Single and Multiple Ionizaton of Ions by Electron and Photon Impact

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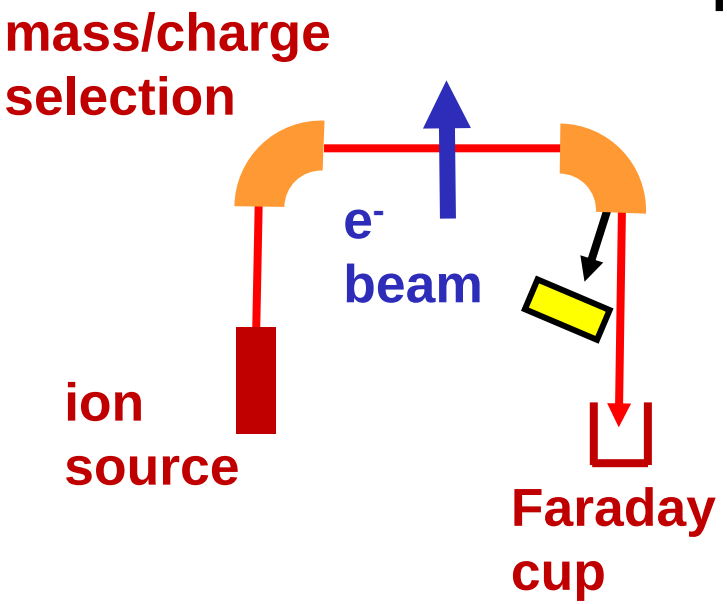
Outline

- **Electron-impact ionization of ions**
  - **Recent results from Giessen crossed-beams setup**
- **Photoionization of ions**
  - **ALS: Valence-shell ionization**
  - **PIPE@PETRA III: Inner-shell ionization**

Electron-Ion Crossed-Beams Method

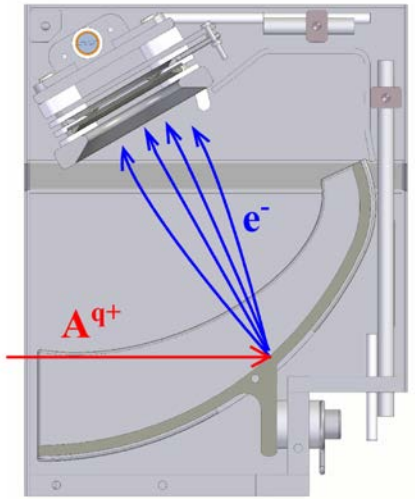
charge-changing collisions



reaction products

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

100% detection efficiency



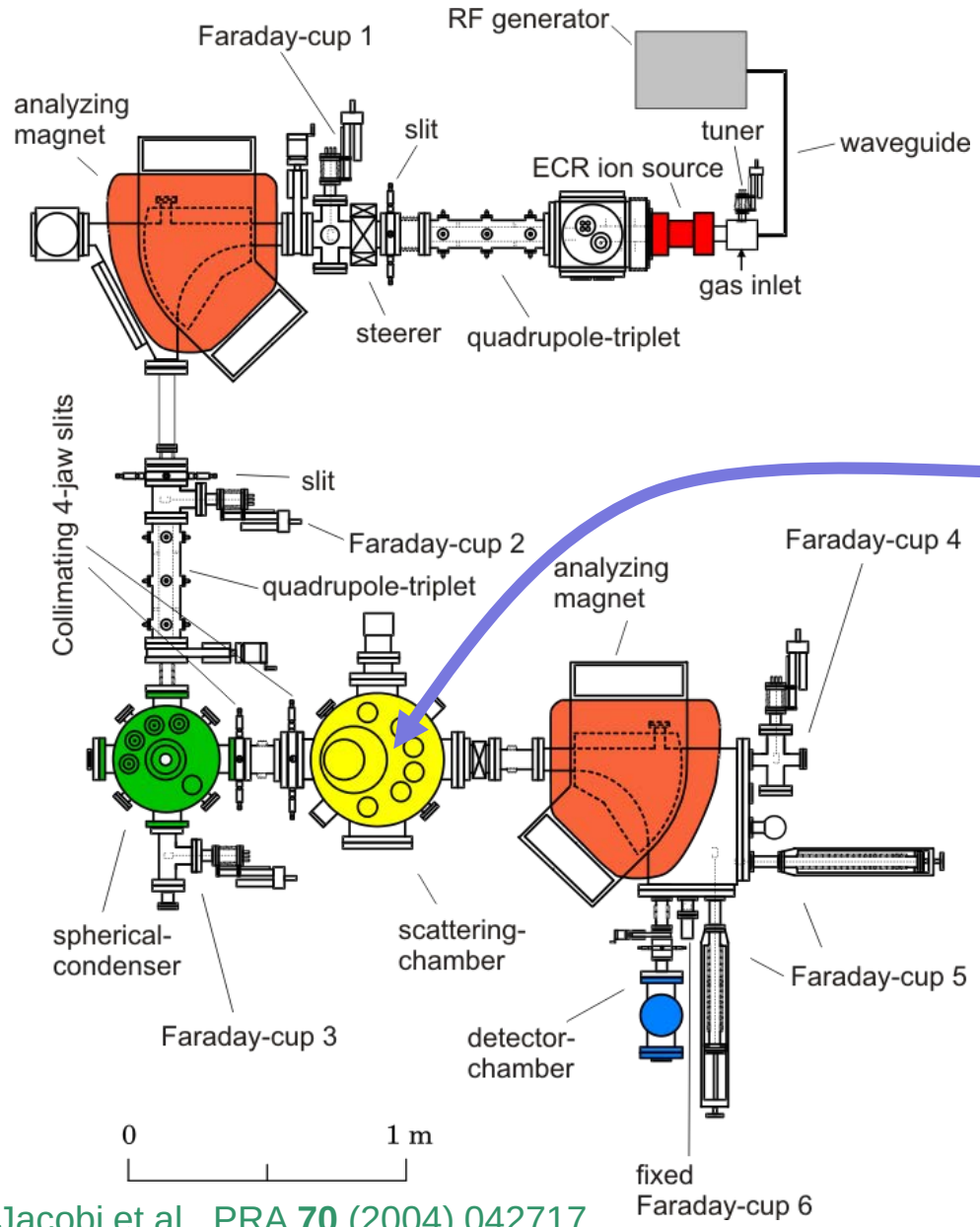
detector based on secondary electron emission

K. Spruck et al., RSI **86** (2015) 023303

pioneered by Dolder et al.
Proc. R. Soc. A **264** (1961) 367

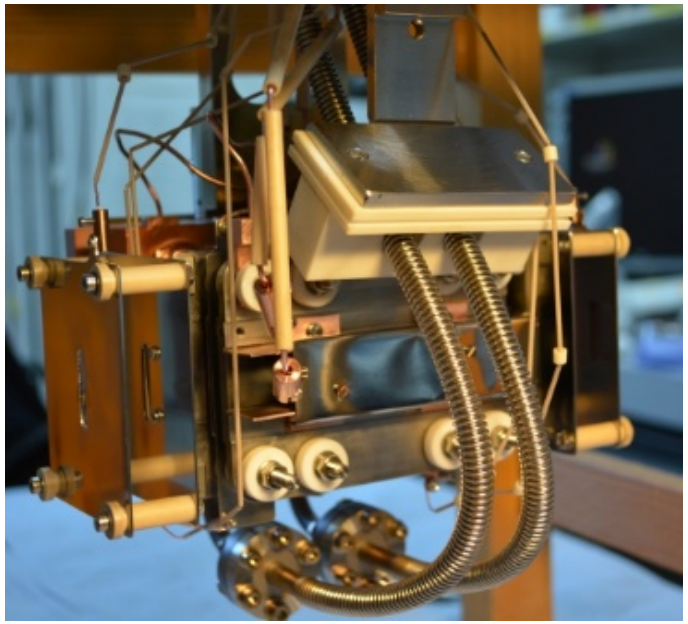
other groups: Giessen, Louvain-La-Neuve, ORNL

Giessen Crossed-Beams-Setup



Jacobi et al., PRA **70** (2004) 042717

high-power electron gun



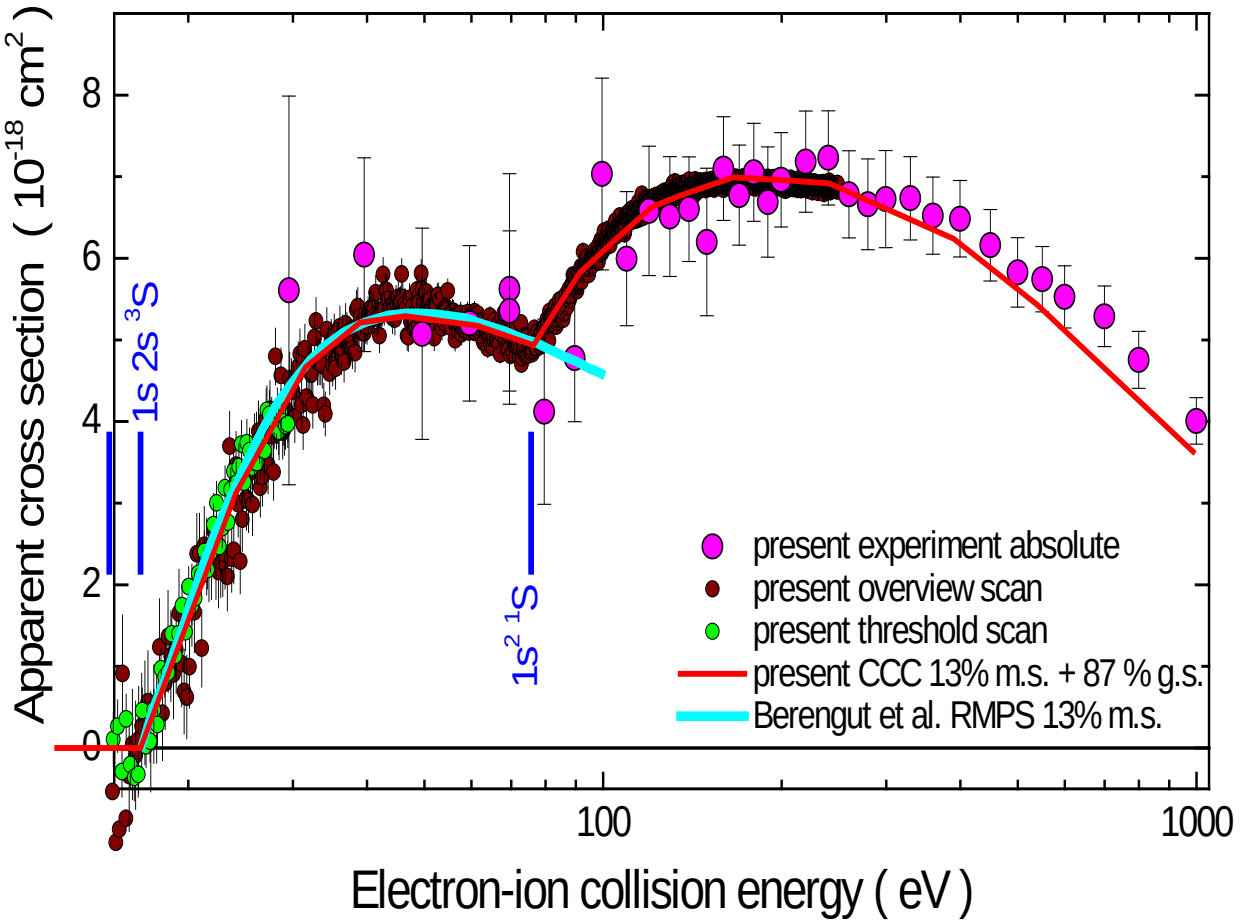
E_{max} = 3.5 keV, I_{max} = 1 A

Ebinger et al., NIMB **408** (2017) 317

animated crossed-beams method
absolute cross sections for electron-impact ionization of ions
typical systematic uncertainty <10%

A Fundamental Collision System: $e^- + Li^+$

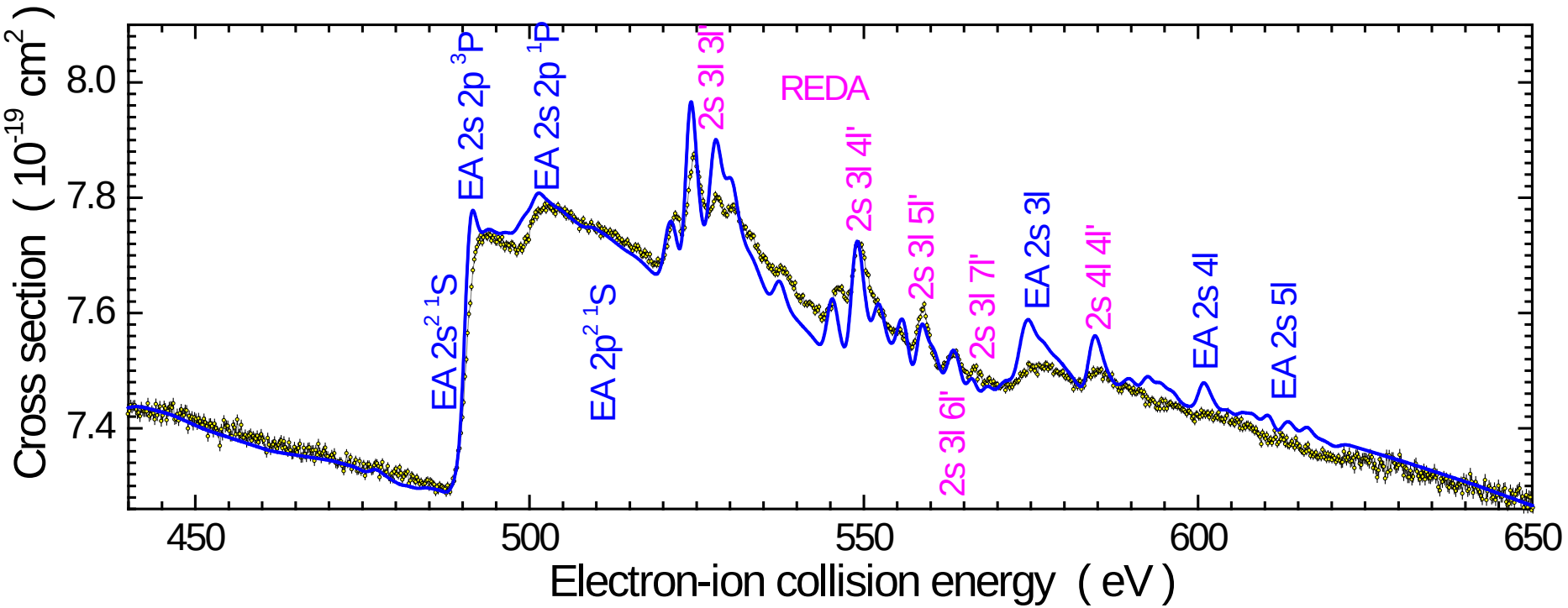
comparison between measurements and CCC calculations for a mixture of $Li^+(1s^2\ ^1S)$ and $Li^+(1s\ 2s\ ^3S)$ ions



A. Borovik, Jr., A. Müller, S. Schippers, D. Fursa, I. Bray, JPB **42** (2009) 025203

Higher-Order Ionization Processes

electron-impact ionization of metastable $N^{5+}(1s\ 2s\ ^3S)$
experiment and CCC calculations



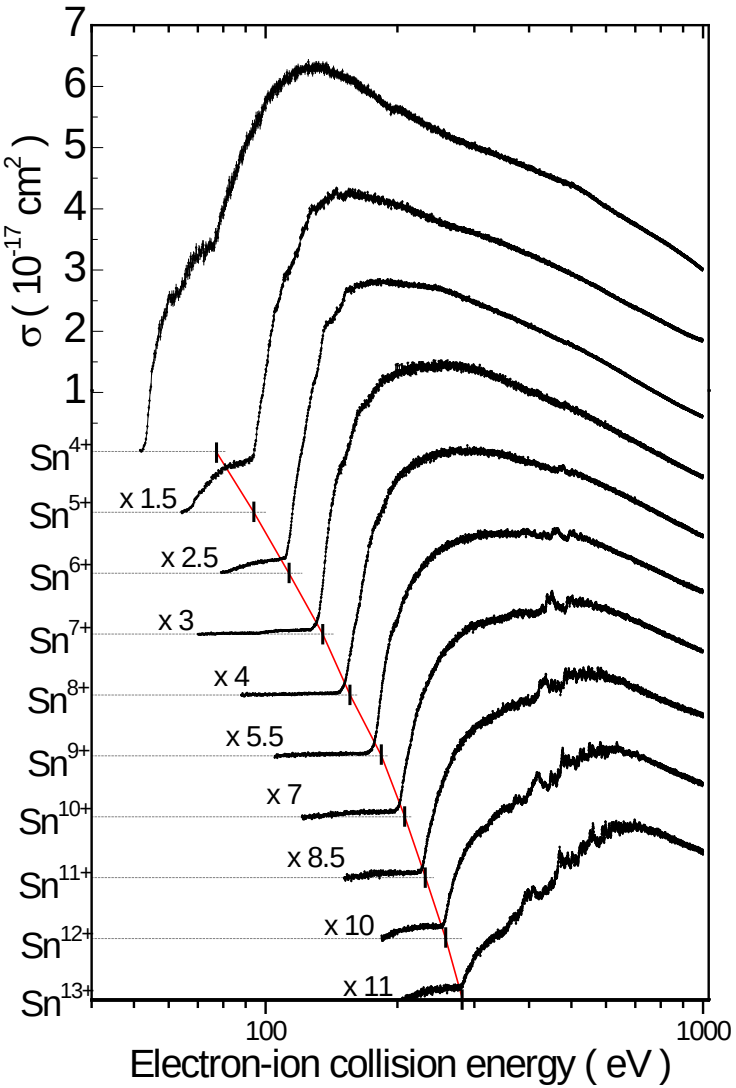
EA: (nonresonant) Excitation followed by Autoionization

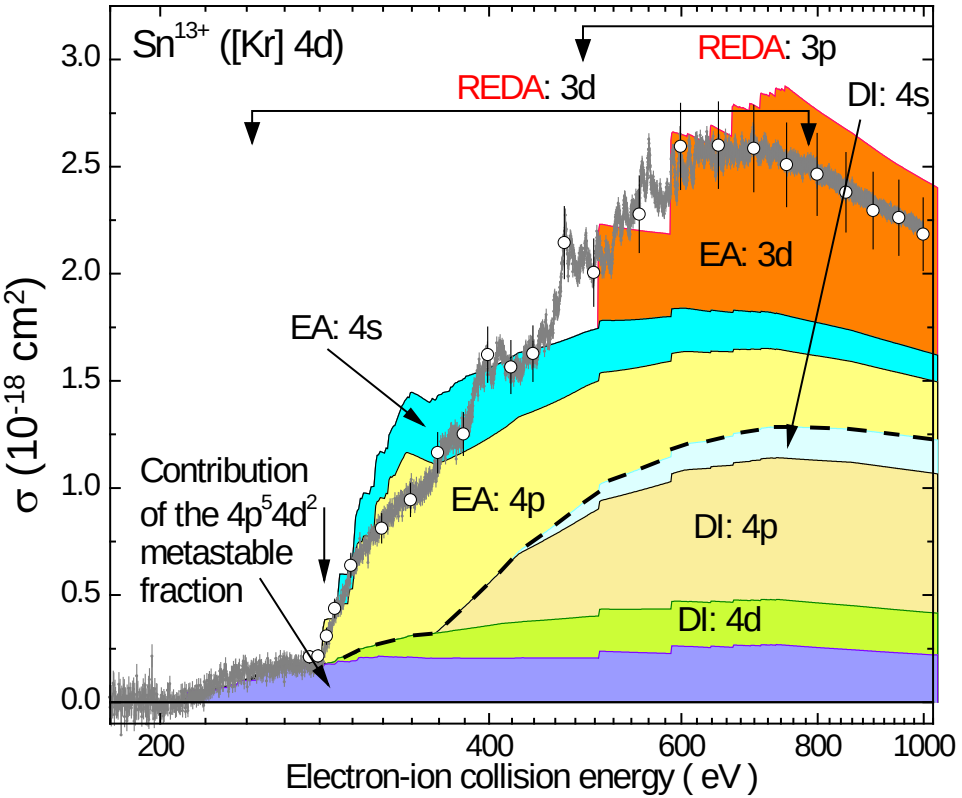
REDA: Resonant Excitation followed by Double Autoionization

A. Müller et al., PRA **90** (2014) 010701(R)

Cross-Section Data for Applications

Ionization of Sn^{4+} - Sn^{13+} for EUV-Lithography





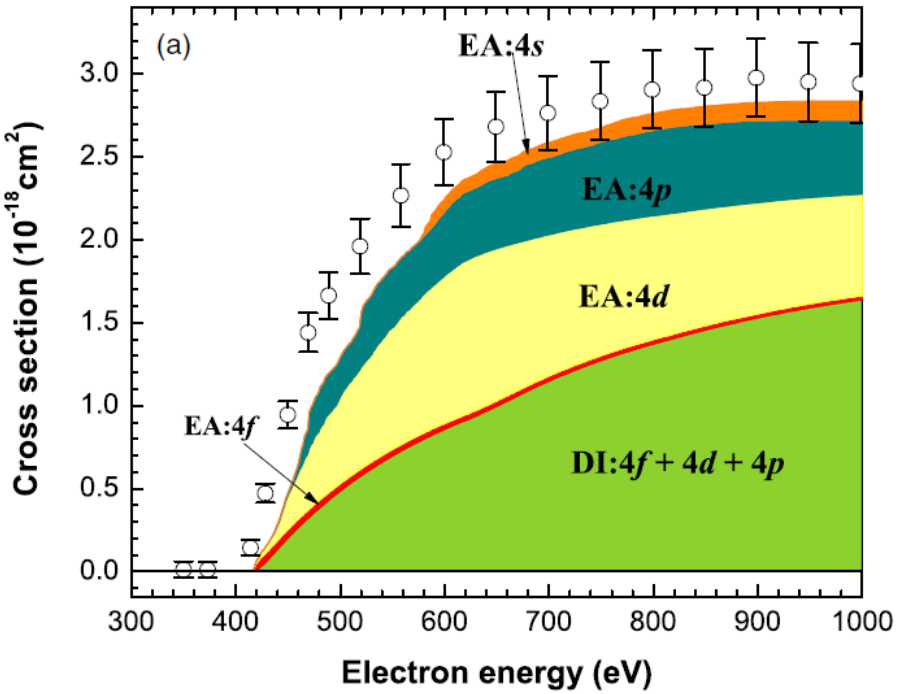
calculations using the LANL codes

Sn ions: A. Borovik, Jr. et al., JPB **46** (2013) 175201
Xe ions: A. Borovik, Jr. et al., JPB **48** (2015) 035203

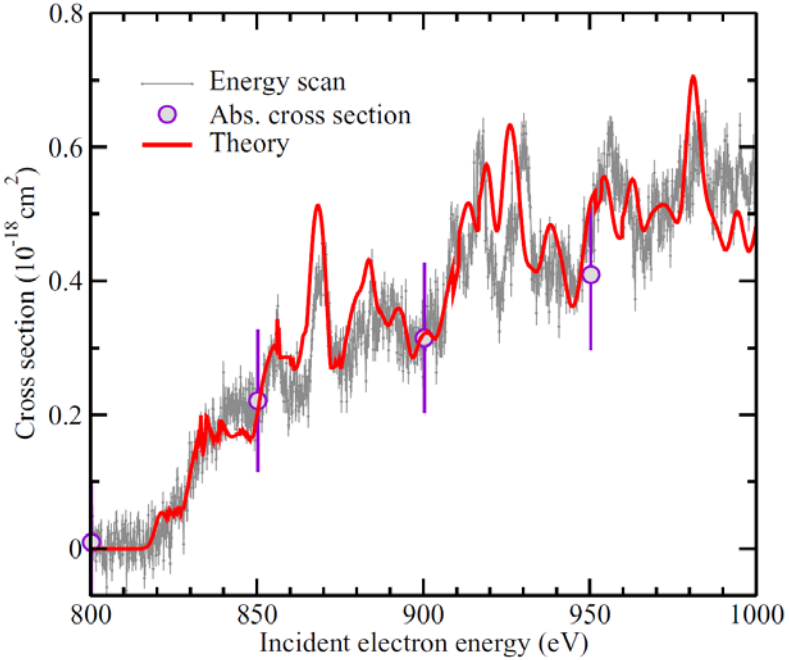
Importance of Indirect Ionization

excitations of up to at least n=25 have to be considered

single ionization of W^{17+}



single ionization of Xe^{24+}



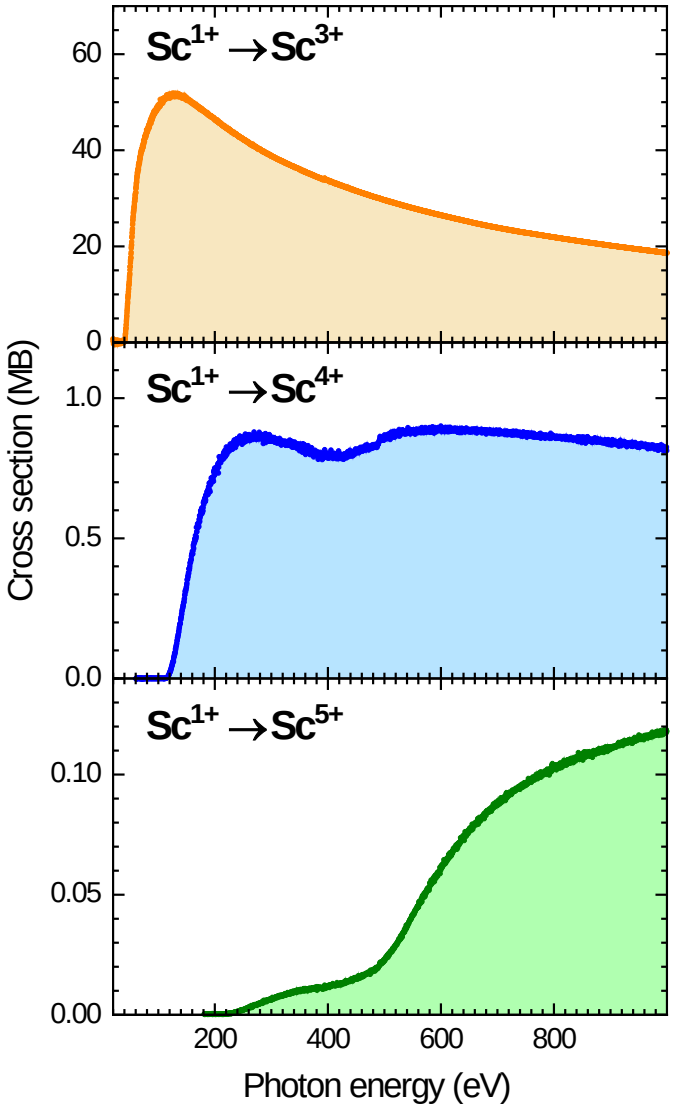
D.-H. Zhang & D.-H. Kwon, JPB **47** (2014) 075202

experimental data from Giessen

P. Liu et al., PRA **92** (2015) 012701

see, e.g., also: D.-H. Kwon & D. W. Savin, PRA **86** (2012) 022701;
V. Jonauskas et al., PRA **91** (2015) 012715;
A. Borovik Jr. et al., PRA **93** (2016) 012708.

Cross Sections for Multiple Ionization



Jacobi et al., JPB **38** (2005) 2015

The Giessen Electron-Ion Team

Benjamin Ebinger

Tobias Molkentin

Michel Döhring

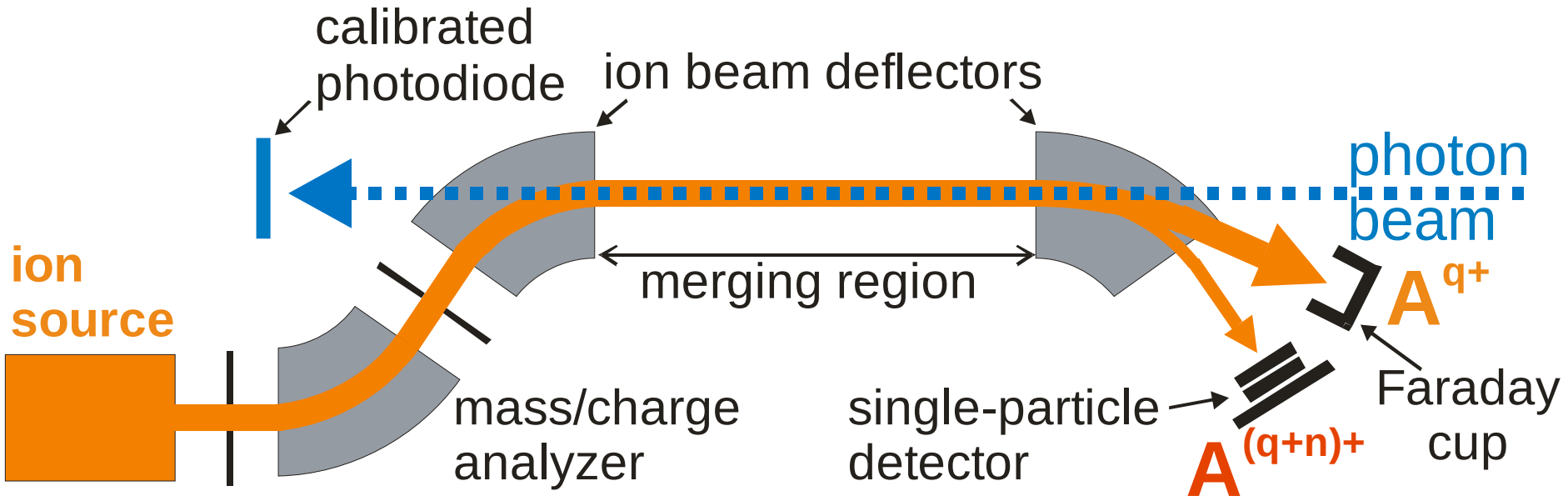
Alexander Borovik Jr.

Alfred Müller

Stefan Schippers

The Photon-Ion Merged-Beams Technique

recent review: Schippers, Kilcoyne, Phaneuf, Müller, Contemporary Physics **57** (2016) 215



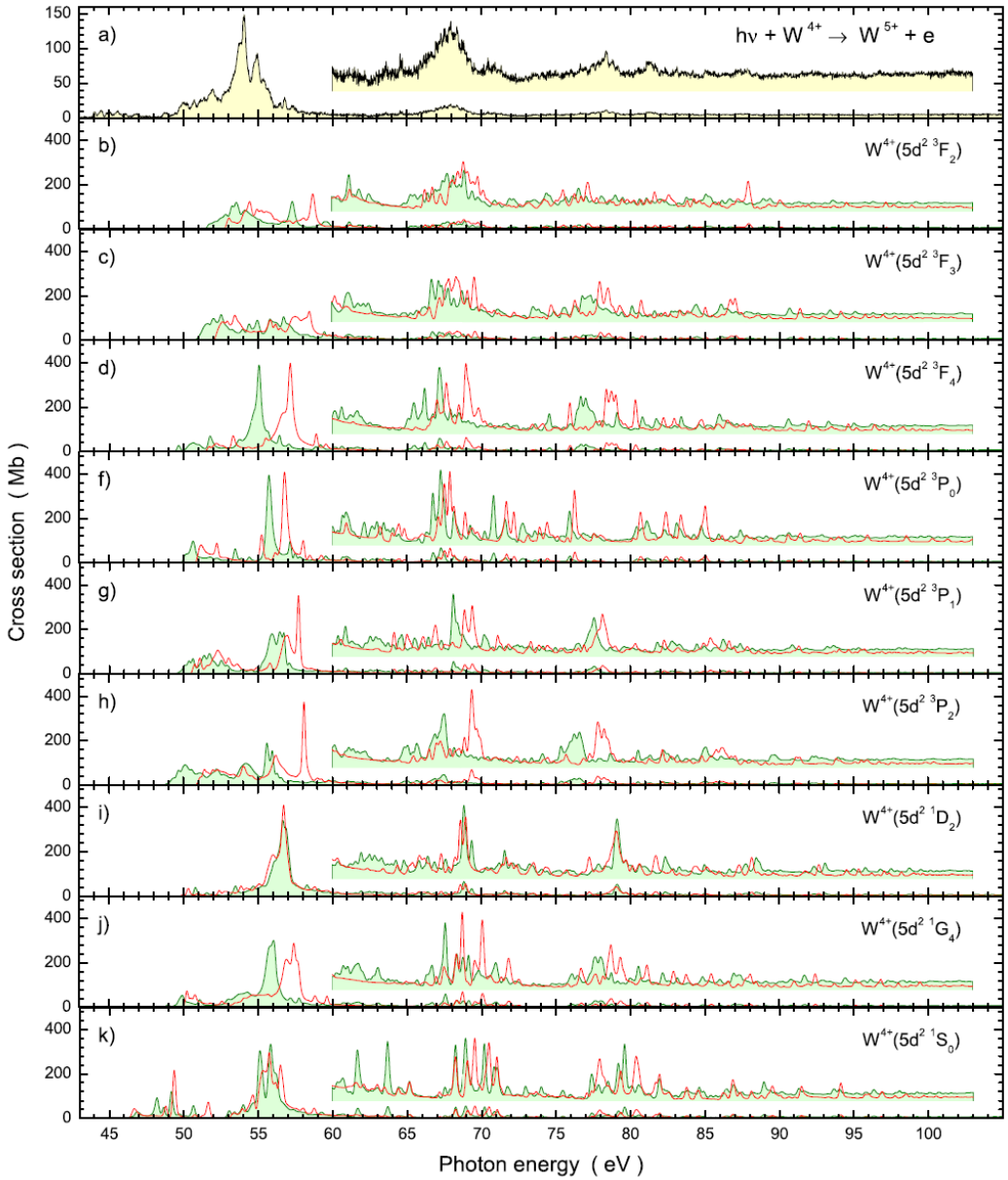
low ion densities: ~ 10^6 cm^{-3}

long interaction region (~ 1 m)
makes up for diluteness of ionic targets

Advanced Light Source

photon-ion end-station at beamline 10.0.1, Covington et al., PRA 66 (2002) 062710

Valence-Shell Photoionization of $W^{4+}(5d^2)$



ALS experiment

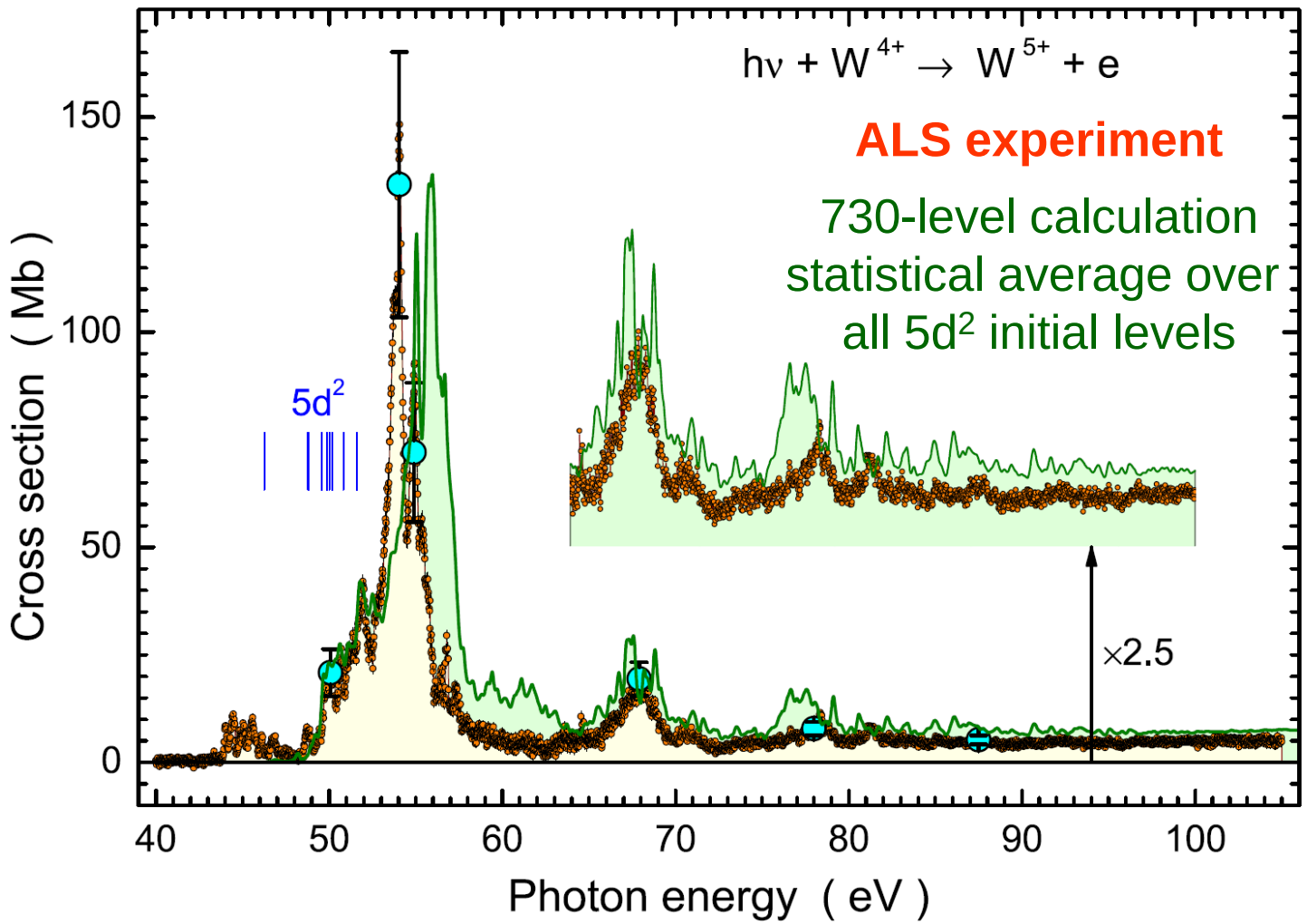
R-matrix theory for different initial levels

52-level calculation

730-level calculation

A. Müller, S. Schippers, J. Hellhund, A. L. D. Kilcoyne, R. A. Phaneuf, B. M. McLaughlin, J Phys. B **50** (2017) 085007

Valence-Shell Photoionization of $W^{4+}(5d^2)$



Müller et al., J Phys. B **50** (2017) 085007

see also Müller et al., J Phys. B **48** (2015) 235203 for W^{1+}

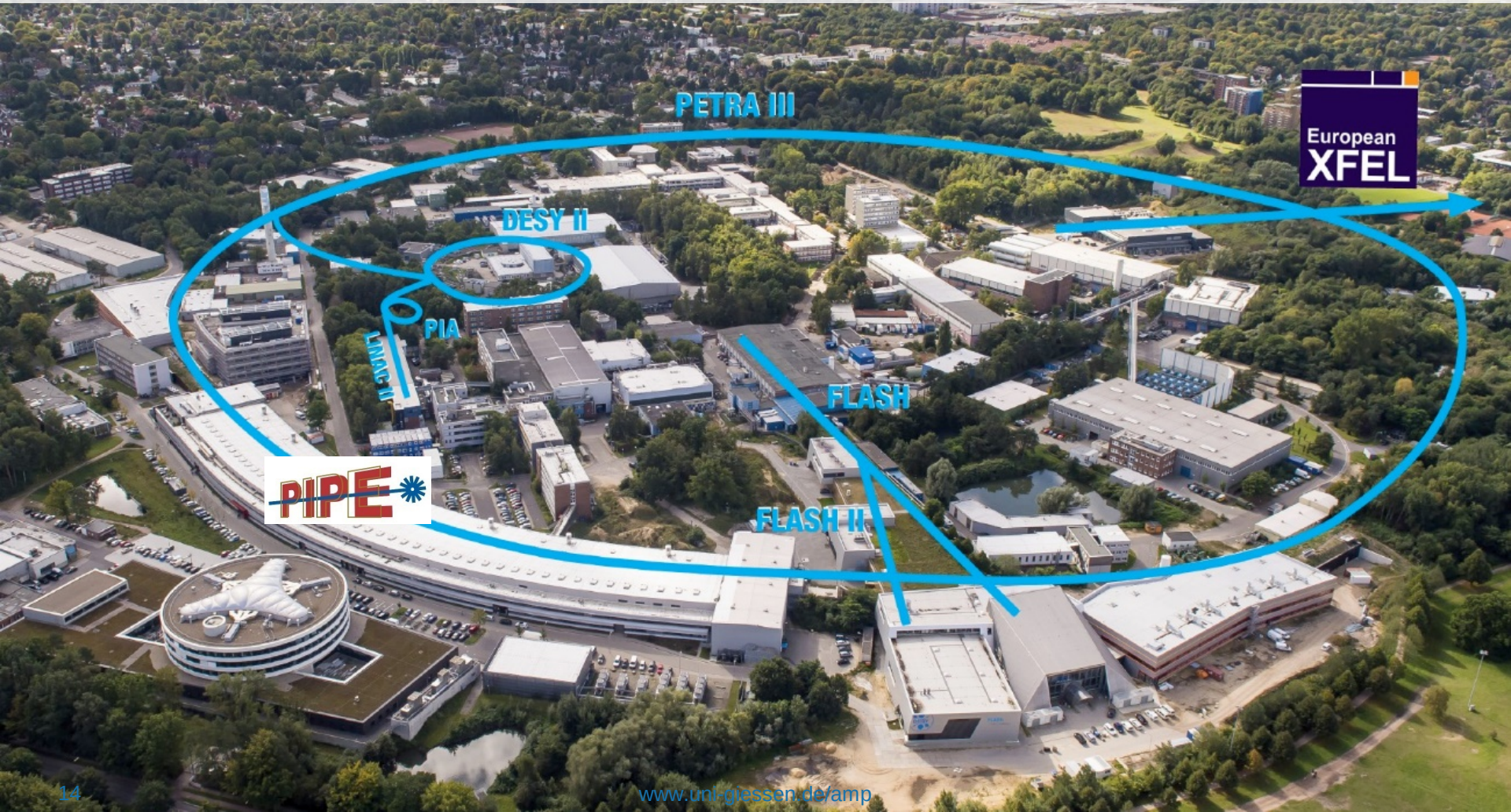
and McLaughlin et al., J. Phys. B 49 (2016) 065201 for W^{2+} and W^{3+}

Photons from PETRA III

aerial view of the DESY site in Hamburg

petra3.desy.de

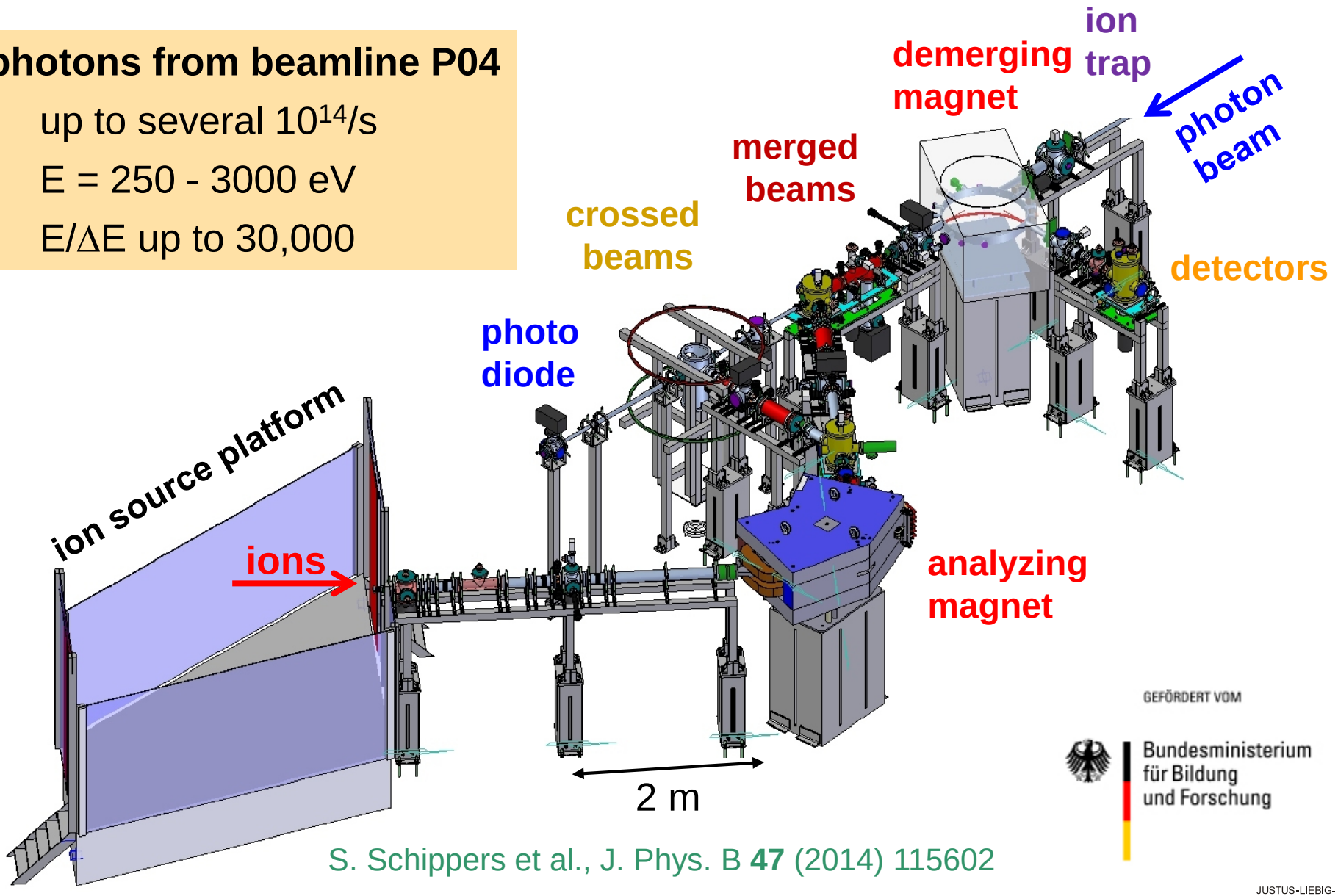
the world‘s most brilliant 3rd generation synchrotron light source



Photon-Ion Spectrometer at PETRA III

photons from beamline P04

- up to several 10^{14}/s
- E = 250 - 3000 eV
- E/ΔE up to 30,000



S. Schippers et al., J. Phys. B **47** (2014) 115602

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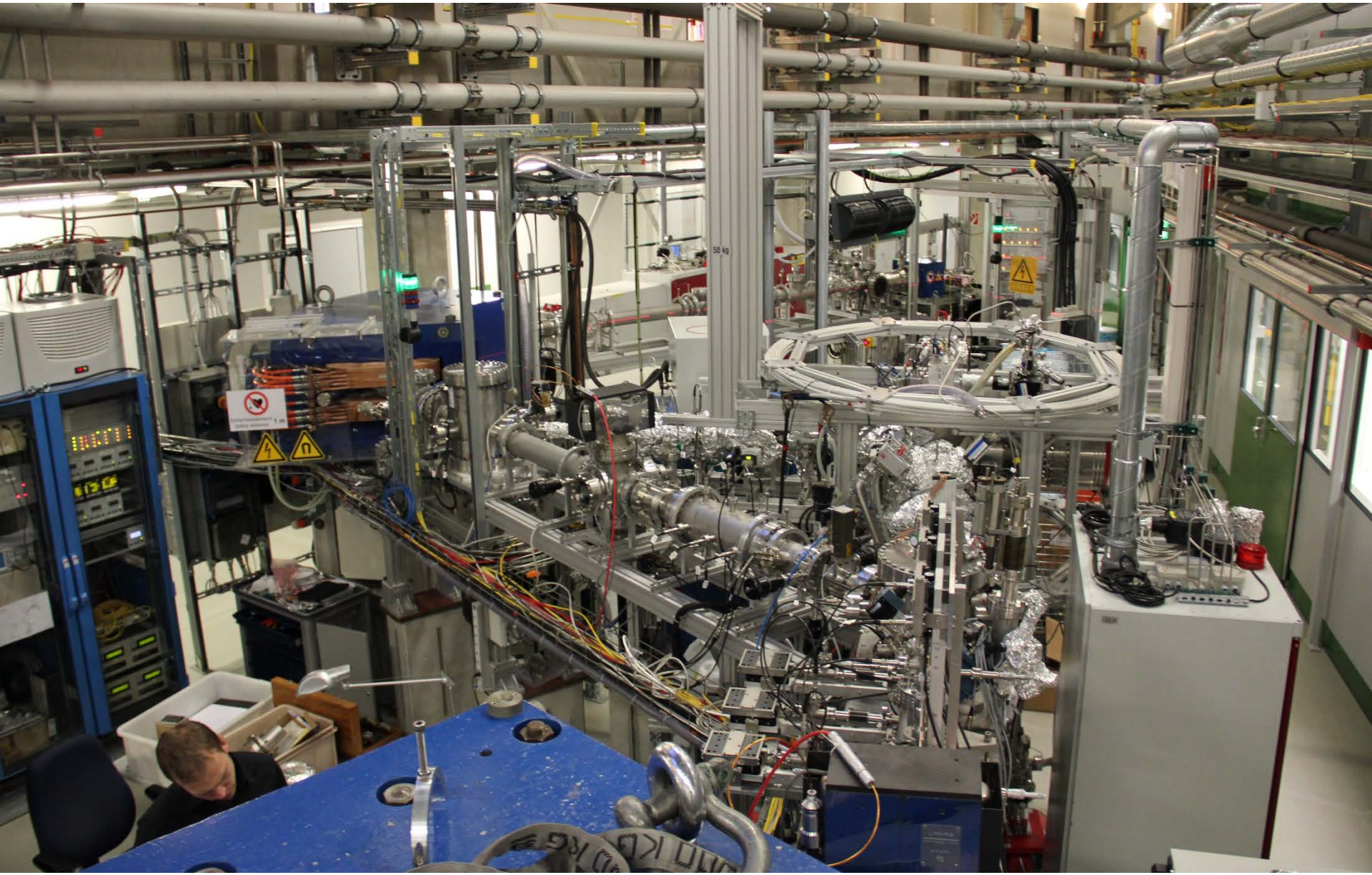
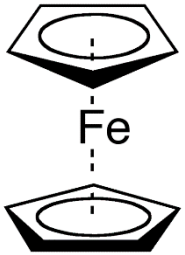
A.L.D. Kilcoyne

University of Nevada, Reno, USA
R. A. Phaneuf

View Towards the Ion Source



Mass/Charge Selection of Ions



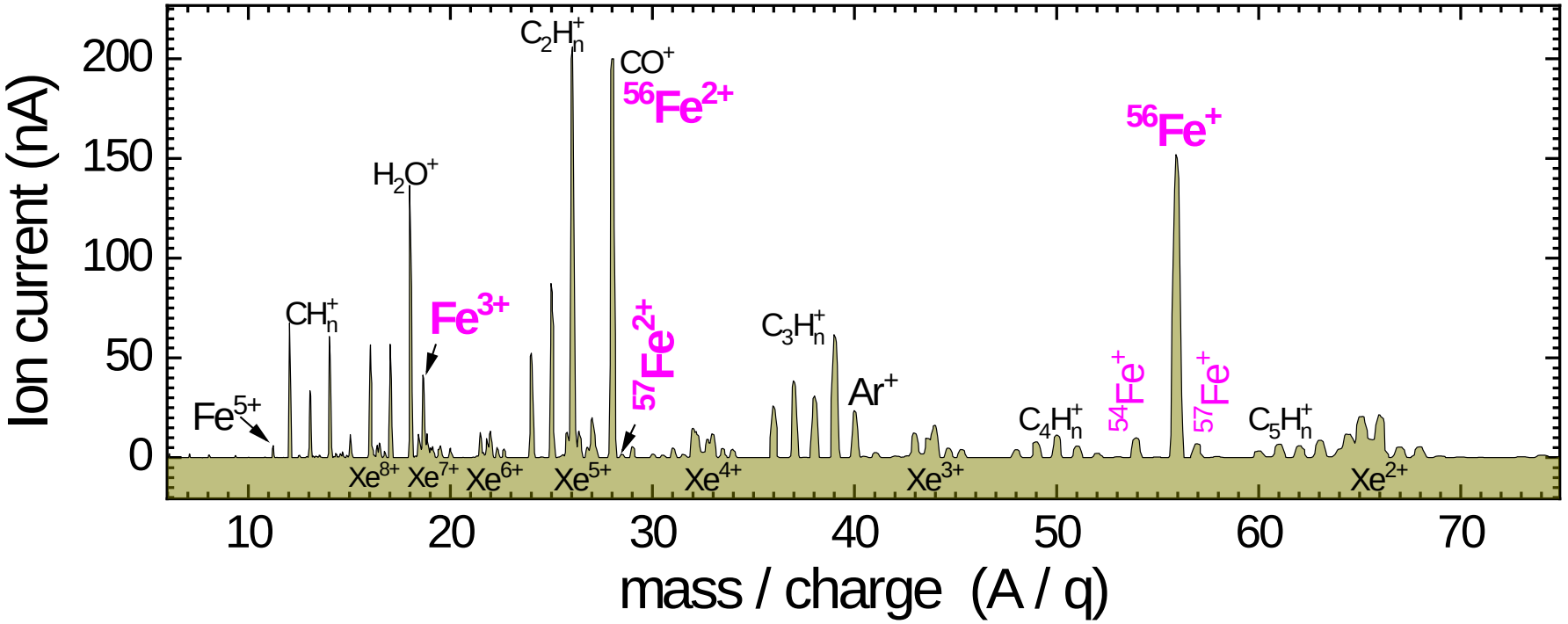
ferrocene

$FeC_{10}H_{10}$

ECR ion source

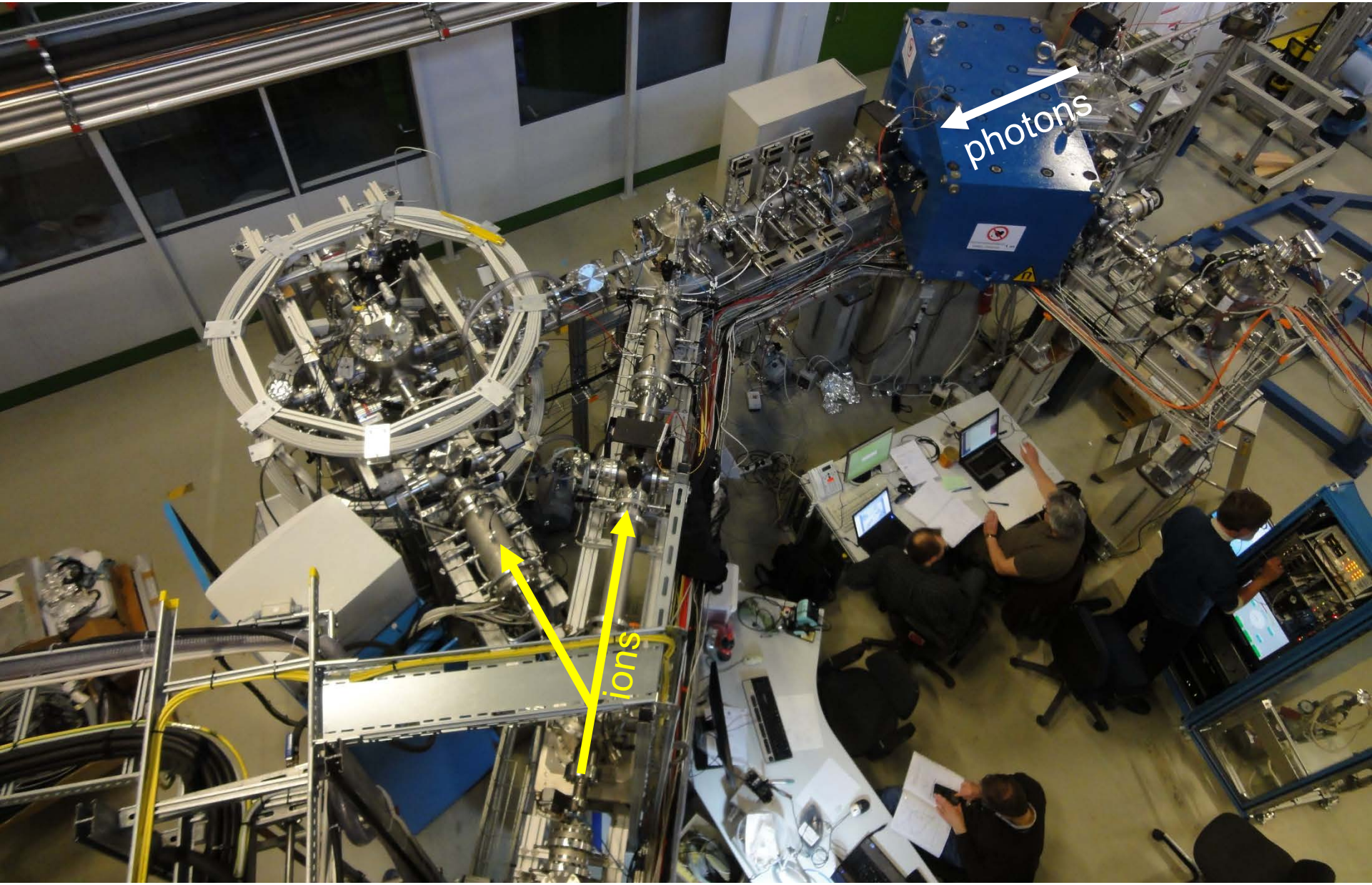
magnet

mass/charge selected ions



experiments with dilute ensembles of mass-selected small quantum systems

View of the Interaction Region



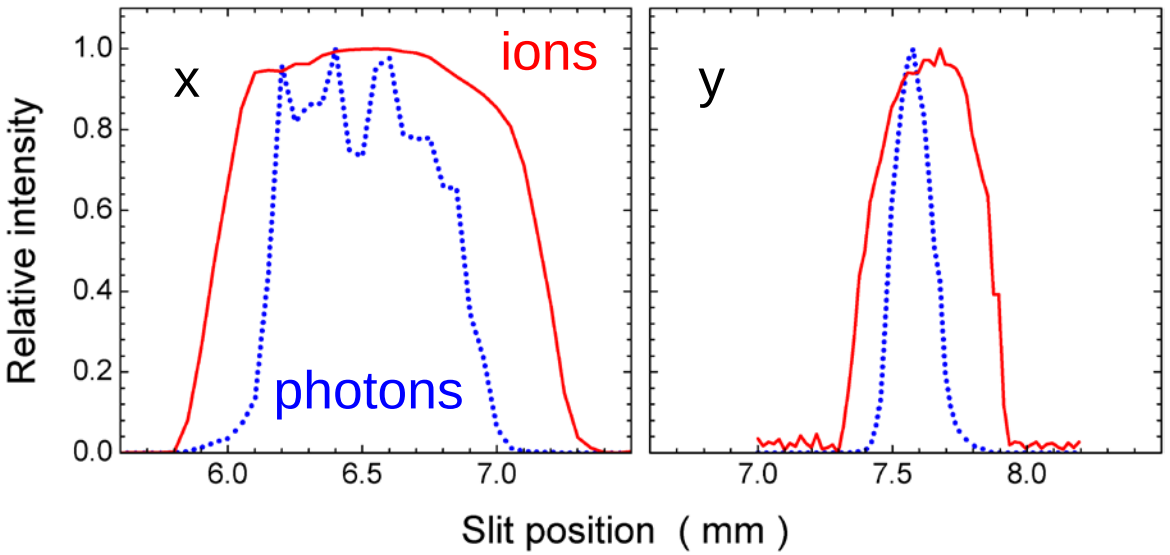
Determination of Absolute Cross Sections

measured count rate: $R = \sigma \frac{I_{ion} L}{q e v_{ion}} \phi_{ph} \frac{1}{F}$

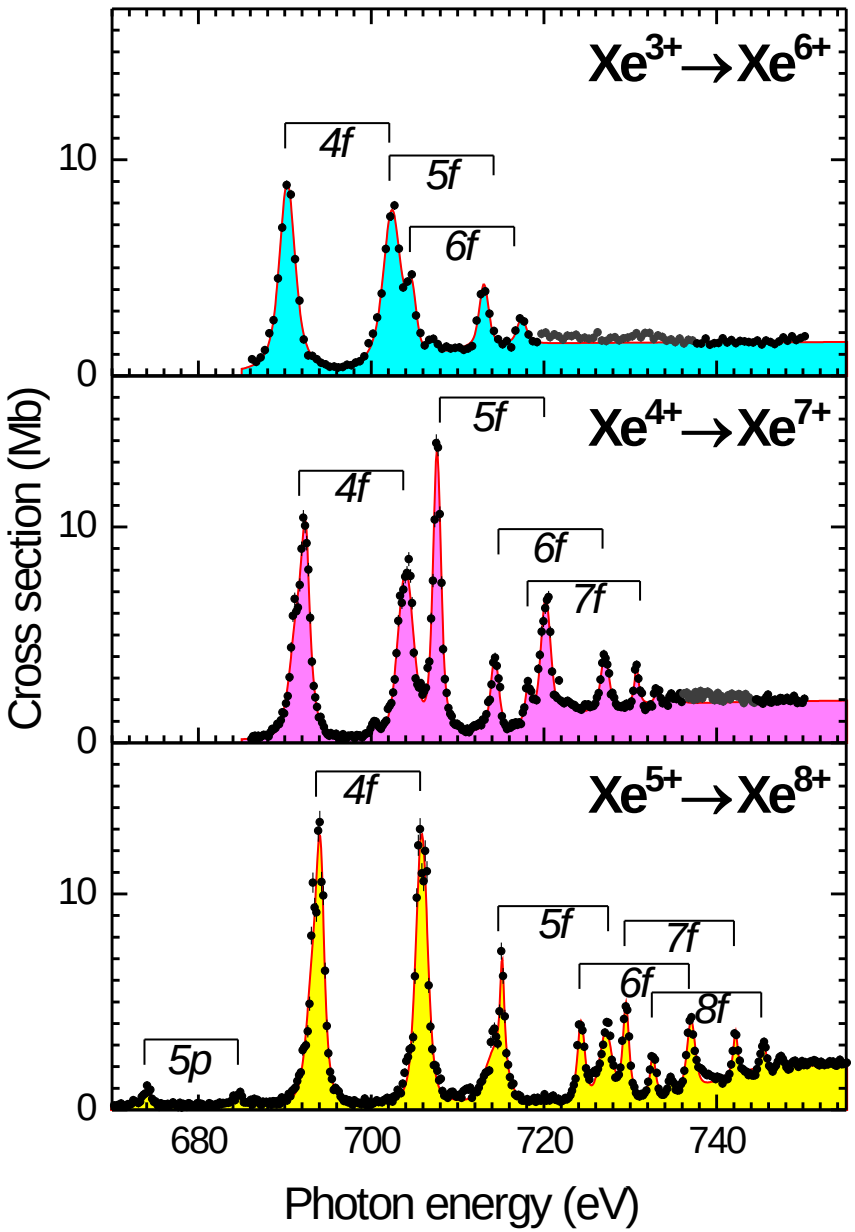
cross section	number of ions	photon flux	beam overlap

typical **uncertainty** of absolute cross section

15%



First Results: 3d-Ionization of Xe Ions



experimental energy spread: 0.16 eV
natural resonance width: ~0.6 eV

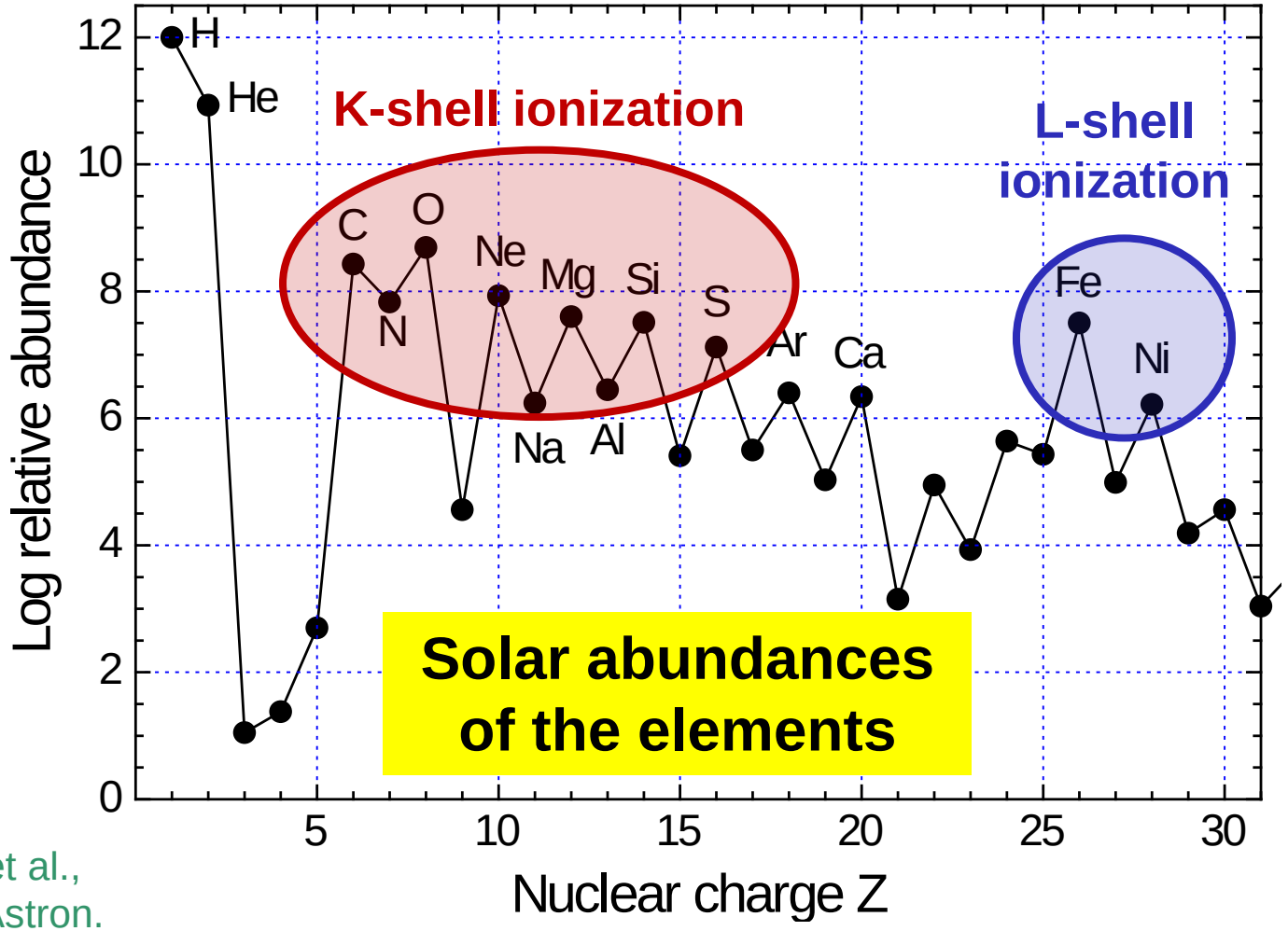
$3d^{-1}$ nf resonances

stepwise collapse
of f-wave functions
with increasing
primary charge state

S. Schippers et al., J. Phys. B **47** (2014) 115602
S. Schippers et al., J. Phys. B **48** (2015) 144003
J. Phys. B Highlights 2014 and 2015

Inner-Shell Ionization of Astrophysically Relevant Ions

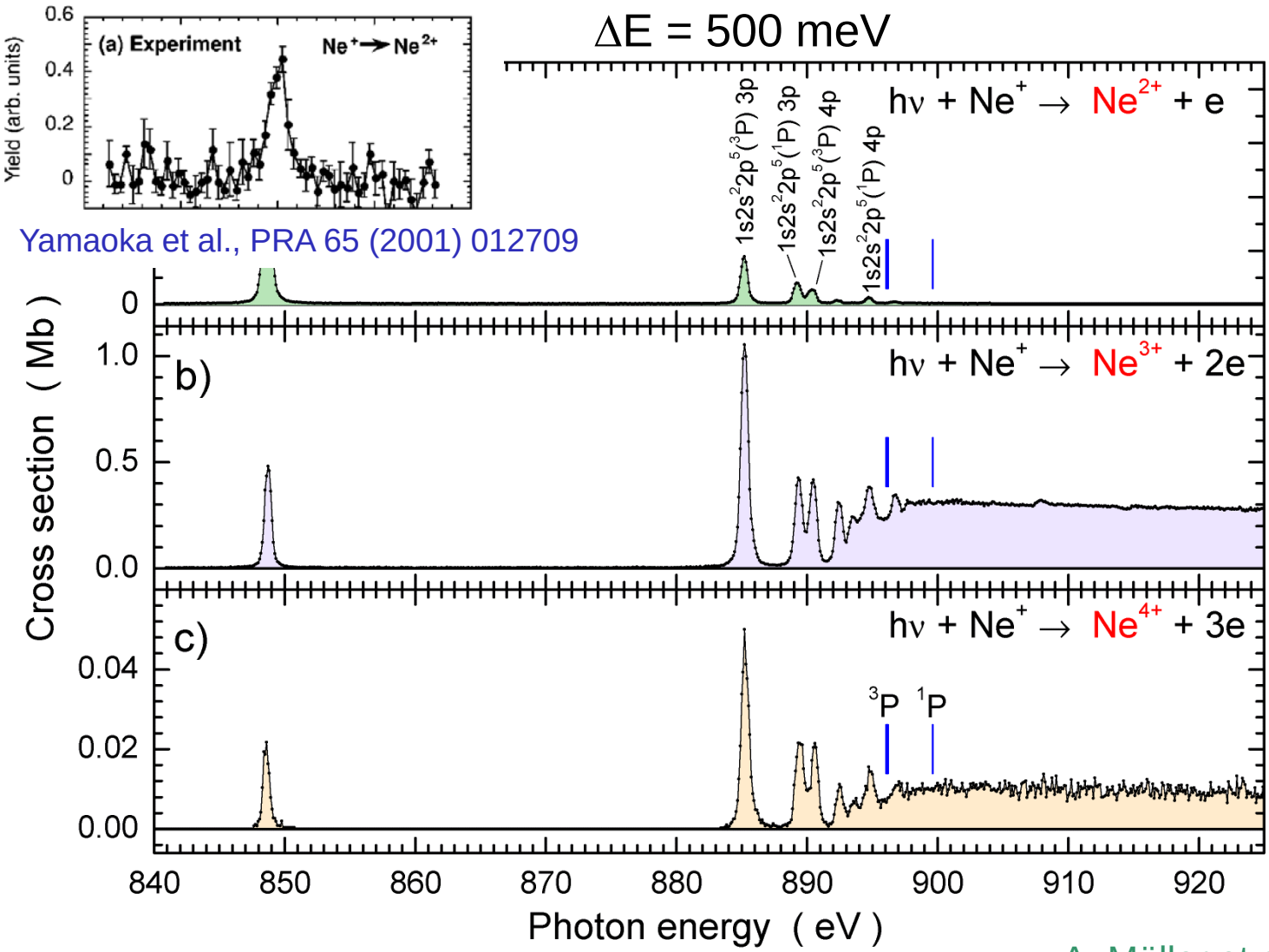
with 250 – 3000 eV photons



M. Asplund et al., Annu. Rev. Astron. Astrophys. **47** (2009) 481

K-Shell Ionization of Ne^+ Ions

PIPE has lead to a breakthrough in inner-shell ionization of ions



Yamaoka et al., PRA 65 (2001) 012709

single ionization

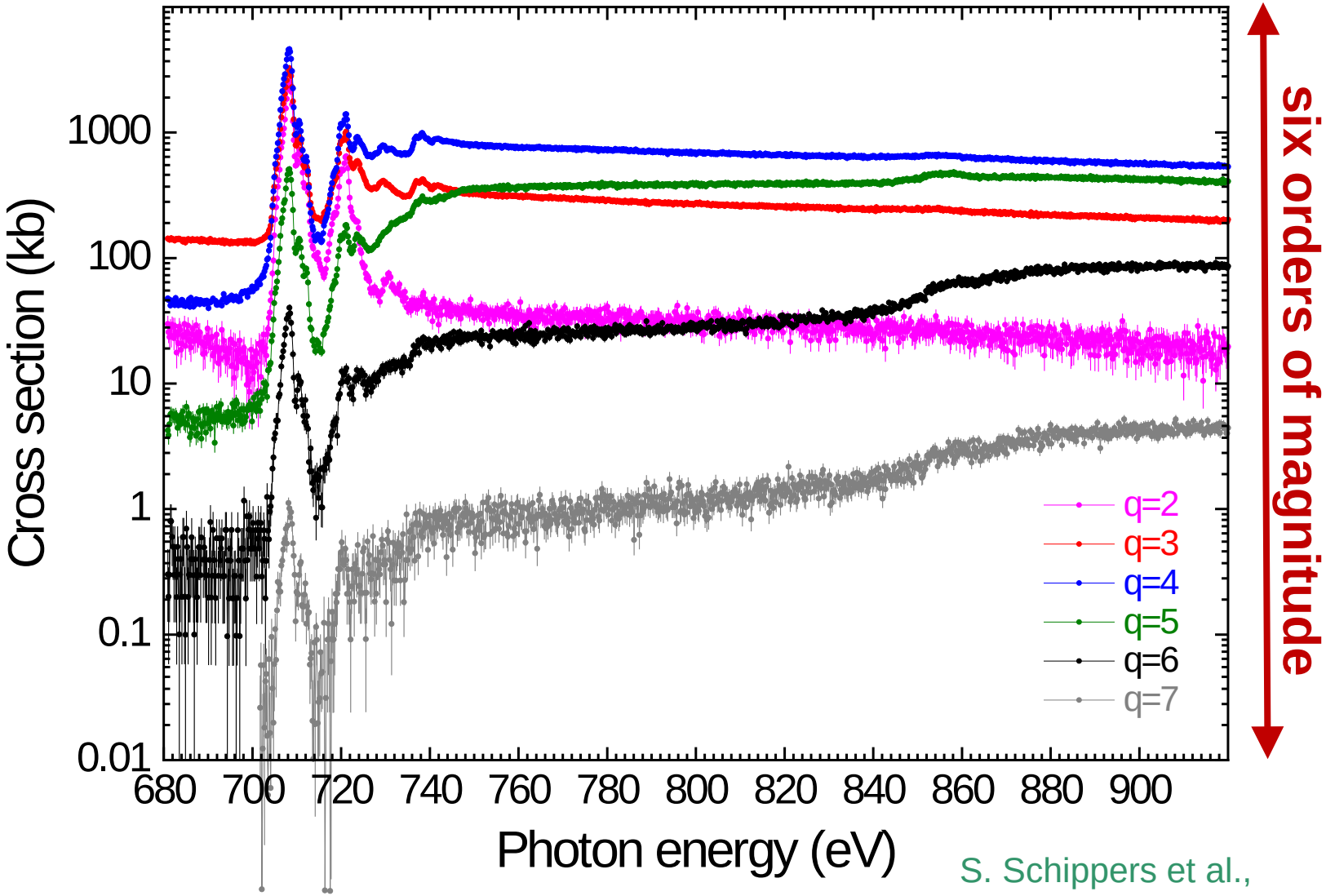
double ionization

triple ionization

A. Müller et al., ApJ **836** (2017) 166

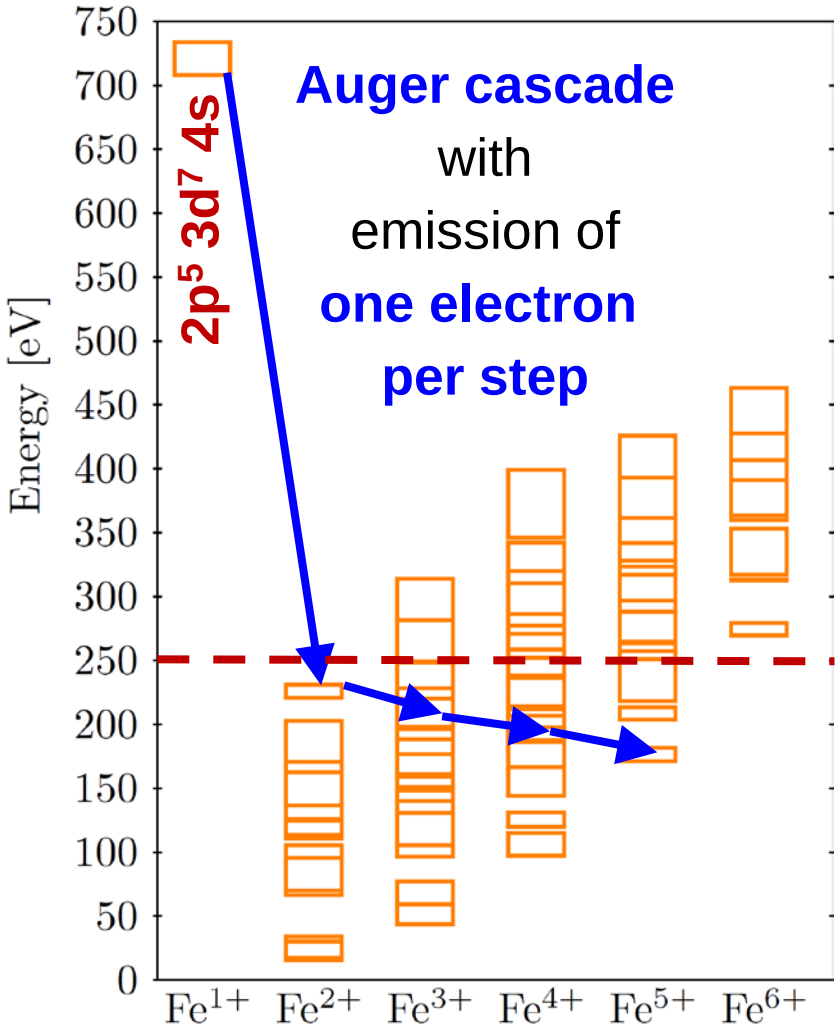
Fe^+: Experimental Cross Sections

$$h\nu + Fe^+ \rightarrow Fe^{q+} + (q-1)\, e^-$$



S. Schippers et al., ApJ **849** (2018) 5

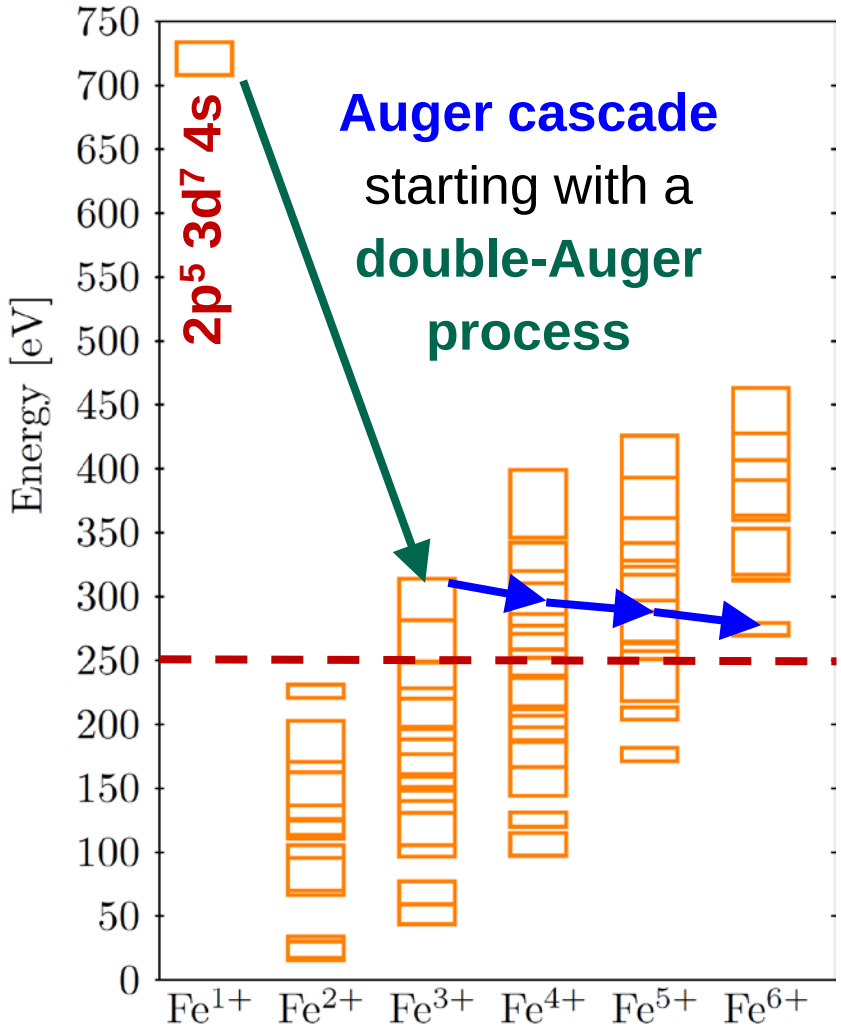
Accessible Energy Levels after 2p Excitation of $Fe^{+}(1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^6\ 4s)$



MCDF energy levels

production of Fe^{6+} by a sequence of one-electron Auger processes energetically impossible

Accessible Energy Levels after 2p Excitation of $Fe^{+}(1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^6\ 4s)$



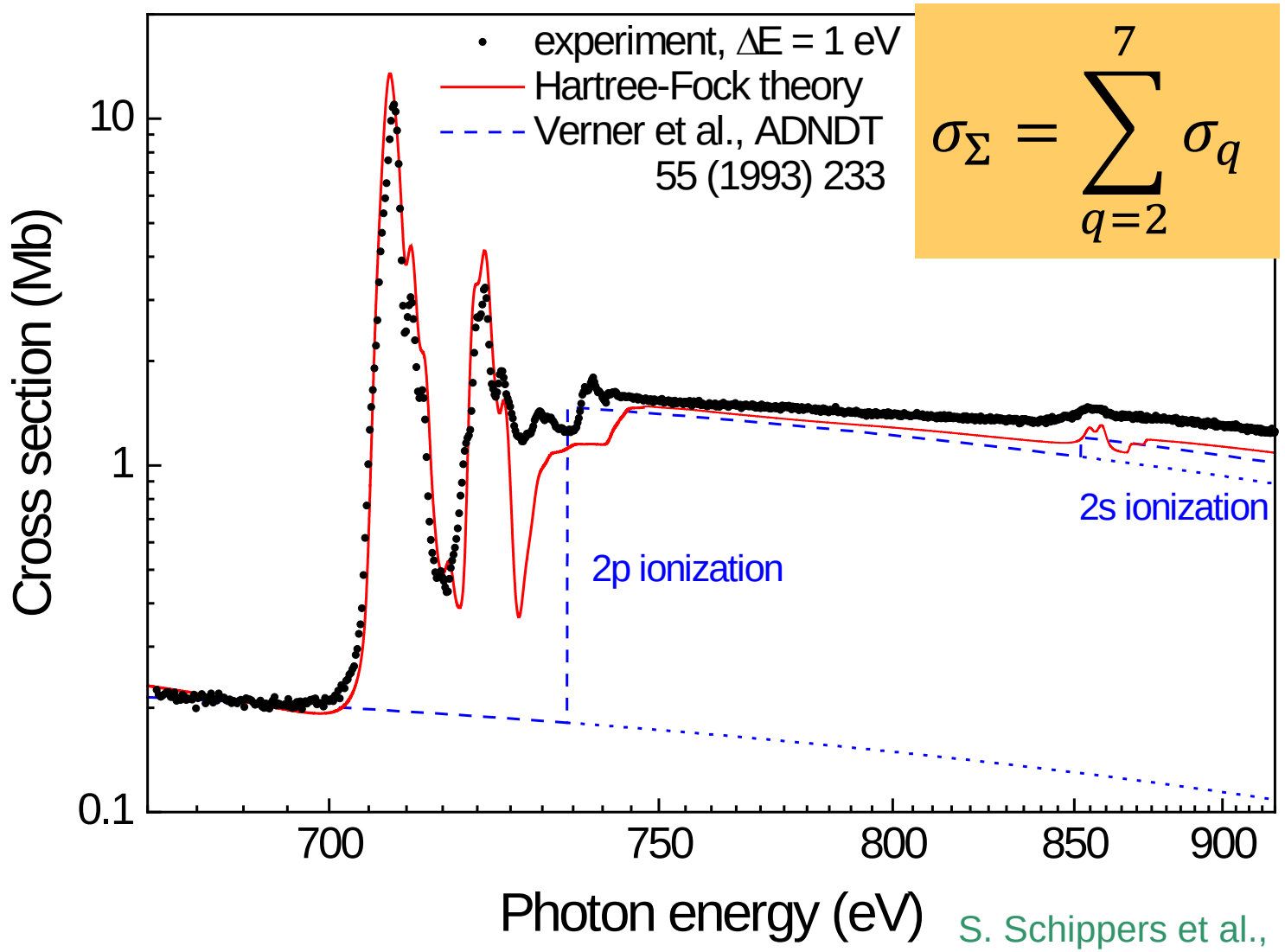
MCDF energy levels

production of Fe^{6+} by a sequence of one-electron Auger processes energetically impossible

double-Auger processes are required for the production of Fe^{6+} and higher charge states

Fe^+ Absorption Cross-Section

filling of L-shell holes by radiative transitions is negligible



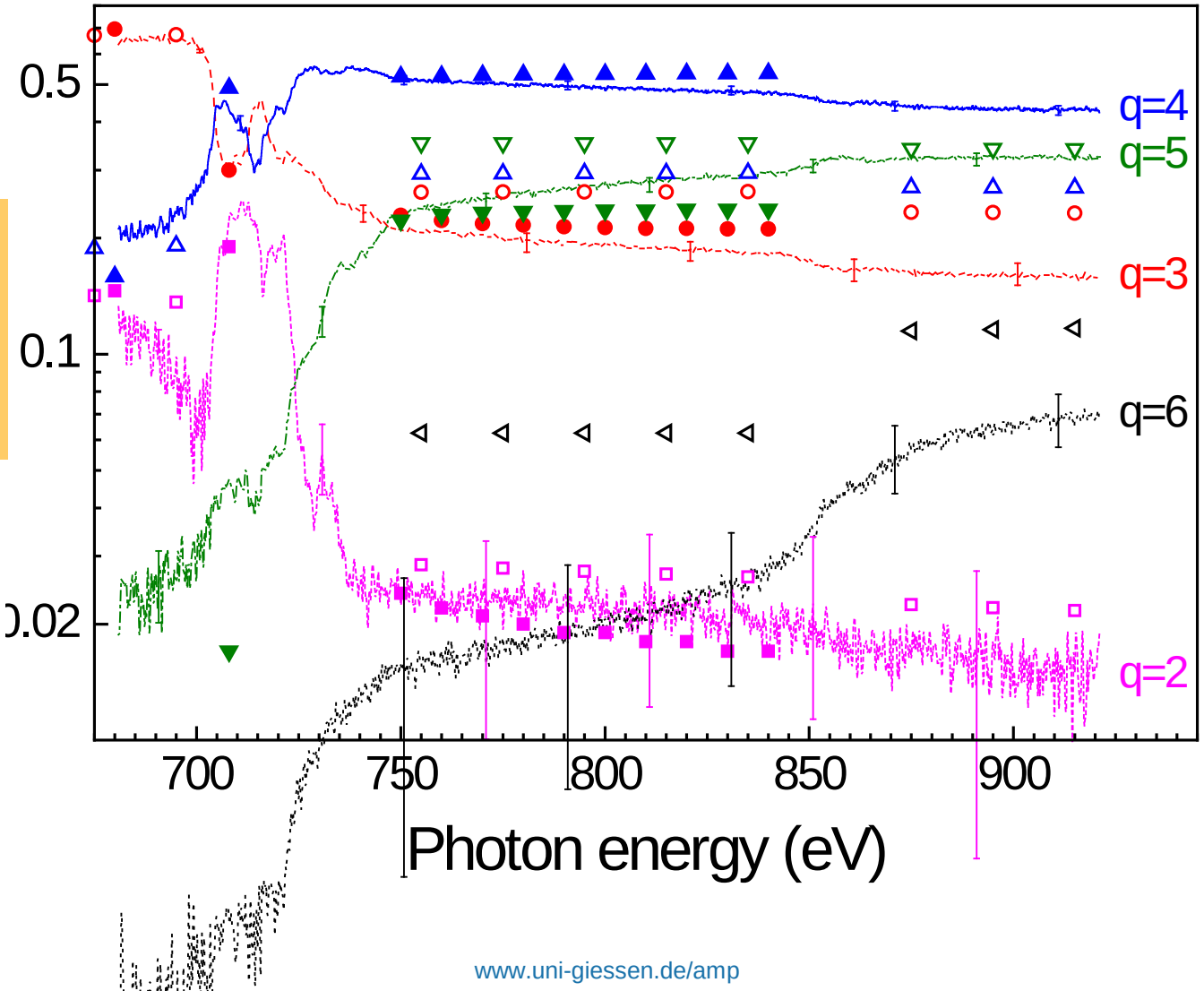
S. Schippers et al., ApJ **849** (2018) 5

Charge-State Fractions

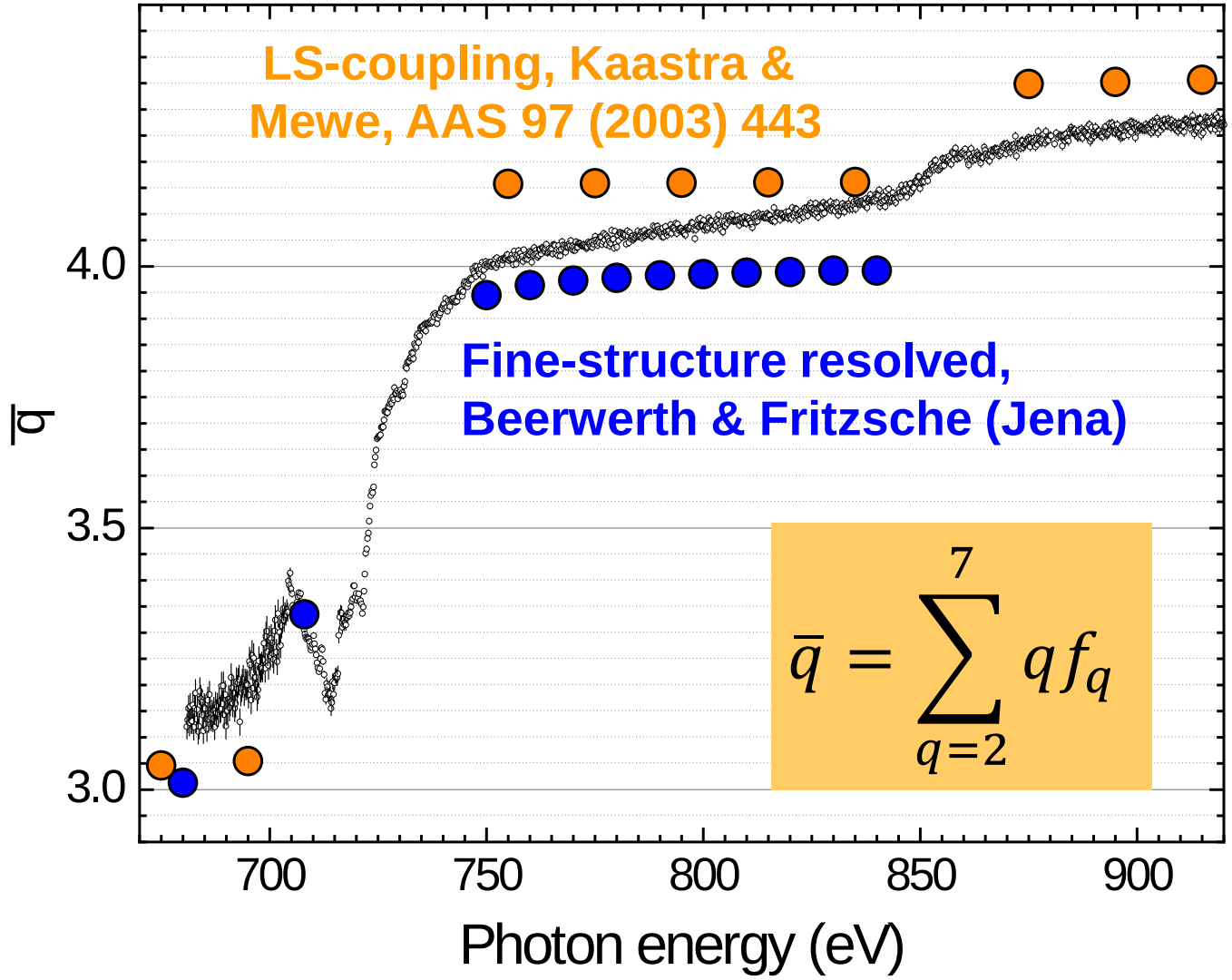
full symbols: Beerwerth & Fritzsche (Jena), **LSJ**-coupling

open symbols: Kaastra & Mewe, AAS (1993), **LS**-coupling

$$f_q = \frac{\sigma_q}{\sigma_\Sigma}$$

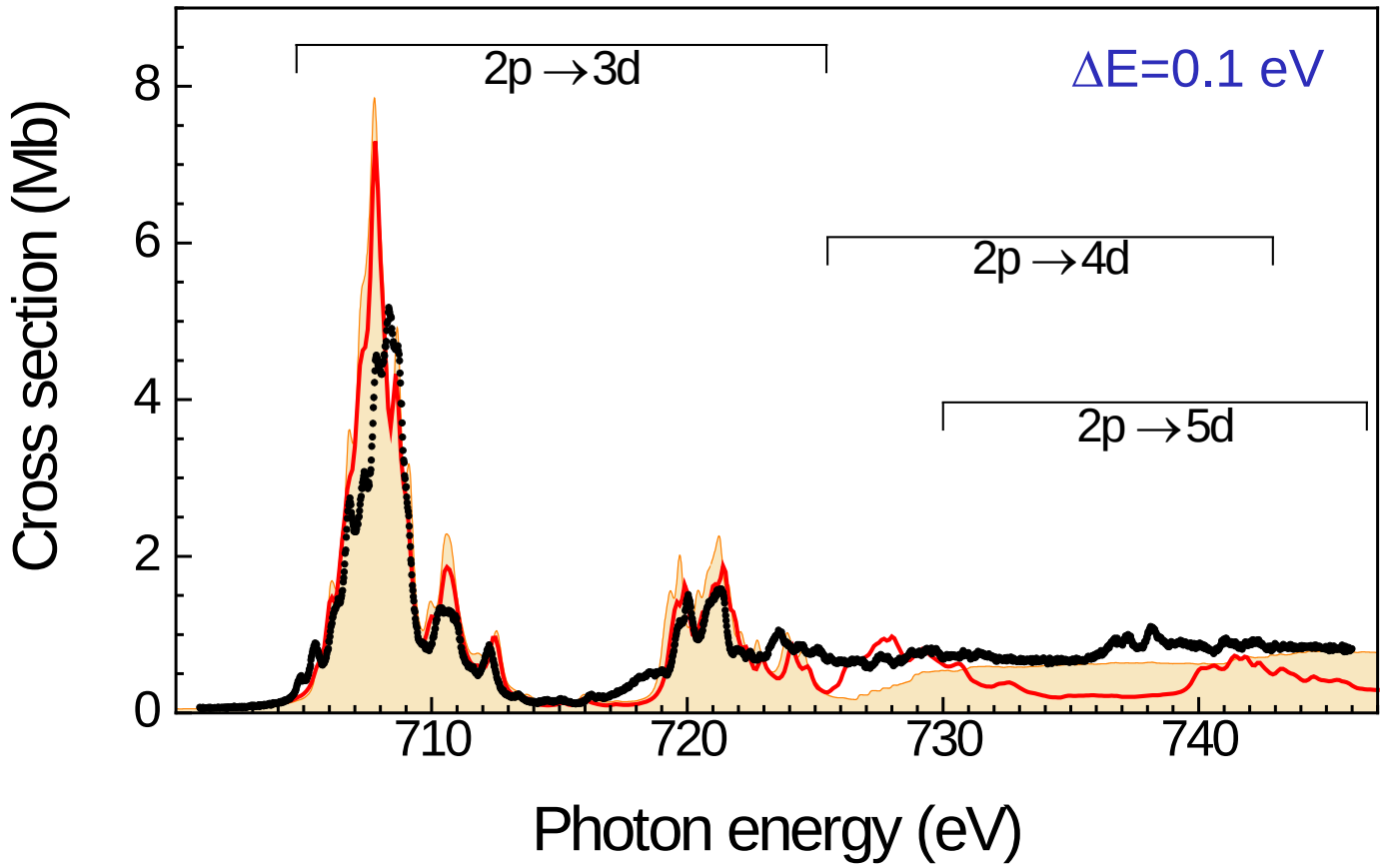


Mean Charge State of Product Ions



High-Resolution Measurement

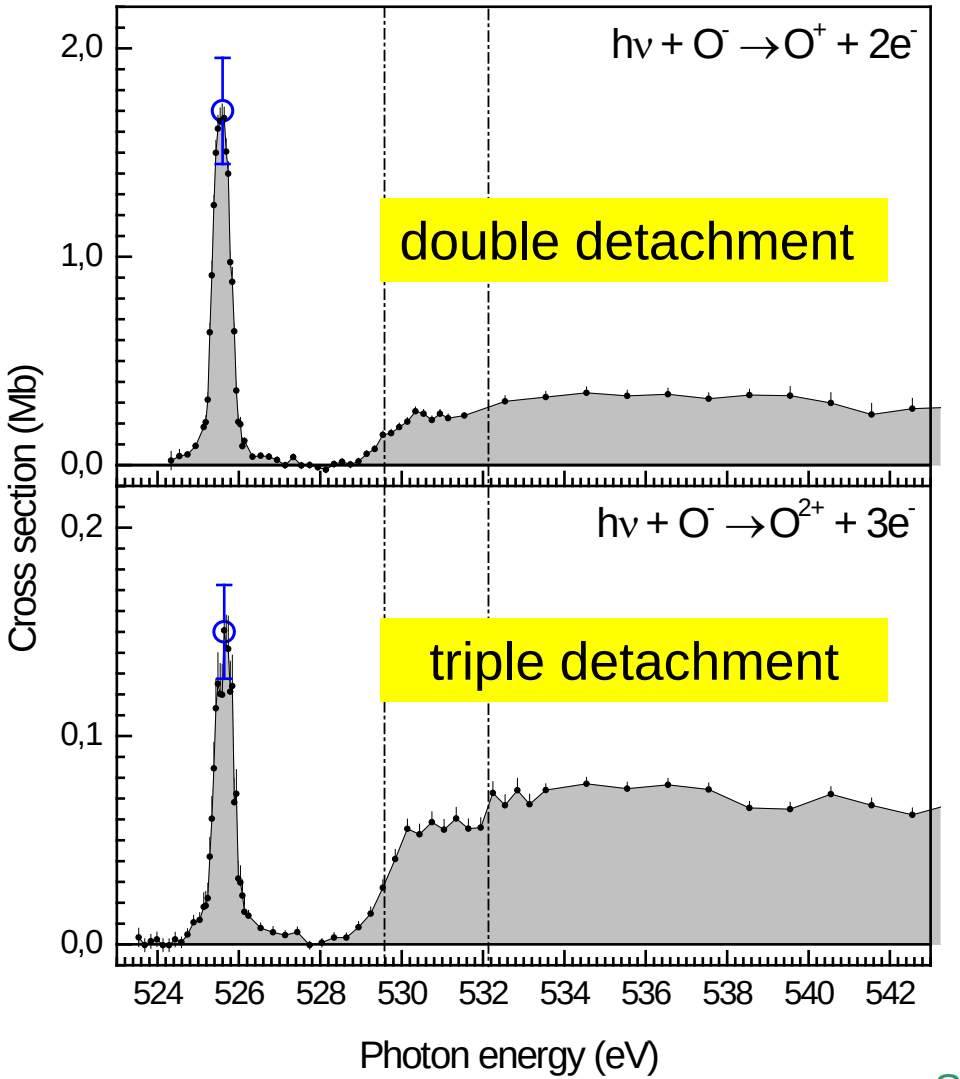
comparison with **Hartree-Fock** and **Dirac-Fock** theory
theoretical curves shifted by -2.8 and 1.0 eV



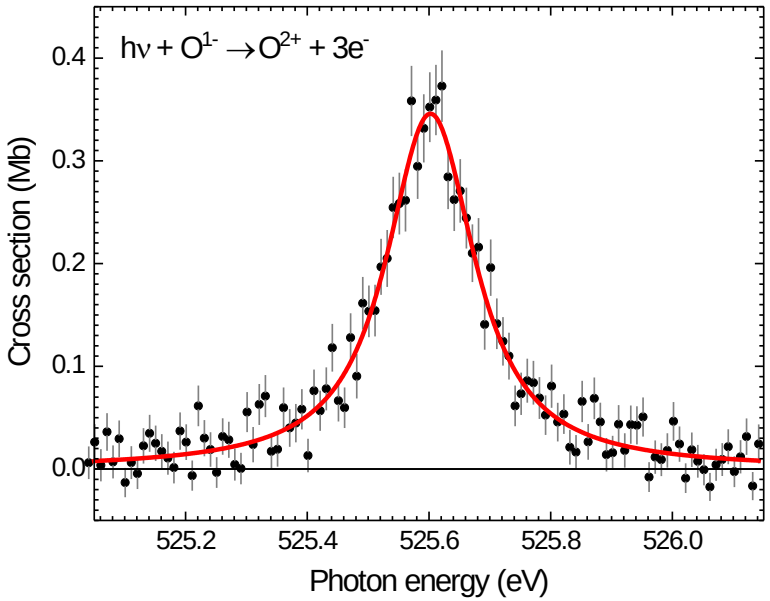
natural line widths: ~ 0.4 eV
uncertainty of the energy scale: ~ 0.2 eV

Photodetachment of Negative Ions

photodetachment of O^-



$1s\ 2s^2\ 2p^6$ resonance



line width: 164 ± 24 meV

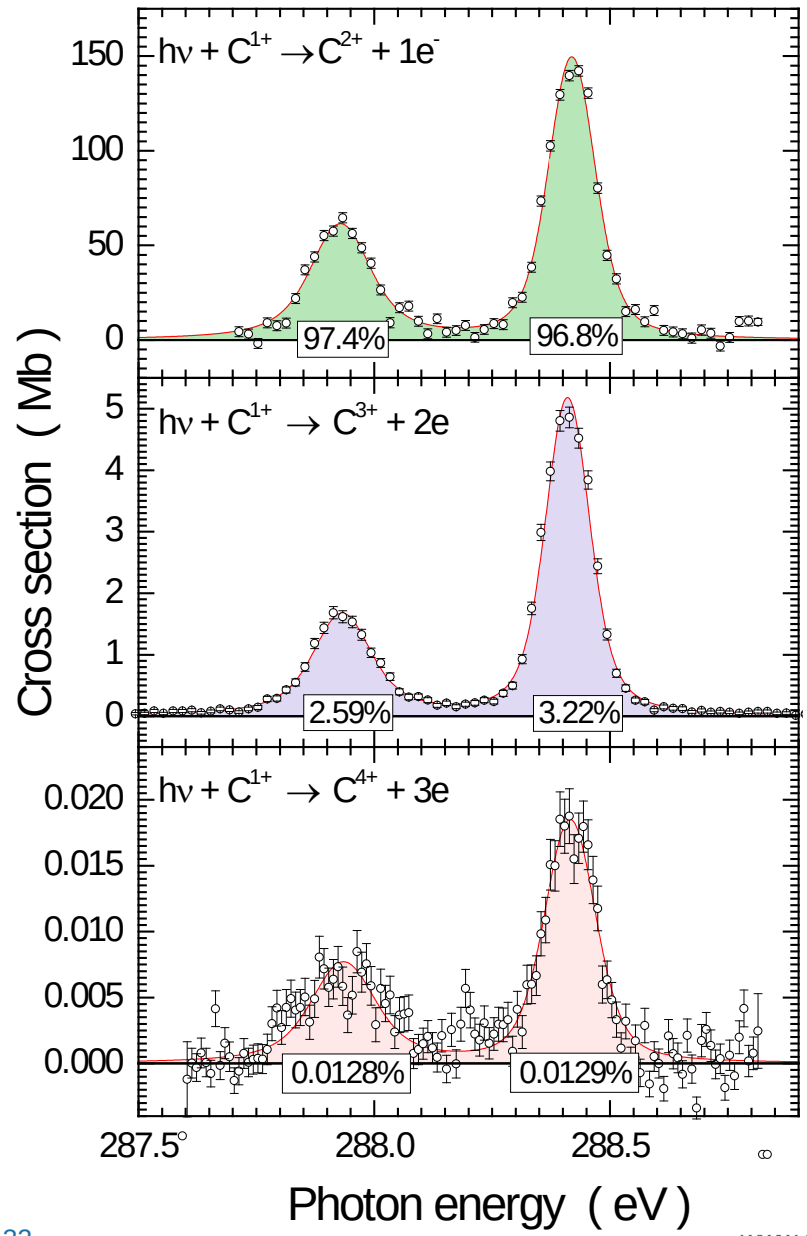
theory by R. Beerwerth and S. Fritzsche, Jena:

triple detachment requires double shake-up during KLL-Auger decay

S. Schippers et al., PRA **94** (2016) 041401(R) (editors' suggestion)

Multi-Electron Auger Processes

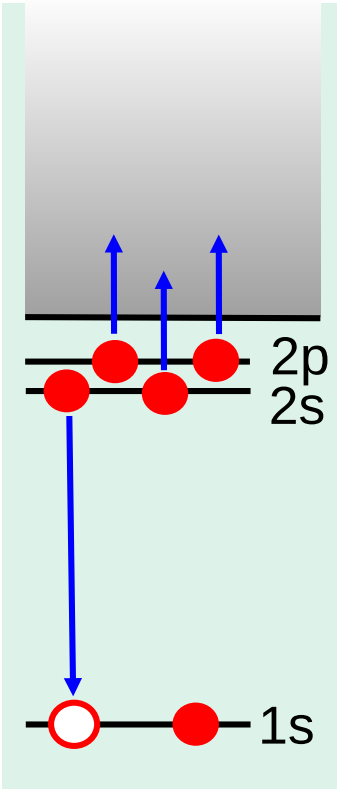
1s 2s² 2p² ²D,²P resonances



single Auger

double Auger

triple Auger



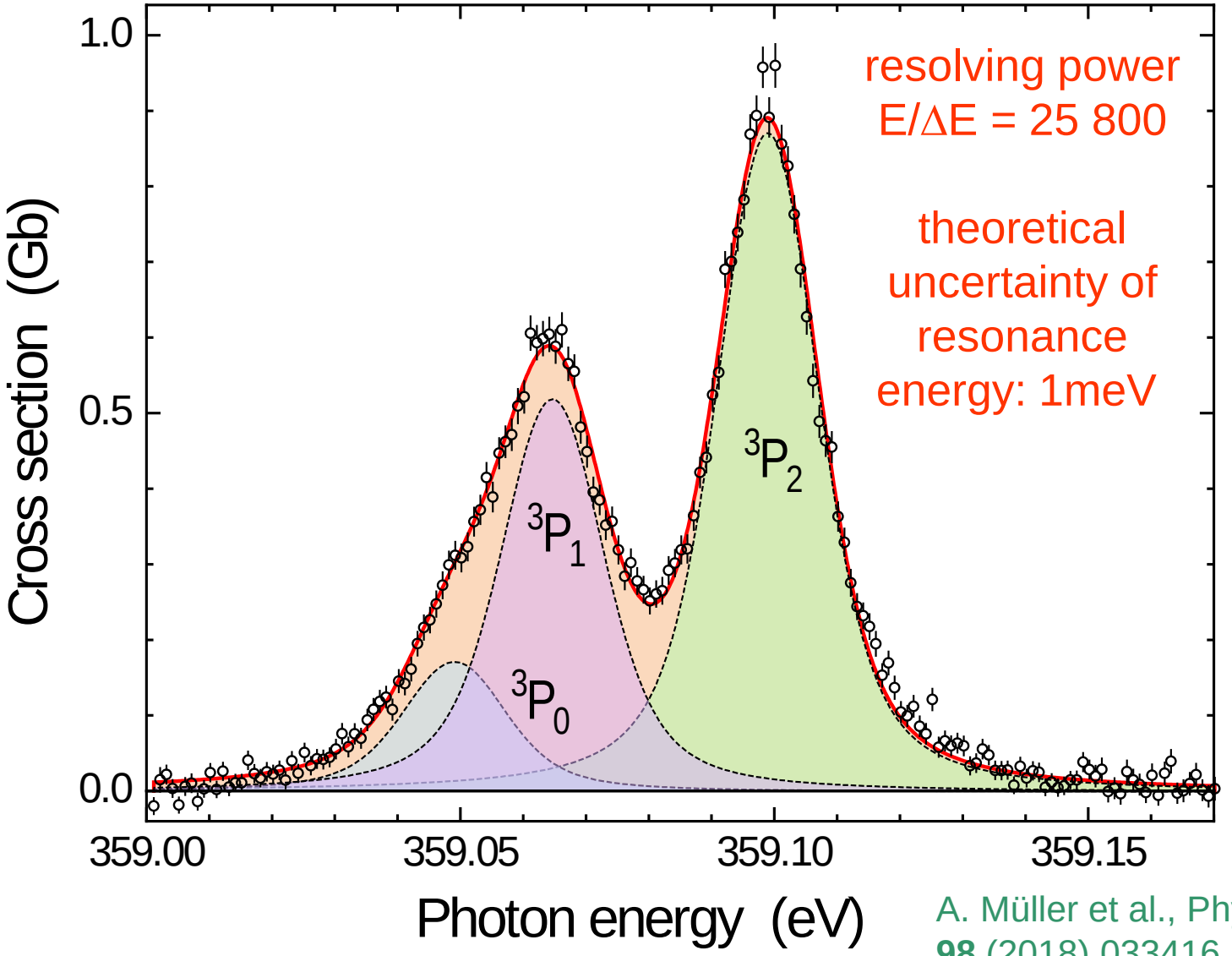
DESY Highlight 2015

A. Müller et al., PRL **114** (2015) 013002

(editors‘ suggestion)

High-Res. Measurements of Resonances

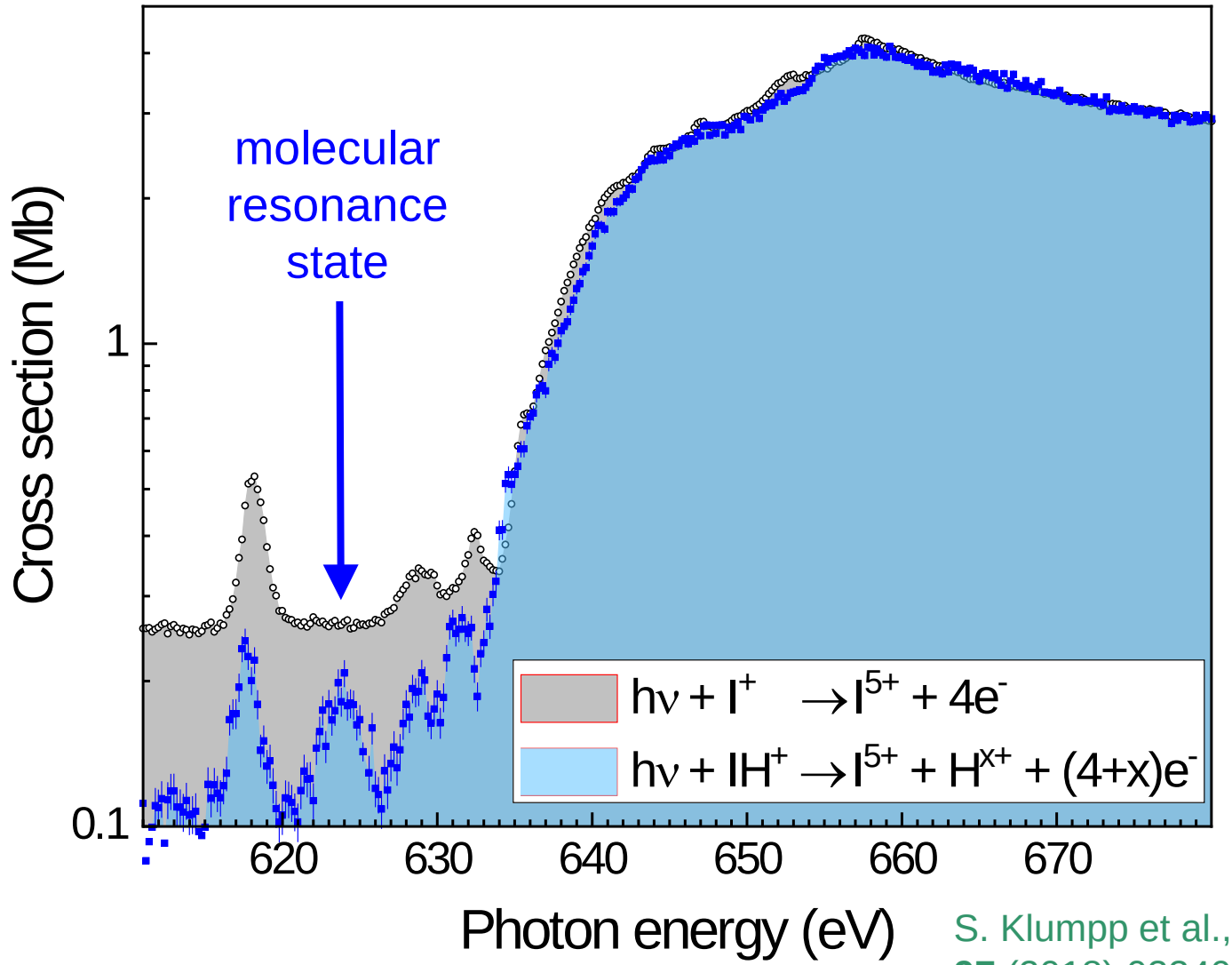
PI of $C^{4+}(1s\,2s\ ^3S)$ - $2s\,2p\ ^3P_J$ resonances



A. Müller et al., Phys. Rev. A **98** (2018) 033416

Small Molecular Ions

ionization of IH^+ at the iodine 3d edge



S. Klumpp et al., Phys. Rev. A **97** (2018) 033401

Summary

- Electron and photon collisions with ions
- Cross sections for (multiple) ionization
- Role of many-electron processes
- Accurate spectroscopy information on multiply excited states
- Benchmarks for atomic structure and atomic collision theories

Thank you for your attention!