(Some) **Neutrino Physics Phenomenology**

Phenomenology Symposium 2026

IOWA

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Neutrinos are unique fundamental particles

Singlet under (unbroken) SM gauge symmetries: **neutral leptons.**

Masses may or may not follow the Higgs mechanism: Dirac? Majorana? Both?

Produced and detected with >99.9999% polarization.

Quantum mechanics in macroscopical distances.

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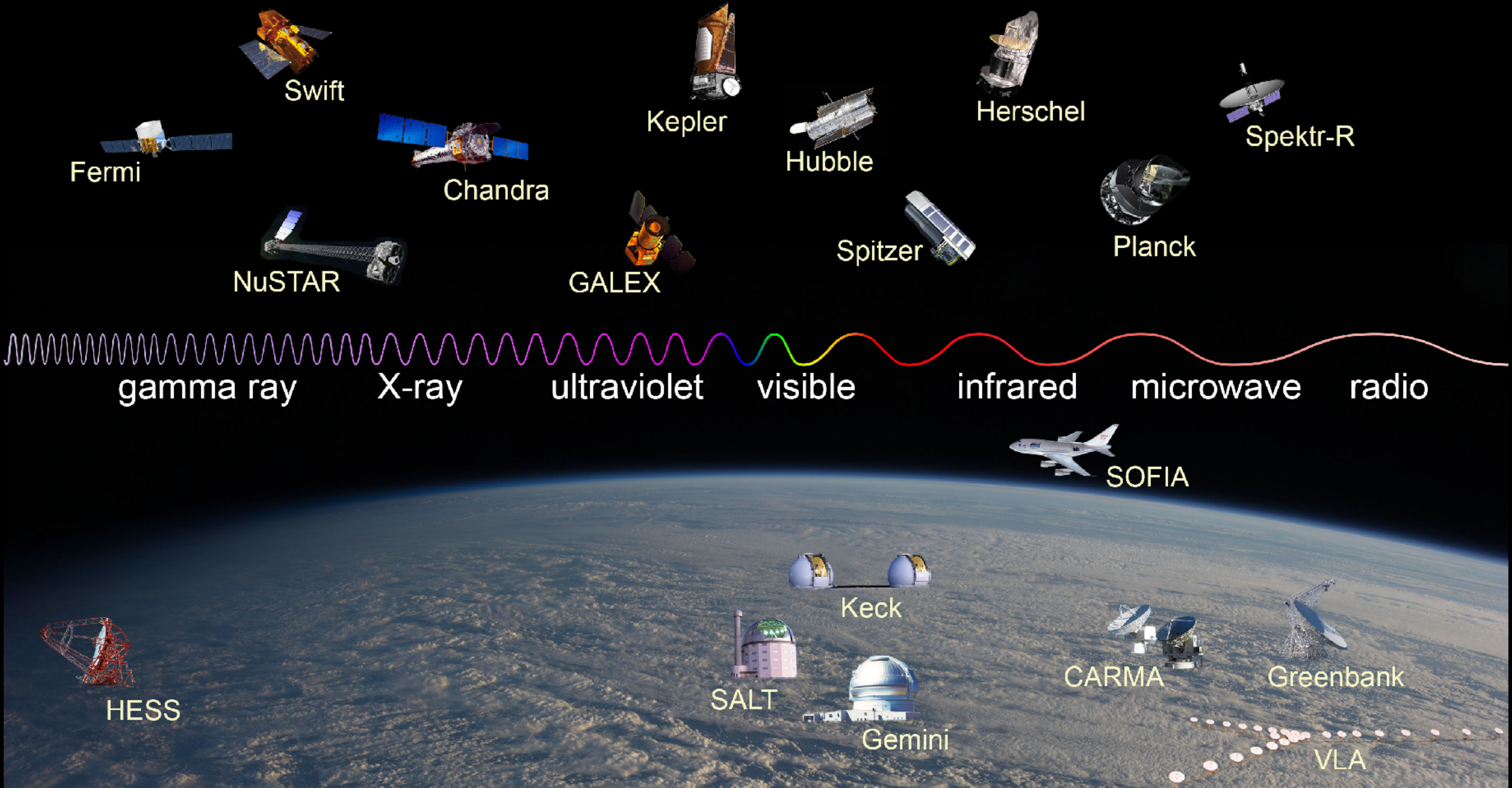
Quantum mechanics in macroscopical distances.

Neutrino experiments are compelling probes of fundamental physics

Built for rare phenomena, pushing intensity frontier.

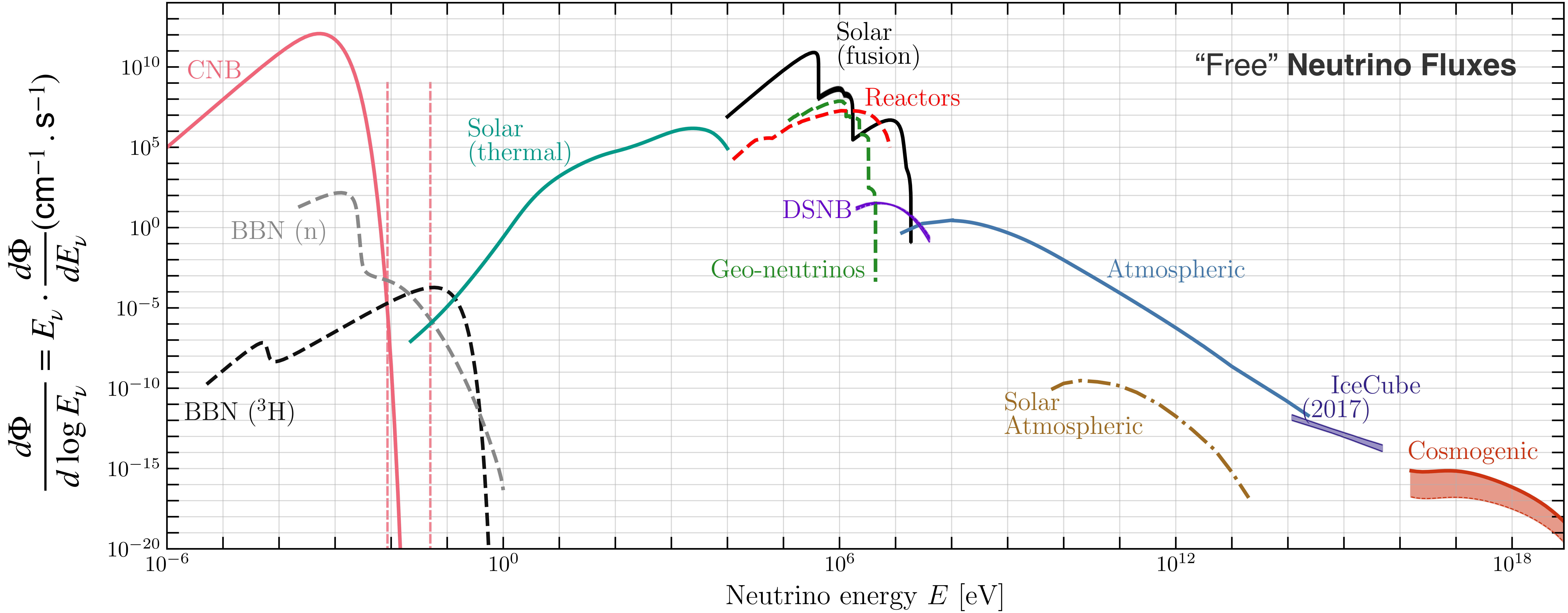
Several puzzles and anomalies to be resolved and **abundance of data.**
(see, e.g., M. Ross-Lonergan's talk)



As of 2013 https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum_observatories1.html

Neutrinos Across Energy Scale

* Adapted from E. Vitagliano, I. Tamborra, G. Raffelt, Rev.Mod.Phys. 92 (2020) 45006



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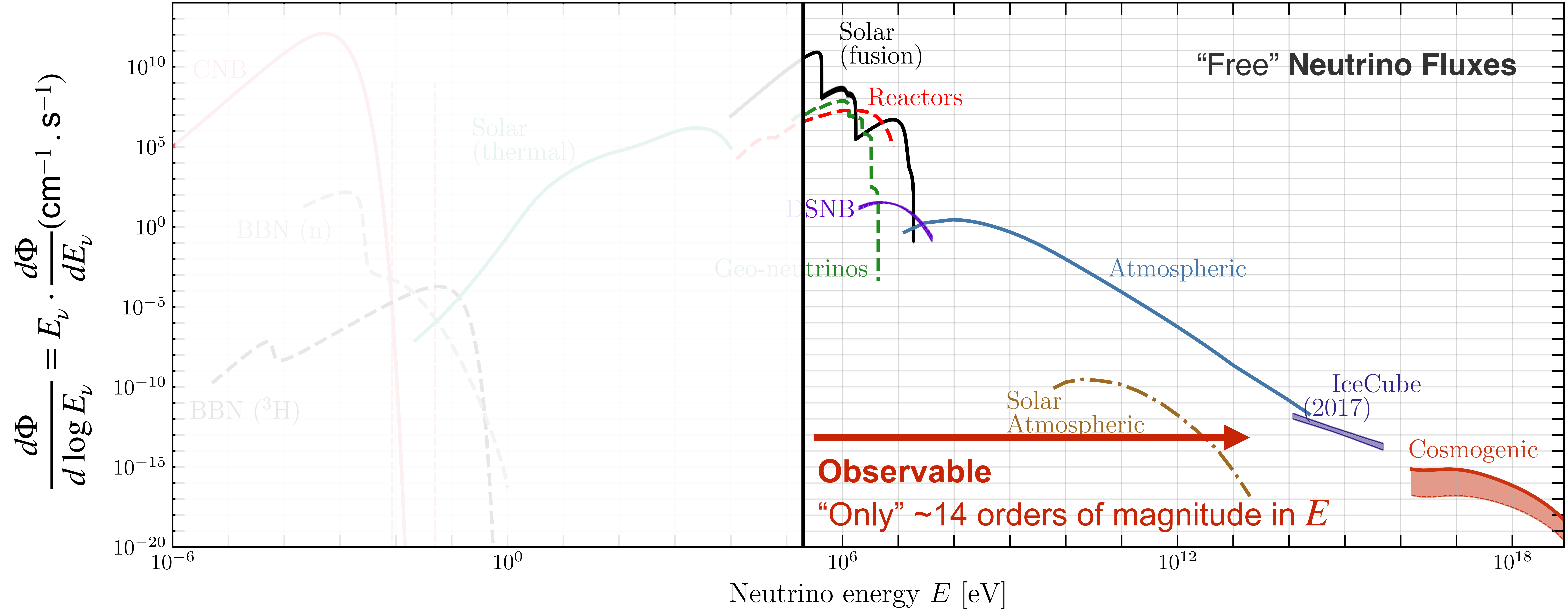

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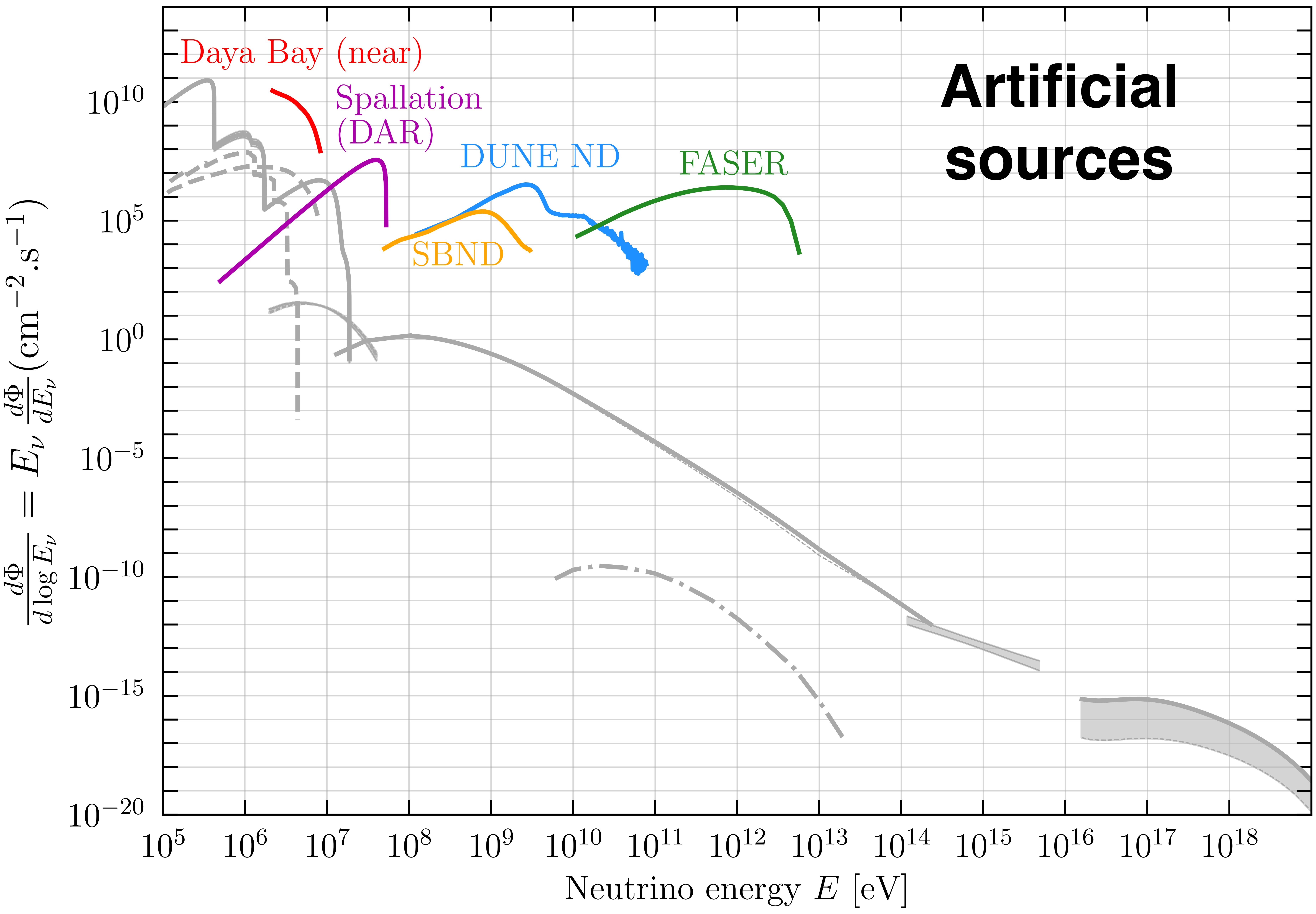
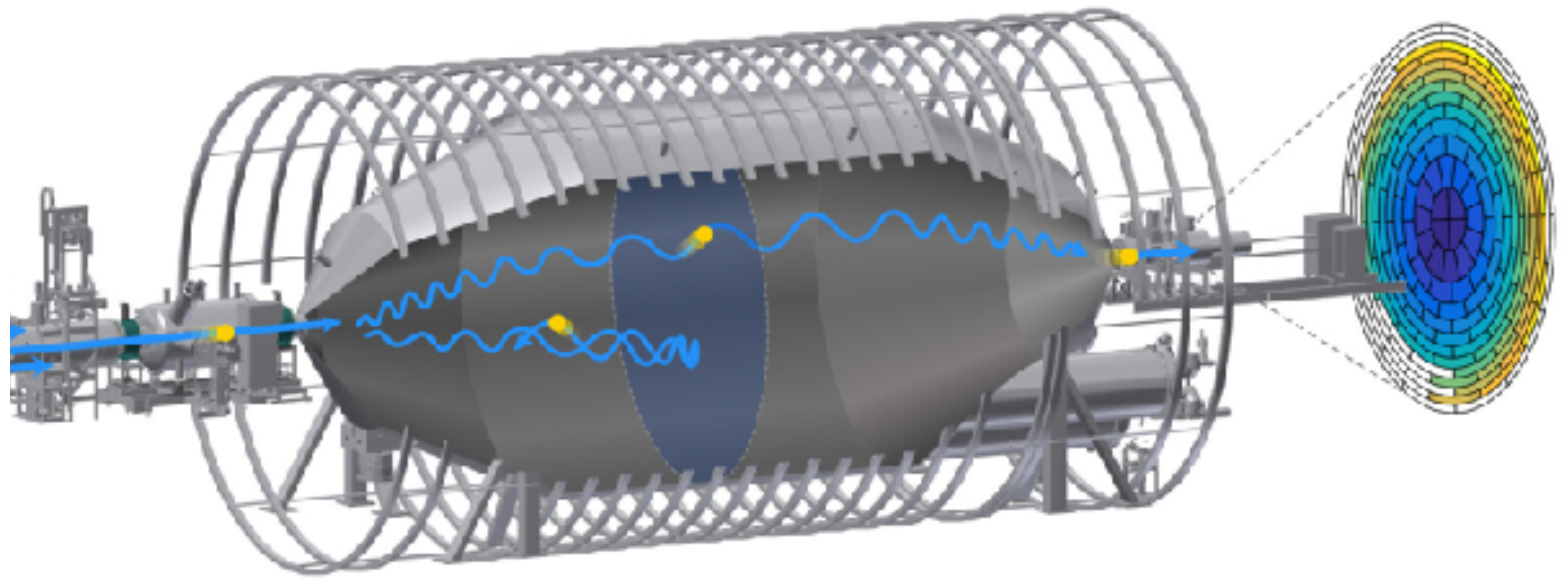


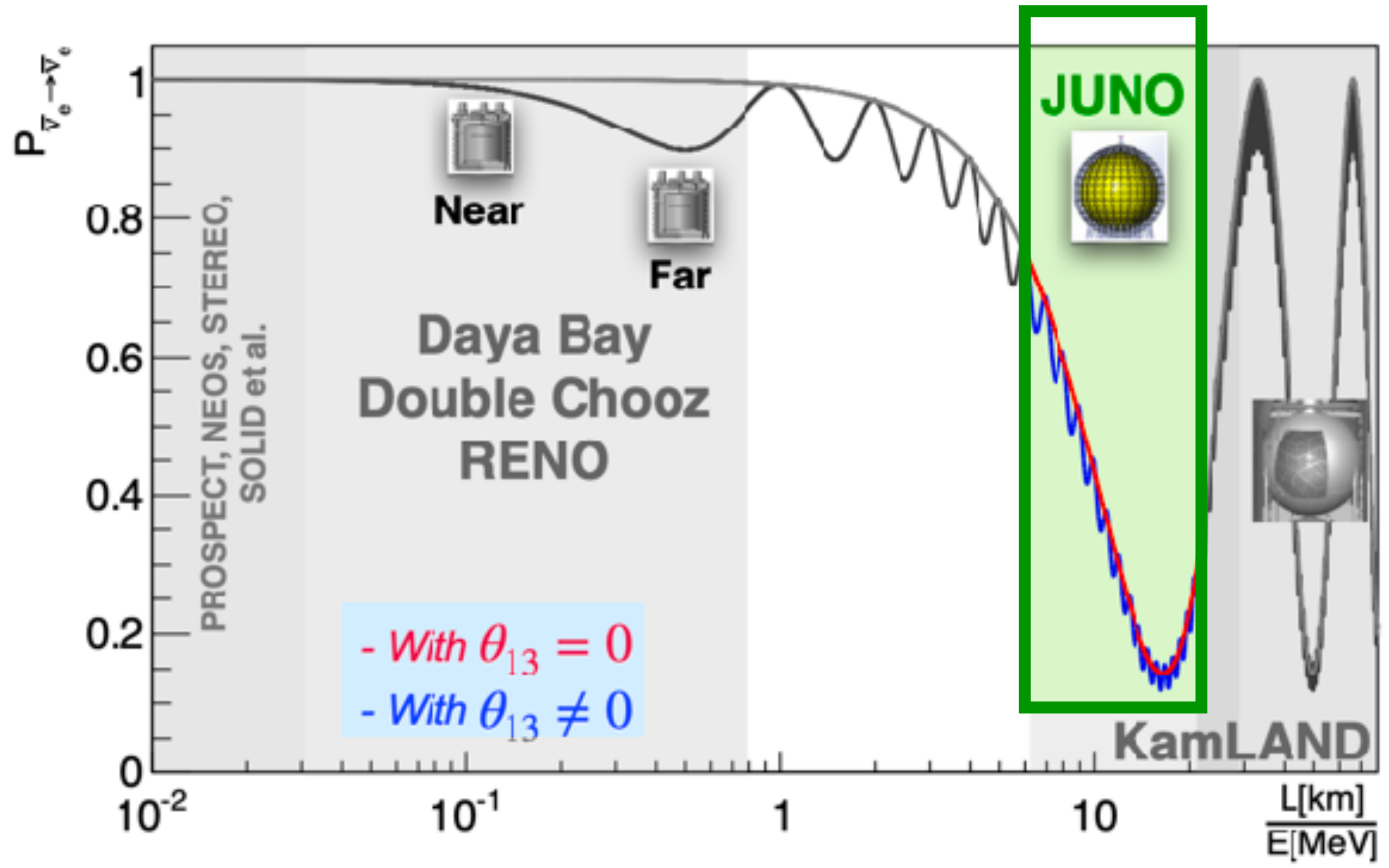
Covering the spectrum from MeV → EeV

Beta decay spectra

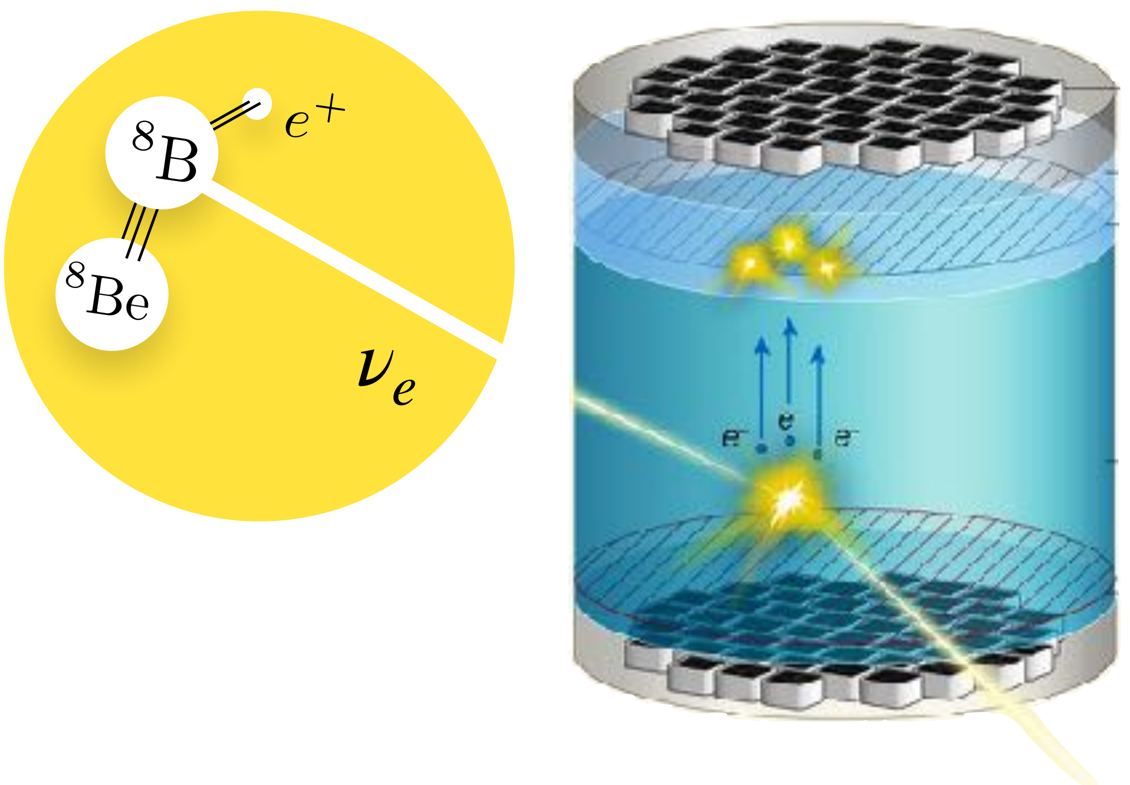


Reactors / Spallation Sources

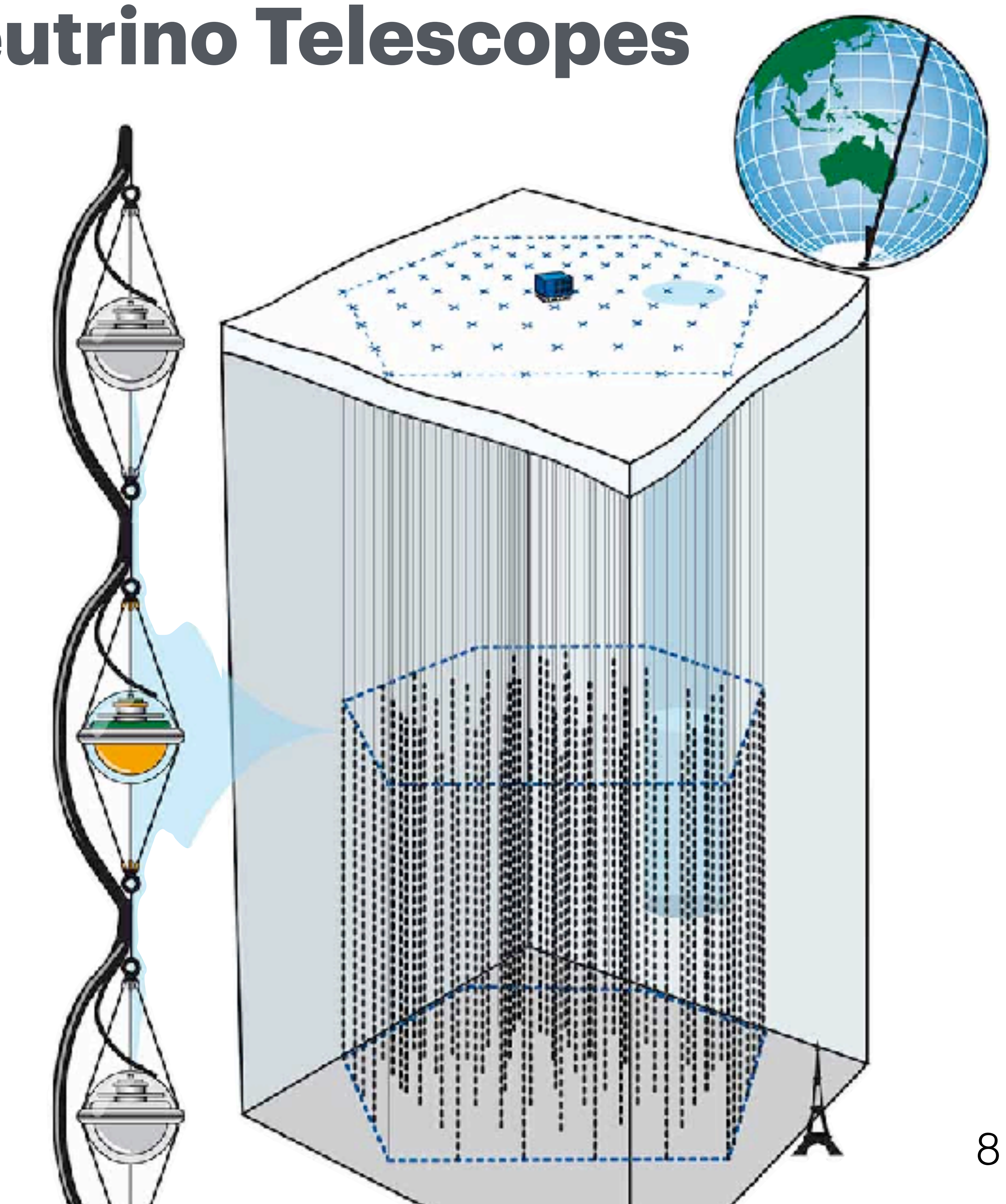
Adapted from P. Ochoa-Ricoux, NPN 2025



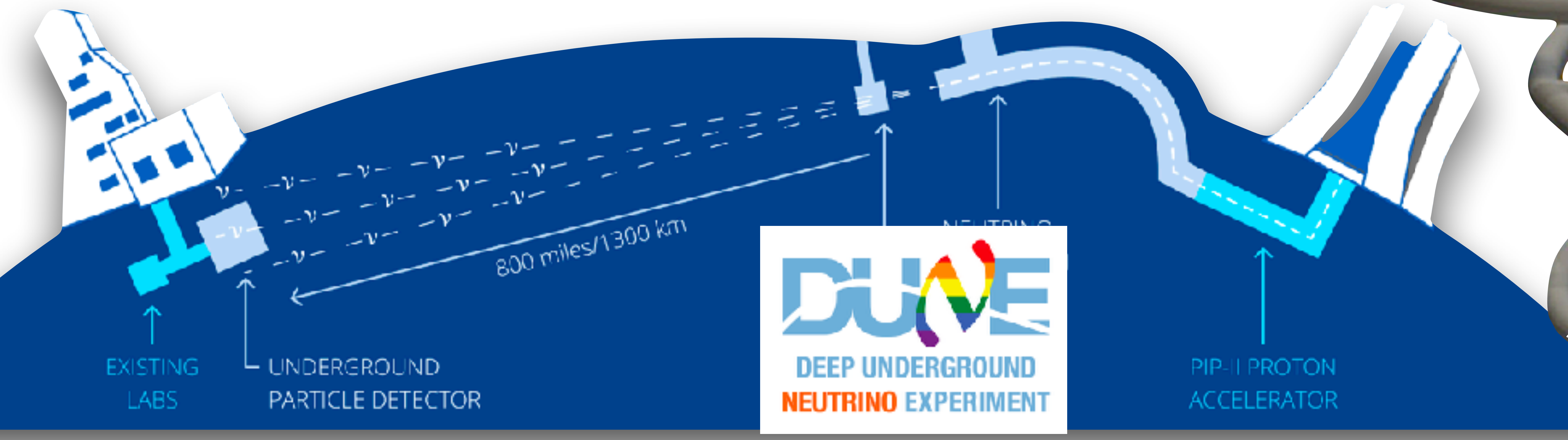
Dark Matter Direct Detection

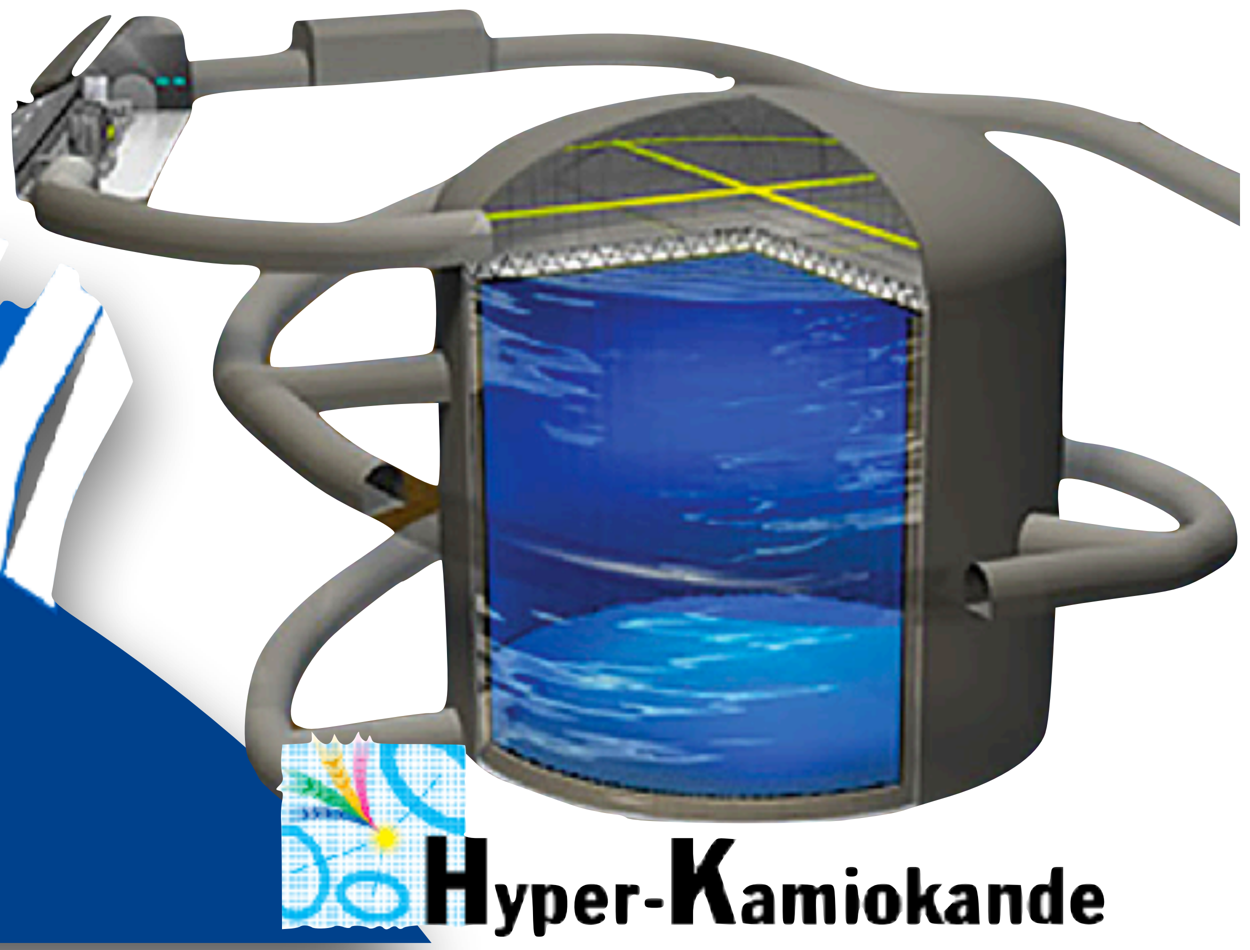


Neutrino Telescopes



Long-Baseline Experiments





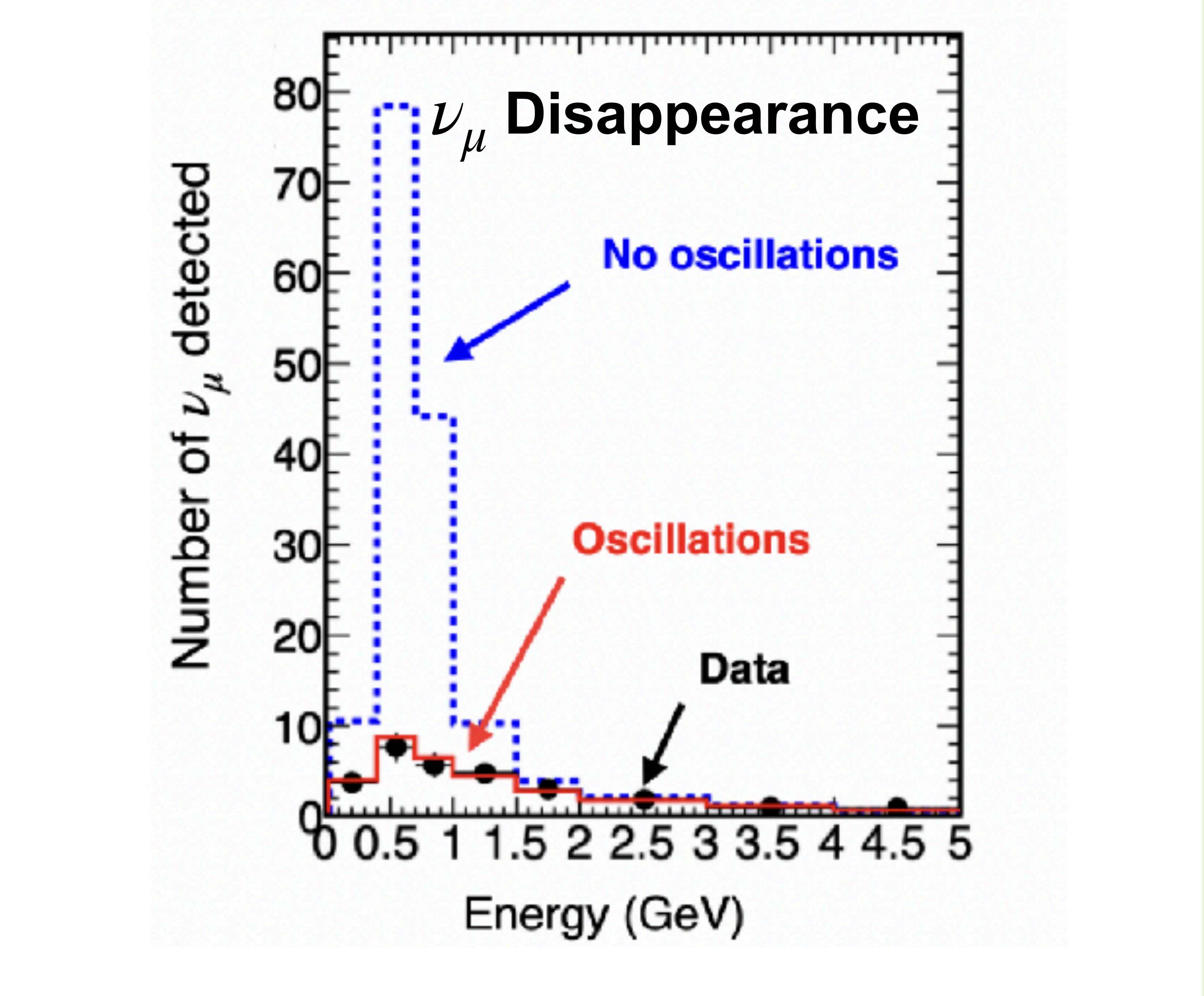
Neutrino Oscillations

$$e^{-i(E_1 - E_2)t} \longrightarrow e^{-i\frac{\Delta m^2 t}{2E}}$$

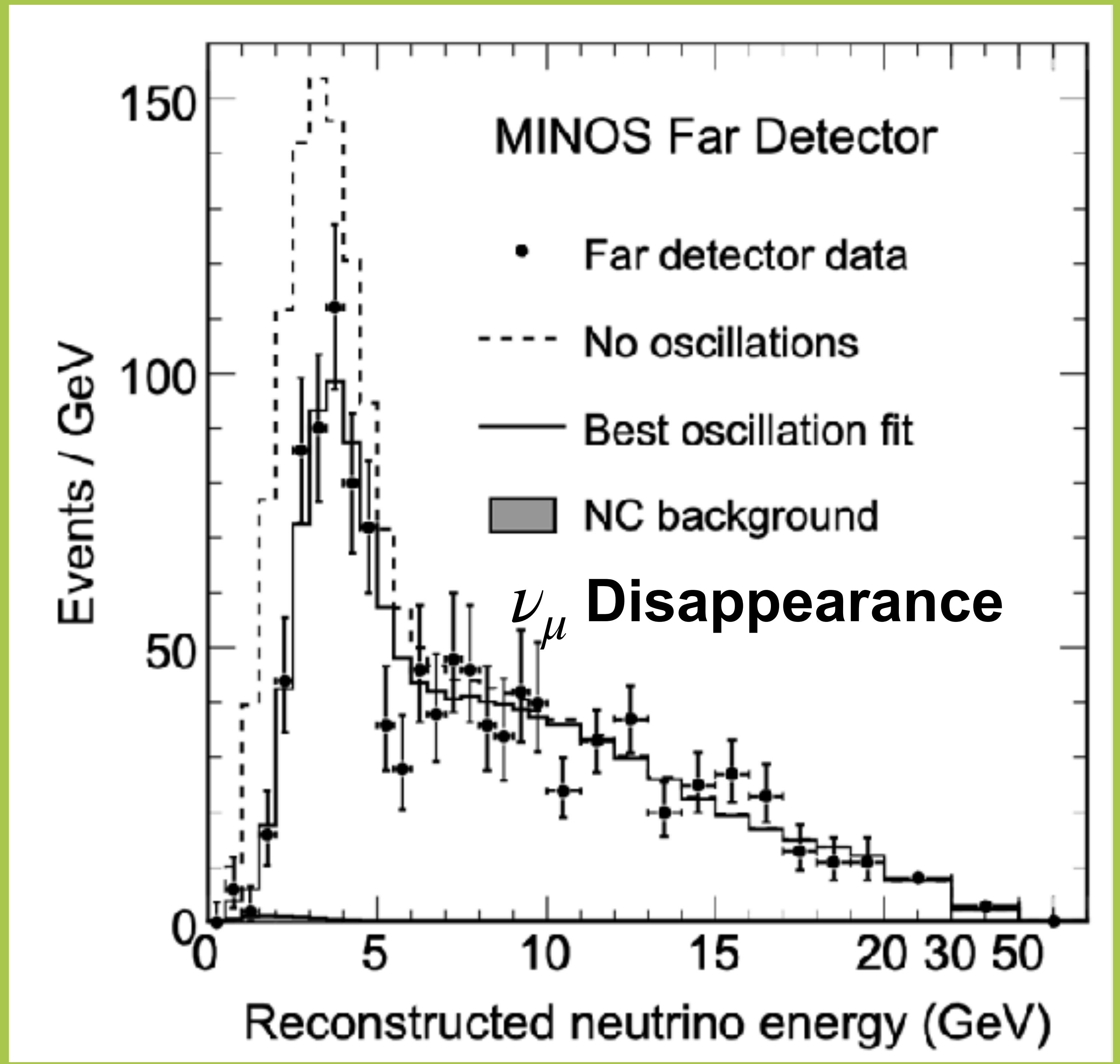
“Earth-Sized Quantum Flavor Interferometers”

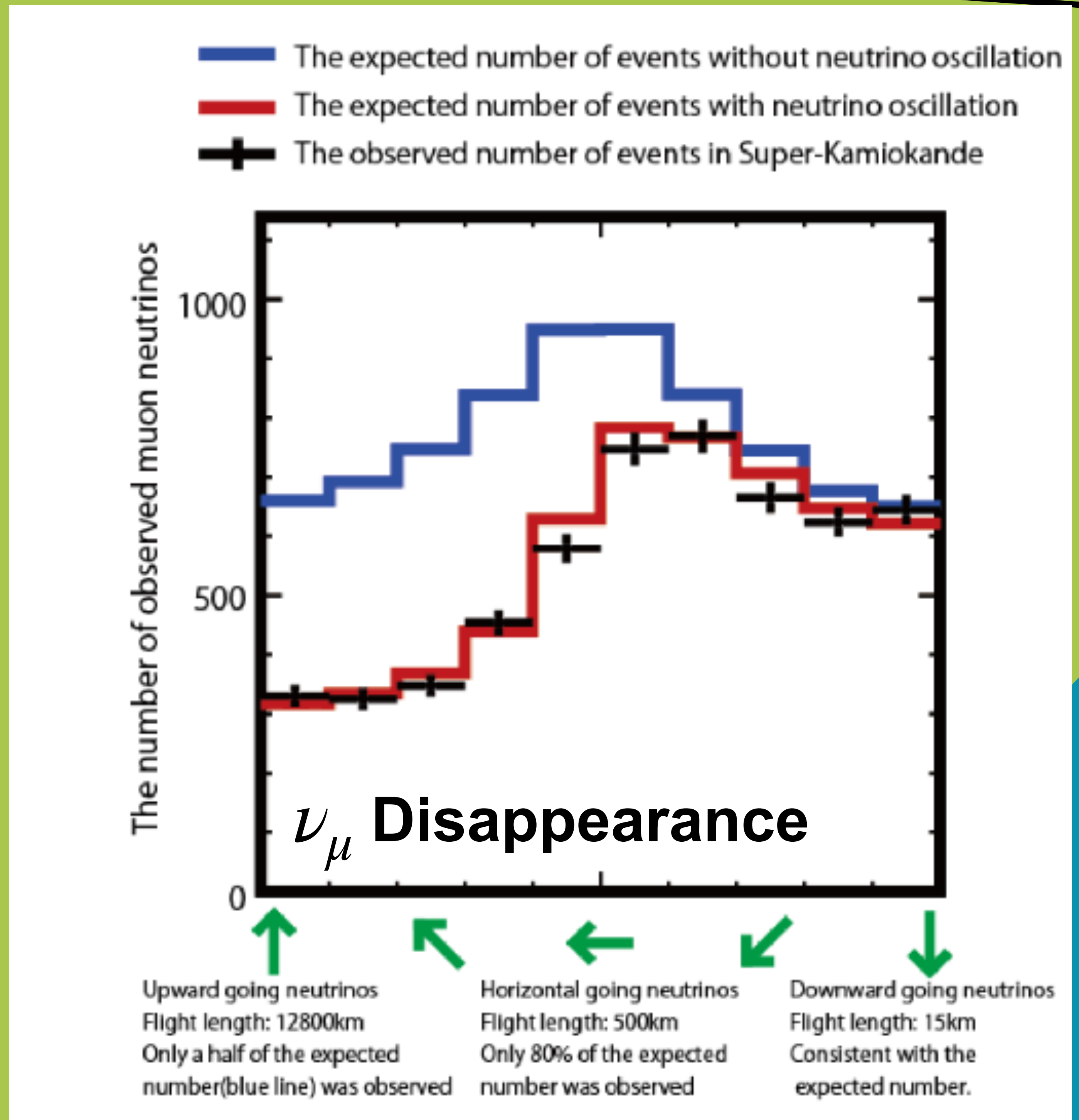
Neutrino Oscillations

MINOS coll., PRL 101:131802, 2008



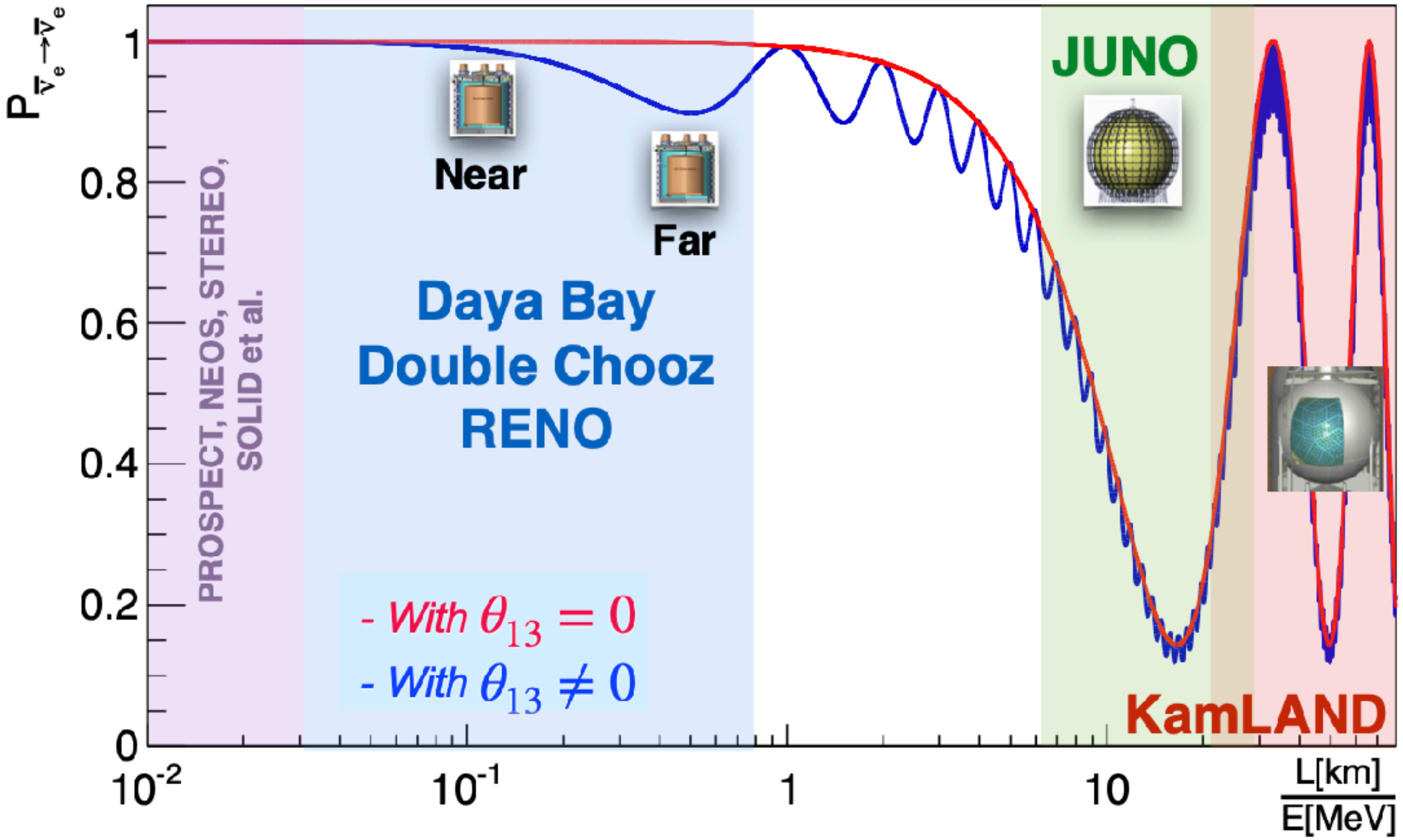
Adapted from T2K coll., 10.1103/PhysRevD.96.011102



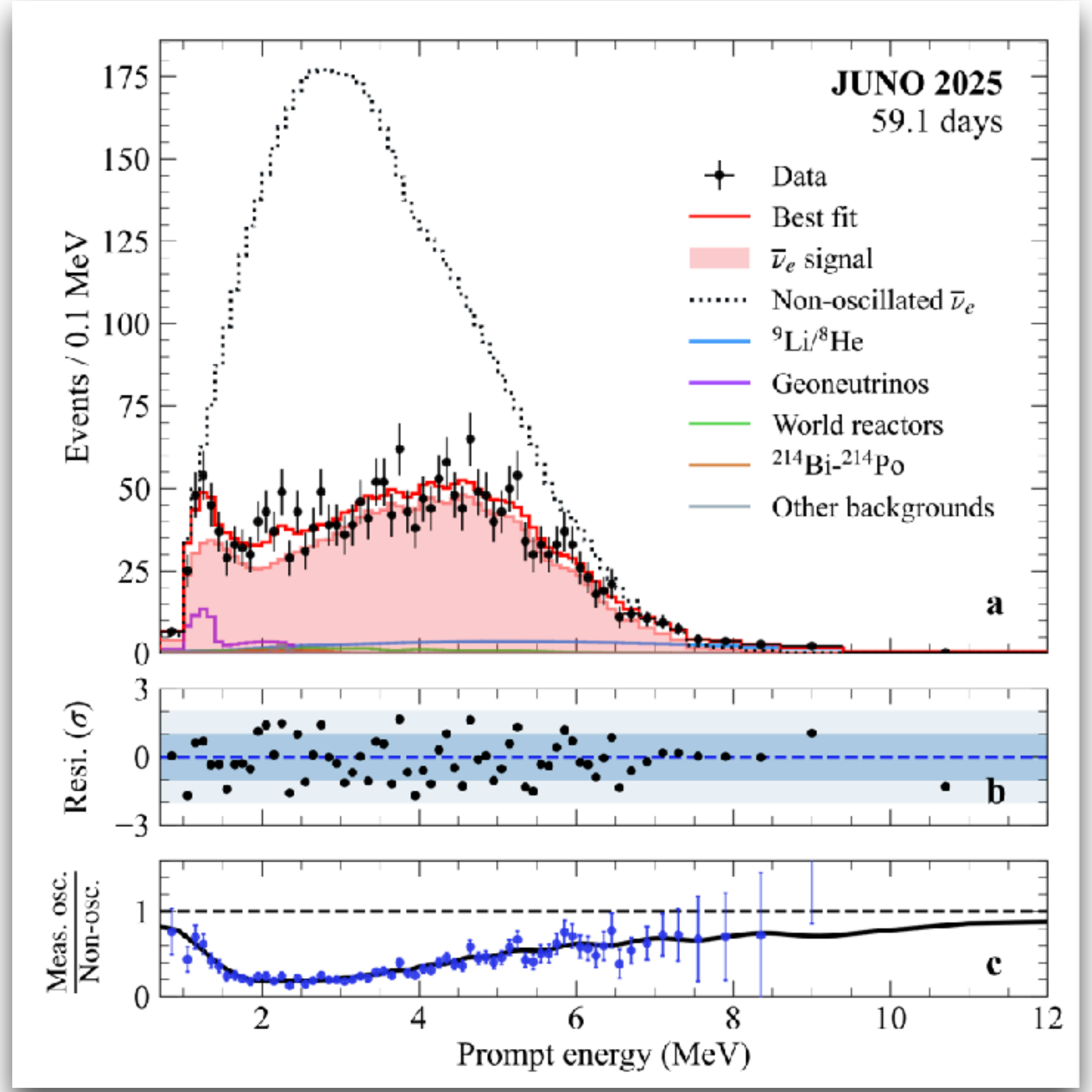


Precision measurement of **3-neutrino oscillations**
$\bar{\nu}_e \rightarrow \bar{\nu}_e$ mode (CP conserving)

Adapted from P. Ochoa-Ricoux, NPN 2025

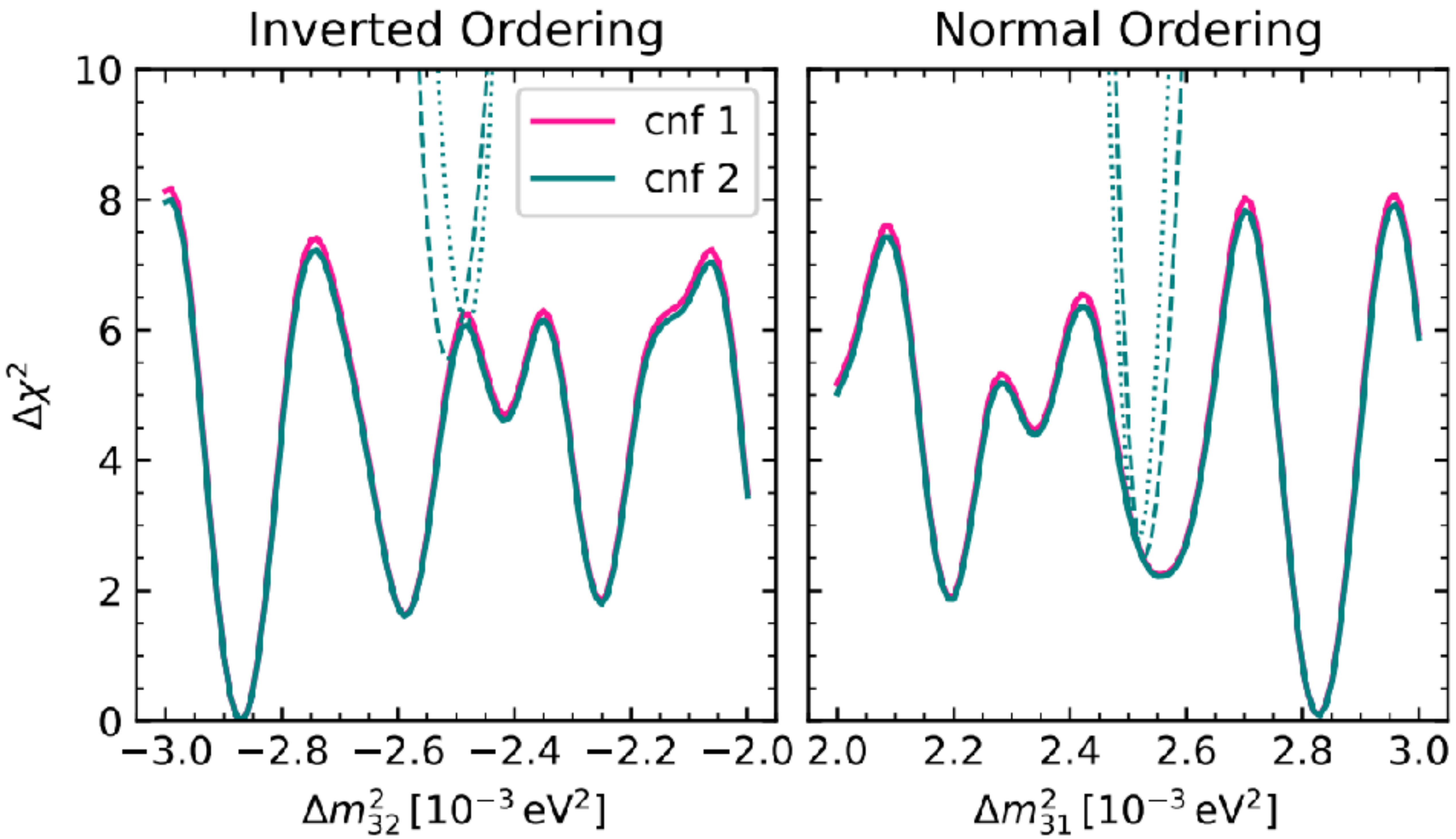


JUNO Coll. arXiv:2511.14593 — 59.1 days of data



Neutrino Mass Ordering

The power of global fits



I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni,
I. Martinez-Soler, J.P. Pinheiro, T. Schwetz
JHEP 04 (2026) 089

NuFIT 6.0

Input from atmospheric neutrinos, long-baseline, and reactors showed no strong preference.

"T2K and NOvA appearance data individually favor normal ordering, but are more consistent with each other for inverted ordering."

NuFIT 6.1 (inc. JUNO's first result)

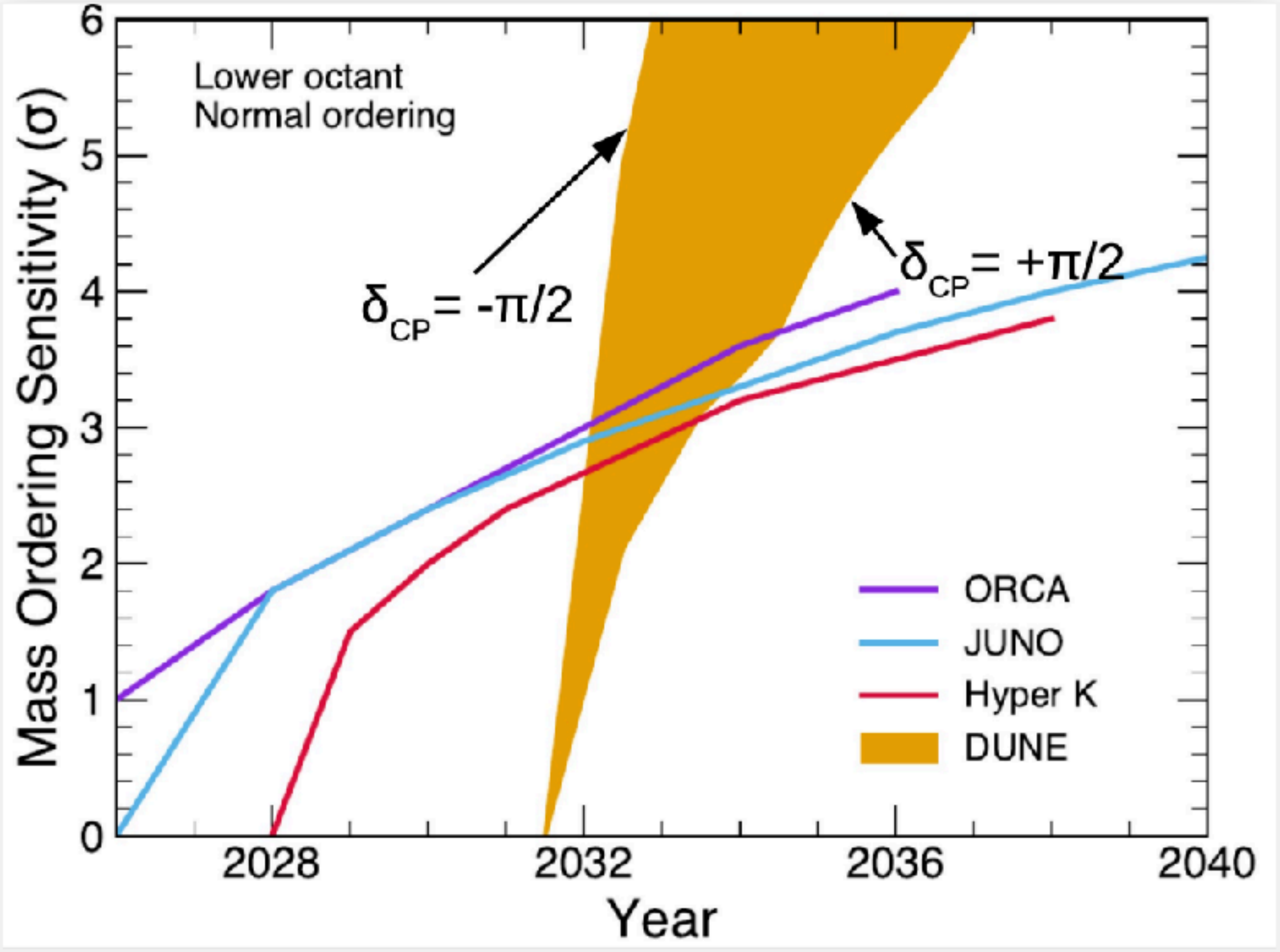
Combination of global data with JUNO amounts to $\gtrsim 2\sigma$ preference for NO.

I will be paying attention to (likely) updates from JUNO this summer.

Completing the 3-neutrino paradigm

Mass ordering

JUNO, atmospheric ν (IceCube/ORCA), HK, and DUNE (robustly).



CP violation in the lepton sector ($\delta_{\rm CP}$)

T2K and NOvA "hints"
HK and DUNE measurement.

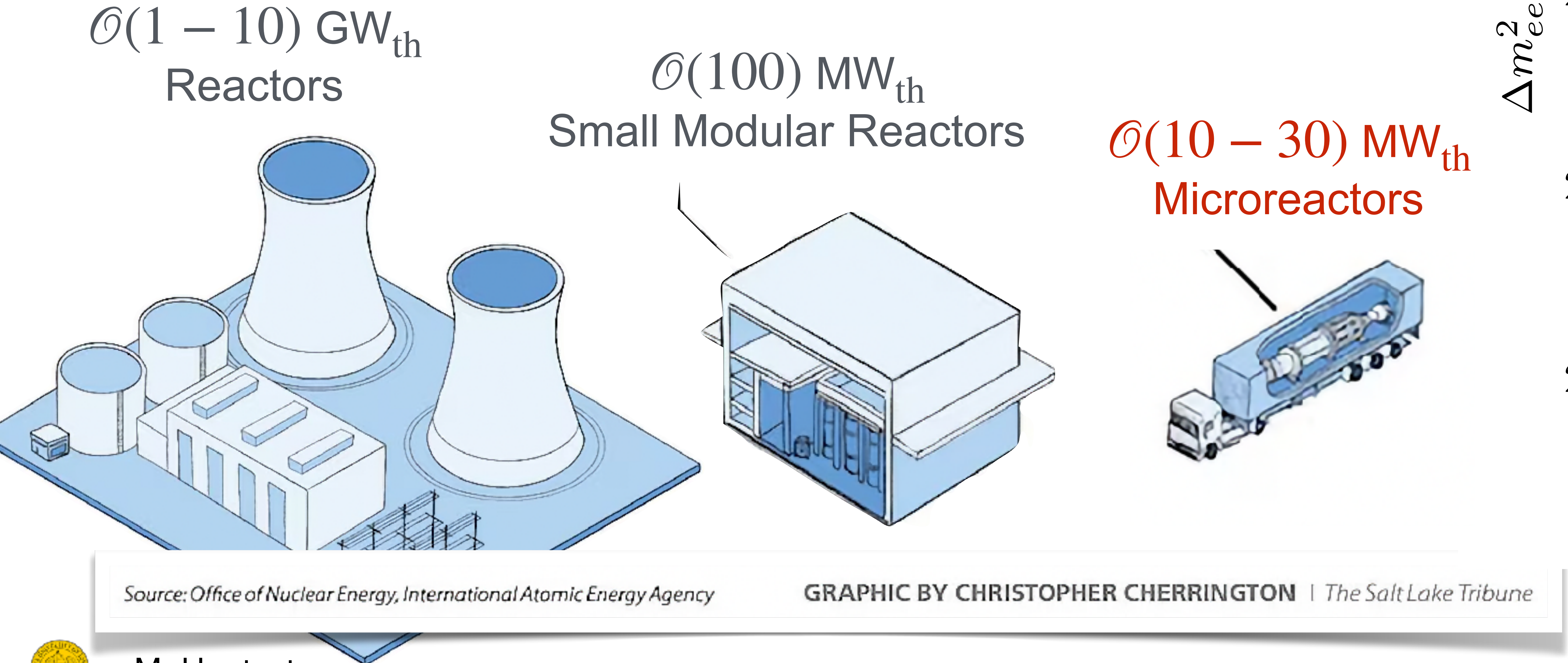
Neutrino masses:

Cosmology ($\sum m_\nu$) *vs* beta decay ($m_\beta = \sum_i |U_{ei}|^2 m_{\nu_i}$) *vs* $0\nu\beta\beta$ decay ($m_{\beta\beta}$).

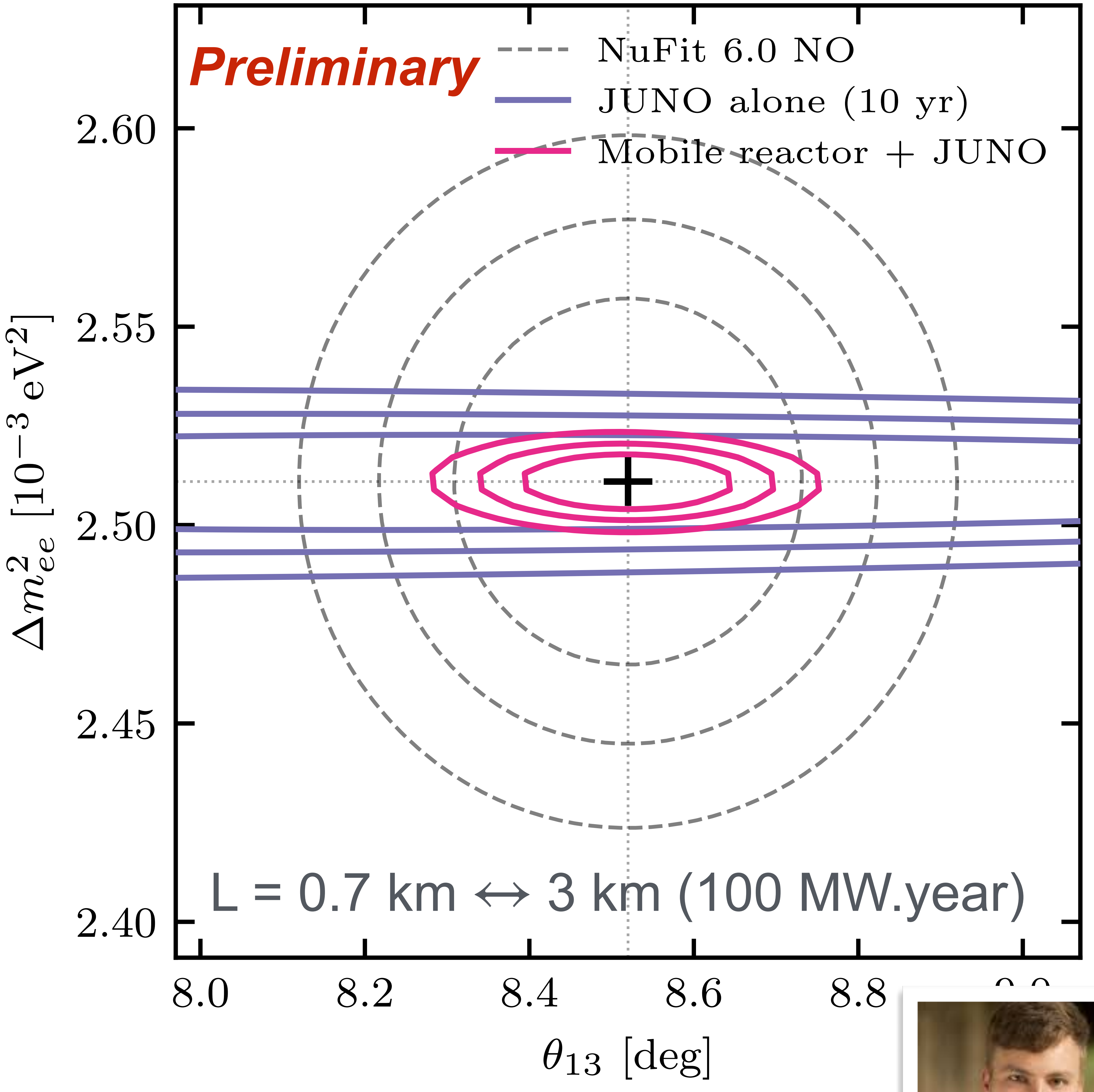
θ_{13} in a post mass-ordering era: movable reactors

Microreactors provide a movable neutrino source.
A few modules can get close to ~100 MW(th) power.

Bring it close to JUNO (or other large volume detector) for a post-mass-ordering program in mid/late 2030's?



Scan baselines for precision measurement of θ_{13} oscillations.



MH, Stephan Meighen-Berger, M. Pospelov (in preparation)

Things we should be ready for:

1) Every experiment **agrees** on oscillation parameters.

Things we should be ready for:

1) Every experiment **agrees** on oscillation parameters.

Case $\delta_{\rm CP} = 0$ or π $\implies$ CP conservation in oscillations.

CP violation **may** still be found through Majorana phases in $0\nu\beta\beta$:

$$m_{\beta\beta} = \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 \right|$$ though not guaranteed.

See also: A. De Gouvea, B. Kayser, R. Mohapatra, PRD 67 (2003) 053004.

Beyond ee sector, see, e.g., A. Dery, S. Gori, Y. Grossman, Z. Ligeti, JHEP 10 (2024) 100

Case $\delta_{CP} = \pi/2$ or $3\pi/2$ $\implies$ maximal CP violation in oscillations.

Yet another reminder that the flavor puzzle is hard.

Things we should be ready for:

1) Every experiment **agrees** on oscillation parameters.

2) Precision oscillation measurements **disagree**:

- Biggest room for disagreement: **mass ordering** or $\delta_{\rm CP}$.
- Beyond oscillations:
  - cosmology ($\sum m_\nu$) *vs* beta decay (m_β) *vs* $0\nu\beta\beta$ decay ($m_{\beta\beta}$).
  - other surprises: "new new physics"

What sort of surprises could there be?

New oscillation frequencies

Are the more neutrino states? Sterile neutrinos, quasi-Dirac neutrinos, etc

New matter potentials

Do neutrinos feel new forces? Do they interact with dark matter?

New particles

Can we stumble on the ν mass mechanism at low energies?

What about light dark matter or dark sectors?

None of it is guaranteed, but it sure would help guide the way forward.

The Ambiguity of Neutrino Masses

Neutrino masses

New scalar particles

Exotic Matter Potentials

ν_R exists

$$(\nu_L \quad \nu_R)\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

ν_L only

$$m_L = \frac{\langle h \rangle^2}{\Lambda}$$

Effective theory

Λ scale

Majorana ν

L violation

The Ambiguity of Neutrino Masses

Neutrino Masses (seesaw)

Interaction (flavor) basis

$$(\vec{\nu}_L \quad \vec{\nu}_R) \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix} \begin{pmatrix} \vec{\nu}_L \\ \vec{\nu}_R \end{pmatrix}$$

Diagonalize →

Mass (physical) states

$$(\vec{\nu} \quad \vec{N}) \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix} \begin{pmatrix} \vec{\nu} \\ \vec{N} \end{pmatrix}$$

As with most things in flavor, this is a matrix problem:

(3x3) **(3x?)** **(?x?)** **(?x3)**

$$M_\nu \sim M_D M_R^{-1} M_D^T$$

Except, we know nothing about the matrix M_R:

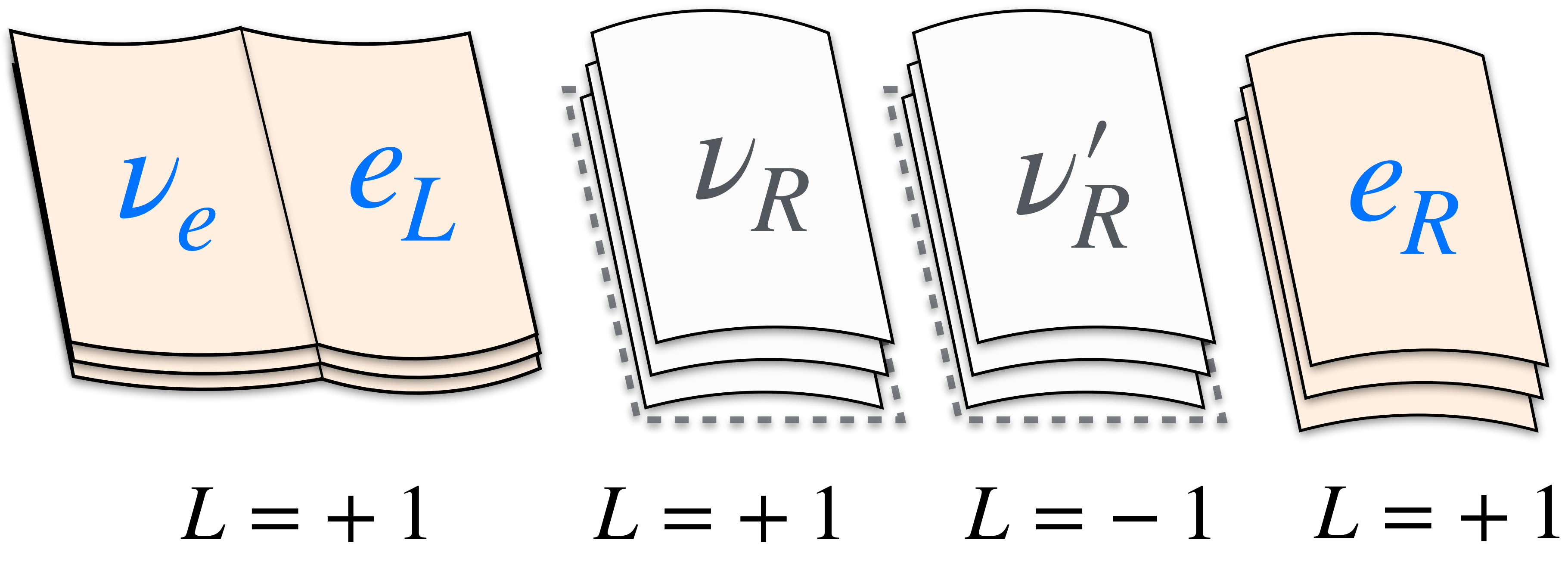
How many states? New symmetries? Interactions?

Neutrino Masses (the *inverse* seesaw)

Interaction (flavor) basis

$$\begin{pmatrix} \nu_L & \nu_R & \nu'_R \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \\ \nu'_R \end{pmatrix}$$

Now there are two kinds of RH neutrinos for a single ν_L



Single generation result:

$m_1 = \frac{m_D^2}{M^2} m_R$ (Majorana particle) and $m_{2,3} \sim M \pm \frac{m_R}{2}$ (quasi-Dirac pair).

1) Approximate conservation of Lepton Number suppresses neutrino masses

2) Heavy-neutrino mixing angles may be much larger than naive seesaw expectation.
(Testable!)

3+1 oscillations

Cosmo & β-decay

Decays in flight &
Rare meson decays

Colliders

m_N/GeV

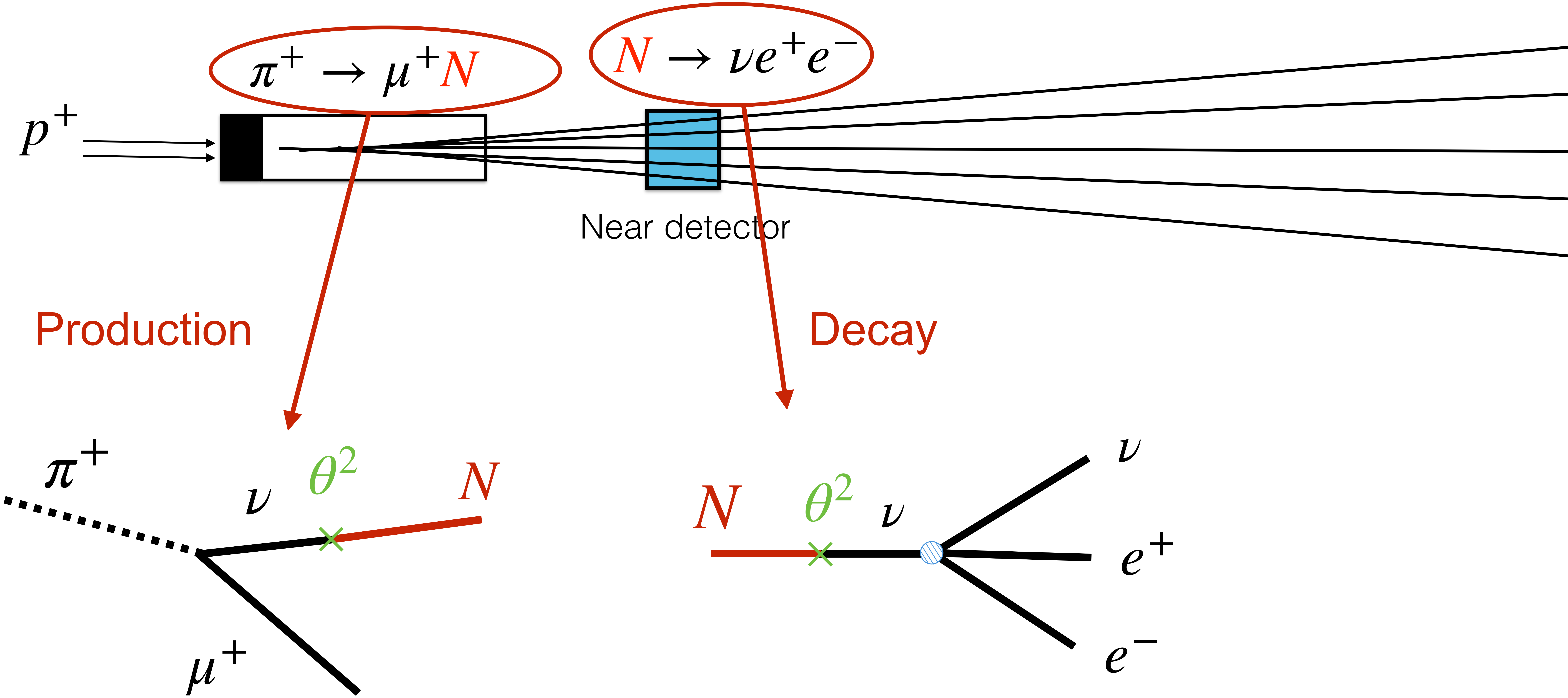
$0\nu\beta\beta$

LFV
(e.g., $\mu^- \to e^\pm$)

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

Accelerator Neutrino Experiments

Near detectors / short-baselines



Accelerator Neutrino Experiments

Near detectors / short-baselines

Beyond Low-Hanging Fruits

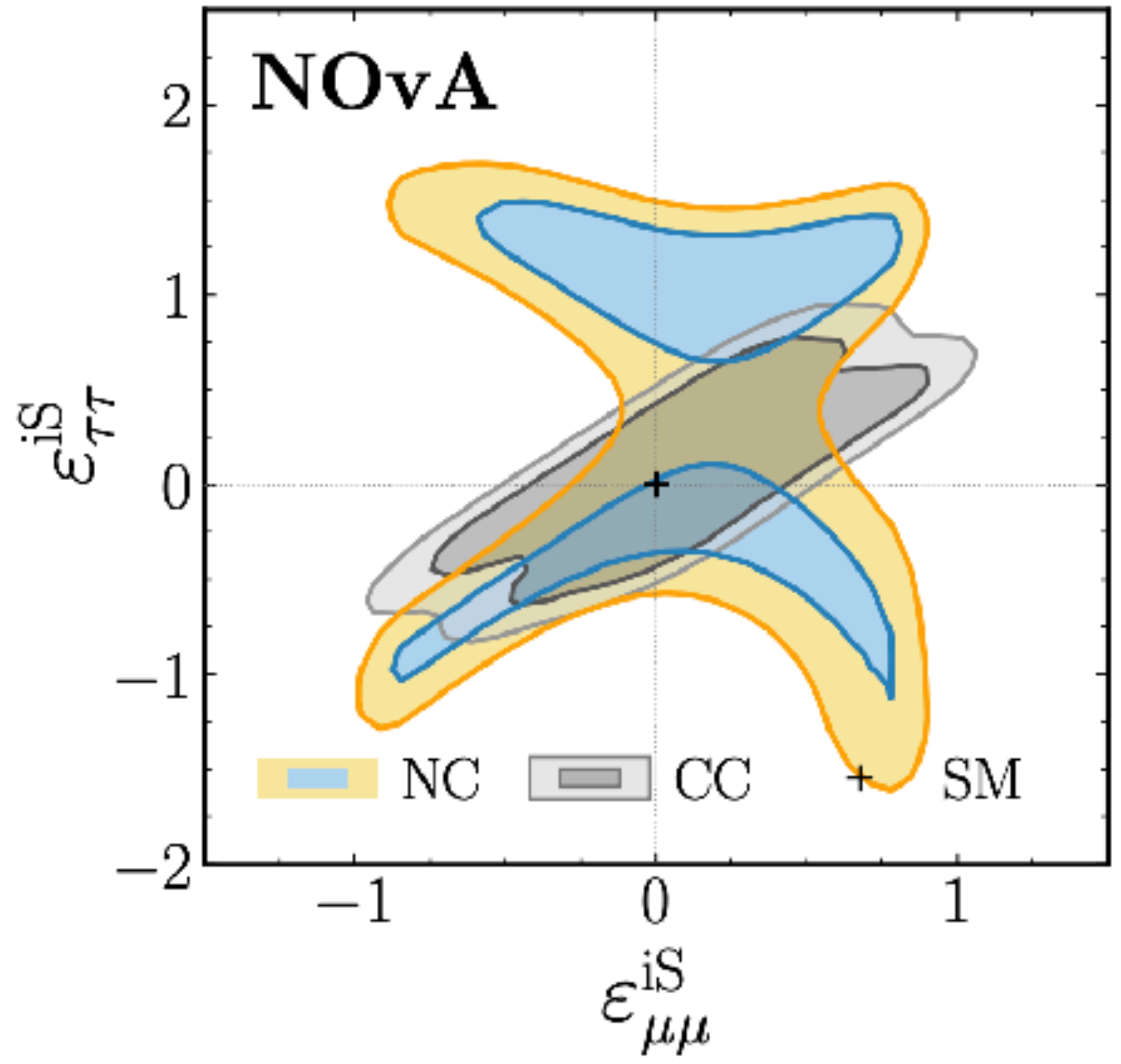
Leveraging New Generation of Neutrino Facilities

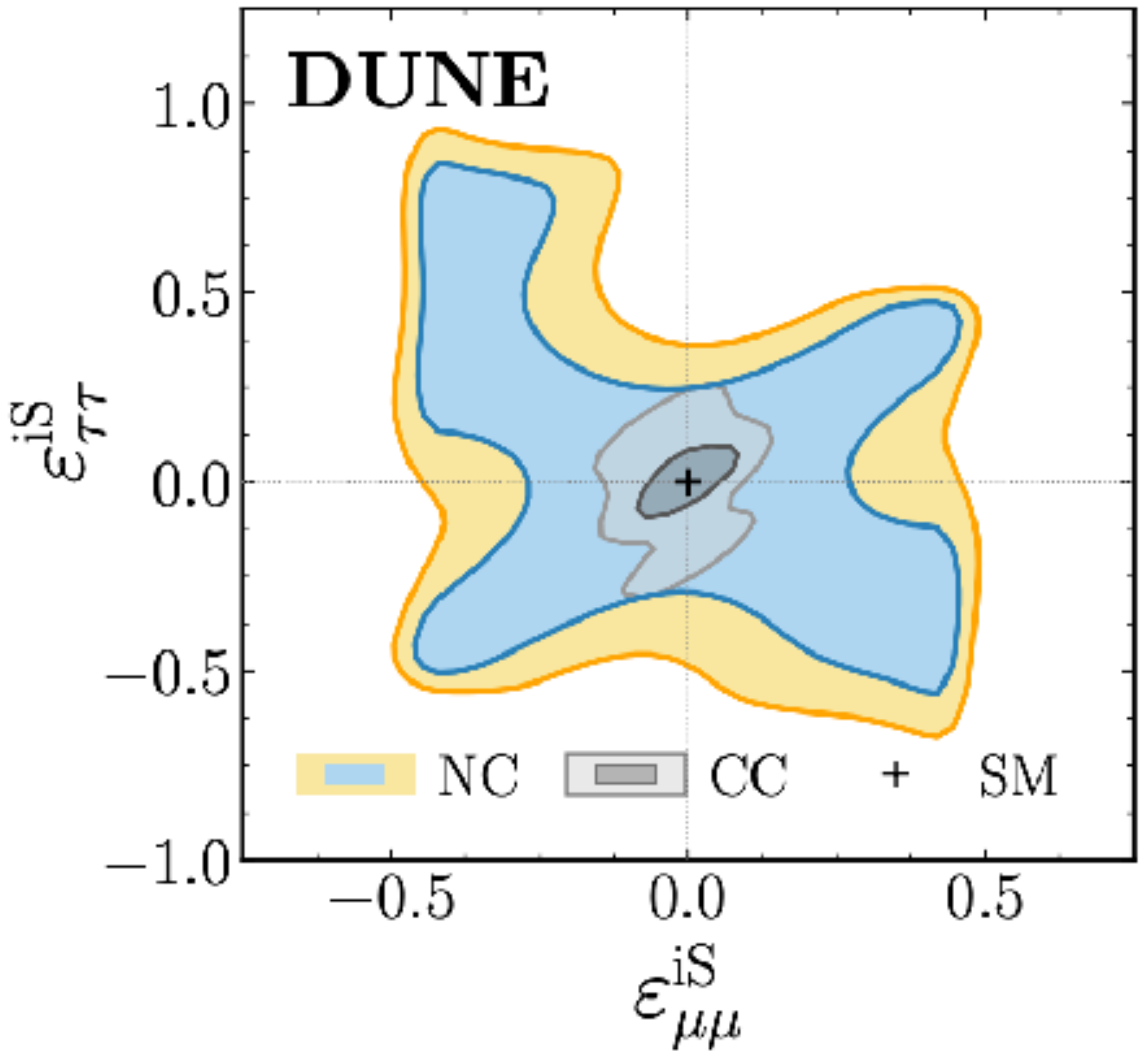
Non-Standard Interactions

Leveraging **CC + NC** sample at both **near** and **far** detectors.

J. Gehrlein, J. Hoefken Zink, P.A.N. Machado, J.P. Pinheiro
arXiv:2604.16176

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{f=u,d,e} \sum_{P=L,R} \varepsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_P f)$$

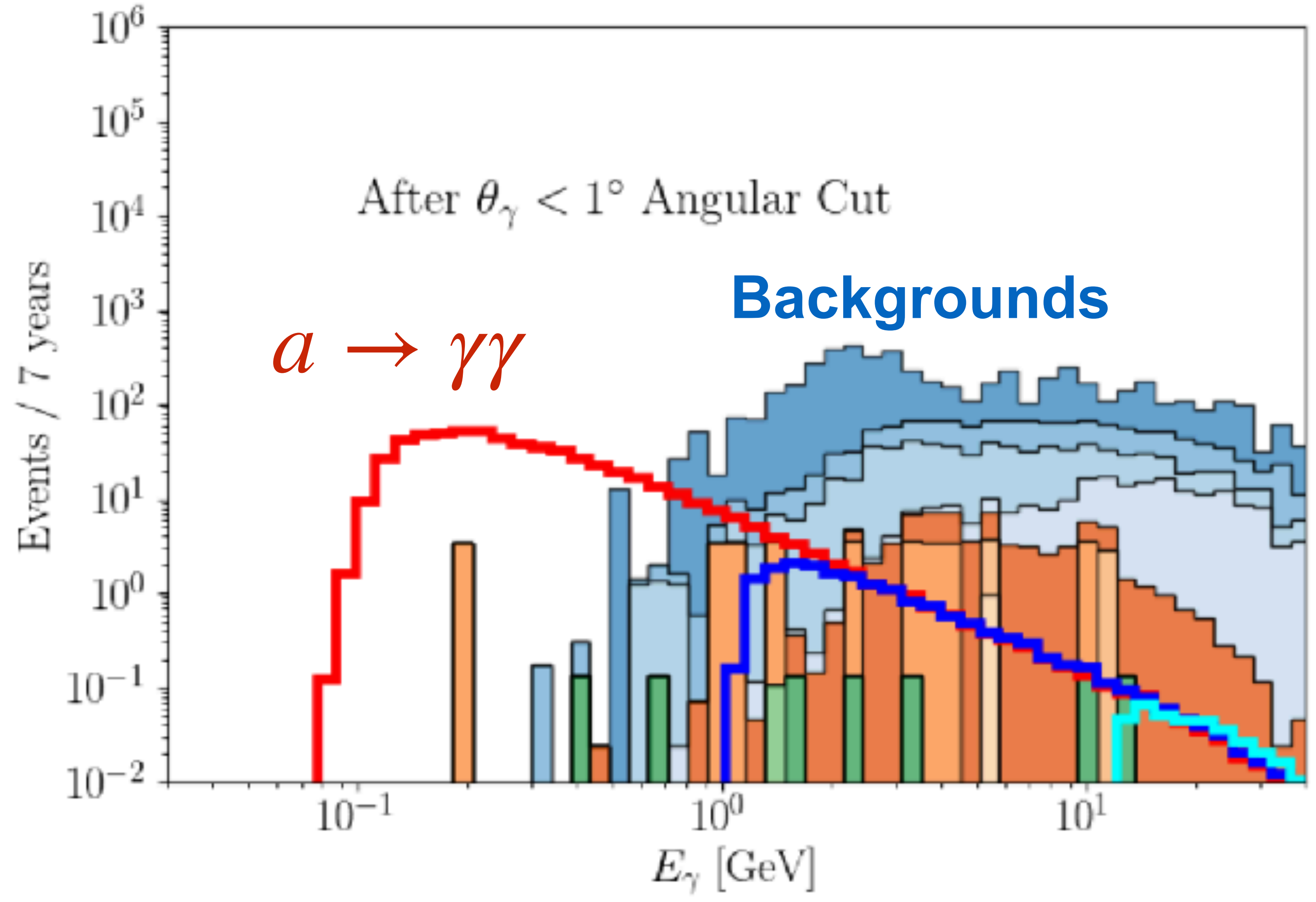




Decay of long-lived particles

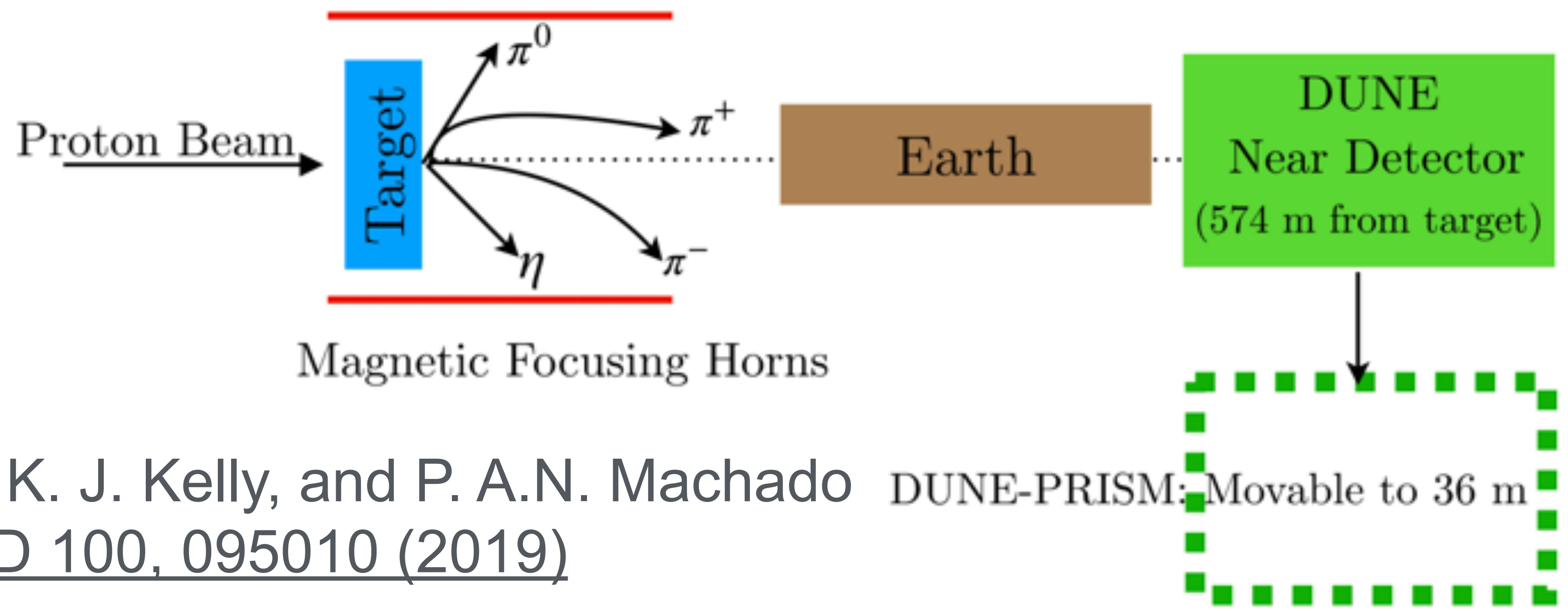
Leveraging PID

V. Brdar, B. Dutta, W. Jang, D. Kim, I. M. Shoemaker, Z. Tabrizi, A. Thompson, J. Yu, PRD 113, 035023, 2026



Light Dark Matter Scattering

Leveraging movable detectors

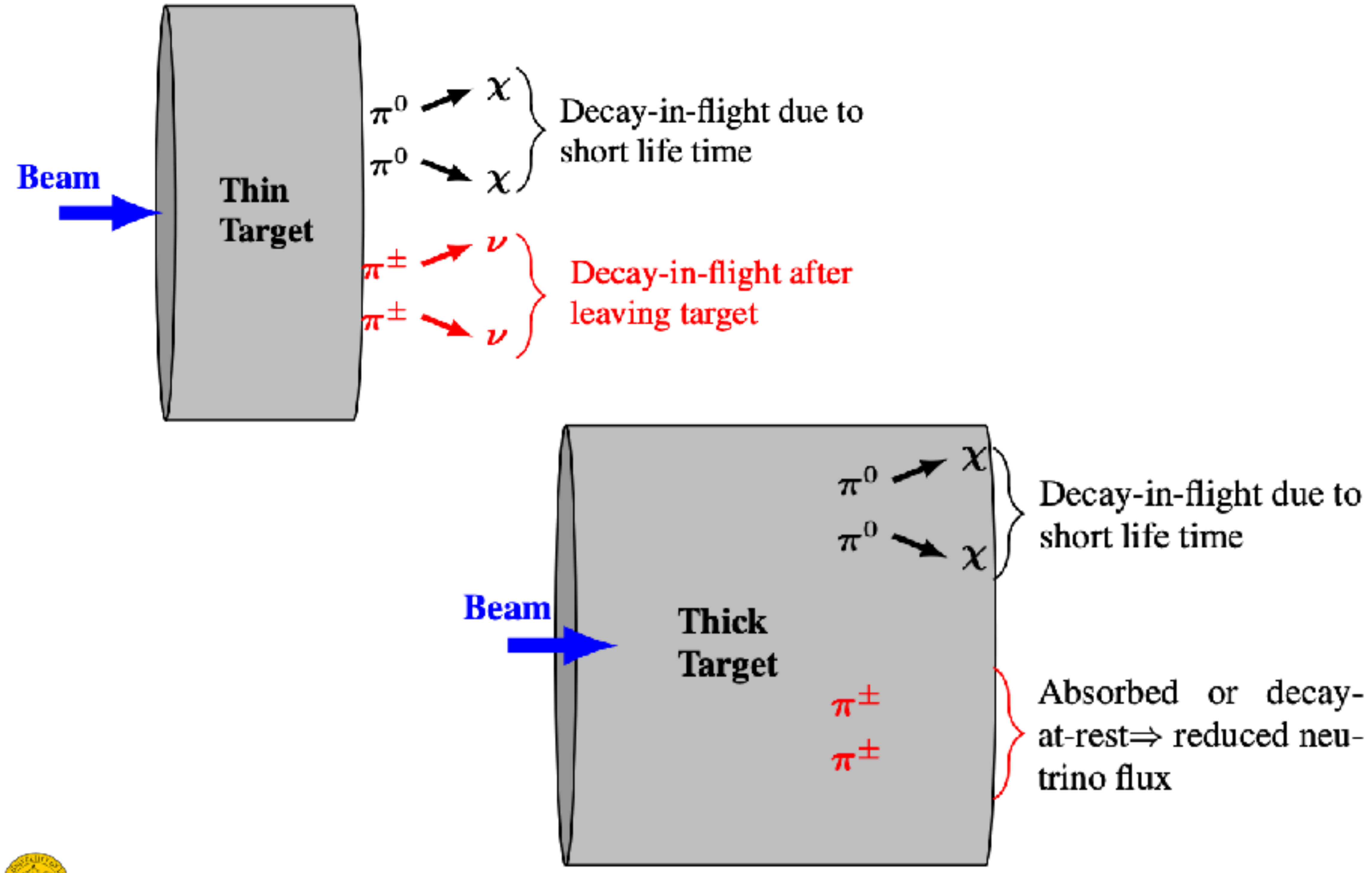


V. De Romeri, K. J. Kelly, and P. A.N. Machado
PRD 100, 095010 (2019)

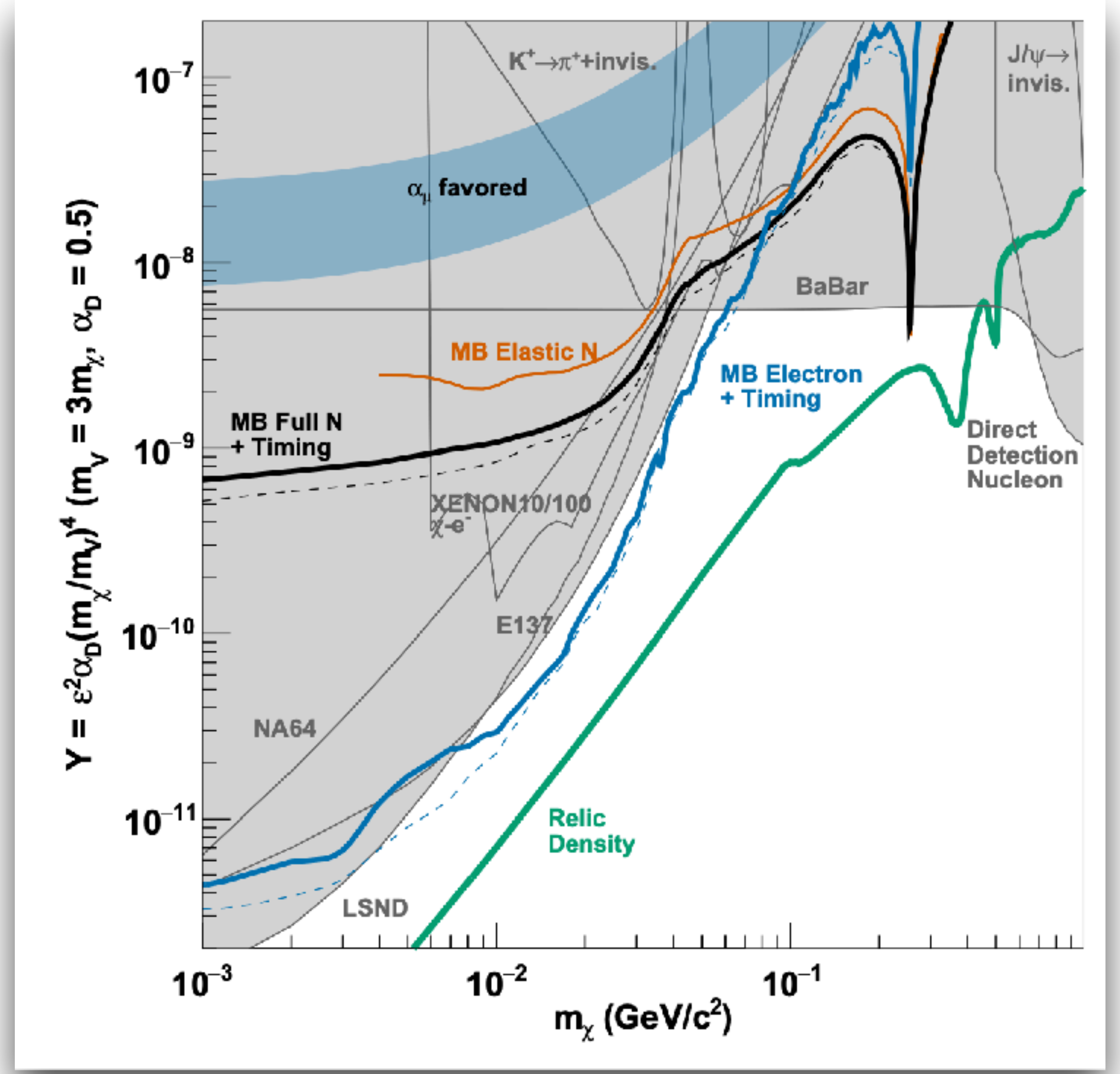
Boosting BSM opportunities

SBND and ICARUS will have huge # of interactions. Already seeing several neutrino results.

On-going discussions to run antineutrino or beam-dump mode (below).



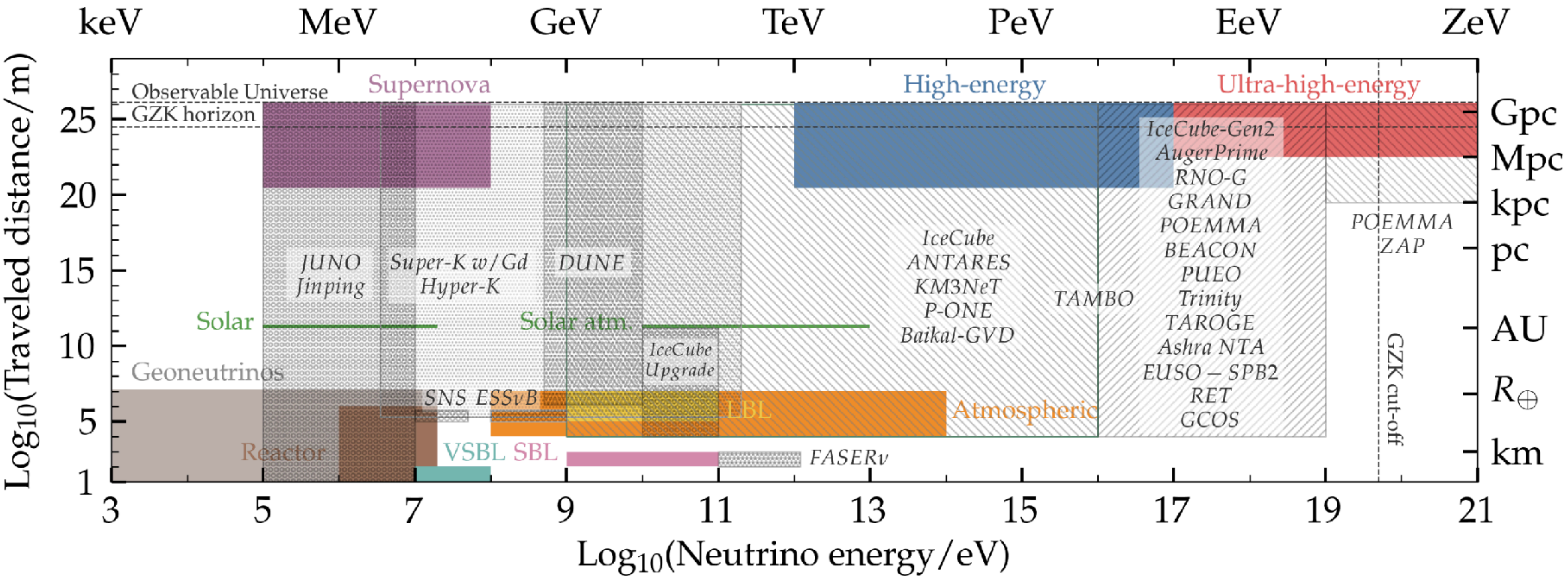
MiniBooNE-DM coll., PRD 98, 112004 (2018)



Off-target mode for SBND

B. Dutta, D. Goswami, A. Karthikeyan, V. Pandey, Z. Tabrizi, A. Thompson, R. G. Van de Water arXiv:2603.25818

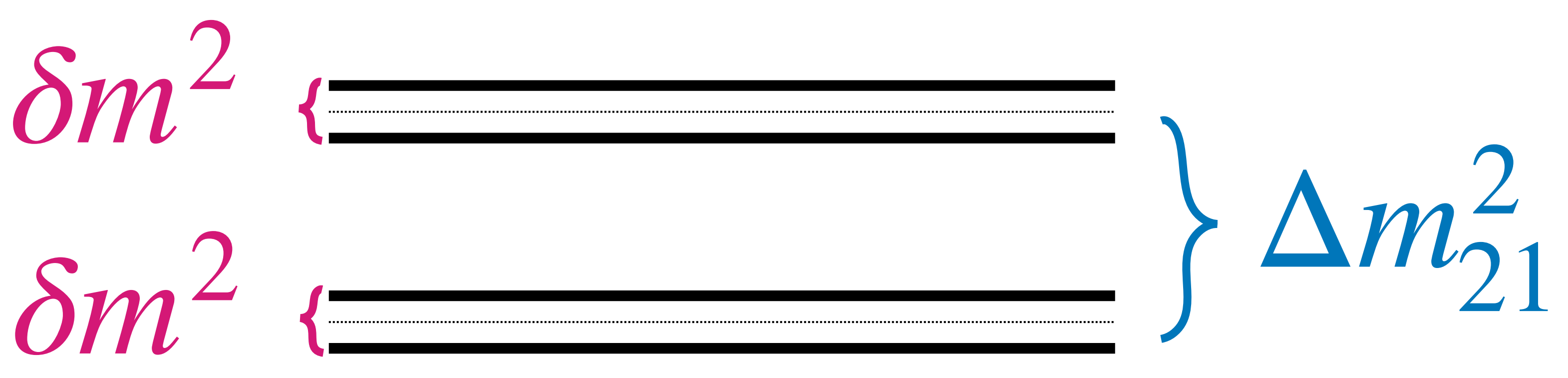
Ultra-long baseline propagation



$$e^{-i(E_1-E_2)t} \longrightarrow e^{-i\frac{\Delta m^2 t}{2E}} \times e^{-it\epsilon_{\text{new physics?}}}$$

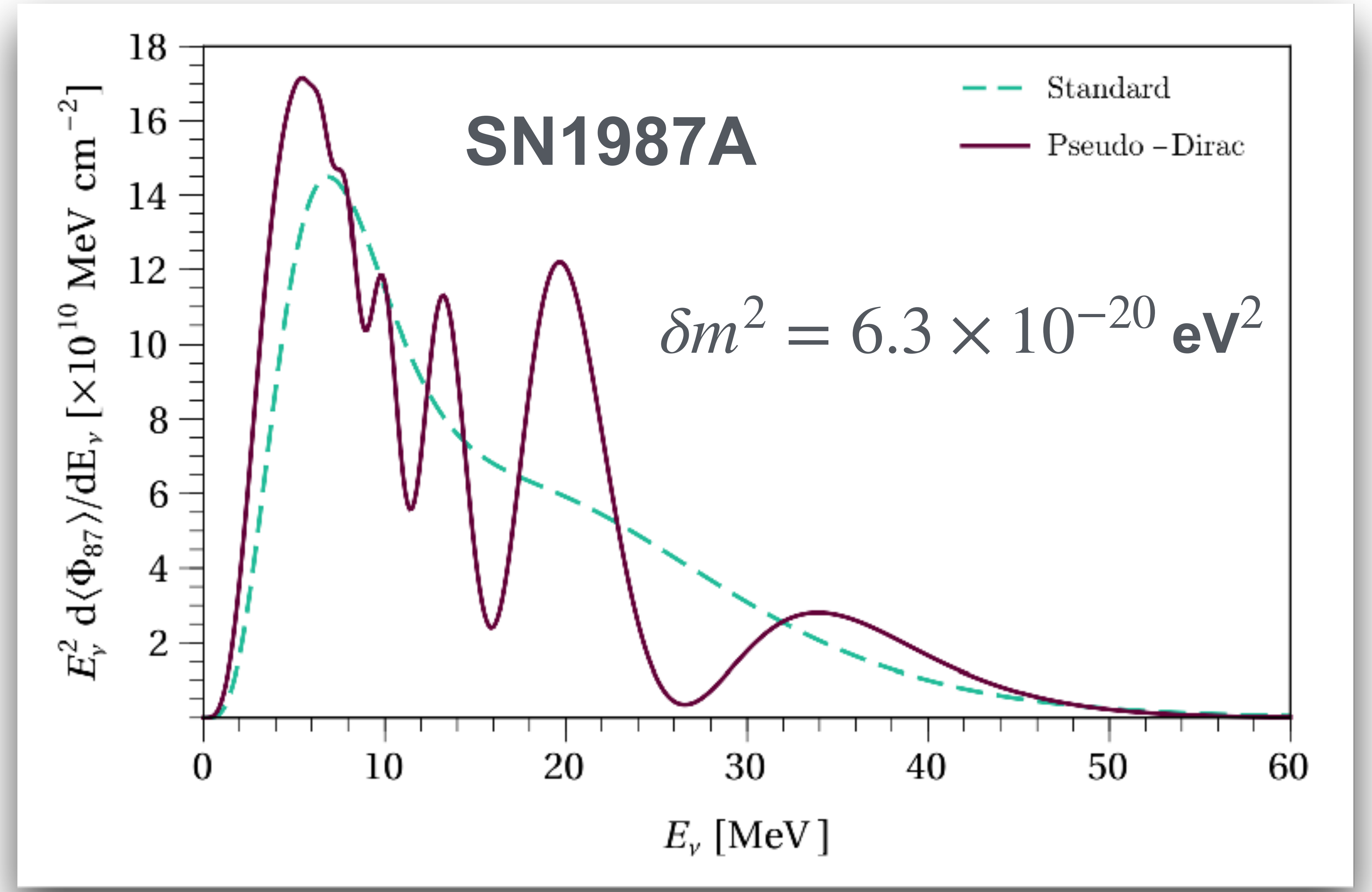
M. Hostert

Ultra-long Oscillation Frequencies

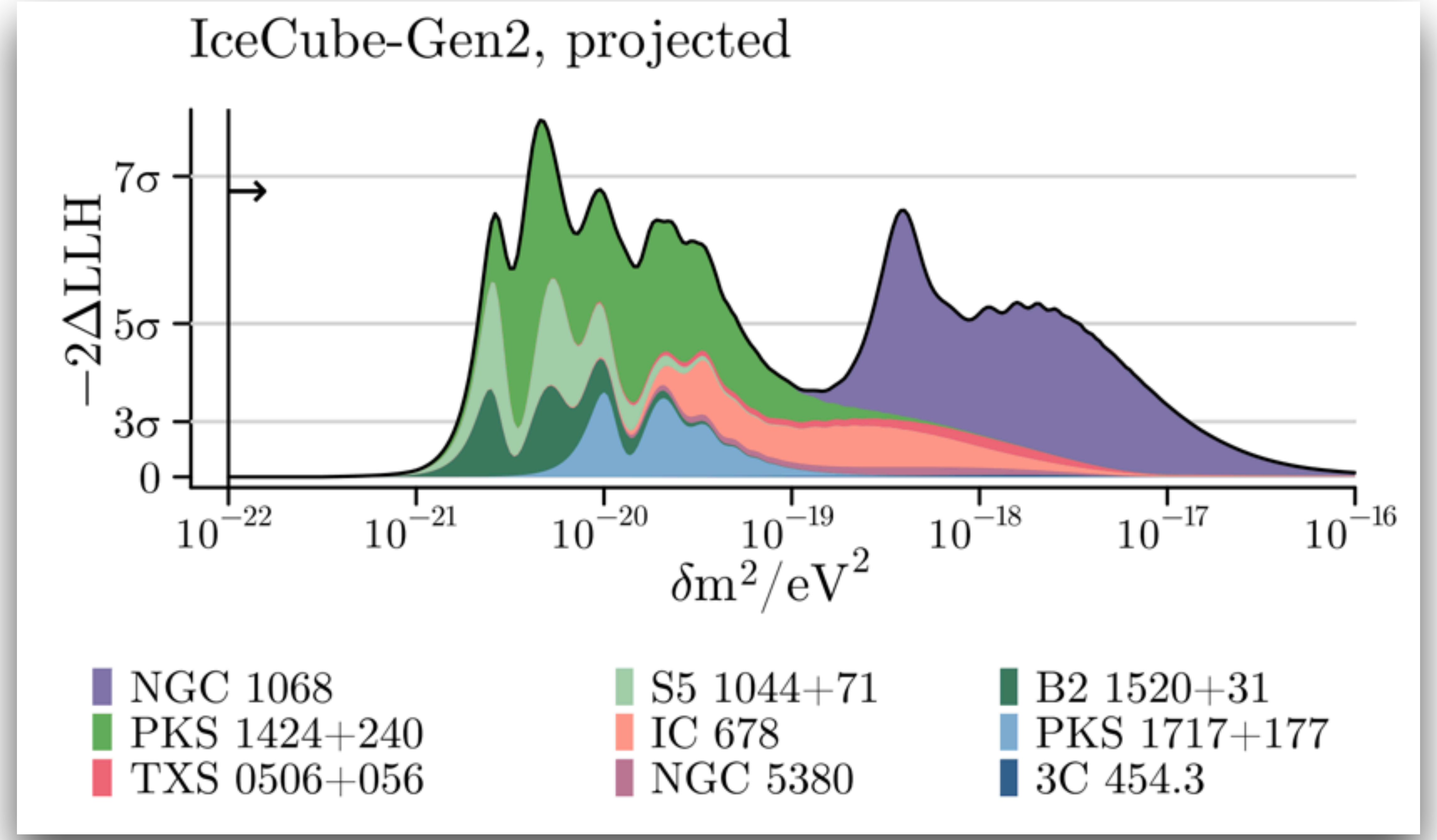


Quasi-Dirac (Pseudo-Dirac) neutrinos can oscillate between **active** and **sterile** states over long distances.

$$\delta m^2 \sim 2\, m_{\rm Dirac}\, \mu_{\rm Majorana}$$

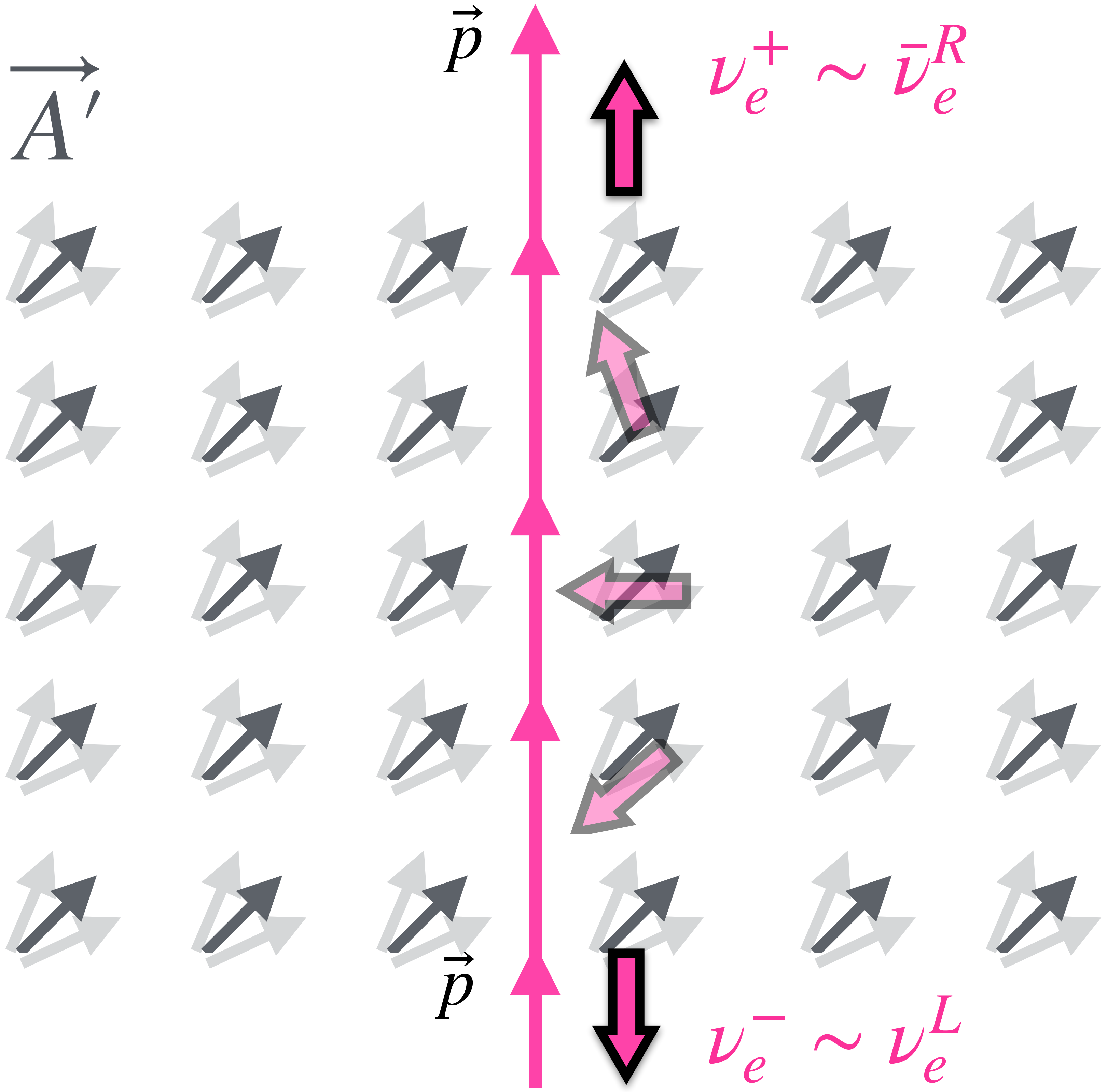


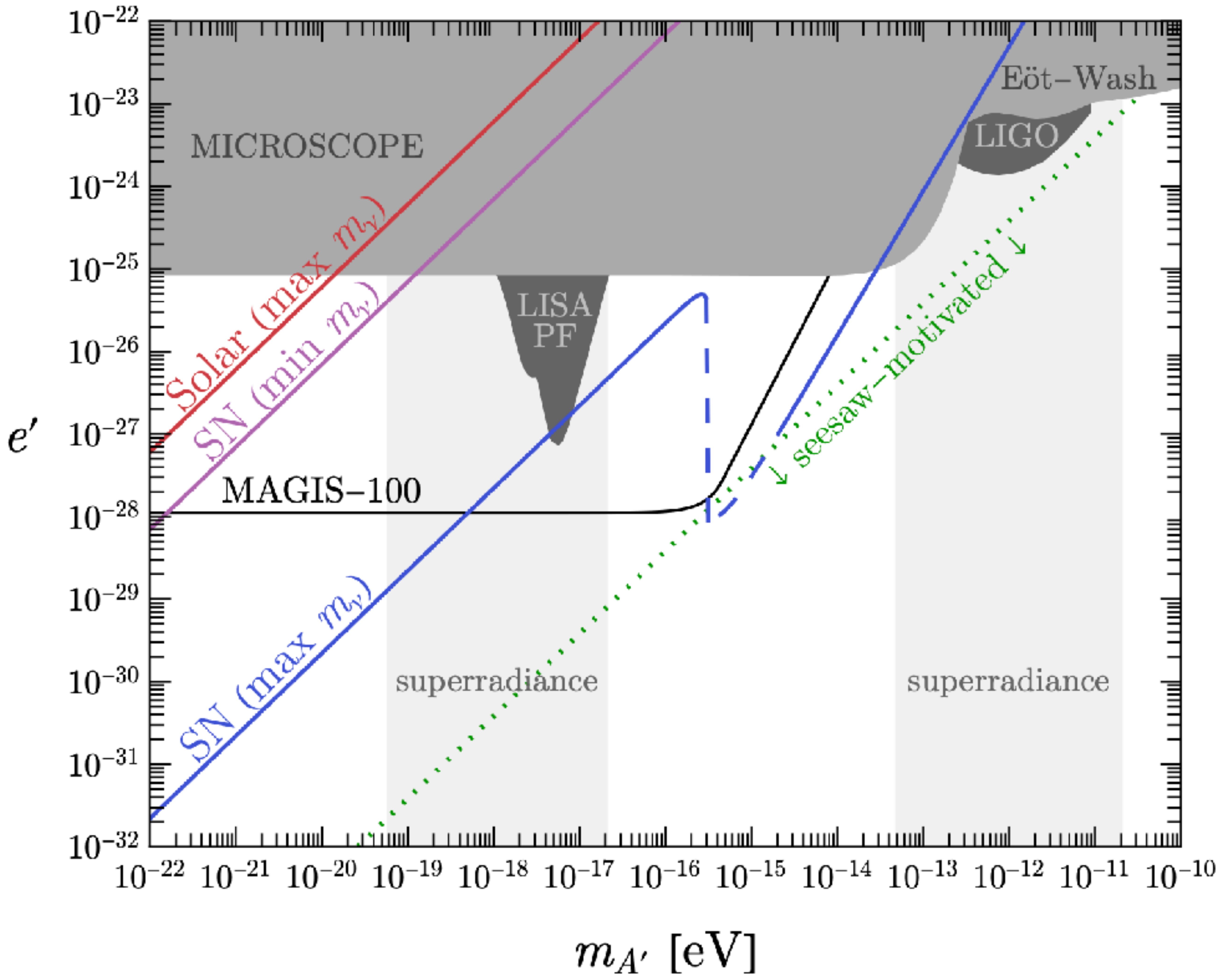
I. Martinez-Soler, Y. F. Perez-Gonzalez, M. Sen
PRD 105 (2022) 095019



K. Carloni, I. Martinez-Soler, C. A. Arguelles, K. S. Babu, P. S. Bhupal Dev
PRD. 109, L051702 (2024)

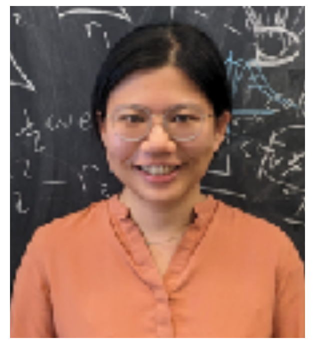
Spin Flip of Majorana Neutrinos in Ultra-Light Vector Dark Matter Background



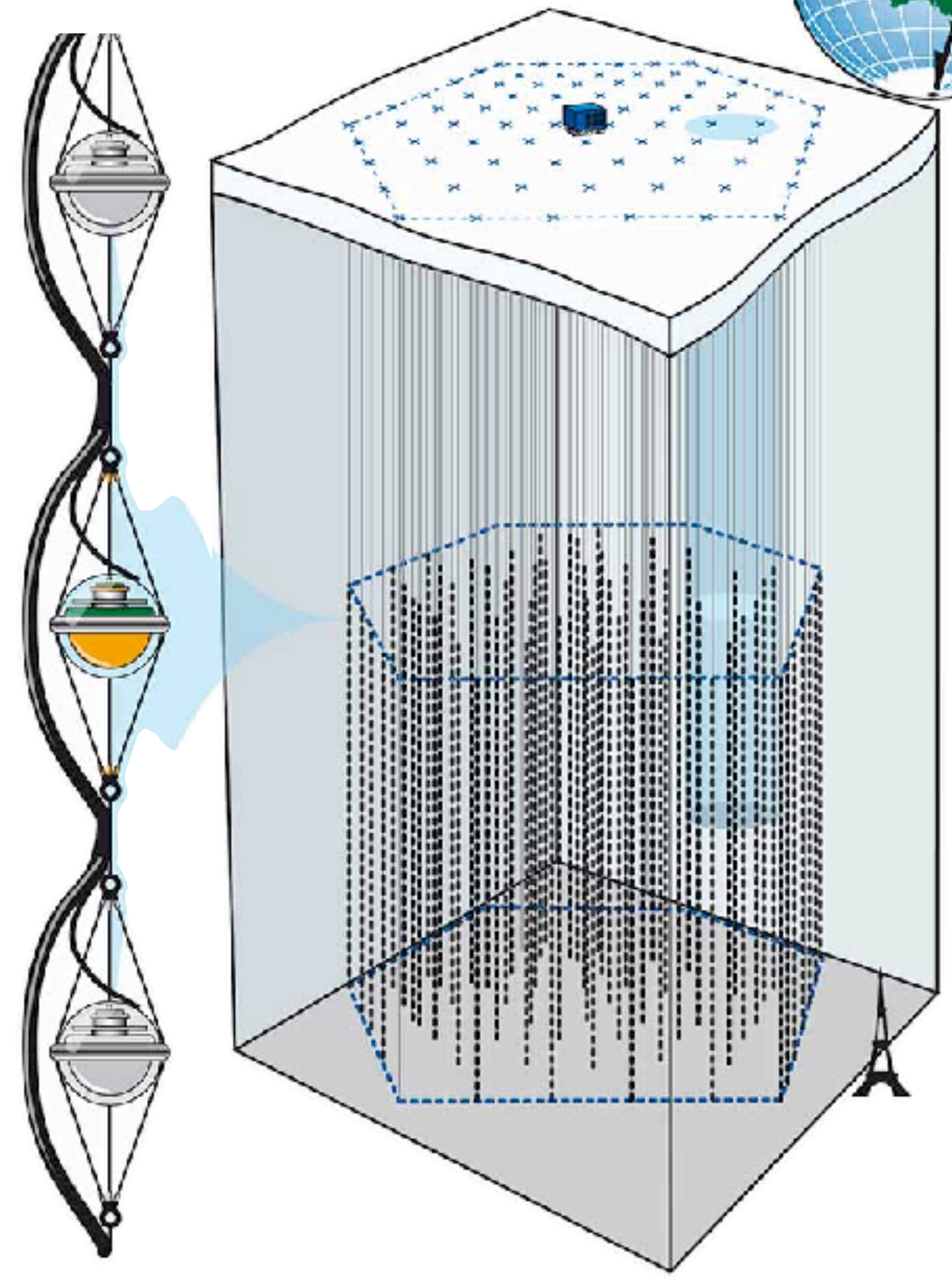


A. Berlin, R. Capdevilla, Ting Cheng (talk)
MH, P. Machado

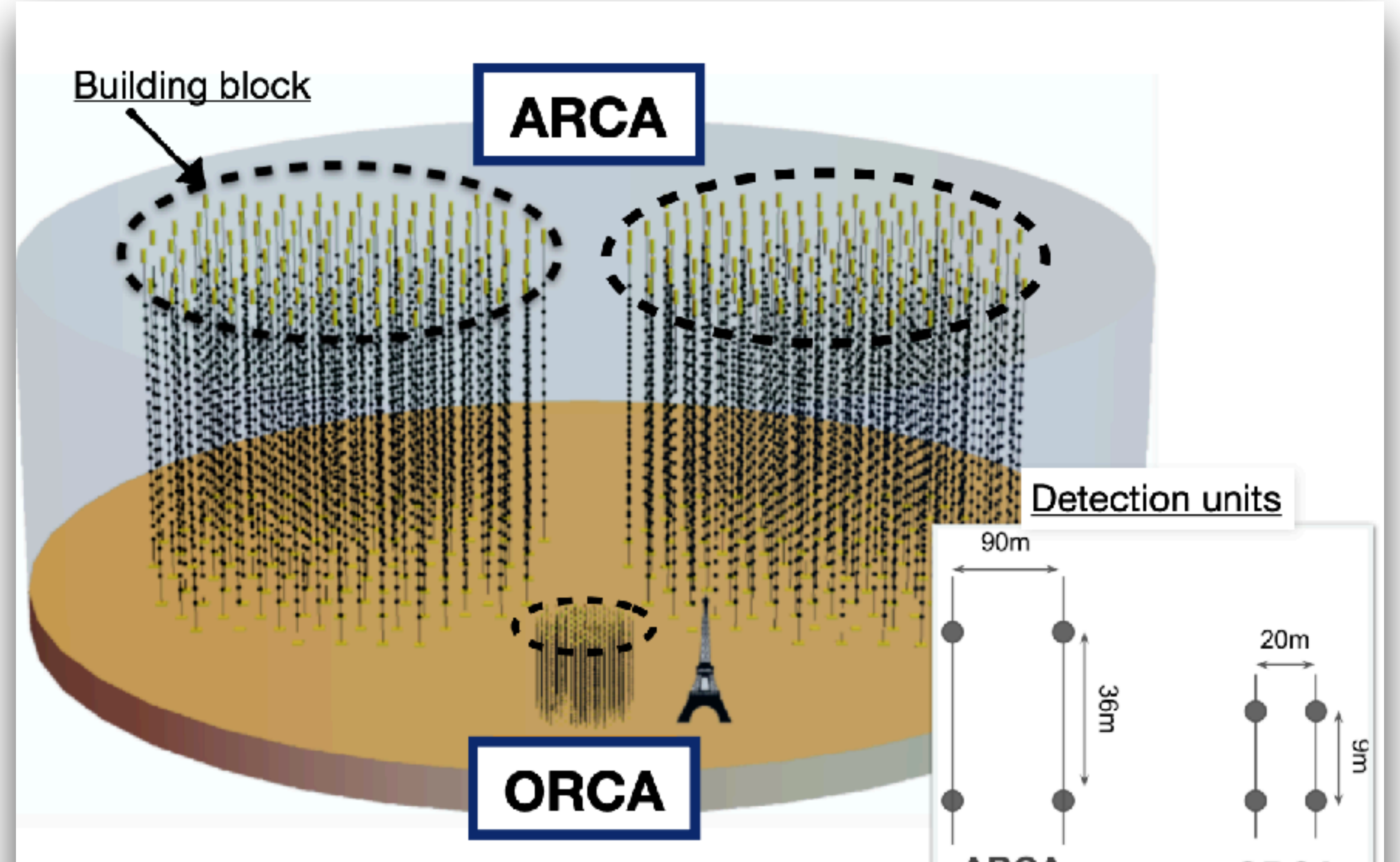





ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

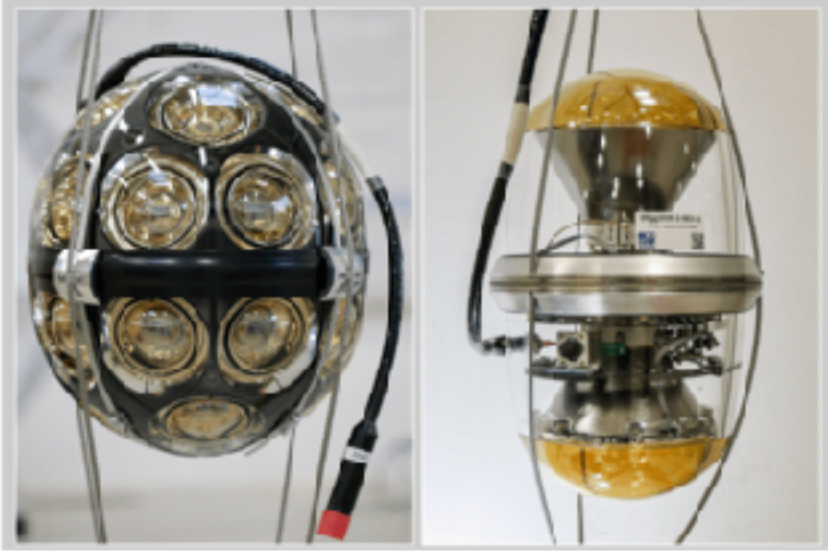


KM3NeT



From Meriem Bendahman, WIN 2025

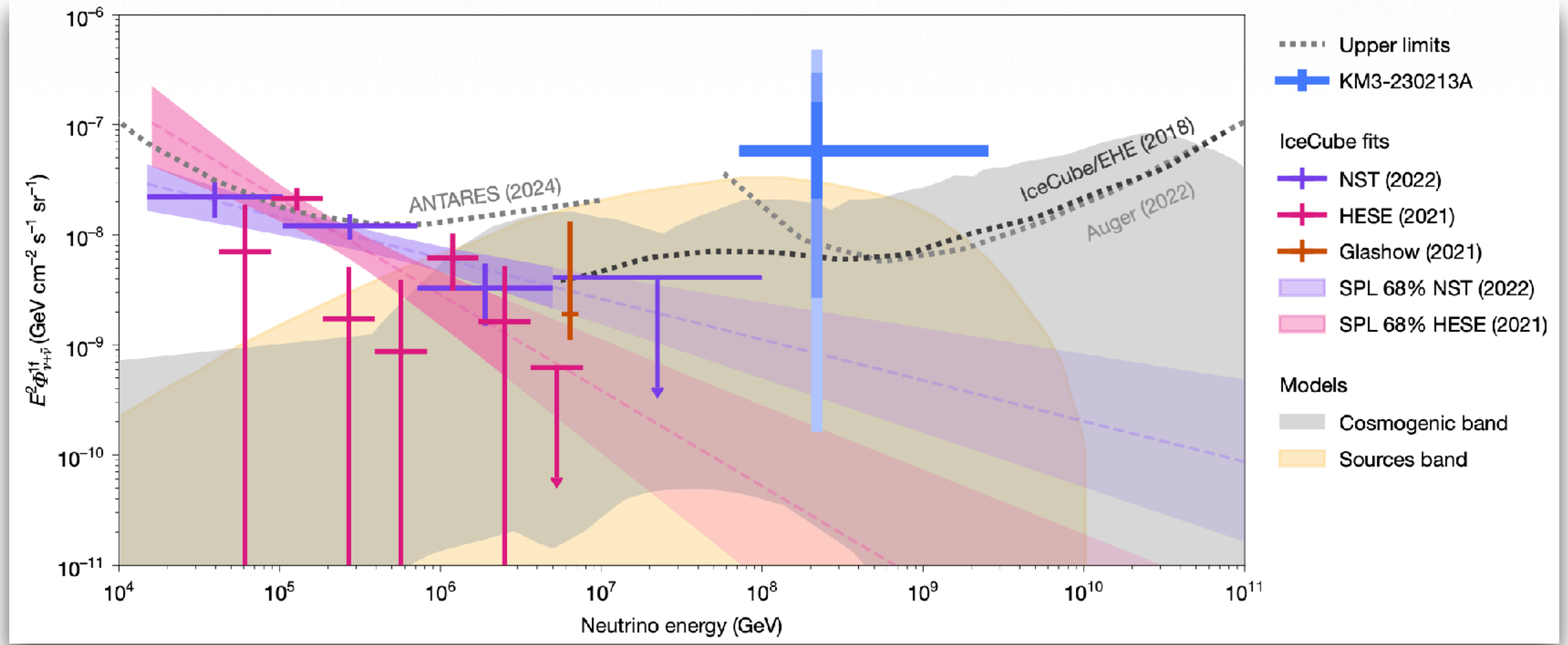
DOM (IceCube)



mDOM + D-Egg
(IceCube Upgrade +86 strings)

Multi-PMT DOM
(31 3' PMTs each)

The Highest Energy Neutrino Event Ever?



KM3NeT, Nature 638, 376–382 (2025)
Observation of an ultra-high-energy cosmic neutrino with KM3NeT

The Highest Energy Neutrino Event Ever? But not seen by IceCube?

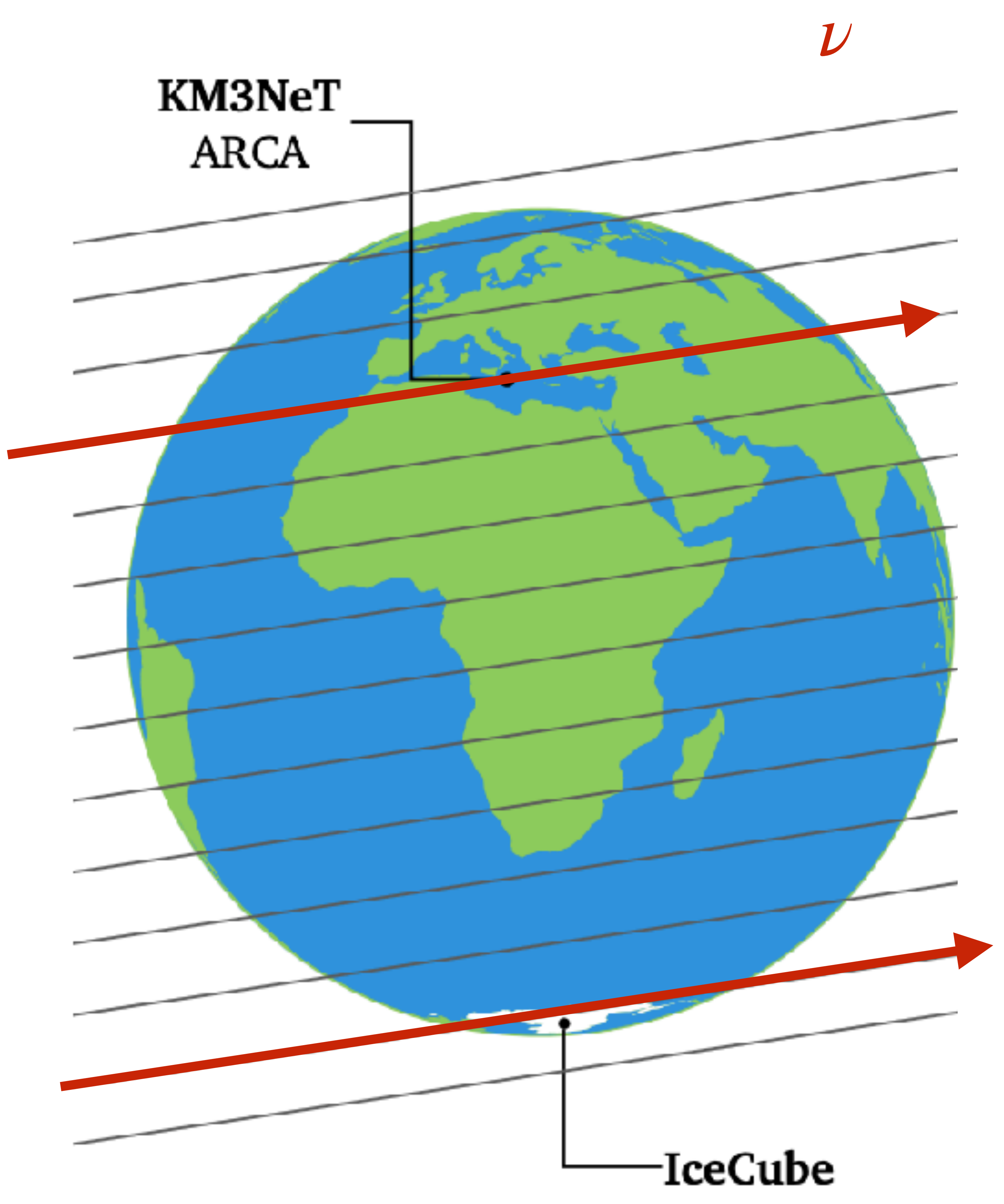
“**Power-law diffuse flux; cosmogenic origins; and point sources**, […] the tension is found to be between 2.9σ **and** 3.6σ.”
“Only a **transient source** would reduce this tension to 2.0σ”

S. W. Li, P. Machado, D. Naredo-Tuero, T. Schwemberger, PLB 875 (2026) 140293

“In all cases, the observed tension between KM3NeT and other datasets is of the order of $2.5\sigma - 3.0\sigma$”

KM3NeT collaboration, PRX 15 (2025) 3, 031016

See also T. Yuan, L. Lu, HiHEP 1 (2025) 2, 19.



Just how lucky was KM3NeT? Statistics or New Physics?

Several hypotheses put forward (>250 citations in just over 1 year)

No obvious point source candidate identified. No diffuse flux explains tension.

May turn out to be just Poisson statistics, but it hasn't stopped us from entertaining new physics.
(Or unidentified backgrounds. Background explanation is very unlikely, but so is the signal…)

Ultra-High-Energy Neutrinos from Primordial Black Holes

Alexandra P. Klipfel[1,*] and David I. Kaiser[1,†]

Evaporation of 10^{15} gram PBH about $\mathcal{O}(10^{-5})$ pc away.

Could a Primordial Black Hole Explosion Explain the extremely high-energy KM3NeT neutrino Event?

Lua F. T. Airoldi,[1,*] Gustavo F. S. Alves,[1,†] Yuber F. Perez-Gonzalez,[2,‡] Gabriel M. Salla,[1,§] and Renata Zukanovich Funchal[1,¶]

Unlikely that such PBHs would have gone undetected in the hours prior to the final "explosion"/evaporation.

Transient sources of dark particles?

V. Brdar, D. S. Chattopadhyay,
PRL 136 (2026) 8, 081001

P. S. Bhupal Dev, B. Dutta, A. Karthikeyan, W. Maitra,
L. E. Strigari, and A. Verma, arXiv:2505.22754

Y. Farzan, MH, JHEP 10 (2025) 208

Ultra-heavy DM? Exotic cosmic ray physics?...

Parting Words

The SM may be incomplete already at low energies.
Neutrino masses are a crucial piece of the puzzle: **we should study them.**

We are **overconstraining the neutrino sector** over the next decade.
Surprises are not out of the question.

Neutrino facilities cast a wide net on new physics, from **ultra-light** to **ultra-heavy dark matter**, new **mass mechanisms**, and a range of **lamppost dark sectors**.

The KM3NeT event is a great reminder that unlikely events can happen.
With this new stream of data, are phenomenologists ready?

Thank you