QED and Beyond with Highly Charged Ions and Exotic Atoms

Nancy Paul and Paul Indelicato

Laboratoire Kastler Brossel, CNRS, Sorbonne Université

LPNHE Seminar

October 11, 2021

The Standard Model and beyond (?)

Figure from Sandbox Studio, Chicago

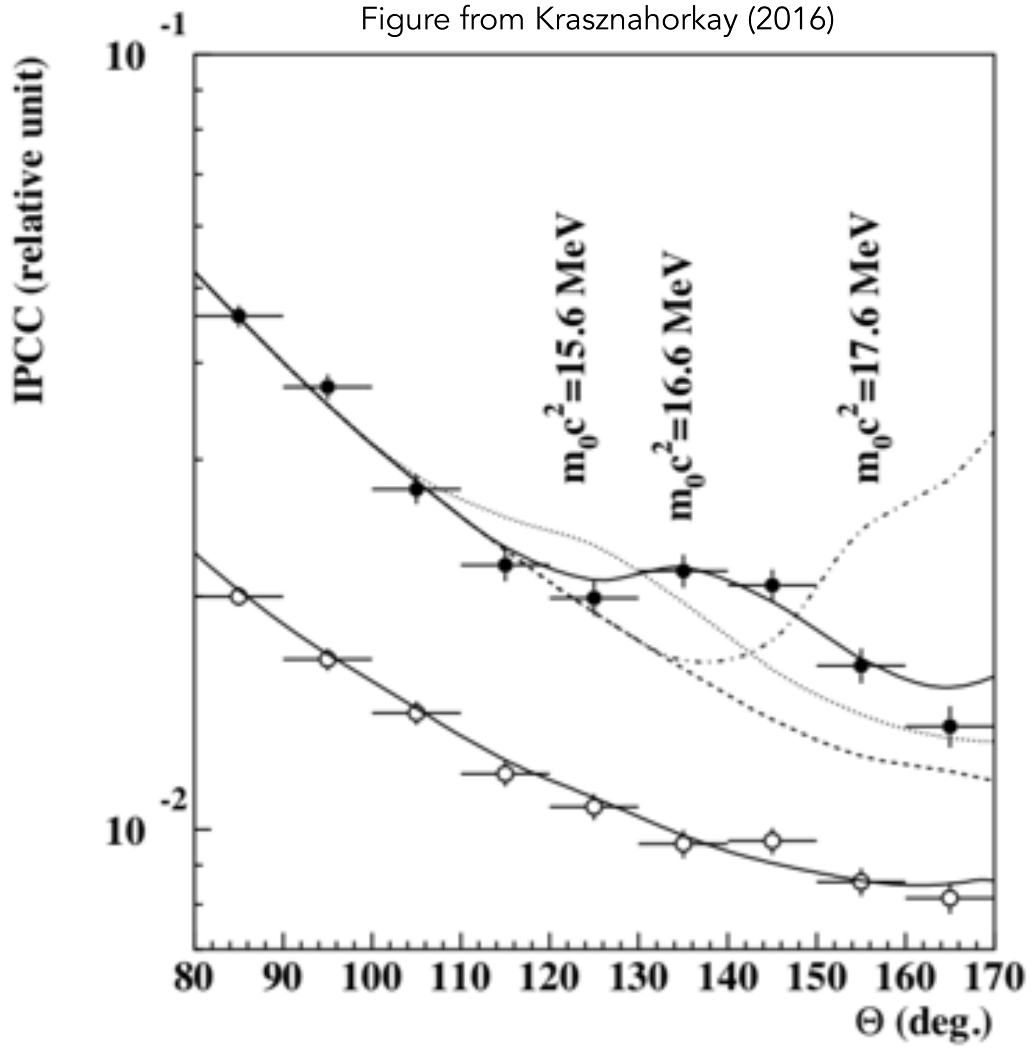
Numerous recent experimental observations cannot be explained by the standard model

- Dark energy, dark matter, neutrino oscillations

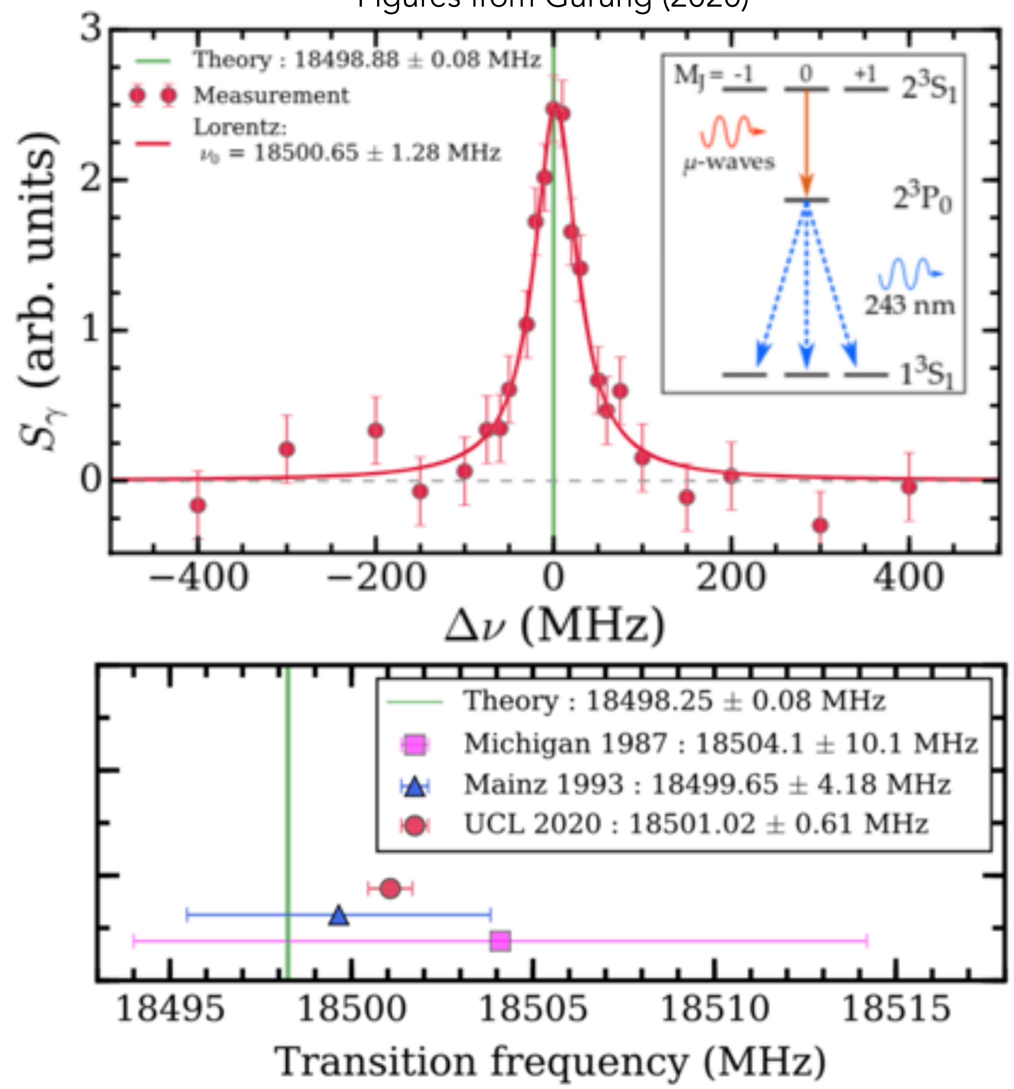
Could be new physics, how to find it?

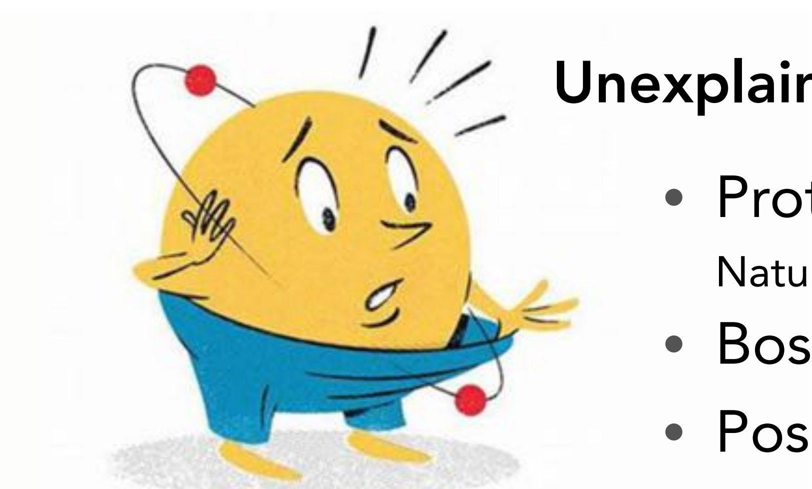
- High energy frontier (LHC)
- Precision frontier with atoms and nuclei (this talk)

Figure from Krasznahorkay (2016)



Figures from Gurung (2020)



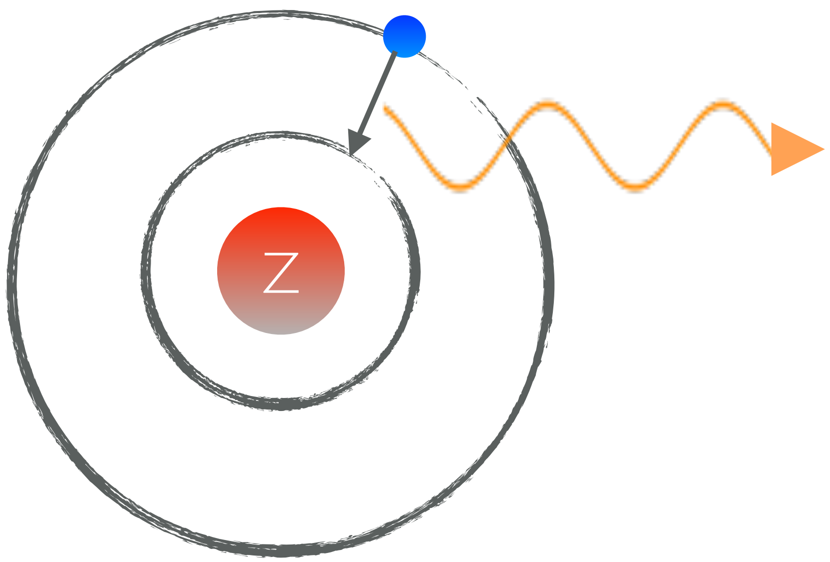


Unexplained phenomena

- Proton radius puzzle (5σ difference between normal and μ-hydrogen)
  Nature 2013, Science
- Boson-X measurement from ATOMKI (7σ signal in decay of light nuclei)
- Positronium puzzle (4.7σ difference from QED predictions)

QED…?

Quantum electrodynamics : interactions between photons and charged particles



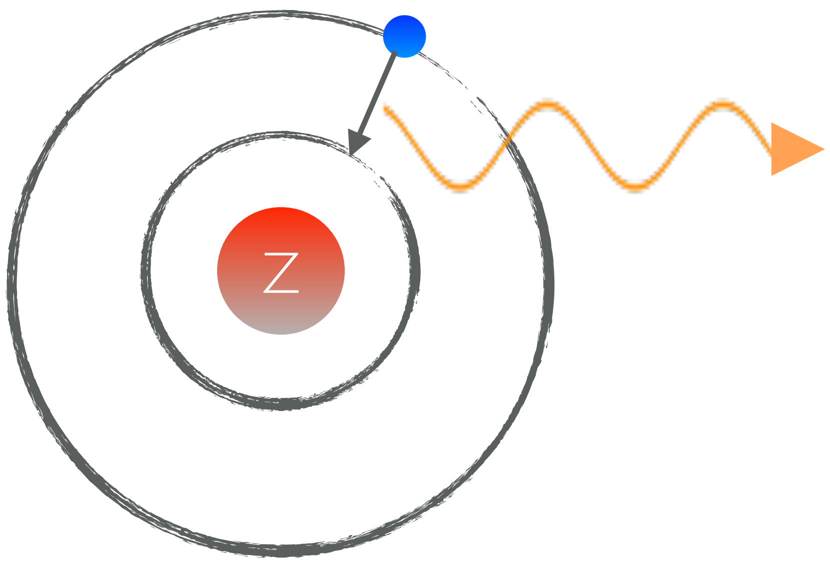
Atomic transitions

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

- E_{Dirac}: Dirac equation
- E_{Nuc}: Nuclear effects
- E_{QED}: **Quantum electrodynamics**

QED…?

Quantum electrodynamics : interactions between photons and charged particles



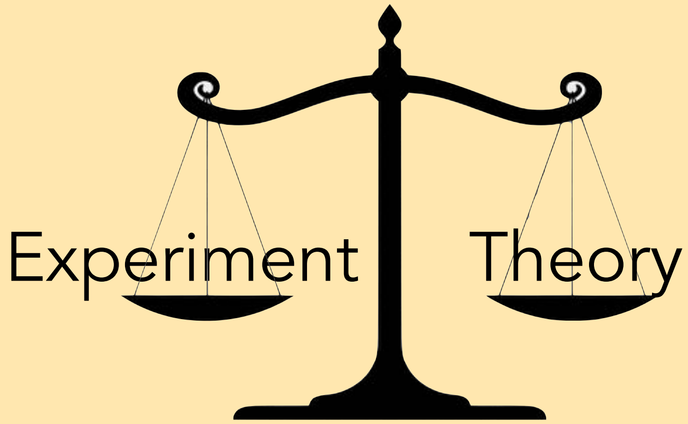
Atomic transitions

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

Dirac equation

Nuclear effects

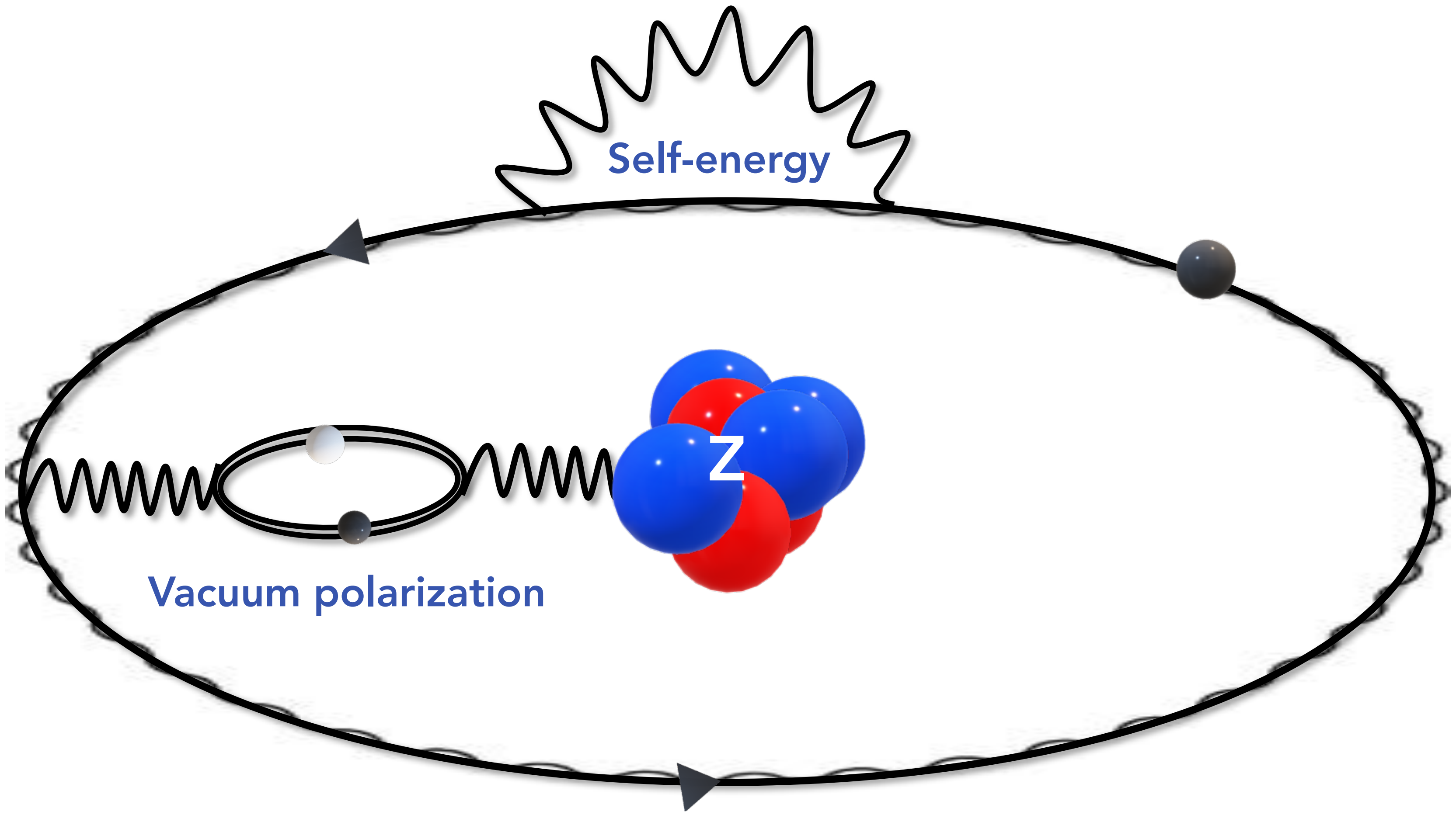
Quantum electrodynamics

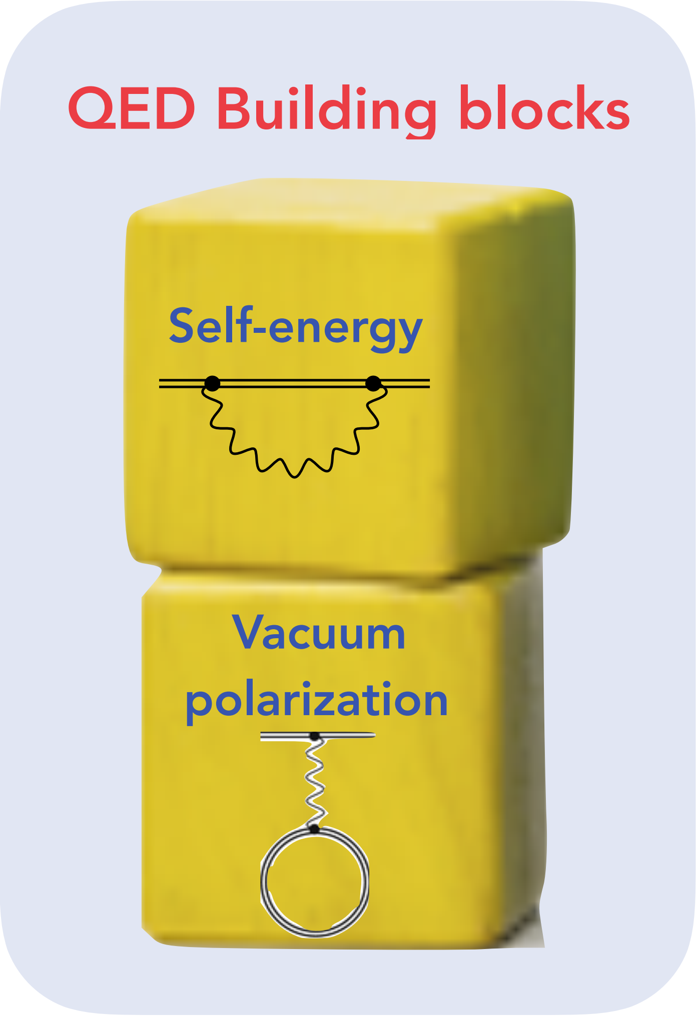


= QED test

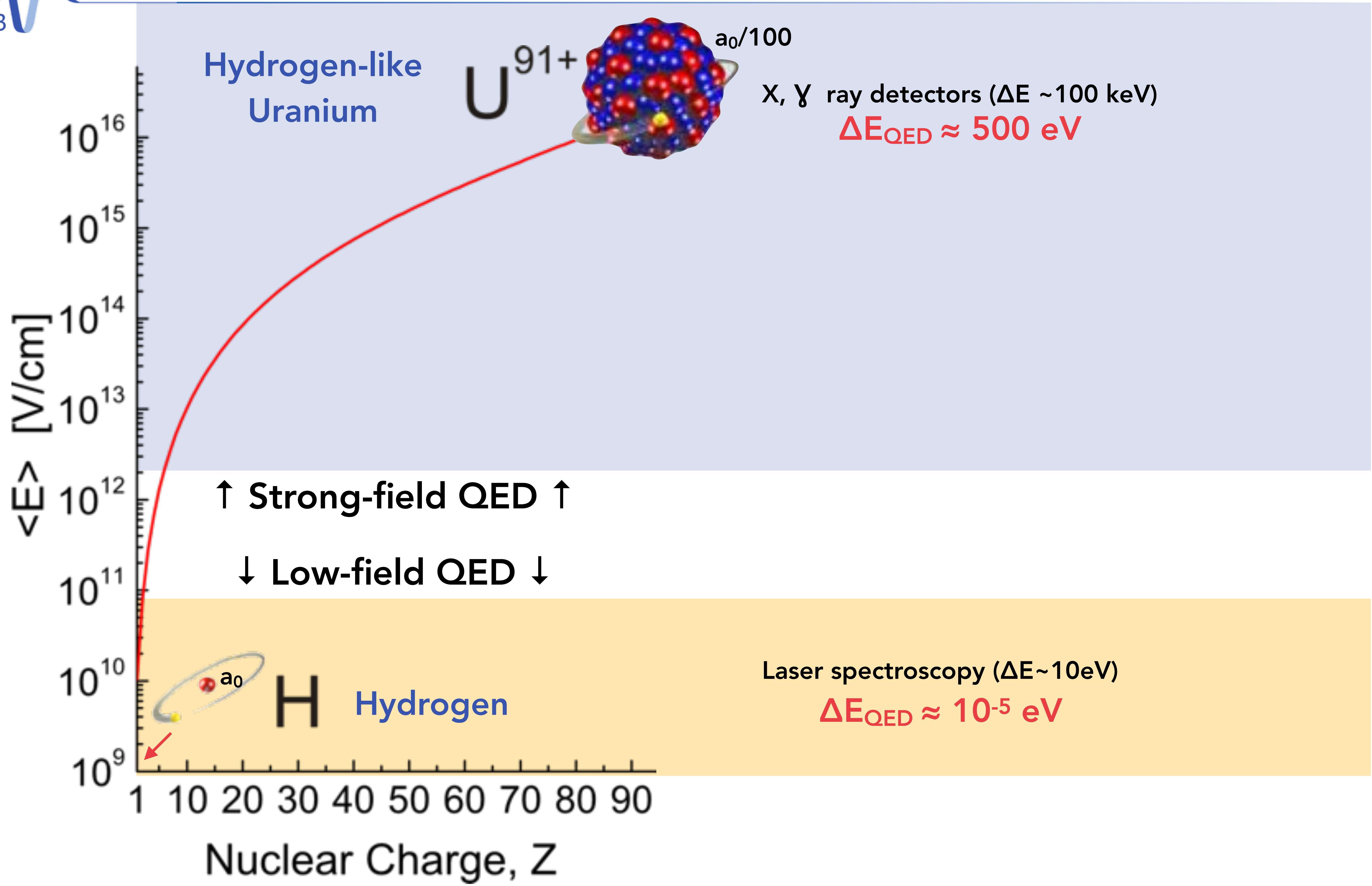
QED…?

Quantum electrodynamics : interactions between photons and charged particles

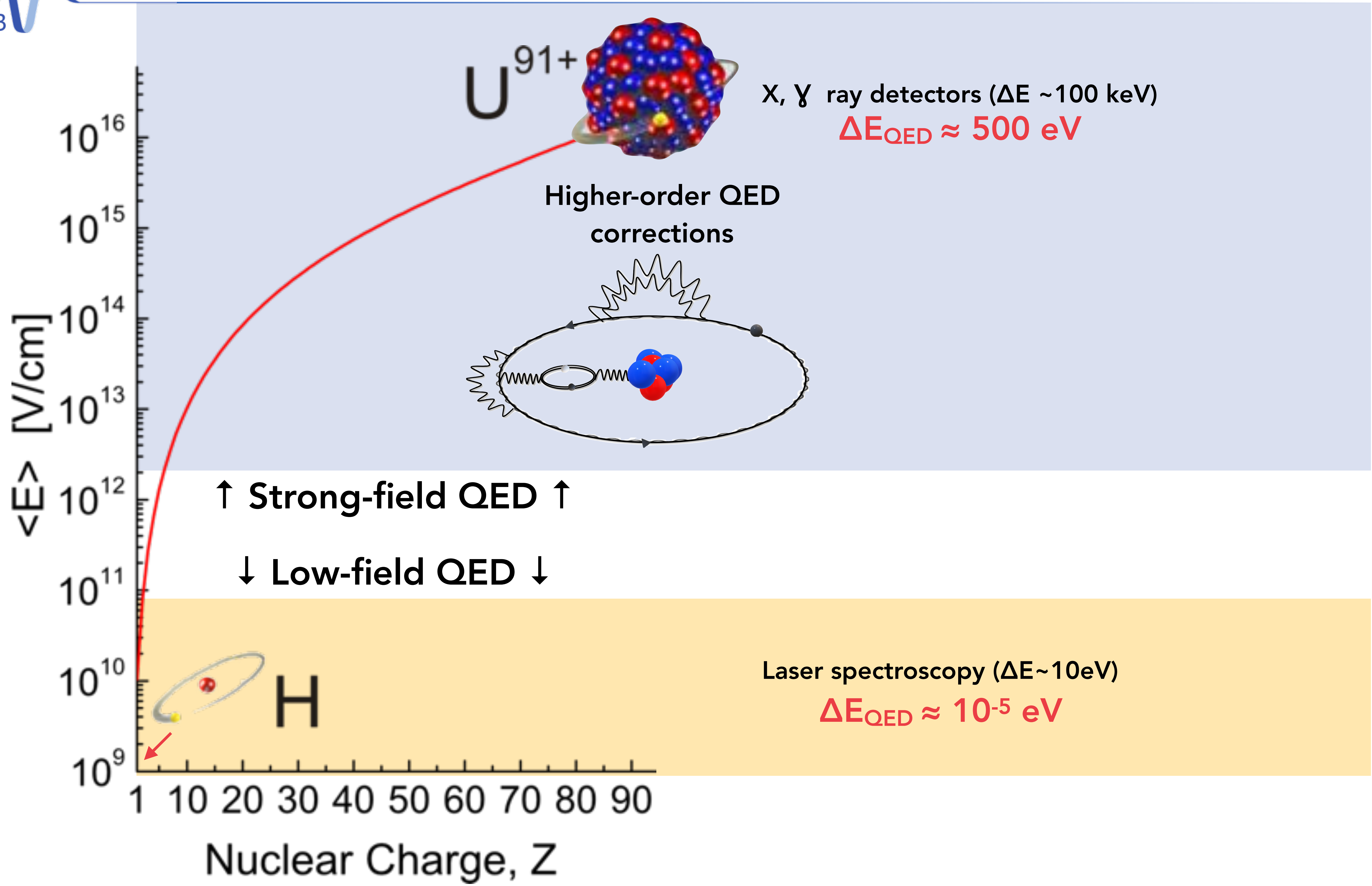




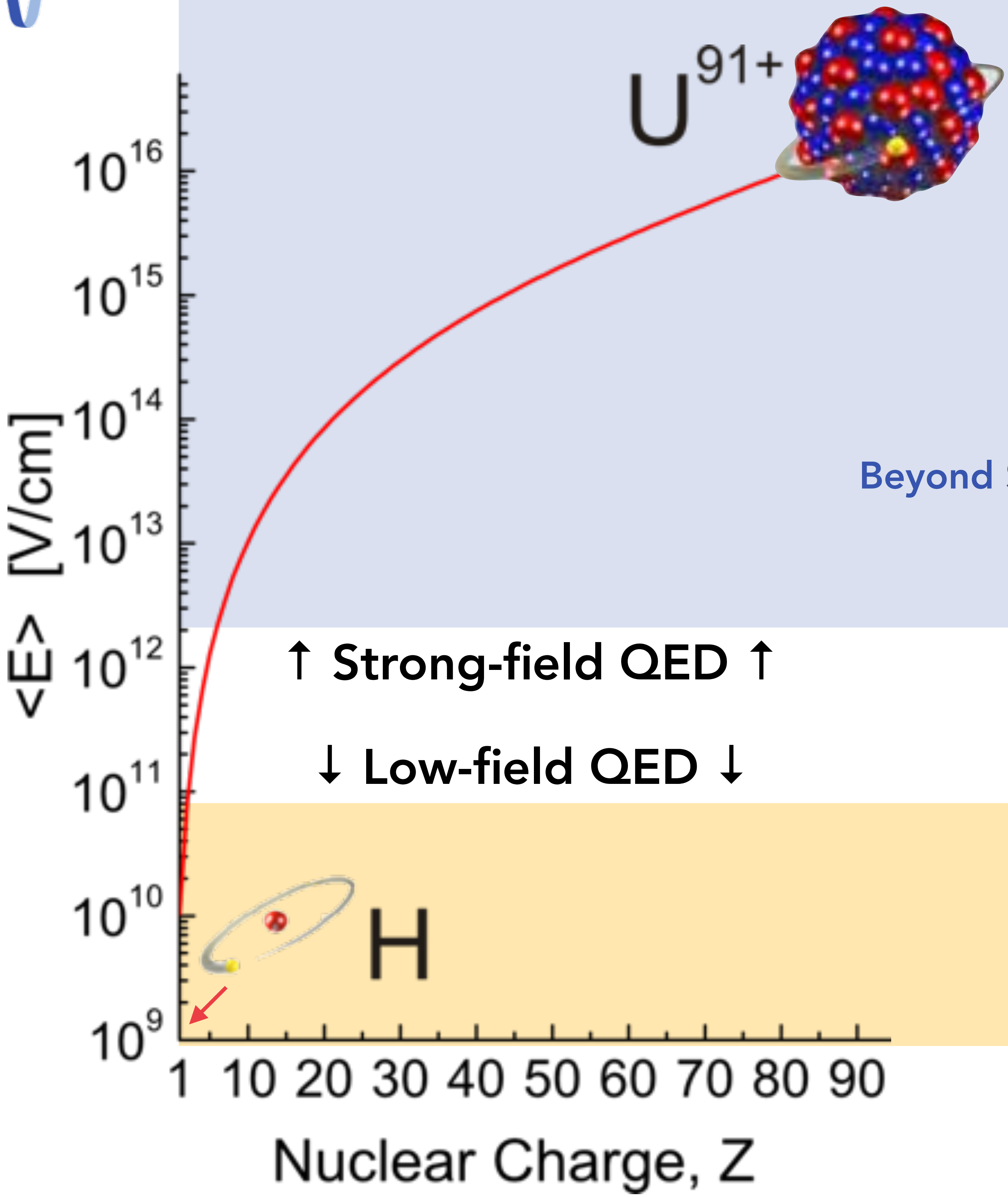
Strong field Bound State QED (BSQED)



Strong field Bound State QED (BSQED)

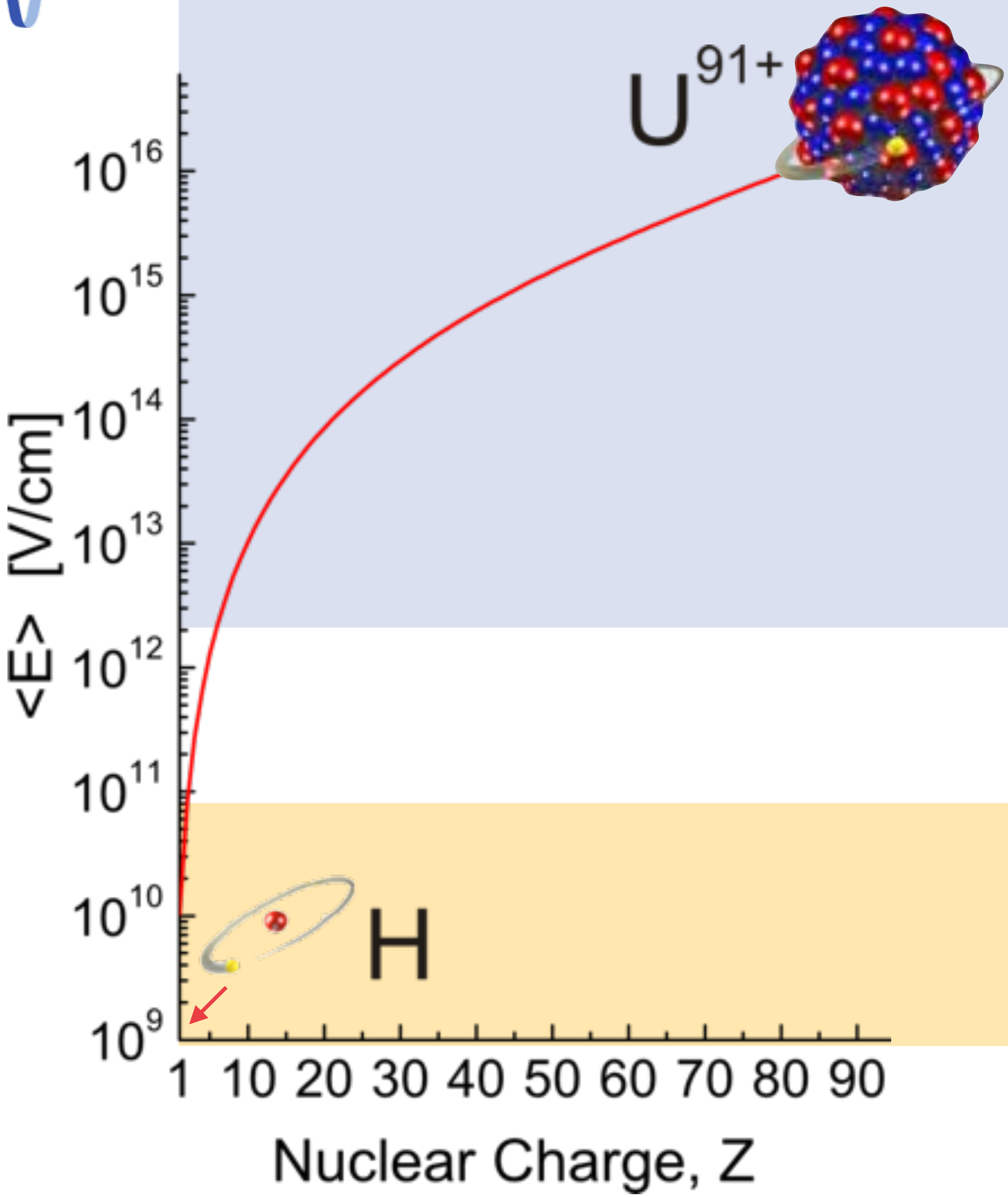


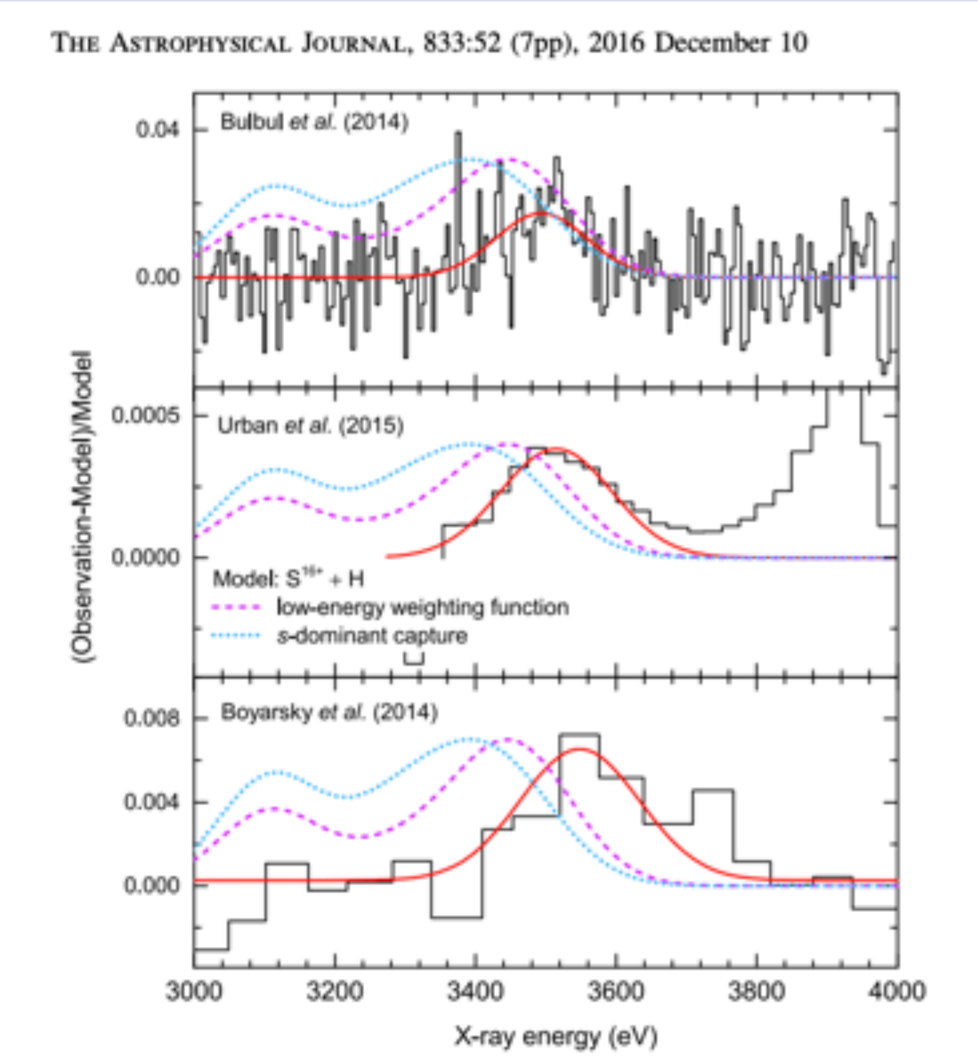
Strong field Bound State QED (BSQED)



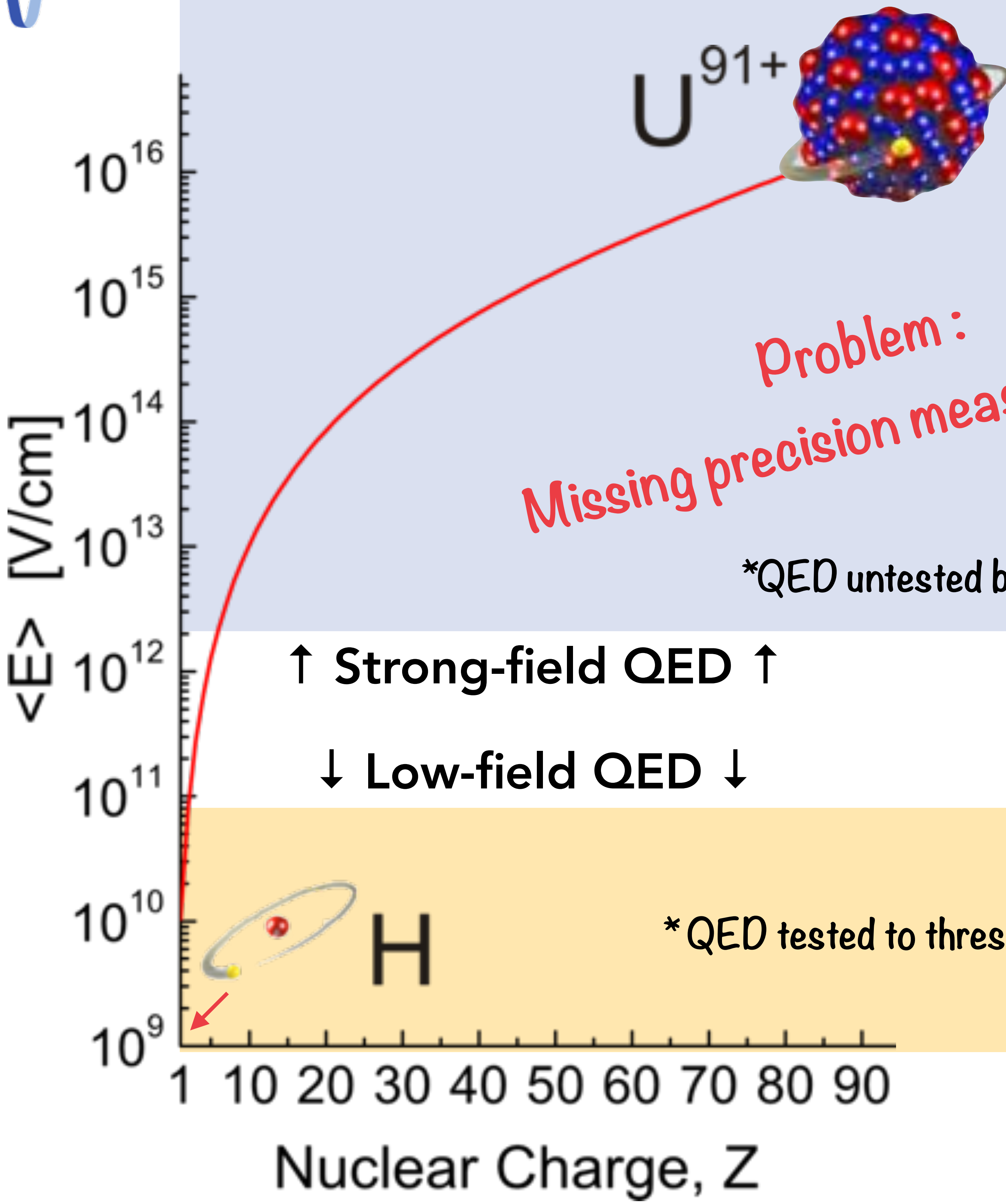
Stellar plasmas
Dark matter
Beyond Standard Model searches

Strong field Bound State QED (BSQED)





Strong field Bound State QED (BSQED)



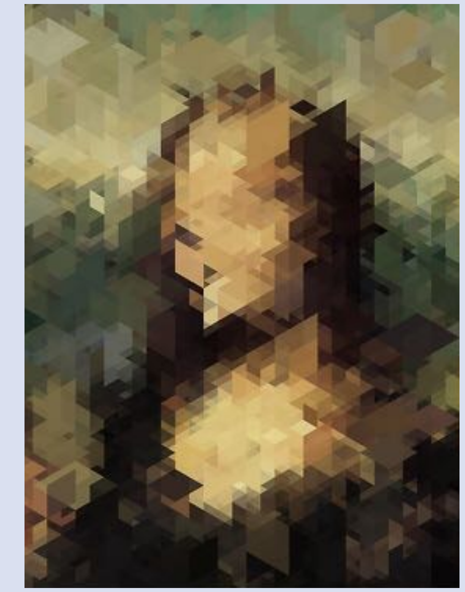
Problem :
Missing precision measurements!

*QED untested beyond 1st order effects

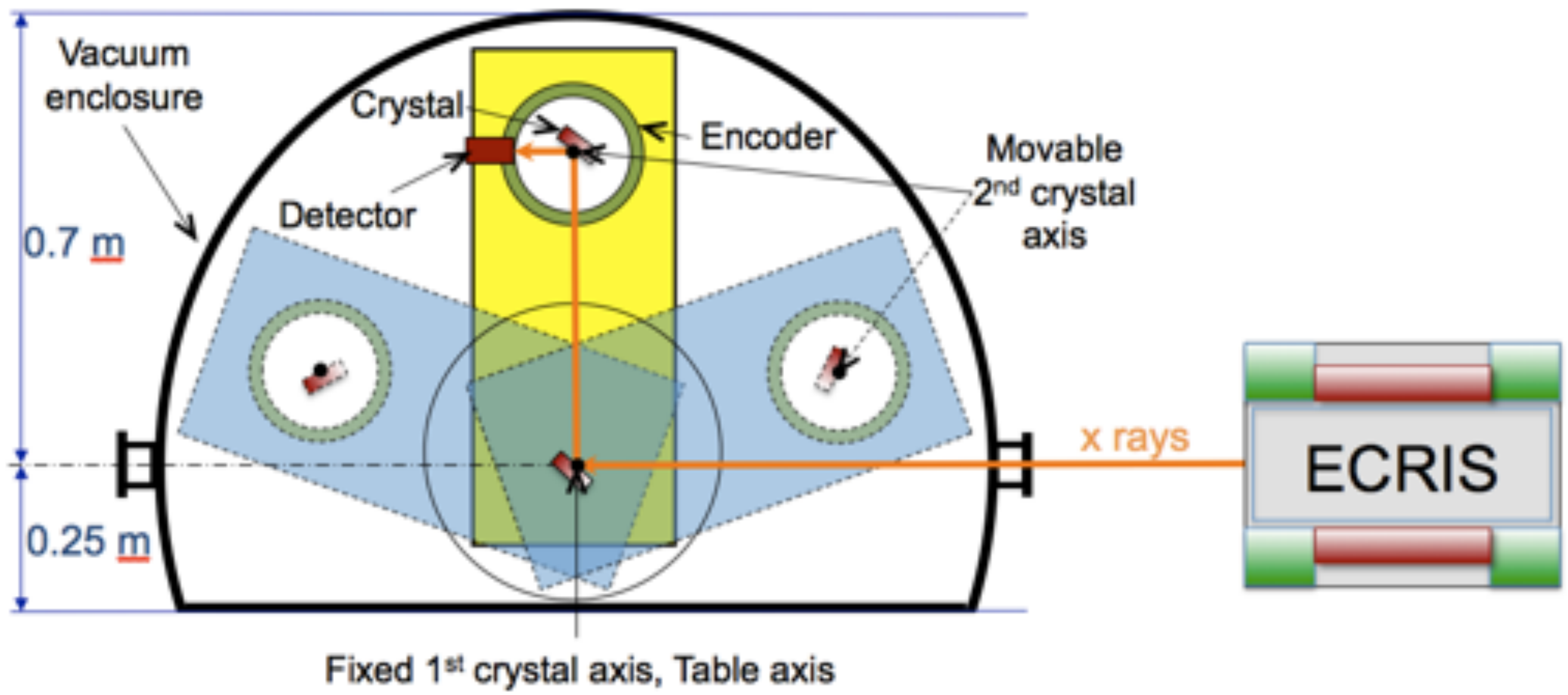
↑ Strong-field QED ↑

↓ Low-field QED ↓

* QED tested to threshold of 3rd order effects



Paris reference-free spectroscopy setup



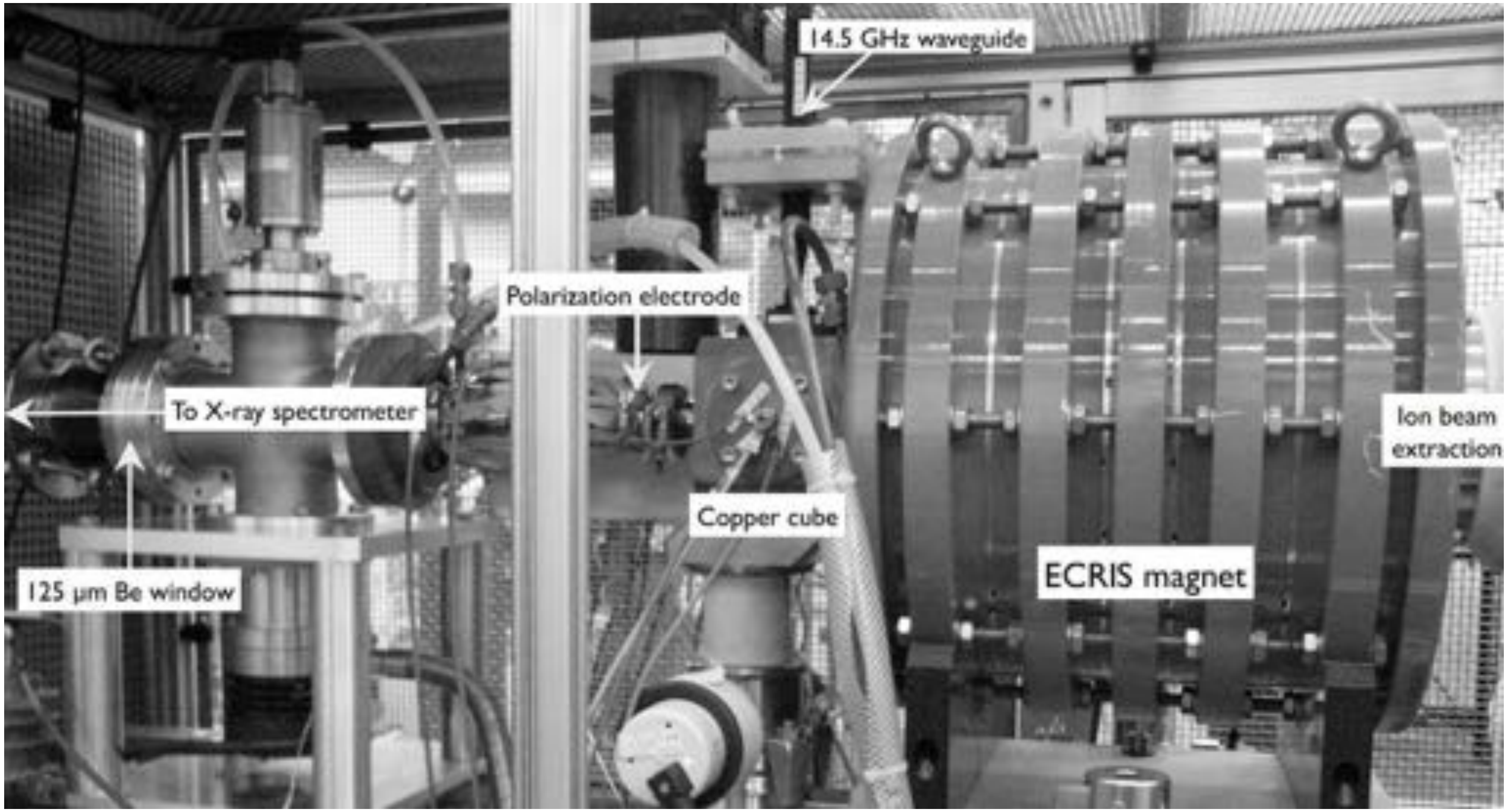
Laboratoire Kastler Brossel :

- **ECR plasma source**
- **Double crystal spectrometer**
- Si_{111} lattice spacing (d) known to 10^{-8}

Reference-free X-ray spectroscopy of highly-charged ions

World's best precision in this energy range (ppm)

SIMPA (Source d'Ions Multichargés de PAris)



INSP Institut des NanoSciences de Paris

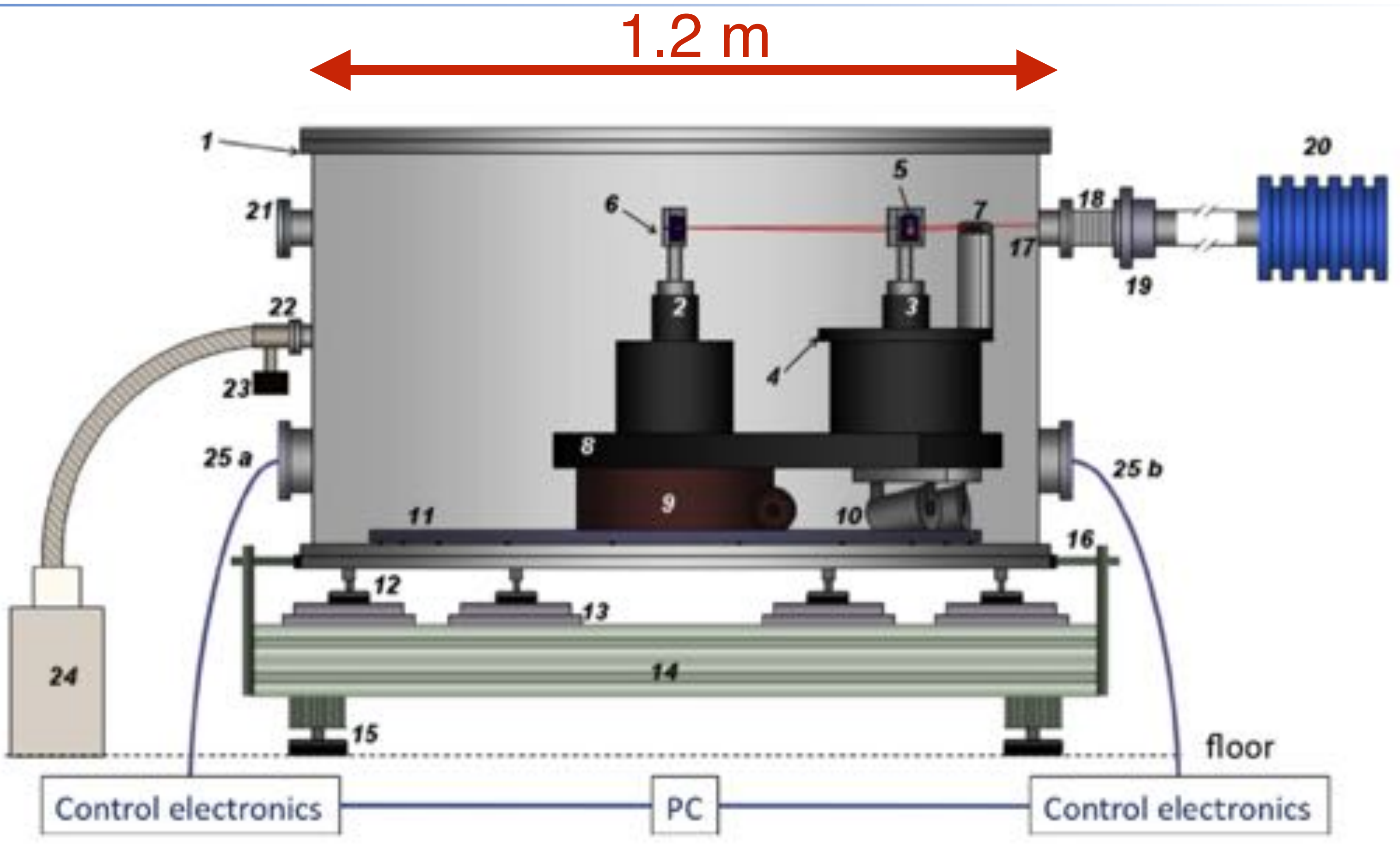
LKB

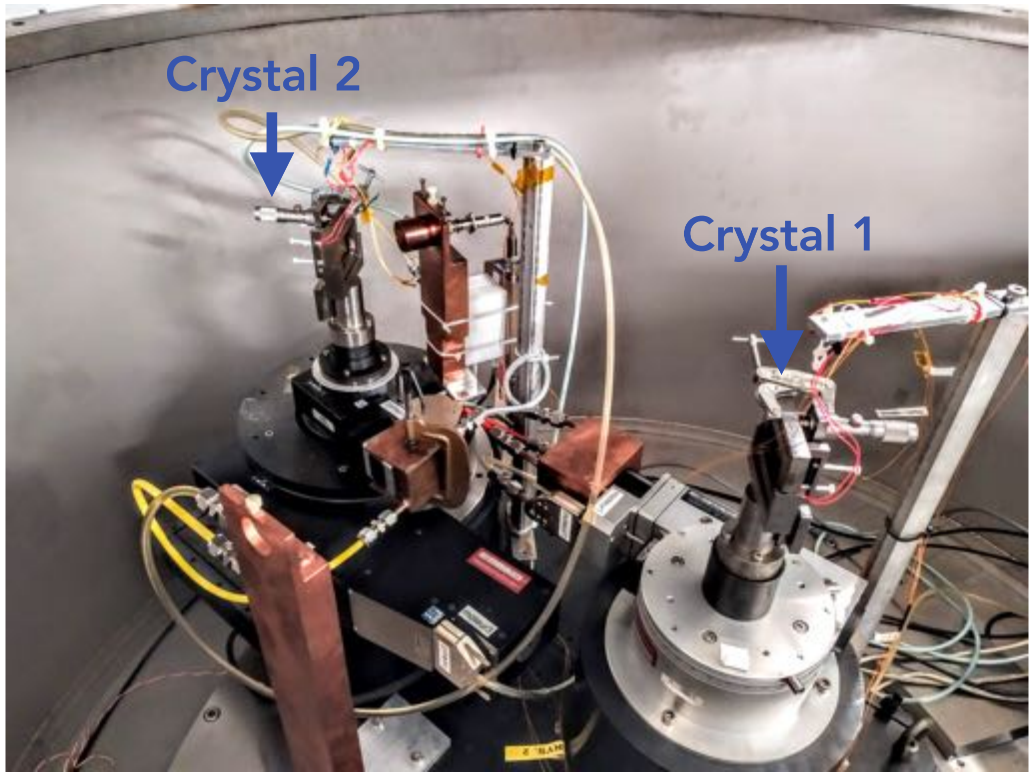
Microwaves : 14.5 GHz

Extraction voltage:
0 V to 25 kV

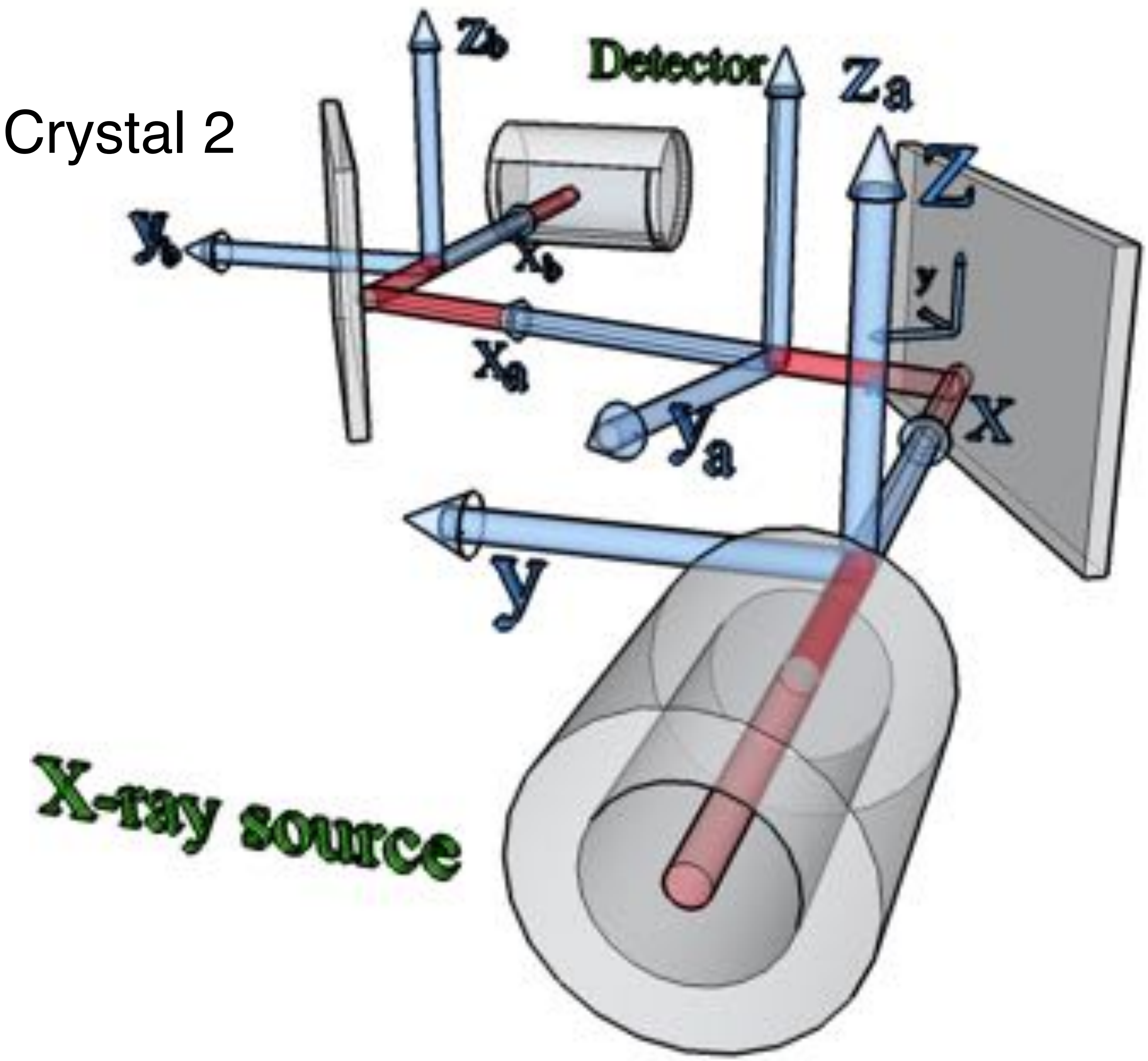
- Direct connection to plasma, 50μm thick Be window
- In the plasma the ions are trapped in the space charge of the electrons (~10^{11} e^{-}/cm^{3}), ~ few eV trapping depth
- Intense source, provides access to forbidden transitions, narrow linewidths

Double Crystal Spectrometer (DCS)



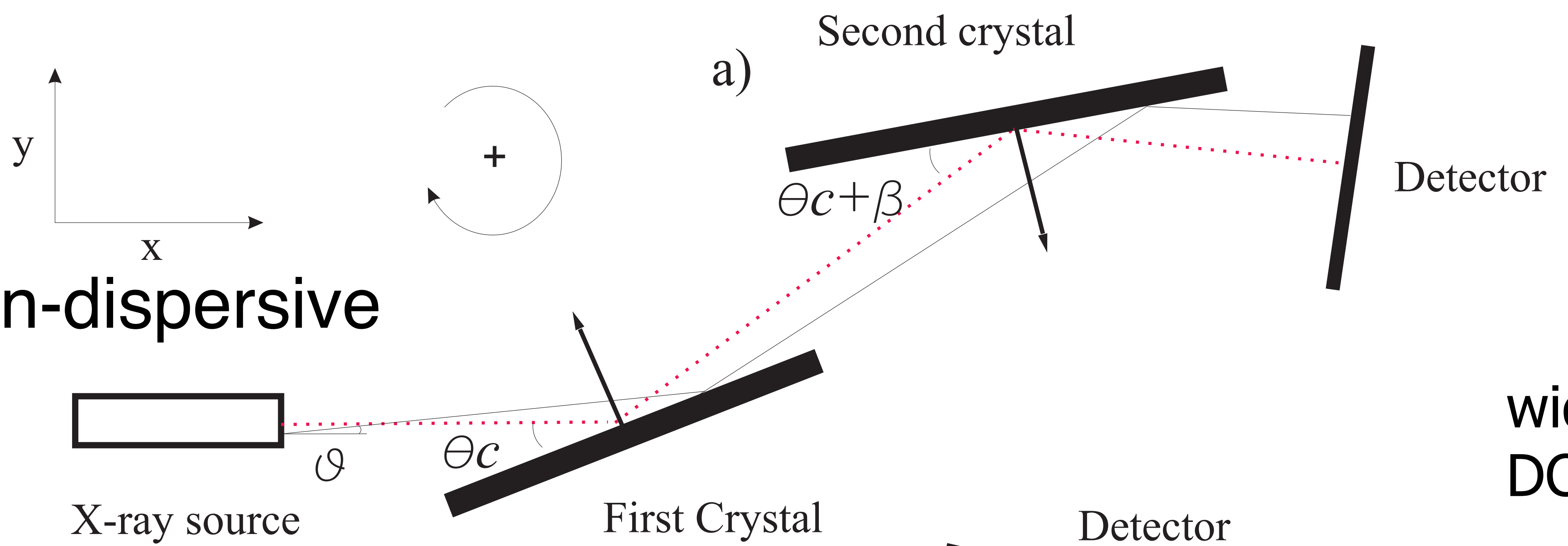


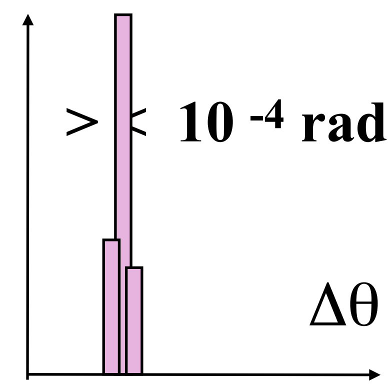
- Si_{111} crystals from NIST, lattice spacing (d) known to 10^{-8}
- Angular encoder for second axis: Heidenhain RON 905 with AWE 1024 interpolator →0.2″ of arc angular accuracy
- Detector : LAAPD (large area avalanche photodiode) cooled at -10°C


Crystal 2
Detector
Crystal 1
X-ray source

DCS Measurement Principle

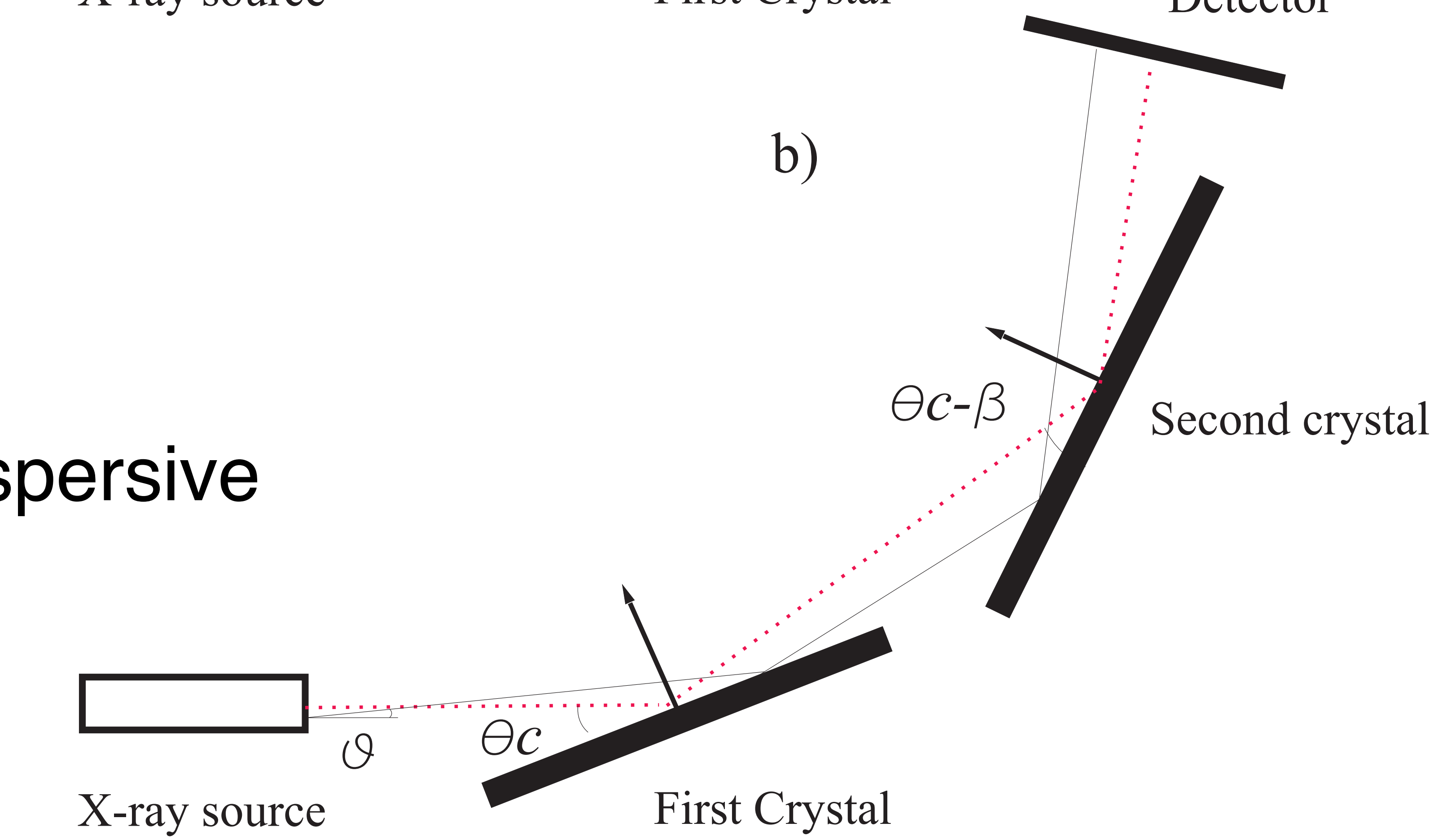
Non-dispersive

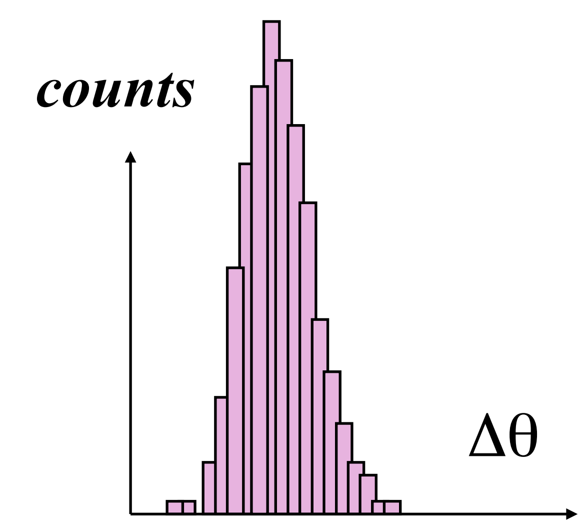




width :
DCS response function

Dispersive





width :
intrinsic line width
Doppler broadening
DCS response function

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)

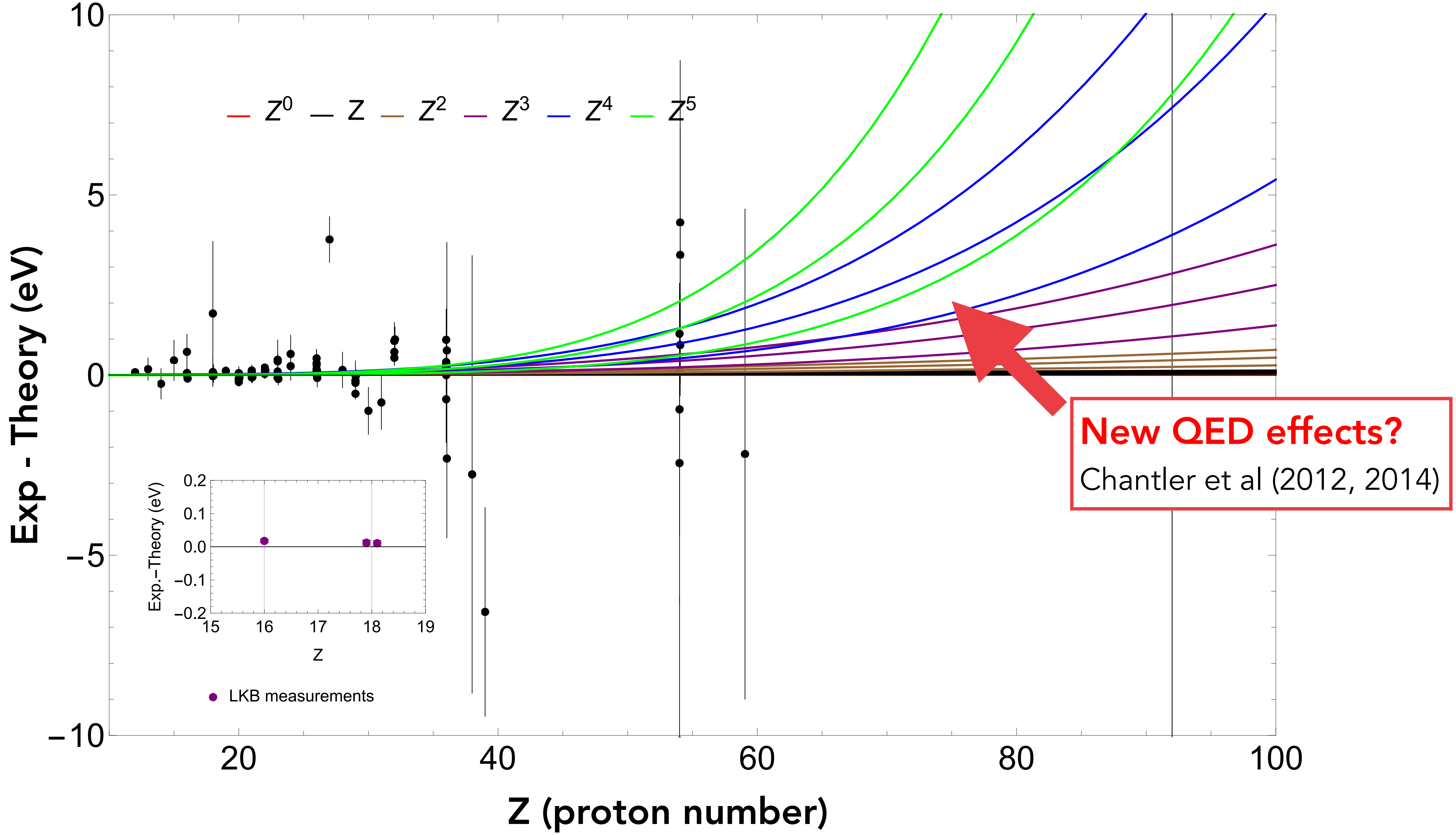
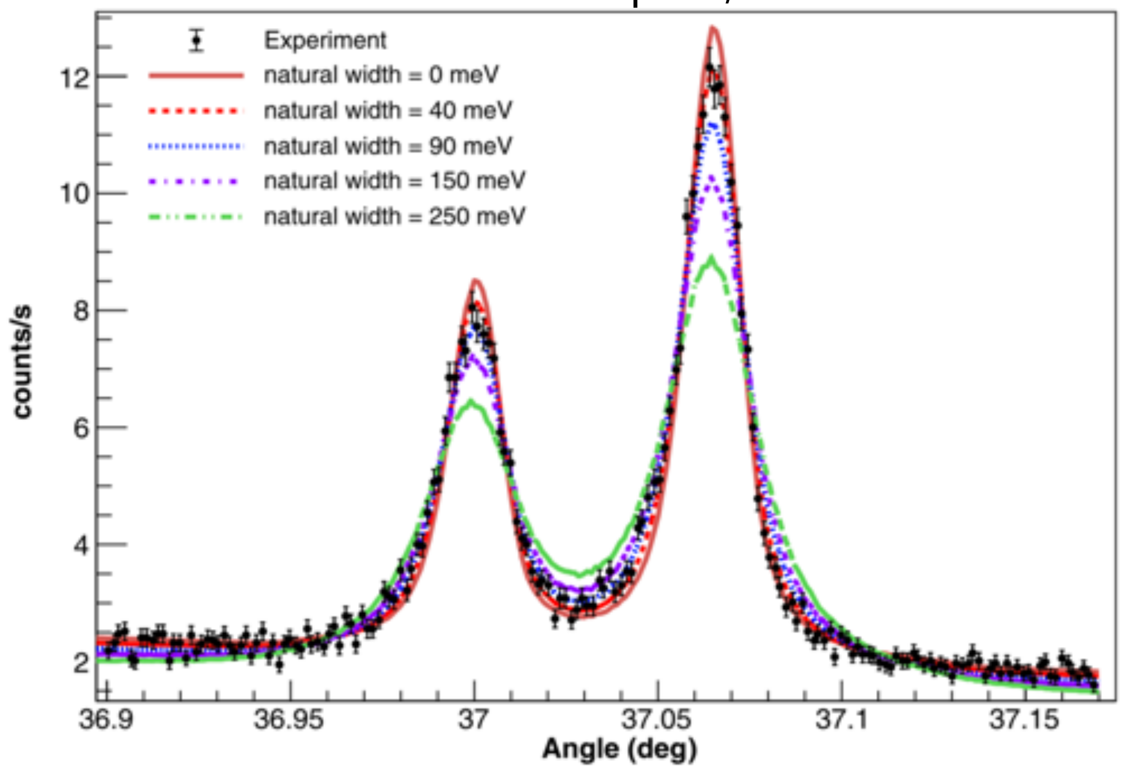


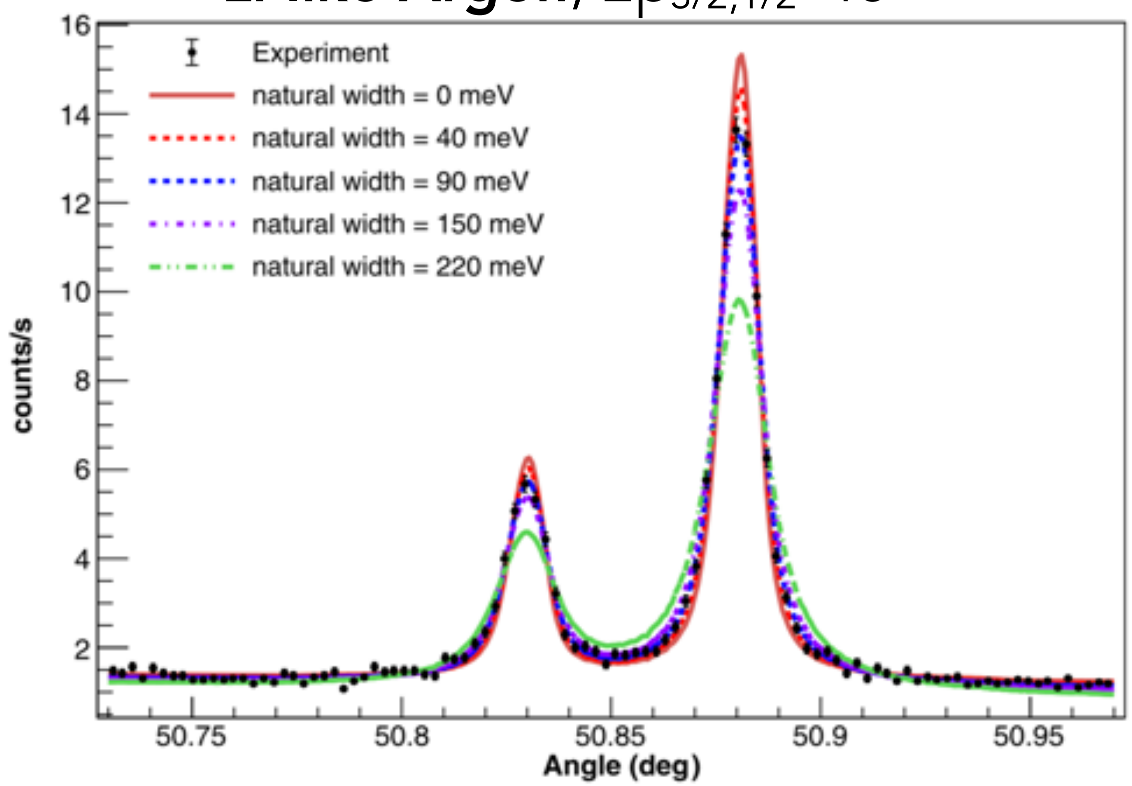
Figure adapted from P. Indelicato, Topical Review: QED tests with highly-charged ions, Journal of Physics B 52 (2019) 232001

Li-like Sulfur and Argon

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



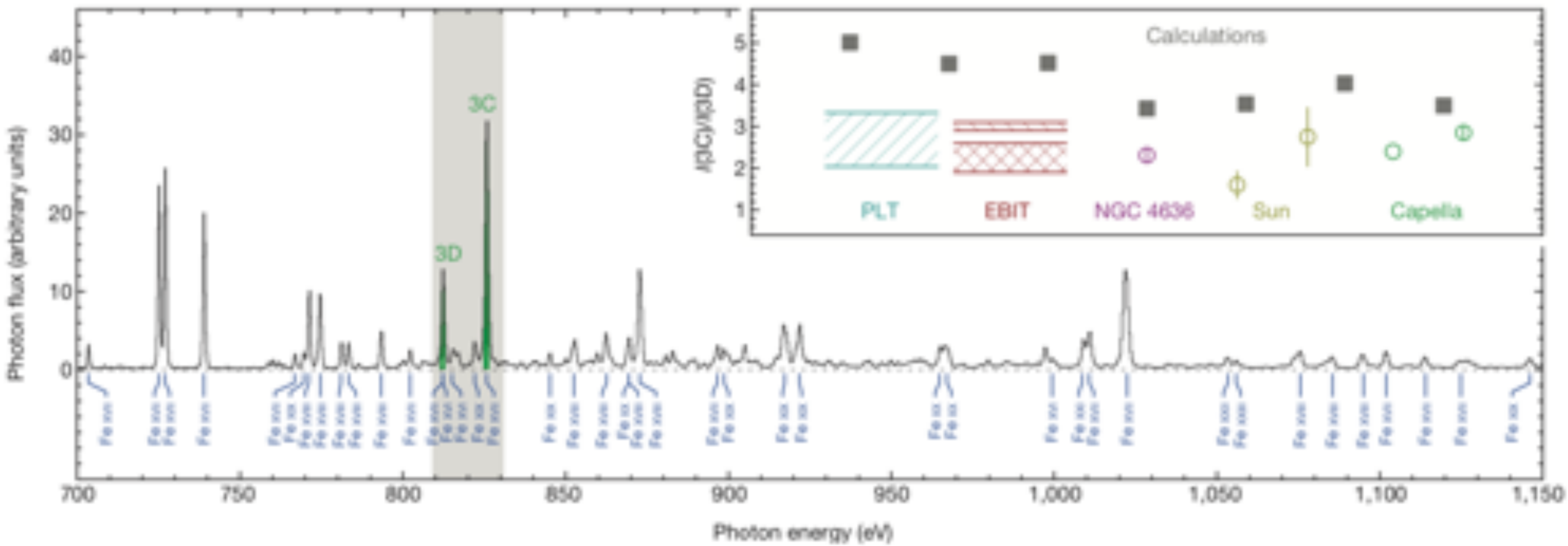
Li-like Argon, $2p_{3/2,1/2}$ -1s



- 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
- Bayesian analysis (NestedFit code by M. Trassinelli) searching for unknown contaminants suggested an additional component, but insufficient to explain the discrepancy.
- Similar to Ne-like iron problem?

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

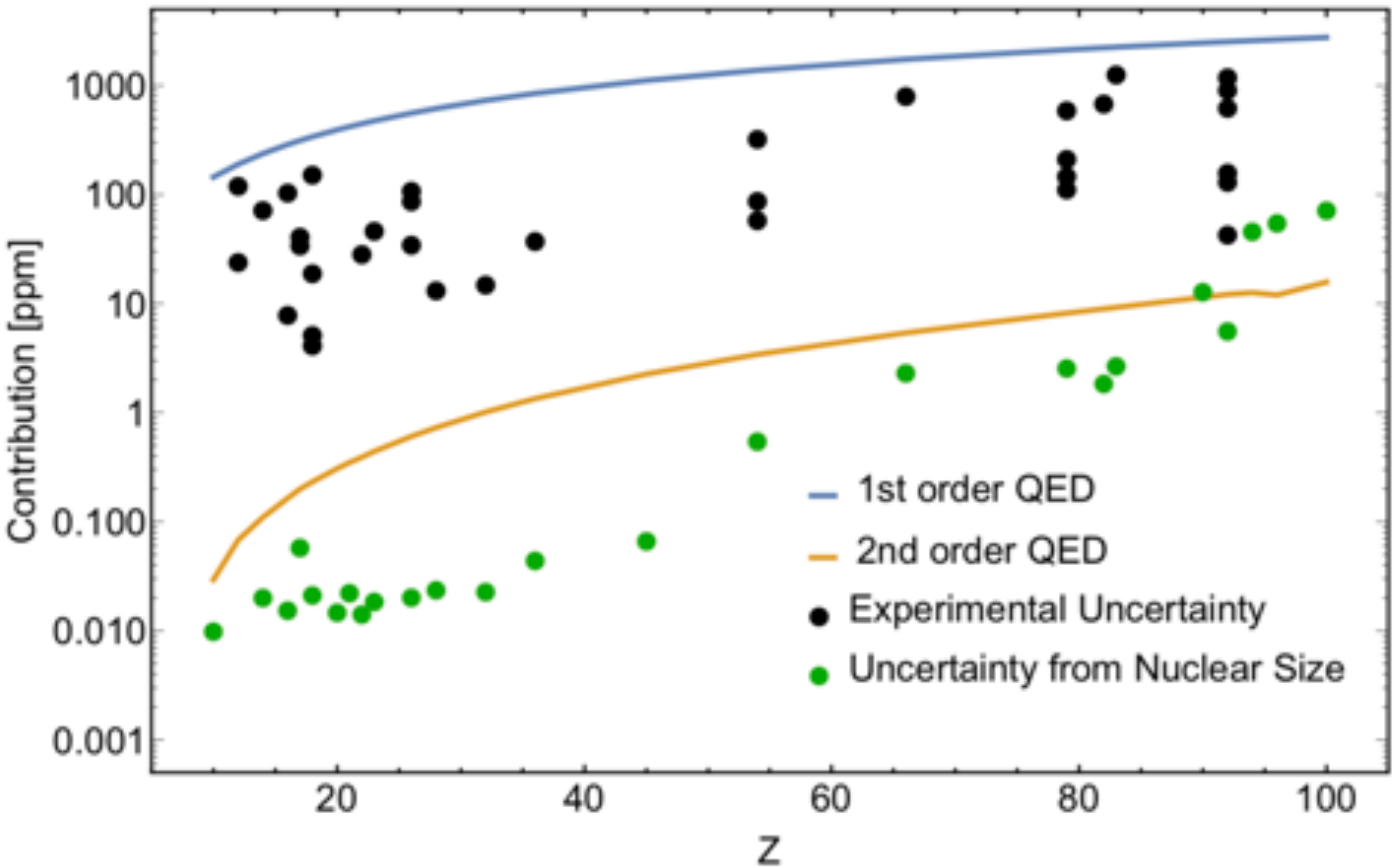
Fe 3C/3D problem



S. Bernitt et al, Nature 492, 25 (2012)

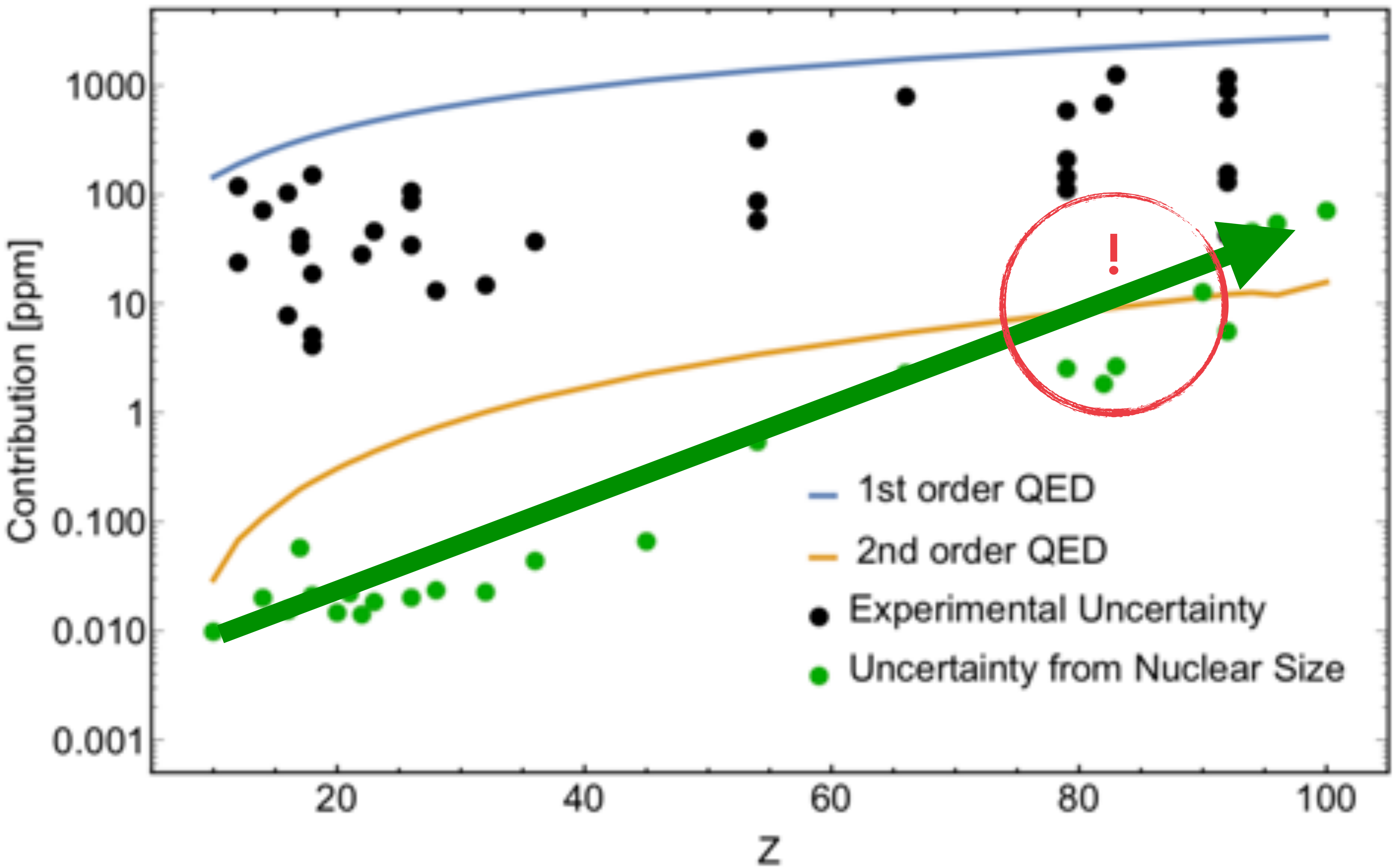
Limitations with HCI : Nuclear physics!

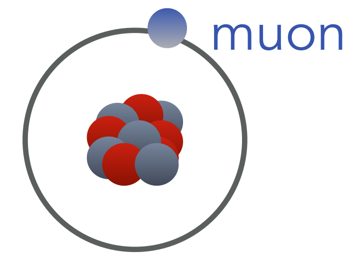
Lyman-α transitions in hydrogen-like ions



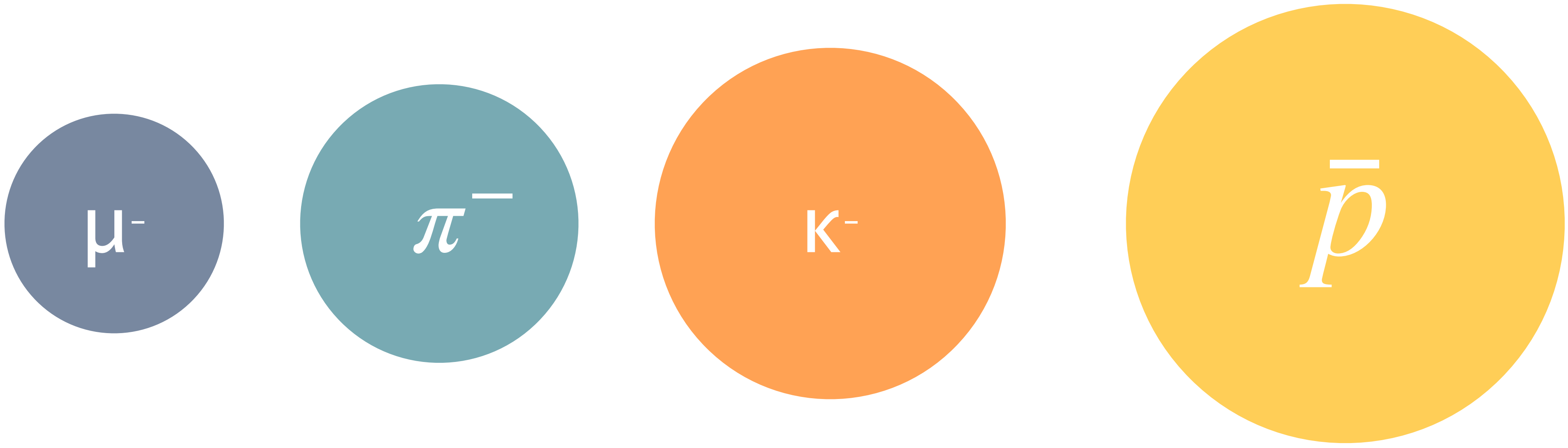
Limitations with HCI : Nuclear physics!

Lyman-α transitions in hydrogen-like ions





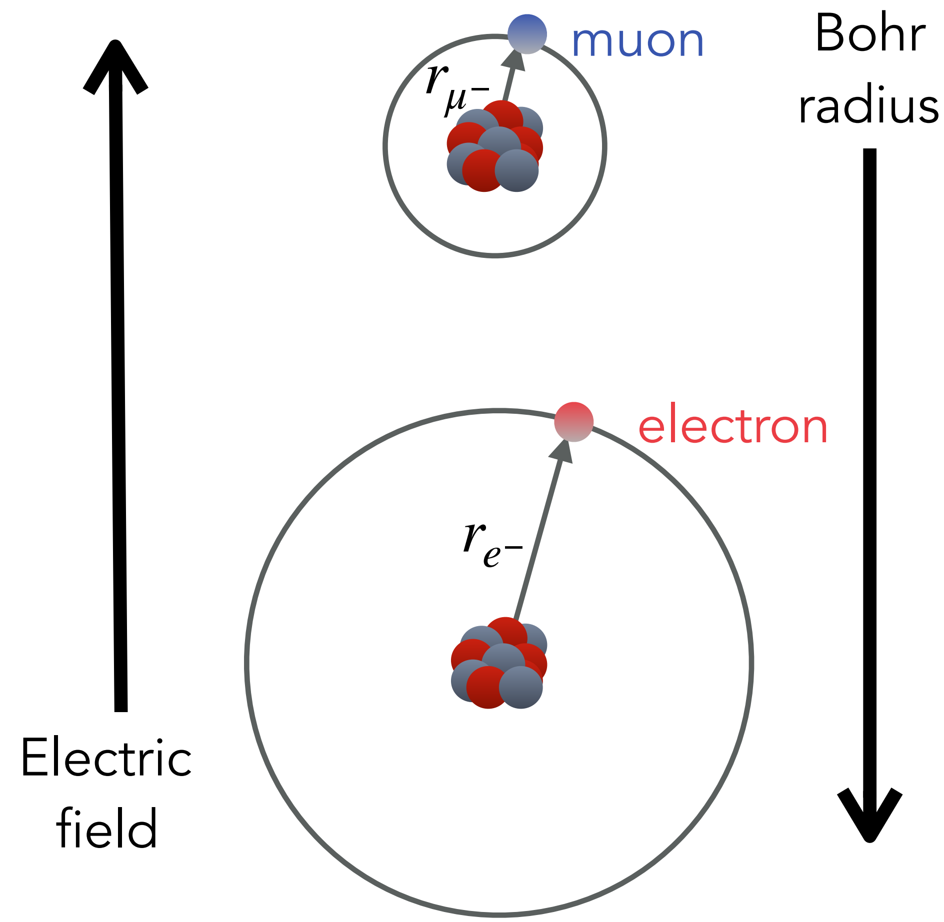
Exotic atoms



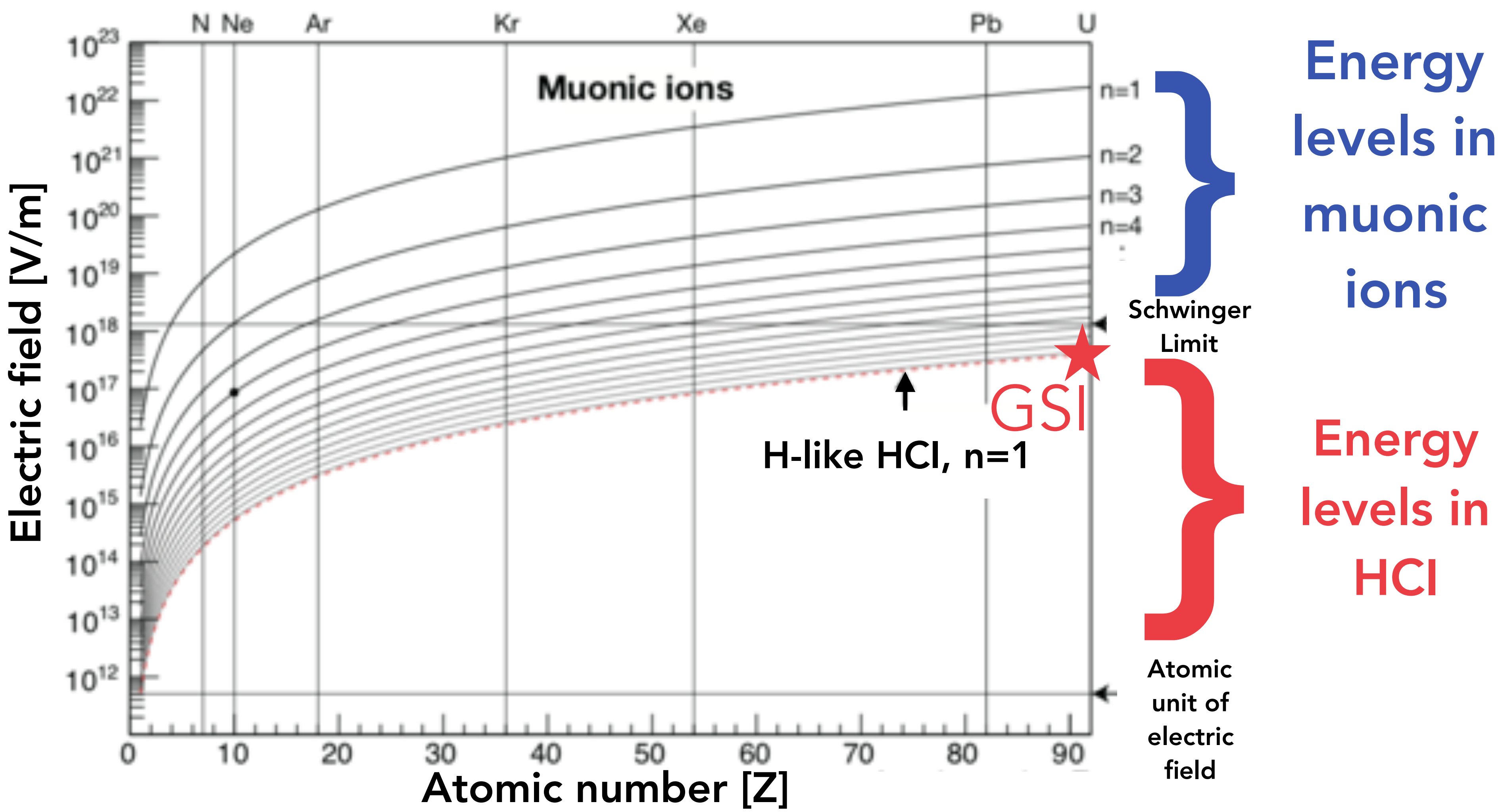
Exotic atoms

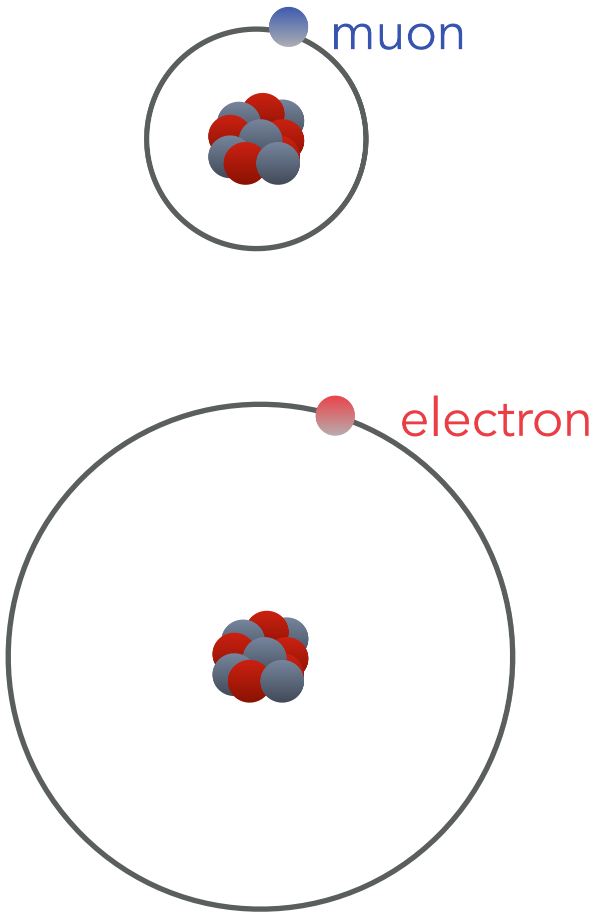
$$m_{\mu^-} = 207 m_{e^-}$$

$$r_{\mu^-} \sim \frac{1}{207} r_{e^-}$$



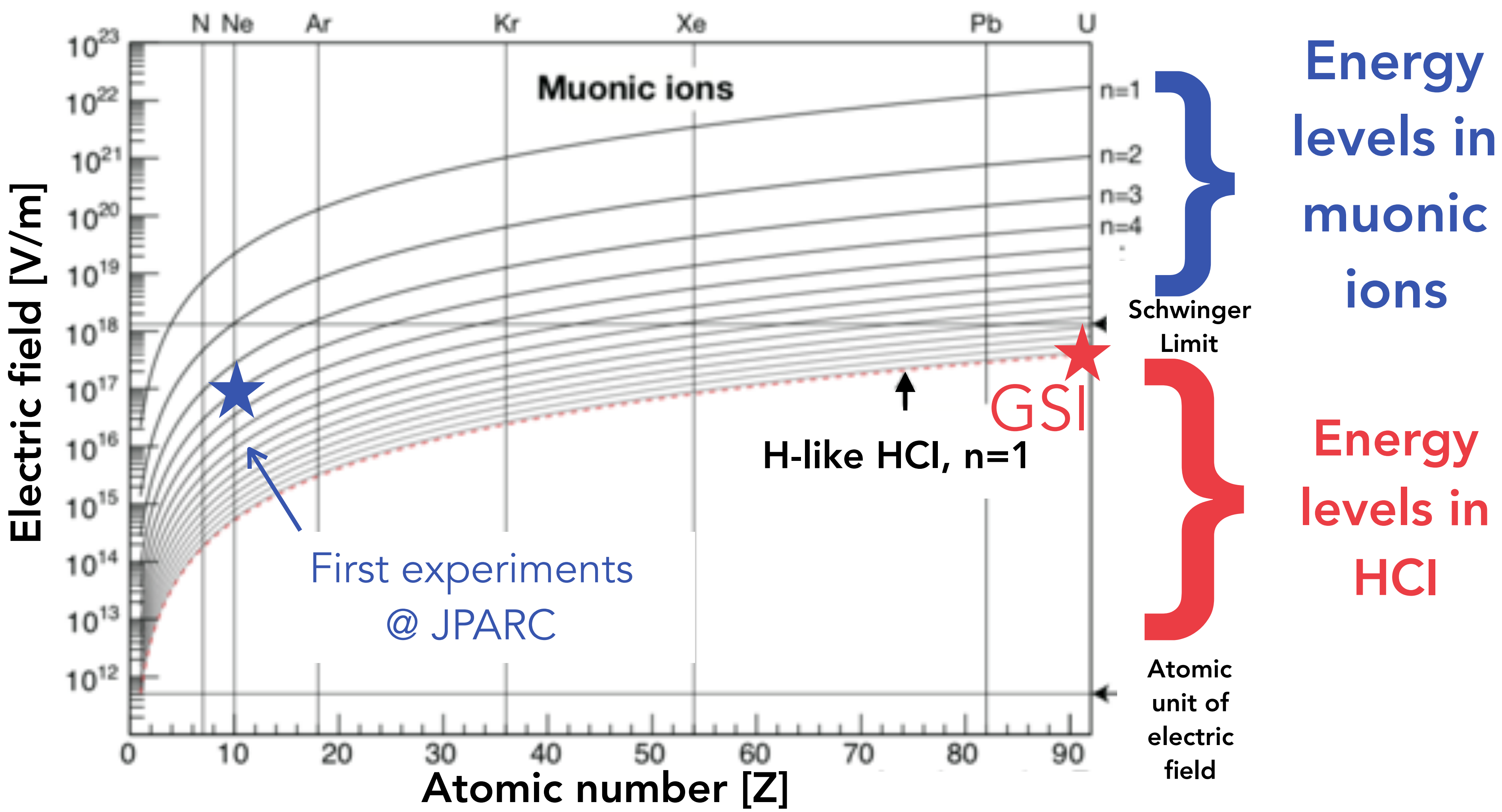
Strong-field QED with muonic atoms

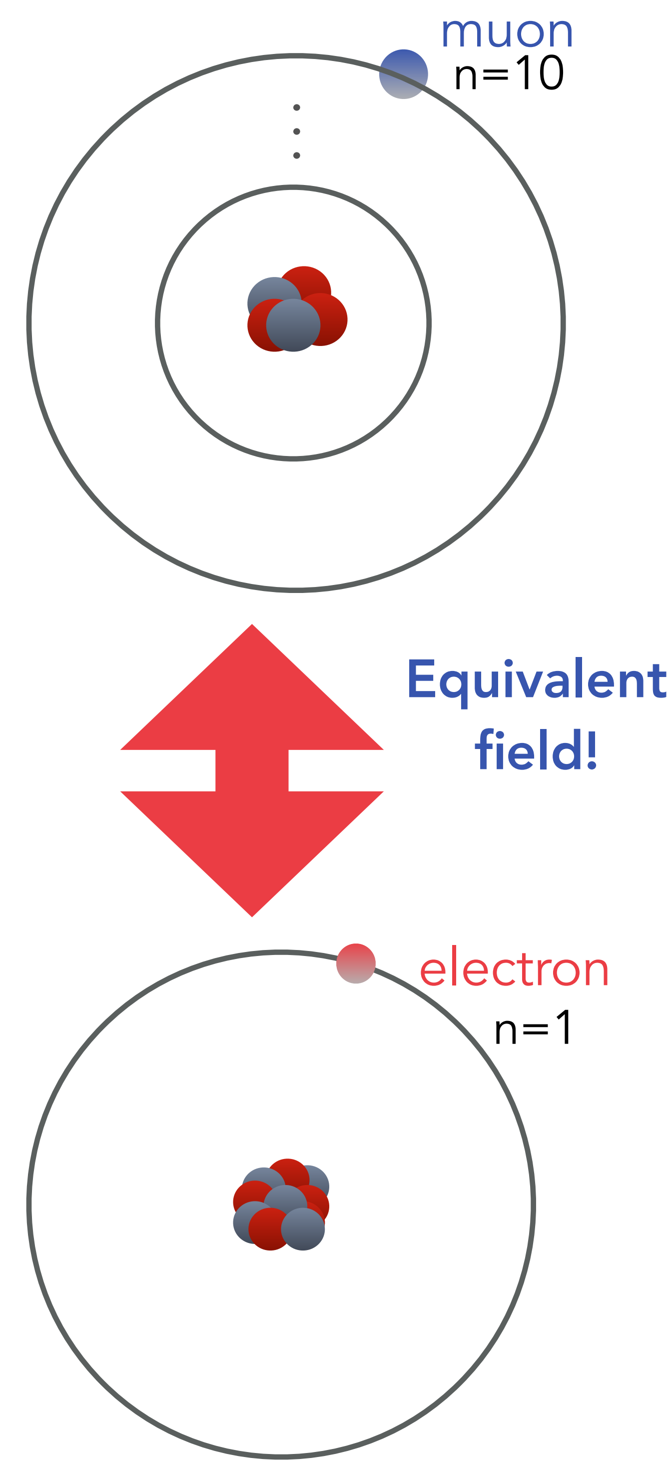




N. Paul et al, PRL 126, 173001 (2021)

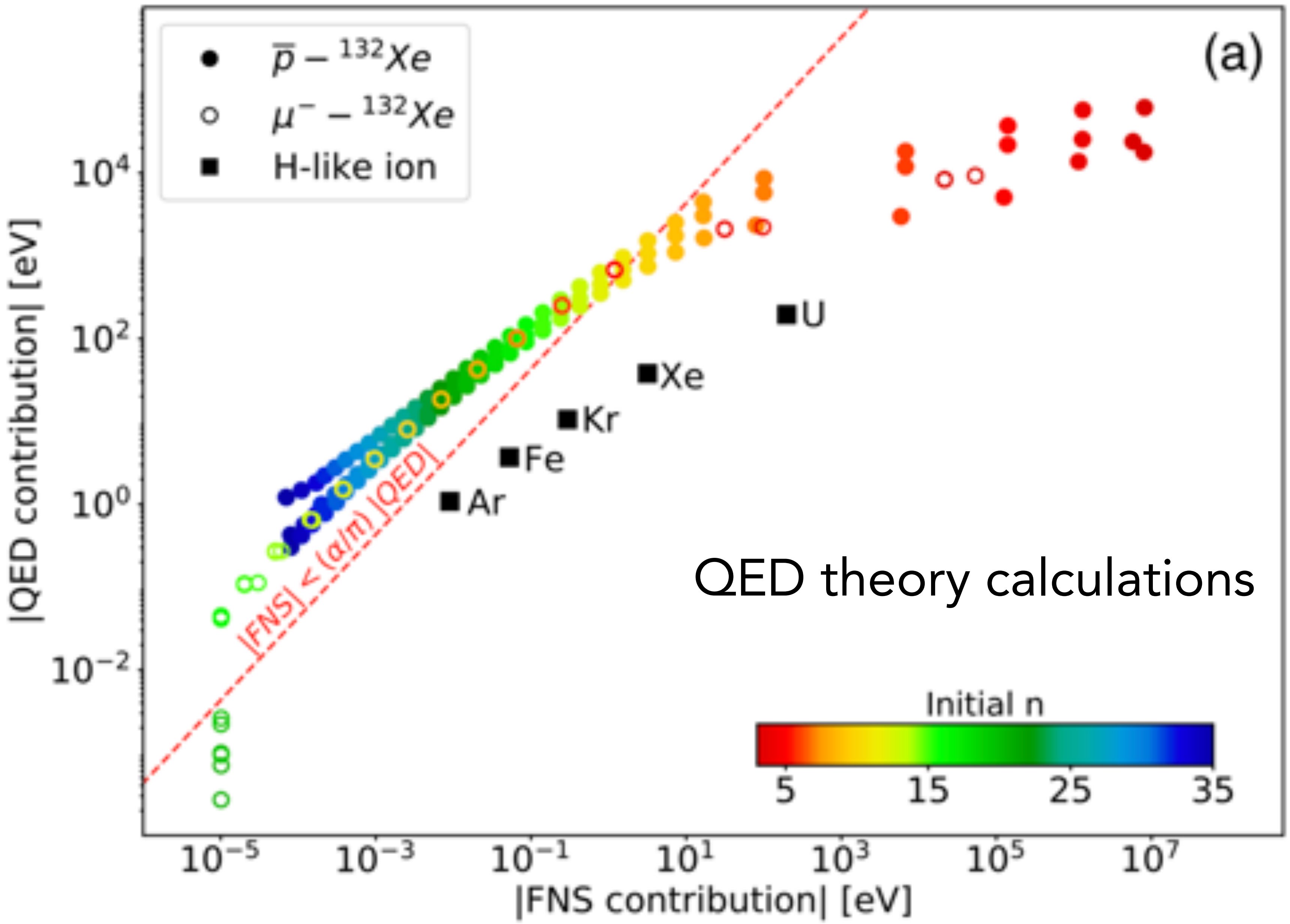
Strong-field QED with muonic atoms





Exotic atoms:
(strong field) x (Rydberg states)
Vanishing nuclear uncertainties!

QED vs Finite Nuclear Size

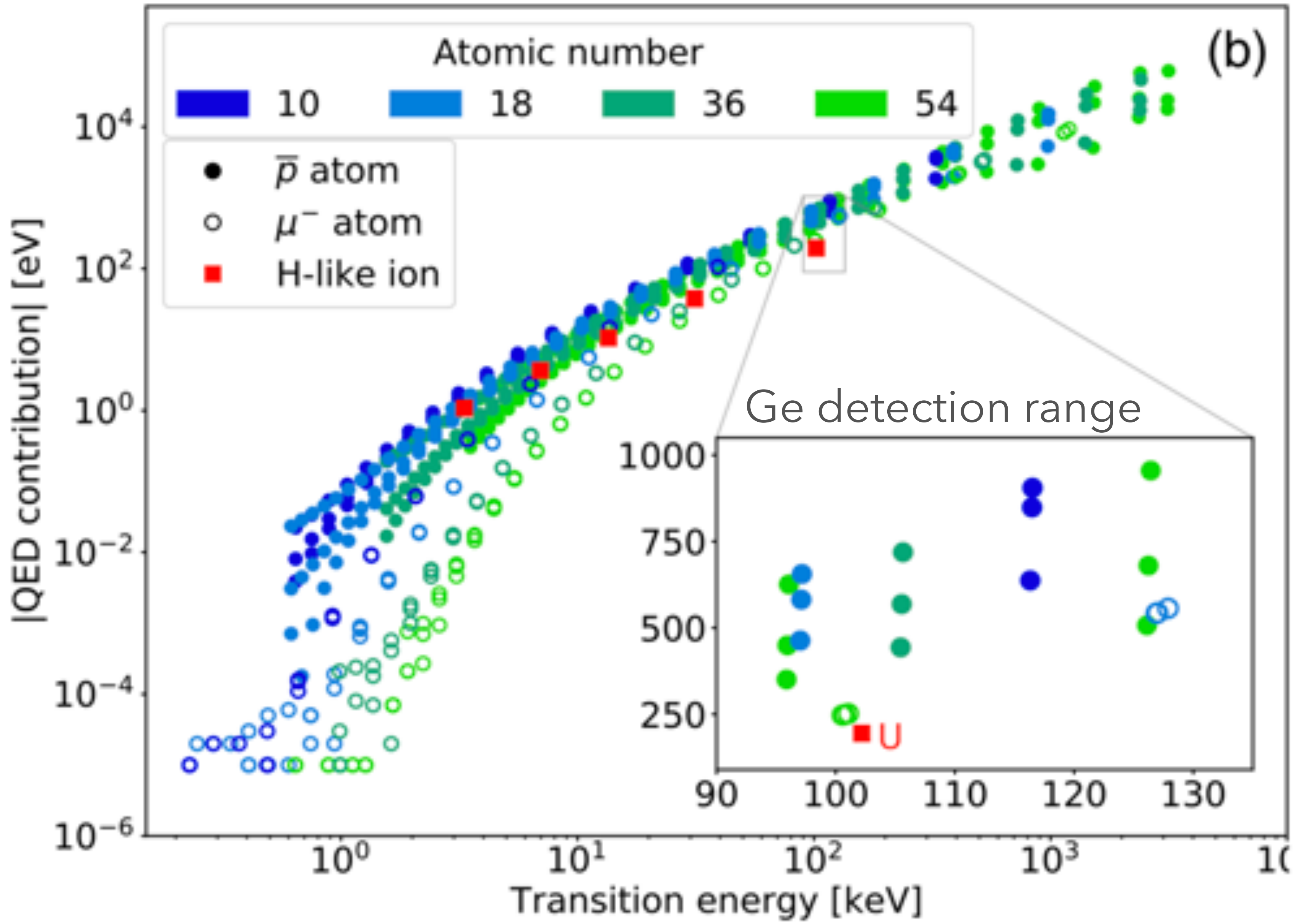


Precision QED calculations performed for radiative cascade in muonic atoms from H →U

Multiconfiguration Dirac Fock code (*MCDFGME*, P. Indelicato, J.P. Desclaux)

One order of magnitude gain in sensitivity compared to normal H-like ions, **by avoiding nuclear physics uncertainties**

QED vs Transition Energy

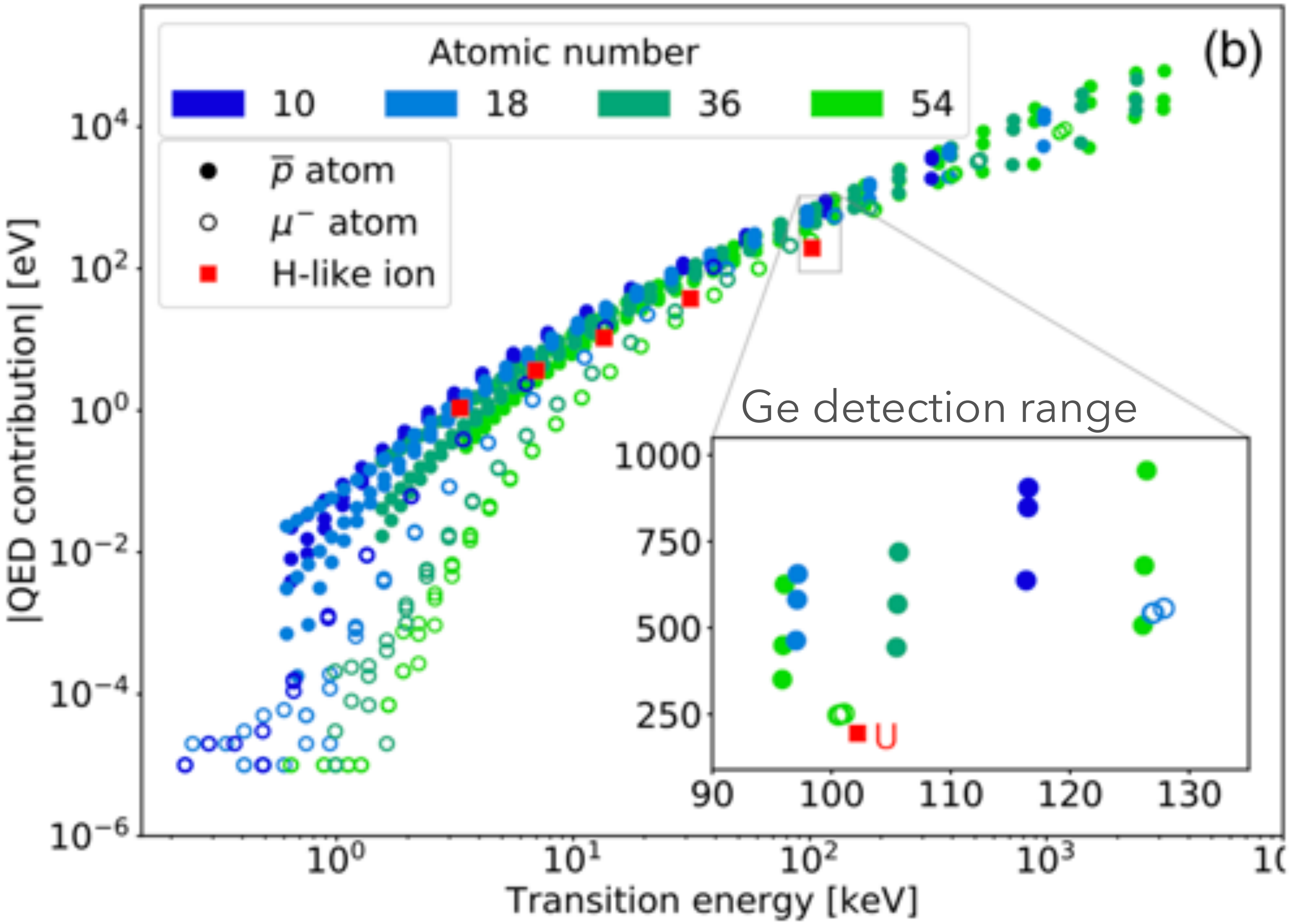


Larger QED contributions to transition energies, accessible for lower-Z ions

Factor of 2-10 gain in QED enhancement for a given detection range

QED effects in exotic atoms are bigger for a given Z, thus easier to measure

QED vs Transition Energy

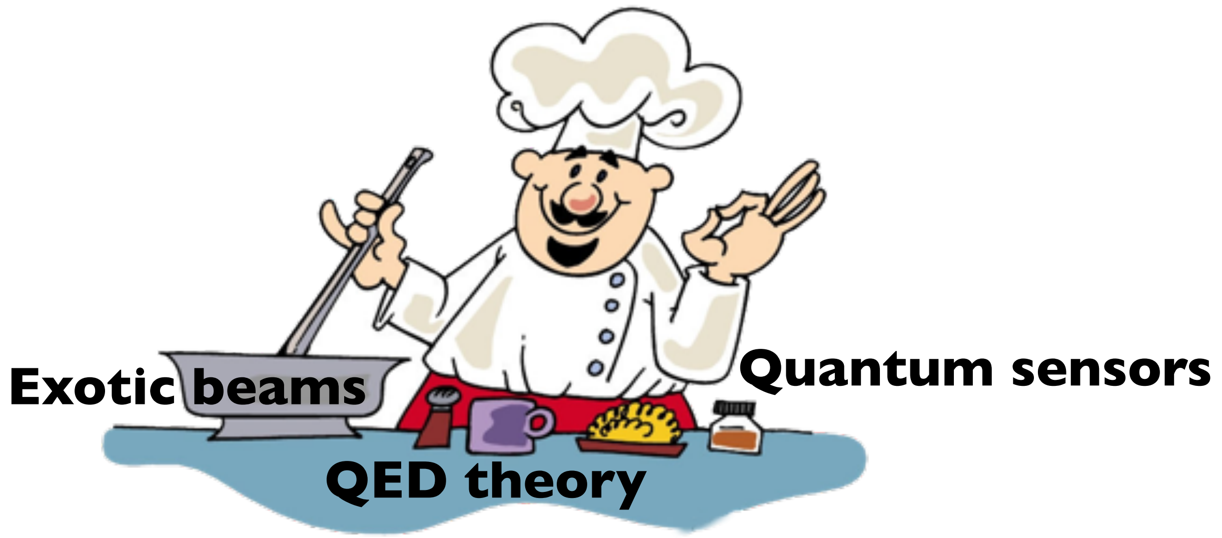


Atom	Transition	Transition energy (eV)	1st order QED	2nd order QED	Nuclear effects	Exp. error
H-like U	Lyman α1	102175.1	2.5×10^{-3}	1×10^{-5}	2×10^{-3}	4×10^{-5}
antiprotonic-Xe	12o21/2→11n21/2	96065.3	6.5×10^{-3}	6×10^{-5}	1×10^{-5}	5×10^{-6}

QED x 3 Nuclear effects / 100

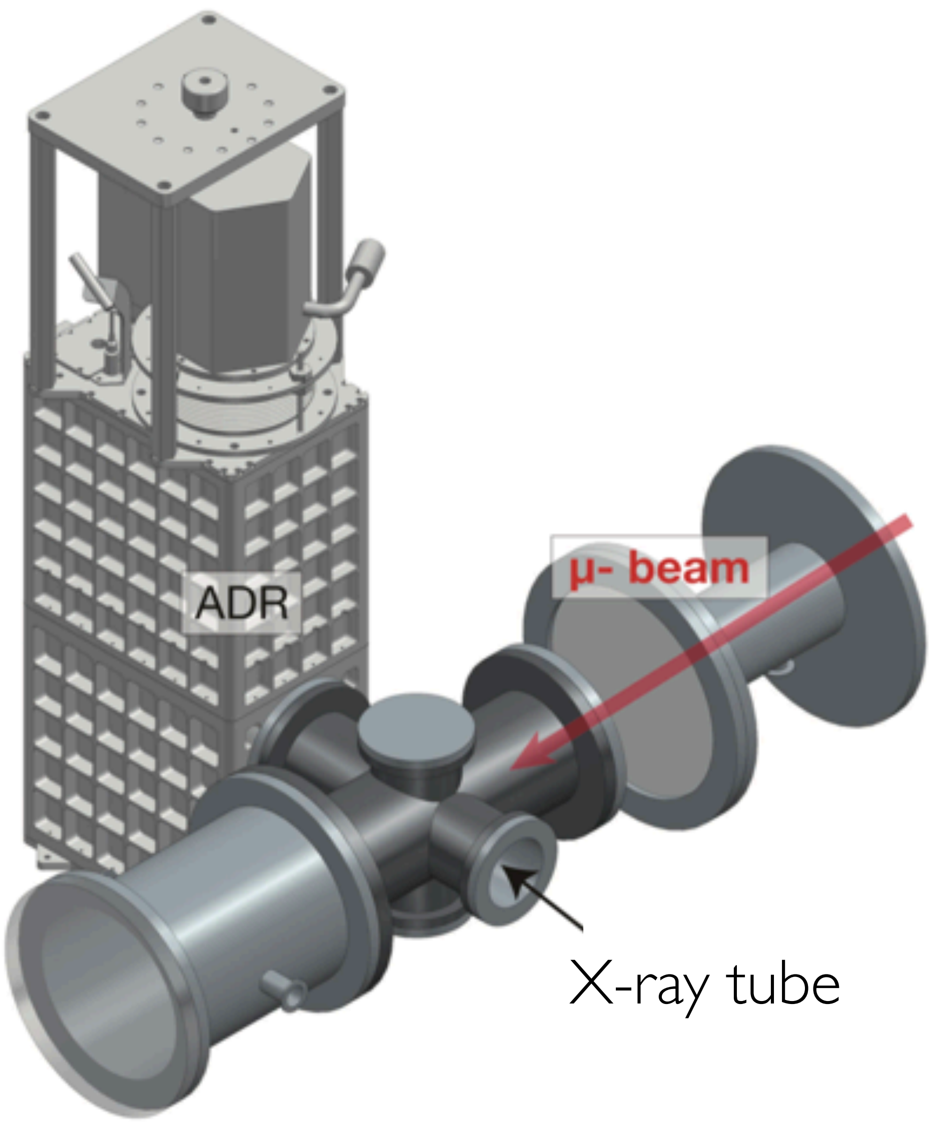
QED with exotic atoms : the essential ingredients

1. **Highest precision QED calculations**, capable of treating non-pertubative, high-field QED including exotic particle properties (finite size, g-2), and nuclear properties (polarizability, finite size, deformation, recoil).
2. **Make the exotic systems** at an accelerator facility (**slow beams** preferentially)
   - μ^-, π^- — Paul Sherrer Institute (continuous beam, Switzerland), JPARC (pulsed muon beam, Japan)
   - Antiprotons — AD/ELENA (CERN), eventually GSI/FAIR (Germany)
3. **Detect** the x-ray cascade with both **high resolution** and **high efficiency**
   - Now possible with quantum detection methods, **micro calorimeters**



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

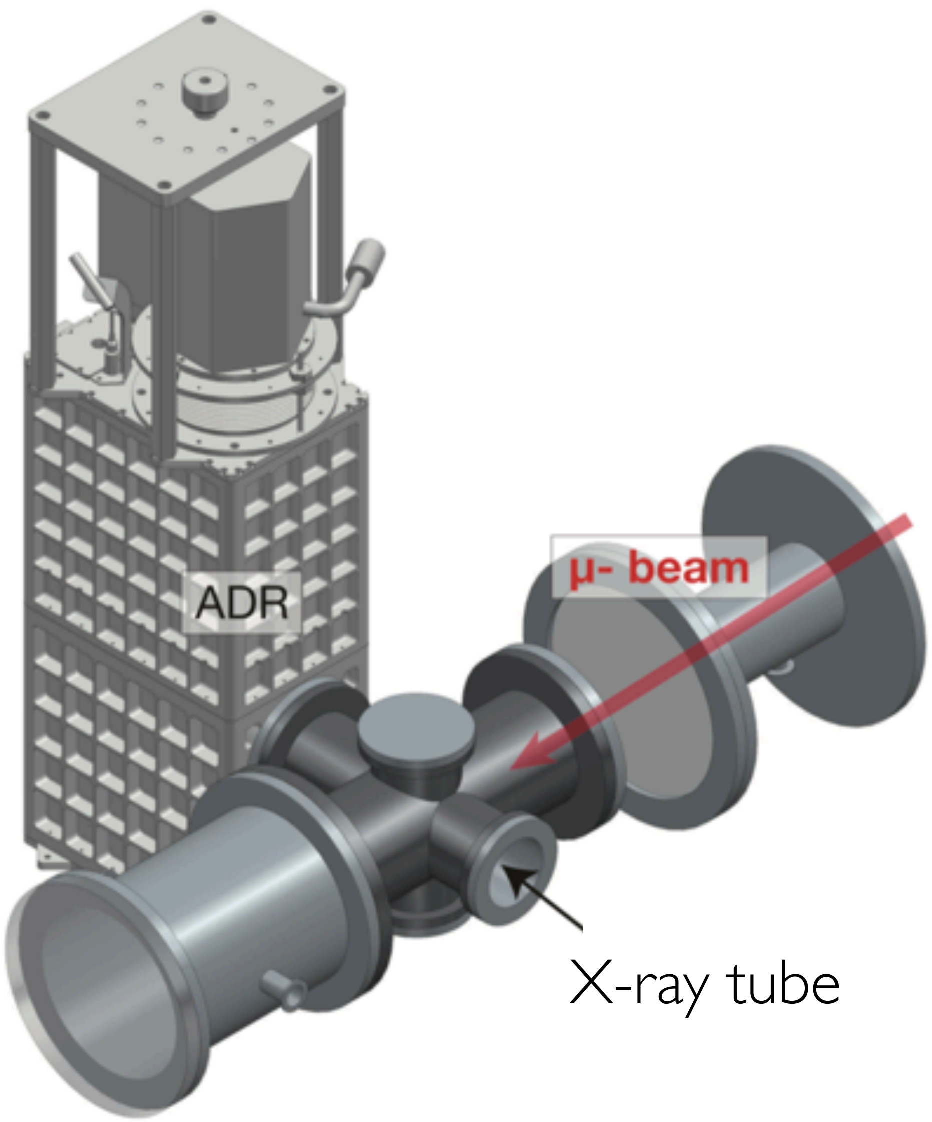


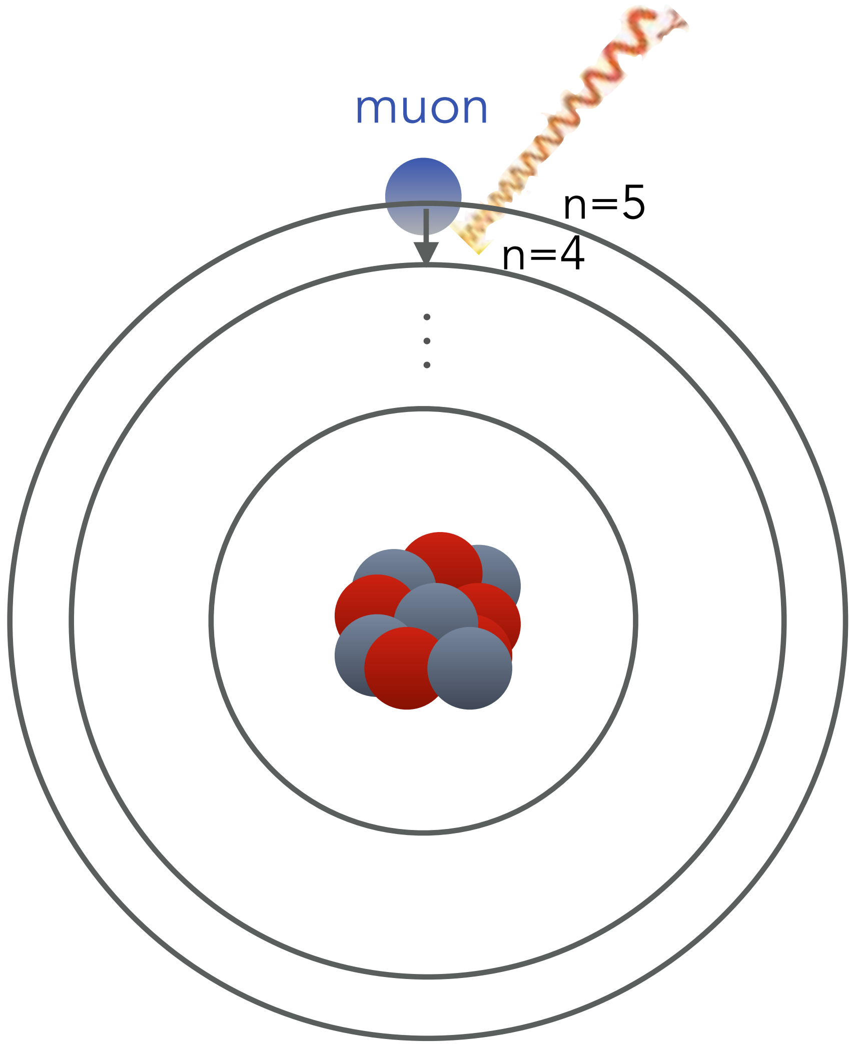
Collaboration: RIKEN, JAEA, JAXA, KEK, Osaka University, Rikkyo University, Tohoku University, Tokyo Metrolopolitan University, NIST, CNRS

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

Quantum x-ray detector (TES)

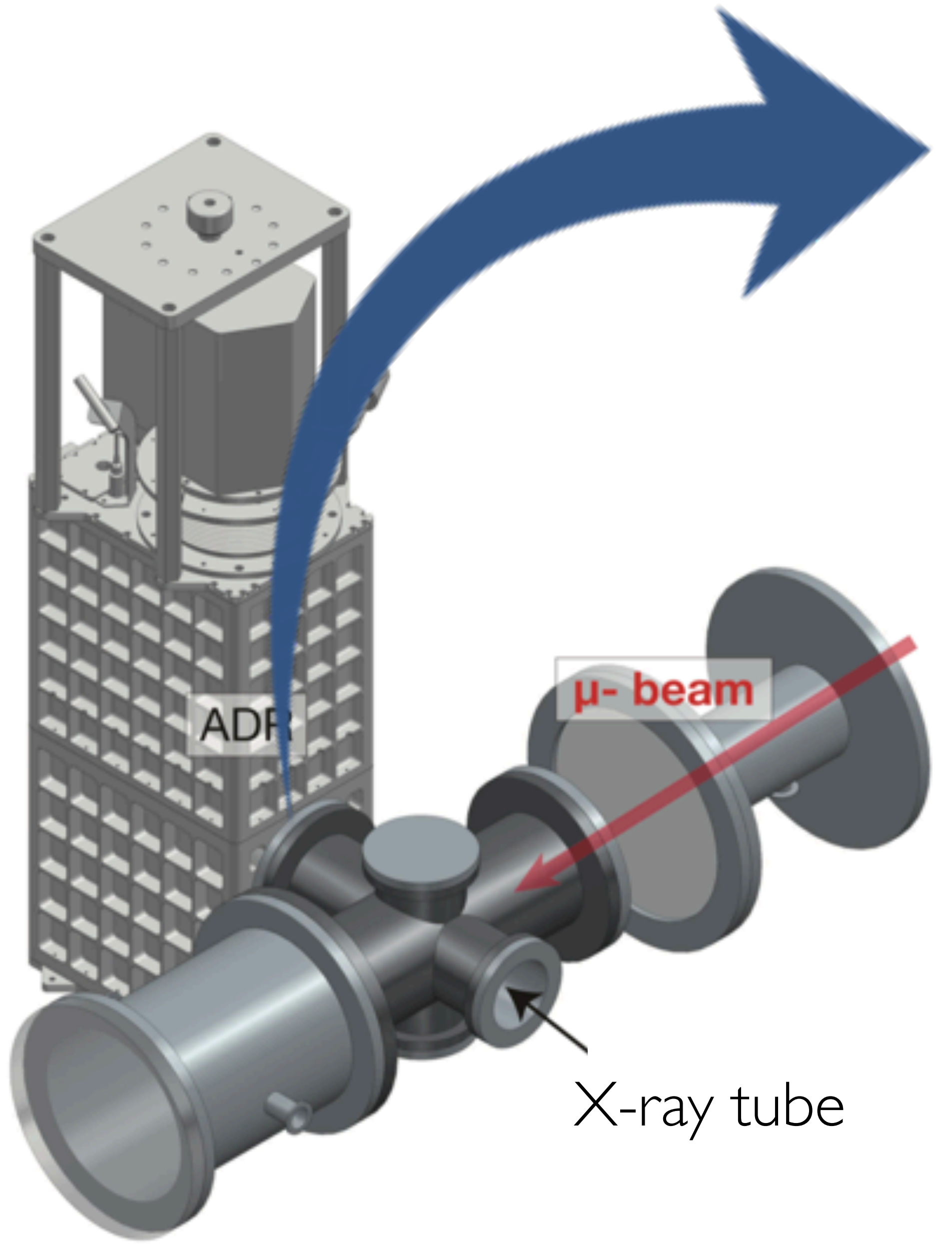




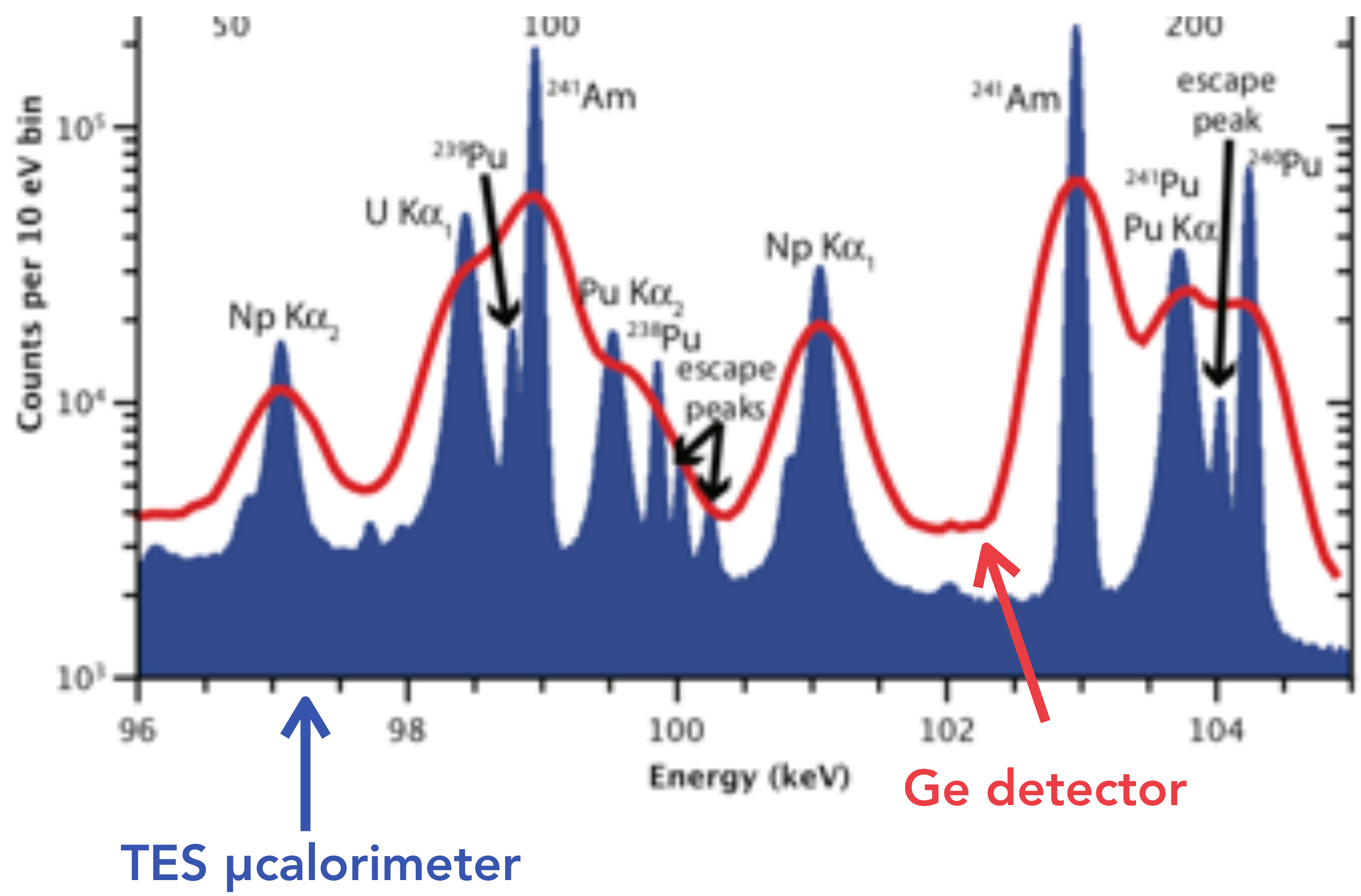
First experiments with muonic atoms at J-PARC

Key technology

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

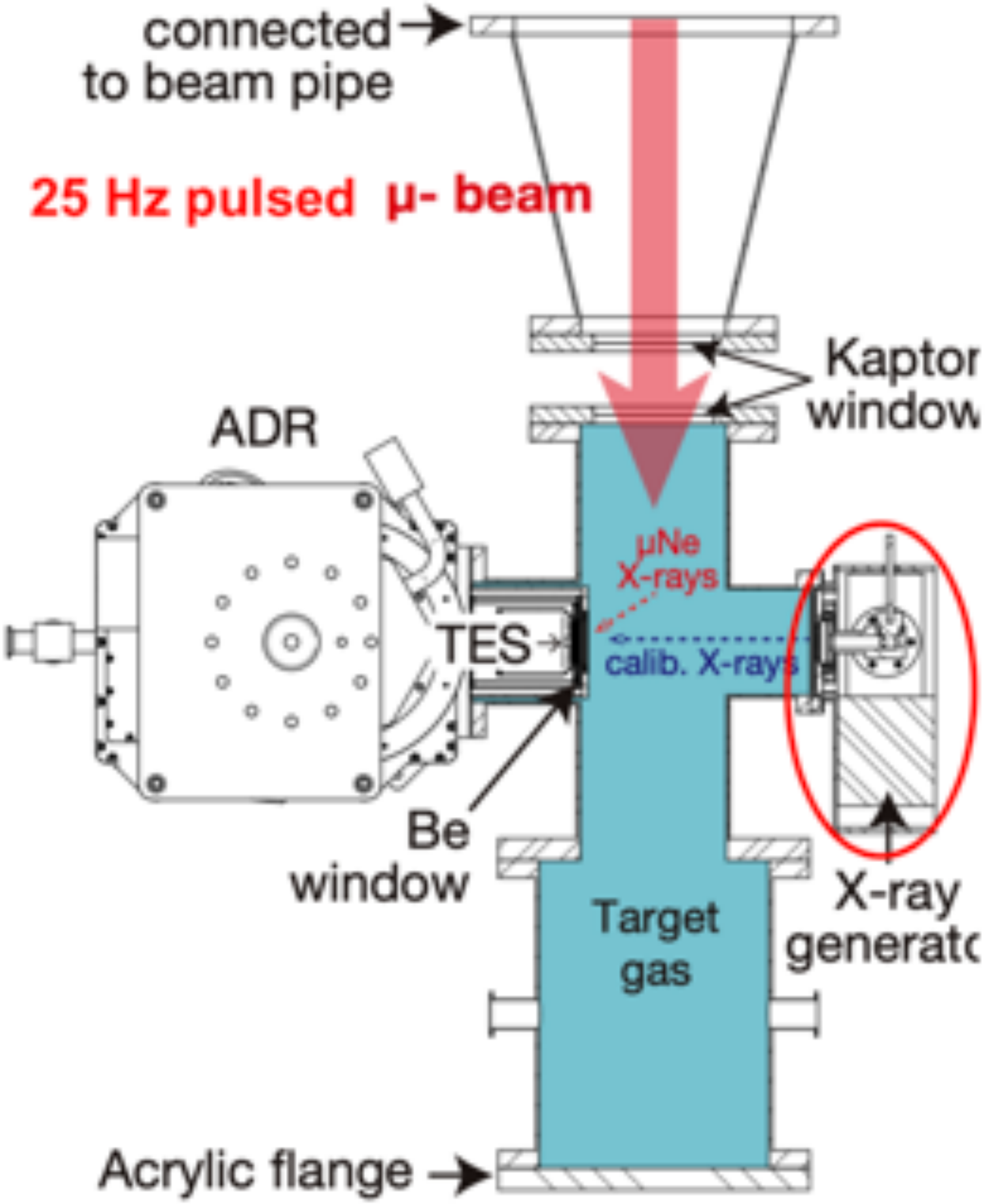


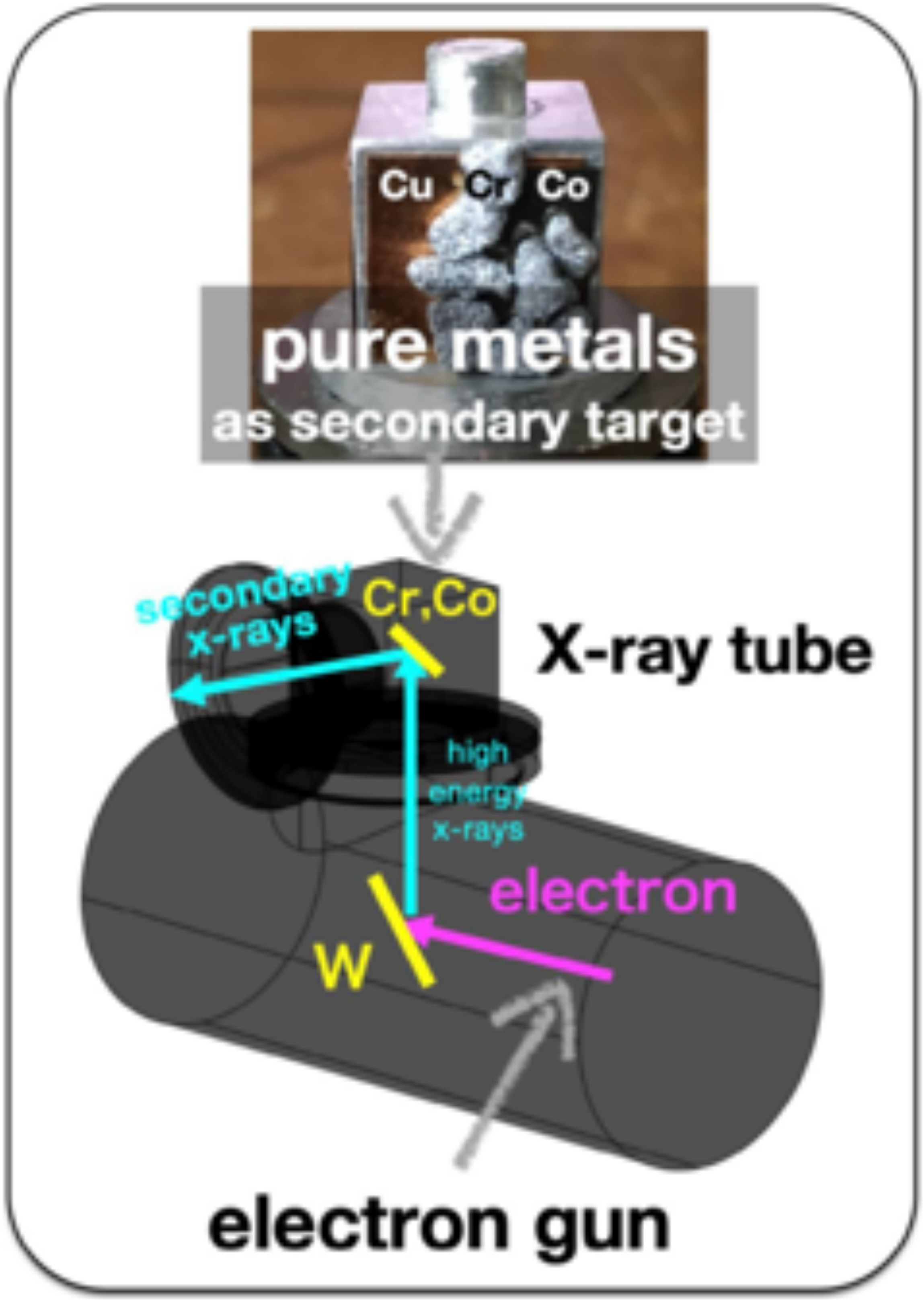
Transition Edge Sensing (**TES**) μcalorimeter (NIST)



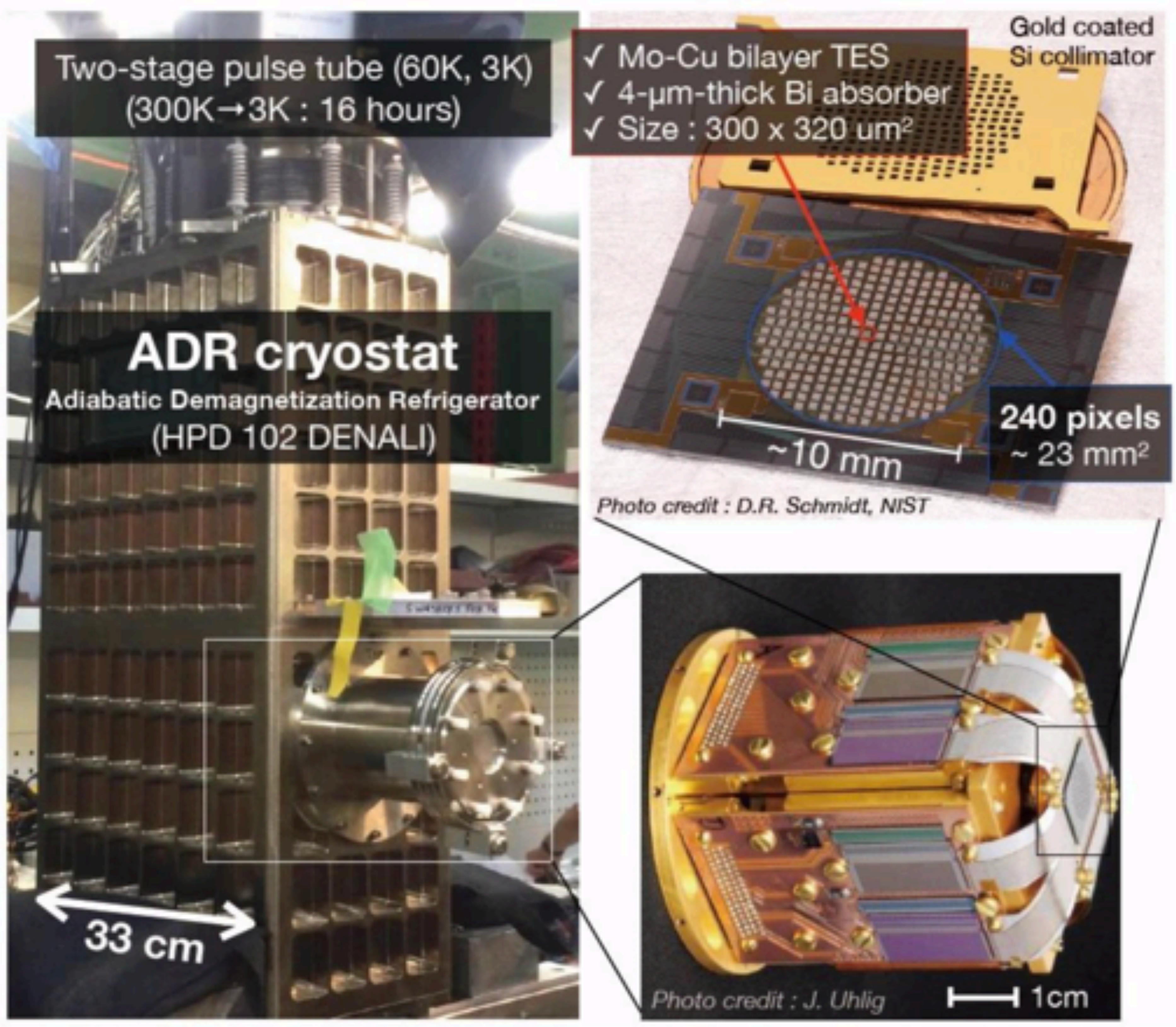
Rev. Sci. Instrum. 83, 093113 (2012)

Experimental setup—details

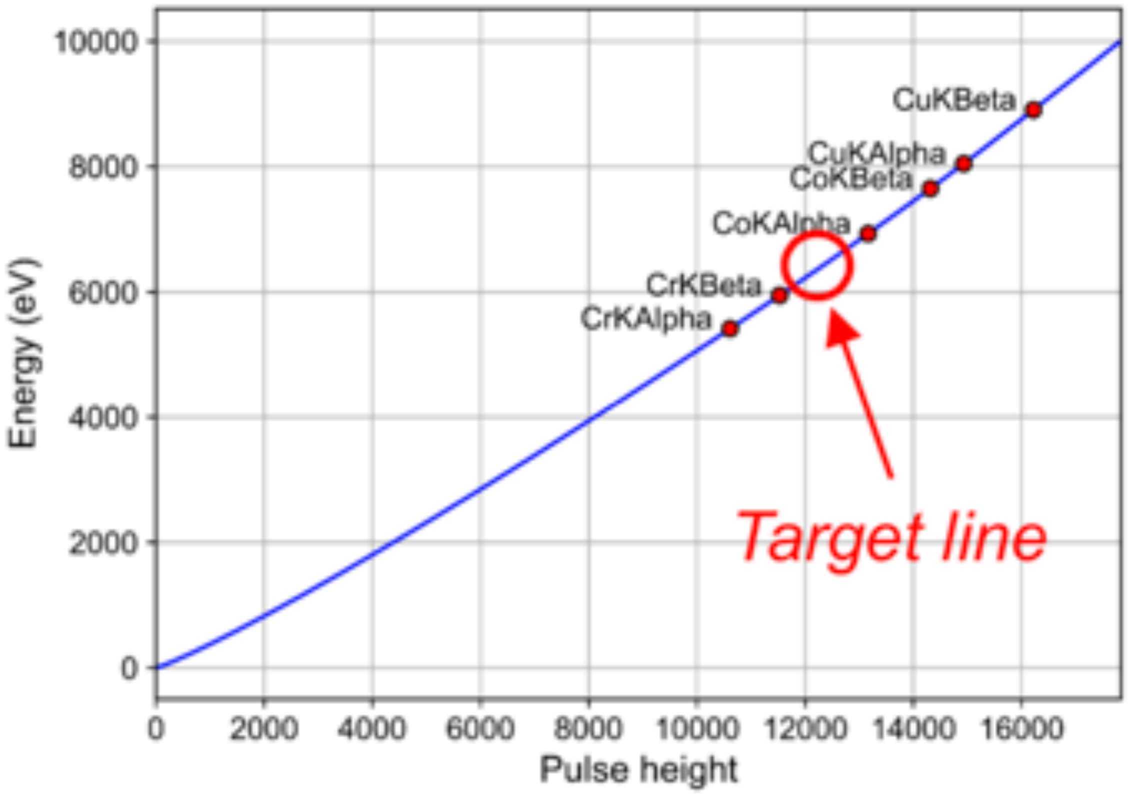


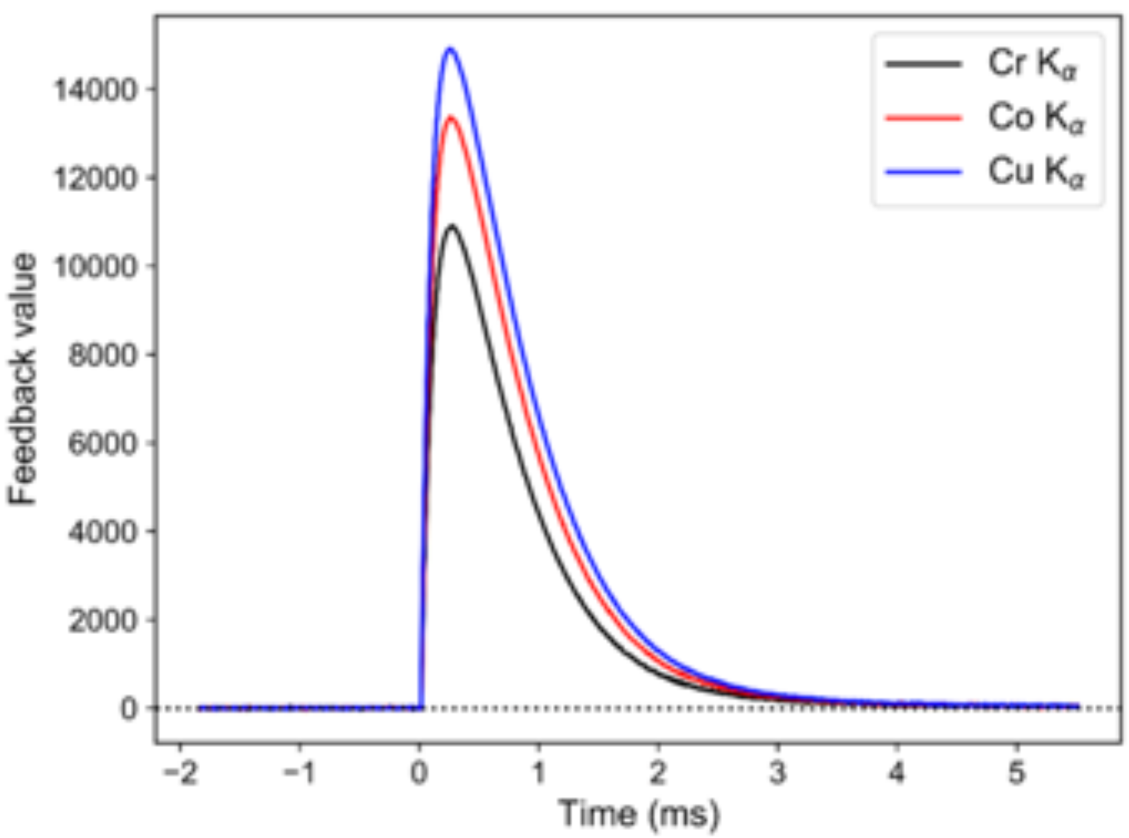


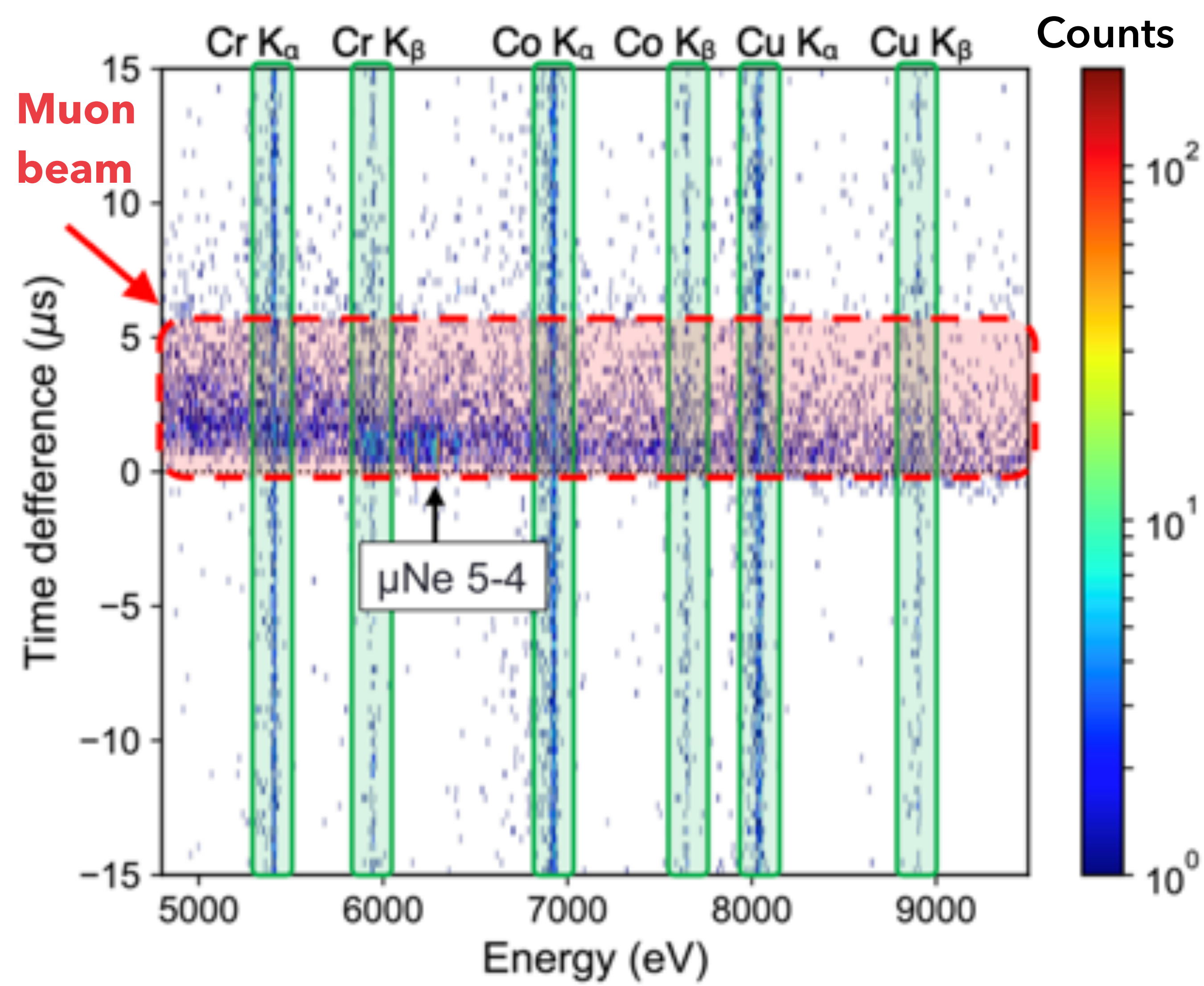
Key technology : Transition Edge Sensing microcalorimeter



TES calibration

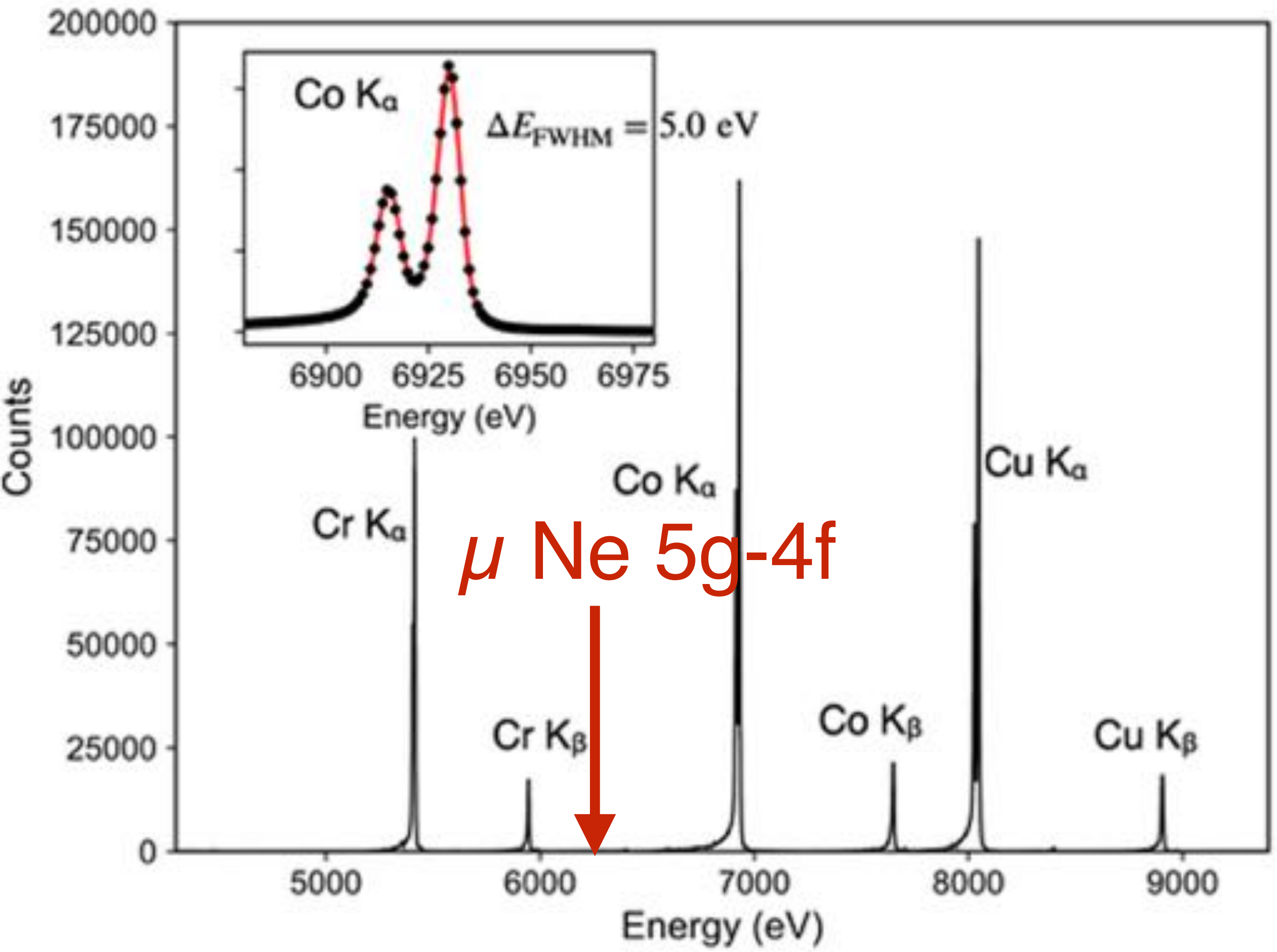


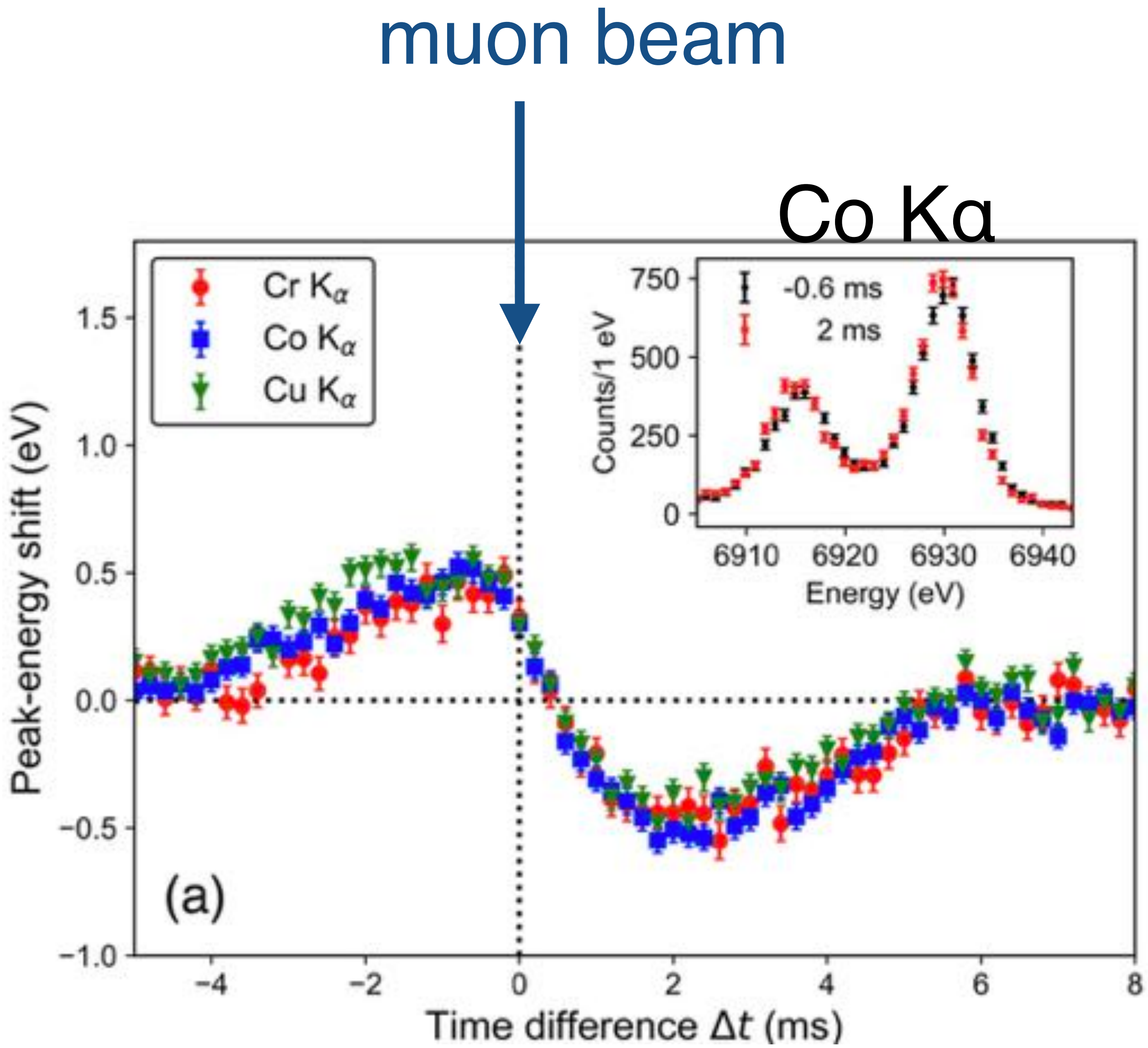




- Pixel-by-pixel energy calibration
- Continuous calibration lines from x-ray gun

Pileup correction



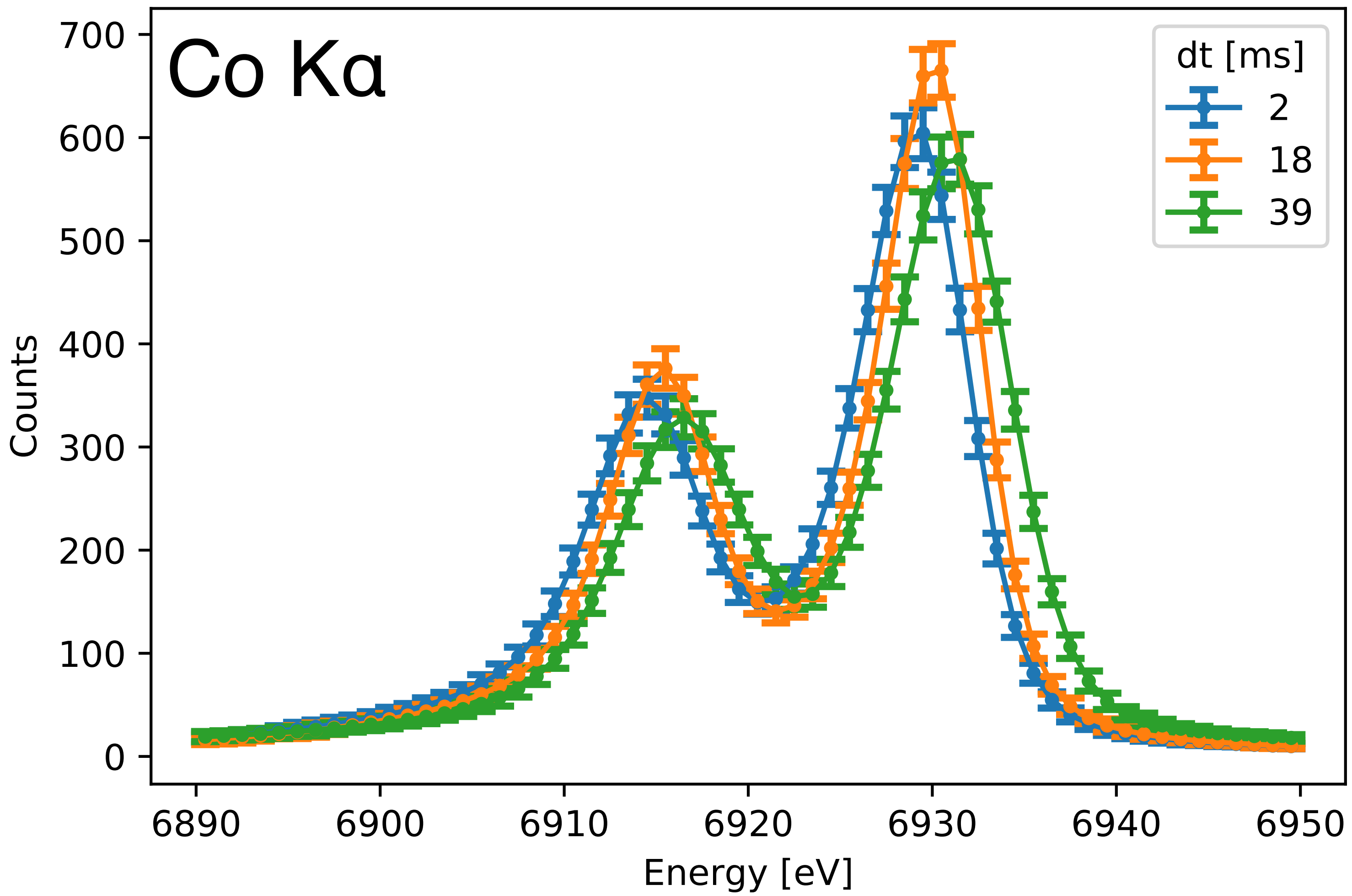


Total calibration spectrum at 0.1 atm

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

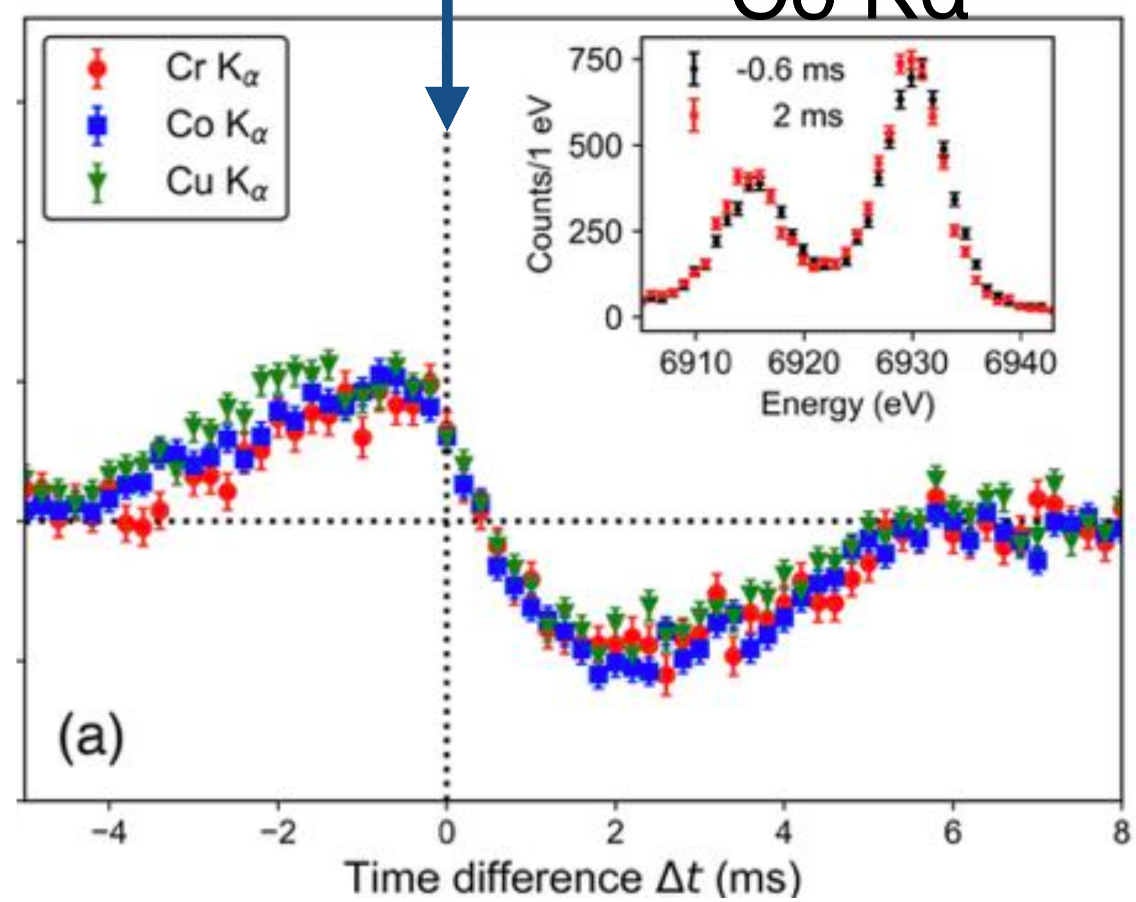
T. Okumura et al, IEEE Transactions on Applied Superconductivity **31,** 1-4 (2021)

Pileup correction



muon beam

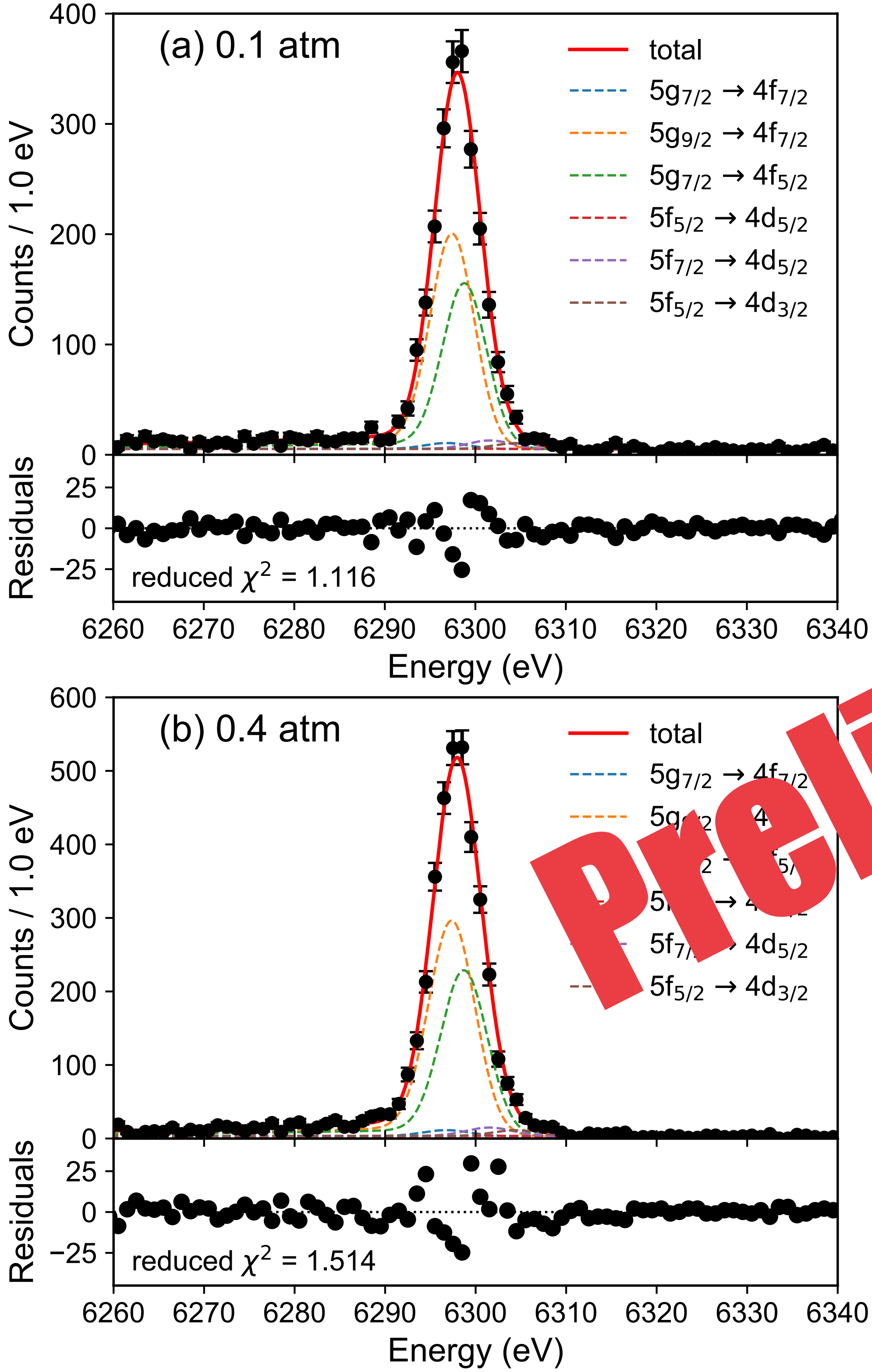
Co Kα

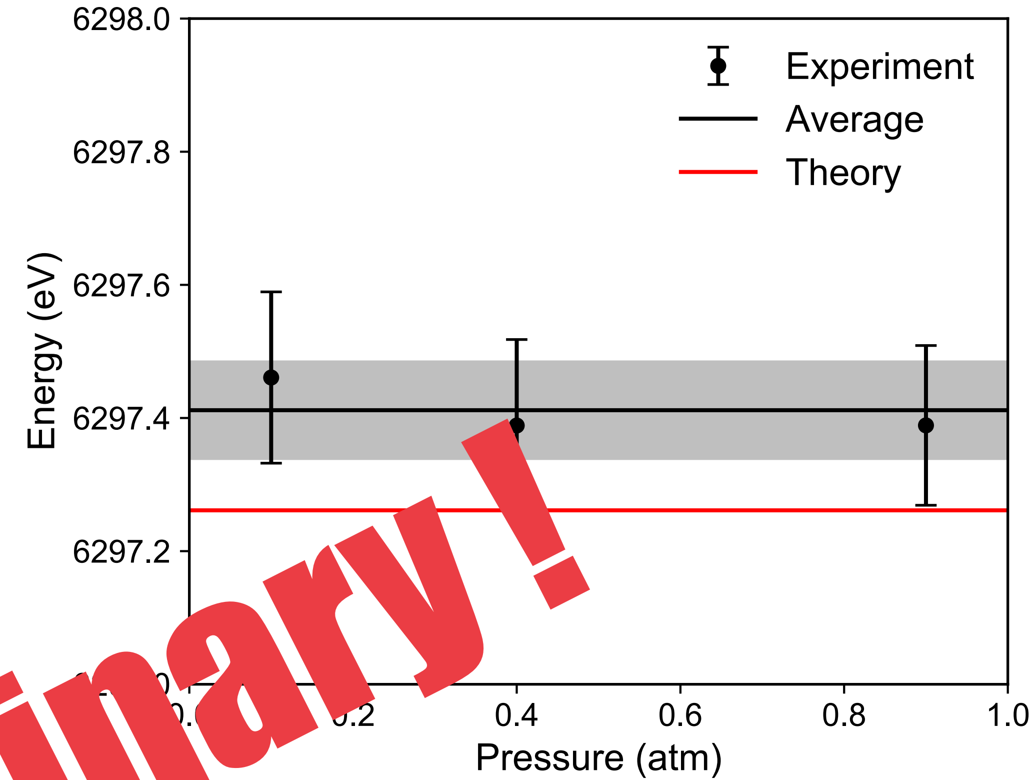


Energy shift (t_{muon}-$t_{x\text{-}ray}$)

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. Durkin, J.W. Fowler, J.D. Gard, T. Hashimoto, R. Hayakawa, G.C. Hilton, Y. Ichinohe, P. Indelicato, T. Isobe, S. Kanda, M. Katsuragawa, N. Kawamura, Y. Kino, K. Mine, Y. Miyake, K.M. Morgan, K. Ninomiya, H. Noda, G.C.O. Neil, S. Okada, K. Okutsu, T. Osawa, N. Paul, C.D. Reintsema, D.R. Schmidt, K. Shimomura, P. Strasser, H. Suda, D.S. Swetz, T. Takahashi, S. Takeda, S. Takeshita, H. Tatsuno, Y. Ueno, J.N. Ullom, S. Watanabe and S. Yamada. IEEE Transactions on Applied Superconductivity **31,** 1-4 (2021).

Experimental μNe spectrum—preliminary results

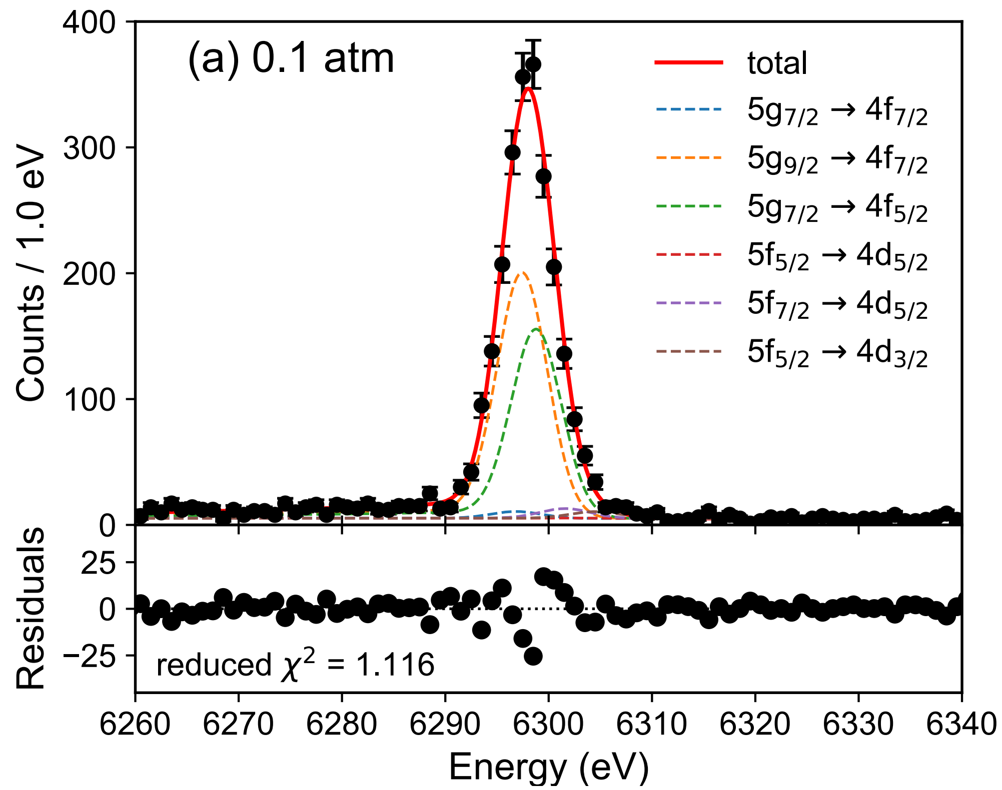


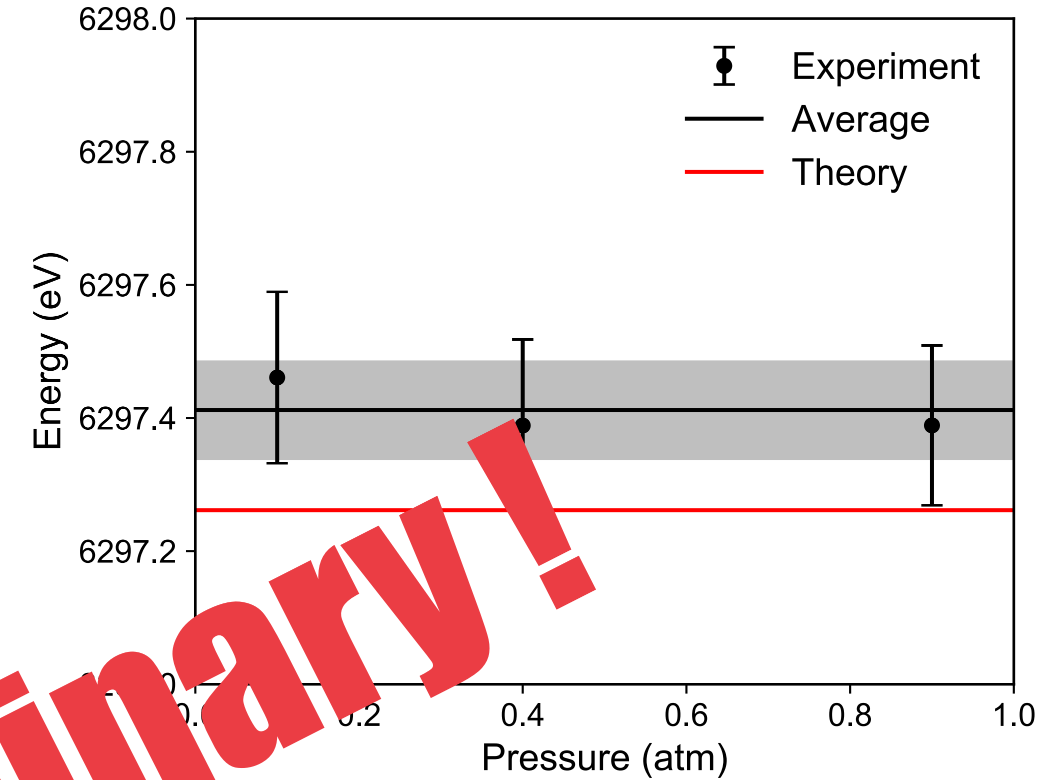


Transition energy and associated uncertainties (eV)	Pressure (atm) 0.1	0.4	0.9
experiment	6297.46	6297.39	6297.39
statistical error	0.06	0.05	0.05
systematic error: total	0.11	0.12	0.11
1) calibration anchors	0.00	0.00	0.00
2) tail-param. for energy calib.	0.02	0.03	0.00
3) interpolation	0.02	0.03	0.01
4) tail-param. for fitting of muonic x-rays	0.01	0.02	0.01
5) pileup correction	0.11	0.11	0.11

shift due to presence of 1 electron: -1.25 eV

Experimental μNe spectrum—preliminary results





Preliminary !

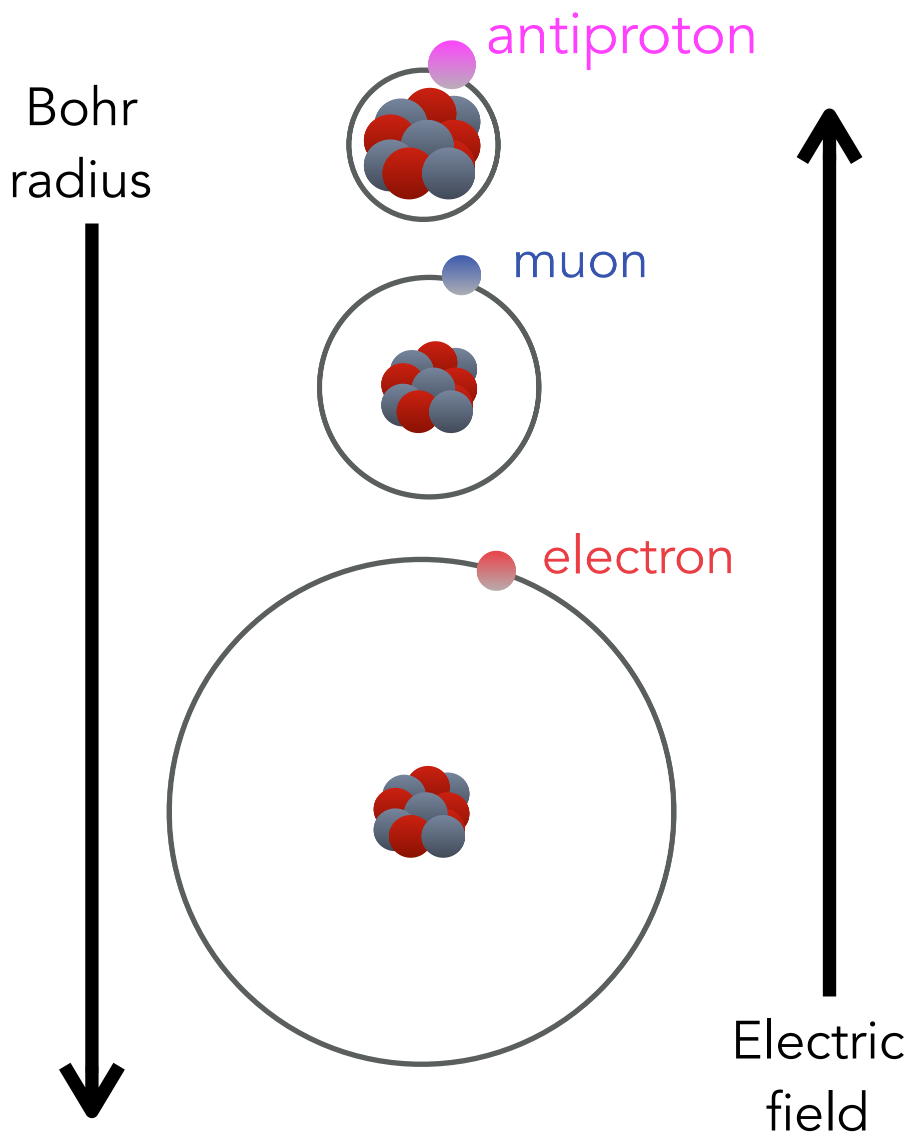
Theoretical Contributions	eV
Vac. Pol. (1st order)	2.3[illegible]061
Self-energy (1st order)	0.0015
Vac. Po. (2nd order)	-0.0212
Finite nuclear size	-0.00031

Transition energy and associated uncertainties (eV)	Pressure (atm) 0.1	0.4	0.9
experiment	6297.46	6297.39	6297.39
statistical error	0.06	0.05	0.05
systematic error: total	0.11	0.12	0.11
1) calibration anchors	0.00	0.00	0.00
2) tail-param. for energy calib.	0.02	0.03	0.00
3) interpolation	0.02	0.03	0.01
4) tail-param. for fitting of muonic x-rays	0.01	0.02	0.01
5) pileup correction	0.11	0.11	0.11

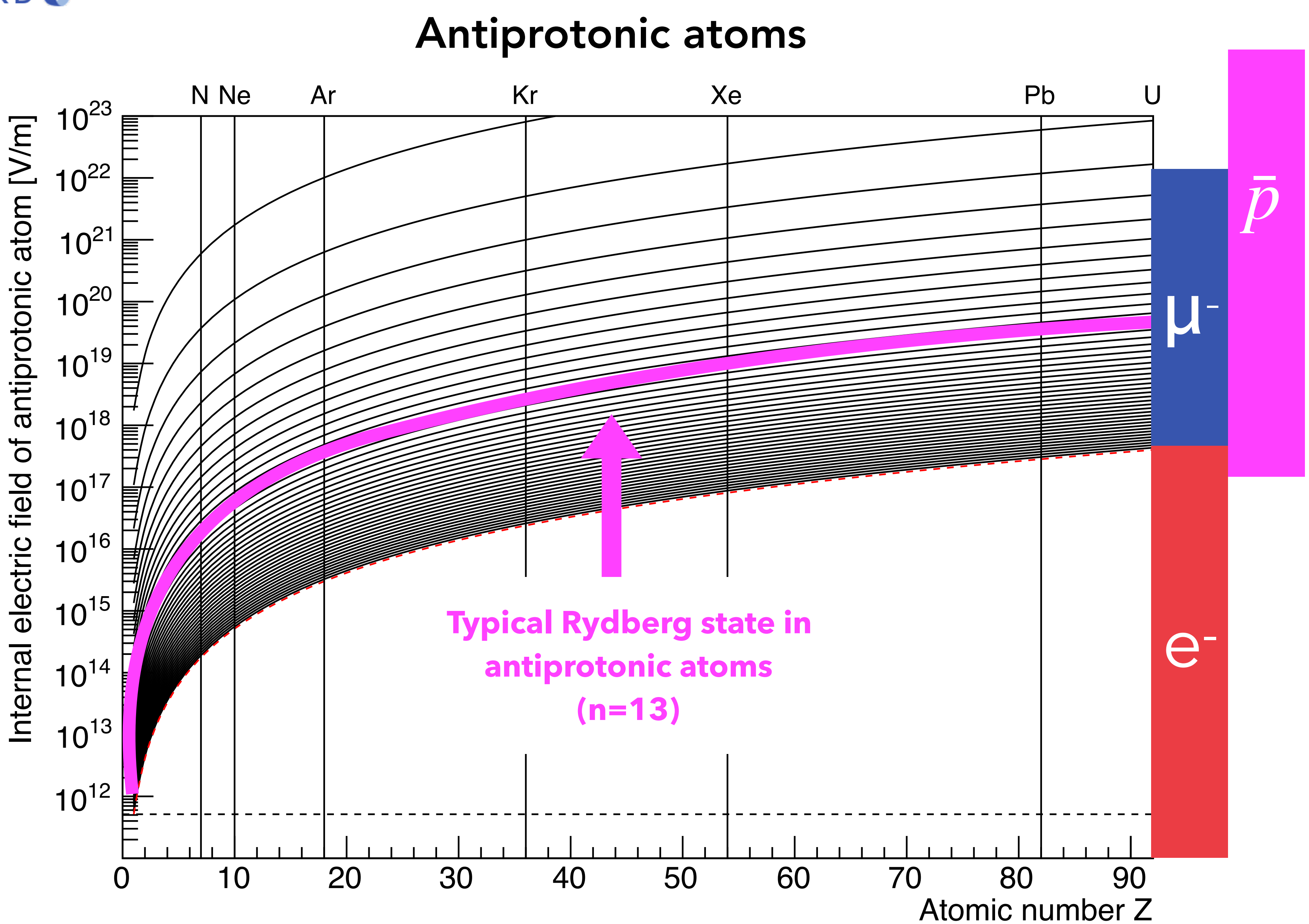
shift due to presence of 1 electron: -1.25 eV

Next step….QED with antiprotons

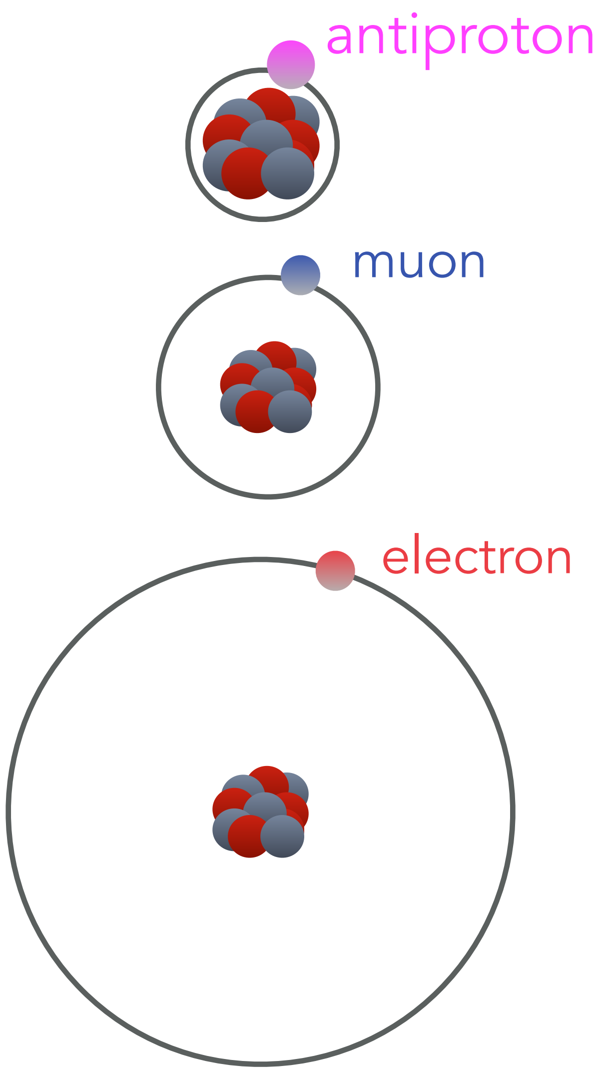
Even stronger field QED!



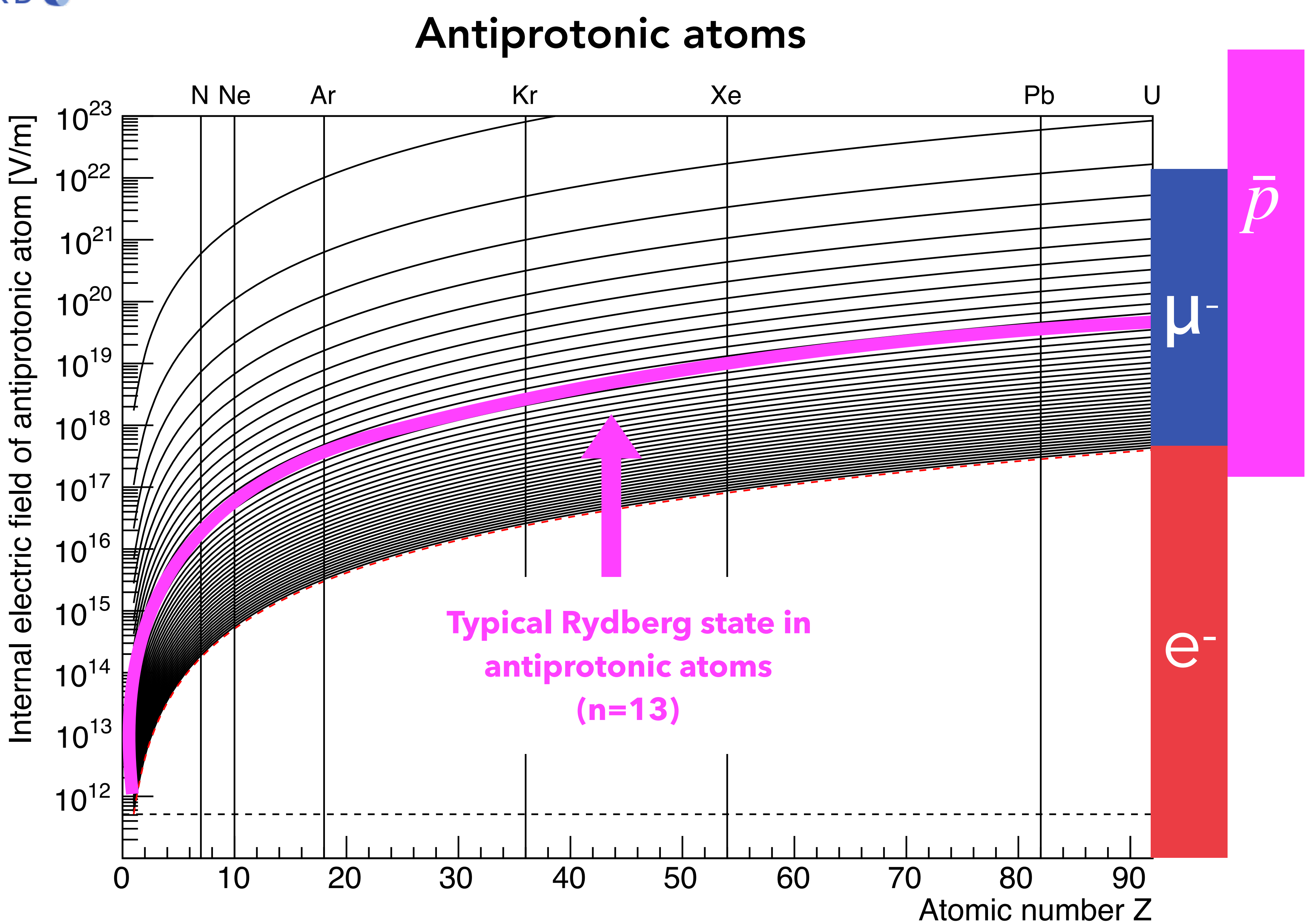
Next step….QED with antiprotons



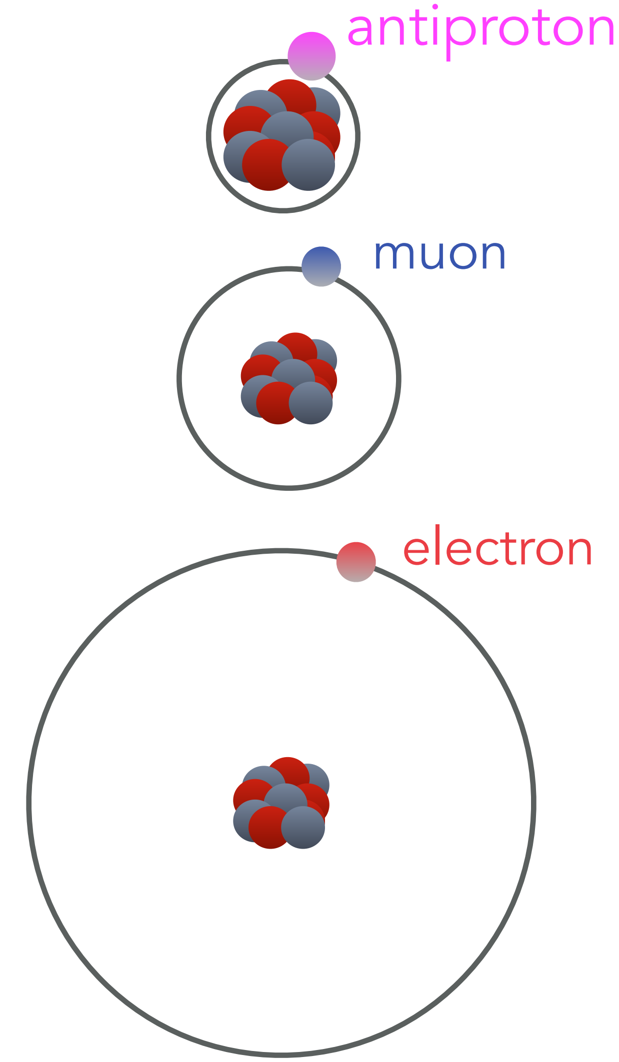
Even stronger field QED!



Next step....QED with antiprotons



Even stronger field QED!

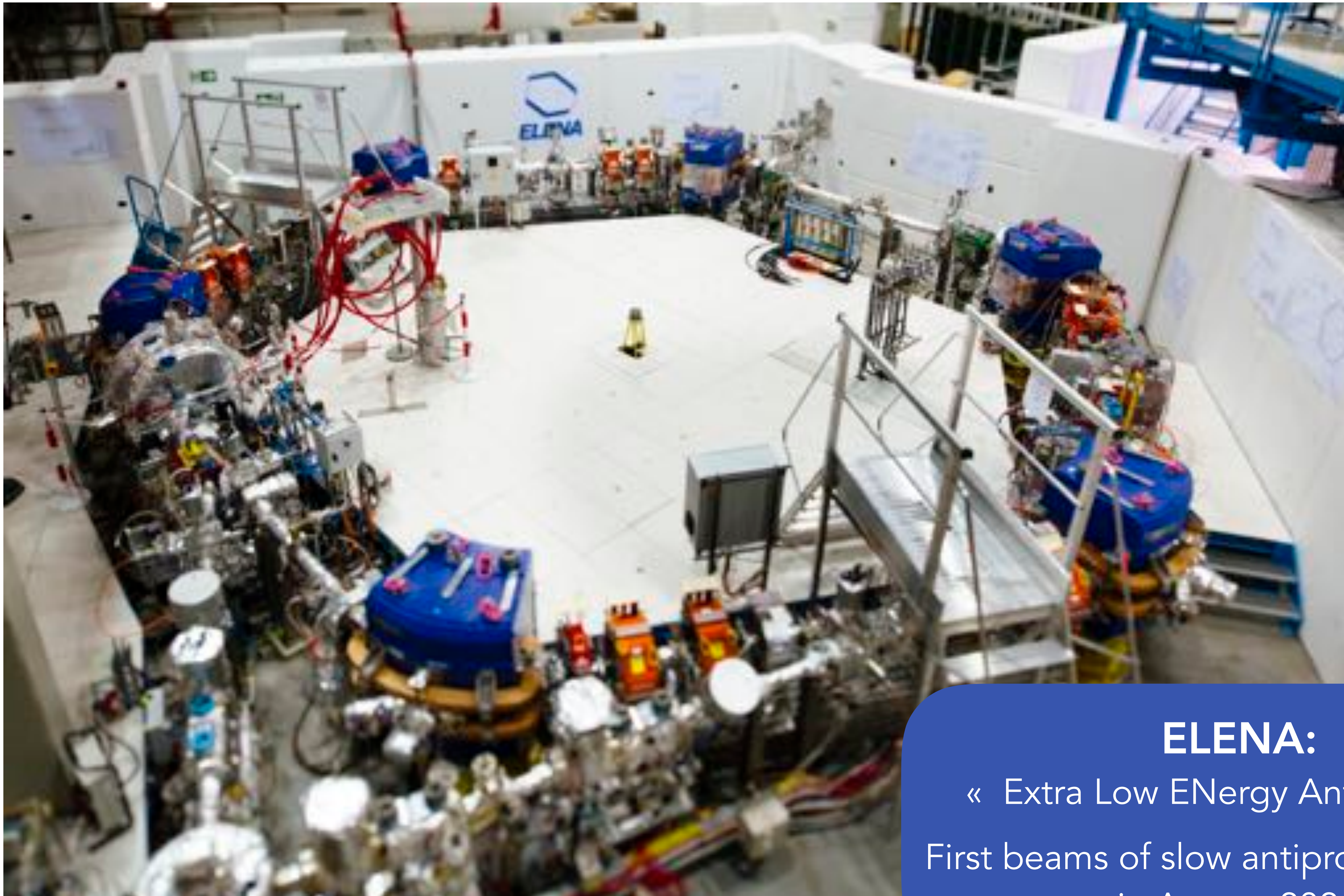


QED with antiprotons
(precision methods) x (antimatter)

Long term project :
Antiprotonic Atom X-ray Spectroscopy

Largest BSQED effects!

Slow antiprotons now available!

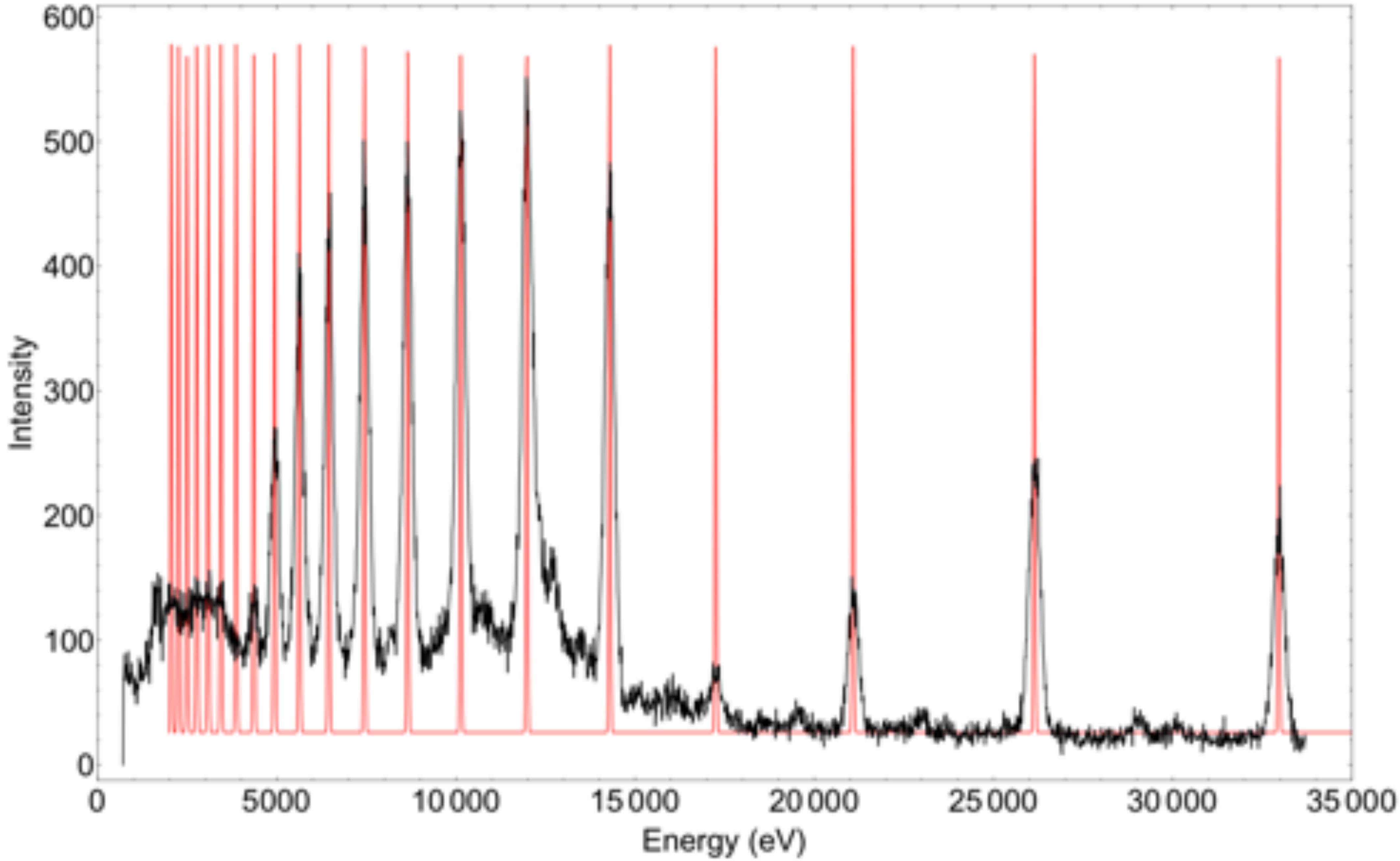


ELENA:

« Extra Low ENergy Antiprotons »

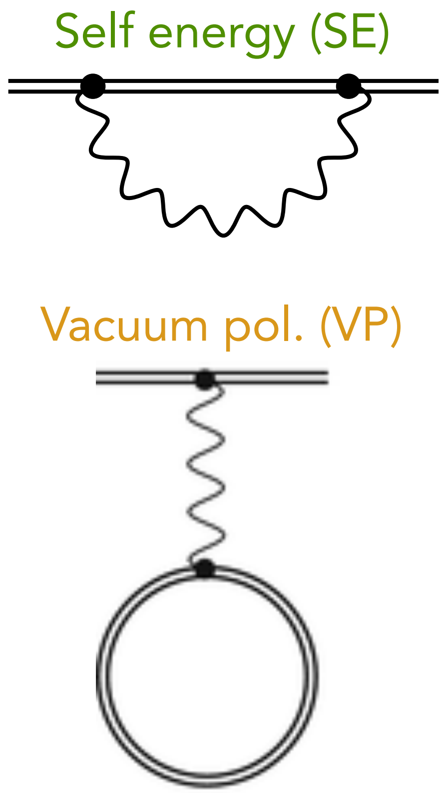
First beams of slow antiprotons starting in August 2021

Perspectives

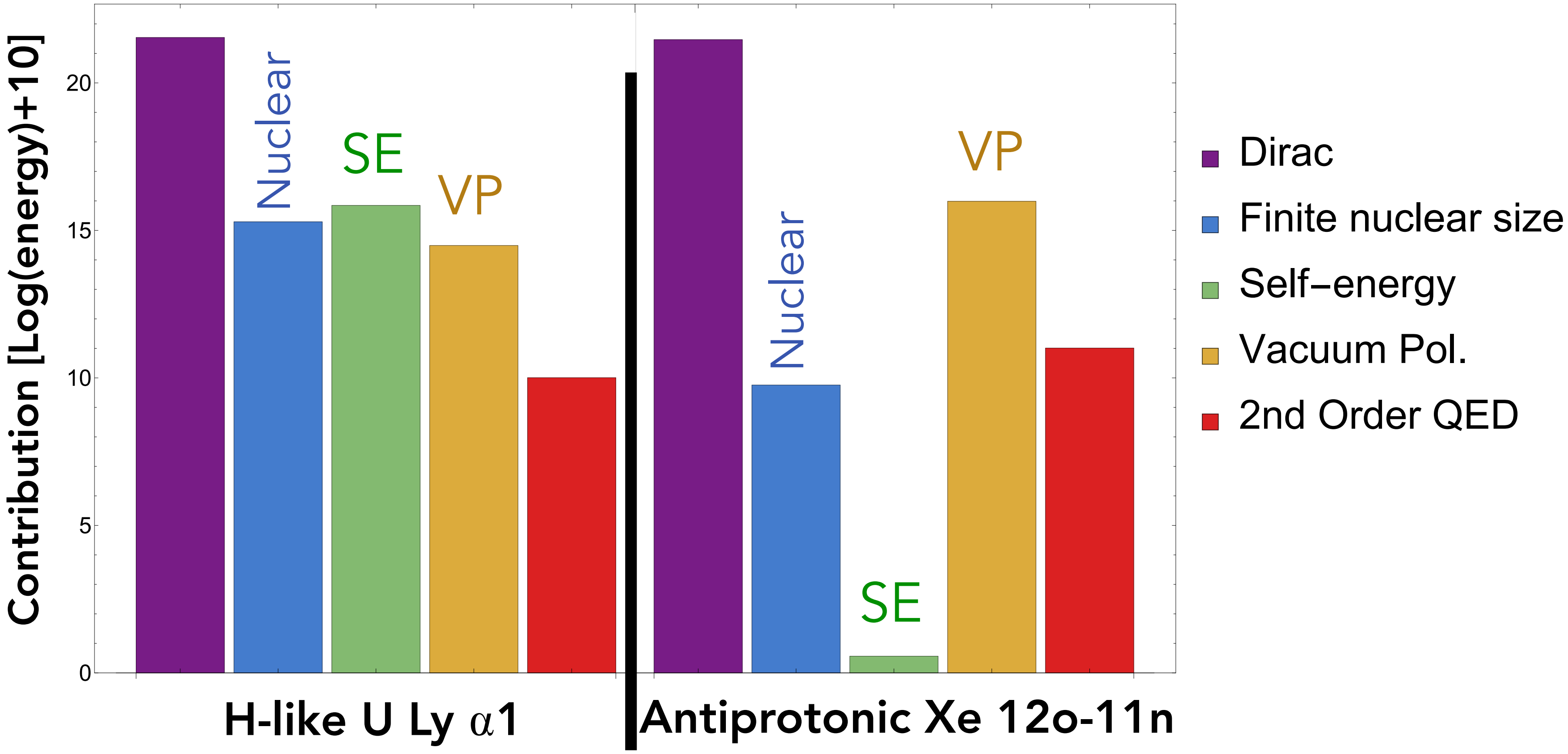


Existing data on antiprotonic cascade Simulated TES data

HCI and Exotic Atoms—a complementary pair



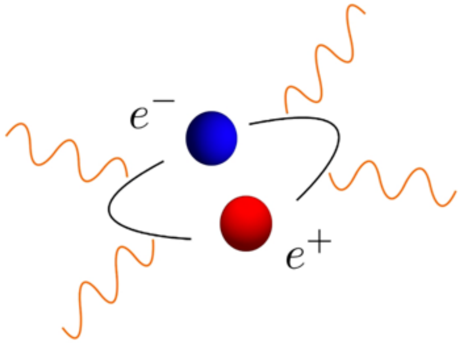
Highly charged ion: SE>VP
Exotic atom: VP>SE



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

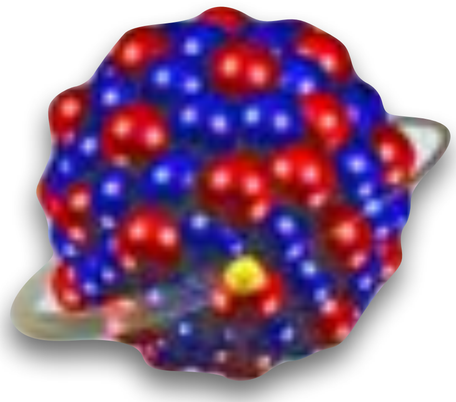
Unique probe of vacuum polarization, *« one of the most interesting phenomena predicted by contemporary quantum electrodynamics »* (Foldy and Eriksen, Physical Review (1954))

Complementary to vacuum studies with high-intensity lasers



Summary

- Precision spectroscopy of atomic systems is a powerful approach for probing the details of the Standard Model and looking for Beyond Standard Model physics
- **High-field quantum electrodynamics** is very **poorly tested** experimentally
- Studies with highly-charged ions are plagued by **nuclear physics uncertainties**
- **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
- New experiments ongoing with **muonic atoms** at JPARC, analysis nearly completed for n=5—>4 transition in μNe.
- New experimental program being developed with **antiprotonic atoms** at CERN.



Thank you for your attention

Laboratoire Kastler Brossel
Physique quantique et applications

P. Indelicato, N. Paul

NIST

D. A. Bennett, W. B. Dories, M. S. Durkin, J. W. Fowler, G. C. Hilton, J. D. Gard, K.S. Morgan, G. C. O'Neil, C. D. Reintsema, D. R. Schmidt, D. S. Swetz, U. Ullom

RIKEN

T. Azuma, T. Okumura, Y. Ueno, T. Isobe, S. Kanda

東京大学
THE UNIVERSITY OF TOKYO

T. Takahasi, P. Caradonna, M. Katsuragawa, T. Minami, K. Mine, S. Nagasawa, S. Takeda, Y. Tsuzuki, G. Yabu

KEK

N. Kawamura, Y. Miyake, K. Shimomura, P. Strasser, S. Tampo, B. S. Takeshita, G. Yoshida

RIKKYO UNIVERSITY

Y. Ichinohe. S. Yamada

THANK YOU

CHUBU UNIVERSITY AICHI JAPAN

S. Okada

JAEA

T. Hashimoto ,T. U. Ito, T. Osawa

KYOTO UNIVERSITY FOUNDED 1897

A. Taniguchi

TOKYO METROPOLITAN UNIVERSITY

R. Hayakawa, H. Suda, H. Tatusno

OSAKA UNIVERSITY

K. Ninoyima, I. Chiu, M. Kasino, H. Noda, K. Terada

TOHOKU UNIVERSITY

Y. Kino, T. Nakamura. T. Okutsu

TOYOTA CENTRAL R&D LABS

I. Umegaki

JAXA Explore to Realize

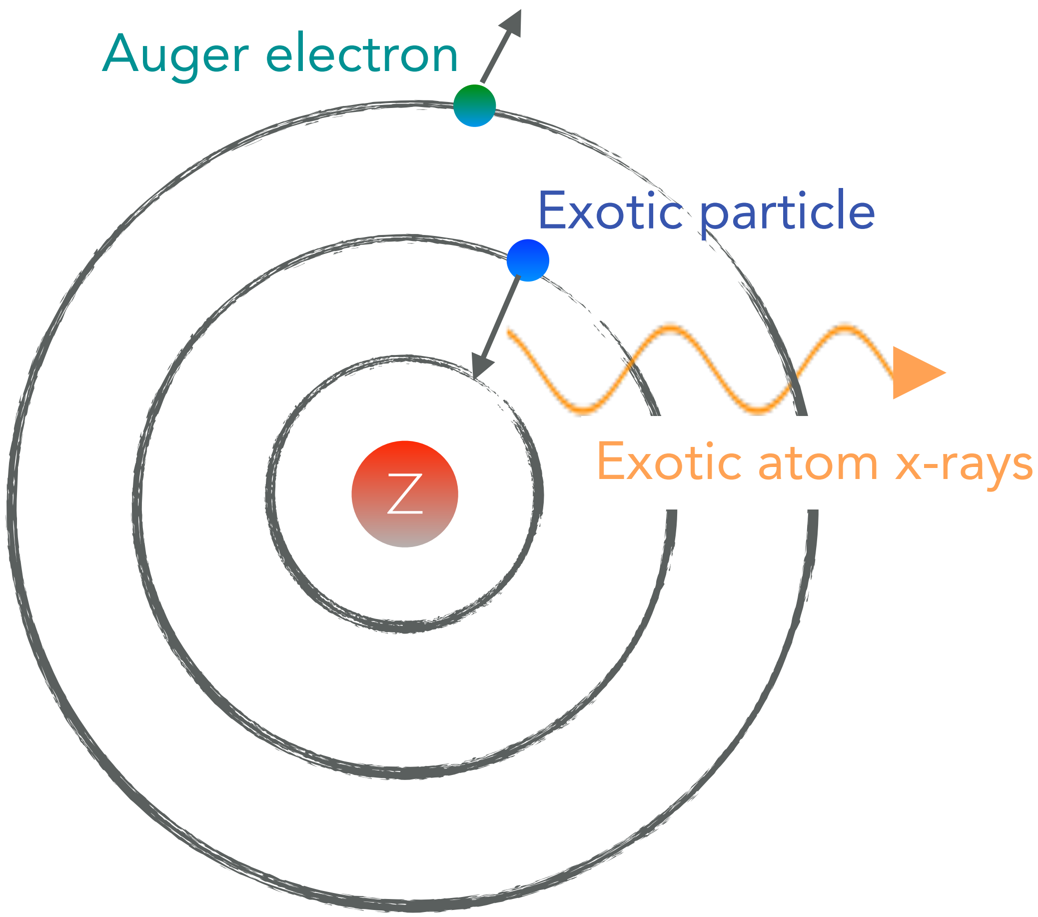
S. Wantanabe

ICU Expanding Potential

K. Kubo

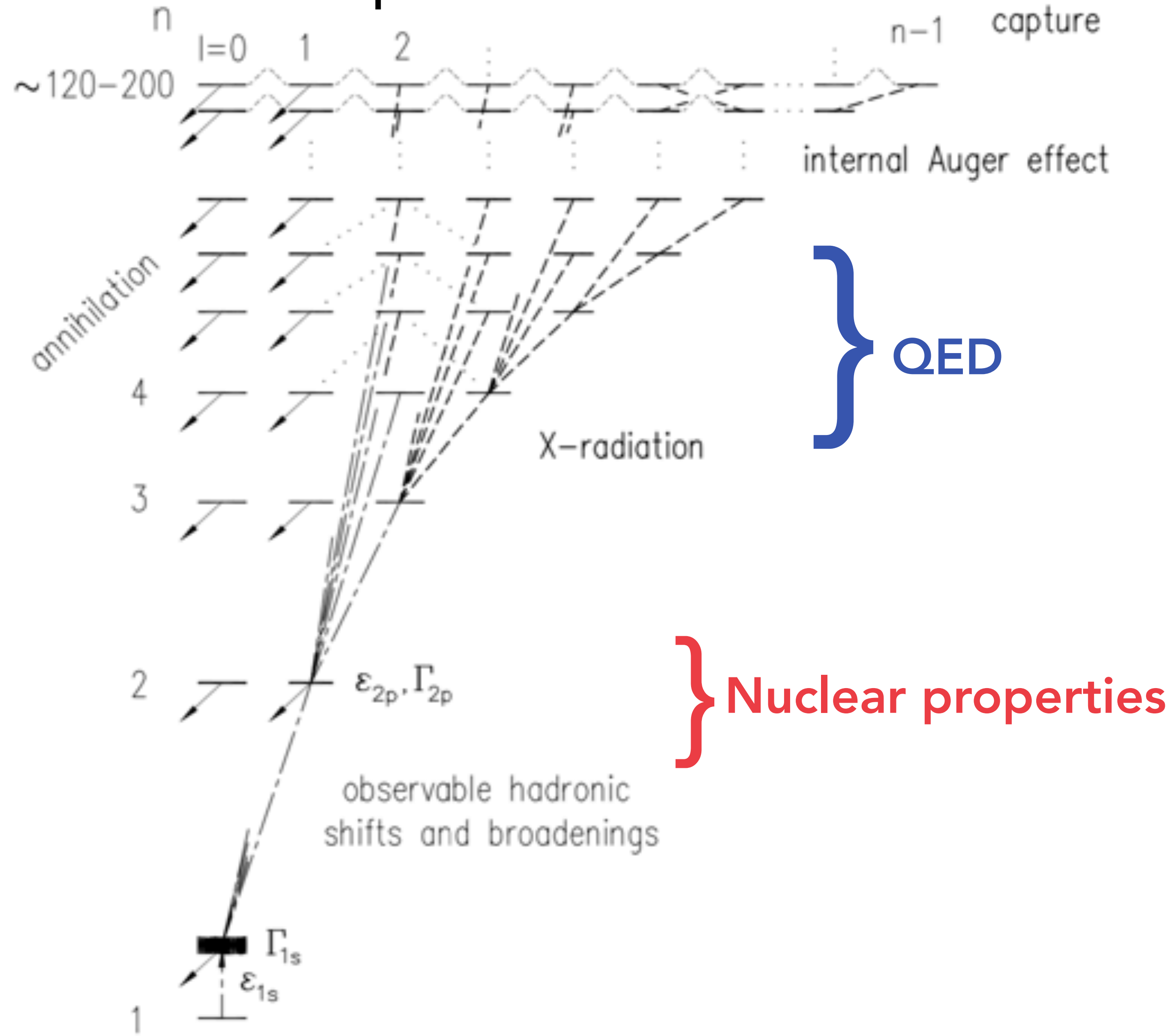
SUPPLEMENT

The exotic atom cascade



$$n_{exotic} \approx n_{e^-}\sqrt{m_{exotic}/m_{e^-}}$$

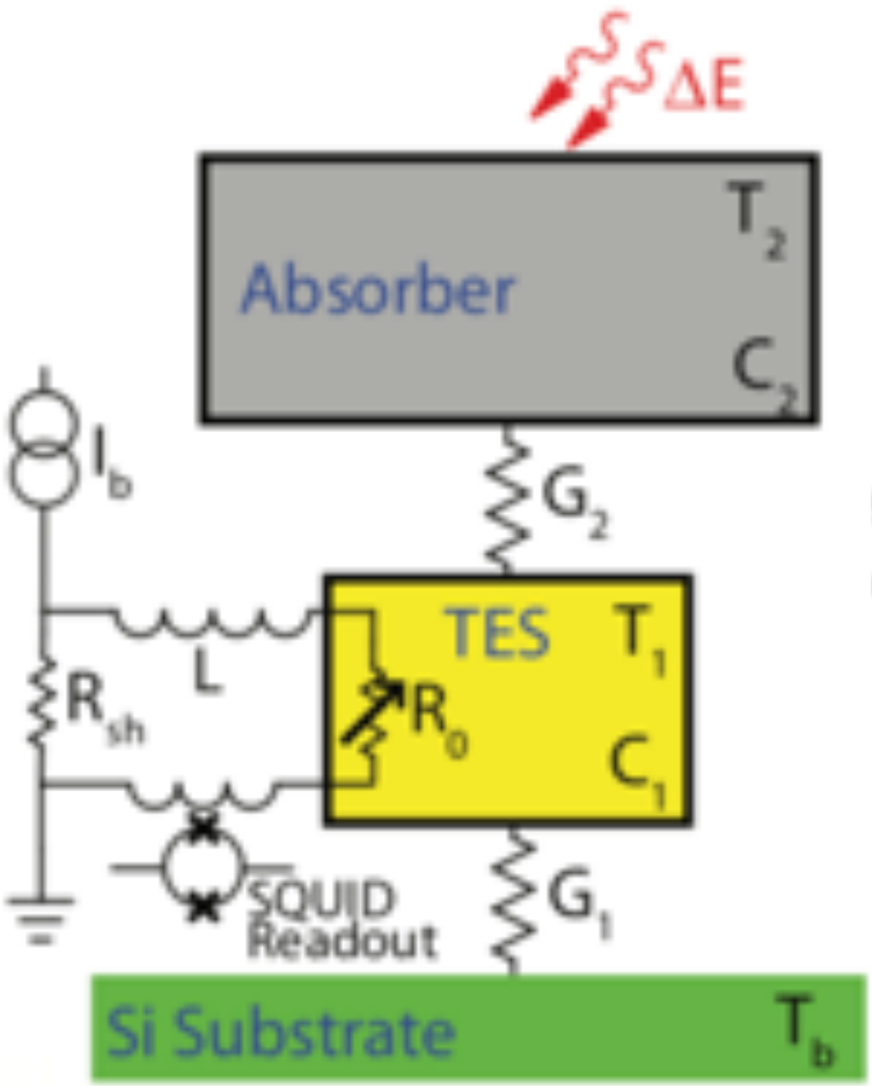
Antiprotonic atom cascade



- The exotic particle captures onto high-n orbitals
- Decays via Auger electrons and radiatively (X-rays)
- Eventually is either captured by nucleus (muons), or annihilates (antiprotons)

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

Quantum Sensing Division



Figures from D. Bennett and Bennett 2013