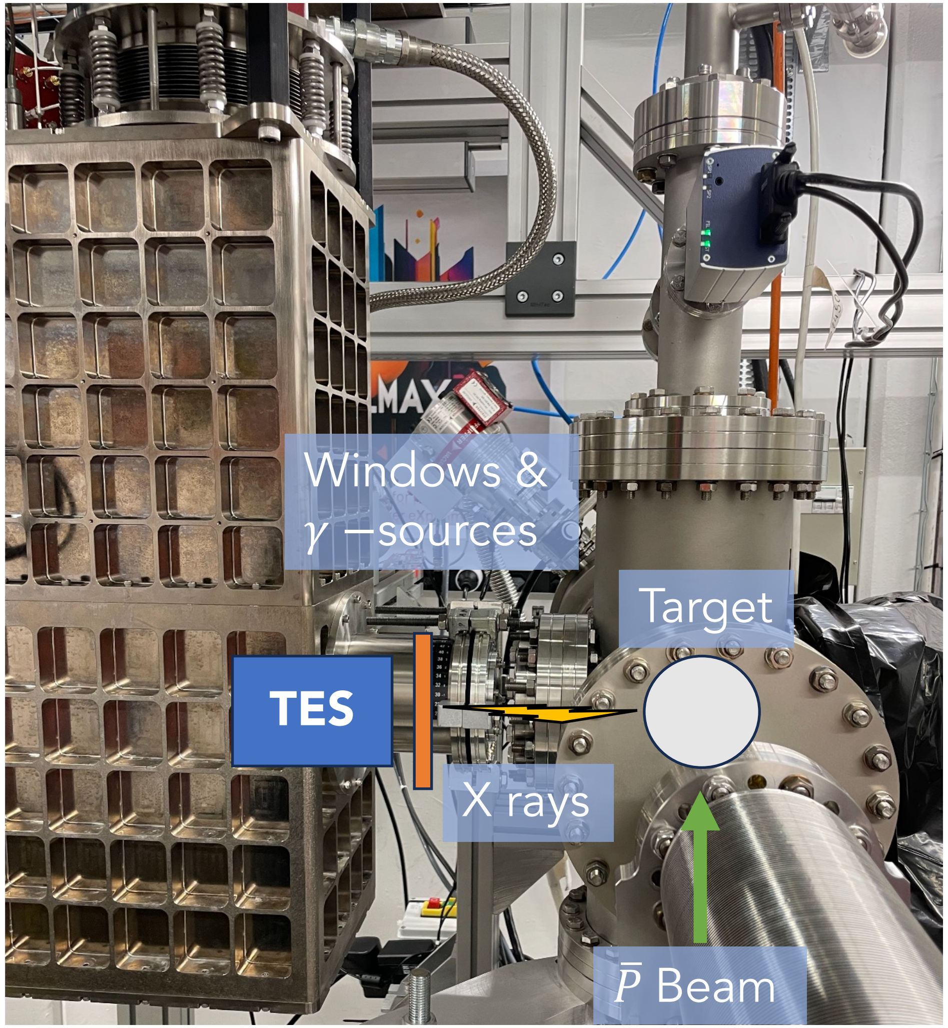
# Transition Edge Sensors for BSQED test via AntiProtonic Atom X-ray spectroscopy

Michael Roosa
Laboratoire Kastler Brossel
FRIF Day 2025

# Outline

- Motivation and background
- Summer 2025 PAX Test beam
- First TES spectra of $\bar{P}$-atom x rays



# The Standard Model and Beyond?

Figure from Sandbox Studio, Chicago

Numerous experimental observations cannot be explained by the Standard Model

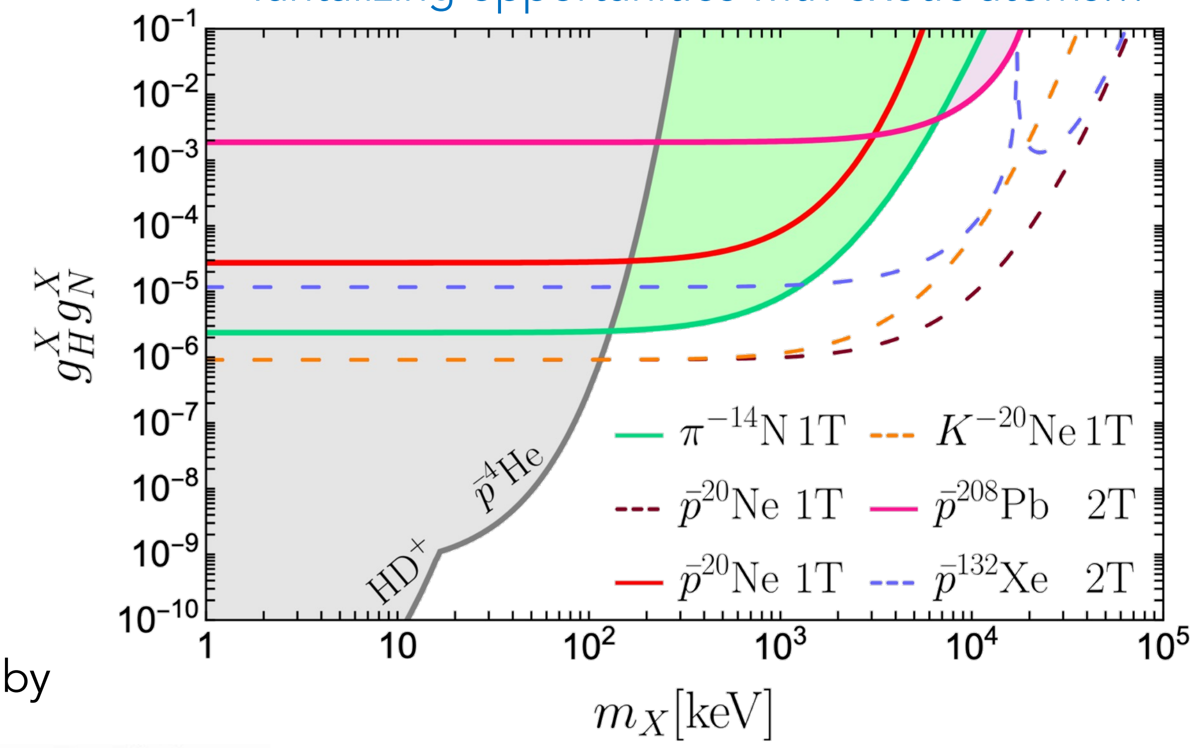
- Dark energy, dark matter, neutrino oscillations

Are signs of new physics, how to find it?

- High energy frontier (LHC)
- Precision frontier with atoms and nuclei (this talk)

# The Standard Model and Beyond?


Tantalizing opportunities with exotic atoms…




Numerous experimental observations cannot be explained by the Standard Model

- Dark energy, dark matter, neutrino oscillations

Are signs of new physics, how to find it?

- High energy frontier (LHC)
- Precision frontier with atoms and nuclei (this talk)

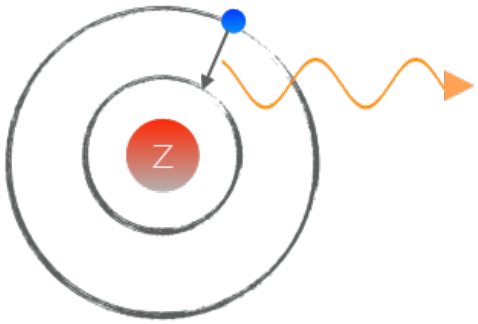
Proposed MeV scale bosons.

H. Lui *et al.* 2025 accepted to PRL

+Untested strong-field QED effects above the Schwinger limit

# Quantum electrodynamics in a nutshell

Quantum electrodynamics : interactions between photons and charged particles



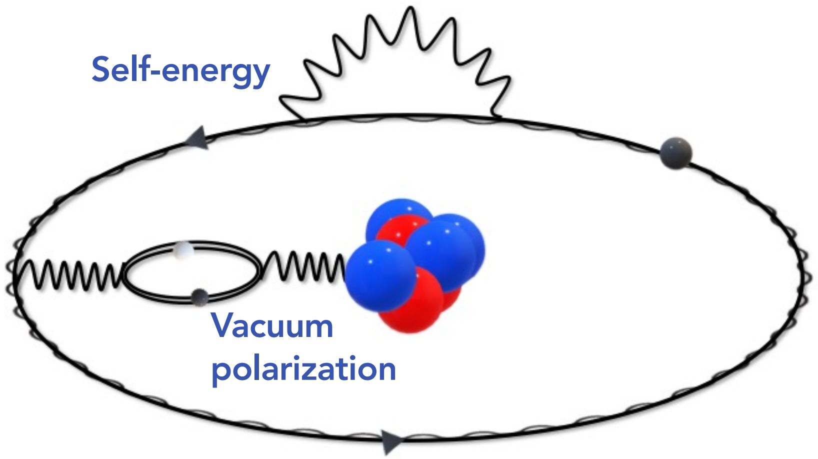

**Atomic transitions**

$$E_\gamma = E_{Dirac} + E_{Nuc} + E_{QED}$$

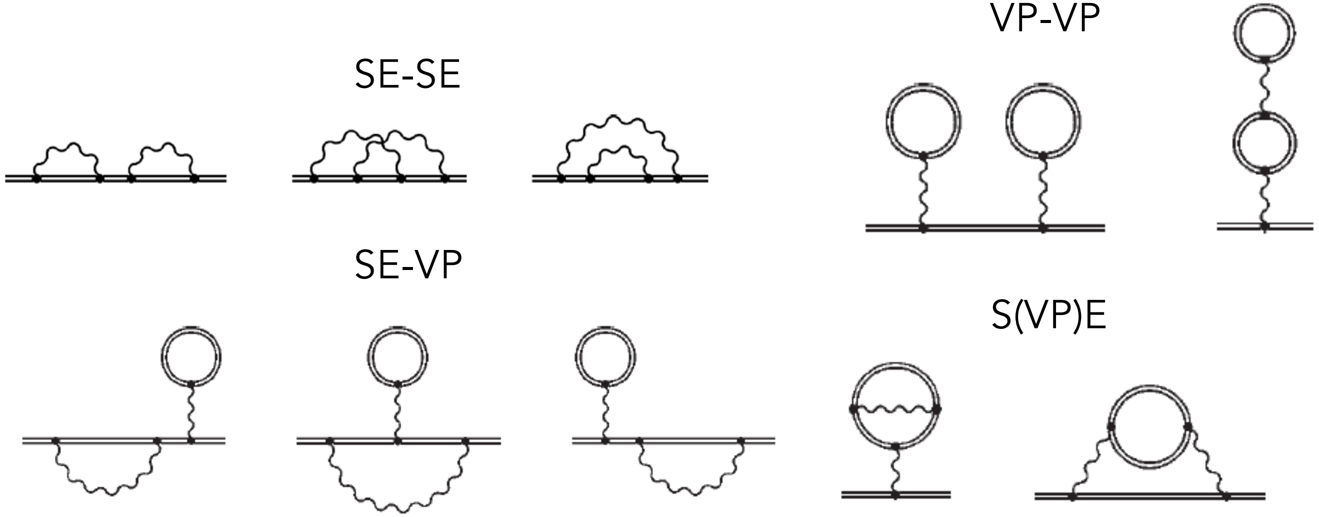
Dirac equation

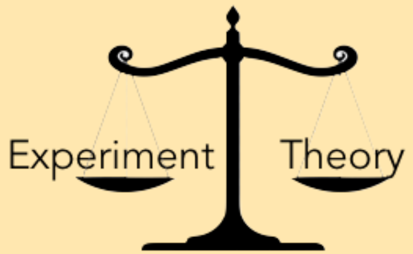
Nuclear effects

Quantum electrodynamics



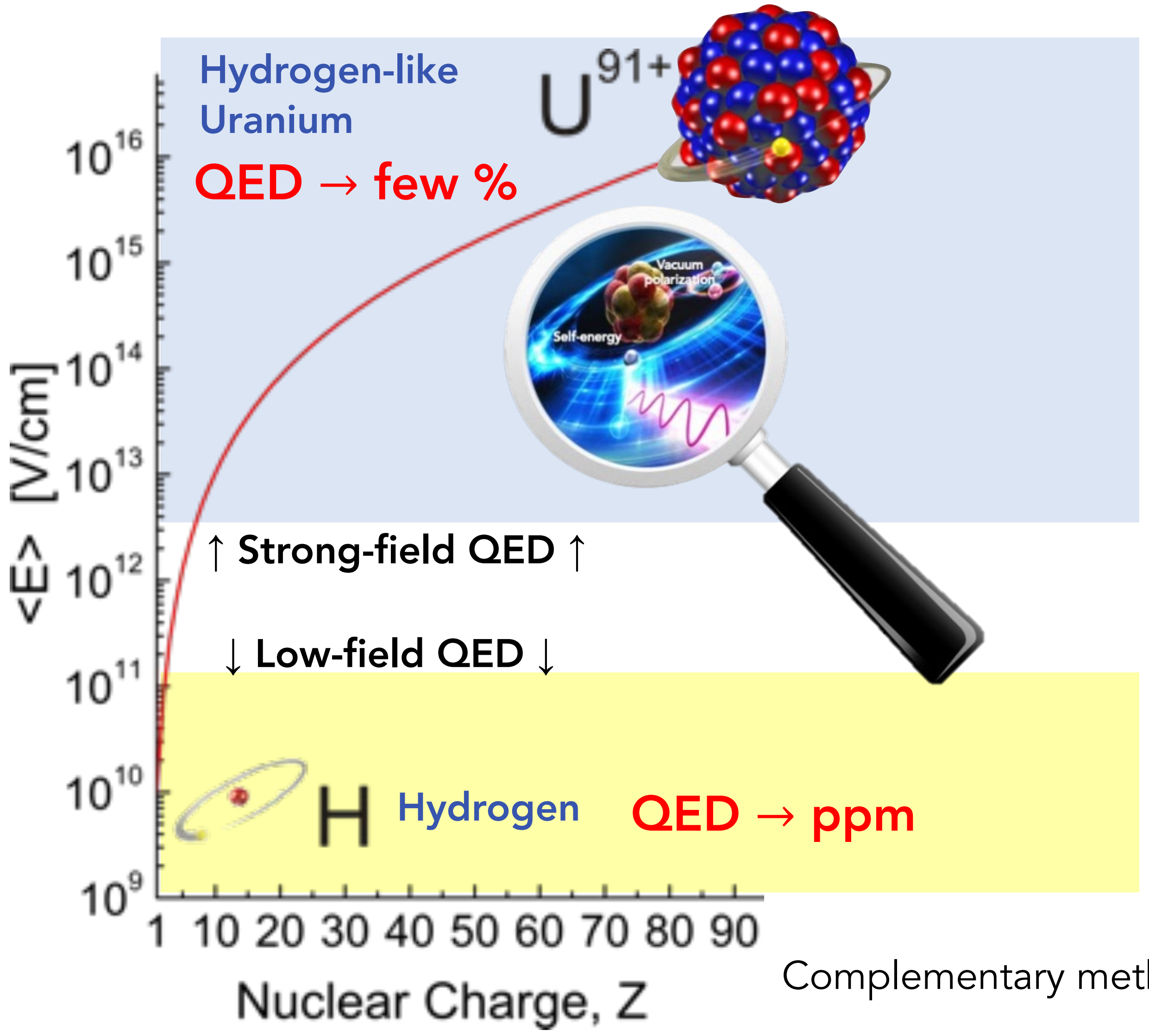

Work of
Dr. J. Sommerfeldt




= **QED test**

# Strong-field QED—experimental frontier




## Low-field QED :

- Tested at the 3-Loop level for low-Z systems

## Strong-field QED:

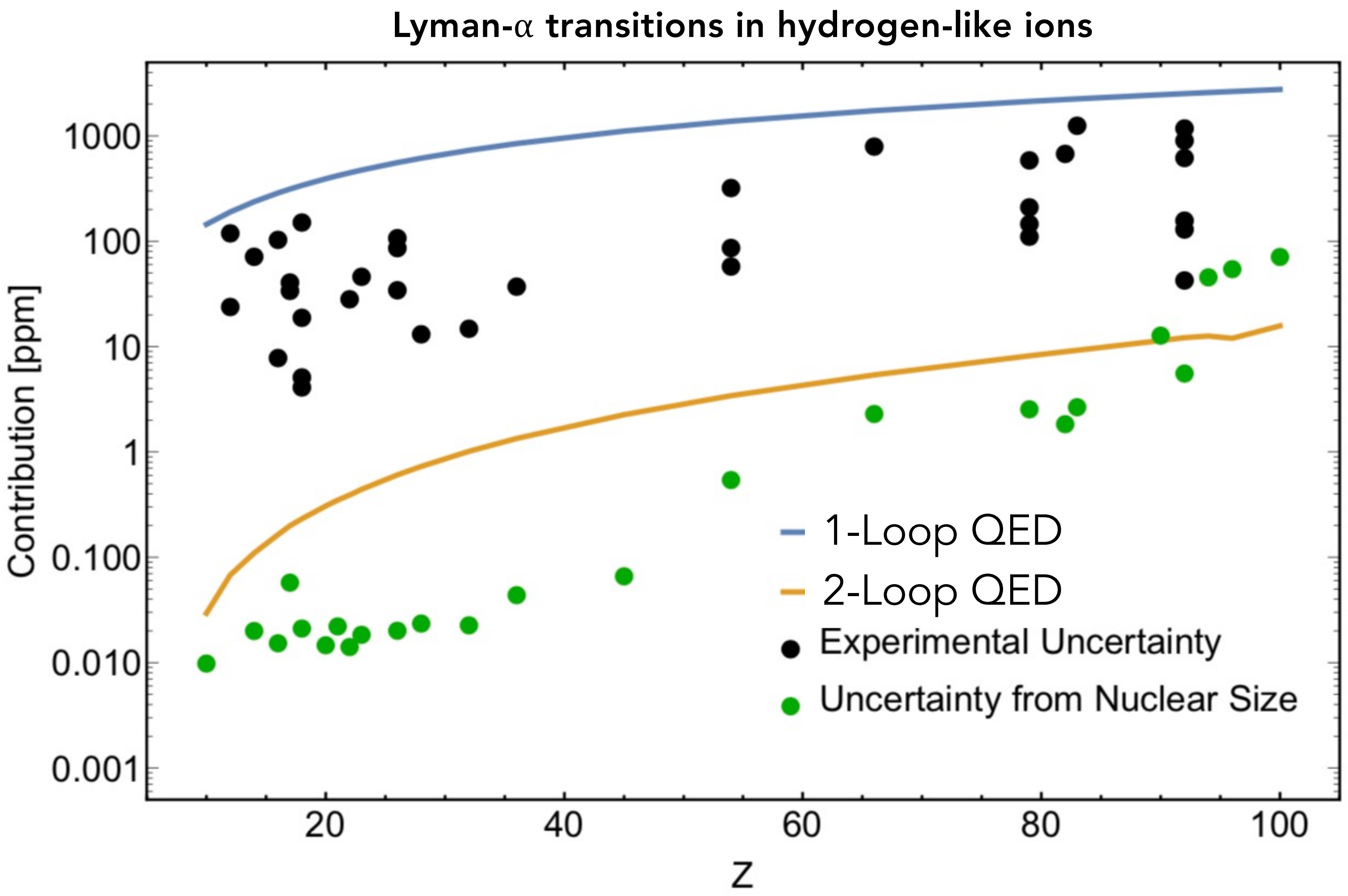
- Qualitatively different: Relativistic, Nonlinear
- QED effects relatively more important
  - predicted but untested effects may be enhanced as well

## Strong-field Challenges:

- Theory non-perturbative ($Z\alpha$)
- X-ray transitions in the ~keV regime
- Production of high-Z HCIs

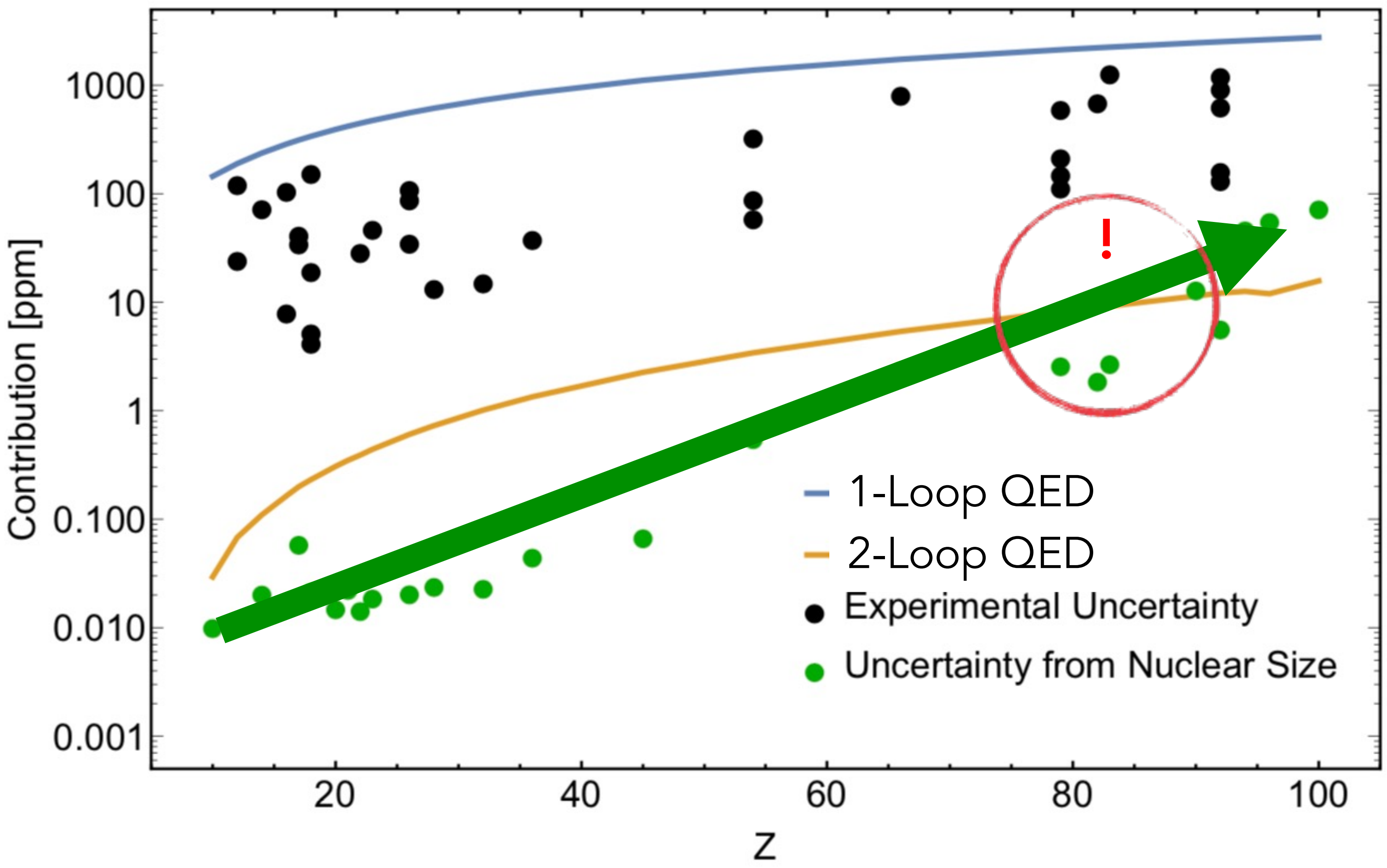
Complementary methods: *Ex. g-factors, Sailer, Nature 606 (2022)*
*Ex. High-intensity lasers, Fedeli, PRL 127 (2021)*

# Strong-field QED: limitations from nuclear physics



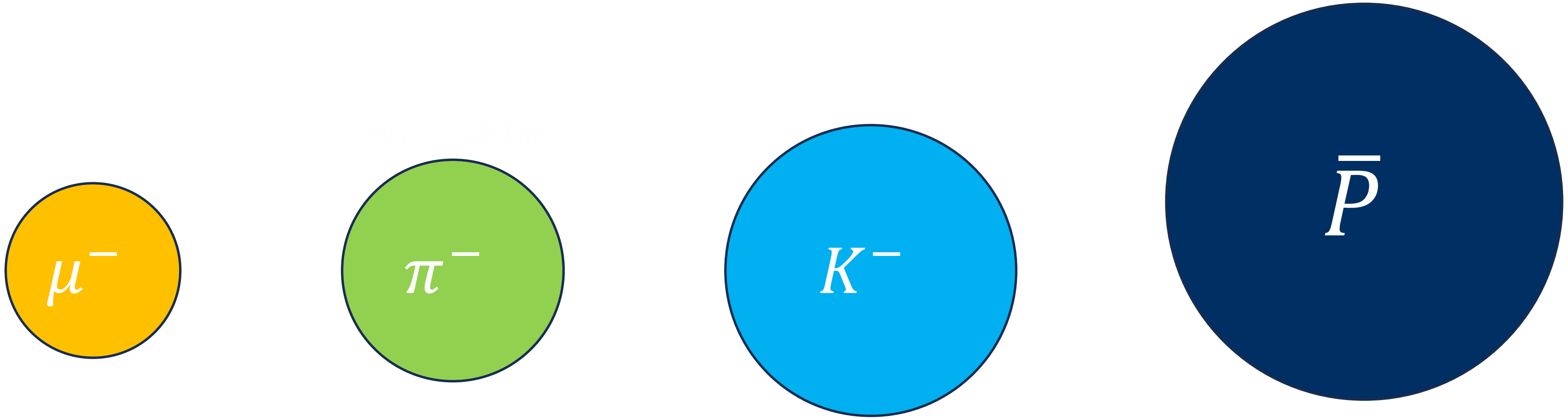
# Strong-field QED: limitations from nuclear physics

Lyman-α transitions in hydrogen-like ions



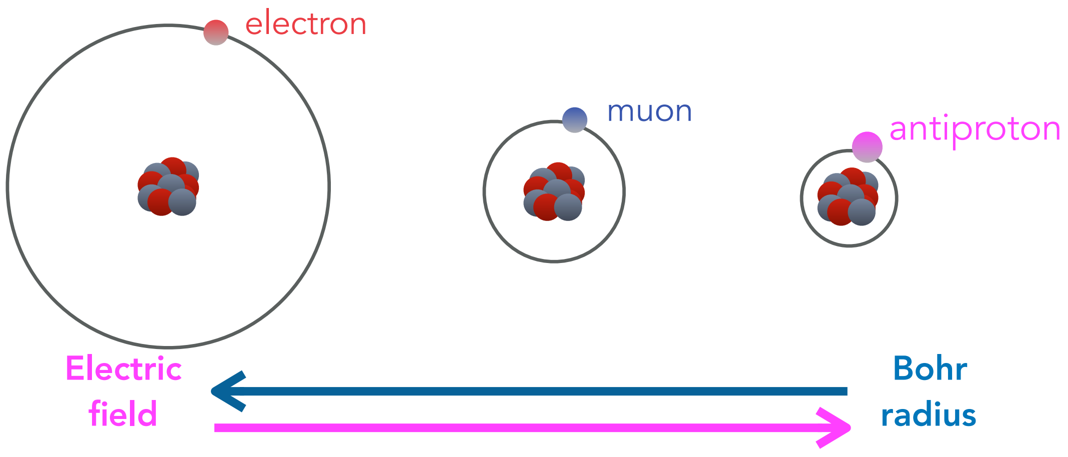
# Strong-field QED with Exotic Atoms

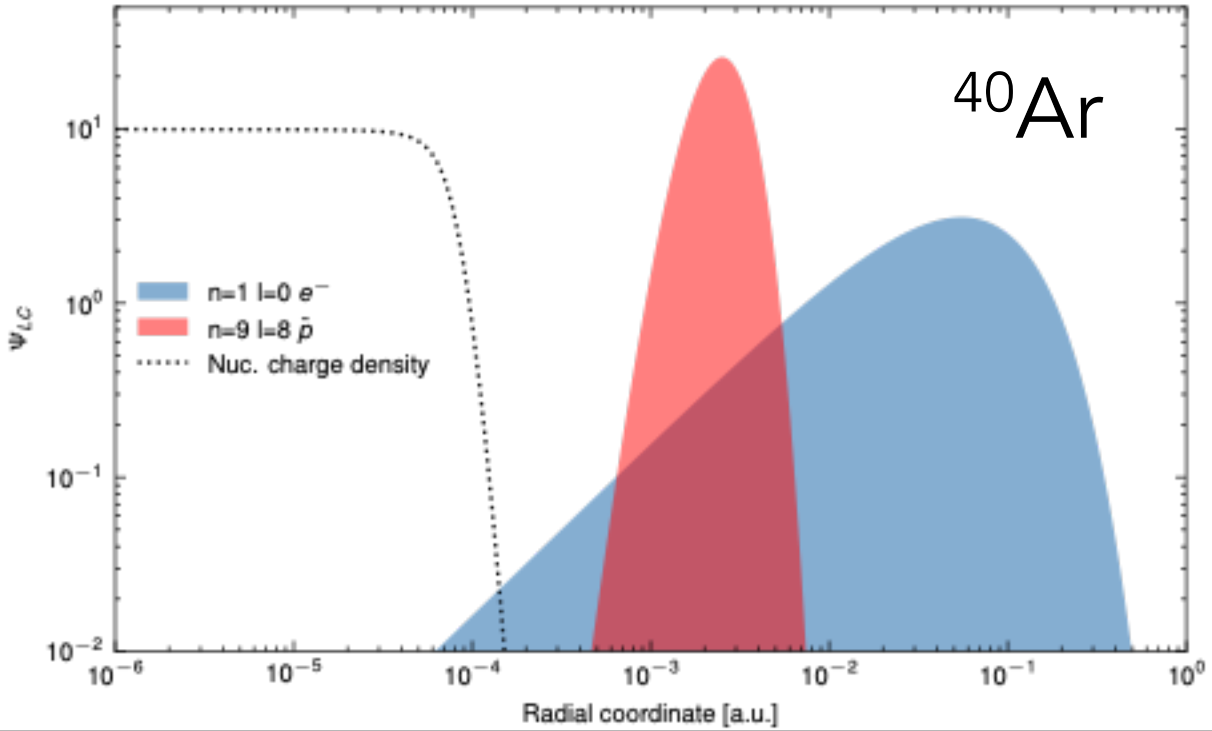
## Exotic Atoms




An atom where electrons are replaced another negatively charged particle.

# Strong-field QED with Antiprotonic Atom Circular Rydberg States




$$m_{\bar{p}} \sim 2000\, m_{e^-}$$

$$r_{\bar{p}} \sim \frac{1}{2000} r_{e^-}$$

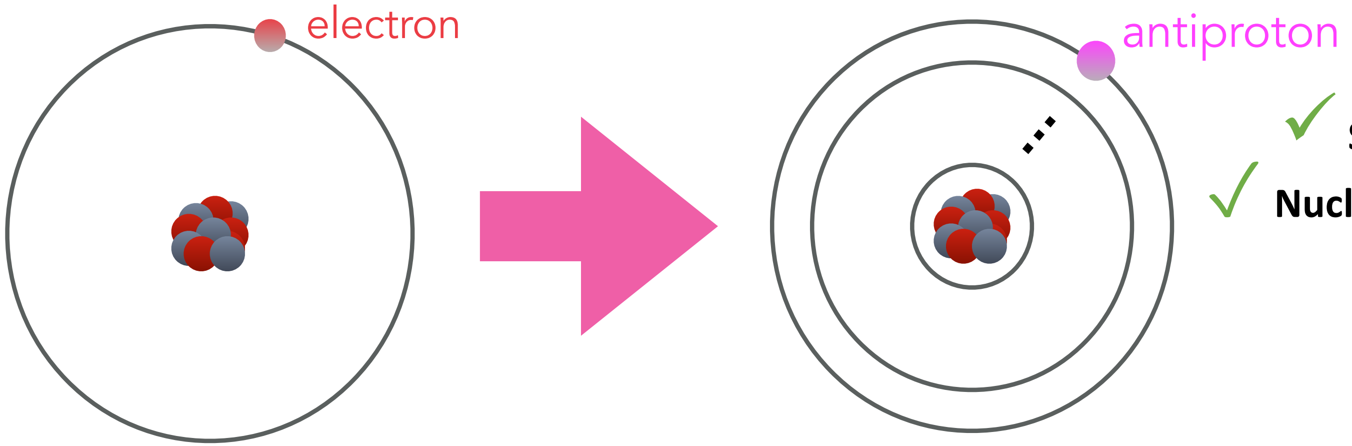
- Heavy exotic particle → Small Bohr radius → Strong electric field
- Higher order QED effects magnified
- Small nuclear overlap → Small sensitivity to nuclear charge radii uncertainties.

Measurement paradigm—N. Paul et al, PRL 126 (2021) and G. Baptista, PoS (EXA-LEAP2024) 2025
Proof-of-principle with muonic atoms—T. Okumura et al, PRL 130 (2023)

# Strong-field QED with Antiprotonic Atom Rydberg States

*2p-1s Lamb Shift in HCI* | *Exotic atom Rydberg transition*

✓ **Strong field QED**
X **Nuclear effects ≥ QED effects**




✓ **STRONGEST field QED**
✓ **Nuclear effects << QED effects**

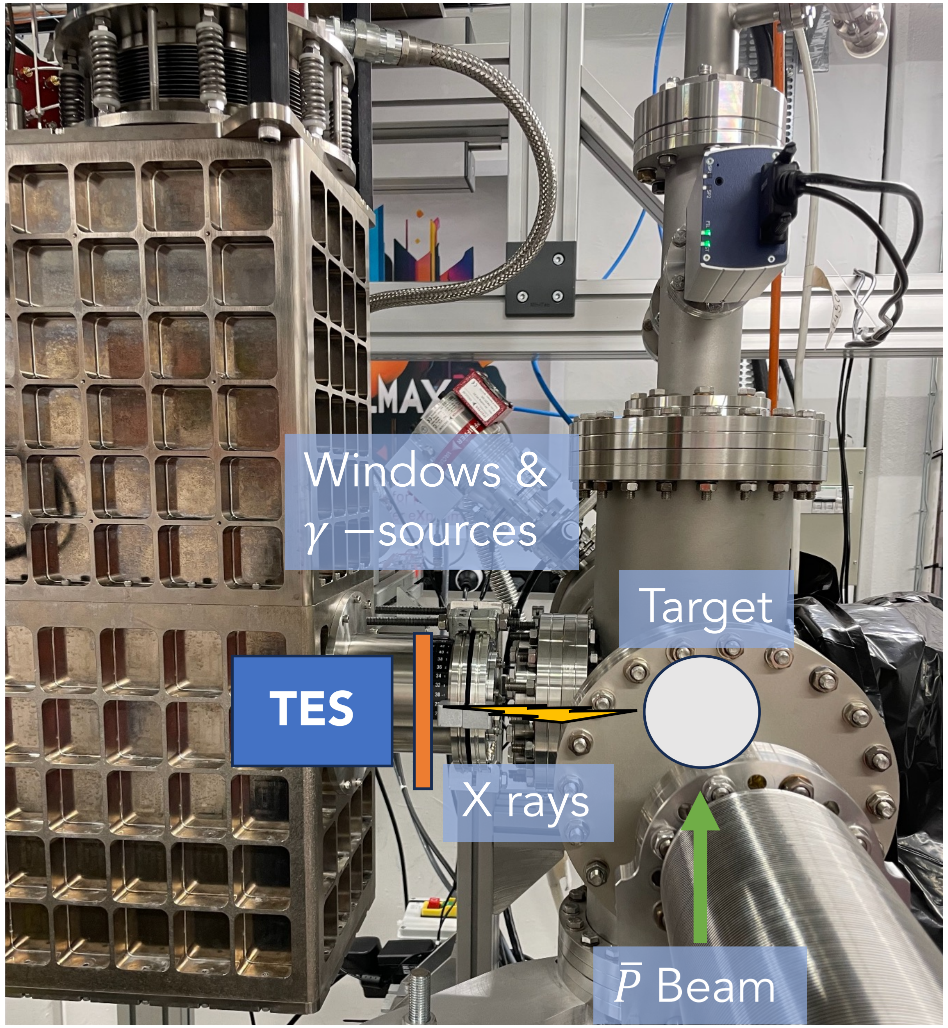
| Atom | Transition | Transition energy | 1st order QED | 2nd order QED* | Nuclear effects |
|---|---|---|---|---|---|
| **H-like U** | Lyman α1 | ~100 keV | $3x10^{-3}$ | $1x10^{-5}$ | $2x10^{-3}$ |
| **$\bar{p}$-Xe** | n=12→n=11 | ~100 keV | $7x10^{-3}$ | $6x10^{-5}$ | $1x10^{-5}$ |

**QED x 3-6** | **Nuclear effects / 100**

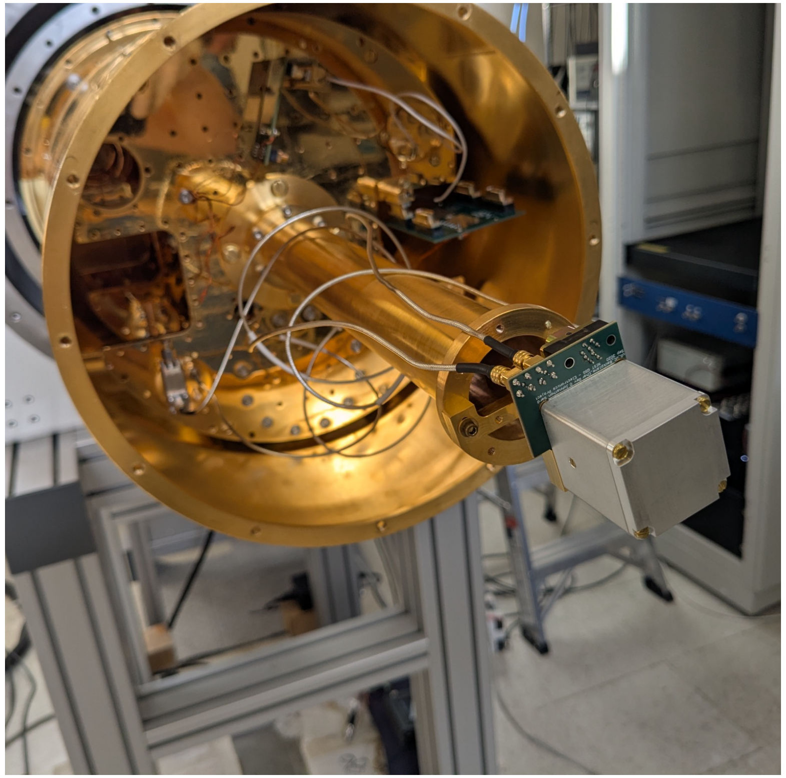
***Different 2-Loop sensitivity:**
H-Like U → Self-Energy
$\bar{p}$-Xe → Vacuum Polarization

# Outline

- Motivation and background
- Summer 2025 PAX Test beam
- First TES spectra of $\bar{P}$-atom x-rays



# Precise energy-dispersive x-ray measurements

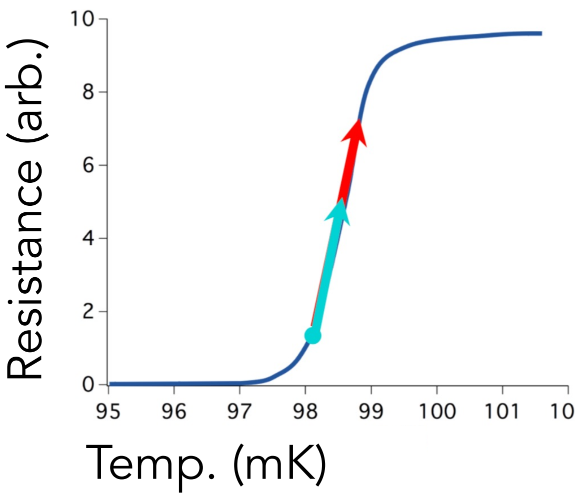



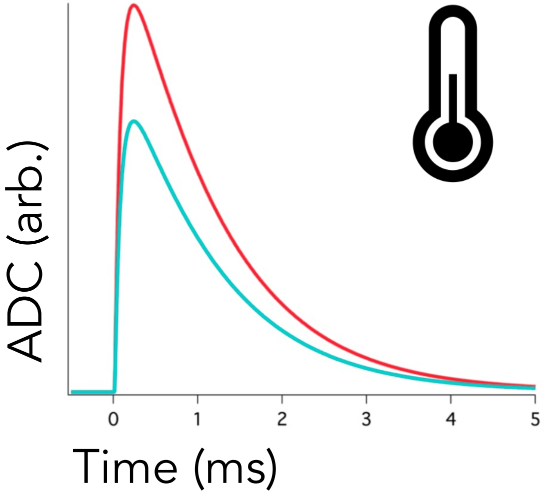
Precision measurement of x rays at 30-300keV?

1. Make a cold-bath
2. Absorb the x ray
3. Measure $\Delta T$

**New approach for precision hard x-ray spec.**

**Superconducting Transition Edge Sensors (TESs)**



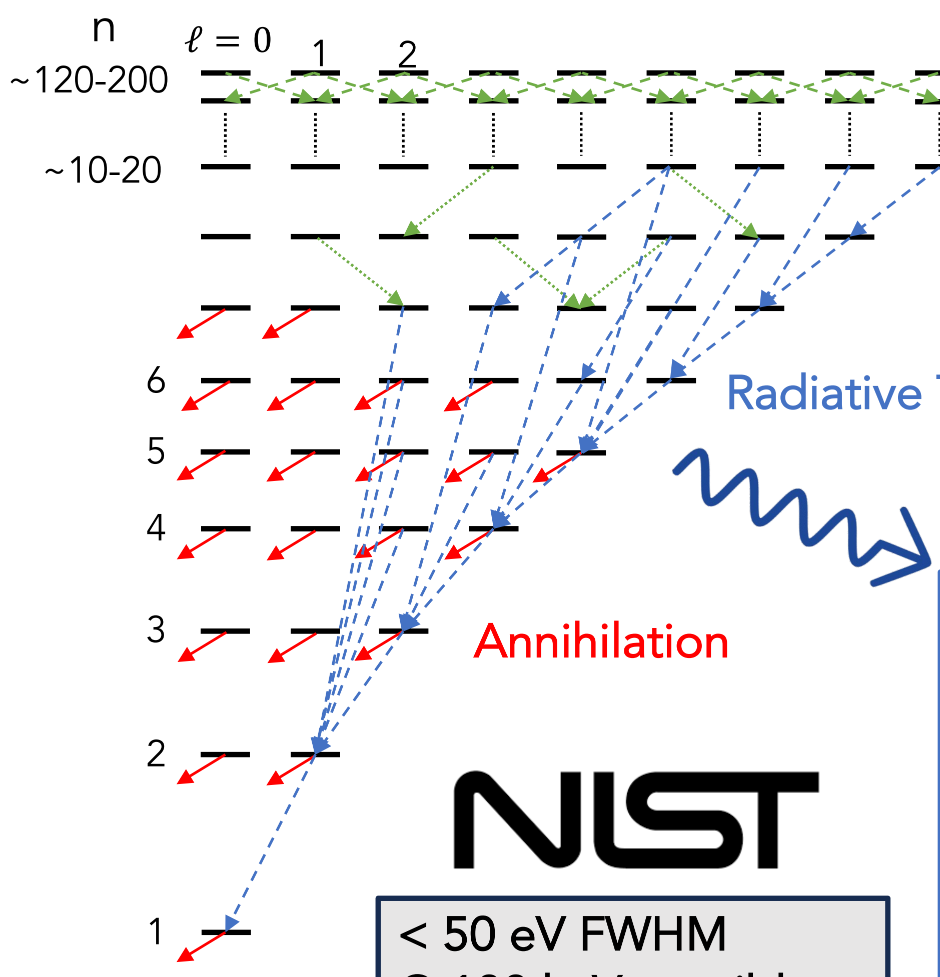



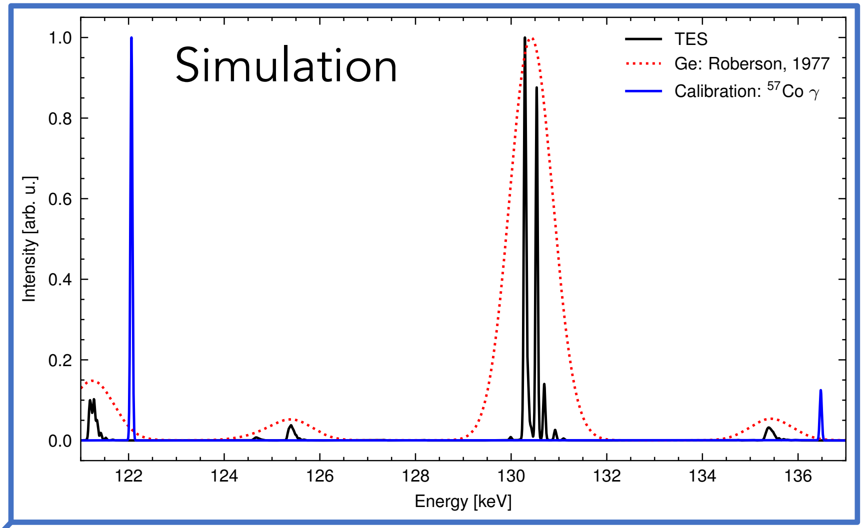

Thermal noise limit:

$$\sigma \propto \sqrt{T}$$

Figures from Ullom and Bennett 2013

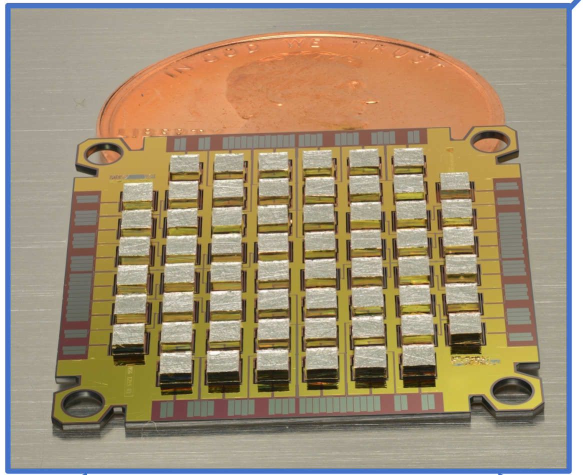
# Key technology: Transition Edge Sensing (TES) Microcalorimeter




$MDFGME$: $\bar{P} - Zr$
near $n = 9 \rightarrow 8$

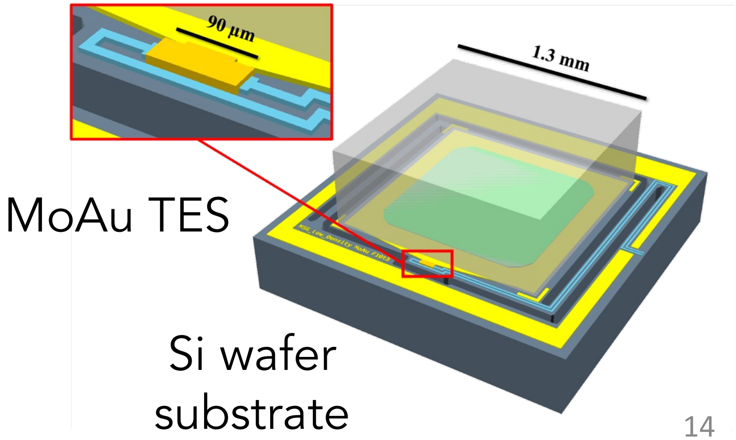
$\bar{P}$AX Prototype



2 cm

NIST

< 50 eV FWHM
@ 100 keV possible

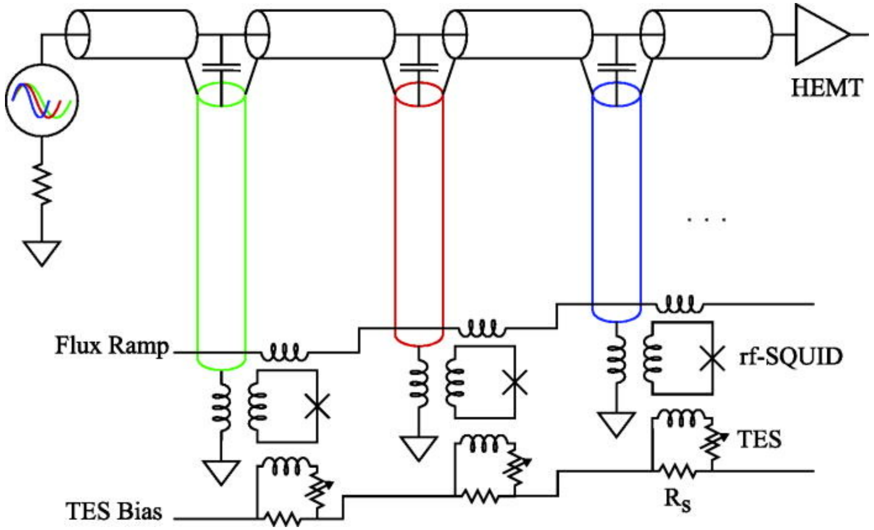


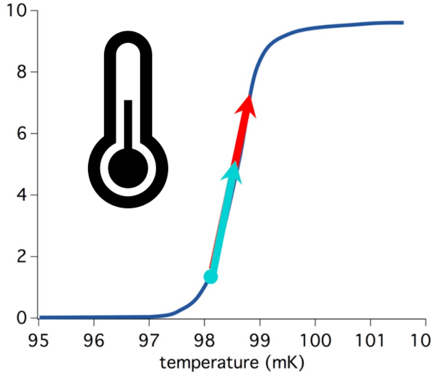

Photos: J. Nobles, M. Keller, K. Morgan (NIST)

# High Channel Density via Microwave Multiplexed Readout

Each detector channel is given a unique microwave resonator frequency

**1 data channel / 100-1000s of detector channels**

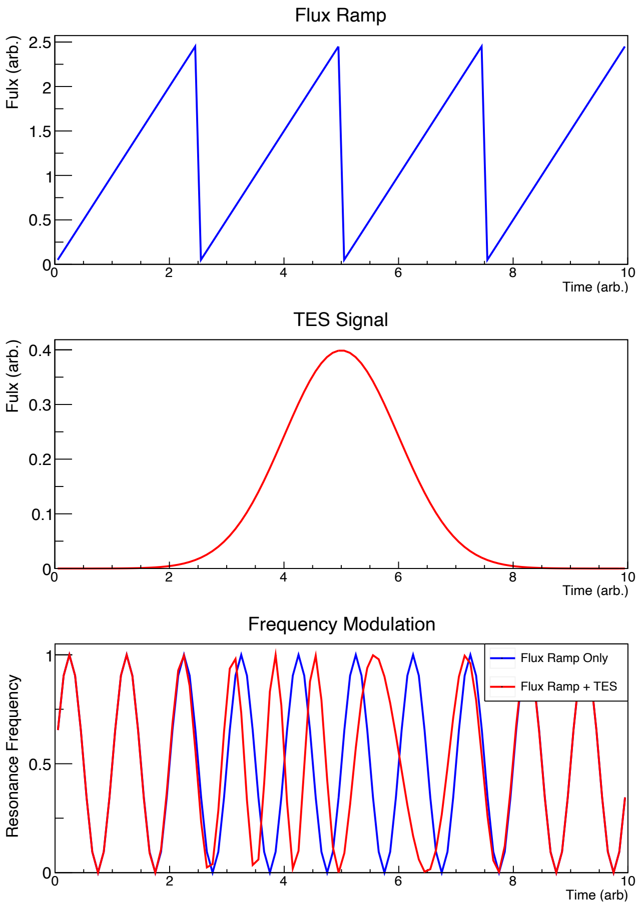


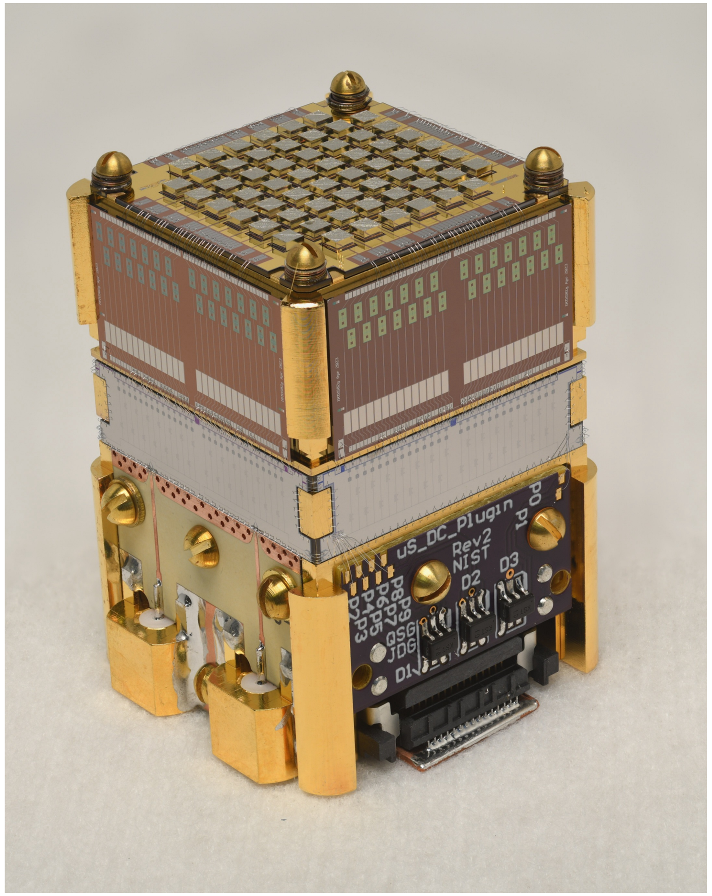

$\Delta T$ in the TES

$\Delta I$ to the inductor

$\Delta \varphi_0$ to the SQuID



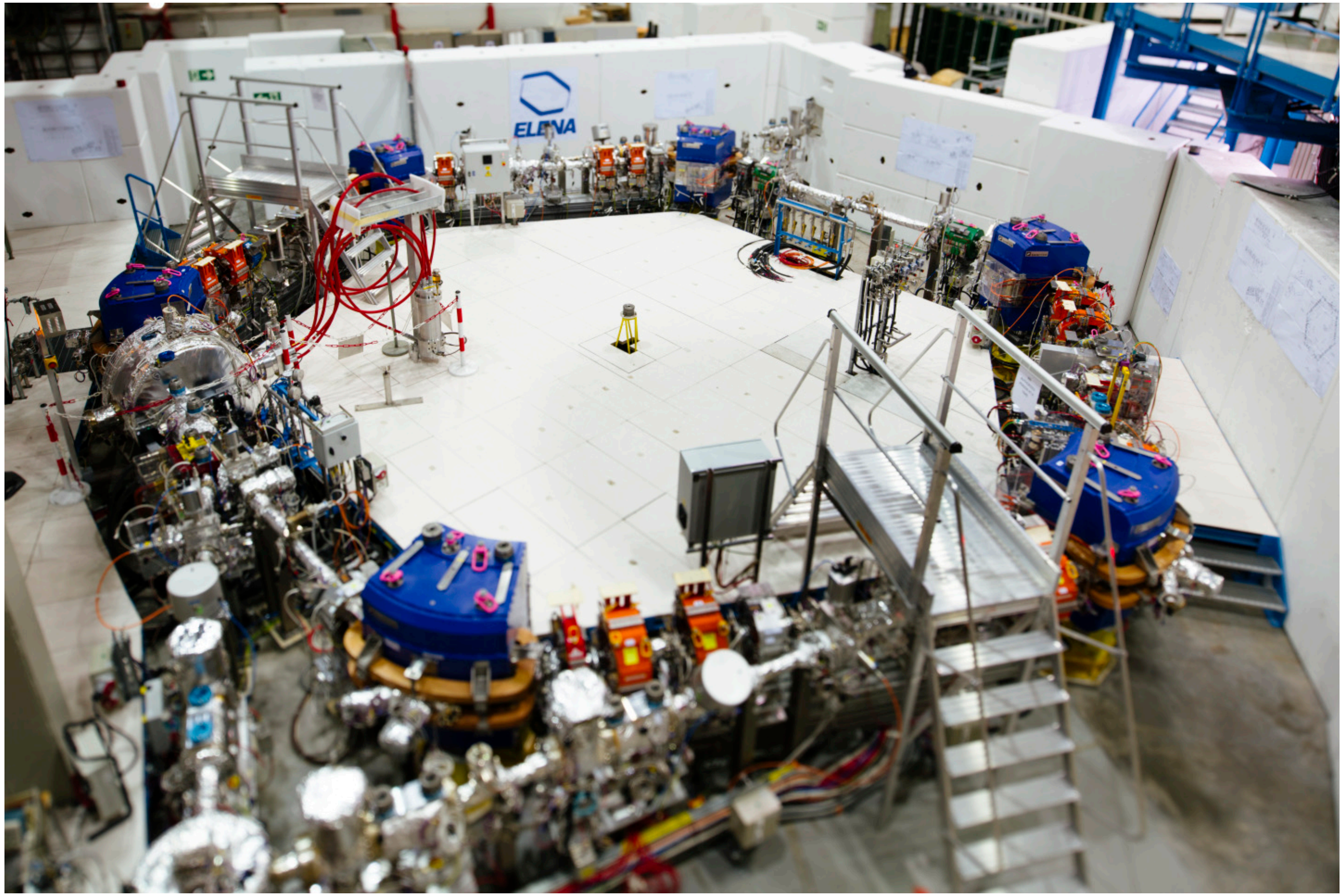

$$f_{res} \approx \sin(ct + S_{TES}(t))$$



Circuit diagram from B. Dober et. al. 2017

Photo provided by J. Nobles and M. Keller (NIST)

# ELENA : slow antiproton beams for precision measurements

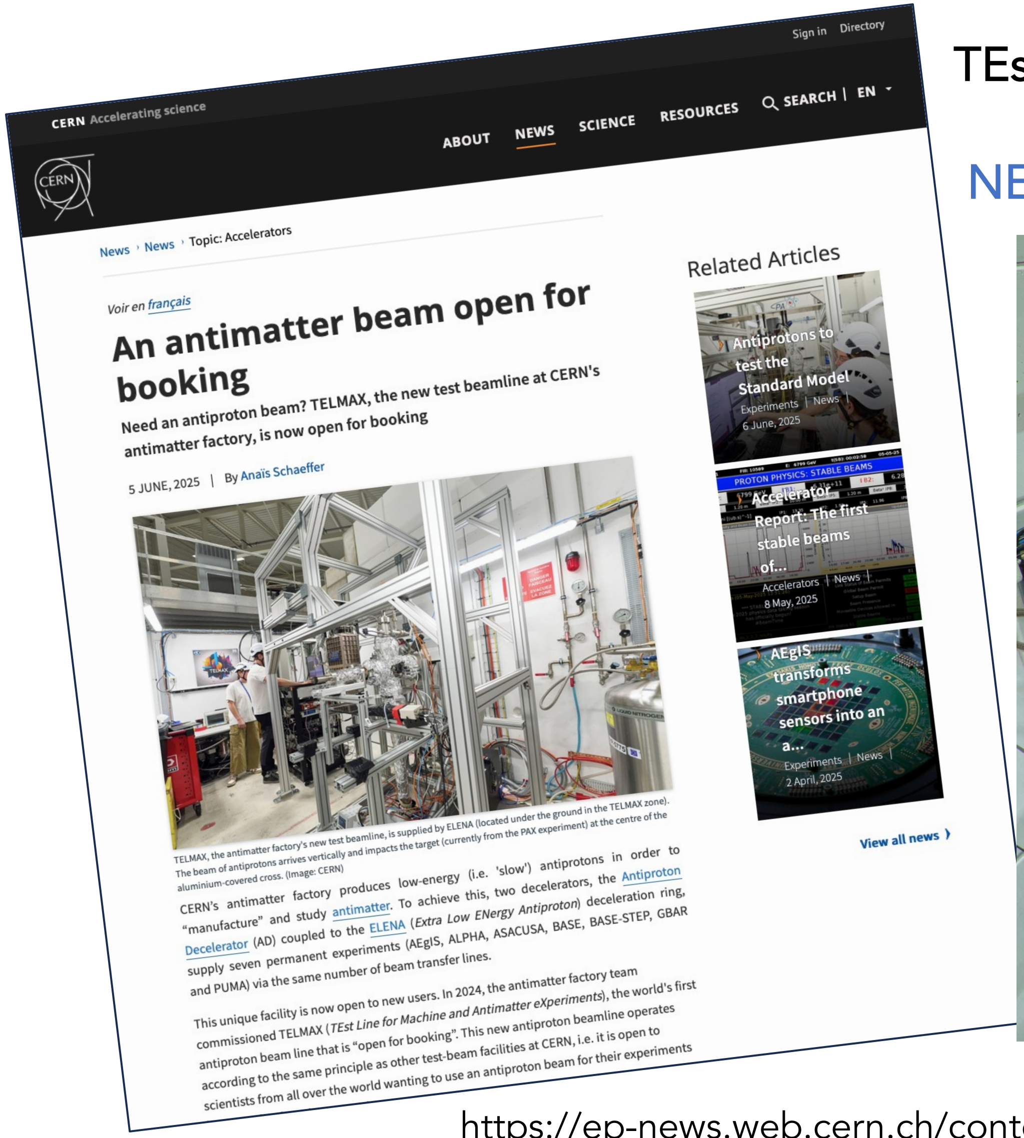



« Extra Low ENergy Antiprotons »
Beams of slow antiprotons since August 2021

## ELENA parameters

| | |
|---|---|
| Beam energy | 100 keV |
| Number of antiprotons/bunch | ~7 x $10^6$ |
| Bunch size (FWHM) | 300 ns |
| Repetition rate | 100 s |

# $\overline{\text{P}}$AX at ELENA's TELMAX zone



Sign in Directory

CERN Accelerating science

ABOUT NEWS SCIENCE RESOURCES SEARCH | EN

News › News › Topic: Accelerators

*Voir en français*

## An antimatter beam open for booking

**Need an antiproton beam? TELMAX, the new test beamline at CERN's antimatter factory, is now open for booking**

5 JUNE, 2025 | By Anaïs Schaeffer

TELMAX, the antimatter factory's new test beamline, is supplied by ELENA (located under the ground in the TELMAX zone). The beam of antiprotons arrives vertically and impacts the target (currently from the PAX experiment) at the centre of the aluminium-covered cross. (Image: CERN)

CERN's antimatter factory produces low-energy (i.e. 'slow') antiprotons in order to "manufacture" and study antimatter. To achieve this, two decelerators, the Antiproton Decelerator (AD) coupled to the ELENA (*Extra Low ENergy Antiproton*) deceleration ring, supply seven permanent experiments (AEgIS, ALPHA, ASACUSA, BASE, BASE-STEP, GBAR and PUMA) via the same number of beam transfer lines.

This unique facility is now open to new users. In 2024, the antimatter factory team commissioned TELMAX (*TEst Line for Machine and Antimatter eXperiments*), the world's first antiproton beam line that is "open for booking". This new antiproton beamline operates according to the same principle as other test-beam facilities at CERN, i.e. it is open to scientists from all over the world wanting to use an antiproton beam for their experiments

Related Articles

Antiprotons to test the Standard Model
Experiments | News
6 June, 2025

Accelerator Report: The first stable beams of...
Accelerators | News
8 May, 2025

AEgIS transforms smartphone sensors into a...
Experiments | News
2 April, 2025

View all news ›

TEst Line for Machine And Antimatter eXperiments (TELMAX)

NEW user facility open at ELENA delivering $\overline{\text{P}}$ beams


**$\overline{\text{P}}$AX** was the first user in **TELMAX** with an extended Summer 2025 test-beam.

**Goal:**

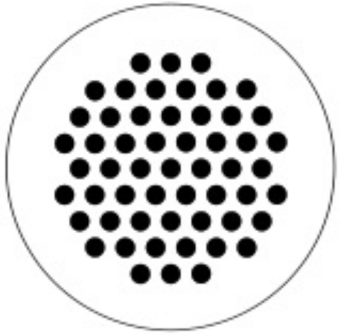
Measure first $\overline{\text{P}}$-atom x rays with a TES !



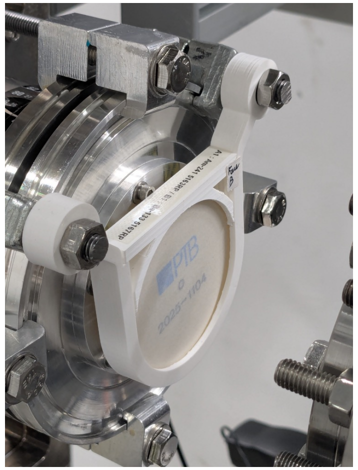
https://ep-news.web.cern.ch/content/telmax-new-era-flexibility-cerns-antimatter-factory

# TES performance checks and calibration

New x-ray-transparent
γ-sources from PTB.

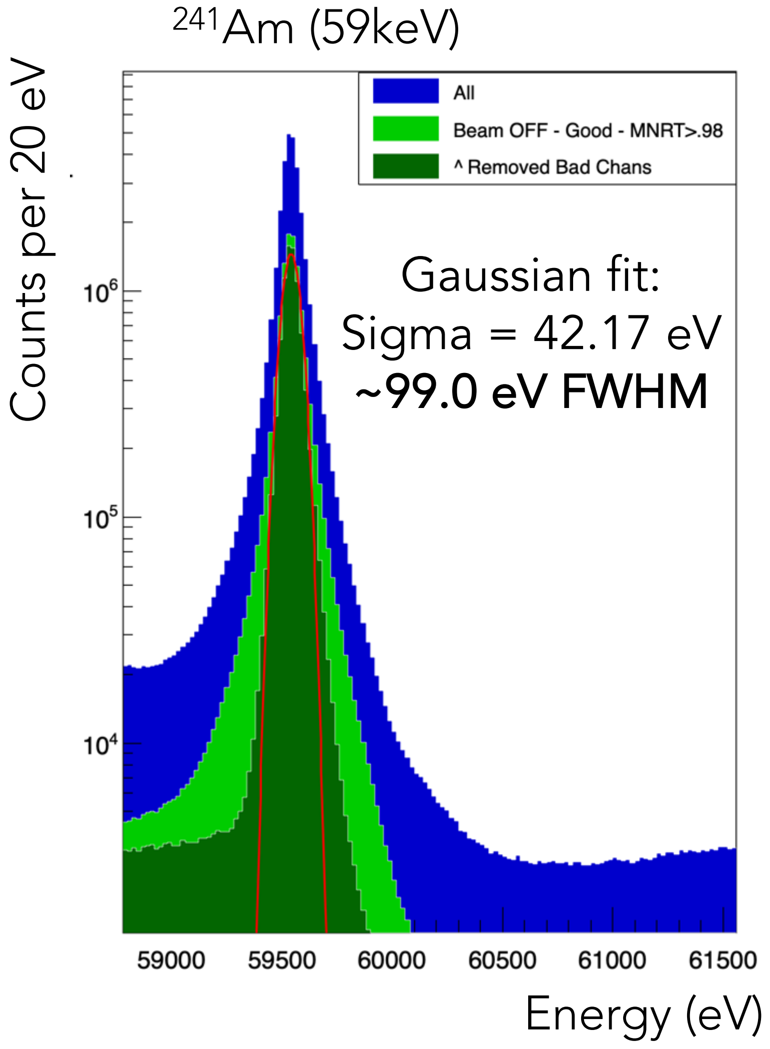


size 2
diameter 50 mm, 55 drops



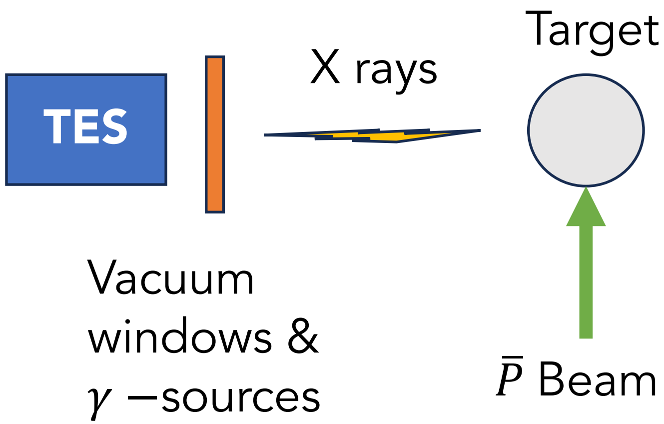
Radioactive microdroplets
on plastic films

**Uniform and continuous calibration**



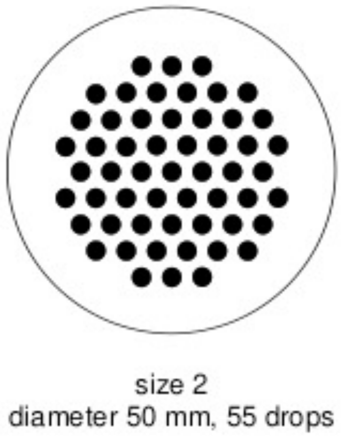

**Calibration sources measured to specified resolution !**
(prototype)

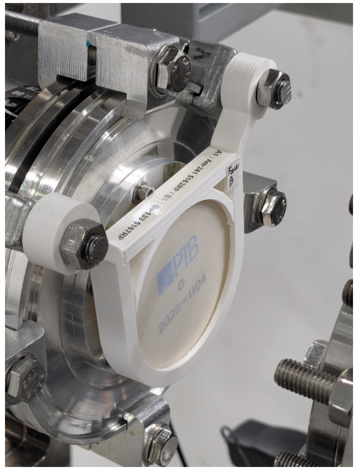
Let's take beam!



# TES performance checks and calibration

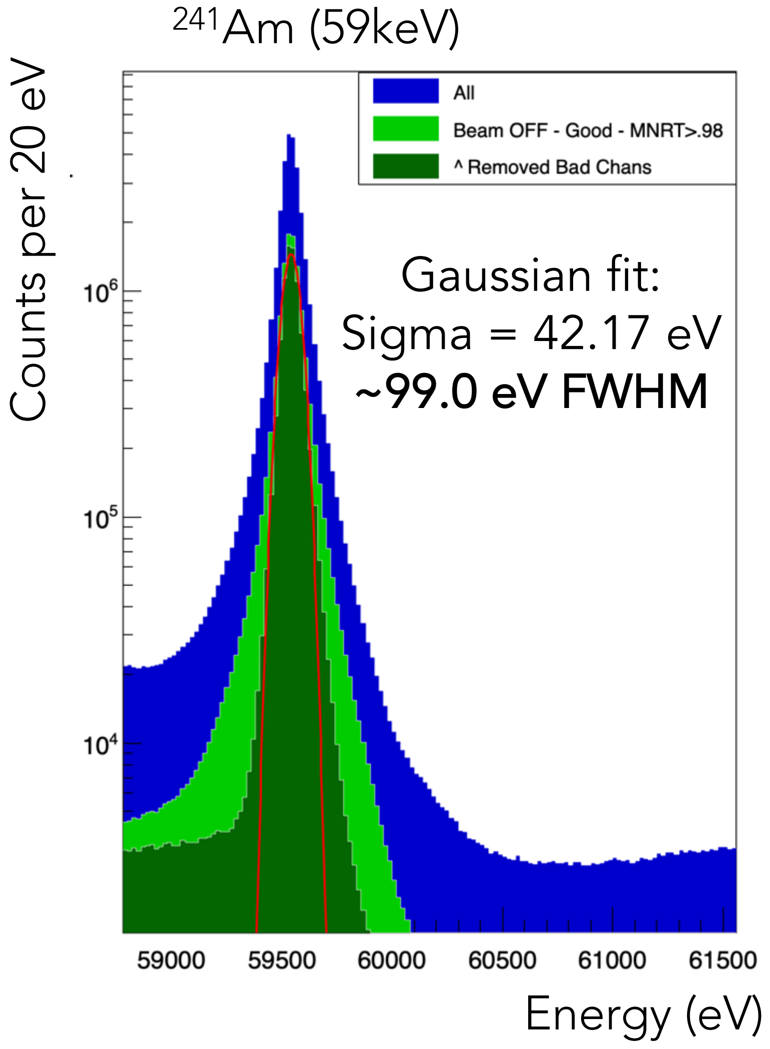
New x-ray-transparent
γ-sources from PTB.



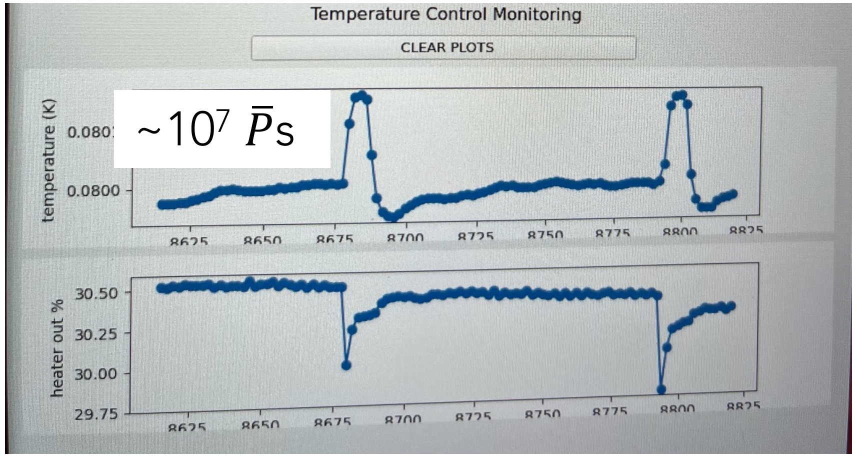
Radioactive microdroplets
on plastic films

**Uniform and continuous calibration**



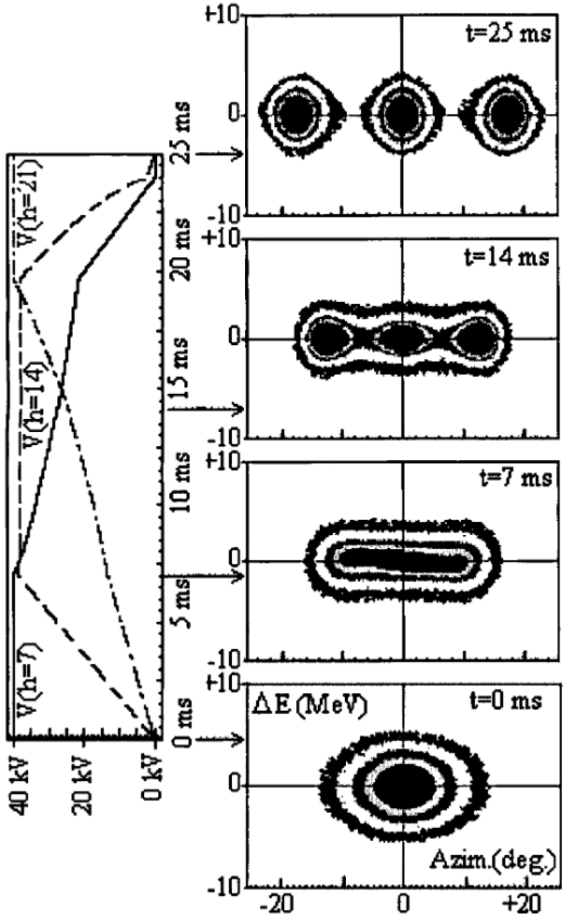

**Calibration sources measured to specified resolution !**
(prototype)

Let's take beam!




100s of μK deposited in to the array

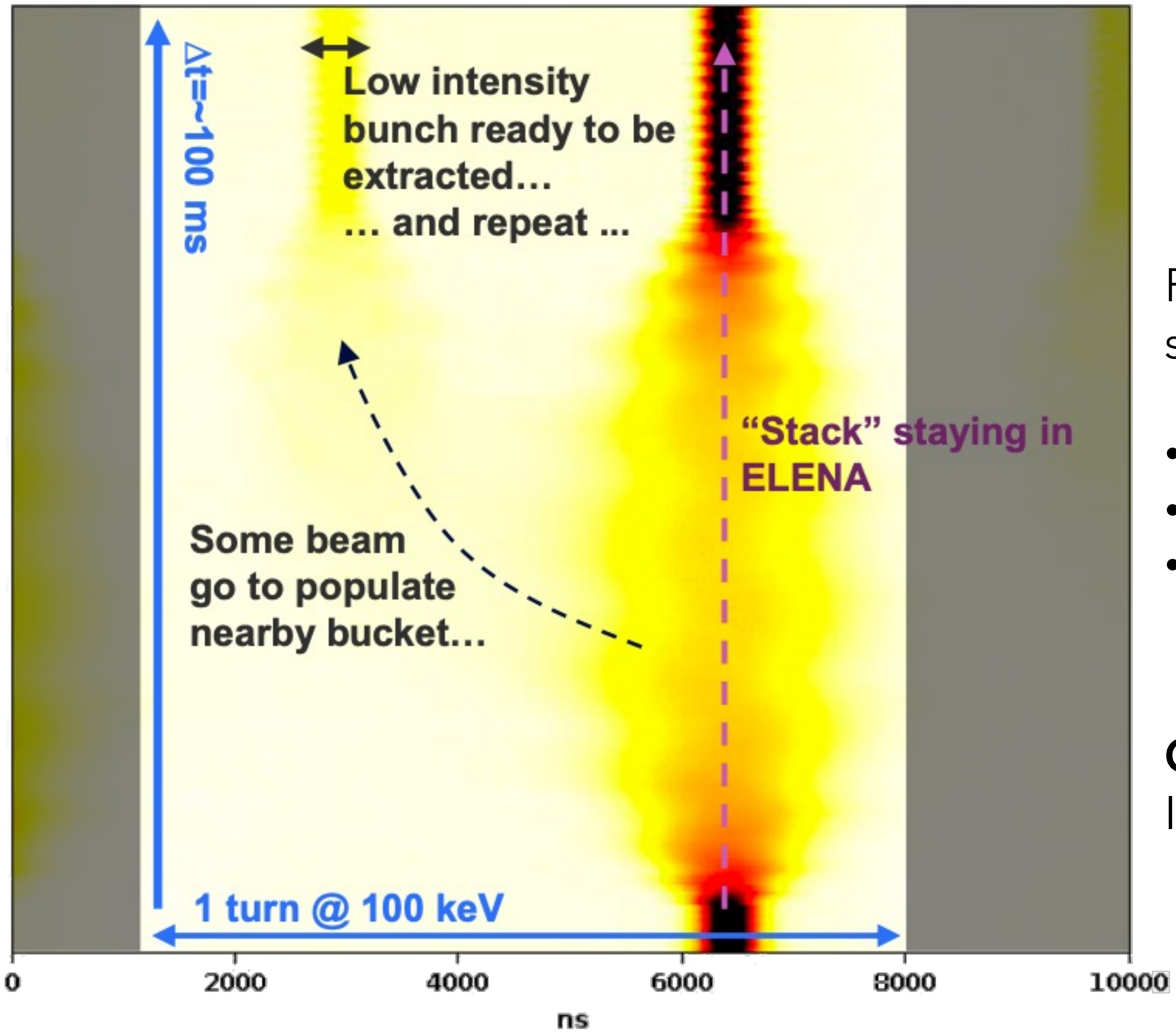
# Multiple Mini-Bunch Extraction




Example from CERN PS.

R. Garoby, et. al 2000

Mini-bunch formation in ELENA



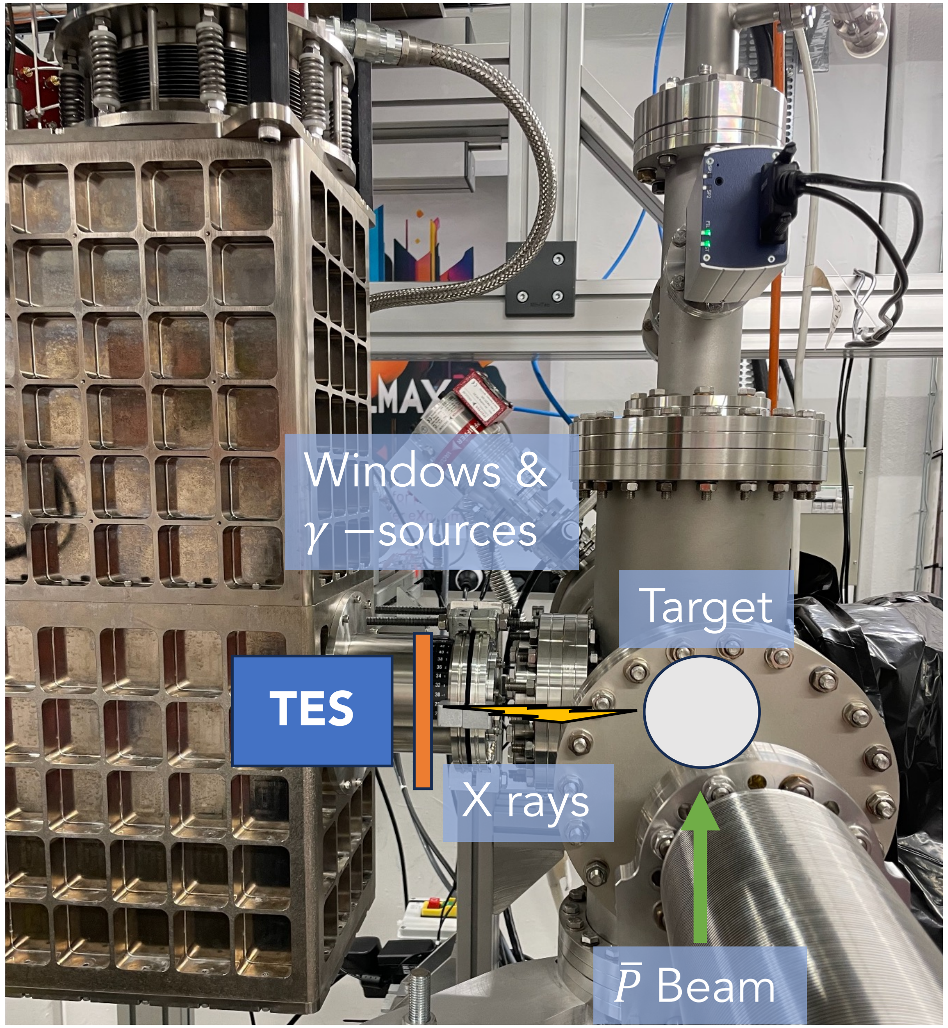

Repeated bunch splitting in ELENA:

- 200 mini-bunches
- 100 $ms$ separation
- Arb. Low Intensity (~$10^3$ $\bar{P}$s per MB)

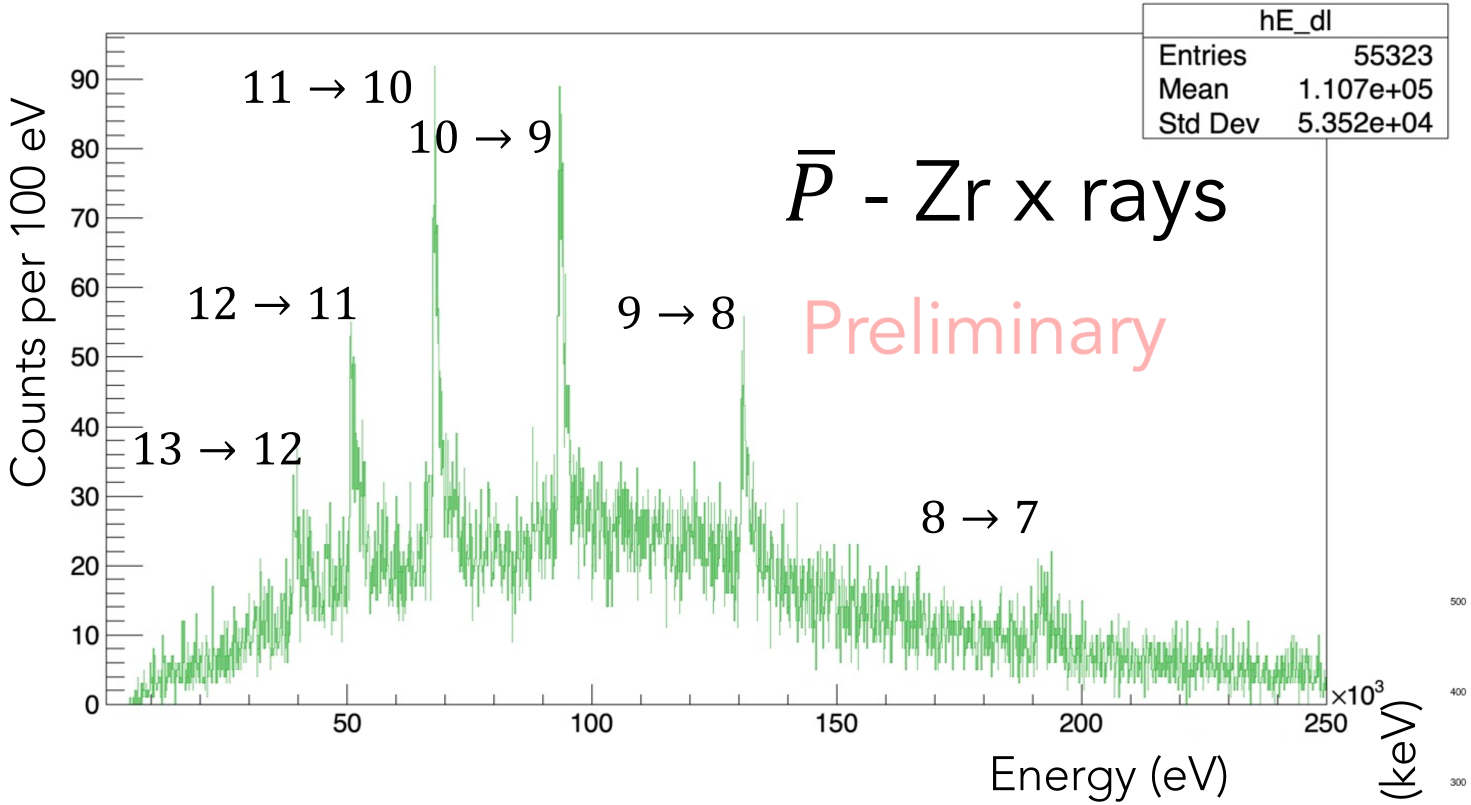
**Challenge:**
Intensity is low
**Measure at target**

# Outline

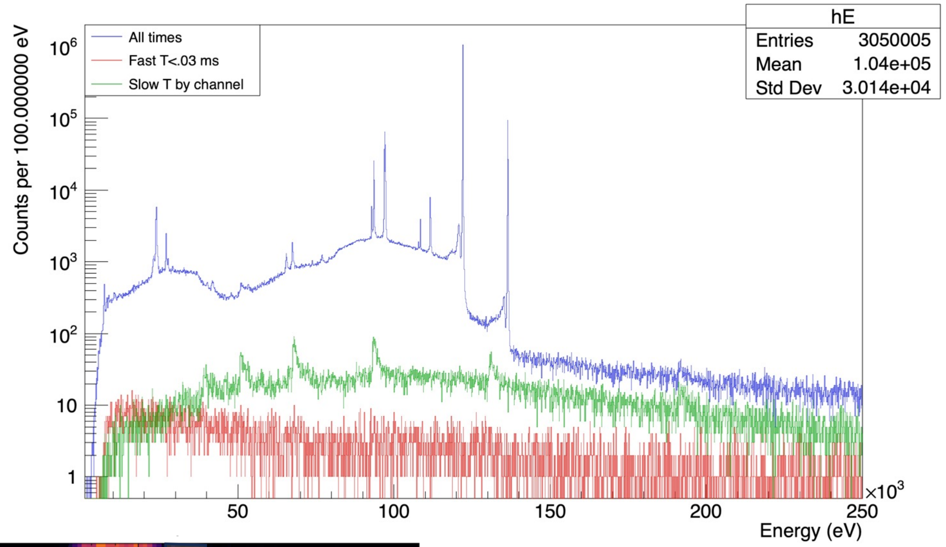
- Motivation and background
- Summer 2025 PAX Test beam
- First TES spectra of $\bar{P}$-atom x-rays

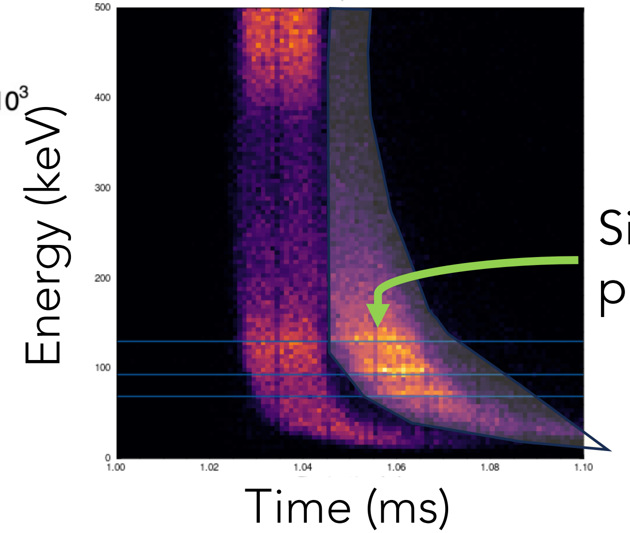


# $\bar{\mathrm{P}}$AX: First ever antiprotonic atom x-rays with a TES



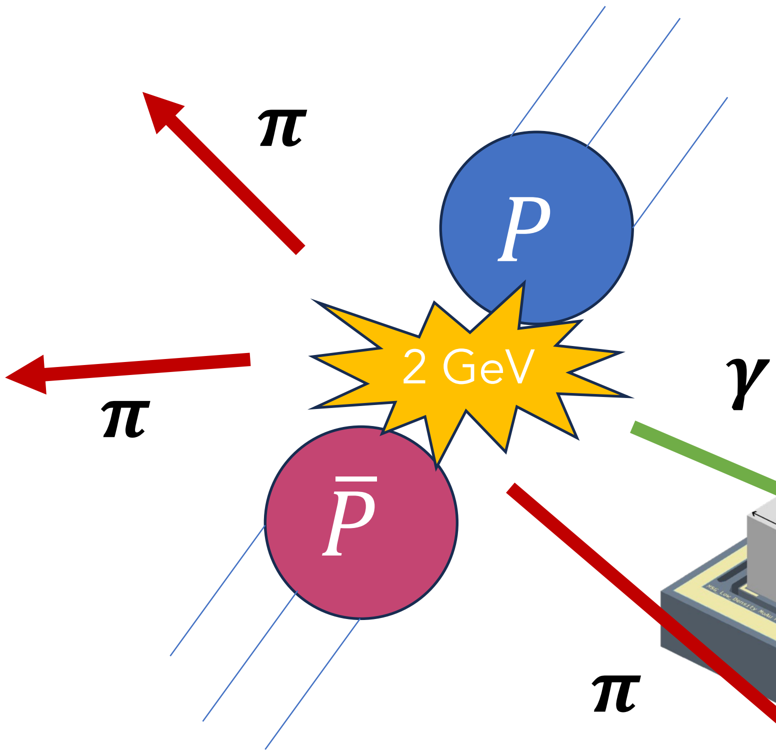

$\bar{\mathrm{P}}$ - Zr cascade from $\mathbf{n} = 13 \rightarrow 7$

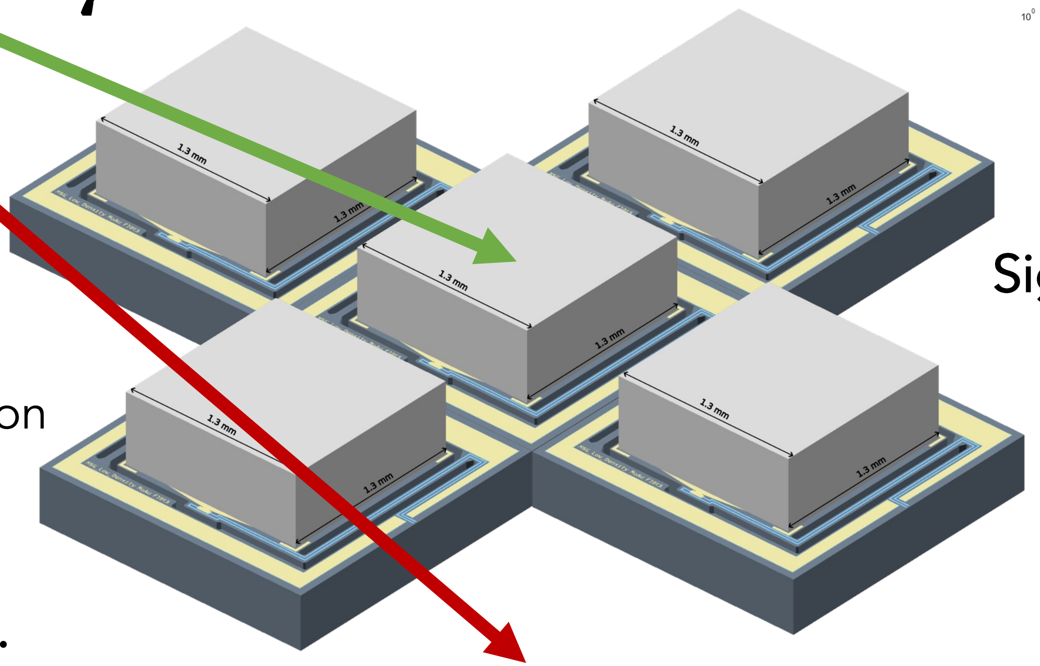



Signal of interest was prompt but “delayed”.

# Sources of background



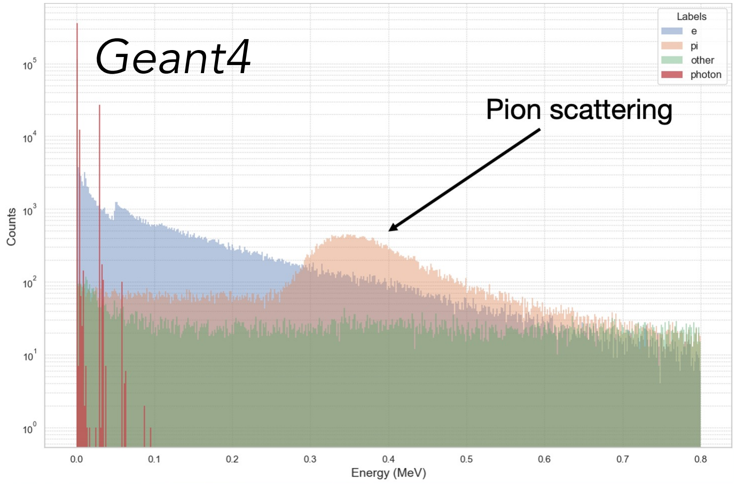




Each $\bar{P}$ - Cascade ends in annihilation

$$E = mc^2 = 2\ GeV$$

$\pi^{\pm}, \gamma, e^{\pm}$, Ions, Neutrons…

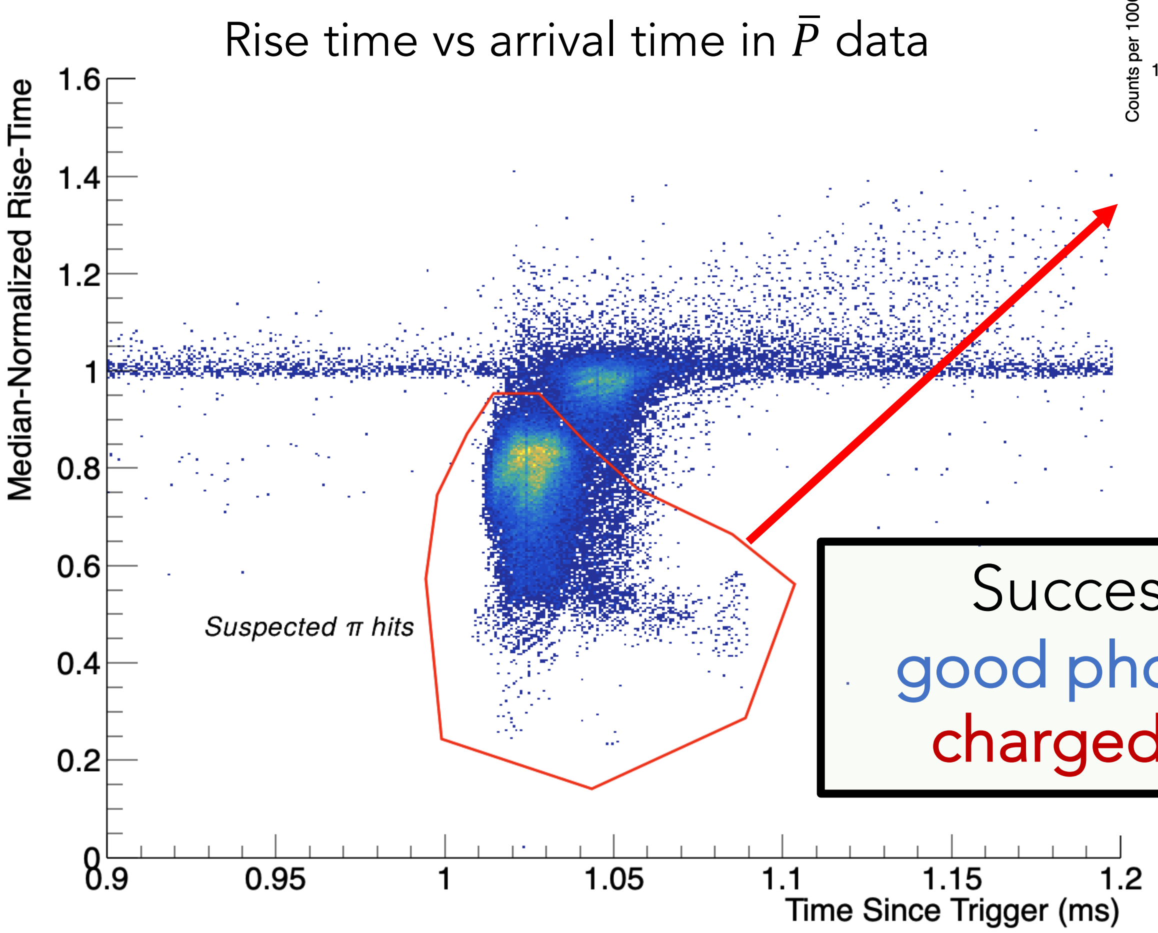
Work of
Q. Senetaire

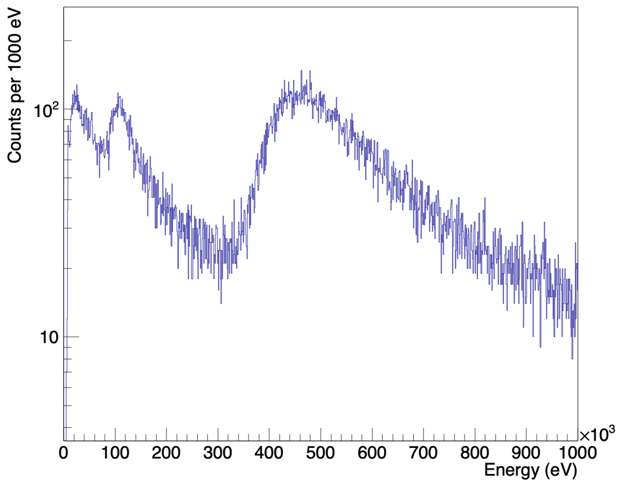


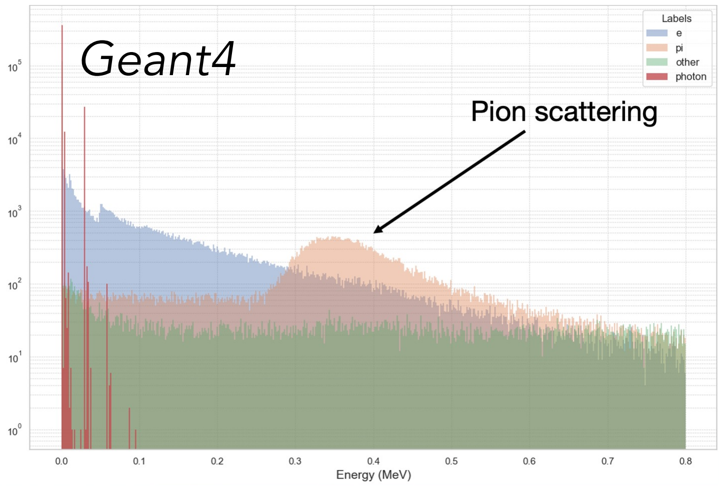

Signal of interest is hidden by:

- Charged particle hits
- Thermal cross-talk

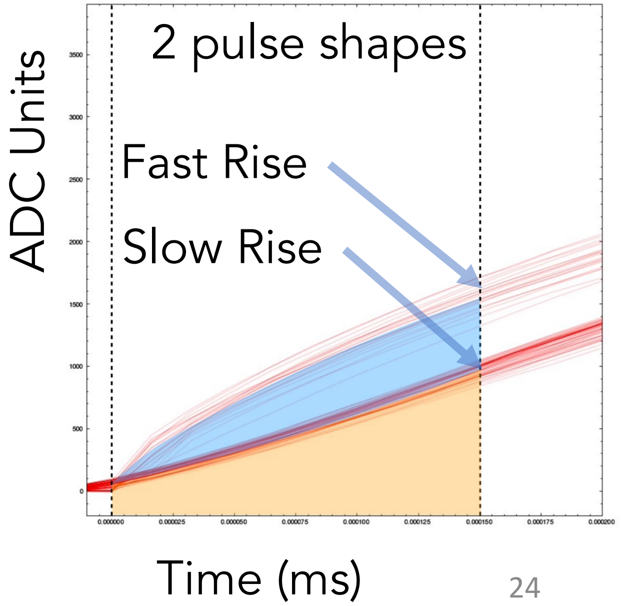
# Demonstrating Pulse Shape Discrimination in TESs



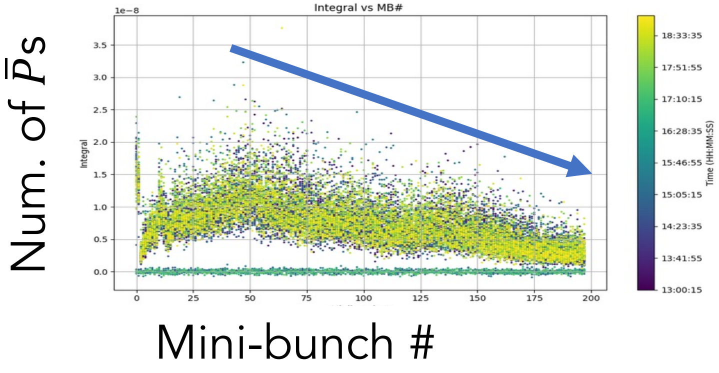

Successfully isolated
good photons (slow) from
charged particles (fast)



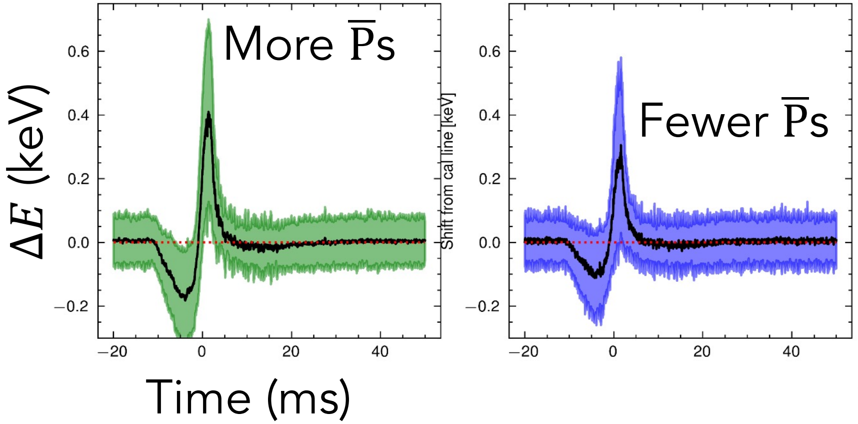
# Beam-induced gain shifts and broadening

Work of
F. Giraud

Intensity decreases over spill




Shift of $^{241}$Am(59 keV)

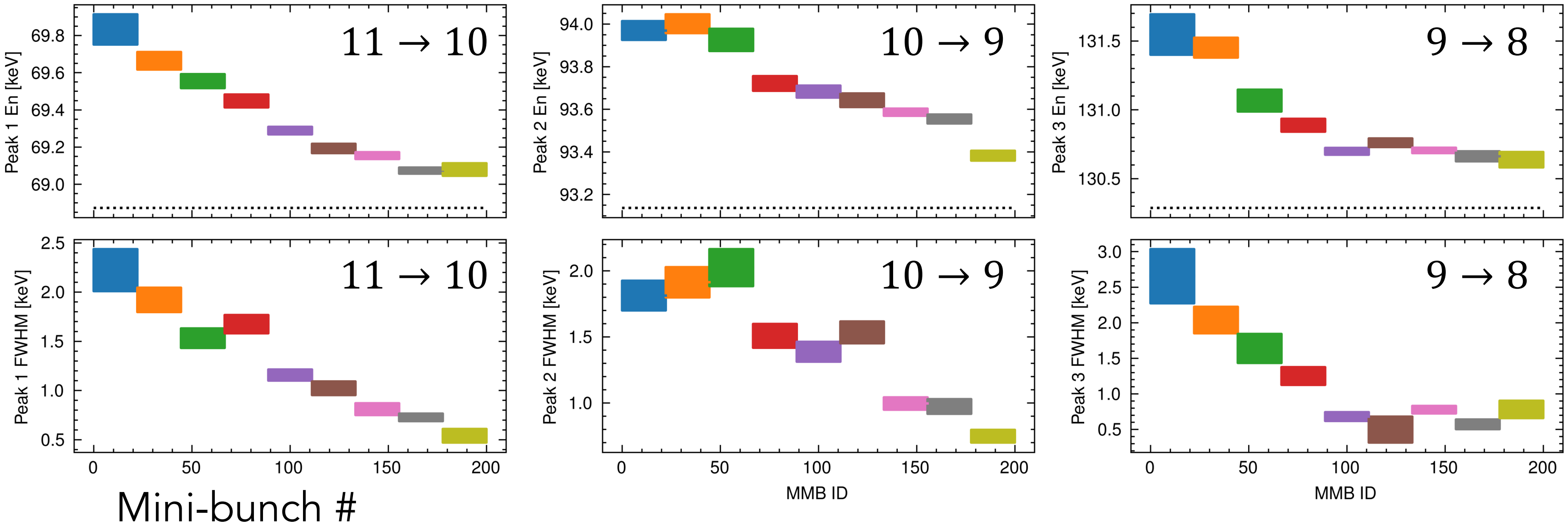



Both shifts and broadenings decrease with beam intensity.

$\bar{P}$ - Zr

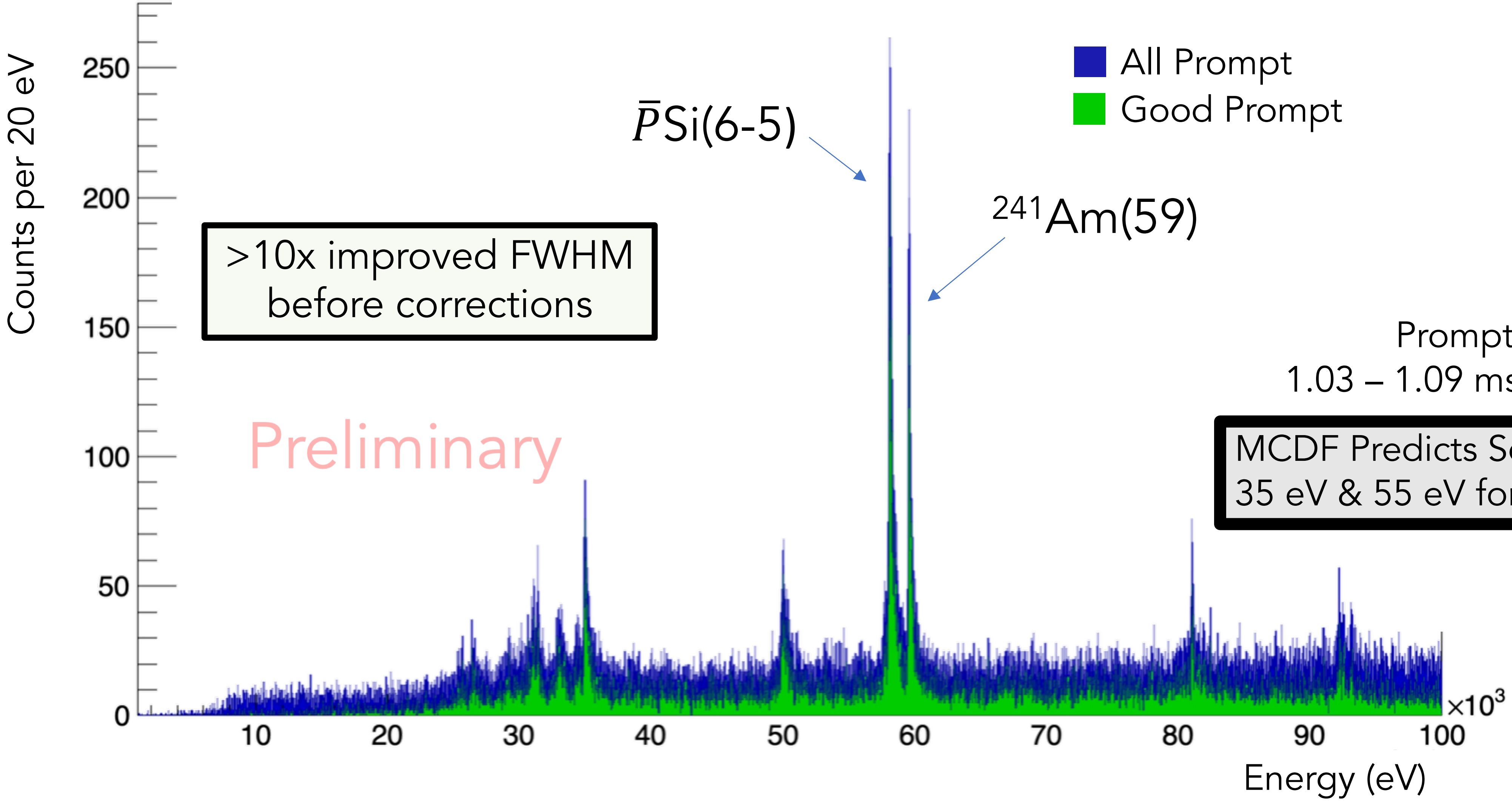
Centroid

FWHM (keV)




Work of
G. Baptista

# $\bar{\text{P}}$AX: Antiprotonic Si



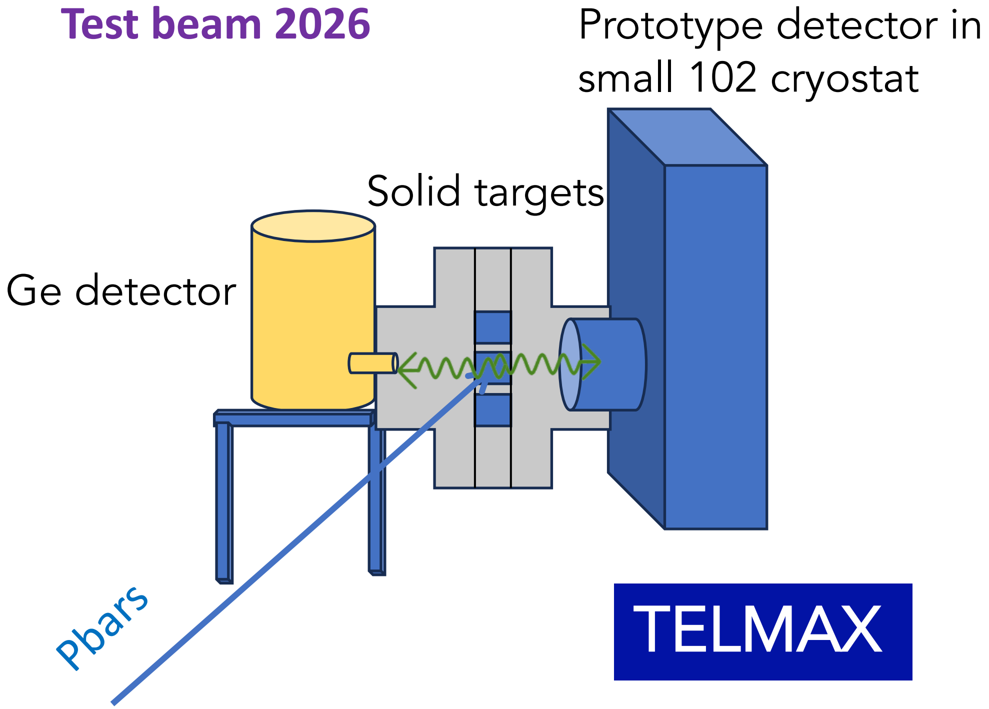

>10x improved FWHM
before corrections

Prompt Spectrum
1.03 – 1.09 ms after trig.

MCDF Predicts Separations of 35 eV & 55 eV for $\bar{P}$Si(6-5).

# The future of $\bar{\mathrm{P}}$AX at ELENA

**Test beam 2026**

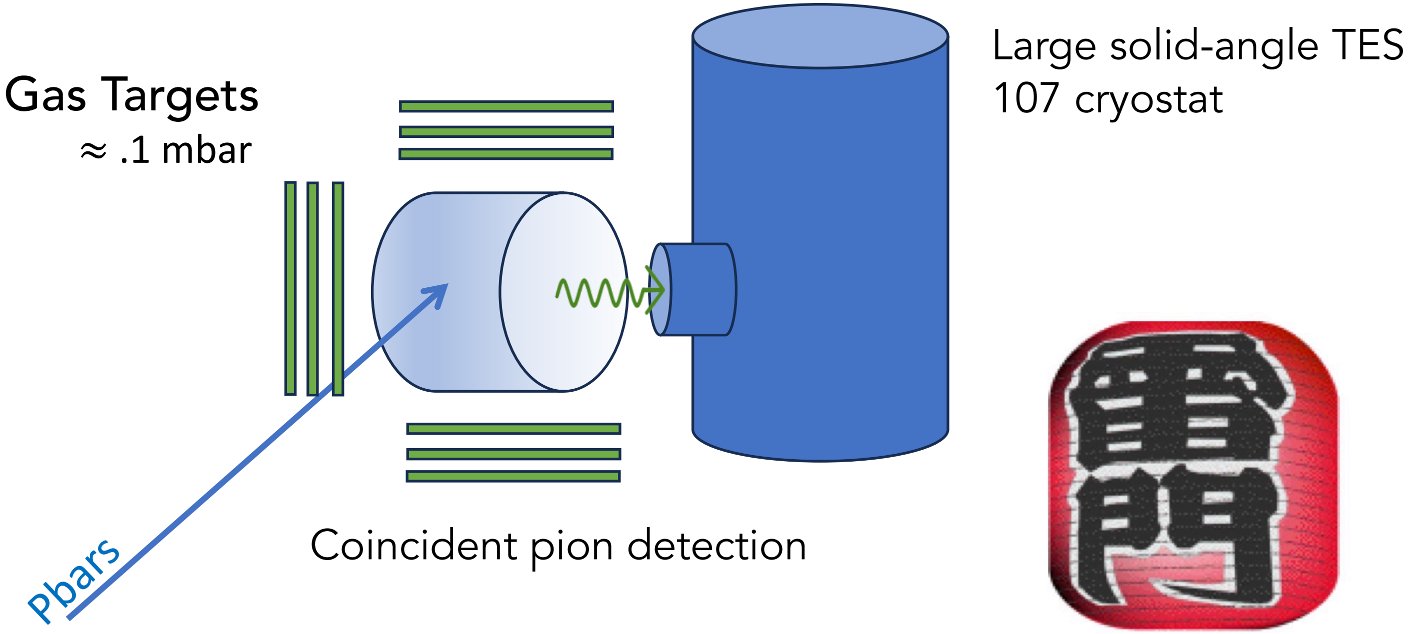



TELMAX

**In-beam test of prototype TES detector**

- Variable p-bar bunches ($10^3$-$10^4$)
- New prototype detector
- Validate pixel design

**Post LS3 (2027-2028)**




ASACUSA

**Full Experiment for QED tests**

- Strong-field QED tests with gases
- 30-200 keV range photon detection
- 2-month campaign
- Long term → Nuclear physics, BSM searches

# Many thanks to our collaborators

Laboratoire Kastler Brossel

G. Baptista
F. Nez
F. Giraud
**P. Indelicato**
N. Paul
S. Rathi
M. Roosa
Q. Senetaire
J. Sommerfeldt
P. Yzombard

NIST

D. Becker
D. Bennet
J. Dean
J. Gard
J. Fowler
M. Keller
K. Morgan
J. Mates
N. Nakamura
J. Nobles
N. Oritz
D. Schmidt
D. Swetz
P. Szypryt
J. Ullom

CERN

F. Butin
D. Gamba

RIKEN

T. Azuma
T. Hashimoto
T. Saito

Institute of SCIENCE TOKYO

H. Fujioka

CHUBU UNIVERSITY AICHI JAPAN

S. Okada

TECHNION Israel Institute of Technology

O. Eizenberg
B. Ohayon

NOVA FACULDADE DE CIÊNCIAS E TECNOLOGIA

**M. Guerra**
J. Machado

LPNHE PARIS

N. Garroum
M. Zito

KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN

T. Higuchi

Imperial College London

M. Hori

cea

JY. Rousse

## Summary

# Thank You!

*X-ray spectroscopy of exotic atoms with quantum sensing x-ray microcalorimeters offers a new way to probe strong-field BSQED while avoiding nuclear physics uncertainties.*

$\overline{\mathrm{P}}$AX has measured first $\bar{\mathrm{p}}$-atom x rays with a TES.

Final physics planned post LS3 with ASACUSA.

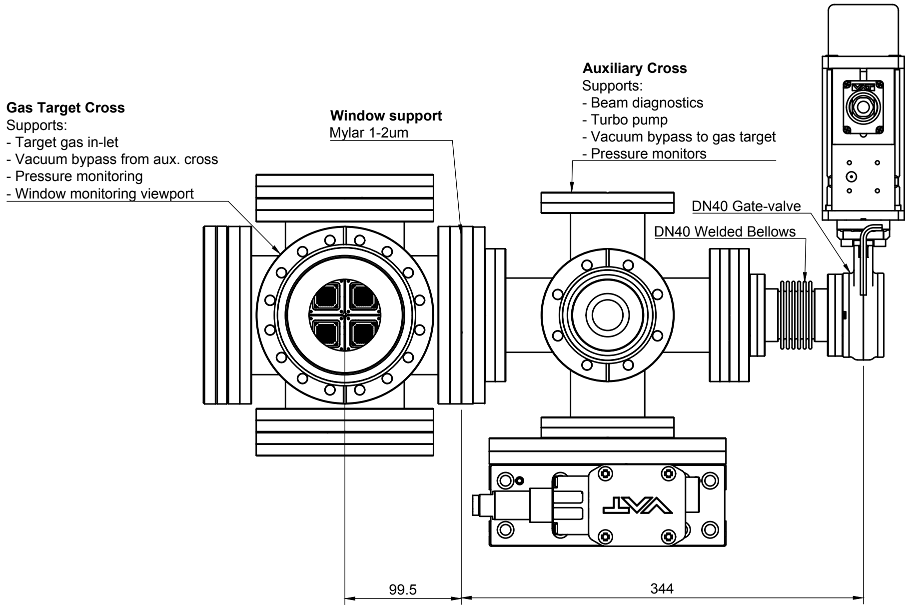
**ASACUSA**
Atomic Spectroscopy And Collisions Using Slow Antiprotons


ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

Acknowledgements:
PAX is funded through ERC-StG-2023.
This project has received funding from the European Union's Horizon Europe research and innovation program under grant agreement No 101057511.

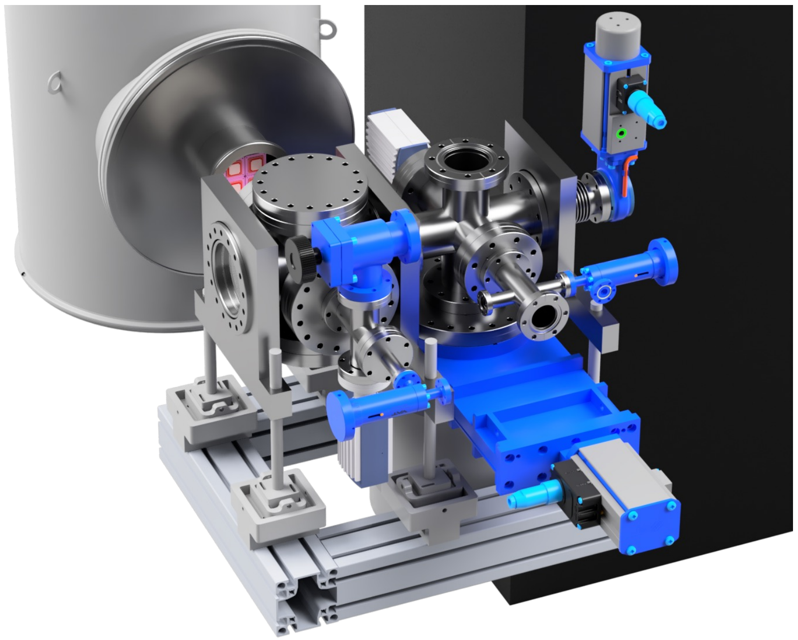
# $\bar{\mathrm{P}}$AX at ASACUSA

Final physics measurements will take place post-LS3 in collaboration with ASACUSA.




ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

ASACUSA



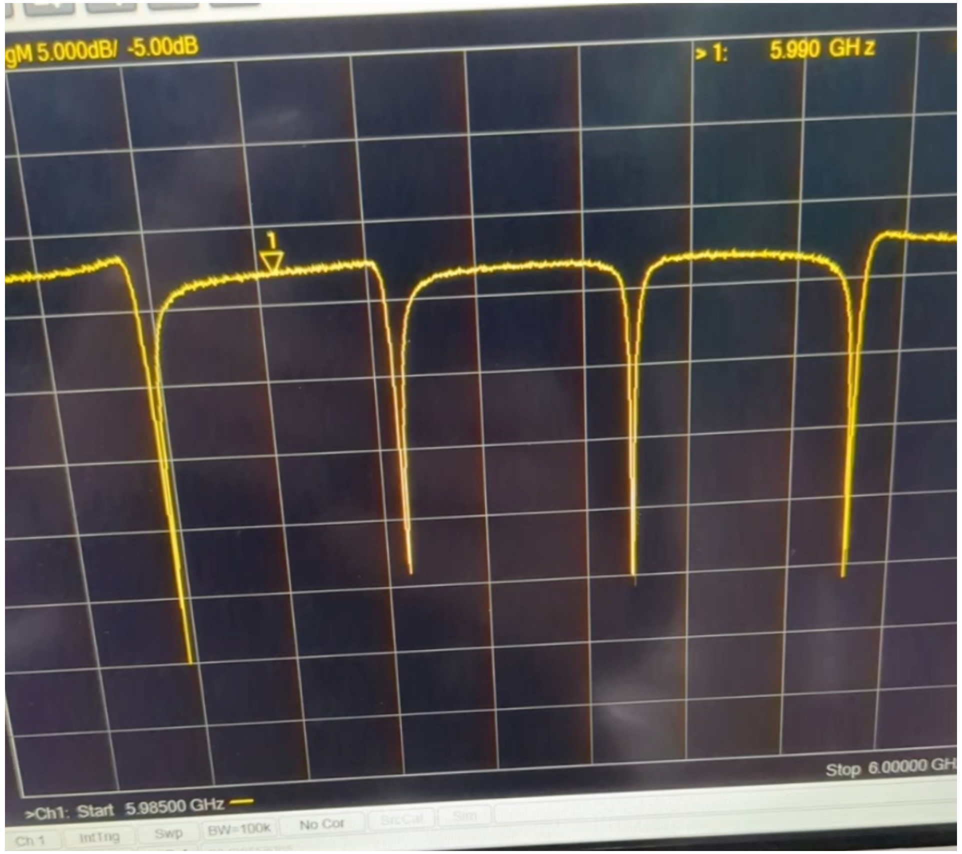
Developments:

- New 5 m beamline designed by CERN beam physicists
- PAX gas target station
- 4x micro-snout TES array with optimized performance

# High Channel Density via Microwave Multiplexed Readout

Each detector channel is given a unique microwave resonator frequency

**1 data channel / 100-1000s of detector channels**

# The $\overline{\mathrm{P}}$AX physics program

| Transition ($n_i \rightarrow n_f$) | Appx. $\Delta E_{f\rightarrow i}$ (keV) | 1st order QED | 2nd order QED | Nuclear effects |
|---|---|---|---|---|
| $^{20}$Ne (6→5) | 30 | 4 E-3 | 3 E-5 | 2 E-6 |
| $^{40}$Ar (6→5) | 100 | 5 E-3 | 5 E-5 | 1 E-5 |
| $^{84}$Kr (9→8) | 100 | 5 E-3 | 5 E-5 | 1 E-5 |
| $^{132}$Xe (10→9) | 170 | 5 E-3 | 5 E-5 | 2 E-5 |
| $^{184}$W (12→11) | 180 | 5 E-3 | 5 E-5 | 2 E-5 |

$$N_x = N_{\bar{p}} M \epsilon_{geo} \epsilon_{det}$$

$N_{\bar{p}} = 1 \times 10^6$/spill
M= 10
$\epsilon_{geo} = 3 \times 10^{-4}$
$\epsilon_{det} = 0.4$

$N_x$=1200 counts/spill

< 1 week measurement time / transition depending on available $\overline{\mathbf{P}}$ beam structure

**Among the highest field systems ever accessed in the laboratory !**

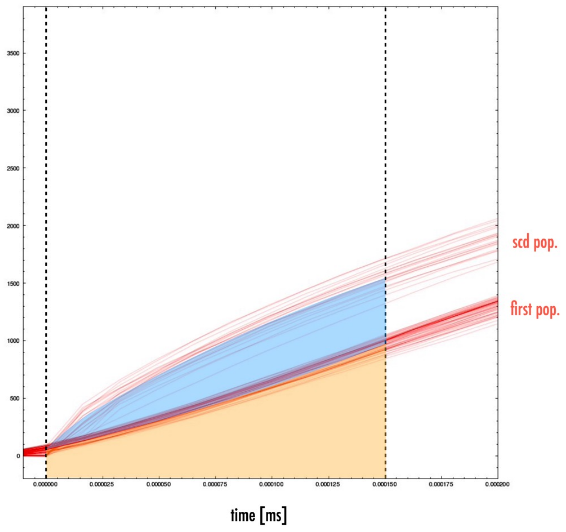
## $\overline{\mathrm{P}}$AX firsts

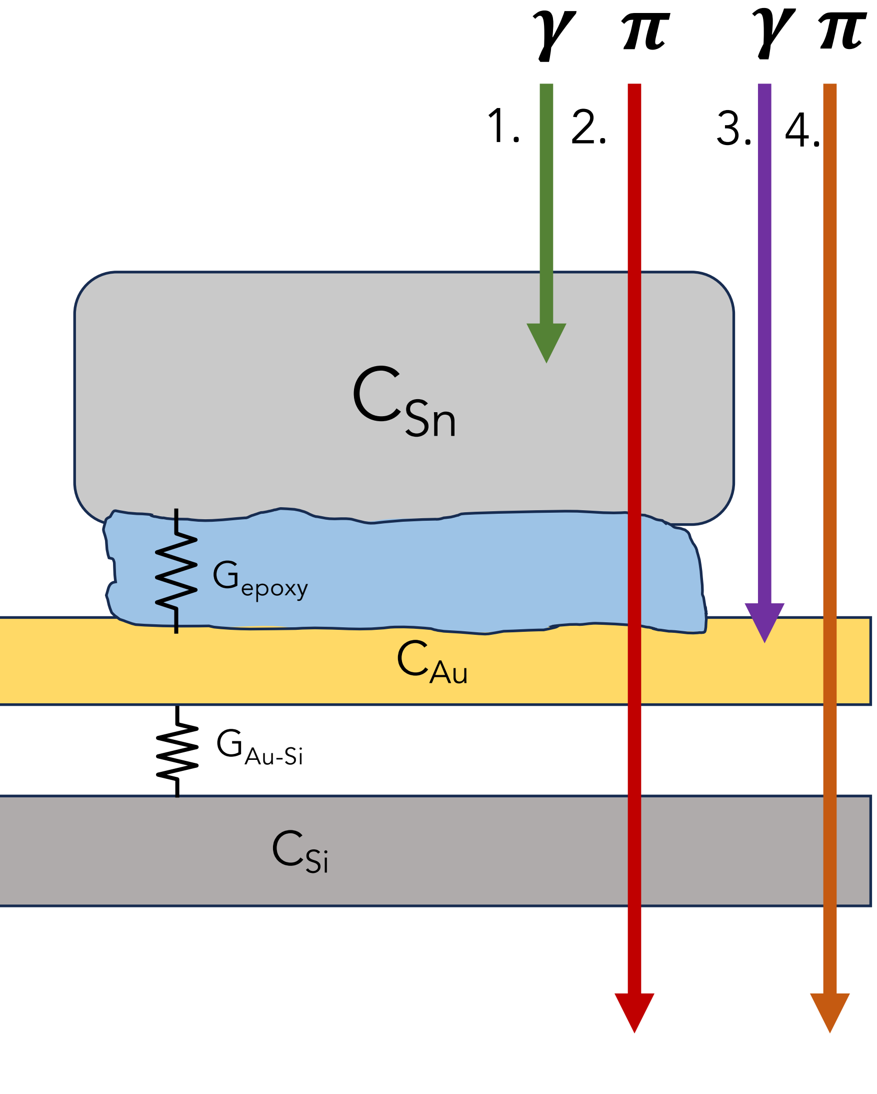
- Study second-order QED effects across $10 \leq Z \leq 74$
- Achieve $10^{-5}$ experimental precision for heavy exotic atom spectroscopy

**Perspectives:** Strong interaction studies, exotic physics searches

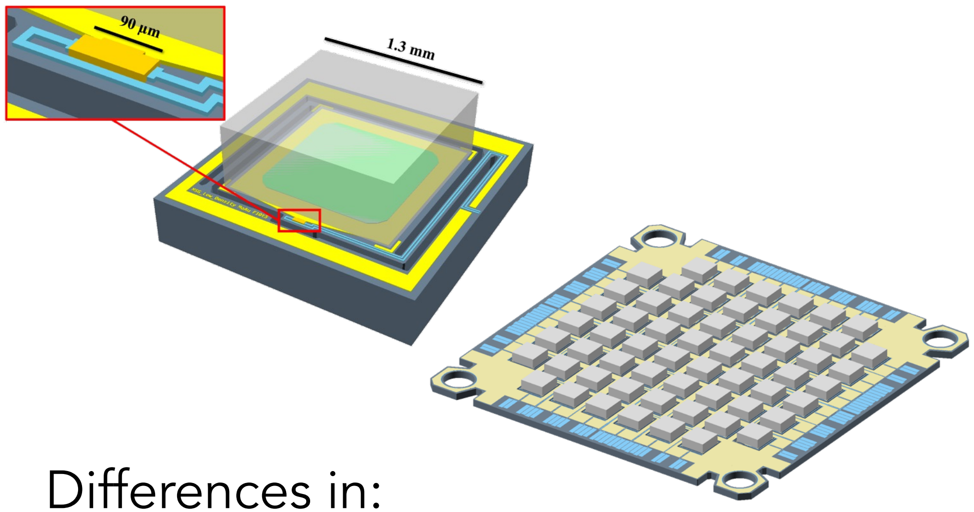
N. Paul, PRL 126, 1773001 (2021)

# Origins of Rise-Time Populations




$\overline{\text{P}}$AX array and pixel drawing

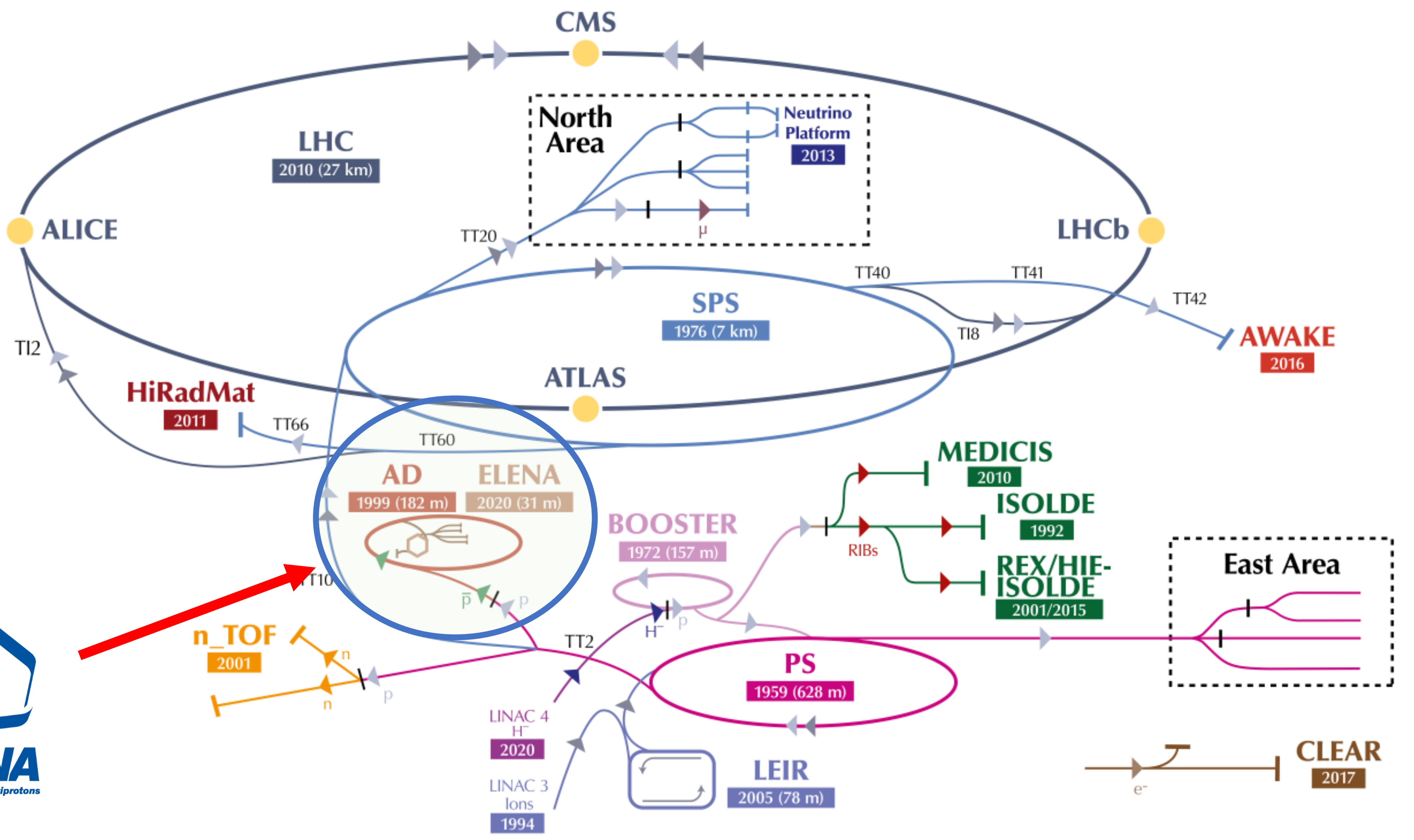



Differences in:

Energy deposition: $\gamma$ vs $\pi$

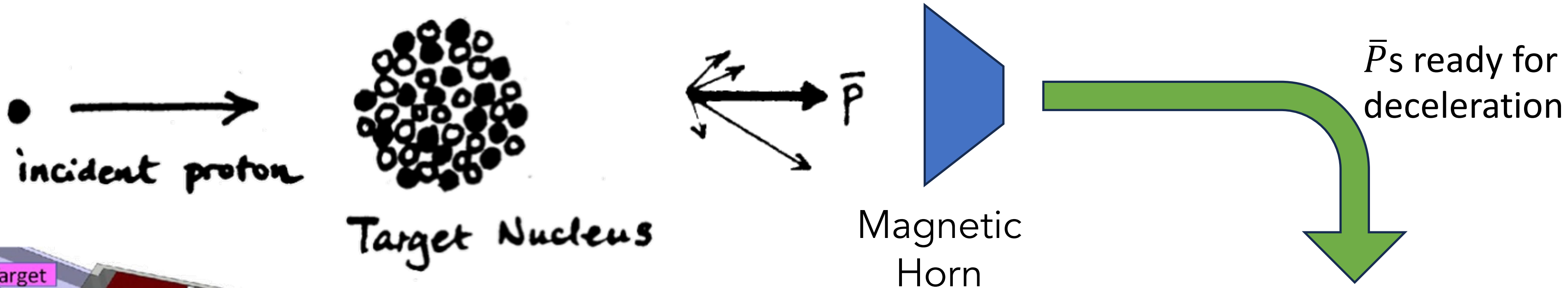
Energy dissipation: $Sn$ vs $Au$

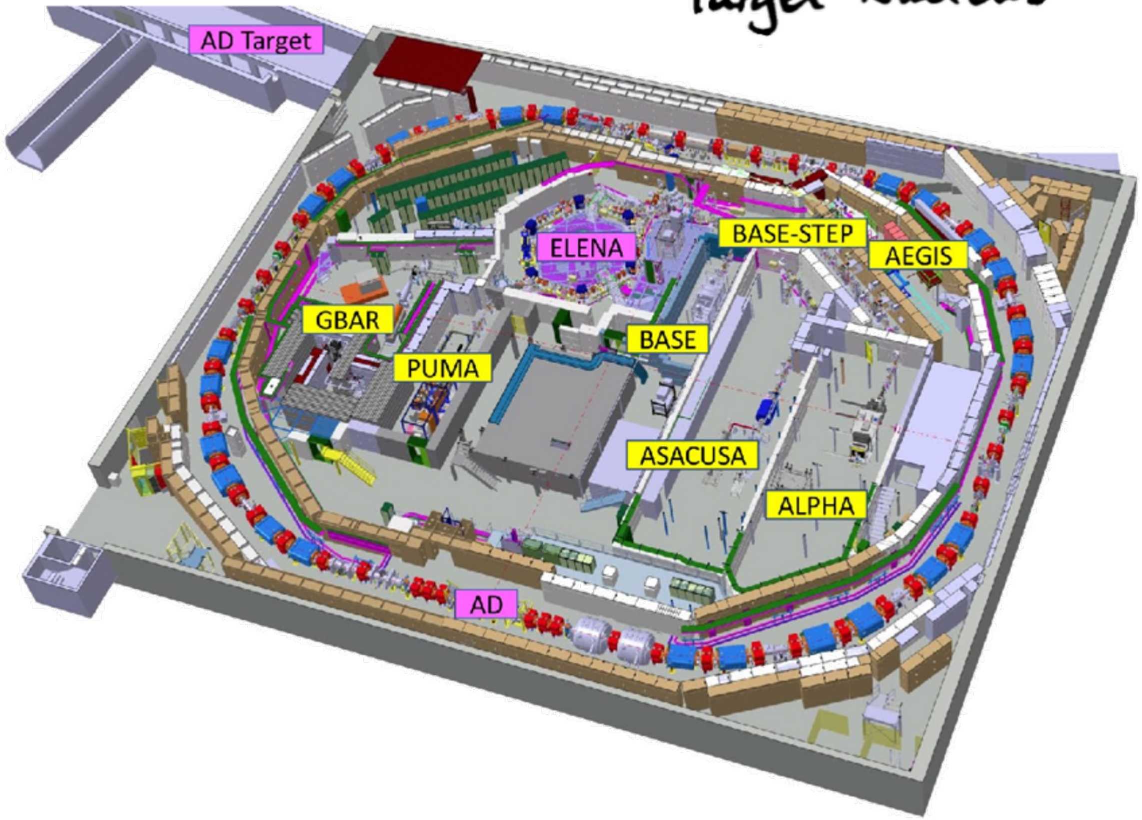
# Antiproton production at CERN




ELENA
Extra Low ENergy Antiprotons

# Antiproton production at CERN

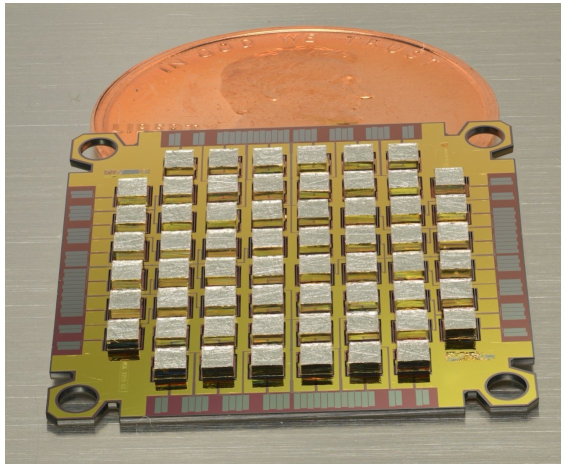


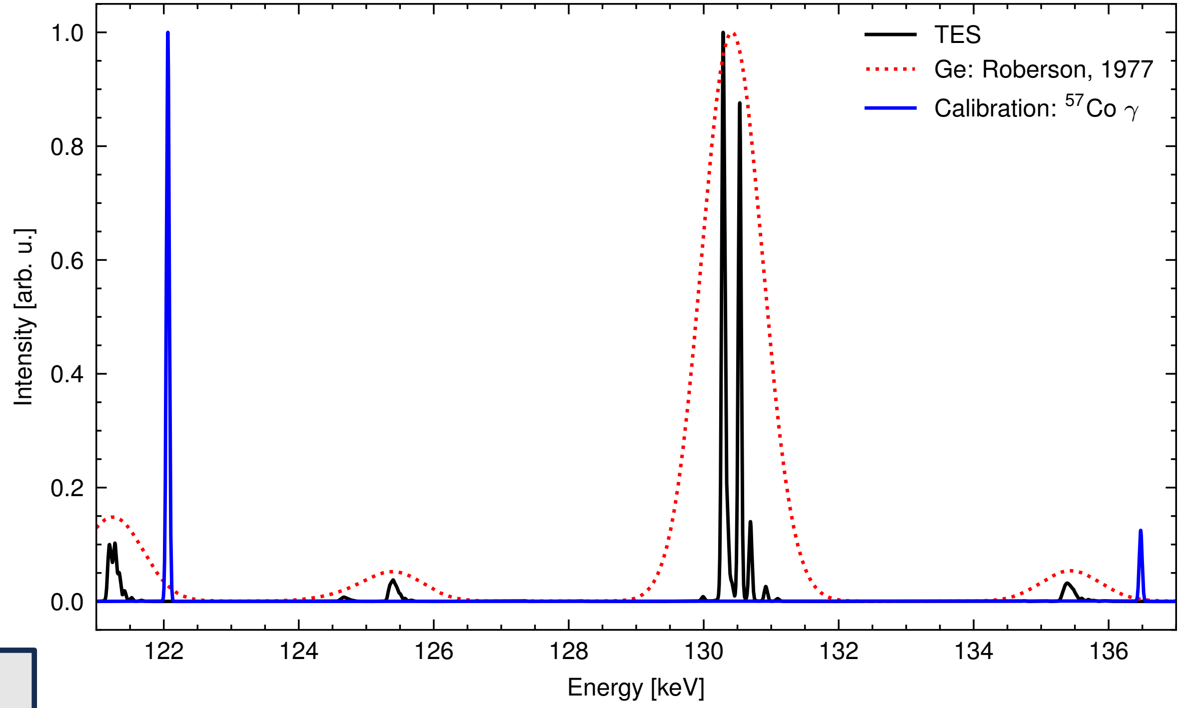

# Key technology: Transition Edge Sensing (TES) Microcalorimeter

**Transition Edge Sensing (TES)** μ-calorimeter

NIST Boulder, CO, USA: Quantum Calorimeters Group

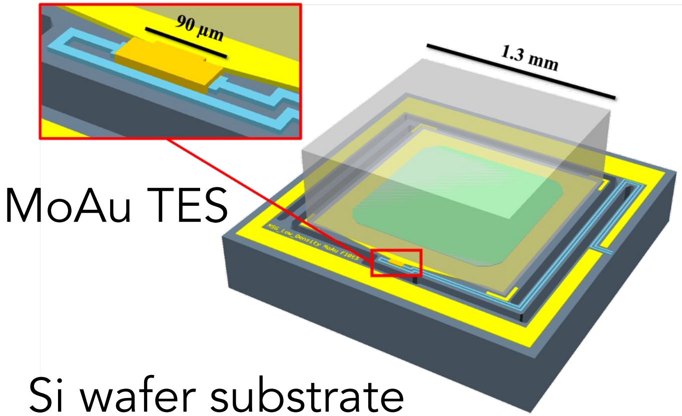


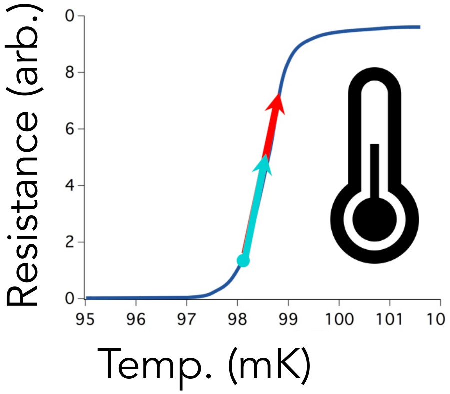
2 cm




*MDFGME* spectrum of $\bar{p} - Zr$ near $n = 9 \rightarrow 8$ transition

Prototype design for $\overline{\mathrm{P}}\mathrm{AX}$



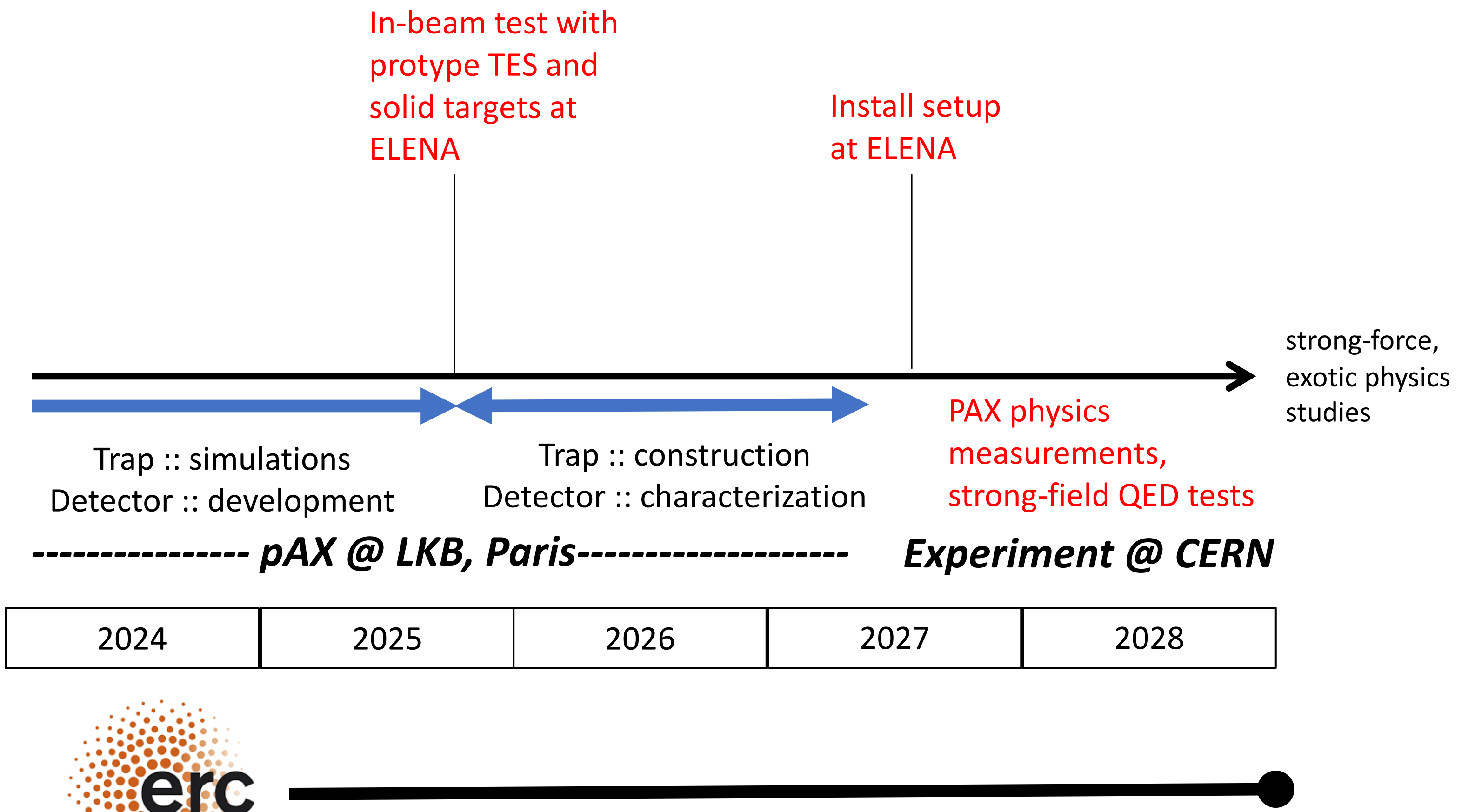

**TES $\mu$-cals can deliver < 50 eV resolution FWHM @ 100 keV.**

Figures from Ullom and Bennett 2013

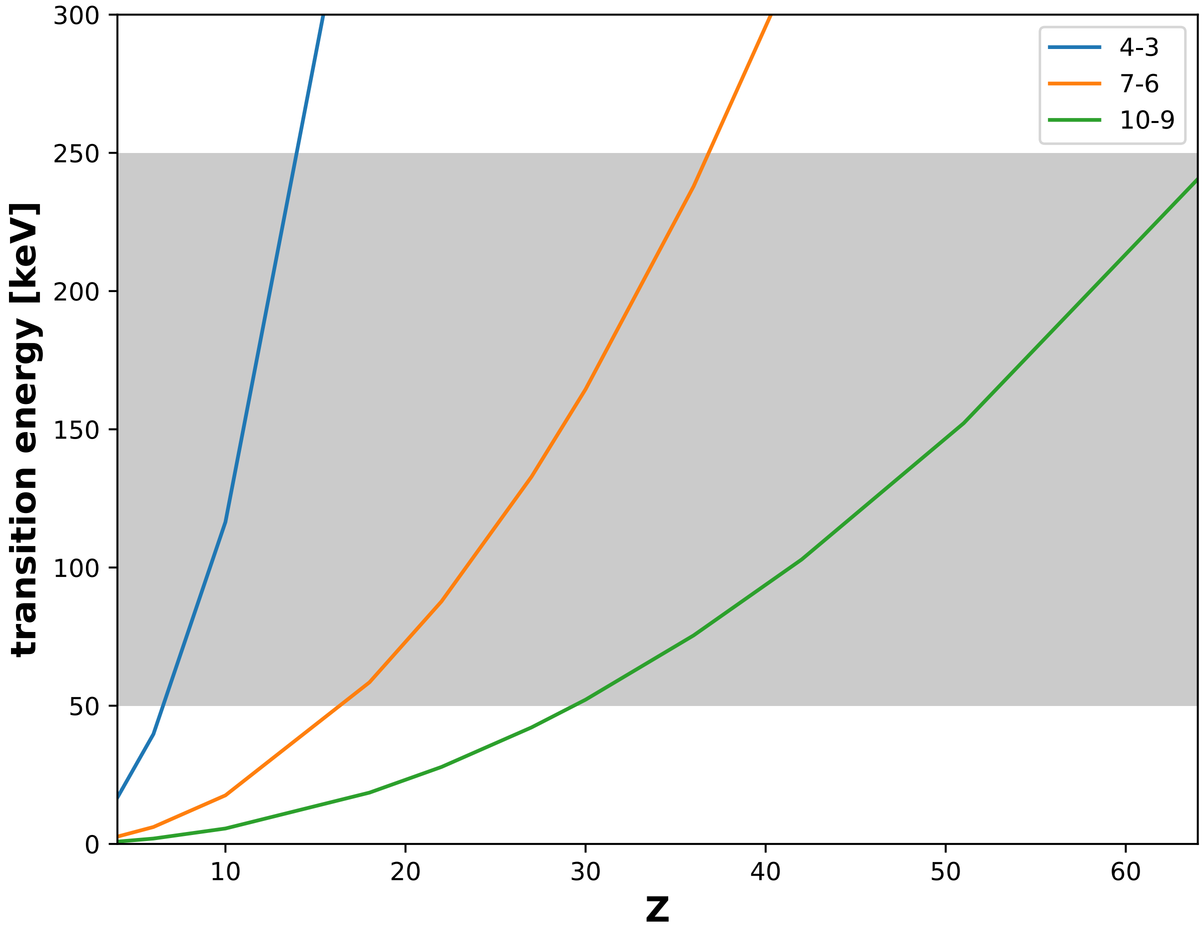
Photo provided by J. Nobles and M. Keller (NIST)

# The $\bar{p}AX$ timeline

**Legend**
Physics/WP
Milestone



# Long term : PAX + PUMA, strong-force shifted x-ray transitions




From the LEAR literature, the 7-6 transition is the last one that one normally sees before annihilation.

- For the energy range detectable with the PAX TES detector, this transition will be measurable from 14<Z<40, i.e. from Si to Zn.
- The typical energy shifts are ~20 eV, which should be easily detectable as this is about ½ the intrinsic resolution of the detector
- Attainable centroid accuracies ~1 eV, validated with JPARC data.