Neutrinos

Lecture 3

TRISEP 2024 Summer School

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McGill University
July 8, 2024

Outline

Lecture 1:
Historical overview –
What we know

- Birth and discovery of neutrinos
- Neutrino sources
- Wu and Goldhaber experiment
- Solar neutrino problem
- Neutrino oscillations

Lecture 2:
What we would like to know

- Neutrino mass measurements
  - KATRIN
  - PROJECT 8
- ~~Sterile neutrinos~~

Lecture 3

- Sterile neutrinos

Neutrinos as messengers –
What we can learn from studying neutrinos

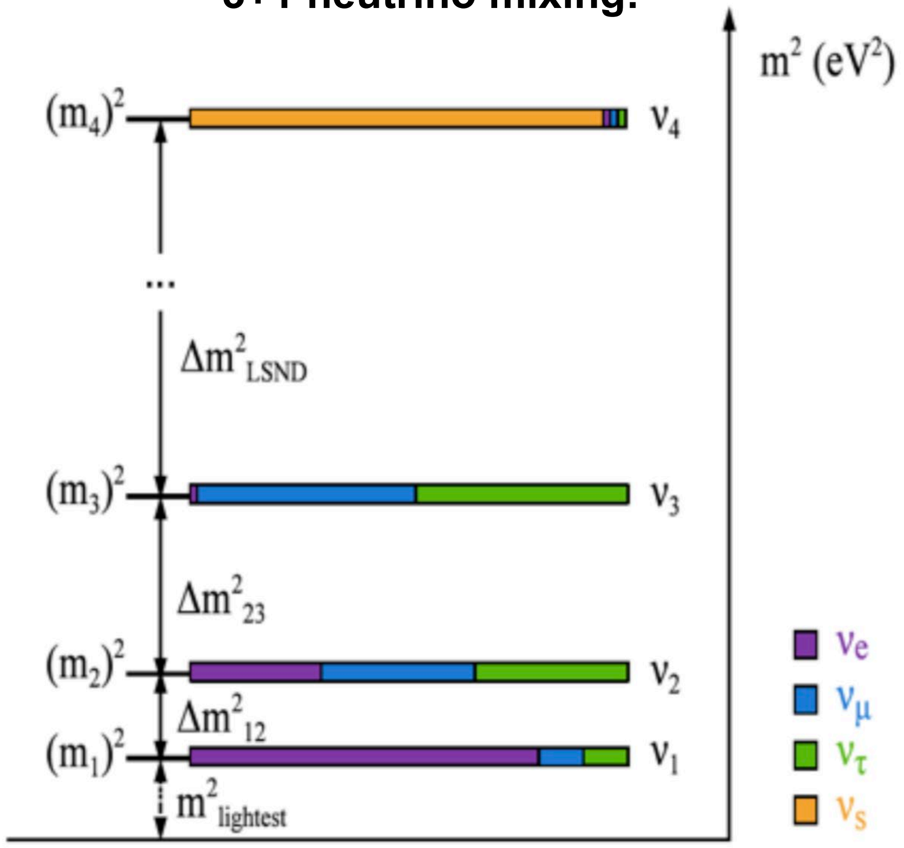
- Neutrinos as messenger particles in astrophysics

Search for Heavy (Mostly Sterile) Neutrino Mass States

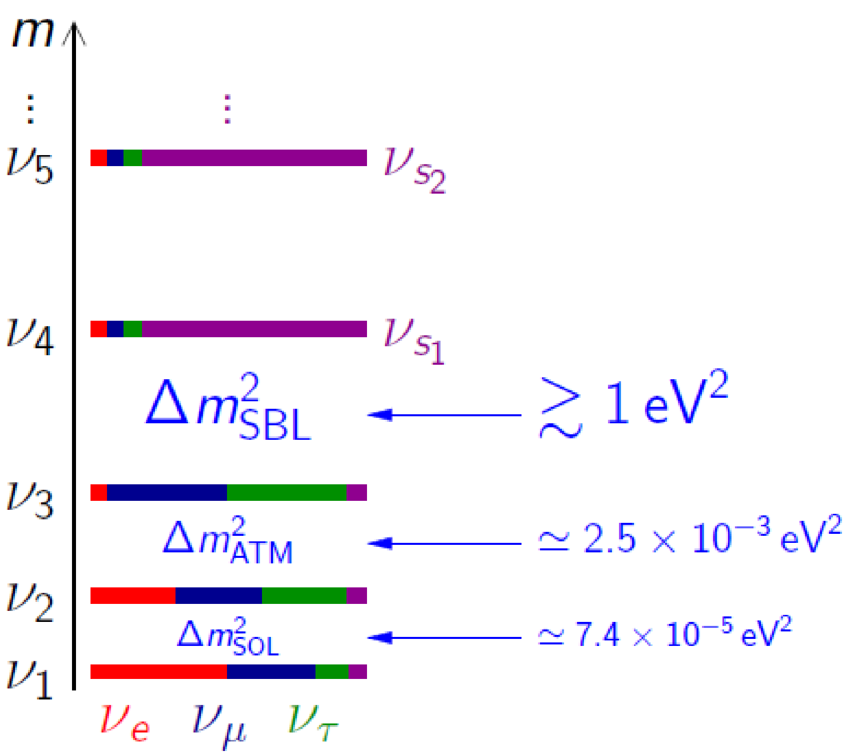
Sterile νs

- Potential explanation for the short baseline data is a small mixing with a light (~eV scale) sterile ν
  - Or maybe 2 more sterile νs are needed to fit the data? (or *n* more?)
  - Sterile neutrinos do not interact weakly

3+1 neutrino mixing:



3+*n* (*n*=2?) neutrino mixing:



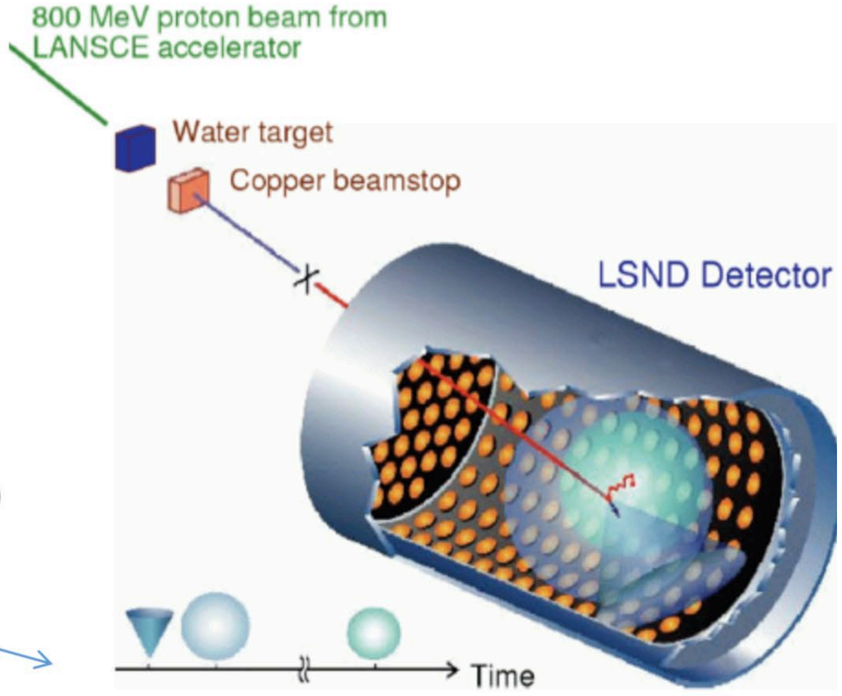
LSND

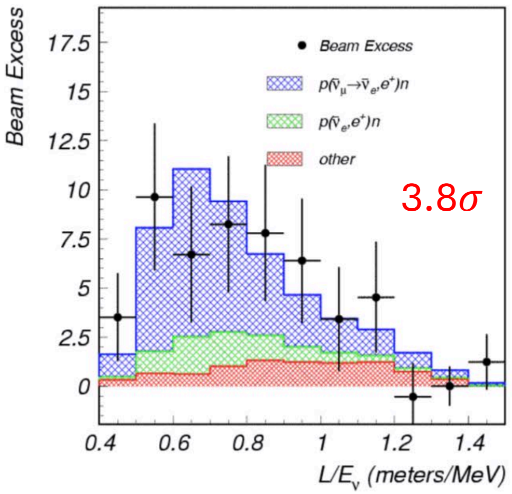
- LSND (Liquid Scintillator Neutrino Detector) operated at Los Alamos in the late 1990s

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\quad\quad \overset{?}{\hookrightarrow} \bar{\nu}_e$$

$\bar{\nu}_e$ appearance

$\bar{\nu} + p \to e^+ n \qquad n + p \to d + \gamma(2.2\text{MeV})$





Observed $87.9 \pm 22.4 \pm 6.0$ events
above background
Oscillation Probability: 0.26%

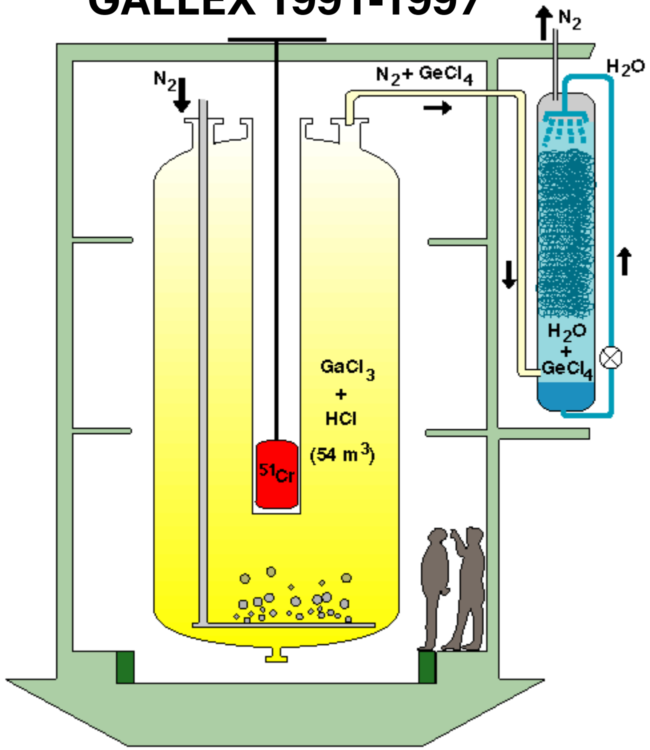
Consistent with a Δm^2 on the order of 1 eV^2
(not consistent with 3 flavor picture)

Gallium anomaly

- Solar nu detectors looking for ν_e capture used specialized EC sources inserted within the detectors (e.g. ^{51}Cr)

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- \qquad \text{(Threshold 0.233 MeV)}$$

GALLEX 1991-1997

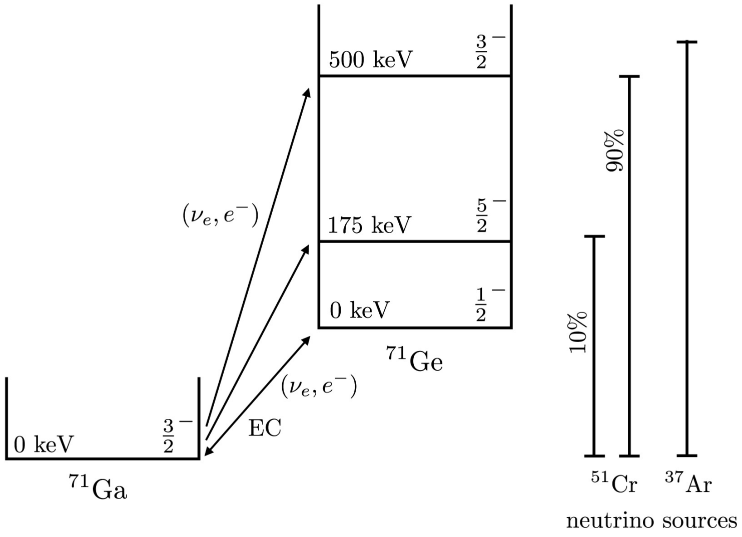


https://lappweb.in2p3.fr/neutrinos/anexp.html

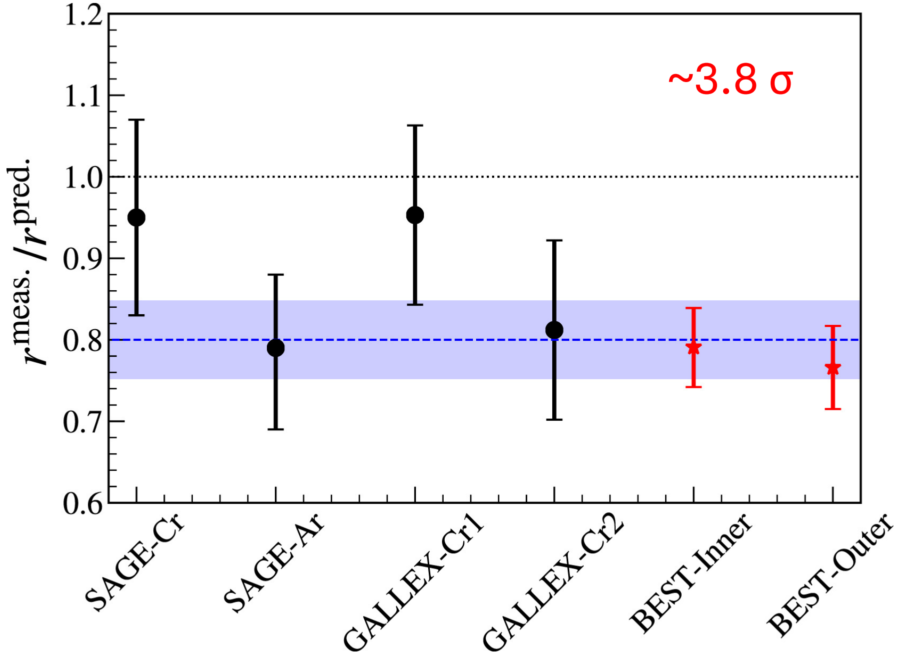
$\nu_e \rightarrow \nu_e \qquad E \sim 0.7\ \mathrm{MeV}$

$\langle L \rangle_{\mathrm{GALLEX}} = 1.9\ \mathrm{m}$

$\langle L \rangle_{\mathrm{SAGE}} = 0.6\ \mathrm{m}$



Deficit relative to expected rate:

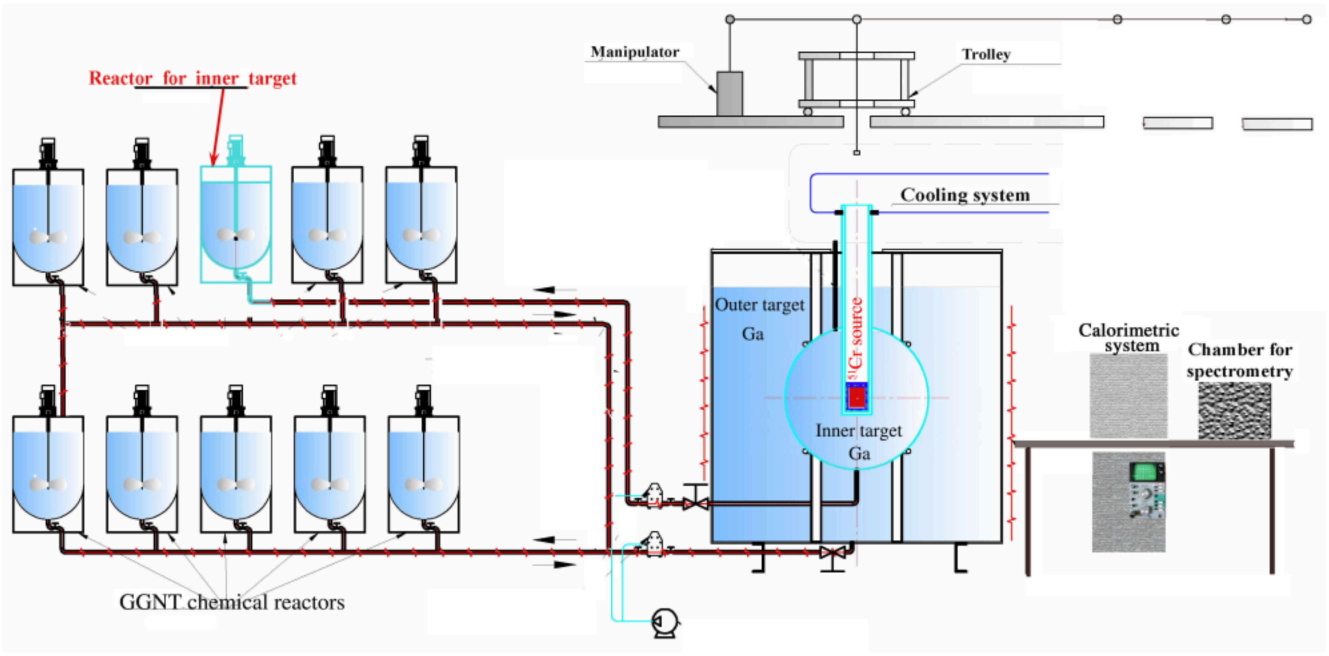


https://doi.org/10.1016/j.ppnp.2023.104082

Gallium anomaly (2021!)

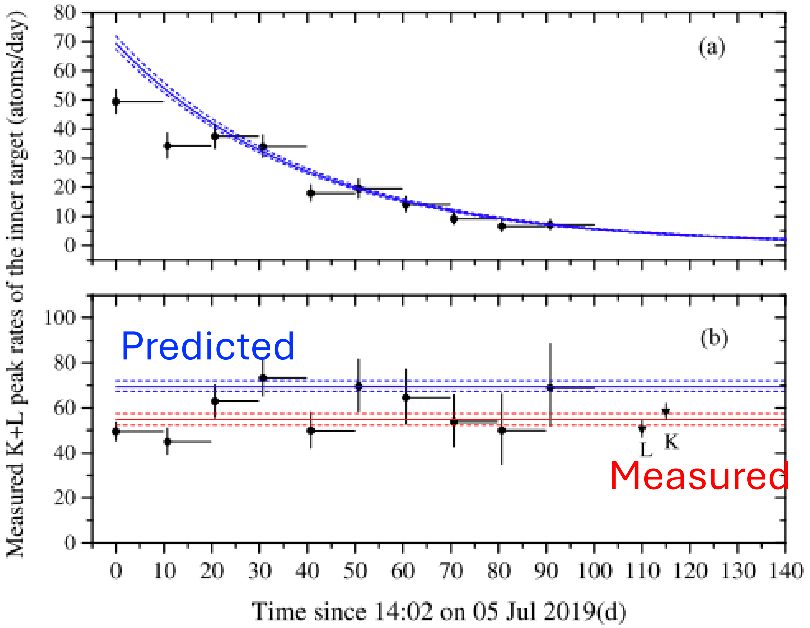
- Brand new Ga experiment to test the Ga anomaly (Baksan Experiment on Sterile Transitions [BEST]):
  - https://arxiv.org/pdf/2109.11482.pdf
- Used inner/outer tank geometry to directly look for oscillations

Experimental setup:

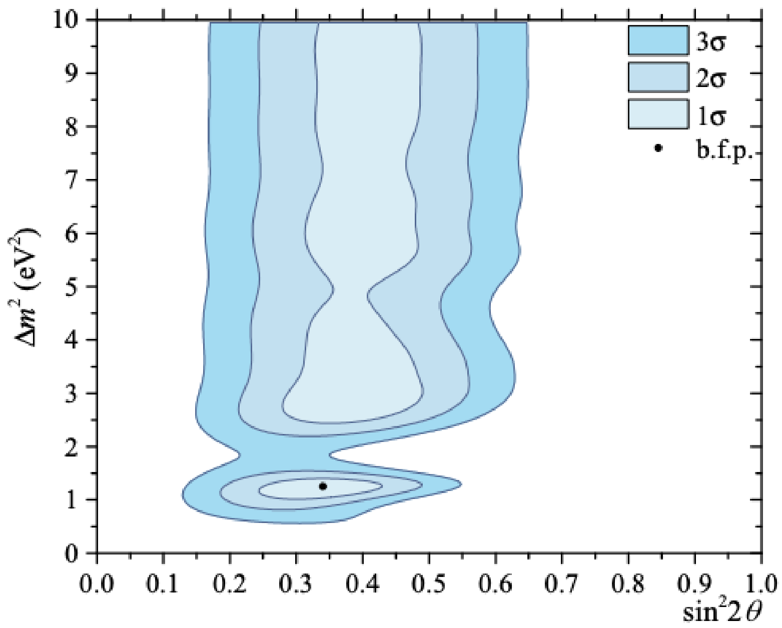


3.414 MCi ^{51}Cr ν_e source (1.3×10^{17} Bq)

Rate vs time (inner volume):



Best fit (+Gallex and SAGE):



ELSEVIER

Progress in Particle and Nuclear Physics

Volume 134, January 2024, 104082

Review

The gallium anomaly

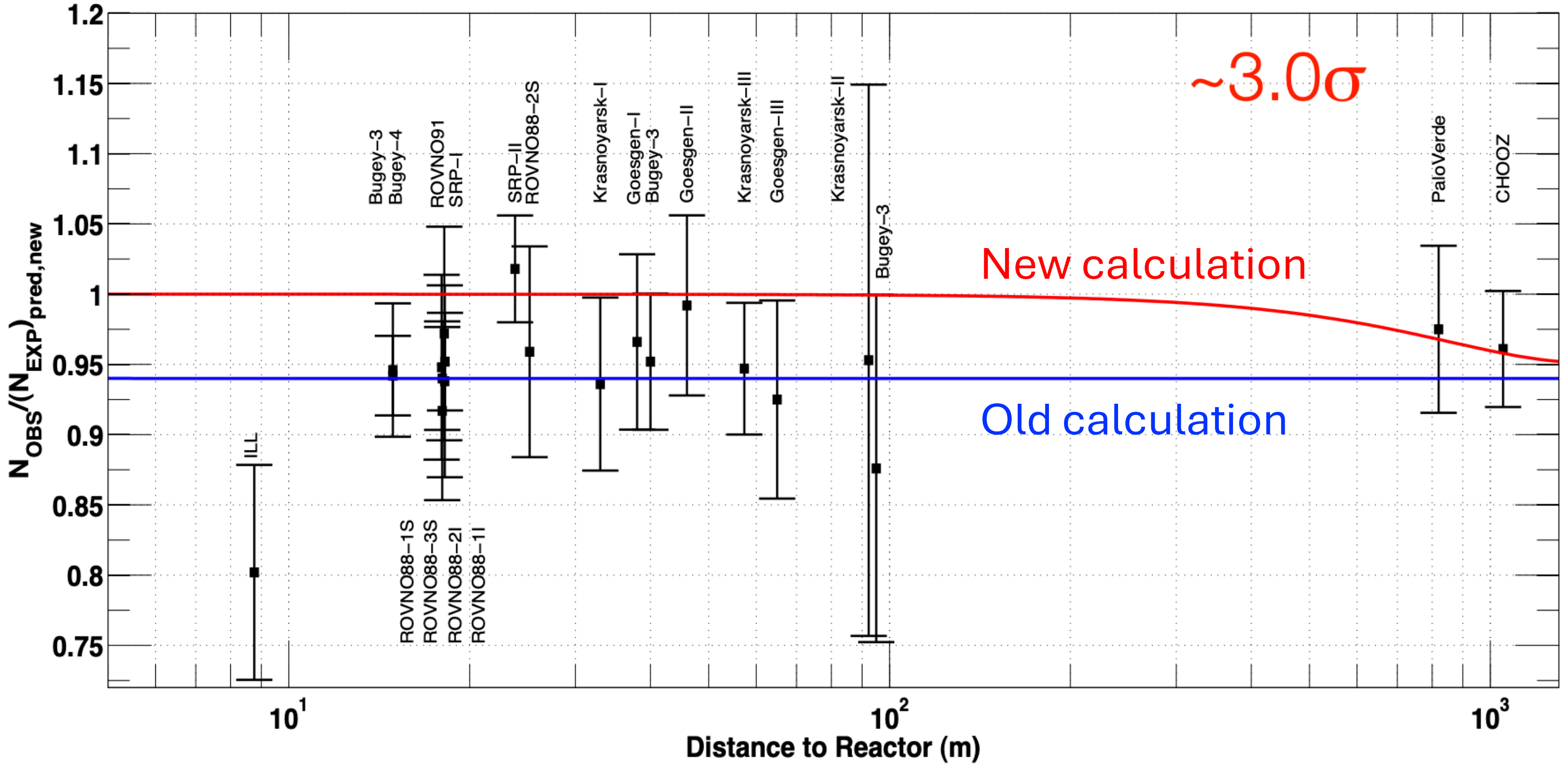
S.R. Elliott [a], V.N. Gavrin [b], W.C. Haxton [c d]

https://doi.org/10.1016/j.ppnp.2023.104082

weak magnetism. With the results from BEST, an anomaly remains even if one retains only the transition to the ^{71}Ge ground state, whose strength is fixed by the known lifetime of ^{71}Ge. We then consider the new-physics solution most commonly suggested to resolve the Ga anomaly, oscillations into a sterile fourth neutrino, $\nu_e \rightarrow \nu_s$. We find such a solution generates substantial tension with several null experiments, owing to the large mixing angle required. While this does not exclude such solutions – the sterile sector might include multiple neutrinos as well as new interactions – it shows the need for more experimental constraints, if we are to make progress in resolving the Ga and other low-energy neutrino anomalies. We conclude by consider the role future low-energy electron-capture sources could play in this effort.

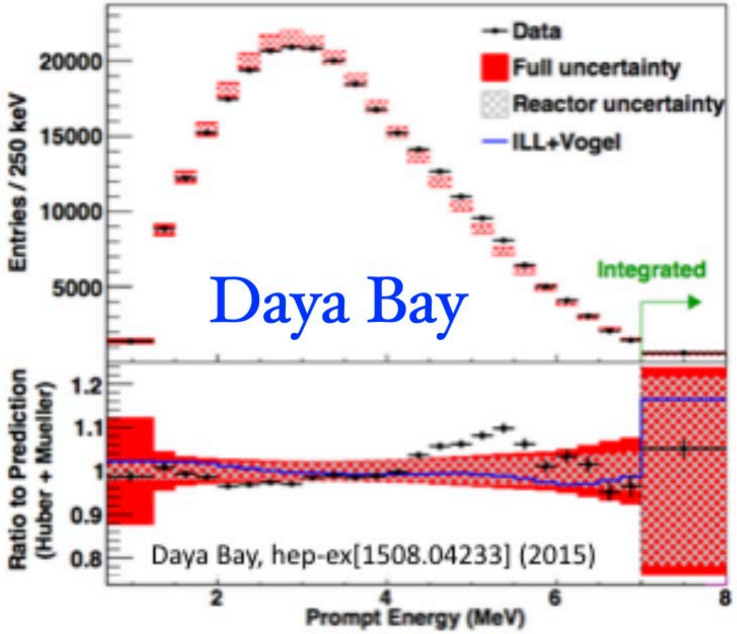
Reactor anomaly

- Reactor experiments (at 10s of meters distances) may also show an anomaly
  - Reasonable agreement until re-evaluation of expected reactor flux (~2011) suggested deficit



G. Mention et al., Phys. Rev. D83 (2011) 073006

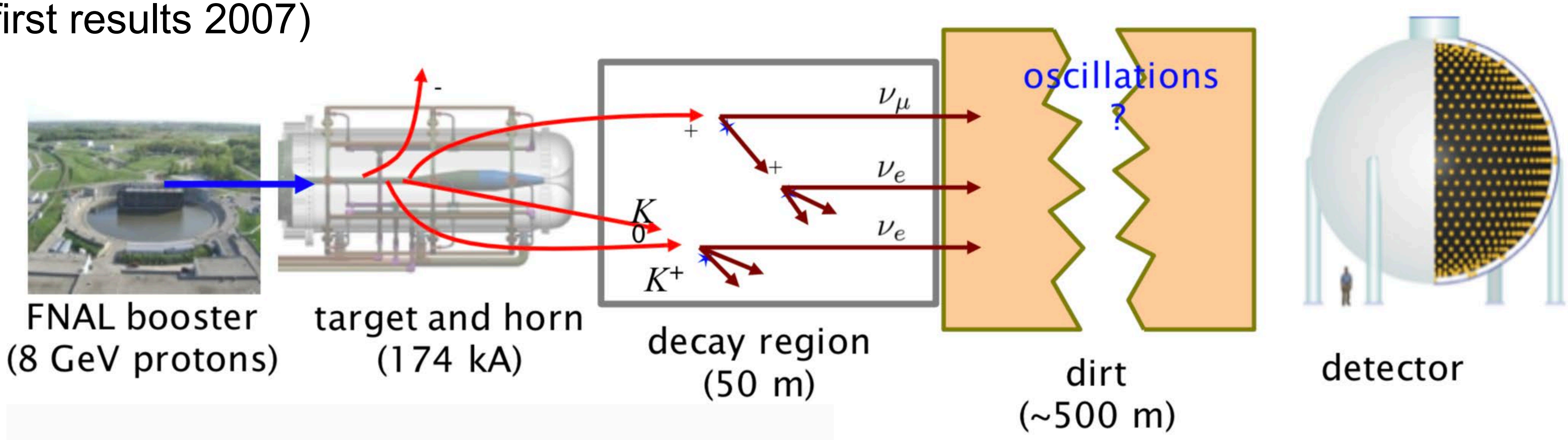
But...



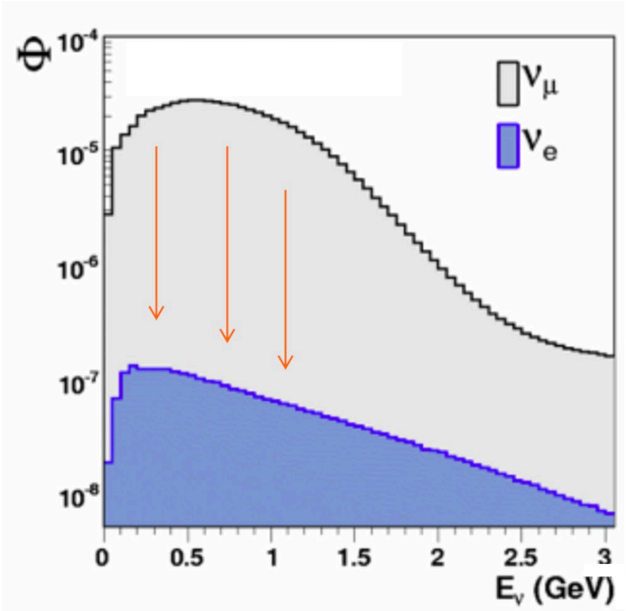
High precision spectral measurements show unexpected "bumps" (Daya Bay, RENO, Double Chooz)

MiniBooNE:

- MiniBooNE experiment was then built at Fermilab to either confirm or refute LSND measurements (first results 2007)

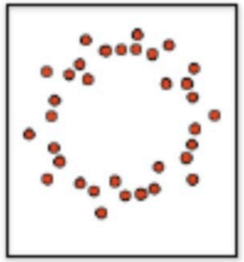


800 tons of mineral oil (ultrarefined methylene compounds), lined with 1,280 PMTs

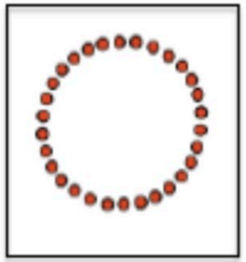


ν_e appearance in a primarily ν_μ beam

Cherenkov imaging detector



Electron, Photon

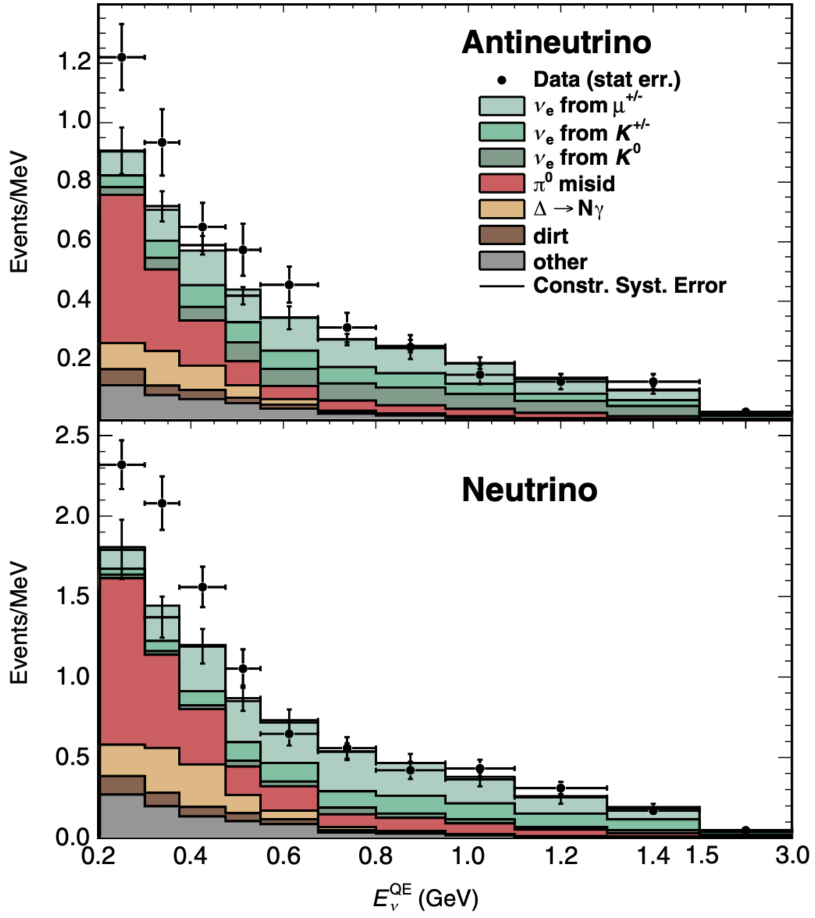


Muon

MiniBooNE:

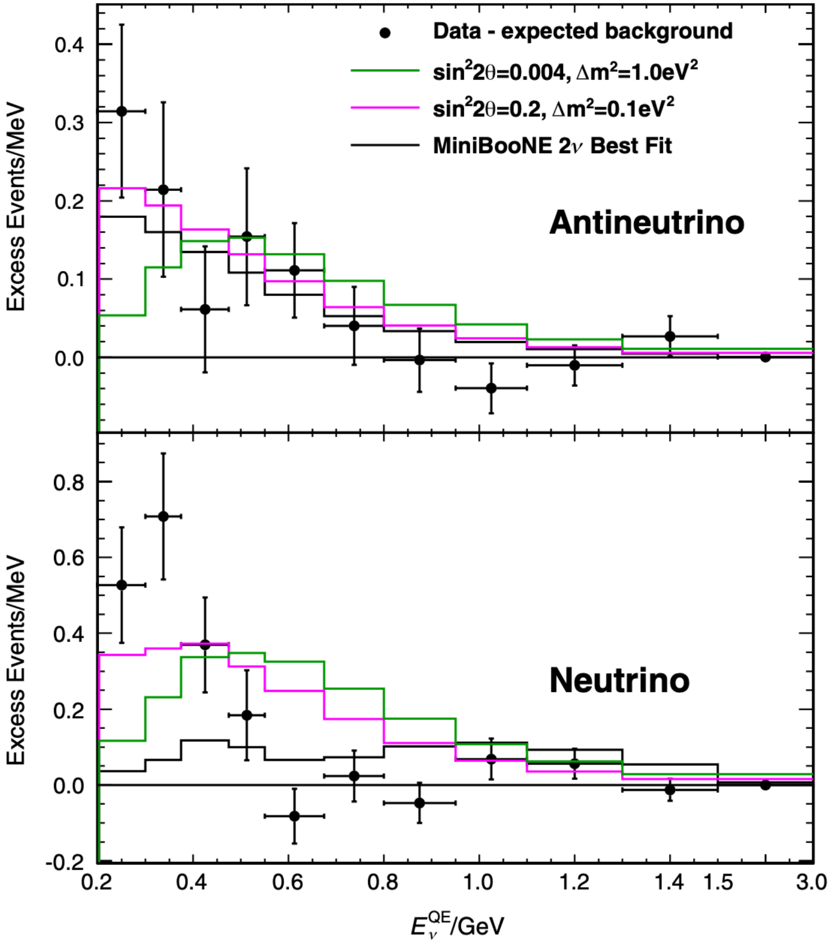
- MiniBooNE experiment was then built at Fermilab to either confirm or refute LSND measurements (first results 2007)

MiniBoone final results (2013):



https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.110.161801

Excess events over backgrounds:



2.8σ excess in antineutrino mode

$$78.4 \pm 20.0(\text{stat}) \pm 20.3(\text{syst})$$

3.4σ excess in neutrino mode

$$162.0 \pm 28.1(\text{stat}) \pm 38.7(\text{syst})$$

Somewhat compatible with LSND, but…:

- Neutrino mode spectral shape is somewhat strange
- Some tension with other global fits to oscillation data (e.g. ν_μ disappearance)

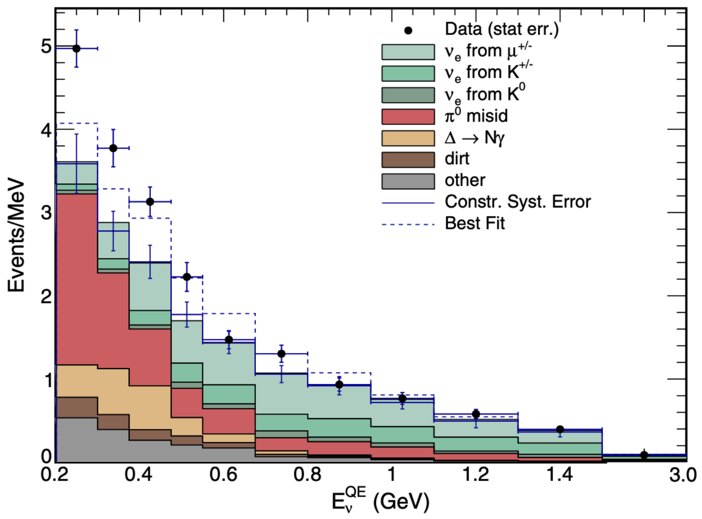
Backgrounds primarily from events producing a single gamma are rising at low energies

MiniBooNE cannot differentiate electrons from gammas

Newer MiniBooNE results (2018)

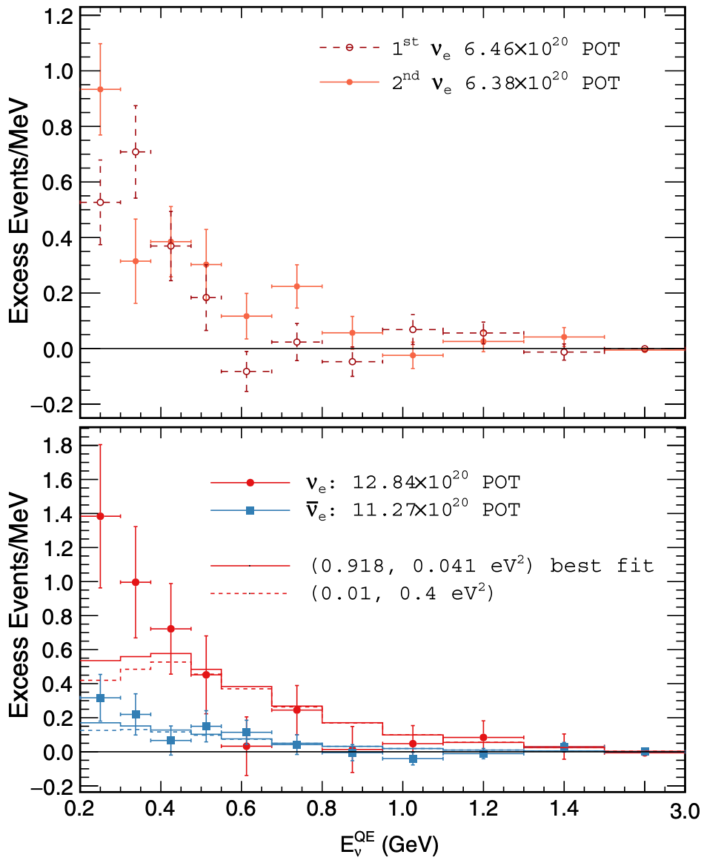
- And new MiniBooNE results (2018) with a factor of 2x more data match between neutrino and anti-neutrino, possibly consistent with LSND!

Updated MiniBooNE neutrino spectrum:

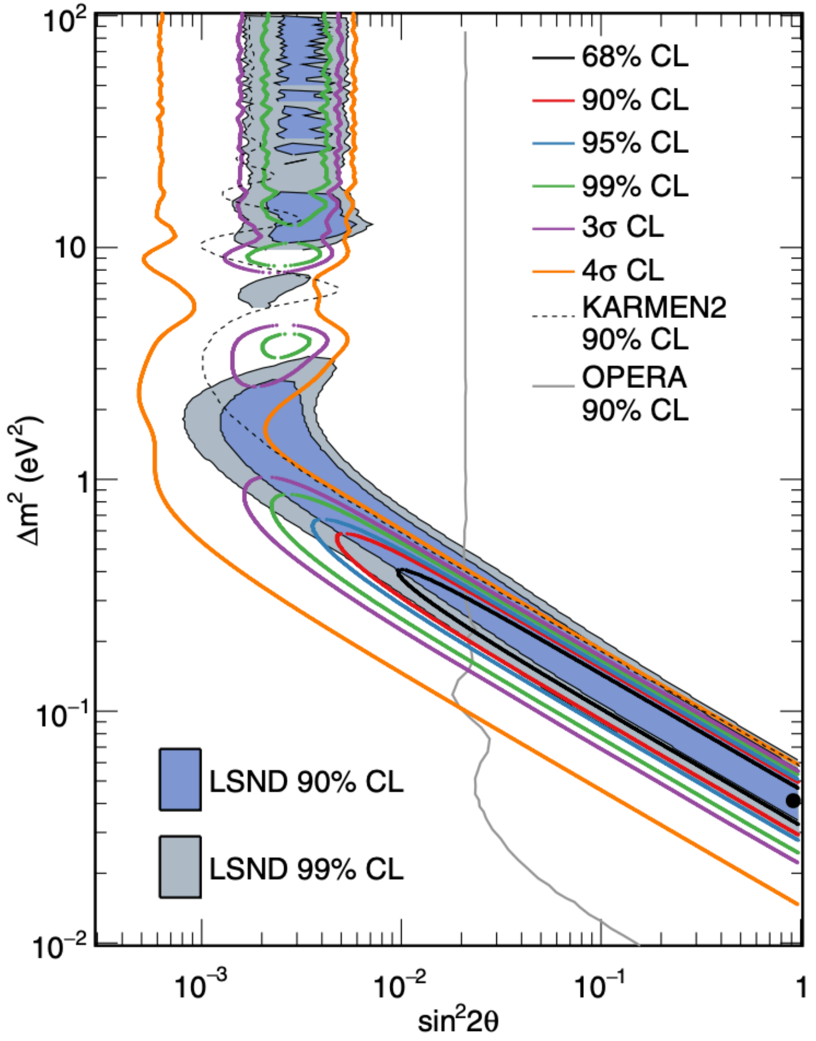


https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.221801

Comparison with previous results:



Best fit regions:



But… (global fits)

- When trying to fit all data together, there is significant tension with a simple 3+1 oscillation picture

Anomalies seen in: ν_e **disappearance**
$\nu_\mu \rightarrow \nu_e$ **appearance**

NOT seen in: ν_μ **disappearance**

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

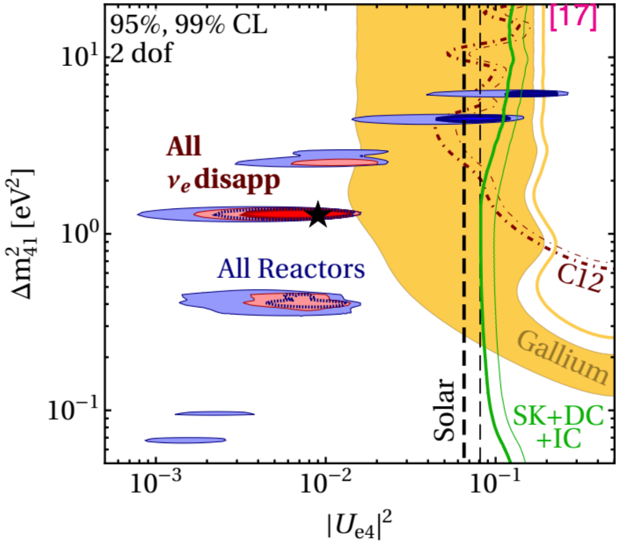
appearance

$$P_{\mu e} = \sin^2 2\theta_{\rm app} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm app} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

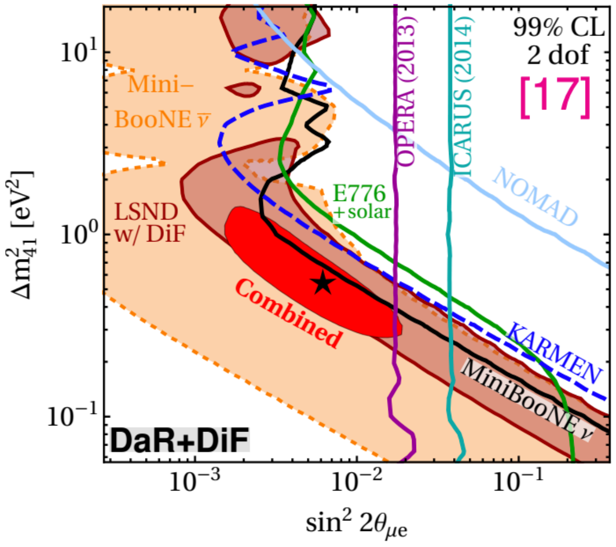
disappearance

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\rm dis} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\rm dis} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

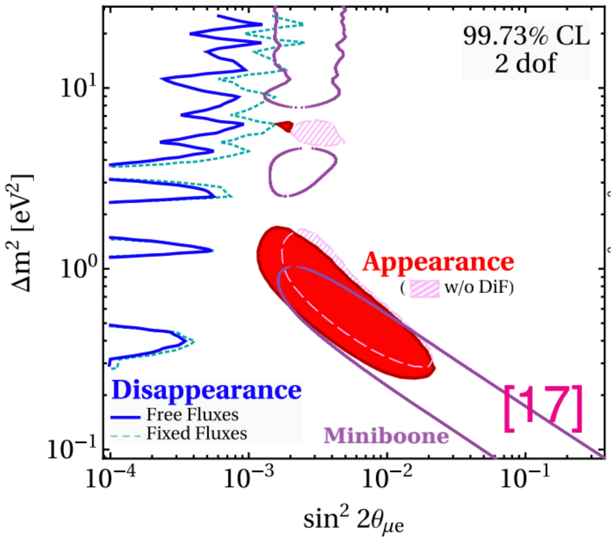
Global analysis of ν_e and $\bar{\nu}_e$ disappearance



$\nu_\mu \rightarrow \nu_e$ appearance



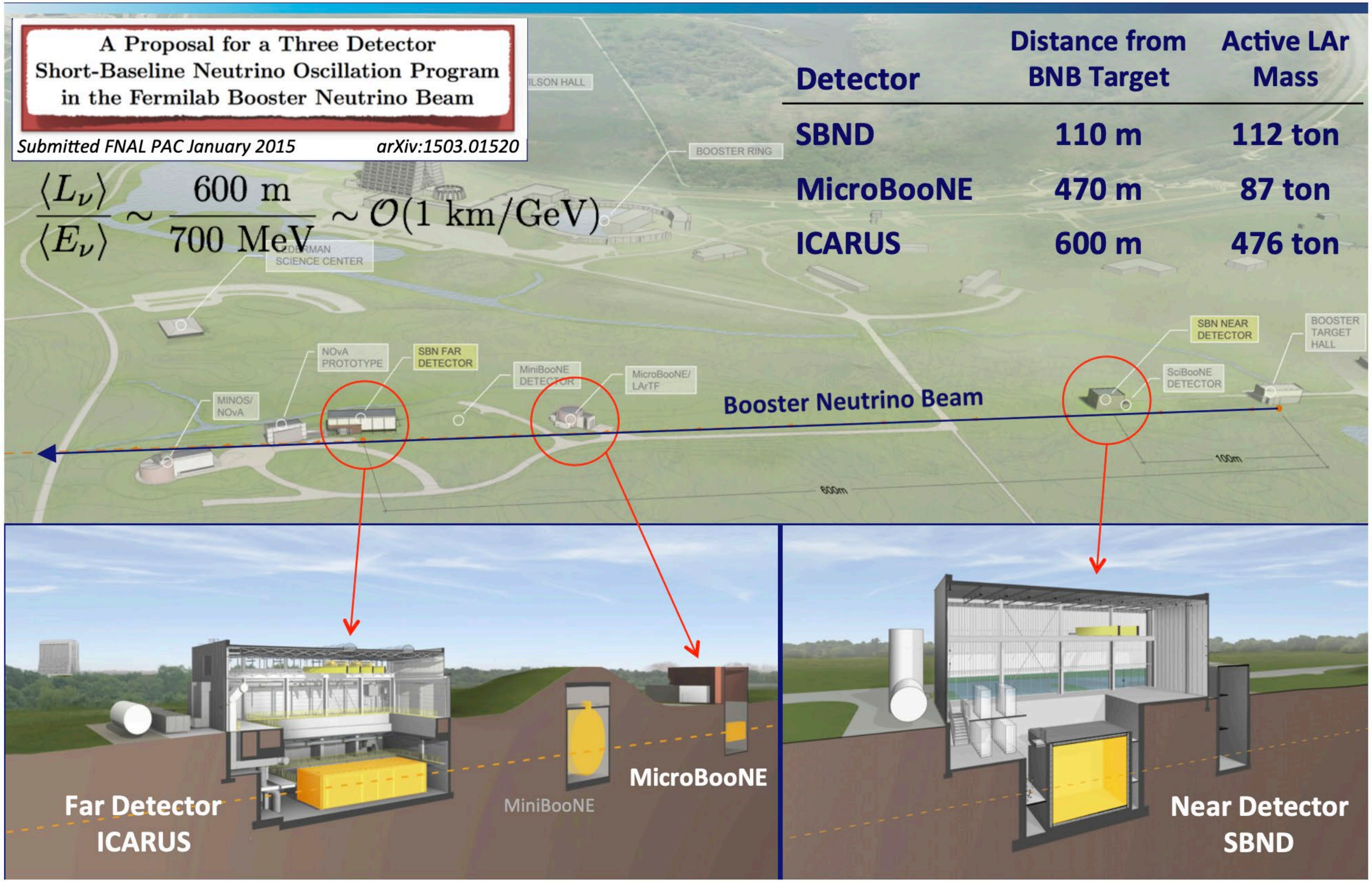
All



[17] Dentler, Hernández-Cabezudo, Kopp, Machado, MM, Martinez-Soler, Schwetz, arXiv:1803.10661.

See also: https://indico.slac.stanford.edu/event/326/contributions/1325/attachments/559/997/Oscillation_Experiments_2.pdf

Dedicated experiments (SBN program)



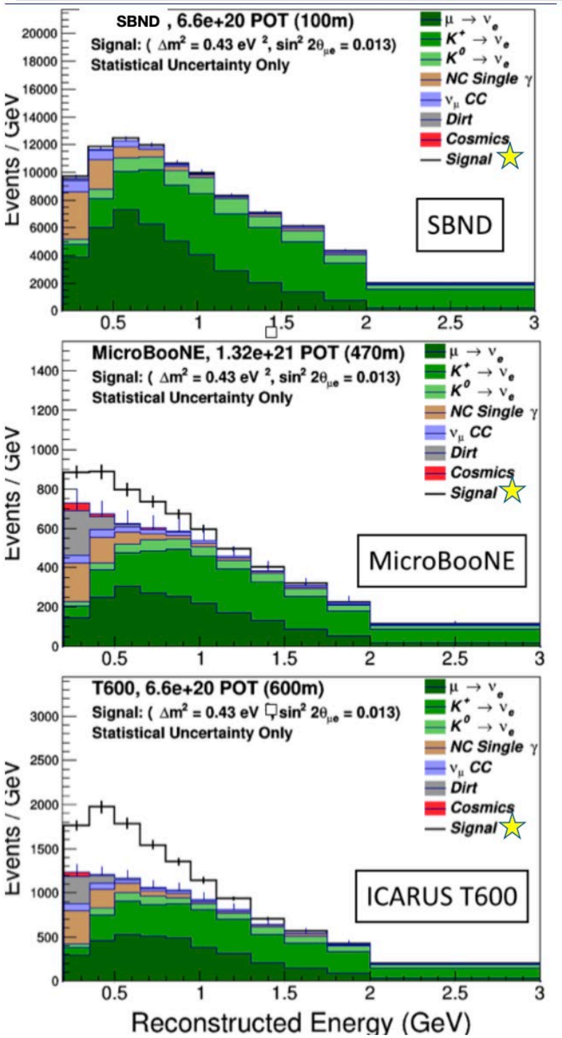
$$\frac{\langle L_\nu \rangle}{\langle E_\nu \rangle} \sim \frac{600\ \mathrm{m}}{700\ \mathrm{MeV}} \sim \mathcal{O}(1\ \mathrm{km/GeV})$$

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

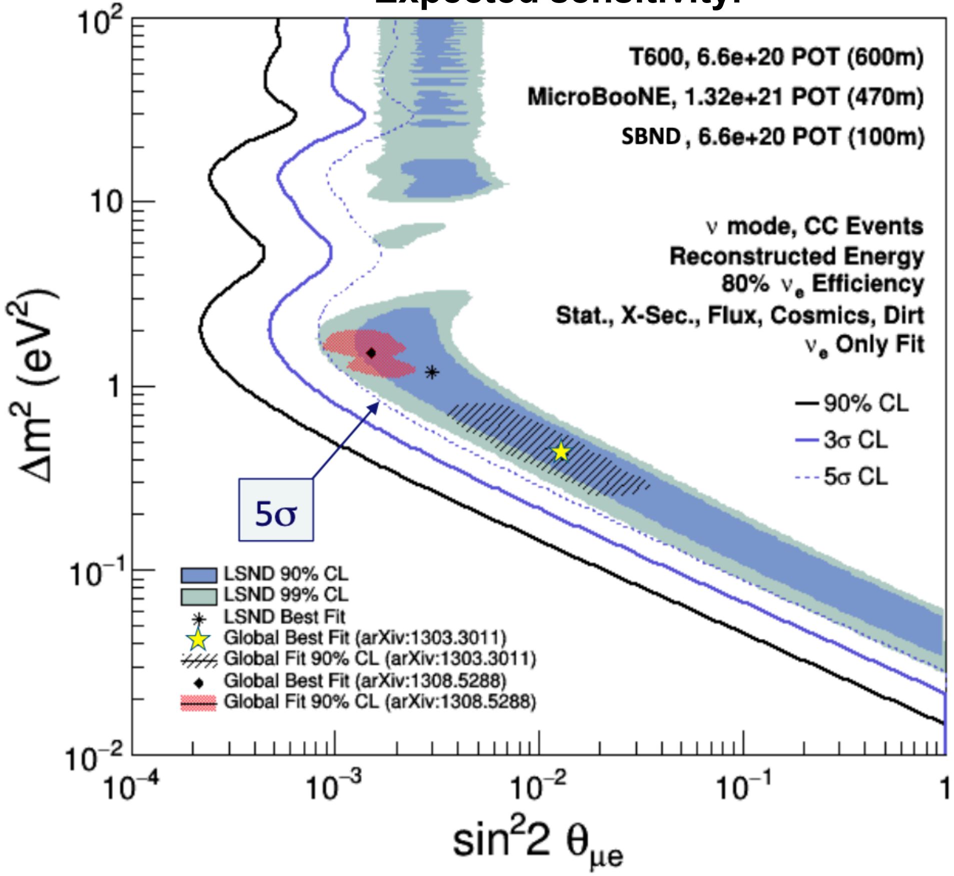
Dedicated experiments (SBN program)

- Three detectors would definitively confirm or rule out the MiniBooNE/LSND results
    - LAr TPCs allow background separation (and in particular e/γ discrimination)

Simulated signal/backgrounds:



Expected sensitivity:

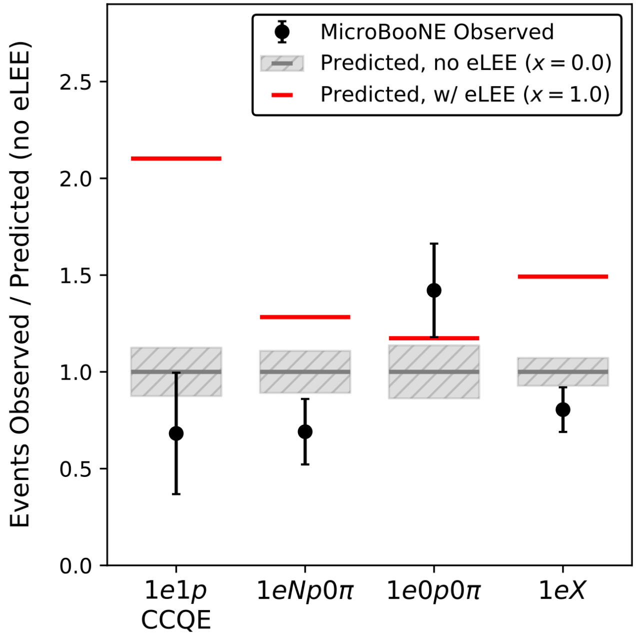


SBN proposal arxiv:1503.01520

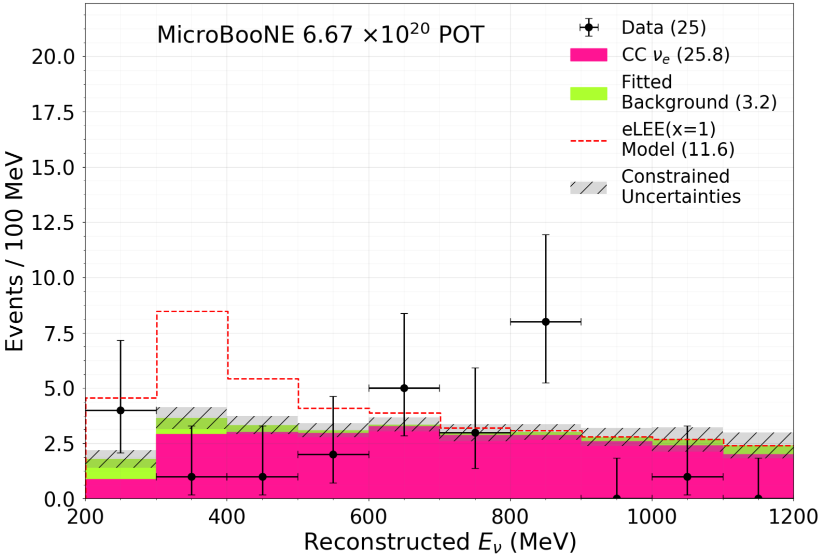
uBooNE results

- MicroBooNE has now released the first results from the SBN program
- Three different analyses with various levels of selection cuts
- No evidence for excess electron-induced events!
  - Also no evidence of an unaccounted for photon background in searches to date:
    - https://arxiv.org/abs/2110.00409

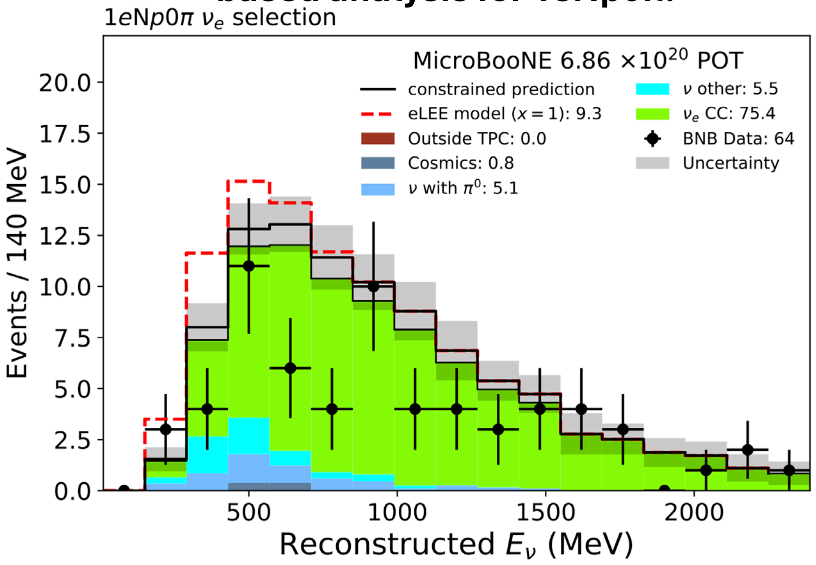
Combined results:



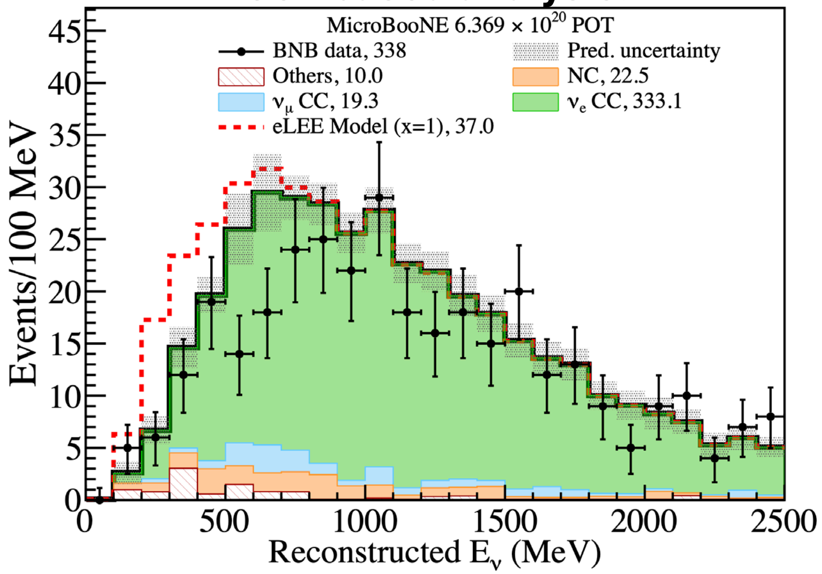
1e1p CCQE candidate events in the deep-learning-based analysis:



Pionless ν_e candidate events in the Pandora-based analysis for 1eNp0π:



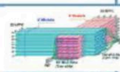
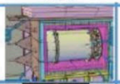
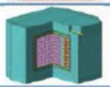
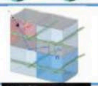
Inclusive ν_e candidate events in the Wire-Cell based analysis:



https://microboone.fnal.gov/electron_analysis_2021/

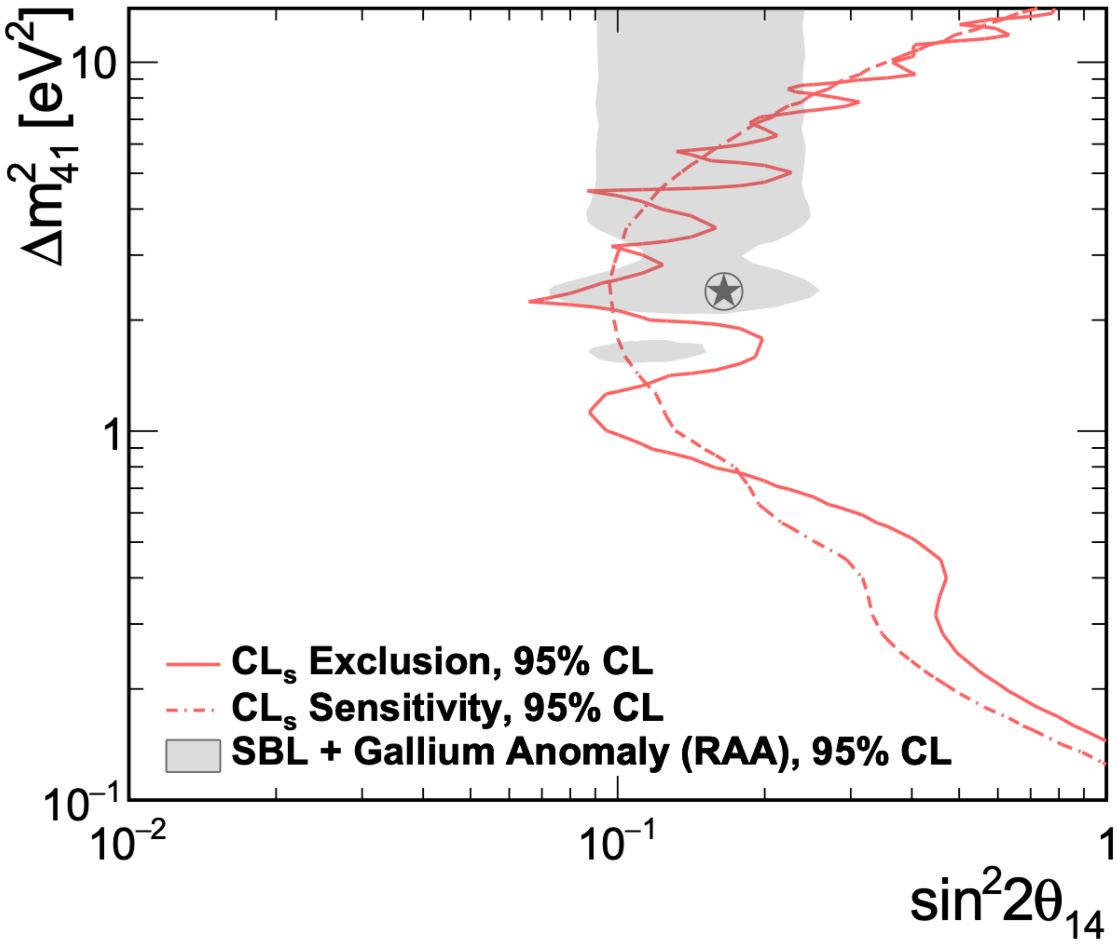
Dedicated experiments (reactors)

- New generation of reactor experiments also coming online (e.g., PROSPECT)

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

N. Bowden AAP 2016

PROSPECT exclusion region (2020):



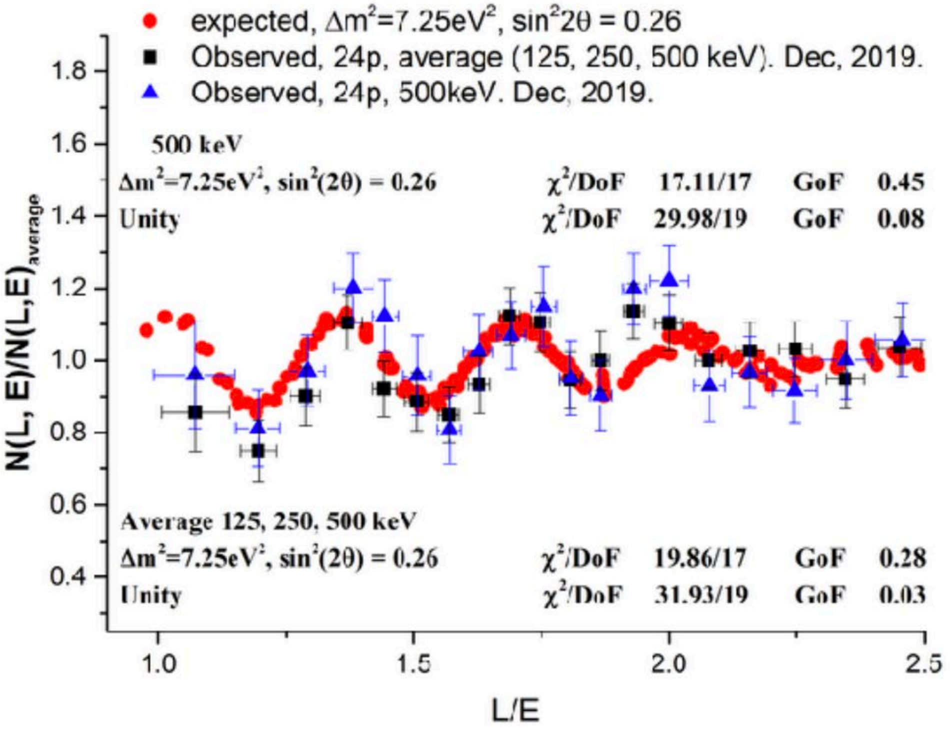
https://arxiv.org/pdf/2006.11210.pdf

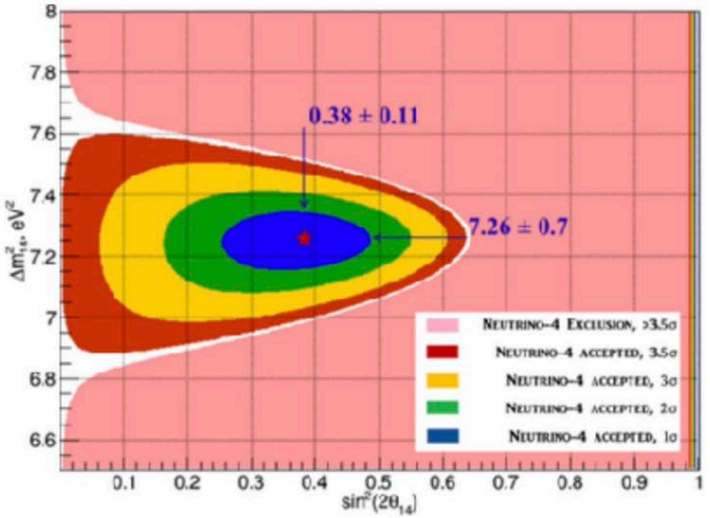
But… Neutrino4

- Neutrino4 apparently observes oscillation in movable detector
  - Movable detector (6 to 12 m) near reactor

A.P.Serebrov, et al.
JETP Letters,
Volume 109, 2019
Issue 4, pp 213–221.

arxiv:1809.10561
arxiv:2003.03199
arxiv:2005.05301





A.Serebrov, Neutrino2020

But… Neutrino4

- Neutrino4 apparent observes oscillation in movable detector

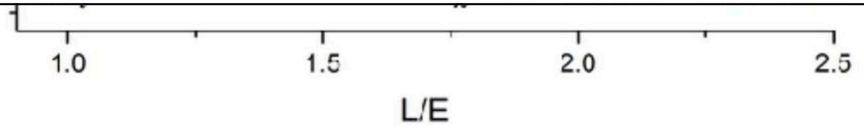
  - Movable detector (6 to 12 m) near reactor

Some controversy remains….

Note on arXiv:2005.05301, 'Preparation of the Neutrino-4 experiment on search for sterile neutrino and the obtained results of measurements'

H. Almazán, M. Andriamirado, A. B. Balantekin, H. R. Band, C. D. Bass, D. E. Bergeron, D. Berish, A. Bonhomme, N. S. Bowden, J. P. Brodsky, C. D. Bryan, C. Buck, T. Classen, A. J. Conant, G. Deichert, P. del Amo Sanchez, M. V. Diwan, M. J. Dolinski, I. El Atmani, A. Erickson, B. T. Foust, J. K. Gaison, A. Galindo-Uribarri, C. E. Gilbert, B. T. Hackett, S. Hans, A. B. Hansell, K. M. Heeger, D. E. Jaffe, X. Ji, D. C. Jones, O. Kyzylova, L. Labit, J. Lamblin, C. E. Lane, T. J. Langford, J. LaRosa, A. Letourneau, D. Lhuillier, M. Licciardi, B. R. Littlejohn, X. Lu, J. Maricic, T. Materna, M. P. Mendenhall, A. M. Meyer, R. Milincic, I. Mitchell, P. E. Mueller, H. P. Mumm, J. Napolitano, C. Nave, R. Neilson, J. A. Nikkel, D. Norcini, S. Nour, J. L. Palomino-Gallo, H. Pessard, D. A. Pushin, X. Qian, J.-S. Réal, C. Roca, R. Rogly, E. Romero-Romero, R. Rosero, V. Savu, S. Schoppmann, T. Soldner, A. Stutz, P. T. Surukuchi, M. A. Tyra, R. L. Varner, D. Venegas-Vargas, M. Vialat, P. B. Weatherly, C. White, J. Wilhelmi, A. Woolverton, M. Yeh, A. Zhang, C. Zhang, X. Zhang

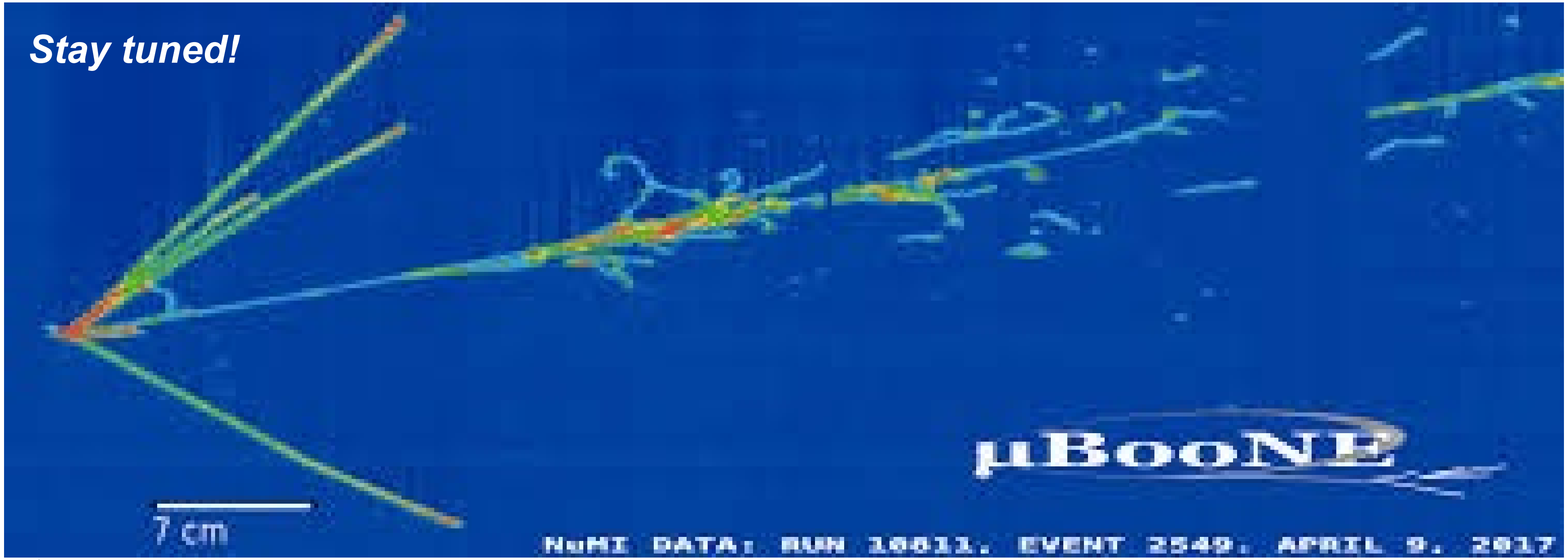
We comment on the claimed observation [arXiv:arXiv:2005.05301] of sterile neutrino oscillations by the Neutrino-4 collaboration. Such a claim, which requires the existence of a new fundamental particle, demands a level of rigor commensurate with its impact. The burden lies with the Neutrino-4 collaboration to provide the information necessary to prove the validity of their claim to the community. In this note, we describe aspects of both the data and analysis method that might lead to an oscillation signature arising from a null experiment and describe additional information needed from the Neutrino-4 collaboration to support the oscillation claim. Additionally, as opposed to the assertion made by the Neutrino-4 collaboration, we also show that the method of 'coherent summation' using the L/E parameter produces similar results to the methods used by the PROSPECT and the STEREO collaborations.



A.Serebrov, Neutrino2020

eV sterile neutrinos summary

- There are a number of intriguing signals in short baseline oscillation experiments
- But:
  - There is not a clear picture of how various results could fit together
  - These experiments are difficult, and backgrounds or systematics are always possible
  - uBoone is now online and hasn't seen an excess consistent with neutrino oscillations or backgrounds
    - Additional searches will search for other new physics explanations



Conclusions

Sterile Neutrinos

- **Short Baseline**

- LSND and MiniBooNE anomalies are disfavored by MicroBooNE
- ν_s explanation of LEE is still possible but contradicts disapp. experiments
- MicroBooNE(NuMI), SBNP and JSNS^2 will soon clarify the situation

- **Gallium**

-GA is in serious tension with many experiments but agrees with Neutrino-4
-Many ideas of possible conventional or BSM explanation but not convincing
- ν_s explanation of GA is still marginally possible
- BEST with ^{65}Zn source – smoking gun test for many explanations

- **Reactor Neutrinos**

- RAA is probably explained by smaller ^{235}U contribution preferred by new experiments (with exception of DANSS) and new Reactor flux models
- Spectral analysis still indicates ν_s with a small $\sin^2 2\theta_{ee}$ at ~3σ
- Neutrino-4 claim of ν_s observation is in tension with many results but not excluded
- Upgraded VSBL reactor experiments will clarify the situation
  Upgraded Neutrino-4+ is already taking data, Neutrino-4M will start in 2024

Cosmological constraints were not discussed but models exist which remove them
See e.g. Davoudiasl,Denton arXiv:2301.09651 Explains Ga, LSND, MiniBooNE, DM

Experimental evidence for ν_s is fading away but not excluded

18

Sterile Neutrinos

Short-Baseline Neutrino Oscillation + Source Measurements in Progress

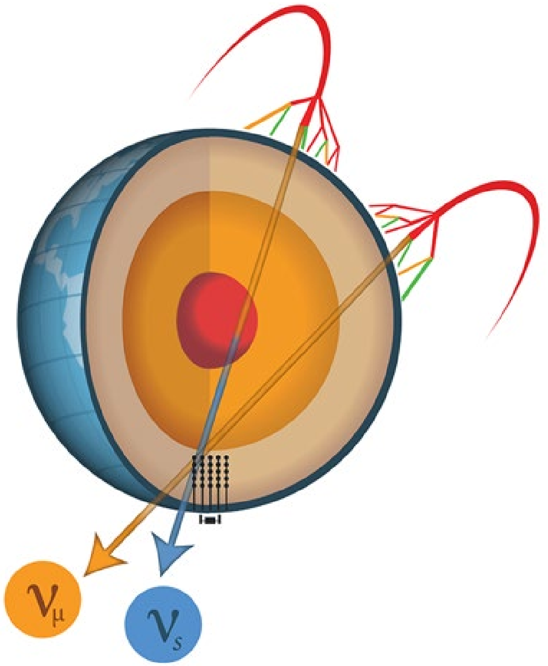
Summary Talk by
M. Danilov at
Moriond Mar 2024

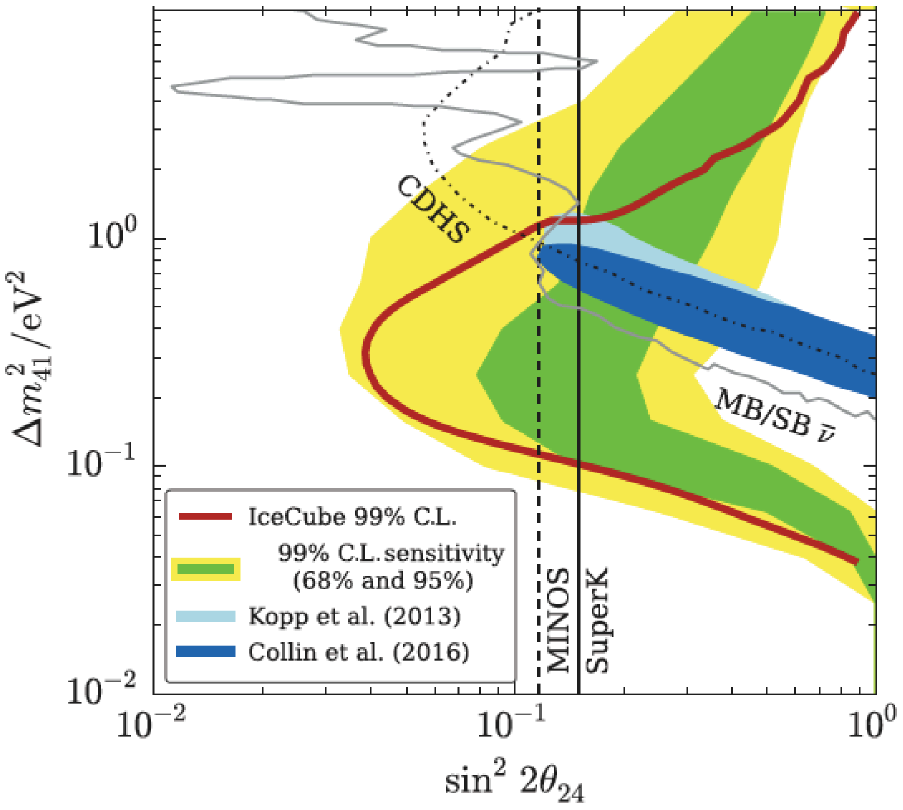
ν_μ disappearance in IceCube

(3+1): $P_{\nu_\mu \to \nu_e} \propto |U_{e4} U_{\mu 4}|^2$ with $\begin{cases} |U_{e4}|^2 \propto P_{\nu_e \to \nu_e}\,, \\ |U_{\mu 4}|^2 \propto P_{\nu_\mu \to \nu_\mu}\,; \end{cases}$

hence, $P_{\nu_\mu \to \nu_e} > 0$ requires $\begin{cases} P_{\nu_e \to \nu_e} > 0\,, \\ P_{\nu_\mu \to \nu_\mu} > 0\,; \end{cases}$

We don't see it!





IceCube Collaboration, *PRL* **117**, 071801 (2016)

Physics Today **69**, 10, 15 (2016); https://doi.org/10.1063/PT.3.3316

SEARCH & DISCOVERY

Sterile neutrinos give IceCube and other experiments the cold shoulder

Recent null results heighten the tension between the bulk of neutrino experiments and the few that hint at the putative particle's existence.

Under kilometers of ice at the South Pole, the IceCube Neutrino Observatory's 5160 optical detectors keep watch for neutrinos that have traveled through Earth from the opposite side of the globe. (See the article by Francis Halzen and Spencer R. Klein, Physics Today, May 2008, page 29.) The observatory was built primarily to serve as a telescope to study neutrinos from astrophysical sources. However, it also detects neutrinos born in the aftermath of cosmic-ray protons crashing into nuclei in the upper atmosphere. About once every six minutes, one of those atmospheric neutrinos finds its way to IceCube's monitoring zone, collides with a nucleus in the ice or bedrock, and produces a charged particle that can be detected from the Cherenkov light it gives off. Figure 1 shows the IceCube Laboratory, which houses the computers that

reactor-neutrino experiment in France,

FIGURE 1. THE ICECUBE LABORATORY

How else could we search for ν_s?

Mostly Sterile keV Neutrino Mass States

- Beta decay is particularly sensitive to keV-MeV mass states
- Mass states in this region have $\tau \approx \tau_{universe}$ and could thus serve as some fraction of the observed DM in our universe
  - Excellent candidates for warm dark matter Dodelson and Widrow, **PRL** 72, 17 (1994)

Image Courtesy: Symmetry Magazine

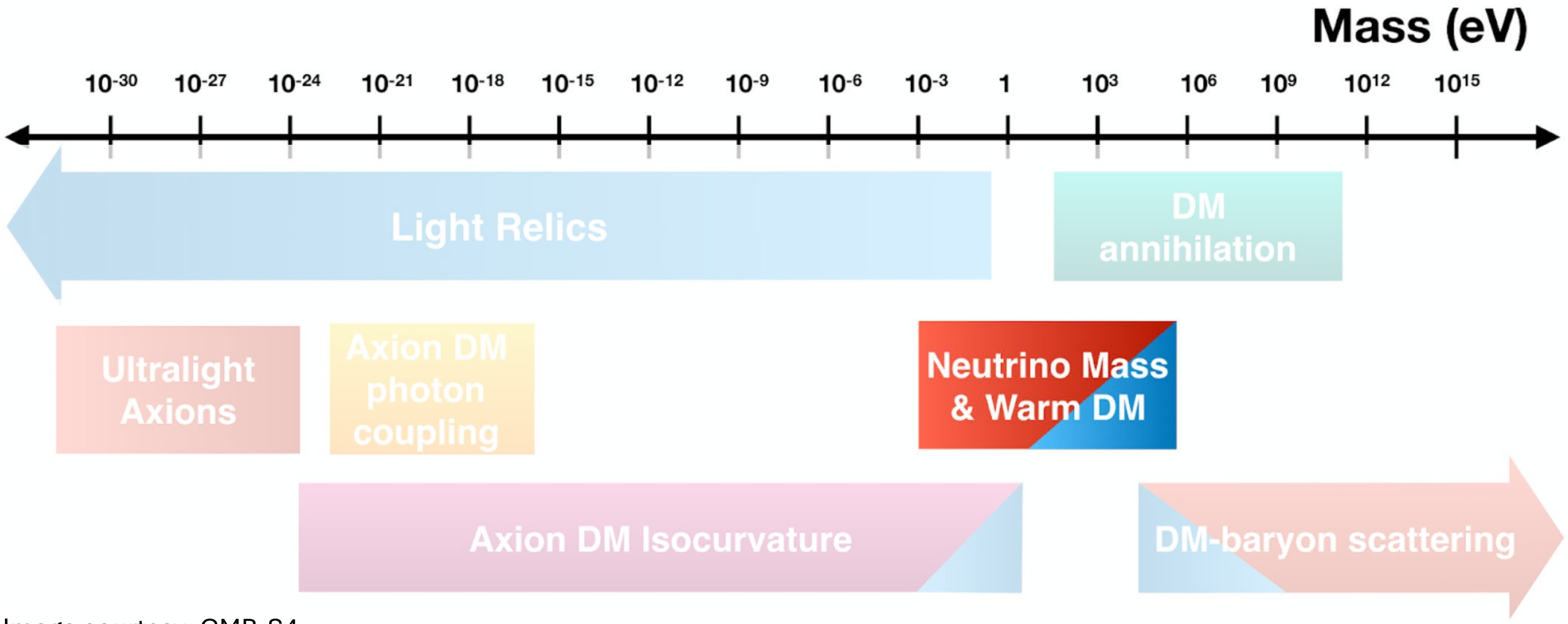
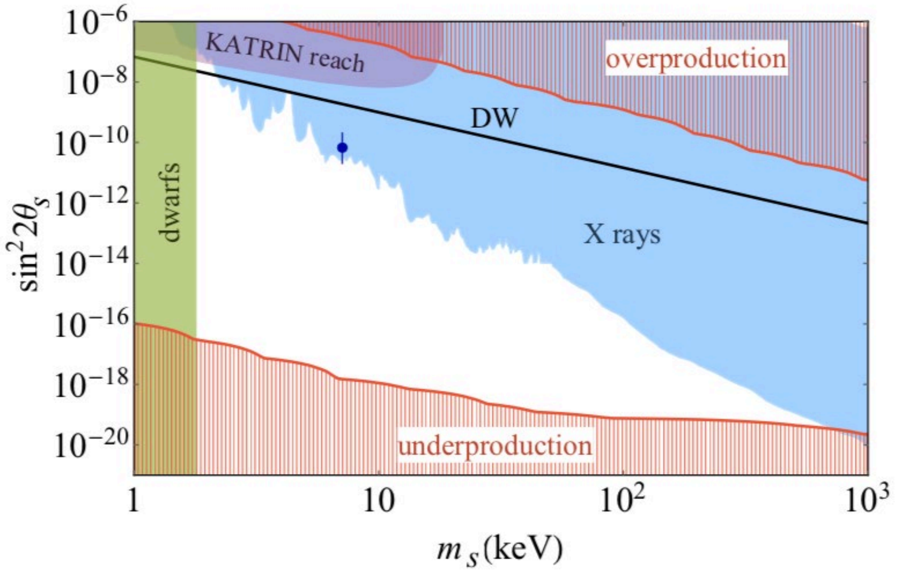


Image courtesy: CMB-S4

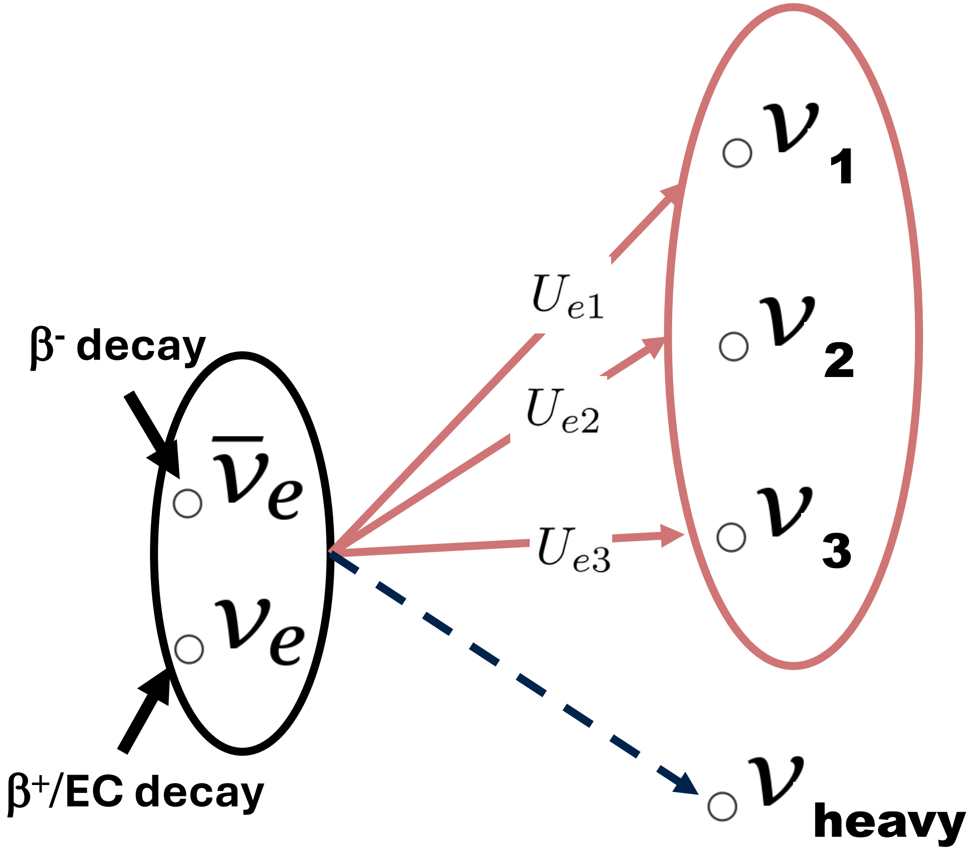


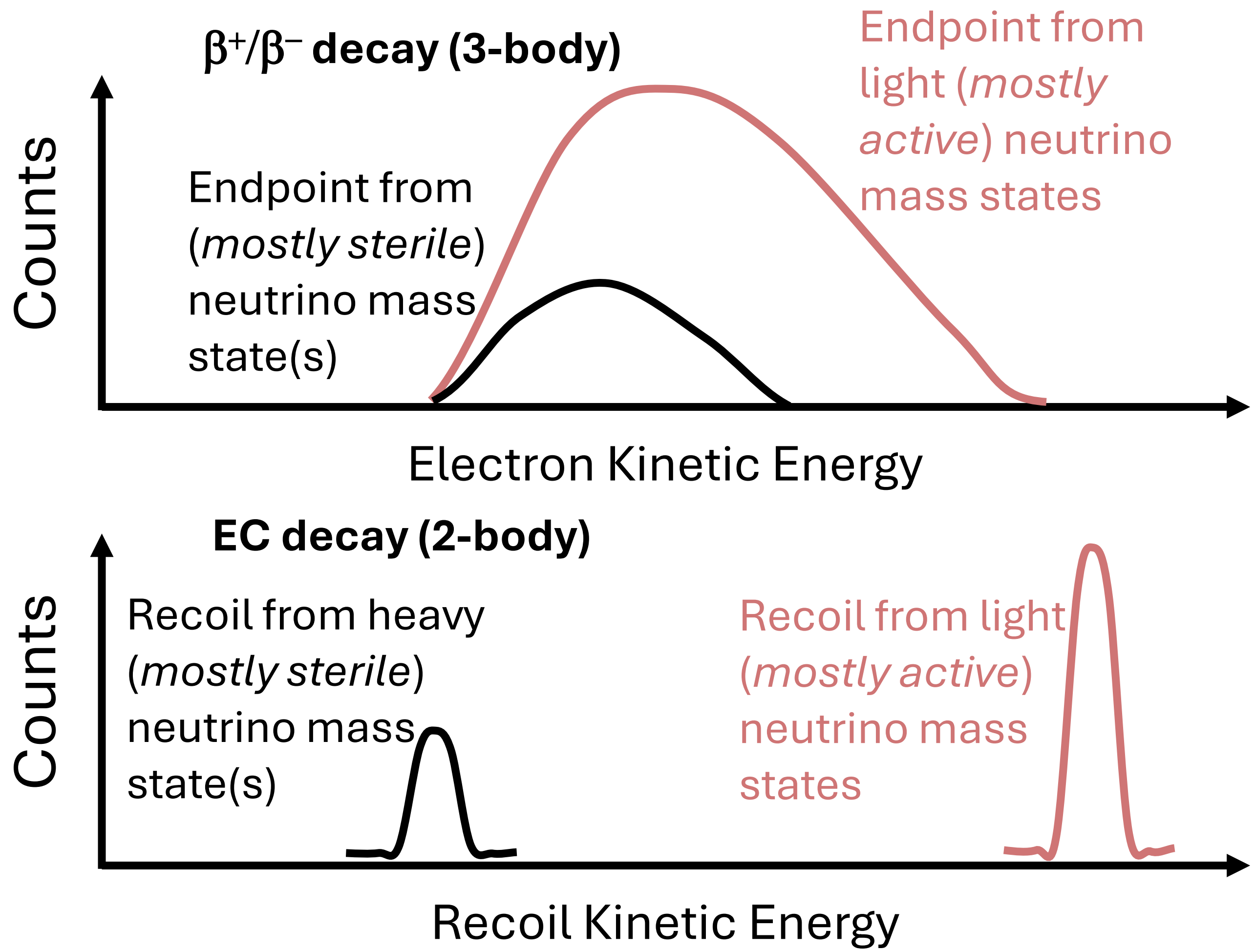
B. Dasgupta and J. Kopp, Phys. Rep. **928**, 1-63 (2021)

How would we search for ν_s in nuclear decays?

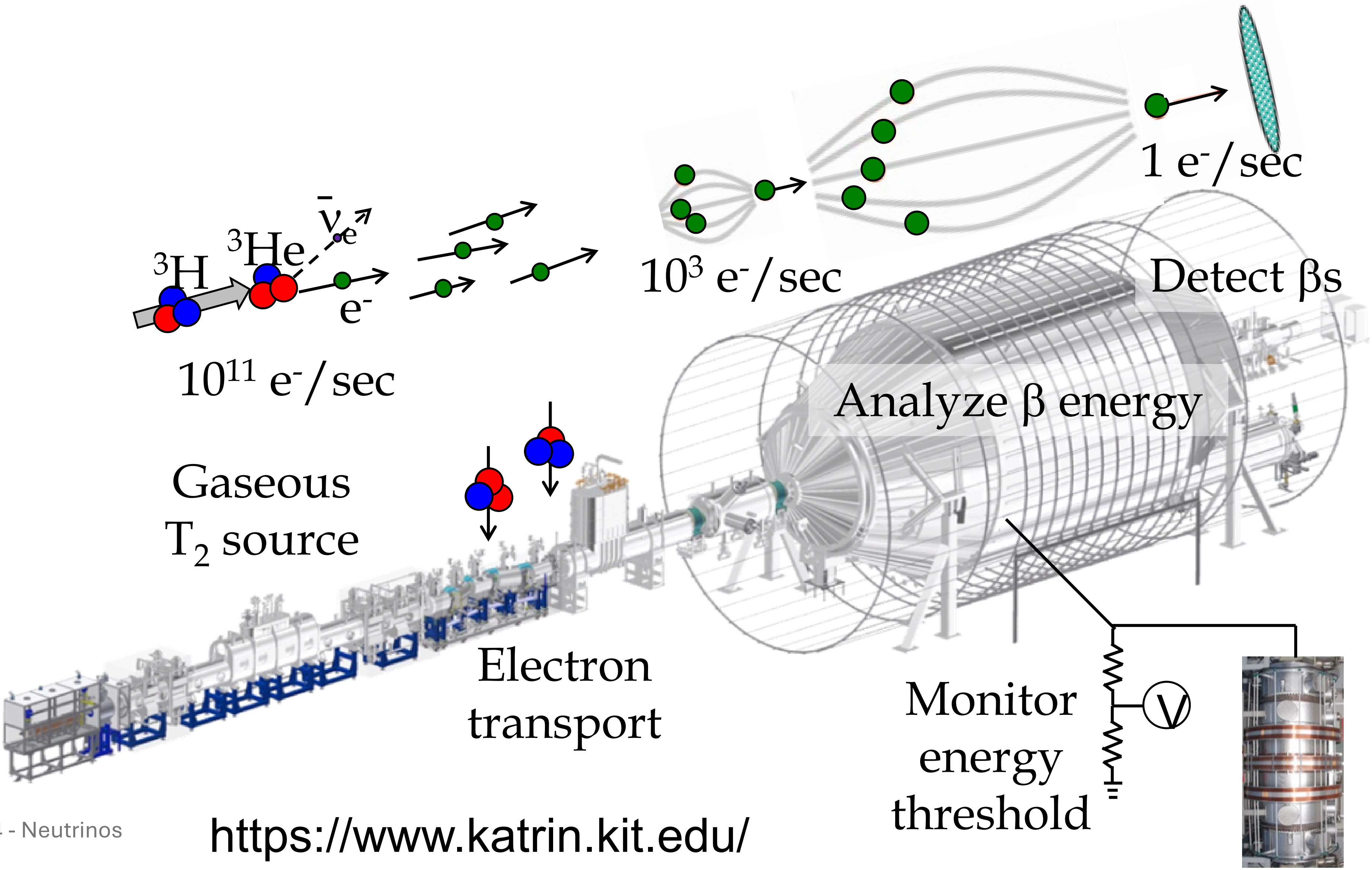
Heavy Neutrino Mass Studies via Coupling to ν_e

- In EC/β^+ and β^- decay, we study the relative coupling of the mass states to $\bar{\nu}_e$ (ν_e)
- Momentum is conserved with the mass states, not flavor states





KArlsruhe TRItium Neutrino experiment

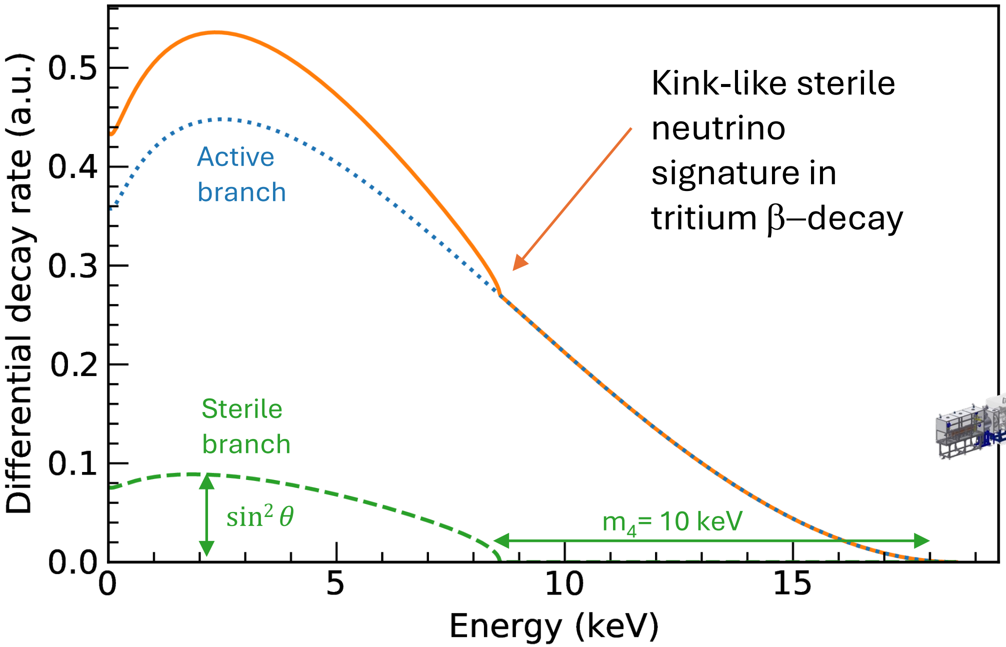


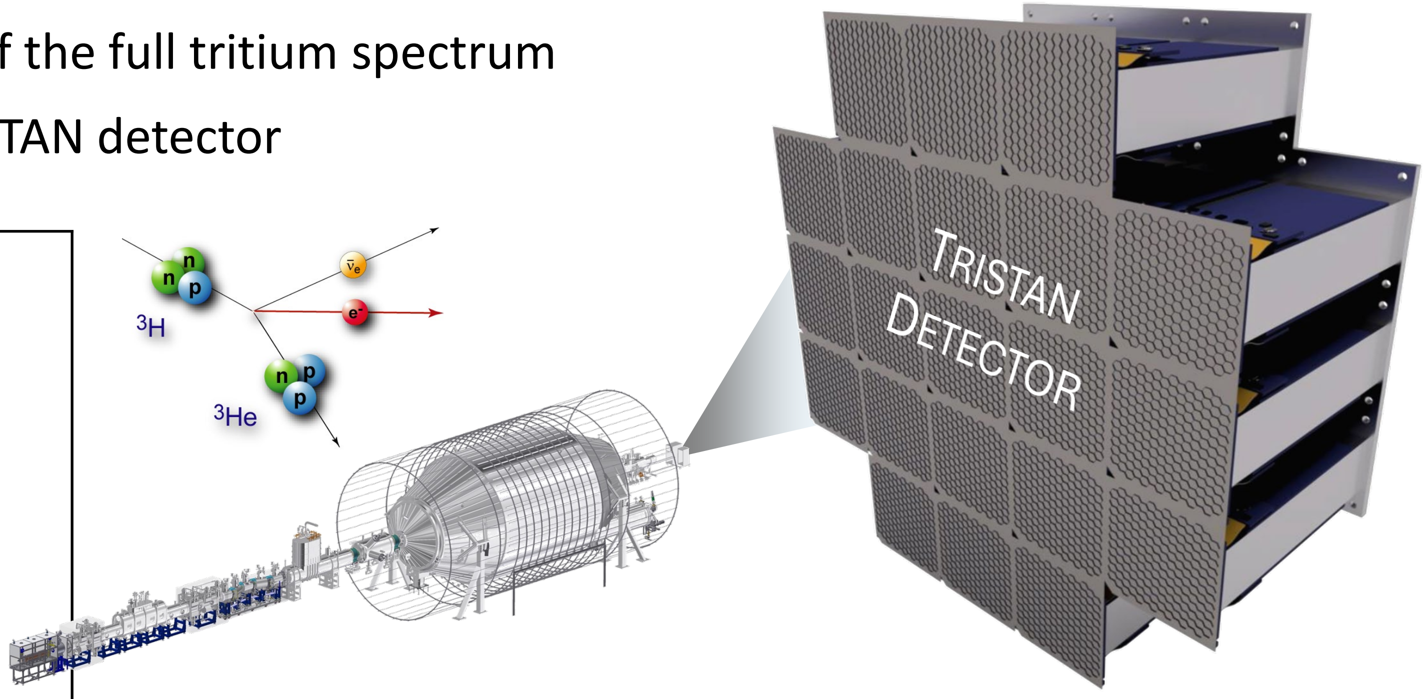
https://www.katrin.kit.edu/

Tritium Endpoint Measurements – KATRIN/TRISTAN

Idea:

- Make use of the strong KATRIN tritium source and beamline
- Perform a differential measurement of the full tritium spectrum
- Requires new detector system → TRISTAN detector





S. Mertens et al. JCAP 1502 (2015)
S. Mertens et al, PRD 91 (2015)

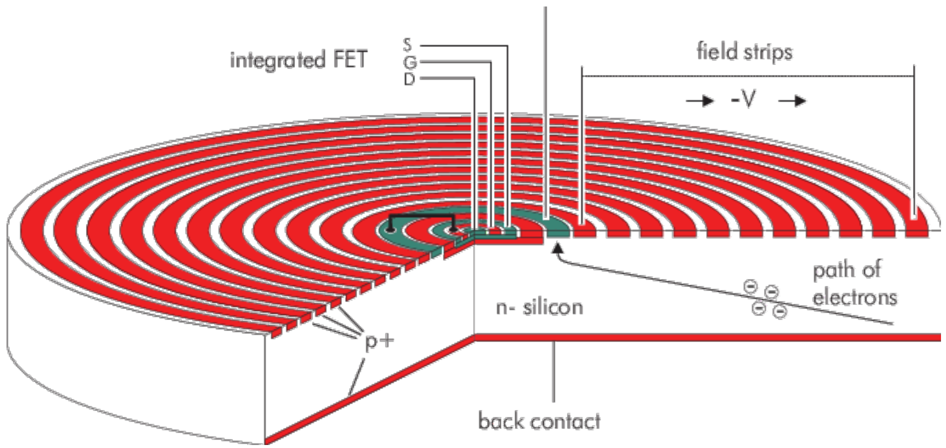
Tritium Endpoint Measurements – KATRIN/TRISTAN

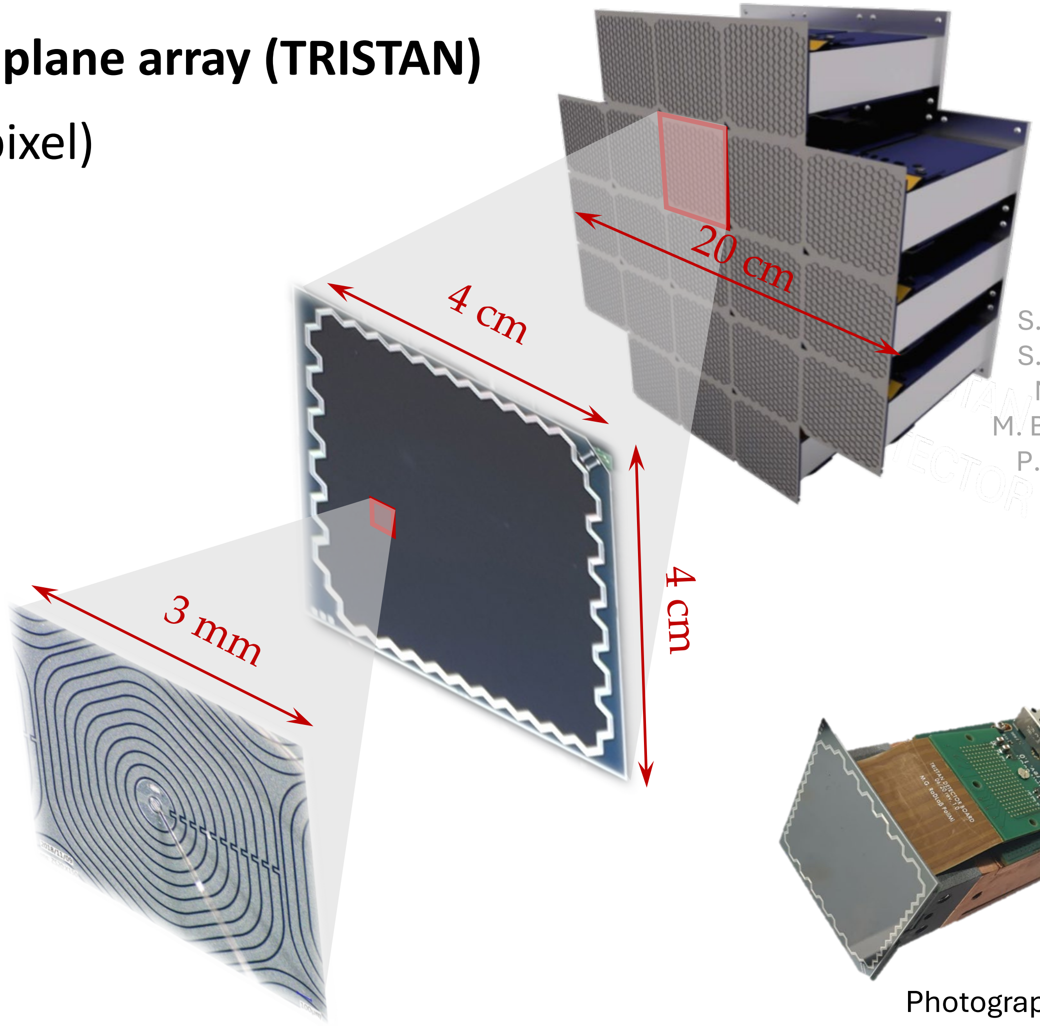
Multi-pixel (>1000) silicon drift detector focal plane array (TRISTAN)

✓ Capability of handling high rates (> 10^5 cps/pixel)

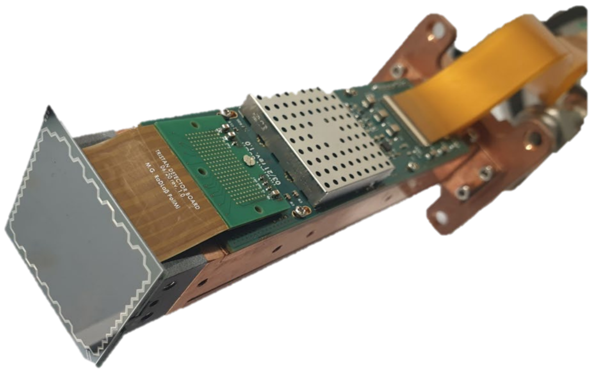
✓ Good energy resolution (300 eV @ 20 keV)

✓ Large focal plane area coverage





S. Mertens et al, J. Phys. G46 (2019)
S. Mertens et al, J. Phys. G48 (2020)
M. Gugiatti et al, NIM-A 979 (2020)
M. Biassoni et al, EPJ. Plus 136 (2021)
P. King et al JINST 16 T07007 (2021)



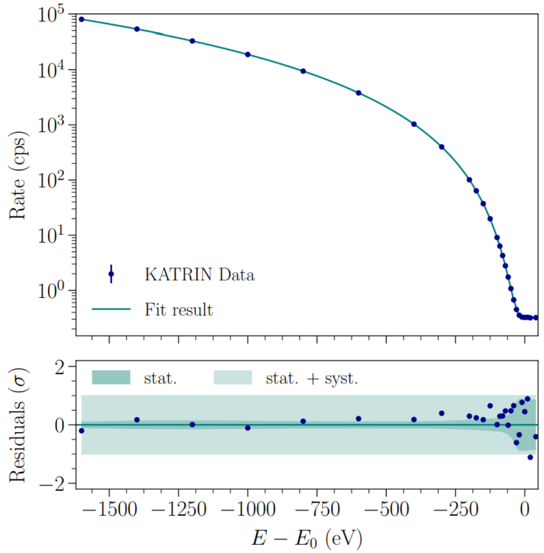
Photograph of TRISTAN module

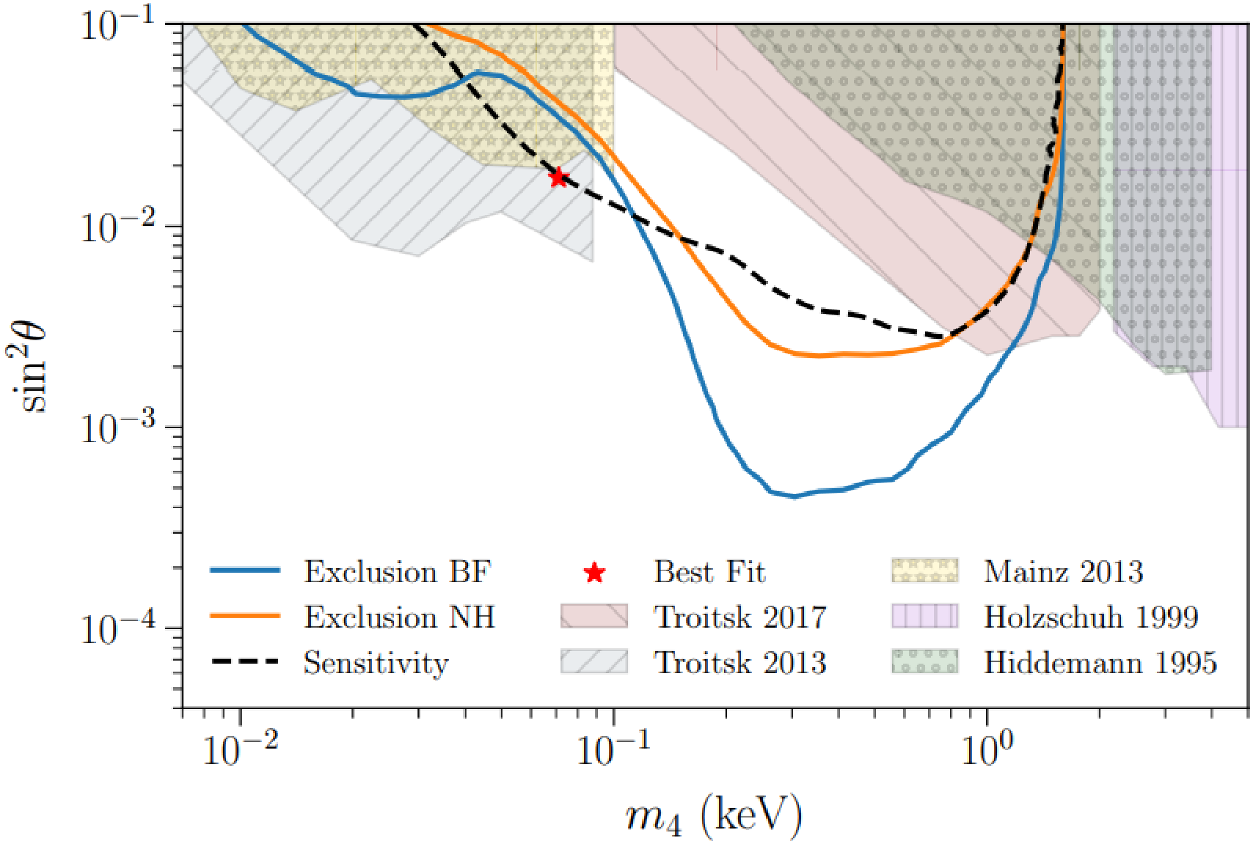
First keV-Mass Neutrino Search with KATRIN Data

2207.06337

Search for keV-scale Sterile Neutrinos with first KATRIN Data

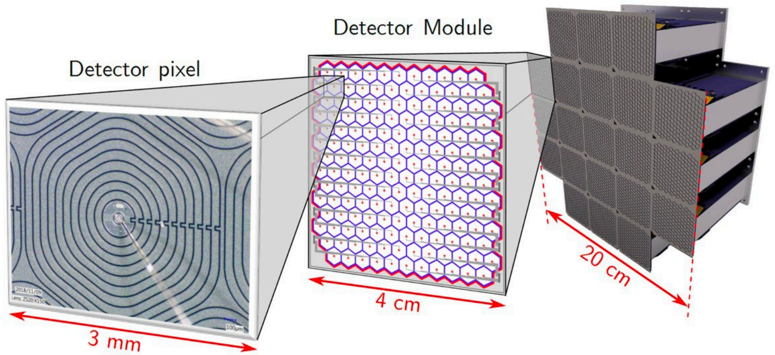
M. Aker,[1] D. Batzler,[1] A. Beglarian,[2] J. Behrens,[1] A. Berlev,[3] U. Besserer,[1] B. Bieringer,[4] F. Block,[5] S. Bobien,[6] B. Bornschein,[1] L. Bornschein,[1] M. Böttcher,[4] T. Brunst,[7,8] T. S. Caldwell,[9,10] R. M. D. Carney,[11] S. Chilingaryan,[2] W. Choi,[5] K. Debowski,[12] M. Descher,[5] D. Díaz Barrero,[13] P. J. Doe,[14] O. Dragoun,[15] G. Drexlin,[5] F. Edzards,[7,8] K. Eitel,[1] E. Ellinger,[12] R. Engel,[1] S. Enomoto,[14] A. Felden,[1] J. A. Formaggio,[16] F. M. Fränkle,[1] G. B. Franklin,[17] F. Friedel,[1] A. Fulst,[4] K. Gauda,[4] A. S. Gavin,[9,10] W. Gil,[1] F. Glück,[1] R. Grössle,[1] R. Gumbsheimer,[1] V. Hannen,[4] N. Haußmann,[12] K. Helbing,[12] S. Hickford,[1] R. Hiller,[1] D. Hillesheimer,[1] D. Hinz,[1] T. Höhn,[1] T. Houdy,[7,8] A. Huber,[1] A. Jansen,[1] C. Karl,[7,8] J. Kellerer,[5] M. Kleifges,[2] M. Klein,[1] C. Köhler,[7,8] L. Köllenberger,[1] A. Kopmann,[2] M. Korzeczek,[5] A. Kovalík,[15] B. Krasch,[1] H. Krause,[1] L. La Cascio,[5] T. Lasserre,[18] T. L. Le,[1] O. Lebeda,[15] B. Lehnert,[11] A. Lokhov,[4] M. Machatschek,[1] E. Malcherek,[1] M. Mark,[1] A. Marsteller,[1] E. L. Martin,[9,10] C. Melzer,[1] S. Mertens,[7,8,*] J. Mostafa,[2] K. Müller,[1] H. Neumann,[6] S. Niemes,[1] P. Oelpmann,[4] D. S. Parno,[17] A. W. P. Poon,[11] J. M. L. Poyato,[13] F. Priester,[1] J. Ráliš,[15] S. Ramachandran,[12] R. G. H. Robertson,[14] W. Rodejohann,[19] C. Rodenbeck,[4] M. Röllig,[1] C. Röttele,[1] M. Ryšavý,[15] R. Sack,[1,4] A. Saenz,[20] R. Salomon,[4] P. Schäfer,[1] L. Schimpf,[4,5] M. Schlösser,[1] K. Schlösser,[1] L. Schlüter,[7,8] S. Schneidewind,[4] M. Schrank,[1] A. Schwemmer,[7,8] M. Šefčík,[15] V. Sibille,[16] D. Siegmann,[7,8] M. Slezák,[7,8] F. Spanier,[21] M. Steidl,[1] M. Sturm,[1] H. H. Telle,[13] L. A. Thorne,[22] T. Thümmler,[1] N. Titov,[3] I. Tkachev,[3] K. Urban,[7,8] K. Valerius,[1] D. Vénos,[15] A. P. Vizcaya Hernández,[17] C. Weinheimer,[4] S. Welte,[1] J. Wendel,[1] M. Wetter,[5] C. Wiesinger,[7,8] J. F. Wilkerson,[9,10] J. Wolf,[5] S. Wüstling,[2] J. Wydra,[1] W. Xu,[16] S. Zadoroghny,[3] and G. Zeller[1]
(KATRIN Collaboration)





Enabled by a low activity phase during commissioning: arXiv:2207.06337

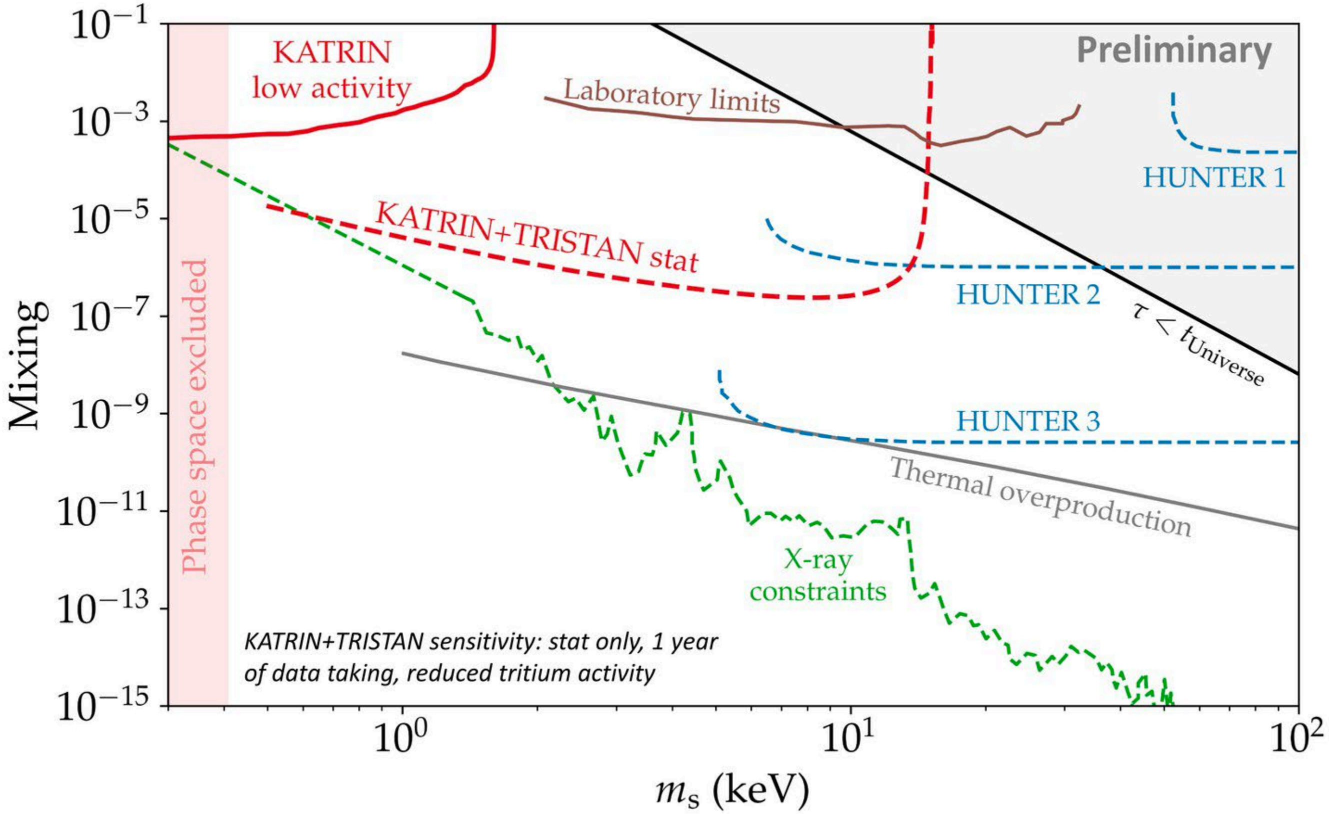
TRISTAN Sensitivity



TRISTAN project in KATRIN:

- New focal plane detector, novel multi-pixel Silicon Drift Detector array
- Large count rates
- Excellent energy resolution
- Prototypes installed as monitoring devices at KATRIN
- Target sensitivity:

  $\sin^2\theta < 10^{-6}$



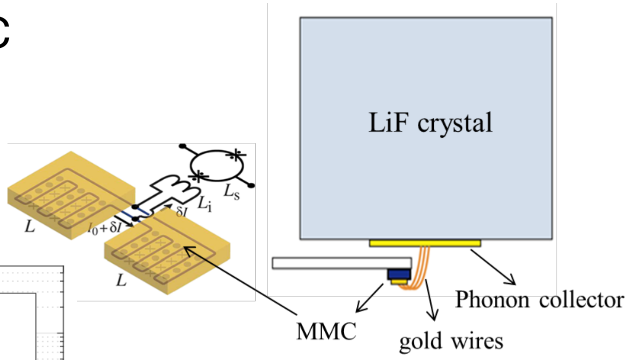
https://www.hll.mpg.de/2967603/TRISTAN

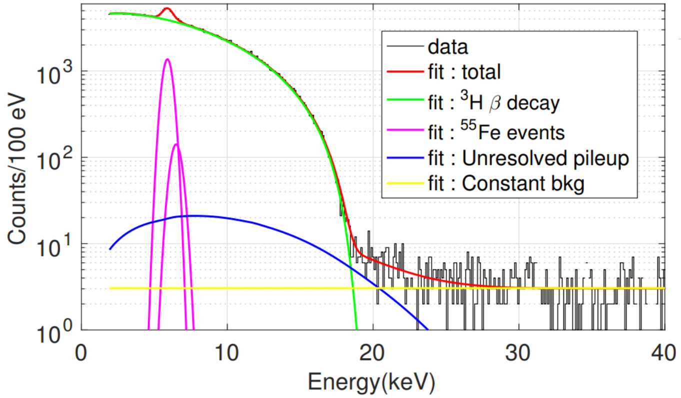
Rare Isotopes in Superconducting Sensors for keV Searches

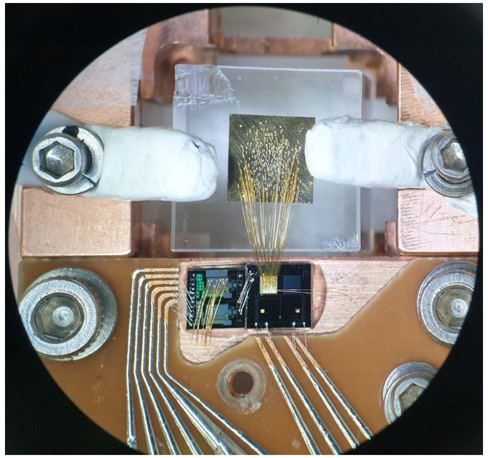
^{3}H in LiF Bolometer + MMC

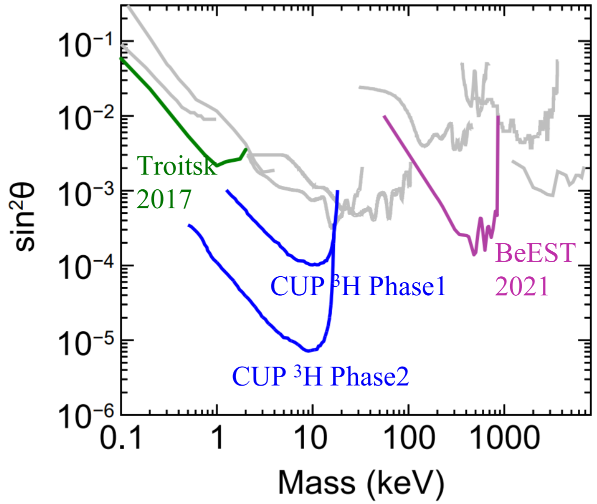
CENTER FOR UNDERGROUND PHYSICS

YC Lee, LTD-19 2021

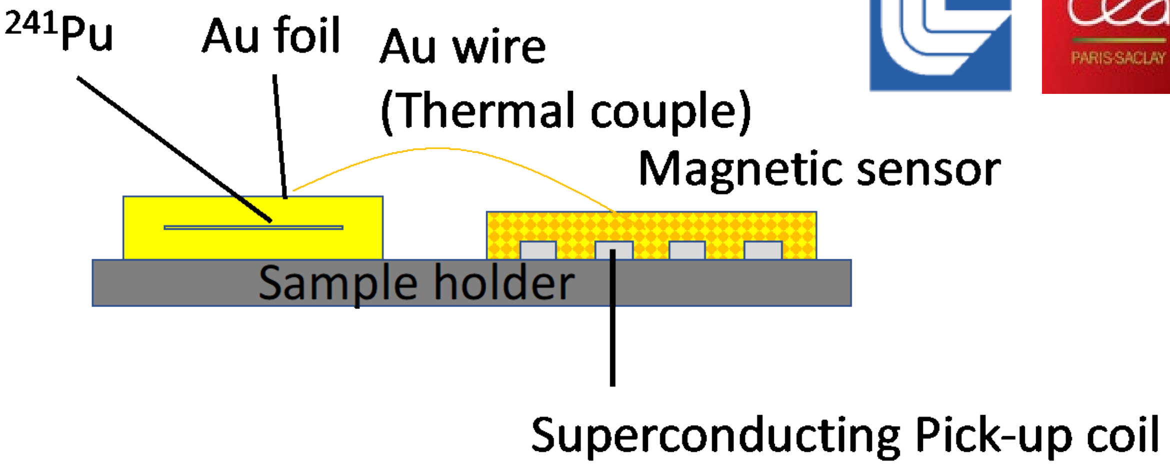


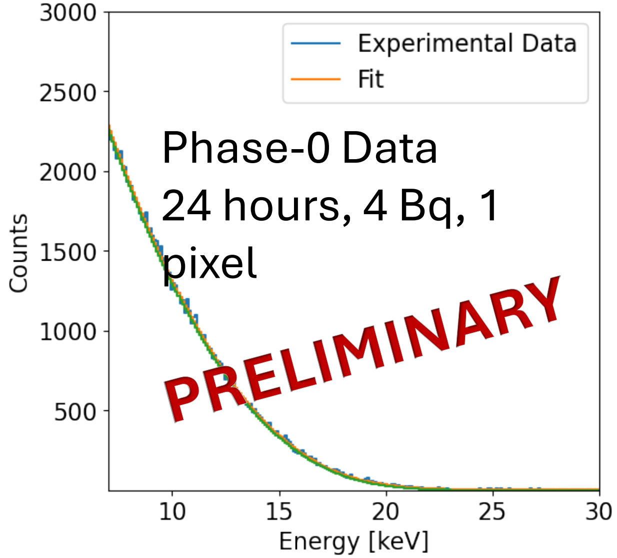


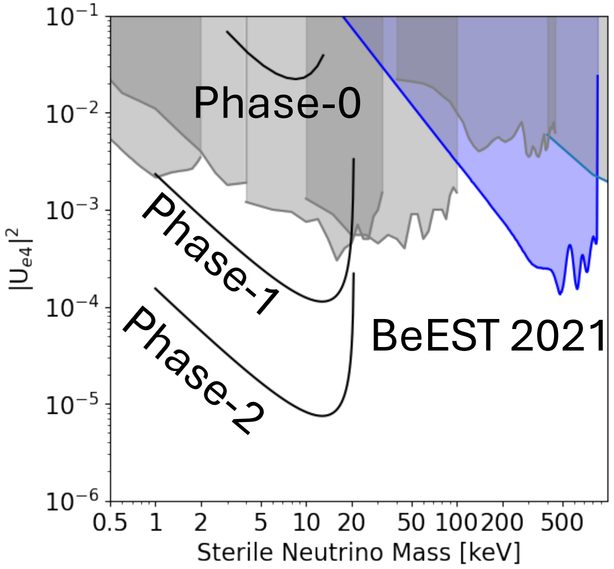




^{241}Pu in Au + MMC : Magneto-ν Experiment

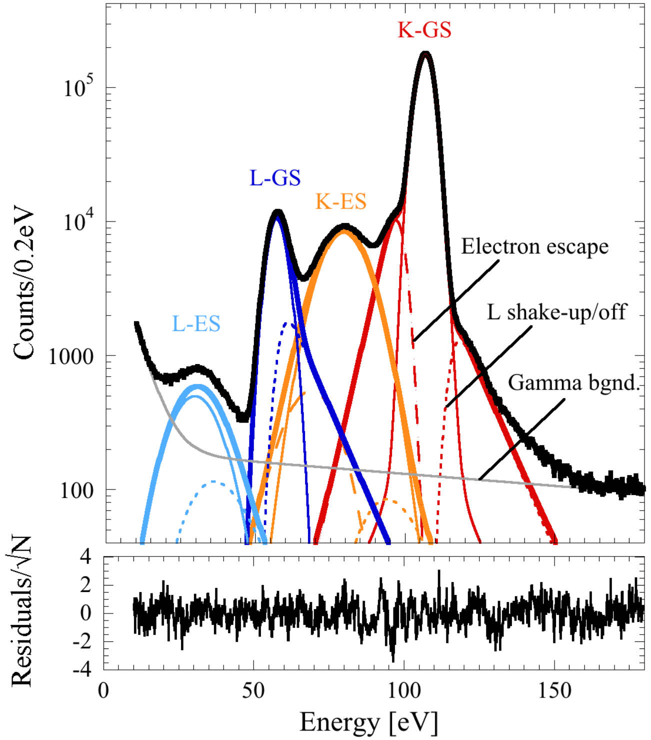




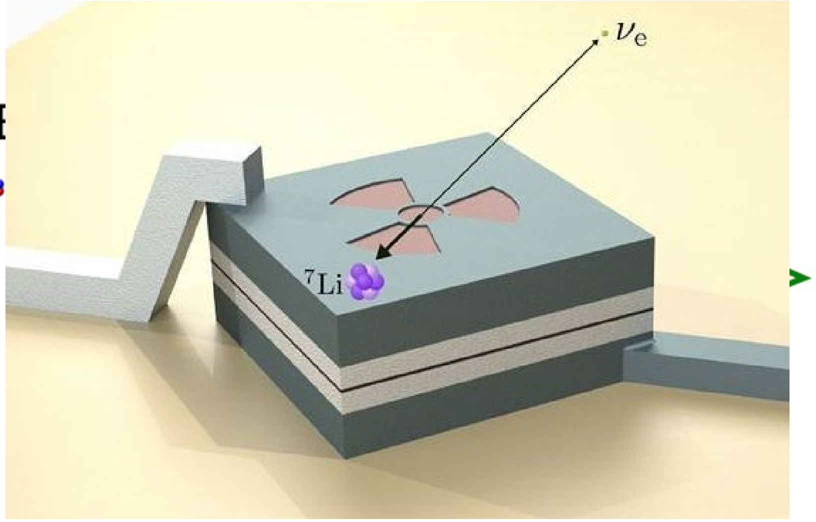


^{7}Be EC Decay - The BeEST Experiment

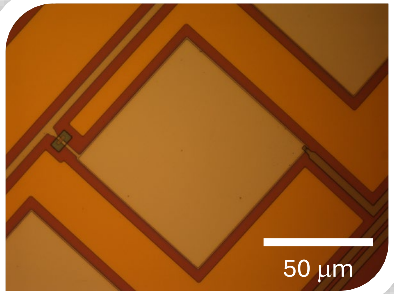
Rare-isotope implantation at TRIUMF-ISAC

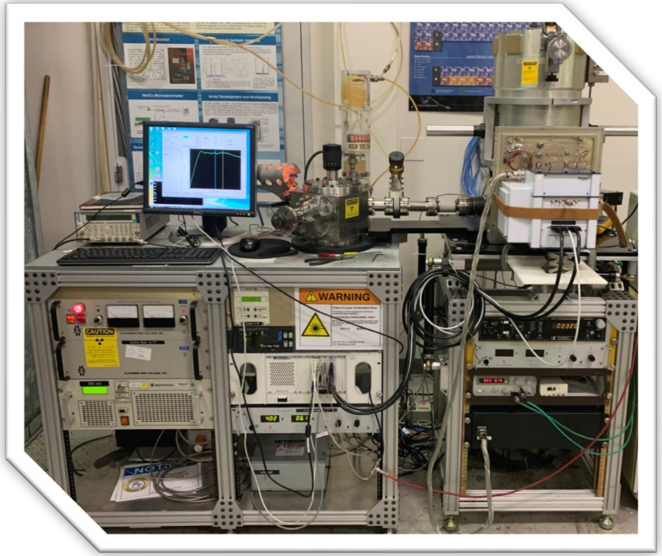


A. Samanta *et al.*, Phys. Rev. Mat. (*in press*) (2022)
S. Friedrich *et al.*, J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al.*, J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al.*, J. Low Temp. Phys. **200**, 200 (2020)



Ta, Al, and Nb-based STJ Sensors





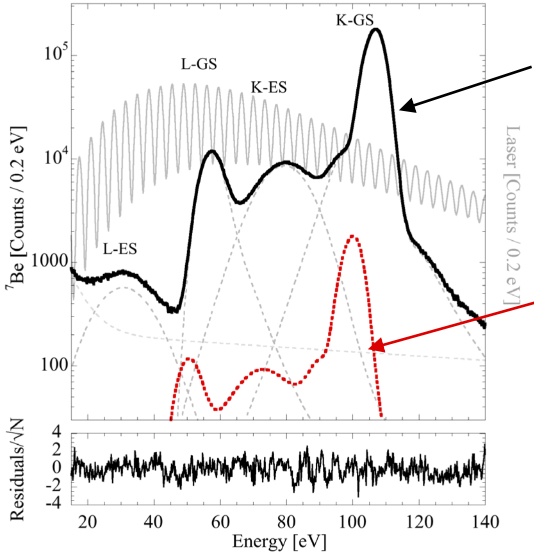
First Limits from “Low-Rate” Phase-II Data

PHYSICAL REVIEW LETTERS **126,** 021803 (2021)

Limits on the Existence of sub-MeV Sterile Neutrinos from the Decay of ^{7}Be in Superconducting Quantum Sensors

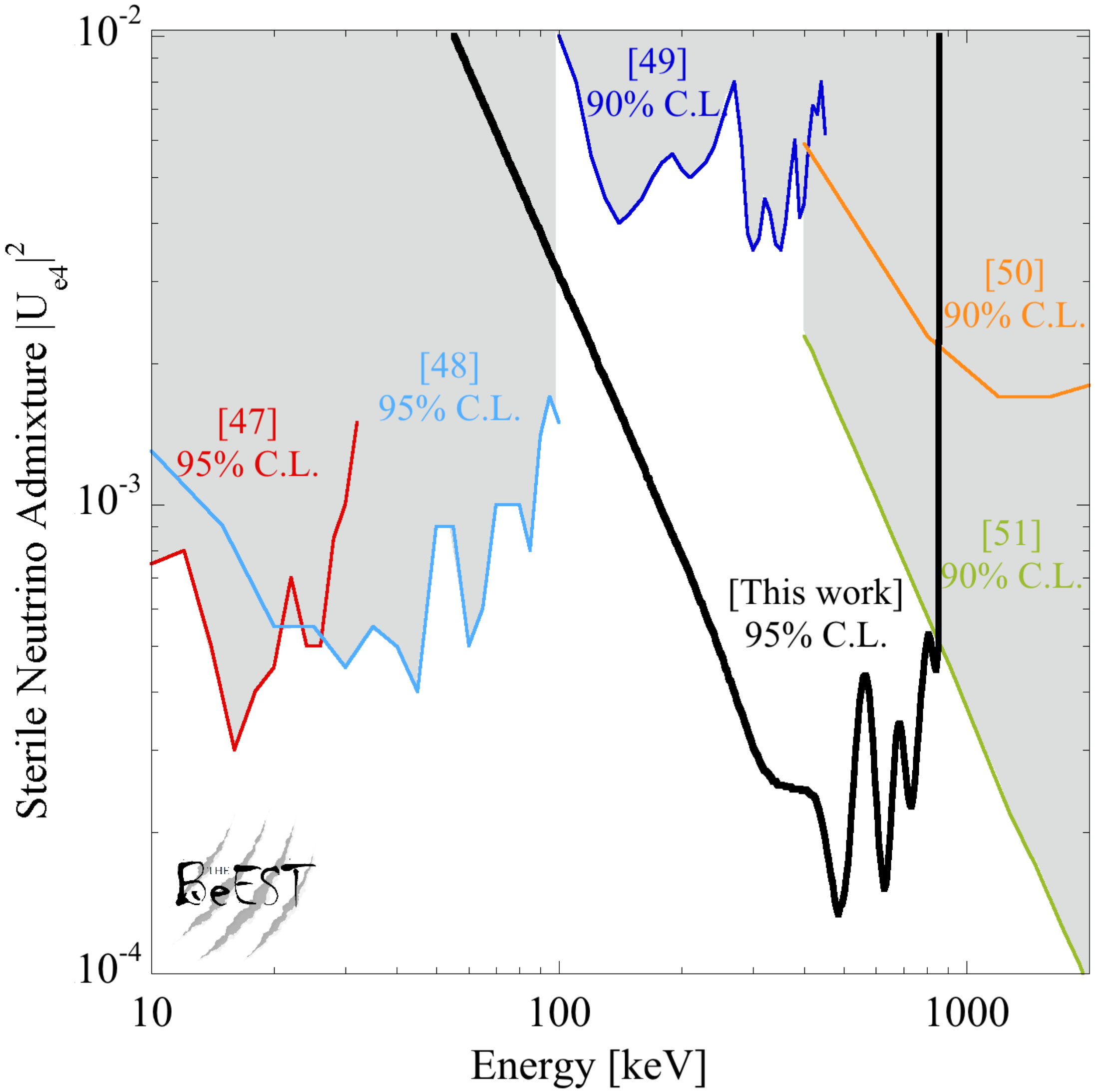
S. Friedrich,[1,*] G. B. Kim,[1] C. Bray,[2] R. Cantor,[3] J. Dilling,[4] S. Fretwell,[2] J. A. Hall,[3] A. Lennarz,[4,5] V. Lordi,[1] P. Machule,[4] D. McKeen,[4] X. Mougeot,[6] F. Ponce,[7,1] C. Ruiz,[4] A. Samanta,[1] W. K. Warburton,[8] and K. G. Leach[2,†]

Phase-II data from a single 138x138 μm² STJ counting at low rate (~10 Bq) for 28 days



Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

Example of signal that would be generated by 300 keV neutrino with 1% mixing



Future Projections for keV-MeV Mass Searches

- Nuclear decay provides a powerful, model-independent probe in the keV – MeV mass range
- Significant progress in measurements over the past 3 years – enabled by quantum sensing
- Experiments poised to increase sensitivity by 5+ orders of magnitude in the next decade

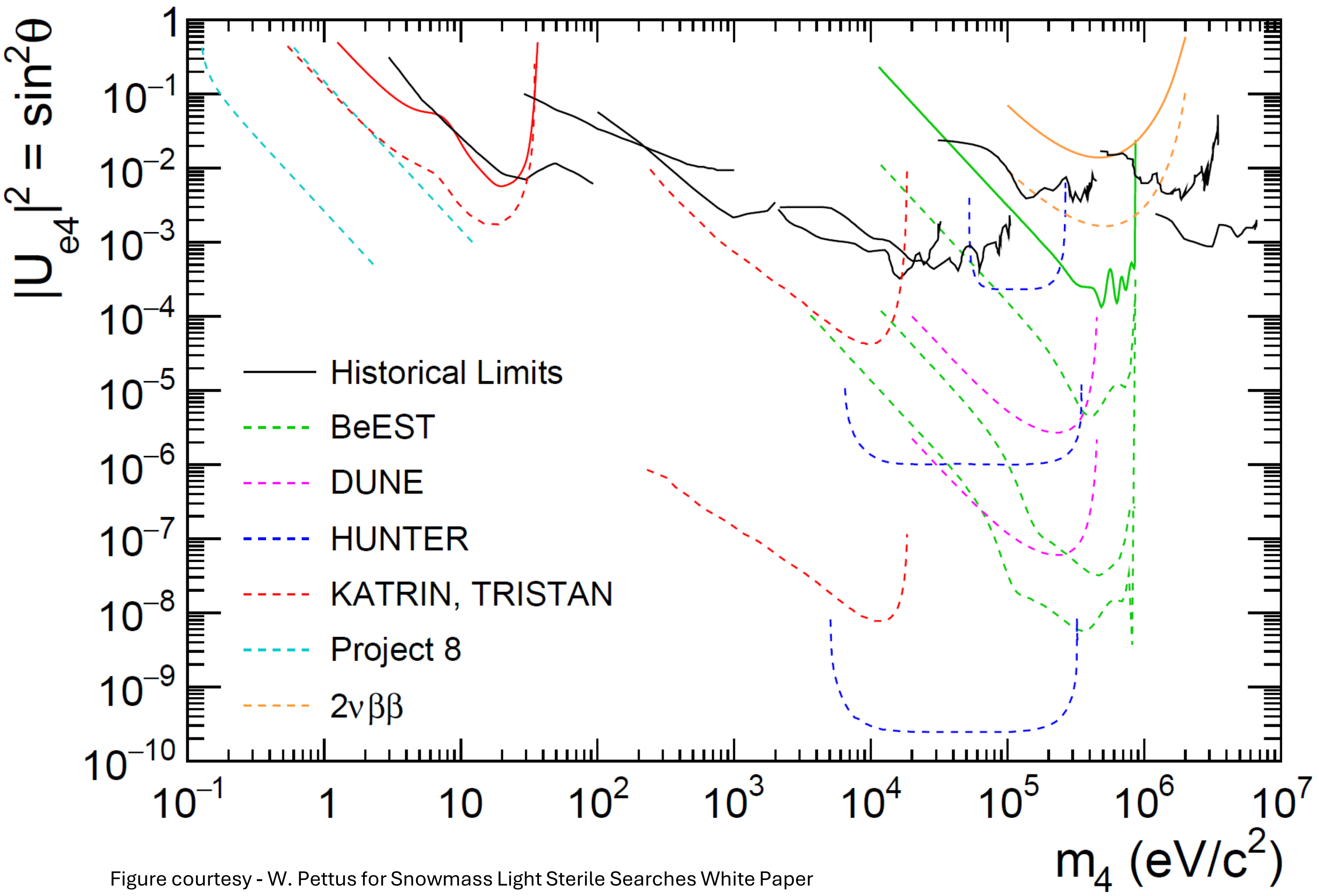
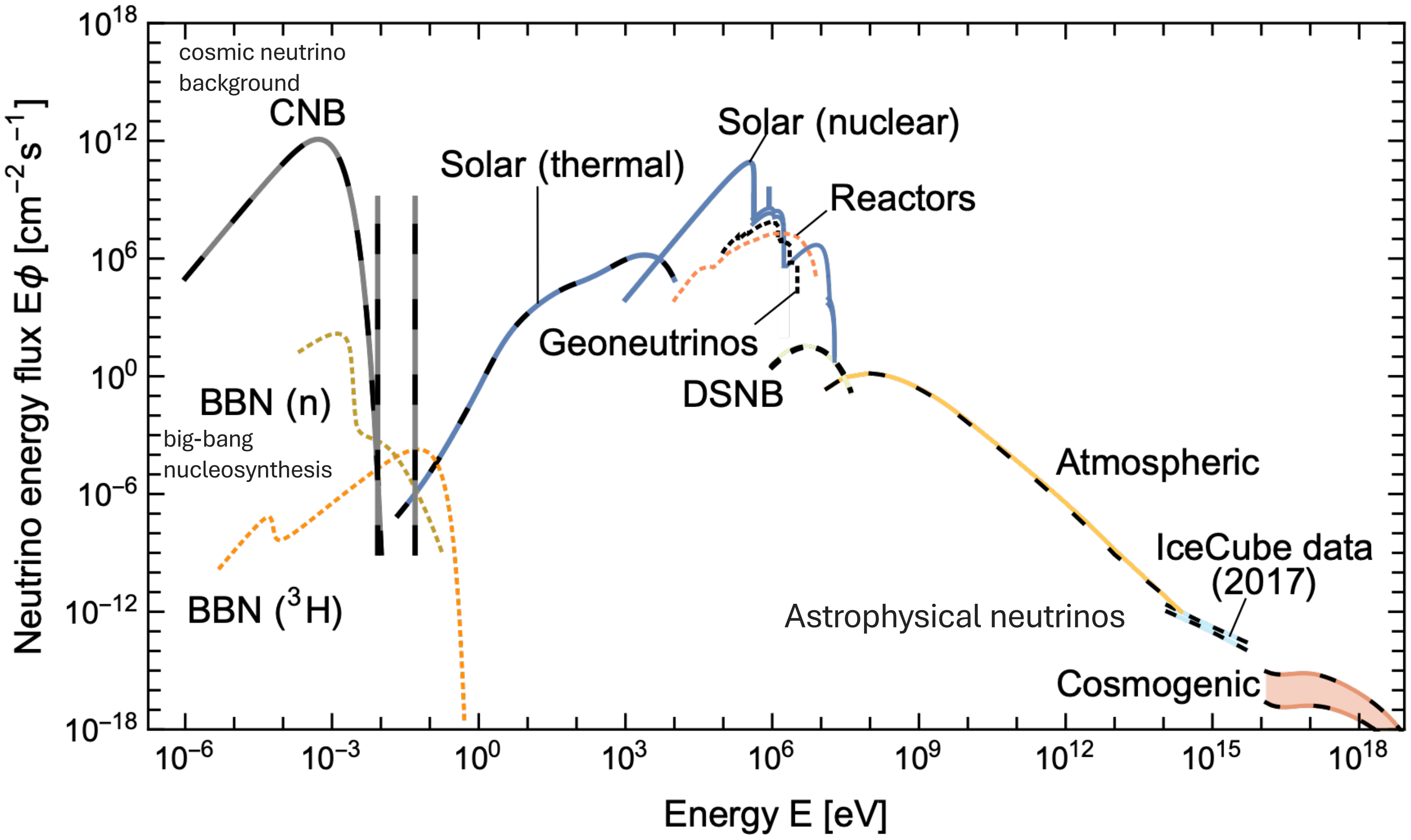


Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper

The following slides were adopted from slides from Michelle Dolinski, Francis Halzen, and Carsten Krauss

Image from https://news.stanford.edu/stories/2022/09/power-awe-cosmos

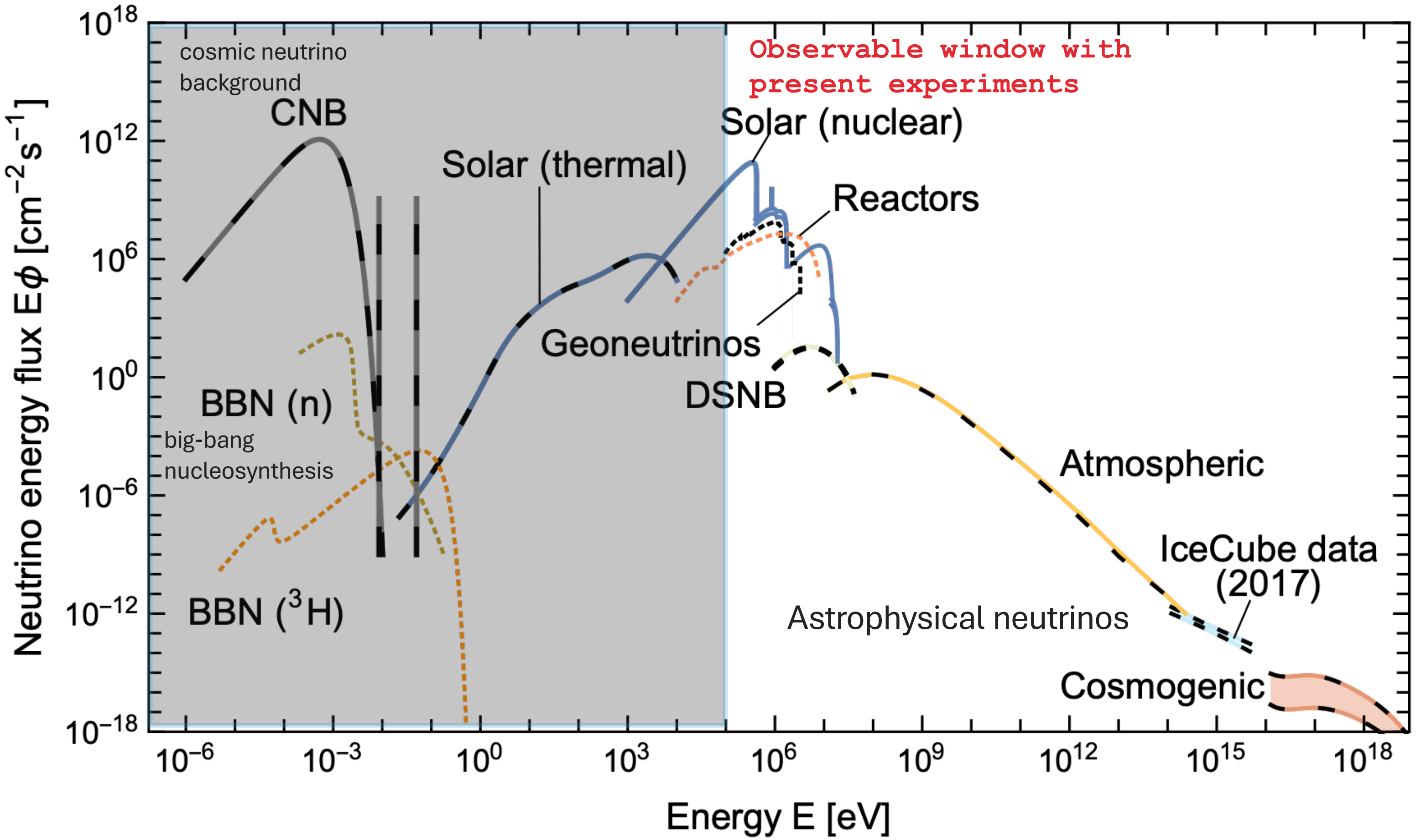
Neutrinos from the Universe



Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavours

modified from Vitagliano, Tamborra and Raffelt, Rev.Mod.Phys 2019, arXiv:1910.11878

Neutrinos from the Universe



Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavours

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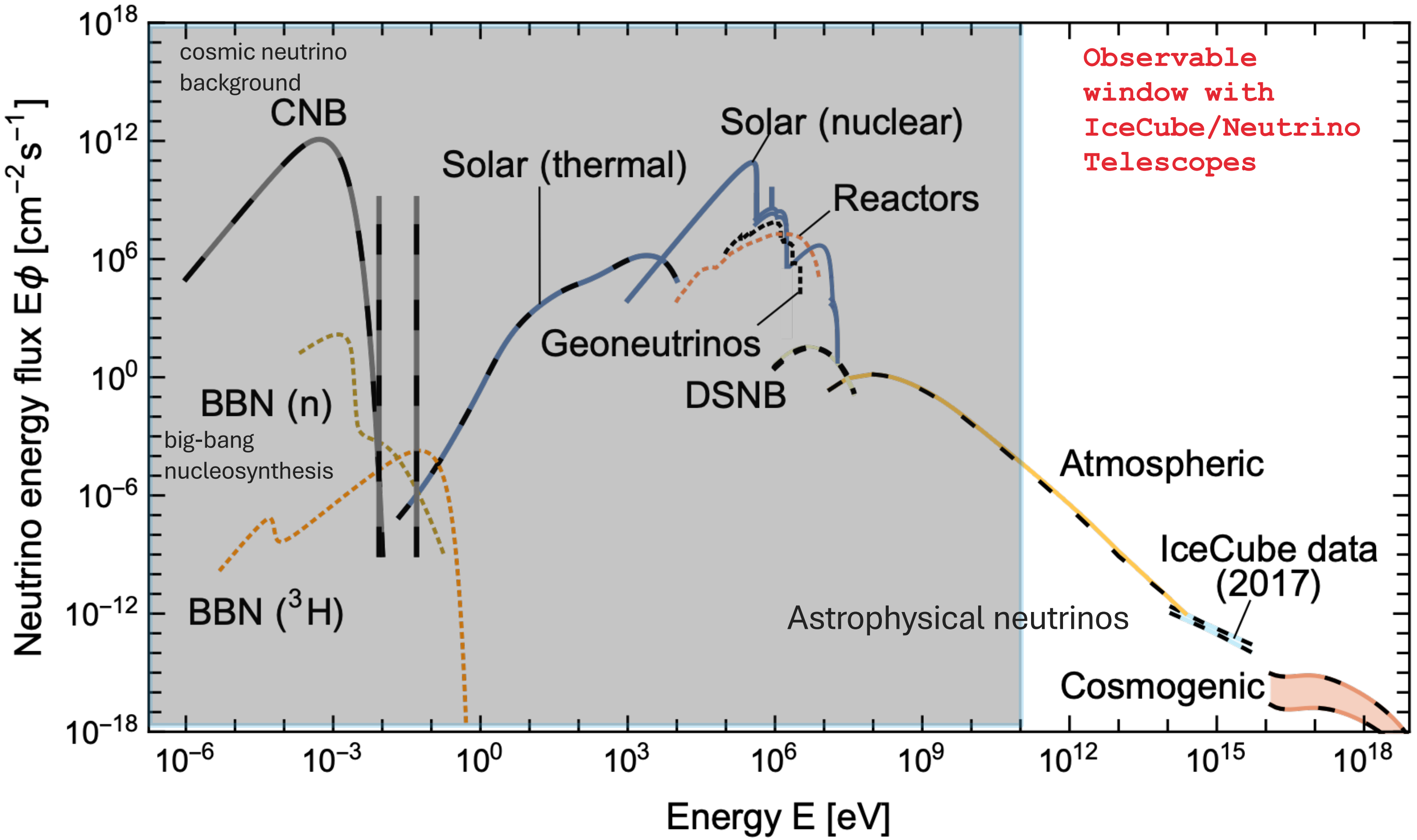
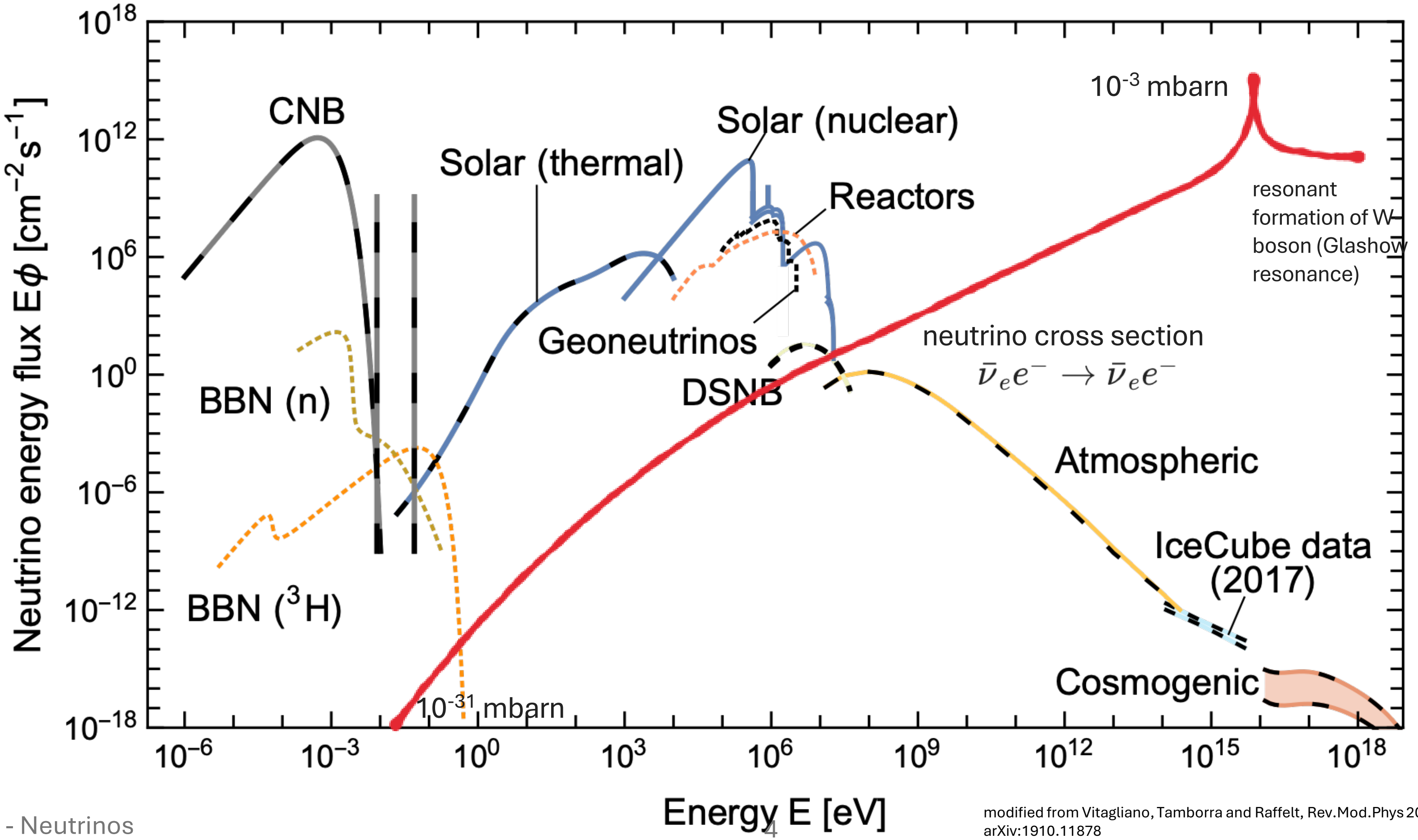
Neutrinos from the Universe



Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavours

modified from Vitagliano, Tamborra and Raffelt, Rev.Mod.Phys 2019, arXiv:1910.11878

Neutrinos from the Universe

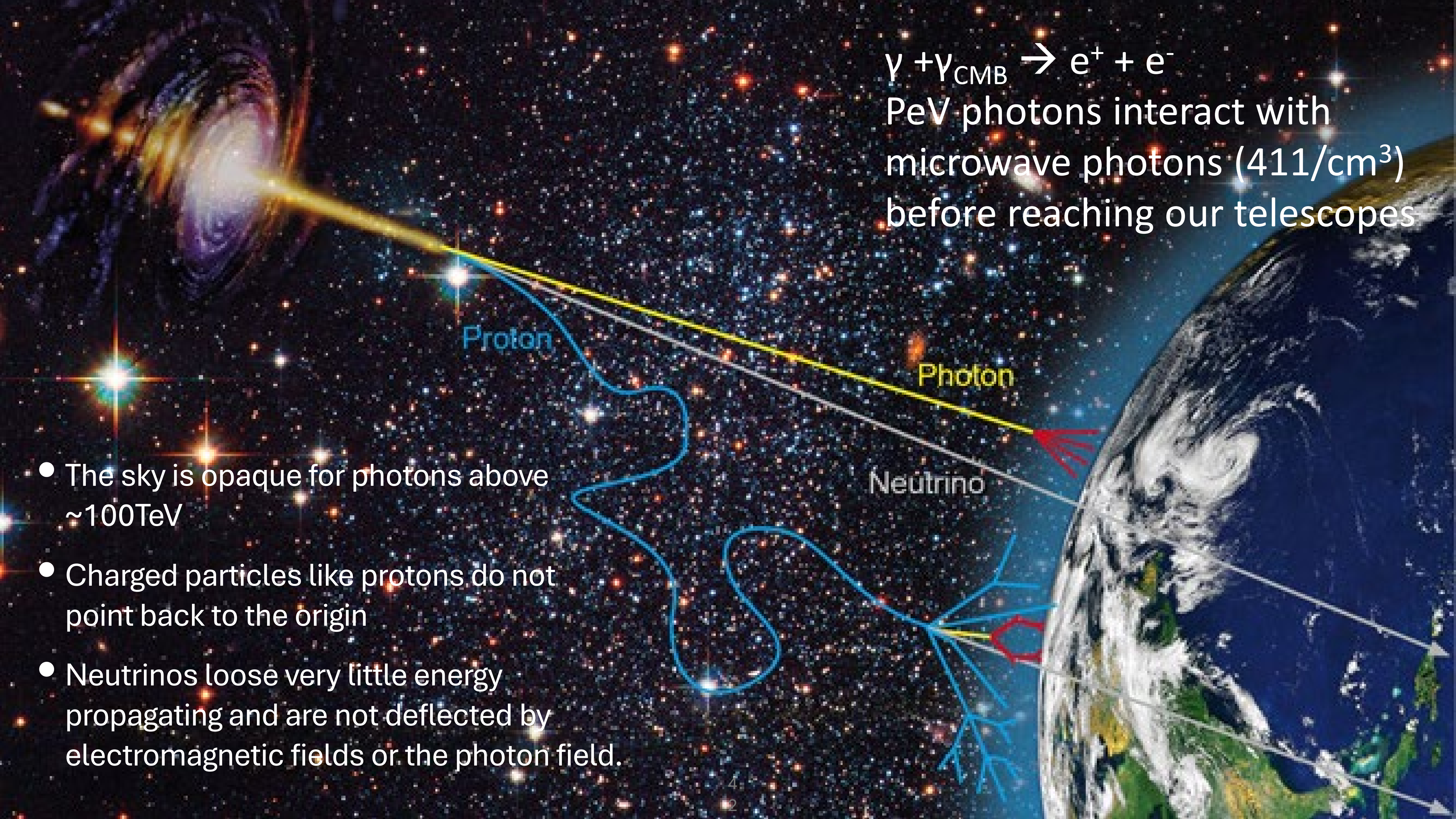


modified from Vitagliano, Tamborra and Raffelt, Rev.Mod.Phys 2019, arXiv:1910.11878

Formaggio, Zeller, Rev. Mod. Phys. 2012, arXiv:1305.7513

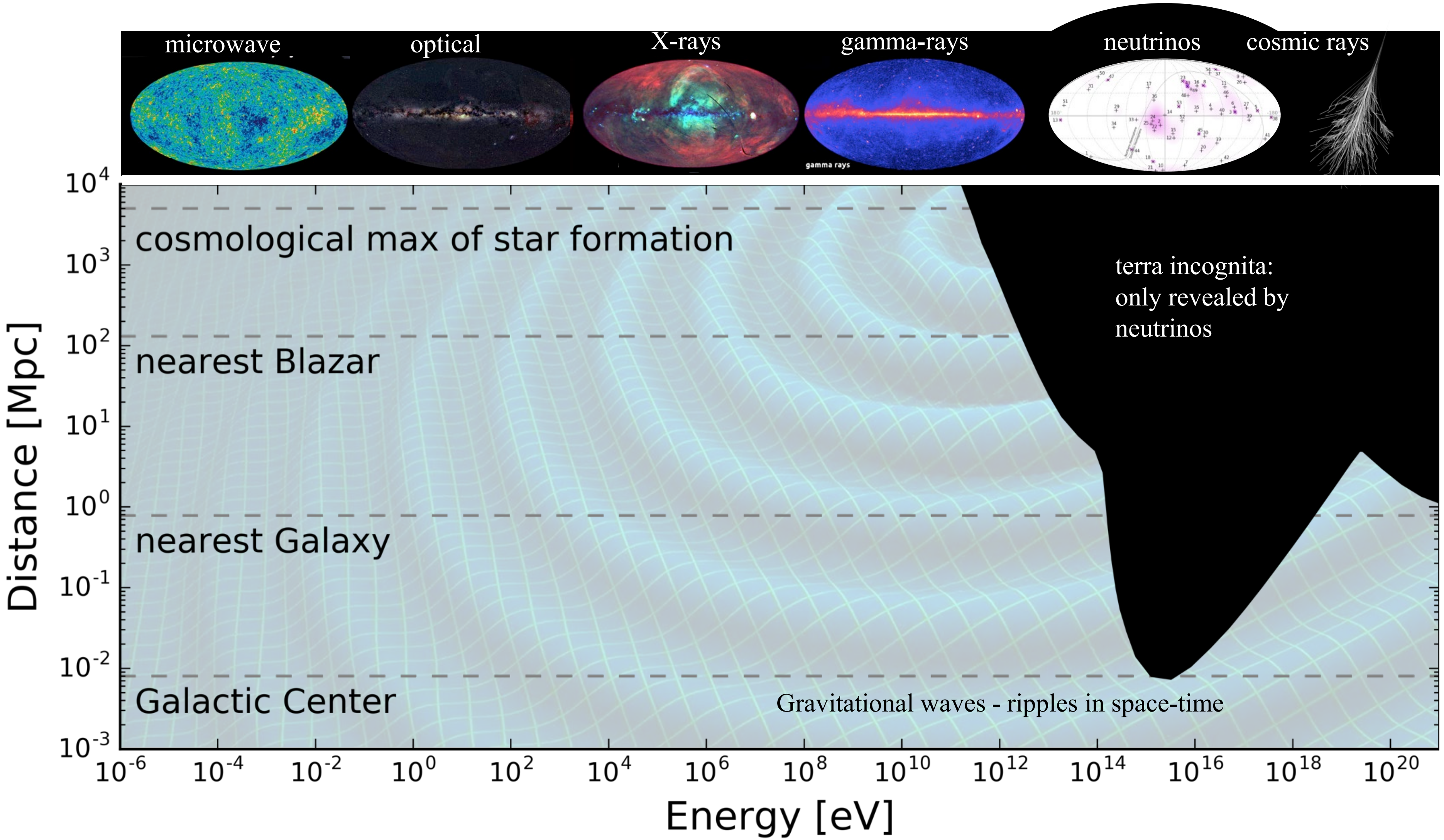
$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$

PeV photons interact with microwave photons (411/cm^3) before reaching our telescopes



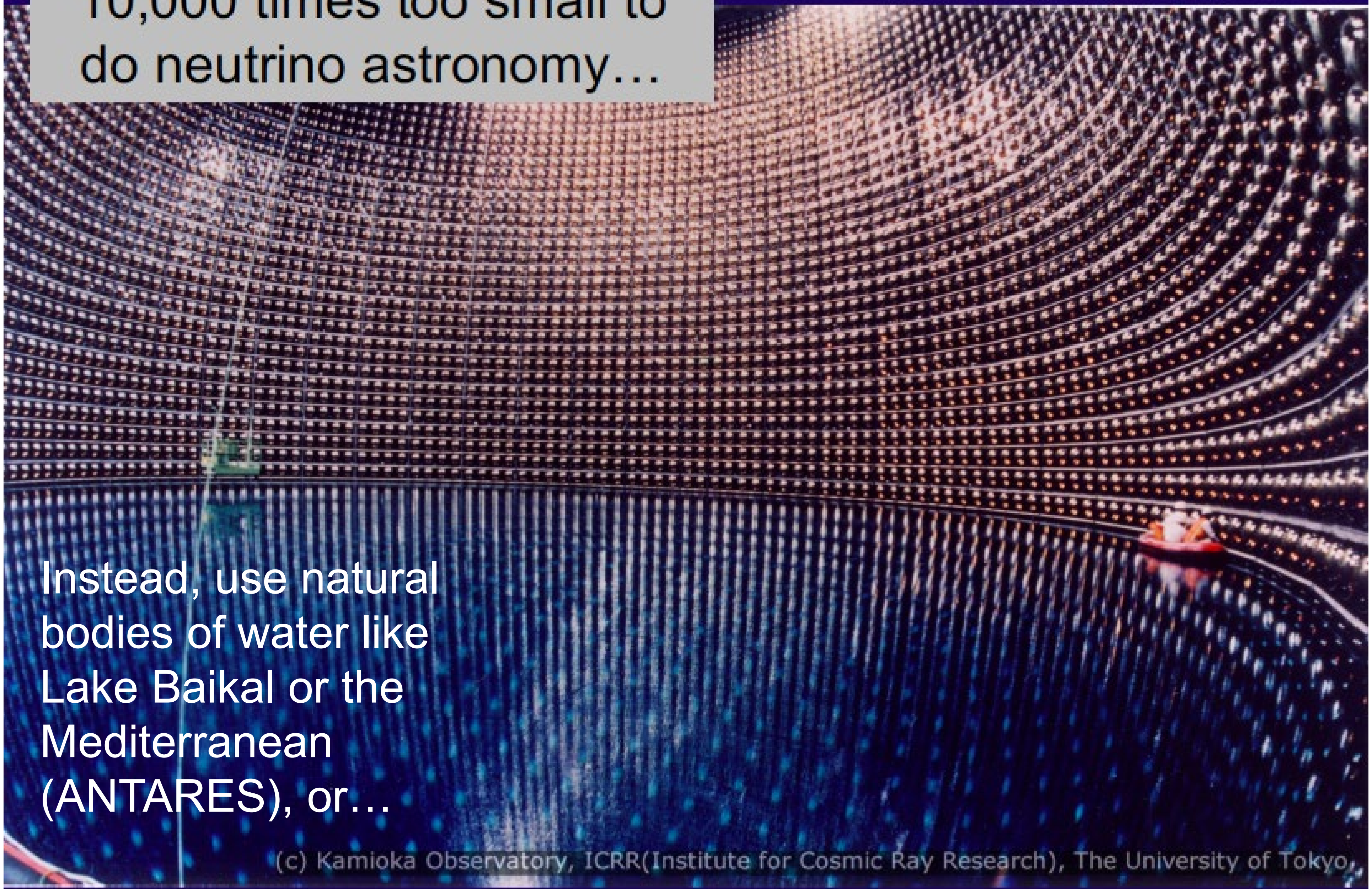
- The sky is opaque for photons above ~100TeV
- Charged particles like protons do not point back to the origin
- Neutrinos loose very little energy propagating and are not deflected by electromagnetic fields or the photon field.

highest energy "radiation" from the Universe: neutrinos and cosmic rays



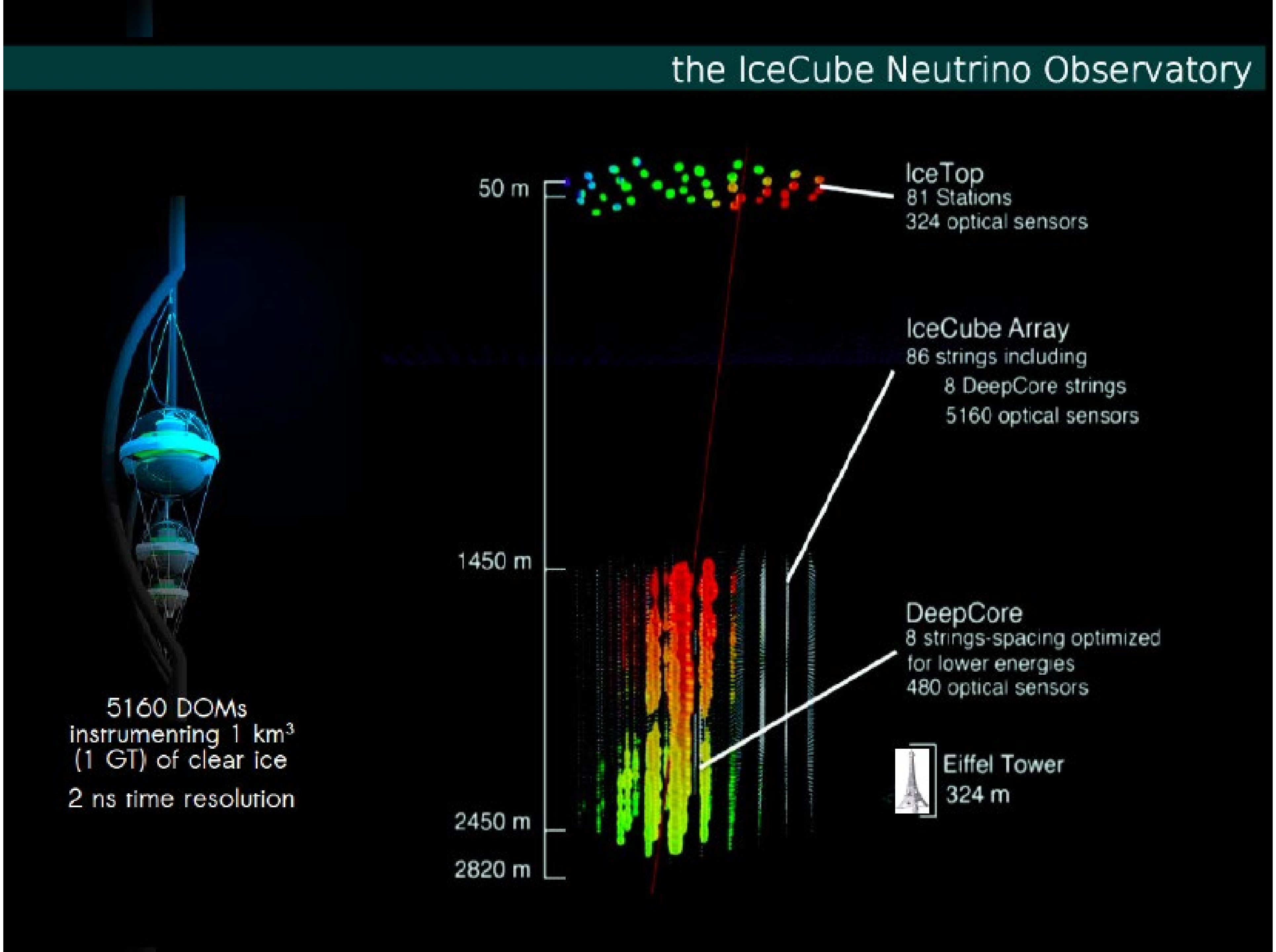
Universe is opaque above ~100 TeV energy

10,000 times too small to do neutrino astronomy…

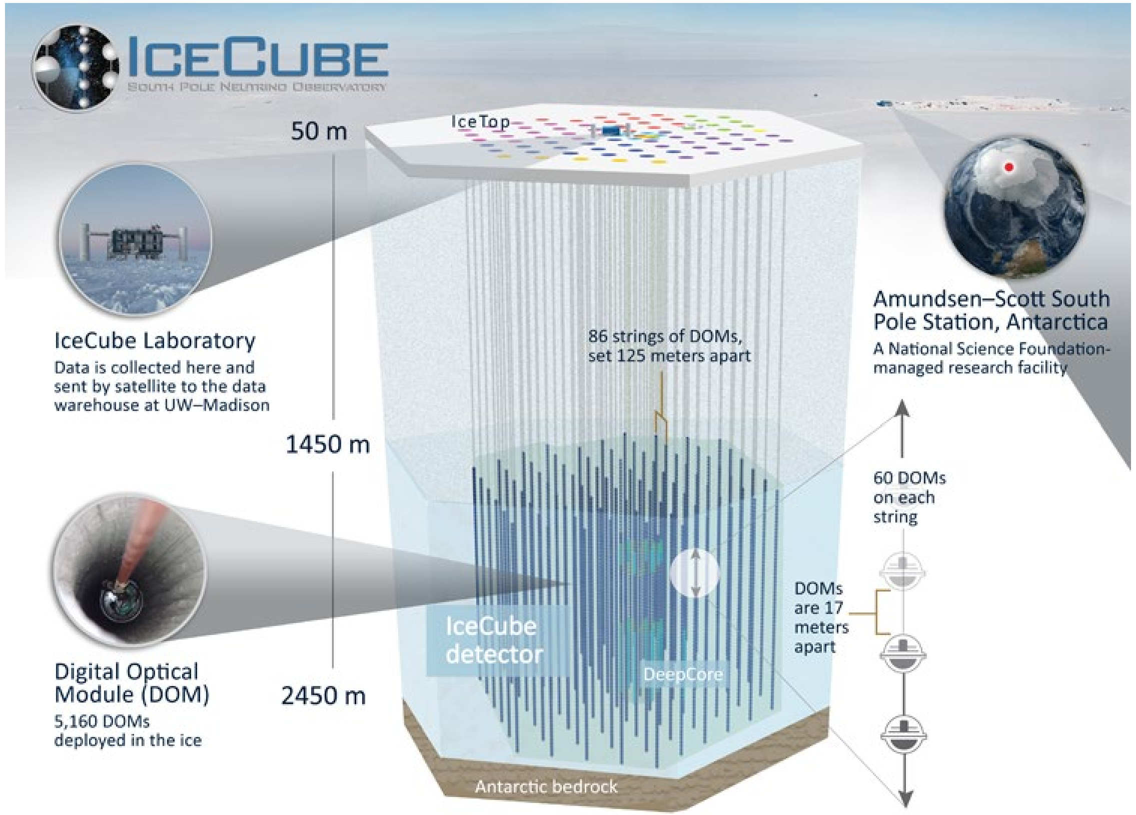


Instead, use natural bodies of water like Lake Baikal or the Mediterranean (ANTARES), or…

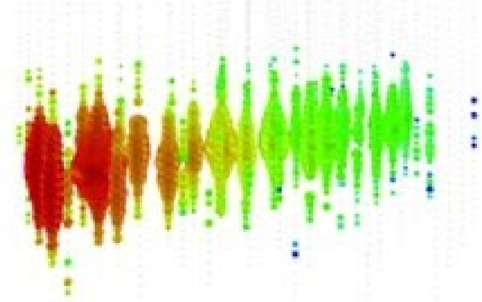

ultra-transparent ice below 1.5 km


the IceCube Neutrino Observatory
50 m
1450 m
2450 m
2820 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including
8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized
for lower energies
480 optical sensors
Eiffel Tower
324 m
5160 DOMs
instrumenting 1 km³
(1 GT) of clear ice
2 ns time resolution

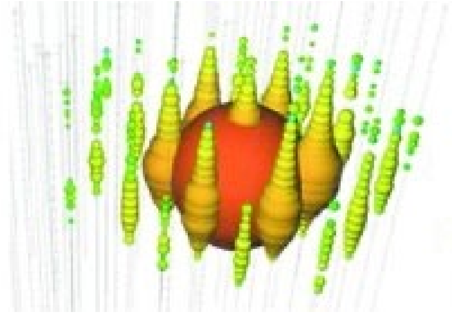
IceCube & DeepCore



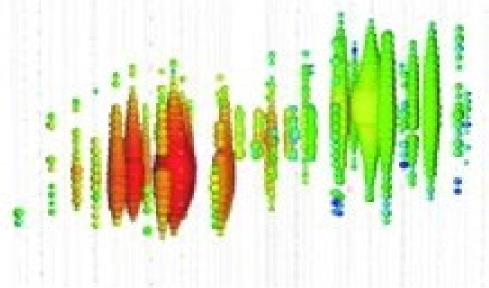
Muon Track



Electron Cascade

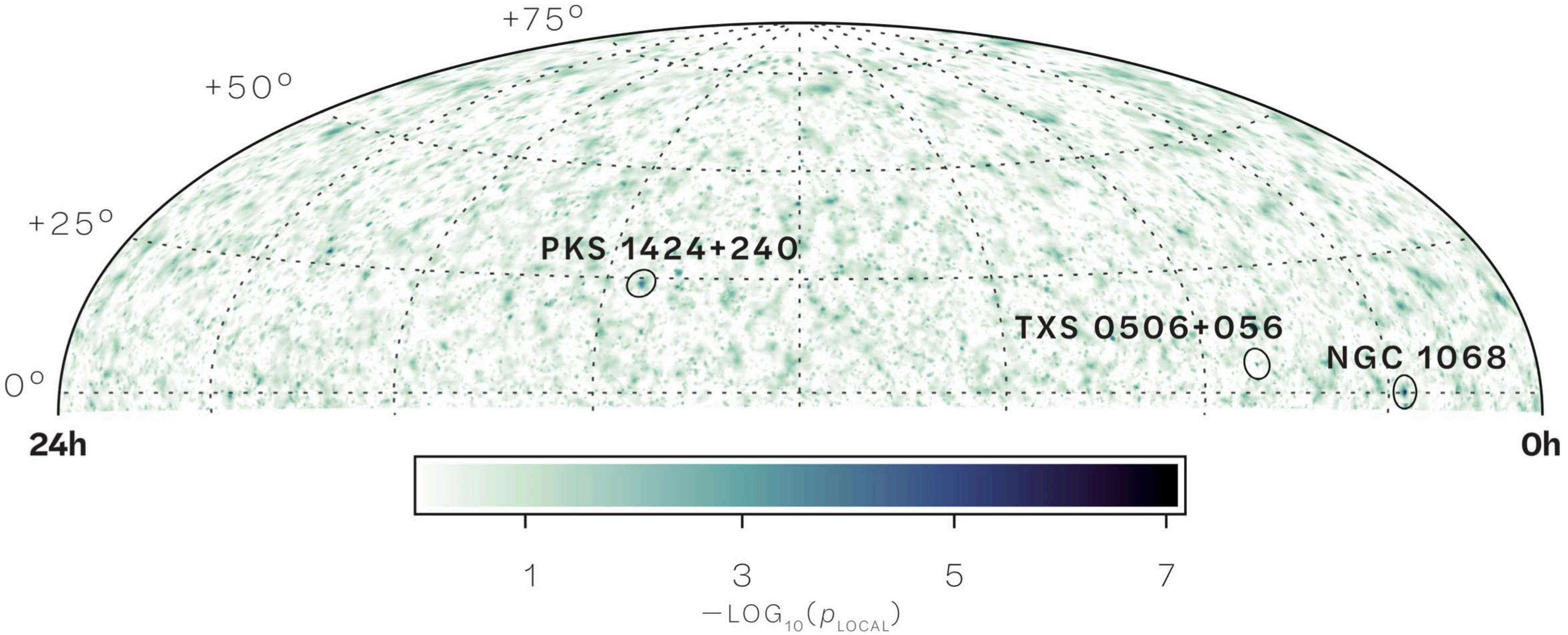


Tau “Double Bang”



- Completed in 2011

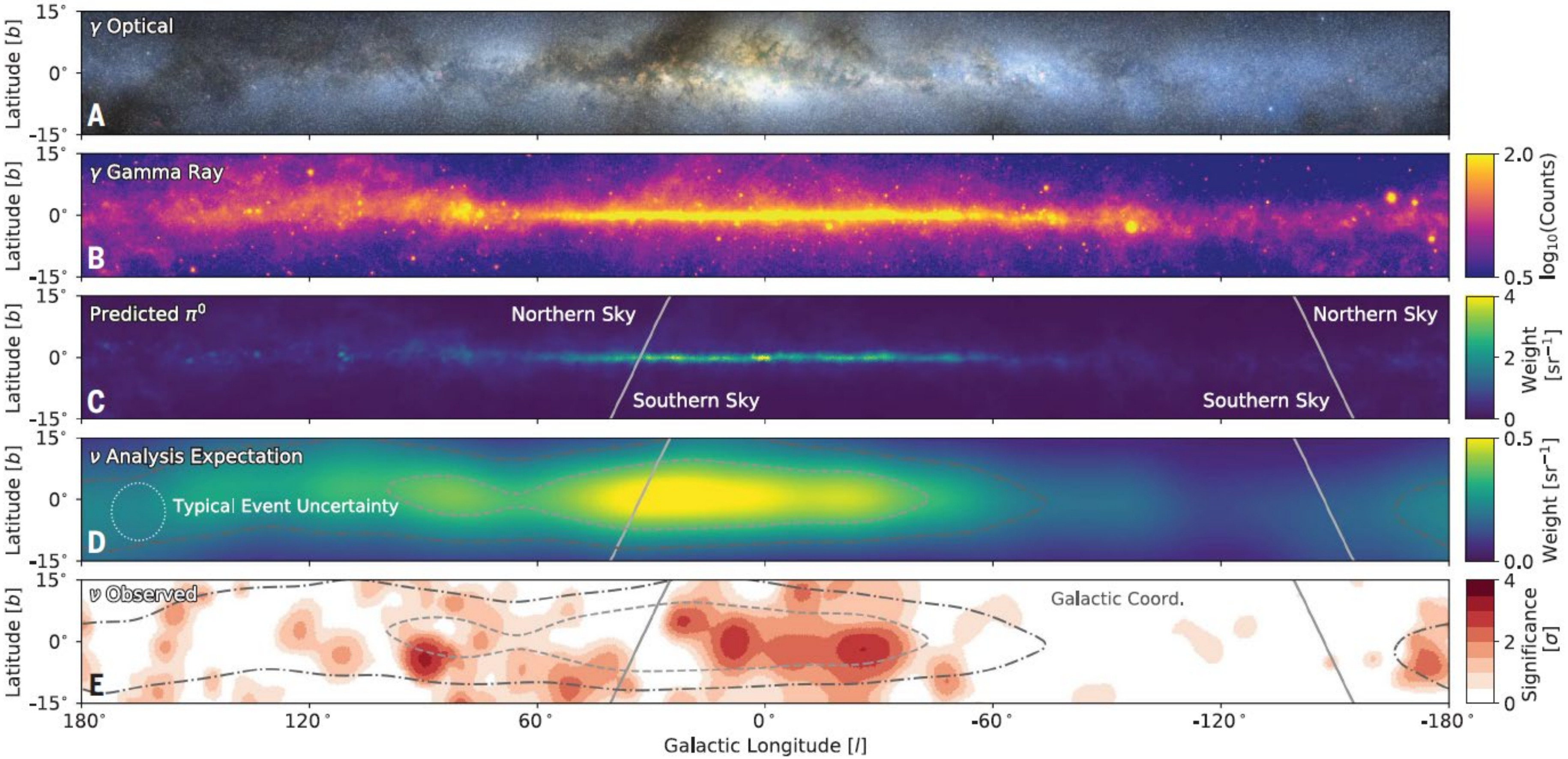
Search for Neutrino Sources



- The first neutrino sources have been identified using IceCube!

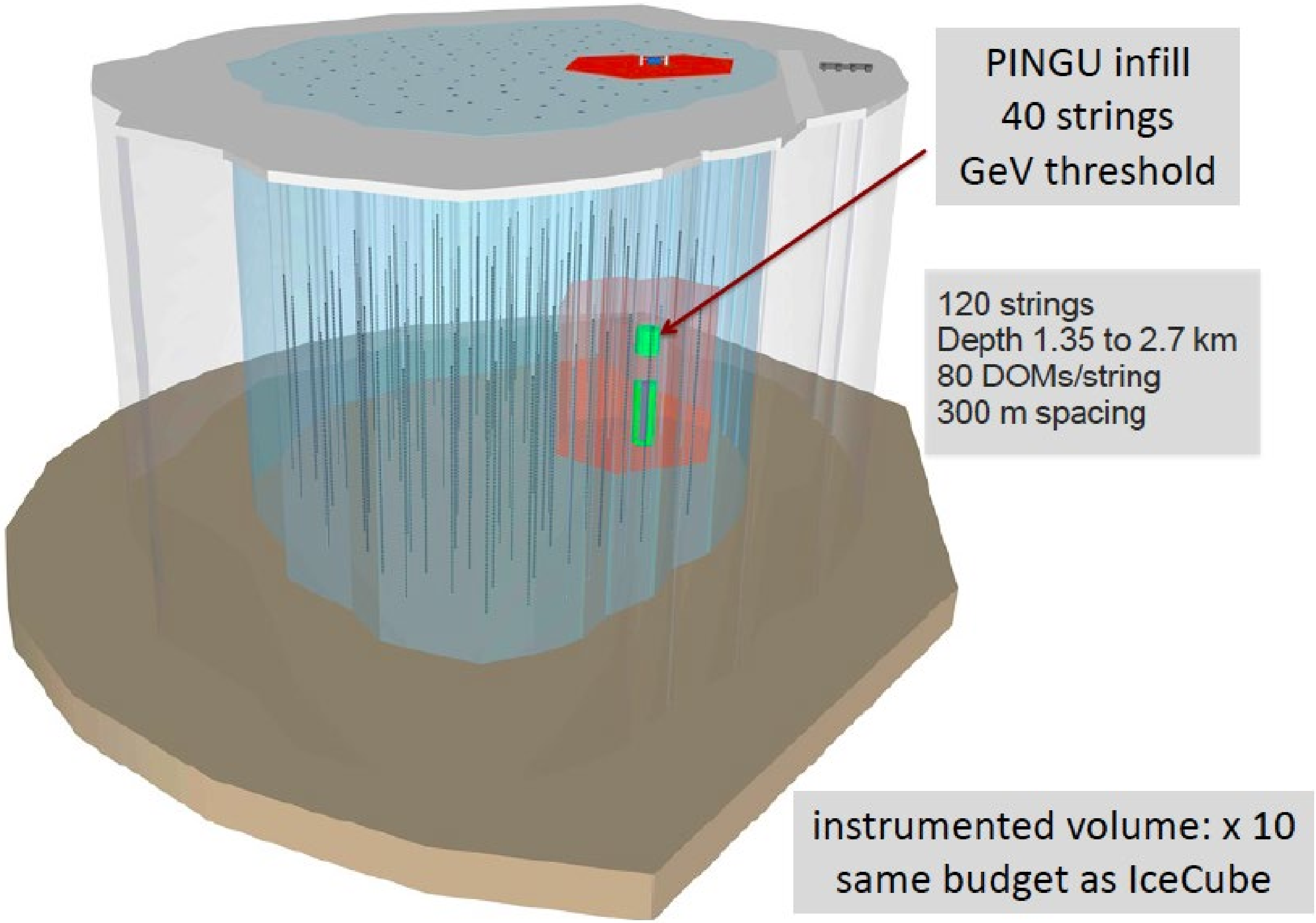
Science 378, 6619, 538-543 (2022)

Observation of high-energy neutrinos from the Galactic plane with IceCube



Science 380, 1338–1343 (2023)

The future of IceCube



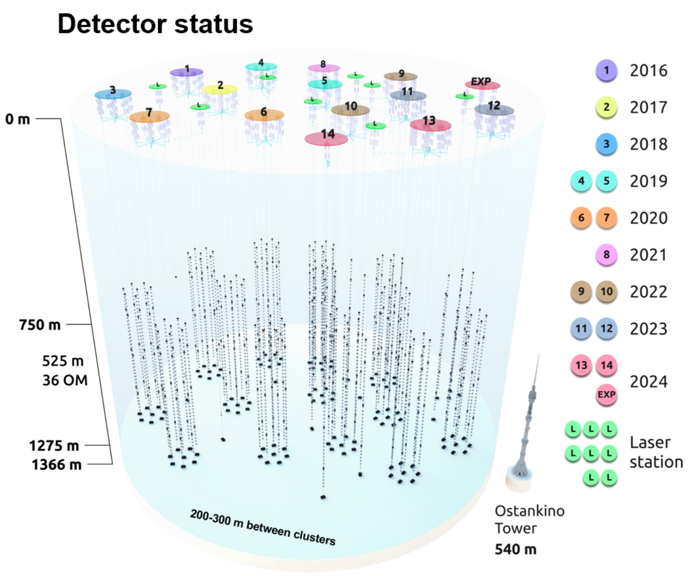
Up-and-coming neutrino telescopes

Baikal-GVD neutrino telescope

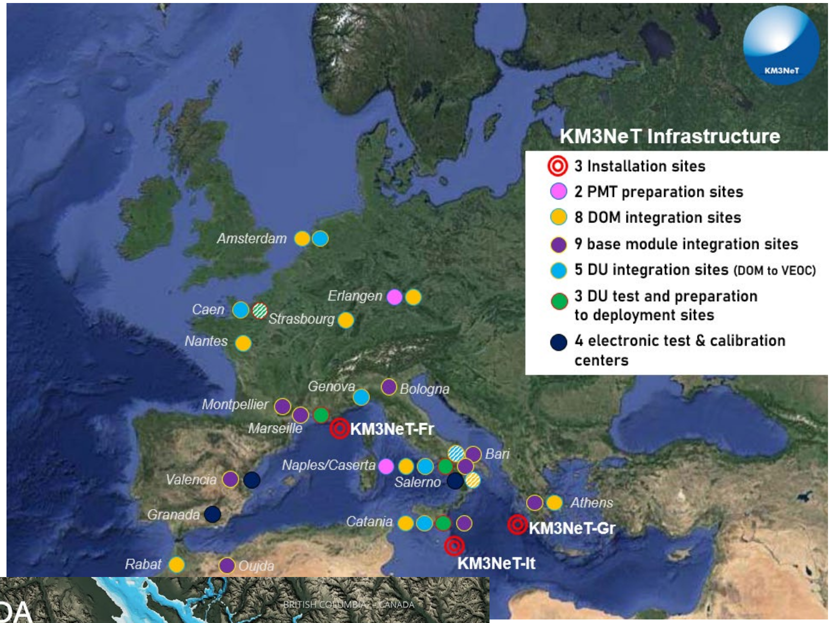
Presently detector consists of 110 strings arranged into 14 independent detectors - **clusters**
- 3960 OMs in total

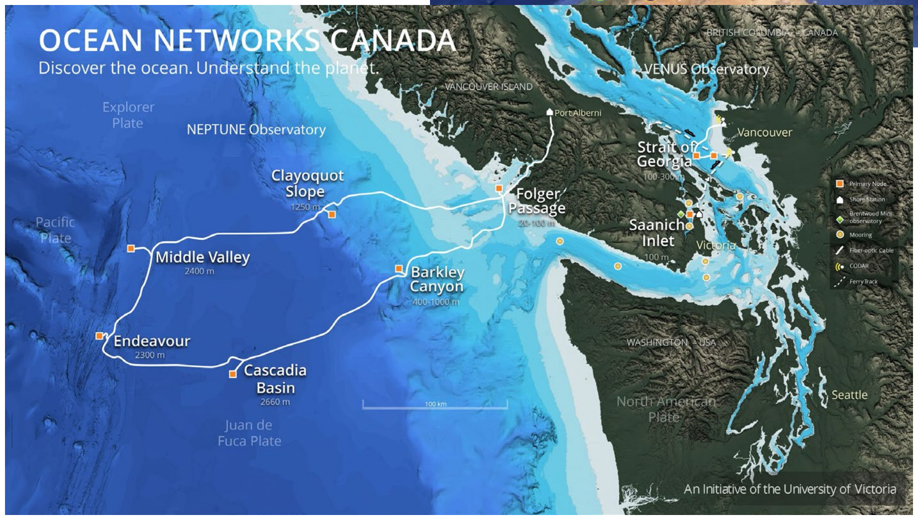
Baikal-GVD cluster:
- 8 regular strings, 525 m is instrumented with optical modules (OM)
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs
- Has its own control, trigger and readout systems

Additional cluster "EXP":
- 4 strings with experimental high-speed DAQ



KM3NeT in Europe





P-ONE

P-ONE

- Alberta, Queen’s, SFU, TRIUMF, TUM, Erlangen (Germany) and Drexel, Maryland, MSU (USA), Krakow (Poland), UCL (UK) Collaboration

- Started in 2018 with the deployment of a test setup to assess the water quality

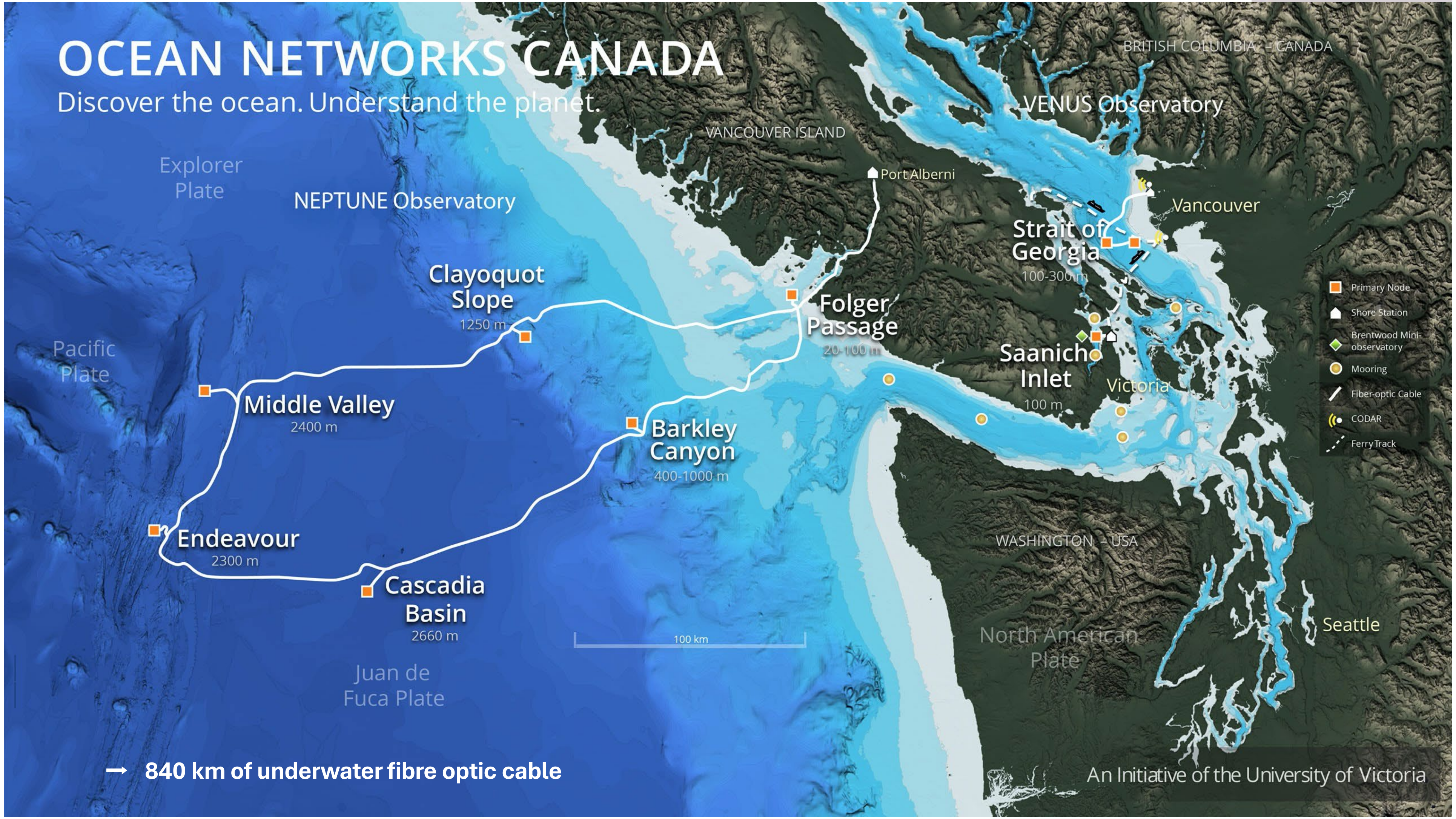
- Significant funding in Germany for the first strings was secured in 2022

- The first US, Canadian and Polish funding was also secured in 2022, allowing for a robust effort to start prototype development and testing

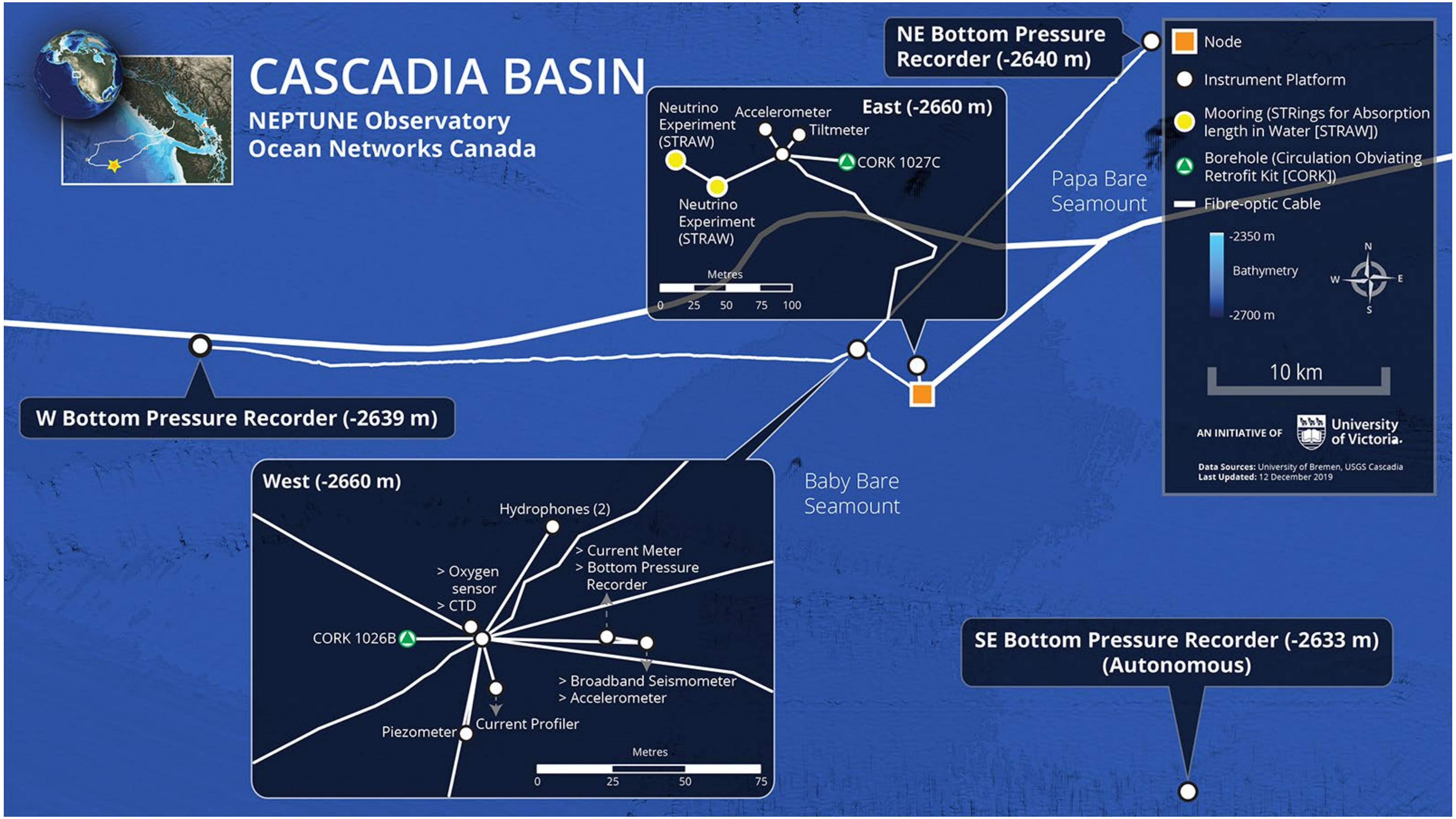
The Cascadia Basin Site

https://www.facebook.com/OceanNetworksCanada/videos/1200365743665048/

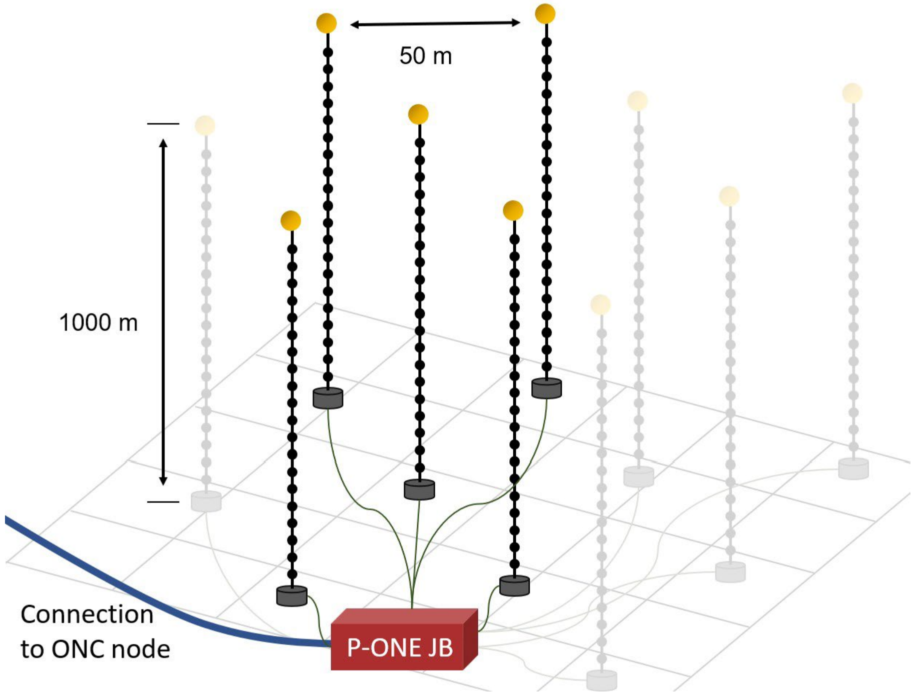
ONC


OCEAN NETWORKS CANADA
Discover the ocean. Understand the planet.
BRITISH COLUMBIA - CANADA
VENUS Observatory
VANCOUVER ISLAND
Explorer Plate
NEPTUNE Observatory
Port Alberni
Vancouver
Strait of Georgia
100-300 m
Clayoquot Slope
1250 m
Folger Passage
20-100 m
Pacific Plate
Saanich Inlet
100 m
Victoria
Middle Valley
2400 m
Barkley Canyon
400-1000 m
Primary Node
Shore Station
Brentwood Mini-observatory
Mooring
Fiber-optic Cable
CODAR
Ferry Track
Endeavour
2300 m
WASHINGTON - USA
Cascadia Basin
2660 m
100 km
Seattle
North American Plate
Juan de Fuca Plate
840 km of underwater fibre optic cable
An Initiative of the University of Victoria

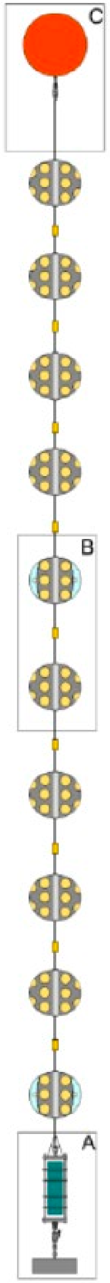
Cascadia Basin Site



Pacific Ocean Neutrino Experiment (P-ONE) Demonstrator

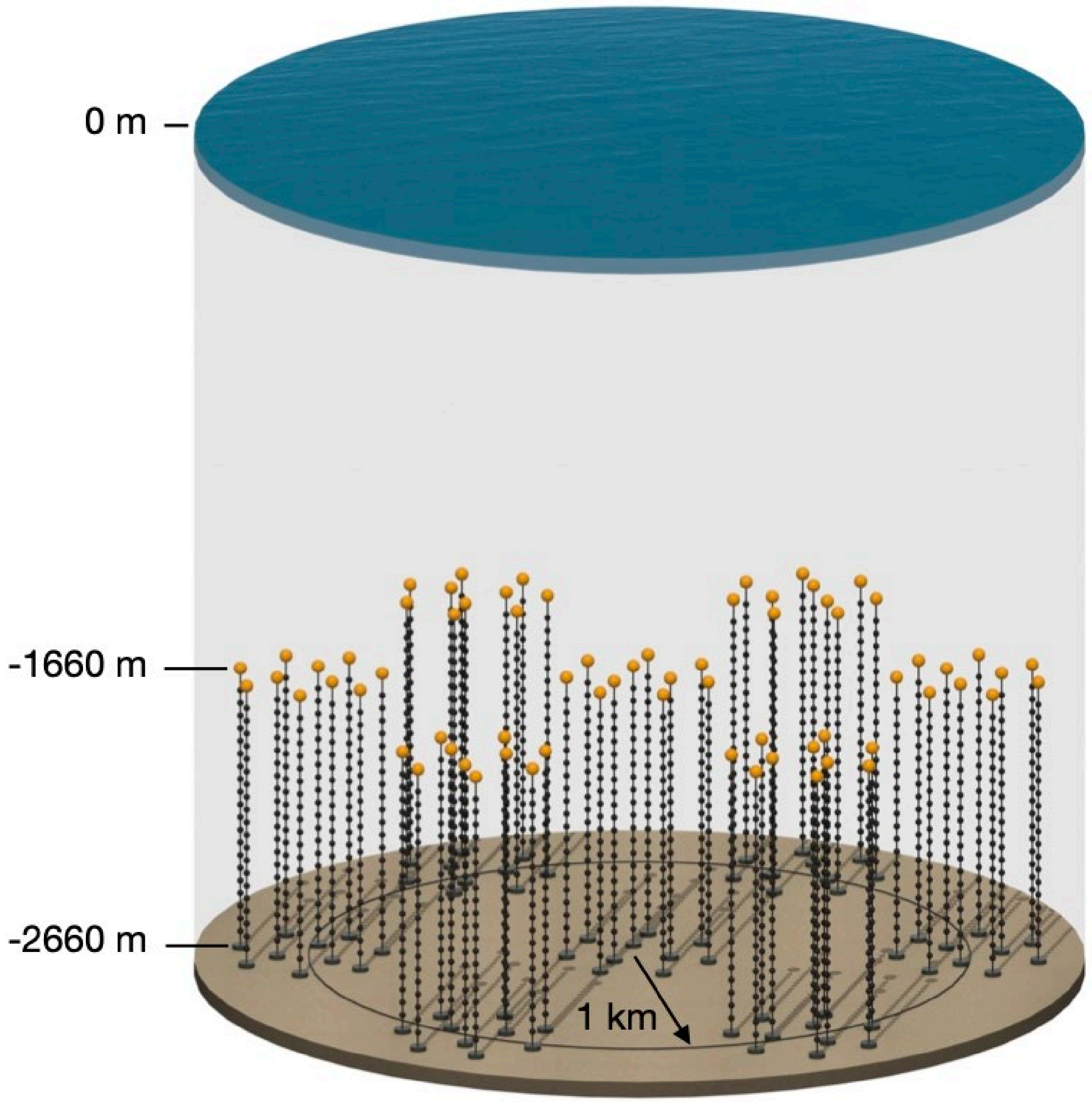


- Time scale for realization: 2024, first mooring line, more in the following years
- 1 km long mooring line
- Up to 10 strings with 20 optical and calibration modules each
- Instrumented volume >1/8 km^3



Pacific Ocean Neutrino Experiment (P-ONE)

- The P-ONE collaboration aims to construct a km^3 scale detector by constructing seven identical modules of the *Demonstrator* type
- The optimal final arrangement is currently under study



P-ONE Collaboration, *Nature Astron*. (2020) e-Print: 2005.09493

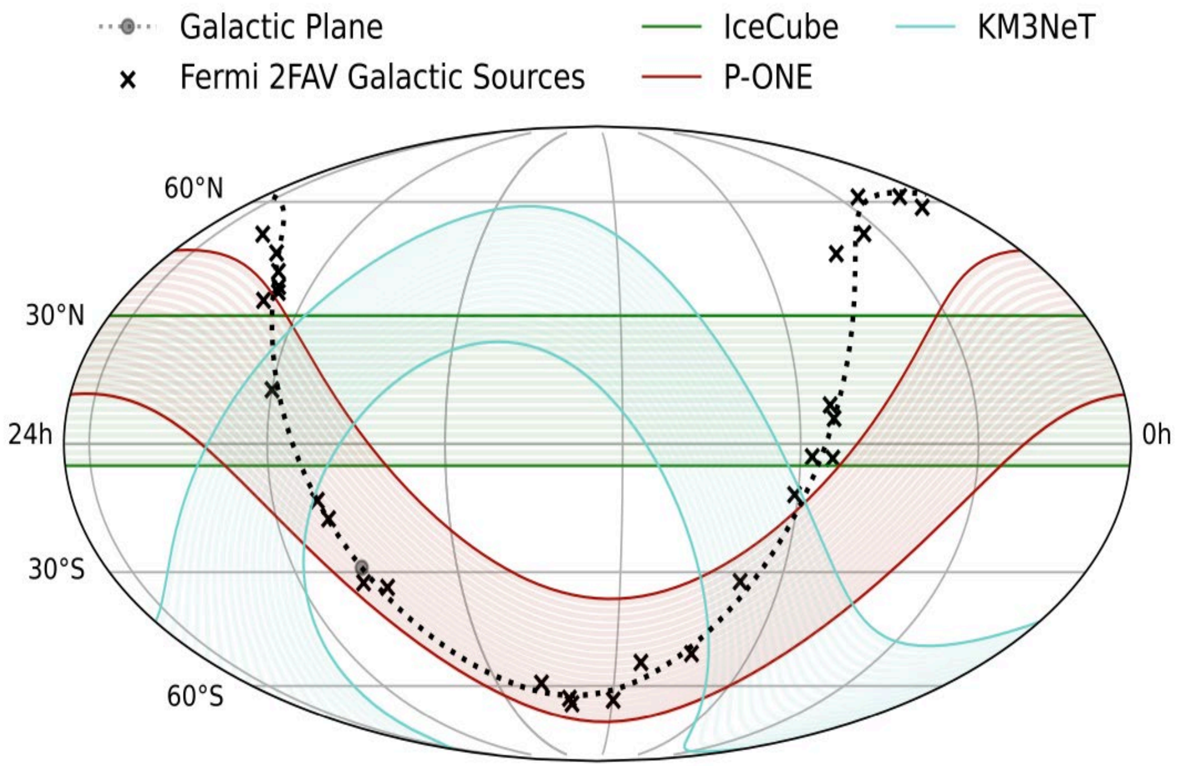
Large Area Photon Detection

- The instrumentation of the ~200 optical modules of P-ONE will use KM3NeT/IceCube-like multi PMT digital optical modules

- 3” PMTs offer a good cost to surface area ratio

- Using a novel, side mounted housing allows obstruction-free observation

P-ONE Goals - Demonstrator



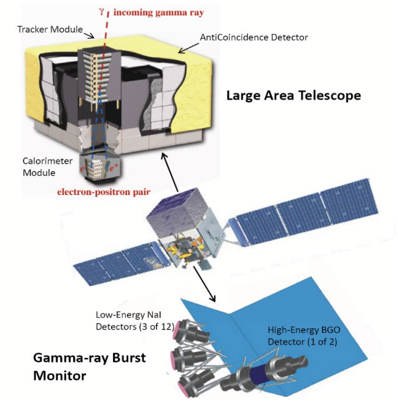
COMMISSIONING! PROOF OF CONCEPT, SUCCESSFUL OPERATION 100% DUTY CYCLE

CALIBRATION! IN-SITU BACKGROUNDS, DETECTORS, ATMOSPHERIC BACKGROUNDS

PHYSICS GOALS:
- FIRST NEUTRINOS IN PACIFIC OCEAN
- IMPLEMENTATION OF MULTI MESSENGER PROTOCOL
- DEVELOPMENT OF ν-FLAVOUR PARTICLE ID

TRIGGER AN INTERNATIONAL EFFORT (P-ONE) SYNERGETIC OPERATION ν-TELESCOPES

Global Coordinate Network (GCN) alert follow-up



Fermi-GBM/LAT:

[T0 - 1 day,T0],
[T0 - 1 day, T0 + 12 hours],
[T0 - 1 day, T0 + 1 day]

LIGO-Virgo-KAGRA:

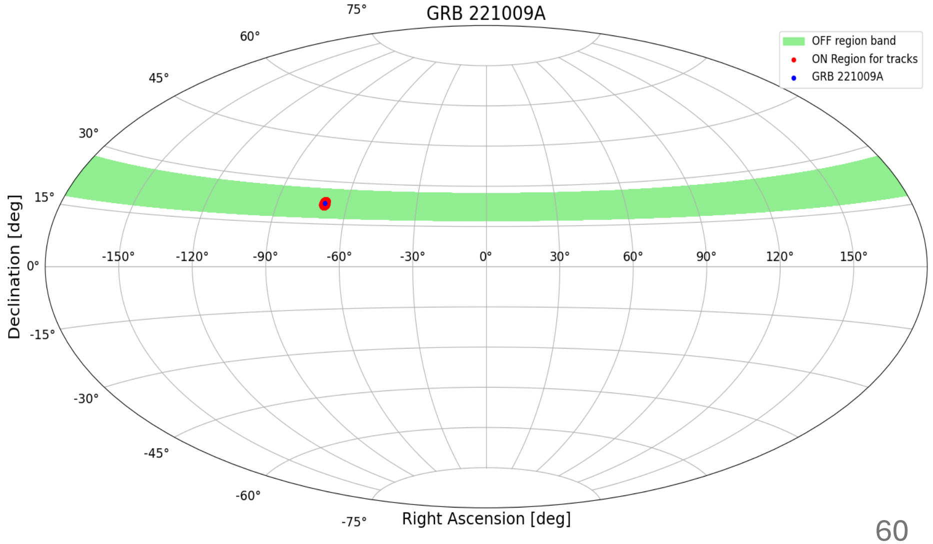
IGWN reception: “significant” = 1
[T0 - 1000 s, T0 + 1000 s],
[T0 - 1000s, T0 + 14 days]

IceCube:

[T0 - 1 h, T0 +1 h]
[T0 - 1 day, T0 +1 day]

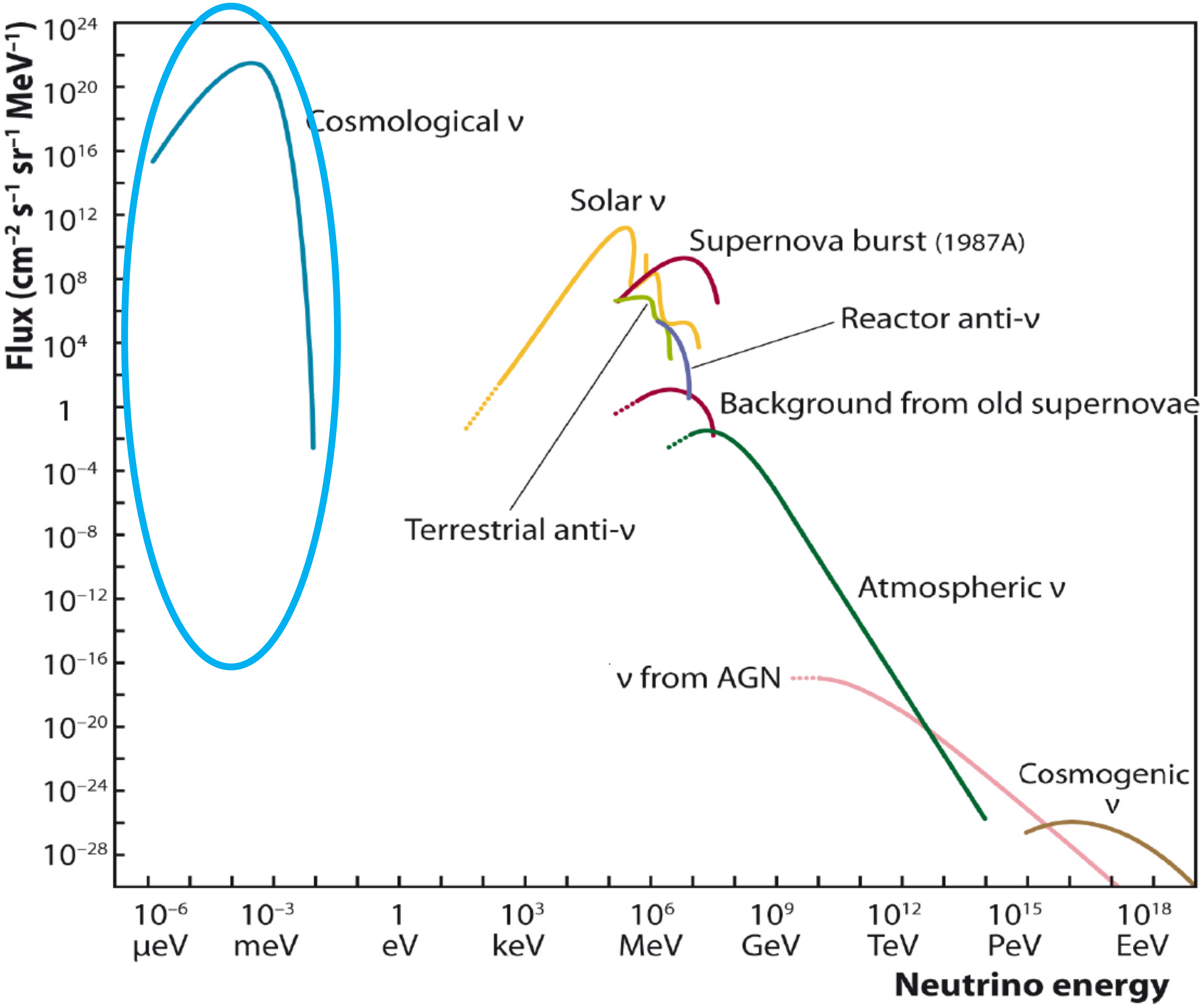
Search for online coincidences:

- ON/OFF method
- ON includes 90% localization error and Baikal-GVD median angular resolution
- OFF is extended within a ± 5 declination band
- OFF is evaluated using real data from previous seasons



Cosmic neutrino background

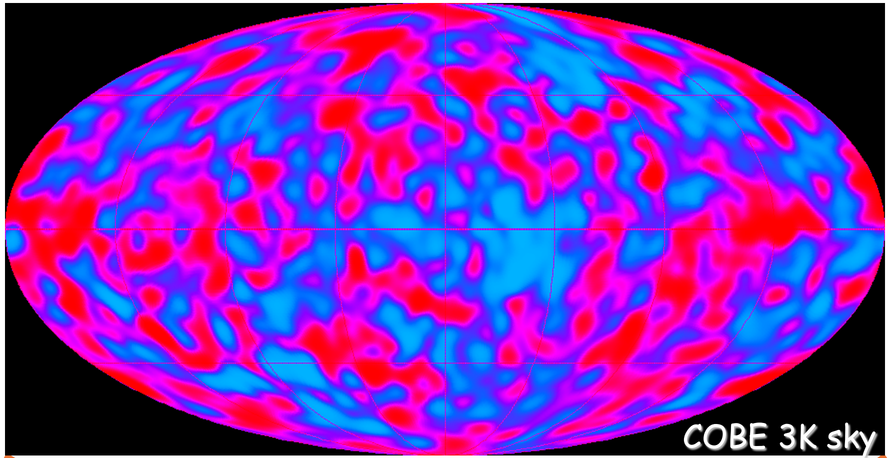
How do we detect these neutrinos?

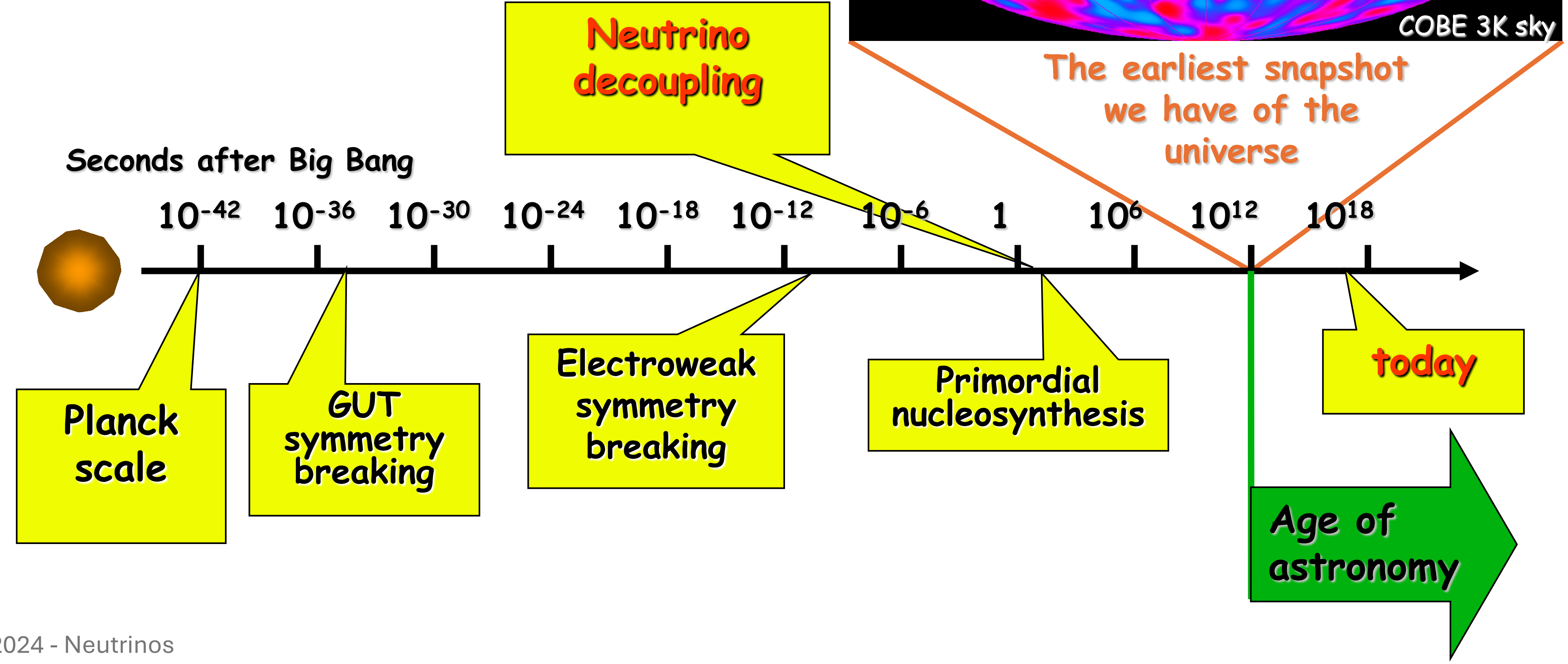


Cosmology

Primordial neutrinos were produced when nuclei formed, at the time the Universe was 1 second old

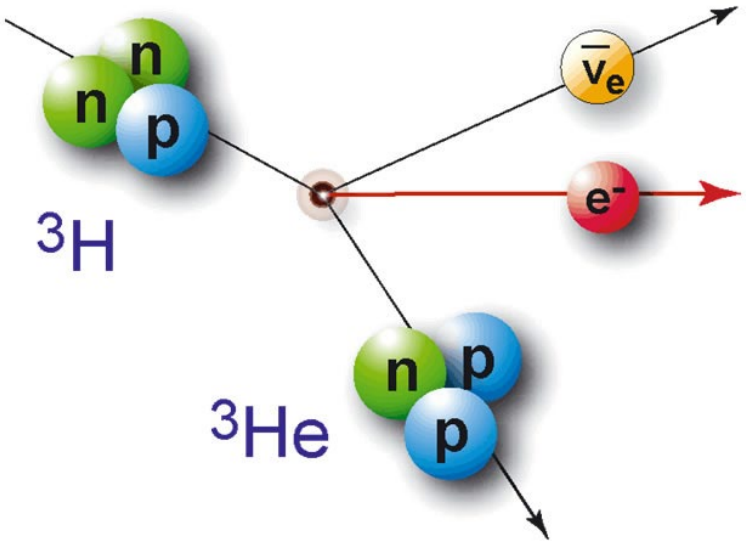
We believe that they are still among us

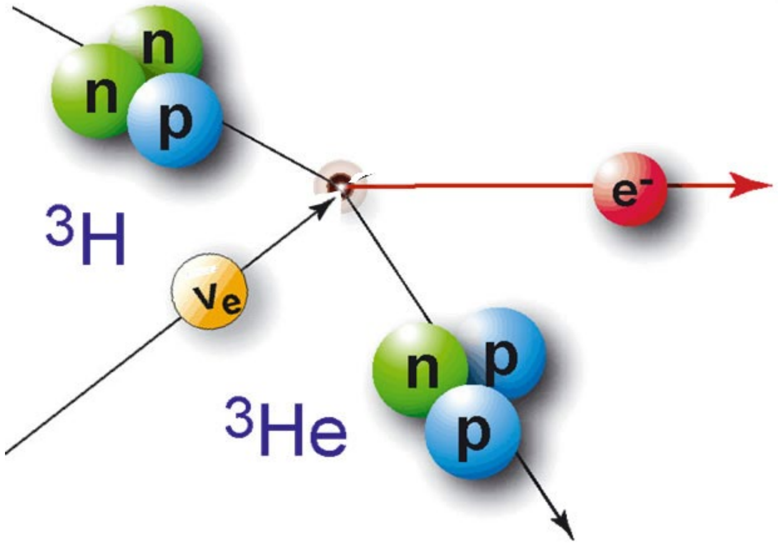




Slide from Giorgio Gratta

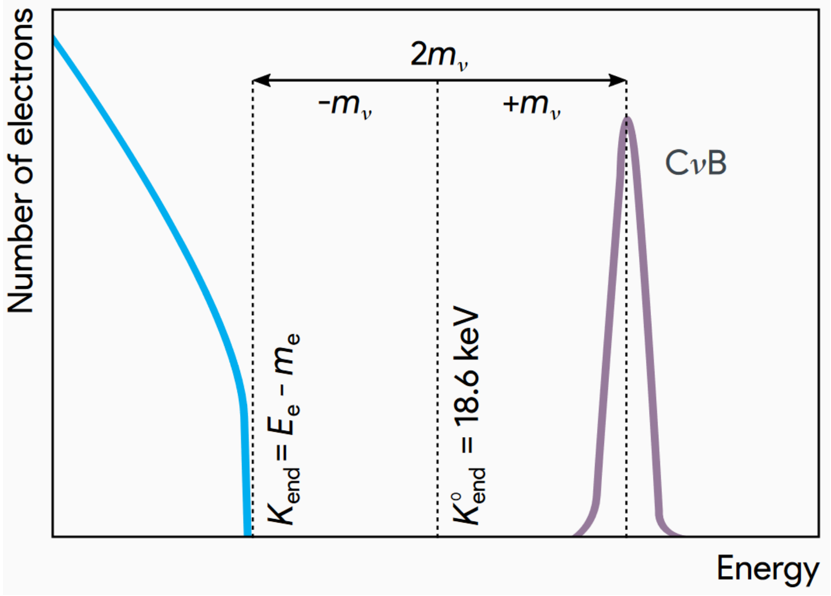
Neutrino capture





Capture cross section * (v/c) ~ 10^{-44} cm^2
(flat up to 10 keV)

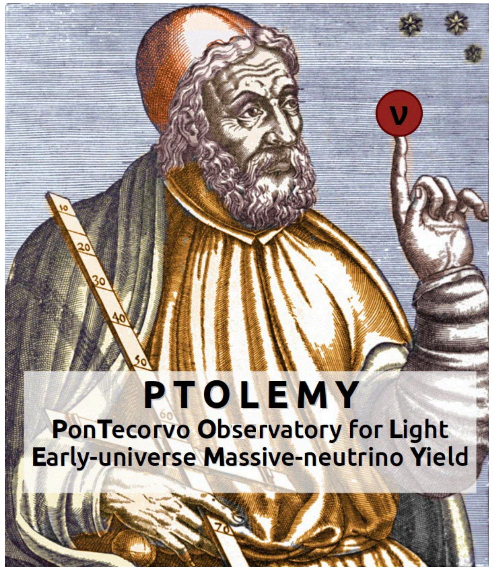
Original idea: Steven Weinberg in 1962, *Phys. Rev.* 128:3, 1457
JCAP 0706 (2007)015, hep-ph/0703075, Cocco, Mangano, Messina

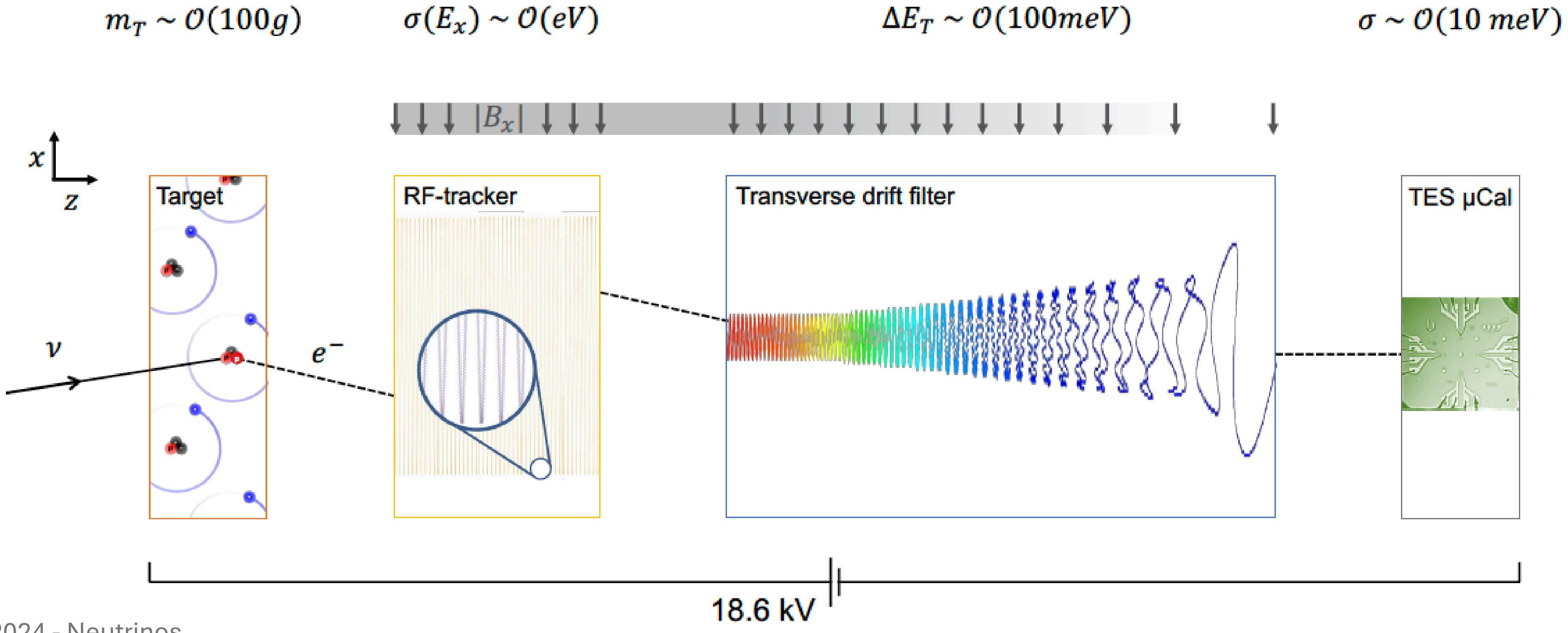


A little bit of everything:

- Compact tritium target
- RF tracking with Cyclotron Radiation Emission Spectroscopy (CRES)
- Electromagnetic filter
- Microcalorimeter detector

See *JCAP* 07 (2019) 047

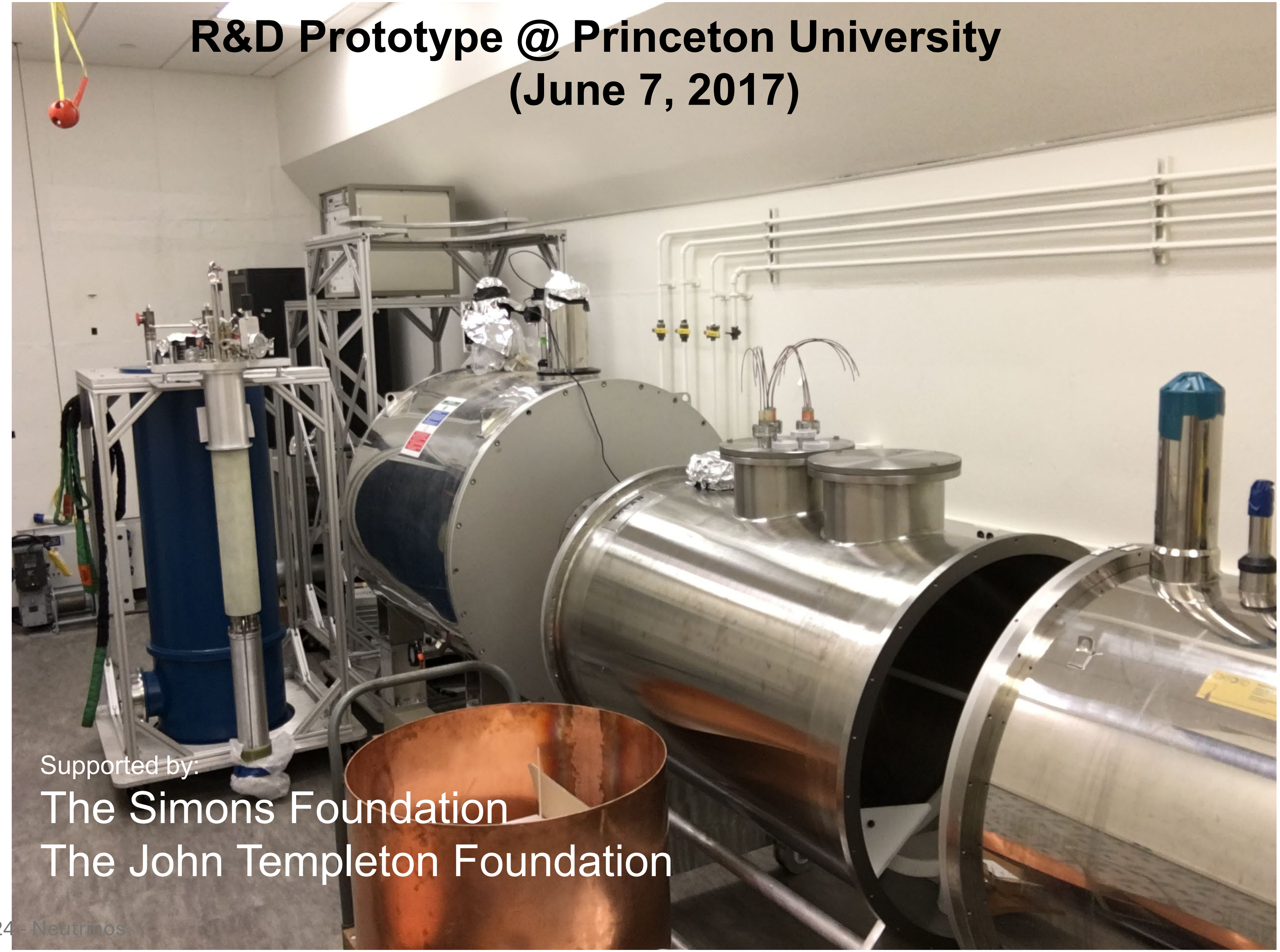




(James Mead, UvA)

$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

R&D Prototype @ Princeton University
(June 7, 2017)



Supported by:

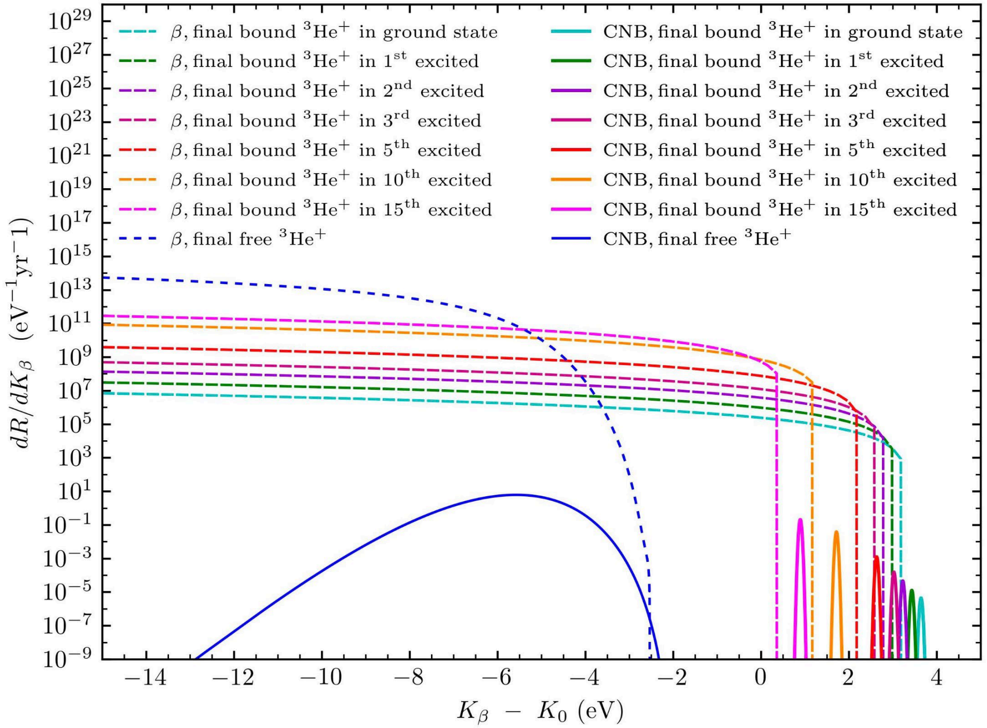
The Simons Foundation

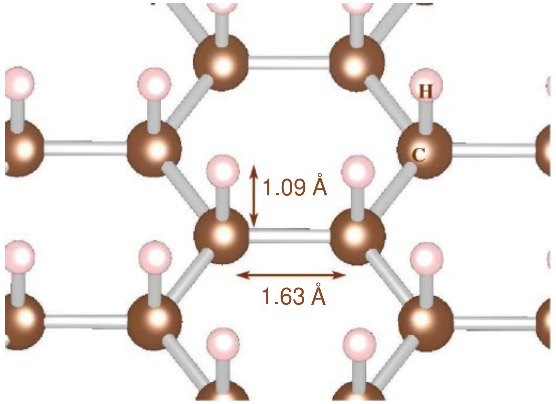
The John Templeton Foundation

Major challenges

(Andrea Casale, Sapienza)

- Reduce molecular smearing
  - New source, tritiated-graphene
  - DFT calculations underway
  - Problem: need to take the uncertainty principle into account! – delocalize!
- Measure the energy spectrum directly with a resolution comparable to the neutrino mass
  - High-resolution electron microcalorimeters
- Compress a 70m spectrometer length – KATRIN's length – down to ~cm scale and replicate it at lower precision – final measurement from microcalorimeter





< 3eV binding energy

Summary

- There has been tremendous progress in our understanding of neutrinos!

<u>Bethe & Peierls 1934:</u>
"... this implies that one evidently never will be able to detect Neutrinos."

- As we improve our measurements, there are regularly surprises along the way.
- Neutrinos likely to have a few more surprises up their sleeves. They may in fact hold some of the keys towards understanding our universe (lepton number violation, sterile neutrinos, ...).
- It is an exciting time to pursue a career in neutrino science.

Final thoughts in neutrinos

It's a Marathon not a Sprint.