BSM Neutrino Physics in Weak Nuclear Decay

Kyle Leach

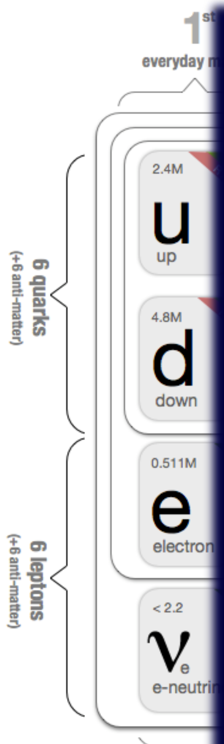
Department of Physics | Quantum Engineering | Nuclear Engineering

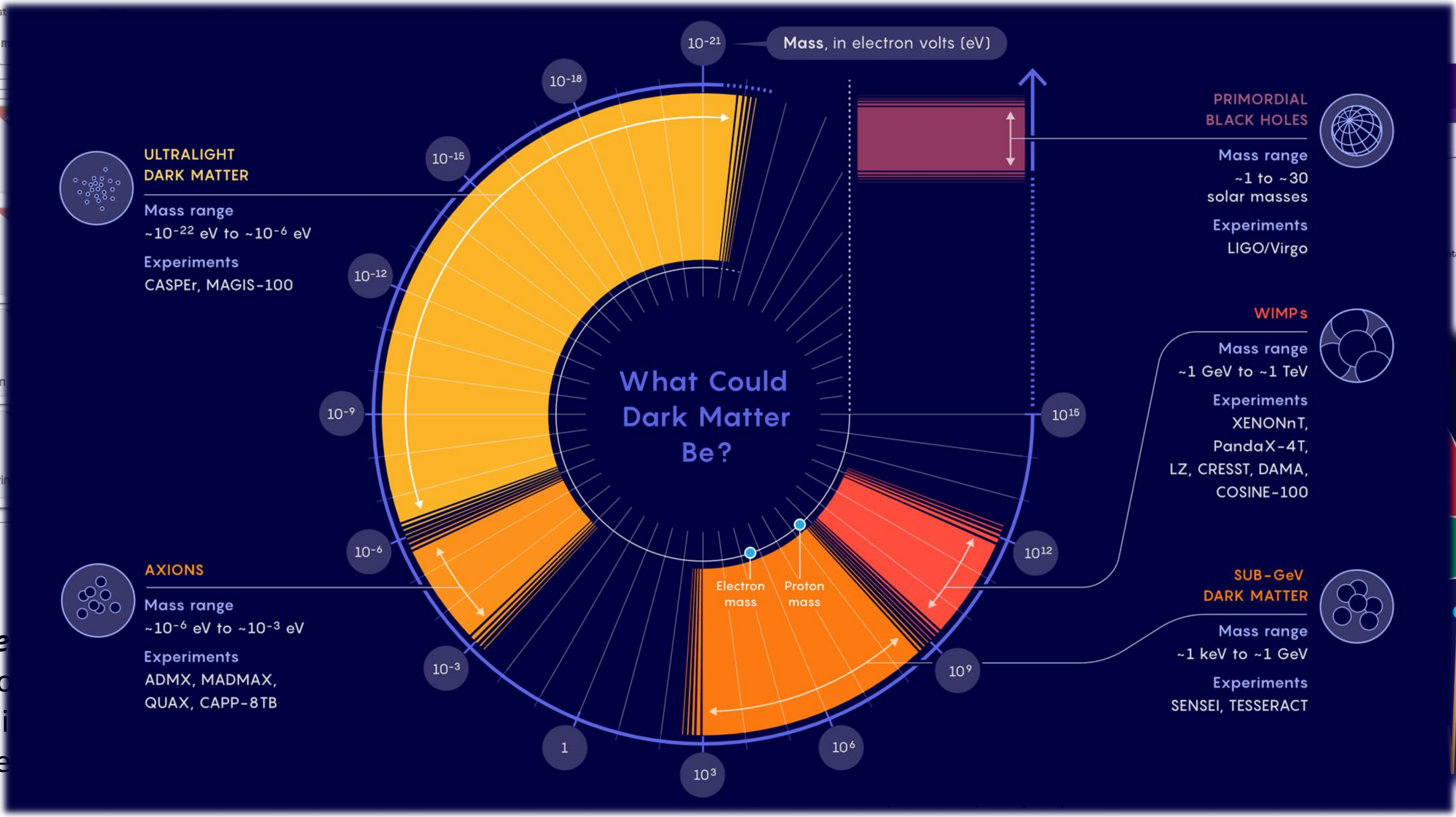
Colorado School of Mines

2022 CAP Congress - Hamilton, ON

June 8, 2022

New Physics: What is it and Where do we Search?





Where doe

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- Tantalizi
- Most ne

Putting the Puzzle Together

2016 THE BREAKTHROUGH PRIZE

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

VOLUME 81, NUMBER 8 — PHYSICAL REVIEW LETTERS — 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

VOLUME 87, NUMBER 7 — PHYSICAL REVIEW LETTERS — 13 AUGUST 2001

Measurement of the Rate of $\nu_e + d \to p + p + e^-$ Interactions Produced by ^{8}B Solar Neutrinos at the Sudbury Neutrino Observatory

First Search for the Majorana Nature of Neutrinos in the Inverted Mass Ordering Region with KamLAND-Zen

2203.02139

$m_{\beta\beta} < 35\text{-}156$ meV

PHYSICAL REVIEW D **101**, 083504 (2020)

$\Sigma m_\nu < 160$ meV **

Cosmological parameters and neutrino masses from the final *Planck* and full-shape BOSS data

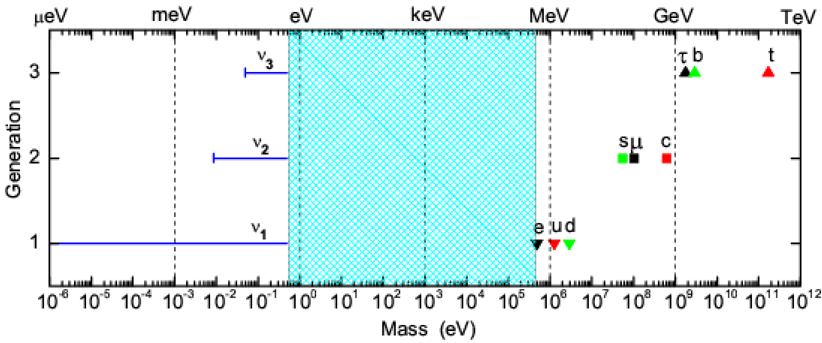
nature physics

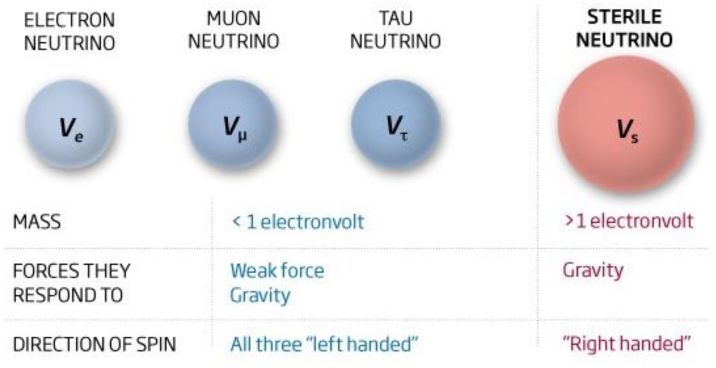
Direct neutrino-mass measurement with sub-electronvolt sensitivity

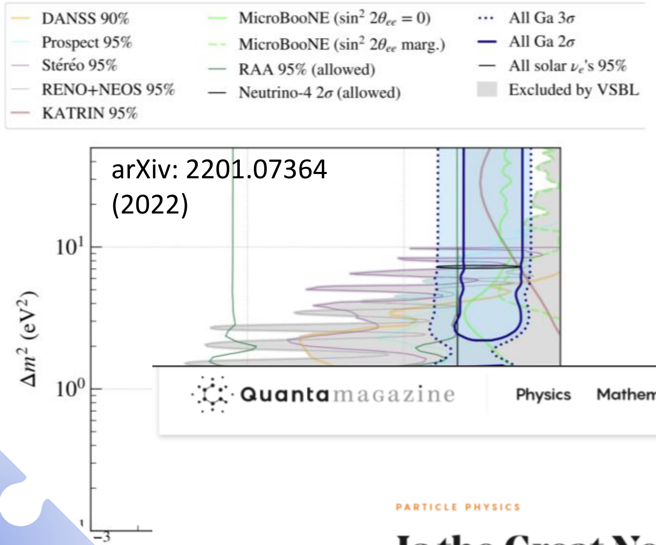
The KATRIN Collaboration

Nature Physics **18**, 160–166 (2022) | Cite this article

$m_{\nu e} < 800$ meV







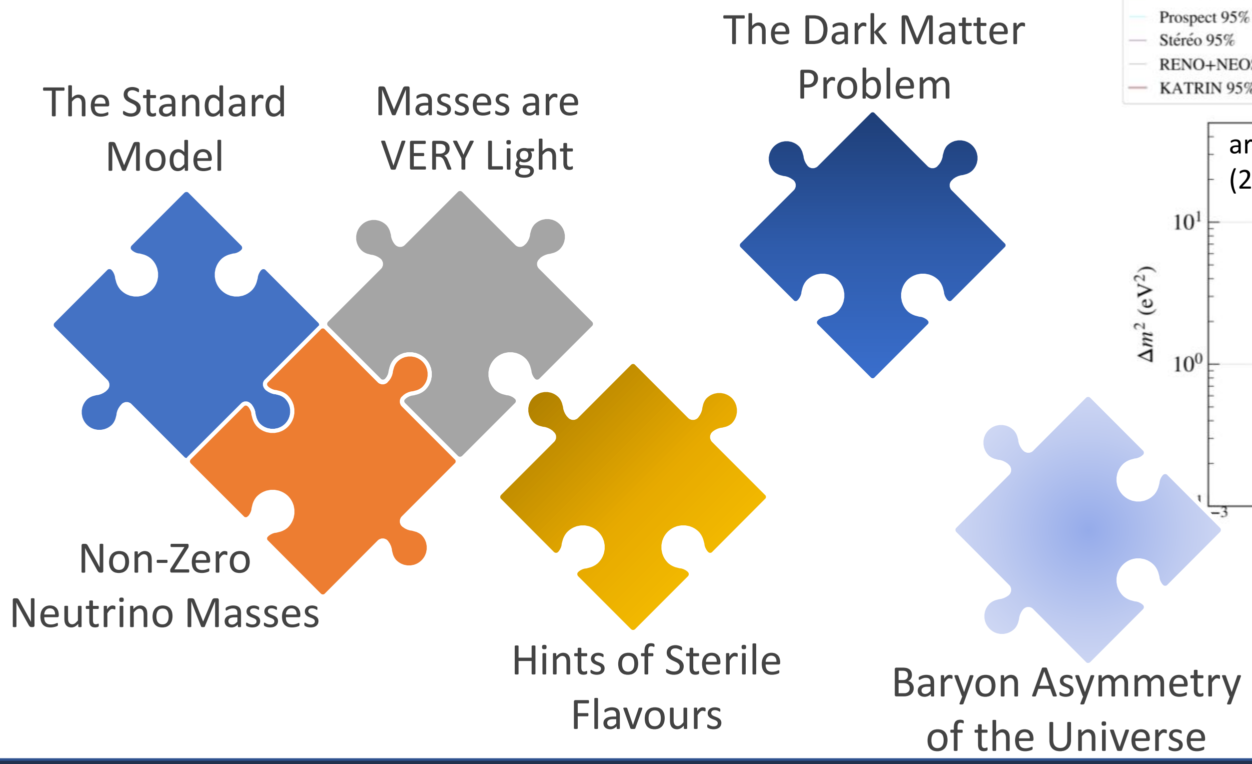
Quantamagazine — Physics — Mathematics — Biology — Computer Science — Topics — Archive

PARTICLE PHYSICS

Is the Great Neutrino Puzzle Pointing to Multiple Missing Particles?

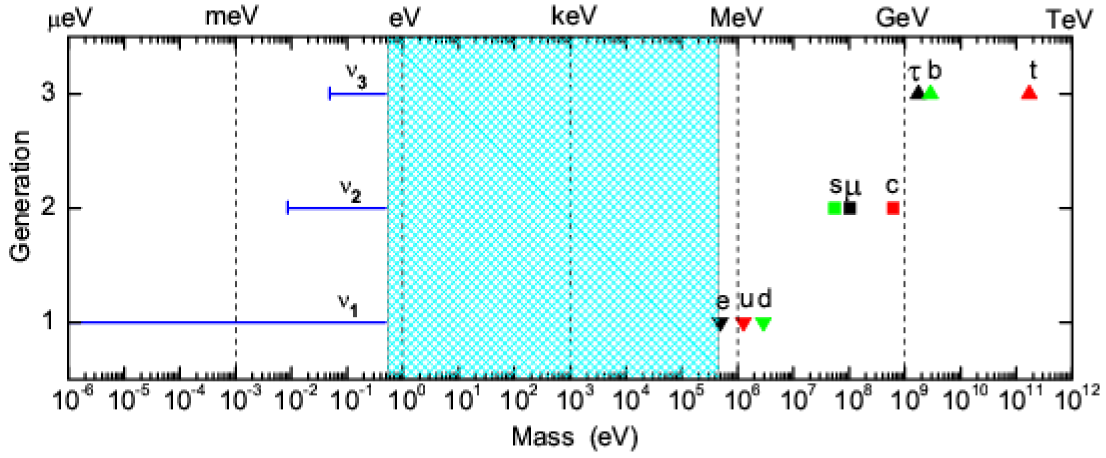
21

Years of conflicting neutrino measurements have led physicists to propose a "dark sector" of invisible particles — one that could simultaneously explain dark matter, the puzzling expansion of the universe, and other mysteries.



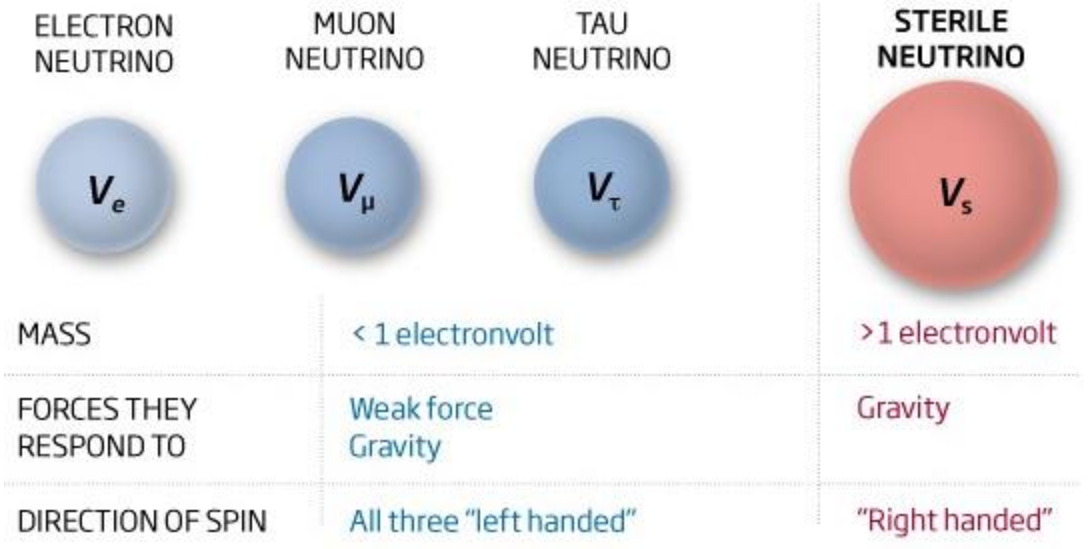
Open Questions in the Neutrino Sector

- Why are these masses so small relative to the other Fermions?
- What is the mass hierarchy?
- How many mass states are there?
- What is the absolute mass scale?
- Do they violate CP symmetry?
- Are they Dirac or Majorana Fermions?
- Are there additional "sterile" neutrino flavours?



As a community, we attack these questions using a wide variety of probes:

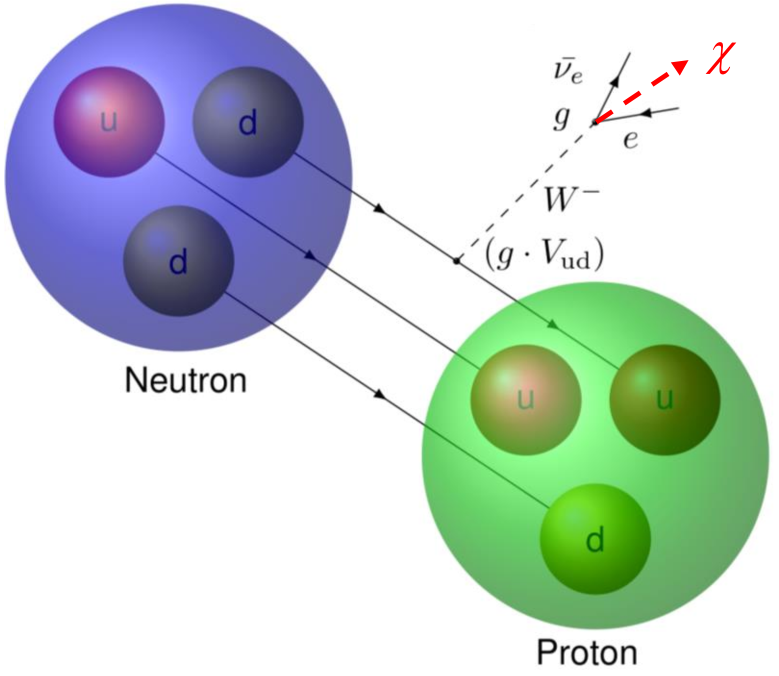
- Cosmological observations
- Accelerators
- Direct detection
- **Precision beta decay**

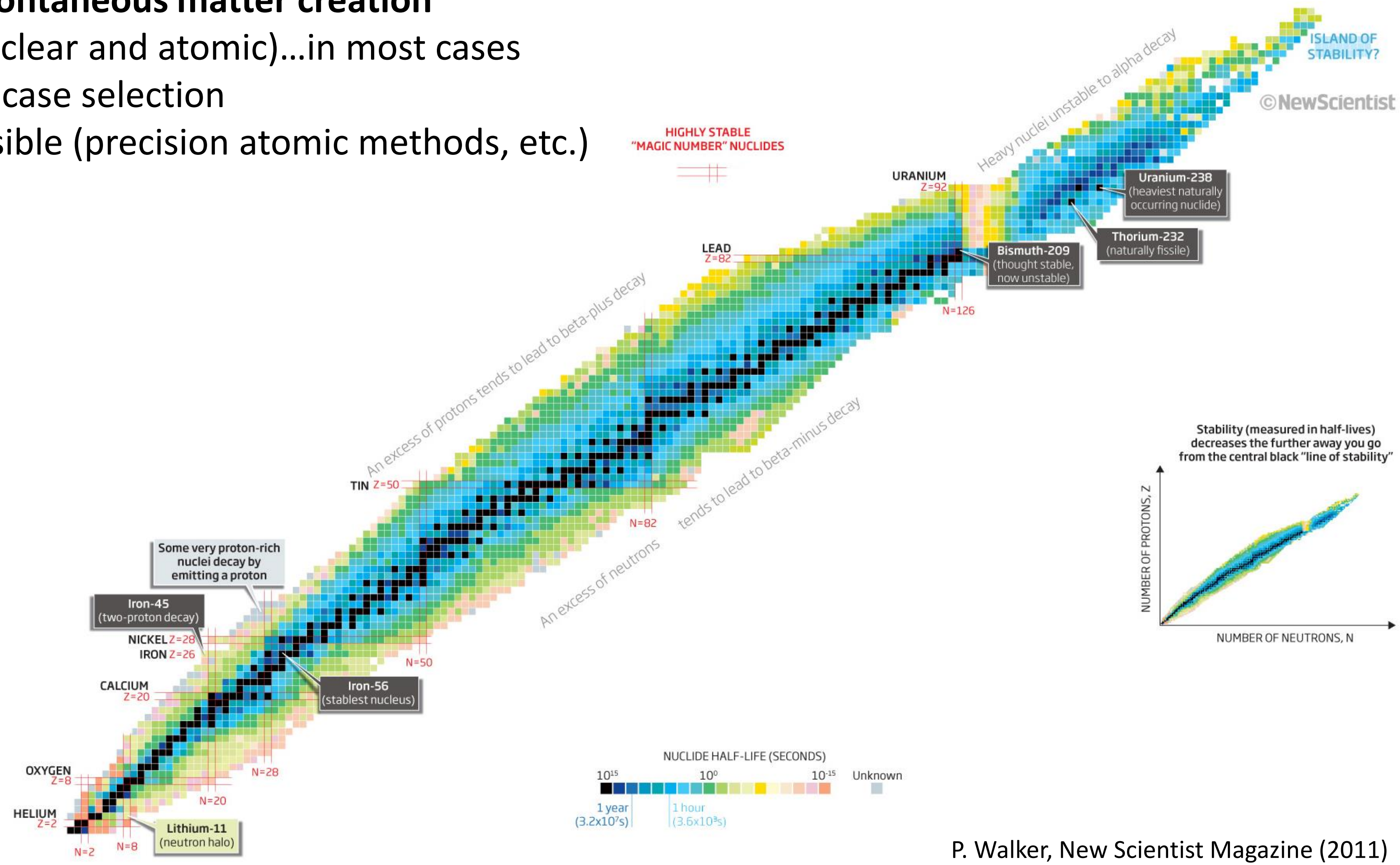


Creating New Physics in the Laboratory with Rare Isotopes

Weak Nuclear Decay is among the *MOST* sensitive BSM physics probes:

- 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.)

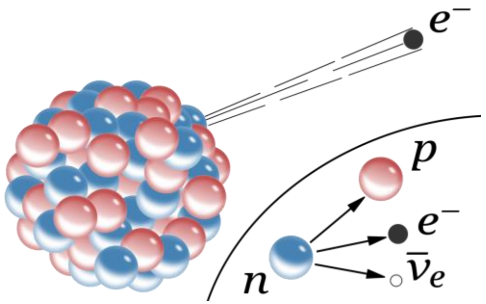




P. Walker, New Scientist Magazine (2011)

Need: Model Independent and *Definitive* Experiments

β/EC decay

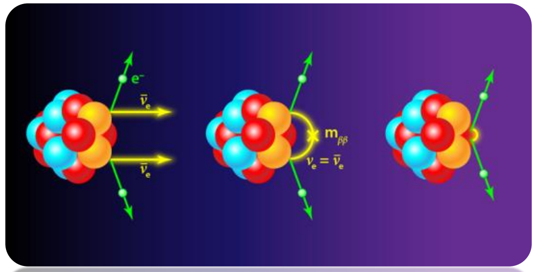


β Decay

- $T_{1/2}$ from a few ms to $\geq 10^{15}$ y
- Observed in > 1000 different nuclei from n to $A \geq 250$

- Energy and momentum conservation
- Model independent search for ANY new physics that couples to the neutrino mass

ββ decay

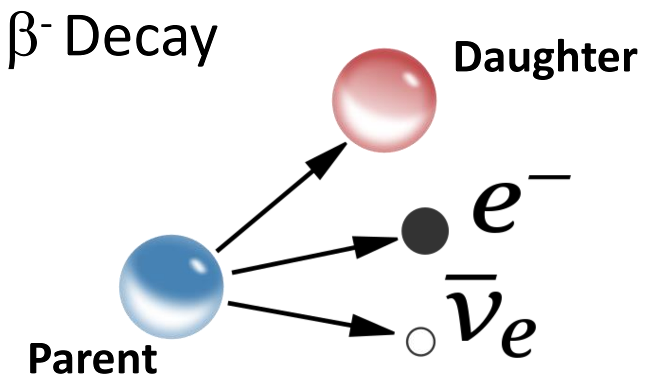


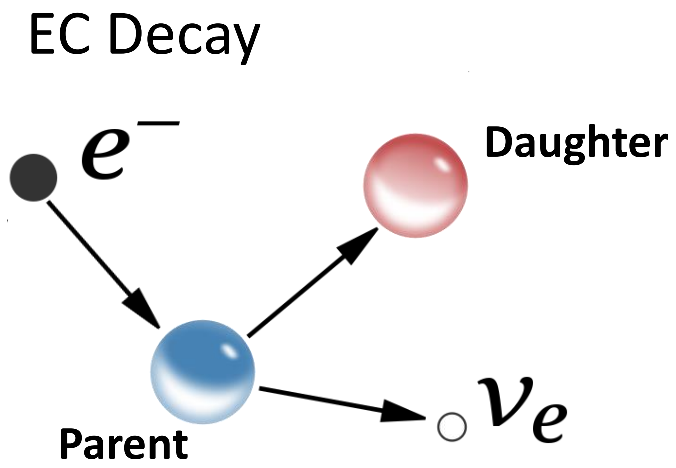
$\beta\beta$ Decay

- $T_{1/2} \sim 10^{19-24}$ y
- Observed in only 11 nuclei from ^{48}Ca to ^{238}U

- Direct observation of "neutrinoless" mode
- Any observation of 0νββ is a smoking gun signature of BSM physics (ie. Majorana)

The Model Independent Nature of Beta Decay





- Decay momentum reconstruction is a simple, model-independent approach to neutrino mass (heavy and light)

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

Absolute Neutrino Mass Scale via β Endpoint Measurements

Neutrinos are a Hot Topic!

NuMass 2022 - Determination of the absolute electron (anti)-neutrino mass

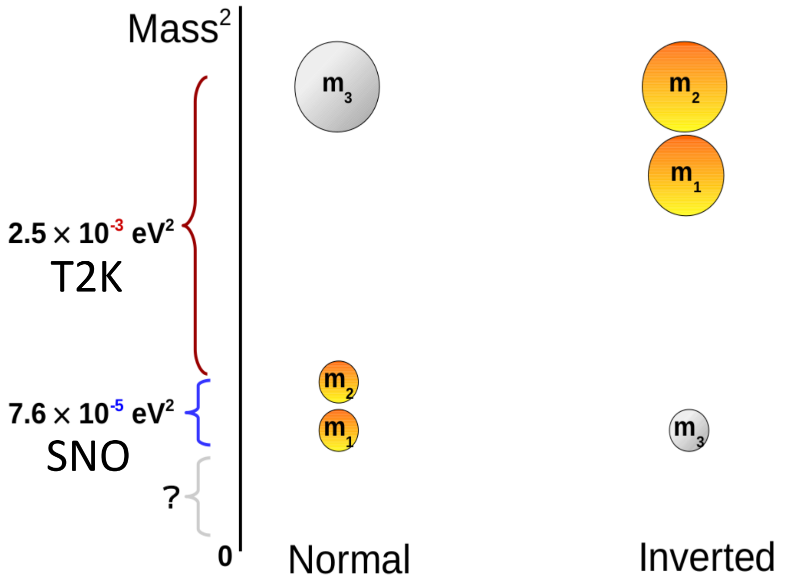
Monday, June 6, 2022 - Friday, June 10, 2022

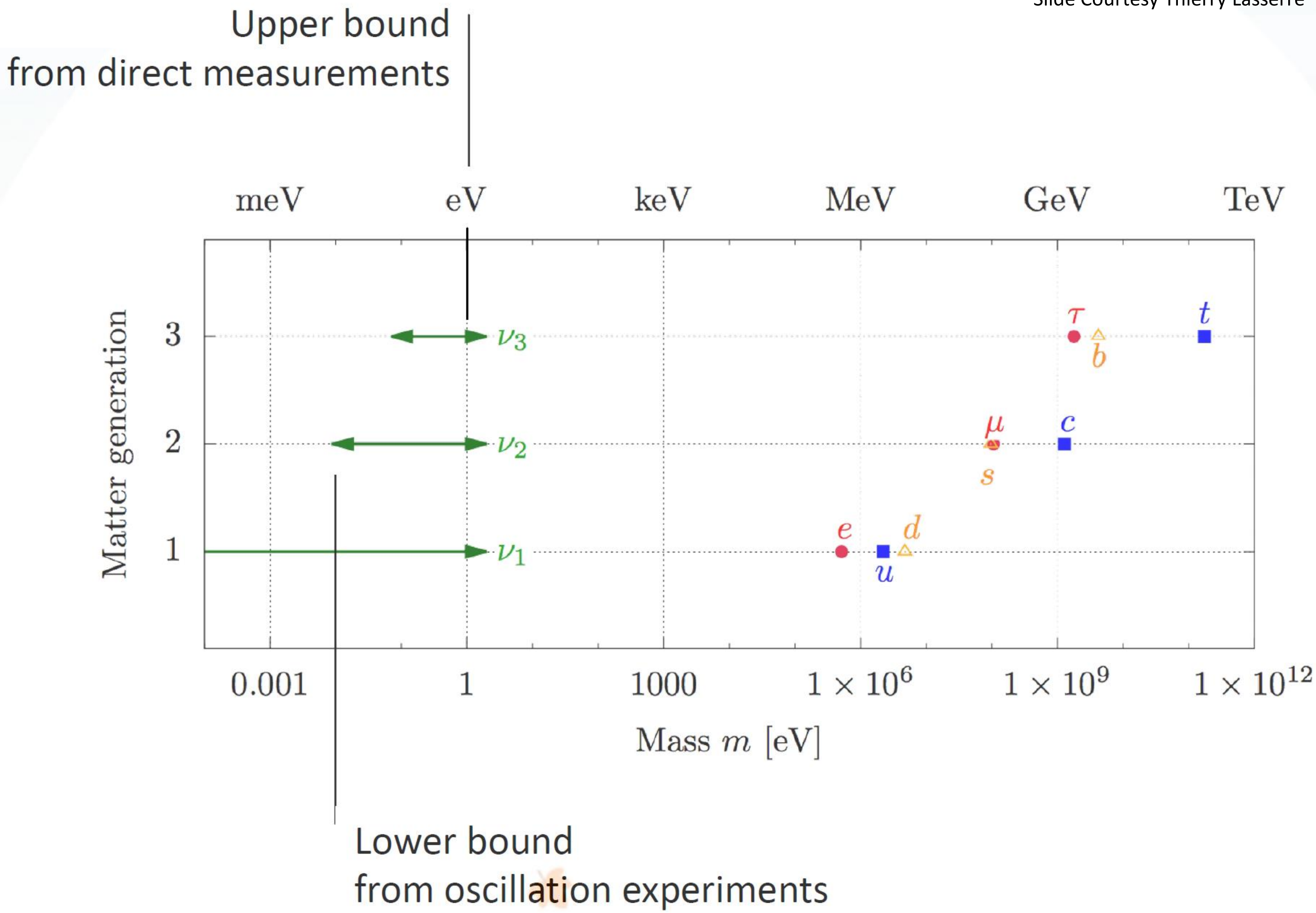
Università degli Studi di Milano-Bicocca

What is the Absolute Scale of the Neutrino Mass?

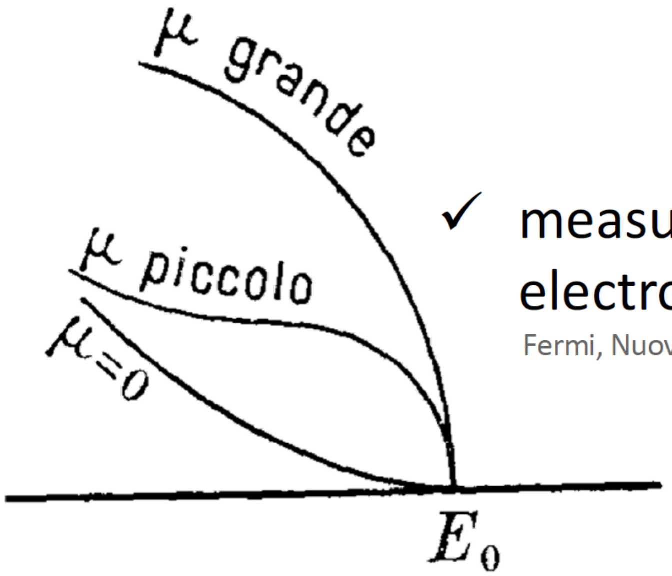
Slide Courtesy Thierry Lasserre

- At least two of the mass states are non-zero
- However, the absolute value for the lightest is not known → and thus the scale of the masses is not set





Beta Spectrum Endpoint Measurements



- ✓ measurement of the electron β −spectrum

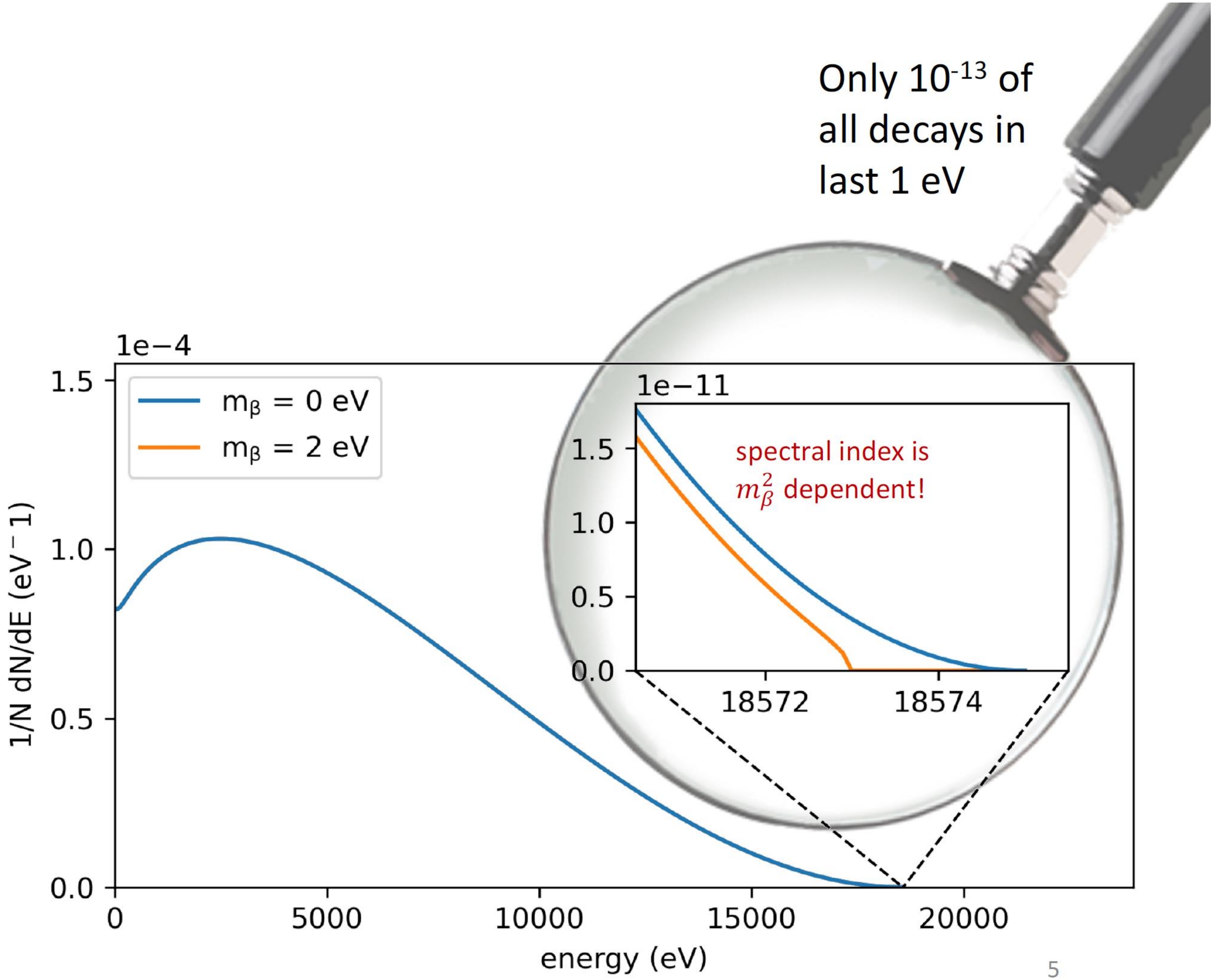
Fermi, Nuovo Cim. 11 (1934) 1-19

Slide Courtesy Thierry Lasserre

Precision Tritium Endpoint Measurement: KATRIN and Project-8

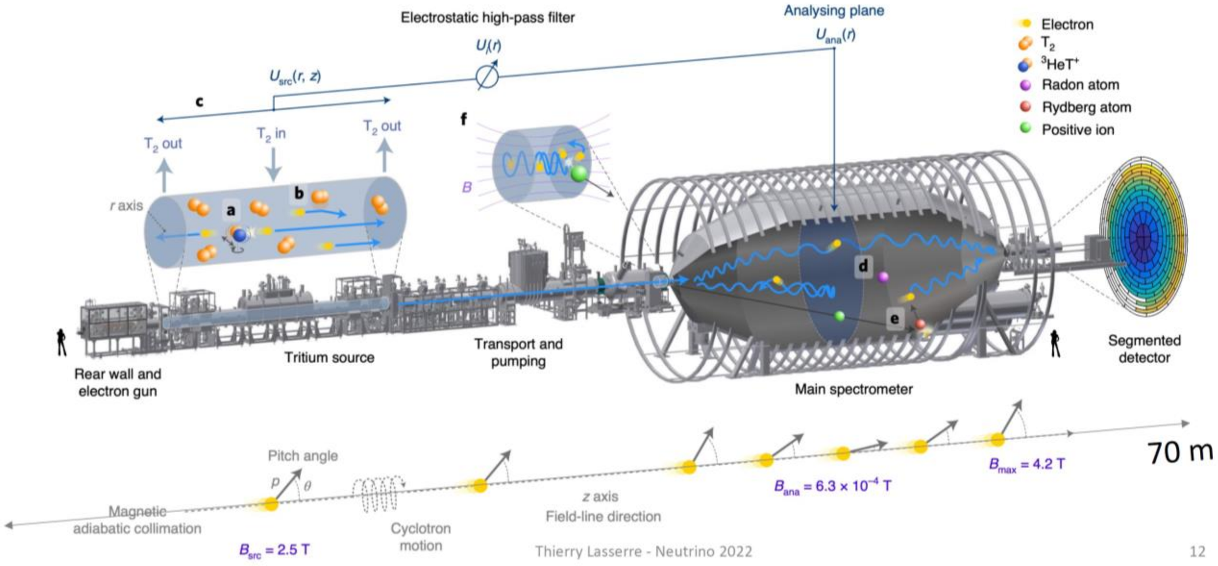
- ✓ strong tritium source: 10^{11} decays/s
- ✓ < 0.1 cps background level
- ✓ ~1 eV energy resolution
- ✓ 0.1% level understanding of the spectrum shape
- ✓ 0.1% level hardware stability controlled over the years

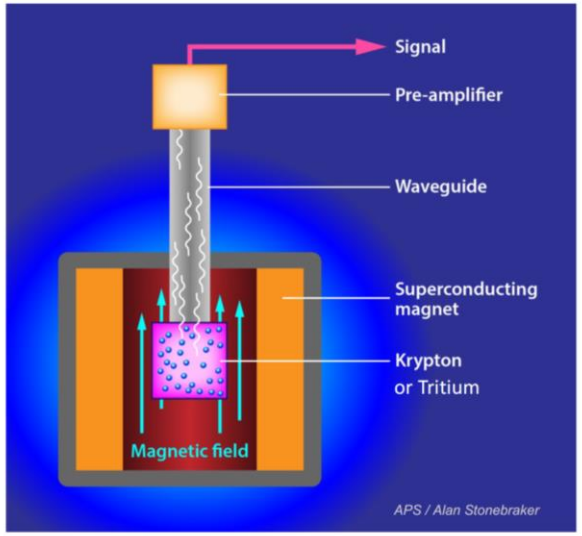
Only 10^{-13} of all decays in last 1 eV

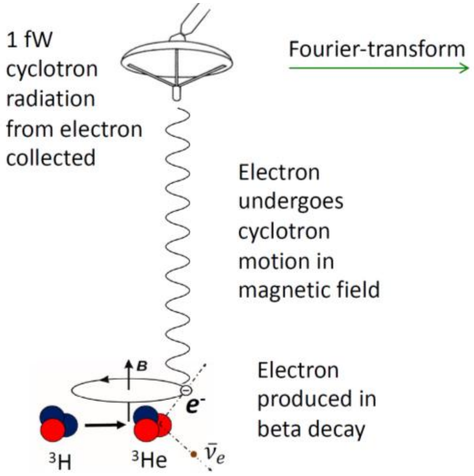


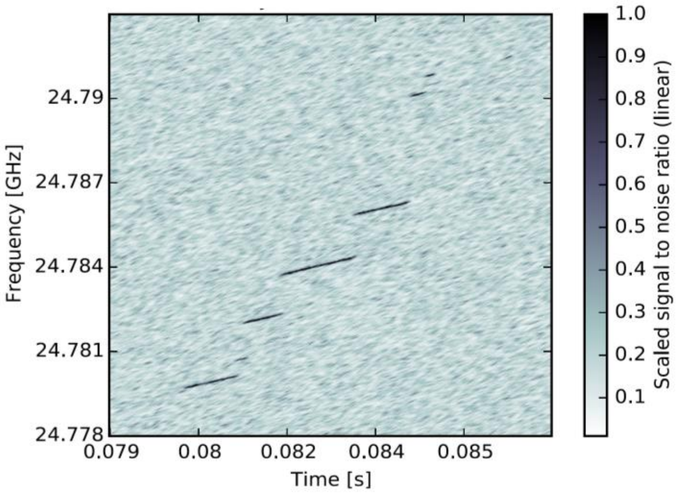
Slide Courtesy Thierry Lasserre

Precision Tritium Endpoint Experiments









First proposal of CRES: B. Monreal and J. Formaggio, Phys. Rev. D 80, 051301(R) (2009)

Slide Courtesy Thierry Lasserre and Elise Novitski

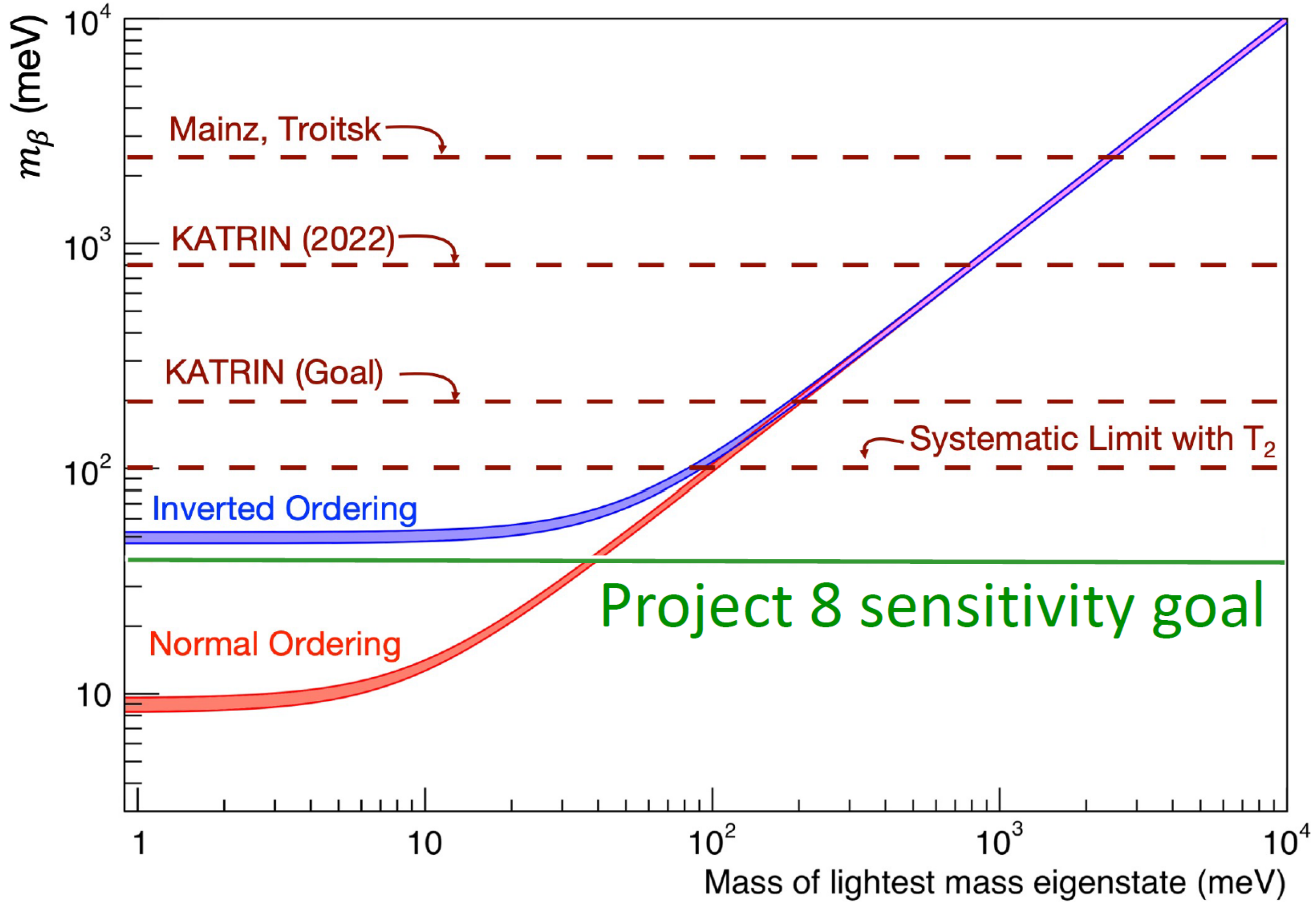
Where do we stand on Neutrino Masses from Tritium Decay?

nature physics **Direct neutrino-mass measurement with sub-electronvolt sensitivity**

The KATRIN Collaboration

Nature Physics **18**, 160–166 (2022) | Cite this article

$m_{\nu e}$ < 0.8 eV



Goals:

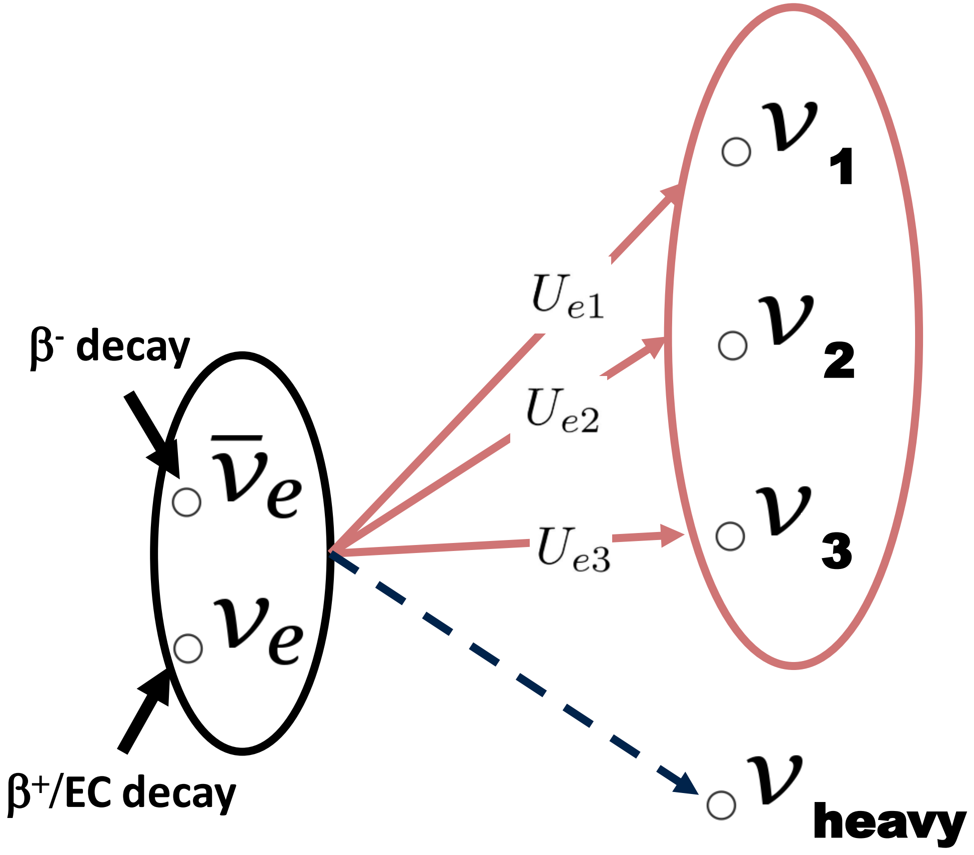
- Sensitivity to 40 meV/c^2 neutrino mass
- Measure neutrino mass or exclude inverted hierarchy
- Simultaneous sensitivity to active and sterile neutrinos

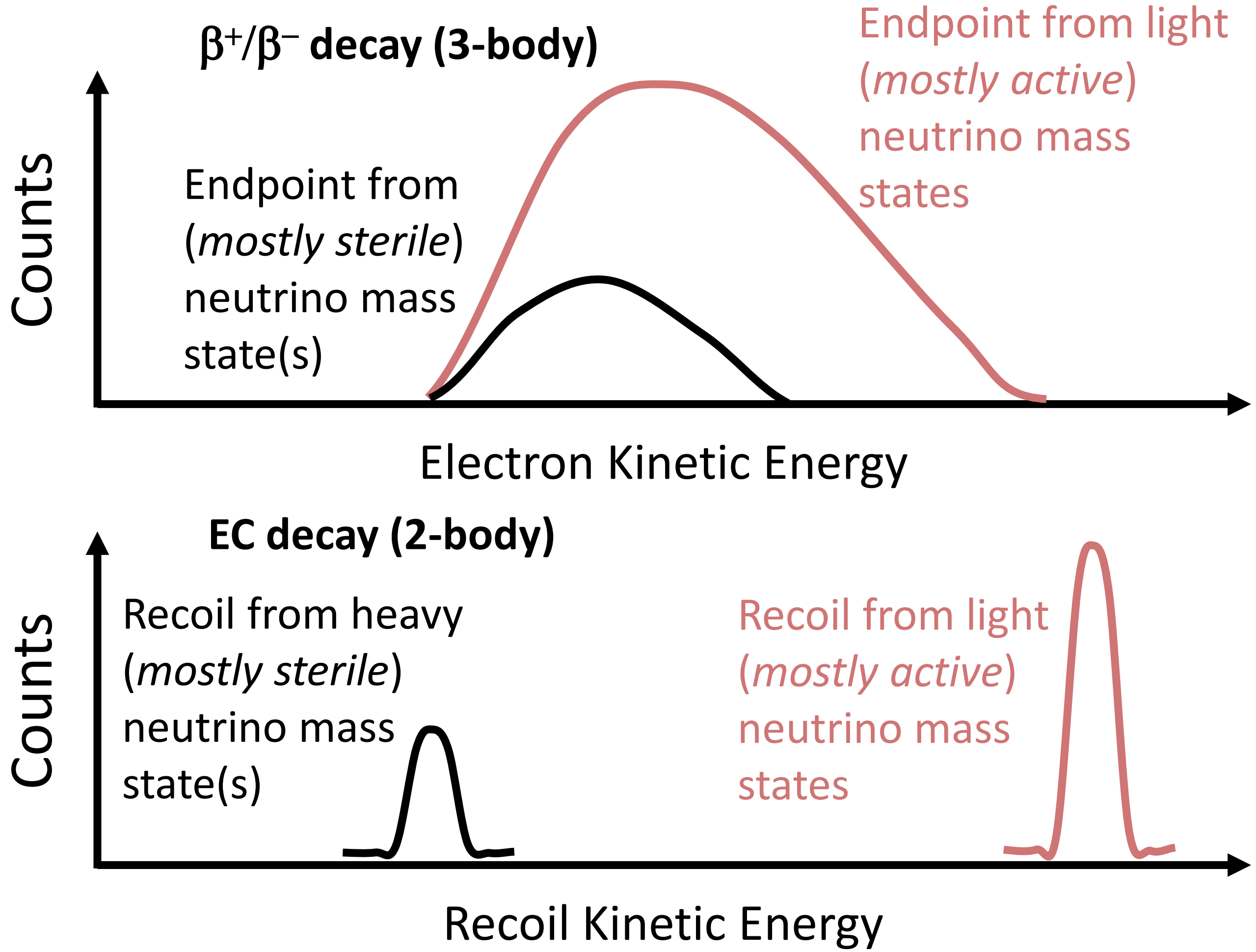
Slide Courtesy Elise Novitzki

Search for Heavy (Mostly Sterile) Neutrino Mass States

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 ν_e ($\bar{\nu}_e$)
- Momentum is conserved with the mass states, not flavor states





keV Neutrinos as Dark Matter

- 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

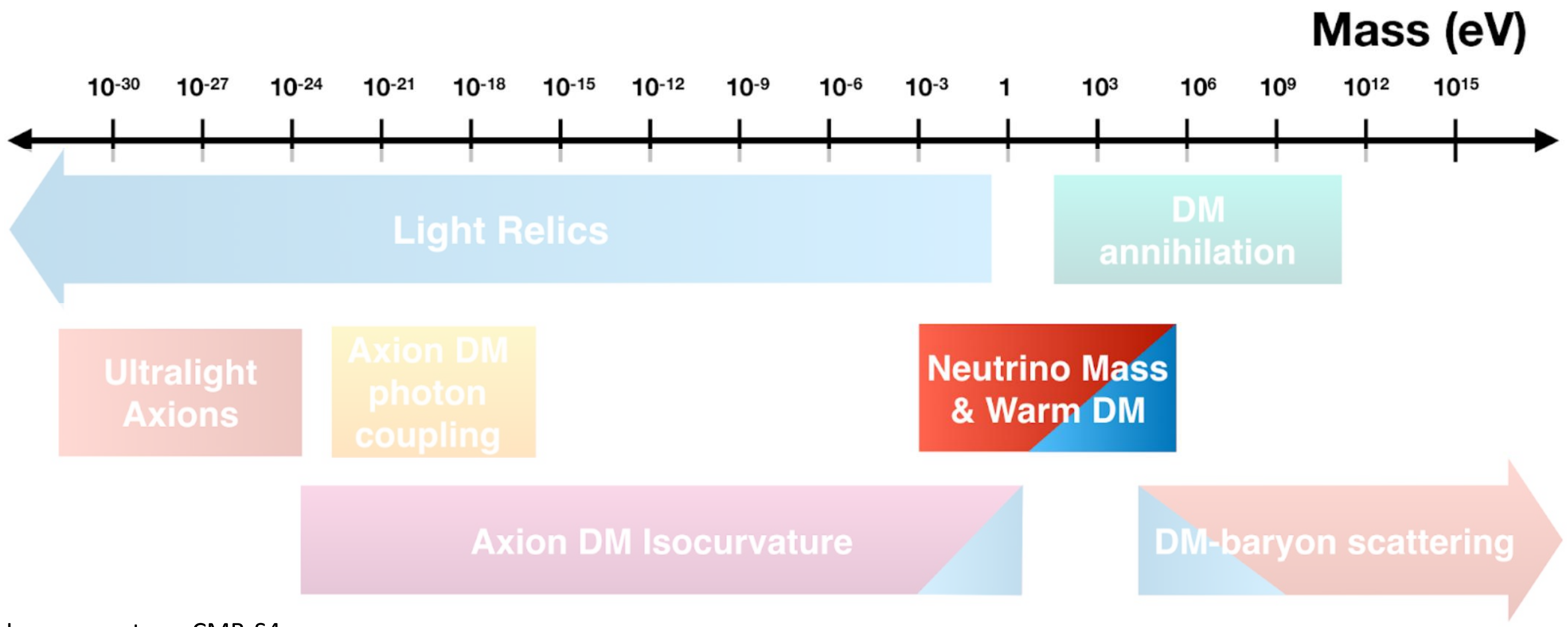
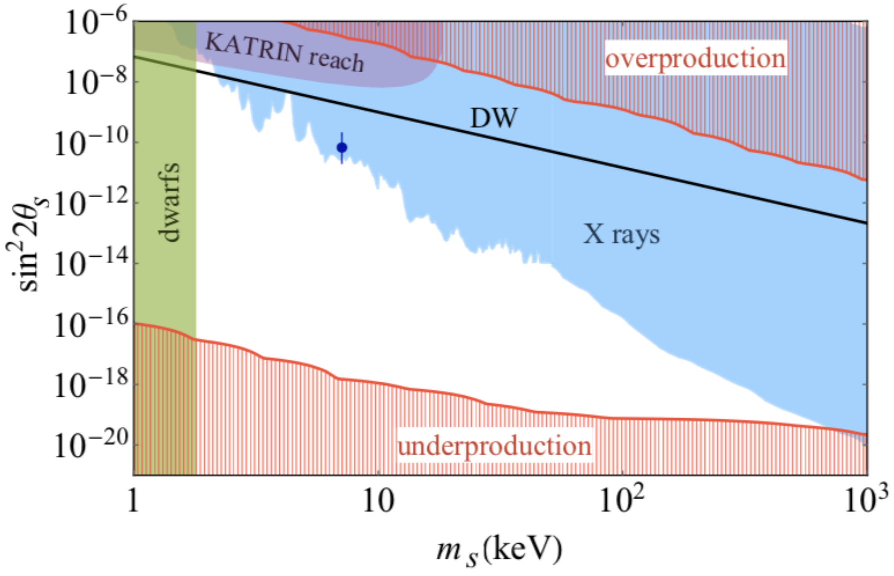


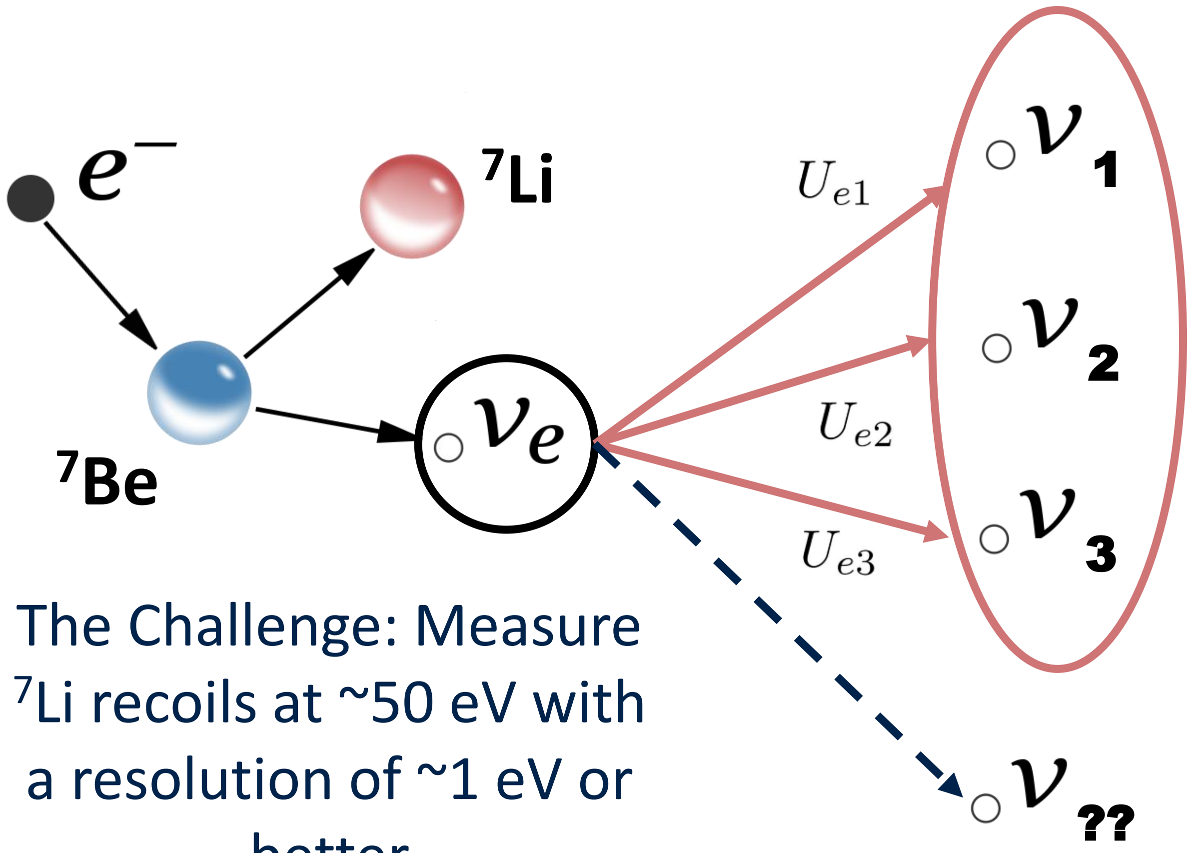
Image courtesy: CMB-S4



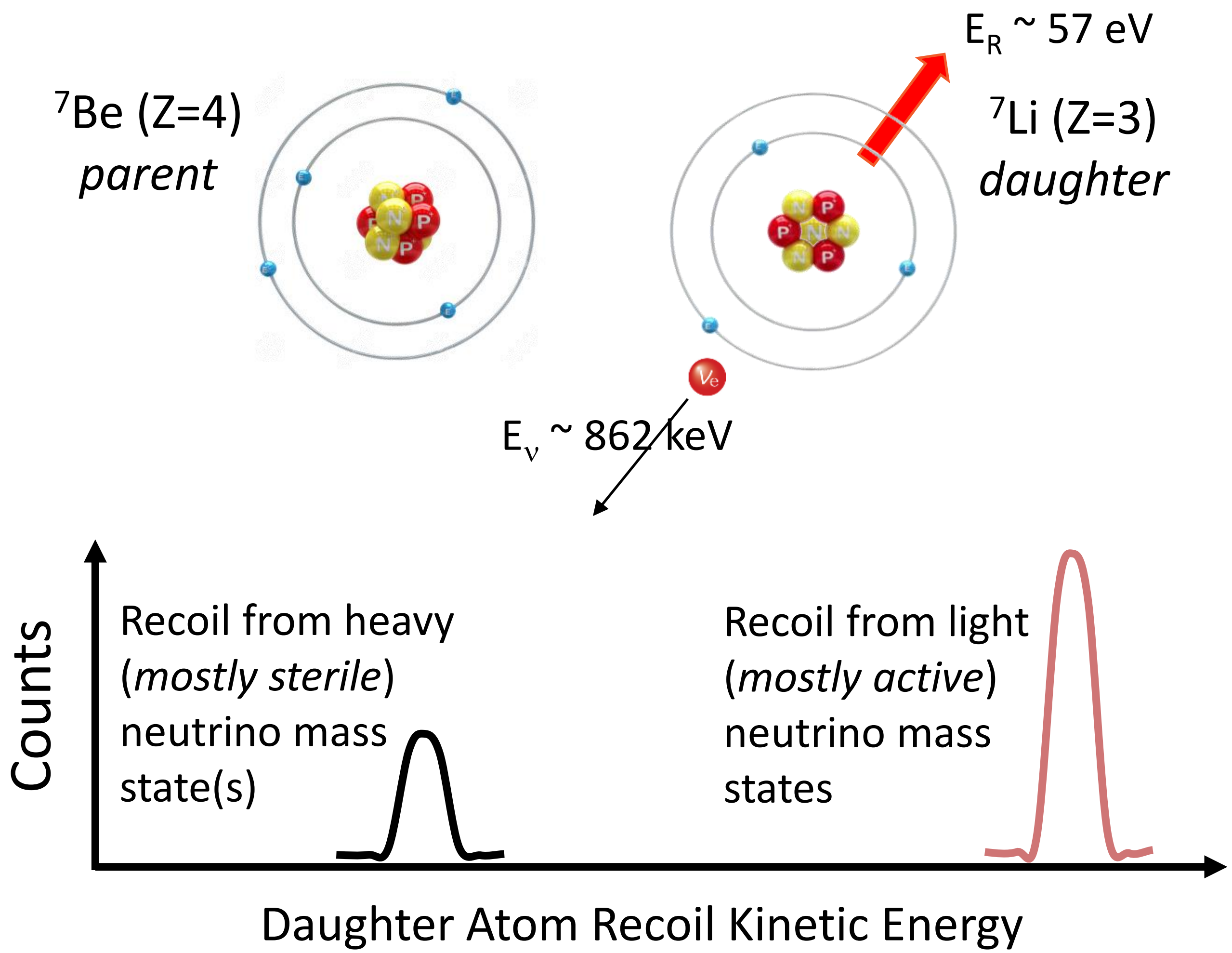
B. Dasgupta and J. Kopp, Phys. Rep. **928**, 1-63 (2021)

Neutrino Studies with the Electron Capture Decay of ^{7}Be

- **^{7}Be is the ideal case to search for heavy mass states (mostly sterile) using EC decay.**
  - Simple atomic and nuclear structure and largest *Q*-value (862 keV) of all pure EC cases
    ➔ Highest maximum recoil energy



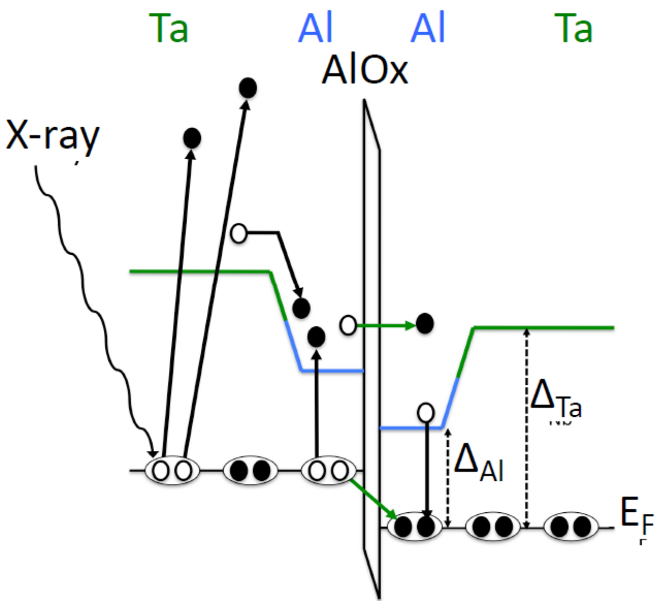
The Challenge: Measure ^{7}Li recoils at ~50 eV with a resolution of ~1 eV or better

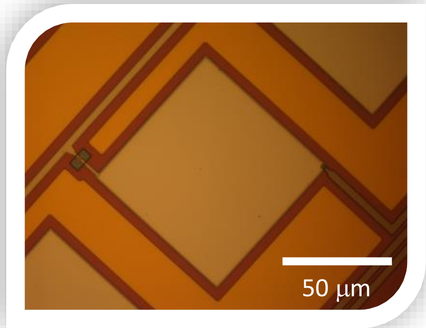


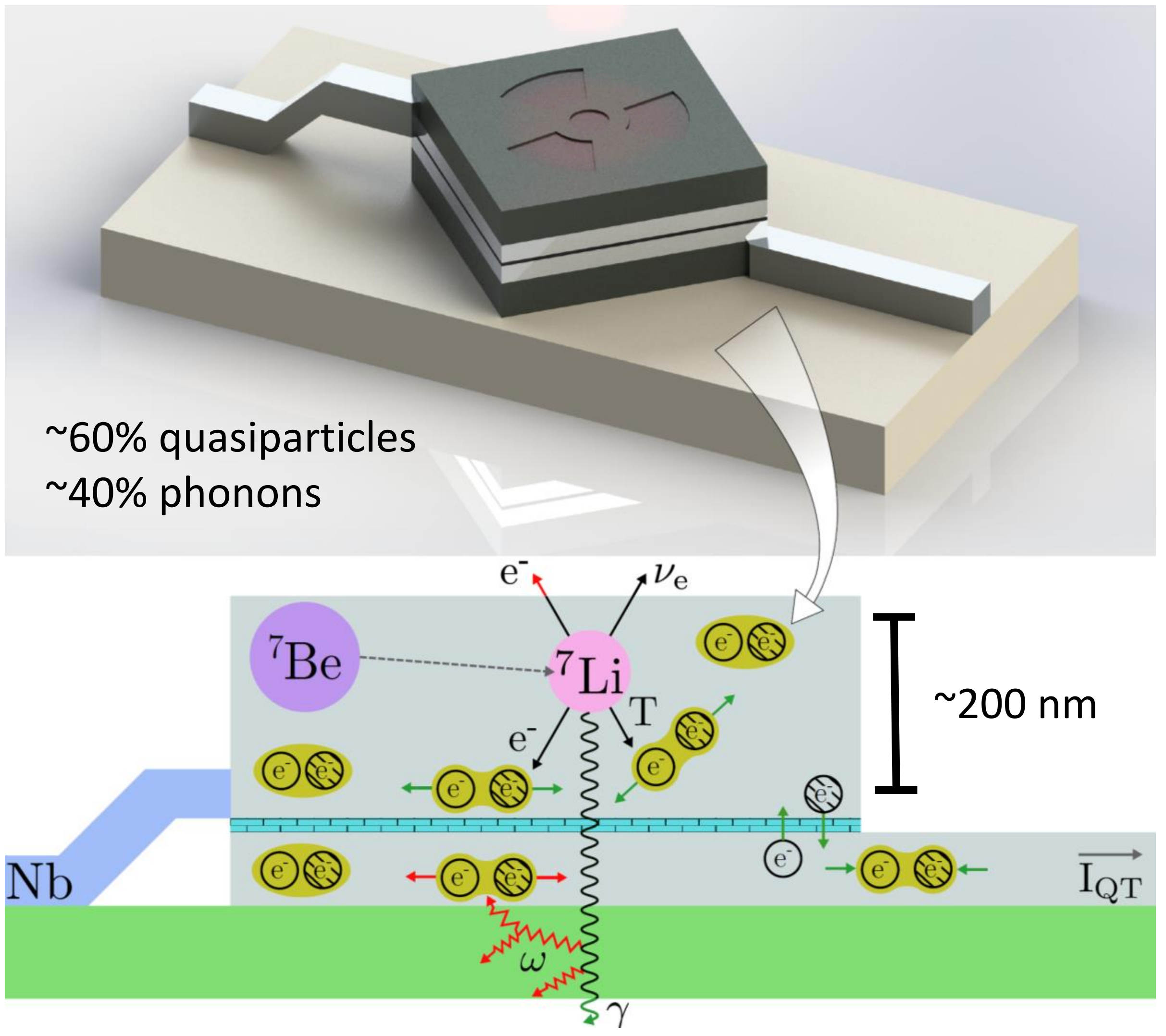
Superconducting Tunnel Junction (STJ) Quantum Sensing

- *Cryogenic-charge* superconducting sensor
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 μs, allowing for faster count rates than most superconducting sensors
  → "High" Rate (10^4 s^{-1} per pixel)

← *Allows us to probe weak couplings*



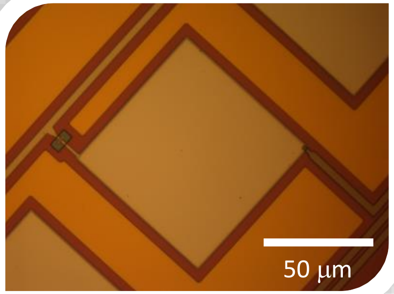




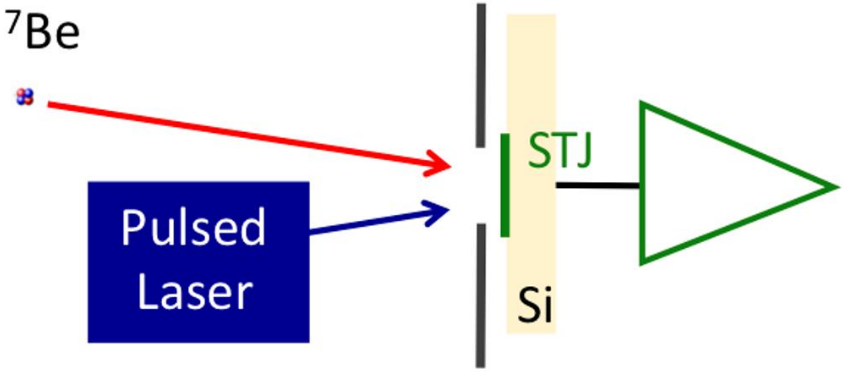
The BeEST Experiment

Rare-isotope implantation at TRIUMF-ISAC

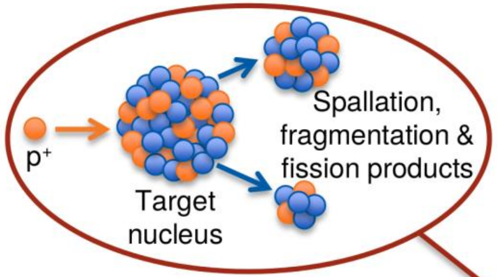
Ta, Al, and Nb-based STJ Sensors

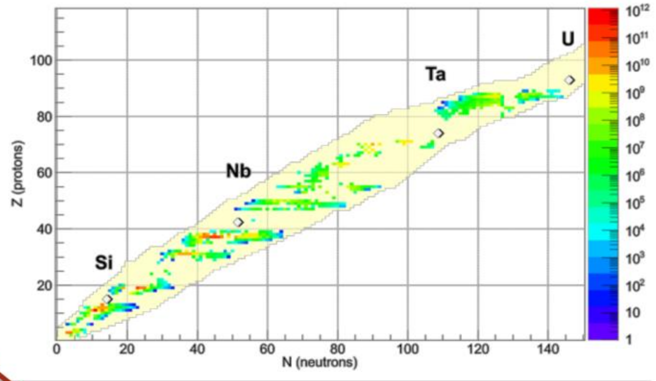


K.G. Leach and S. Friedrich, arXiv:2112.02029 (2021)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

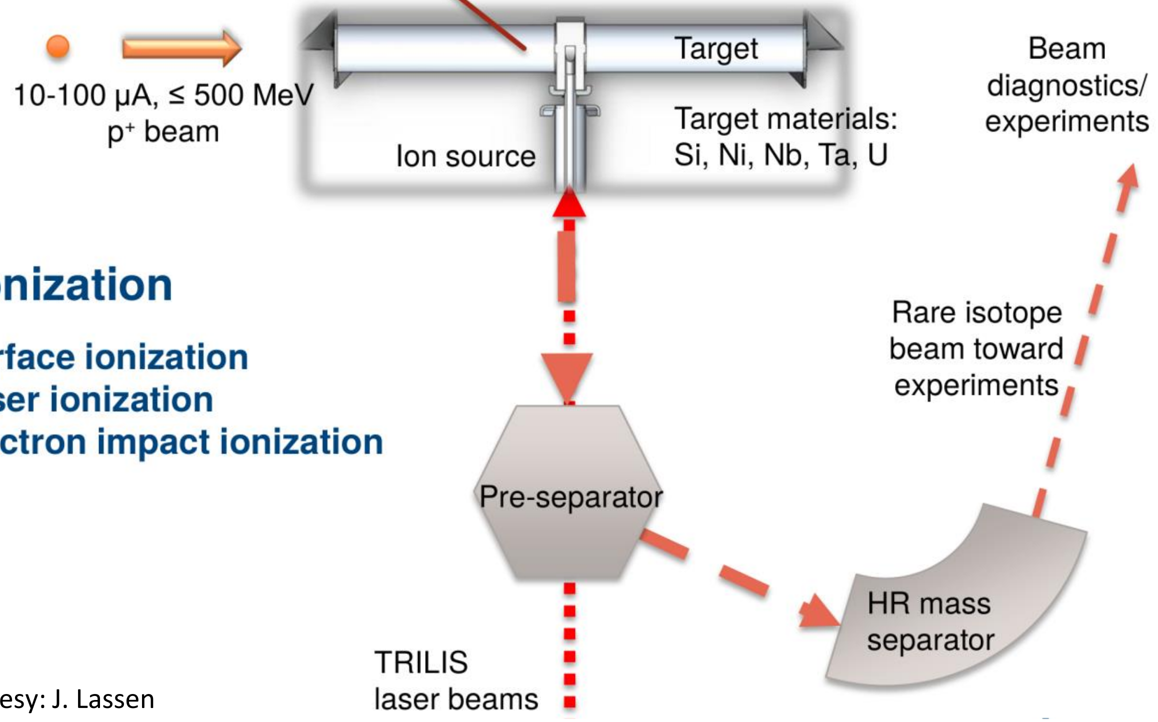


Producing the ^{7}Be Sample via the ISOL Technique



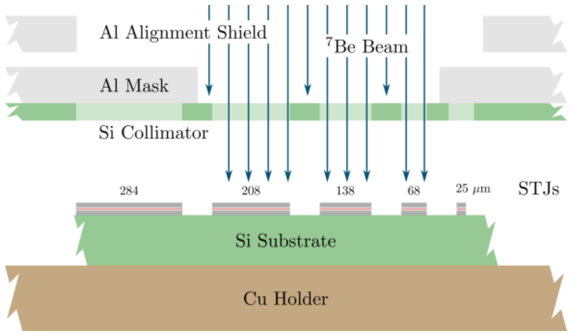


1. Isotope production

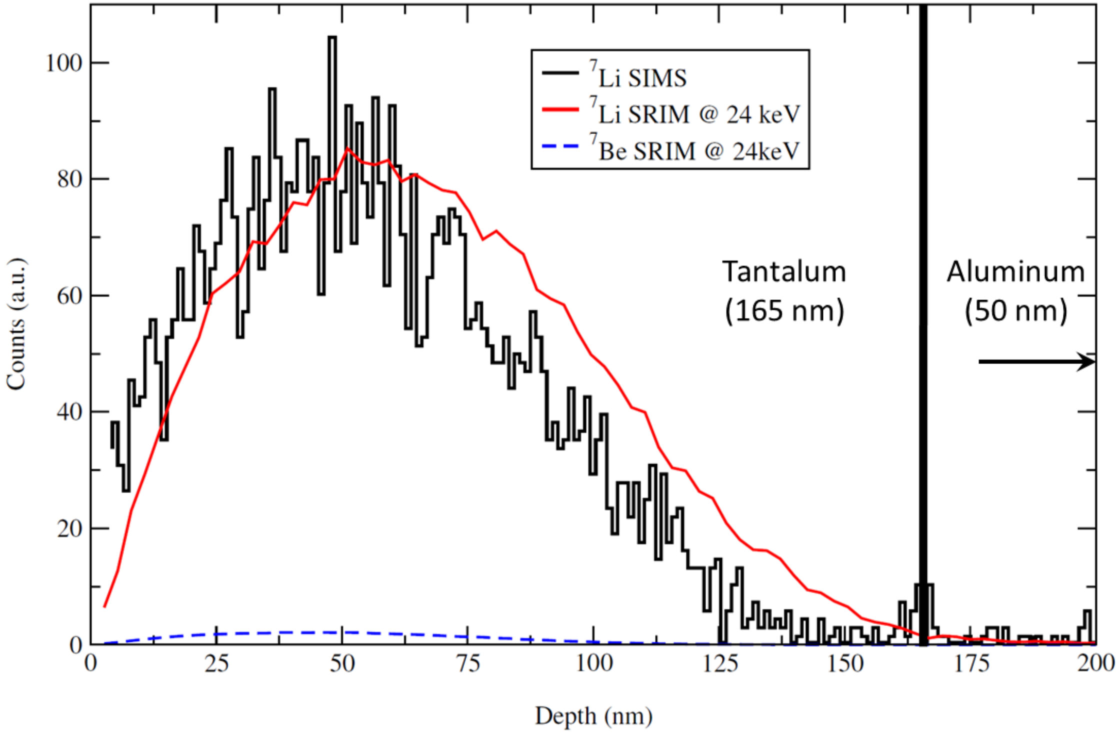


2. Ionization

- Surface ionization
- Laser ionization
- Electron impact ionization



Implant atoms "deep" into the top STJ layer to avoid unknown loss and surface effects

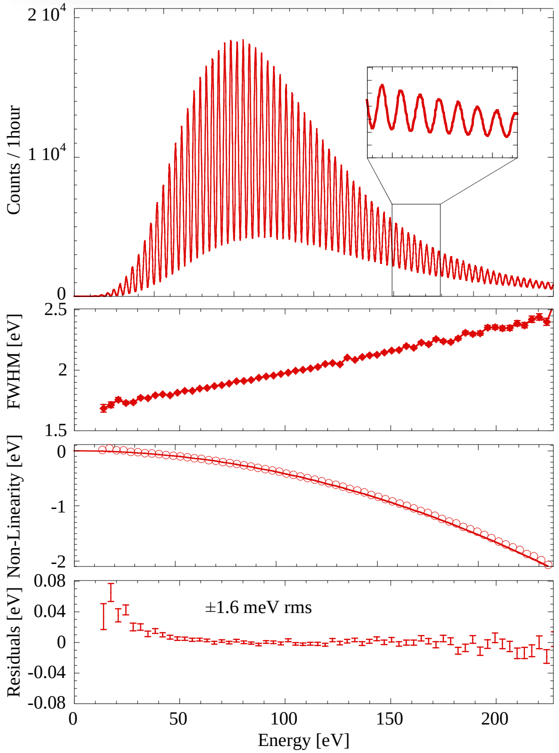


Slide Courtesy: J. Lassen

The BeEST Experiment

TRIUMF

Rare-isotope implantation at TRIUMF-ISAC



S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

THE BeEST

K.G. Leach and S. Friedrich, arXiv:2112.02029 (2021)
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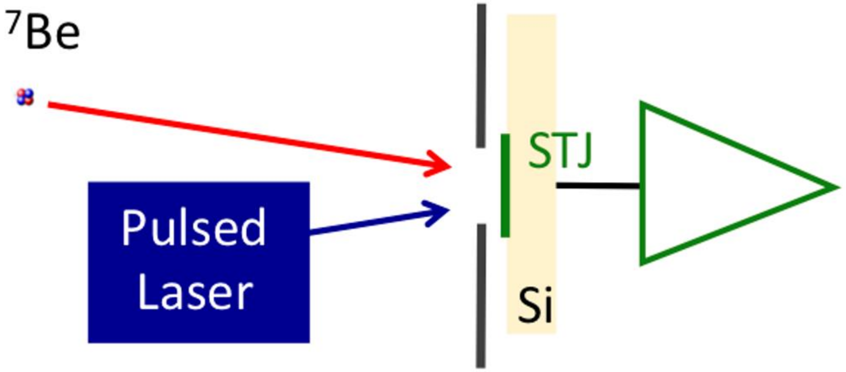
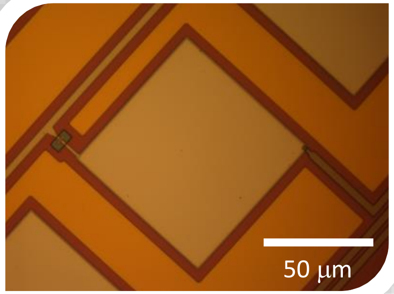
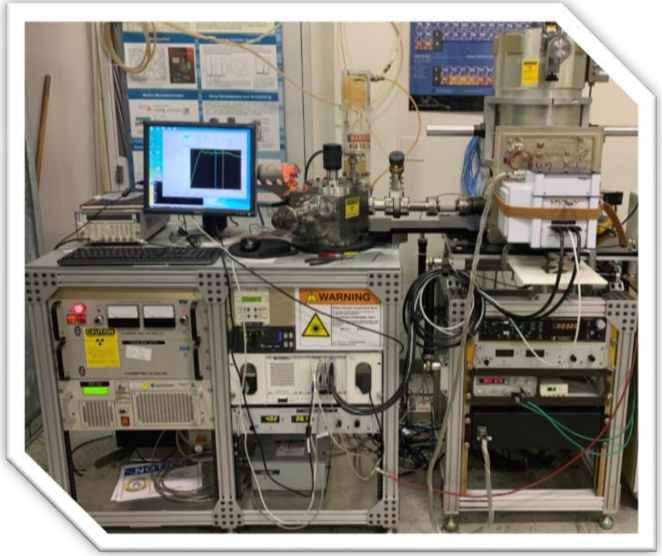


High-precision *In-situ* calibration and characterization

Ta, Al, and Nb-based STJ Sensors



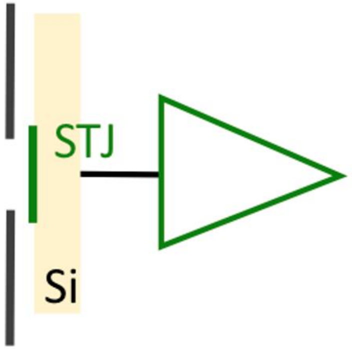
STAR CRYOELECTRONICS



Lawrence Livermore National Laboratory

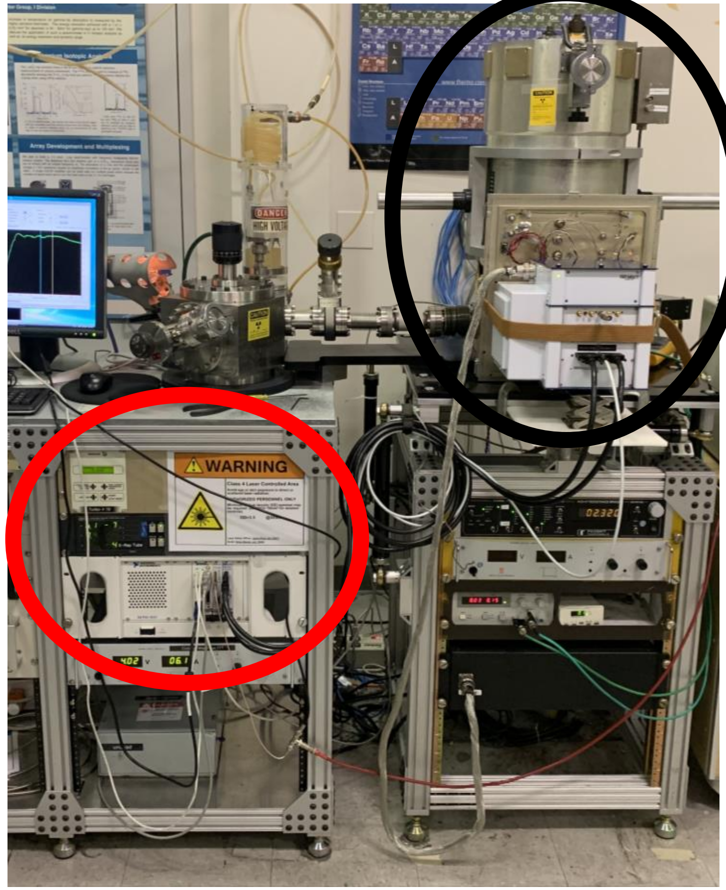
Cooling (<0.1 K) and measurement in ADR at LLNL

STJ Performance and Characterization



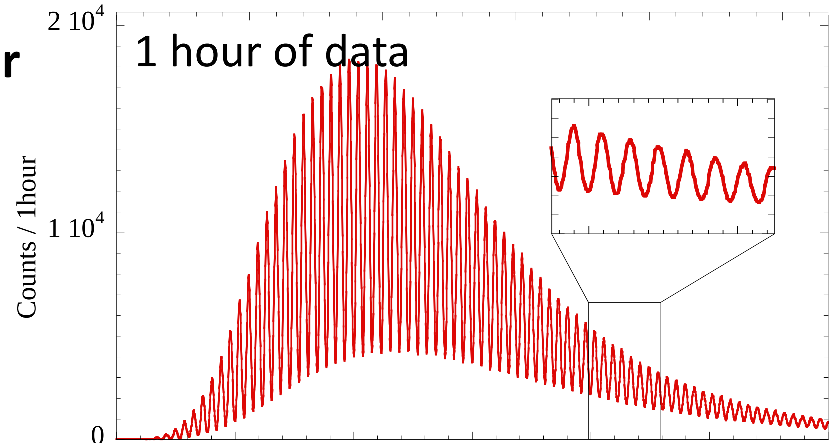
- Pulsed 355 nm (3.49965(15) eV) laser at 5 kHz fed through optical fiber to 0.1 K stage
- Illumination of STJ provides a comb of peaks at integer multiples of 3.5 eV
- Intrinsic resolution of our Ta-based devices is between ~1.5 and ~2.5 eV FWHM at ~10 – 200 eV
- Stable response and small quadratic non-linearity (10^{-4} per eV)

Adiabatic Demagnetization Refrigerator (ADR) – Base Temp ~70 mK



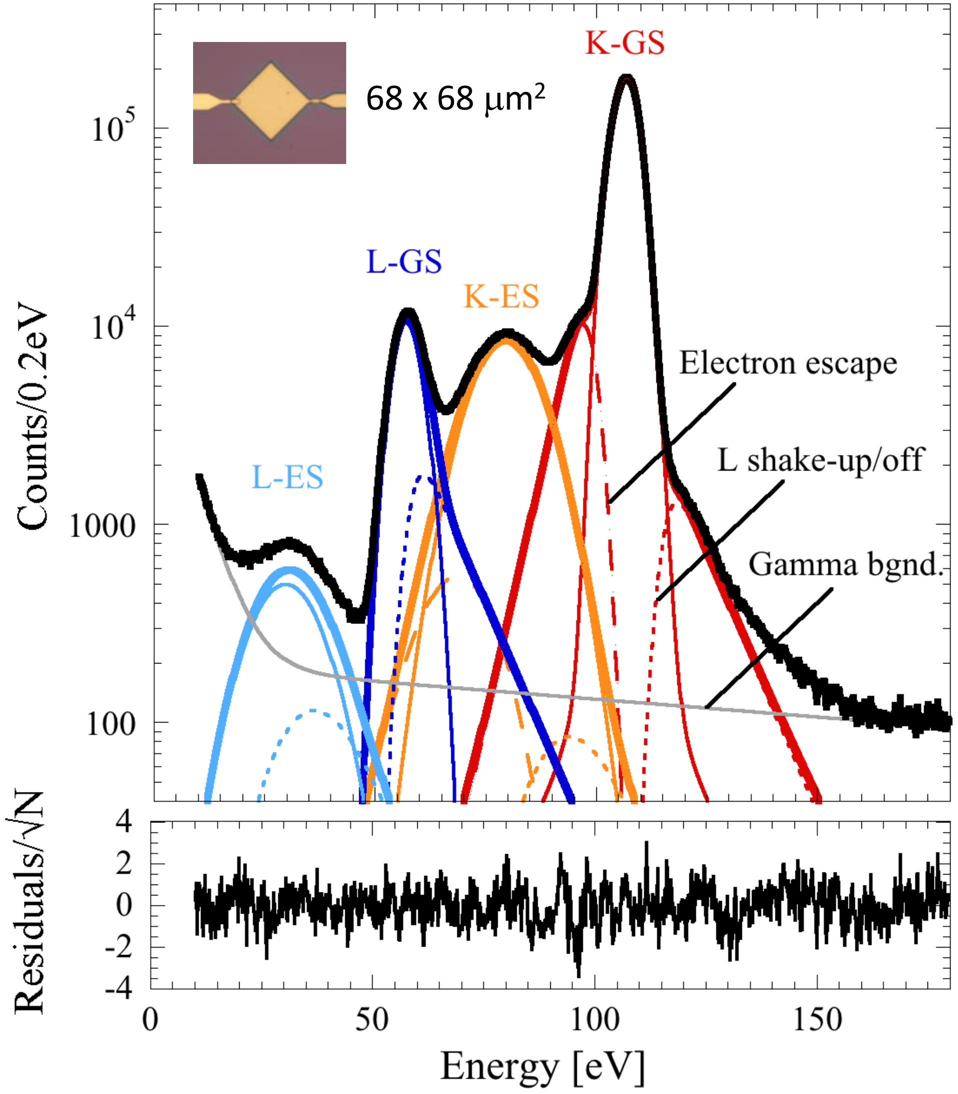
Laser

Lawrence Livermore National Laboratory

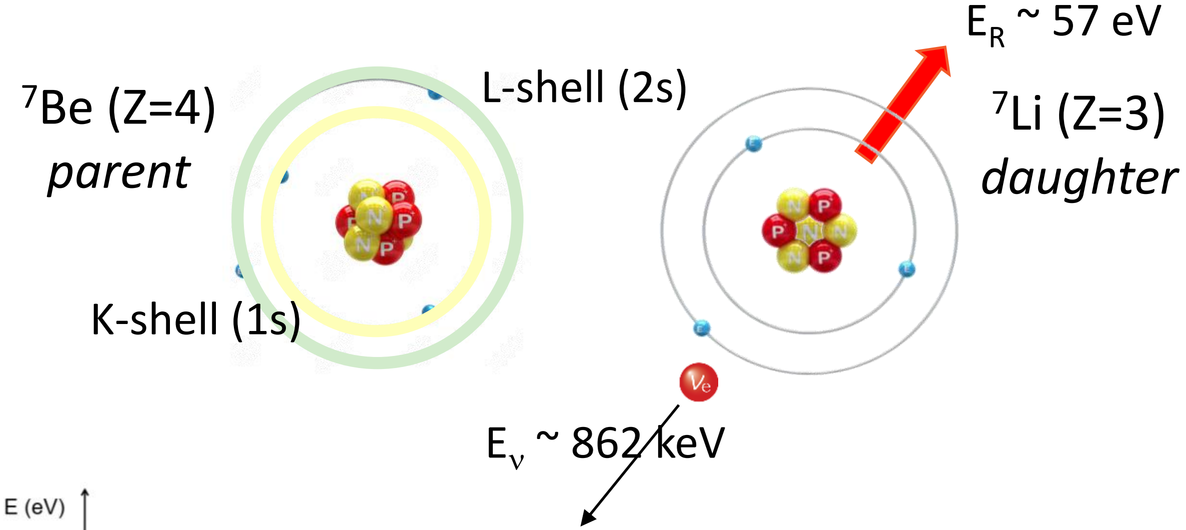


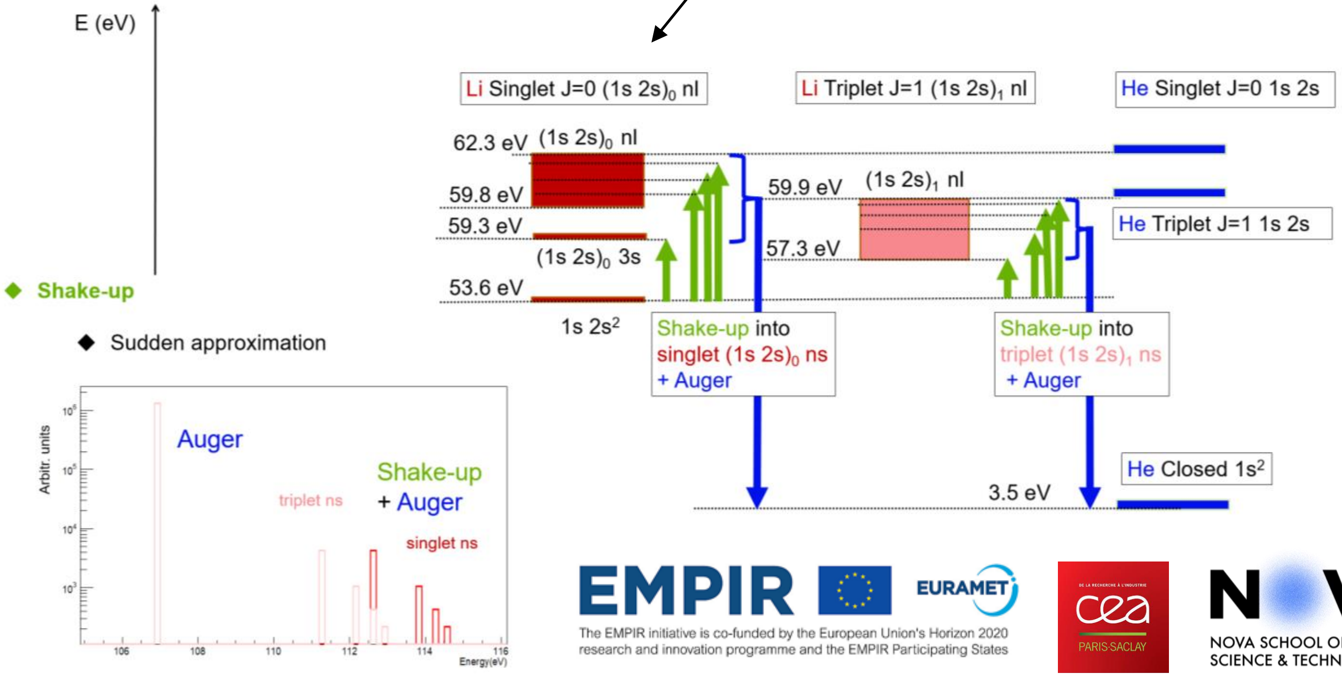
S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

Phases-I and –II: First Nuclear Recoil Experiments with STJs



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



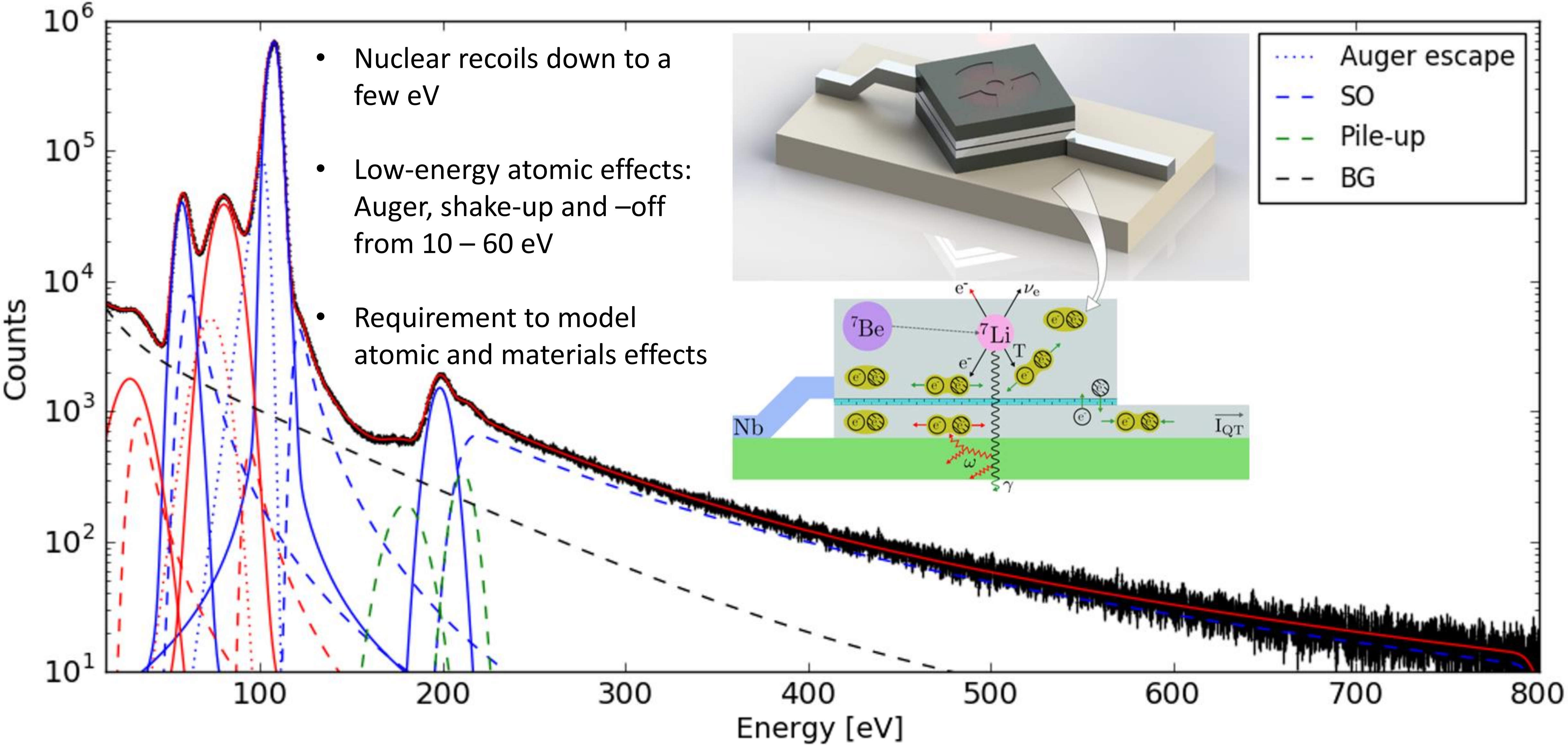


The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

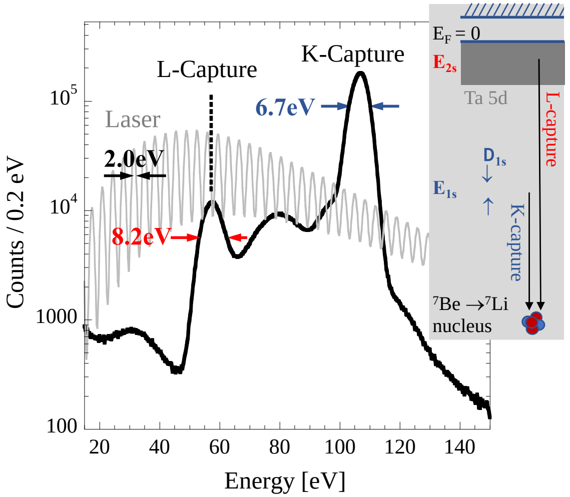
NOVA SCHOOL OF SCIENCE & TECHNOLOGY

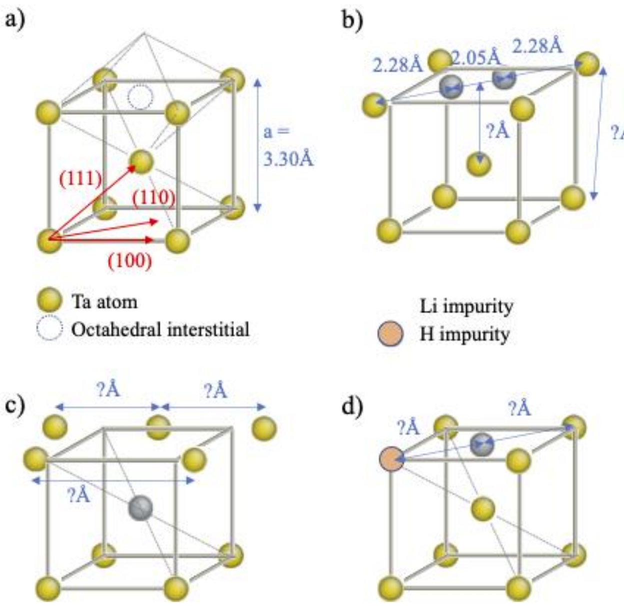
Precision Measurements of Effects in the Data

- Nuclear recoils down to a few eV
- Low-energy atomic effects: Auger, shake-up and –off from 10 – 60 eV
- Requirement to model atomic and materials effects

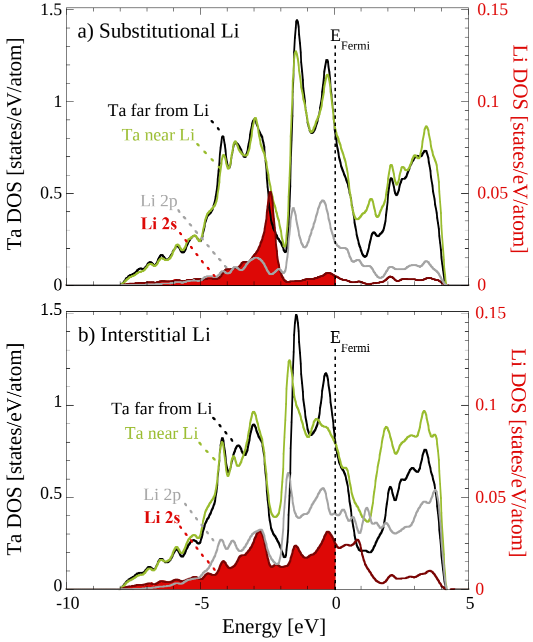


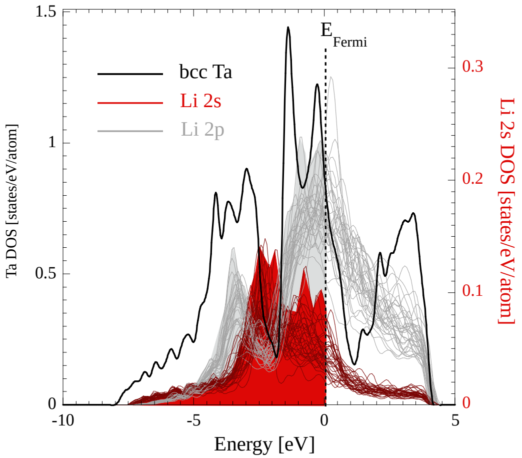
Atomistic Calculations of Chemical Shifts in Materials

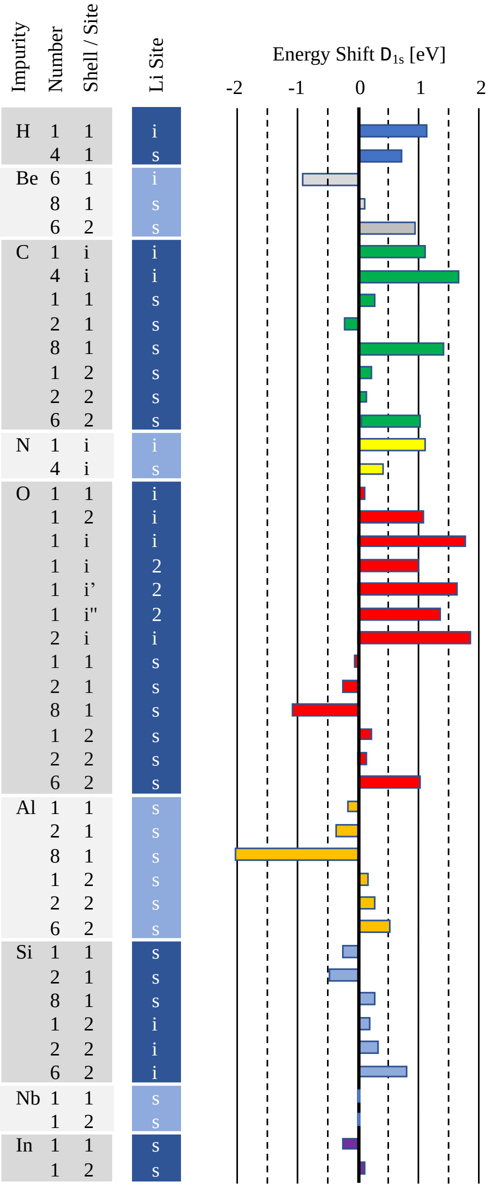




- Putting Be/Li in the sensors hybridizes the atomic orbitals
- These effects depend strongly on the specific local environment for the EC decaying atom
- Detailed atomistic DFT calculations show that variations in the chemical energy shifts away from the vacuum case range from 1-5 eV.

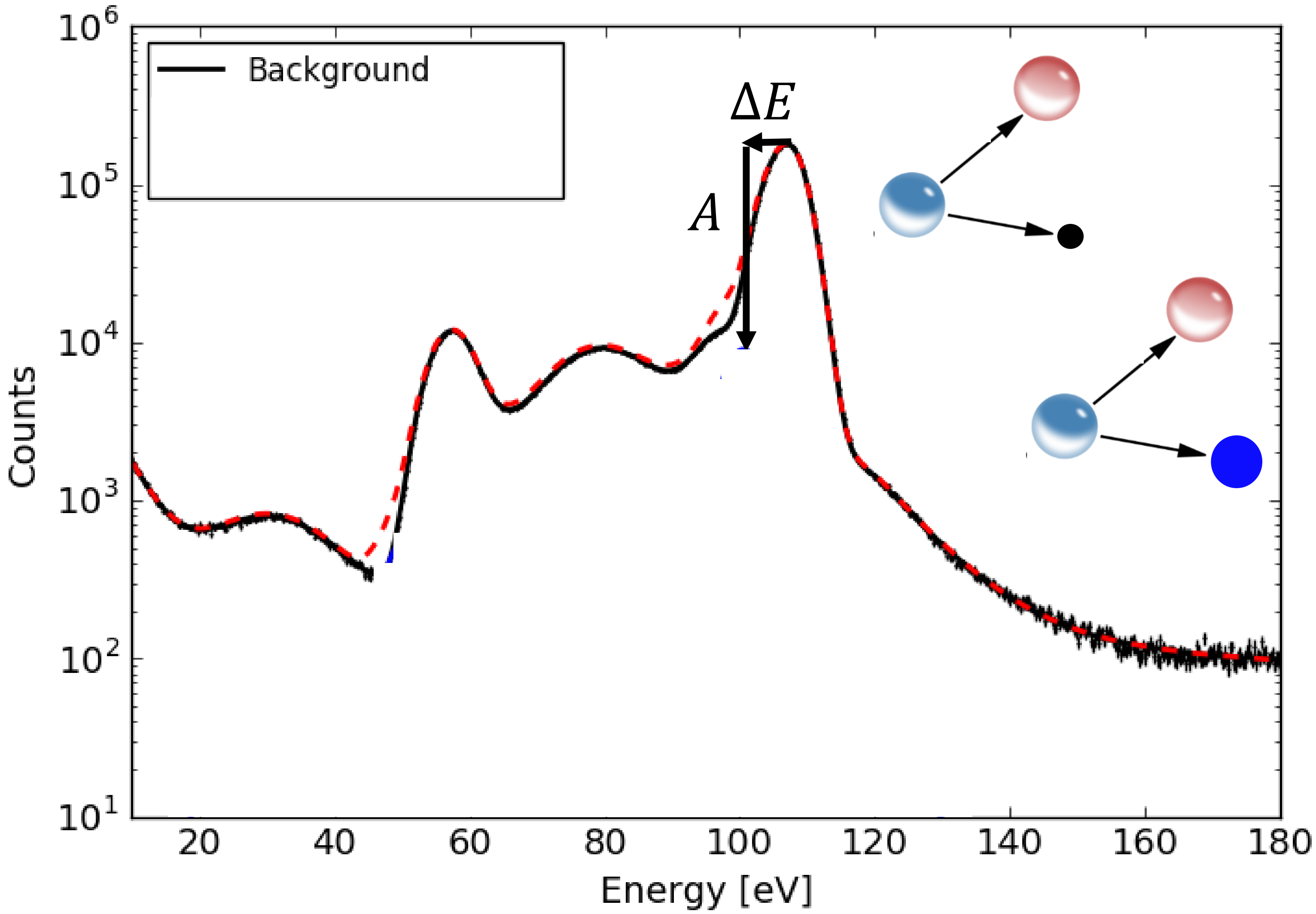






A. Samanta, S. Friedrich, K.G. Leach, and V. Lordi, arXiv:2206.00150 (2022)

Searching for Heavy Neutrinos in the BeEST Data



Sterile neutrino will add a similar spectrum with:
1) Shifted recoil energy $\Delta E(m_s)$
2) Reduced amplitude ($A \propto |U_{e4}|^2$)

$$f(E) = \underbrace{[1 - A(U_{e4})]\, f_0(E)} + \underbrace{A(U_{e4})\, f_0(E - \Delta E)}$$

Background:
Active neutrino contribution
+ other background

Signal:
Sterile neutrino contribution

f_0= EC spectral shape with active neutrinos

Slide Courtesy: Geon-Bo Kim (LLNL)

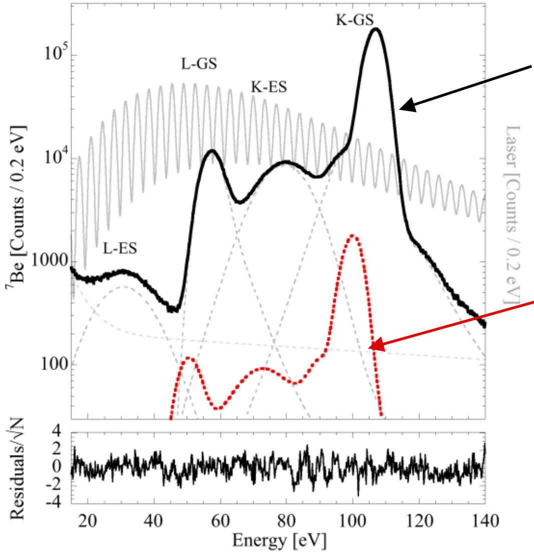
First Limits from "Low-Rate" Phase-II Data

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

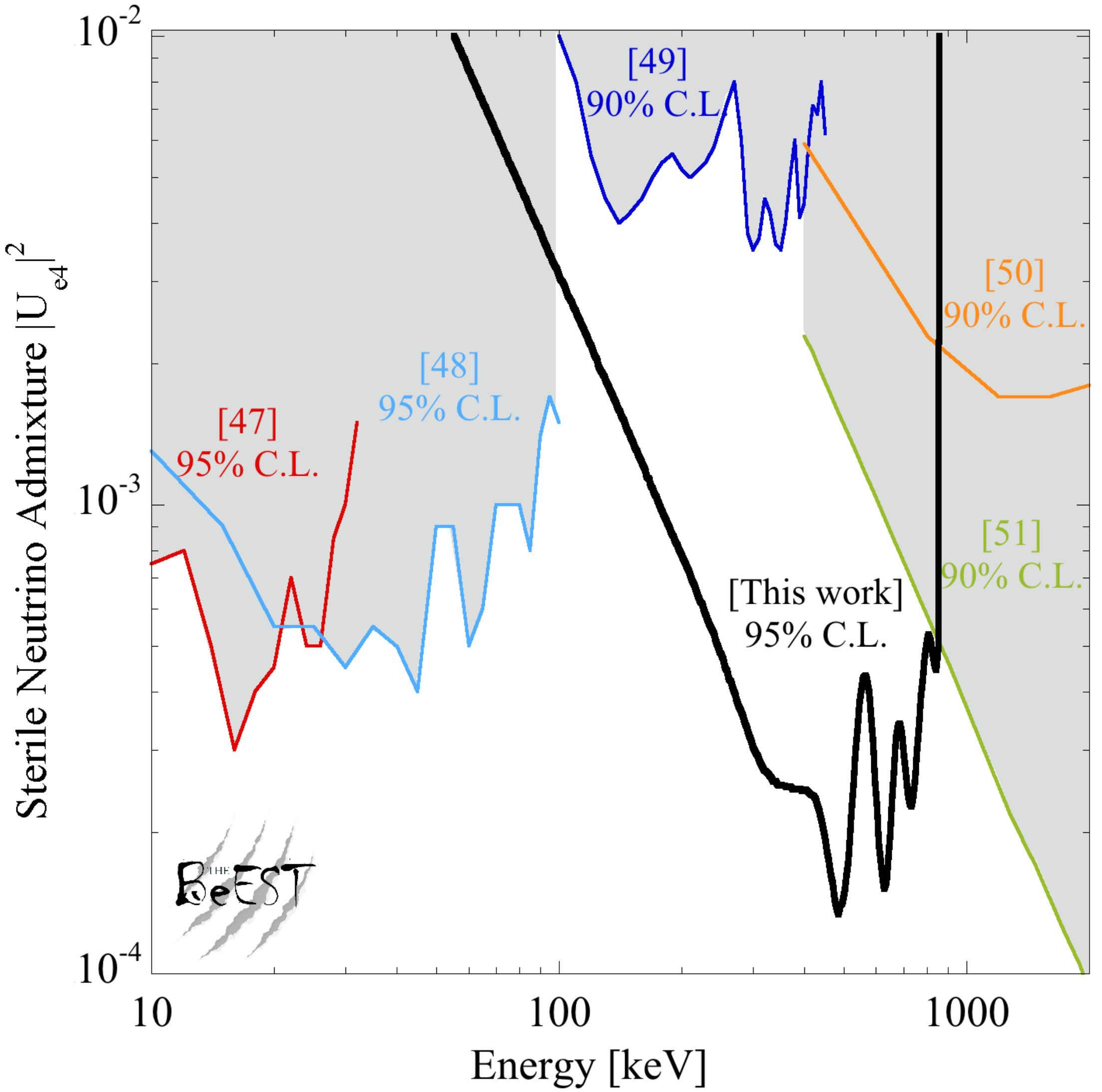
S. Friedrich,[1,*] G. B. Kim,[1] C. Bray,[2] R. Cantor,[3] J. Dilling,[4] S. Fretwell,[2] J. A. Hall,[3] A. Lennarz,[4,5] V. Lordi,[1] P. Machule,[4] D. McKeen,[4] X. Mougeot,[6] F. Ponce,[7,1] C. Ruiz,[4] A. Samanta,[1] W. K. Warburton,[8] and K. G. Leach[2,†]

Phase-II data from a single 138x138 μm^2 STJ counting at low rate (~10 Bq) for 28 days

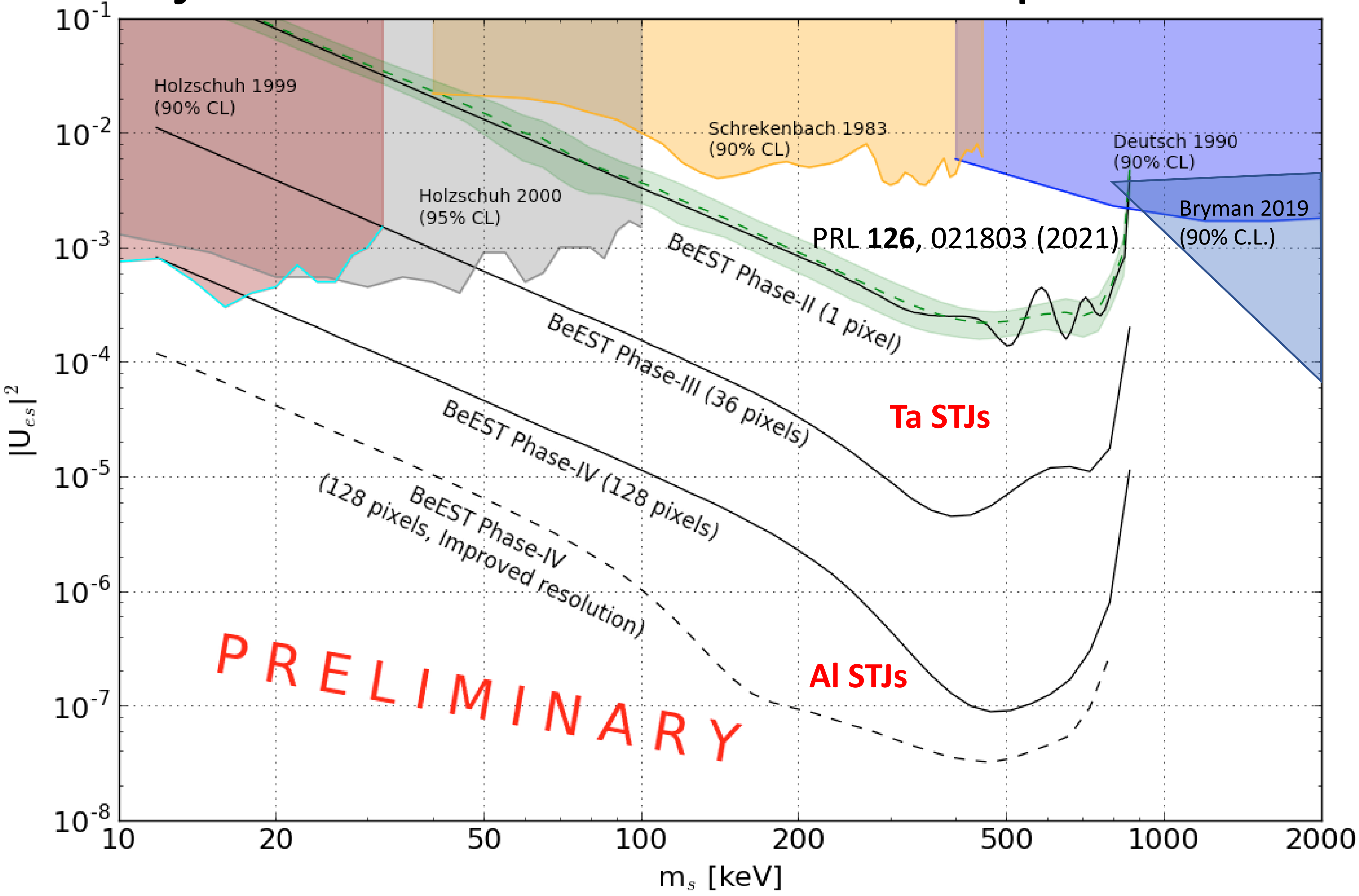


Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

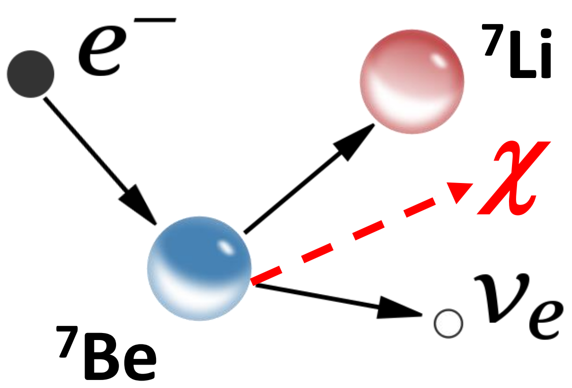
Example of signal that would be generated by 300 keV neutrino with 1% mixing



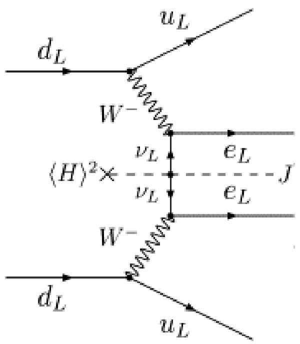
Projected Limits of the BeEST Experiment

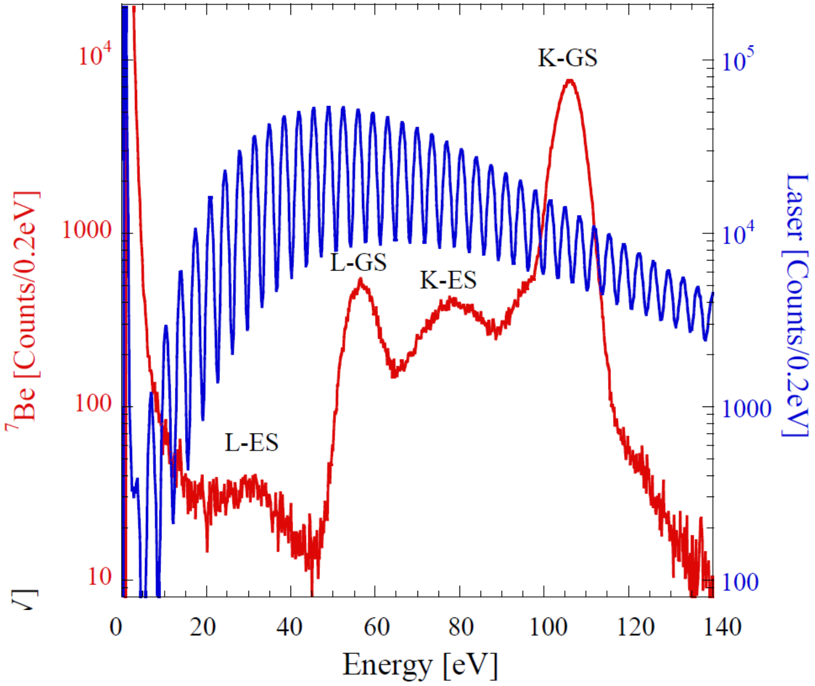


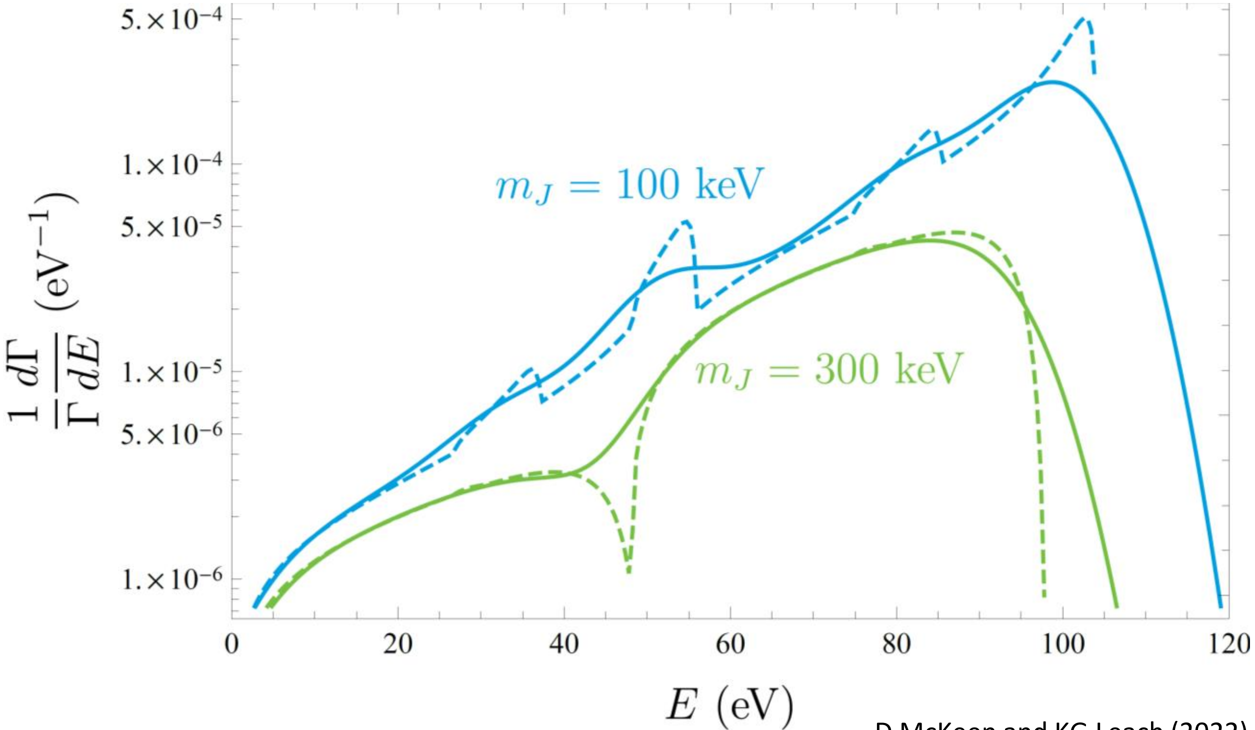
Sensitive to *ALL* New Physics that Couples to Neutrino Masses



Momentum reconstruction in EC decay is sensitive to any deviation from the SM recoil signal (e.g. Majoron emission)







D McKeen and KG Leach (2022)

The BeEST

Faculty/Staff
PDF
Graduate
Undergraduate

Colorado School of Mines

Connor Bray
David Diercks
Spencer Fretwell
Cameron Harris
Kyle Leach *(Spokesperson)*
Drew Marino
Caitlyn Stone-Whitehead
Sergio Oscar Nuñez Silva

Lawrence Livermore National Laboratory

Stephan Friedrich
Geon-Bo Kim
Vincenzo Lordi
Amit Samanta

TRIUMF

Ryan Abell
Annika Lennarz
Peter Machule
Dave McKeen
Chris Ruiz

NOVA School of Science & Technology

Pedro Amaro
Mauro Guerra
Jorge Machado
José Paulo Santos

Université de Strasbourg

Adrien Andoche
Paul-Antoine Hervieux

NC State University

Leendert Hayen

Pacific Northwest National Laboratory

Francisco Ponce

STAR Cryoelectronics

Robin Cantor
Ad Hall

XIA

Jack Harris
Bill Warburton

cea Paris-Saclay

Xavier Mougeot

Oak Ridge National Laboratory

Jens Dilling

U.S. Department of Energy Office of Science
Lawrence Livermore National Laboratory
TRIUMF
NSERC CRSNG
EMPIR EURAMET

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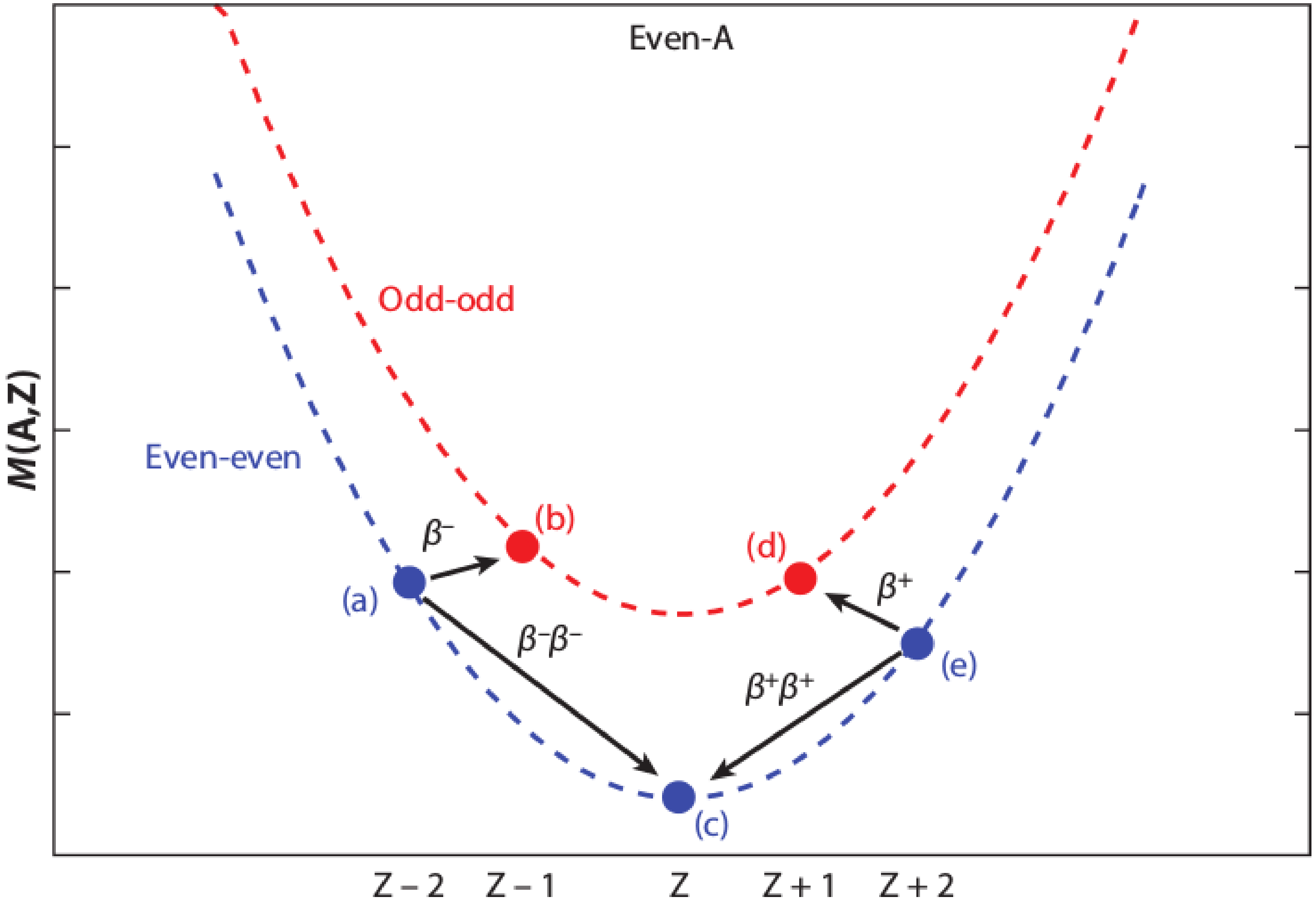
NNSA National Nuclear Security Administration
APS physics
Gordon and Betty Moore Foundation

Neutrinoless Double Beta Decay

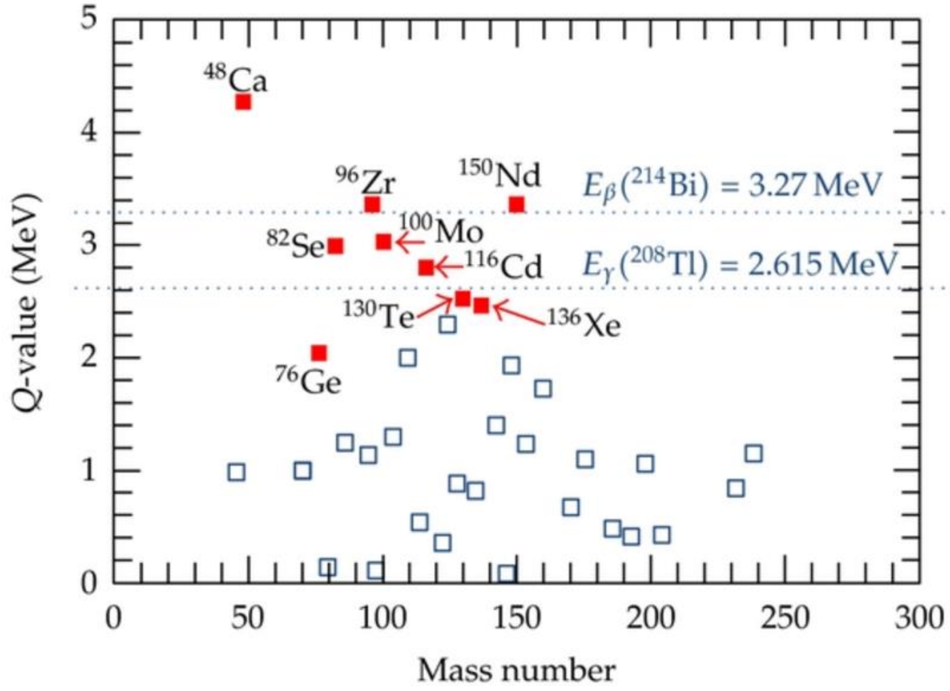
Nuclear "Double" Beta Decay



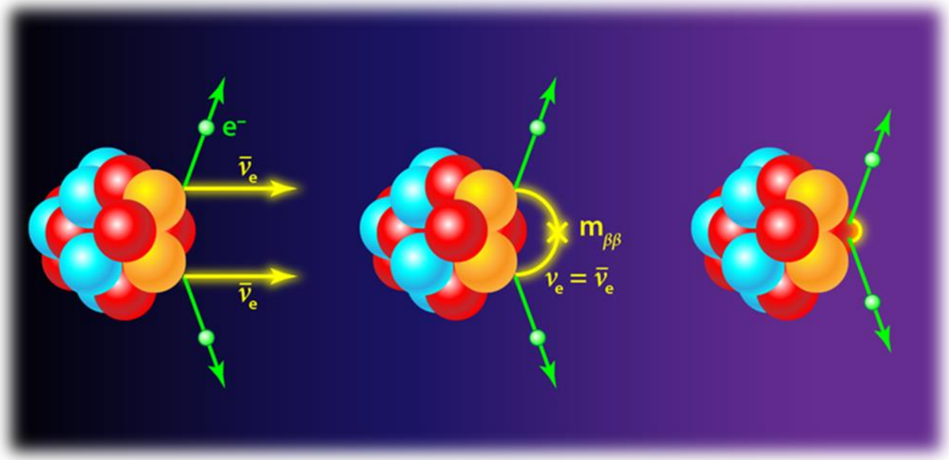
Ruben Saakyan, Ann. Rev. Nucl. Part. Sci. **63**, 503-529 (2013)

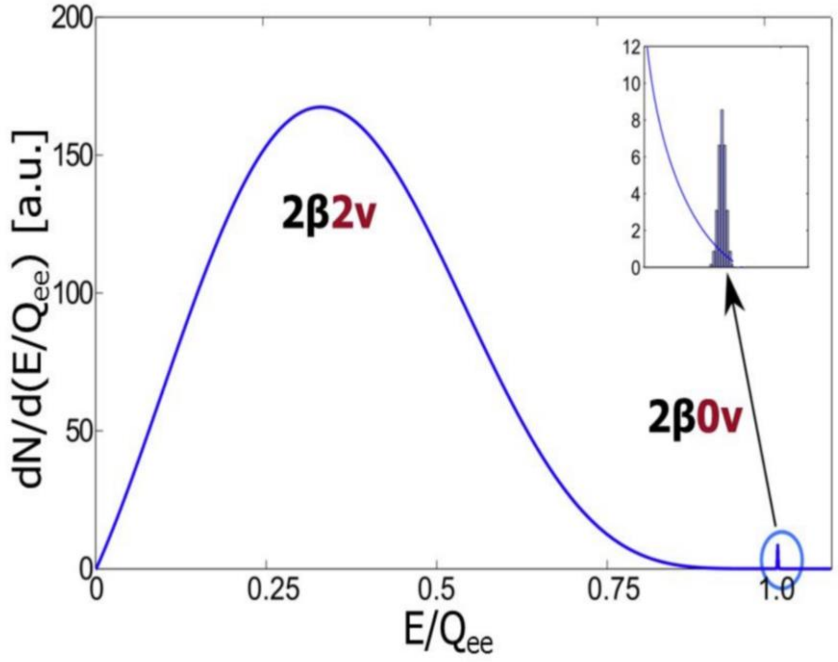
- Observed in cases where single β emission is energetically forbidden

- These "stable" systems can still undergo the higher-order process of double β decay



Neutrinoless Double Beta Decay





Possible process that requires BSM physics:

- Majorana nature of the neutrino
- Lepton number violation

Signature is clean, and can provide powerful limits on new physics scales:

- Two electrons with total energy *Q*
- Determine effective Majorana mass of the neutrino

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

Measurements require large volumes of material (next-gen on the tonne-scale), and ultra-low-background experiments

LEGEND ^{76}Ge CUORE ^{130}Te nEXO next ^{136}Xe

$0\nu\beta\beta$ Decay: The Smoking Gun Approach

1) **Lepton number conservation is violated**

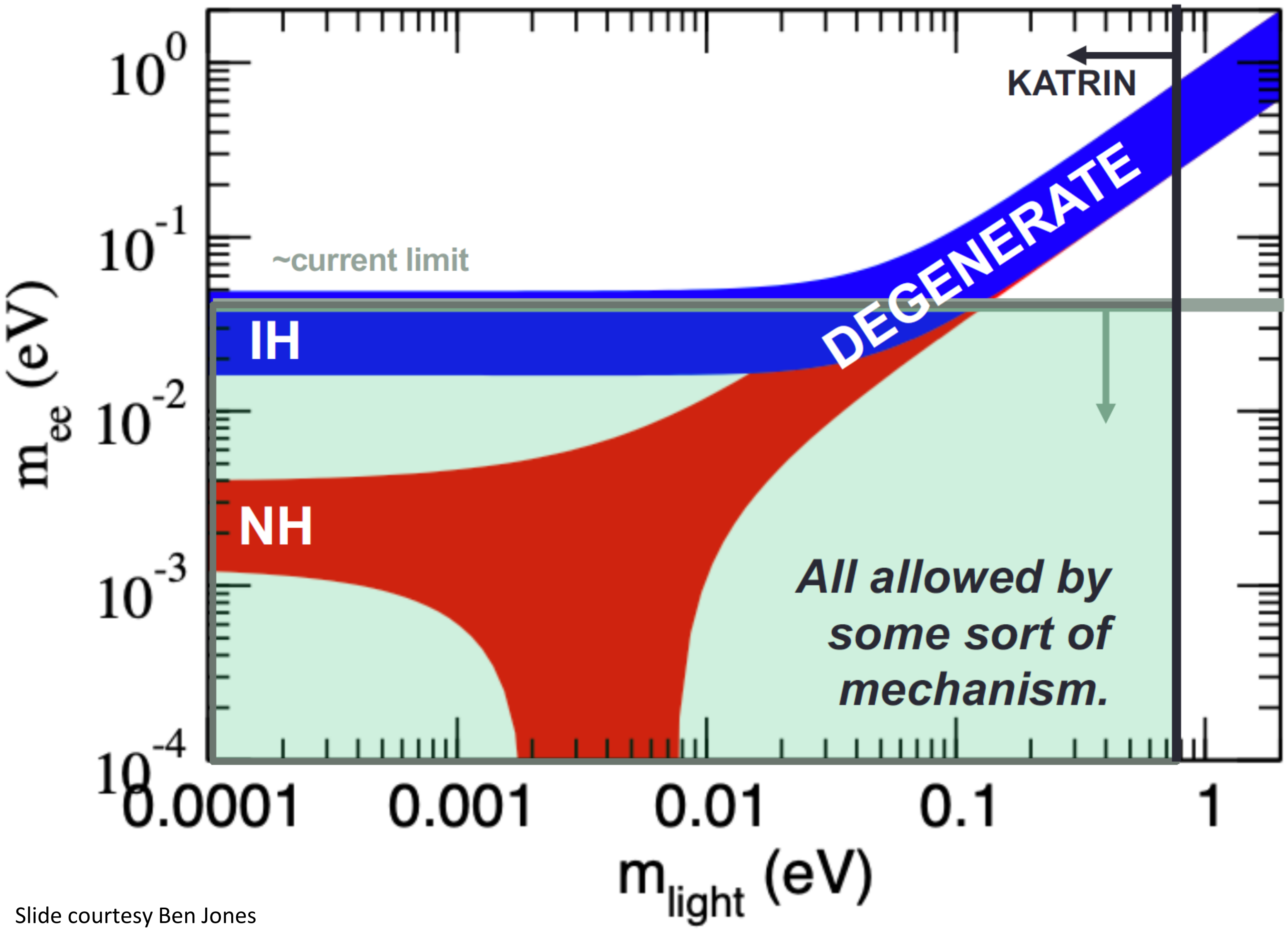
2) **Massive fermions exist that are neither matter or antimatter but something else (Majorana fermions)**

3) **The SM with the Majorana term is non-renormalizable → Thus the SM is definitely a low energy effective theory**

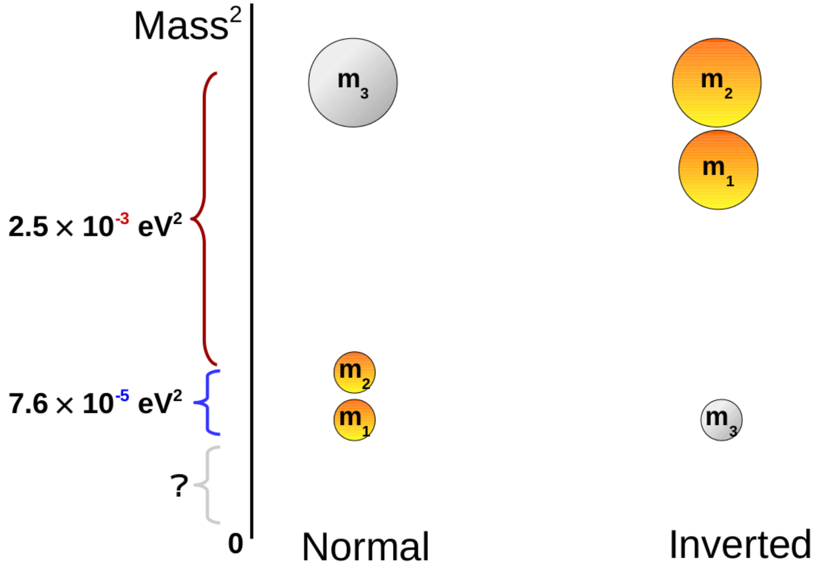
4) **There are other mass generating mechanisms in nature beyond the standard Higgs mechanism**

Further, Majorana neutrinos are a prediction of the theory of Leptogenesis that *may* generate observed matter/anti-matter asymmetry of the Universe (if leptonic CPV)

Interesting Search Region for 0νββ Decay

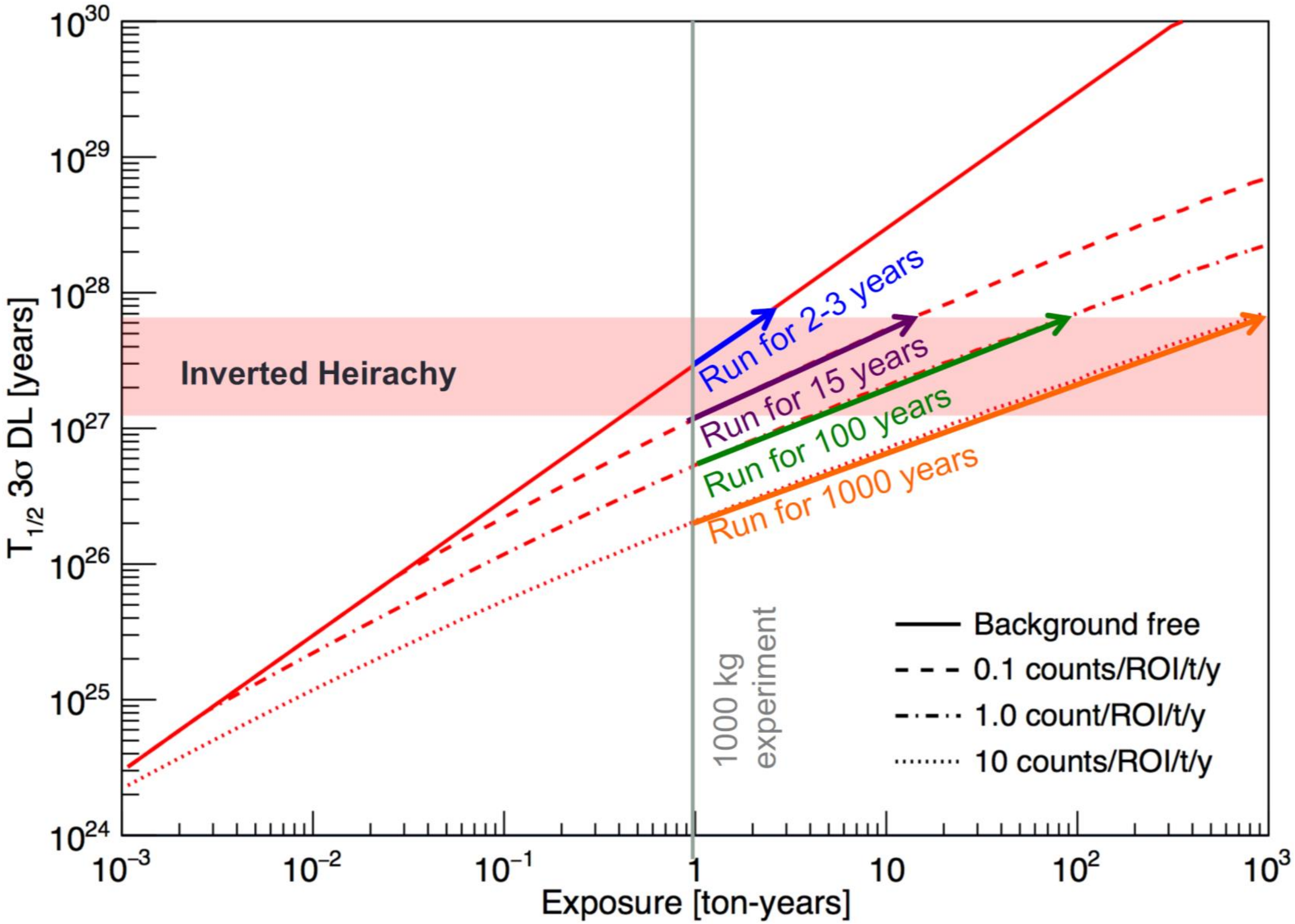


- The ordering of the neutrino mass states is not known, only their relative splittings
- Model predictions vary



Slide courtesy Ben Jones

Backgrounds, Backgrounds, Backgrounds…..



Slide courtesy Ben Jones

Conclusions

- We appear to be on the cusp of discovering a rich physical sector that lies beyond the SM and our best approach is to search for new observables predicted in simple neutrino mass extensions – in particular sub-MeV neutrino mass states and its possible Majorana nature

- Nuclear β decay is a powerful, model-independent probe of BSM physics that couples to the neutrino mass

- A number of new technologies have driven this field forward and we are just at the very beginning of exploring this developing research space

- Planned future work with superconducting sensors can expand this work to a larger range of quantum systems for addition BSM physics and applications!