Electron-Ion Collisions in Heavy-Ion Storage-Rings

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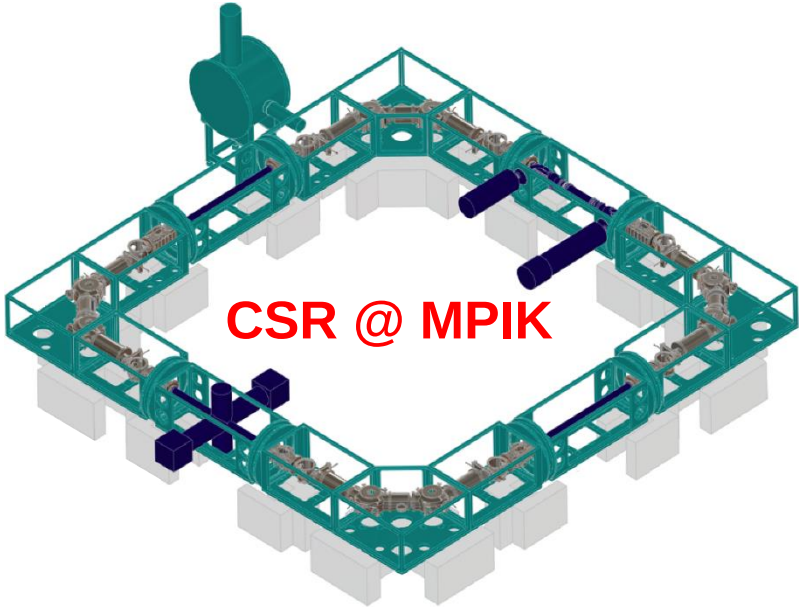
Overview

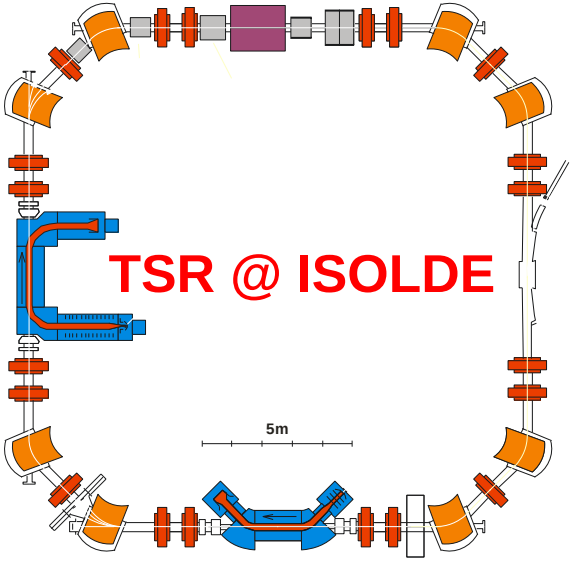
- **Electron-ion collisions at storage rings**

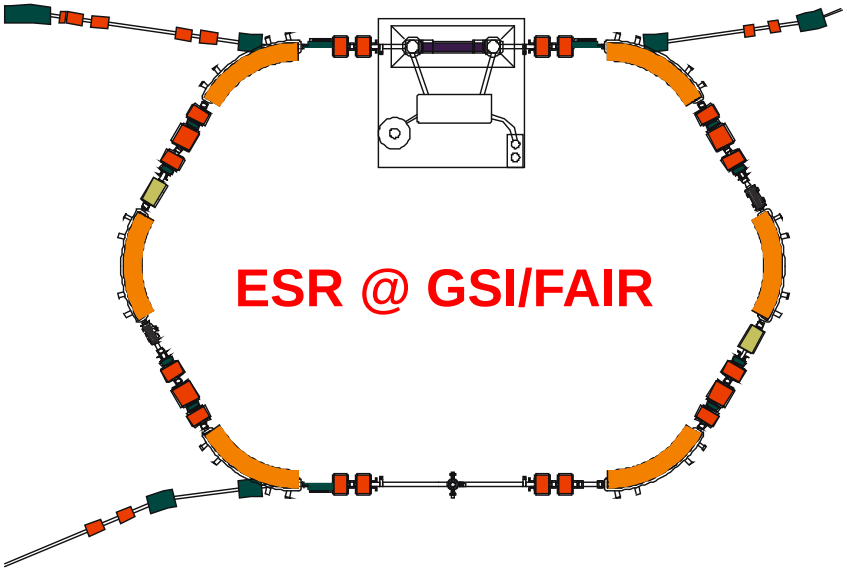
- **Atomic structure**
  - Electron-ion collision spectroscopy
  - Nuclear and QED effects on atomic structure
  - Lifetimes of atomic levels (exotic decay modes)

- **Atomic collisions**
  - Absolute cross sections (important for applications in astrophysics and plasma physics)
  - Electron-ion recombination
  - Electron-impact ionization of ions

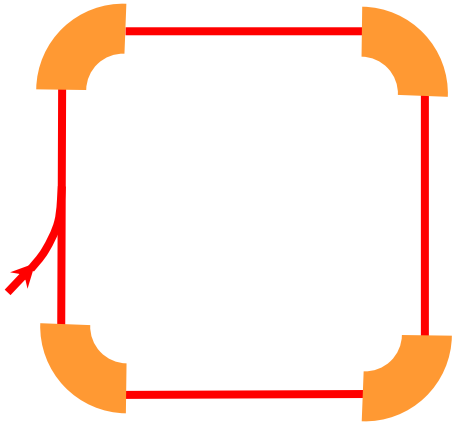
Ion-Storage Rings



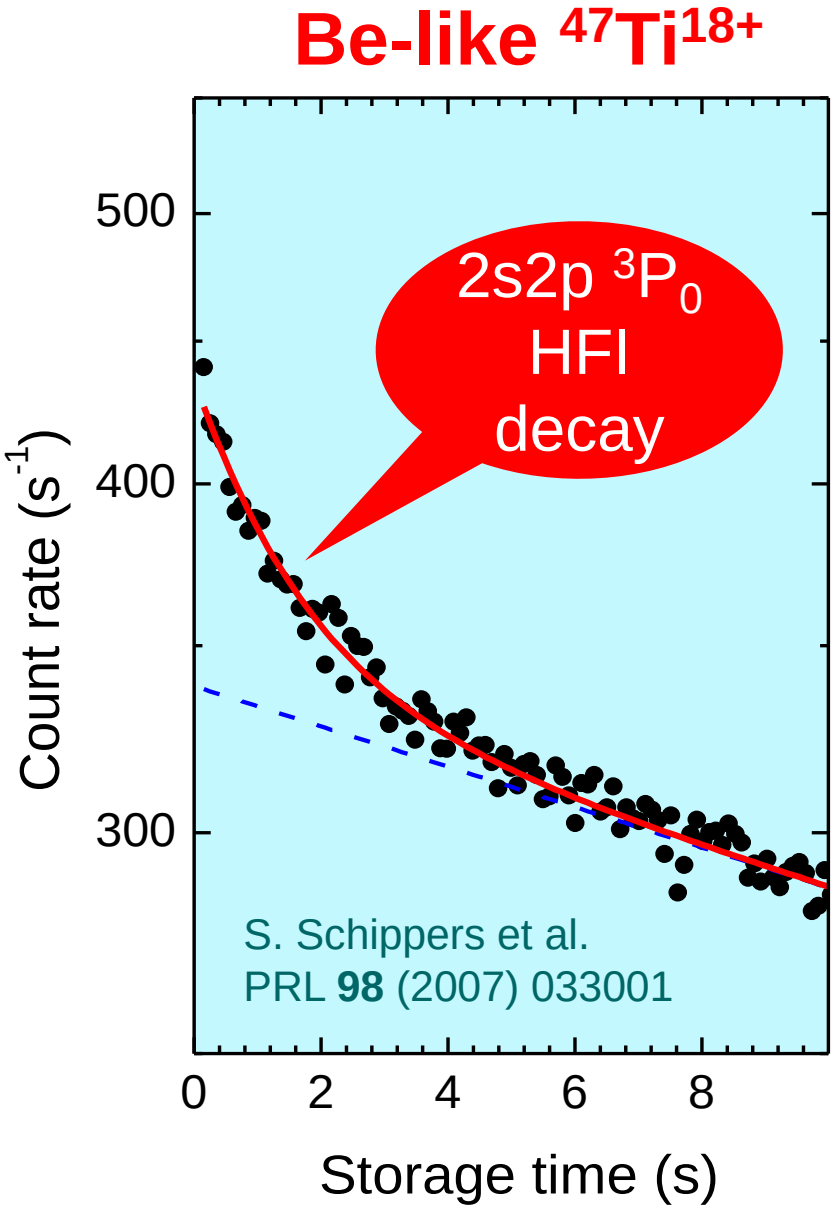




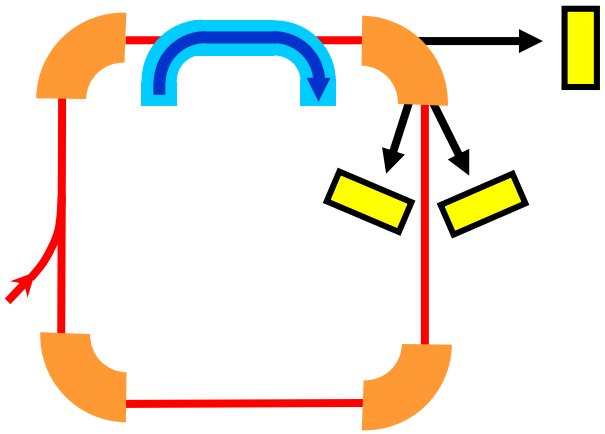
Decay of Excited States



Simply wait until metastable ions have relaxed to their ground state.



Reactions



Reaction products

- beams of high directionality
- high particle energies in lab frame

100% detection efficiency

collision experiments with dilute ensembles of particles

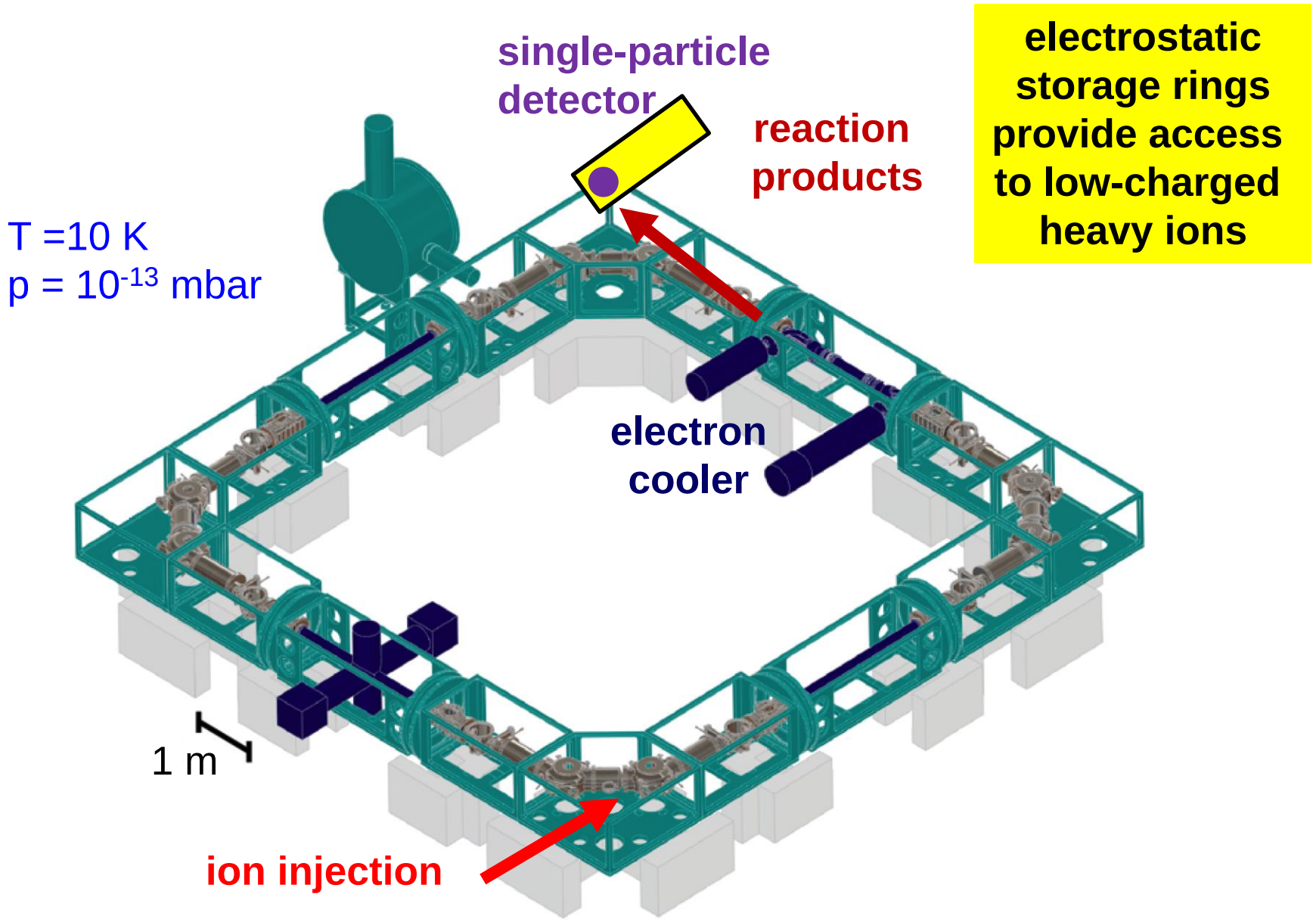
tunable relative energy: sub **meV** to sub **MeV**

cross sections on an absolute scale

electron-ion recombination

electron-impact ionization of ions

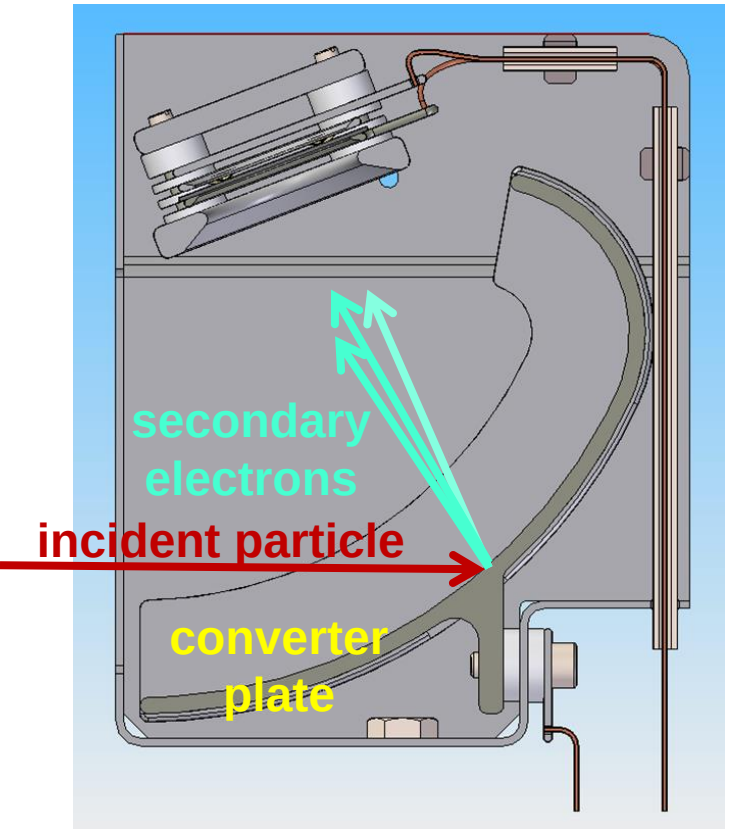
Recombination of Ions in the CSR



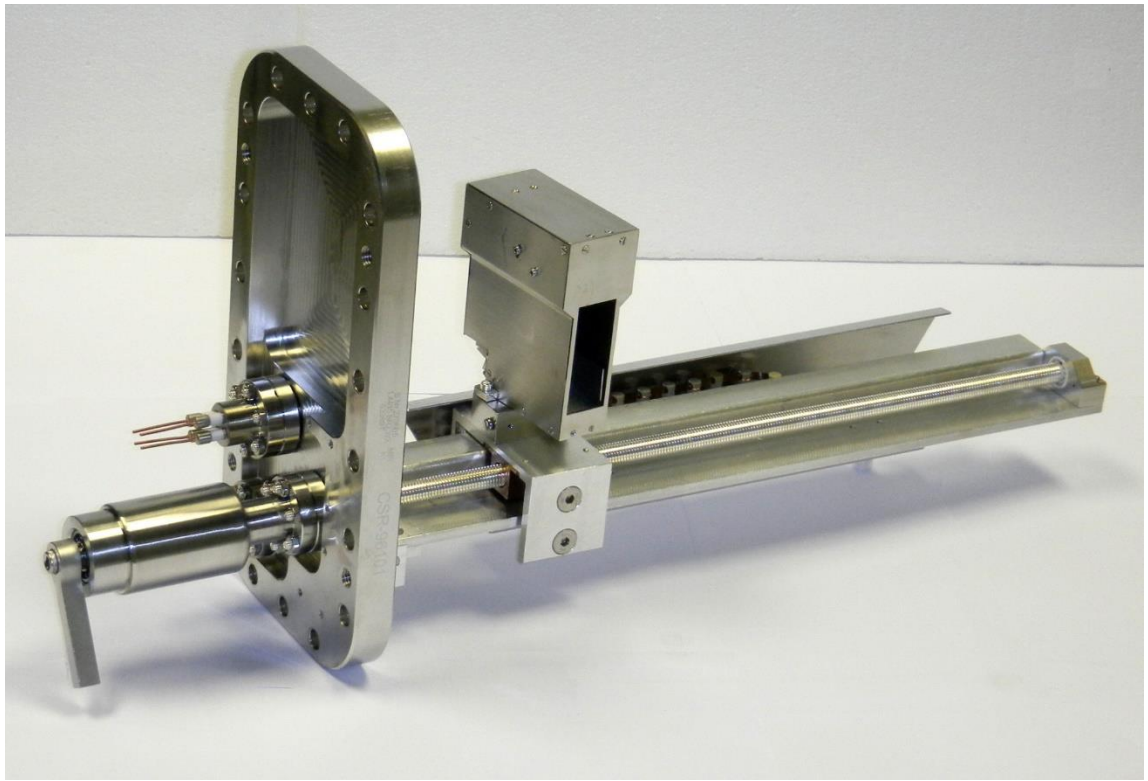
electrostatic storage rings provide access to low-charged heavy ions

Single-Particle Detector

~100% detection efficiency



adapted to cryogenic environment



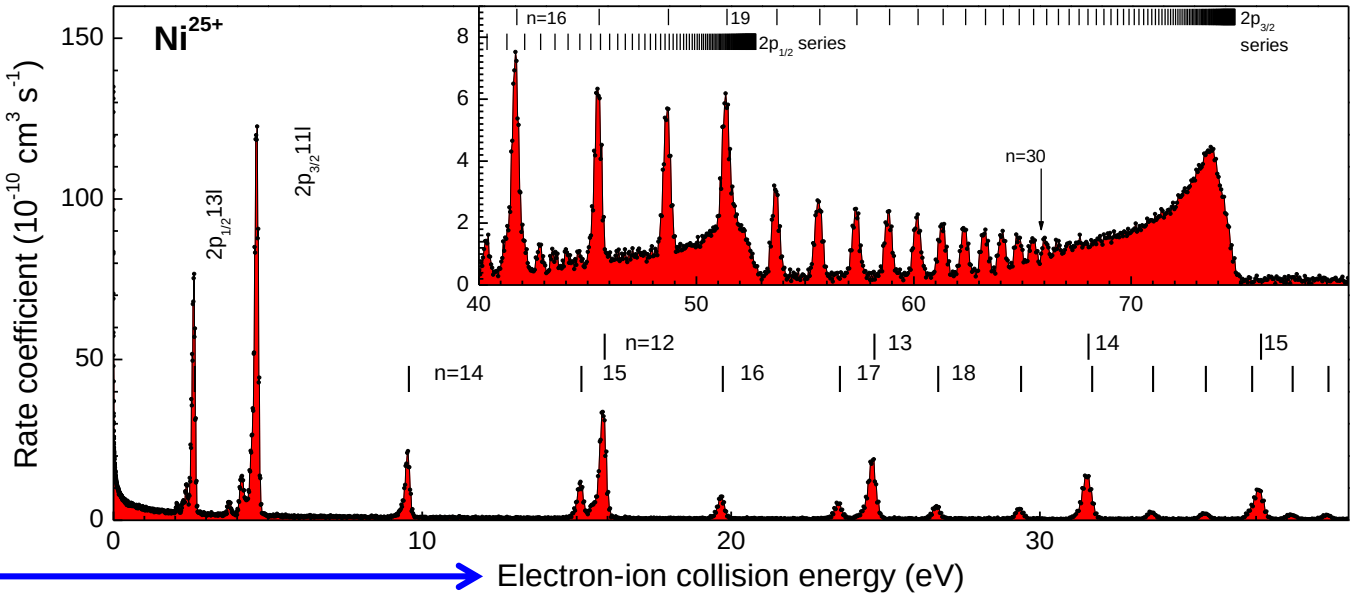
Kaija Spruck, Claude Krantz et al.

Dielectronic Recombination (DR)

recombination of a q-fold charged ion with a free electron
(time-inverse of photoionization)

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

intermediate resonance state



S. Schippers et al., PRA **62** (2000) 022708

Strong Astrophysical Relevance

absolute rate coeffcients

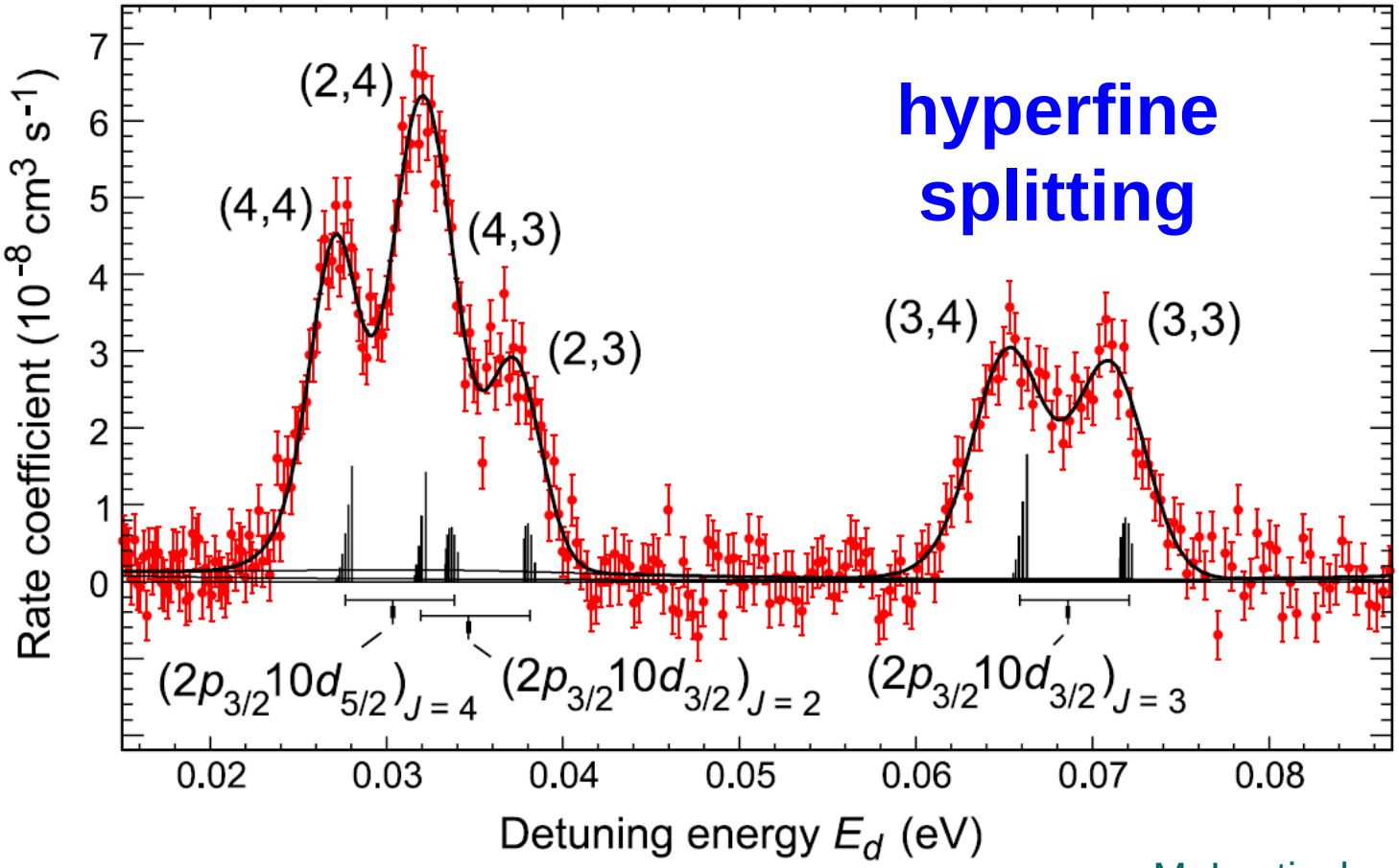
D.W. Savin, JPCS **88** (2007) 012071
S. Schippers, JPCS **388** (2012) 012010
A. Müller and S. Schippers,
in *Atomic Processes in Basic and Applied Physics*,
V. Shevelko and H. Tawara (eds.),
Springer Series on Atomic, Optical,
and Plasma Physics 68 (2012) Chapter 2

Also many papers from CRYRING, e.g.
Ali et al., A&A **557** (2013) A2
Orban et al., ApJ **721** (2010) 1603

Electron-Ion Collision Spectroscopy

DR of Li-like Sc^{18+}

TSR electron target with LN_2-cooled photocathode

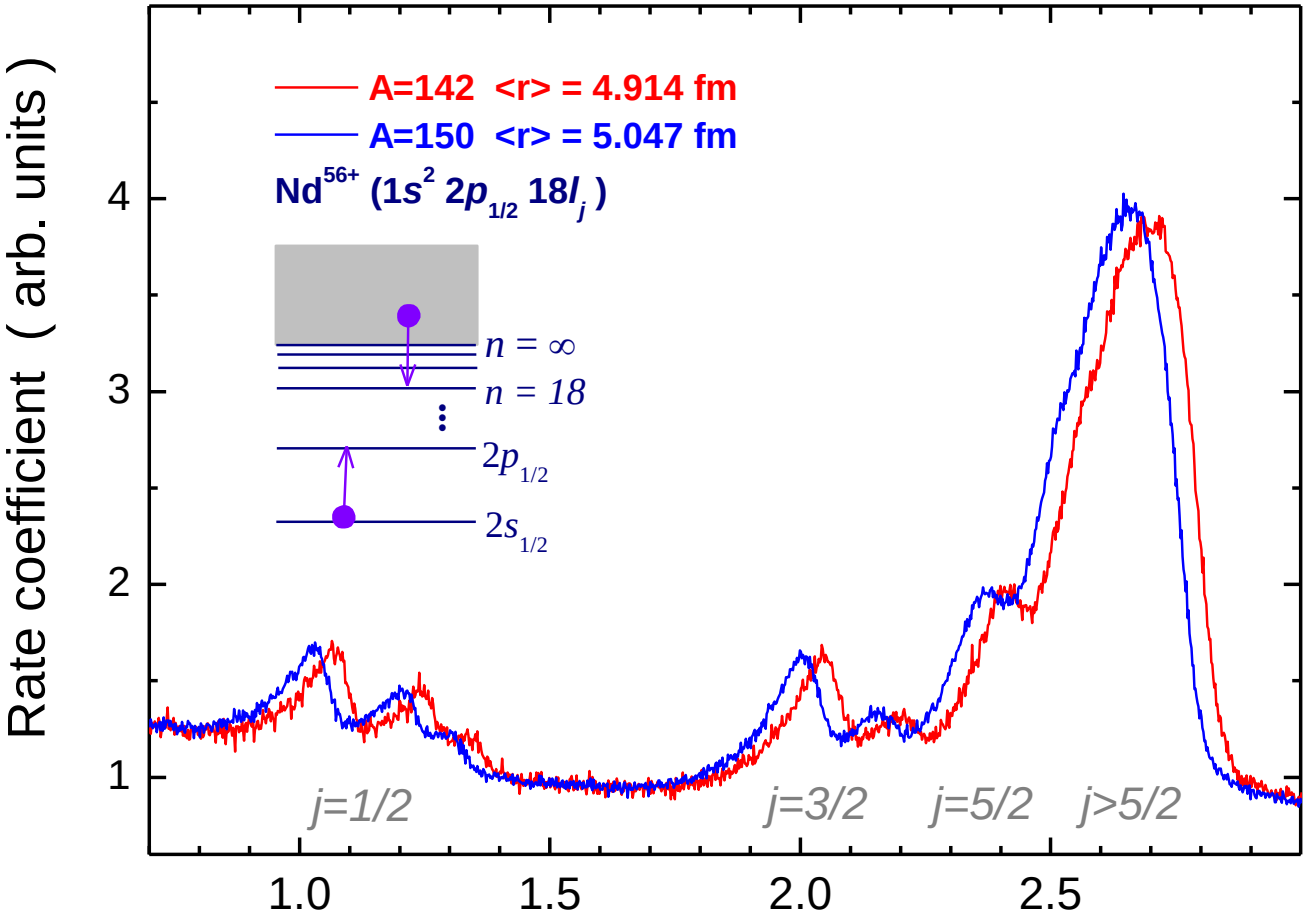


uncertainty of resonance energies: 0.1 meV

M. Lestinsky et al.,
PRL **100** (2008) 033001

Sensitivity to Nuclear Size

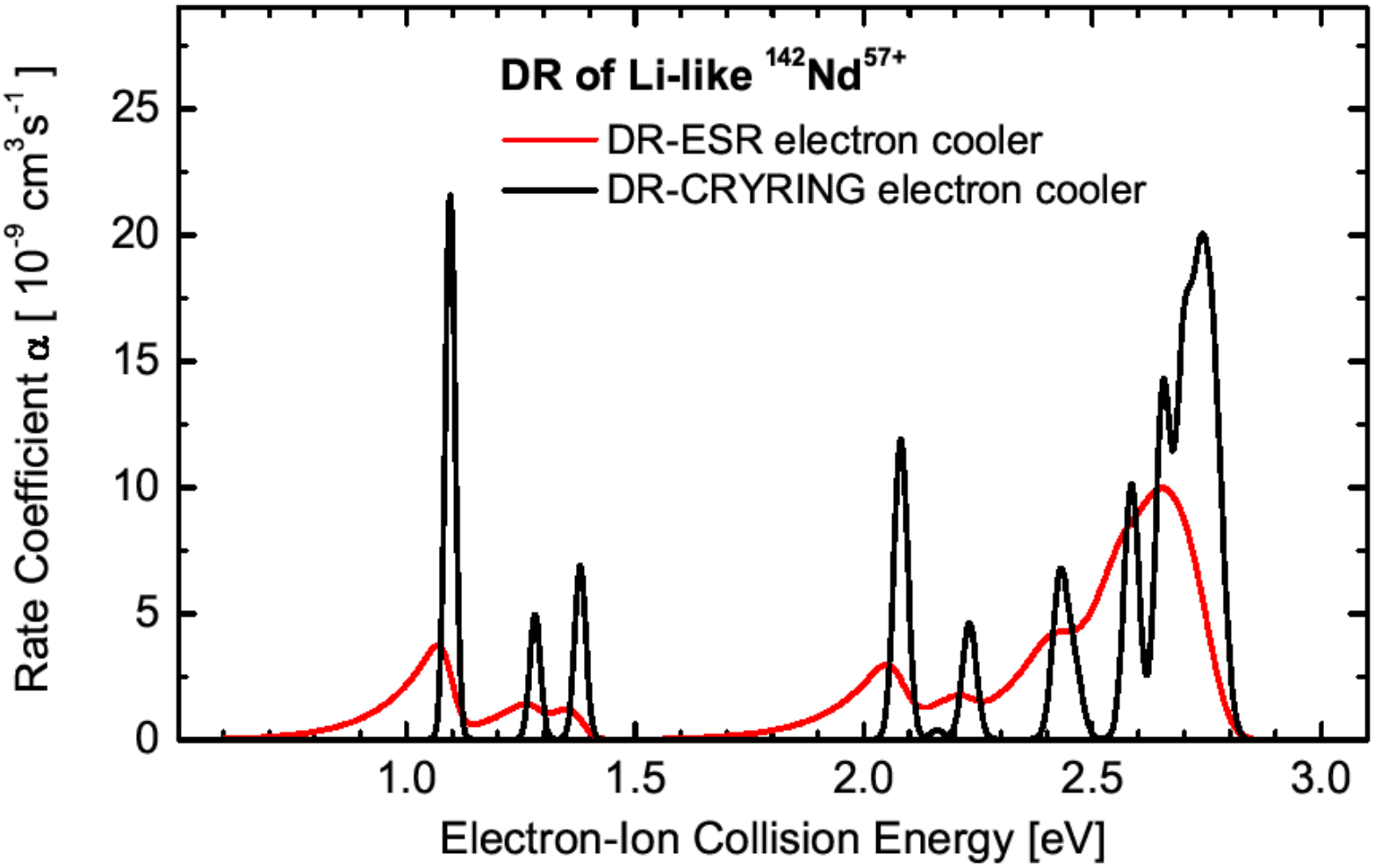
recombination of Li-like Nd^{57+} - two different isotopes



C. Brandau, et al.,
PRL **100** (2008) 073201;
see also R. Schuch et al. PRL **95** (2005) 183003

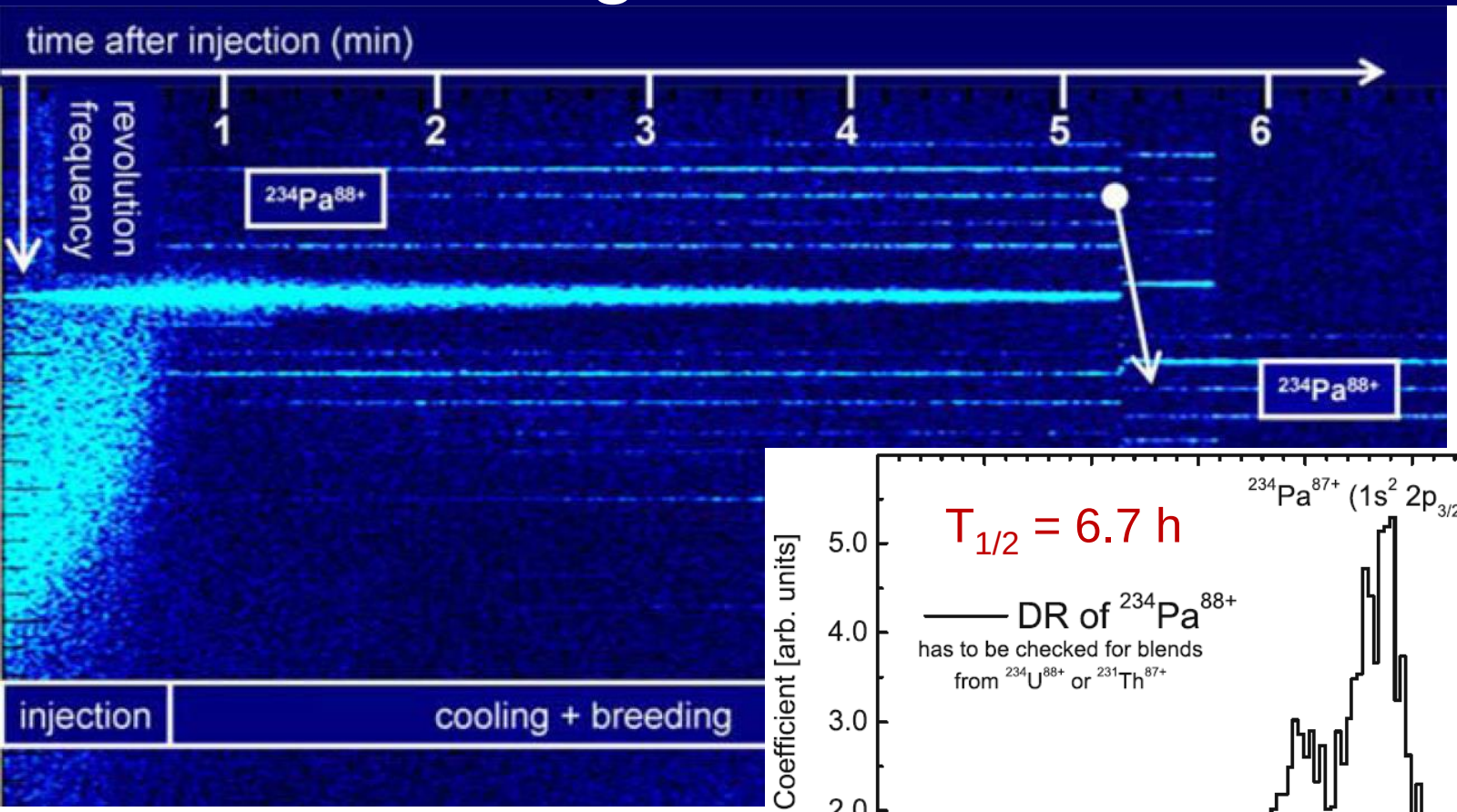
ESR – CRYRING Comparison

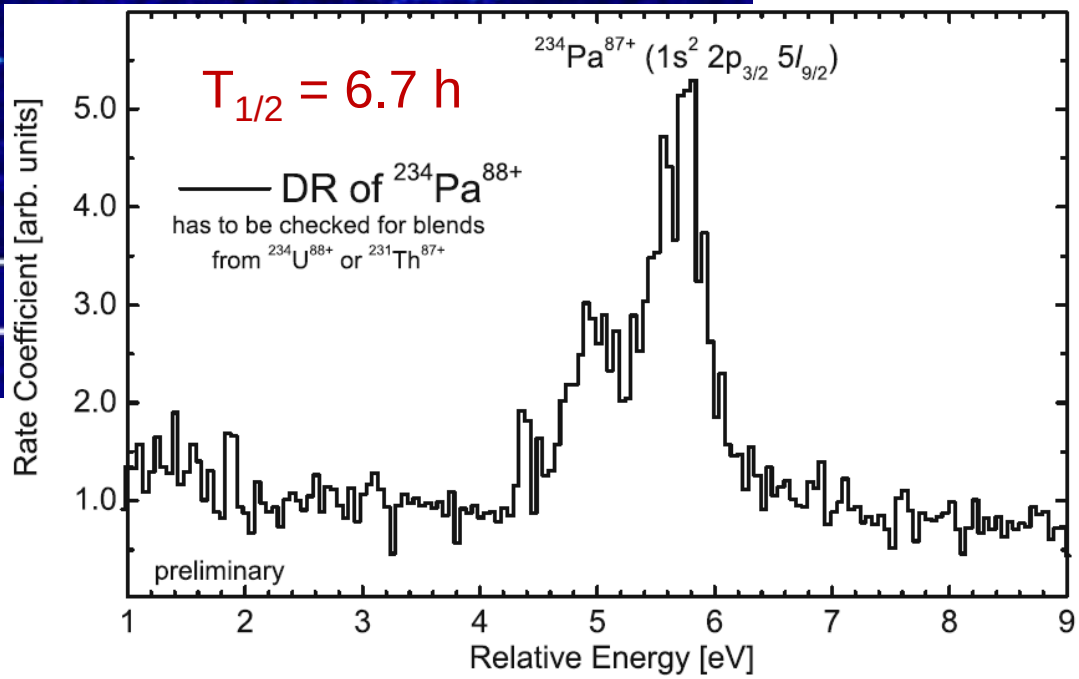
higher resolving power → higher energy-precision



courtesy of C. Brandau

Electron-Ion Recombination with In-Flight Produced Nuclei

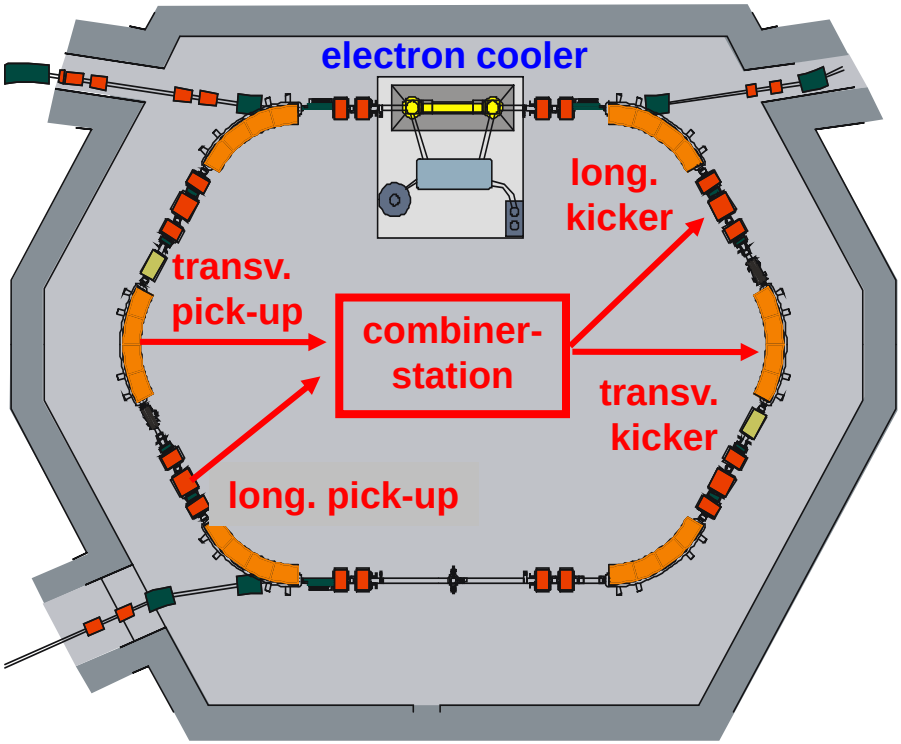




C. Brandau, et al.,
HFI **196** (2010) 115

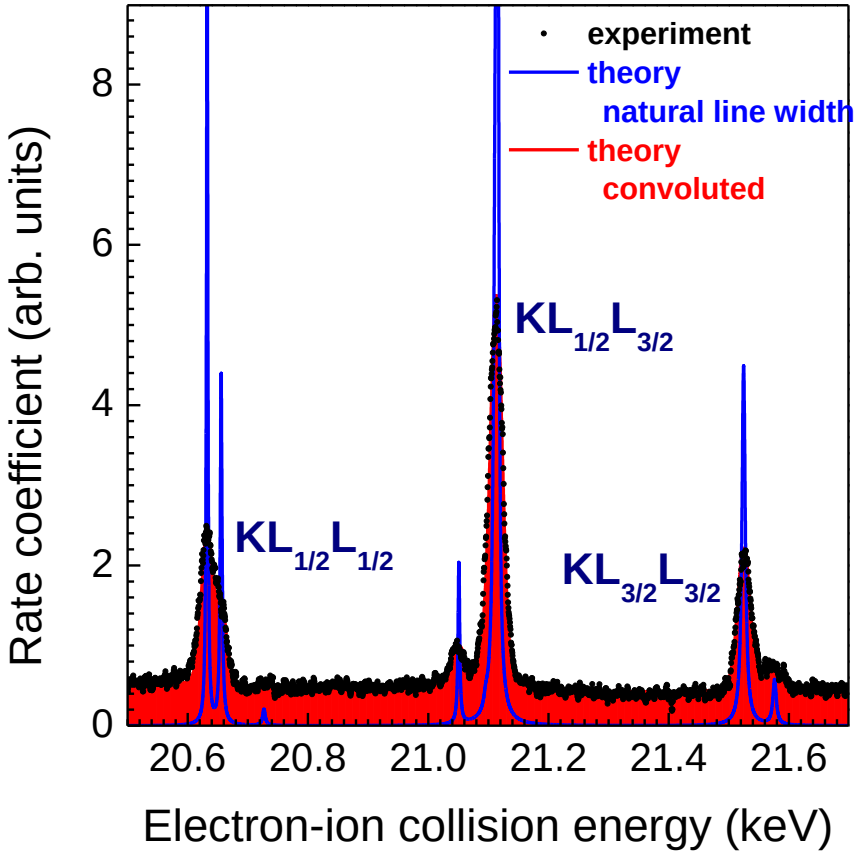
DR of Stochastically Cooled Ions @ ESR

ESR storage ring, GSI Darmstadt



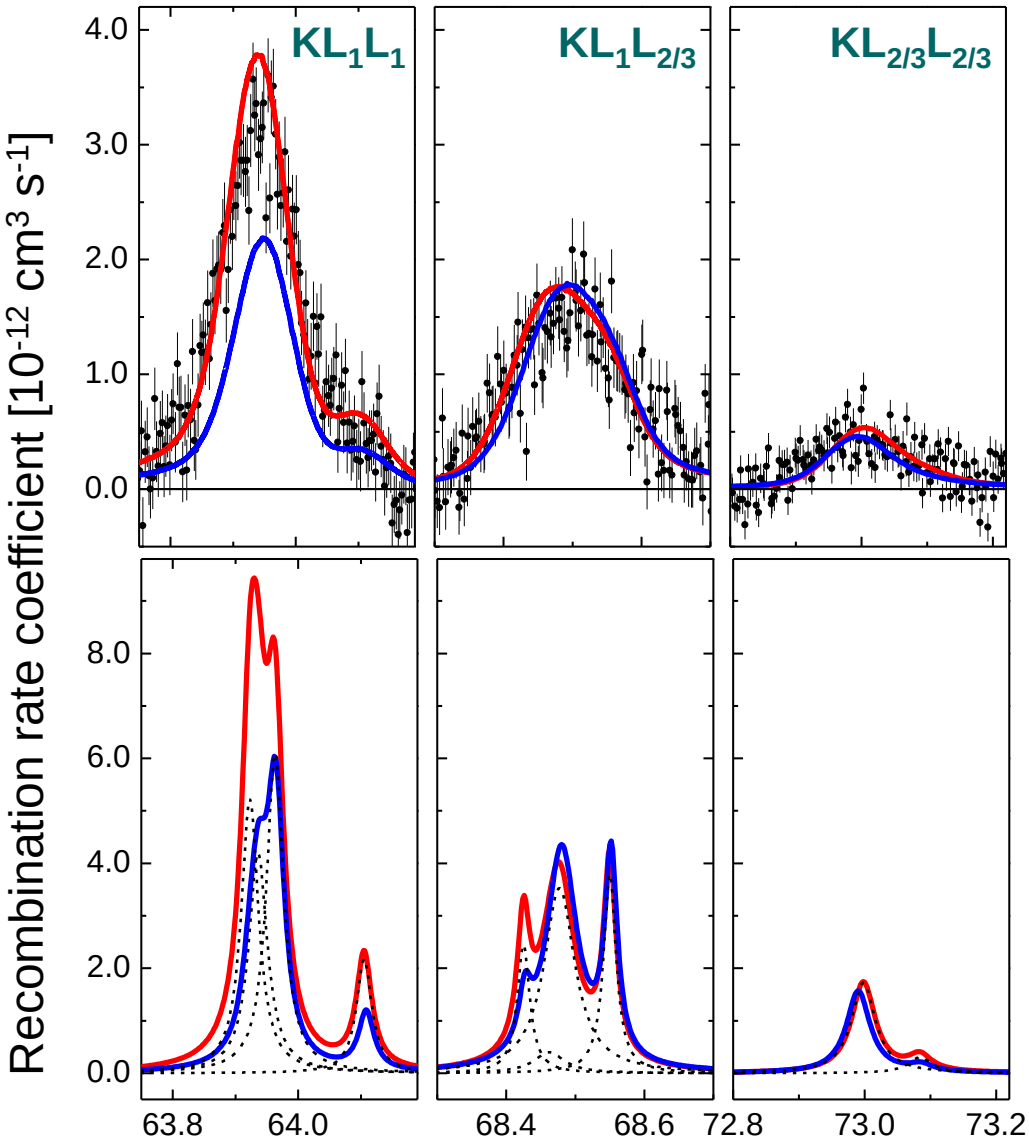
The ion beam is cooled stochastically, the electron cooler is exclusively used as an electron target.

KLL-DR of H-like Xe^{53+}



C. Kozhuharov, C. Brandau et al., ICPEAC 2003

KLL-DR of Hydrogen-like U^{91+}



MCDF-calculations by
Z. Harman, T. Steih, W. Scheid et al.

Coulomb only

Coulomb + Breit

up to 44% Breit

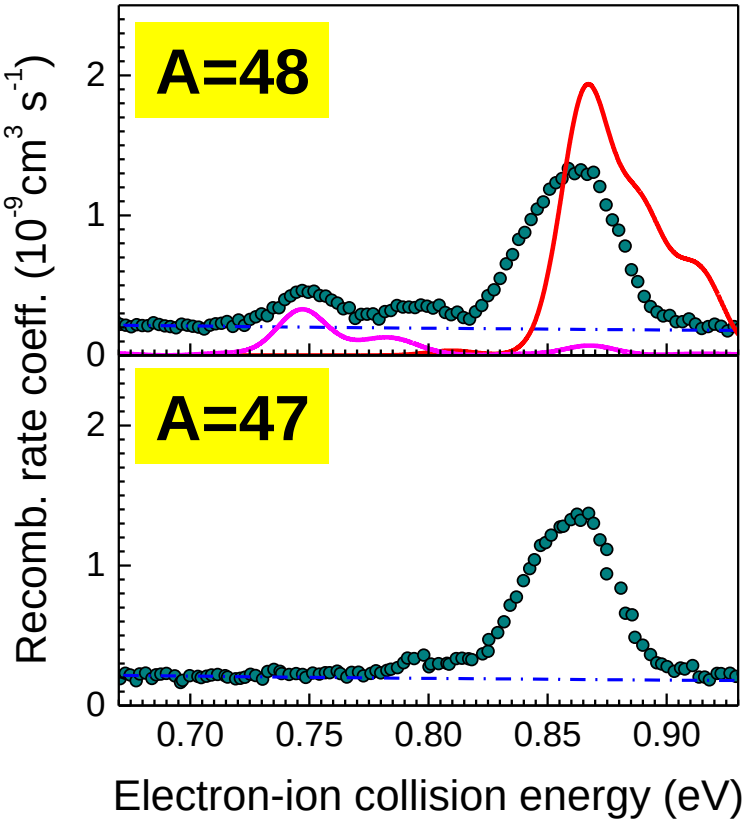
experiment and theory
independently
on absolute scales

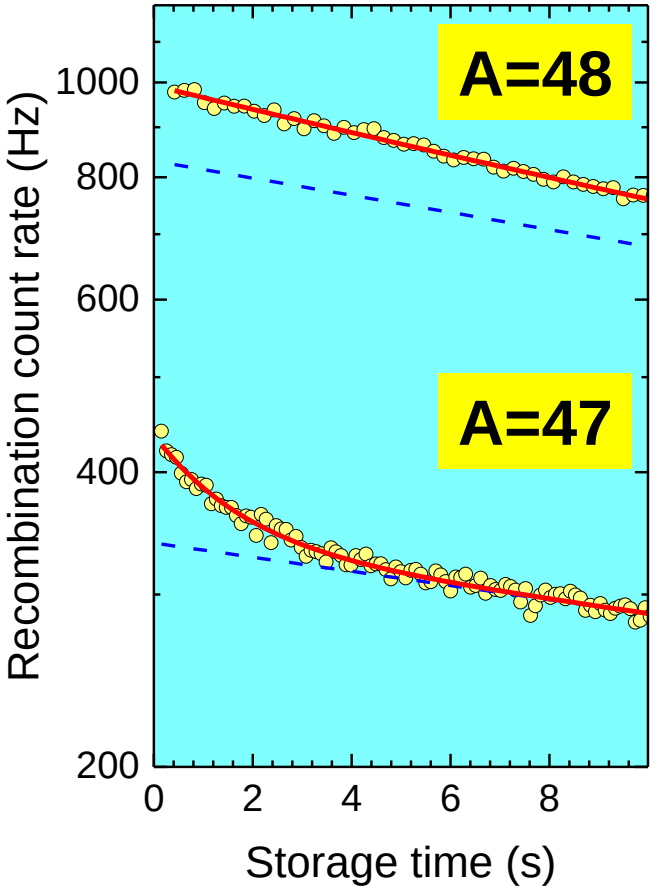
experimental resolution
close to
natural linewidths

D. Bernhardt et al., PRA **83** (2011) 020701

Exotic Atomic Decay Modes

hyperfine induced $2s2p\ ^3P_0 \rightarrow 2s^2\ ^1S_0$ transition in $^{47}Ti^{18+}$

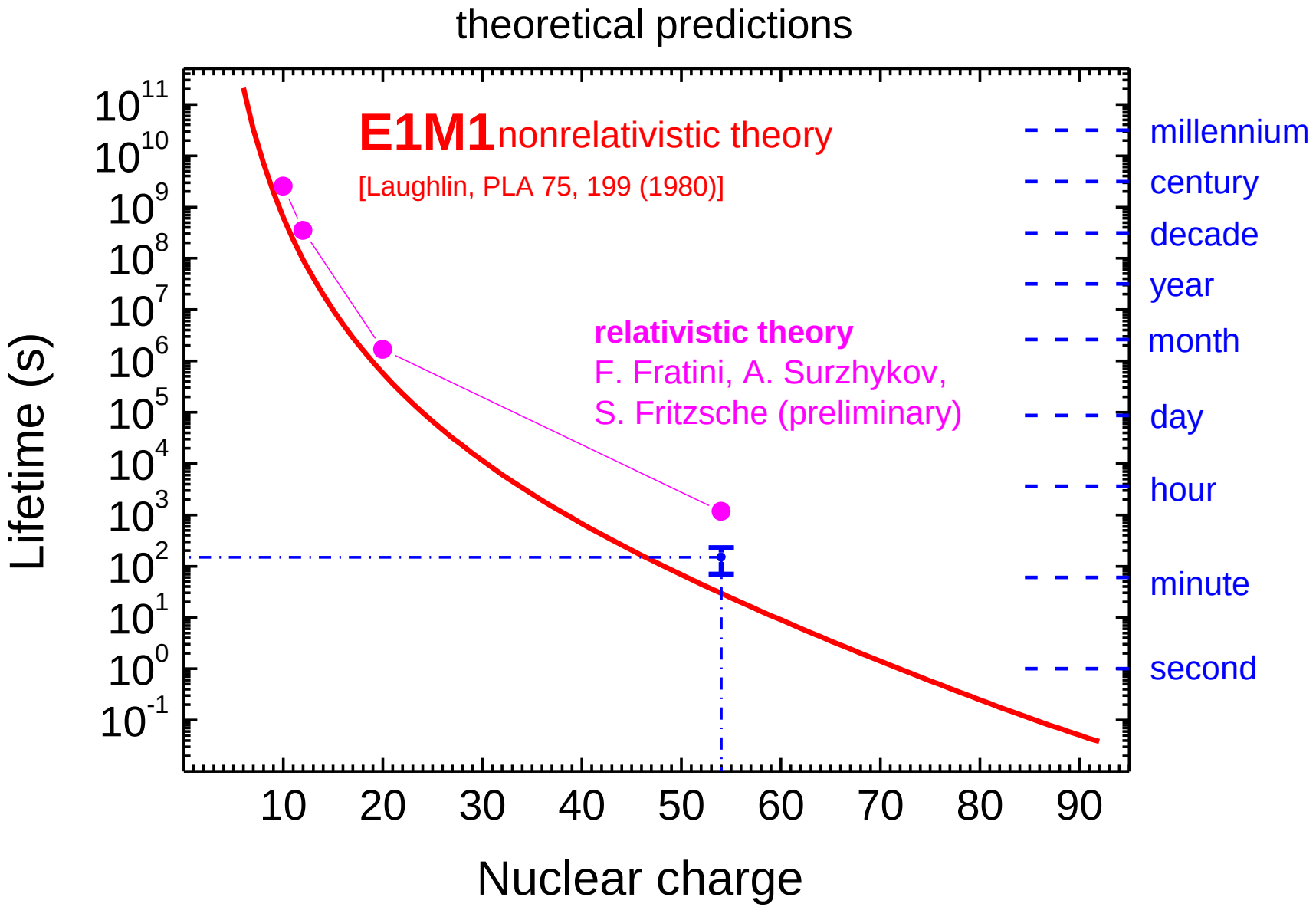




S. Schippers et al., PRL **98** (2007) 033001

τ_{HFI} = 1.8(1) s

E1M1 Two-Photon $2s2p\ ^3P_0 \rightarrow 2s^2\ ^1S_0$ Decay



Exotic Recombination Pathways

VOLUME 91, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 25 JULY 2003

Observation of Trielectronic Recombination in Be-like Cl Ions

M. Schnell,[1] G. Gwinner,[1] N. R. Badnell,[2] M. E. Bannister,[3] S. Böhm,[4] J. Colgan,[5] S. Kieslich,[4] S. D. Loch,[5] D. Mitnik,[6] A. Müller,[4] M. S. Pindzola,[5] S. Schippers,[4] D. Schwalm,[1] W. Shi,[4] A. Wolf,[1] and S.-G. Zhou[1,7]

PRL 107, 143201 (2011) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2011

Prominent Higher-Order Contributions to Electronic Recombination

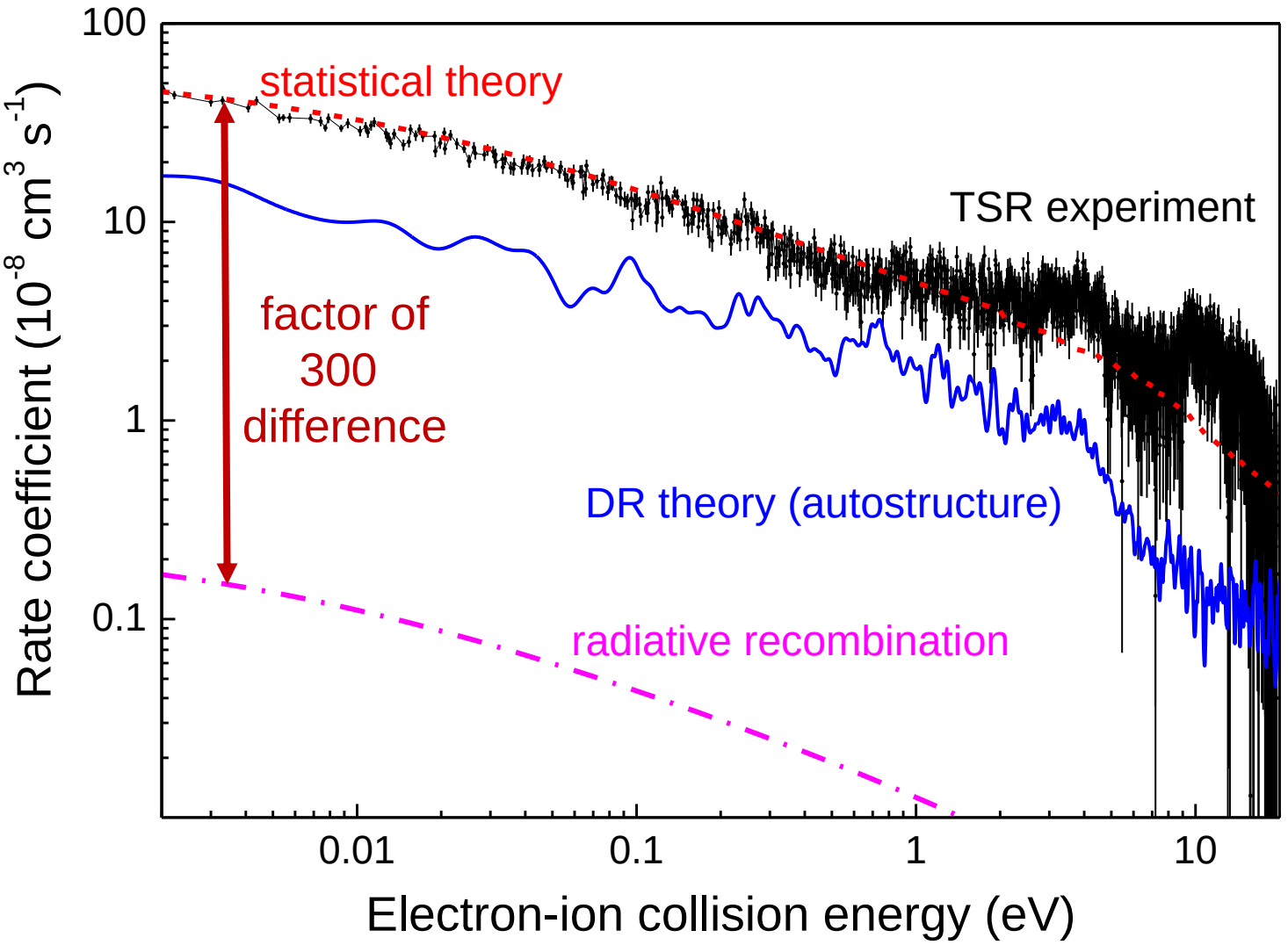
C. Beilmann,[1] P. H. Mokler,[1] S. Bernitt,[1] C. H. Keitel,[1] J. Ullrich,[1] J. R. Crespo López-Urrutia,[1] and Z. Harman[1,2]

PHYSICAL REVIEW A 86, 022714 (2012)

Chaos-induced enhancement of resonant multielectron recombination in highly charged ions: Statistical theory

V. A. Dzuba,[1] V. V. Flambaum,[1] G. F. Gribakin,[2] and C. Harabati[1]

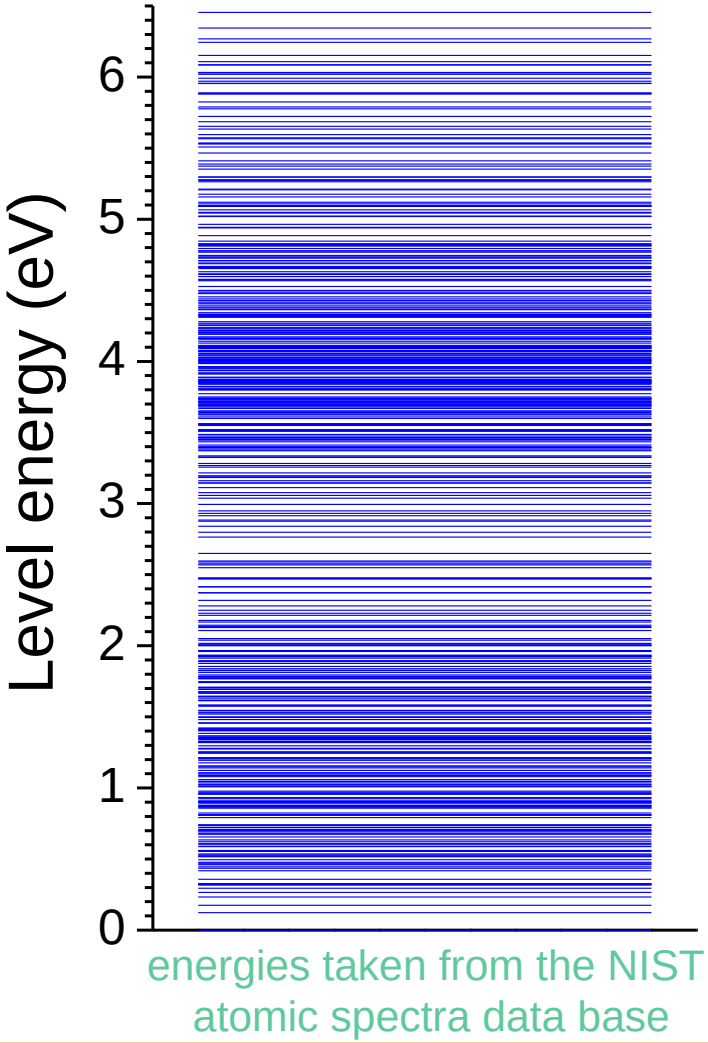
Recombination of $W^{18+}([Kr]\ 4d^{10}\ 4f^{10})$



K. Spruck, N. R. Badnell, C. Krantz et al., in preparation

Many-Electron Systems with High Level Densities

first 491 levels of Ce^+



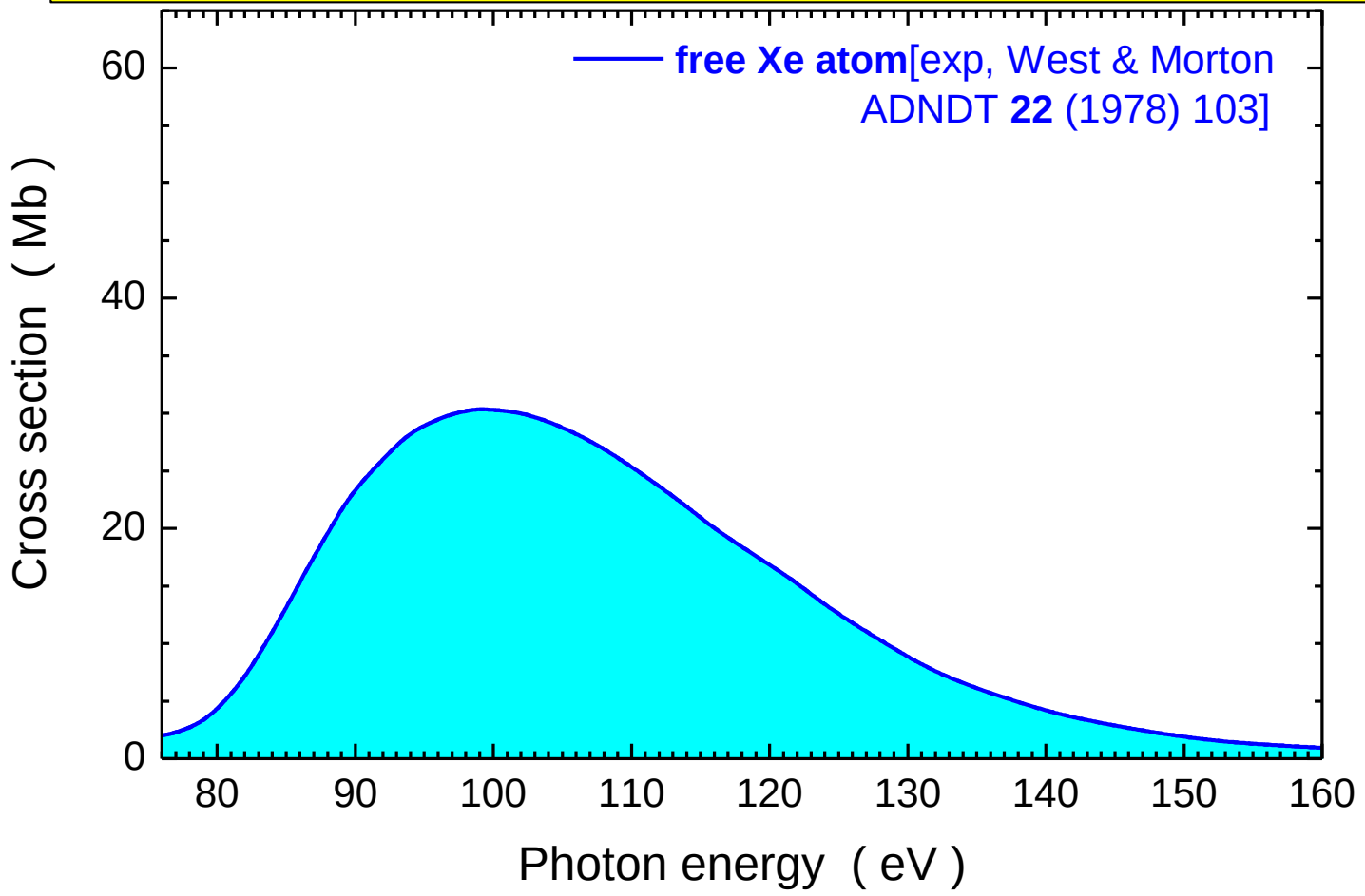
In principle, a Rydberg series of DR resonances is associated with the excitation of each level.

$4f\,(^2F)\,5d^2\,(^3F)\,{}^4H_{7/2}$ ground state

Giant Atomic Resonances

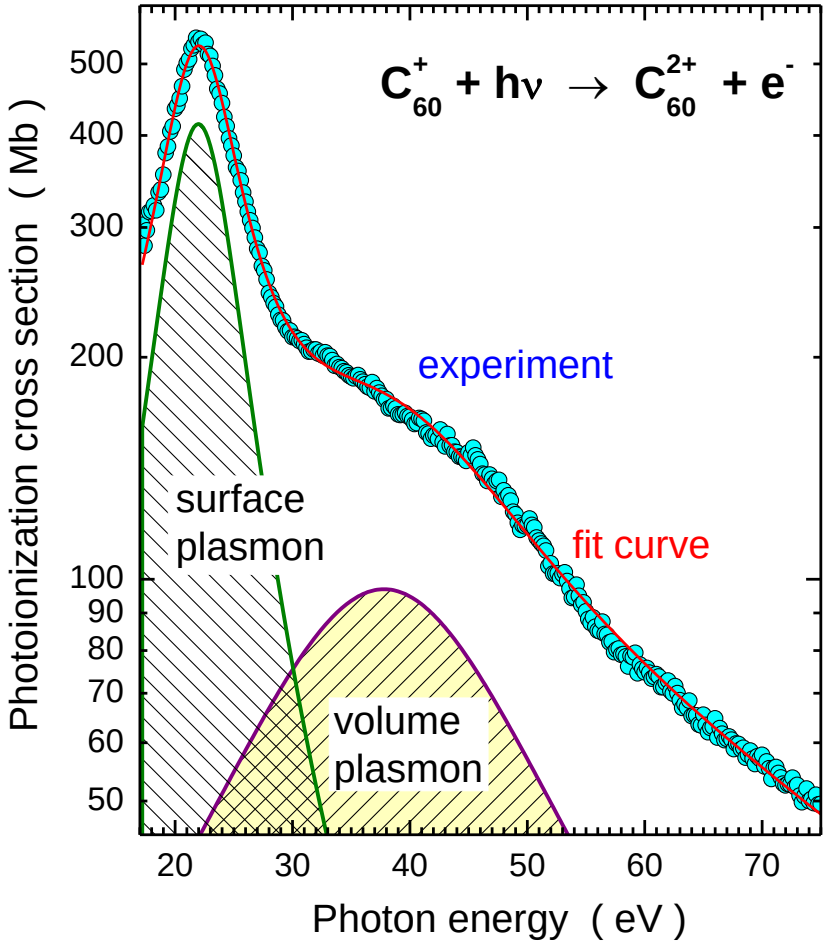
Photoionization of Xe(4d) shell

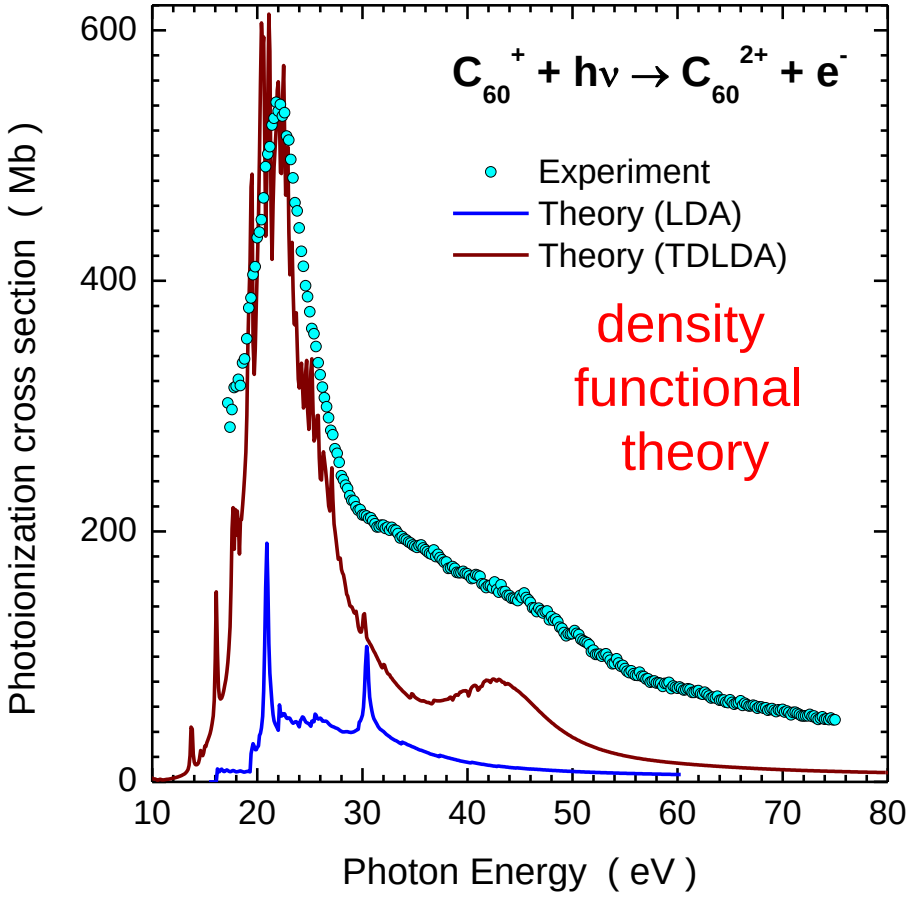
Time inverse process:
Recombination via collective excitation of 10 4d electrons



Plasmon Excitations in C_{60}^+

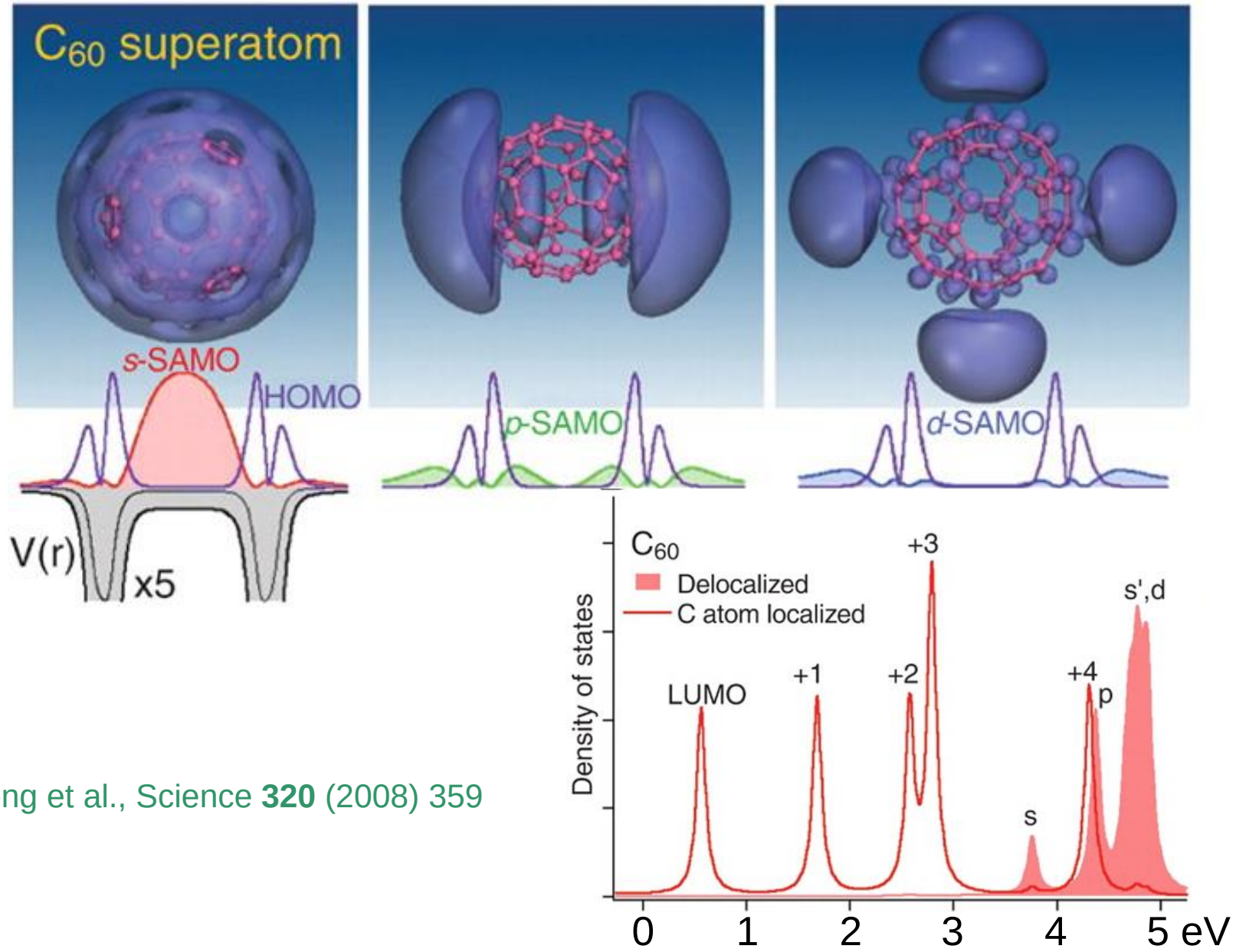
Photoionization of ions at the ALS
(Gießen-Reno-Berkeley-Dresden collaboration)





S. Scully et al., PRL **94** (2005) 065503

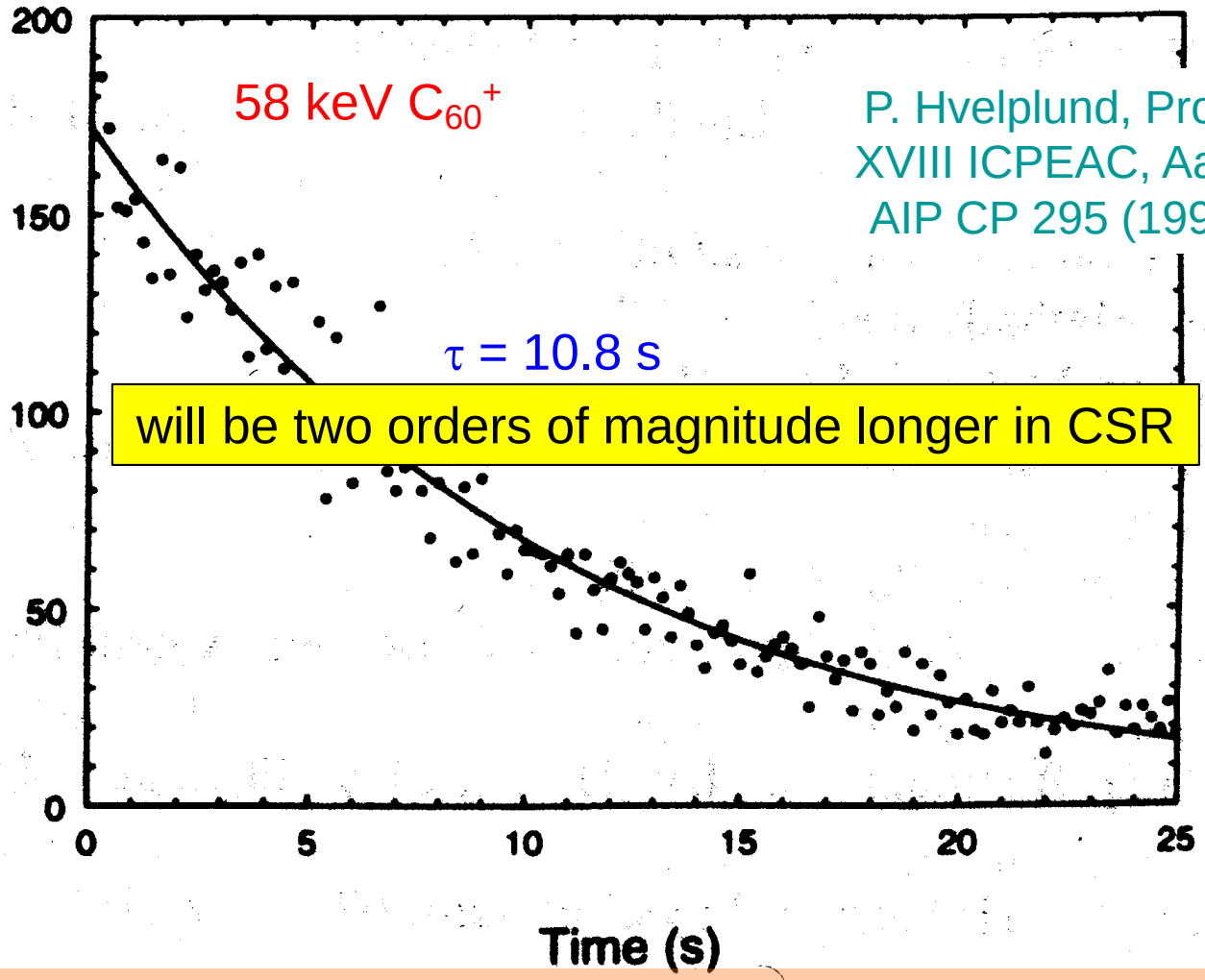
Access to Super-Atom States



Feng et al., Science **320** (2008) 359

Beam lifetime of stored C_{60}^+ ions

stored in ASTRID at room temperature



Collaborators

Justus-Liebig-Universität Gießen:

D. Bernhardt, S. Böhm, J. Jacobi, S. Kieslich, H. Knopp, A. Müller, E. W. Schmidt, W. Shi, K. Spruck, D. Yu
N. Grün, W. Scheid, T. Steih

Max-Planck-Institut für Kernphysik Heidelberg:

A. Becker, M. Beutelspacher, M. Grieser, G. Gwinner, C. Krantz, D. A. Orlov, R. Repnow, M. Schnell, F. Sprenger,
A. Wolf, Z. Harmann, U. D. Jentschura, C. H. Keitel

Columbia Astrophysics Laboratory New York:

M. Hahn, D. Lukic, O. Novotný, D. W. Savin

Stockholm University:

H. Danared, N. Eklöw, E. Lindroth, R. Schuch, M. Tokman

GSI, Darmstadt:

K. Beckert, P. Beller, F. Bosch, D. Boutin, C. Brandau, C. Dimopoulou, B. Franzke, A. Gumberidze, H.-J. Kluge,
P.-M. Hillenbrandt, C. Kozhuharov, M. Lestinsky, Yu. A. Litvinov, P. H. Mokler, F. Nolden, R. Reuschl,
U. Spillmann, M. Steck, T. Stöhlker, D. F. A. Winters

and

N. R. Badnell (Glasgow), M. Bannister (Oak Ridge), F. J. Currell, B. O'Rourke (Belfast), S. Fritzsche (Jena),
D. C. Griffin & D. M. Mitnik (Rollins College), R. A. Phaneuf (Reno), Z. Stachura (Krakow), A. S. Terekov (Novosibirsk),
A. N. Artemyev, Y. S. Kozhedub, V. M. Shabaev, I. I. Tupitsyn (St. Petersburg), R. Krücken (Munich)

Summary

- **Dielectronic recombination**
  - sensitive to nuclear charge and magnetic moment
  - sensitive to relativistic and QED effects
  - absolute cross sections important for astro- and plasma physics

- **New opportunities at new and relocated storage rings**
  - high-resolution electron-ion collision spectroscopy
  - access to long atomic lifetimes
  - rare isotopes
  - low-charged ions (atoms, molecules, clusters)
  - exploration of exotic recombination path-ways