Frascati, 6 November 2017

Study of quantum electrodynamics and chromodynamics in atomic bound systems

M. Trassinelli

Chargé de recherche du CNRS

Institut des NanoSciences de Paris,
CNRS et Univ. Pierre et Marie Curie – Sorbonne Univ., France

Seminar organized within the project **Hunt for the Impossible atoms**
Founded by the **John Templeton Foundation**

Exotic atomic systems

- Simple atomic systems

→ accurate theoretical predictions

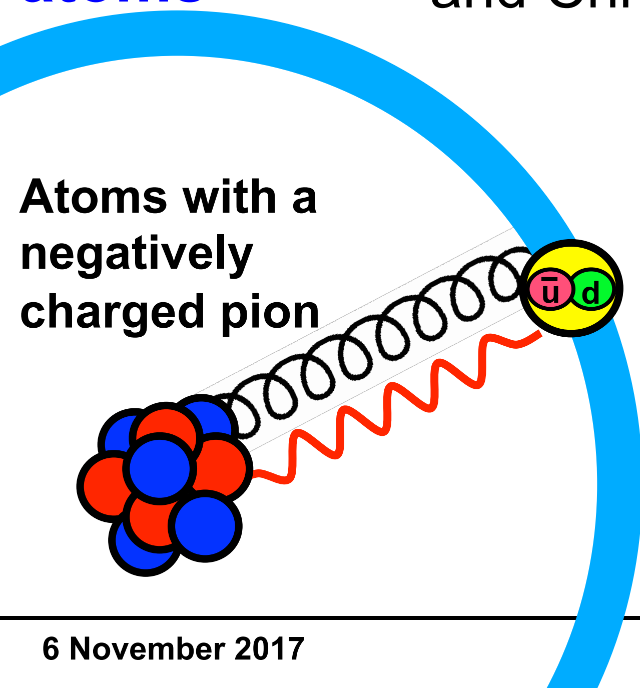
→ simple spectra

➔ accurate test of fundamental interactions:

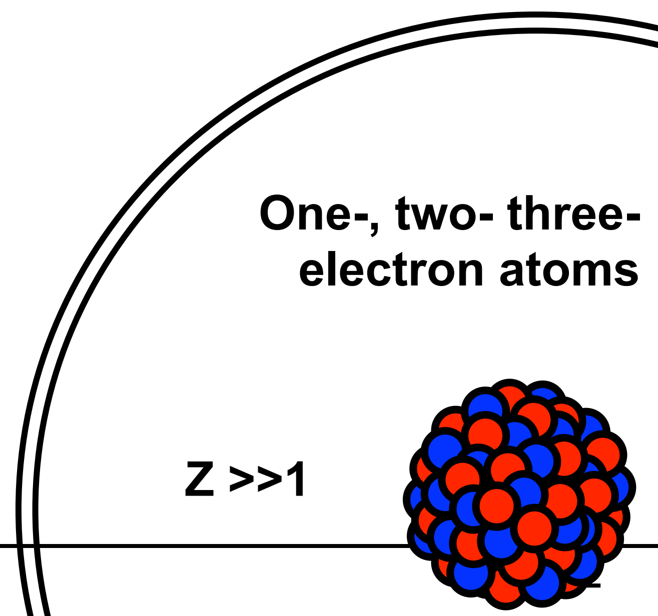
Quantum Electrodynamics (in strong filed)

and Chromidynamics (at low energy)

Pionic atoms



Highly charged ions



Summary

- Introduction
  - Test of QED in strong field
  - Study of strong interaction force at low energy
- Heavy highly charged ions
  - Production
  - Lamb shift measurement
  - Vacuum decay experiment
- Pionic atoms
  - Production
  - Pionic hydrogen and deuterium spectroscopy
  - Pion mass measurement
- Conclusions and outlooks

Summary

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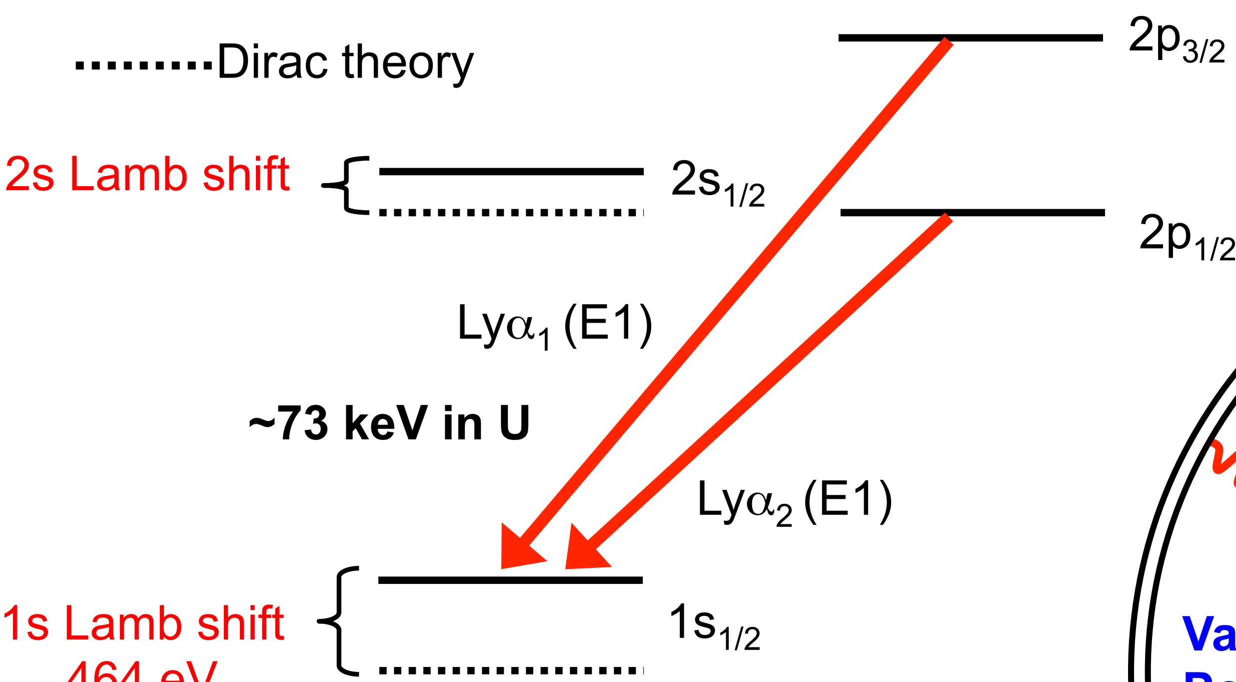
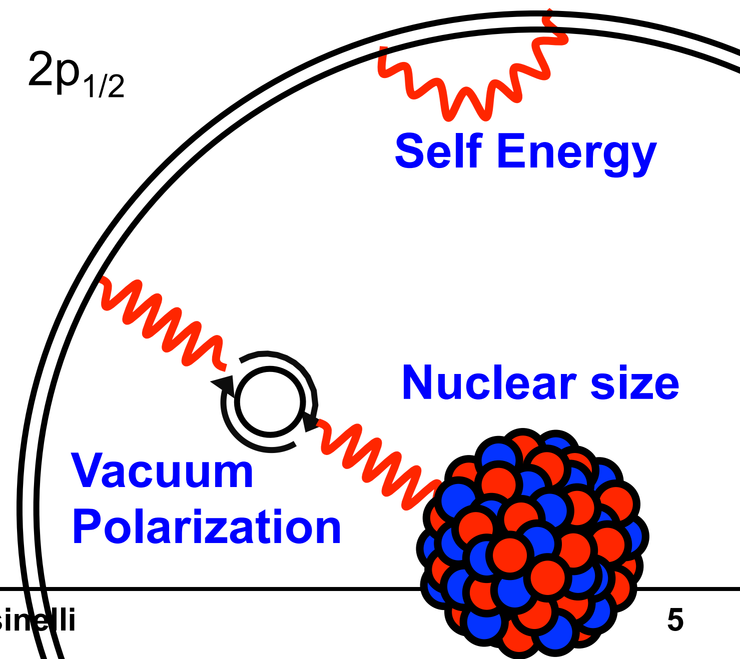
Highly charged ions

Dirac equation (spin-1/2 particles) ➔

$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}}$$

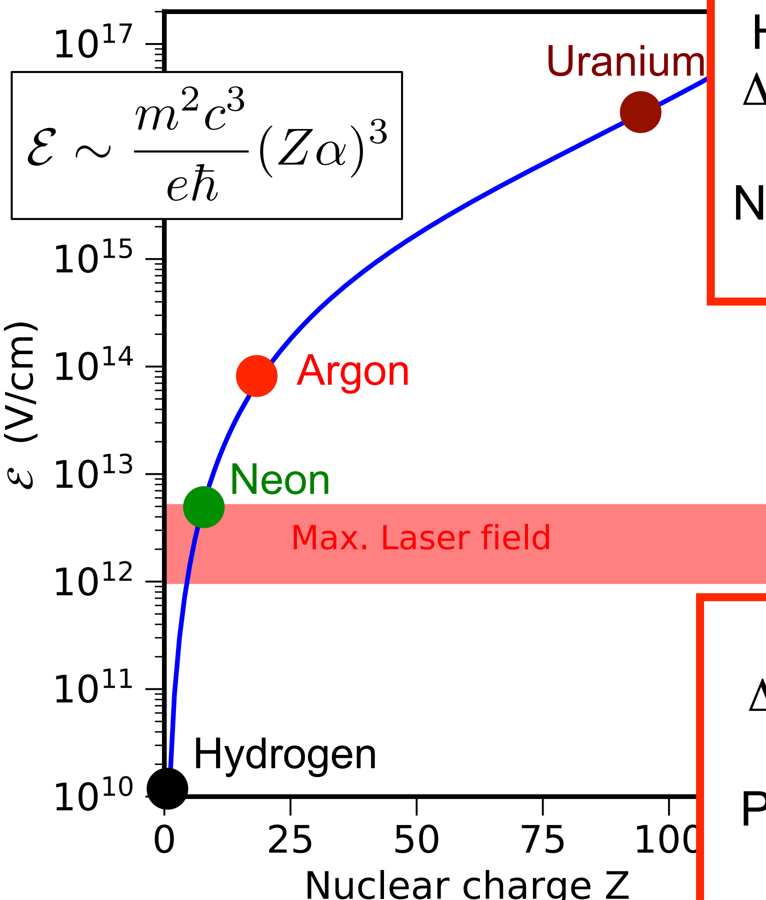
- Simple atomic systems
  → accurate theoretical predictions
  → simple spectra





Few electrons heavy charged ions

$$E_n = mc^2 \frac{(Z\alpha)^2}{2n^2} + \mathcal{O}\left[(Z\alpha)^4\right]$$

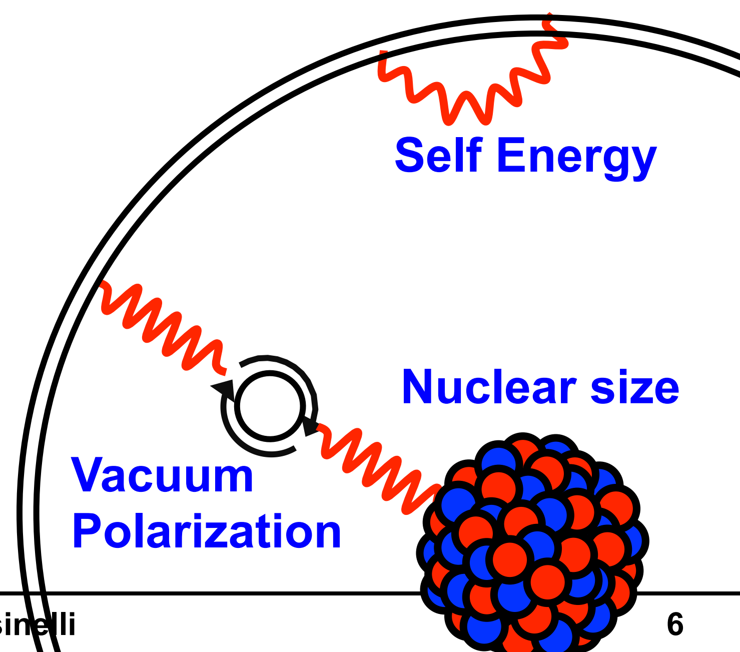


$$\mathcal{E} \sim \frac{m^2 c^3}{e\hbar}(Z\alpha)^3$$

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

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

- Simple atomic systems
  → accurate theoretical predictions
  → simple spectra
- Strong electric field
  → Quantum Electrodynamic effects enhanced
  → Large perturbation during collisions with other atoms



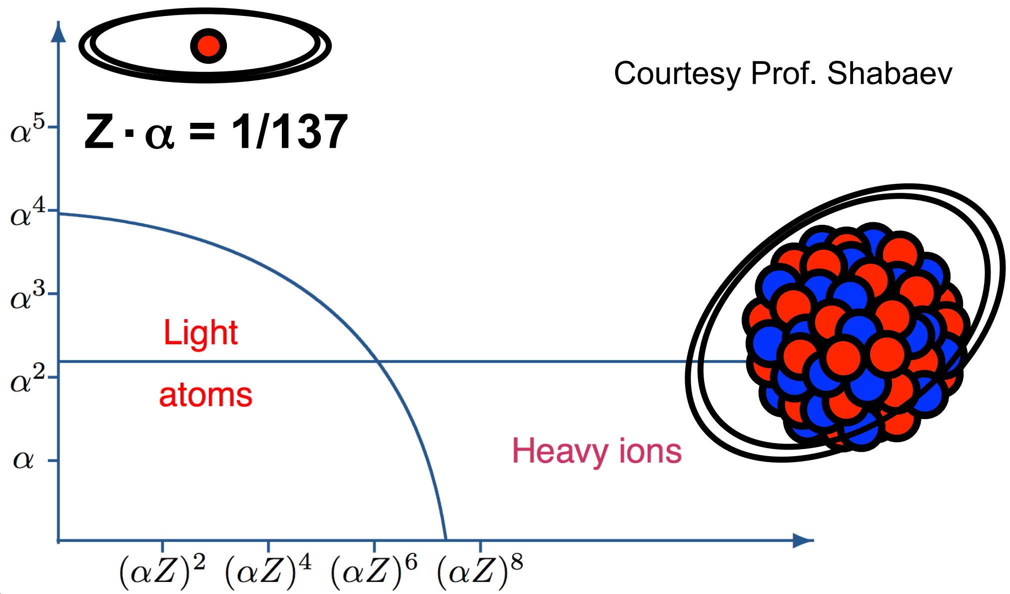
Tests of QED calculations at strong-coupling regime

α and Zα expansion

$$E^{nj} = mc^2 - mc^2\frac{(Z\alpha)^2}{2n^2} + mc^2(Z\alpha)^4\left[a(n,j) + \alpha b(n,j) + \alpha^2 c(n,j) + \ldots\right] + \\ + mc^2(Z\alpha)^6\left[a'(n,j) + \alpha b'(n,j) + \alpha^2 c'(n,j) + \ldots\right] + \ldots$$

M.I. Eides *et al.*, Phys. Rep. **342**, 63-261 (2001)
P.J. Mohr *et al.*, Rev. Mod. Phys. **88**, 035009 (2016).

Courtesy Prof. Shabaev



Z·α ≈ 1

Dirac eq.

QED, reduced mass and finite size contrib.

α expansion, all-order in Zα

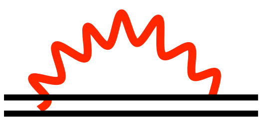
$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}} + \alpha F(Z\alpha) + \alpha^2 G(Z\alpha) + \ldots$$

Non-perturbative bound system QED

First order in α

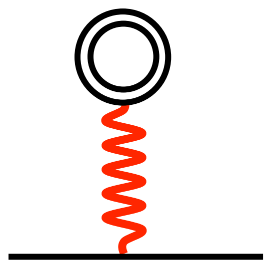
Self- energy

P.J. Mohr, Annals of Physics **88**, 26-51 (**1974**)



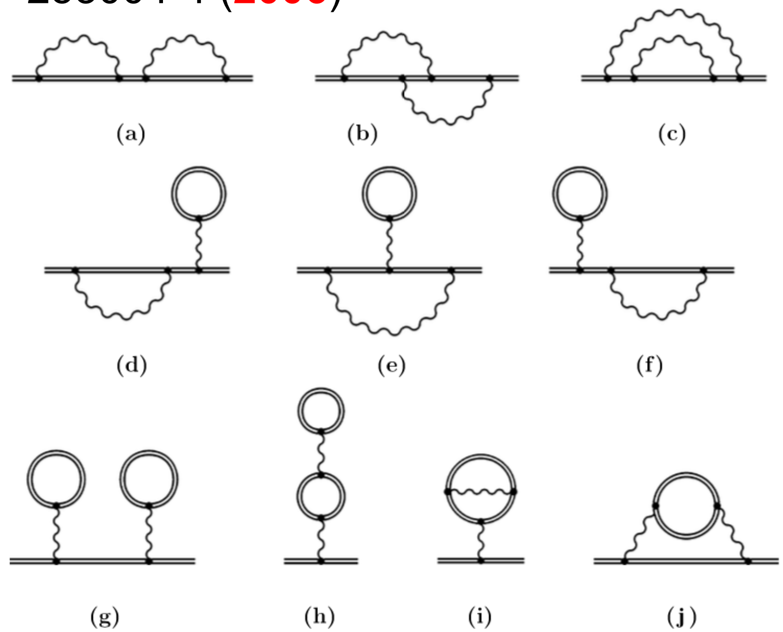
Vacuum polarization

N.L. Manakov *et al.*, Sov. Phys. JETP **68**, 673-679 (**1989**)
G. Soff *et al.*, Phys. Rev. A **38**, 5066-5075 (**1988**)



Second order in α

V.A. Yerokhin *et al.*, Phys. Rev. Lett. **97**, 253004-4 (**2006**)



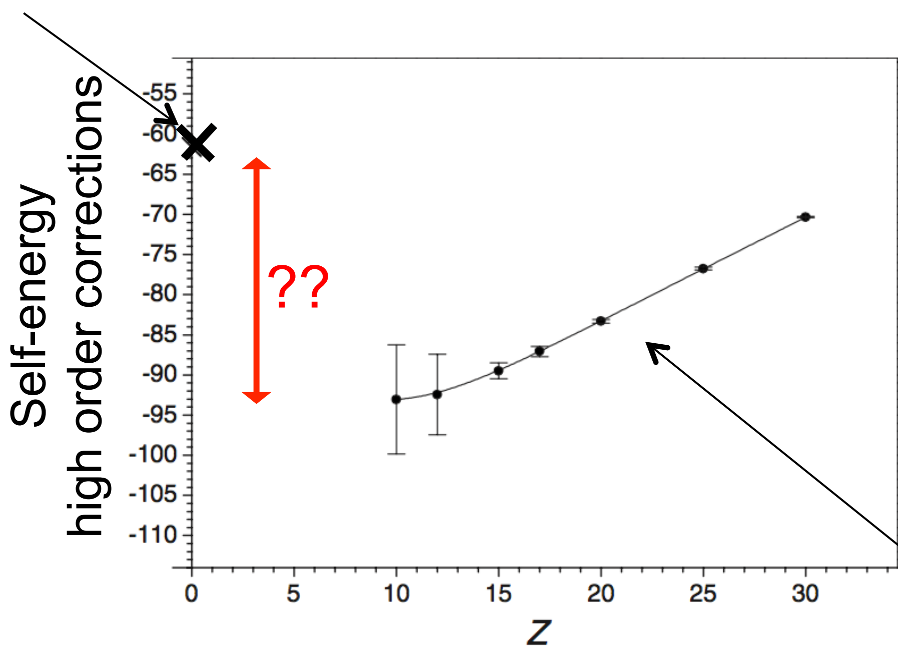
Dirac eq. (**1928**)

$$E^{nj} = \frac{mc^2}{\sqrt{1+\frac{(Z\alpha)^2}{\left[n-j-1/2+\sqrt{(j+1/2)^2-(Z\alpha)^2}\right]^2}}} + \alpha F(Z\alpha) + \alpha^2 G(Z\alpha) + \ldots$$

Self-energy predictions

α and Zα expansion

$$E^{nj} = mc^2 - mc^2\frac{(Z\alpha)^2}{2n^2} + mc^2(Z\alpha)^4\left[a(n,j) + \alpha b(n,j) + \alpha^2 c(n,j) + \ldots\right] + \\ + mc^2(Z\alpha)^6\left[a'(n,j) + \alpha b'(n,j) + \alpha^2 c'(n,j) + \ldots\right] + \ldots$$



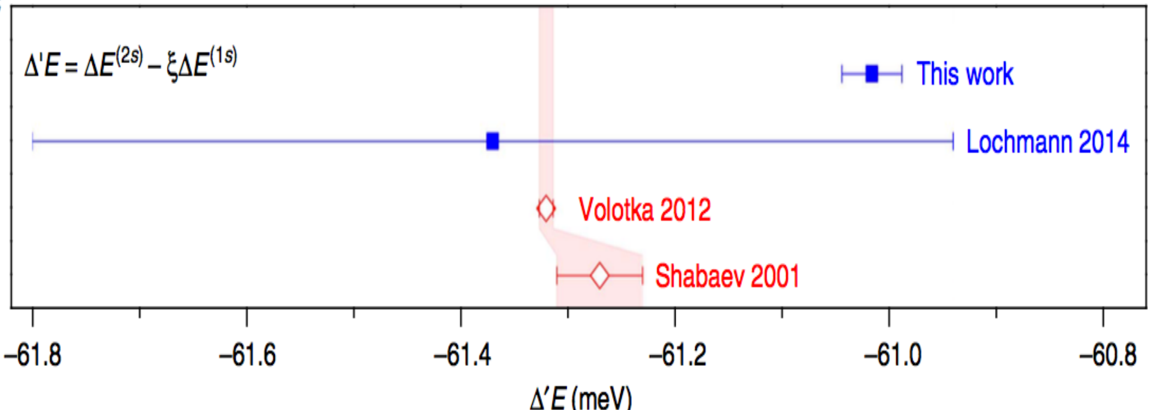
V.A. Yerokhin, Phys. Rev. A **80**, 040501 (2009)

α expansion, all-order in Zα

$$E^{nj} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - j - 1/2 + \sqrt{(j+1/2)^2 - (Z\alpha)^2}\right]^2}}} + \alpha F(Z\alpha) + \alpha^2 G(Z\alpha) + \ldots$$

Quantum electrodynamics tests in atomic systems: open questions

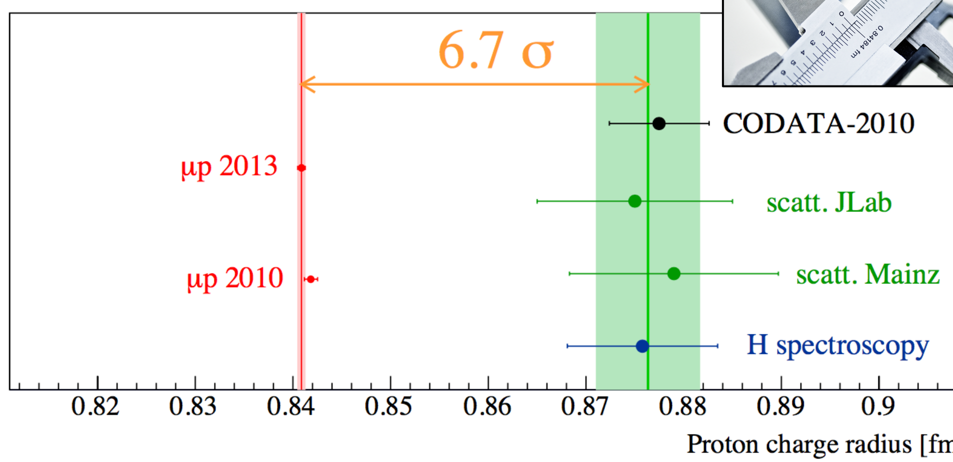
Hyperfine structure of H- and Li-like Bismuth



J. Ullmann *et al.*, Nat. Commun. **8**, 15484 (2017)

Laser spectroscopy of stored heavy ions

Proton radius puzzle



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

Strong disagreement between **hydrogen** and **muonic hydrogen** spectroscopy

$m_\mu = 200\, m_e$

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

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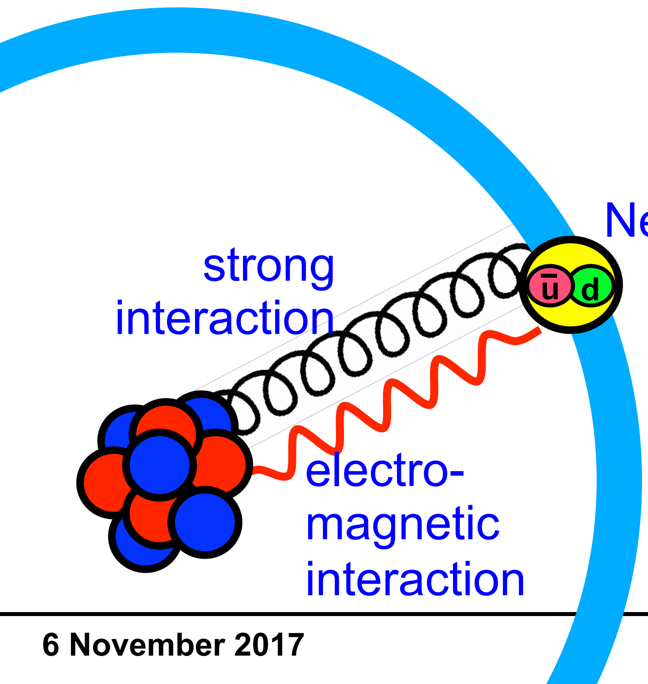
Pionic atoms

- Simple atomic systems
  - → accurate theoretical predictions
  - → simple spectra

Klein-Gordon equation (spin-0 particles) ➔

$$E^{nl} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - l - 1/2 + \sqrt{(l+1/2)^2 - (Z\alpha)^2}\right]^2}}}$$



Negative charged pion

- $m_\pi = 254\ m_e$
- lifetime=26 ns

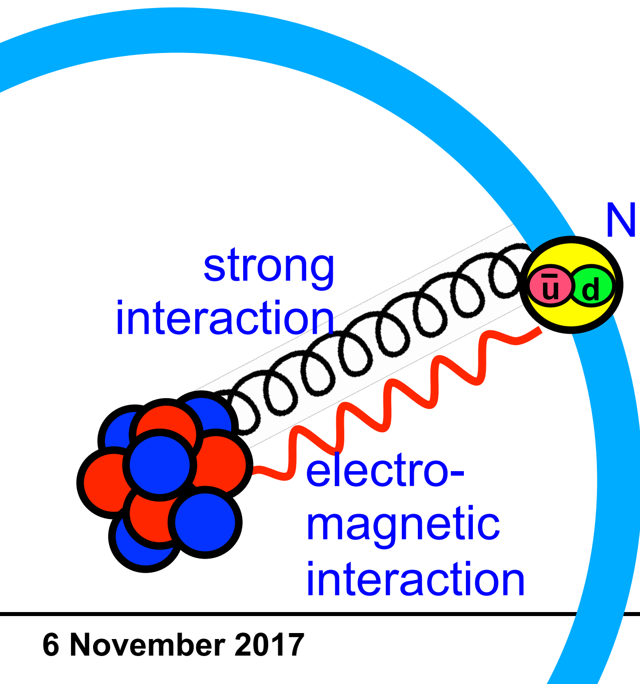
Hydrogen-like atoms

Pionic atoms

- Simple atomic systems
  → accurate theoretical predictions
  → simple spectra
- Strong electric field
  → Quantum Electrodynamic effects enhanced
- Presence of strong interaction
- Small Bohr radius

$$E^{nl} = \frac{mc^2}{\sqrt{1 + \frac{(Z\alpha)^2}{\left[n - l - 1/2 + \sqrt{(l+1/2)^2 - (Z\alpha)^2}\right]^2}}}$$

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



Negative charged pion

- m_π = 254 m_e
- lifetime=26 ns

Hydrogen-like atoms

Pionic atoms

- Electromagnetic interaction → bound system

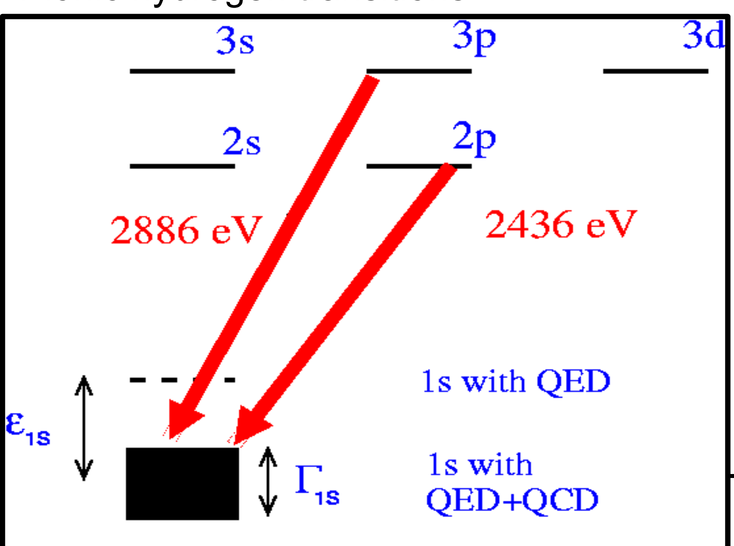
$$E_n = mc^2 \frac{(Z\alpha)^2}{2n^2} + \mathcal{O}\left[(Z\alpha)^4\right]$$

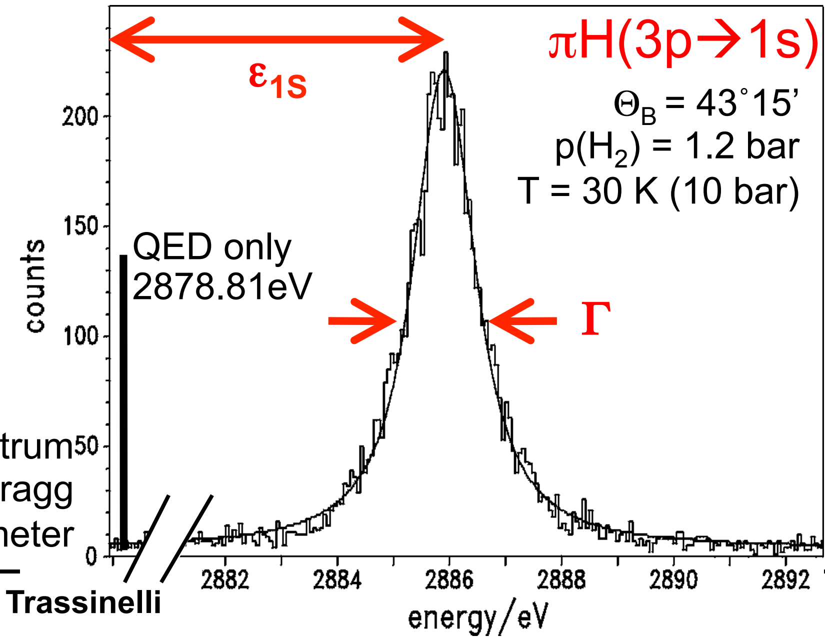
- **Strong interaction!!**

  Attraction or repulsion → shift of the energy transition ε

  Reaction with the nucleus → ground state instable
  - lifetime of the atom not infinite
  - non-zero linewidth Γ of the atomic transitions

Pionic hydrogen transitions





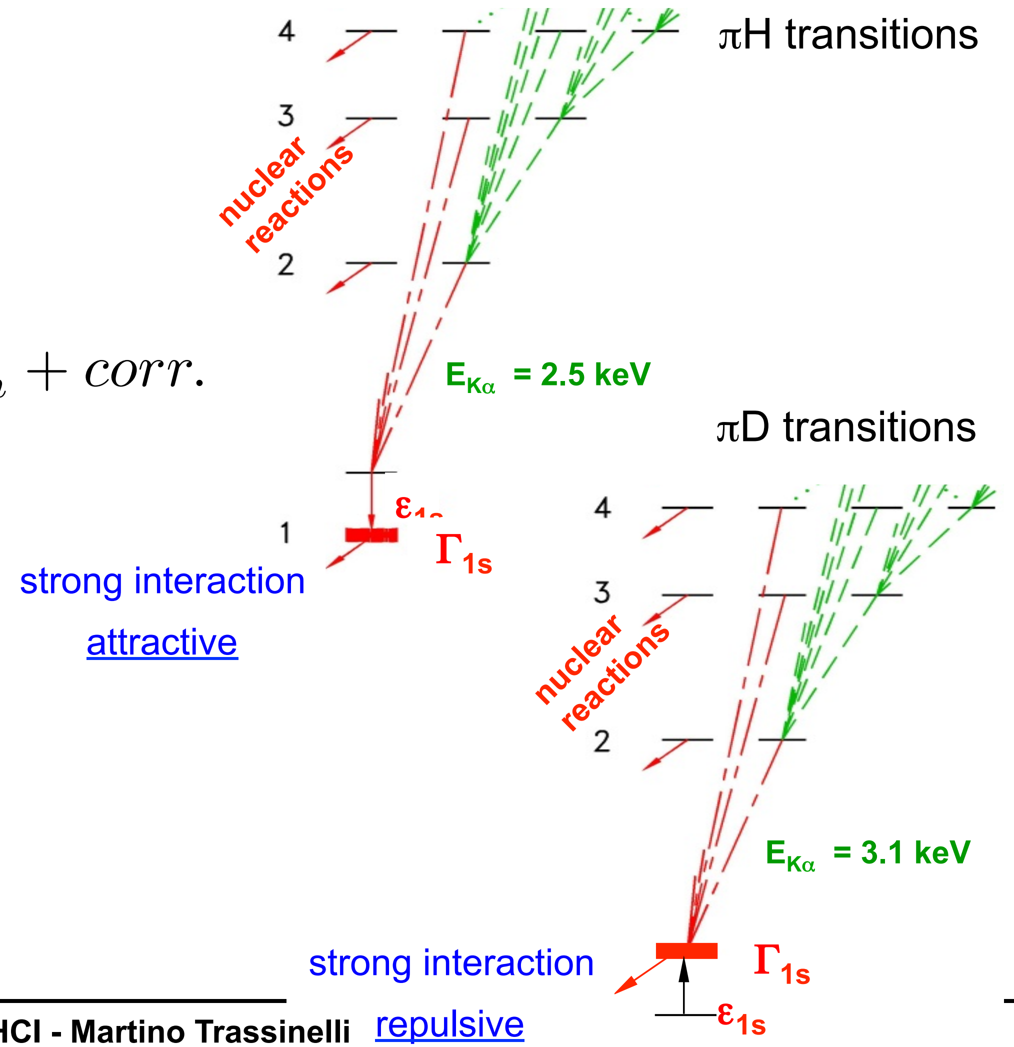
Experimental spectrum obtained with a Bragg spectrometer

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH
$$\begin{cases} \epsilon^{\pi H}_{1s} \propto a_{\pi^- p\to\pi^- p} + corr. \\ \Gamma^{\pi H}_{1s} \propto (a_{\pi^- p\to\pi^0 n})^2 + corr. \end{cases}$$

πD
$$\begin{cases} \epsilon^{\pi D}_{1s} \propto a_{\pi^- p\to\pi^- p} + a_{\pi^- n\to\pi^- n} + corr. \\ \Gamma^{\pi D}_{1s} \propto \Im m(a_{\pi d\to\pi d}) \end{cases}$$



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Shift and width related to the pion-nucleus scattering length and cross sections

πH

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr.$$

$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr.$$

πD

$$\epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr.$$

$$\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d})$$

→ Basic pion-nucleon interaction properties

→ Pion production cross section from p–p collisions

Highly charged ions and pionic atoms

- Simple atomic systems

$$E_n = mc^2 \frac{(Z\alpha)^2}{2n^2} + \mathcal{O}\left[(Z\alpha)^4\right]$$

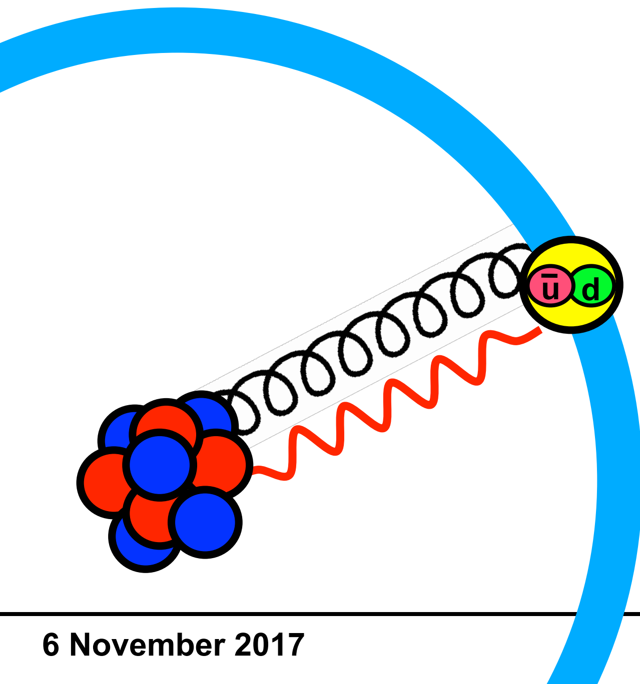
⇨ X-ray spectroscopy

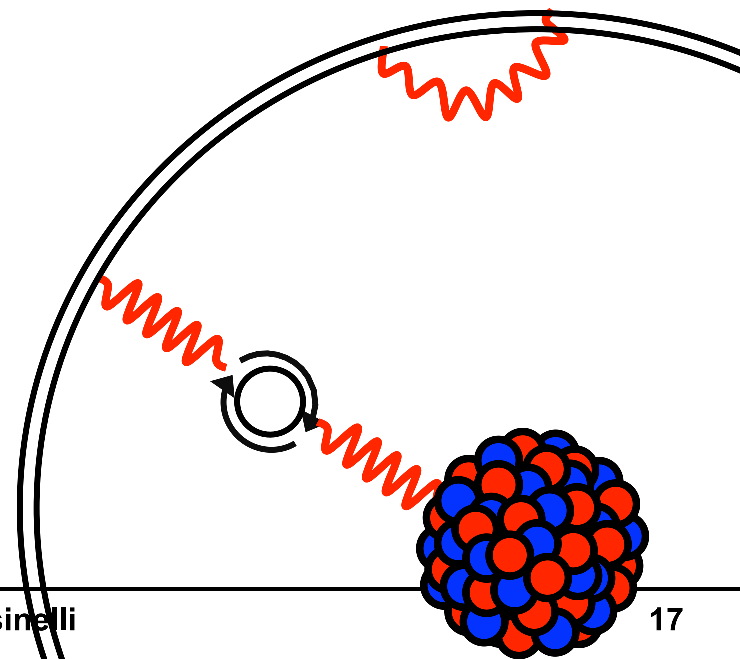
- Strong electric field

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

- Small Bohr radius

$$r_n \sim \frac{\hbar n^2}{mcZ\alpha}$$





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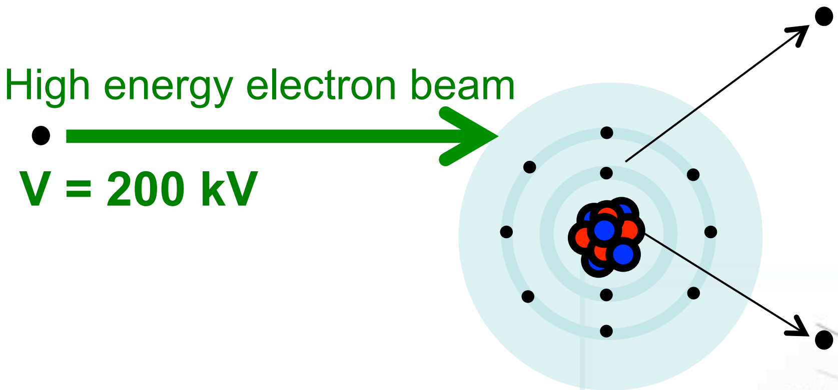
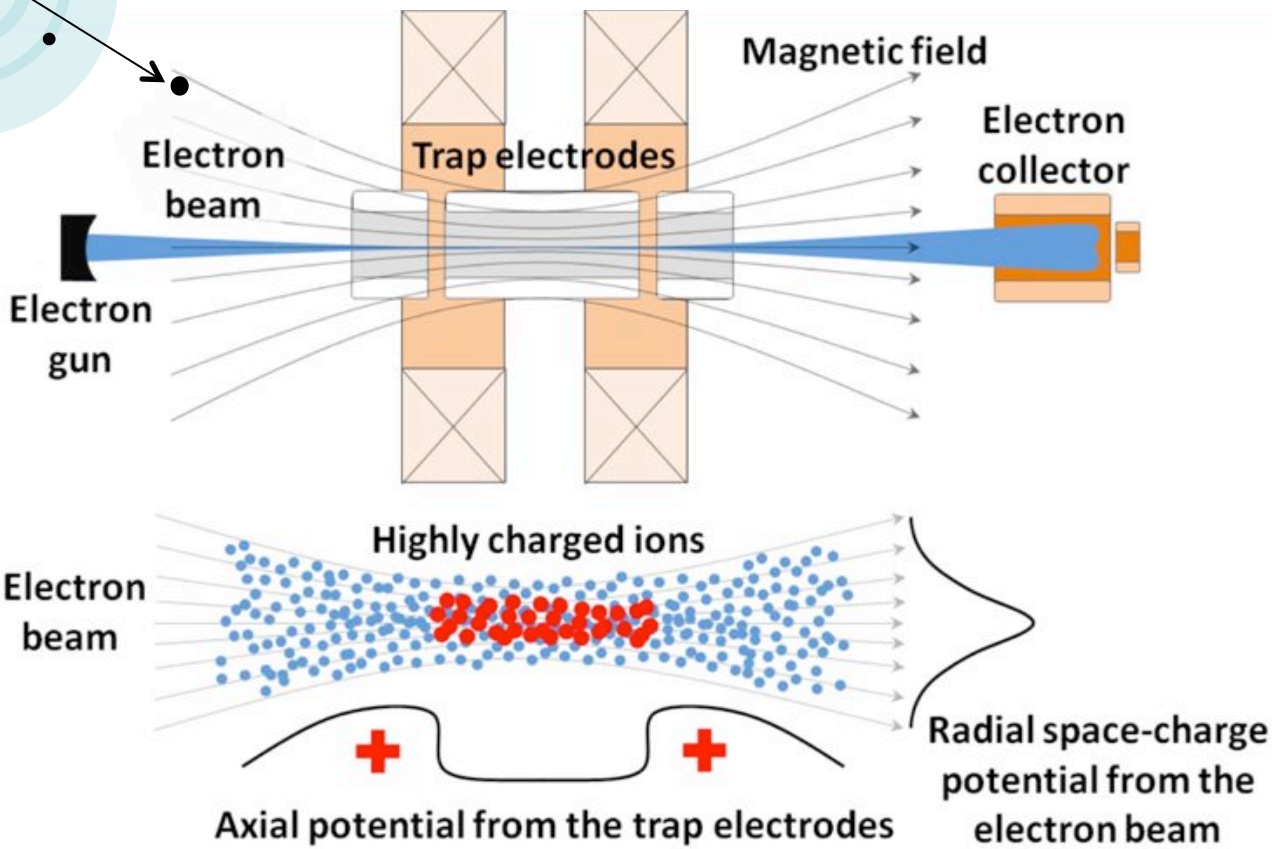
Highly charged ion production and studies

Electron impact and trapping



Electron Beam Ion Trap (EBIT) principle



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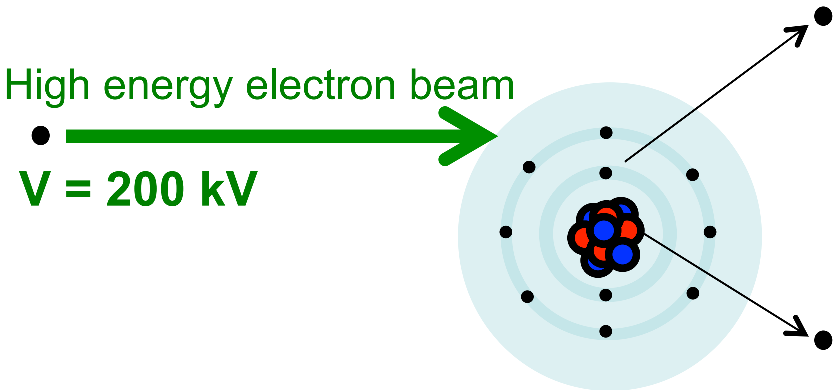
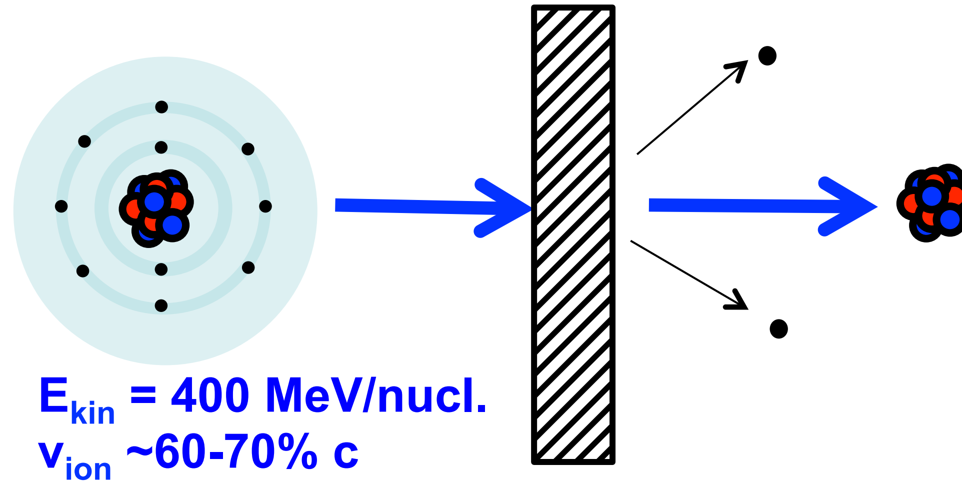
Electron impact and trapping



- Max Planch Inst., Heidelberg, Germany
- NIST, Gaithersburg, USA
- …

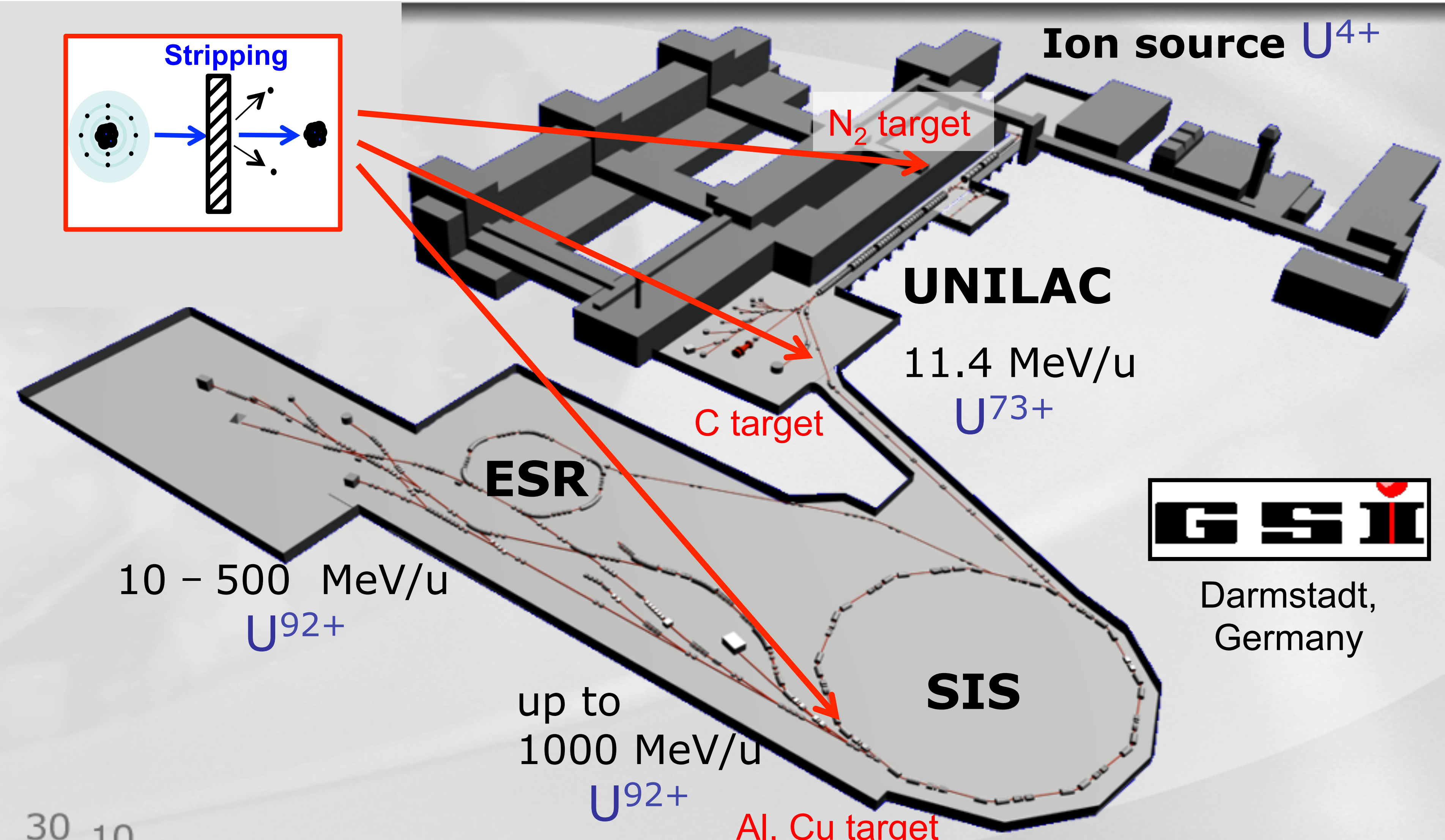
Acceleration and stripping



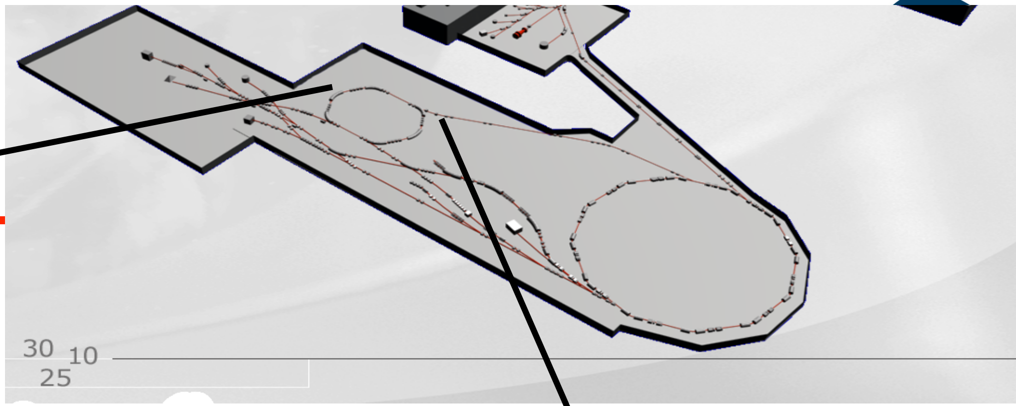
Solid target (graphite, aluminum, copper, …)
Thickness ~ 100 mg/cm^2

- GSI, Darmstadt, Germany
- IMP, Lanzhou, China
- …

Highly charged ion production

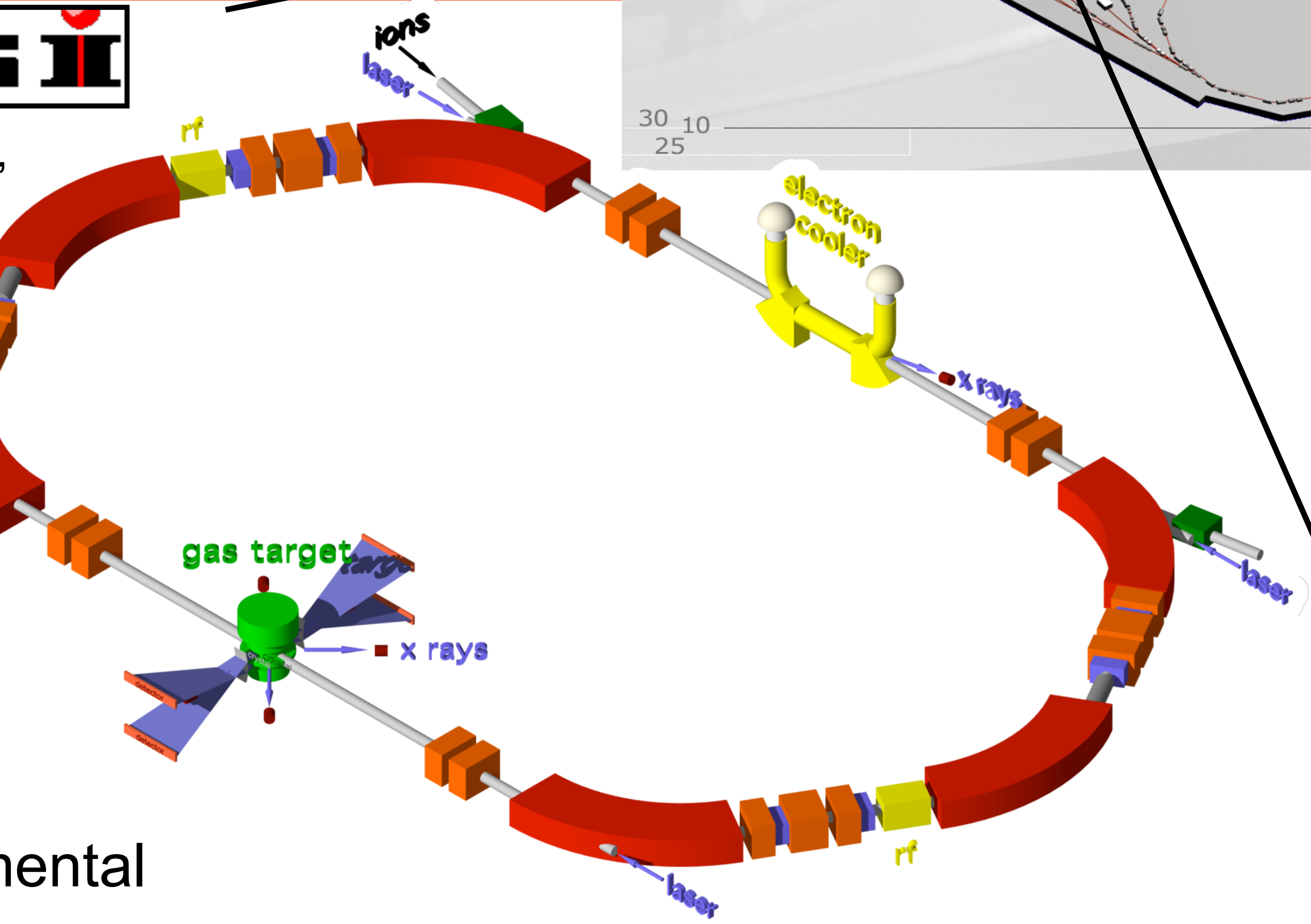


ESR storage ring at GSI



GSI

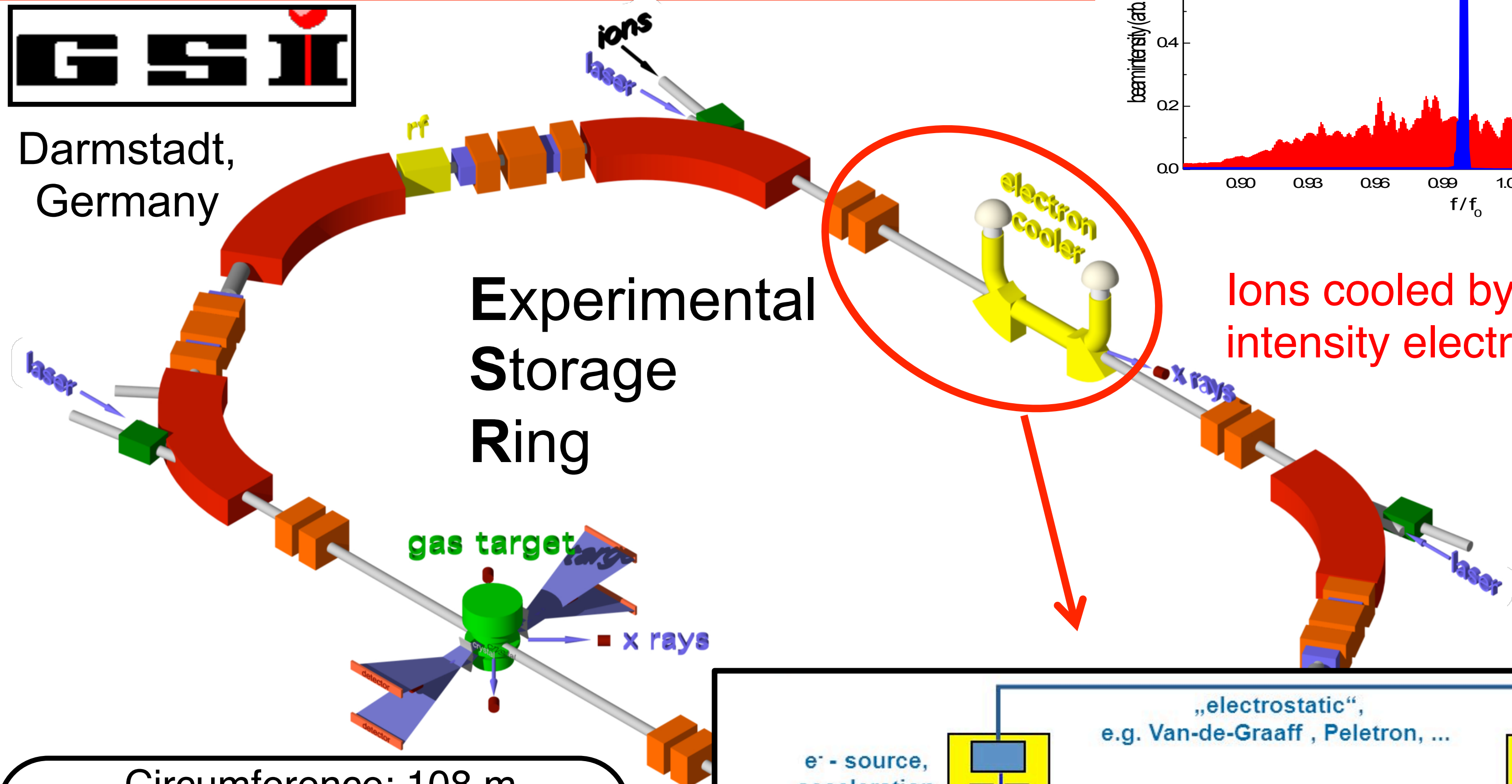
Darmstadt, Germany



Experimental
Storage
Ring

ESR storage ring at GSI

Darmstadt, Germany



Experimental
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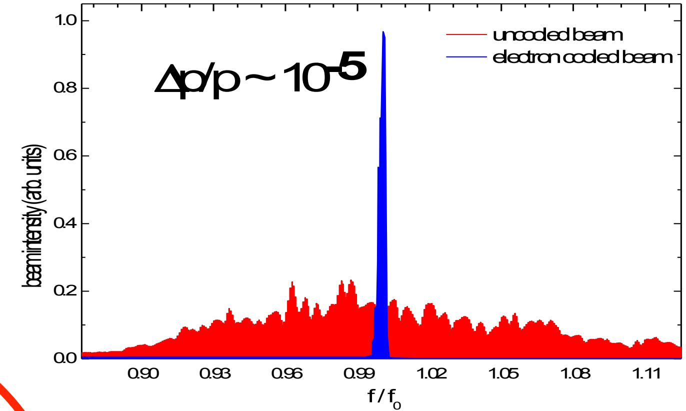
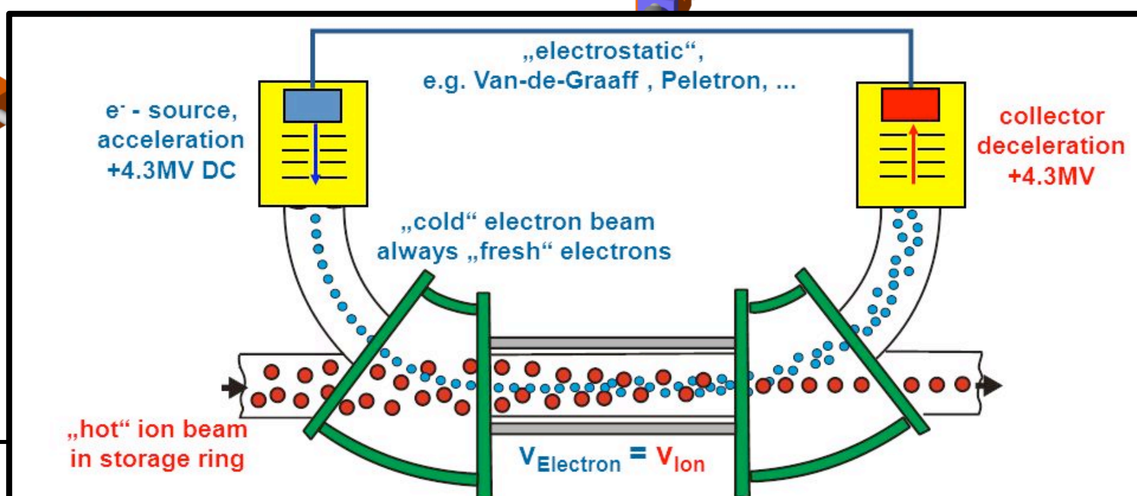
Ring



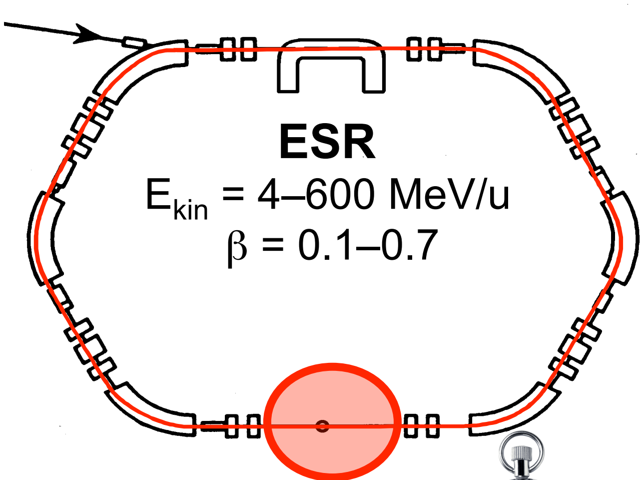
Ions cooled by an high intensity electron beam

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



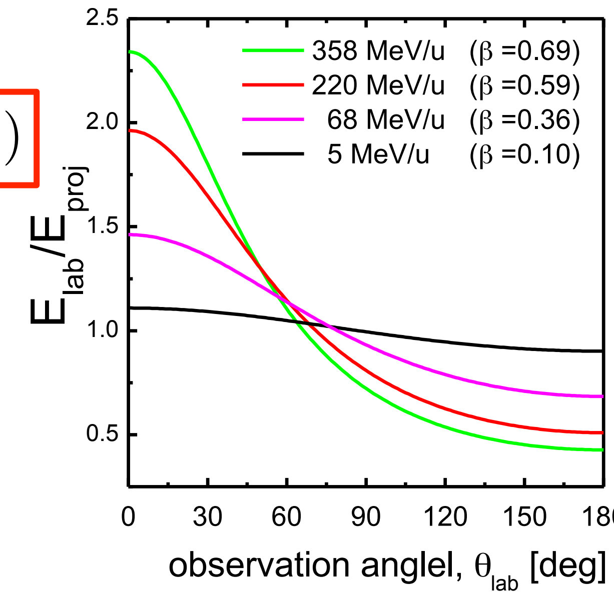
6 November 2017

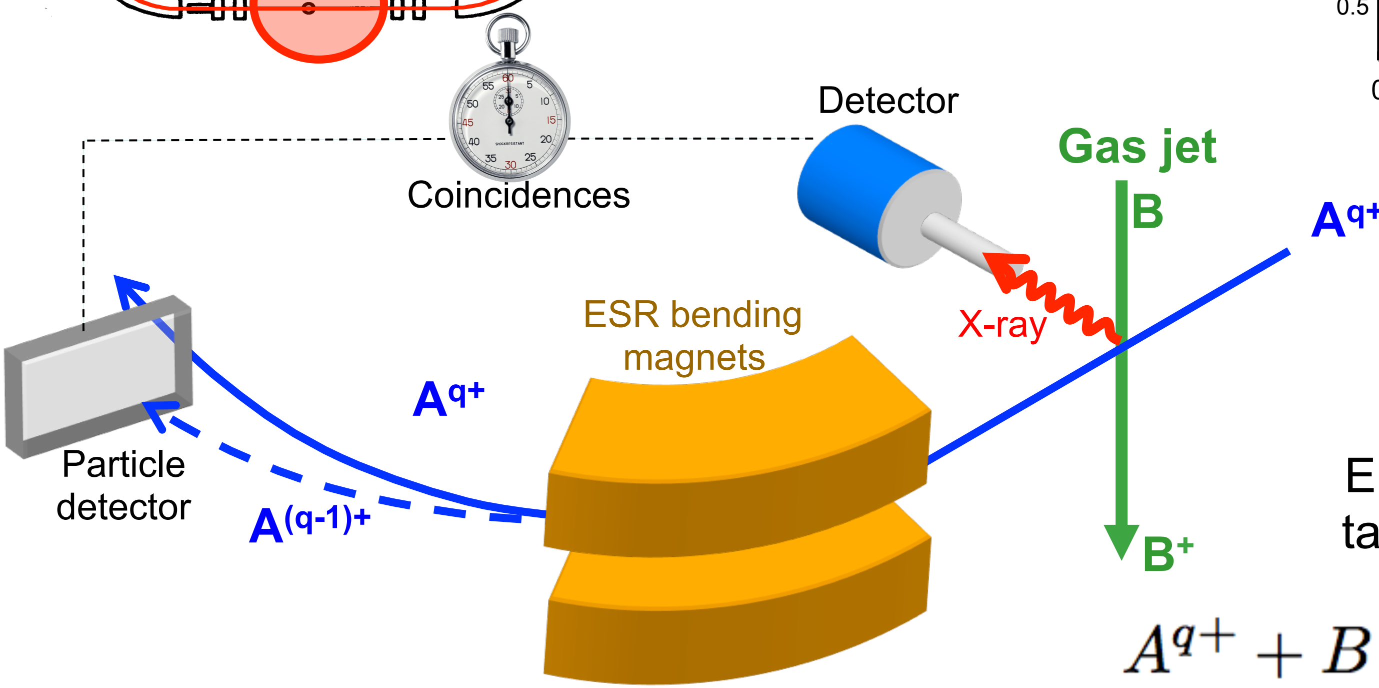
Experiments at the gas jet-target



Relativistic Doppler shift

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

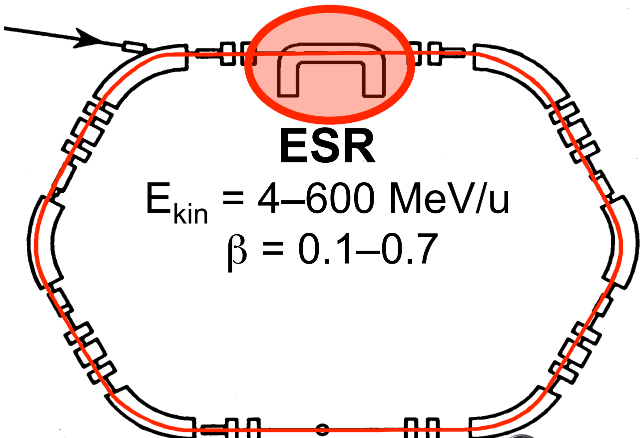




Electron transfer from the target atom to the fast ion

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{+}$$

Experiments at e-cooler



Relativistic Doppler shift

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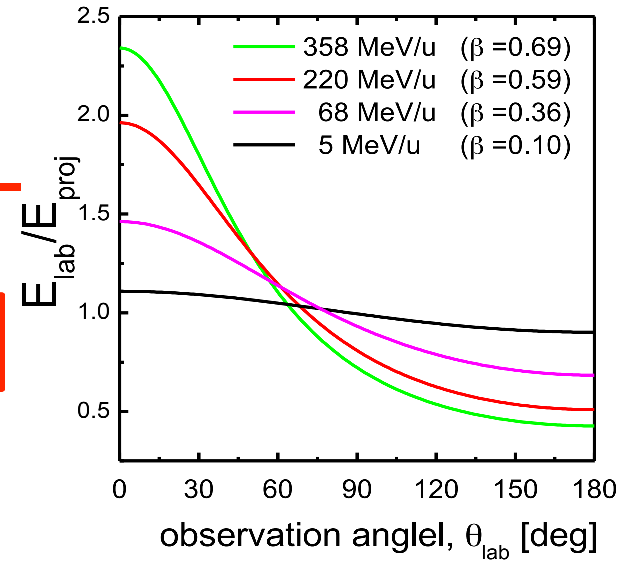

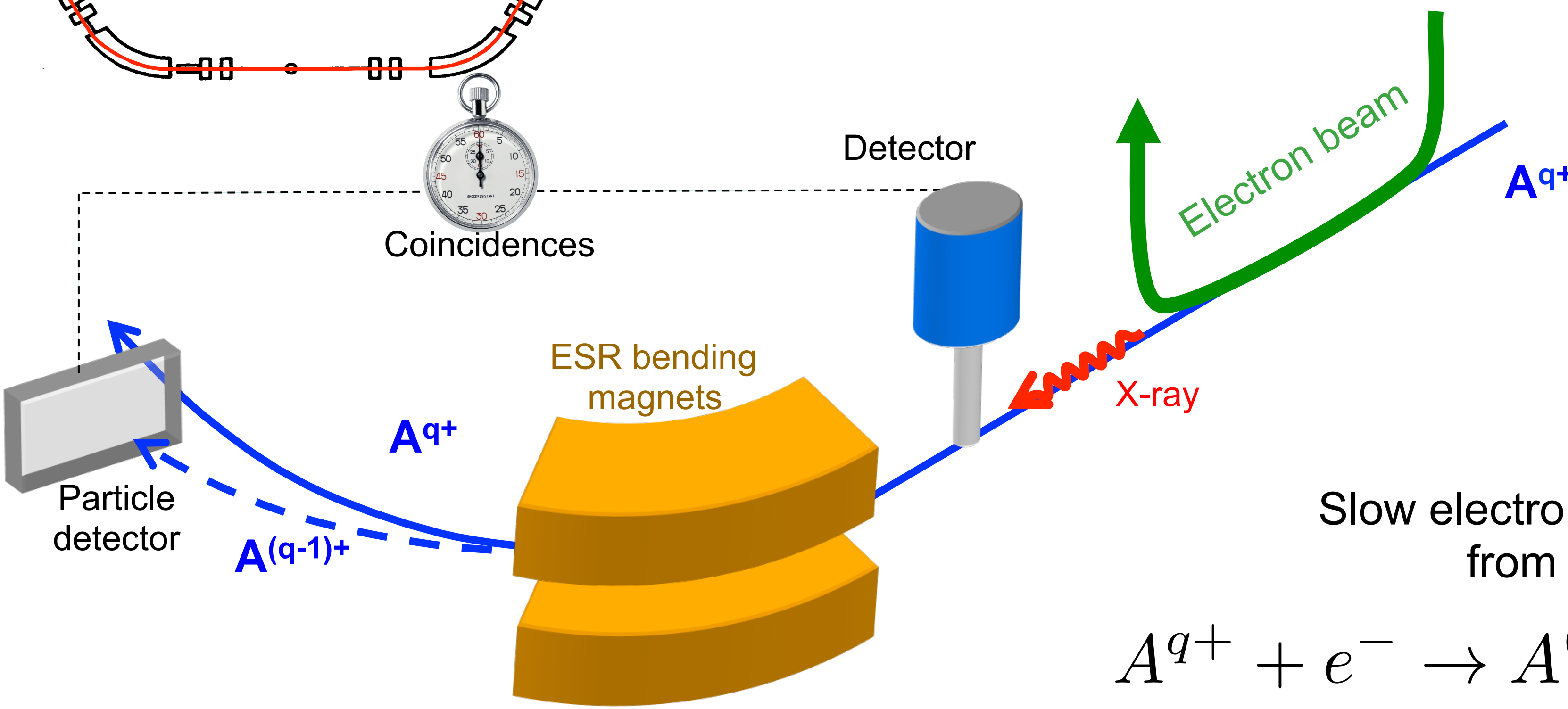

Slow electron captured from thefast ion

$$A^{q+} + e^- \rightarrow A^{(q-1)+}$$

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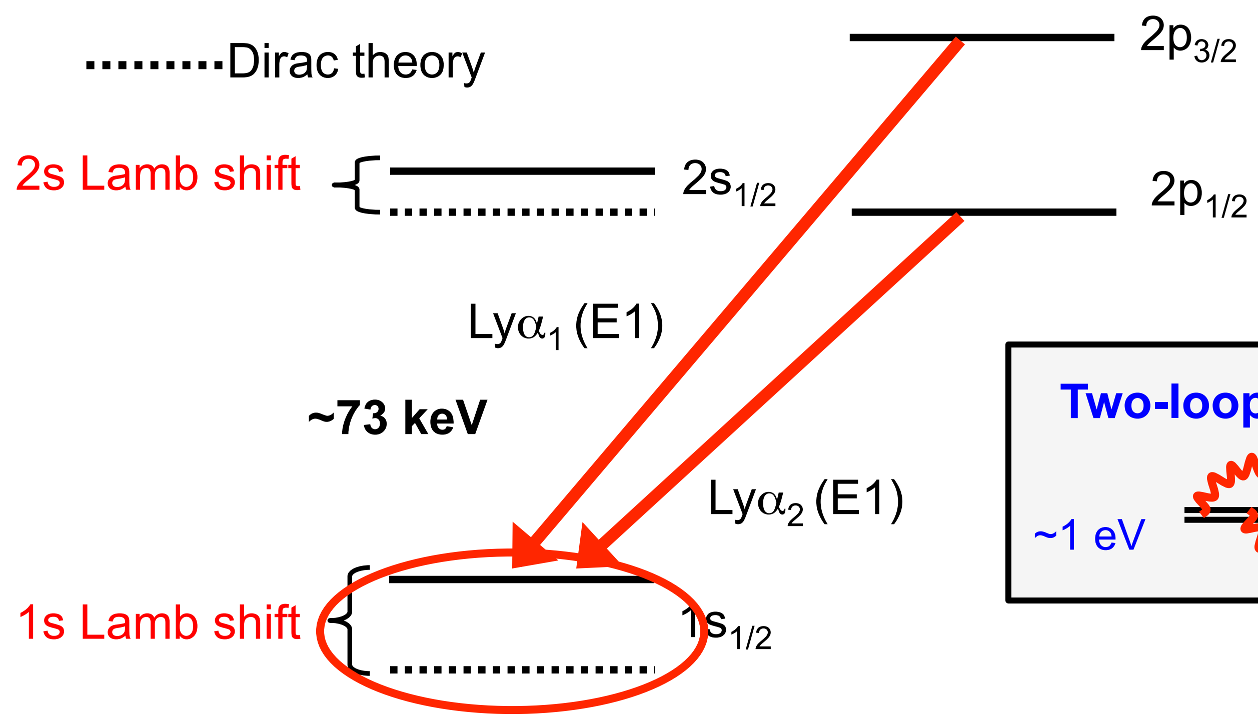
Lamb shift of H-like Uranium



QED corrections

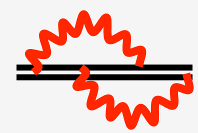
$\Delta E \sim Z^4/n^3$

Z: nuclear charge
n: principal quantum number

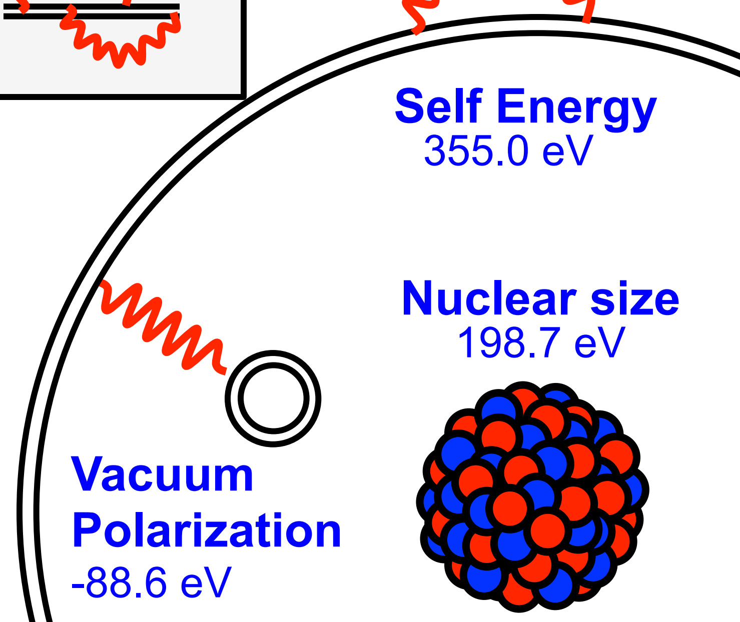
Important for s-states

Two-loop QED

~1 eV



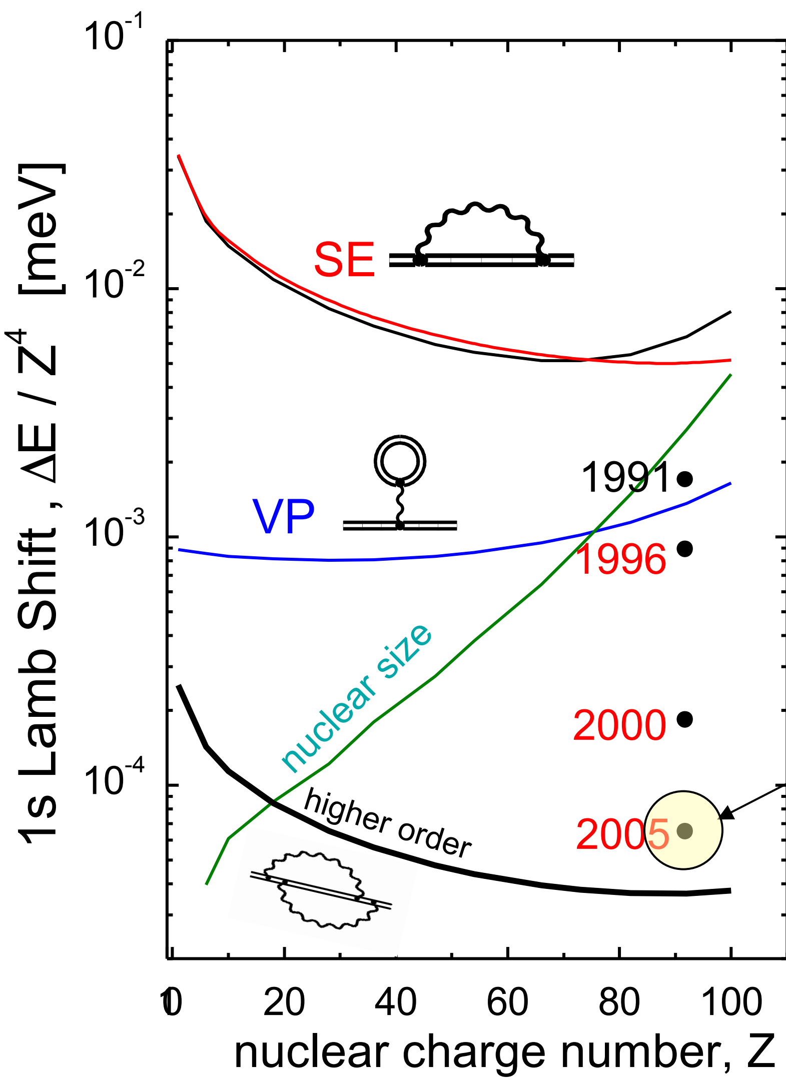
In Uranium



Theory: 463.8 ± 0.5 eV

V.A. Yerokhin *et al.*, J. Phys. Chem. Ref. Data **44**, 033103 (2015).

Lamb shift of H-like Uranium



Latest experiment

QED corrections

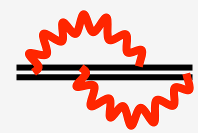
$\Delta E \sim Z^4/n^3$

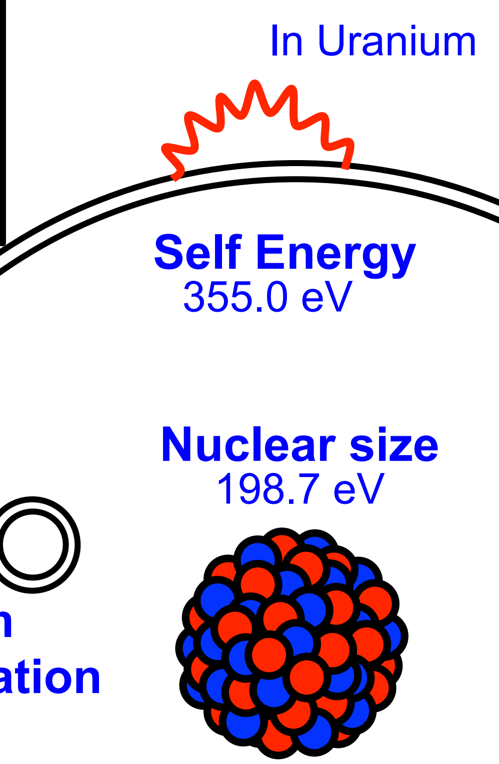
Z: nuclear charge
n: principal quantum number

Important for s-states

Two-loop QED

~1 eV





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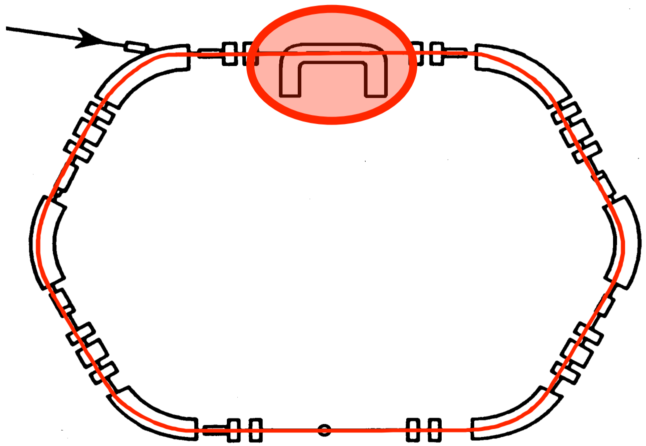
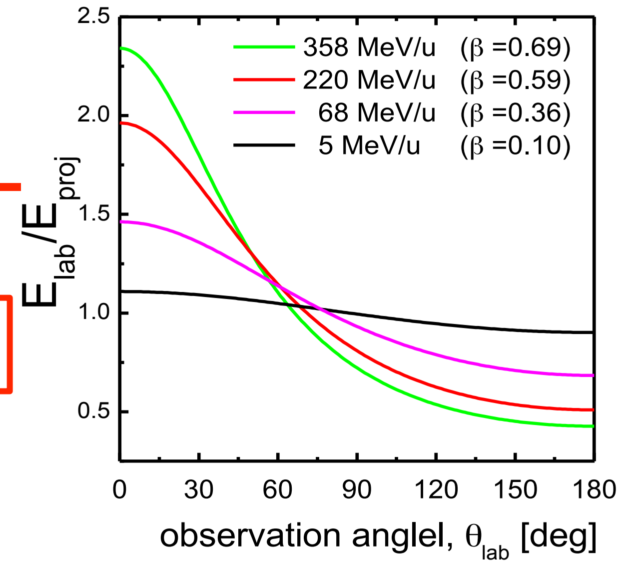
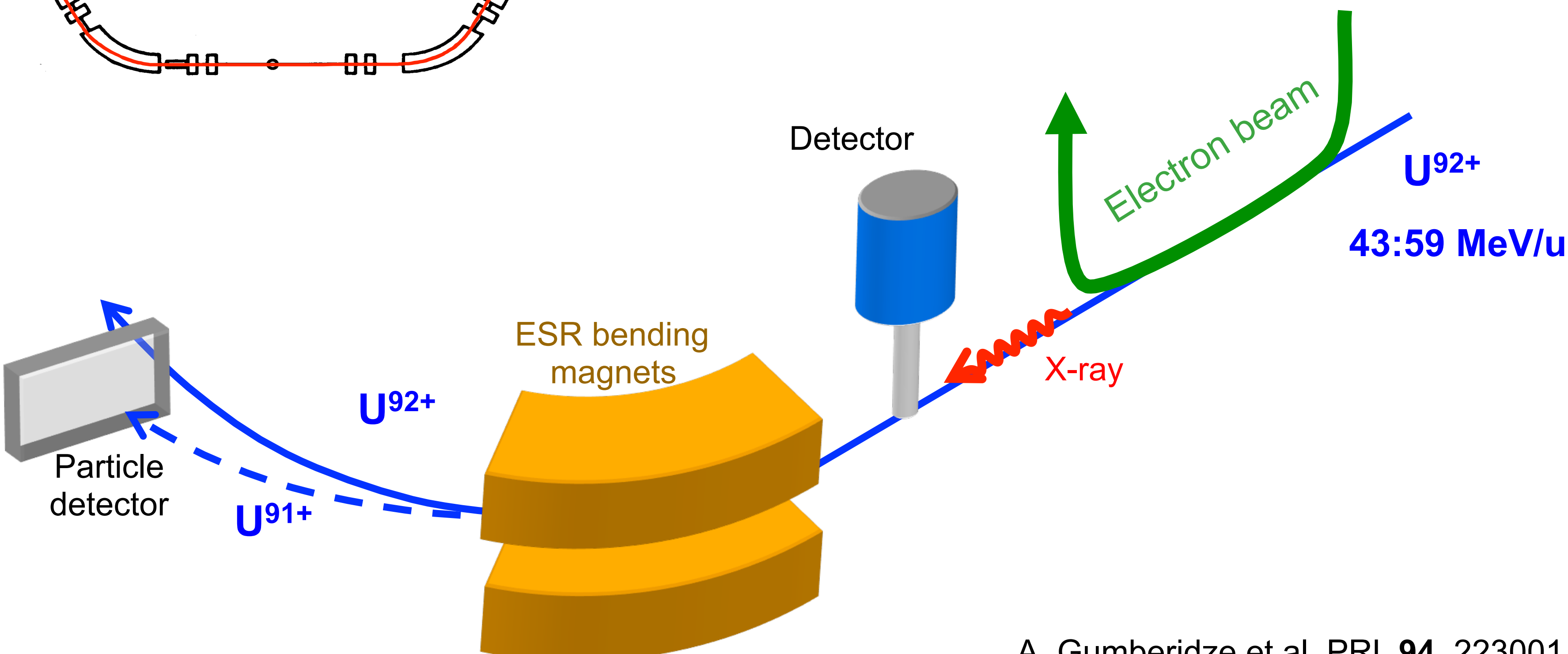


Relativistic Doppler shift

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

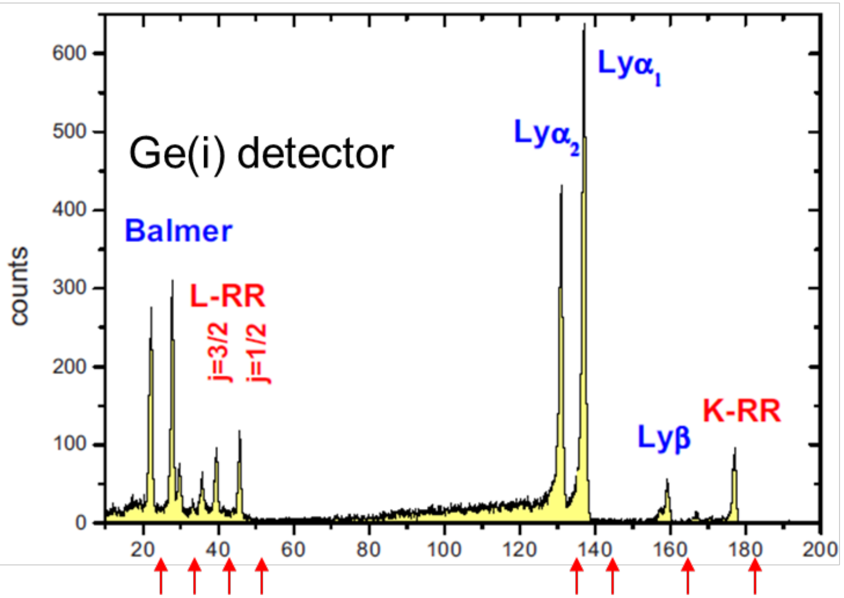




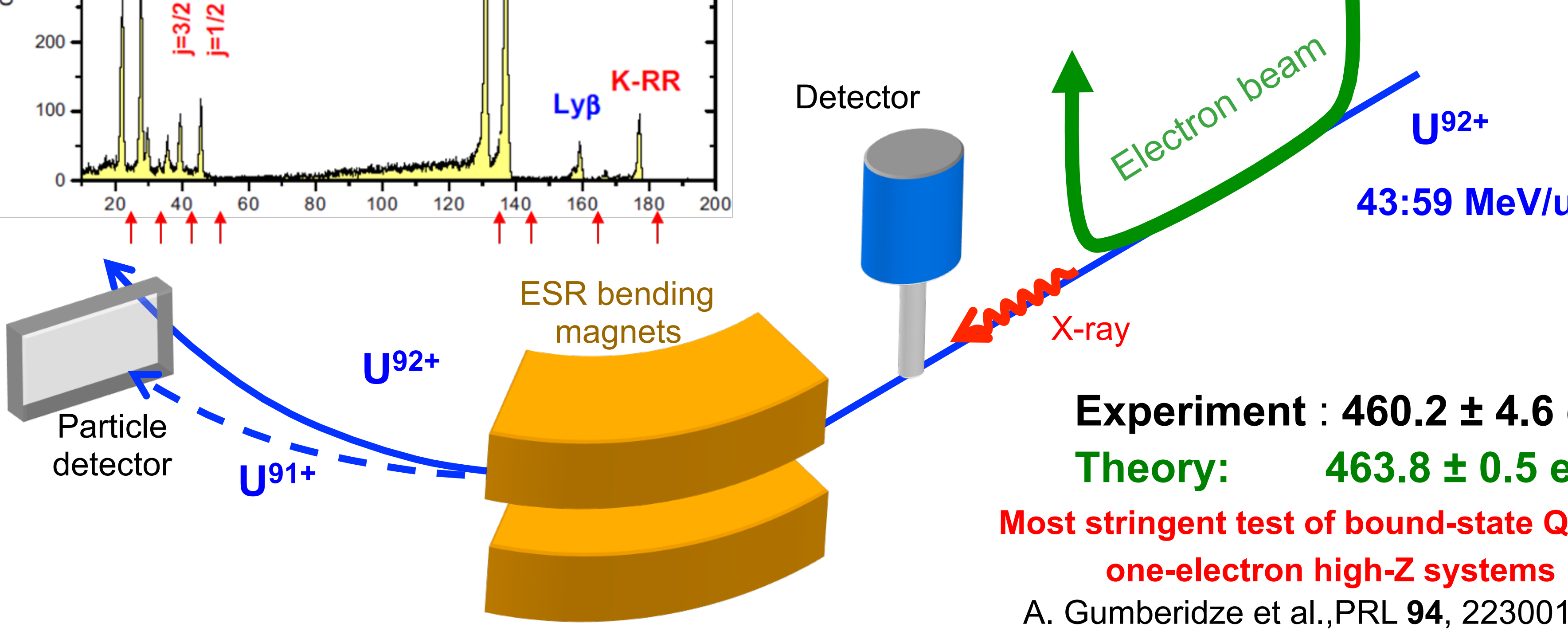
A. Gumberidze et al.,PRL **94**, 223001 (2005)

Experiments at e-cooler

Many lines providing intrinsic energy calibration and redundant data.



- **decelerated ions**
- **close to 0-deg observation geometry**
- **standard germanium detector**



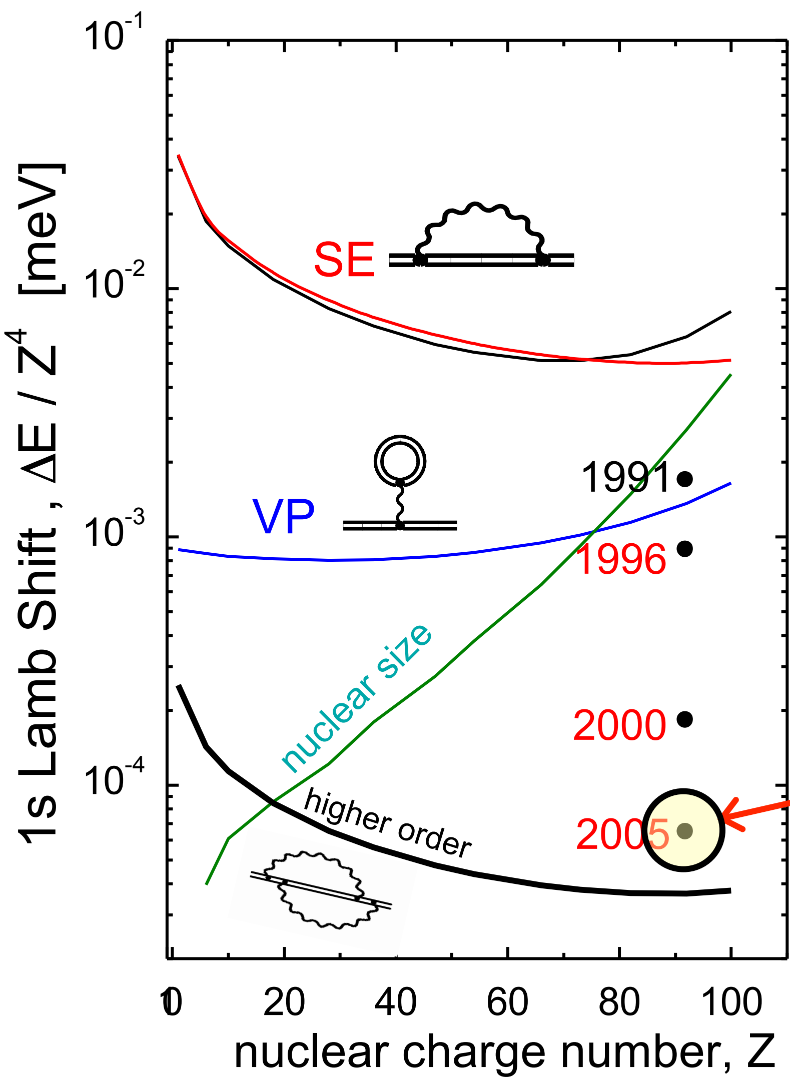
Experiment : 460.2 ± 4.6 eV

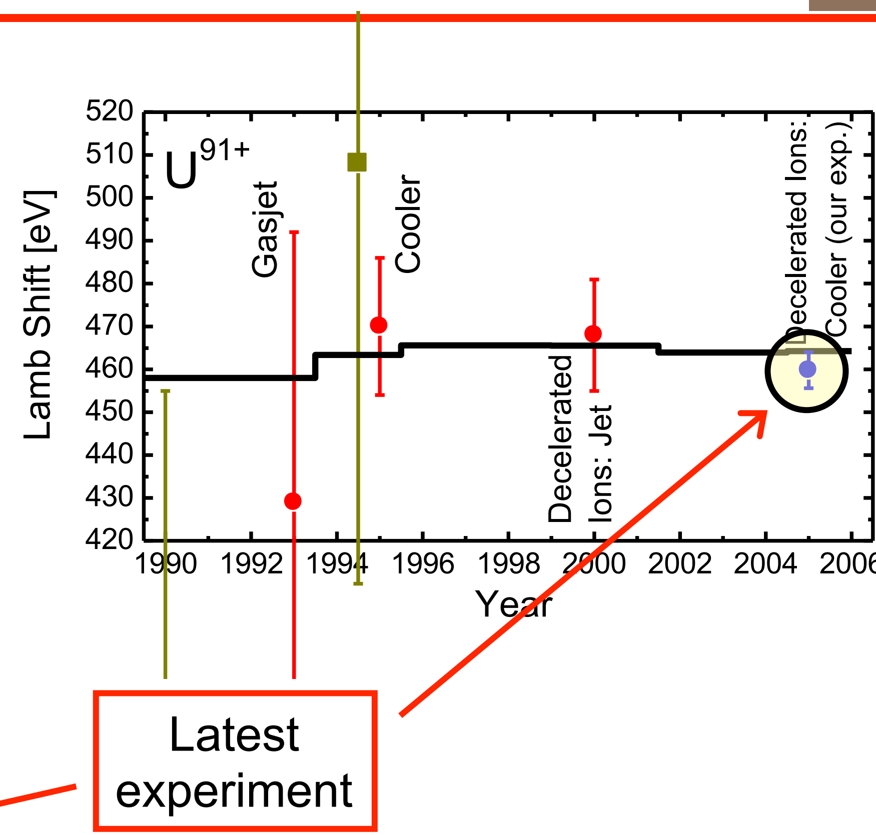
Theory: 463.8 ± 0.5 eV

Most stringent test of bound-state QED for one-electron high-Z systems

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

Lamb shift of H-like Uranium





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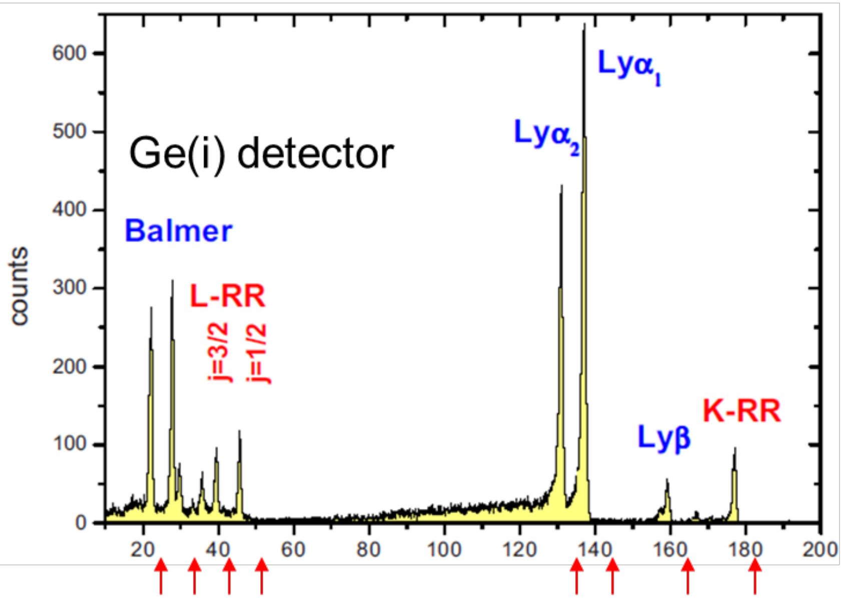

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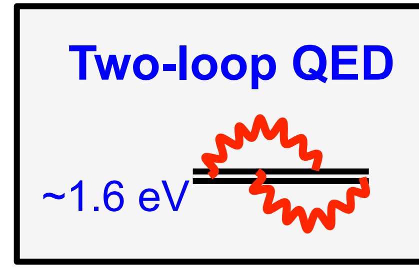

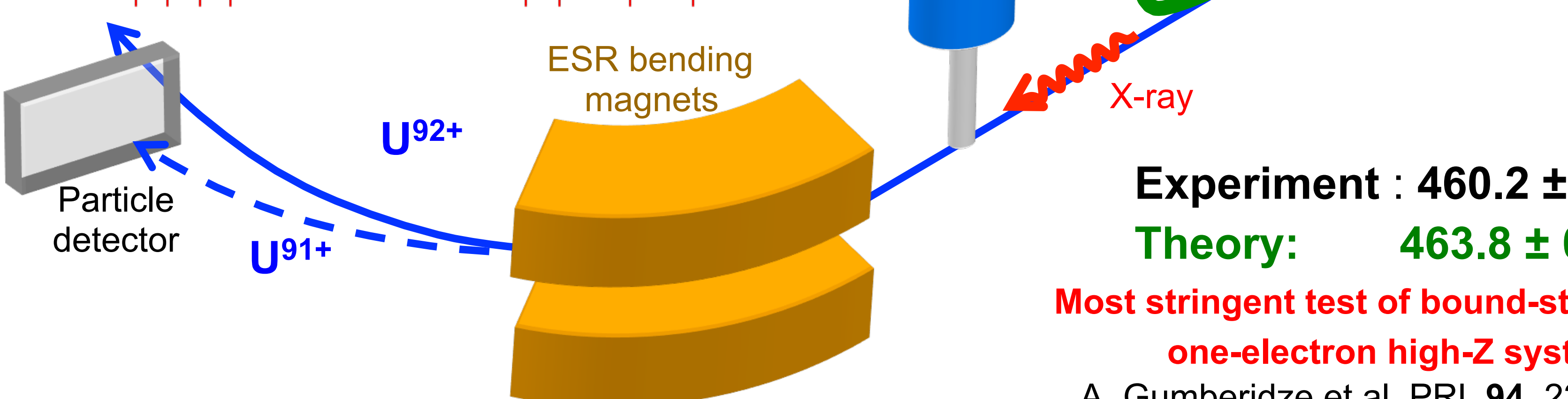

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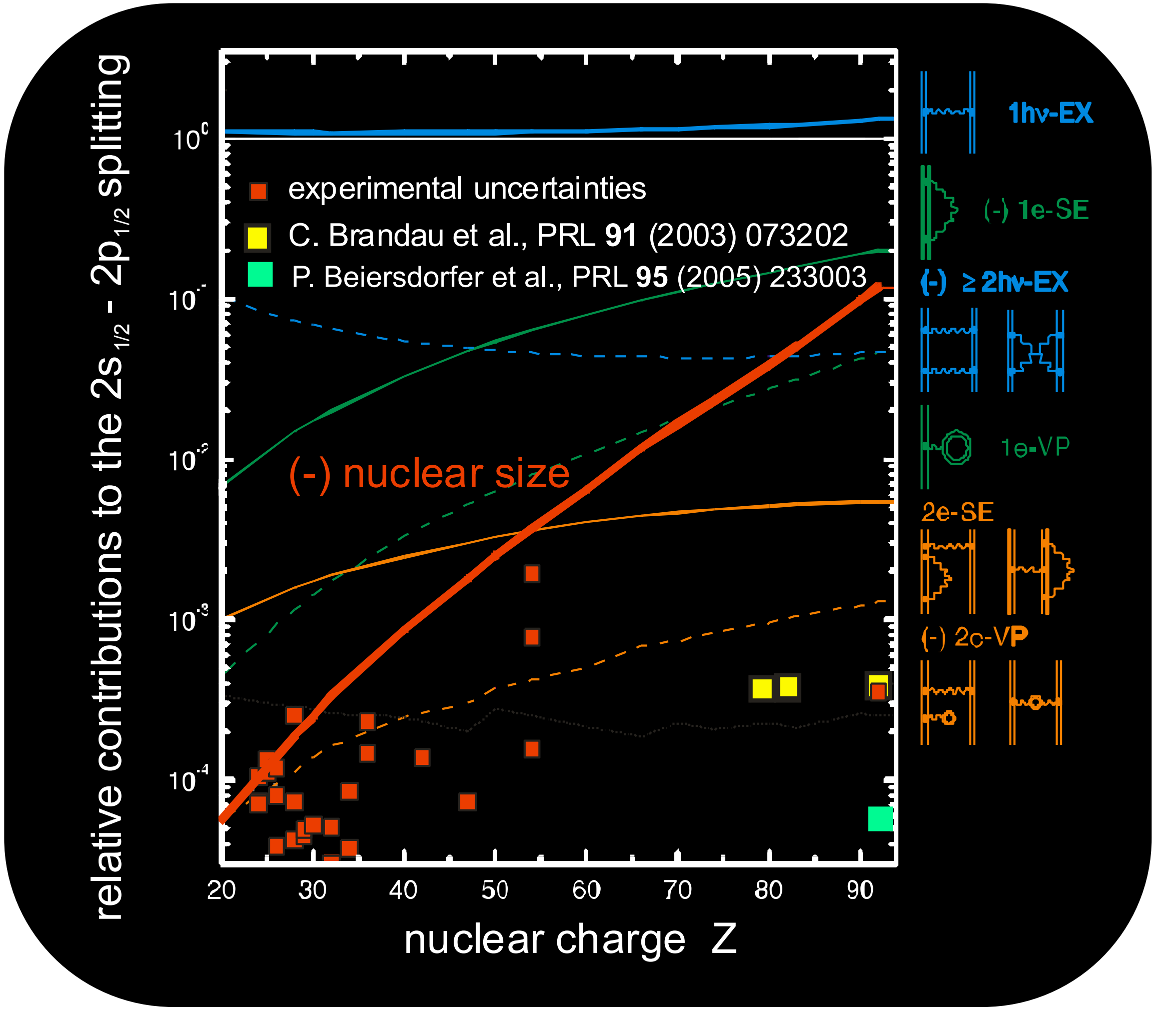
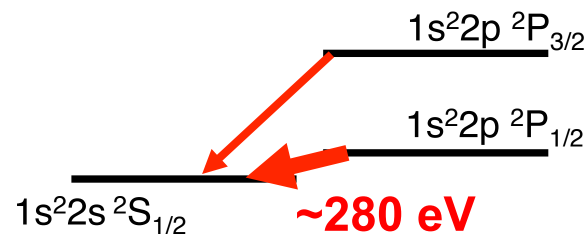
Most stringent test of bound-state QED for one-electron high-Z systems

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

Most precise spectroscopy tests in Li-like systems



Li-like Uranium (3 el.)



XUV spectroscopy

Detailed knowledge about the nucleus is vital for strong field QED studies (nuclear size but also nuclear structure ⇒ nuclear polarization)

Summary

- Introduction
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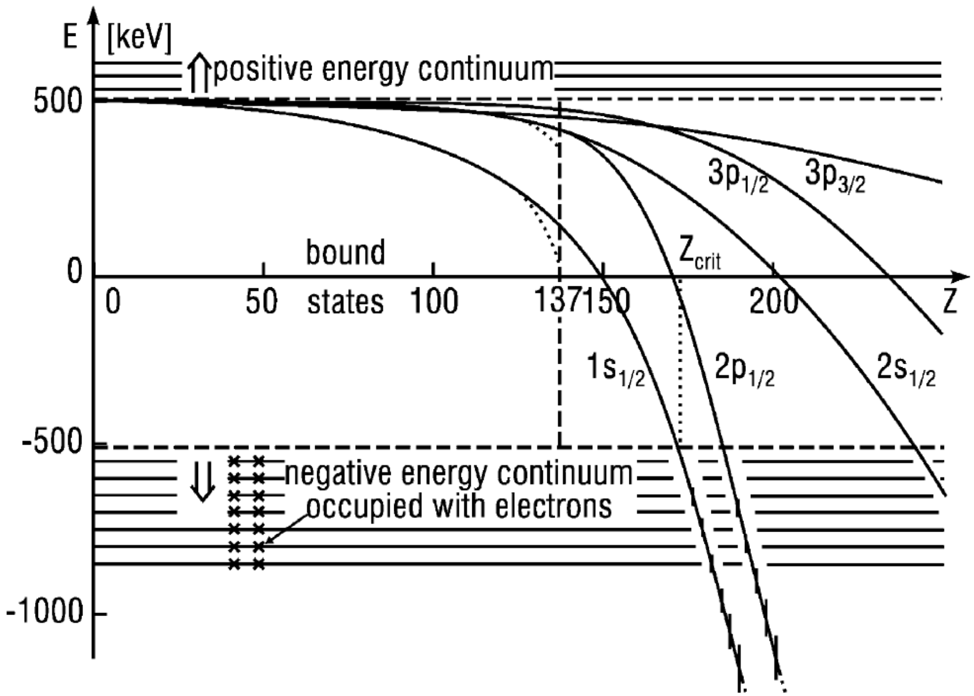
  - Study of strong interaction force at low energy
- Heavy highly charged ions
  - Production
  - Lamb shift measurement
  - **Vacuum decay experiment**
- Pionic atoms
  - Production
  - Pionic hydrogen and deuterium spectroscopy
  - Pion mass measurement
- Conclusions and outlooks

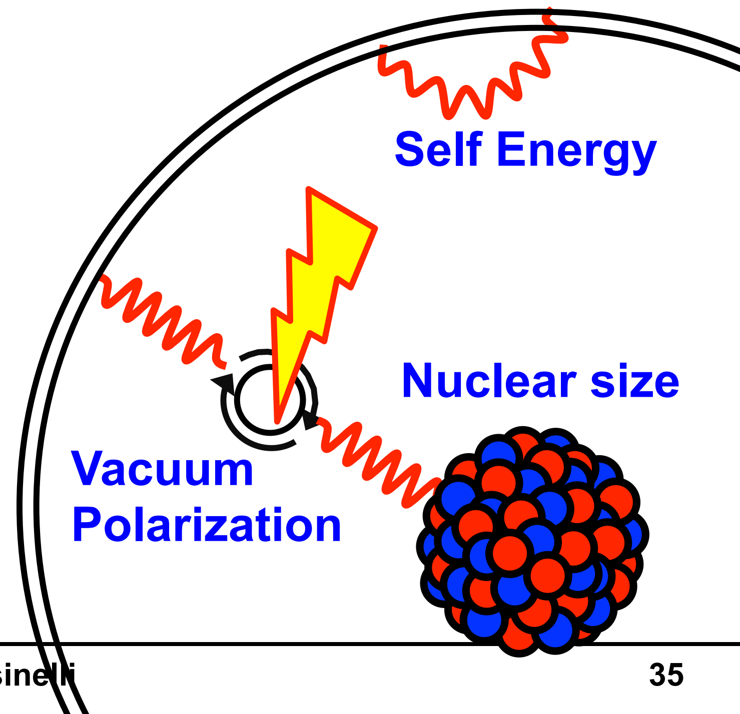
Supercritical fields

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

Z > 1/α = 137 → electron/positron pair creation

Finite nucleus size → Z_{crit} = 173





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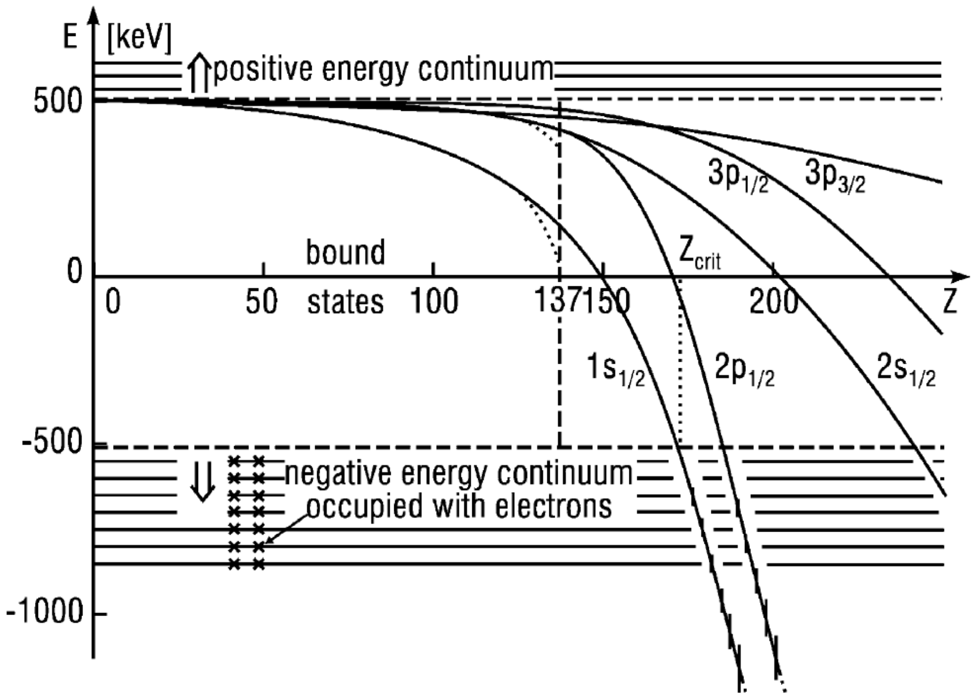
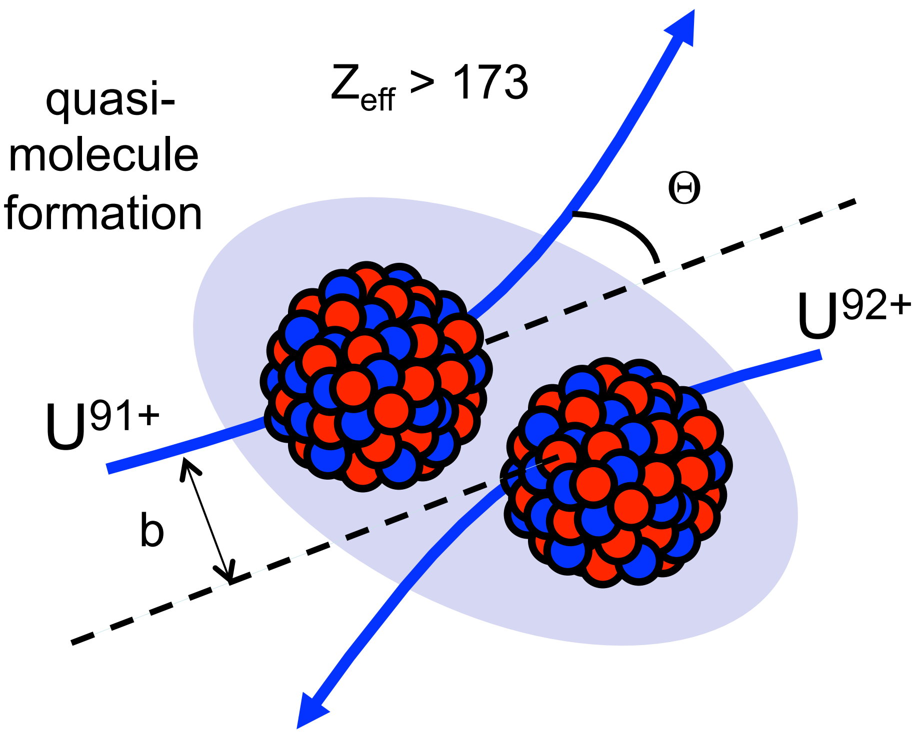
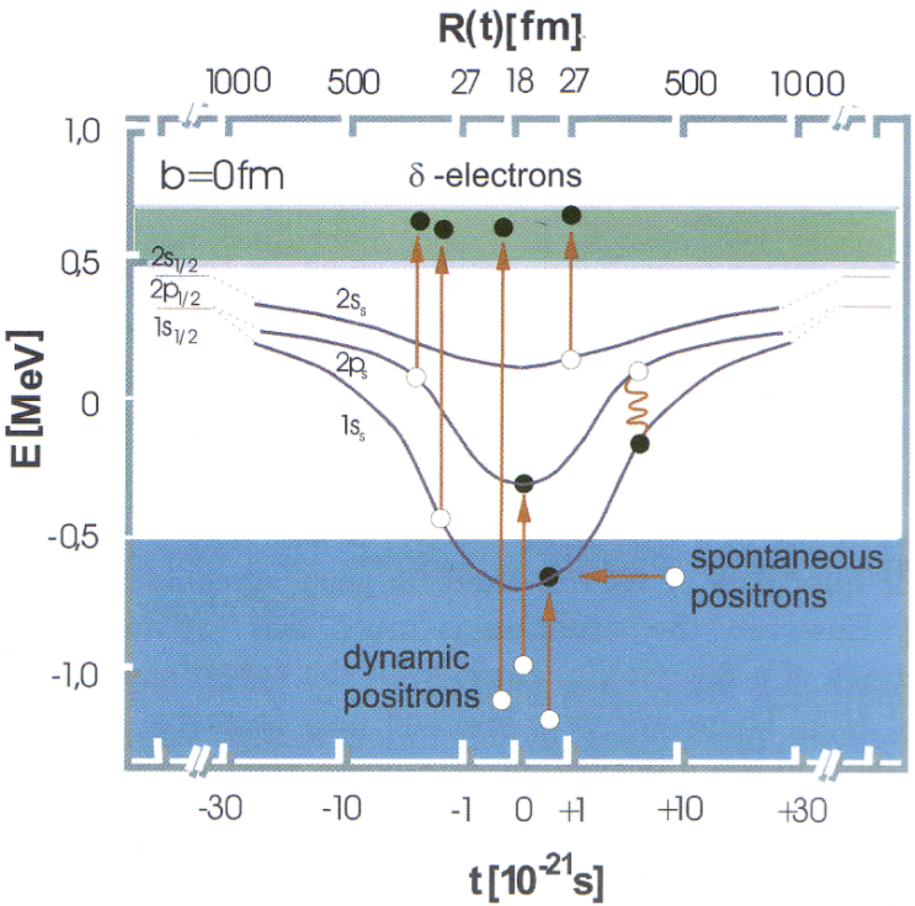
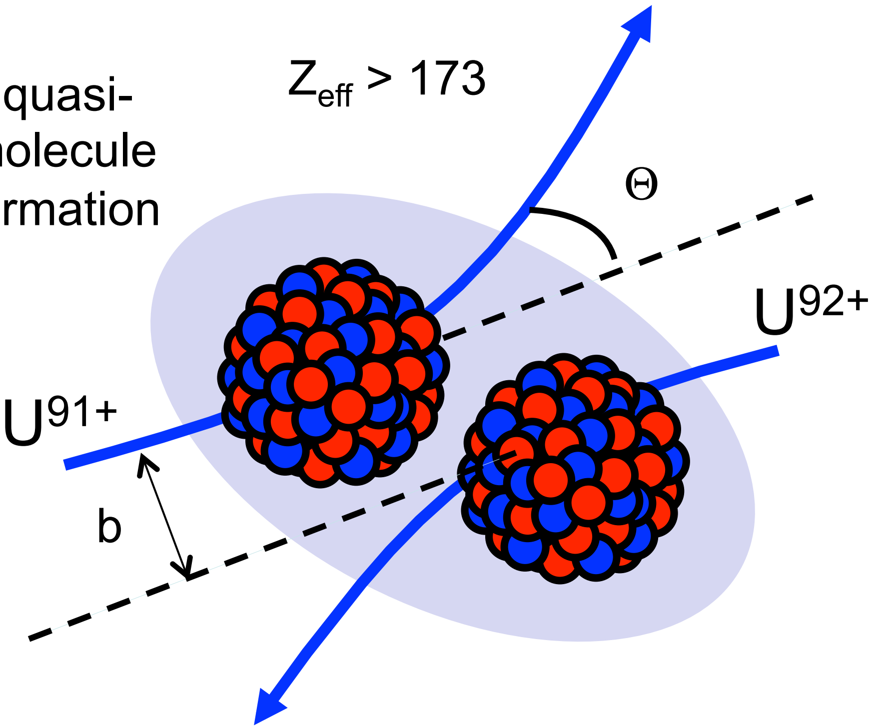




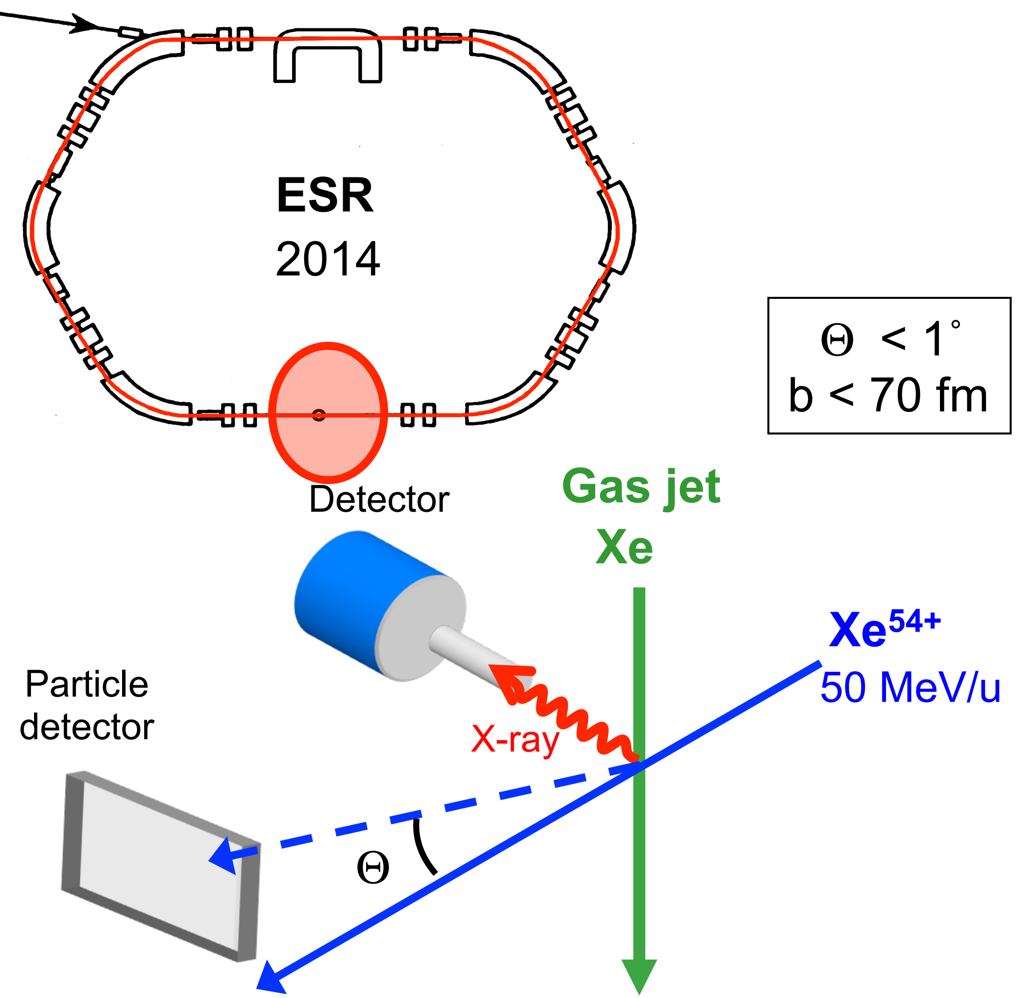
Supercritical Fields:
formation of super heavy quasi-molecules

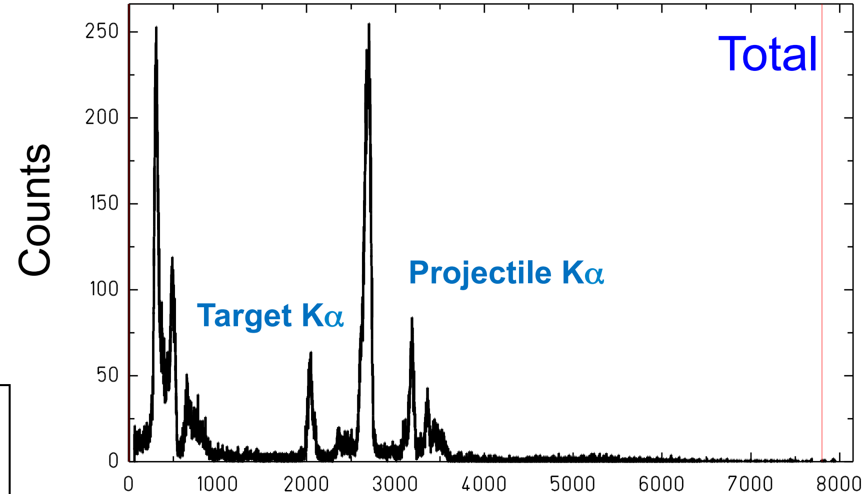


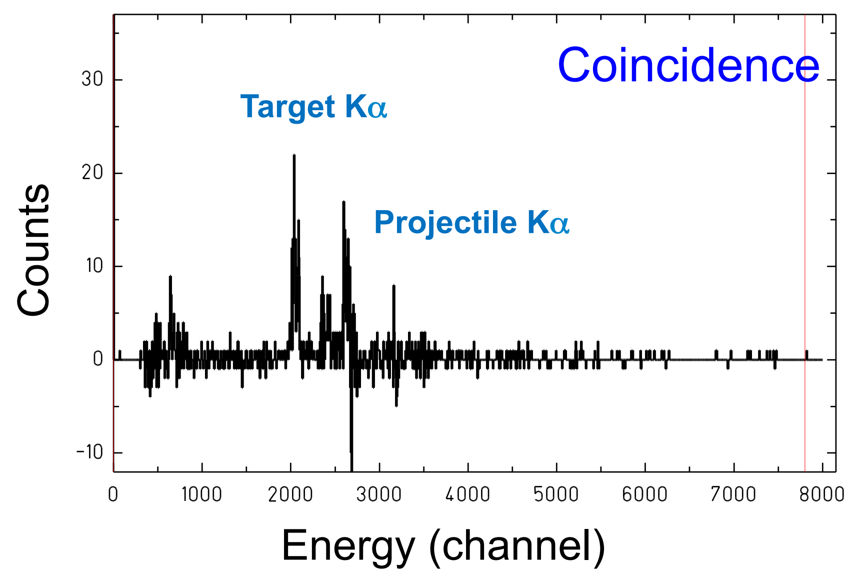
Slow ion – ion collision
~ 5 MeV/u



First steps to supercritical fields







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  - **Production**
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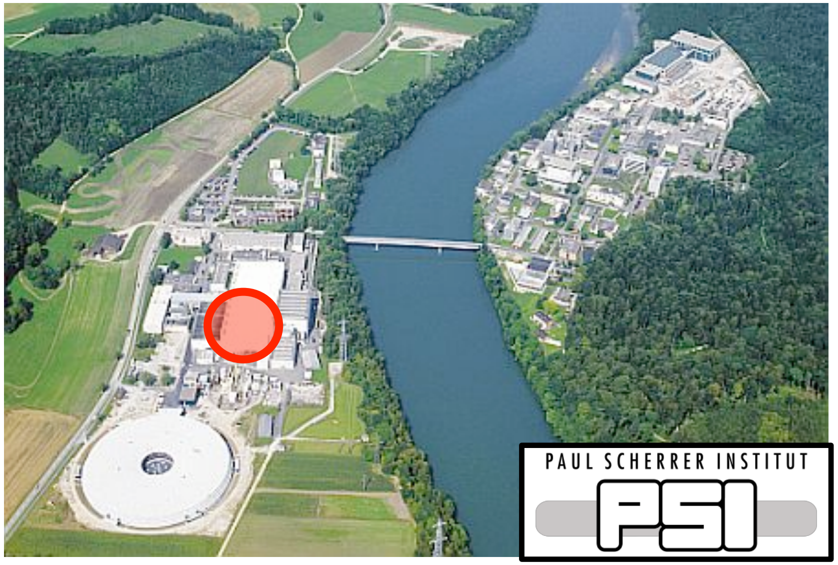
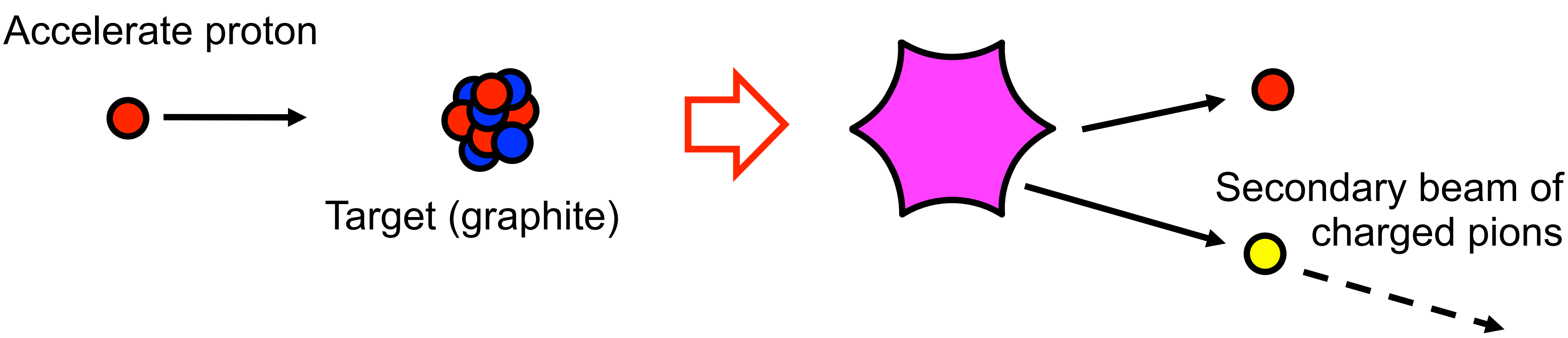
Pion beam production



Production at the Paul Scherrer Institut (Villigen, Switzerland)

- Proton beam :E_{kin}=590 MeV/c, I=1.9 mA
- Graphite target

- 10^8 pions/sec, E_{kin}=110 MeV/c

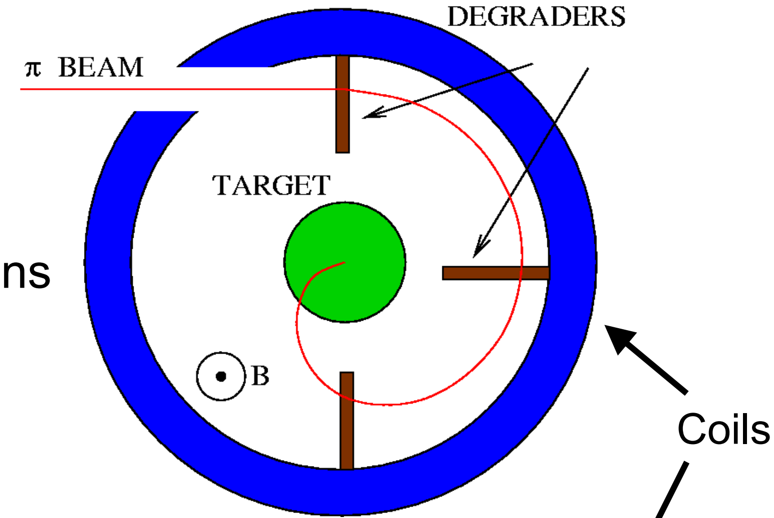


Pionic and muonic atoms production

- Cyclotron trap to stop the pions:
  - strong magnetic field (B_{max}=3.5 Tesla)
  - plastic degraders (energy loss)

- Gaseous target:
  - T: from 14 K to room temperature
  - effective pressure: from ~0 to 40 bars

τ_{π^-}= 26 ns

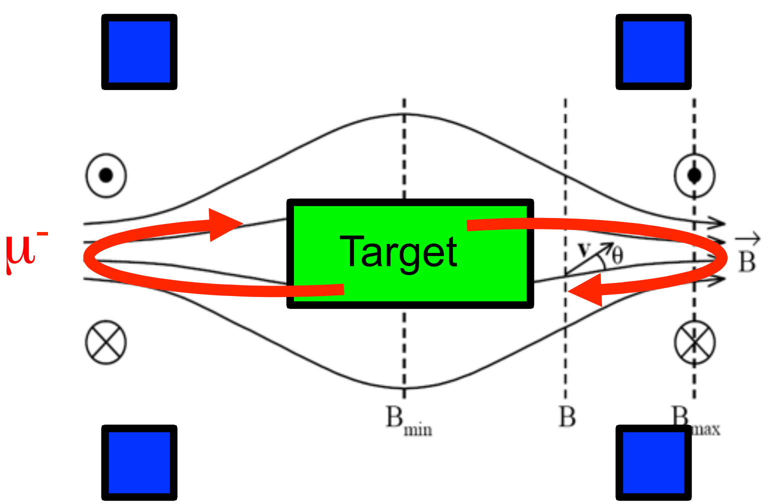


⇩

0.5% (per bar) of the incoming pions are stopped inside the target

- Production and trapping of the muons

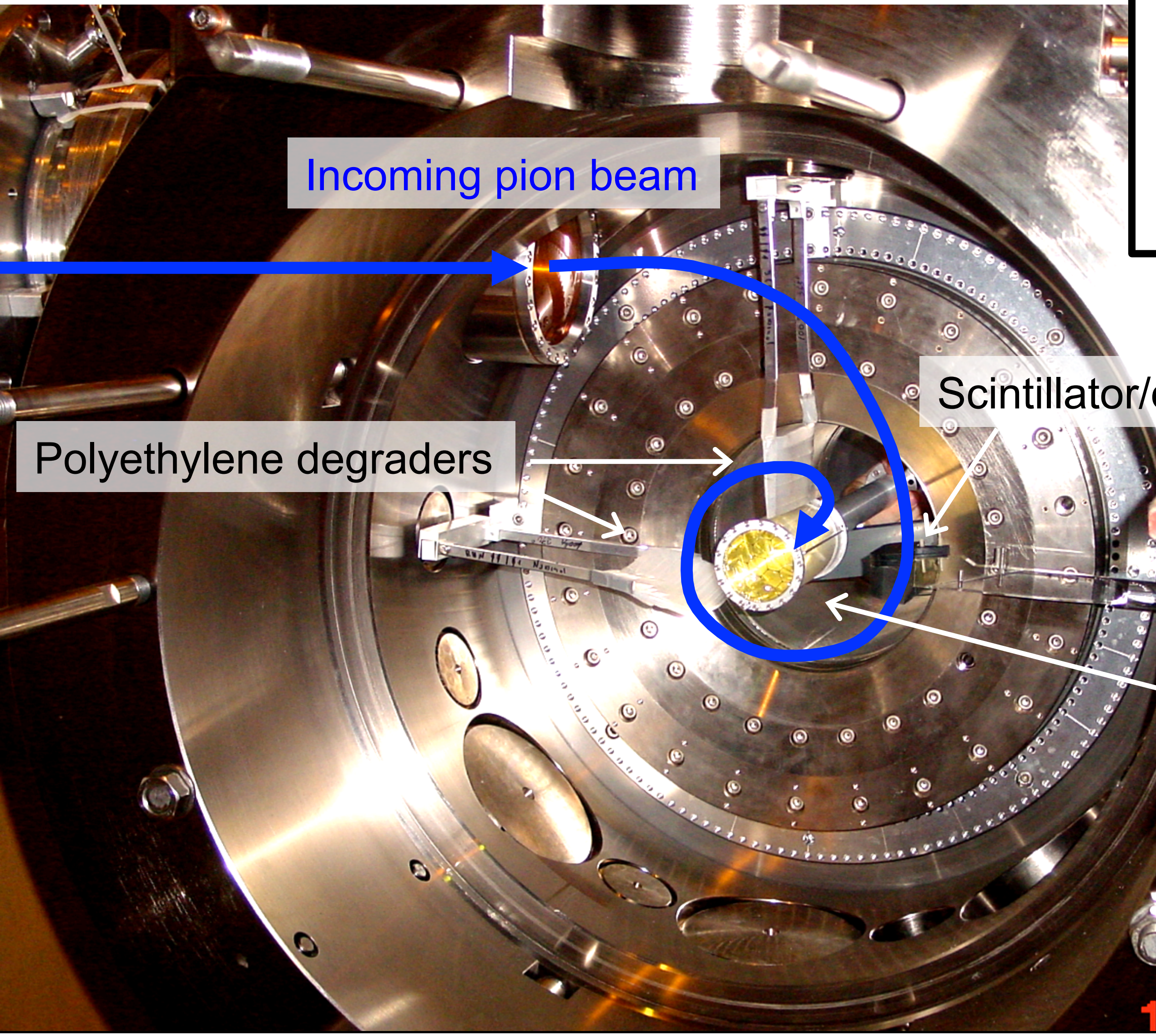
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

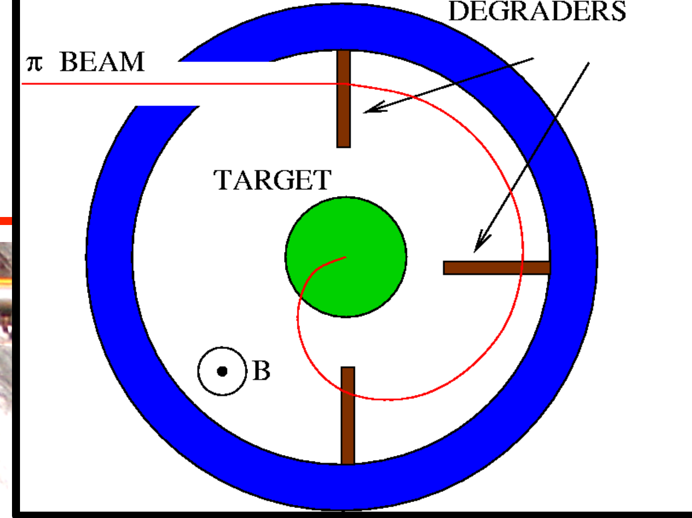


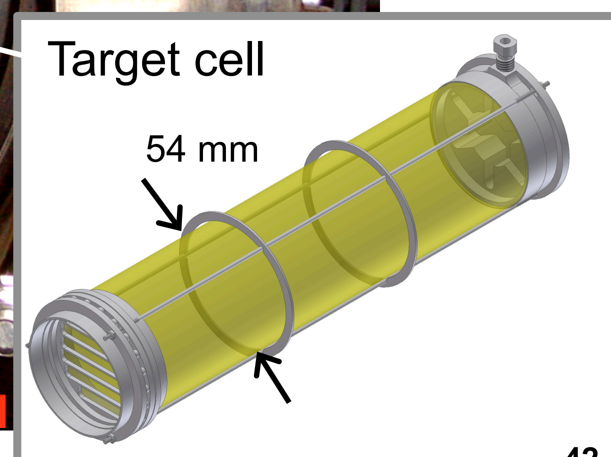
⇩

Formation of muonic and pionic atoms

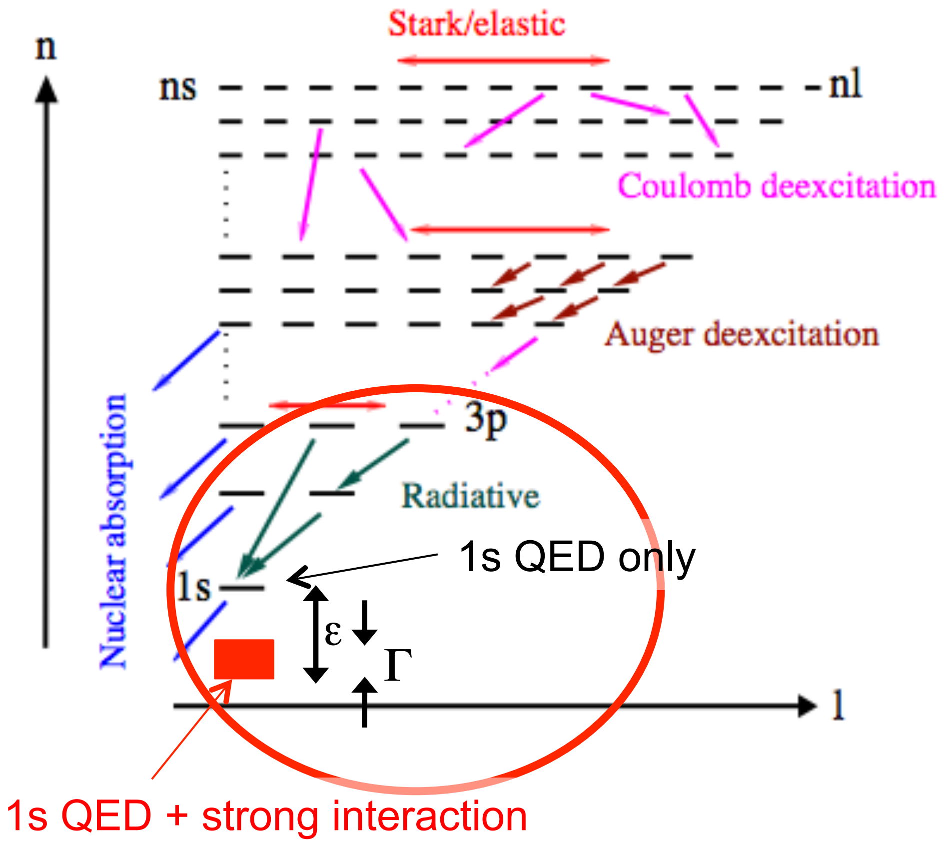
Cyclotron trap

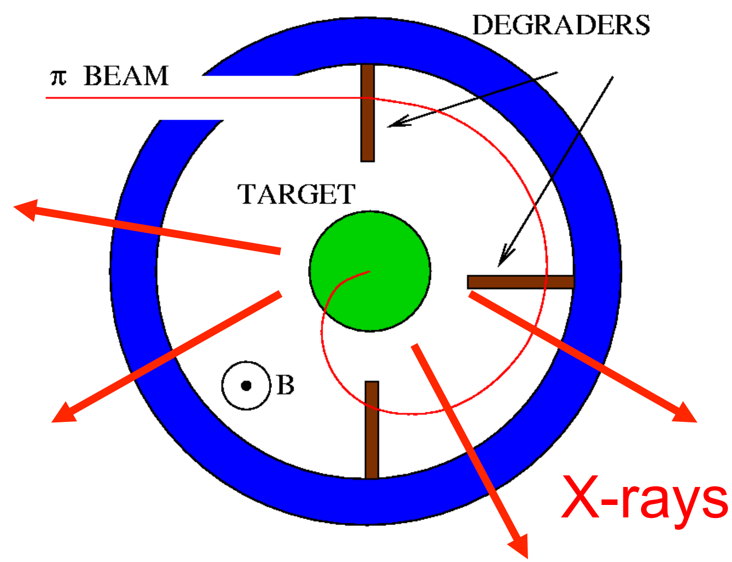






X-ray emission and detection



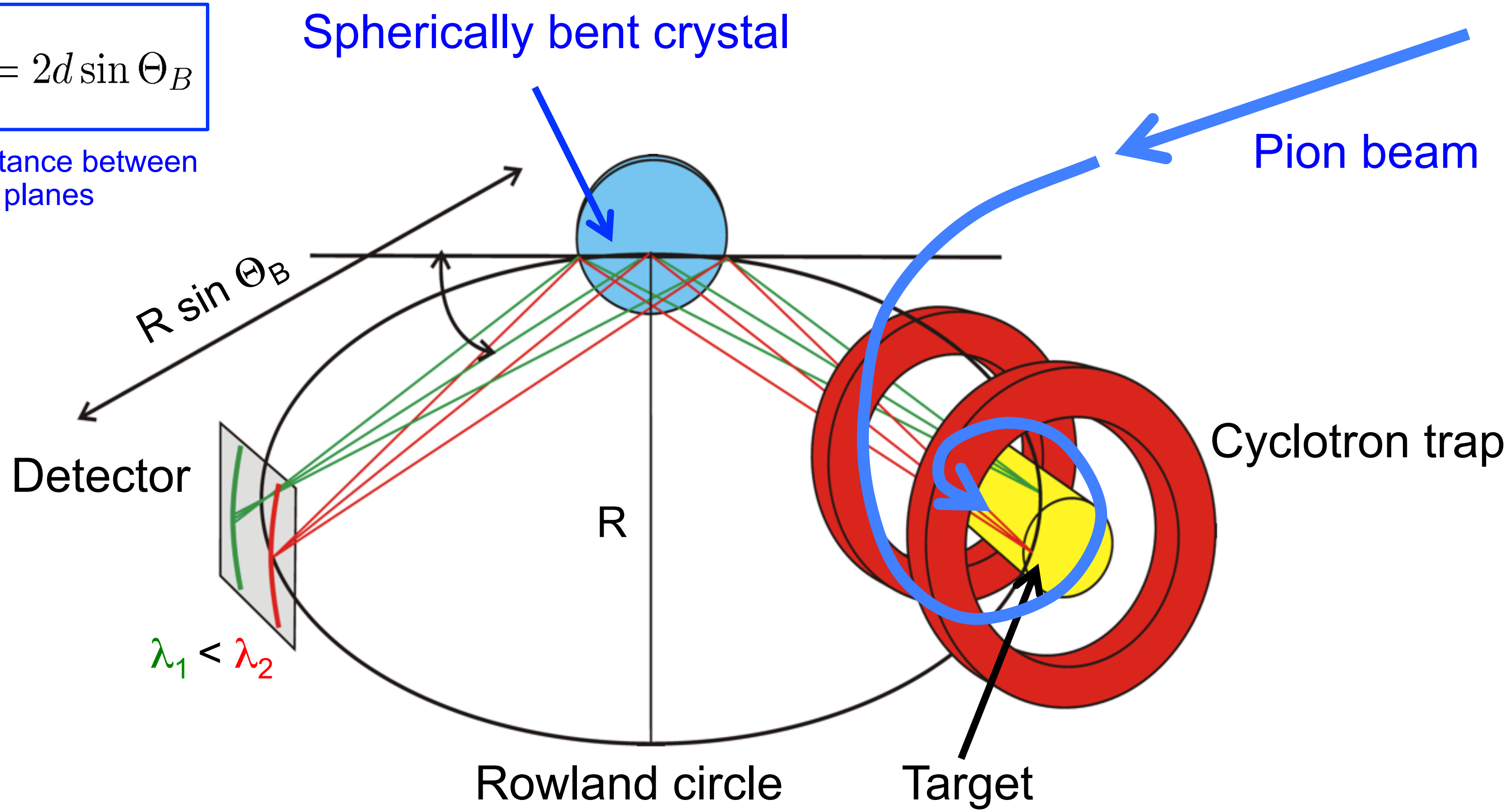


High power resolution for 2-4 keV X-ray required ⇨ Bragg crystal spectroscopy

Johann-type Bragg spectrometer

$$\frac{h\ c}{E} = 2d \sin \Theta_B$$

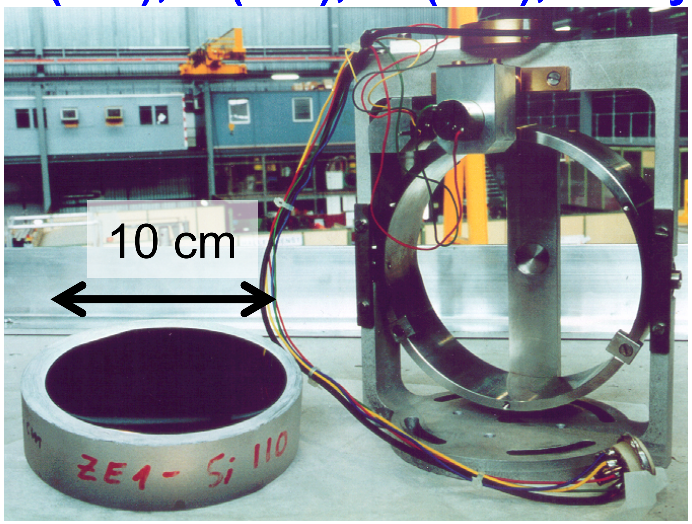
d = distance between crystal planes



[1] H.H. Johann, Zeitschrift für Physik **69**, 185 (1931)
[2] J. Eggs *et al.*, Zeitschrift für angewandte Physik **20**, 118 (1965)
[3] D. Gotta, Progress in Particle and Nuclear Physics **52**, 133 (2004)
[4] D. Gotta *et al.*, Spectrochim. Acta, Part B **120**, 9 (2016)

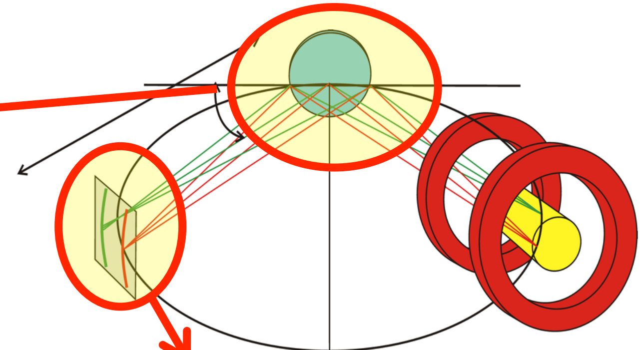
Diffraction crystal and position sensitive detector

Si(110), Si(111), Qz(100), … crystal [1]

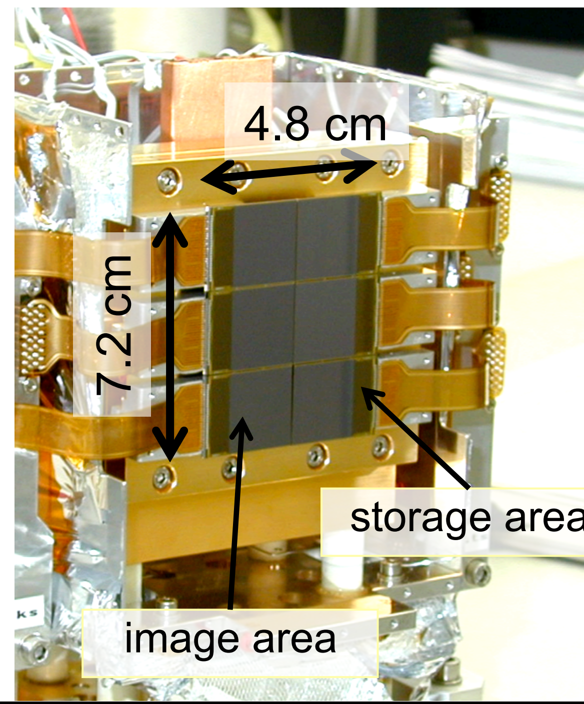


Radius of curvature: ~ 3 m
Diameter: 10 cm
Thickness: 290 μm
Support: polished quartz lens

Produced by Zeiss (Oberkochen, Germany)



2 × 3 X-ray CCD array with frame buffer [2,3]



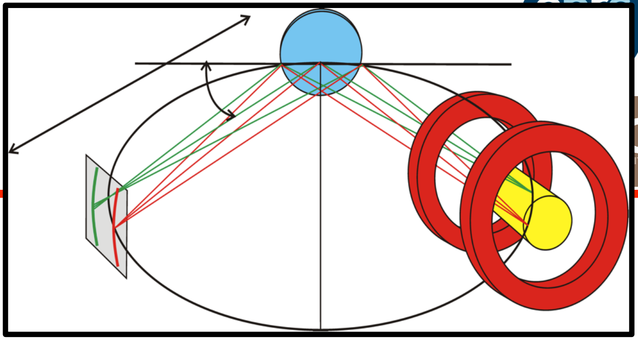
pixel size 40 μm × 40 μm
600 × 600 pixels per chip
frame transfer ≈ 10 ms

data processing ~24 s
operates at – 100°C

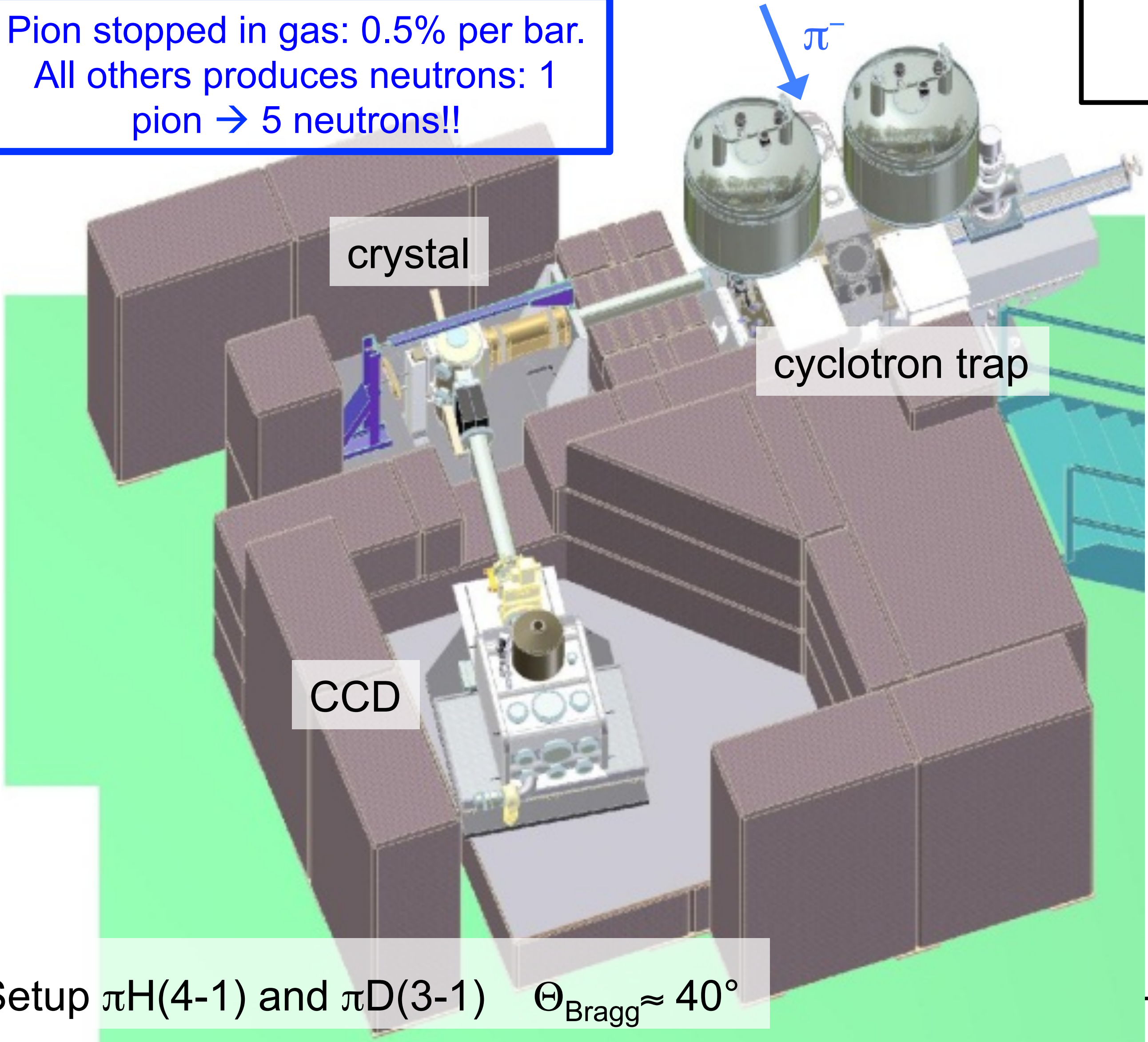
$\Delta E \approx$ 150 eV @ 4 keV
Efficiency ≈ 90%

[1] D.S. Covita *et al.*, Rev. Sci. Instum. **79**, 033102-3 (2008)
[2] N. Nelms *et al.*, Nucl. Instrum. Methods A **484**, 419 (2002)
[3] P. Indelicato *et al.*, Rev. Sci. Instum. **77**, 043107 (2006)

Typical set-up at PSI



Pion stopped in gas: 0.5% per bar.
All others produces neutrons: 1 pion → 5 neutrons!!



Setup πH(4-1) and πD(3-1) $\Theta_{Bragg} \approx 40°$

huge background on the CCD

⇩

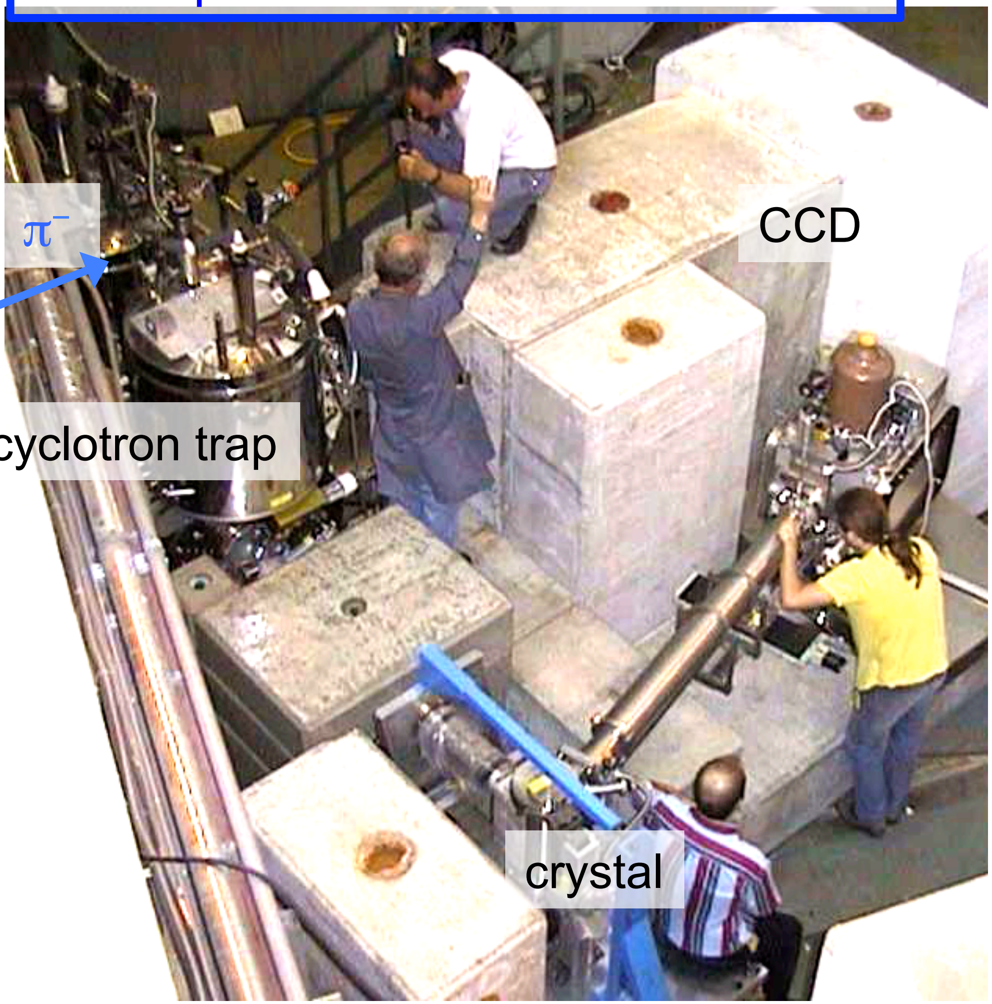
heavy concrete

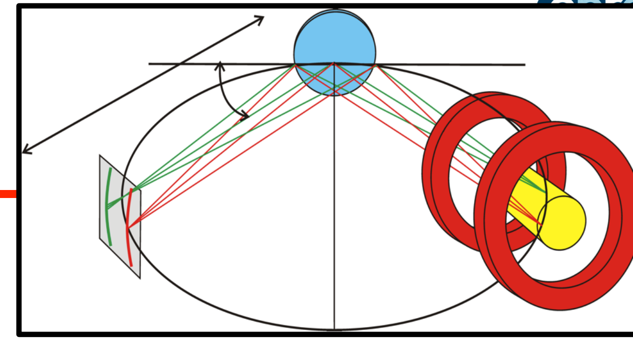
⇩

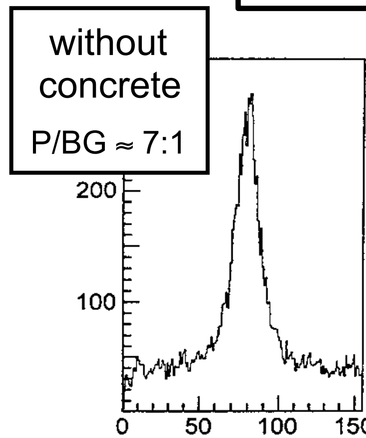
peak-to-background reduced by a factor of 10

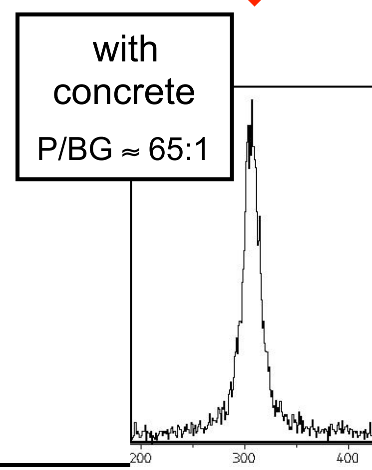
Typical set-up at PSI

Pion stops in gas: few % all others:
1 pion makes 5 neutrons!!









huge background on the CCD

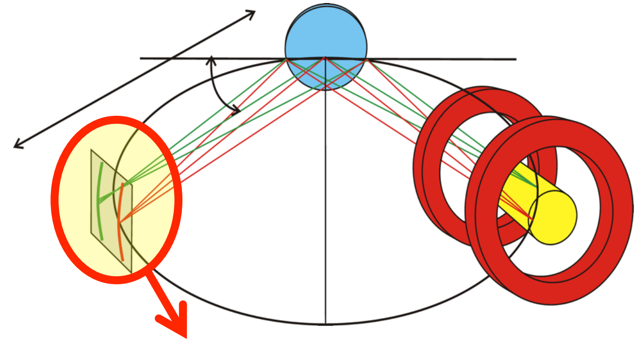
heavy concrete

peak-to-background reduced by a factor of 10

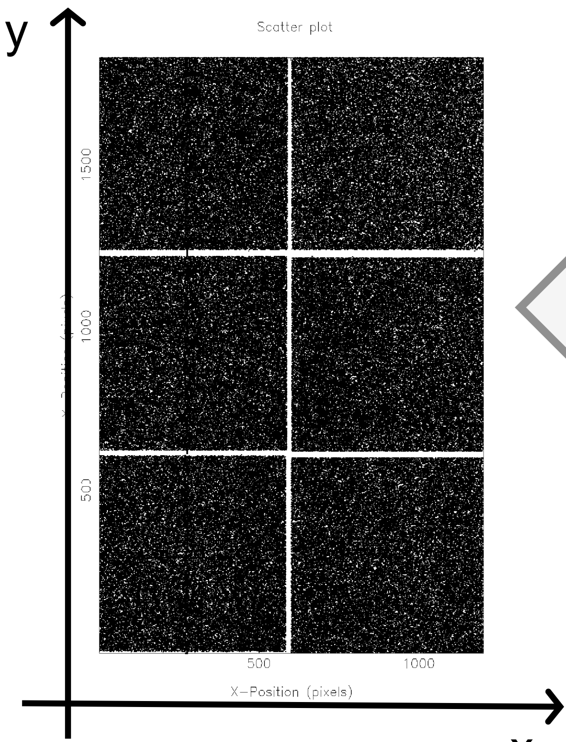
Data acquisition and pre-analysis

Several weeks of data collection …

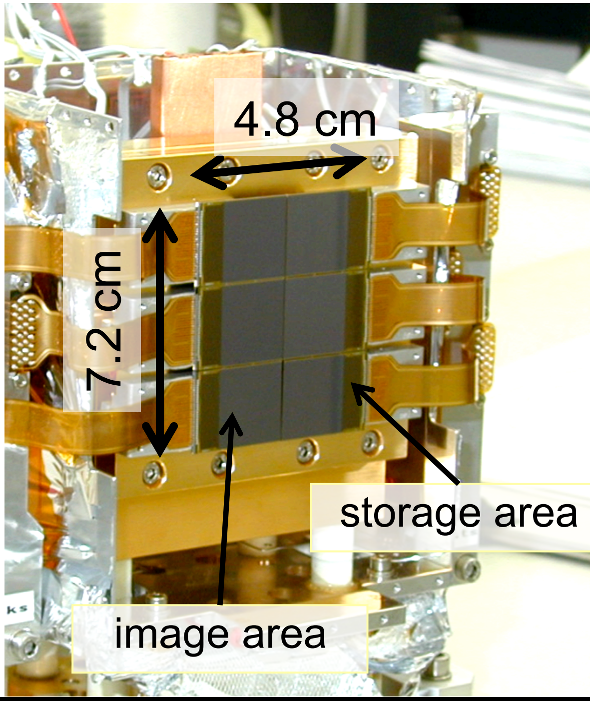
Spectrometer transmission: ~5x10^{-8}



2 × 3 X-ray CCD array with frame buffer [2,3]



Raw data



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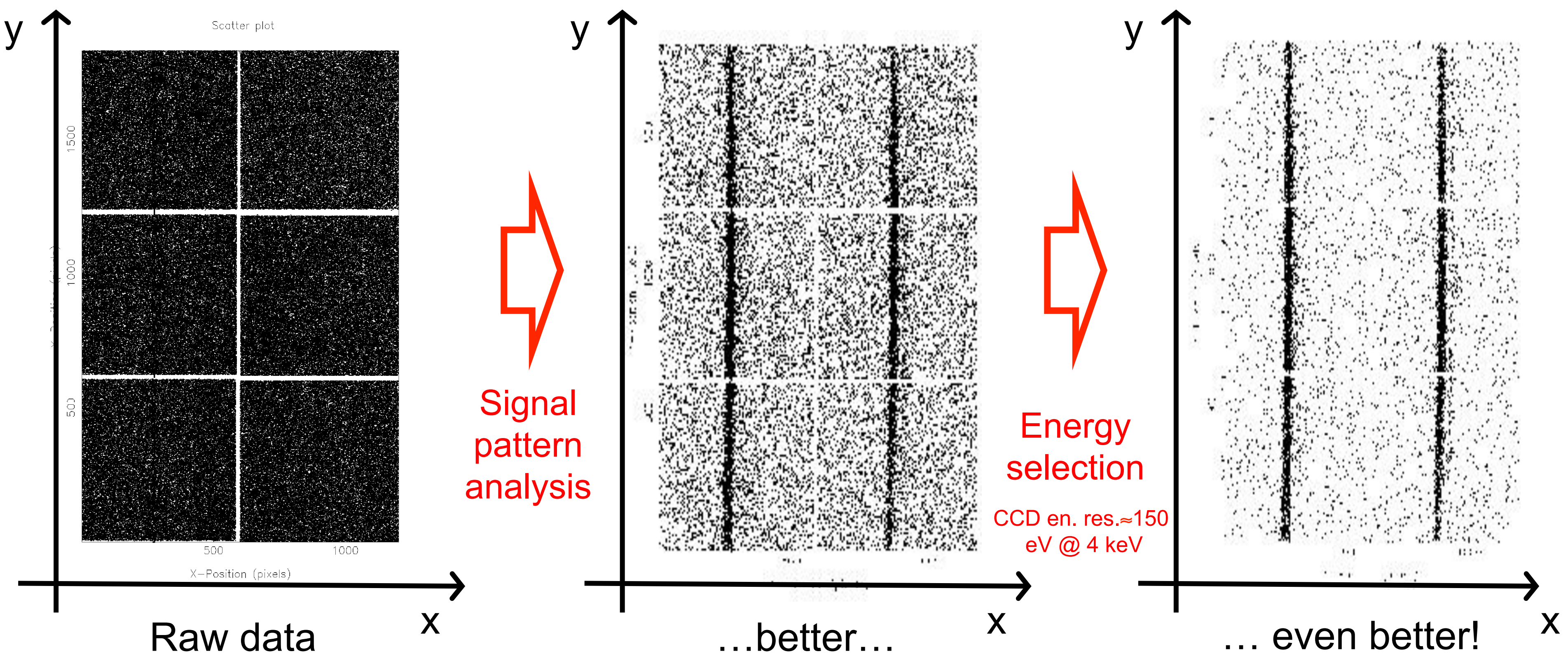

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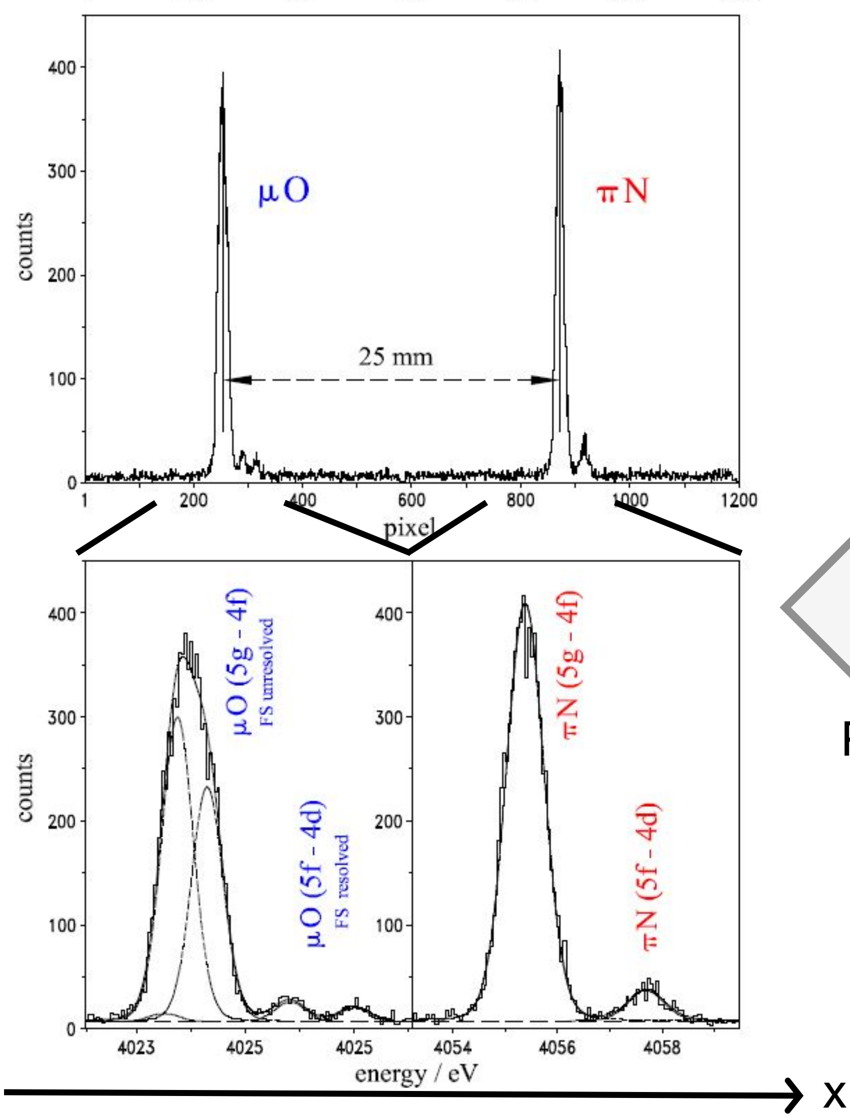
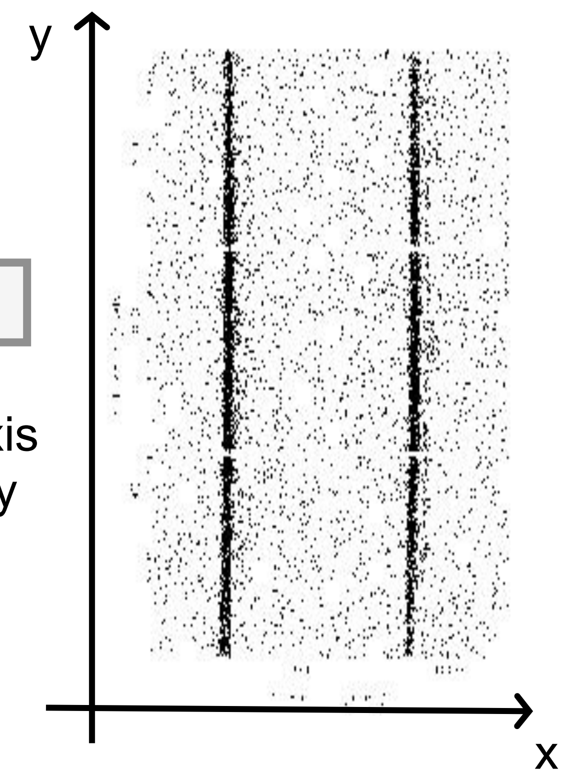


Projection on the x-axis (spectrometer energy dispersion axis)



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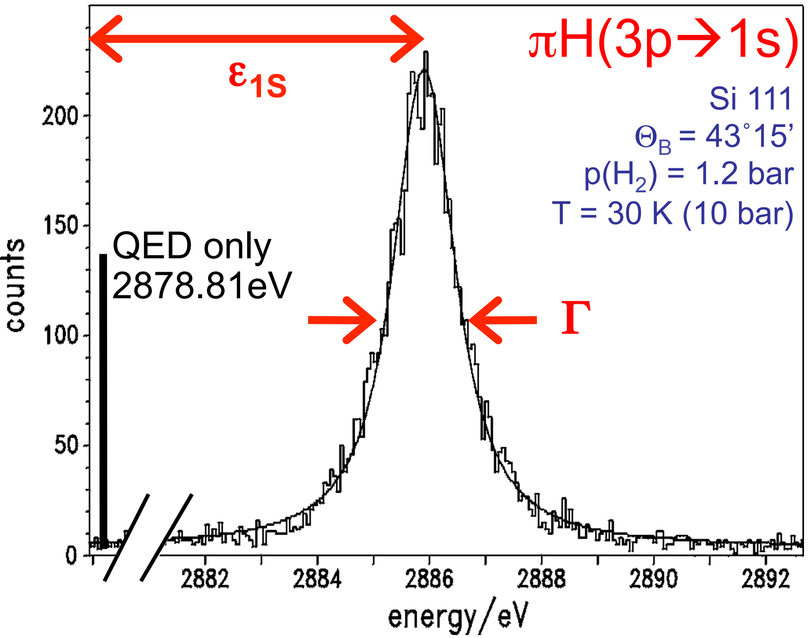
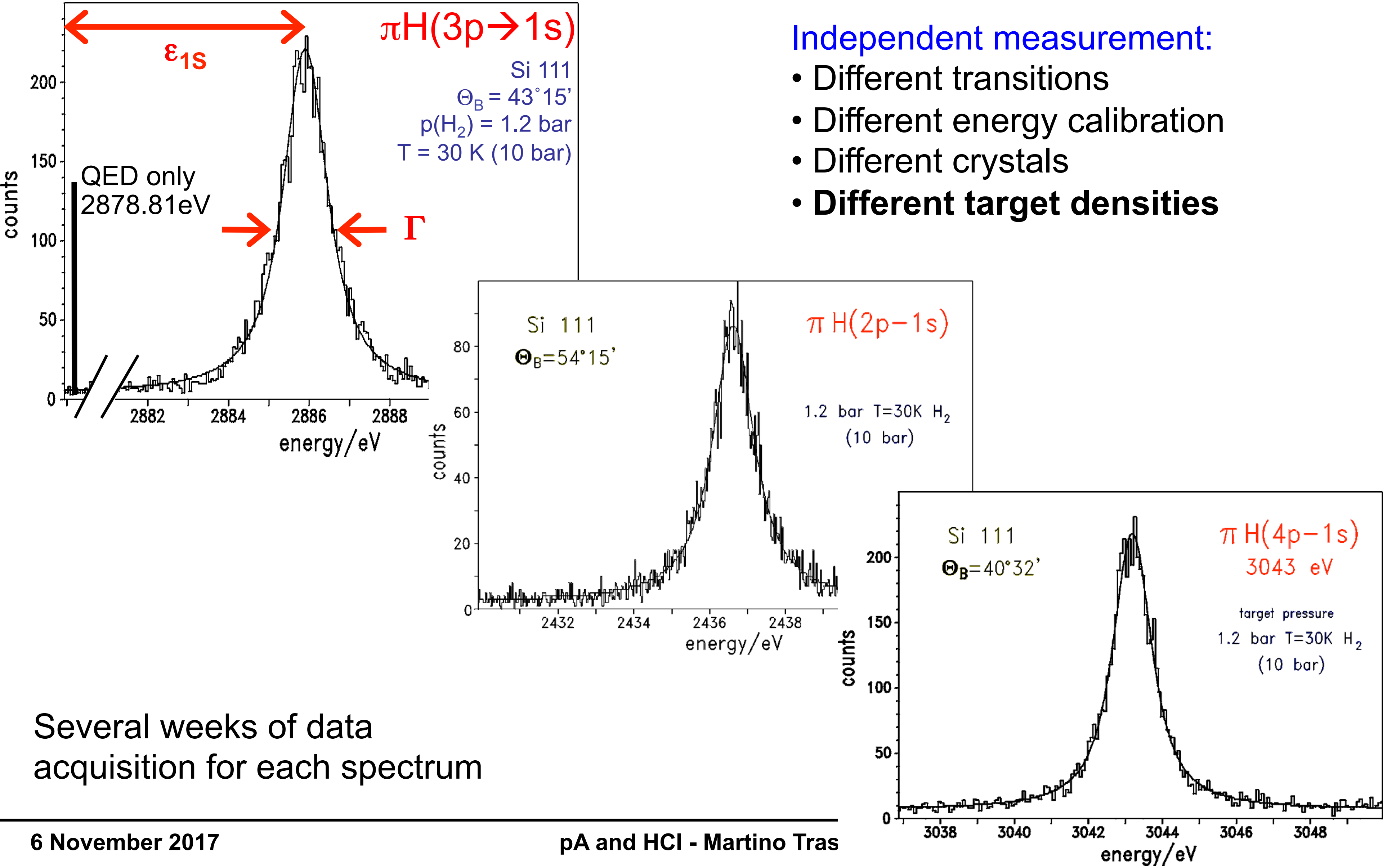
Pionic hydrogen results



Several weeks of data
acquisition for each spectrum

Pionic hydrogen results

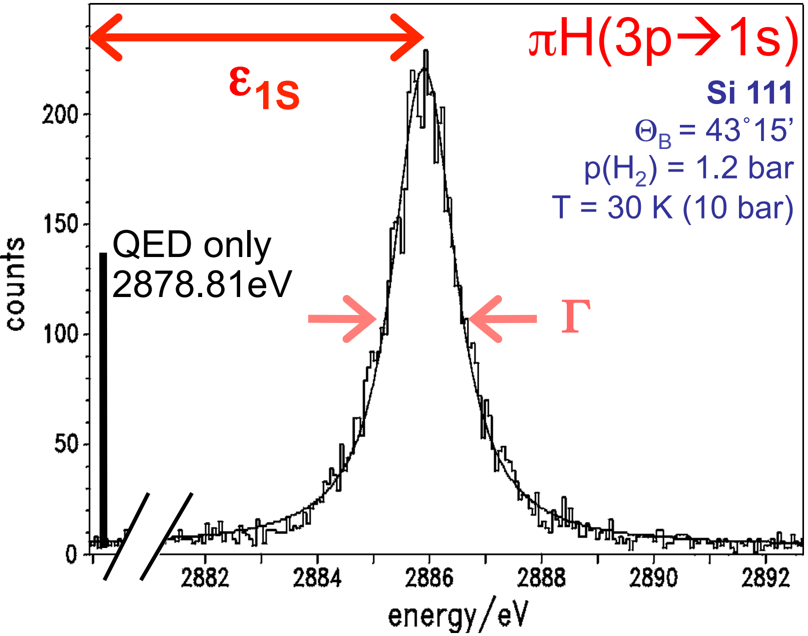


Independent measurement:

- Different transitions
- Different energy calibration
- Different crystals
- **Different target densities**

Several weeks of data acquisition for each spectrum

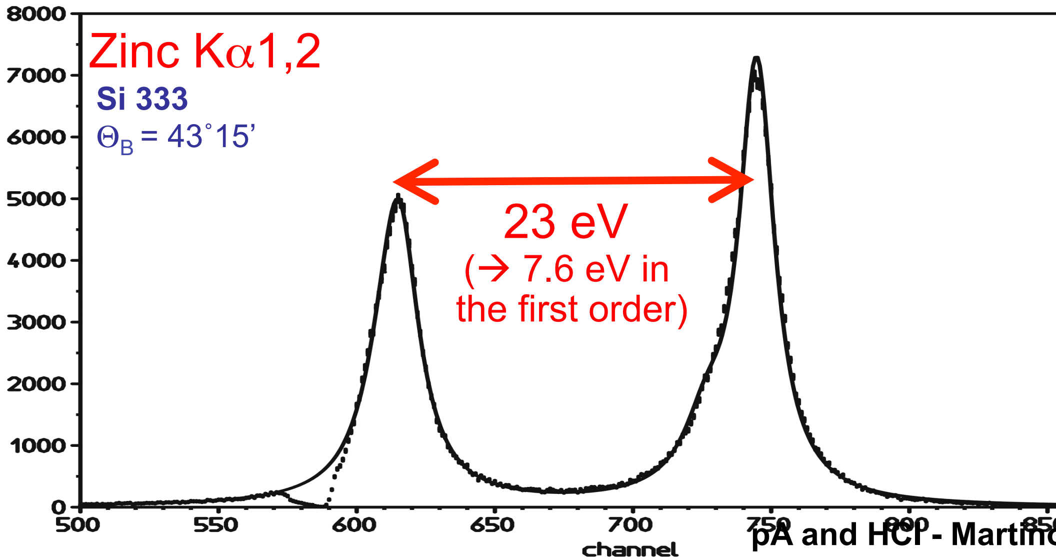
Pionic hydrogen (and deuterium) shift measurement

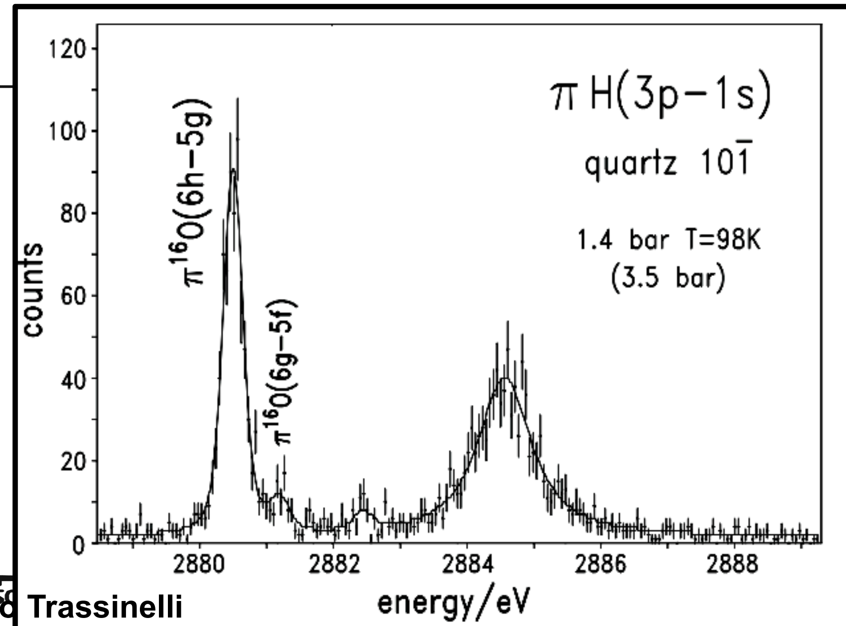


Calibrations

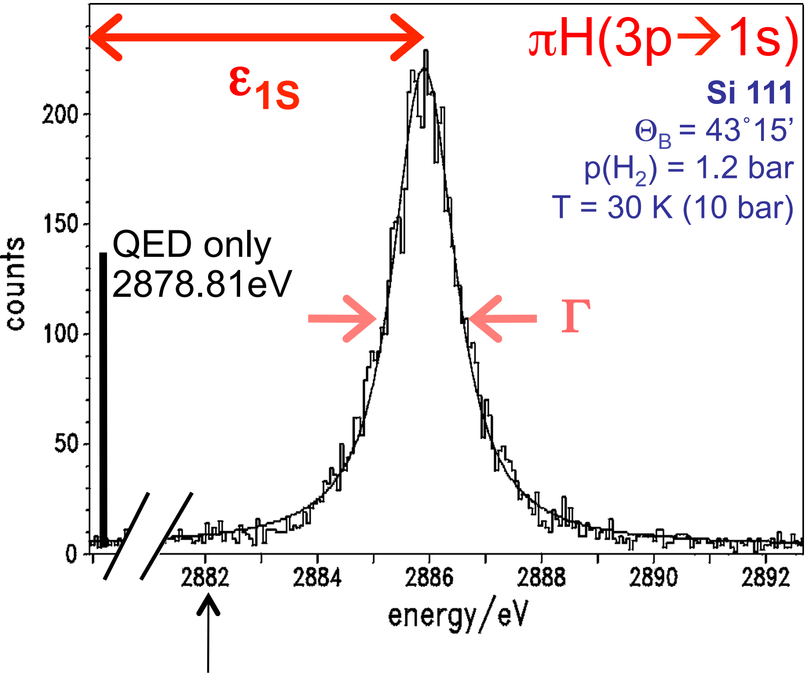
- Kα fluorescence from selected target (different reflection order)
- from other exotic atom transitions (where strong interaction effects are negligible)

smaller systematic errors from crystal spectrometer aberrations and possible chemical shifts and pion mass accuracy

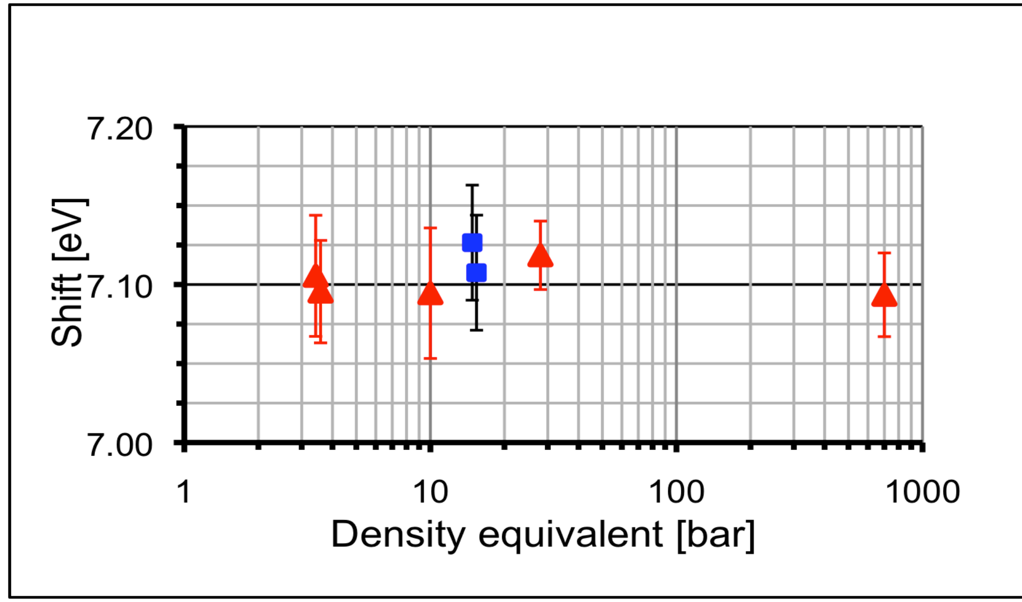




Pionic hydrogen shift measurement (preliminary result)



Satellite position



ETHZ-PSI previous experiment – Ar Kα
H.-Ch.Schröder et al. Eur. Phys.J.C 1 **473** (2001)

ε_{1s} = + 7.0869 ± 0.0071 ± 0.0064 eV (± 0.13%) [1]

(attractive force)

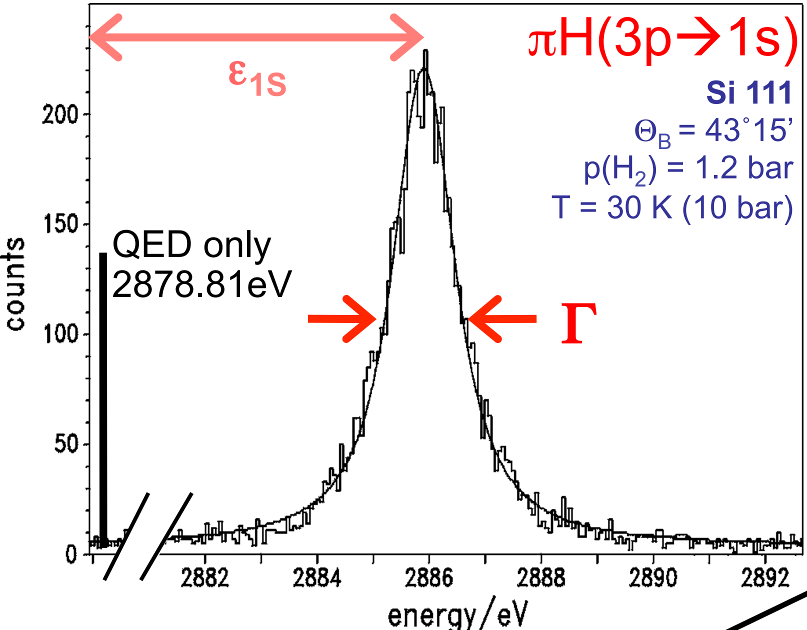
0.001 eV from QED predictions [4]
→ **from the pion mass**

Results

- No satellite from molecular X-ray detected (theoretical predictions [2] not confirmed)
- New value for the strong interaction shift in πH [3] (more 3 times smaller uncertainty)

[1] M. Hennebach *et al.*, Eur. Phys. J. A **50**, 1-10 (2014)
[2] S.Kilic et al., Phys. Rev. A **70** 042506 (2004)
[3] D. Gotta, et al., Lect. Notes Phys. **745** 165 (2008)
[4] Schlesser et al., Phys. Rev. C **84**, 015211 (2011)

Pionic hydrogen (and deuterium) width measurement



Much more complex!!

$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$

from the strong interaction (goal!)

from the fast movement of the ions

from the response function of the instrument

⇩

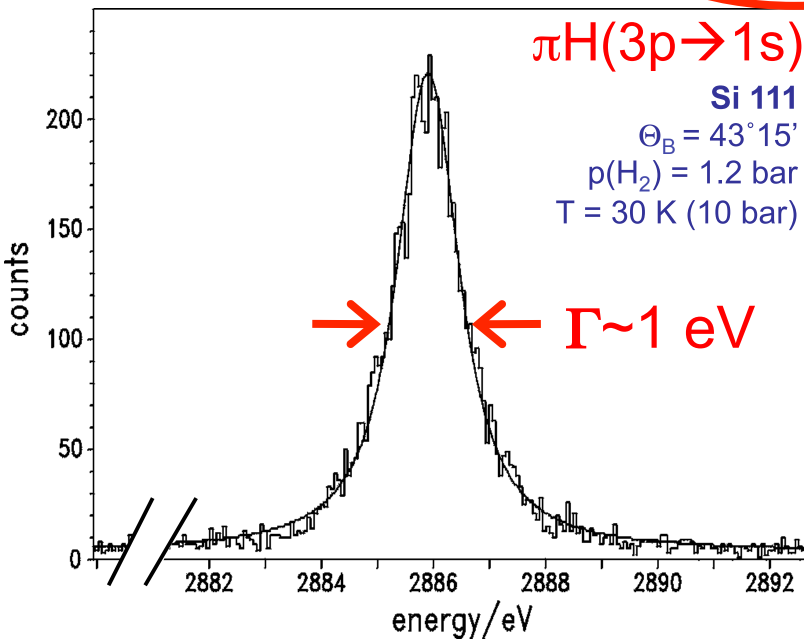
Accurate investigation to the atomic cascade
- new theoretical approaches
- new experiment with muonic hydrogen

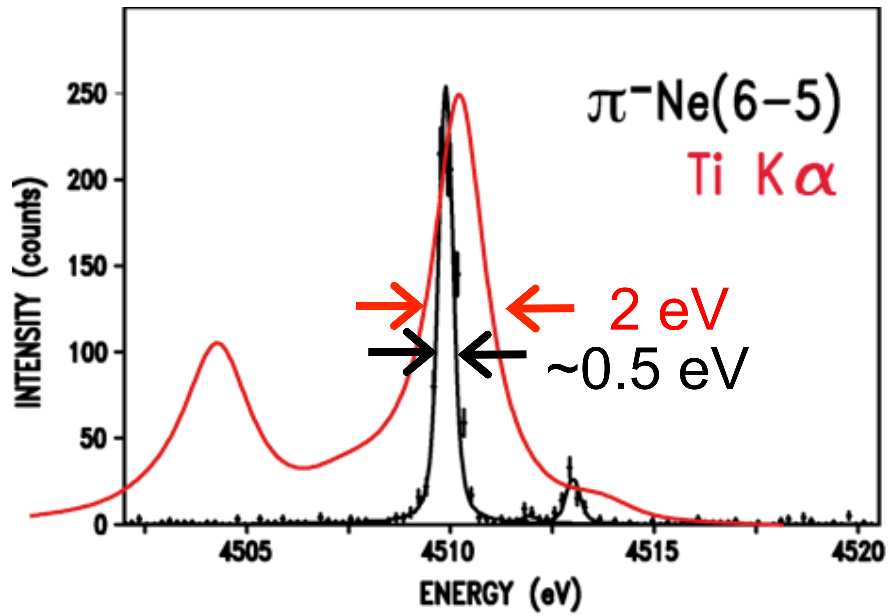
⇩

Characterization of the spectrometer [1,2]
- new measurements highly charged ion X-ray transitions
- simulation of the instrument

Crystal spectrometer characterization

$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$



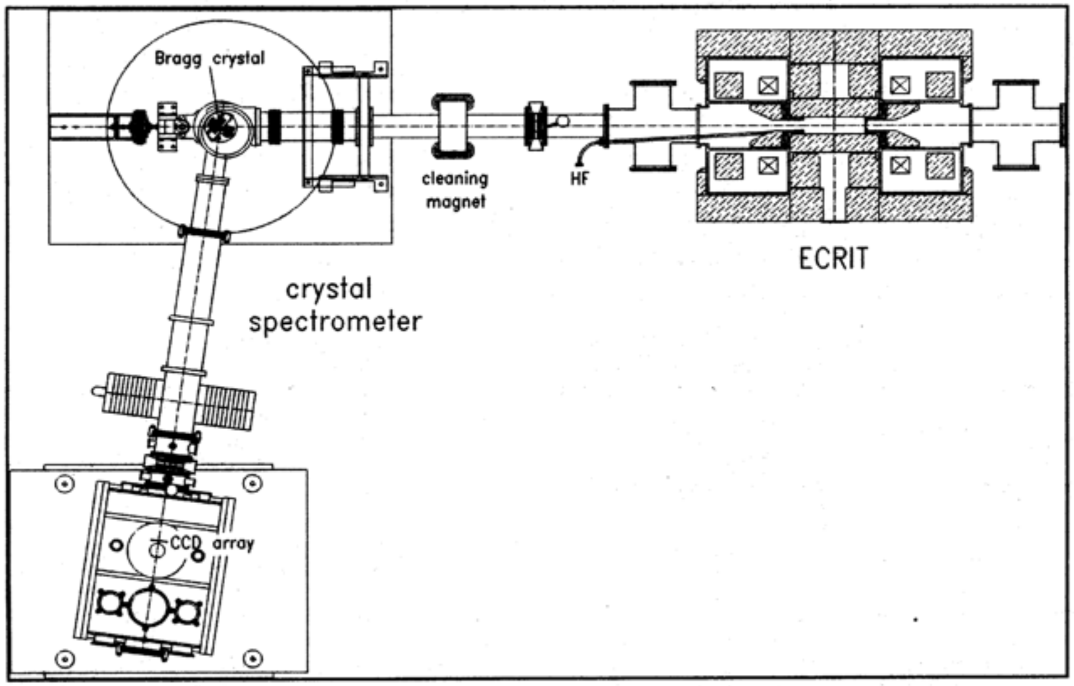


How to characterize the response function of the spectrometer?

Where to find a X-ray line with a Γ<0.5 eV?

- Fluorescence X-ray: too broad!!
- Pionic atoms (no Coulomb explosion): too low count rate!!
- … highly charged ion radiation!!

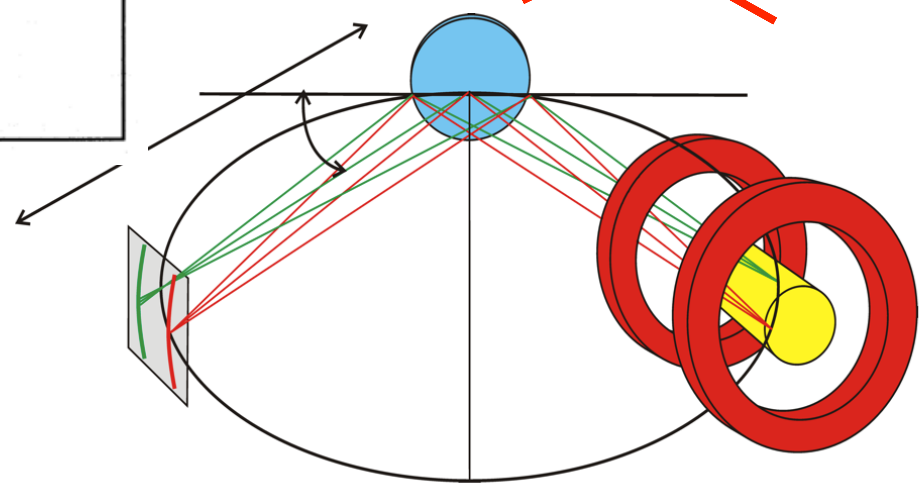
ECRIT X-ray emission

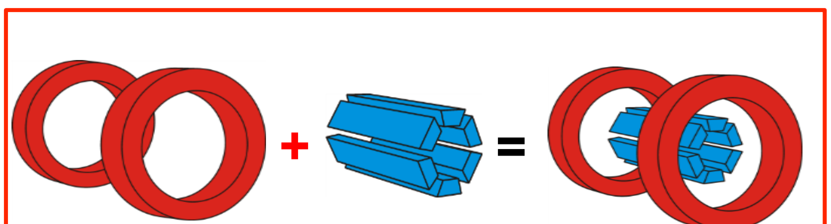


High intense radiation from He-like ions

Electron-cyclotron resonance ion trap

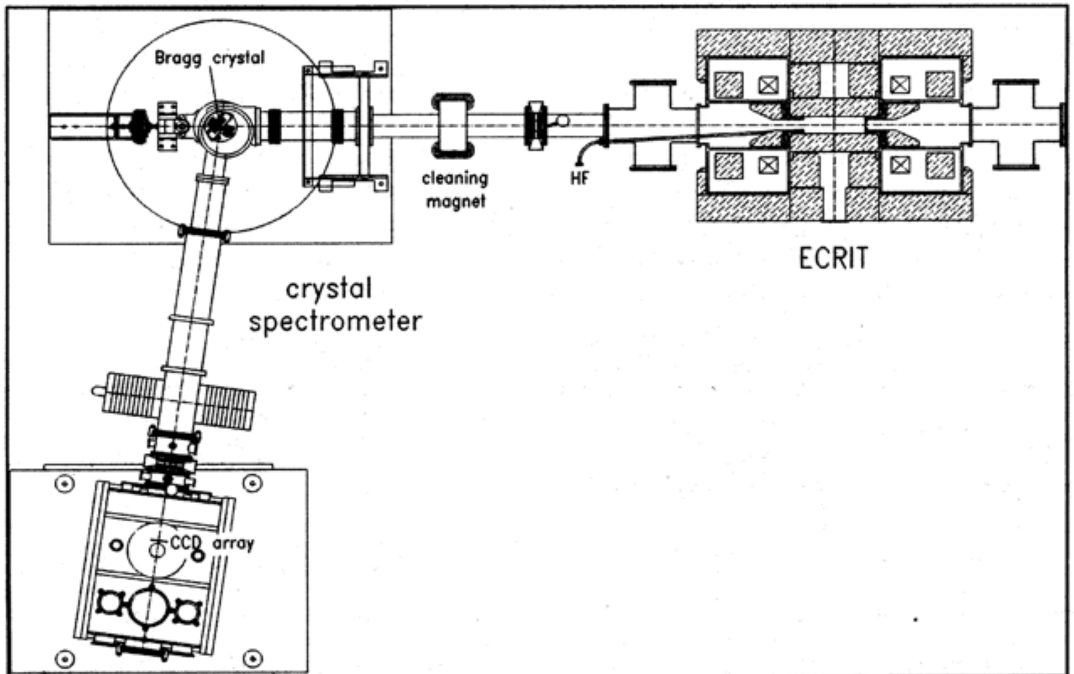
~~Cyclotron trap~~





Biri et al., Rev. Sci. Instum. **71**, 1116-18 (2000).
Hitz et al., Nucl. Instrum. Meth. B **205**, 168-172 (2003).

ECRIT X-ray emission

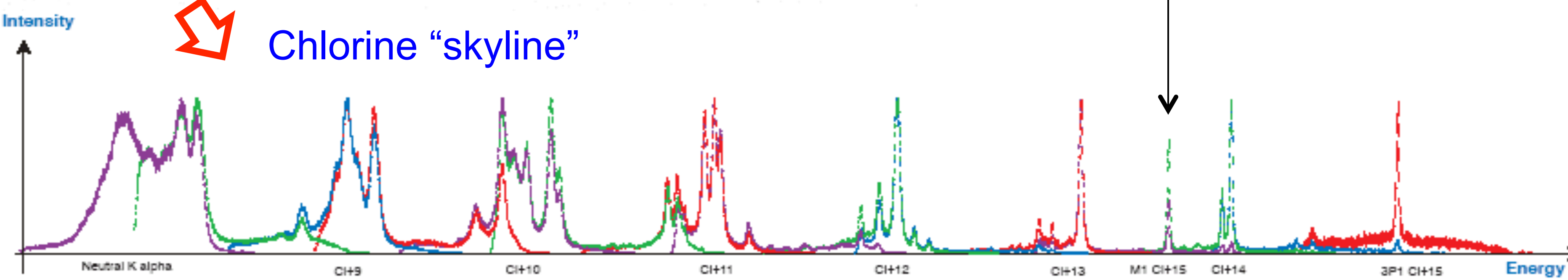


High intense radiation from He-like ions

Electron-cyclotron resonance ion trap

$1s2s\ ^3S_1 \rightarrow 1s_2\ ^1S_0$
(M1)

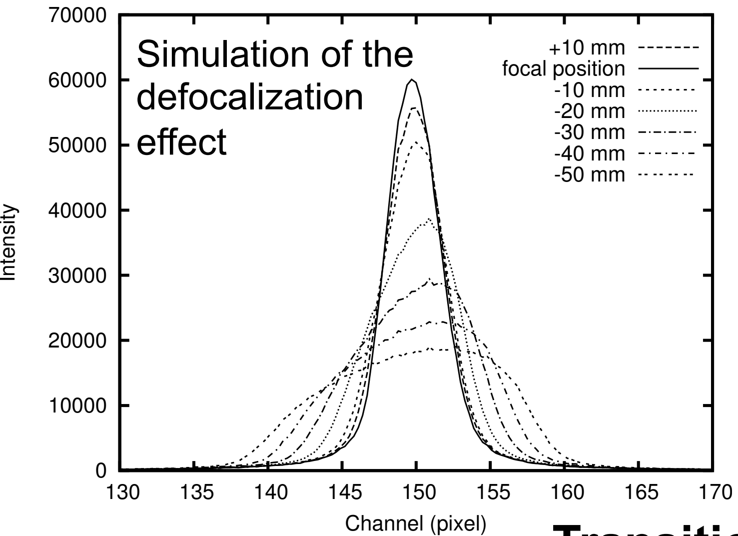
Chlorine "skyline"



Anagnostopoulos et al., Nucl. Instrum. Metl
Anagnostopoulos et al., Nucl. Instrum. Metl
M.T. et al., J. Phys. CS **58**, 129 (2007)

Covita et al., Rev. Sci. Instum. **79**, 033102 (2008)
Schlesser *et al.*, Phys. Rev. A **88**, 022503 (2013)
Gotta and Simons, Spectrochim. Acta, Part B **120**, 9-18 (2016)

Spectrometer characterization from He-like S, Cl, Ar M1 transitions

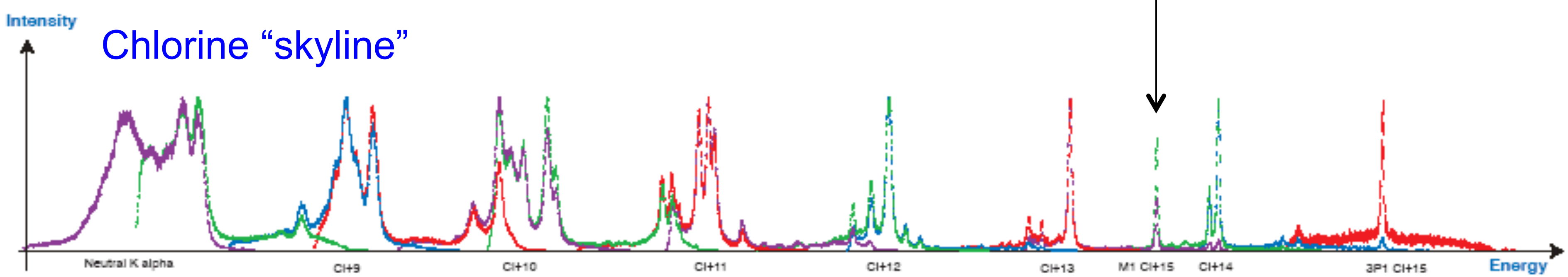


Ideal for spectrometer response function studies

Measurement with:
- Different crystal
- Different crystal aperture
- Different focal position
- Different X-ray energies (Ar, Cl, S)

- **Transition width << 1meV**
- **Doppler broadening < 40 meV**

1s2s $^3S_1$ → $1s_2$ $^1S_0$ (M1)



Anagnostopoulos et al., Nucl. Instrum. Metl
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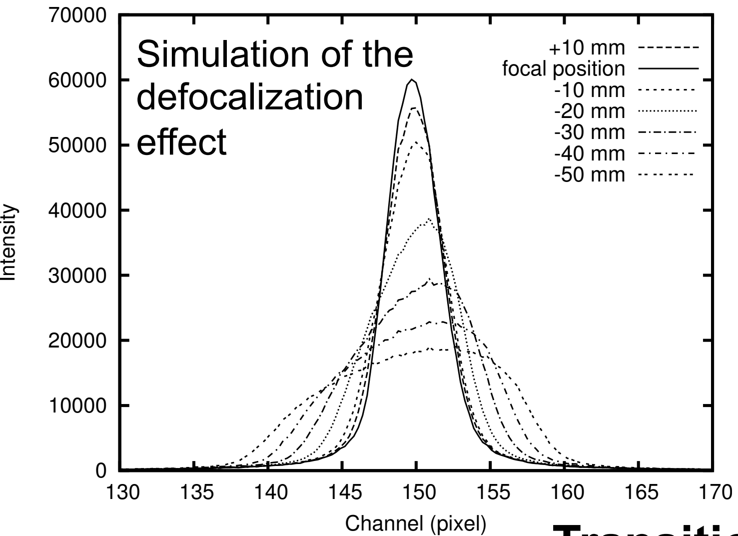

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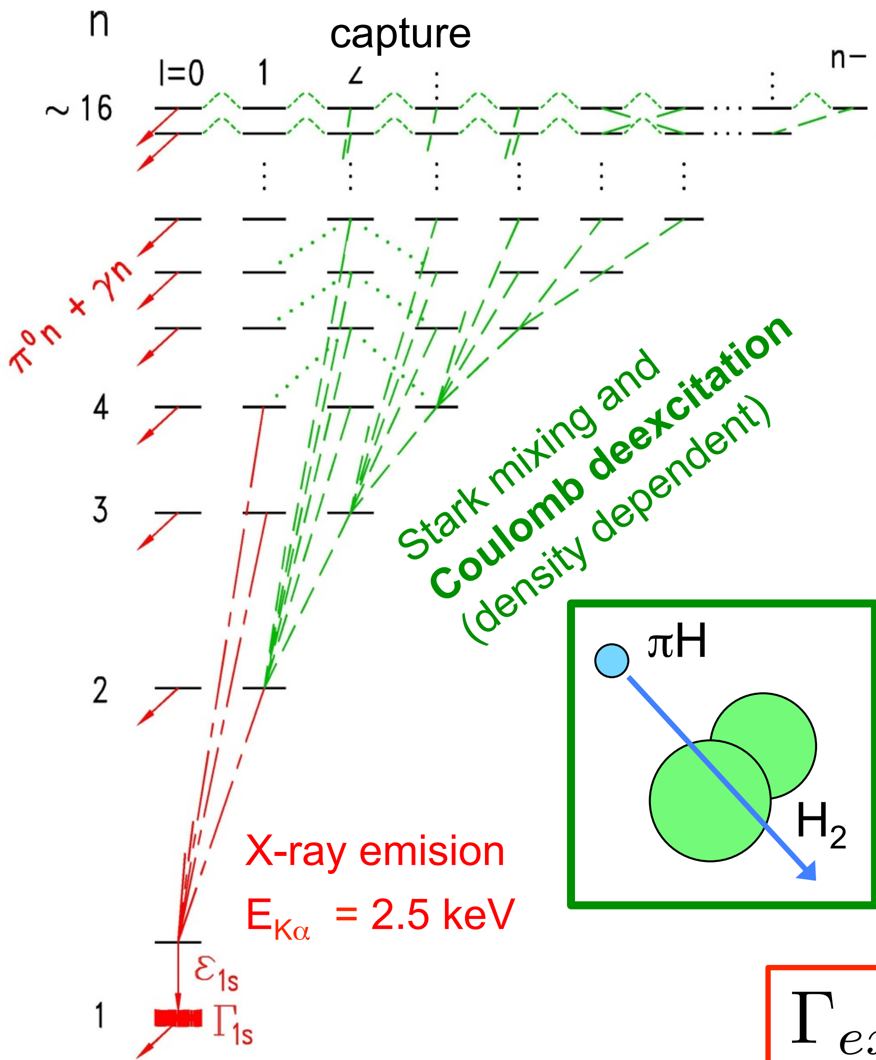
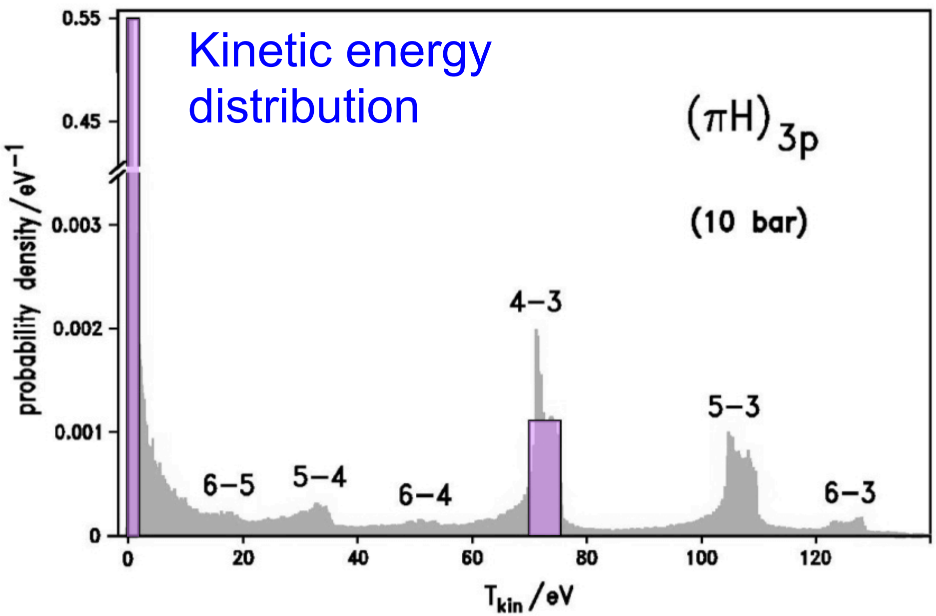
$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$

Anagnostopoulos et al., Nucl. Instrum. Metl
Anagnostopoulos et al., Nucl. Instrum. Metl
M.T. et al., J. Phys. CS **58**, 129 (2007)
Covita et al., Rev. Sci. Instum. **79**, 033102 (2008)
Schlesser *et al.*, Phys. Rev. A **88**, 022503 (2013)
Gotta and Simons, Spectrochim. Acta, Part B **120**, 9-18 (2016)

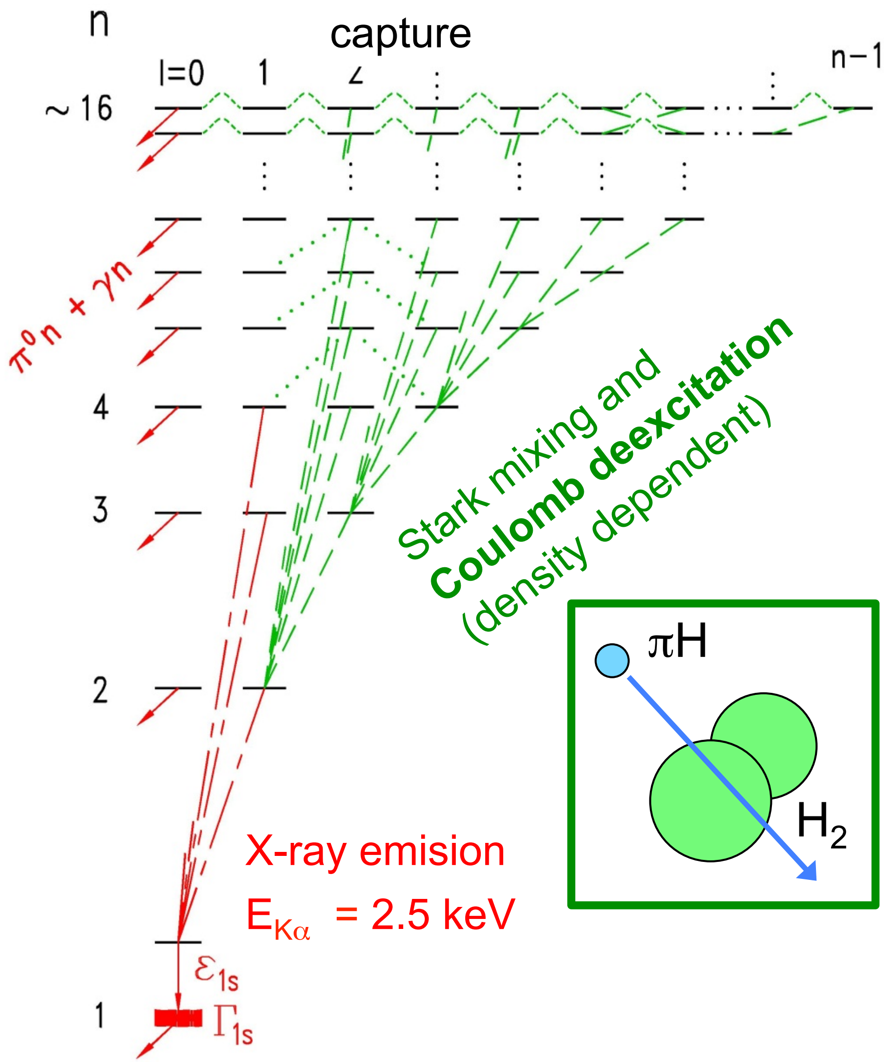
Transitions induced by collisions in πH

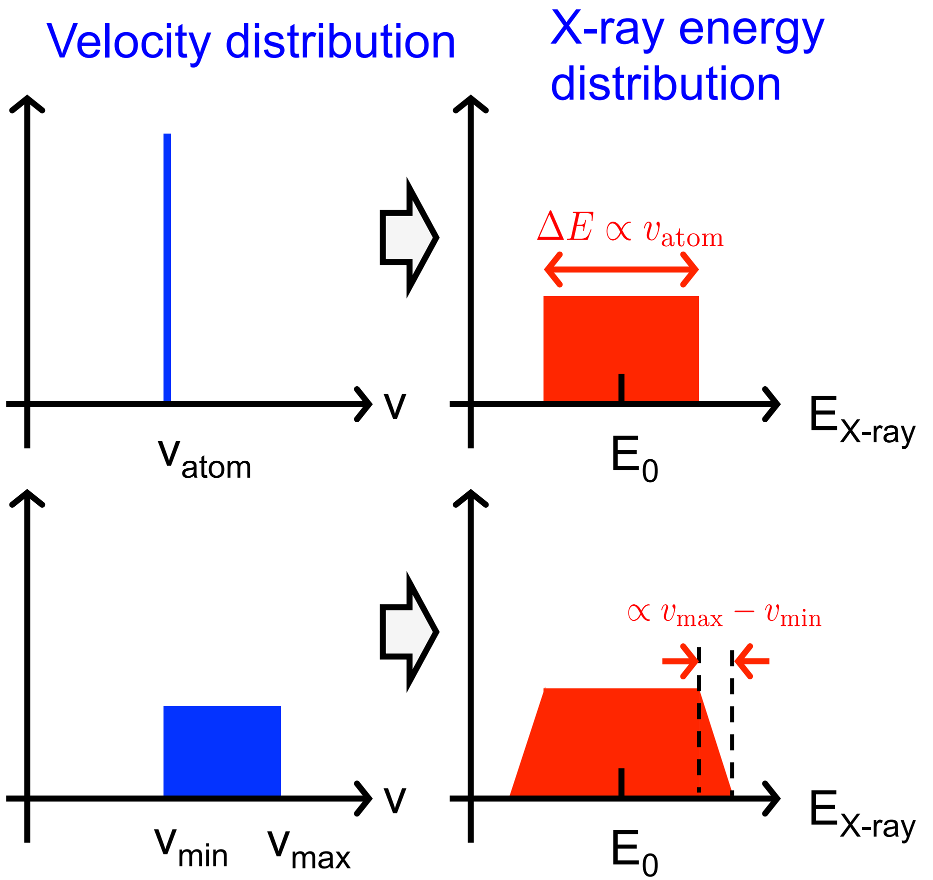




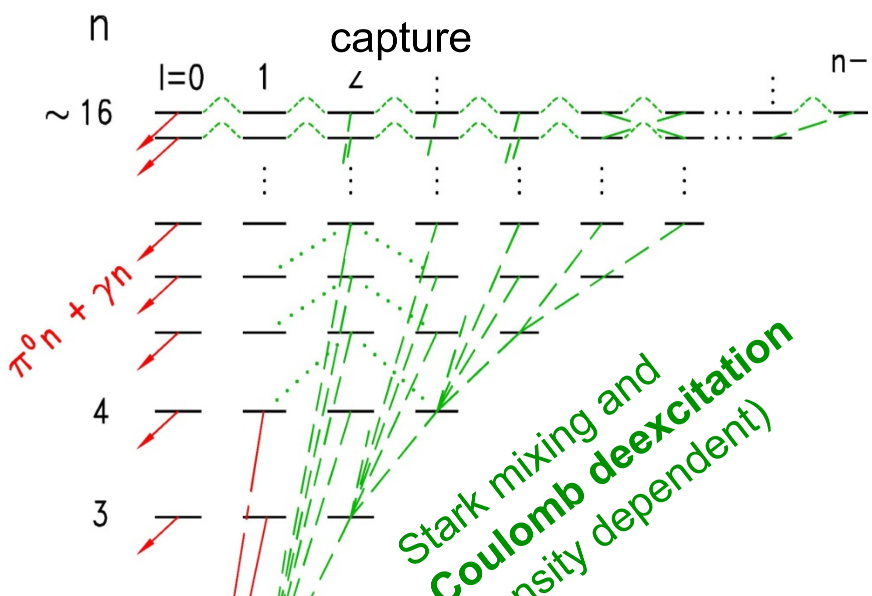
$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$

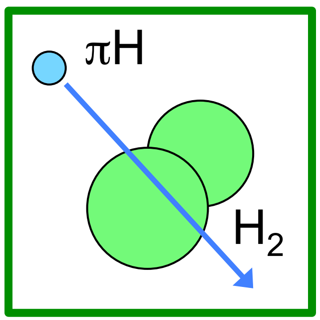
Transitions induced by collisions in πH

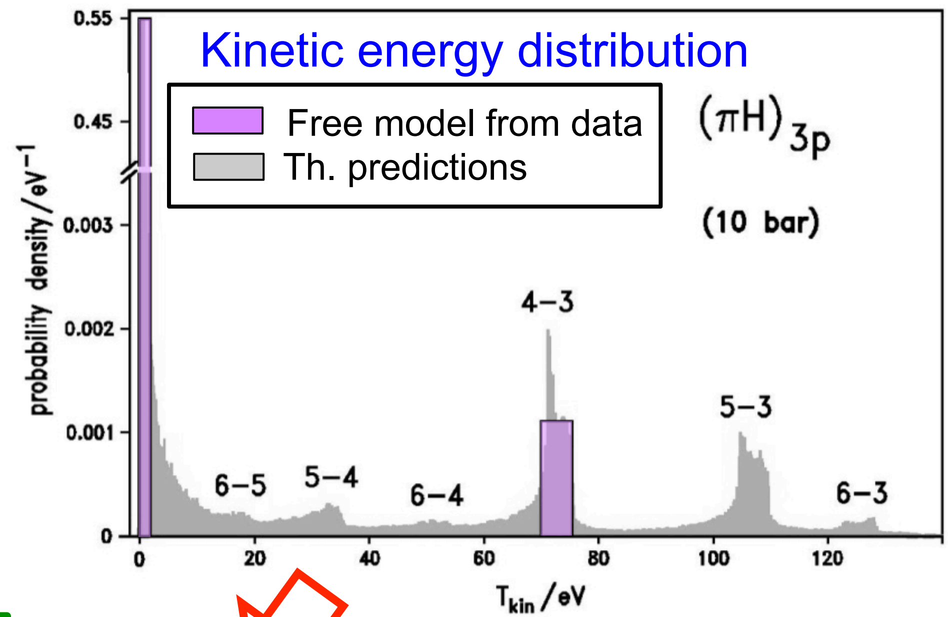


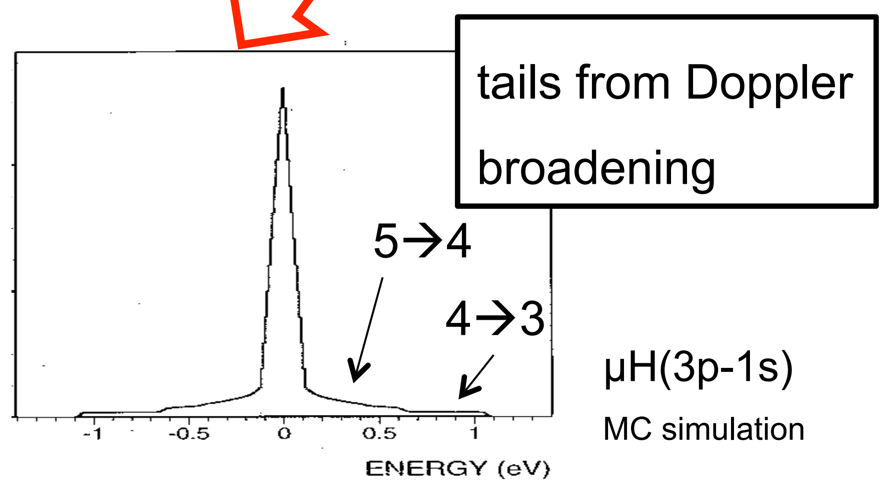


Transitions induced by collisions in πH





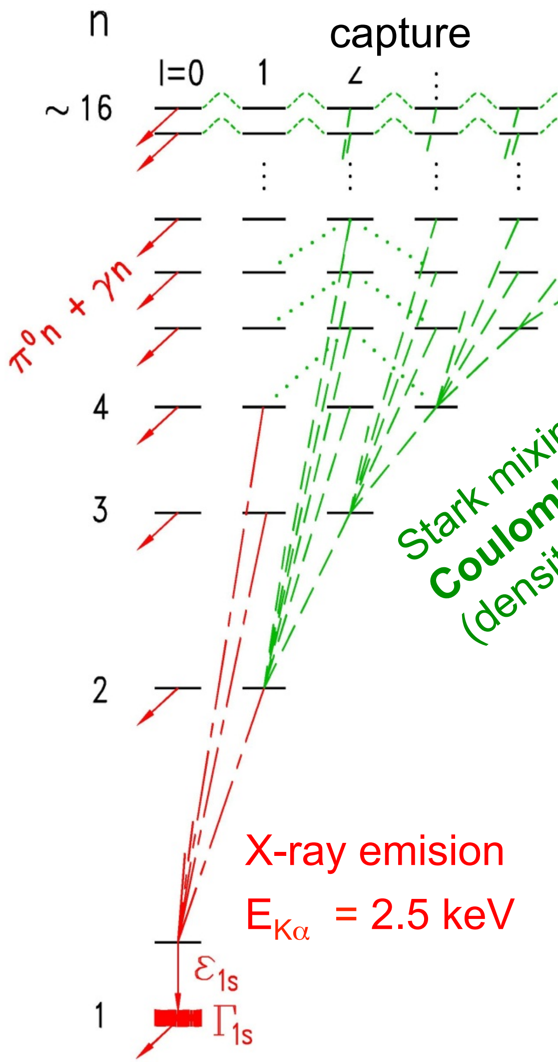


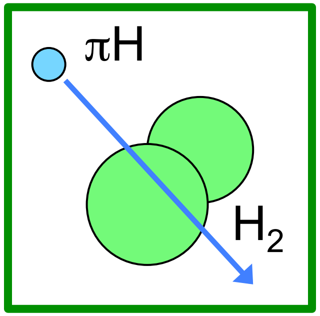


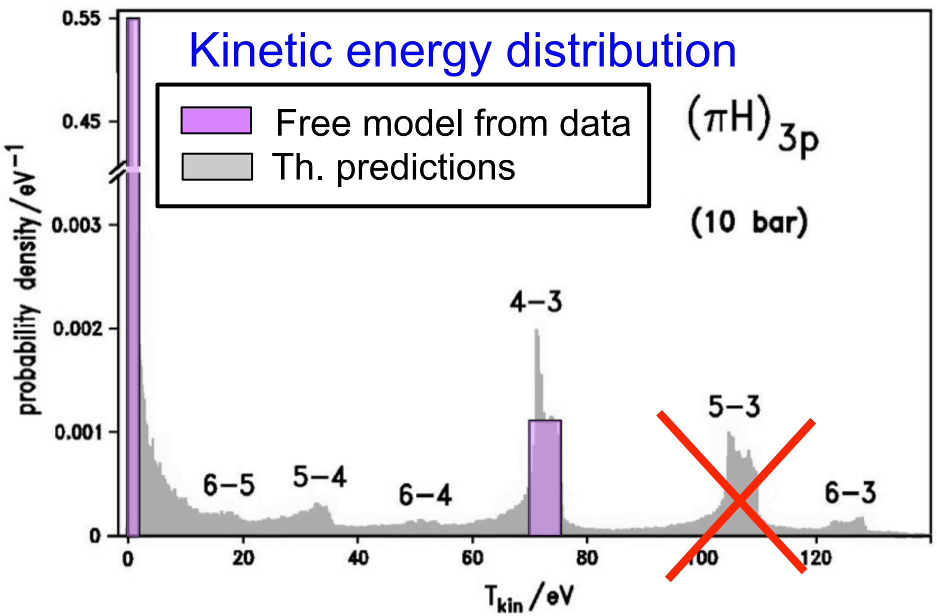
μH(3p-1s)

MC simulation

Transitions induced by collisions in πH



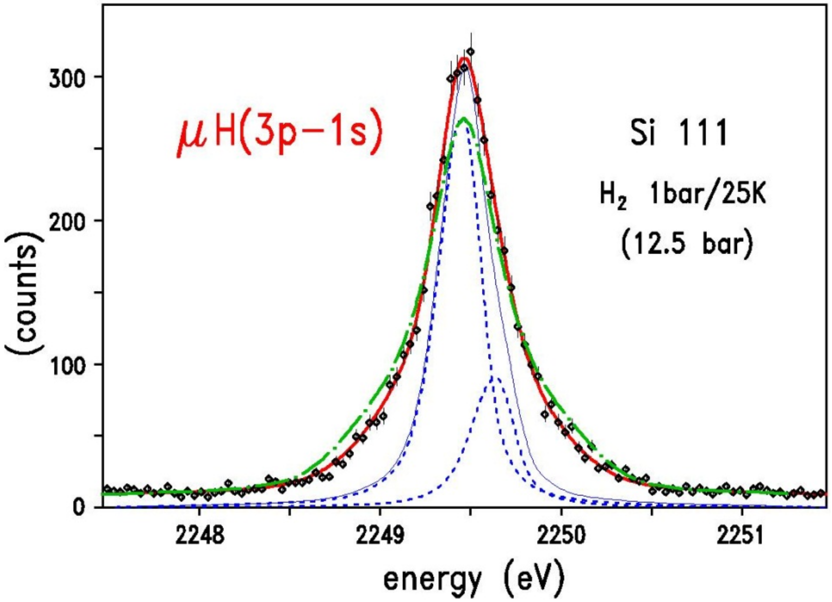




Consistency to check!

→ Study of μH: strong interaction absorption in s-states

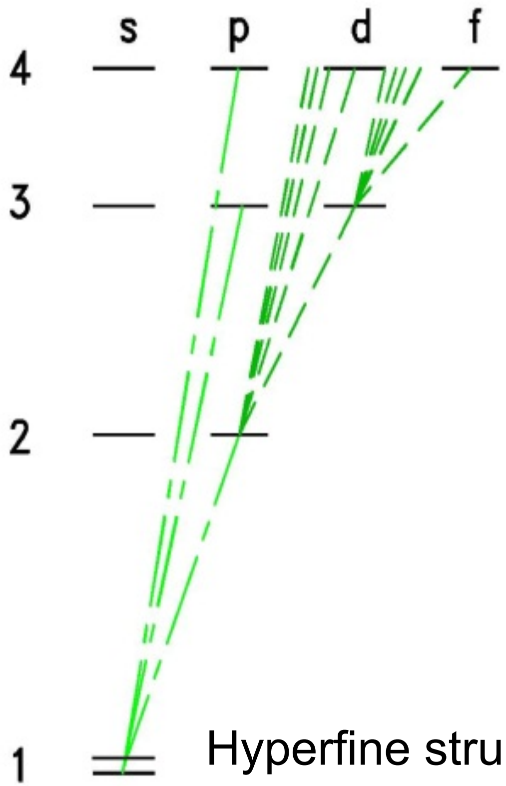
Simpler: transitions induced by collisions in μH!!



High spectroscopy of μH

⇩

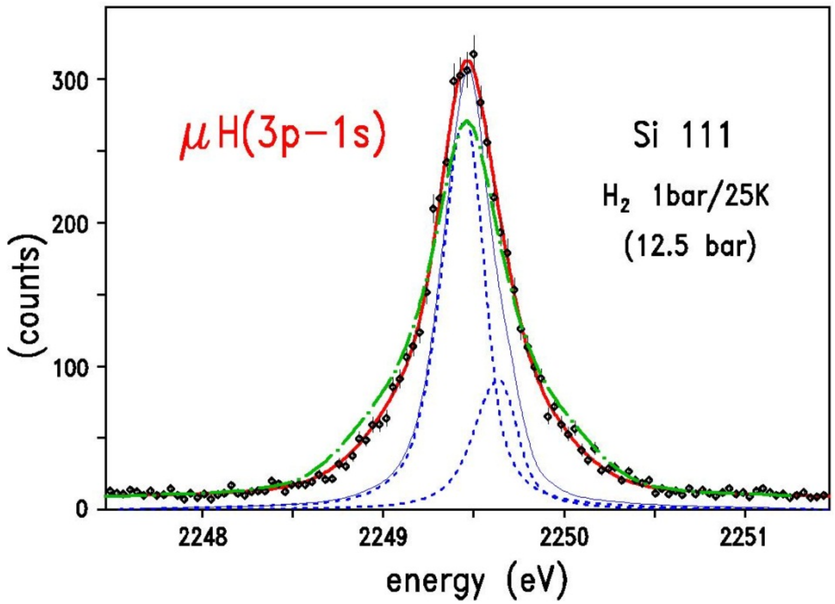
- Test of the cascade model



Hyperfine structure

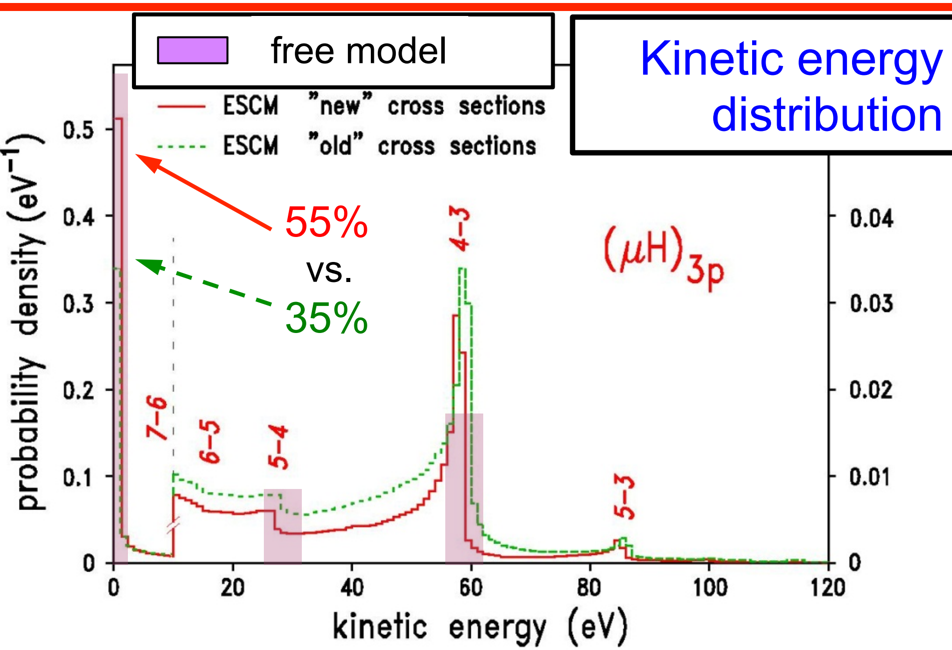
No strong interaction effects:
nuclear absorption and energy shift

Simpler: transitions induced by collisions in μH!!



High spectroscopy of μH

- Test of the cascade model
- Test of the cross sections
→ recalculation required
- First measurement of μH hyperfine (HF) splitting



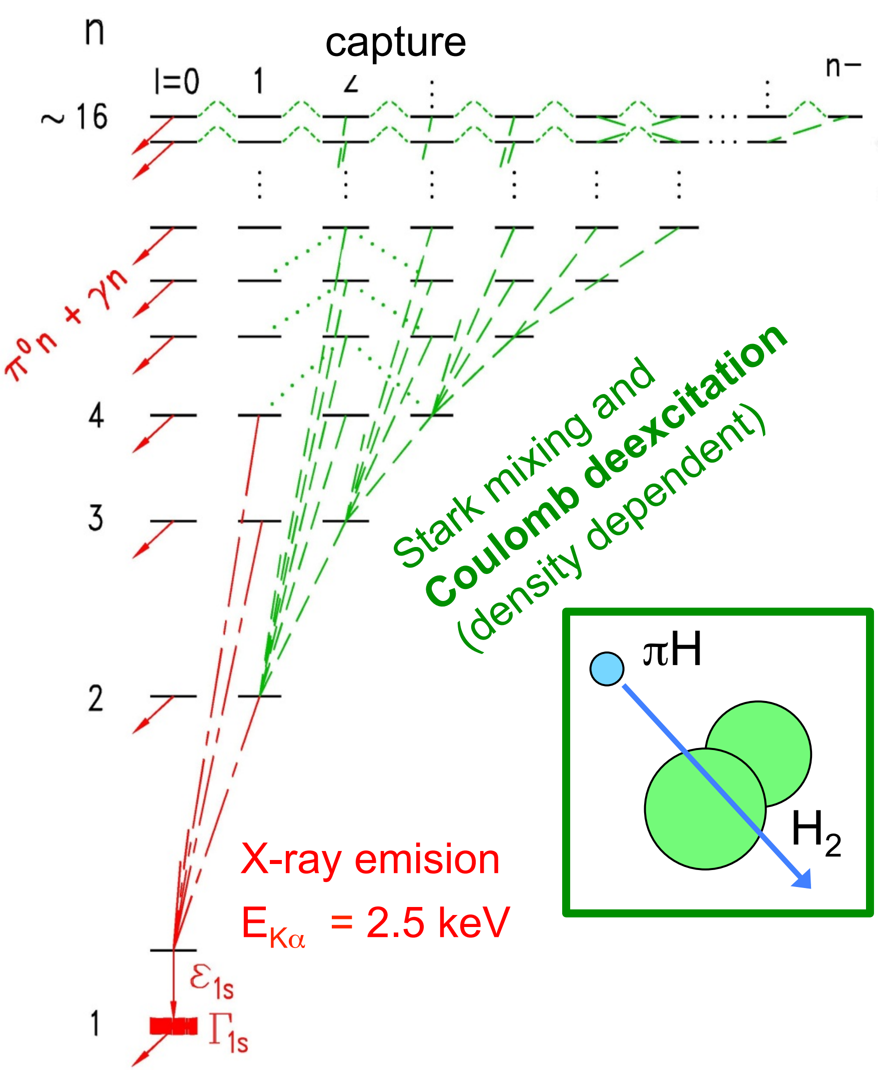
Good agreement with a free model with only 3 "kinetic population boxes"!!!

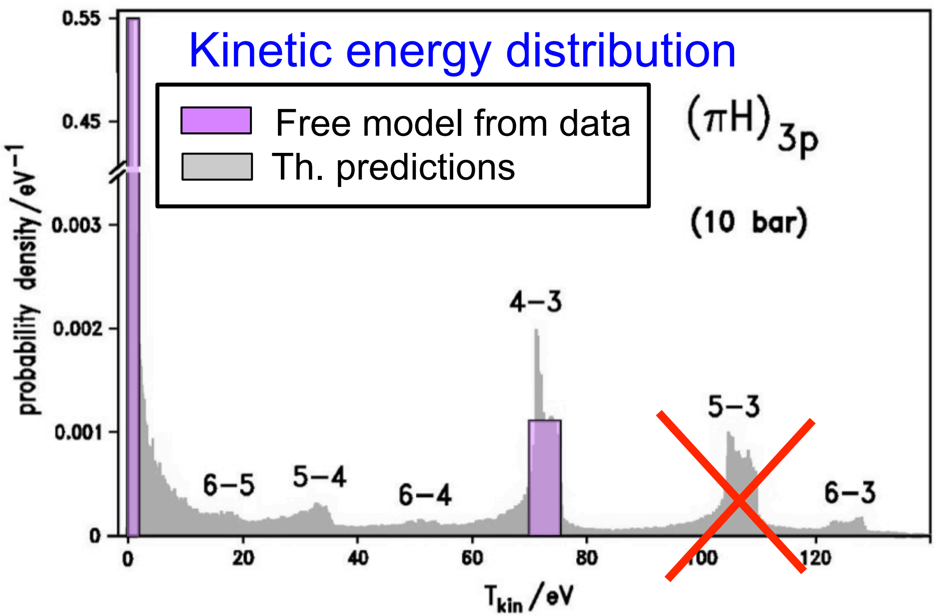
- HF splitting = 194 ± 12 meV
- Relative intensity ratio = 3.0 ± 0.3

(HF splitting fixed by theory = 182:725 ± 0.062 meV)

Covita et al., Phys. Rev. Lett. **102**, 023401-4 (2009).

Transitions induced by collisions in πH





Still inconsistency between empirical findings and theory

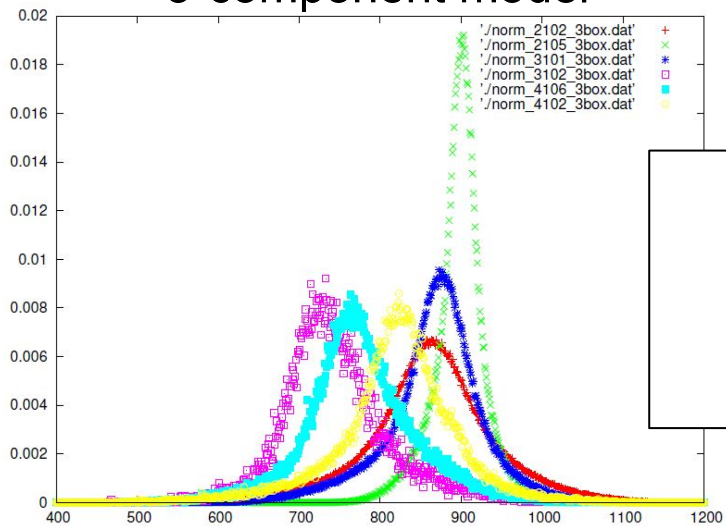
Pionic hydrogen hadronic width summary

Work in progress

$$\Gamma_{exp} = \Gamma_{crystal} \otimes \Gamma_{Doppler} \otimes \Gamma_{1s}$$

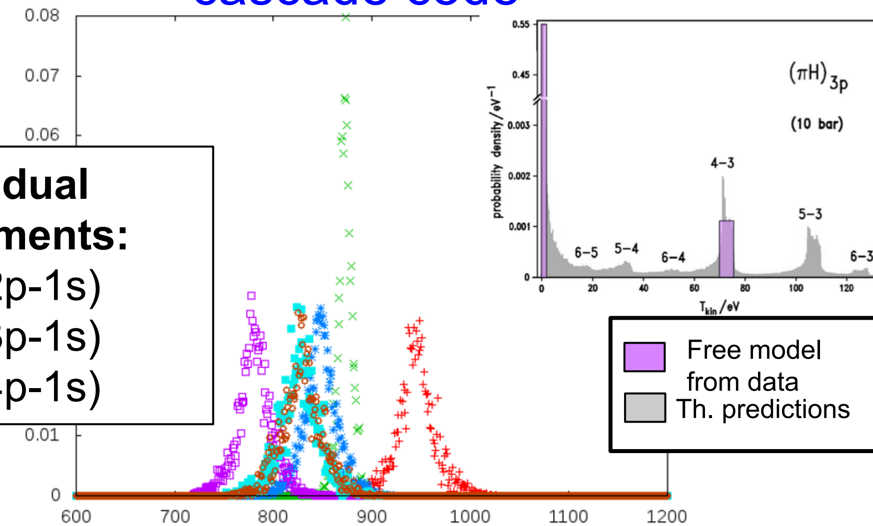
Phenomenological approach

3-component model



6 individual measurements:
2 x πH(2p-1s)
2 x πH(3p-1s)
2 x πH(4p-1s)

Kinetic energy distribution from cascade code



$\Gamma_{1s} = 0.85^{+0.04}_{-0.05}$ eV(± 4-5%) preliminary

Already 3-4 times better accuracy than Sigg et al. Phys. Rev. Lett. **75** 3245 (1995)

$\Delta\Gamma \rightarrow \Delta\Gamma/2$ with a good cascade understanding

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr.$$ ✔

$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr.$$ Ok…

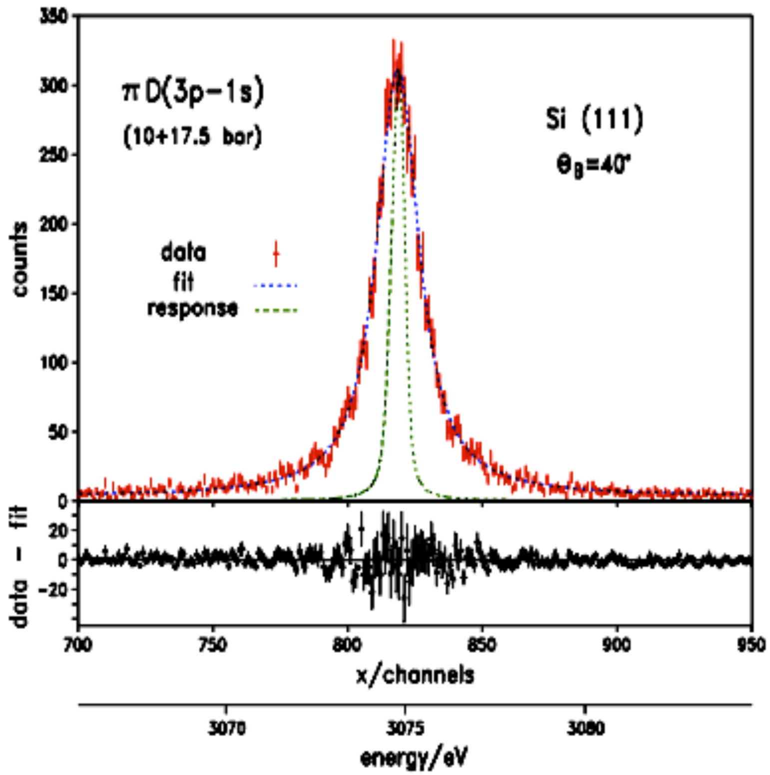
πD

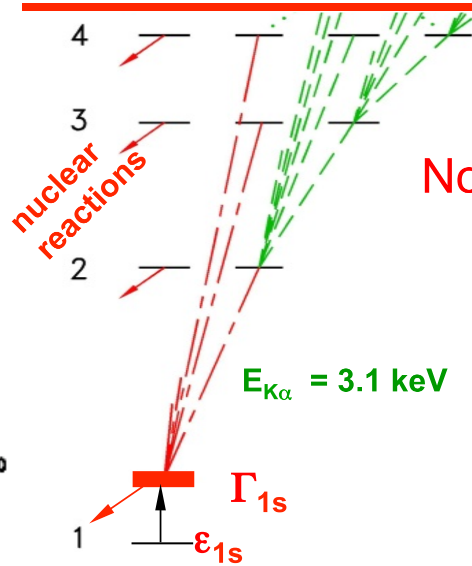
$$\epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr.$$

$$\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d})$$

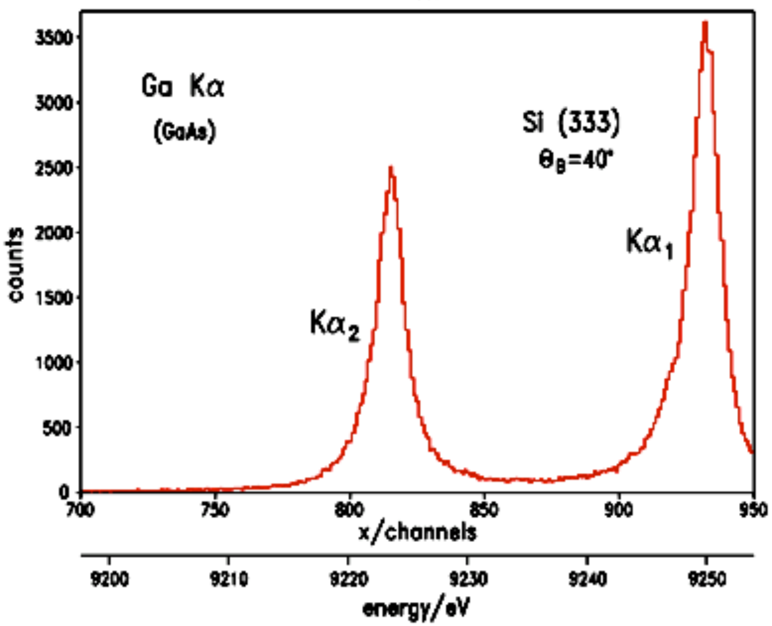
→ Basic pion-nucleon interaction properties

Pionic deuterium results: shift





No molecular formation observed



Uncertainty budget

± 27 meV Ga $K\alpha_2$
± 10 meV statistics
± 8 meV pion mass
± 5 meV systematics
± 2 meV QED

ε_{1s} = - 2.356 ± 0.031 (± 1.3%) (repulsive force)

3 times better accuracy than [2]

PhD thesis: Th. Strauch, Cologne 2009
[1] Th. Strauch et al., Phys.Rev.Lett.**104** 142503(2010);
Eur. Phys.J A **47** **88** (2011)
[2] Chatellard et al., Phys. Rev. Lett. **74**, 4157 (1995)

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr.$$ ✔

$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr.$$ Ok…

πD

$$\epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr.$$ ✔

$$\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d})$$

→ Basic pion-nucleon interaction properties

Strong interaction in simple bound systems

Shift and width related to the pion-nucleus scattering length and cross sections

πH

$$\epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr. \qquad \propto a^+ + a^- + f_{LEC}(c_1, f_1, f_2)$$

$$\Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr. \qquad \propto (a^-)^2 + g(c_1, f_2)$$

Low energy constants of the effective Chiral Perturbation Lagrangian

πD

$$\epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr. \quad \propto a^+ + h.o.(a^+, a^-) + h_{LEC}(c_1, f_1, f_2)$$

$$\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d})$$

Isospin cattering lengths $a^{\pm}$

πN isospin symmetry
(2 quark flavour only)

$$1 \otimes 1/2 \Rightarrow 1/2 \oplus 3/2$$

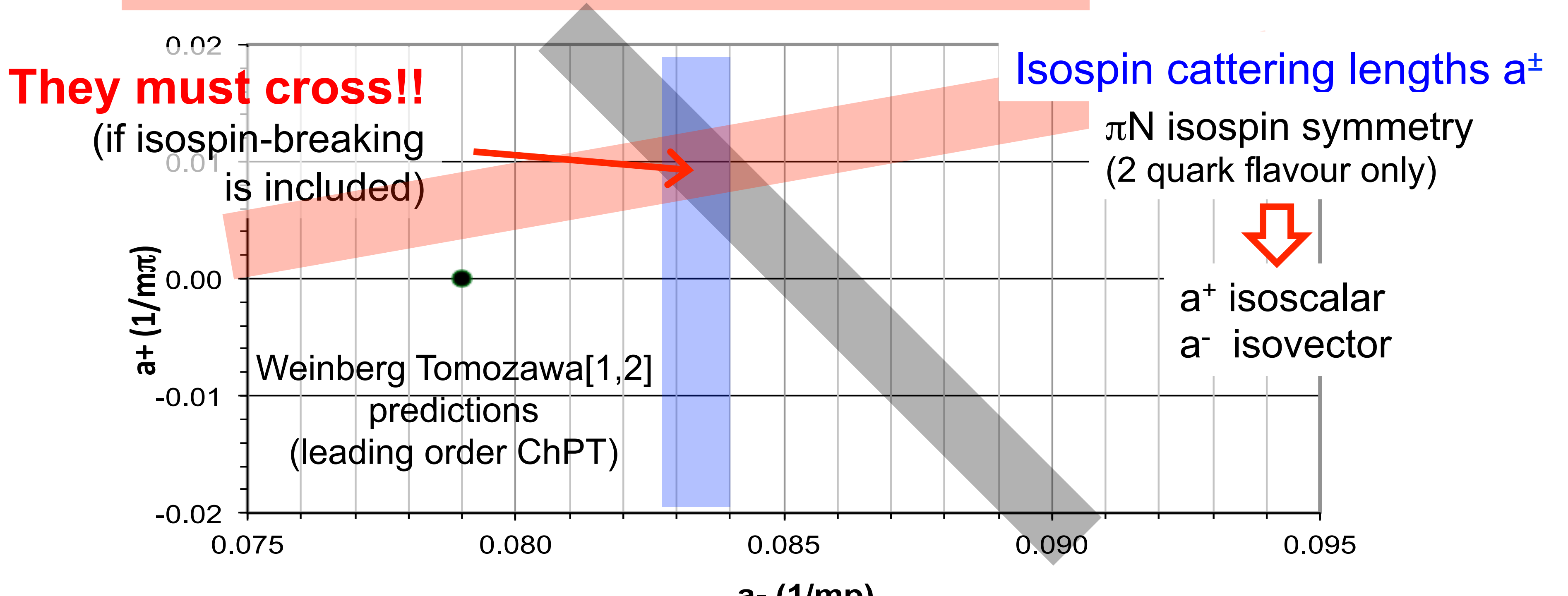
⇨ **a^+ isoscalar**
a^- isovector

πN scattering lengths results

πH
$$\epsilon_{1s}^{\pi H} \propto a^+ + a^- + f_{LEC}(c_1, f_1, f_2)$$
$$\Gamma_{1s}^{\pi H} \propto (a^-)^2 + g(c_1, f_2)$$

πD
$$\epsilon_{1s}^{\pi D} \propto a^+ + h.o.(a^+, a^-) + h_{LEC}(c_1, f_1, f_2)$$

Qualitatively comparison with the Chiral Pert. Theory predictions



[1] Weinberg, Phys. Rev. Lett. **17**, 616 (1966)
[2] Y. Tomozawa, Nuovo Cim. A **46** 707 (1966)

πN scattering lengths results

πH:

$$\epsilon_{1s}^{\pi H} \propto a^+ + a^- + f_{LEC}(c_1, f_1, f_2)$$

$$\Gamma_{1s}^{\pi H} \propto (a^-)^2 + g(c_1, f_2)$$

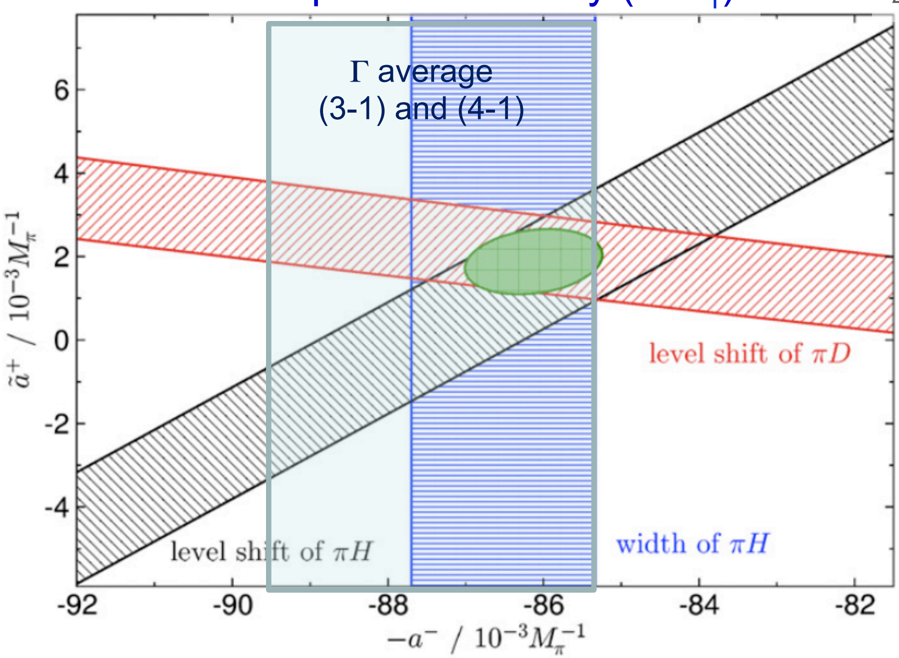
πD:

$$\epsilon_{1s}^{\pi D} \propto a^+ + h.o.(a^+, a^-) + h_{LEC}(c_1, f_1, f_2)$$

Quantitatively comparison with the Chiral Pert. Theory predictions

Δ exp ≈ 2 × Δ theory (no f_1)

Δ exp << Δ theory (with correction with f_1 involved)



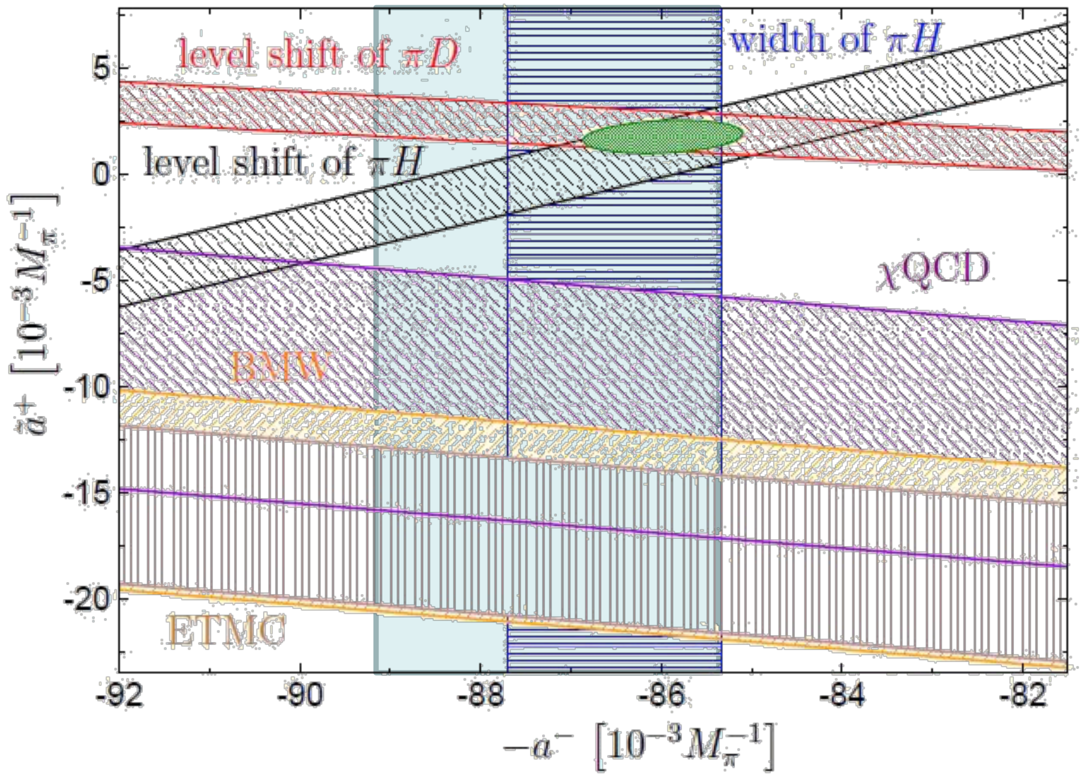
Δ exp << Δ theory (with correction with f_1 involved)

- consistency ✓
- $a^+ > 0$!!
- Constraints on f_1
- **πD decisive**

Fig. 2. Combined constraints in the $\tilde{a}^+$–a^- plane from data on the width and energ shift of πH, as well as the πD energy shift.

Baru et al., Phys. Lett. B **694**, 473-477 (2011).
Baru et al., Nucl. Phys. A **872**, 69-116 (2011).

Beyond chiral perturbation theory, lattice calculations and dark matter detection



← pionic atoms analysis

?

← Lattice predictions of the **sigma term**

M. Hoferichter, J. Ruiz de Elvira, B. Kubis, and U.-G. Meißner, Phys. Lett. B **760**, 74-78 (2016)

a^+ → **sigma term** $\sigma_{\pi N} = \frac{m_u + m_d}{4M} \langle p | \bar{u}u + \bar{d}d | p \rangle \leftrightarrow \langle p | \bar{s}s | p \rangle$ **contents** ➔ 59.1 ± 3.5 MeV

Crucial for the interpretation of dark-matter direct-detection experiments!!

J. Ellis, K.A. Olive, and C. Savage, Phys. Rev. D **77**, 065026 (2008)

a^- → pion–nucleus coupling constant via GMO sum rule

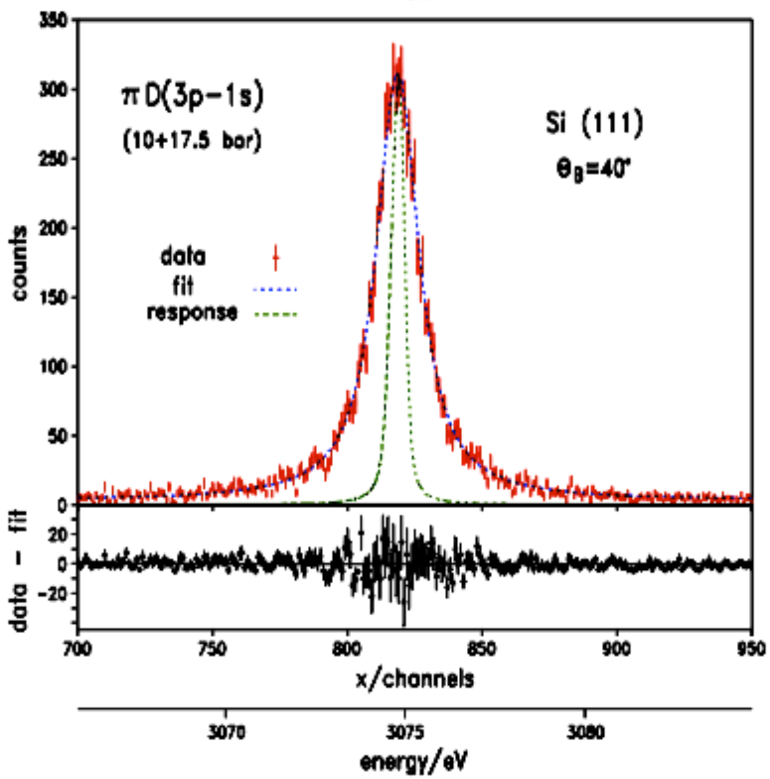
Pionic deuterium width

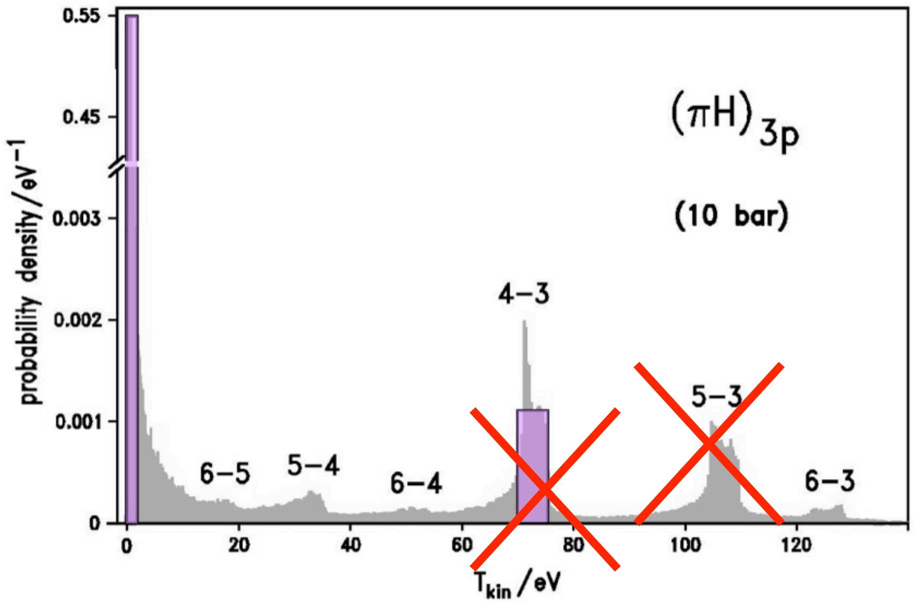
πH
$$\begin{cases} \epsilon_{1s}^{\pi H} \propto a_{\pi^- p \to \pi^- p} + corr. \\ \Gamma_{1s}^{\pi H} \propto (a_{\pi^- p \to \pi^0 n})^2 + corr. \end{cases}$$

πD
$$\begin{cases} \epsilon_{1s}^{\pi D} \propto a_{\pi^- p \to \pi^- p} + a_{\pi^- n \to \pi^- n} + corr. \\ \Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d}) \end{cases}$$

→ Pion production cross section from p–p collisions

Pionic deuterium results: width





$\Gamma_{1s} = 1171^{+23}_{-49}$ meV (2-4%) [1]

4 times better accuracy than [2]

no (small) high-energy components due to the isotopic effect [3]

PhD thesis: Th. Strauch, Cologne 2009
[1] Strauch et al., Phys.Rev.Lett.**104** 142503(2010); Eur. Phys.J A **47 88** (2011)
[2] Chatellard et al., Phys. Rev. Lett. **74**, 4157 (1995)
[3] Popov and V.N. Pomerantsev, Phys. Rev. A **95**, 022506 (2017)

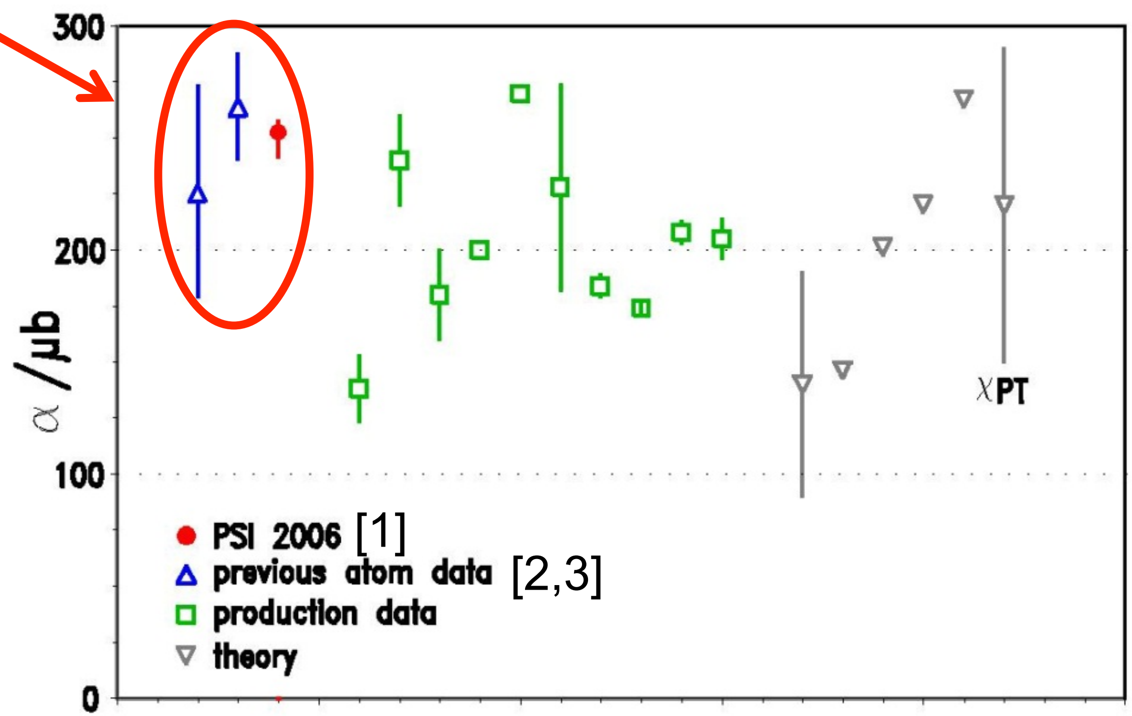
Pion production cross section

correction factor due to the Coulomb interaction contribution (large uncertainty)

πD $\Gamma_{1s}^{\pi D} \propto \Im m(a_{\pi d \to \pi d}) \propto \alpha$

$$\sigma_{pp\to\pi^+ d} = \alpha C_0^2 \frac{p_\pi}{m_\pi} + \beta C_1^2 \left(\frac{p_\pi}{m_\pi}\right)^3 + \dots$$

Pionic atoms results



ChPT Next to Leading Order

ChPT Leading Order

[1] Th. Strauch et al., Phys.Rev.Lett.**104** 142503 (2010) Eur. Phys.J A **47** 88 (2011) 88

[2] D. Chatellard et al. Phys. Rev. Lett. **74** 4157 (1995) Nucl. Phys. A 625 (1997) 855

[3] P. Hauser et al. Phys. Rev. C **58** R1869 (1998)

Summary

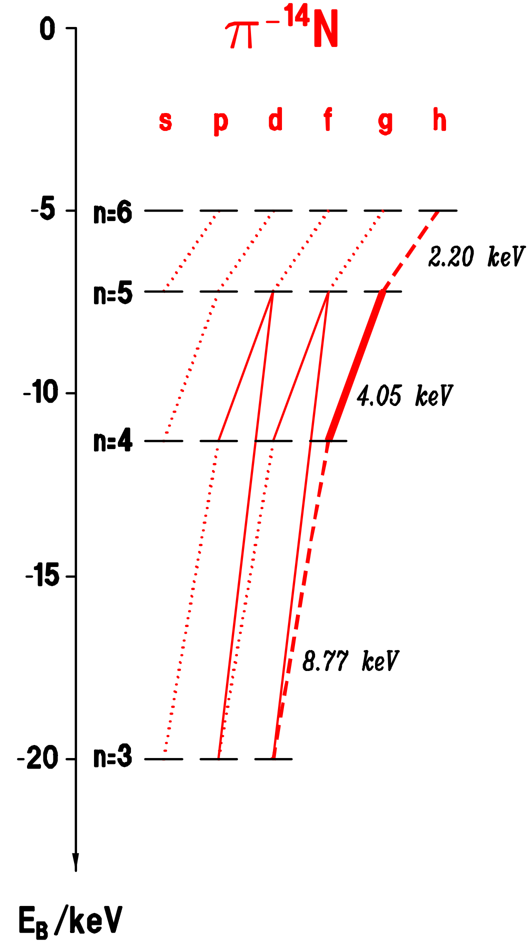
- Introduction
  - Test of QED in strong field
  - Study of strong interaction force at low energy
- Heavy highly charged ions
  - Production
  - Lamb shift measurement
  - Vacuum decay experiment
- Pionic atoms
  - Production
  - Pionic hydrogen and deuterium spectroscopy
  - **Pion mass measurement**
- Conclusions and outlooks

Pion mass measurement from πN and μO X-ray spectroscopy

Pion mass (unknown) or
muon mass (reference)

$$E_{\text{X-ray}} = mc^2 \frac{(Z\alpha)^2}{2}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) + \mathcal{O}(Z^4\alpha^4)$$

QED calculation only

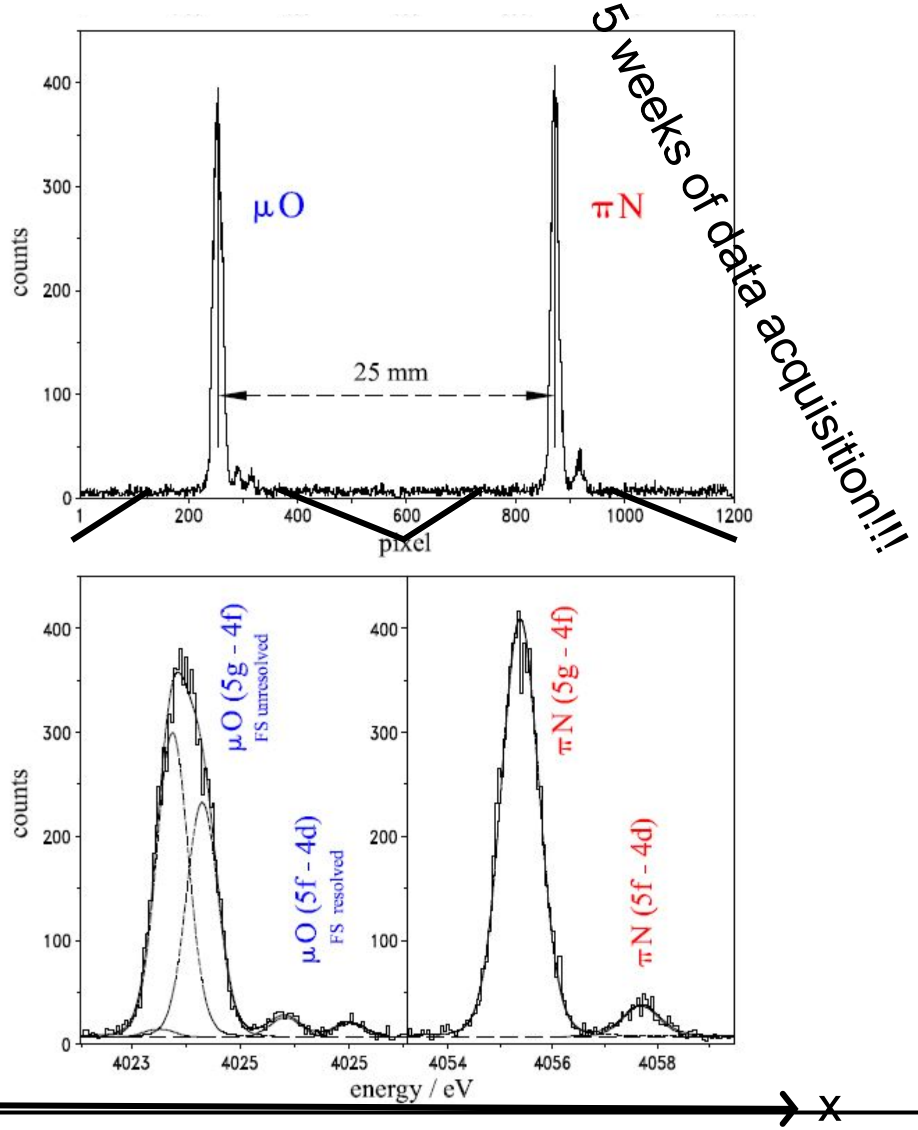


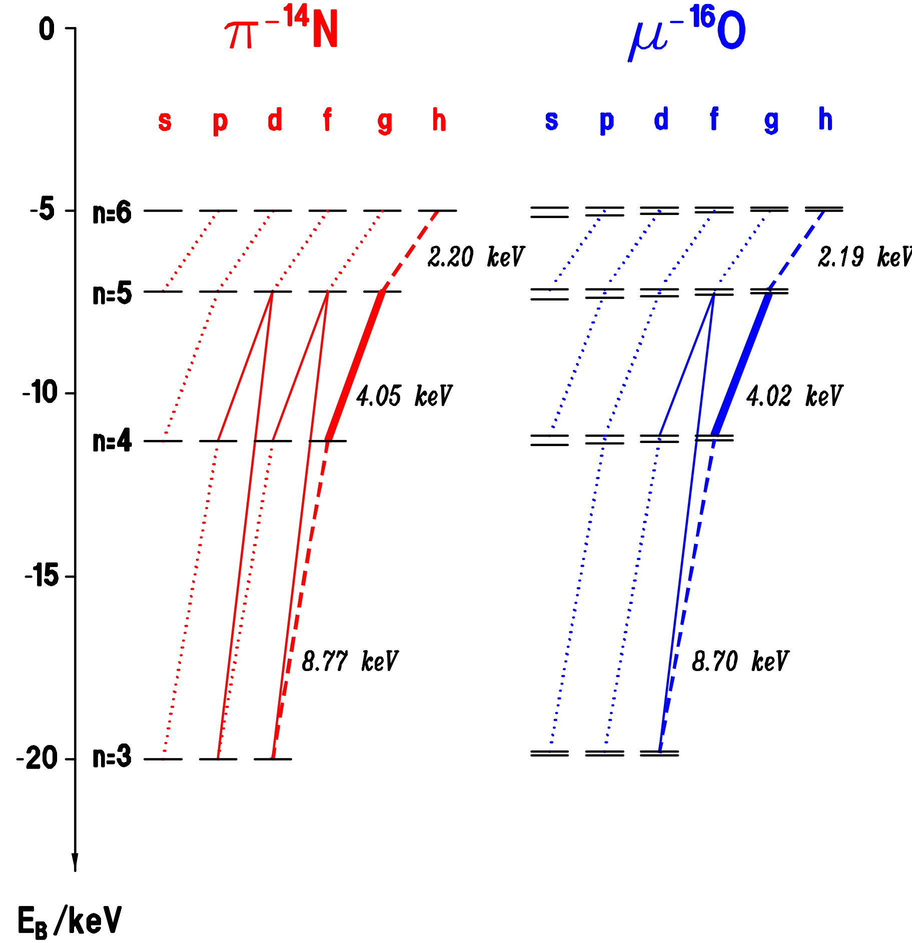
Circular transition enhanced

$$|n, \ell = n\rangle \rightarrow |n-1, \ell = n-1\rangle$$

Strong interaction effects minimized

5g-4f transitions in πN and μO





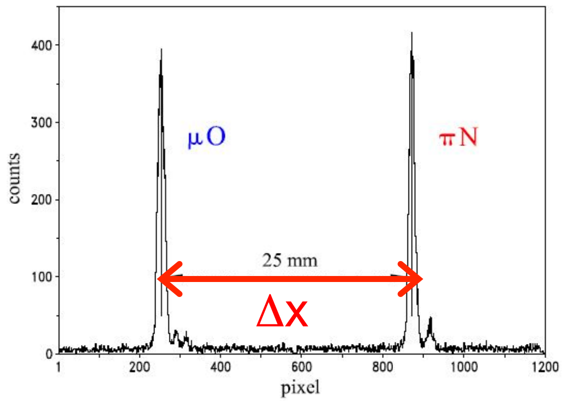
Muon = ½-spin particle

→ fine structure in μO

From the line position to the pion mass

From the spatial diff. to the angular position diff.

$$\Delta\Theta = -2\arctan\left(\frac{\Delta x}{2D}\right)$$



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

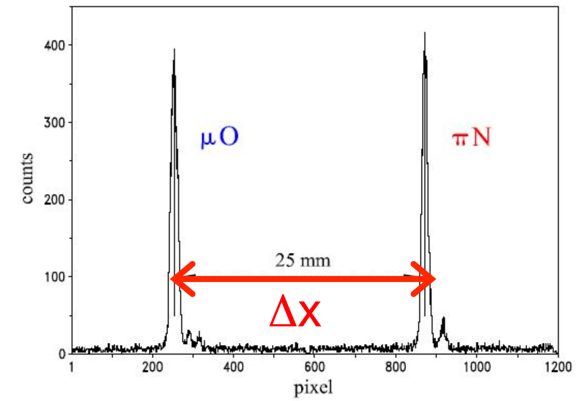
Bragg law

[1] M.T. and P. Indelicato, Phys. Rev. A **76**, 012510(2007)

From the line position to the pion mass

From the spatial diff. to the angular position diff.

$$\Delta\Theta = -2\arctan\left(\frac{\Delta x}{2D}\right)$$



From the angular position diff. to the transition energy

$$E_{\pi N} = E_{\mu O}\frac{1}{\cos\Delta\Theta - \frac{\sqrt{1-[hc/(2dE_{\mu O})]^2}}{hc/(2dE_{\mu O})}\sin\Delta\Theta}$$

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

Bragg law

where

$$E_{\mu O} = f_{\substack{\mathrm{QED}\\ \mathrm{Dirac}}}(m_\mu) = \tilde{m}_\mu c^2\frac{(Z\alpha)^2}{2}\left(\frac{1}{n_f^2}-\frac{1}{n_i^2}\right) + \mathcal{O}_{\substack{\mathrm{QED}\\ \mathrm{Dirac}}}(Z^4\alpha^4)$$

[1] M.T. and P. Indelicato, Phys. Rev. A **76**, 012510(2007)

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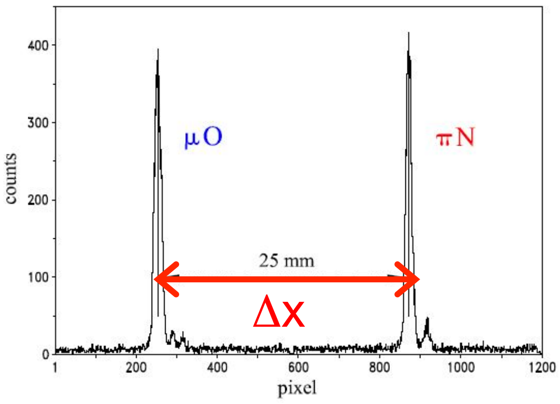

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From the transition energy to the **pion mass**

$$m_\pi = f^{-1}_{\substack{\text{QED}\\\text{Klein-Gordon}}}(E_{\pi N})$$

QED calculation (for πN) [1], ...

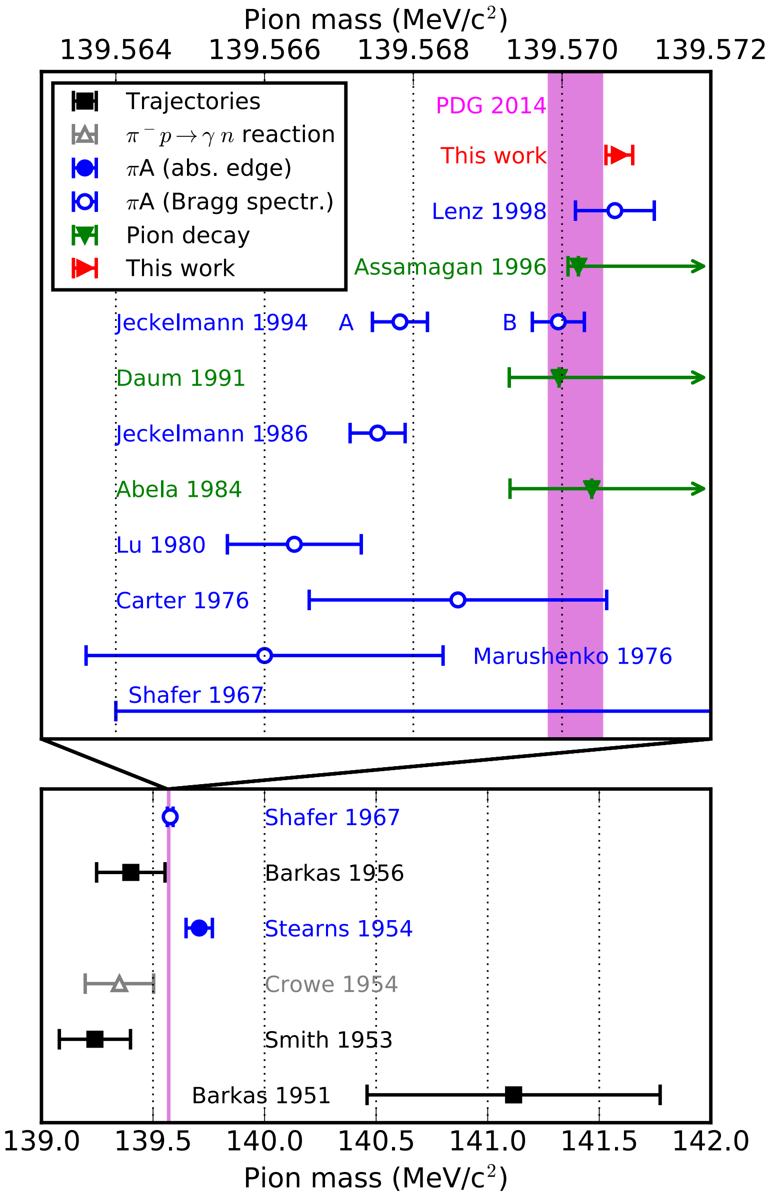
[1] M.T. and P. Indelicato, Phys. Rev. A **76**, 012510(2007)

List of systematic effects

type of uncertainty	μO / arcsec	πN / arcsec	total / arcsec	uncertainty / ppb
index of refraction shift	13.22	12.94	- 0.28	± 20
silicon lattice constant				± 2
bending correction	14.01	13.71	0.30	± 20
penetration depth correction	-0.07	-0.07	0	± 4
focal length				± 670
CCD alignment				± 340
pixel distance				± 120
alignment of detector normal				$^{+0}_{-30}$
detector height offset				$^{+0}_{-35}$
shape of target window				± 100
shape of reflection				± 225
individual curvature correction				± 150
temperature correction				± 30
response function and Doppler broadening				$^{+290}_{-350}$
line pattern modelling				$^{+190}_{-290}$
fit interval				± 15
QED energy				± 350
conversion constant *hc*				± 2
$4f$ strong interaction 45 μeV		0.003	-0.003	± 10
$5g$ strong interaction 0.2 μeV		0.000	0.000	± 0
K electron screening				± 0
total systematic error				$^{+950}_{-1000}$
statistical error				± 820

Total uncertainty: 1.3×10^{-6}
Statistical: 0.8×10^{-6}
Systematics: $\sim 1 \times 10^{-6}$

The new measurement of the pion mass



Particle data group [1]:
139.57018 ± 0.00035 MeV/c^2
→ **2.5x10^{-6}** accuracy

Our work [2]:
139.57077 ± 0.00018 MeV/c^2
→ **1.3x10^{-6}** accuracy

- No effect of eventual remaining K-shell electrons (<10^{-9})
- High accuracy calibration line (0.25x10^{-6} from theory calc.)

⇨ **Improved accuracy for X-ray standards from pionic atoms [3]**

[1] Particle Data Group. Chinese Phys. C **38**, 090001 (2014)
[2] M.T. *et al.*, Phys. Lett. B **759**, 583-588 (2016)
[3] D.F. Anagnostopoulos *et al*, Phys. Rev. Lett. **91**, 240801 (2003)

Summary

- Introduction
  - Test of QED in strong field
  - Study of strong interaction force at low energy
- Heavy highly charged ions
  - Production
  - Lamb shift measurement
  - Vacuum decay experiment
- Pionic atoms
  - Production
  - Pionic hydrogen and deuterium spectroscopy
  - Pion mass measurement
- **Conclusions and outlooks**

Conclusions and perspectives for pionic atoms

- End of a long measurement campaign
- New input for investigation on strong interaction at low energy
- Deeper understanding (but not yet complete) of the atomic cascade and cross sections in exotic atomic systems
- New measurement of the pion mass

Next…

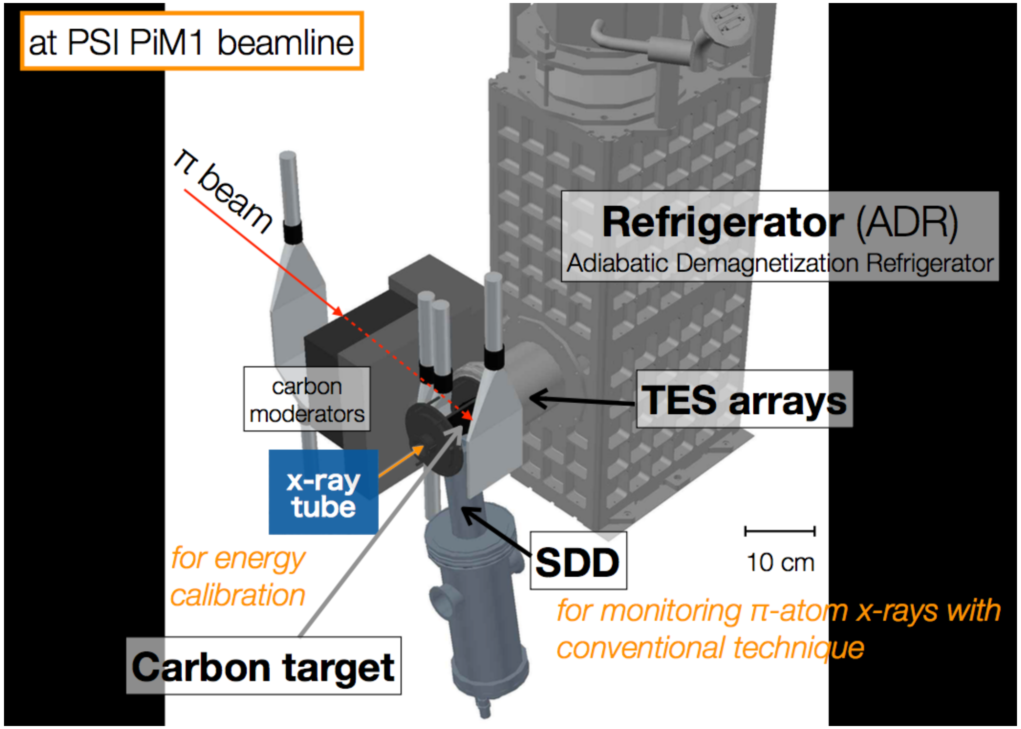
- Atomic cascade and cross sections calculations has to be improved
- New high-resolution experiments with πT and πHe? → Additional constraints on a^+ a^-
- …
- Resolution improvement?
  - Crystal spectrometer: 0.5 → 0.2 eV?
  - Microcalorimeter [1]? Lower resolution but higher efficiency
- New measurement of the pion mass: laser spectroscopy of πHe^+

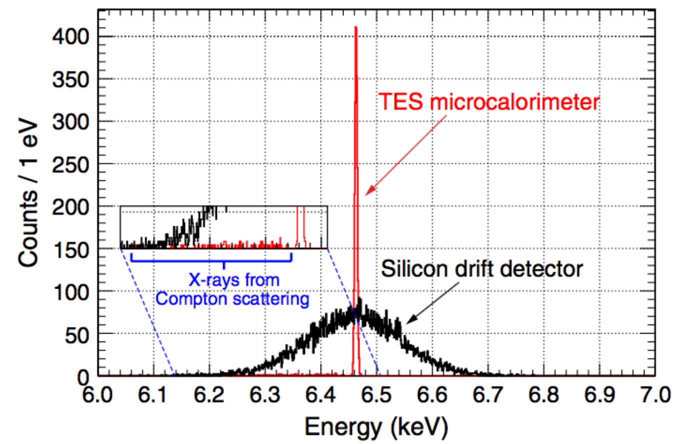
Proposed experiment at PSI from Hori and co. [2]

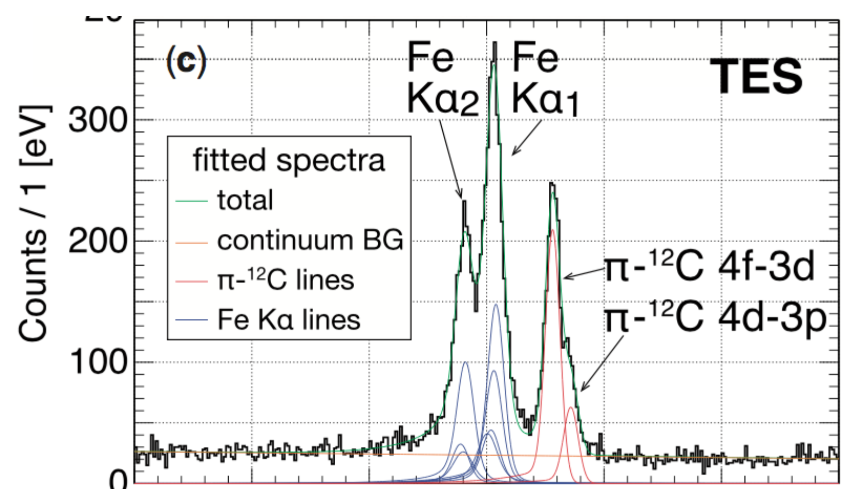
[1] S. Okada *et al.*, Prog. Th.Exp. Phys. **2016**, (2016)

[2] M. Hori *et al.*, Phys. Rev. A **89**, 042515 (2014)

Microcalorimeter measurement of πA and KA

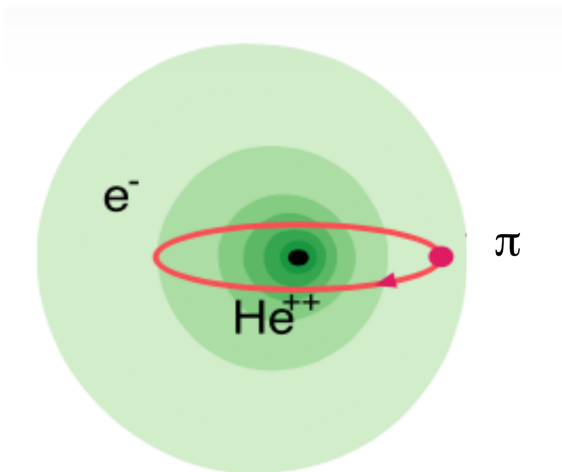


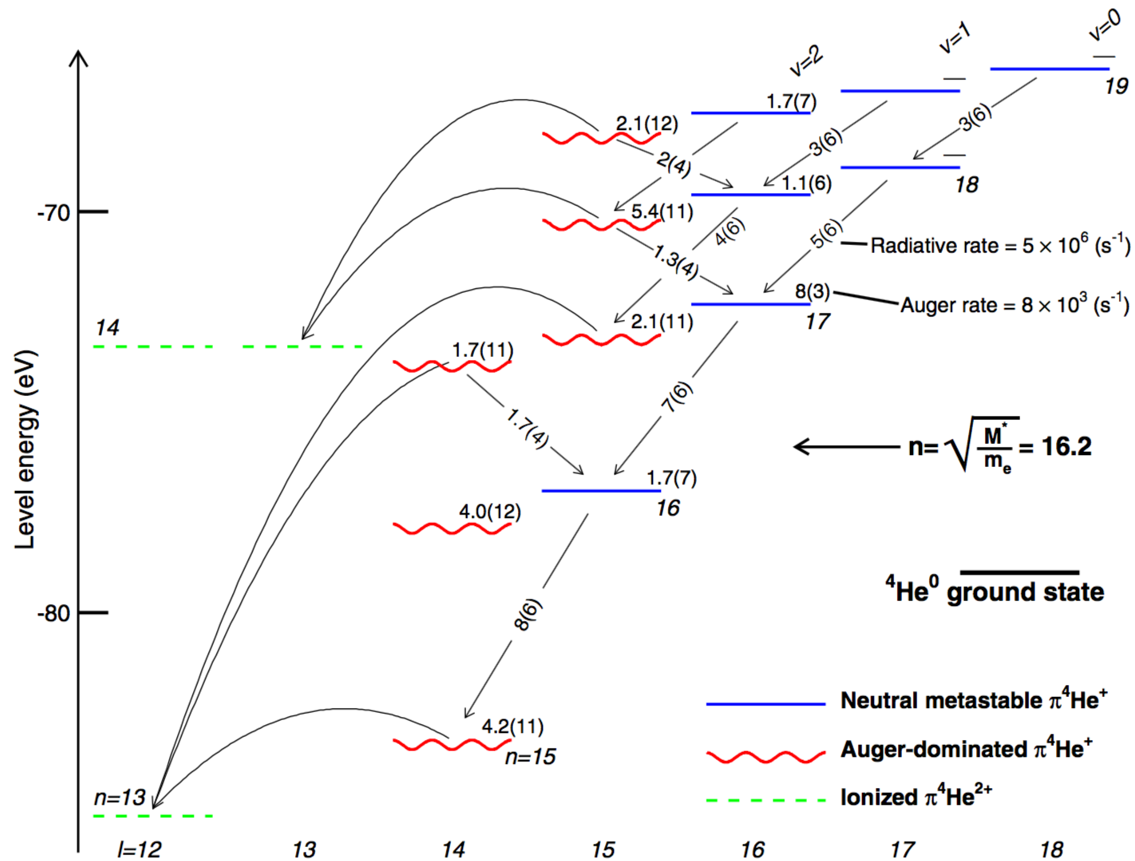




S. Okada, D.A. Bennett, C. Curceanu *et al.*, Progress of Theoretical and Experimental Physics **2016**, (2016)
S. Okada, D.A. Bennett, W.B. Doriese *et al.*, J. Low Temp. Phys. **176**, 1015-1021 (2014)

Pion mass measurement by laser spectroscopy of πHe^+





Goal accuracy: better than 1ppm

M. Hori *et al.*, Hyperfine Interact. **233**, 83-87 (2015).
M. Hori *et al.*, Phys. Rev. A **89**, 042515 (2014).

Conclusions and perspectives for heavy highly charged ion

- New QED tests in the strong Coulomb field (non perturbative regime)
- New phenomenon expected (spontaneous emission of positrons from the vacuum decay)
- Two-loop QED not yet tested in hydrogenlike systems

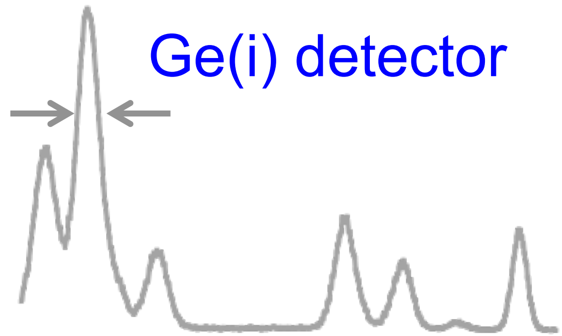
Next…

- Many new experiments already in preparation for the future
- New experimental methods in development
- New FAIR facility in construction and commissioning

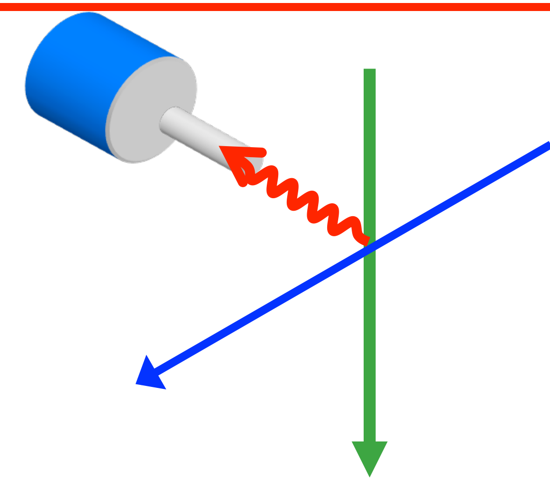
Towards an accuracy of 1 eV of the 1s level Lamb shift

Resolution:
400 eV at 60 keV

$\varepsilon = 10^{-4}$



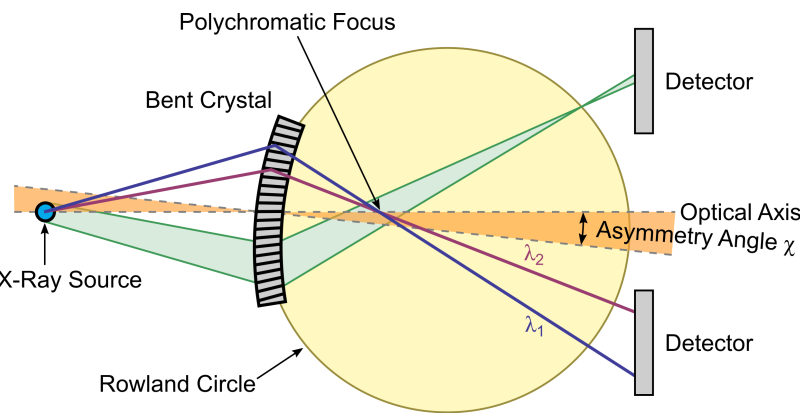
Ge(i) detector



U^{91+} Lamb shift δE =4.6 eV

Crystal spectroscopy

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



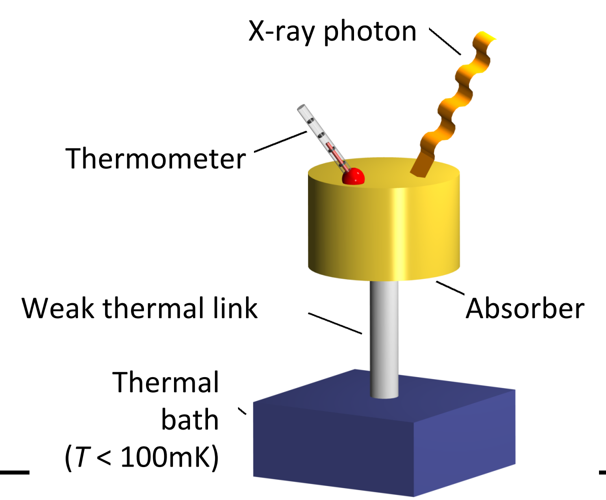
FOCAL spectrometer
T. Gassner, M.T. et al submitted to PRL

Microcalorimeters

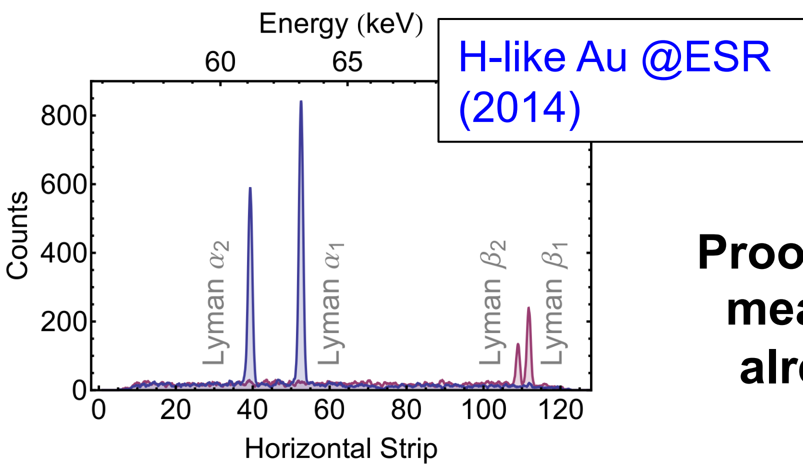
Res: ~**50 eV** at 60 keV **$\varepsilon = 10^{-4-6}$**

Resistive and magnetic microcalorimeters

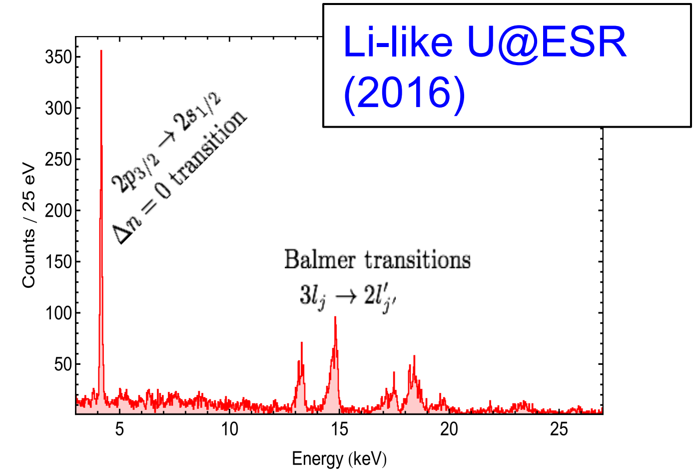
S. Kraft-Bermuth *et al.*, J. Phys. B **50**, 055603 (2017)
C. Pies *et al.*, J. Low Temp. Phys. **167**, 269-279 (2012)



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



Proof of principle measurements already done!

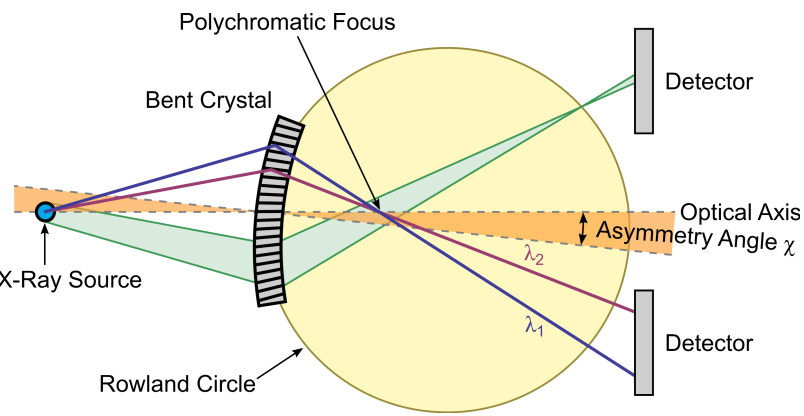


Crystal spectroscopy

Res: ~50 eV at 60 keV **ε = 10^{-8}**

Microcalorimeters

Res: ~50 eV at 60 keV **ε = 10^{-4-6}**



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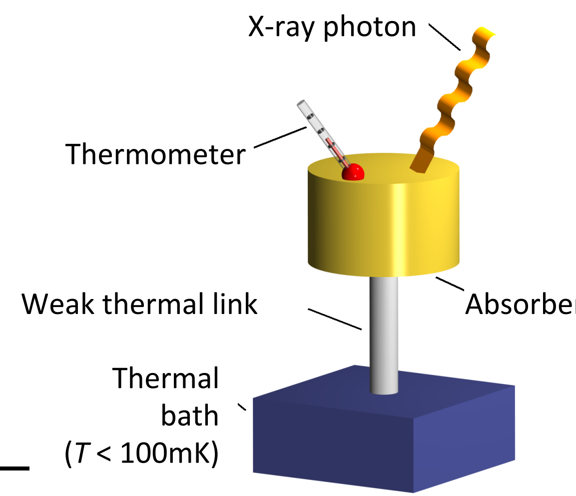
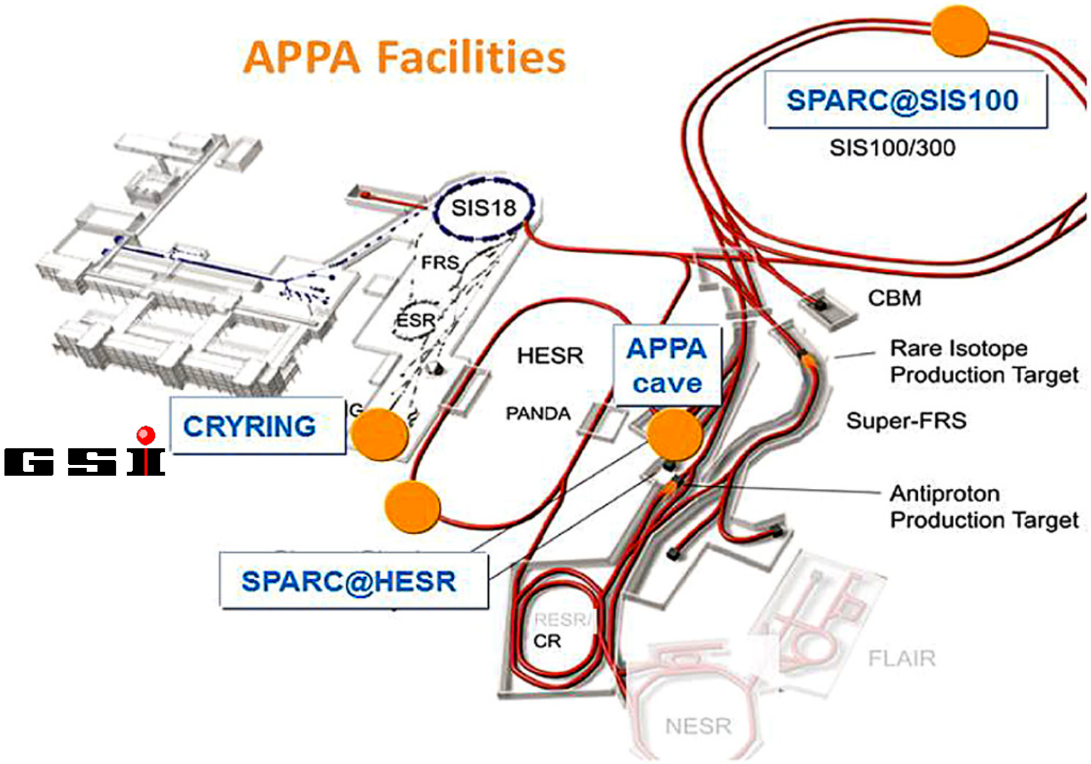
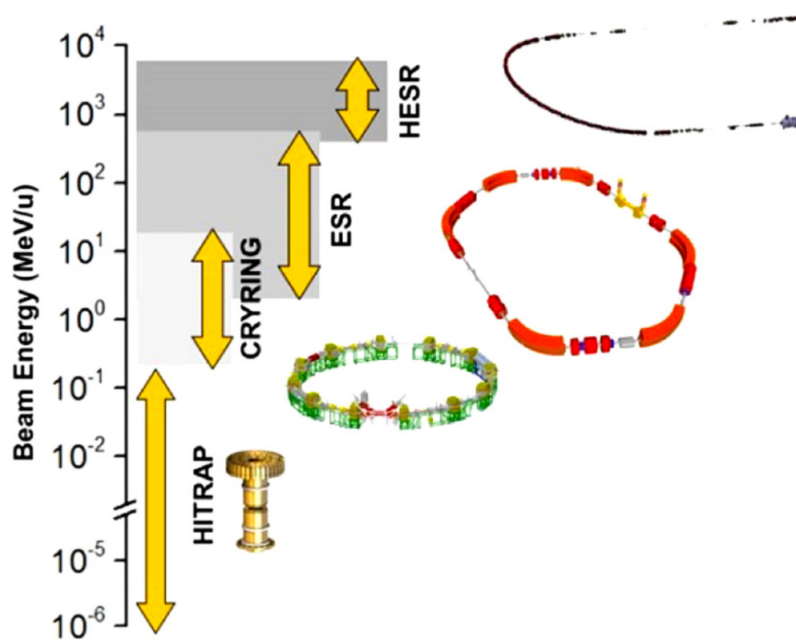


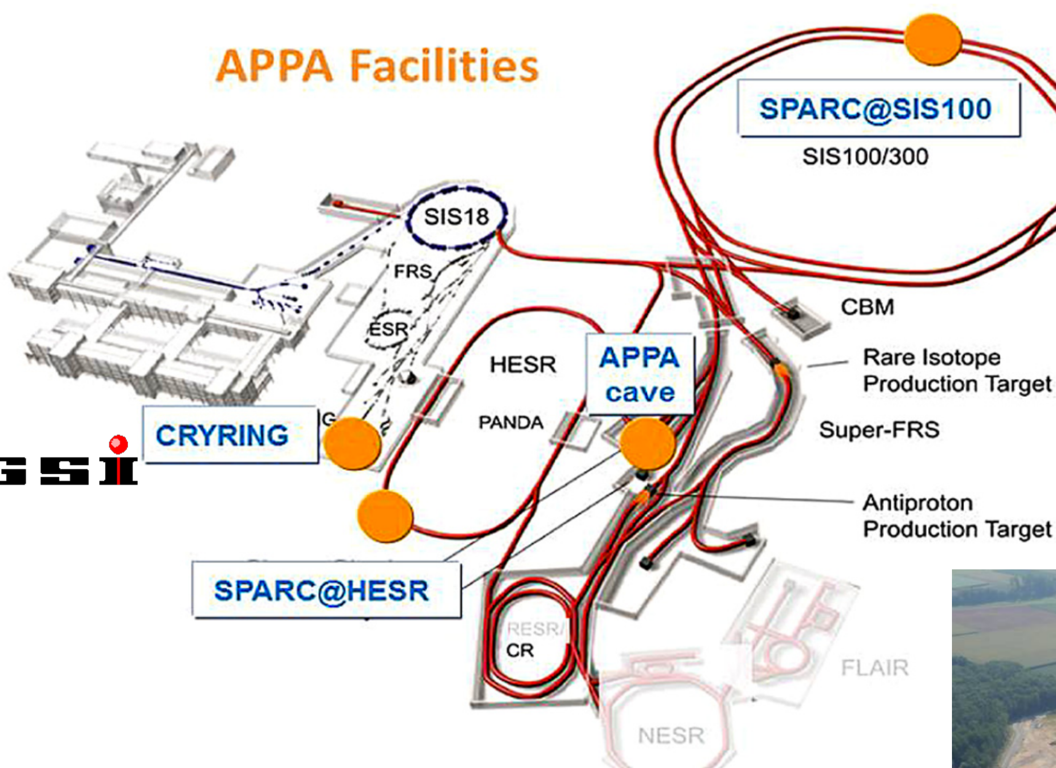
FAIR facility





Availability of highly charged ions
up to bare U with energies between
10 GeV/u to rest

FAIR facility



FAIR

Phase-0: 2018-2019
Phase-1: 2024

Availability of highly charged ions
up to bare U with energies between
10 GeV/u to rest

Thank you!

D. Banas, H.F. Beyer, K.H. Blumenhagen, F. Bosch, C. Brandau, A. Bräuning-Demian, H. Bräuning, W. Chen, Chr. Dimopoulou, E. Förster, T. Gaßner, S. Geyer, A. Gumberidze, S. Hagmann, S. Heß, R. Heß, P.-M. Hillenbrand, P. Indelicato, P. Jagodzinski, T. Kampfer, Chr. Kozhuharov, M. Lestinsky, D. Liesen, Yu.A. Litvinov, R. Loetzsch, B. Manil, R. Märtin, F. Nolden, N. Petridis, M.S. Sanjari, K.S. Schulze, M. Schwemlein, A. Simionovici, U. Spillmann, M. Steck, Th. Stöhlker, C.I. Szabo, S. Trotsenko, I. Uschmann, G. Weber, O. Wehrhan, N. Winckler, D. Winters, N. Winters, E. Ziegler

F. D. Amaro, D. F. Anagnostopoulos, A. Blechmann, S. Biri, P. Bühler, D. S. Covita, J. M. F. dos Santos, H. Fuhrmann, H. Gorke, D.Gotta, A. Gruber, M. Hennebach, A. Hirtl, T. Ishiwatari, Th. Jensen, E.-O. Le Bigot, V. E. Markushin, J. Marton, M. Nekipelov, V. Pomerantsev, V. Popov, S. Schlesser, A. Schmelzbach, Ph. Schmid, L. M. Simons, Th. Strauch, M. Theisen, J. F. C. A. Veloso, J. Zmeskal

S. Cervera, V. Gafton, T. Kirchner, E.V. Gafton, D. Hannani, S. Hidki, E. Lacaze, E. Lamour, A. Lévy, S. Macé, M. Maranglolo, J. Mérot, F. Mezdari, J.-Y. Pacquet, C. Prigent, J.-M. Ramillon, J.-P. Rozet, A. Salehzadeh, S. Steydli, D. Vernhet