QUARTET

QUAntum inteRacTions for Exotic aToms

QUARTET goals :

Develop a dedicated, transportable experimental setup for x-ray spectroscopy of exotic atom cascade with microcalorimeters.

Measure nuclear charge radii and BSQED effects, constraints on new physics

Demonstrate quantum sensing detectors and metrology for exotic atoms

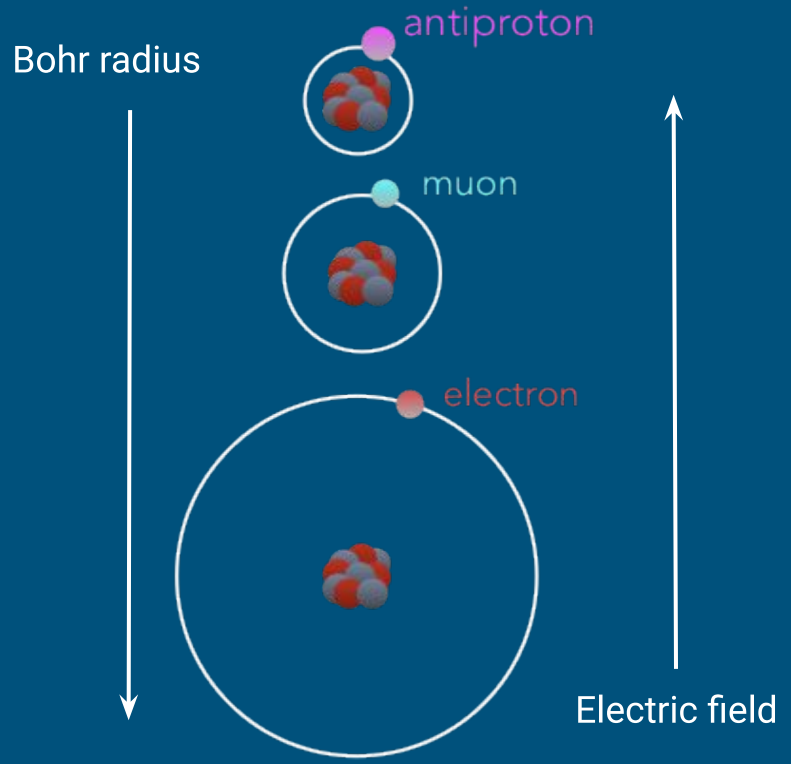
The physics of exotic atoms

Exotic particle is heavier, closer to the nucleus

- Sensitive to nuclear properties
- Strong coulomb field regime

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

$\rightarrow$ overlap with nucleus x 10^7 !!!

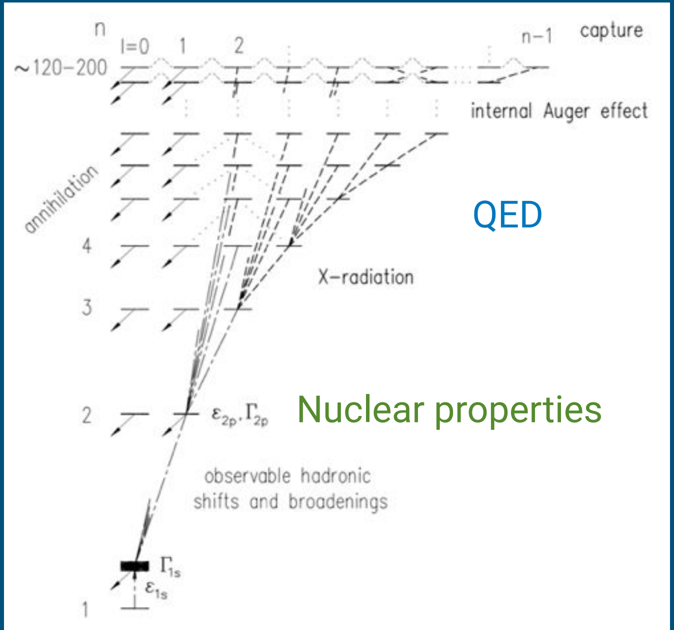


One observable—lots of physics

First Auger emission →H-like system

Radiative cascade follows the yrast band (highest angular momentum states)

- **High-n** circular Rydberg states –pure QED systems, vacuum polarization
- **Low-n** –nuclear radii and strong interaction effects

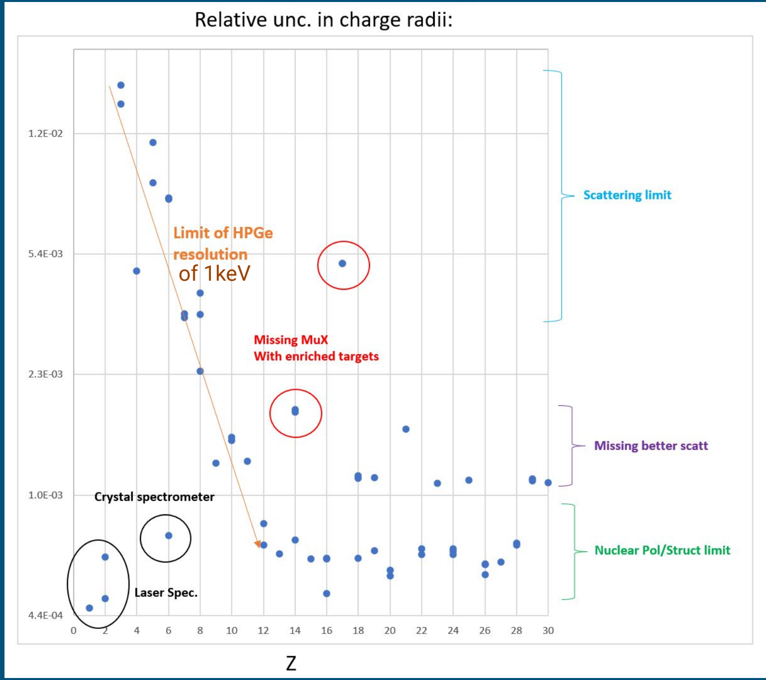


The limits of existing x-ray detectors

Method	Intrinsic Resolution	Typical Efficiency	Energy Range
HPGe	10^{-3} & ~500 eV	3×10^{-2}	>50 keV
Crystal spectrometers	10^{-6}	10^{-7}	<30 keV Narrow Band!
MCs	10^{-4}	10^{-4}	1-300 keV

MC's provide broadband high efficiency and resolution in the hard X-ray regime, never before available

Muonic atoms–nuclear charge radii



Nuclear charge radii in light systems (Z=3-10) currently limited by HPGe resolution

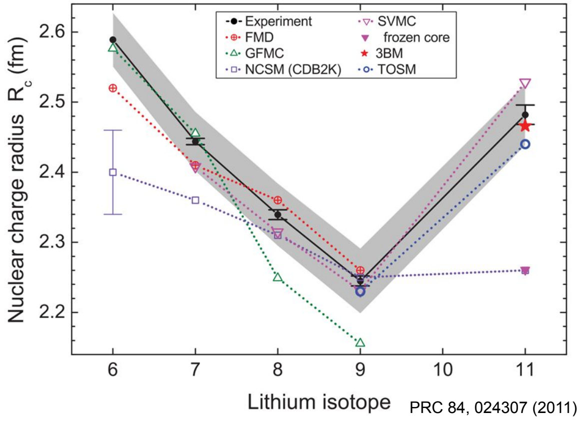
New high resolution @5-200 keV will have major impact

Absolute radii

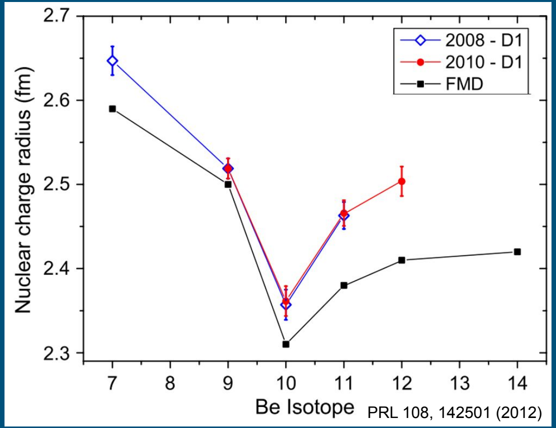
Absolute radii to anchor chains of isotope shift measurements. Test nuclear models.

Isot.	E_{1S-2P} keV	δ_{exp} eV	δ_{NP} eV	fm/keV	δ_r 10^{-3} fm	Gain	Good for
^{11}B	52	$5 \to 0.10$	$0.2 \to 0.05$	-6.7	$21 \to 0.8$	26	Mir., HLI, Chain
^{9}Be	33	$10 \to 0.07$	$0.1 \to 0.03$	-16	$12 \to 1.3$	9	Mir., HLI, Chain
^{7}Li	19	$60 \to 0.05$	$0.03 \to 0.01$	-47	$42 \to 2.4$	17	Mir., Chain

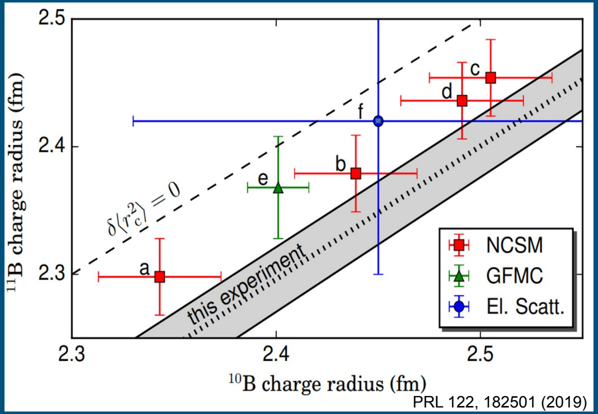
Lithium chain, limited by reference.
Can improve by factor ~50
No more grey band



Be chain, limited by reference.
Can improve by factor ~9



Improve ^{10,11}B absolute and IS
By factor ~30
~size of blue datapoint

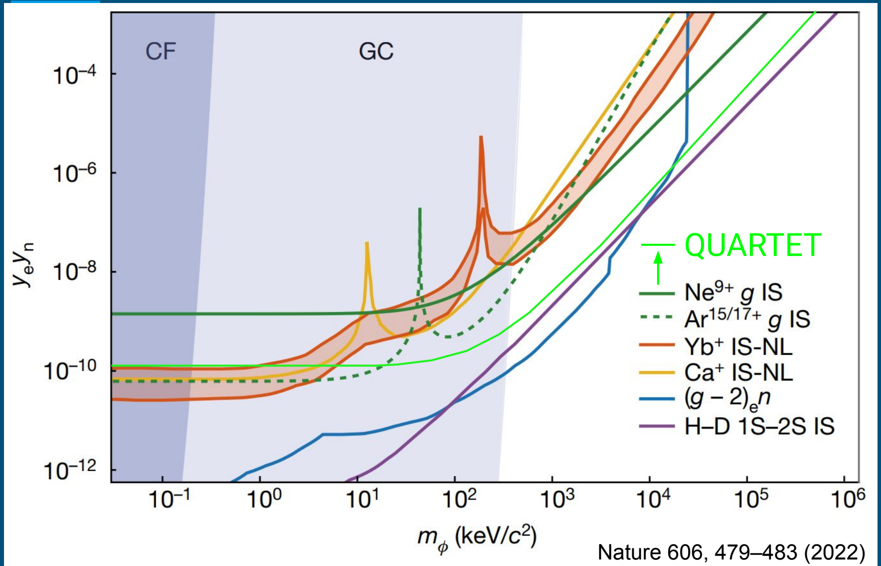


Critical for upcoming ^{8}B measurement

Up to N now accessible with No Core Shell Model with Continuum
Benchmark ab initio theory

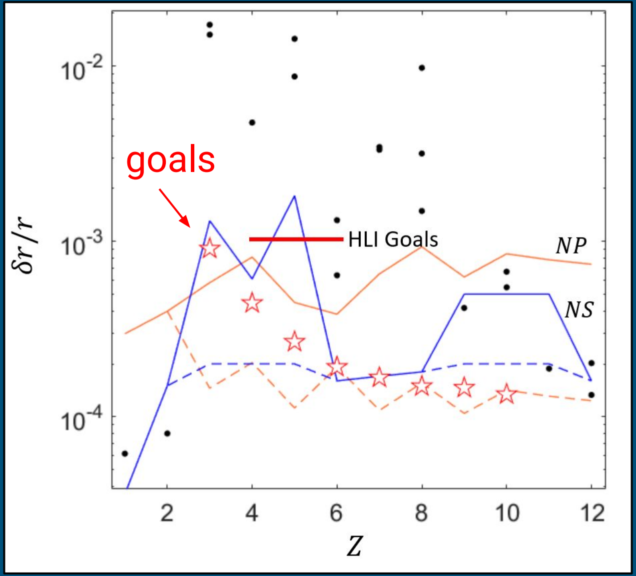
New Physics searches

“Fifth Force” searches through radii difference comparisons



Pair	ΔE_{2P-1S} eV	δ_{exp} eV	δ_{NP} eV	fm/keV	$\delta_{\Delta r}$ 10^{-3}fm	Gain	Good for
^{20,22}Ne	230	$6 \to 0.5$	$2 \to 0.5$	-0.4	$4.3 \to 0.4$	11	Δg
^{16,18}O	28	$10 \to 0.2$	$0.7 \to 0.3$	-1.0	$9.8 \to 0.3$	33	Δg

Compare **absolute** radii with upcoming from Helium-like ions



Isot.	E_{1S-2P} keV	δ_{exp} eV	δ_{NP} eV	fm/keV	δ_r 10^{-3} fm	Gain	Good for
^{12}C	75	$0.5 \to 0.15$	$0.3 \to 0.15$	-3.2	$1.9 \to 0.7$	3	χPT, HLI
^{11}B	52	$5 \to 0.10$	$0.2 \to 0.05$	-6.7	$21 \to 0.8$	26	Mir., HLI, Chain
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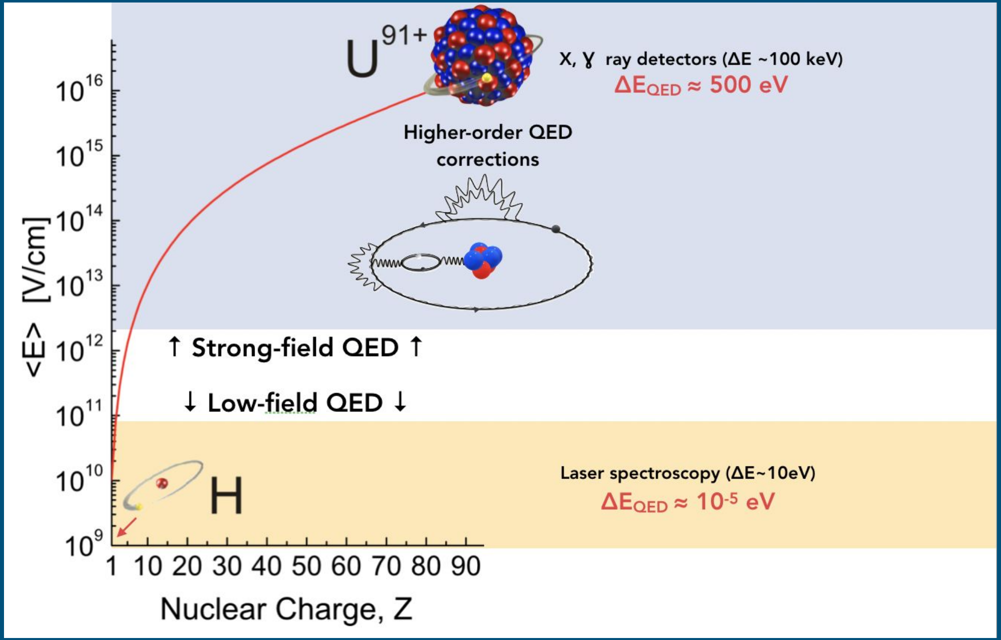
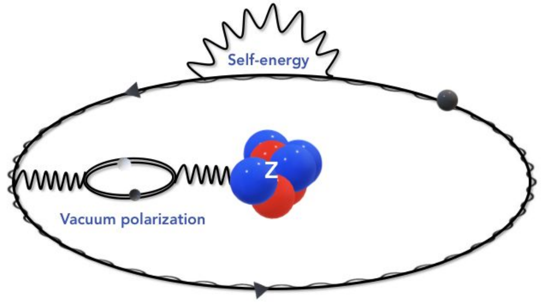
Strong-field Bound State QED

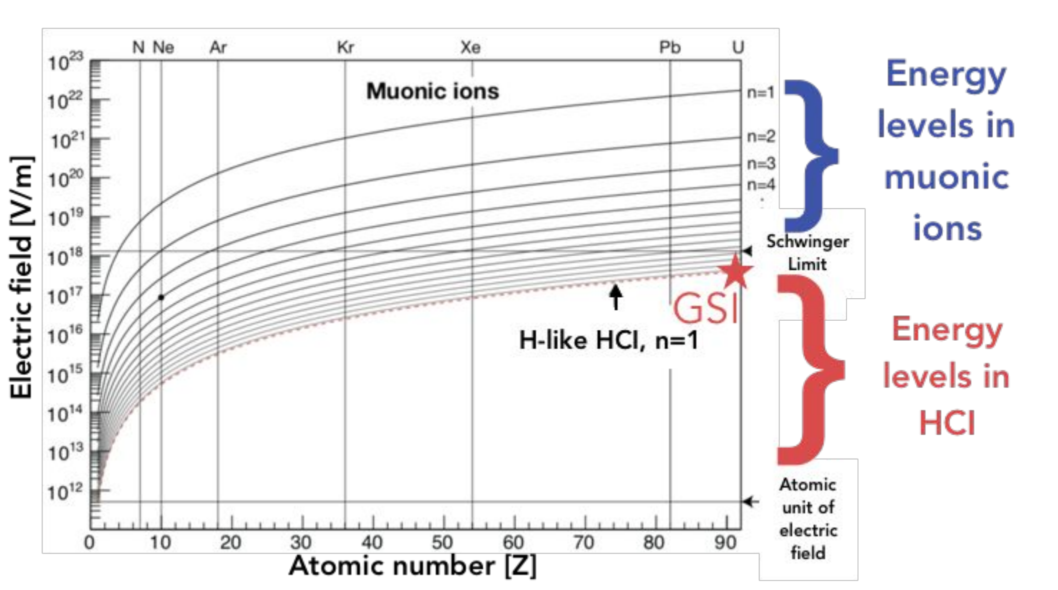




BSQED in strong field regime poorly probed, due to lack of lasers and large nuclear uncertainties

- H tested at 3rd order QED
- H-like U only at threshold of 2nd order (GSI)

Strong-field Bound State QED



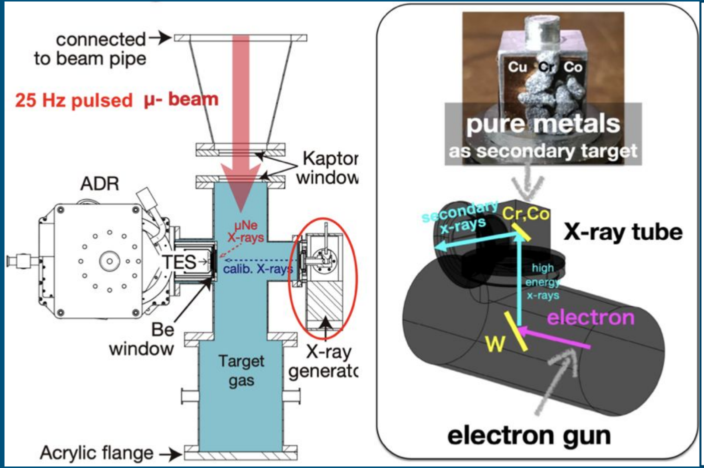
Exotic atoms offer orders of magnitude higher Coulomb fields

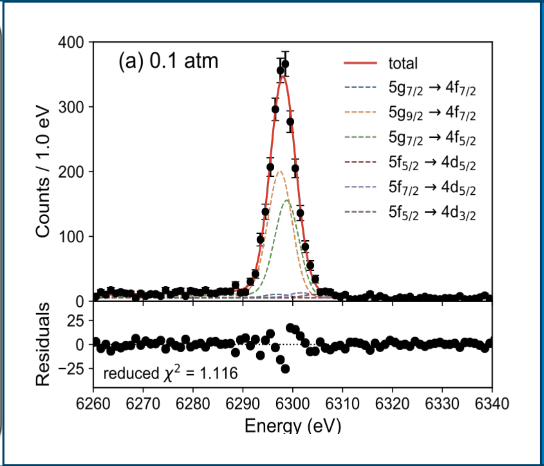
Rydberg states–negligible nuclear uncertainties

Sensitivity to 2nd order QED for large range of Z

N. Paul et al, PRL 126 (2021)

Proof of principle : JPARC with TES





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

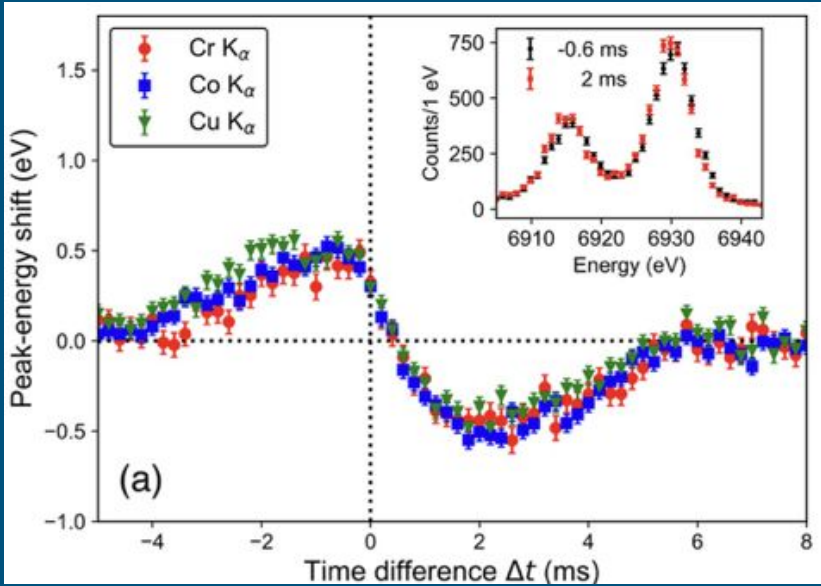
HEATES collaboration with NIST-TES

N-=5→ 4 transition in muonic Ne

Probe strong-field vacuum polarization

T. Okumura et al, submitted

JPARC limitation : charged particle background



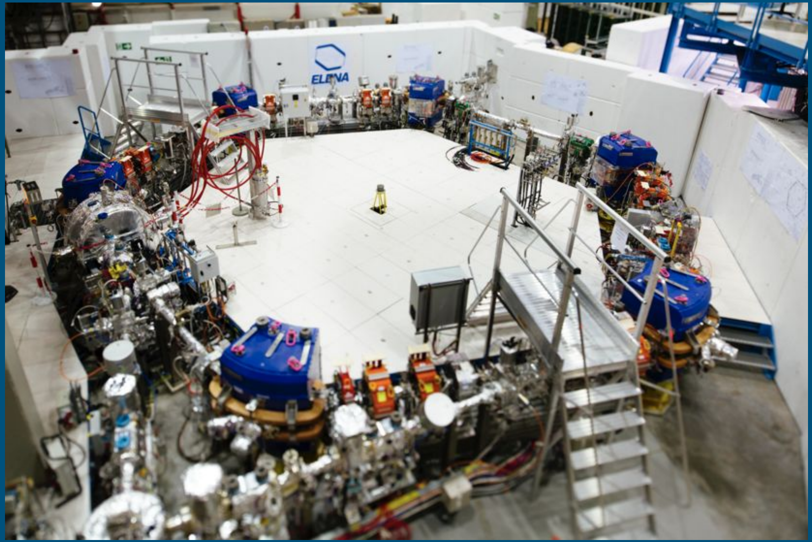
Transition energy and associated uncertainties (eV)	Pressure (atm) 0.1	0.4	0.9
experiment	6297.46	6297.39	6297.39
statistical error	0.06	0.05	0.05
systematic error: total	0.11	0.12	0.11
1) calibration anchors	0.00	0.00	0.00
2) tail-param. for energy calib.	0.02	0.03	0.00
3) interpolation	0.02	0.03	0.01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

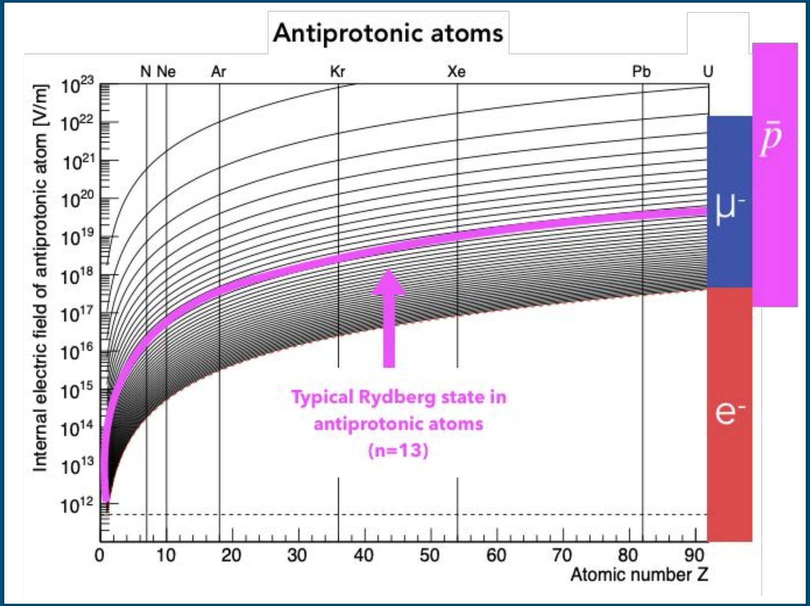
0.5 eV shift from charged particle background! Largest systematic uncertainty

Conclusions from JPARC

1. MC spectroscopy is possible, but JPARC isn't optimal (pile-up from 50 muons/ns)
2. PSI: tagged rate 50 muons/ms (million times less pileup)
3. Calibration at low energies works well with x-ray tubes. Needs to be online!
4. Can stop muons in ~Bar of neon. Showed no electrons left (no screening).
5. Absorption in windows/gas not limiting above ~keV

And then.. BSQED with antiprotons

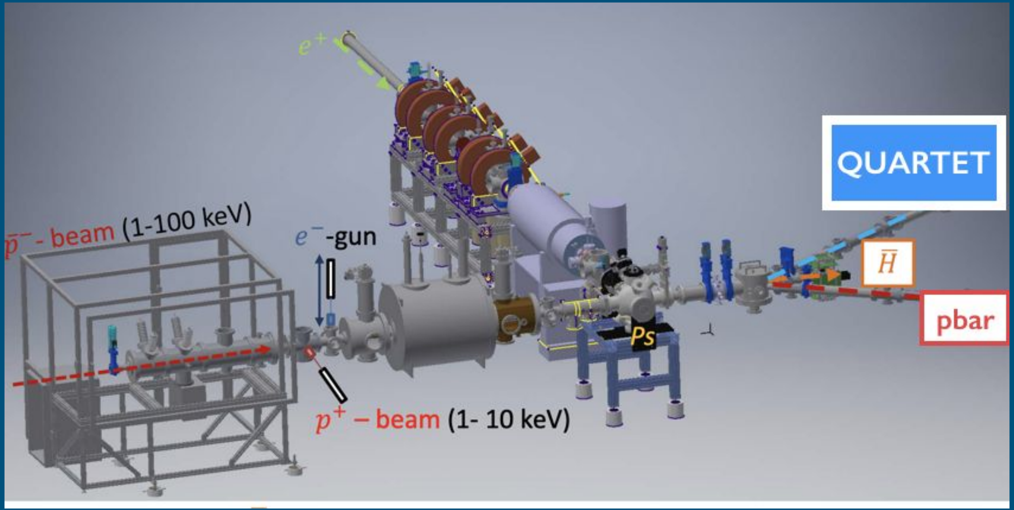


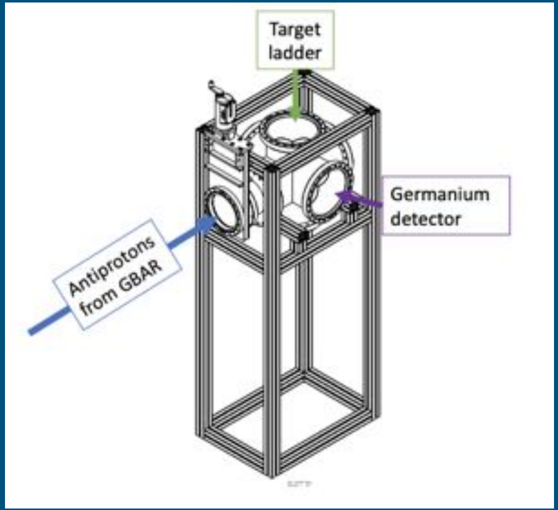


Extra Low Energy Antiprotons (ELENA) now at CERN

Strongest field BSQED tests, highest sensitivity, same experimental method as for charge radii

QUARTET @ GBAR

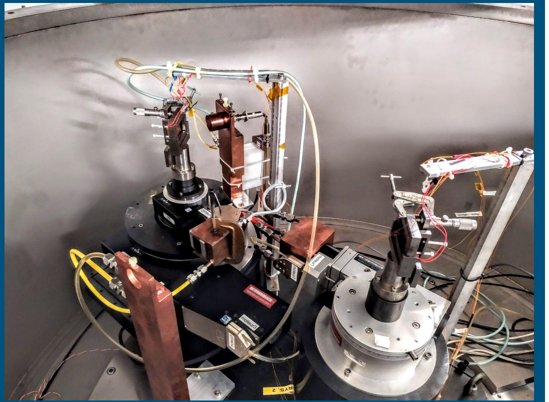


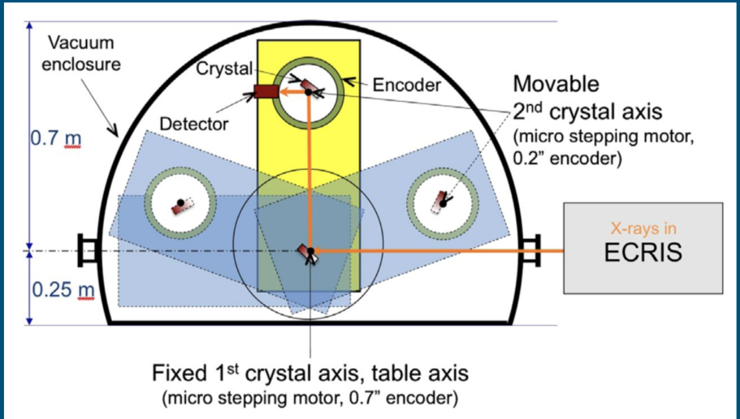


Proof of principle tests for x-ray spectroscopy at GBAR will begin in fall 2022

Test chamber + Ge detector, solid targets, study background for MC detector

Metrology of MCs?





$\Delta E/E=10^{-6}$

~meV for 3 keV x ray

Paris Double Crystal Spectrometer (DCS) = reference-free spectroscopy, crystal lattice spacing directly connected to the definition of the meter.

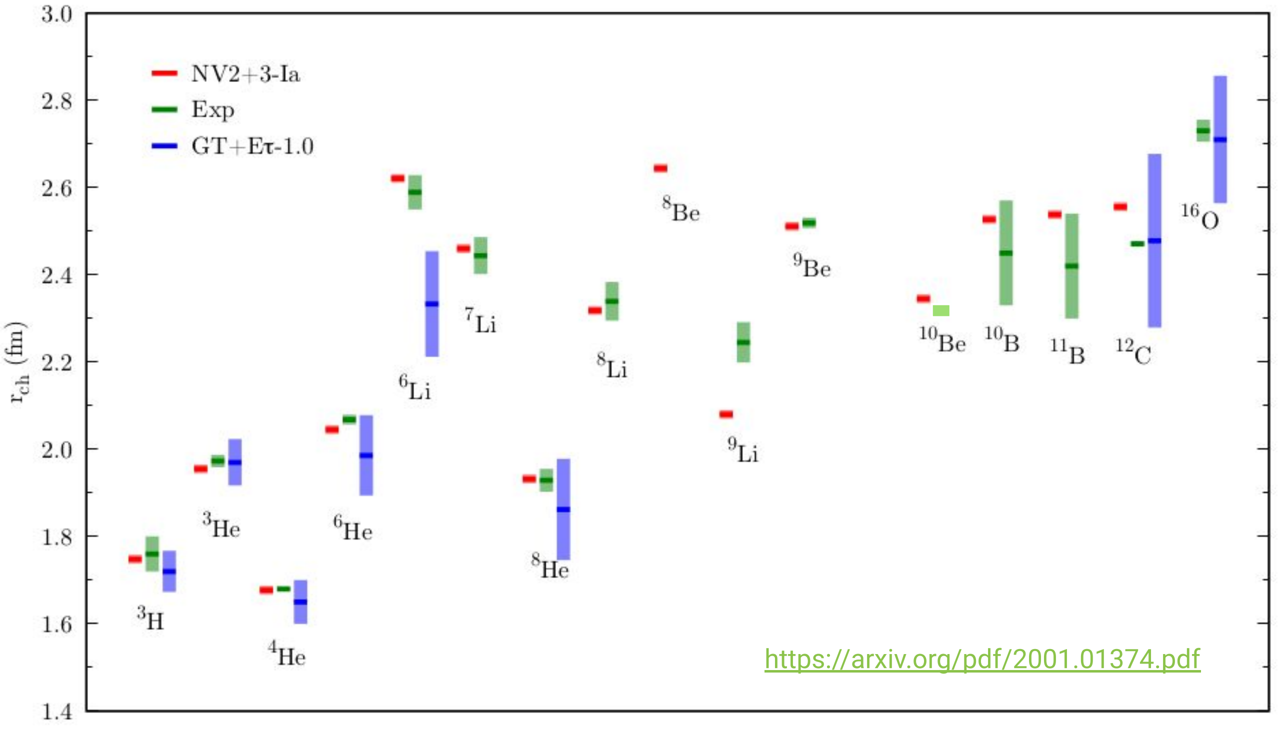
Absolute line shapes from DCS, **calibrate response function of MMC (<30 keV)**

Improve accuracy of MMCs?

J W Fowler et al 2021 Metrologia **58** 015016 (2021)

Extra

Low Z <r2> and ab-initio/EFT/NN calculations



https://arxiv.org/pdf/2001.01374.pdf