

# Journées FAIR-France

## Quantum Electrodynamics tests in strong field with heavy ions



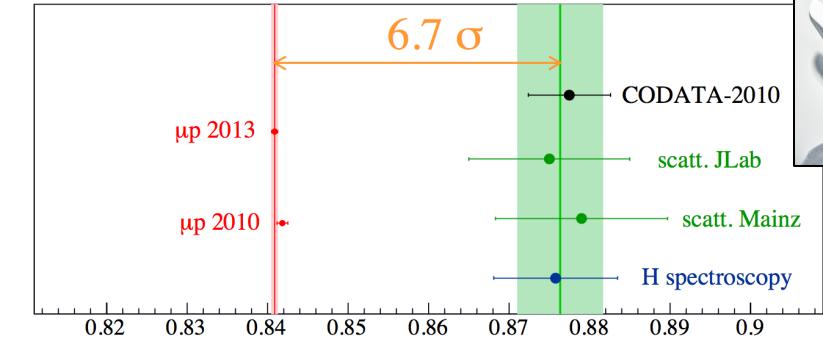
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INSTITUT  
FÜR PHYSIK



# Quantum electrodynamics tests in atomic systems: open questions

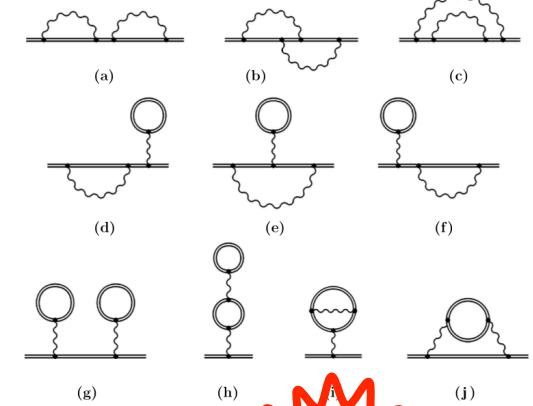


## Proton radius puzzle

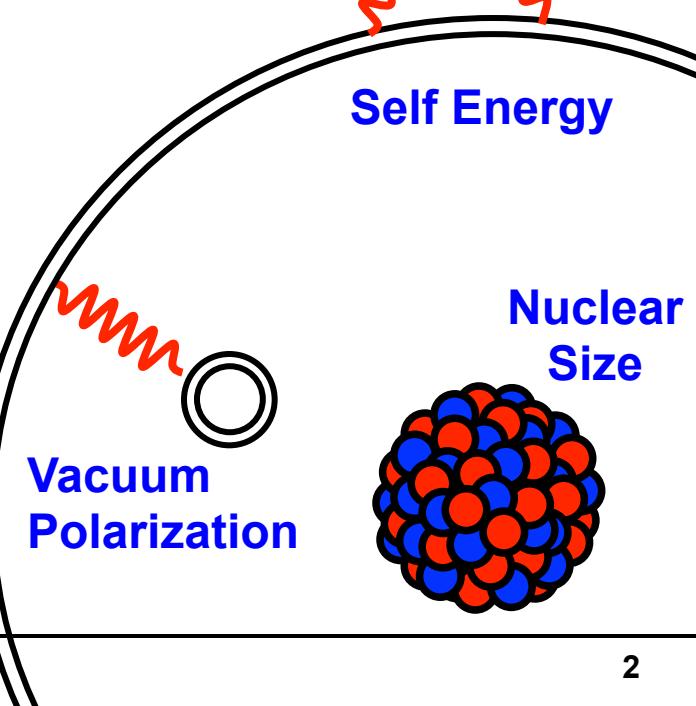
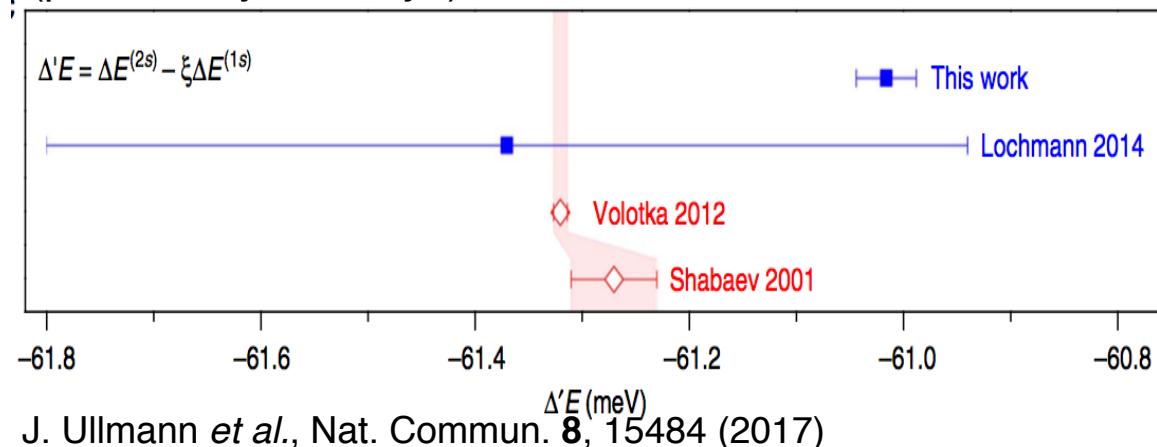


A. Antognini *et al.*, Science **339**, 417-420 (2013)  
R. Pohl *et al.*, Nature **466**, 213-216 (2010)

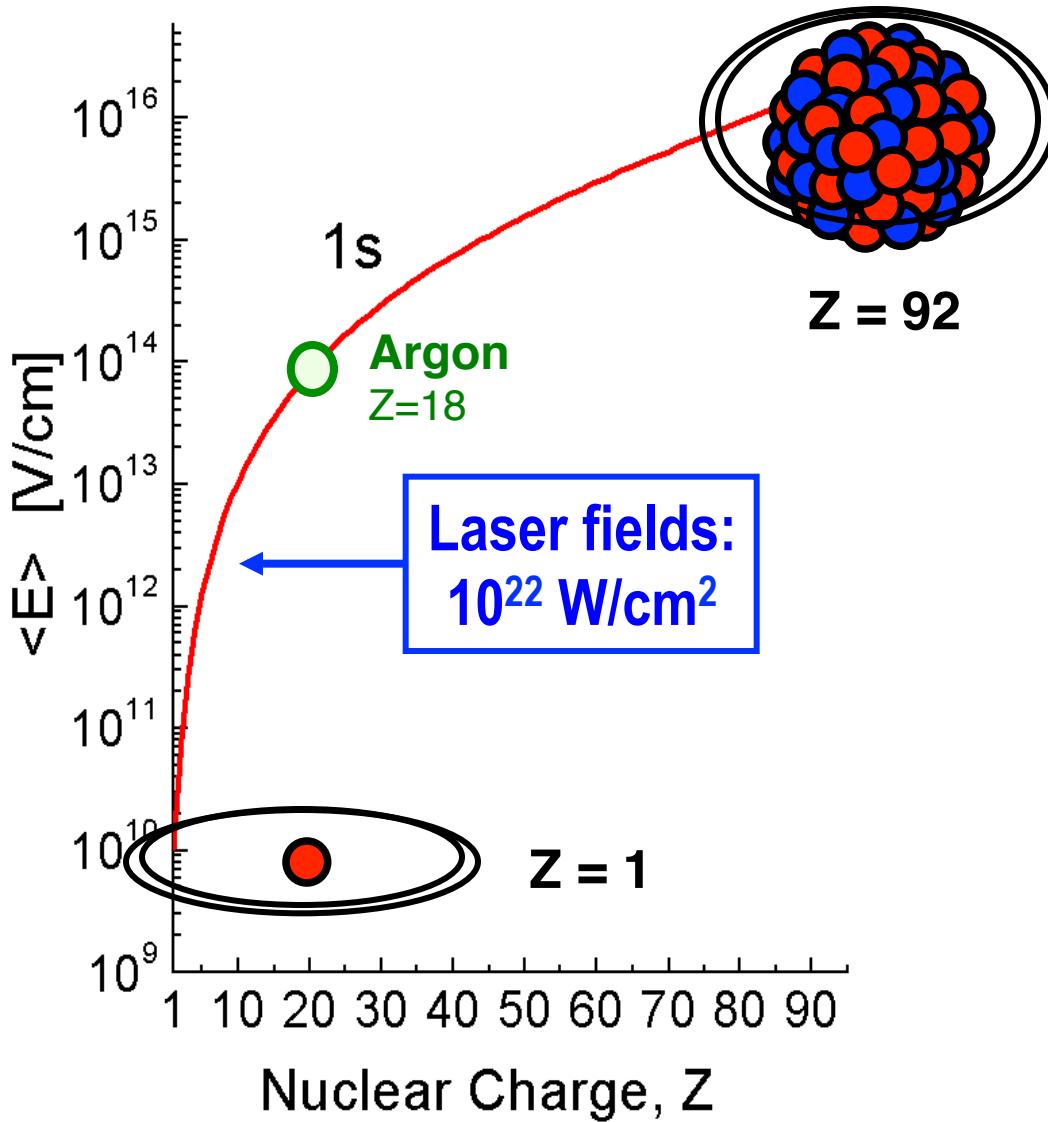
## 2<sup>nd</sup> order QED contributions



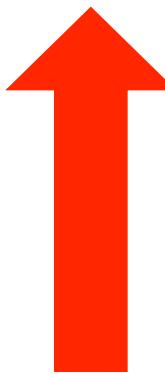
## Hyperfine structure of H- and Li-like Bismuth (published yesterday!!)



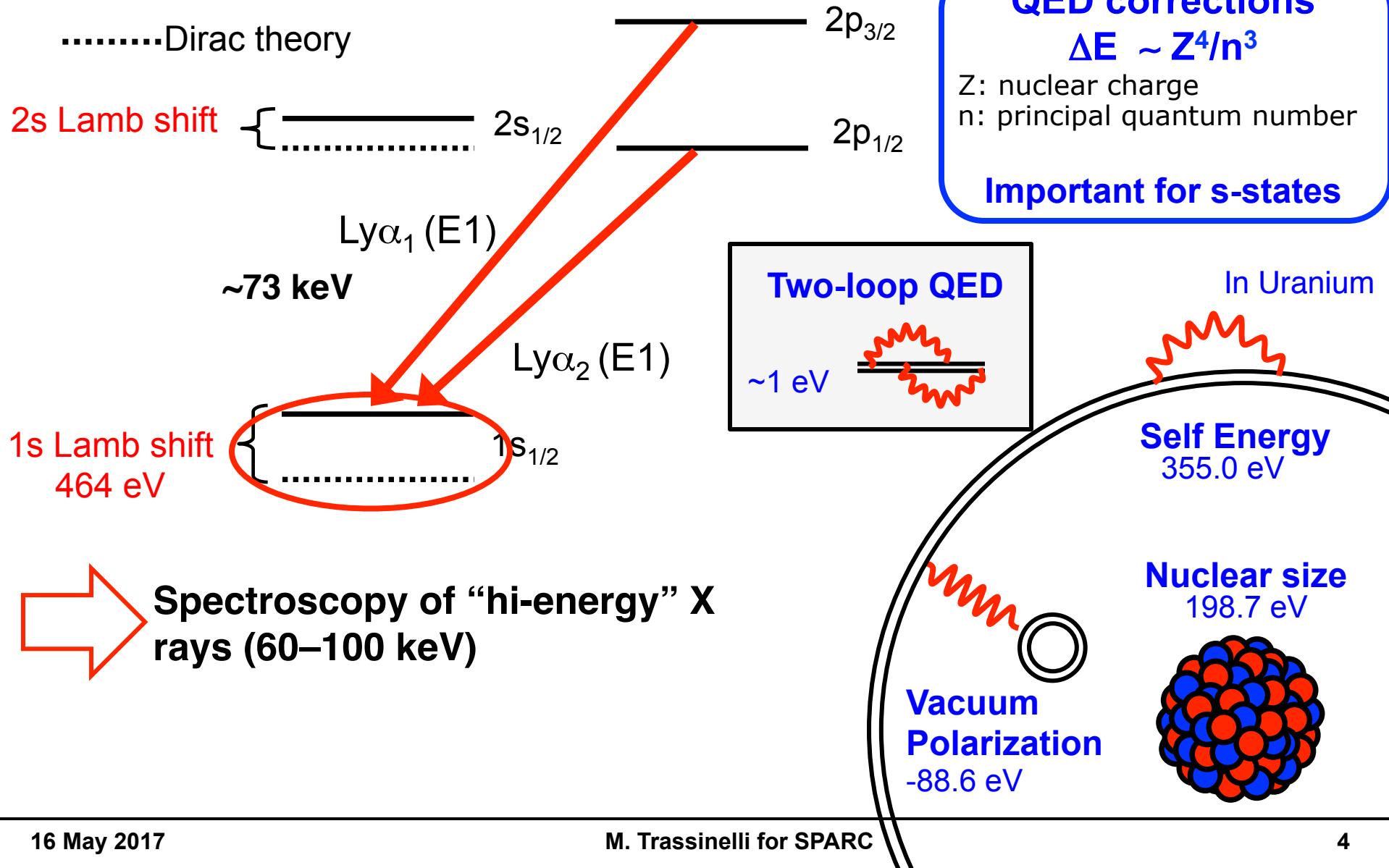
# Atomic Physics in Extremely Strong Coulomb Fields



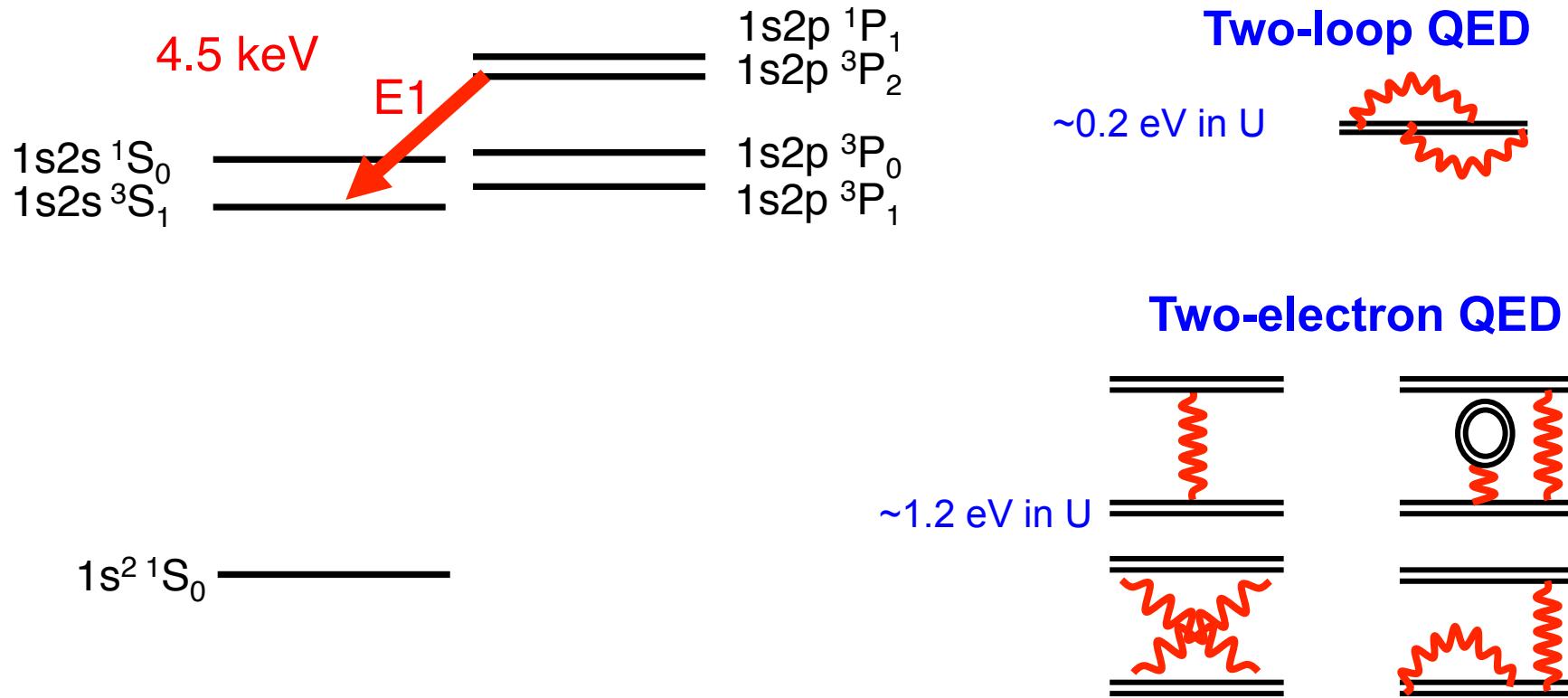
**H-like Uranium**  
 $\Delta E_{\text{QED}} \approx 500 \text{ eV}$   
 $Z \cdot \alpha \approx 1$   
**Non perturbative in  $Z\alpha$**

  
**Hydrogen**  
 $\Delta E_{\text{QED}} \approx 10^{-6} \text{ eV}$   
 $Z \cdot \alpha \approx 10^{-2}$   
**Perturbative in  $\alpha$  and  $Z\alpha$**

# Atomic structure of H-like ions

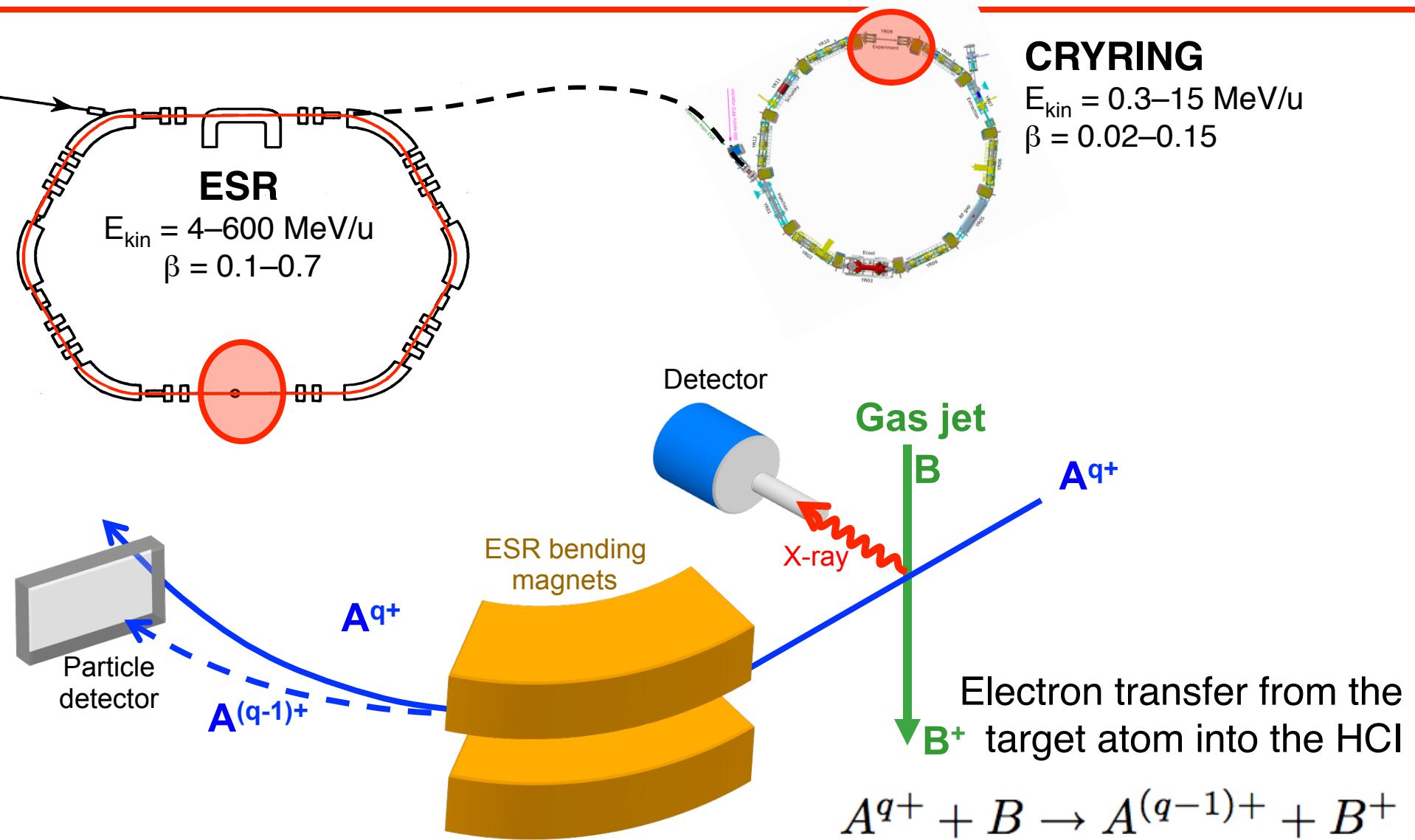


# Atomic structure of He-like ions

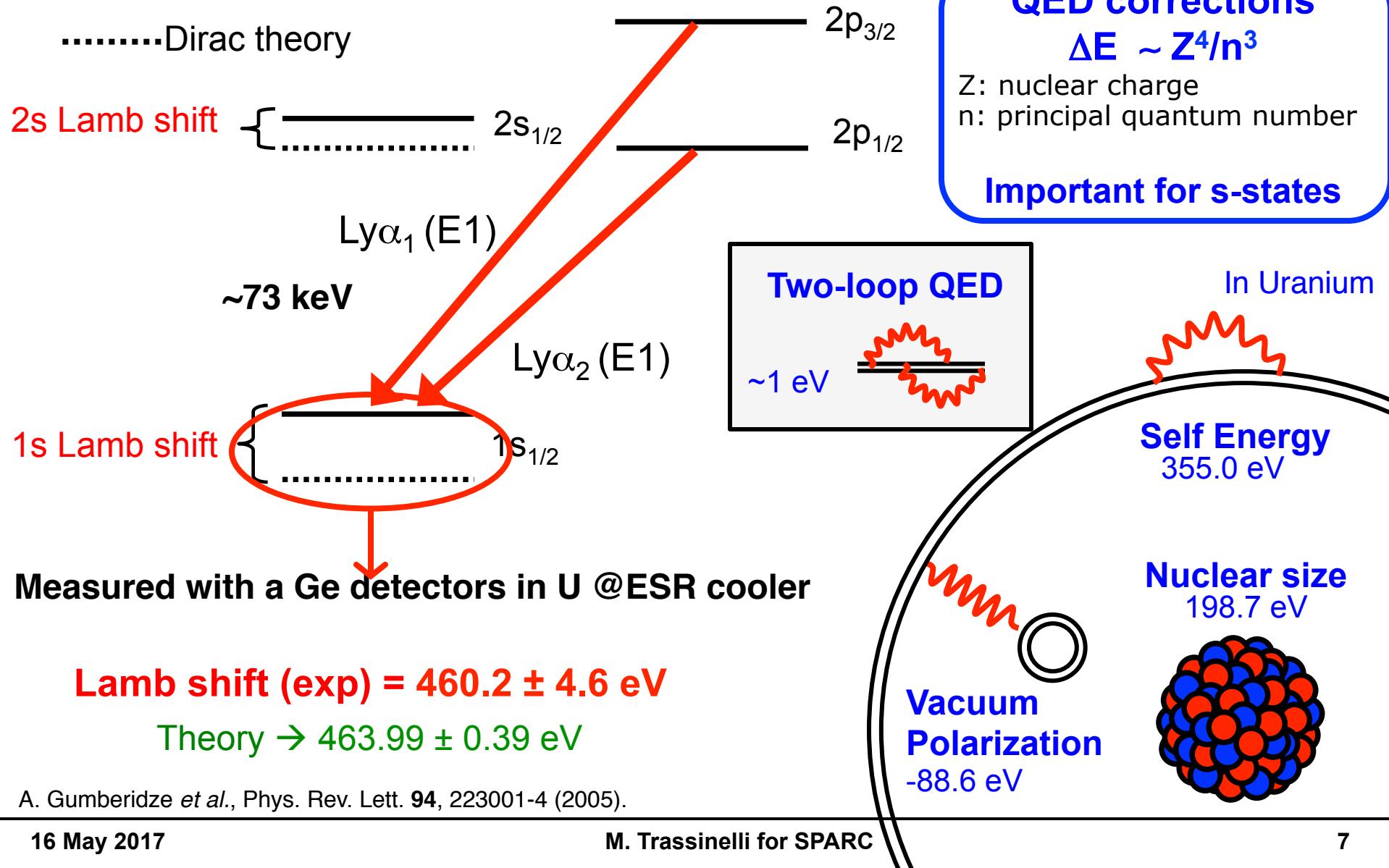


**Spectroscopy of “low-energy”  
X rays (few keVs)**

# Experiments at the gas jet-target



# Atomic structure of H-like ions

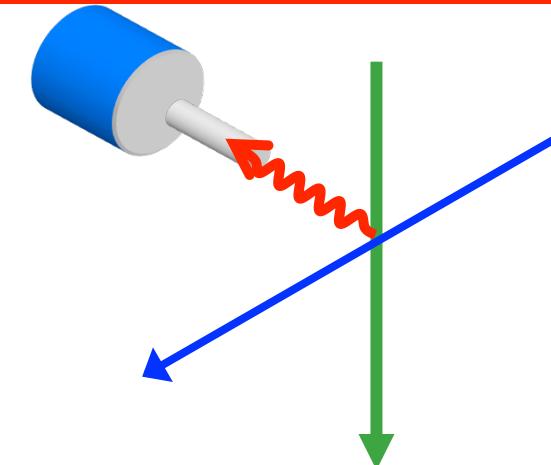
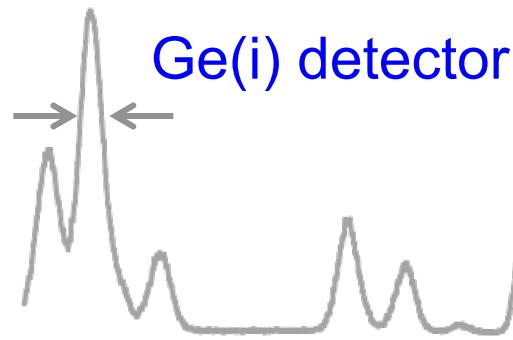


# Towards an accuracy of 1 eV of the 1s level Lamb shift



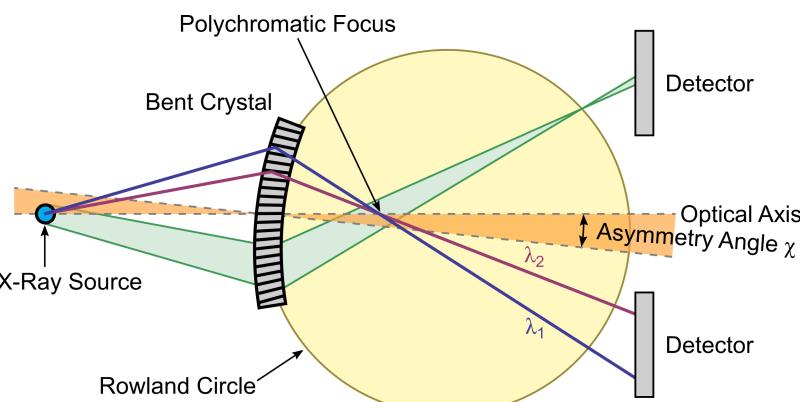
Resolution:  
**400 eV at 60 keV**

$$\epsilon = 10^{-4}$$



## Crystal spectroscopy

Res:  $\sim 50$  eV at 60 keV  $\epsilon = 10^{-8}$

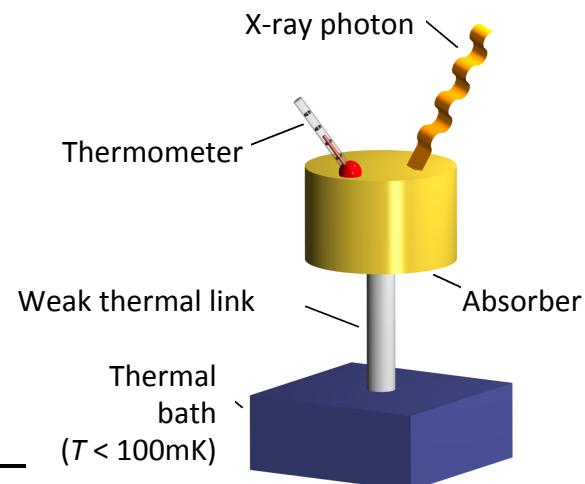


## FOCAL spectrometer

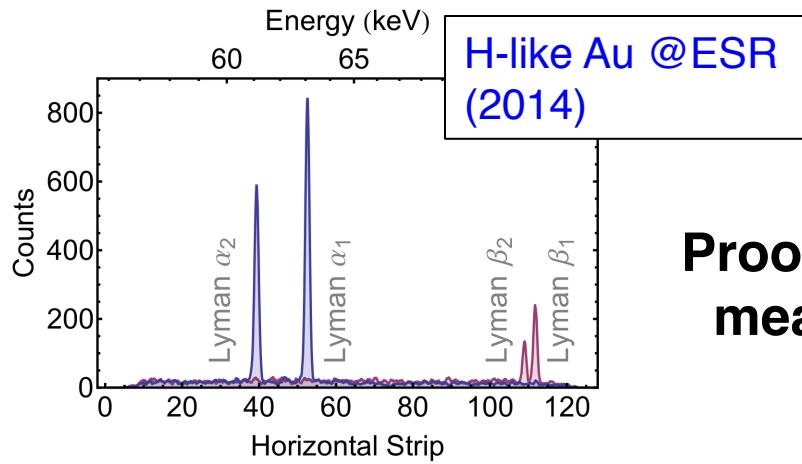
T. Gassner, M.T. et al. in prep. for PRL

## Resistive and magnetic microcalorimeters

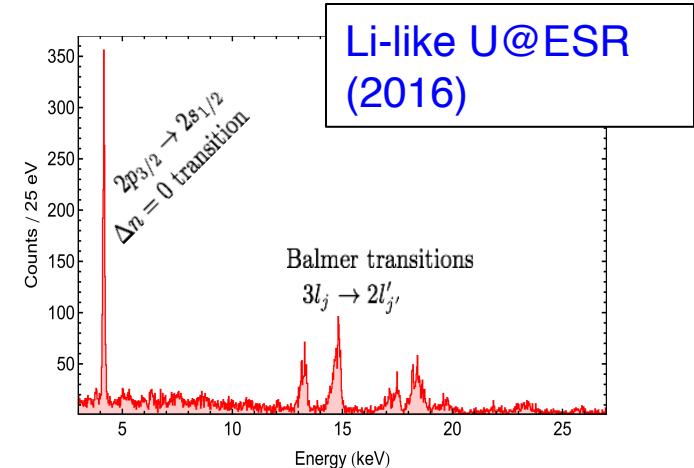
- S. Kraft-Bermuth *et al.*, J. Phys. B **50**, 055603 (2017)  
C. Pies *et al.*, J. Low Temp. Phys. **167**, 269-279 (2012)



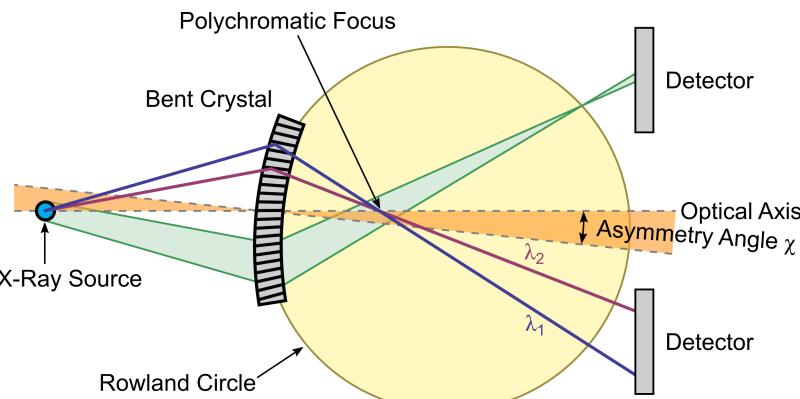
# Towards an accuracy of 1 eV of the 1s level Lamb shift



## Proof of principle measurements



**Crystal spectroscopy**  
Res:  $\sim 50$  eV at 60 keV  $\epsilon = 10^{-8}$

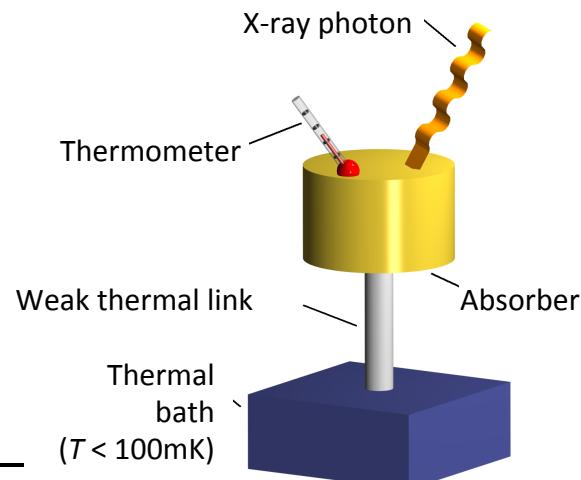


**FOCAL spectrometer**  
T. Gassner, M.T. et al. in prep. for PRL

**Microcalorimeters**  
Res:  $\sim 50$  eV at 60 keV  $\epsilon = 10^{-4-6}$

## Resistive and magnetic microcalorimeters

- S. Kraft-Bermuth *et al.*, J. Phys. B **50**, 055603 (2017)  
C. Pies *et al.*, J. Low Temp. Phys. **167**, 269-279 (2012)



# Towards an accuracy of 1 eV of the 1s level Lamb shift

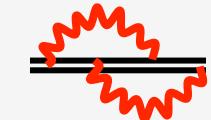


New proposal for FAIR phase 0 2018-19

Accuracy goal < 0.5 eV

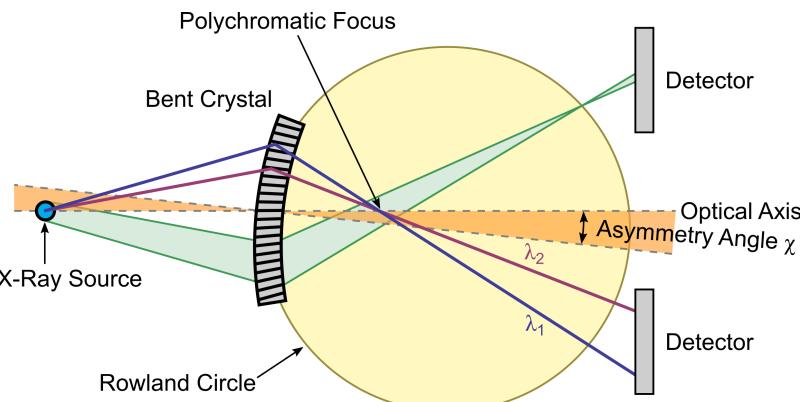
Two-loop QED

~1 eV



## Crystal spectroscopy

Res: ~50 eV at 60 keV  $\epsilon = 10^{-8}$



## FOCAL spectrometer

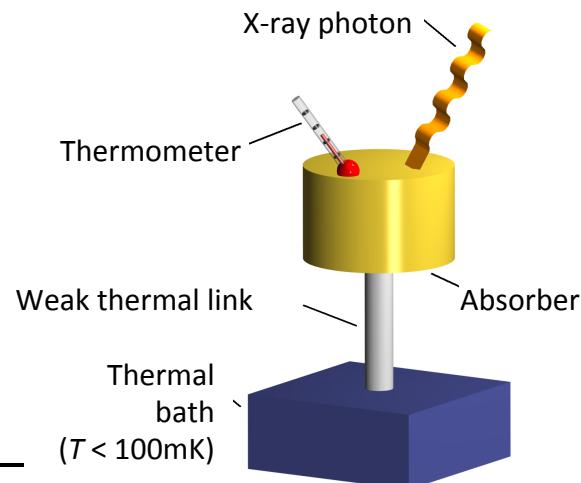
T. Gassner, M.T. et al. in prep. for PRL

## Microcalorimeters

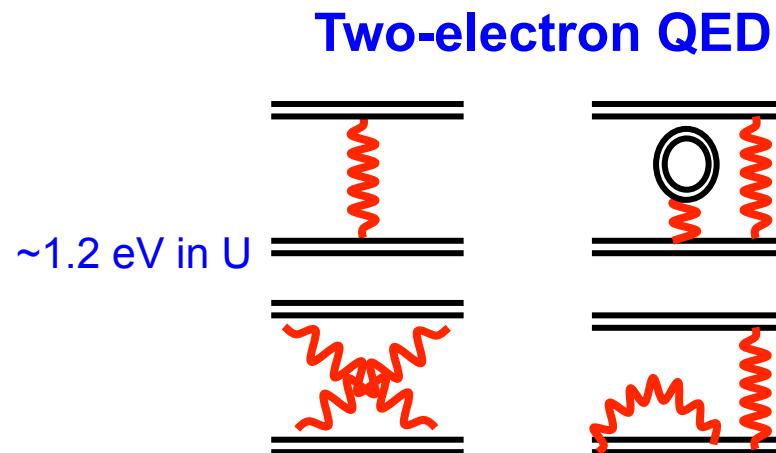
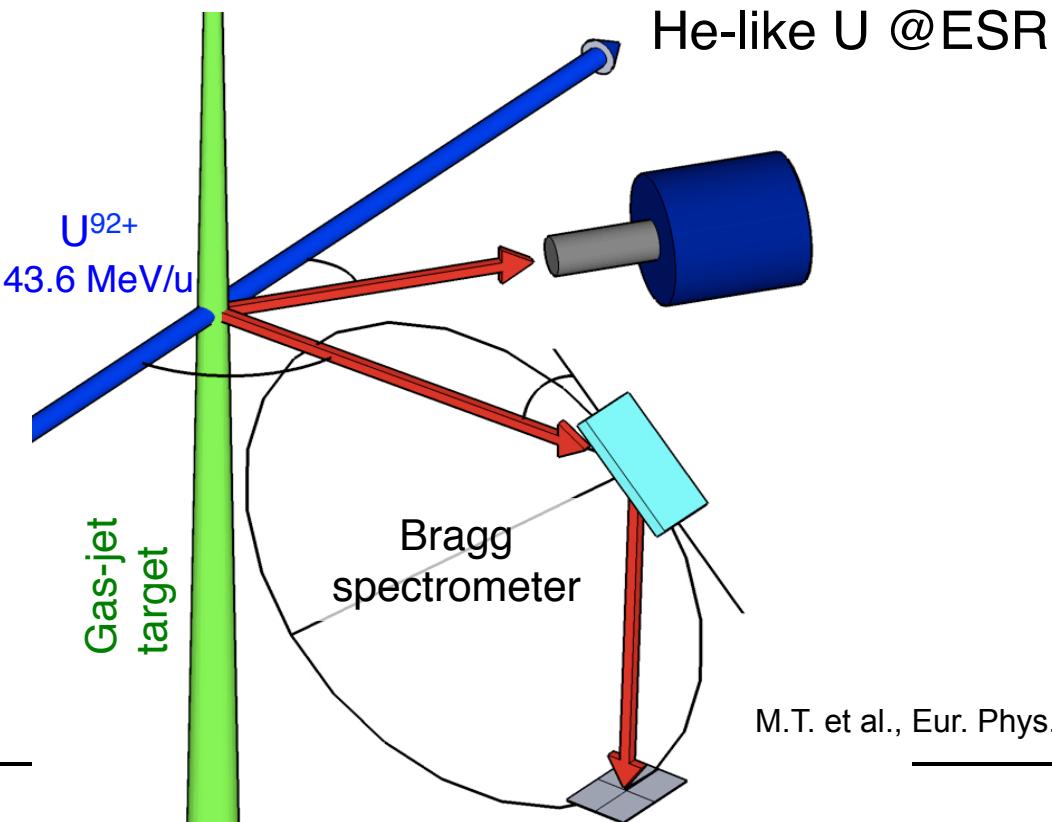
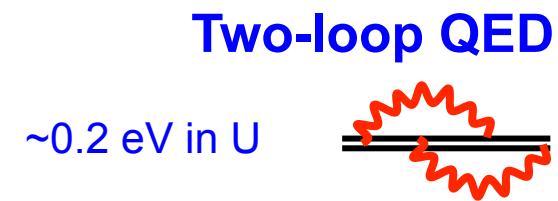
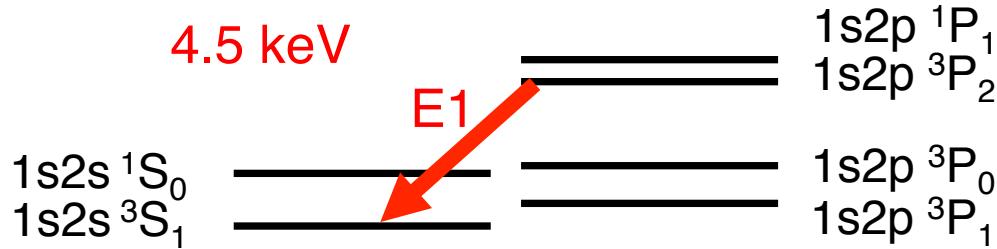
Res: ~50 eV at 60 keV  $\epsilon = 10^{-4-6}$

## Resistive and magnetic microcalorimeters

- S. Kraft-Bermuth *et al.*, J. Phys. B **50**, 055603 (2017)  
C. Pies *et al.*, J. Low Temp. Phys. **167**, 269-279 (2012)

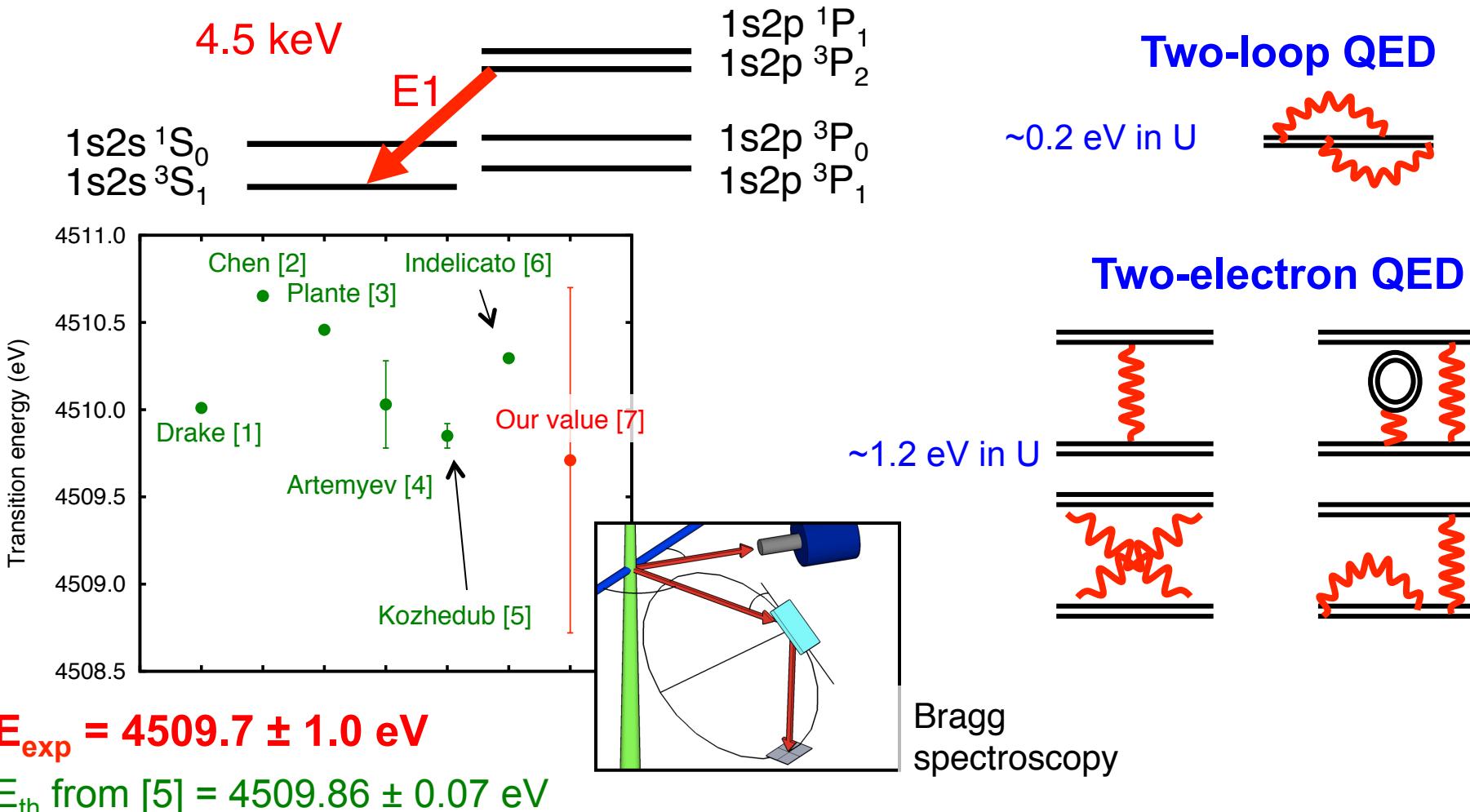


# Atomic structure of He-like ions



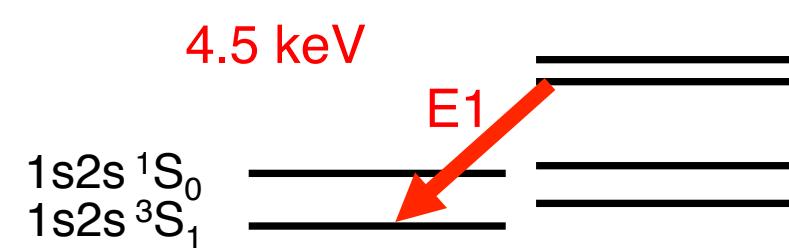
M.T. et al., Eur. Phys. Lett. **87**, 63001 (2009)

# Atomic structure of He-like ions



- [1] Drake, Can. J. Phys. **66**, 586 (1988), [2] Chen et al., Phys. Rev. A **47**, 3692 (1993),
- [3] Plante et al., Phys. Rev. A **49**, 3519 (1994), [4] Artemyev et al., Phys. Rev. A **71**, 062104 (2005),
- [5] Kozhedub and Shabaev, unpublished (2008), [6] Indelicato, unpublished (2008),
- [7] M.T. et al., Eur. Phys. Lett. **87**, 63001 (2009), Trassinelli et al., Phys. Scr. **T144**, 014003 (2011)

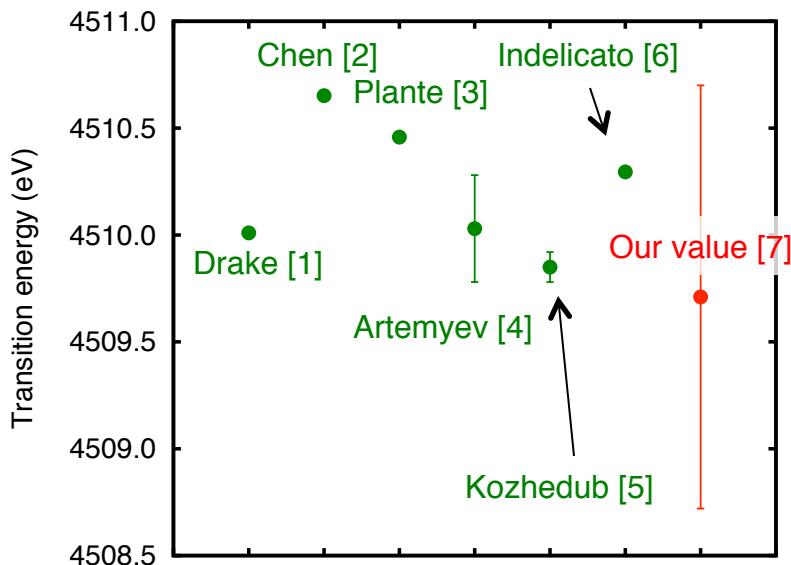
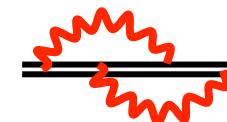
# Atomic structure of He-like ions



$1s2p\ ^1P_1$   
 $1s2p\ ^3P_2$   
 $1s2p\ ^3P_0$   
 $1s2p\ ^3P_1$

Two-loop QED

$\sim 0.2 \text{ eV in U}$

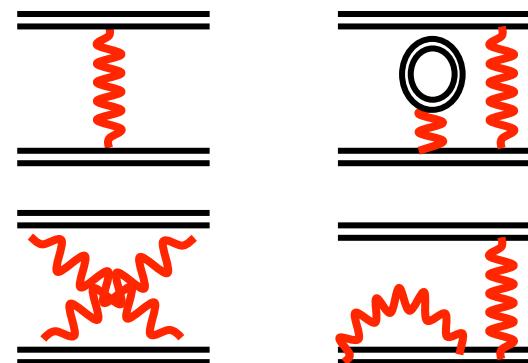


$$E_{\text{exp}} = 4509.7 \pm 1.0 \text{ eV}$$

$$E_{\text{th}} \text{ from [5]} = 4509.86 \pm 0.07 \text{ eV}$$

$\sim 1.2 \text{ eV in U}$

Two-electron QED



New proposal for FAIR phase 0 2018-19

Accuracy goal  $< 0.05 \text{ eV}$

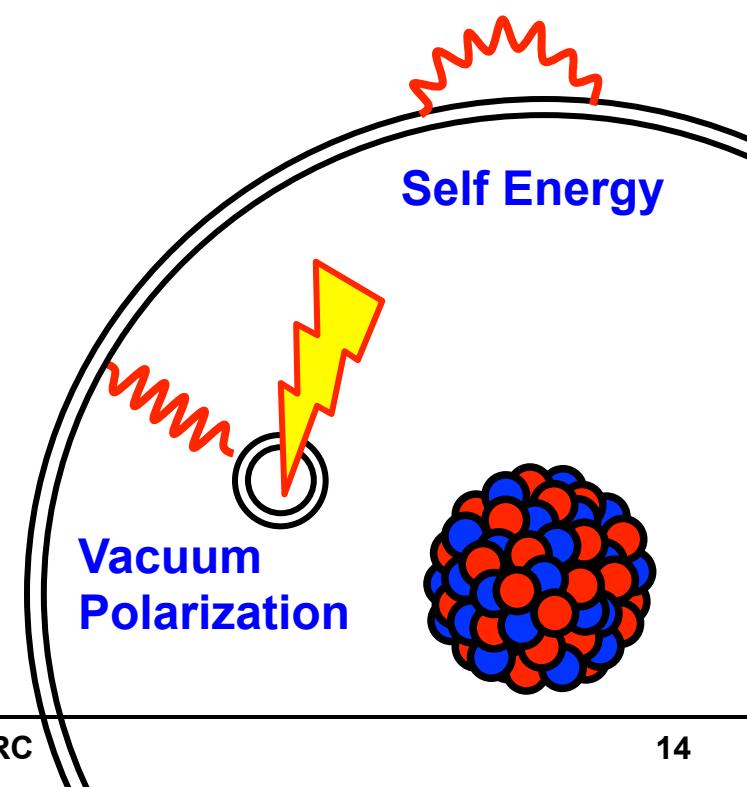
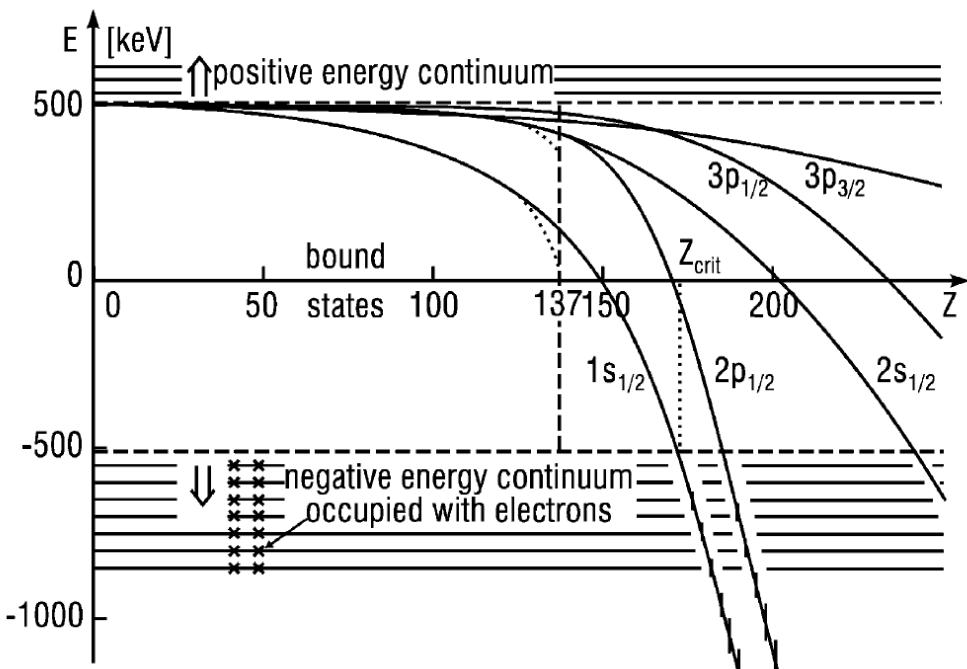
- [1] Drake, Can. J. Phys. **66**, 586 (1988), [2] Chen et al., Phys. Rev. A **47**, 3692 (1993),
- [3] Plante et al., Phys. Rev. A **49**, 3519 (1994), [4] Artemyev et al., Phys. Rev. A **71**, 062104 (2005),
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- [7] M.T. et al., Eur. Phys. Lett. **87**, 63001 (2009), Trassinelli et al., Phys. Scr. **T144**, 014003 (2011)

# Supercritical fields

Dirac equation:  $E_{1s} = mc^2 \sqrt{1 - (Z\alpha)^2}$

$Z > 1/\alpha = 137 \rightarrow$  electron/positron pair creation

Finite nucleus size  $\rightarrow Z_{\text{crit}} = 173$

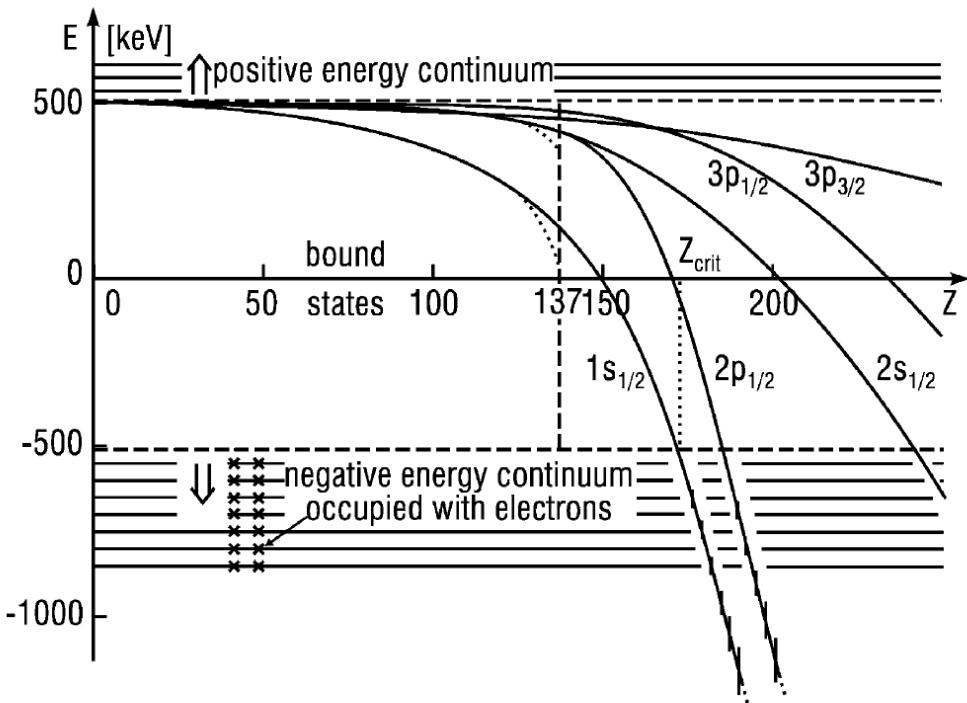


# Supercritical fields

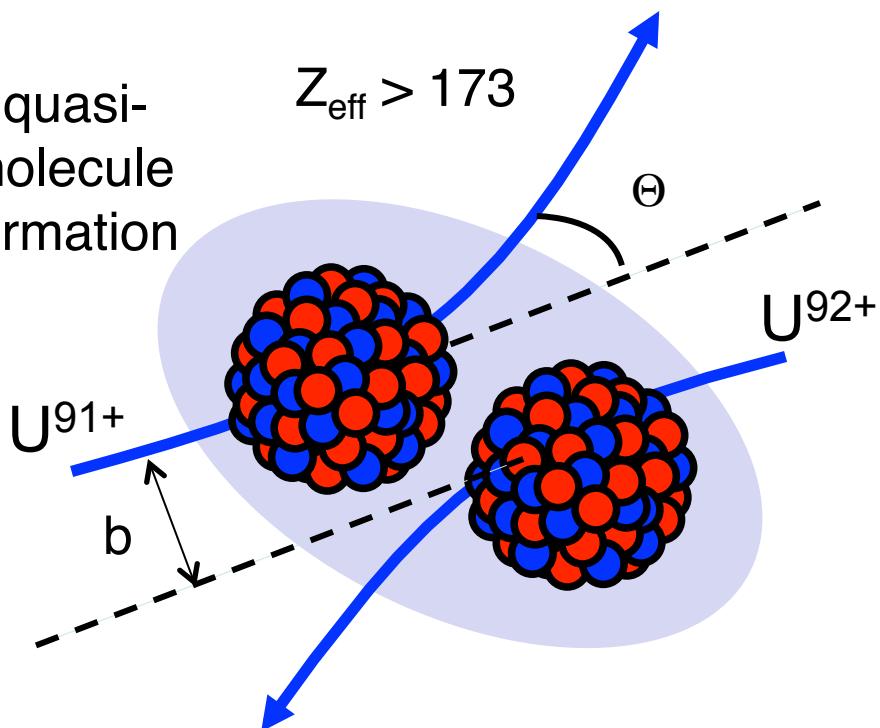
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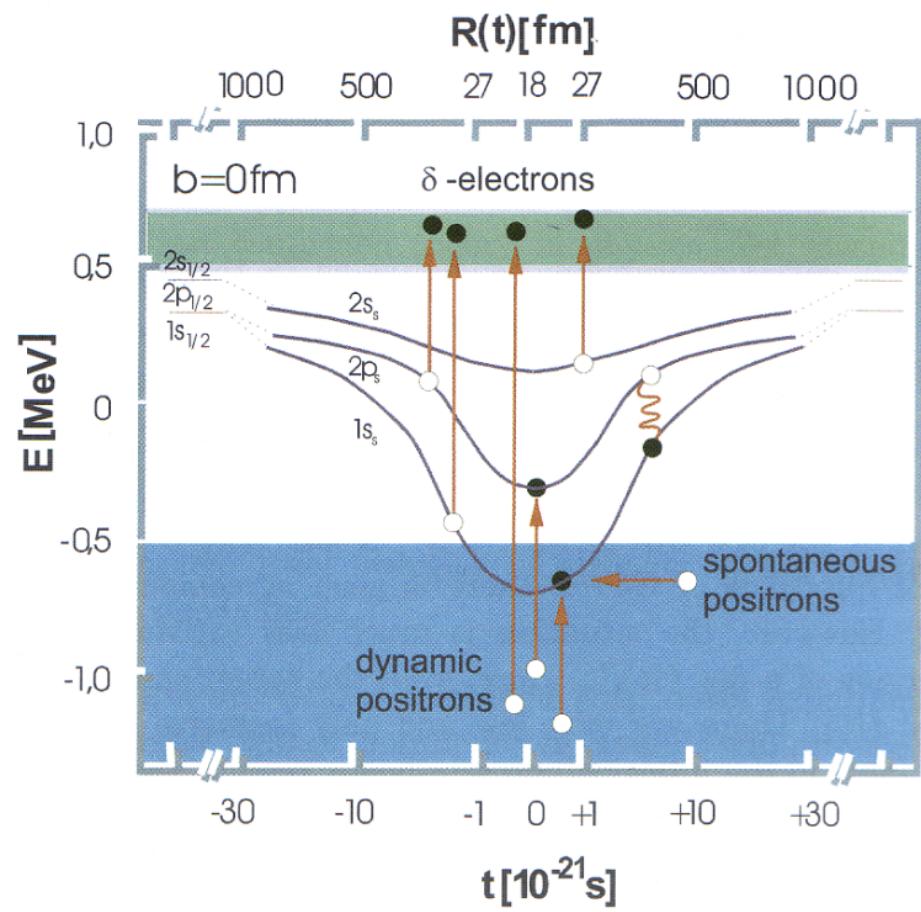
Finite nucleus size  $\rightarrow Z_{\text{crit}} = 173$



quasi-molecule formation

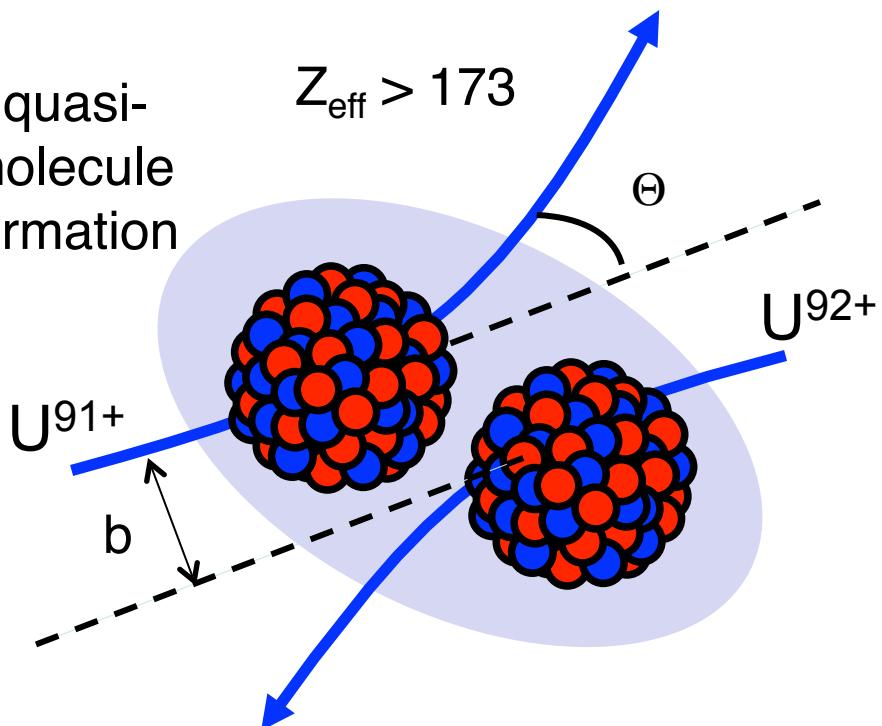


# Supercritical Fields: formation of super heavy quasi-molecules

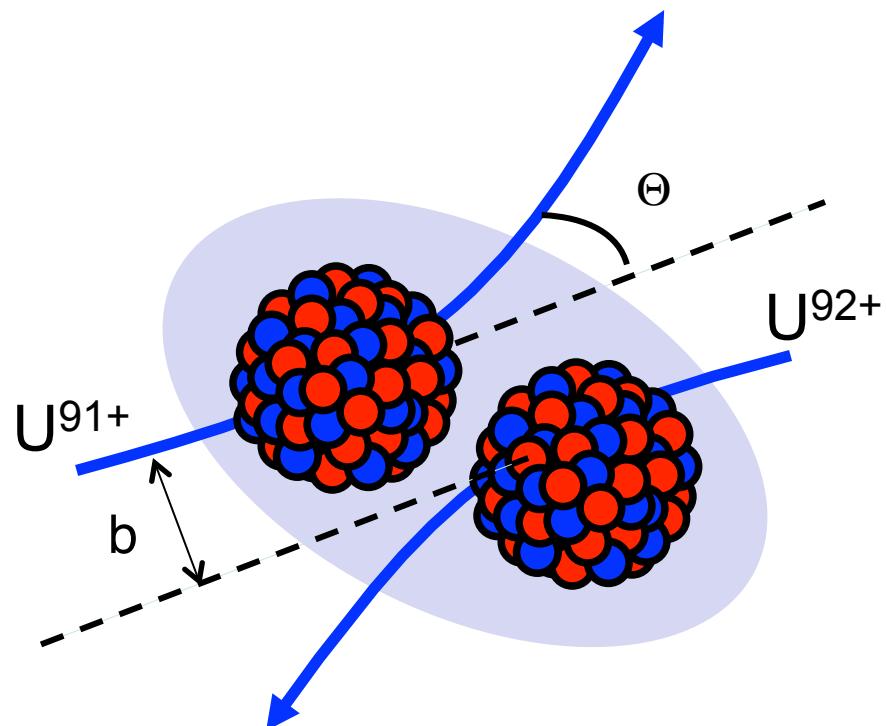
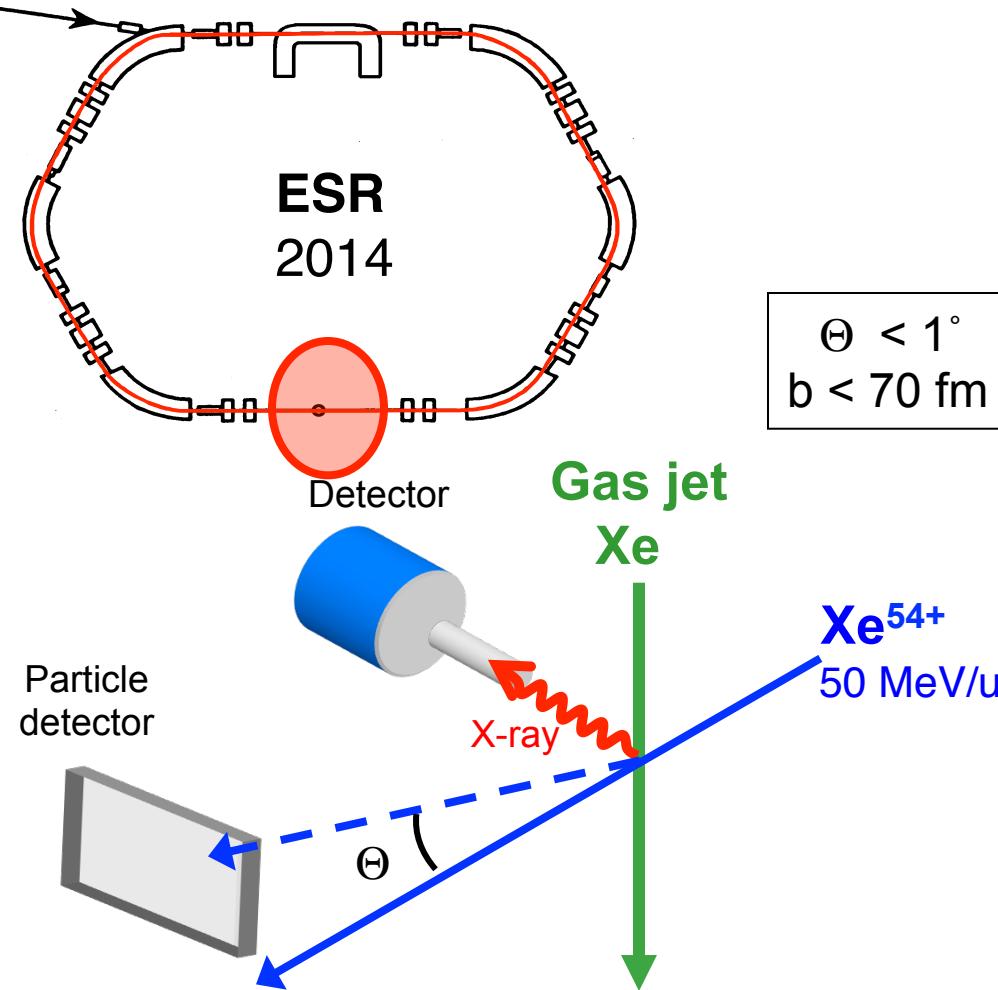


Slow ion – ion collision  
 $\sim 5 \text{ MeV/u}$

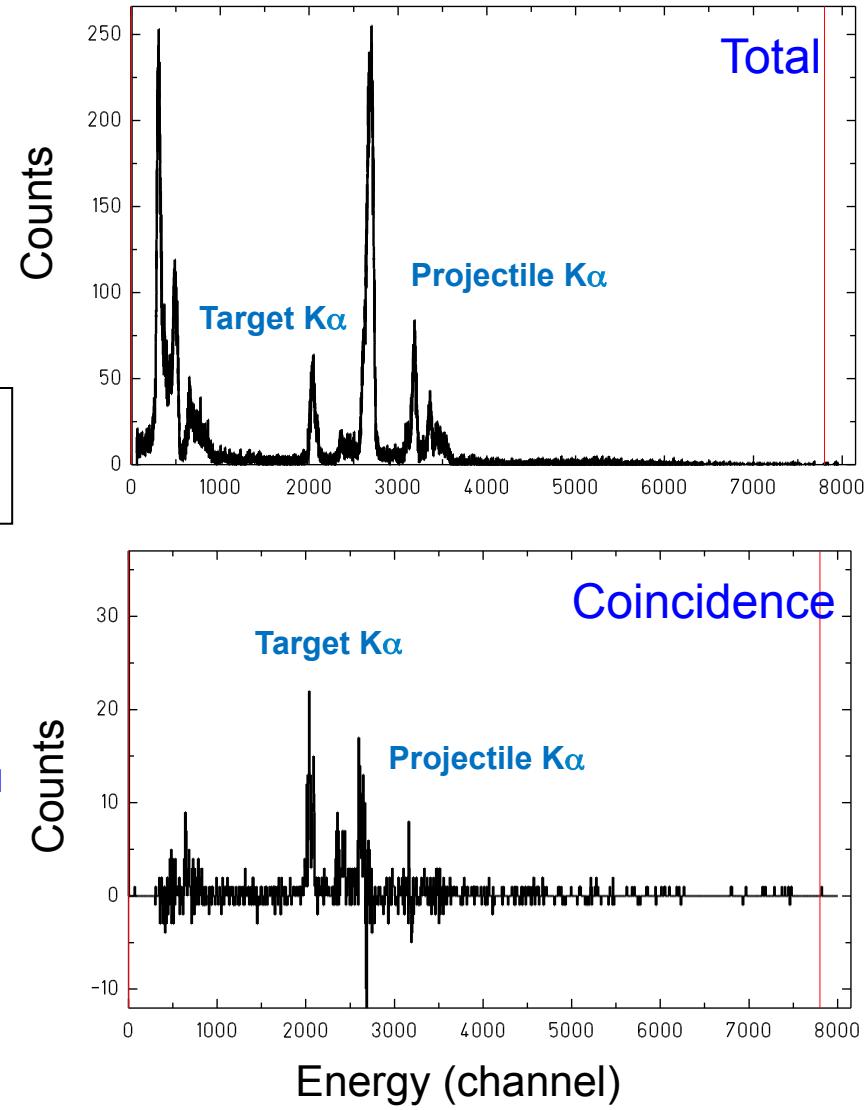
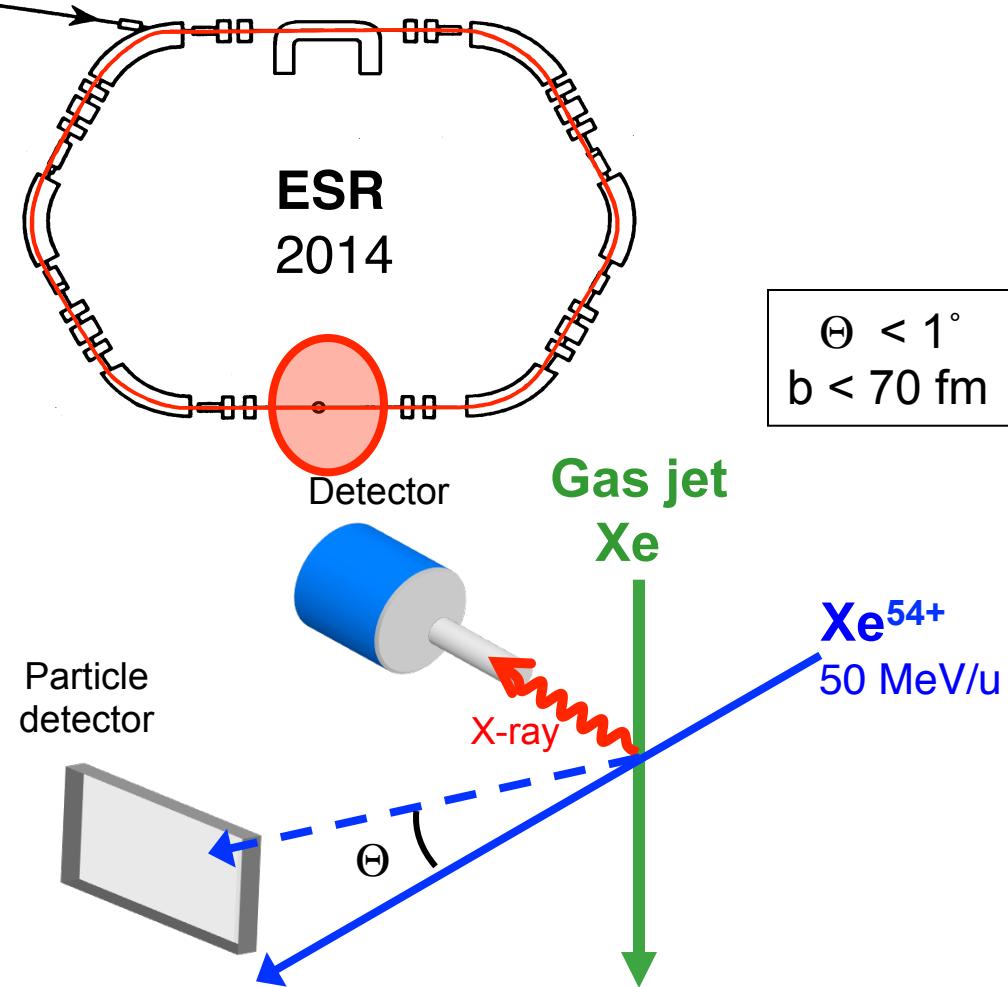
quasi-molecule formation



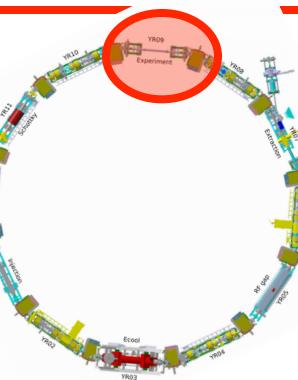
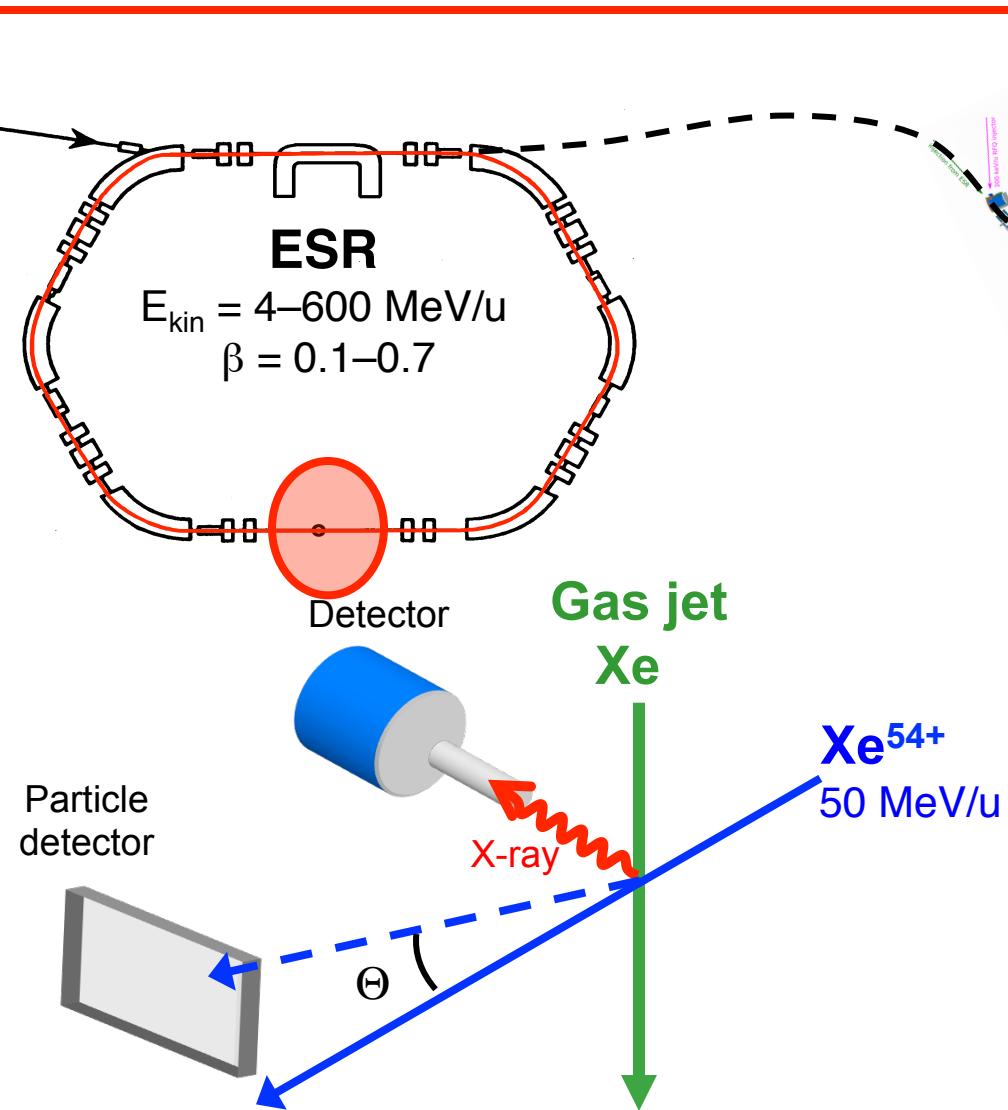
# First steps to supercritical fields



# First steps to supercritical fields



# Experiments at the Jet-target



## CRYRING

$E_{\text{kin}} = 0.3\text{--}15 \text{ MeV/u}$   
 $\beta = 0.02\text{--}0.15$

Much more adapted to produce quasi-molecular states ( $\sim 5 \text{ MeV/u}$ )

New experiments coming at  
CRYRING@FAIR

+ FISIC?

Real ion–ion collisions !!

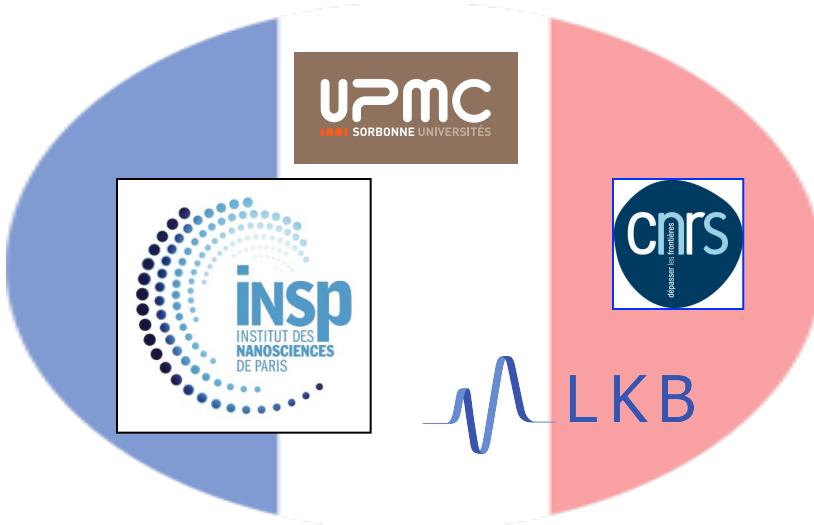
# Quantum electrodynamics tests in atomic systems



- Tests of QED at strong-coupling regime in H- and He-like ions
- Tests of QED at supercritical regime in quasi-molecules

New experiments at FAIR!!

# Thank you !!



**Stored Particles Atomic Physics Research**



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