

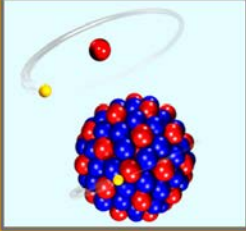
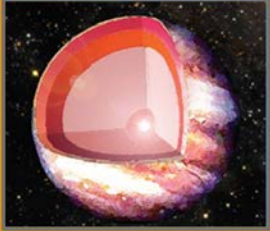
Stored Particles Atomic Physics Research Collaboration

Atomic, Quantum, and Fundamental Physics

Alexandre Gumberidze
GSI-Darmstadt and University of Frankfurt



On behalf of the SPARC collaboration

Atomic Physics	Plasma	Materials	Bio
			
SPARC strong field research ... probing fundamental laws of physics	HED warm dense matter ... states of matter common in astrophysical objects	MAT/BIOMAT radiation hardness ... mechanical and electrical degradation of materials	BIO/BIOMAT space travel ...cosmic radiation risk and shielding particle therapy radioactive beams FLASH therapy

APPA covers a broad variety of highly interdisciplinary research fields and user communities

FACILITY CAPABILITY

- Highest Charge States
- Relativistic energies
- High Intensities
- High Charge at Low Velocity

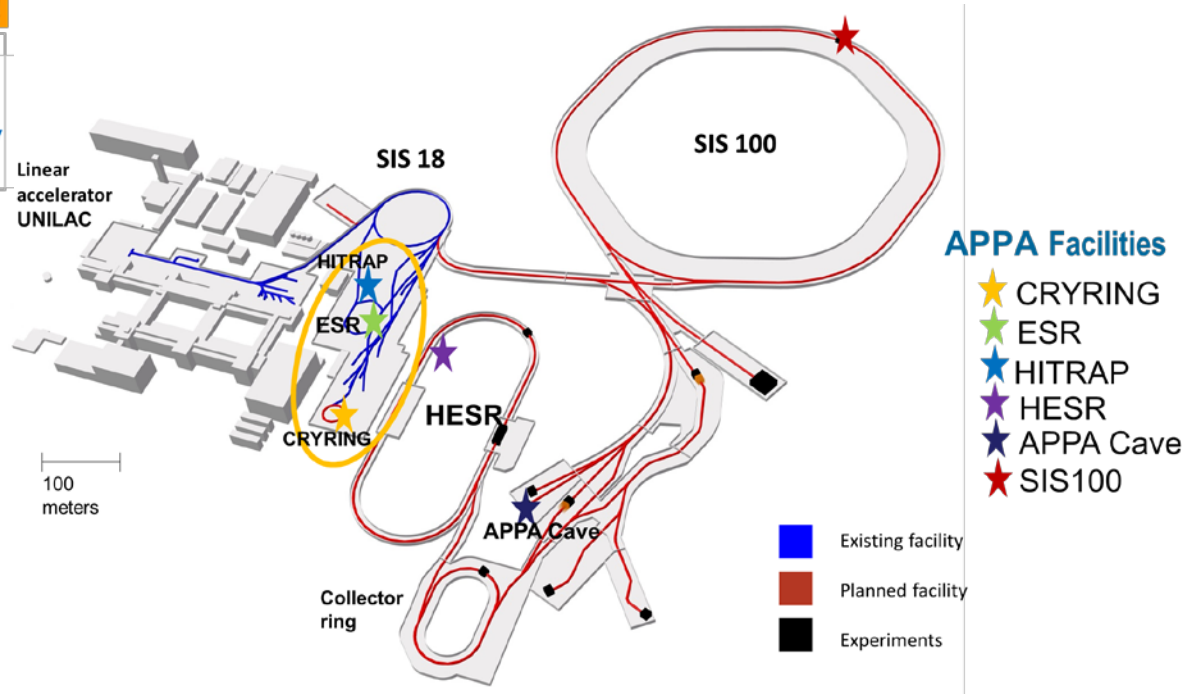
SCIENTIFIC CAPABILITY

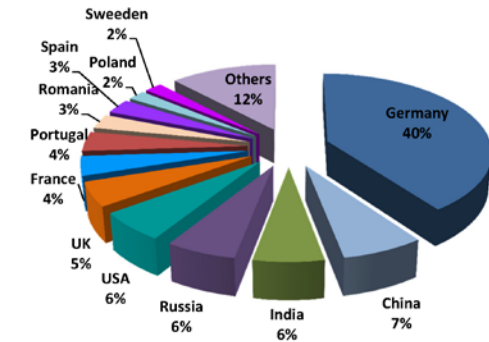
- Extreme Static Fields
- Extreme Dynamical Fields
and Ultrashort Pulses
- Very High Energy Densities
and Pressures
- Large Energy Deposition

Atomic Physics	Plasma	Materials	Bio
SPARC strong field research ... probing fundamental laws of physics	HED warm dense matter ... states of matter common in astrophysical objects	MAT/BIOMAT radiation hardness ... mechanical and electrical degradation of materials	BIO/BIOMAT space travel ... cosmic radiation risk and shielding particle therapy radioactive beams FLASH therapy

APPA science program aims at exploiting the full parameter range of FAIR beams at different experimental areas.

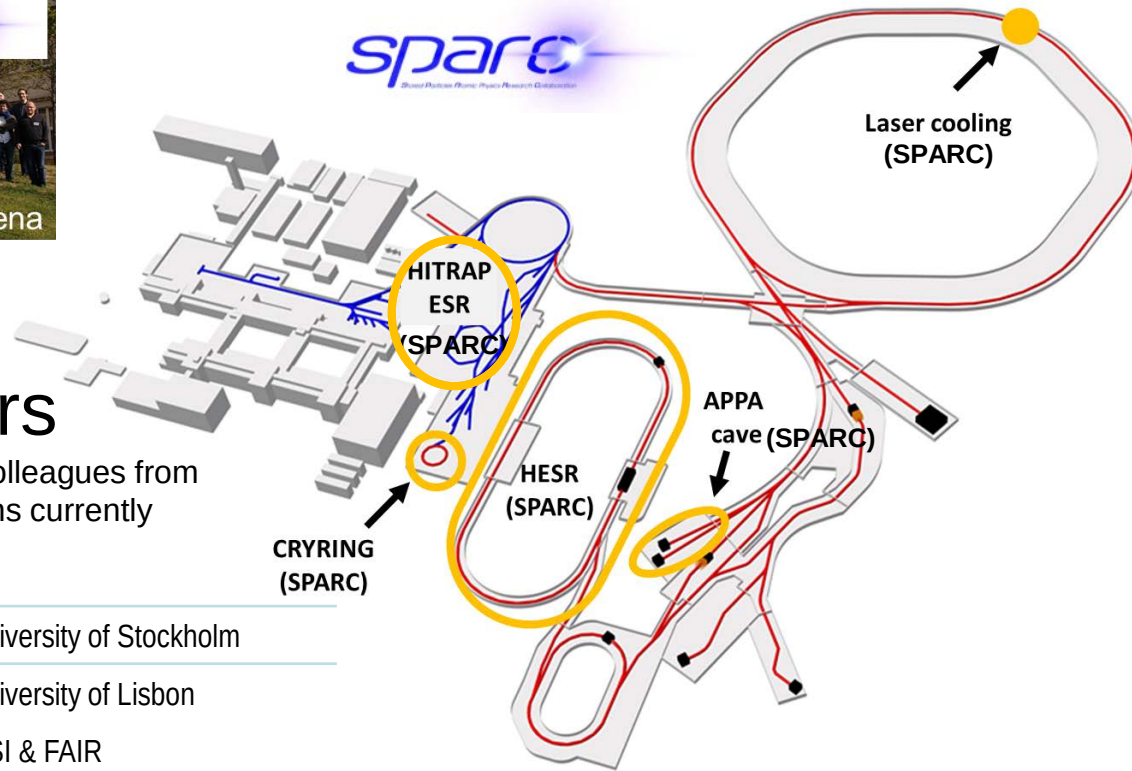
APPA has been formed to jointly coordinate common experimental installations such as the APPA cave and to use synergies in selected research projects.





430 Members

(participation of colleagues from Russian institutions currently suspended)



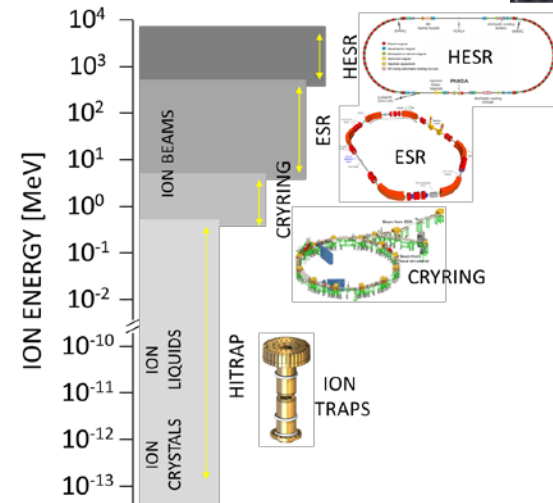
Spokesperson	Reinhold Schuch	University of Stockholm
Vice Spokesperson	Jose-Paulo Santos	University of Lisbon
Coordinator	Angela Bräuning-Demian	GSI & FAIR
Hostlab Liaison	Thomas Stöhlker	HI Jena & GSI
Polish representative	Marek Pajek	JKU Kielce

<https://www.gsi.de/SPARC>

HITRAP, CRYRING@ESR, ESR: Existing Facilities of MSV

Worldwide
Unique !

From rest to relativistic
energies (up to 4.9 GeV/u)

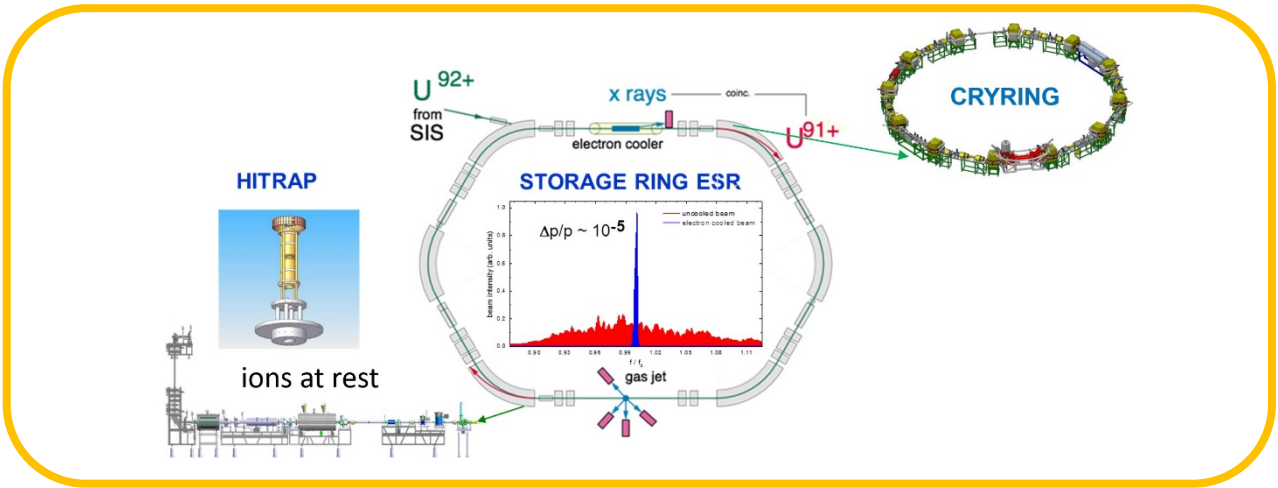
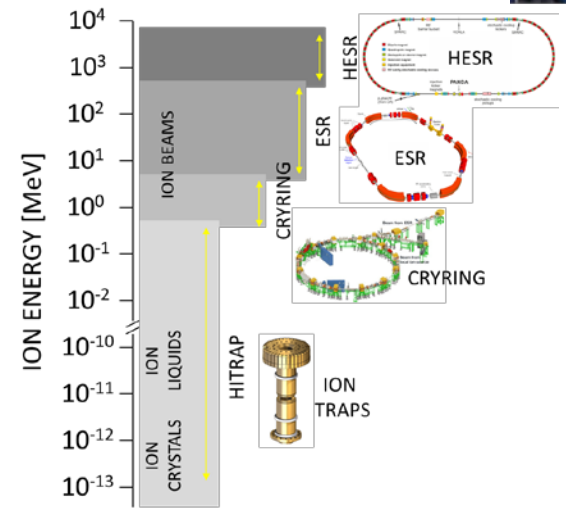


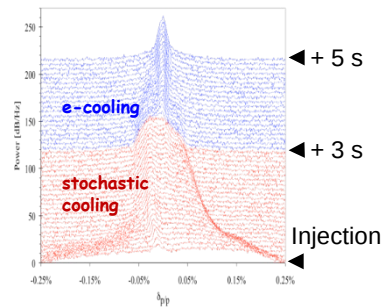
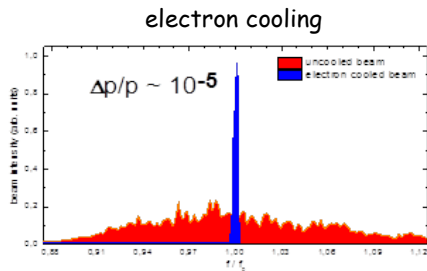
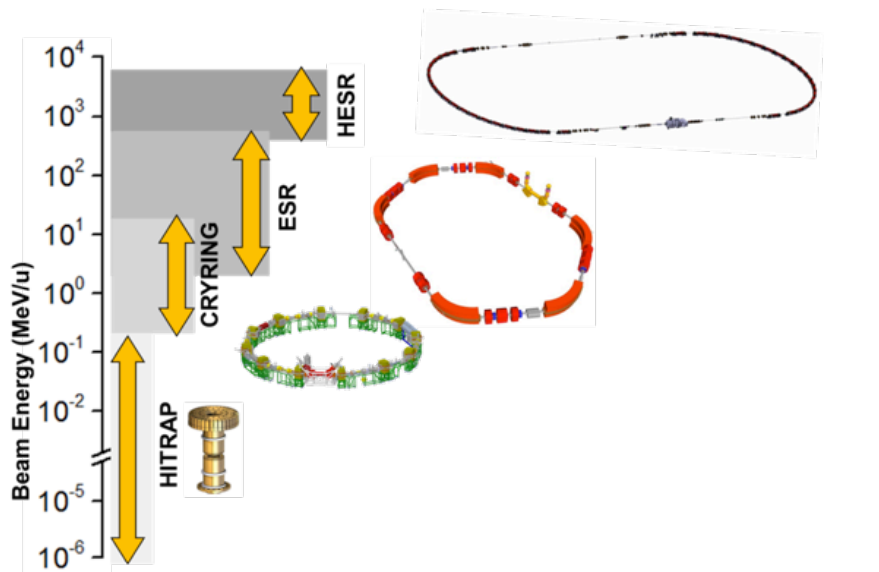
CRYRING@ESR: Swedish in-kind to FAIR; in operation since 2020

HITRAP: Re-commissioning has started in 2022

HITRAP, CRYRING@ESR, ESR: Existing Facilities of MSV

From rest to relativistic energies (up to 4.9 GeV/u)

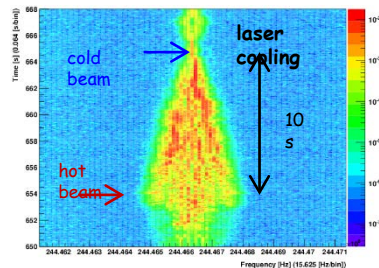
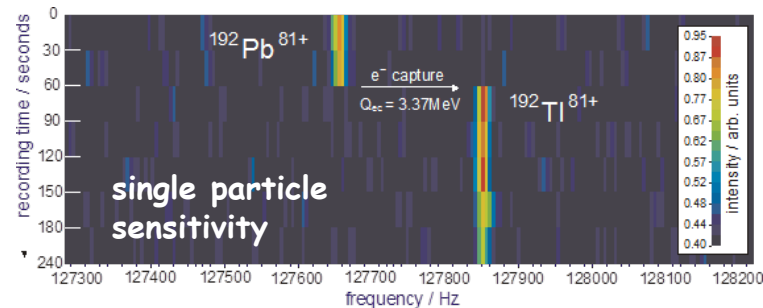




Stored and Cooled!

Highly-Charged Ions (e.g. U^{92+}) and Exotic Nuclei
From Rest to Relativistic Energies (up to 4.9 GeV/u)

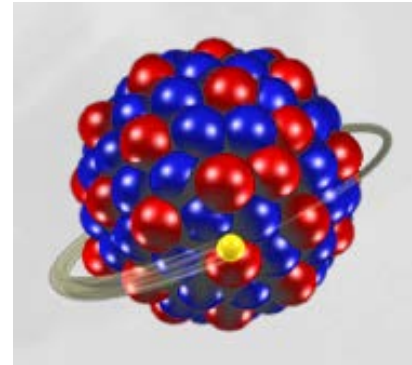
prepared in a desired quantum state over a broad energy range



Hydrogen



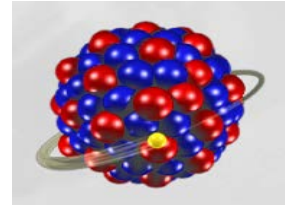
Hydrogen-like uranium: 92 Protons in the nucleus and only one electron



Smaller distance between electron and nucleus
 (for uranium: electron is **about 100 times closer to the nucleus**
 than in hydrogen)

Electrons move very fastly; they are relativistic
 (for uranium: K-shell electron moves
 with **about 70% of the speed of light**)

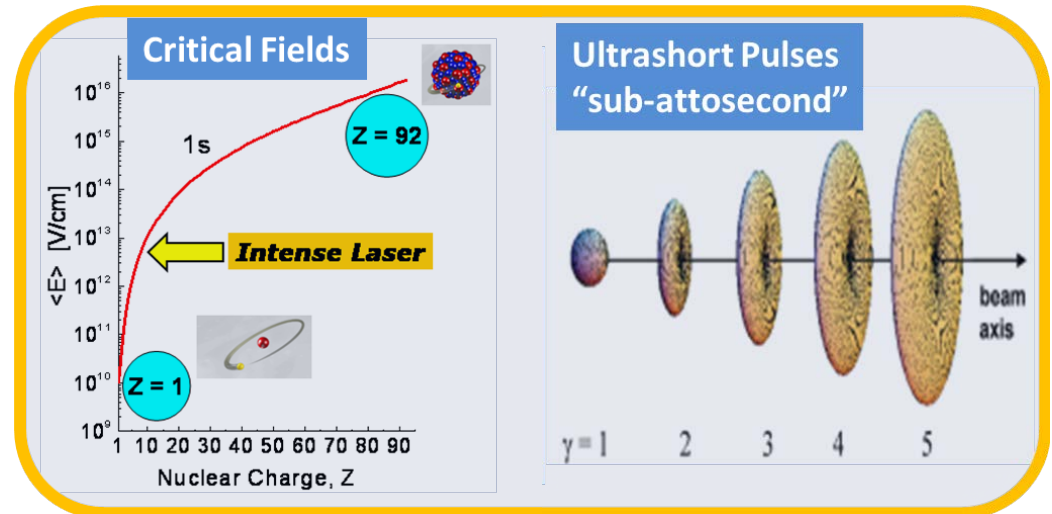
QED at the Schwinger-Limit
Correlated multi-body dynamics
Astrophysical phenomena involving exotic ions/nuclei
Borderline between atomic and nuclear physics
Fundamentals



H-like Uranium
 $\langle E \rangle \sim 10^{16}$ V/cm

$$\alpha Z \approx 1$$

- Fundamental phenomena:
 - become accessible due to:
 - simpler electronic structure
 - scaling of effects with high powers of Z (QED, nuclear effects,...)
- Laboratory and astrophysical plasmas:
 - Almost all luminous matter is ionized
- Frequency and X-ray standards
- Fundamental constants





Richard Feynman
1918-1988

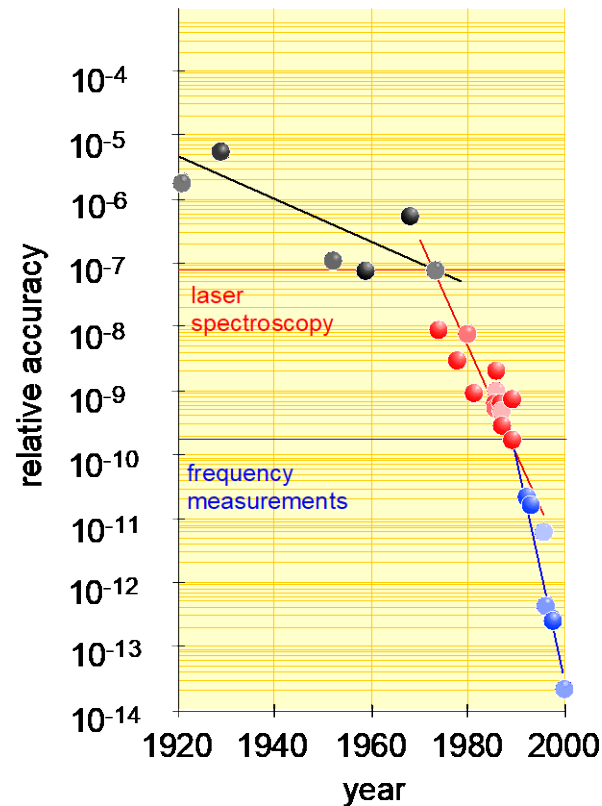
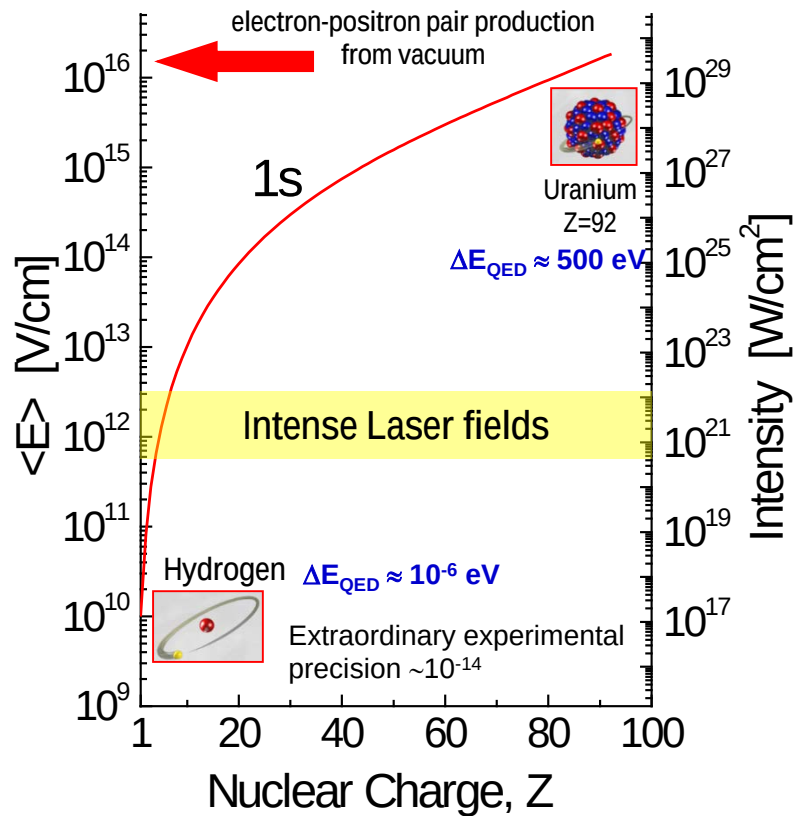
... having to resort to such
hocus, focus, renormali-
zation, has prevented us from
proving that the theory of
QED is mathematically
self-consistent.

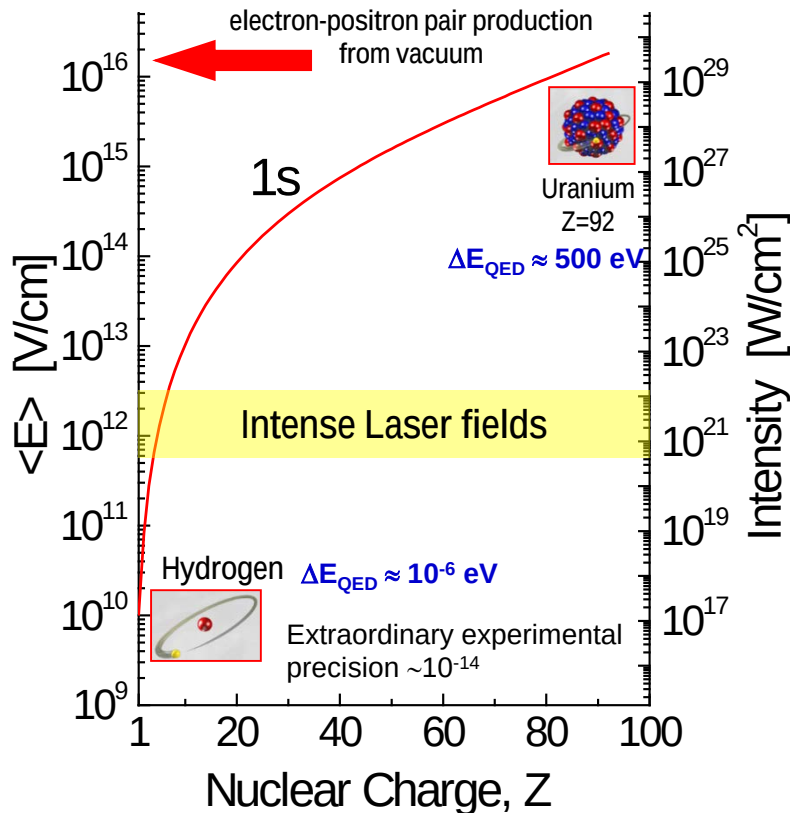
R. Feynman, 1983
[renormalization] is what
I would call a dippy process.

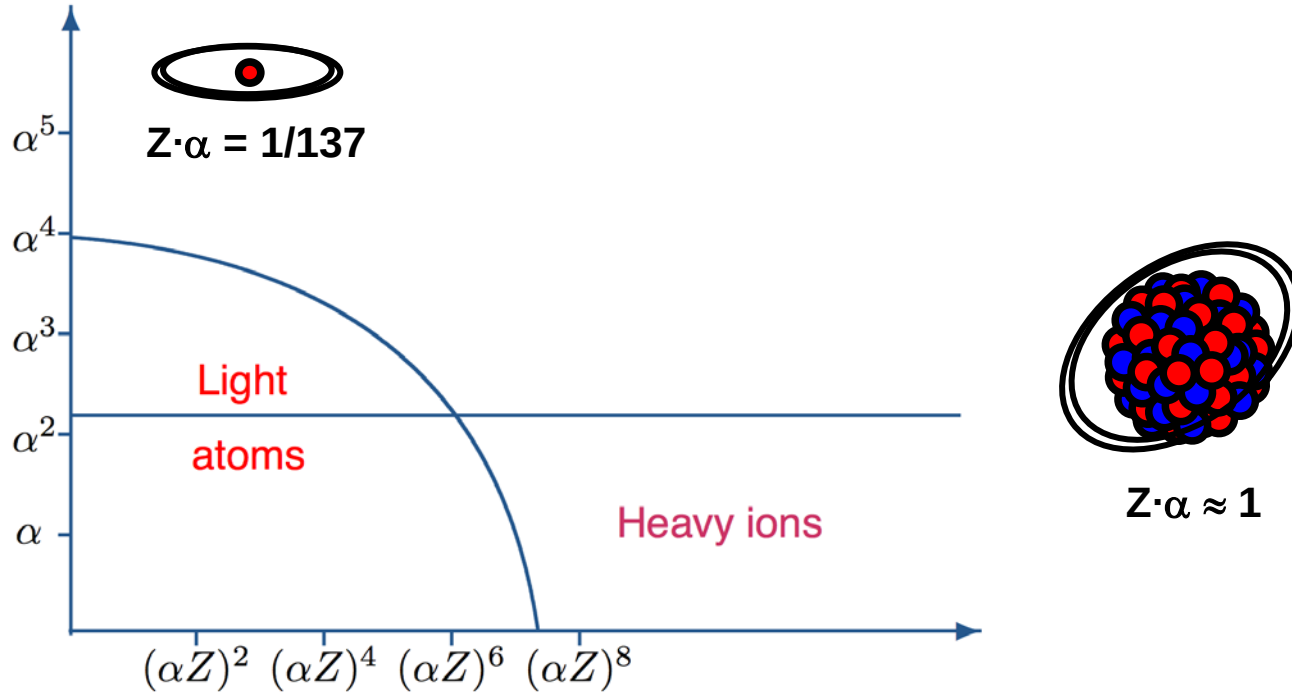
R. Feynman, 1985

Quantum electrodynamics (QED) is a theory of EM interactions or light-matter interaction.

Historically and conceptually it is a basis of the Standard Model and of other field theories.





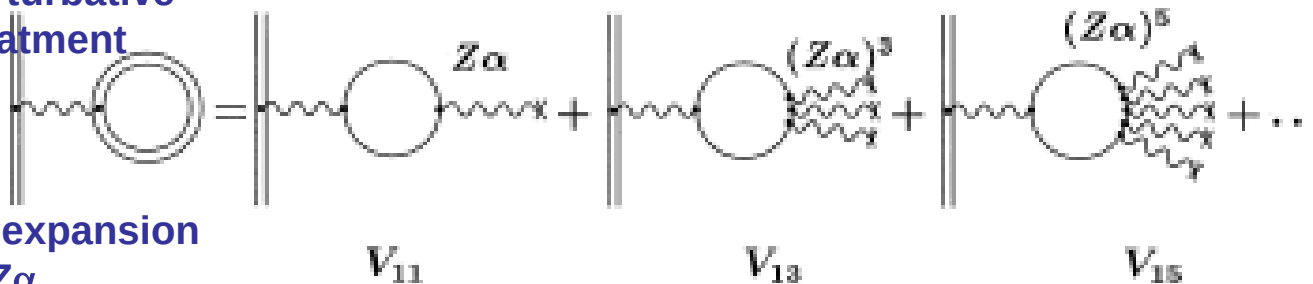


Extremely strong fields: test of QED to lowest orders in α and all orders in $Z\alpha$

non-
perturbative
treatment

no expansion
in $Z\alpha$

perturbative treatment: expansion in $Z\alpha$



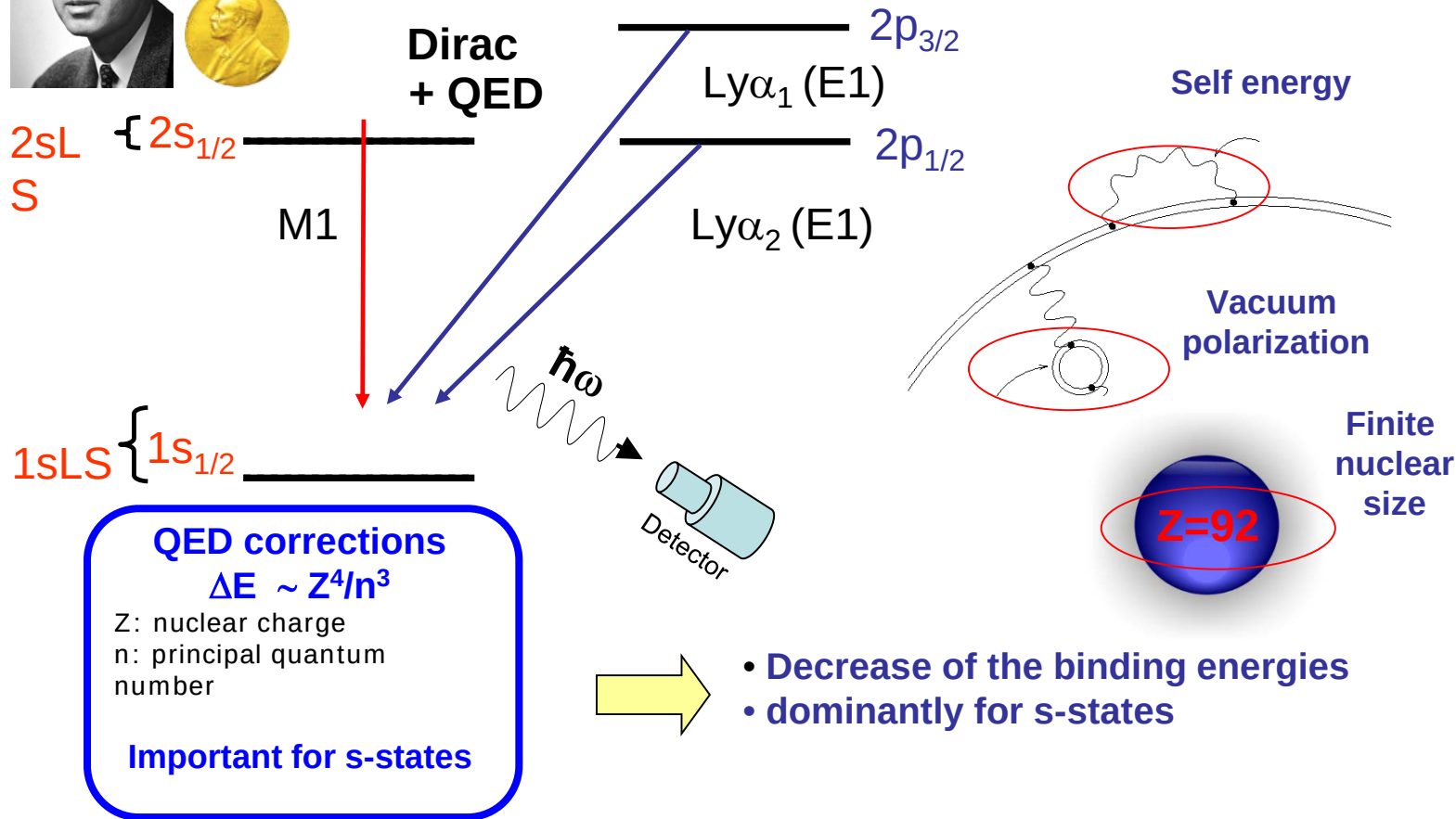
Non-perturbative bound-state QED was developed in the decades by excellent theoreticians like:

Beier, Blundell, Breit, Czarnecki, Glazov, Jentschura, Johnson, Karshenboim, Lindgren, Lee, Milstein, Mohr, Pachucki, Persson, Plunien, Salomonson, Sapirstein, Shabaev, Soff, Sunnergreen, Terekhov, Tupitsyn, Volotka, Yerokhin, and others.

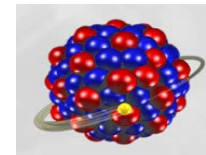


Atomic Structure of One-electron System

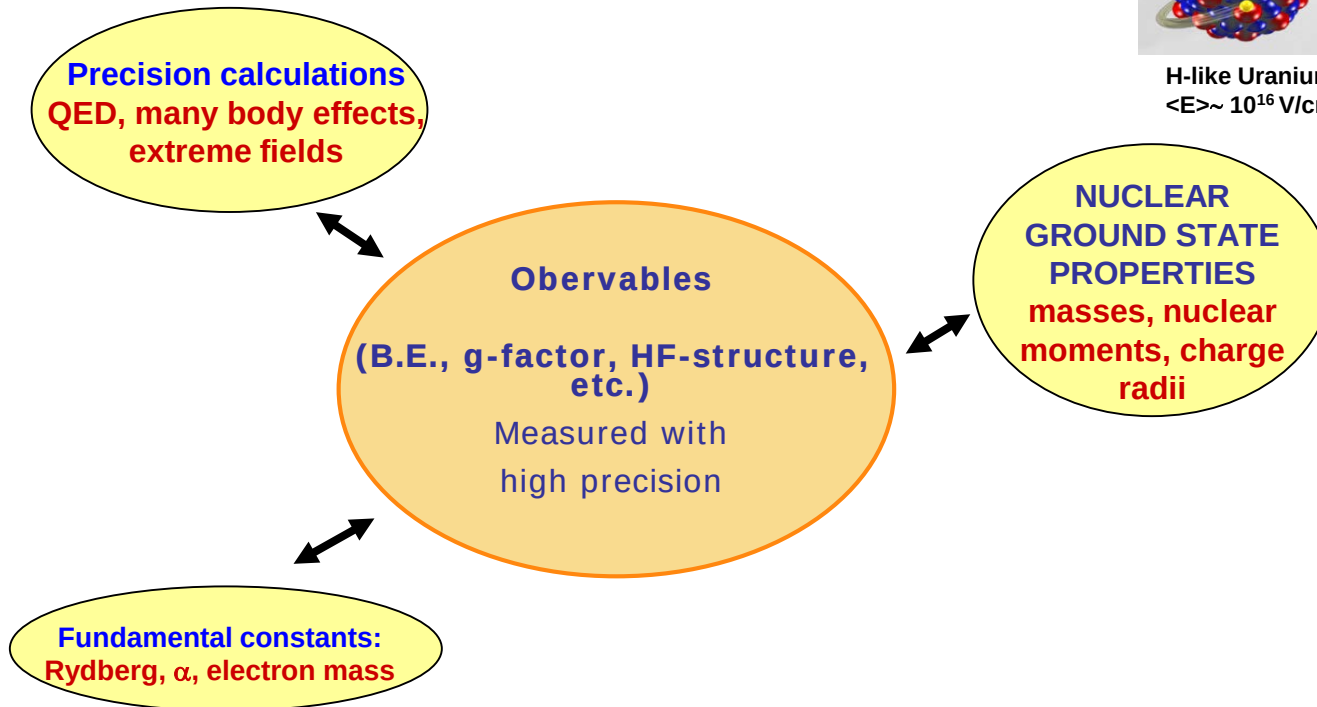
Experiment: Lamb-Retherford 1947; Theoretical Explanation; Bethe 1947



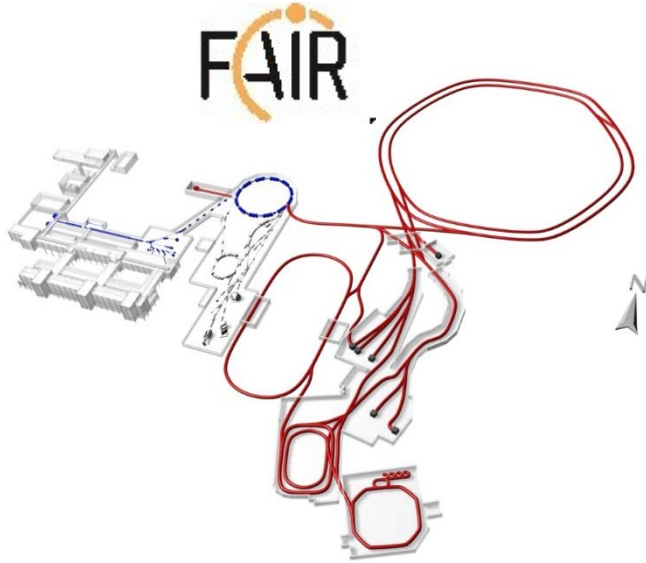
Testing our current understanding of EM interactions (QED)
in different regimes with fundamental atomic systems



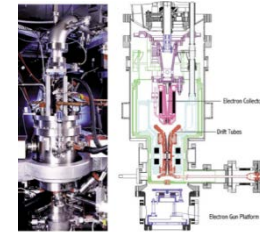
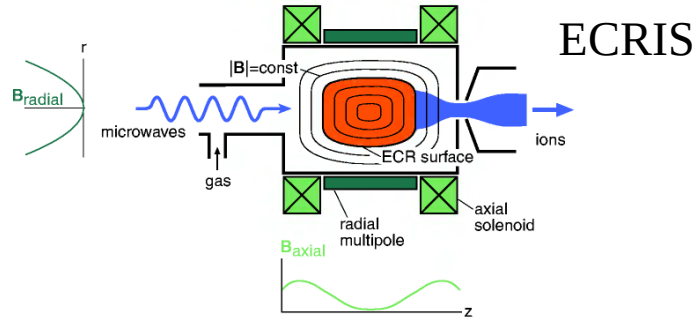
H-like Uranium
 $\langle E \rangle \sim 10^{16}$ V/cm



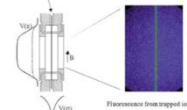
How to make HCI ?



~100s of meters



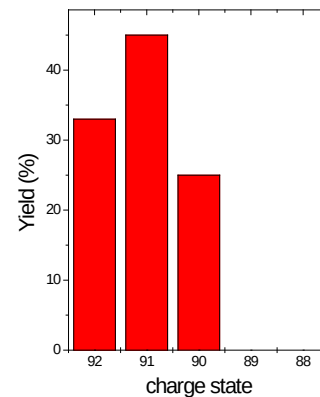
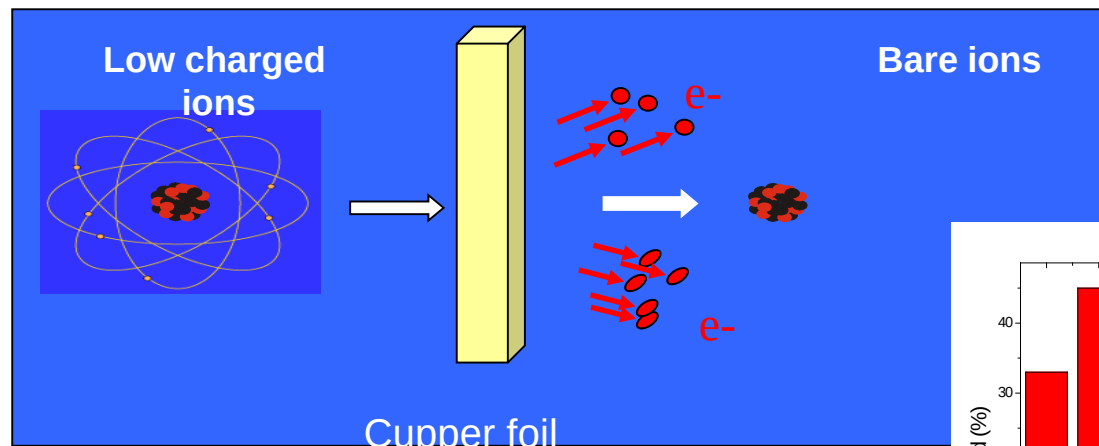
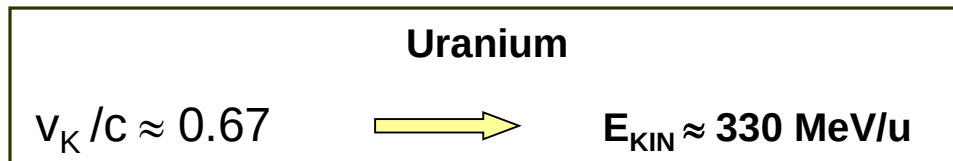
EBIT

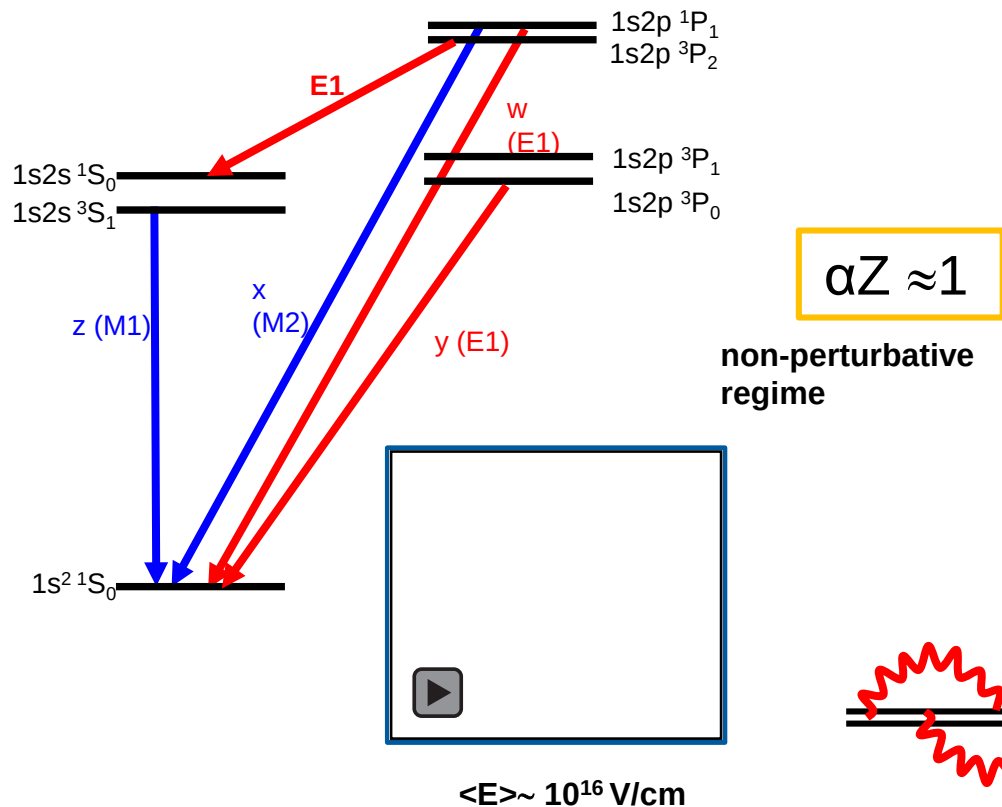


~few meters

Why relativistic velocities?

Bohr criteria: *Largest ionization cross section at* $V \approx V_K$



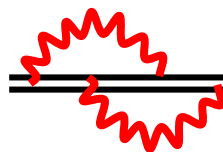


interplay between radiative QED and e-e correlation effects; two-electron QED

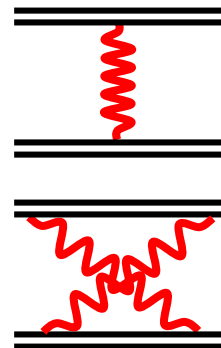
important also for proposed PNC studies

Up to now only very few measurements available in the high-Z regime

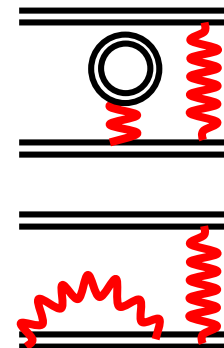
Electron-electron interaction
in the regime of extreme fields



Two-loop QED

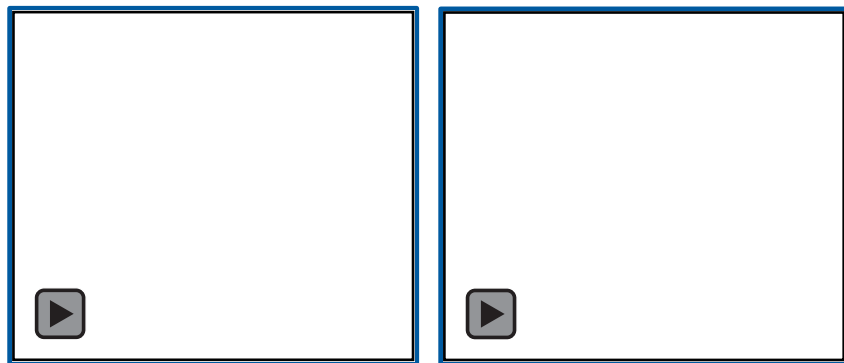


Non-radiative
QED

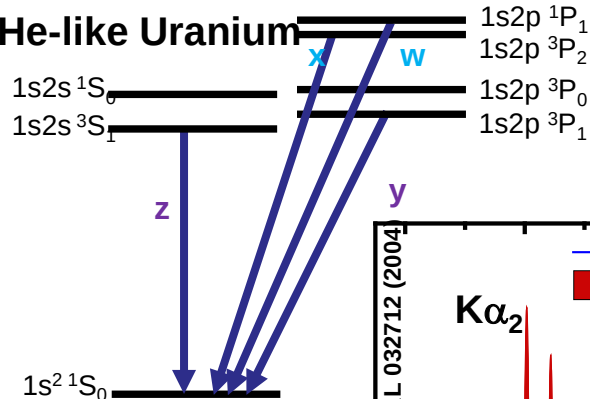


Radiative
QED

High-Resolution Spectroscopy of X-Ray Transitions in He-like Uranium at CRYRING@ESR



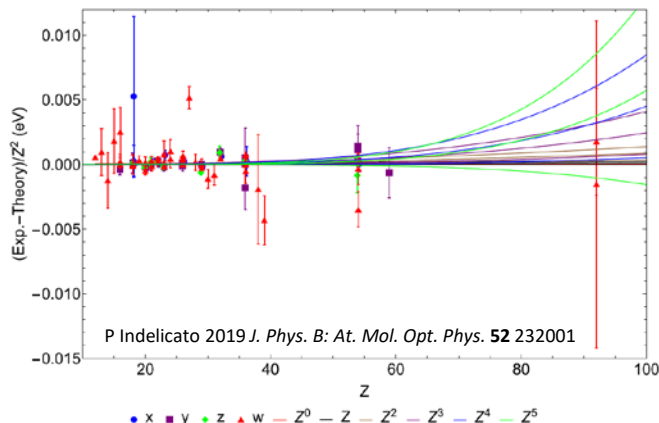
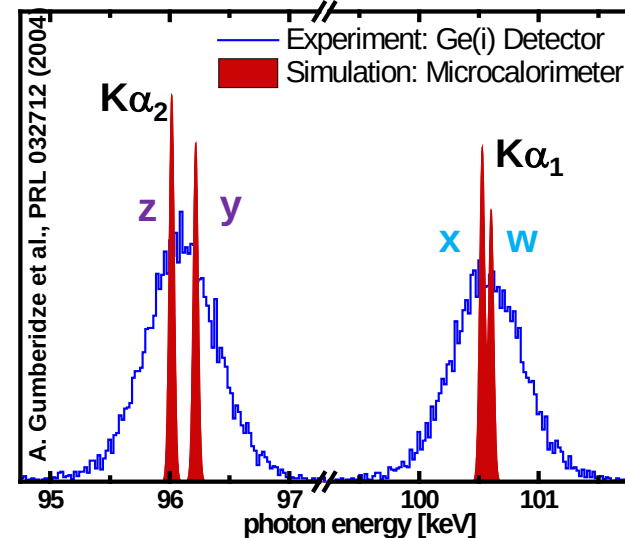
He-like Uranium



$$\Delta(w-x) = 74 \text{ eV}$$

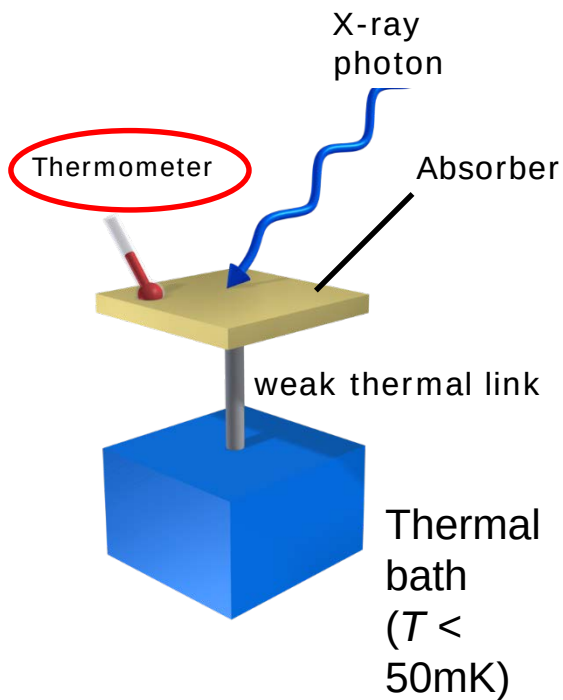
$$\Delta(y-z) = 142 \text{ eV}$$

Y. S. Kozhedub et al., Phys. Rev. A 100, 062506 (2019)



No high-resolution measurements
for $K \rightarrow L$ transitions
available for He-like systems
with $Z > 54$.

For high-Z systems a spectral resolution of <100 eV FWHM is necessary to resolve the $n=2$ level structure and benchmark state-of-the-art theory.



Main observable: temperature change

should be large

to be measured

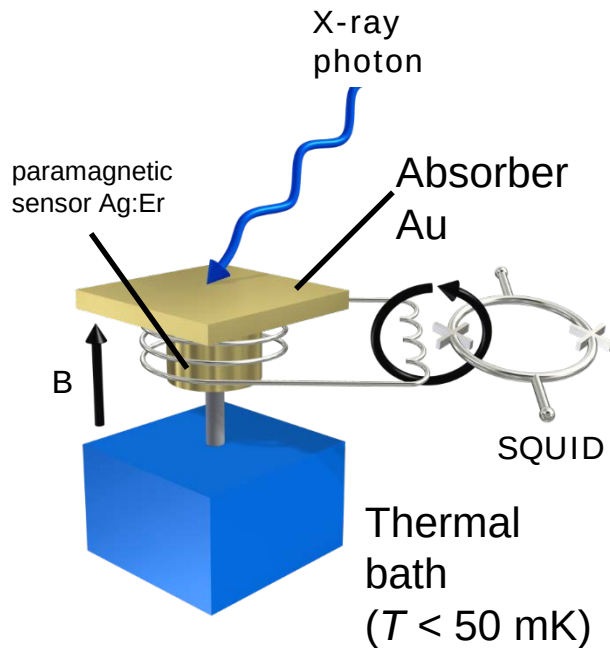
$$\delta T = \frac{E_\gamma}{C}$$

As small as possible;
hence **Micro**calorimeter

Heat capacity of a conductor:

$$C = V(\gamma T + \beta T^3)$$

=> small volume at superconducting temperature



D. Hengstler et al. Phys. Scr. **T166**, 014054 (2015)

Univ. Heidelberg

C. Enss, A. Fleischmann

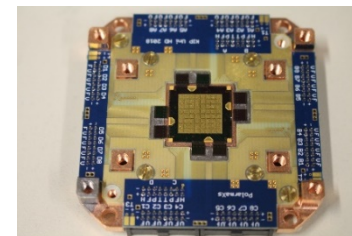
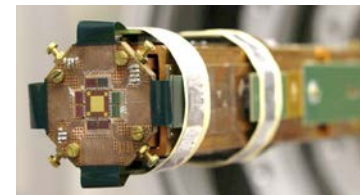
Metallic Magnetic calorimeter

- photon heats absorber
- change of magnetization in paramagnetic sensor
- change of induced current measured by SQUID

Features (maXs-30)

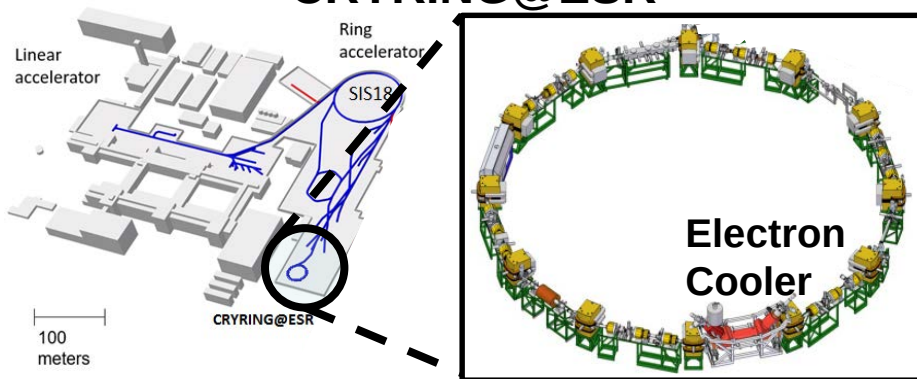
- number of pixels: 64
- pixel absorber size: $0.5 \times 0.5 \text{ mm}^2$
- energy range: 2 - 30 keV
- energy resolution: < 10 eV

(e.g. Ge(Li) detector: 200 eV @ 6 keV)

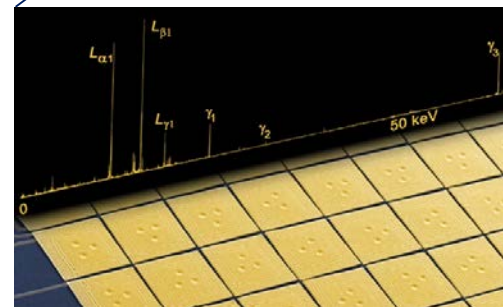
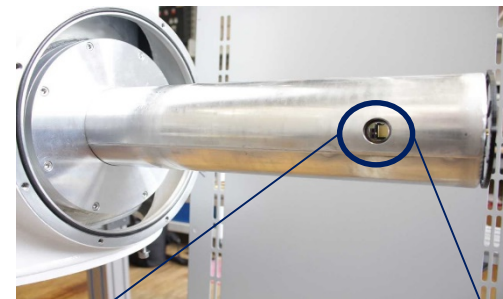
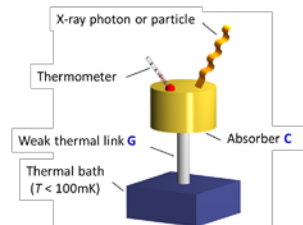


A new experimental approach: Combining the best of two worlds

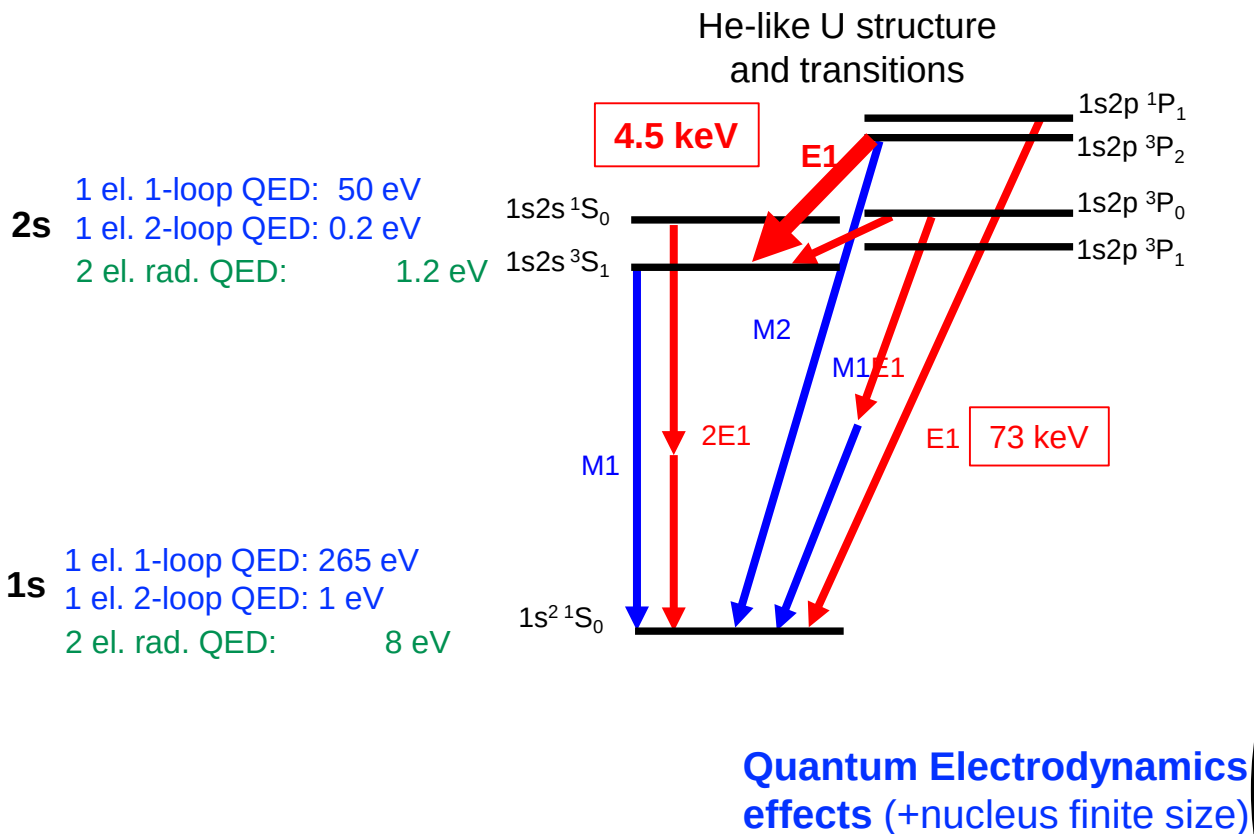
CRYRING@ESR



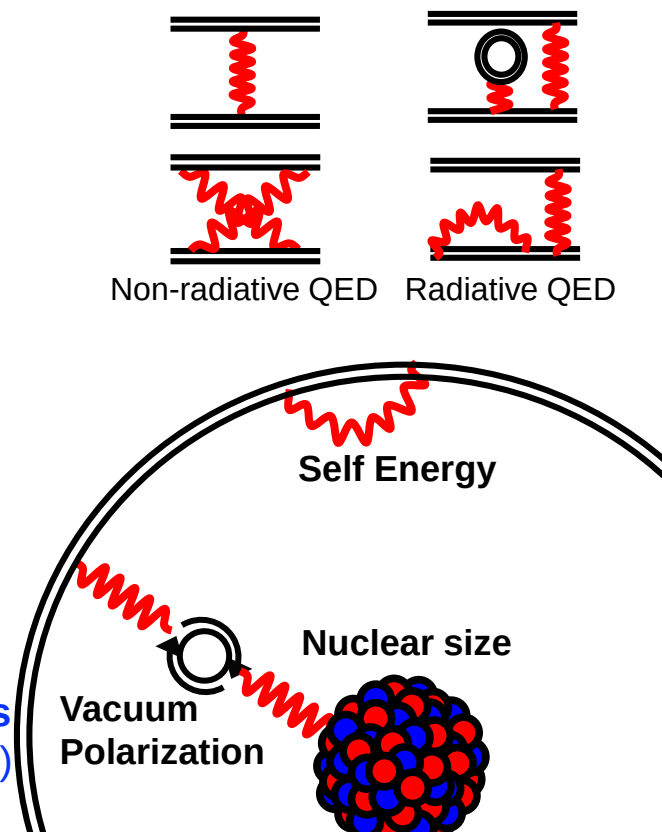
Metallic Magnetic Microcalorimeter (MMC) Detectors



Combination of high spectral resolution and broad bandwidth acceptance offers unique possibilities.



Two-electron QED interaction



PHYSICAL REVIEW A

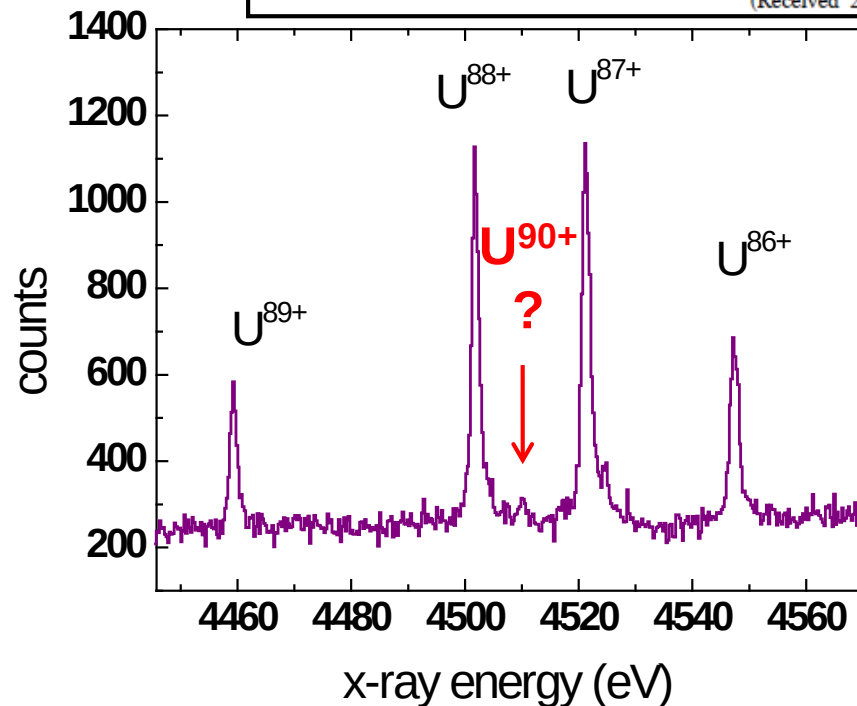
VOLUME 53, NUMBER 6

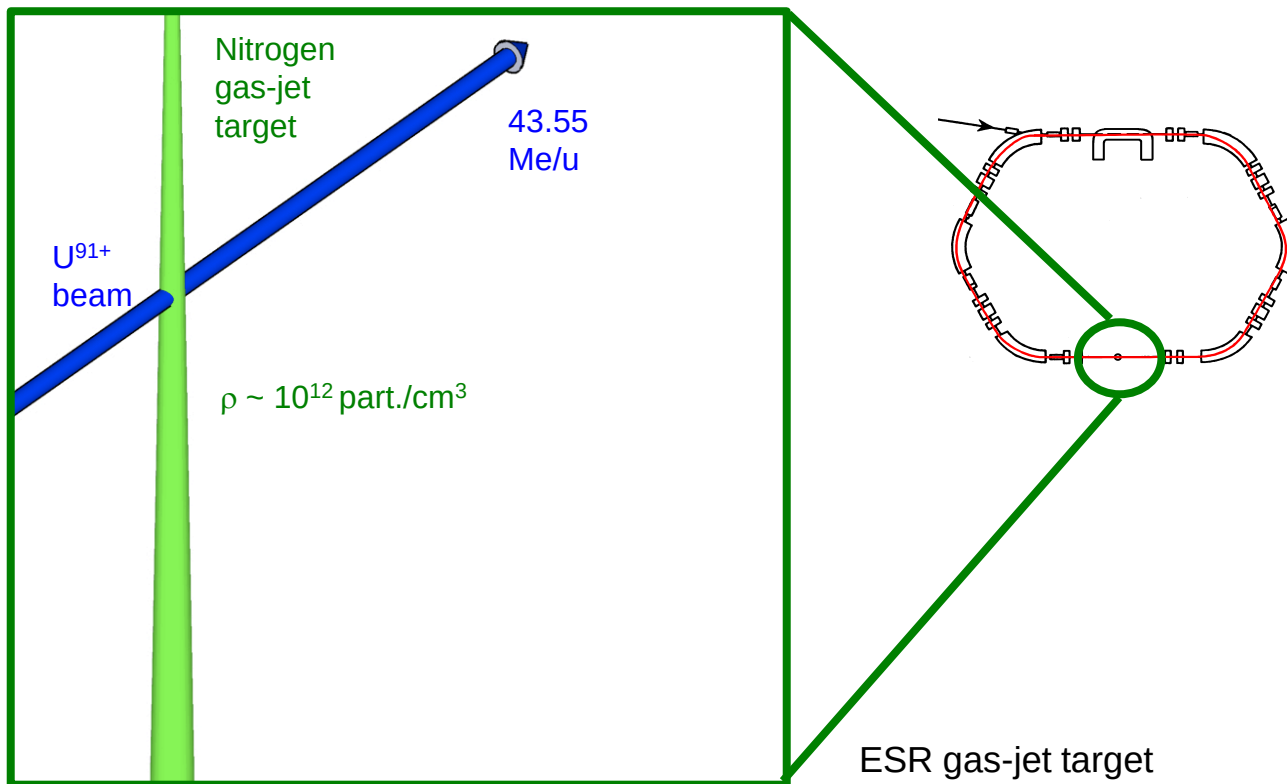
JUNE 1996

Search for $1s2s\ ^3S_1-1s2p\ ^3P_2$ decay in U^{90+}

P. Beiersdorfer, S. R. Elliott,* A. Osterheld, Th. Stöhlker,[†] J. Autrey,[‡] G. V. Brown,[§] A. J. Smith,[‡] and K. Widmann
Department of Physics and Space Technology, Lawrence Livermore National Laboratory, Livermore, California 94550

(Received 20 December 1995)





Electron capture



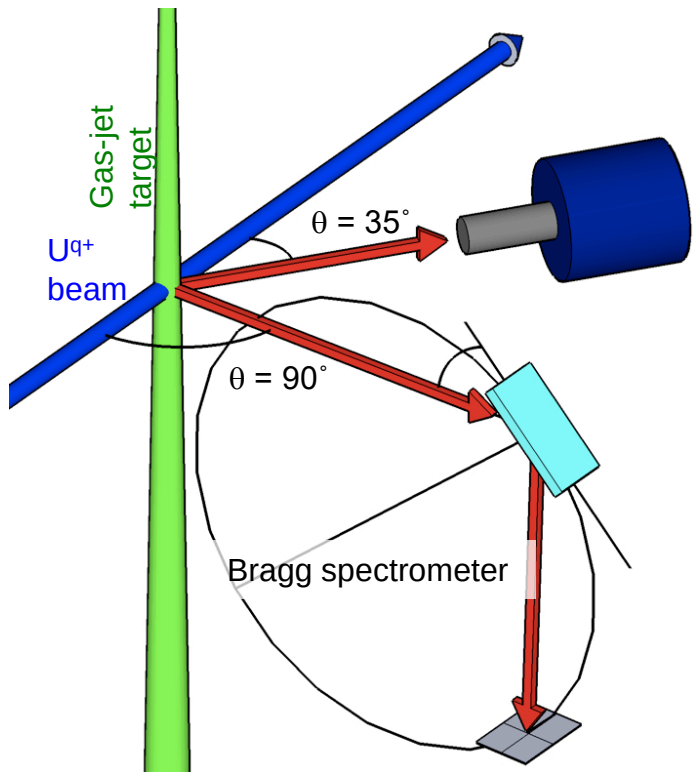
- Low ion velocity
- Low-Z target



electron capture
in $n = 2-5$ levels



Efficient population of
the $1s2p \ ^3\text{P}_2$ state!



$$E_{\text{ion}} = E_{\text{lab}} \gamma (1 - \beta \cos \theta)$$

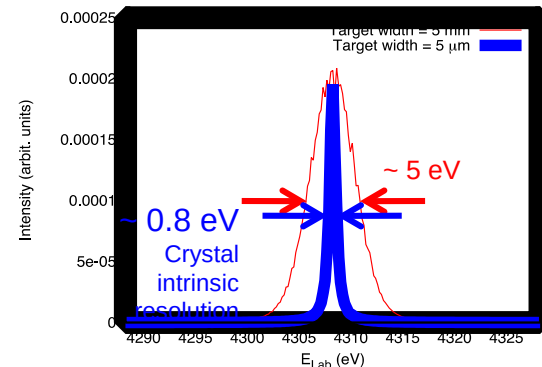
→ Peak broadening
→ Higher statistical errors

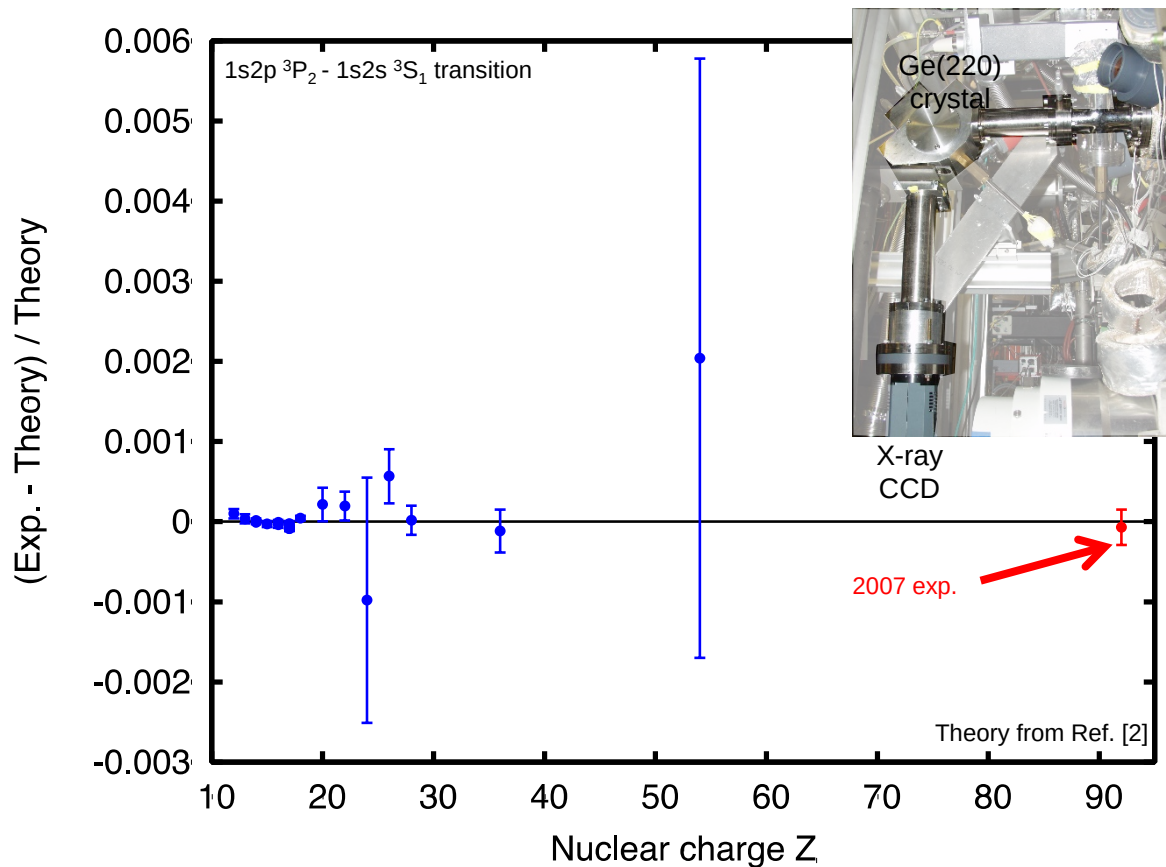
$$\Delta(E_{\text{ion}})_{\theta} = E_{\text{lab}} \gamma \beta \sin \theta \Delta \theta$$

→ Systematic uncertainties

$$\delta(E_{\text{ion}})_{\theta} = E_{\text{lab}} \gamma \beta \sin \theta \delta \theta$$

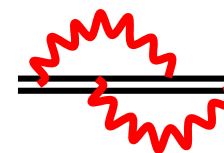
$$\delta(E_{\text{ion}})_{\gamma} = E_{\text{lab}} \frac{\beta - \cos \theta}{\beta} \delta \gamma$$



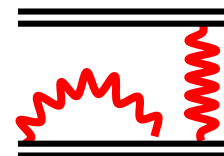


Target chamber

Energy of the intra-shell transition:
 4509.71 ± 0.99 eV [1]



Two loop QED = 0.20 eV [2]

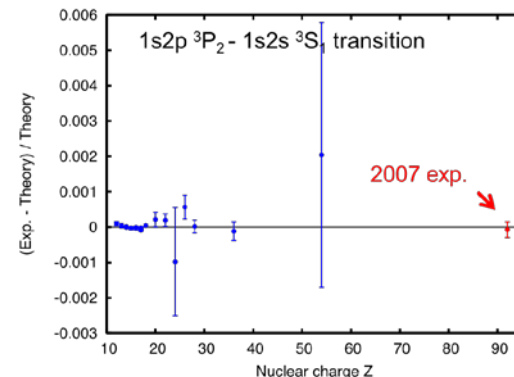
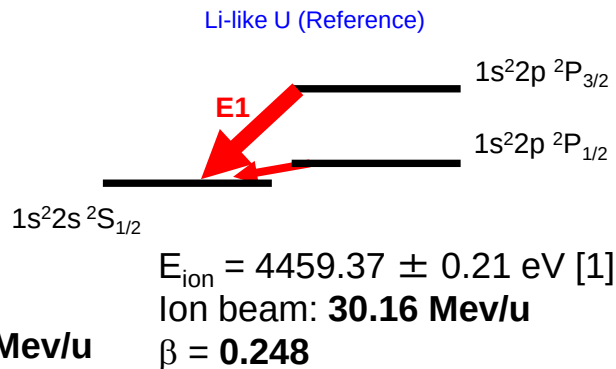
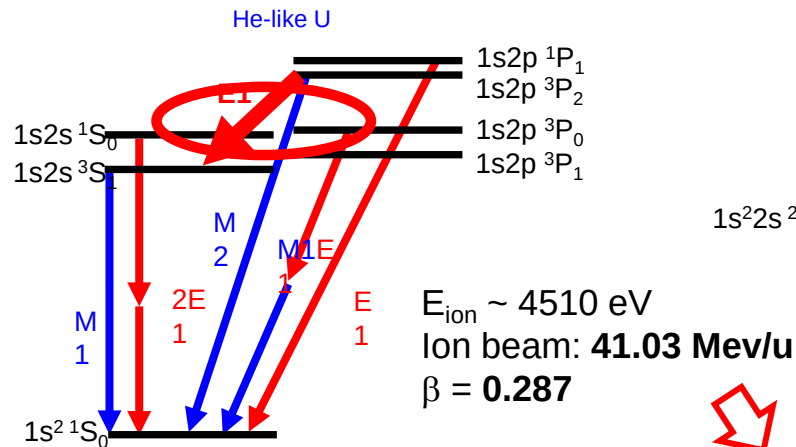


Two electron QED = 0.76 eV [2]

[1] Trassinelli *et al.*, Eur. Phys. Lett. **87**, 63001 (2009)

[2] Artemyev *et al.*, Phys. Rev. A **71**, 062104 (2005)

Relativist Doppler tuning with He-, Li-like, and Be-like Uranium



Same energy in the laboratory frame

$$E_{\text{lab}} = \frac{E_{\text{ion}}}{\gamma(1 - \beta \cos \theta)} = \frac{E_{\text{ion}}^0}{\gamma_0(1 - \beta_0 \cos \theta)}$$

Unknown E

Reference E_0

$E_{\text{lab}} \sim 4319\text{ eV}$

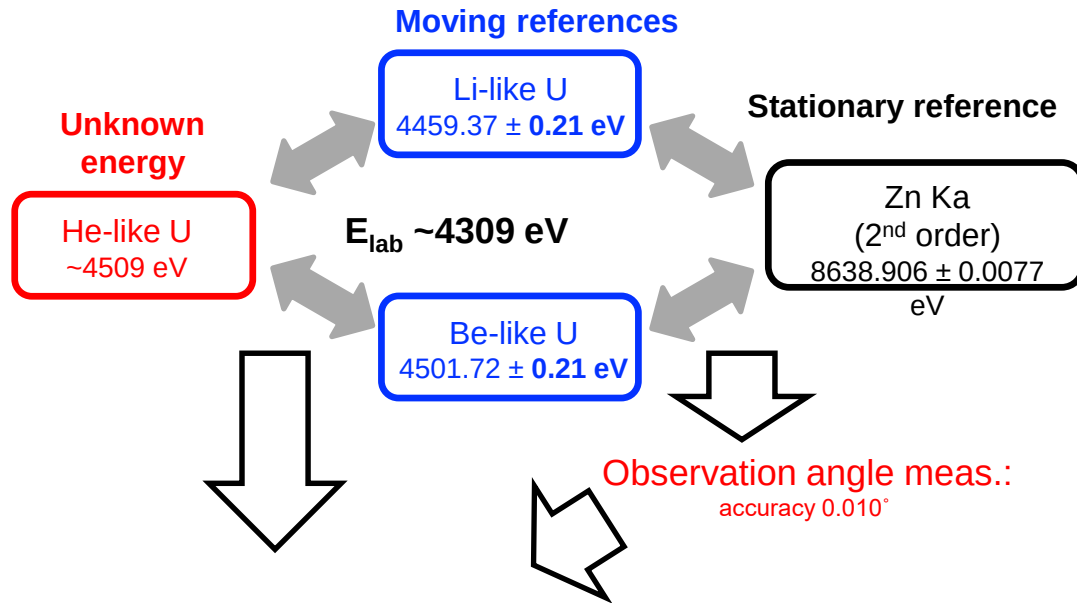


$E_{\text{ion}} = 4501.72.37 \pm 0.21\text{ eV [1]}$
 Ion beam: **39.29 Mev/u**
 $\beta = 0.282$

Towards testing three-loop effects of bound-state QED in He-like uranium

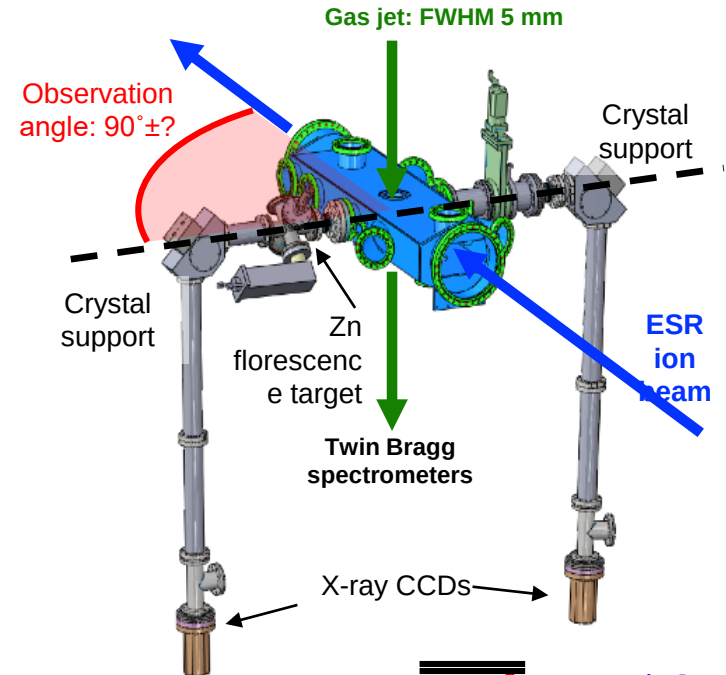
2021 measurement strategy:

High-accuracy X-ray spectroscopy using as reference moving and stationary sources



Measurement of

- He-like U abs. energy accuracy: **0.03 eV (stat.)** and **0.16 eV (syst.)**
- Energy diff. He-, Li-, Be- acc.: **0.04 eV (stat.)** and **-0.03 eV (syst.)**



Theory [1]:
 4509.88 ± 0.11 eV

[1] Kozhedub *et al.*, Phys. Rev. A **100**, 062506 (2019).

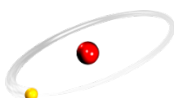


Two el. QED
 $= 0.76$ eV



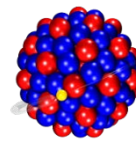
1 el. wo loop QED
 $= 0.20$ eV

hydrogen

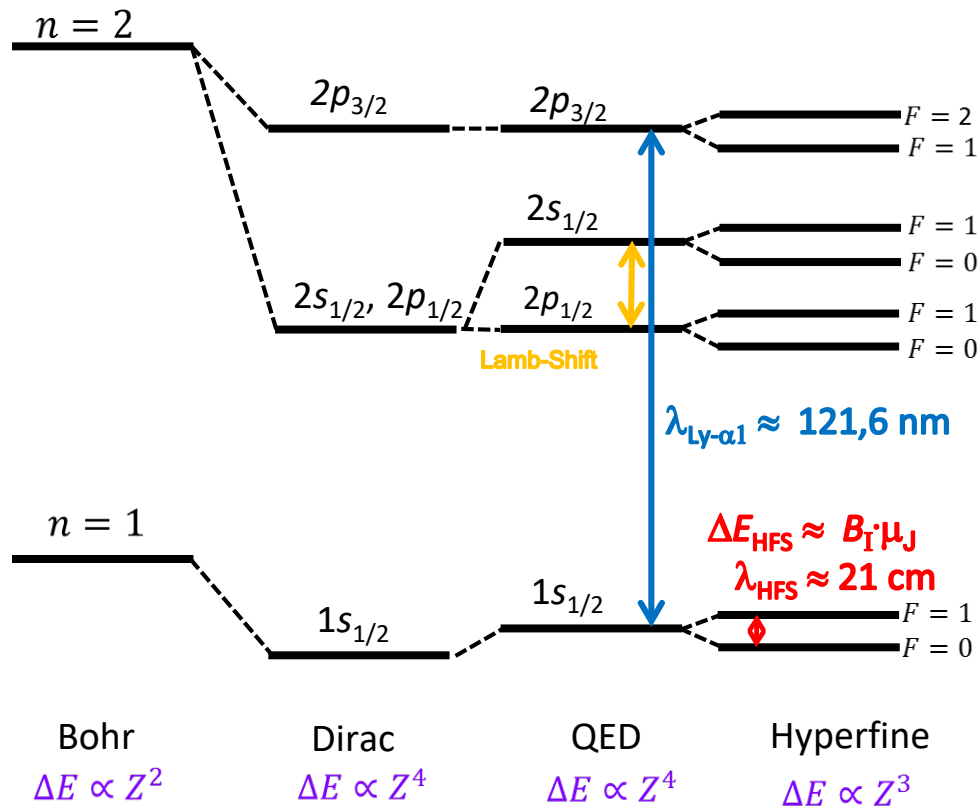


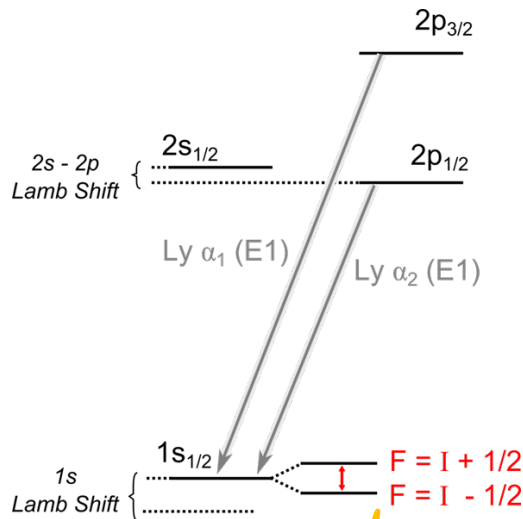
$Z=1$
 $E_b = 13.6 \text{ eV}$
 $Z \cdot \alpha \ll 1$

uranium ion



$Z=92$
 $E_b = 132 \text{ keV}$
 $Z \cdot \alpha \approx 1$



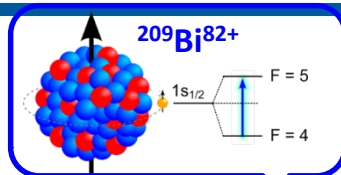


Hyperfine Splitting

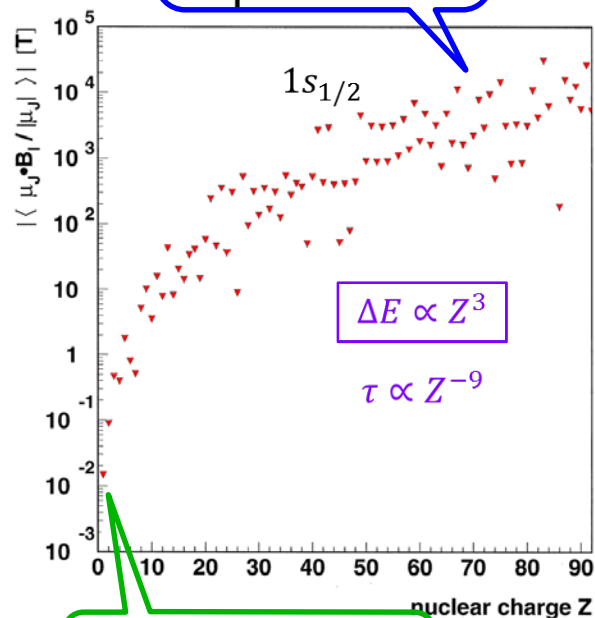
$$\Delta E_{HFS} = -\vec{\mu}_J \cdot \vec{B}_I$$

$$\lambda = 243 \text{ nm}$$

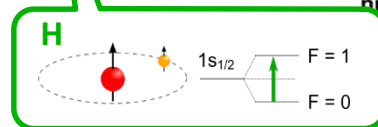
$$\tau = 400 \mu\text{s}$$



Nuclear Surface:
 $B \approx 10^9 - 10^{10} \text{ T}$



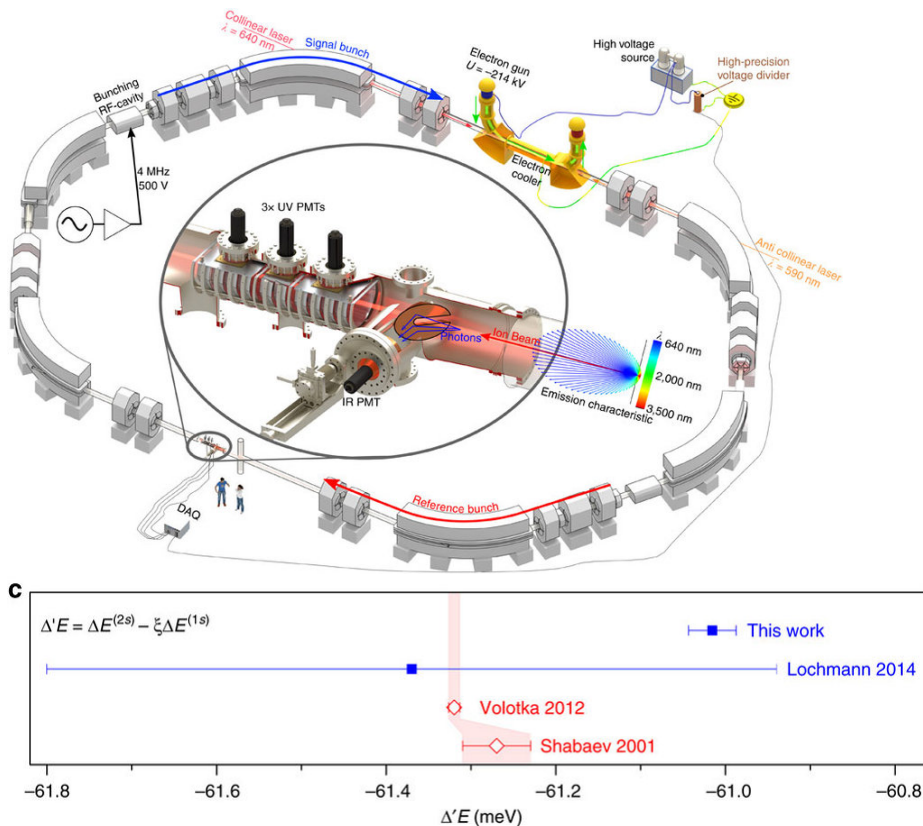
Hyperfine Structure probes extremely strong magnetic fields very close to the nuclear surface.



$$\lambda = 21 \text{ cm}$$

$$\tau = 11 \text{ MA}$$

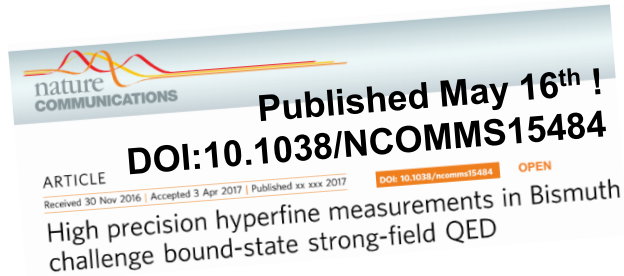
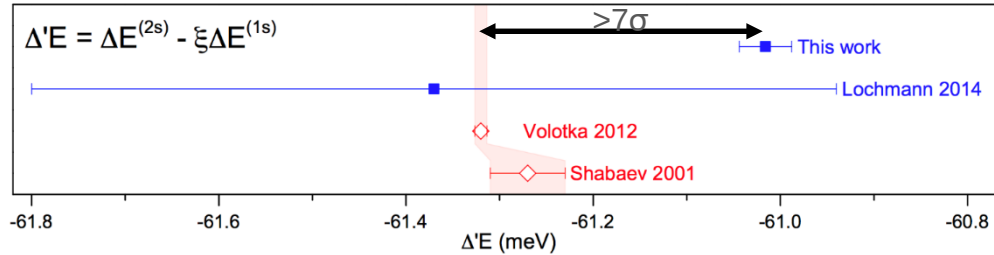
High precision hyperfine measurements in Bismuth challenge bound-state strong-field QED



Measurement of the so-called specific difference between the hyperfine splittings in hydrogen-like and lithium-like bismuth $^{209}\text{Bi}^{82+,80+}$ with a precision that is improved by more than an order of magnitude.

Even though this quantity is believed to be largely insensitive to nuclear structure and therefore the most decisive test of QED in the strong magnetic field regime, we find a 7- σ discrepancy compared with the theoretical prediction.

High precision hyperfine measurements in Bismuth challenge bound-state strong-field QED



QUANTUM ELECTRODYNAMICS

Hyperfine puzzle?

Improved-accuracy measurements of the ground-state hyperfine splitting in highly charged bismuth ions reveal a surprising discrepancy with the predictions of quantum electrodynamics.

Jean-Philippe Karr



BRENNPUNKT

Quantenelektrodynamik auf dem Prüfstand

Die Hyperfeinaufspaltung in wasserstoff- und lithiumähnlichen Bismut-Ionen weicht deutlich von der theoretischen Vorhersage ab.

Experiment

- ~~Our experimental value is wrong?!~~ unlikely
- The literature value of the nuclear magnetic moment of ^{209}Bi is wrong?!
(Dirac term of the ground state hfs is proportional to the experimental value)

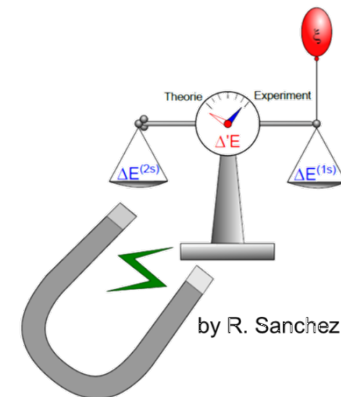
Theory

- The specific difference does not work as expected?!

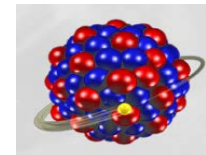
$$\Delta'E = \Delta E^{(2s)} - \xi \Delta E^{(1s)}$$

- ~~BS Strong Field QED is wrong?!~~

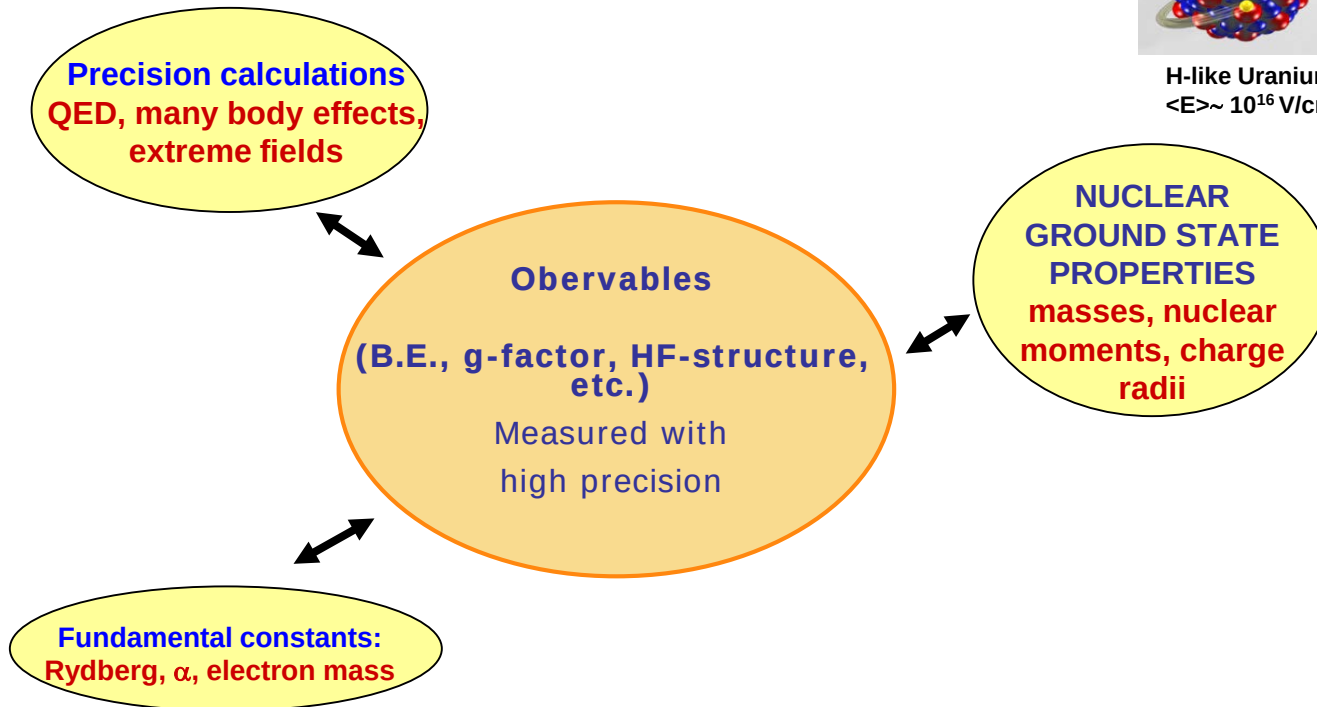
First exclude other possibilities !



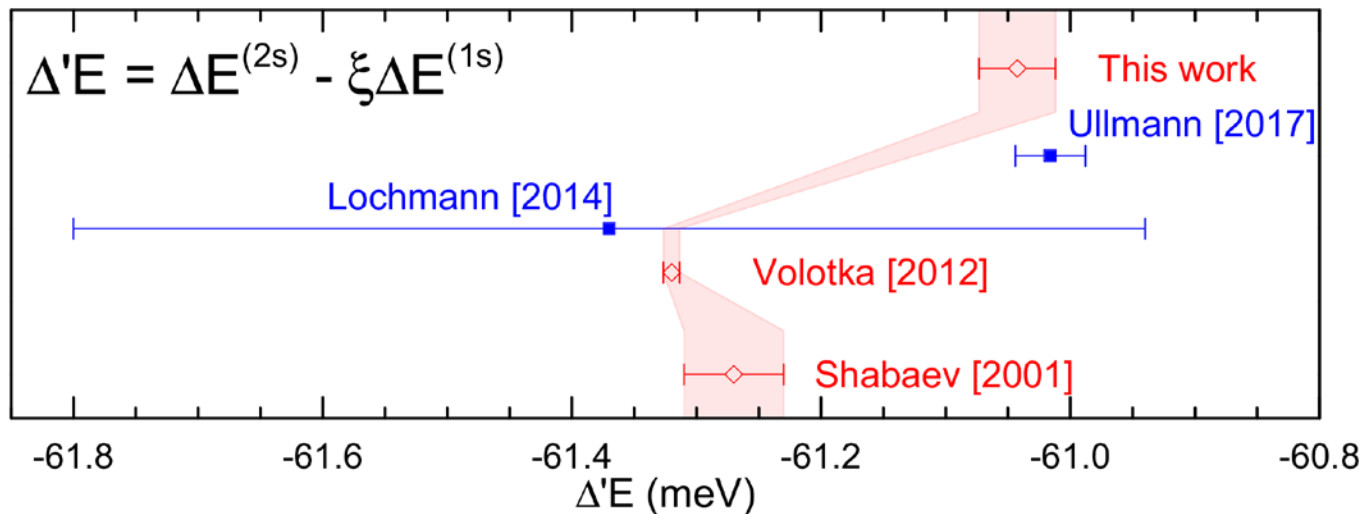
Testing our current understanding of EM interactions (QED)
in different regimes with fundamental atomic systems



H-like Uranium
 $\langle E \rangle \sim 10^{16}$ V/cm

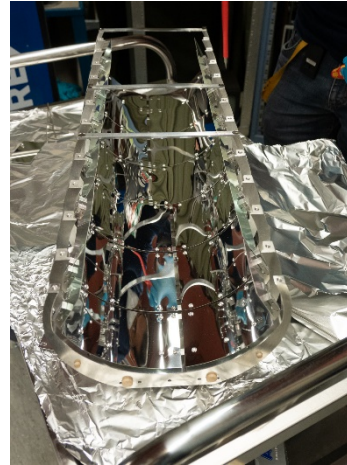
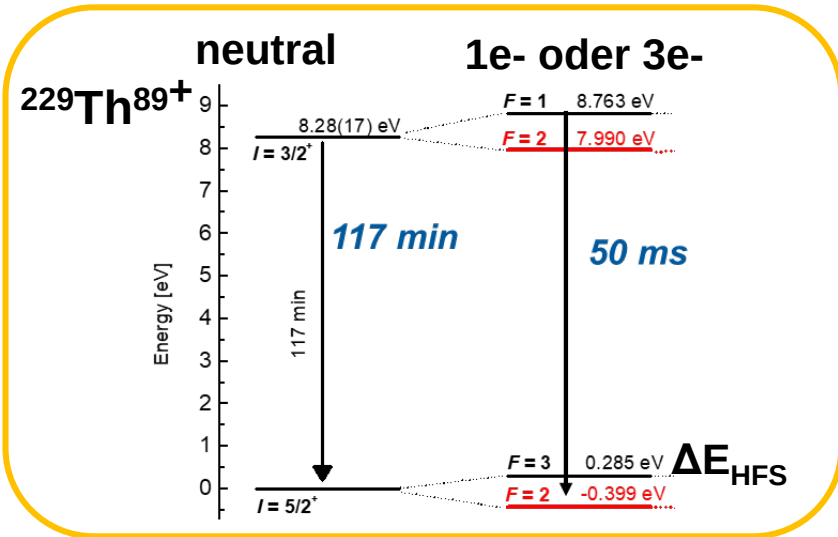


L. Skripnikov et al., Phys. Rev. Lett. **120** 093001 (2018)



Courtesy of Prof. Wilfried Nörtershäuser

H-like $^{229}\text{Th}^{89+}$: Acceleration of nuclear decay by coupling of electrons to nuclear spin (hyperfine interaction).



Achievements
at ESR in 2022

- $2 \cdot 10^4$ bunched $^{229}\text{Th}^{89+}$ in ESR per 10^9 ^{238}U ions in SIS.
- Intense „10 eV“-laser exploiting the Doppler Shift.



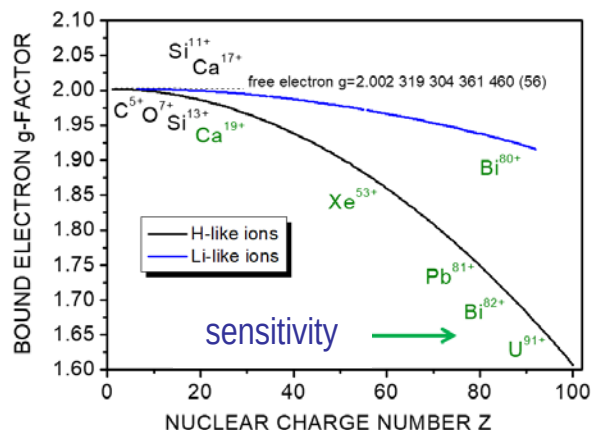
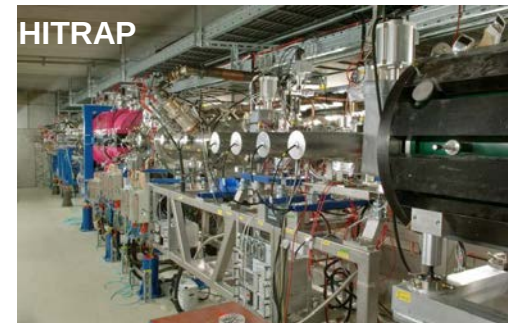
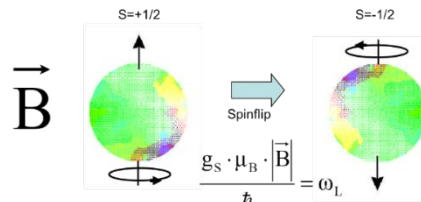
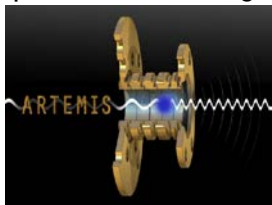
Novel in-ring VUV fluorescence detection system

MgF₂-coated Al-mirrors for the detection of photons bellow 115nm
(Collaboration Fraunhofer IOF, Jena)

Feasibility of the measurement method demonstrated

(but due to restrictions only 15-20% of targeted scan range covered)

Bound-electron g-factor
(magnetic moment at ARTEMIS),
precision Penning trap



black: done, green: to be explored

$$\frac{\delta\alpha}{\alpha} \propto \frac{1}{(Z\alpha)^2} \frac{\delta g}{g} \quad \text{for } \delta g/g \sim 10^{-11} \text{ feasible}$$

S. Sturm et al., 2014,
Nature (London) 506, 467

g-Factor measurements
in a series of elements up to U^{91+}

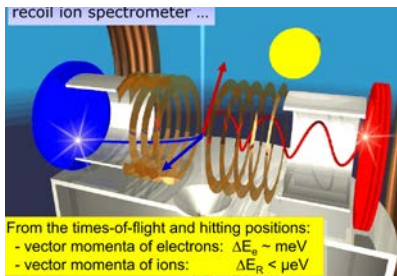
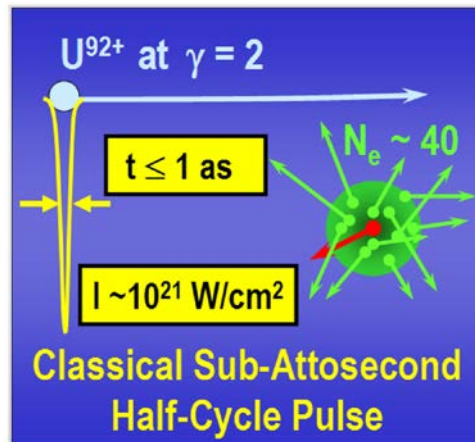
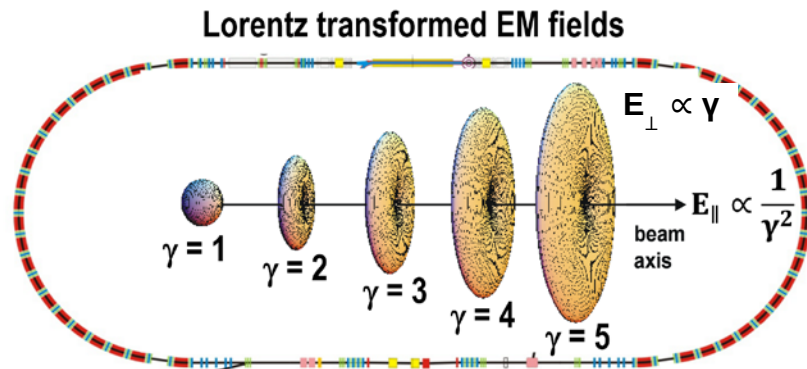
- medium-Z $\rightarrow$ fine-structure constant α
- high-Z $\rightarrow$ test of strong-field QED

Topics

- Precision measurements of bound-electron and nuclear magnetic moments
- High-precision test of strong-field QED
- Fundamental constants
- Heavy HCI with ultra-low energies
- Ion-surface interaction

Reaction Microscope Combined With Ion Storage Rings

kinematically complete and 4π acceptance
(i.e. full momentum and energy information)



Probing many-electron dynamics

- on an subattosecond time scale
- in extremely intense fields
- no postcollision interaction

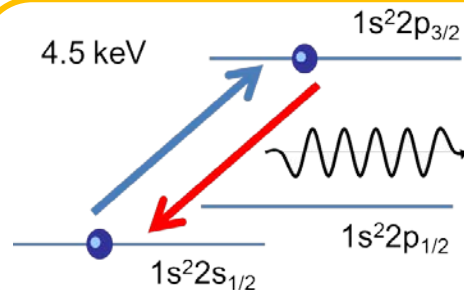
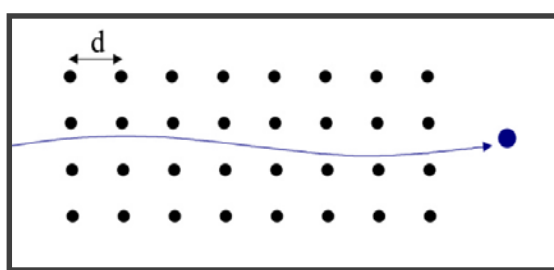
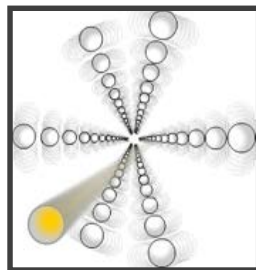
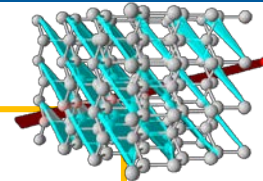
Selected Physics Cases

- Attosecond science / Laser spectroscopy in the soft x-ray range
- Multi-body dynamics / Recoil ion spectroscopy
- Pair creation in strong fields / Negative continuum DR
- Relativistic photon matter interaction

SPARC Experiments at APPA Cave / SIS100

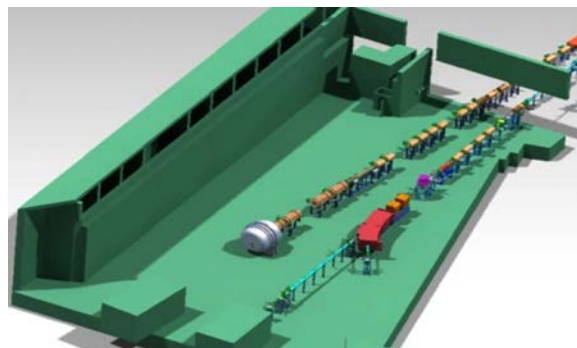


Resonant Coherent Excitation at Relativistic Energies



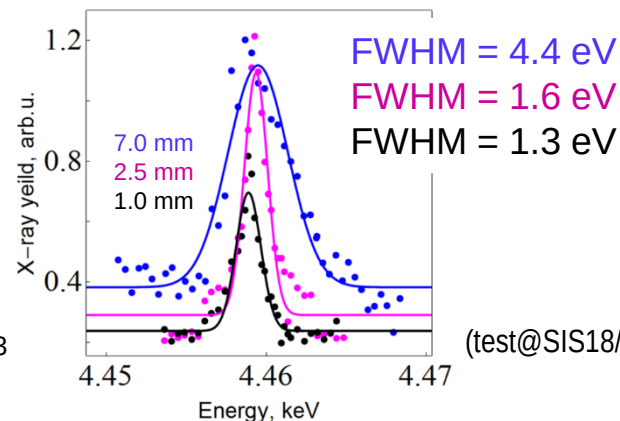
U⁸⁹⁺

FAIR SIS100: Excitation of 1s-2p in U⁹¹⁺ via RCE possible for the first time



$$\Delta E = h \frac{v\gamma}{d}$$

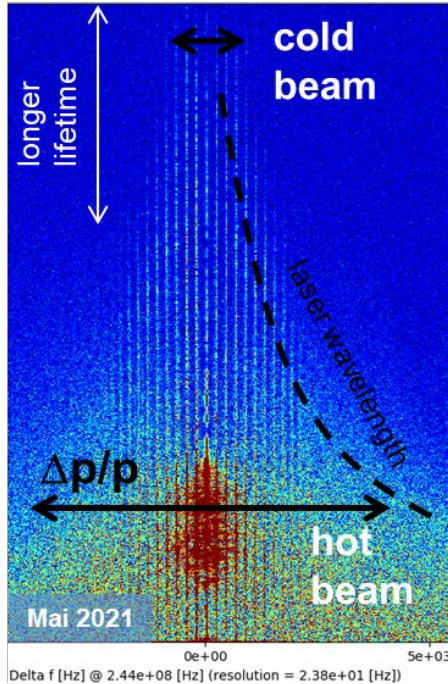
Phys. Rev. A 87, 060501(R) 2013



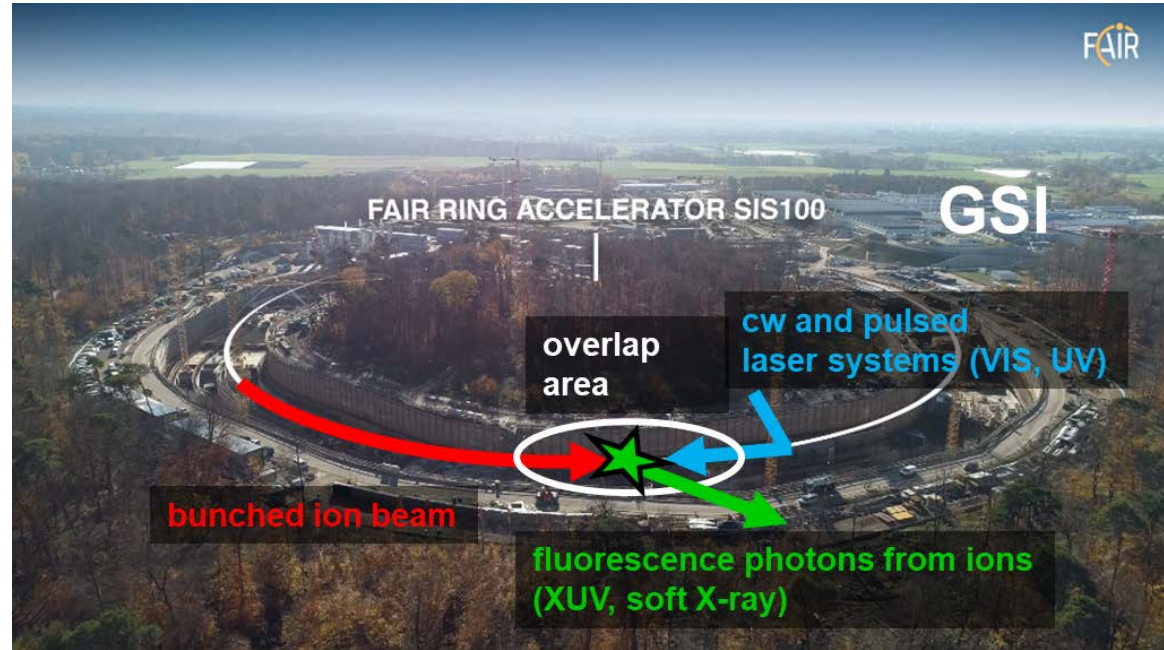
(test@SIS18/ESR: 2014)

Only moderate beam intensities are required !

Laser Cooling of Bunched Relativistic Ion Beams at SIS100 with $\gamma \sim 12$

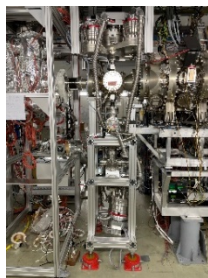


World-wide unique!

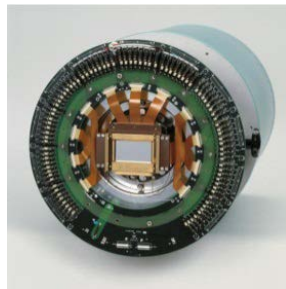
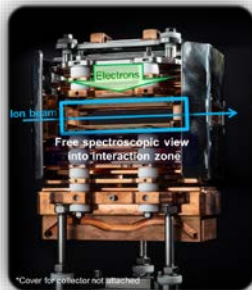


© GSI/FAIR/L. Möller | picture taken Nov. 2020

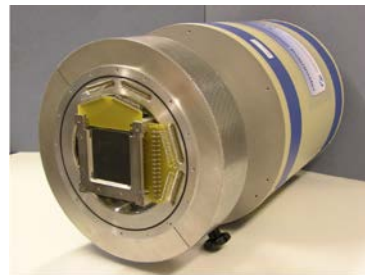
- Laser-cooled relativistic heavy-ion beams ($Z = 10 - 60$)
- Only cooling method at SIS100 energies ($\Delta p/p$ down to 10^{-7} in a few sec.)
- Extraction of very cold and very short ultra-relativistic ion bunches



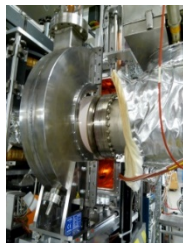
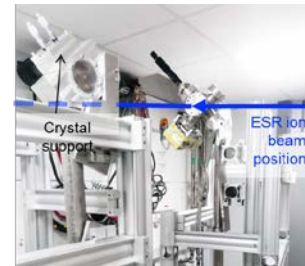
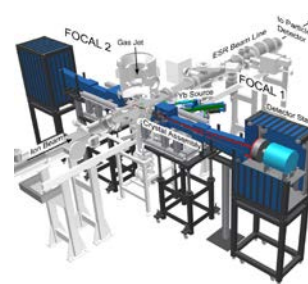
Targets



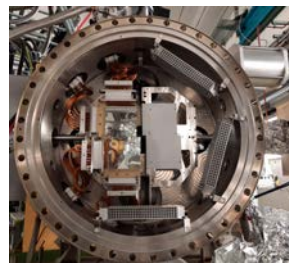
2D micro-strip Ge(i) detectors



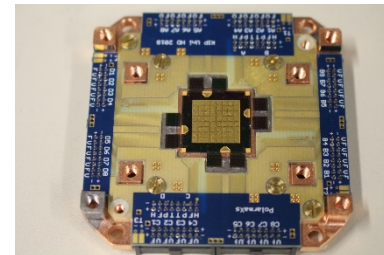
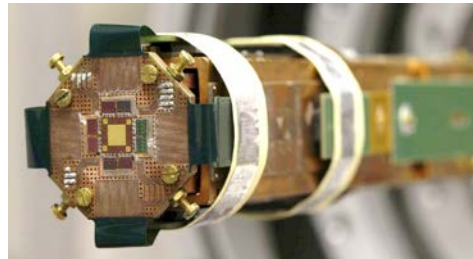
crystal spectrometers



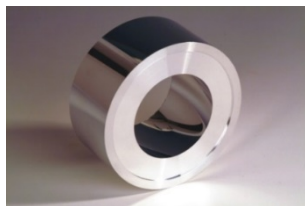
Particle detectors



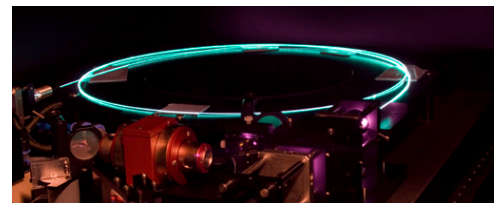
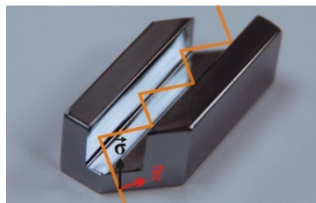
microcalorimeters



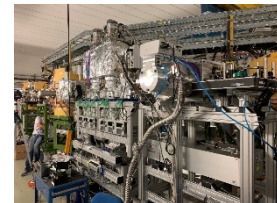
Traps



X-ray optics, channel-cut crystals



versatile Laser systems



- For the **next decade and beyond** FAIR and its storage and trapping facilities offer novel, worldwide unique research opportunities with large discovery potential for SPARC.
- The current experimental program of SPARC (with FAIR Phase-0) has just started and focuses on the **exploitation of the already existing MSV facilities HITRAP, CRYRING@ESR, ESR**.
- At **HESR**, using stored and cooled relativistic HCI beams with **γ values up to 6**, the research program can be greatly enhanced with a broad range of exciting, novel topics (e.g. sub-attosecond science with heavy ions).
- At **SIS100** and **APPA cave**, **Laser cooling/spectroscopy** and **Resonant Coherent Excitation** can be extended into hitherto unexplored regimes using SIS100 beams with **γ factors up to 12**.

Thank you very much for your attention!