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New Results from Laboratory keV Neutrino Searches

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keV Sterile Neutrinos as Dark Matter

- Sterile neutrinos are natural extensions to the SM
- To generate mostly sterile mass states on the keV-MeV scale, additional new physics is required
- …however, 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

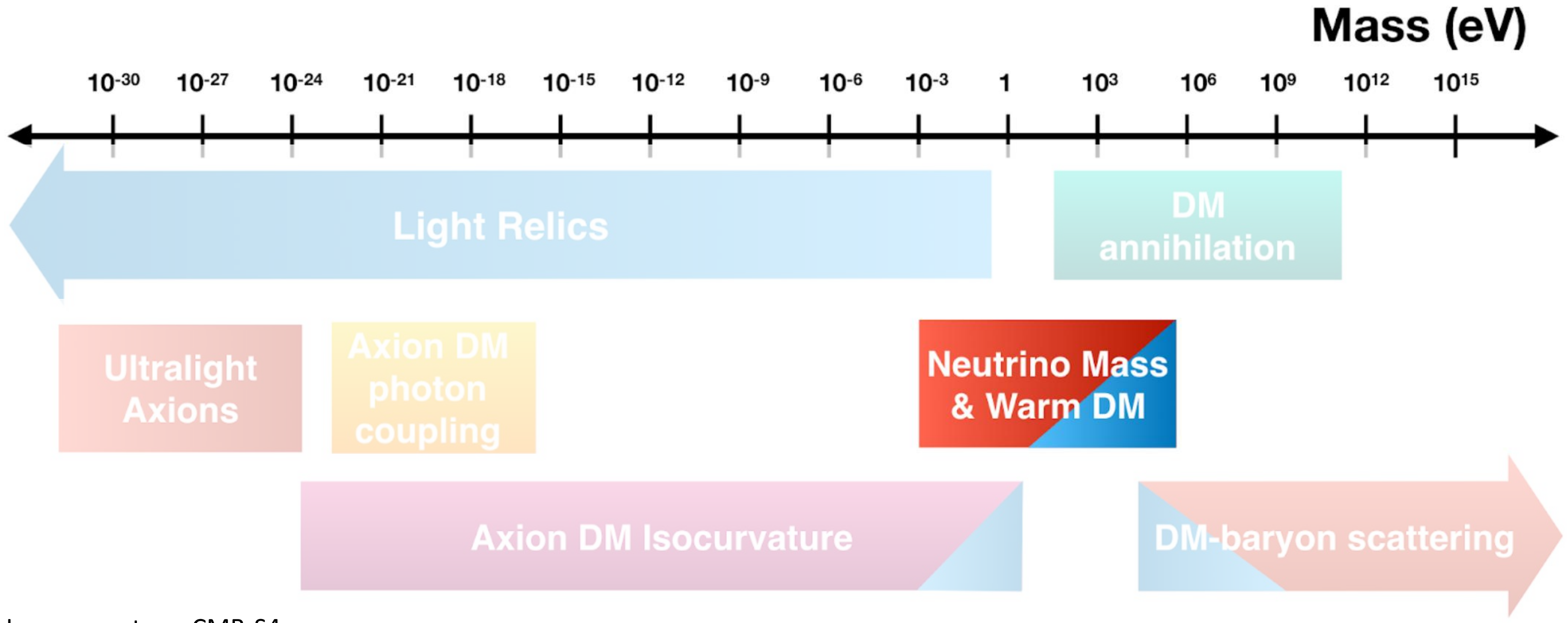
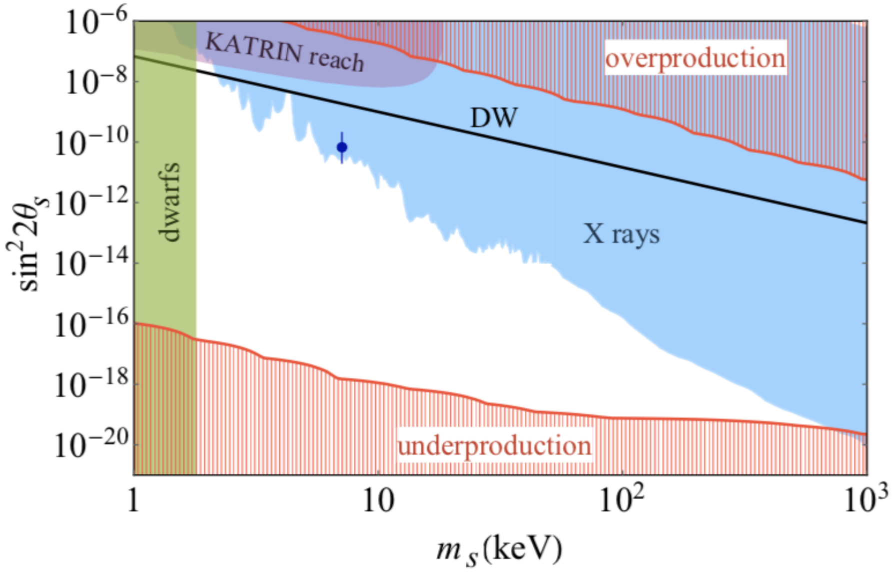


Image courtesy: CMB-S4



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

keV-Scale Sterile Neutrinos

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Review

Sterile neutrino Dark Matter

A. Boyarsky [a], M. Drewes [b,c,*], T. Lasserre [d,e,f,g], S. Mertens [f,h], O. Ruchayskiy [i]

- Since Neutrino 2020, a great deal of laboratory work has been done – primarily using weak nuclear decay in superconducting sensors

- In this talk I will focus on these recent *model-independent* searches in two main mass areas
  - “Light” keV (1 – 10 keV)
  - “Heavy” keV (10’s keV – 100’s keV)

arXiv:2203.07323

White Paper on Light Sterile Neutrino Searches and Related Phenomenology

NF02 Contributed Paper to Snowmass 2021

M. A. Acero,[2,*] C. A. Argüelles,[22,*] M. Hostert,[55,56,67,*] D. Kalra,[13,*] G. Karagiorgi,[13,*] K. J. Kelly,[11,*] B. R. Littlejohn,[30,*] P. Machado,[19,*] W. Pettus,[32,*] M. Toups,[19,*] M. Ross-Lonergan,[13,*] A. Sousa,[12,*] P. T. Surukuchi,[98,*] Y. Y. Y. Wong,[63,*]

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Journal of Cosmology and Astroparticle Physics

An IOP and SISSA journal

A White Paper on keV sterile neutrino Dark Matter

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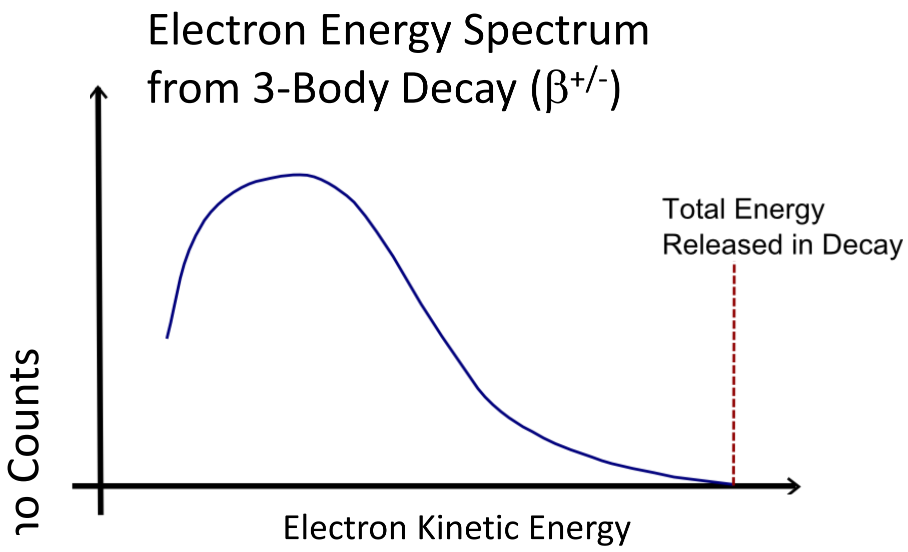
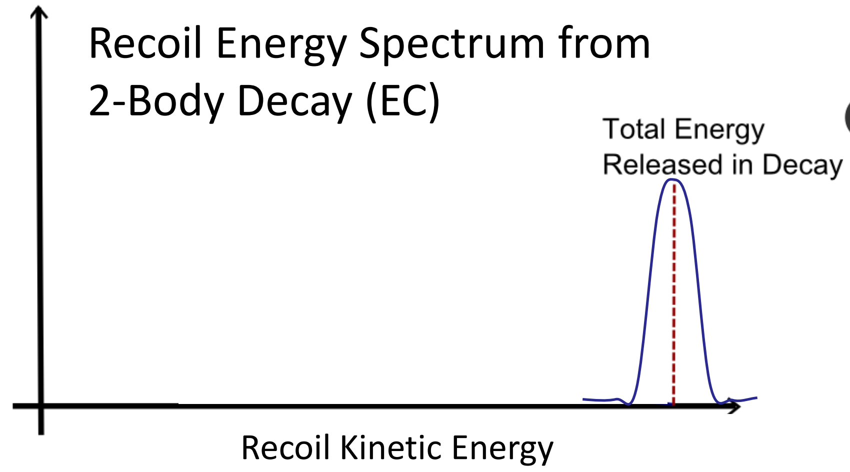
Much of the work I will present is recently published or unpublished, and represents a current snapshot of where the field is (and hopefully where it is going)

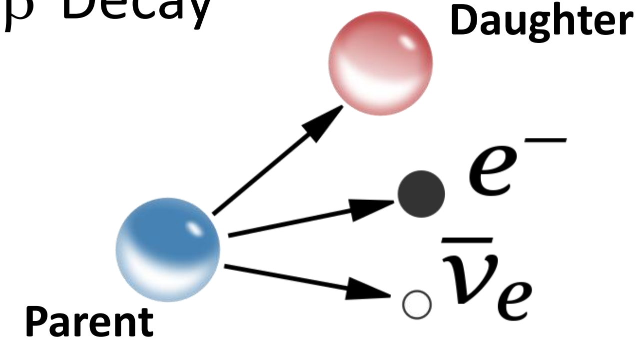
…(*standard disclaimer*) **this talk is not meant to be an exhaustive review…**

The Model Independent Nature of Beta Decay

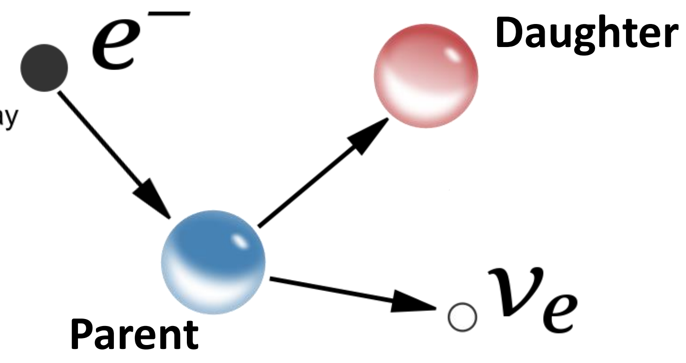




β^- Decay



EC Decay



- Decay momentum reconstruction is a simple, model-independent approach to heavy neutrino searches

R. Davis, Phys. Rev. **86**, 976 (1952)
R. Shrock, Phys. Lett. B **96**, 159 (1980)
G. Finocchiaro and R.E. Shrock, Phys. Rev. D **46**, R888(R) (1992)
M.M. Hindi *et al.*, Phys. Rev. C **58**, 2512 (1998)

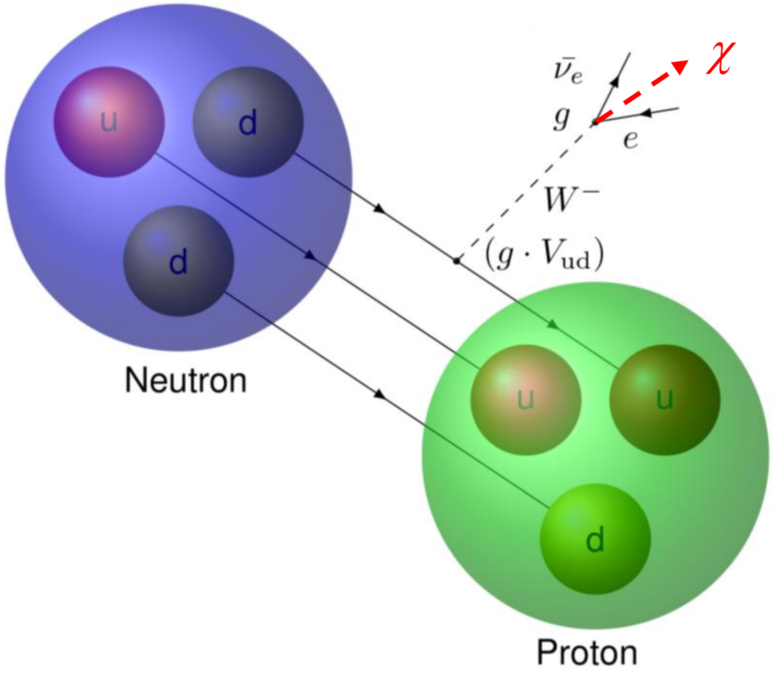
- If *any* new physics couples to the neutrino mass, energies of the other particles in the decay will be altered and can be observed

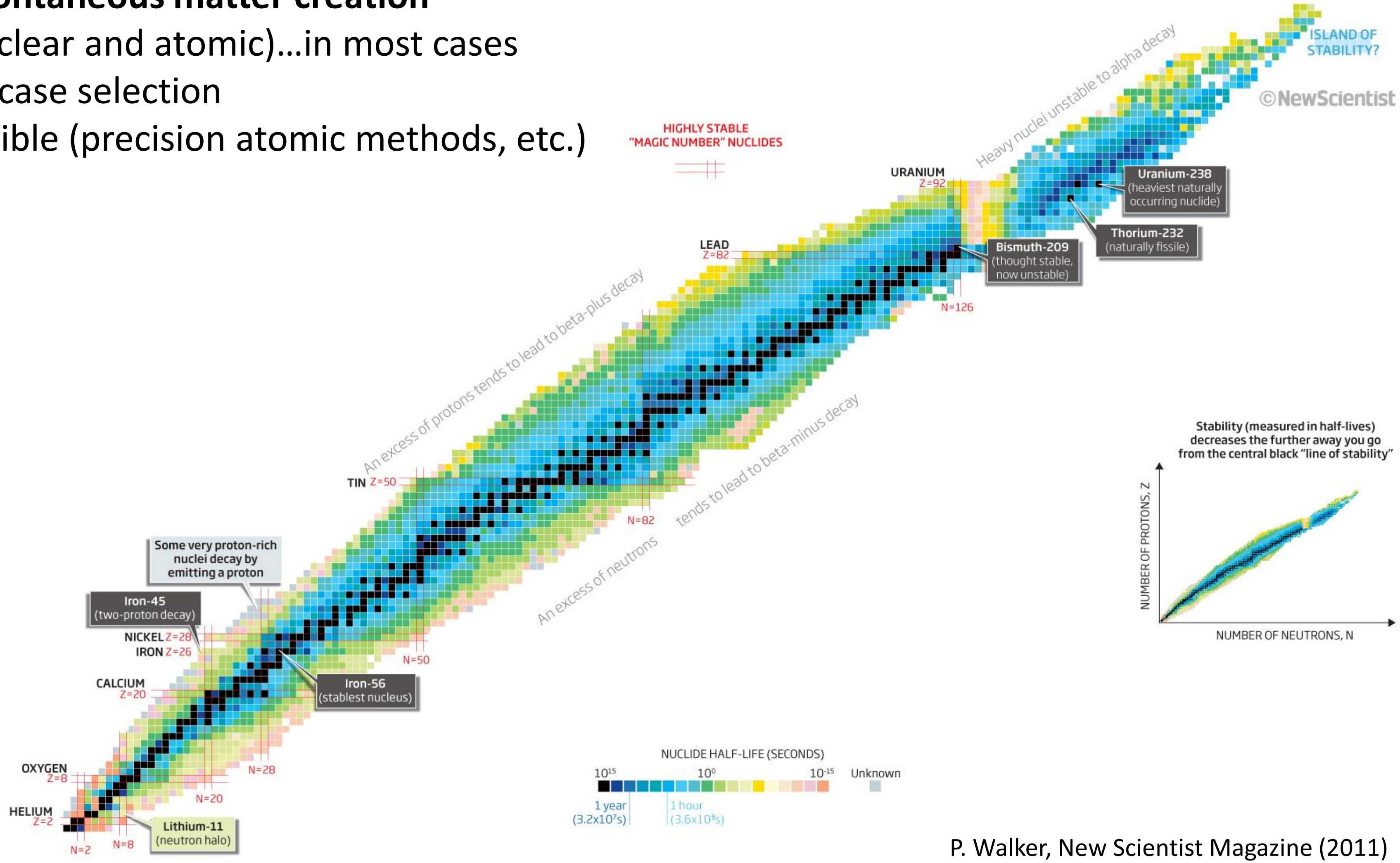
β decay provides a sensitive, model independent probe of any new physics in the neutrino sector that couples to their mass states

keV Neutrino Searches in the Laboratory with Rare Isotopes

Weak nuclear decay is among the most sensitive BSM physics probes – and particularly powerful for keV-MeV neutrinos

- Pure energy-to-matter conversion: **spontaneous matter creation**
- Complex, but understood systems (nuclear and atomic)…in most cases
- More than 3500 different systems for case selection
- Exceptional experimental control possible (precision atomic methods, etc.)

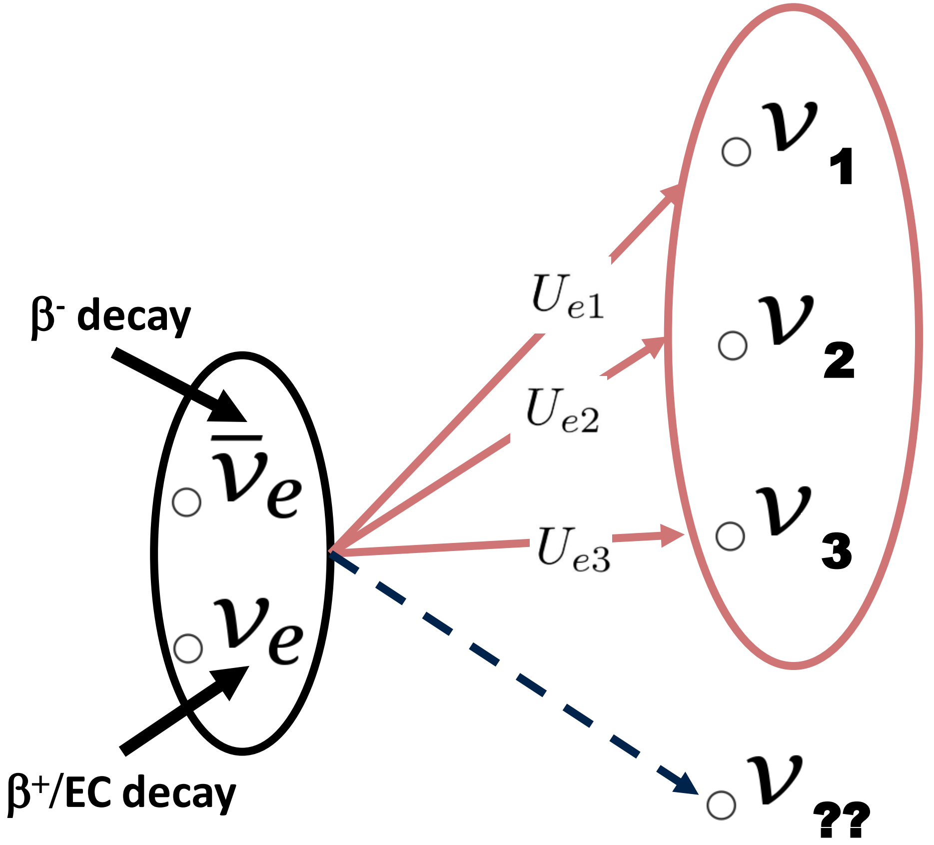


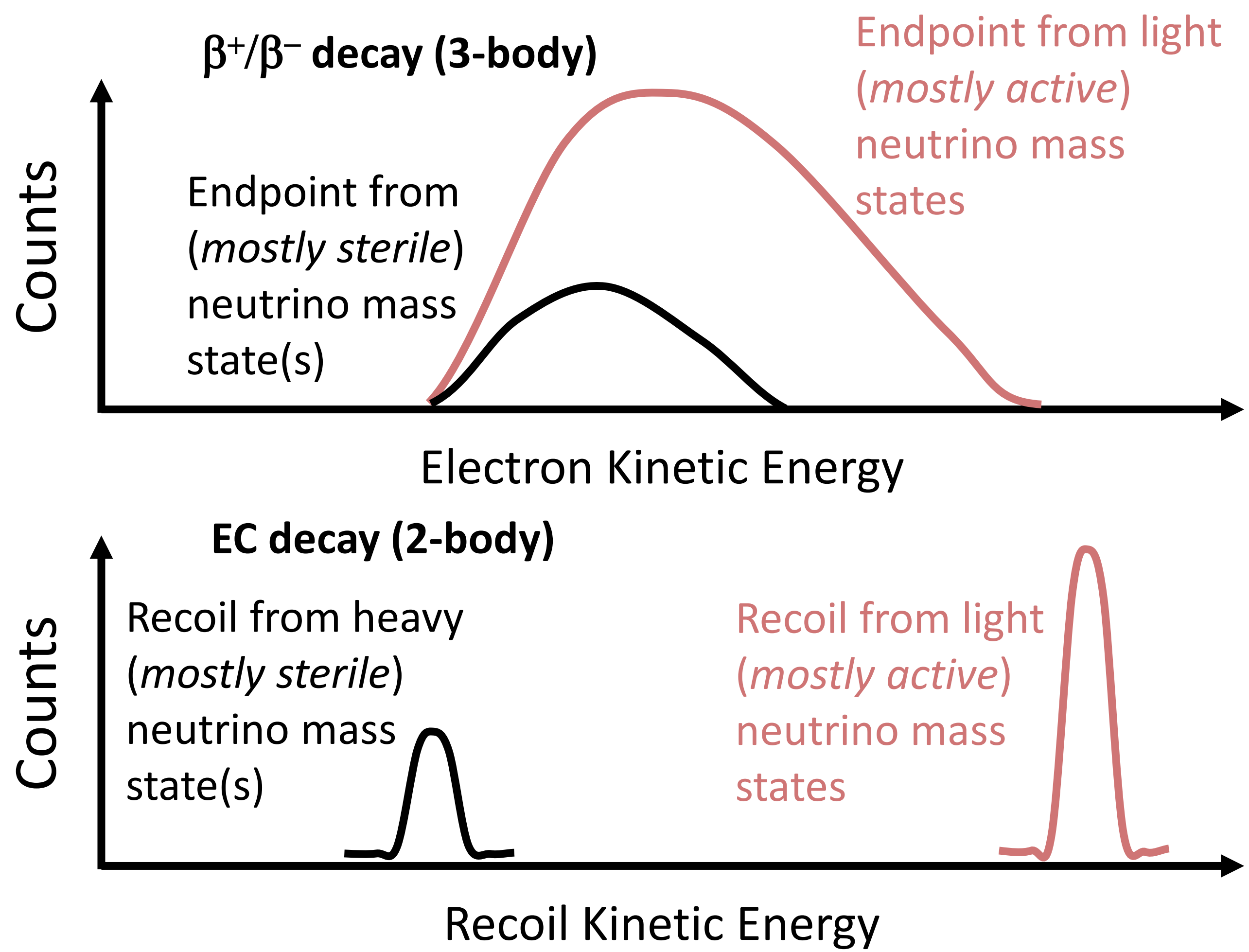


P. Walker, New Scientist Magazine (2011)

keV Neutrino Mass Studies via Coupling to ν_e

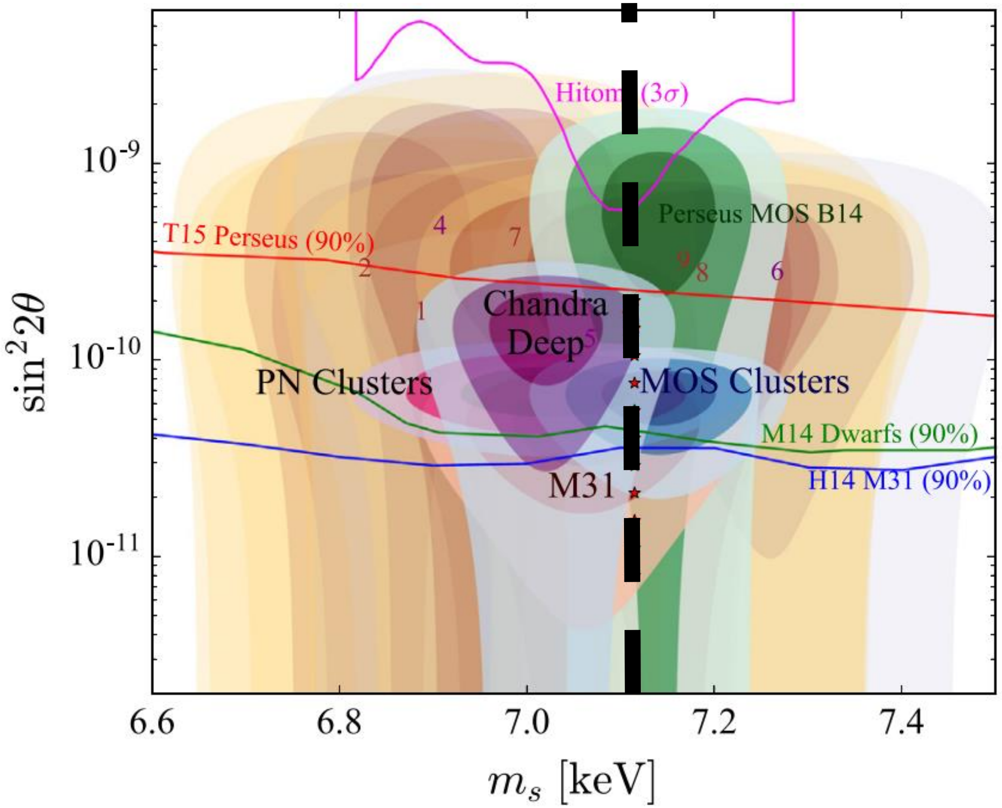
- In EC/β^+ and β^- decay, we study the relative coupling of the mass states to ν_e ($\bar{\nu}_e$)
- Momentum is conserved with the mass states, not flavor states

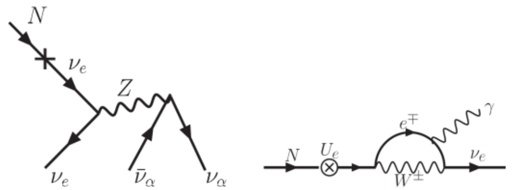




“Light” keV Searches (1 – 10 keV) – Hints?

- Few keV mass neutrinos are strong WDM candidates
- Deep-field X-ray measurements of galactic clusters *hint* at a 3.5 keV line





R. Adhikari et al., JCAP **25** (2017)

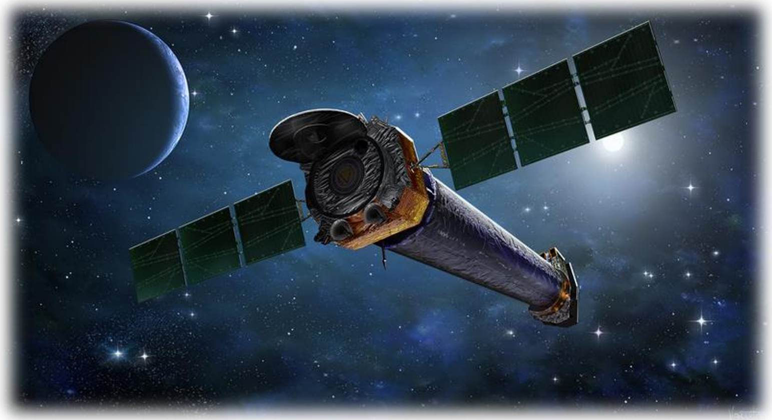


Image Courtesy: Chandra/NASA

7.1 keV neutrino?

N. Cappellutiet al., Astrophys. J **854**, 179 (2018)
F.A. Aharonian et al., Astrophys. J **837**, L15 (2017)
A. Boyarsky et al., Phys. Rev. Lett. **113**, 251301 (2014)

Or something else?

Dessert *et al*., Science **367**, 1465–1467 (2020)

Image Courtesy: HITOMI/NASA

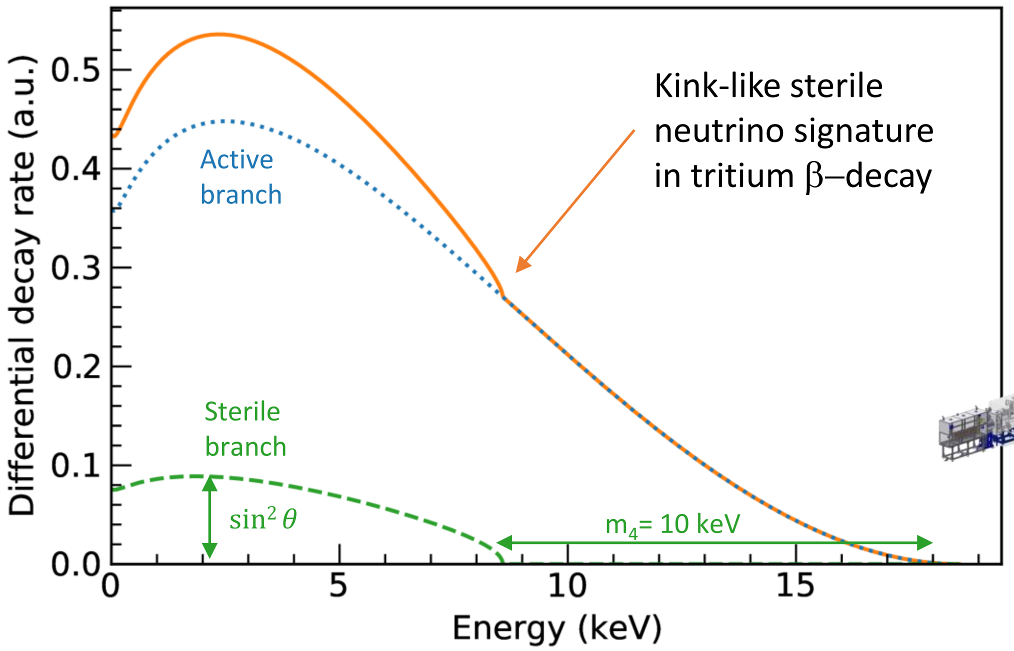
These measurements provide intriguing hints of new physics, BUT we need model independent measurements across a wide mass range for definitive searches….

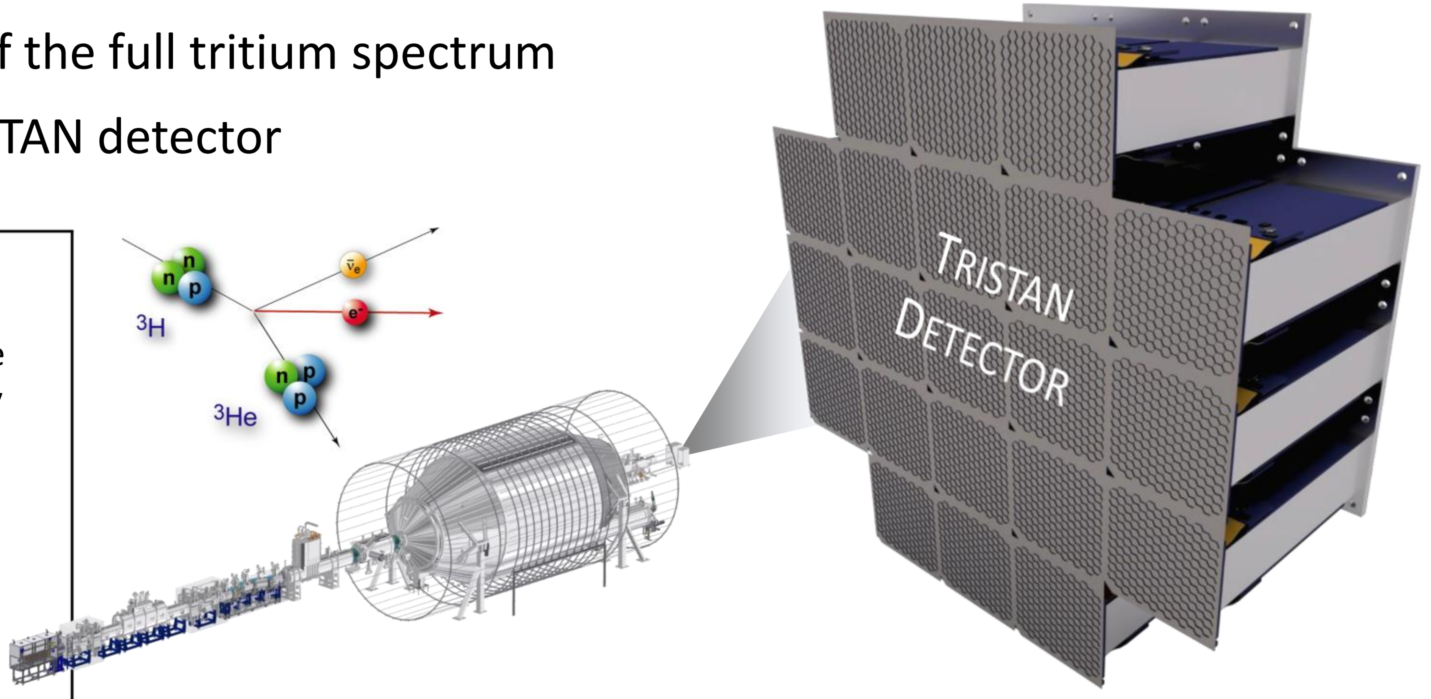
Here is where the power of beta decay plays a major role!

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



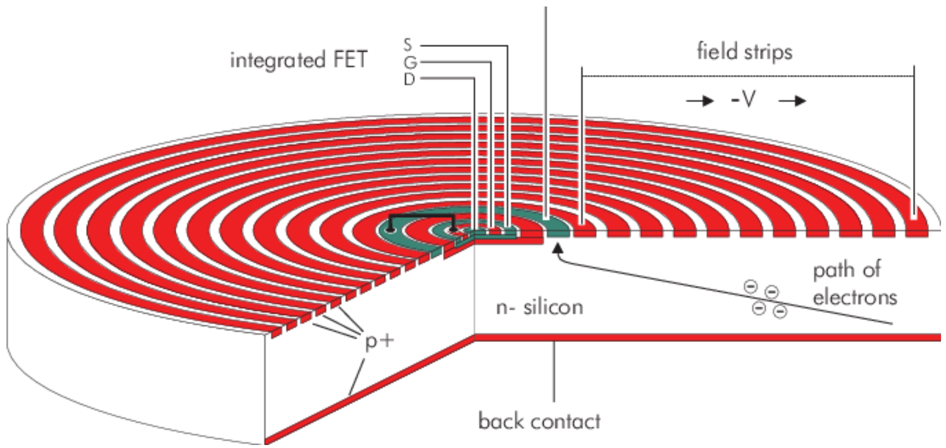


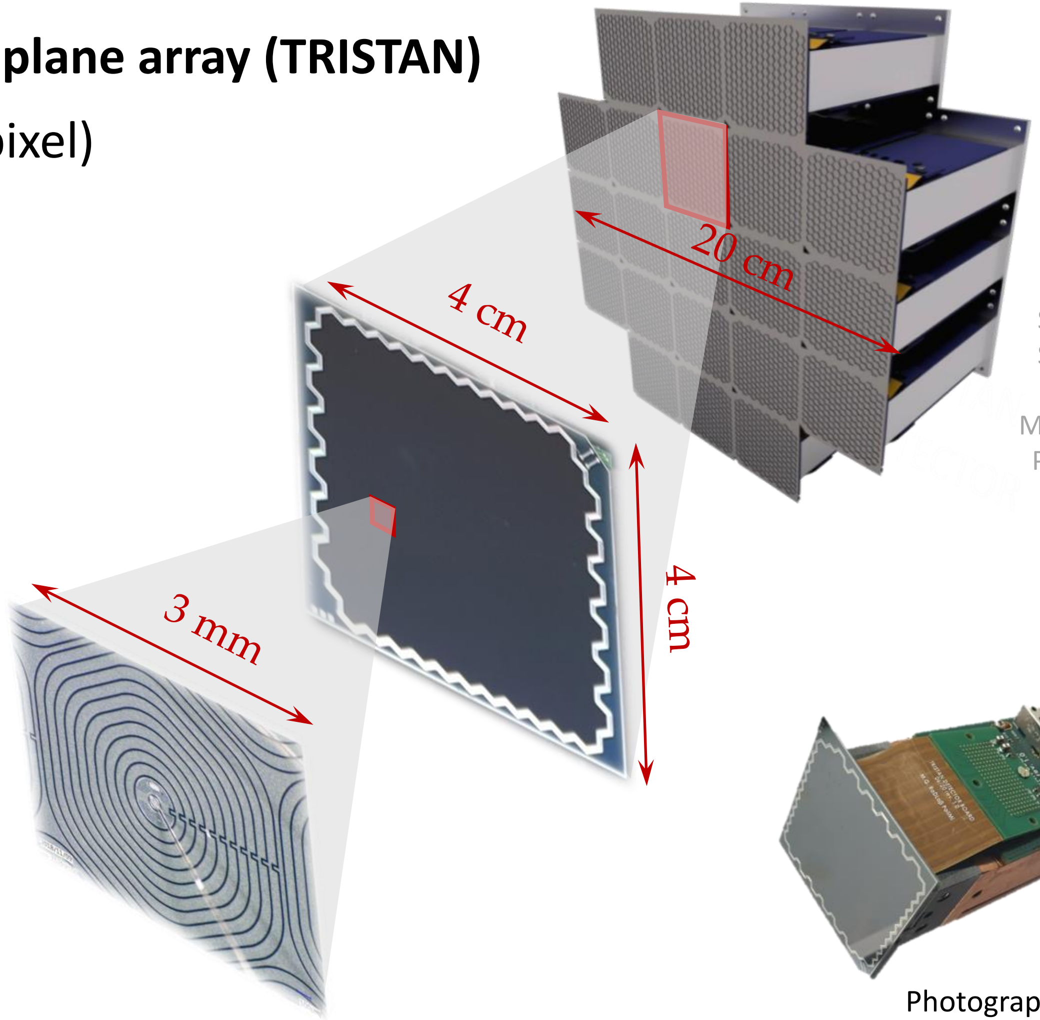
S. Mertens et al. JCAP 1502 (2015)
S. Mertens et al, PRD 91 (2015)

Tritium Endpoint Measurements – KATRIN/TRISTAN

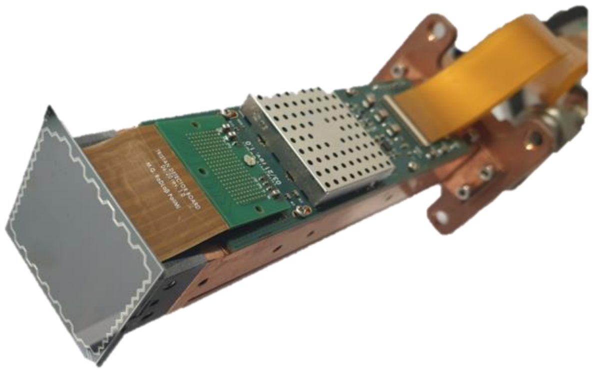
Multi-pixel (>1000) silicon drift detector focal plane array (TRISTAN)

- ✓ 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)



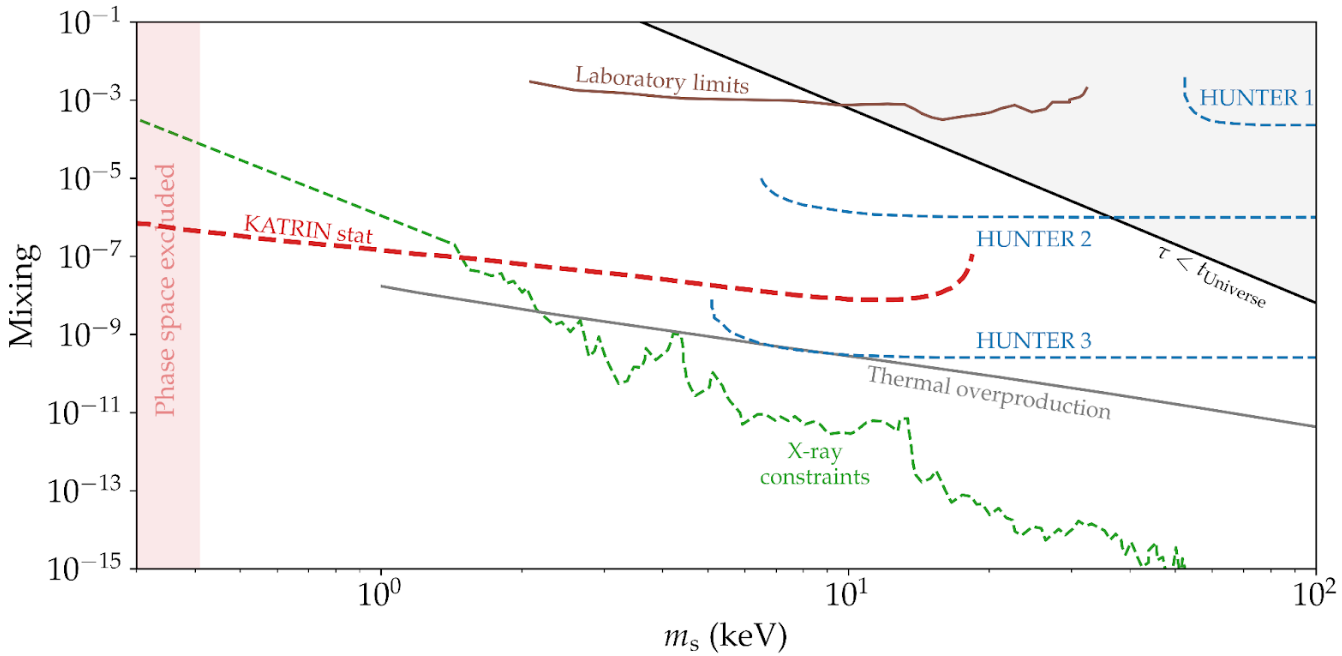
Photograph of TRISTAN module

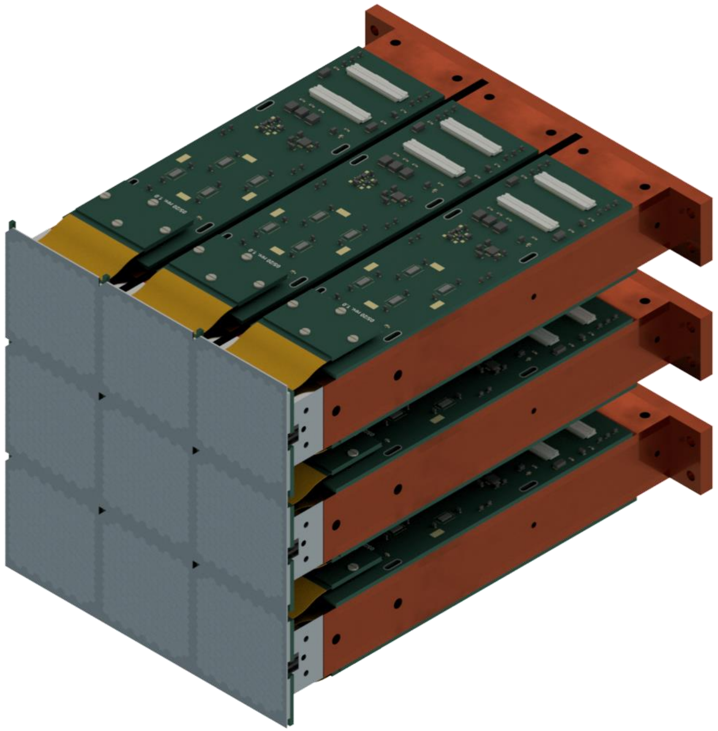
Tritium Endpoint Measurements – KATRIN/TRISTAN

Outlook

✓ Integration of 9 modules in KATRIN beamline planned for 2025

✓ Goal: ppm-level sensitivity (realistic systematics under investigation)



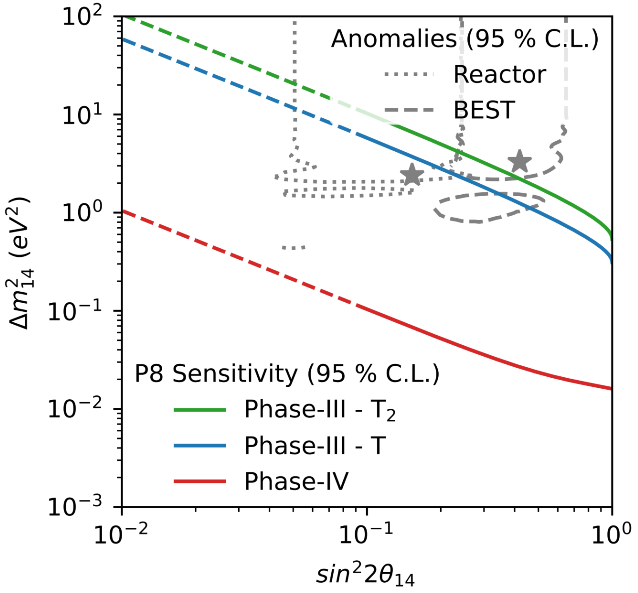


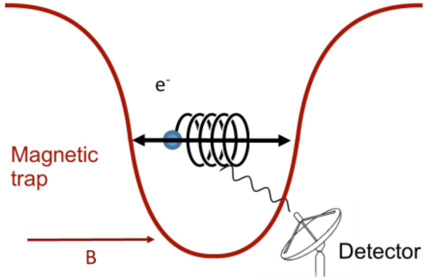
1) ***Sterile neutrino search at the keV mass scale with KATRIN*** **→ (ZEP location: 2F. Dirac, DT14-715)**

2) ***Tritium spectrum modelling for keV-sterile neutrino search with KATRIN*** **→ (ZEP location: 2F. Dirac, DT14-713)**

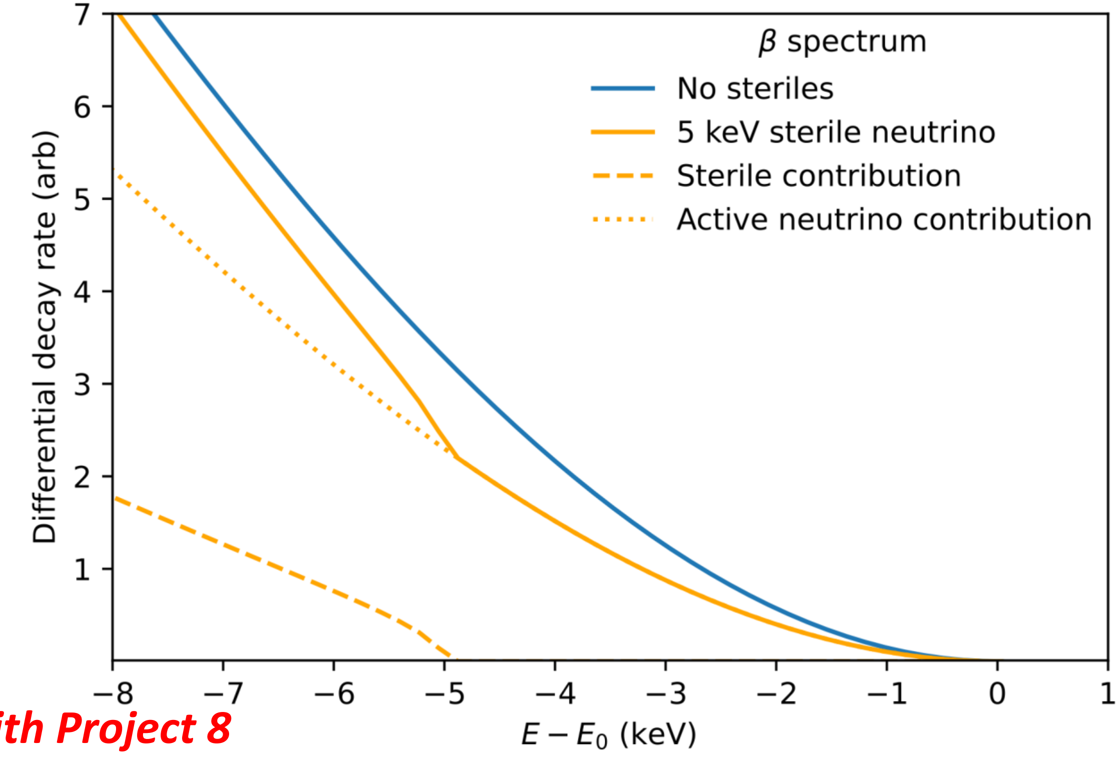
Tritium Endpoint Measurements – Project-8

- Project 8 plans to search for eV-scale sterile neutrino; could be extended to search for keV-scale steriles





$$\omega = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + E}$$



- Spectrum needs to be measured to keV energies below the end point
- Frequency dependence of detection at lower energies need to be well-understood

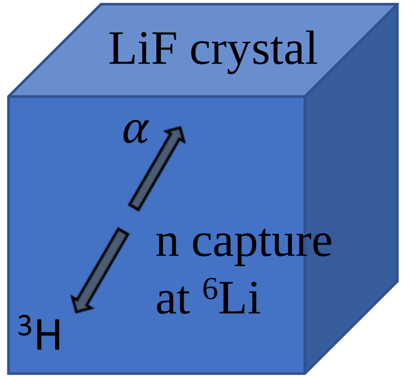
Physics Opportunities Beyond the Neutrino Mass Measurement with Project 8
→ (ZEP location: 2F. Dirac, DT14-715)

Tritium Endpoint Measurements – CUP Tritium Experiment

- ^{3}H ions are implanted in $1 \times 1 \times 1$ cm^3 LiF crystals by ^{6}Li$(n,\alpha)^3$H reaction using two AmBe and one ^{252}Cf neutron sources surrounded by PE bricks.

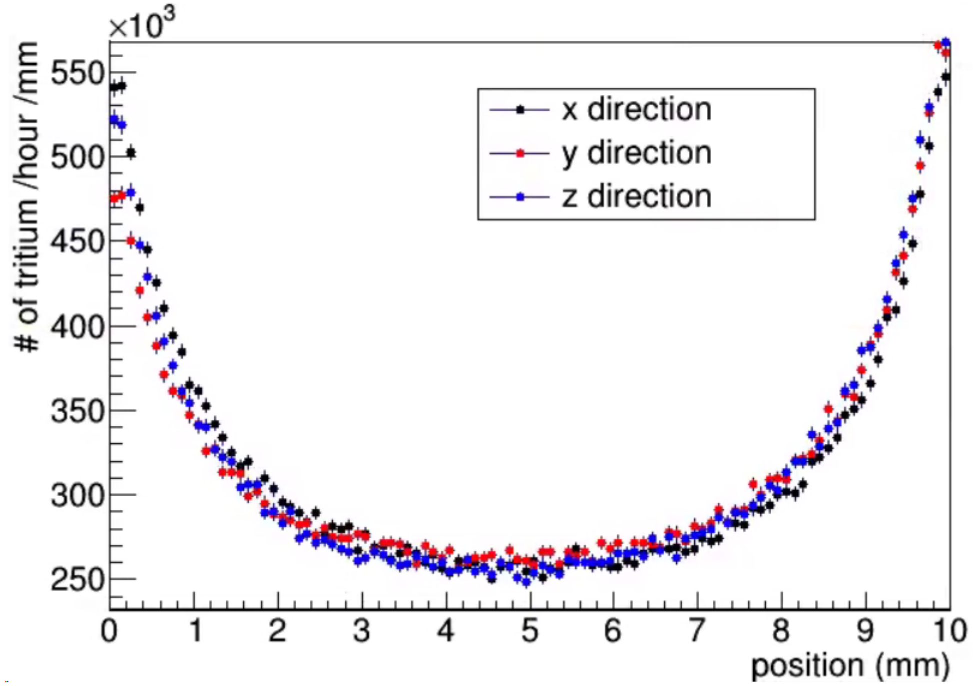
- Tritium distribution in the crystal is nearly uniform.
- From Geant-4 simulation using realistic geometry and source activities

Thermal neutron

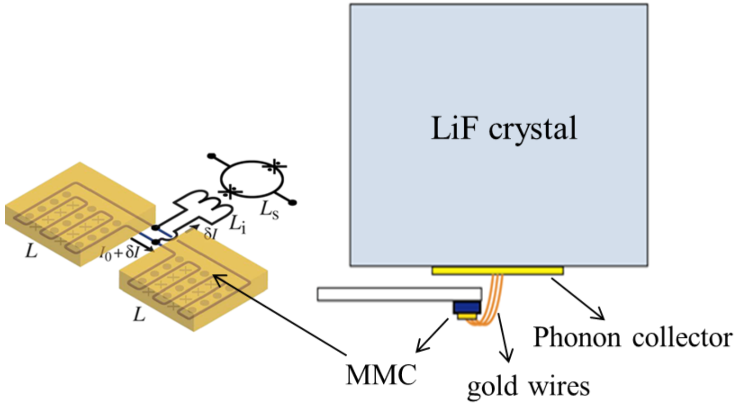


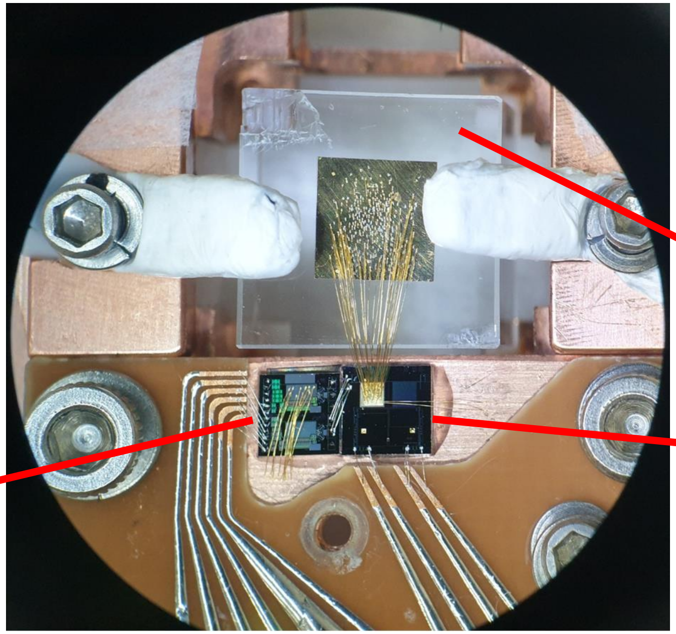
Mean free path of thermal neutrons: 2.3 mm in LiF (7.6% ^{6}Li)

- Irradiation time : 7 days
- Event rate: ~ 20 Bq (measured)

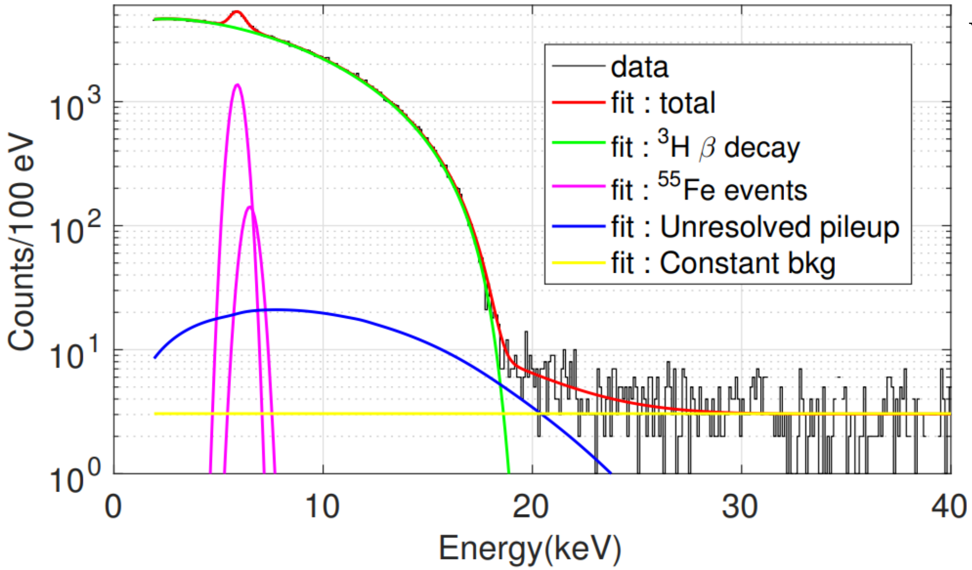


Tritium Endpoint Measurements – CUP Tritium Experiment



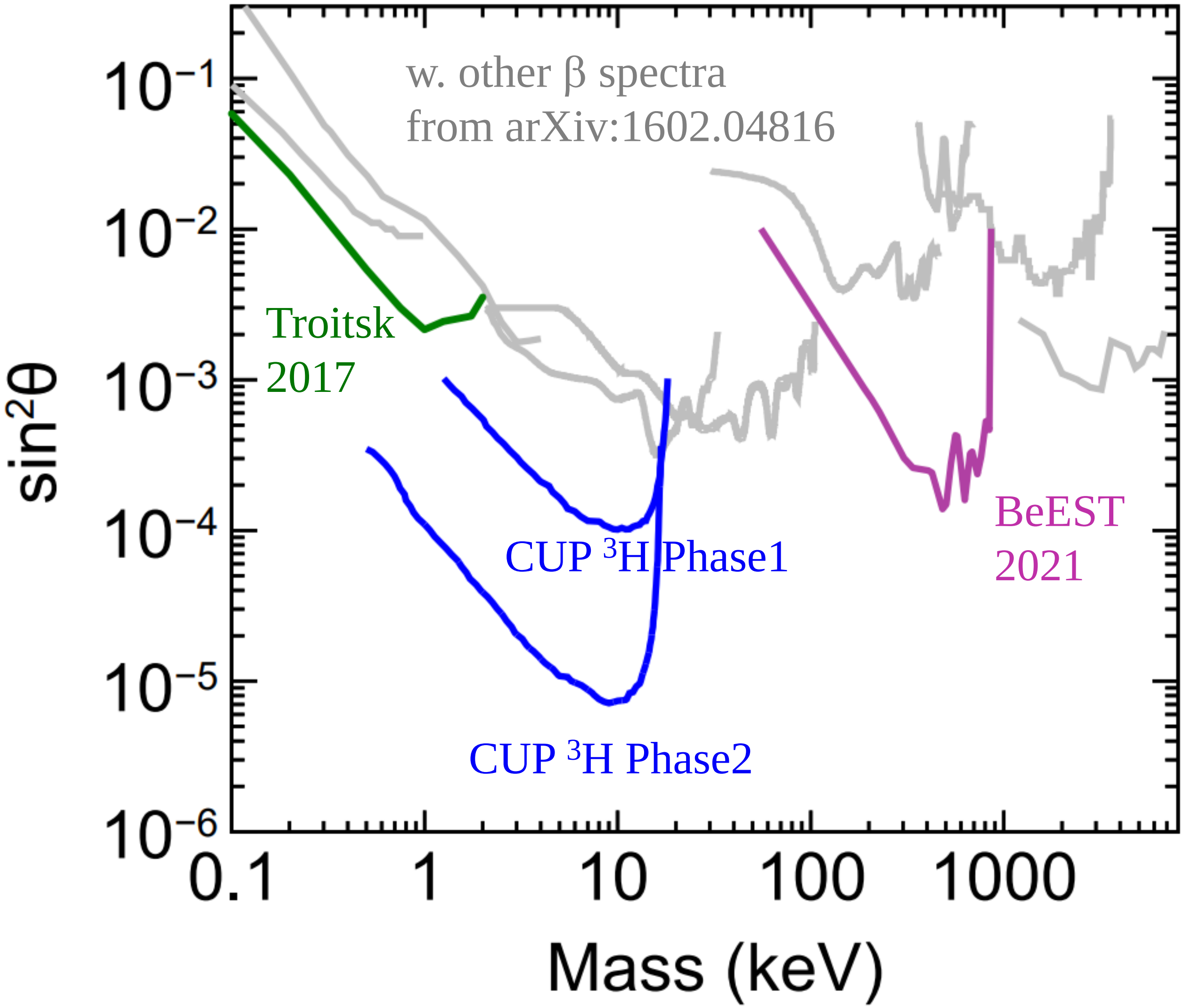


- Thermal calorimetric detection: LiF + MMC (Magnetic microcalorimeter)
- Calibration: A Fe55 internal source and Am241 external source (removed when taking ^{3}H beta spectrum)
- ^{3}H beta events were measured at 40 mK in an ADR for 10 hours.
- Trigger efficiency: 95% and 100% at 1.45keV and 2keV.
  FWHM energy resolution : 0.8 keV at 6 keV



YC Lee LTD-19 2021

Tritium Endpoint Measurements – CUP Tritium Experiment



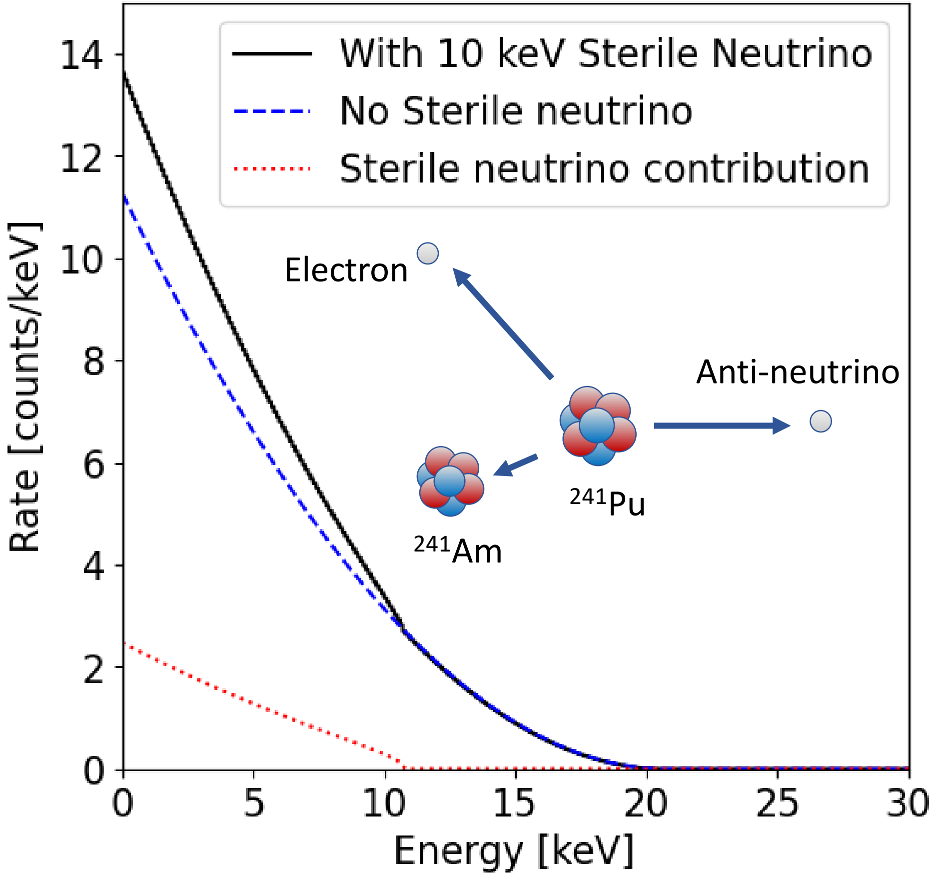
- Currently investigating better calibration methods and possible background origins.

- **Future plan: CUP ^{3}H Phase1**
- Search region of mixing amplitude
  $|U_{e4}|^2 (= \sin^2\theta)$: $10^{-4} - 10^{-3}$
- Target statistics : 3 detectors × 40 Bq × 10 month
- Currently in preparation to begin 2022

- **Future plan: CUP ^{3}H Phase2**
- Search region of mixing amplitude
  $|U_{e4}|^2 (= \sin^2\theta)$: $10^{-5} - 10^{-4}$
- Target statistics : 100 detectors × 100 Bq × 3 year
- To be arranged

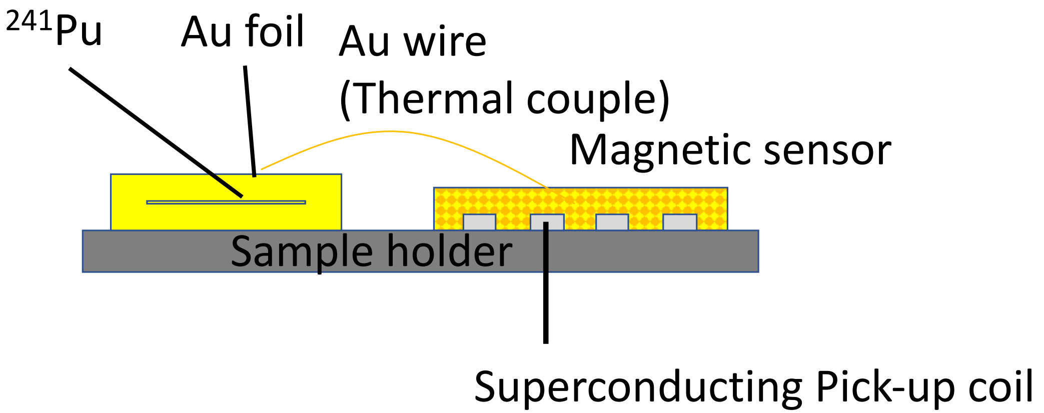
^{241}Pu Endpoint Measurement – MAGNETO-ν

^{241}Pu Beta Spectrum



- Singla beta branch to the ground state
- 20 keV endpoint energy (ideal for 1-20 keV neutrino search)

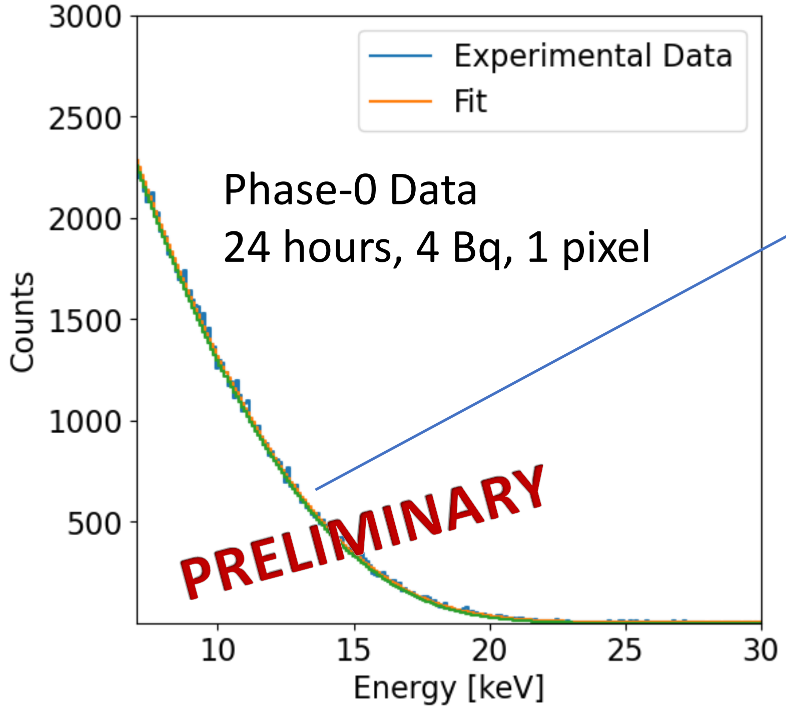
Detector: Magnetic Quantum Sensors with Gold foils



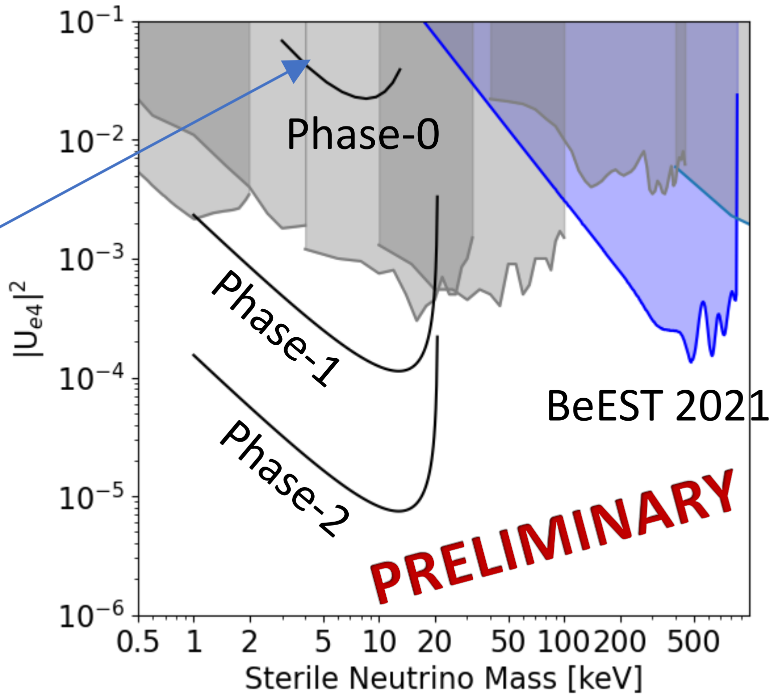
- ^{241}Pu source is fully enclosed by gold foils for 4π detection
- Detector performance goal:
  - 50 eV energy resolution
  - 4π detection and ~100% detection efficiency
  - 1,000 cps counting speed per pixel (under development)

^{241}Pu Endpoint Measurement – MAGNETO-ν

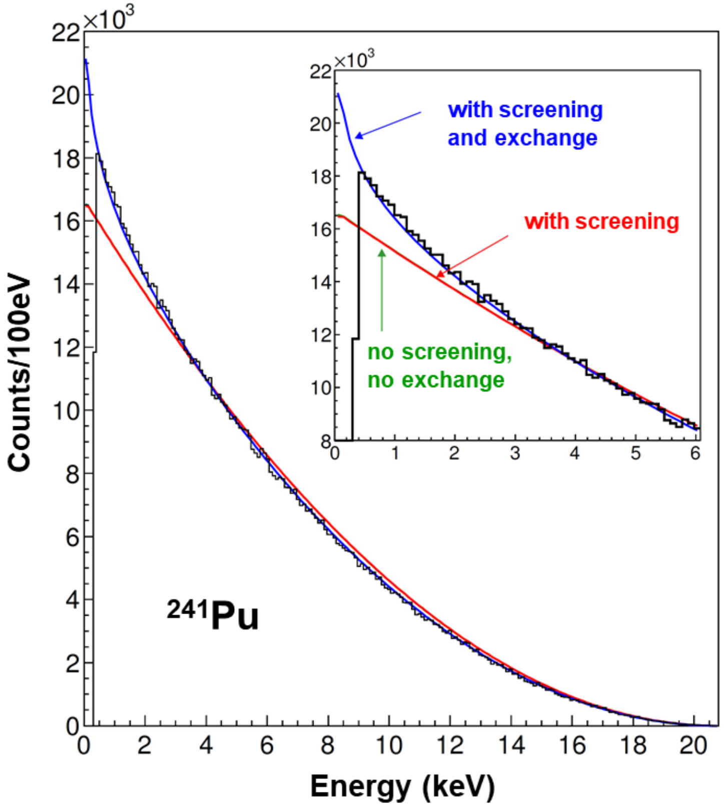
Phase-0 Experimental Data



Sensitivity to keV ν Search



Theoretical Calculation



Phys. Rev. A **86**, 042506 (2012)

Beta Shape Calculation with nuclear and atomic effects

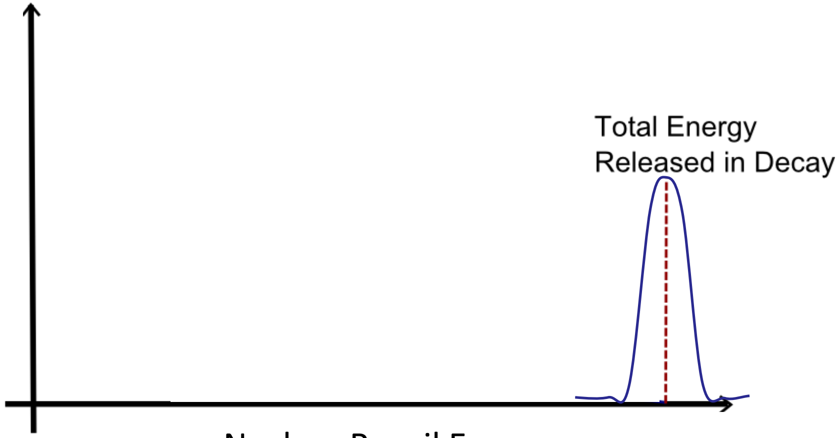
Searching for a keV sterile neutrino via 241Pu beta spectrum

→ (ZEP location: 2F. Dirac, DT14-776)

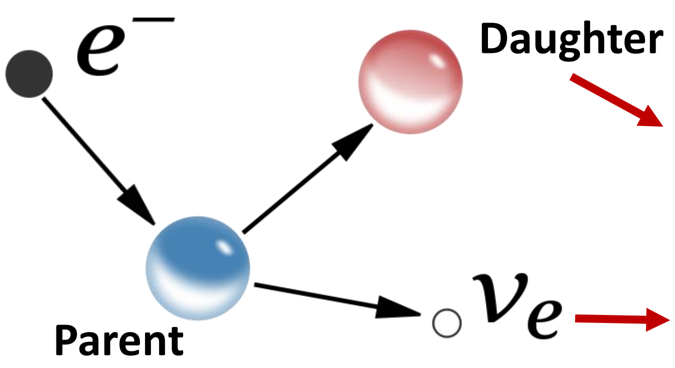
“Heavy” keV Neutrino Searches (10’s keV – 100’s keV)

- To search at higher energies, small *Q*-value decays (^{3}H=18.6 keV, ^{241}Pu=20 keV, ^{163}Ho=2.8 keV) can no longer be used due to phase-space limitations

- Significant increase in sensitivity at these higher masses can also be achieved by moving from β decay (3-body) to EC (2-body) and *directly detecting the nuclear recoil*



EC Decay

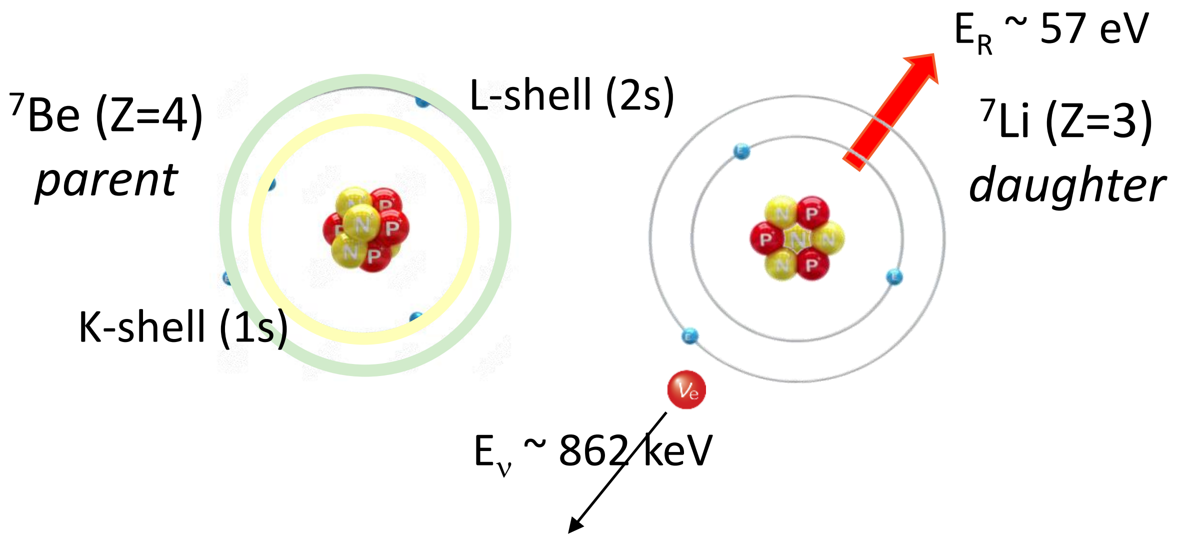


$$T_d = \frac{Q_{EC}^2 + m_\nu^2 c^4}{2\left(Q_{EC} + m_d c^2\right)}$$

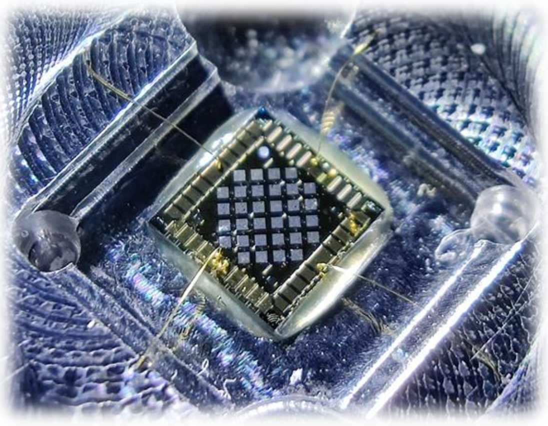
$$T_\nu = \frac{\left(m_\nu c^2 + Q_{EC}\right)\left(c^2\left(m_\nu + 2m_d\right) - Q_{EC}\right)}{2\left(m_d c^2 + Q_{EC}\right)}$$

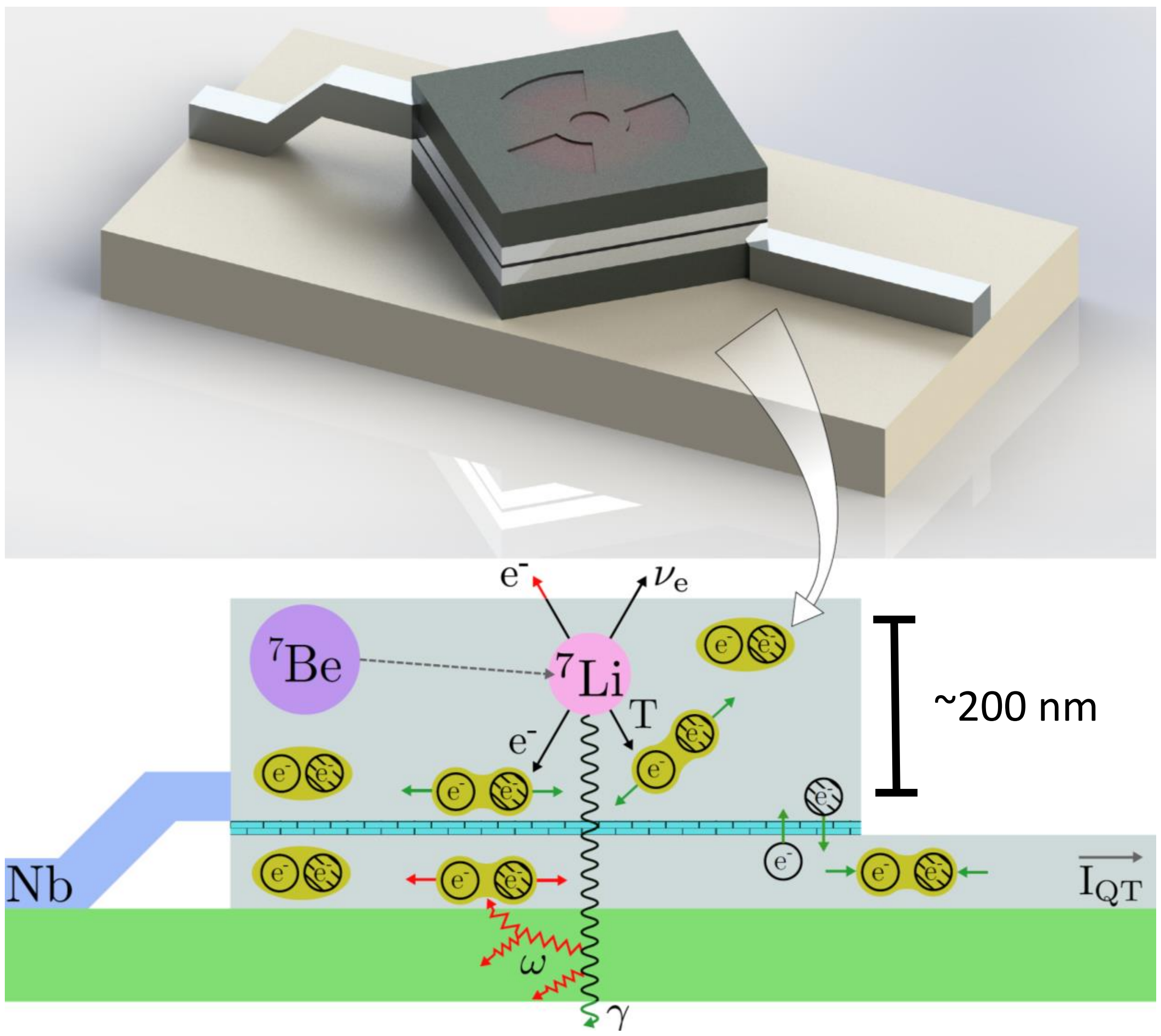
- Higher masses imply weaker active-sterile couplings, so higher sensitivity required in experiments

EC Decay of ^{7}Be - The BeEST Experiment



Superconducting Tunnel Junctions (STJs)



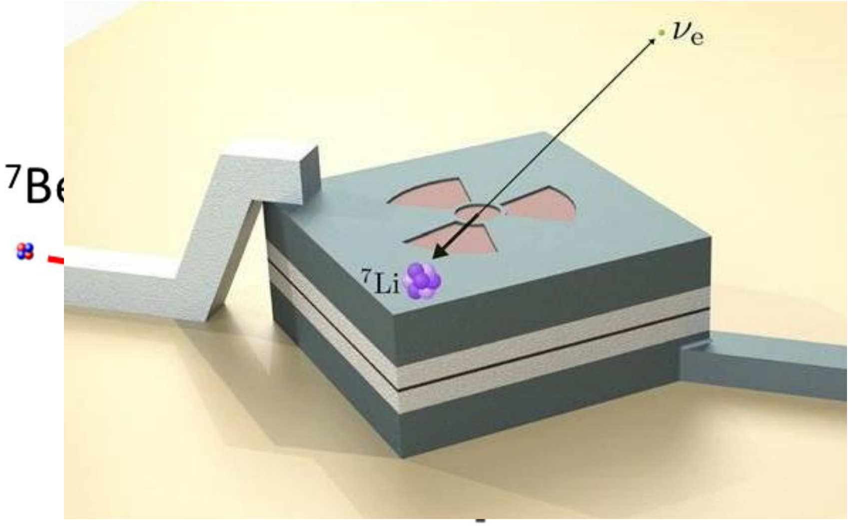


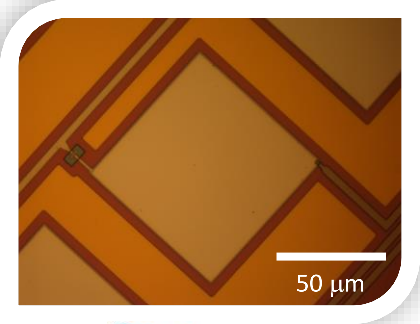
EC Decay of ^{7}Be - The BeEST Experiment

- Direct nuclear recoil measurement of ^{7}Li daughter
- Simple atomic and nuclear system
- Sub-keV measurements with resolution of ~2 eV

THE BeEST

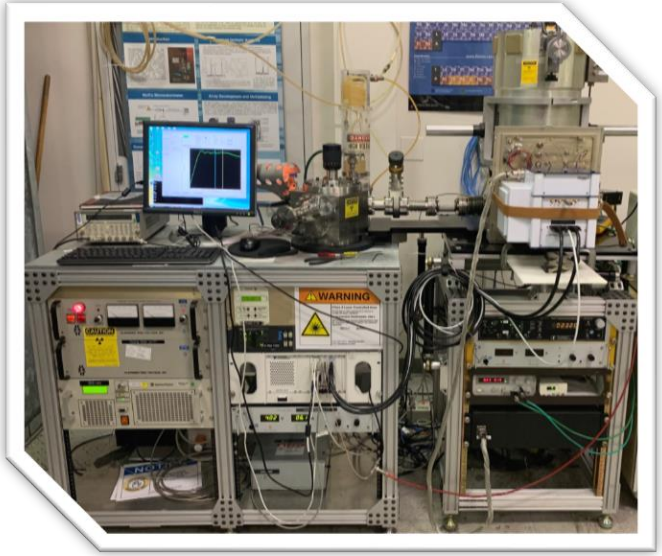
TRIUMF





STAR CRYOELECTRONICS

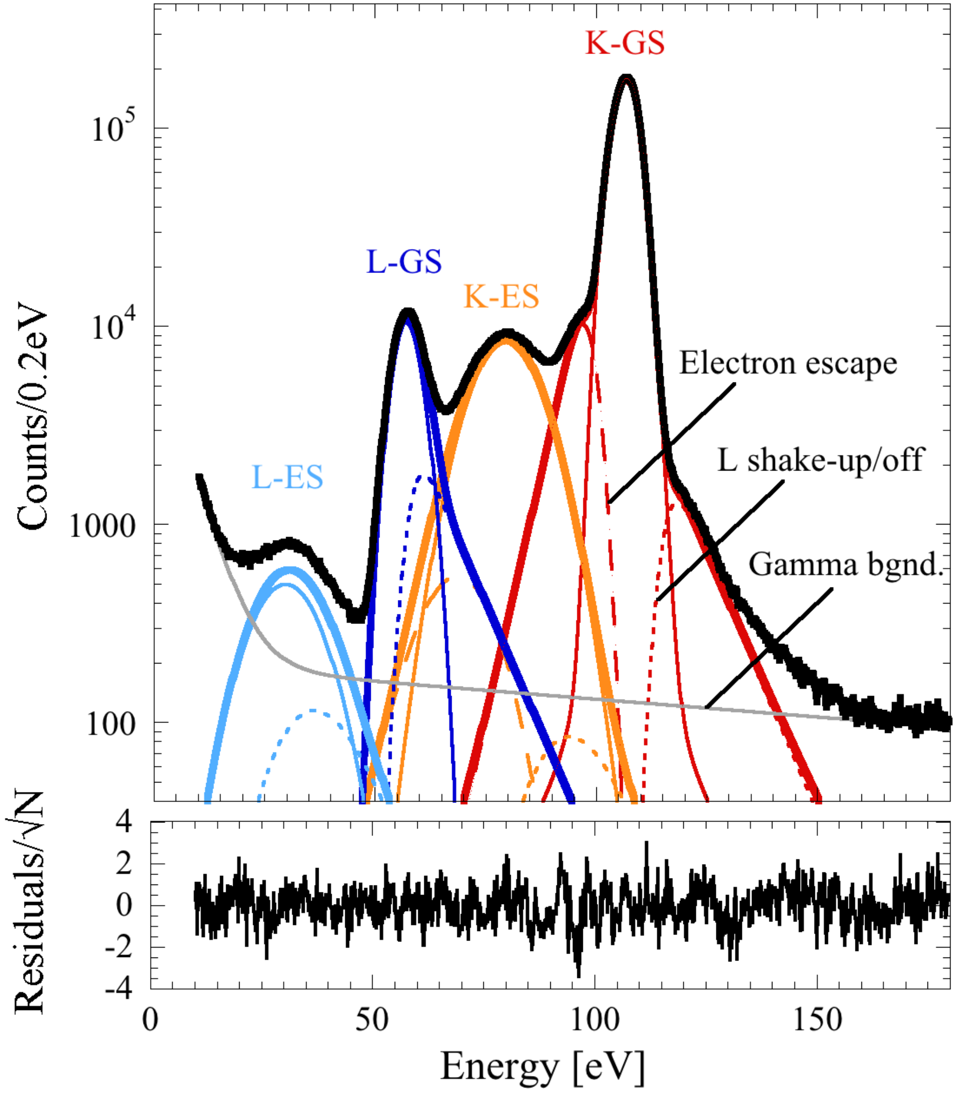
Lawrence Livermore National Laboratory



The BeEST Experiment: Searching for keV Sterile Neutrinos in the ^{7}Be Electron Capture Decay
→ (ZEP location: 2F. Dirac, DT14-678)

U.S. DEPARTMENT OF ENERGY | Office of Science
NSERC CRSNG
EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
NNSA National Nuclear Security Administration

EC Decay of ^{7}Be - The BeEST Experiment

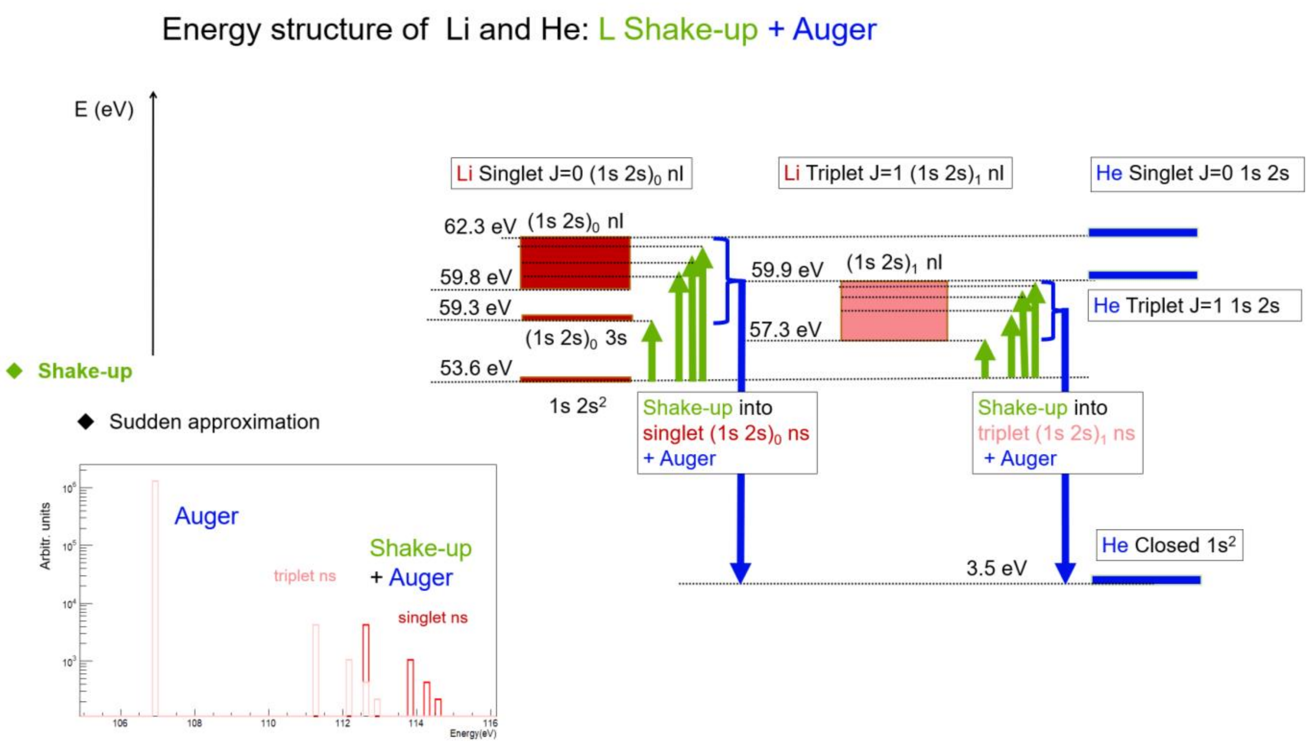


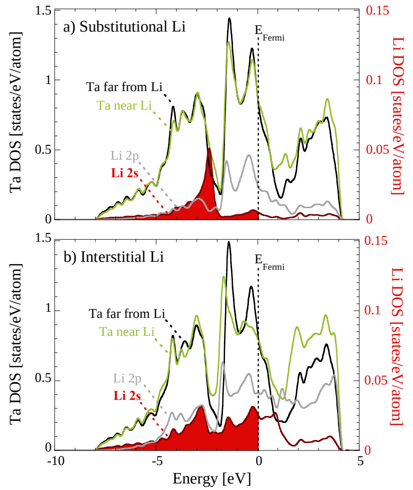
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

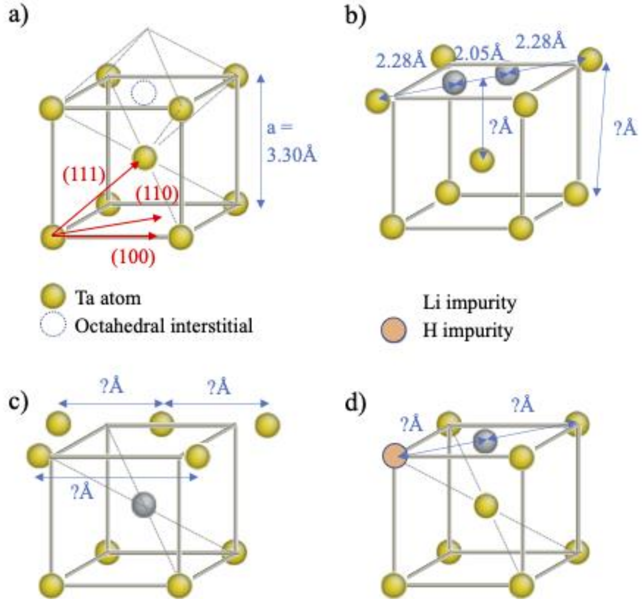
- Experiment measures direct nuclear recoils and atomic electrons from few eV to 1 keV.
- "Rare-event" search, but requires high rates of ^{7}Be decay
- Decays from two atomic capture (K and L shell) and to two nuclear states in 7Li (GS and 478 keV ES) generate 4 primary peaks in the spectrum
- Evidence of a heavy neutrino emission would result in the entire spectrum shifted to lower energies for some fraction of events
- The BeEST has completed its first two phases
  - Phase-I: Proof-of-concept -> PRL **125**, 032701 (2020)
  - Phase-II: Precision calibration and first limits -> PRL **126**, 021803 (2021)
- Higher-order atomic and material processes also observed

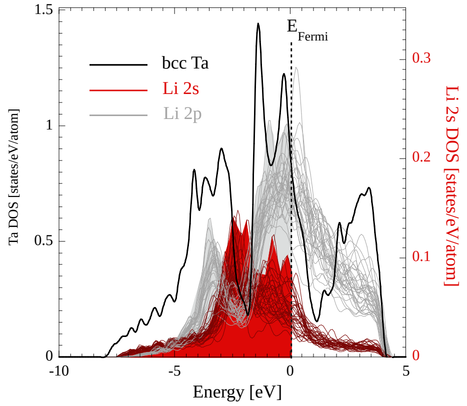
EC Decay of ^{7}Be - The BeEST Experiment

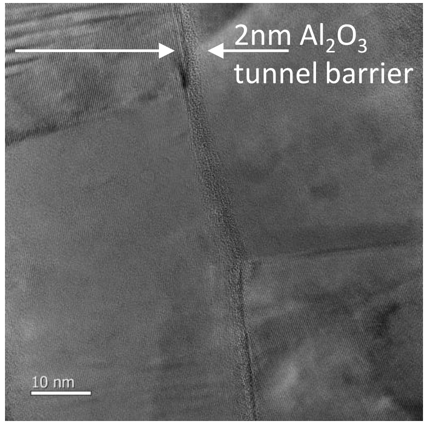
- At these energies, modeling atomic and materials effects are required
- The BeEST aims at *atomic-level* mapping of the sensor and implanted ^{7}Be











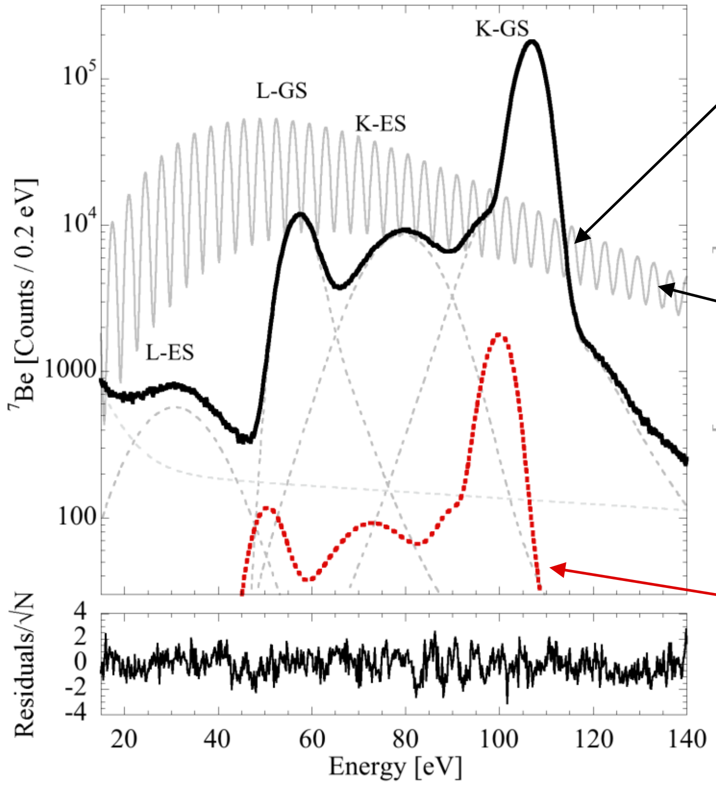
Atomic structure calculations of the ^{7}Be electron capture decay for BSM neutrino studies

→ (ZEP location: 2F. Dirac, DT14-709)

A. Samanta, S. Friedrich, KGL, and V. Lordi, *submitted to PRM* (2022)

EC Decay of ^{7}Be - The BeEST Experiment

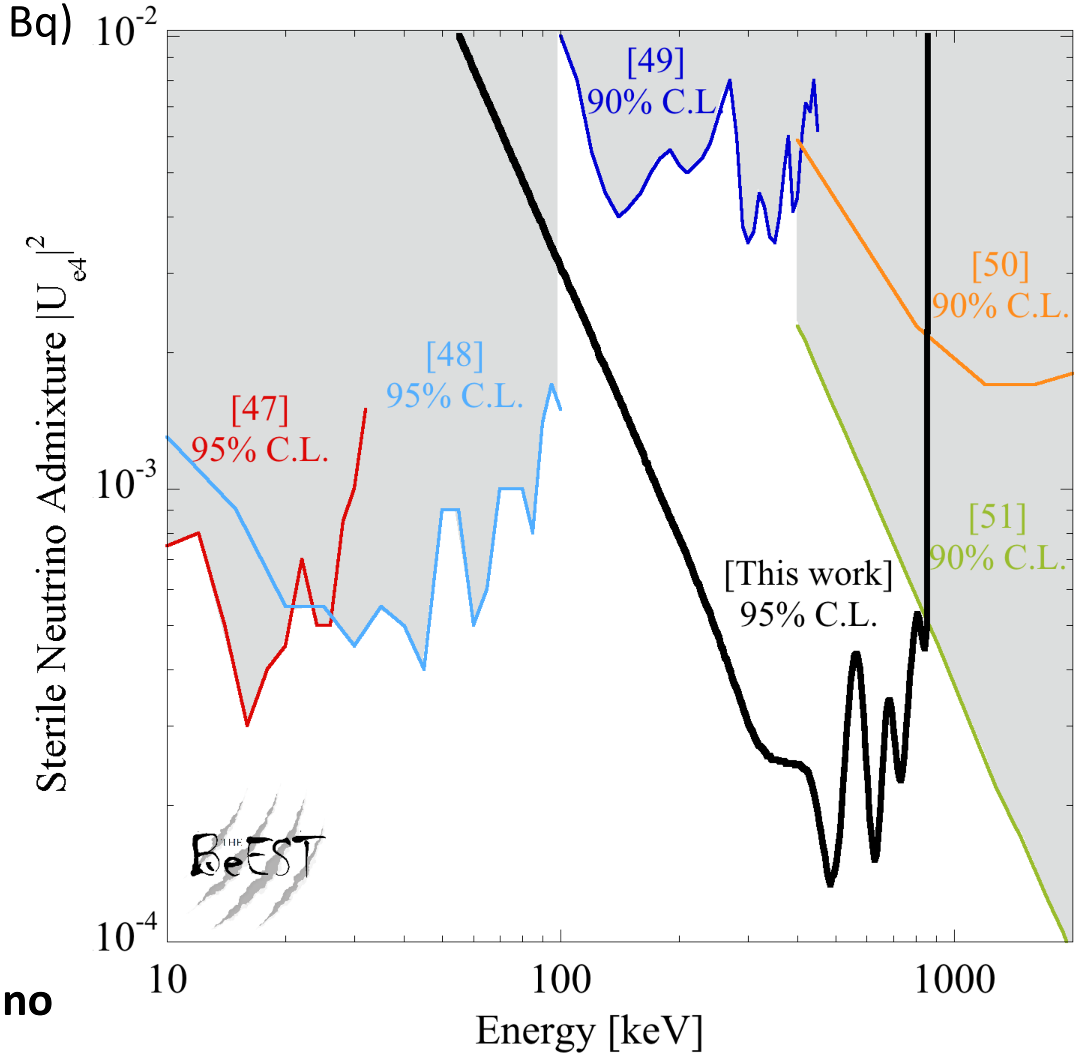
- Phase-II data from a single 138x138 μm^2 STJ counting at low rate (~10 Bq)



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

Simultaneously acquired laser calibration spectrum

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



- **Up to an order of magnitude improvement for limits on heavy neutrino admixtures to ν_e for masses of 100 – 850 keV**

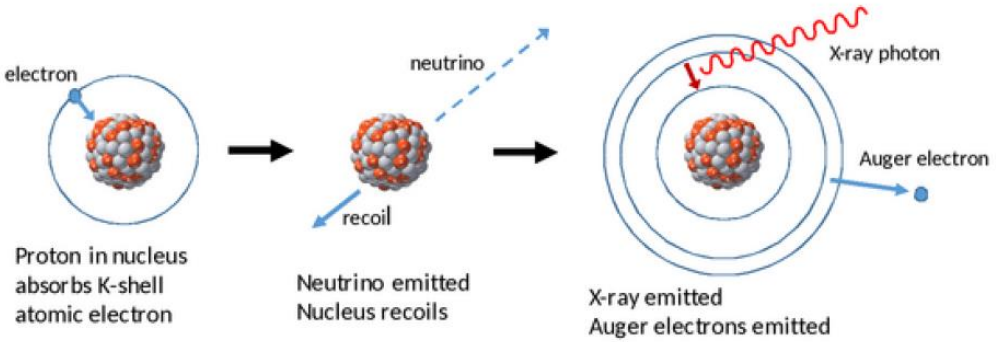
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

EC Decay of ^{131}Cs - HUNTER

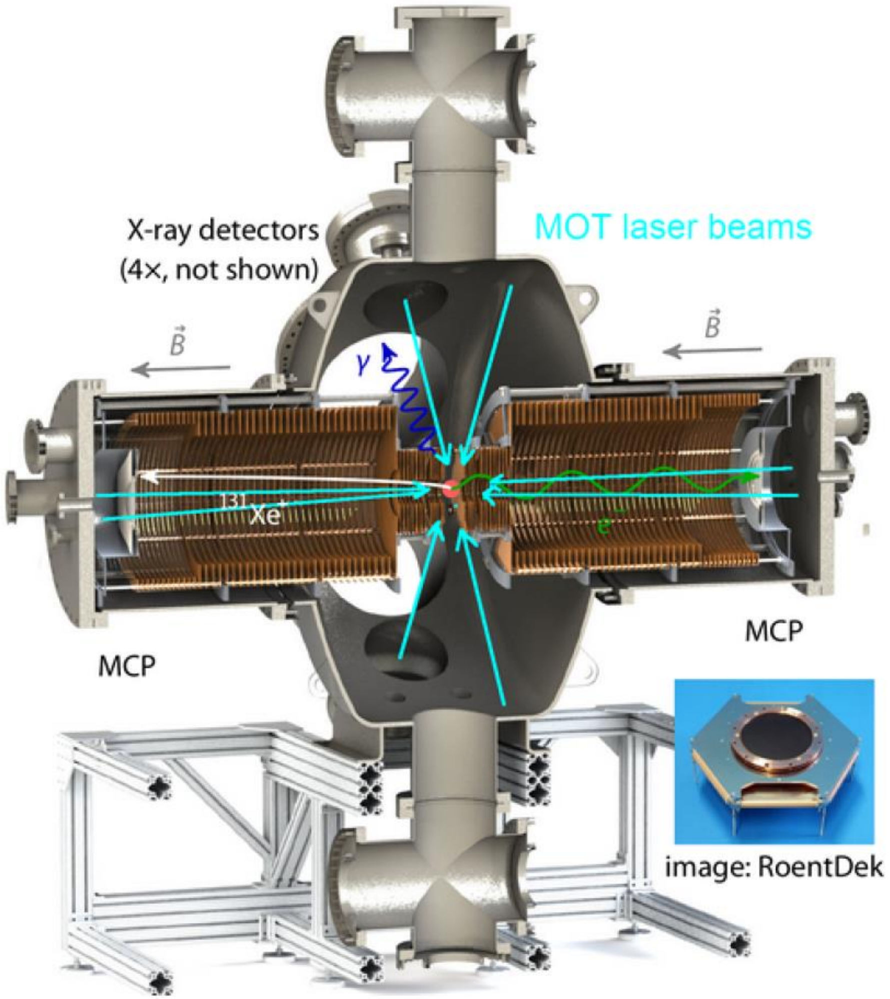
*H*eavy
*U*nseen
*N*eutrinos by
*T*otal
*E*nergy-Momentum
*R*econstruction

W.M. KECK FOUNDATION

GORDON AND BETTY MOORE FOUNDATION



- Elementary EC decay is two-body but reality is not so kind.
- $^{131}\mathrm{Cs} \rightarrow {}^{131}\mathrm{Xe}^{+(2)} + \gamma + (2)e^{-} + \nu_e$
- Two high-resolution electrostatic spectrometers plus x-ray detectors needed to detect all final state particles

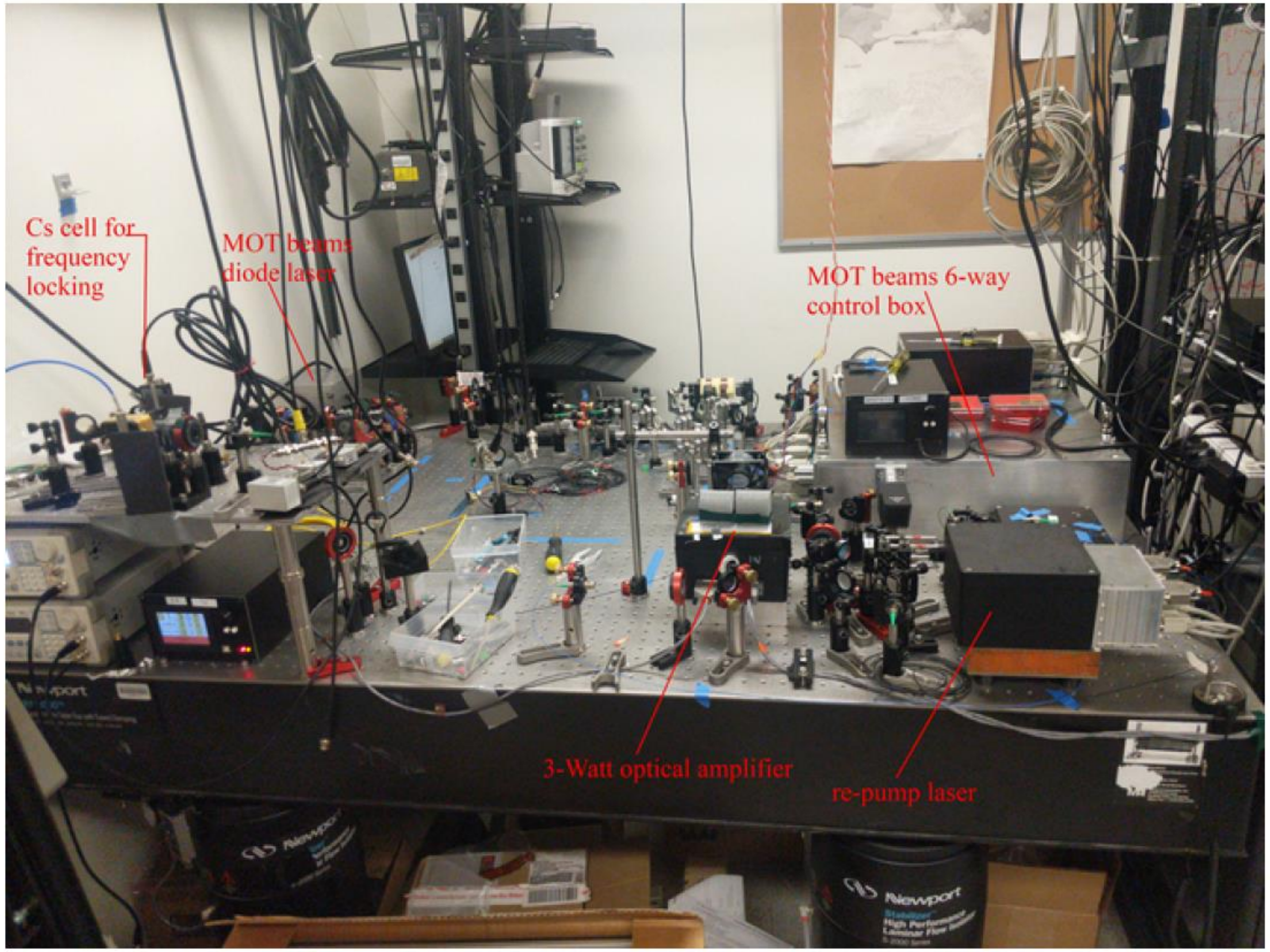


HUNTER: Heavy Unseen Neutrinos from Total Energy Reconstruction
→ (ZEP location: 2F. Dirac, DT14-084)

J. Martoff *et al.*, Q. Sci. Tech. **6**, 024008 (2021)

EC Decay of ^{131}Cs - HUNTER

Commissioning expected CY 2022



Conclusions and Outlook

- 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

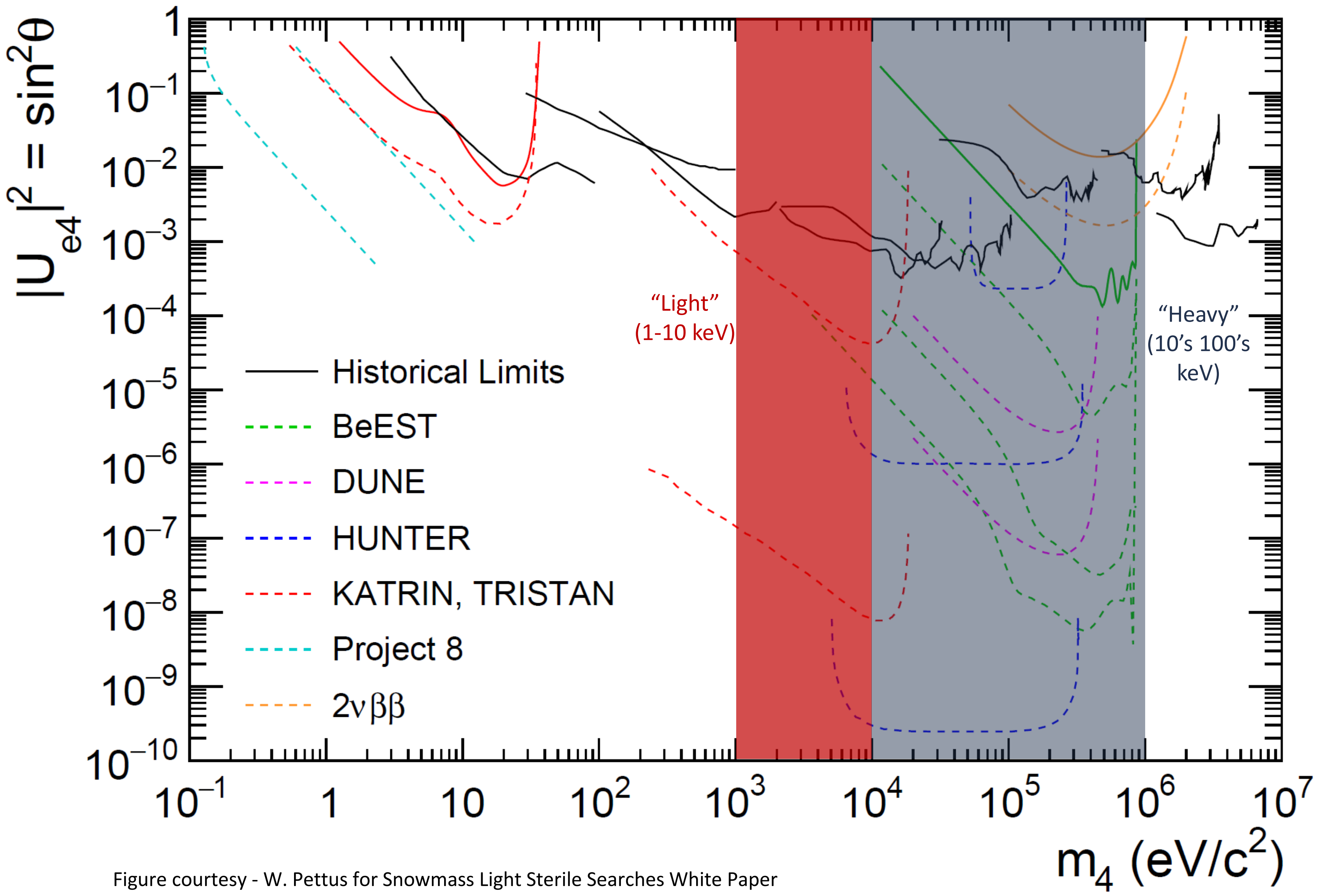


Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper

Content Acknowledgements

- Joe Formaggio
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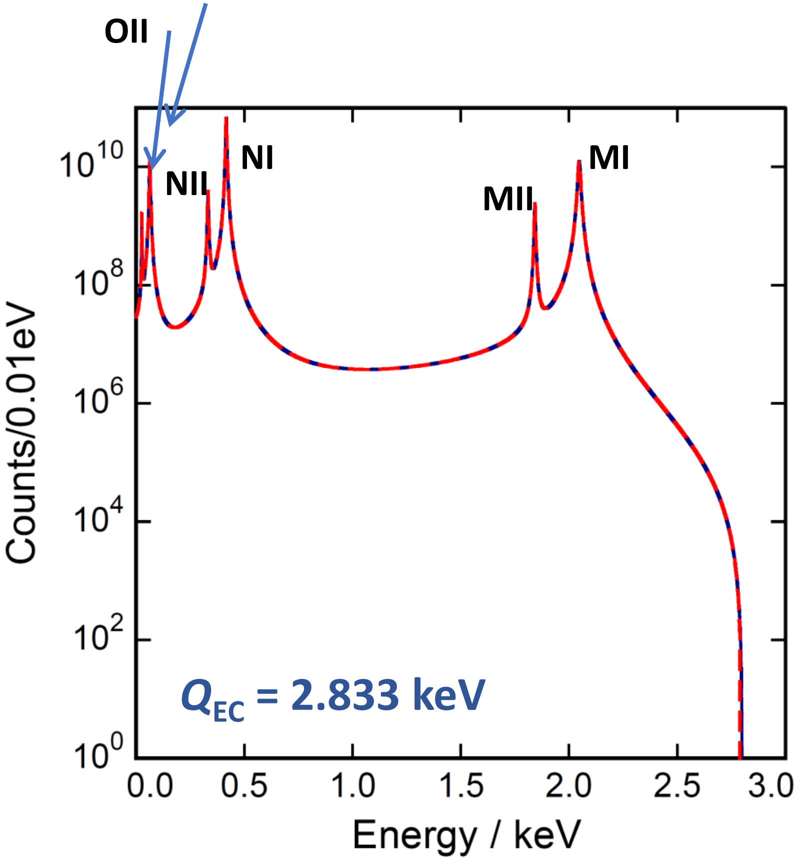
- Sunkee Kim
- Yong-Hamb Kim
- Jeff Martoff
- Suzanne Mertens
- Angelo Nucciotti
- Walter Pettus
- Pranava Surukuchi

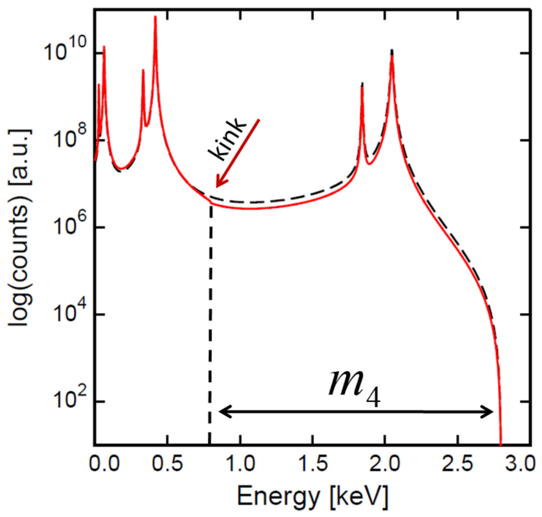
Backup Slides

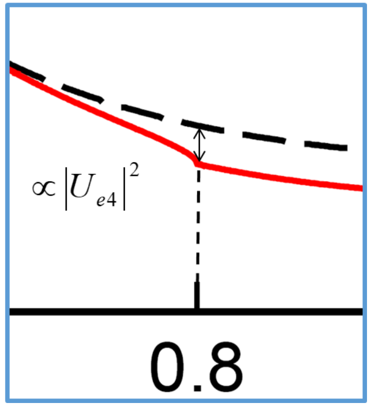
^{163}Ho EC Neutrino Mass Measurements

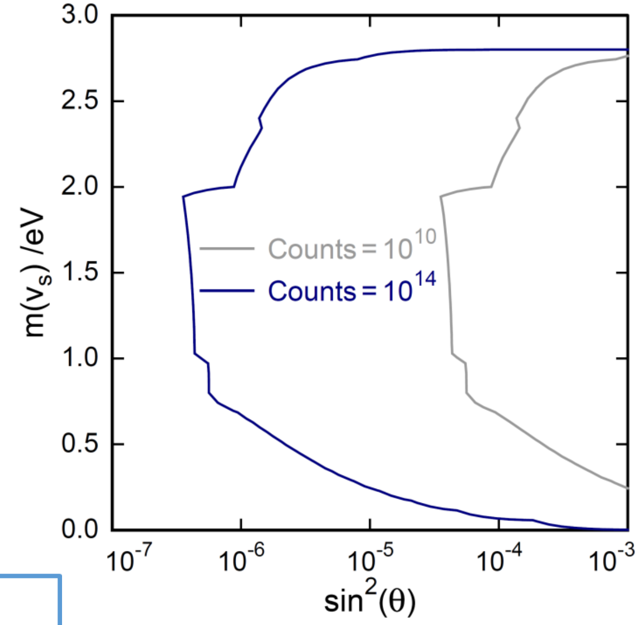
- In principle, the Ho neutrino mass measurement programs can also be used to set limits (ECHo, HOLMES)
- However, given the small Q-value and complex atomic deexcitation, there are some challenges:
  - Limited mass range (< 2.8 keV)
  - Presence of resonances complicate analysis and limit sensitivity



- ➢ postion of kink => m_4
- ➢ depth of kink => $|U_{e4}|^2$







KeV-scale sterile neutrino search with KATRIN

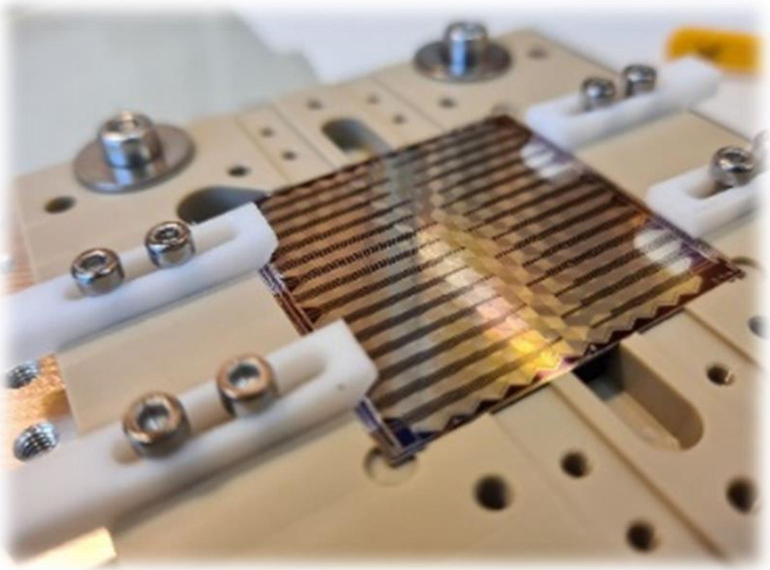
S. Mertens et al, J. Phys. G46 (2019)
S. Mertens et al, J. Phys. G48 (2020)
M. Gugiatti et al, NIM-A 979 (2020)
M. Biassoni et al, EPJ. Plus 136 (2021)
P. King et al JINST 16 T07007 (2021)

Status

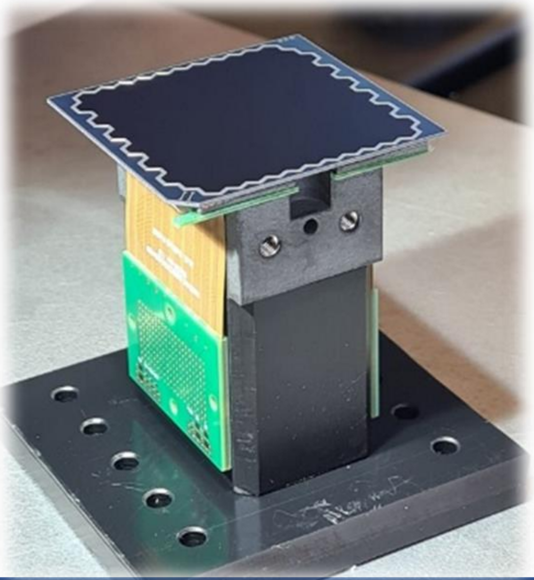
✓ Successful characterization and operation of individual TRISTAN modules

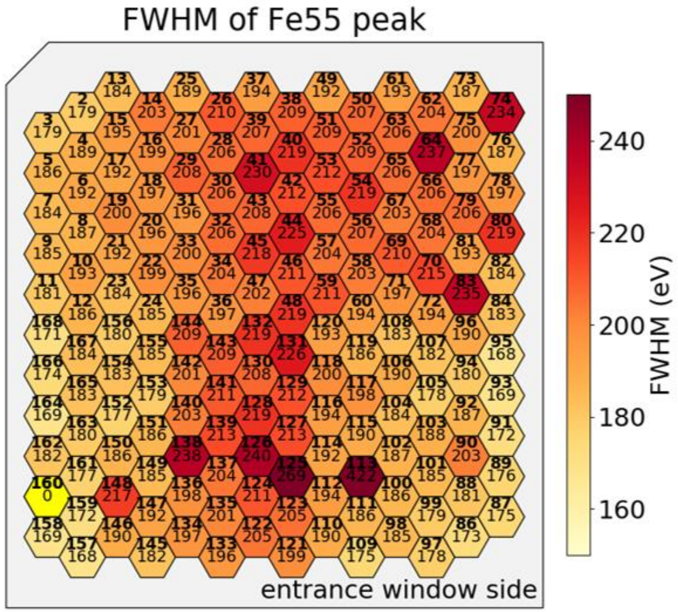
✓ Good performance (noise, linearity, stability) demonstrated for x-rays and electron

Backside of TRISTAN module (166 pixel)



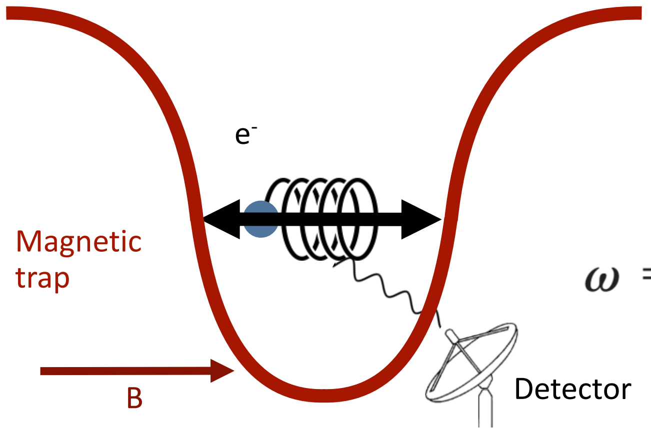
Fully mounted TRISTAN module



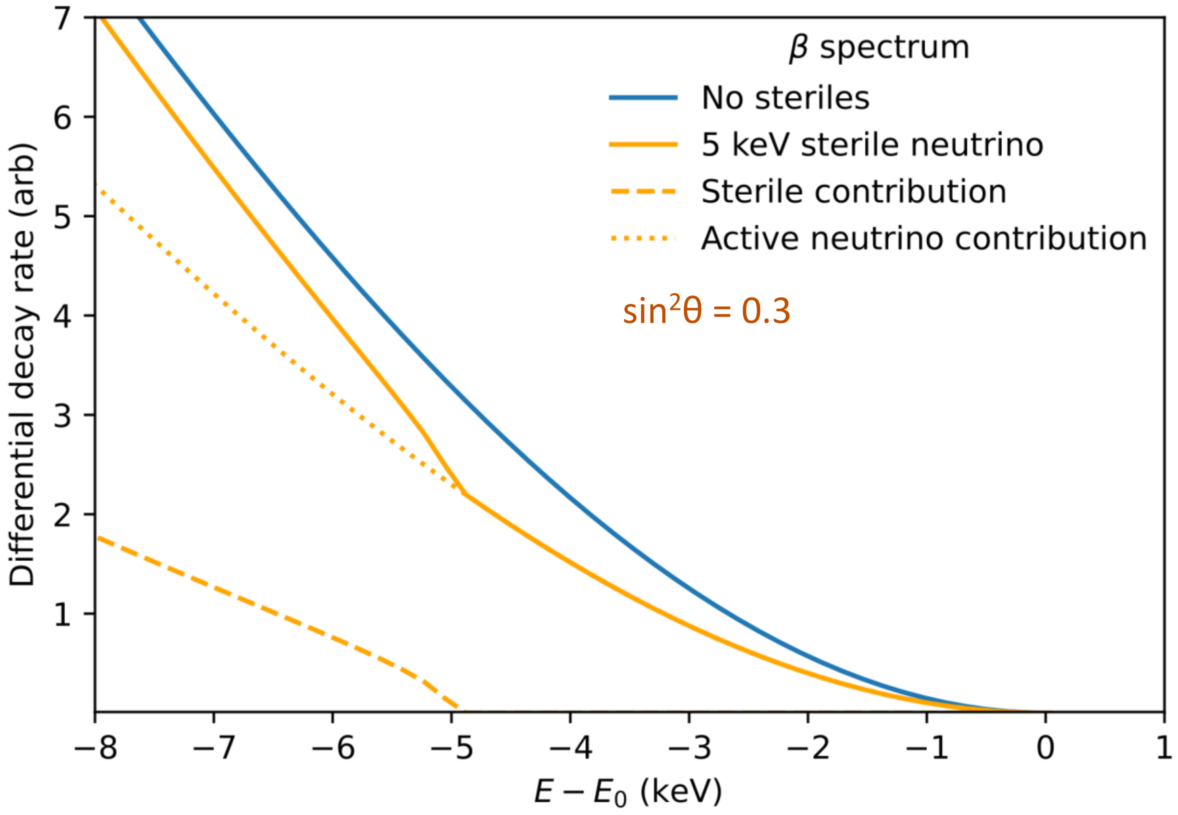


Project 8: Beta-decay Spectrum Measurement

- Project 8 experiment uses cyclotron radiation emission spectroscopy (CRES) to perform differential spectrum measurement of tritium beta decay
- In CRES method, the spectrum is measured by measuring the cyclotron frequency of electron in magnetic field
- The main goal of the experiment is to precisely measure neutrino mass
- Additional sterile neutrino state causes a distortion (kink) in the tritium beta decay spectrum
- Location of the kink depends on the mass of the sterile state and the magnitude depends on the mixing angle



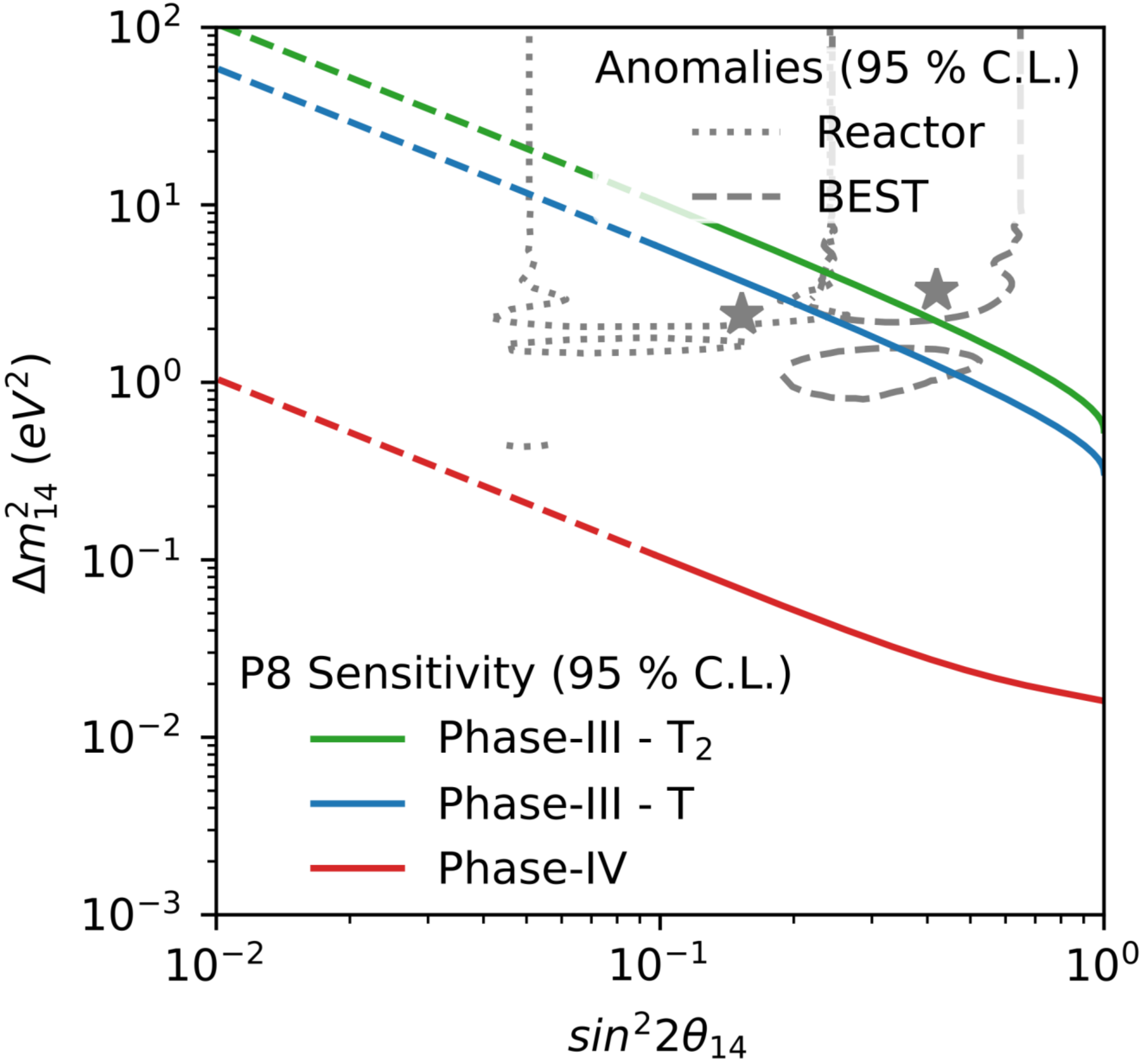
$$\omega = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + E}$$



$$\frac{dN}{dE} = \cos^2\theta \frac{dN}{dE}(m_\beta) + \sin^2\theta \frac{dN}{dE}(m_s)$$

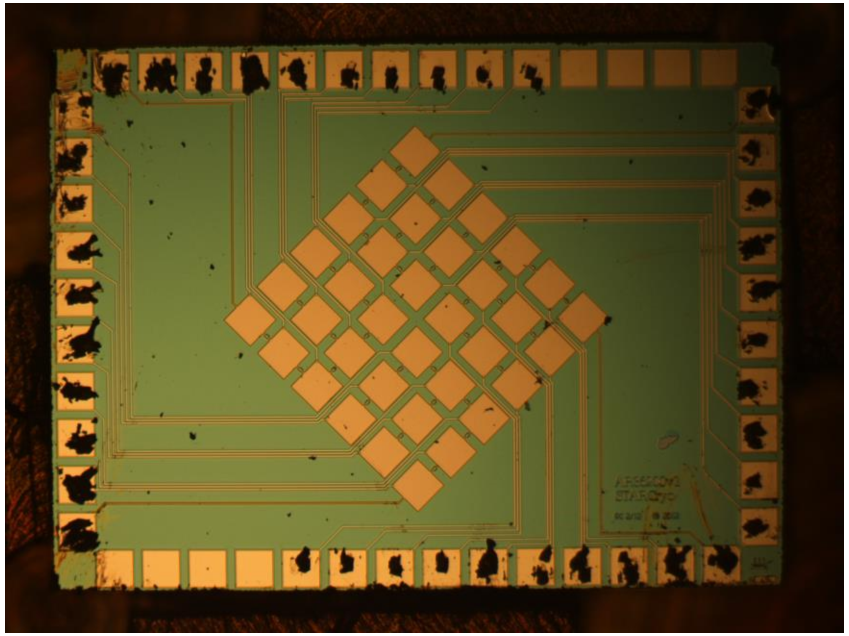
Project 8: Sensitivity to Sterile Neutrinos

- Differential beta decay spectrum measurement by Project 8 allows for simultaneous measurement of active neutrino mass and search for sterile neutrinos
- Low backgrounds, good resolution, and high event rates targeted by Project 8 for precise neutrino mass measurement also benefit search for sterile neutrinos
- Project 8 plans to search for eV-scale sterile neutrino; could be extended to search for keV-scale steriles
- Spectrum needs to be measured to keV energies below the end point
- Depends on the detection and readout technology; frequency dependence of detection at lower energies need to be well-understood

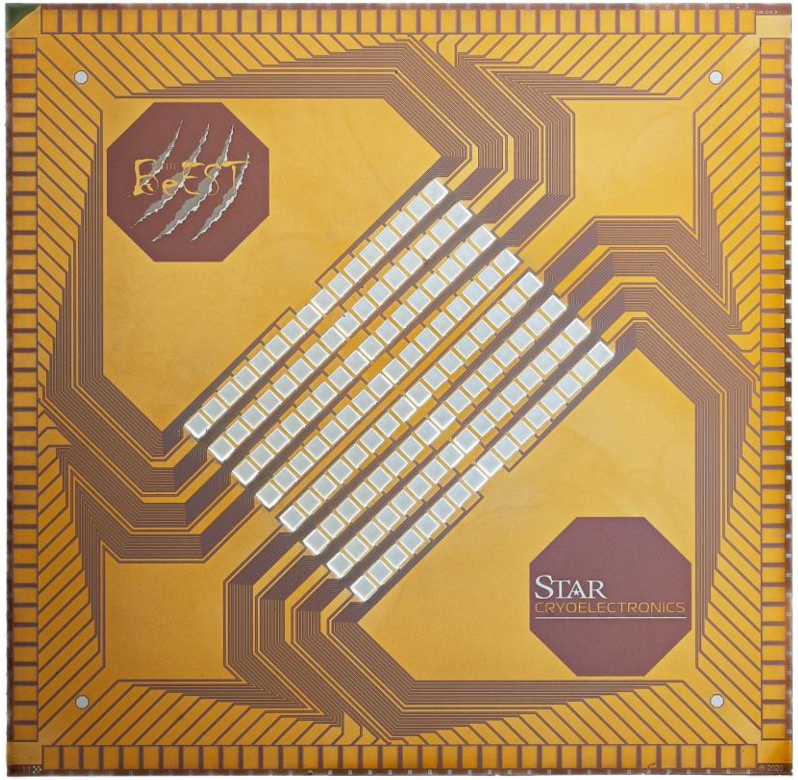


The BeEST Phases –III and –IV (2022 – 2025)

Phase-III: Scaling to 36-pixel arrays of Ta STJs
(Ongoing, measurements in progress)

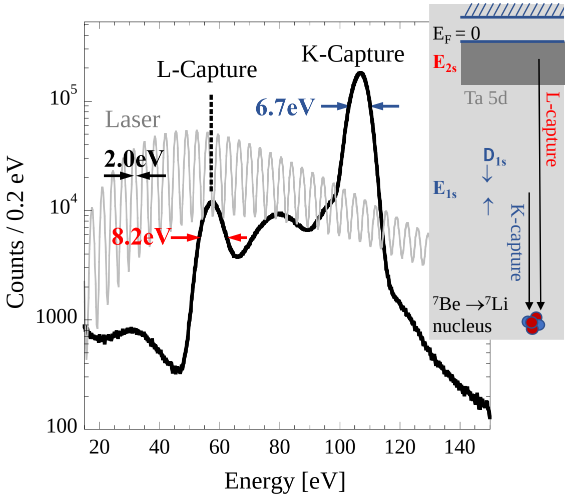


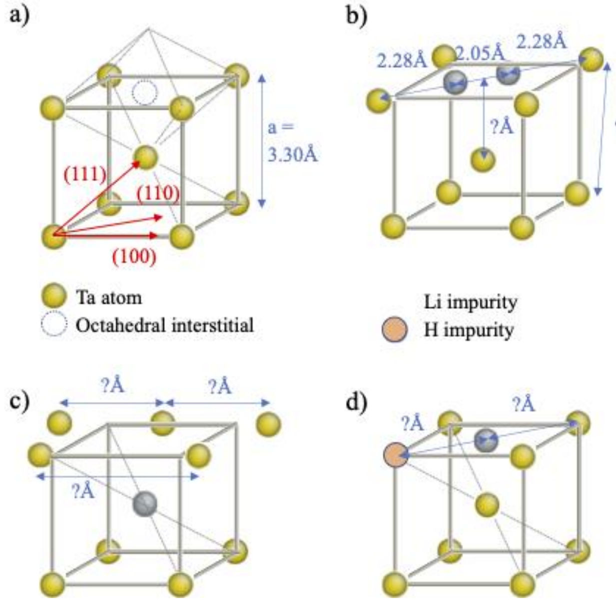
Phase-IV: 128-pixel arrays of Al STJs
(Sensor design complete, fab and testing)



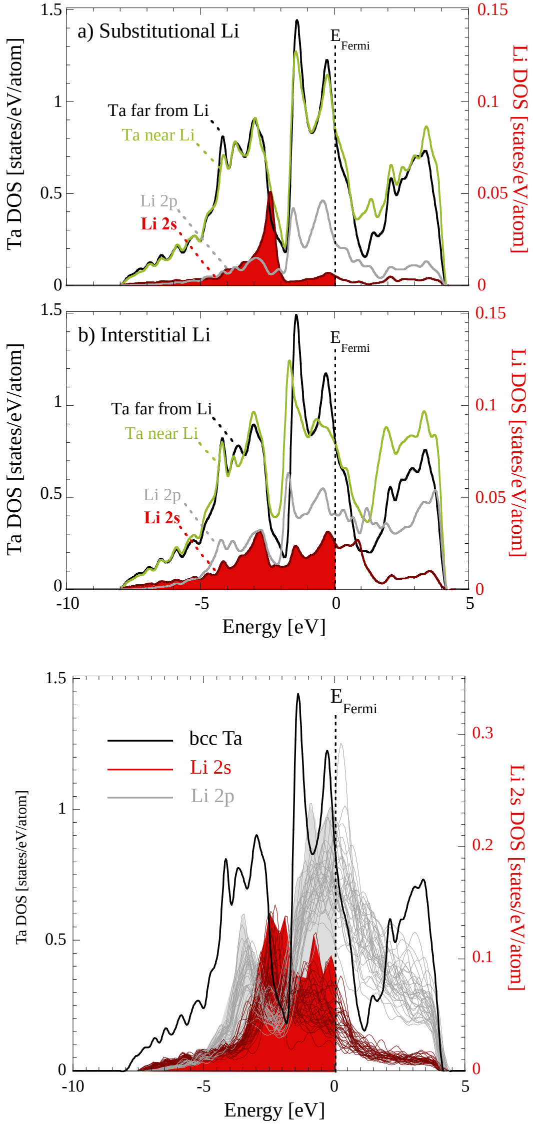
K.G. Leach and S. Friedrich, 2112.02029

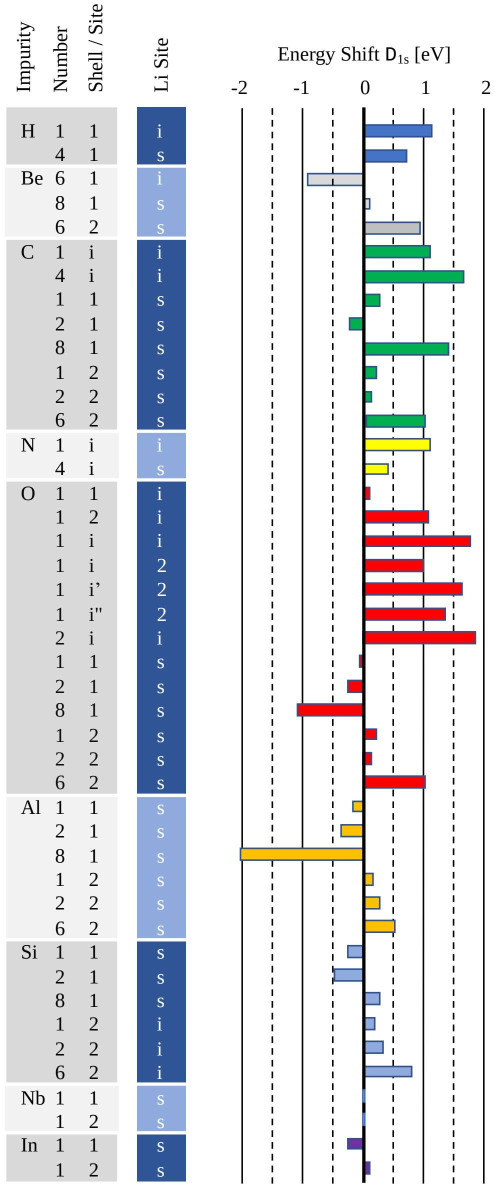
Atomistic Calculations of Chemical Shifts in Materials





- Putting Be/Li in the sensors hybridizes the atomic orbits
- These effects depend strongly on the specific local environment for the EC decaying atom
- Detailed atomistic DFT calculations show that variations in the chemical energy shifts away from the vacuum case range from 1-5 eV.





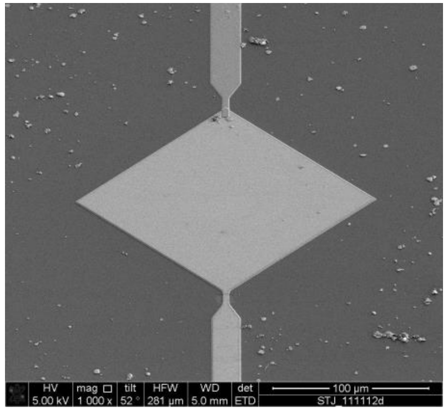
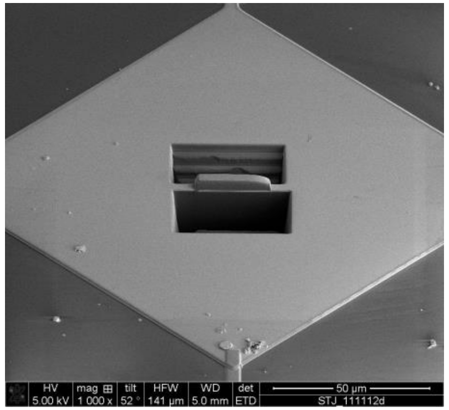
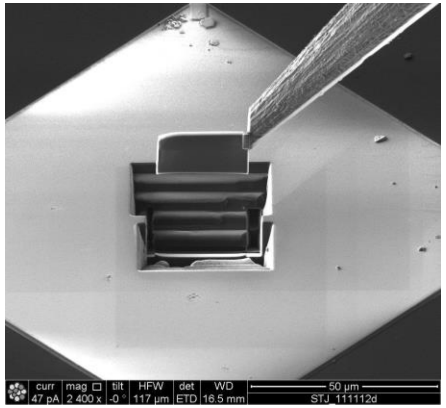
A. Samanta, S. Friedrich, KGL, and V. Lordi, *submitted to PRM* (2022)

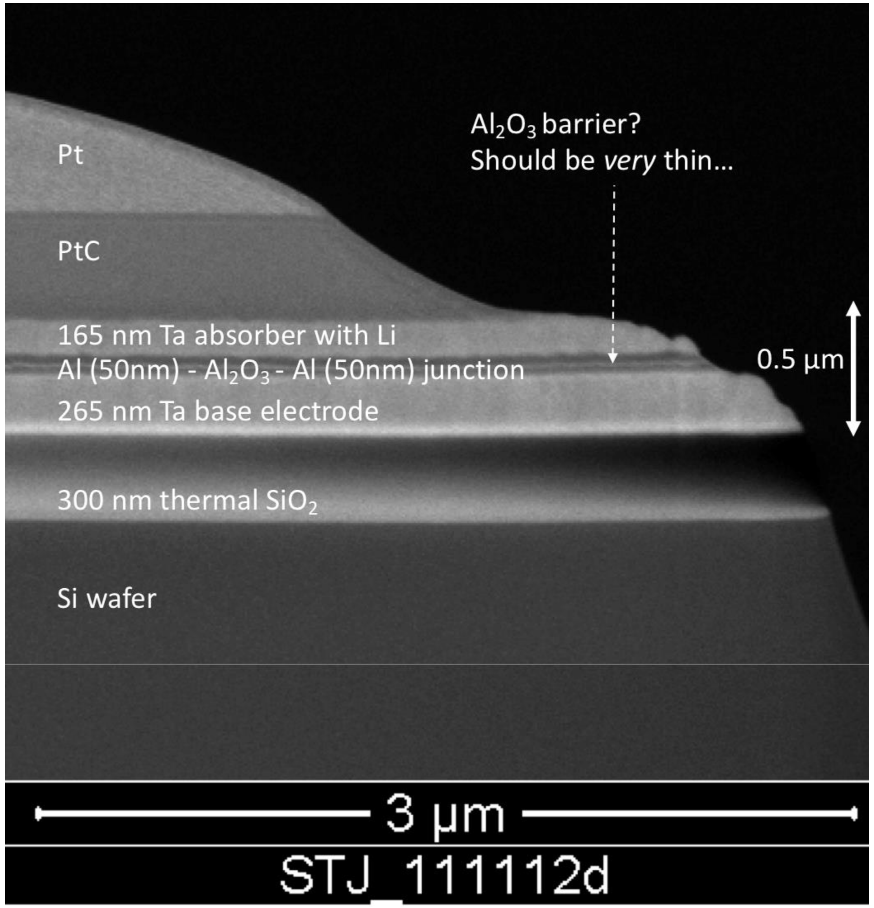
Atom-by-Atom Characterization of the BeEST

- The sensitivity of our experiment (and technique in general) is currently limited by our understanding of where the atoms we implanted are, and how they interact with the detector

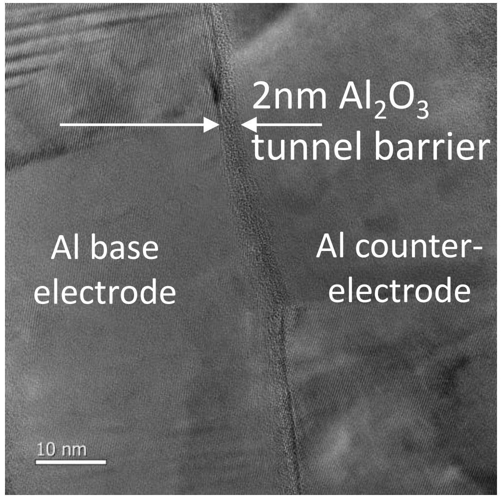
THE GOAL: Create an atom-by-atom map of the detector

"How does Be location in the matrix affect binding and emission energies?"



- Materials imaging done at Mines, Berkeley, and LLNL
- DFT quantum simulations performed at LLNL using the supercomputers to map material-dependent energies



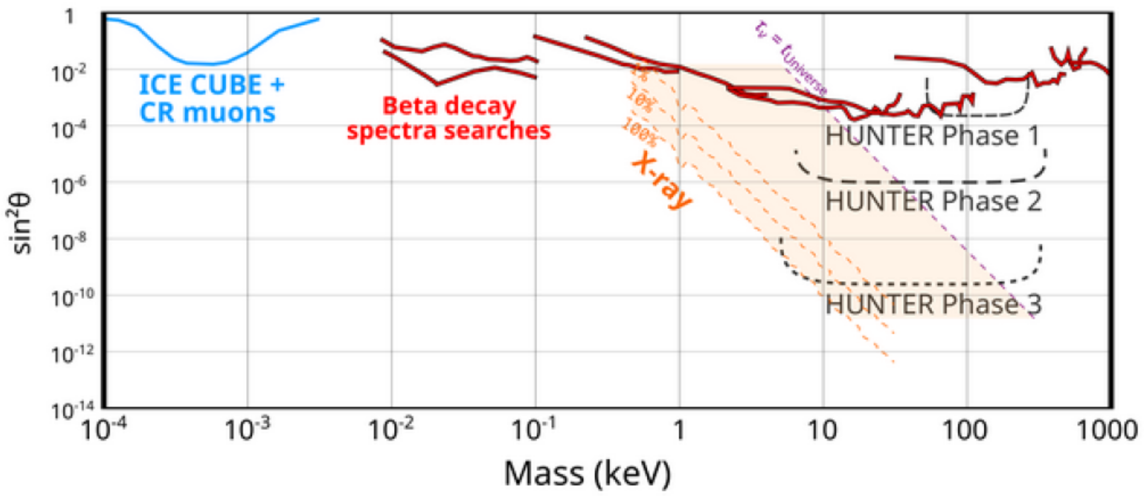
A. Samanta, D. Diercks, S. Friedrich, C. Harris, K.G. Leach, and V. Lordi (2021)

𝓗eavy
𝓤nseen
𝓝eutrinos by
𝓣otal
𝓔nergy-Momentum
𝓡econstruction

W.M. KECK FOUNDATION

GORDON AND BETTY MOORE FOUNDATION

Temple University: C. J. Martoff; V. Palmaccio, (F. Granato, X. Yu)
UCLA: E. Hudson, P. Hamilton, P. F. Smith, (Ch. Schneider); E. Chang, S. Khamis, J. Rivera
Hebrew University of Jerusalem: G. Ron, A. Prosnyakov
Princeton U.: P. Meyers
U. Houston: A. Renshaw; F. Malatino
UCLA theorists G. Gelmini, A. Kusenko
UCI theorist K. Abazajian



Projected HUNTER limits (Q. Sci. Tech. **6**, 024008 (2021))