# Tin ions:

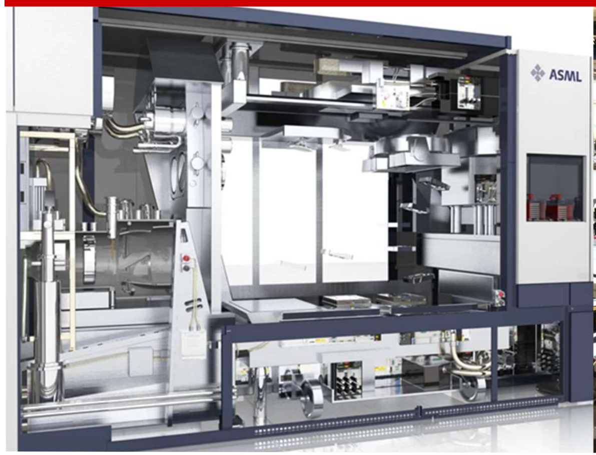
# Spectroscopy and Interactions

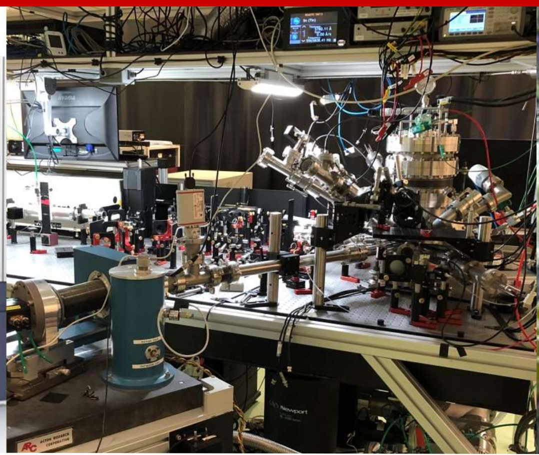
*Ronnie Hoekstra*

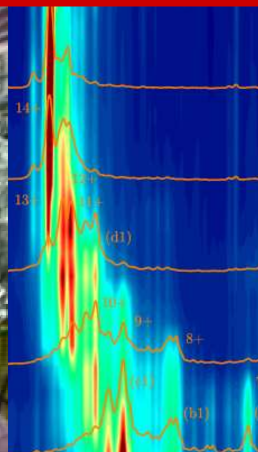
ARCNL
ADVANCED RESEARCH CENTER FOR NANOLITHOGRAPHY

NWO FOM Institute AMOLF Universiteit van Amsterdam VU Vrije Universiteit Amsterdam Gemeente Amsterdam Provincie Noord-Holland ASML

university of groningen 2014 | 400 years
zernike institute for advanced materials

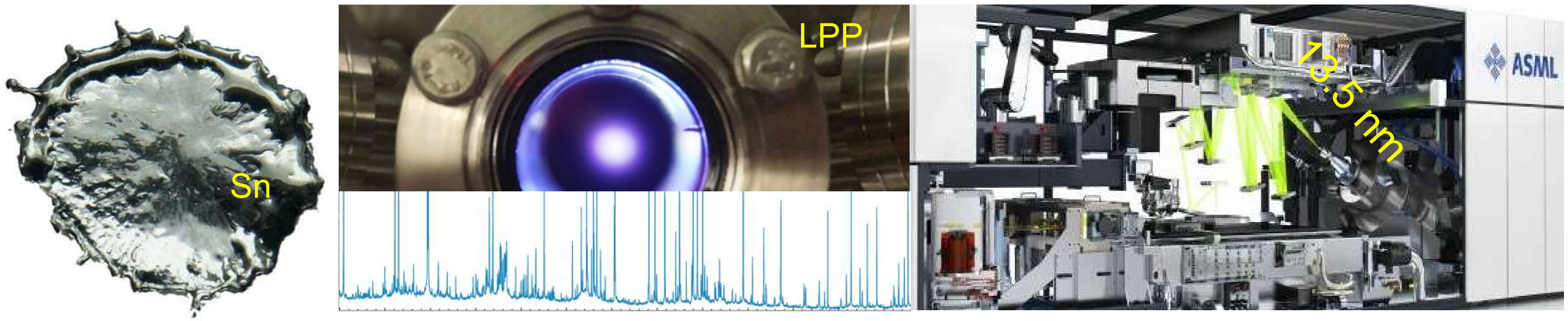




# outline

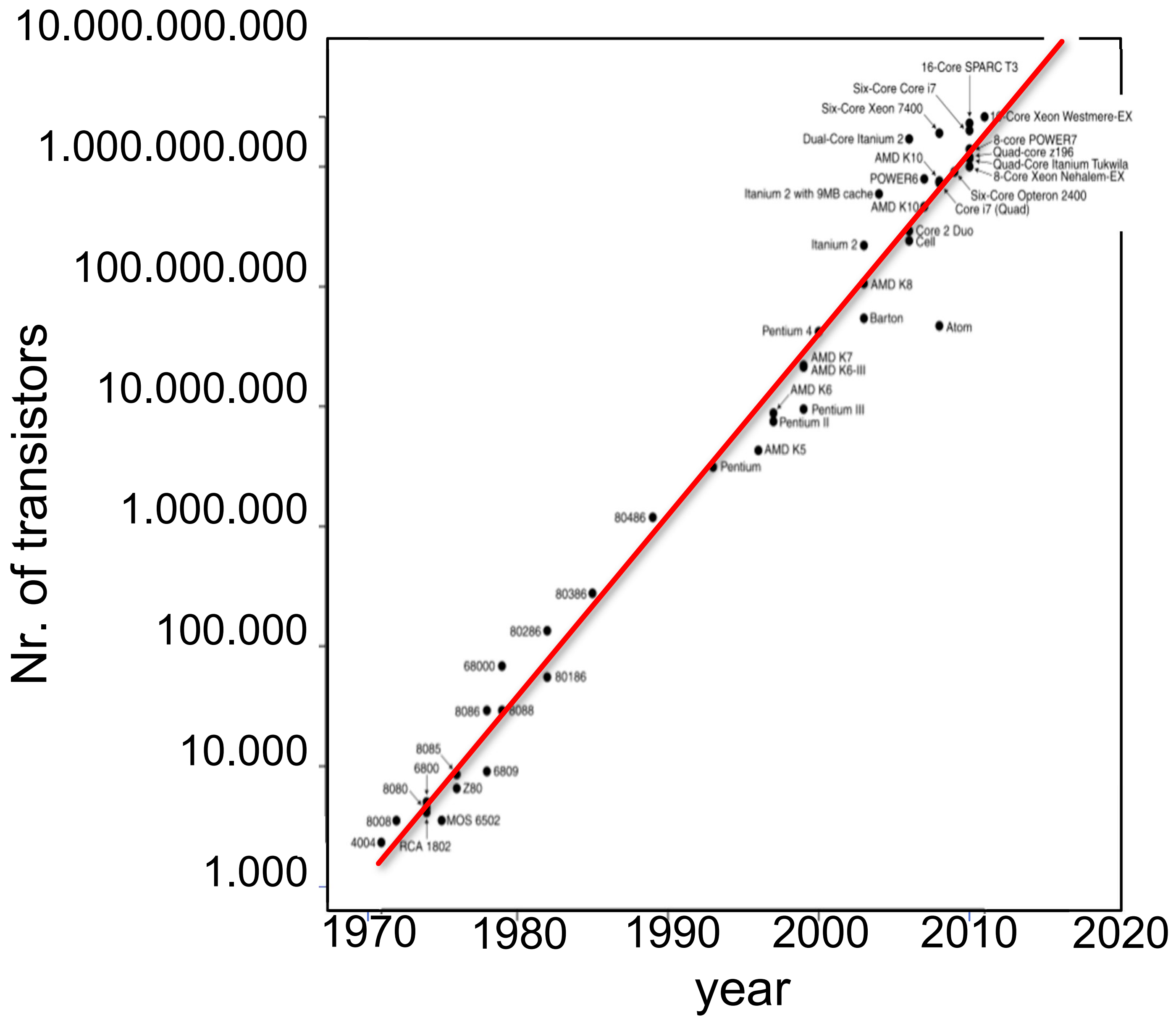
- introduction on lithograpy
- ARCNL
  advanced research center for nanolithography



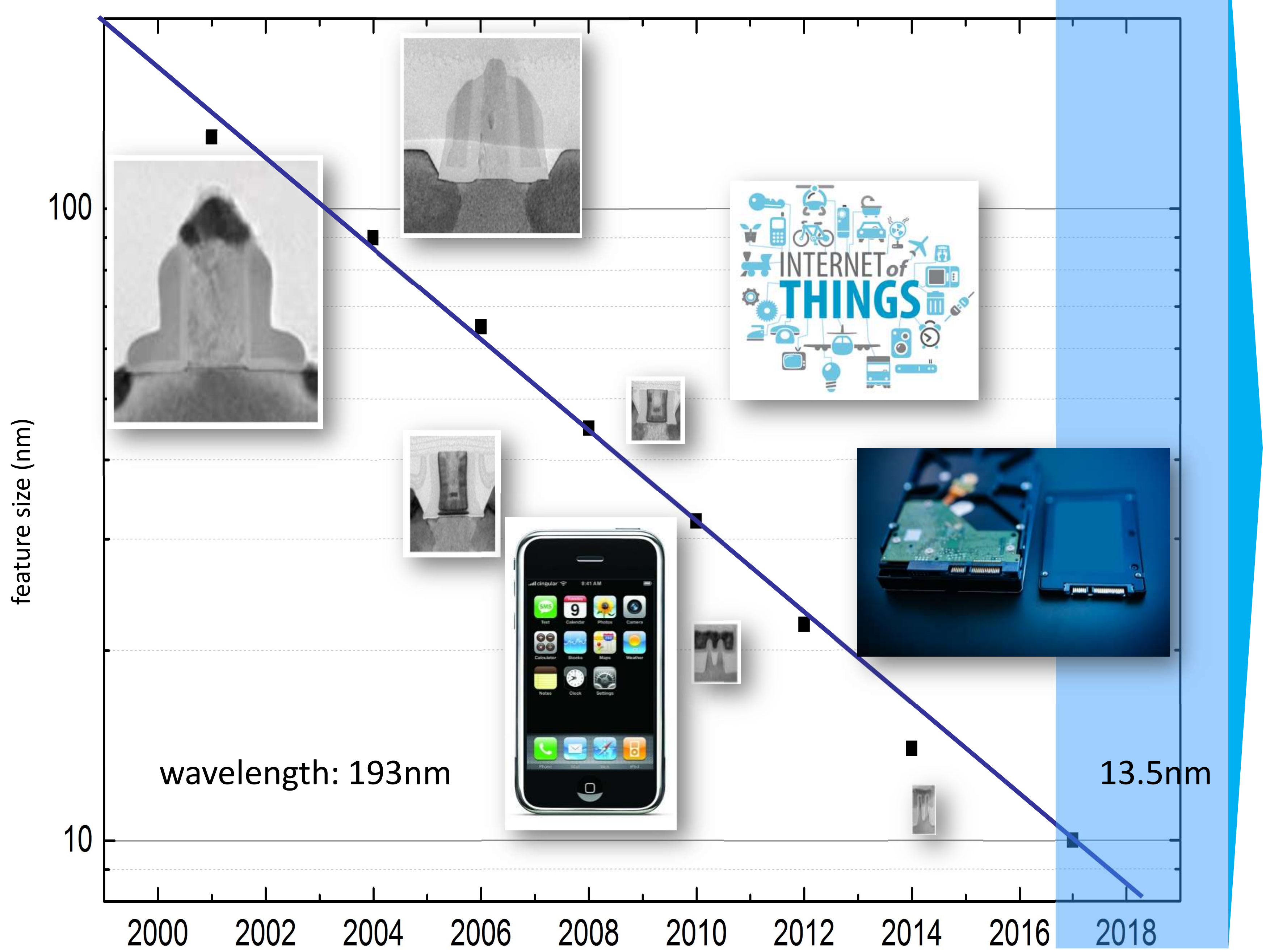

- Fundamental physics aspects of EUV generation
  - (propulsion and deformation of tin droplets)
  - tin ion spectroscopy for diagnostics
  - energetic-ion emission and plasma-wall interactions

# Moore’s law

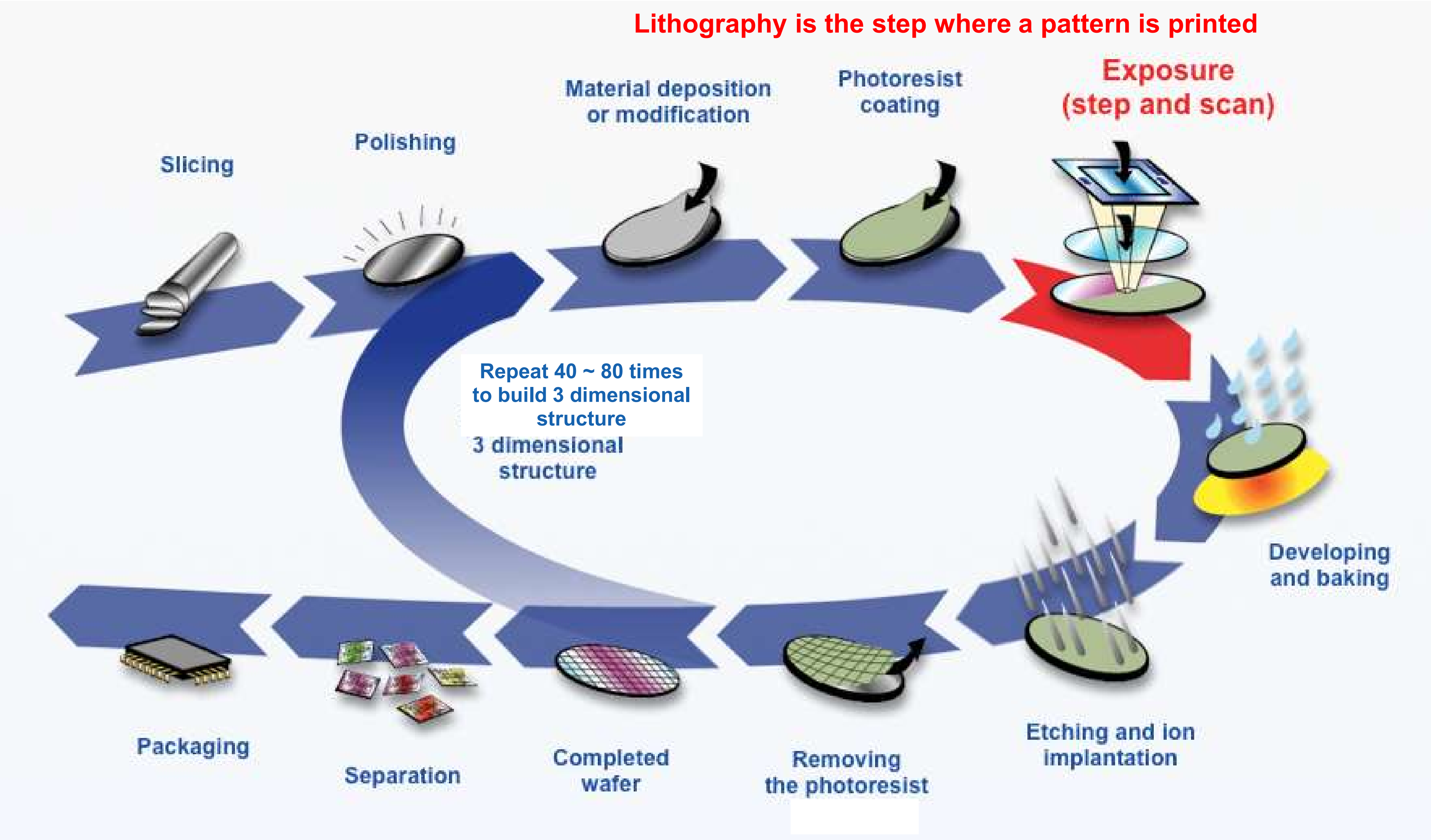
**number of transistors in *affordable* CPU doubles every two years !!!**



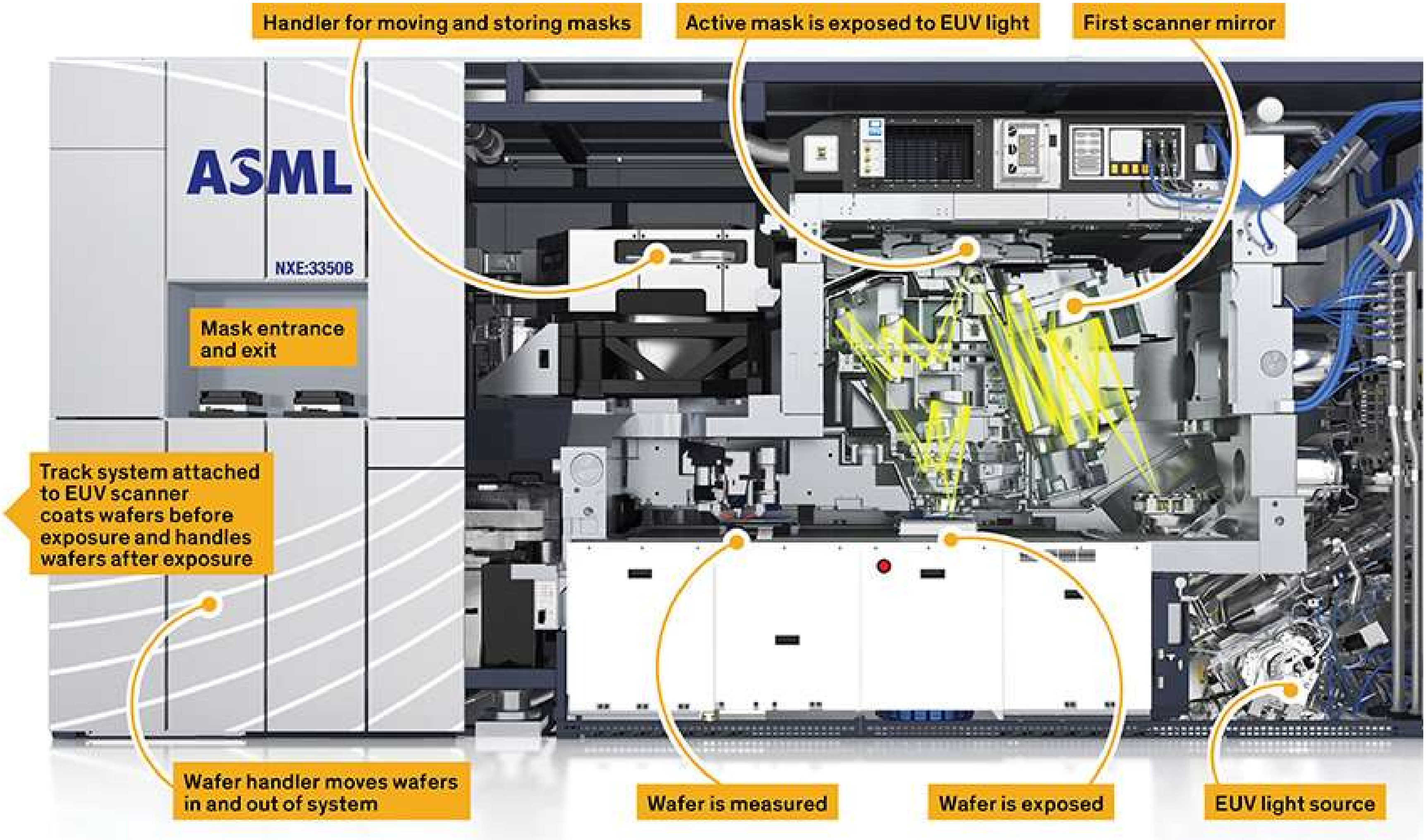
# .. driving minituarization and innovation



# manufactering a repetitive process



# elements of nanolithography tools



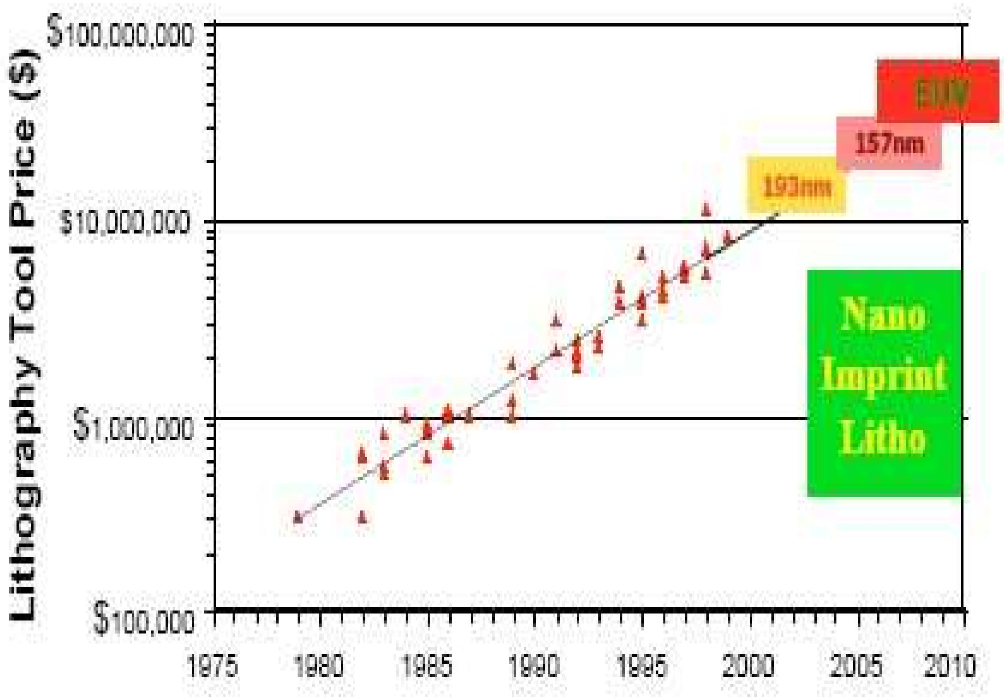
# Moore’s second or Rock’s law

law 1:
number of transistors in *affordable* CPU doubles every two years

**law 2:**
**costs of a semiconductor chip fabrication line double every 4 years**

**→ costs per transistor decrease**

Samsung’s 2015 DRAM plant investment 14 B$



# ARCNL facts

focus: fundamental and applied physics
in the context of technologies for (nano)-lithography,
primarily for the semiconductor industry

- *Concept:* 2013 by ASML
- *Partners:* ASML and FOM/NWO, UvA, VU
- *Start:* Jan. 2014
- *Financial:* M€ 7 /yr base funding; M€ 5 start up Amsterdam + Noord-Holland
- *Size:* Currently 75 fte (84 'faces'); growing to ~100 fte
- *Location:* Science Park, Amsterdam
- *Housing:* temporary office + lab buildings – long-term housing now
- *Facilities/support:* shared with AMOLF

www.arcnl.nl
arcnlsecretariaat@arcnl.nl
https://twitter.com/nanolithography

# long-term housing: Matrix VII

January 2019
moved to new building
restart experiments April

from artist impression to realization =>

# scientific program

ARCNL

**SOURCE**
- EUV Plasma Processes — *Ronnie Hoekstra, Wim Ubachs & Oscar Versolato*
- 'EUV Plasma Modeling' — *vacancy*

**METROLOGY**
- EUV Generation & Imaging — *Stefan Witte & Kjeld Eikema*
- EUV Targets — *Paul Planken*

**SCANNER**
- Nanolayers — *Joost Frenken*
- Contact Dynamics — *Steve Franklin*
- Materials & Surface Science for EUVL — *vacancy*

**PROCESSES**
- Nanophotochemistry — *Fred Brouwer*
- EUV Photoresists — *Sonia Castellanos*

**EXTRA**
- AMOLF-ARCNL Projects — *Coord.: Huib Bakker*
- Accelerator-based EUV — *Ronnie Hoekstra*

HHG and EUV Science Group — *Peter Kraus*

**INTEGRATION**

*Joost Frenken (ARCNL), Marjan Fretz (ARCNL) & Wim van der Zande (ASML)*

# research team

ARCNL

ARCNL EUV PP team:

Francesco Torretti (PhD)
Joris Scheers (PhD)
Ruben Schupp (PhD)
Mart Johan Deuzeman (PhD)
Subam Rai (PhD)
Bo Liu (PhD)
Zoi Bouza (PhD)
Lucas Poirier (PhD)
Lars Behnke (PhD)
............. (2x PhD)
Alex Bayerle (postdoc)
Dmitry Kurilovich (postdoc)
..............(postdoc)
John Sheil (postdoc/tenure track)
Laurens van Buuren (technician)
Wim Ubachs (group leader)
Oscar Versolato (group leader)
Ronnie Hoekstra (group leader)

ARCNL EUV G&I team:

Tiago de Faria Pinto (PhD)
Randy Meijer (PhD)
Stefan Witte (group leader)

ASML team

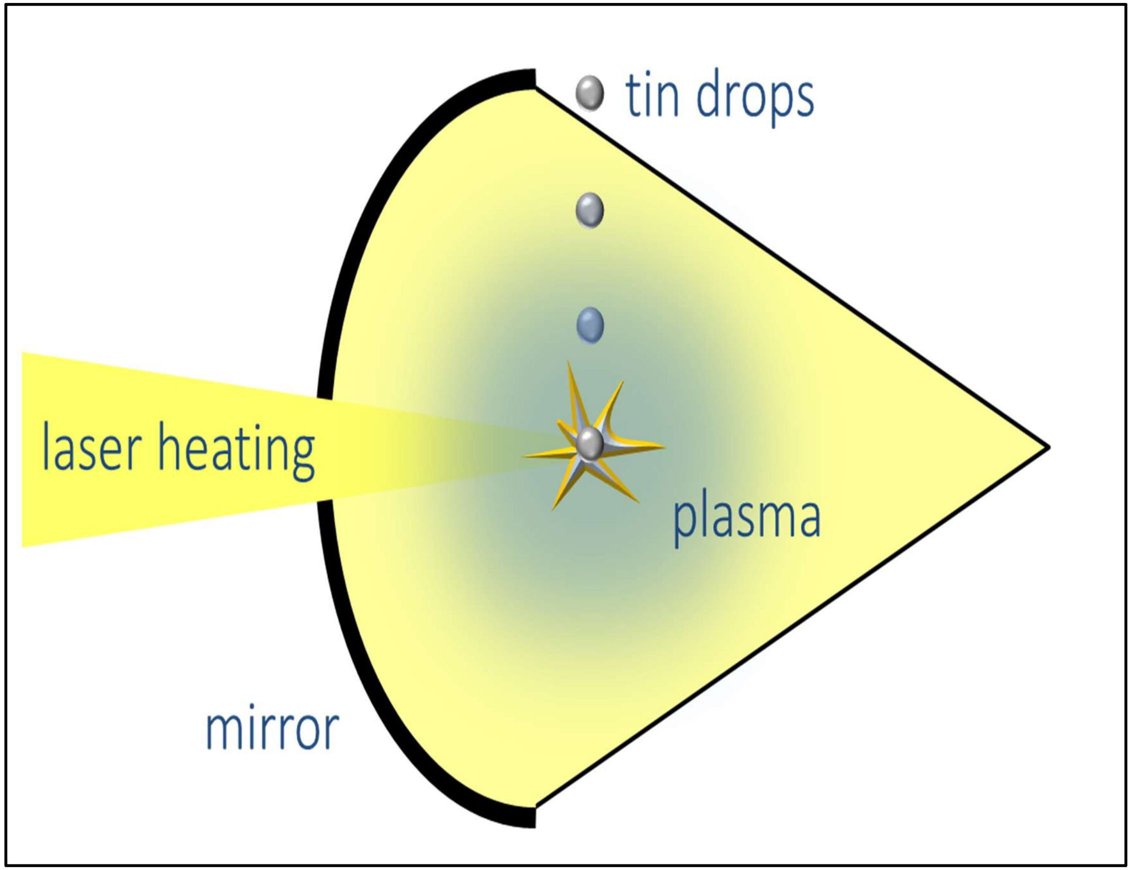
Harry Kreuwel
Andrei Yakunin
Konstantin Tsigutkin
Alexandr Bratchenia
Adam Lassise
Wim van der Zande
Jayson Stewart
Andrew Laforge
Alex Schafgans
Rob Rafac
Igor Fomenkov ... a.o.

Collaborators:

J.R. Crespo López-Urrutia *et al.* (MPIK)
H. Gelderblom (University of Twente)
A. Klein (University of Twente)
S. Reijers (University of Twente)
A. Ryabtsev (ISAN)
M. Basko (KIAM, ISAN)
D. Kim (ISAN)
A. Borschevsky (University of Groningen)
J. Berengut (UNSW Australia)
E. Kahl (UNSW Australia)
M. Bayraktar (University of Twente)
F. Bijkerk (University of Twente)
H. Scott (LLNL):
J. Colgan (LANL)
P. Mora (CNRS Paris)
L. Mendez (UAM Madrid)
I. Rabadan (UAM Madrid)
.................

NWO AMOLF Universiteit van Amsterdam VU Vrije Universiteit Amsterdam Gemeente Amsterdam Provincie Noord-Holland ASML

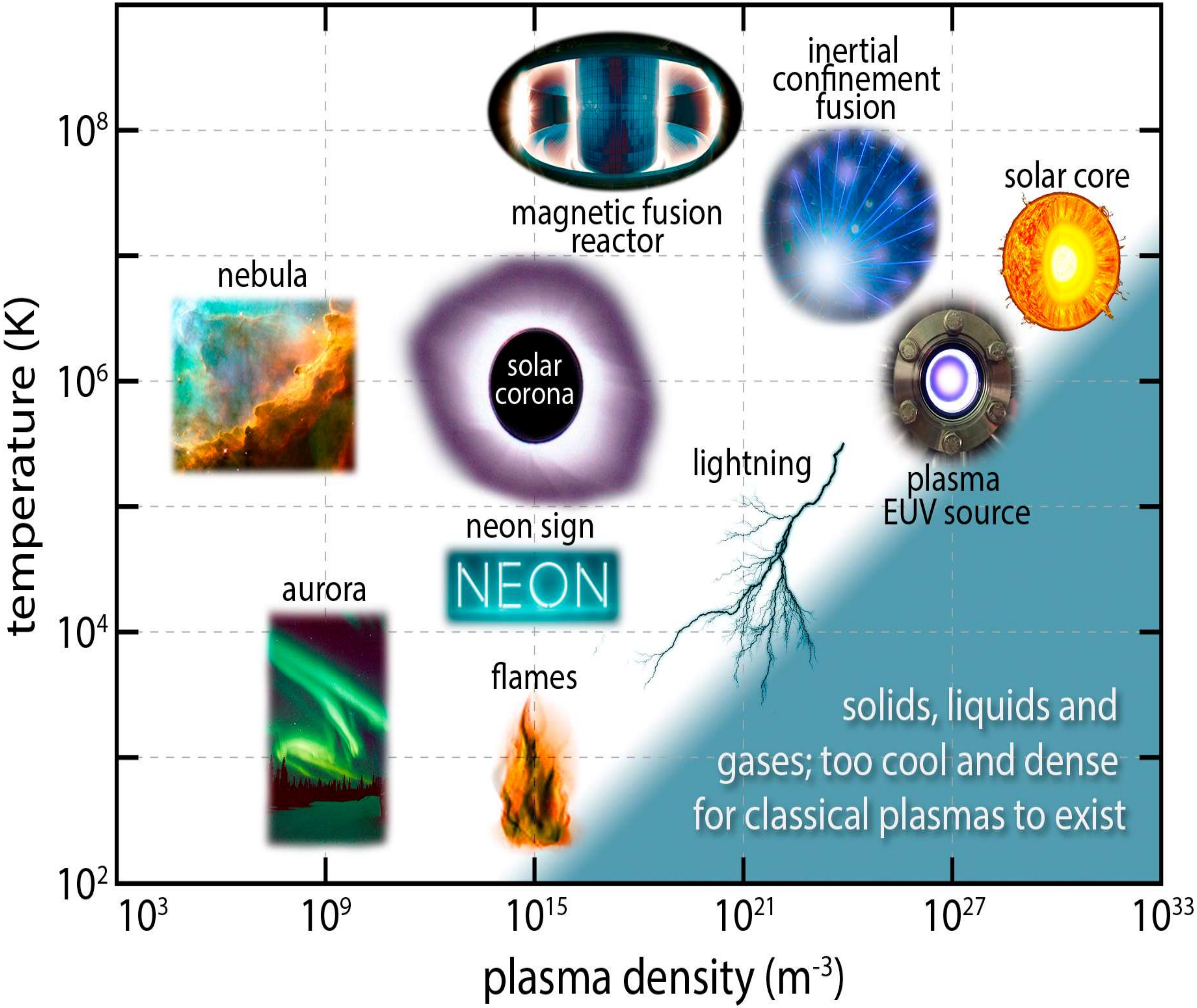
# laser produced plasma for EUV sources



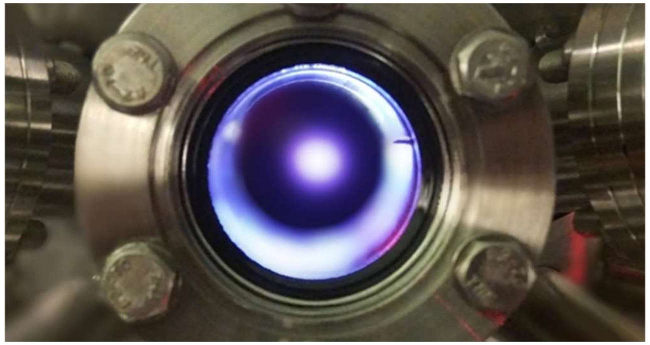

why tin? Sn ions (7-14+) all radiate around 13.5 nm

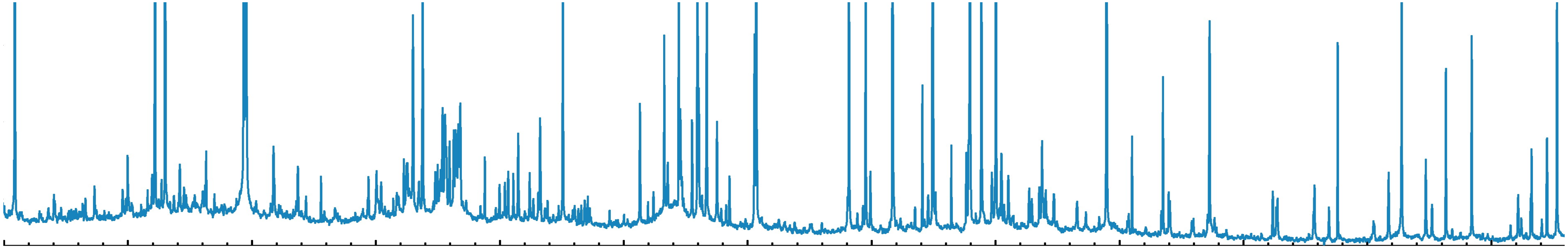
why 13.5 nm? EUV optics - MoSi mirrors

# the plasma landscape



# monitoring EUV generating plasma



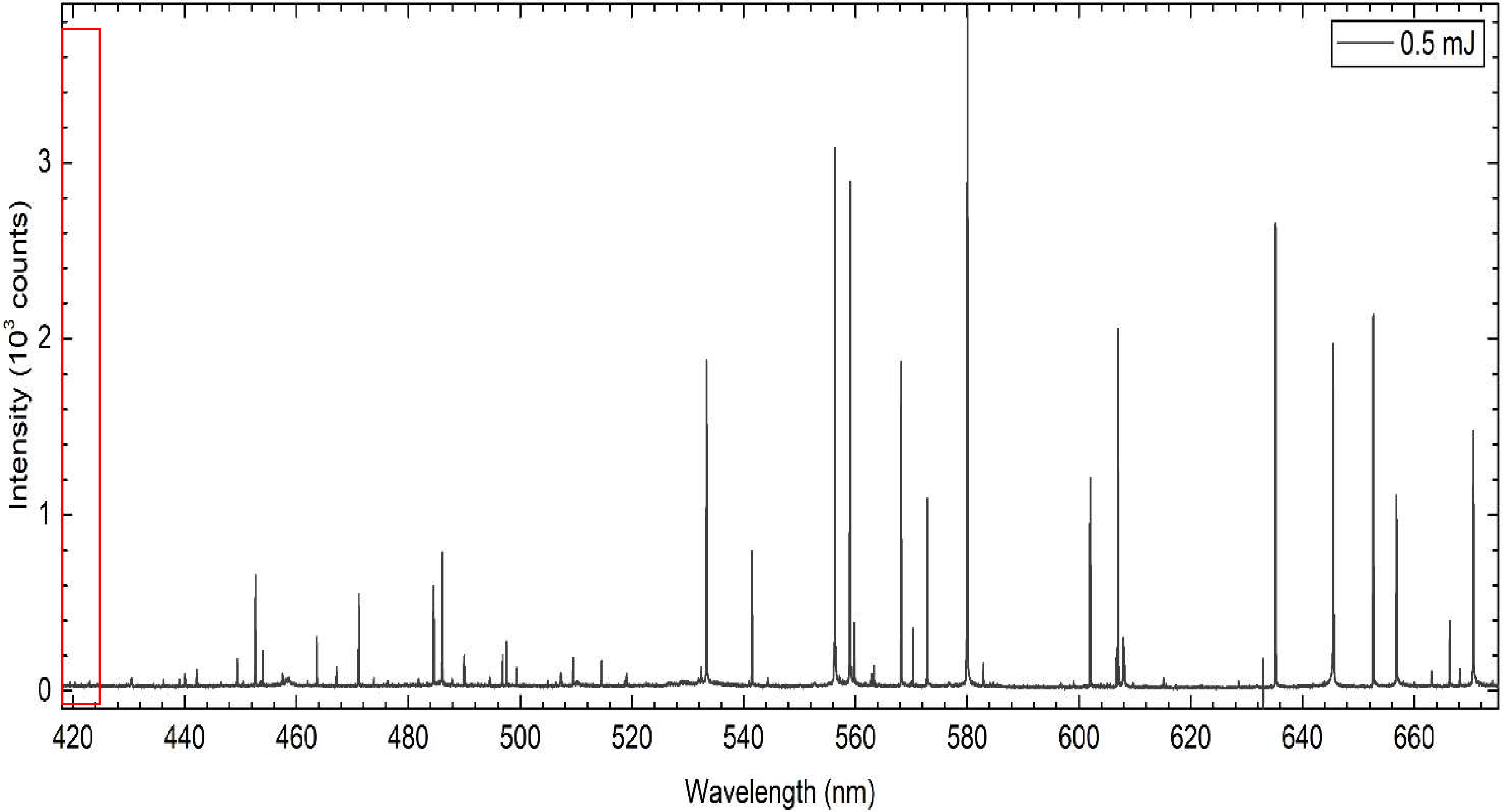


Just do it, buy spectrometers and monitor the spectrum. But..

- most transitions in low-, medium charged tin ions (q<20+) are unknown.
- cross section / reaction rates for excitation are totally unknown.
- the dependence on the “environment” is unknown.
- ……..

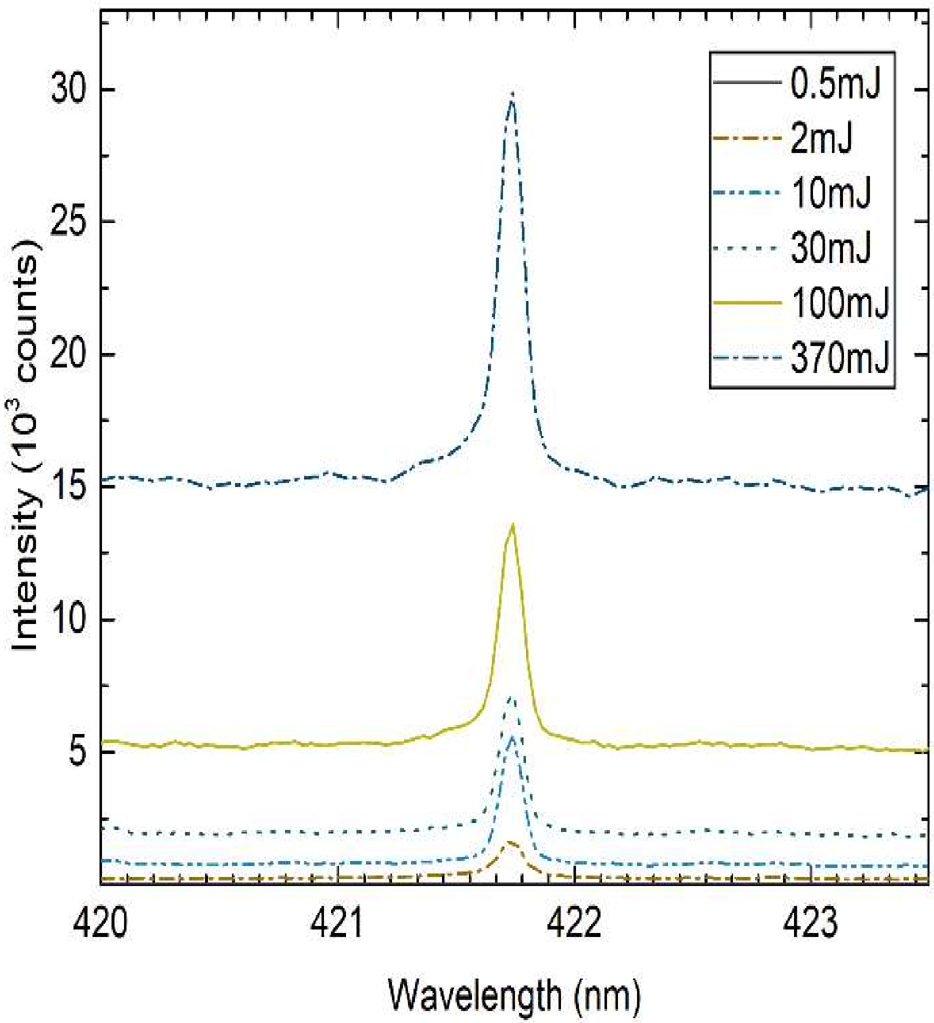
**fundamental atomic data is called for!**

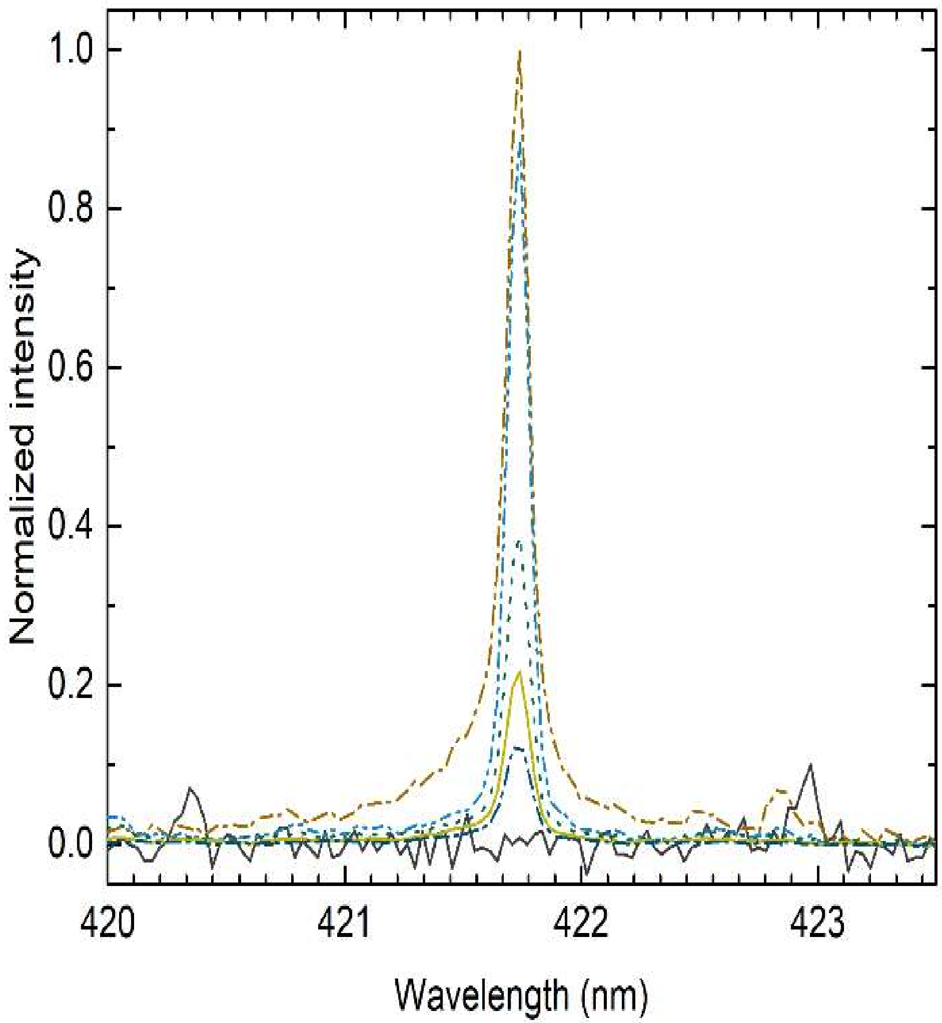
# optical spectra of low-charge state Sn



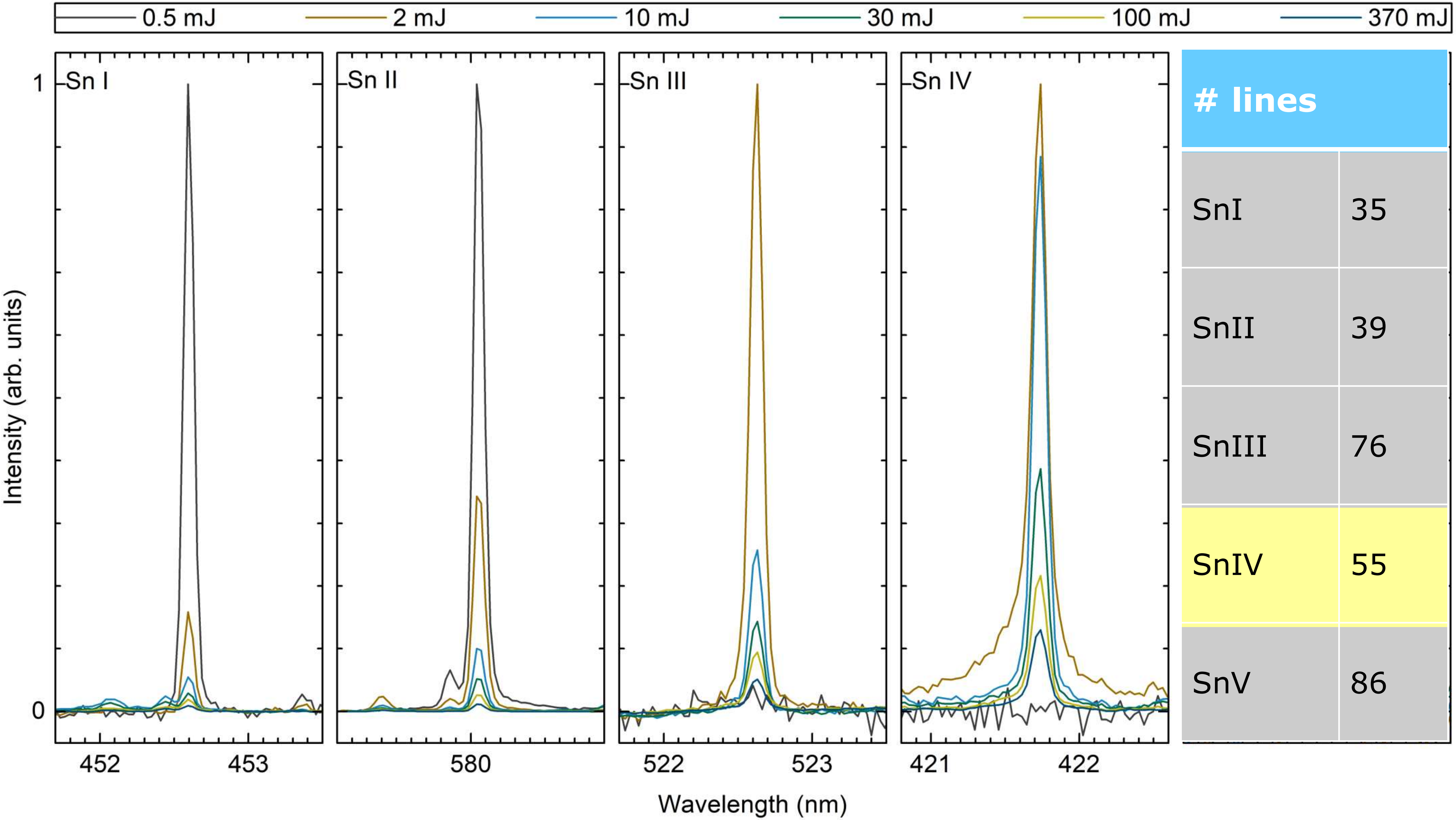
# normalized, relative line intensity

6s $^2S_{1/2}$ – 6p $^2P_{1/2}$



# line intensities




$5p^2\ ^1S_0 - 5p6s\ ^1P_1$   $5d\ ^2D_{5/2} - 4f\ ^2F_{7/2}$   $6s\ ^1S_0 - 6p\ ^1P_1$   $6s\ ^2S_{1/2} - 6p\ ^2P_{1/2}$

| # lines | |
|---|---|
| SnI | 35 |
| SnII | 39 |
| SnIII | 76 |
| SnIV | 55 |
| SnV | 86 |

# SnIV / $Sn^{3+}$

| # lines | |
|---|---|
| SnIV | 55 |

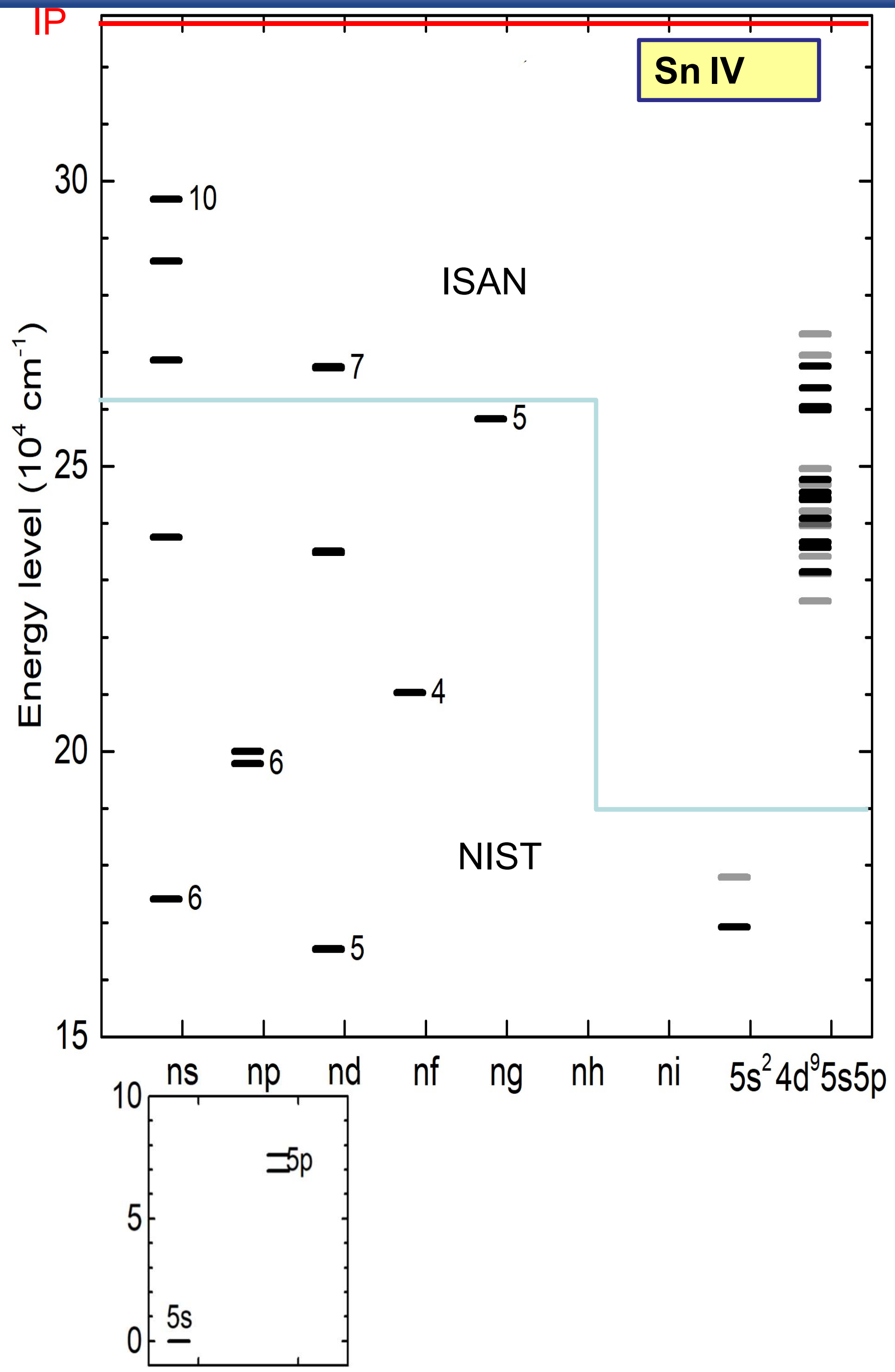
$Sn^{3+}$ [Ag like]
quasi-one-electron system
$[Kr]4d^{10}5s$

most simple tin ion
one electron outside a closed $4d^{10}$ shell

existing information:
NIST database: Moore 1958
ISAN EUV spectroscopy: Ryabtsev *et al*, 2006

4f $^2F$ term most studied by theory
inverted, narrow fine structure
AgI, CdII, InIII, SnIV,
SbV, TeVI, IVII, XeVIII ……
[ground levels: $j = l + \frac{1}{2}$ and $j = l - \frac{1}{2}$ ]

of the **55** SnIV lines observed only **20** can be linked to the known levels



# line identification

level predictions:

- COWAN code (Ryabtsev)
- FSCC - Fock Space CoupledCluster (Borschevsky)

"issue": High-resolution in the optical

| uncertainty | $\Delta E$ cm$^{-1}$ | $\Delta\lambda$ nm |
|---|---|---|
| 0.1% | ~250 | ~5 |

Quantum defect method (Edlen (1964)):
binding energy w.r.t. ionization level

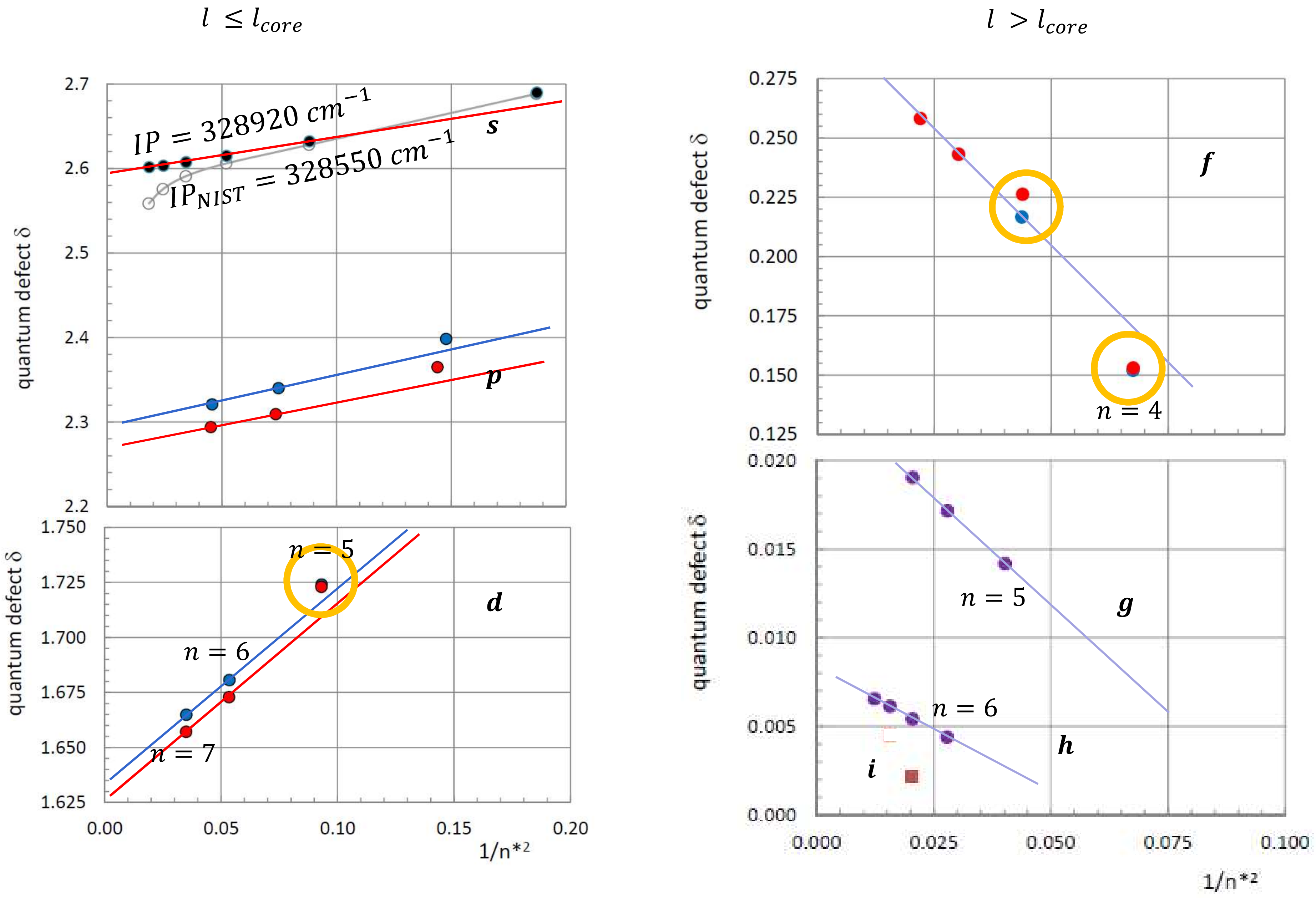
$$E_{nl} = -R\frac{Z^2}{(n^*)^2} = -R\frac{Z^2}{(n-\delta_l)^2}$$

Taylor expansion:

$$\delta_l = a\left(\frac{1}{(n^*)^2}\right) + b\left(\frac{1}{(n^*)^2}\right)^2 + \cdots.$$

# Quantum defect scaling

$Sn^{3+}$: [Kr]$4d^{10}nl$ core is $d^{10}$ $l_{core} = "d"$



# anomalous 5d fine structure

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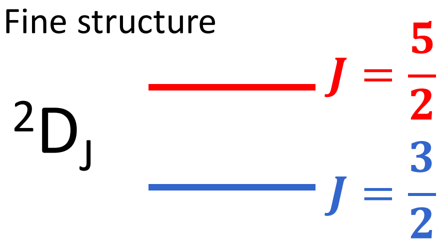
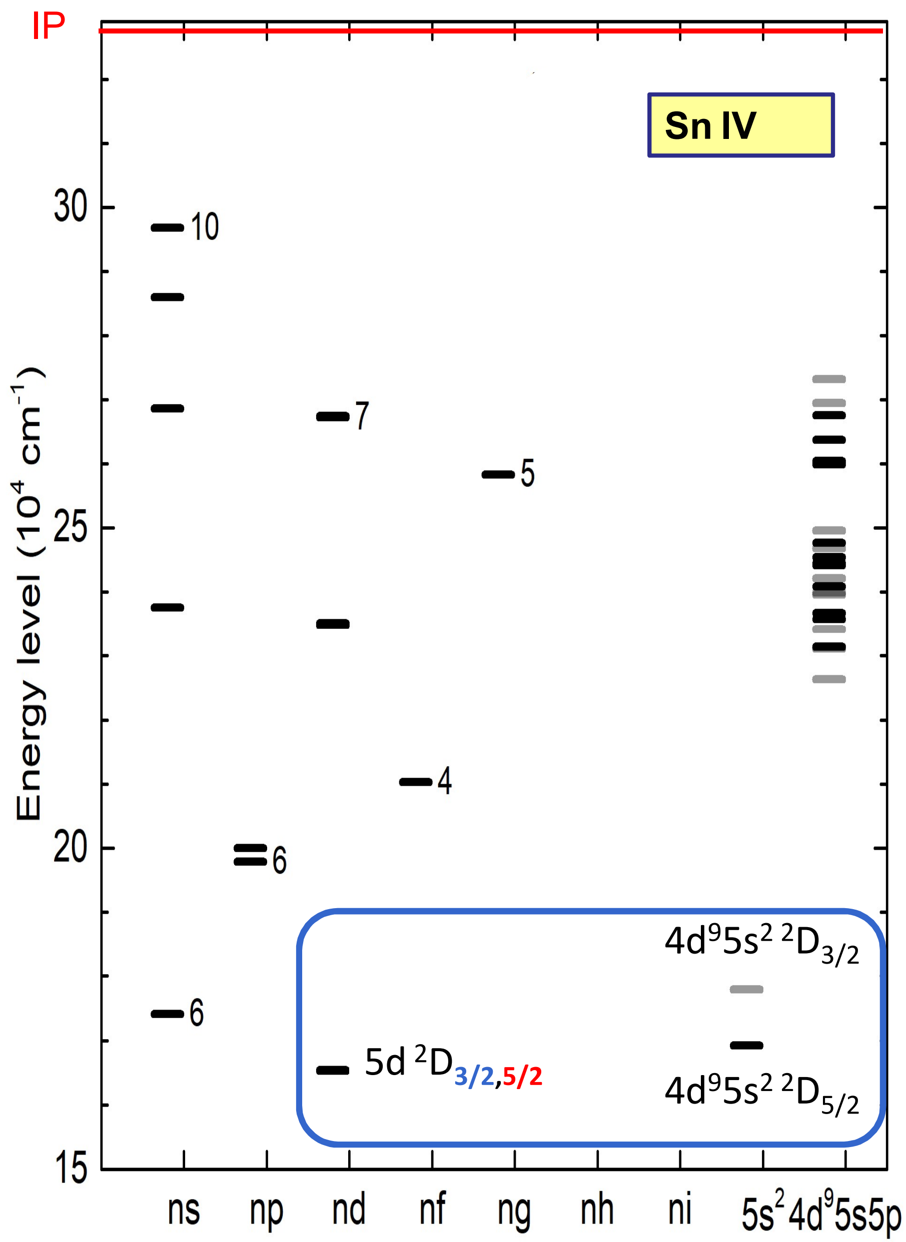



| 5d $^2D_J$ fine structure | $\Delta E_{FS}$ [$cm^{-1}$] |
| --- | --- |
| NIST database | 106 |
| RMBPT* | 745 |
| this work | |
| Experiment | 105 |
| FSCC | 735 |
| (FSCC)+ MBPT – CI | 120 |

* RMBPT: Safronova *et al,* PRA **68**, 062505 (2003)

mainly shift of 5d $^2D_{5/2}$ due to configuration interaction with $4d^95s^2$ $^2D_{5/2}$ ~600 $cm^{-1}$

$$\Psi_{5d} = a\phi_{5d} + b\phi_{4d^95s^2}$$



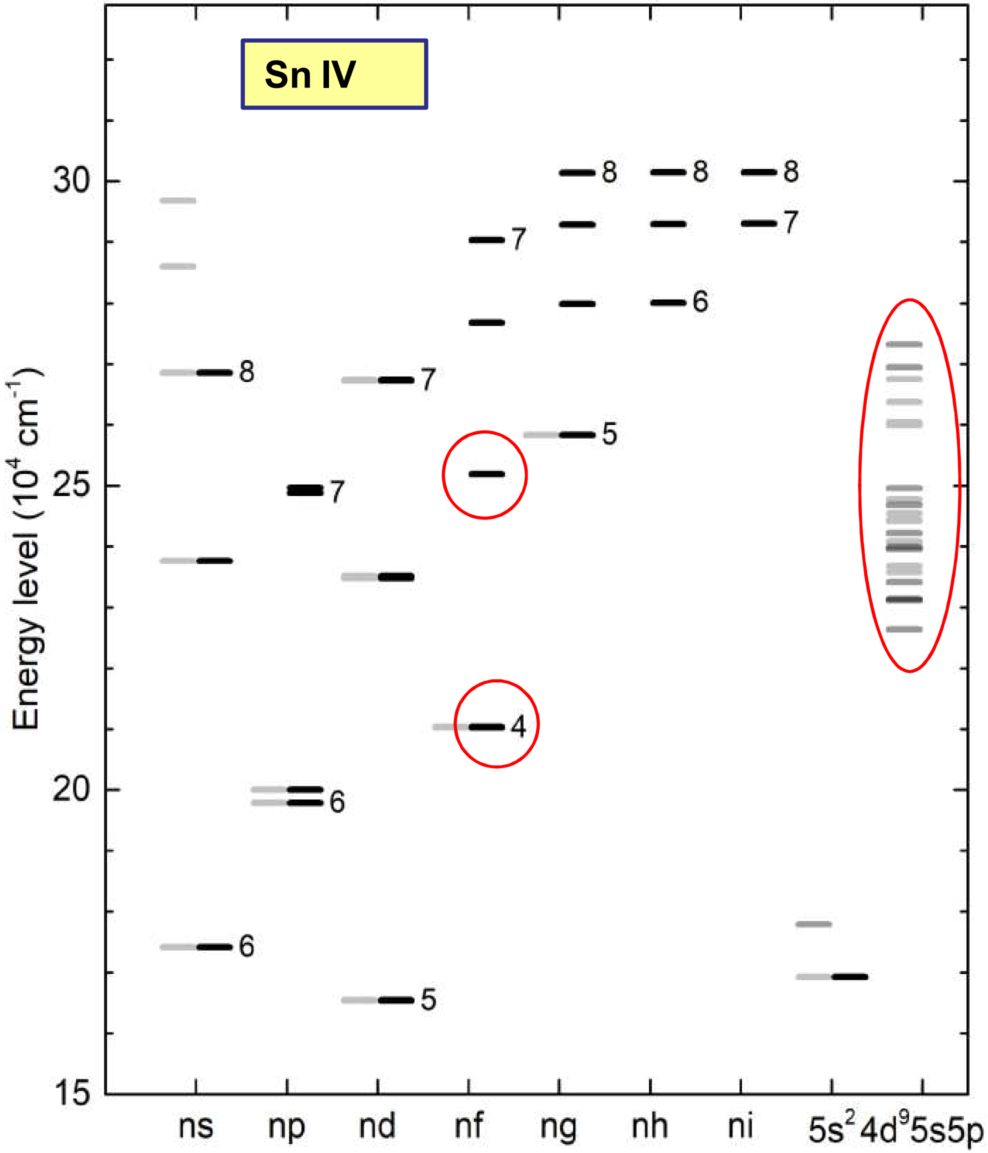
# the inverted fine structure of nf $^2F$

| **4f $^2F_J$** | $\Delta E_{FS}$ [$cm^{-1}$] |
|---|---|
| NIST database | -61 |
| RMBPT* | -74 |
| RPTMP# | -60 |
| MCDHF$ | -71 |
| ARCNL | |
| experiment | -60 |
| FSCC | -62 |
| MBPT | -62 |
| **5f $^2F_J$** | $\Delta E_{FS}$ [$cm^{-1}$] |
| RMBPT* | -44 |
| RPTMP# | -22 |
| ARCNL | |
| experiment | -308 |
| FSCC | -39 |
| (FSCC)+ MBPT+CI | -412 |

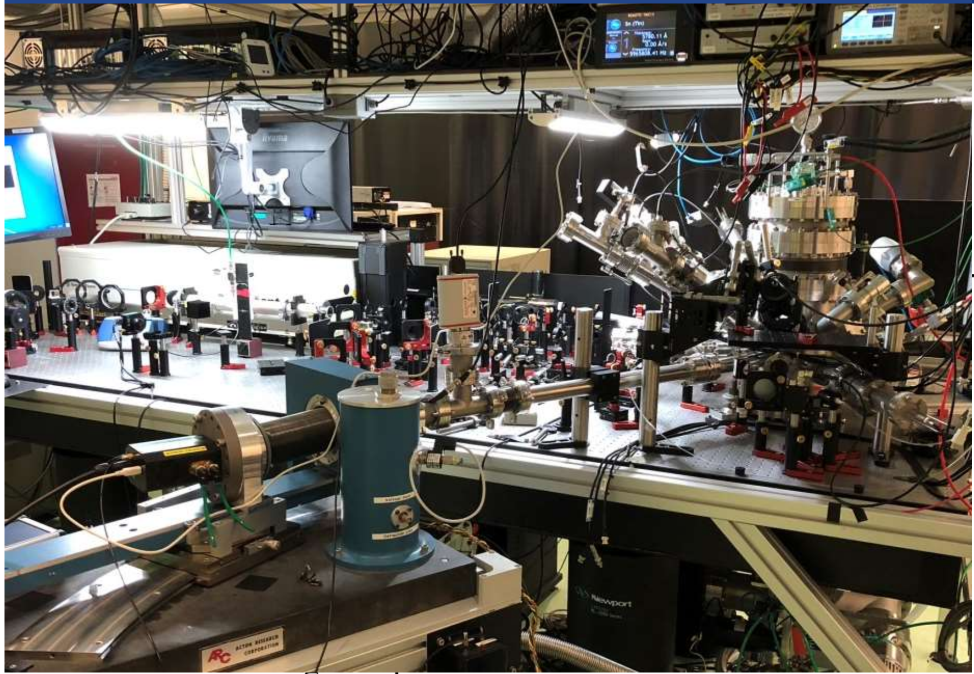
*RMBPT: Safronova *et al,* PRA **68**, 062505 (2003)

# RPTMP: Ivanova, ANDT, **97**, 1 (2011)

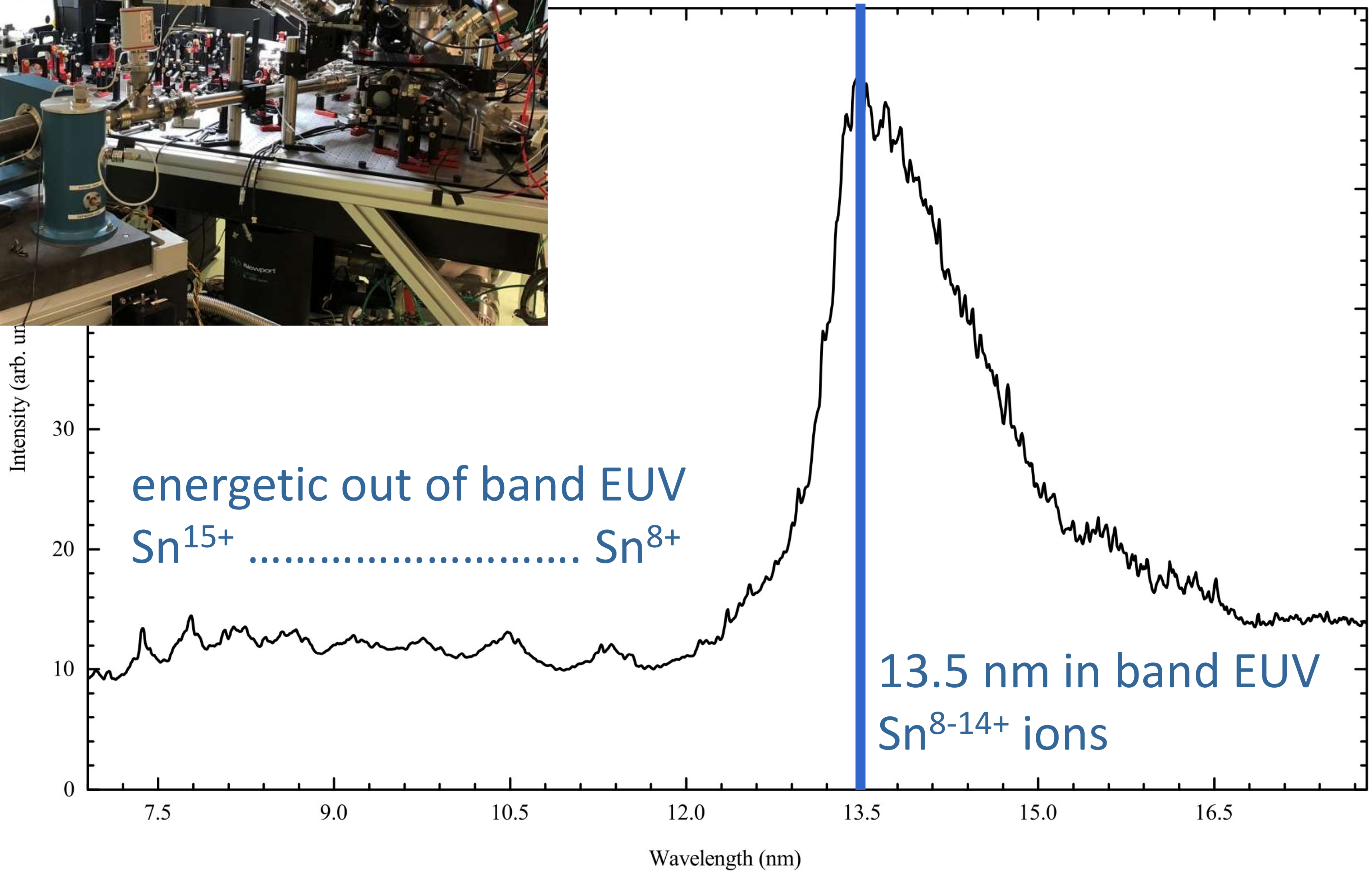
$MCDHF: Grumer *et al*, PRA **89**, 062511 (2014)



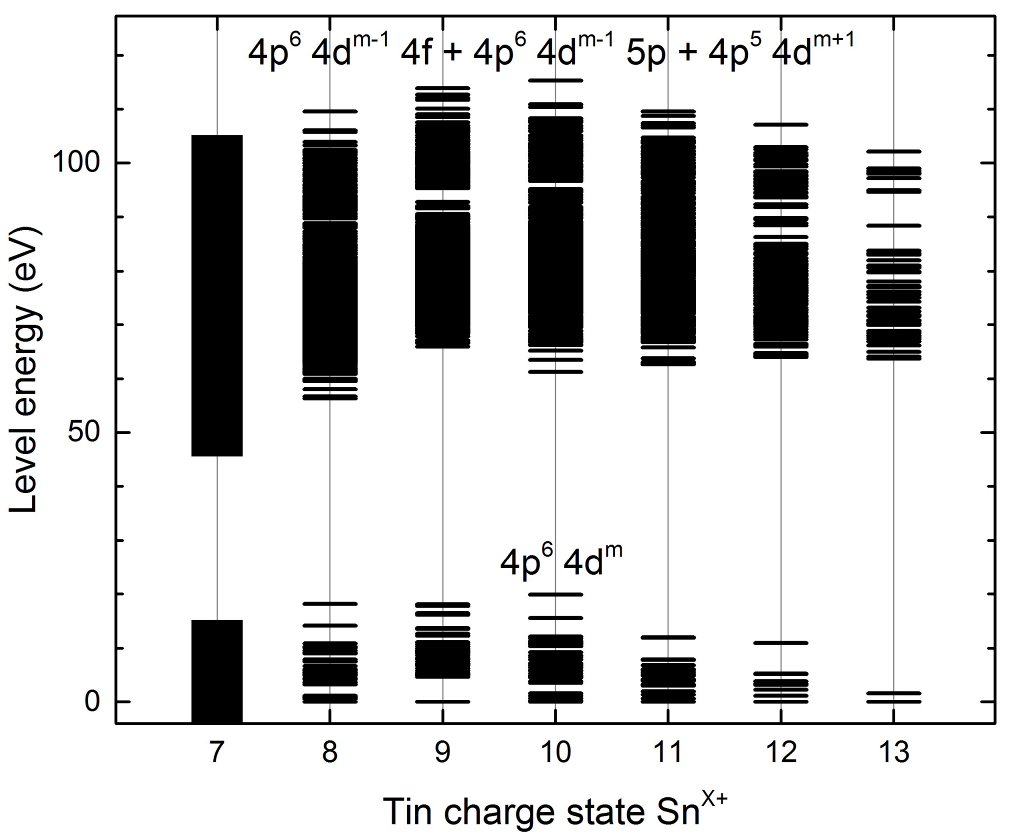
# EUV emisssion

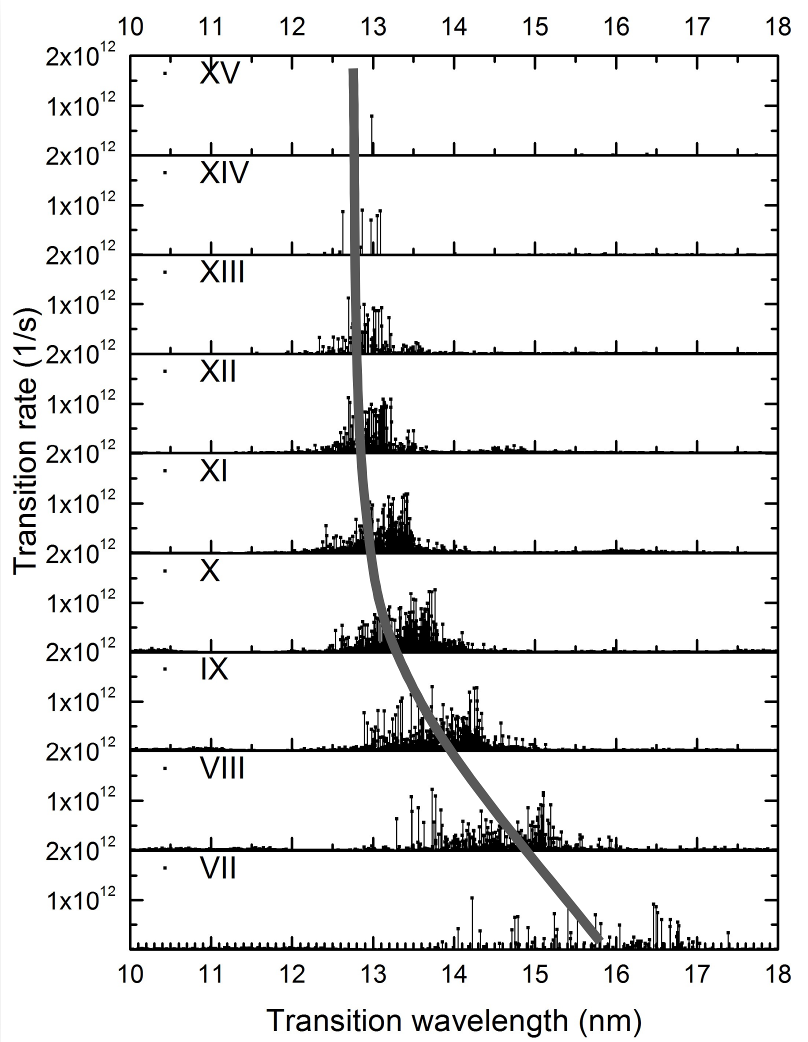


## LPP EUV spectrum

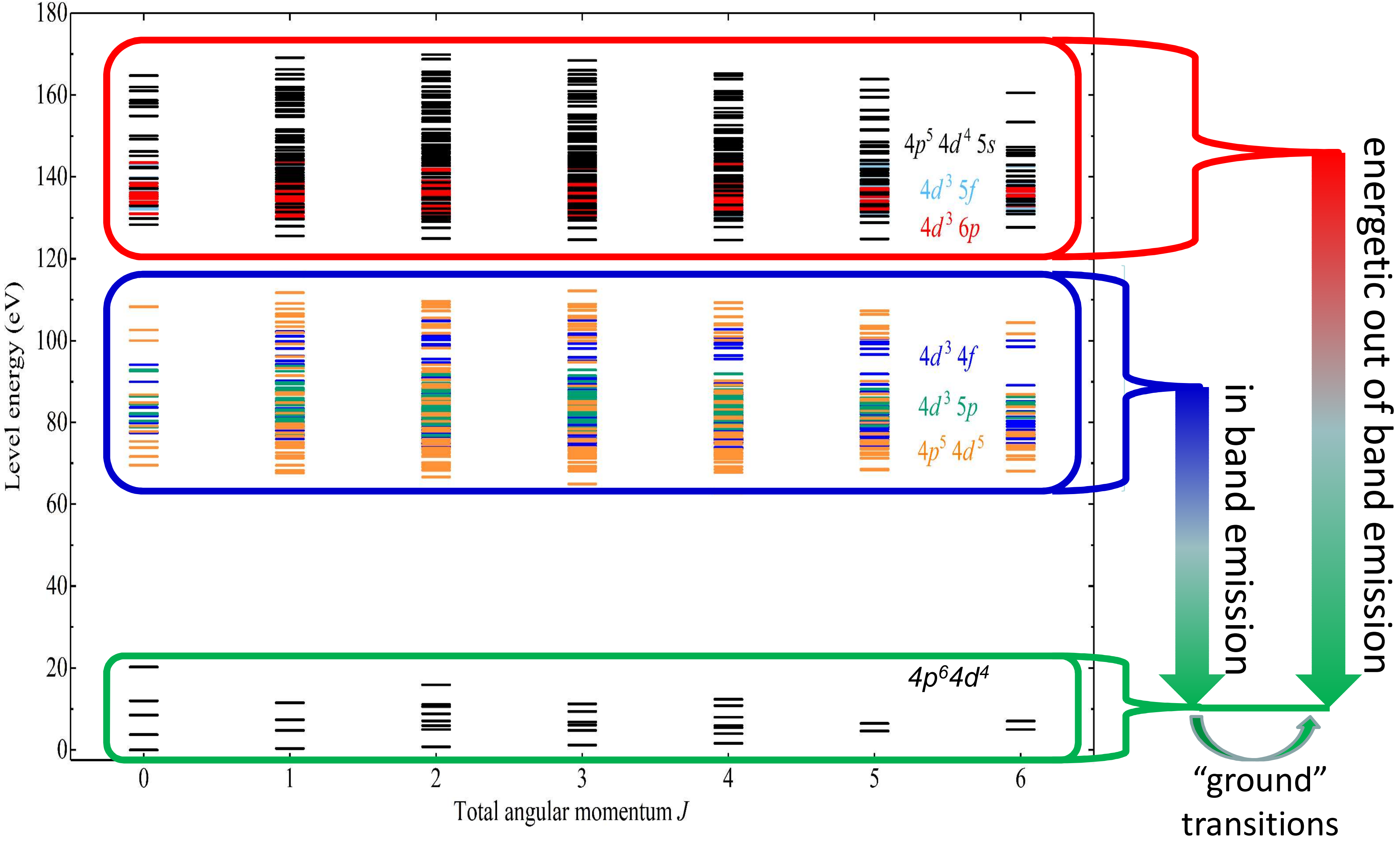


# atomic origins of EUV light



# detailed example: $Sn^{10+}$ (SnXI)



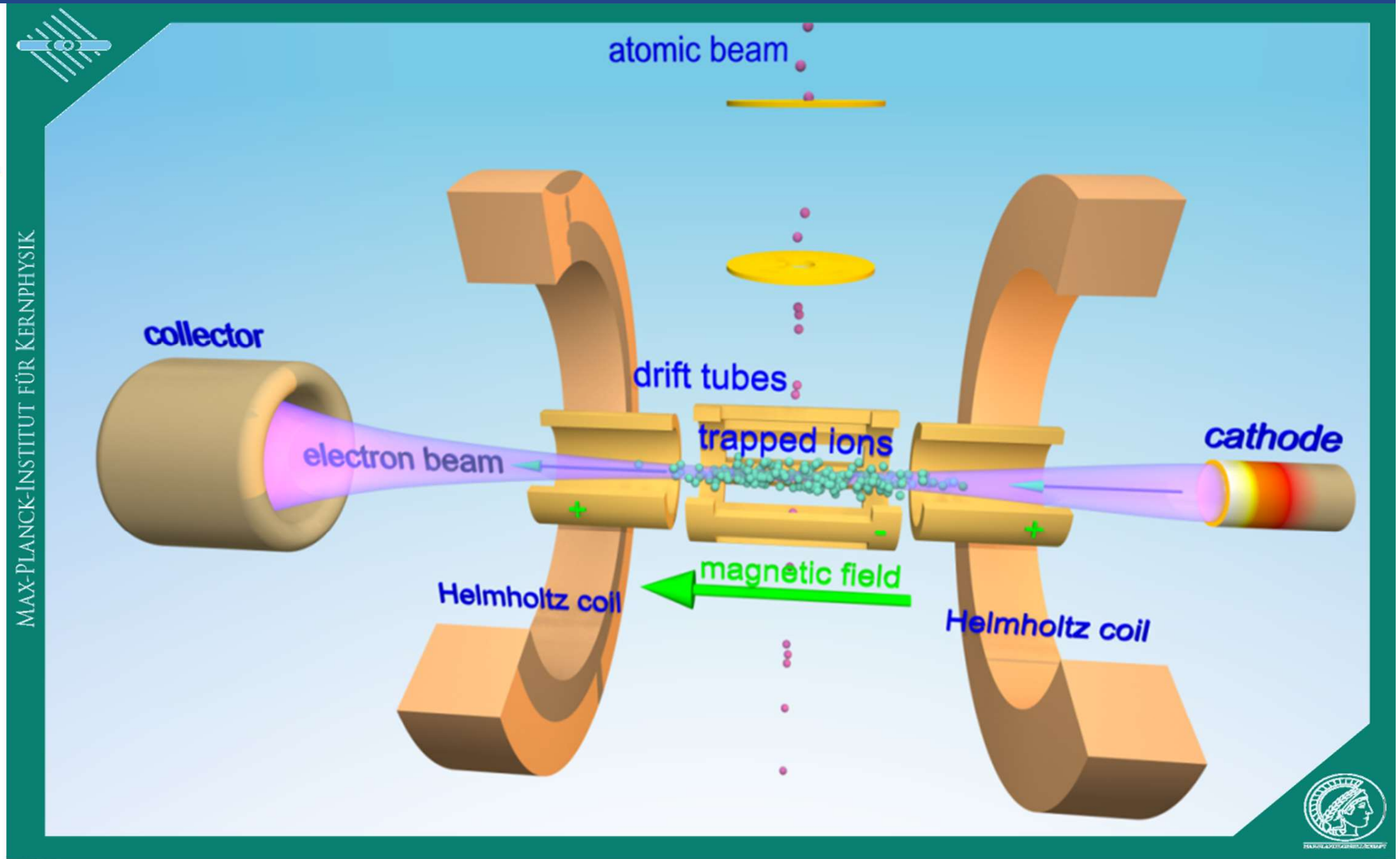
# In-EBIT spectroscopy

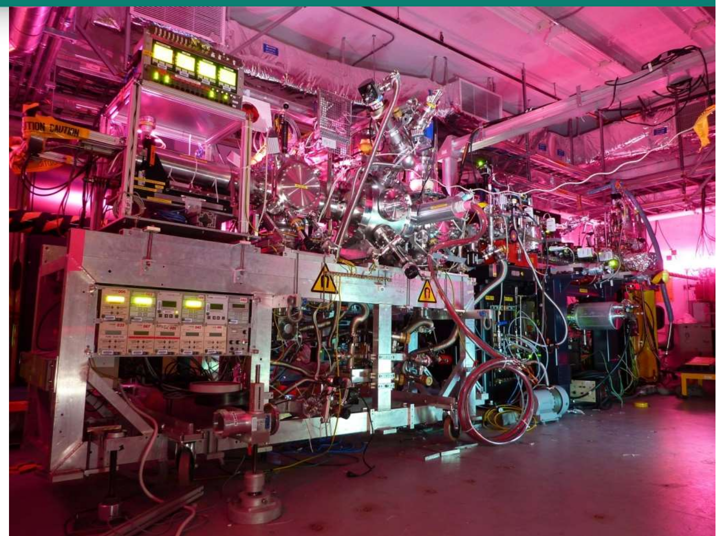
ARCNL

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

EBIT group:
**J. Crespo López-Urrutia**
H. Bekker
S. Dobrodey
A. Windberger

electron impact excitation of trapped Sn ions in charge states 7 - 20+



*theory*

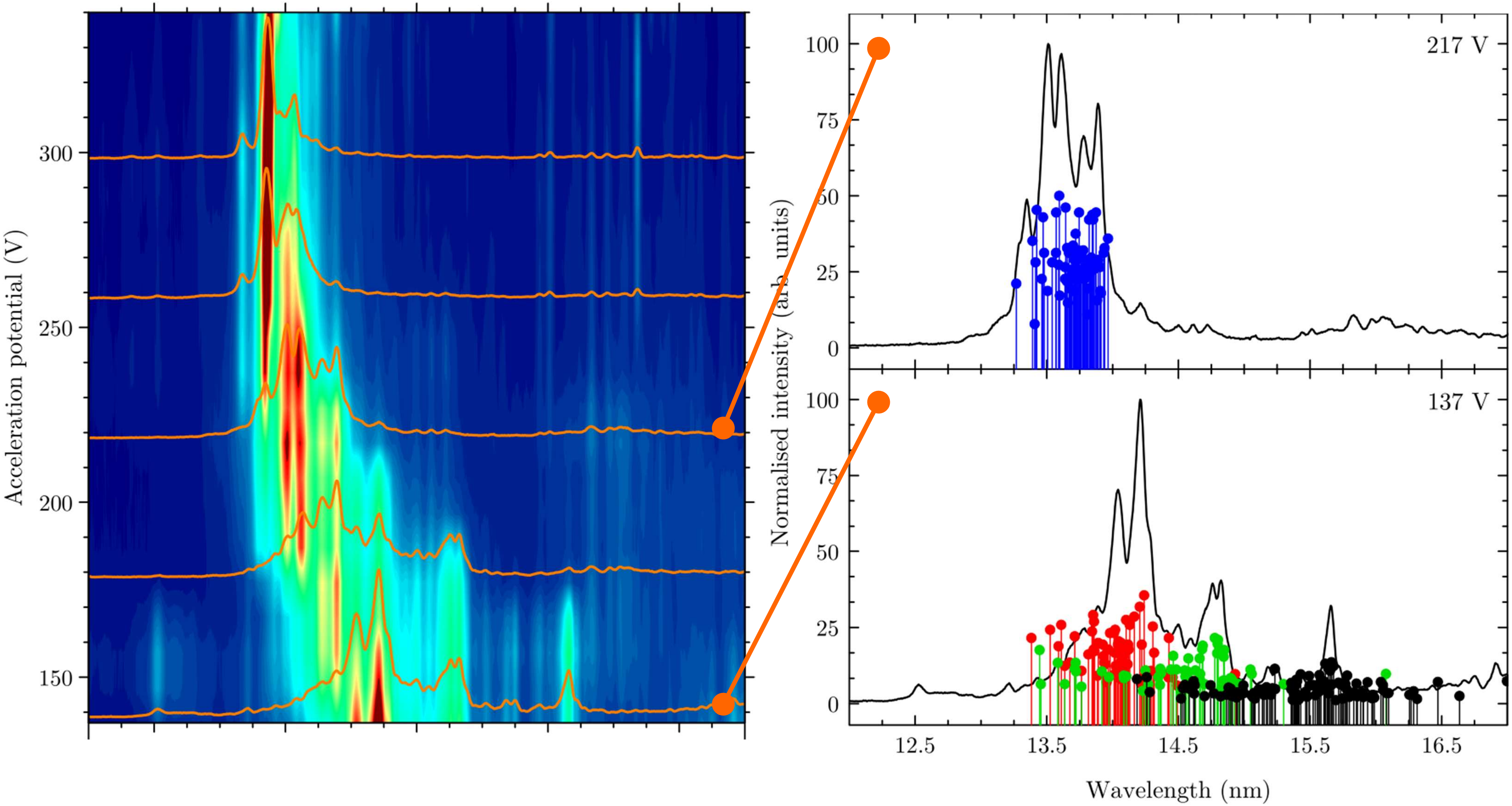
ISAN Troitsk
A. Ryabtsev

School of Chemistry
E. Eliav and U. Kaldor

Van Swinderen Institute
A. Borschevsky

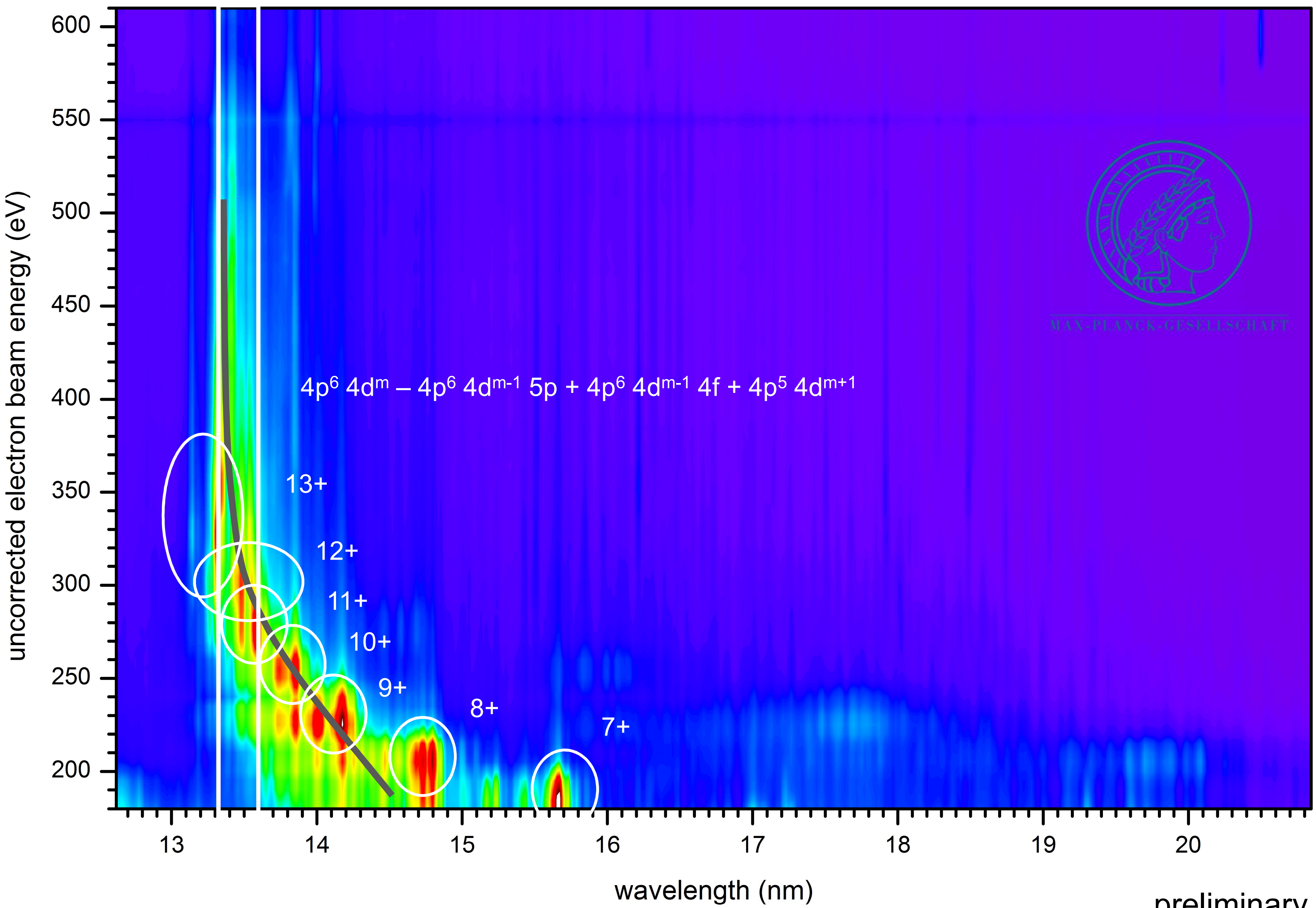
School of Physics
J. Berengut and E. Kahl

# charge state identification



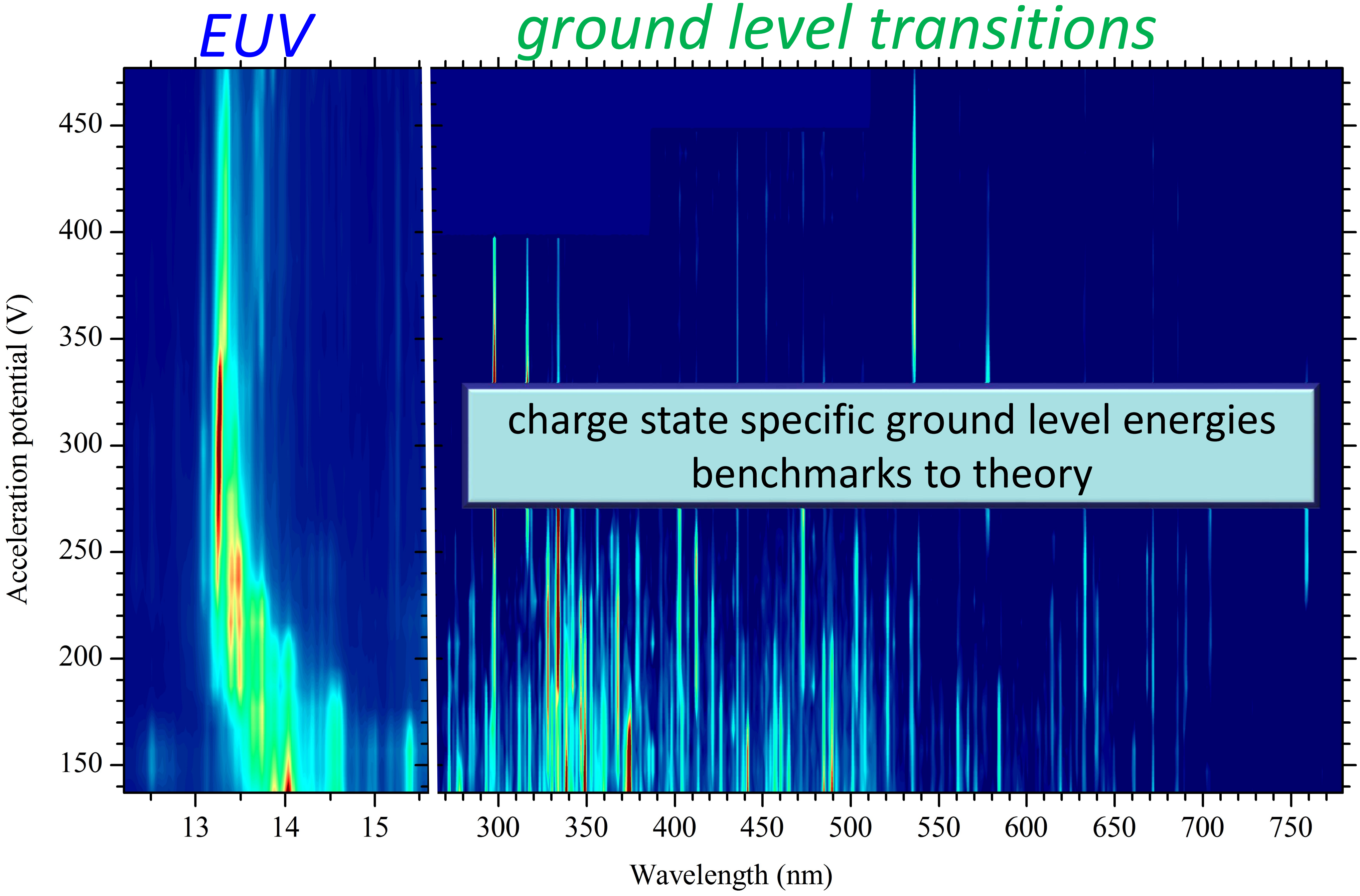

A. Windberger et al., Phys. Rev. A 94, 012506 (2016); F. Torretti et al, Phys. Rev. A 95, 042503 (2017)

# the tin serendipidity



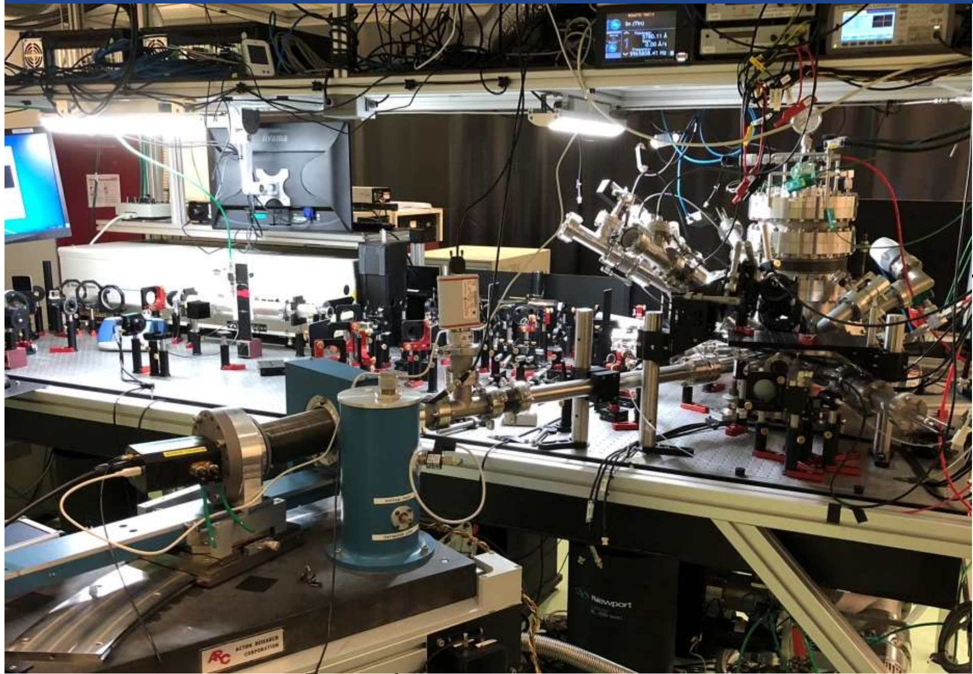

preliminary data

# “forbidden” transitions

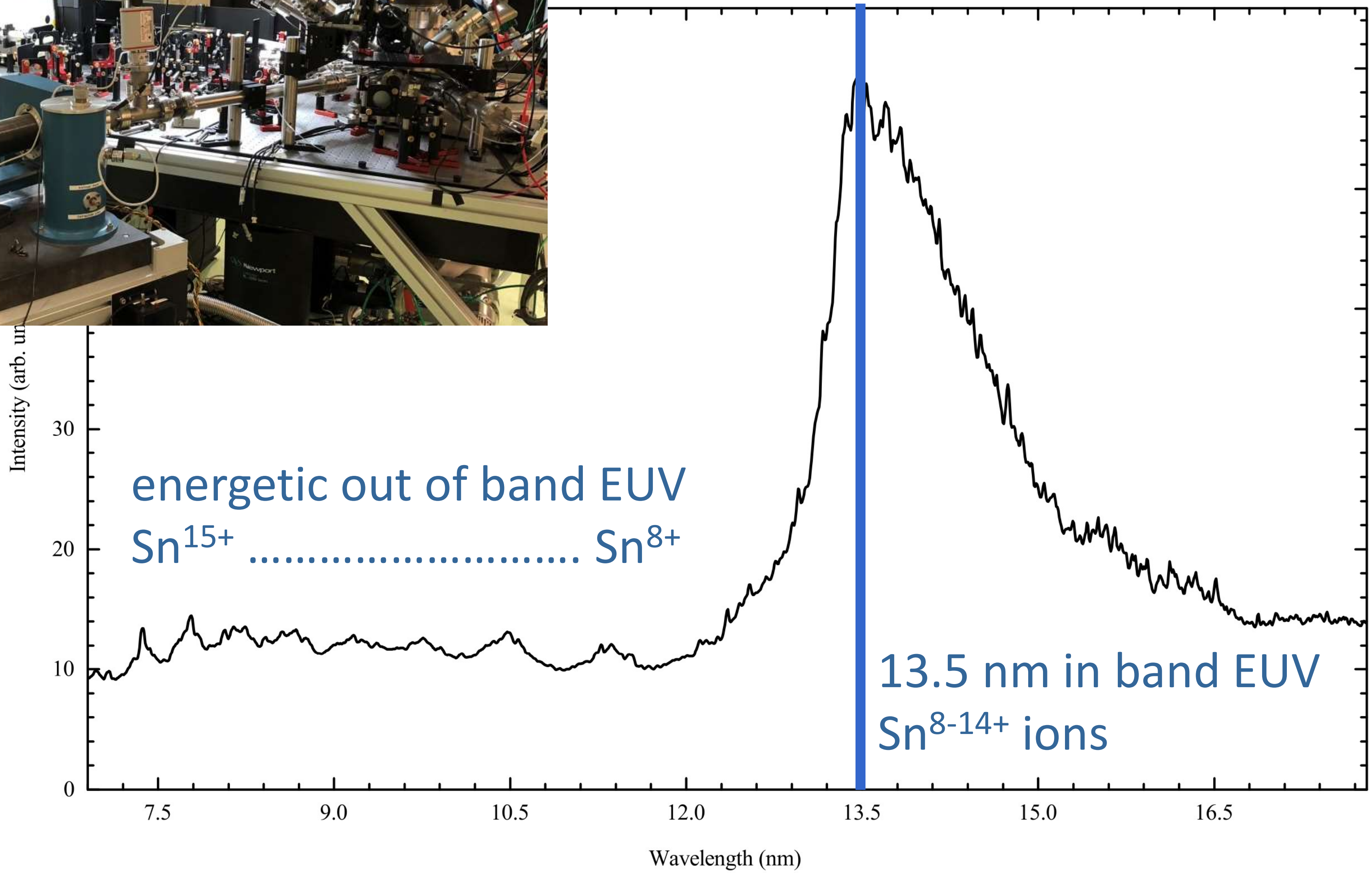



A. Windberger et al., Phys. Rev. A 94, 012506 (2016); F. Torretti et al, Phys. Rev. A 95, 042503 (2017)

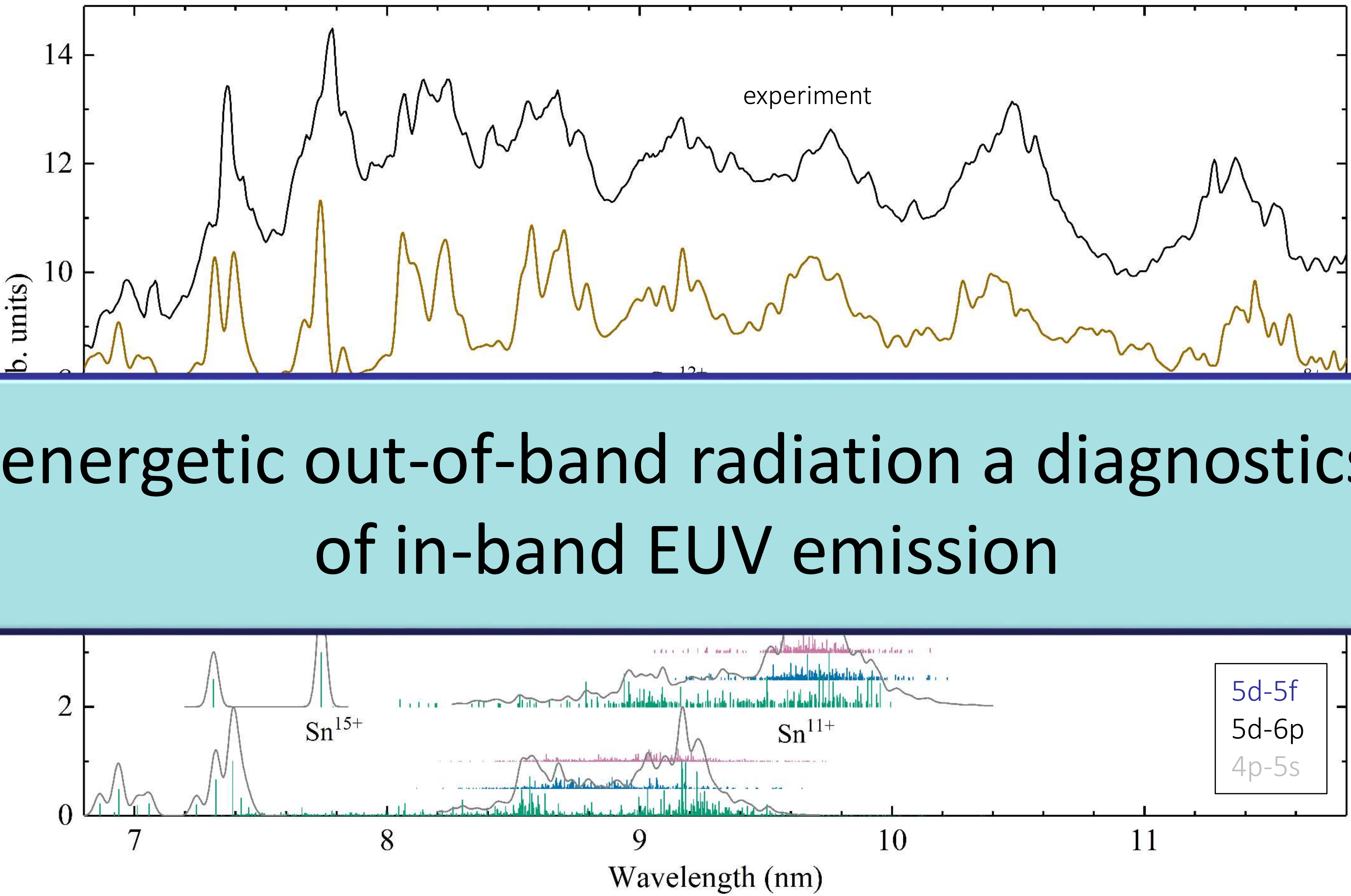
# EUV emisssion



## LPP EUV spectrum



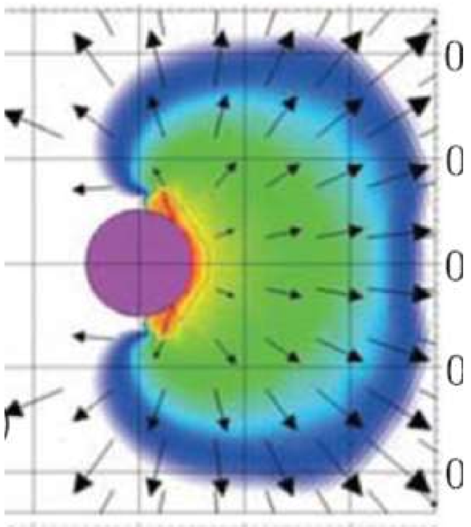
# $Sn^{8+}$ … $Sn^{15+}$ transitions

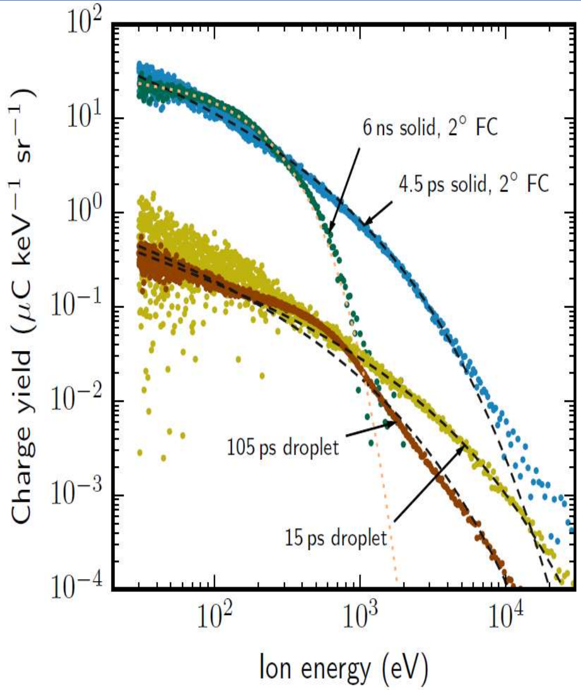


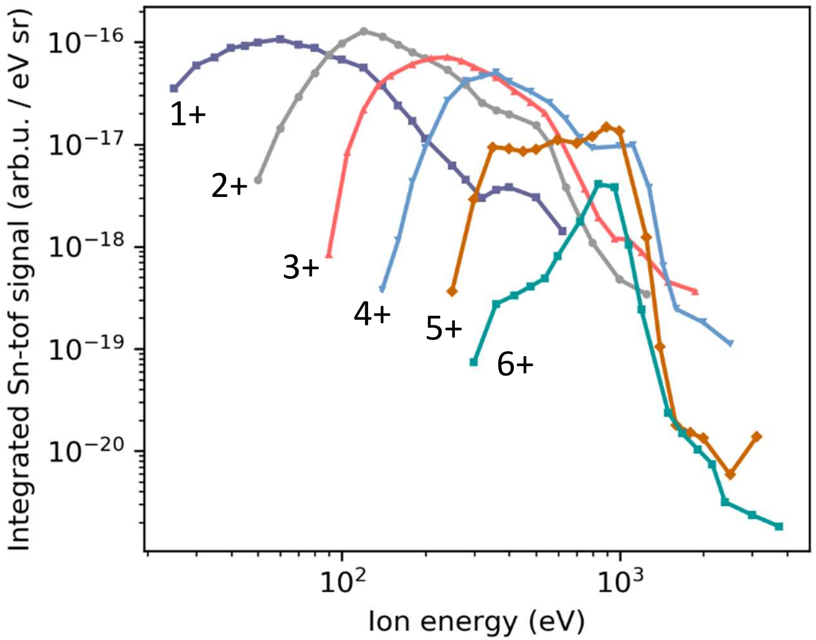

energetic out-of-band radiation a diagnostics of in-band EUV emission

F. Torretti et al, J. Phys. B **51**, 045005 (2018)

# energetic ion ejection





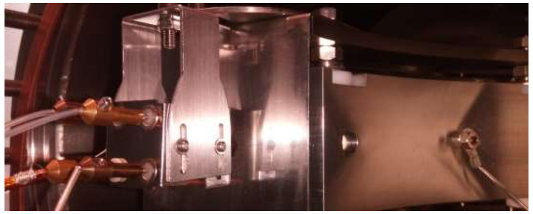
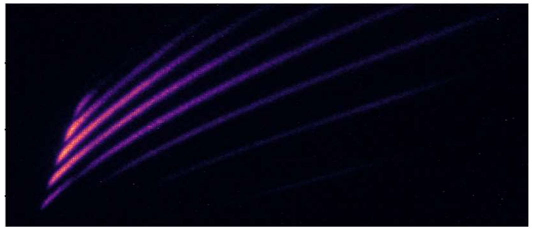


energetic tin “bullets” damage plasma facing material
pragmatic solution: hydrogen stopping gas

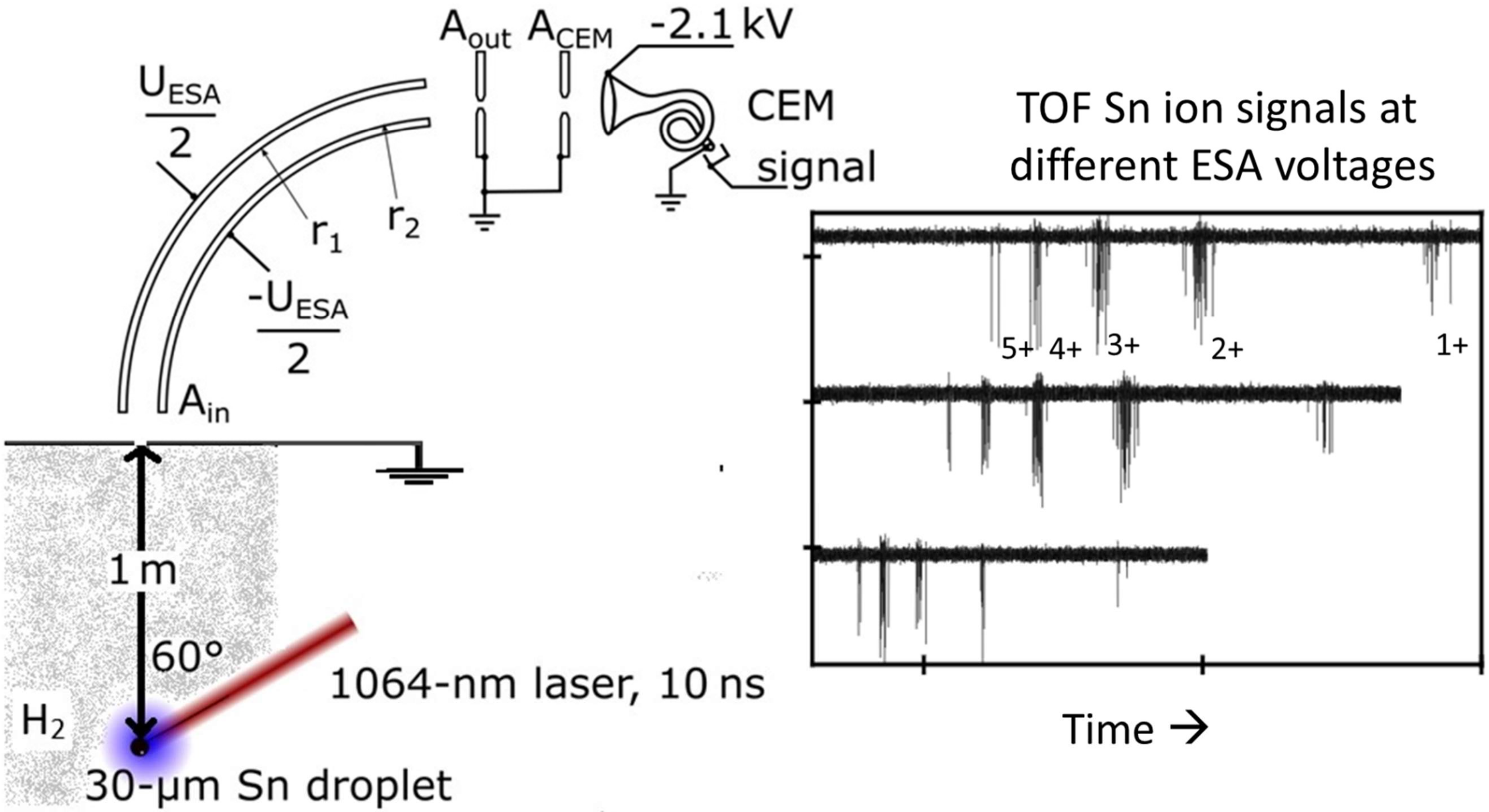
Open Questions:

- what are the actual damage thresholds?
- what is the charge state distribution?
- what is the ionic-energy spectrum?
- what do the ions do to $H_2$ gas and vice versa?
- ……..
- how are the ions exactly generated?

# ion detectors at ARCNL's LPP source

| Sn Ion detectors | |
|---|---|
| Open Faraday Cups  | current measurement |
| | energy distribution from ToF |
| | no charge state resolution |
| Retarding Field FC | current measurement |
| | energy distribution from ToF<br>charge state information from retarding fields<br>charge state resolution |
| | grids in ion path |
| Electrostatic Analyser  | direct energy measurement (E/q)<br>full charge state resolution via ToF |
| | dynamic range - space charge effects<br>ion detection efficiency |
| | scan energy |
| Thomson Parabola  | simultaneous energy and charge state measurement |
| | absolute ion detection efficiencies<br>ion trajectories |
| | |

# experimental lay out of ion measurements

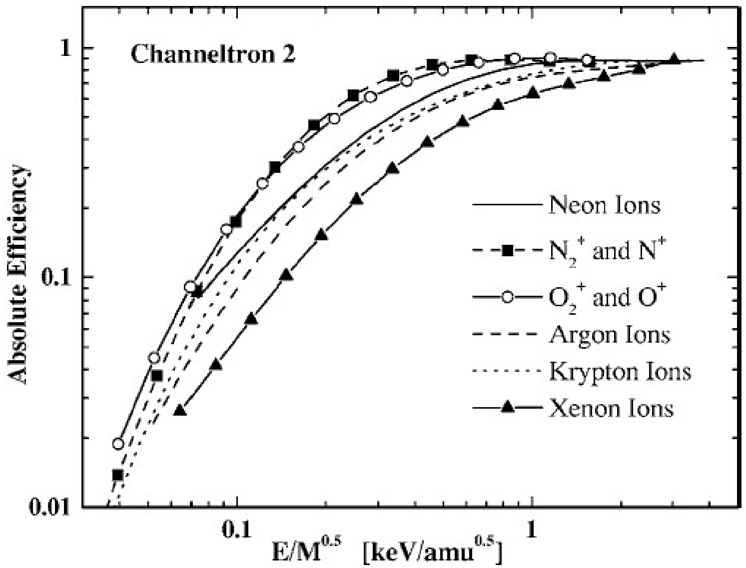


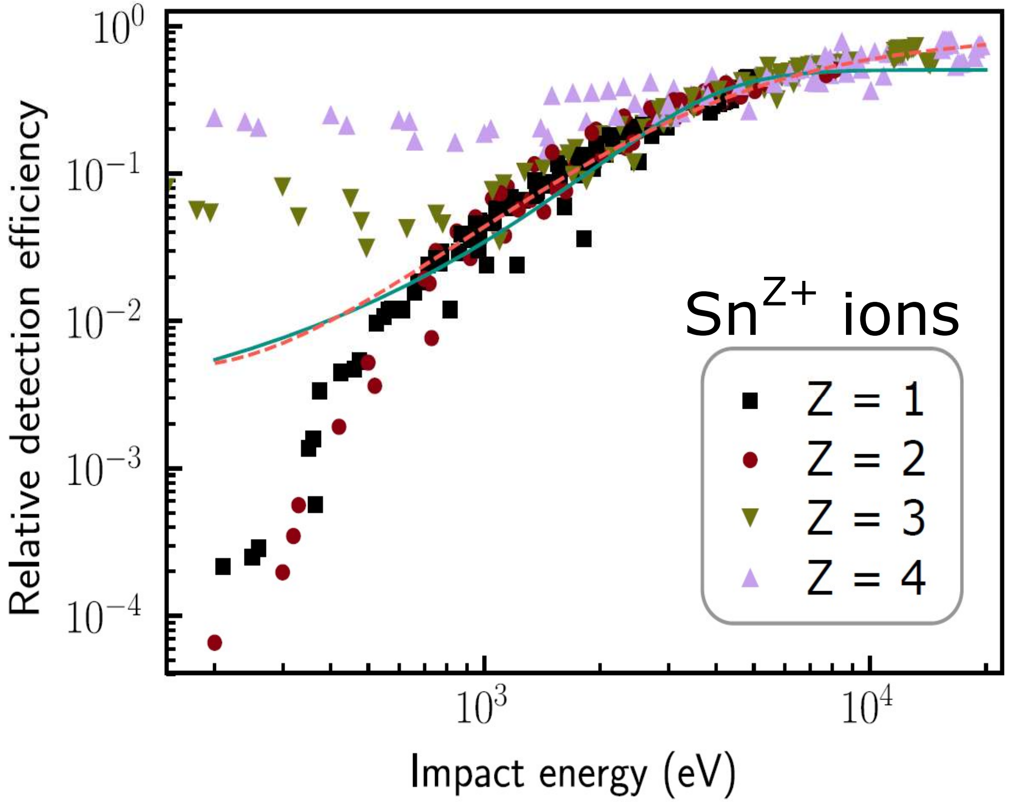
# detection of tin ions

Channel electron multiplier and channelplate efficiencies for detecting positive ions

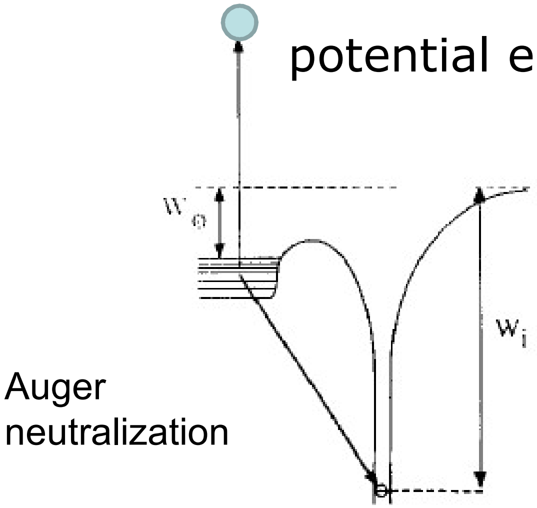
M. Krems, J. Zirbel, M. Thomason, and R. D. DuBois[a]

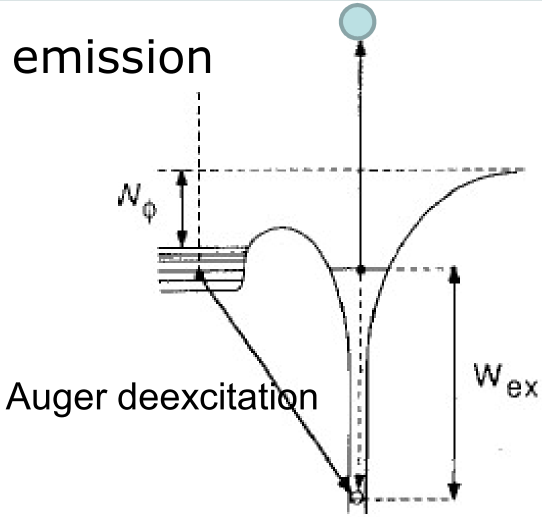
REVIEW OF SCIENTIFIC INSTRUMENTS 76, 093305 (2005)




## potential electron emission




Sn ions on $SiO_2$

W ~ 9 eV

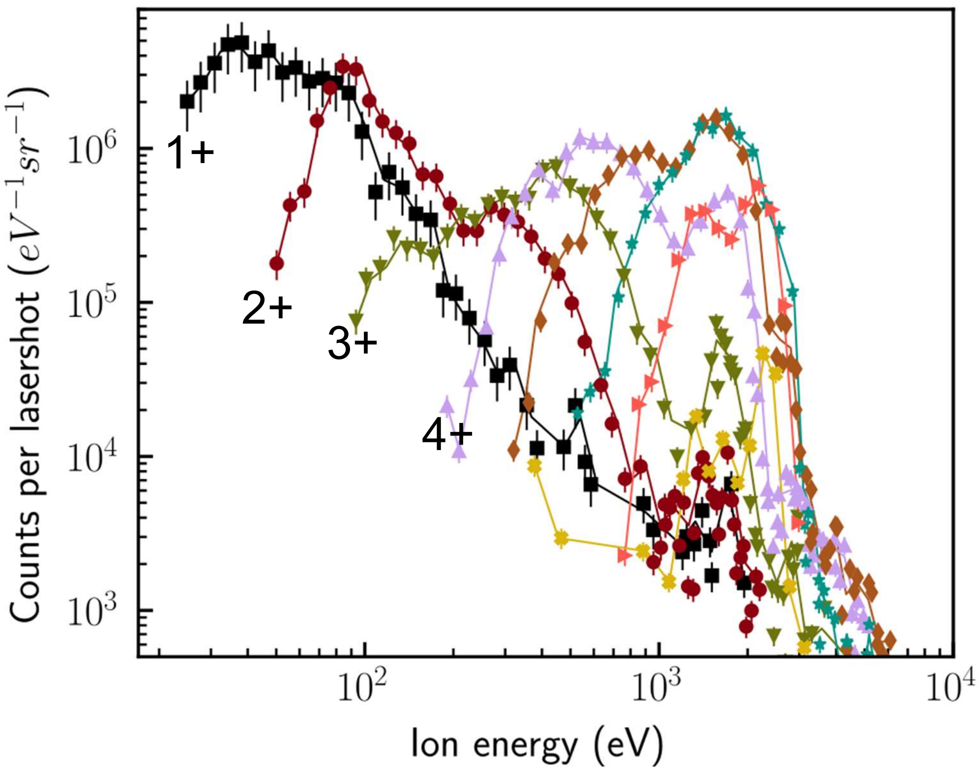
$E_{ion}$

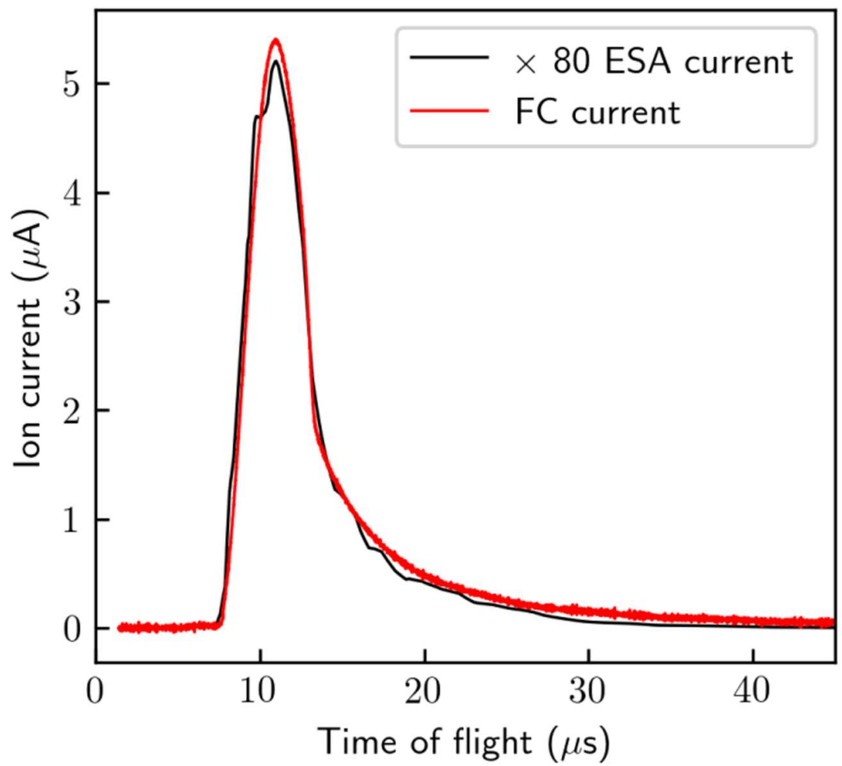
1+ - 7 eV $\gamma_{pot} = 0$

2+ - 14 eV $\gamma_{pot} = 0$

3+ - 28 eV $\gamma_{pot} =$ "small" order 0.1

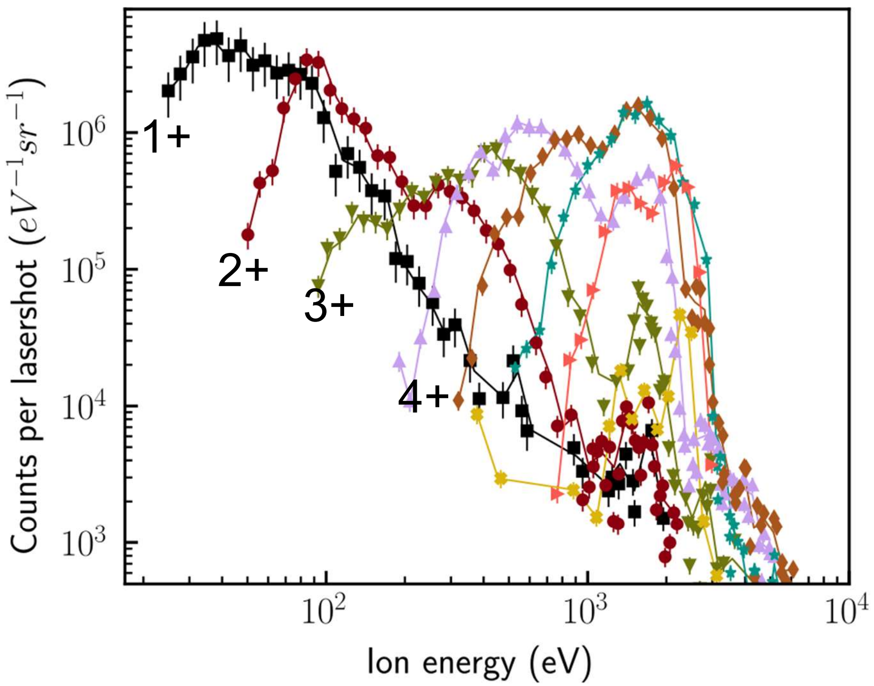
# comparison FC and ESA



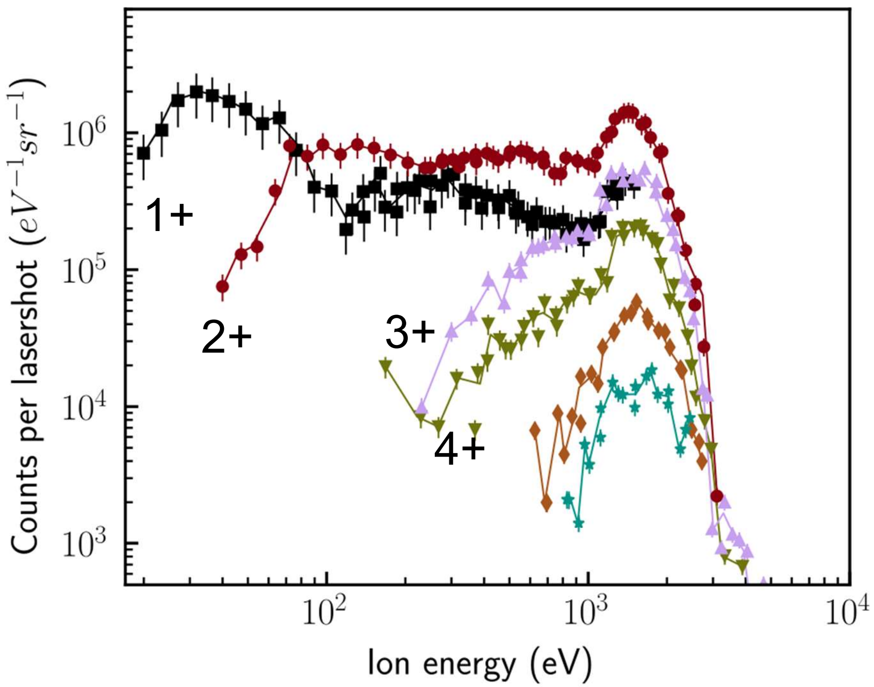



# effect of $H_2$ buffer gas on ion distribution

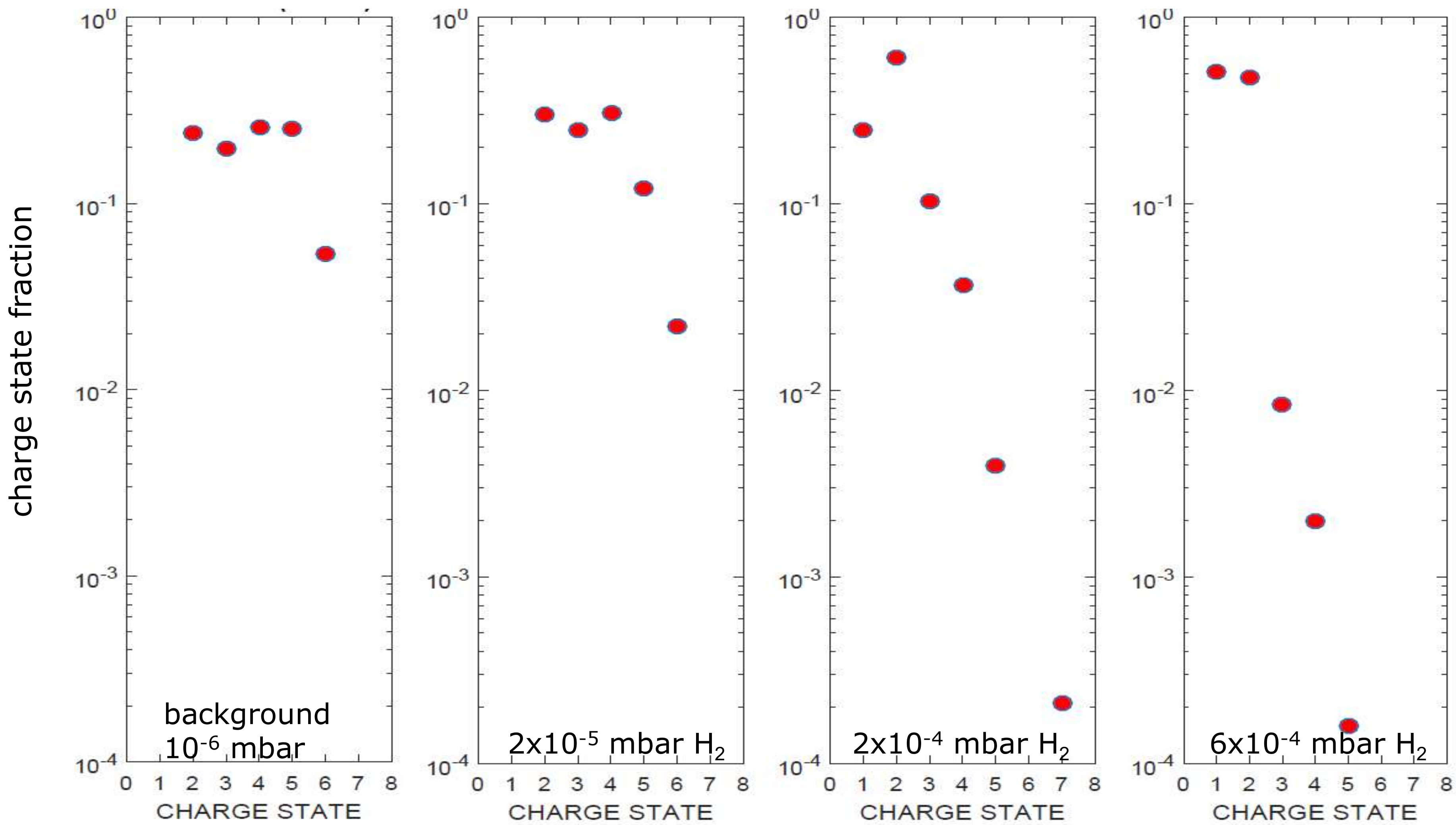
## background $10^{-6}$ mbar




## $2x10^{-4}$ mbar $H_2$

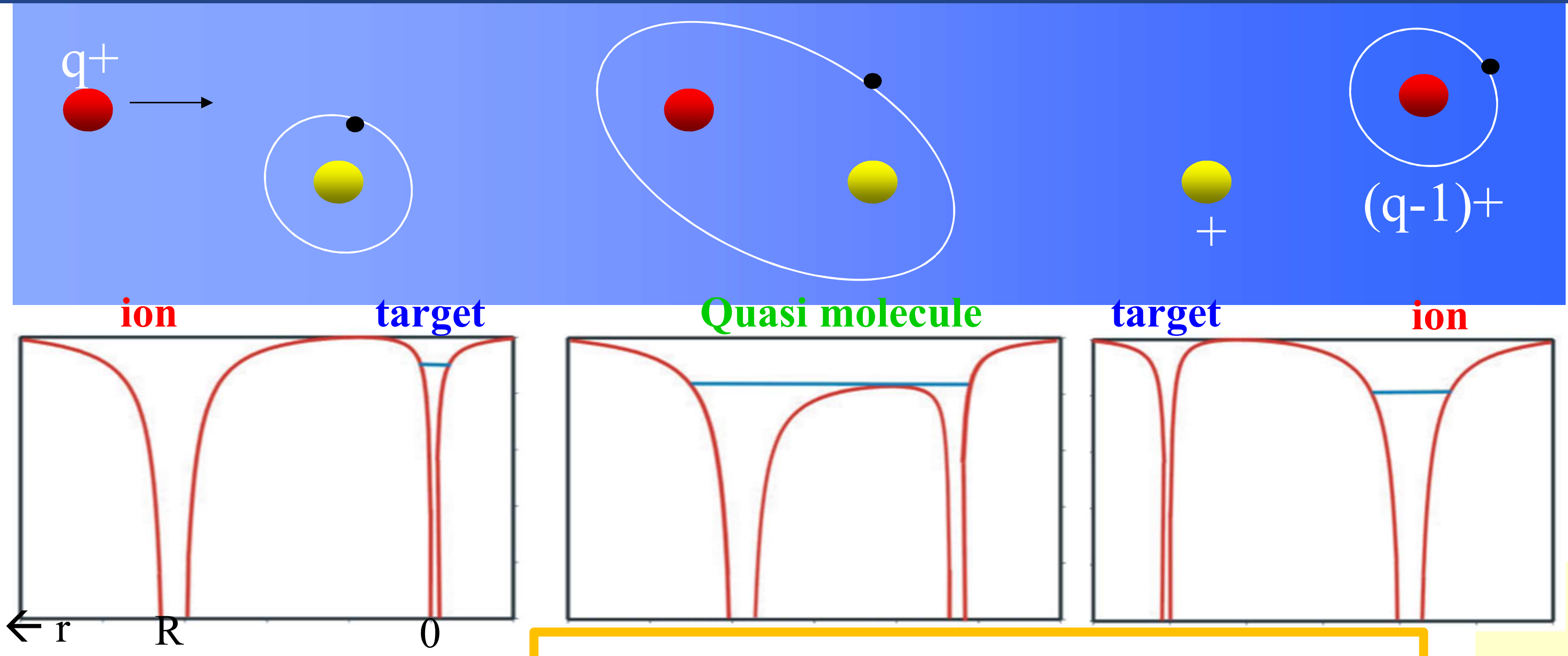


# 1 keV Sn ion charge state distributions




$$\frac{dN_q}{dx} = \sigma_{q+1} n_{H_2} N_{q+1} - \sigma_q n_{H_2} N_q$$

# overbarrier estimate of CX cross sections



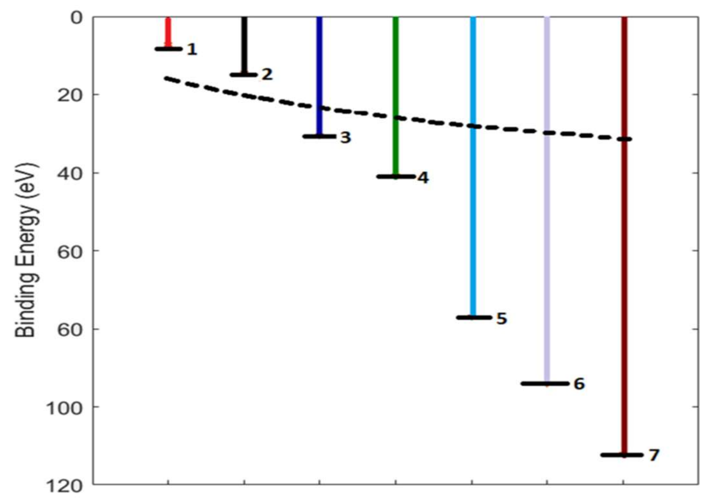

$$Sn^{q+} + H_2 \rightarrow Sn^{(q-1)+} + H_2^+$$

$$R_{capt} = \frac{1 + 2\sqrt{q}}{I}$$

$$\boldsymbol{\sigma = \pi R_{capt}^2}$$

$$E_{final} = I + \frac{(q-1)}{R_{capt}}$$

$$I_{H_2} = 16.1\ eV$$




$$A^{q+} + B \rightarrow A^{(q-2)+**} + B^{2+} \rightarrow A^{(q-1)+*} + B^{2+} + e$$

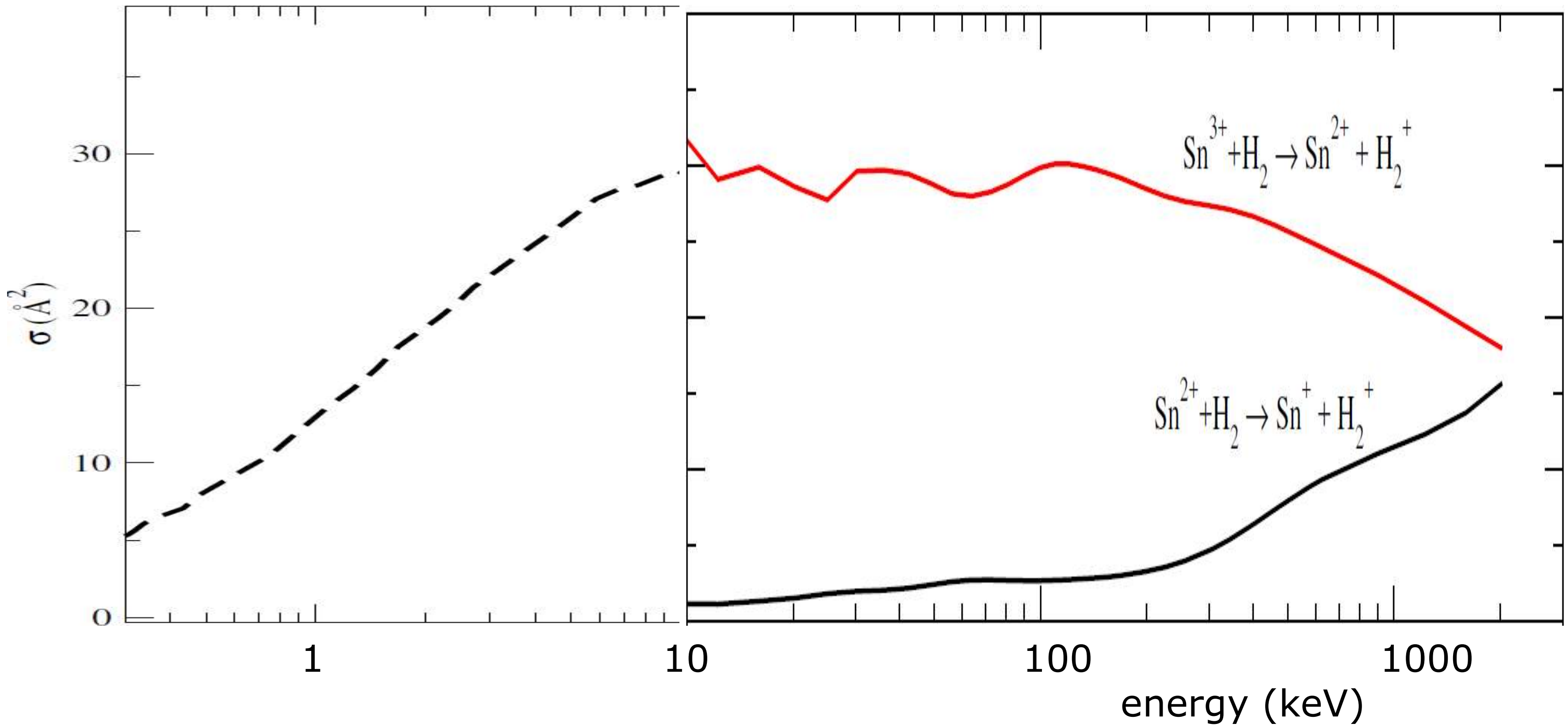
$$A^{q+} + B \rightarrow A^{(q-2)+*} + B^{2+}$$

| | OvB | OvB adj |
|---|---|---|
| | $10^{-16}$ cm$^2$ | |
| $Sn^{1+}$ | 23 | 1 |
| $Sn^{2+}$ | 37 | 10 |
| $Sn^{3+}$ | 50 | |
| $Sn^{4+}$ | 63 | |
| $Sn^{5+}$ | 75 | |
| $Sn^{6+}$ | 87 | |
| $Sn^{7+}$ | 99 | |

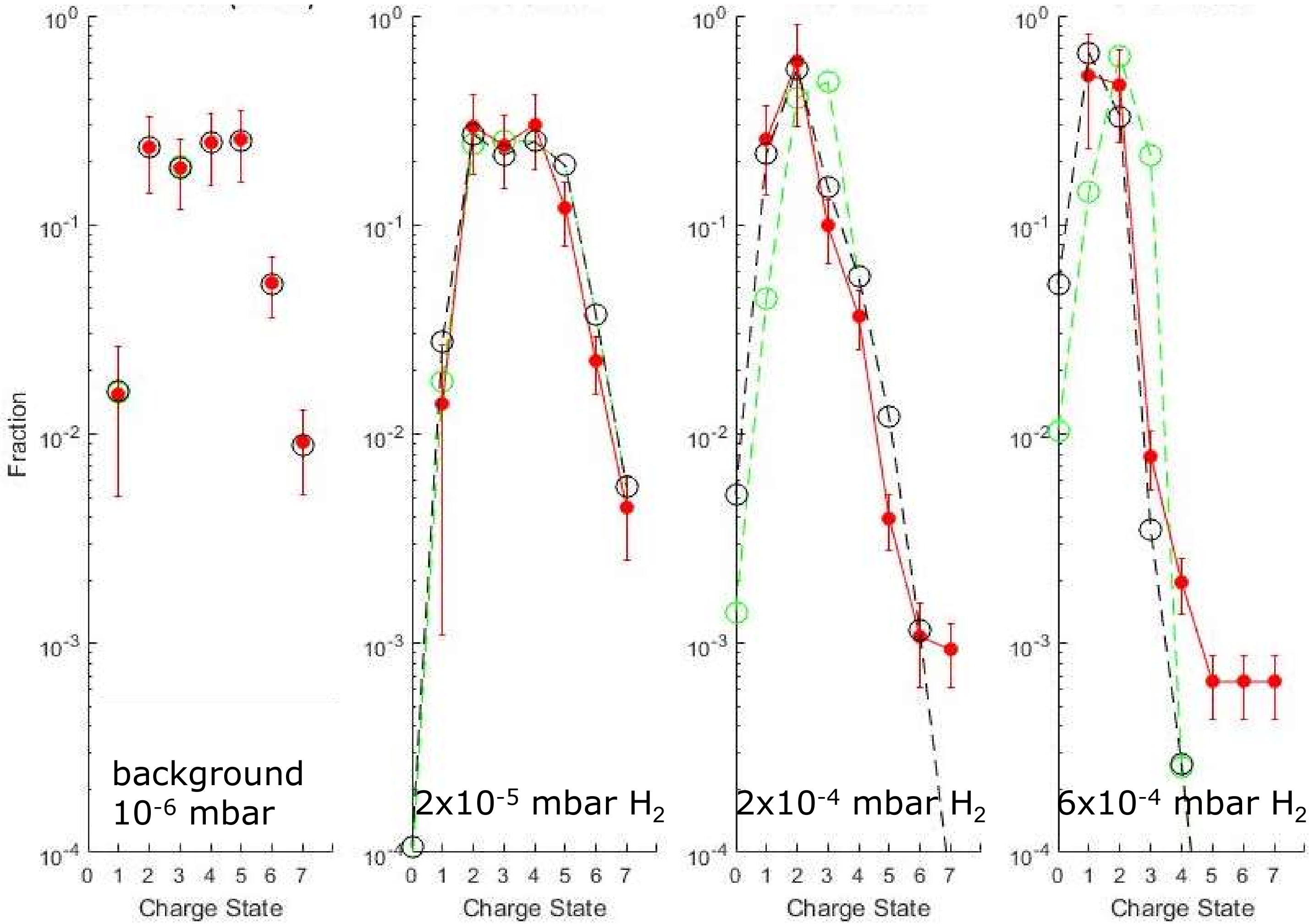
# Preliminary CX calculations

Luis Mendez and Ismanuel Rabadan

Universidad Autónoma de Madrid

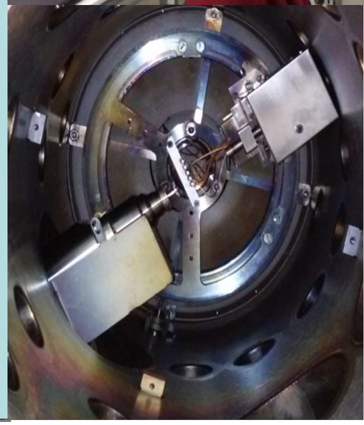


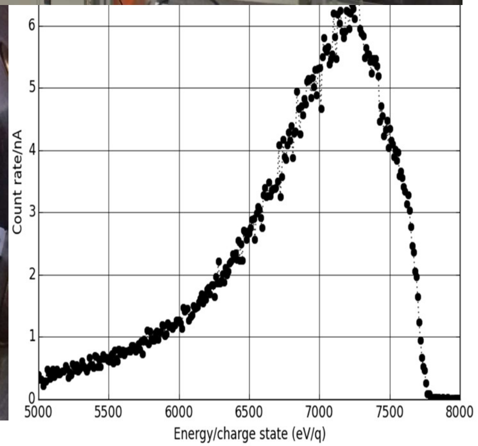
# 1 keV Sn ion charge state distributions




| | OvB | adj. | M&R |
|---|---|---|---|
| | $10^{-16}$ cm² | | |
| $Sn^{1+}$ | 23 | 1 | |
| $Sn^{2+}$ | 37 | 10 | 2 |
| $Sn^{3+}$ | 50 | | 12 |
| $Sn^{4+}$ | 63 | | |
| $Sn^{5+}$ | 75 | | |
| $Sn^{6+}$ | 87 | | |
| $Sn^{7+}$ | 99 | | |

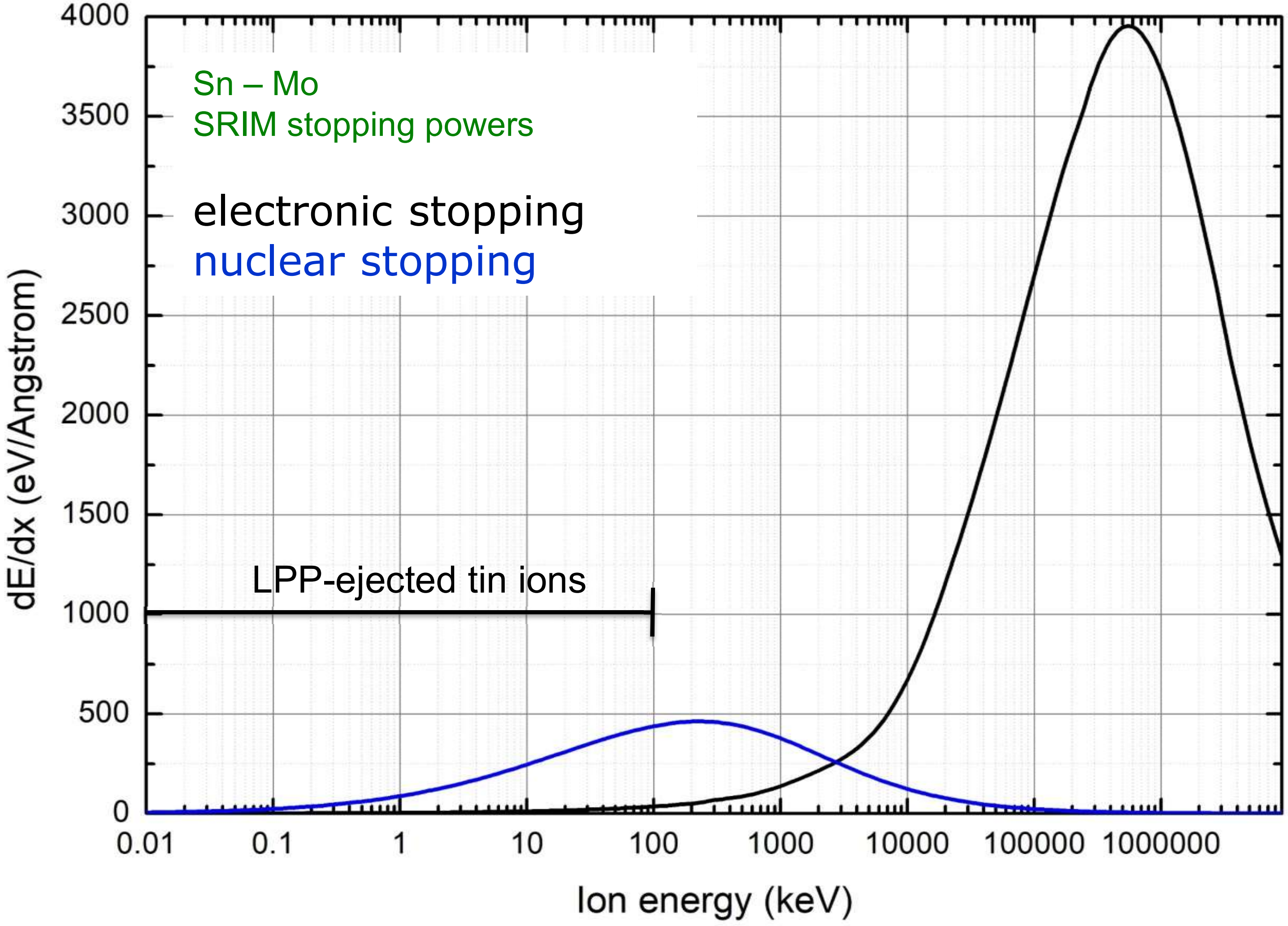
# ZERNIKELEIF @ university of groningen / zernike institute for advanced materials — ARCNL

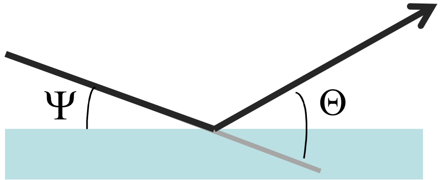



energy, mass and charge state selected $Sn^{q+}$ ion beam facility with a full suite of auxiliary analysis equipment

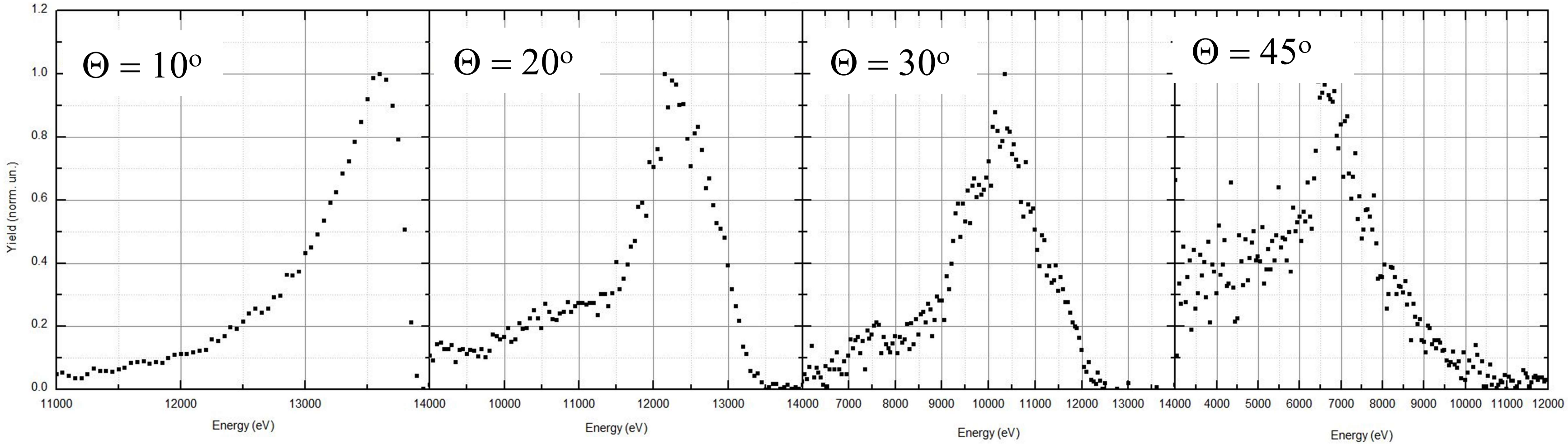
# type of interactions



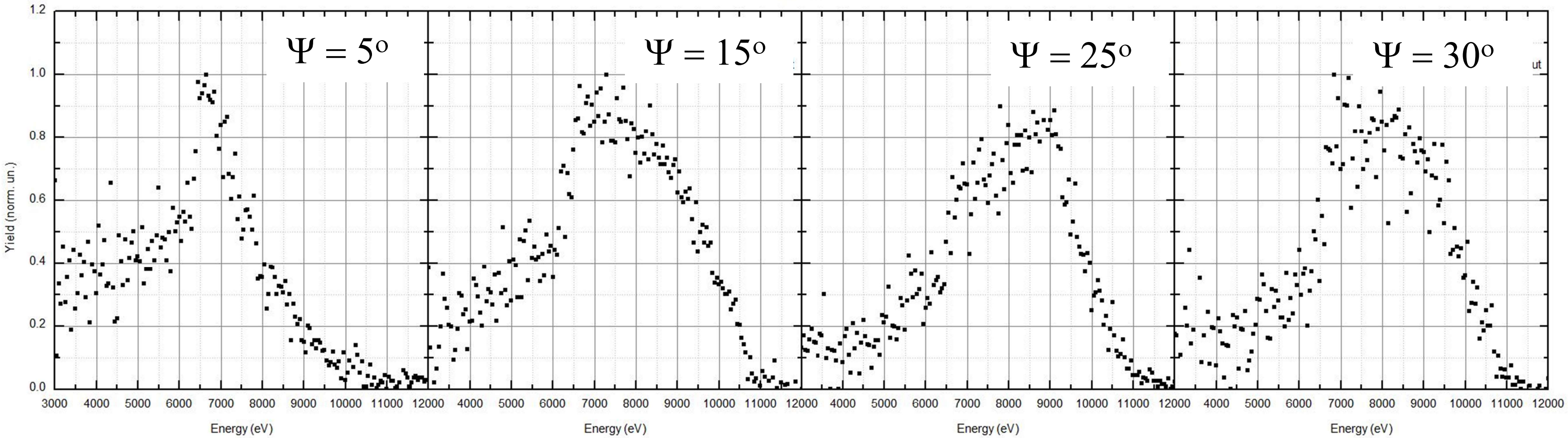
# typical spectra 14 keV $Sn^{2+}$ - Mo



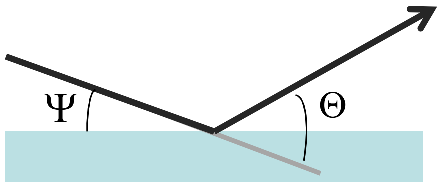

Ψ = 5°



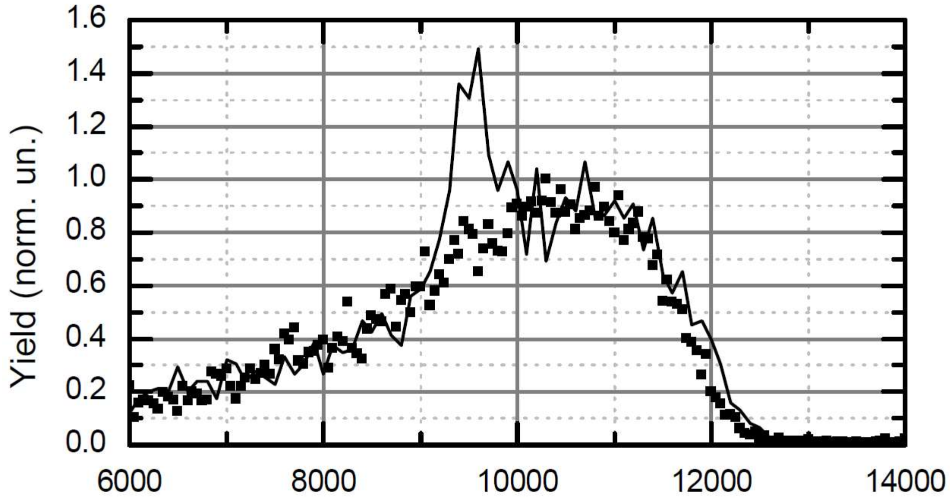

Θ = 45°



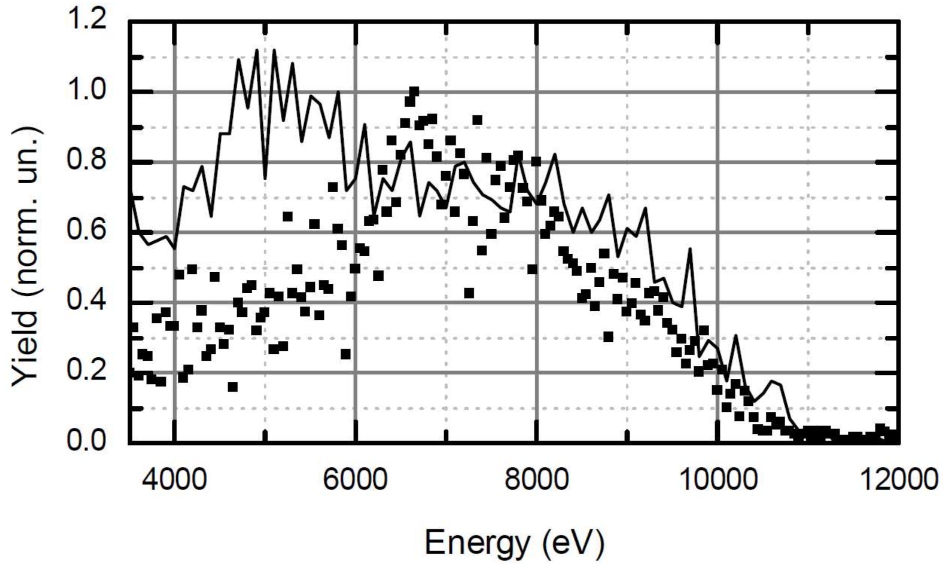
# 14 keV $Sn^{2+}$ - Mo: SRIM vs experiment

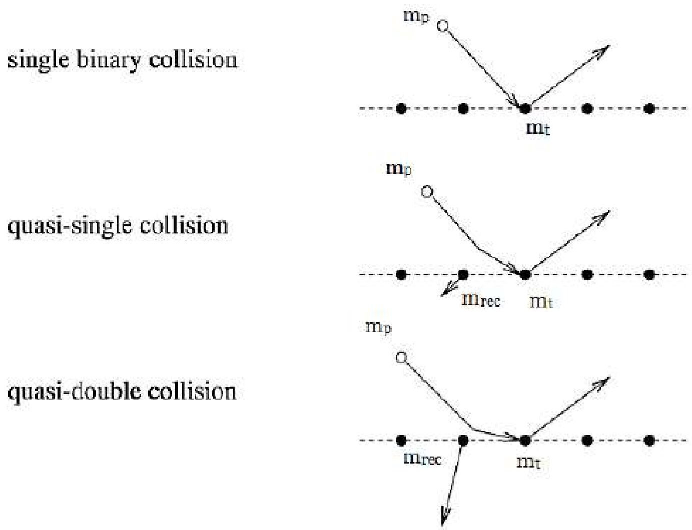



15-30

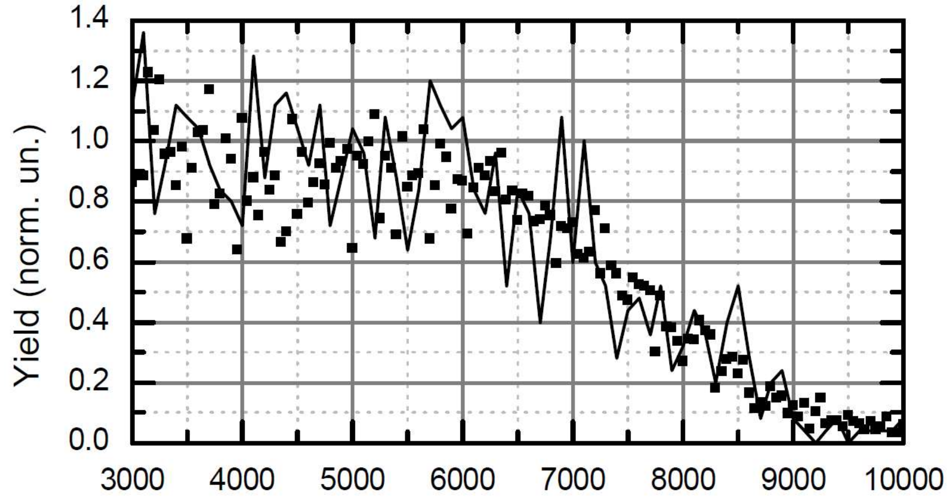



15-45



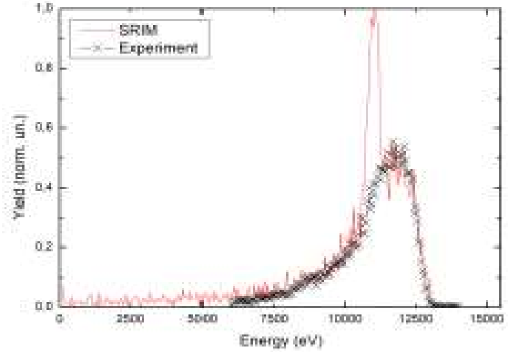

30-60



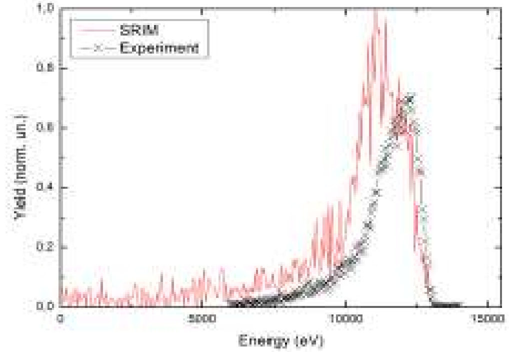
# tests of "SRIM – experiment difference"

| **original experiment: 14 keV $Sn^{2+}$ - Mo** | | |
|---|---|---|
| incoming charge state | $Sn^{1+ - 4+}$ | as 14 keV $Sn^{2+}$ |
| energy | 5 – 30 keV | as 14 keV $Sn^{2+}$ |
| ion species | $He^{1+}$, $Ne^{1+}$ | no difference between exp. and SRIM |
| | $Xe^{1+ - 2+}$ | as 14 keV $Sn^{2+}$ |
| | $Kr^{2+}$ | larger difference than 14 keV $Sn^{2+}$ |
| outgoing charge state | neutrals | being tested for Ru<br>ToF system and beam chopper installed |
| target | Ru | larger difference than 14 keV $Sn^{2+}$ |

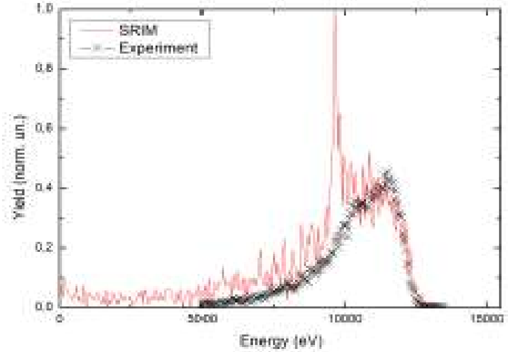
# first data 14 keV $Sn^{2+}$ - Ru



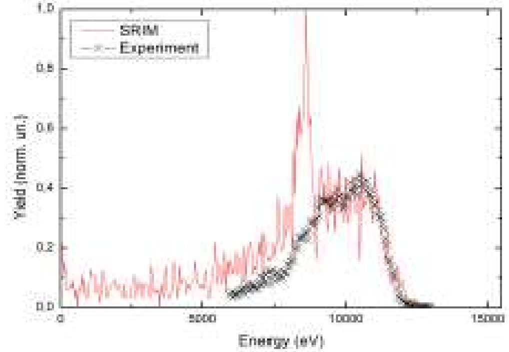

(a) $\varphi = 10°$ and $\theta = 25°$.



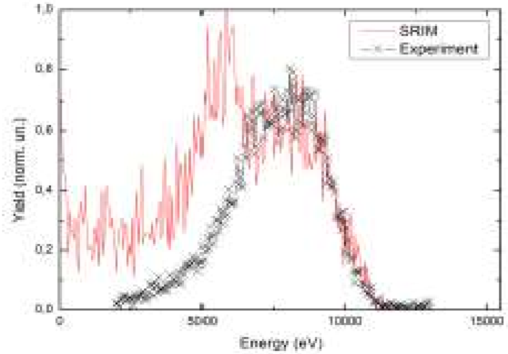

(b) $\varphi = 15°$ and $\theta = 25°$.



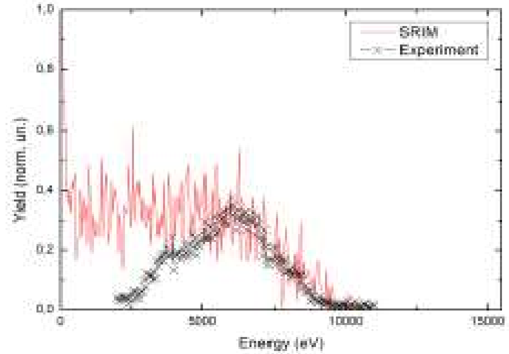

(c) $\varphi = 15°$ and $\theta = 30°$.




(d) $\varphi = 15°$ and $\theta = 35°$.




(e) $\varphi = 15°$ and $\theta = 45°$.




(f) $\varphi = 30°$ and $\theta = 60°$.

# scattering potentials

$$U = \frac{Z_1 Z_2}{r}\chi\left(\frac{r}{a}\right)$$

## Bohr

$$\chi = e^{-r/a}$$

$$a = \frac{1}{\left(Z_1{}^{2/3} + Z_2{}^{2/3}\right)^{1/2}}$$

## TFM-F

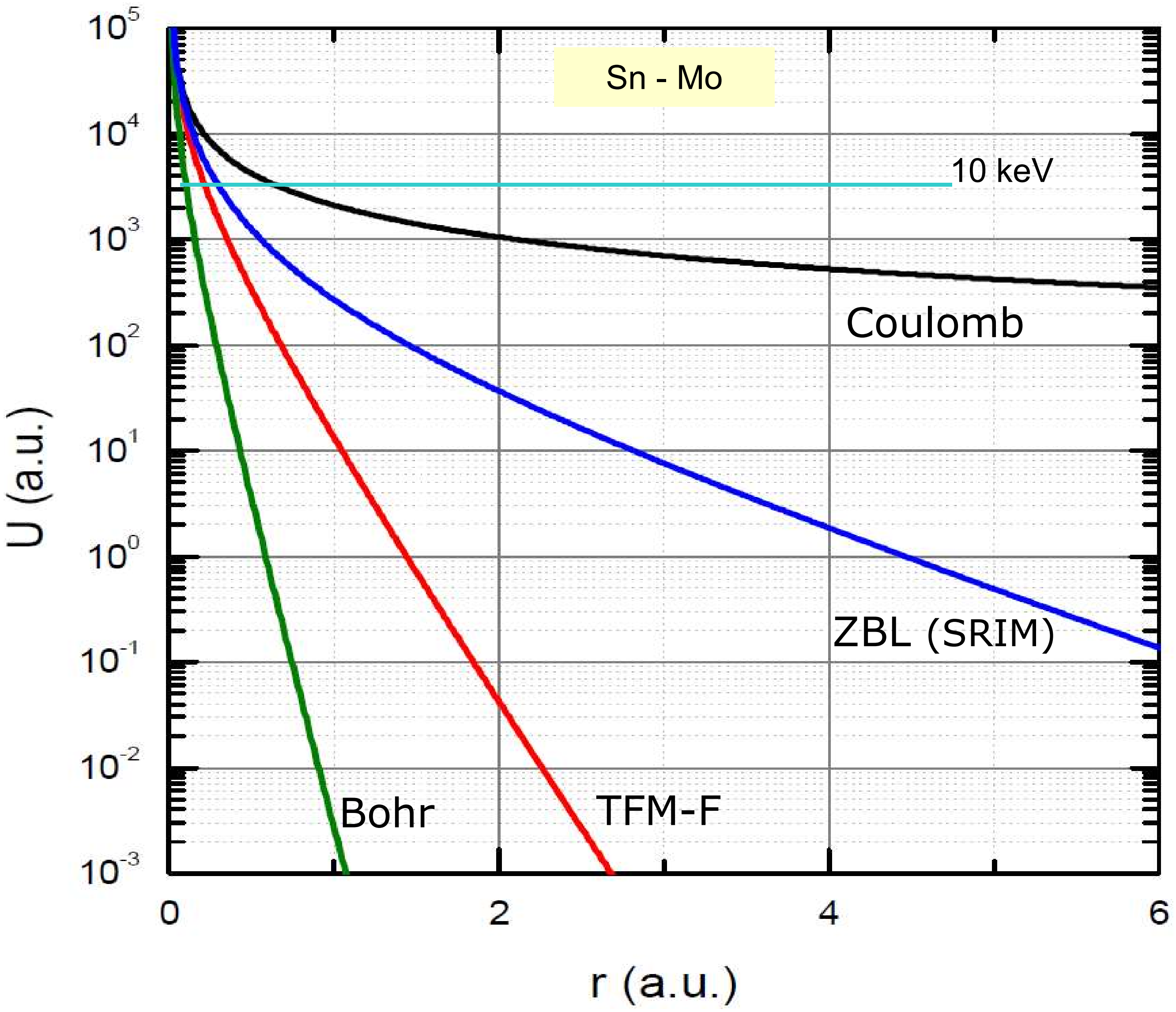
$$\chi = 0.35e^{-3r/a} + 0.55e^{-1.2r/a} + 0.1e^{-6r/a}$$

$$a = \frac{0.8853}{\left(Z_1{}^{2/3} + Z_2{}^{2/3}\right)^{1/2}}$$

## ZBL (SRIM)

$$\chi = 0.1818e^{-3.2r/a} + 0.5099e^{-0.9423\ /a} + 0.2802e^{-0.4028r/a} + 0.2817e^{-0.2016r/a}$$

$$a = \frac{0.8853}{Z_1{}^{0.23} + Z_2{}^{0.23}}$$




next step: SRIM → SDTrimSP-2D

# conclusions

## "ARCNL's" tin ion spectroscopy and interactions program

- EUV source plasma conditions and densities not to dissimilar from tokamaks
- Spectroscopy:
  - well underway
  - strong collaboration with theory (structure)/ opacity investigations starting
  - experiments on EUV source plasma and external facilities
- ZERNIKELEIF facility for energy, mass, and charge state selected beams of Sn ions operational
- Interactions
  - First scattering experiments on Mo and Ru surfaces hint at issues with SRIM
  - Set-up for CX in H2 is being commissioned