Atomic physics at the ESR: recent results and perspectives

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HELMHOLTZ
GEMEINSCHAFT

Helmholtz-Institut Jena

The Collaboration

Grenoble

Mainz

Paris

Frankfurt

Heidelberg

Lanzhou

Caen

Darmstadt

Jülich

Cracow

Madison

Jena

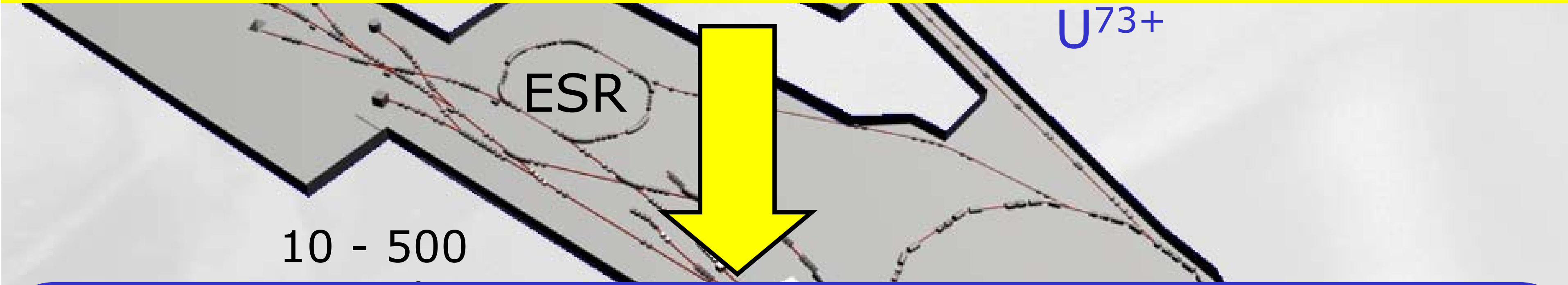
Greenbelt

- Introduction and Motivation: Strong Fields
- Accelerators and storage rings for HCI
- Test of QED in strong fields
  - H-like ions (1s-Lamb Shift)
  - He-like ions (PNC, 2E1 decay)
  - HFS
  - super-critical fields
- Outlook: FAIR

GSI-Accelerator Facility

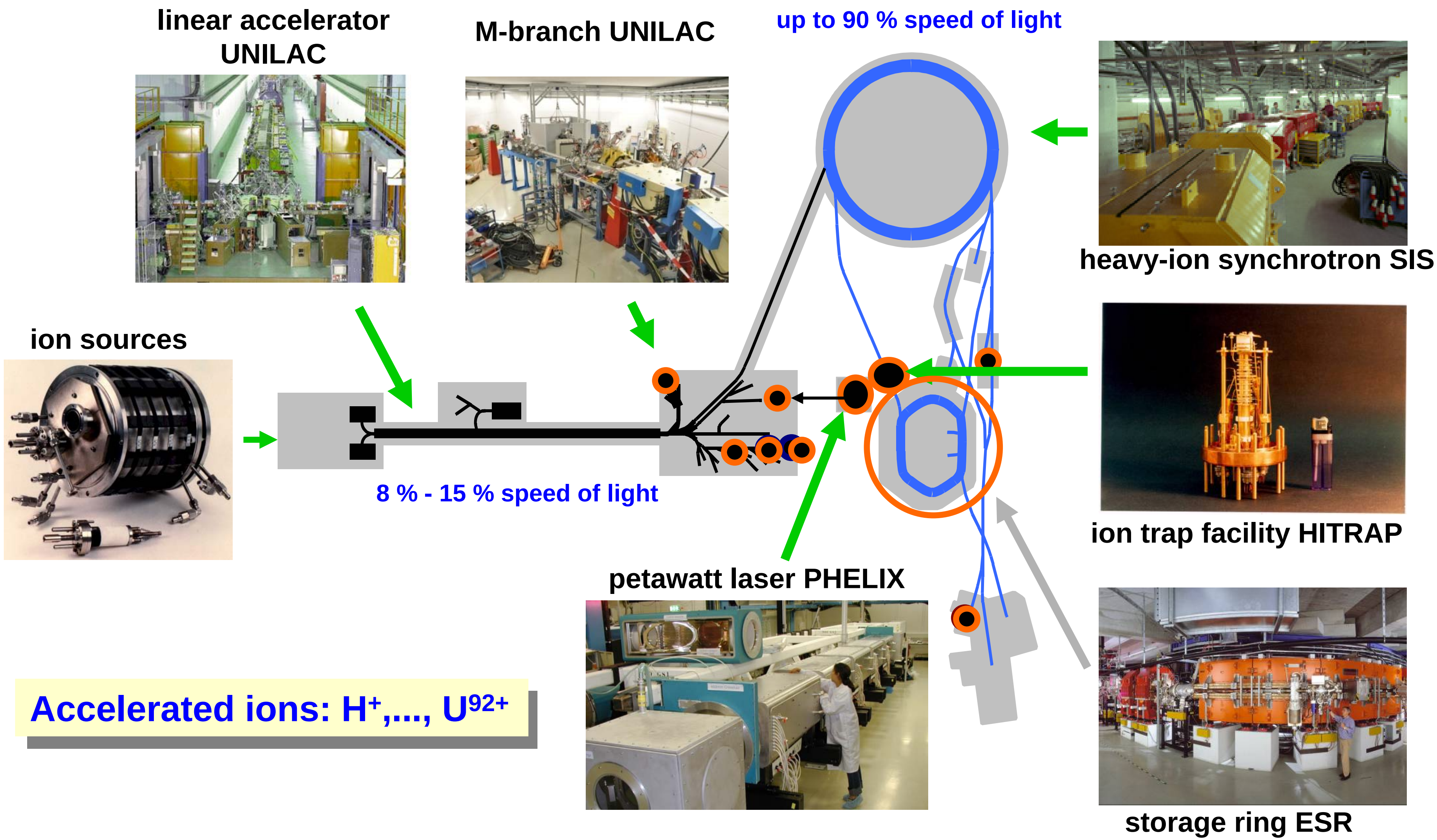
- **Every element in arbitrary charge state up to bare uranium are available for experiments**

- **Energies: from rest up to 1 GeV/u**



The fundamental physics of critical and supercritical fields is the central focus for atomic physics with HCI

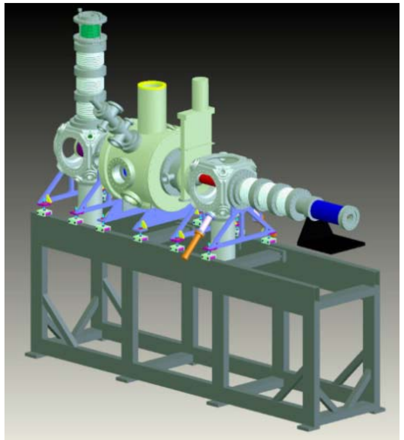
The GSI Accelerator Facility for Heavy Ions

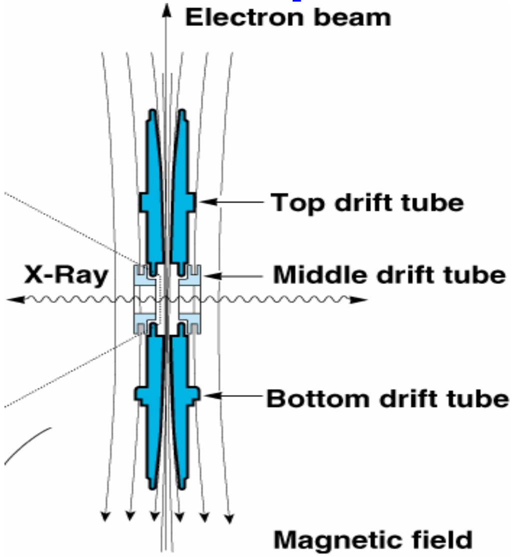


Accelerated ions: H^{+},..., U^{92+}

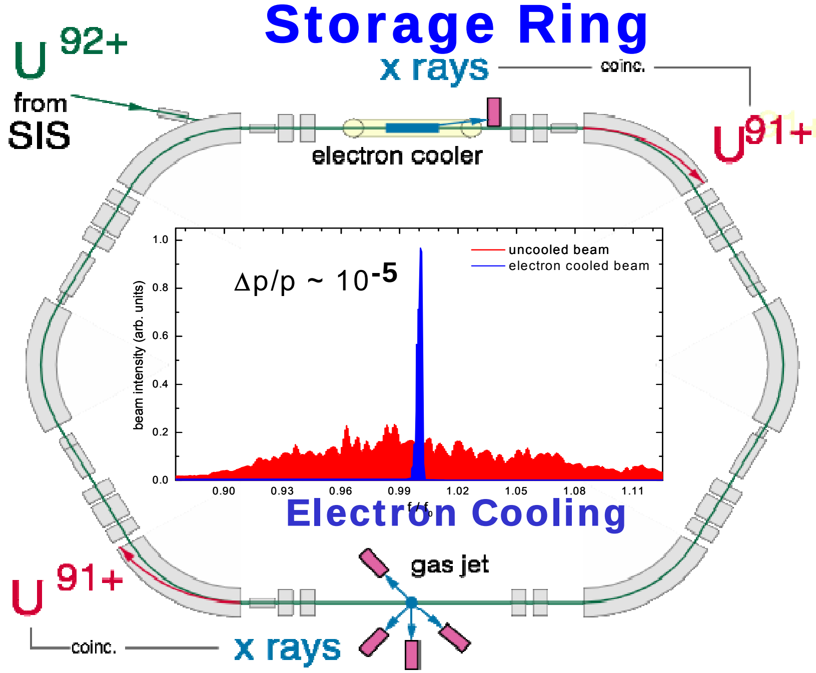
Production, Storage, and Cooling of HCI

Electron Beam Ion Trap





Storage Ring



Cooling in traps

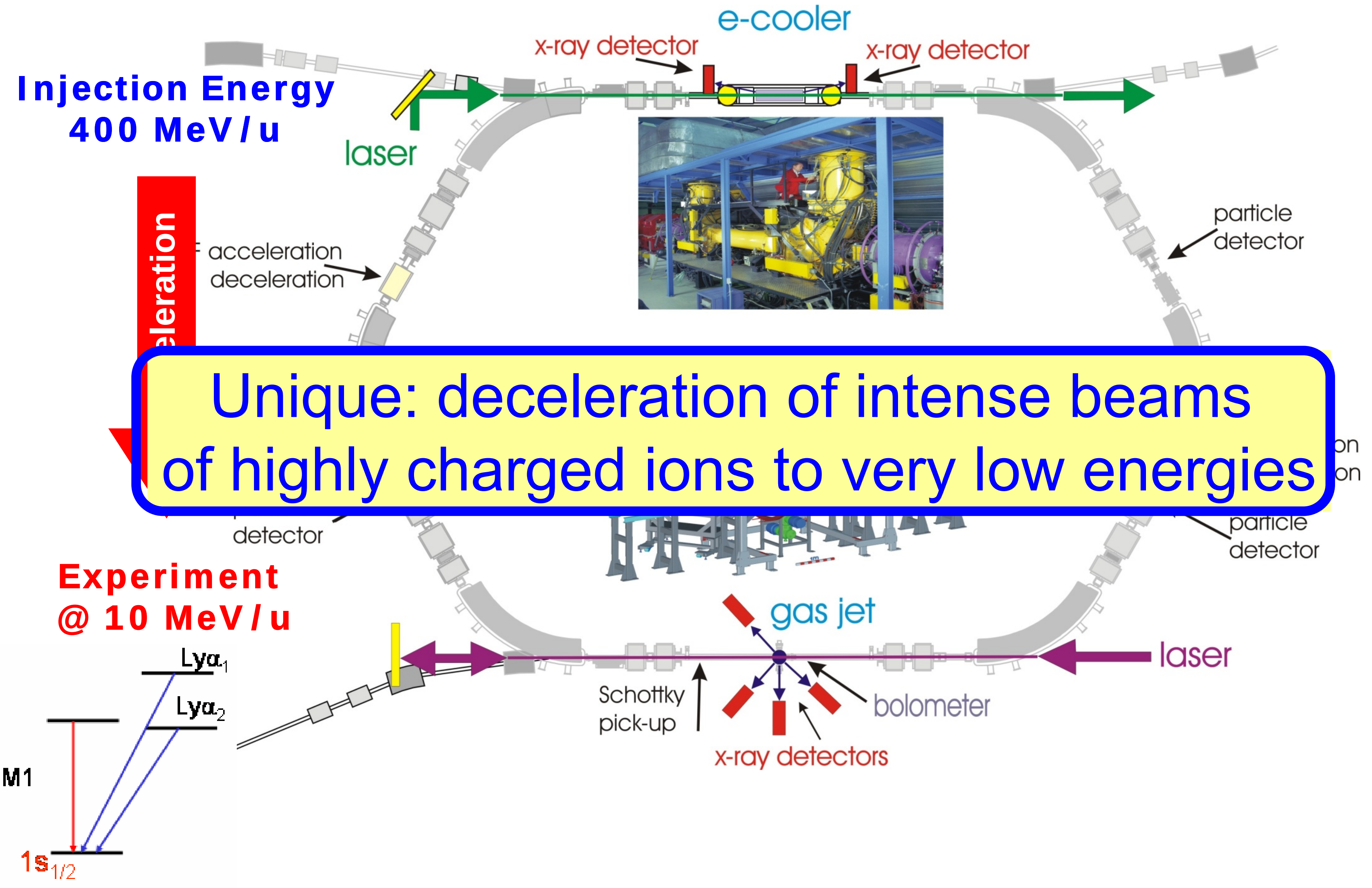
resistive cooling
evaporative cooling
laser cooling
electron cooling

Cooling in Storage Rings

electron cooling
stochastic cooling
laser cooling

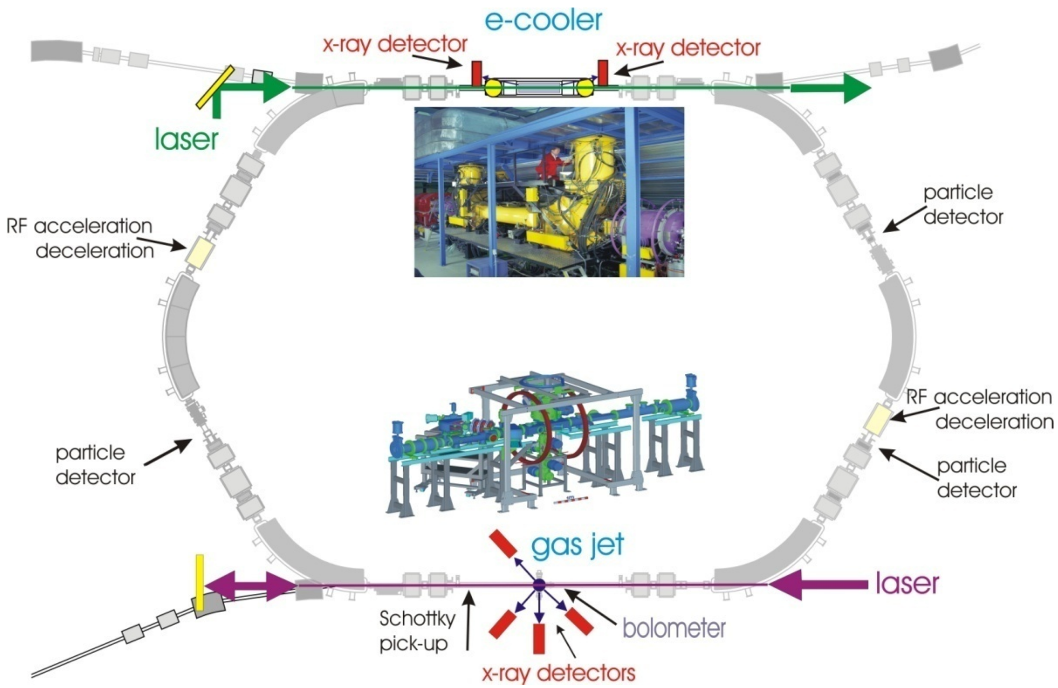
Storing and Cooling is the key for precision

X-Ray Spectroscopy at the ESR

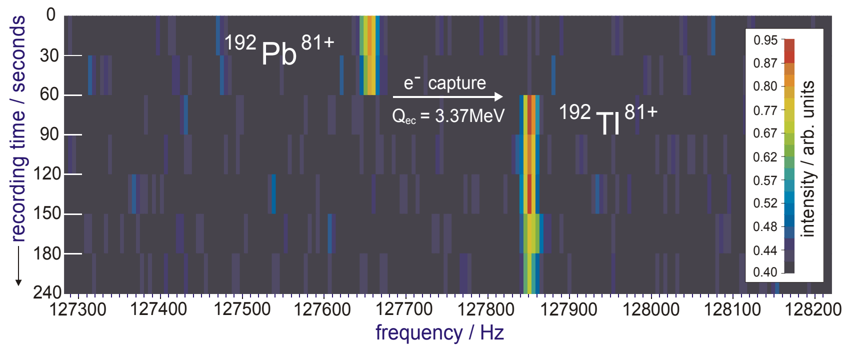


Unique: deceleration of intense beams
of highly charged ions to very low energies

The Experiment Storage Ring ESR

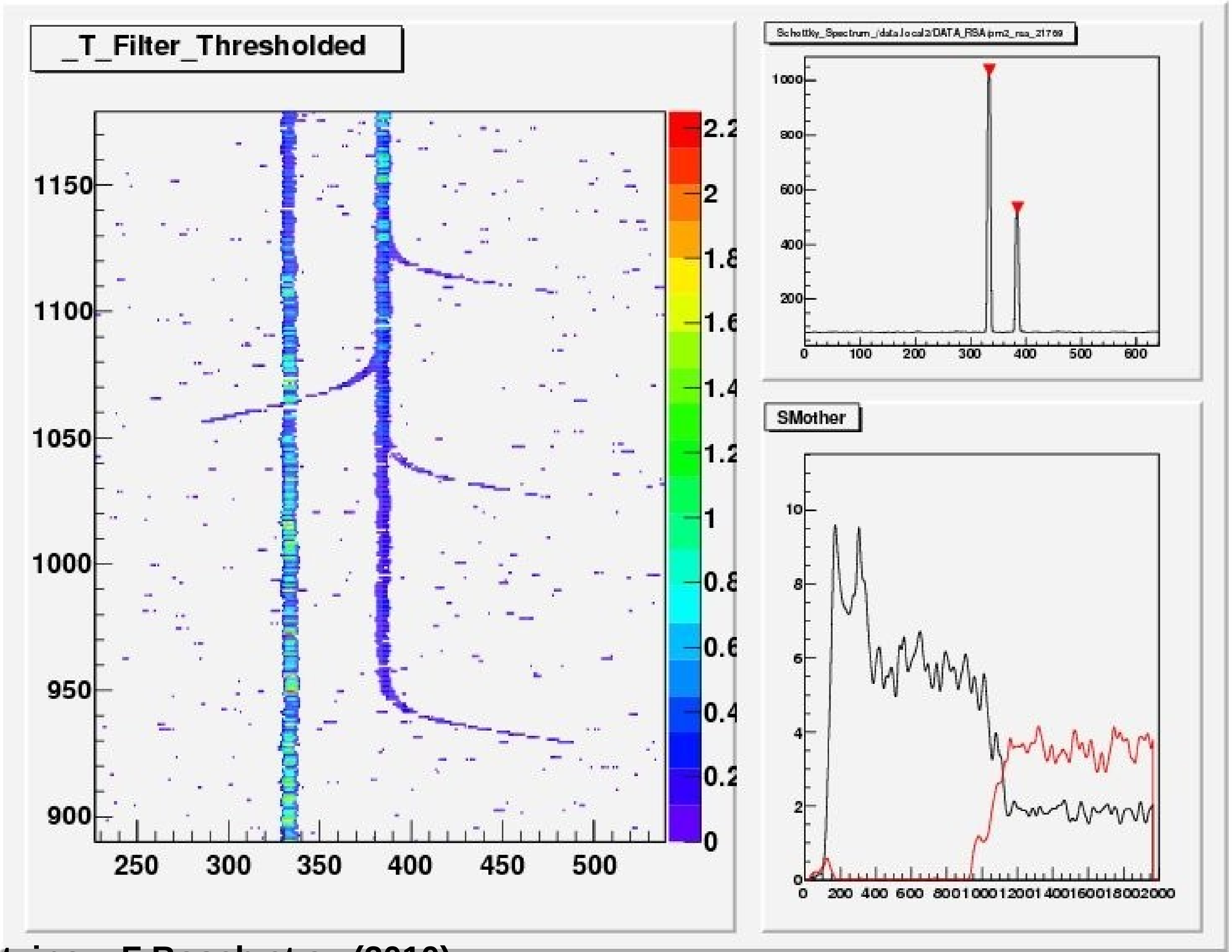


Single-Ion Detection



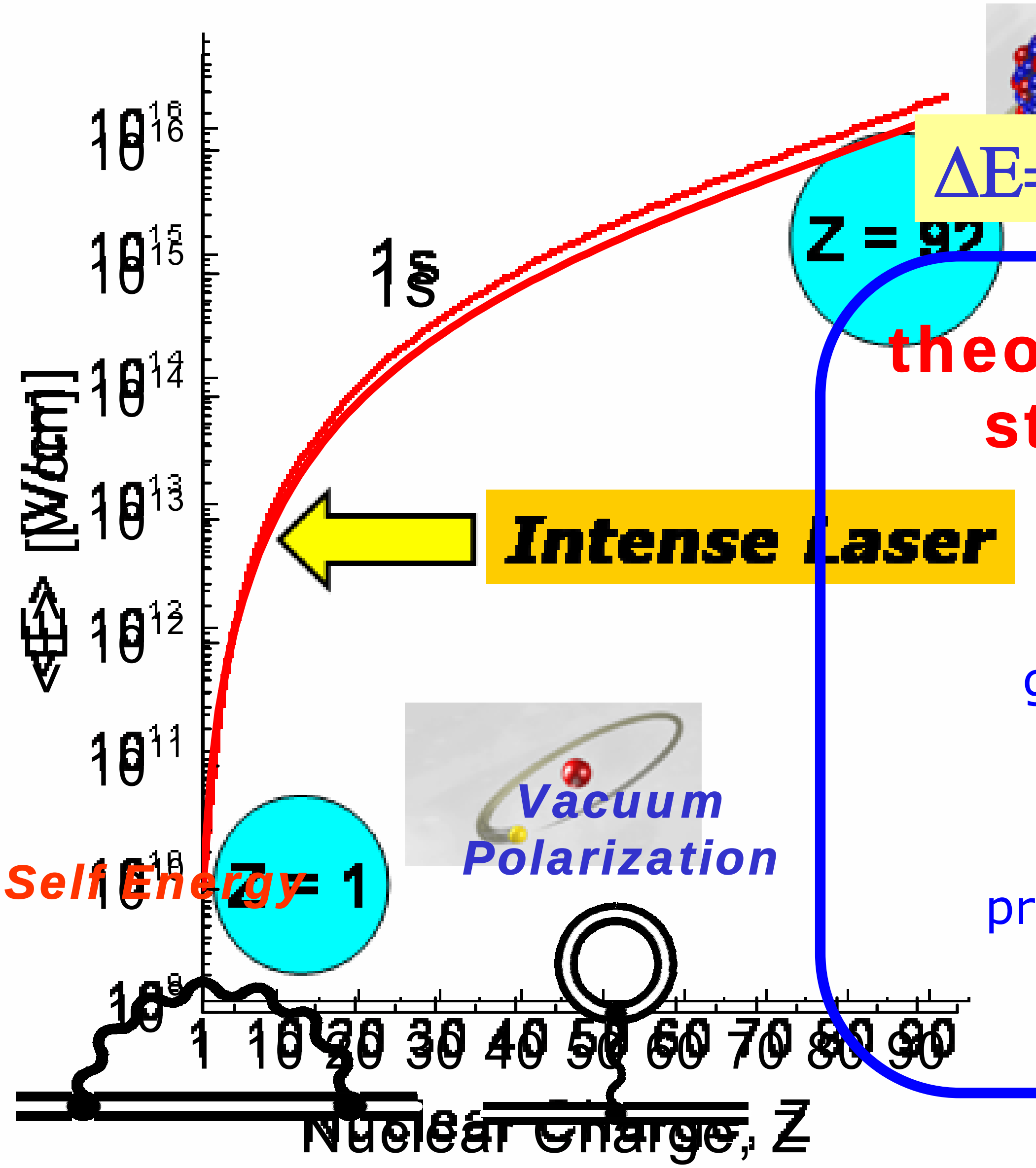
Key features / instrumentation

- *Stochastic and electron cooling*
- *Relativistic ions (typically 400 MeV/u)*
- *Deceleration (down to 4 MeV/u)*
- *Schottky and TOF mass and lifetime spectroscopy (single ion sensitivity)*
- *Internal gas jet target*
- *Superfluid targets*
- *Position sensitive x-ray and particle detectors*
- *Crystal spectrometer*
- *Microcalorimeter detectors*
- *Collinear laser spectroscopy.*
- *Electron spectrometer*
- *Recoil ion spectrometer*



Y. Litvinov, F Bosch et a., (2010)

Atomic Physics in Extremly Strong Coulomb Fields



H-like Uranium

$\Delta E = \alpha/\pi\ (\alpha Z)^4\ F(\alpha Z)\ m_e c^2$

theory of bound-state QED still valid at high-Z ?

1s, 2s Lamb Shift

g-factor of bound electrons

hyperfine structure

precision mass measurements

super-critical fields

Hydrogen

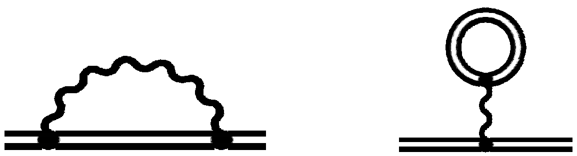
E_K = -13.6 eV

$\langle E \rangle = 1 \bullet 10^{10}$ V/cm

Atomic Physics in Extremely Strong Fields

The 1s-LS in H-like Uranium

Self energy **Vacuum polarization**



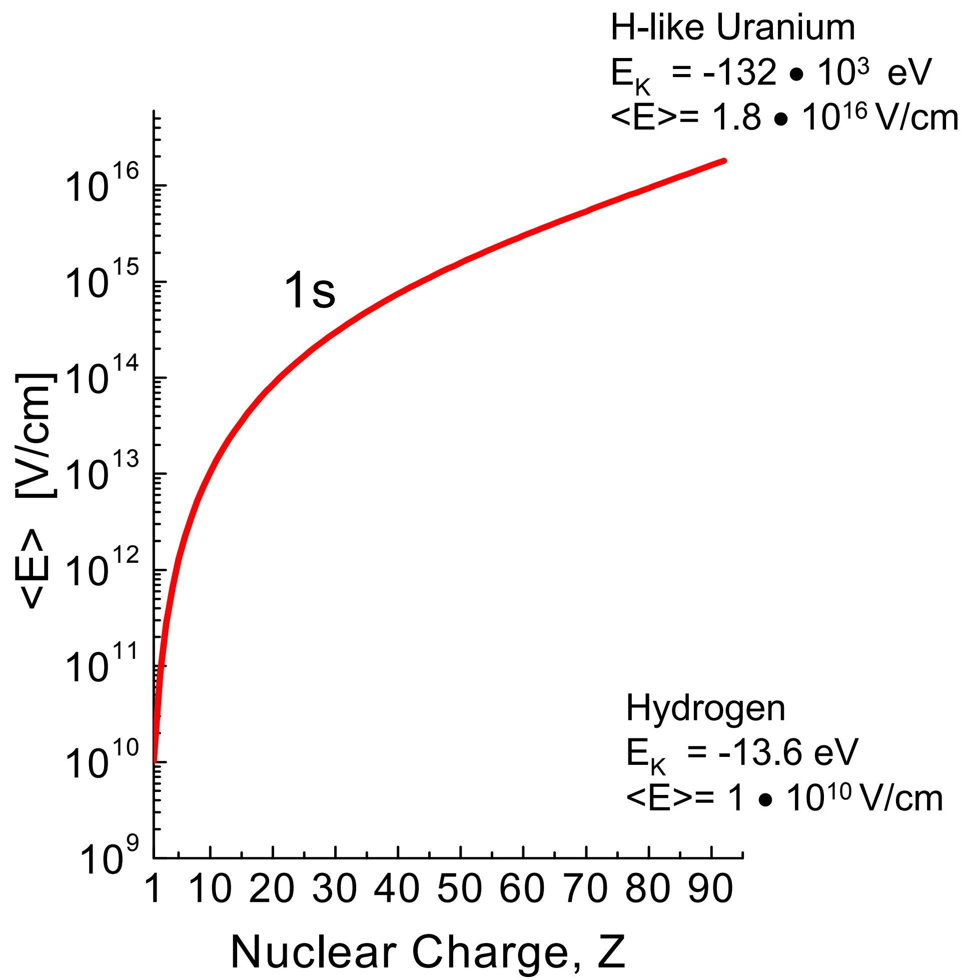
Low Z: $\alpha Z \ll 1$

$F(\alpha Z)$: series expansion in αZ

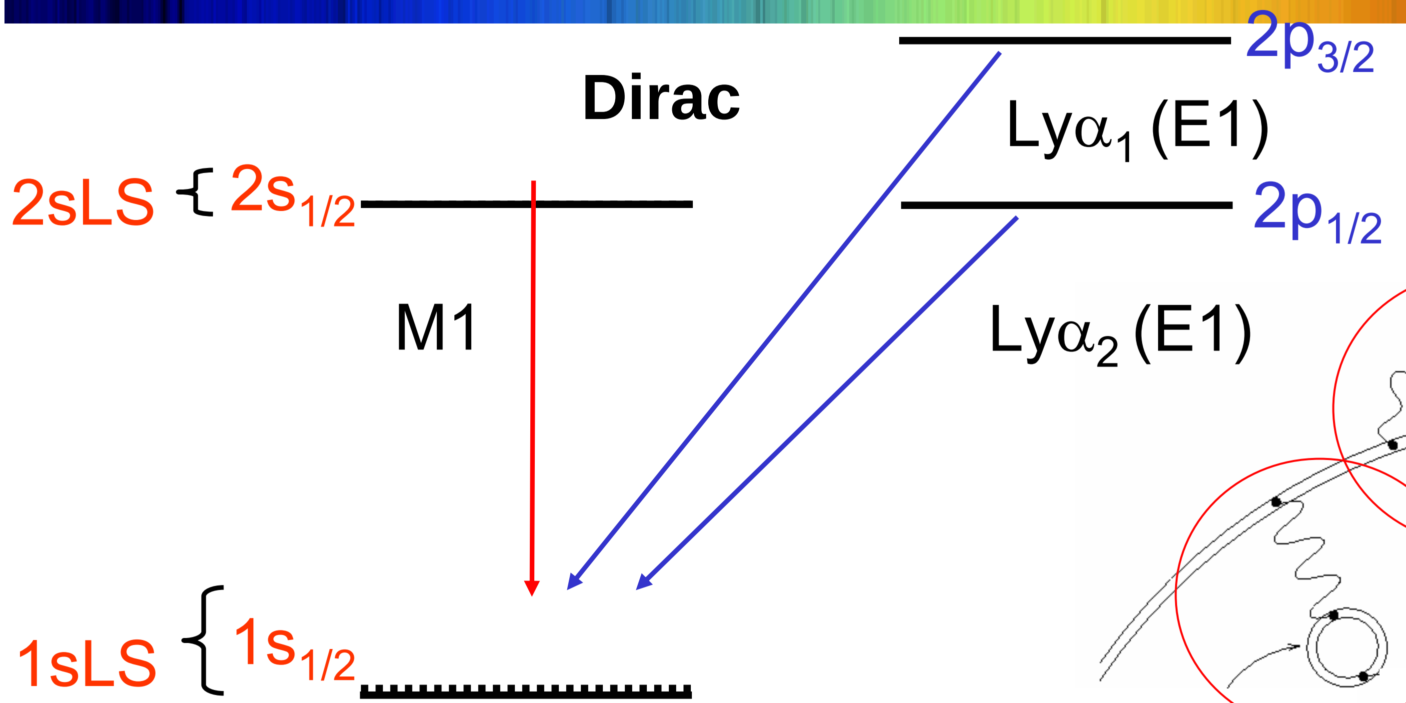
$$\Delta E = \alpha/\pi \, (\alpha Z)^4 \, F(\alpha Z) \, m_e c^2$$

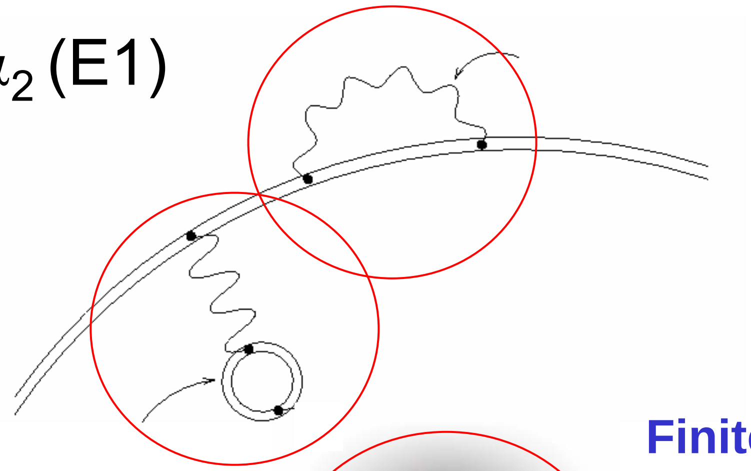
High Z: $\alpha Z \approx 1$

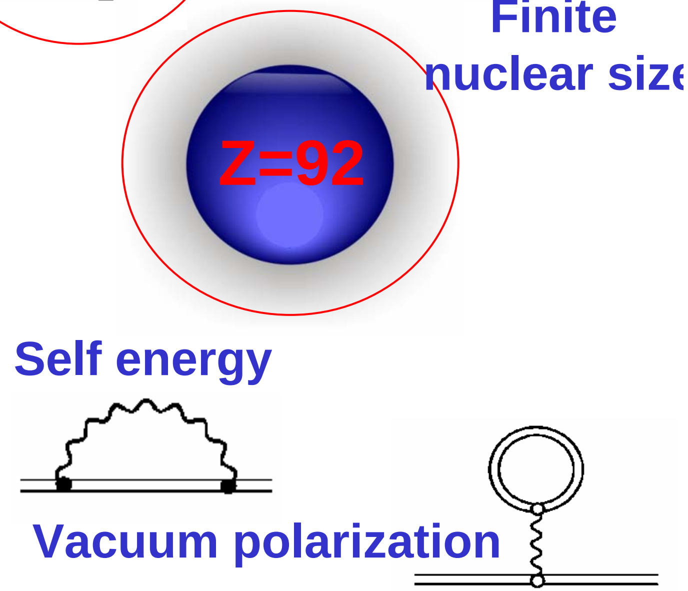
$F(\alpha Z)$: series expansion in αZ not appropriate



The Structure of One-Electron Systems







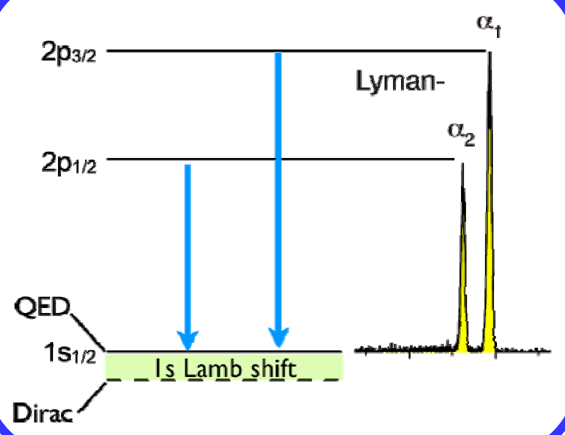
QED corrections

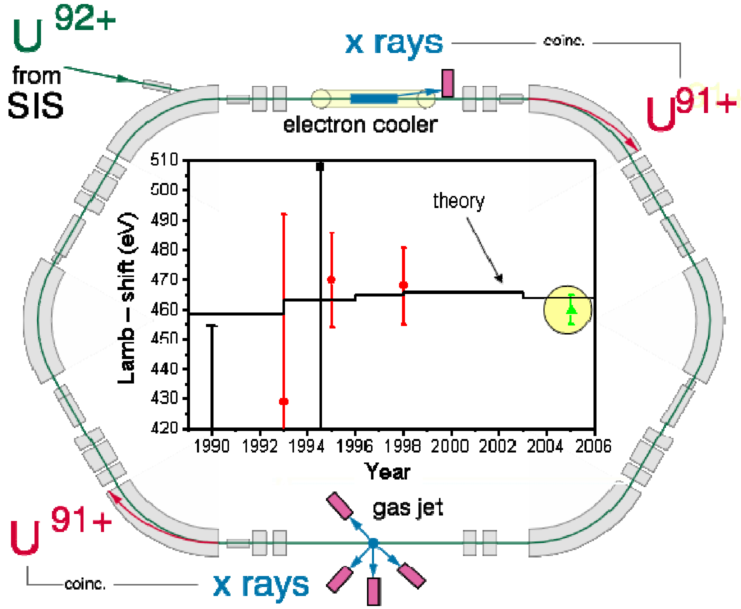
$\Delta E \sim Z^4/n^3$

Z: nuclear charge
n: principal quantum number

QED in the Extreme Field Limit: Experiments at the the Heavy-Ion Storage Ring ESR

High Precision X-Ray Spectroscopy: 1s Lamb-Shift





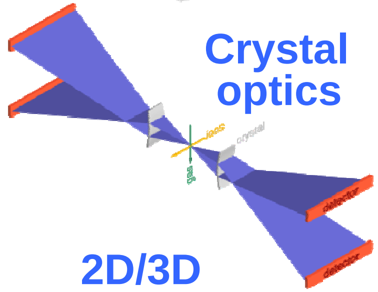
Experiment
459.8 eV ± 4.6 eV

A. Gumberidze,PRL 94, 223001 (2005)

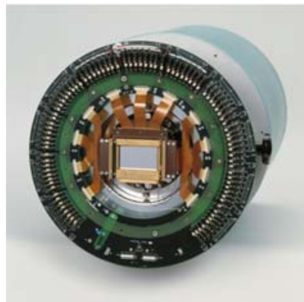
Research Highlights
Nature **435**, 858-859
(16 **June 2005**)

FOCAL

Crystal optics



2D/3D detectors

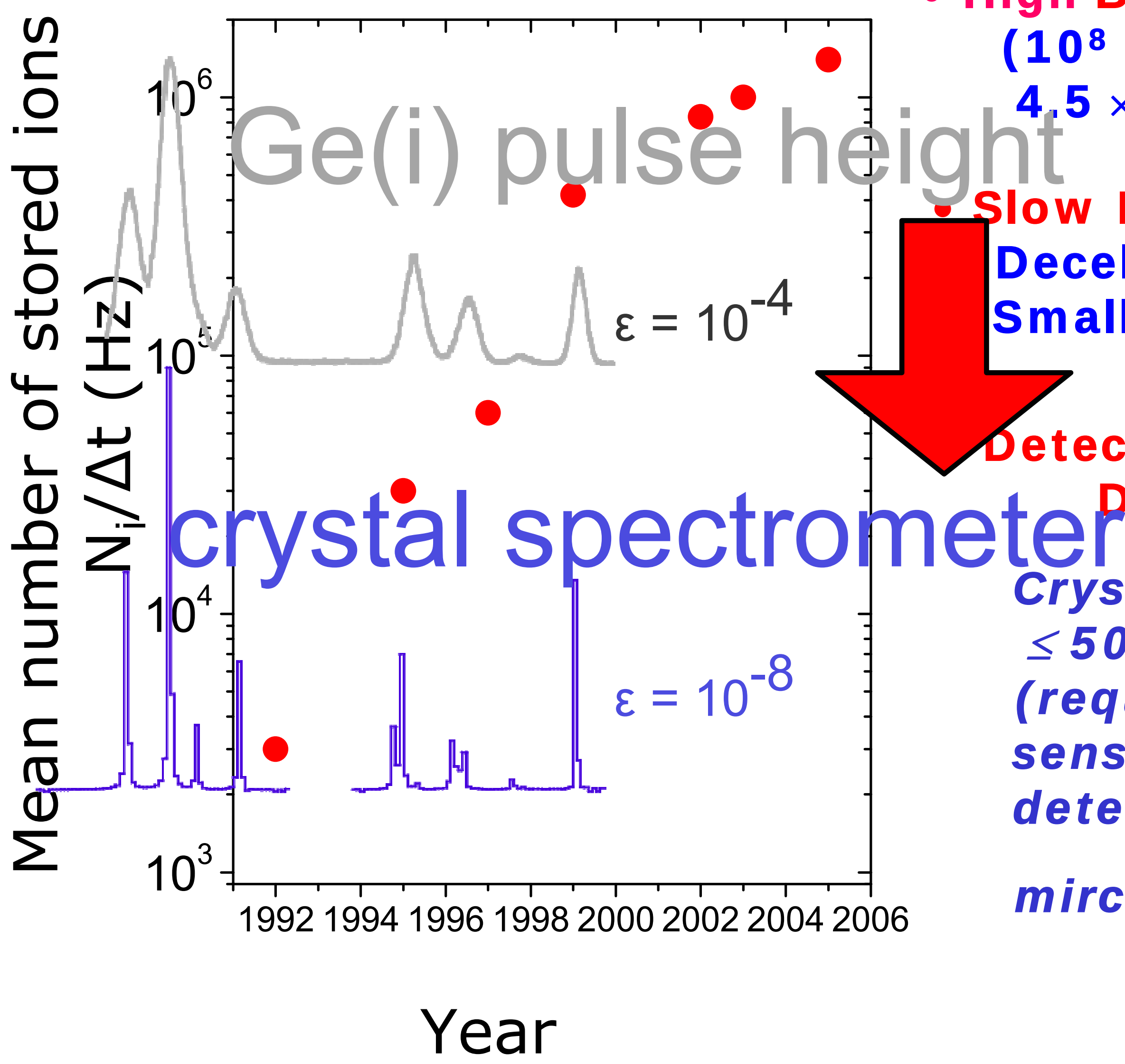


Challenge:

Further accuracy gain by a factor 5 to 10
(detector, spectrometer, and target development required)

Caen | Cracow | Greenbelt | Grenoble | Grenoble | Heidelberg | Jena | Jülich | Kielce | Madison | Mainz | Paris

Towards an Accuracy of 1 eV



- **High Beam intensities**
  (10^8 Ions per Minute ⇒ 4.5×10^5 Photons in 4π)
- **Slow Ions or Ions in Rest**
  Deceleration of the Ions
  Small Doppler correction

Detector and Spectrometer Development

Crystal spectrometer $\leq$ 50 eV (requires position sensitive solid state detectors)

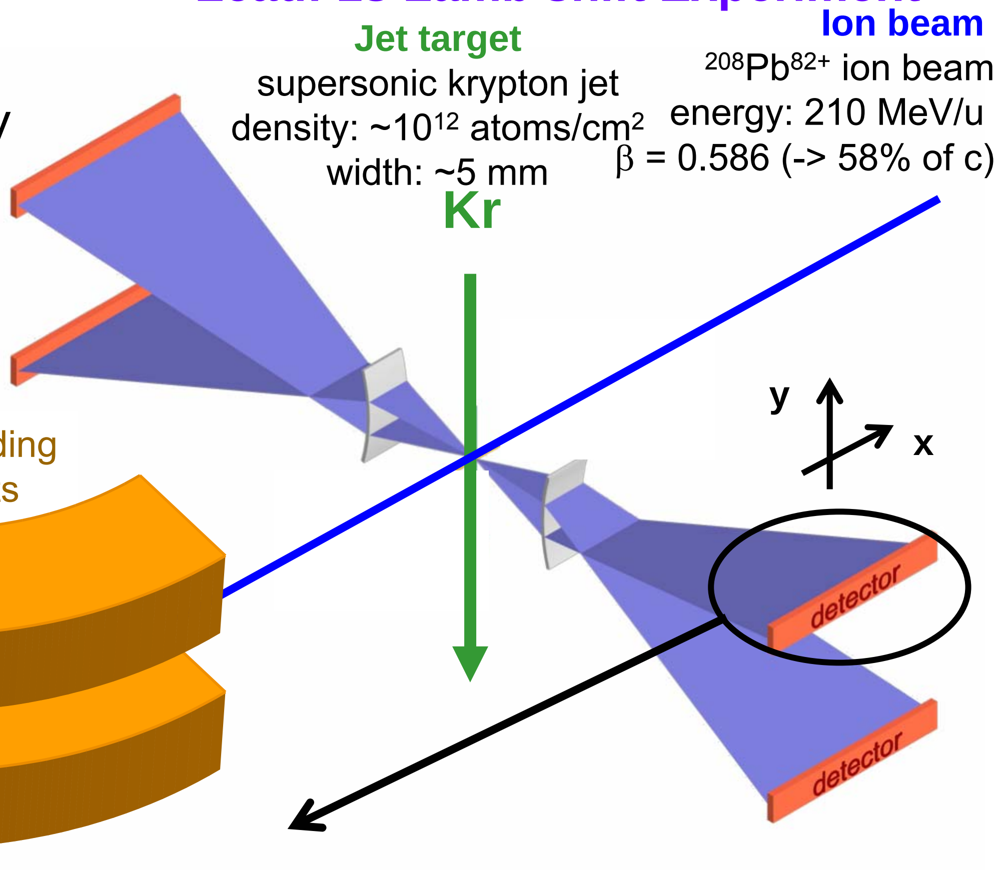
mircocalorimeter

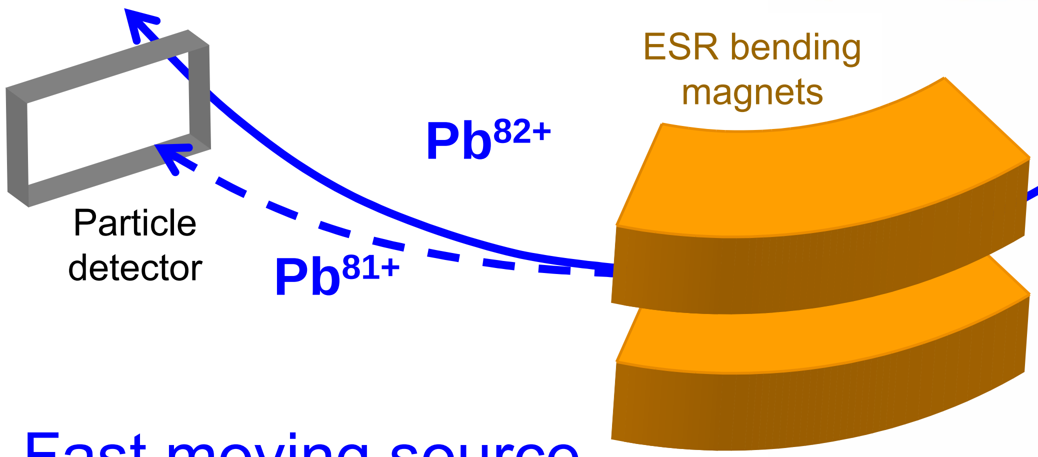
The FOCAL Crystal spectrometers together with Position-sensitive Ge Detectors

FOCAL Laue crystal spectroscopy

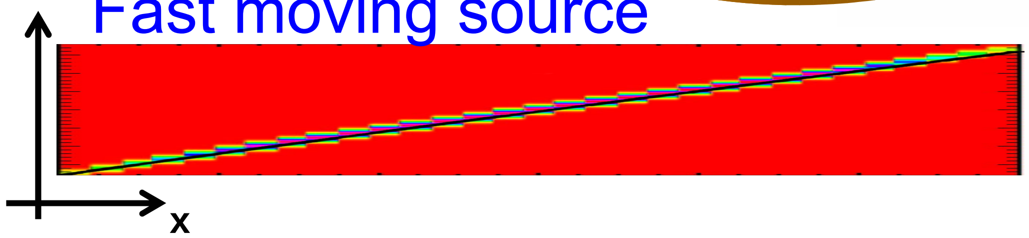
- Transmission Bragg spectrometer
- Theoretical resolution: ~ 50 eV @ 60 keV
- Bent crystal -> focusing properties
- Efficiency: 10^{-8}

Lead: 1s Lamb shift Experiment



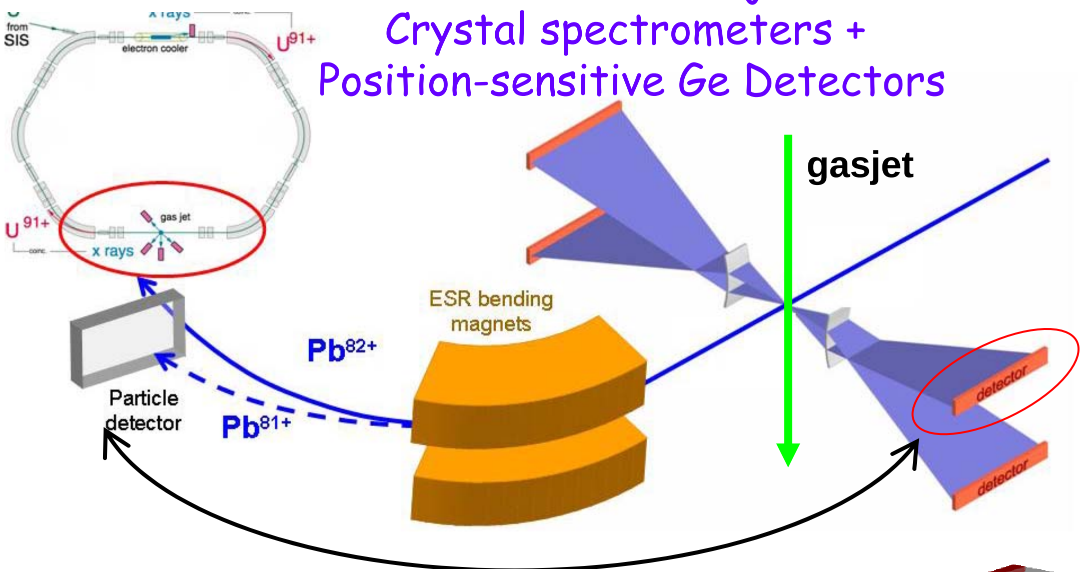


Fast moving source

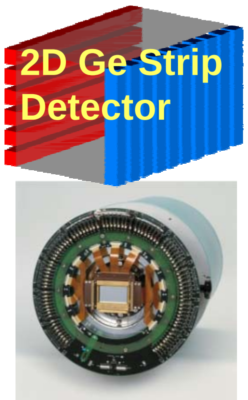


PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS
HIGH-RESOLUTION DETECTION DEVICES AT THE ESR

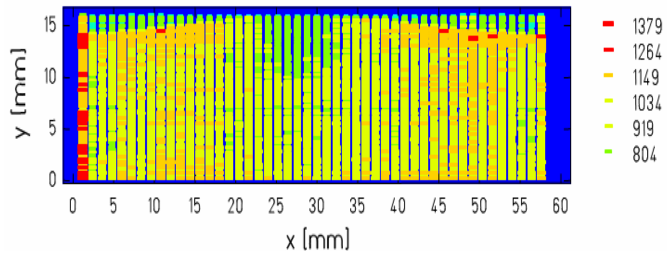
The **FOCAL** Project
Crystal spectrometers +
Position-sensitive Ge Detectors



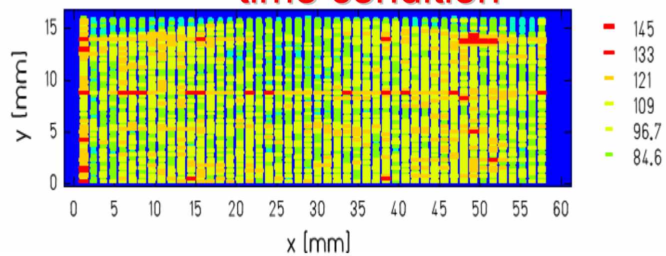
coincidences between particle and x-ray detectors



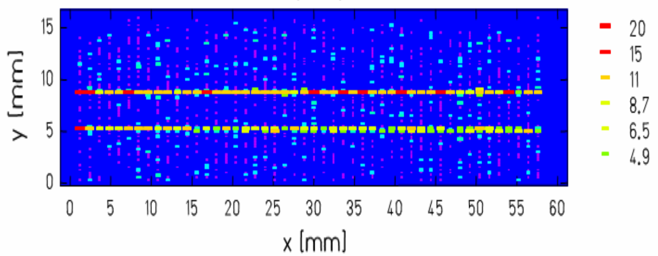
x-ray image (10 keV to 130 keV)



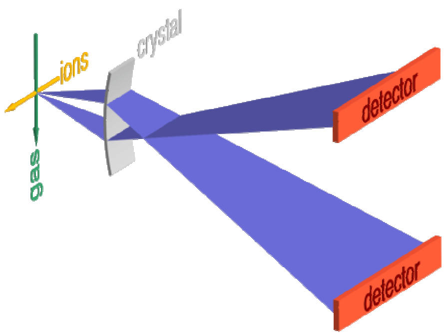
x-ray image (10 keV to 130 keV)
+ time condition



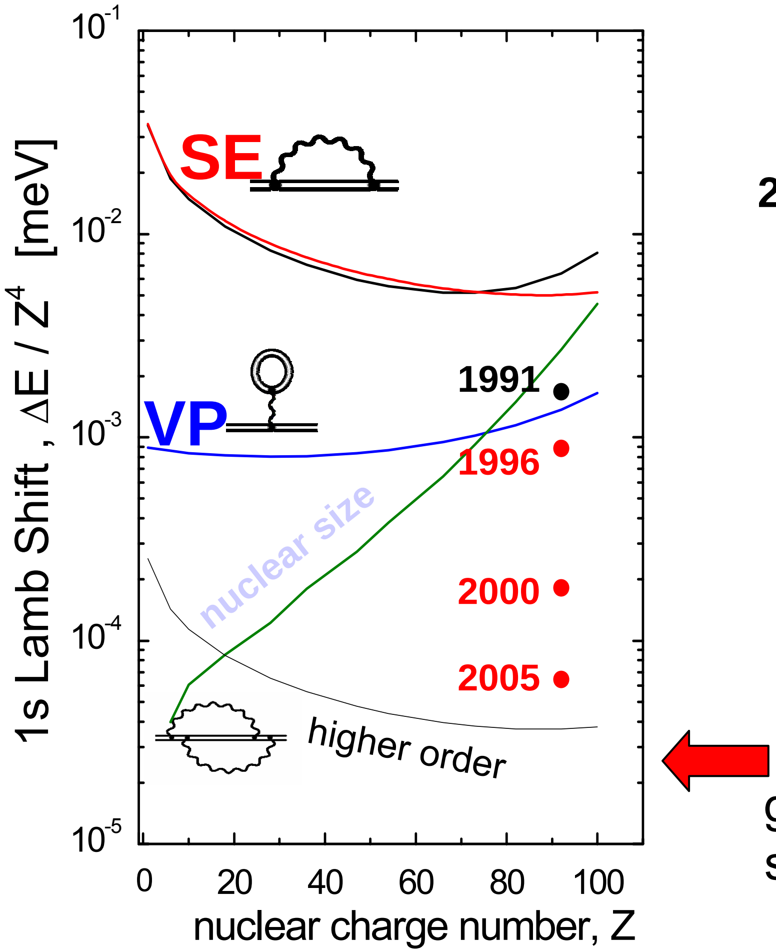
x-ray image (58 keV to 65 keV)
+ time condition



Test of Quantum Electrodynamics (1s-LS)

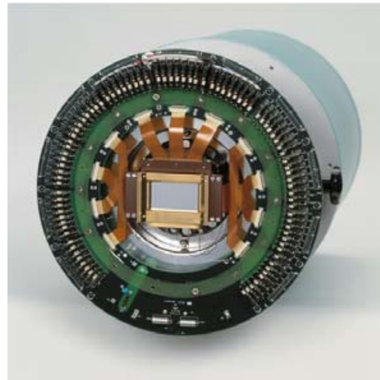


efficiency: ≈ 10^{-7}
resolution: 75 eV @ 60 keV



goal: ΔE = ± 1 eV
sensitive to higher order corrections

2D μ-strip Ge-detector



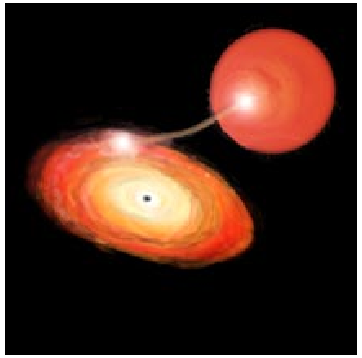
X-Ray Spectroscopy of Cosmic Sources

Direct Insight into Celestial Chemistry

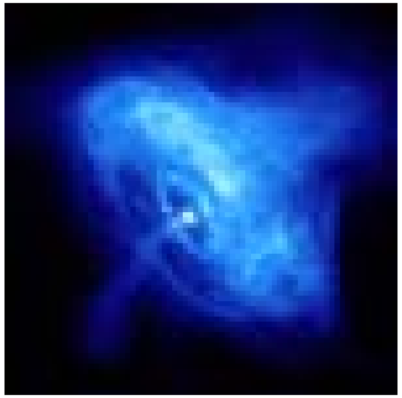
Spectral Properties Provide Knowledge Of

gas temperature, density, ionization state, elemental abundance, and gas velocity

active regions of surface of star (Our Sun)

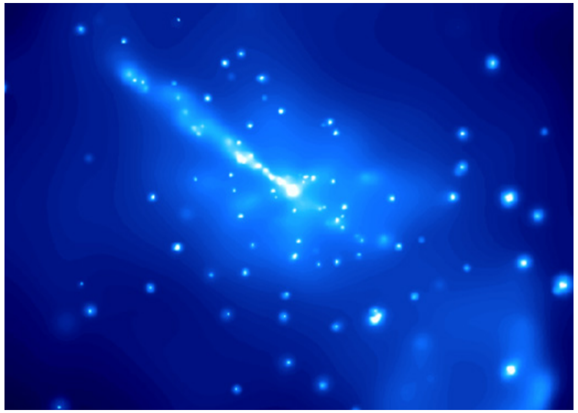


mass exchange binary systems

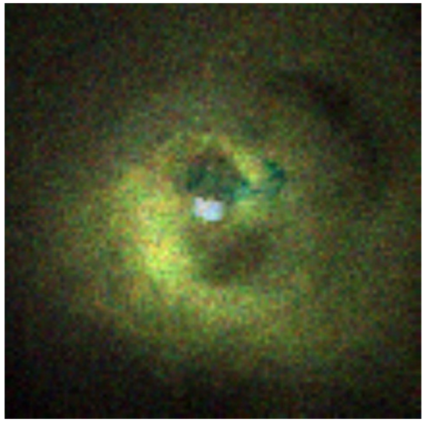


Pulsars (Crab)

supernova remnants (Kepler)

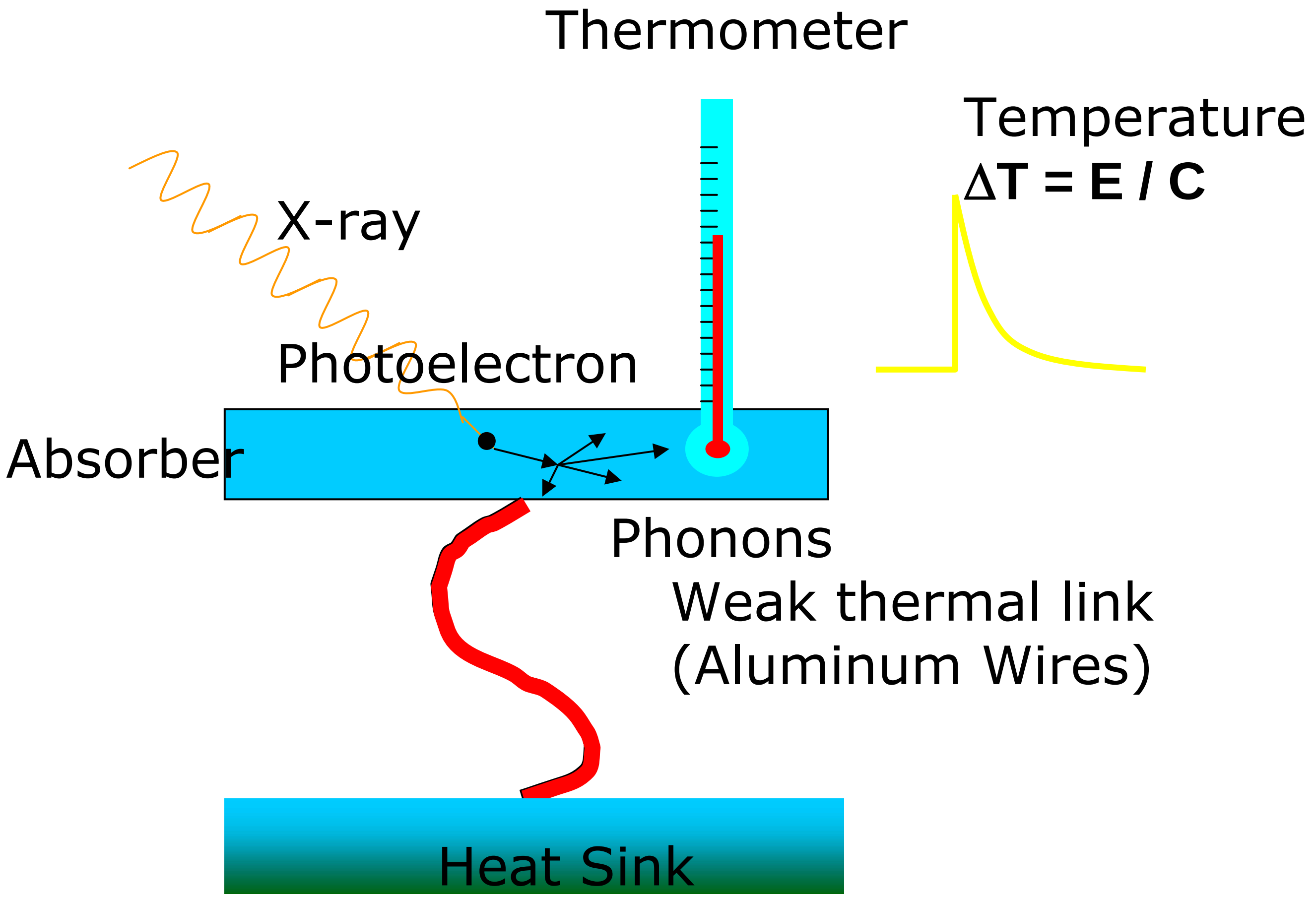


active galactic nuclei (AGN) (Centaurus A)



Intergalactic matter of clusters of galaxies (Perseus)

Micro-Calorimeter



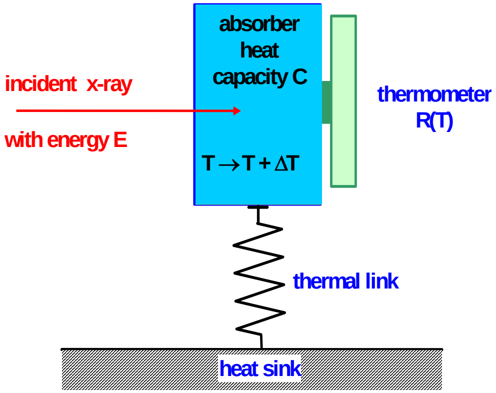
Heat capacity: $C = c \cdot m$
$C \sim T^3$
Spezific heat capacity : c
Detector mass: m

Detector operates at about 50 mK

***Micro-calorimeter detector*: large wavelength acceptance, large quantum efficiency, and excellent energy resolution (4 keV@5eV => 35 keV@30 eV).**

First Test Experiment for Lamb Shift Measurements on Hydrogen-like Heavy Ions with Cryogenic Detectors

Detection principle



$\Delta T = E/C \sim E/T^3$

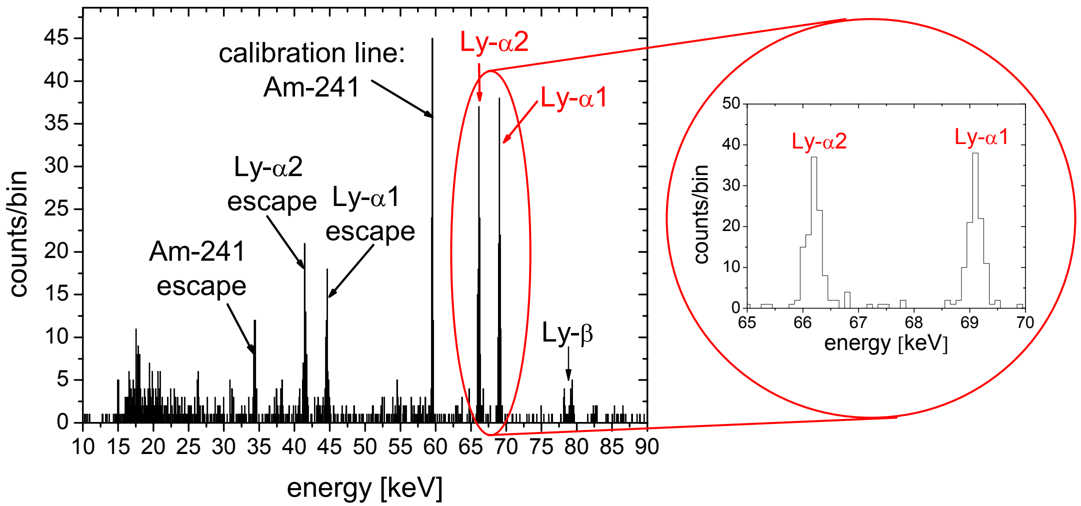
⇒ low operating temperature ($T \approx 50$ mK)

Potential advantage in

⇒ energy resolution

⇒ detection efficiency

2 days of $^{238}U^{91+}$ beam time at the ESR

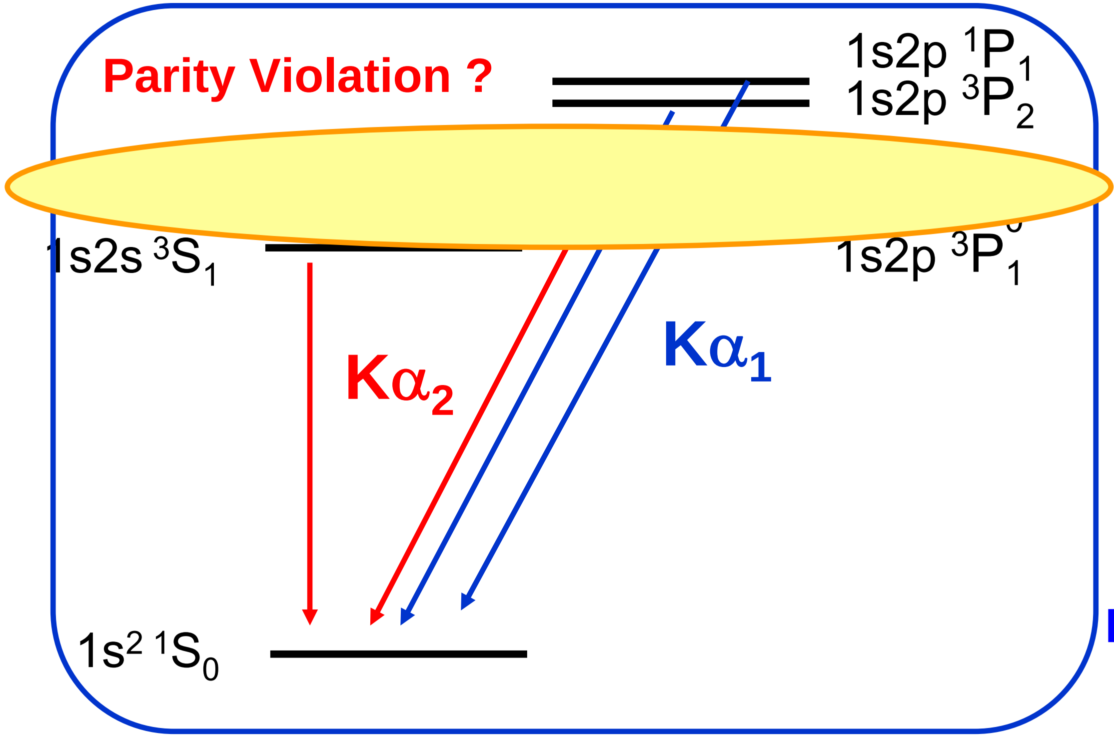


- Lyman-α lines unambigously identified
- achieved energy resolution: ΔE = 149 eV
- detection efficiency (4 pixels): 1×10^{-7}
- **perspectives:** detector array with 32 pixels

⇒ **detection efficiency: 8×10^{-7}**

P. Egelhof et al.

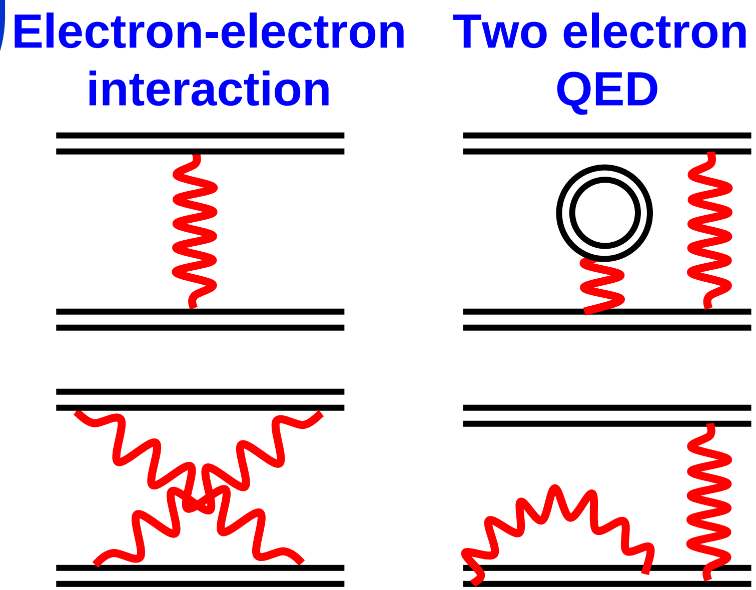
Atomic Structure of He-like Ions



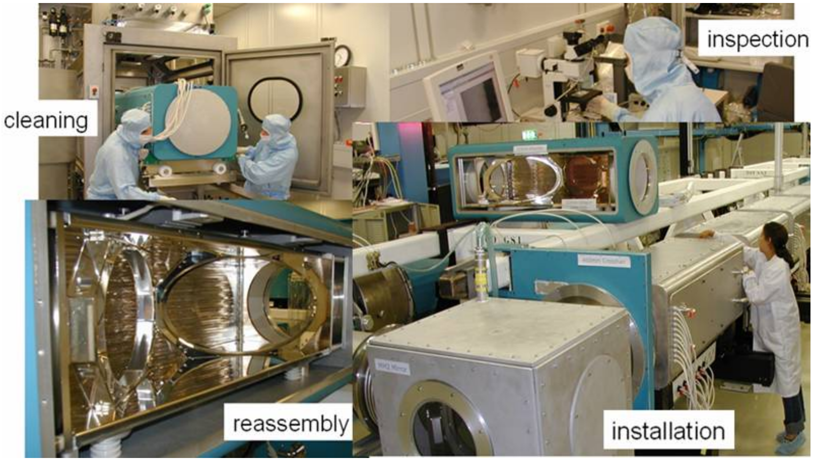
Intense photon pulse is required !

- exotic decay modes: M2, 2E1, E1M1

- electron correlation and QED in the relativistic domain



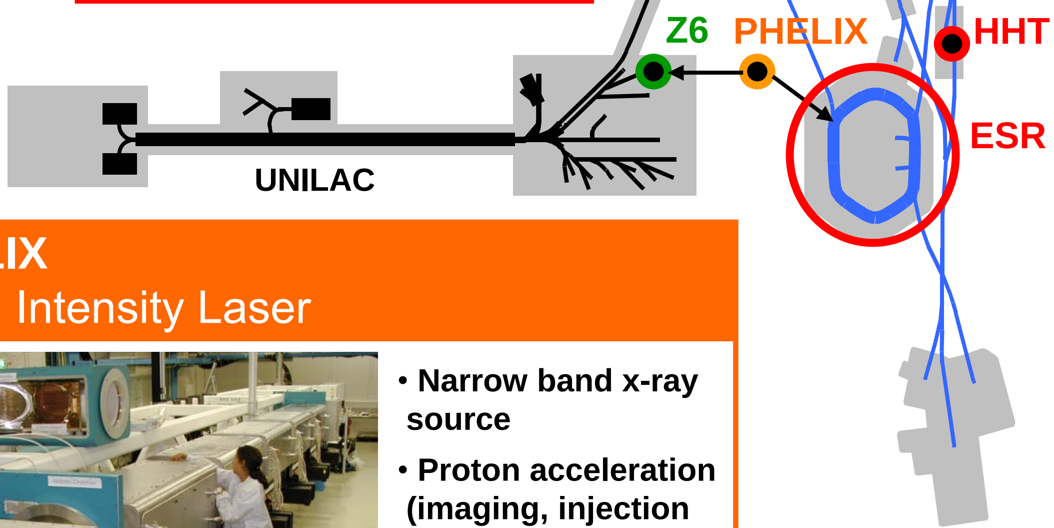
Experimental Facilities, PHELIX



ESR

4 - 500 MeV/u; all ions up to U^{92+}

Structure and collision studies with cooled heavy ions



PHELIX
High Energy / High Intensity Laser

Laser bay: 0.5 PW, 250 J @ 500 fs

2008: 0.2 PW, 100 J @ 500 fs

Z6: 0.3 – 1 kJ @ 1 – 15 ns

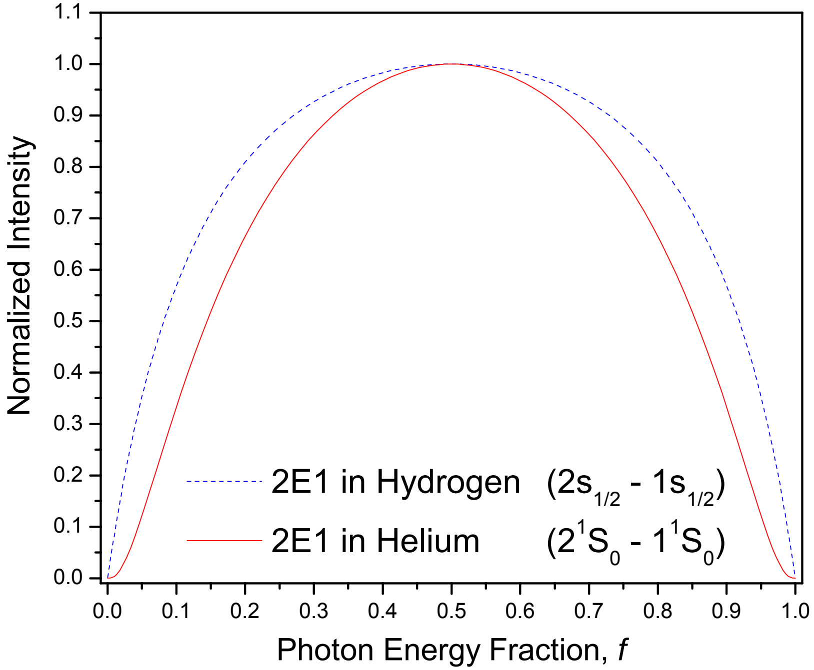
50 J @ 0.5 – 2 ps (100 TW)

2008: 300 J @ ~ns

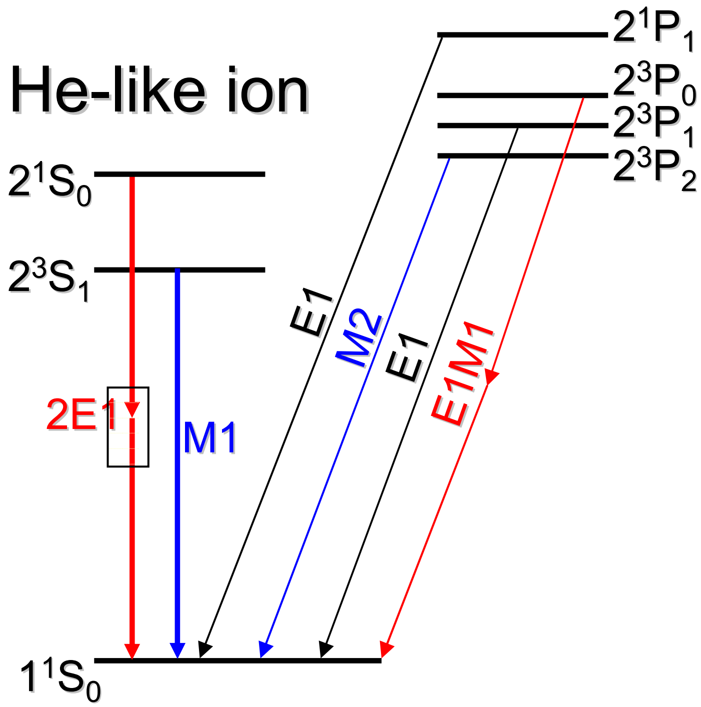
- **Narrow band x-ray source**
- **Proton acceleration (imaging, injection in accelerator)**
- **High field effects in highly charged ions**

Two-photon transition in He-like system

Calculated photon energy distribution



$$\hbar\omega_1 + \hbar\omega_2 = E_i - E_f$$



Single photon J=0 ↛ J=0
transition is forbidden

References:
[M. Göppert, Naturwissenschaften 17 (1929) 932]
[M. Göppert-Mayer, Ann, Phys. 9 (1931) 273]
[Derevianko and Johnson, Phys. Rev. A 56 (1997) 1288]

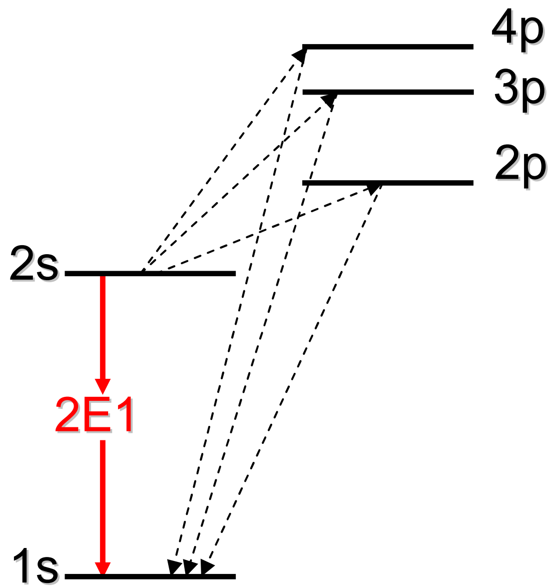
Two-photon studies: theoretical approach

- Analysis of the two-photon decay requires knowledge about the complete spectrum of the ion:

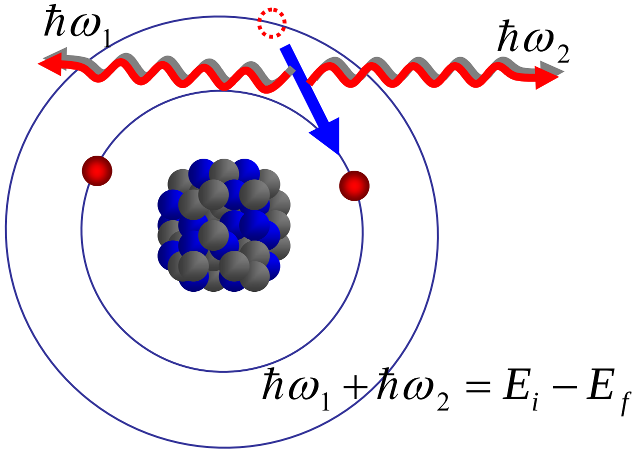
$$M_{fi} \propto \sum_{\nu} \frac{\langle \psi_f | \boldsymbol{\alpha}\, \boldsymbol{\varepsilon}_2\, e^{-i\boldsymbol{k}\boldsymbol{r}_2} | \psi_\nu \rangle \langle \psi_\nu | \boldsymbol{\alpha}\, \boldsymbol{\varepsilon}_1\, e^{-i\boldsymbol{k}\boldsymbol{r}_1} | \psi_i \rangle}{E_\nu - E_i + \hbar\omega_1}$$

- The calculation of the second-order transition amplitude includes a summation over the discrete part of the spectrum as well as an integration over the positive and negative-energy continua.

Study of the two-photon decay is sensitive to the complete structure of the ion.



Two-photon studies of He-like isoelectronic sequence



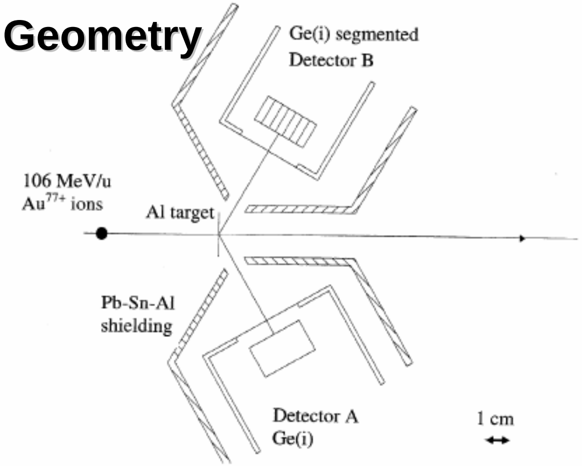
- The simplest multielectron system
- Interplay between relativistic effects and e^--e^- correlation
- Test of the complete level structure

- A number of two-photon studies has been performed over the last decades to mainly investigate two-photon total decay rates.
- Only a few experimental studies of spectral distributions are available.

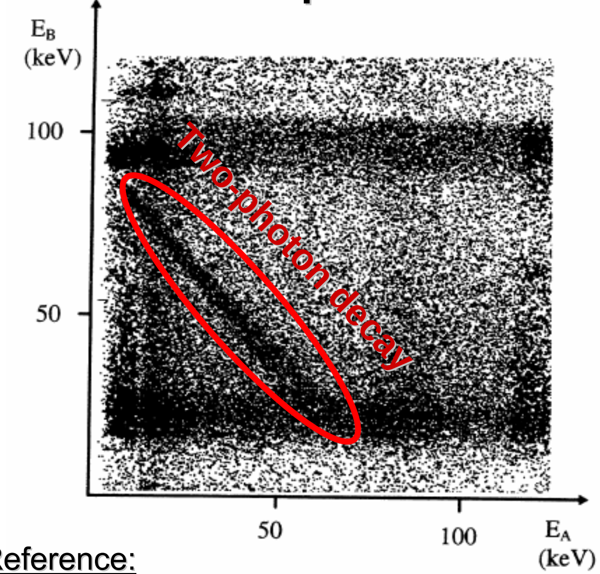
- Previous data are inconclusive to test relativistic effects

Current state of the art – photon-photon coincidence technique

Geometry

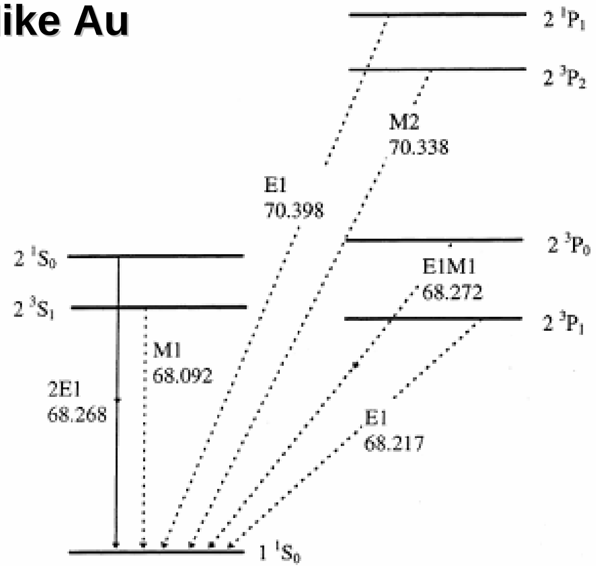


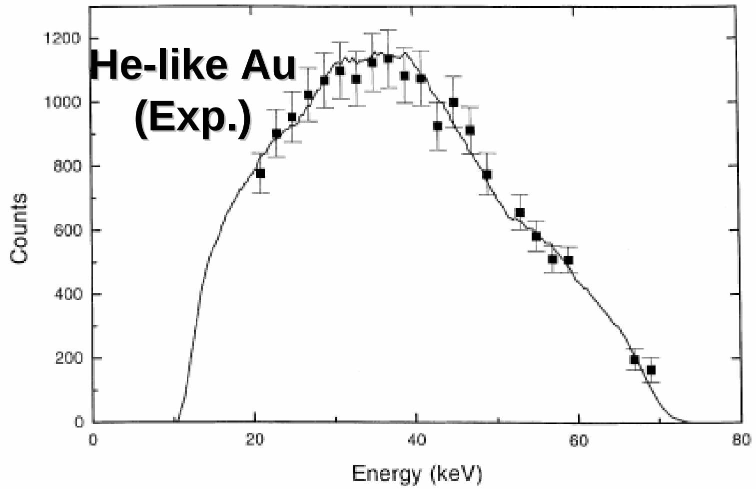
Coincidence spectrum



Reference:
[H.W. Schäffer et al. Phys. Lett. A 260 (1999) 489]

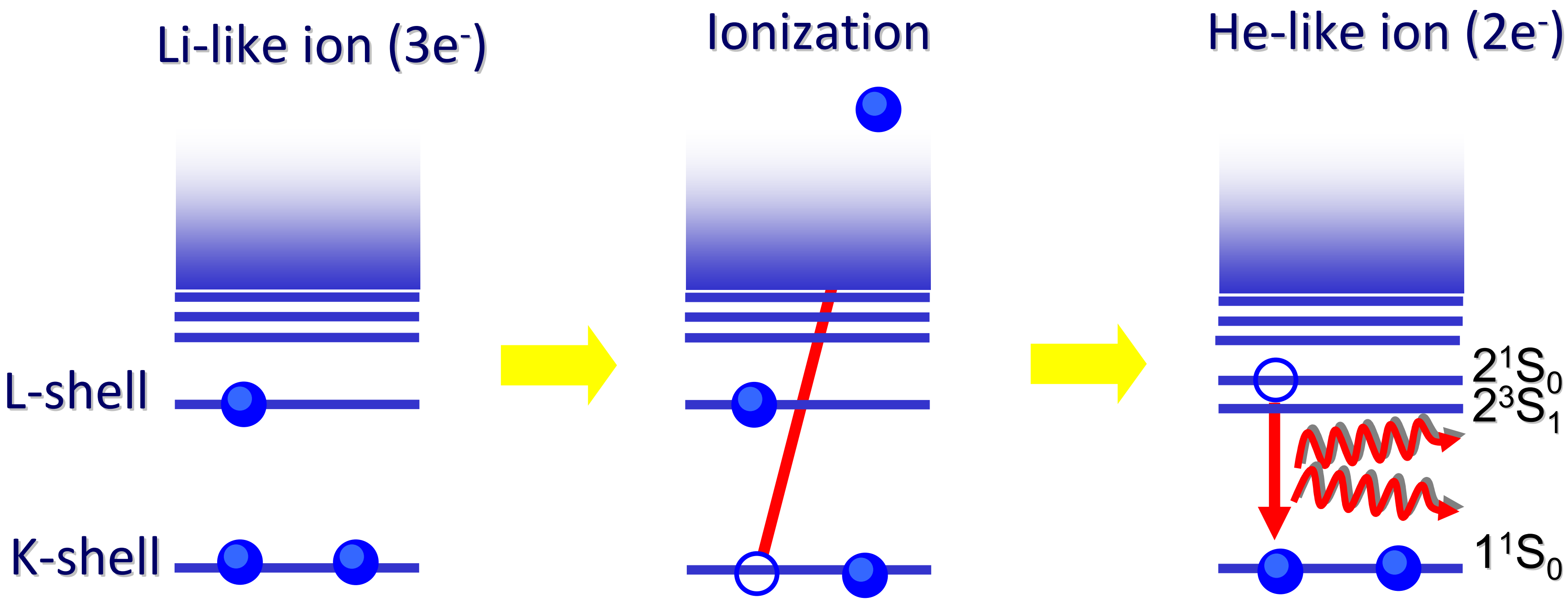
He-like Au





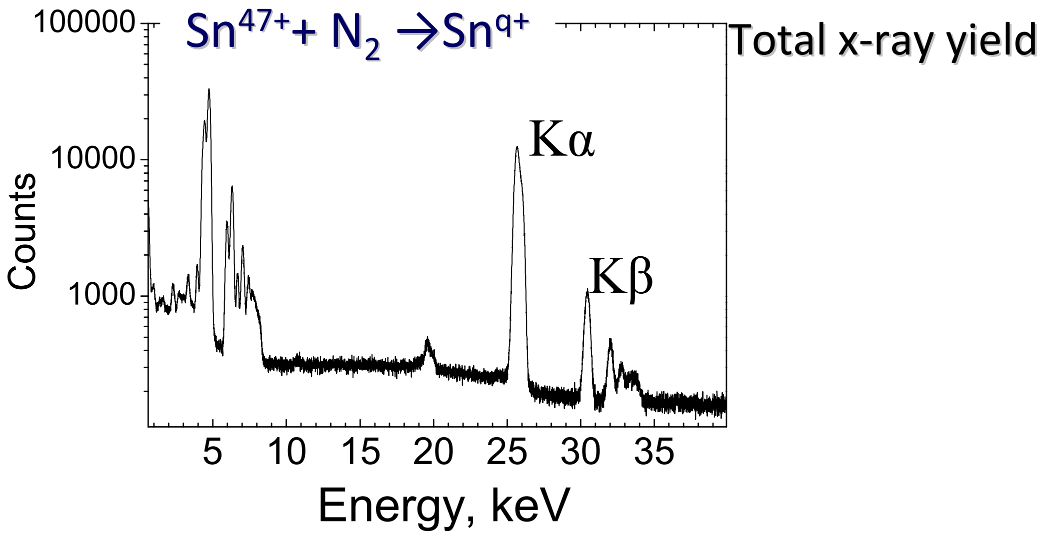
Novel experimental approach

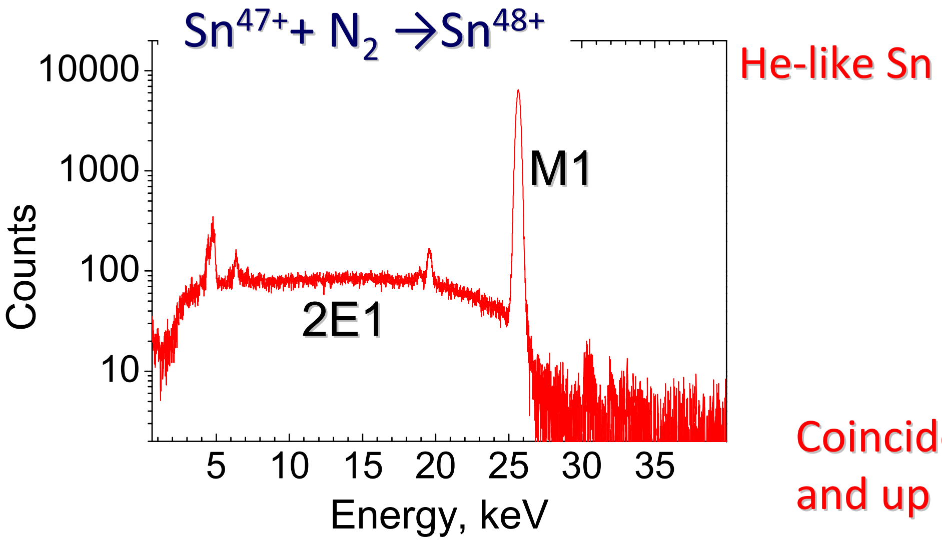
Production of the excited state by selective K-shell ionization

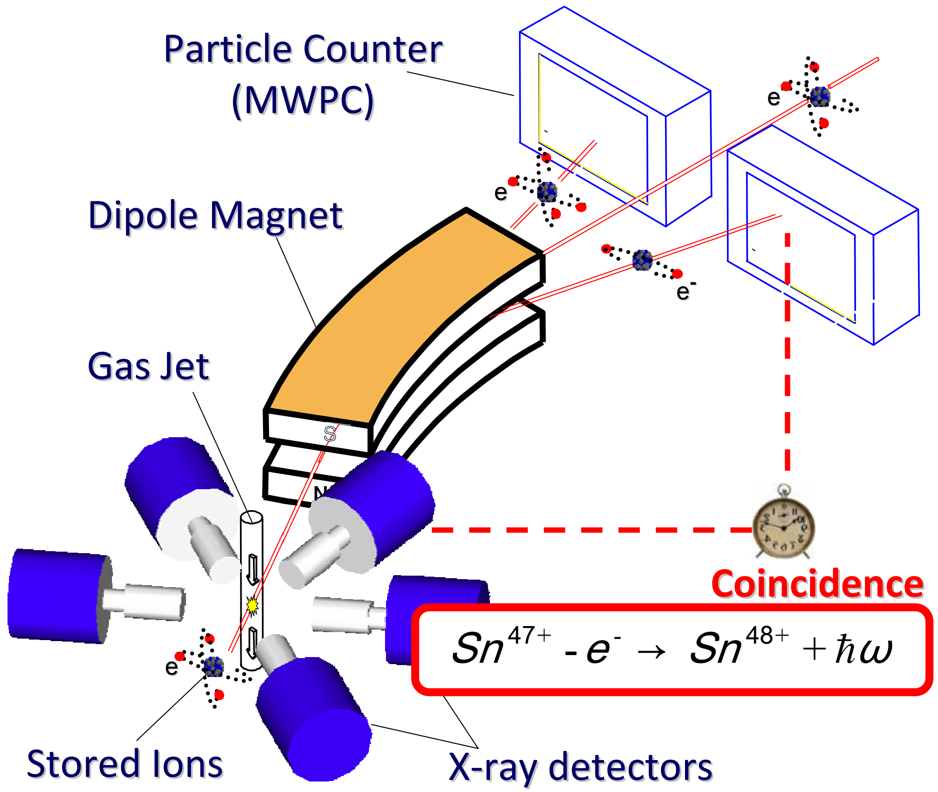


References:
[D. C. Ionescu, Th. Stöhlker, Phys. Rev. A 67 (2003) 022705]
[J. Rzadkiewicz et al., Phys. Rev. A 74 (2006) 012511]

X-Ray spectra produced in 300 MeV/u Li-like tin collisions with N_2



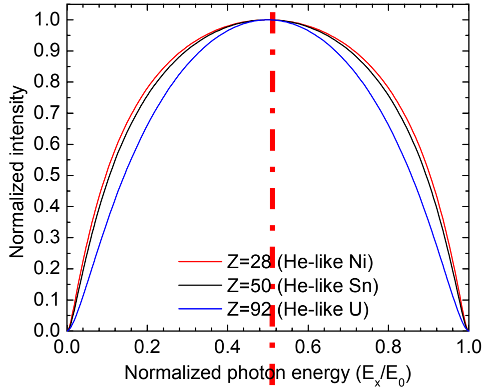




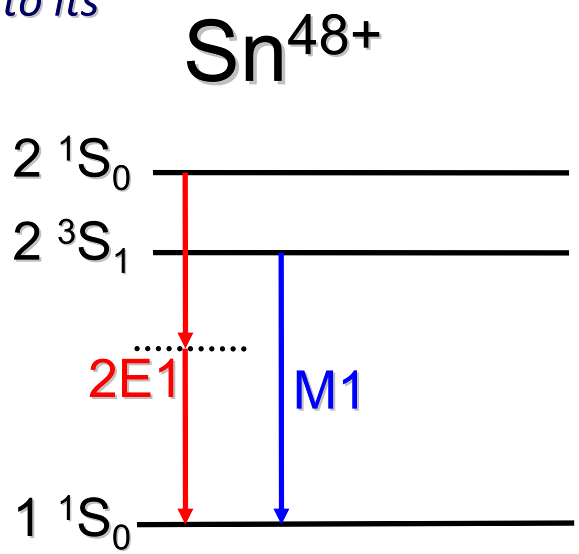
Coincidence registration of x-rays and up charged (**He-like**) ions

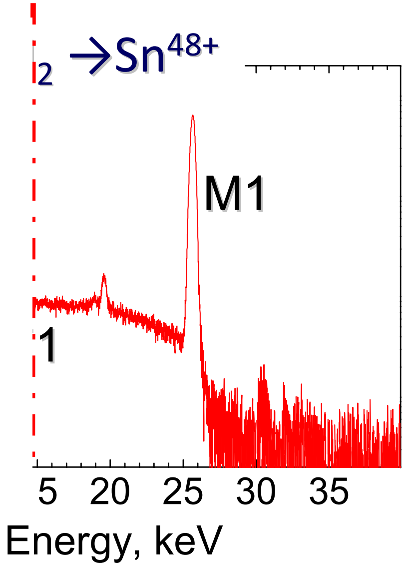
X-Ray spectra produced by K-shell ionization of initially Li-like ions

Theory: Spectral Shape



Two-photon energy distribution is symmetric with respect to its center.

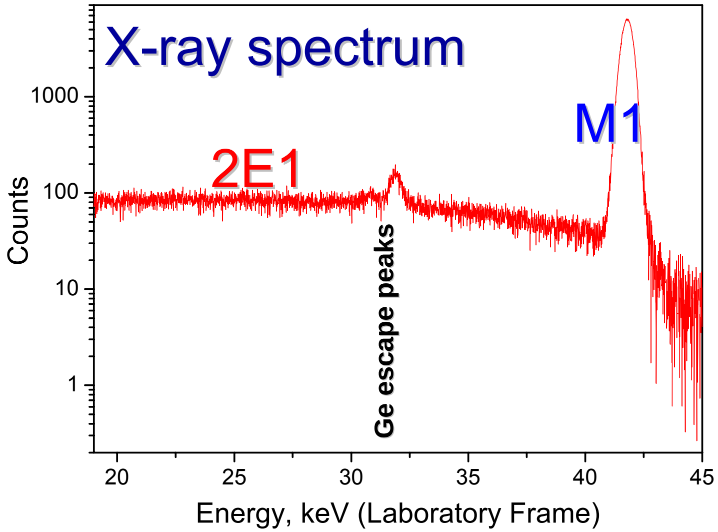


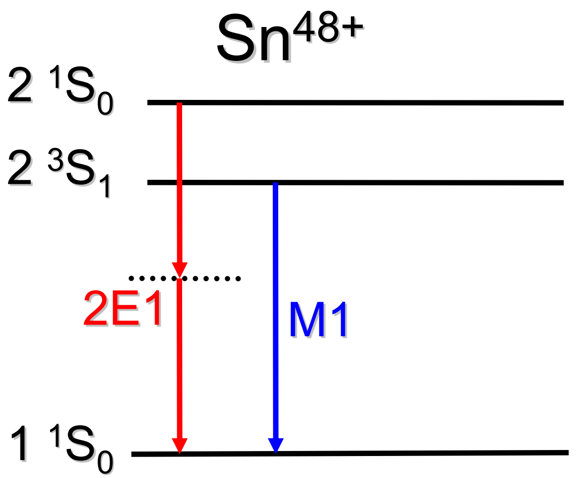


He-like Sn

Coincidence registration of x-rays and up charged (**He-like**) ions

Novel technique for the study of the two-photon decay
Decay of the 2s-excited states in He-like tin

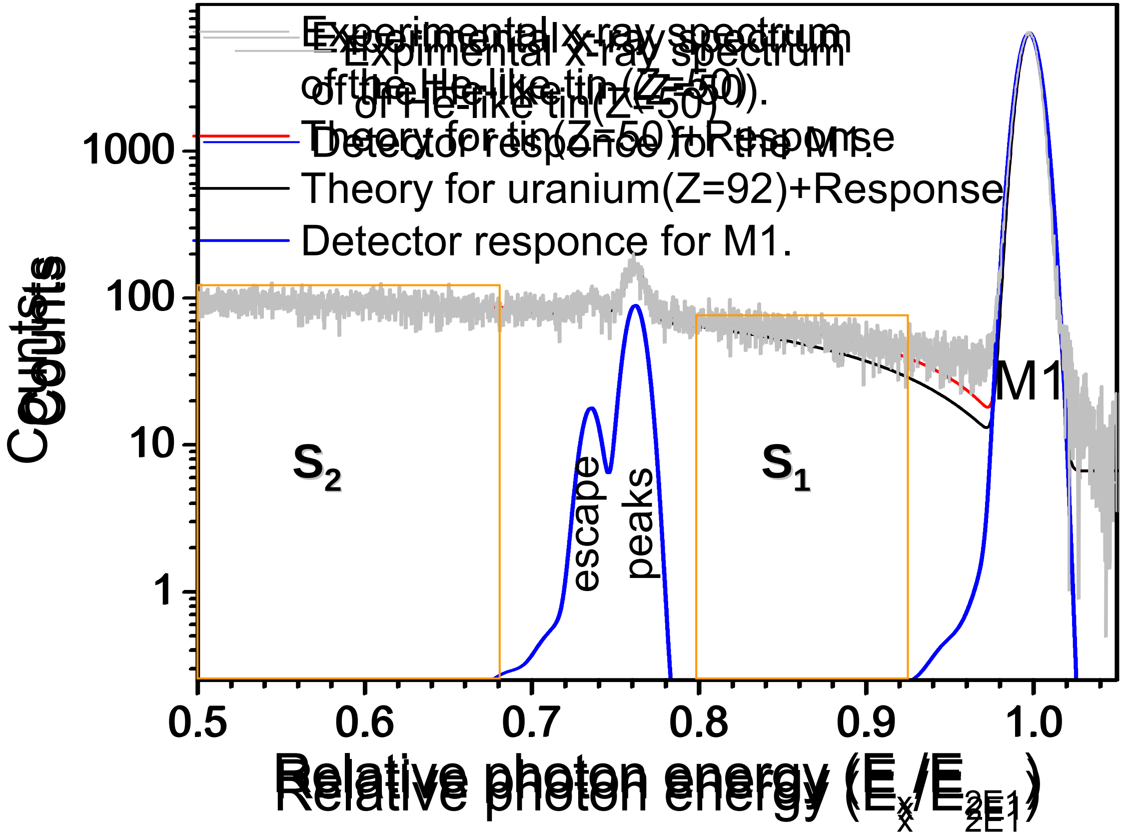


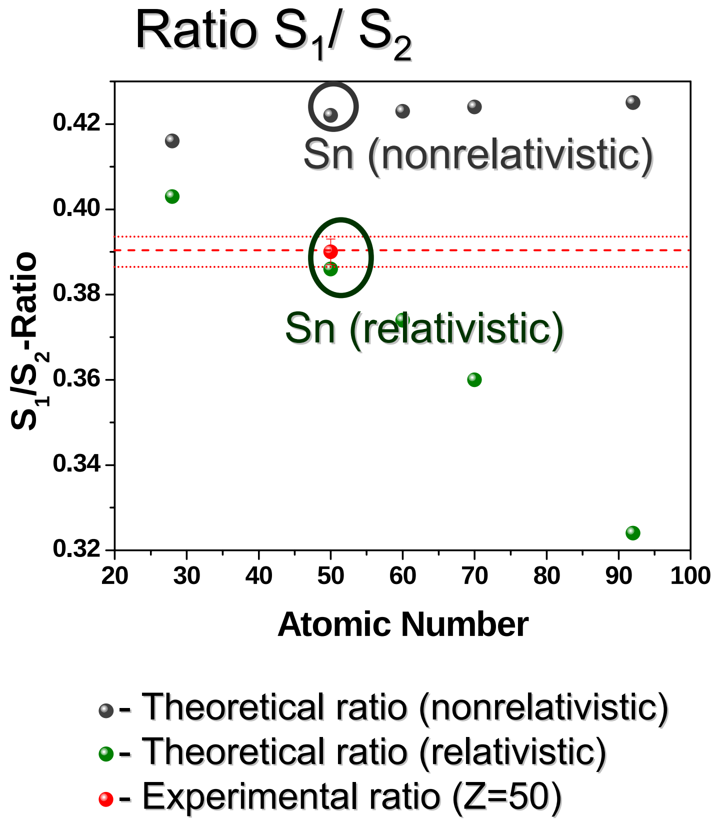


Advantages of the novel technique:

- Selective population of the excited state
- Substantial reduction of the background
- No need for photon-photon coincidences
- Few orders of magnitude larger solid angles
- Substantial gain in statistics
- Strongly reduced systematic uncertainty
- Well-defined detector response function
- No background from cascade contribution
- No contribution from E1M1 (2^3P_0 not populated)

Data analysis and comparison with theory

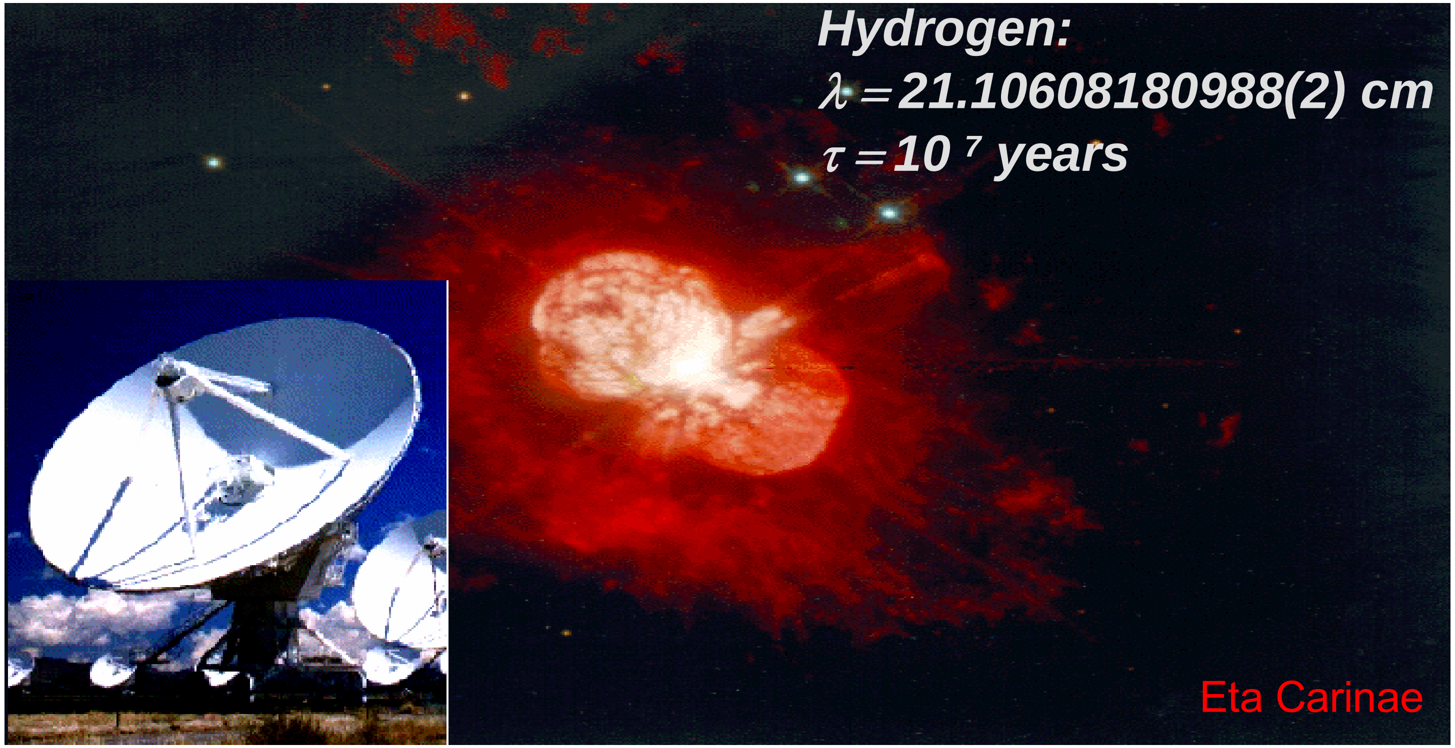


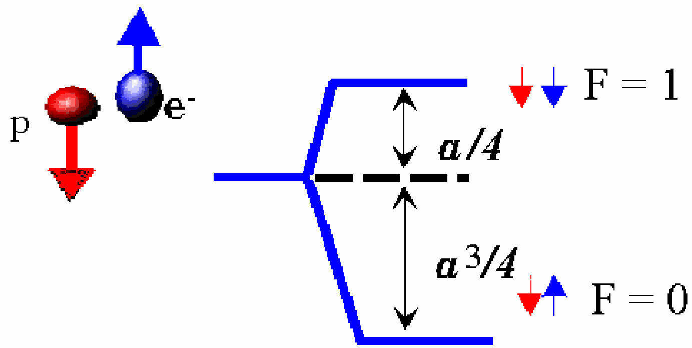


- For the first time that is possible to clearly distinguish relativistic and non-relativistic theories.
- For the first time a quantitative result is received.

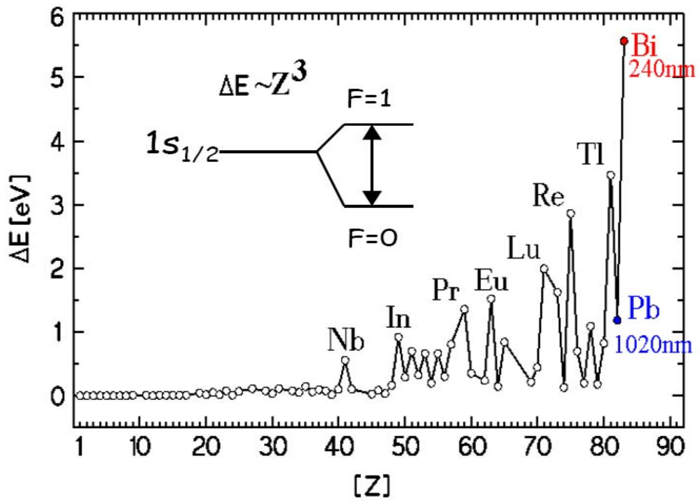
S. Trotsenko et al. Phys. Rev. Lett. 104, 033001 (2010)

Hyperfine Structure at High-Z





Transitions in H-Like and Li-like Ions



	$^{209}Bi^{82+}$ H-like [Sun95]	$^{209}Bi^{80+}$ Li-like [Sha00]
rms radius magnetic moment (corrected)	5,519 fm 4,1106(2) μ_N	
Point nucleus (Dirac) Breit-Schawlow Bohr-Weisskopf	212,320(1) nm 238,791(50) nm 243,91 (38) nm	 -0,1138 (2) eV -0,0134 (2) eV
Total QED	1,22(10)nm	-0,0051 (2) eV
Theory incl.QED	245,13(58) nm	1555,44 (39) nm
Experiment	243,87(1) nm	

[Sun95] Sunnergren P. et al., Phys. Rev. A 58 (1998)
[Sha00] Shabaev V.M. et al., Hyperfine Interactions 127 (2000)

H-like (1s)

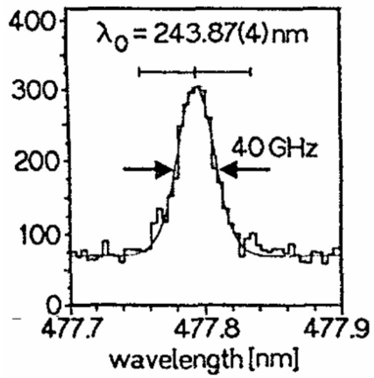
$^{209}Bi^{82+}$

τ=351(16) µs

λ=243.87(4) nm

ΔE_{HFS} = 5.0841(8) eV

I. Klaft et al., PRL 73 (1994)



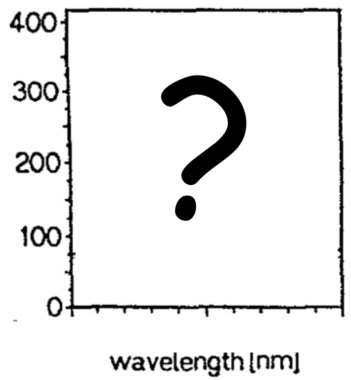
Li-like (2s)

$^{209}Bi^{80+}$

τ ~ 50 ms

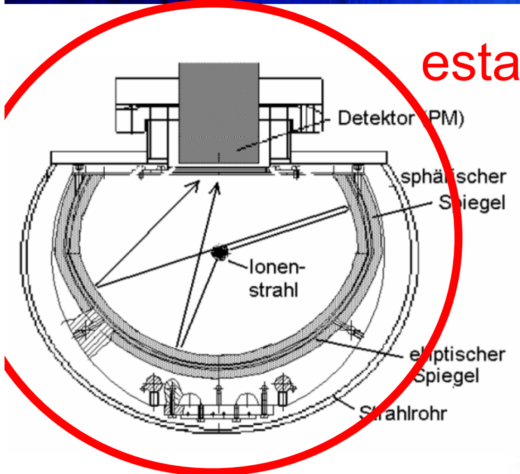
λ=1555 (?) nm

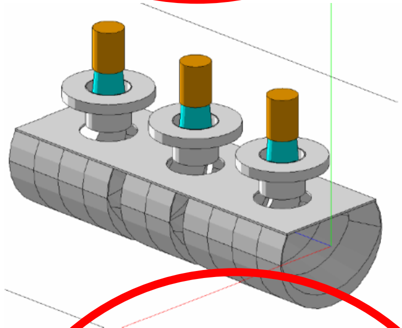
ΔE_{HFS} ~790 meV

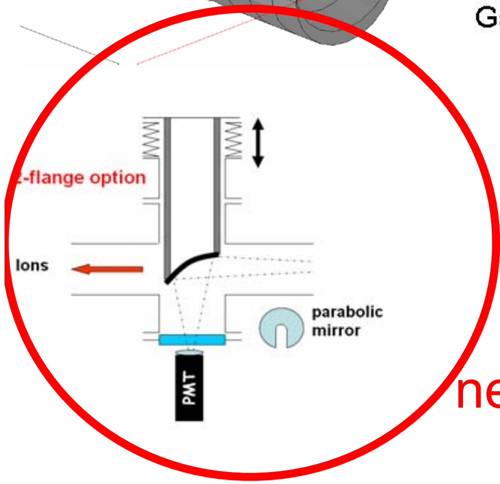


Excitation and Detection at the ESR

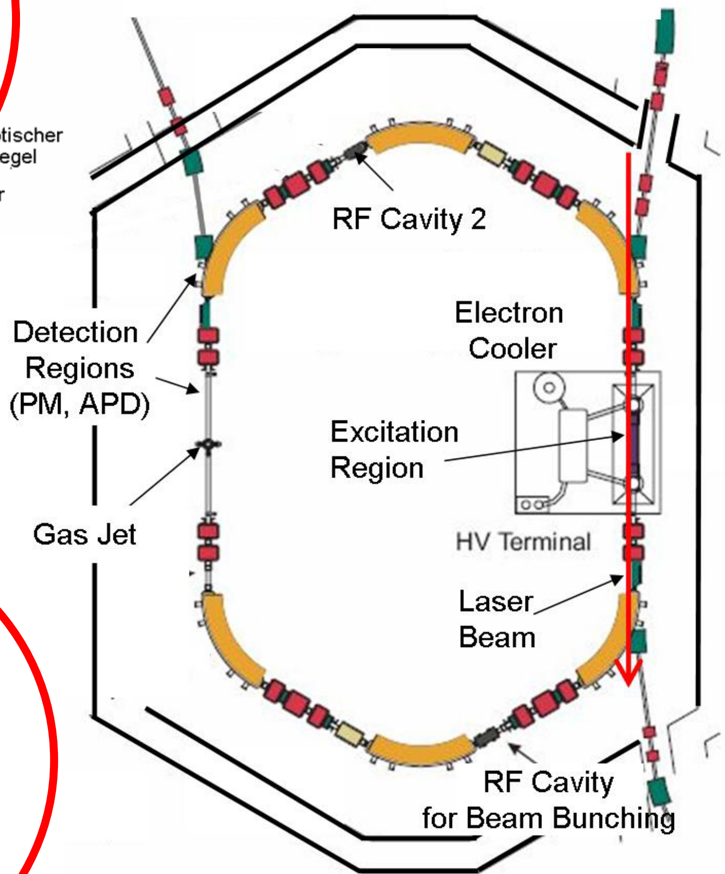
established

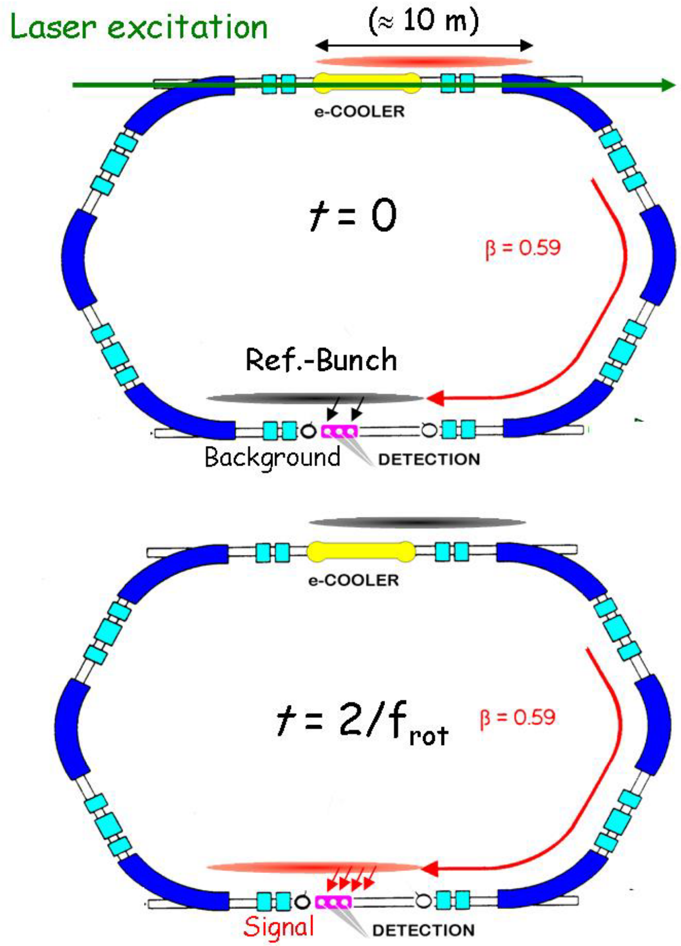






new development

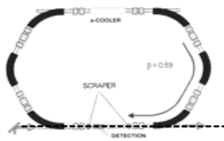




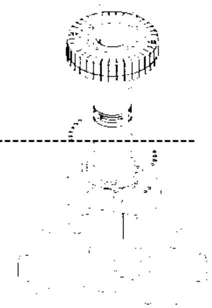
W. Nörtershäuser, M. Vogel, D. Winters et al.

Advantages of Trap-Assisted Spectroscopy

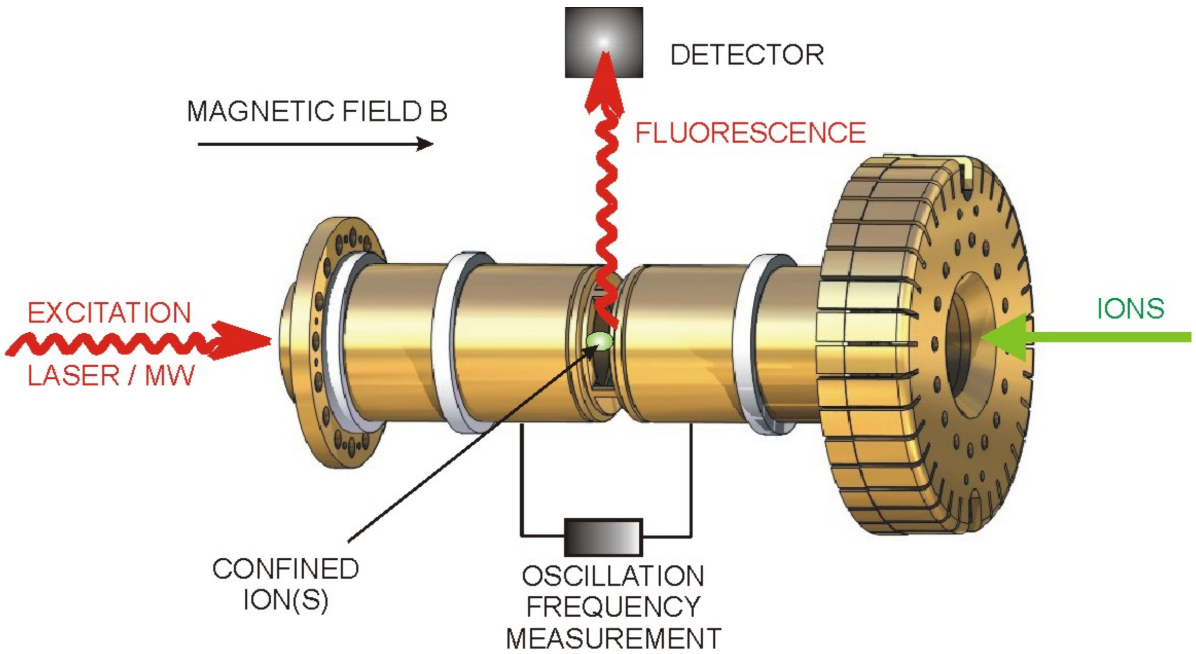
laser spectroscopy of highly charged ions at ...



ESR → **SPECTRAP**



- Ion bunches of 10 m length → well localized ion cloud
- fast ion beam ($\Delta\nu_{Doppler}$~ 50 GHz) → cooled ions ($\Delta\nu_{Doppler}$ ~30 MHz)
- pulsed 50 Hz laser system → narrow-bandwidth continuous laser system



Advantages:

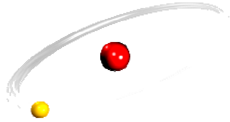
High resolution laser spectroscopy with accuracy of $\Delta\lambda/\lambda < 10^{-7}$

increase in resolution for testing QED by 1-2 orders of magnitude

W. Nörtershäuser, M. Vogel, D. Winters et al.

Quantum Electrodynamical Effects in Extreme Electromagnetic Fields

hydrogen

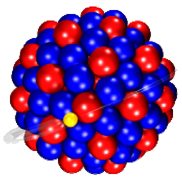


Z=1

E_b = 13.6 eV

$Z\cdot\alpha \ll 1$

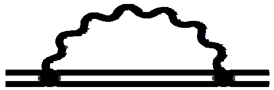
uranium ion



Z=92

E_b = 132 keV

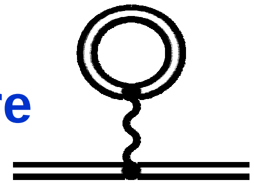
$Z\cdot\alpha \approx 1$

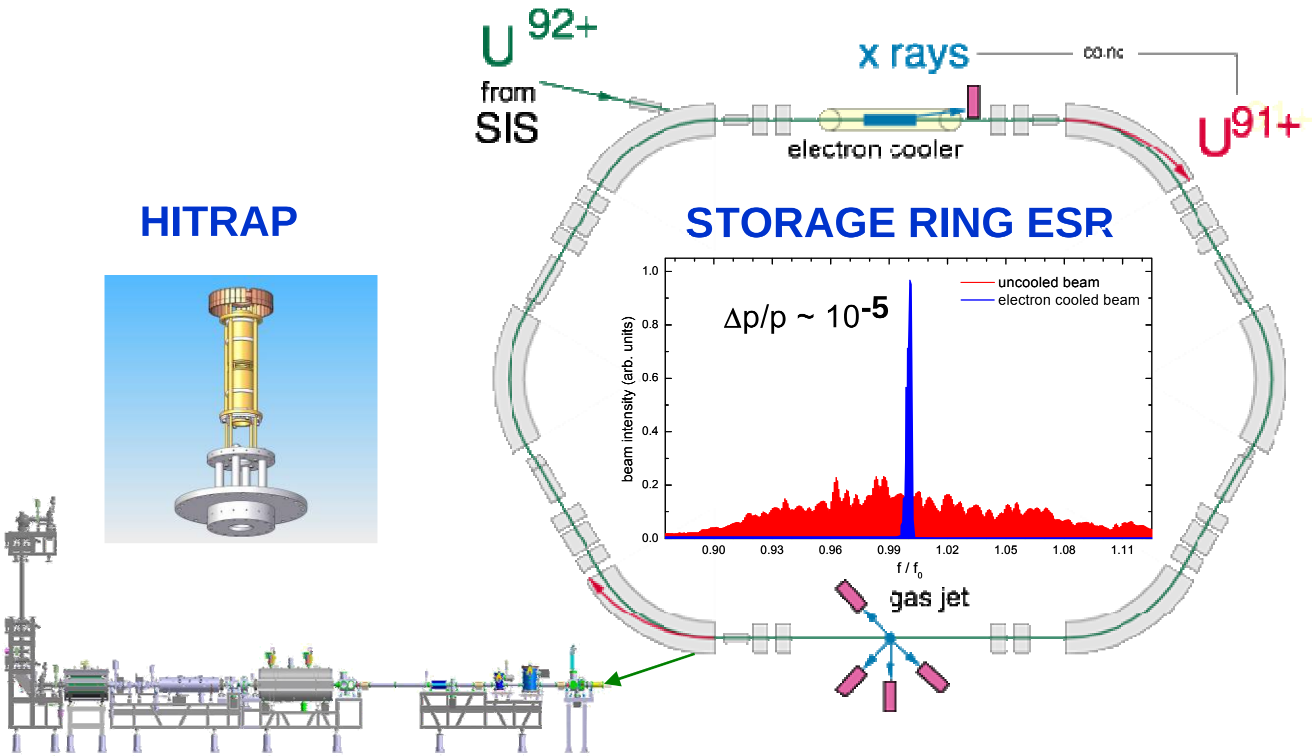


Lamb Shift

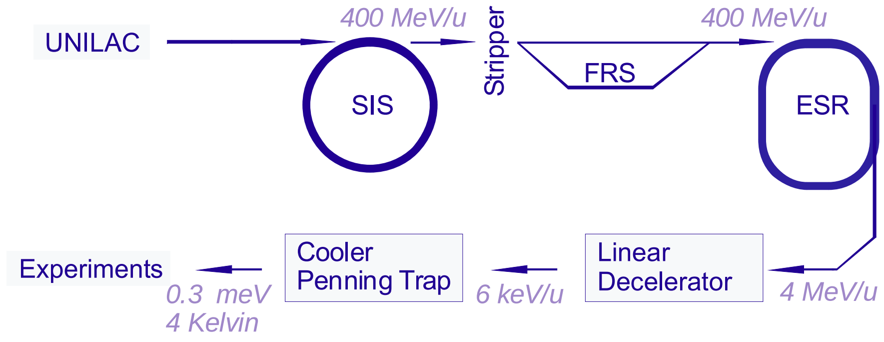
Hyperfine Structure

g-Factor





The HITRAP Facility

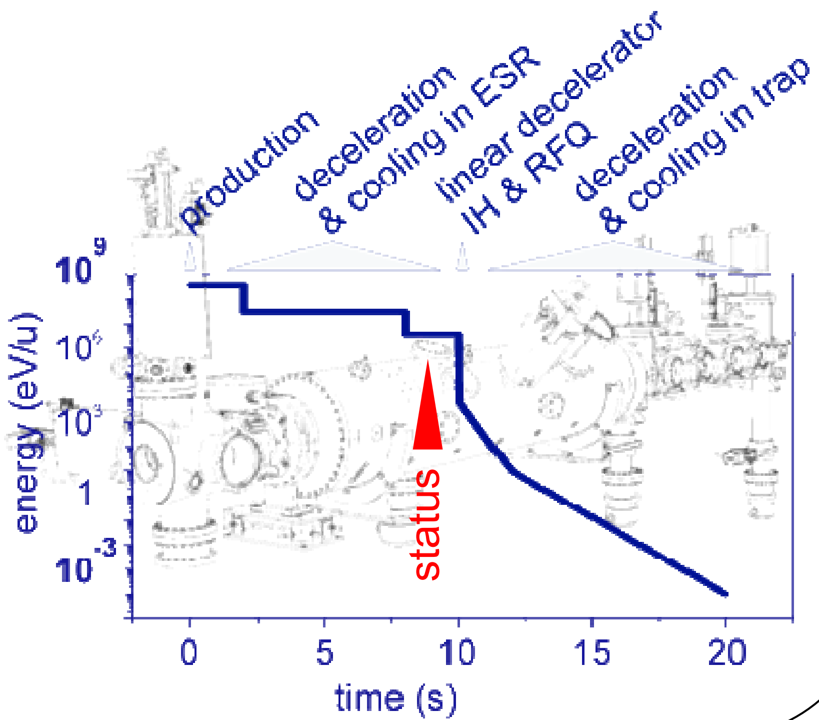


F. Herfurth, O. Kester,
C. Kozhuharov, W. Quint, et al.

Beam available to users – intense source of HCI

type	A/q < 3 (U^{92+} ...)
ions/sec	10^4
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV

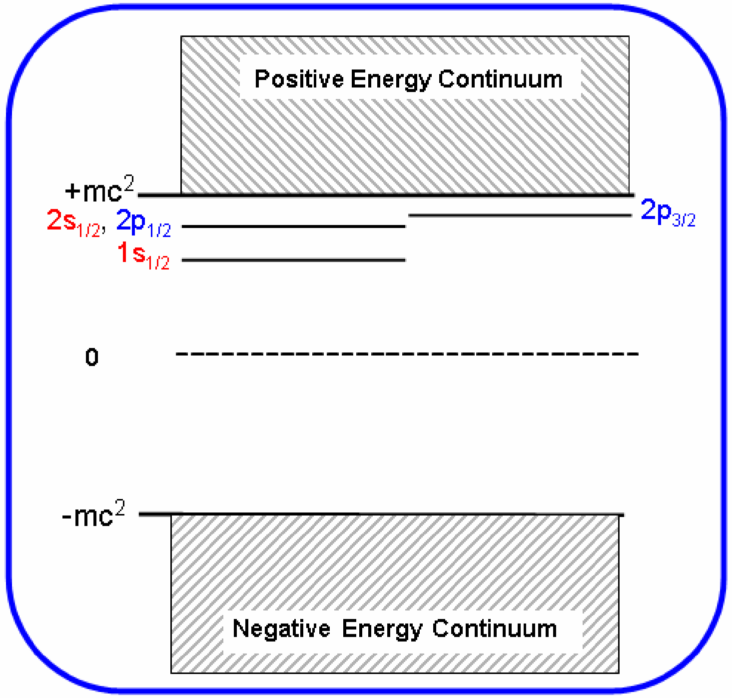
Deceleration cycle – 13 orders of magnitude reduction in energy



Dirac

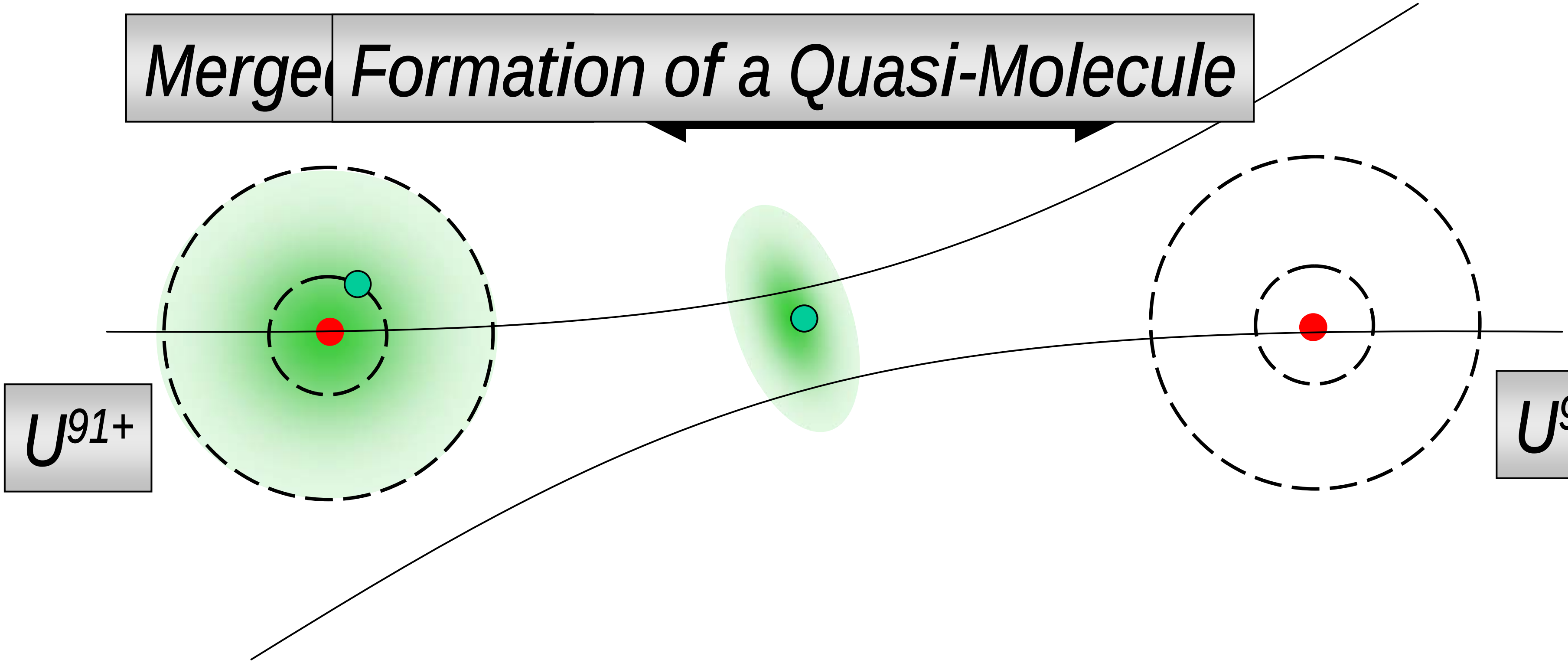
$$E_{1s} = mc^2\sqrt{1-(Z\alpha)^2}$$ (total energy)

First excited states of one-electron ions

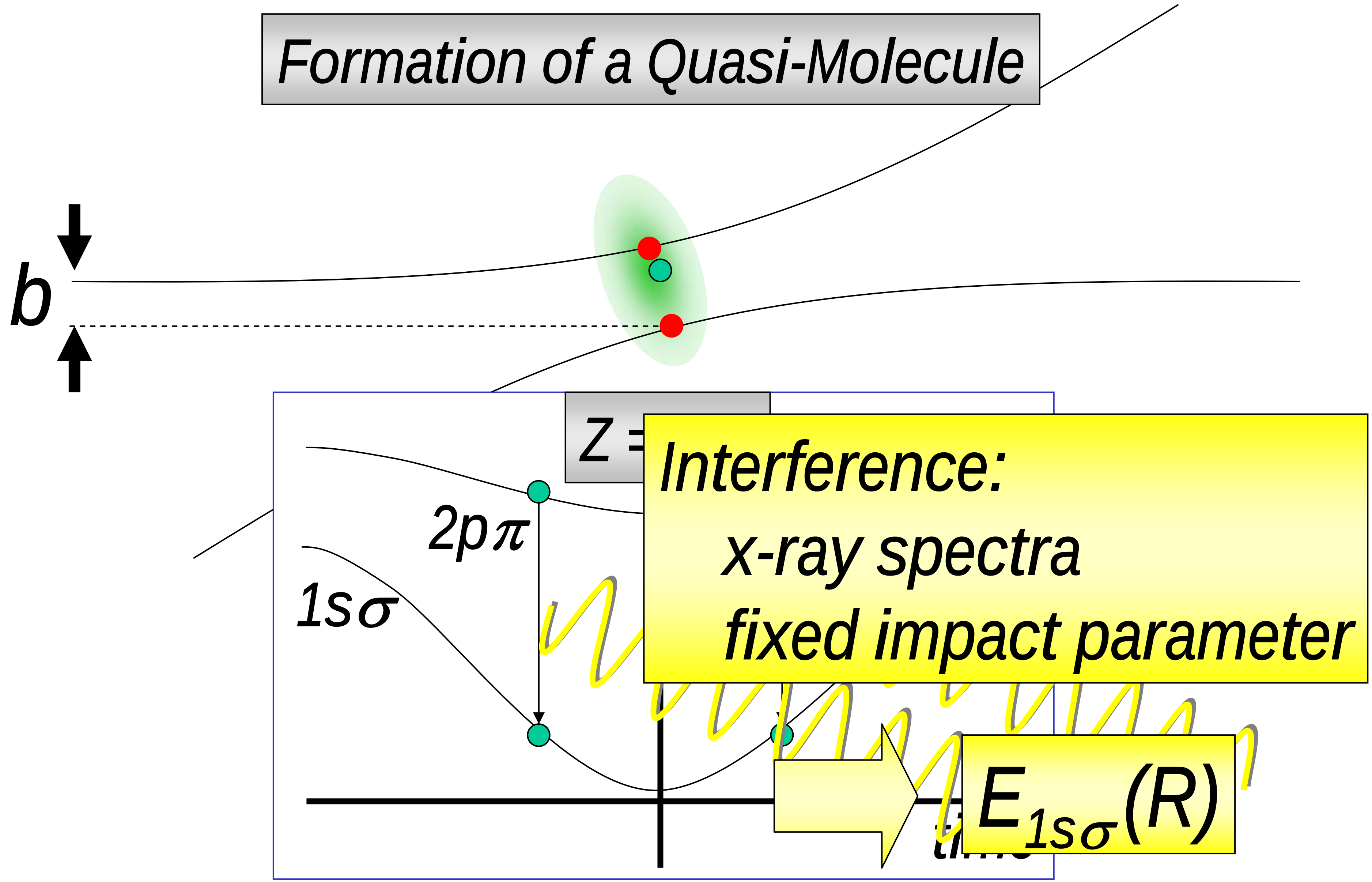


What about super-critical fields ?

Supercritical fields

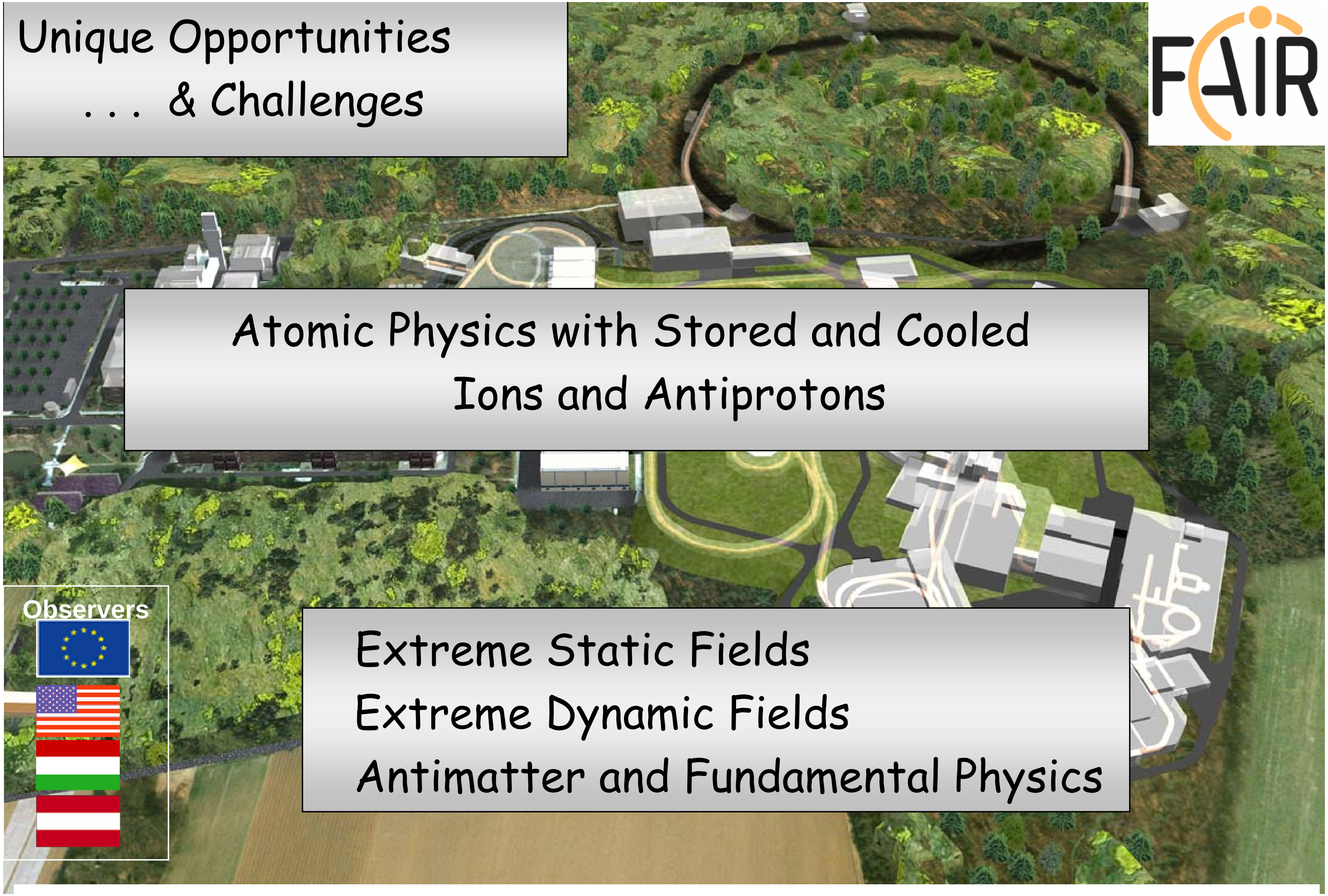


Supercritical fields



Unique Opportunities
. . . & Challenges

FAIR



Atomic Physics with Stored and Cooled Ions and Antiprotons

Extreme Static Fields
Extreme Dynamic Fields
Antimatter and Fundamental Physics

Observers

CN DE ES FI FR GB GR IN IT PL RO RU SE