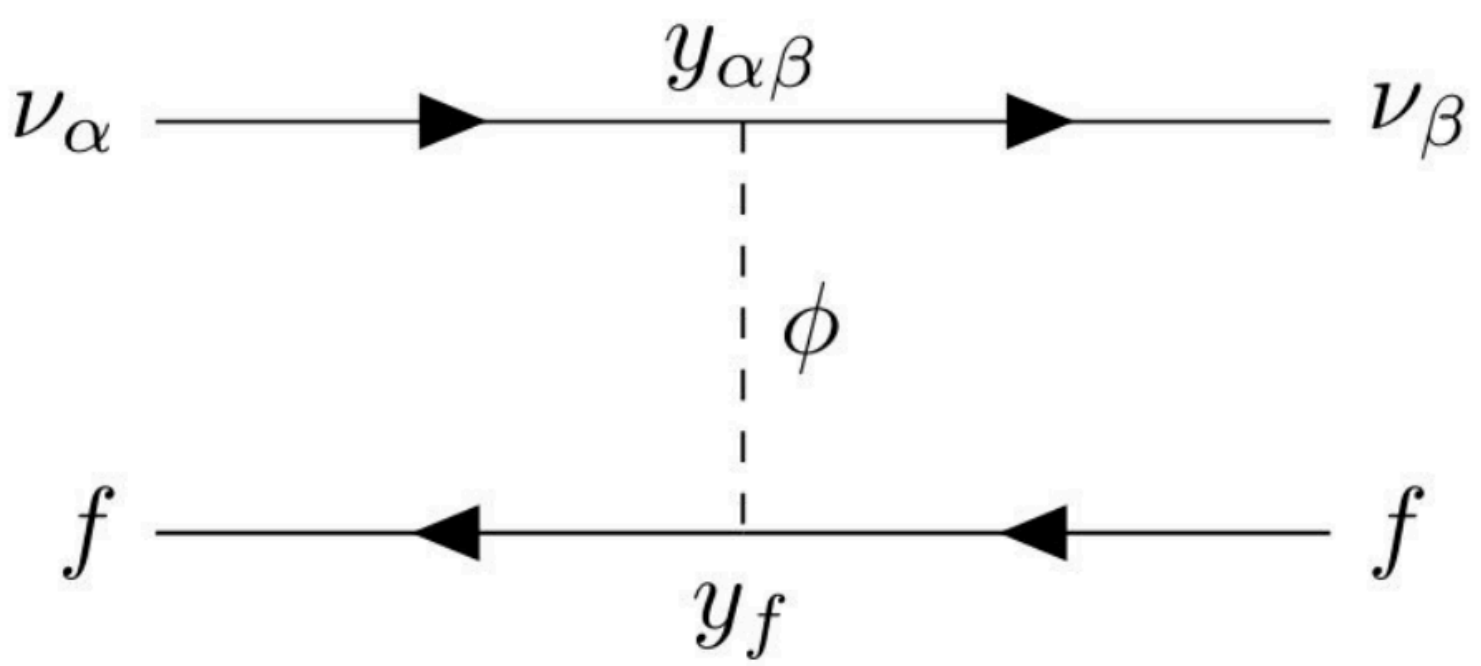
Moon Moon Devi (Tezpur University)
Adrian Thompson (Northwestern University)

Scalar NSI's from long-range forces:

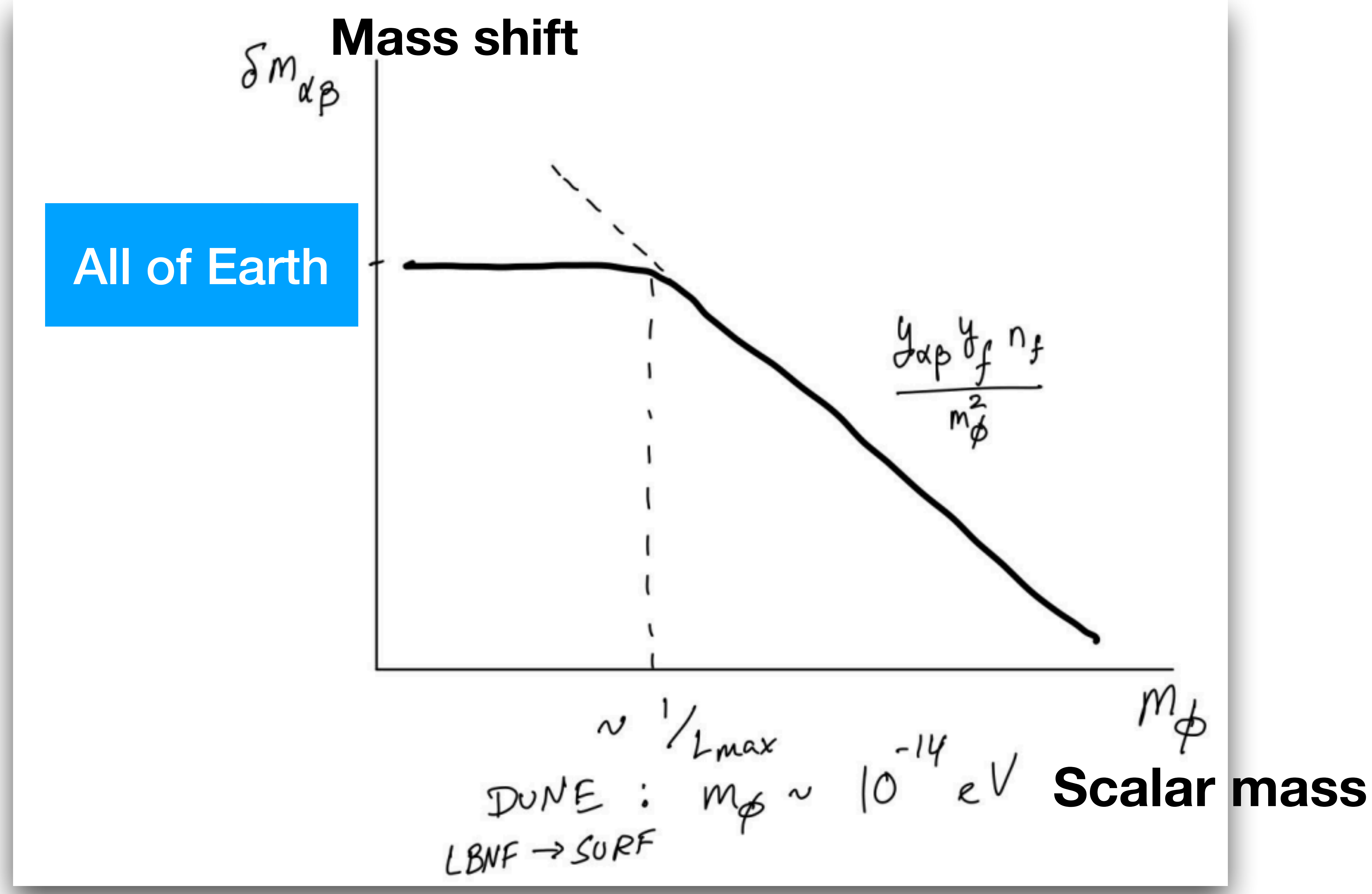
$$\mathcal{L}_S^6 \supset \frac{(y_\nu)_{\alpha\beta} y_f}{m_\phi^2} (\bar{f} f)(\bar{\nu}_\alpha \nu_\beta)$$

Leads to an effective neutrino mass shift:

$$H_{\alpha\beta} = \frac{1}{2E_\nu} (\mathbb{M} + \delta\mathbb{M})^\dagger_{\alpha\beta} (\mathbb{M} + \delta\mathbb{M})_{\alpha\beta} + V_{CC}$$



Adrian Thompson

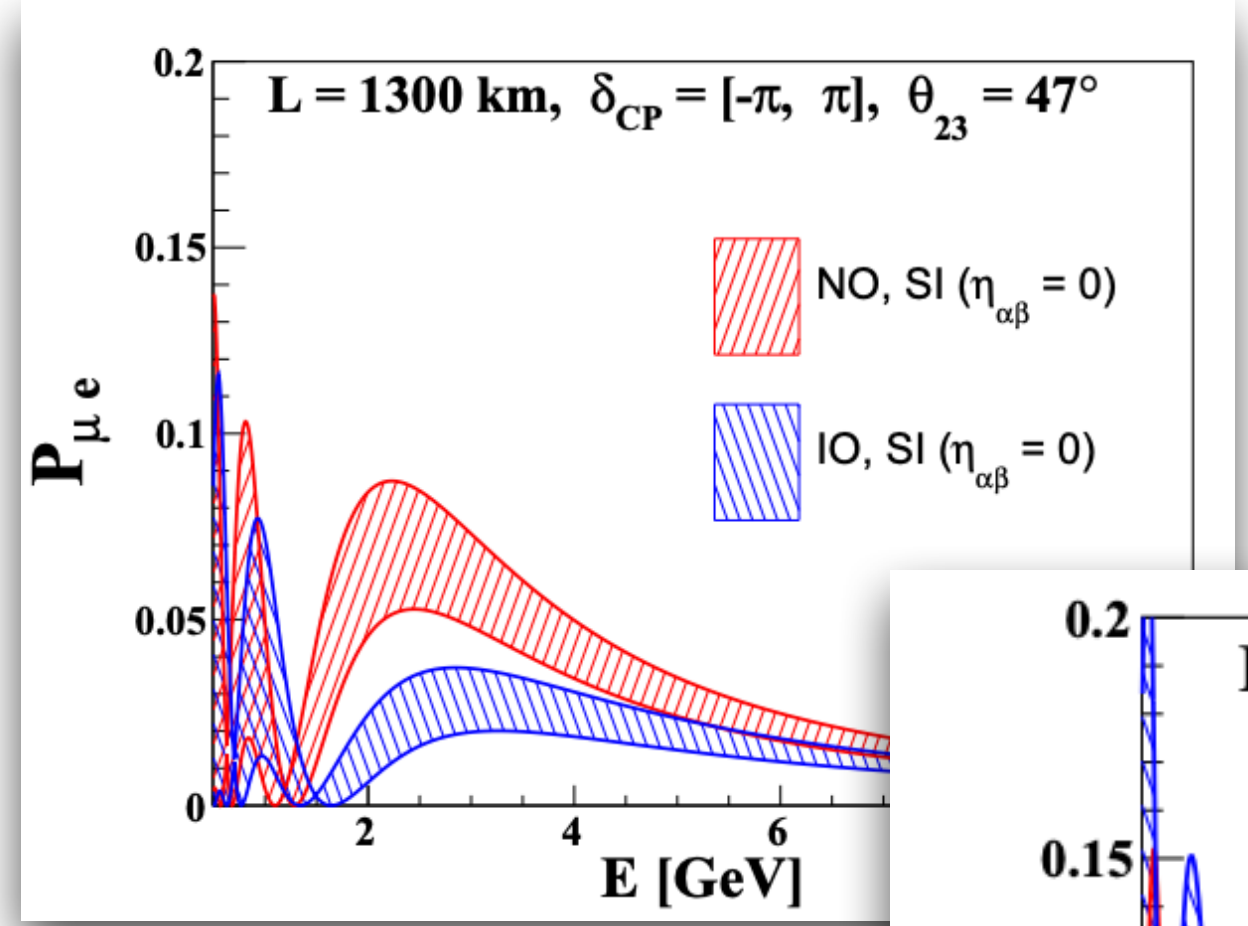


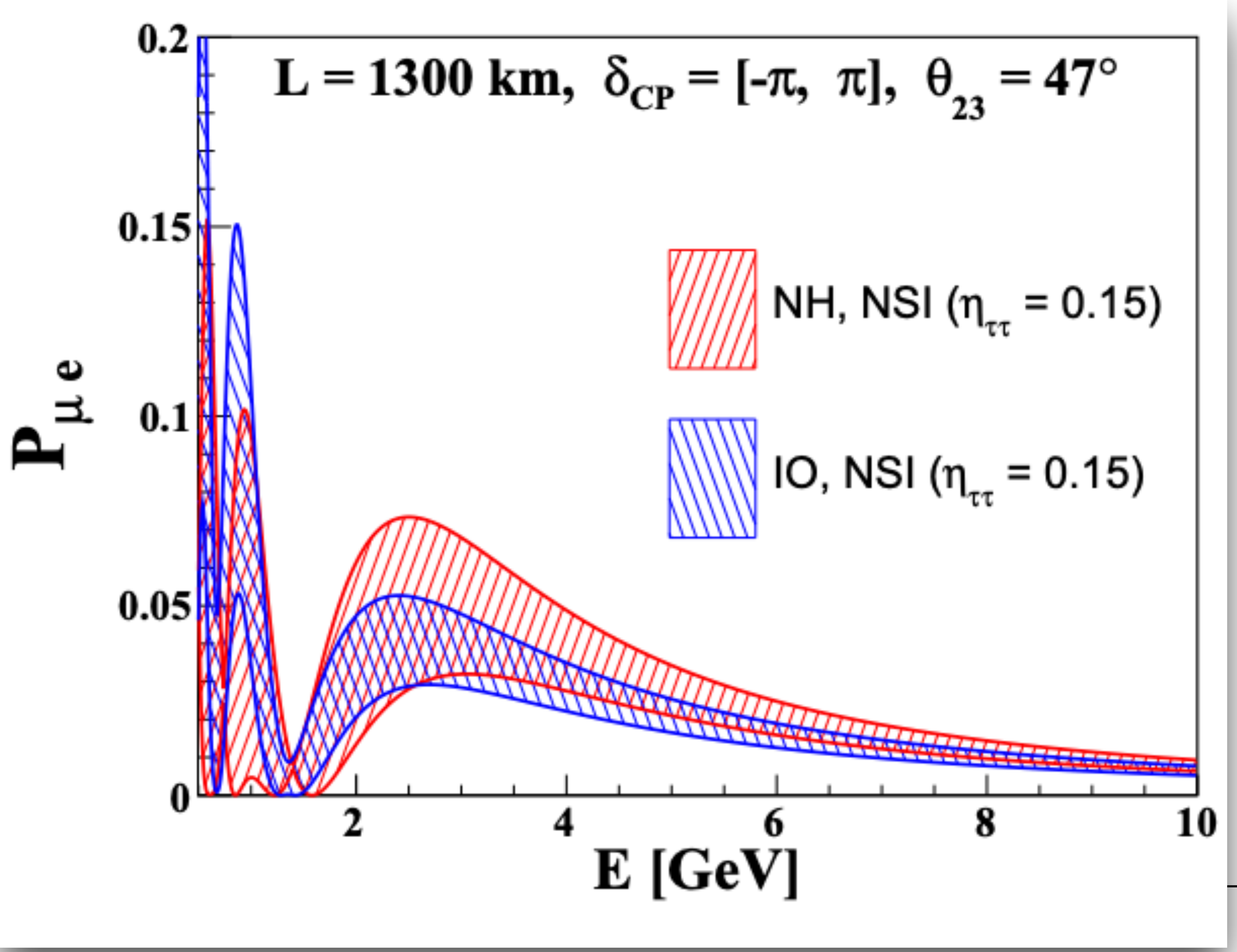
Long-range forces @ WG1+WG5
Scalar non-standard interactions

Moon Moon Devi (Tezpur University)
Adrian Thompson (Northwestern University)

Moon Moon Devi:

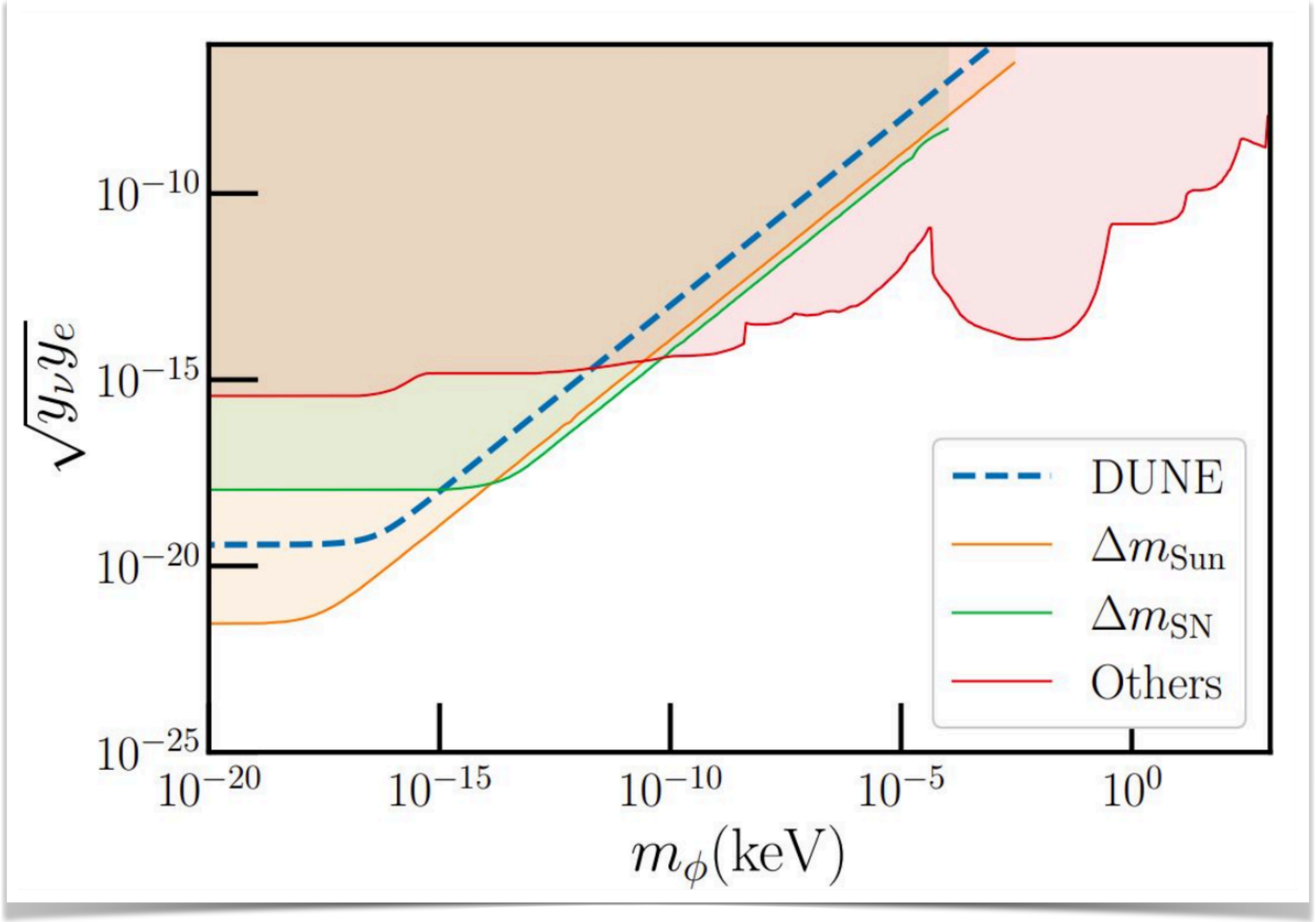
Ordering cases become degenerate for large $\eta_{\tau\tau}$





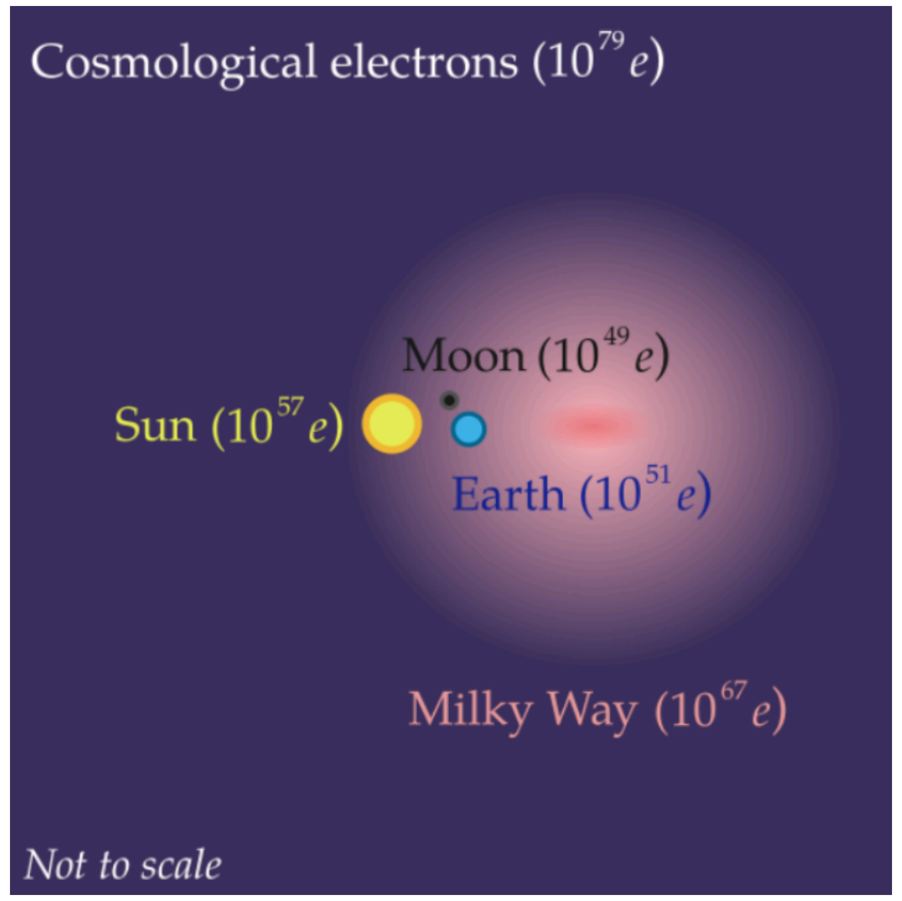
Adrian Thompson

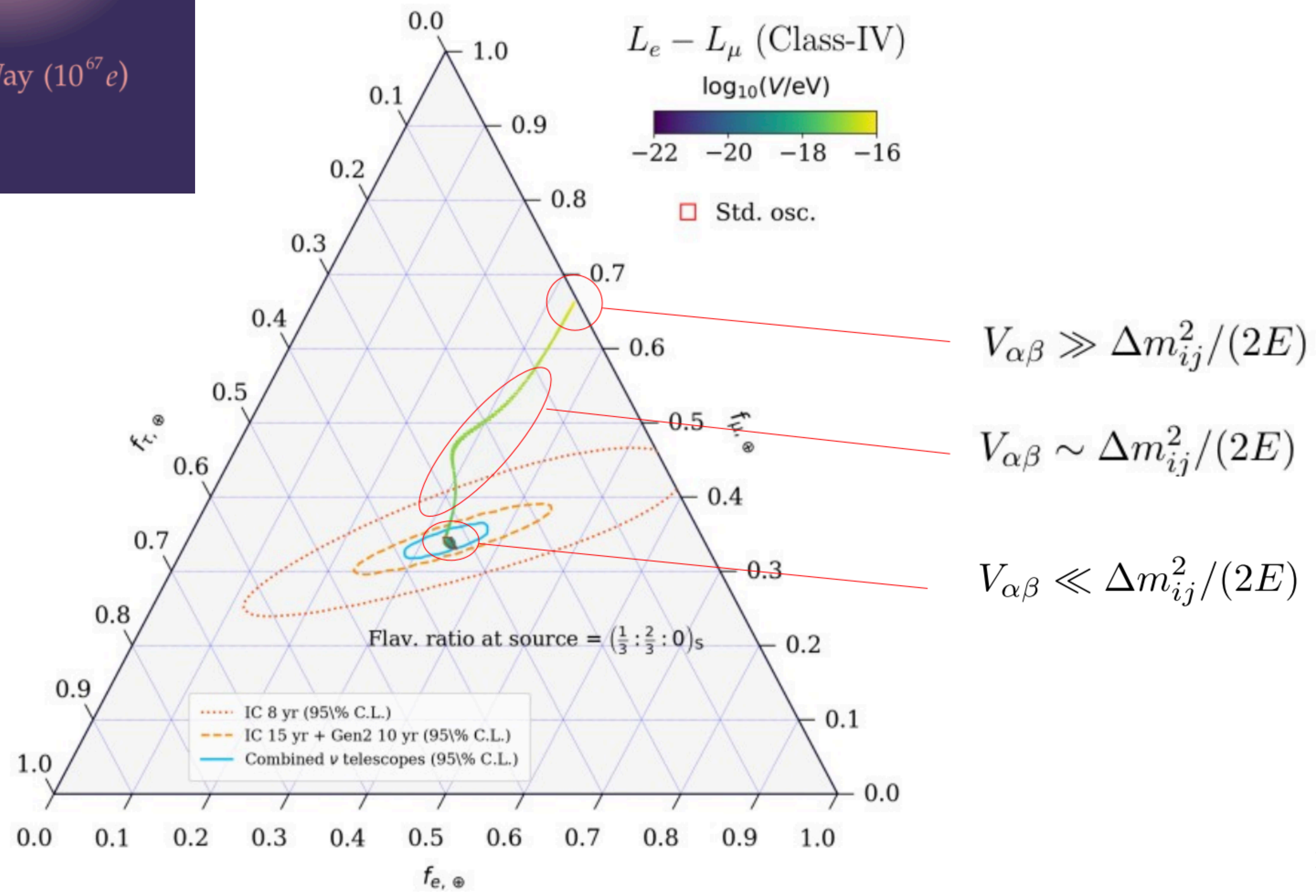
DUNE sensitivity -- but other limits apply and LBL exps **not as sensitive as solar neutrinos!**

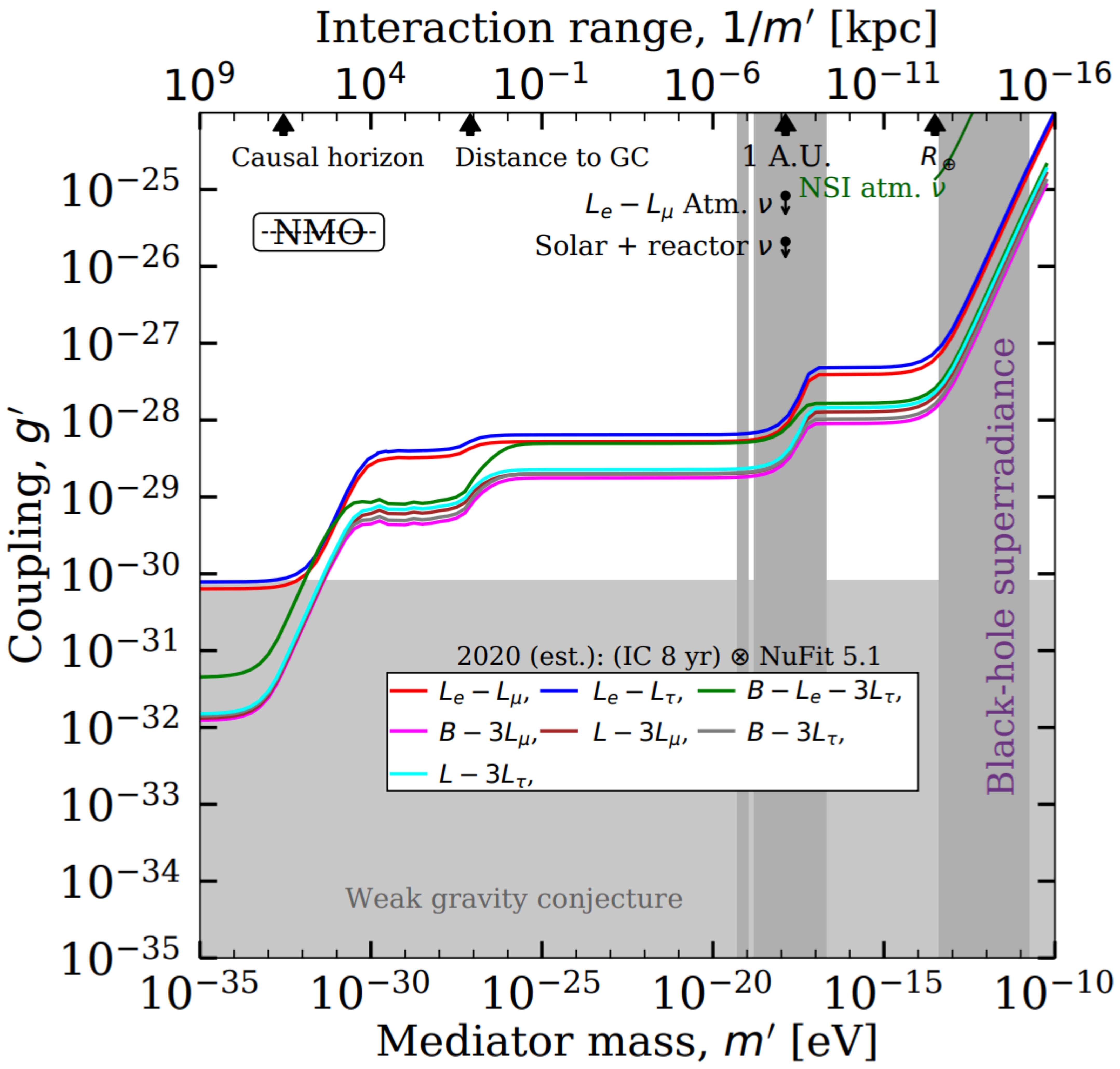


Long-range forces @ WG1+WG5
Celestial bodies

Sudipta Das (Institute of Physics, Bhubaneswar)
Mason Singh (Institute of Physics, Bhubaneswar)
Pragyanprasu Swain (Institute of Physics, Bhubaneswar)







Long-range forces @ WG1+WG5
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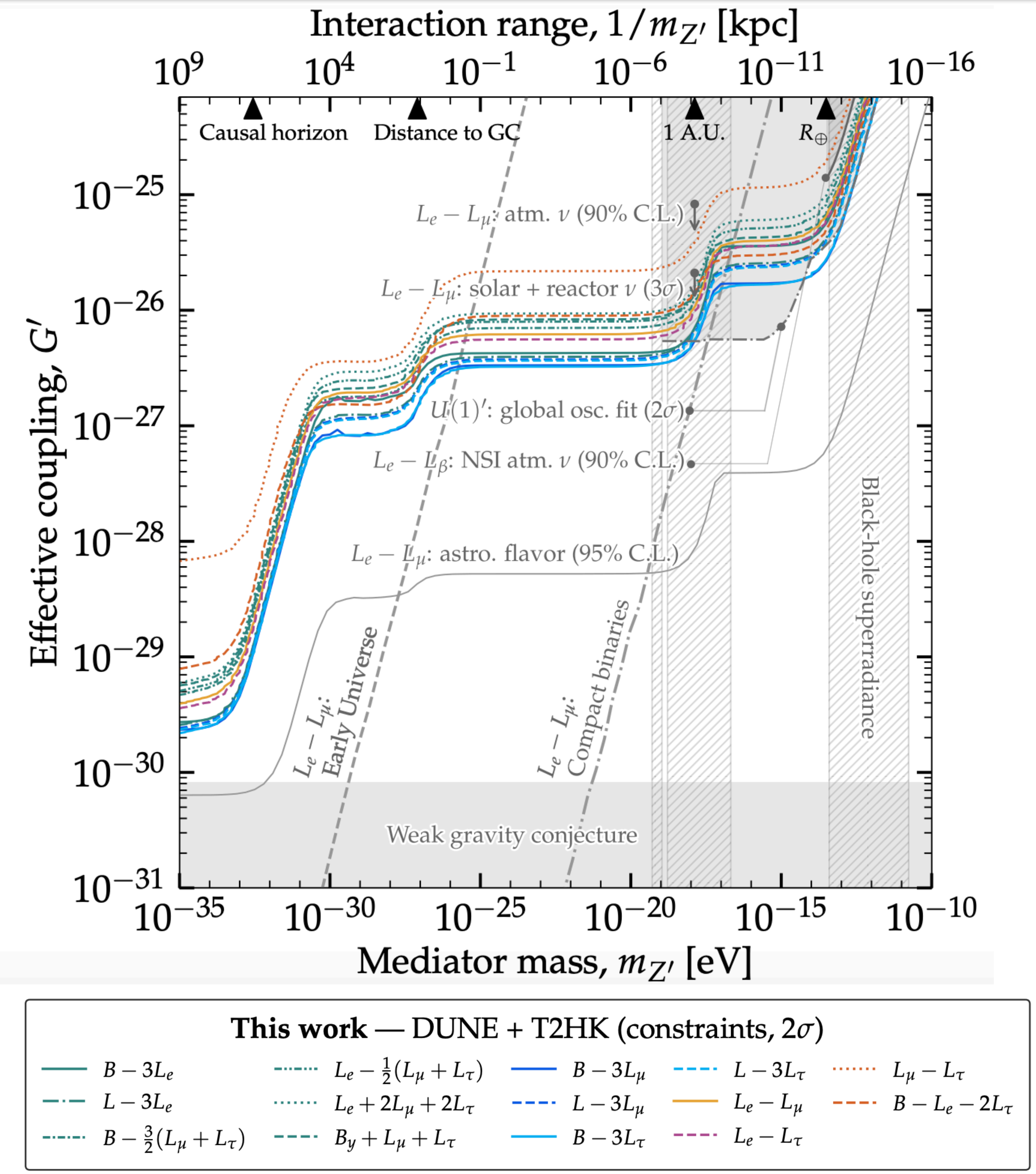
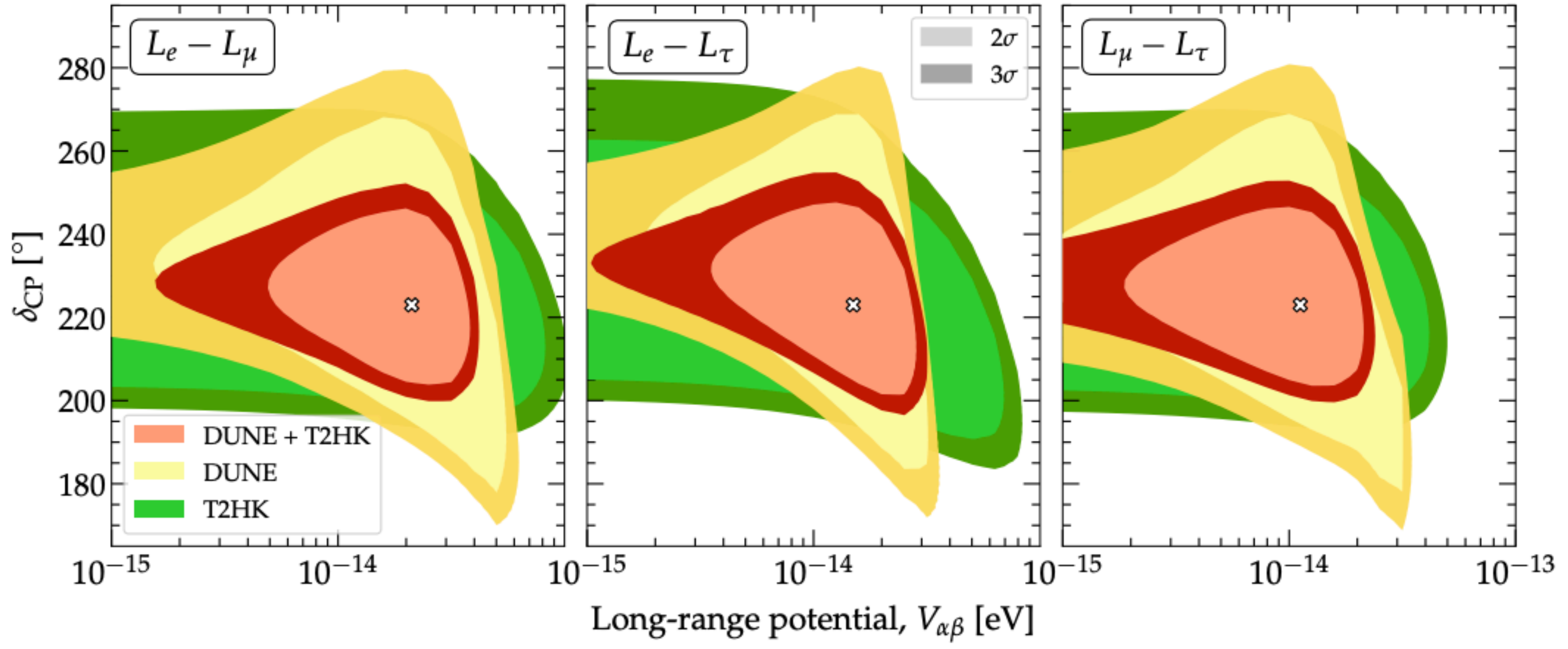


DUNE & T2HK sensitivity



DUNE + T2HK complement each other and remove inherent degeneracies in standalone experiments.

Complementary approach to CP phase measurement

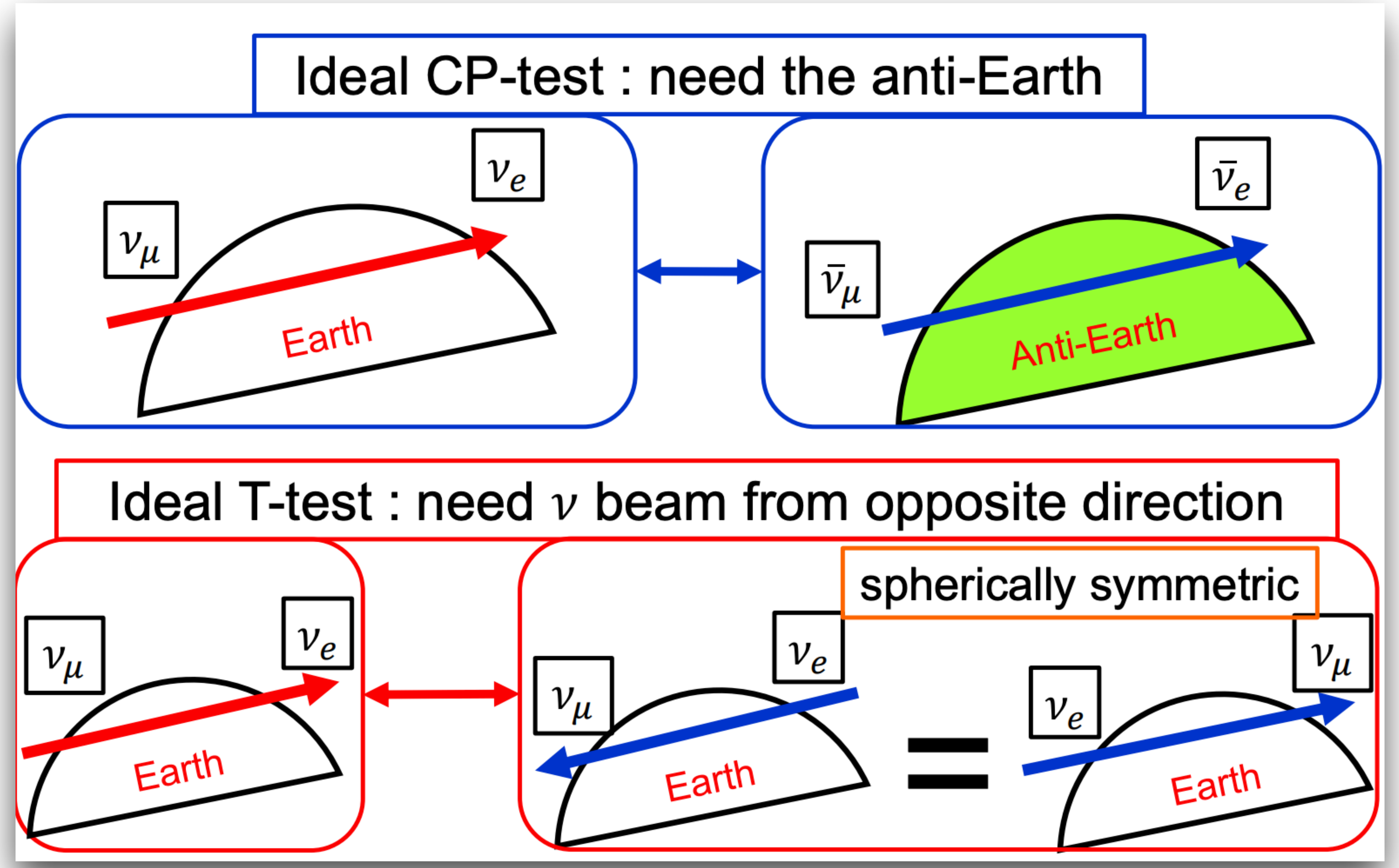
T violation

Sho Sugama (Yokohama National Univ)

CP observables: sensitive to matter effects

T observables: INsensitive to matter effects*

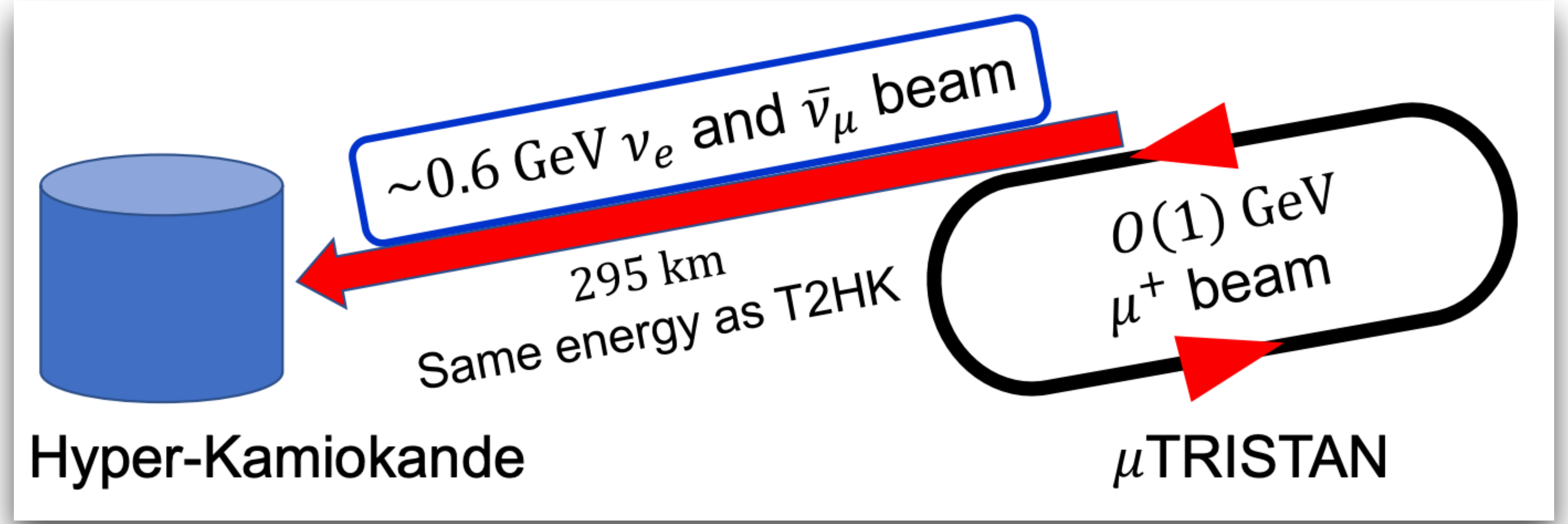
*provided matter profile is symmetric.

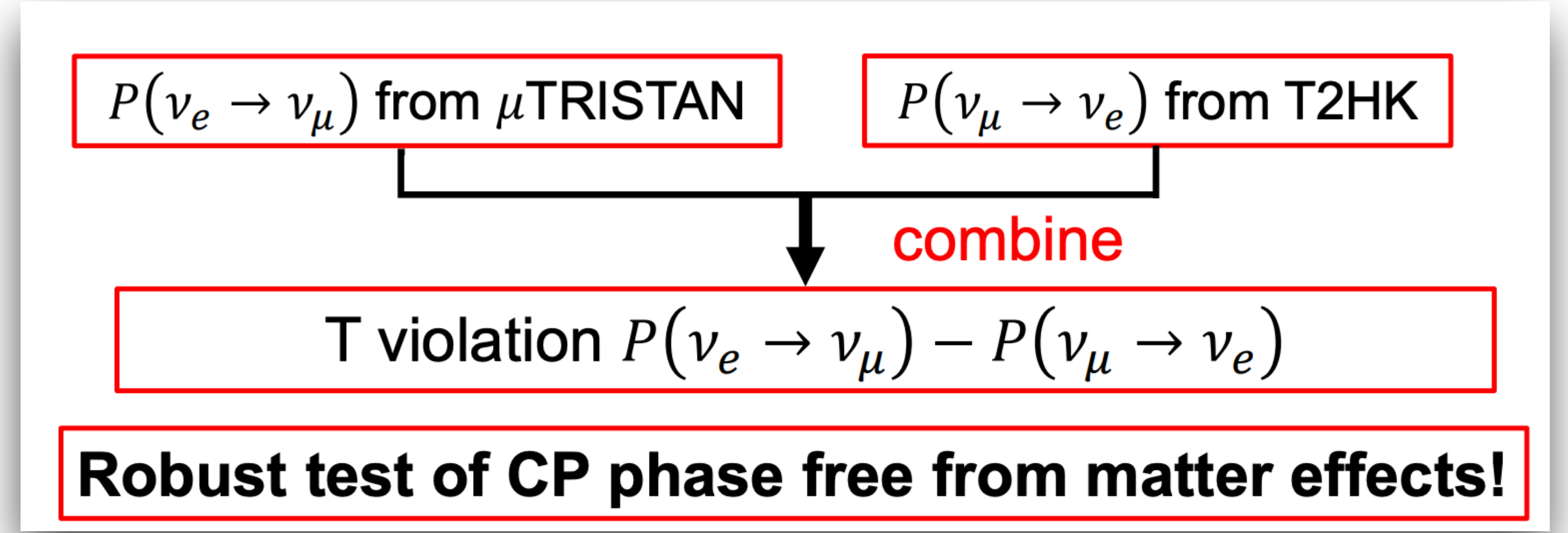


μTRISTAN

Muon factory based on μ^+ beam

(Can only do μ^+ with muonium cooling)





1) Where do we look for the most valuable hints of **the origin of neutrino masses**?

Complement oscillations with dark sector searches and indirect tests (e.g. p^+ decay!)

2) How to identify connections between **neutrinos and dark matter** (theory & experiment)?

Dark sectors! The famous "wide net" is just now being cast with real data!

3) Have we already stumbled on new physics, e.g., at **short baselines**?

Maybe?! No excesses at reactors or MicroBooNE -- but data still puzzles me!
SBN and JSNS^2 soon to weigh in.

4) How do we exploit the dawn of new probes of **astrophysical neutrinos** to learn about new physics?

Galactic neutrinos, solar neutrinos, astrophysical, cosmogenic(??);
Huge complementarity between low and high energy neutrino astro

5) Oscillations can be modified by many new effects. How to best leverage the worldwide neutrino program to **disentangle "*new*" new physics in oscillations**?

Overconstrain the system! More experiments: "competition" --> "completion".

Thank you

See you in 2025!

WG5 parallel sessions
Monday (1 session)

Leveraging high statistics of neutrino interactions and high-resolution detectors.

New physics at short-baseline neutrino experiments.

New physics
in neutrino interactions

Chair: Julia Gehrlein (Colorado State University)

MicroBooNE's Beyond Standard Model Physics Program	*Keng Lin*
E1100, #402	13:45 - 14:05
Constraints on new physics with (anti)neutrino-nucleon scattering data	*Richard Hill*
E1100, #402	14:05 - 14:25
Searching for anomalous photon and dark-sector e+e- pairs in the MicroBooNE detector	*Erin Yandel*
E1100, #402	14:25 - 14:45
Search for a Long-Lived $\mu\mu$ Resonance at ICARUS in SBN	*Nathaniel Rowe*
E1100, #402	14:45 - 15:05
Model-independent new-physics simulation with GENIE	*Komninos-John Plows*
E1100, #402	15:05 - 15:25

WG5 parallel sessions
Tuesday (1/2 sessions)

Looking up at the sky for messengers of new physics.

New ideas to study the highest energy neutrinos and the cosmic neutrino background

and how they can reveal new forces.

New physics
in astrophysical neutrinos

Chair: Shiqi Yu (Utah University)

Unlocking high energy tau-neutrino astronomy with the TAMBO deep-valley detector array	*Robert-Mihai Amarinei*
E1100, #402	13:45 - 14:05
Probing self-interacting sterile neutrino dark matter with the diffuse supernova neutrino background	*Ann Suliga*
E1100, #402	14:05 - 14:25
Constraining long-range interaction using the flavor composition estimates from astrophysical neutrino experiments *Sudipta Das*	
Neutron Stars as a Probe of Cosmic Neutrino Background	*Garv Chauhan*
E1100, #402	14:45 - 15:05

WG5 parallel sessions
Tuesday (2/2 sessions)

More with astrophysical neutrinos, now at low energies with coherent elastic neutrino-nucleus scattering.

Even newer experimental ideas: paleo detectors.

Neutrino x dark matter complementarity

Chair: Peter Denton (Brookhaven National Laboratory)

Probing new physics from neutrinos at dark matter direct detection experiments	*Gonzalo Herrera*
E1100, #402	16:15 - 16:35
Looking at the flavor composition of solar neutrinos	*Nityasa Mishra*
E1100, #402	16:35 - 16:55
Investigating the future of proton decay searches using paleo detectors	*Cassandra Little*
E1100, #402	16:55 - 17:15
Physics opportunities with kaon decay-at-rest neutrinos: search for sterile neutrino and non-standard interactions *Mr Aman Gupta*	
A comprehensive analysis of supernova neutrino-dark matter interactions	*Deepak Sathyan*
E1100, #402	17:35 - 17:55

WG5 parallel sessions
Thursday (1/2 sessions)

Constraining short-baseline neutrino oscillations and testing longstanding anomalies:

Testing MiniBooNE and LSND with the SBN program, JSNS^2, and reactor neutrinos.

Looking for sterile neutrino oscillations

Chair: Minerba Betancourt (Fermilab)

Status of the Short-Baseline Near Detector at Fermilab	*Tereza Kroupova et al.*
E1100, #402	13:45 - 14:05
First Results of the ICARUS Experiment at Fermilab	*Jacob Zettlemoyer*
E1100, #402	14:05 - 14:25
New results in the JSNS2 experiment	*DongHa Lee*
E1100, #402	14:25 - 14:45
Latest results from MicroBooNE's electron neutrino Low Energy Excess Search	*Fan Gao et al.*
E1100, #402	14:45 - 15:05
The STEREO neutrino experiment: Overview & latest results.	*Dr Ilham El Atmani*
E1100, #402	15:05 - 15:25

Joint WG1 + WG5 parallel session
Thursday (2/2 sessions)

Leveraging precision measurements of oscillation to test tiny deviations from PMNS.

Non-standard interactions and the role of new fundamental symmetries.

Exotic flavor evolution in oscillations

Chair: Vishvas Pandey (विश्वास पाण्डेय) (Fermilab)

Neutrino mass ordering sensitivities at DUNE, HK and KNO in presence of scalar NSI	*Dr Moon Moon Devi*
A1100, #401	16:15 - 16:35
T violation at a future neutrino factory	*Sho Sugama*
A1100, #401	16:35 - 16:55
A plethora of long-range neutrino interactions probed by DUNE and T2HK	*Pragyanprasu Swain*
A1100, #401	16:55 - 17:15
Flavor-Dependent Long-Range $\mathbf{\nu}$ Interactions in DUNE and T2HK: Synergy Breeds Power	*Masoom Singh*
A1100, #401	17:15 - 17:35
Neutrino NSI from Ultralight Scalars	*Adrian Thompson et al.*
A1100, #401	17:35 - 17:55