High Resolution Electron Collision Spectroscopy at the TSR

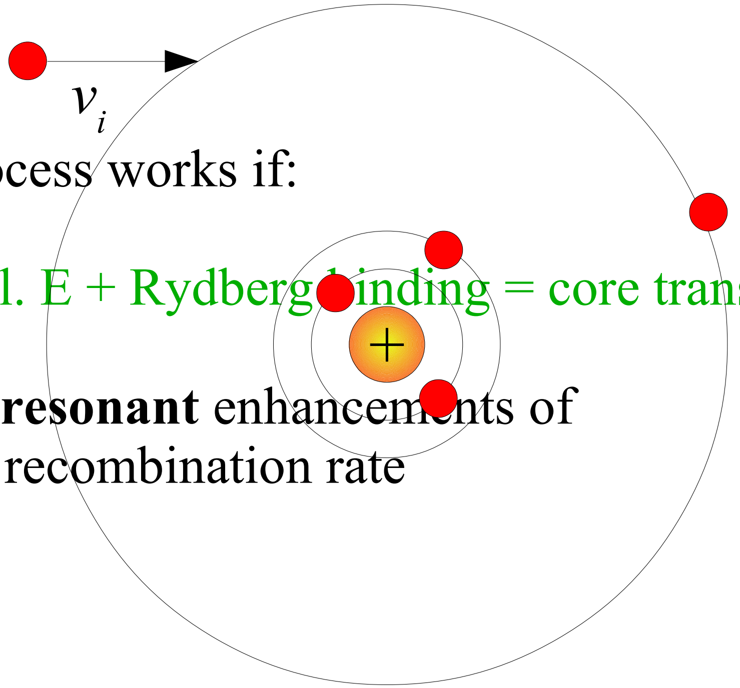
Claude Krantz

Electron Collision Spectroscopy at the TSR

- **Dielectronic Recombination (DR)**
- **Merged electron-ion beams**
  - Basics
  - Precision
  - Resolution limits
- **The Setup at TSR**
  - Twin electron beams
  - High-resolution electron target
- **High resolution DR measurements**
  - Lithiumlike systems: Sc^{18+}
  - Towards multiple valence electrons: Be-like Ge^{28+}, B-like Fe^{21+}
- **Conclusion**

Dielectronic Recombination

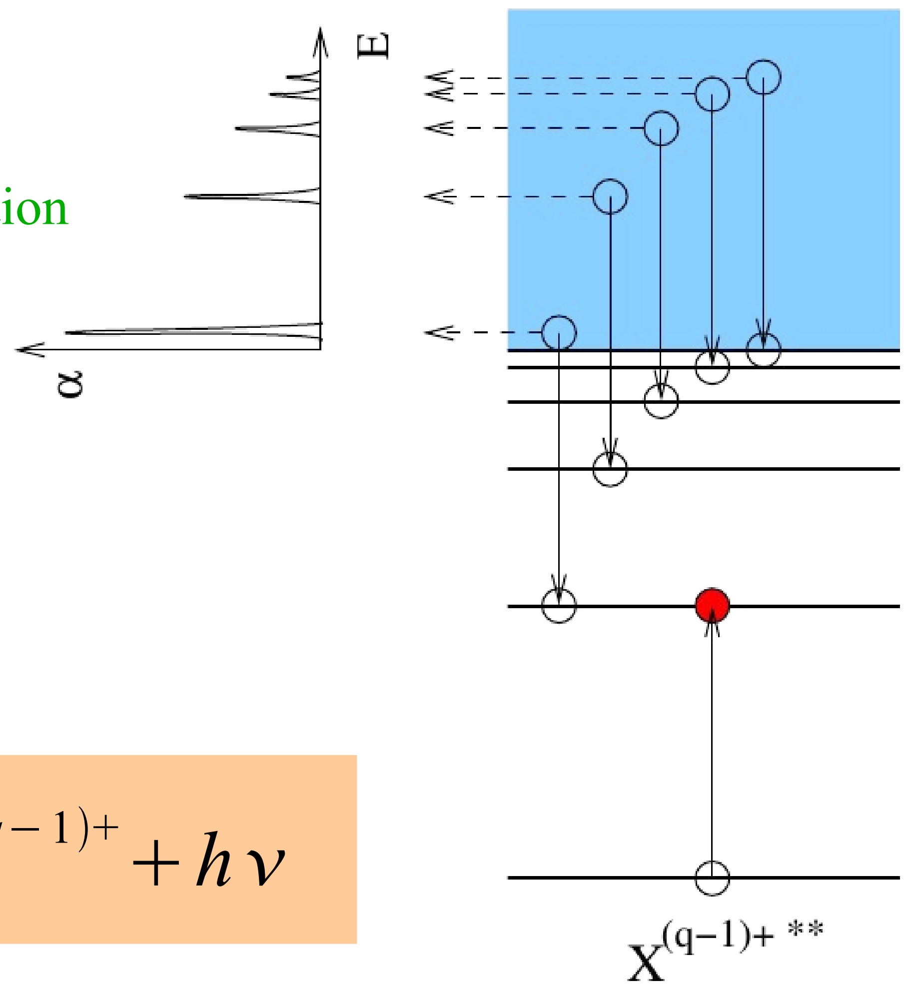
- Recombination via doubly excited resonances: DR



process works if:

coll. E + Rydberg binding = core transition

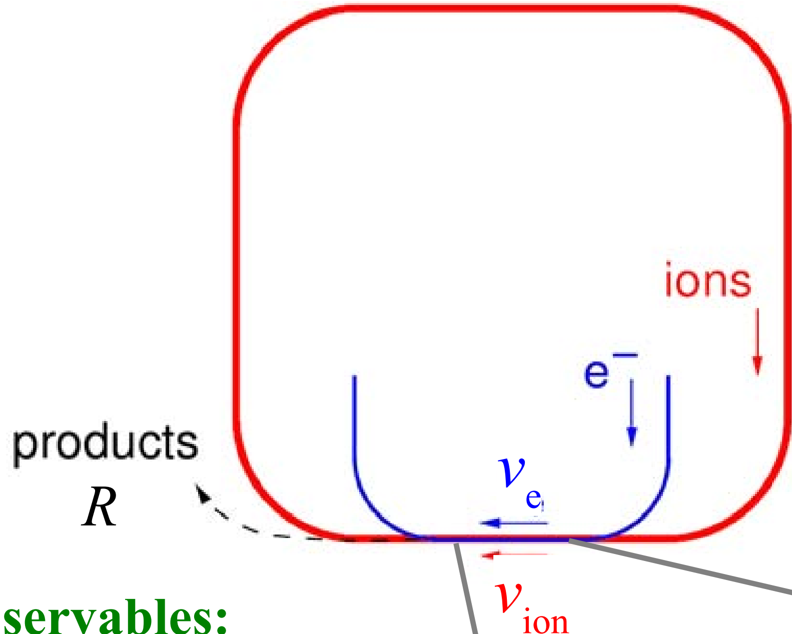
→ **resonant** enhancements of recombination rate



$$X^{q+} + e^- \rightarrow \left(X^{(q-1)+}\right)^{**} \rightarrow X^{(q-1)+} + h\nu$$

Merged electron-ion beams

- Merged electron and ion beams



$$E_{rel} \approx \frac{1}{2} m_e \Delta v^2 \approx \left(\sqrt{E_e} - \sqrt{\frac{m_e}{m_{ion}} E_{ion}} \right)^2$$

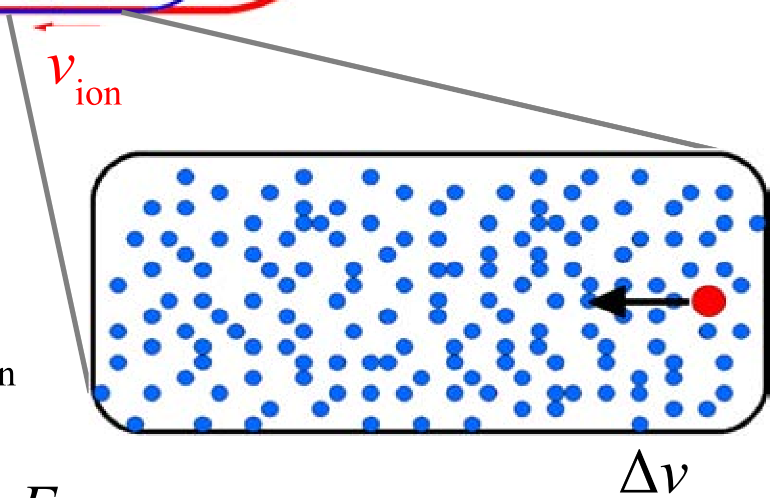
$$E_{rel} = 0 \quad \Leftrightarrow \quad \boxed{E_e = \frac{m_e}{m_{ion}} E_{ion}}$$

“cooling”

Observables:

1. recomb. rate coef.

$$\alpha = \frac{R}{N_{ion} n_e} \frac{C}{L} \gamma_{ion}^2$$

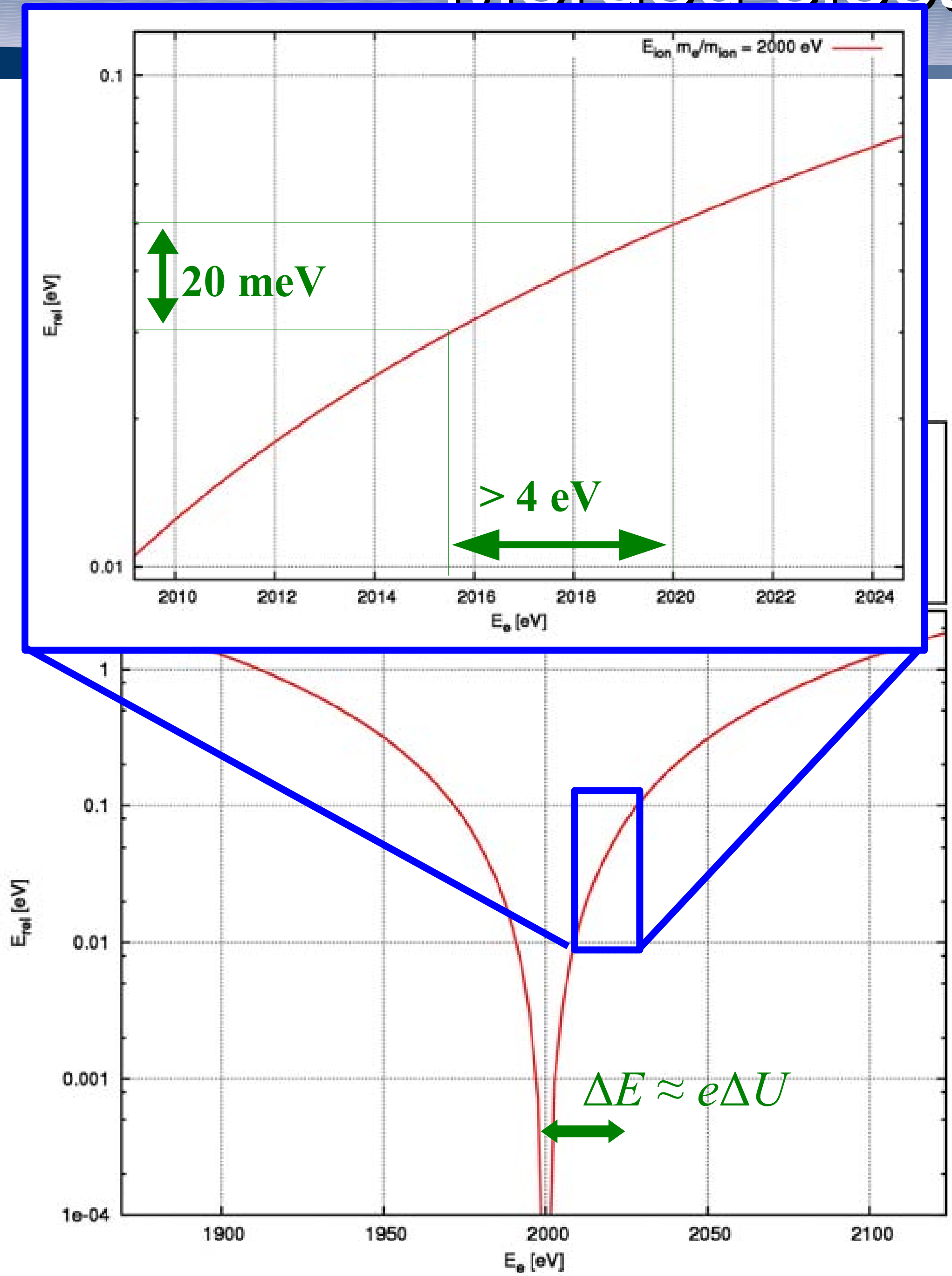


with: $E_{ion} \sim$ few MeV/u

$\rightarrow$ **$E_e \sim 1$ keV**

2. e-ion collision energy E_{rel}

Merged electron-ion beams



$$E_{rel} \approx \left(\sqrt{E_e} - \sqrt{\frac{m_e}{m_{ion}} E_{ion}} \right)^2 \approx \frac{m_{ion}}{m_e} \frac{(\Delta E)^2}{4 E_{ion}}$$

with $\Delta E = E_e - \frac{m_e}{m_{ion}} E_{ion} \approx e \Delta U$

$\boldsymbol{E_{rel} \sim (\Delta U)^2}$:

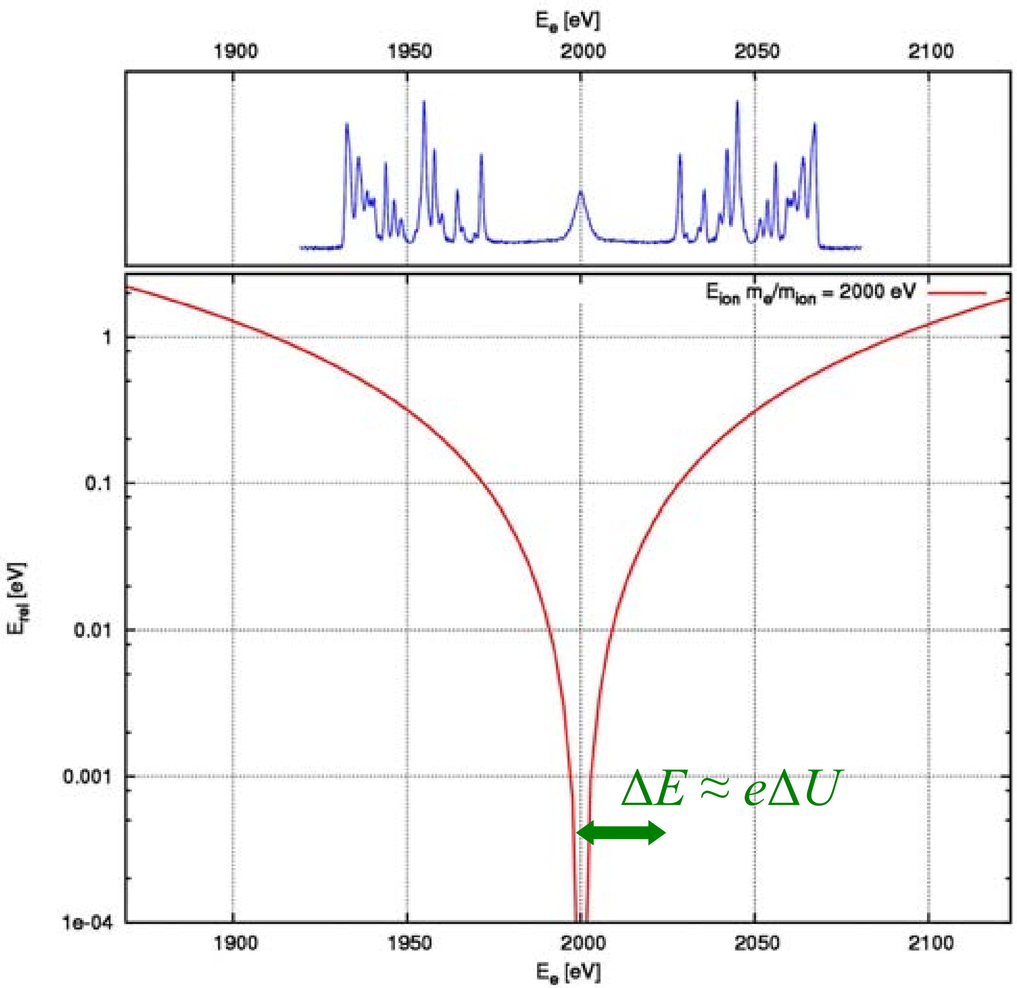
very small E_{rel} in the c.m. frame

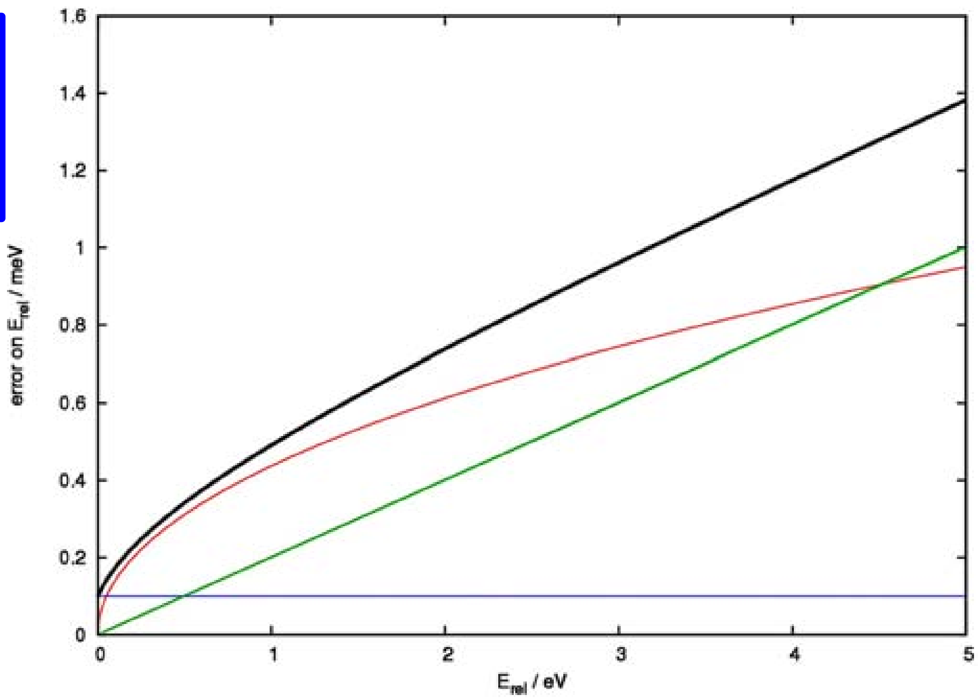
↔ measurable ΔU in the lab.

Merged electron-ion beams

- Precision

$$E_{\text{rel}} \approx \frac{m_{\text{ion}}}{m_{\text{e}}} \frac{(\Delta E)^2}{4\, E_{\text{ion}}}$$



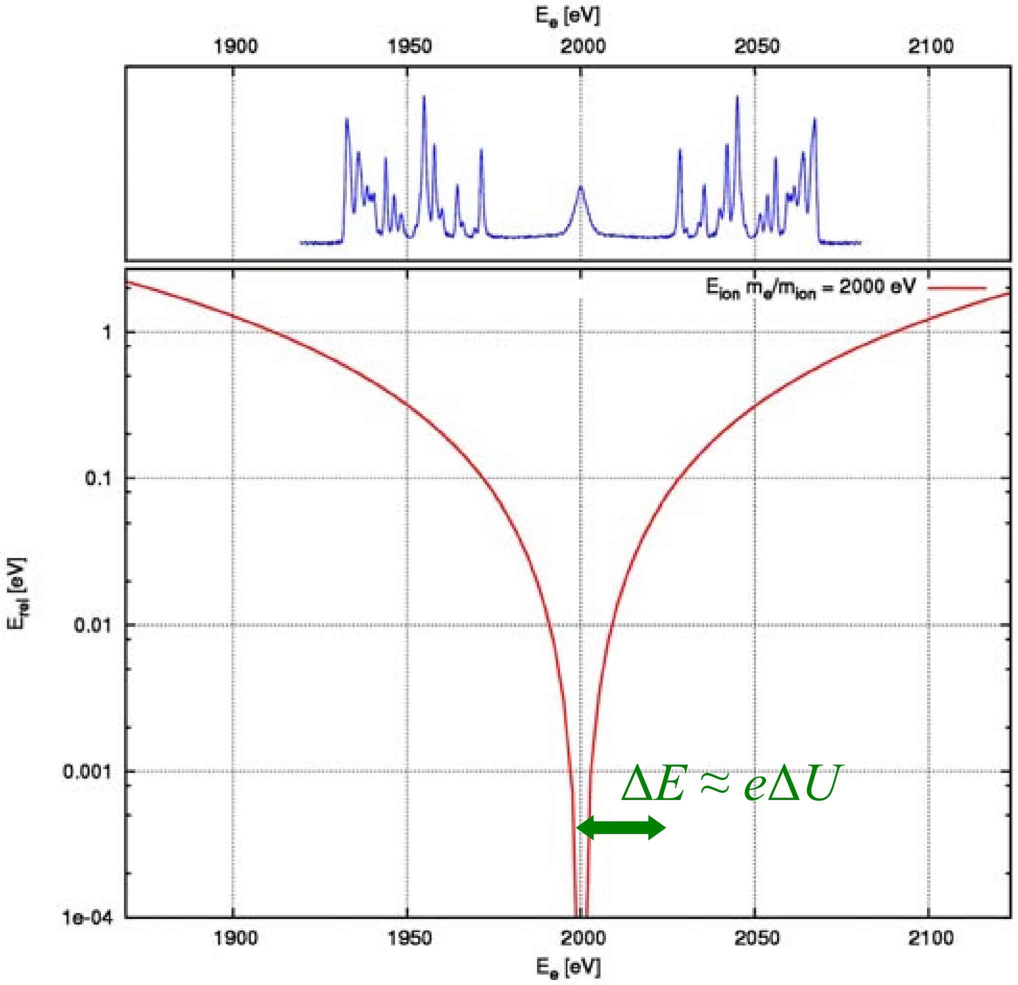


- ΔU can be measured to 10^{-4}
- at $E_{\text{rel}} \leq$ **few eV**:
  accuracy of ΔE is limited by det. of E_{ion}
  and by beam alignment (±0.2 mrad)
- error on E_{ion} **at fixed** ΔE :
  negligible!
- Spacecharge correction is **small** (~ 1 eV)
  and **≈ constant**.

Merged electron-ion beams

- Precision

$$E_{\text{rel}} \approx \frac{m_{\text{ion}}}{m_{\text{e}}} \frac{(\Delta E)^2}{4 E_{\text{ion}}}$$

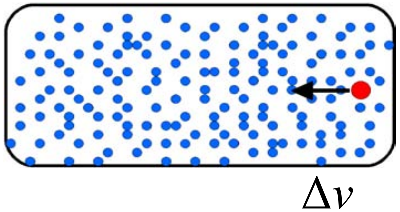


Two **additional limitations**:

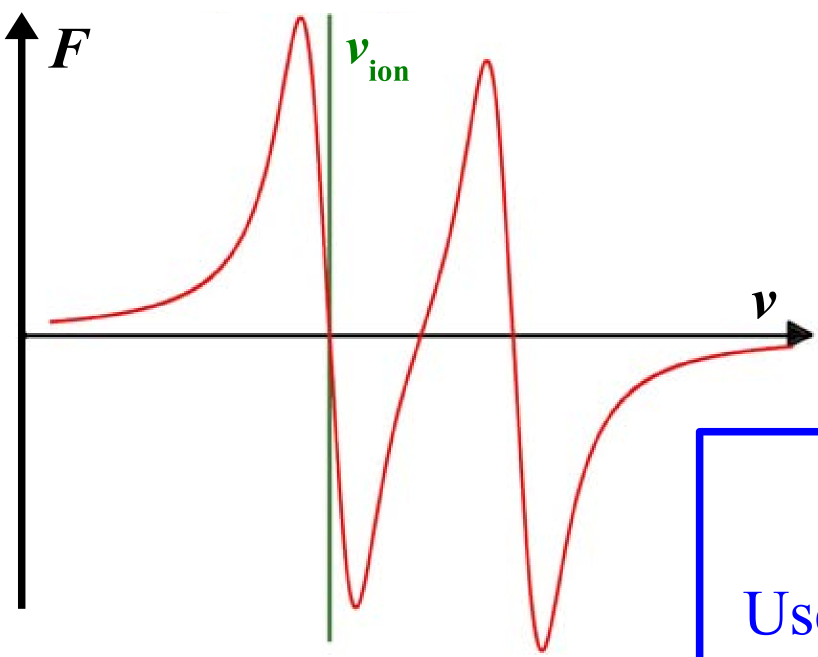
- Detuning the e-beam to $E_{\text{rel}} \neq 0$ may change E_{ion}.
- Experimental resolution is limited by the temperature of the e-beam.

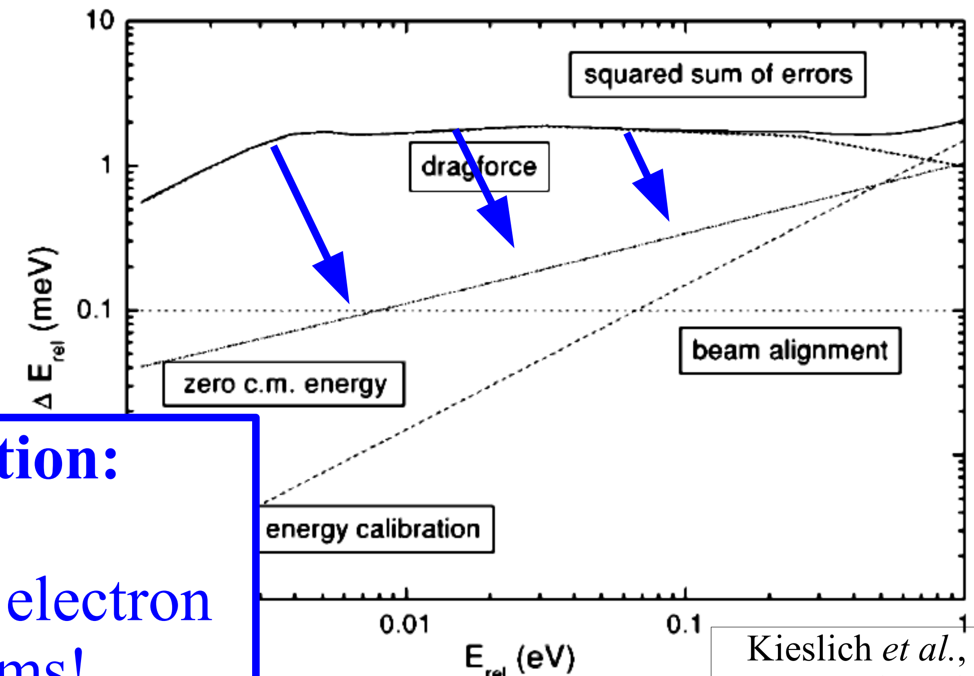
Merged electron-ion beams

- Changes of E_{ion}



  - If $E_{\text{rel}} \neq 0$, electrons pull the ion beam to the new “cooling” point
  - The “friction” force rises $\sim \Delta v$ for small detunings
    → **largely dominating uncertainty** on E_{rel} if unattended!





Solution:

Use *two* electron beams!

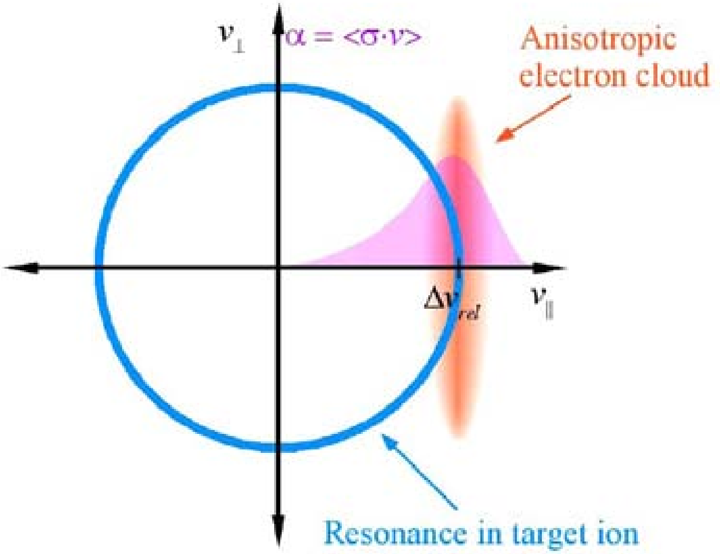
Kieslich *et al.*, PRA **70** (2004)

Merged electron-ion beams

- Electron temperature

flattened Gauß distribution:

$$f(\vec{v},\Delta v)=\sqrt{\frac{m_e^3}{(2\pi k)^3 T_{\parallel}^2 T_{\perp}}}\ \exp\left(\frac{-m_e v_{\perp}^2}{2kT_{\perp}}-\frac{m_e(v_{\parallel}-\Delta v)^2}{2kT_{\parallel}}\right)$$



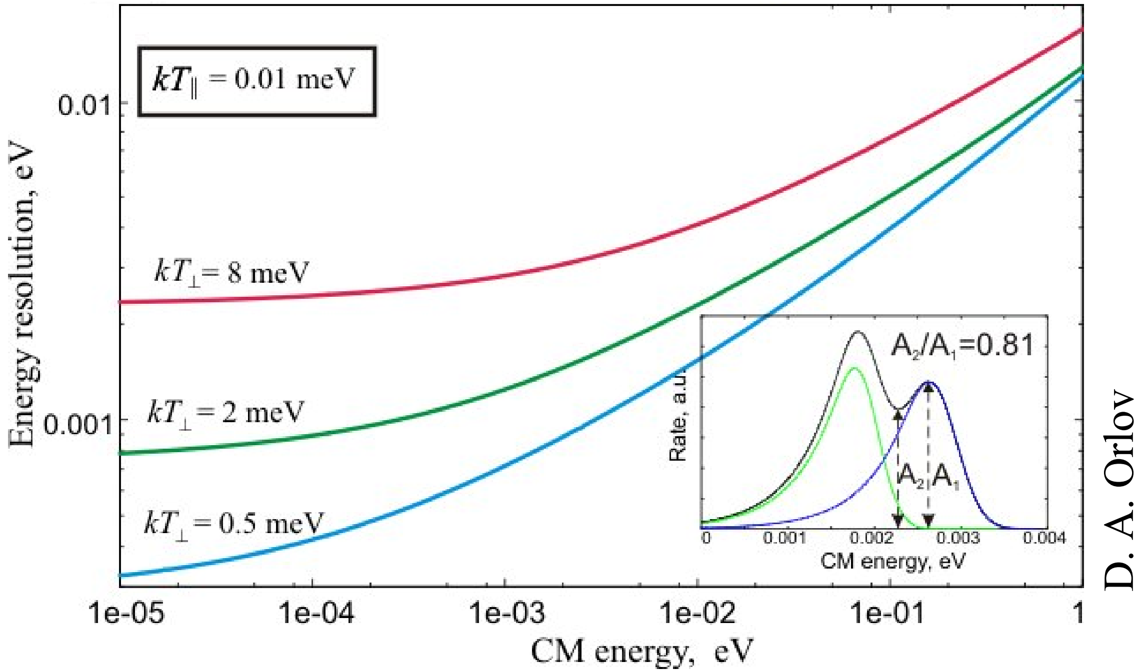
convolution with resonance gives exp. lineshape:

$$\alpha=\int_0^\infty \sigma(v)\, v\, f(\vec{v},v)\, \mathrm{d}v^3$$

Limits resolution for low E_{rel}

Solution:

Use a *cold* electron beam!



The Setup at TSR

- Twin electron beams

Electron Cooler:

- e-beam of energy $\frac{m_e}{m_{ion}} E_{ion}$:

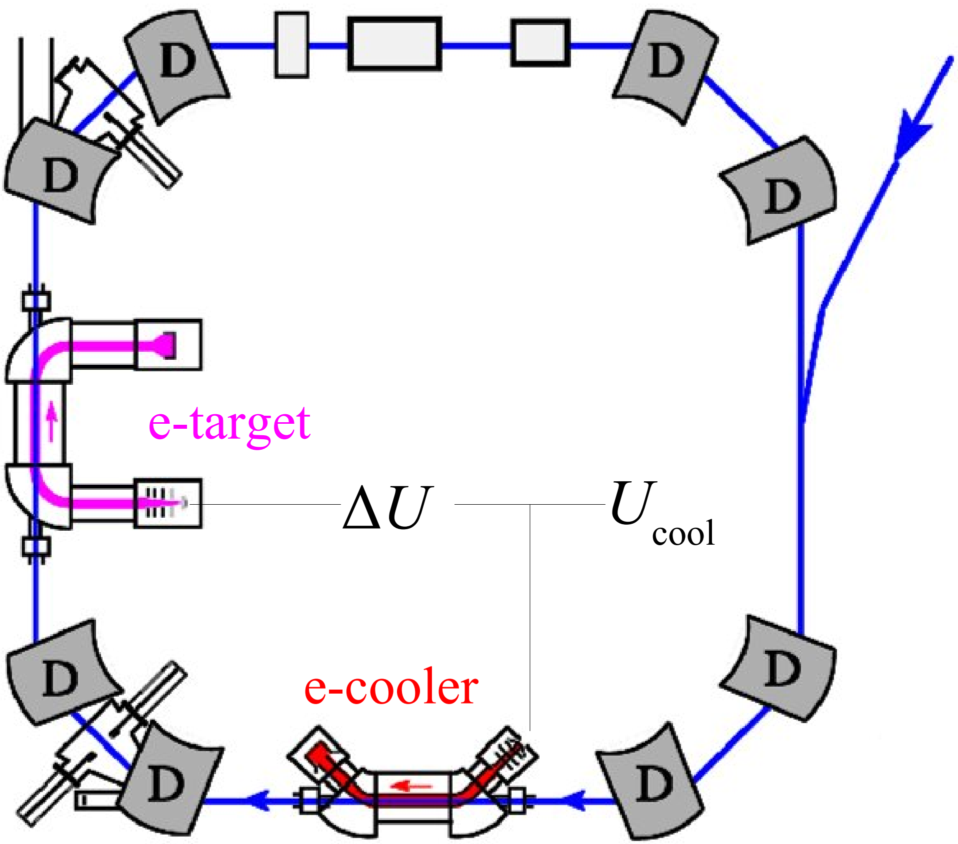
  → **no changes of E_{ion}** ✓

  phase-space **cooling** of ions

- slow, stable **HV-supply**: "U_{cool}"

- **thermocathode**:

  high currents (~ 100 mA), high n_e



Electron Target:

- e-beam of energy $E_e \neq \frac{m_e}{m_{ion}} E_{ion}$

  scans of E_{rel}

- base **HV from cooler** + fast ΔU

  → **no relative drifting** ✓

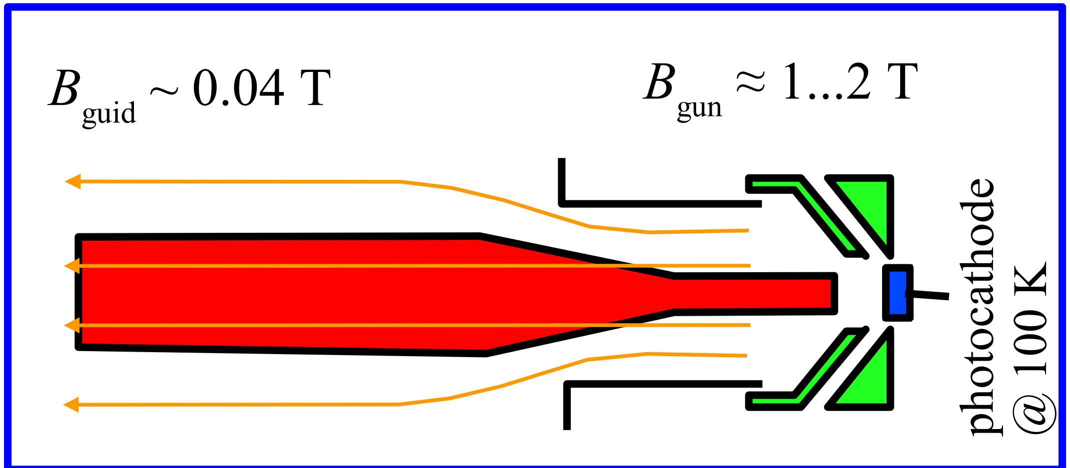
- **photocathode**:

  low currents (≤ 1 mA), low n_e,

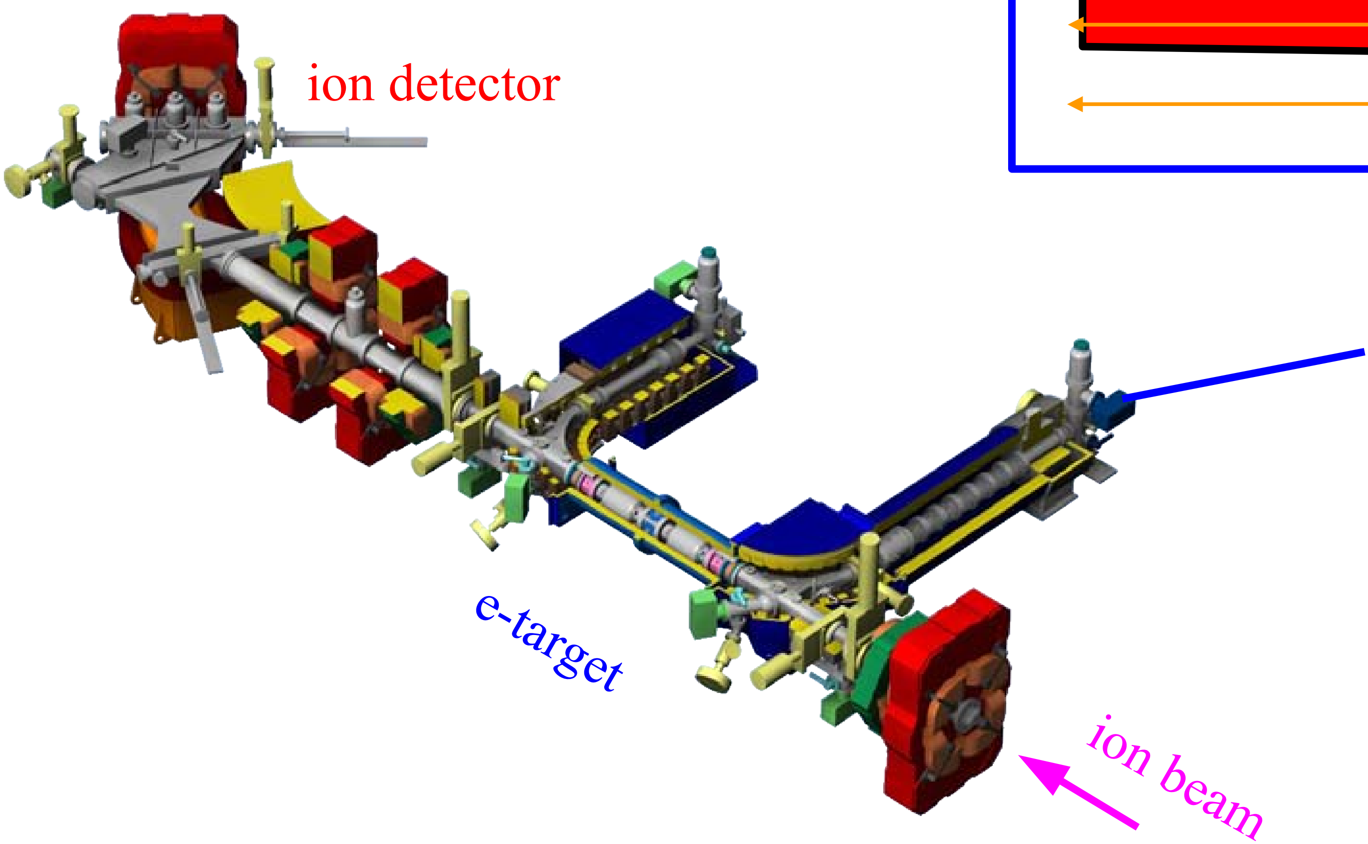
  high resolution

The Setup at TSR

- High-resolution electron target



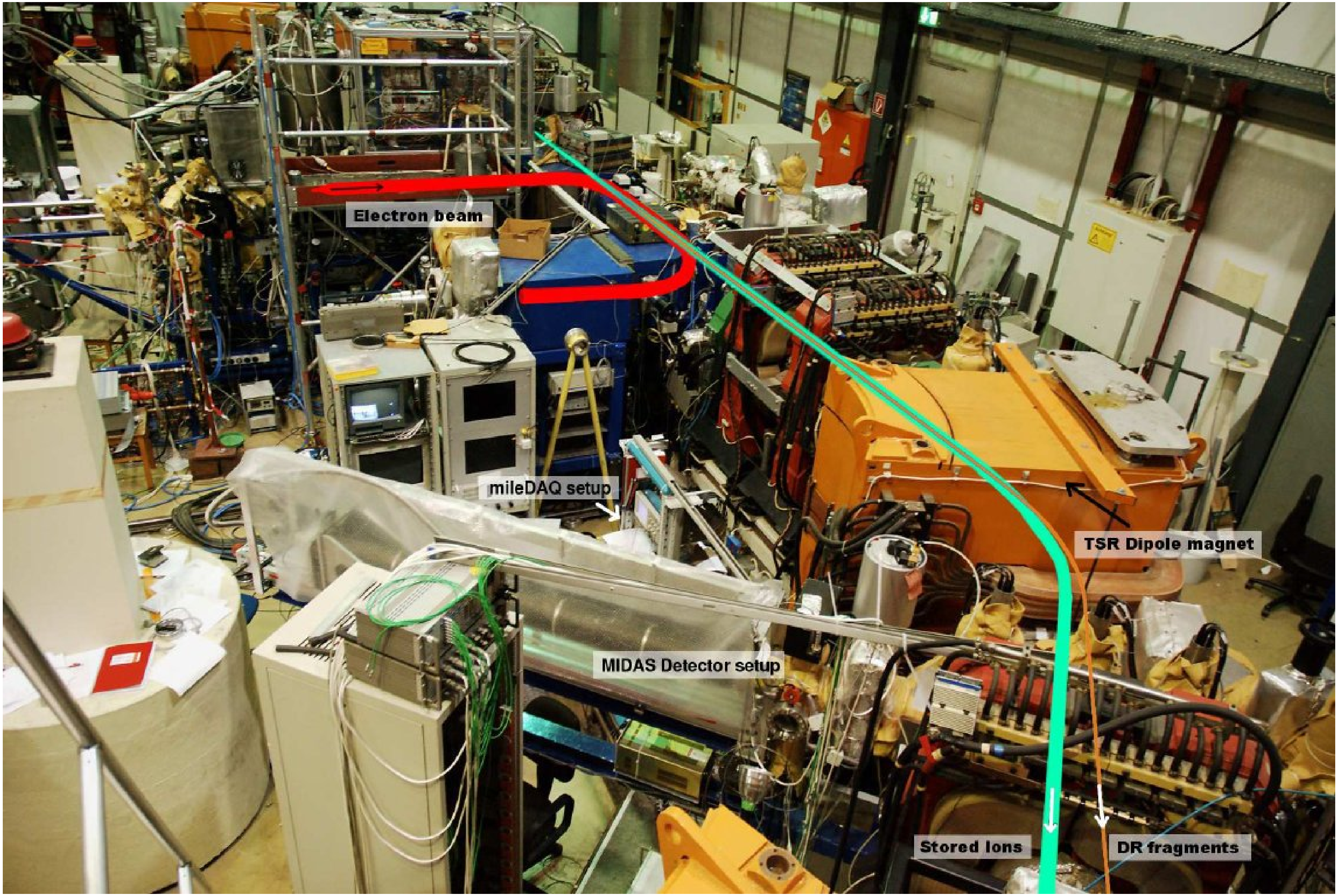
(see talk by
D. Orlov,
next session)



$$k_b T_\perp \approx 1\ \mathrm{meV}$$
$$k_b T_\parallel \approx 20\ \mu\mathrm{eV}$$

✓

The Setup at TSR



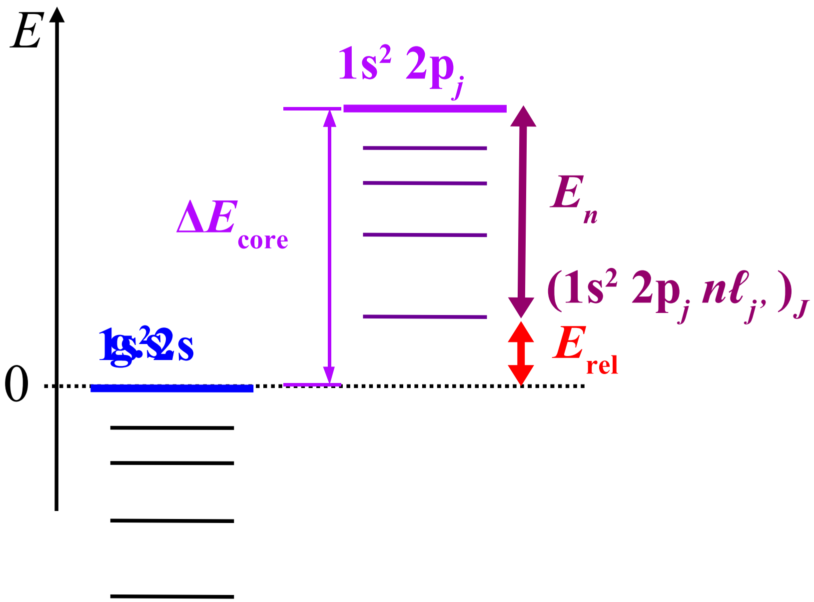
High Resolution DR

- High-resolution DR measurements

... can deliver the quantity $E_{\mathrm{rel}} = (\Delta E_{\mathrm{core}} - E_n)$ with high precision

... provide an opportunity to

1. take E_n from RMBPT and measure $\Delta E_{\mathrm{core}} \rightarrow$ test QED
2. probe RMBPT

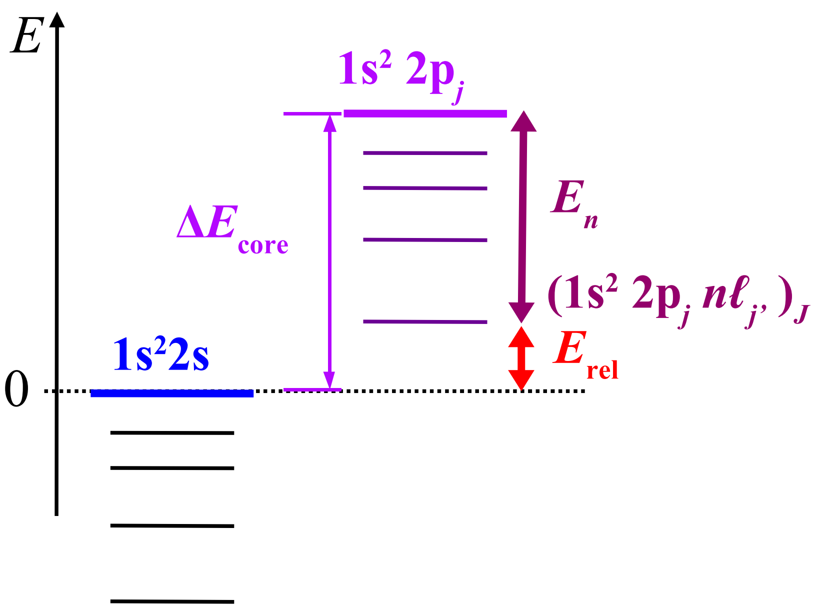


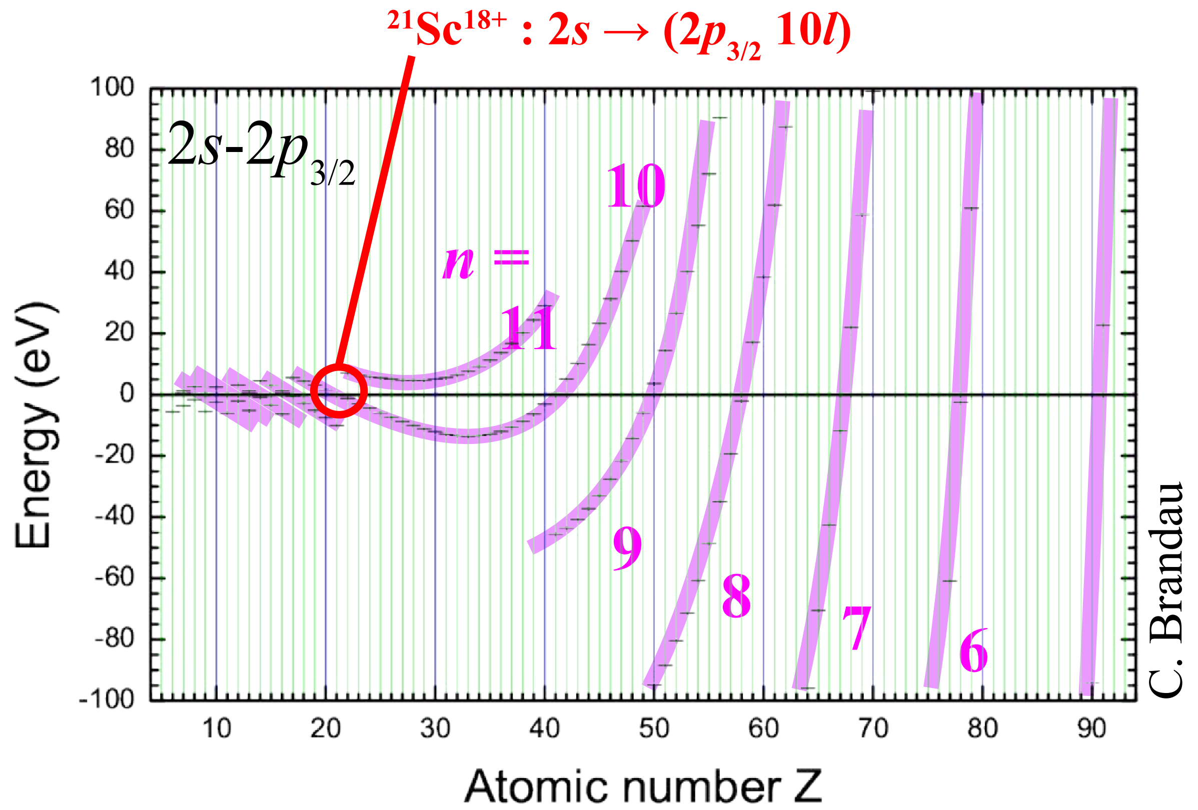
Lithiumlike systems:

- ground state $1s^2\ 2s$
- doubly-excited system: $(1s^2\ 2p_j\ nl_{j'})_J$
- theoretically very well understood (RMBPT)

High Resolution DR

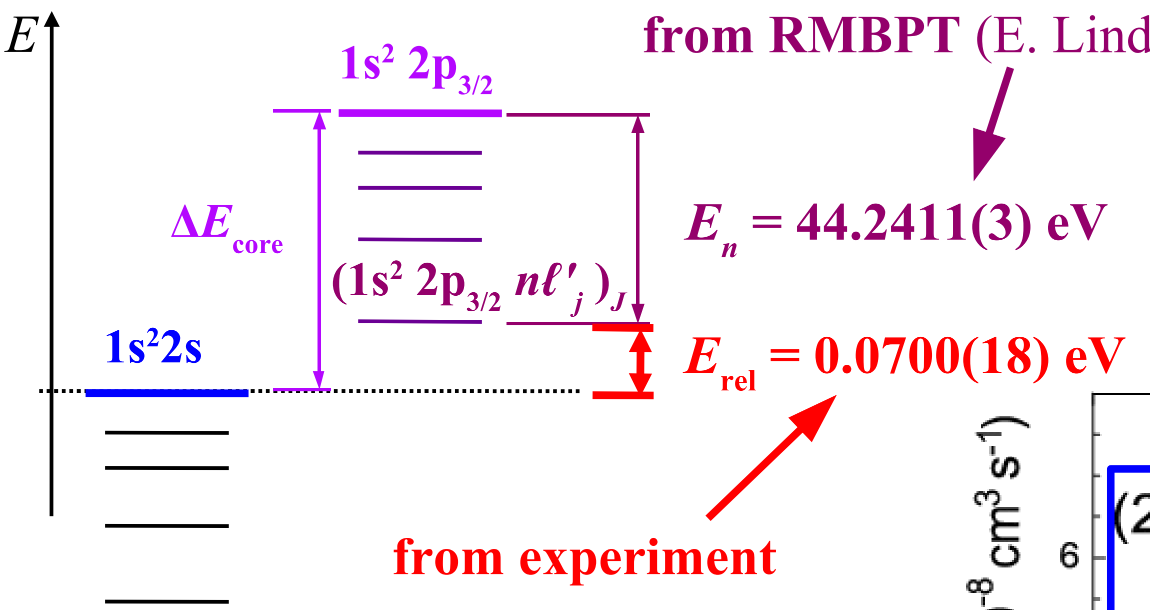
- Lithiumlike systems
  - ... can be produced and stored at the TSR in the range Z up to 30.
  - In order to get high resolution, we want $E_{\mathrm{res}} \approx 0$.





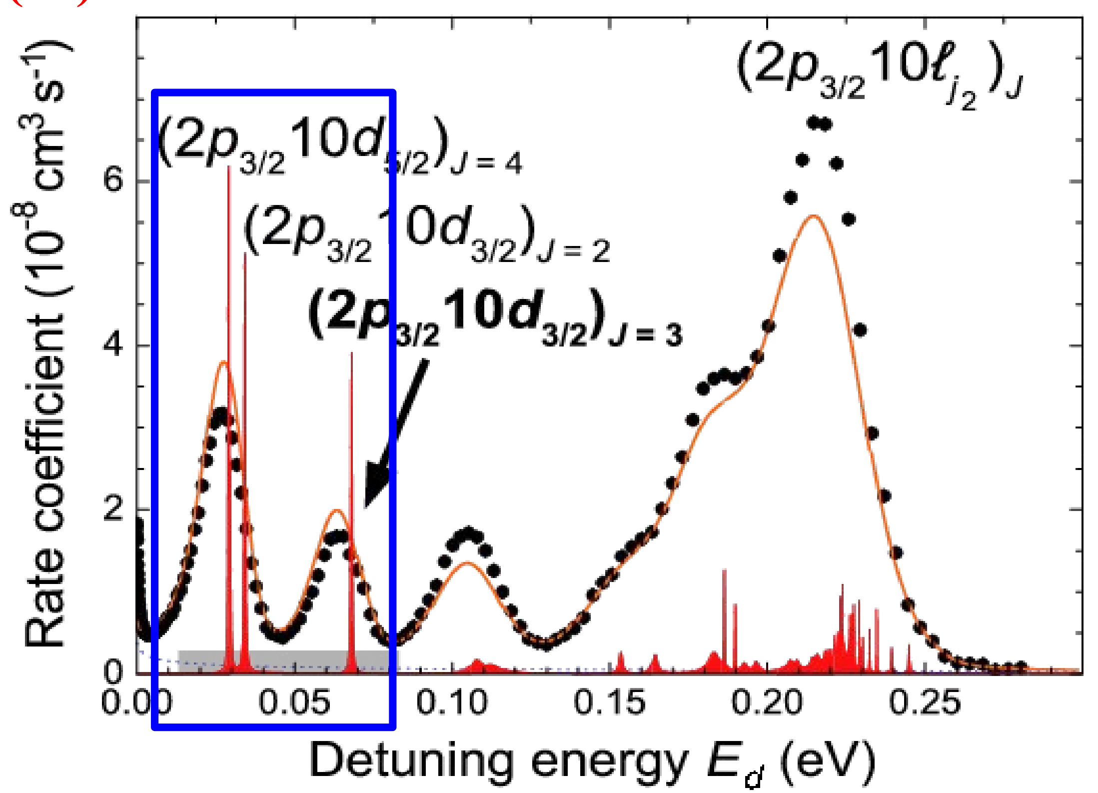
High-Resolution DR

- Lithiumlike Sc^{18+}: DR-measurement with **TSR cooler**



$k_bT_\perp \approx$ **7.2 meV**
$k_bT_\parallel \approx$ **180 μeV**

Kieslich *et al.*, PRA **70** (2004)



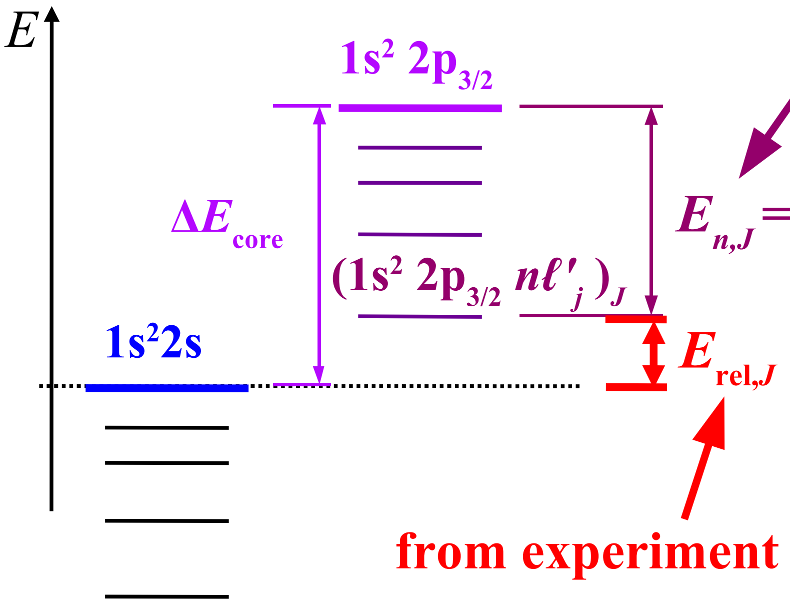
$2s_{1/2} \rightarrow 2p_{3/2}$ core transition:

ΔE_{core} = **44.3107(19) eV**

[optical spectroscopy:
ΔE_{core} = 44.312(35) eV]

High-Resolution DR

- Lithiumlike Sc^{18+}: DR-measurement with **TSR e-target**



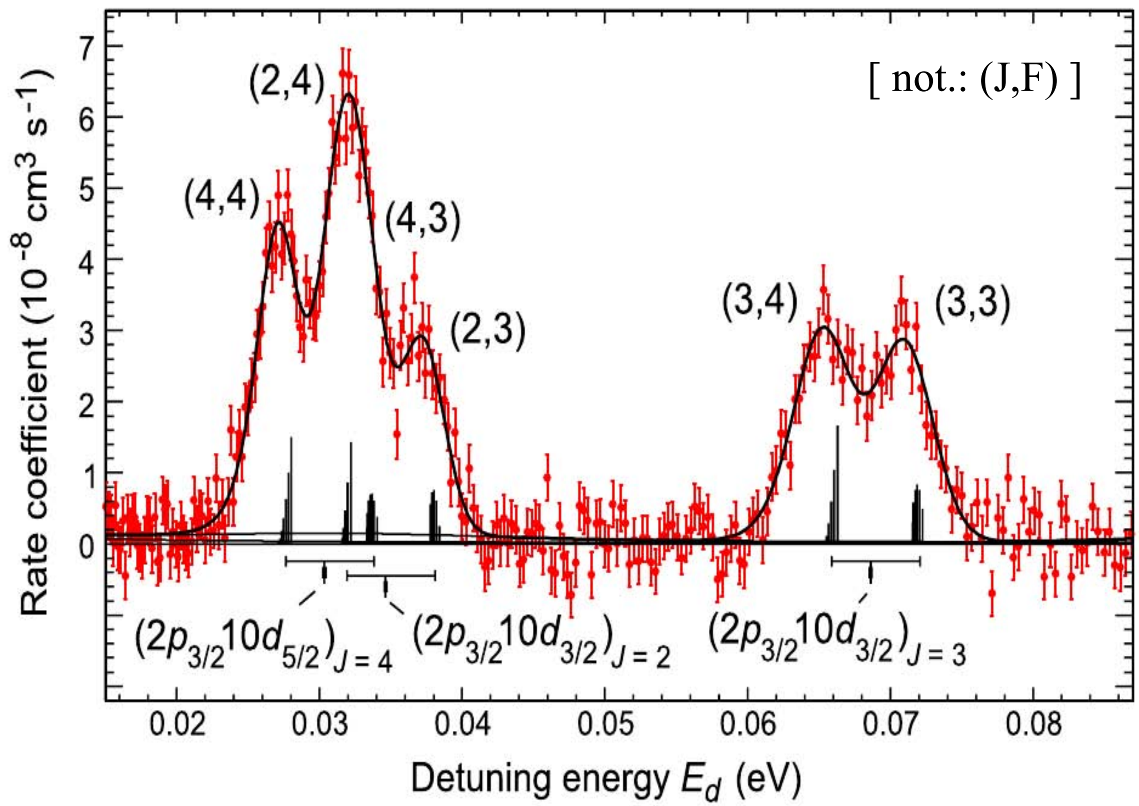
from RMBPT (E. Lindroth)

$$E_{n,J} = \begin{cases} 44.27916(11)\ \text{eV} \\ 44.27480(11)\ \text{eV} \\ 44.24071(9)\ \text{eV} \end{cases}$$

$$E_{rel,J} = \begin{cases} 0.03036(10)\ \text{eV} \\ 0.03465(10)\ \text{eV} \\ 0.06861(10)\ \text{eV} \end{cases}$$

$k_b T_\perp \approx$ **1.1 meV**
$k_b T_\parallel \approx$ **20 µeV**

Lestinsky *et al.*, PRL **100** (2008)

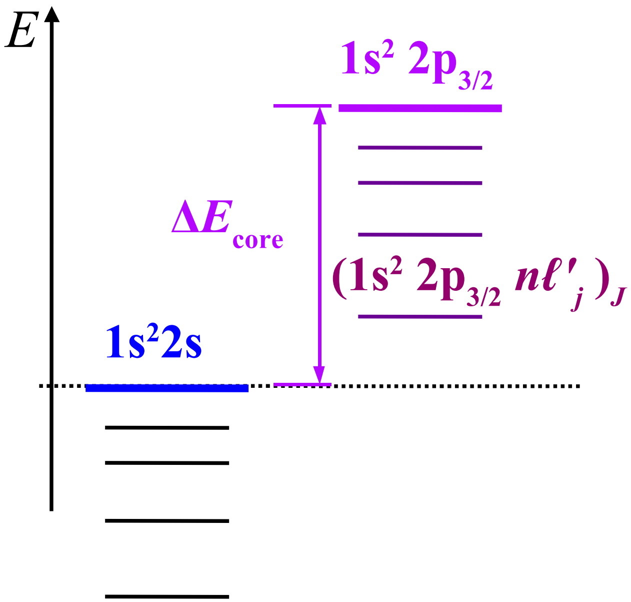


$2s \rightarrow 2p_{3/2}$ transition:

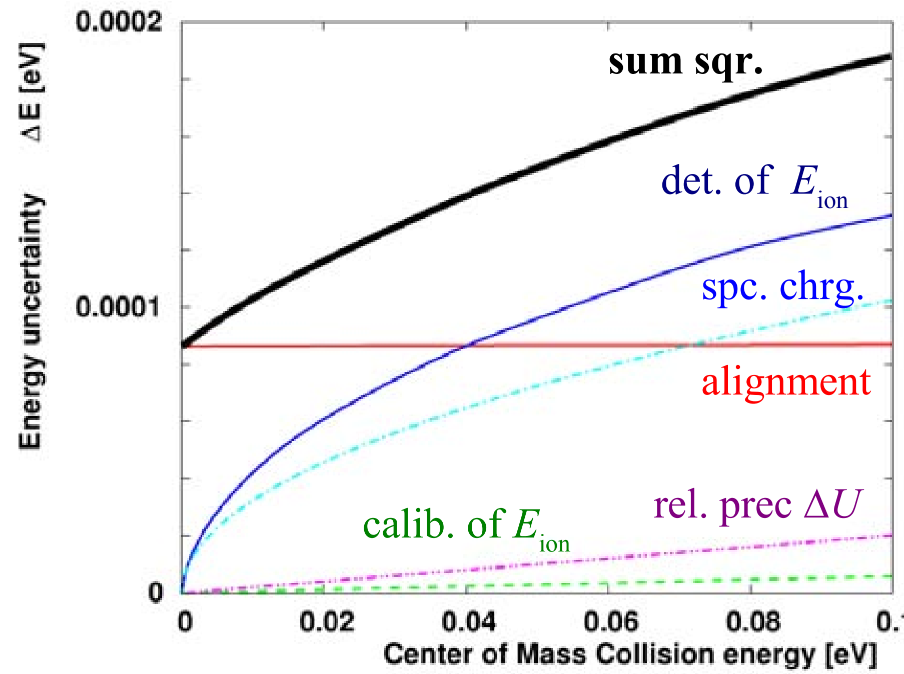
ΔE_{core} **= 44.30943(20) eV**

High-Resolution DR

- Lithiumlike Sc^{18+}: DR-measurement with **TSR e-target**



Lestinsky *et al.*,
PRL **100** (2008)



$2s_{1/2} \rightarrow 2p_{3/2}$ core transition energy:

TSR Target: $\Delta E_{core} = 44.30943(20)$ eV

TSR Cooler: $\Delta E_{core} = 44.3107(19)$ eV

Optical spec: $\Delta E_{core} = 44.312(35)$ eV

QED: $\Delta E_{core} = 44.3091(21)$ eV

precision: ± 0.0002 eV or 4.6 ppm

≈ 0.1 % of radiative corrections
≈ 1 % of few-body corrections
on rad. corrections

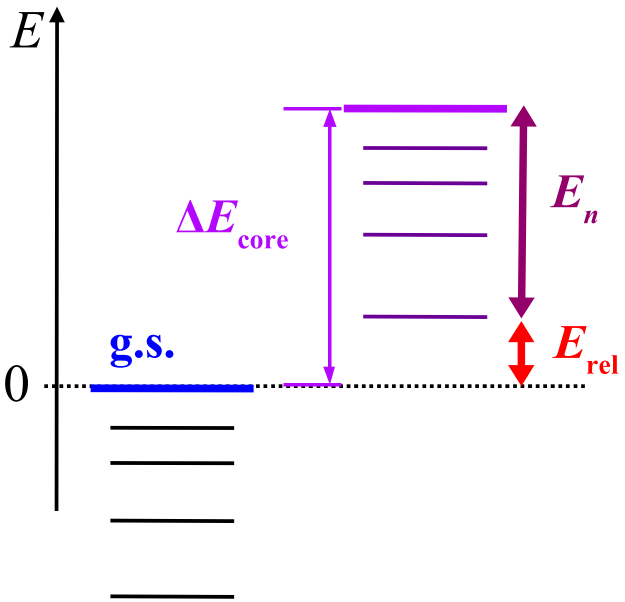
High Resolution DR

- High resolution DR measurements

... can deliver the quantity $E_{rel} = (\Delta E_{core} - E_n)$ with high precision

... provide an opportunity to

1. take E_n from RMBPT and measure $\Delta E_{core} \rightarrow$ test QED **?**
2. probe Many Body Calculations (RMBPT ...) **!**

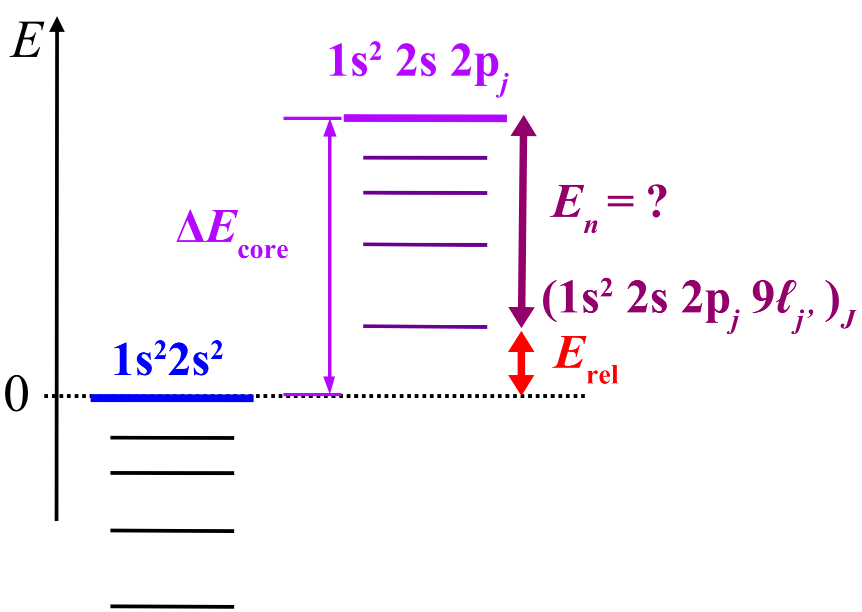


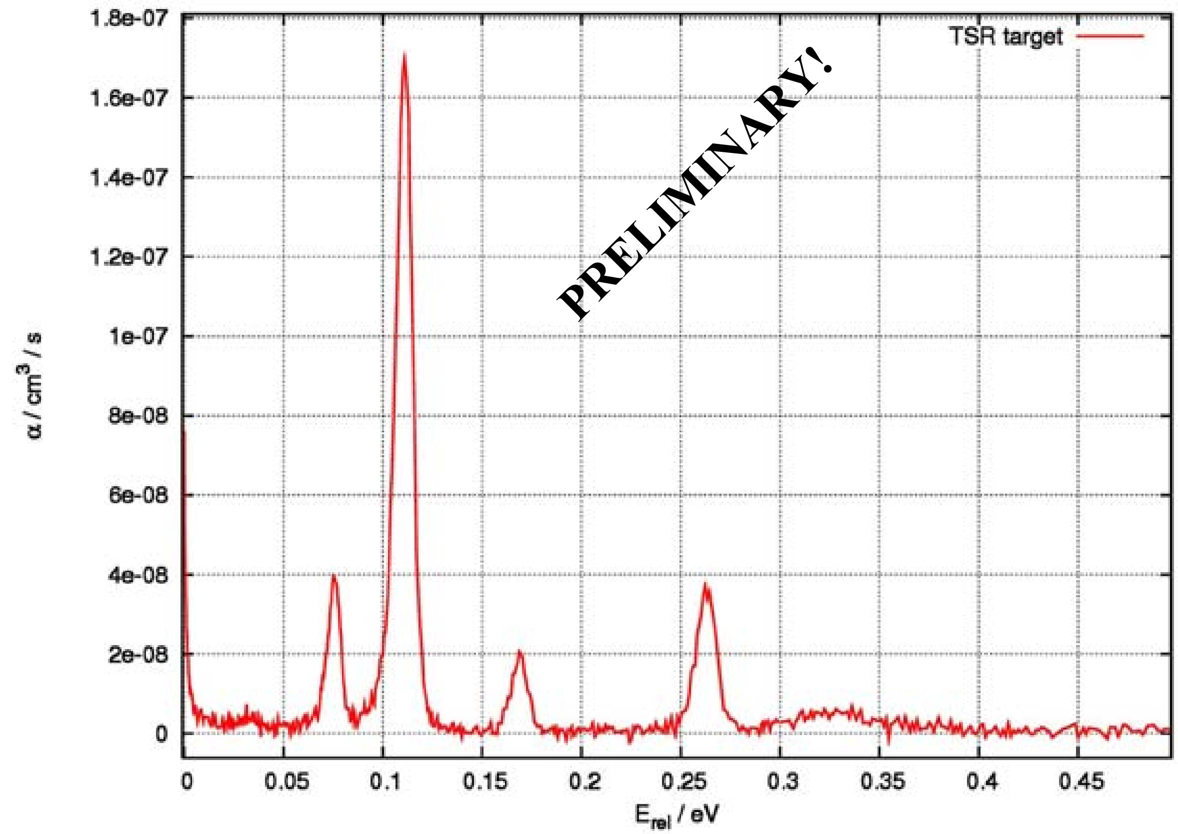
More than one valence electron:

- Number of electrons in open shells rises.
- RMBPT does not reach the accuracy of Li-like systems (yet).

Towards More Valence Electrons ...

- Berylliumlike Ge^{28+}
  - **testbench** for precise many-body calculations (Be-like)
  - may eventually allow to probe **QED** on a similar level than Li-like systems.



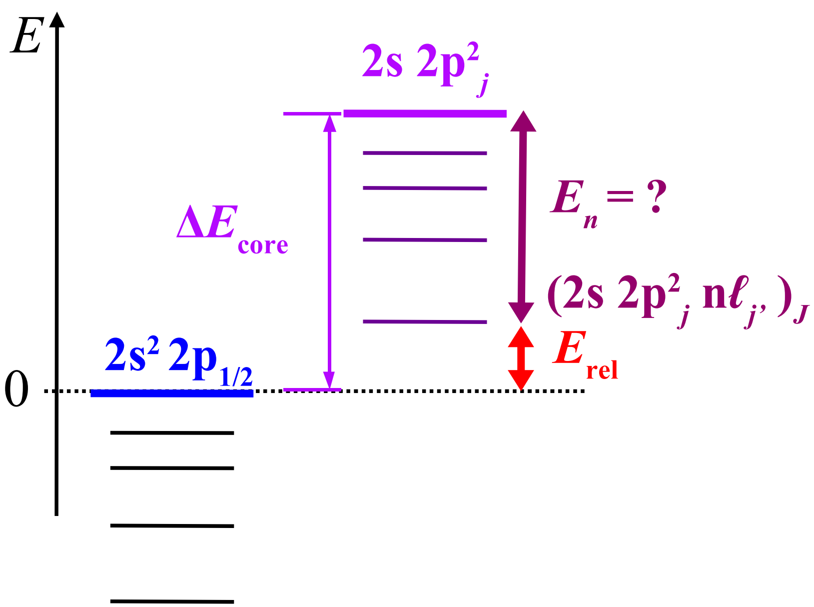


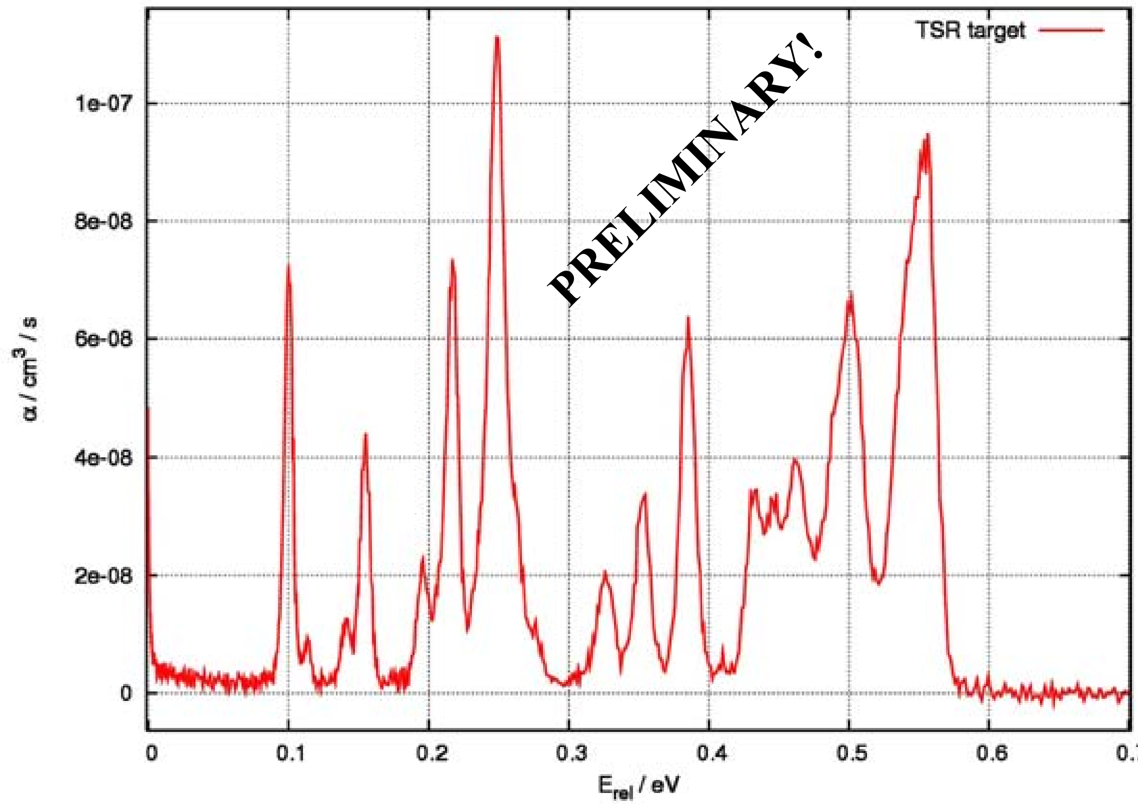
similar E-scale than for Ge28+

Exp.: D. A. Orlov, april 2008

Towards More Valence Electrons ...

- Boronlike Fe^{21+}
  - **testbench** for precise many-body calculations (B-like)
  - may eventually allow to probe **QED** on a similar level than Li-like systems.





D. W. Savin *et al.*, APJ Sup S. (2003)

Exp.: C.K., april 2008

Conclusions

- High resolution DR can compete with optical spectroscopy for ionic systems with **low-lying DR resonances**.

- The TSR’s **twin-electron beam setup** is a significant advantage as it eliminates electron-induced changes of the ion energy E_{ion} and features a **low-*T* target** e-beam.

- The core transition of a **Li-like system** has been measured with precision **0.2 meV or 4.6 ppm**.

- High resolution DR-measurements of ionic systems with **several valence electrons** have been performed and may serve as **benchmarks** for highly precise atomic structure calculations.

Thank you for your Attention

Andreas Wolf

Dmitry A. Orlov
Michael Lestinsky
Jens Hoffmann

Manfred Grieser
Robert von Hahn
Roland Repnow
C.K.

IAMP
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Stefan Schippers
Alfred Müller
Eike W. Schmidt
Dietrich Bernhard

Atomic Physics FYSIKUM

Eva Lindroth

GSI

Carsten Brandau
Christophor Kozhuharov