

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

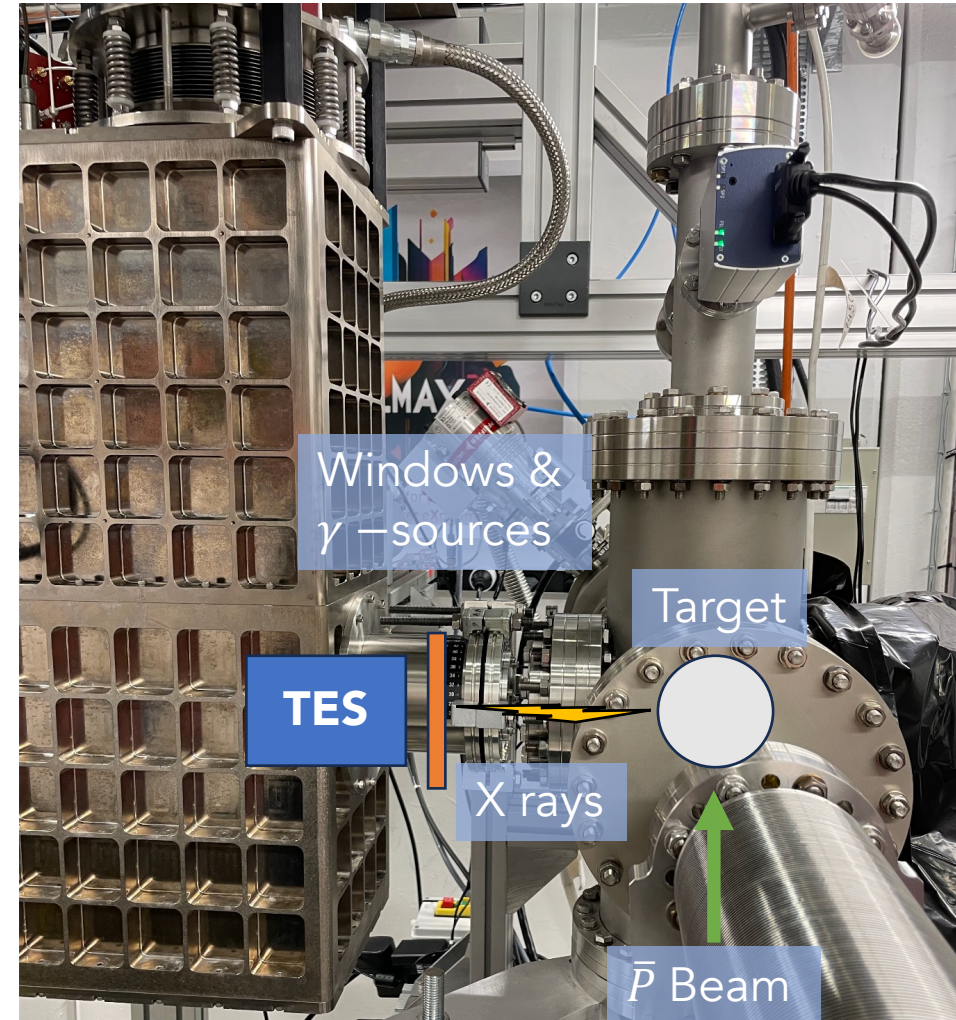


Michael Roosa  
Laboratoire Kastler Brossel  
Nuclear Photonics 2025

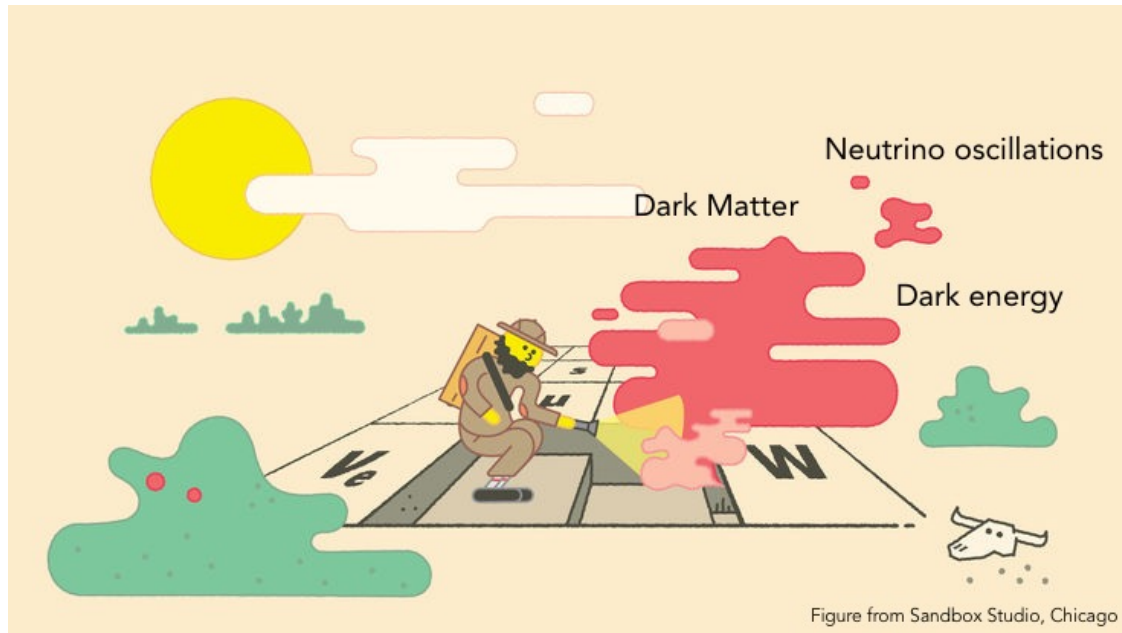


# Outline

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



# The Standard Model and Beyond?



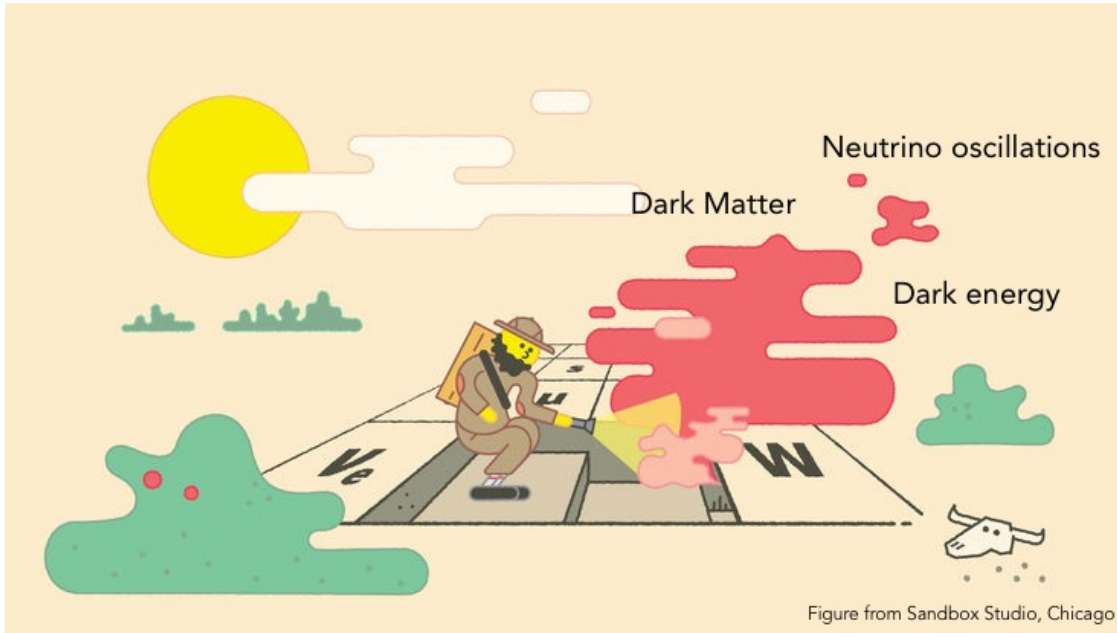
Numerous experimental observations cannot be explained by the Standard Model

- 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?

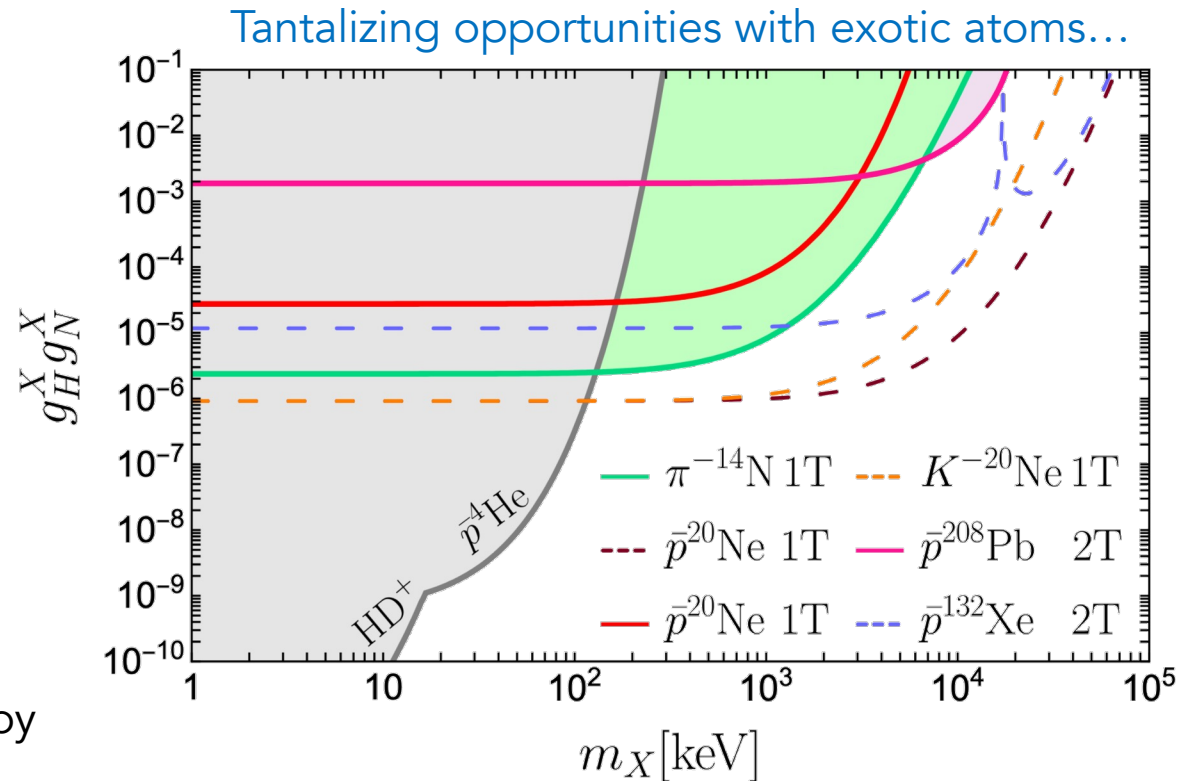


Numerous experimental observations cannot be explained by the Standard Model

- Dark energy, dark matter, neutrino oscillations

Are signs of new physics, how to find it?

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Proposed MeV scale bosons.

H. Lui et al. 2025 accepted to PRL

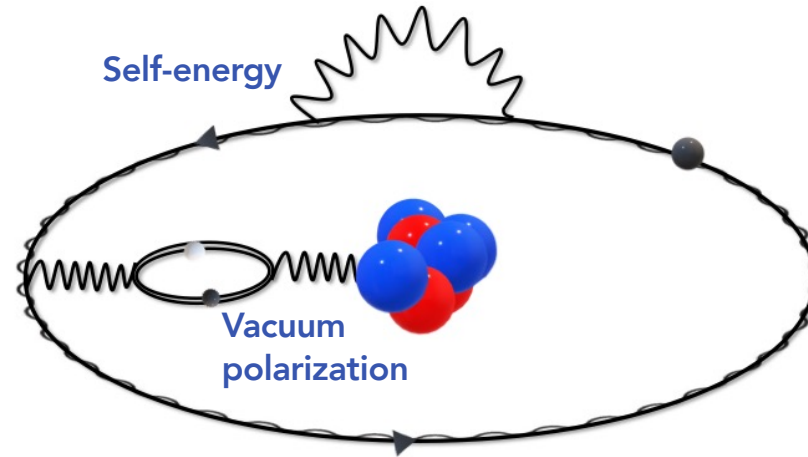
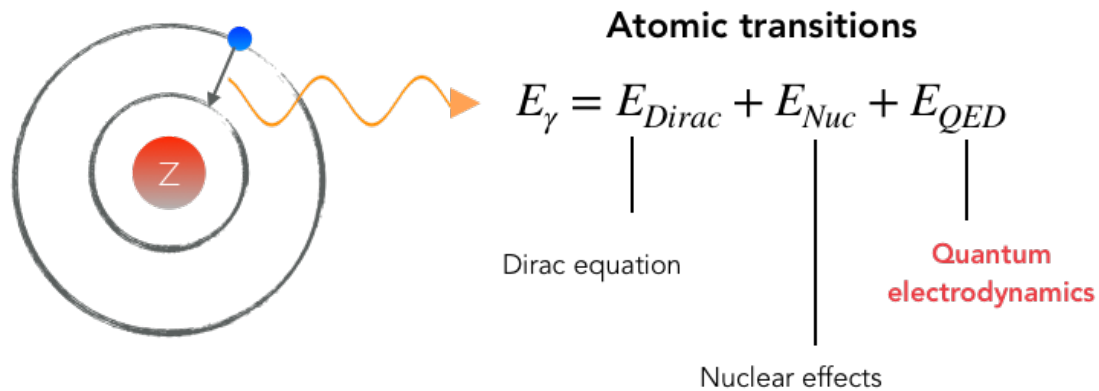


+Untested strong-field QED effects  
above the Schwinger limit

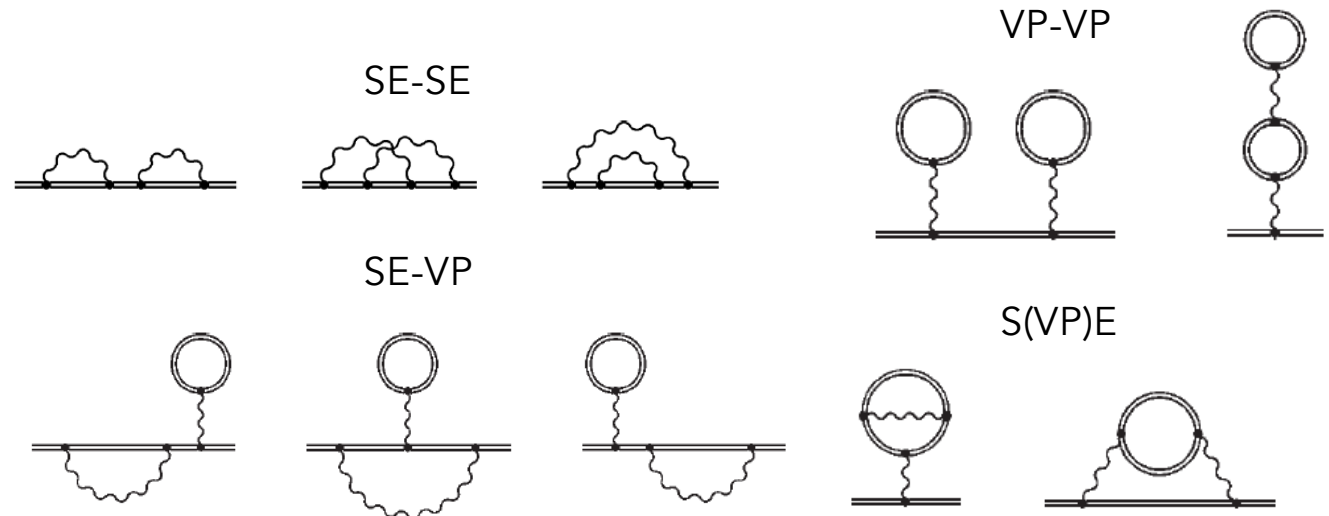
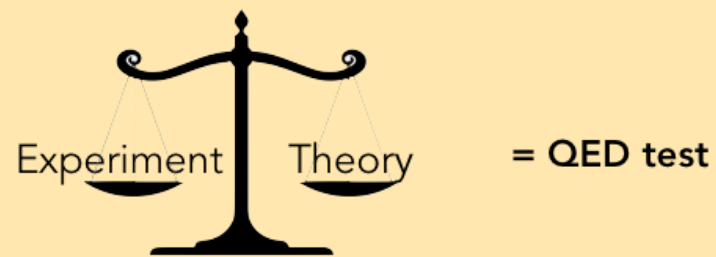


# Quantum electrodynamics in a nutshell

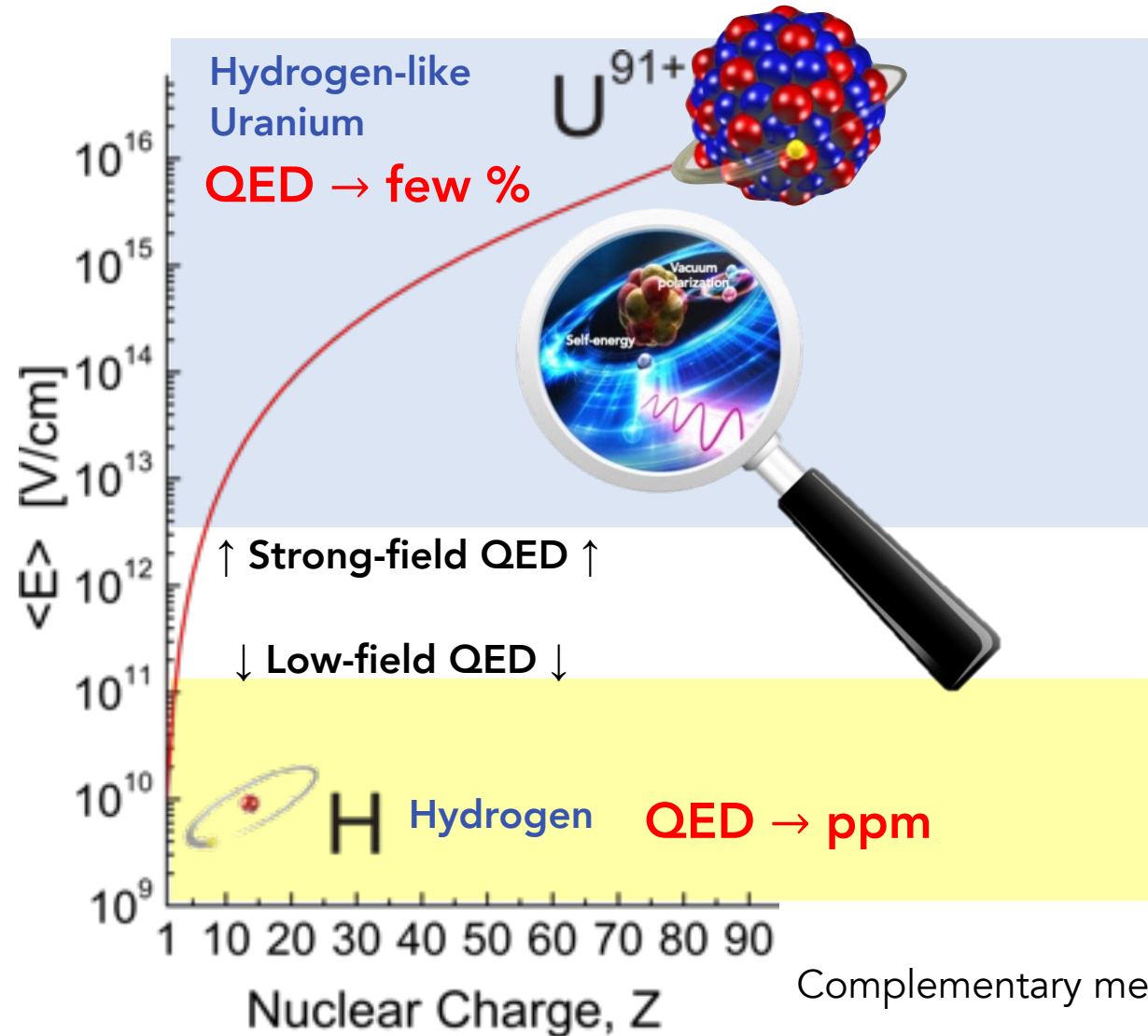
Quantum electrodynamics : interactions between photons and charged particles



Work of  
Dr. J. Sommerfeldt



# 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

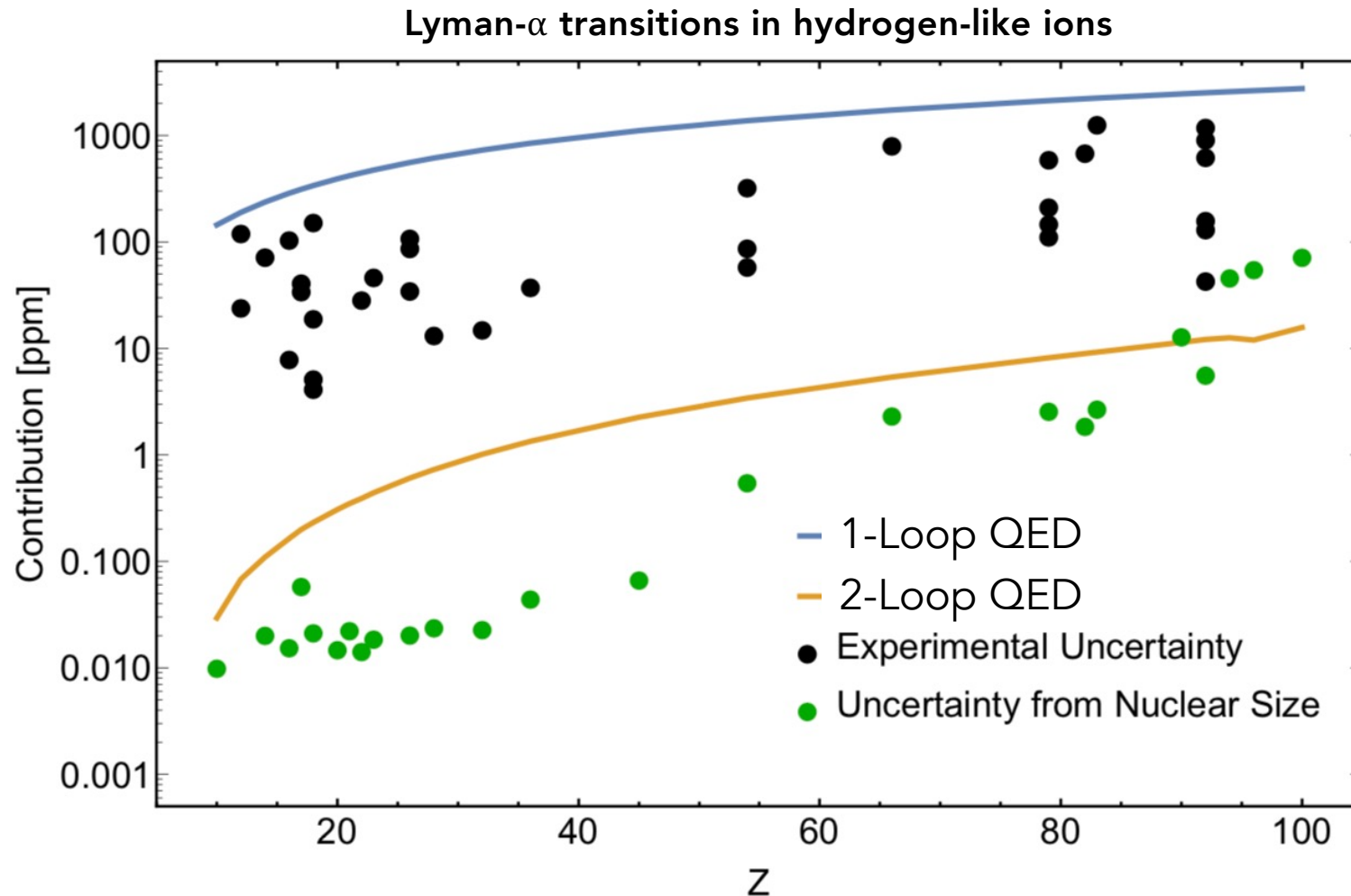
## Strong-field Challenges:

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

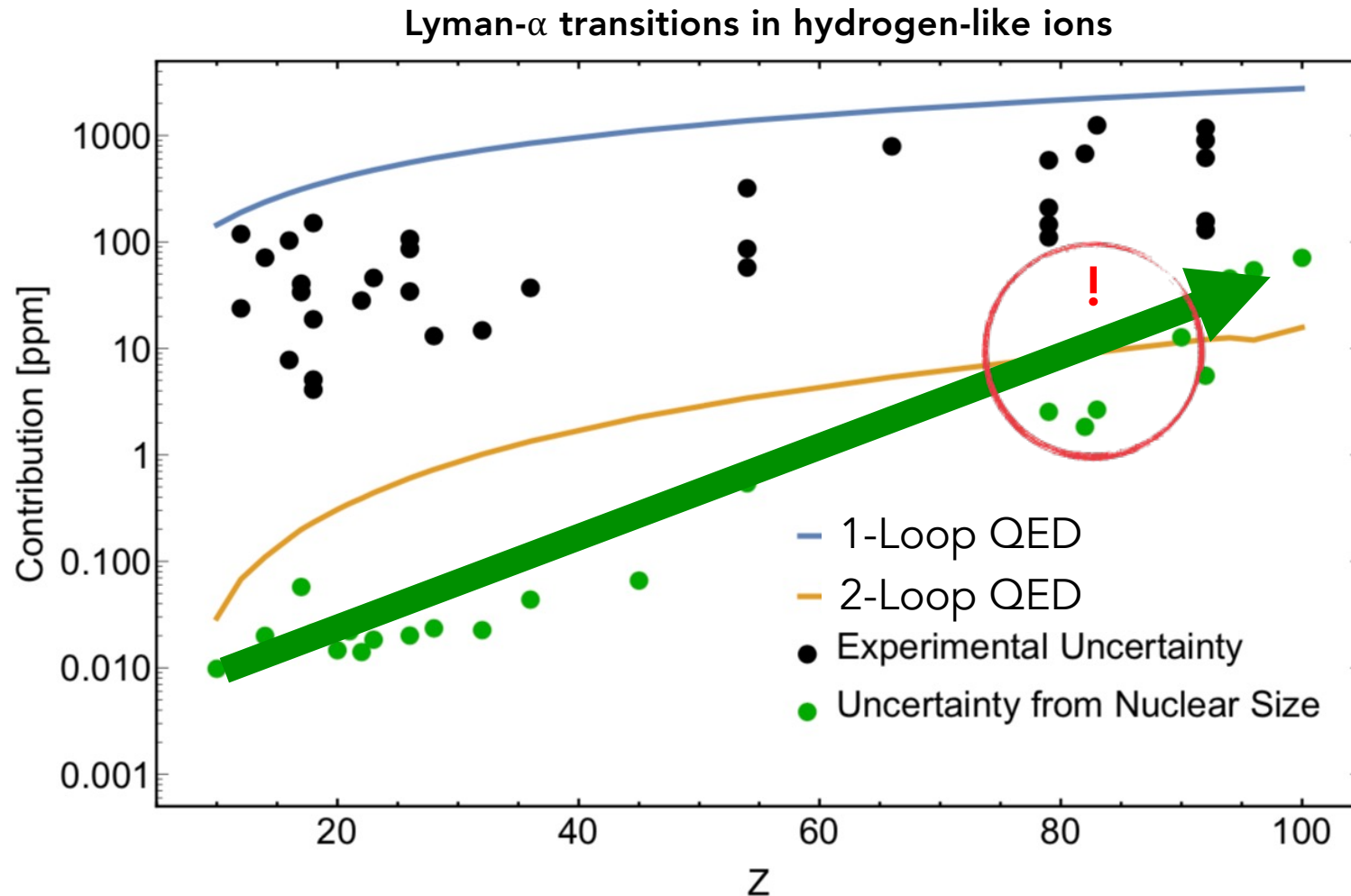
Complementary methods: Ex.  $g$ -factors, Sailer, *Nature* 606 (2022)

Ex. High-intensity lasers, Fedeli, *PRL* 127 (2021) 6

# Strong-field QED: limitations from nuclear physics



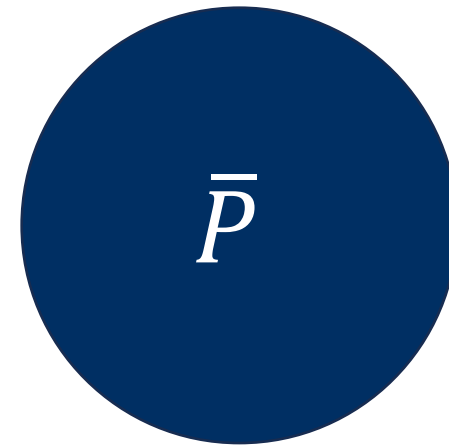
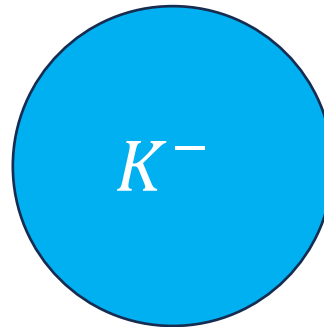
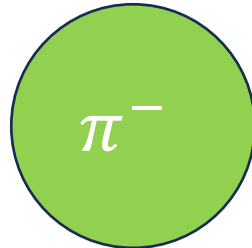
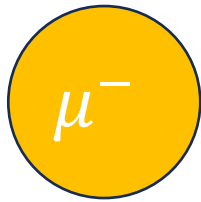
# Strong-field QED: limitations from nuclear physics





# Strong-field QED with Exotic Atoms

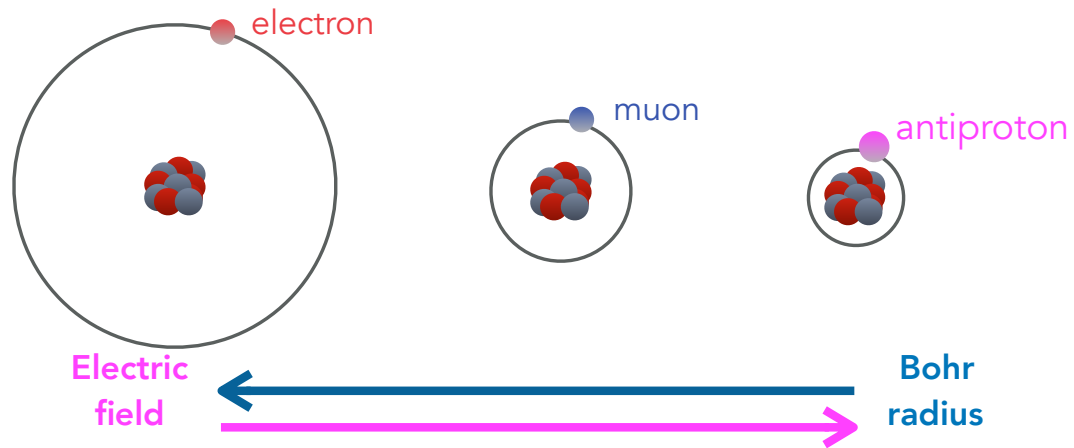
## Exotic Atoms



An atom where electrons are replaced  
another negatively charged particle.

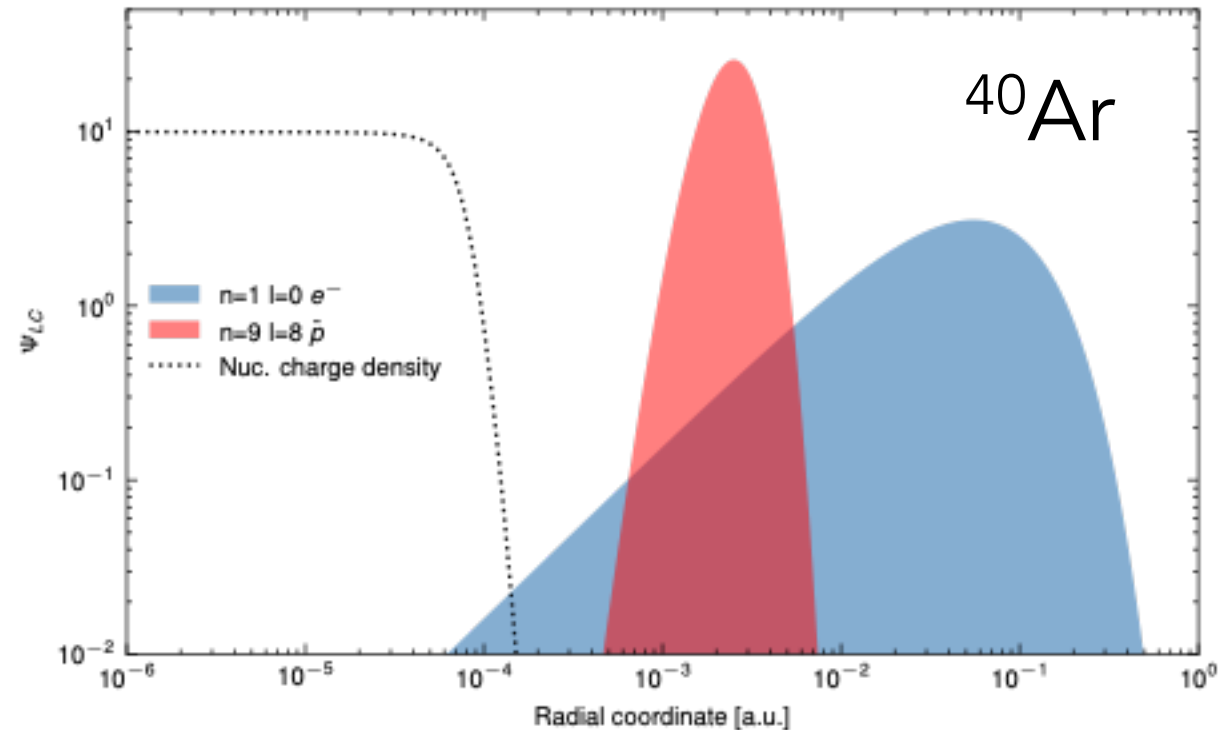


# Strong-field QED with Antiprotonic Atom Circular Rydberg States



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

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



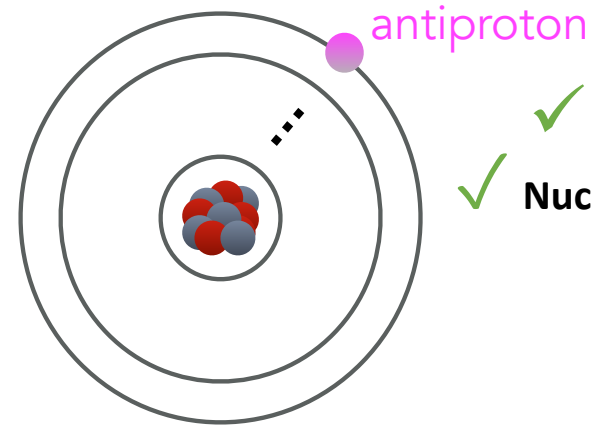
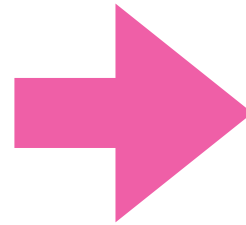
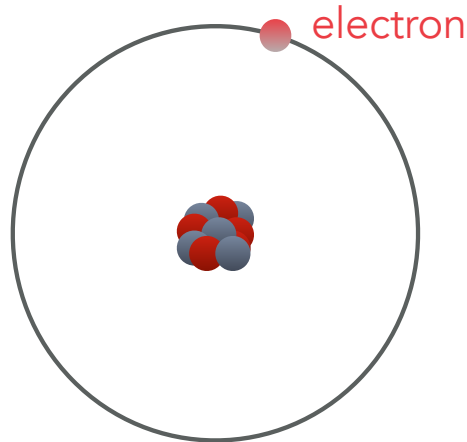
- Heavy exotic particle  $\rightarrow$  Small Bohr radius  $\rightarrow$  Strong electric field
- Higher order QED effects magnified
- Small nuclear overlap  $\rightarrow$  Small sensitivity to nuclear charge radii uncertainties.

# Strong-field QED with Antiprotonic Atom Rydberg States

*2p-1s Lamb Shift in HCl*

*Exotic atom Rydberg transition*

✓ Strong field QED  
✗ Nuclear effects  $\geq$  QED effects



✓ STRONGEST field QED  
✓ Nuclear effects  $\ll$  QED effects

Atom	Transition	Transition energy	1 <sup>st</sup> order QED	2 <sup>nd</sup> order QED*	Nuclear effects
H-like U	Lyman $\alpha$ 1	$\sim 100$ keV	$3 \times 10^{-3}$	$1 \times 10^{-5}$	$2 \times 10^{-3}$
$\bar{p}$ -Xe	$n=12 \rightarrow n=11$	$\sim 100$ keV	$7 \times 10^{-3}$	$6 \times 10^{-5}$	$1 \times 10^{-5}$

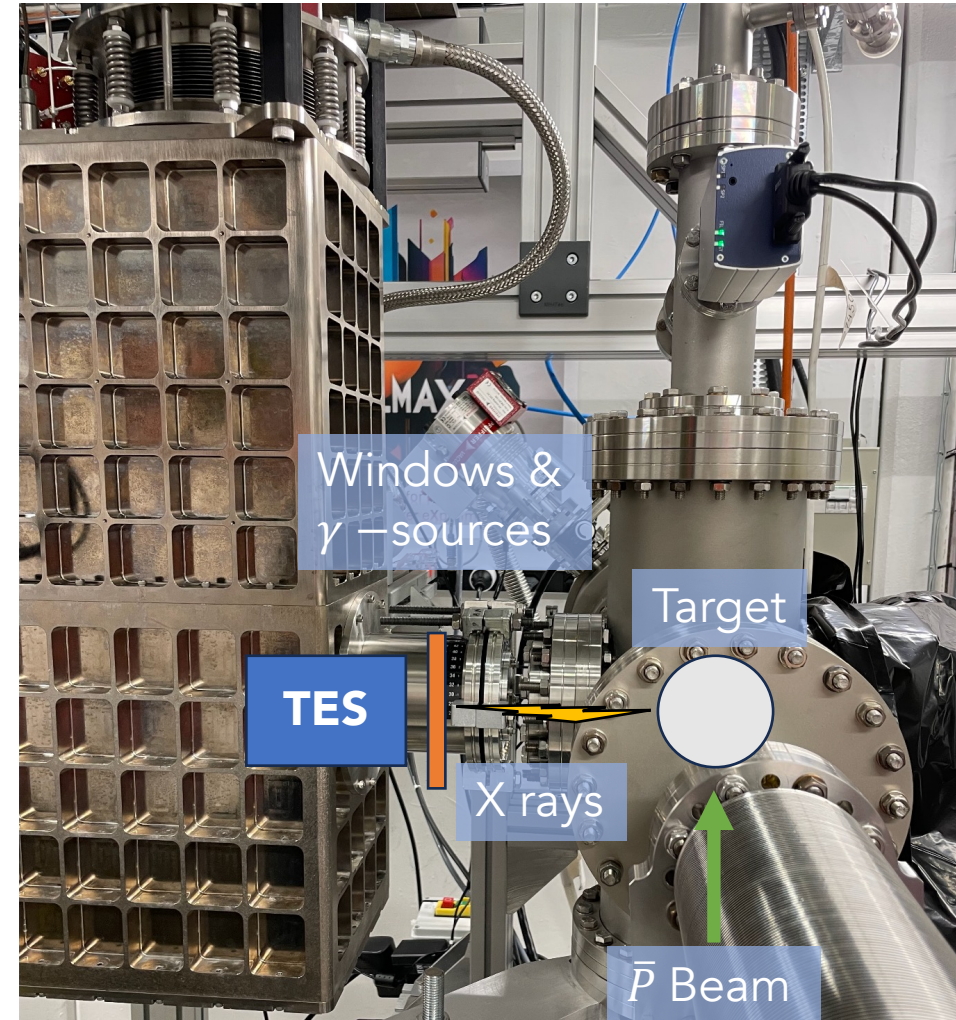
\*Different 2-Loop sensitivity:  
H-Like U  $\rightarrow$  Self-Energy  
 $\bar{p}$ -Xe  $\rightarrow$  Vacuum Polarization

QED  $\times$  3-6

Nuclear effects / 100

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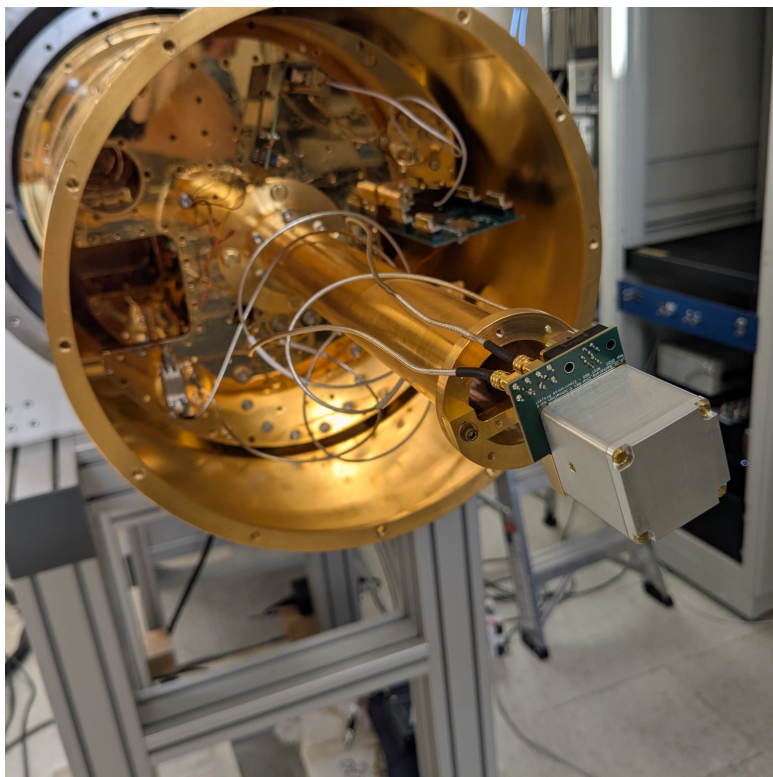




# Precise energy-dispersive x-ray measurements



NIST

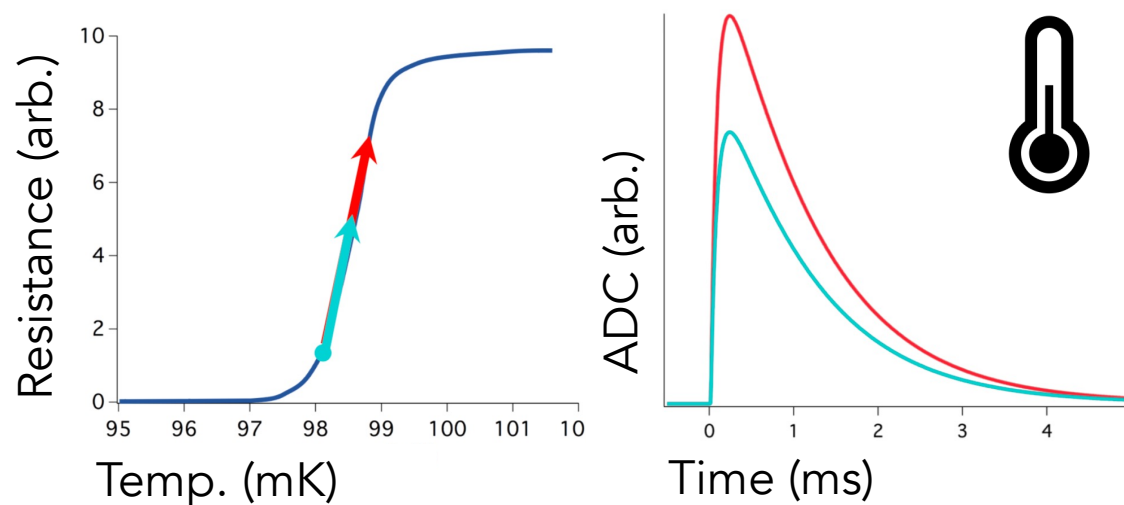


How to measure the energy of x rays at 30-300keV?

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

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

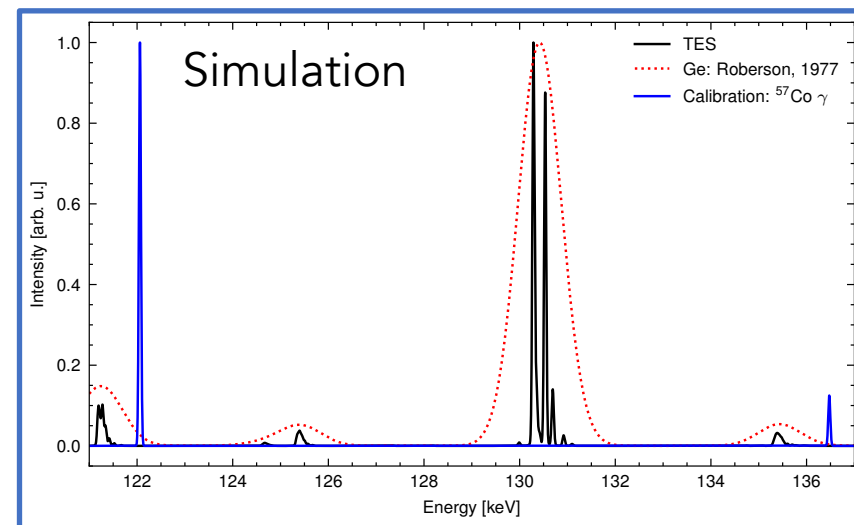
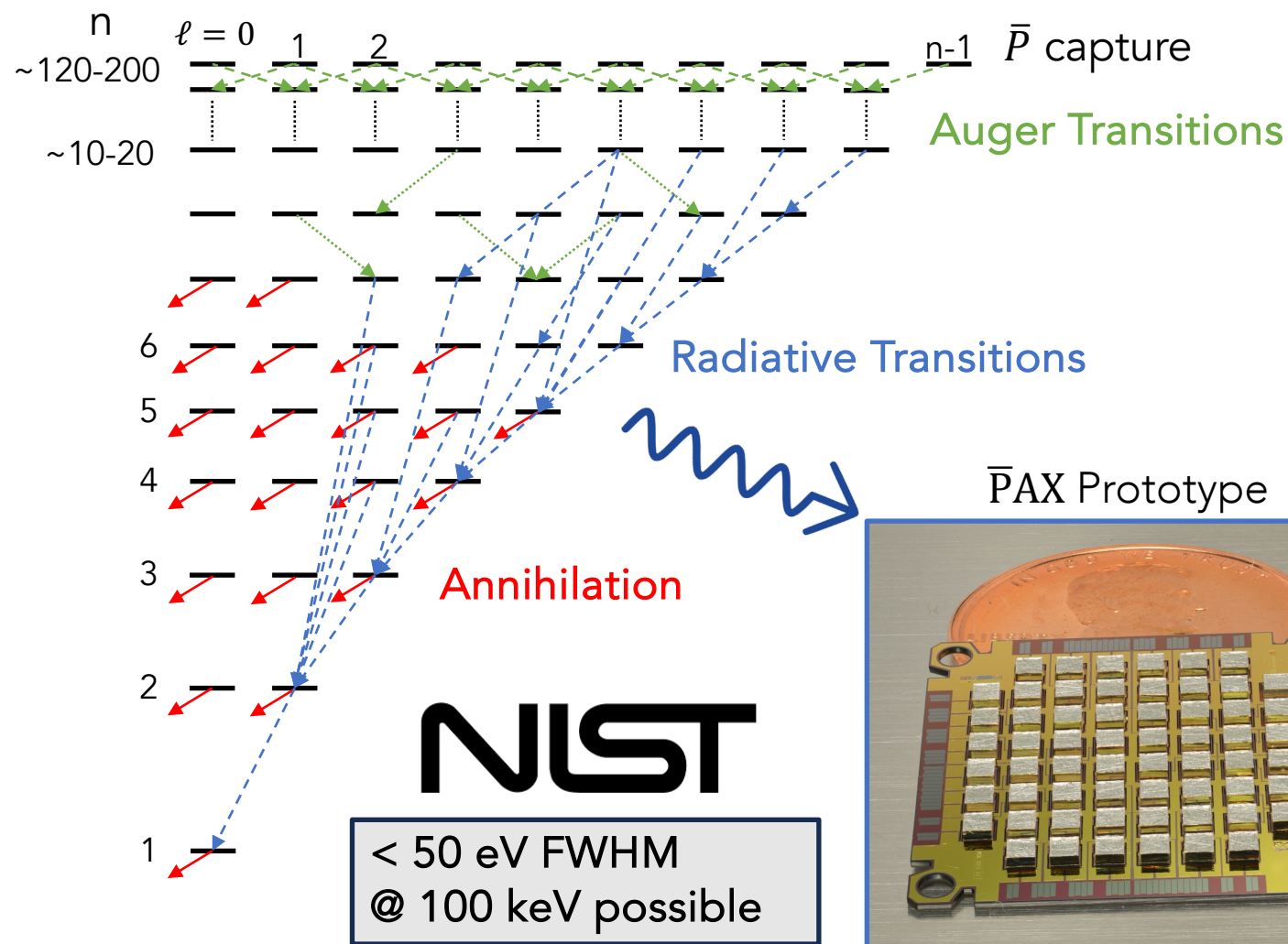
**Superconducting Transition Edge Sensors (TESs)**



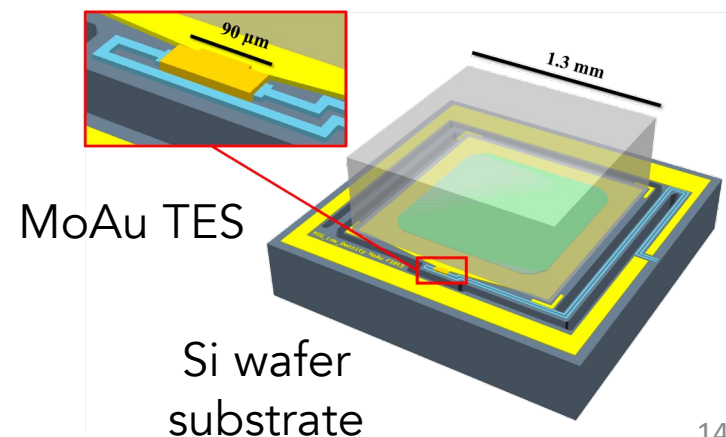
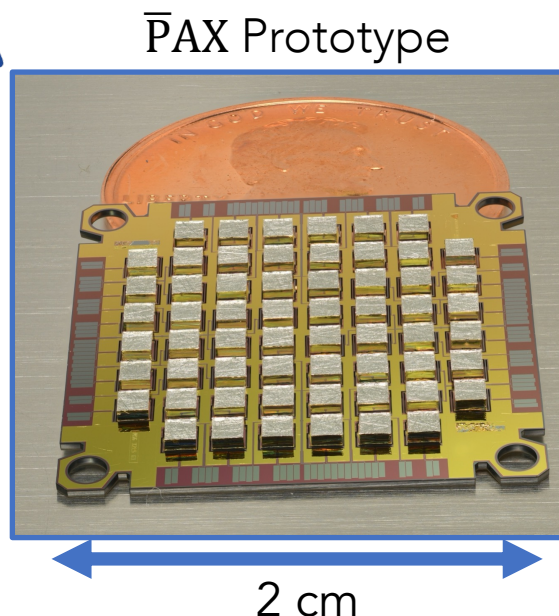
Thermal noise limit:

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

# Key technology: Transition Edge Sensing (TES) Microcalorimeter

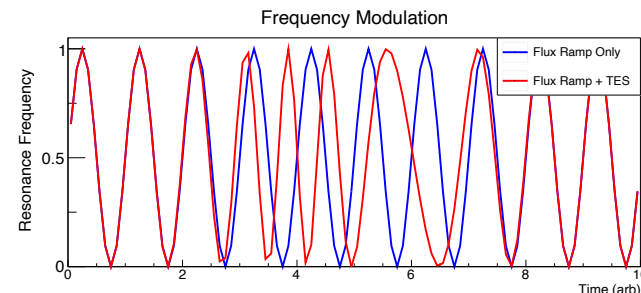
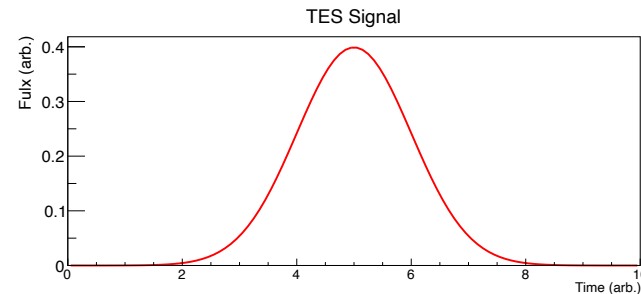
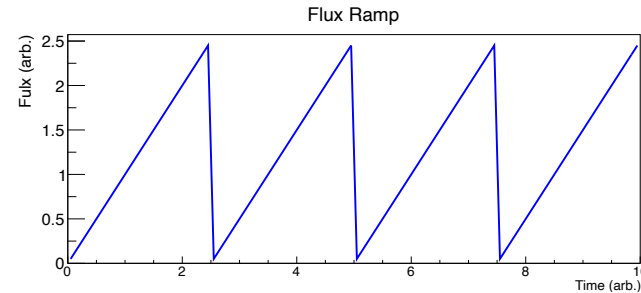
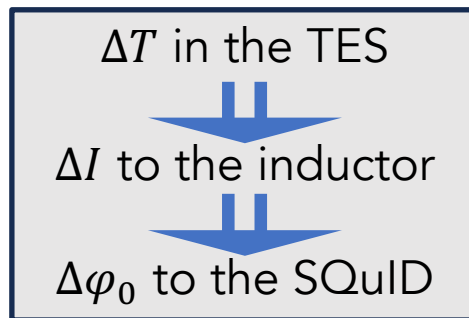
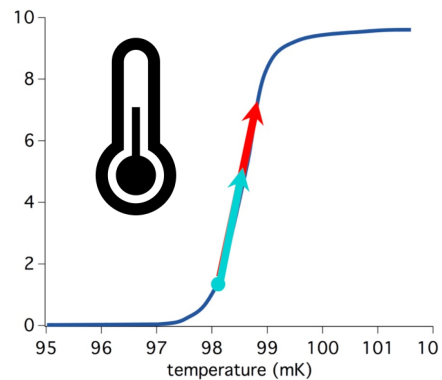
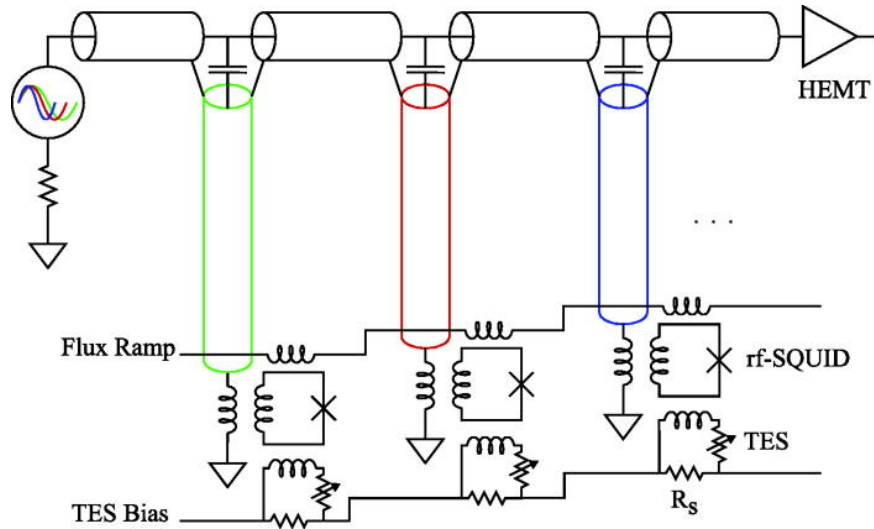


MDFGME:  $\bar{P} - \text{Zr}$   
near  $n = 9 \rightarrow 8$



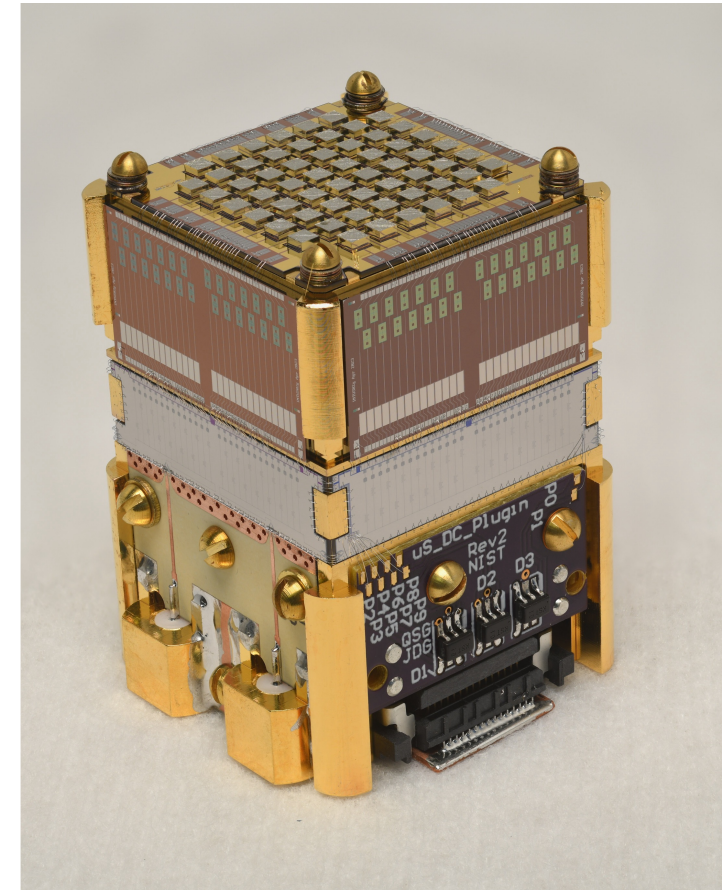
# High Channel Density via Microwave Multiplexed Readout

Each detector channel is given a unique microwave resonator frequency  
**1 data channel / 100-1000s of detector channels**



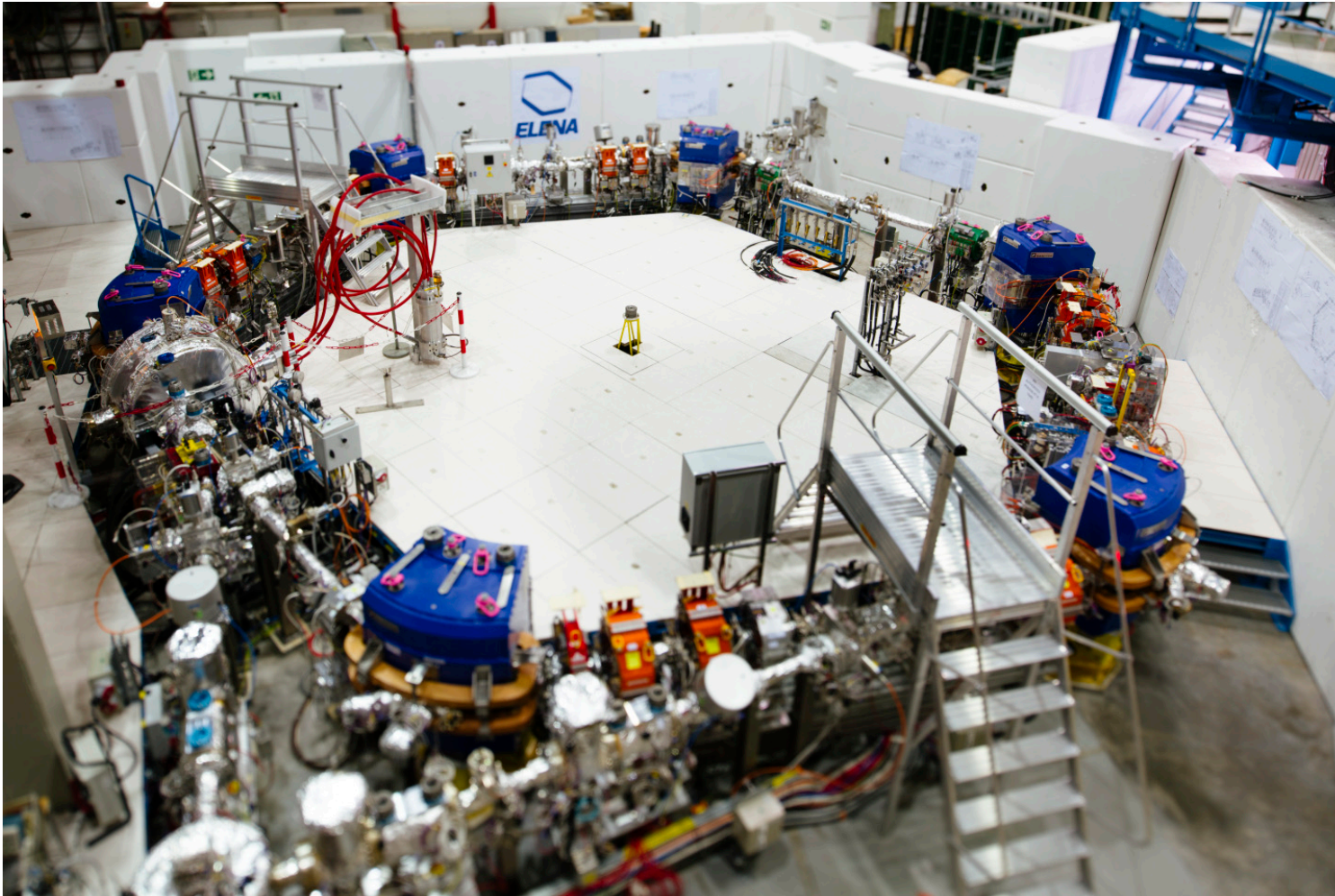
$$f_{res} \approx \sin(ct + S_{TES}(t))$$

NIST





# ELENA : slow antiproton beams for precision measurements



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

## ELENA parameters

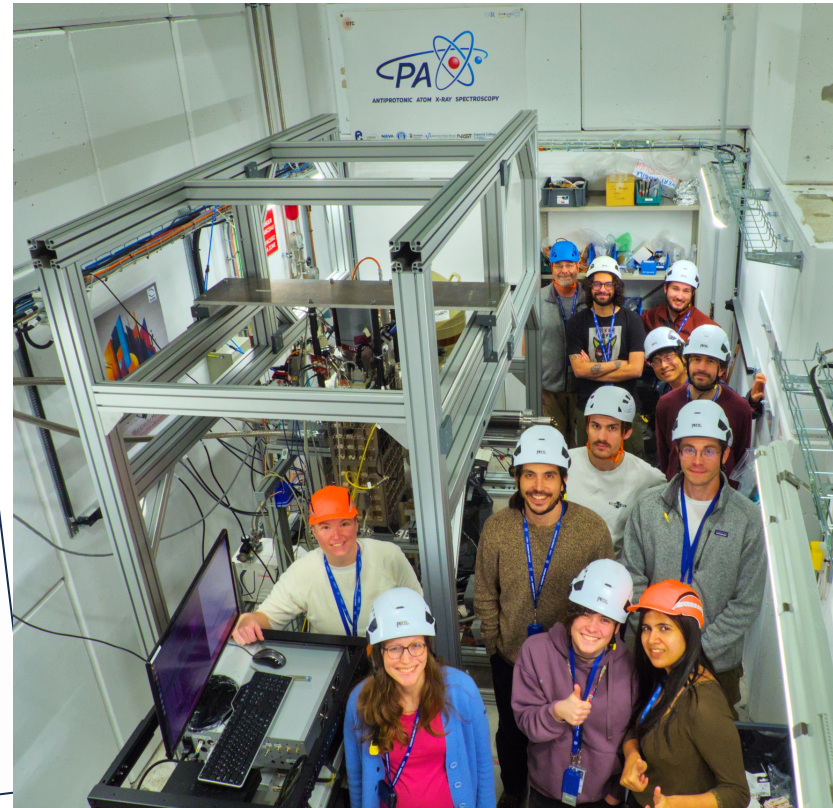
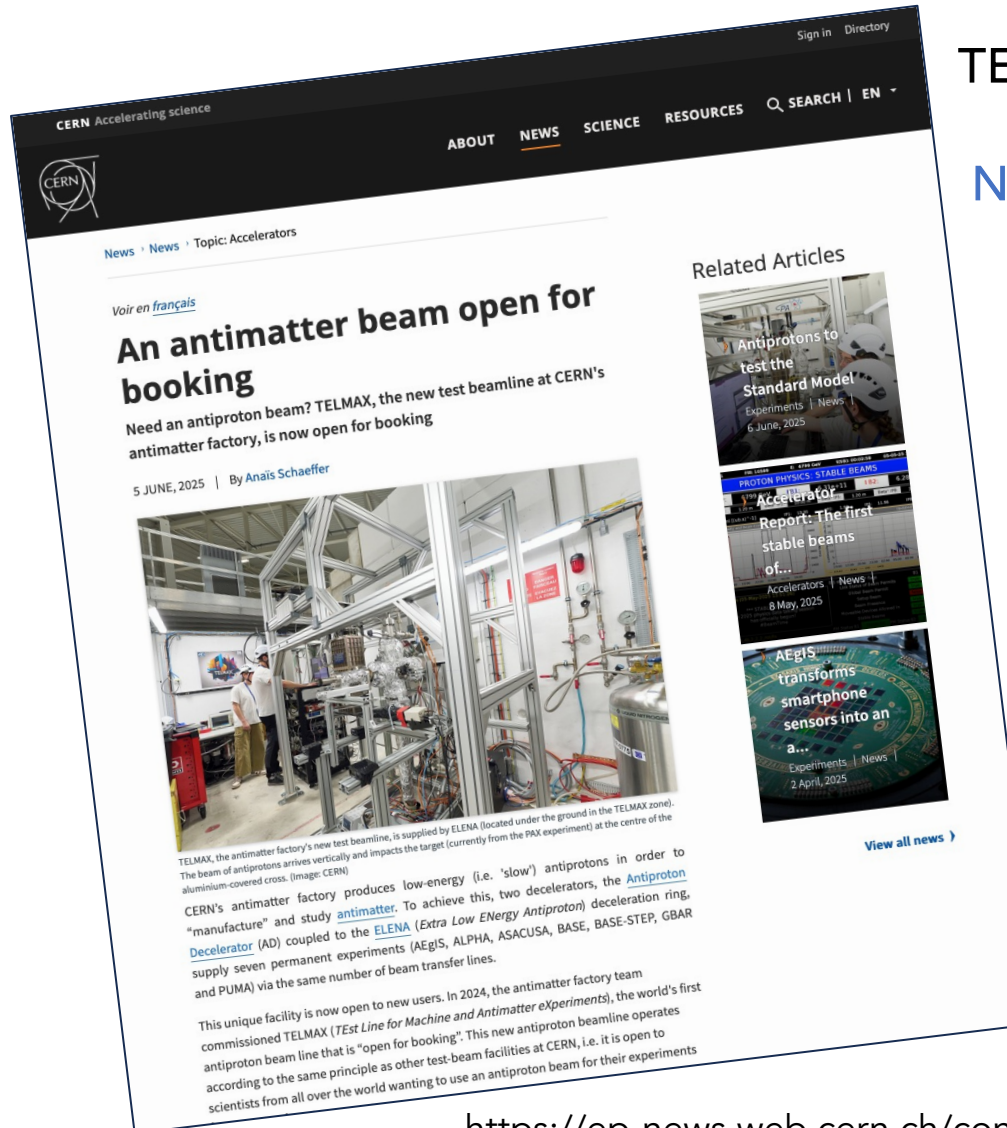
Beam energy	100 keV
Number of antiprotons/bunch	$\sim 7 \times 10^6$
Bunch size (FWHM)	300 ns
Repetition rate	100 s



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

TEst Line for Machine And Antimatter eXperiments (TELMAX)

**NEW** user facility open at ELENA delivering  $\bar{P}$  beams

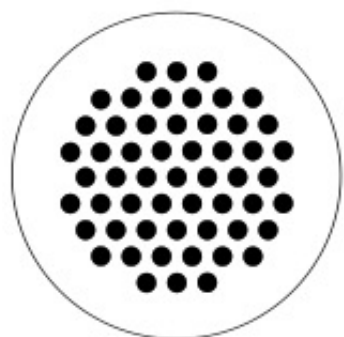


$\bar{P}$ AX was the first user in TELMAX with an extended Summer 2025 test-beam.

Goal:  
Measure first  $\bar{P}$ -atom x rays with a TES !

# TES performance checks and calibration

New x-ray-transparent  
 $\gamma$ -sources from PTB.

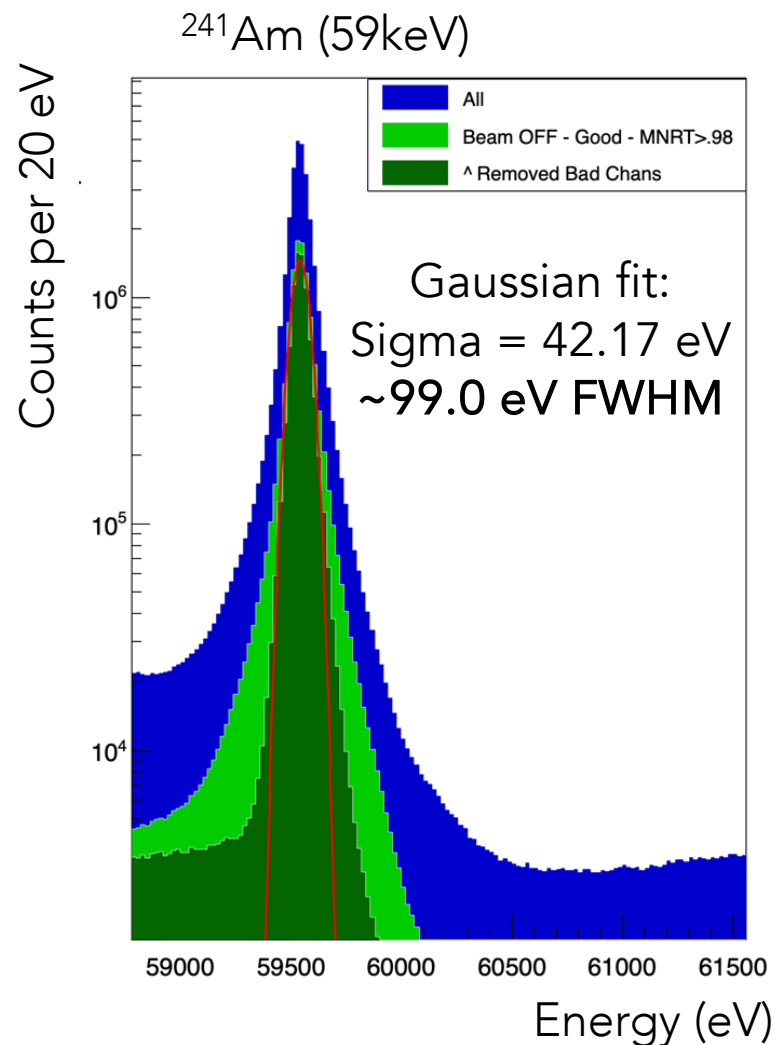


size 2  
diameter 50 mm, 55 drops



Radioactive microdroplets  
on plastic films

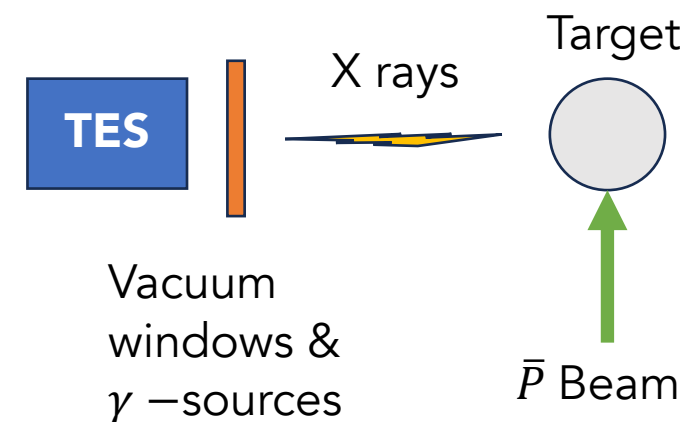
**Uniform and continuous calibration**



**Calibration sources measured  
to specified resolution !**

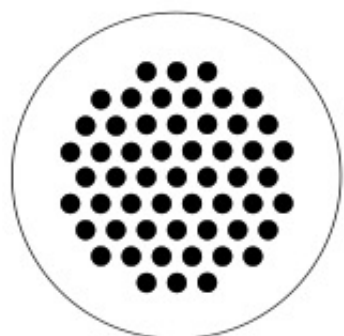
(prototype)

Let's take beam!



# TES performance checks and calibration

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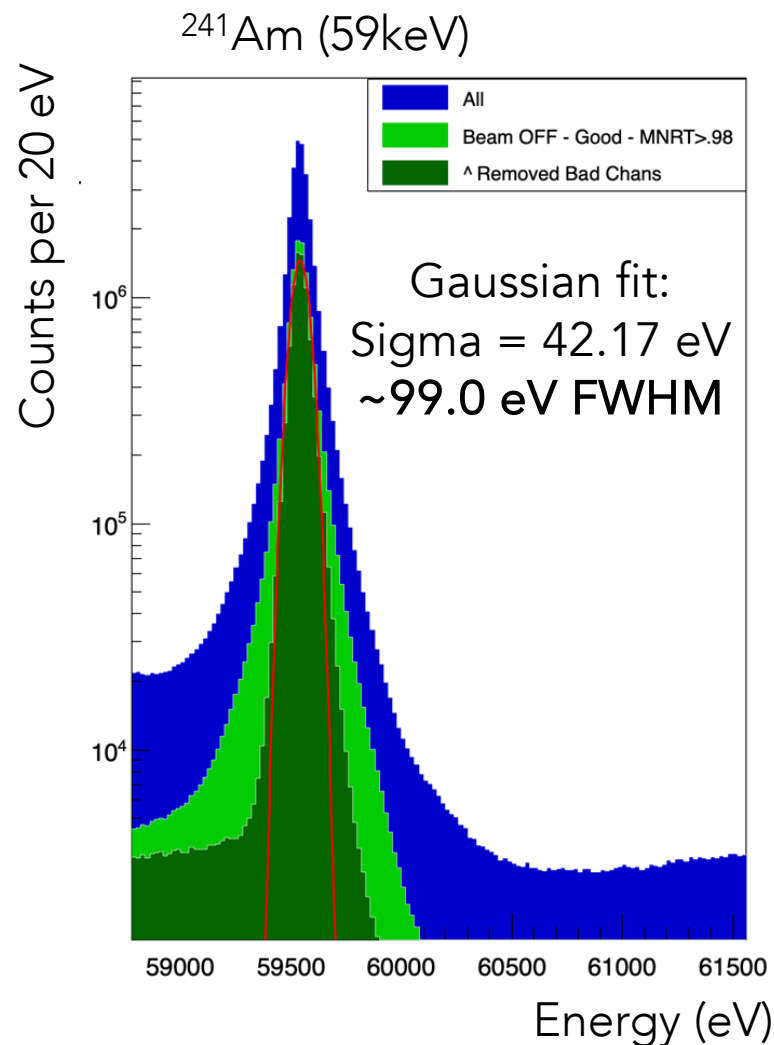


size 2  
diameter 50 mm, 55 drops



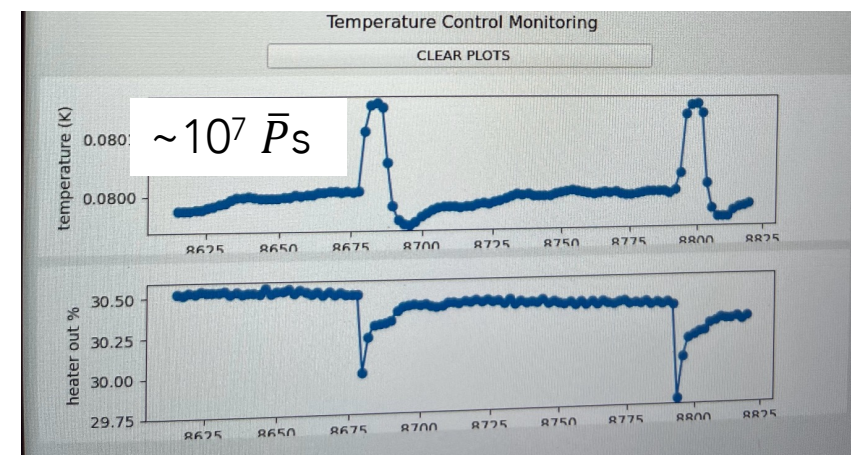
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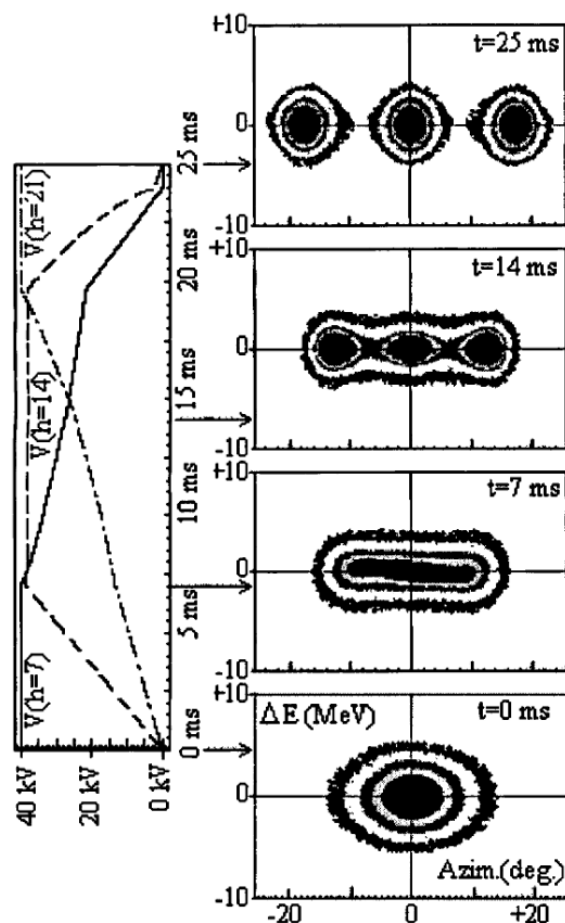
Let's take beam!



100s of  $\mu\text{K}$  deposited in to the array



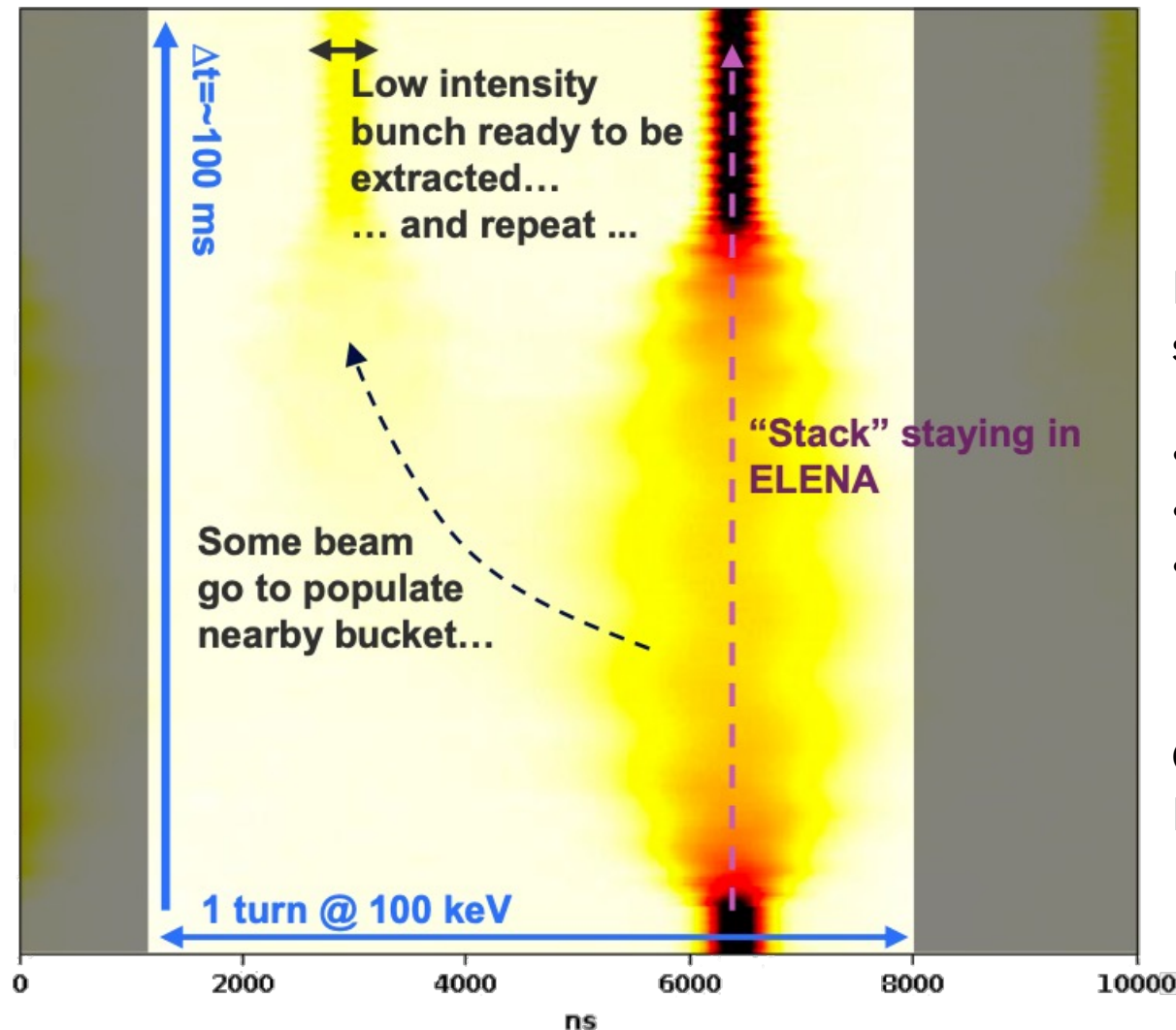
# Multiple Mini-Bunch Extraction



Example from CERN PS.

R. Garoby, et. al 2000

## Mini-bunch formation in ELENA



Repeated bunch splitting in ELENA:

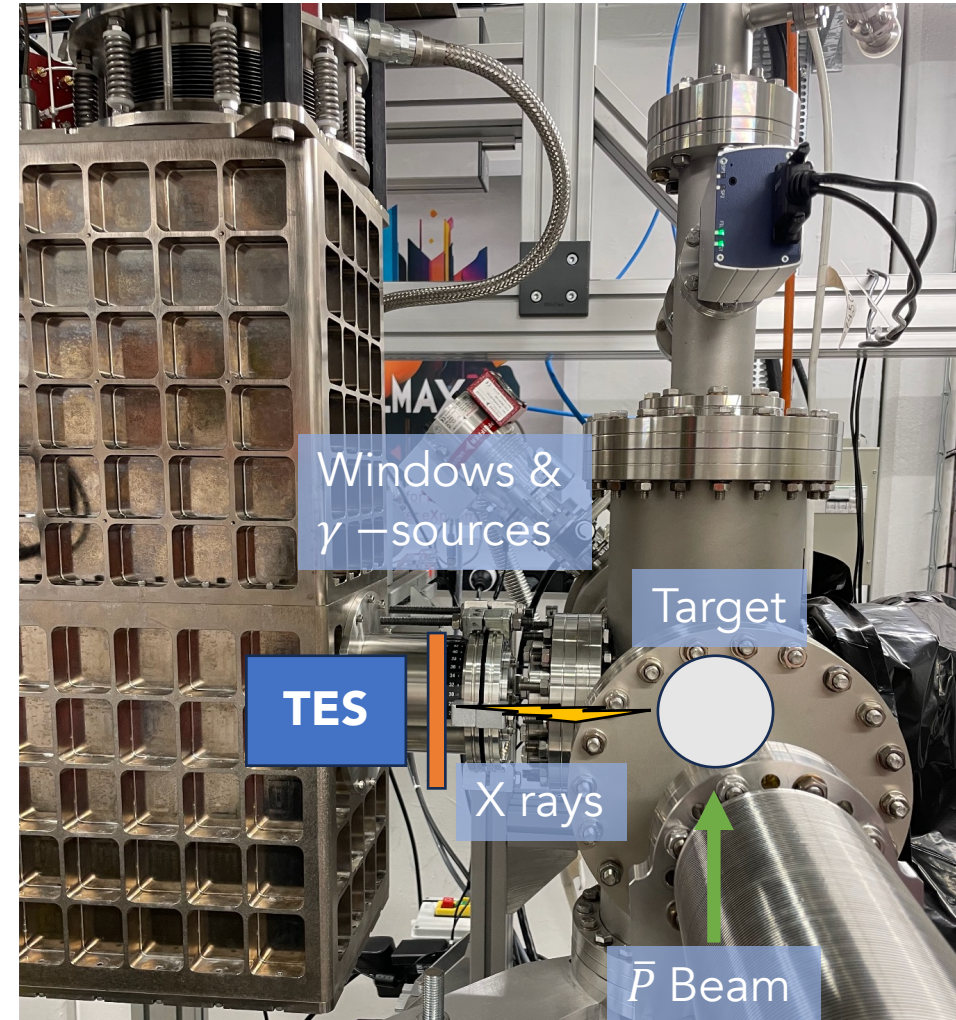
- 200 mini-bunches
- 100 ms separation
- Arb. Low Intensity ( $\sim 10^3 \bar{P}$ s per MB)

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

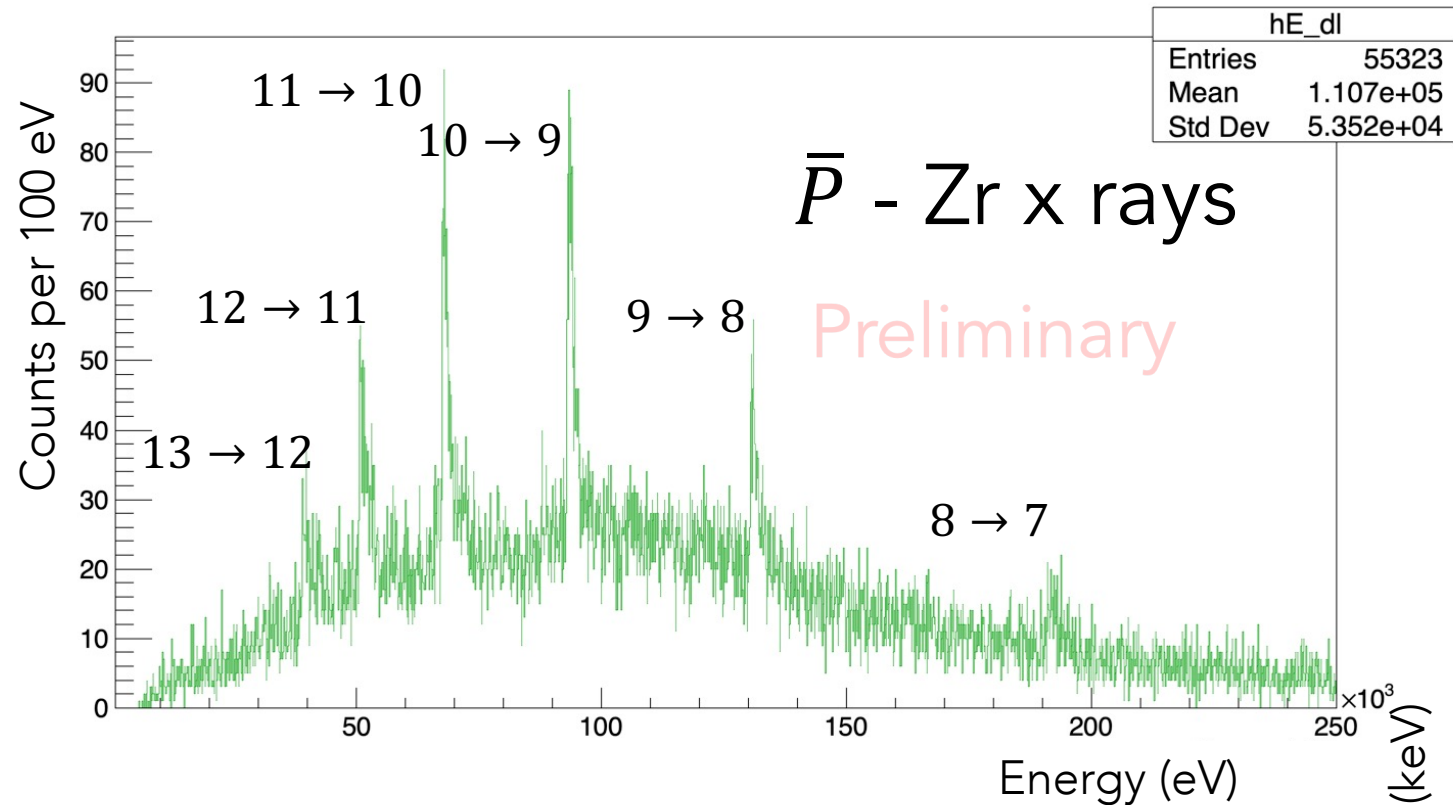


# Outline

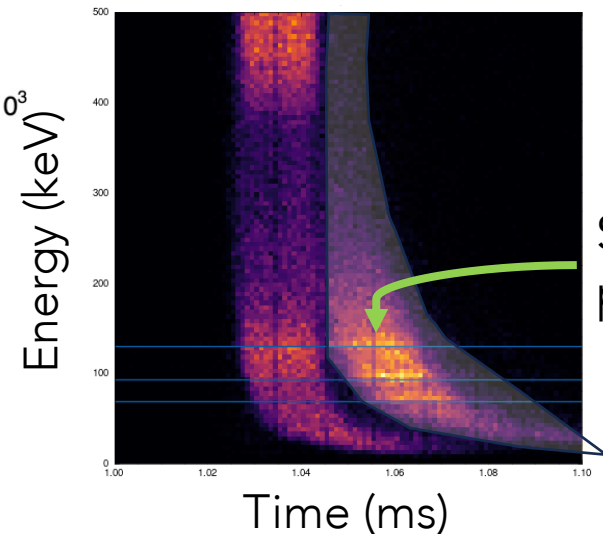
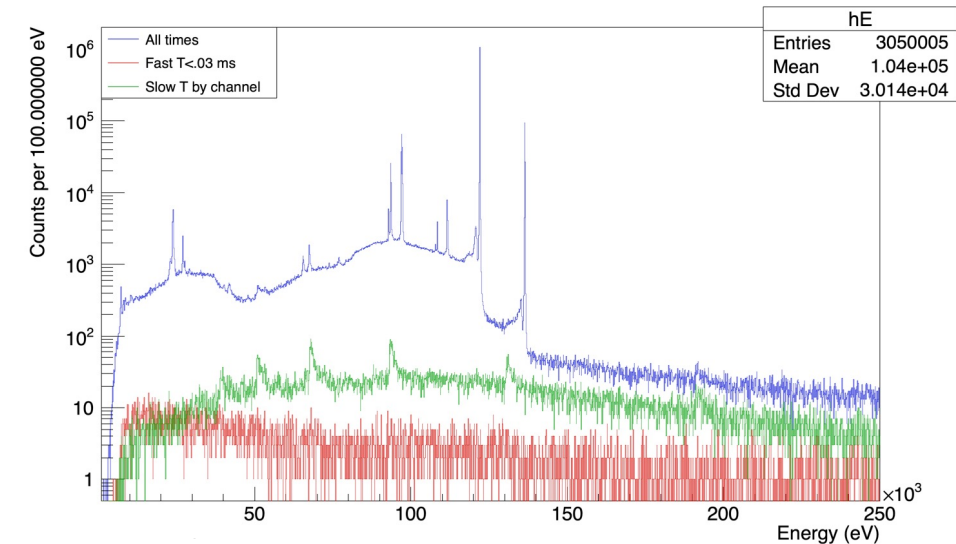
- Motivation and background
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- First TES spectra of  $\bar{P}$ -atom x-rays



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



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

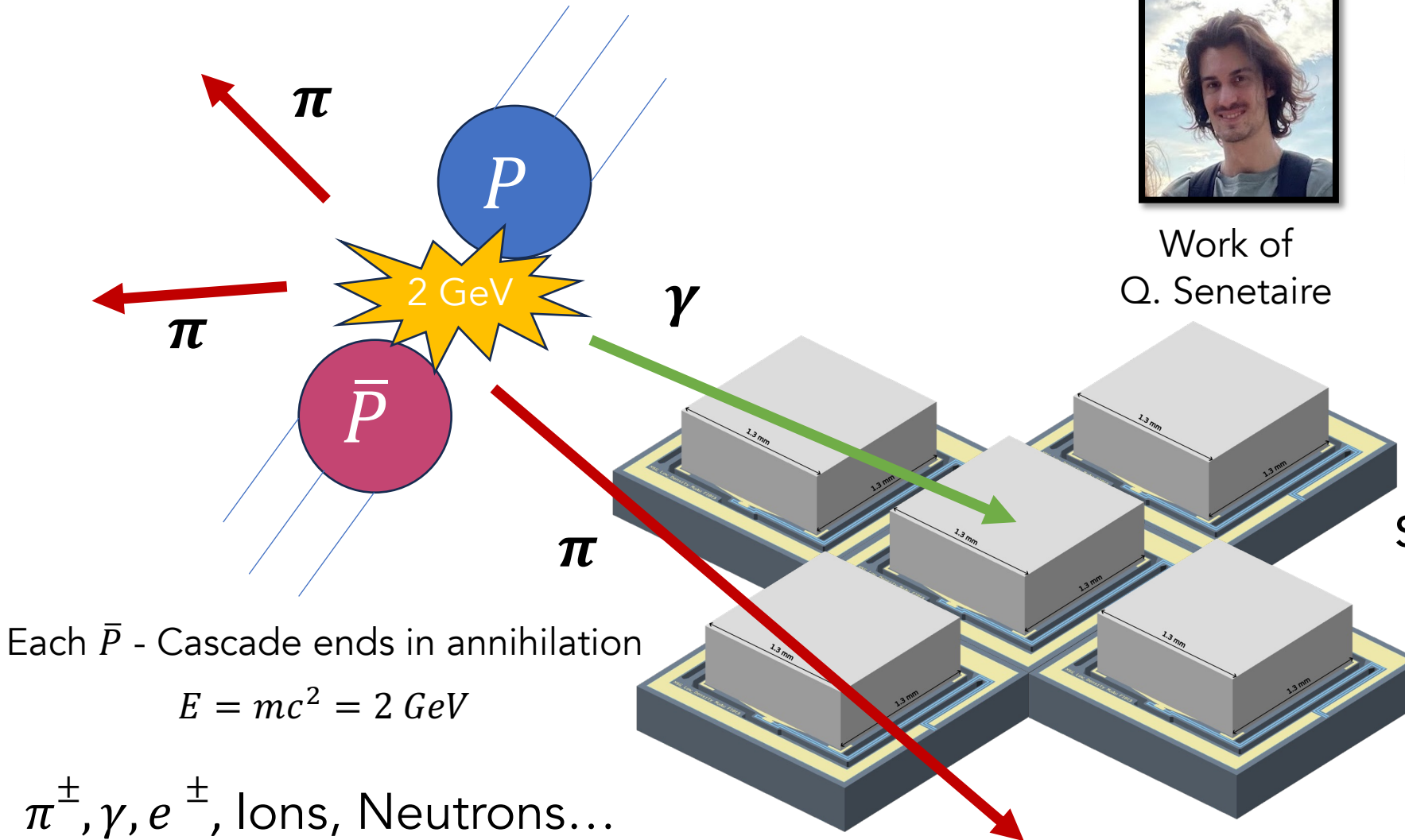
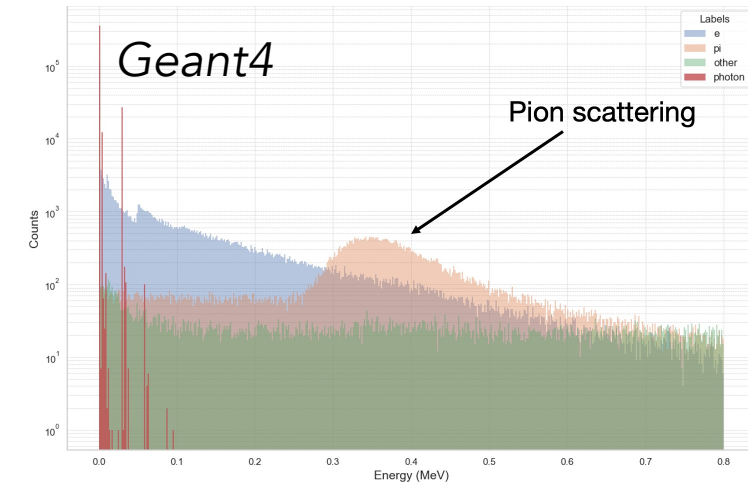


Signal of interest was prompt but "delayed".

# Sources of background



Work of  
Q. Senetaire

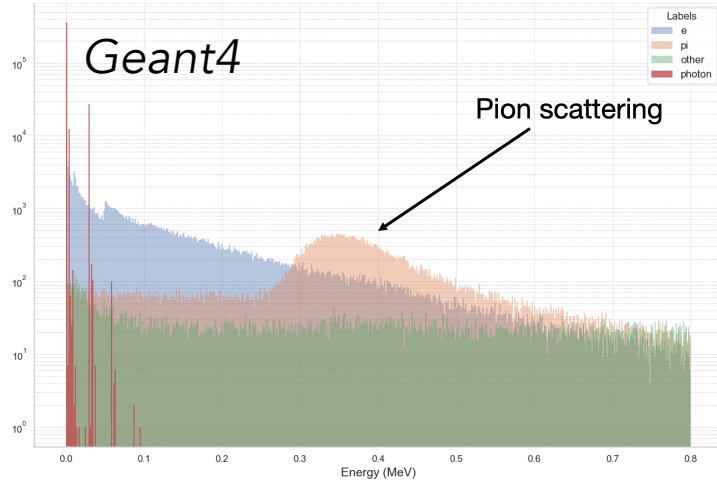
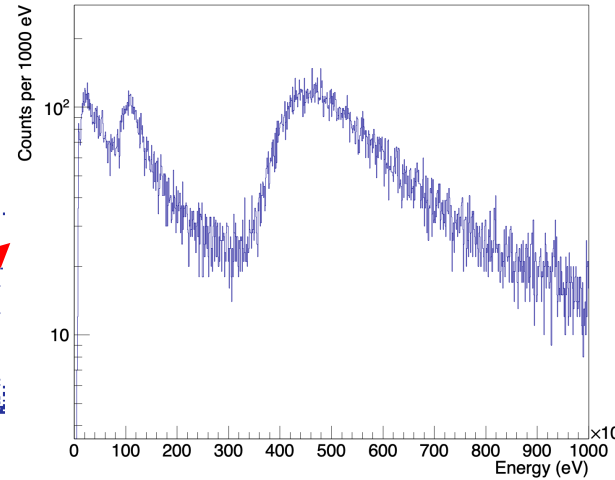
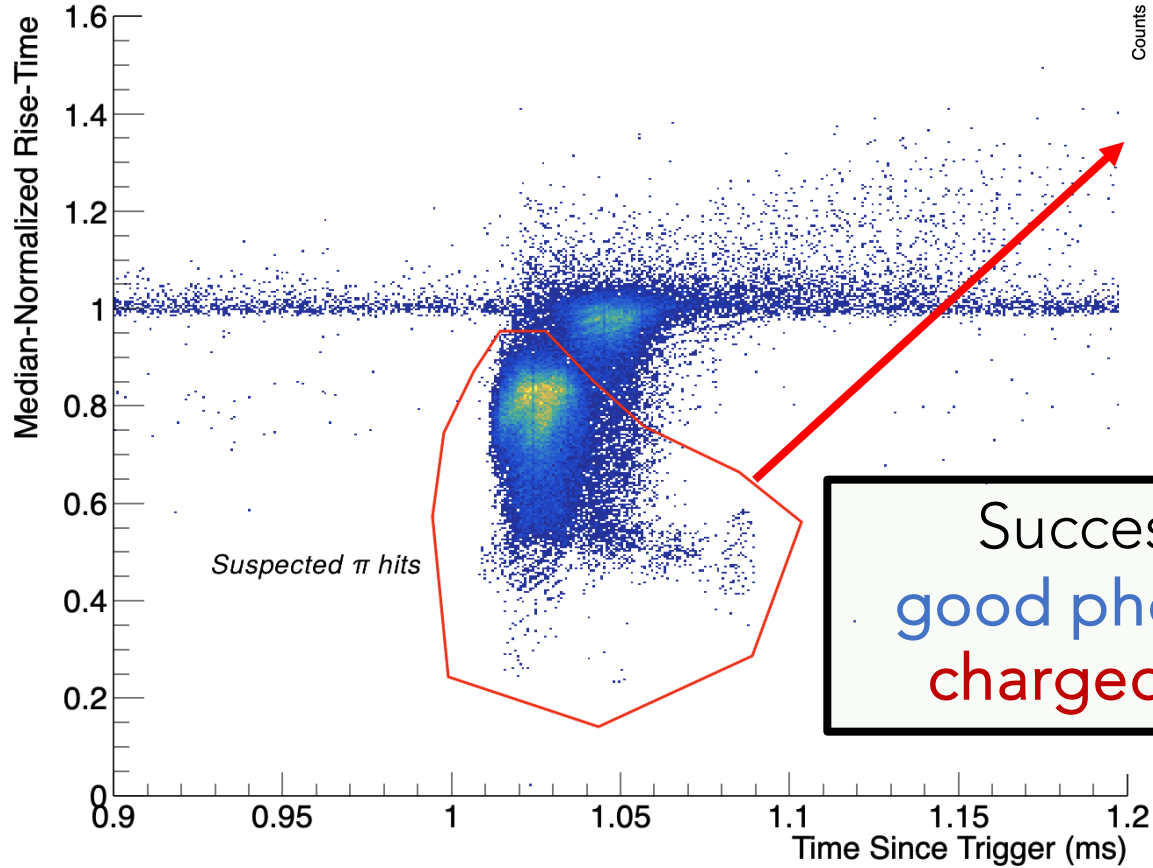


Signal of interest is hidden by:

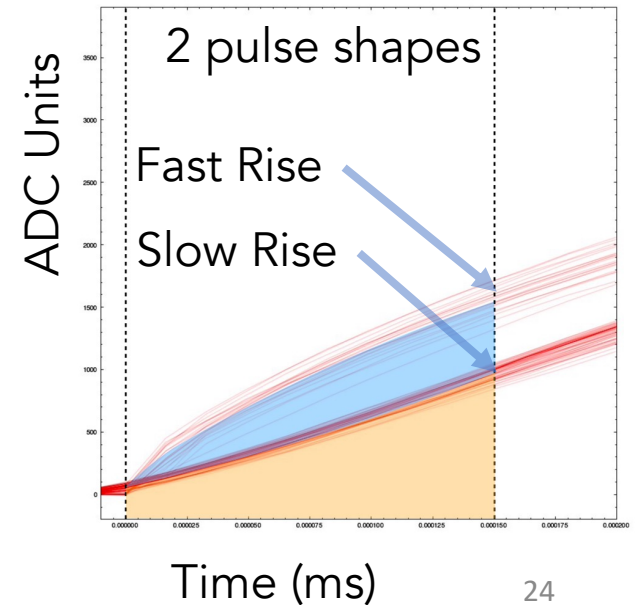
- Charged particle hits
- Thermal cross-talk

# Demonstrating Pulse Shape Discrimination in TEs

Rise time vs arrival time in  $\bar{P}$  data



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

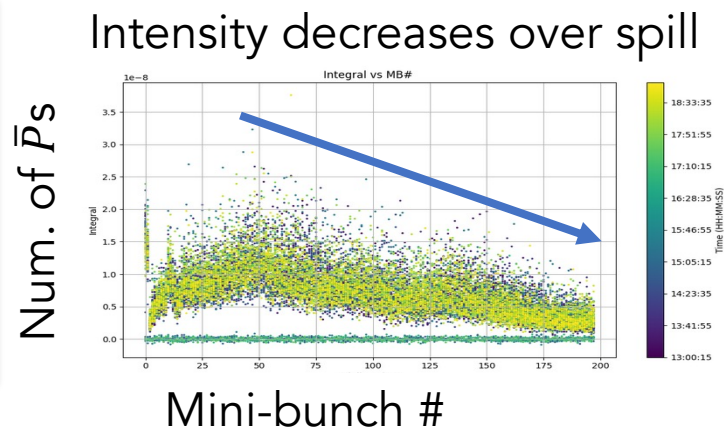




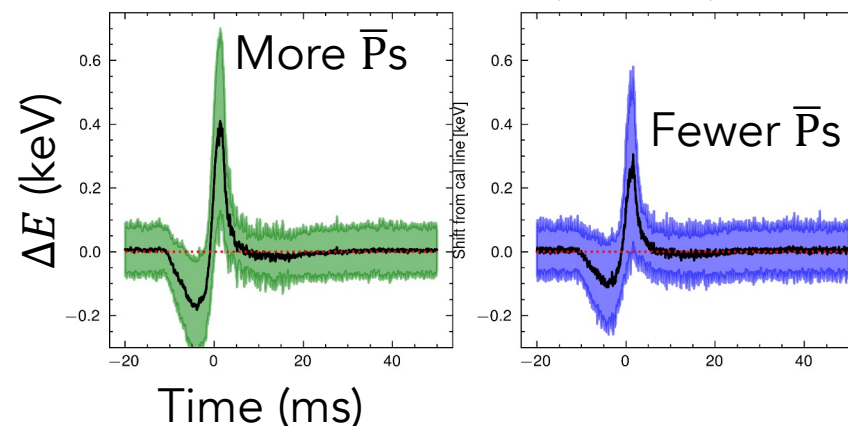
# Beam-induced gain shifts and broadening



Work of  
F. Giraud

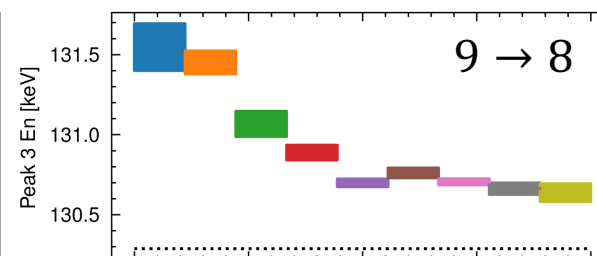
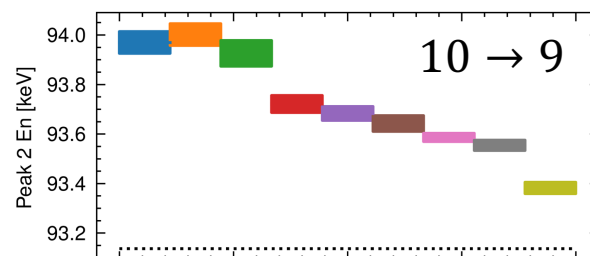
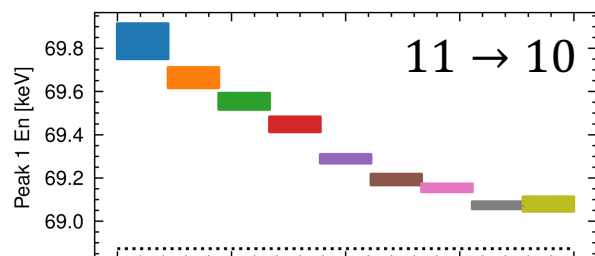


Shift of  $^{241}\text{Am}$ (59 keV)

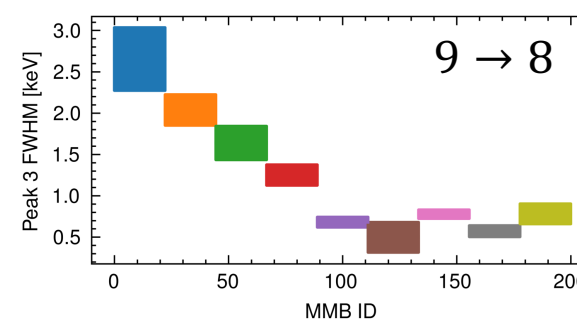
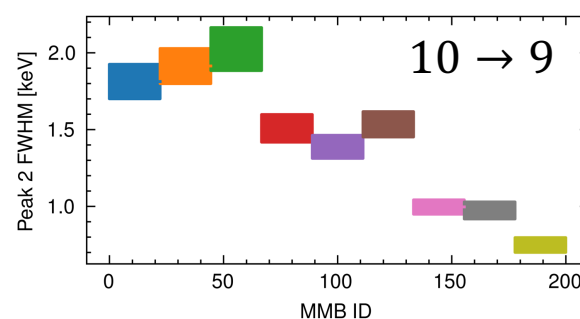
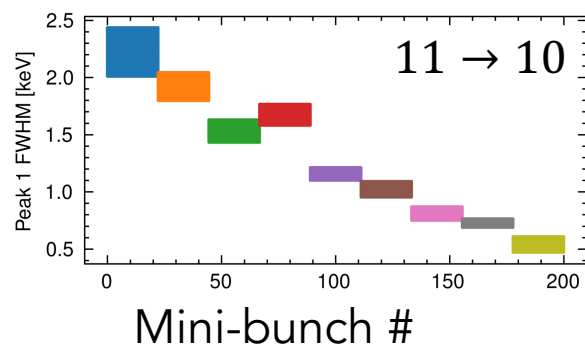


Both shifts and  
broadenings  
decrease with  
beam intensity.

$\bar{P}$  - Zr  
Centroid



FWHM  
(keV)



Work of  
G. Baptista

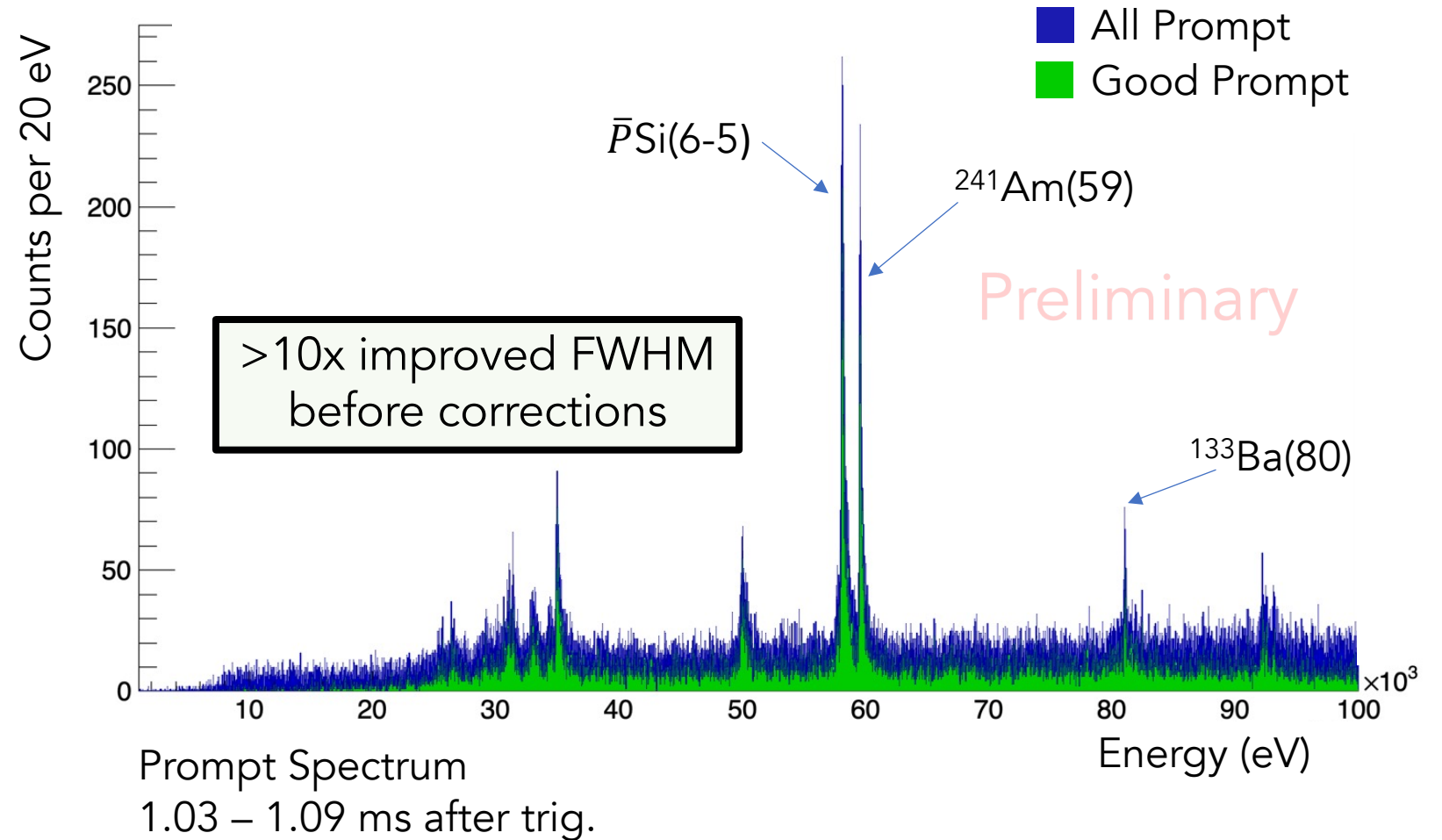


# $\bar{P}$ AX: Antiprotonic Si

Other Prompt Peaks ID'd:

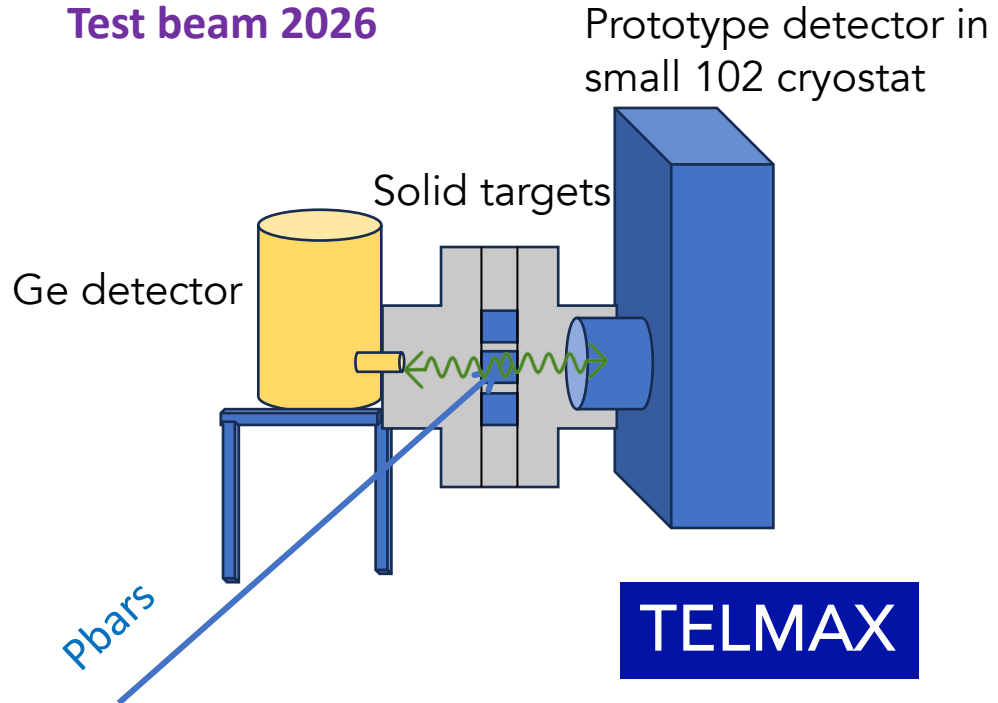
- $\bar{P}Al(5-4)$  @ 92 keV
- $\bar{P}Si(5-4)$  @ 107 keV
- $\bar{P}Si(8-6)$  @ 57.6 keV

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



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

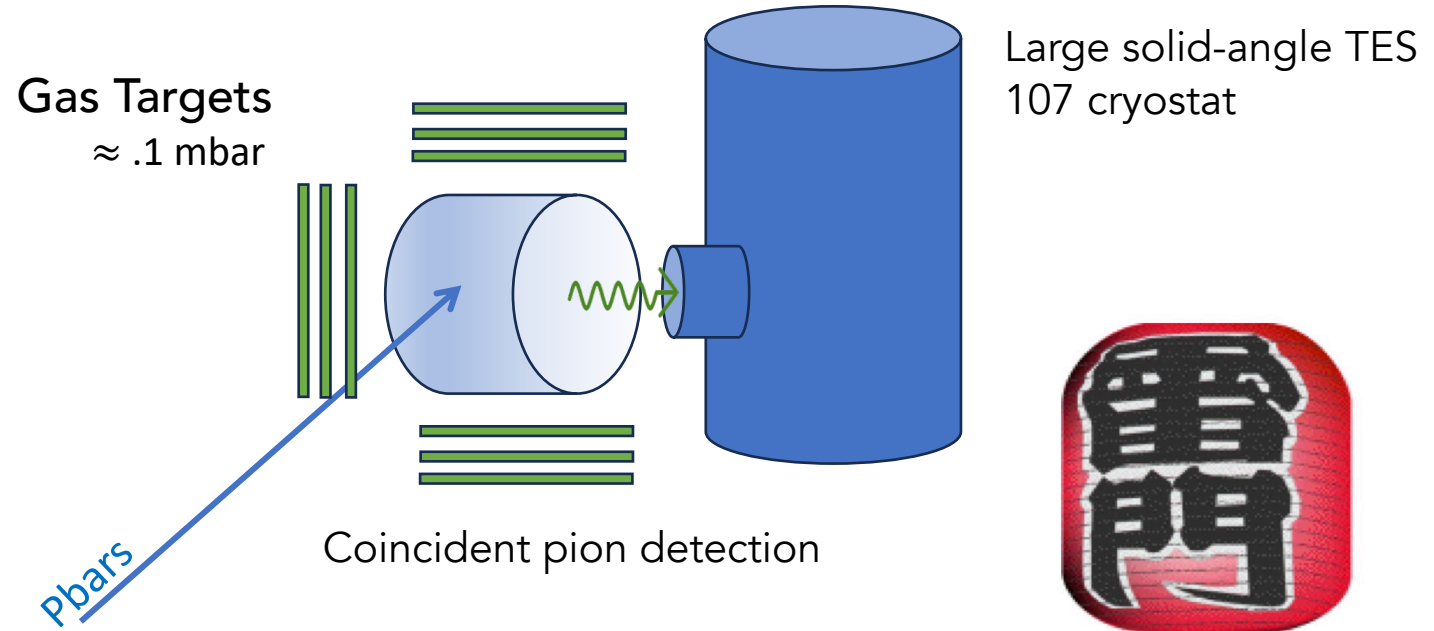
## Test beam 2026



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  $\rightarrow$  Nuclear physics, BSM searches

# Many thanks to our collaborators



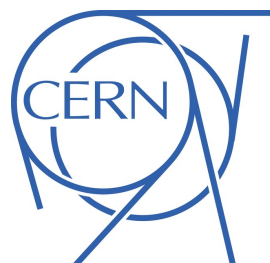
G. Baptista  
F. Nez  
F. Giraud  
P. Indelicato  
N. Paul

S. Rath  
M. Roosa  
Q. Senetaire  
J. Sommerfeldt  
P. Yzombard



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



F. Butin  
D. Gamba



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of Technology

O. Eizenberg  
B. Ohayon



N. Garroum  
M. Zito



**Imperial College**  
London

M. Hori



T. Azuma  
T. Hashimoto  
T. Saito



S. Okada



M. Guerra  
J. Machado



T. Higuchi



JY. Rousse

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.

$\bar{P}$ A X has measured first  $\bar{p}$ -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**

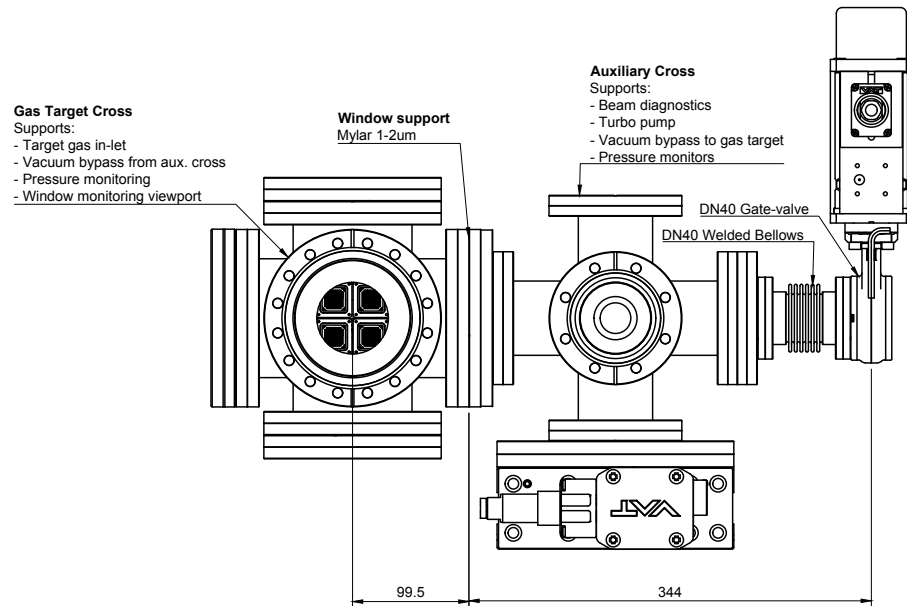
Acknowledgements:

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.

# PAX at ASACUSA

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



## Developments:

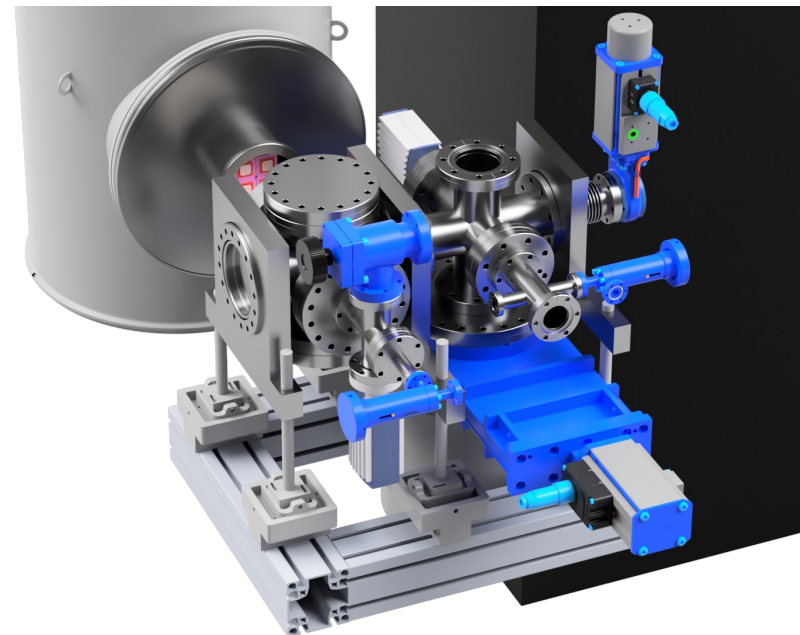
- New 5 m beamline designed by CERN beam physicists
- PAX gas target station
- 4x micro-snout TES array with optimized performance



ANTIPROTONIC ATOM X-RAY SPECTROSCOPY



ASACUSA

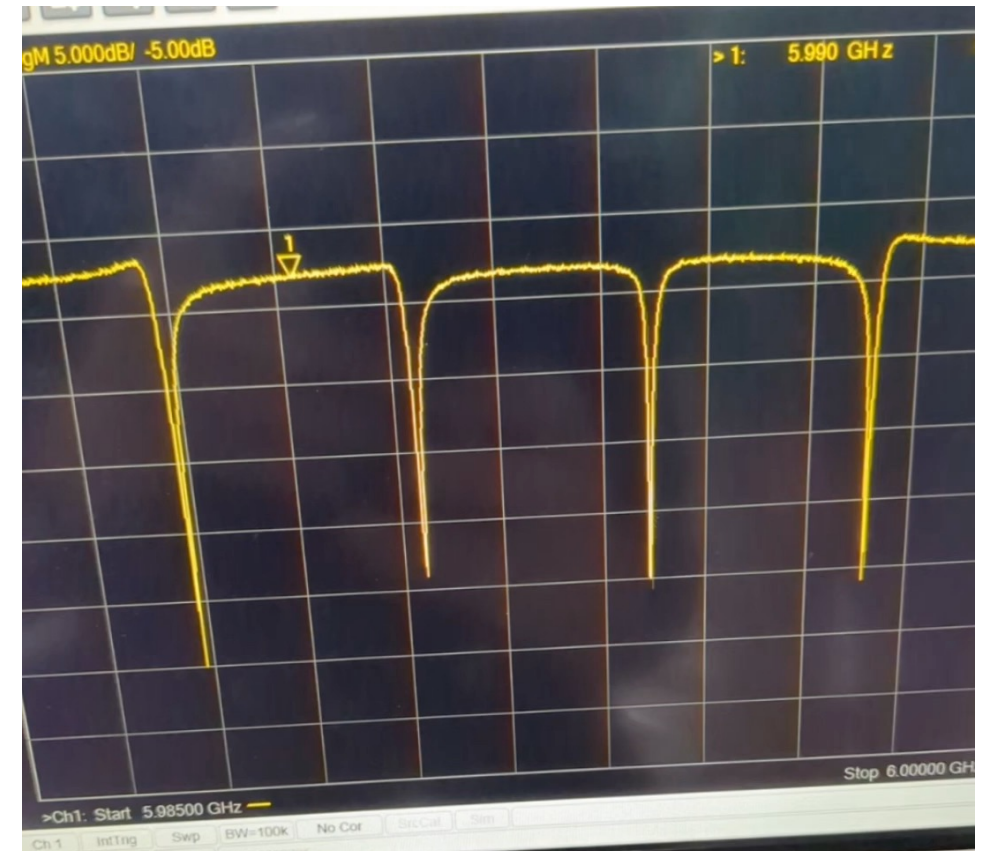
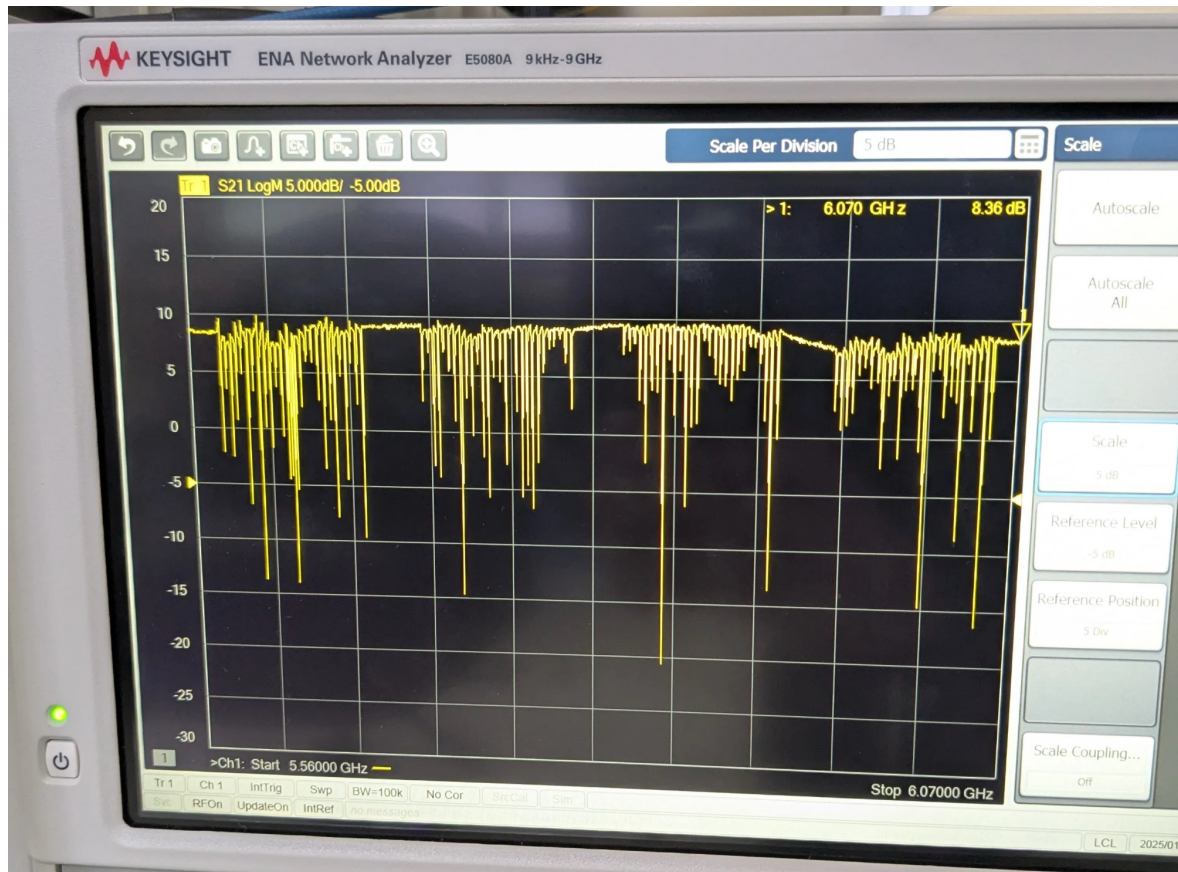




# High Channel Density via Microwave Multiplexed Readout

Each detector channel is given a unique microwave resonator frequency  
1 data channel / 100-1000s of detector channels

NIST



# The $\bar{P}AX$ physics program

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

Among the highest field systems ever accessed in the laboratory !

## $\bar{P}AX$ 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)

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

$$N_{\bar{p}} = 1 \times 10^6 / \text{spill}$$

$$M = 10$$

$$\epsilon_{geo} = 3 \times 10^{-4}$$

$$\epsilon_{det} = 0.4$$

$$N_x = 1200 \text{ counts/spill}$$

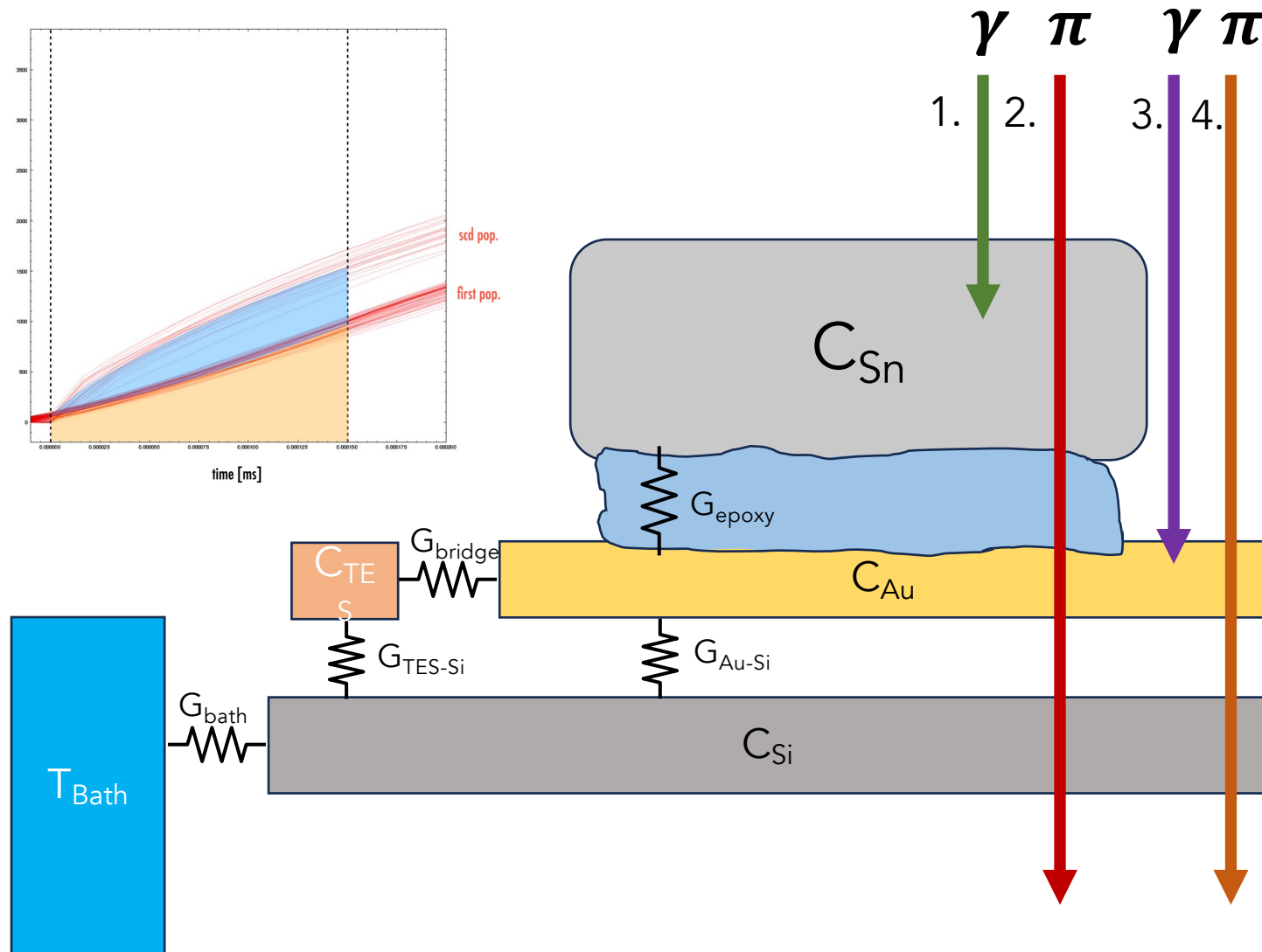
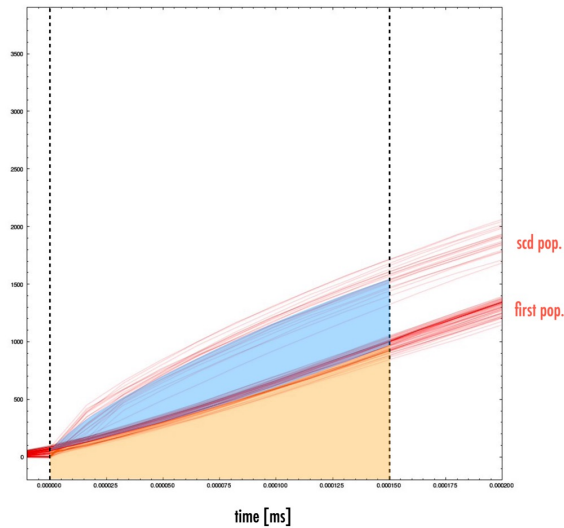


< 1 week

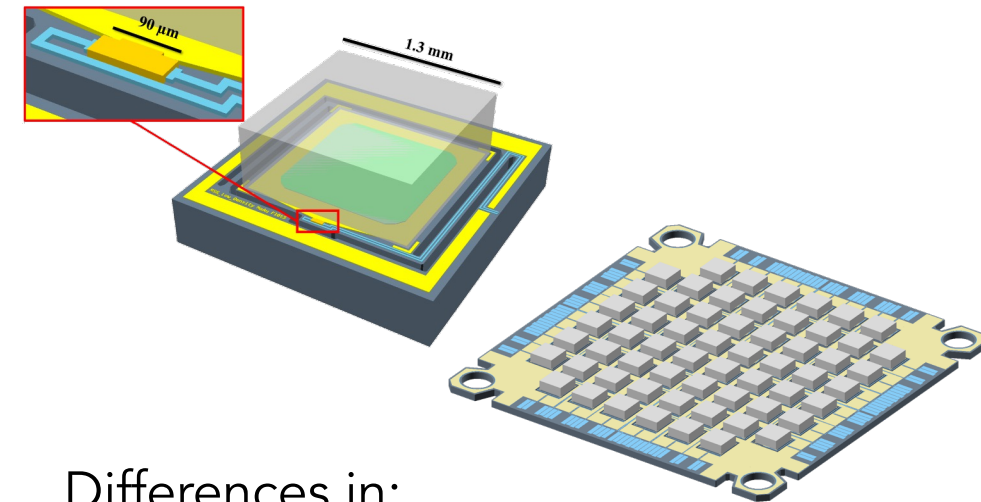
measurement time /  
transition

depending on available  
 $\bar{P}$  beam structure

# Origins of Rise-Time Populations



$\overline{PAX}$  array and pixel drawing

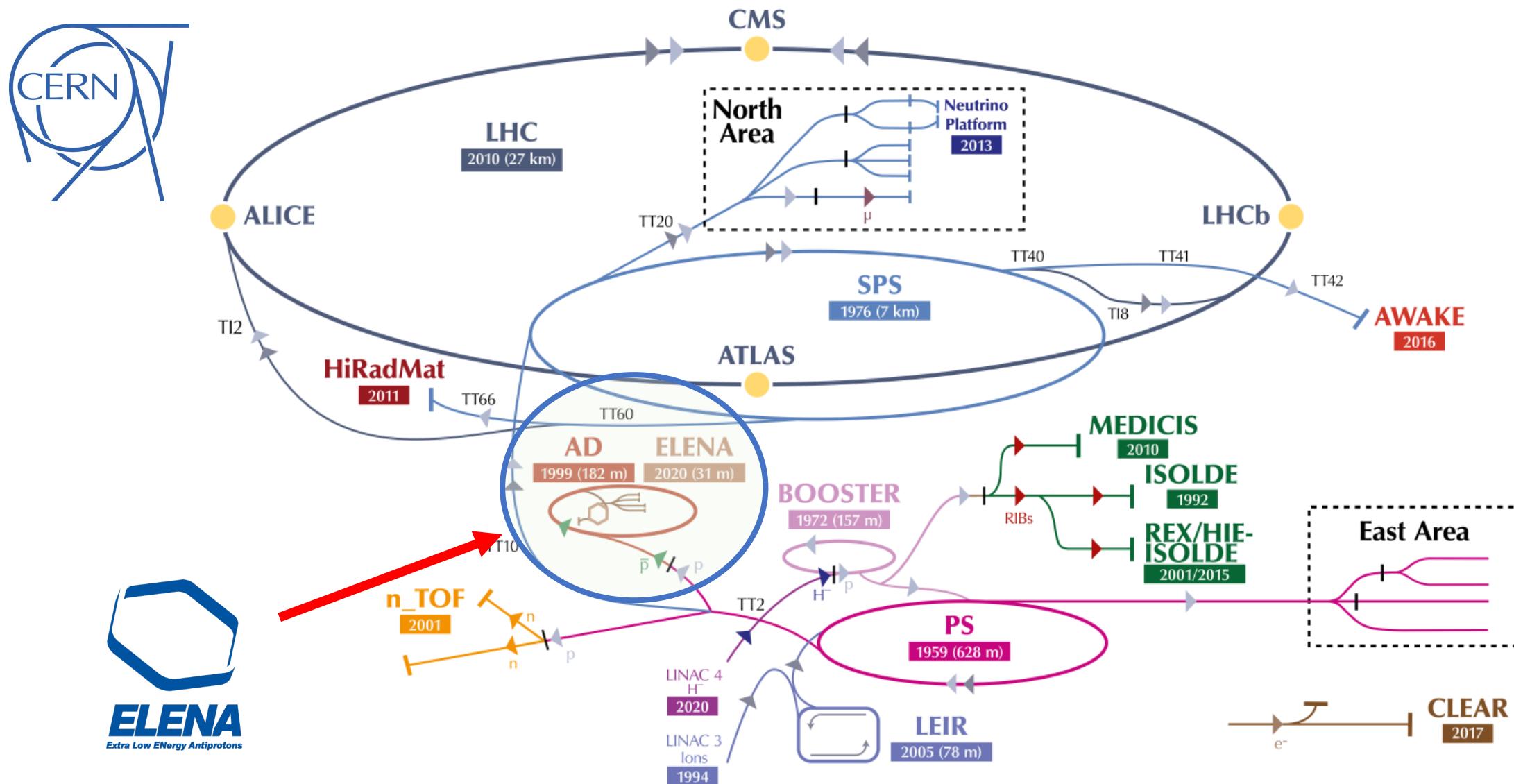


Differences in:

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

Energy dissipation:  $Sn$  vs  $Au$

# Antiproton production at CERN





# Antiproton production at CERN

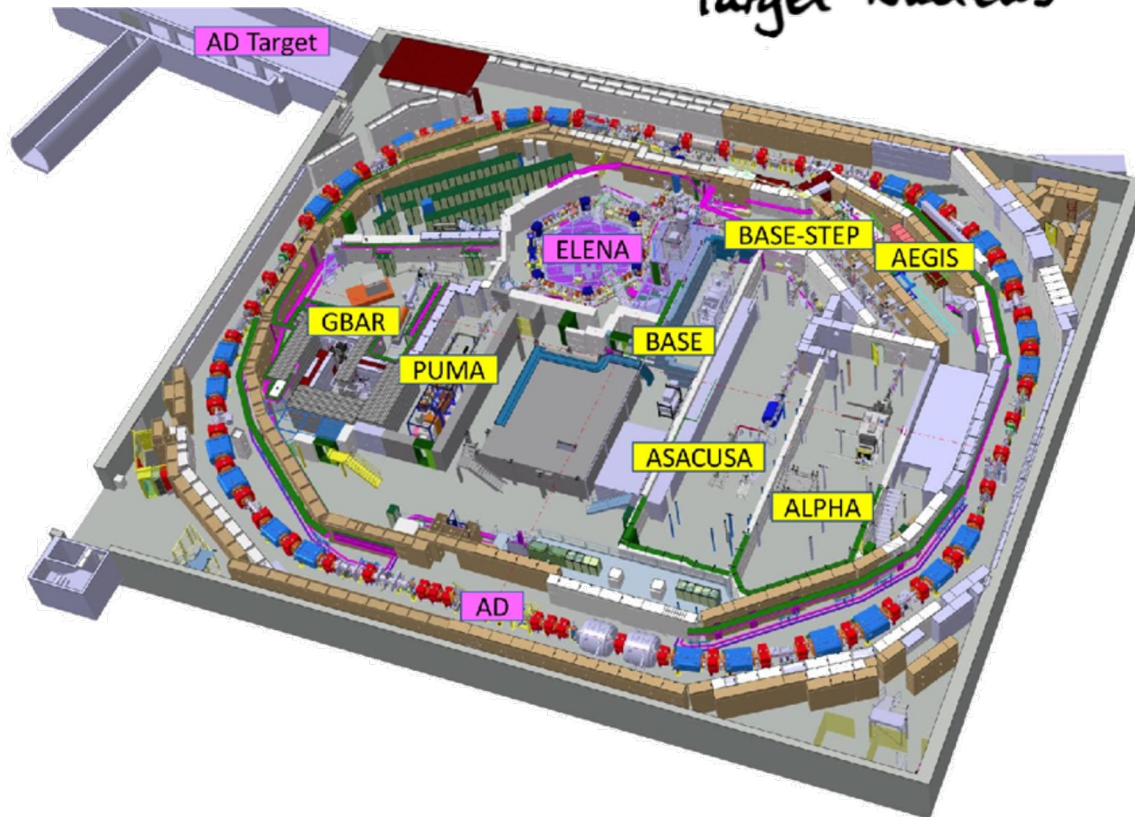


● →  
incident proton

Target Nucleus

$\bar{p}$   
Magnetic Horn

$\bar{p}$ s ready for deceleration

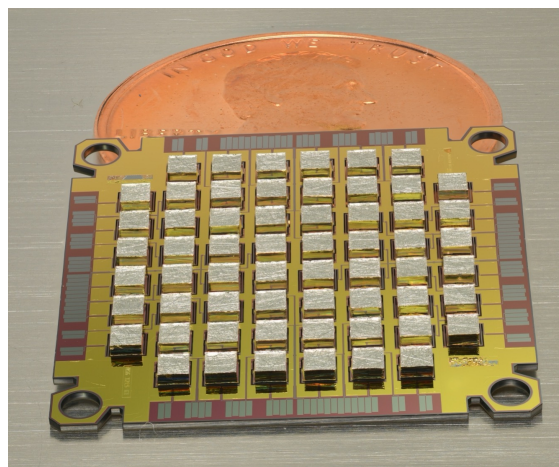


# Key technology: Transition Edge Sensing (TES) Microcalorimeter

## Transition Edge Sensing (TES) $\mu$ -calorimeter

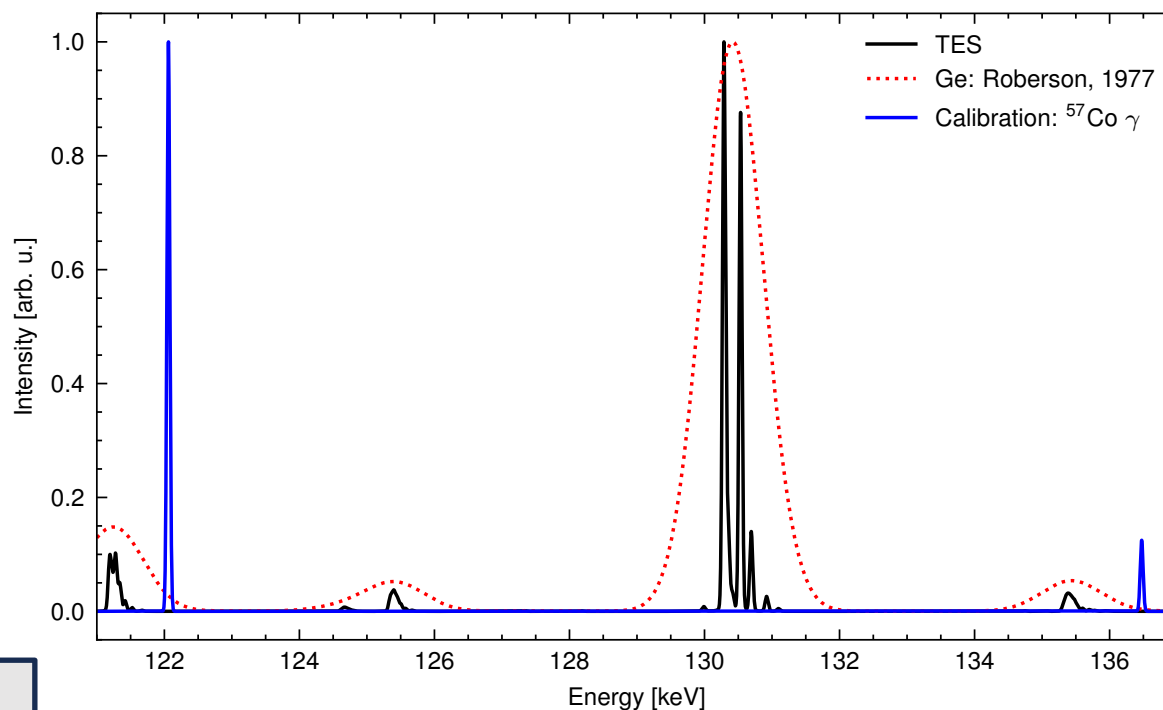
NIST Boulder, CO, USA: Quantum Calorimeters Group

NIST



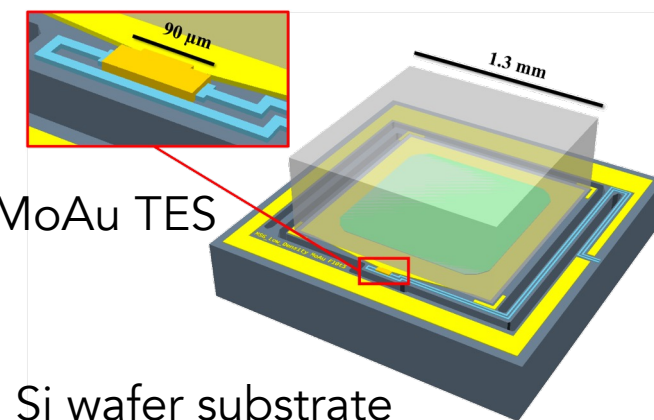
2 cm

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

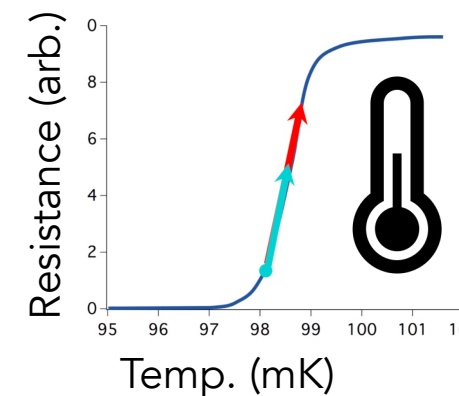


MDFGME spectrum of  $\bar{p} - \text{Zr}$   
near  $n = 9 \rightarrow 8$  transition

Prototype design for  $\bar{\text{PAX}}$



Si wafer substrate

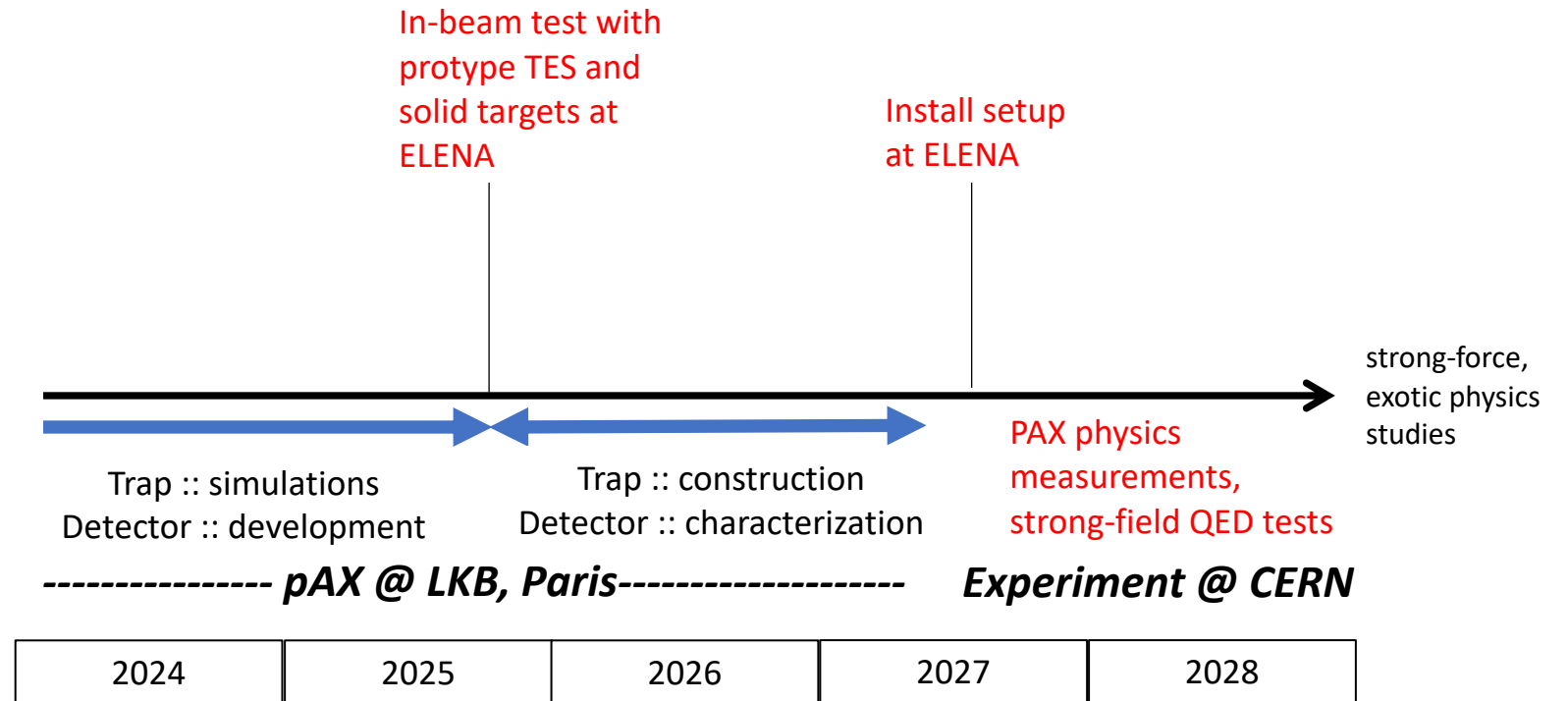
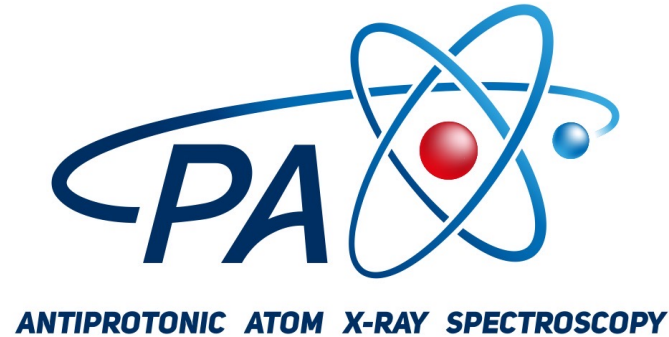


Figures from Ullom and Bennett 2013

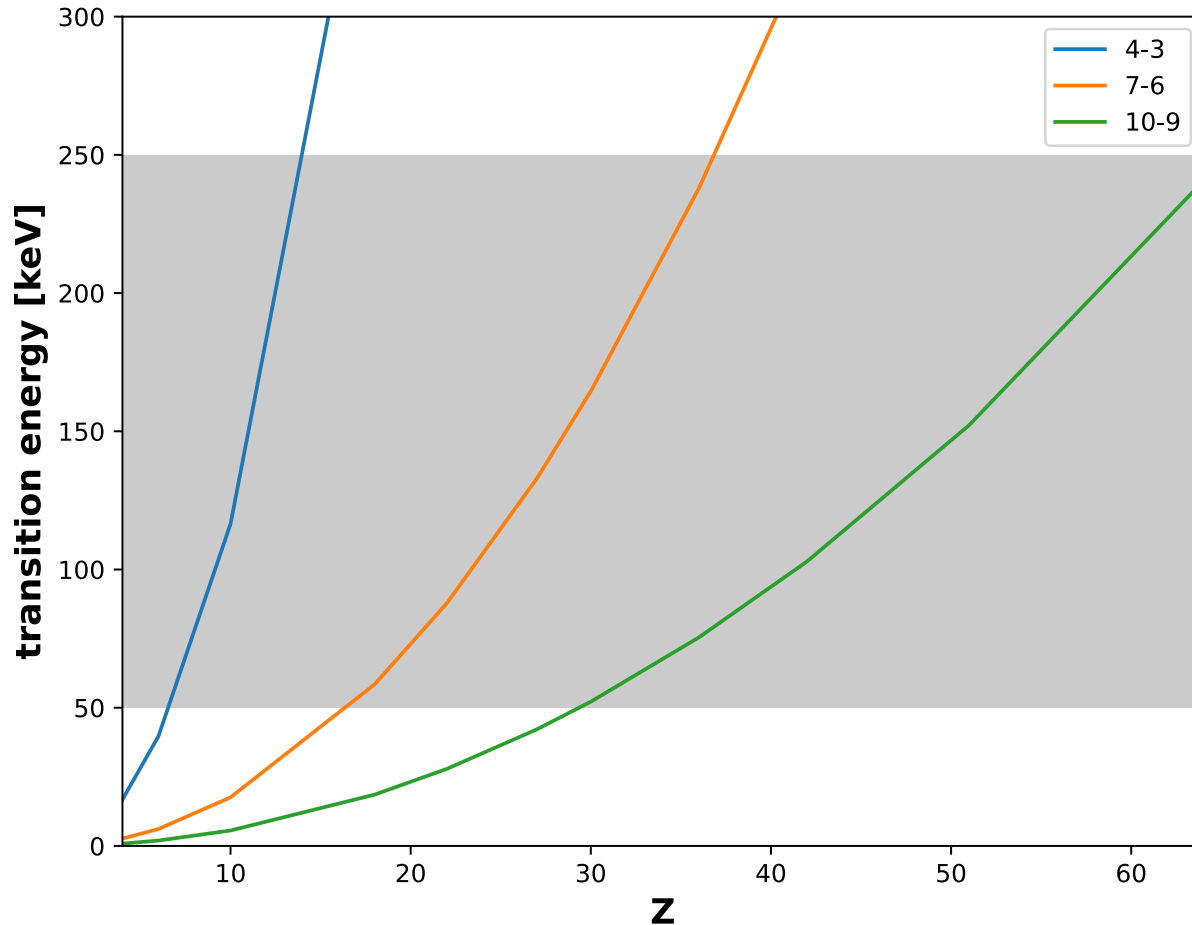
Photo provided by J. Nobles and M. Keller (NIST)

# 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  $\sim 20$  eV, which should be easily detectable as this is about  $\frac{1}{2}$  the intrinsic resolution of the detector
- Attainable centroid accuracies  $\sim 1$  eV, validated with JPARC data.