

CPAD WORKSHOP · OCT 20, 2026 · SEATTLE, WA

Instrumentation for High Energy and Nuclear Physics at the University of Washington

Quentin Buat

Department of Physics and CENPA

W UNIVERSITY *of* WASHINGTON



CENPA
Center for Experimental
Nuclear Physics and Astrophysics
UNIVERSITY *of* WASHINGTON

Inside of the FN Tandem Van De Graaff accelerator at CENPA. Visible in the top half of the picture is the polished shield for the main high voltage terminal. The 9 MV terminal itself is supported by the original glass and metal column extending across the whole tank from the 1960s. The tank, usually closed and pressurised with a mixture of electrically insulating gases, is routinely opened by the staff to perform maintenance.

Our activities organized in four instrumentation themes

... and from lowest to highest energy scale

01

RF and quantum sensing

RDC 2 · 5 · 6 · 7 · 8

ADMX

Axion dark matter, cavity and quantum amplifiers

Project 8

Neutrino mass from cyclotron radiation emission spectroscopy (CRES)

He6-CRES

CRES as a precision β spectrometer

02

Single-charge imaging

RDC 1 · 3 · 7

DAMIC-M

Skipper CCDs counting single electrons

LEGEND

Germanium arrays for $0\nu\beta\beta$ decay

Selena

Selenium on CMOS pixel imagers

03

Tracking, calorimetry and triggering at high rate

RDC 3 · 4 · 5

PIONEER

Rare pion decays: calorimeter and active target

ATLAS

Carbon-composite support tubes for ITk

A3D3

Fast ML for triggering

04

Precision metrology

Eöt-Wash

Torsion balances testing gravity

01

RF and quantum sensing

ADMX

Axion dark matter, cavity and quantum amplifiers

Project 8

Neutrino mass from cyclotron radiation emission spectroscopy (CRES)

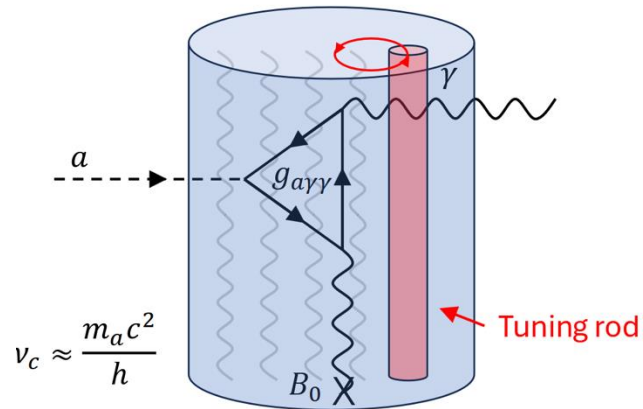
He6-CRES

CRES as a precision β spectrometer

ADMX

Hearing axion dark matter as microwave photons

- Axions convert to photons in a 7.6 T field; a tunable 136-liter copper cavity resonantly enhances the signal
- **Quantum-limited readout with a flux-biased Josephson parametric amplifier**



GHz EM field with 10^{-23} W power
(~ 10 μeV axion masses)



ADMX
AXION DARK MATTER EXPERIMENT

The ADMX insert is being extracted from the magnet bore and moved into the clean room for testing and repairs of the quantum electronics package.

ADMX

Hearing axion dark matter as microwave photons

- Axions convert to photons in a 7.6 T field; a tunable 136-liter copper cavity resonantly enhances the signal
- **Quantum-limited readout with a flux-biased Josephson parametric amplifier**

Cyclotron Radiation Emission Spectroscopy

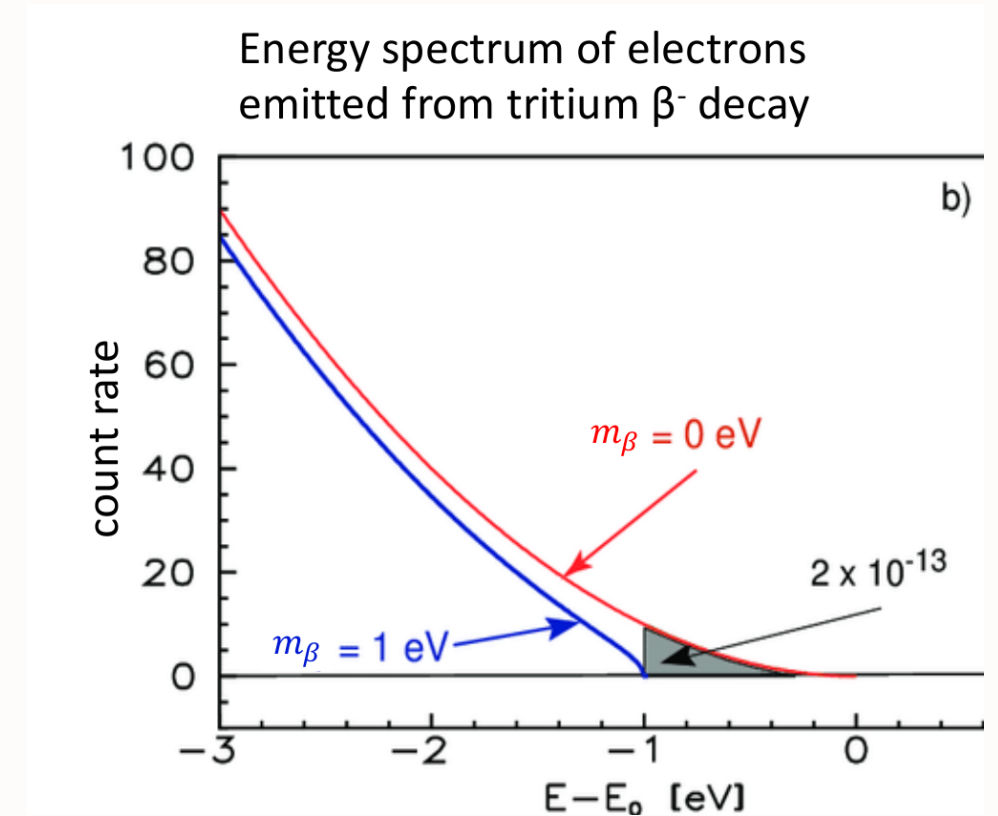
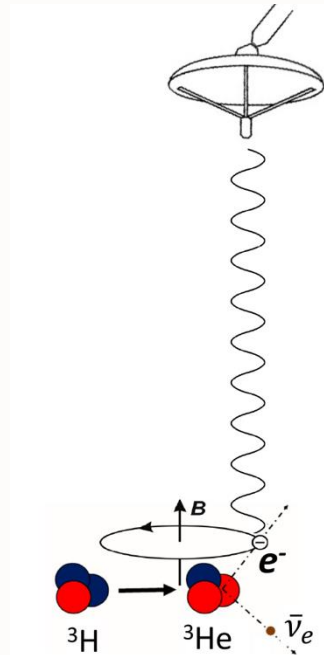
Measuring electron energy as a frequency

PROJECT 8

$$f = eB / 2\pi(m_e + E/c^2)$$

Trap β electrons in a magnetic bottle and record their fW cyclotron radiation

Project 8 goal: measure neutrino mass ($m_\beta^2 = \sum |U_{ei}|^2 m_i^2$) with < 40 meV precision to address the mass hierarchy question



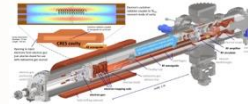
PROJECT 8

EXPERIMENTAL CHALLENGES

To reach sensitivity goal, need about 1000 m³ of tritium:

- Move from waveguide to a cavity (CCA)
- Scale to a large apparatus for deployment (LFA)
- Use atomic tritium instead of molecular tritium to avoid smearing of the beta spectrum

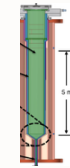
R&D UNDER WAY



Cavity CRES Apparatus (CCA): precision

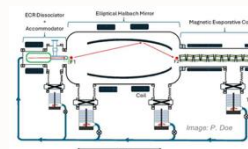
26 GHz cavity in a 1 T MRI magnet at CENPA; target ~0.3 eV FWHM; final commissioning

Contributions A. Kurnus (poster) · P. Kolbeck, ³He NMR (poster)



Low-Frequency Apparatus (LFA): scale

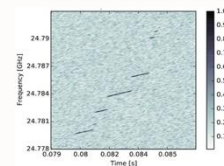
1.5 m³ cavity at 560 MHz, 0.02 T: first CRES in a large volume, later with atomic T



Atomic tritium source

ECR dissociator, magnetic guiding and evaporative cooling, to avoid T₂ final-state smearing

Contribution M. Wynne, beam diagnostics (poster)



Triggering and reconstruction

Real-time models to find CRES tracks: frequency chirps, with jumps at each scatter

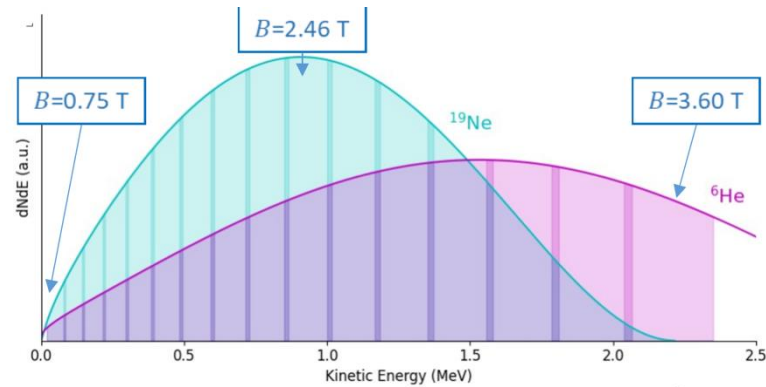
Contribution Y. Yin, state-space model for CRES (talk)

He6-CRES

CRES 'Spin-off' application

MEASUREMENT GOAL

β -energy spectra of ${}^6\text{He}$ to search for spectral distortion



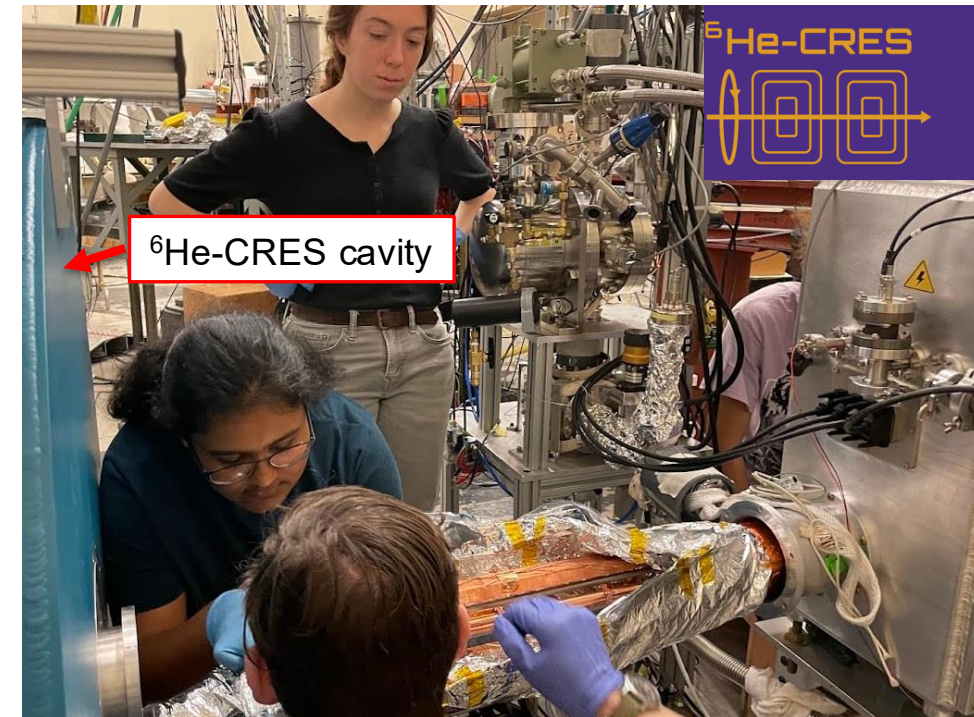
$$dN/dE \propto (\text{SM spectrum}) \times (1 + \mathbf{b} \cdot \mathbf{m}_e/E)$$

Experiment performed using UW in-house VdG accelerator

Sensitivity goal: shape deviation of 1 part in 1000

Requires precise control of the detector efficiency over a wide range of frequencies

UW tandem Van de Graaff produces ${}^6\text{He}$



02

Single-charge imaging

DAMIC-M

Skipper CCDs counting single electrons

LEGEND

Germanium arrays for $0\nu\beta\beta$ decay

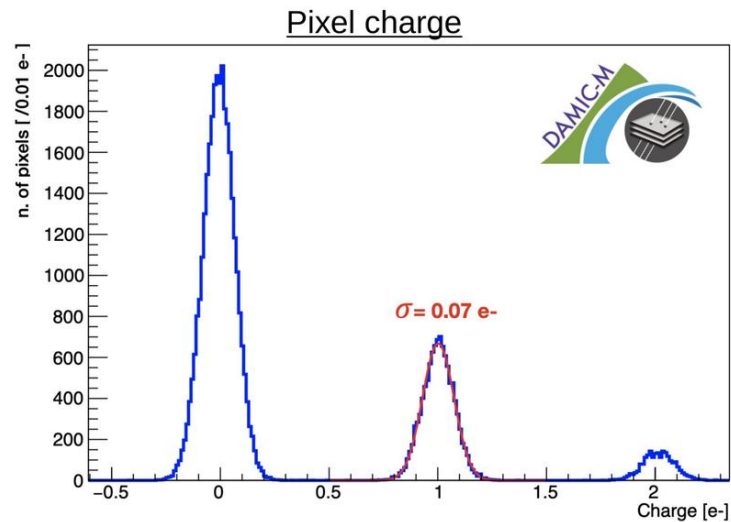
Selena

Selenium on CMOS pixel imagers

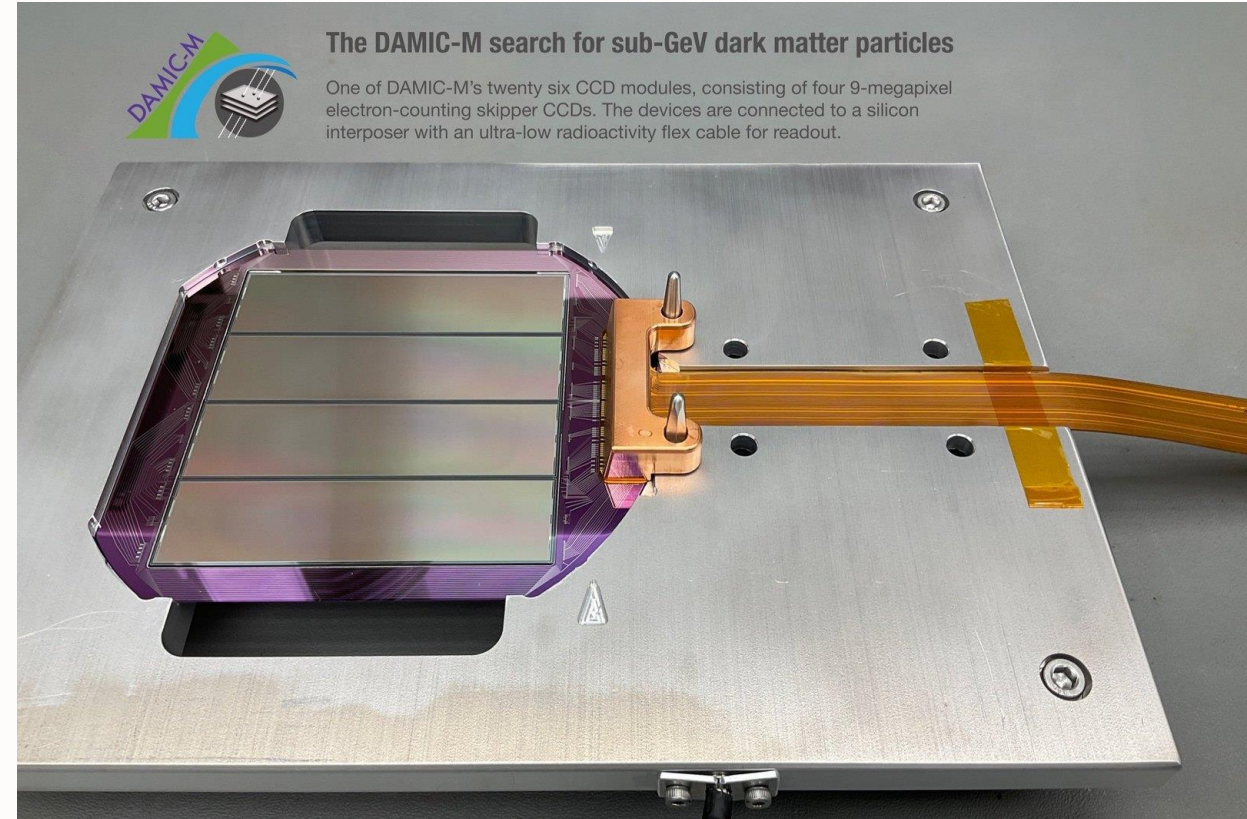
Skipper CCDs for DM search

The DAMIC experiment

- Skipper readout measures each pixel's charge repeatedly: single-charge sensitivity
- 2024 at UW: tested 188 CCDs, best ones built into 28 modules, now taking data at LSM lab in Modane
- ~1 gigapixel, for kg-year exposures
- **Most stringent Light Dark Matter limits to date in the 10-100 MeV/c regime**



Most sensitive device to the interactions
between sub-GeV DM and atoms

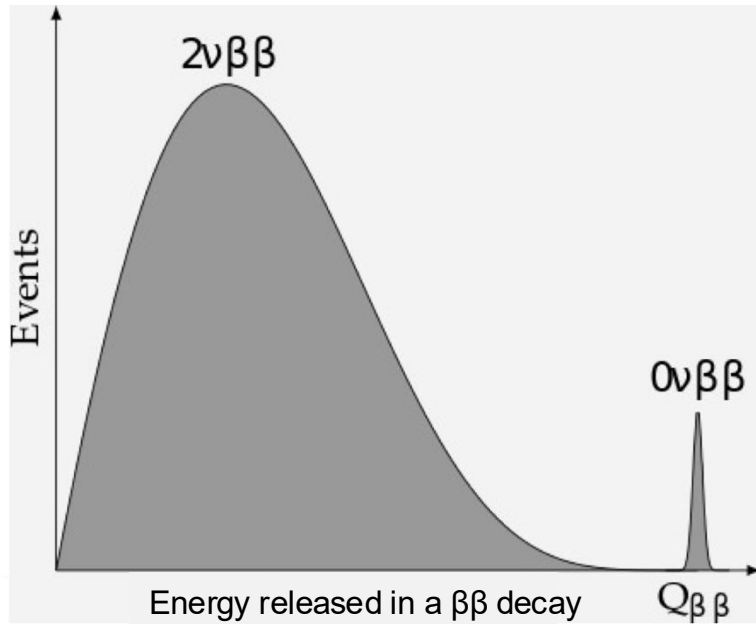


Searching for $0\nu\beta\beta$ decay

Semiconductor as a source and a detector

LEGEND: Enriched ^{76}Ge crystal

Selena: Amorphous ^{82}Se CMOS sensor



Experimental challenges

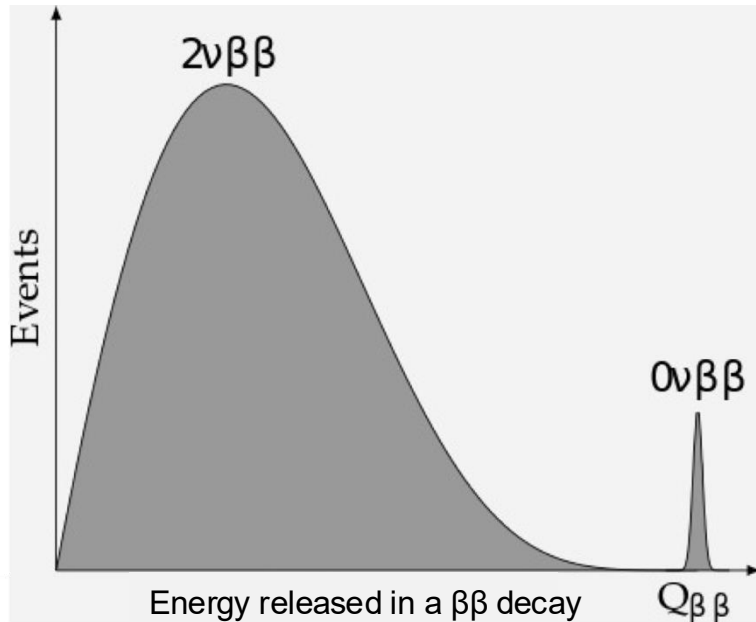
- Must achieve $<0.1\%$ FWHM resolution on $Q(\beta\beta)$
- Large scale apparatus for statistics
- Shielding and experimental background suppression

Searching for $\nu\bar{\nu}\beta\beta$ decay

Semiconductor as a source and a detector

LEGEND: Enriched ^{76}Ge crystal

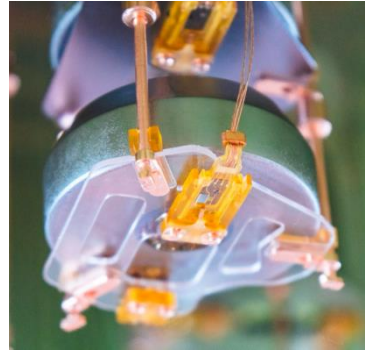
Selena: Amorphous ^{82}Se CMOS sensor



Experimental challenges

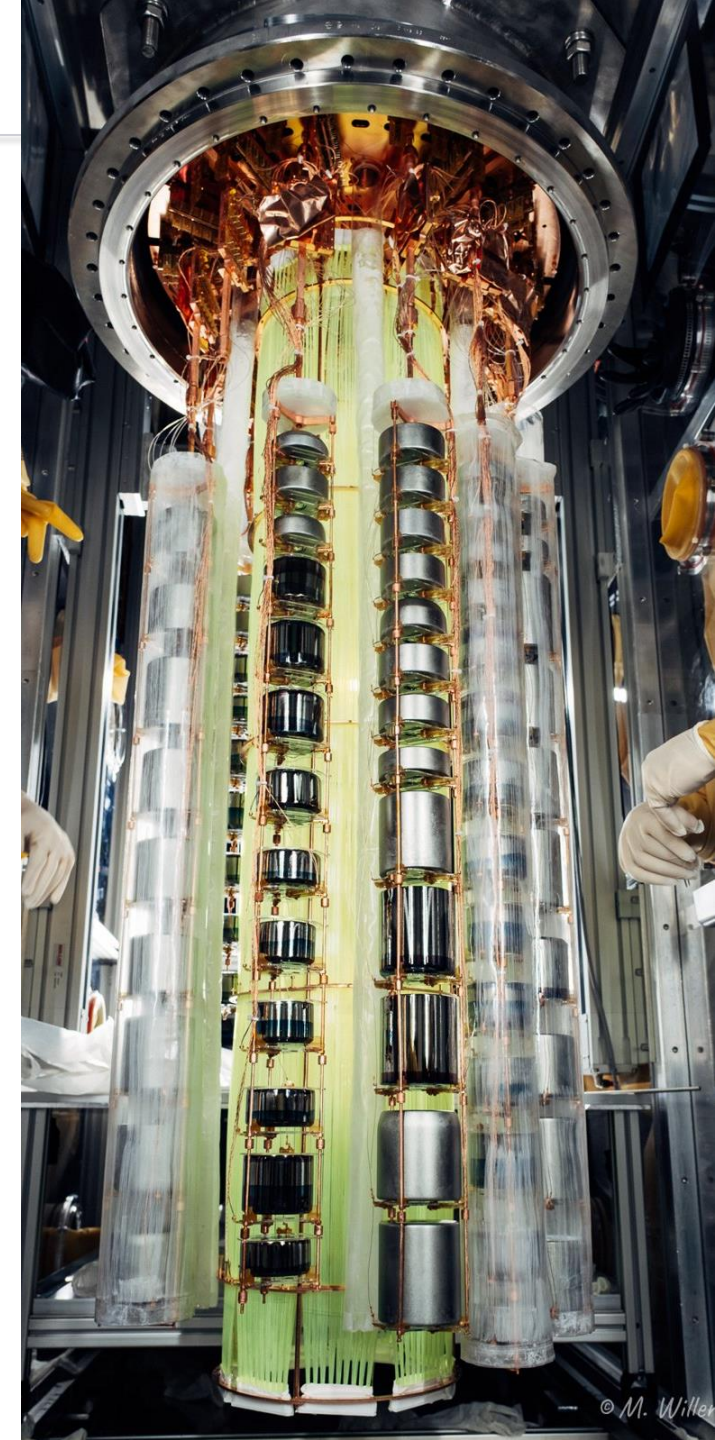
- Must achieve $<0.1\%$ FWHM resolution on $Q(\beta\beta)$
- Large scale apparatus for statistics
- Shielding and experimental background suppression

LEGEND



^{76}Ge cell

Major UW contribution
LEGEND lock system
to efficiently cycle
through ^{76}Ge strings

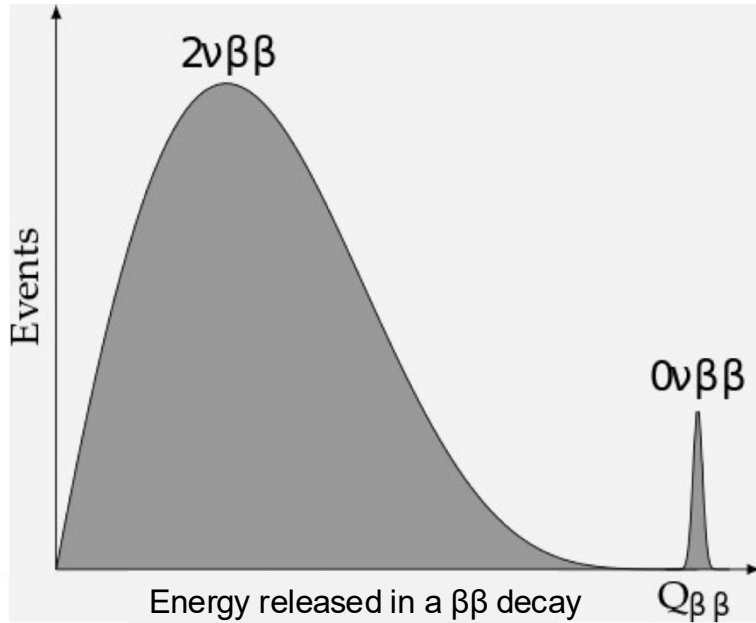


Searching for $\nu\beta\beta$ decay

Semiconductor as a source and a detector

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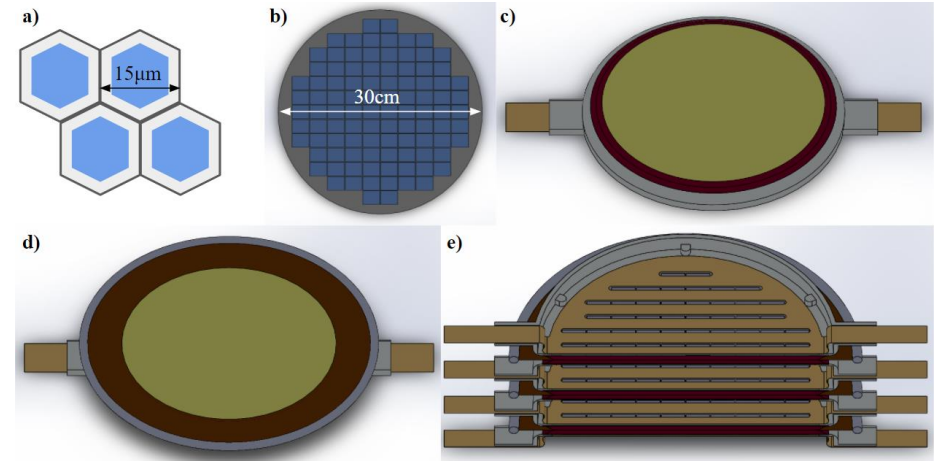


Experimental challenges

- Must achieve $<0.1\%$ FWHM resolution on $Q(\beta\beta)$
- Large scale apparatus for statistics
- Shielding and experimental background suppression

SELENA

a 10-ton ^{82}Se active target of hybrid CMOS imagers with ~ 5 mm aSe layers

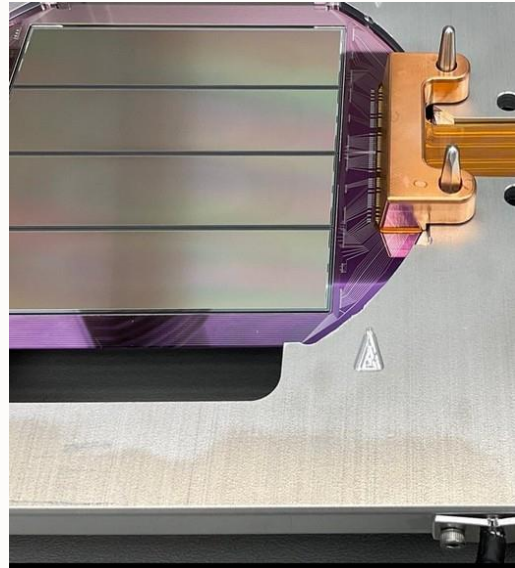


Leverages industrial CMOS fabrication and aSe deposition to scale

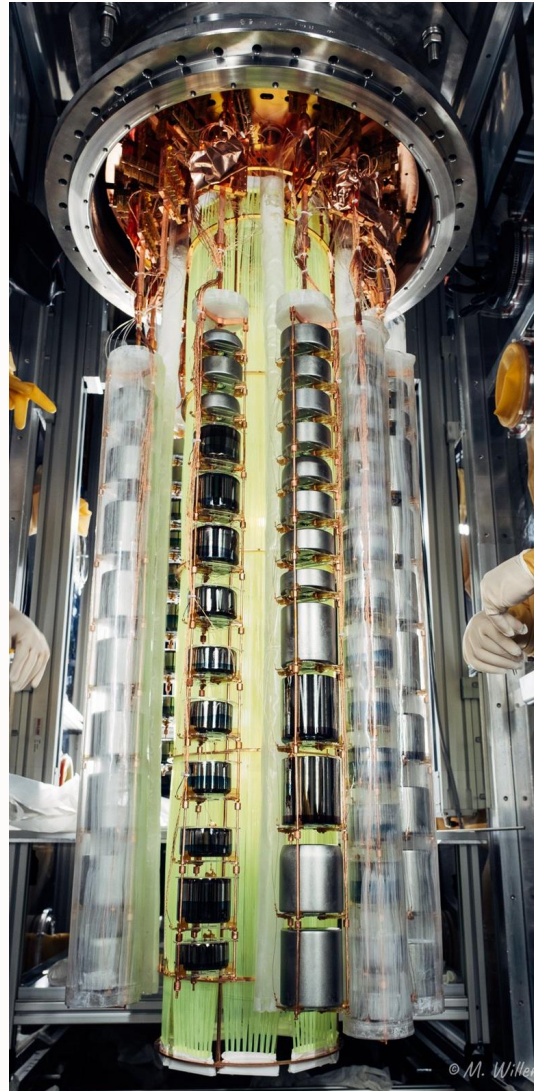
Bragg-peak ID suppresses single-electron background by 10^{-3} at 50% acceptance

R&D with small pixelated devices:
 $\sim\text{MeV}$ electron tracks imaged

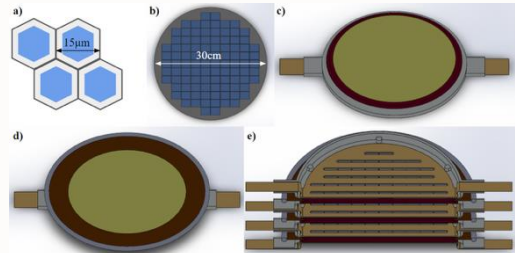
DAMIC-M



LEGEND



SELENA



UW CONTRIBUTIONS AT CPAD 2026

DAMIC-M

The DAMIC-M CCD Array

Contribution A. Chavarria (talk)

RDC 7 Low-Background Detectors · Tue 20 Oct, 15:40

SELENA

The Selena Packaging Trajectory

Contribution E. L. Solis (talk)

RDC 3 Solid State Tracking · Wed 21 Oct, 17:50

ARGON R&D

Development of a Liquid Argon Purity Monitor Utilizing Electron Drift

Contribution S. Bellman (talk)

RDC 1 Noble Element Detectors · Tue 20 Oct, 16:47

ARGON R&D

Study of scintillation properties of solid argon

Contribution C. Savarese (talk)

RDC 1 Noble Element Detectors · Tue 20 Oct, 14:00

03

Tracking, calorimetry
and triggering at high
rate

ATLAS ITk

Carbon-composite support tubes

PIONEER

Rare pion decays: calorimeter and active target

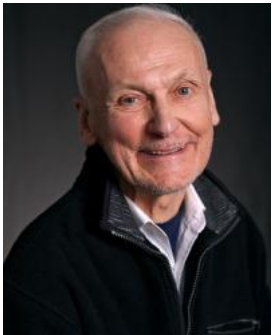
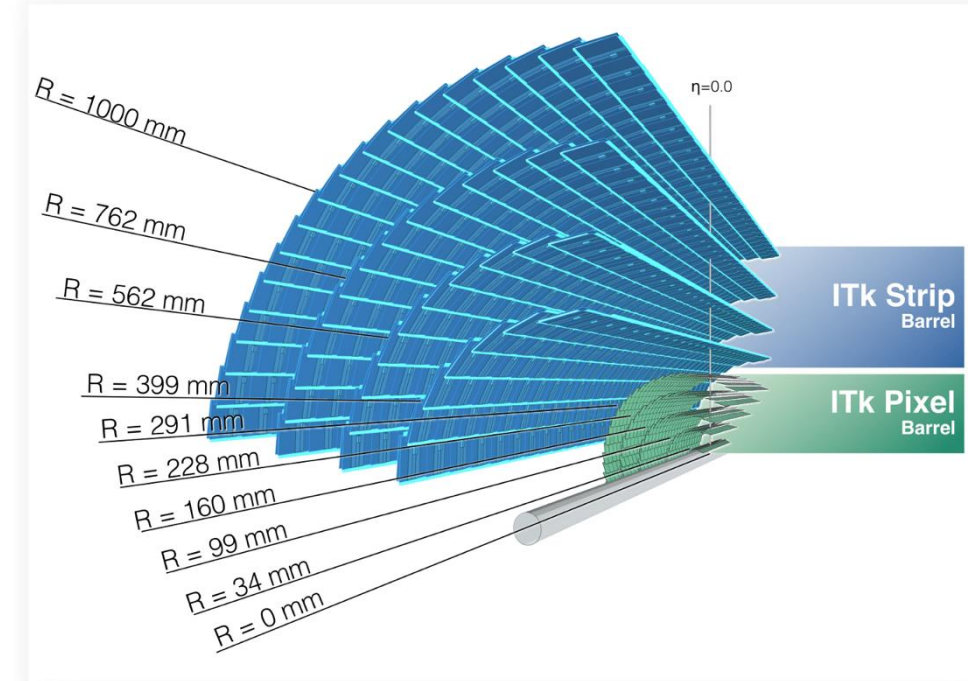
A3D3

Real-time AI on FPGAs and GPUs

Tracking – Mechanical support

Large-scale carbon-composite support tubes for the HL-LHC Inner Tracker of the ATLAS experiment (ITk)

- UW built two innermost ITk tubes:
 - IST for the Inner Pixel System,
 - IPT for the beampipe
- Five sections each, made in the UW ME composites lab (2025)
- Alignment tooling from the UW physics machine shop



IN MEMORIAM

Henry Lubatti

1937 – 2026

Special session on Thursday morning

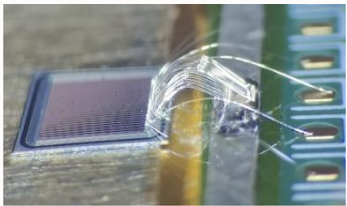


5D Tracking with LGADs

Measure energy, time and position with thin silicon strips

Bespoke and challenging requirements of PIONEER

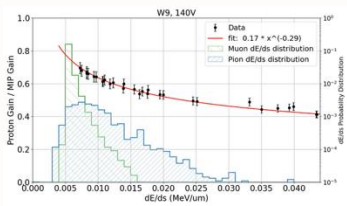
- 4800 channels in a 20 X 20 X 6mm³ volume
- About 2 ns pulse-pair resolution
- 1000X dynamic range
- Long analog lines to measure energy
- O(100μm) position determination



ATAR-8: first ATAR prototype

8 planes, ~500 channels: Ti-LGADs from FBK, FAST3 front-end boards from UW; PSI test beam in fall 2026

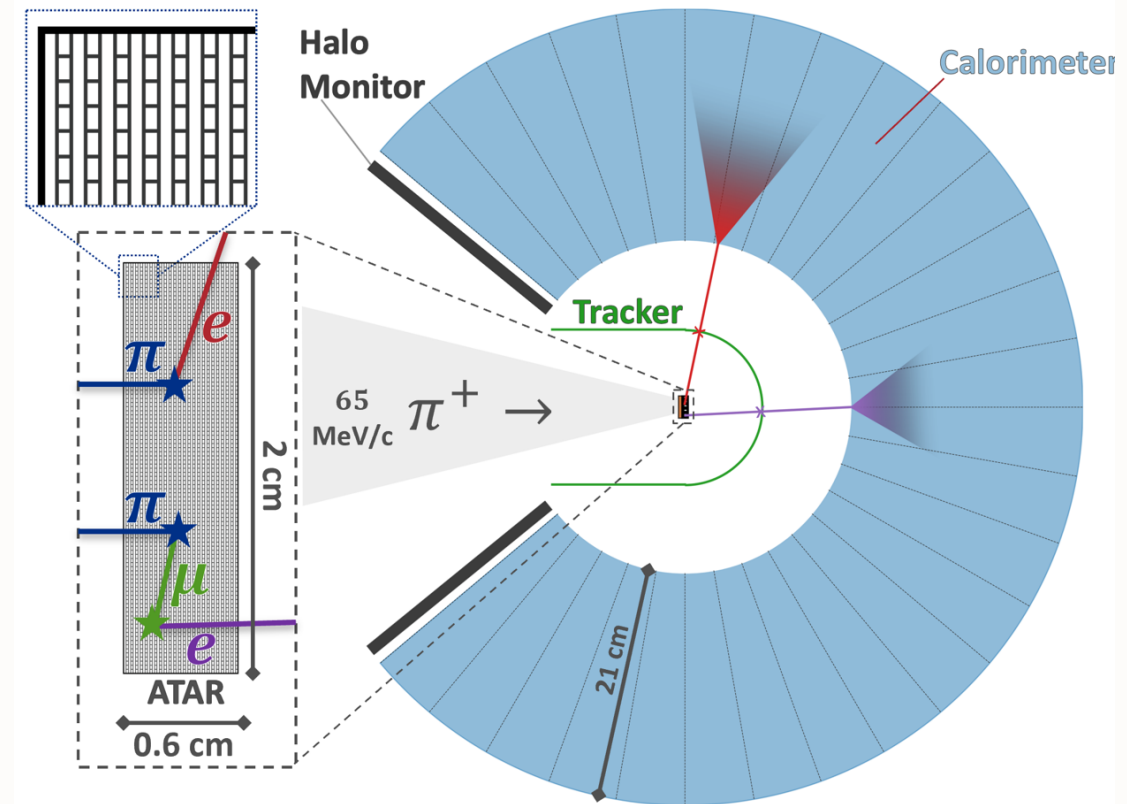
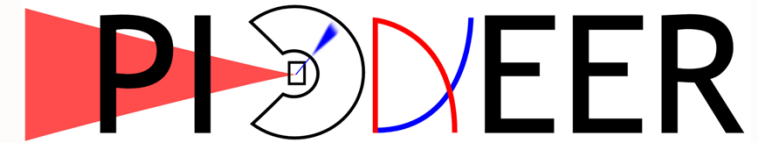
Contribution F. Gray (talk)



LGAD gain saturation

Gain for highly ionizing particles drops with dE/ds; measured with protons across the pion and muon range

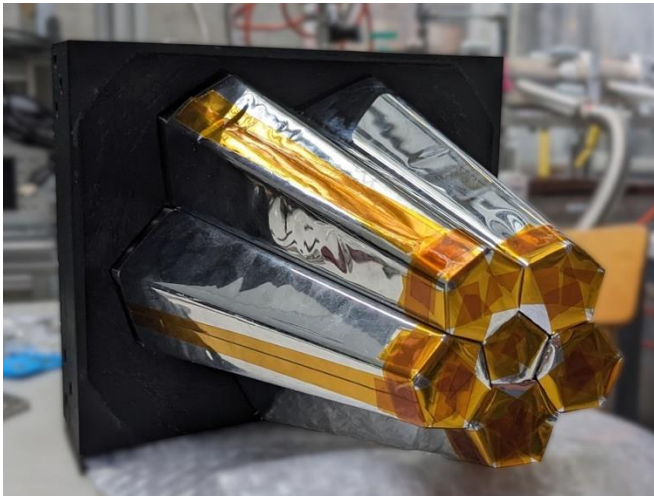
Contribution J. Yang (talk)



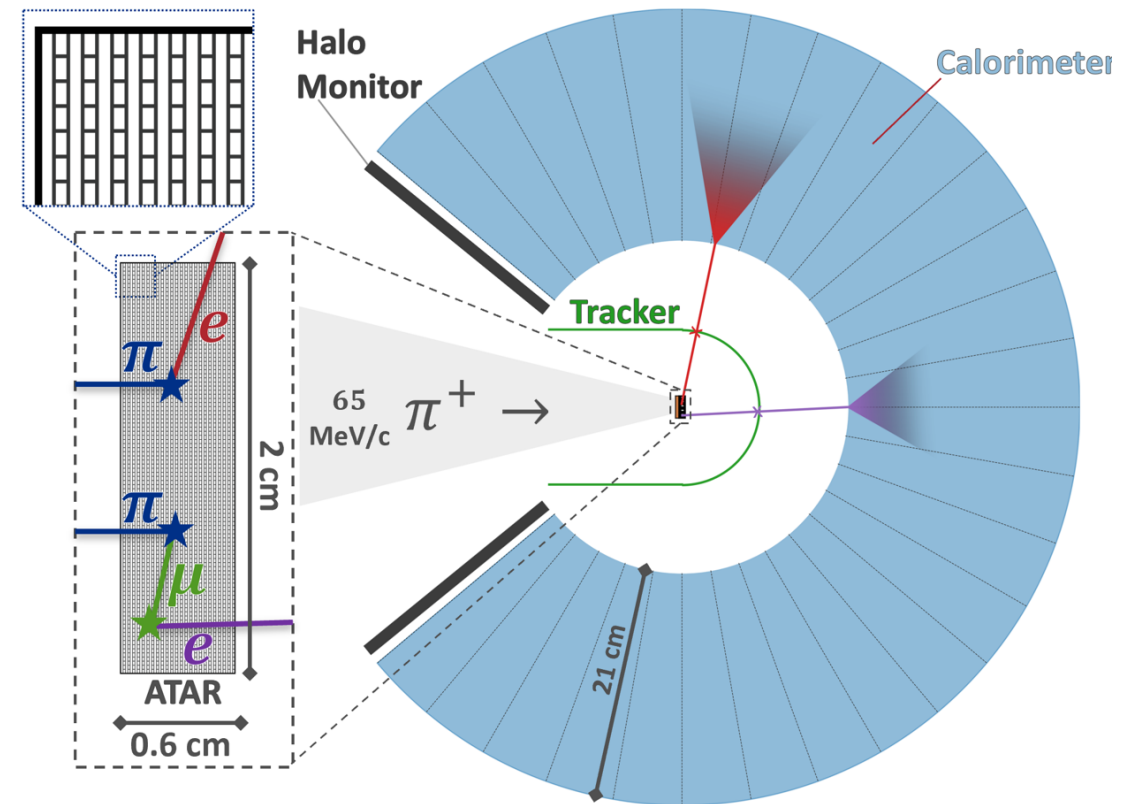
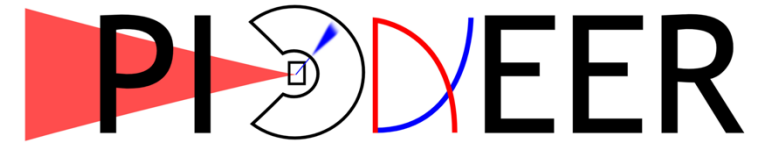
Calorimetry

LYSO has fast ($<50\text{ns}$) light collection, ideal for high rate experiments

- Group expertise carried from the Muon $g-2$ experiment
- 311 of the largest LYSO crystals ever grown, $19 X_0$
- 2023 and 2025 test beams: $\leq 2\%$ at 70 MeV, 100 ps
- Crystals retain satisfactory linearity after tapering
- Final crystal shapes meet spec



Tapered array characterize in 2025 test beam at PSI
arXiv:2607.09226 (submitted to JINST)





A3D3: real-time AI for science

Fast machine learning on FPGAs and GPUs, led from UW

A3D3 INSTITUTE

- NSF Harnessing the Data Revolution institute, launched in 2021: nine universities, led by UW
- Mission: real-time AI at scale, co-designing algorithms with FPGAs and GPUs
- Science drivers: high energy physics, multi-messenger astrophysics and neuroscience
- Tools: AI inference as a service on heterogeneous computing; FPGA inference for triggers and detectors

40 MHz

LHC collision rate that A3D3 tools aim to process in real time

GPU tracking as a service

Keeping GPU tracking-as-a-service in sync with ATLAS Athena software through shared memory

Technology selected by ATLAS for the Run 4 HLT farm

Contribution O. Huang (poster)

4D Fabric: a NIFTY pixel readout chip

Simulation of a fault-tolerant, network-based 4D pixel ROC

Contribution C. Ceravolo (poster)

04

Precision metrology

Eöt-Wash

Torsion balances testing gravity

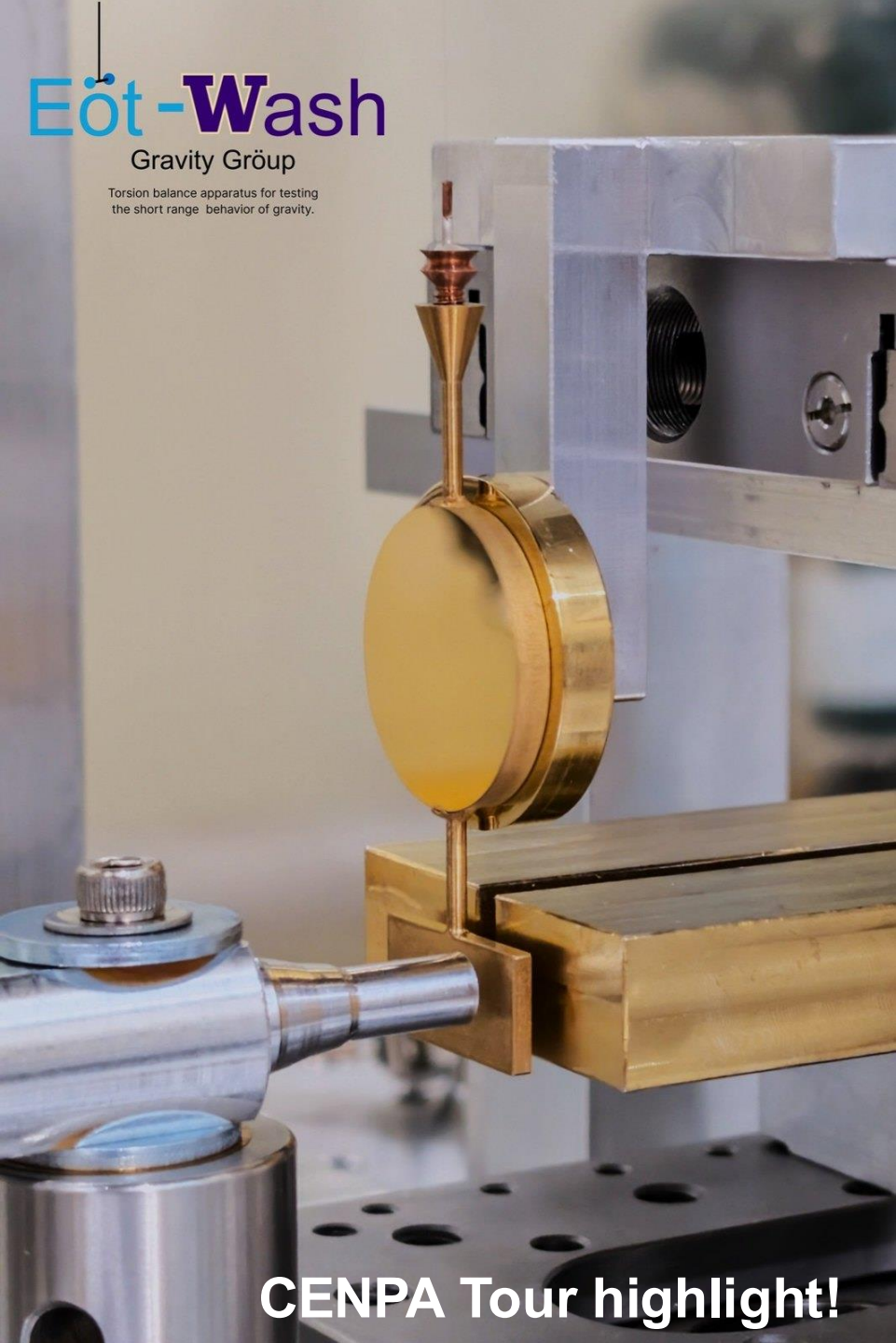
Eöt-Wash Gravity Lab

Measuring forces far weaker than gravity

- **Fundamental Physics:**
 - Most sensitive equivalence principle test using a rotating torsion balance
 - Long range dark matter–ordinary matter coupling $\leq 2.6 \times 10^{-5}$ of gravity
 - Next: testing the inverse-square law of gravity down to 20 μm separations
- **Instrumentation:**
 - Developing ground rotation sensors to support LIGO
 - Sensors for rotational seismometry

$\eta \leq 2.1 \times 10^{-13}$ Limit on equivalence-principle violation toward the Sun (Be–Al)

$$G = (6.674125 \pm 0.000092) \times 10^{-11} \text{ m}^3/\text{kg}/\text{s}^2$$



OUR CAMPUS

Facilities

CENPA

Center for Experimental Nuclear Physics and Astrophysics

UW Physics main instrumentation facility
Hosts ADMX and our VdG accelerator

Tour on Friday afternoon

WNF · Fluke Hall

WASHINGTON NANOFAB FACILITY

Largest nanofabrication facility in the Pacific Northwest

Tour on Wednesday and Thursday

PHYSICS & ASTRONOMY BUILDING

Hosts the CCD packaging lab, and Project 8 in the basement lab space

Physics & Astronomy

CPAD Venue

Instrumentation in HENP at the University of Washington

- 1 Precision through frequency
CRES, cavity haloscopes
- 2 Single-quantum sensitivity
Single electrons in CCDs, single microwave photons
- 3 Ultra-low backgrounds
CCDs, germanium and selenium in clean environments
- 4 Precision at high rate
LYSO calorimetry and LGAD 5D tracking; Fast ML (A3D3), ATLAS ITk mechanics

UW CONTRIBUTIONS AT THIS WORKSHOP

ADMX O. Kim · K.ENZIAN · M. Carhart · J. Sinnis (talks)

Project 8 Y. Yin (talk) · M. Wynne, P. Kolbeck, A. Kurmus (posters)

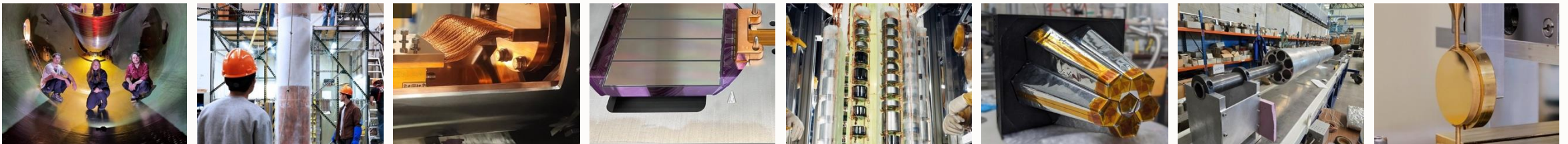
DAMIC-M A. Chavarria (talk)

Selena E. L. Solis (talk)

PIONEER F. Gray · J. Yang (talks)

A3D3 (Fast ML) O. Huang · C. Ceravolo (posters)

Legend S. Bellman · C. Savarese (talks)



Backup

ADDITIONAL SLIDES

CENPA · WNF · ADMX · DAMIC-M · LEGEND ·
PIONEER

CENPA

1948

Nuclear Physics Lab
founded; CENPA since
1998

DOE

Center of Excellence;
Nuclear Physics core grant

9 MV

Tandem Van de Graaff, in
service since 1966

BUILD

Design, machining and electronics in-house

28 DAMIC-M CCD modules · LEGEND-1000 argon lock · KATRIN
detector · PIONEER ATAR boards · Project 8 e-gun

TEST

A local tandem beam plus test stands

He6-CRES ^{19}Ne , ^{79}Kr · PIONEER LGADs · LEGEND ^{41}Ar , ^{56}Co ·
SiPM and Ge scanners

TRAIN

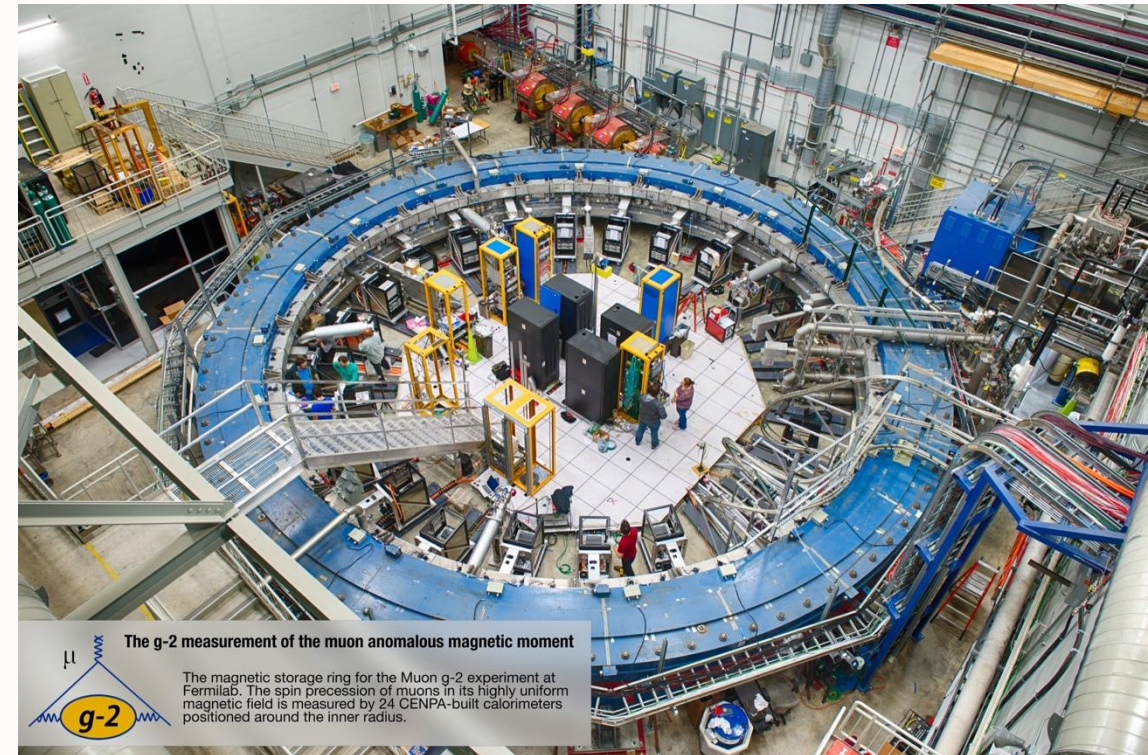
~20 graduate students

Students operate the accelerator, have access to the machining and
welding, clean rooms, etc.

Across campus UW Physics: ITk readout (ATLAS) · CCD packaging lab (DAMIC)

Muon g-2

Shared by the Brookhaven and Fermilab collaborations, including the
UW team; the spin precession is measured by 24 CENPA-built
calorimeters.



Earlier prizes 2021 Eöt-Wash · 2016 SNO, KamLAND

Washington Nanofabrication Facility

A campus clean room open to detector R&D, in Fluke Hall

THE FACILITY

- Largest nanofabrication facility in the Pacific Northwest
- \$37.5M renovation in 2017: 3× larger and 1000× cleaner
- Publicly accessible: 144 academic and 105 industry users

FOR DETECTOR DEVELOPMENT

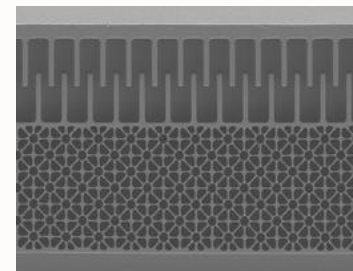
- Prototype sensors and microstructures in-house: MEMS, silicon photonics, microfluidics
- Work on site after training, or have staff engineers run your process flow
- Staff consultations help scope a new project

15,000 ft²

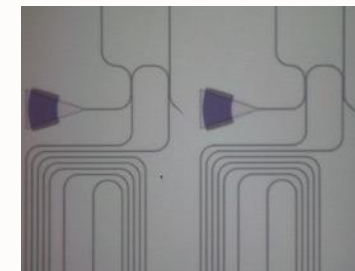
Lab, clean-room and user space

ISO 5–7

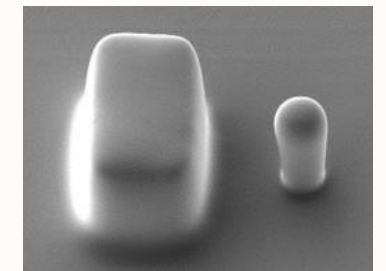
Clean-room classes



MEMS



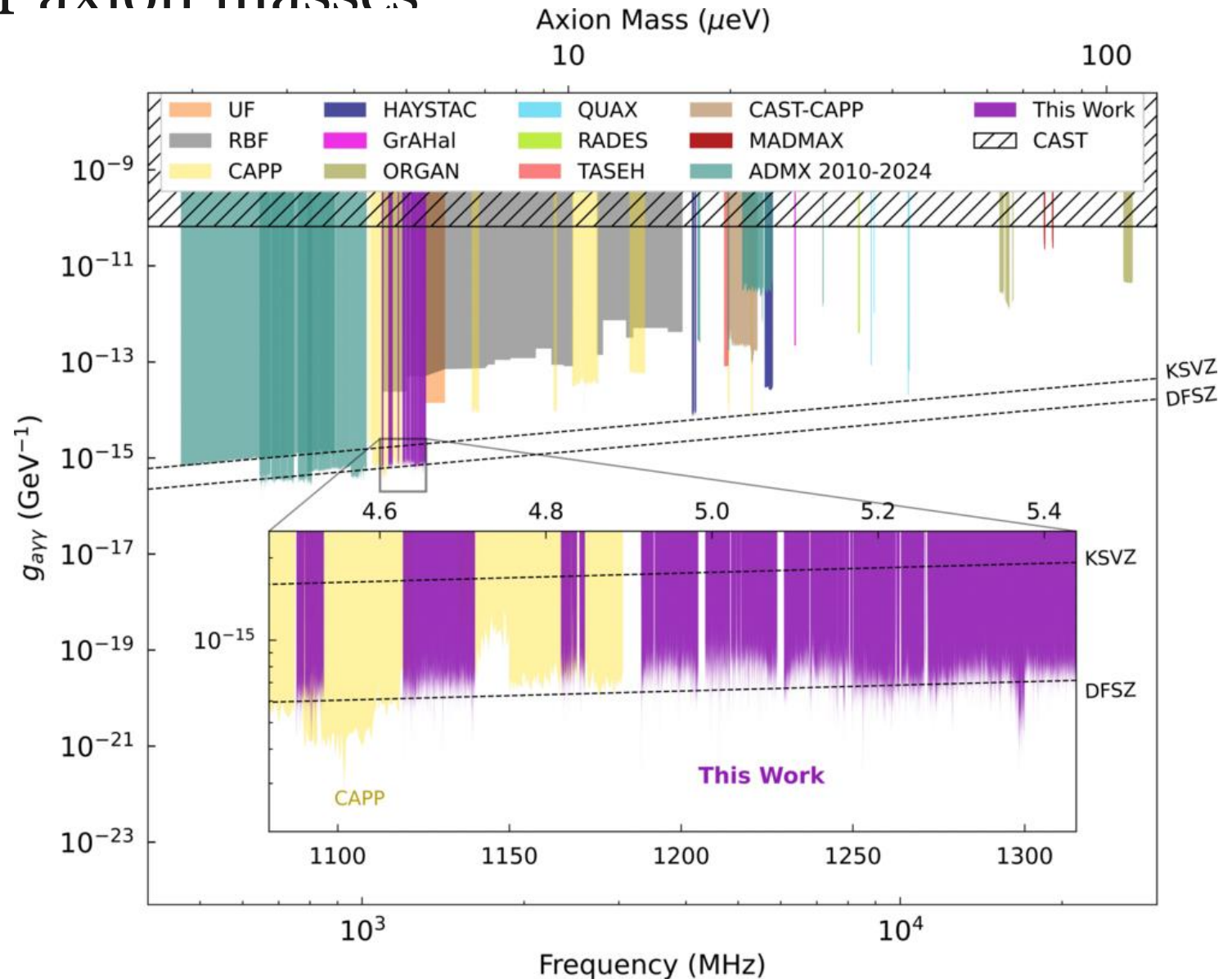
Silicon photonics



Microfluidics

ADMX: pushing to higher axion masses

ADMX was the first experiment to reach DFSZ sensitivity



ADMX 2024 exclusion: Carosi et al.,
PRL (2025)

Project 8

PROJECT 8

Measuring electron energy as a frequency: CRES for neutrino mass

- Trap β electrons from ^3H decay in a magnetic bottle and record their $\sim\text{fW}$ cyclotron radiation

$$f = eB / 2\pi(m_e + E/c^2)$$

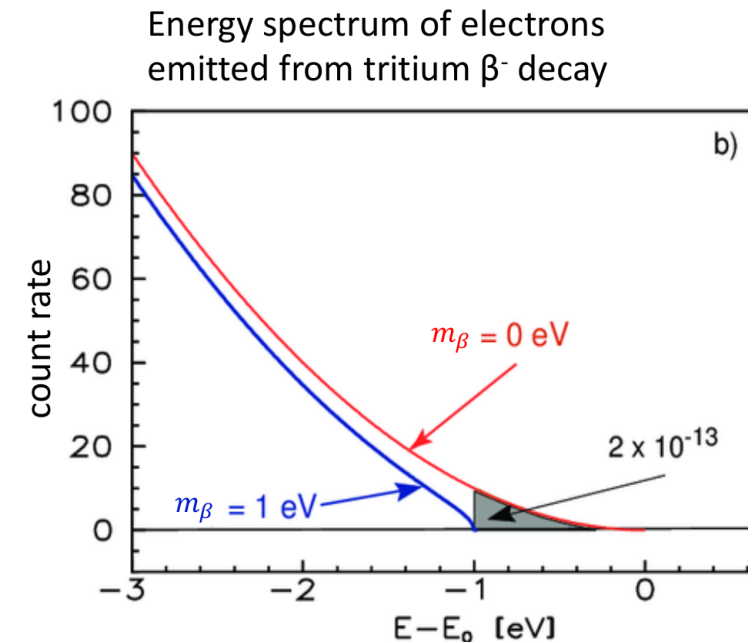
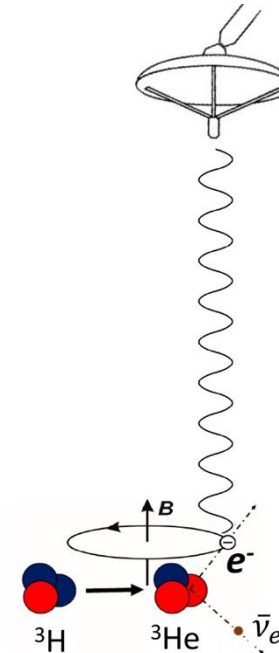
The frequency gives each electron's kinetic energy E ; the spectrum's shape just below the endpoint E_0 constrains m_β

ACHIEVED

- KATRIN: CENPA-built detector ran all 1,000 days
- Phase I (2015): first single-electron cyclotron radiation
- Phase II at CENPA (T_2): 1.7 eV FWHM, $m_\beta < 155$ eV
- No background events above the endpoint
- Gas is both source and detector: no electron transport

PLANNED

- Phase III: ~ 0.3 eV resolution (CCA), m^3 volumes (LFA), atomic tritium
- Phase IV: ~ 1000 m^3 of atomic tritium, m_β sensitivity of 40 meV

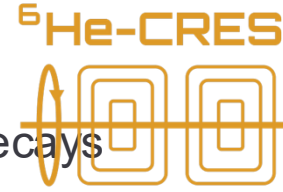


40 meV

Phase IV target sensitivity on m_β , where $m_\beta^2 = \sum |U_{ei}|^2 m_i^2$; below ~ 50 meV it tests the neutrino mass ordering

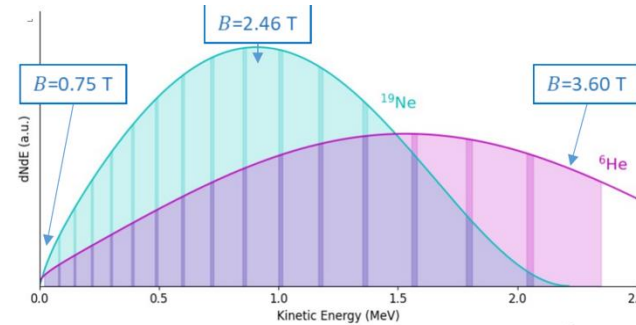
He6-CRES

Probing physics beyond the TeV scale with nuclear β decays



MEASUREMENT

The full β -energy spectra of ${}^6\text{He}$ (β^-), fitted for the Fierz term $\mathbf{b}$: a spectral distortion $\propto m_e/E$



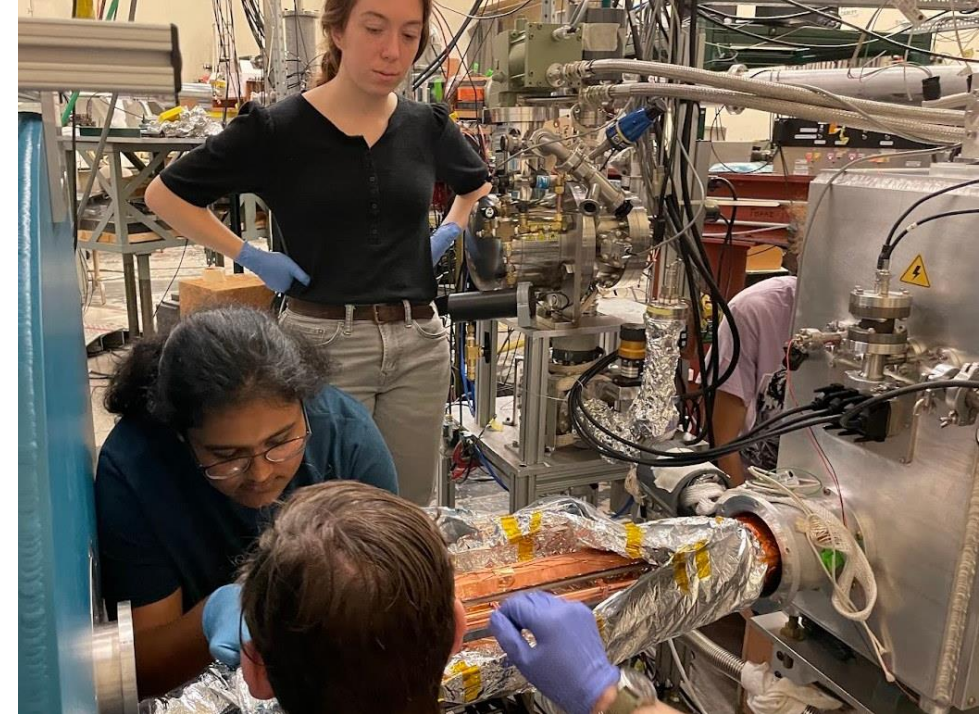
$$dN/dE \propto (\text{SM spectrum}) \times (1 + \mathbf{b} \cdot m_e/E)$$

- A non-zero Fierz term would indicate chirality-flipping (scalar, tensor) currents from TeV-scale physics
- Search for spectral deviation in the ${}^6\text{He}$ (β^-) spectrum, use ${}^{19}\text{Ne}$ (β^+) as control channel
- CRES measures each β energy at creation, with no scattering background
- Isotopes from the CENPA tandem; can couple to ion traps at FRIB, GANIL, TRIUMF

Expressing results on $\epsilon(T)$, the strength of a BSM tensor interaction

Statistics in hand for $\epsilon(T) < 10^{-2}$, analysis in progress.

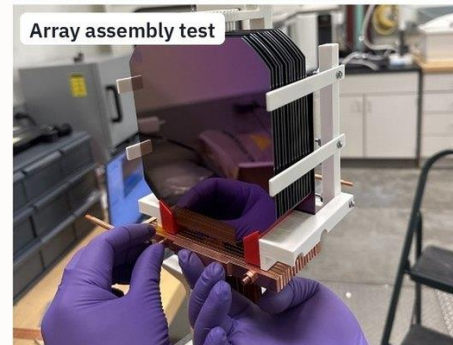
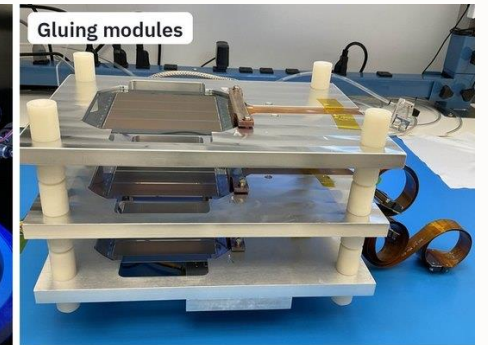
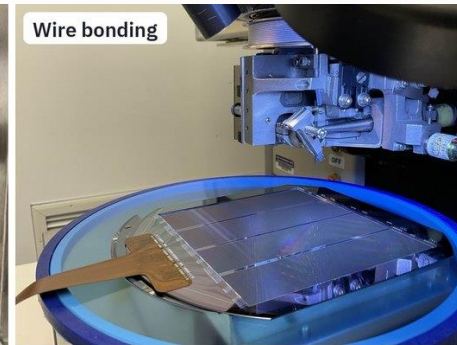
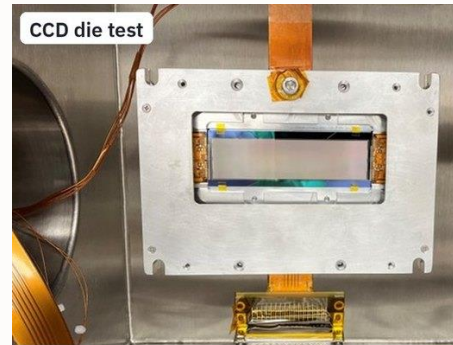
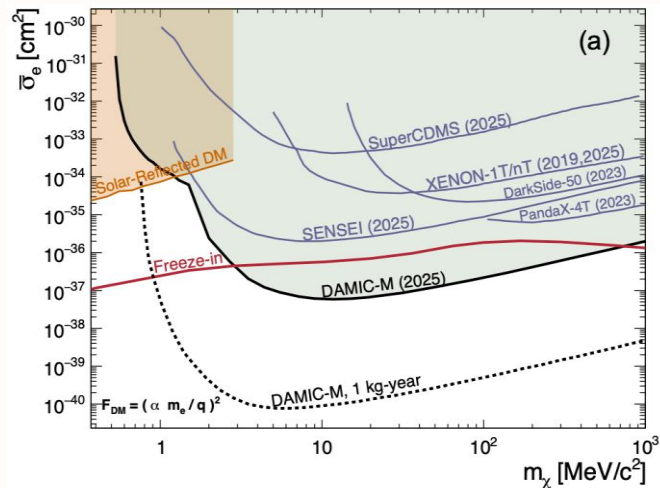
Planned beam upgrades to reach 10^{-3} in a 1-week run



DAMIC-M: modules built at UW

From CCD testing in Seattle to a low-background array at LSM

- 2024 at UW: tested 188 CCDs, best ones built into 28 modules, now at LSM
- Shielded transport, radon-free storage, clean-room operations
- Low-radioactivity flexes, underground copper, light-tight IR shield
- 20× reduction in ^3H activation



arXiv:2509.06943; PRD 102, 102006 (2020); NIMA 959, 163573 (2020)

LEGEND

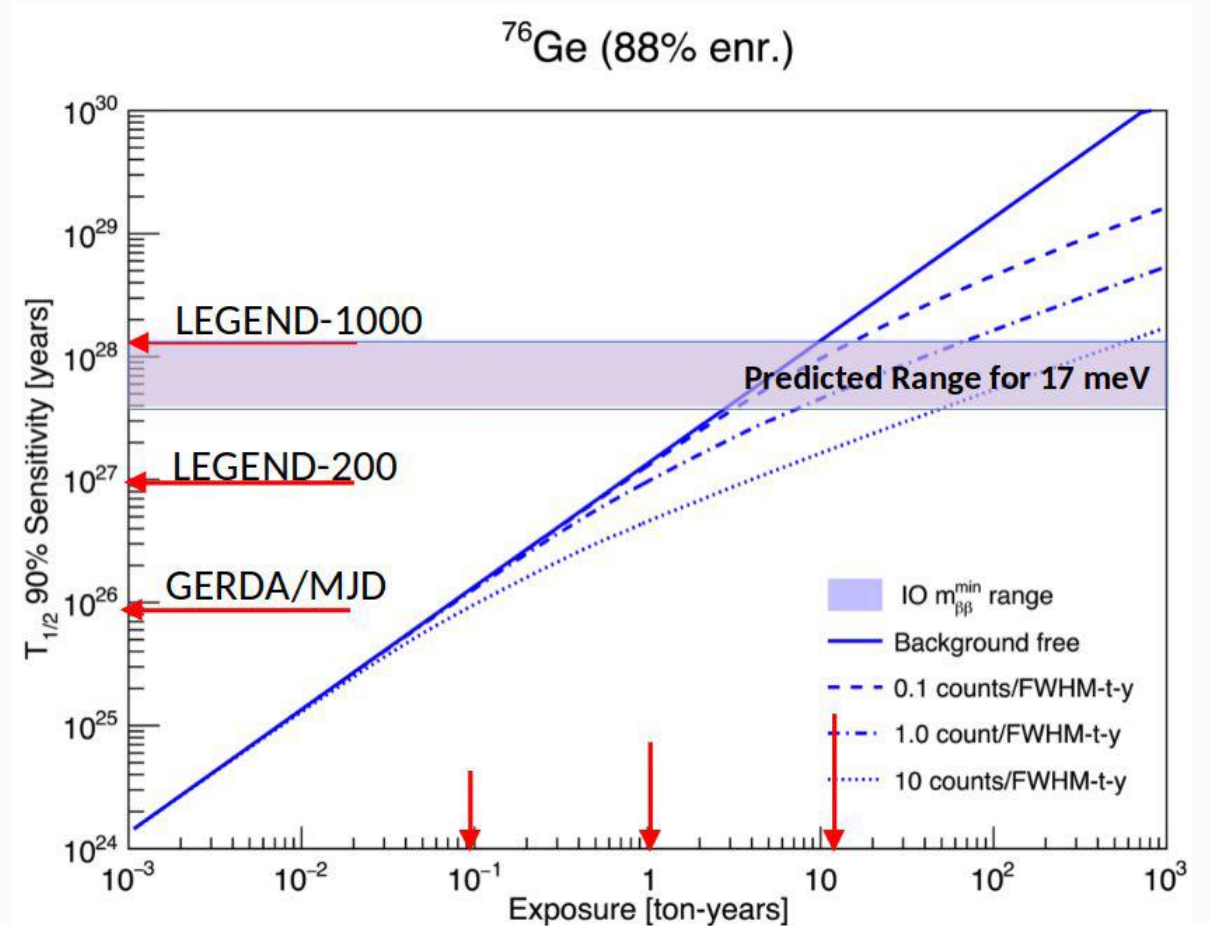
Searching for neutrinoless double-beta decay of ^{76}Ge

WHY $0\nu\beta\beta$

- Would show that lepton number ($B - L$) is not conserved and that neutrinos are Majorana particles, with $m(\beta\beta) \neq 0$
- If observed, points to new physics at $\sim 10\text{--}100$ TeV, depending on the operator

CONCEPT

- Enriched ^{76}Ge crystals are both source and detector, with $\sim 0.1\%$ FWHM resolution at $Q(\beta\beta)$
- Staged program: LEGEND-200 now running at LNGS, then LEGEND-1000



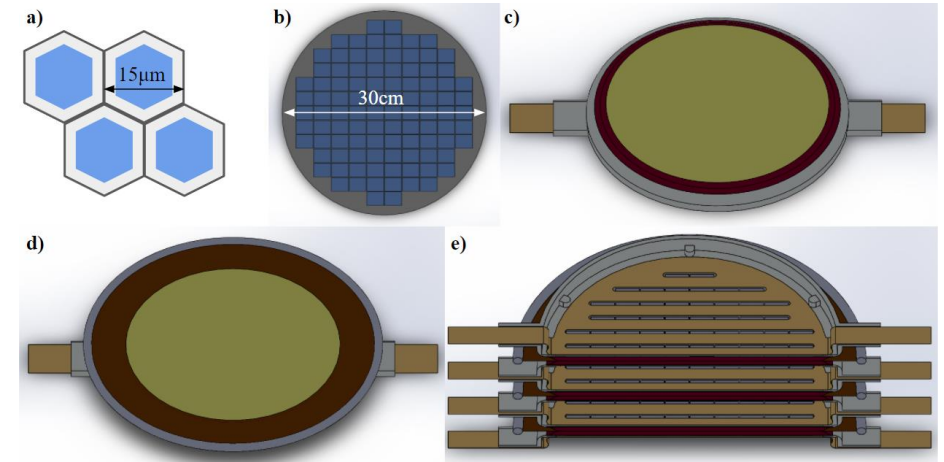
$$T_{1/2} > 1.9 \times 10^{26} \text{ yr}$$

No $0\nu\beta\beta$ observed: combined ^{76}Ge limit, H. Acharya et al., PRL 136, 022701 (2026)

Selena

Imaging $\beta\beta$ -decay tracks in amorphous ^{82}Se on CMOS pixels

- Concept: a 10-ton ^{82}Se active target of hybrid CMOS imagers with ~ 5 mm aSe layers
- Leverages industrial CMOS fabrication and aSe deposition to scale
- Bragg-peak ID suppresses single-electron background by 10^{-3} at 50% acceptance
- R&D with small pixelated devices: $\sim \text{MeV}$ electron tracks imaged



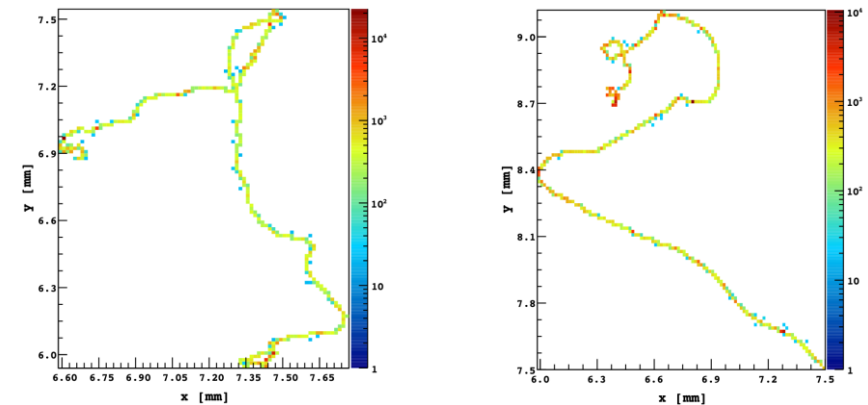
Concept: Snowmass white paper, arXiv:2203.08779

$$< 6 \times 10^{-5}$$

/ (keV·ton·yr) background rate, 100 ton-year simulation

$$2 \times 10^{28} \text{ yr}$$

3σ discovery potential for the ^{82}Se $0\nu\beta\beta$ half-life



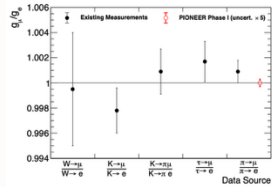
Double e ($\beta\beta$):
two Bragg peaks

Single e:
one Bragg peak

PIONEER

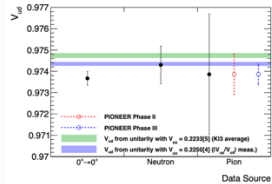
A next-generation rare pion decay experiment at PSI

SCIENTIFIC MOTIVATION



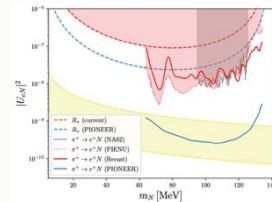
Lepton flavor universality

$R(e/\mu)$ to 0.01%, 15× the world's best; BSM reach to 1100 TeV



Cabibbo angle anomaly

Pion β decay gives V_{ud} free of nuclear-theory limits

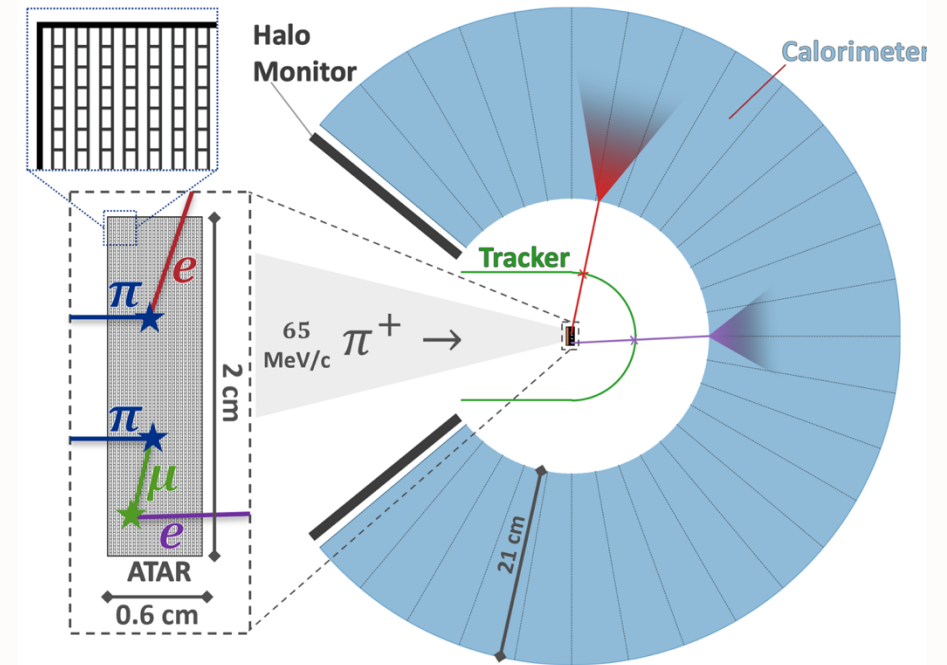
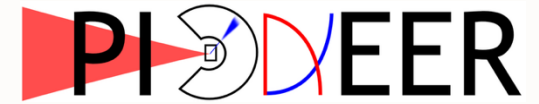


Exotic pion decays

Sterile neutrinos and feeble interactions, 10–100 MeV

0.01%

Phase I precision on $R(e/\mu)$, a 15-fold gain



BEAM

$3 \times 10^5 \pi^+/s$ from PSI $\pi E5$

ATAR

48-layer LGAD active target

CALO

311 LYSO crystals, $19 X_0$, $\sim 3\pi$ sr