Fundamental Interactions and Beyond with X-ray Spectroscopy of Exotic Atoms

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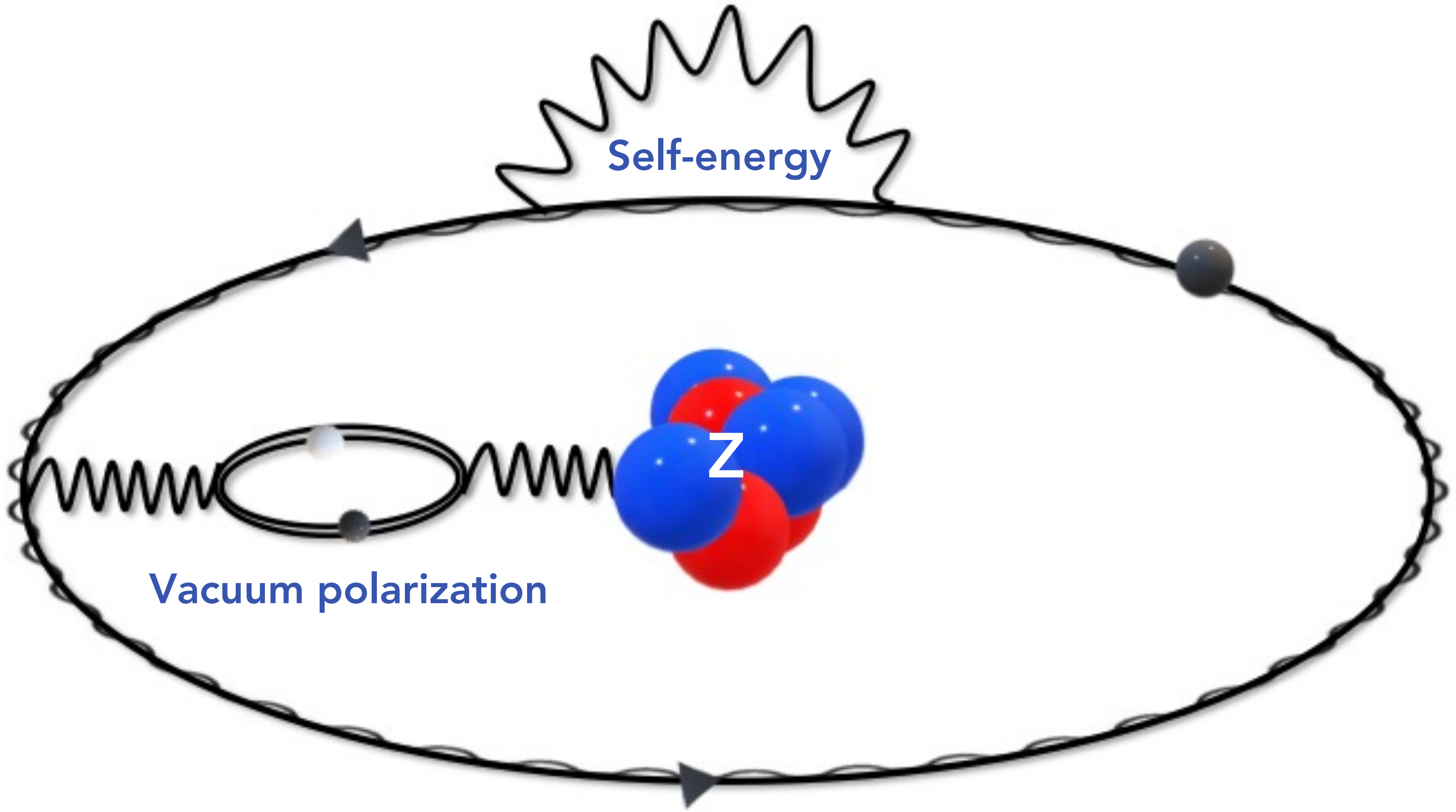
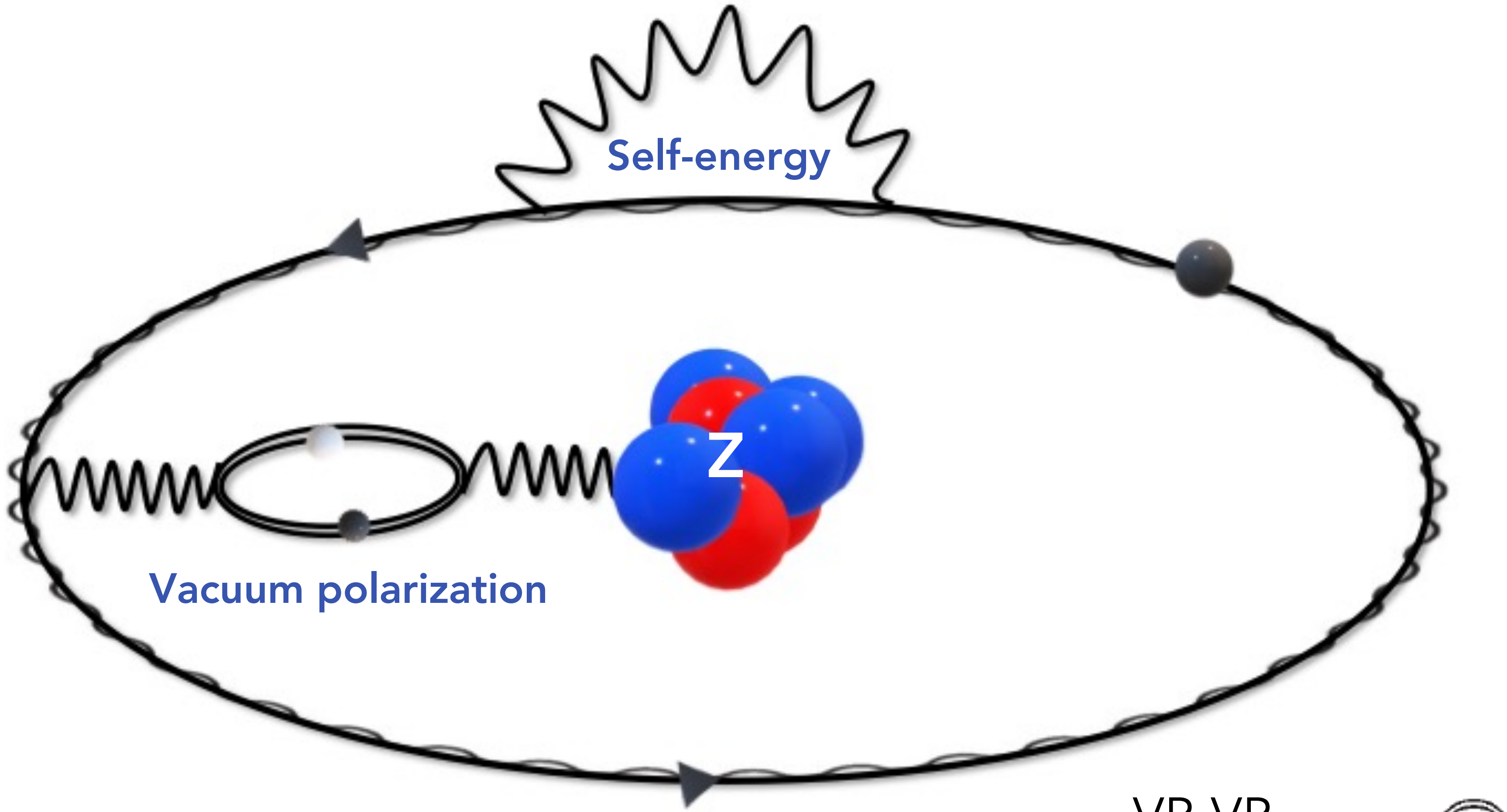
Laboratoire Kastler Brossel

ASOS 2023
July 12th, 2023

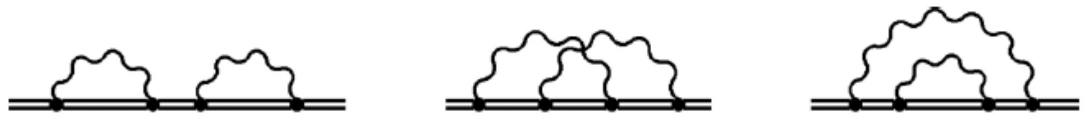
Bound state QED—a rich landscape



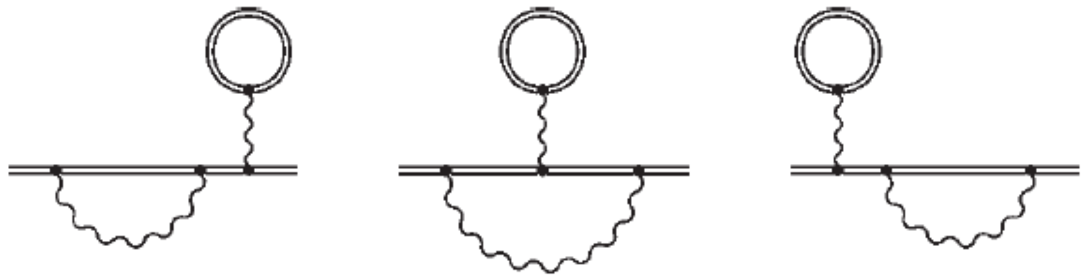
Bound state QED—a rich landscape



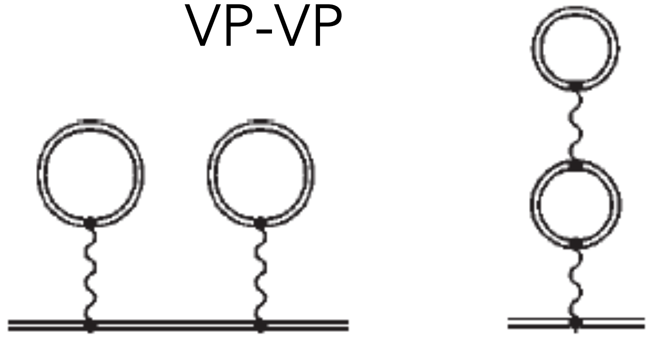
SE-SE



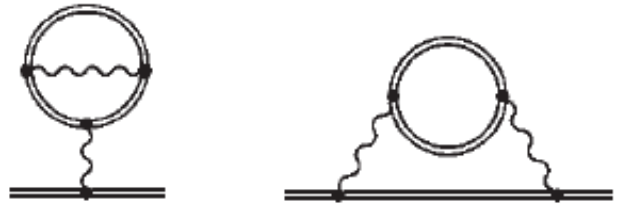
SE-VP



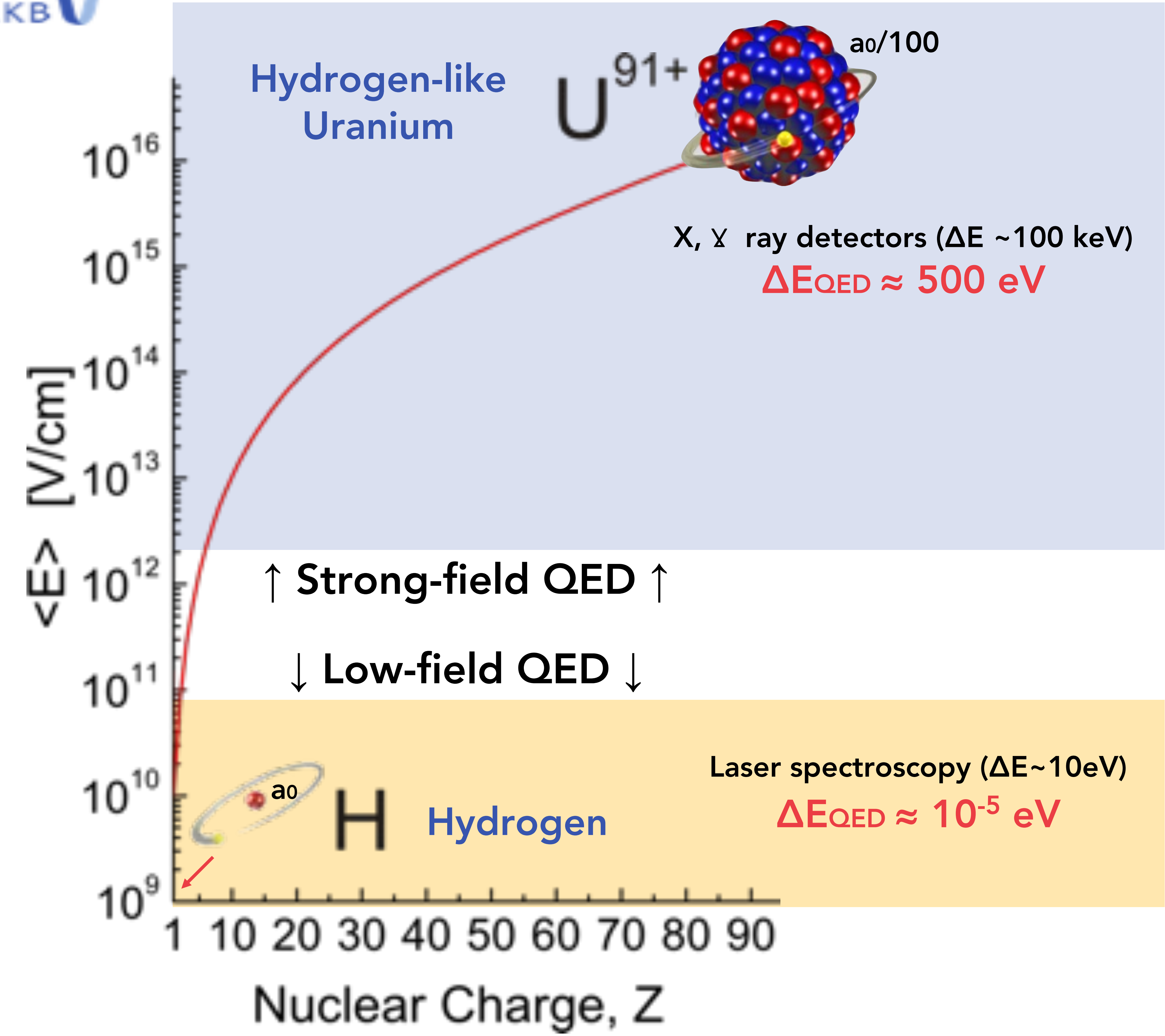
VP-VP



S(VP)E



Strong field Bound State QED (BSQED)



Hydrogen-like Uranium

X, ɣ ray detectors (ΔE ~100 keV)

$\Delta E_{QED} \approx 500$ eV

↑ **Strong-field QED** ↑

↓ **Low-field QED** ↓

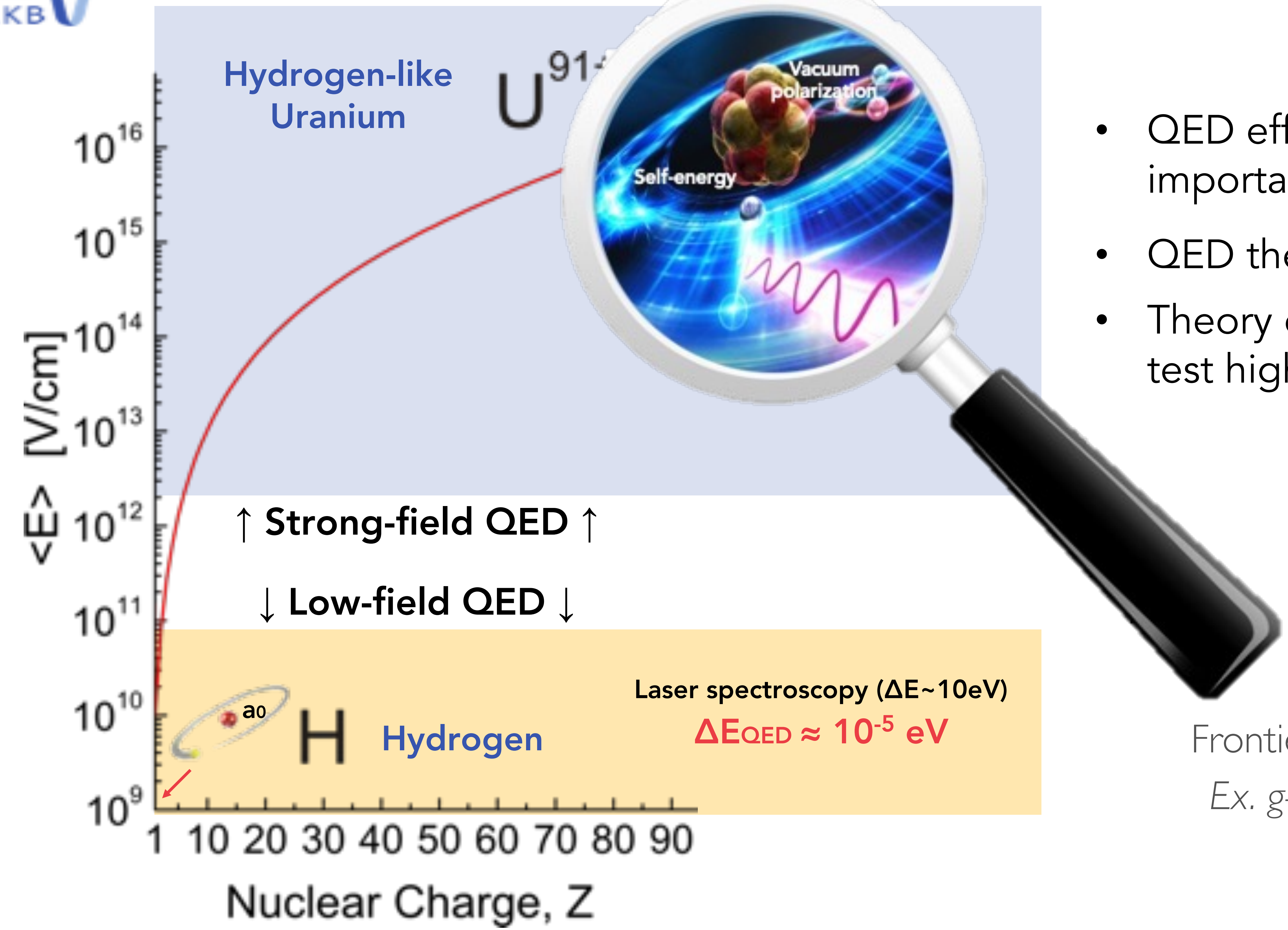
Hydrogen

Laser spectroscopy (ΔE~10eV)

$\Delta E_{QED} \approx 10^{-5}$ eV

- 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

Strong field Bound State QED (BSQED)

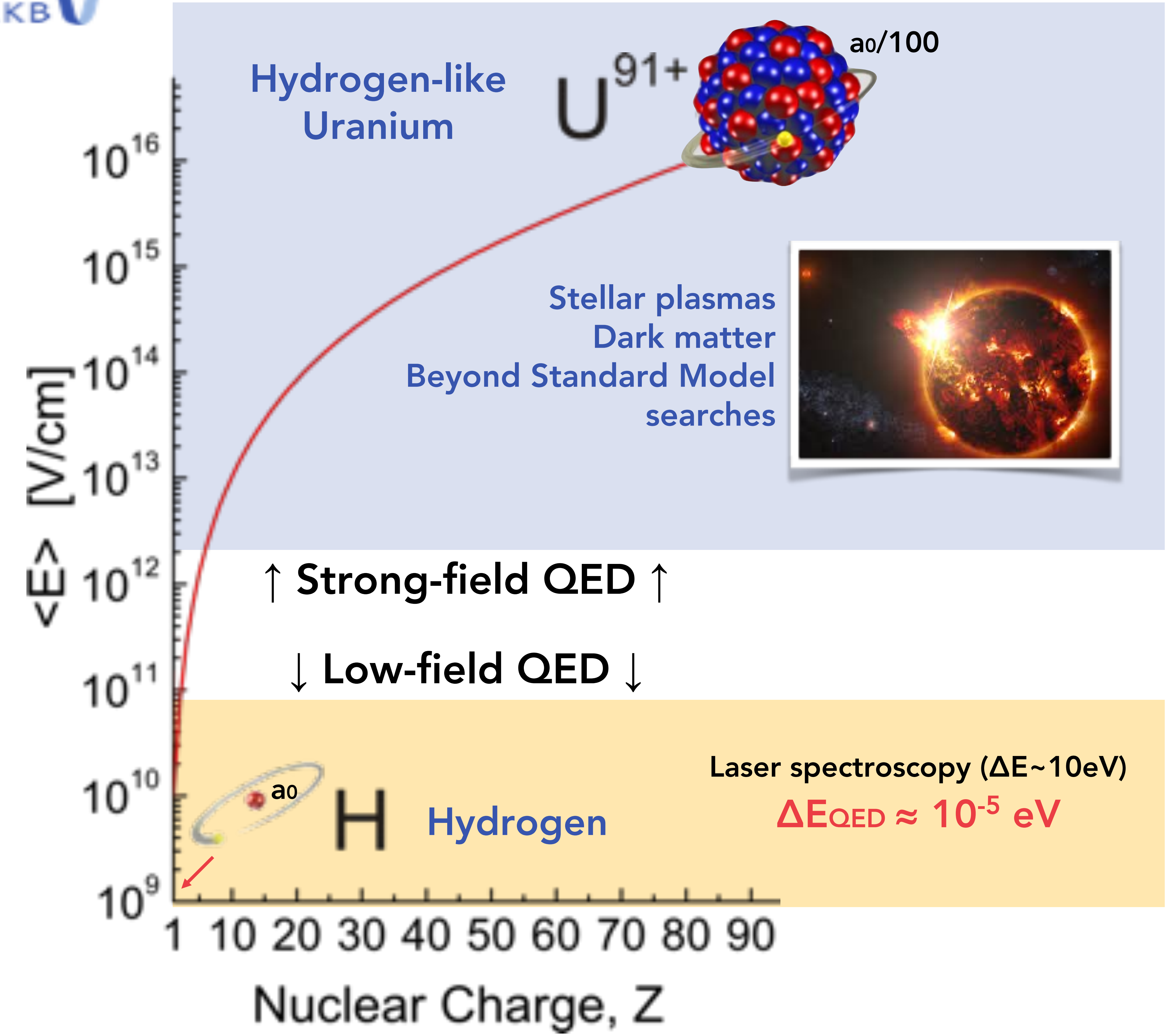


- QED effects become relatively more important
- QED theory non-perturbative ($Z\alpha$)
- Theory exists but experiments difficult to test higher-order QED contributions

Frontier via complementary methods

Ex. g-factors, high-intensity lasers, …

Strong field Bound State QED (BSQED)



Hydrogen-like Uranium

Stellar plasmas
Dark matter
Beyond Standard Model searches

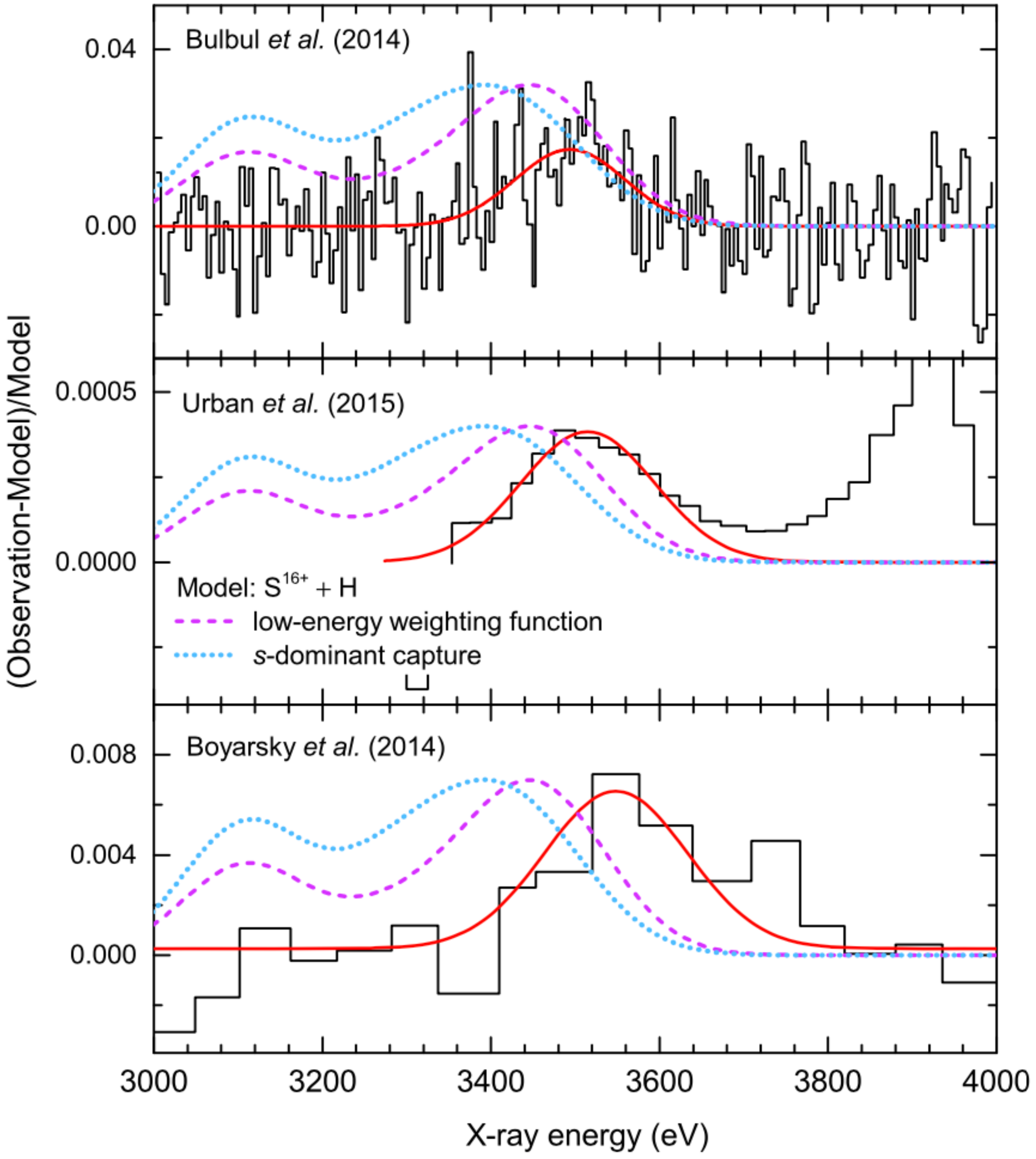
↑ **Strong-field QED** ↑

↓ **Low-field QED** ↓

Hydrogen

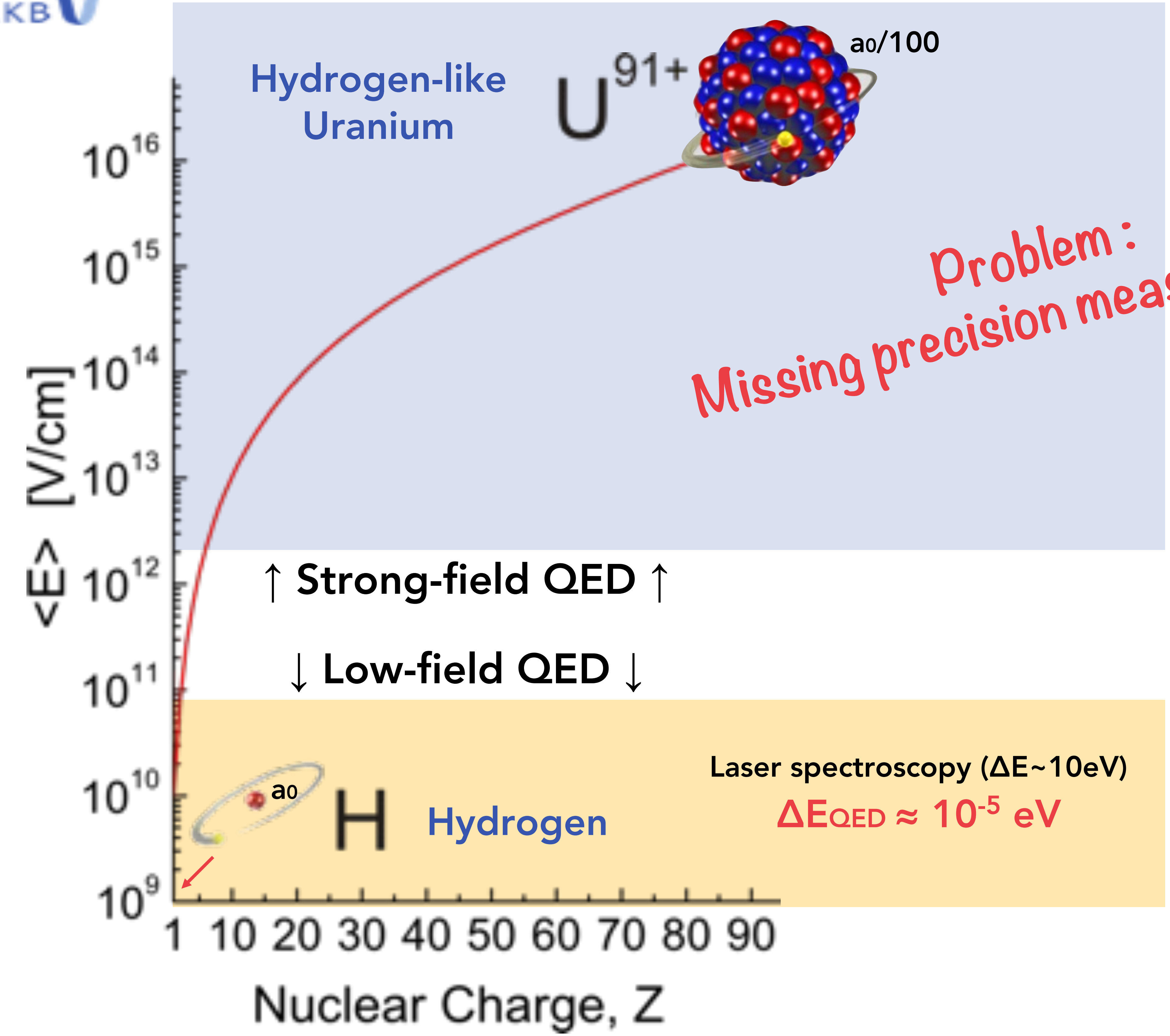
Laser spectroscopy (ΔE~10eV)

$\Delta E_{QED} \approx 10^{-5}$ eV



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

Strong field Bound State QED (BSQED)



Hydrogen-like Uranium

↑ Strong-field QED ↑

↓ Low-field QED ↓

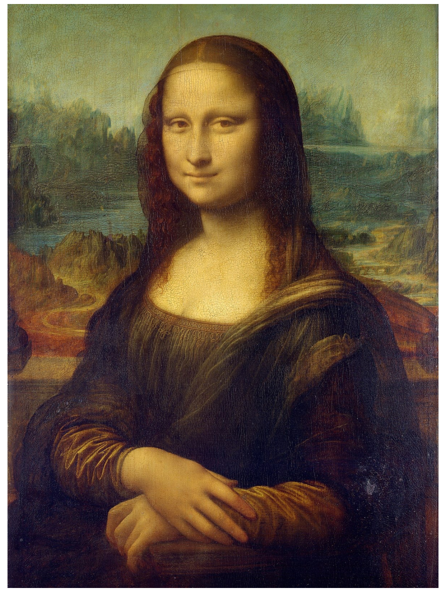
Hydrogen

Laser spectroscopy (ΔE~10eV)

$\Delta E_{QED} \approx 10^{-5}$ eV

Problem :
Missing precision measurements!

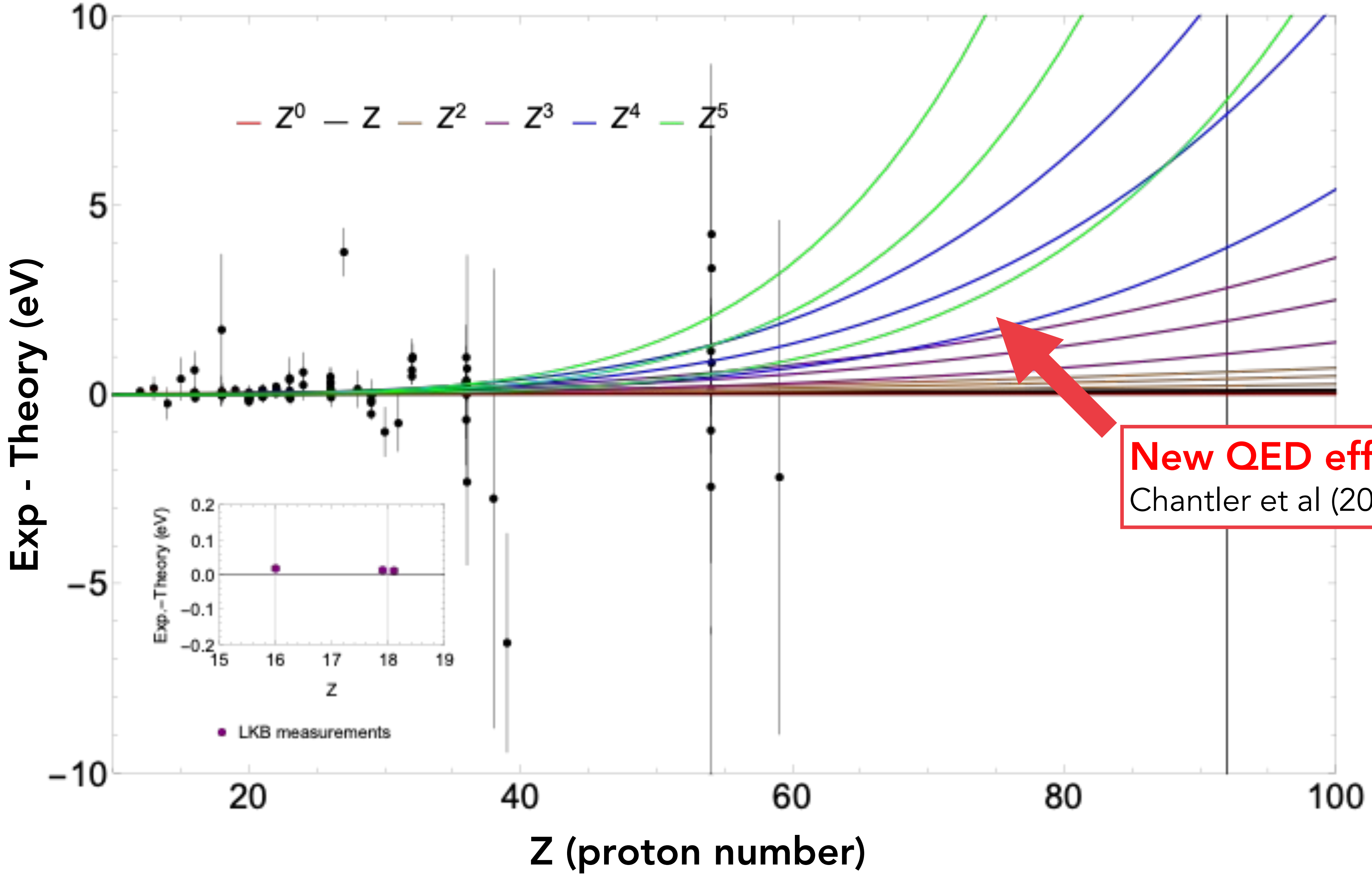
*QED untested beyond 1st order effects,
2nd order QED is ppm effect and currently untested!



* QED tested to threshold of 3rd order effects

Precision spectroscopy of highly-charged ions (HCI)

Theory-experiment comparison of QED effects in two-electron atoms (He-like) for transitions to the ground state (Lyman-alpha)



New QED effects?
Chantler et al (2012, 2014)

Figure adapted from P. Indelicato, Topical Review: QED tests with highly-charged ions, Journal of Physics B 52 (2019) 232001

The Double Crystal Spectrometer

Highest precision x-ray spectroscopy (2 keV—200 keV)

→crystal spectrometers

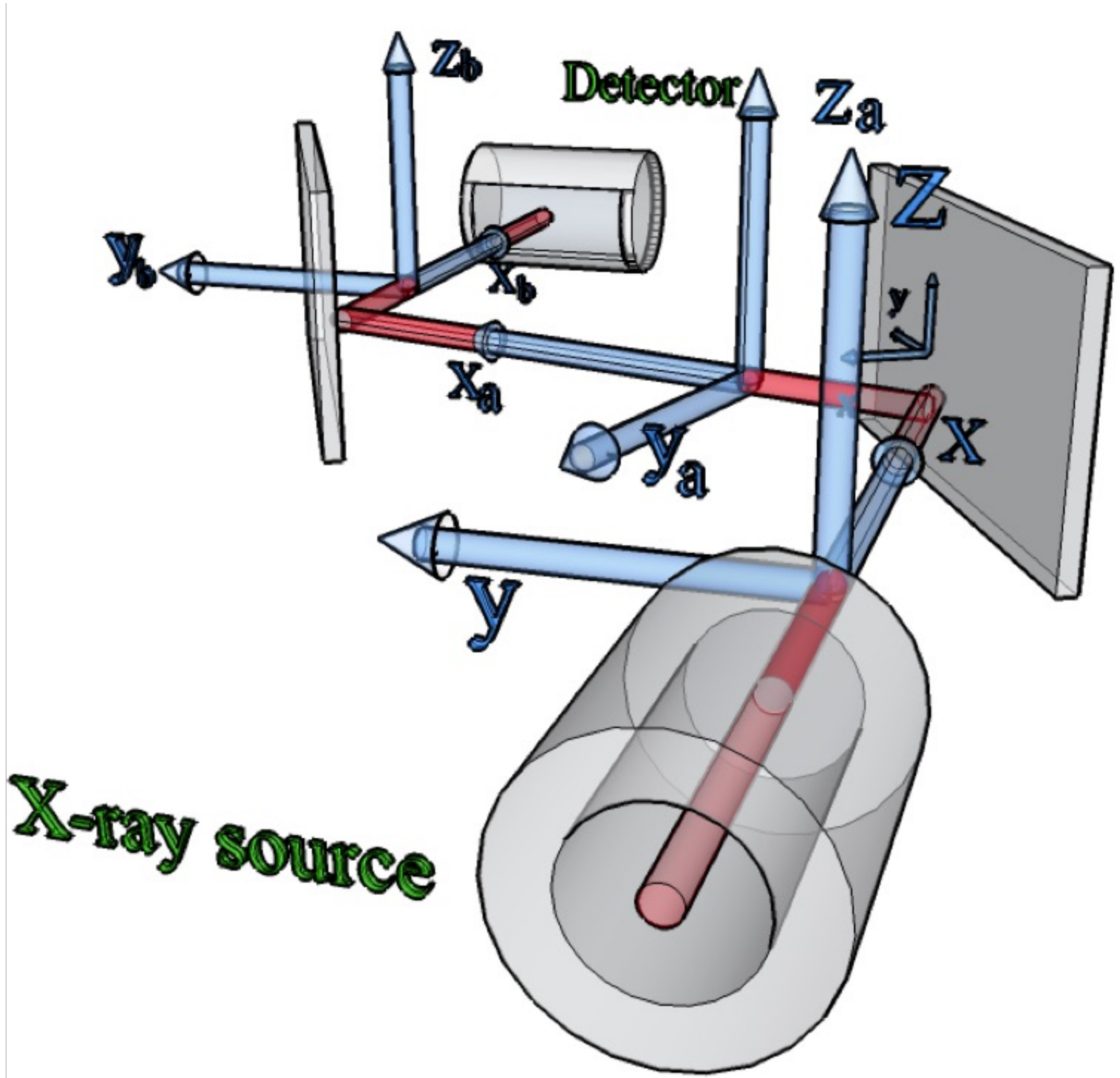
- Analyse x rays based on Bragg diffraction from crystal lattice
- Requires precise knowledge of crystal structure and dynamical diffraction theory

$$n\lambda = 2d sin(\theta_{Bragg})$$

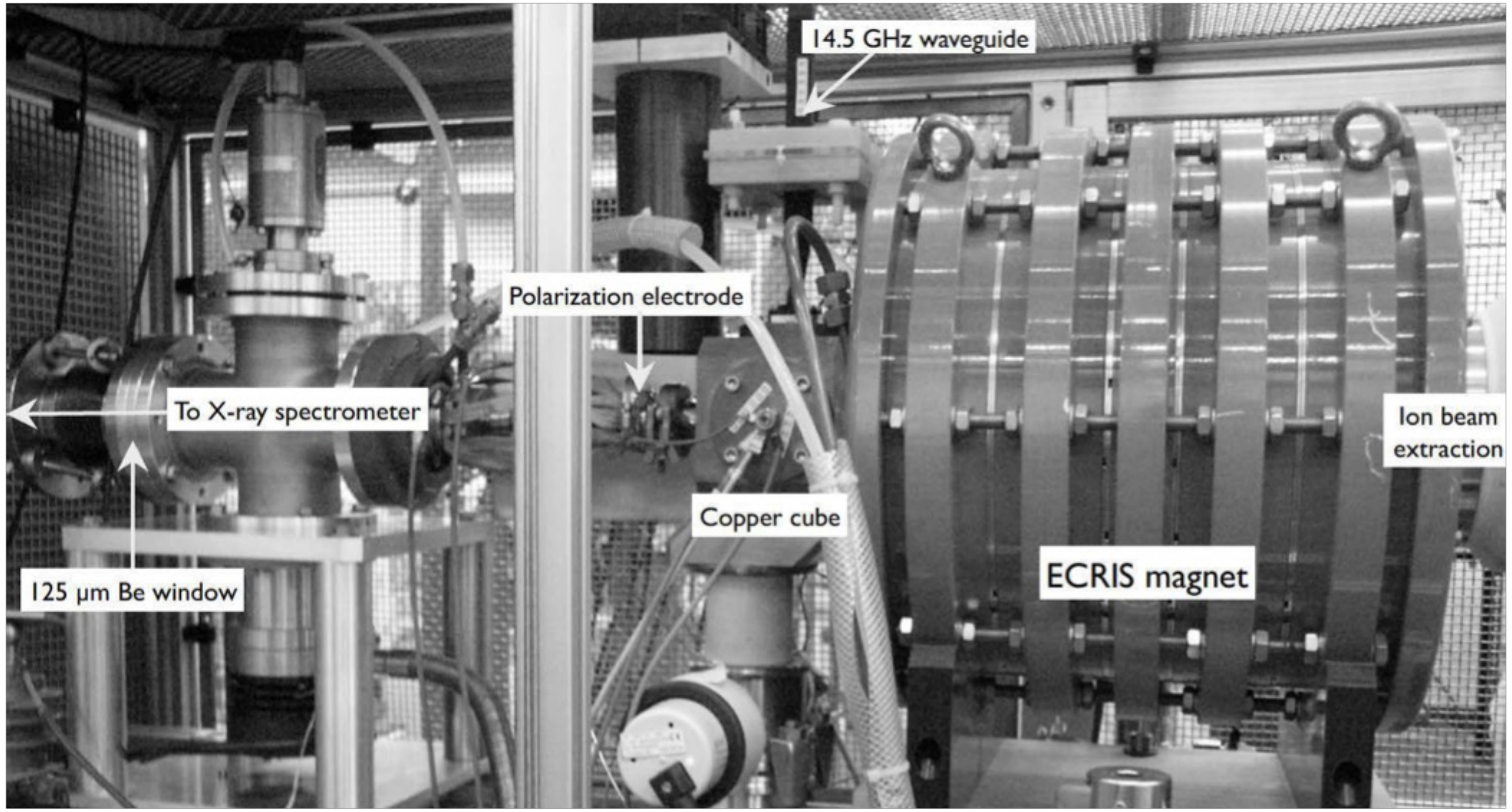
X-ray wavelength

Crystal lattice spacing

Measured Bragg angle

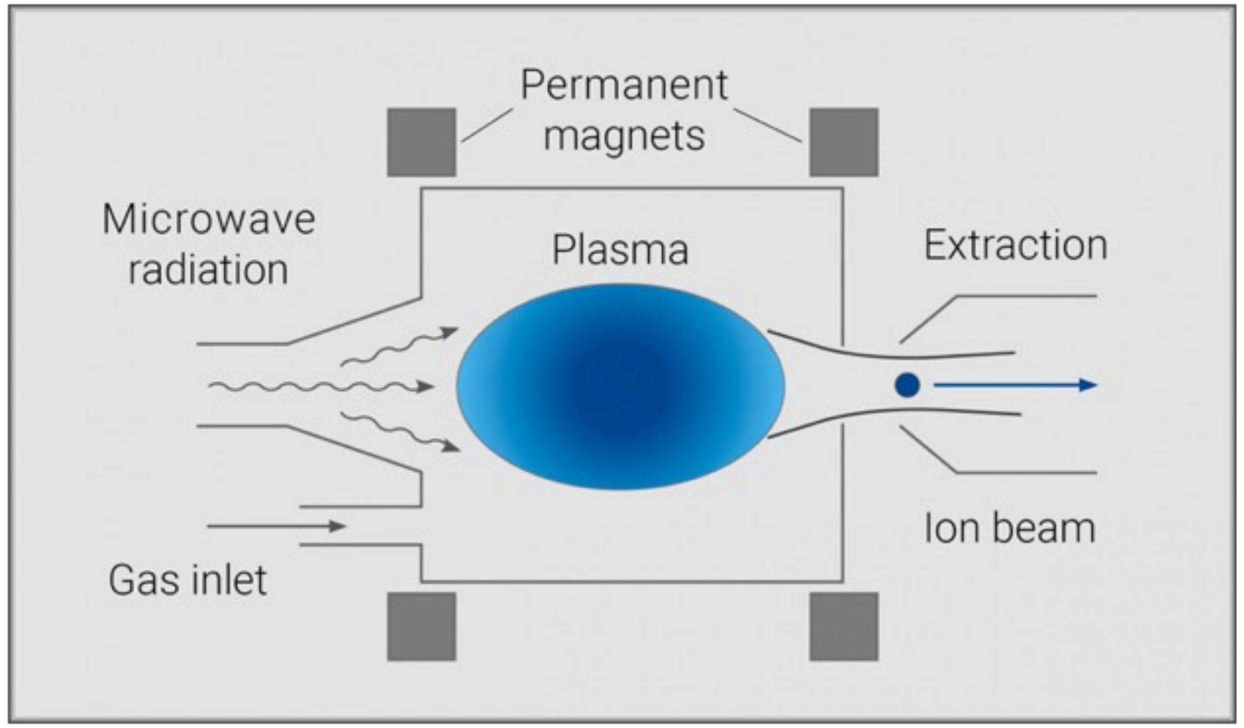


The Source “SIMPA” for highly-charged ion production



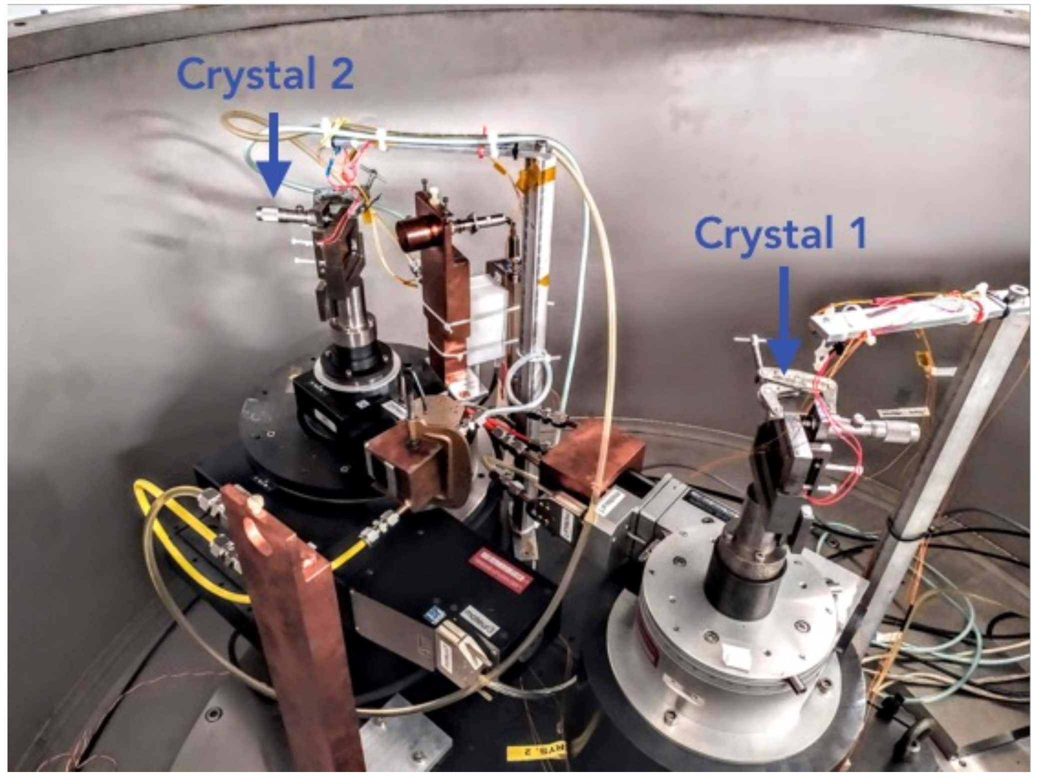
Microwaves : 14.5 GHz

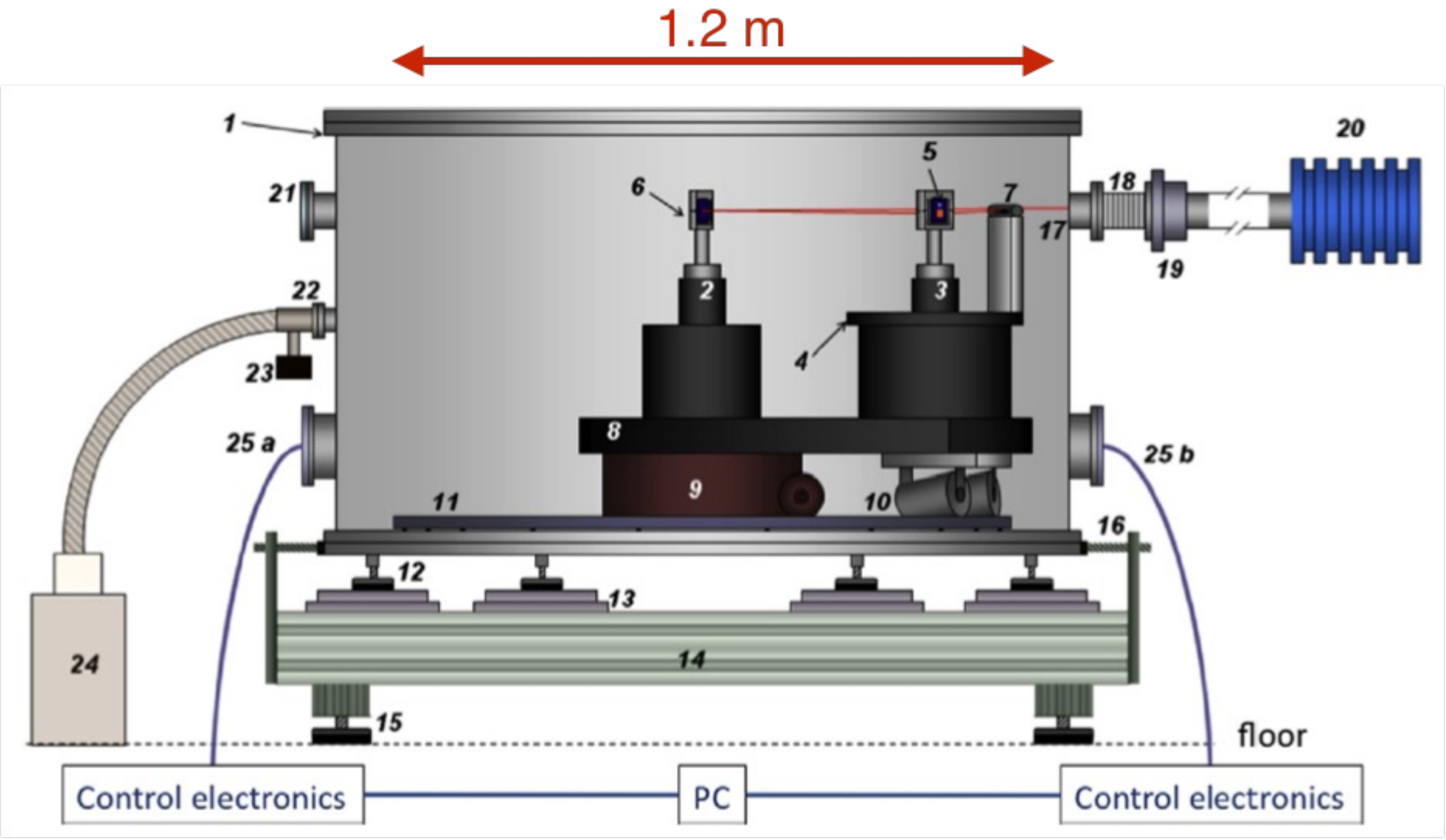
Extraction voltage: 0 V to 25 kV



- Direct connection to plasma, 50µm thick Be window
- In the plasma the ions are trapped in the space charge of the electrons (~10^{11} e^-/cm^3), ~ few eV trapping depth
- Intense source, provides access to forbidden transitions, narrow linewidths

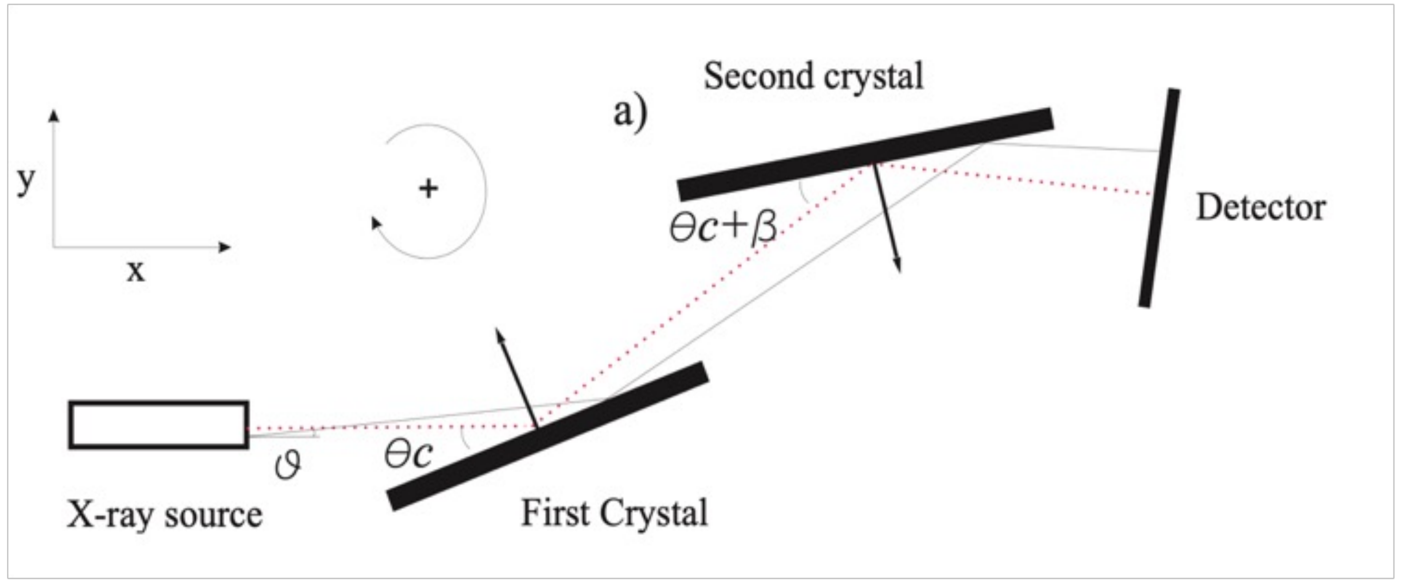
The Paris Double Crystal Spectrometer

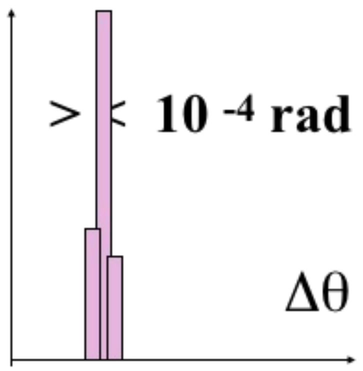




- Si$_{111}$ crystals from NIST, lattice spacing (d) known to 10^{-8}
- Angular encoder for second axis: Heidenhain RON 905 with AWE 1024 interpolator →0.2" of arc angular accuracy
- Detector : LAAPD (large area avalanche photodiode) cooled at -10°C

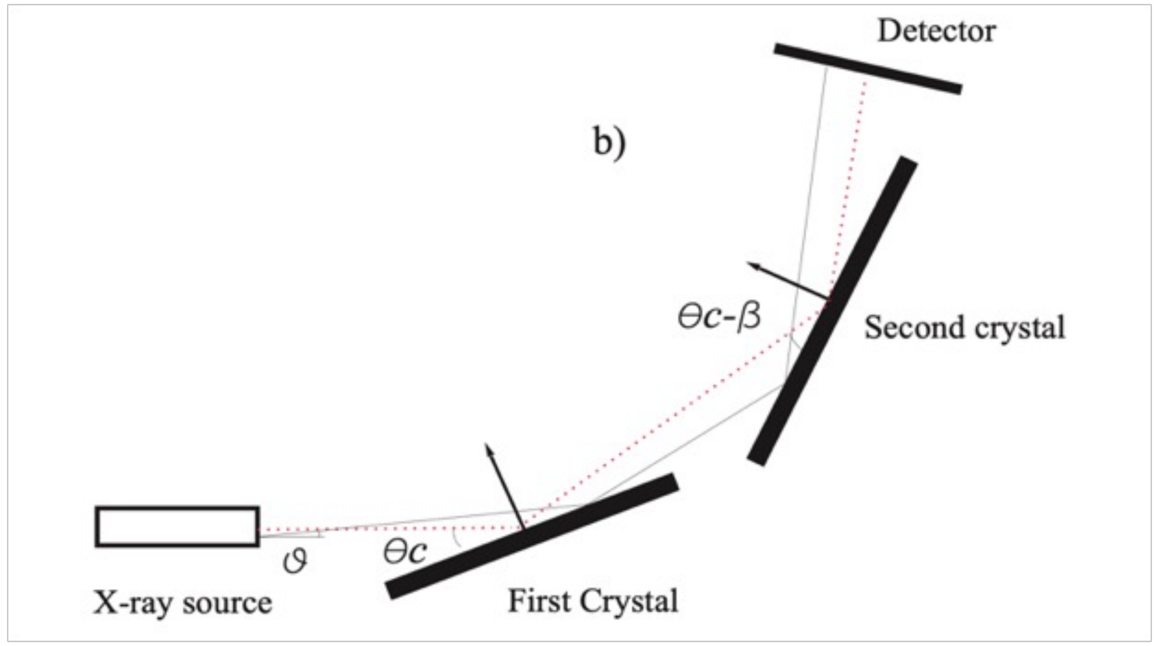
Parallel
Energy
Non-dispersive

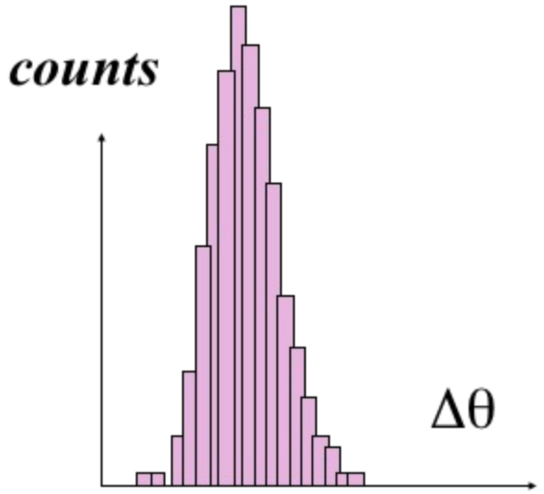




width :
DCS response function

Antiparallel
Energy Dispersive

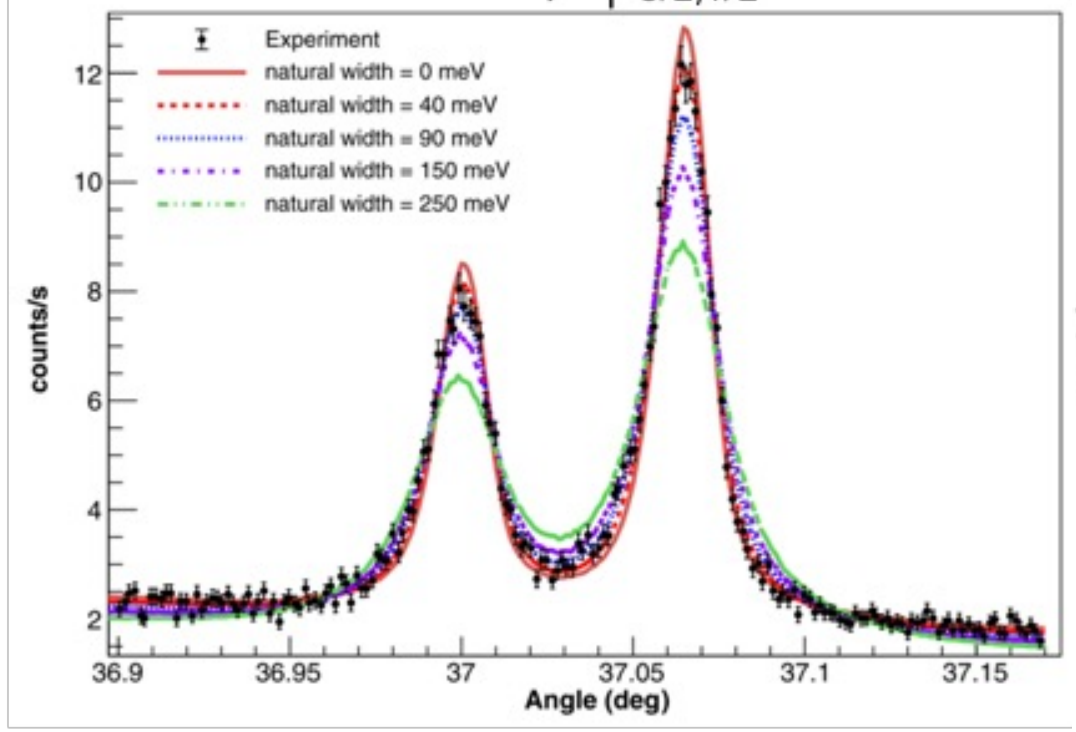




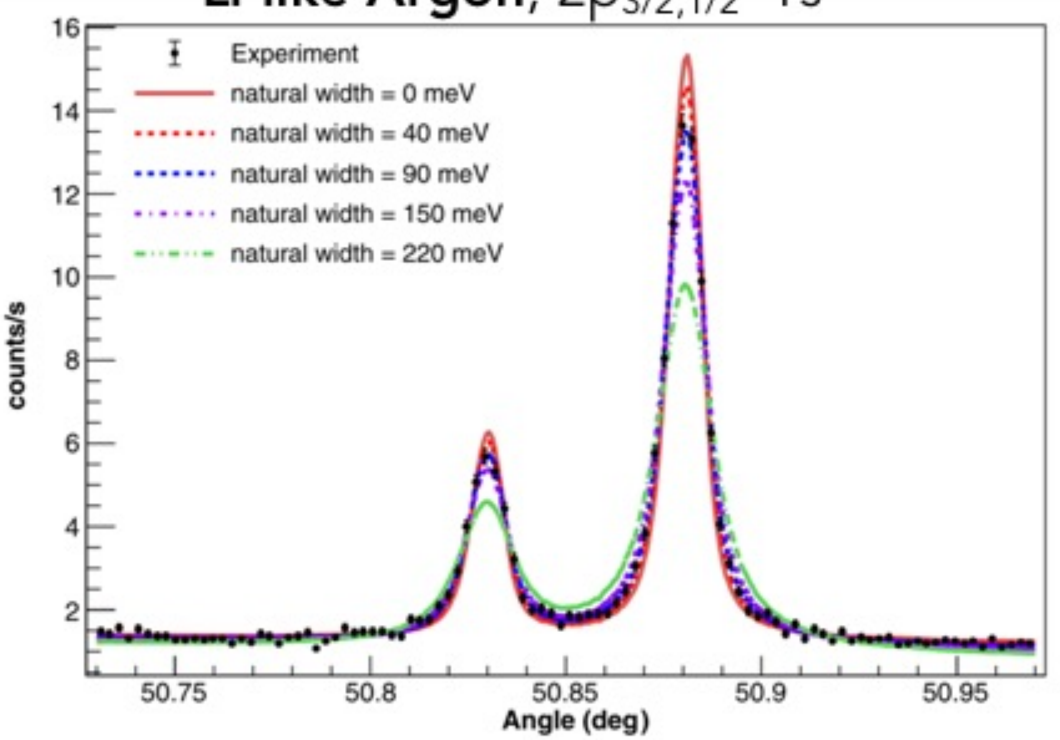
width :
intrinsic line width
Doppler broadening
DCS response function

DCS Recent Results

Li-like Sulfur, $2p_{3/2,1/2}$-1s



Li-like Argon, $2p_{3/2,1/2}$-1s

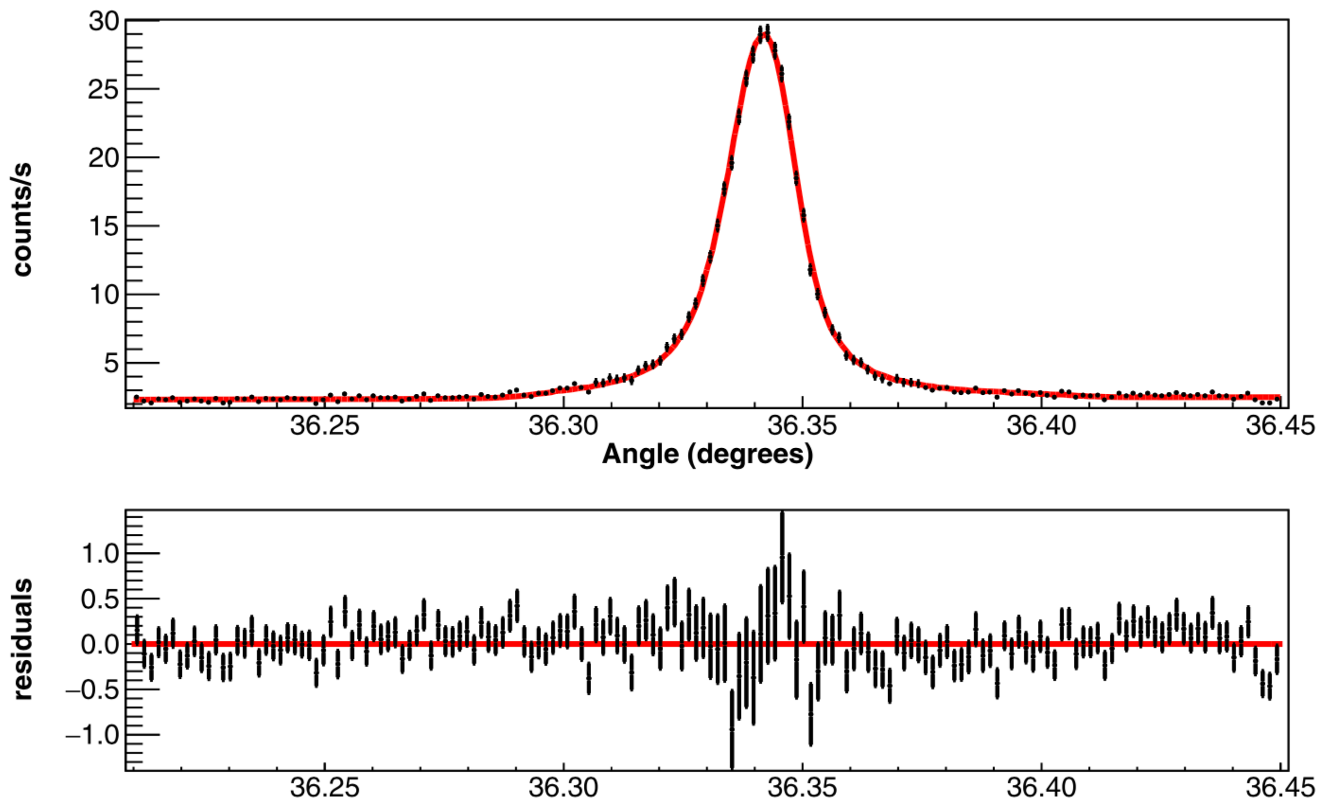


Highest precision, reference-free measurements in core-excited Li-like ions

Sulfur peak ratio : 0.46 [theory], 0.627(22) [exp]
Argon peak ratio : 0.44 [theory], 0.397(14) [exp]
Cannot be explained by known contaminant lines

J. Machado, G. Bian, N. Paul, et al,
PRA 101, 062505 (2020)

He-like Sulfur $1s2s\ {}^3S_1 \rightarrow 1s^2\ {}^1S_0$

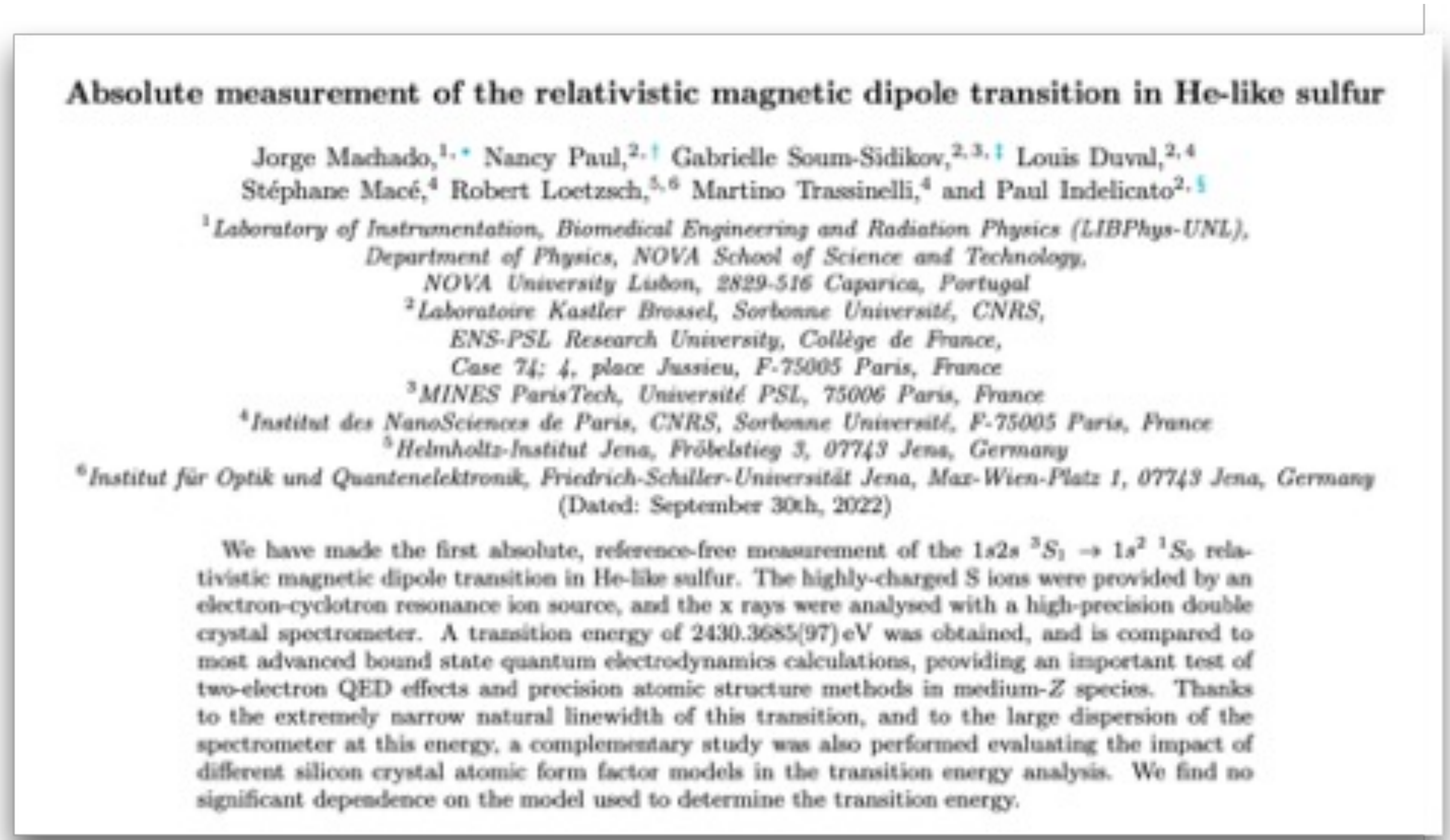


First ppm measurements of the relativistic magnetic dipole transition in He-like S

Test of 2e QED effects, sensitive to crystal form factors

J. Machado, N. Paul, et al,
PRA 107, 032821 (2023)

Impact of He-like S M1 measurement



Absolute measurement of the relativistic magnetic dipole transition in He-like sulfur

Jorge Machado,[1,*] Nancy Paul,[2,†] Gabrielle Soum-Sidikov,[2,3,‡] Louis Duval,[2,4]
Stéphane Macé,[4] Robert Loetzsch,[5,6] Martino Trassinelli,[4] and Paul Indelicato[2,§]

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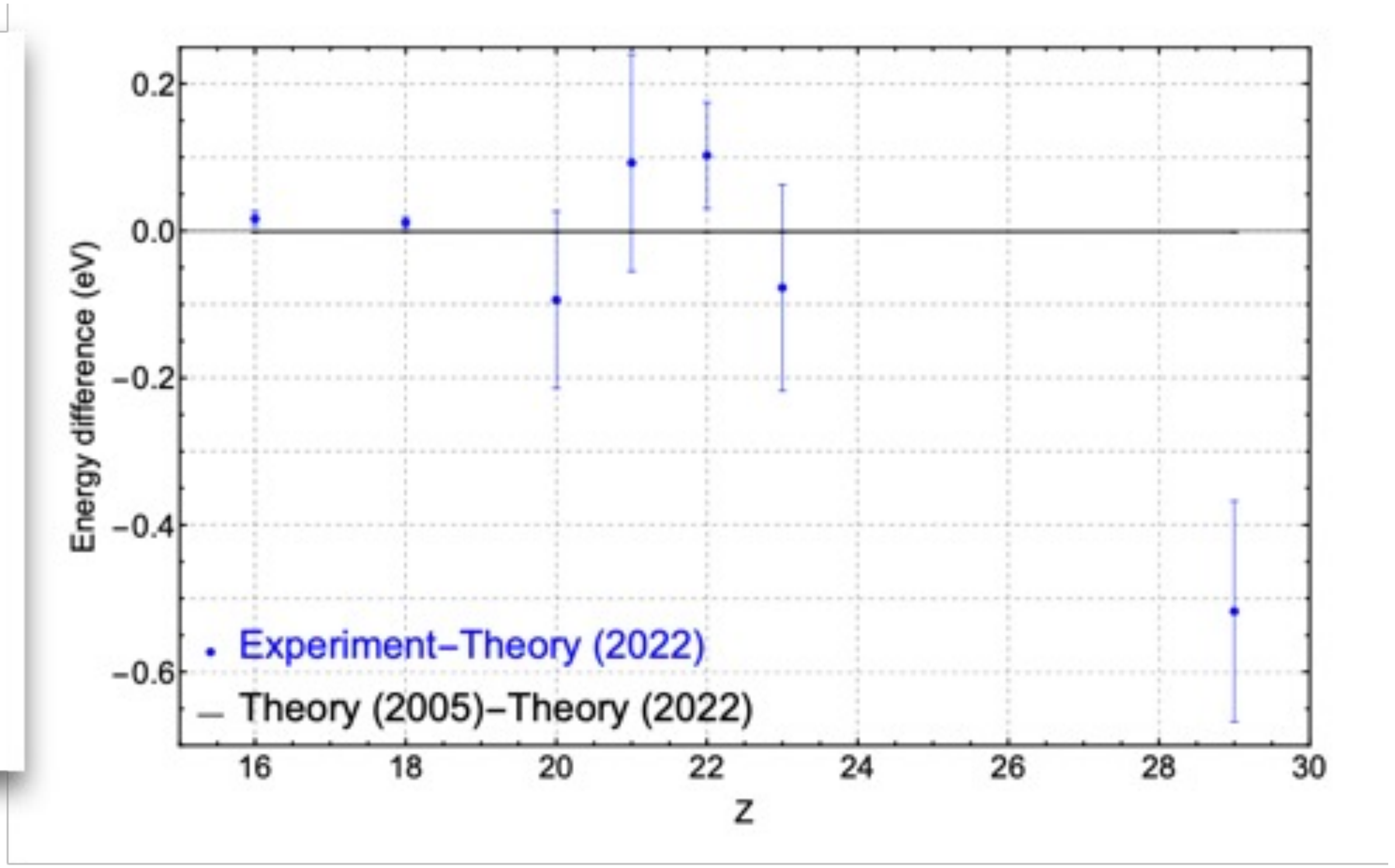
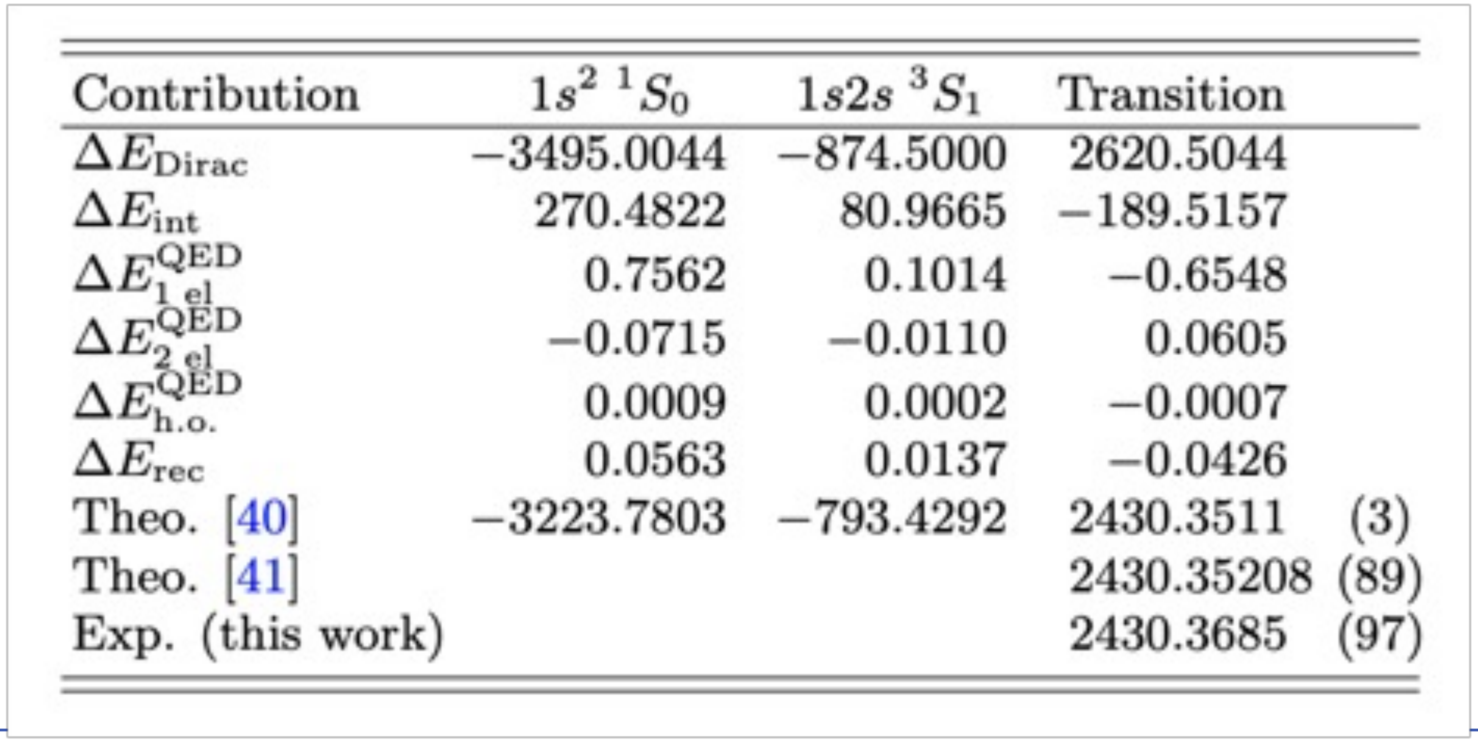
NOVA University Lisbon, 2829-516 Caparica, Portugal
[2]Laboratoire Kastler Brossel, Sorbonne Université, CNRS,
ENS-PSL Research University, Collège de France,
Case 74; 4, place Jussieu, F-75005 Paris, France
[3]MINES ParisTech, Université PSL, 75006 Paris, France
[4]Institut des NanoSciences de Paris, CNRS, Sorbonne Université, F-75005 Paris, France
[5]Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany
[6]Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany
(Dated: September 30th, 2022)

We have made the first absolute, reference-free measurement of the $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ relativistic magnetic dipole transition in He-like sulfur. The highly-charged S ions were provided by an electron-cyclotron resonance ion source, and the x rays were analysed with a high-precision double crystal spectrometer. A transition energy of 2430.3685(97) eV was obtained, and is compared to most advanced bound state quantum electrodynamics calculations, providing an important test of two-electron QED effects and precision atomic structure methods in medium-Z species. Thanks to the extremely narrow natural linewidth of this transition, and to the large dispersion of the spectrometer at this energy, a complementary study was also performed evaluating the impact of different silicon crystal atomic form factor models in the transition energy analysis. We find no significant dependence on the model used to determine the transition energy.



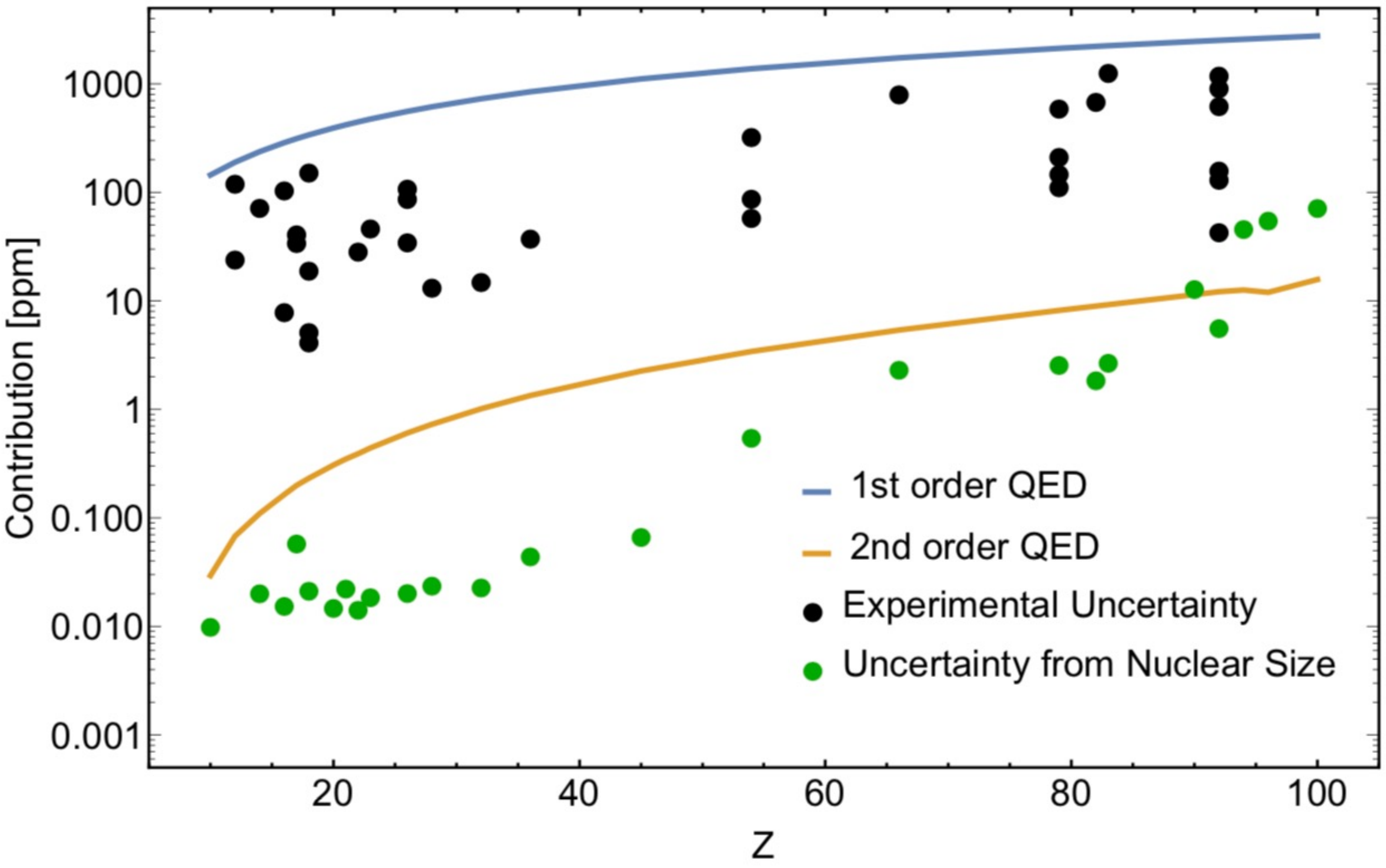
- Now 2 data points with ppm accuracies in this Z region, important for analyses of He-like QED agreement (Chantler 2012, 2014)
- Complementary to studies of He-like U at GSI (experiment E125)



Contribution	$1s^2\ ^1S_0$	$1s2s\ ^3S_1$	Transition
ΔE_{Dirac}	−3495.0044	−874.5000	2620.5044
ΔE_{int}	270.4822	80.9665	−189.5157
$\Delta E^{\text{QED}}_{\text{1 el}}$	0.7562	0.1014	−0.6548
$\Delta E^{\text{QED}}_{\text{2 el}}$	−0.0715	−0.0110	0.0605
$\Delta E^{\text{QED}}_{\text{h.o.}}$	0.0009	0.0002	−0.0007
ΔE_{rec}	0.0563	0.0137	−0.0426
Theo. [40]	−3223.7803	−793.4292	2430.3511 (3)
Theo. [41]			2430.35208 (89)
Exp. (this work)			2430.3685 (97)

Limitations with HCI : Nuclear physics!

Lyman-α transitions in hydrogen-like ions



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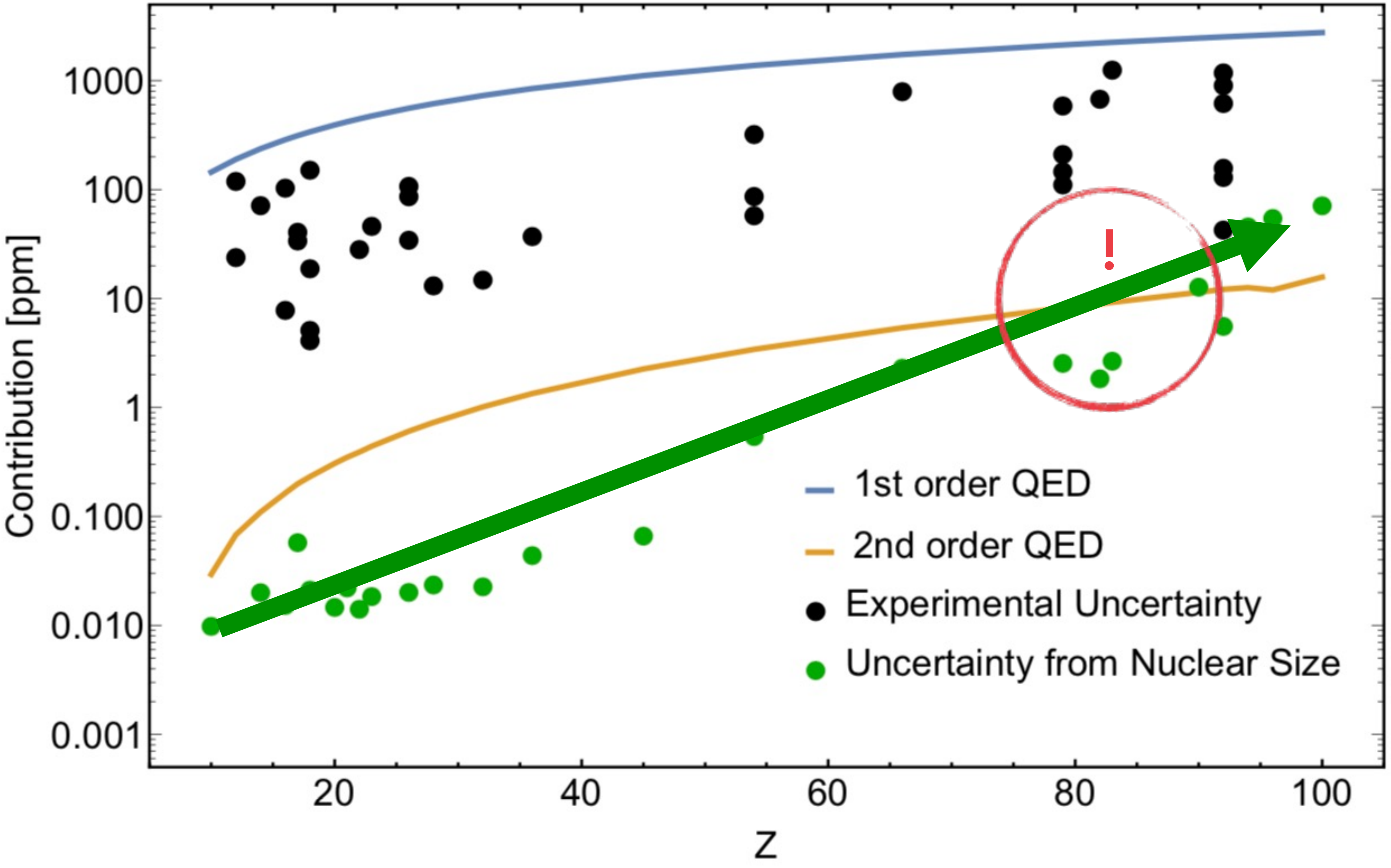
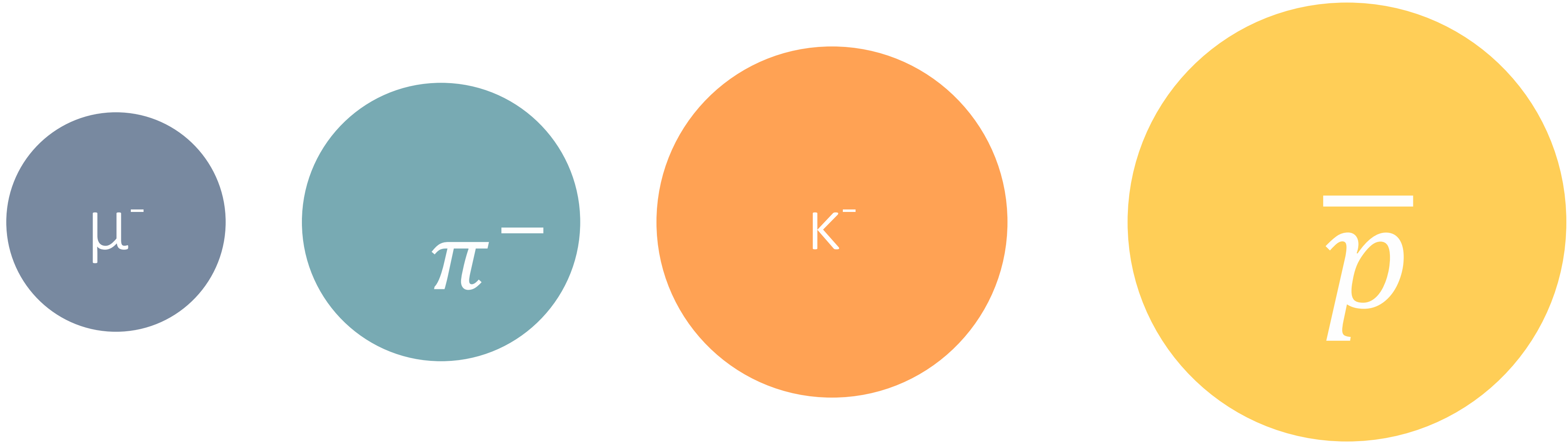


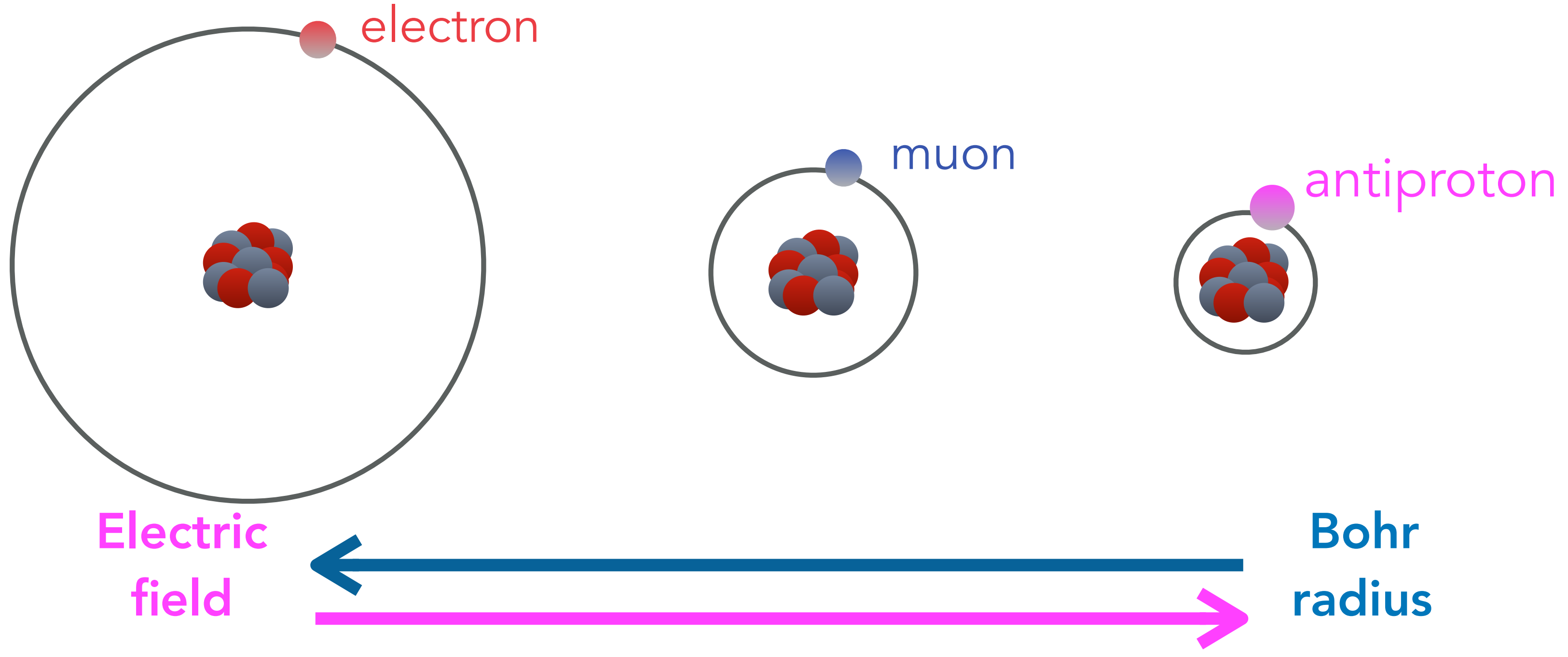
Strong-field QED with exotic atoms

Exotic atoms



Strong-field QED with exotic atoms

Strongest field QED → Highest sensitivity

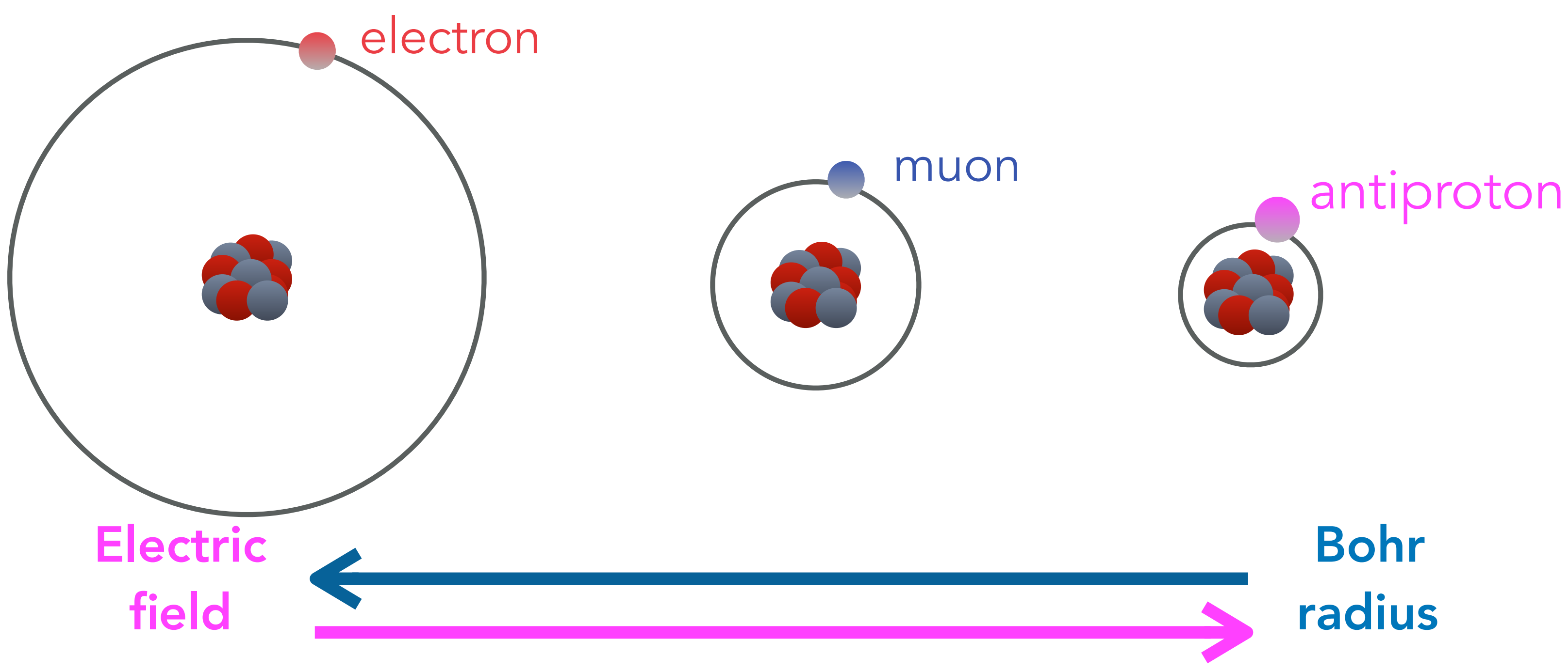


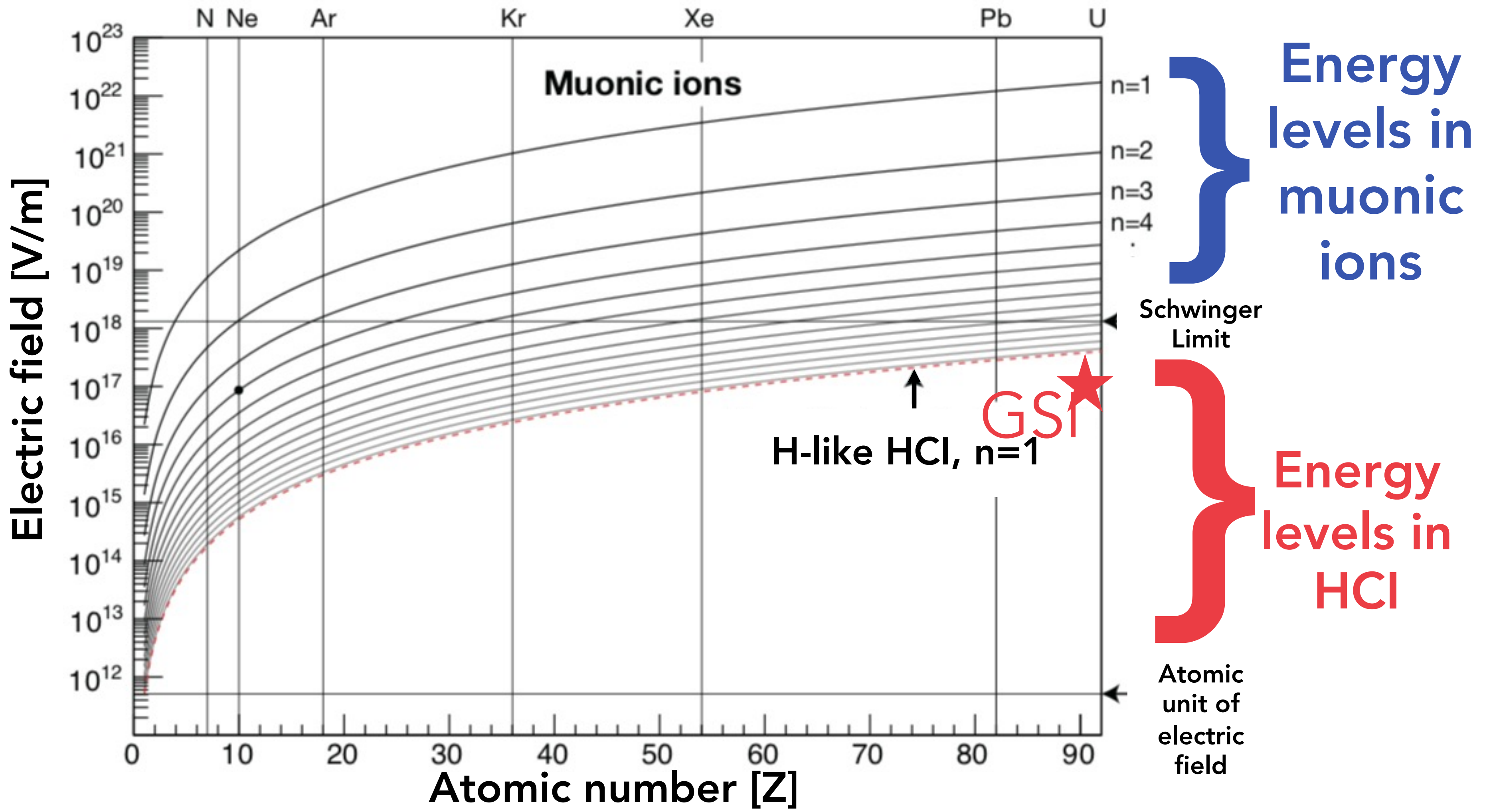
$$m_\mu \sim 200\, m_{e^-}$$

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

Strong-field QED with exotic atoms

Strongest field QED → Highest sensitivity





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

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

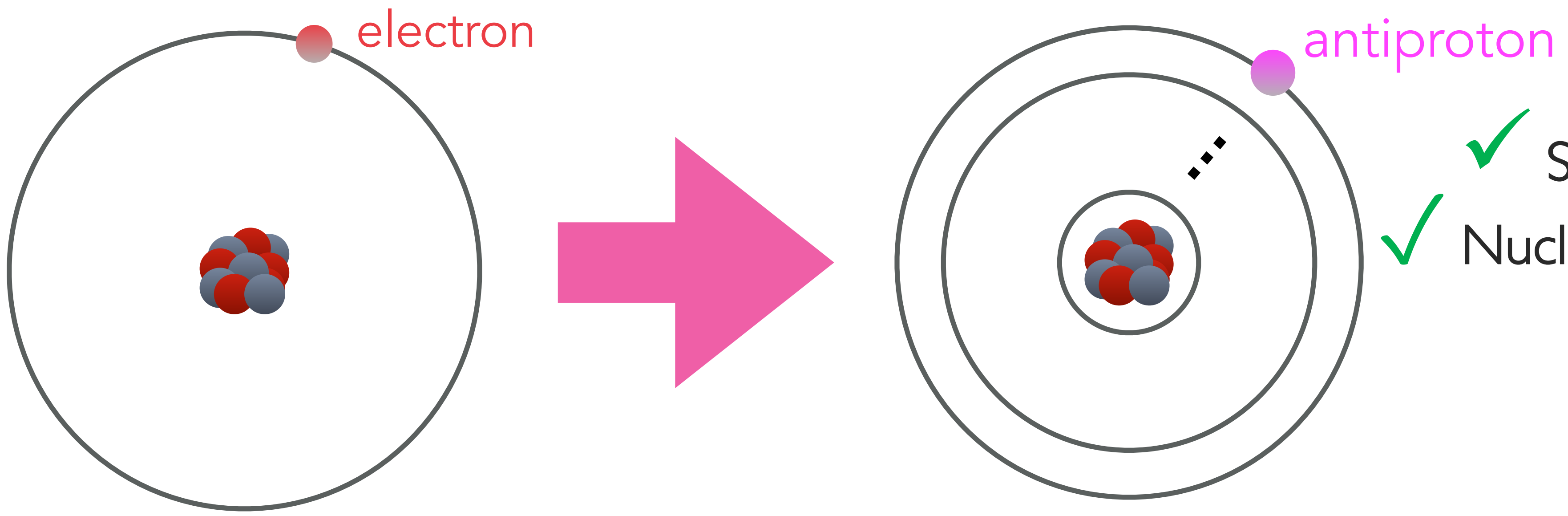
- Heavy exotic particle →small Bohr radius →strong electric field strength
- Higher order QED effects magnified and become measurable with new techniques

PAX theory 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

✓ Strong field QED

X Nuclear effects ≥ QED effects



✓ STRONGEST field QED

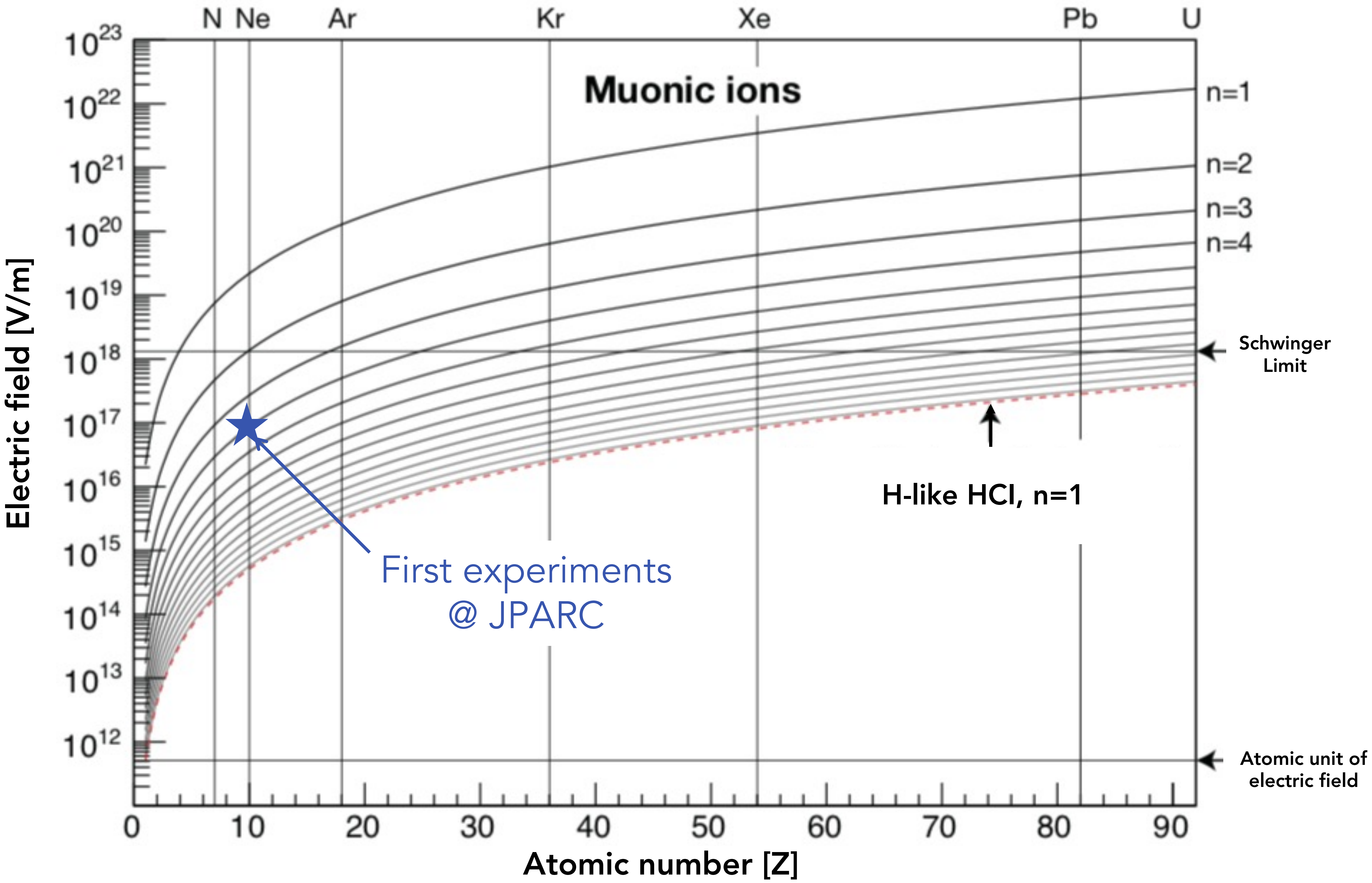
✓ Nuclear effects << QED effects

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	$n=12 \rightarrow n=11$	~100 keV	$7x10^{-3}$	$6x10^{-5}$	$1x10^{-5}$

QED x 3-6

Nuclear effects / 100

Strong-field QED with muonic atoms



First experiments @ JPARC

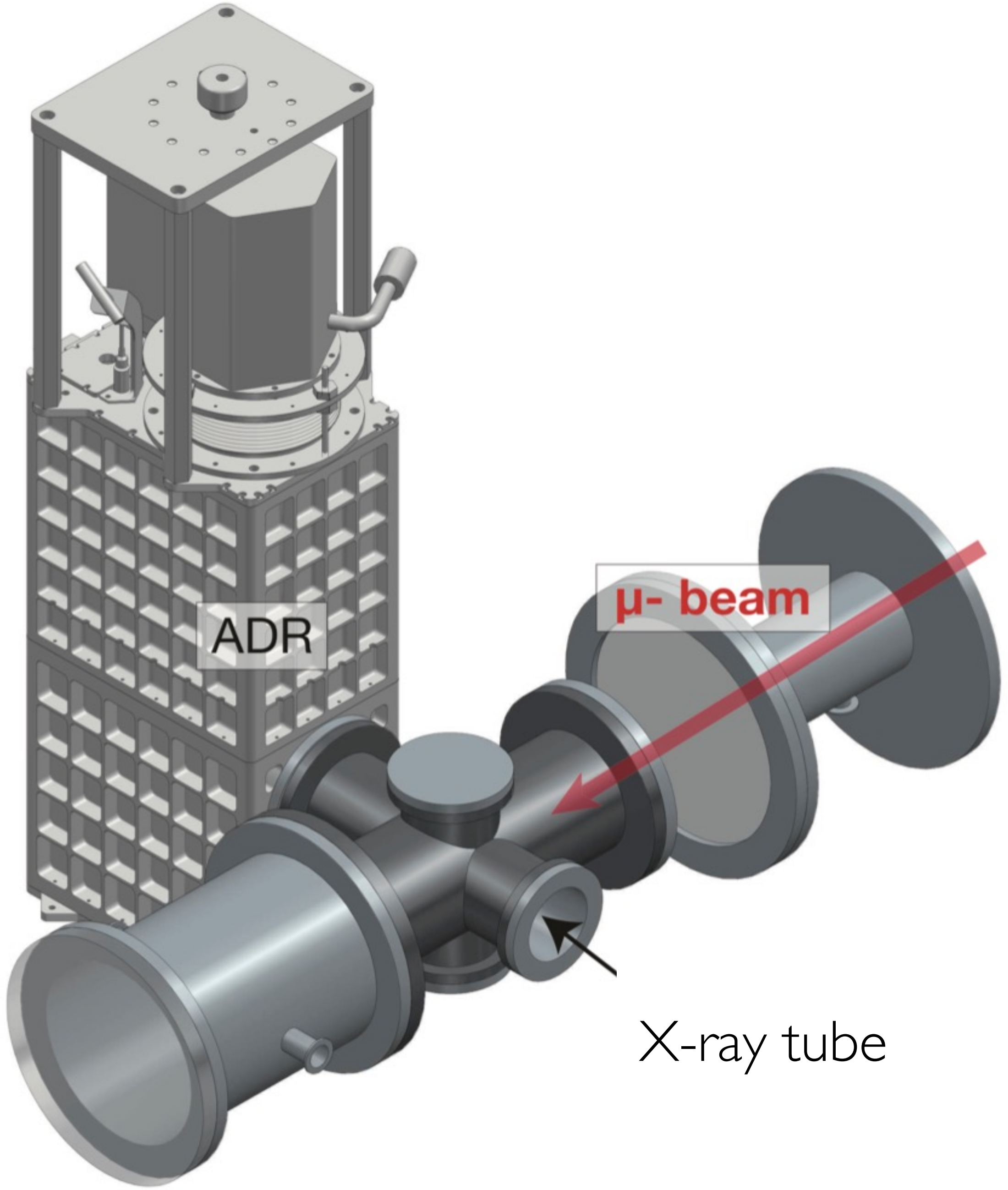
H-like HCI, n=1

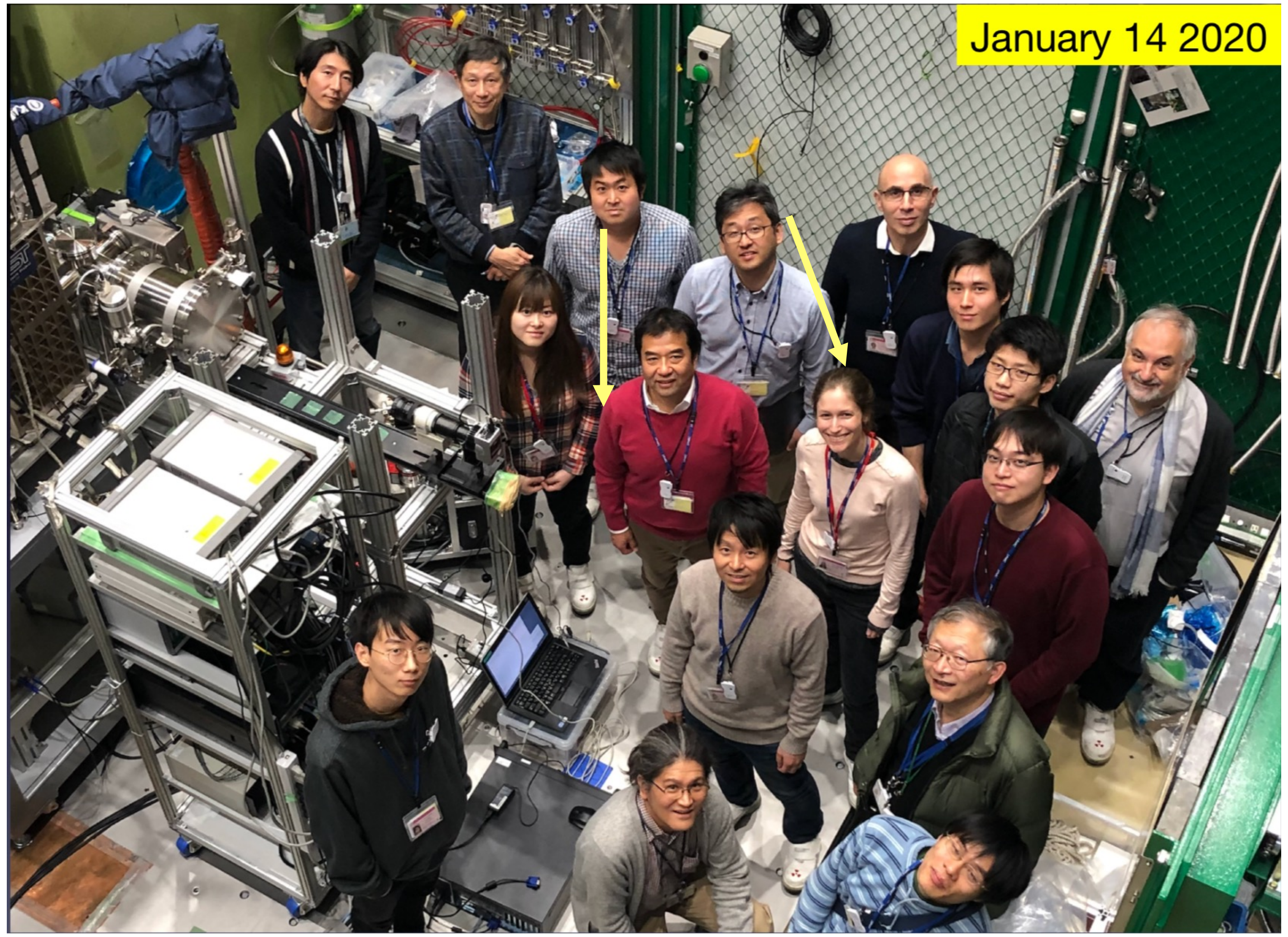
Schwinger Limit

Atomic unit of electric field

First experiments with muonic atoms at J-PARC

- **5-year accepted scientific program** at J-PARC muon facility in Japan (2020-2025)
- QED tests=precision x-ray spectroscopy of Rydberg states in muonic atoms



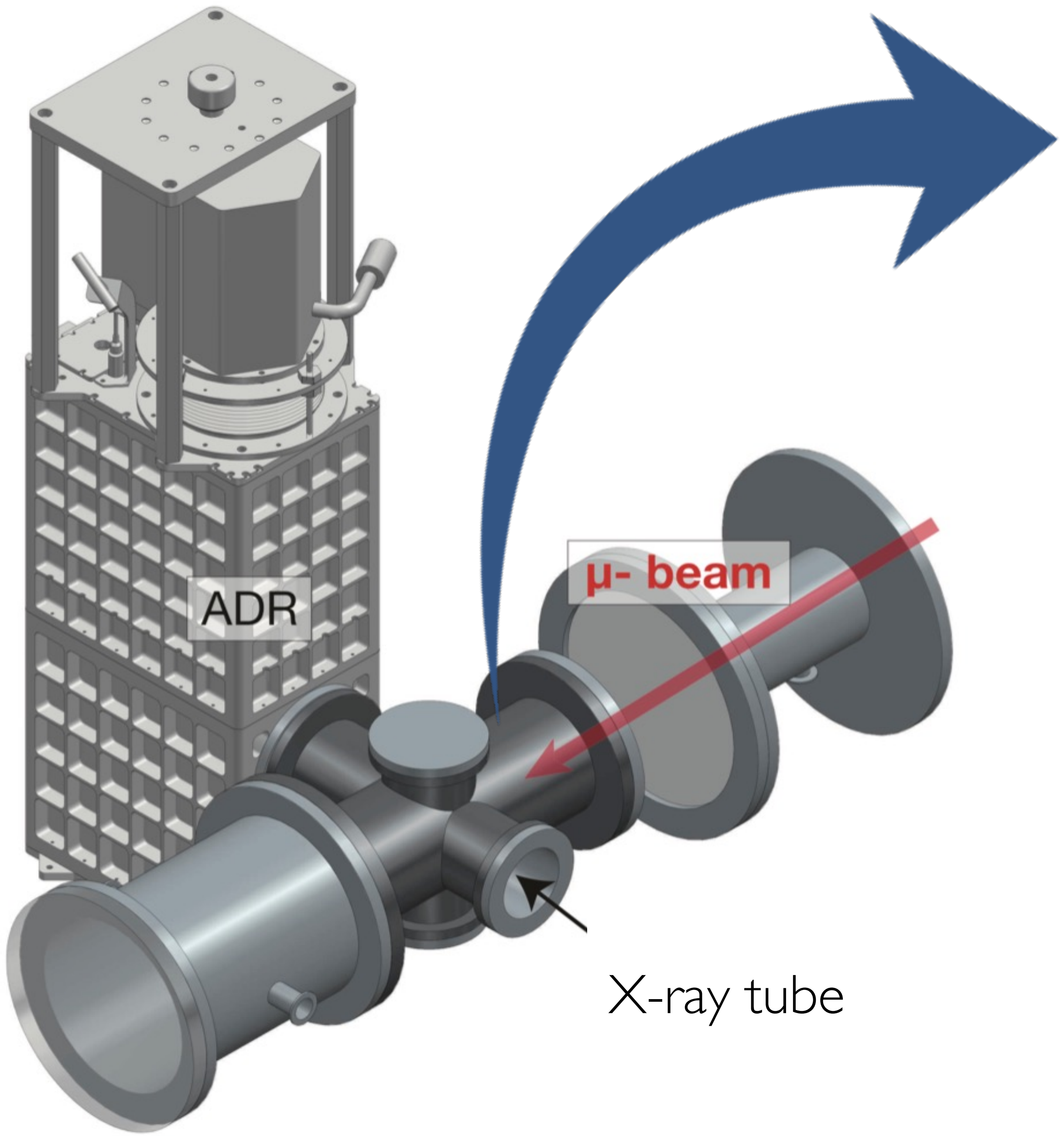


HEATES Collaboration: RIKEN, JAEA, JAXA, KEK, Osaka University, Rikkyo University, Tohoku University, Tokyo Metrolopolitan University, NIST, CNRS

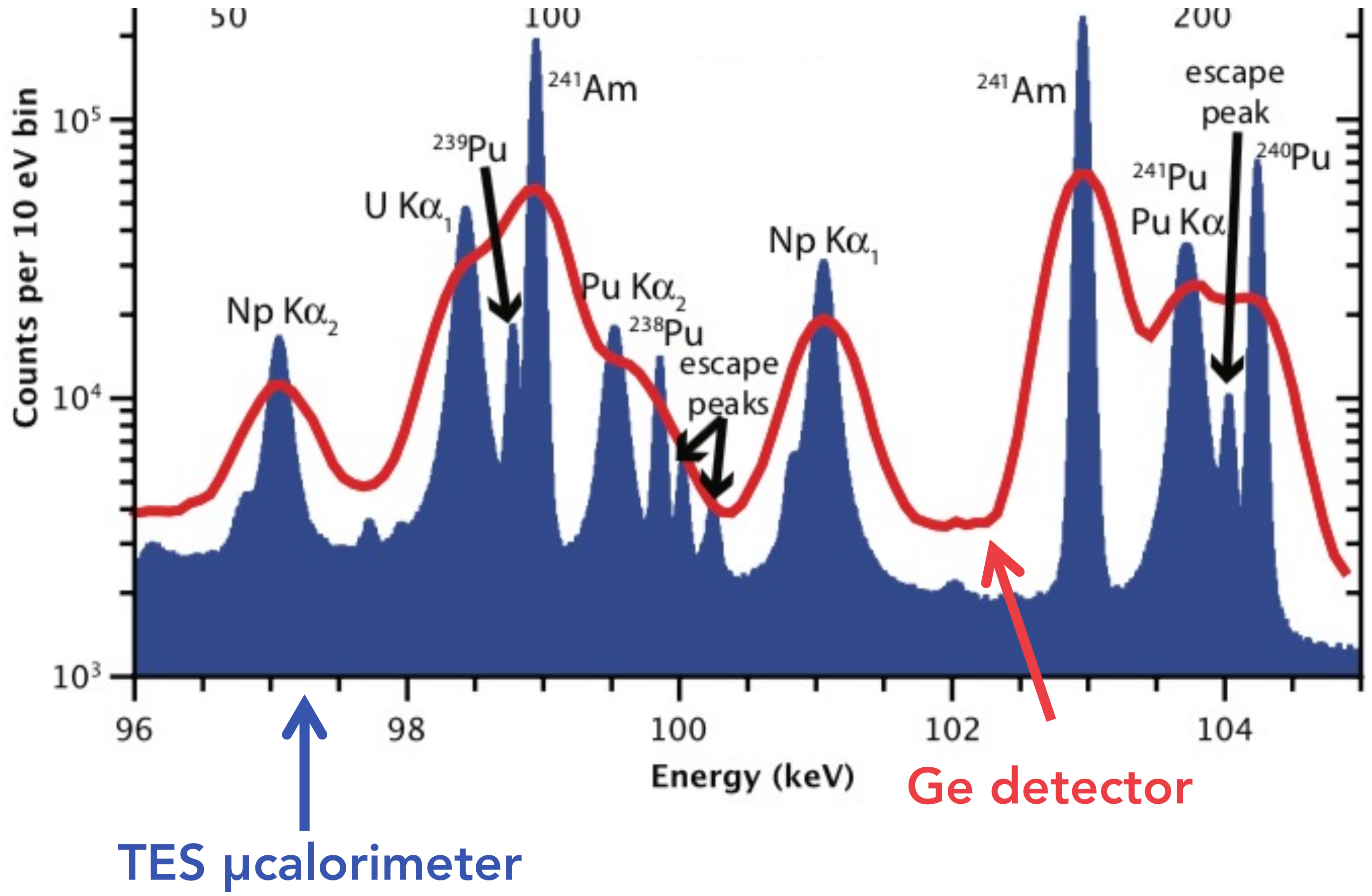
First experiments with muonic atoms at J-PARC

Key technology

- High energy resolution (ΔE/E ~10^{-4})
- High efficiency (~10^{-4})

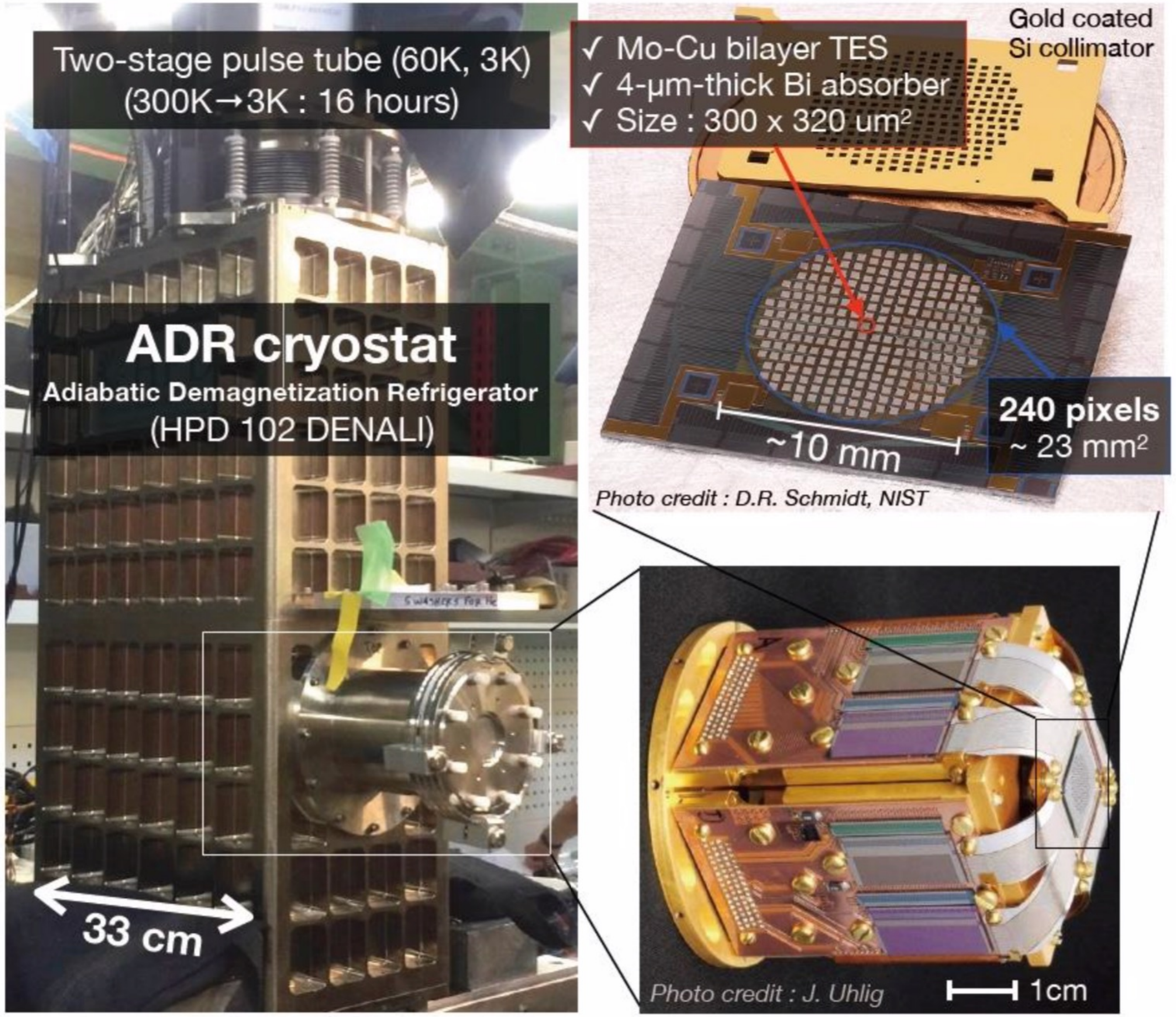


Transition Edge Sensing (**TES**) µcalorimeter (NIST)



Rev. Sci. Instrum. 83, 093113 (2012)

Key technology : Transition Edge Sensing microcalorimeter



Two-stage pulse tube (60K, 3K)
(300K→3K : 16 hours)

ADR cryostat
Adiabatic Demagnetization Refrigerator
(HPD 102 DENALI)

✓ Mo-Cu bilayer TES
✓ 4-μm-thick Bi absorber
✓ Size : 300 x 320 um^2

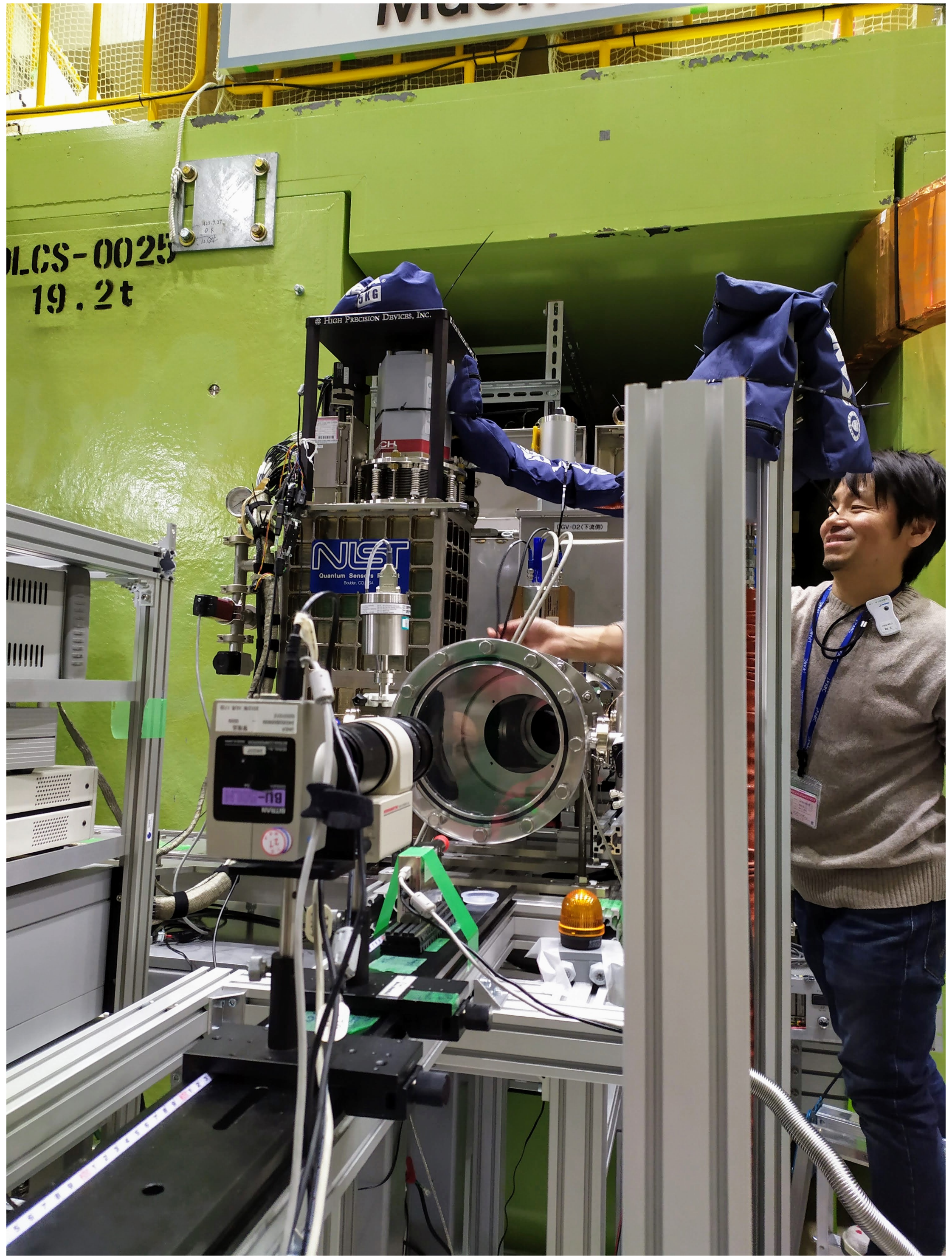
Gold coated Si collimator

240 pixels
~ 23 mm^2

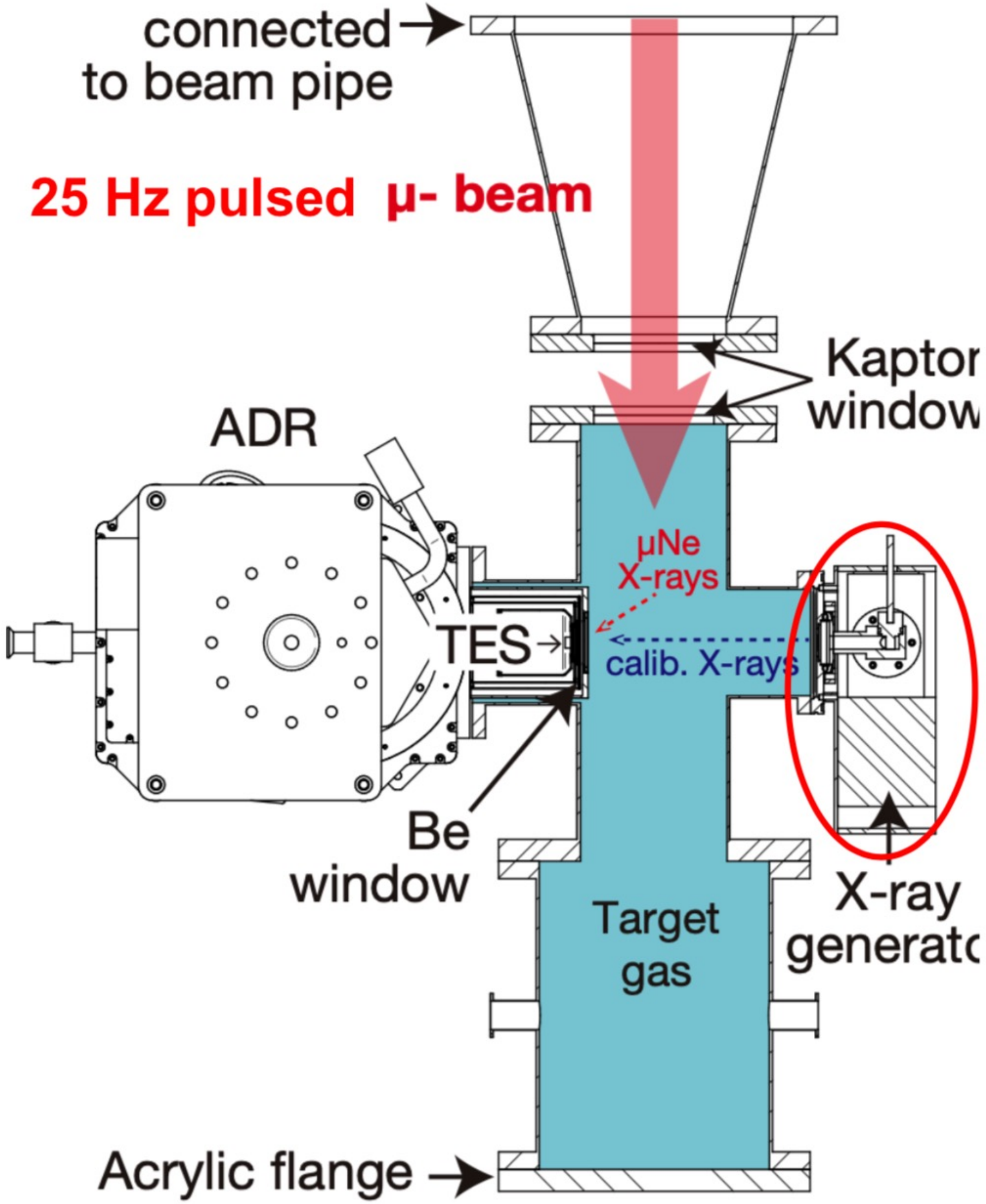
Photo credit : D.R. Schmidt, NIST

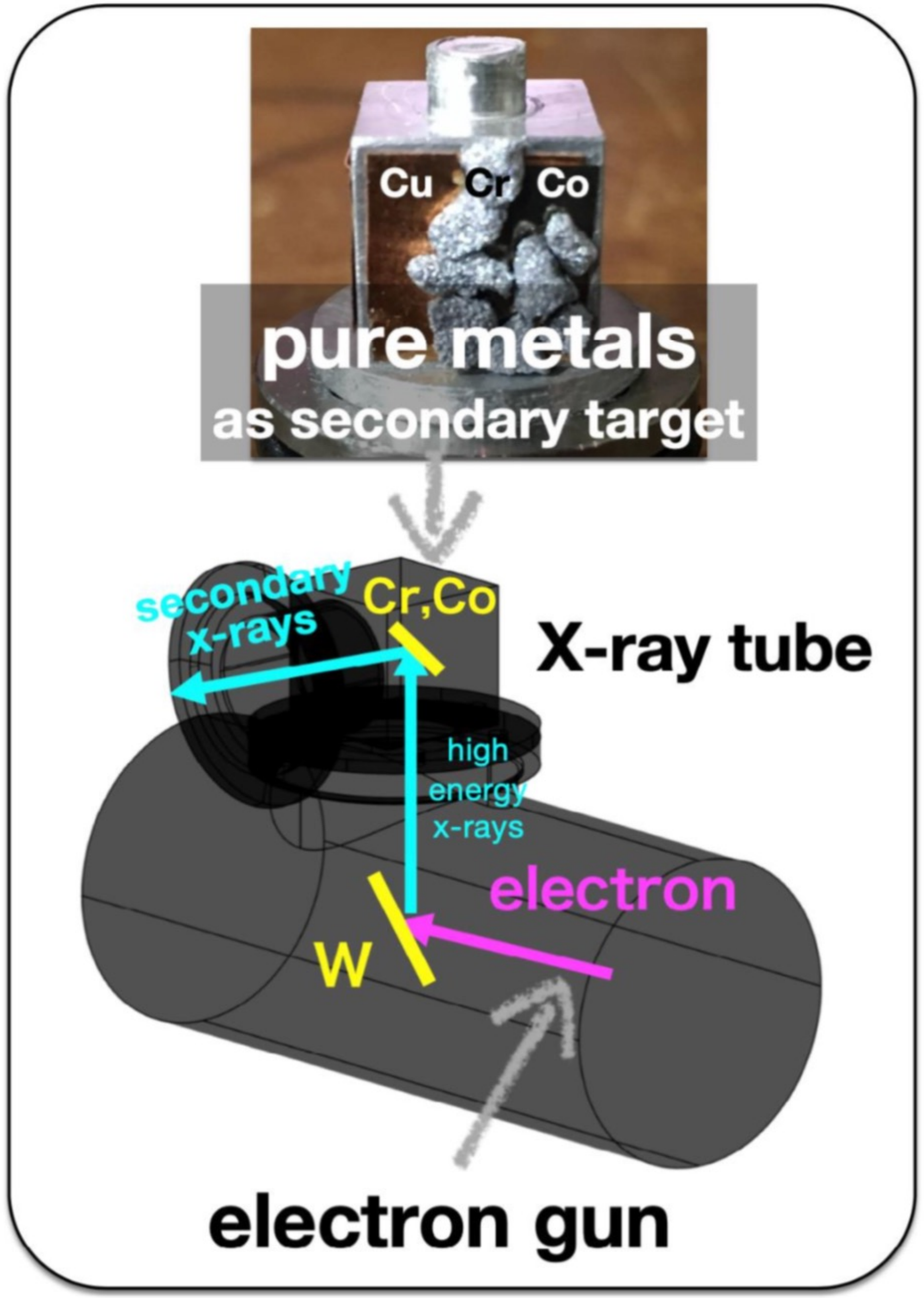
Photo credit : J. Uhlig

HEATES TES @ J-PARC D2



Experimental setup—details

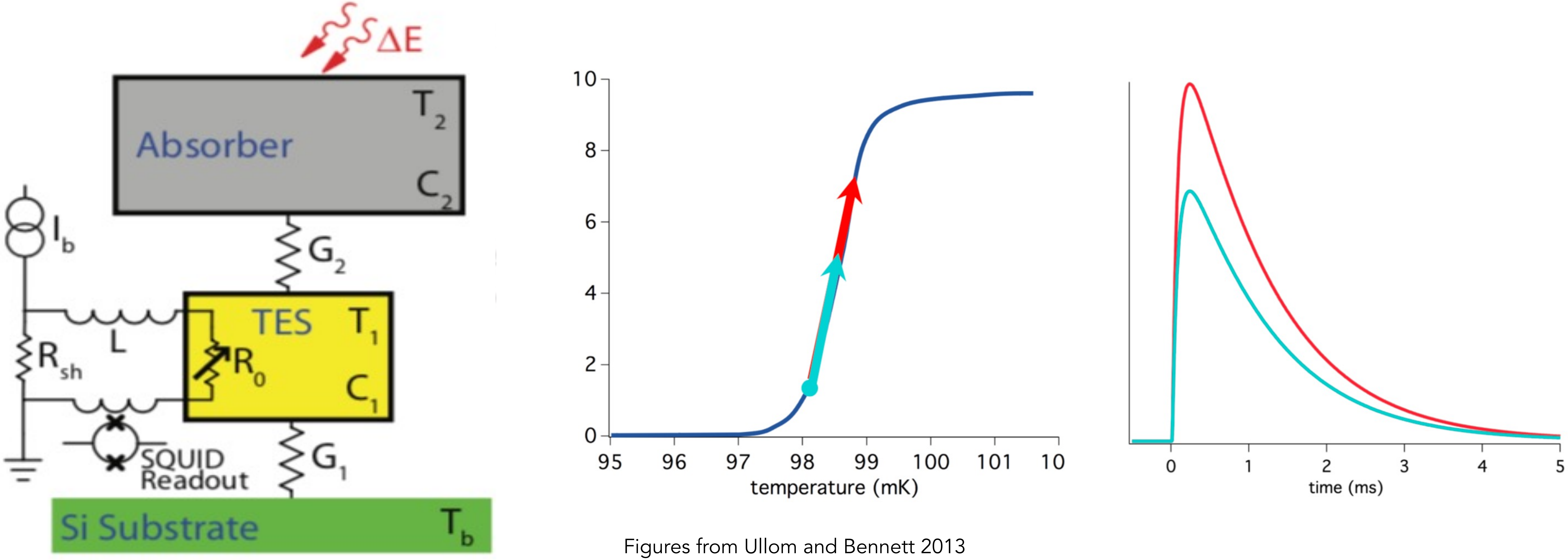




Key technology—TES x-ray detector

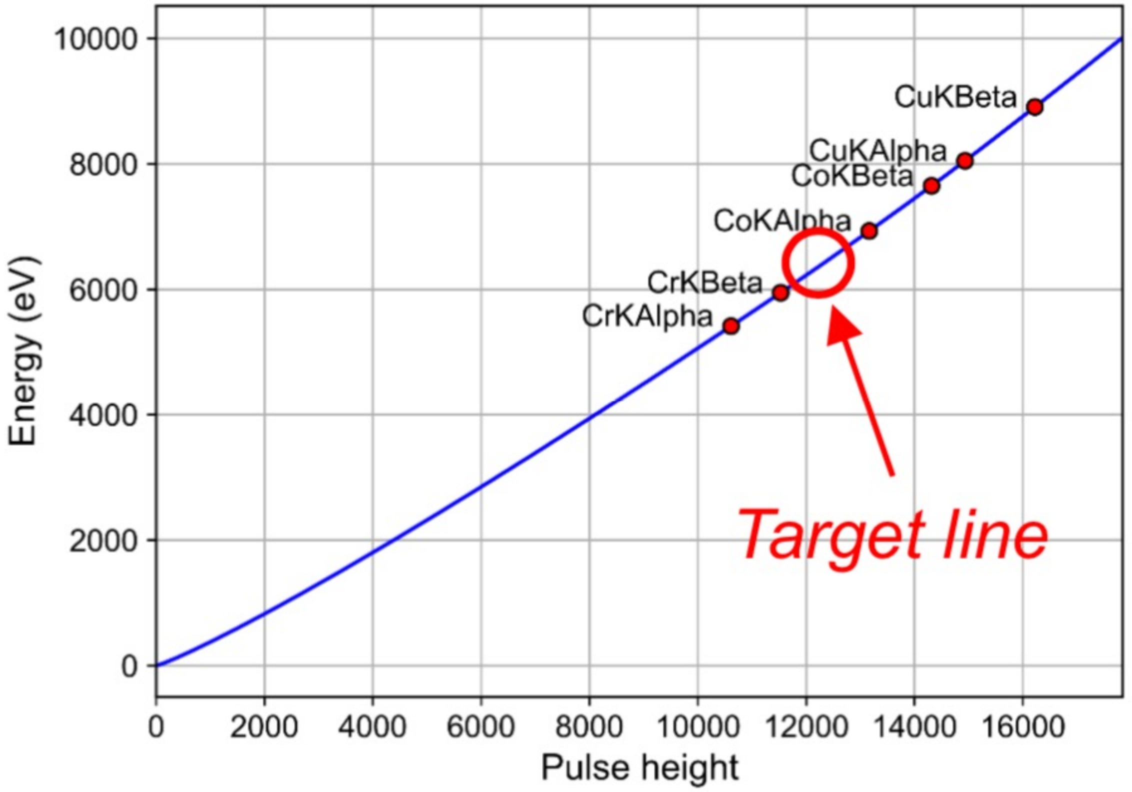
Transition Edge Sensing (TES) μcalorimeter (NIST, Boulder, CO, USA)

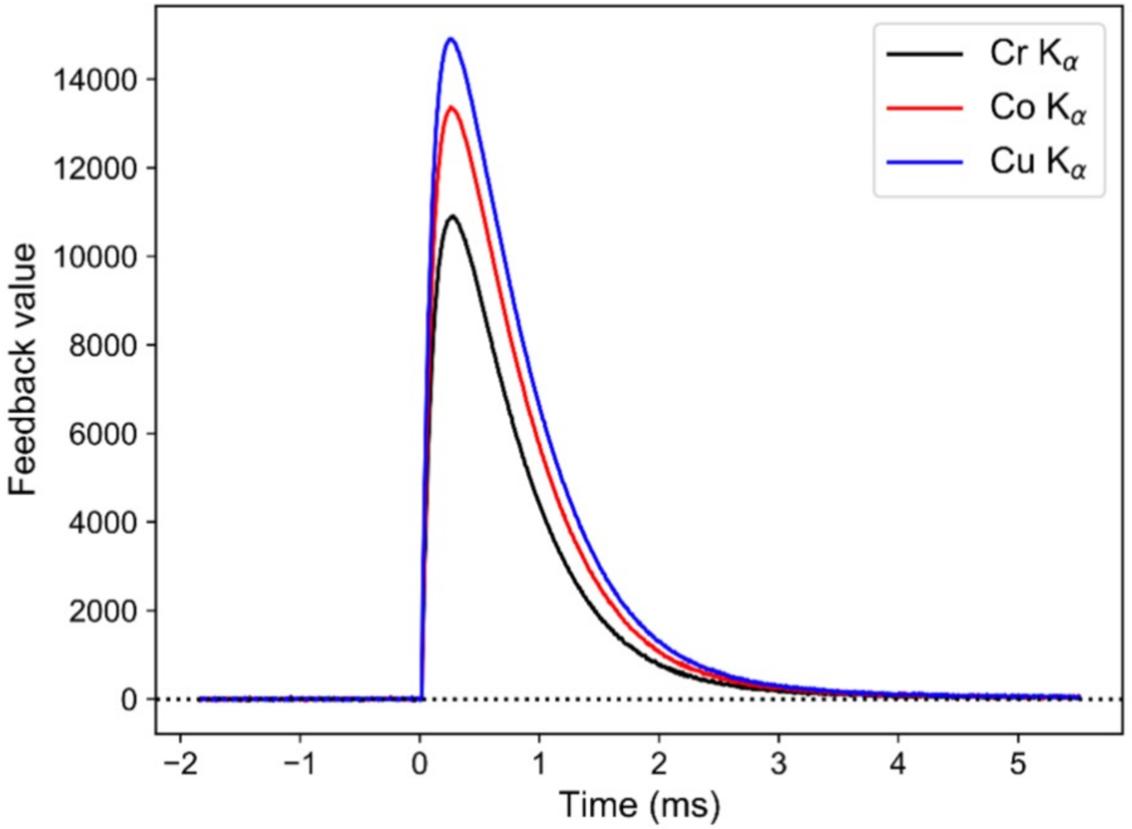
Quantum Sensing Division

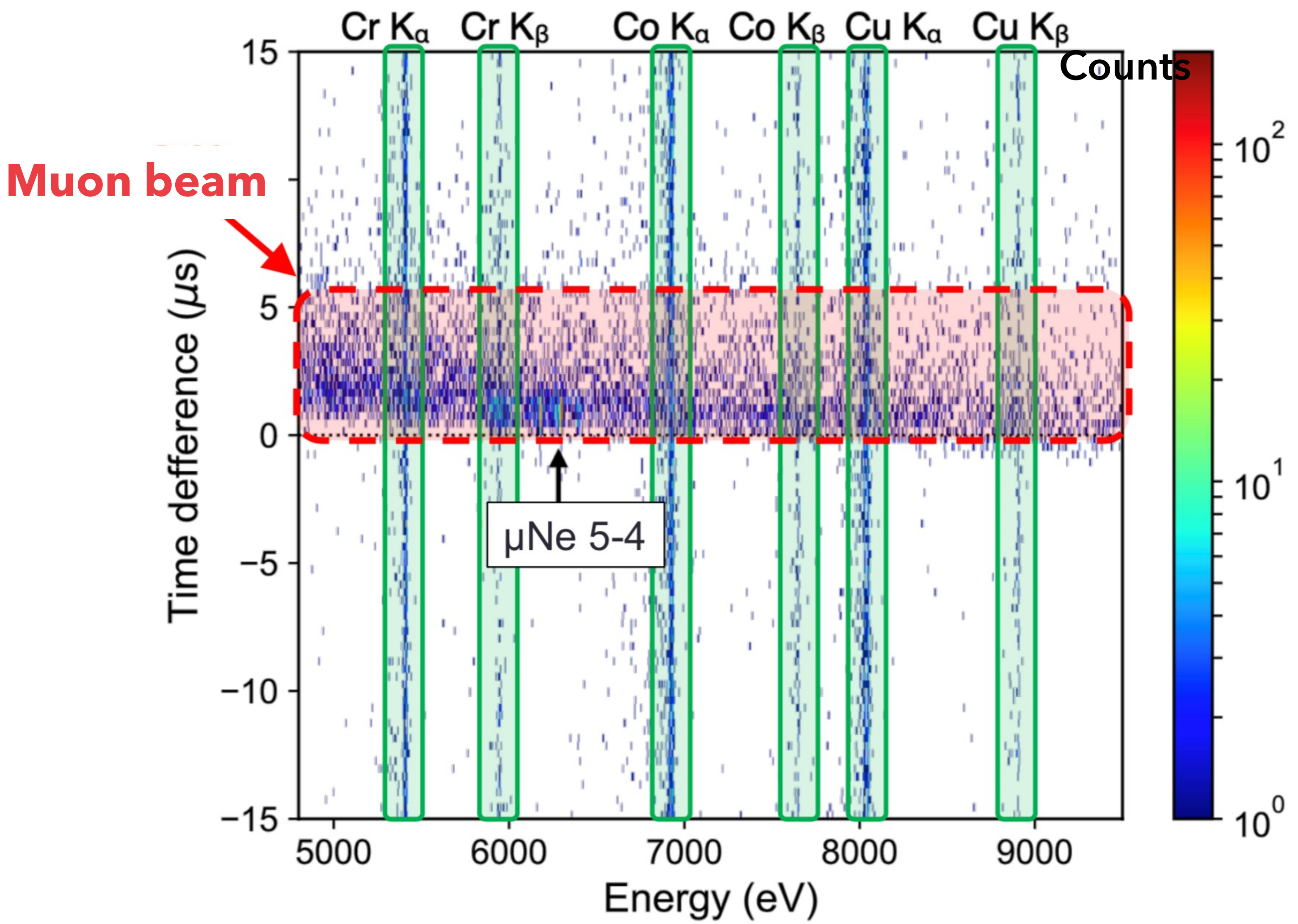


Figures from Ullom and Bennett 2013

TES calibration

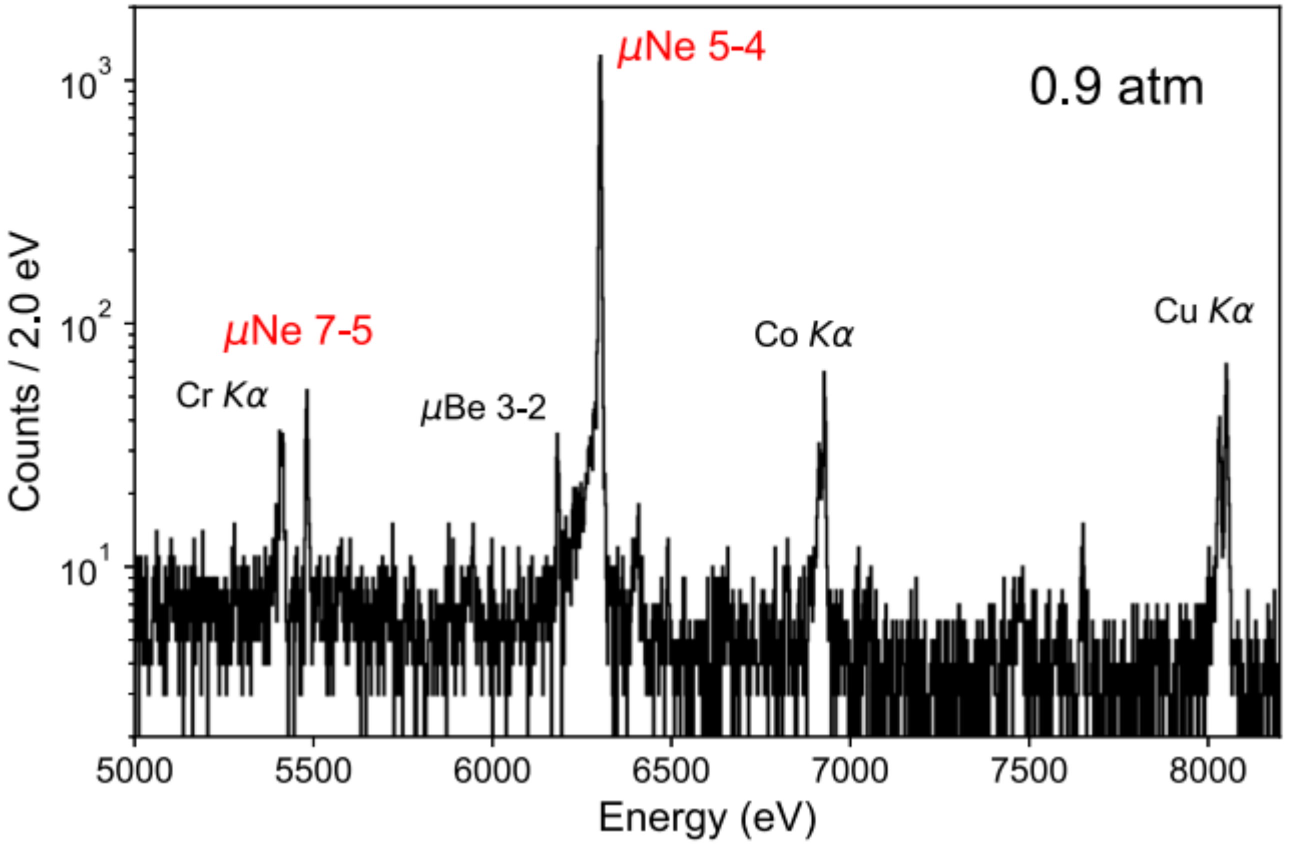


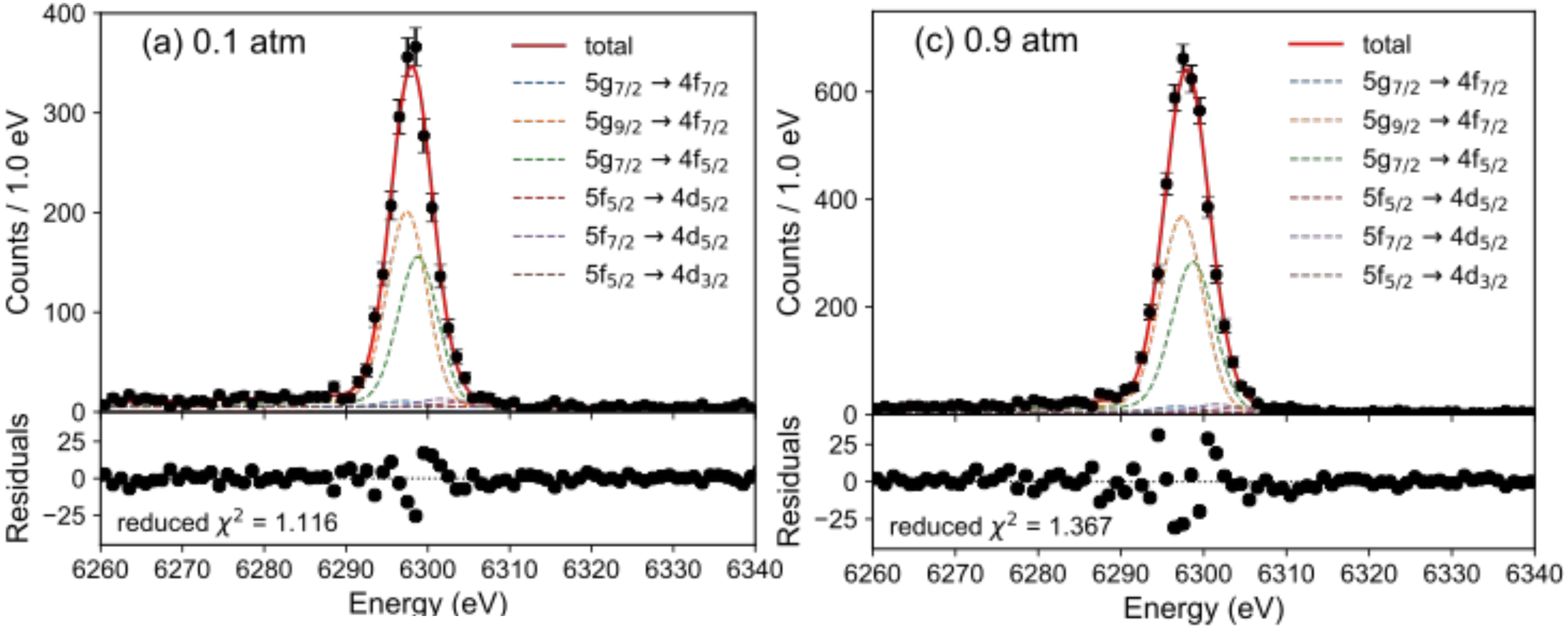


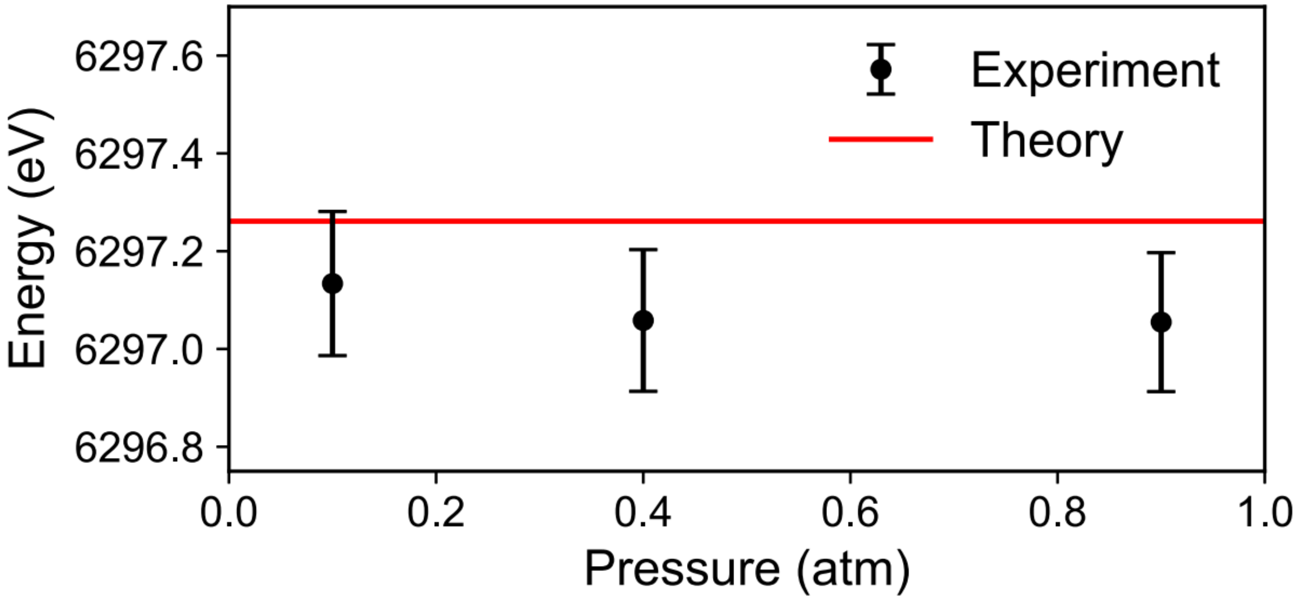


- Pixel-by-pixel energy calibration
- Continuous calibration lines from x-ray gun

Experimental μNe spectrum Okumura et al, PRL 130 (2023)







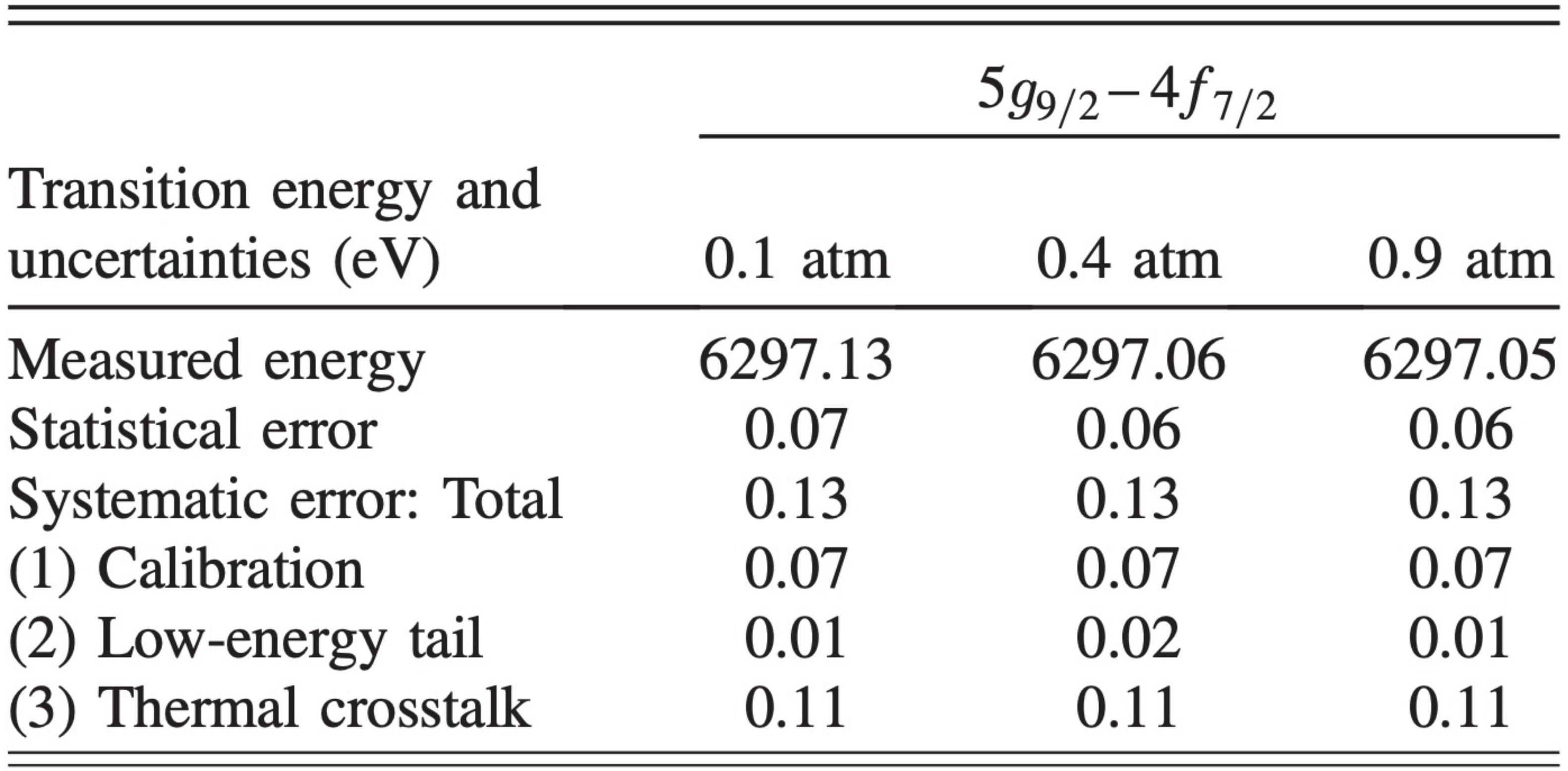
Transition energy and uncertainties (eV)	$5g_{9/2}-4f_{7/2}$		
	0.1 atm	0.4 atm	0.9 atm
Measured energy	6297.13	6297.06	6297.05
Statistical error	0.07	0.06	0.06
Systematic error: Total	0.13	0.13	0.13
(1) Calibration	0.07	0.07	0.07
(2) Low-energy tail	0.01	0.02	0.01
(3) Thermal crosstalk	0.11	0.11	0.11

shift due to presence of 1 electron: ~1.5 eV

Theory and Sensitivity

Okumura et al, PRL 130 (2023)

Theoretical Contributions (5g9/2→4f7/2)	eV
Vac. Pol. (1st order)	-2.34061
Self-energy (1st order)	0.0015
Vac. Po. (2nd order)	-0.0212
Finite nuclear size	-0.00031



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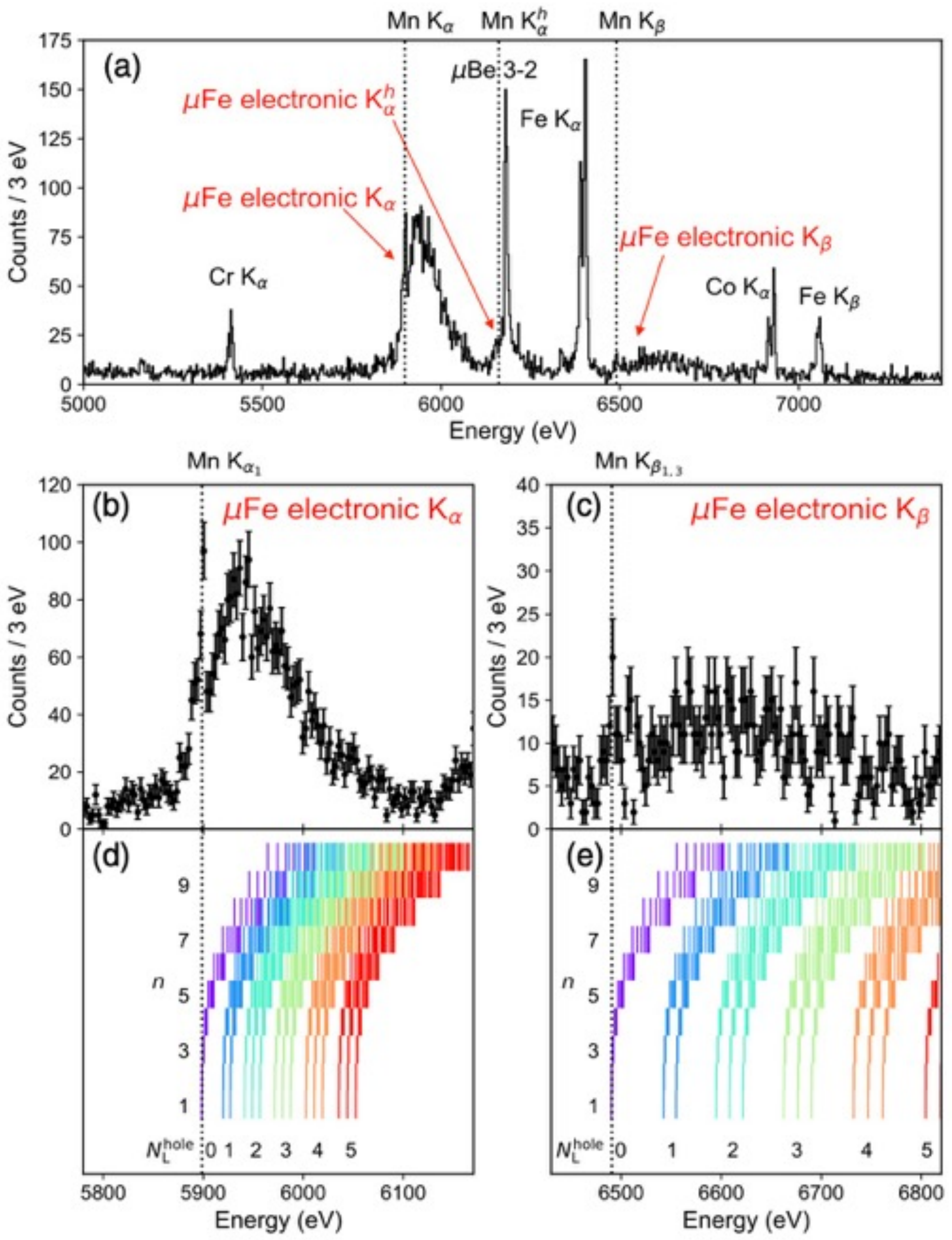
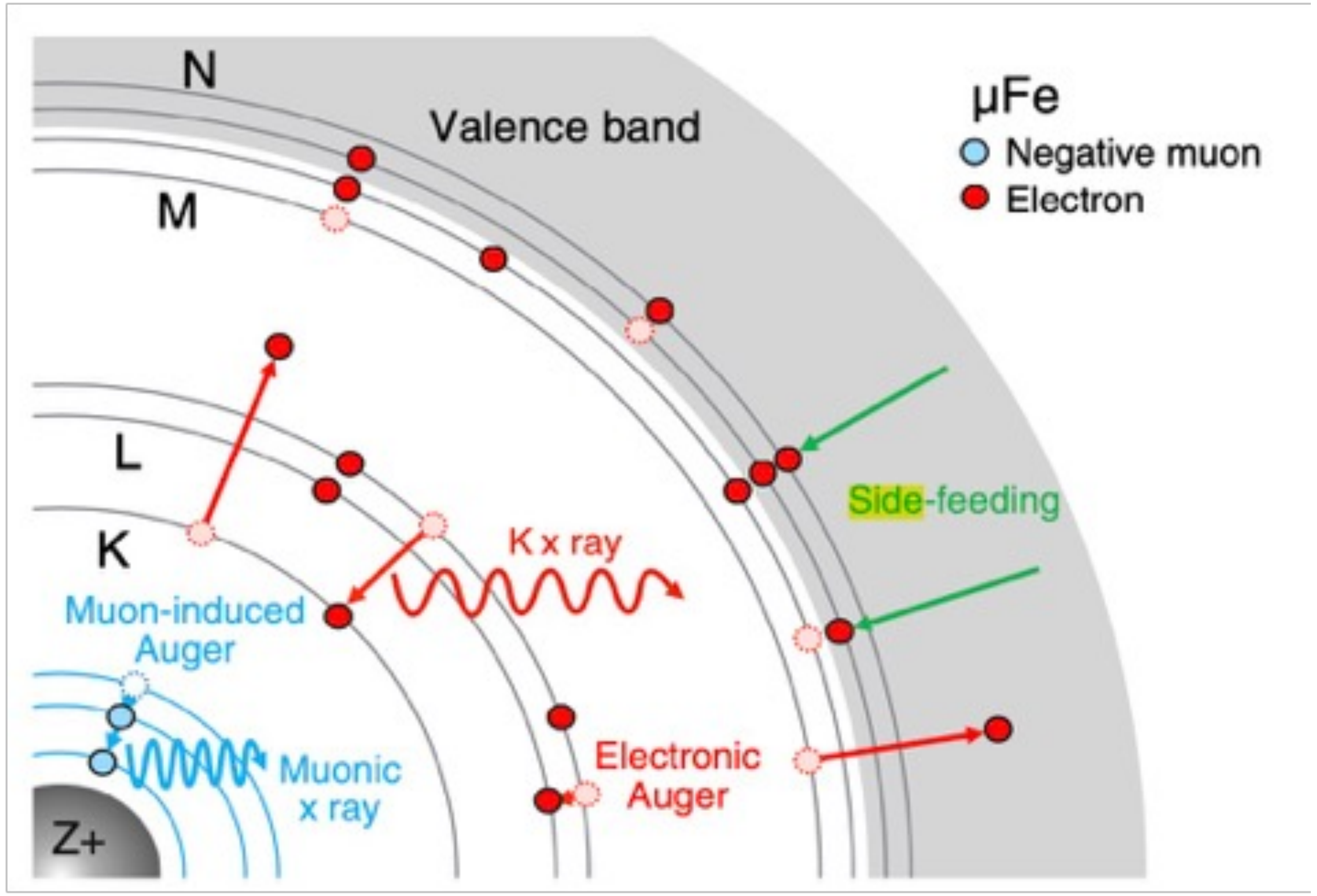
Muonic atom cascade and electronic transitions

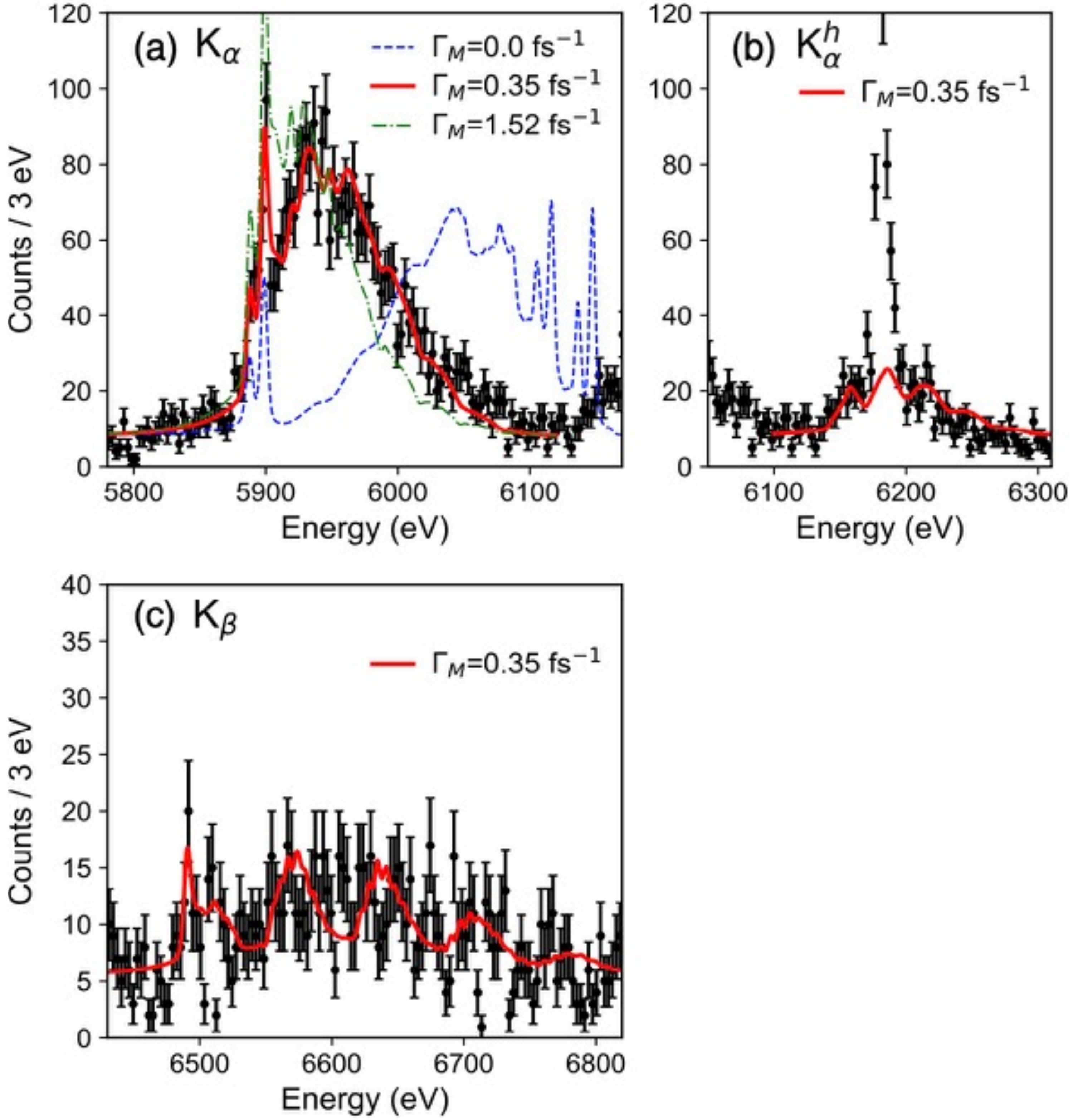


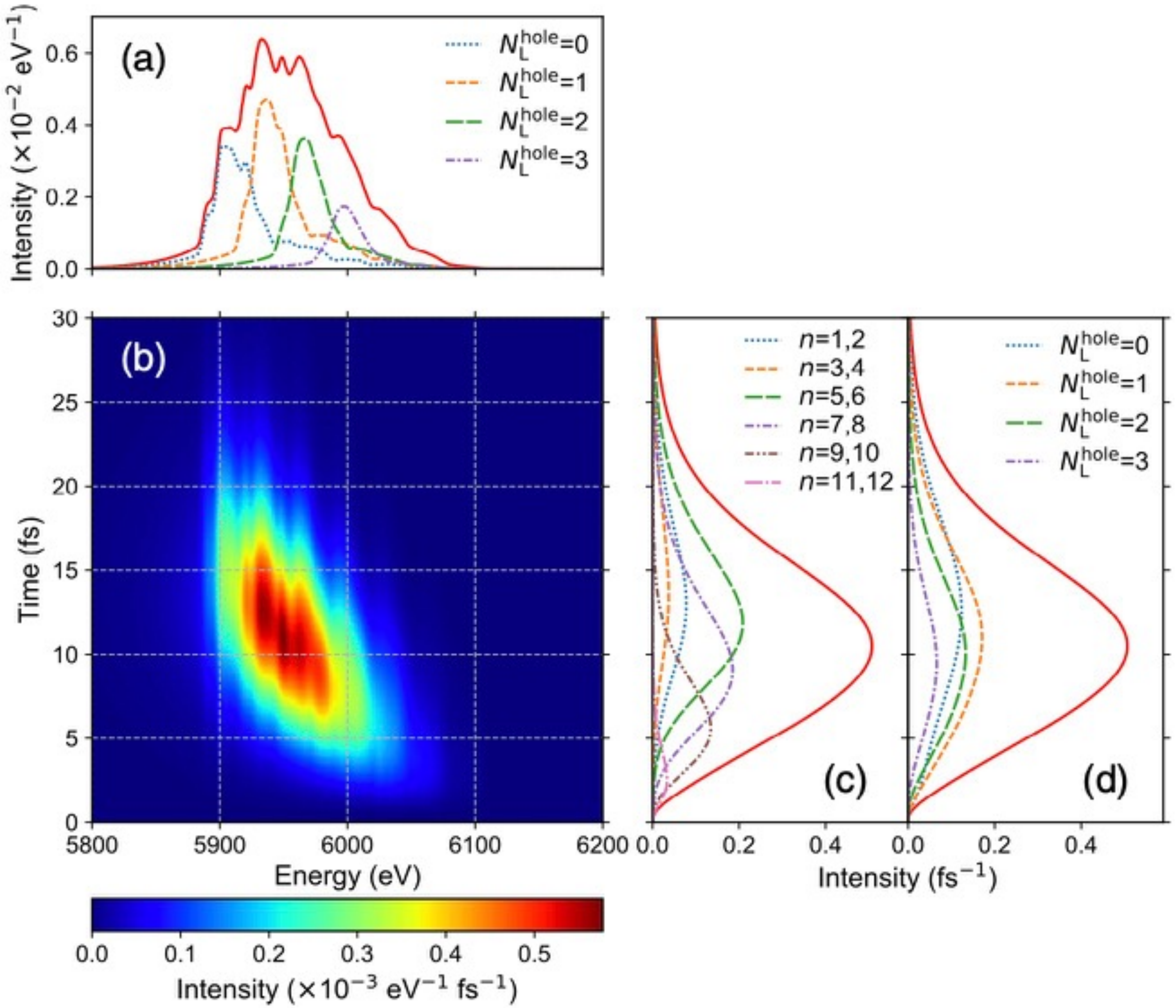
spectrum of muonic Fe with Mn Kα transitions



T. Okumura et al., Phys. Rev. Lett. 127, 053001 (2021).

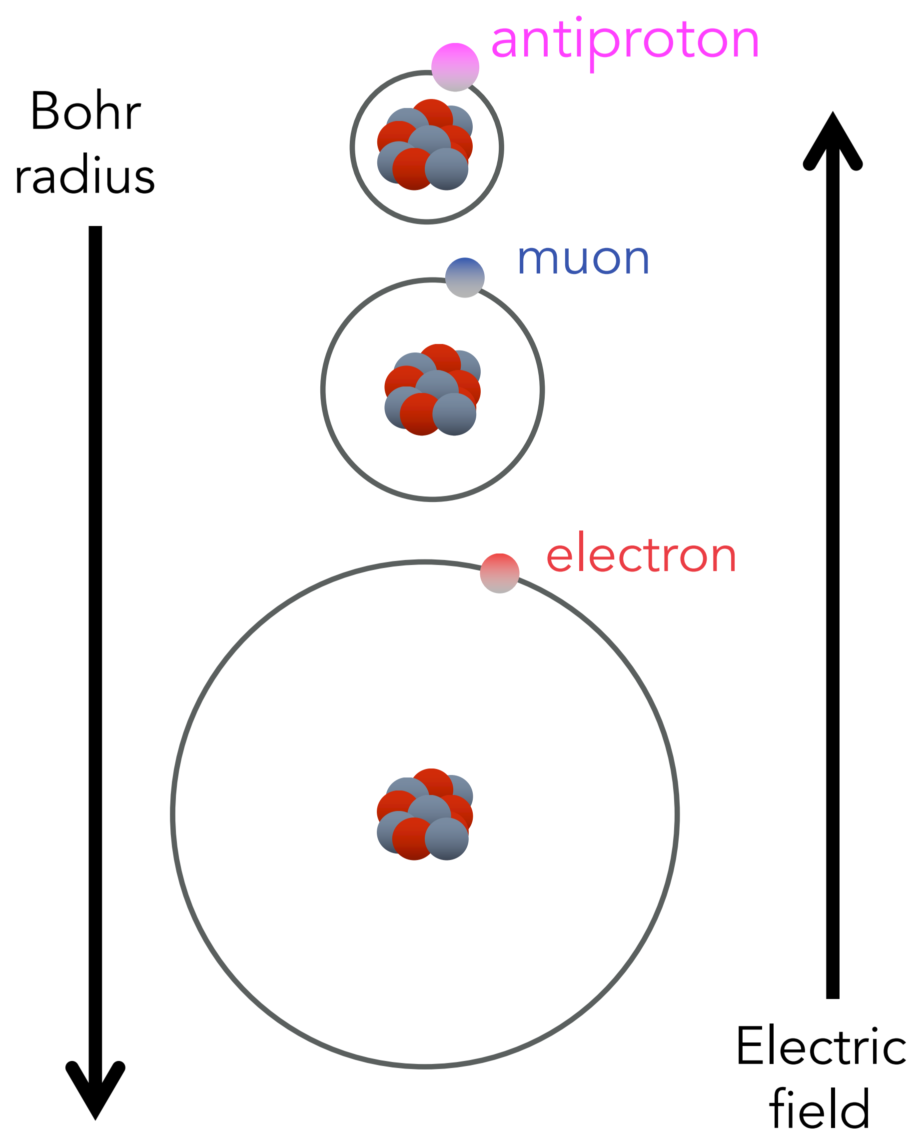
Muonic atom cascade and electronic transitions





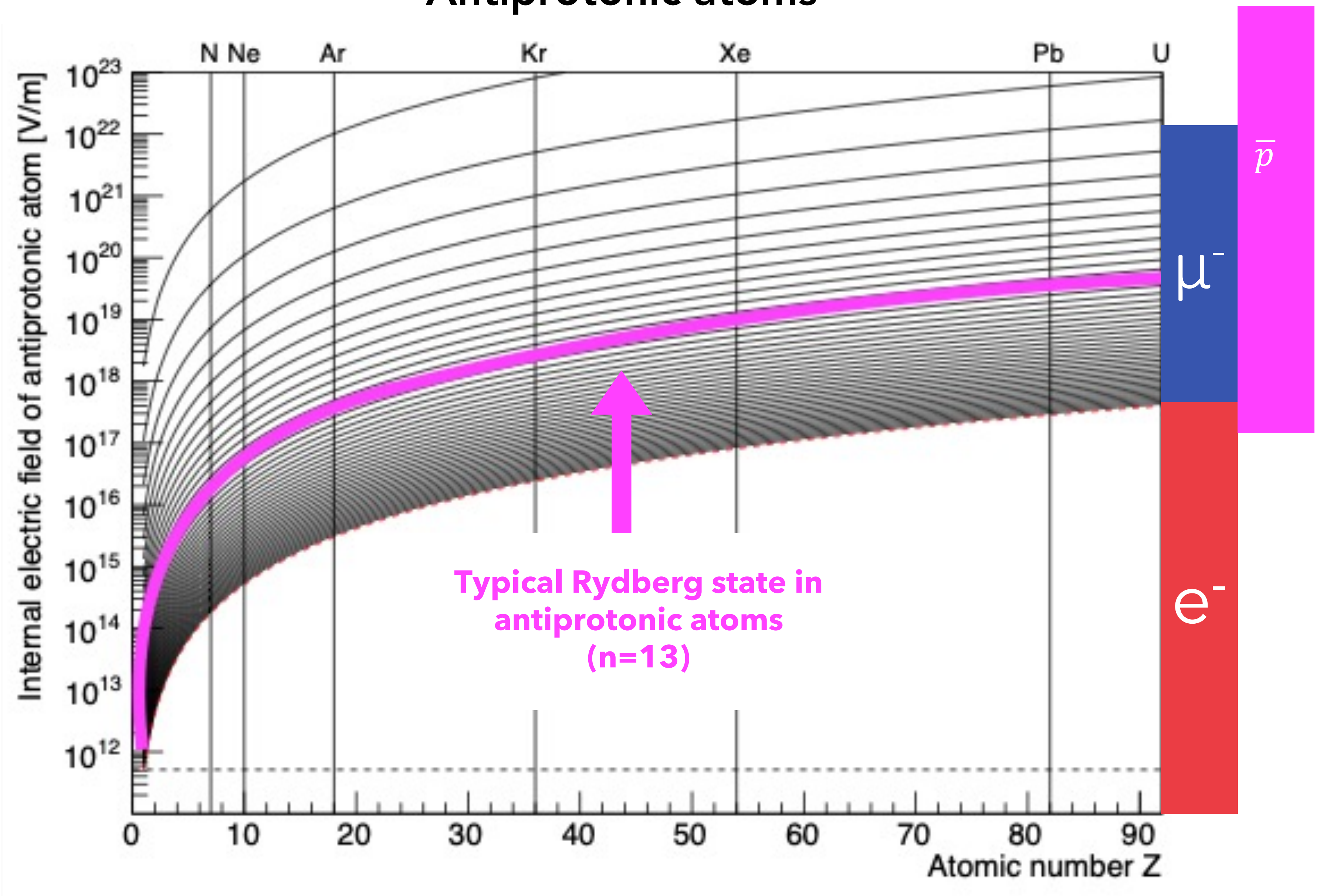
Next step….QED with antiprotons

Even stronger field QED!



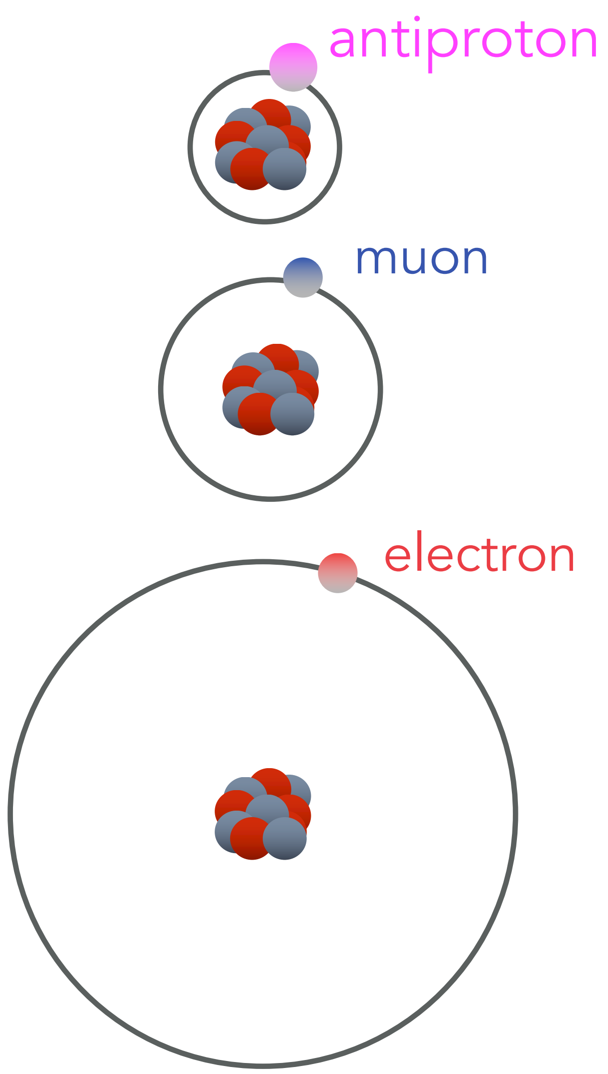
Next step….QED with antiprotons

Antiprotonic atoms



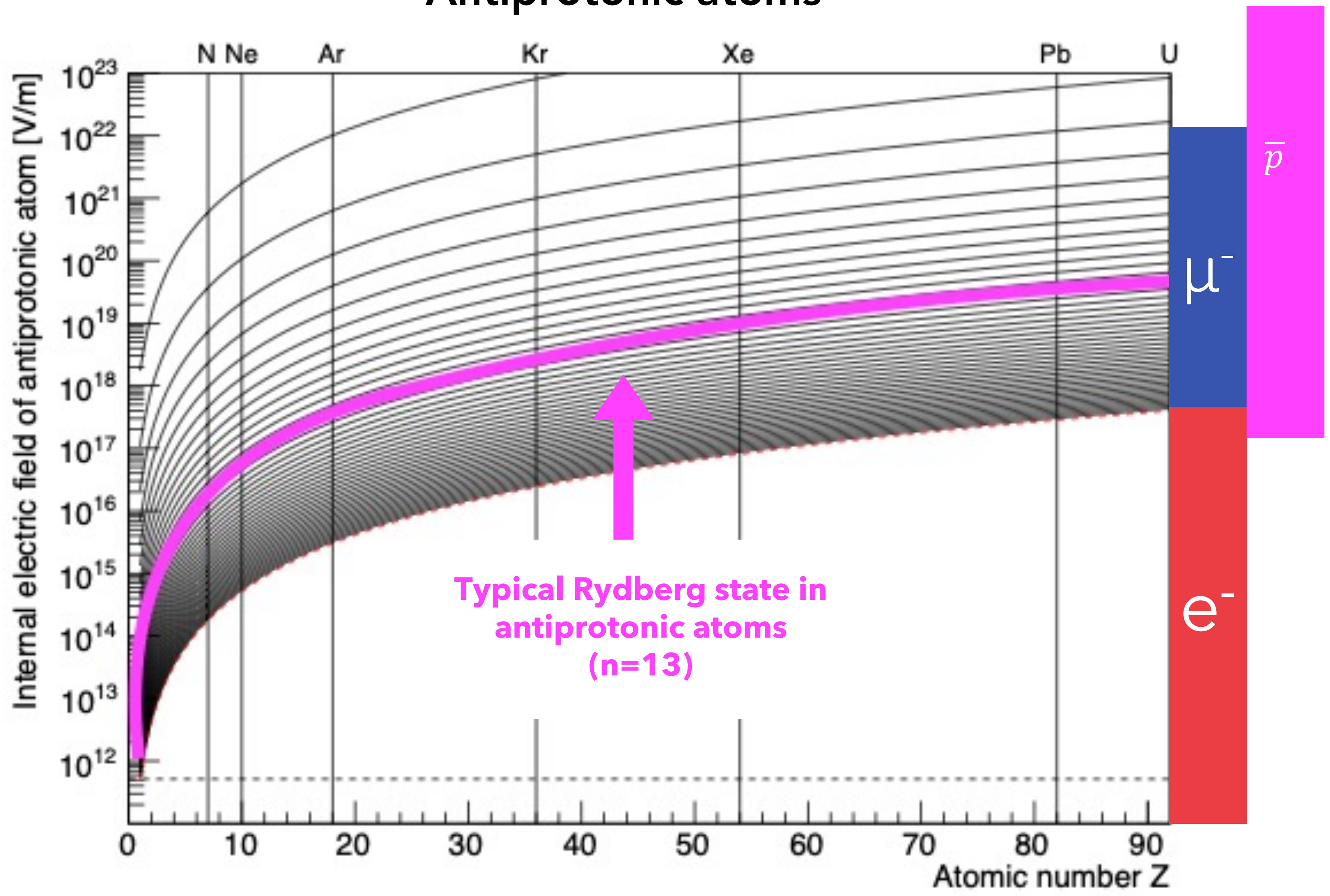
Typical Rydberg state in antiprotonic atoms (n=13)

Even stronger field QED!



Next step….QED with antiprotons

Antiprotonic atoms



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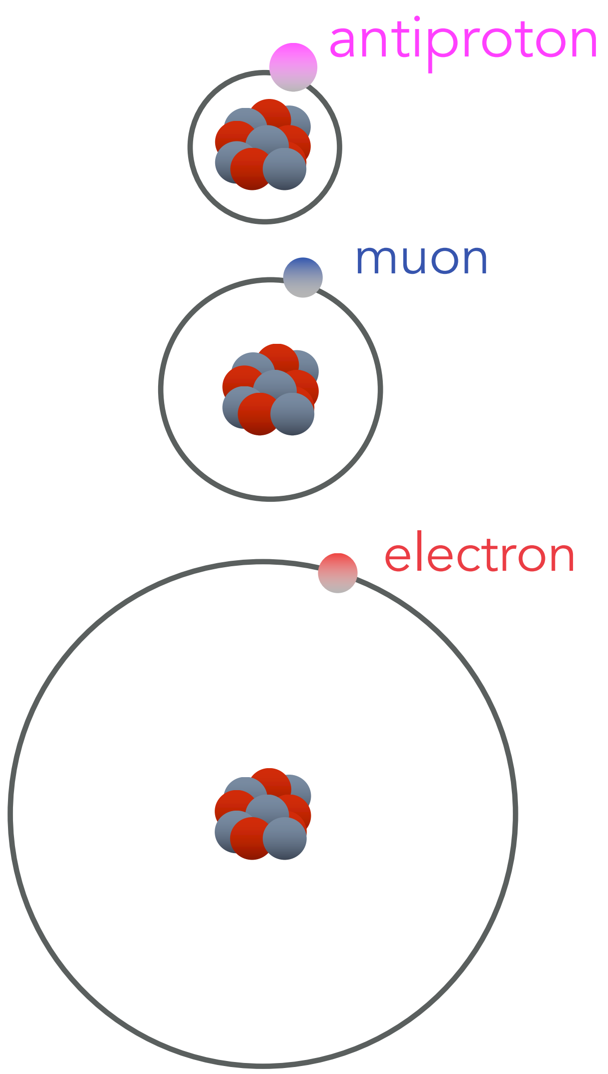


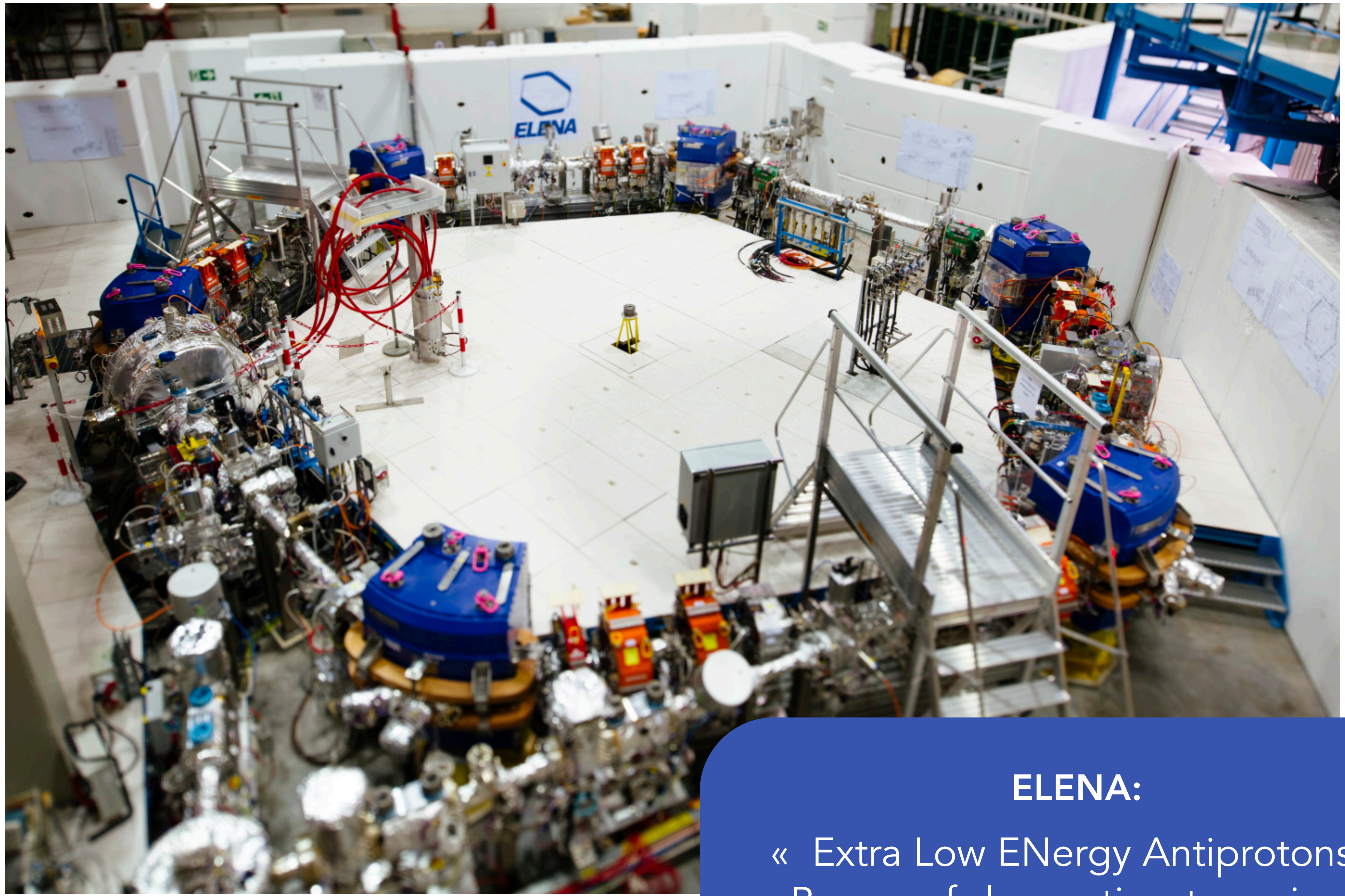
QED with antiprotons

(precision methods) x (antimatter)

Largest BSQED effects!

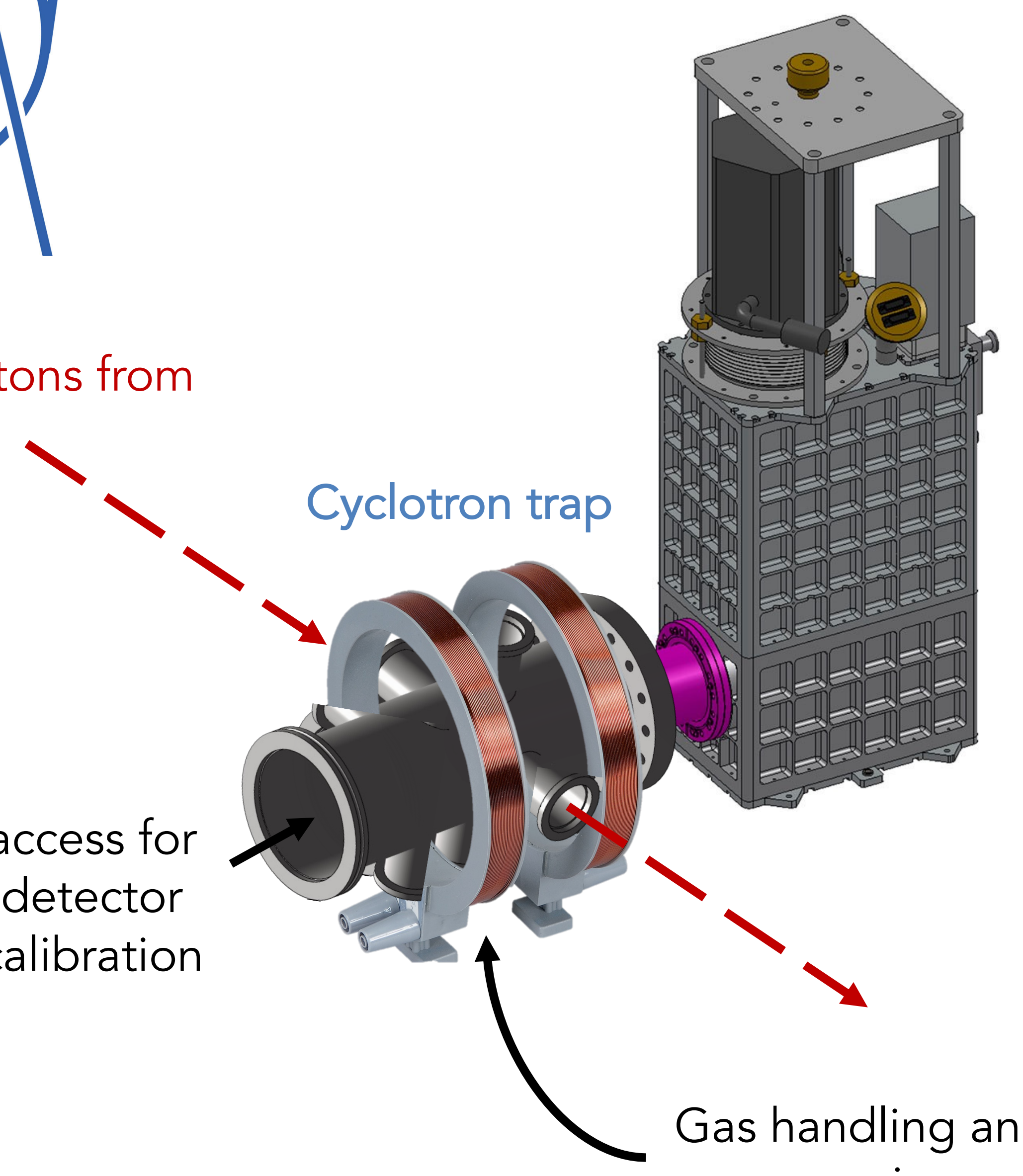
The $\overline{p}AX$ project—antiprotonic Atom X-ray spectroscopy

$\bar{p}AX$ at ELENA



ELENA:

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



TES x-ray detector

100 keV antiprotons from ELENA

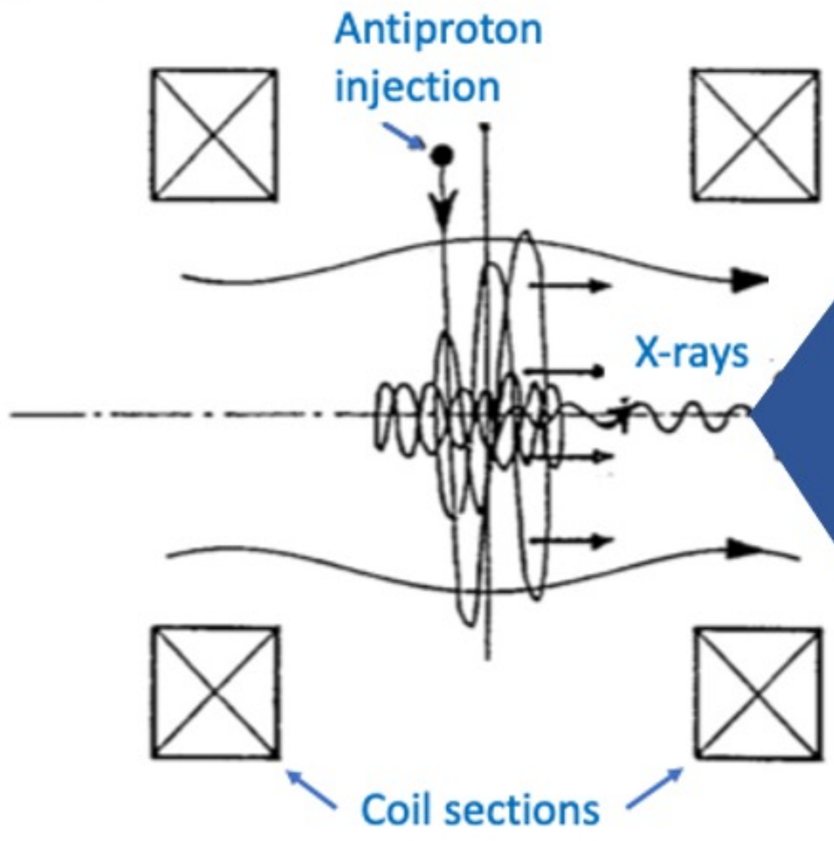
Cyclotron trap

access for detector calibration

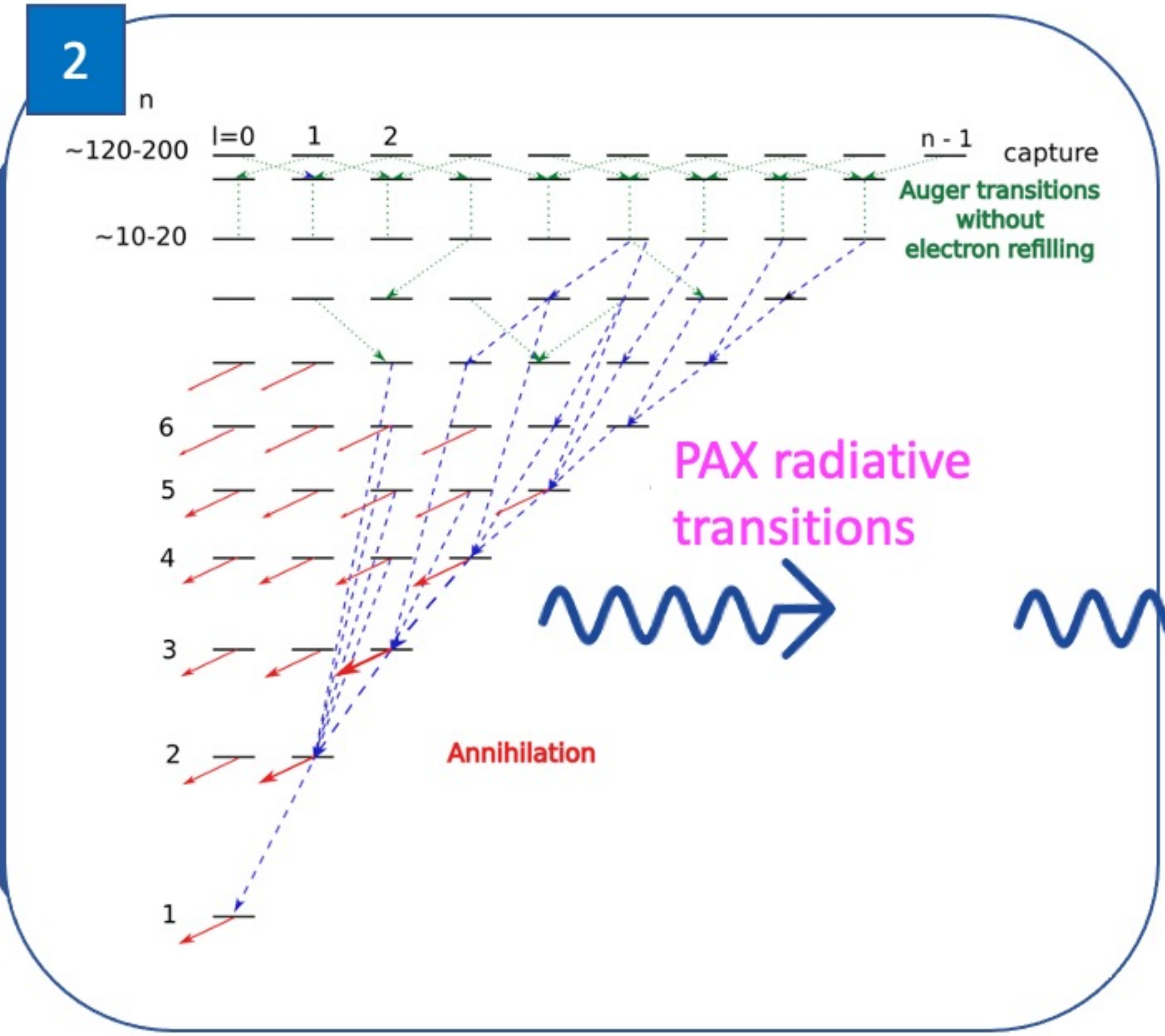
Gas handling and pumping

$\bar{p}AX$ in detail

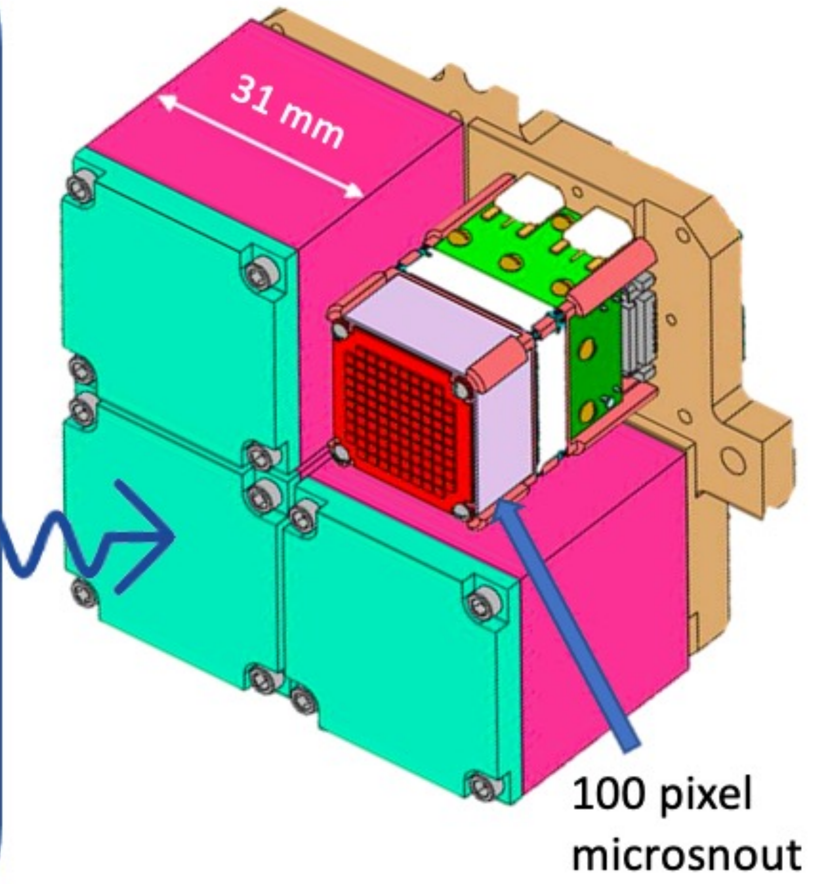
1 *Novel new device*



2



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 $(6 \rightarrow 5)$	30	4 E-3	3 E-5	2 E-6
^{40}Ar $(6 \rightarrow 5)$	100	5 E-3	5 E-5	1 E-5
^{84}Kr $(9 \rightarrow 8)$	100	5 E-3	5 E-5	1 E-5
^{132}Xe $(10 \rightarrow 9)$	170	5 E-3	5 E-5	2 E-5
^{184}W $(12 \rightarrow 11)$	180	5 E-3	5 E-5	2 E-5

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

$$N_p = 1 \times 10^6/\text{spill}$$
$$\text{M} = 10$$
$$\epsilon_{geo} = 6 \times 10^{-4}$$
$$\epsilon_{det} = 0.4$$
$$\epsilon_{trap} = 0.5$$

N_x=1200 counts/spill

< 1 week
measurement time / transition

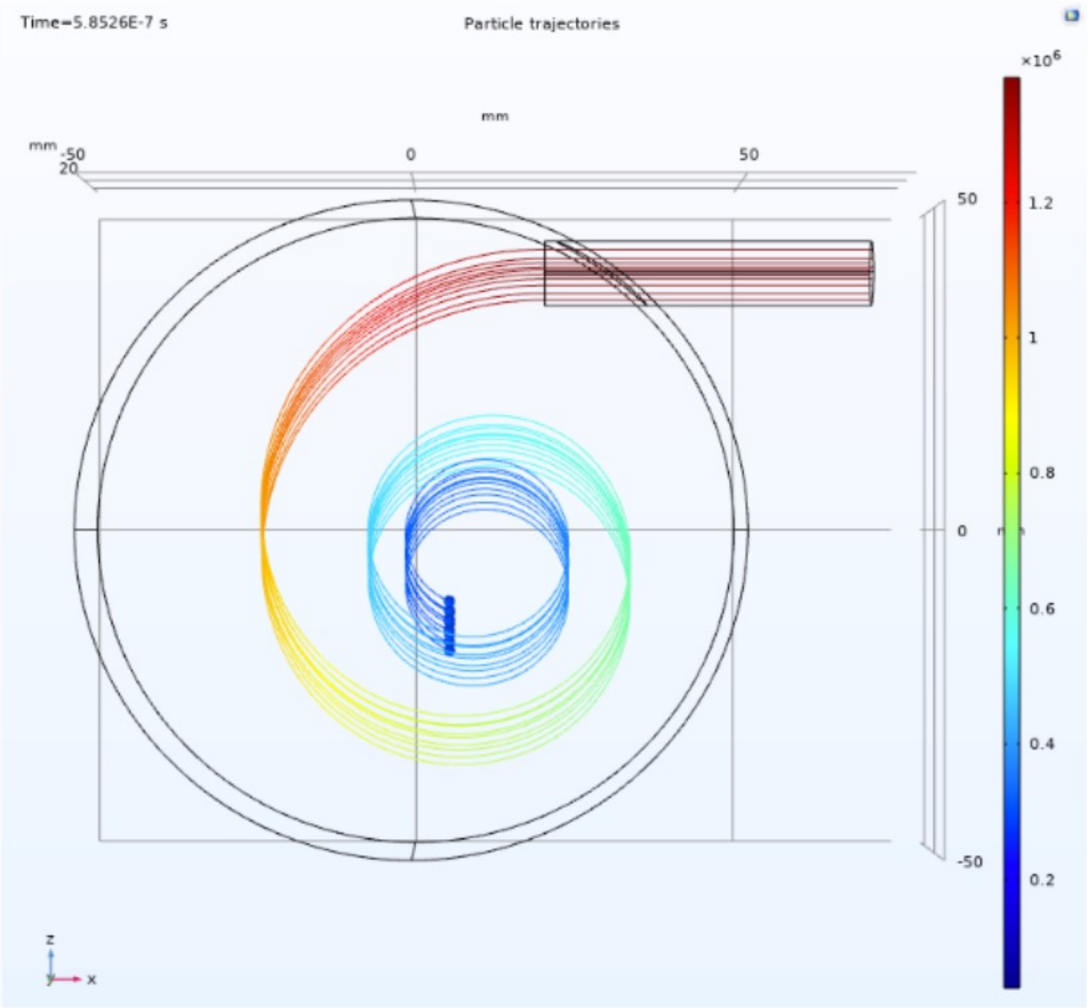
Highest field system ever accessed in the laboratory !

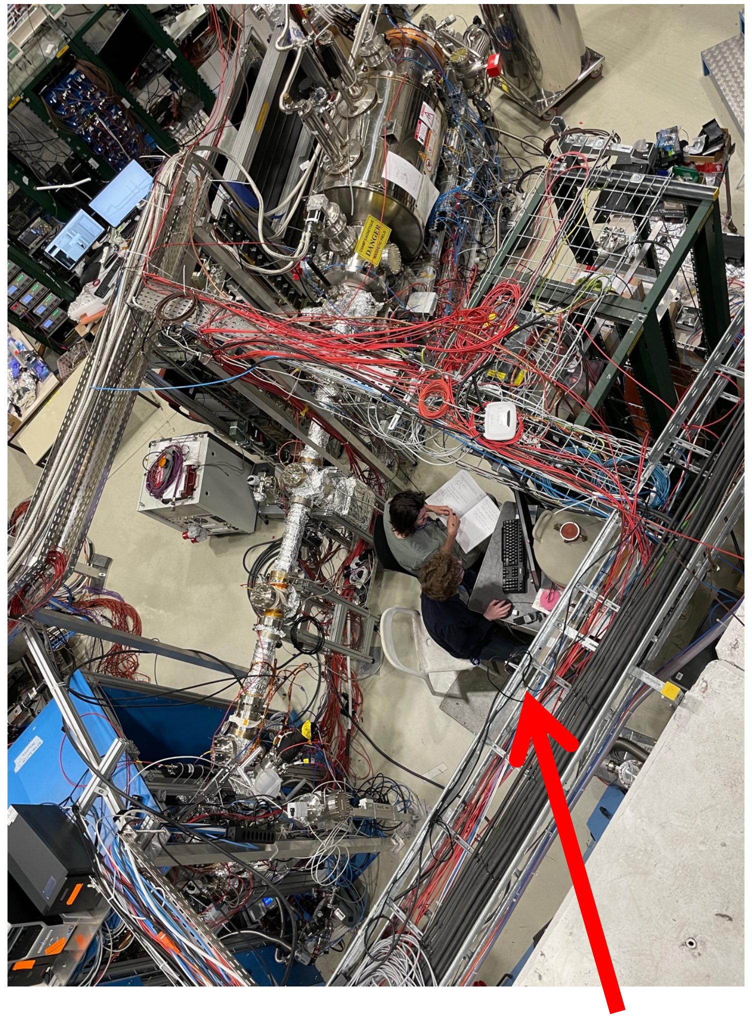
$\bar{p}AX$ firsts

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

Perspectives: Strong interaction studies, exotic physics searches

The $\bar{p}AX$ next steps



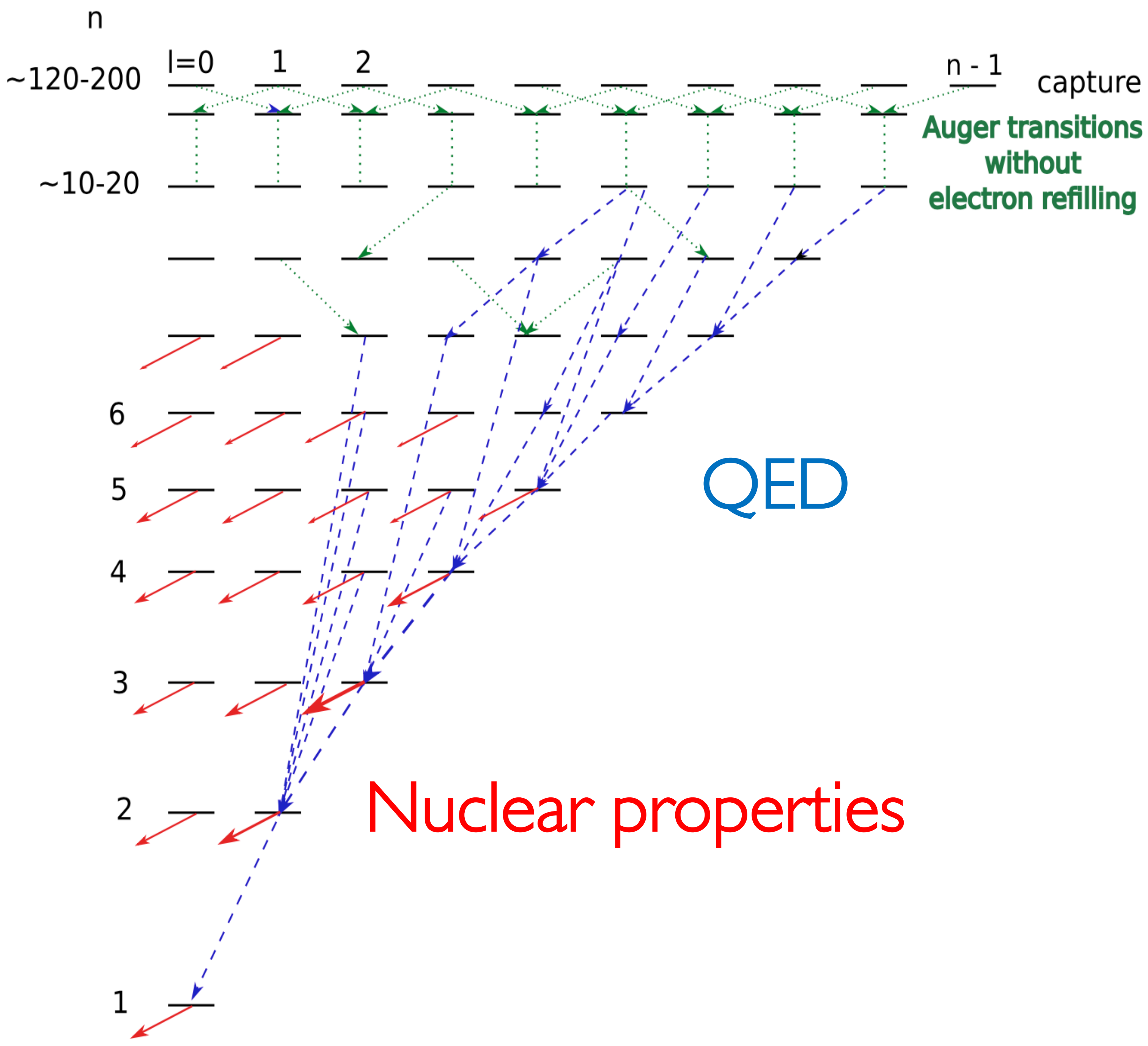


Test setup at GBAR

- Full simulations and design of cyclotron trap and vacuum solution

- Simulation and measurement of annihilation background
- In beam test with prototype TES at ELENA (*2025*)

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



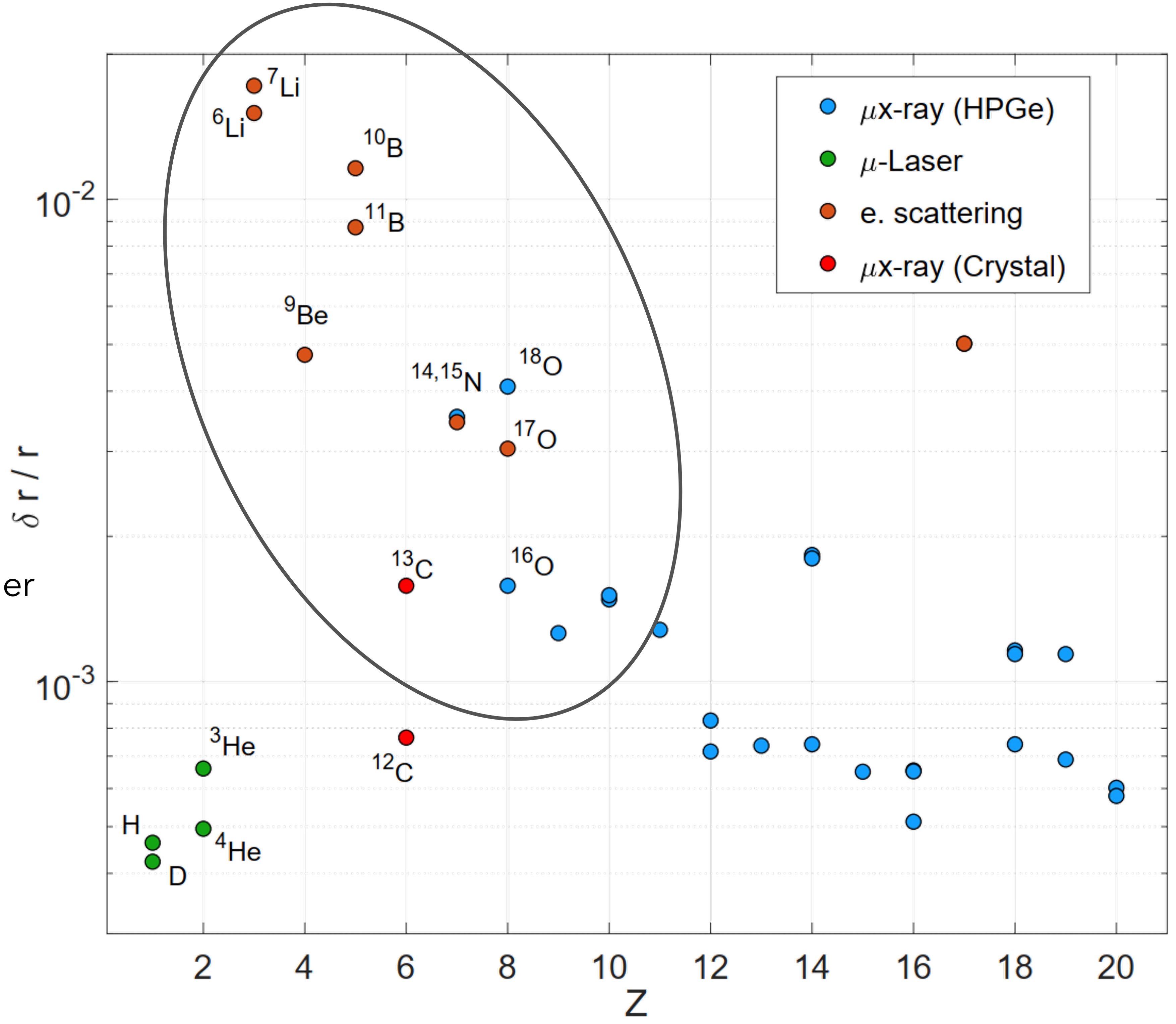
Determinations of nuclear RMS charge radii

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

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

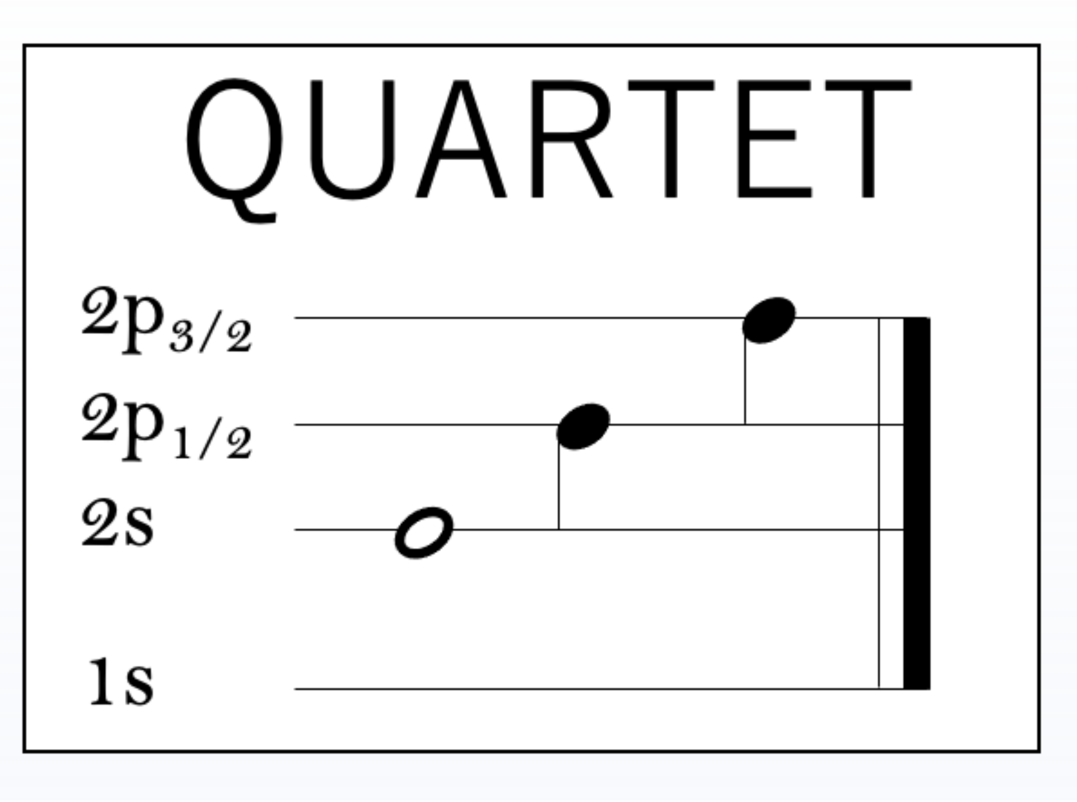
- **For $\mathbf{Z = 3-5}$, and others:**
  Electron scattering, less accurate and systematics usually NOT under control

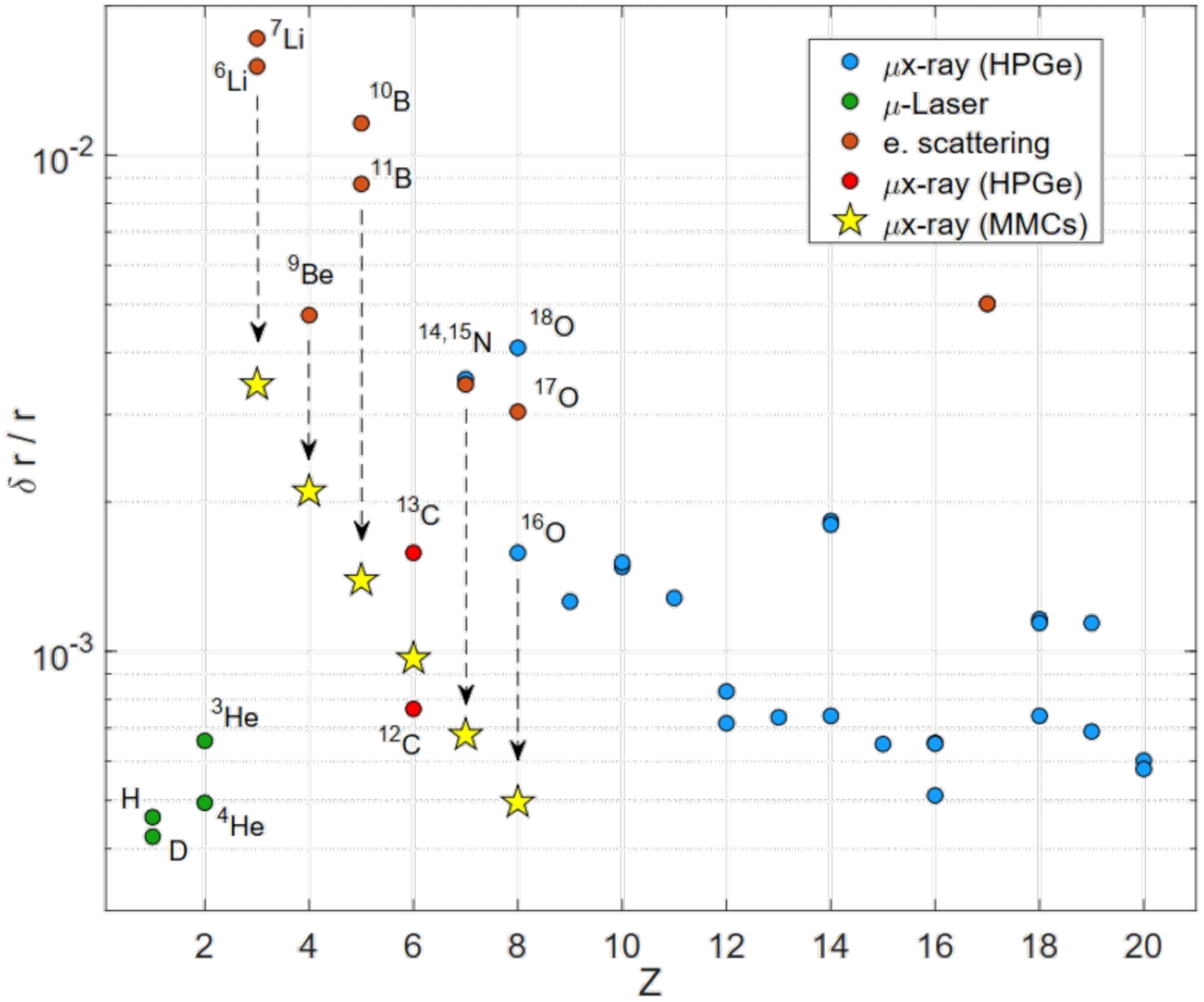
- **For $\mathbf{Z = 6}$**
  E(2P-1S)~75 keV, measured with crystal spectrometer. Limited by resolution ~75 eV



QUARTET precision goals

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

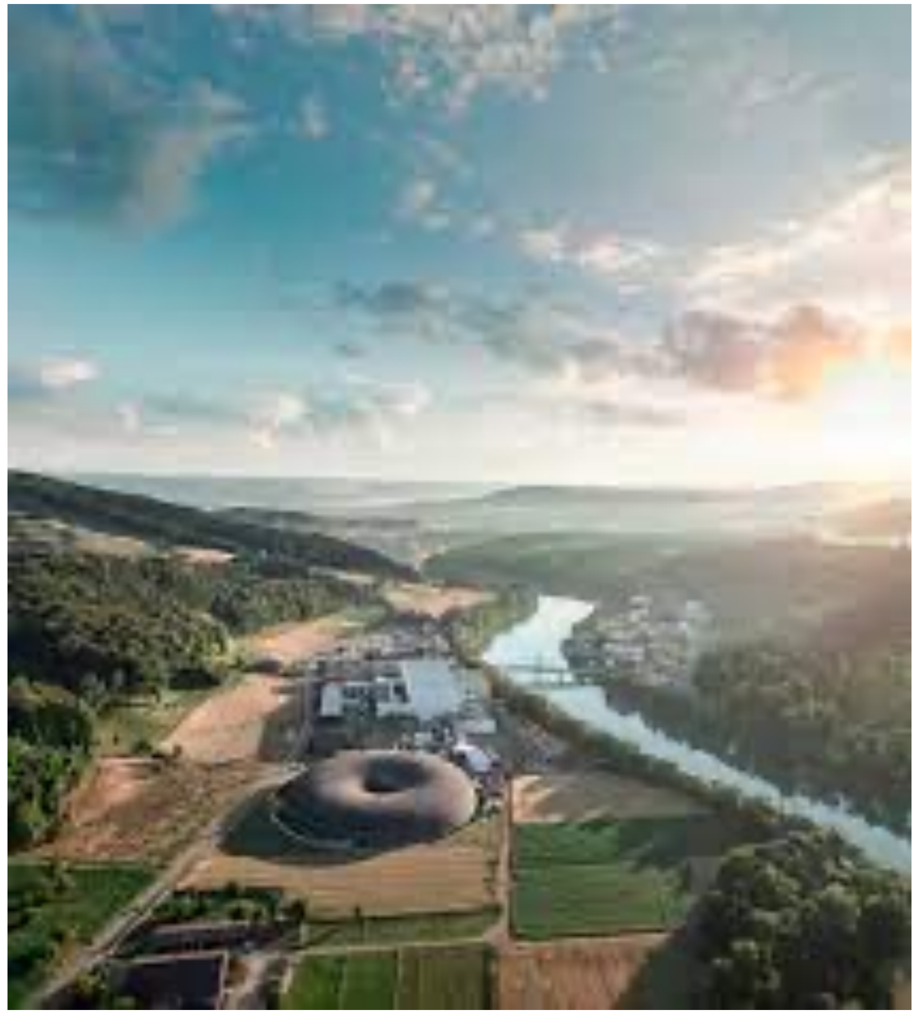




The QUARTET experiments

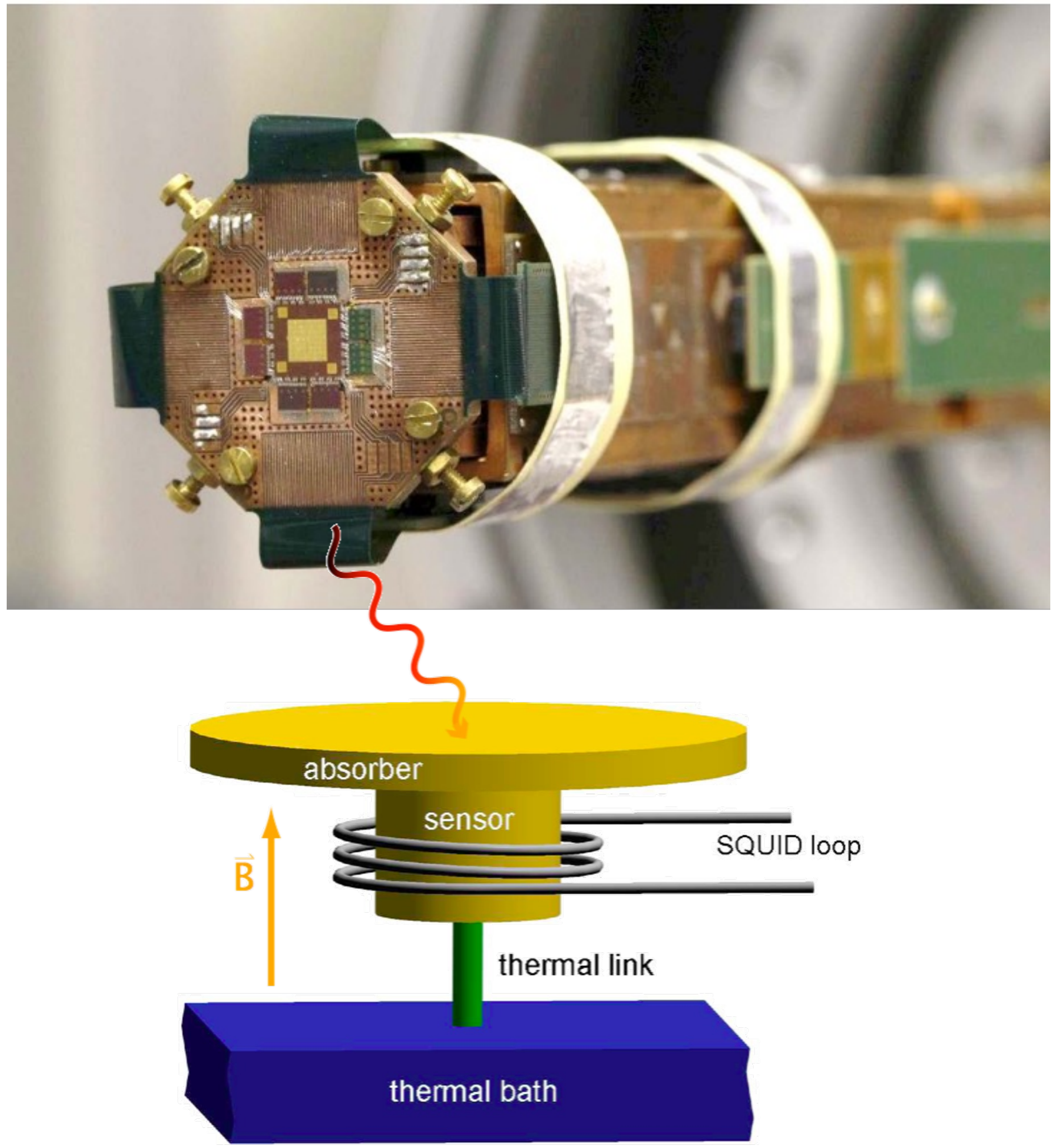
PAUL SCHERRER INSTITUT

PSI

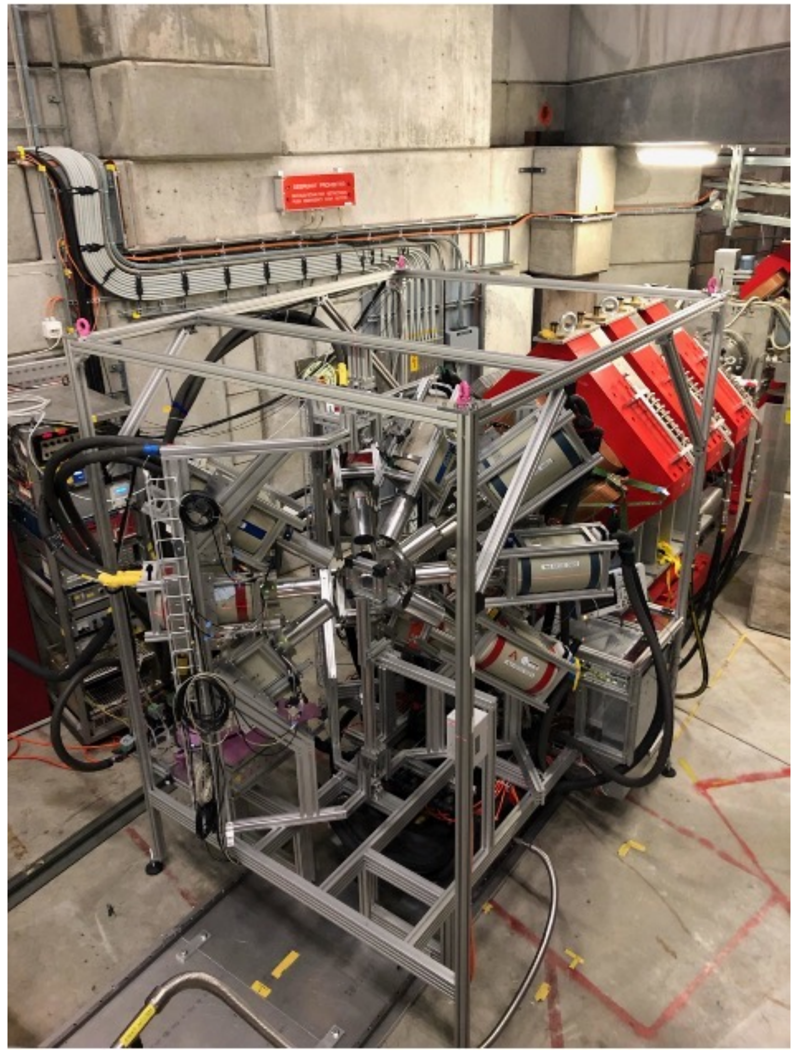


The Heidelberg Metallic magnetic calorimeter (MMC)

maXs-30 mounted on coldfinger of a dry dilution fridge



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



Picture courtesy of the MIXE collaboration

The QUARTET collaboration

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Quantum Sensors group

Experimenters in exotic atoms

Ab. Initio. Nuclear theory

QED in exotic atoms

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Petr Navratil

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T. Cocolios

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Sketch of test experiment and rates

Expected rates:

$$0.8\times10^{-4}\times\frac{10^{3}}{s} = 0.1\ event/s$$

Detection efficiency

Solid angle

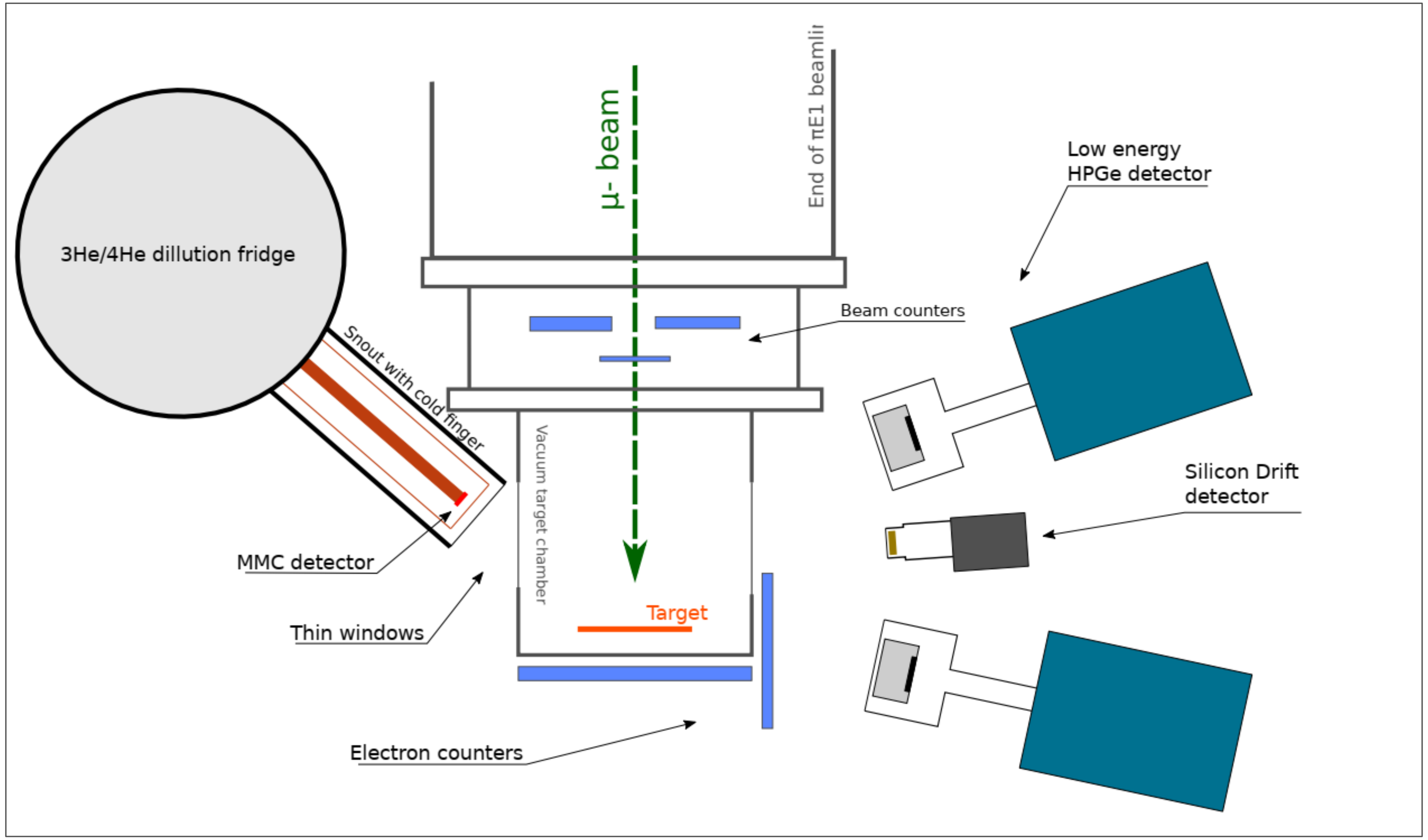
2P-1S rate

Stat. accuracy per nominal week:

$$\frac{10\ eV}{2.4} / \sqrt{10^{5}} \sim 0.02\ \text{eV}$$

Resolution

Events



First test beam in October 2023

μ-^{6,7}Li, μBe, μ-^{10}B

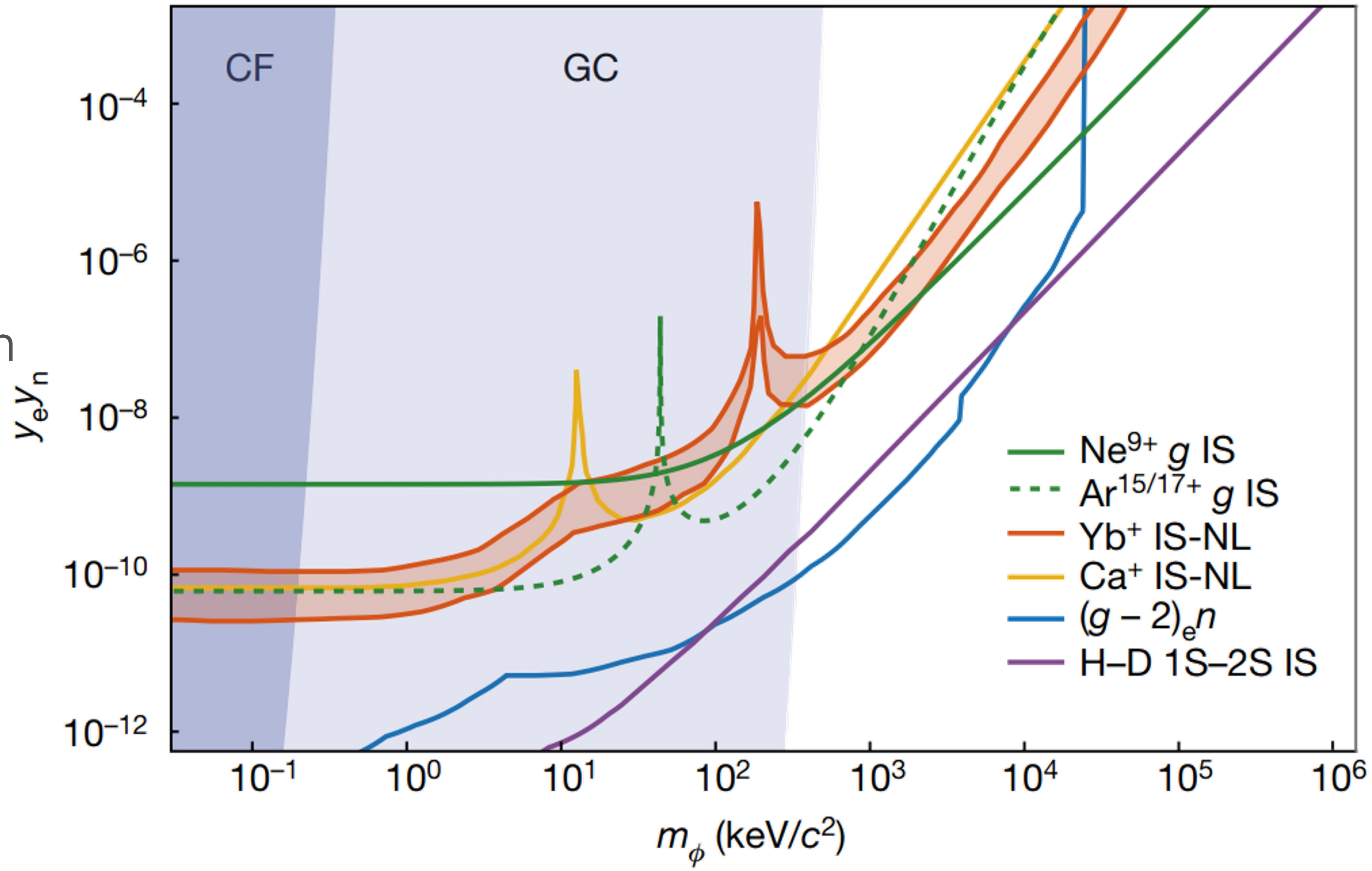
Impact on BSM physics searches

- Combining isotope shifts between electronic and muonic atoms to search for new lepton-neutron interactions

- Best limits come from Hydrogen-Deuterium pair. Z enhancement favors heavier pairs.

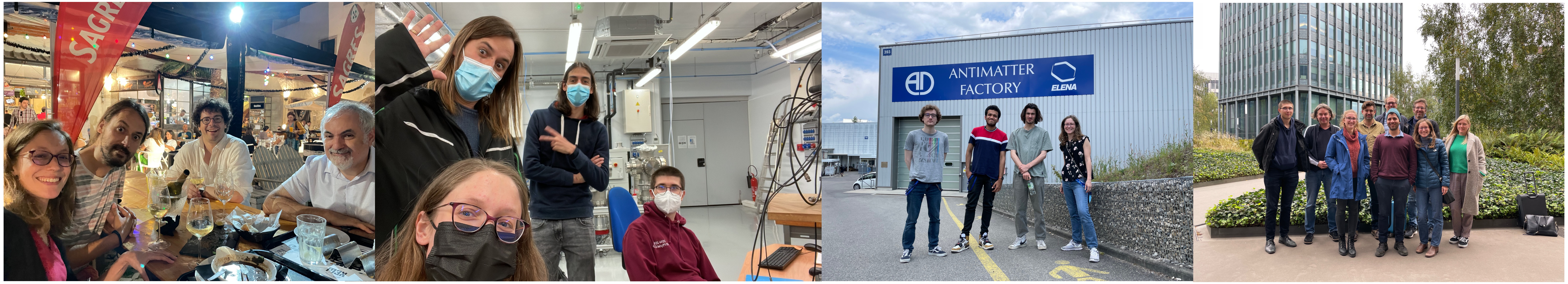
- Novel measurements of bound electron g-factors in H-like ions **limited by muonic isotope shifts**

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



Summary

- **World-leading precision x-ray spectroscopy at LKB for strong-field QED tests**
- **Exotic atoms** offer a new way to probe high-field QED by avoiding the problems associated with nuclear physics
- New **quantum sensor detector technologies** make precision studies of exotic atoms possible
- Experiments ongoing with **muonic atoms** at JPARC, Ne, Ar, Xe
- *New experimental program*, **pAX**, with **antiprotonic atoms** for **BSQED**
- *New experimental program*, **QUARTET**, with **muonic atoms** at PSI for **charge radii**.



LKB Laboratoire Kastler Brossel
Physique quantique et applications

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THANK YOU

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TOYOTA CENTRAL R&D LABS

I. Umegaki

JAXA Explore to Realize

S. Wantanabe

ICU Expanding Potential

K. Kubo

SUPPLEMENT

What are radii good for?

First application, with MaXs-30 (10 eV resolution up to 60 keV)

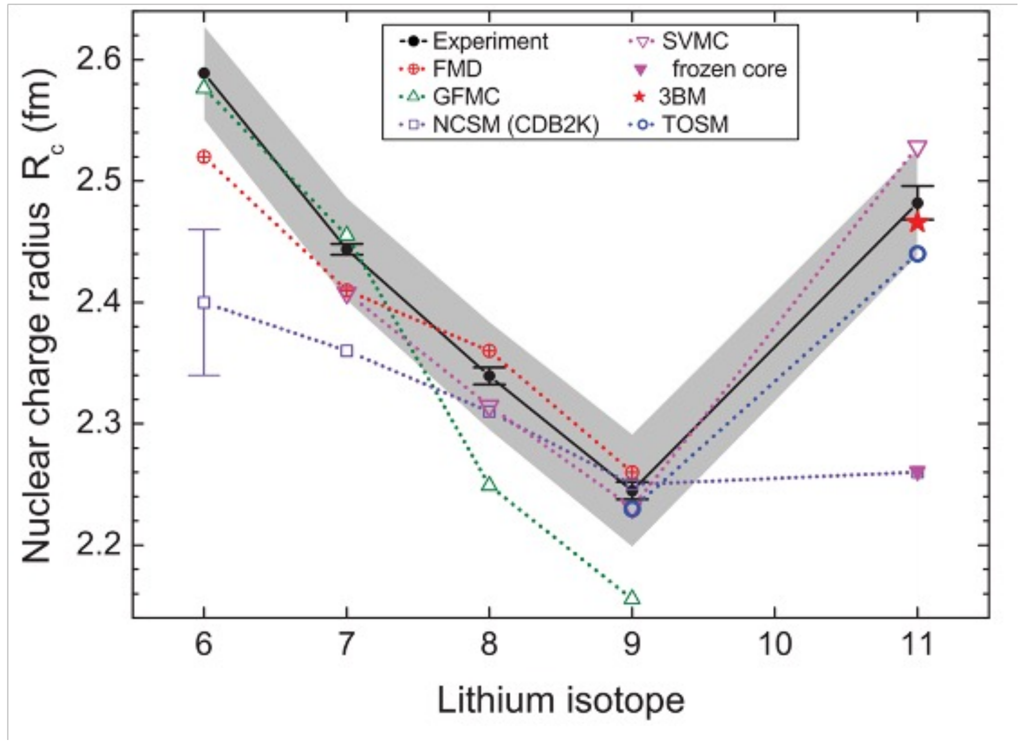
- Li/Be/B absolute radius → calibrate entire chains, test nuclear calculations inc. ^{7}Li-^{7}Be and (future) ^{8}Li-^{8}B mirrors

- ^{6}Li-^{7}Li and ^{10}B-^{11}B isotope shifts (can be determined with higher accuracy) → compare with optical IS to test many-body QED (mostly recoil) and search for new physics.

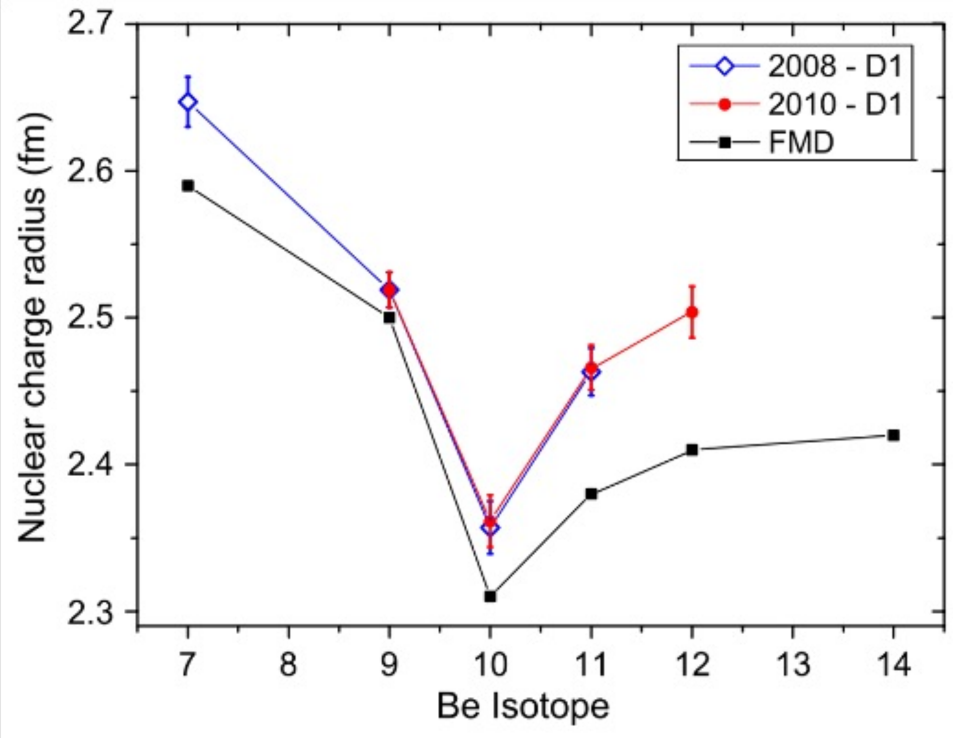
- Upcoming optical determinations of absolute radii for helium-like Li to C (Wuhan, Mainz). Important cross check and strong test for new physics beyond isotope shifts.

All limited by reference

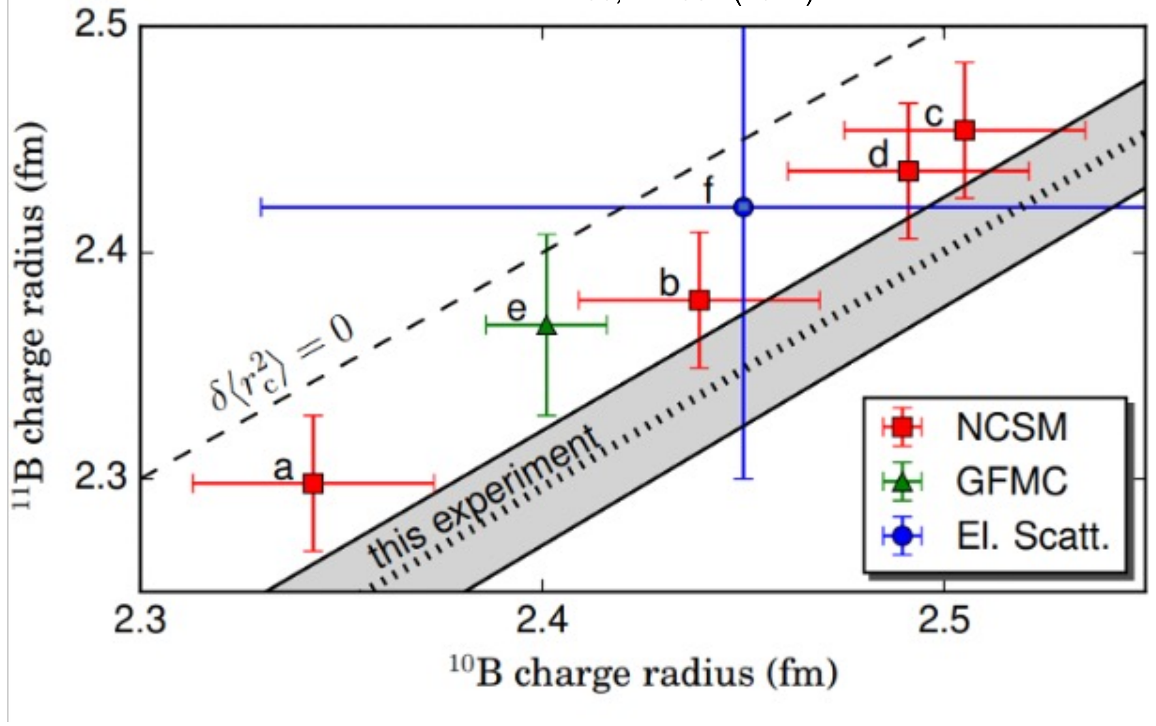
PRC 84, 024307 (2011)



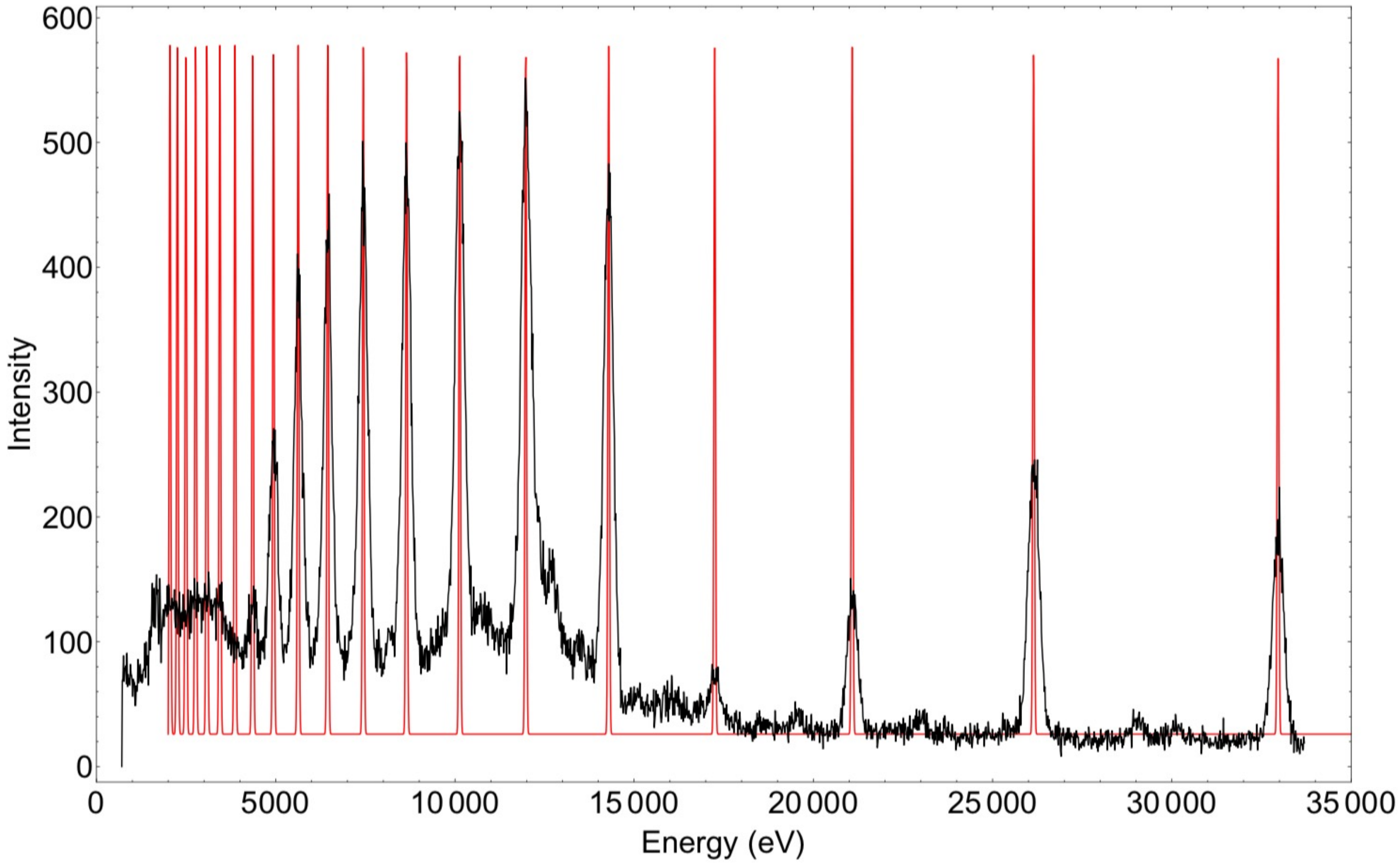
PRL 122, 182501 (2019)



PRL 108, 142501 (2012)



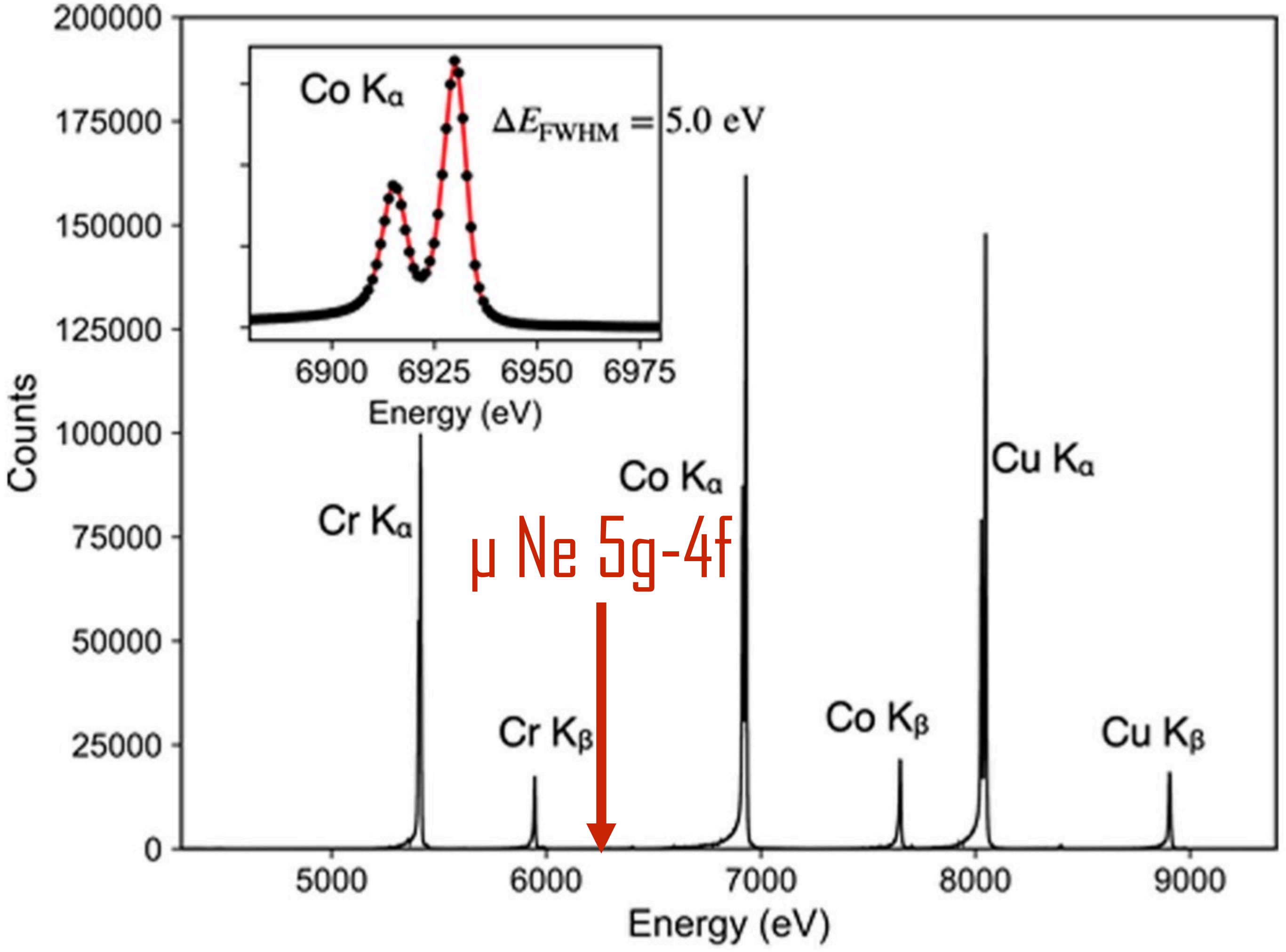
Perspectives

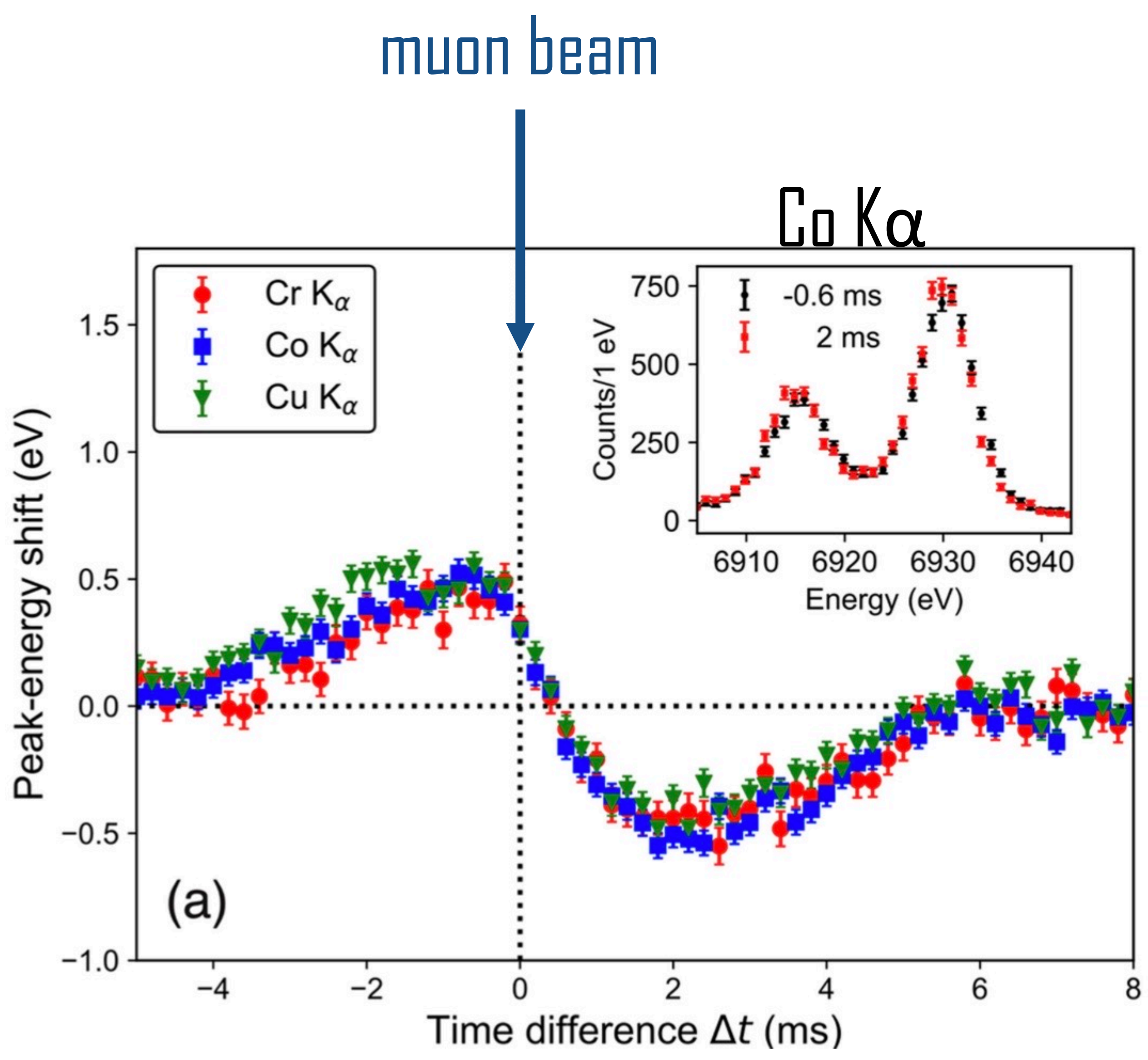


Existing data on antiprotonic cascade

Simulated TES data

Pileup correction



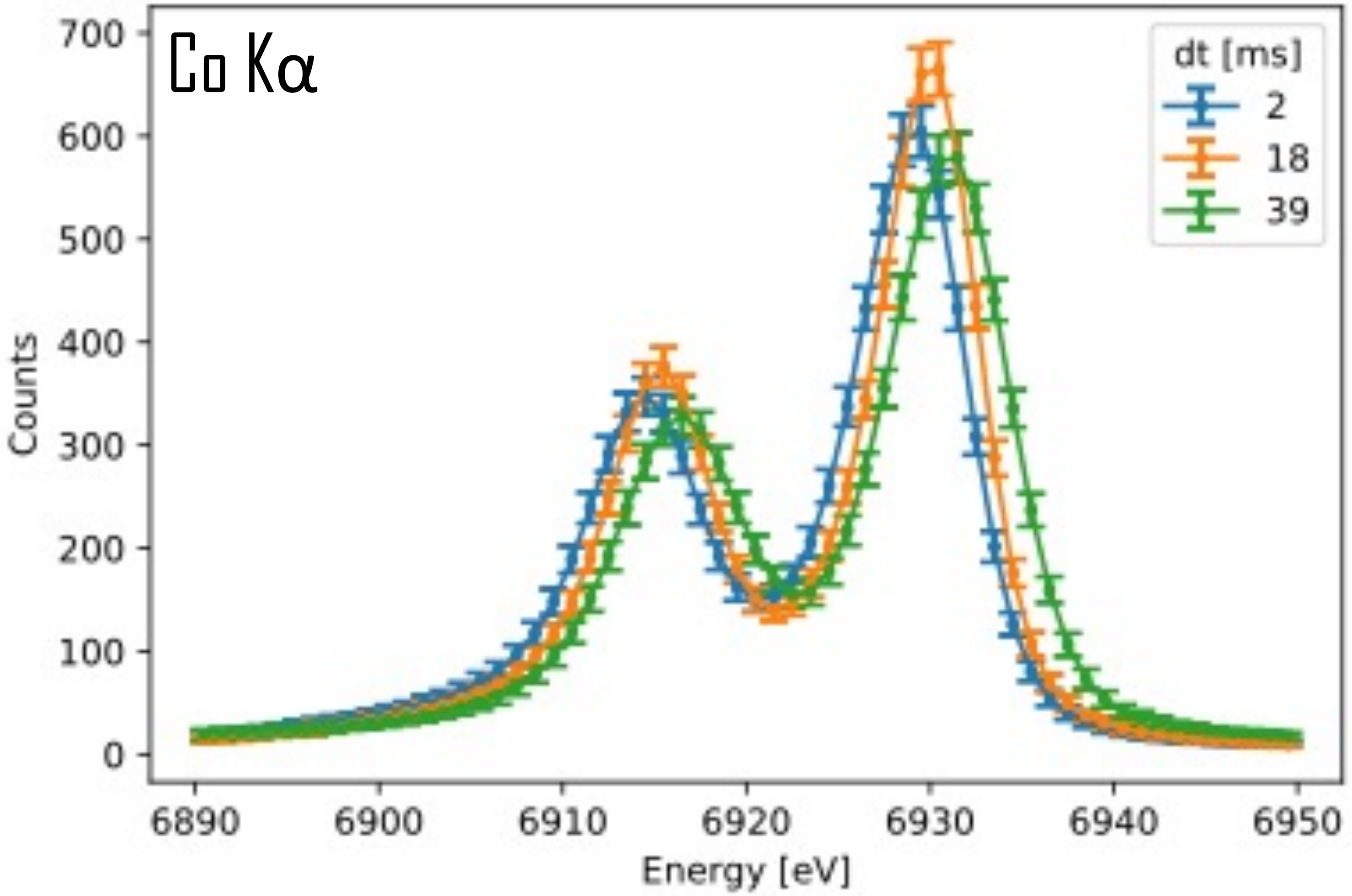


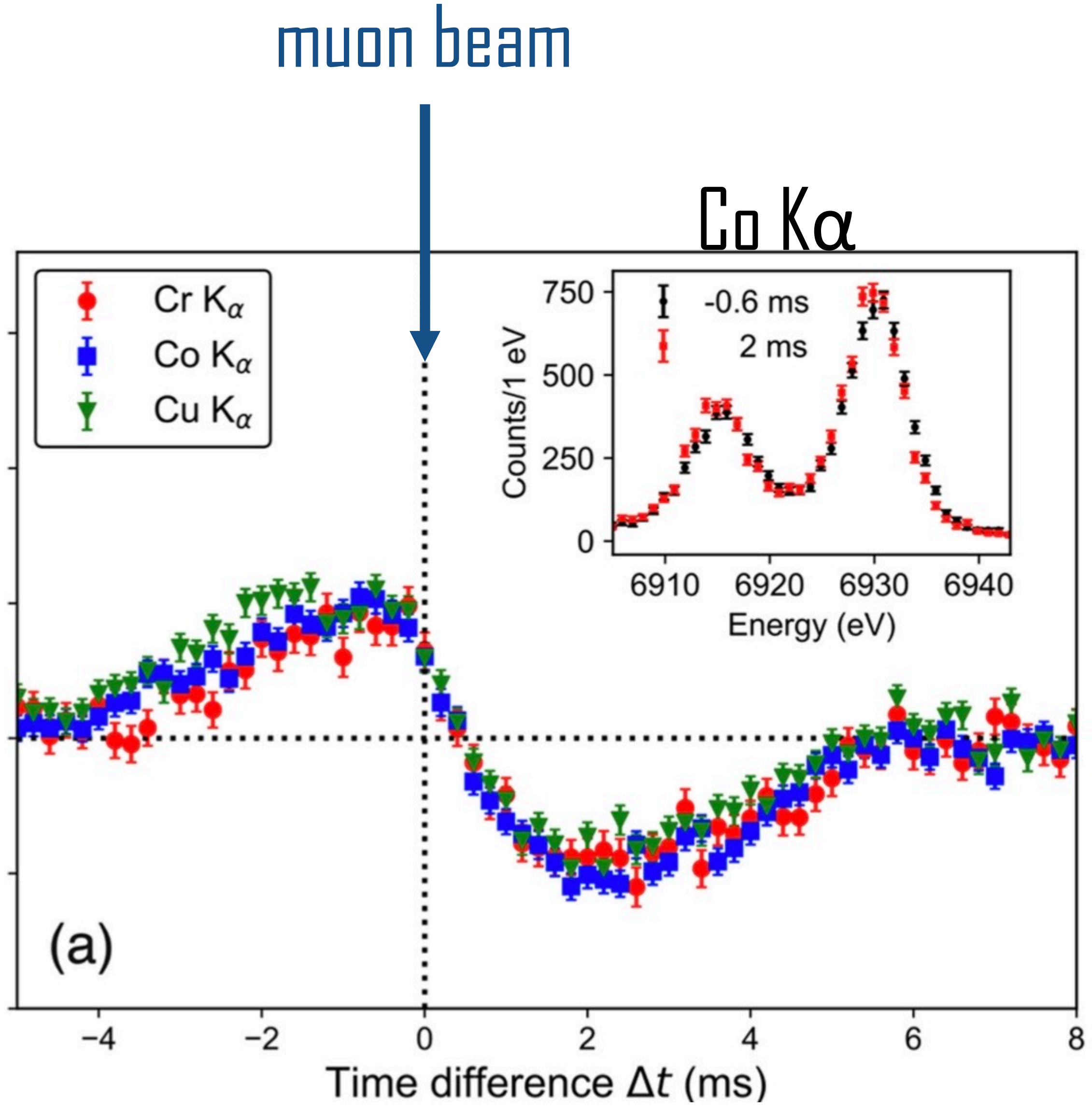
Total calibration spectrum at 0.1 atm

Energy shift (t_{muon}-$t_{x\text{-}ray}$)

T. Okumura et al, IEEE Transactions on Applied Superconductivity **31,** 1-4 (2021)

Pileup correction





Energy shift (t_{muon}-$t_{x\text{-}ray}$)

Dynamical Response of Transition-Edge Sensor Microcalorimeters to a Pulsed Charged-Particle Beam, T. Okumura, T. Azuma, D.A. Bennett, P. Caradonna, I.H. Chiu, W.B. Doriese, M.S. Durk