Model-Independent Searches for sub-MeV Dark Particles via Weak Decay Recoil Spectroscopy

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and

Facility for Rare Isotope Beams
Michigan State University

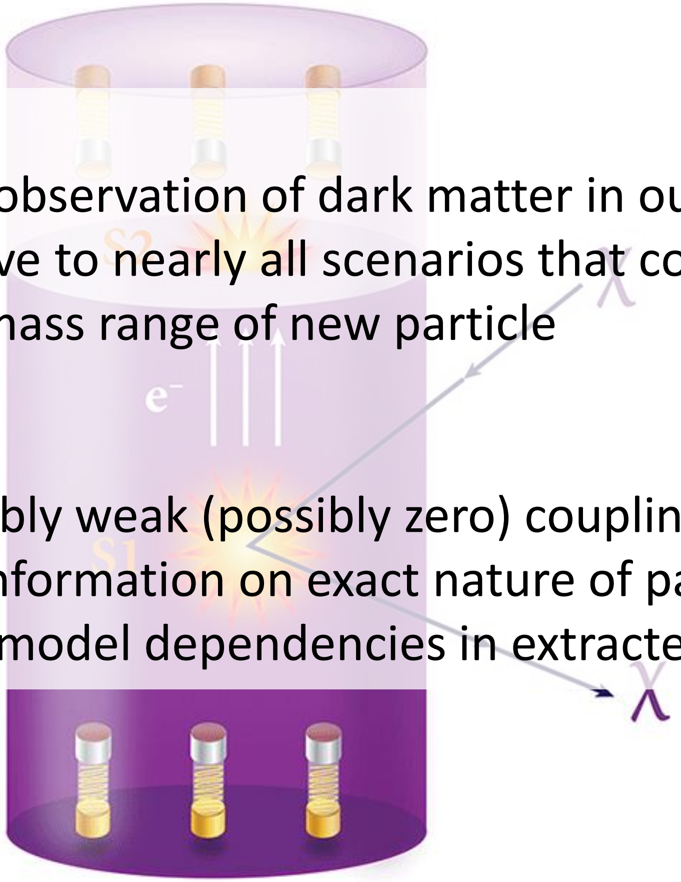
SALER

THE BeEST

beest.mines.edu

Searching for Dark Matter: Direct vs. Indirect Methods

Direct Search
(Large Volume Detectors, Rare Interaction)

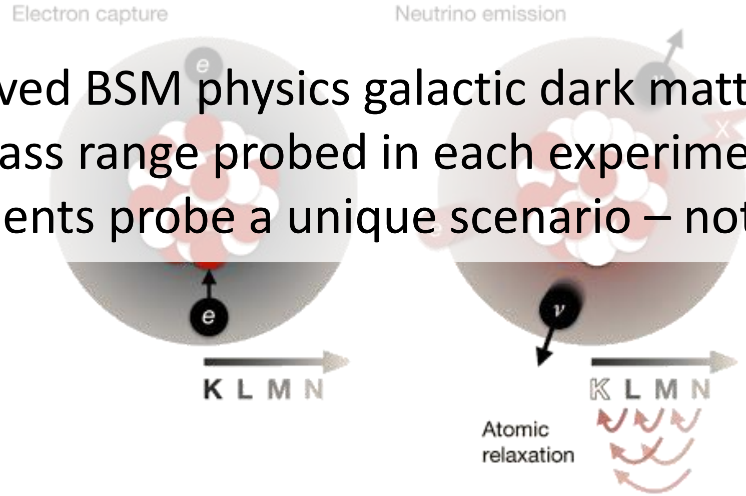


PROs:
- Direct observation of dark matter in our galaxy
- Sensitive to nearly all scenarios that couple to SM
- Wide mass range of new particle

CONs:
- Incredibly weak (possibly zero) couplings to SM
- Little information on exact nature of particle
- Heavy model dependencies in extracted physics

Indirect Search
(“Table-top” Precision Experiments, Quantum)

PROs:
- Search for specific class of BSM physics
- Model dependencies can be small in most cases
- Large SM signals allow for in-situ calib./charac.

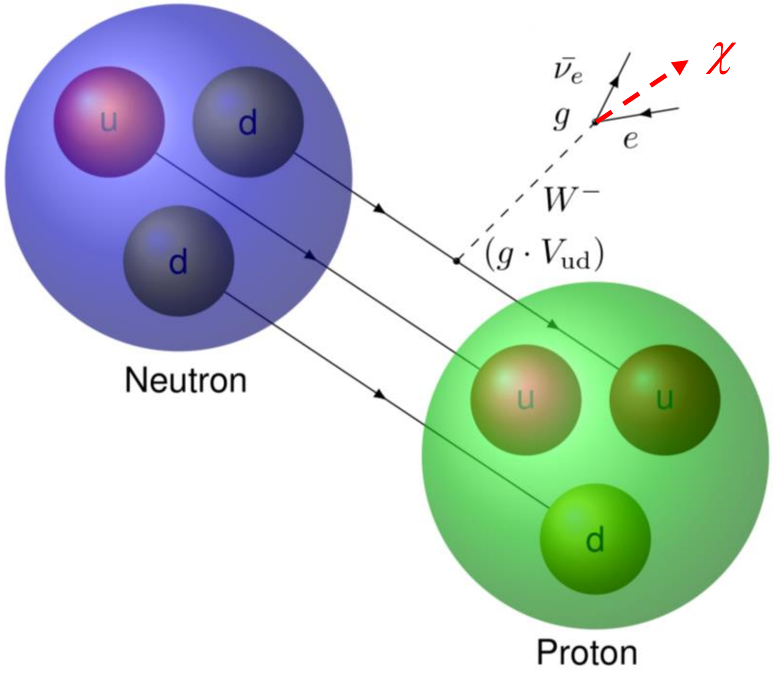


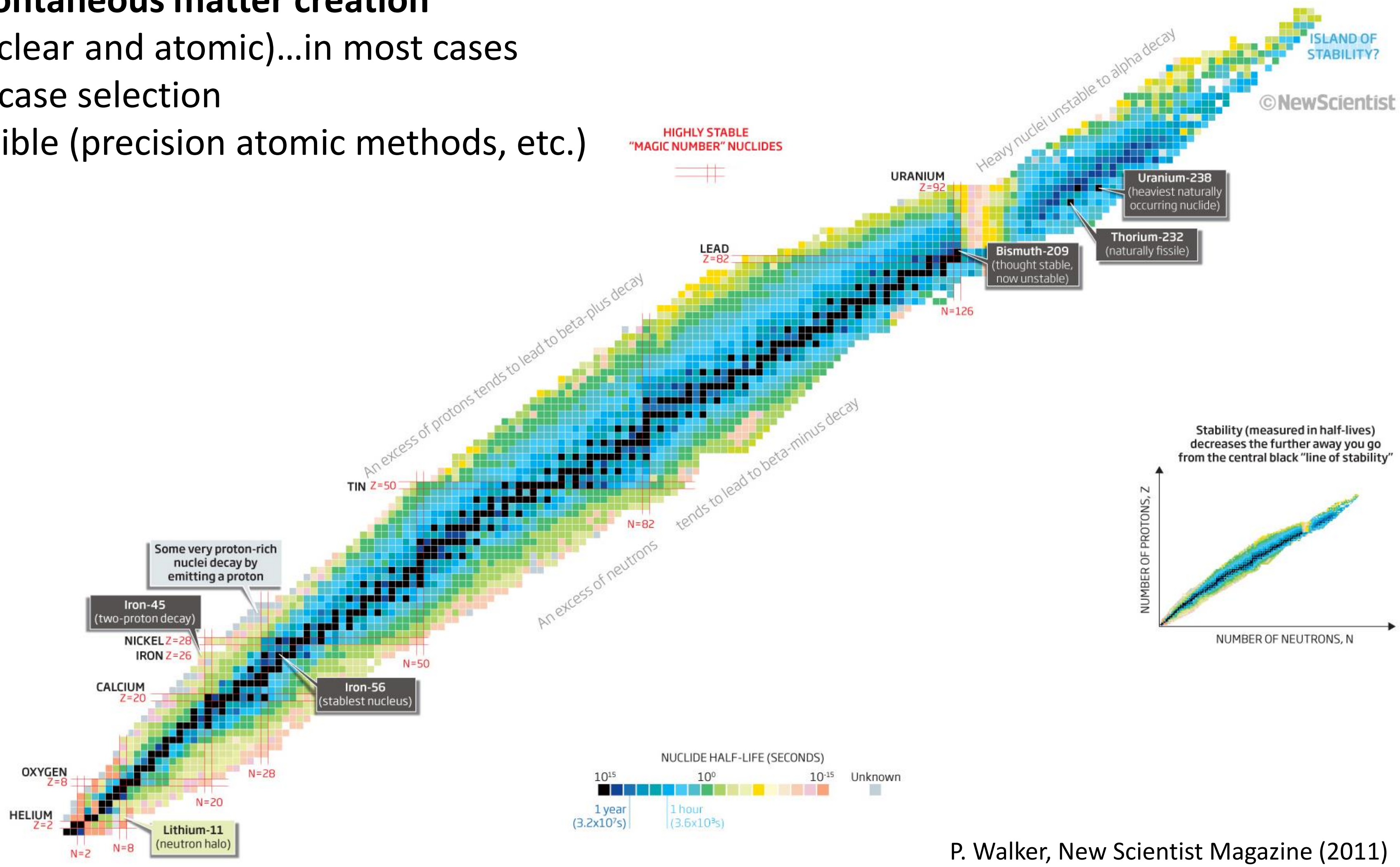
CONs:
- Is observed BSM physics galactic dark matter?
- Small mass range probed in each experiment
- Experiments probe a unique scenario – not universal

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)

Characterizing Nuclear β/EC Decay

Precision β decay typically performed via measurements of:

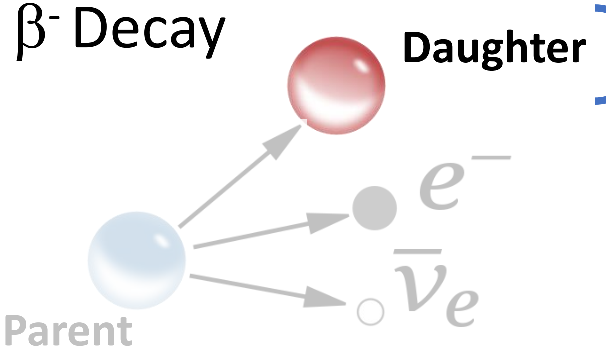
- Electrons (β^-, atomic Auger, CE, etc.)
- Positrons (β^+ and IPC)
- Photons (γ-ray, bremsstrahlung, and X-rays)

~ 0.1 – 10 **MeV**

***Unique* probe of:**

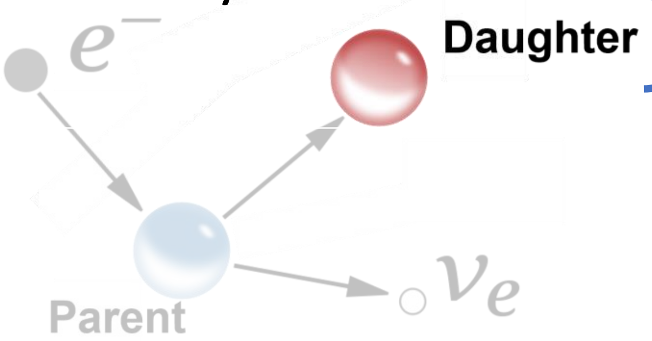
- Quantum nature of radioactive decay
- Rare SM effects
- Weakly coupled new physics
- Exotic new particles and interactions

β^- Decay

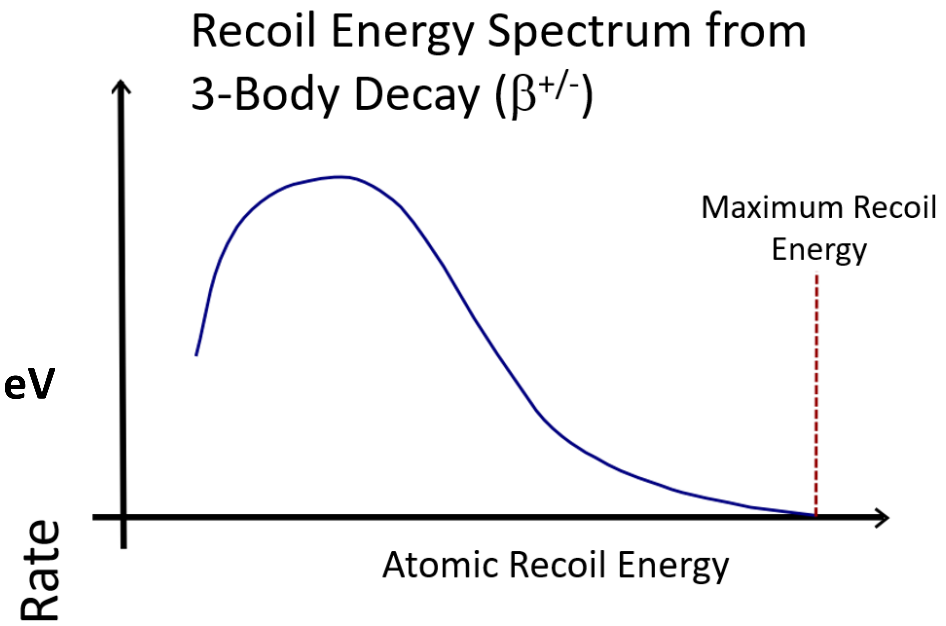


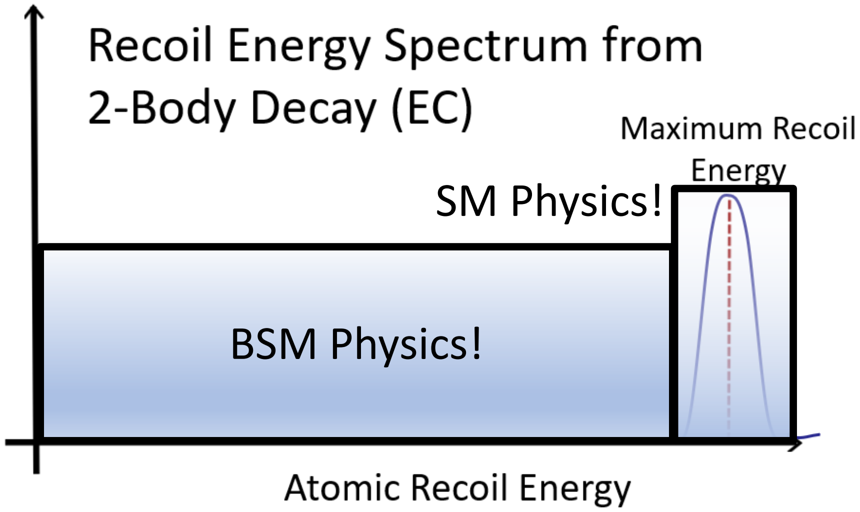
~ 0.1 – 100 **eV**

EC Decay



< 60 **eV**





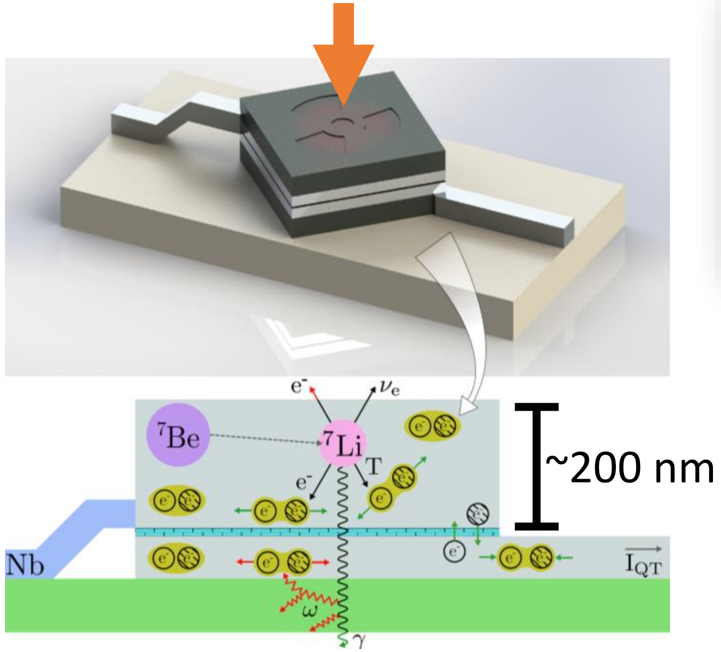
High Precision Decay Recoil Spectroscopy

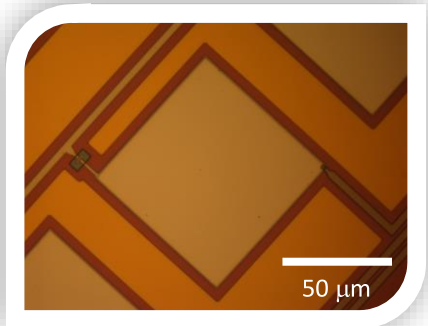
Superconducting Tunnel Junctions

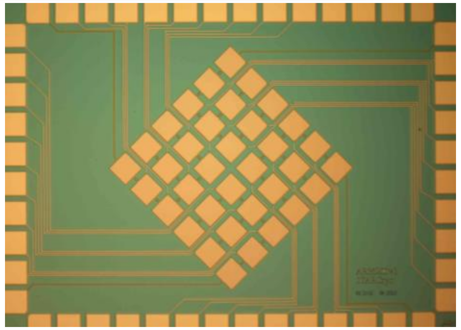
High-precision energy-resolving sensor

- “Cryogenic-charge” superconducting sensor
  - → High Energy Resolution (~1 eV)
  - → Low energy threshold for recoils (~2.5 eV)
  - → Well understood linearity and response
  - → “High” Rate (10^4 s^{-1} per pixel)

Rare Isotope Beam Implantation





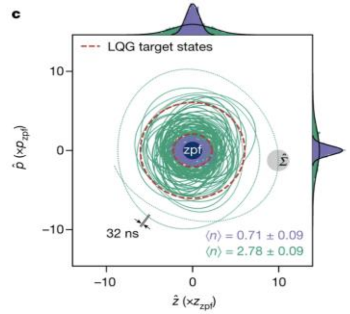


Optically Levitated Nanospheres

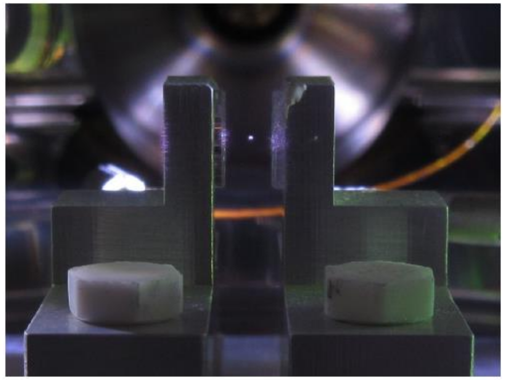
High precision, quantum-based, momentum/force sensor

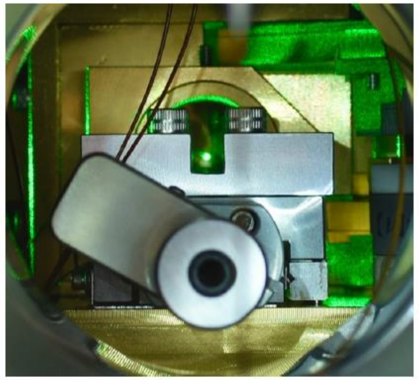
- Force/acceleration sensitive optomechanical sensor
  - → High sensitivity to small forces (~10^{-24} N)
  - → Quantum limited measurements (SQL)
    - *-- Potential to manipulate beyond SQL*
  - → “Event-by-event” decay reconstruction

Radioisotope Loading

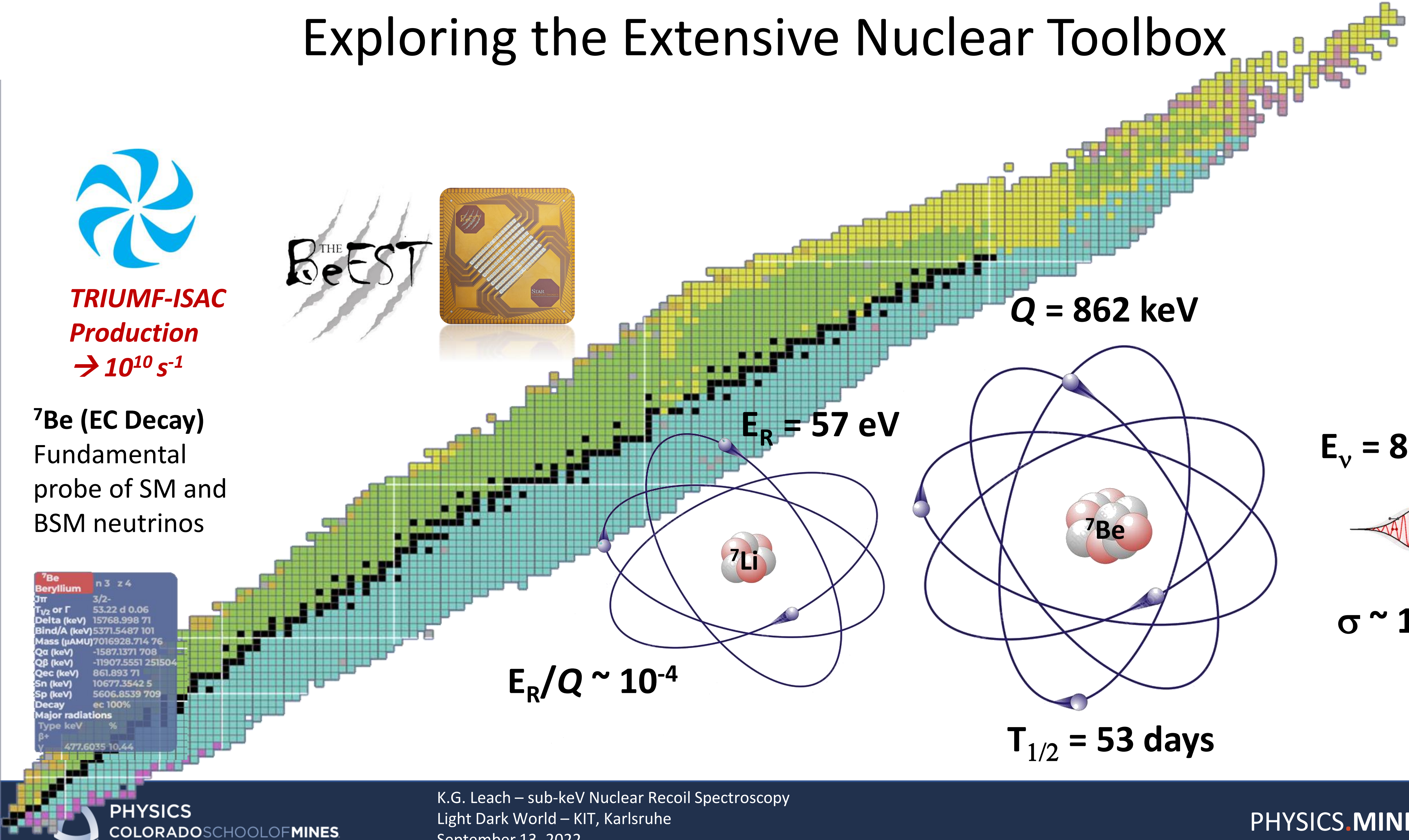


Images from Dave Moore





Exploring the Extensive Nuclear Toolbox



^{7}Be Beryllium	n 3 z 4
Jπ	3/2-
$T_{1/2}$ or Γ	53.22 d 0.06
Delta (keV)	15768.998 71
Bind/A (keV)	5371.5487 101
Mass (μAMU)	7016928.714 76
Qα (keV)	-1587.1371 708
Qβ (keV)	-11907.5551 251504
Qec (keV)	861.893 71
Sn (keV)	10677.3542 5
Sp (keV)	5606.8539 709
Decay	ec 100%
Major radiations	
Type keV	%
β+	
γ 477.6035	10.44

TRIUMF-ISAC Production
→ 10^{10} s^{-1}

^{7}Be (EC Decay)
Fundamental probe of SM and BSM neutrinos

THE BeEST

Q = 862 keV

E_R = 57 eV

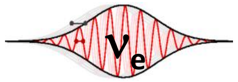
^{7}Li

^{7}Be

$E_R/Q \sim 10^{-4}$

$T_{1/2}$ = 53 days

E_ν = 862 keV

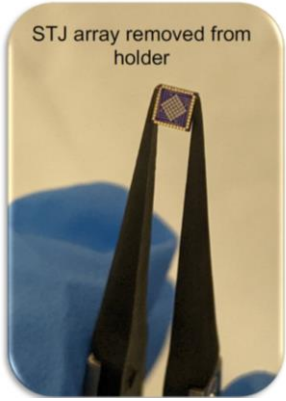


$\sigma \sim 10^{-22}$ b

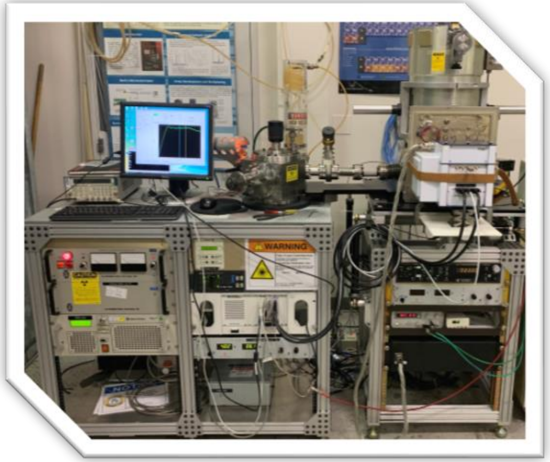
Beryllium Electron Capture in Superconducting Tunnel Junctions

TRIUMF

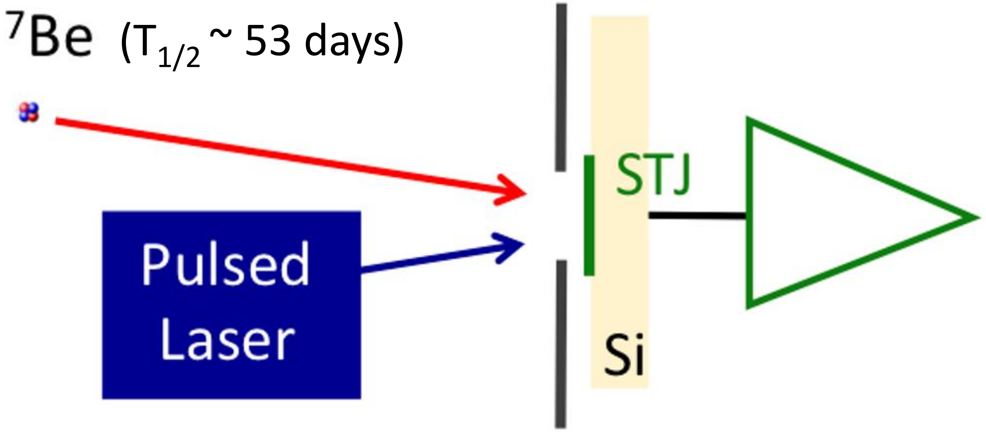
Rare-isotope implantation at TRIUMF-ISAC



Lawrence Livermore National Laboratory

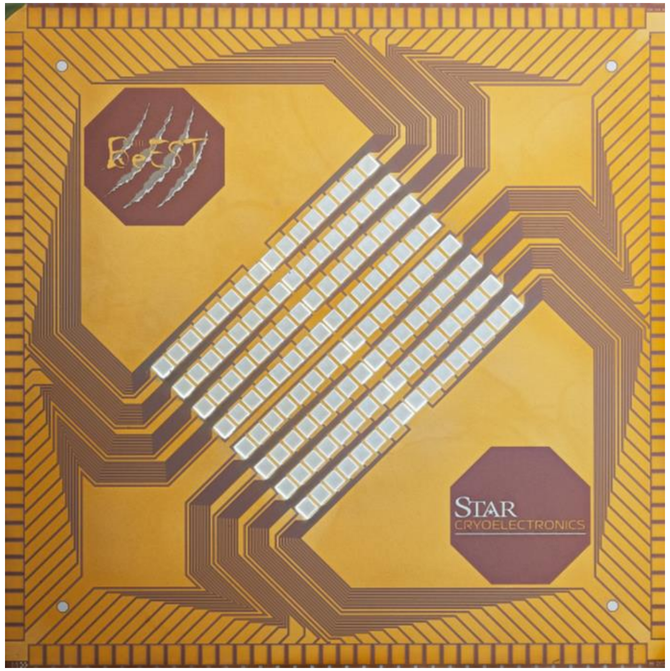


THE BeEST



STAR CRYOELECTRONICS

Ta, Al, and Nb-based STJ Sensor Arrays

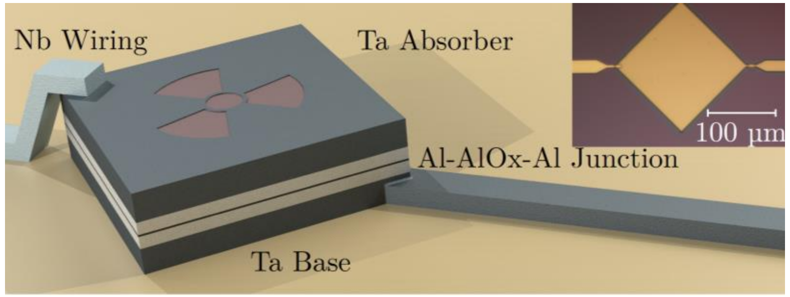


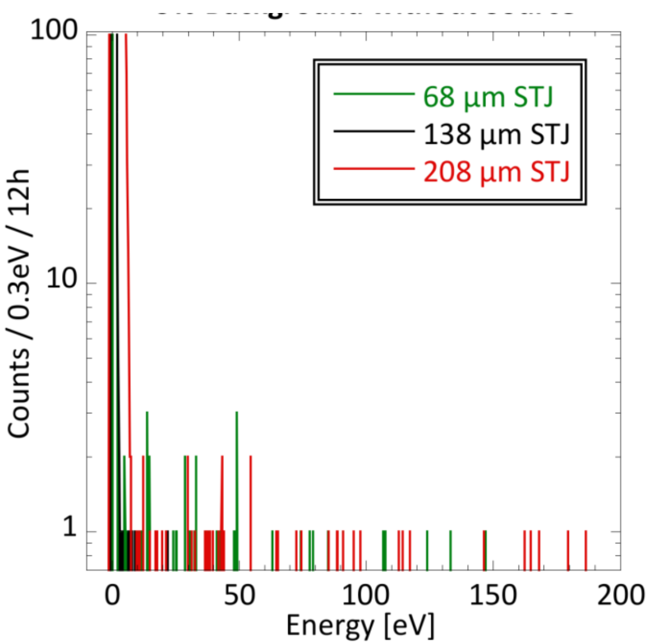
Phase I: PRL **125**, 032701 (2020)
Phase II: PRL **126**, 021803 (2021)
Phase III: ***In Progress (data taking complete)***

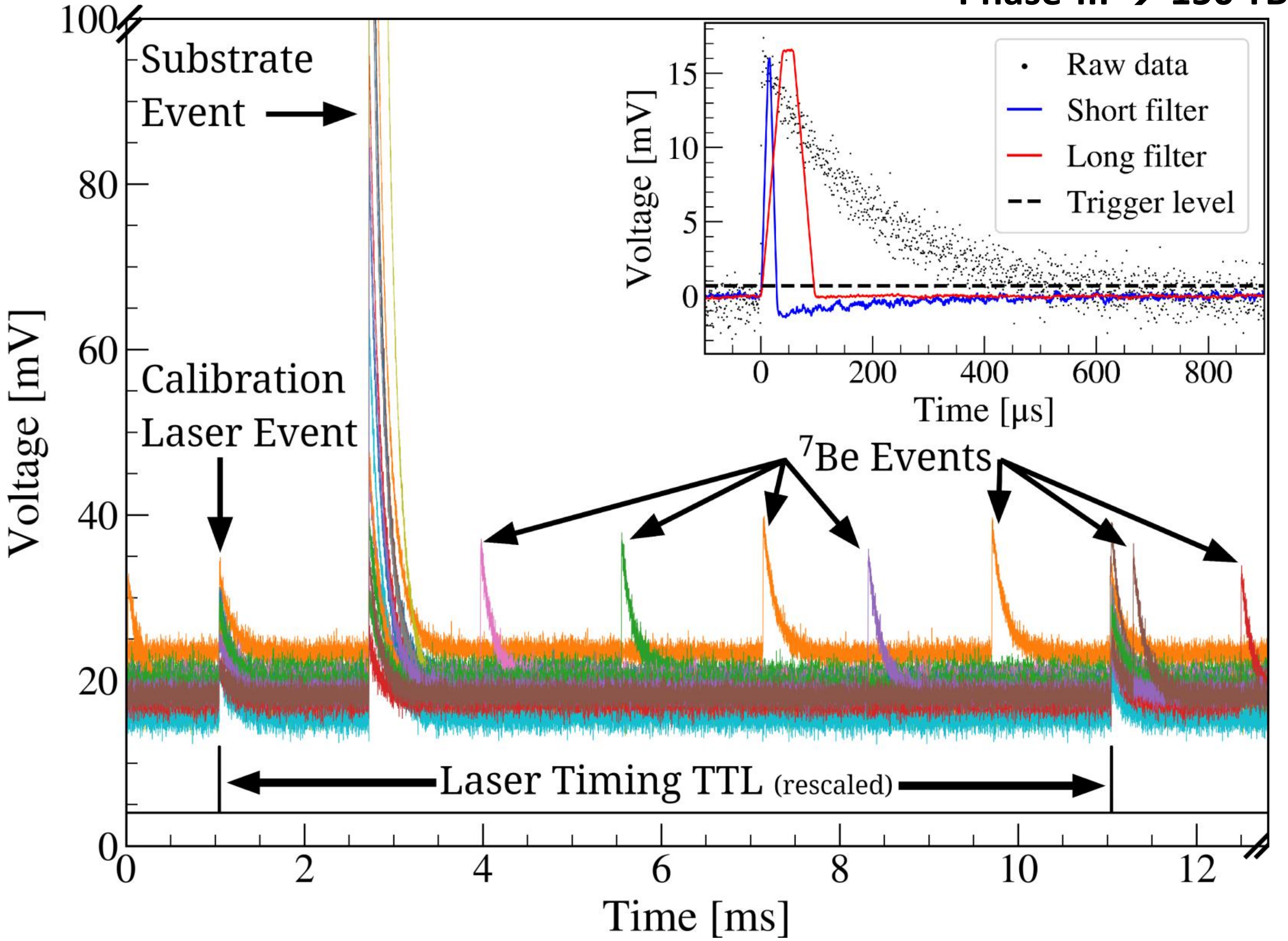
U.S. DEPARTMENT OF ENERGY Office of Science
GORDON AND BETTY MOORE FOUNDATION
EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Signals, Sensitivity, and Backgrounds

Phase-III → 150 TB

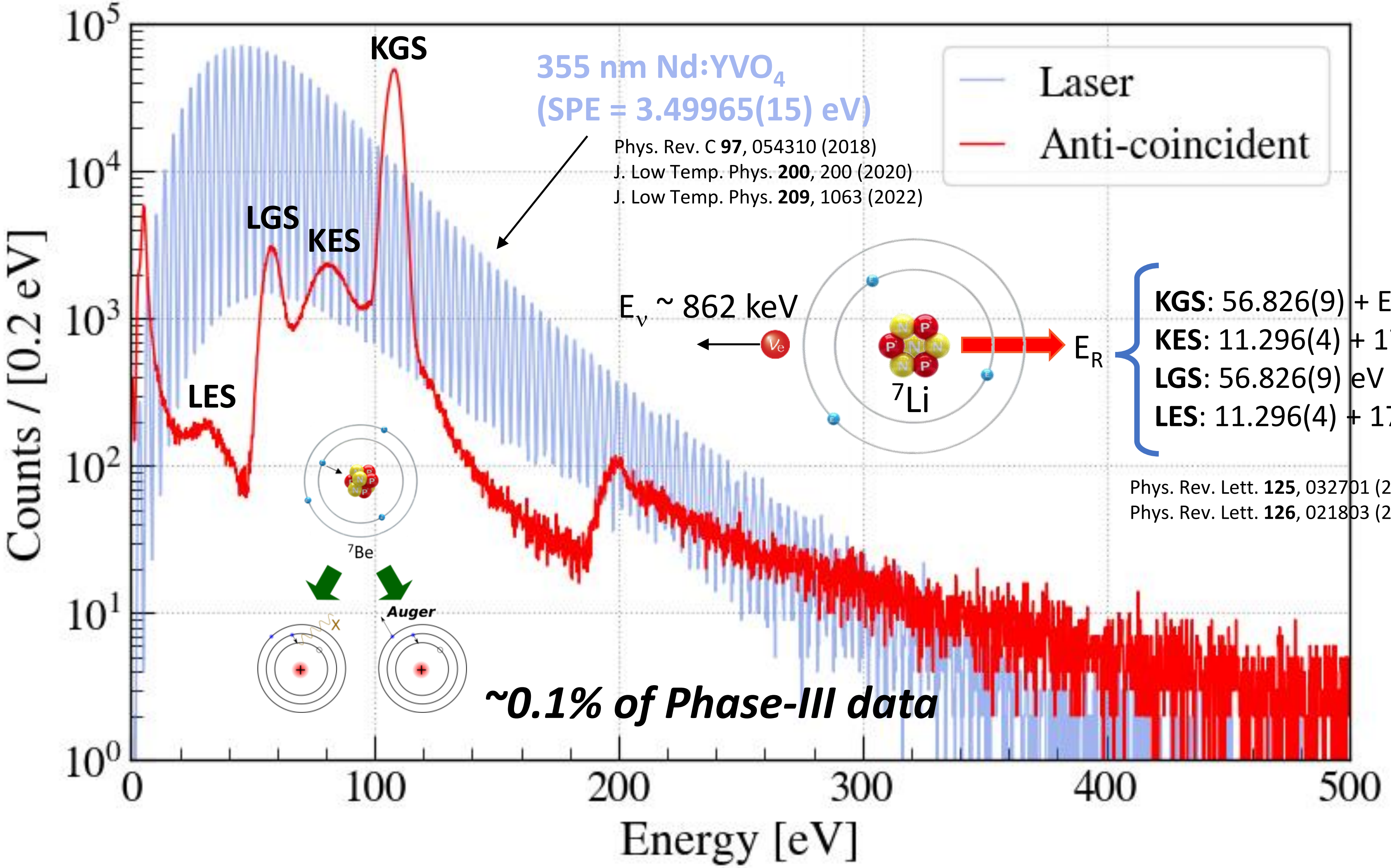


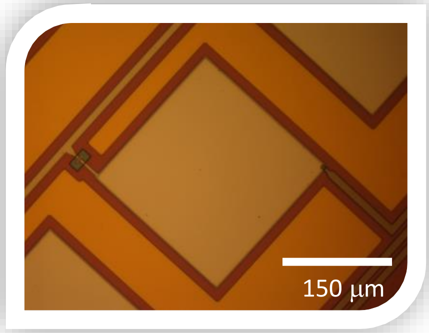




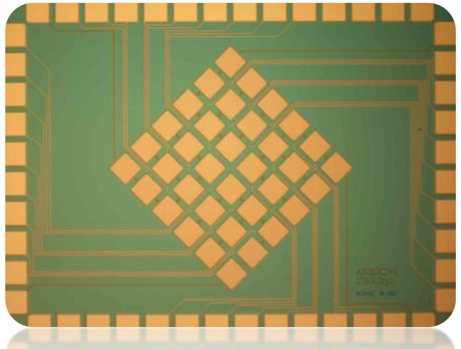
- Intrinsically "low-background"
- Absorber layer 100 – 200 nm
- Threshold ~2 eV

^{7}Be Recoil Spectrum: A Rich Playground for Fundamental Physics





- Single pixel
- 20 hours
- 50 Bq

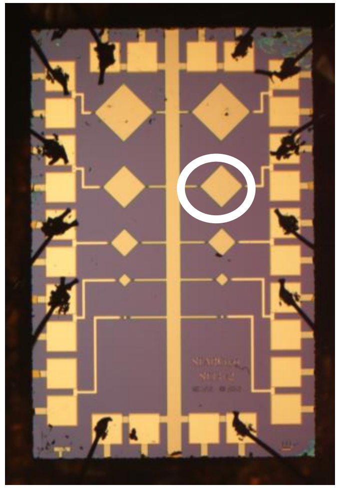


- 36 pixels
- 50 days
- 50 Bq/pixel

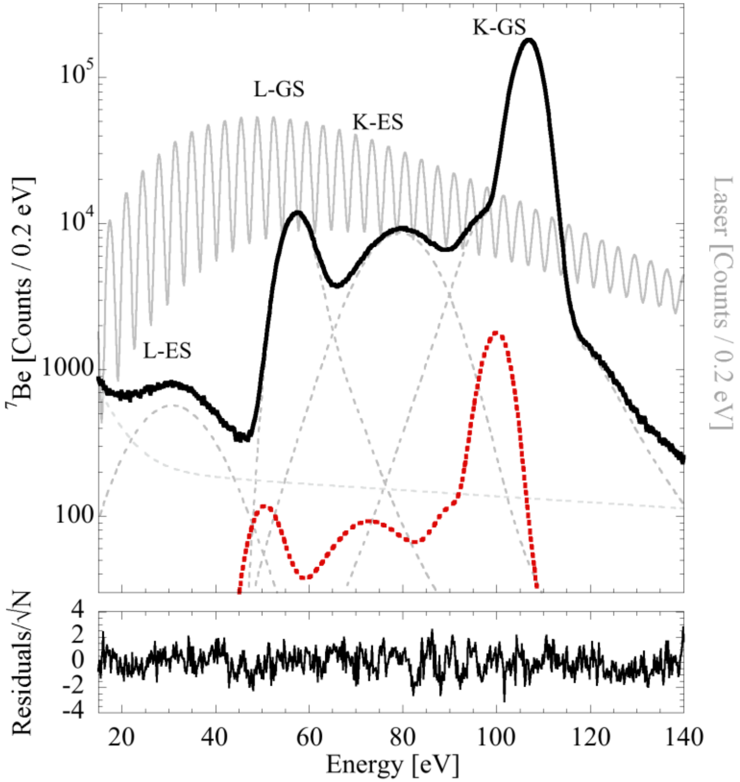
Limits from BeEST Phase-II Data

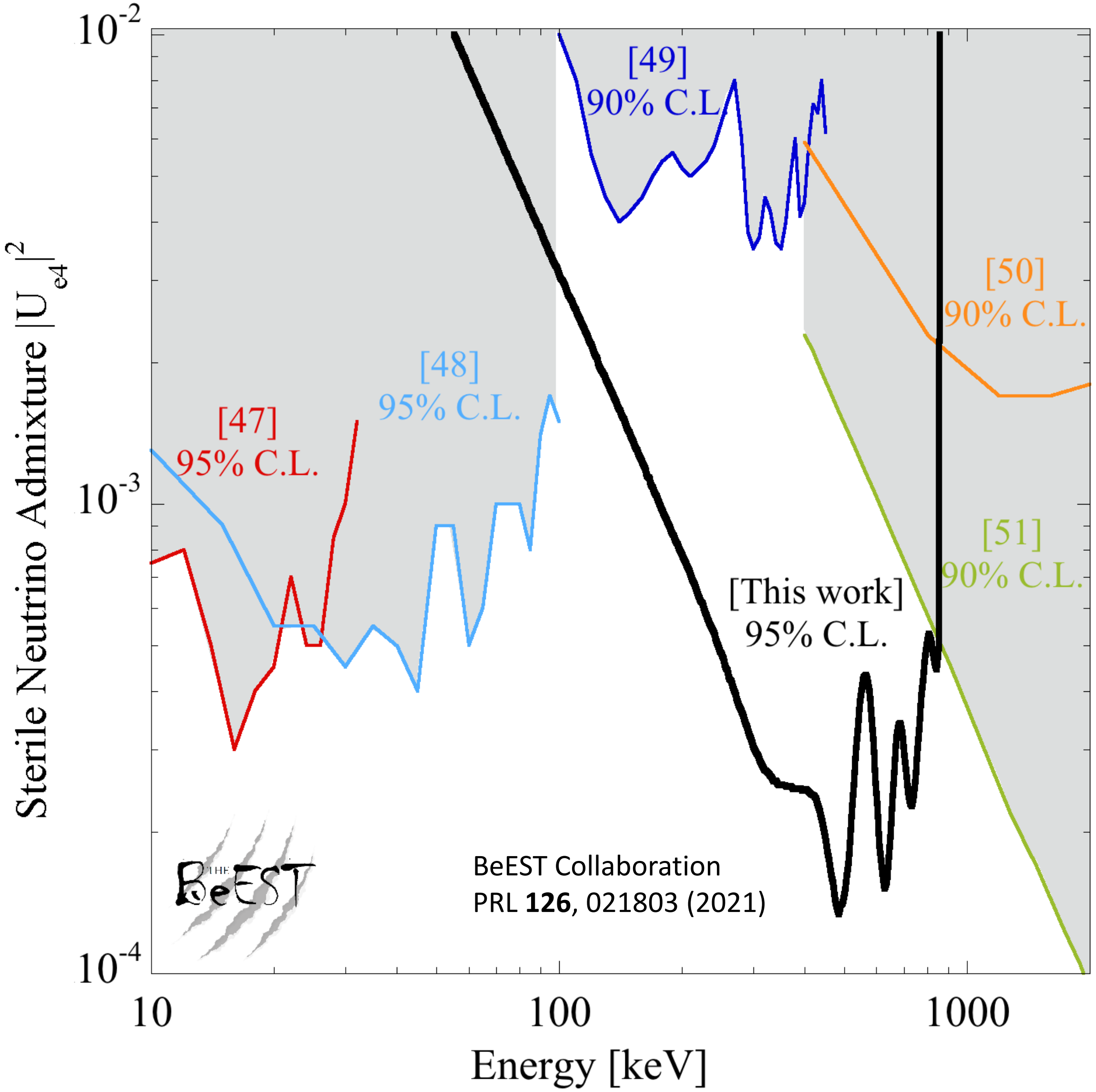
Heavy neutrino signature is overlayed spectrum with:

1) Shifted recoil energy $\Delta E(m_s)$
2) Reduced amplitude ($A \propto |U_{e4}|^2$)



- Single pixel
- 10 Bq
- 28 days



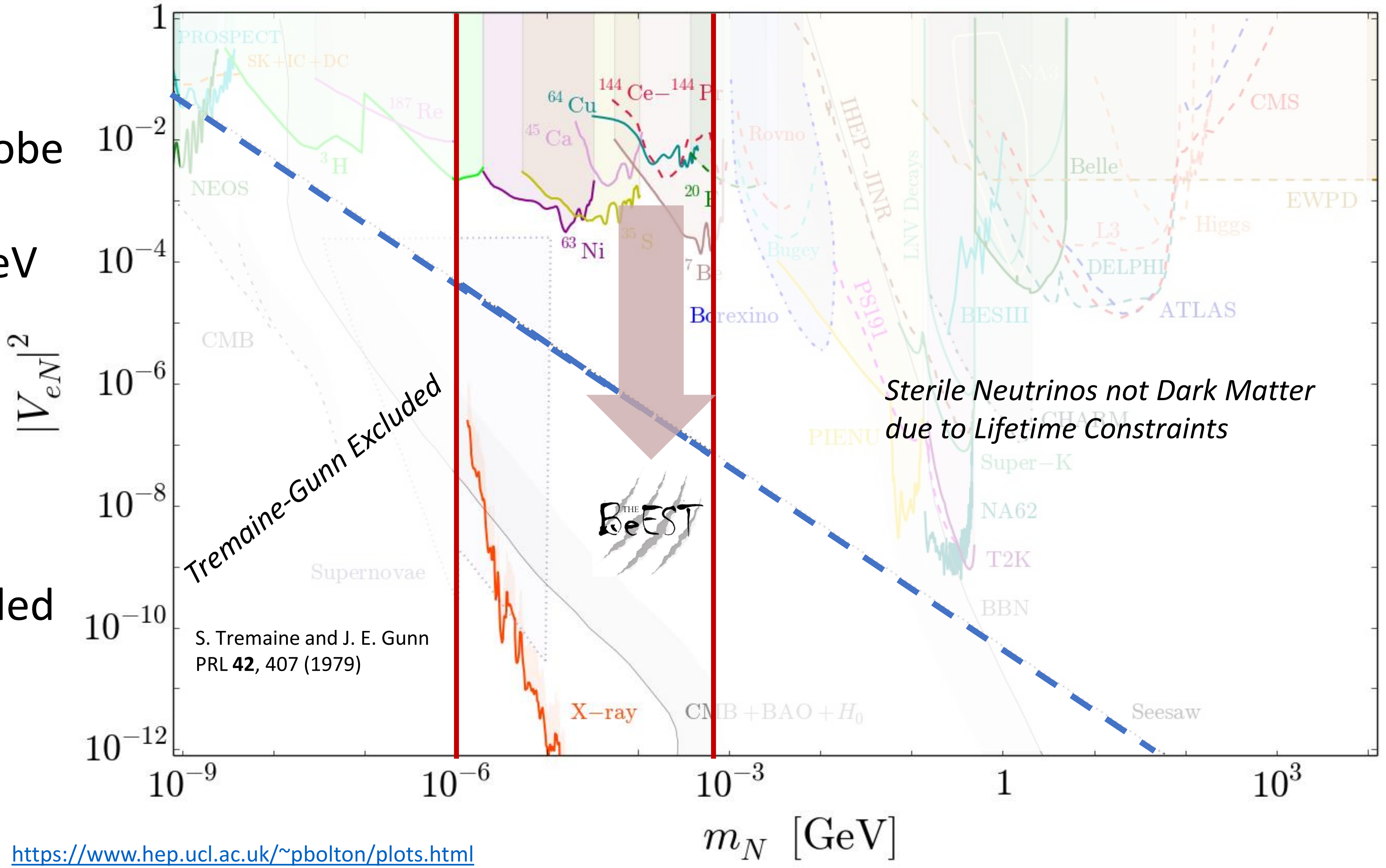


Phase-II of the BeEST currently sets the most stringent laboratory limits on sub-MeV neutrino masses

Synergy Between Cosmology and Laboratory Measurements

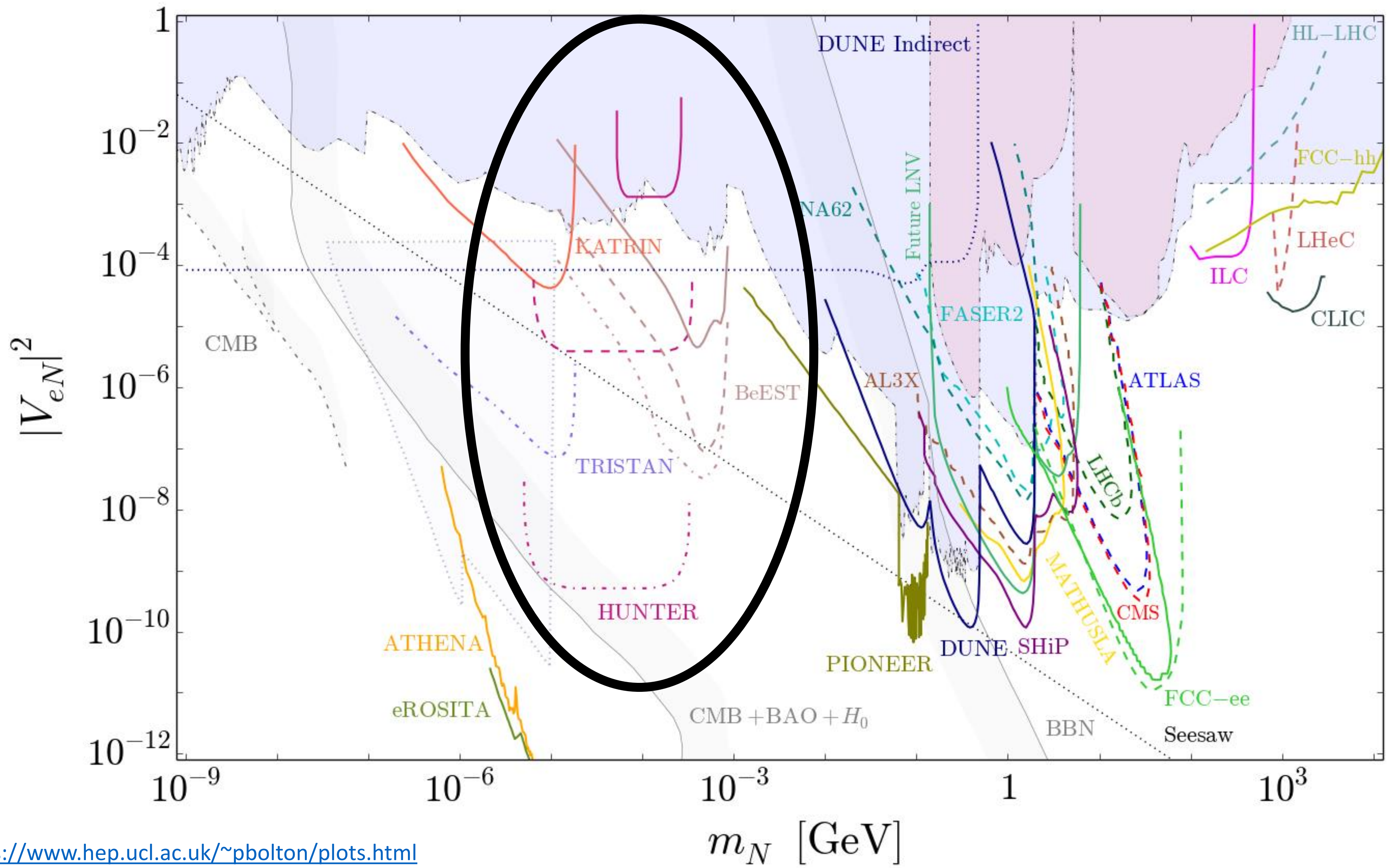
- Phase–IV of the BeEST experiment aims to probe the canonical seesaw mechanism for sub-MeV masses
  - DM candidate

- Beyond Phase-IV, the experiment will be scaled to larger arrays with increased activities (SuperBeEST)



https://www.hep.ucl.ac.uk/~pbolton/plots.html

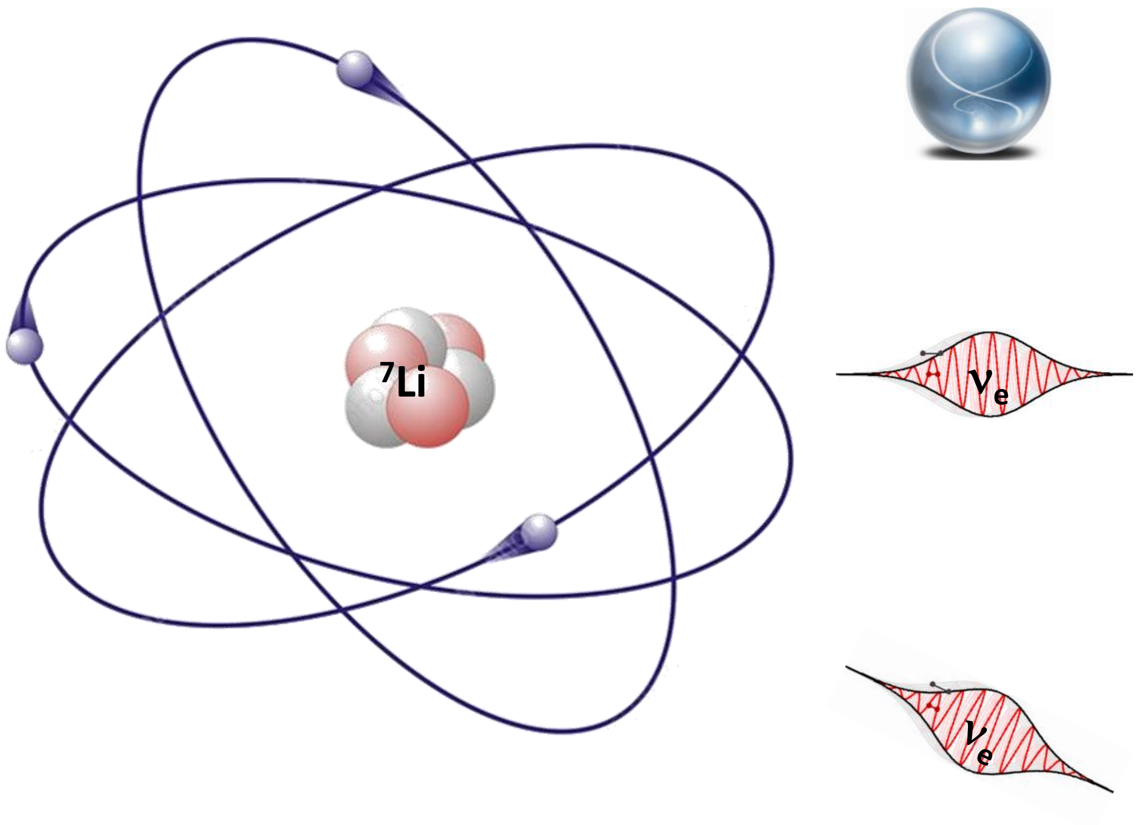
Future of Decay Experiments and Synergy with Cosmology

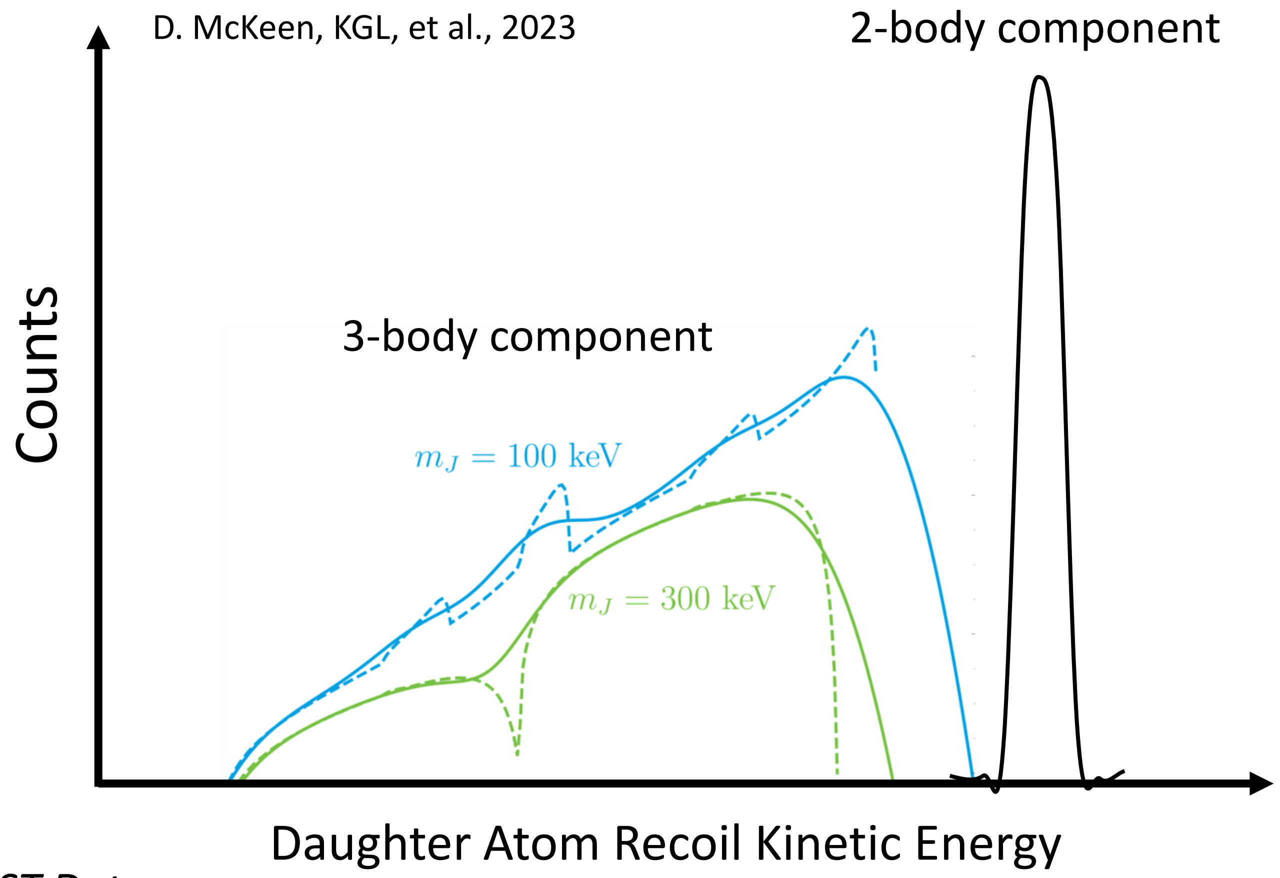


https://www.hep.ucl.ac.uk/~pbolton/plots.html

3-Body Decay Search: Neutrino-Coupled Light Bosons

New bosons coupled to neutrinos can address problems in cosmology

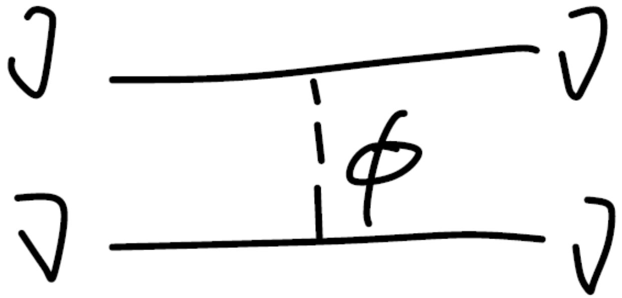




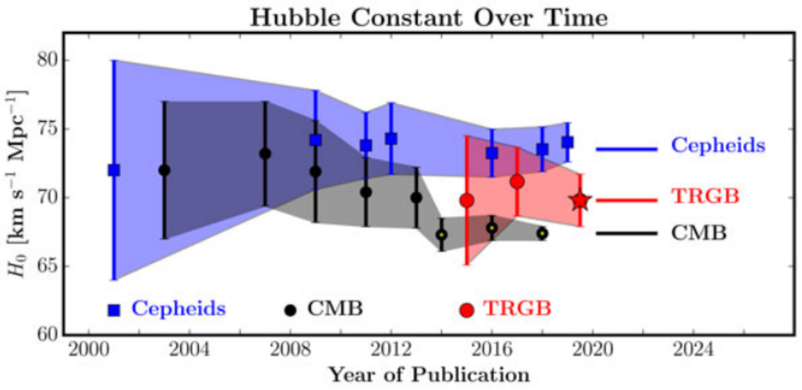
Example: Majoron signature in the BeEST Data

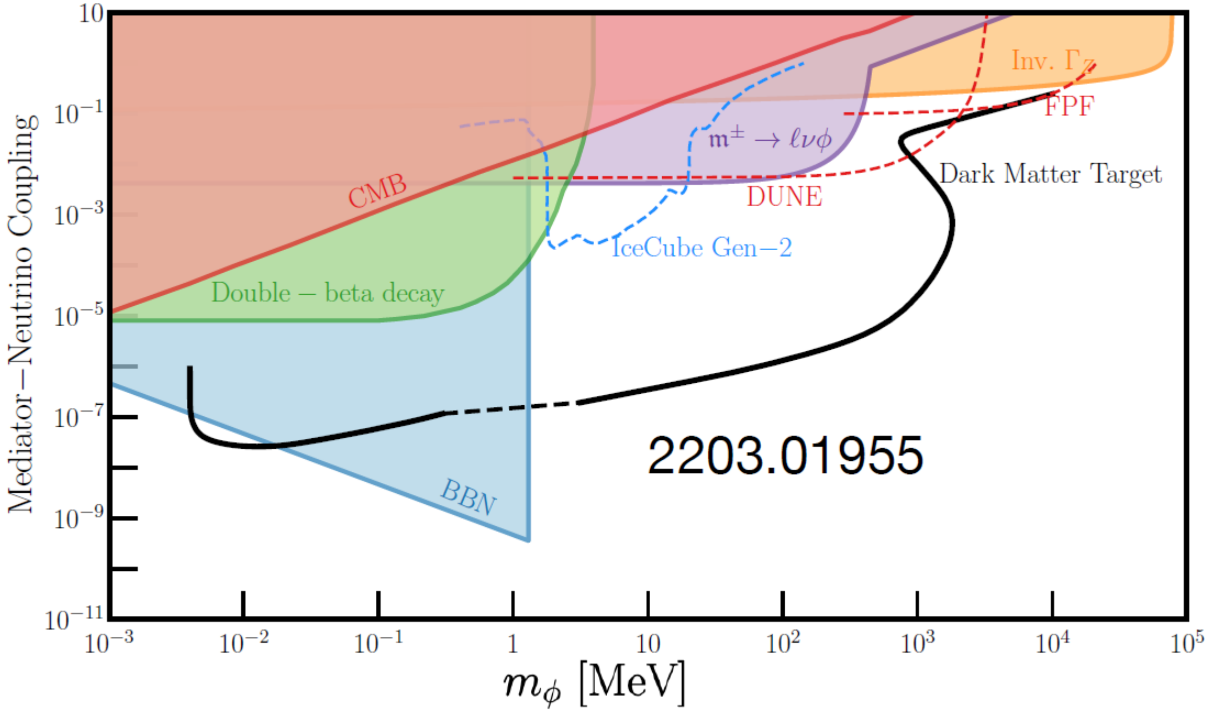
Search for Neutrino-Coupled Light Bosons

Light bosons coupled to neutrinos can help resolve the H_0 tension (see Cyr-Racine et al.)



Neutrino free-streaming delayed
$\Rightarrow$CMB acoustic peaks shifted





($\phi\beta\beta$ and BBN bounds can be avoided)

Search for this boson emitted from ν in 3-body ^{7}Be decays!

Slide from Dave McKeen (TRIUMF)

The BeEST Collaboration

Keith Borbridge, Connor Bray, David Diercks, Spencer Fretwell, Abbi Gillespie, Cameron Harris, Calvin Hinkle, Amii Lamm, Kyle Leach, Drew Marino, John Taylor, Ben Waters, Joe Smolsky, Caitlyn Stone-Whitehead
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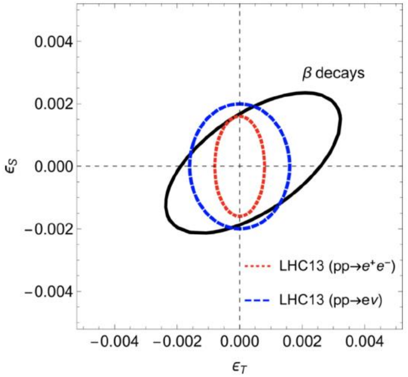
EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
NNSA National Nuclear Security Administration


2023 Collaboration Meeting
Livermore, California

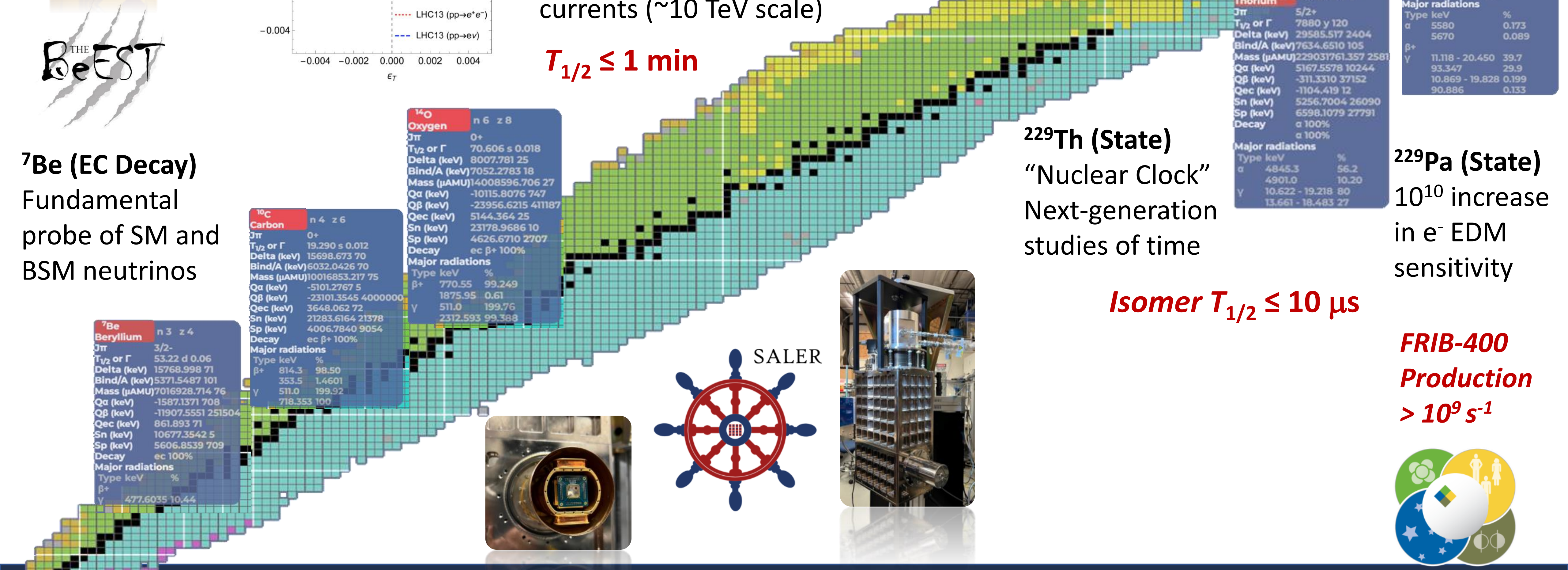
Fully Explore the Extensive Nuclear Toolbox with STJs



N≈Z Systems (β⁺ Decay)
Most sensitive laboratories for CKM unitarity tests and searches for exotic currents (~10 TeV scale)

$T_{1/2}$ ≤ 1 min

^{7}Be (EC Decay)
Fundamental probe of SM and BSM neutrinos



^{229}Th (State)
"Nuclear Clock"
Next-generation studies of time

^{229}Pa (State)
10^{10} increase in e⁻ EDM sensitivity

Isomer $T_{1/2}$ ≤ 10 μs

FRIB-400 Production > 10^{9} s^{-1}

SALER

Coupling Superconducting Sensor Arrays to the RI Beamline

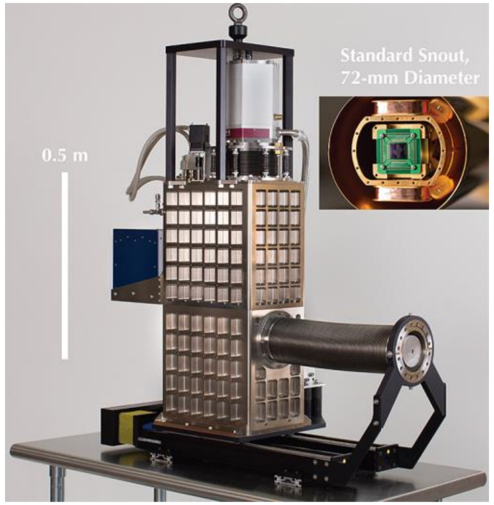
Short-Lived Rare Isotopes ($T_{1/2} > 0.1$ s)

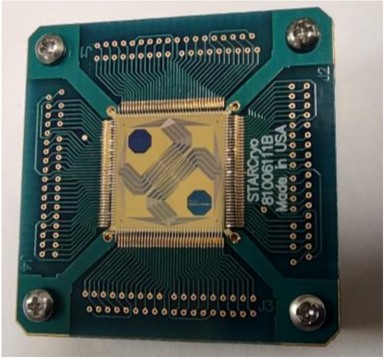
- Nearly all nuclei can be studied
- Measurements performed *in-situ* with beamline coupled ADR

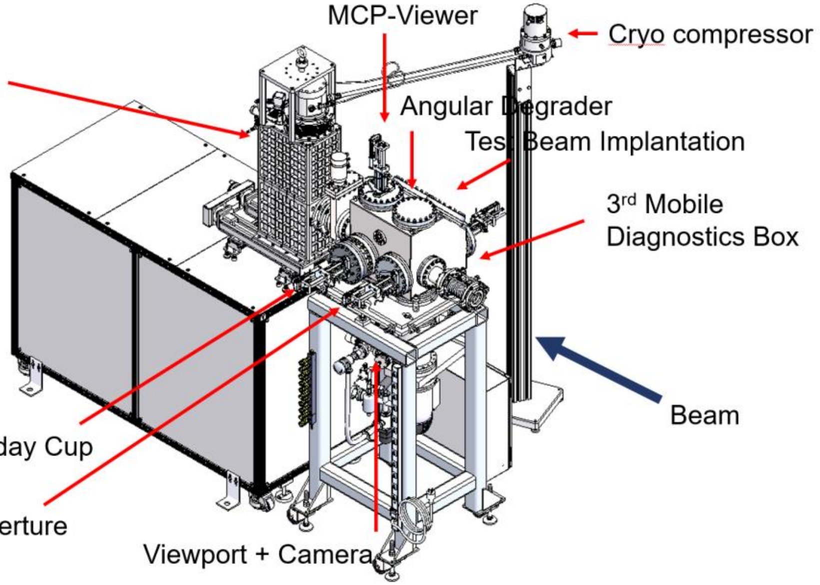
SALER @ FRIB

Construction of apparatus nearly complete

- Delivery to FRIB in October 2023

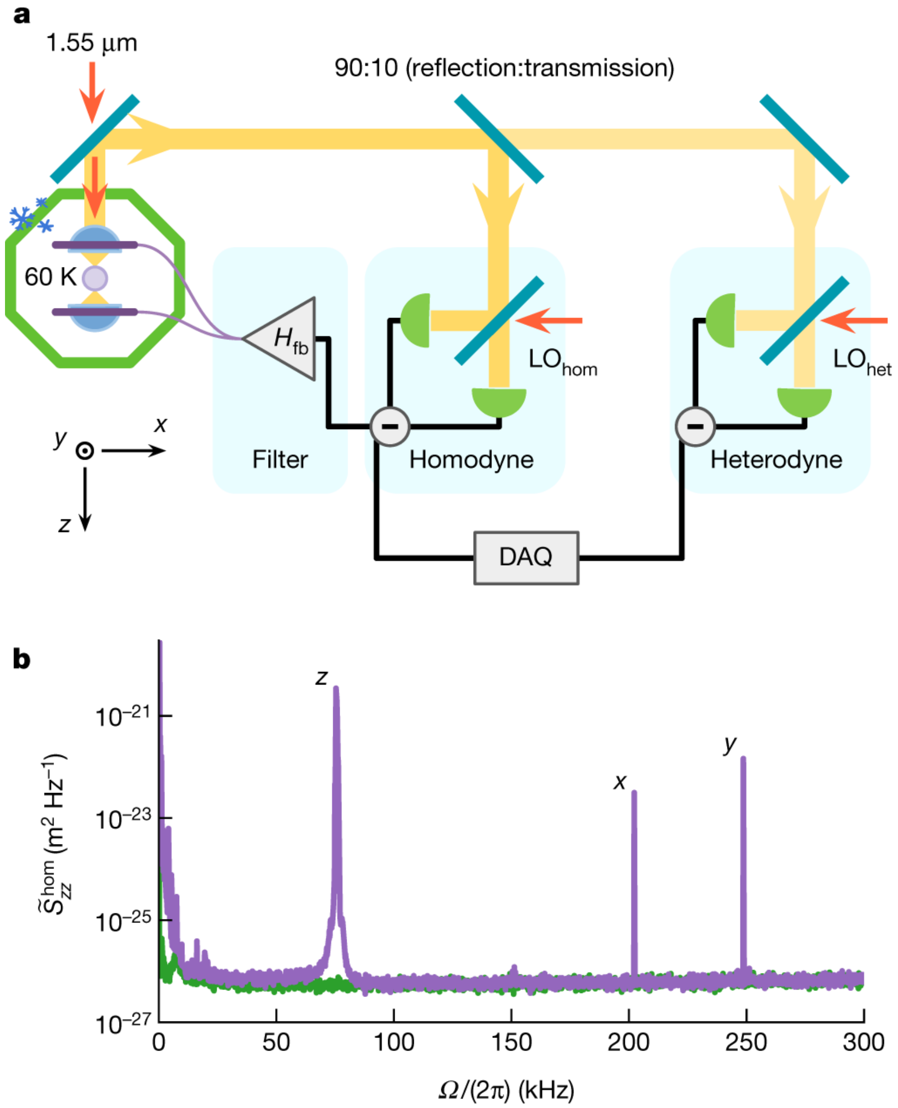






Pushing Beyond Superconductors: Optomechanics

- Our weak decay recoil experiments can be further improved by directly measuring *momentum*
- Prepare femtogram glass beads with embedded rare isotopes and optically levitate
- A weak continuous measurement of position and momentum for the quantum harmonic oscillator
- When the particle moves, there is an optical phase shift (due to path length for scattered light) that produces a voltage change on the homodyne detector.



F. Tebbenjohans *et al.*, Nature **595**, 378 (2021)

Neutrino Mass Studies with Optically Levitated Nanospheres

PRX QUANTUM 4, 010315 (2023)

Editors' Suggestion | Featured in Physics

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Searches for Massive Neutrinos with Mechanical Quantum Sensors

Daniel Carney,[1] Kyle G. Leach,[2,3] and David C. Moore[4,*]

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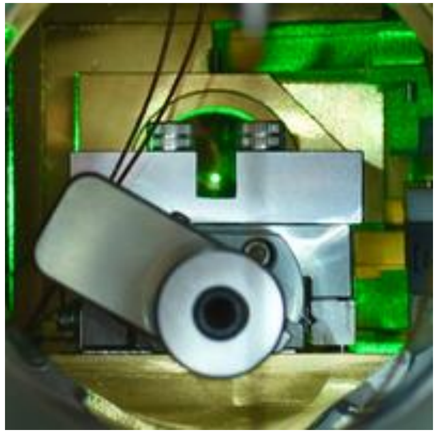
[2] Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA
[3] Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA
[4] Wright Laboratory, Department of Physics, Yale University, New Haven, Connecticut 06511, USA

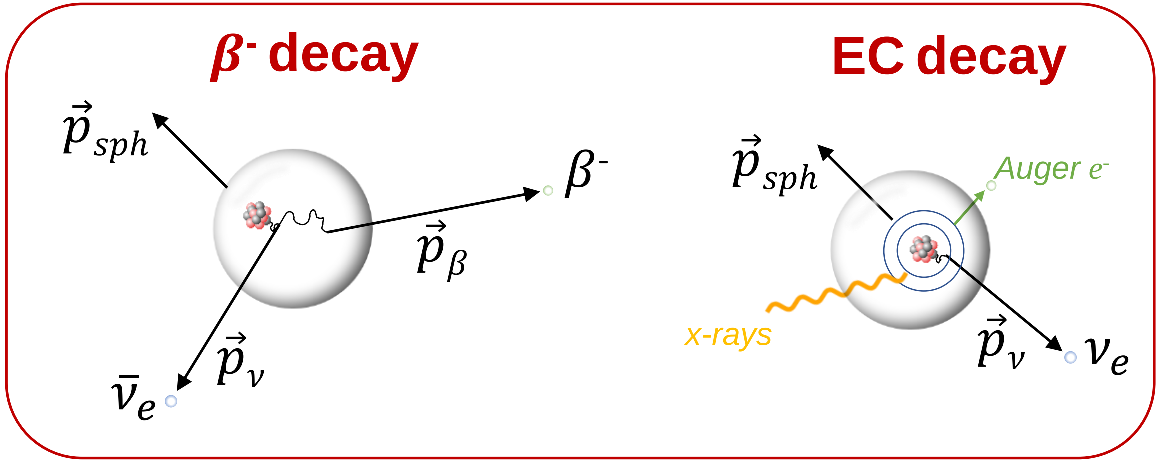
Physics — SYNOPSIS

Searching for Ghost Particles with a Mechanical Sensor

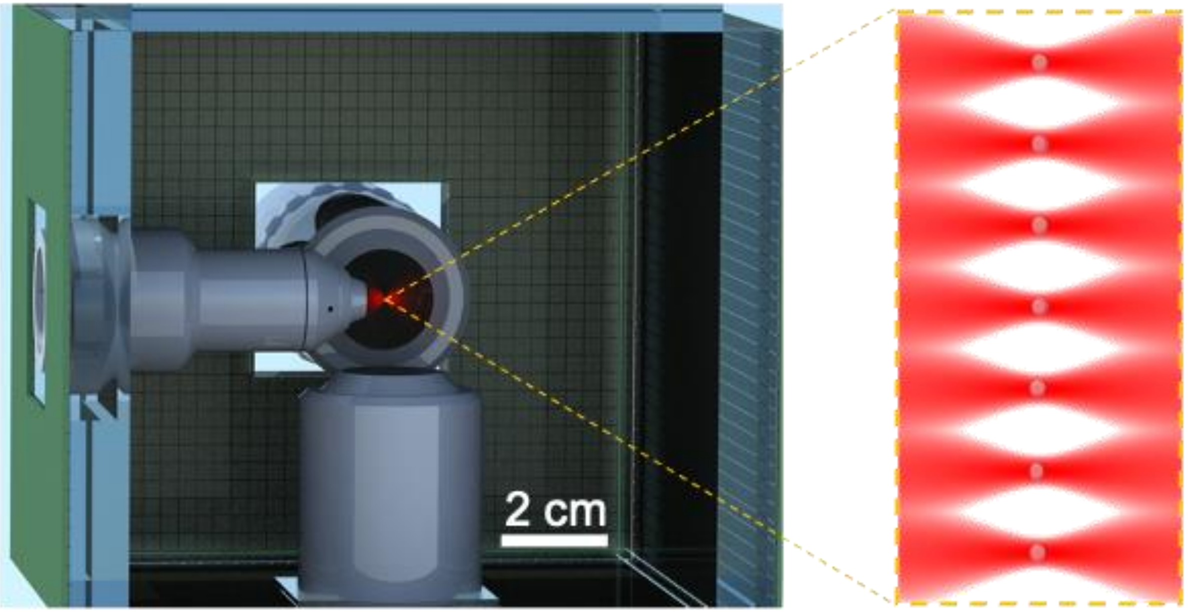
Researchers have proposed a new method to search for invisible particles called sterile neutrinos using a glass nanoparticle suspended by laser light.

By Katie McCormick





Detector concept:

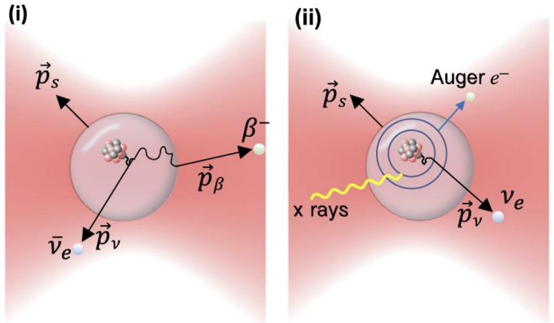


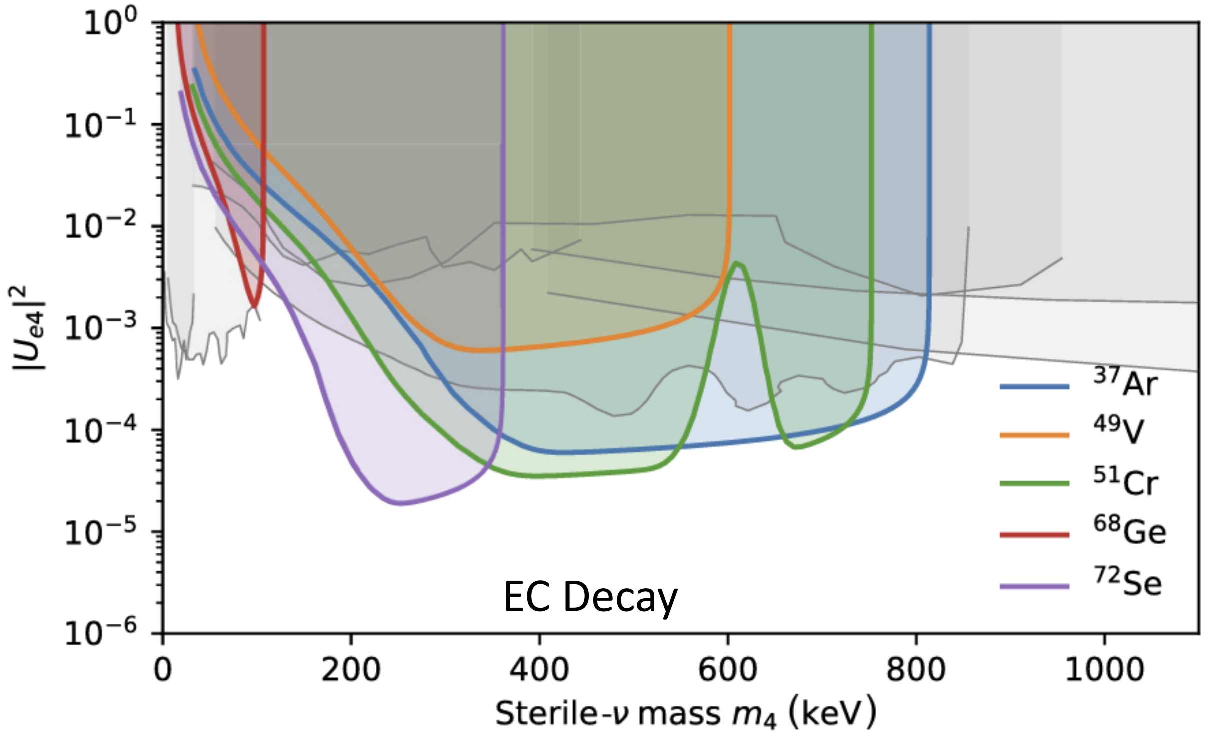
"smaller than 1 quadrillionth of the momentum transferred by a feather landing on your shoulder"

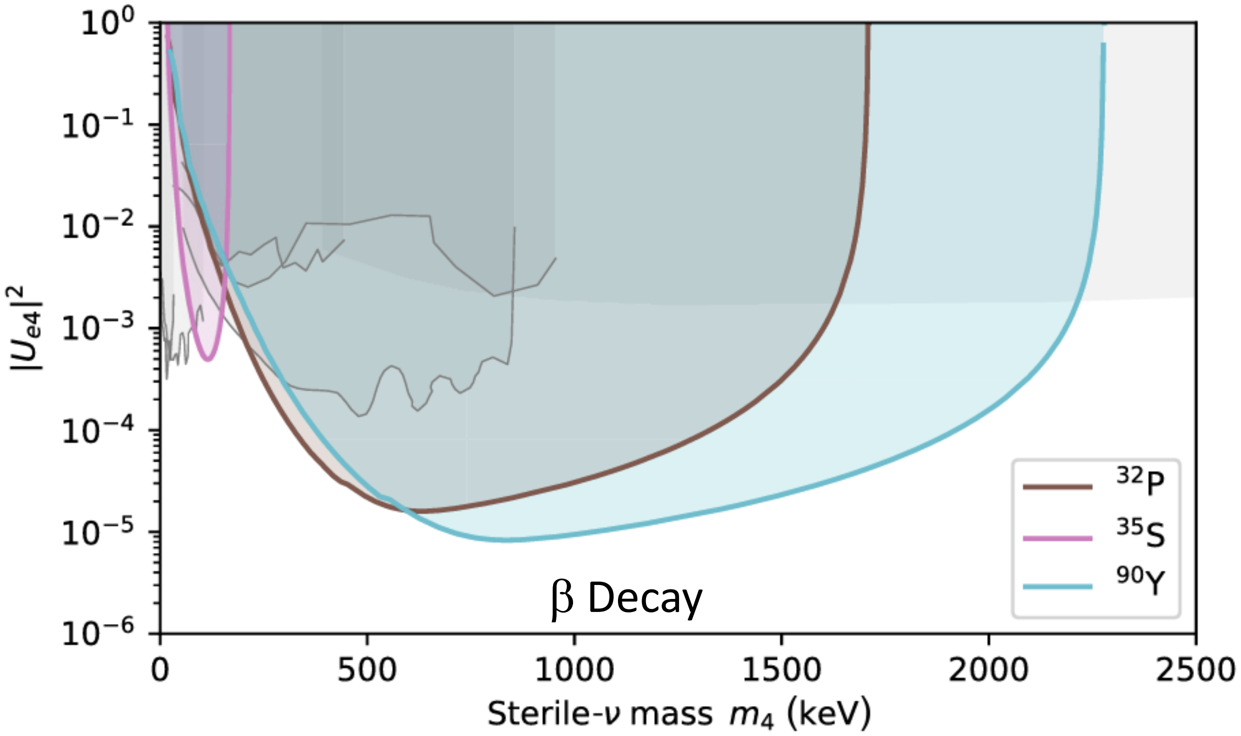
physics.yale.edu

Heavy (Mostly Sterile) Mass State Searches

- Single 100 nm diameter sphere
- 1 month measurement time
- 1% loading by mass of radioisotope







D. Carney, KGL, D.C. Moore, PRX Quantum **4**, 010315 (2023)

Conclusions

- Implanted rare isotopes in STJs and levitated nanospheres are a powerful tool for sub-keV nuclear decay spectroscopy

- Since 2018 we have done precision measurements in the EC decay of ^{7}Be – motivated primarily by heavy BSM neutrino searches (the BeEST experiment).

- Using STJs, we are able to measure radiation from ~2.5 eV to 1 keV with high precision

- We have extended the BeEST concept to develop the superconducting array for low-energy radiation (SALER) to perform nuclear recoil spectroscopy using short-lived RIBs on-line.

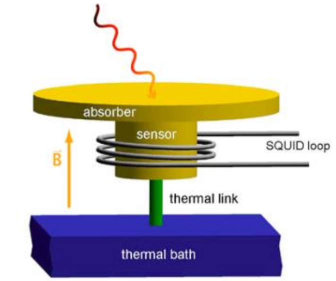
- The first step for SALER will be offline commissioning in Fall 2023 and first beam tests at FRIB in 2024

Backup Slides

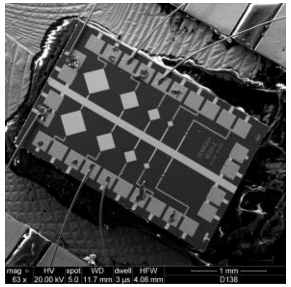
Cryogenic Charge vs. Thermal Sensors

	Charge Detectors (STJ)	Thermal Detectors (TES, MMC, etc.)
Operating principle	E ⟶ **ΔQ** ⟶ ΔI	E ⟶ **ΔT** ⟶ ΔM or ΔI ⟶ ΔV
Energy Resolution	$\Delta E = 2.355\sqrt{F\varepsilon E}$ **Scales with E** and energy gap Achieved: **1 - 10 eV FWHM**	$\Delta E = 2.355\sqrt{k_B T^2 C}$ **Scales with T** and detector volume Achieved: **<eV - keV FWHM**
Energy Suitability	**Photons: eV – keV**	**< 1 MeV photons**
	e-: eV – keV; heavy ions: eV – MeV	**e-: < few MeV; High-energy HI's**
Rate	**< 10,000 counts/s** per pixel	**~10 counts/s** per pixel
Operating T	~100 mK – (ADR -> Dil Fridge)	~10 mK – (Dil Fridge)
Readout	FET (300 K)	SQUID (4 K)

Magnetic Microcalorimeter (MMC)



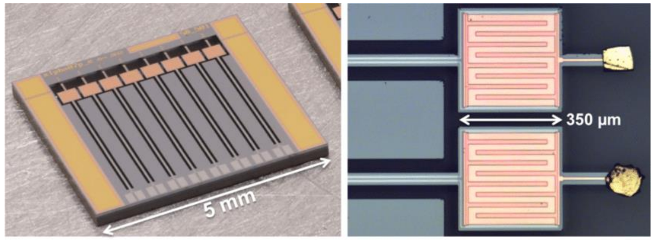
Superconducting Tunnel Junction (STJ)



- Both classes of detectors are currently being used for experimental nuclear physics from the eV to MeV scale and are characterized by their exceptionally high energy resolution

- Applications in NP thus far range from small-to-large scale neutrino physics experiments, low-energy nuclear structure (ie. ^{229}Th), geochronometry, and nuclear safeguards

Transition Edge Sensor (TES)



Slide Courtesy: Stephan Friedrich