Testing quantum electrodynamics at extreme fields in the heaviest few-electron atoms

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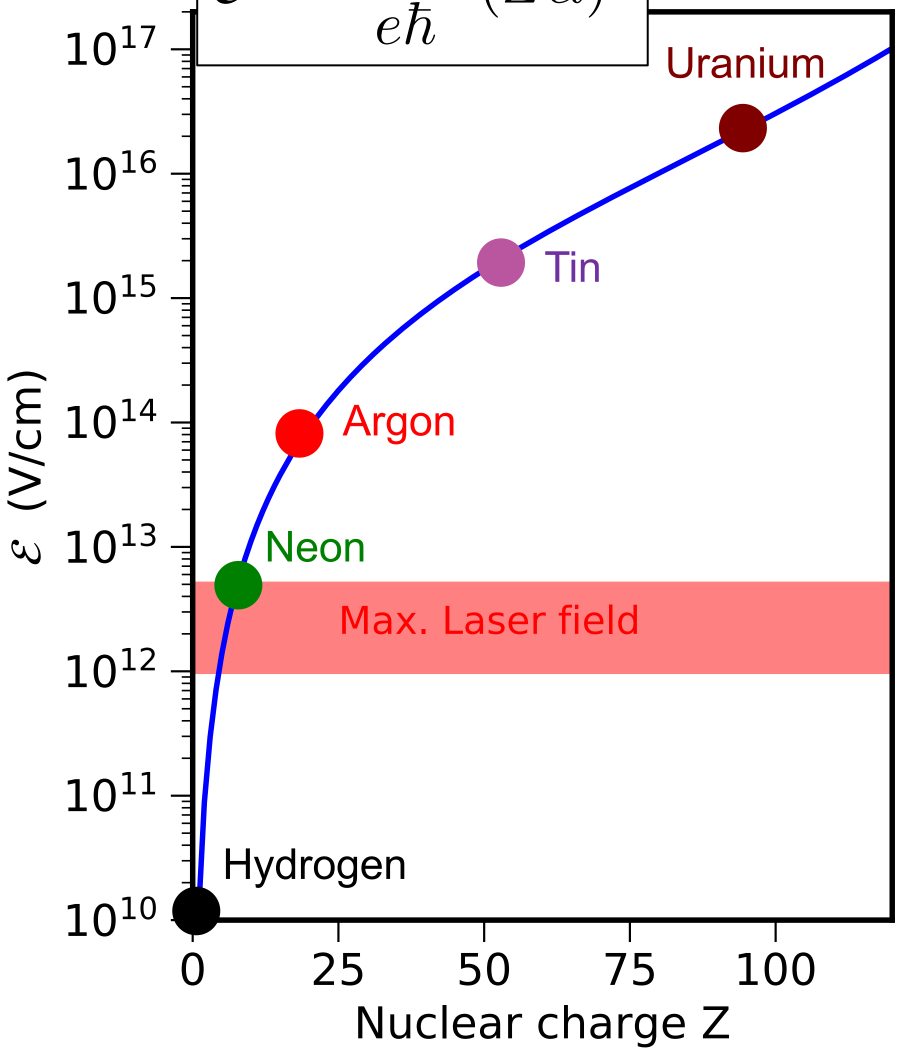
For the SPARC collaboration

PSAS 2024

Switzerland, 13 June 2024

Strong Coulomb field in highly charged ions

$$\mathcal{E} \sim \frac{m^2 c^3}{e\hbar}(Z\alpha)^3$$



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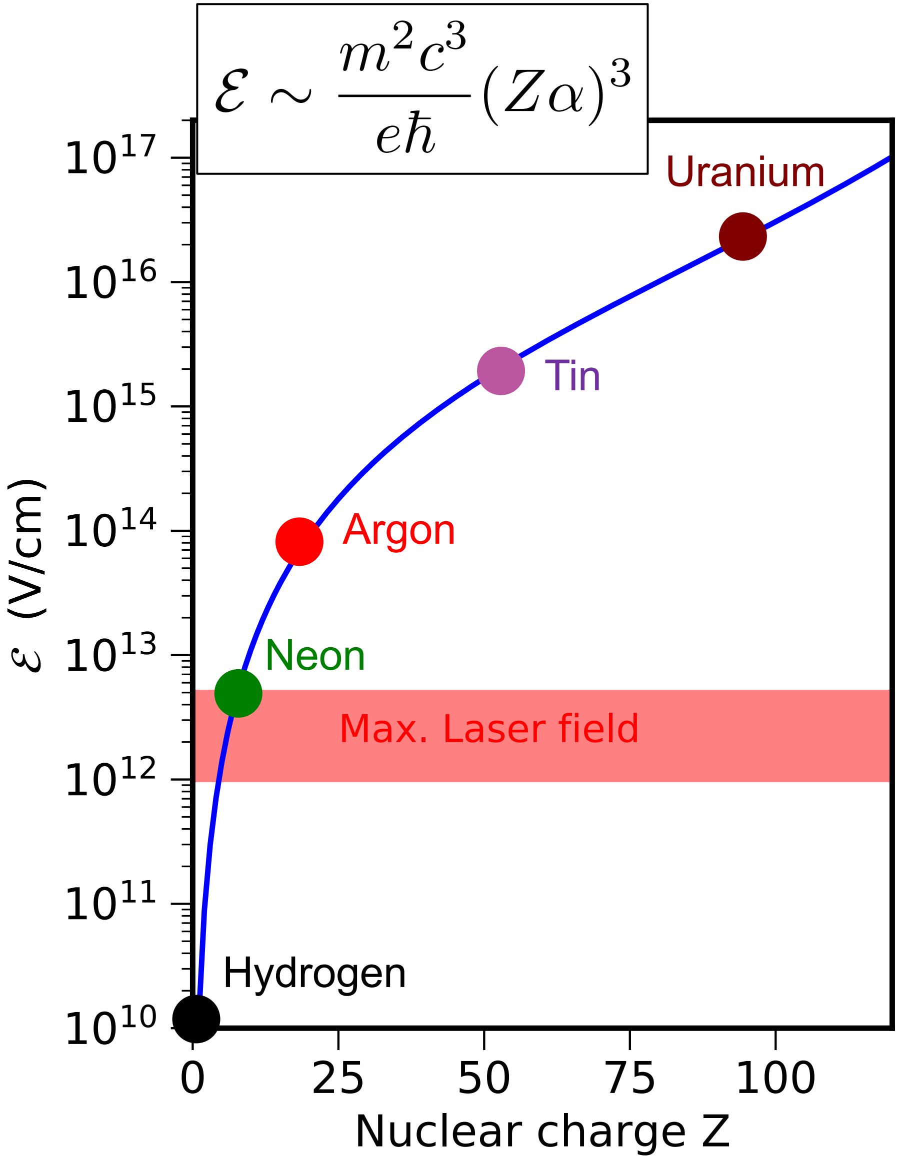
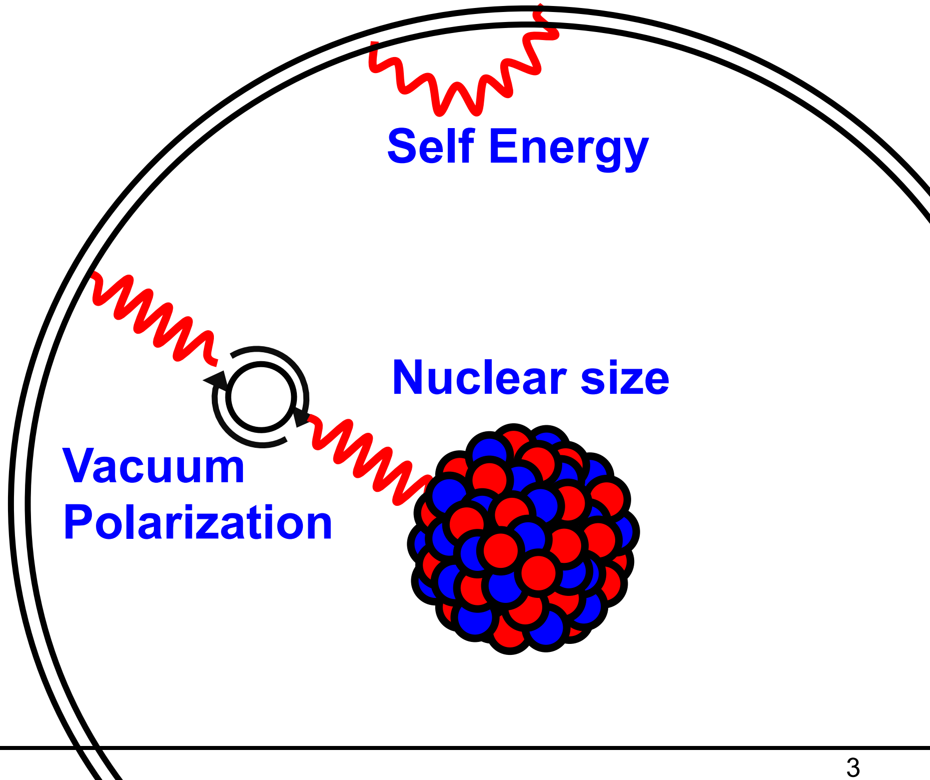


- Strong electric field
  → Quantum Electrodynamic effects enhanced



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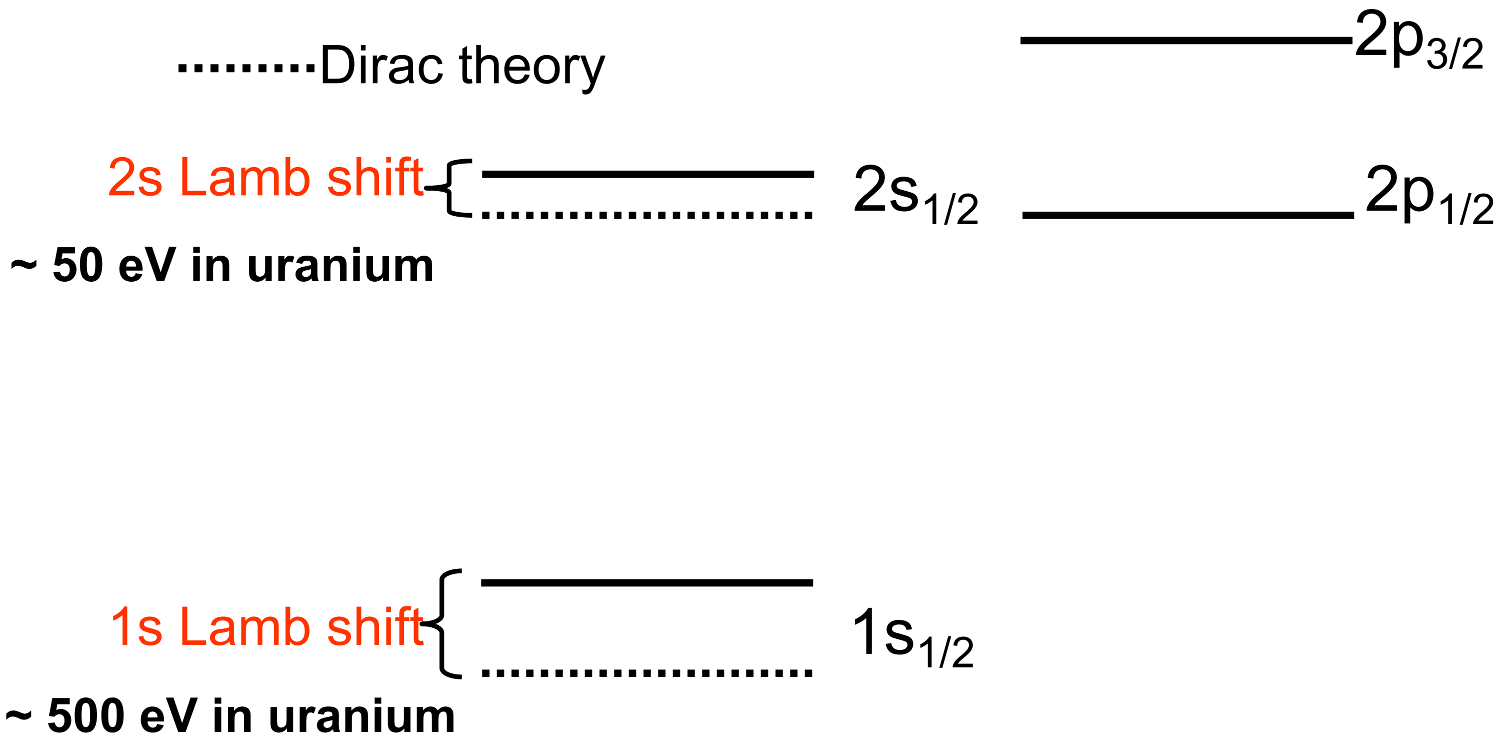


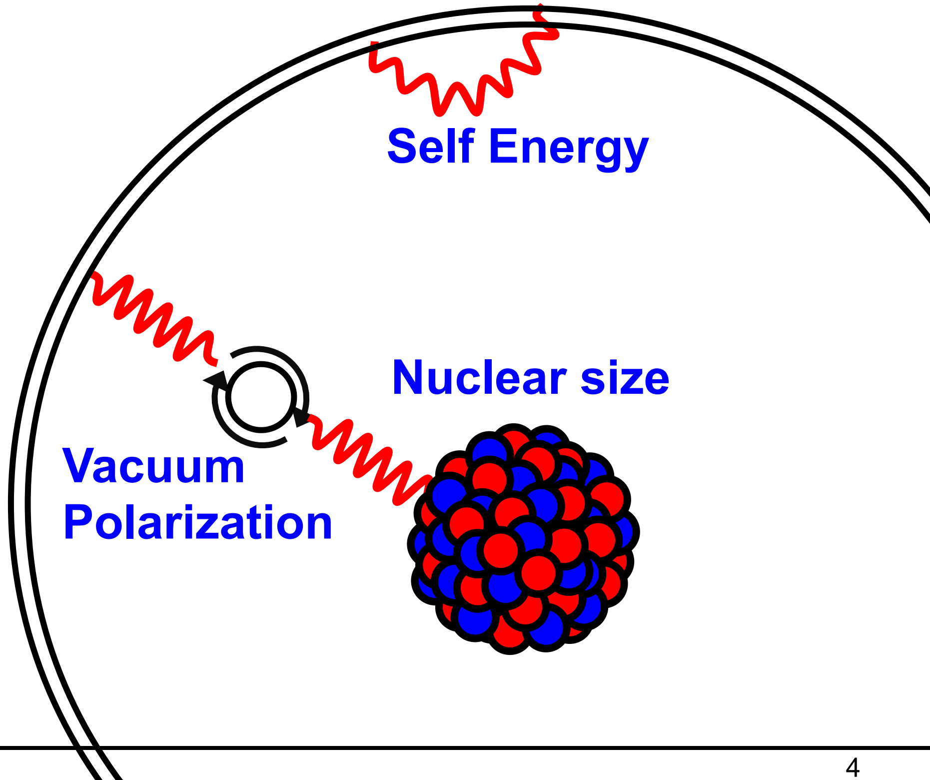
QED corrections

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

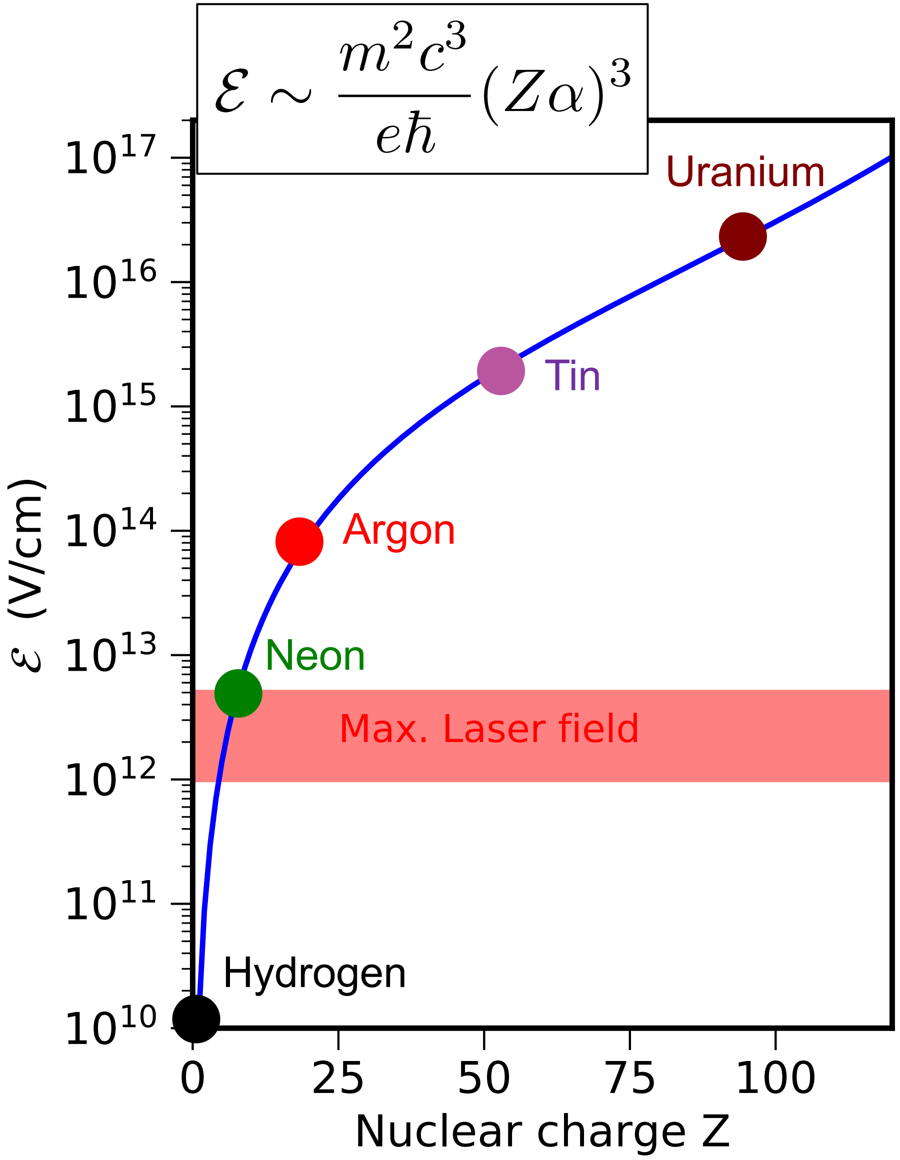
Z: nuclear charge
n: principal quantum number

Important for s-states

- Strong electric field
  → Quantum Electrodynamic effects enhanced



Strong Coulomb field in highly charged ions

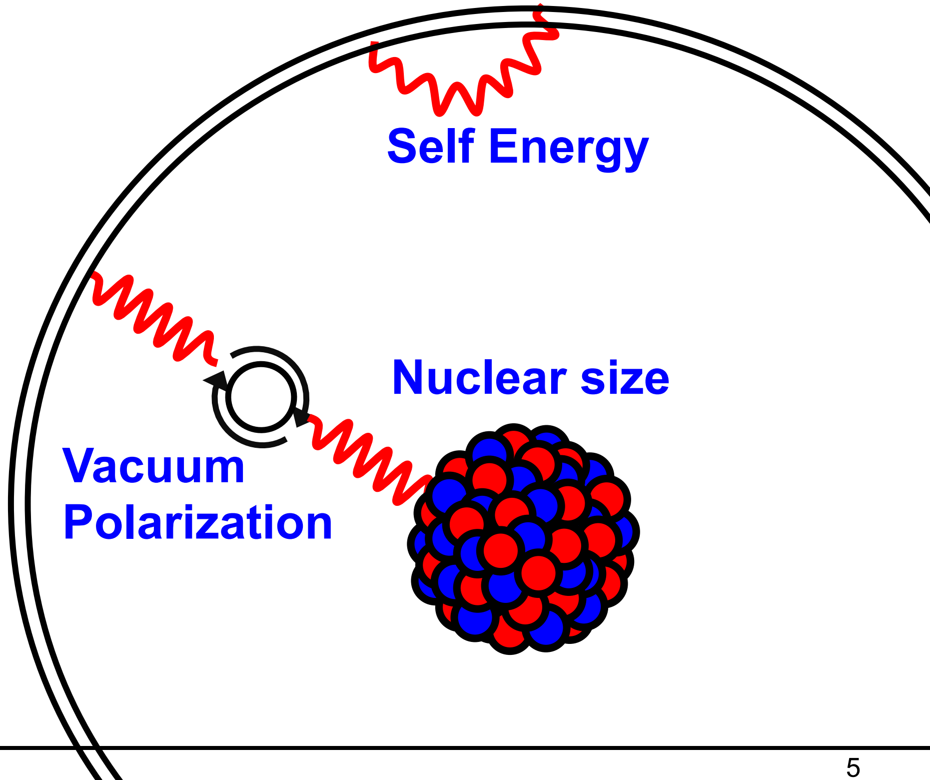


Hydrogen
$\Delta E_{QED} \approx 10^{-6}$ eV
$Z \cdot \alpha \approx 10^{-2}$
Perturbative in α and $Z\alpha$

⇧

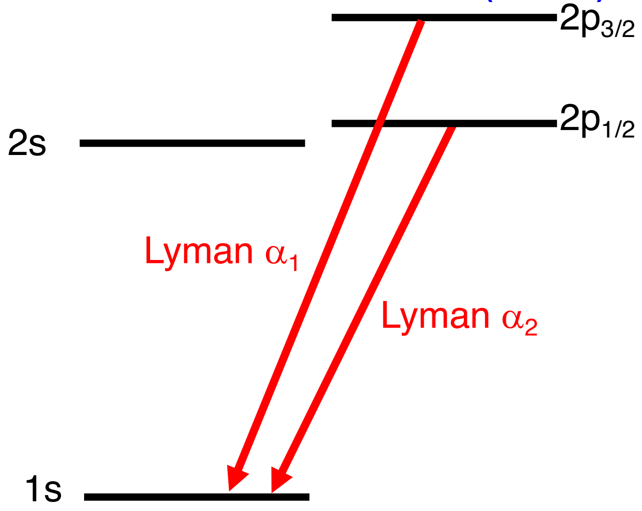
H-like Uranium
$\Delta E_{QED} \approx 500$ eV
$Z \cdot \alpha \approx 1$
Non-perturbative in $Z\alpha$

- Strong electric field
  → Quantum Electrodynamic effects enhanced
- Non-perturbative theory required
  Non-perturbative in $Z\alpha$ but perturbative in α
  α^2 not fully tested
  α^3 not predicted

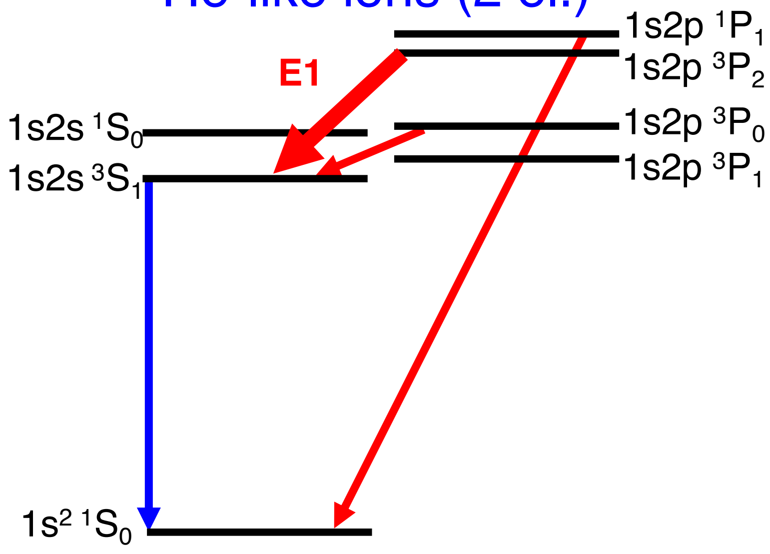


Spectroscopy of few electrons heavy charged ions

H-like ions (1 el.)



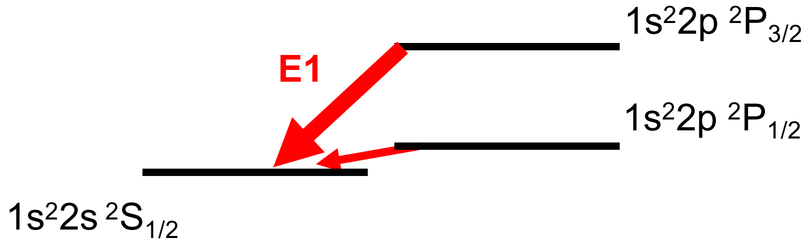
He-like ions (2 el.)



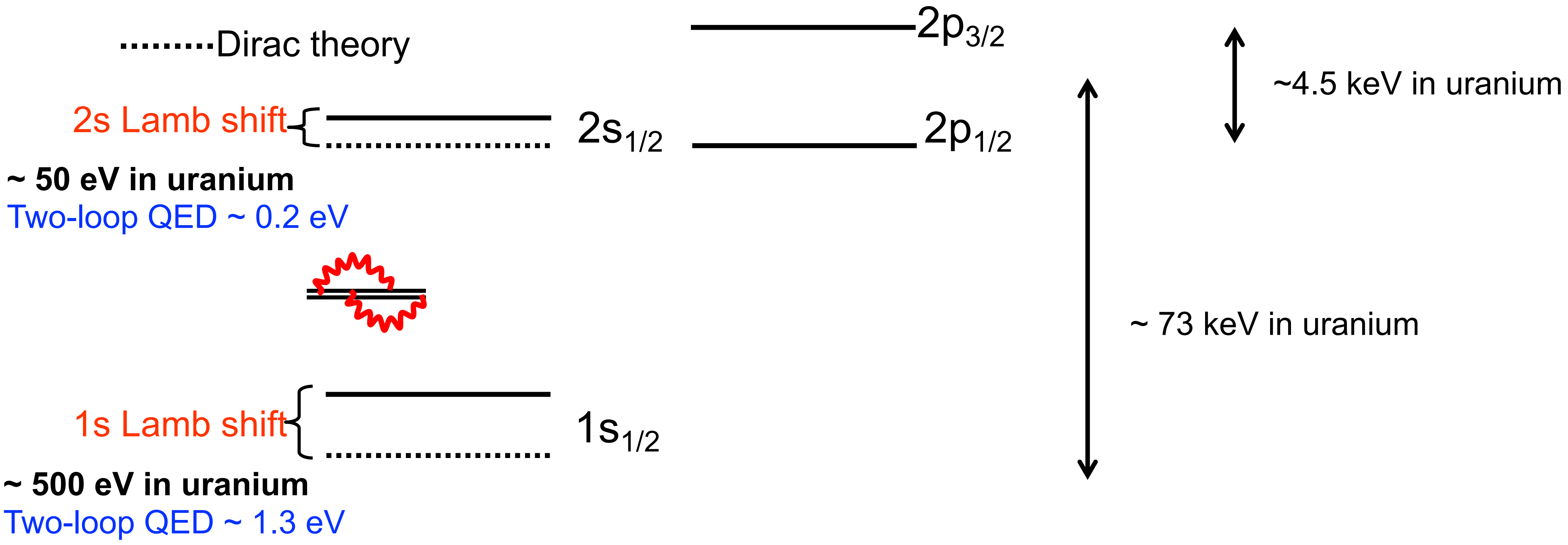
Stringent theory test

High-precision measurements
of different (and simple!) systems

Li-like ions (3 el.)



Spectroscopy of few electrons heavy charged ions



- **No lasers for such an energies!**
- **Heavy highly charged ions are difficult to produce**

Spectroscopy of few electrons heavy charged ions

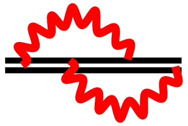
·········Dirac theory

$2p_{3/2}$

2s Lamb shift { $2s_{1/2}$ $2p_{1/2}$

~ 50 eV in uranium

Two-loop QED ~ 0.2 eV



1s Lamb shift { $1s_{1/2}$

~ 500 eV in uranium

Two-loop QED ~ 1.3 eV

Most stringent tests (before 2021)**:**

1s Lamb shift of **H-like U**:

460.2 ± 4.6 eV

GSI

A. Gumberidze et al.,PRL **94**, 223001 (2005)

2s Lamb shift of **Li-lke U:**

41.485 ± 0.015 eV

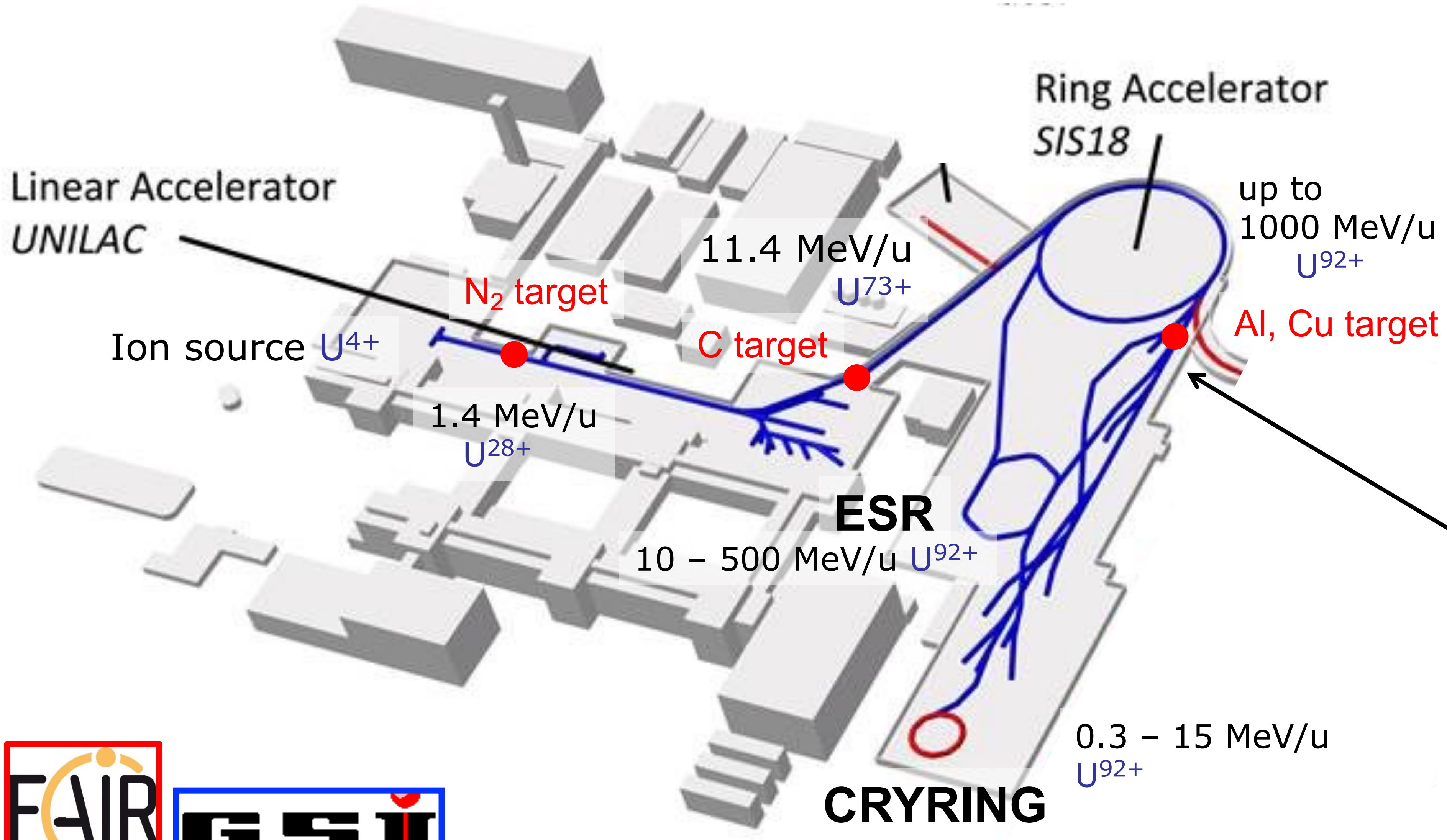
@ Livermore SuperEBIT

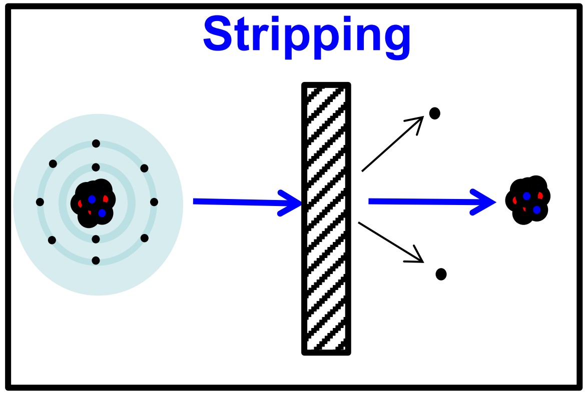
Beiersdorfer et al., Phys. Rev. Lett. 95, 233003 (2005)

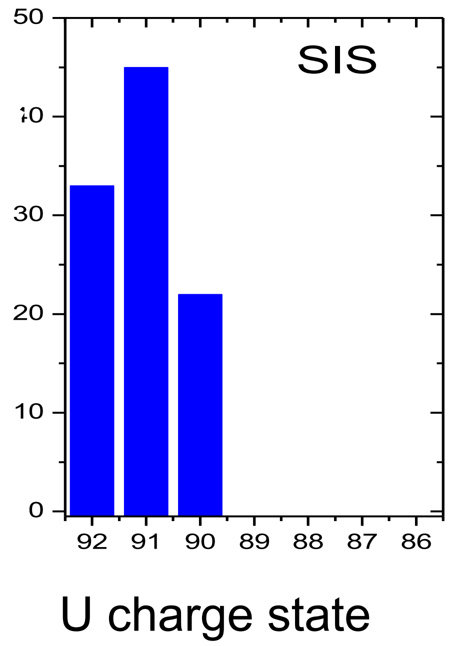
But too many electrons!

Many-electrons and 1-electron QED terms all together

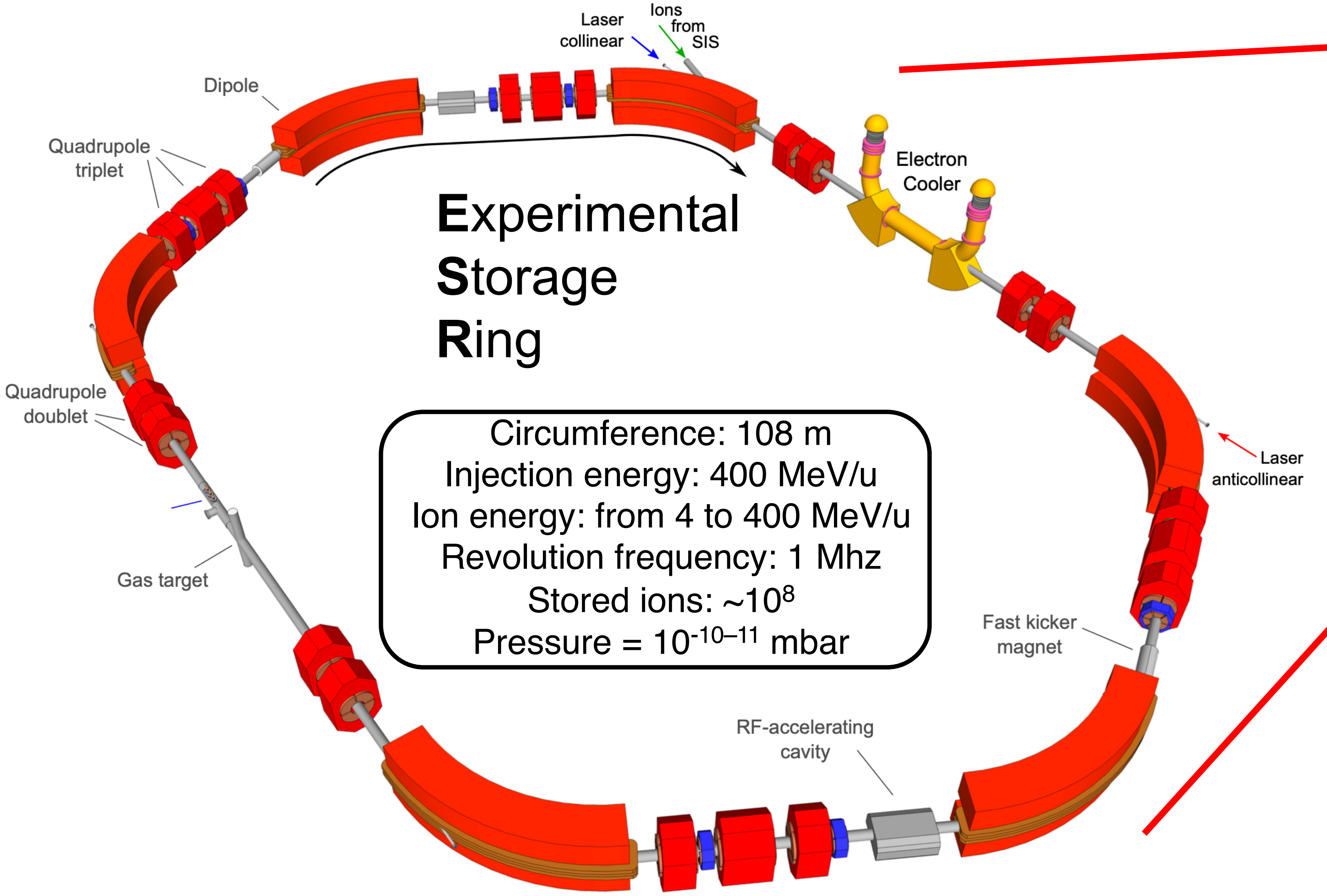
Highly charged ion production and storage





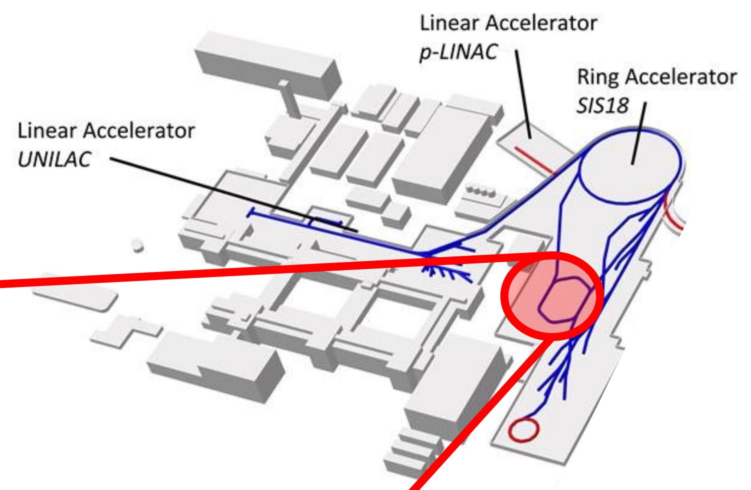


ESR storage ring at GSI



Experimental **S**torage **R**ing

Circumference: 108 m
Injection energy: 400 MeV/u
Ion energy: from 4 to 400 MeV/u
Revolution frequency: 1 Mhz
Stored ions: ~10^8
Pressure = $10^{-10–11}$ mbar



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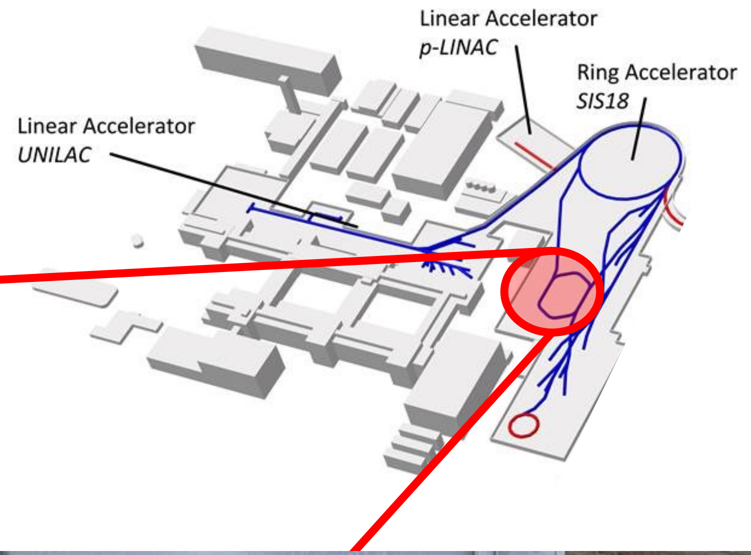

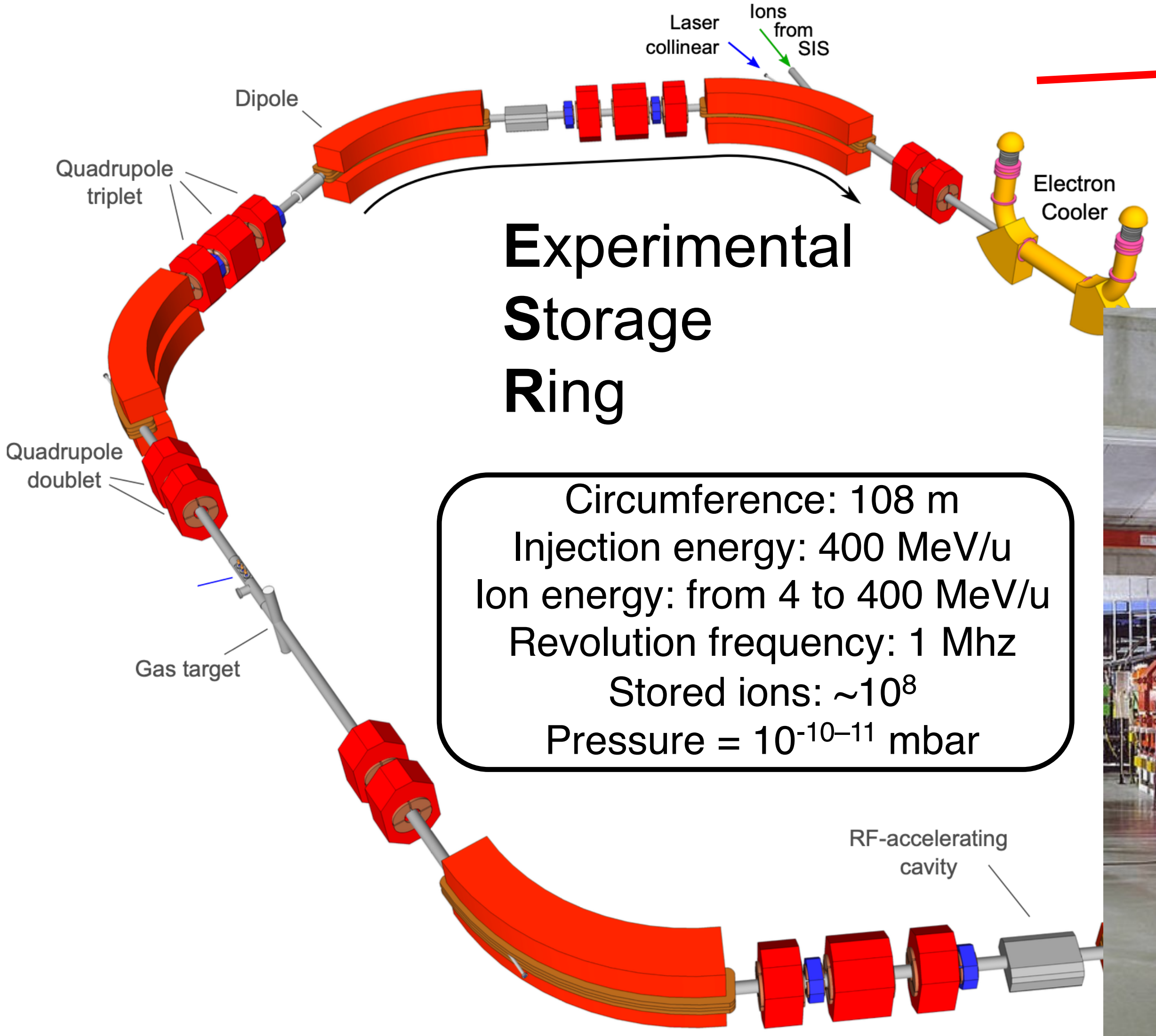

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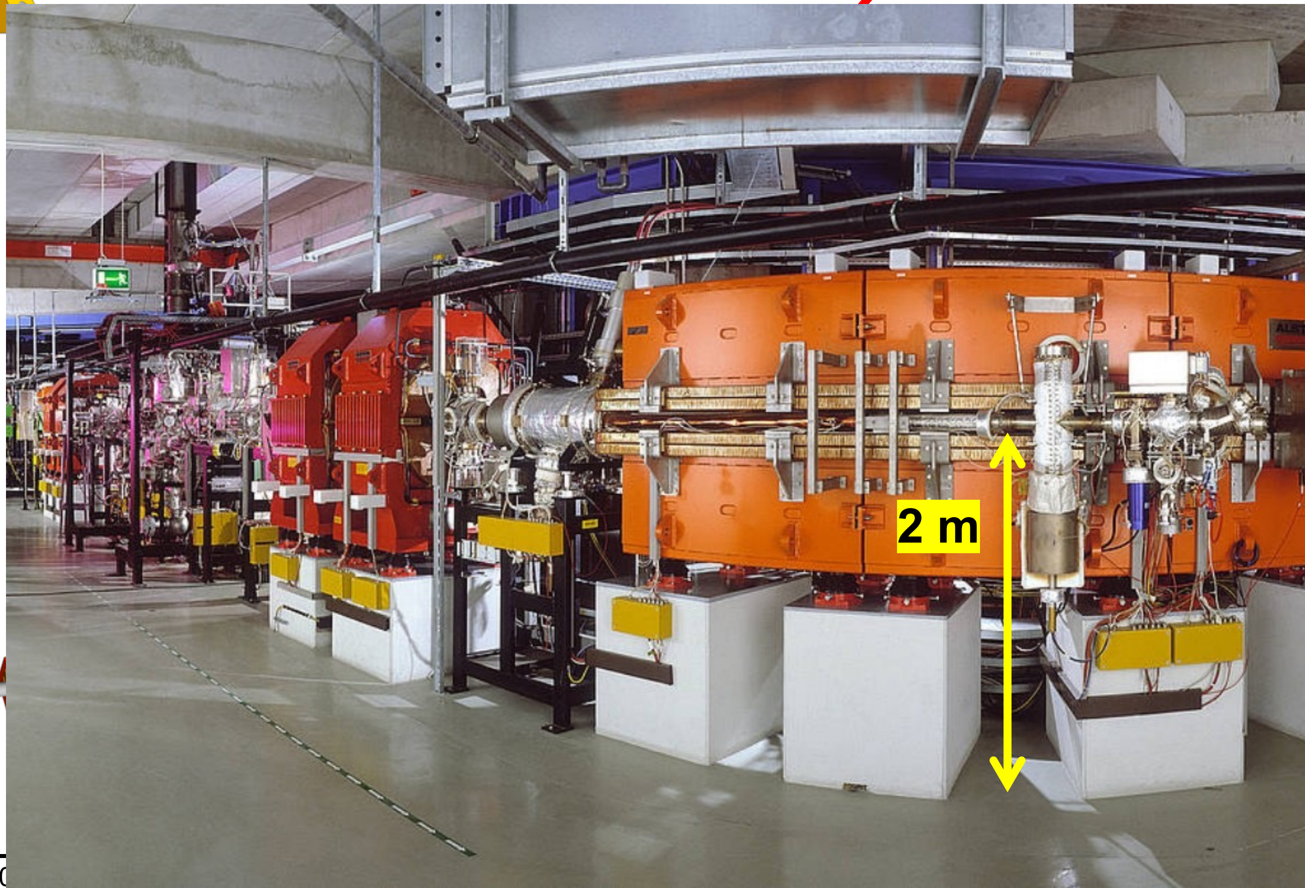
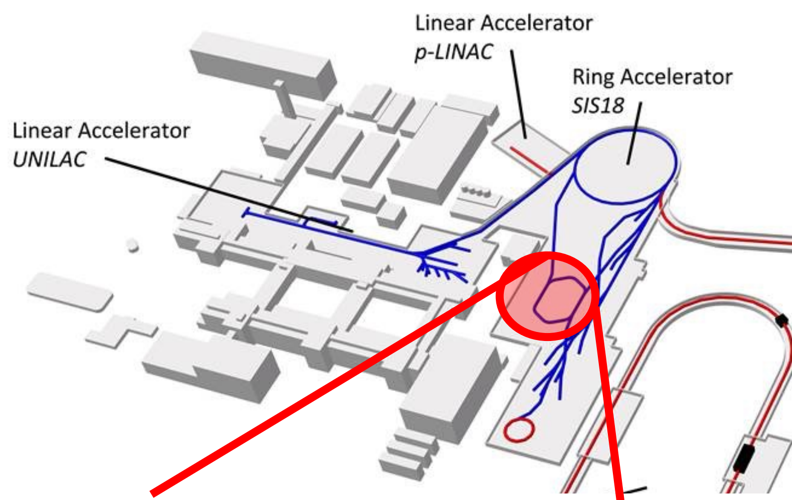
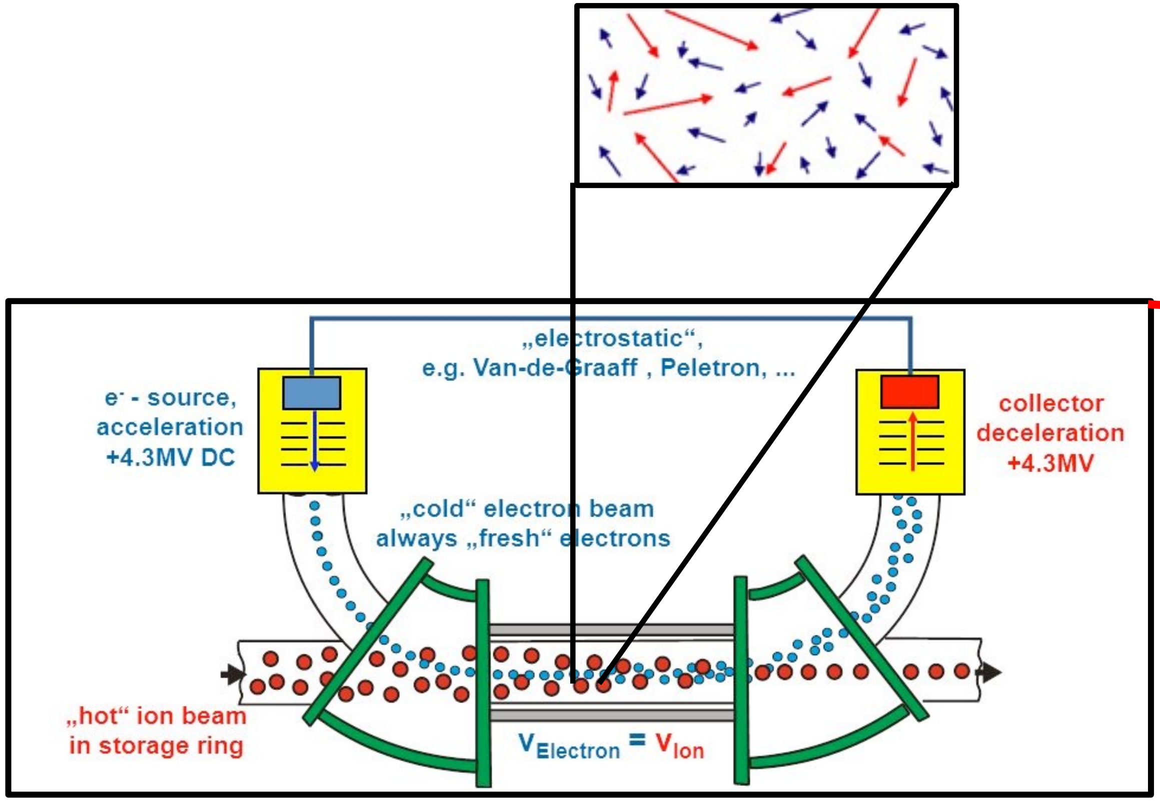
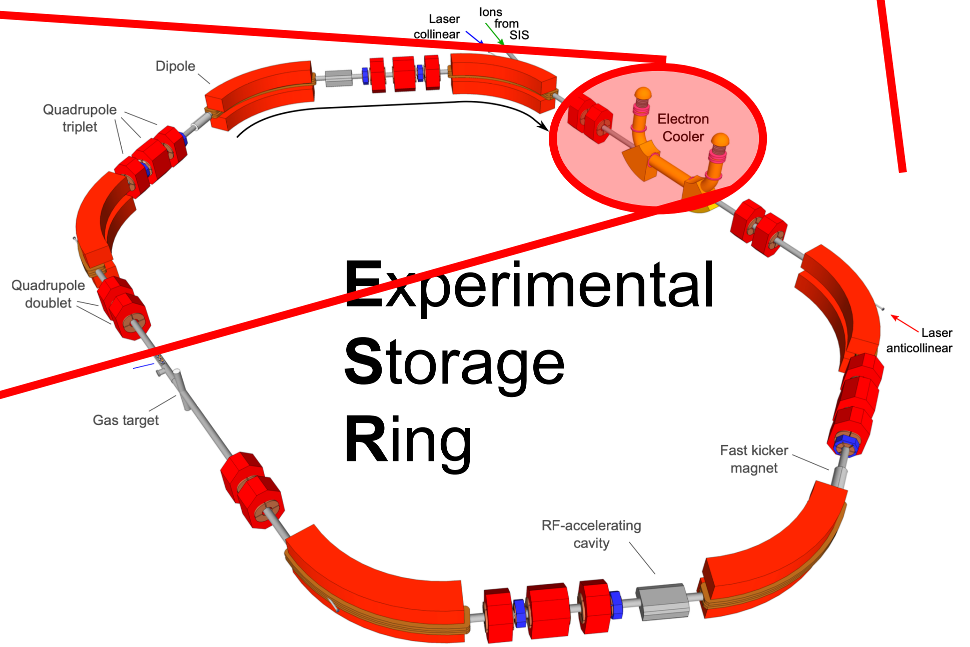


X-ray spectroscopy of few electrons heavy



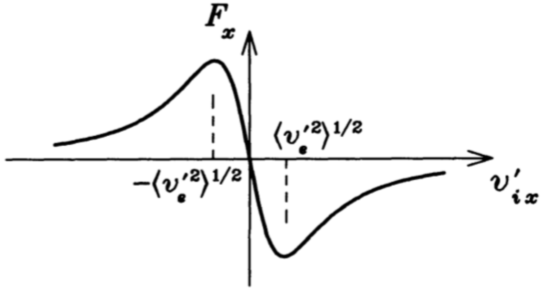


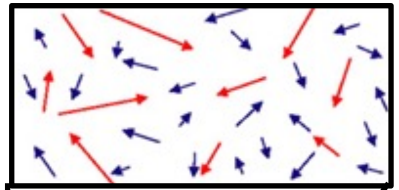


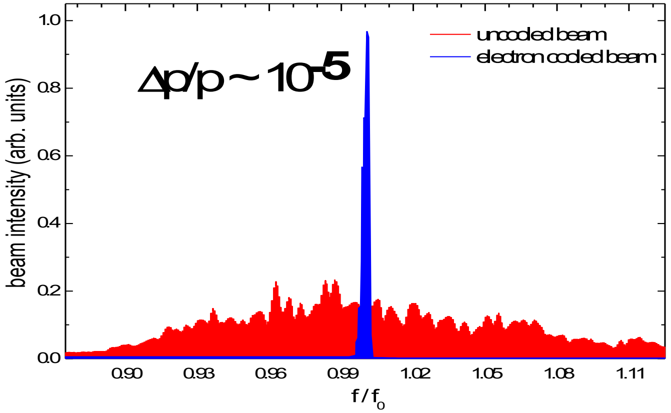
- Ions cooled by the high intensity electron beam
- Ion velocity determined by the electron velocity

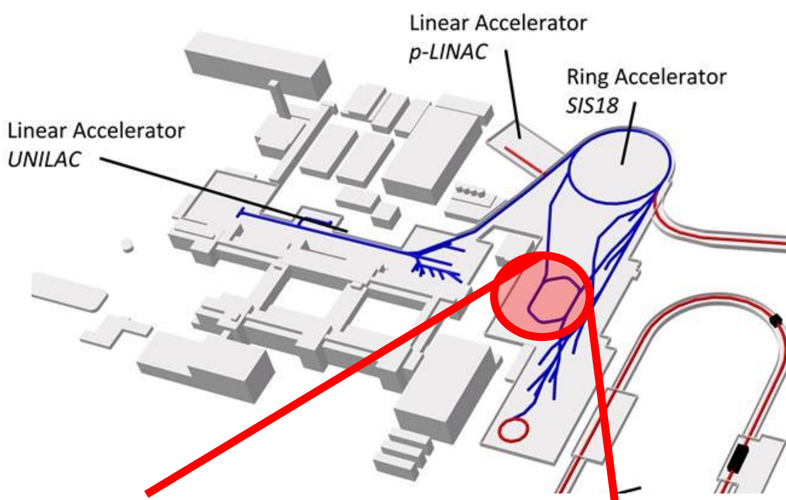
X-ray spectroscopy of few electrons heavy

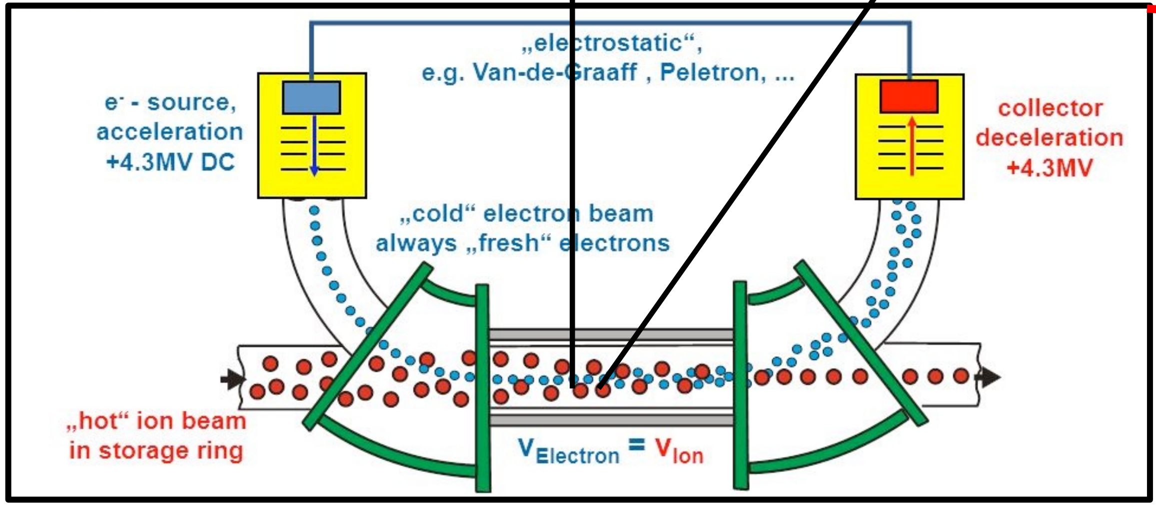
Cooling force

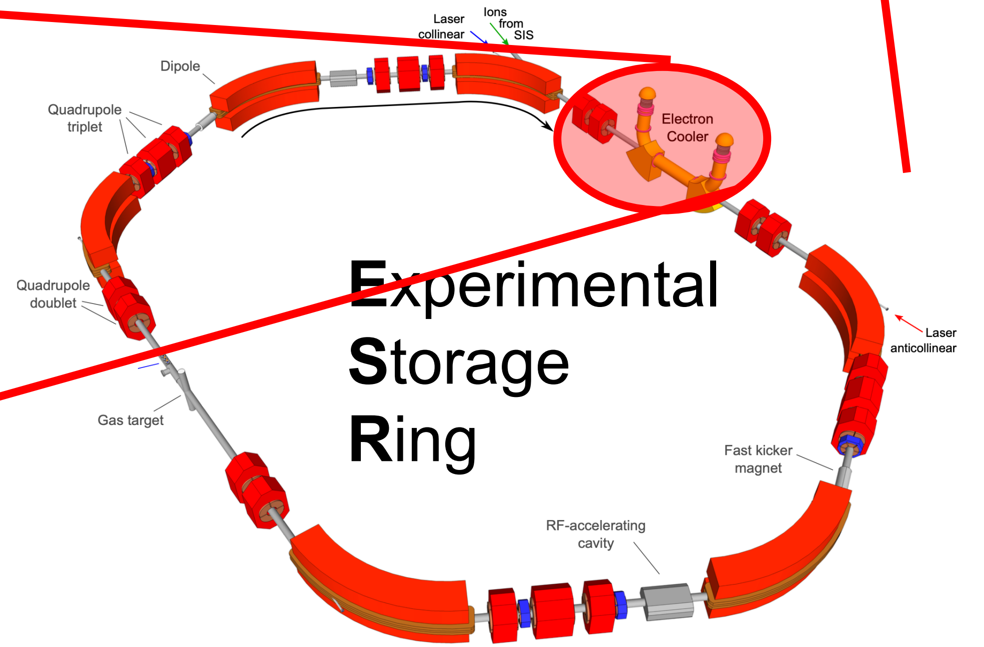












- Ions cooled by the high intensity electron beam
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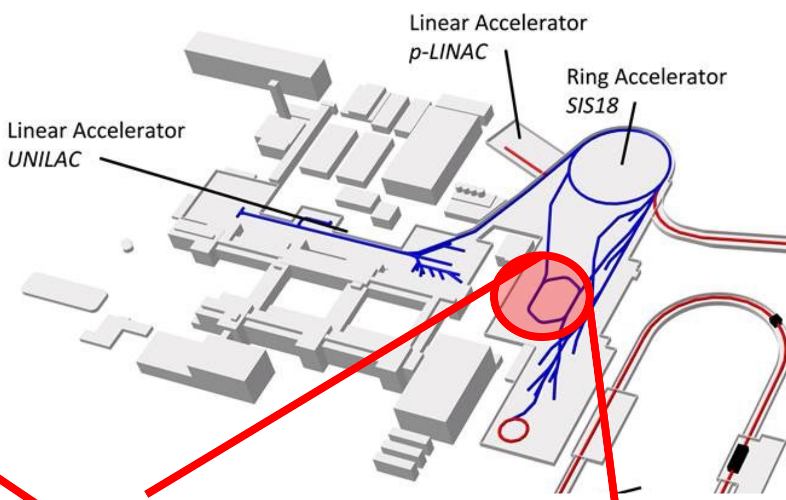
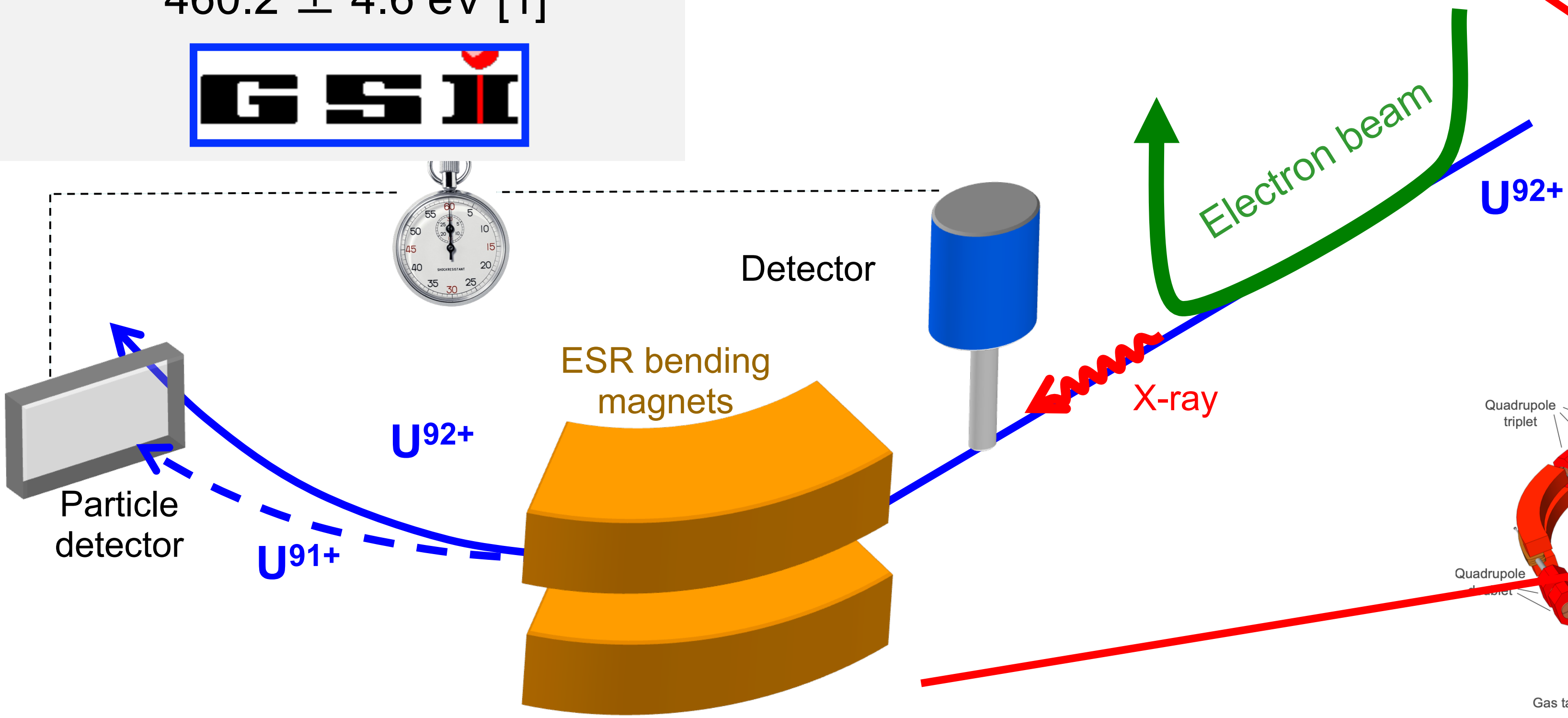
Lamb shift of H-like Uranium

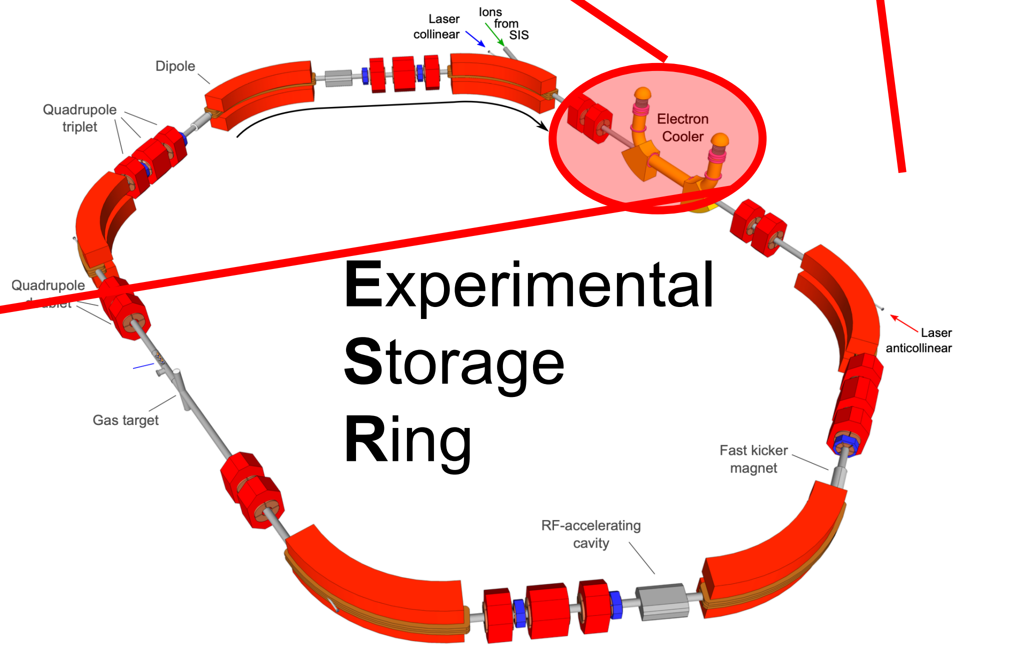


1s Lamb shift of **H-like U**:

460.2 ± 4.6 eV [1]

$$U^{92+} + e^{-} \rightarrow U^{91+}$$





[1] A. Gumberidze et al.,PRL **94**, 223001 (2005)
[2] V.A. Yerokhin et al., Eur. Phys. J. D **25**, 203-238 (2003)

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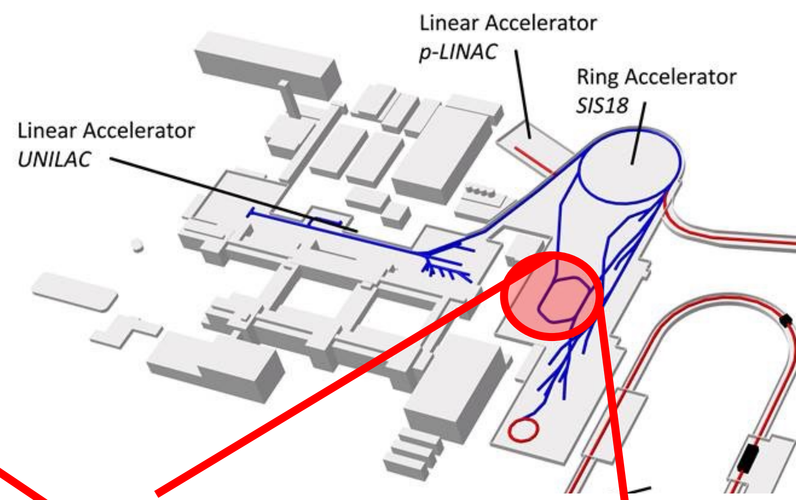

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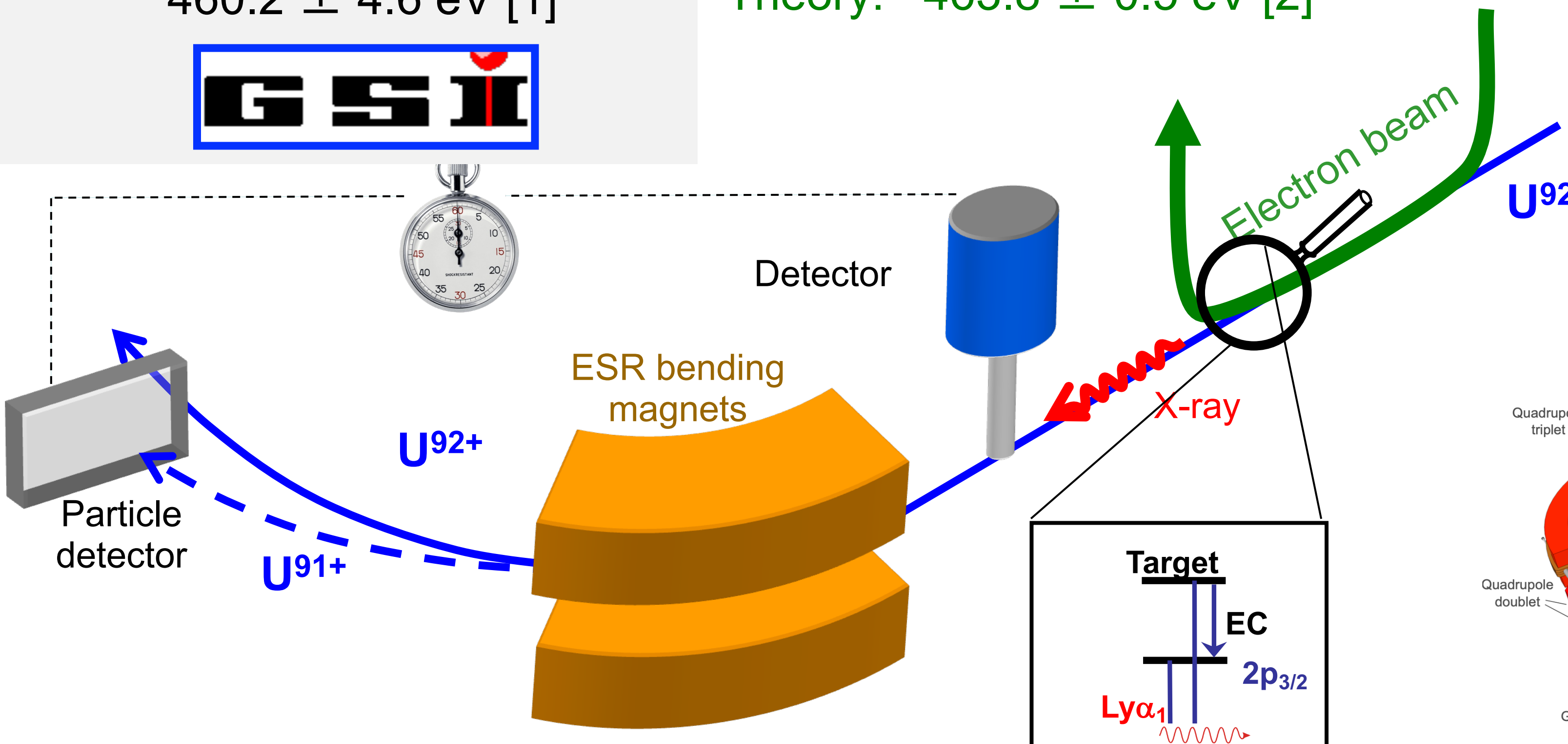
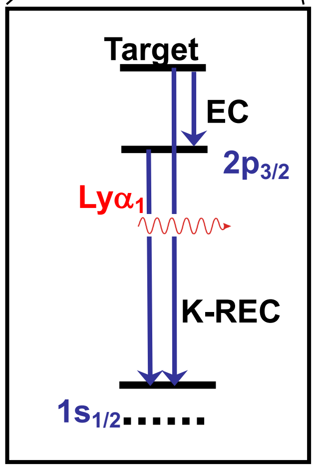
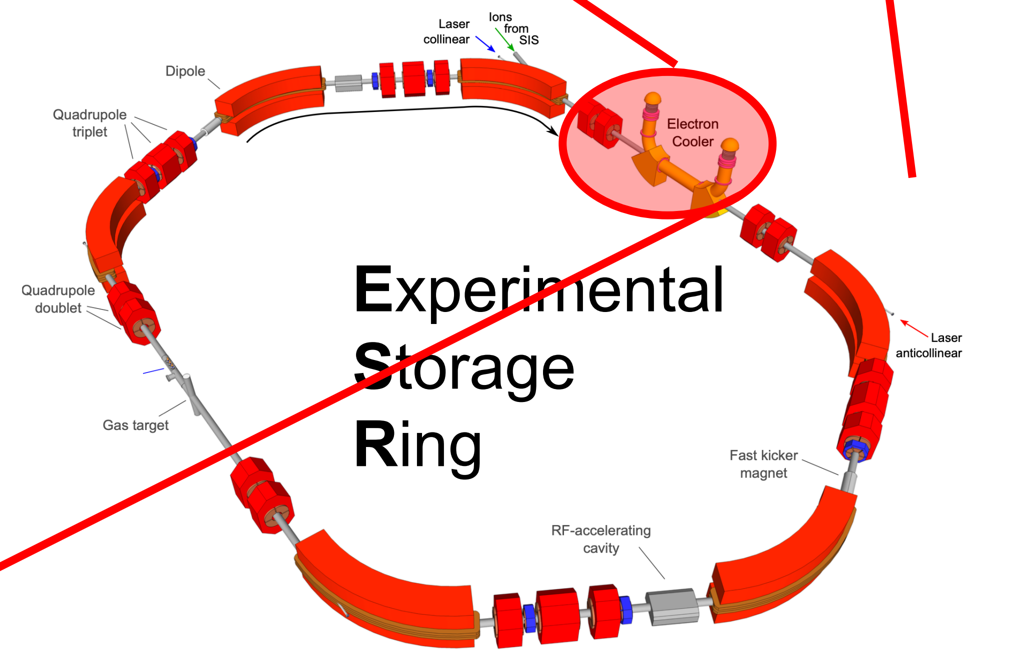
Theory: 463.8 ± 0.5 eV [2]







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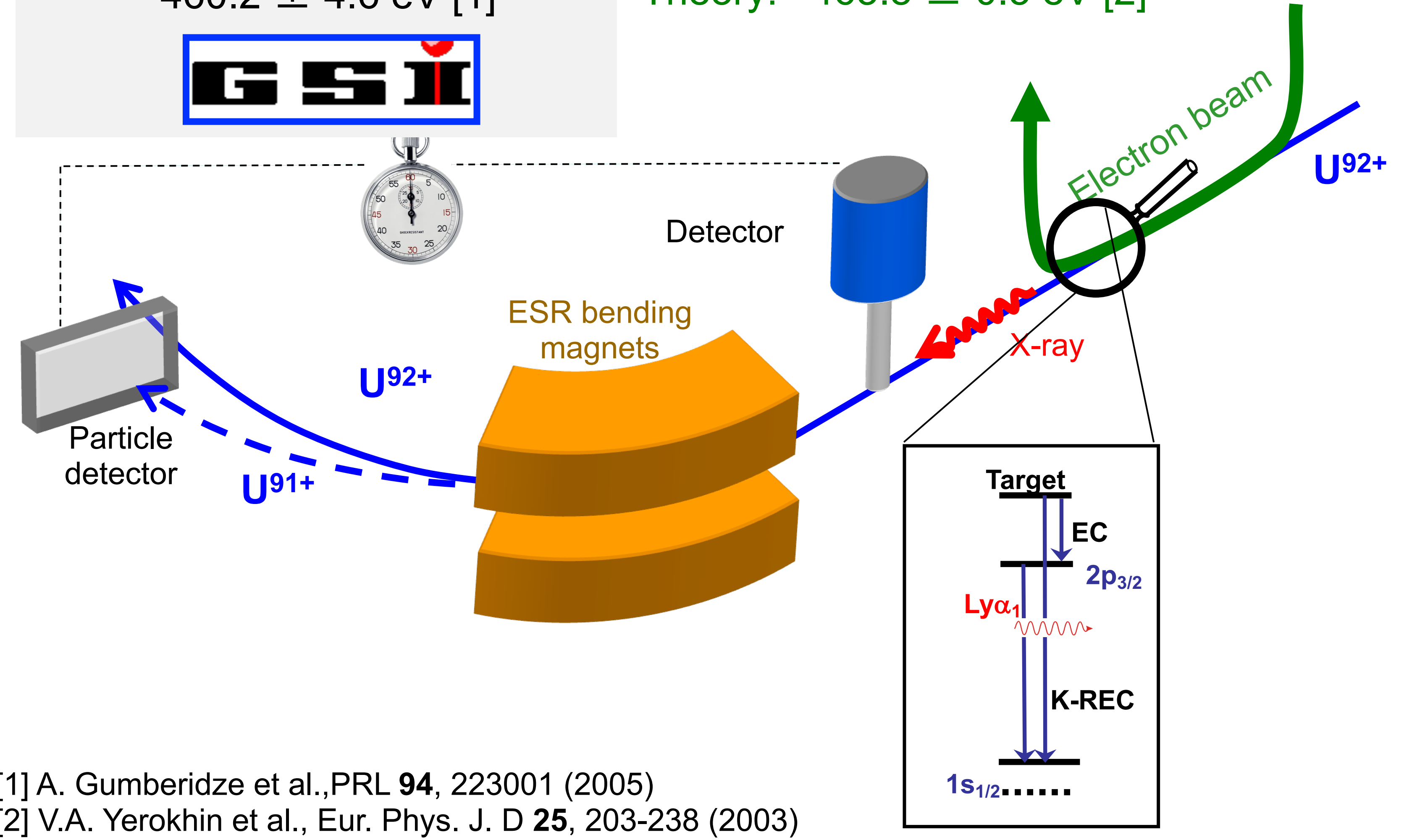
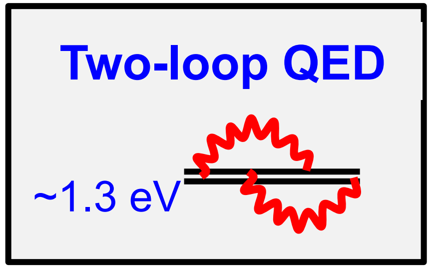




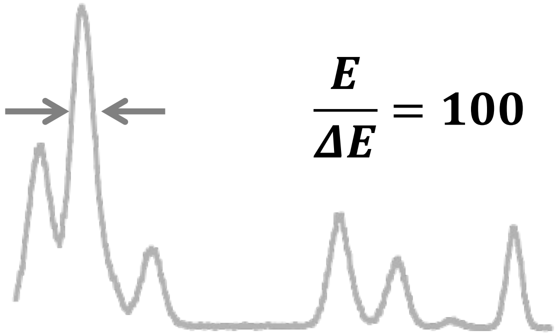
Good… but not enough

[1] A. Gumberidze et al.,PRL **94**, 223001 (2005)
[2] V.A. Yerokhin et al., Eur. Phys. J. D **25**, 203-238 (2003)

Accuracy limitations

Detector resolution

Resolution:
400 eV at 60 keV



$$\frac{E}{\Delta E} = 100$$

Ge detector

Accuracy limitations

Detector resolution

Resolution:
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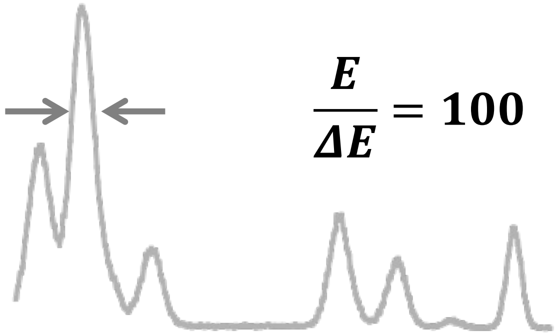


$$\frac{E}{\Delta E} = 100$$

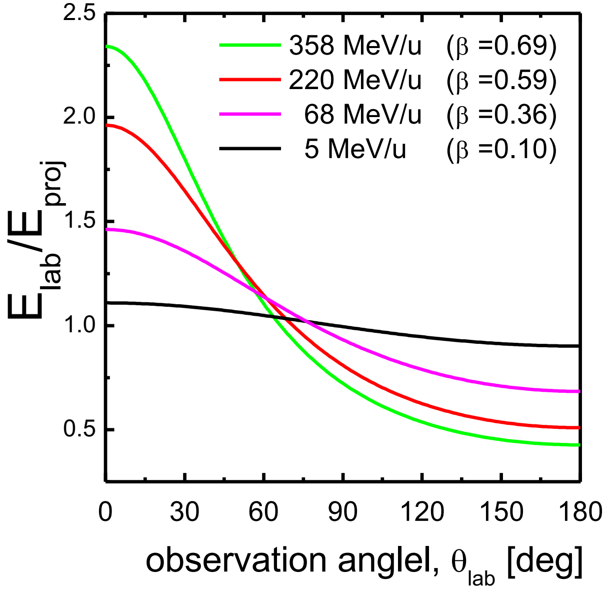
Ge detector

Doppler systematic effect

Relativistic Doppler shift

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

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}; \beta = \frac{v}{c}$$ c: light speed



new systematic uncertainties…

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

$$\delta(E_{\rm ion})_\beta = E_{\rm lab}\gamma^3|\beta-\cos(\theta)|\delta\beta$$

Lamb shift of H-like Uranium

Accuracy limitations

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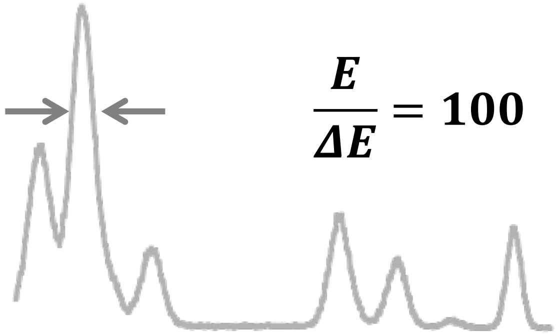

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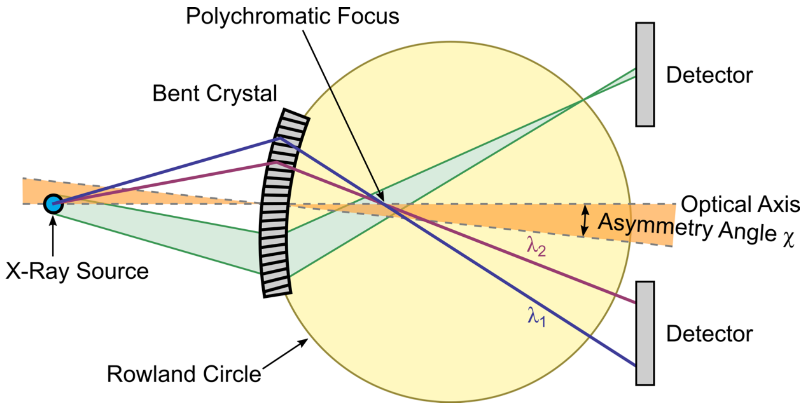
New recent developments

Crystal spectroscopy: the FOCAL experiment (2012)

Resolution:
~60 eV at 60 keV



$$\frac{E}{\Delta E} = 1000$$

Final result too much affected by Doppler systematic effects…

Gassner *et al.*, New J. Phys. **20**, 073033 (2018)
Gassner *et al.*, X-Ray Spectrom. **49**, 204-208 (2020

Lamb shift of H-like Uranium

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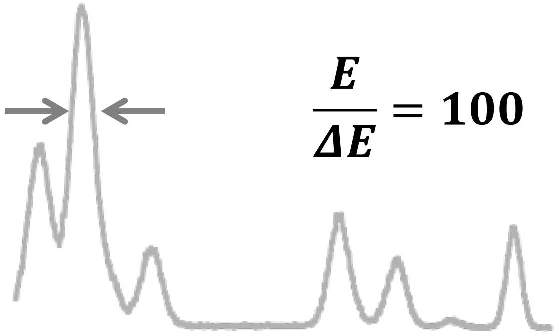

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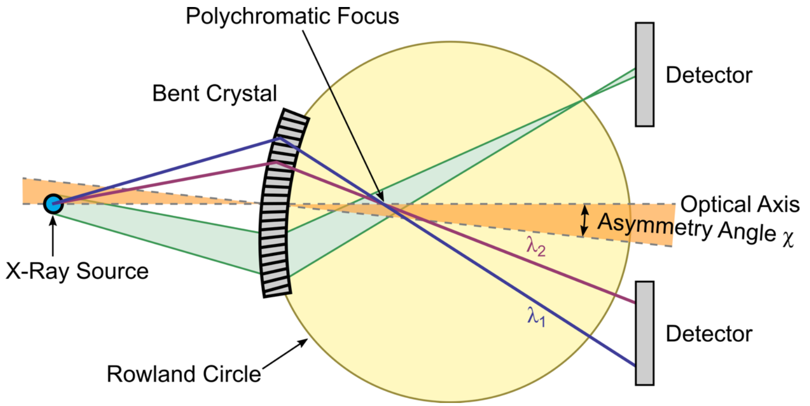

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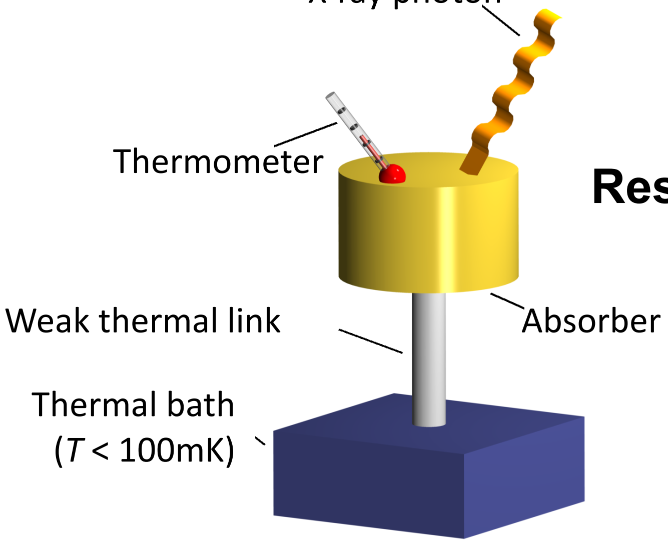
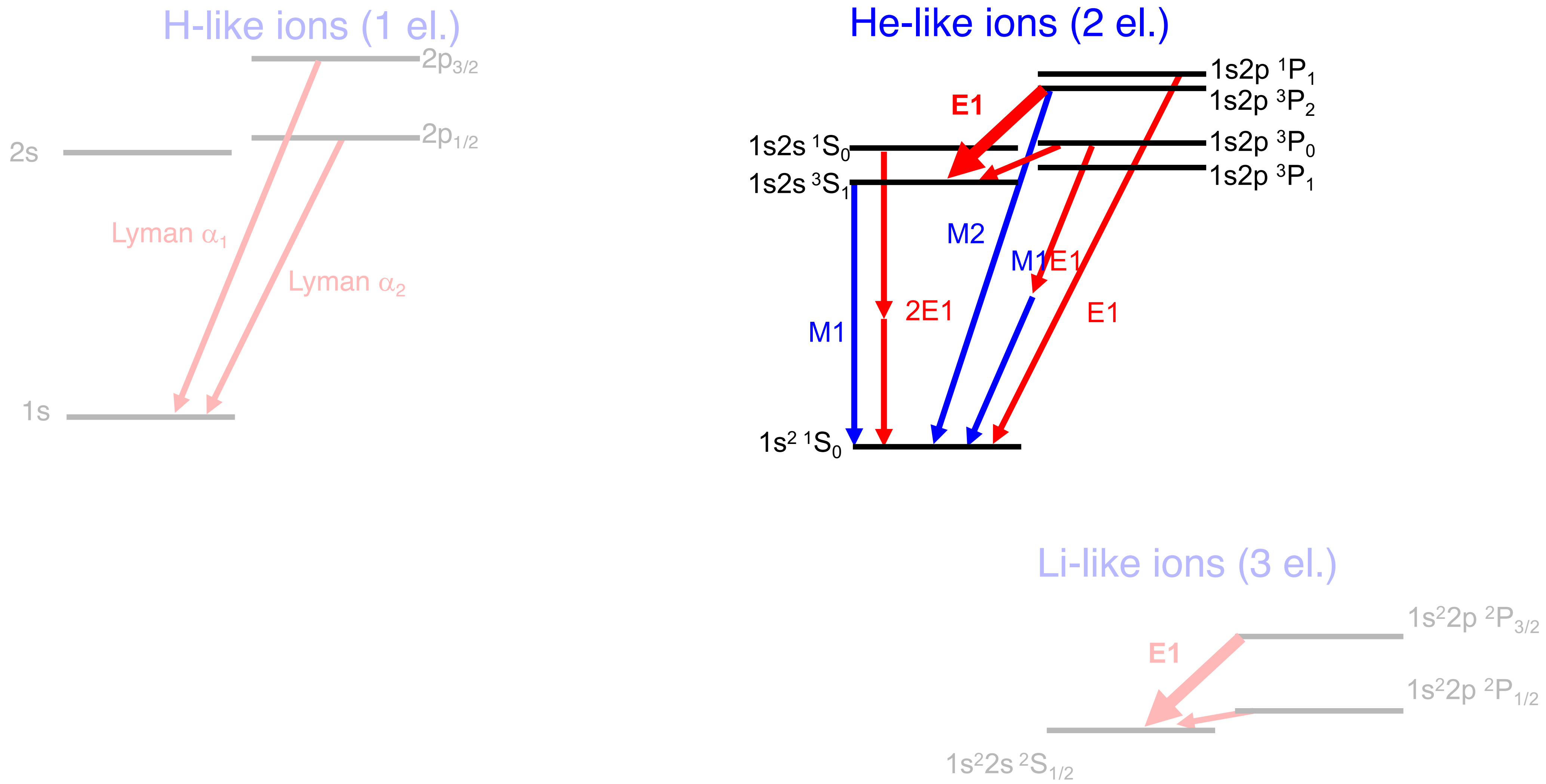


Resisitive and magnetic Microcalorimeters

Resolution:
~60 eV at 60 keV

Pfäfflein *et al.*, Atoms **11**, 5 (2023)
Kröger *et al.*, Atoms **11**, 22 (2023)

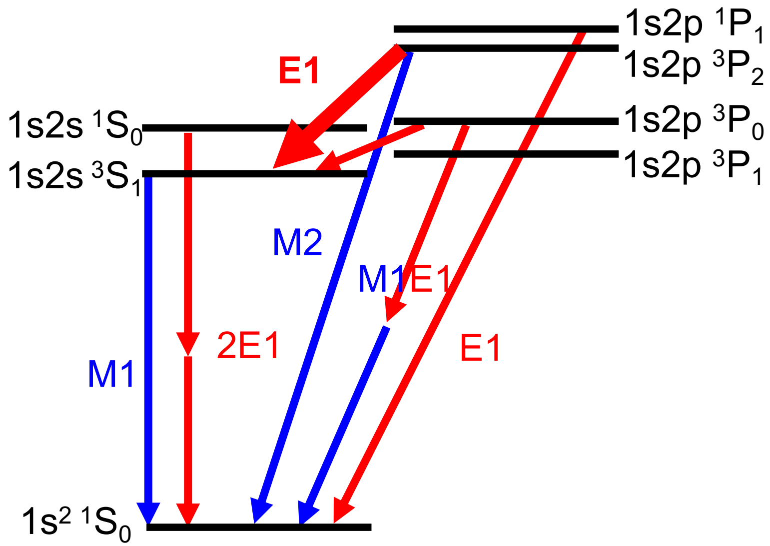
X-ray spectroscopy of few electrons heavy charged ions



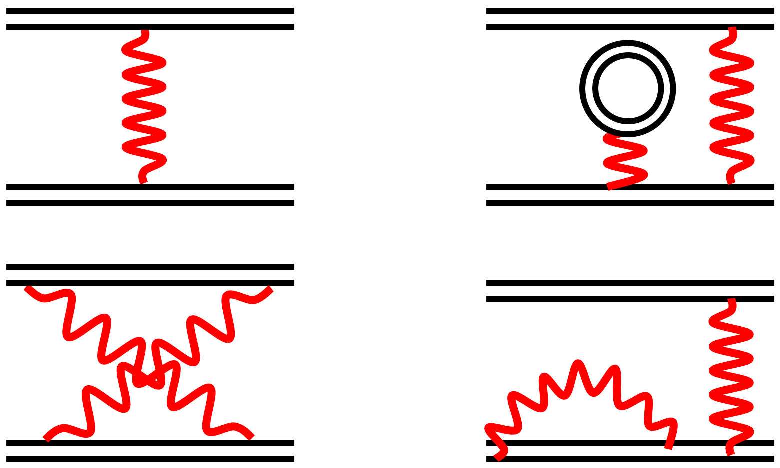
He-like heavy charged ions

… more electrons → more ingredients

He-like ions (2 el.)



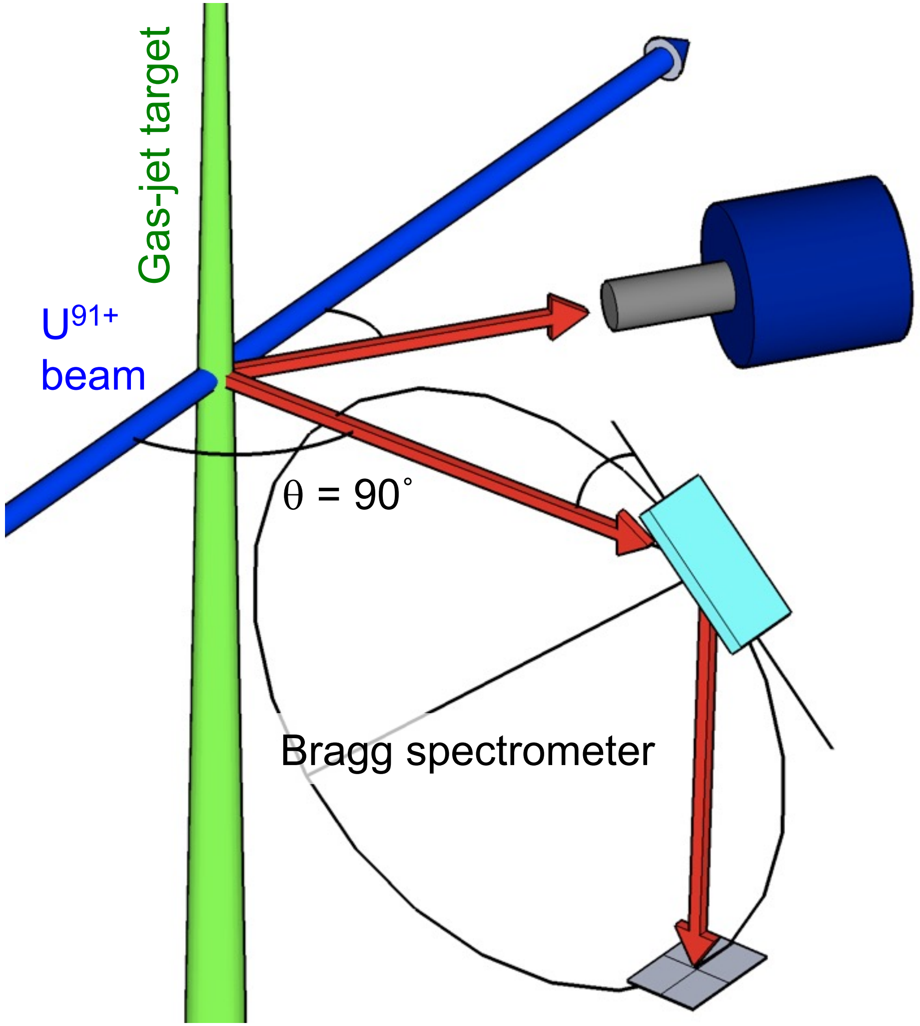
Electron-electron interaction

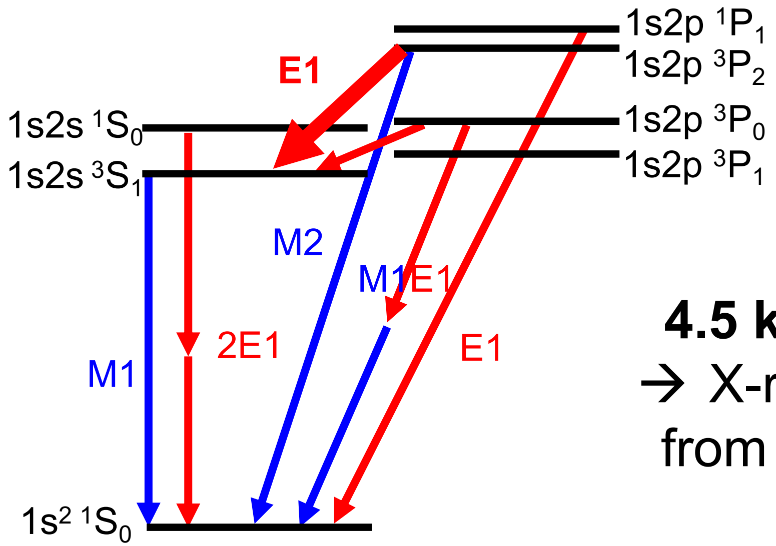


Non-radiative QED

Radiative QED

Intra-shell transition measurement



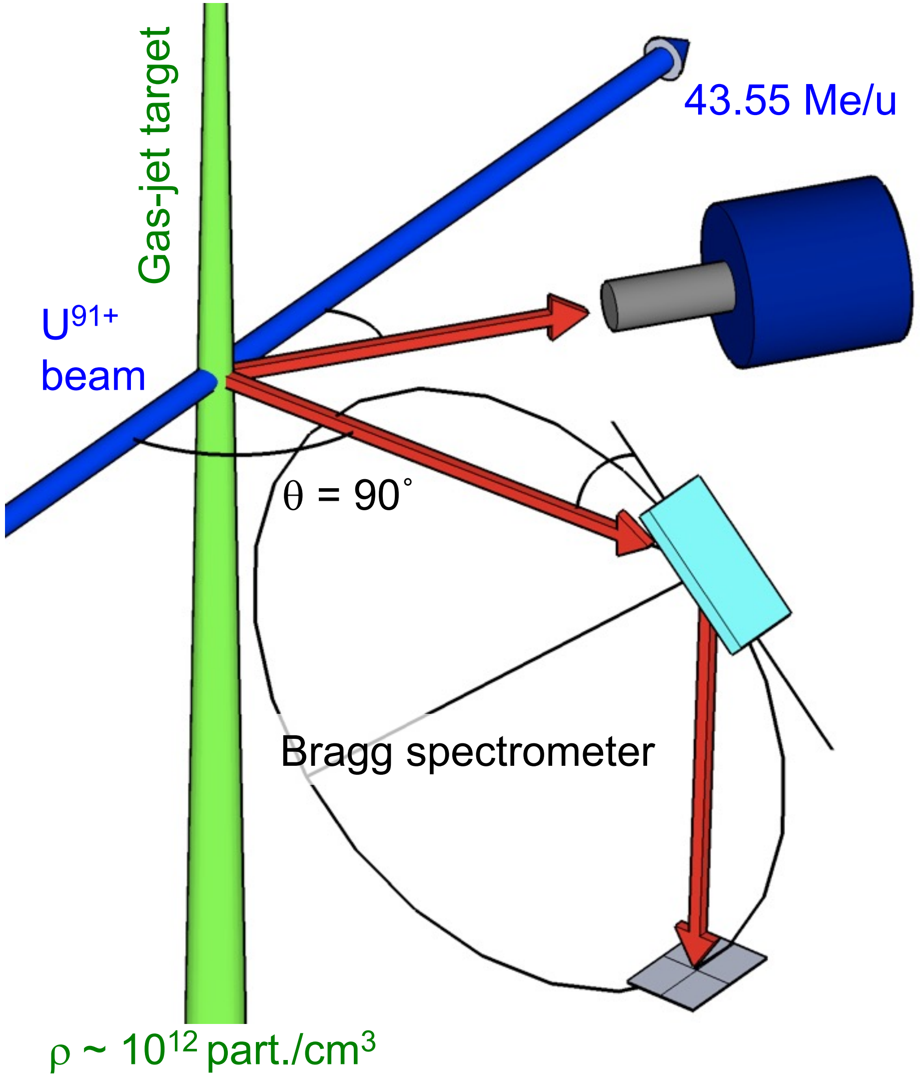


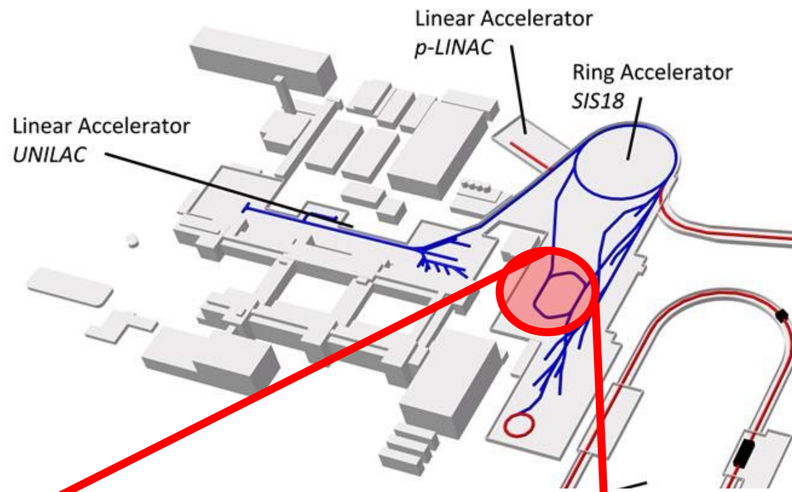
4.5 keV in He-like U
→ X-ray spectroscopy from Bragg reflection

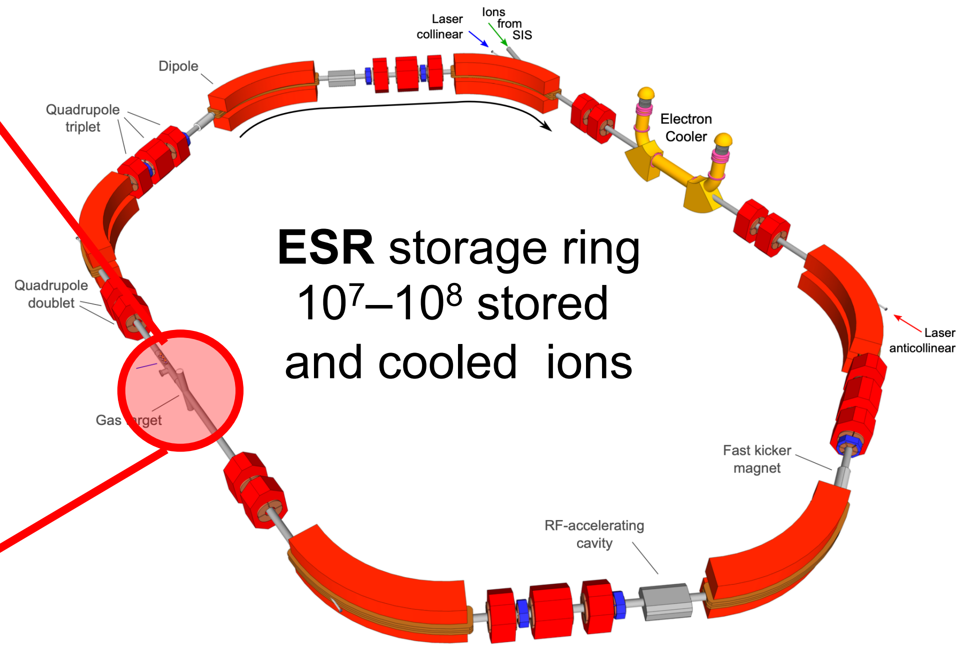
Resolution: 0.5 eV

$$\frac{E}{\Delta E} = 10000$$

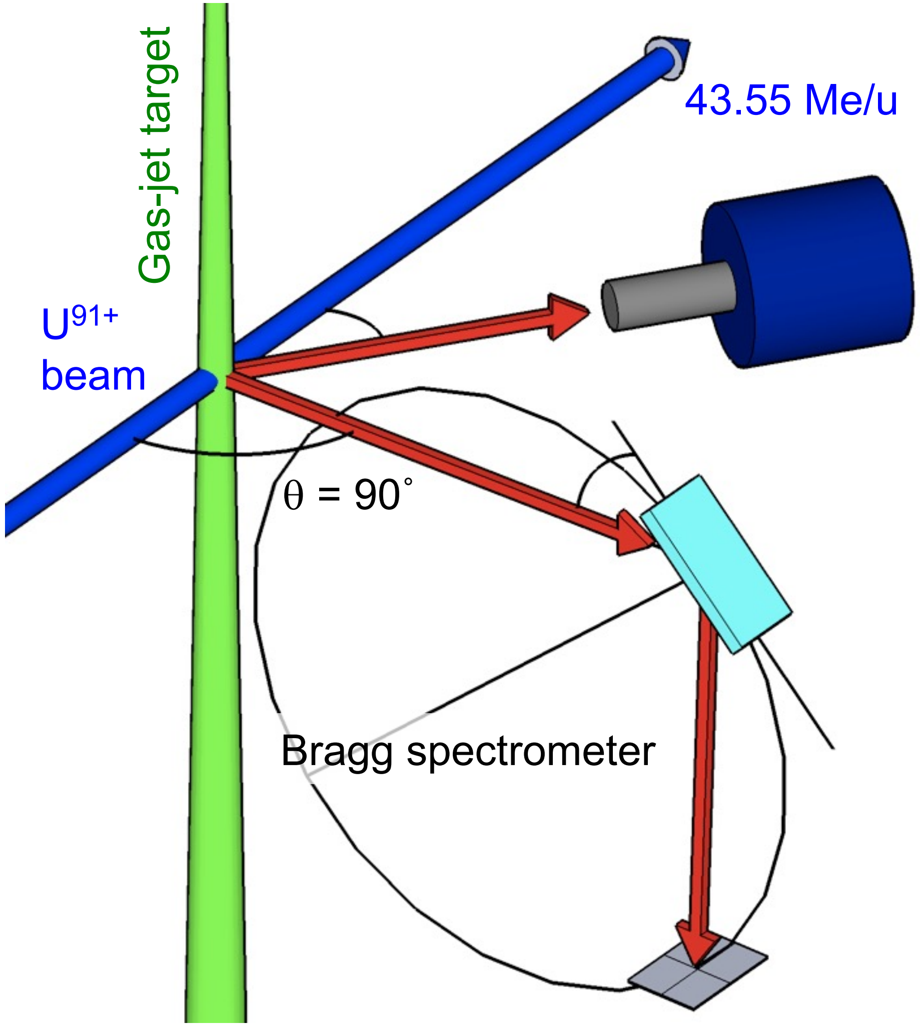
Production at ESR@GSI/FAIR







Production at ESR@GSI/FAIR



$\rho \sim 10^{12}$ part./cm^3

Electron capture

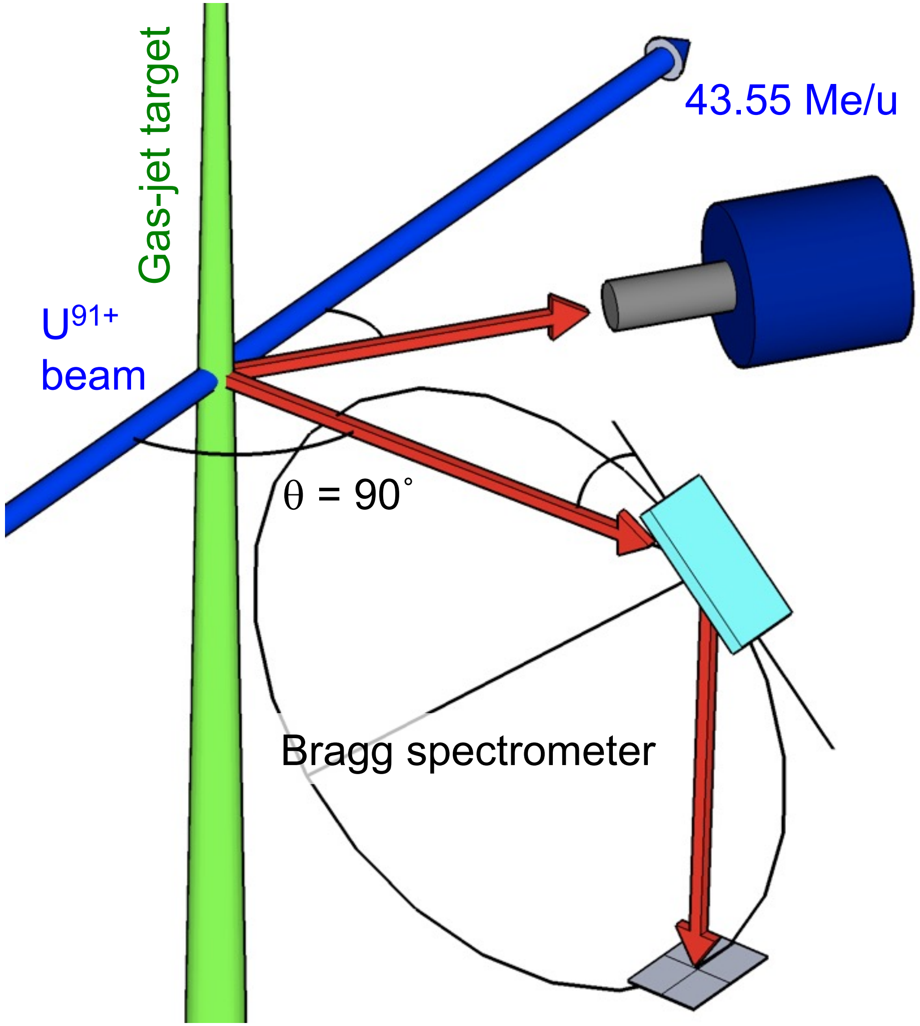
$U^{91+} + N_2 \rightarrow U^{90+} + N^{+} + \ldots$

- Low ion velocity
- Low-Z target

Single electron capture
in n = 2-5 levels

Efficient population of the
He-like 1s2p $^3P_2$ state!

Intra-shell transition measurement



But Doppler effect still well present…

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

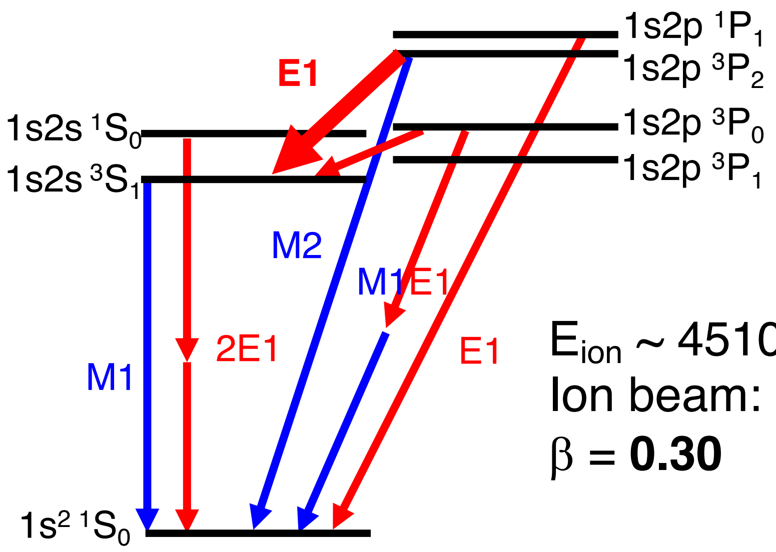
→ Systematic uncertainties

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

$$\delta(E_{\text{ion}})_\beta = E_{\text{lab}}\gamma^3|\beta - \cos(\theta)|\delta\beta$$

Doppler tuned intra-shell transition spectroscopy

Heavy He-like U



E_{ion} ~ 4510 eV
Ion beam: **43.55 Mev/u**
β = **0.30**

E_{lab} ~ 4310 eV

→ Same Bragg angle than **Zn Ka** line in second order reflection, for which

$$\frac{\delta(E_{\rm ion})_\theta}{E_{\rm ion}} = \gamma^2\beta\delta\theta$$

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

Unknown E

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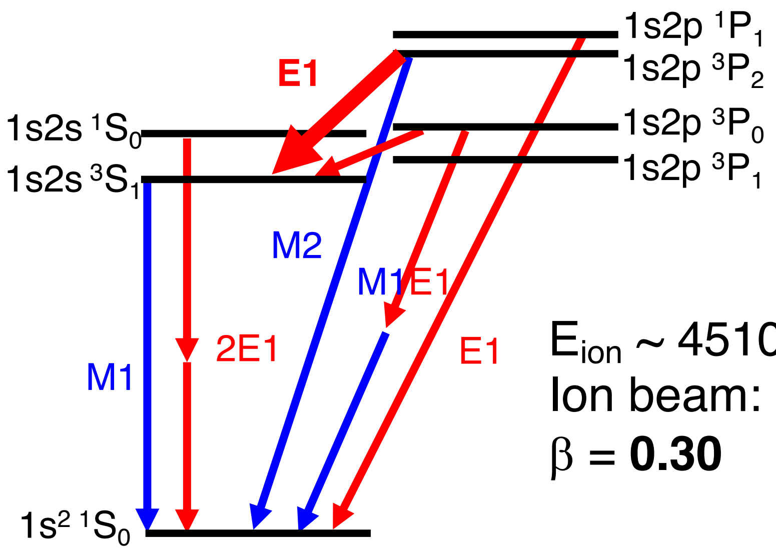
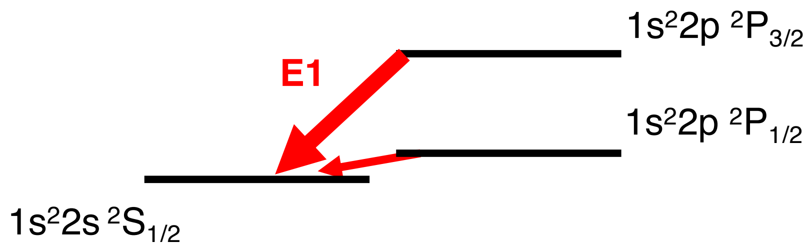


E_{ion} ~ 4510 eV
Ion beam: **43.55 Mev/u**
β = **0.30**

Heavy Li-like U (reference)



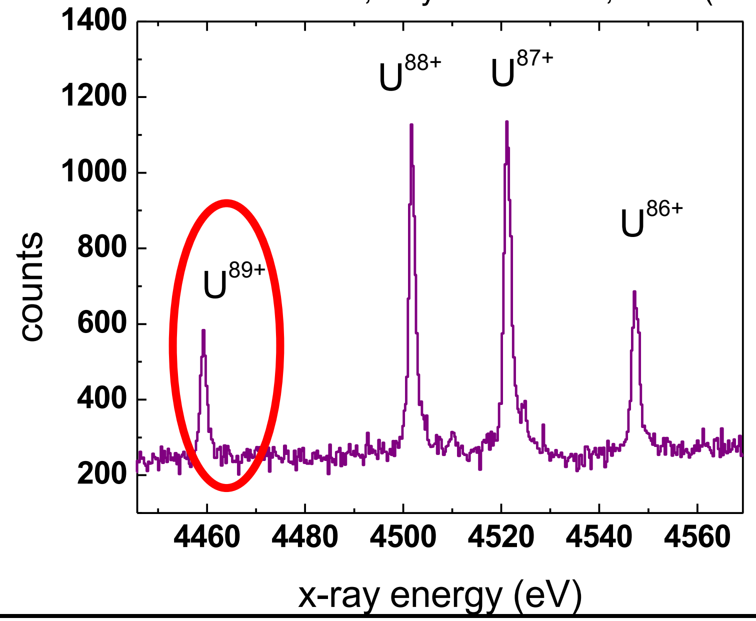
E_{ion} = 4459.37 ± 0.21 eV
Ion beam: **32.60 Mev/u**
β = **0.26**

E_{lab} ~ 4310 eV

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

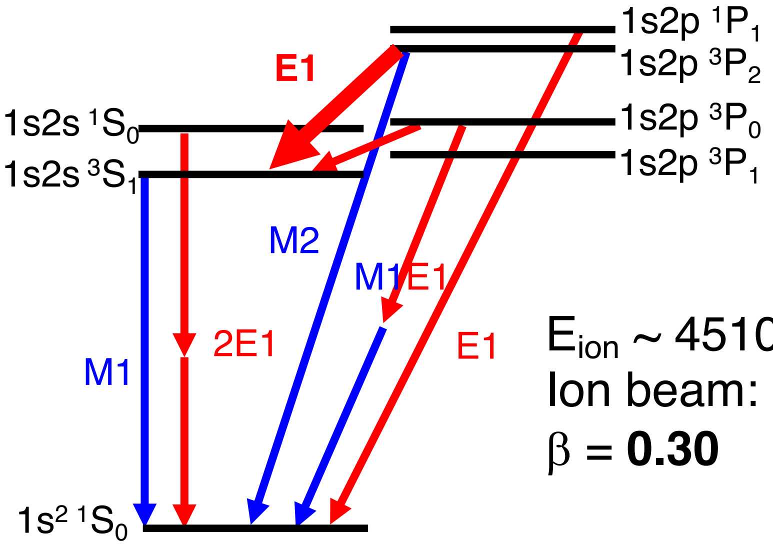
Unknown E — Reference E_0

Measured at Livermore SuperEBIT
Beiersdorfer *et al.*, Phys. Rev. A **53**, 4000 (1996)



Doppler tuned intra-shell transition spectroscopy

Heavy He-like U



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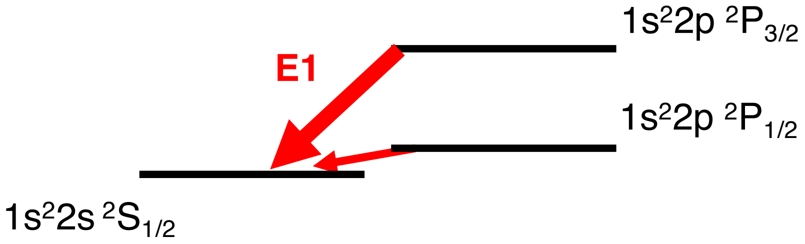

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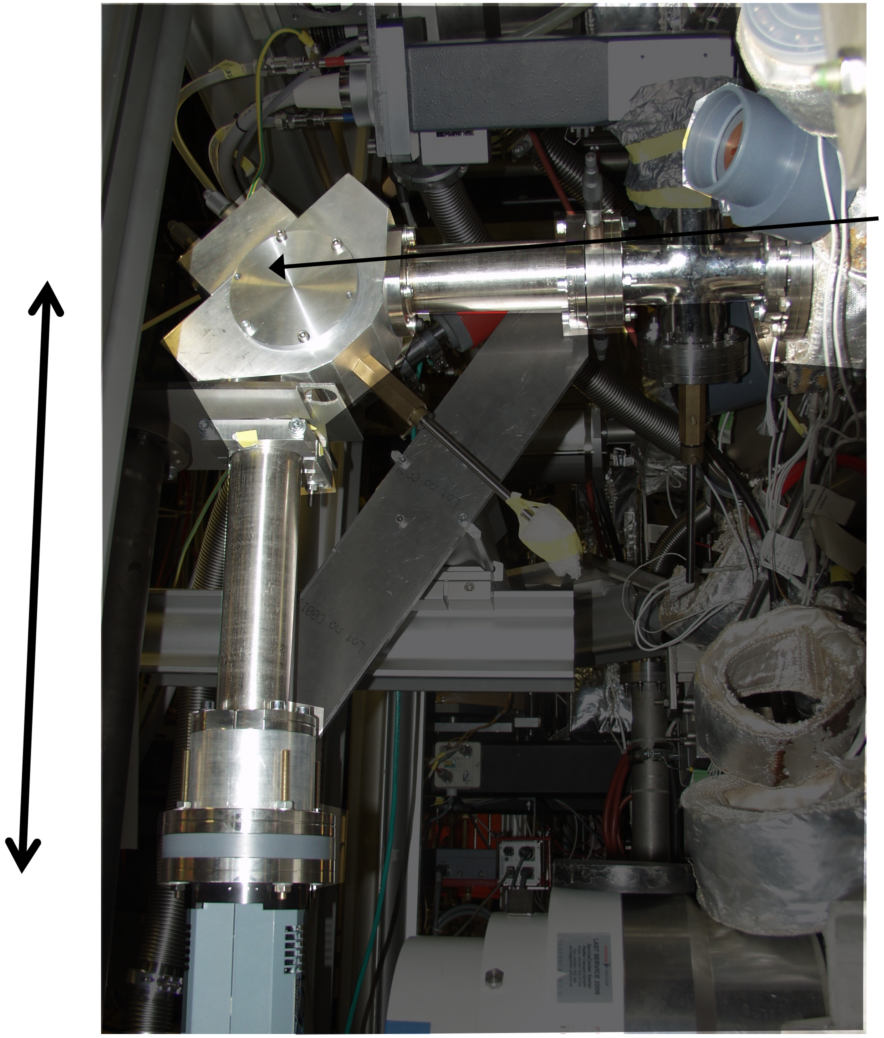
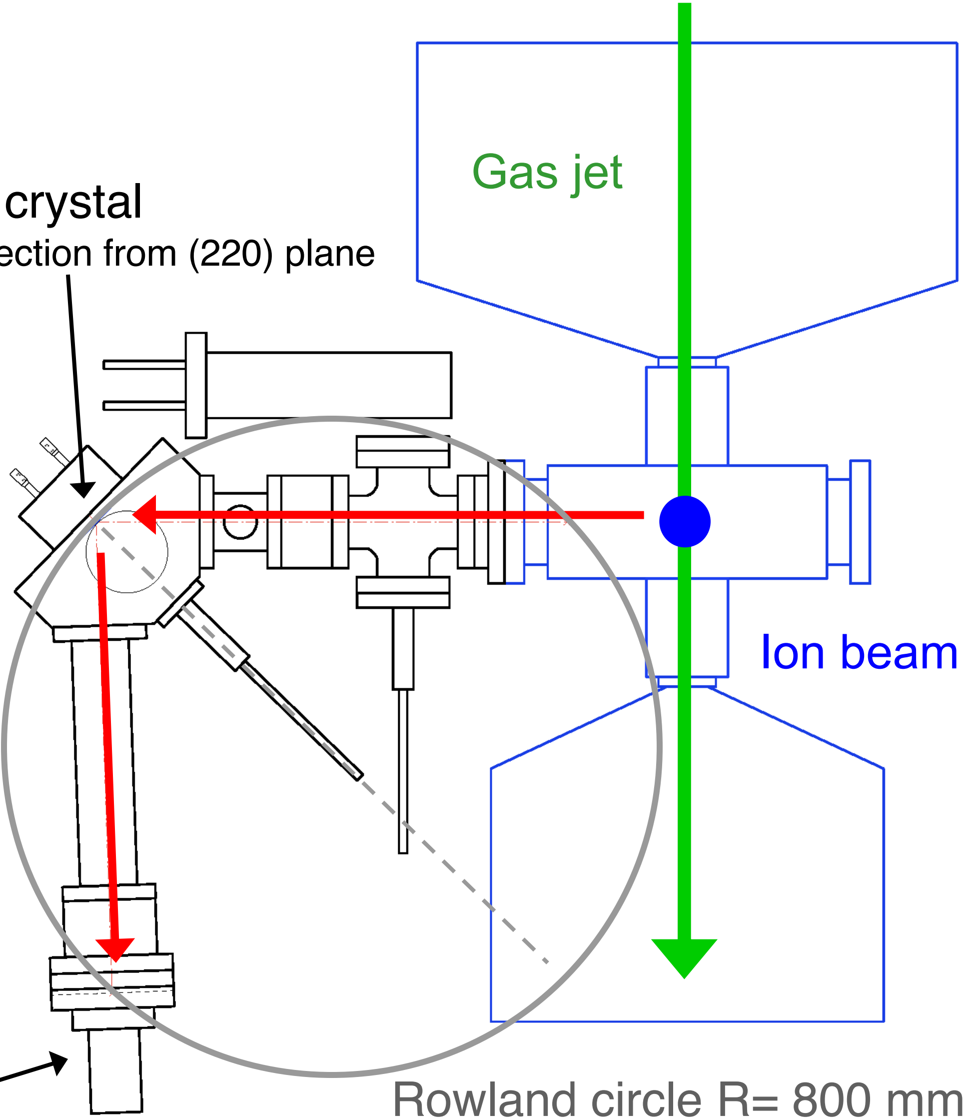
Unknown E   Reference E_0

Strong reduction of main systematic errors
and in particular…

$$\frac{\delta(E_{\rm ion})_\theta}{E_{\rm ion}} = \gamma^2\beta\delta\theta \Rightarrow \gamma^2|\beta-\beta_0|\delta\theta$$

2007 experiment at ESR





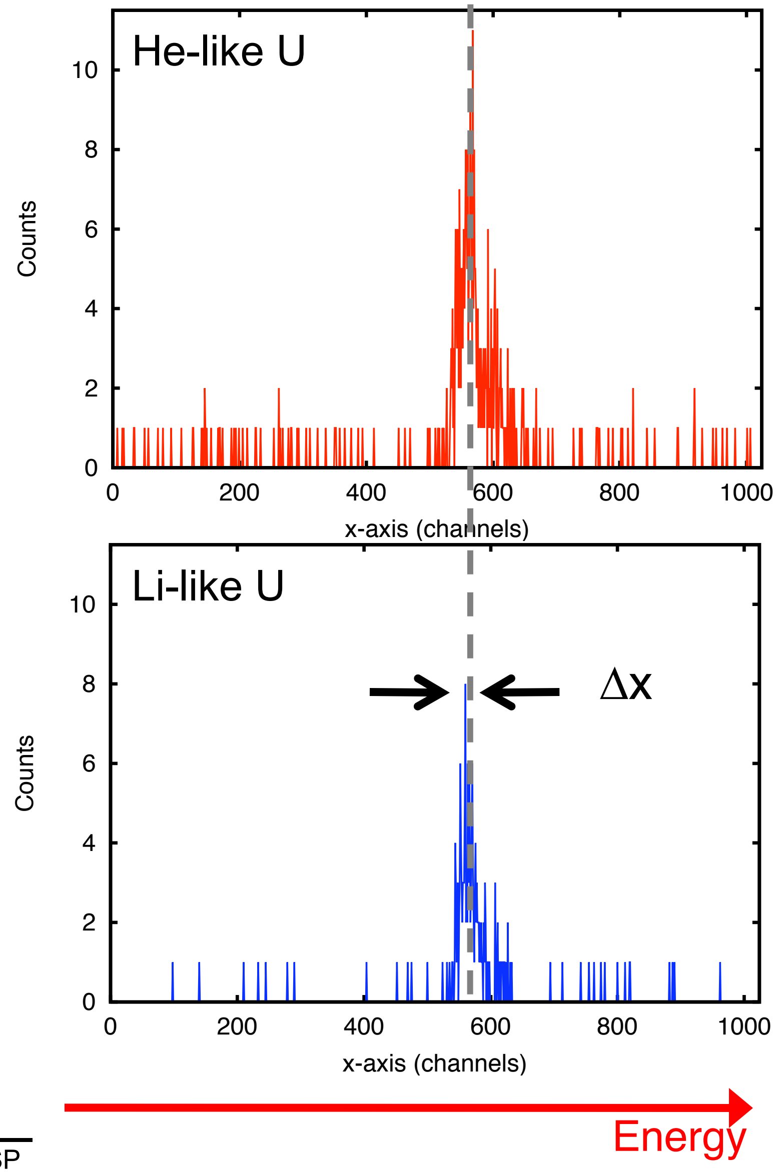
He-like uranium 1s2p $^3P_2$ - 1s2s $^3S_1$

- Counts: ~ 300
- Acquisition time: **24.6 hours**

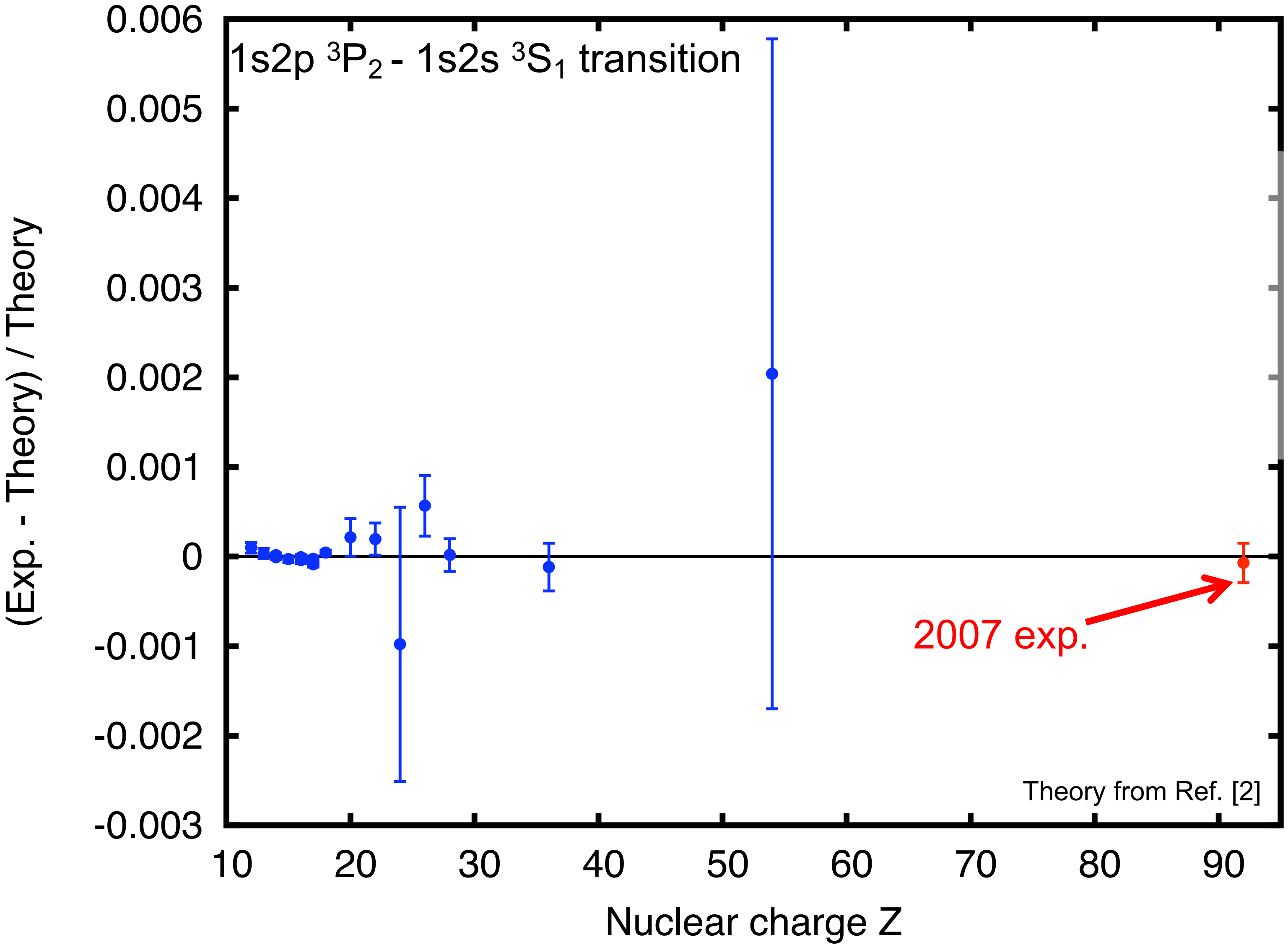
$$E_{\rm He} = E_{\rm Li}\frac{\gamma_{\rm He}}{\gamma_{\rm Li}}\left(1+\frac{\Delta x}{\tan\Theta_B\ D}\right)$$

Li-like uranium $1s^22p$ $^2P_{3/2}$ - $1s^22s$ $^2S_{1/2}$

- Counts: ~160
- Acquisition time: **4.6 hours**



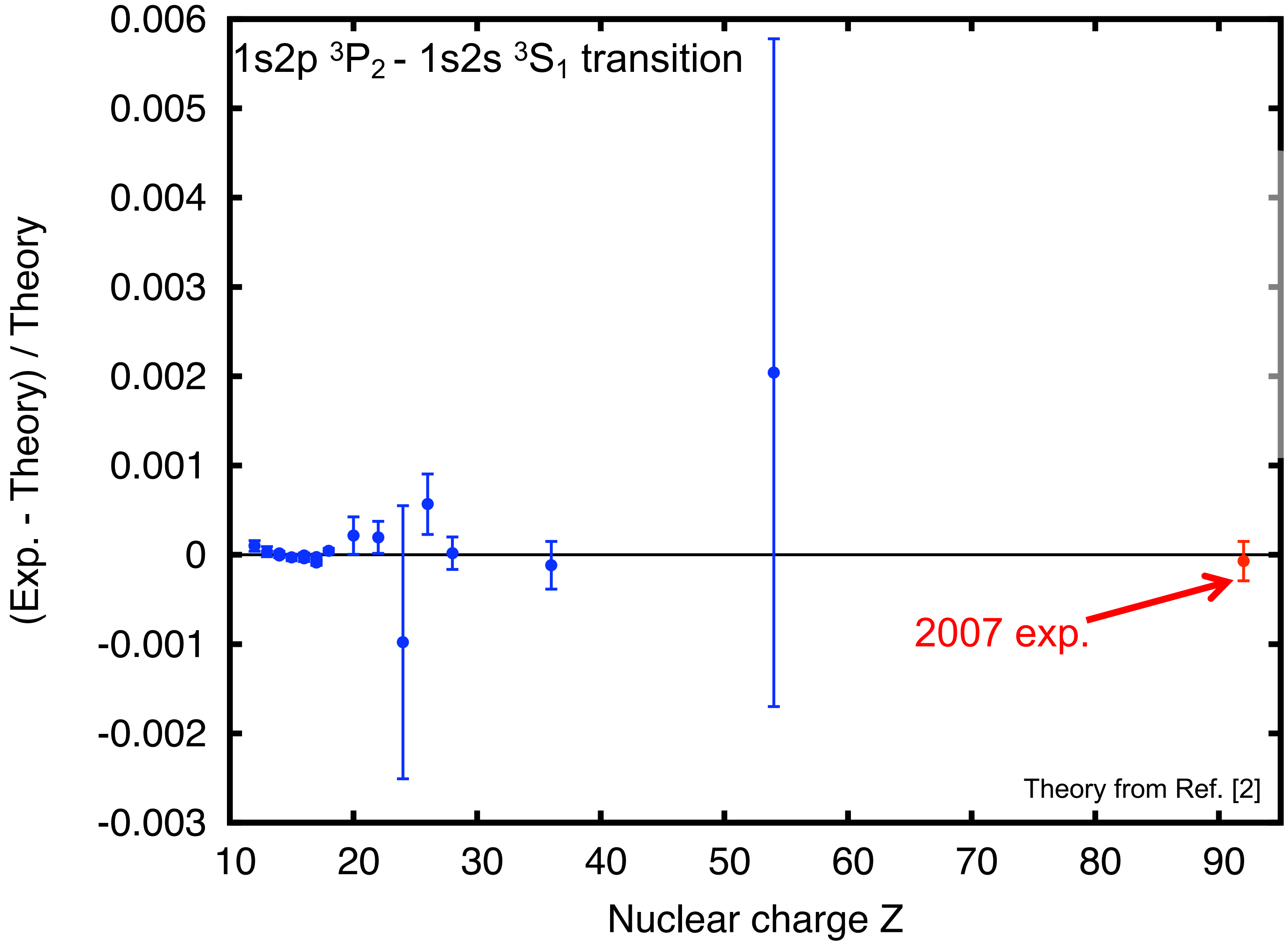
2007 experimental result



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

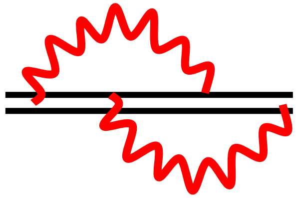
[1] MT *et al.*, Eur. Phys. Lett. **87**, 63001 (2009)

2007 experimental result

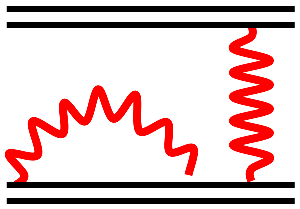


Energy of the intra-shell transition:
4509.71 ± 0.99 eV [1]

Good… but not enough!



Two-loop QED = 0.20 eV [2]



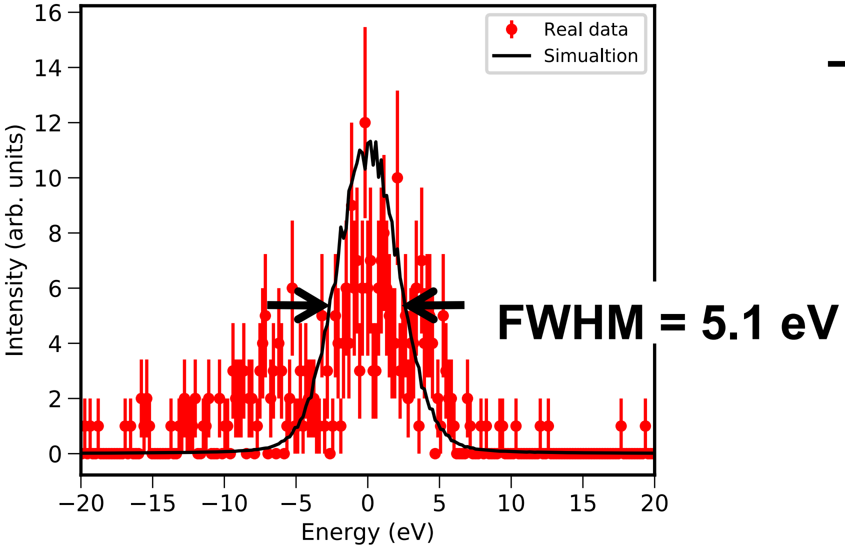
Two-electron QED = 0.76 eV [2]

[1] MT *et al.*, Eur. Phys. Lett. **87**, 63001 (2009)
[2] Artemyev et al., Phys. Rev. A **71**, 062104 (2005)

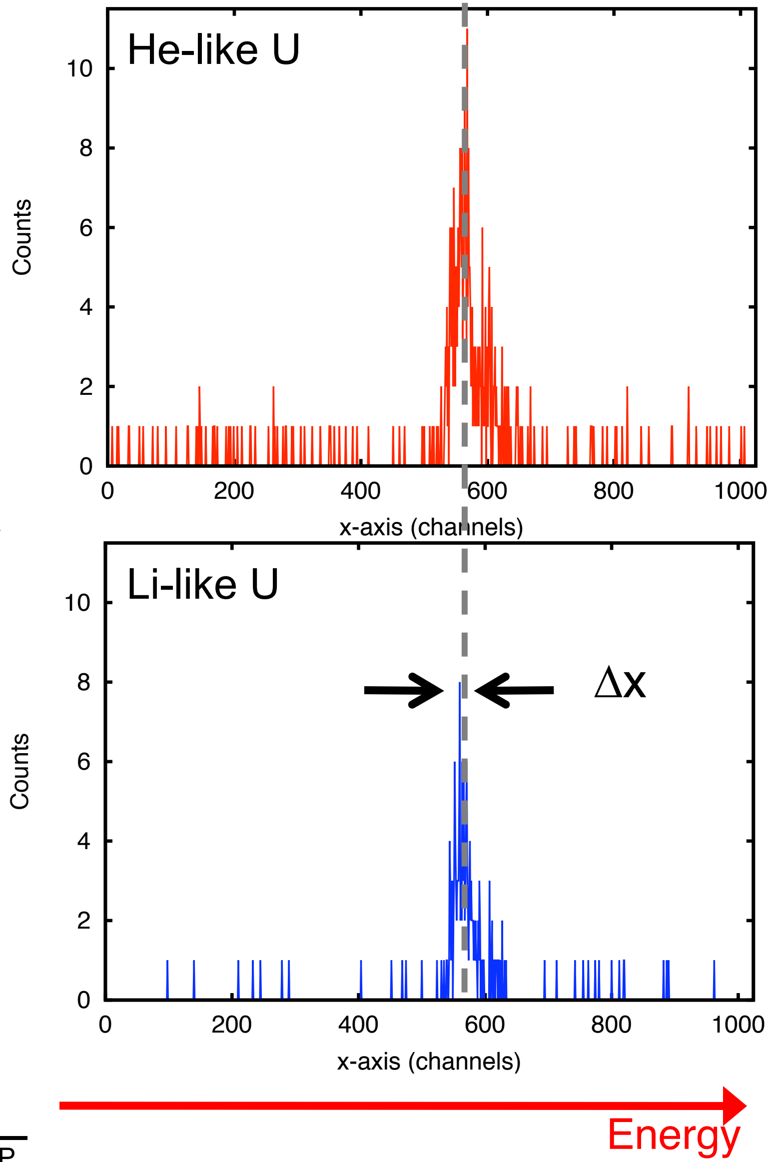
2007 experimental result

Very bad crystal employed in the spectrometer!!

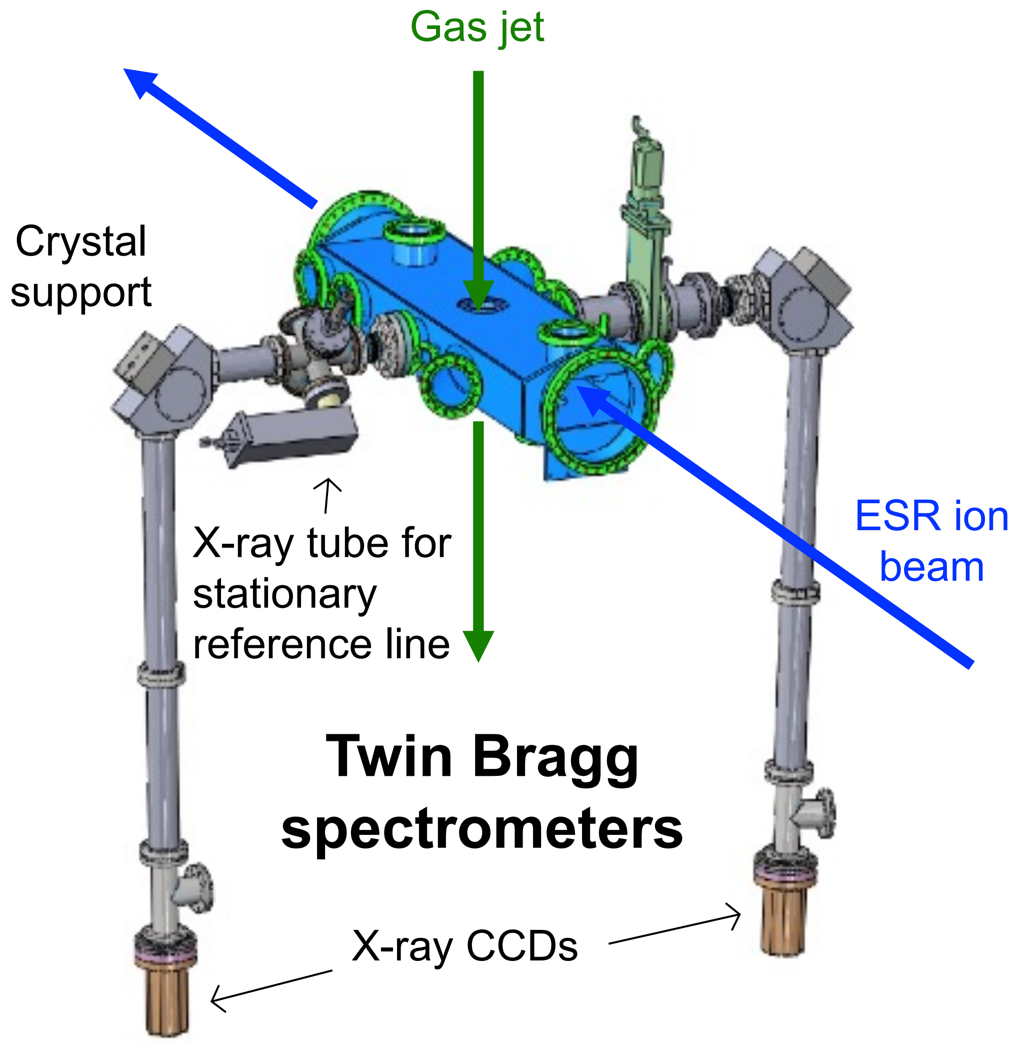
Ge (220) X-ray crystal reflection map



→Low resolution
→Low reflectivity



14 years later… the 2021 set-up



- **Double spectrometer**

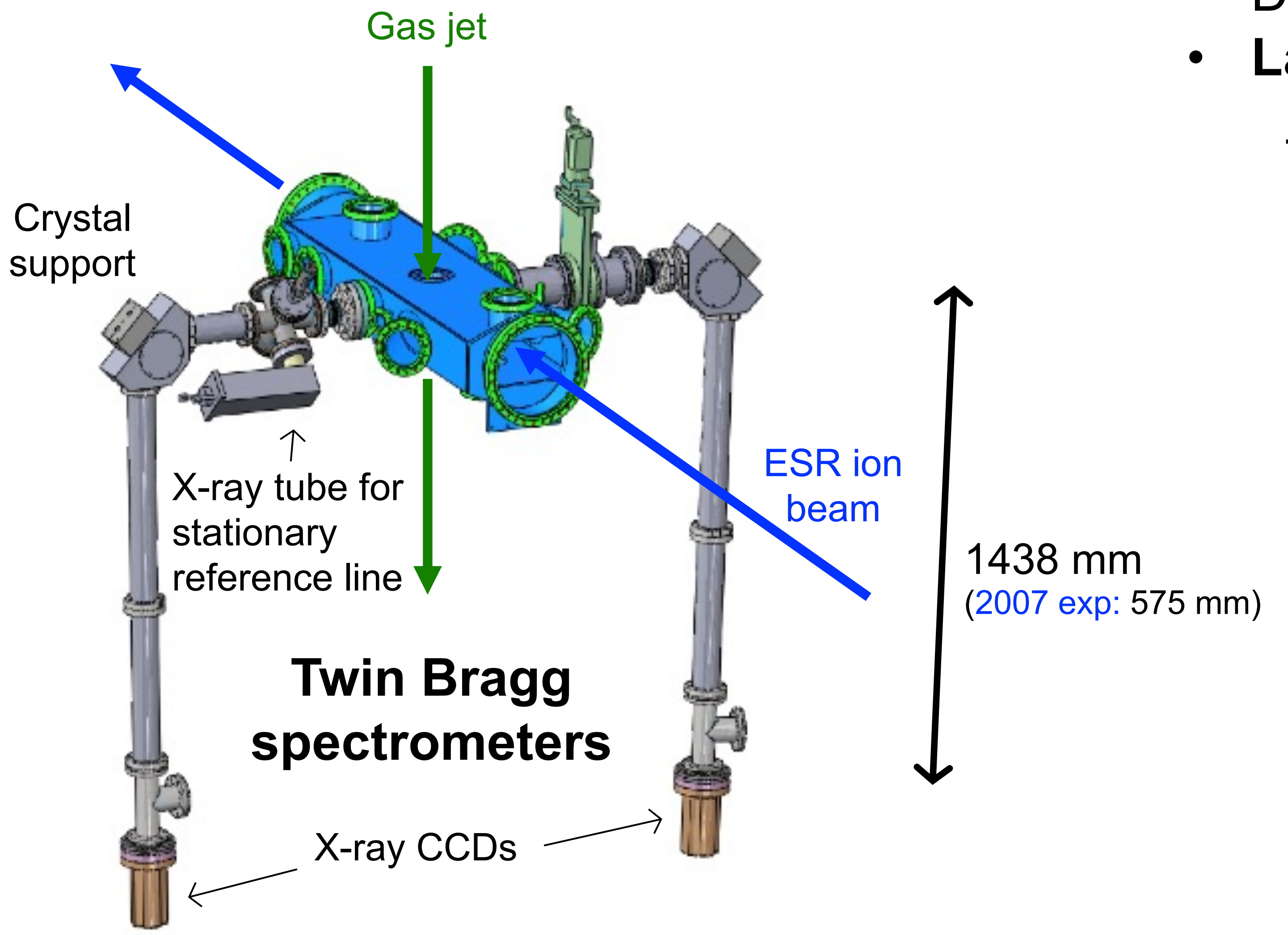
→ Higher luminosity
→ Better control of systematics

Phase-0

14 years later… the 2021 set-up

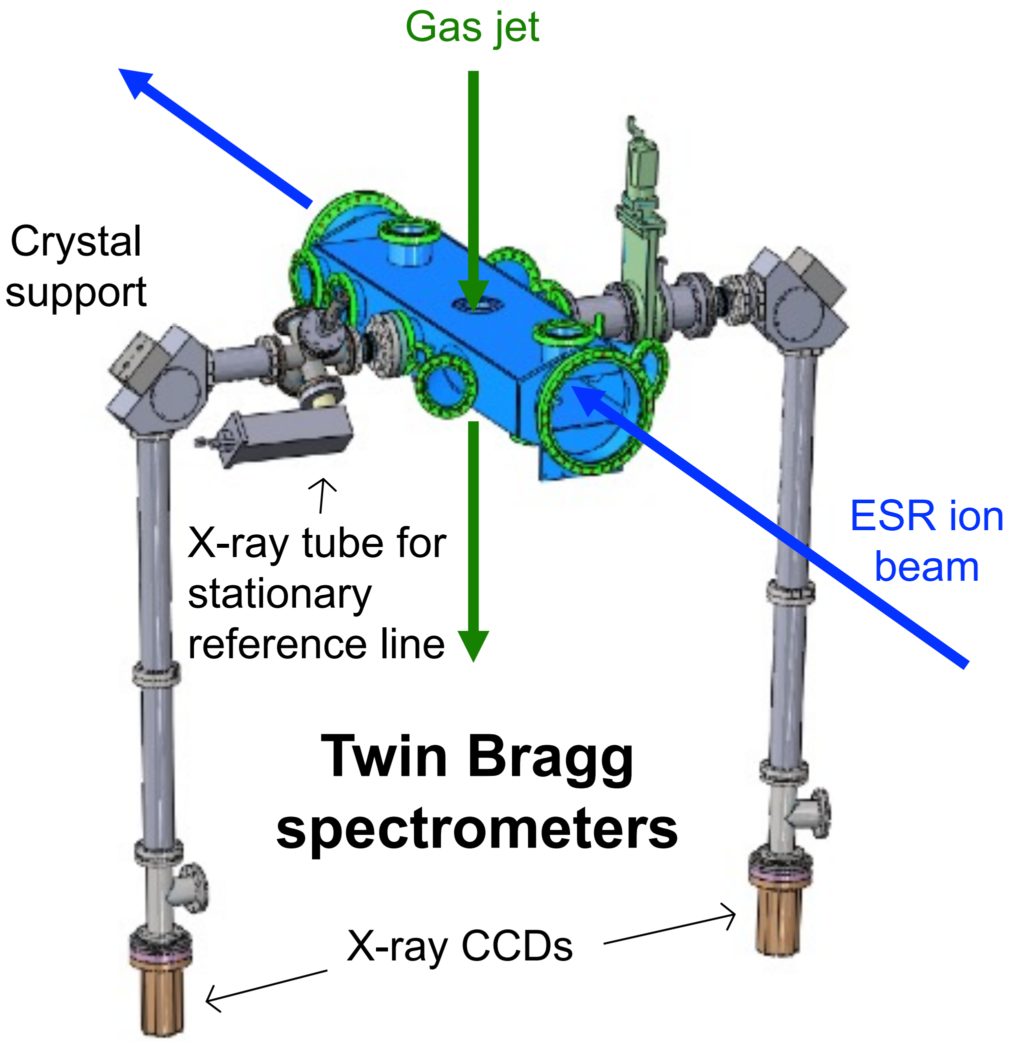
- Double spectrometer
- **Larger bending radius**

  → Higher resolution



Phase-0

14 years later… the 2021 set-up

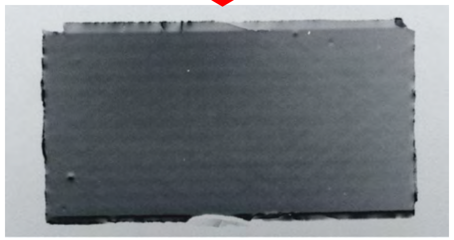


FAIR Phase-0

- Double spectrometer
- Larger bending radius
- **New crystals**

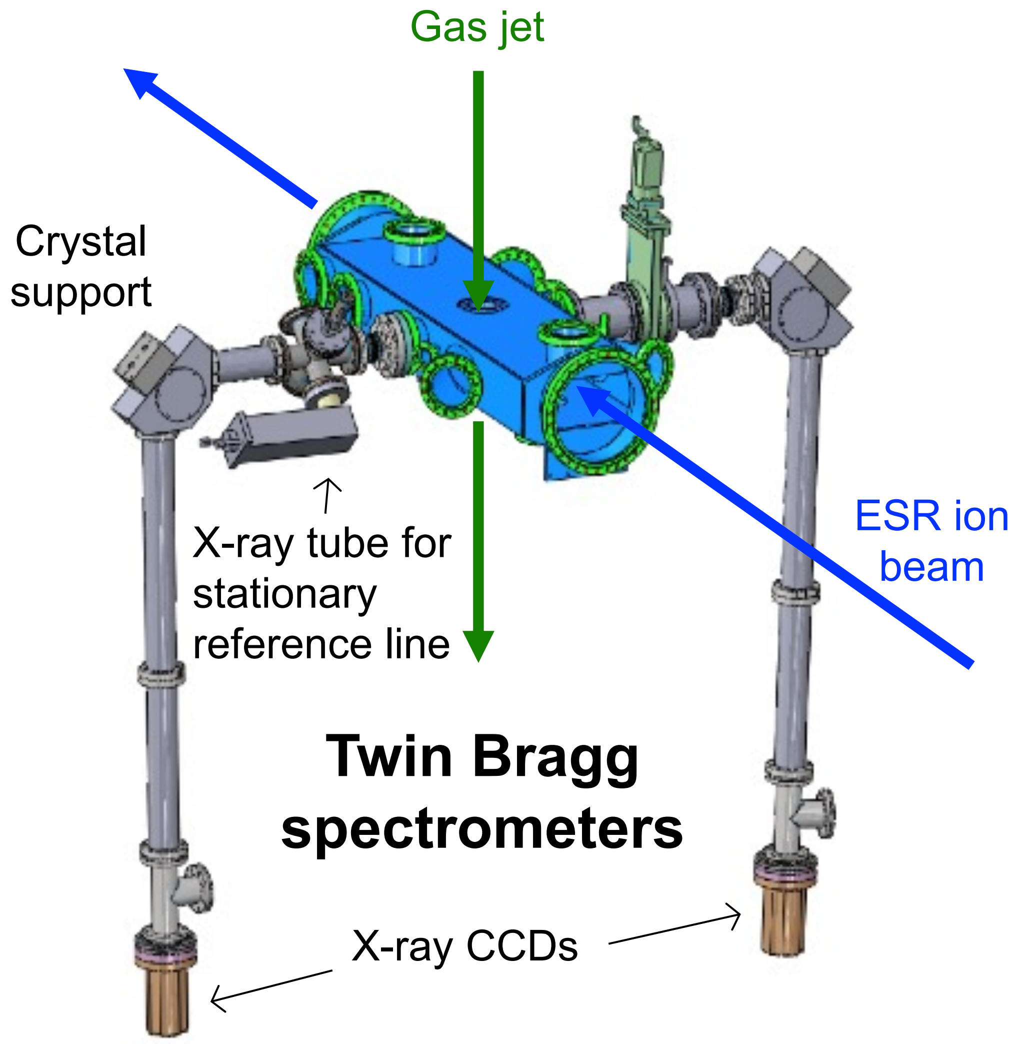
→ No more aberrations
→ Higher luminosity

2007 exp:



Ge (220) X-ray crystal reflection map

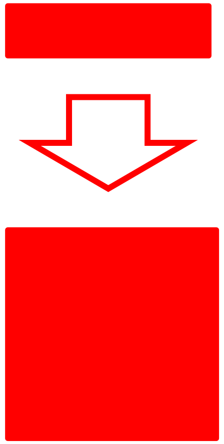
14 years later… the 2021 set-up



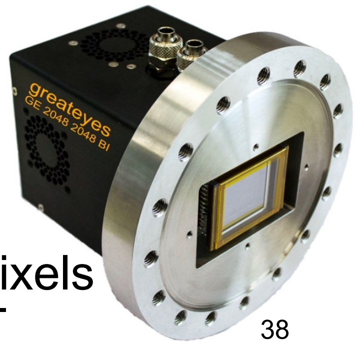
- Double spectrometer
- Larger bending radius
- New crystals
- **New detectors**

→ 8 x higher luminosity

2007 exp:
1024x256x26 μm^2 pixels



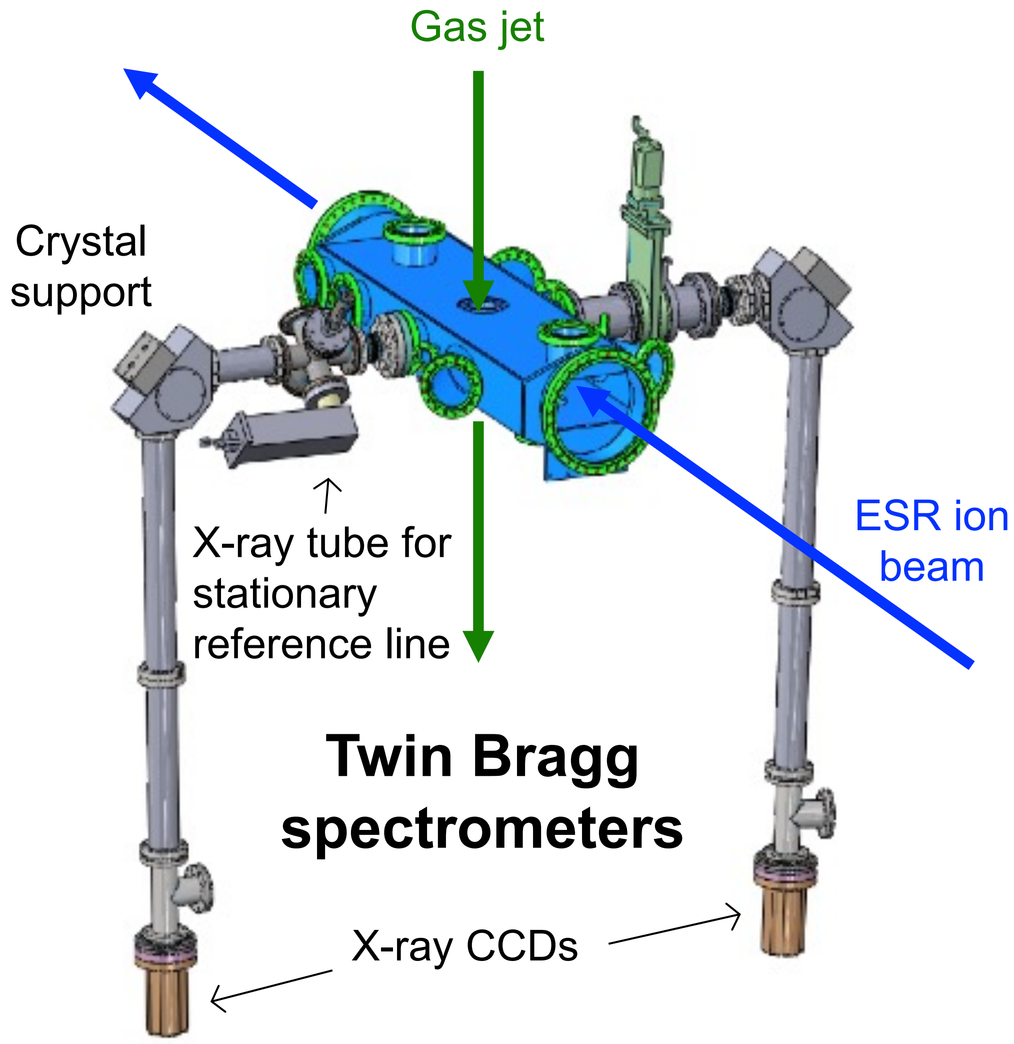
2 x

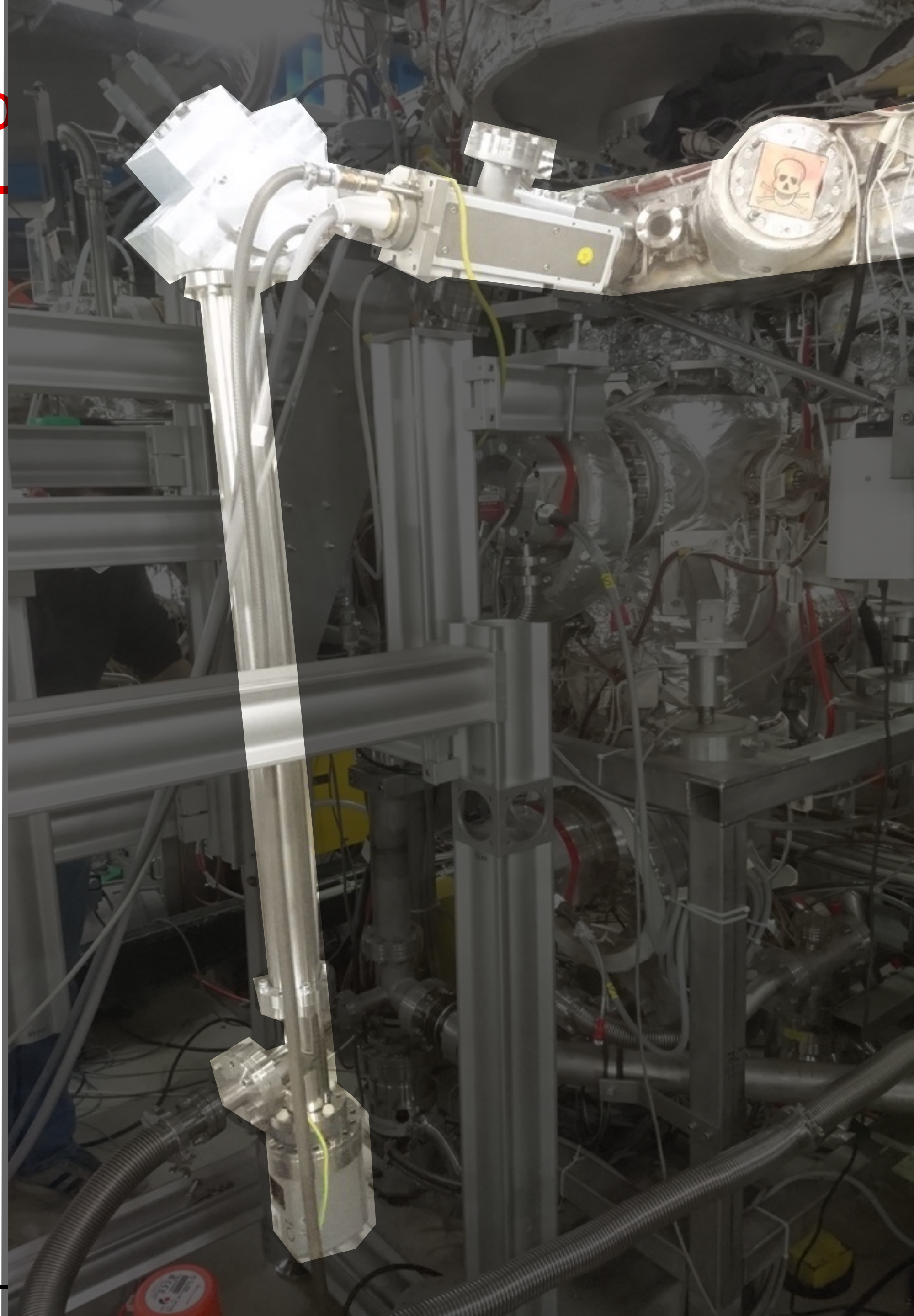


2 x 2048 x 2048 x 13,5 μm pixels

FAIR Phase-0

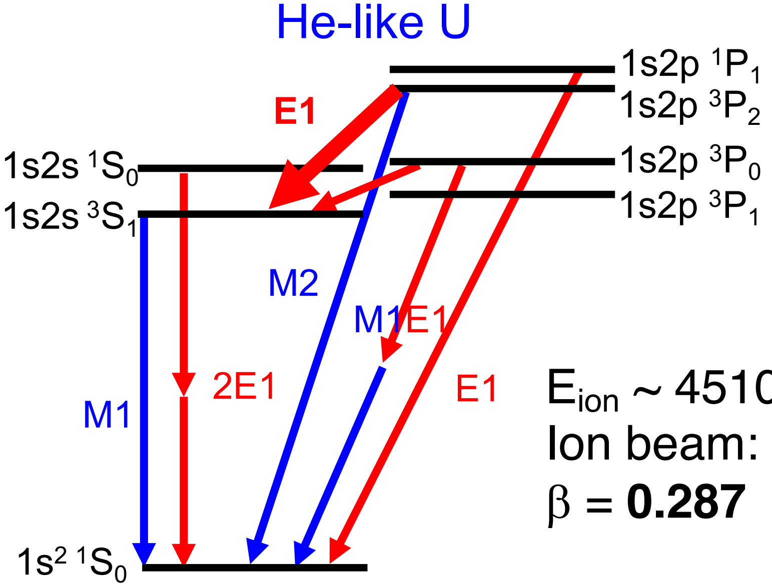
14 years later… the 2021 set-up



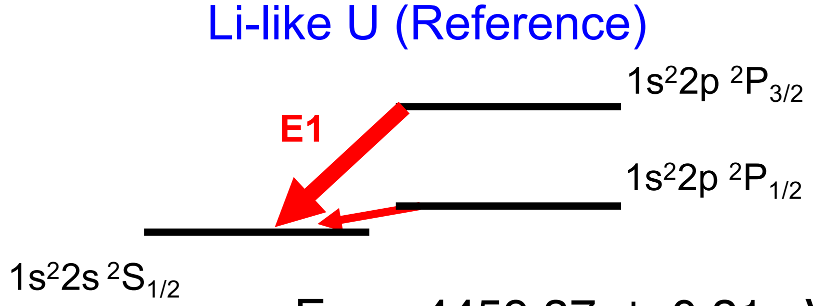


FAIR Phase-0

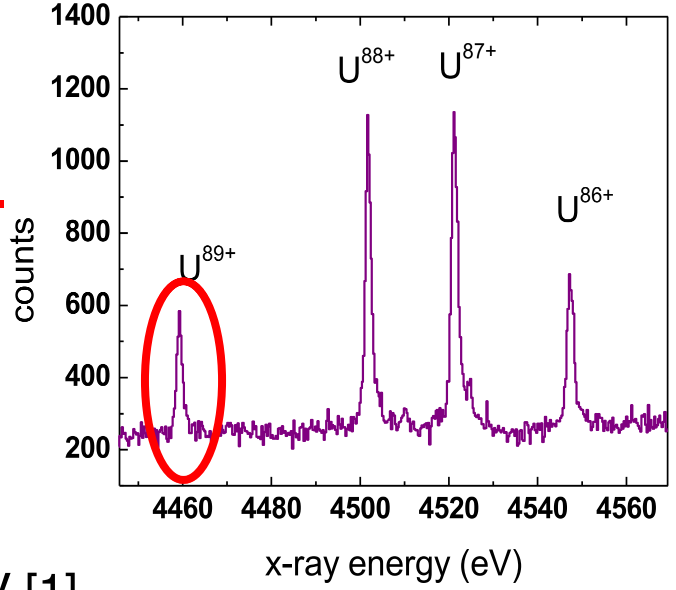
Relativist Doppler tuning with He- and Li-like U and Be-like



E_{ion} ~ 4510 eV
Ion beam: **41.03 Mev/u**
β = **0.287**



E_{ion} = 4459.37 ± 0.21 eV [1]
Ion beam: **30.16 Mev/u**
β = **0.248**



E_{lab} ~ 4319 eV

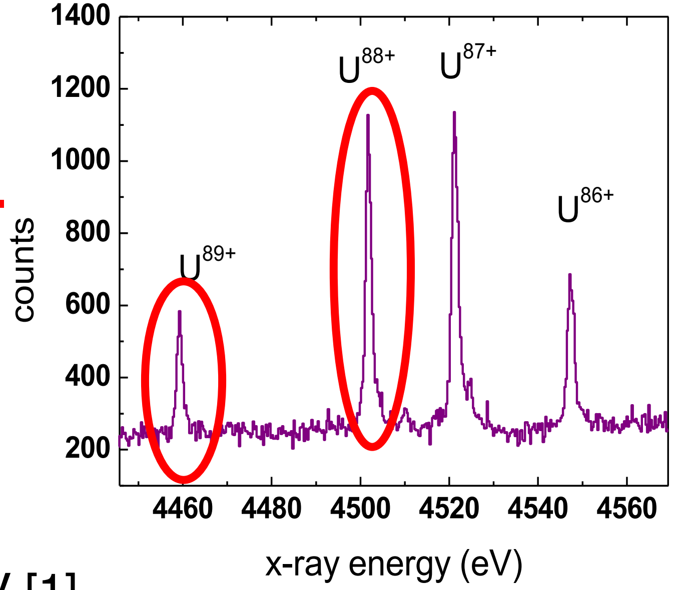
Same energy in the laboratory frame

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

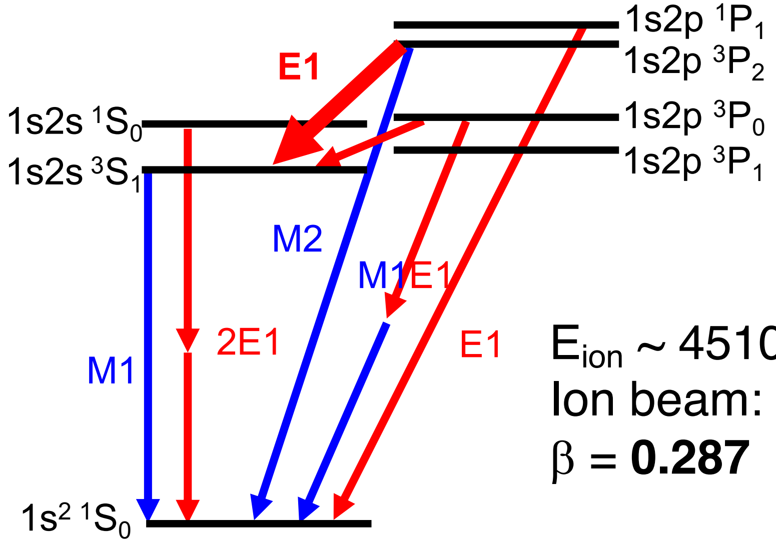
Unknown E — Reference E_0

[1] P. Beiersdorfer et al., Phys. Rev. Lett. **71**, 3939 (1993), P. Beiersdorfer, Nucl. Instrum. Meth. B **99**, 114 (1995)

Relativist Doppler tuning with He- and Li-like U and Be-like

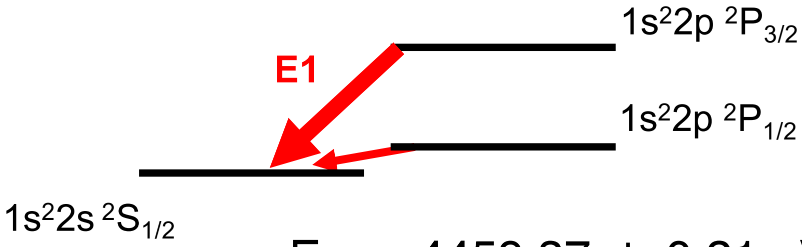


He-like U



E_{ion} ~ 4510 eV
Ion beam: **41.03 Mev/u**
β = **0.287**

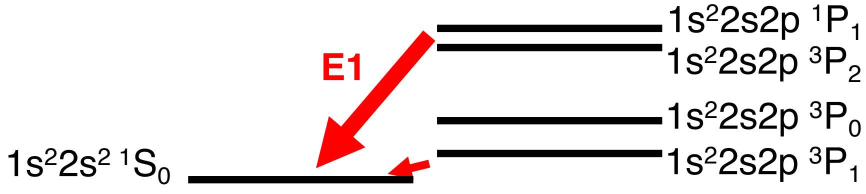
Li-like U (Reference)



E_{ion} = 4459.37 ± 0.21 eV [1]
Ion beam: **30.16 Mev/u**
β = **0.248**

NEW !

Be-like U (2nd reference)



E_{ion} = 4501.72.37 ± 0.21 eV [1]
Ion beam: **39.29 Mev/u**
β = **0.282**

E_{lab} ~ 4319 eV

Same energy in the laboratory frame

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

Unknown E — Reference E_0

[1] P. Beiersdorfer et al., Phys. Rev. Lett. **71**, 3939 (1993), P. Beiersdorfer, Nucl. Instrum. Meth. B **99**, 114 (1995)

2021 beam time

No beam
Injection of Li-like U with 60 MeV
Injection of He-like U with 296 MeV
Injection of H-like U with 296 MeV
Injection of Li-like U with 296 MeV

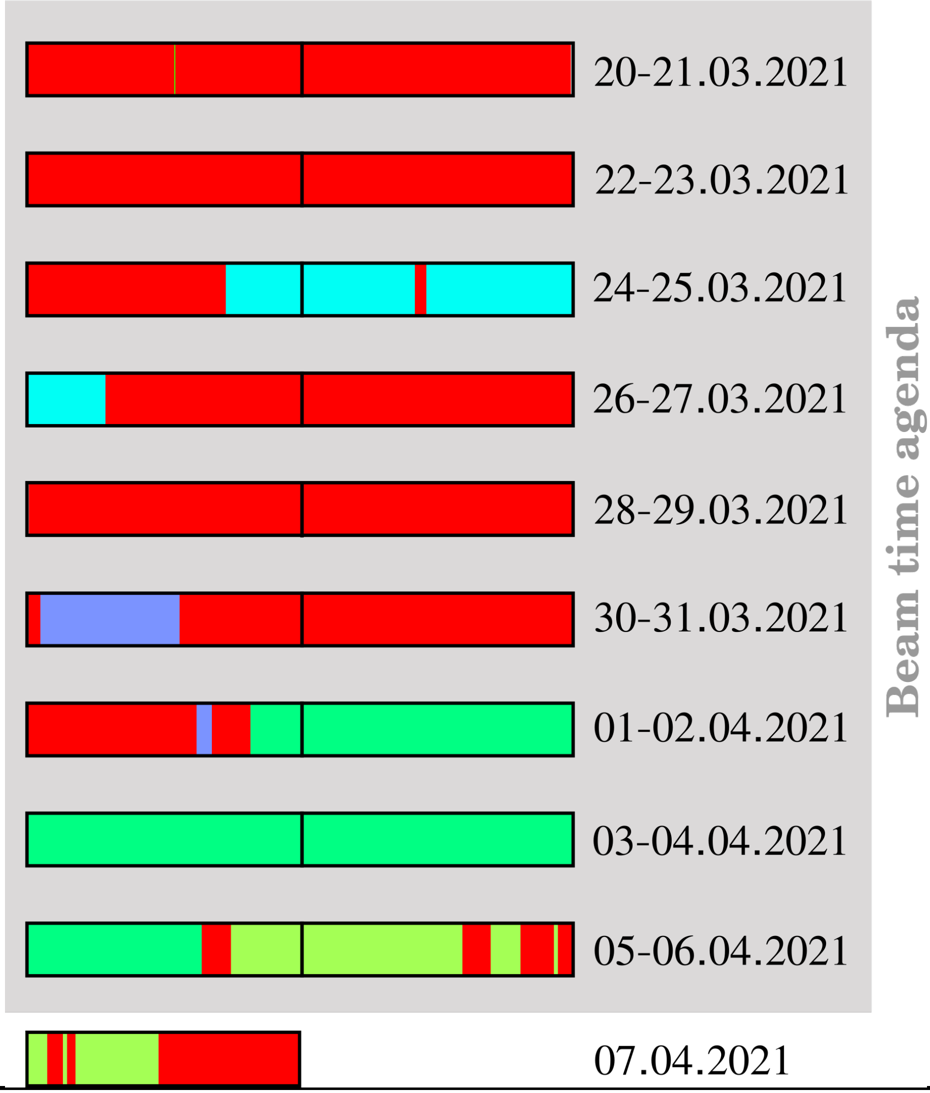
Beam time acquisition:

He-like U → ~ 84h → 1800 photons per arm (1 photon every 3 cycles, 3’)

Li-like U → ~ 11h → 1400 photons (~2 photon per cycle. 1’)

Be-like U → ~ 24h → ~700 photons

(out of ~400h beam time)



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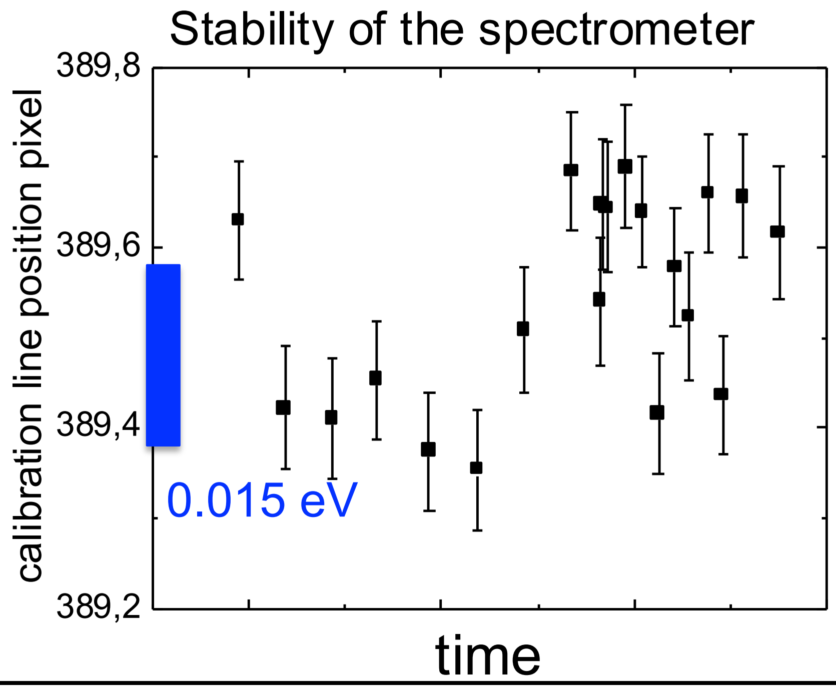
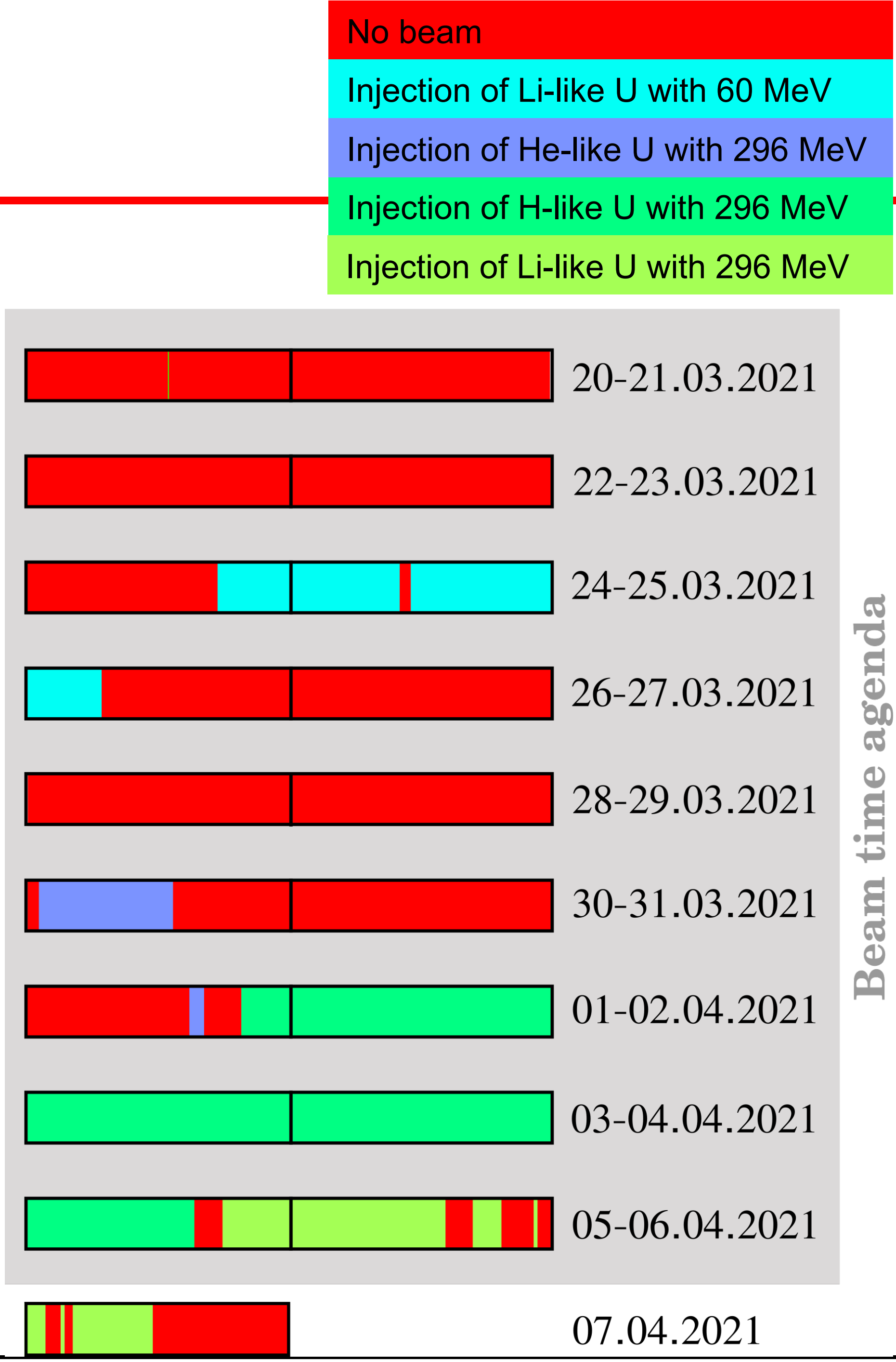
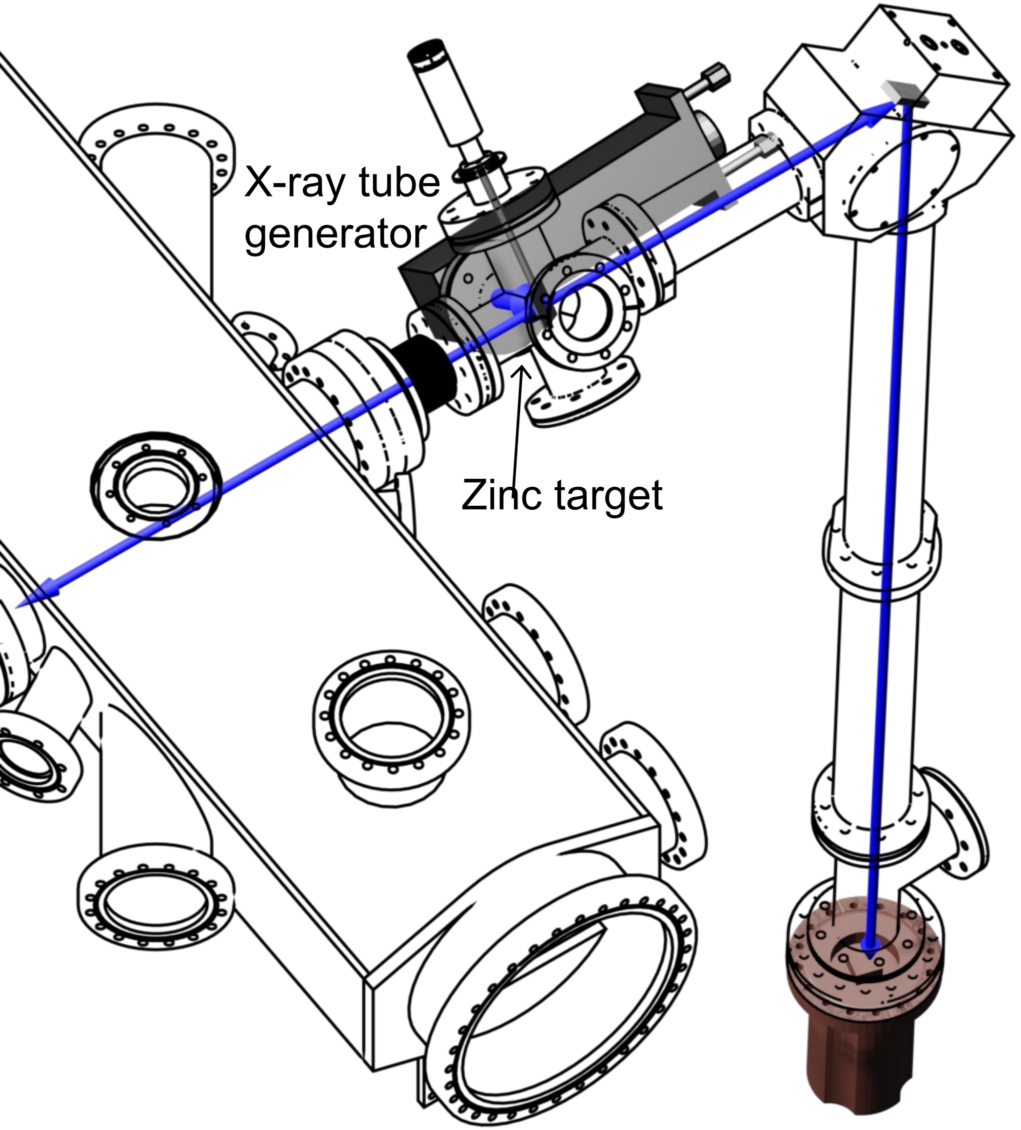
(out of ~400h beam time)

Stability check using Kα zinc line reflection (at the second order)

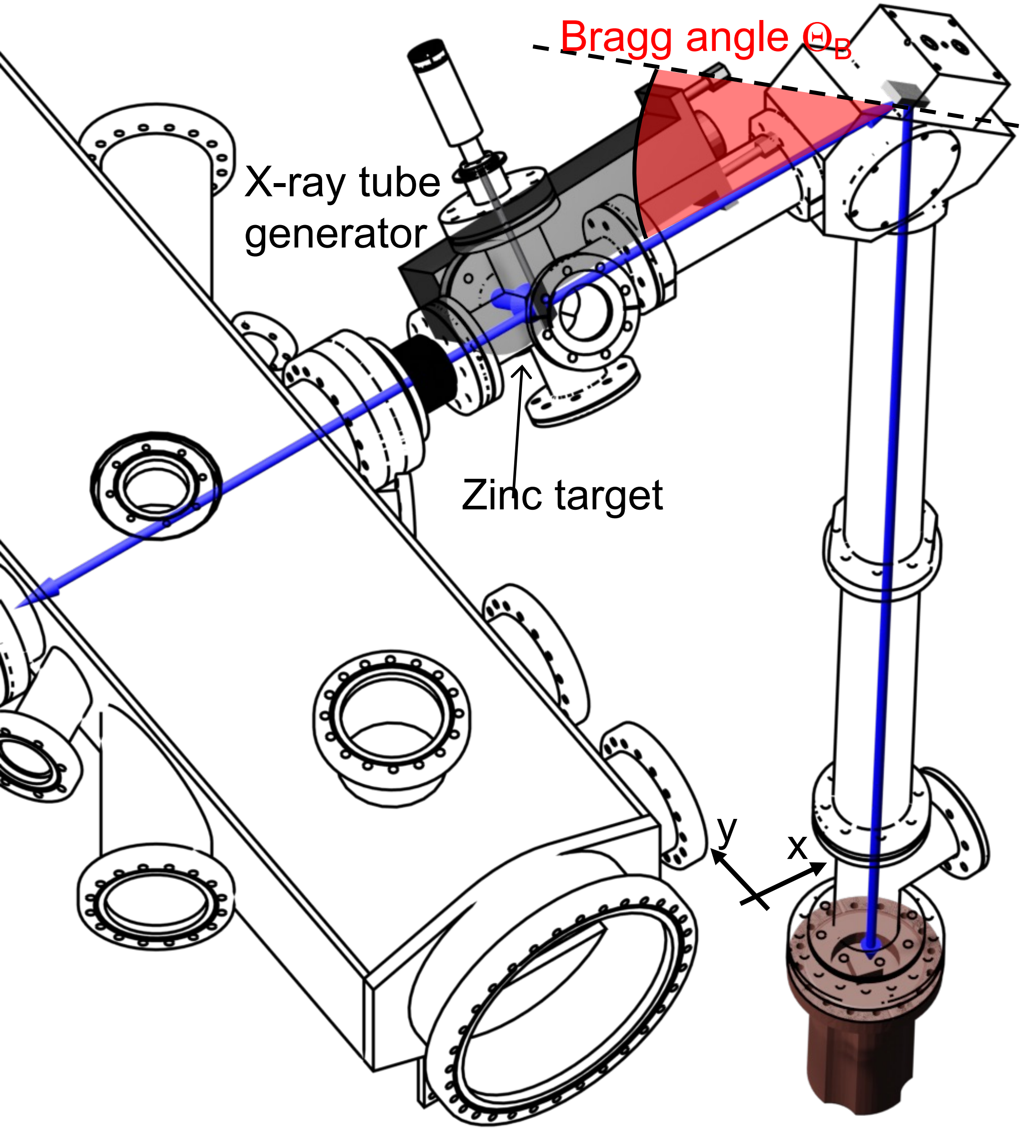


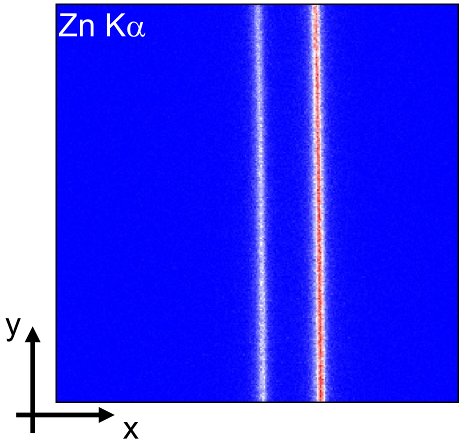


Double reference measurement method



Double reference measurement method





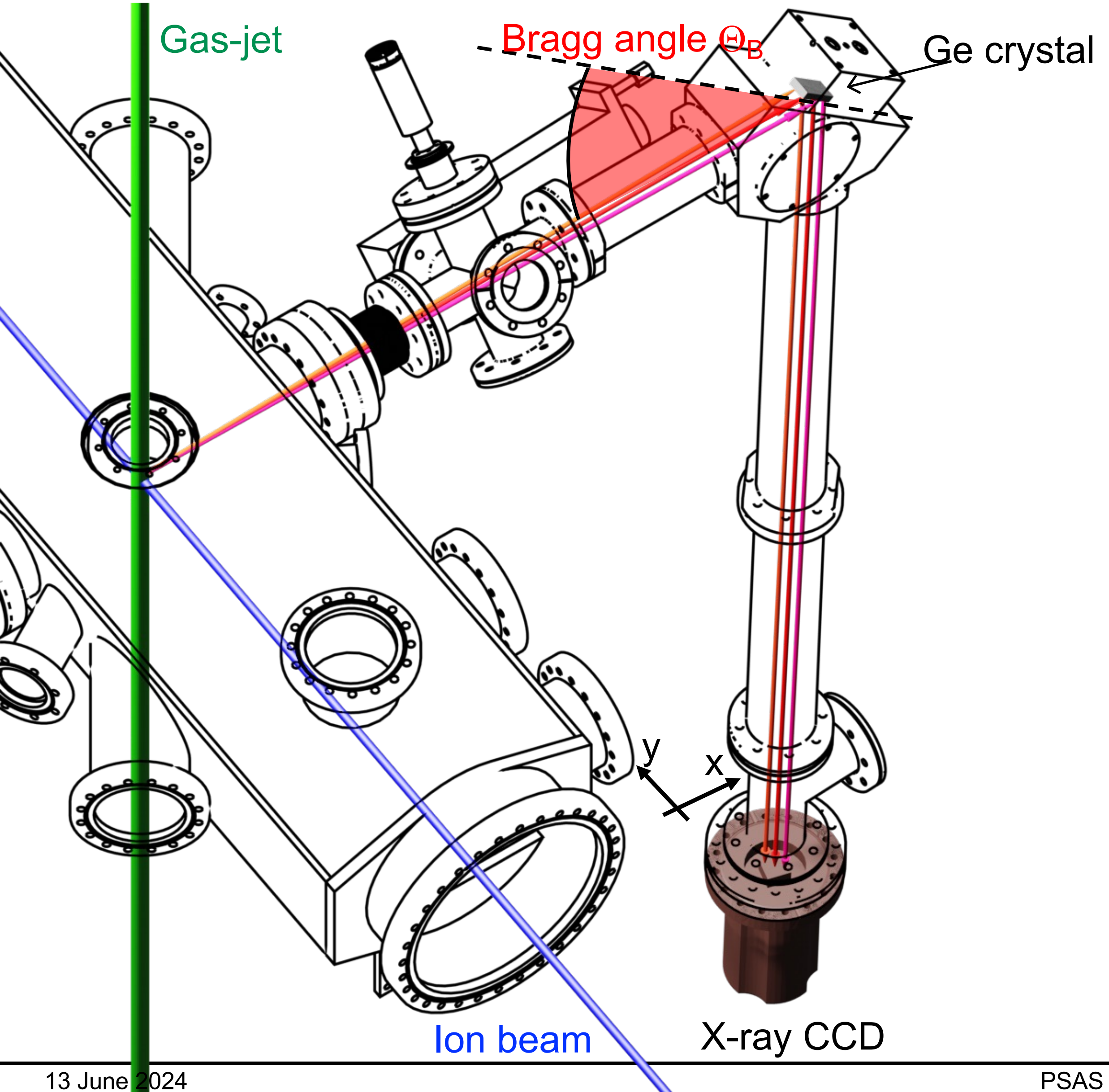
x-axis → dispersion axis (prop. to E)

Bragg law of diffraction

$$n\frac{hc}{E} = 2d\sin\Theta_B$$

n: diffraction order
2d: crystal planes spacing

Double reference measurement method



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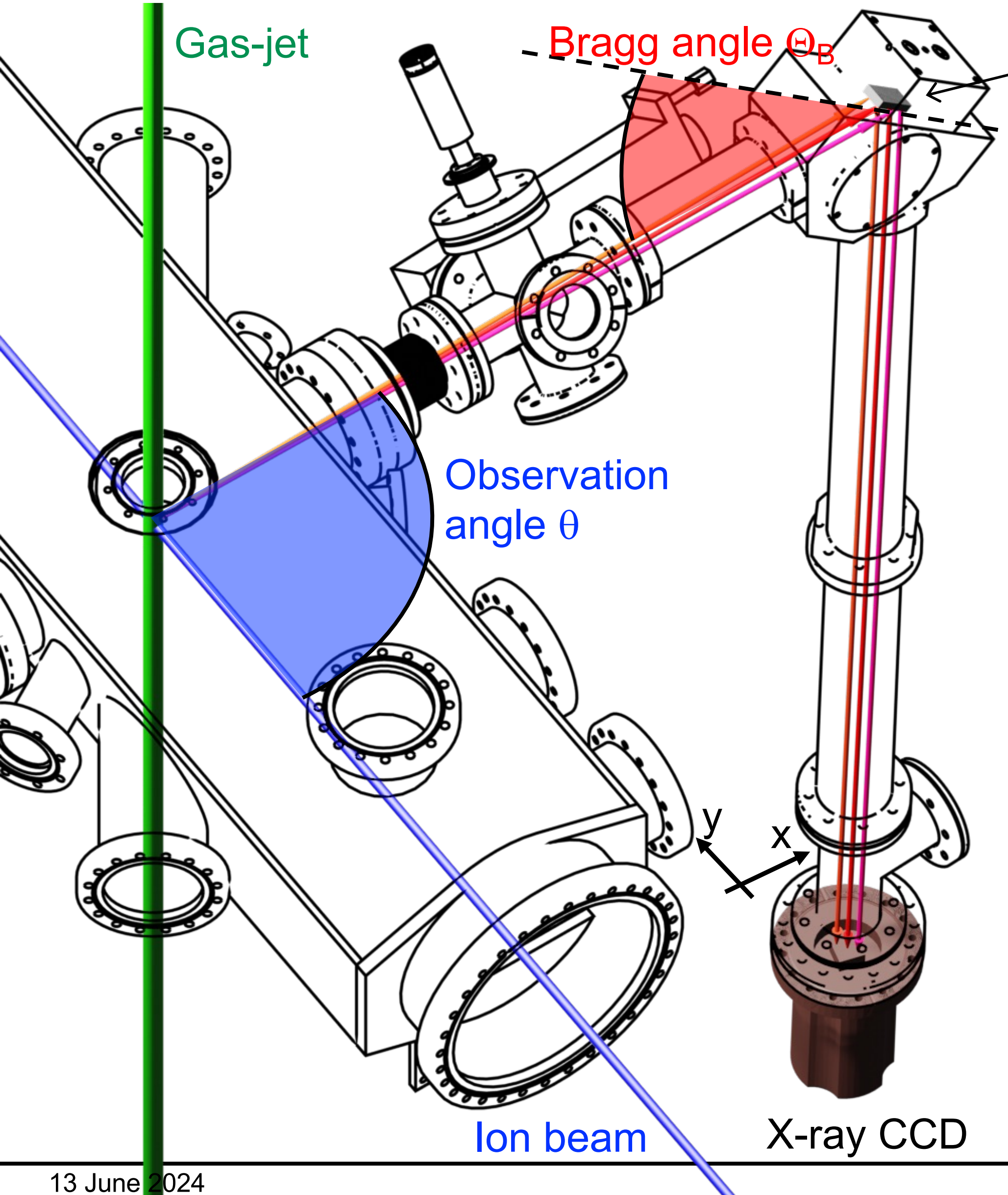
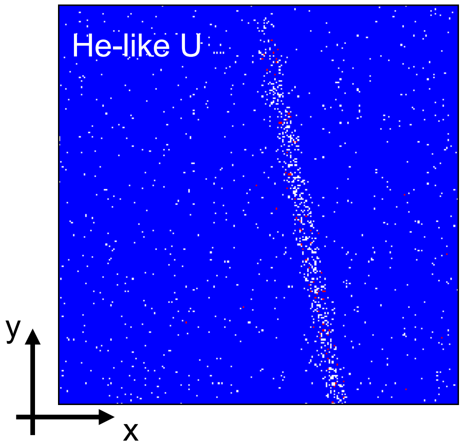


$$\frac{E}{\Delta E} = 2000$$



x-axis → dispersion axis (prop. to E)

Bragg law of diffraction

$$n\frac{hc}{E} = 2d\sin\Theta_B$$

n: diffraction order
2d: crystal planes spacing

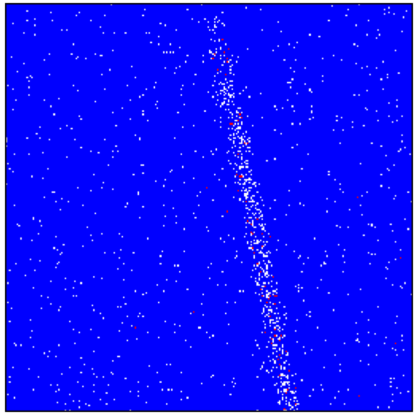
Relativistic Doppler shift

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

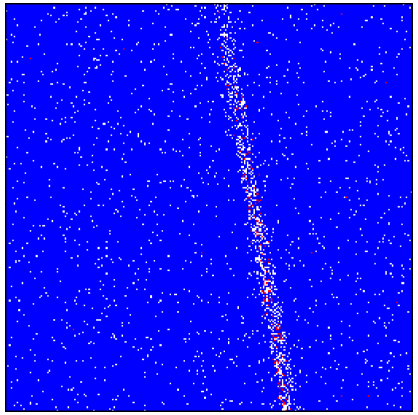
$$\gamma = \frac{1}{\sqrt{1-\beta^2}} ; \beta = \frac{v}{c}$$ c: light speed

Spectral line positions

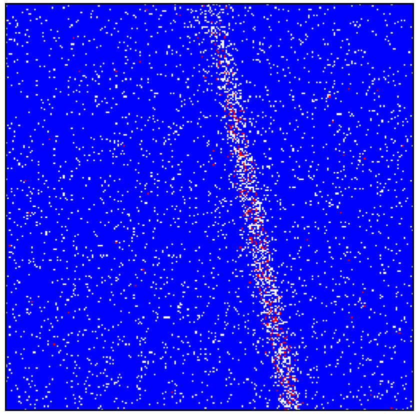
He-like U



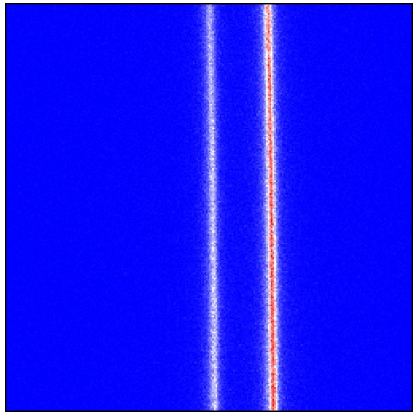
Moving ref.
Li-like U



Moving ref.
Be-like U

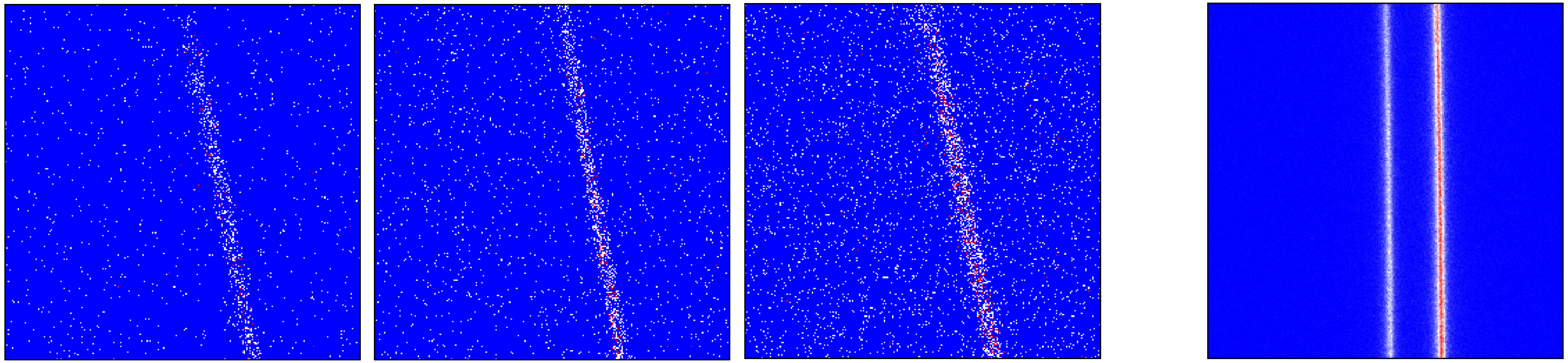


Stationary ref.
Zn Kα fluorecence

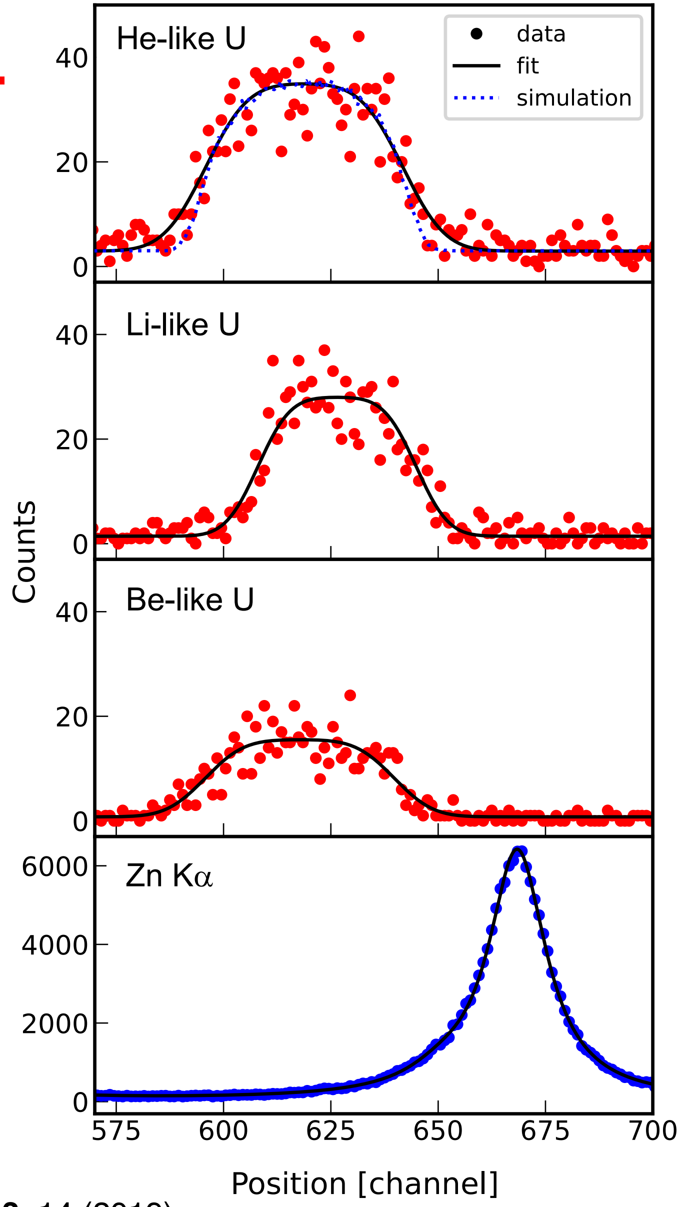


Spectral line positions

He-like U	Moving ref. Li-like U	Moving ref. Be-like U	Stationary ref. Zn Kα fluorecence



Projection on the dispersion axis



- **Fit using Nested_fit code** (Bayesian methods) [1,2]

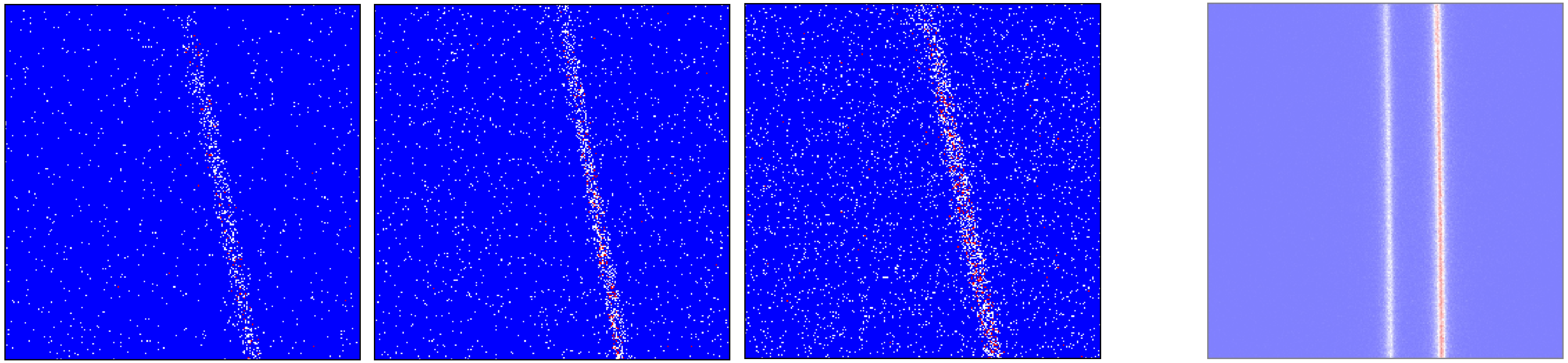
- **Poisson likelihood**
  adapted for very low count rate (here the background ~ 0 counts/ch)

- **2D analysis**
  $F(x,y) = f[x - (a + b\,y)] + bg$

[1] MT, Proceedings **33**, 14 (2019)
[2] https://github.com/martinit18/nested_fit

Spectral line positions

He-like U | Moving ref. Li-like U | Moving ref. Be-like U | Stationary ref. Zn Kα fluorecence



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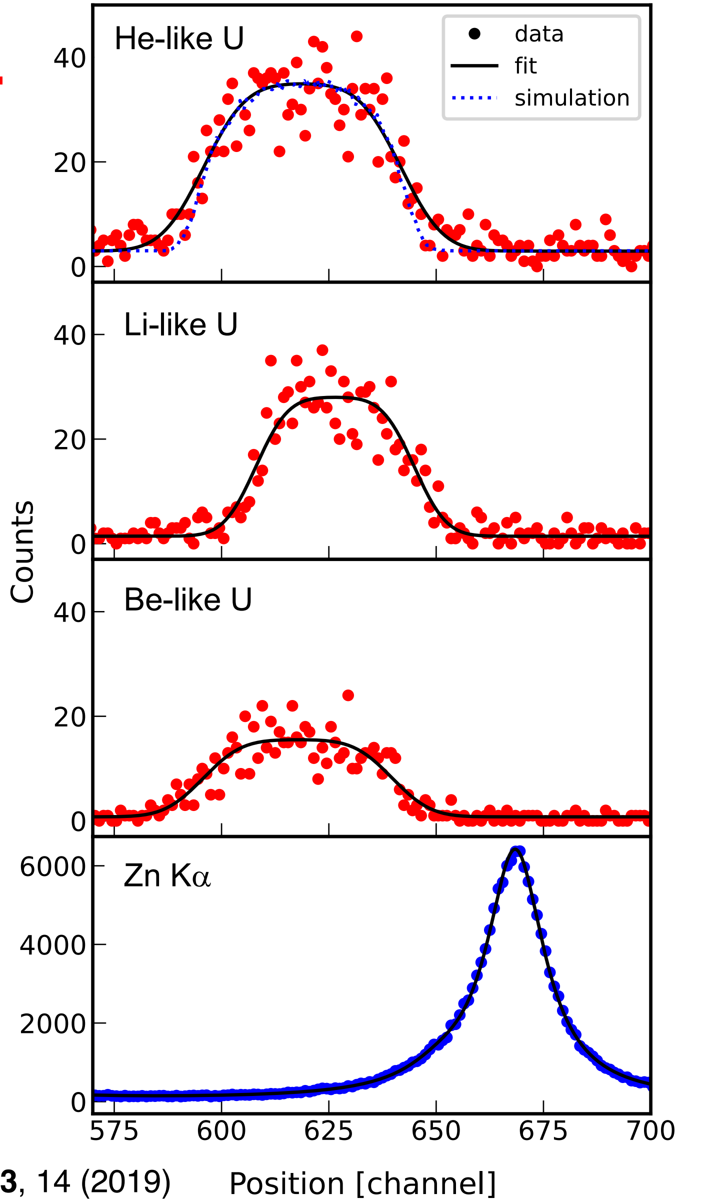

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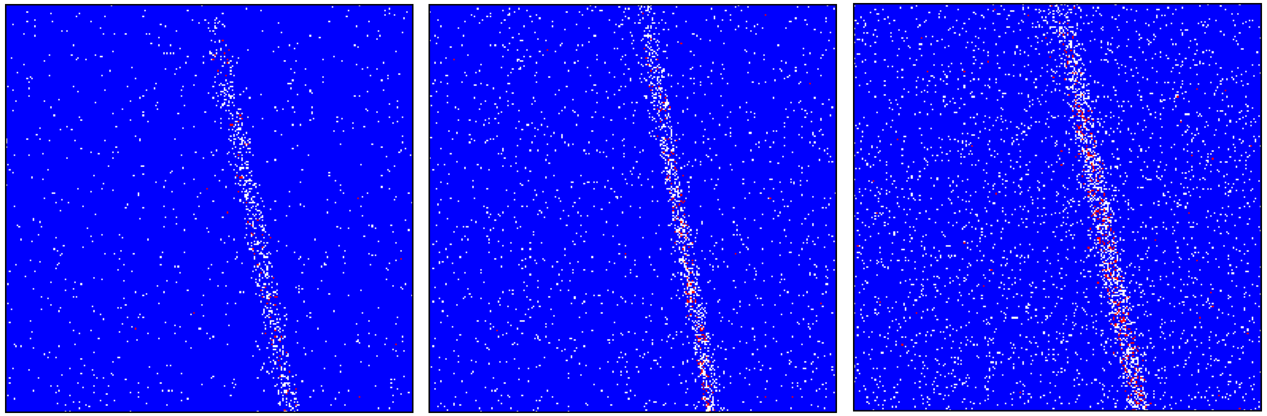
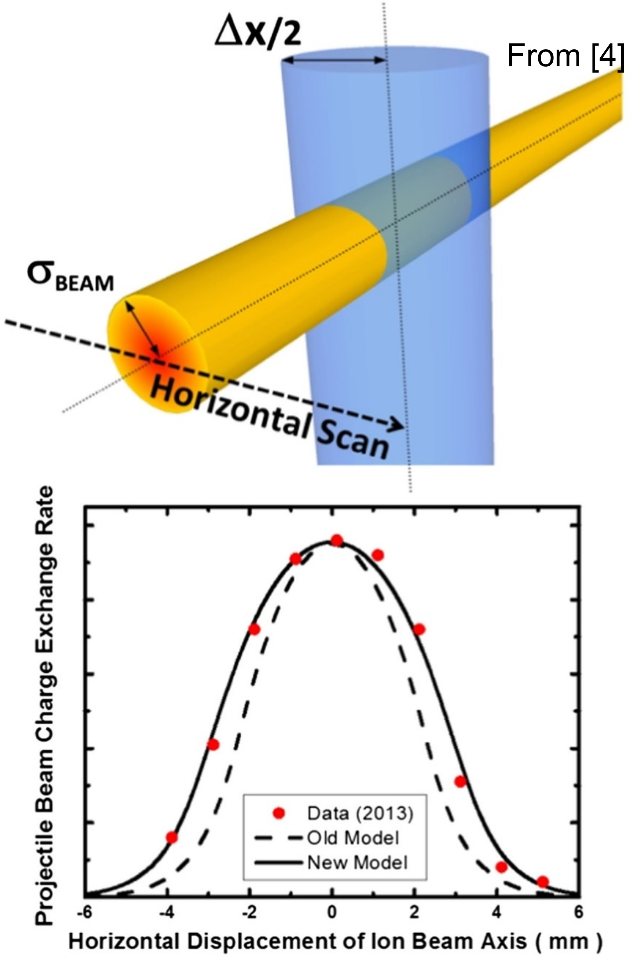
- **2D analysis**
  $F(x,y) = f[x - (a + b\,y)] + bg$
- **Modelling tests of the line profile by Bayesian methods**
  f[x]: single convolution between a Gaussian and a flat profile [3]
  No satellites!

[1] MT, Proceedings **33**, 14 (2019)
[2] https://github.com/martinit18/nested_fit
[3] MT, Atoms **11**, 64 (2023)

Spectral line positions

He-like U	Moving ref. Li-like U	Moving ref. Be-like U





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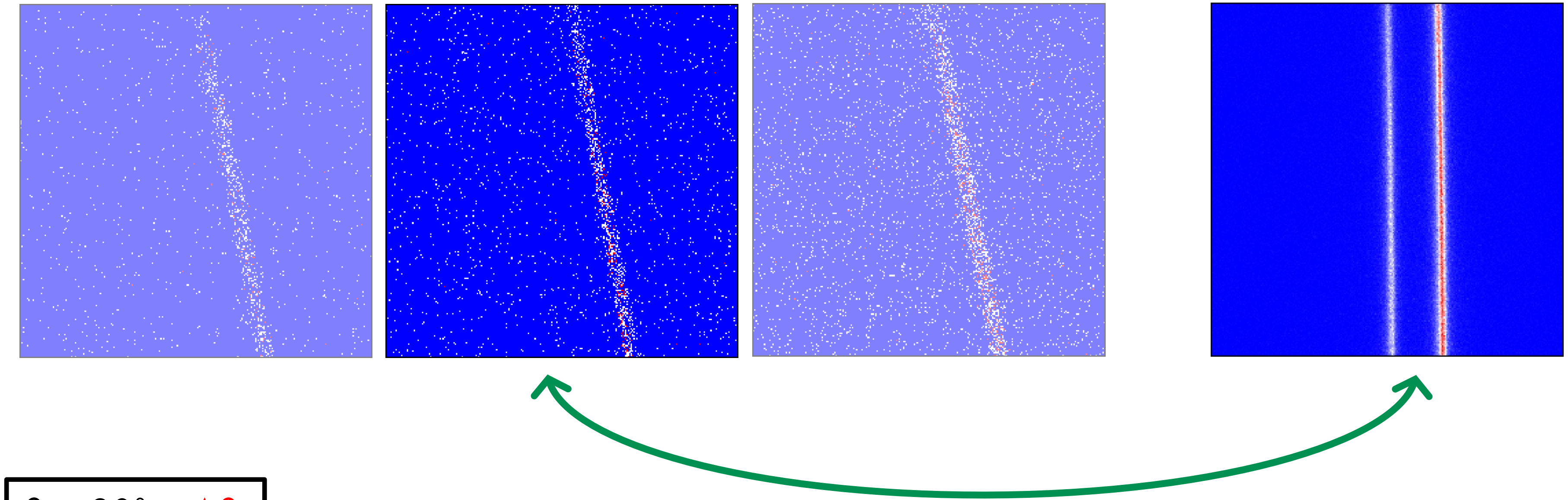
[2] https://github.com/martinit18/nested_fit
[3] MT, Atoms **11**, 64 (2023)
[2] Weber *et al.*, Phys. Rev. ST AB **18**, 034403 (2015)

Extraction of He-like transition energy

He-like U | Moving ref. Li-like U | Moving ref. Be-like U | Stationary ref. Zn Kα fluorecence



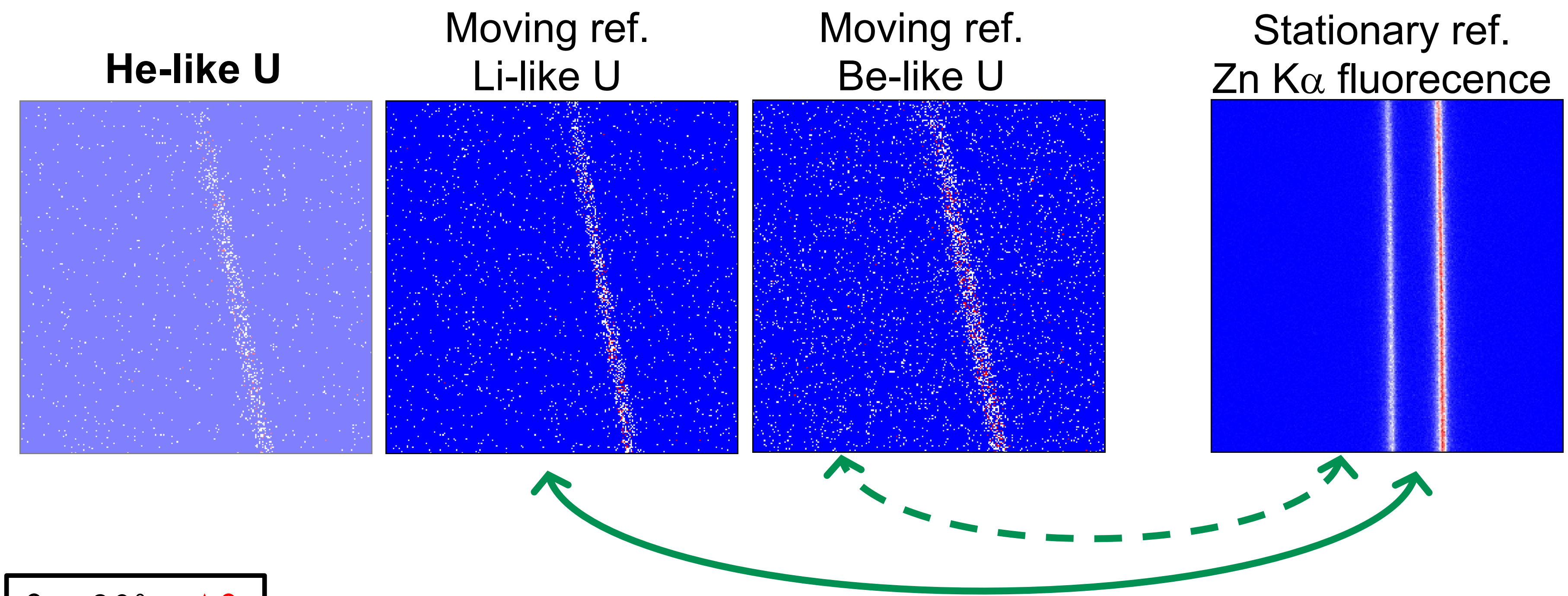
2 kind of references:
moving and stationary

$\theta = 90^\circ + \Delta\theta$

$$E_0^{\mathrm{Mov}} = E_0^{\mathrm{Stat}} \frac{1}{2}\gamma_0 (1+\beta_0 \sin \Delta\theta) \left(1 + \frac{x^{\mathrm{Mov}} - x^{\mathrm{Stat}}}{D \tan \Theta}\right)$$

- **$\Delta\theta \pm \delta\theta$: observation angle misalignment**

Extraction of He-like transition energy



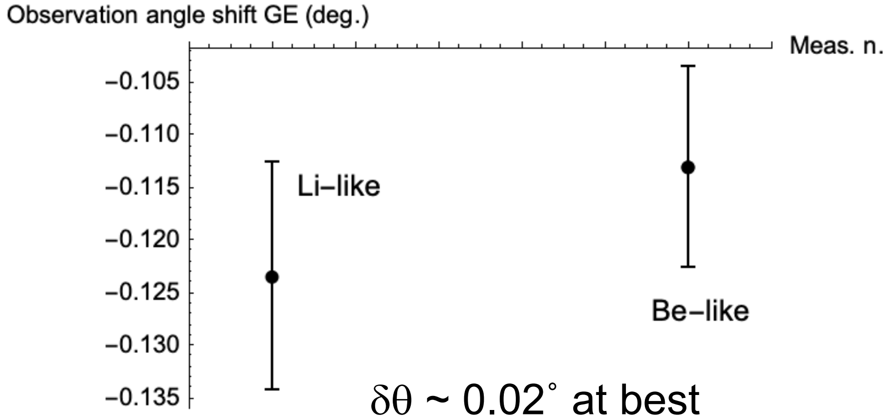
2 kind of references:
moving and stationary

2 moving references
(Li- and Be-like)

$\theta = 90^\circ + \Delta\theta$

$$E_0^{\mathrm{Mov}} = E_0^{\mathrm{Stat}} \frac{1}{2} \gamma_0 (1 + \beta_0 \sin \Delta\theta) \left(1 + \frac{x^{\mathrm{Mov}} - x^{\mathrm{Stat}}}{D \tan \Theta}\right)$$

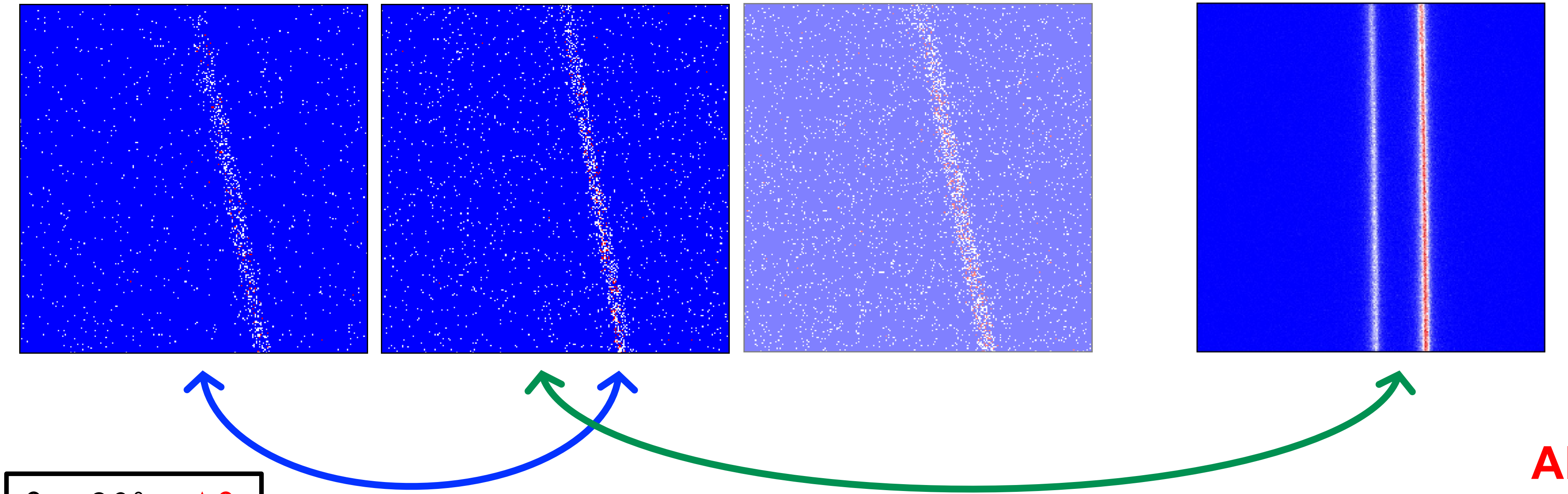
Accuracy of 0.01° !!



δθ ~ 0.02° at best
from optical alignment

Extraction of He-like transition energy

He-like U | Moving ref. Li-like U | Moving ref. Be-like U | Stationary ref. Zn Kα fluorecence



2 kind of references: moving and stationary

$\theta = 90^\circ + \Delta\theta$

$$\begin{cases} E_0^{\mathrm{Mov}} = E_0^{\mathrm{Stat}} \dfrac{1}{2}\gamma_0 (1 + \beta_0 \sin\Delta\theta) \left(1 + \dfrac{x^{\mathrm{Mov}} - x^{\mathrm{Stat}}}{D\tan\Theta}\right) \\ \boldsymbol{E} = E_0^{\mathrm{Mov}} \dfrac{\gamma(1+\beta\sin\Delta\theta)}{\gamma_0(1+\beta_0\sin\Delta\theta)} \left(1 + \dfrac{x - x^{\mathrm{Mov}}}{D\tan\Theta}\right) \end{cases}$$

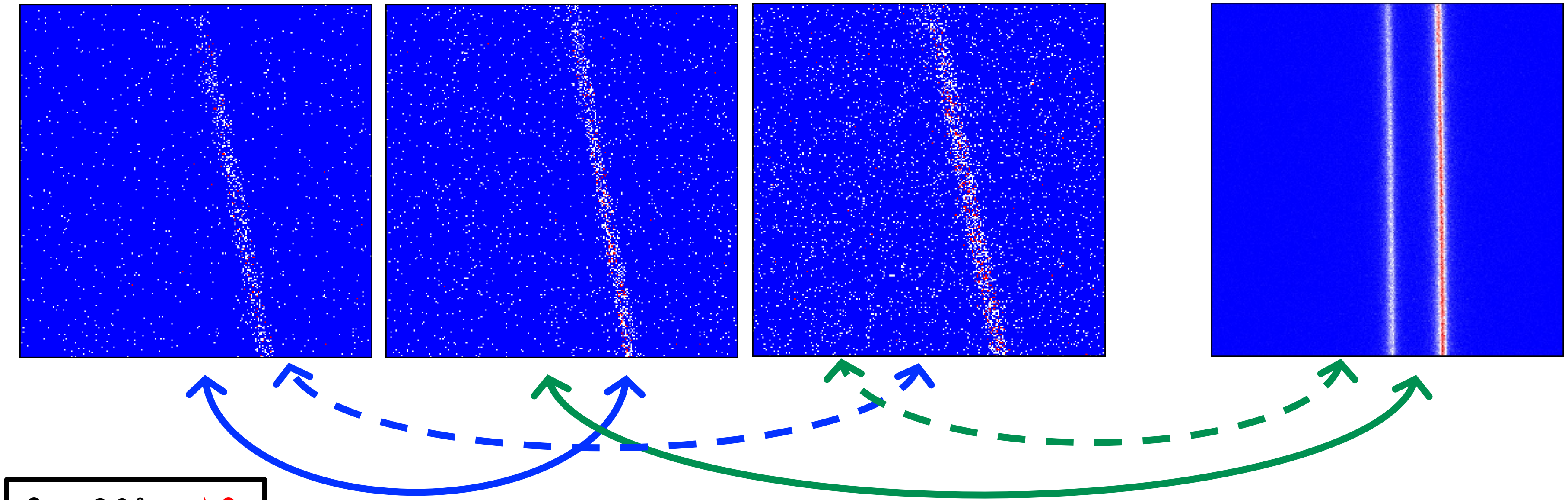
Alignment systematic error reduction

$$\frac{\delta(E_{\mathrm{ion}})_\theta}{E_{\mathrm{ion}}} = \gamma^2 |\beta - \beta_0| \delta\theta$$

- **Δθ±δθ: observation angle misalignment**
- **E±δE: He-like U energy**

Extraction of He-like transition energy

He-like U | Moving ref. Li-like U | Moving ref. Be-like U | Stationary ref. Zn Kα fluorecence



2 kind of references: moving and stationary

2 moving references (Li- and Be-like)

2 spectrometer arms

→ 4 (dependent) measurements

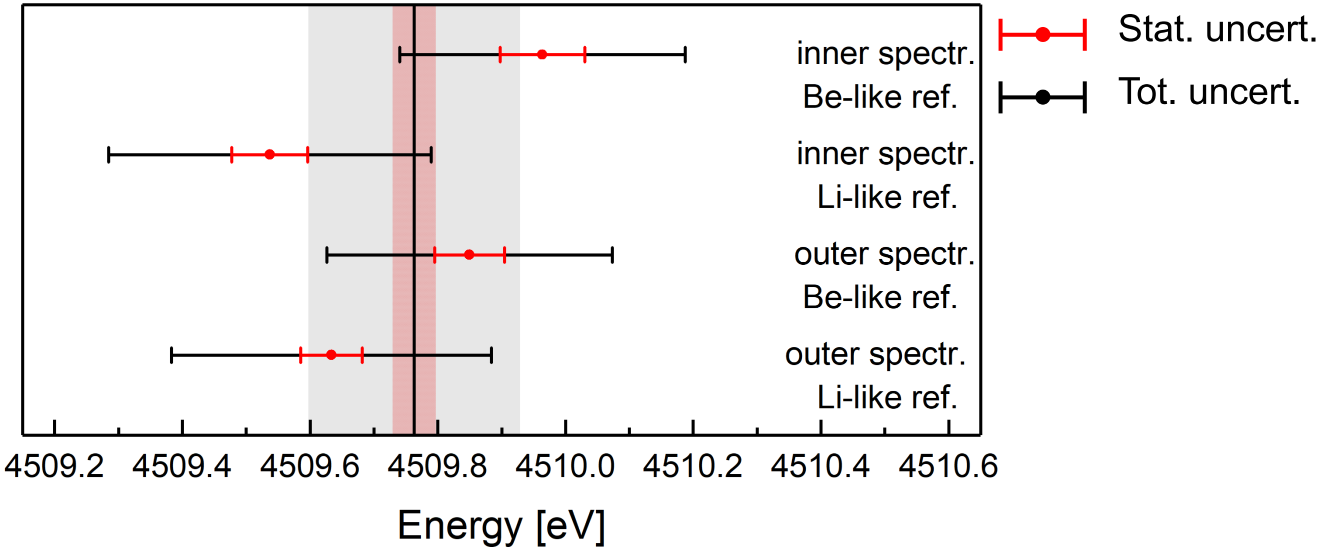
$\theta = 90^\circ + \Delta\theta$

$$
\begin{cases}
E_0^{\mathrm{Mov}} = E_0^{\mathrm{Stat}} \frac{1}{2} \gamma_0 (1 + \beta_0 \sin \Delta\theta) \left(1 + \frac{x^{\mathrm{Mov}} - x^{\mathrm{Stat}}}{D \tan \Theta}\right) \\
\boldsymbol{E} = E_0^{\mathrm{Mov}} \frac{\gamma (1 + \beta \sin \Delta\theta)}{\gamma_0 (1 + \beta_0 \sin \Delta\theta)} \left(1 + \frac{x - x^{\mathrm{Mov}}}{D \tan \Theta}\right)
\end{cases}
$$

- **Δθ±δθ: observation angle misalignment**
- **E±δE: He-like U energy**

He-like U energy evaluations

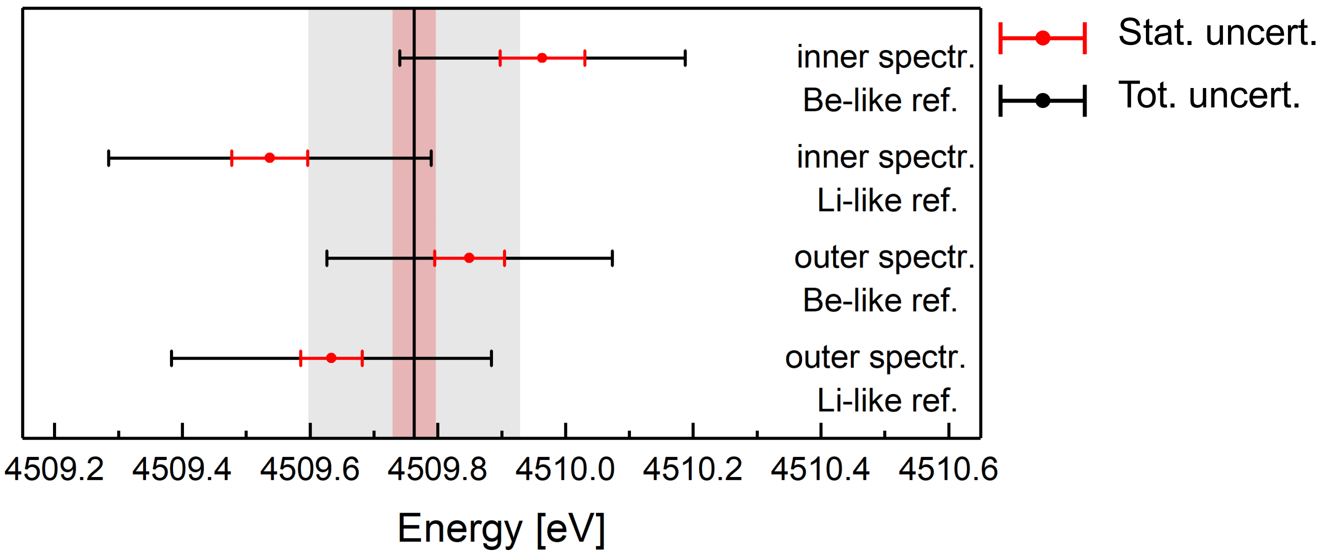
2 spectrometers x 2 moving reference → **4 dependent measurements**



$$\begin{cases} E_0^{\mathrm{Mov}} = E_0^{\mathrm{Stat}} \dfrac{1}{2} \gamma_0 (1 + \beta_0 \sin \Delta\theta) \left(1 + \dfrac{x^{\mathrm{Mov}} - x^{\mathrm{Stat}}}{D \tan \Theta}\right) \\ \boldsymbol{E} = E_0^{\mathrm{Mov}} \dfrac{\gamma(1 + \beta \sin \Delta\theta)}{\gamma_0 (1 + \beta_0 \sin \Delta\theta)} \left(1 + \dfrac{x - x^{\mathrm{Mov}}}{D \tan \Theta}\right) \end{cases}$$

Uncertainty budget

2 spectrometers x 2 moving reference → 4 dependent measurements



Uncertainties for each meas. in eV	
Statistical	0.066
E moving Ref.	**0.246**
E stationary Ref.	0.006
V cooler (bias)	0.007
V cooler (linearity)	0.001
Spectr. arm lenght	0.000
Residual align.	0.003

$$E_0^{\rm Mov} = E_0^{\rm Stat} \frac{1}{2} \gamma_0 (1 + \beta_0 \sin \Delta\theta) \left(1 + \frac{x^{\rm Mov} - x^{\rm Stat}}{D \tan \Theta} \right)$$

$$\boldsymbol{E} = E_0^{\rm Mov} \frac{\gamma(1 + \beta \sin \Delta\theta)}{\gamma_0 (1 + \beta_0 \sin \Delta\theta)} \left(1 + \frac{x - x^{\rm Mov}}{D \tan \Theta} \right)$$

Moving source: Li- and Be-like uranium

$E^{\text{Li-like}}$ = 4459.37 ± **0.21 eV**

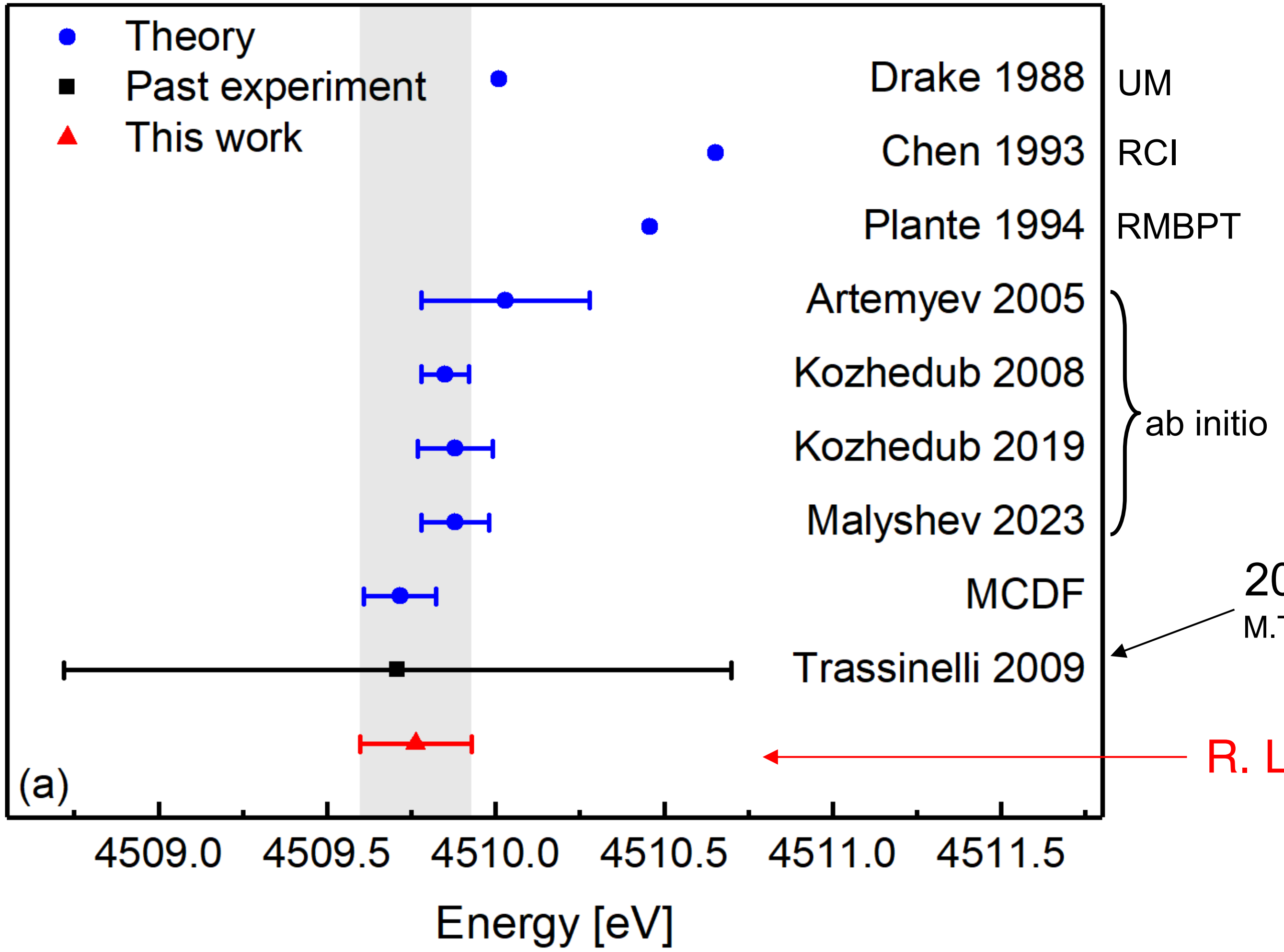
$E^{\text{Be-like}}$ = 4501.72 ± **0.21 eV**

Beiersdorfer *et al.*, Phys. Rev. Lett. **71**, 3939 (1993).

He-like U energy evaluation

Result absolute energy of He-like U:

$E_{\text{He-like U}}$ = **4509.763 ± 0.034$_{stat}$ ± 0.162$_{syst}$ (±0.166) eV**



2007 exp. result: 4509.71 ± 0.99 eV
M.T. *et al.*, Eur. Phys. Lett. **87**, 63001 (2009)

R. Loetzsch *et al.*, Nature **625**, 673-678 (2024)

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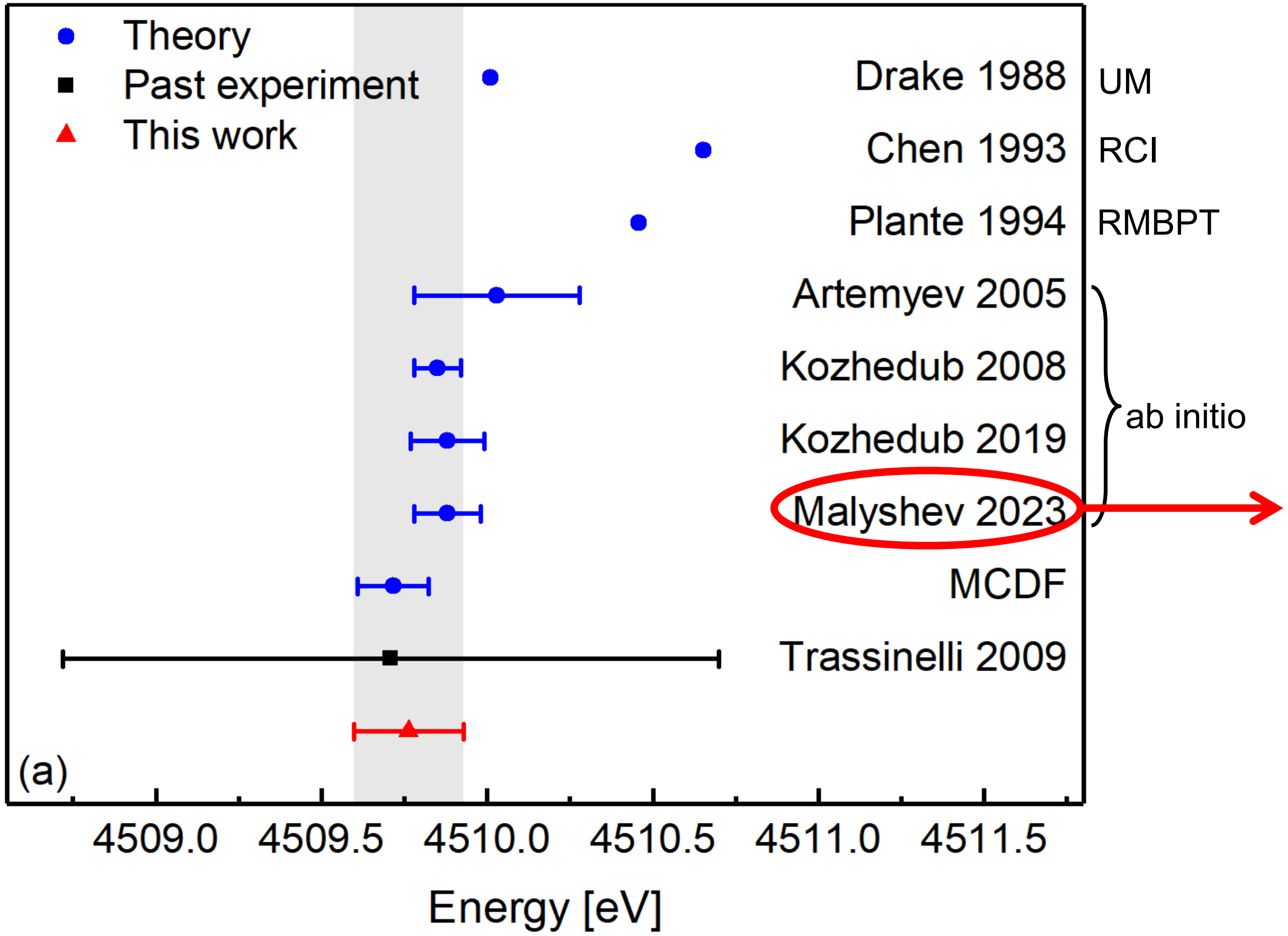
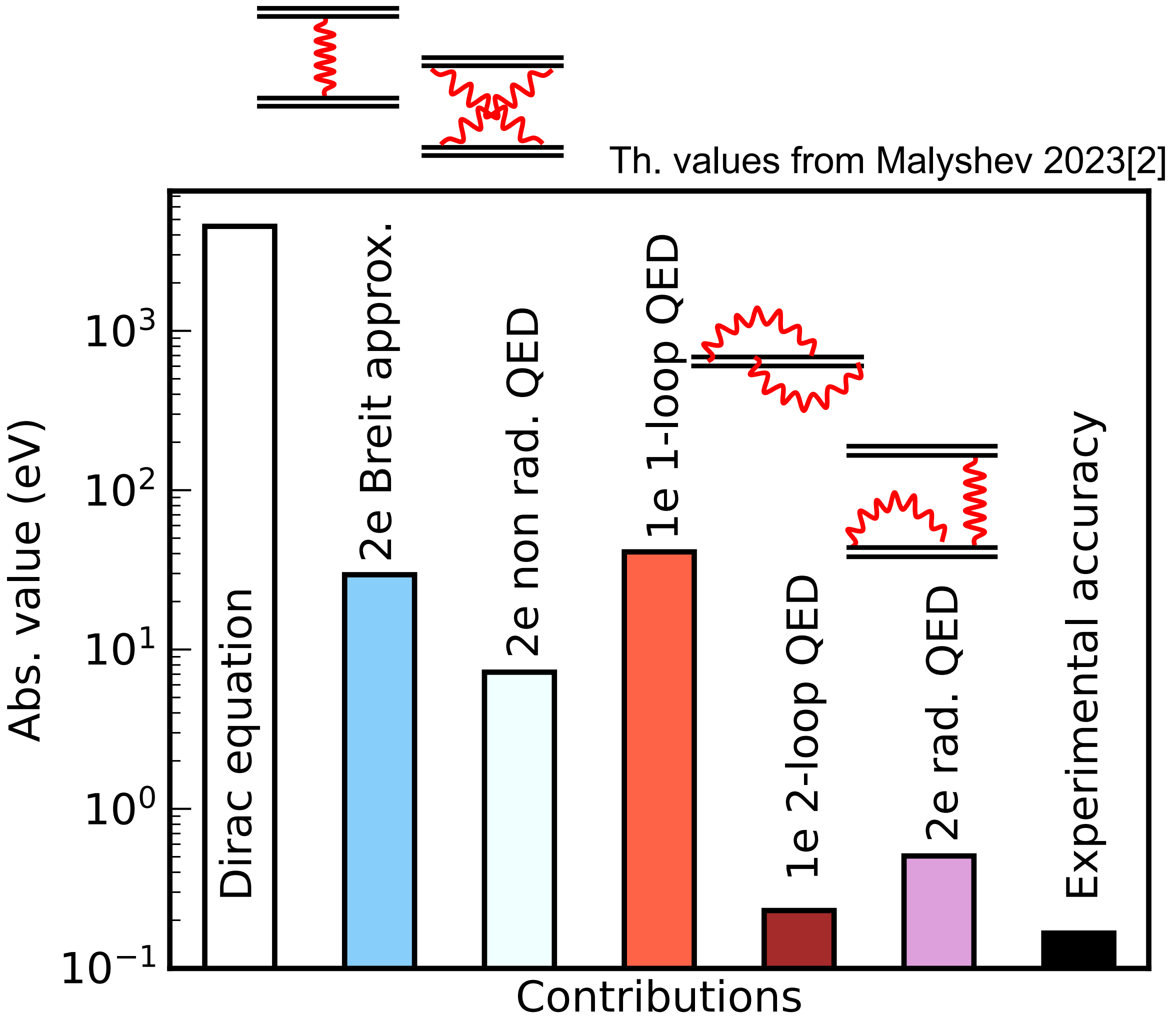


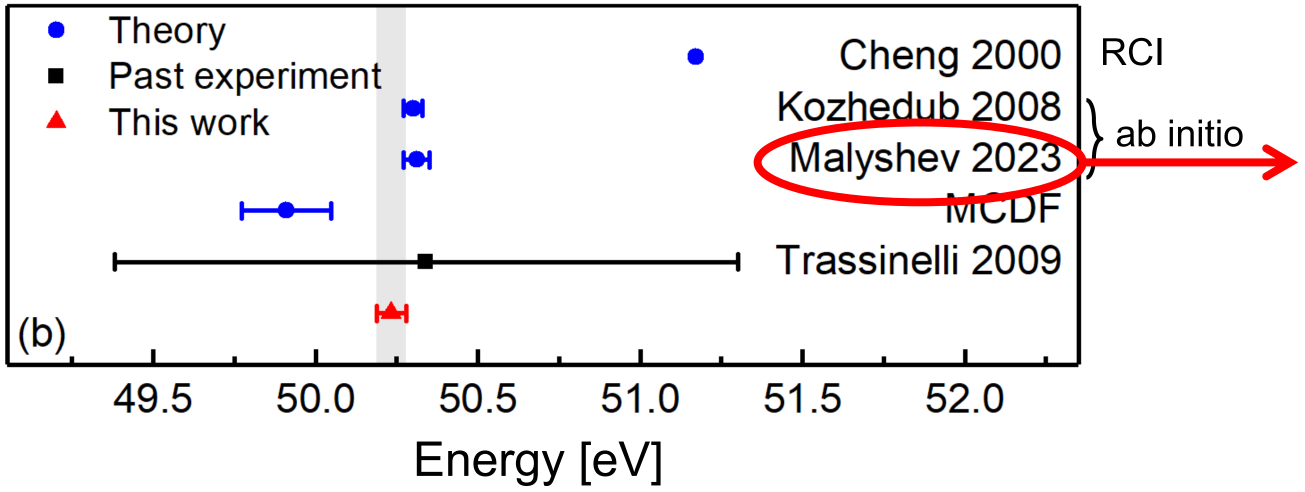


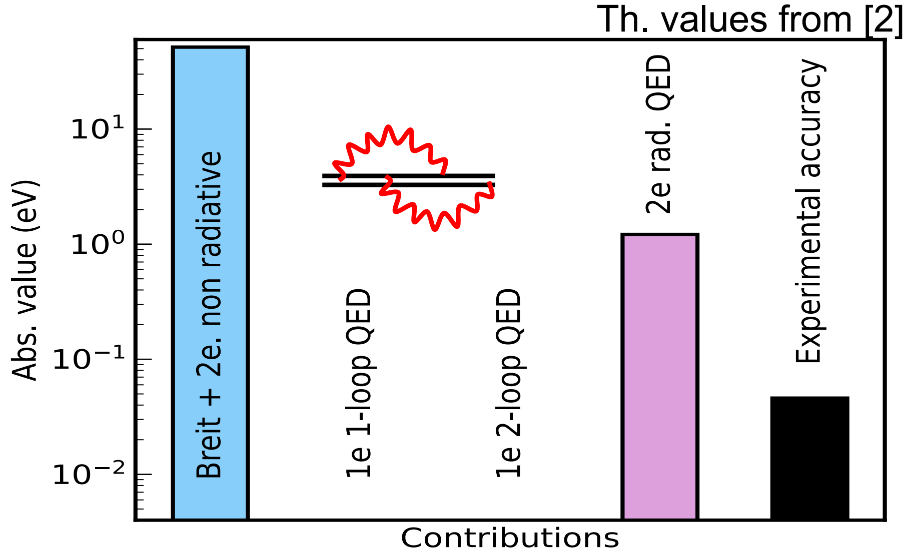
[1] R. Loetzsch *et al.*, Nature **625**, 673-678 (2024)
[2] A.V. Malyshev *et al.*, Phys. Rev. A **107**, 042806 (2023)

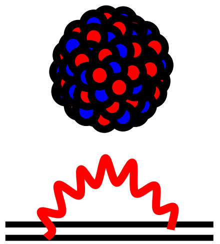
He- Li-like U relative energy

Result He- – Li-like energy difference:

$\Delta E_{\text{Li-Be-like U}}$ = **50.233 ± 0.037$_{stat}$ ± 0.037$_{syst}$ (±0.046) eV [1]**







- Same nucleus
- Same 1 el. QED contribution

Disentanglement between one-electron QED and two-electron QED

[1] R. Loetzsch *et al.*, Nature **625**, 673-678 (2024)
[2] A.V. Malyshev *et al.*, Phys. Rev. A **107**, 042806 (2023)

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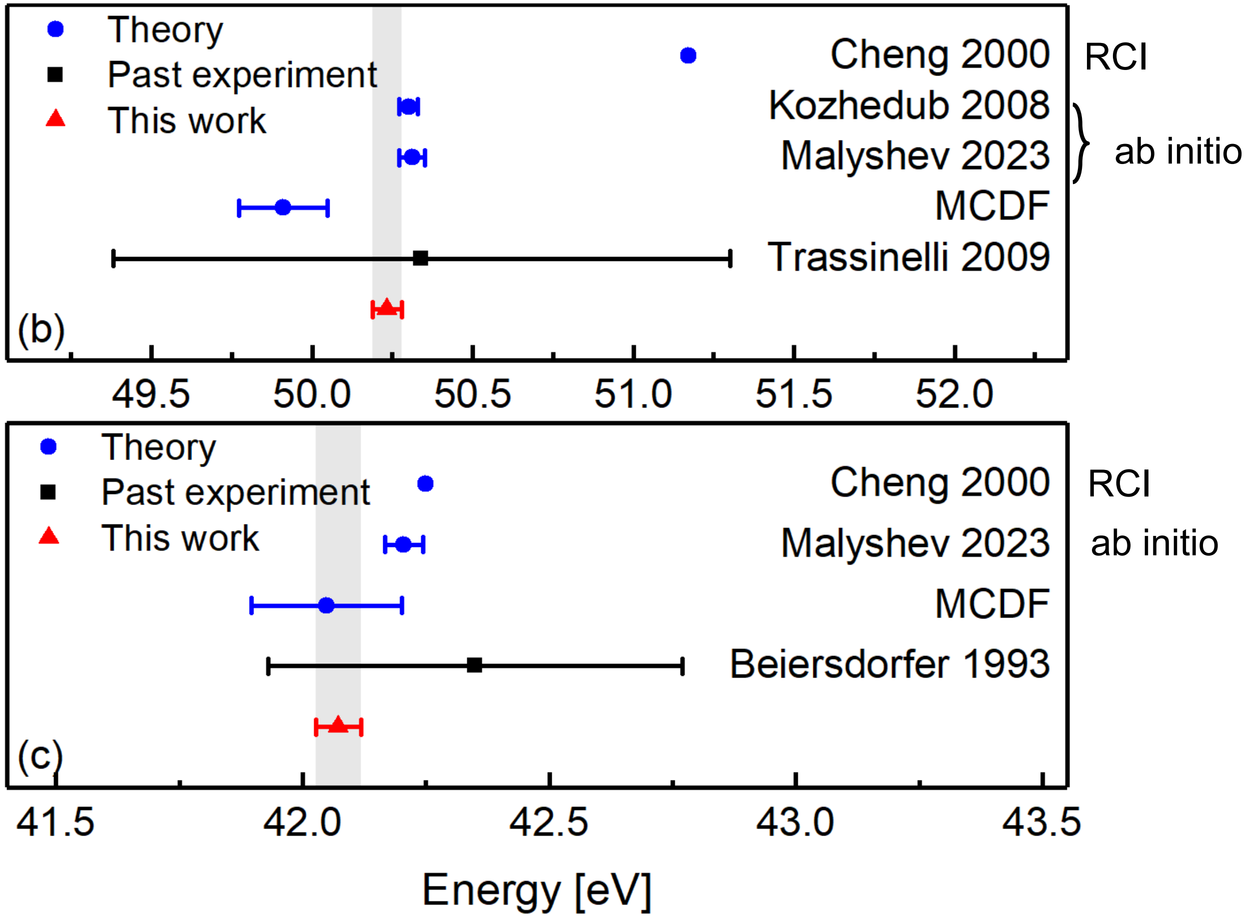
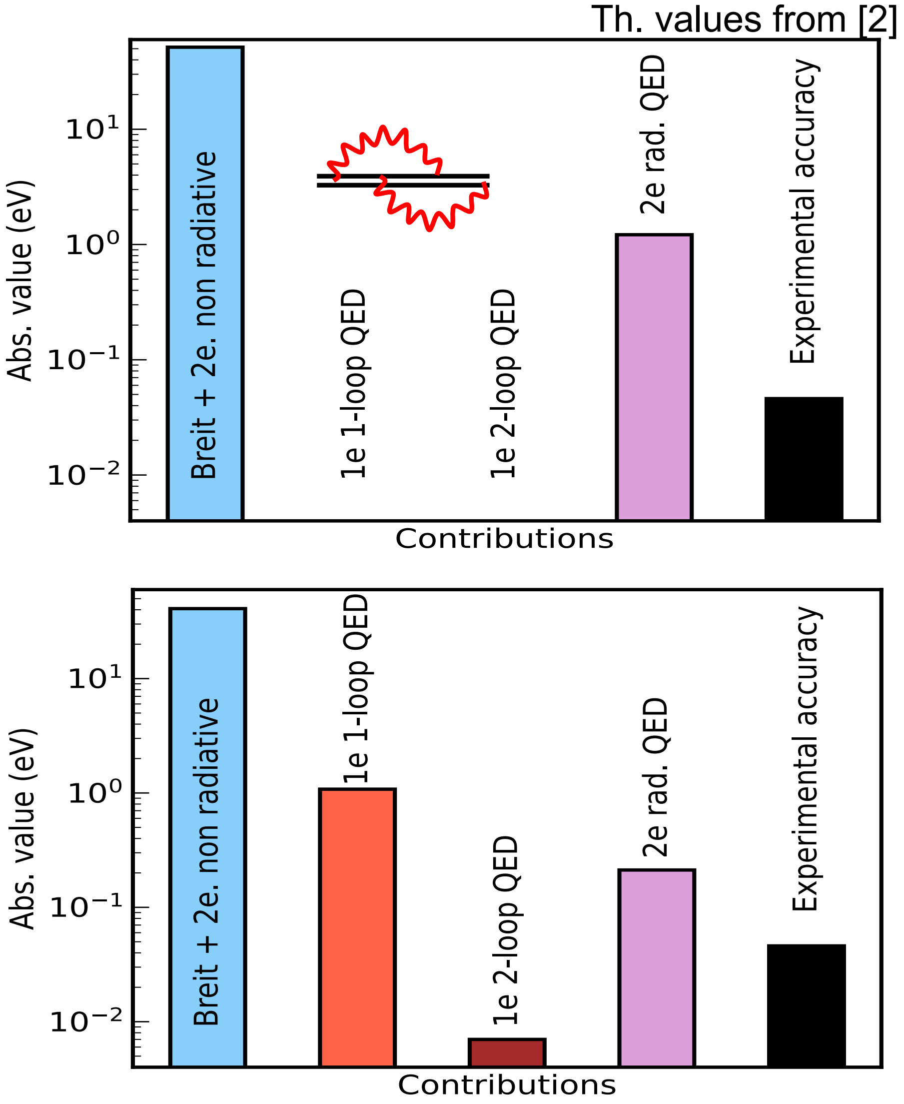




Result Be- – Li-like energy difference:

$\Delta E_{\text{He-Be-like U}}$ = **42.072 ± 0.041$_{stat}$ ± 0.031$_{syst}$ (±0.046) eV [1]**

[1] R. Loetzsch *et al.*, Nature **625**, 673-678 (2024)
[2] A.V. Malyshev *et al.*, Phys. Rev. A **107**, 042806 (2023)

Main present limitation and outlooks

Result absolute energy of He-like U:

$E_{\text{He-like U}}$ = **4509.763 ± 0.034$_{stat}$ ± 0.162$_{syst}$ eV**

Main present limitation and outlooks

Result absolute energy of He-like U:

$E_{\text{He-like U}}$ = **4509.763 ± 0.034$_{\text{stat}}$ ± 0.162$_{\text{syst}}$ eV**

Possible outlooks:

1) Wait …

Main present limitation and outlooks

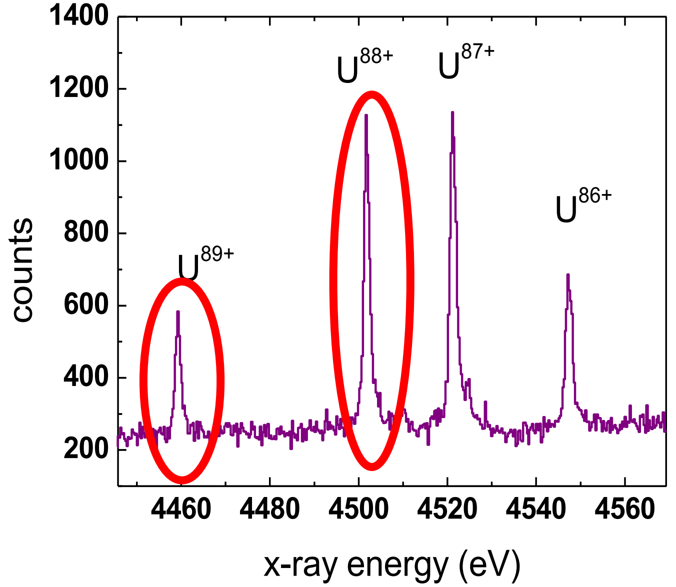
Result absolute energy of He-like U:

$E_{\text{He-like U}}$ = **4509.763 ± 0.034$_{stat}$ ± 0.162$_{syst}$ eV**

Possible outlooks:

1) Wait for calibration improvements
   a) in a Super-, Hyper-EBIT

Soon in Heidelberg?
GSI?

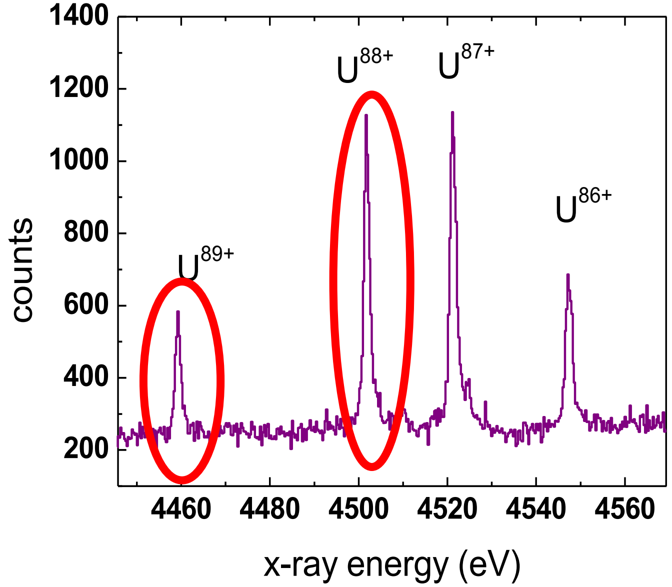


Present accuracy = 0.21 eV

Main present limitation and outlooks

Result absolute energy of He-like U:

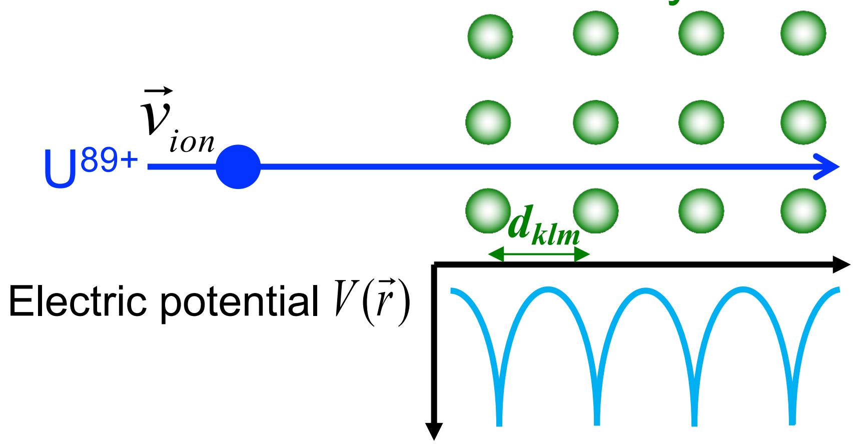
$E_{\text{He-like U}}$ = **4509.763 ± 0.034$_{\text{stat}}$ ± 0.162$_{\text{syst}}$ eV**



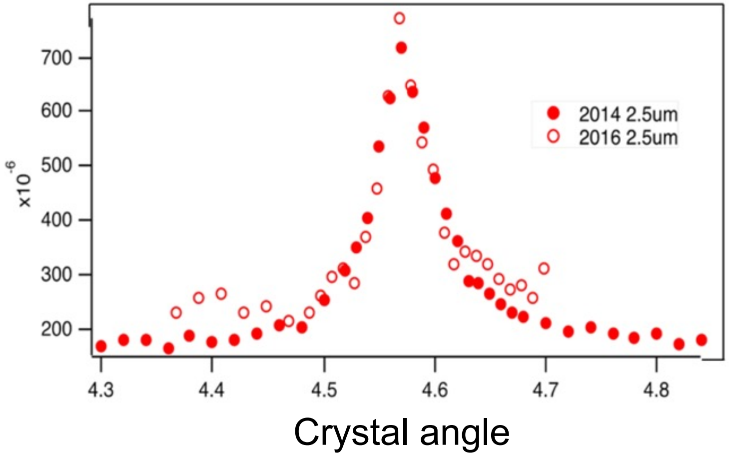
Present accuracy = 0.21 eV

Possible outlooks:

1) Wait for calibration improvements
   a) in a Super/Hyper-EBIT
   b) with resonant coherent excitation method (inverted laser)



Li-like $2p_{3/2} – 2s_{1/2}$



2024 beam time

Present accuracy = 2 eV

Goal accuracy: 0.01eV

Main present limitation and outlooks

Result absolute energy of He-like U:

$E_{\text{He-like U}}$ = **4509.763 ± 0.034$_{stat}$ ± 0.162$_{syst}$ eV**

Possible outlooks:

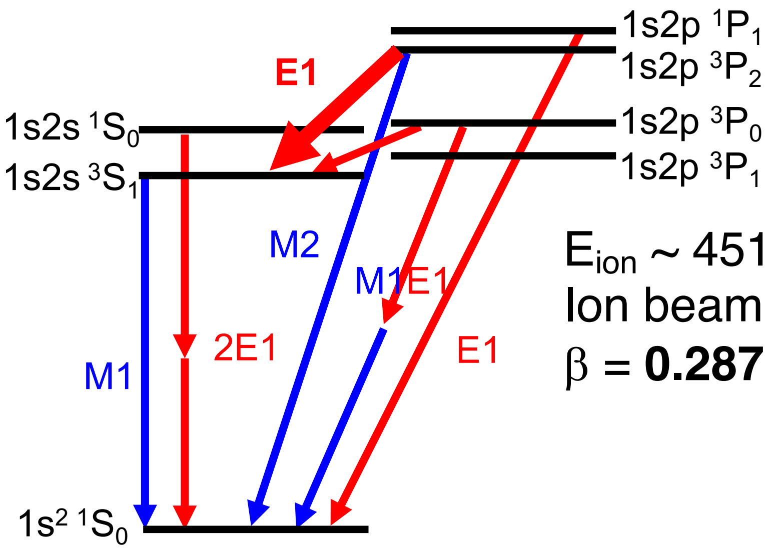
1) Wait for calibration improvements (Li- and/or B-like U)
2) Use another calibration

2024-25 beam time proposal

Use hydrogenlike scandium (Z=21) instead of uranium (Z=92)

→ Negligible 2-loop QED effects (0.0017 eV only)
→ **Systematic uncertainty: from 0.162 to 0.005 eV** (due to the HFS)

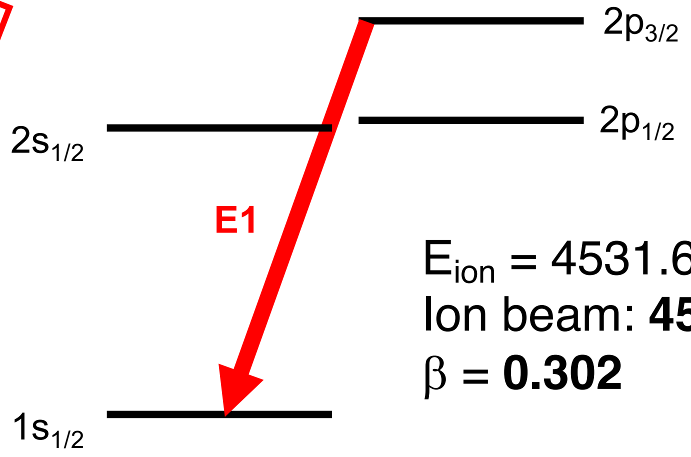
He-like U



E_{ion} ~ 4510 eV
Ion beam: **41.03 Mev/u**
β = **0.287**

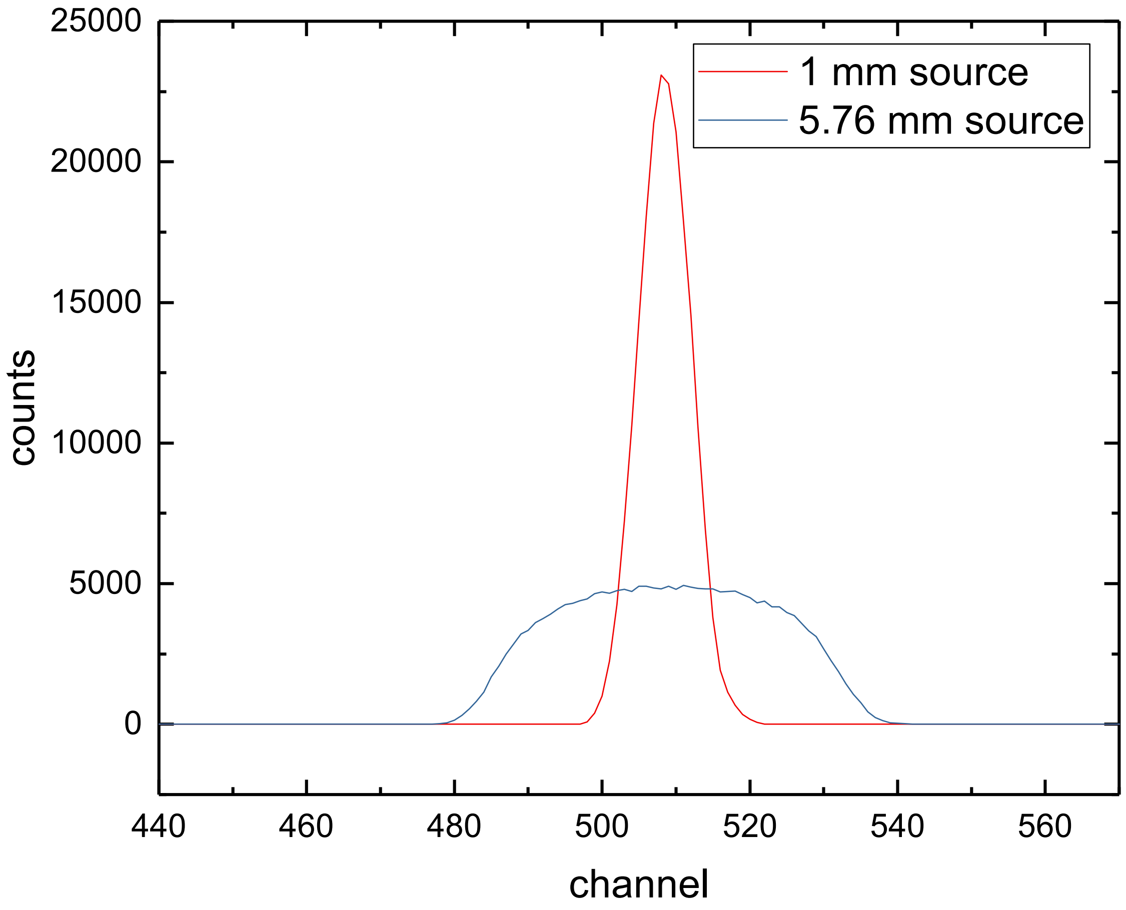
E_{lab} ~ 4319 eV

H-like Sc (Reference)



E_{ion} = 4531.624 ± **0.005 eV**
Ion beam: **45.74 Mev/u**
β = **0.302**

2024-25 beam time proposal



Use hydrogenlike scandium (Z=21) instead of uranium (Z=92)

→ Negligible 2-loop QED effects (0.0017 eV only)

→ **Systematic uncertainty: from 0.162 to 0.003 eV**

Smaller gas-get as target (from 5 to 1 mm of diameter)

→ Higher resolution power

→ **Statistical uncertainty: from 0.034 to 0.008 eV**

Higher gas density

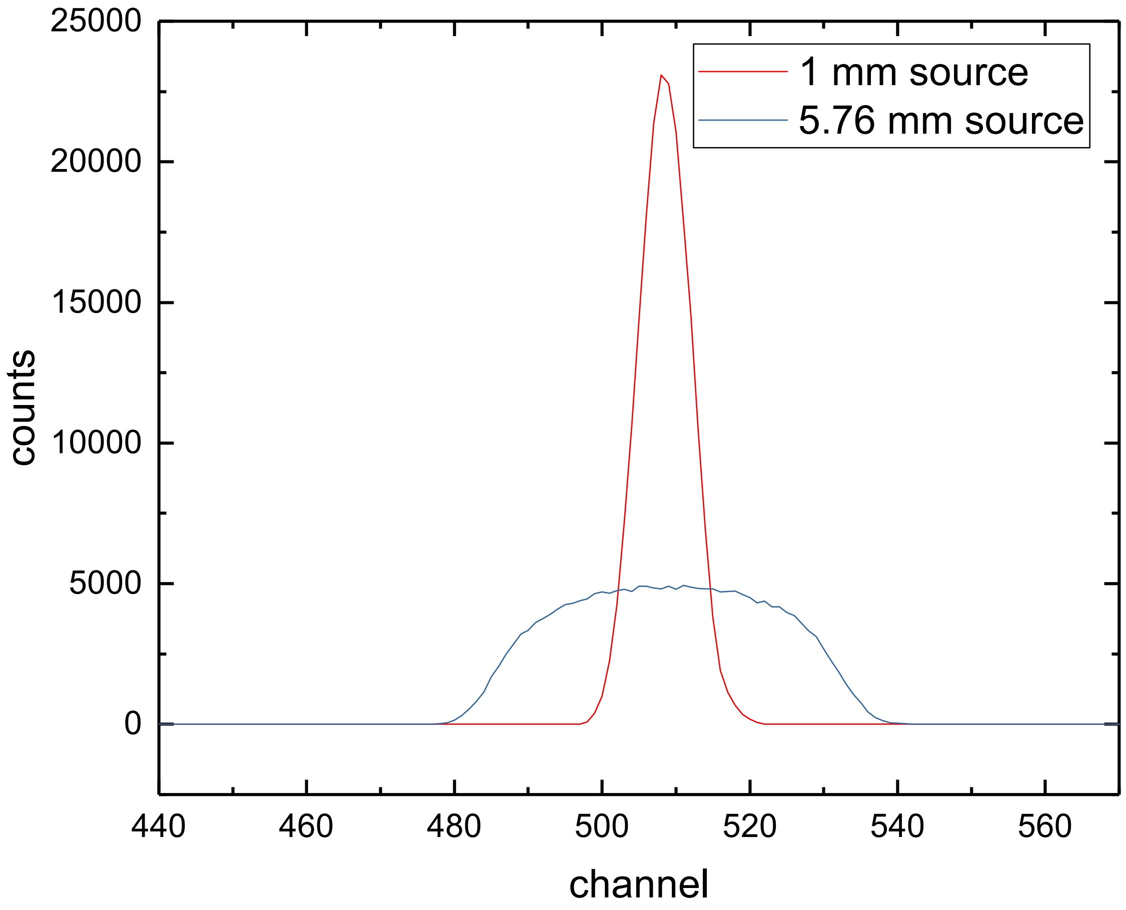
⇩

Higher probability of double capture

⇩

Coincidences required

2024-25 beam time proposal



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→ **Statistical uncertainty: from 0.034 to 0.008 eV**

New detectors (Timepix3 tech.)

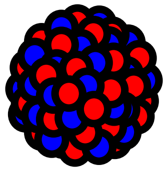
→ Spatial and **time-resolution** for single capture only

CheeTah detector
Timepix3 CERN tech.
Time resolution: a few ns
Space resolution: 55 μm

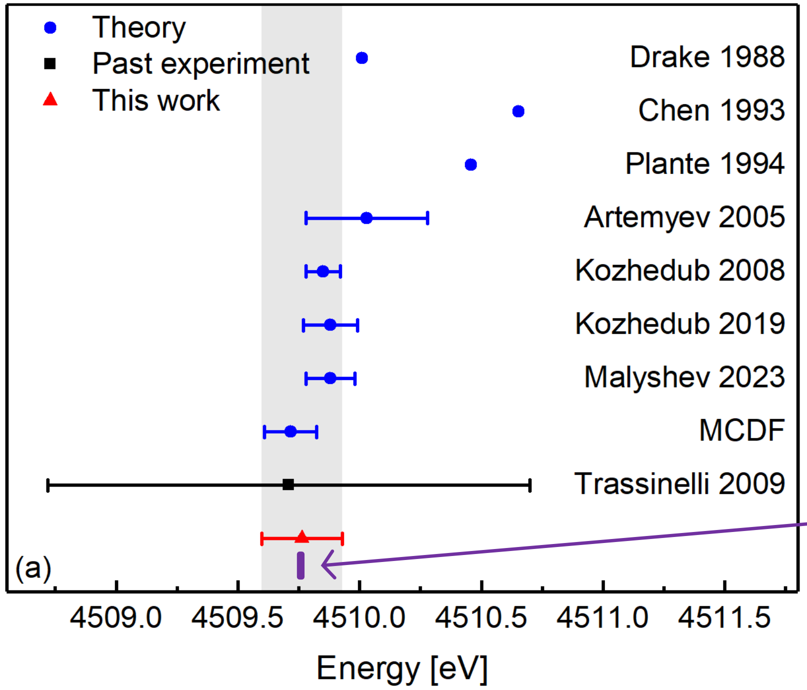
AMSTERDAM SCIENTIFIC INSTRUMENTS

2024-25 beam time proposal

- Lower than nucleus size uncertainty contribution **± 0.034 eV**



- Sensitive to uncalculated QED effects (3-photon exchange QED) **± 0.017 eV**



Expected error bar (barely visible…)

Use hydrogenlike scandium (Z=21) instead of uranium (Z=92)

→ Negligible 2-loop QED effects (0.017 eV only)

→ **Systematic uncertainty: from 0.162 to 0.003 eV**

Smaller gas-get as target (from 5 to 1 mm of diameter)

→ Higher resolution power

→ **Statistical uncertainty: from 0.034 to 0.008 eV**

New detectors (Timepix3 tech.)

→ Spatial and **time-resolution** for single capture only

Total expected accuracy on the new proposal: 0.009 eV

Main present limitation and outlooks

Result absolute energy of He-like U:

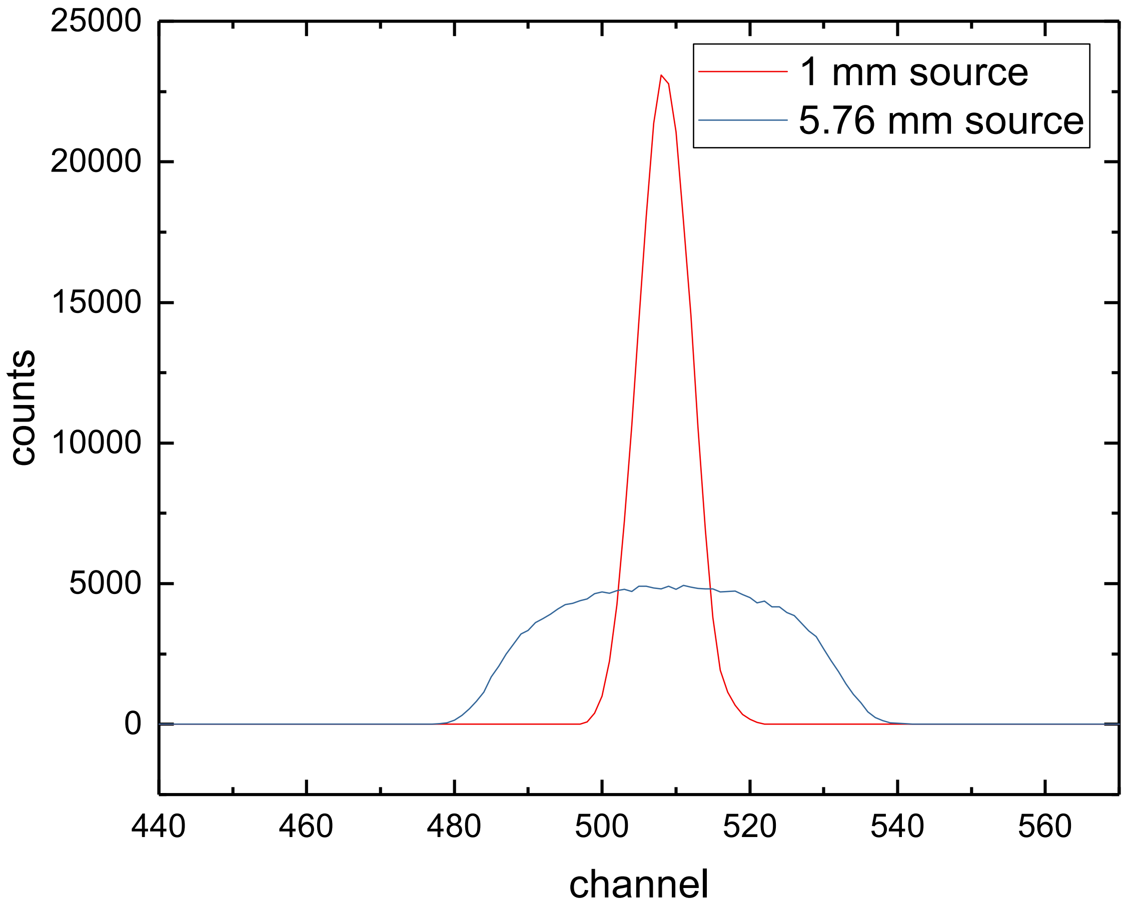
$E_{\text{He-like U}}$ = **4509.763 ± 0.034$_{stat}$ ± 0.162$_{syst}$ eV**

Possible outlooks:

1) Wait for calibration improvements (Li- and/or B-like U)
2) Use another calibration (He-like Sc)
3) Do something else …

Further plans (2026-27 beamtime proposal?)

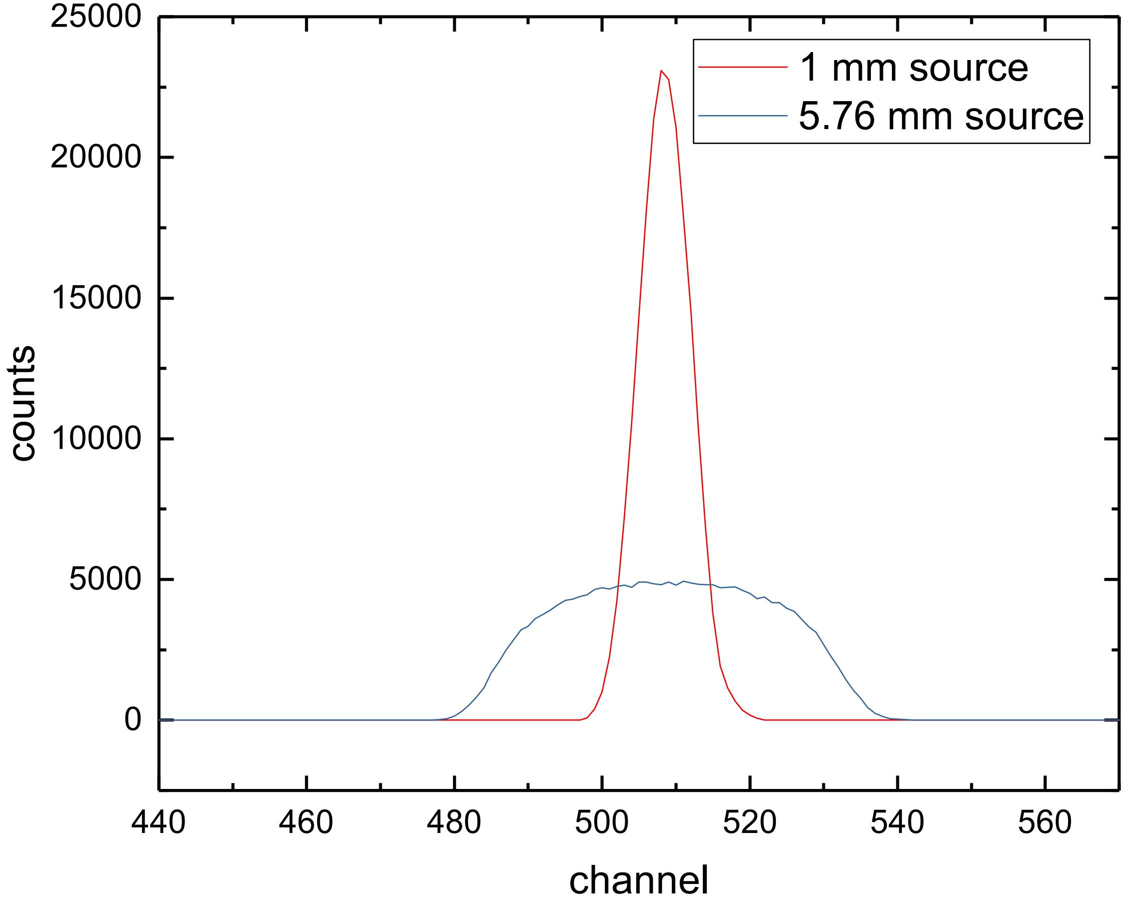
Relative measurements
→ Uncertainty dominated by statistics
(for almost coinciding transitions)



Smaller gas-get as target
(from 5 to 1 mm of diameter)
→ Higher resolution power
→ **Statistical uncertainty: from 0.037 to 0.009 eV**

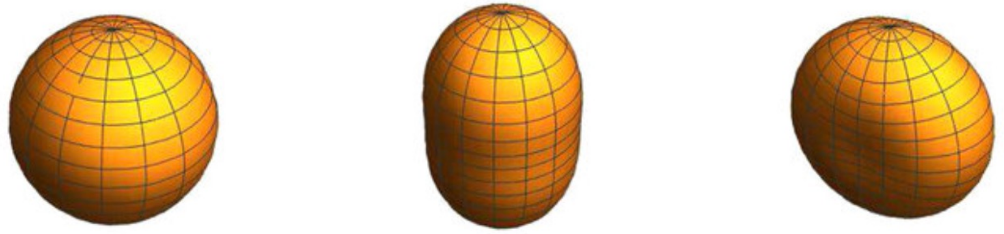
Further plans (2026-27 beamtime proposal?)

Relative measurements
→ Uncertainty dominated by statistics
(for almost coinciding transitions)



Smaller gas-get as target
(from 5 to 1 mm of diameter)
→ Higher resolution power
→ **Statistical uncertainty: from 0.037 to 0.009 eV**

Transition energy comparisons between isotopes

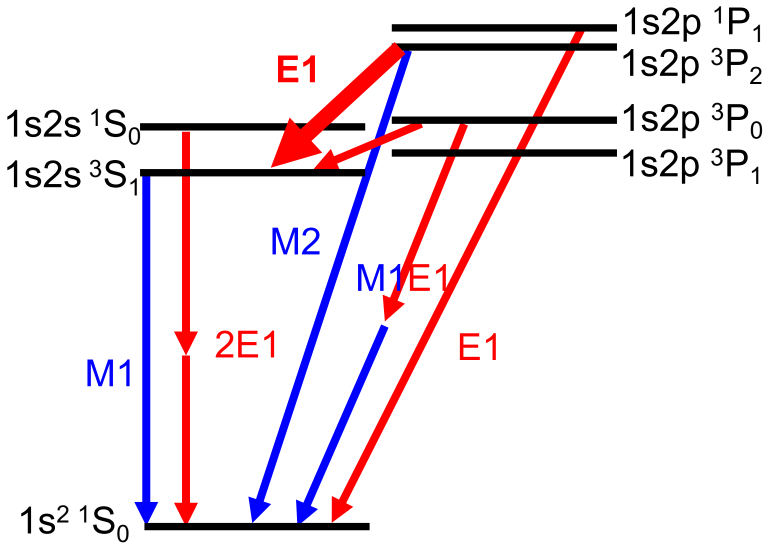


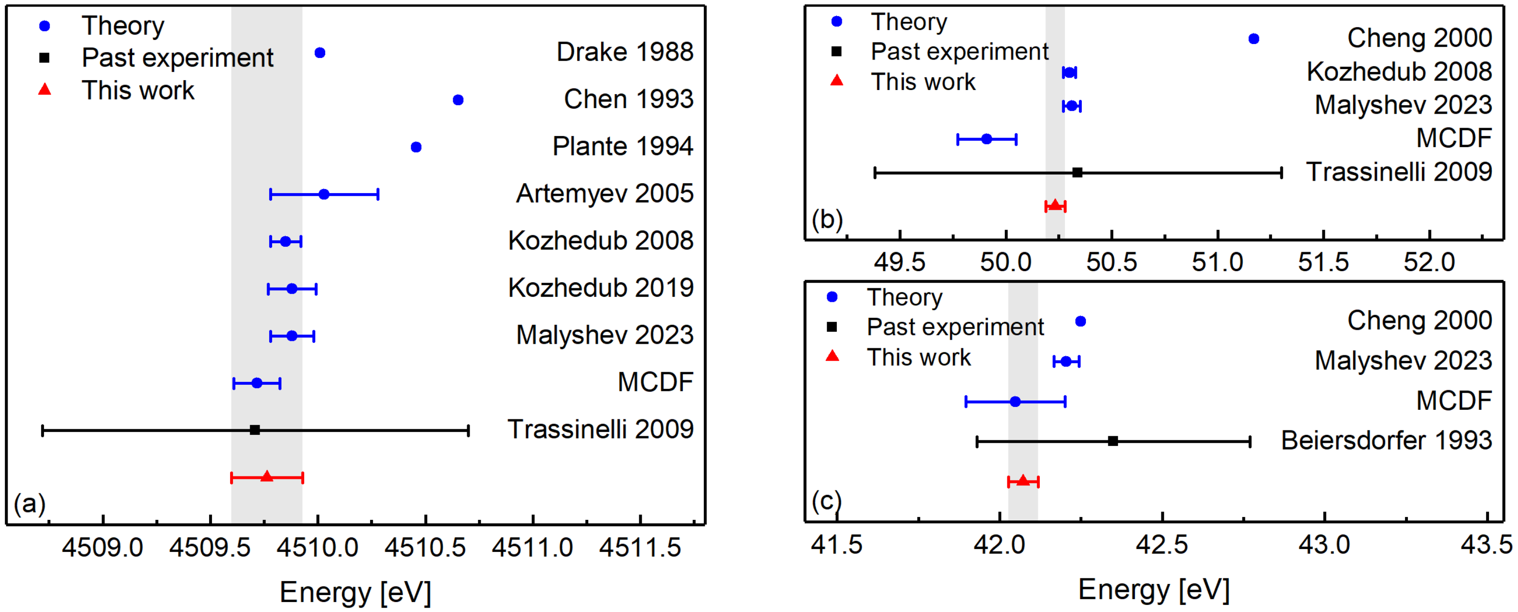
- Present nuclear radius uncertainty (for ^{238}U): **0.034 eV** [1]
  - Expected deformation effects: **0.02 eV** [2]

[1] V.A. Yerokhin *et al.*, J. Phys. Chem. Ref. Data **44**, 033103 (2015)
[2] Z. Sun *et al.*, arXiv preprint arXiv:2309.07780 (2023)
+ N. Oreshkina private communication

Conclusions

- New high-resolution X-ray spectroscopy measurement of He-like uranium ions
- New calibration method to reduce the Doppler effect systematics
- **Disentangled** measured of **one-electron** and **many-electrons QED**
- New benchmark test for bound system QED in strong field
- New proposals planned for next FAIR beamtimes





R. Loetzsch *et al.*, Nature **625**, 673-678 (2024)

Collaboration and sponsors

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MT
D. Vernhet

A. Gumberidze
U. Spillmann
Th. Stöhlker
H. Beyer

F. Kröger
J. Glorius
R. Grisenti
R. Hess
P.-M. Hillenbrand
B. A. Lorentz

S. Litvinov
Yu. A. Litvinov
N. Petridis
M. Steck
M. Scheidel
R. Sidhu
S. Trotsenko

Thank you!

HI Jena
Helmholtz Institute Jena

R. Lötzsch
I. Uschmann
G. Paulus

IOQ JENA
Friedrich-Schiller-Universität

G. Weber

LKB

L. Duval
P. Indelicato
N. Paul

Jan Kochanowski University

D. Banas
P. Jagodzinski
K. Szary

FACULDADE DE CIÊNCIAS E TECNOLOGIA
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Alexander von Humboldt
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