Probing Fundamental Interactions through Precision Spectroscopy of Exotic Atoms

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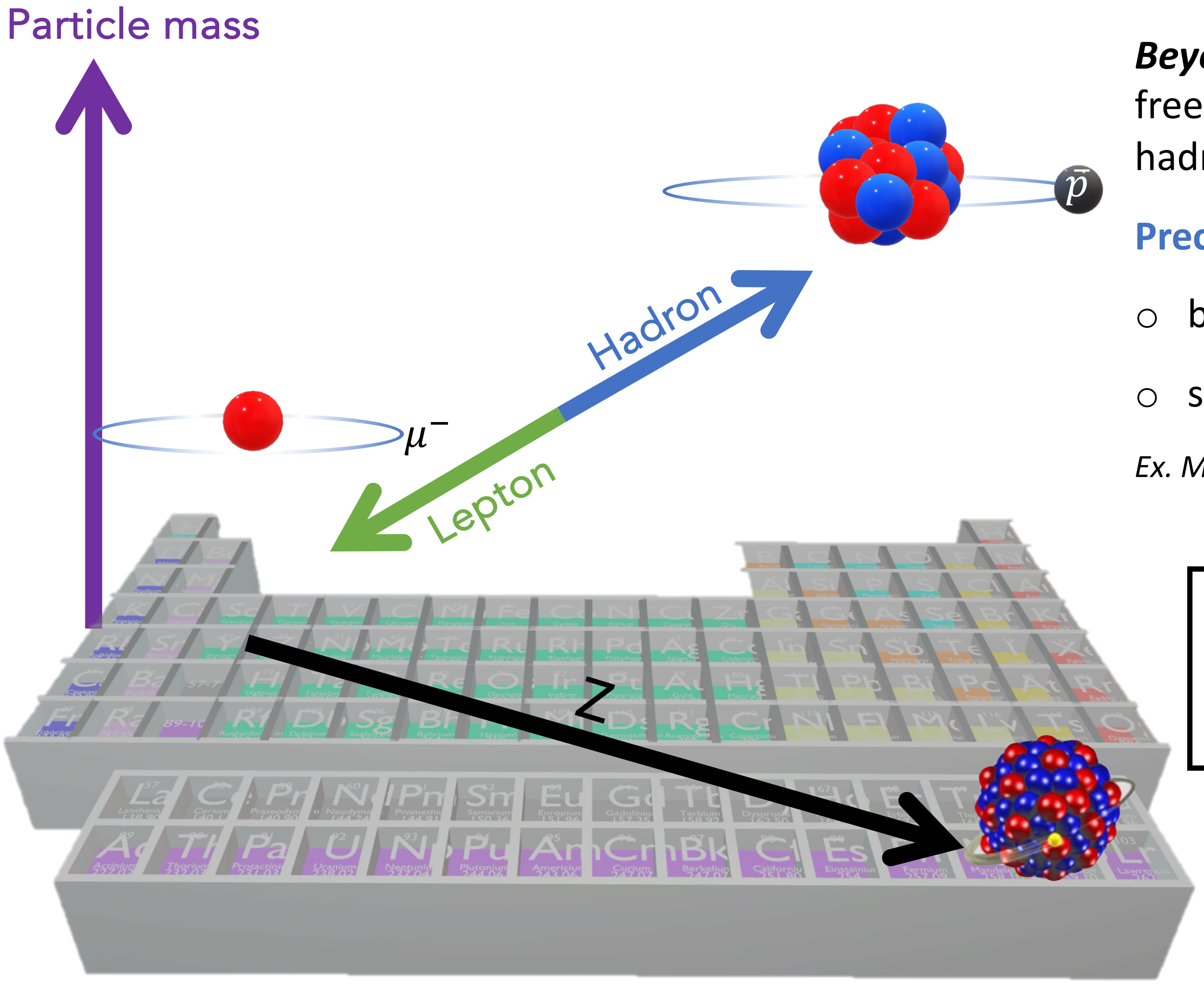
Bormio Winter Meeting
January 20th, 2026

Beyond Mendeleev—exotic atoms



Beyond Mendeleev—exotic ions exploit other degrees of freedom like charge state, particle mass, leptonic and hadronic interactions

Precision studies of complementary, simple systems

- benchmark theory
- search for beyond Standard Model physics

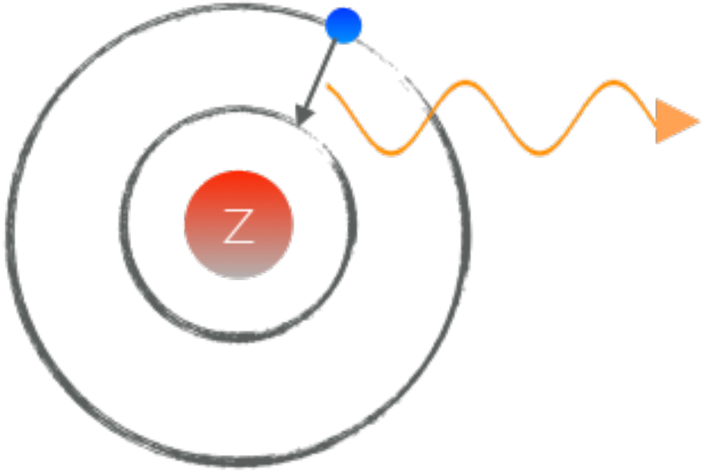
Ex. Muonic vs electronic hydrogen → proton radius puzzle

Current precision measurements limited to lightest systems (low Z)

- ❑ ***What happens for high-Z systems?***

Quantum electrodynamics in a nutshell

Quantum electrodynamics : interactions between photons and charged particles



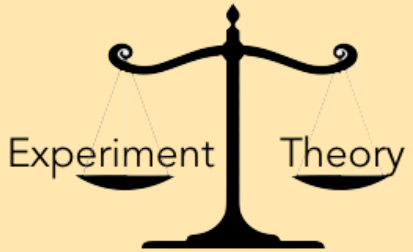
Atomic transitions

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

Dirac equation

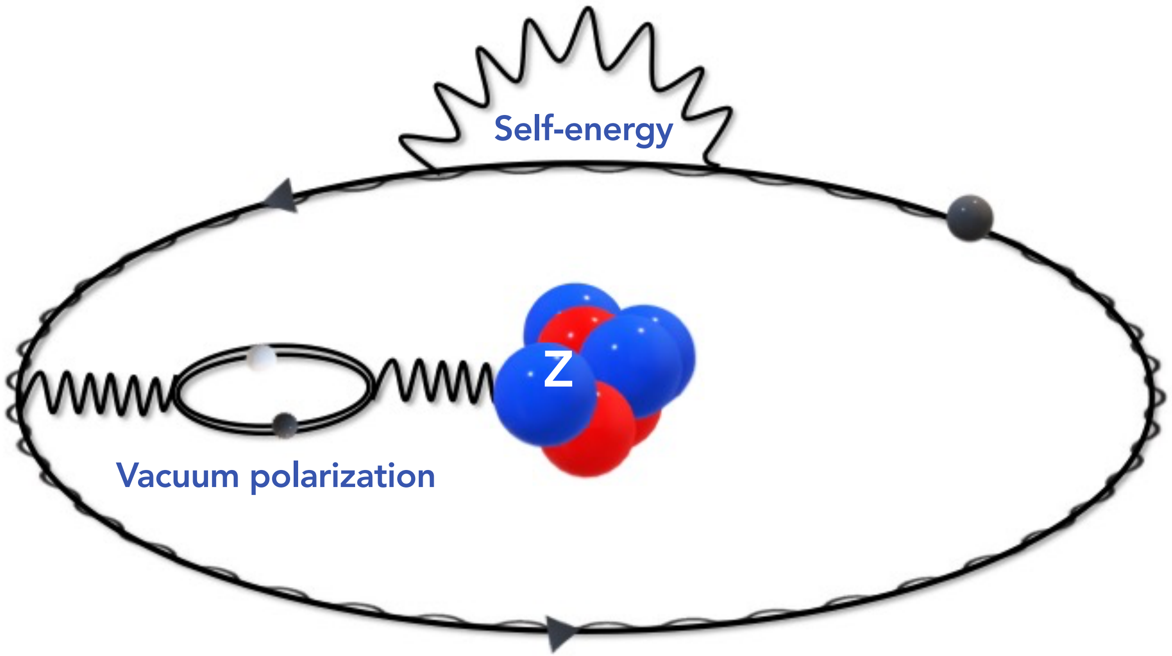
Nuclear effects

Quantum electrodynamics

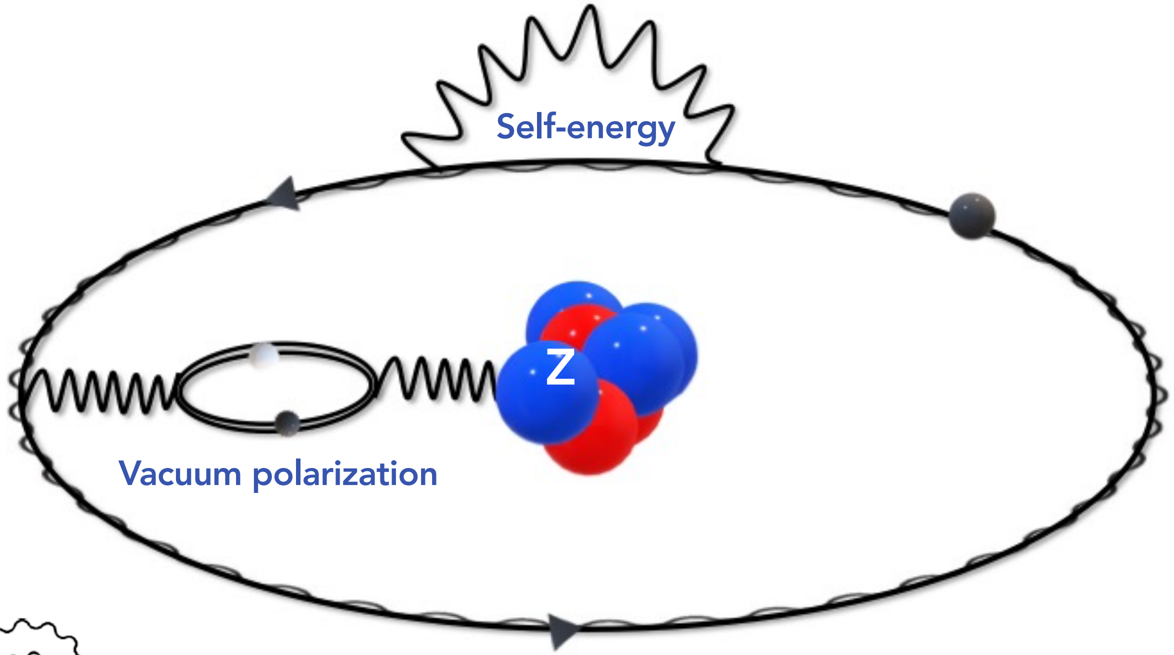


= **QED test**

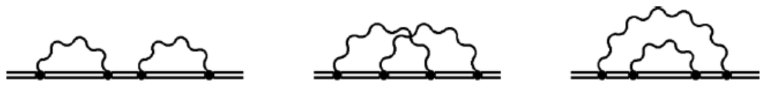
Bound-state QED, a rich landscape



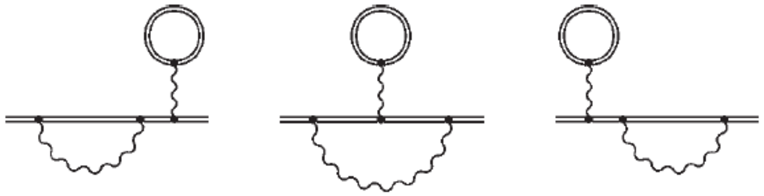
Bound-state QED, a rich landscape



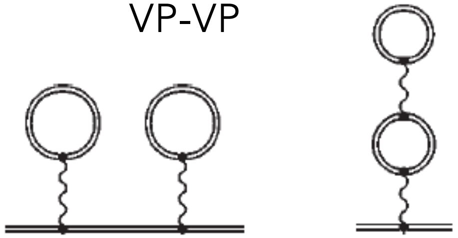
SE-SE



SE-VP

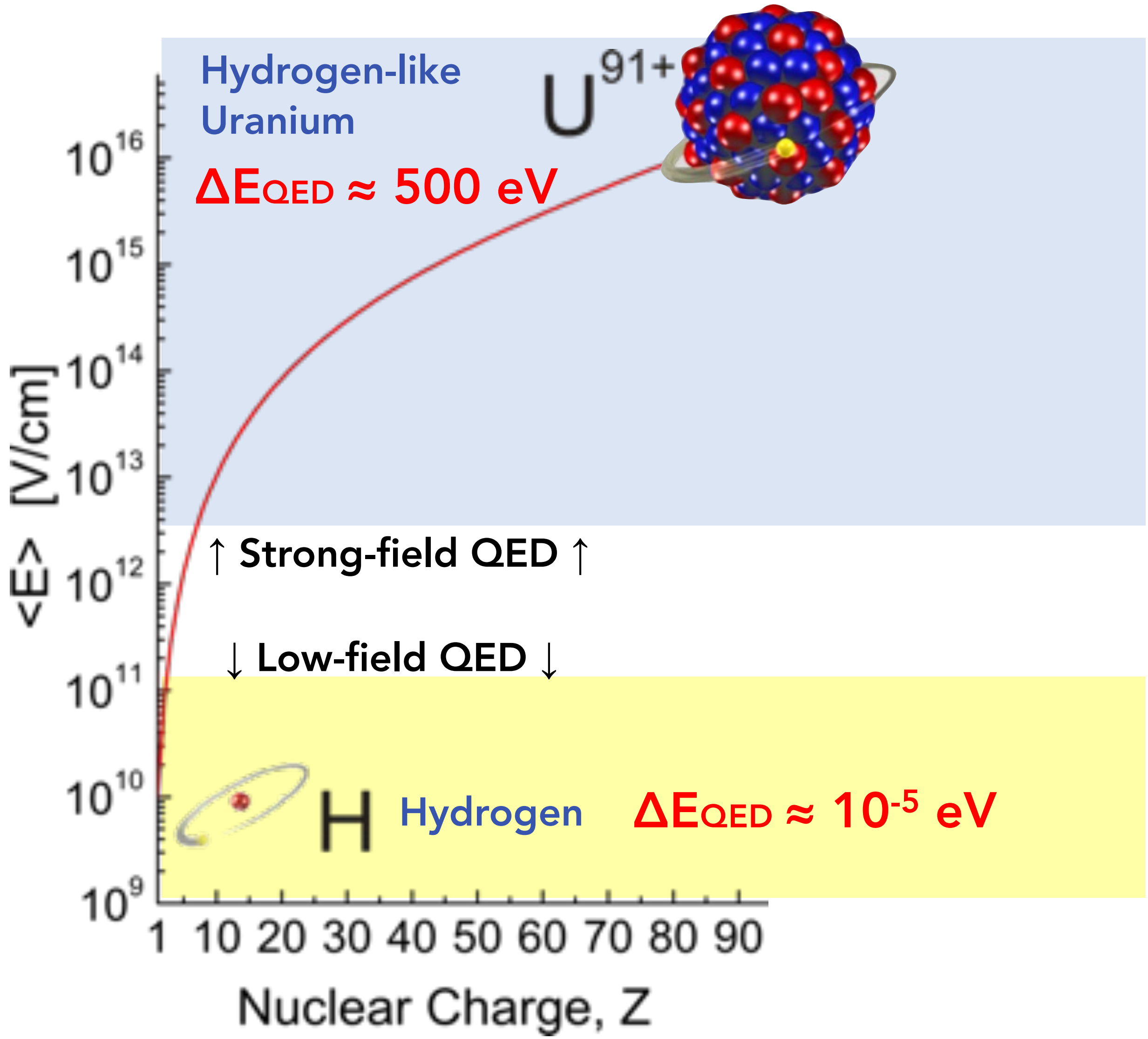


VP-VP



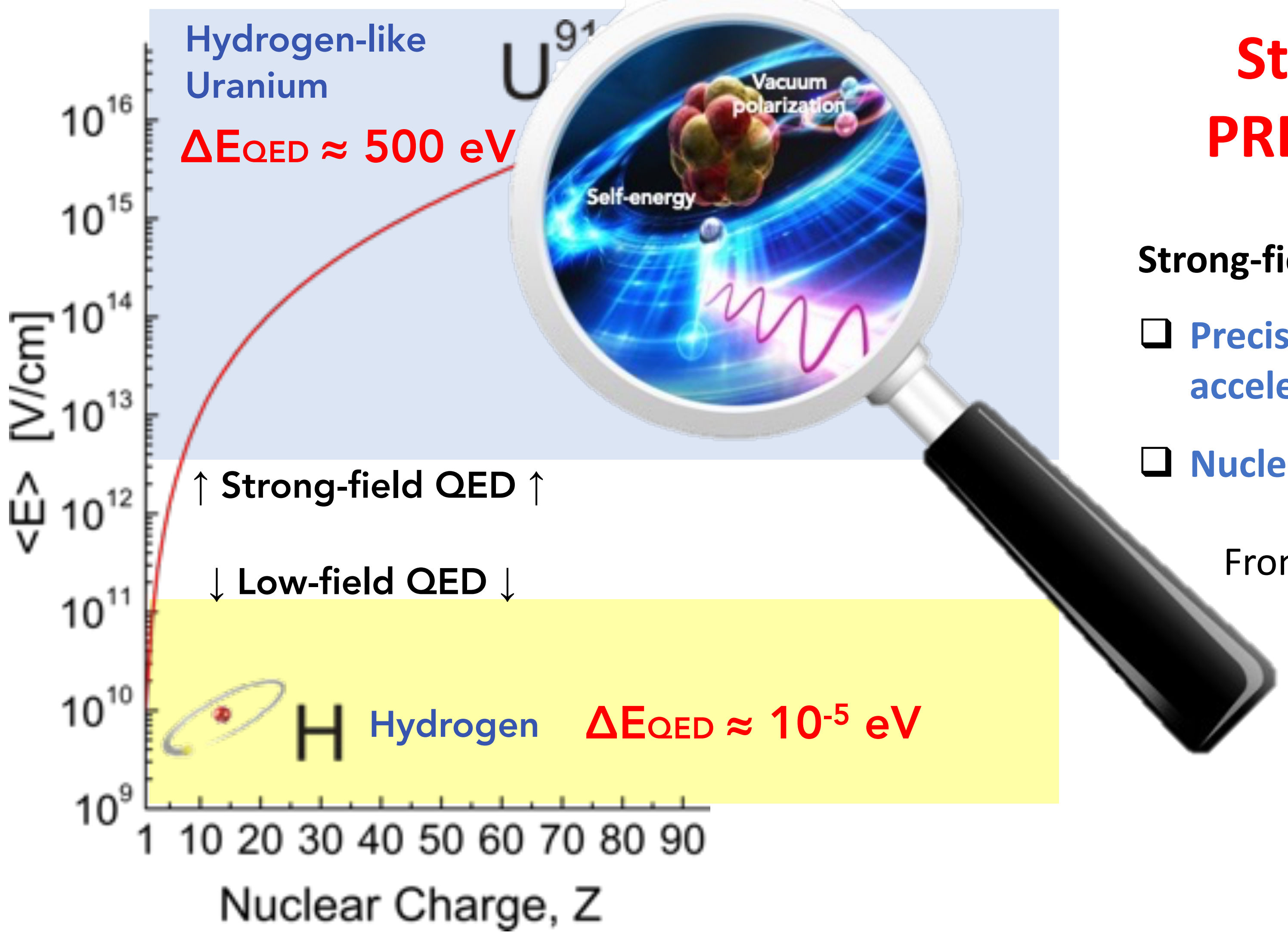
S(VP)E

Strong-field QED—experimental frontier



- High precision comparison between theory and experiment possible for low-Z systems (H, He, D)
- Strong-field QED transitions in the ~keV regime, no direct laser spectroscopy
- QED effects become relatively more important
- QED theory non-perturbative (Zα)
- Theory exists but experimentally difficult to test higher-order QED contributions

Strong-field QED—experimental frontier



Strong-field QED effects PREDICTED but UNTESTED

Strong-field QED with highly charged ions limited by:

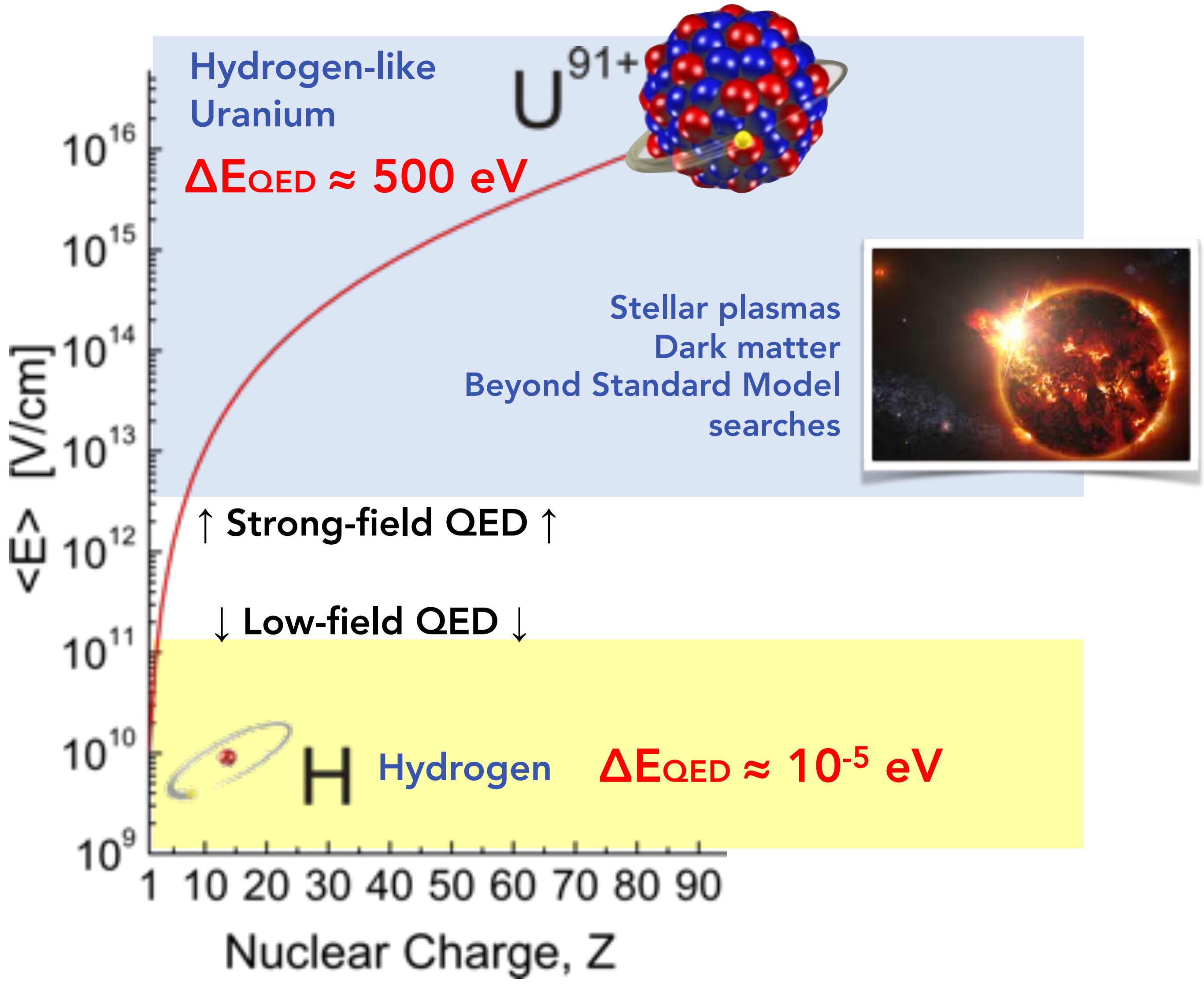
- **Precision hard x-ray spectroscopy methods at accelerators**
- **Nuclear physics uncertainties**

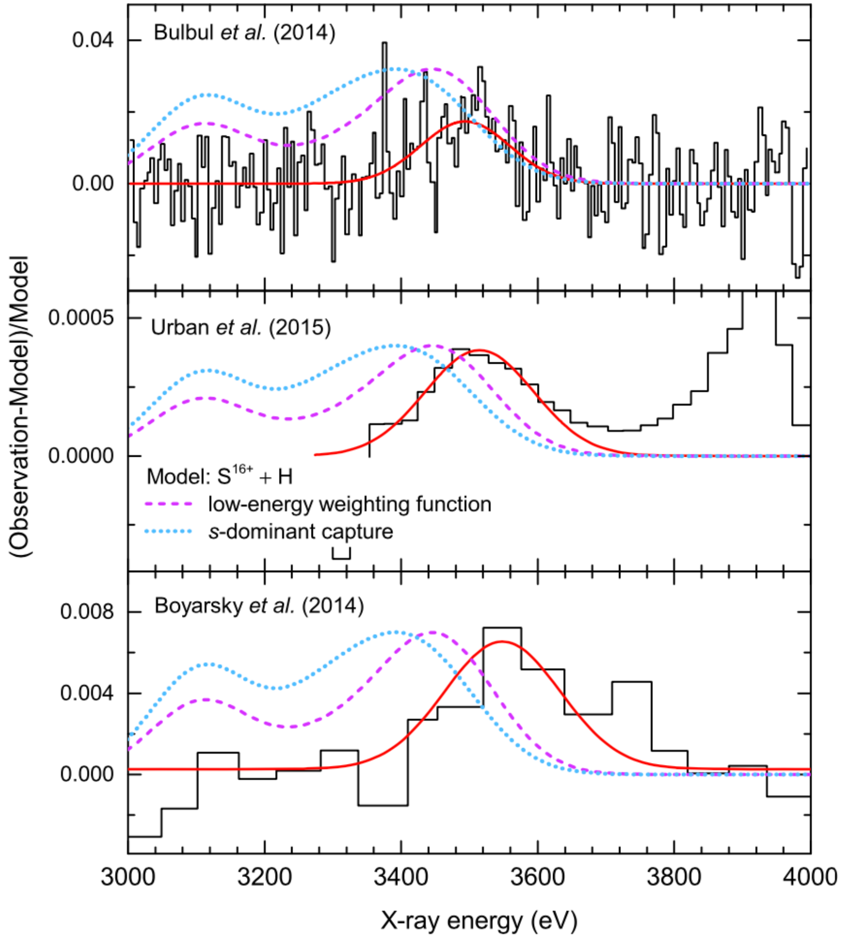
Frontier pursued by complementary methods

Ex. g-factors, Sailer, Nature 606 (2022)

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

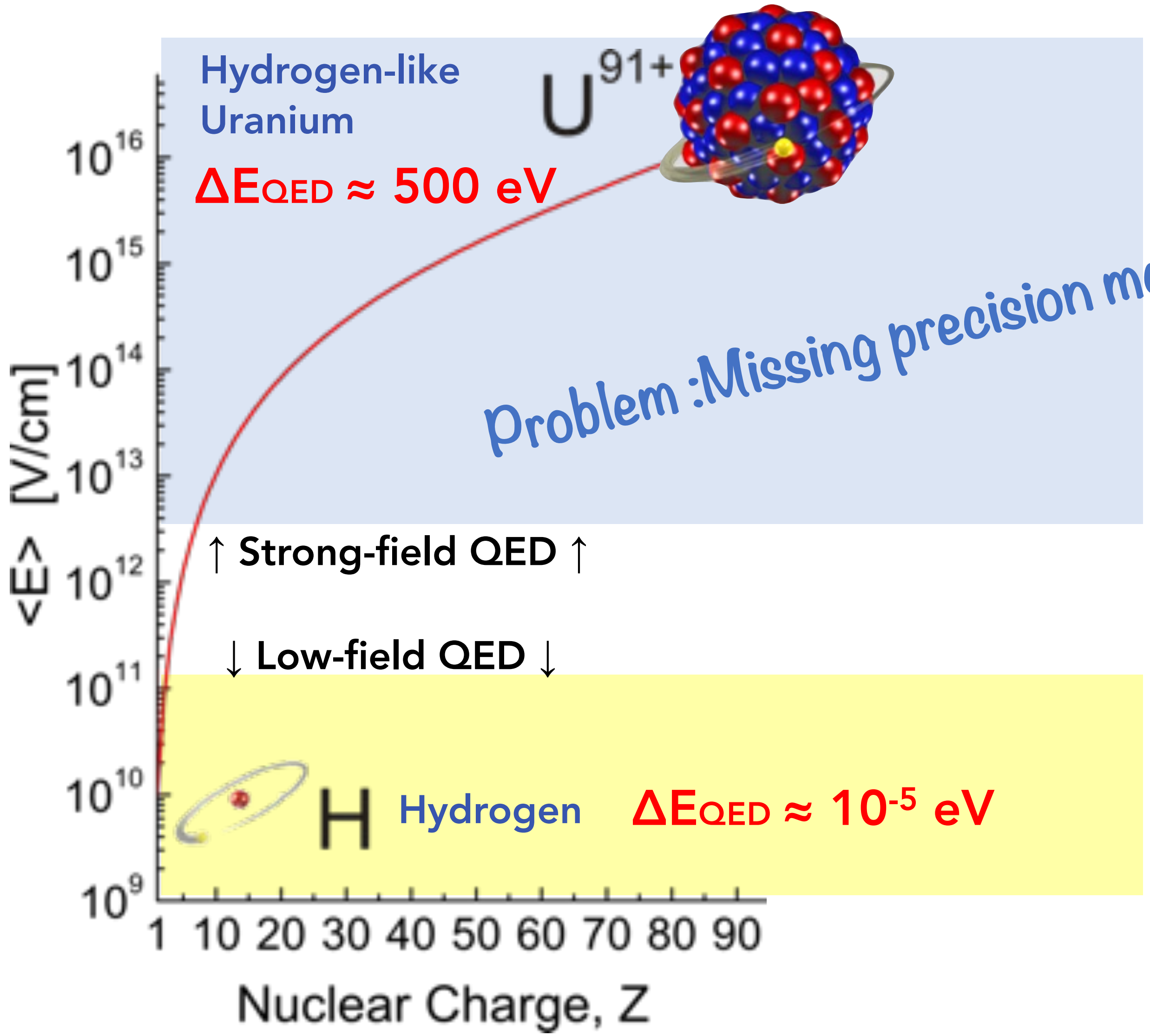
Strong-field QED—experimental frontier





Highly-charged S emission:
Boyarsky et al, **Physical Review Letters** (2014)
Shah et al, The Astrophysical Journal (2016)

Strong-field QED—experimental frontier

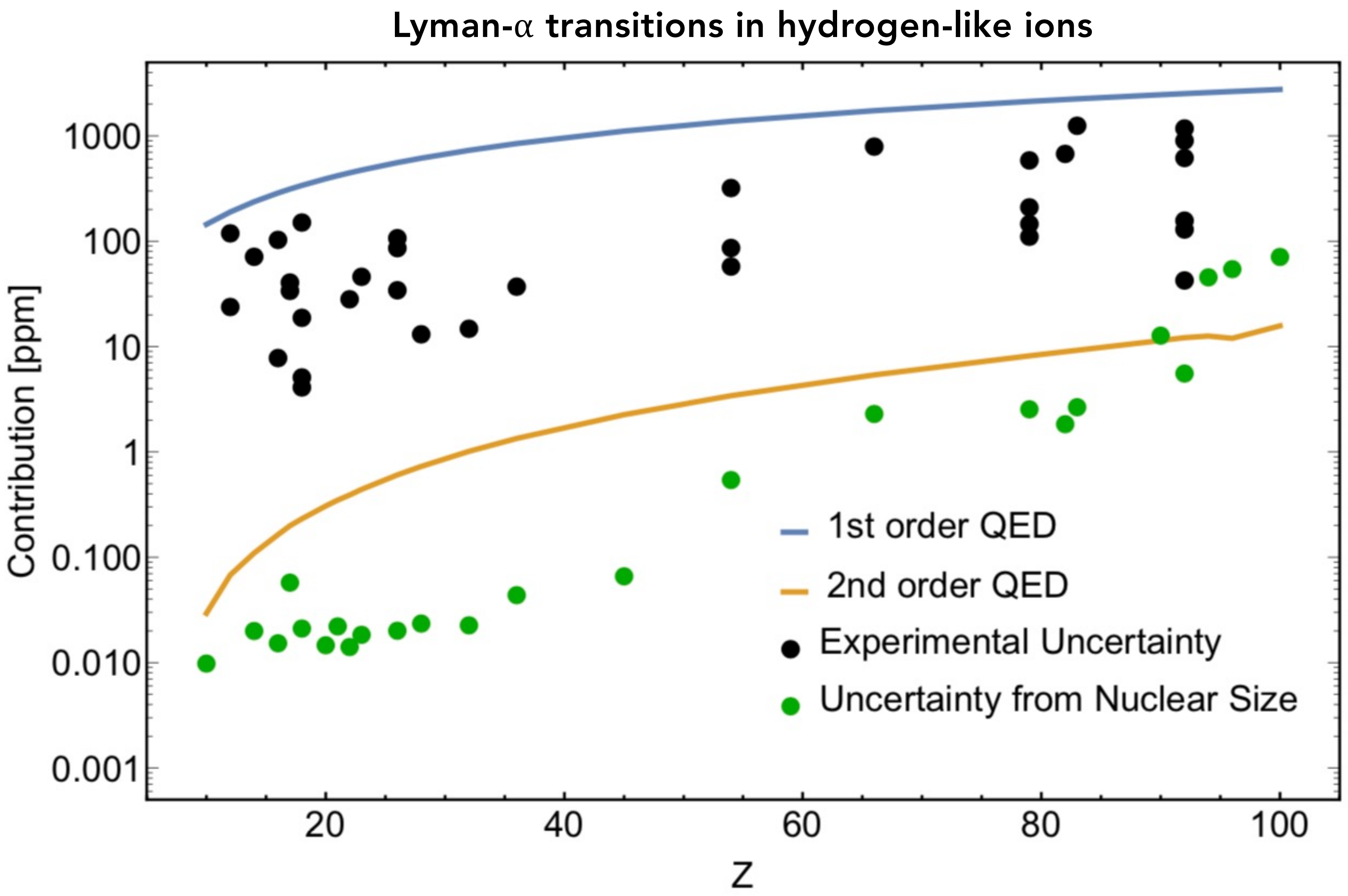


Problem :Missing precision measurements!

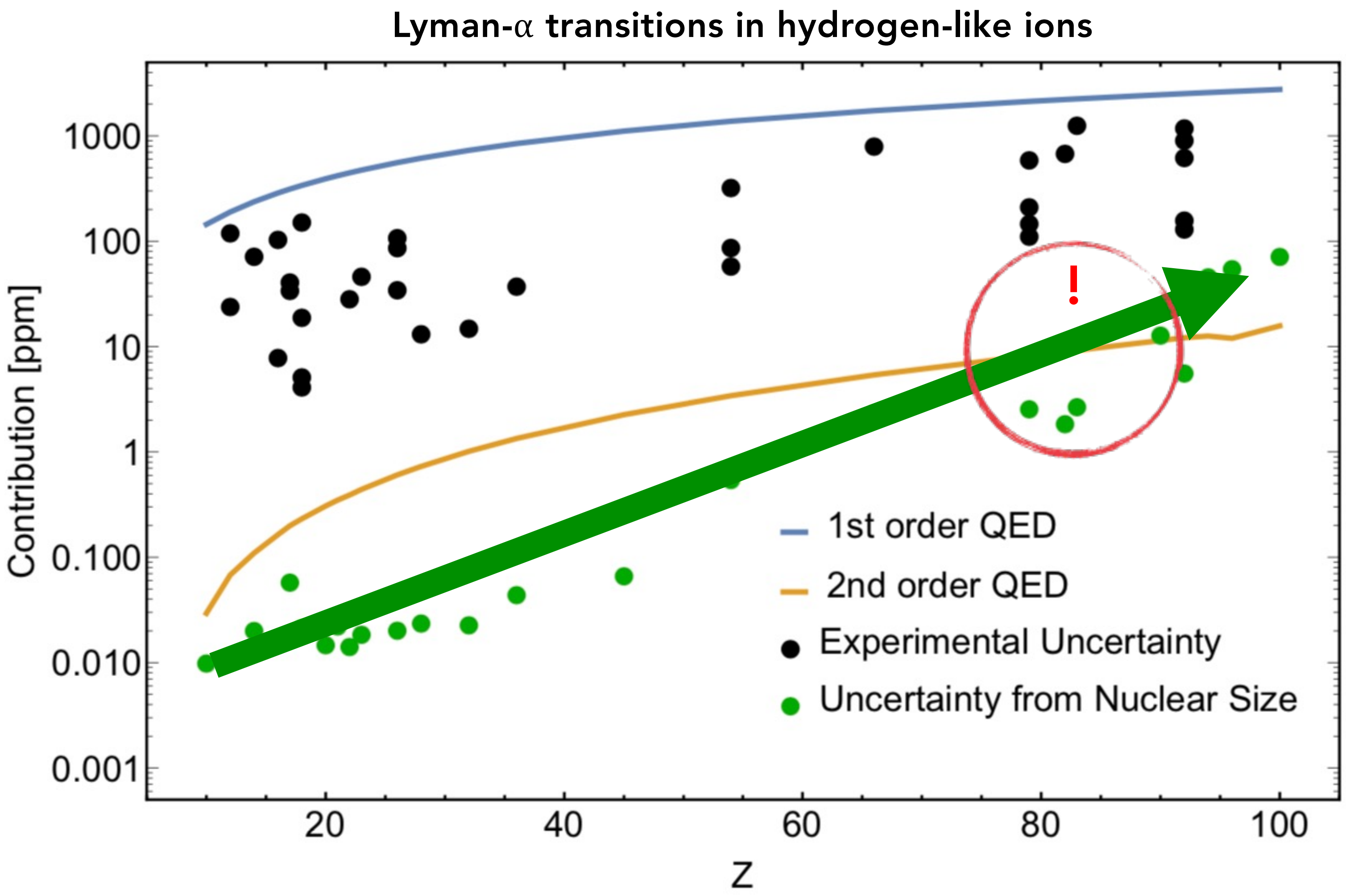
*QED untested beyond 1st order effects,
2nd order QED is ppm effect and currently untested!

*QED tested to threshold of 3rd order effects

Strong-field QED: limitations from nuclear physics



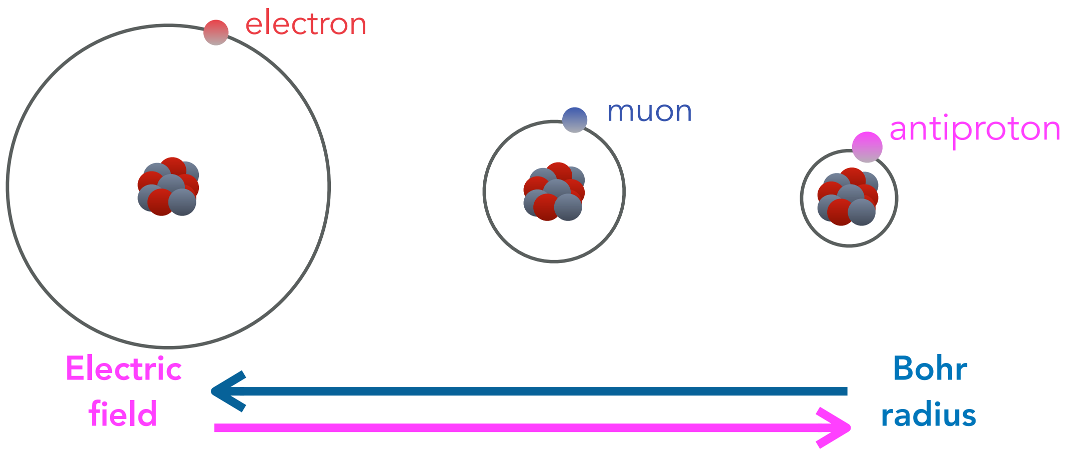
Strong-field QED: limitations from nuclear physics



Strong-field QED with exotic atoms

Exotic atoms

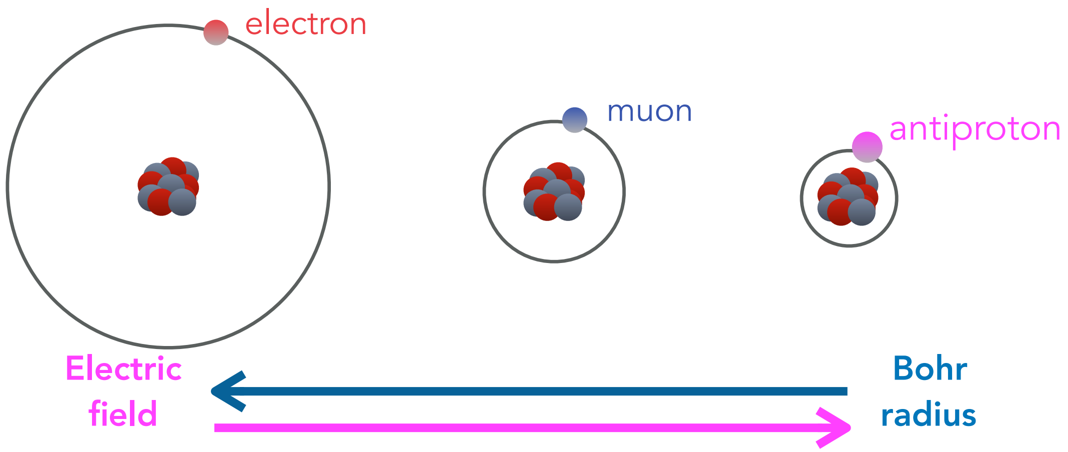
Strong-field QED with exotic atoms

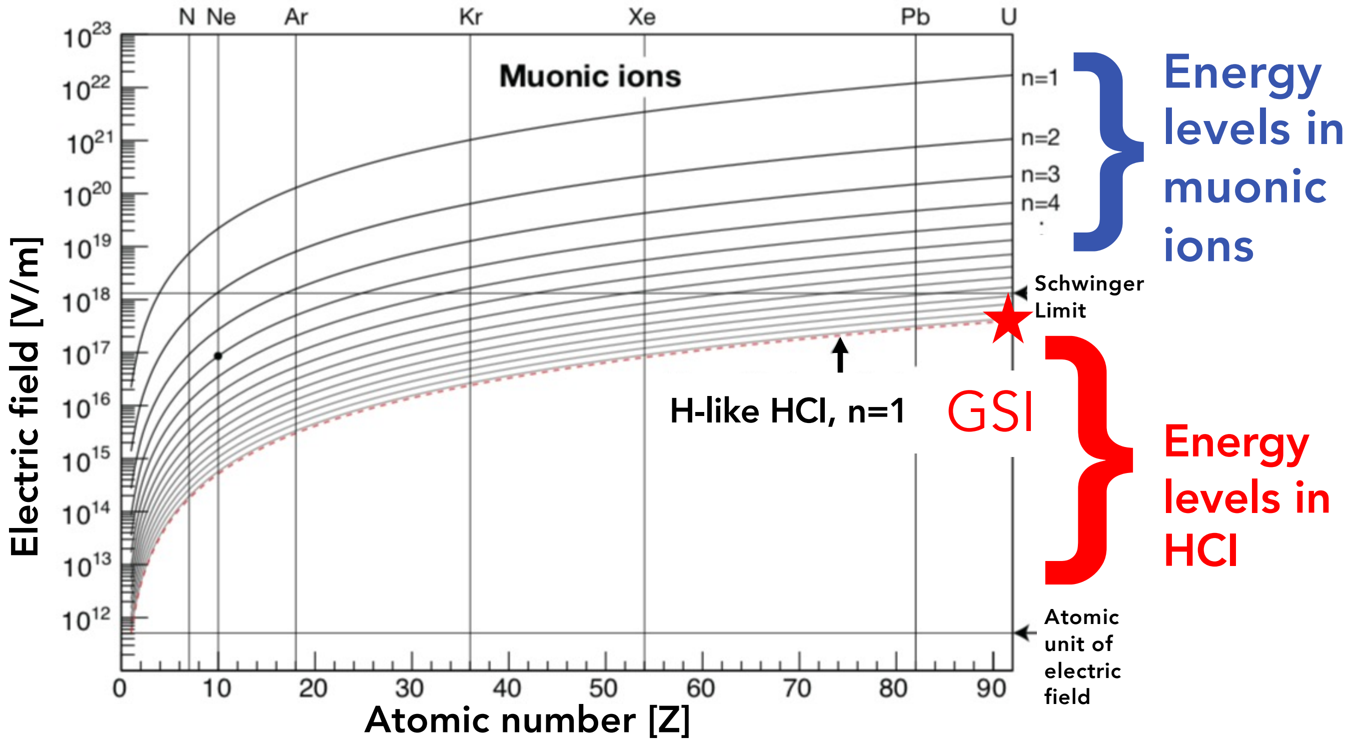


$$m_\mu \sim 200\, m_{e^-}$$

$$r_\mu \sim \frac{1}{200} r_{e^-}$$

Strong-field QED with exotic atoms





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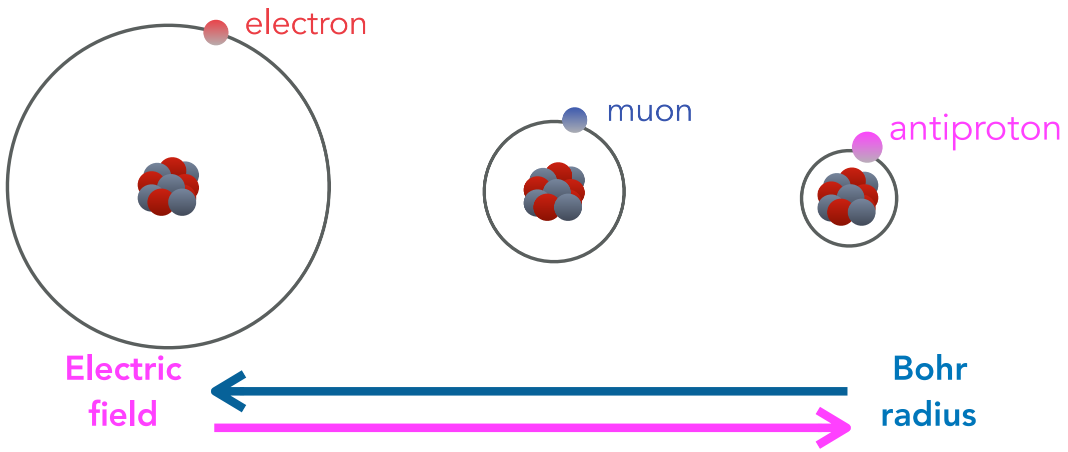
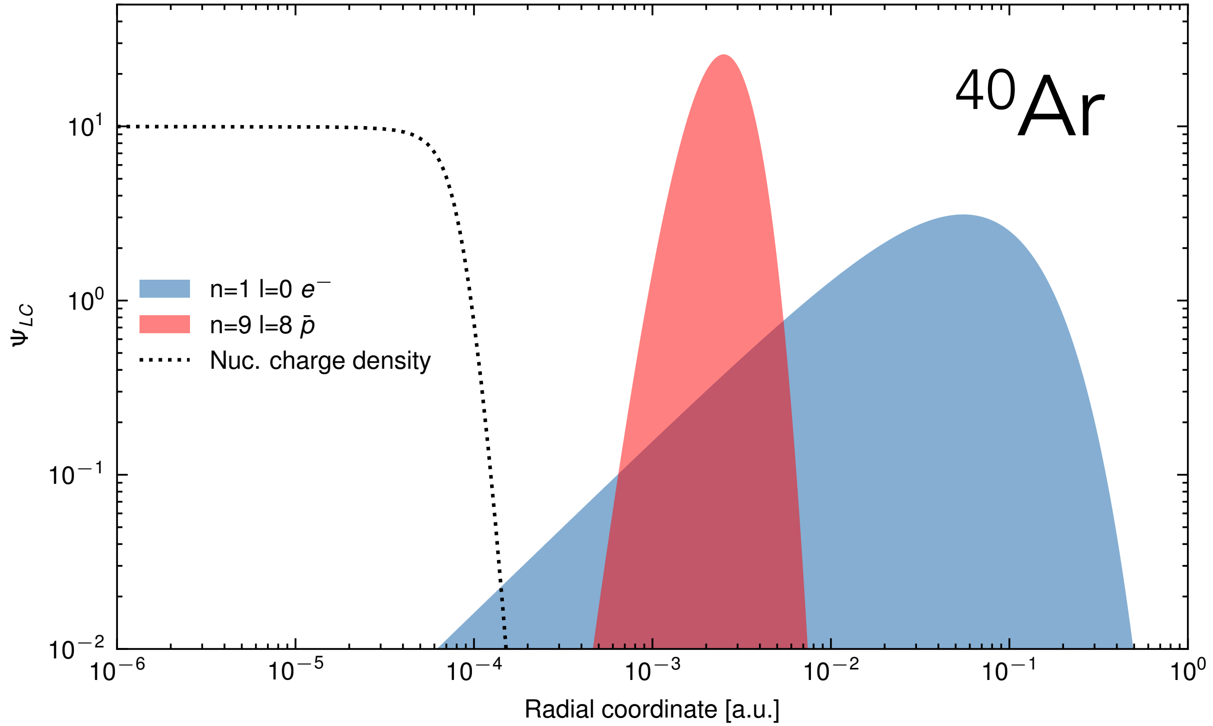
$$r_\mu \sim \frac{1}{200} r_{e^-}$$

- Heavy exotic particle →small Bohr radius →strong electric field strength
- Higher order QED effects magnified and become measurable with new techniques

Measurement paradigm—N. Paul et al, PRL 126 (2021)
First proof-of-principle with muonic atoms—T. Okumura et al, PRL 130 (2023)

Strong-field QED with exotic atoms





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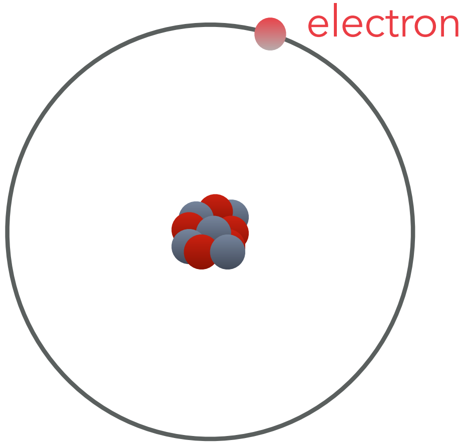
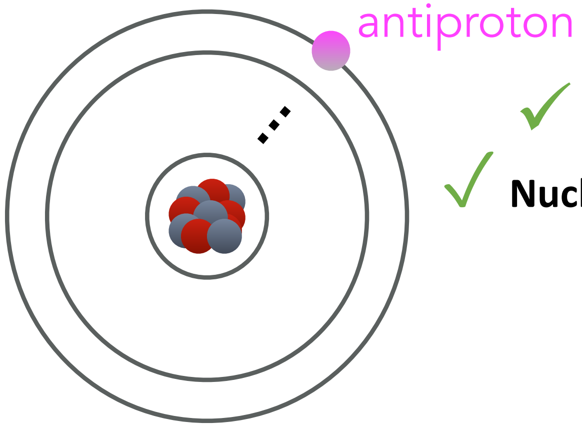
The concept: strong field QED with exotic atom Rydberg states

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

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



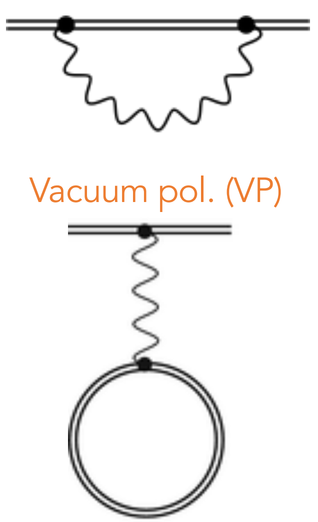


✓ **STRONGEST field QED**
✓ **Nuclear effects << QED effects**

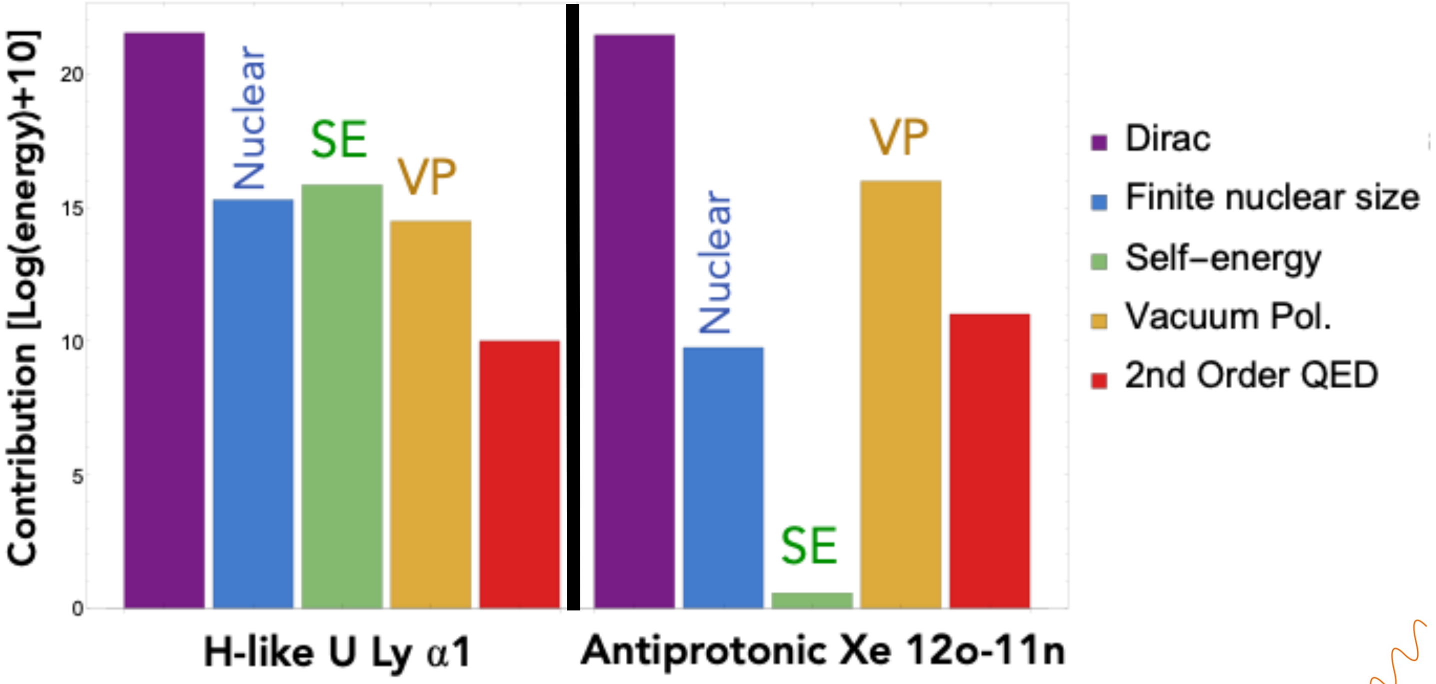
Atom	Transition	Transition energy	1st order QED	2nd order QED	Nuclear effects
H-like U	Lyman α1	~100 keV	$3x10^{-3}$	$1x10^{-5}$	$2x10^{-3}$
antiprotonic-Xe	n=12→n=11	~100 keV	$7x10^{-3}$	$6x10^{-5}$	$1x10^{-5}$

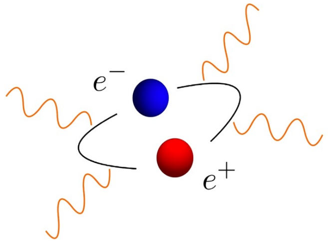
QED x 3-6 **Nuclear effects / 100**

HCI and exotic atoms: a complementary pair



Highly charged ion: SE>VP
Exotic atom: VP>SE



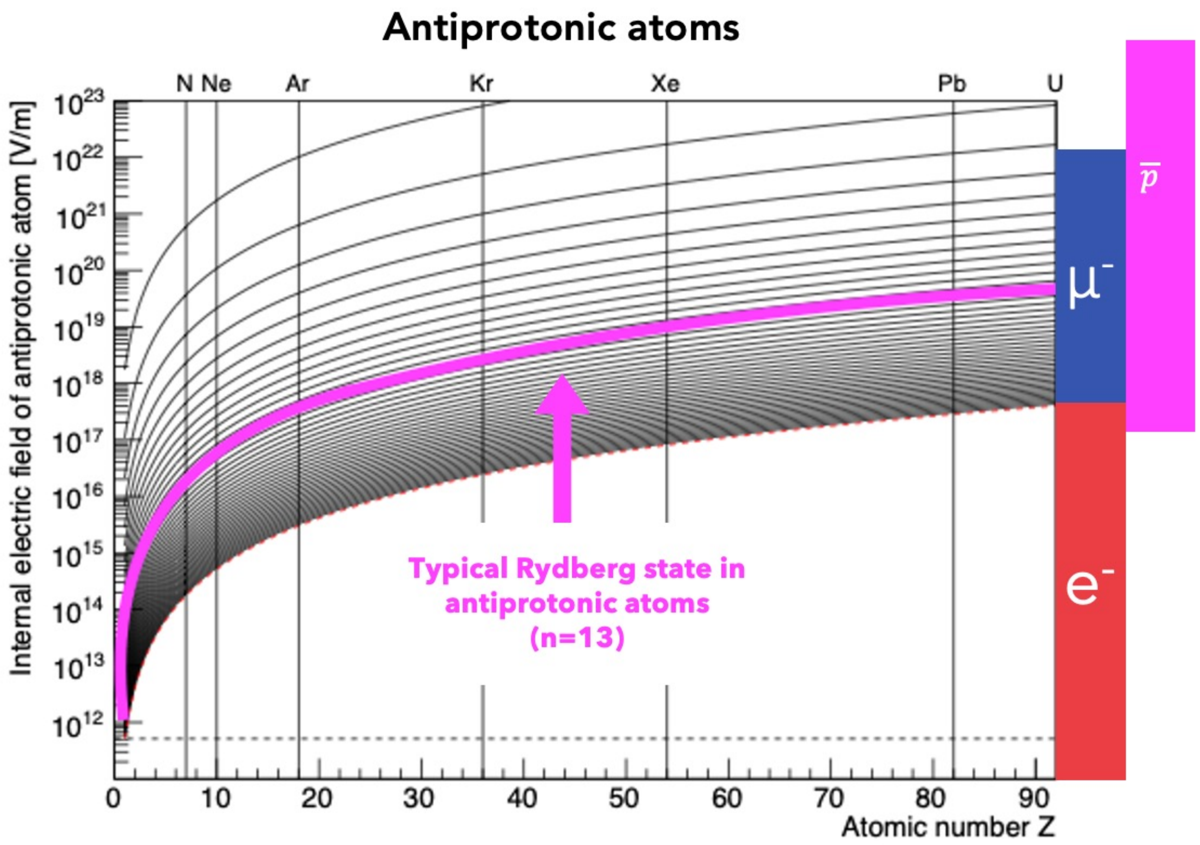


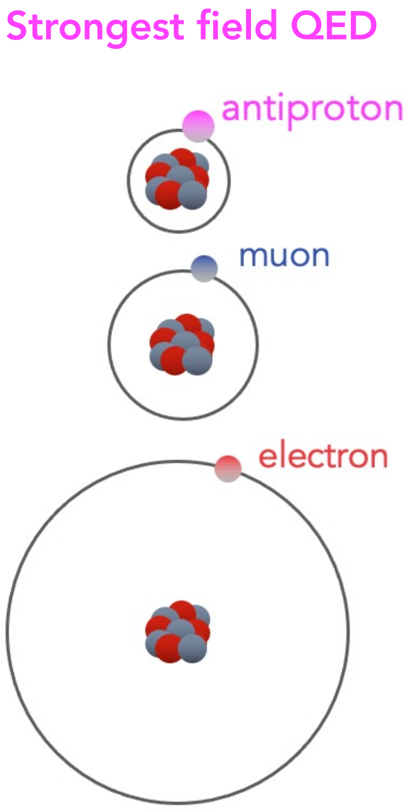
Self-energy is dominant in HCI, vacuum polarization is dominant in exotic atoms

Unique probe of vacuum polarization, « *one of the most interesting phenomena predicted by contemporary quantum electrodynamics* » (Foldy and Eriksen, Physical Review (1954))

Complementary to vacuum studies with high-intensity lasers

Next step…strong field QED with antiprotons





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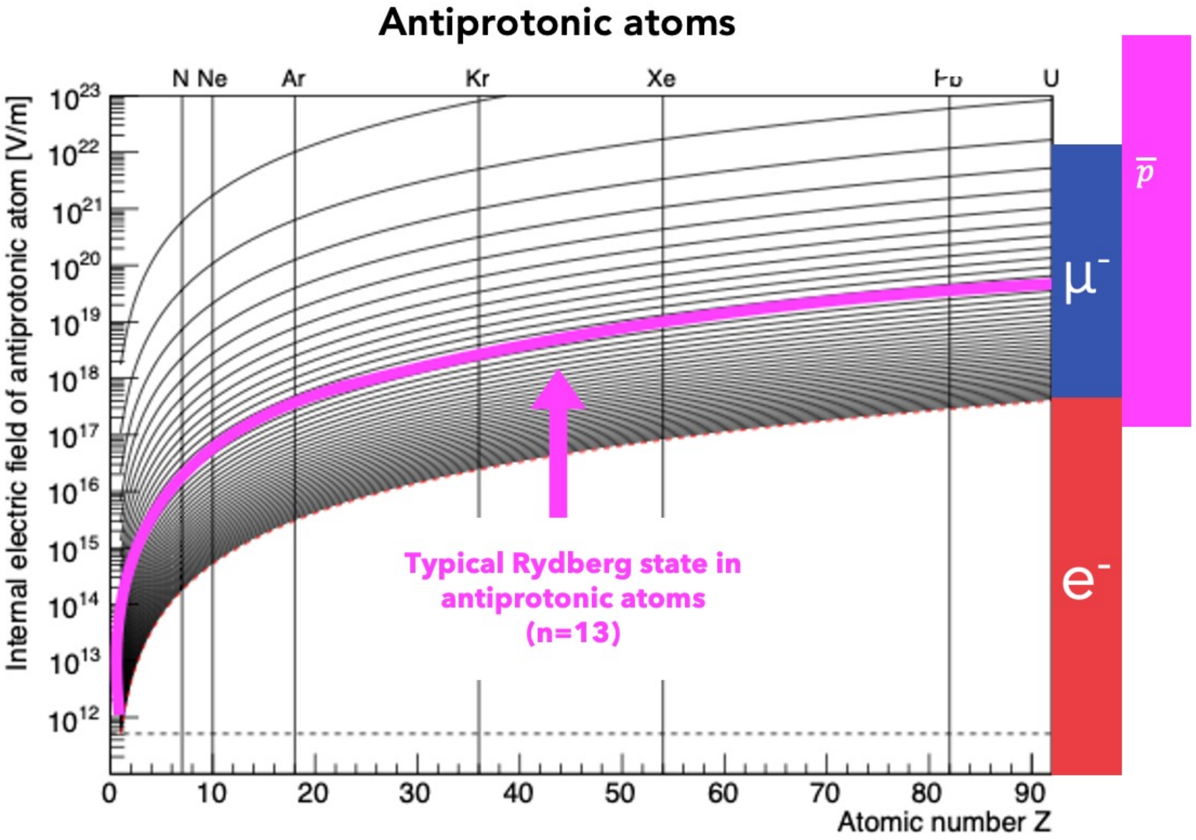
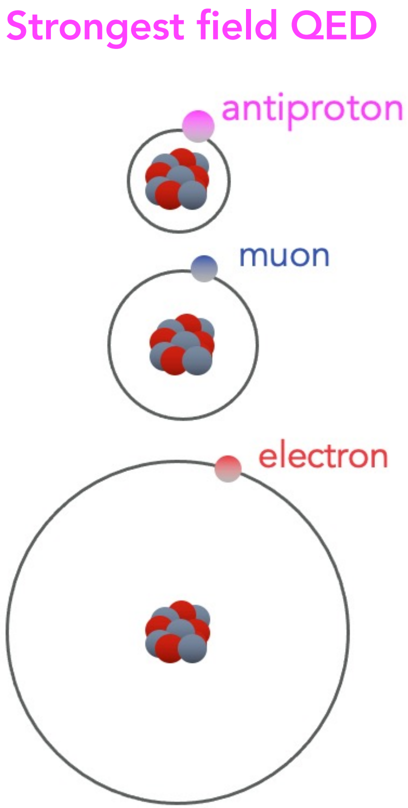
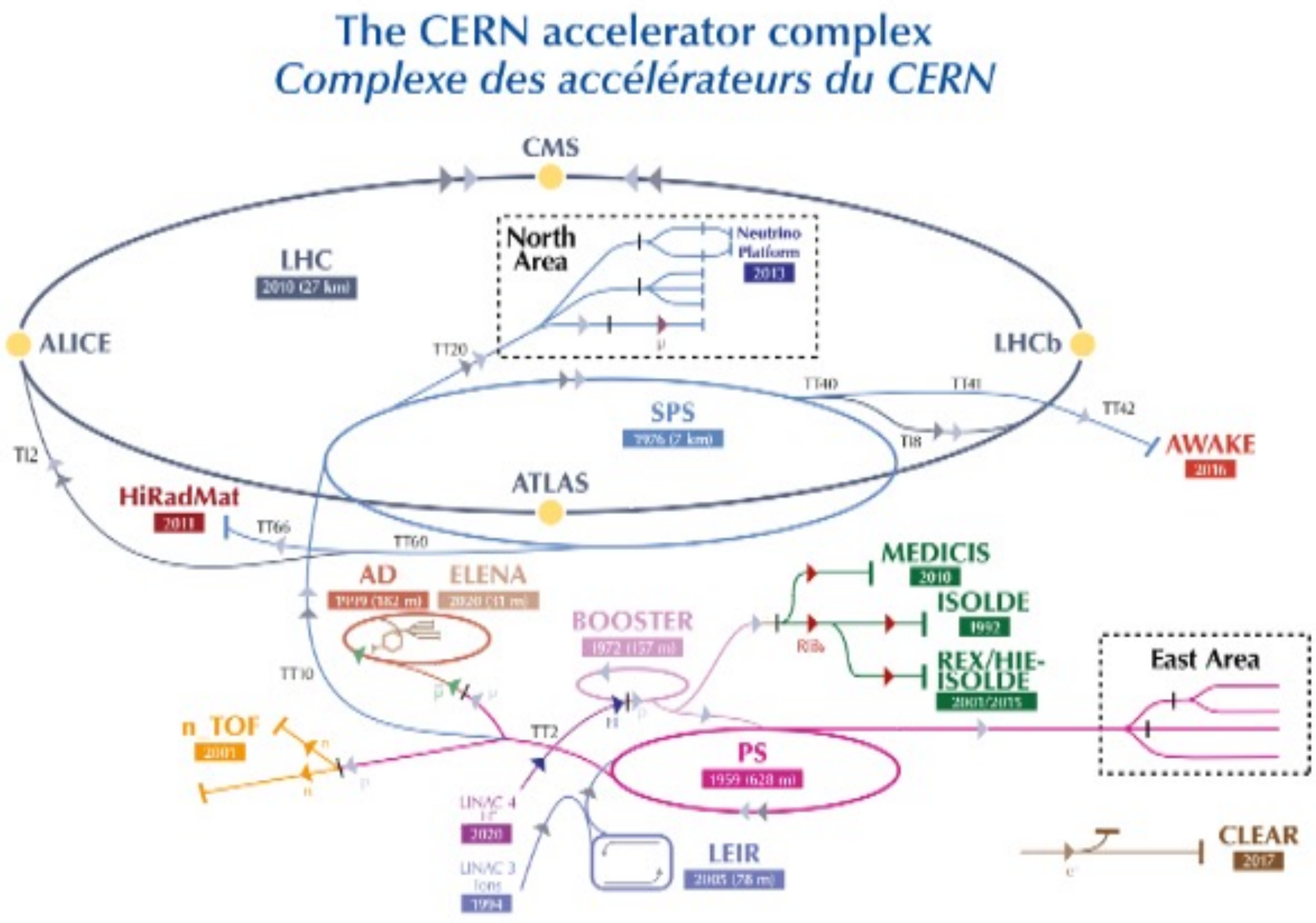




The $\bar{p}AX$ project—antiprotonic Atom X-ray spectroscopy

ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

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	~3 x 10^6
Bunch size (FWHM)	100 ns
Repetition rate	100 s

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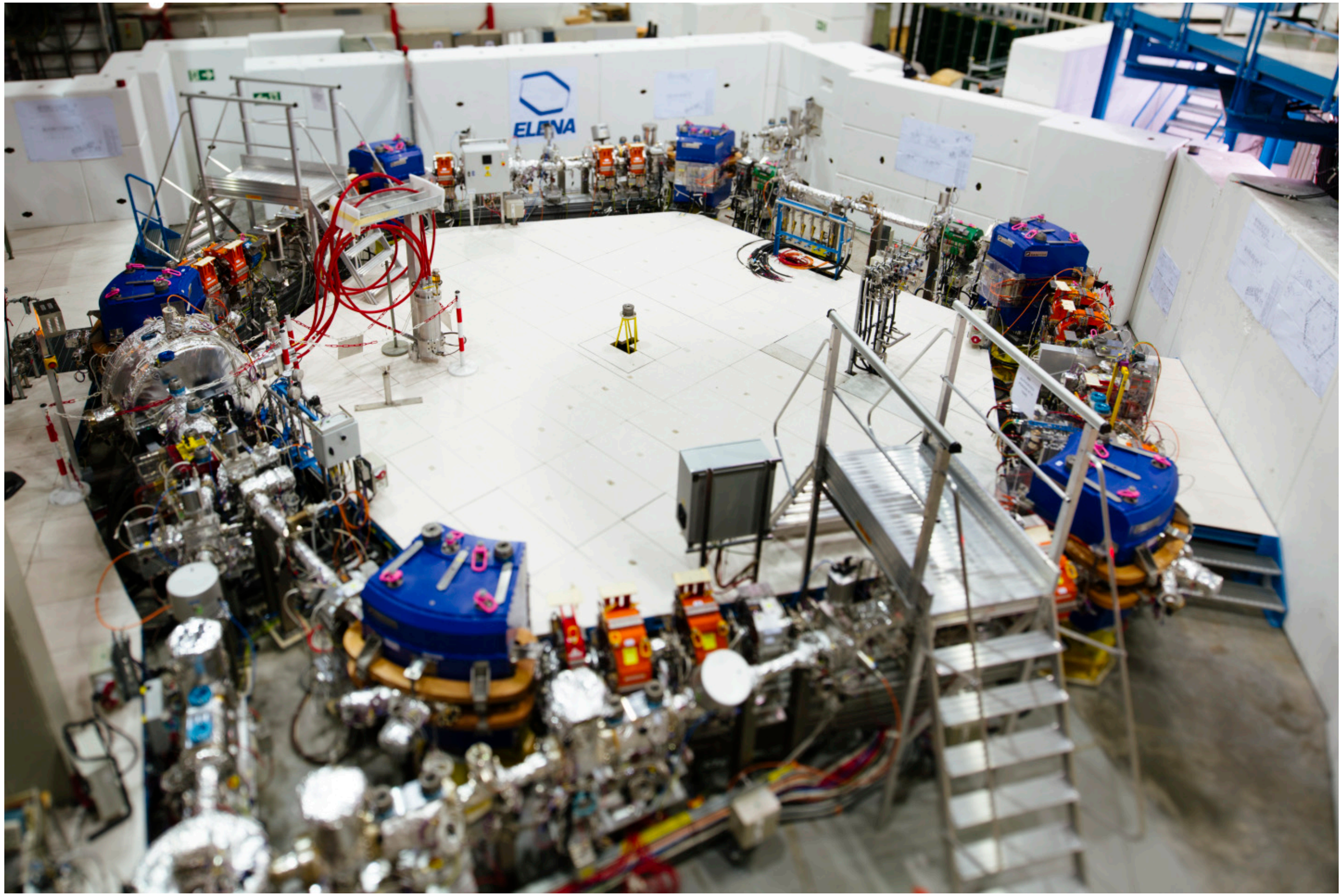

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Beams of slow antiprotons since August 2021

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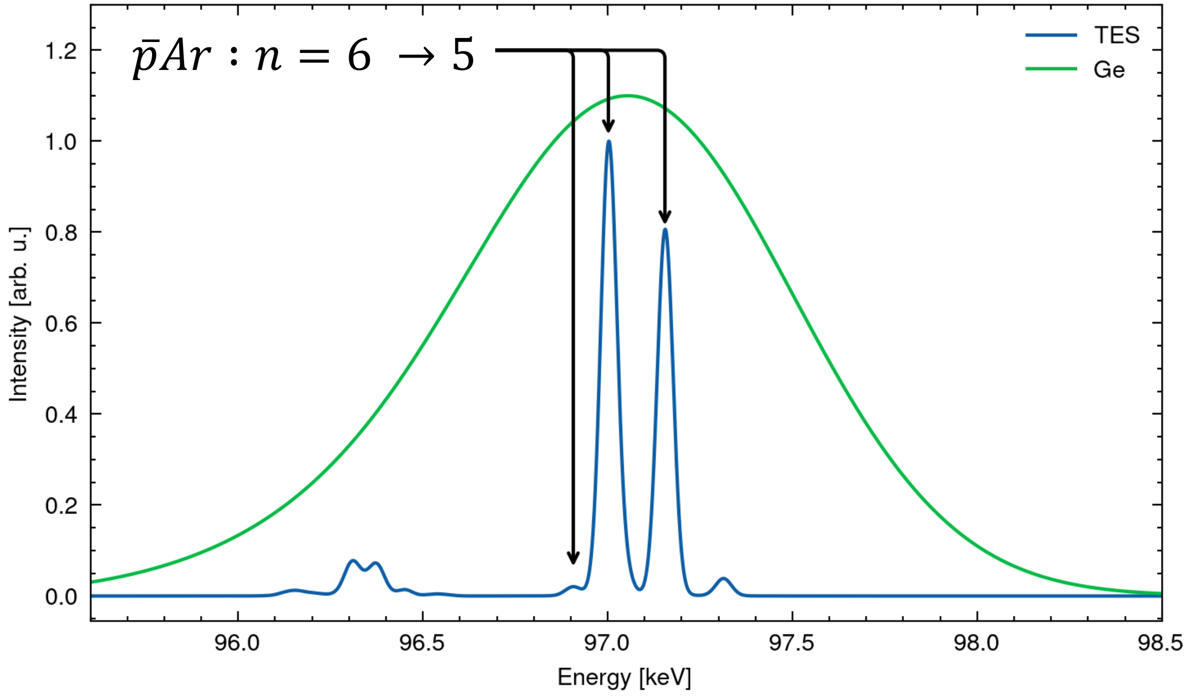
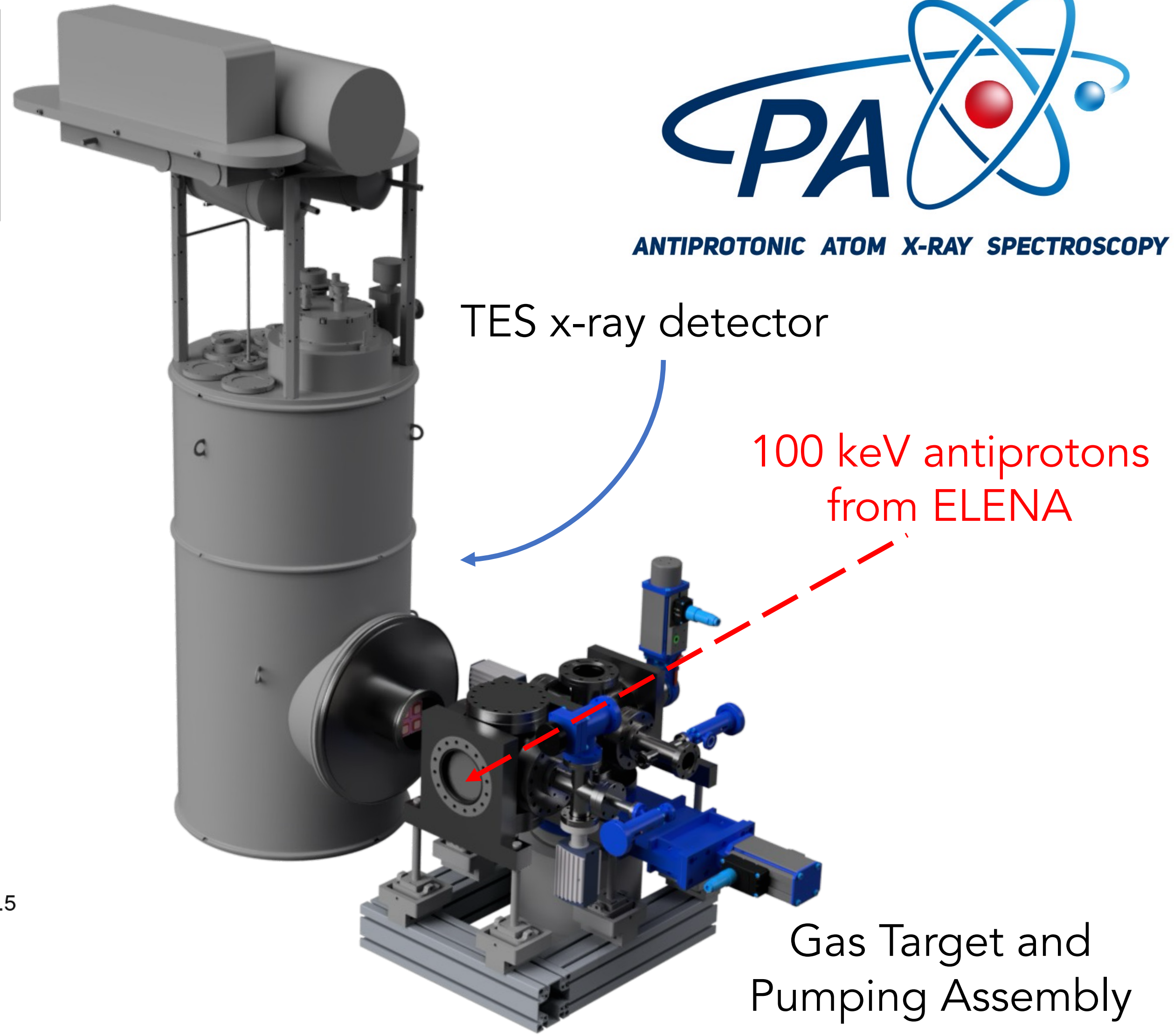
The $\bar{p}AX$ approach: quantum sensing detectors + antiprotonic atoms

New experimental approach with $\bar{p}AX$:

- **Original method with Transition Edge Sensor (TES) detector → 50 x gain in intrinsic resolution**

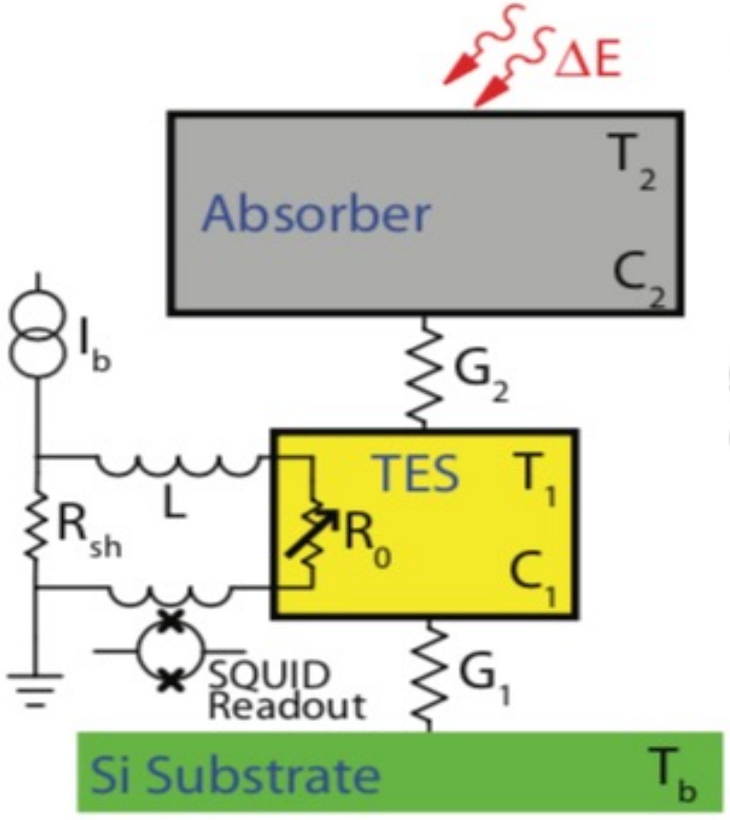


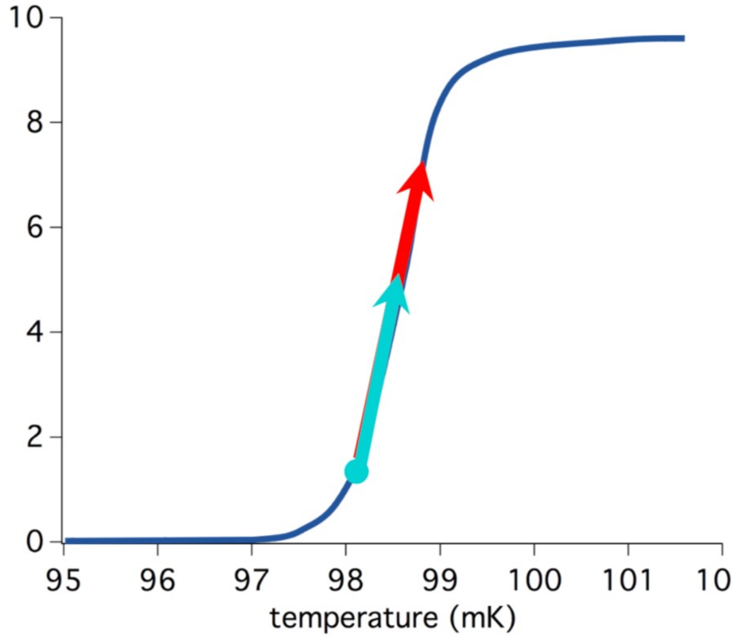


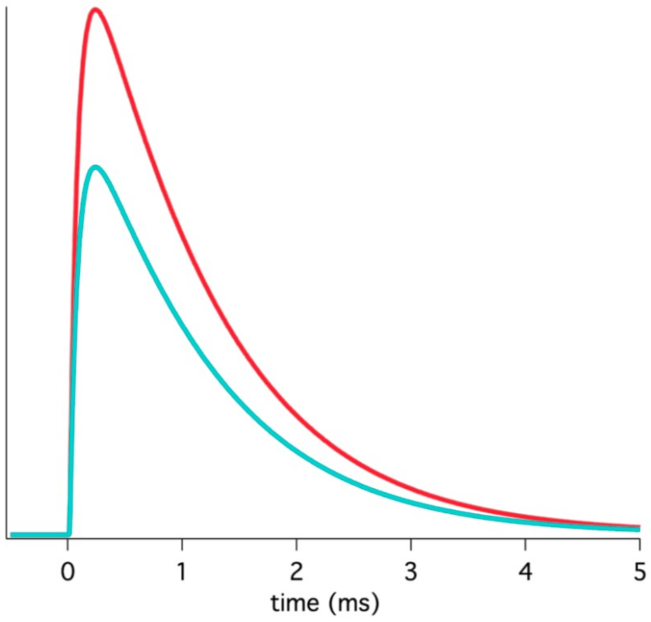
Key technology: Transition Edge Sensor (TES) microcalorimeter

Transition Edge Sensing (TES) μcalorimeter (NIST, Boulder, CO, USA)

Quantum Sensing Division





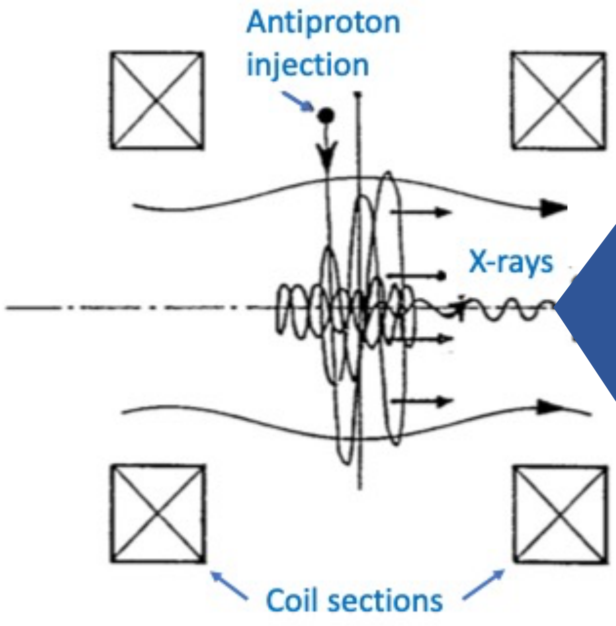


Figures from Ullom and Bennett 2013

The $\bar{p}AX$ approach—in detail

1

Novel new device



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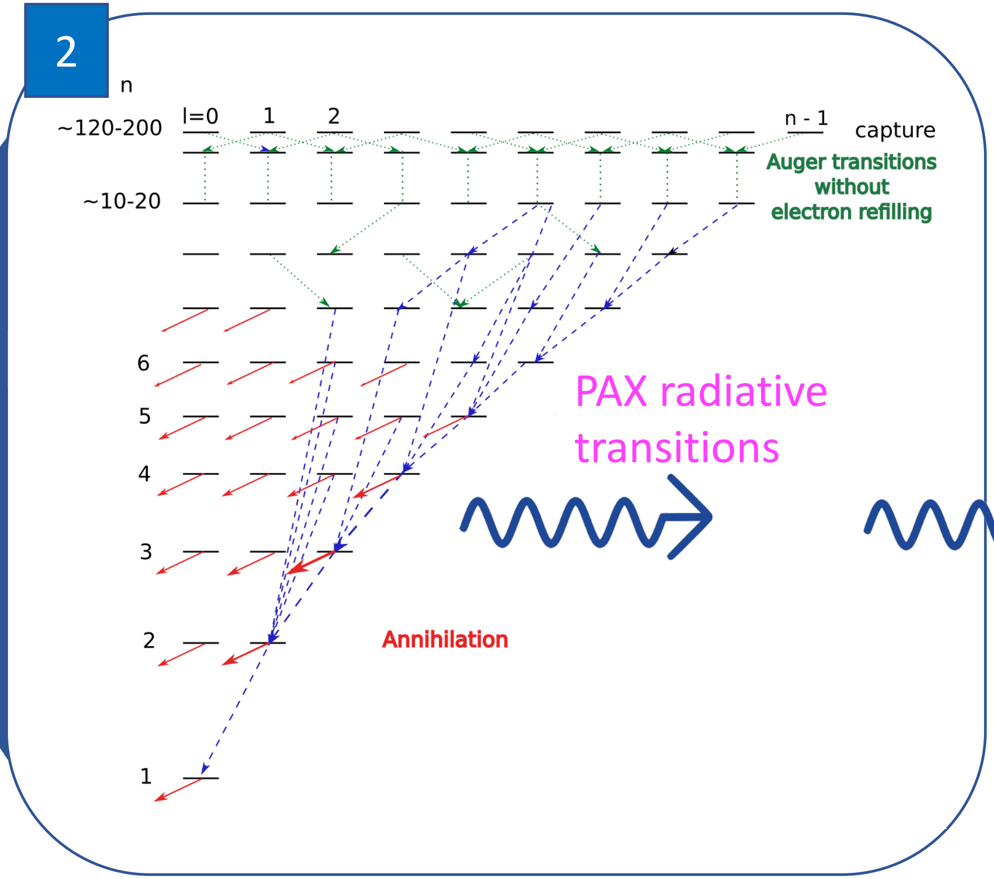
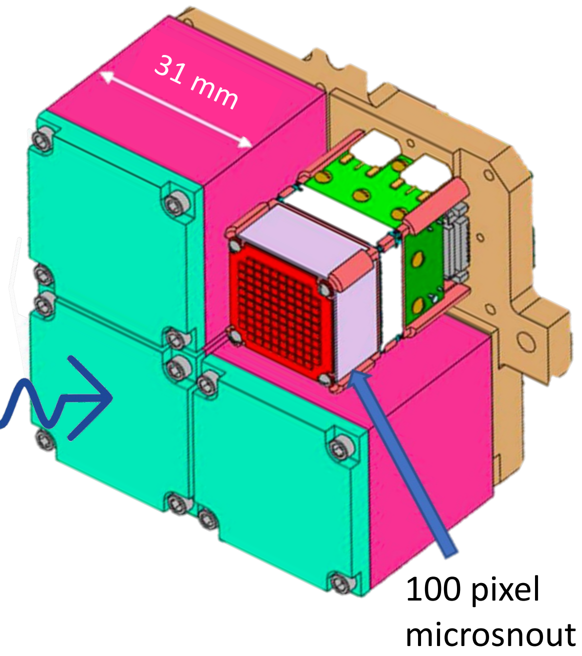


3

First-ever application to antimatter beams



Antiprotons stop in gas-filled trap → Antiprotons capture and emit radiative x-ray cascade → X-ray spectroscopy with large-area TES detector

The $\bar{p}AX$ physics program

Transition ($n_i \rightarrow n_f$)	Appx. Transition energy (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

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

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

M= 10

$\epsilon_{geo} = 6 \times 10^{-4}$

$\epsilon_{det} = 0.4$

$\epsilon_{trap} = 0.5$

N_x=1200 counts/spill

Among the highest field systems ever accessed in the laboratory !

$\bar{p}AX$ firsts

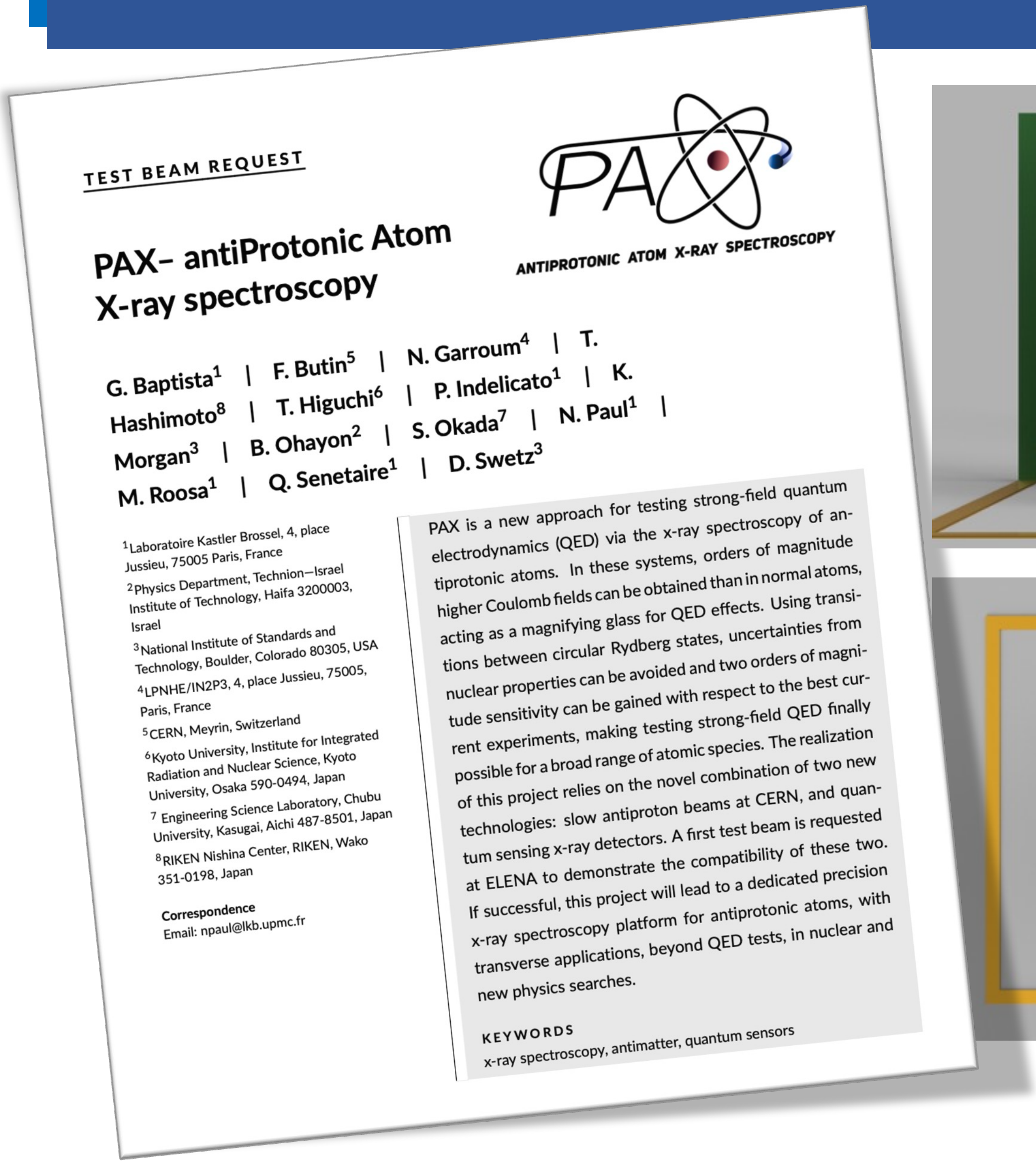
- **Study second-order QED effects across 10 ≤ Z ≤ 74**
- **Achieve 10^{-5} experimental precision for heavy exotic atom spectroscopy**

< 1 week measurement time / transition

depending on available pbar beam structure

Perspectives: Strong interaction studies, exotic physics searches

Quantum sensors + antimatter beams?→ Test beam in 2025 !



TEST BEAM REQUEST

PAX– antiProtonic Atom X-ray spectroscopy

PAX ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

G. Baptista[1] | F. Butin[5] | N. Garroum[4] | T. Hashimoto[8] | T. Higuchi[6] | P. Indelicato[1] | K. Morgan[3] | B. Ohayon[2] | S. Okada[7] | N. Paul[1] | M. Roosa[1] | Q. Senetaire[1] | D. Swetz[3]

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[5]CERN, Meyrin, Switzerland
[6]Kyoto University, Institute for Integrated Radiation and Nuclear Science, Kyoto University, Osaka 590-0494, Japan
[7] Engineering Science Laboratory, Chubu University, Kasugai, Aichi 487-8501, Japan
[8]RIKEN Nishina Center, RIKEN, Wako 351-0198, Japan

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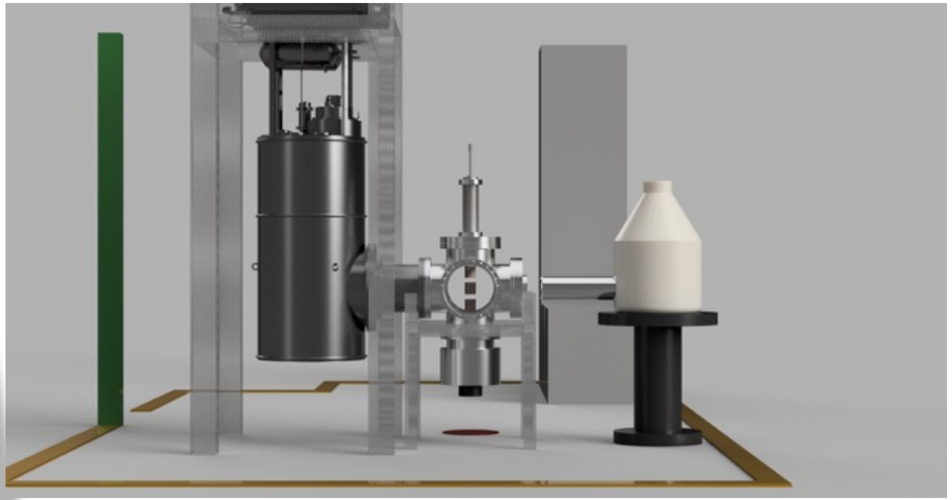
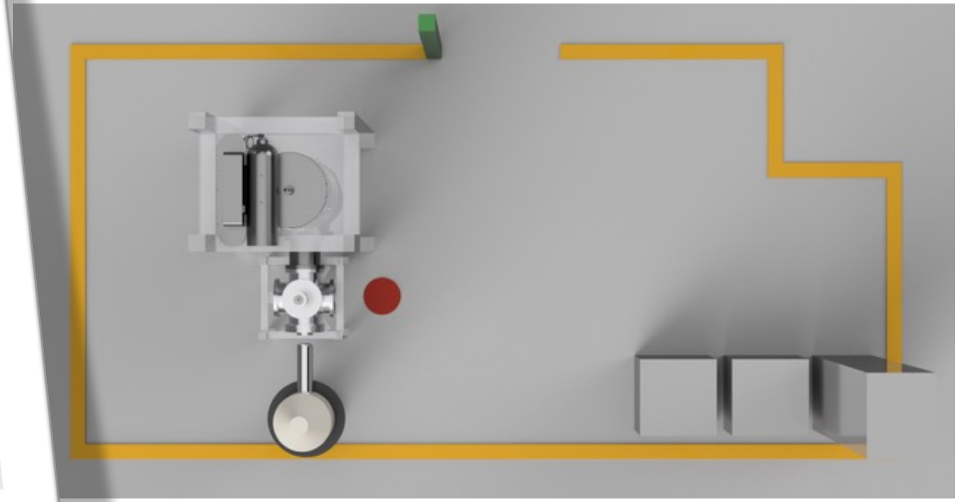
PAX is a new approach for testing strong-field quantum electrodynamics (QED) via the x-ray spectroscopy of antiprotonic atoms. In these systems, orders of magnitude higher Coulomb fields can be obtained than in normal atoms, acting as a magnifying glass for QED effects. Using transitions between circular Rydberg states, uncertainties from nuclear properties can be avoided and two orders of magnitude sensitivity can be gained with respect to the best current experiments, making testing strong-field QED finally possible for a broad range of atomic species. The realization of this project relies on the novel combination of two new technologies: slow antiproton beams at CERN, and quantum sensing x-ray detectors. A first test beam is requested at ELENA to demonstrate the compatibility of these two. If successful, this project will lead to a dedicated precision x-ray spectroscopy platform for antiprotonic atoms, with transverse applications, beyond QED tests, in nuclear and new physics searches.

KEYWORDS
x-ray spectroscopy, antimatter, quantum sensors





2025

- Test beam in TELMAX zone at ELENA
- Full SPSC proposal submitted with ASACUSA

Quantum sensors + antimatter beams?→ Test beam in 2025 !


TEST BEAM REQUEST

PAX– antiProtonic Atom X-ray spectroscopy

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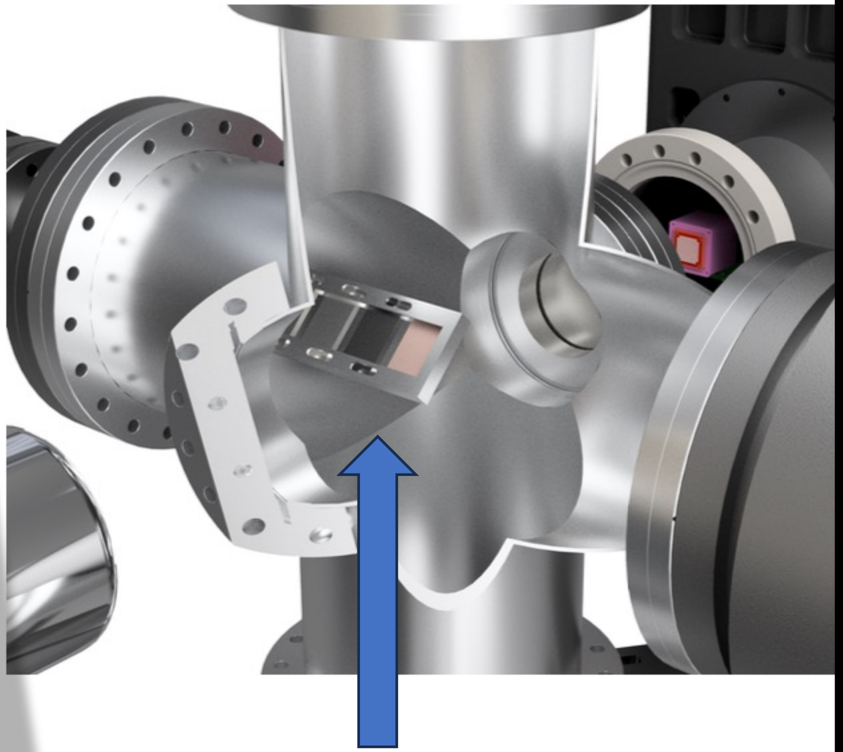
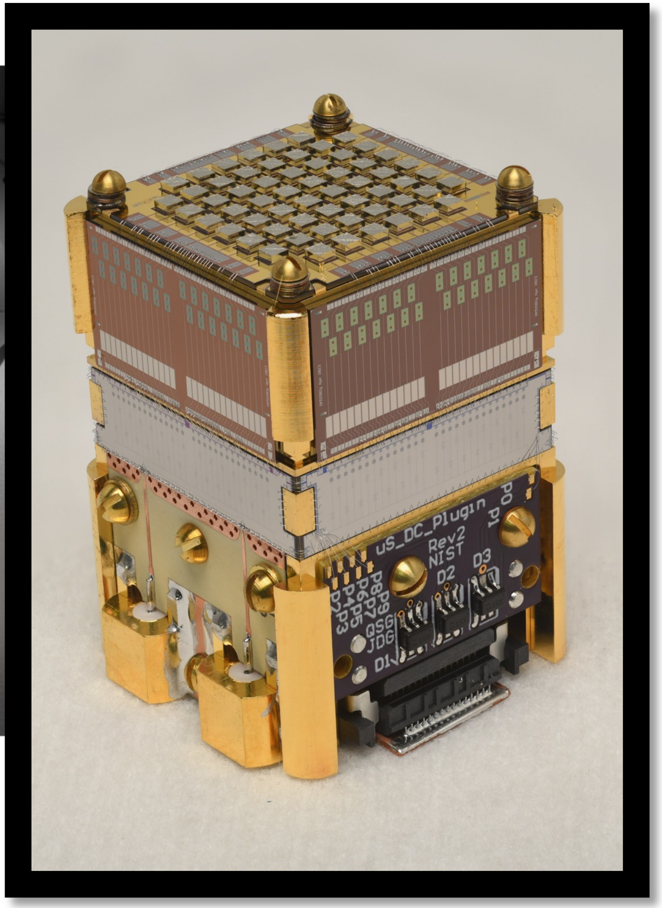
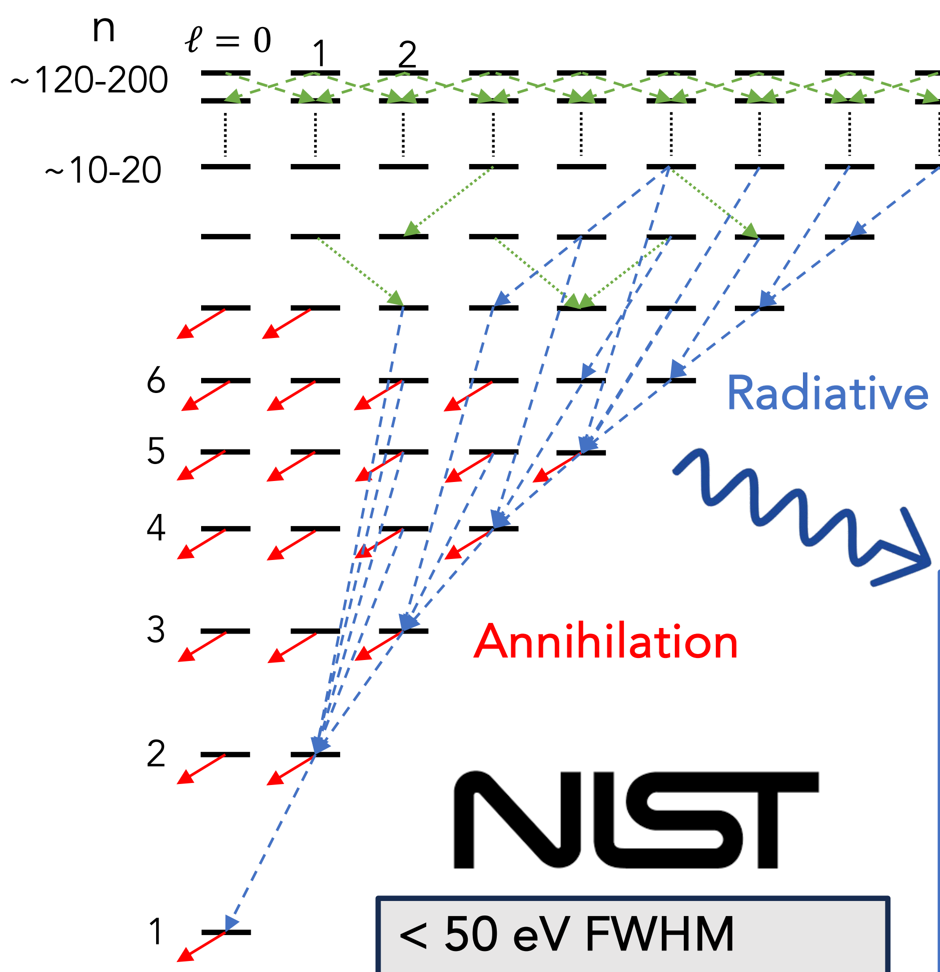


antiprotons from ELENA



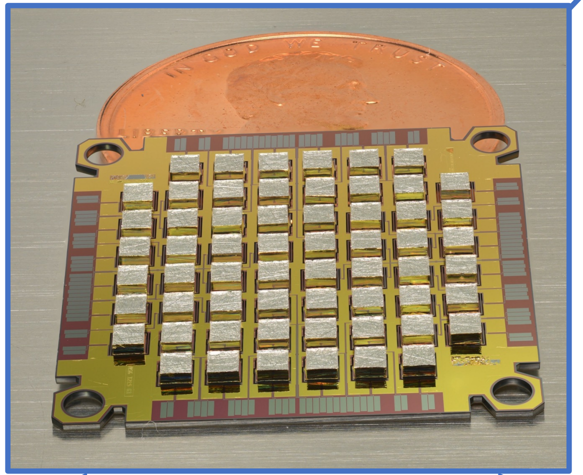
- New TES design from NIST
- First ever test of TES technology with antimatter

Key technology: Transition Edge Sensing (TES) Microcalorimeter

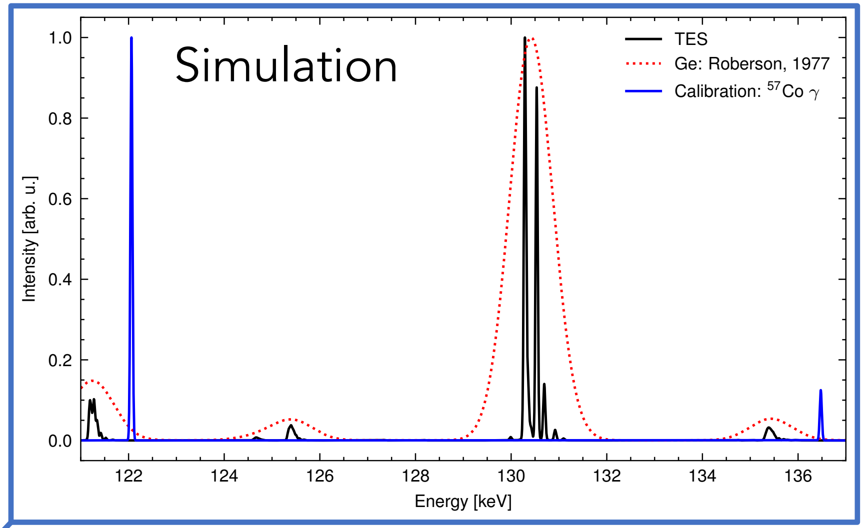


< 50 eV FWHM
@ 100 keV possible

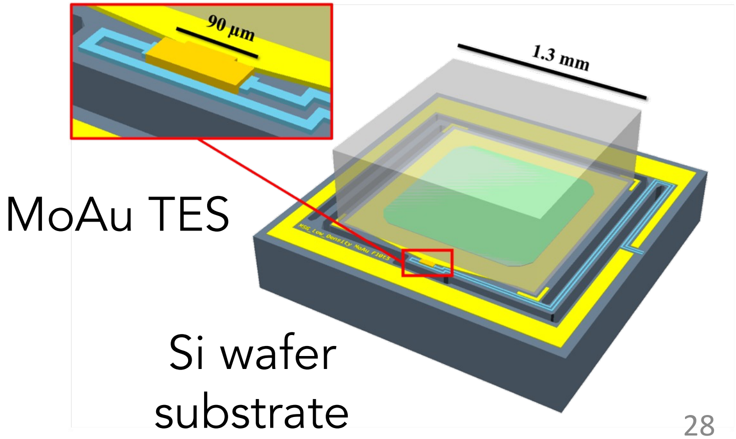
$\bar{\text{P}}$AX Prototype



2 cm



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

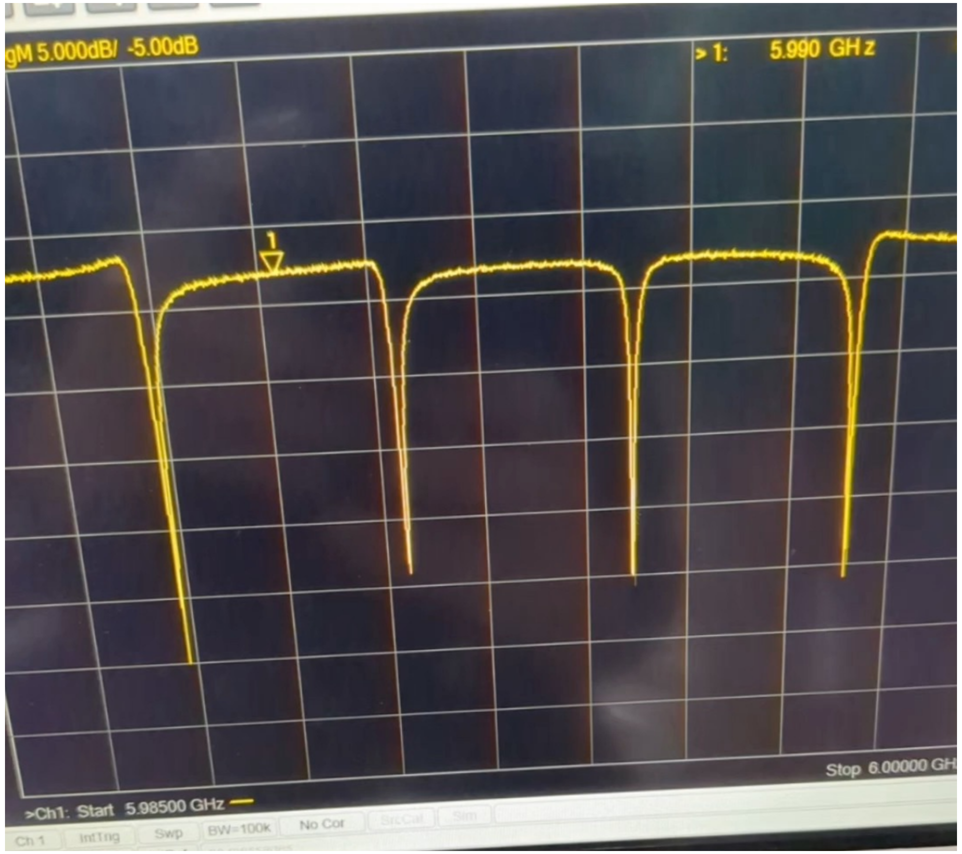


Photos: J. Nobles, M. Keller, K. Morgan (NIST)

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



Quantum sensors + antimatter beams?→ Test beam in 2025 !

- Setup in April 2025
- **First test beam May 5-19**
- High statistics run June 2-13
- International collaboration
- ~20 collaborators during 6 weeks (LKB, NIST, Technion, LPNHE, Lisbon, Kyoto, Imperial college)

Quantum sensors + antimatter bea... in 2025 !

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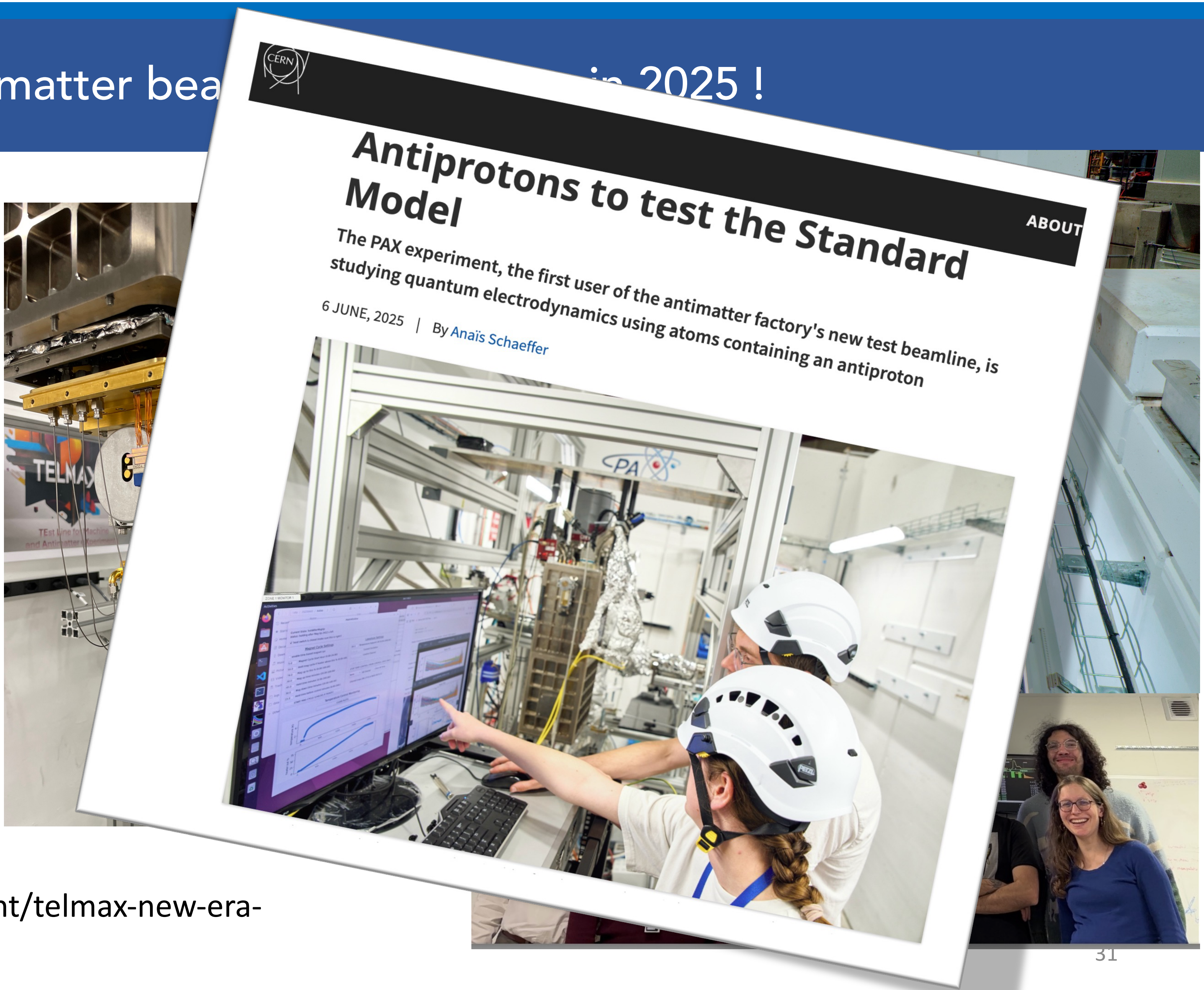


Antiprotons to test the Standard Model

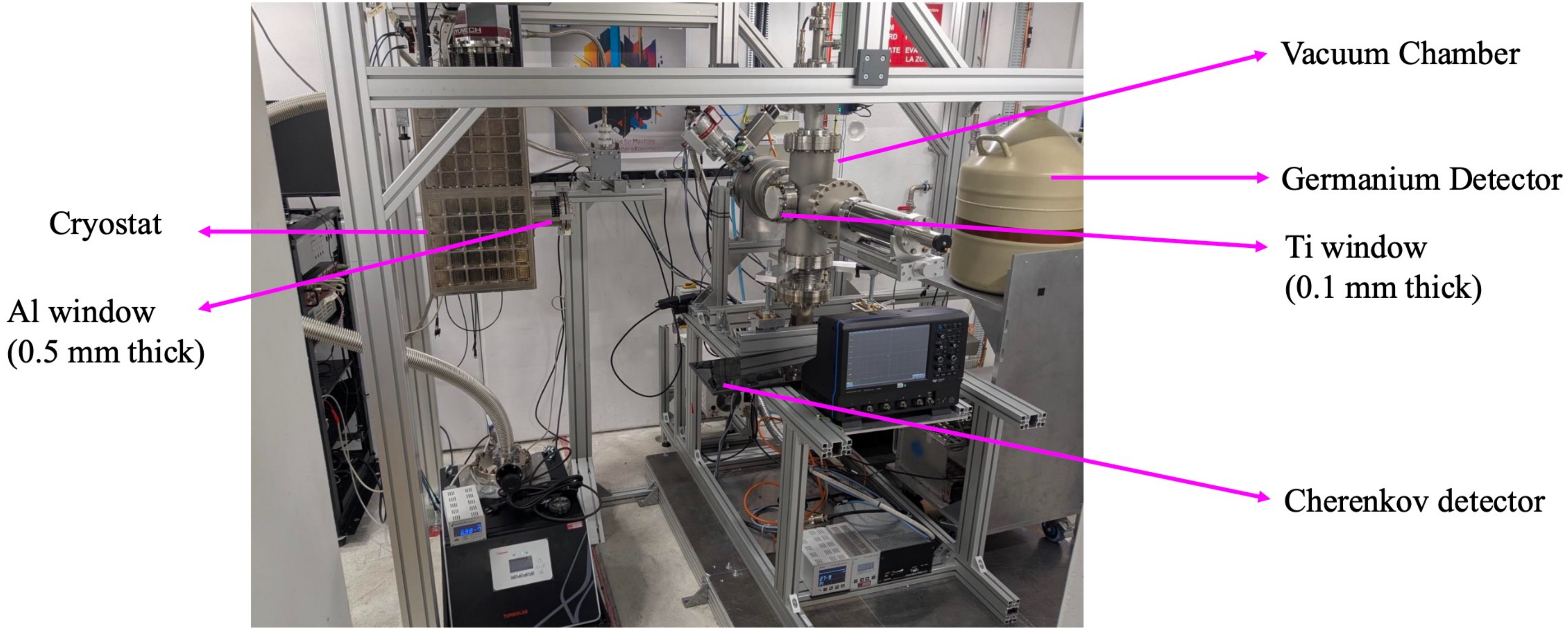
The PAX experiment, the first user of the antimatter factory's new test beamline, is studying quantum electrodynamics using atoms containing an antiproton

6 JUNE, 2025 | By Anaïs Schaeffer

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

The $\bar{p}AX$ test beam setup—2025

$\bar{p}AX$ @ TELMAX



The $\bar{p}AX$ test beam setup—2025

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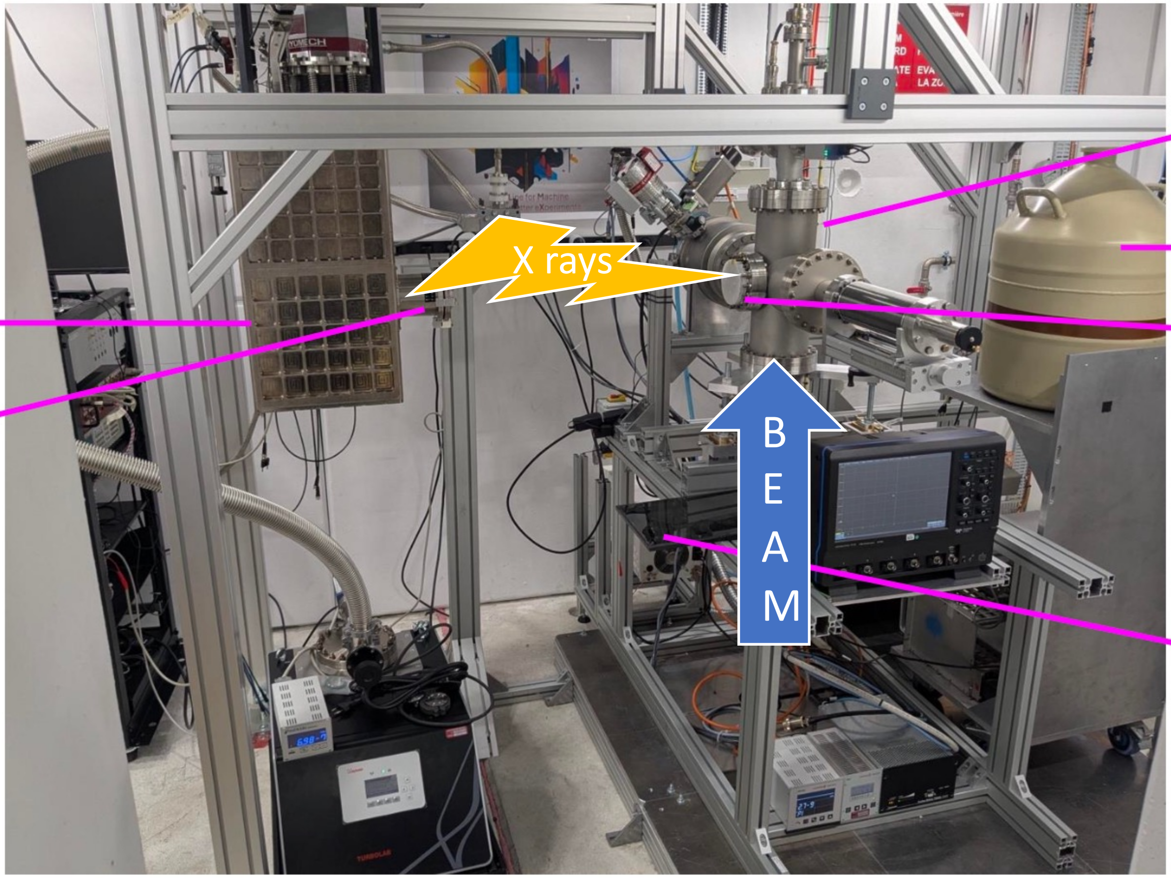
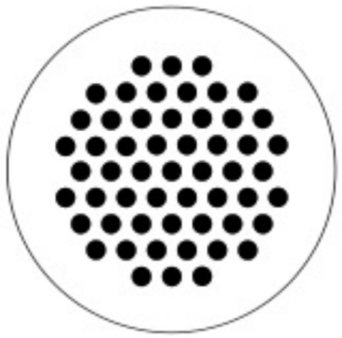
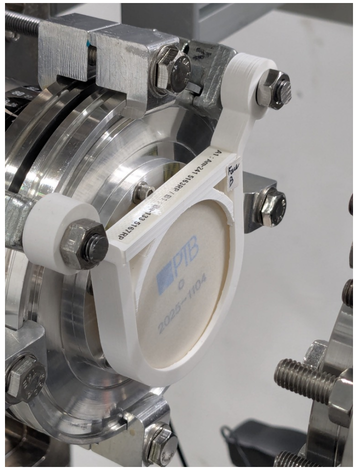


TES performance checks and calibration

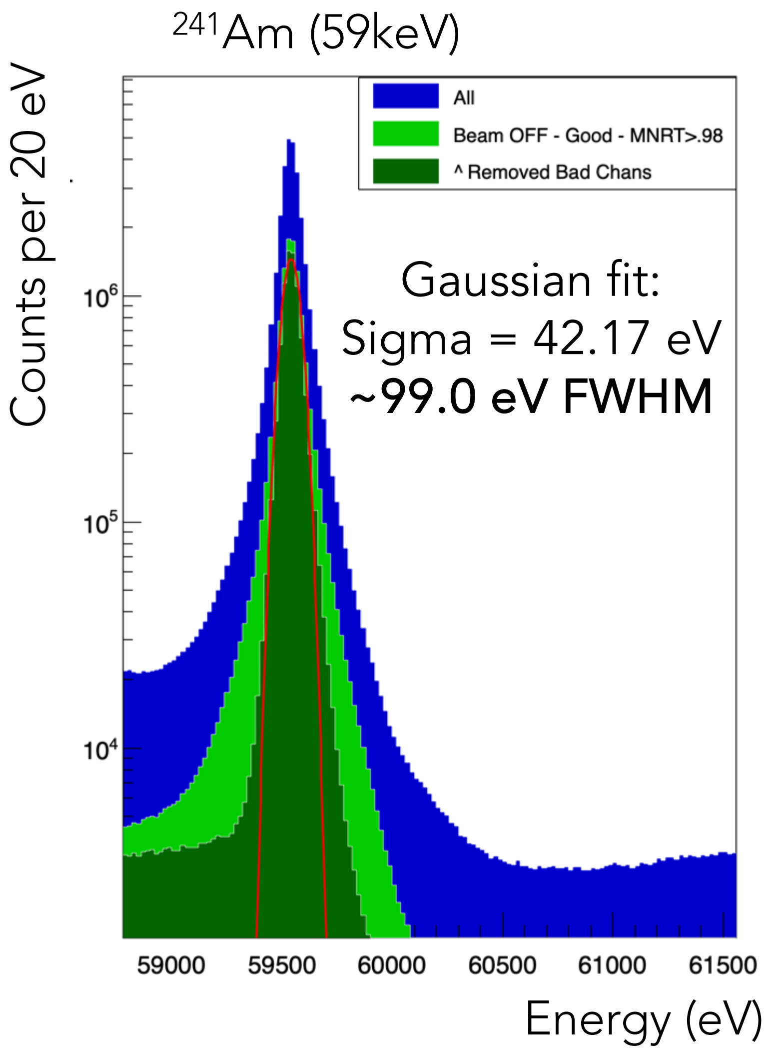
New x-ray-transparent
γ-sources from PTB.





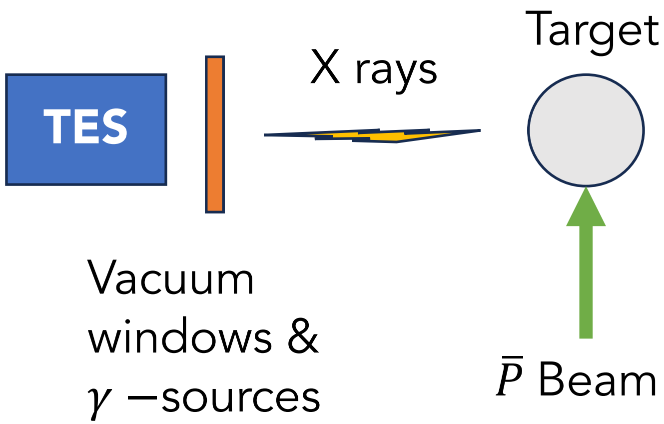
Radioactive microdroplets
on plastic films

Uniform and continuous calibration



Calibration sources measured to specified resolution !
(prototype)

Let's take beam!



TES performance checks and calibration

New x-ray-transparent
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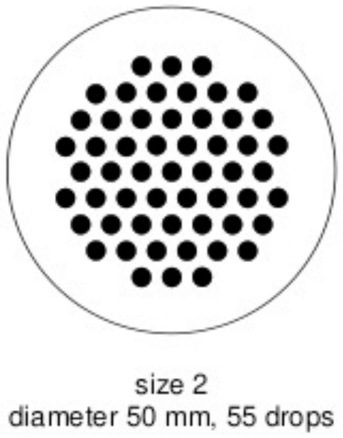
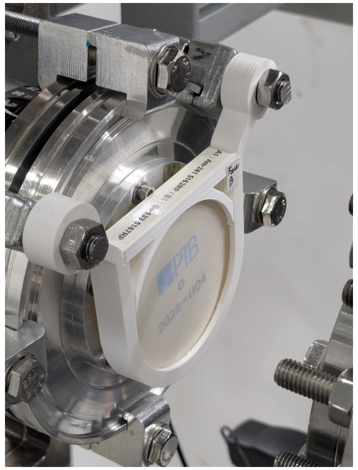
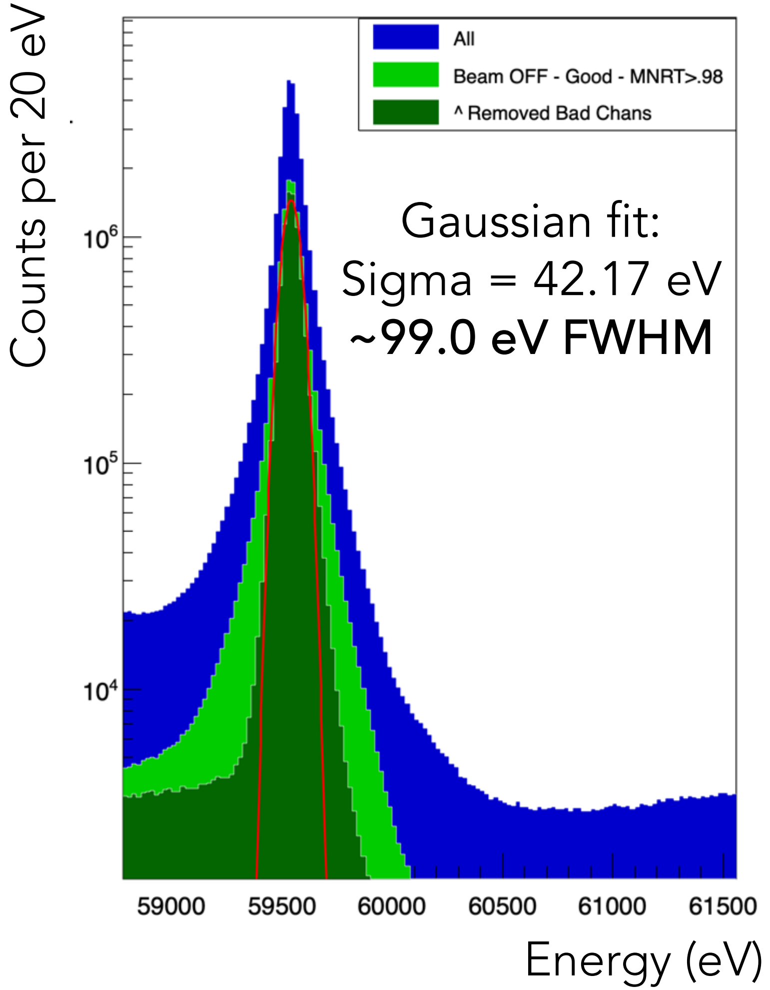




Radioactive microdroplets
on plastic films

Uniform and continuous calibration

^{241}Am (59keV)



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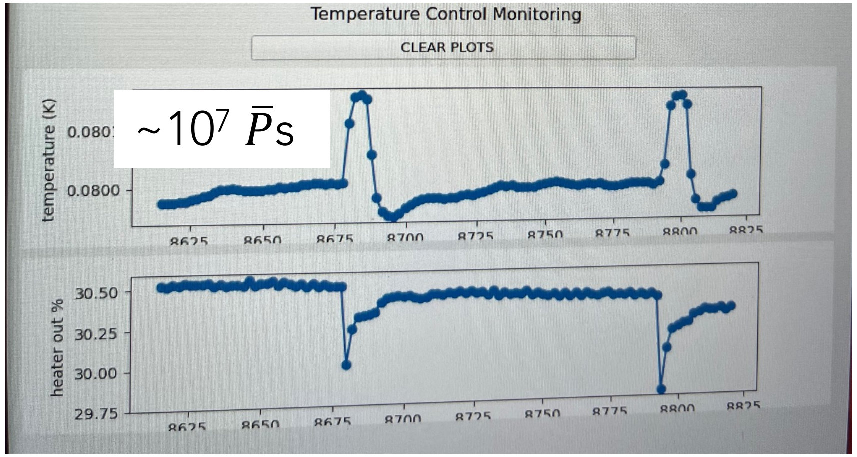
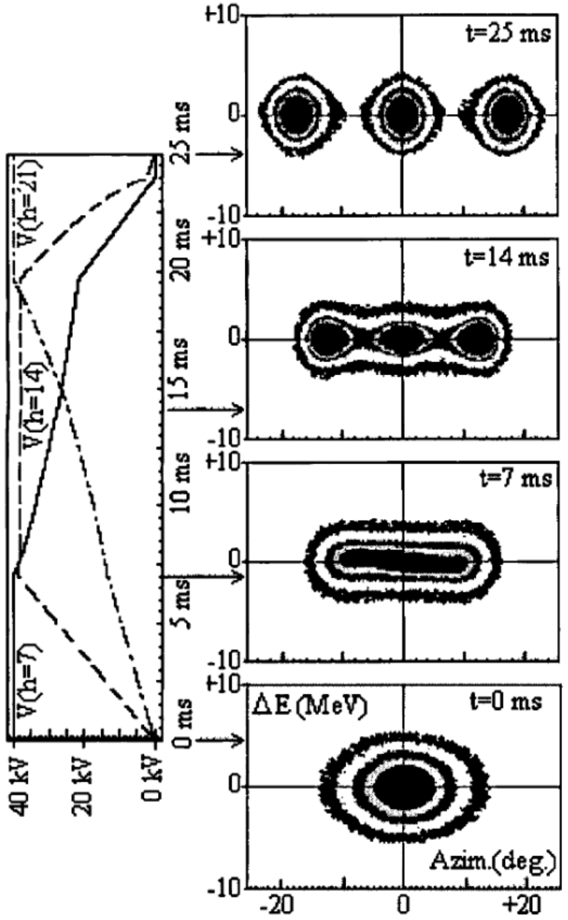


100s of μK deposited in to the array

Multiple Mini-Bunch Extraction

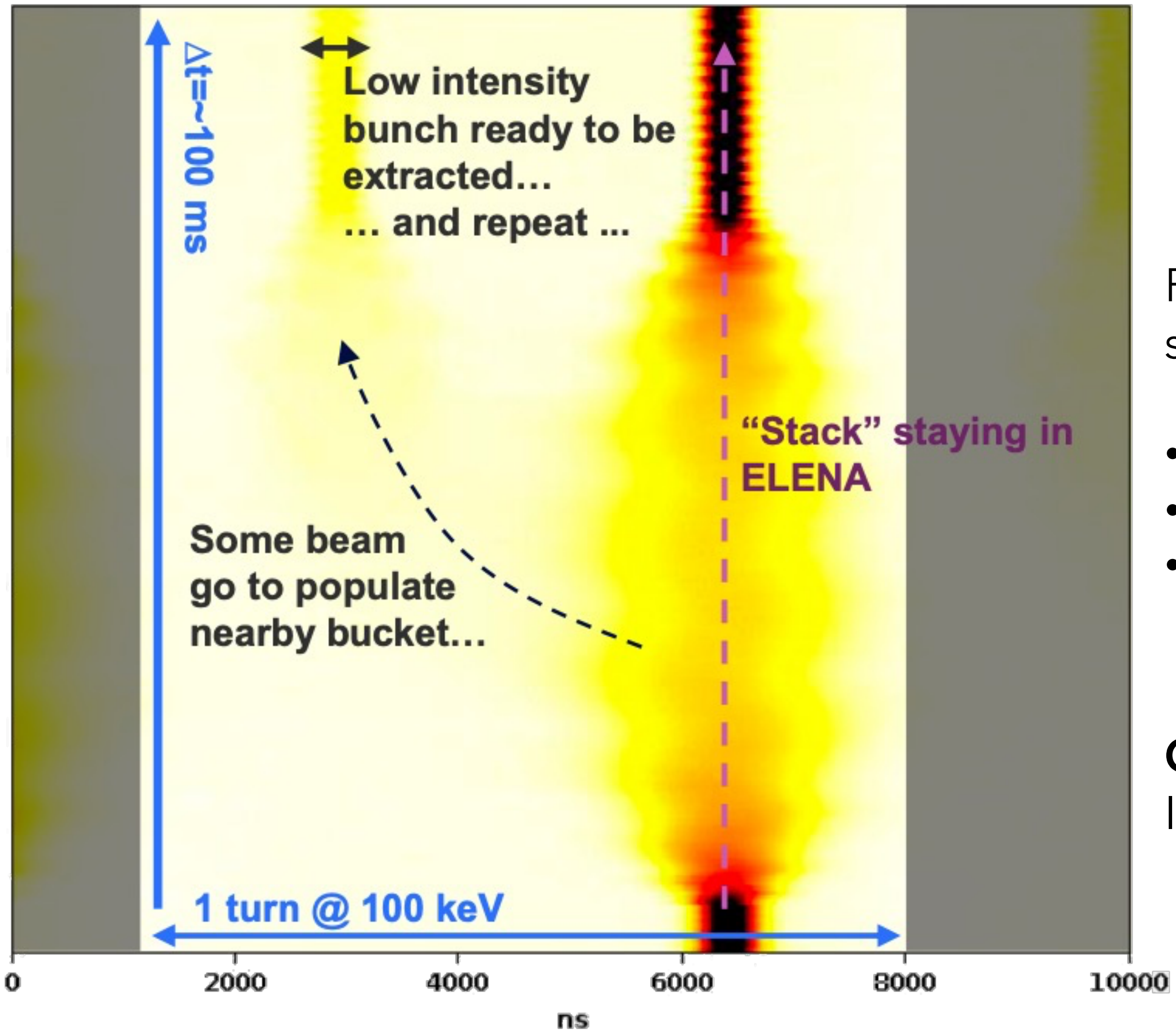
Development by
D. Gamba (CERN)



Example from CERN PS.

R. Garoby, et. al 2000

Mini-bunch formation in ELENA



ELENA
Extra Low ENergy Antiprotons

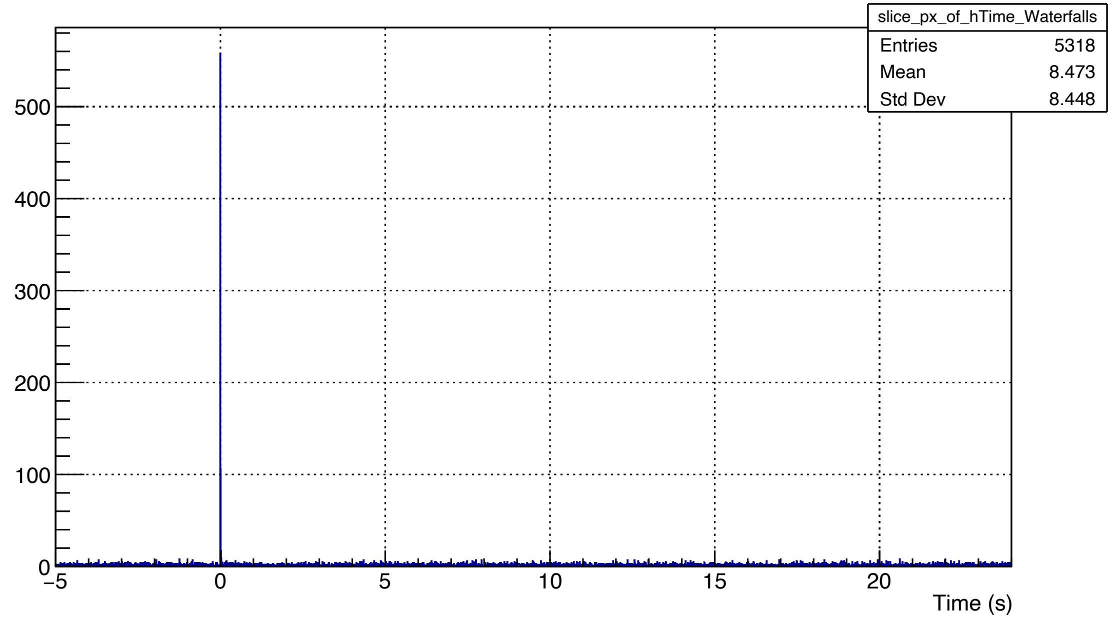
Repeated bunch splitting in ELENA:

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

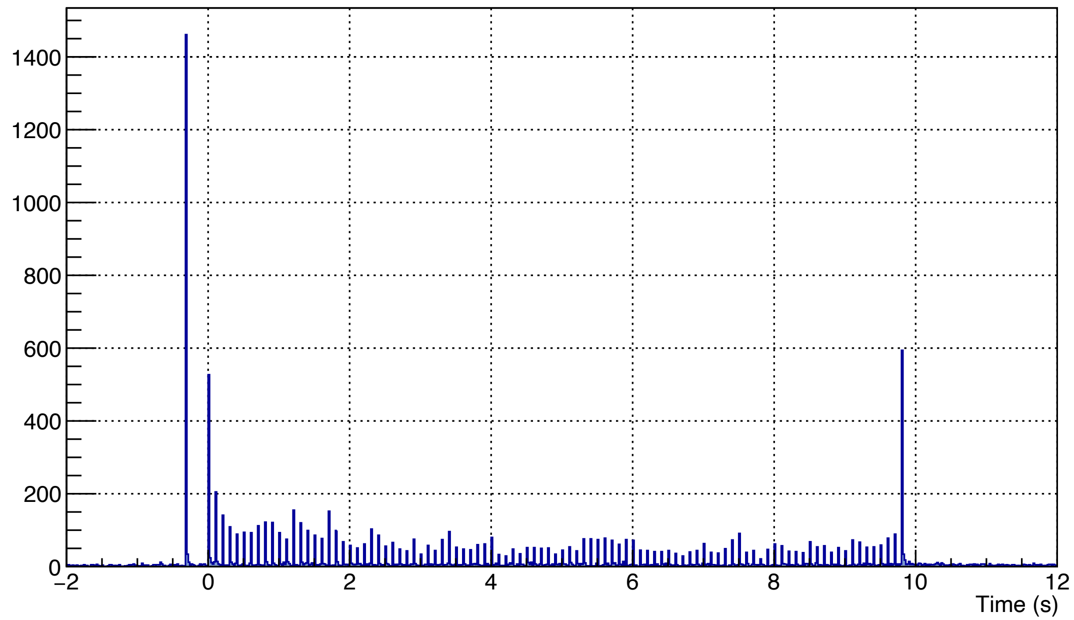
Challenge:
Intensity is low
Measure at target

The $\bar{p}AX$ test beam setup—First scintillator spectra of antiproton mini bunches

Normal bunches

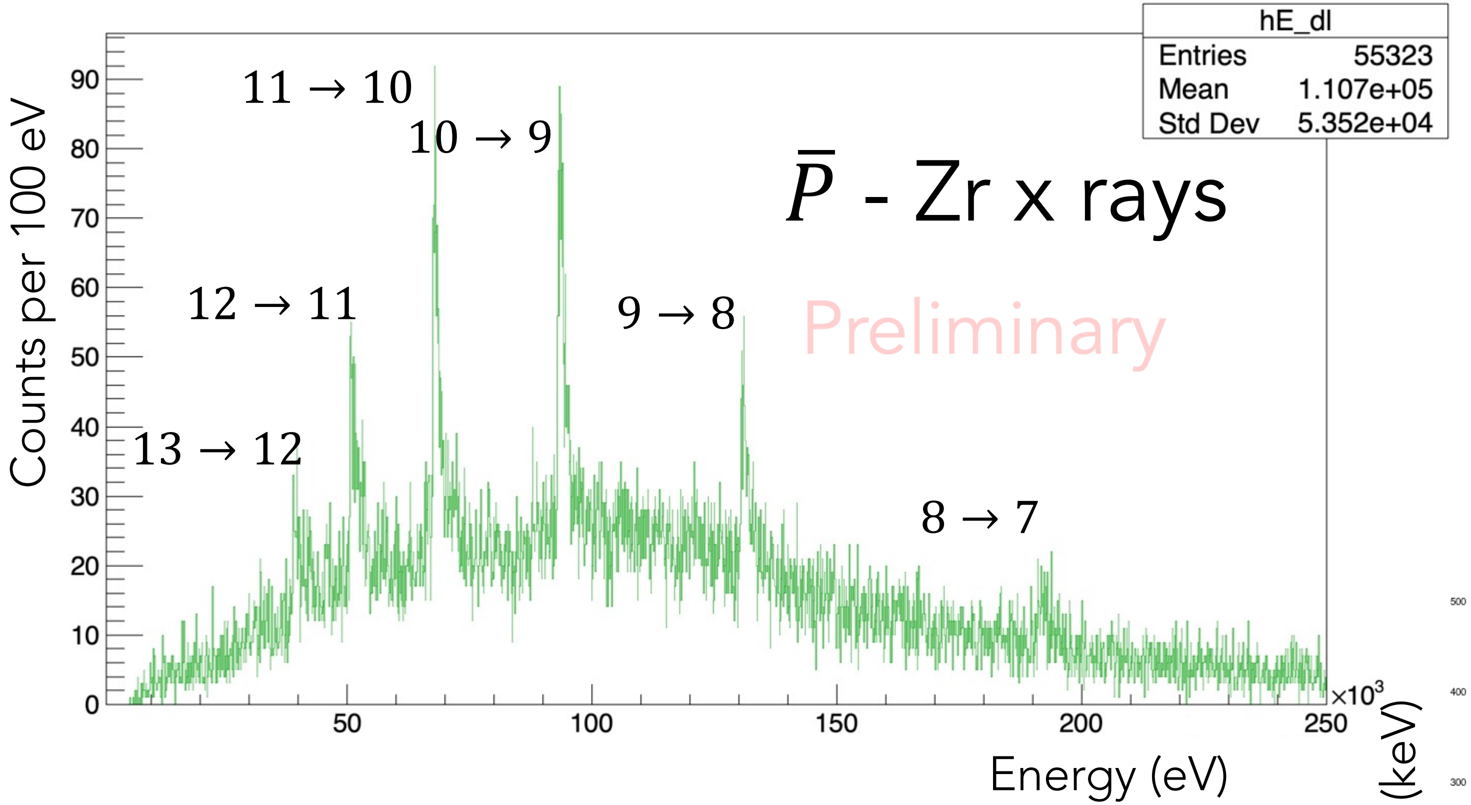


Minibunches

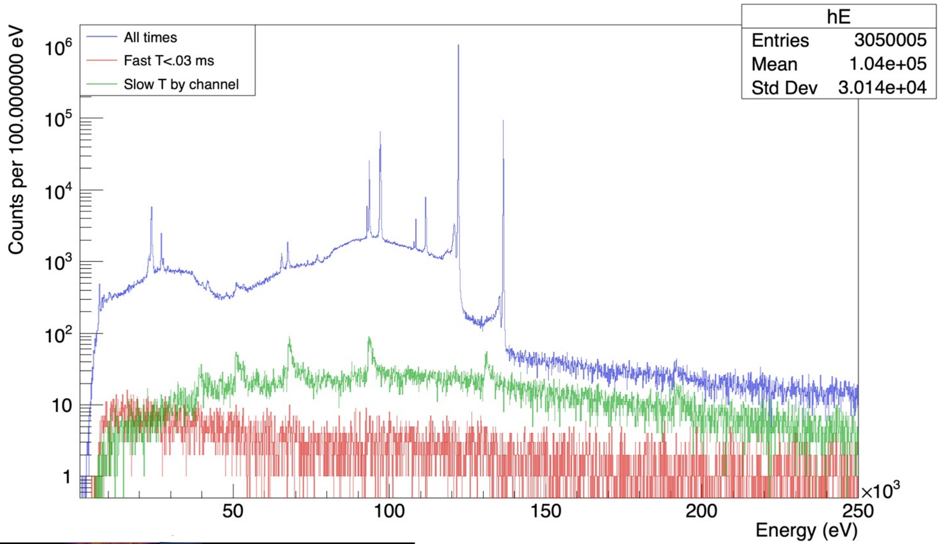


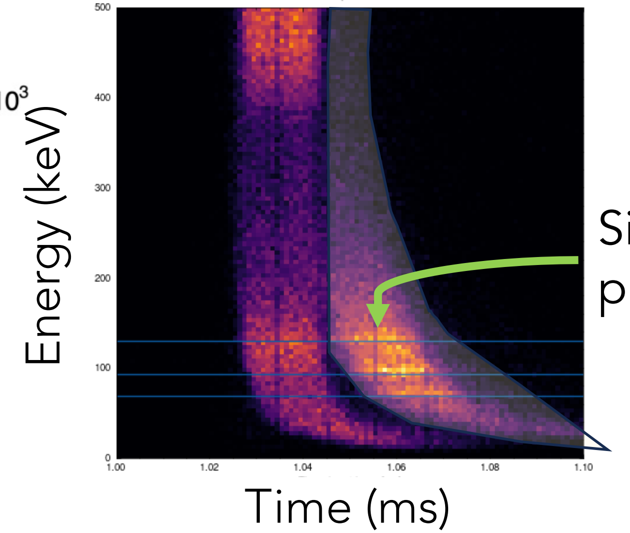
✓ Development of new antiproton extraction method at CERN for PAX project (Davide Gamba + ELENA ops team)

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



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

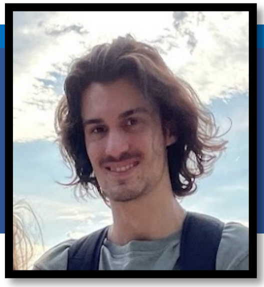


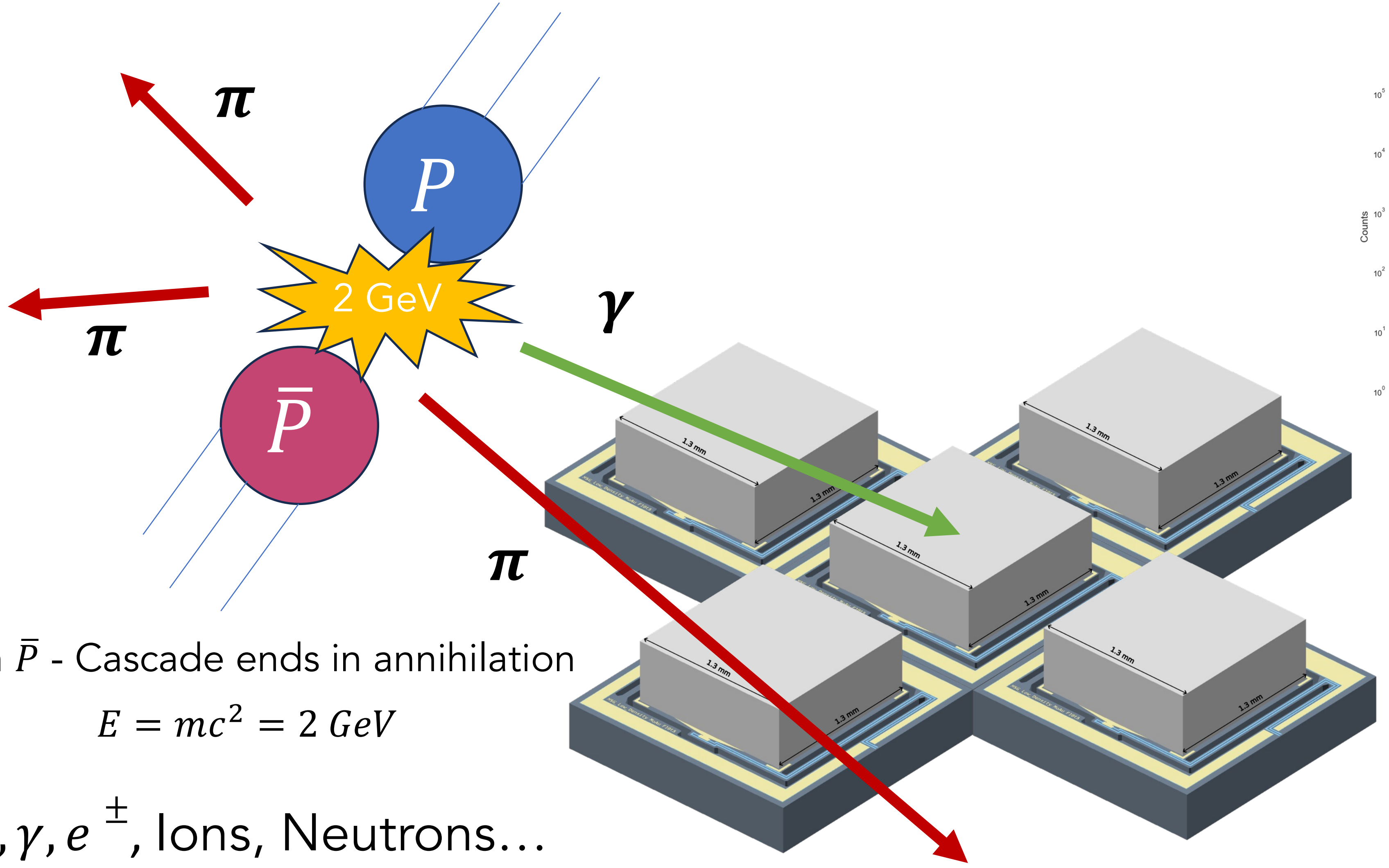


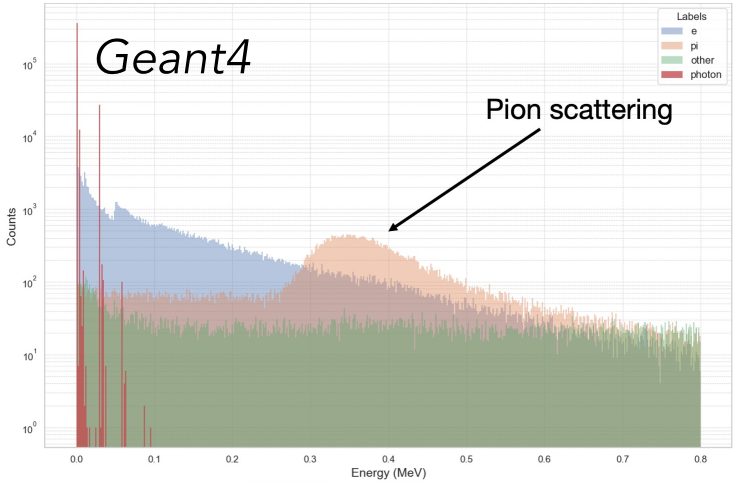
Signal of interest was prompt but “delayed”.

Sources of background

Work of Q. Senetaire







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

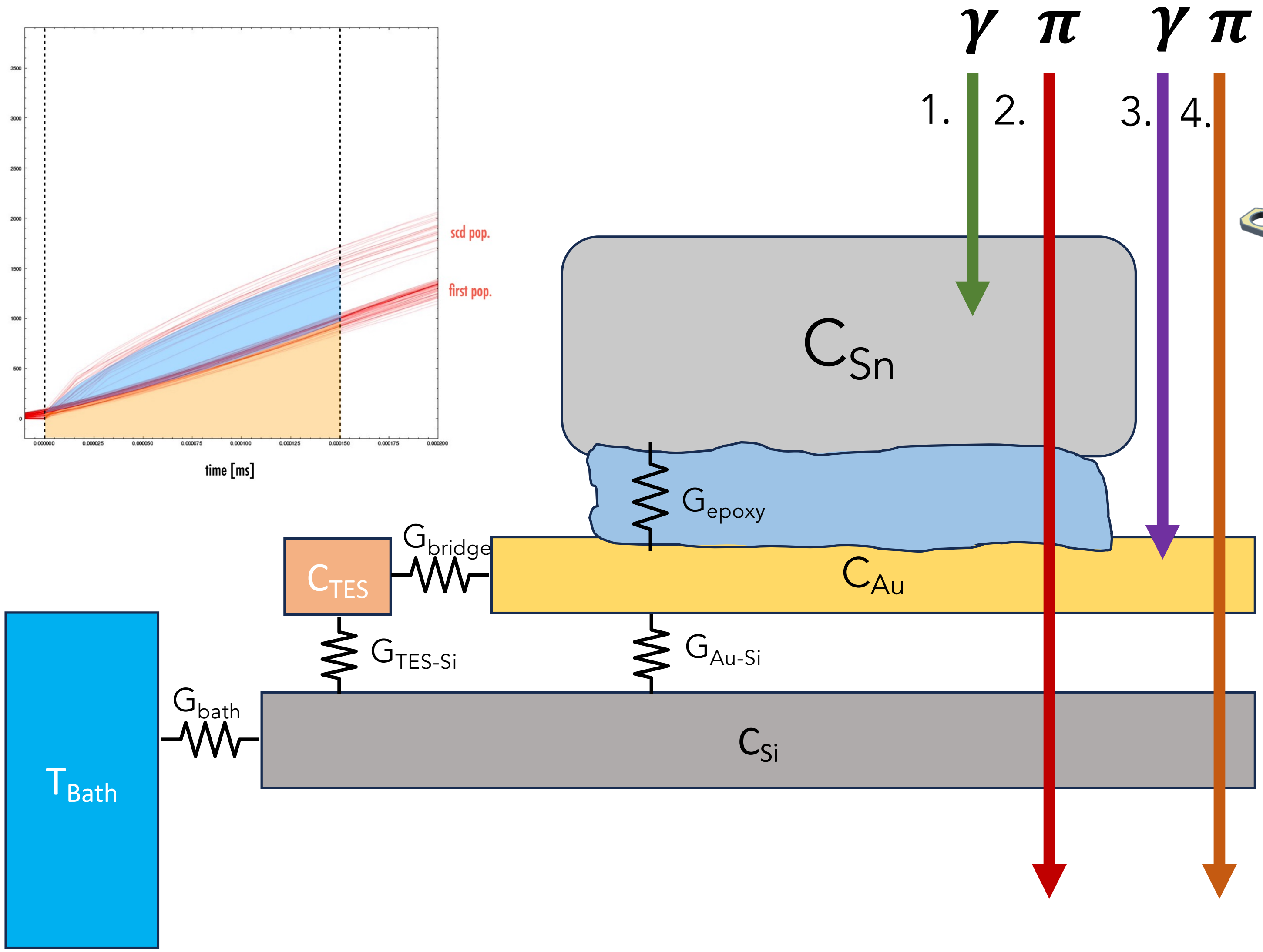
$$E = mc^2 = 2\ GeV$$

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

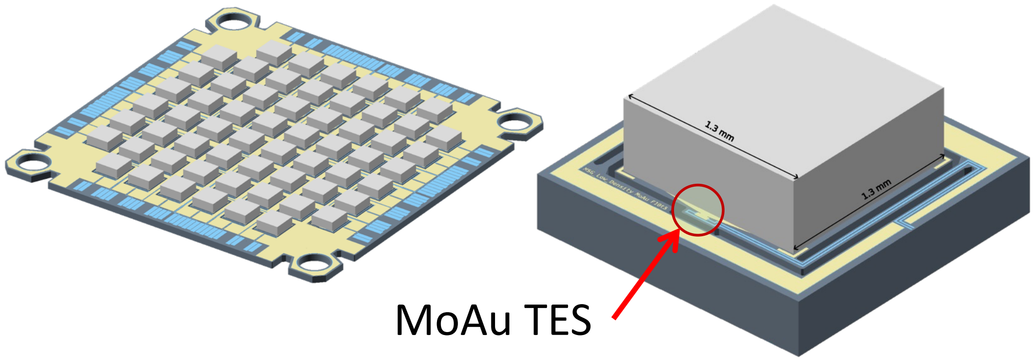
Signal of interest is hidden by:

- Charged particle hits and
- Thermal cross-talk

Origins of Rise-Time Populations



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



Differences in:

Energy deposition: γ vs π

Energy dissipation: Sn vs Au

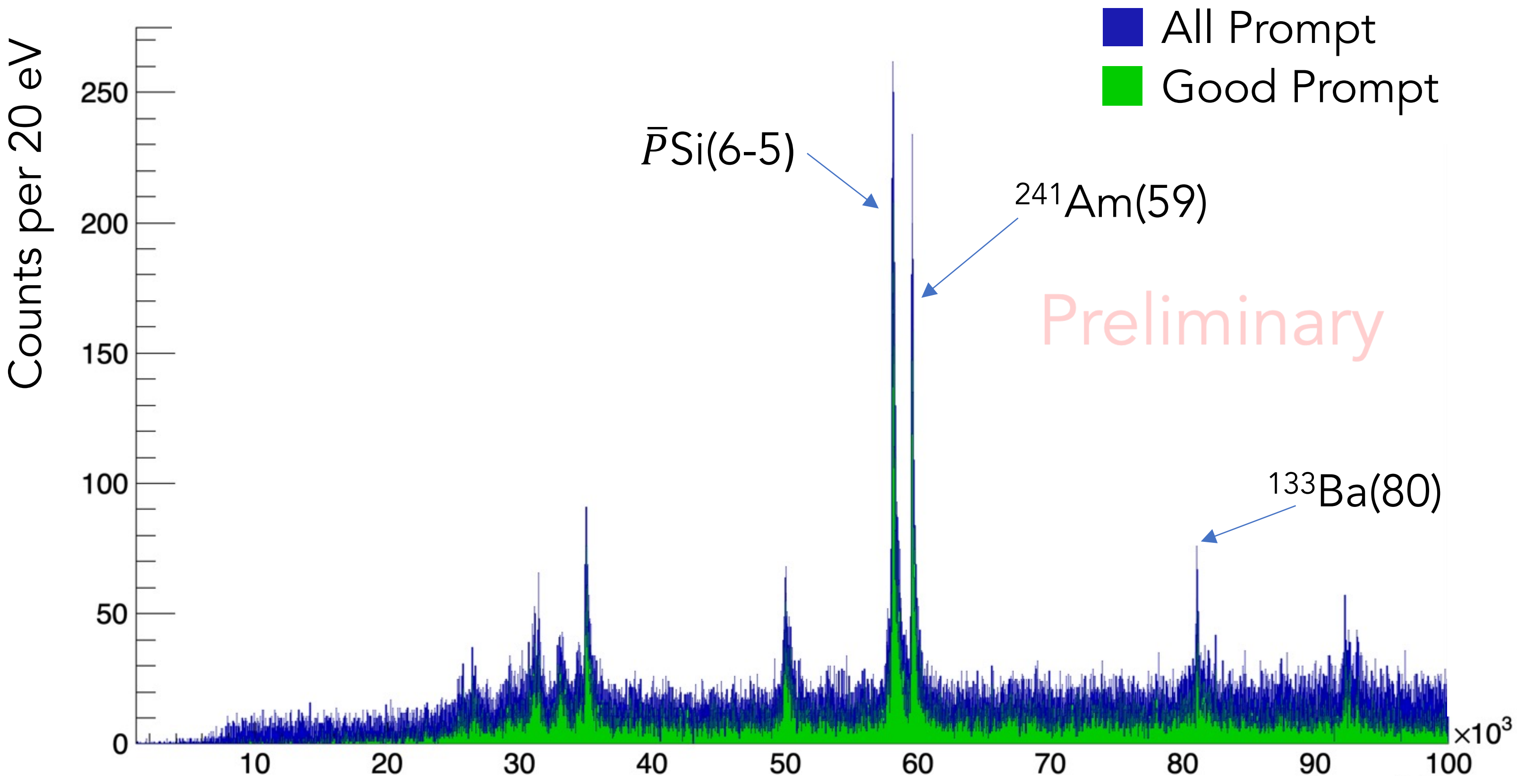
Reduced intensity → better spectra!

- Second data set : **Si target**
- Moved back detector from 30->51 cm from target
- >10x improved FWHM before corrections with lower beam intensity

Estimated 2500 counts of $\bar{P}$Si(6-5)

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

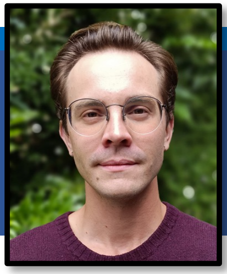


Prompt Spectrum
1.03 – 1.09 ms after trig.

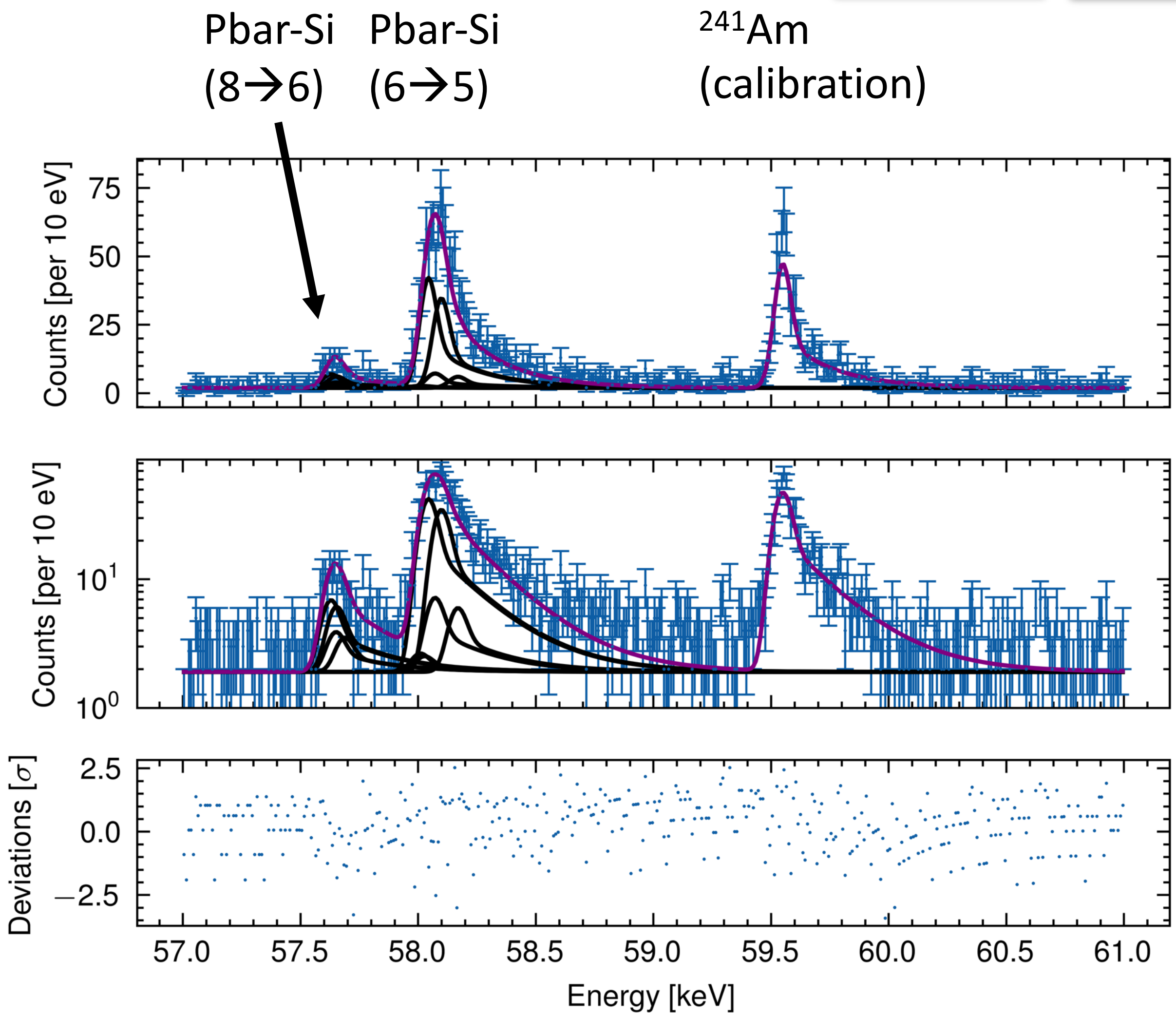
165 hours of beam-on-target

Reduced intensity → better spectra!

Work of Dr. M. Roosa
and G. Baptista



- Simultaneous fitting of calibration (^{241}Am) and transitions in antiprotonic Si.
- Statistical uncertainty on centroid is
  <5 eV → eV accuracy is within reach !



→ Spring 2026 test beam @ TELMAX:
- **more calibration sources**
- **lower beam intensity**

→ GOAL : demonstrate 1 eV acccuracy and further constrain systematics.

The $\bar{p}AX$ project : Next steps

- More test beam in 2025-2026 to study beam intensity induced effects (before LS3)
- During LS3 move to **ASACUSA collaboration**
  - New beamline
  - Large area TES detector
- **Physics campaigns 2028-2029**
- **Long term :**
  - **Antideuteronic atom spectroscopy** at ELENA
  - Combine with PUMA setup for **strong-interaction studies**

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

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TECHNION Israel Institute of Technology

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M. Guerra
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N. Garroum
M. Zito

KYOTO UNIVERSITY FOUNDED 1897

T. Higuchi

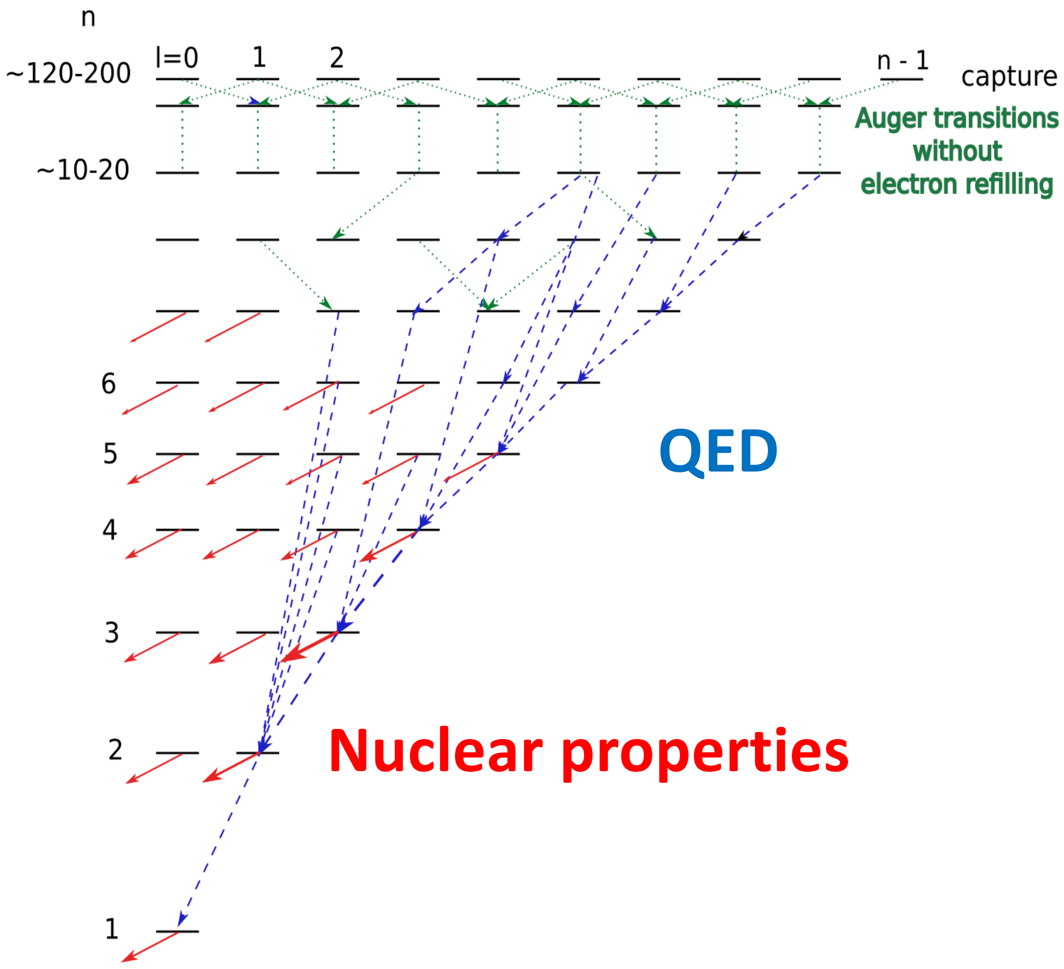
Imperial College London

M. Hori

cea

JY. Rousse

And now lets use the idea backwards…
For nuclear physics !



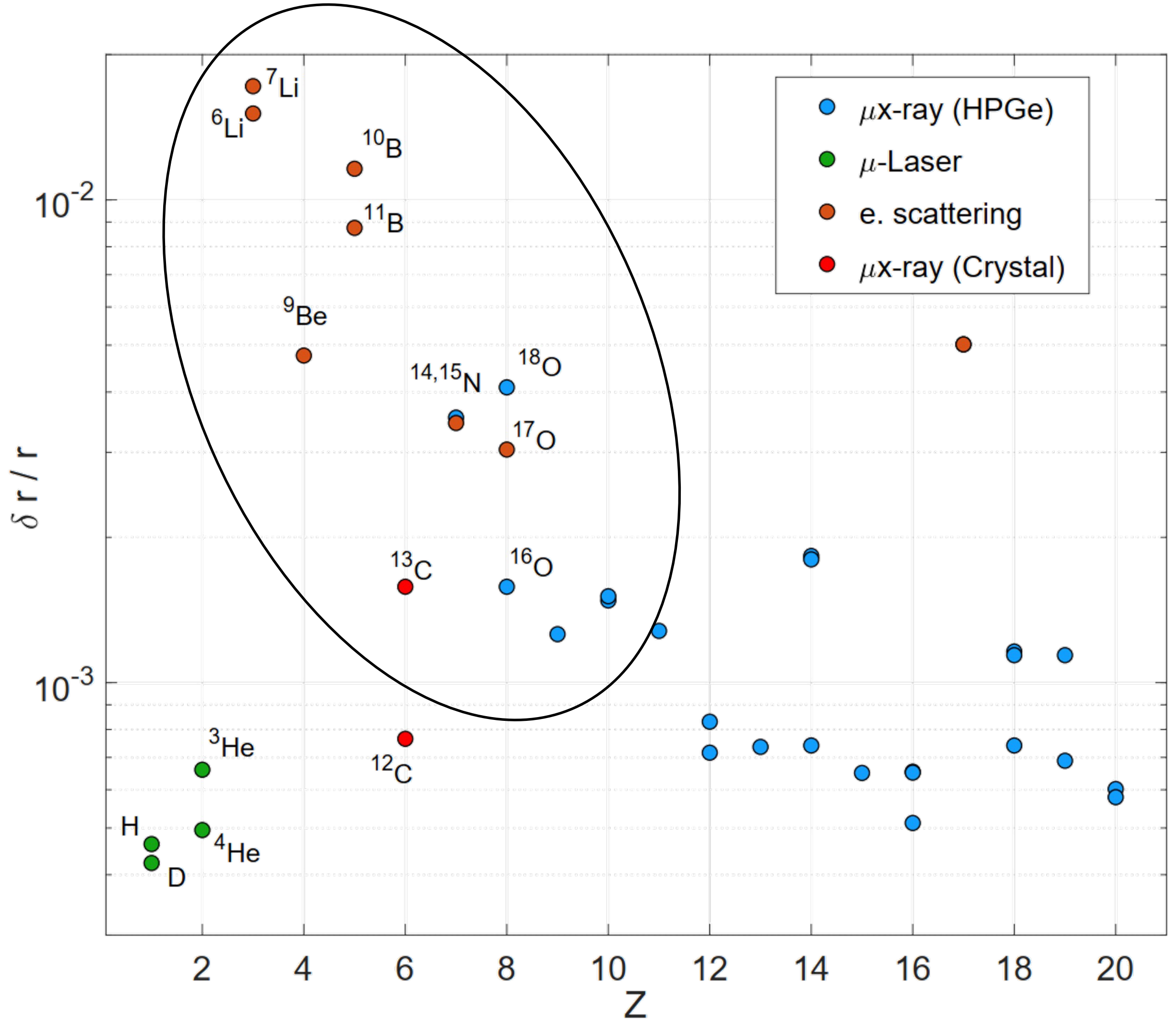
Determinations of nuclear RMS charge radii

- **For $Z < 3$:**
  Laser spectroscopy of muonic atoms, limited by nuclear theory

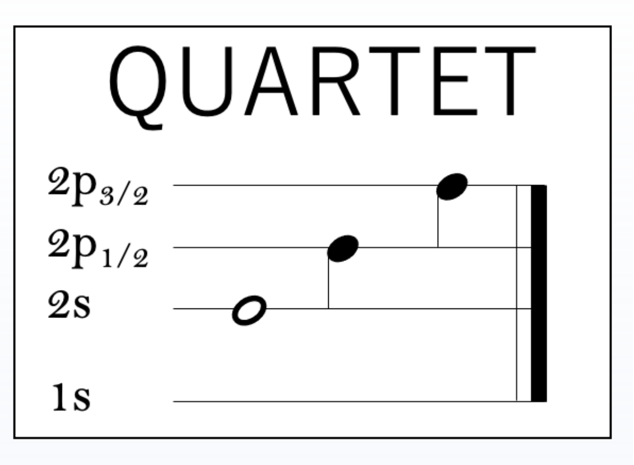
- **For $Z > 6$:**
  Measured x-rays from muonic atoms using solid-state detectors.
  10<Z: limited by theory.
  Z<10: limited by experiment (resolution).

- **For $Z = 3 - 5$, and others:**
  Electron scattering, less accurate and systematics usually NOT under control

- **For $Z = 6$**
  E(2P-1S)~75 keV, measured with crystal spectrometer.
  Limited by resolution ~75 eV

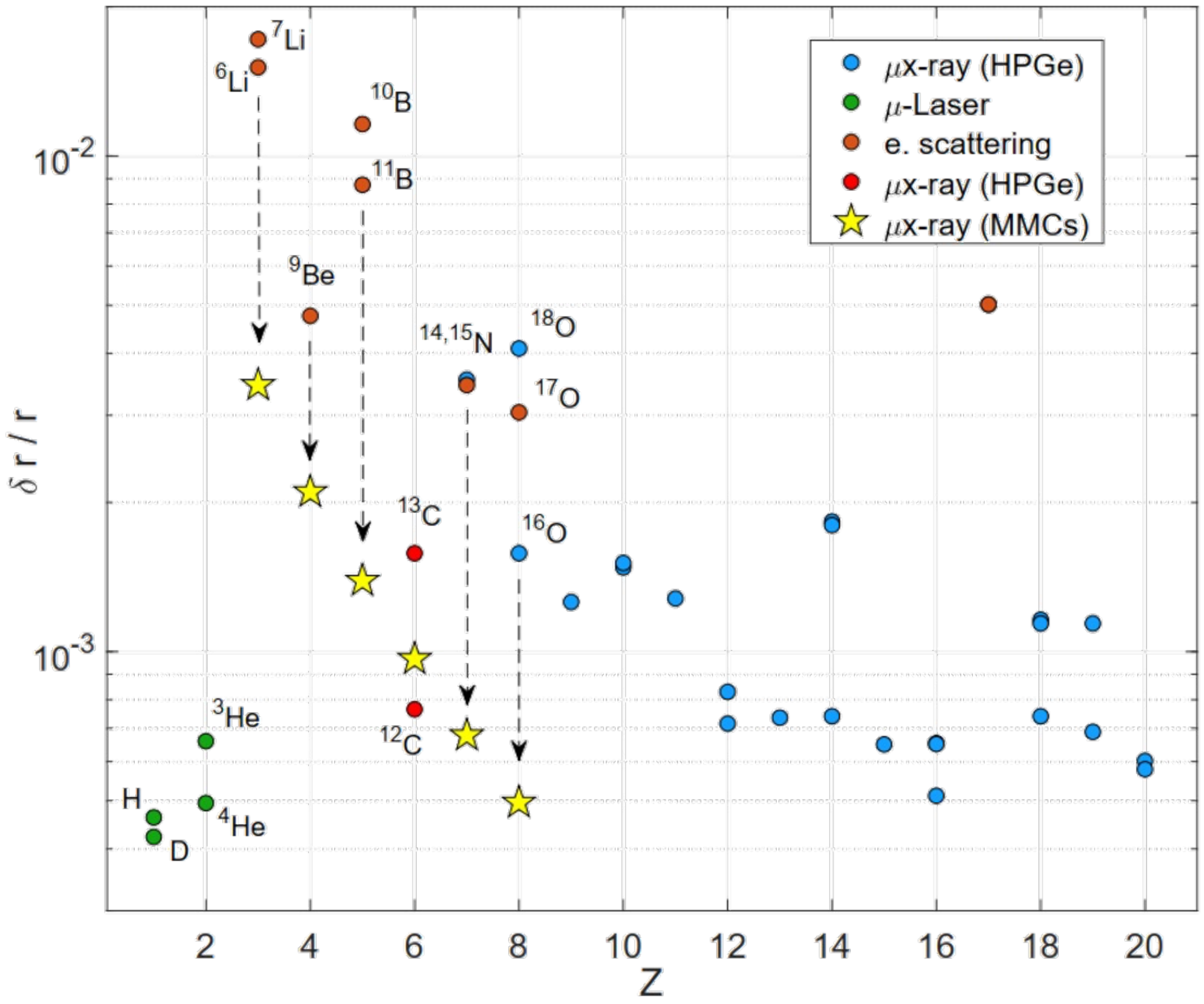


The QUARTET collaboration and precision goals



QUAntum inteRacTions with Exotic aToms

Spokespersons: B. Ohayon (Technion) and NP (LKB)

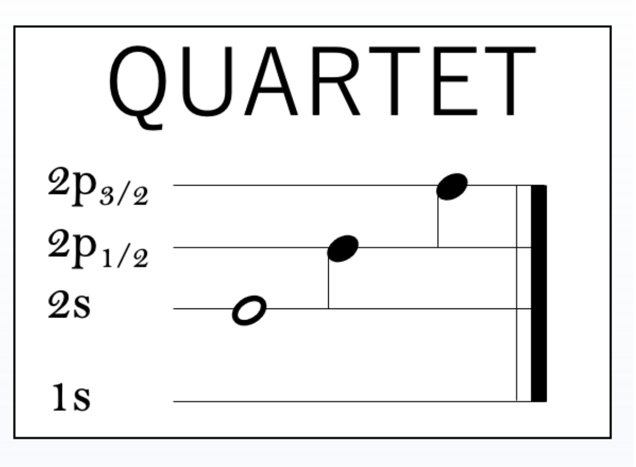


Goals

- Determine E(2P-1S) for 3≤Z≤8 with 10 ppm accuracy 0.2-1 eV .

- Improve radii by factor 3-10.

The QUARTET collaboration and precision goals



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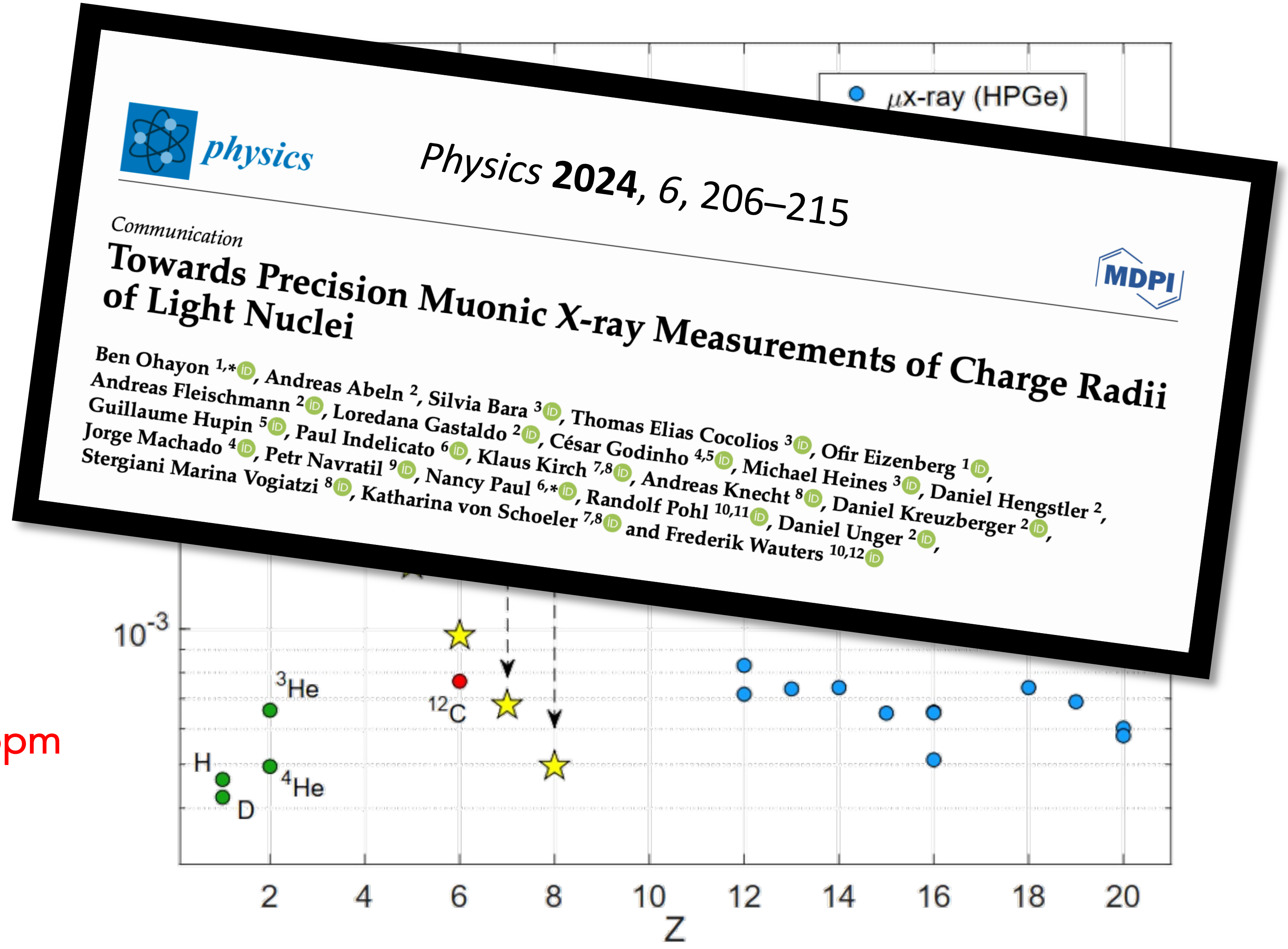

physics Physics **2024**, 6, 206–215

MDPI

Communication

Towards Precision Muonic X-ray Measurements of Charge Radii of Light Nuclei

Ben Ohayon [1,*], Andreas Abeln [2], Silvia Bara [3], Thomas Elias Cocolios [3], Ofir Eizenberg [1], Andreas Fleischmann [2], Loredana Gastaldo [2], César Godinho [4,5], Michael Heines [3], Daniel Hengstler [2], Guillaume Hupin [5], Paul Indelicato [6], Klaus Kirch [7,8], Andreas Knecht [8], Daniel Kreuzberger [2], Jorge Machado [4], Petr Navratil [9], Nancy Paul [6,*], Randolf Pohl [10,11], Daniel Unger [2], Stergiani Marina Vogiatzi [8], Katharina von Schoeler [7,8] and Frederik Wauters [10,12]

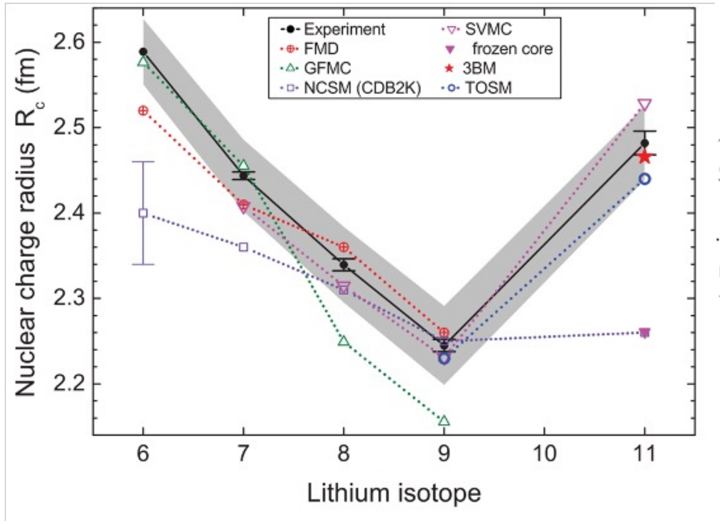
Goals

- Determine E(2P-1S) for 3≤Z≤8 with 10 ppm accuracy 0.2-1 eV .
- Improve radii by factor 3-10.

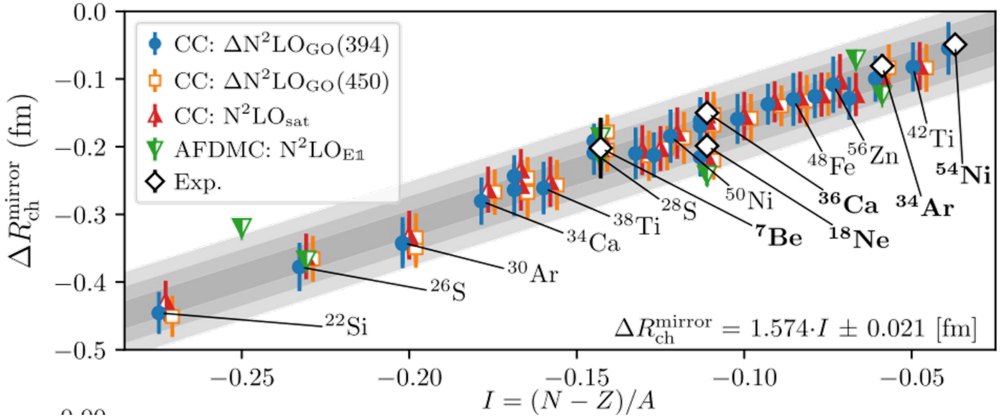
What are radii good for?

- **Absolute radius:** Li/Be/B → calibrate entire chains, test nuclear chiral EFT
- **Isotope shifts:** compare electronic and muonic atoms to search for new lepton-neutron interactions
- Absolute radii for helium-like laser spectroscopy Li to C (Wuhan, Mainz).
- Novel measurements of g-factors in H-like ions **limited by muonic isotope shifts for new physics searches.**

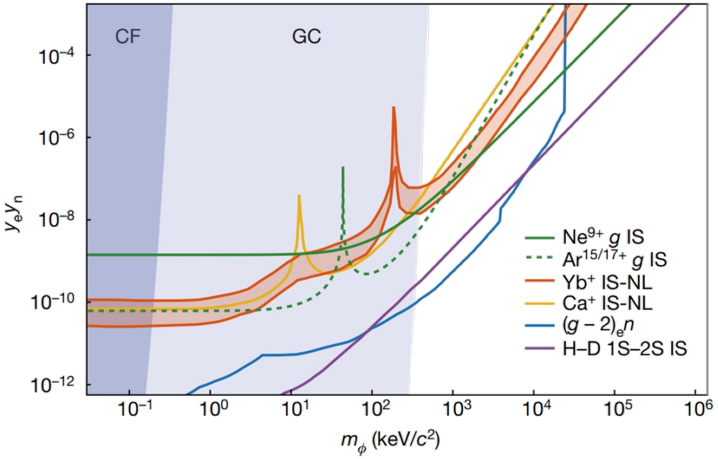
PRC 84, 024307 (2011)



S. J. Novario, *et. al.*, PRL 130, 032501 (2023)



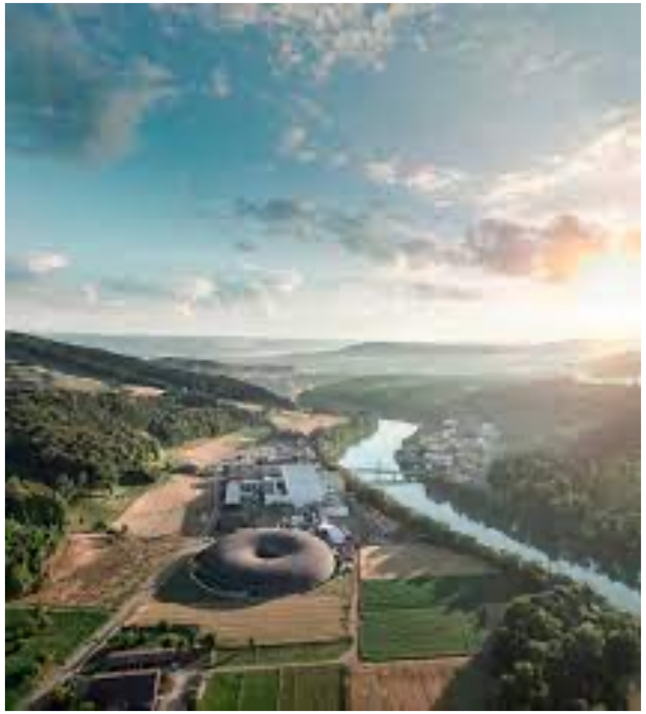
T. Sailer *et. al.*, Nature 606 (2022)



All limited by reference radii

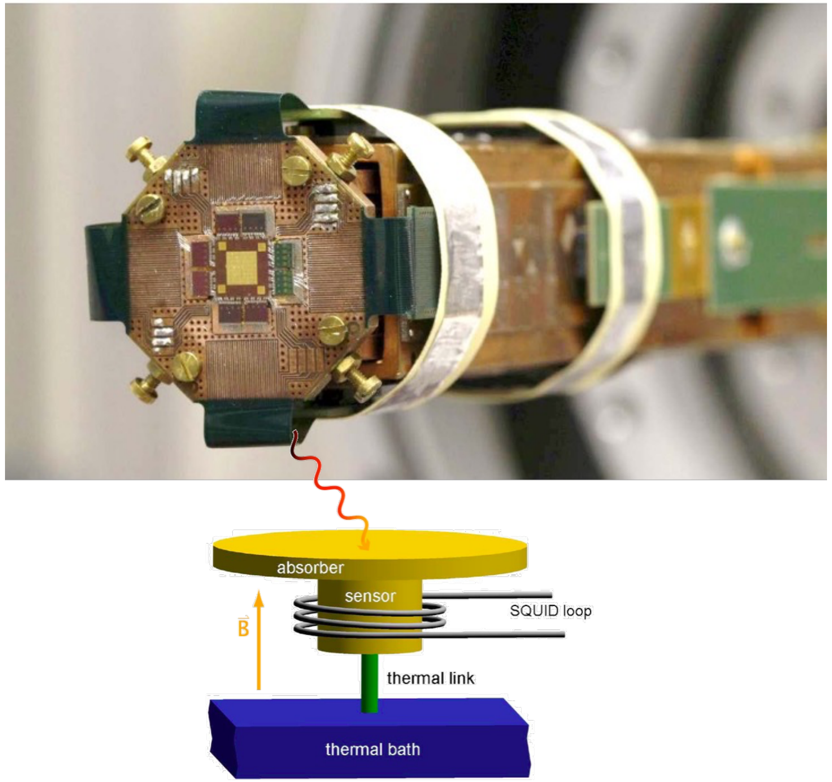
The QUARTET experiments at the Paul Scherrer Institute

PAUL SCHERRER INSTITUT
PSI

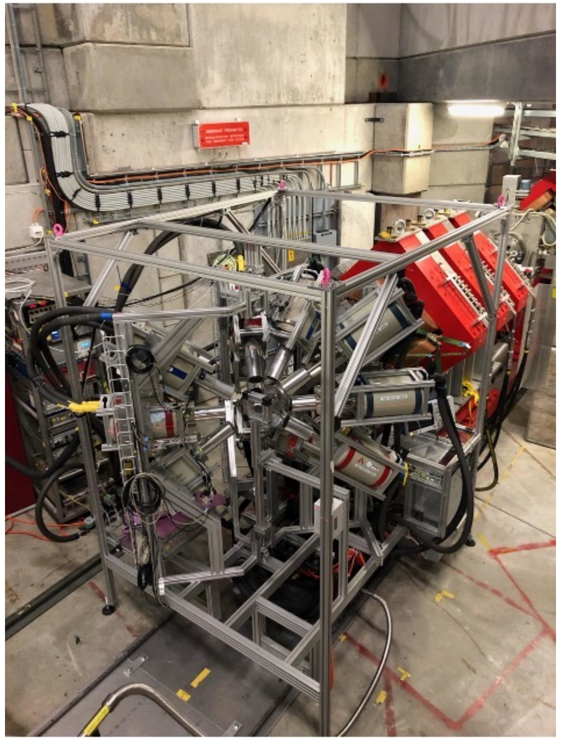


The Heidelberg Metallic Magnetic Calorimeter (MMC)

maXs-30 mounted on coldfinger of a dry dilution fridge

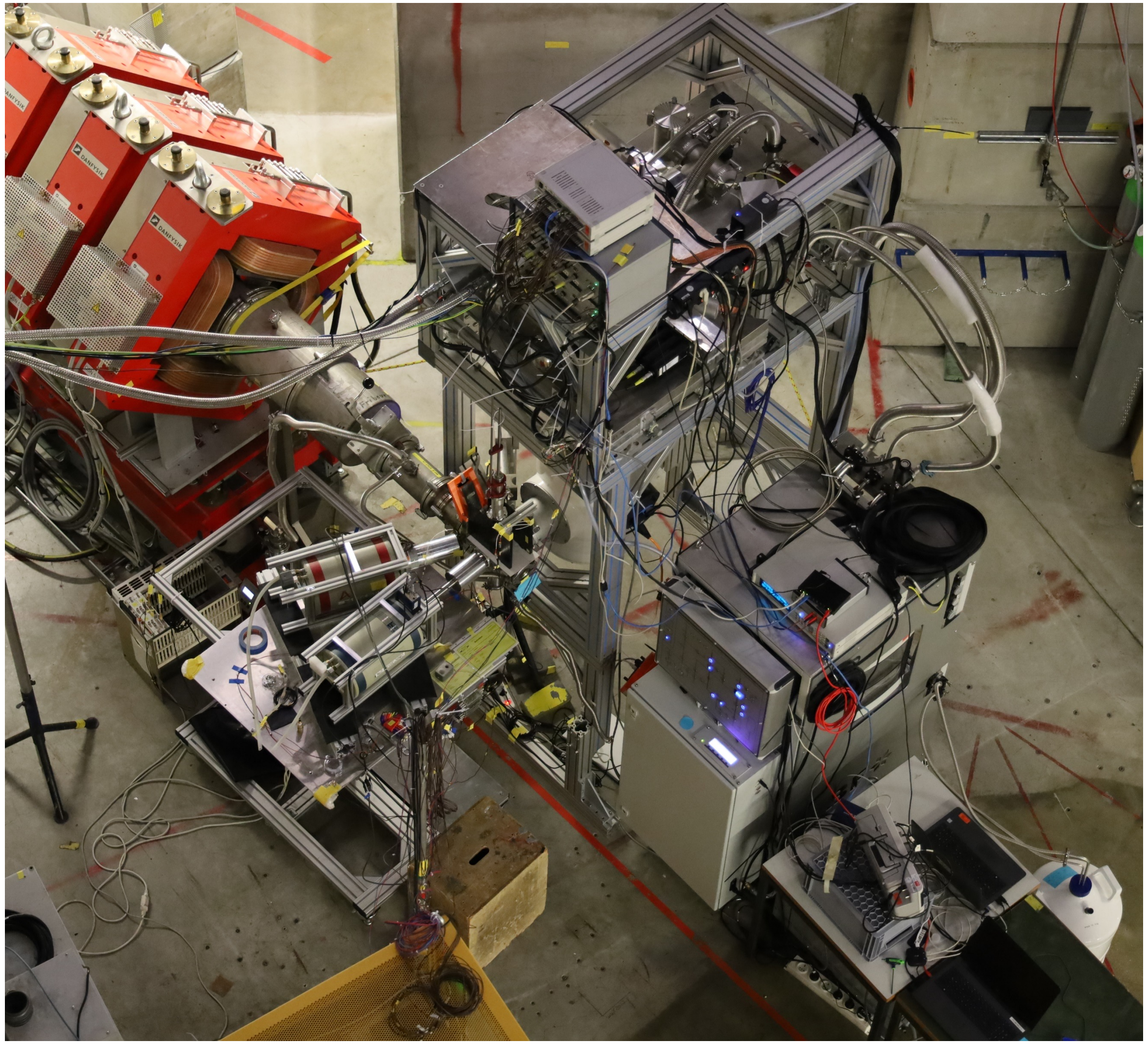


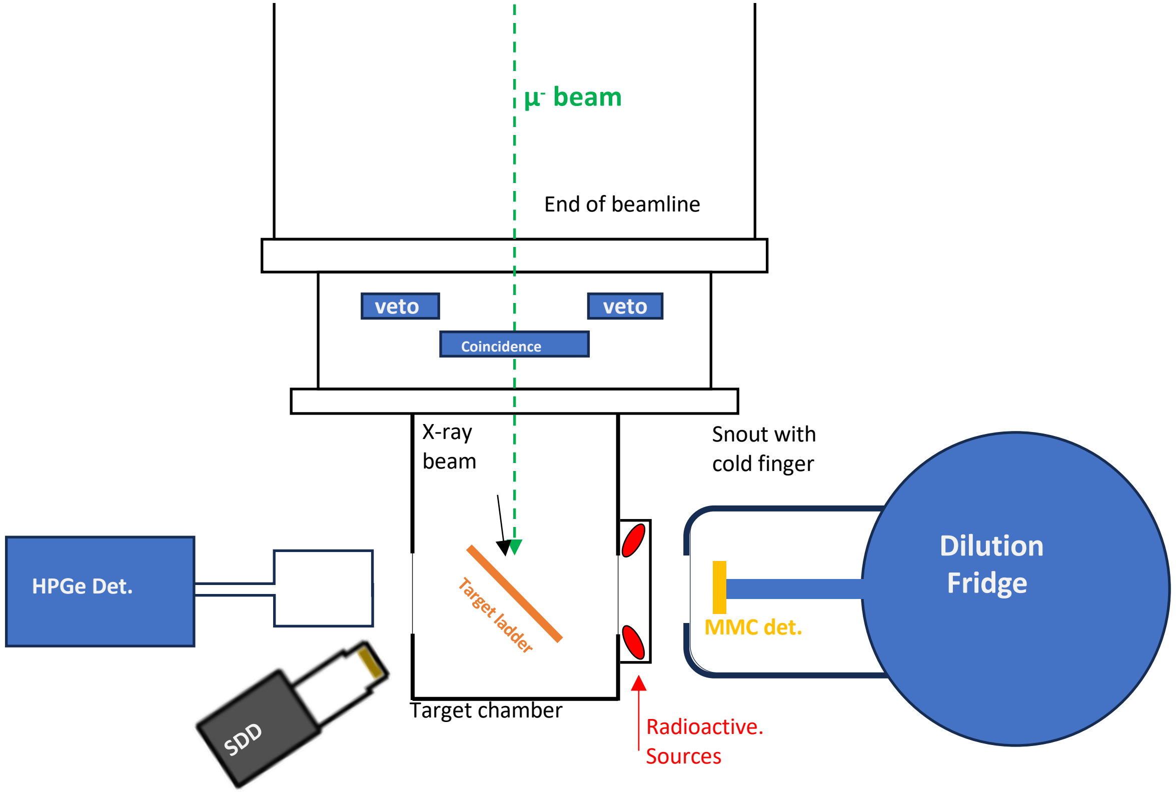
PIE1 beamline at PSI,
continuous ~50kHz μ^- /s



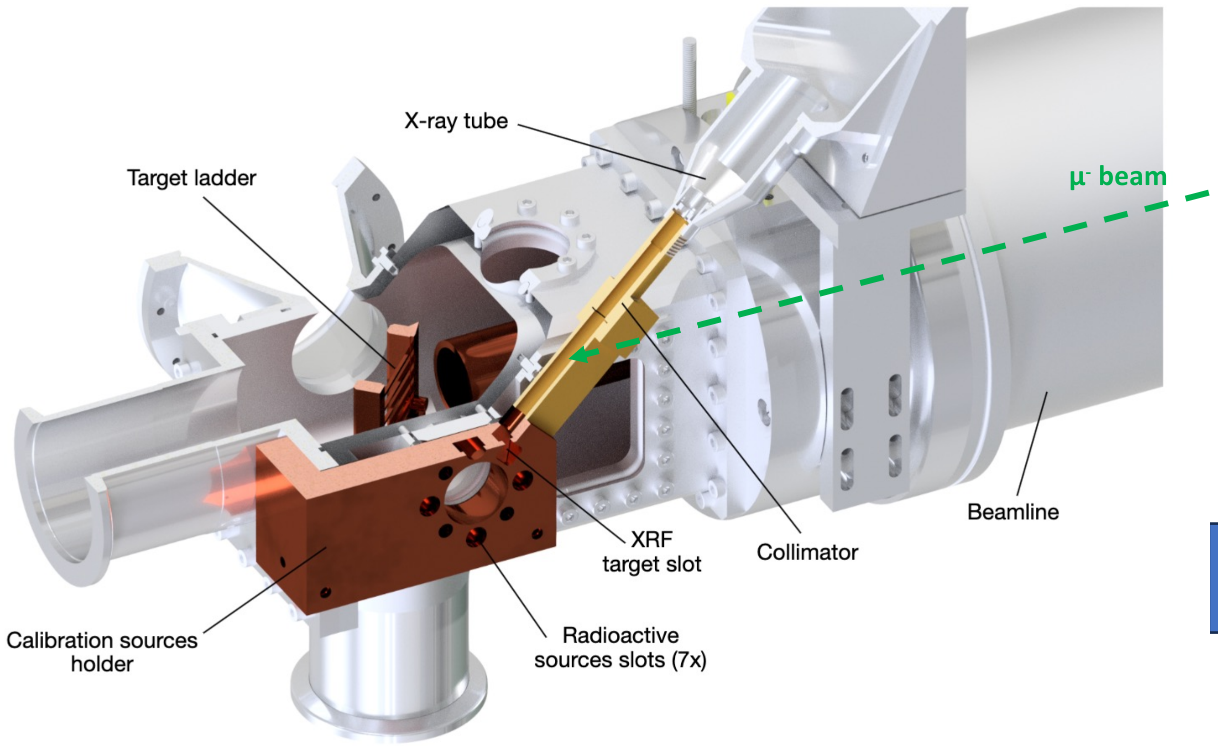
ETH zürich · JOHANNES GUTENBERG UNIVERSITÄT MAINZ · TECHNION Israel Institute of Technology · KIRCHHOFF-INSTITUT FÜR PHYSIK · Laboratoire Kastler Brossel Physique quantique et applications · NOVA SCHOOL OF SCIENCE & TECHNOLOGY · KU LEUVEN

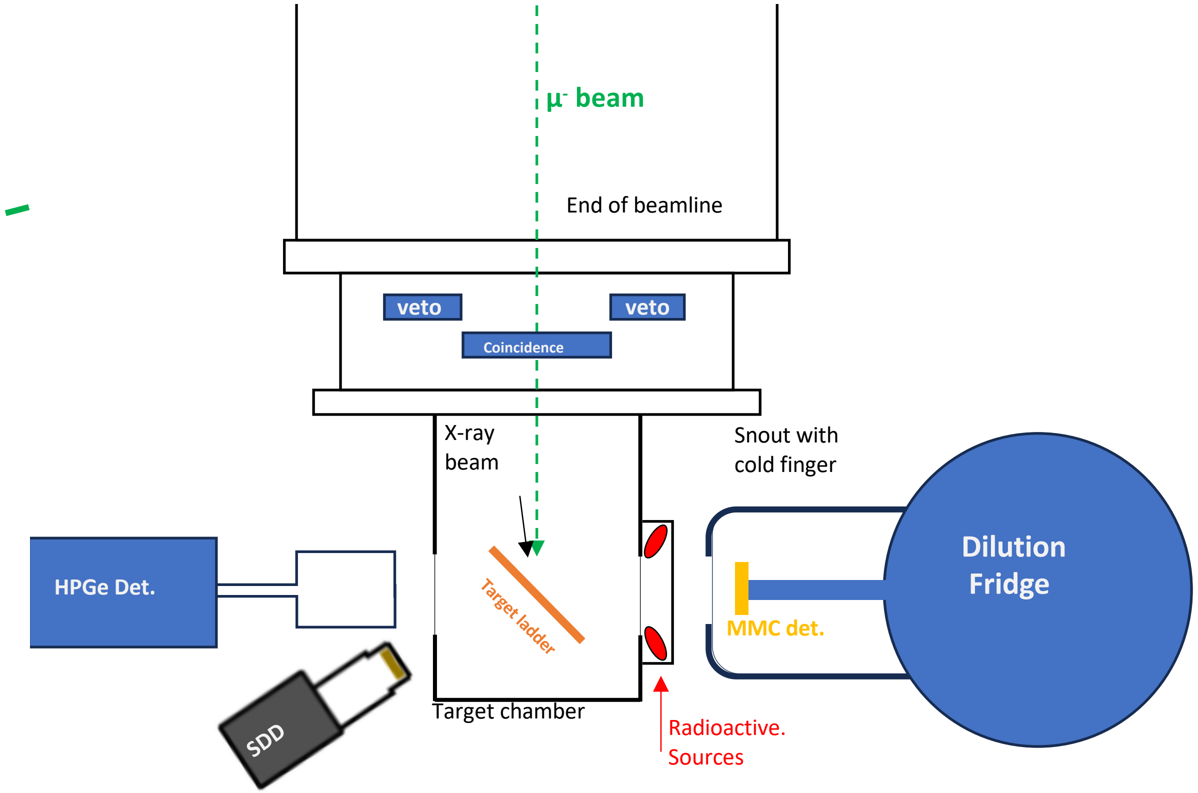
The QUARTET experimental setup—2023-2024



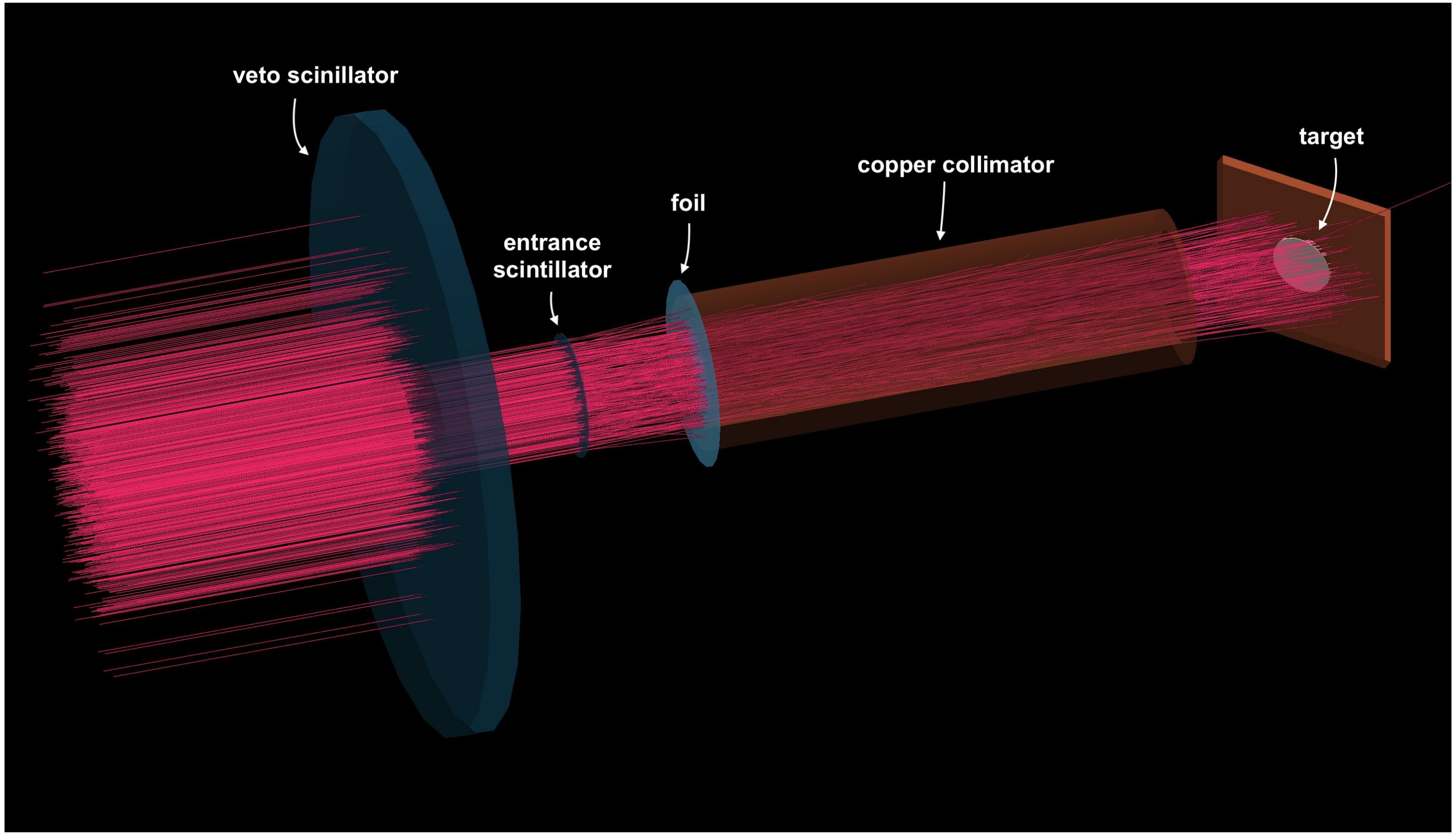


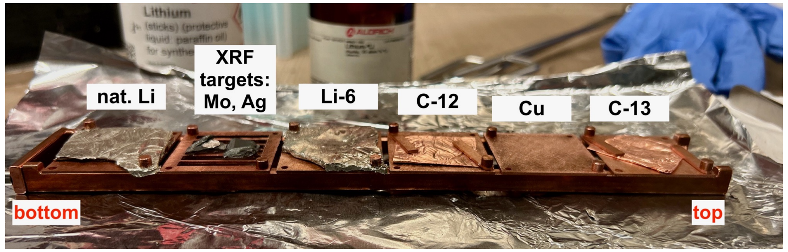
The QUARTET experimental setup—2023-2024

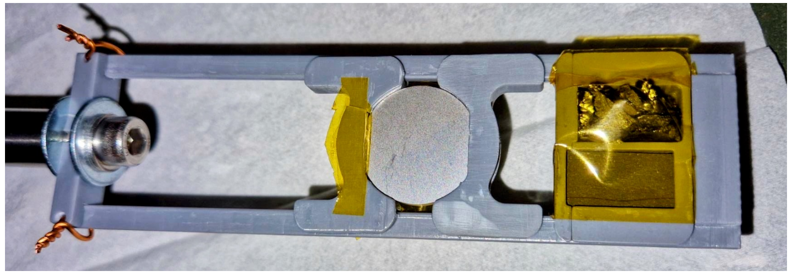


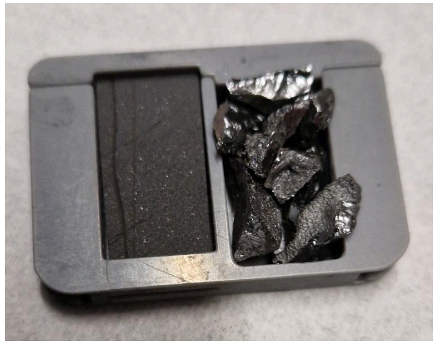


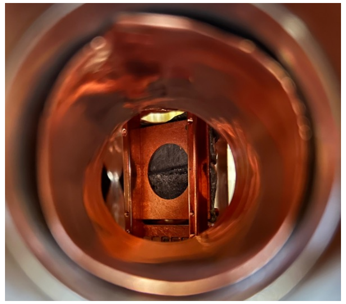
Muon beam and target ladders





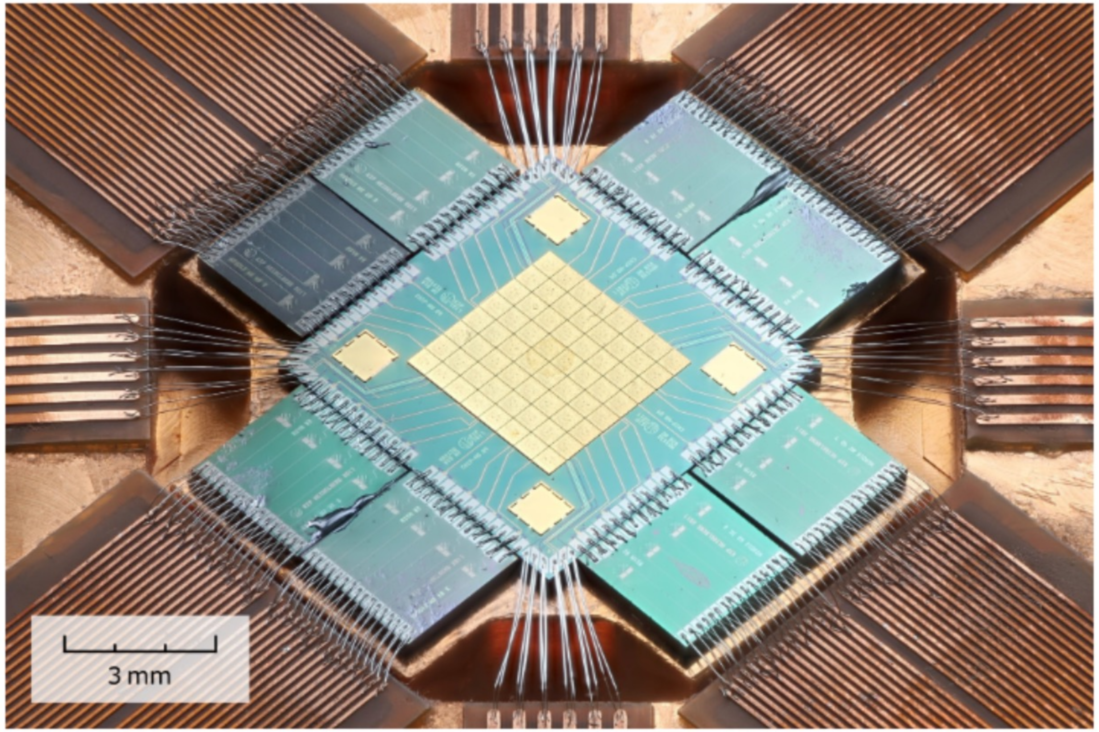


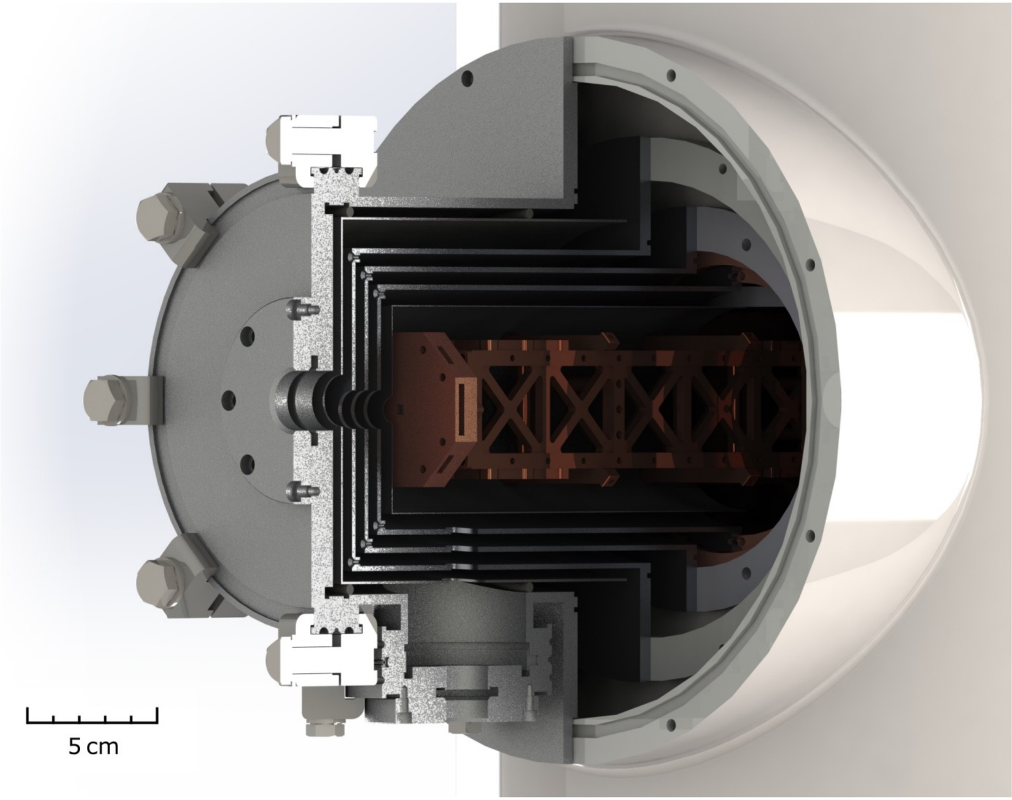




Half $^{(6),7}$Li, Half ^{6}Li
^{12}C Alu pouch, Mo-Ag

The QUARTET detector



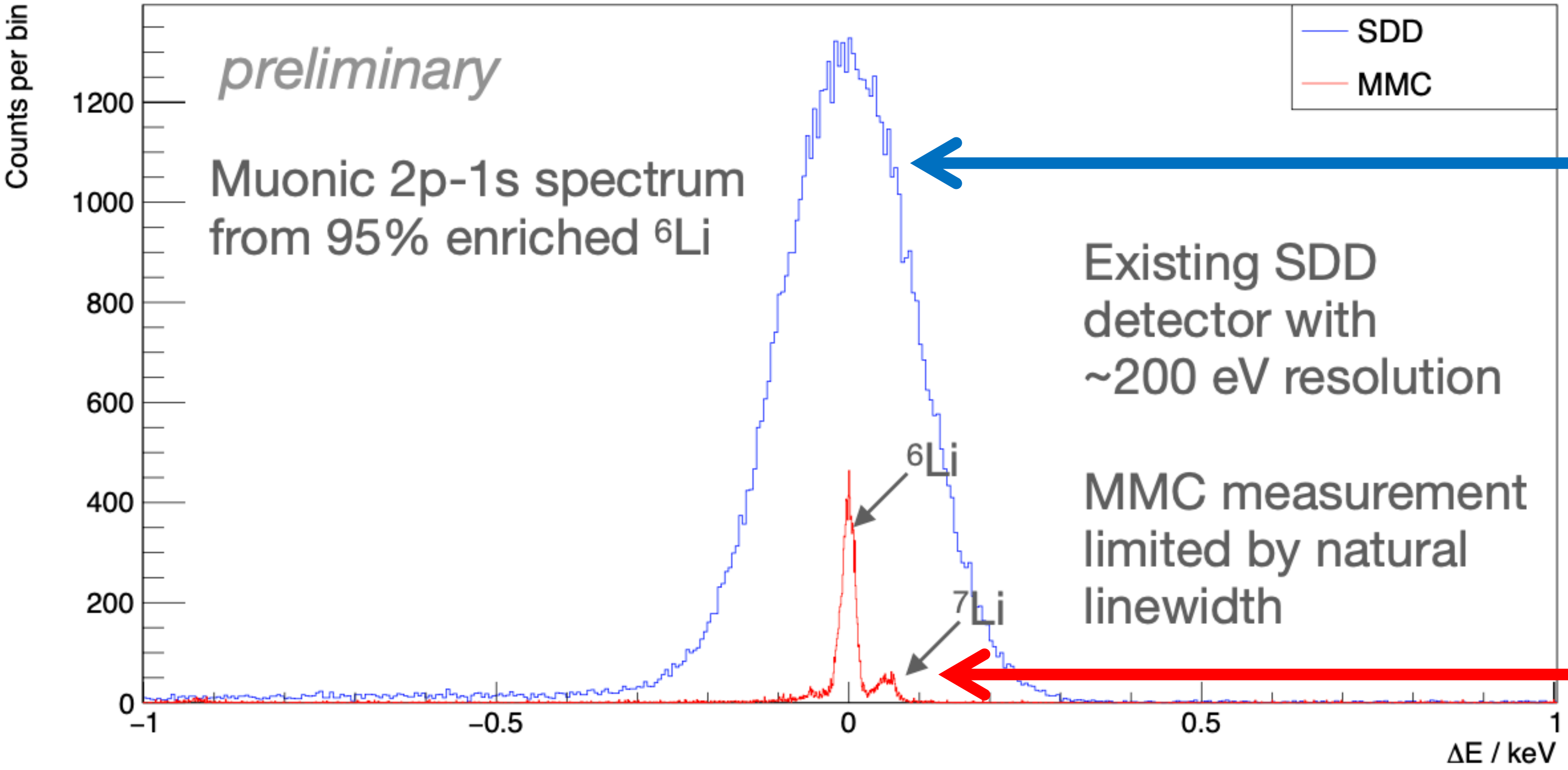


- 64 pixel maX-30 MMC detector, *developed for IAXO experiment*
- Mounted in custom sidearm designed to reduce vibrations
- 5 thermal shields and x-ray windows
- Calibration sources mounted outside the detector

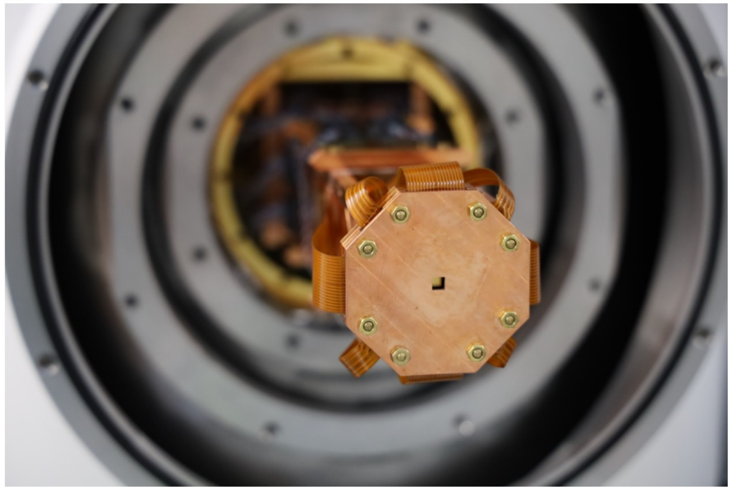
Figures from D. Unger et al LTD2023 proceeding, for the QUARTET collaboration

Comparison with Si detector

PhD work of Katharina v. Schoeler

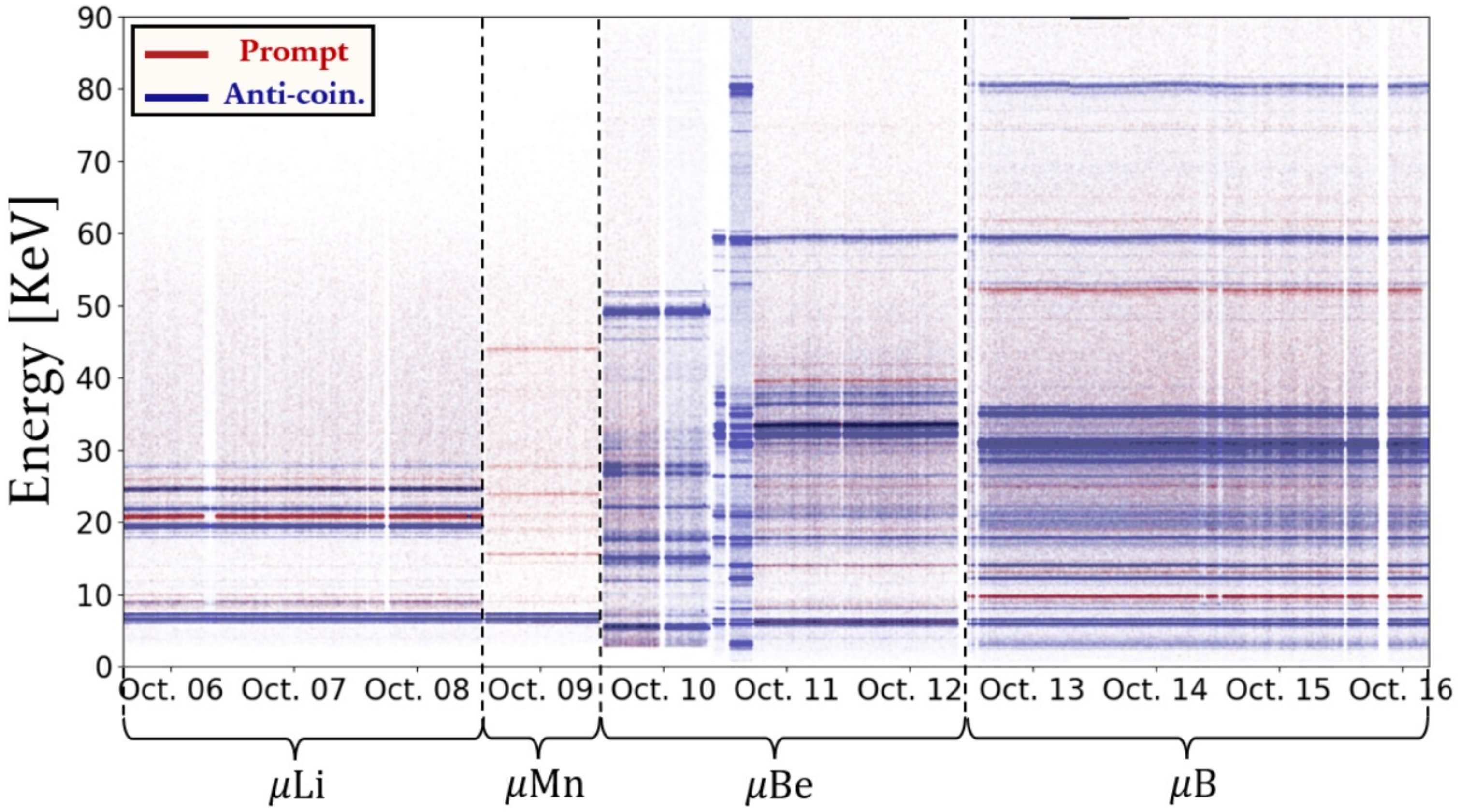


Existing SDD detector with ~200 eV resolution

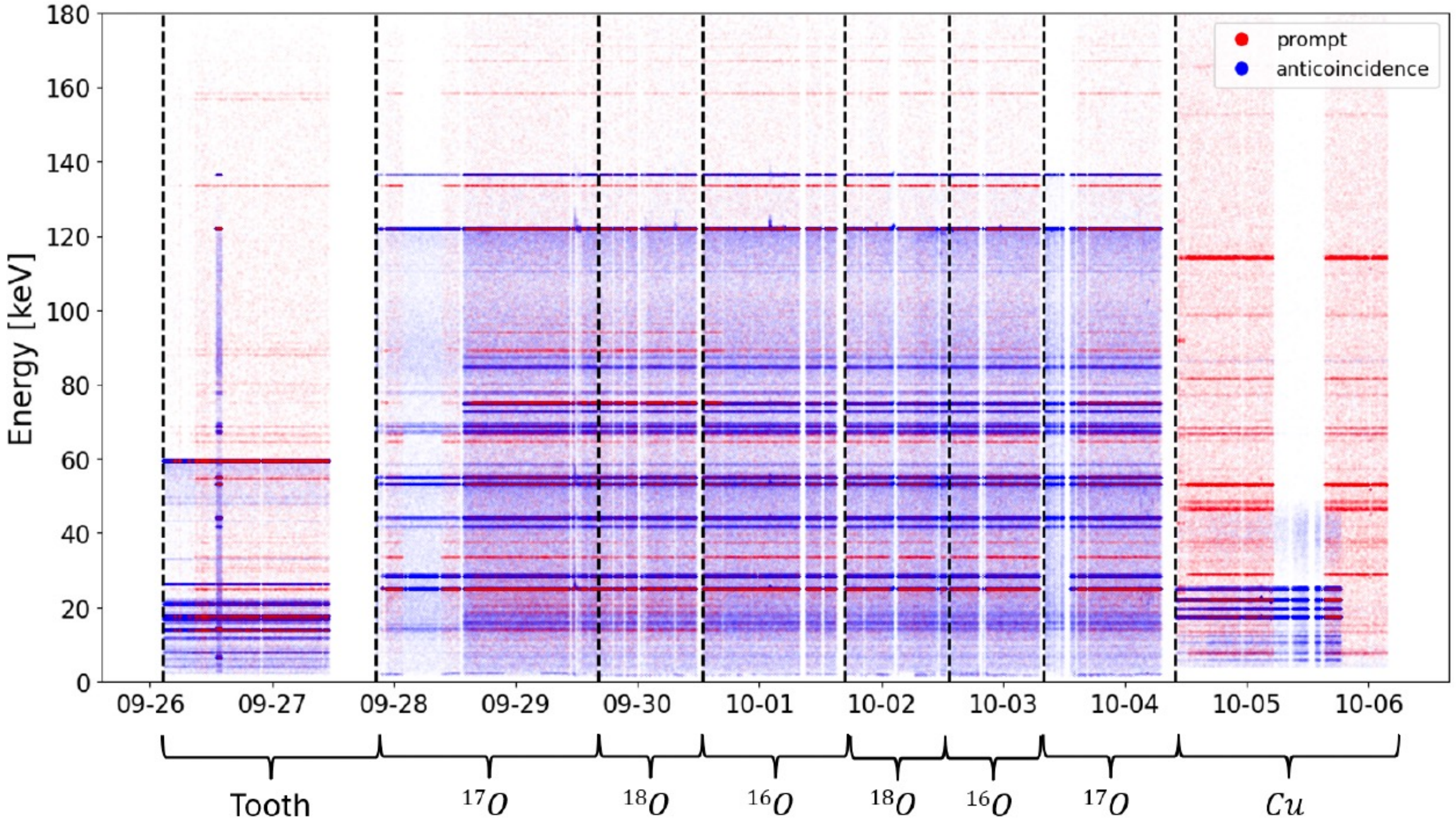


MMC measurement limited by natural linewidth

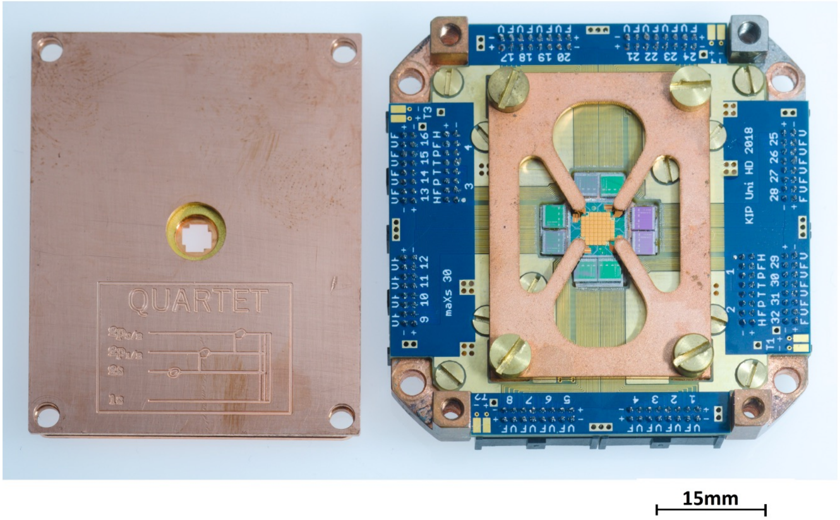
QUARTET 2024 beamtime—towards an optimized setup



QUARTET 2025 beamtime—Oxygen and anthropology



New dedicated 100 keV detector

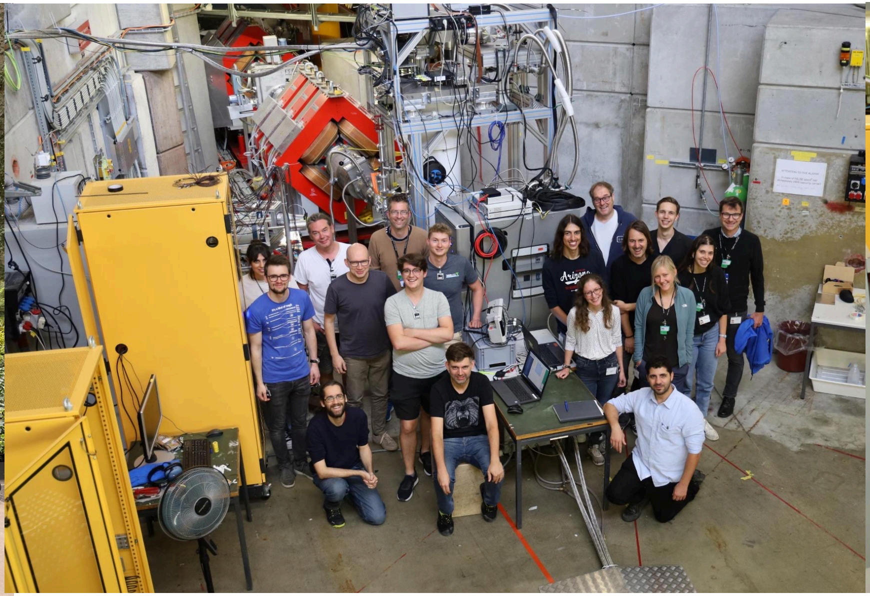


See Tim's poster for the preliminary Oxygen spectra !

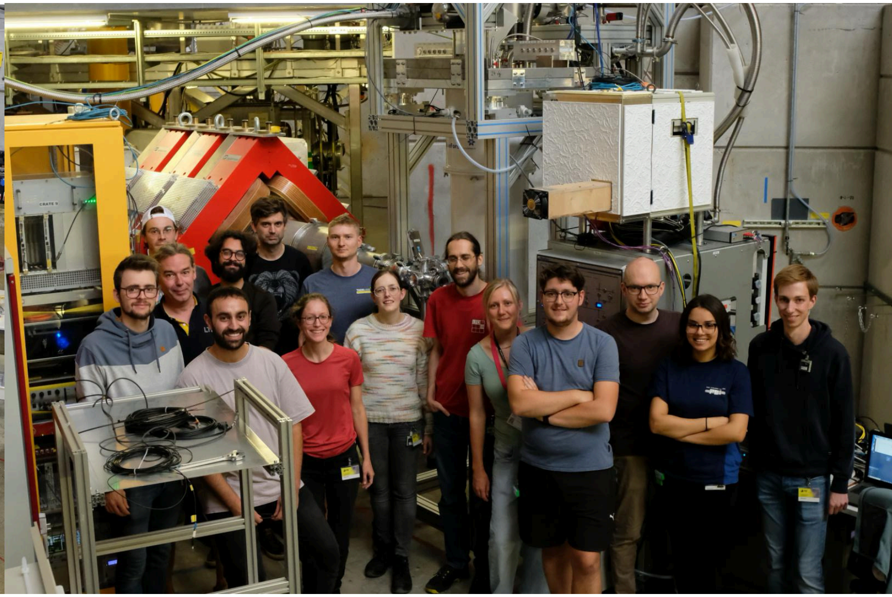
The QUARTET collaboration timeline

First meeting @ Jussieu (2022)

Test beam @ PSI (2023)



Li/Be/B beamtime (2024)



Oxygen charge radii (2025)

C to Ne charge radii (2026/2027)

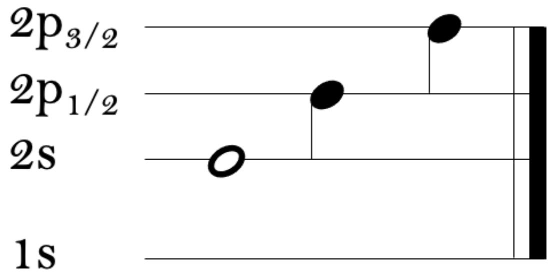
Summary

- **Spectroscopy of exotic atoms** offers a unique window be sensitive to fundamental interactions
- Quantum **sensing x-ray microcalorimeter detectors** make precision studies possible

ANTIPROTONIC ATOM X-RAY SPECTROSCOPY

- Strongest-field QED with antiprotonic atoms
- Test beam at TELMAX in 2025 with prototype detector
- Physics measurements @ ELENA post LS3
- Long term nuclear physics/NP applications

QUARTET



- Charge radius measurements of low-Z nuclei with MMC
- Li, Be, B, O data taking
- x3-10 improvement of charge radii for Li-Ne nuclei 2024-2027

New long-term programs of x-ray spectroscopy of exotic atoms for fundamental physics

Thank You!