Reliable atomic data for fusion research and astrophysics:

Benchmarking calculations for highly charged ions

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HCI as resource for fundamental physics

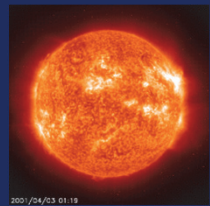
- Atoms are key assets in fundamental studies:
  - universally reproducible
  - spectroscopic frequency references from MW to VUV
  - mass references for nuclear, neutrino physics, etc.
  - EDM searches for interactions beyond the SM
  - atomic interferometric probes of space-time, relativity
- Limitation: Unstable at high interaction energies
- Using HCI expands these possibilities:
  - high intrinsic stability against perturbations
  - stable at high photon energies up to the 0.1 MeV
  - in greater variety than atoms or singly charged ions

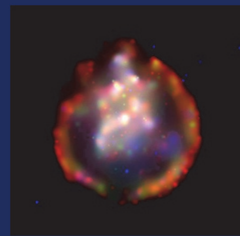
Review of Modern Physics coming up:

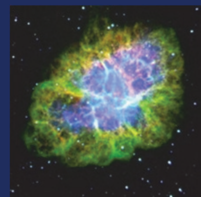
(arXiv, Kozlov, Safronova, JRC, Schmidt 2018)

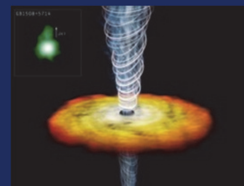
In the Universe, elements are mostly highly ionized: Highly charged ions (HCI)

- Interior of the Sun (15 MK)
- Solar corona (2 MK)
- Solar wind (MK)
- Supernova remnants
- Active galactic nuclei (100 MK)
- Warm-hot intergalactic medium (0.1-1 MK)









In the laboratory:

- Fusion machines (50 MK)
- Accelerators, laser produced plasmas (1 MK)
- Electron beam ion traps (e. g. in Heidelberg)

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State of the art in the field of HCI

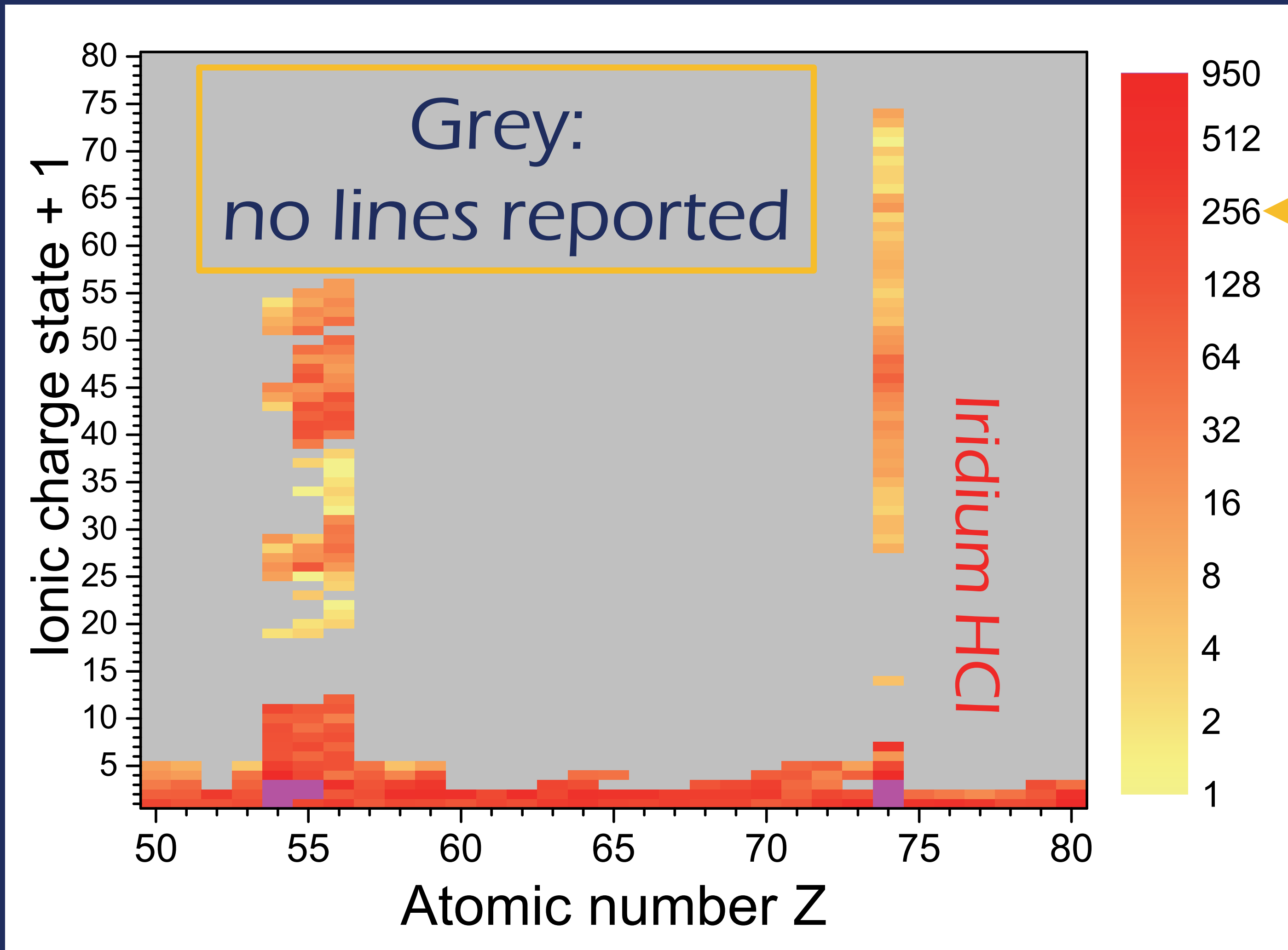
• X-ray photon energies	1.5 ppm
• VUV photon energies	4 ppm
• Optical photon energies	0.3 ppm
• Lifetimes (ns... ms)	0.15 %
• Natural linewidths X-rays:	resolved

Accuracy is 12 orders of magnitude lower than in frequency metrology

Stone-age spectroscopy at the 10^{-6} level

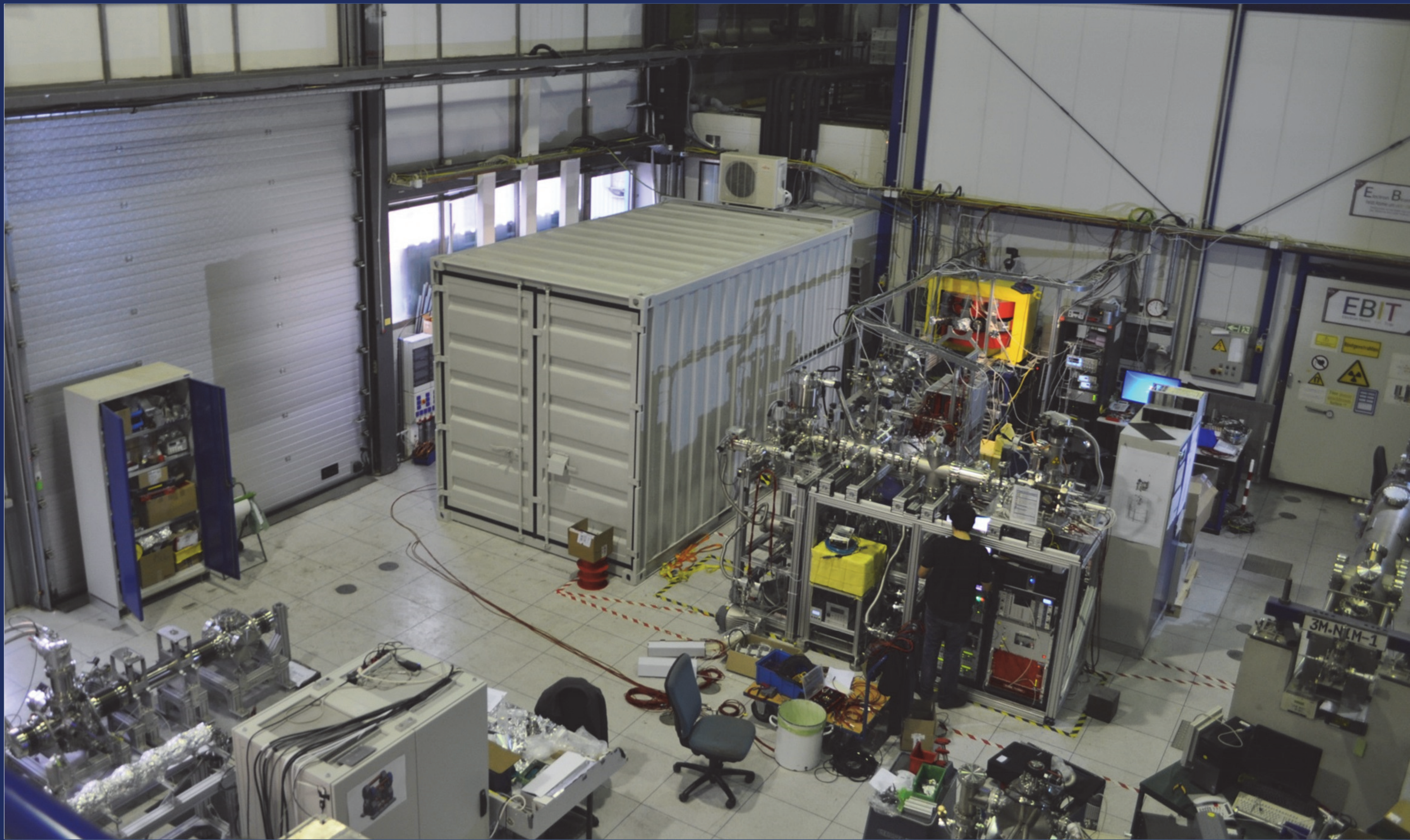
HCI: Under way in the "spectral desert"

- No reports about the ions of interest and no transition data available for most ions!
- HCI production in EBIT easy, identification much harder



Color scale: Number of known transitions

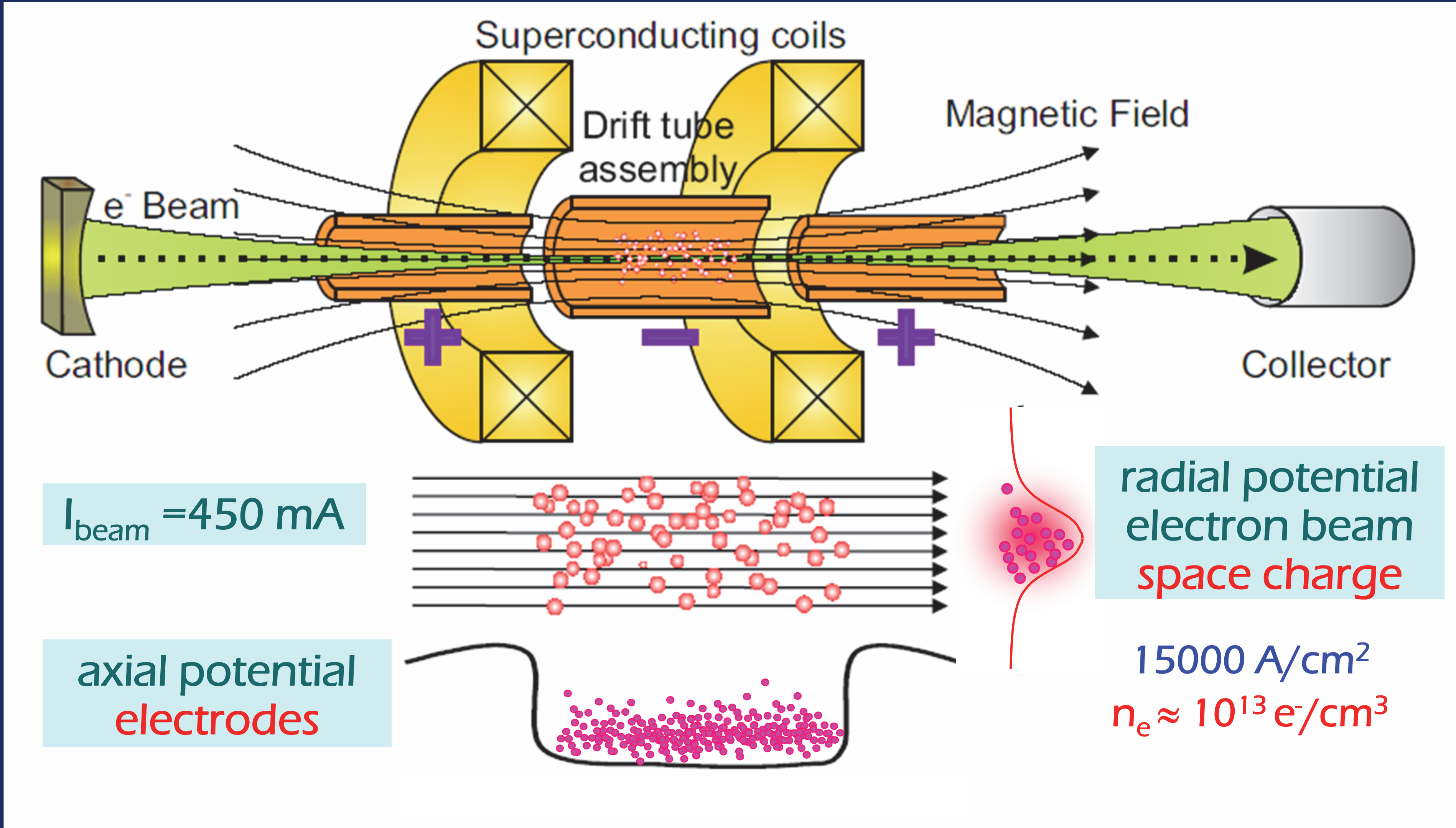
EBIT facility at MPIK



Overview

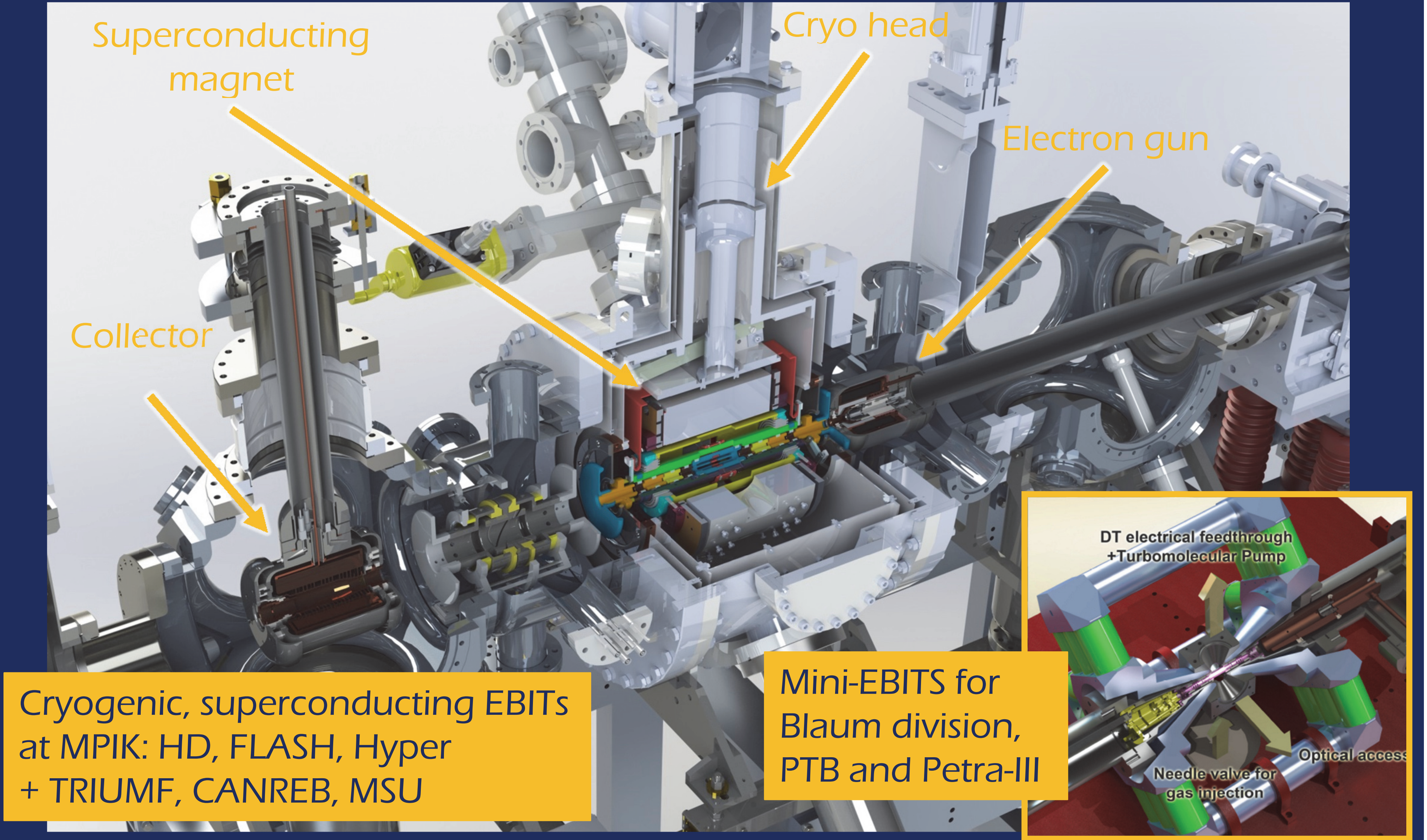
- Electron beam ion traps
- Photon excitation studies
- Electron excitation studies
- Optical and EUV spectroscopy
- Charge exchange
- Frequency metrology

HCI production with electron beam ion trap



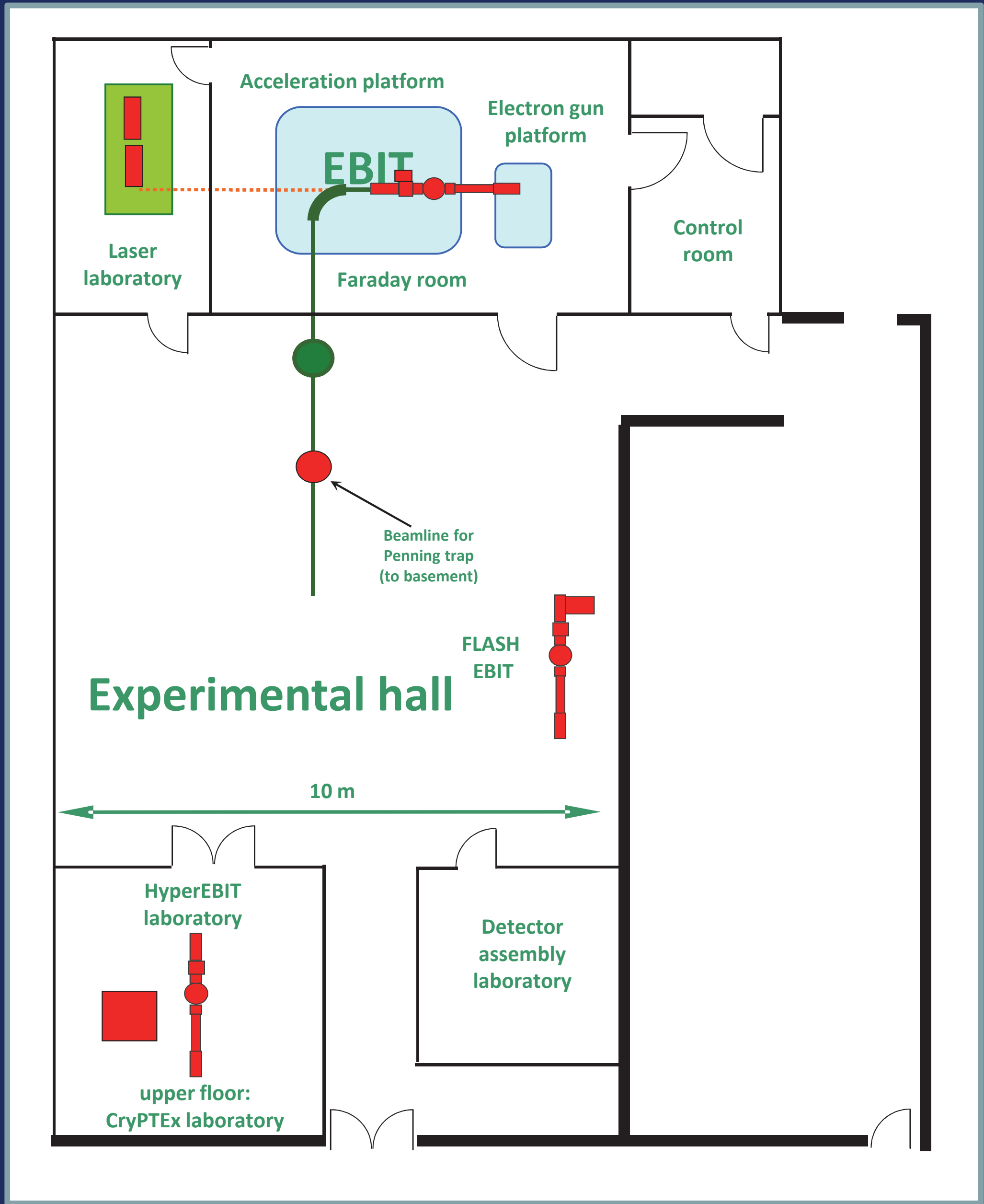
Electron beam drives ionization, excites and traps the ions inside a cylindrical volume

Electron beam ion traps big and small

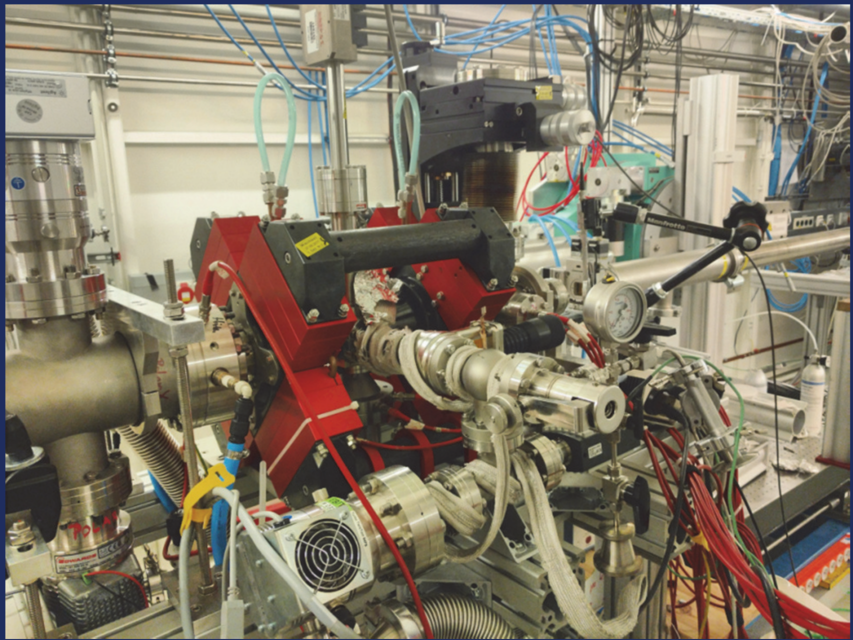


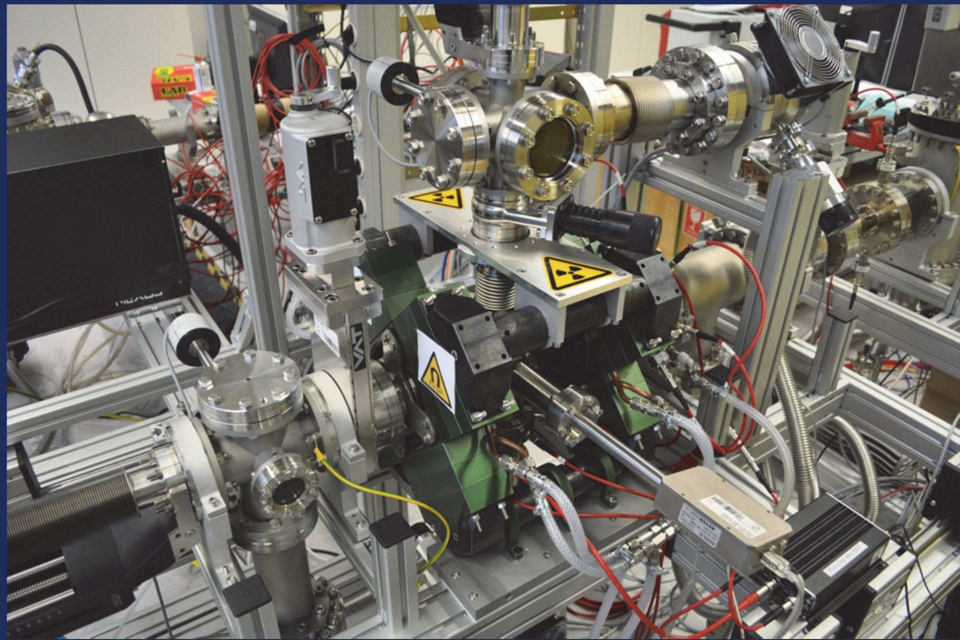
- Unique facility at MPIK, supporting Pfeifer and Blaum division
- Out of ~20 research EBITs worldwide, 10 are at or come from MPIK

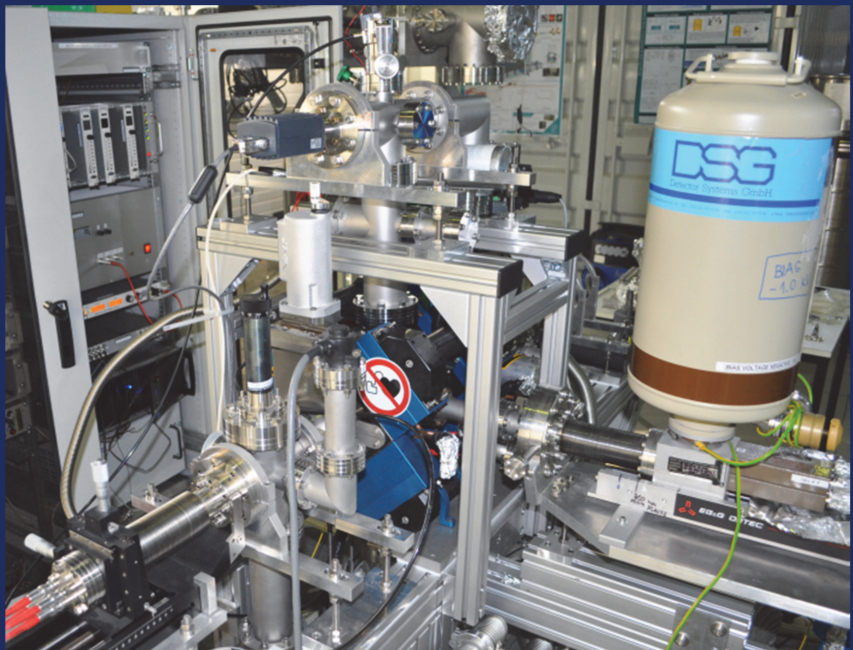
EBIT facility at MPIK



Some compac EBITs







Electron beam ion traps at MPIK

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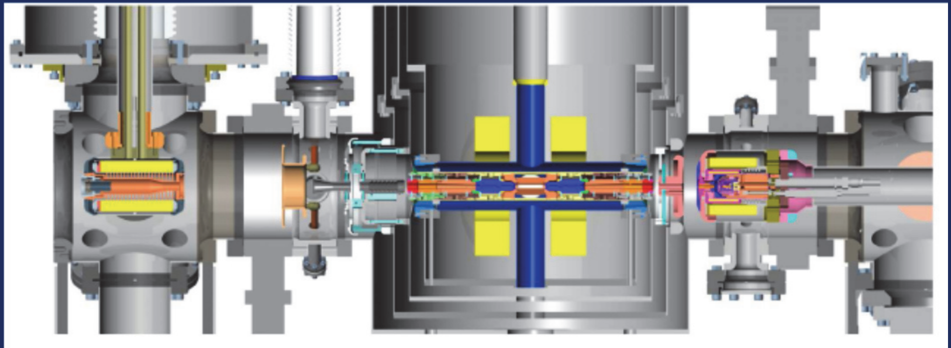
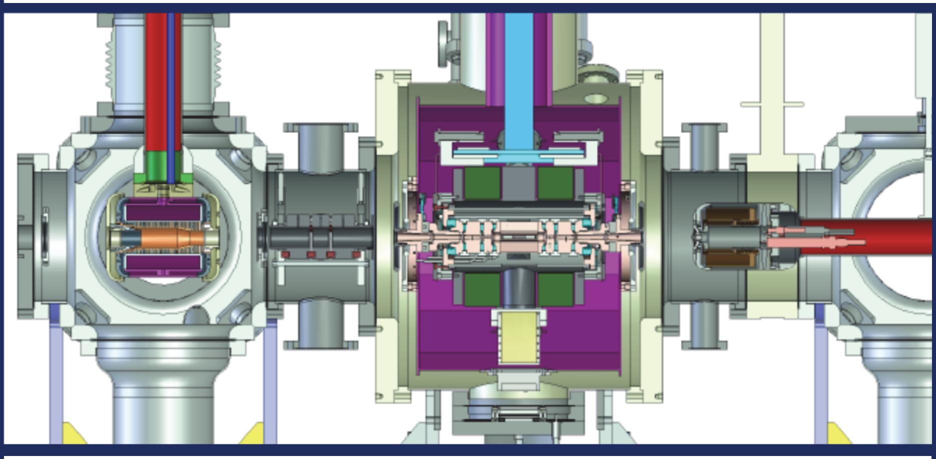
Cryogenic devices:

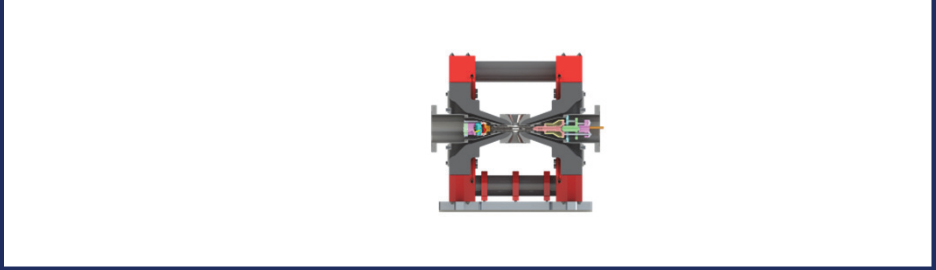
- HD EBIT: stationary machine built in 1999 (former FreeEBIT)
- FLASH EBIT: transportable for beamtimes at FLASH, BESSY, LCLS and PETRAIII
- Hyper EBIT



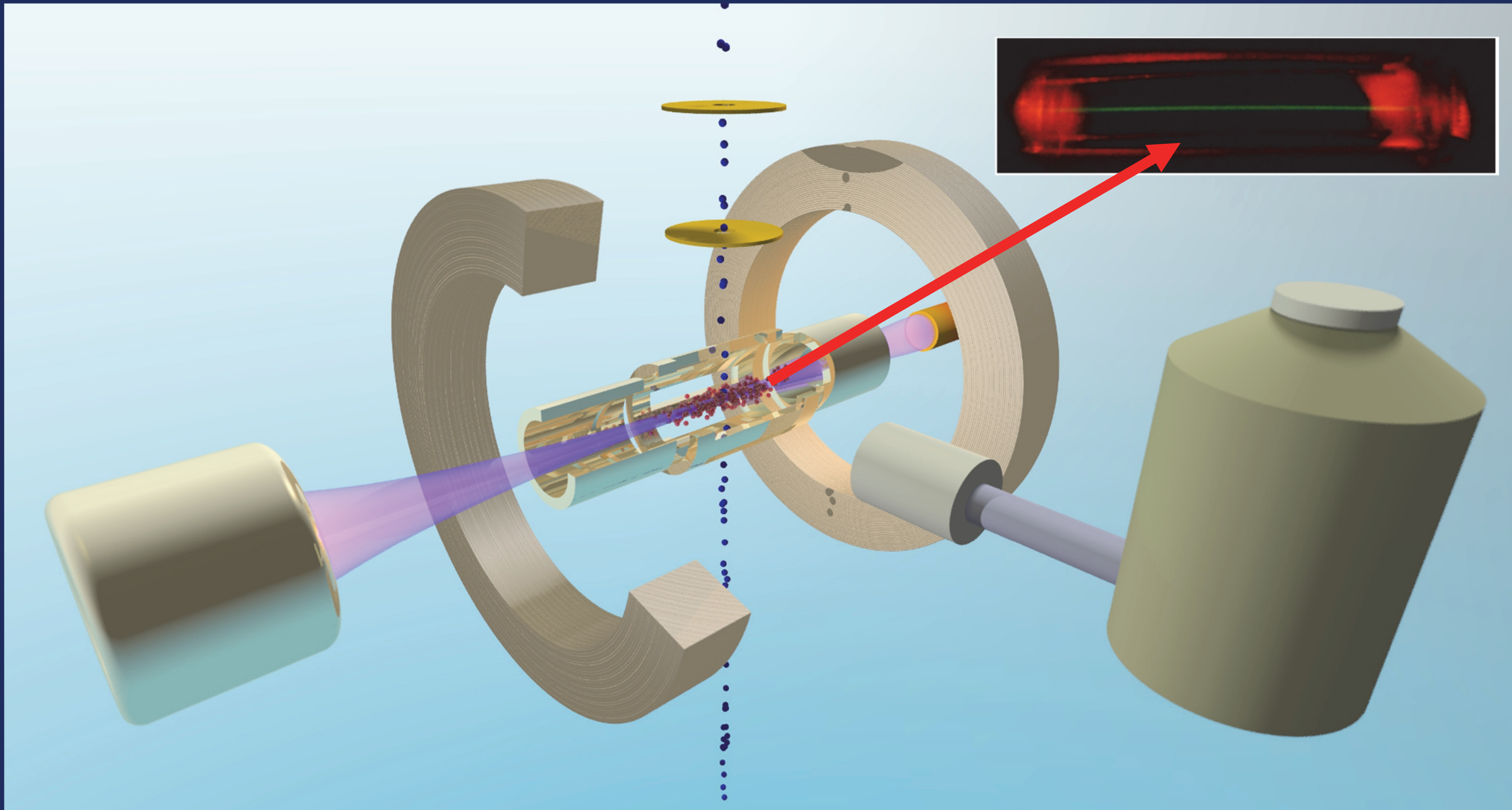


Miniature:

- Polar-X EBIT (at PETRAIII)
- Tip-EBIT (Blaum division)
- TT-EBIT (Blaum division)
- CryPTEx-II-EBIT

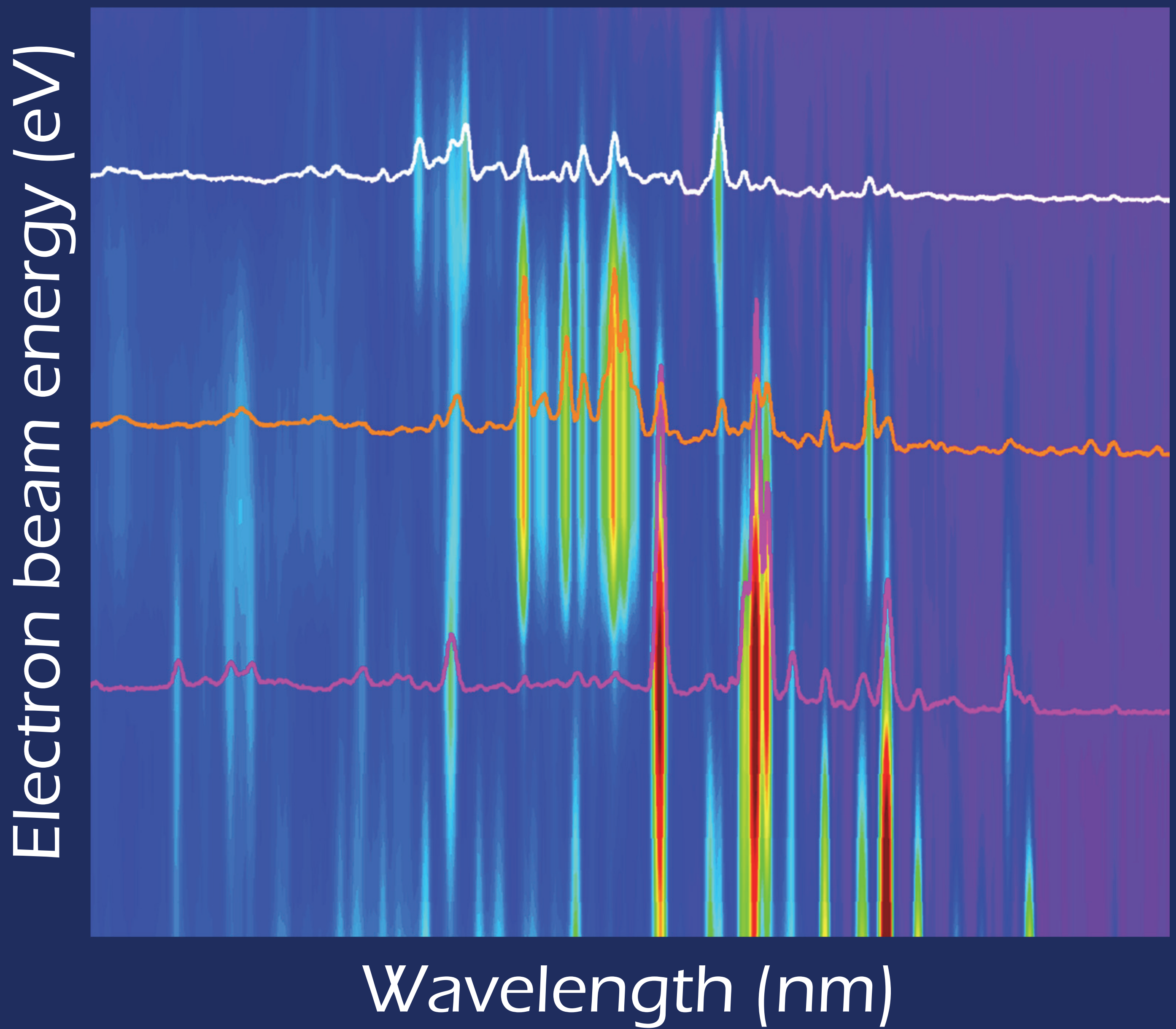


Strong excitation by electron impact and resonant photorecombination



Ge, Si detectors, crystal and grating spectrometers, microcalorimeters, etc., for X-ray diagnostics

Choice of charge state by dialing electron beam energy



What we do with EBITs

- Photorecombination processes: radiative + dielectronic, trielectronic and quadruelectronic recombination,
- Photoionization of HCI with synchrotron radiation, from N^{3+} (from 60 eV) to Kr^{33+} (at 14 keV)
- High-resolution spectroscopy from optical to X-rays
- Free-electron laser soft x-ray spectroscopy (<800 eV)
- High-resolution x-ray metrology with synchrotron radiation (<14.4 keV)
- Laser spectroscopy of forbidden optical lines in HCI
- Sympathetic cooling of HCI for frequency metrology
- Charge-exchange studies

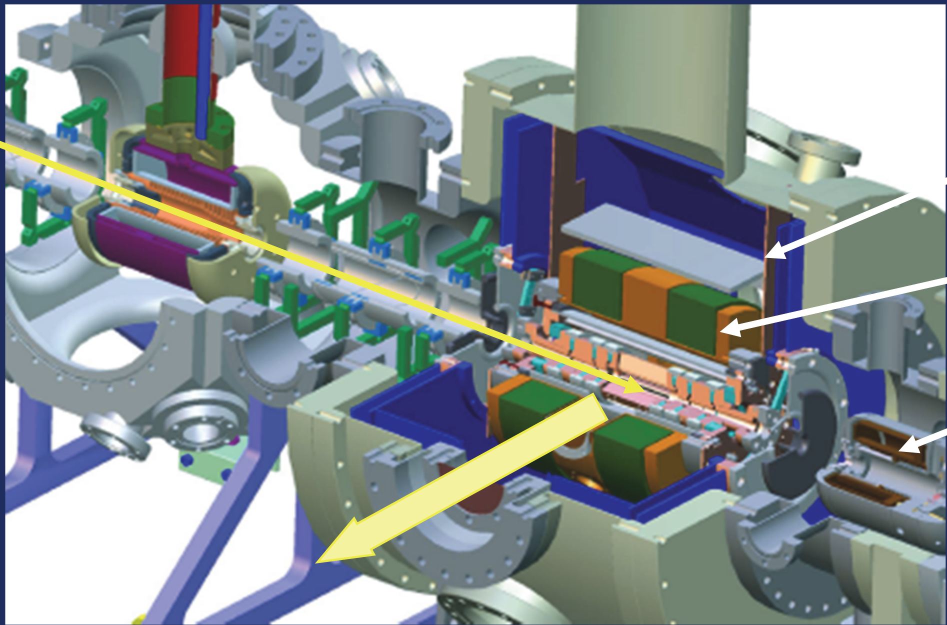
Free-electron laser and synchrotron-radiation excitation and photoionization of highly charged ions

Photonic interactions with HCI

Combine novel X-ray sources (free-electron lasers, synchrotrons) with electron beam ion trap (EBIT)

- to measure excitation energies beyond current accuracy limits
- to determine cross sections and line profiles for photoexcitation, photoionization HCI benchmarking atomic theory

Interaction with photon beams



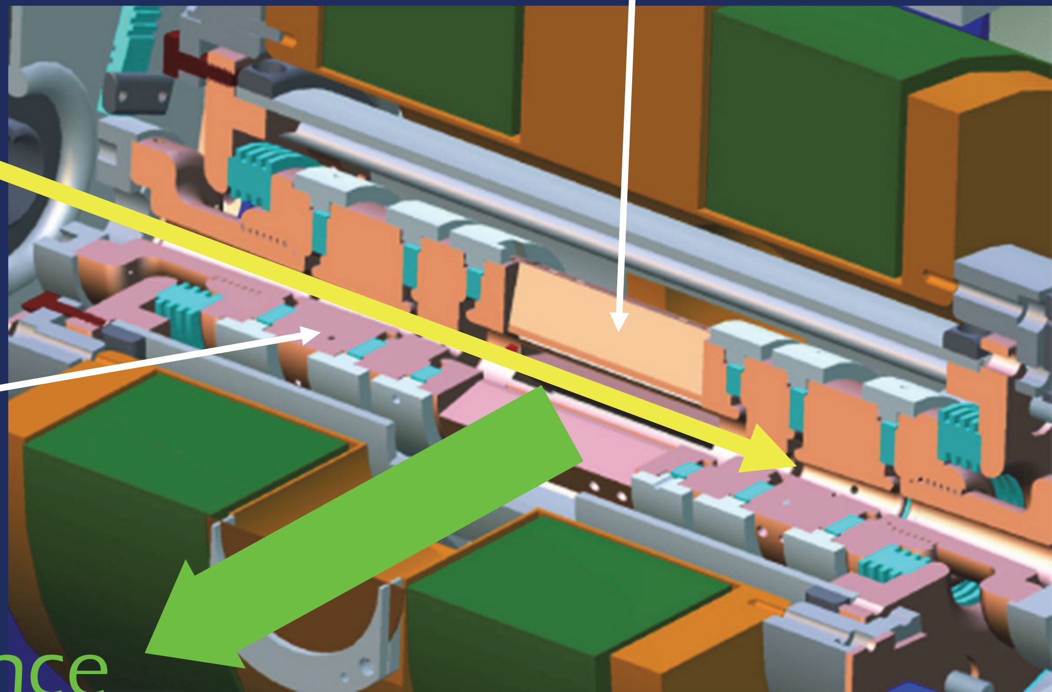
cryostat

superconducting magnet

electron gun

trapped ions

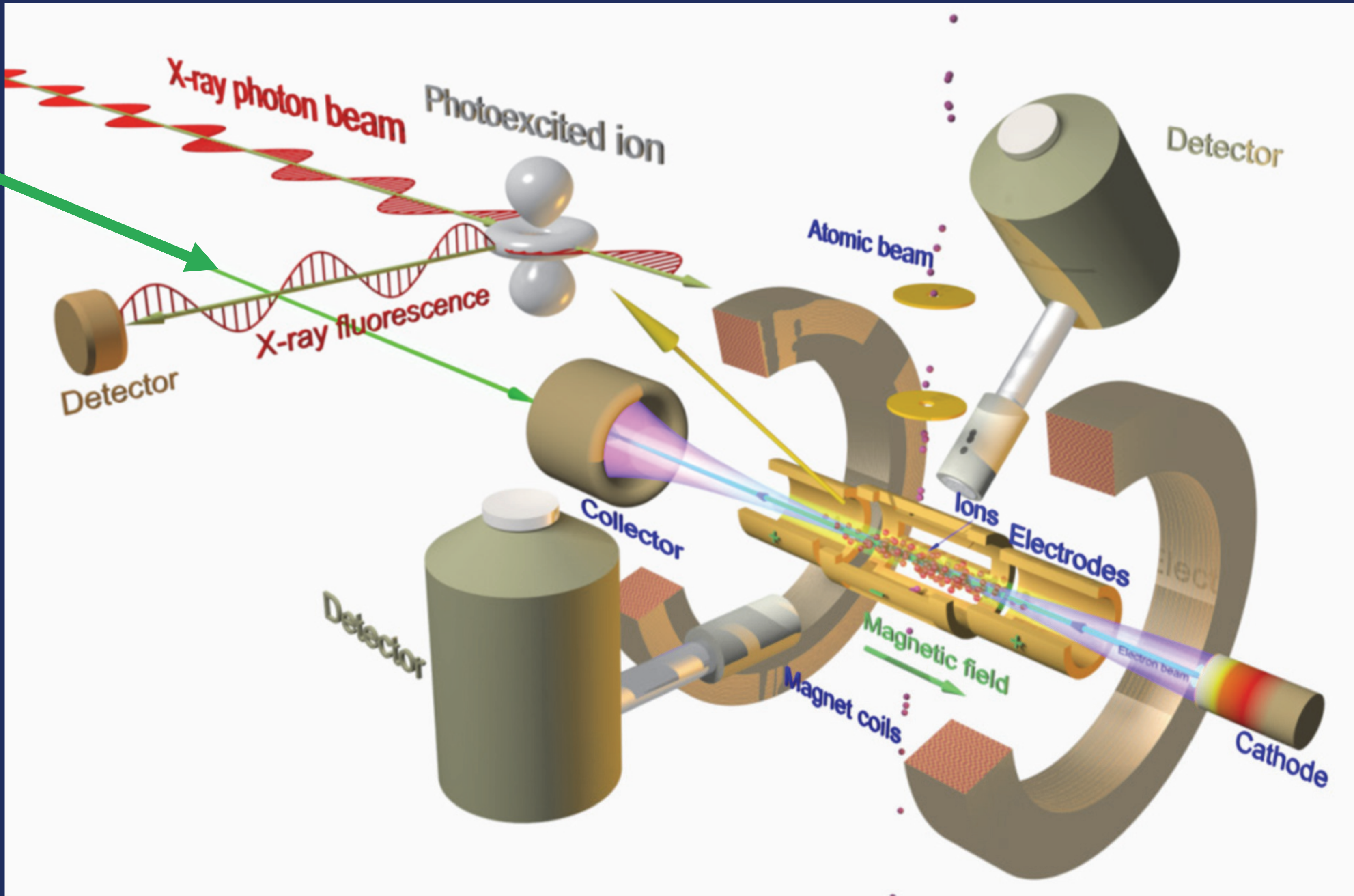
photon beam



drift tubes

fluorescence

Resonant photon excitation in EBIT

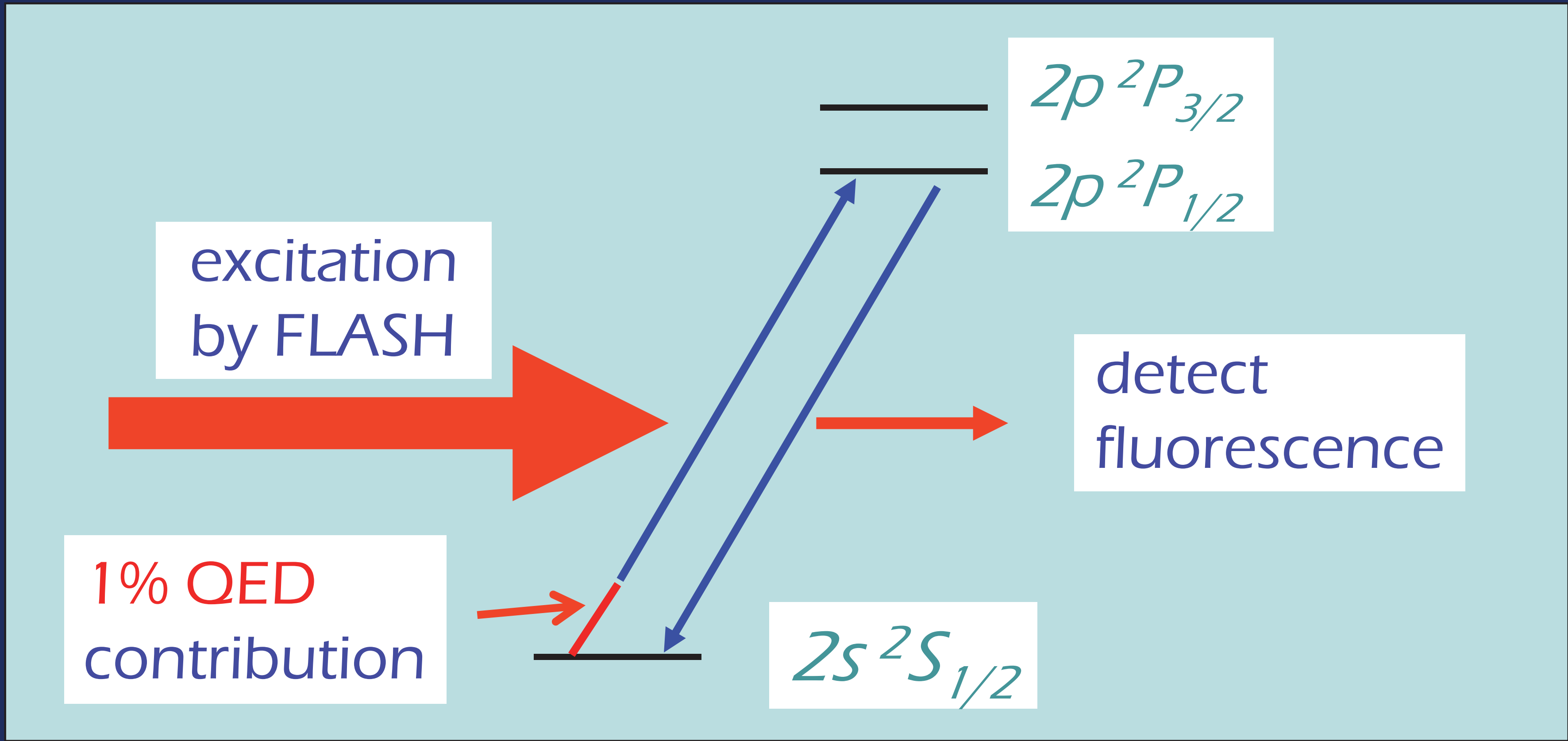


- Synchrotron radiation (PETRAIII),
- Free-electron lasers (LCLS) ,

provide X-rays with high power and energy resolution

Soft X-ray laser spectroscopy at FLASH

FEL 50 eV beam excites resonantly
the *2s-2p* transition in Li-like Fe^{23+} at 50 eV



S. W. Epp *et al.*, Phys. Rev. Lett. **98** (2007) 183001

LCLS: Linac Coherent Light Source

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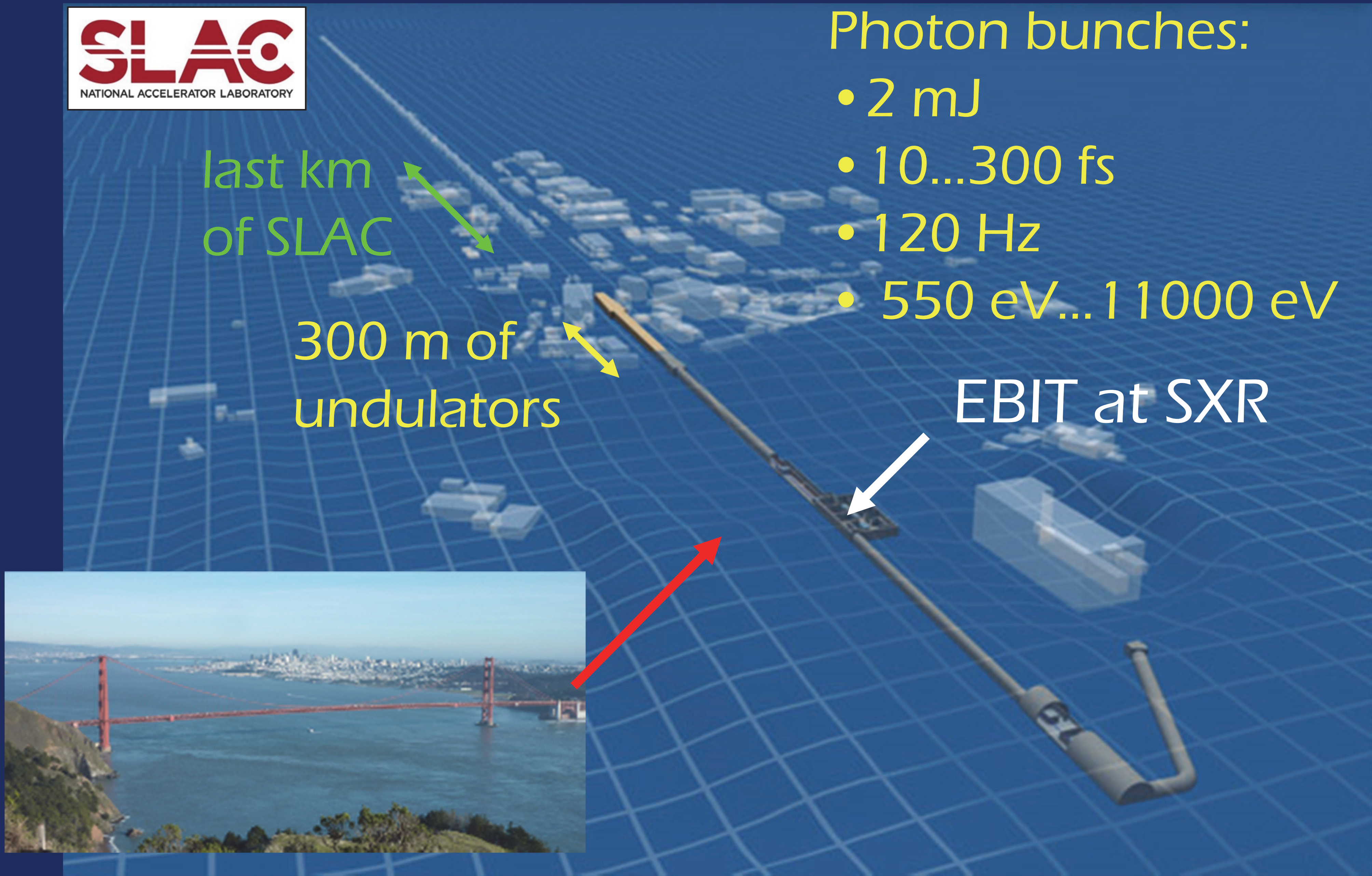
SLAC NATIONAL ACCELERATOR LABORATORY



Photon bunches:

- 2 mJ
- 10...300 fs
- 120 Hz
- 550 eV...11000 eV

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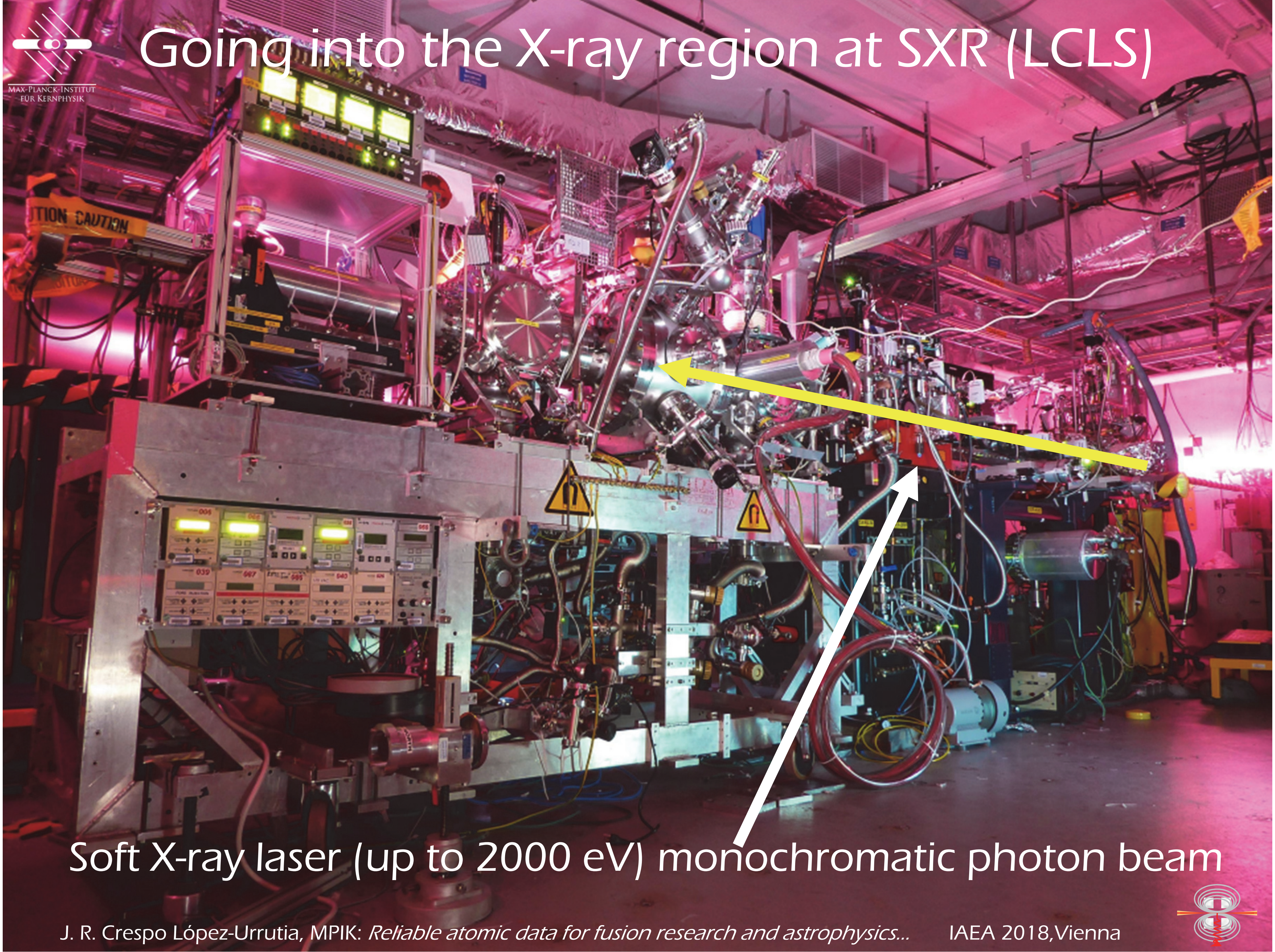
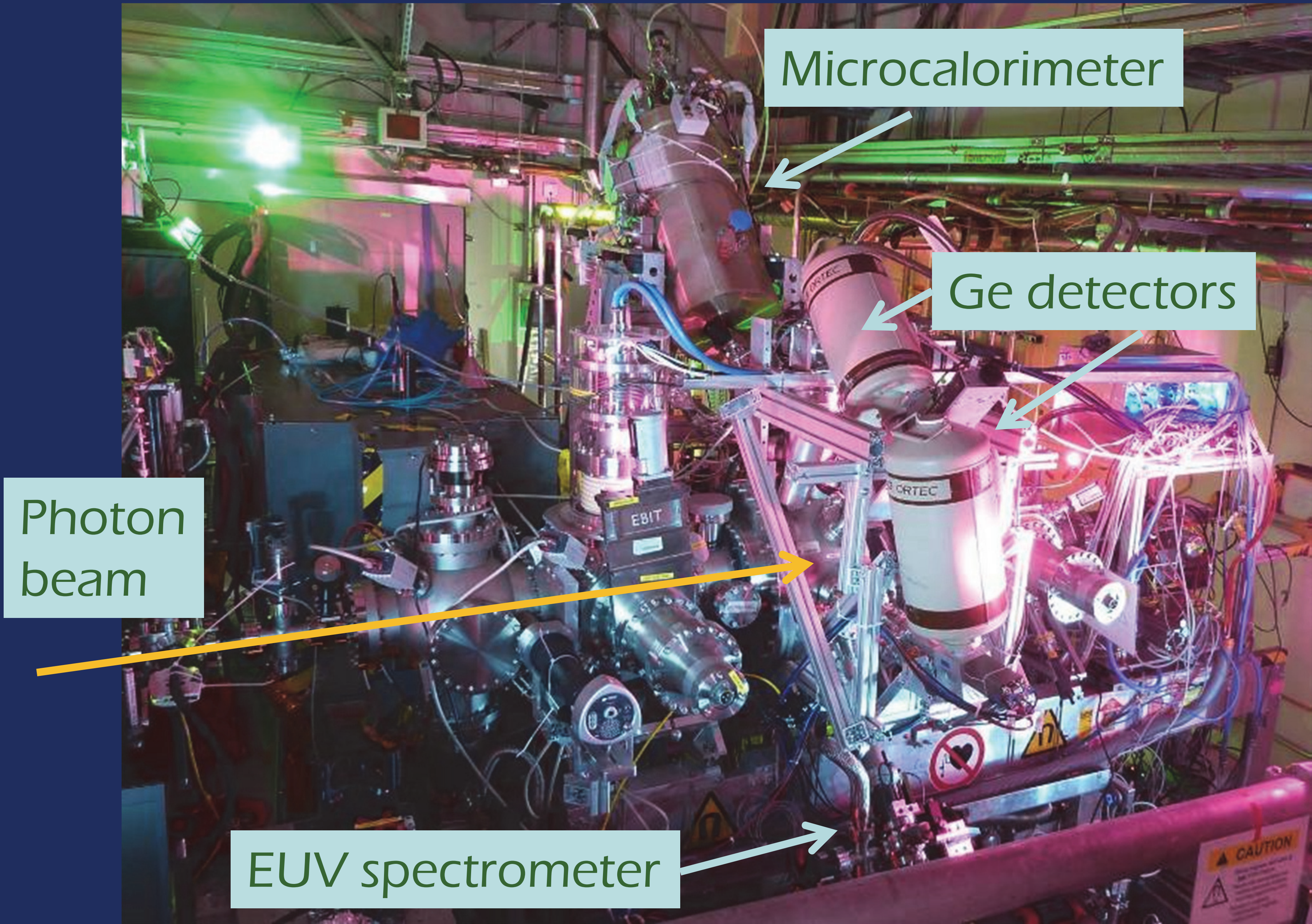
Going into the X-ray region at SXR (LCLS)

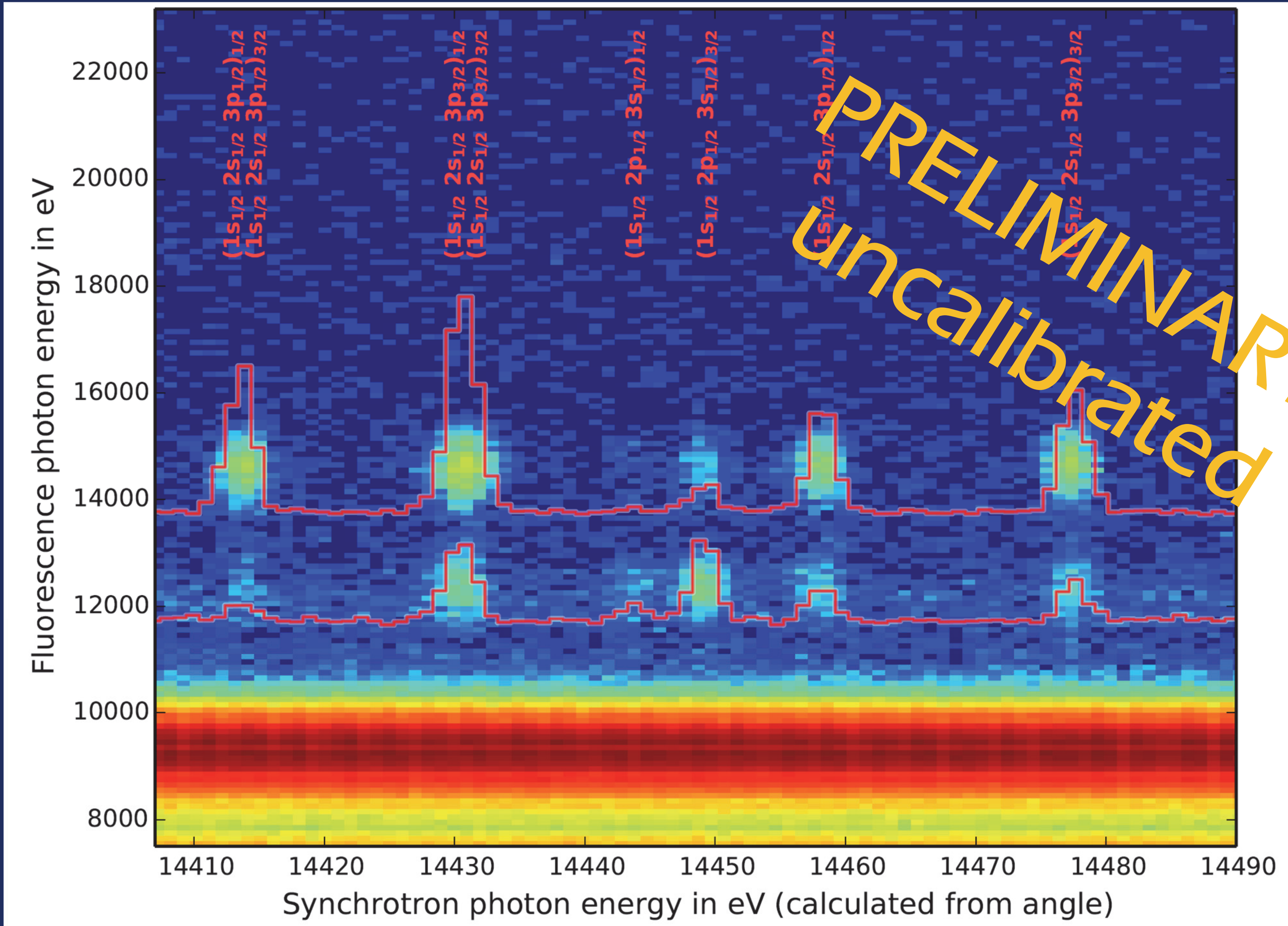


Soft X-ray laser (up to 2000 eV) monochromatic photon beam

Adding X-ray fluorescence detectors

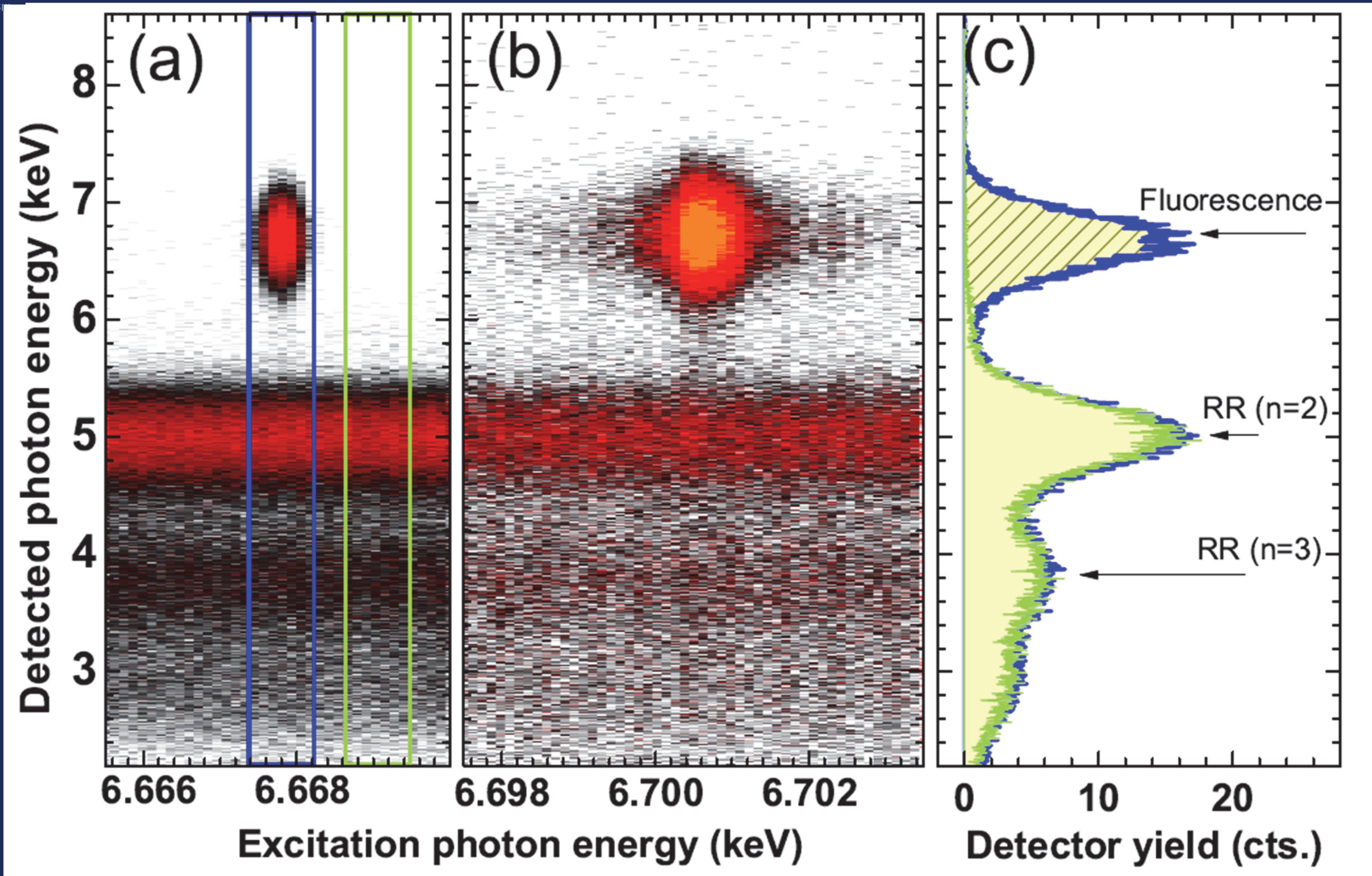


New results: Overview spectra of Br^{33+} (Li-like)



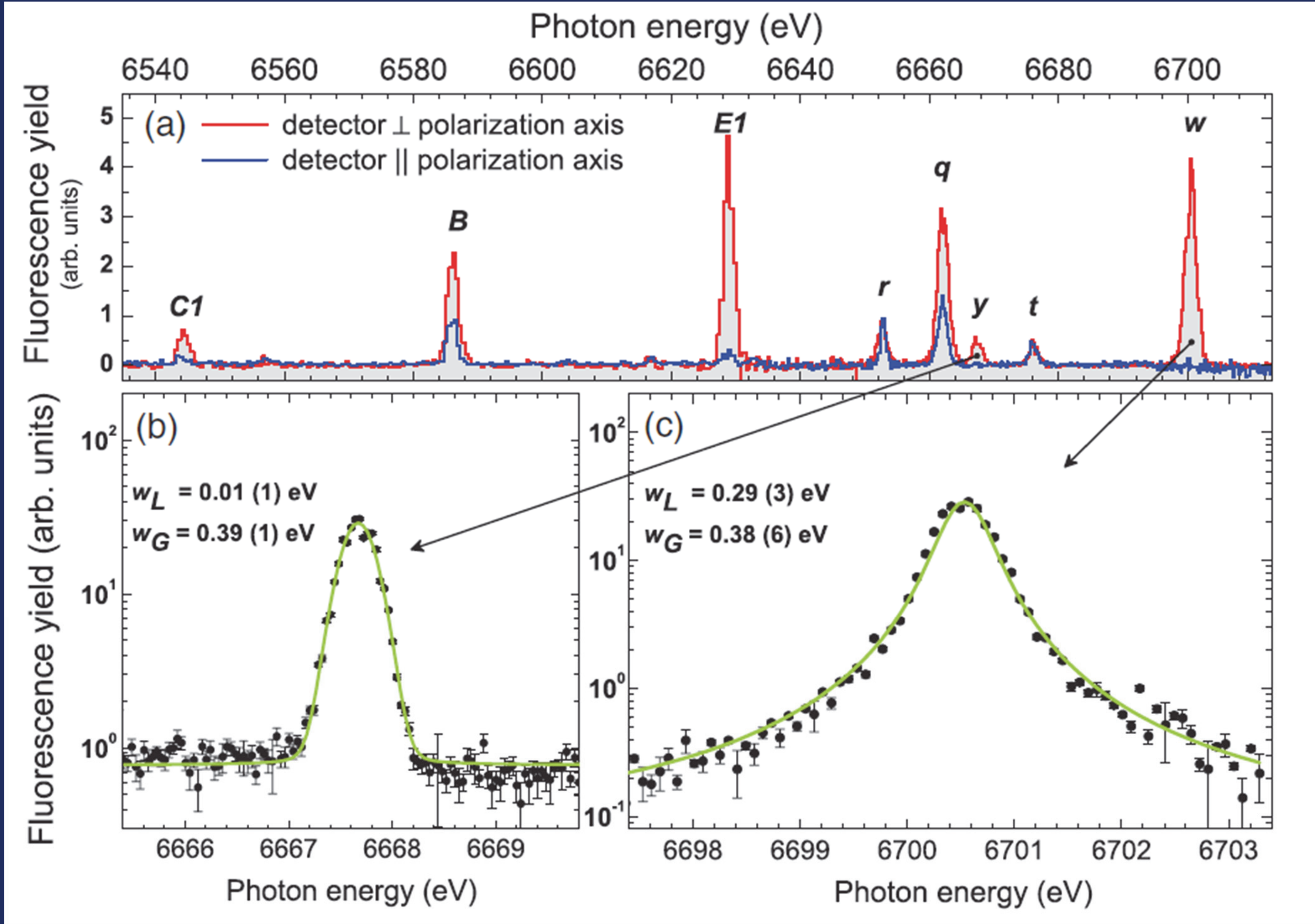
S. Bernitt, MPIK (2016)

High resolution scans show line widths



X-ray energy scanned by monochromator

Overview and detailed scans



Linewidth determinations in Fe^{23+} and Fe^{24+}

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			MCDF		
Line	Experiment	Theory	Radiative	Auger	Total
w	311 (10)	301 [49]	301	0	301
		301 [35]			
		303 [33]			
		315 [50]			
q	255 (31)	310 [33]	312	0.081	312
r	250 (11)	226 [33]	208	32	241
t	131 (29)	167 [33]	112	52	163
*E*1	437 (12)	382 [33]	292	95	387
*E*2	178 (34)	149 [33]	31	136	167
*C*1	524 (12)	499 [33]	218	334	552
*C*2	385 (207)	611 [33]	412	135	547
*N*1	565 (45)	498 [33]	146	400	546
*N*2	594 (50)	504 [33]	164	338	502
*N*3	570 (109)	505 [33]	155	360	515
*O*1	859 (229)	756 [33]	264	529	793
*O*2	772 (228)	785 [33]	304	518	822
F	998 (203)	989 [33]	351	651	1020

Natural linewidths wL of 1s → 2p transitions (in meV)

J. K. Rudolph et al., PRL 111, 103002 (2013)

Transition energies

TABLE I. X-ray transitions of heliumlike to fluorinelike iron ions resonantly excited from the ground state with synchrotron radiation. X-ray fluorescence was detected as a function of photon energy. Energies are given in units of eV. The calibration is based on the absorption edge technique. The experimental uncertainties are shown as (statistical)(systematic). Relative energies are not affected by the systematic uncertainty which accounts for a shift of the absolute scale. Angle brackets enclose results affected in their accuracy by line blends.

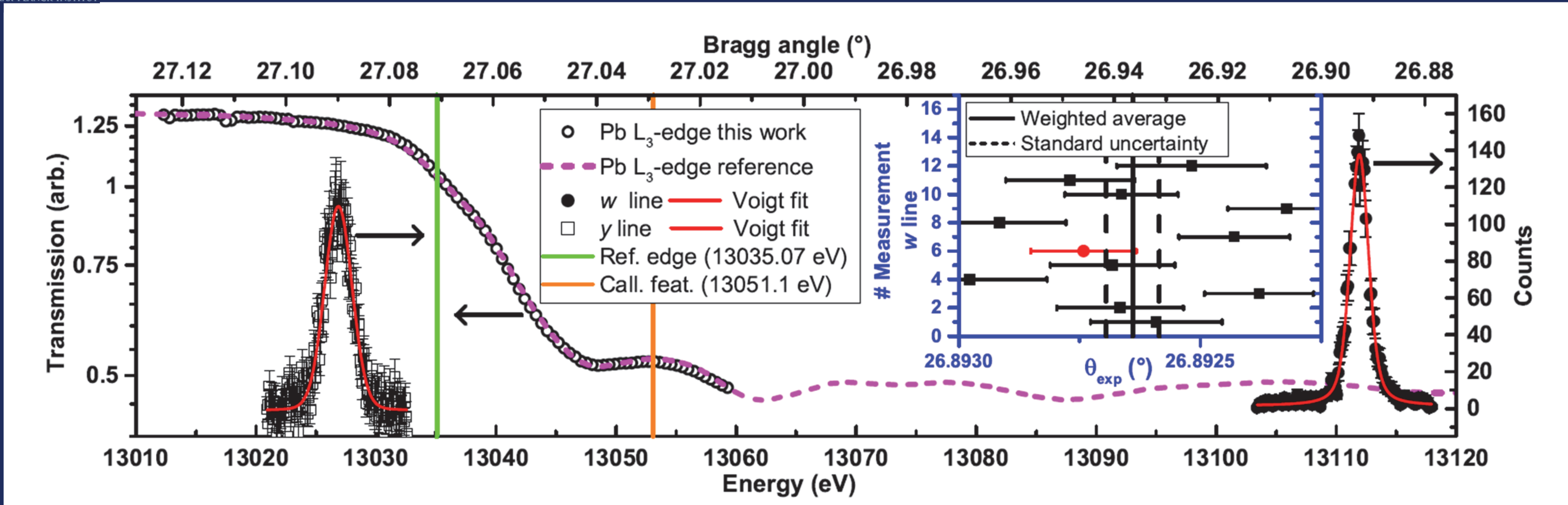
Ion	Line	Initial state	Final state	This experiment	Theory		Theory		Experiment	
Fe^{24+}	w	$1s^2\,{}^1S_0$	$1s\,2p\,{}^1P_1$	6700.549 (5) (70)	6700.4347 (11)	[32]	6700.4	[33]	6700.8	[22]
					6700.490	[34]	6700.4	[35]	6700.4	[23]
									6700.9	[36]
Fe^{24+}	y	$1s^2\,{}^1S_0$	$1s\,2p\,{}^3P_1$	6667.671 (3) (69)	6667.5786 (12)	[32]	6667.6	[33]	6667.9 (4)	[22]
					6667.629	[34]	6667.6	[35]	6667.5	[23]
									6667.5	[36]
Fe^{23+}	t	$1s^2\,2s\,{}^2S_{1/2}$	$1s\,2s\,2p\,{}^2P_{1/2}$	6676.202 (3) (69)	6676.129 (47)	[37]	6676.4	[33]	⟨6676.8 (7)⟩	[22]
					6675.8	[38]			6676.3	[23]
Fe^{23+}	q	$1s^2\,2s\,{}^2S_{1/2}$	$1s\,2s\,2p\,{}^2P_{3/2}$	6662.240 (6) (69)	6662.188 (11)	[37]	6661.9	[33]	6662.1 (5)	[22]
					6661.9	[38]			6662.2	[23]
Fe^{23+}	r	$1s^2\,2s\,{}^2S_{1/2}$	$1s\,2s\,2p\,{}^2P_{1/2}$	6652.826 (3) (69)	6652.776 (25)	[37]	6653.5	[33]	⟨6654.2 (7)⟩	[22]
					6652.6	[38]			6652.5	[23]
Fe^{23+}	u	$1s^2\,2s\,{}^2S_{1/2}$	$1s\,2s\,2p\,{}^4P_{3/2}$	6616.629 (4) (68)	6616.559 (11)	[37]	6616.7	[33]	⟨6617.9 (1.2)⟩	[22]
									6616.6	[23]
Fe^{22+}	$E1$	$1s^2\,2s^2\,{}^1S_0$	$1s\,2s^2\,2p\,{}^1P_1$	6628.804 (5) (68)	6631.057	[39]	6628.7	[33]	6628.9 (3)	[22]
					$6627.4^a/6628.3^b$		6627.39	[40]	6628.7	[23]
Fe^{22+}	$E2$	$1s^2\,2s^2\,{}^1S_0$	$1s2s^22p^3P_1$	6597.858 (3) (67)	6596.55	[40]	6595.8	[33]		
					$6596.1^a/6597.7^b$					
Fe^{21+}	B	$1s^2\,2s^2\,2p\,{}^2P_{1/2}$	$1s\,2s^2\,2p^2\,{}^2P_{1/2}$	⟨6586.085 (7) (67)⟩	$6586.3^a/6585.1^b$		6586.3	[33]	⟨6585.9 (5)⟩	[22]
			$1s\,2s^2\,2p^2\,{}^2D_{3/2}$	⟨6586.085 (7) (67)⟩	$6587.0^a/6585.8^b$		6586.5	[33]	⟨6585.7⟩	[23]
					⟨6587.2⟩	[41]				
Fe^{20+}	$C1$	$1s^2\,2s^2\,2p^2\,{}^3P_0$	$1s\,2s^2\,2p^3\,{}^3D_1$	6544.225 (4) (66)	$6544.8^a/6544.0^b$		6543.6	[33]	⟨6544.6 (9)⟩	[22]
									⟨6544.4⟩	[23]
Fe^{20+}	$C2$	$1s^2\,2s^2\,2p^2\,{}^3P_0$	$1s\,2s^2\,2p^3\,{}^3S_1$	6556.879 (16) (66)	$6557.3^a/6556.3^b$		6555.0	[33]		
Fe^{19+}	$N1$	$1s^2\,2s^2\,2p^3\,{}^4S_{3/2}$	$1s\,2s^2\,2p^4\,{}^4P_{5/2}$	6497.067 (5) (65)	$6497.5^a/6497.2^b$		6496.6	[33]	⟨6497.7 (1.4)⟩	[22]
									6497.3	[23]
Fe^{19+}	$N2$	$1s^2\,2s^2\,2p^3\,{}^4S_{3/2}$	$1s\,2s^2\,2p^4\,{}^2P_{3/2}$	6506.845 (7) (65)	$6507.3^a/6506.9^b$		6506.0	[33]	⟨6509.6 (1.4)⟩	[22]
									⟨6509.1⟩	[23]
Fe^{19+}	$N3$	$1s^2\,2s^2\,2p^3\,{}^4S_{3/2}$	$1s\,2s^2\,2p^4\,{}^4P_{1/2}$	6509.133 (14) (65)	$6509.6^a/6509.1^b$		6508.1	[33]	⟨6509.6 (1.4)⟩	[22]
									⟨6509.1⟩	[23]
Fe^{18+}	$O1$	$1s^2\,2s^2\,2p^4\,{}^3P_2$	$1s\,2s^2\,2p^5\,{}^3P_2$	6466.900 (14) (64)	$6467.4^a/6466.5^b$		6564.4	[33]	6467.6 (1.7)	[22]
					6466.3	[41]			⟨6466.5⟩	[23]
Fe^{18+}	$O2$	$1s^2\,2s^2\,2p^4\,{}^3P_2$	$1s\,2s^2\,2p^5\,{}^3P_1$	6474.318 (33) (64)	$6474.9^a/6473.9^b$		6473.0	[33]	⟨6472.7 (2.7)⟩	[22]
					6473.7	[41]			⟨6474.7⟩	[23]
Fe^{17+}	F	$1s^2\,2s^2\,2p^5\,{}^2P_{3/2}$	$1s\,2s^2\,2p^6\,{}^2S_{1/2}$	6435.239 (14) (63)	$6435.7^a/6434.6^b$		6434.8	[33]	6436.1 (2.0)	[22]
									6434.8	[23]

[a]Our theoretical results obtained in the framework of the multiconfiguration Dirac-Fock (MCDF) method [29]
[b]Our theoretical results using the Flexible Atomic Code (FAC) of Gu with the standard configuration-interaction package [42].

16 dominant transitions measured with high precision

J. K. Rudolph et al., PRL 111, 103002 (2013)

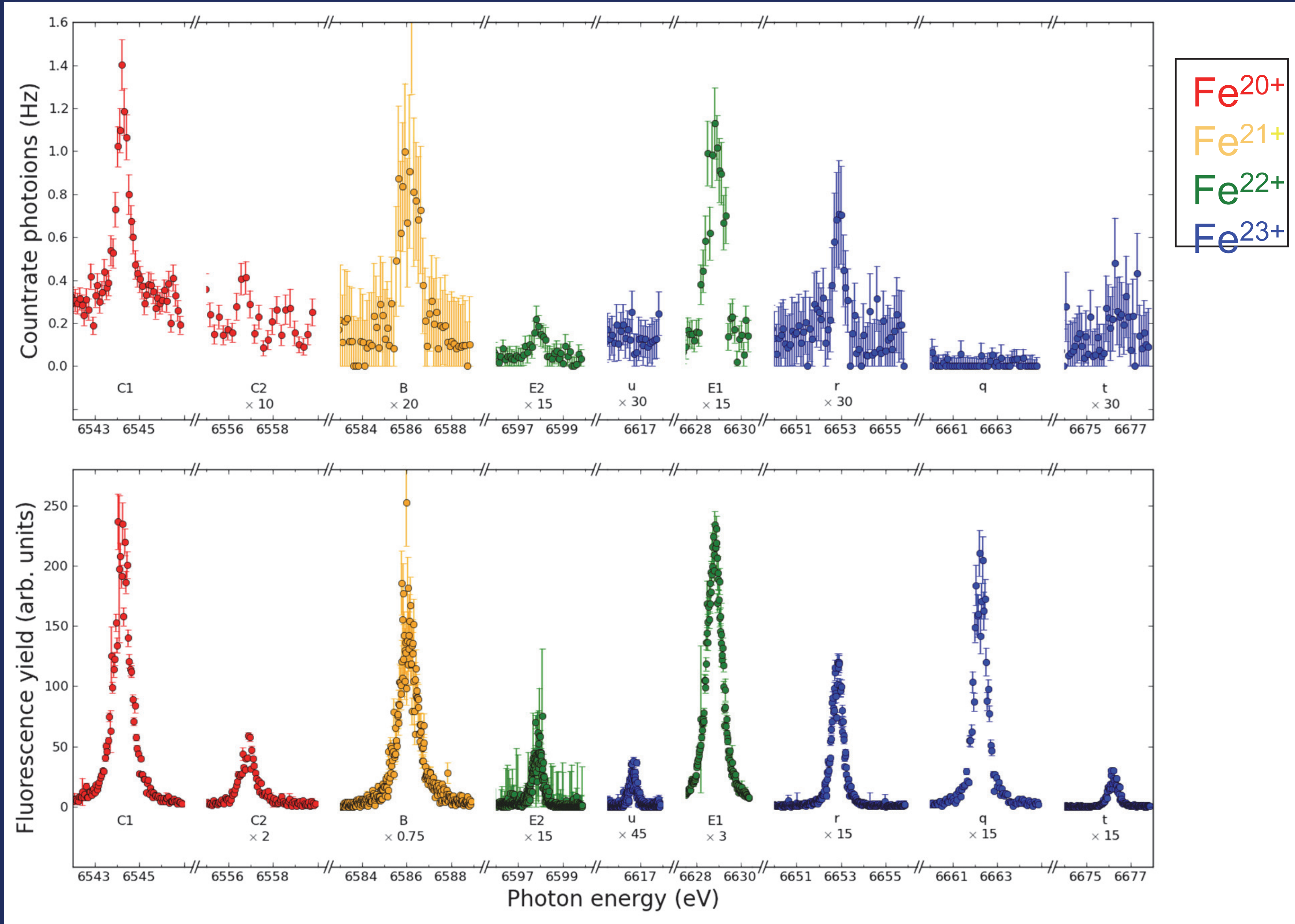
Petra III: Kr^{34+} resonant excitation



Experimental raw data (Si(333)) of the w and y line along with the Pb L3-edge absorption spectrum (PbL) for energy calibration. The w data points show a result from a single scan (15 minutes). Fitted Bragg angle is 26.89274(4) degrees. The y line is an overlay of 25 single scans. PbL (open circles): our data scaled to the (dashed) reference data . Inset (blue): Centroids from12 individual scans of w.

Epp et al, PRA 92, 020502(R) (2015)

Fluorescence vs. photoion yield



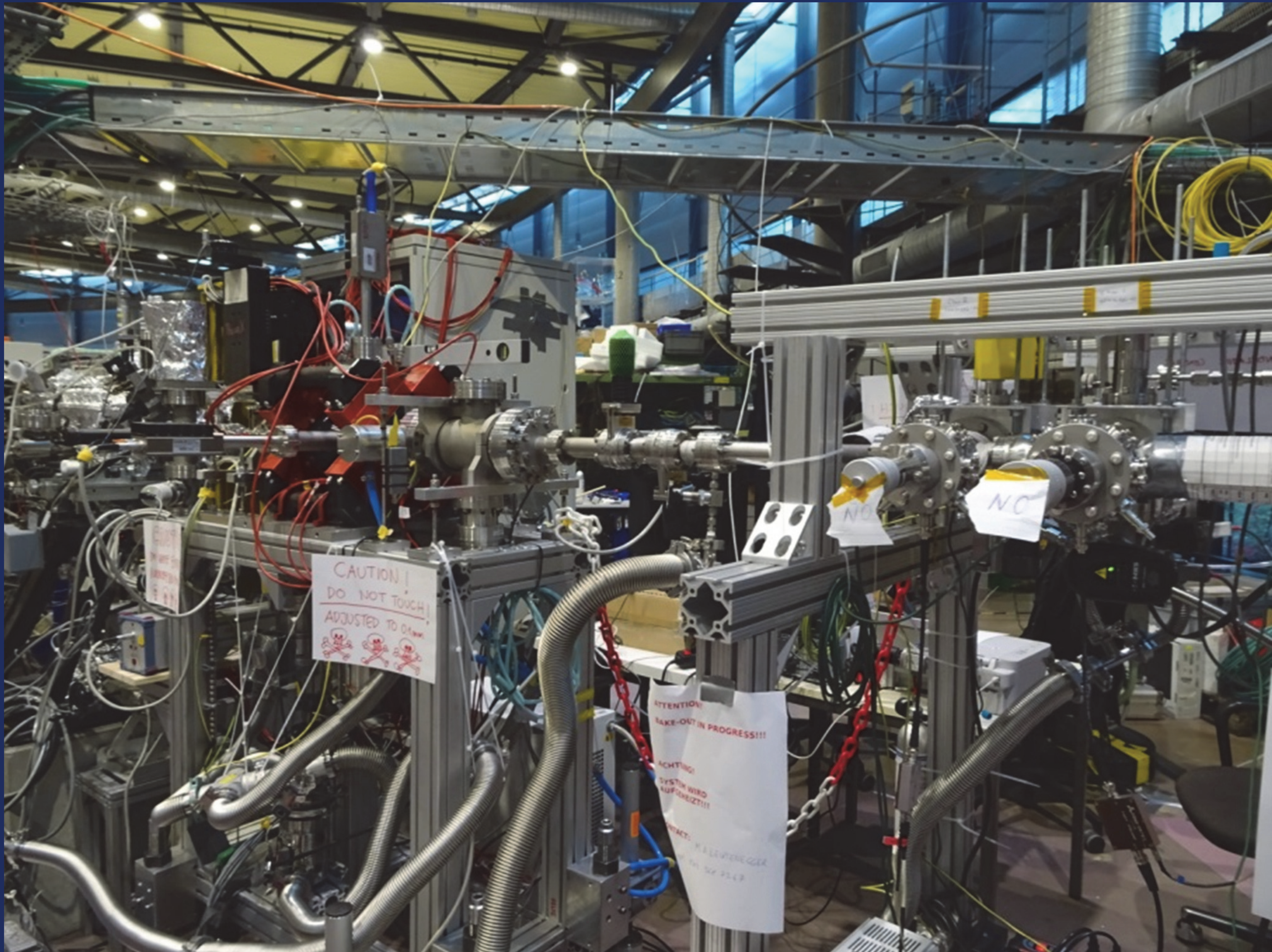
R. Steinbrügge et al., PRA 91, 032502 (2015)

Transition energies for He-like and Li-like ions

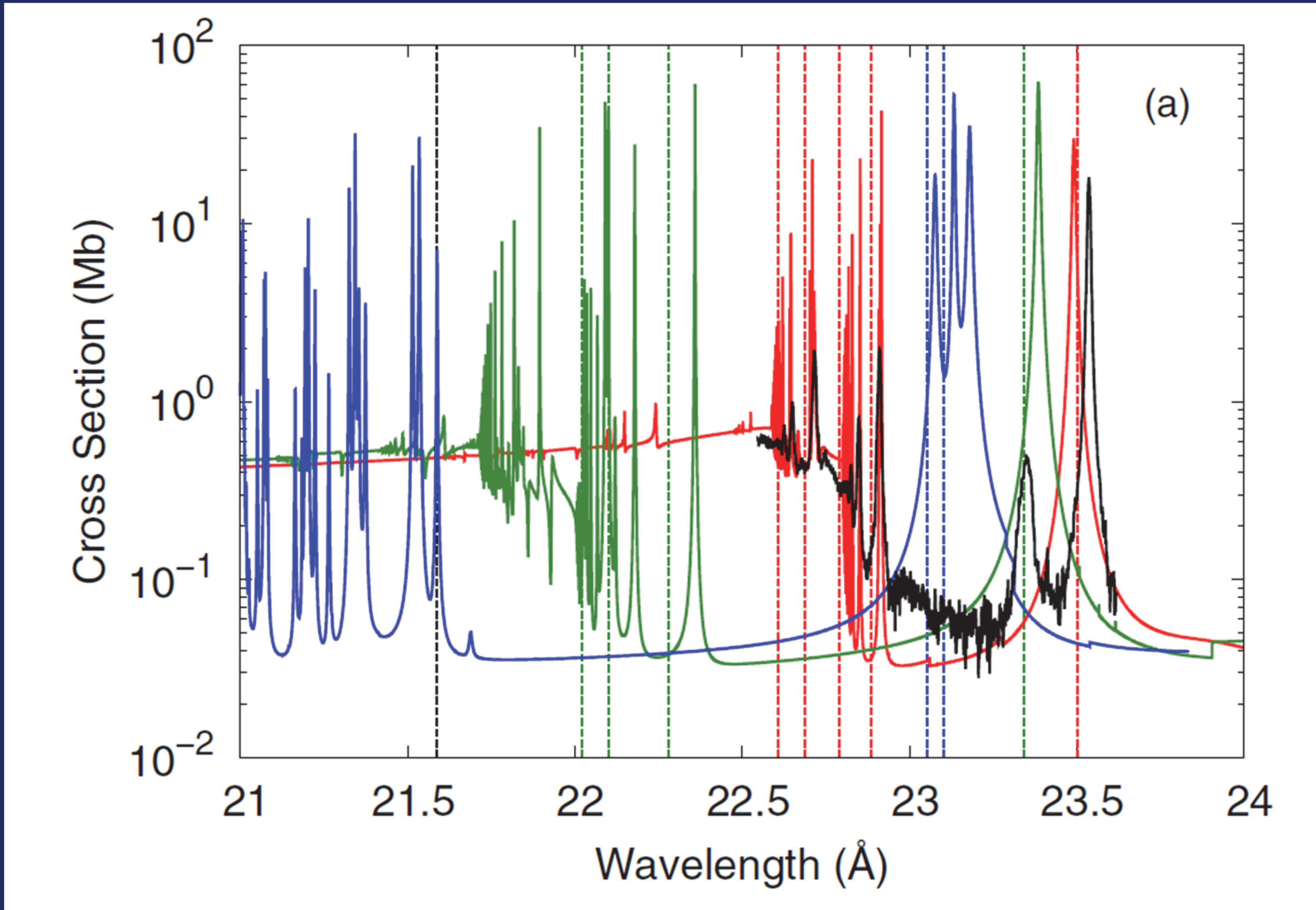
- 70 meV systematic uncertainty of the calibration
- 5 meV typical statistical uncertainties
- For Z>18 never measured so precisely

J. K. Rudolph et al., PRL 111, 103002 (2013)

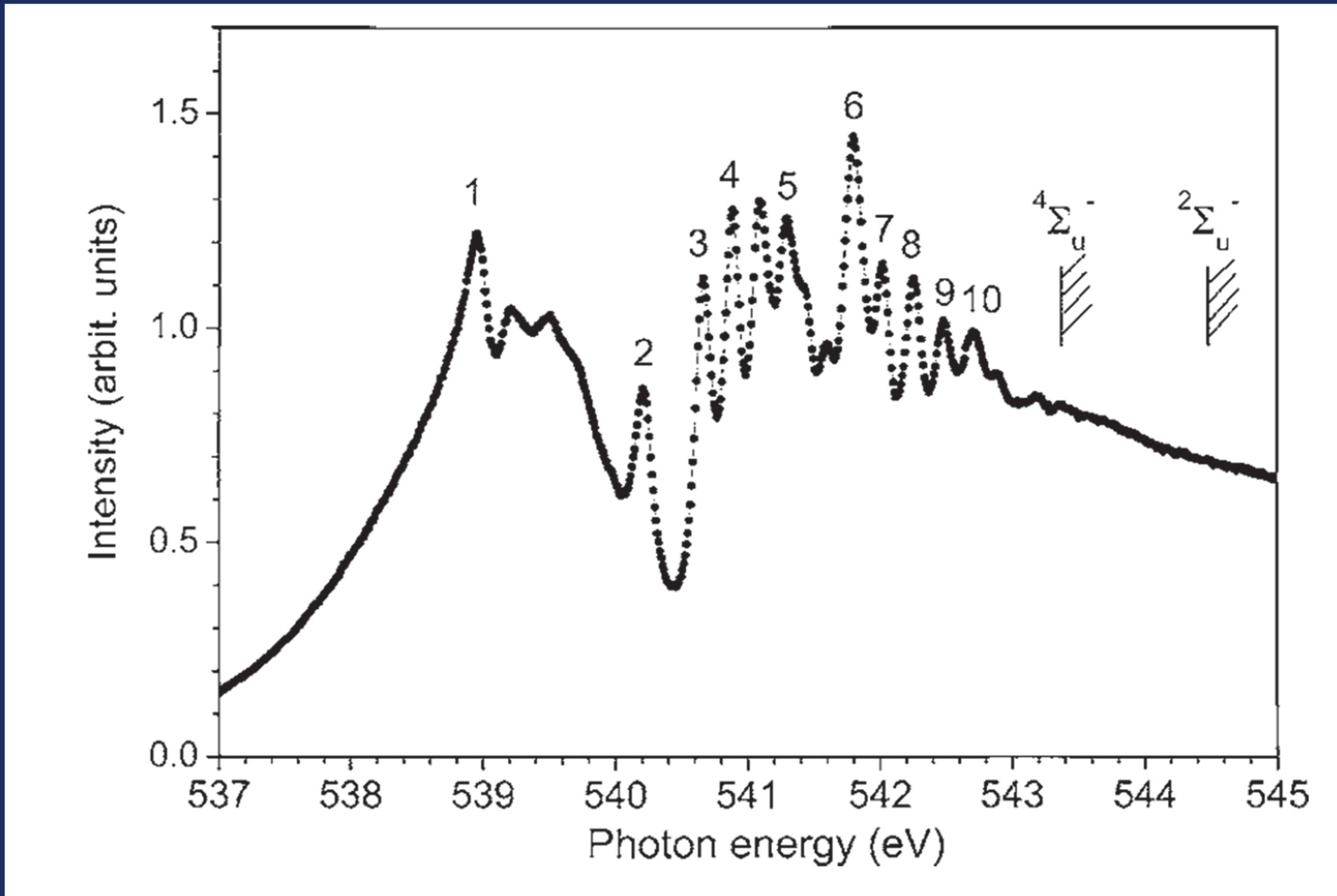
PolarX-EBIT and gas-cell setup



Some theory models vs. experiments

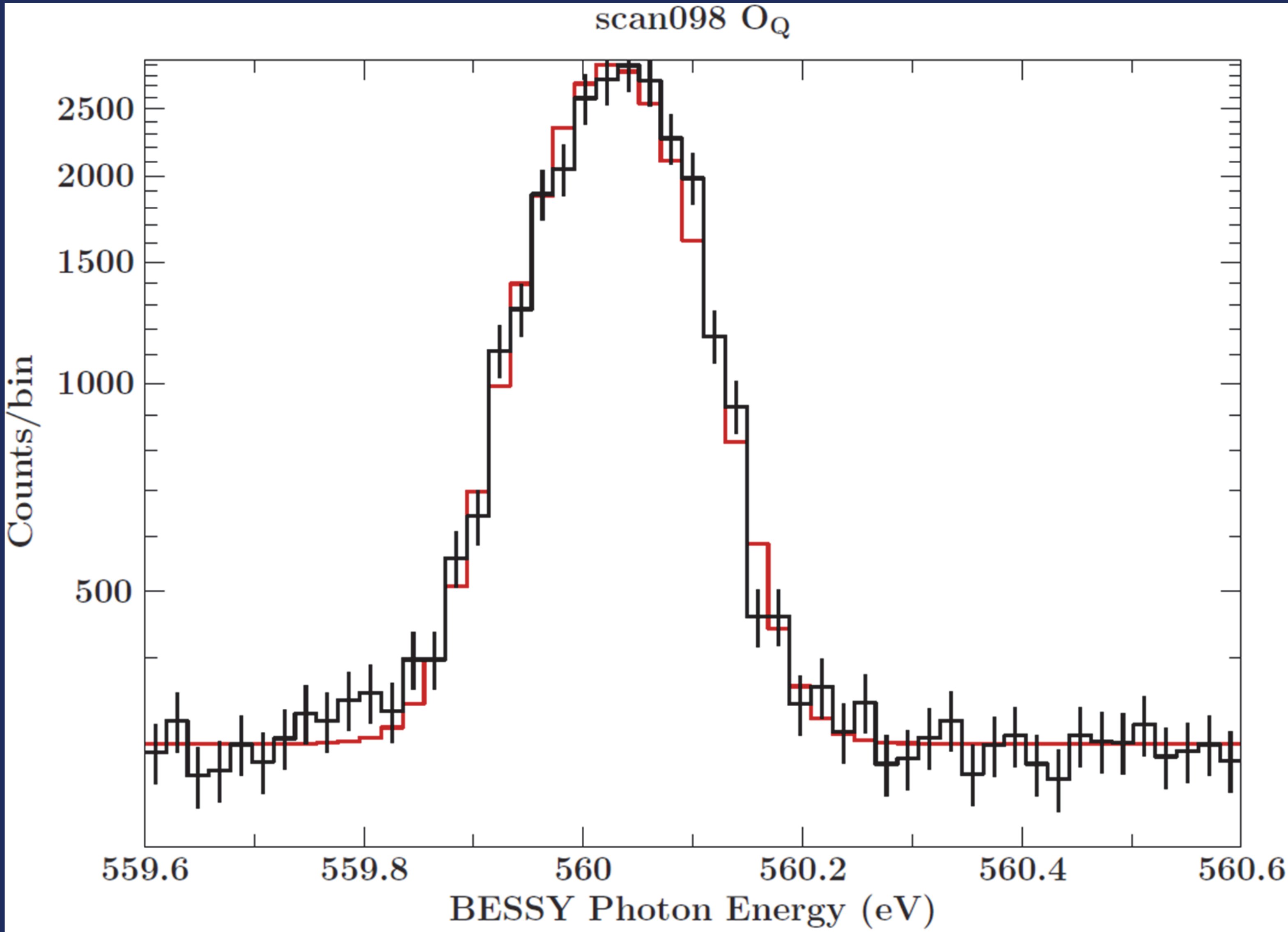


O_2 photoabsorption

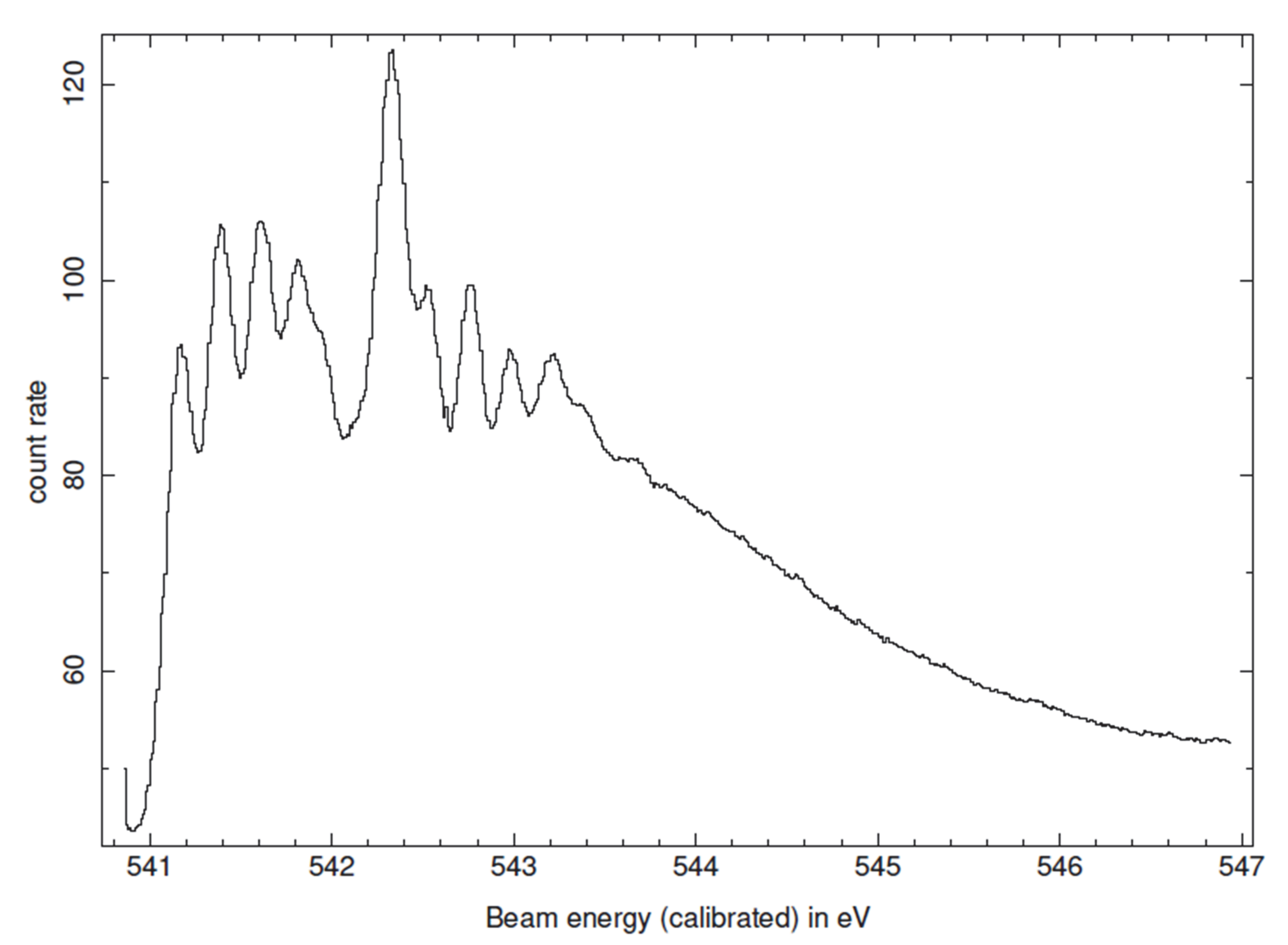


From: Feifel et al.

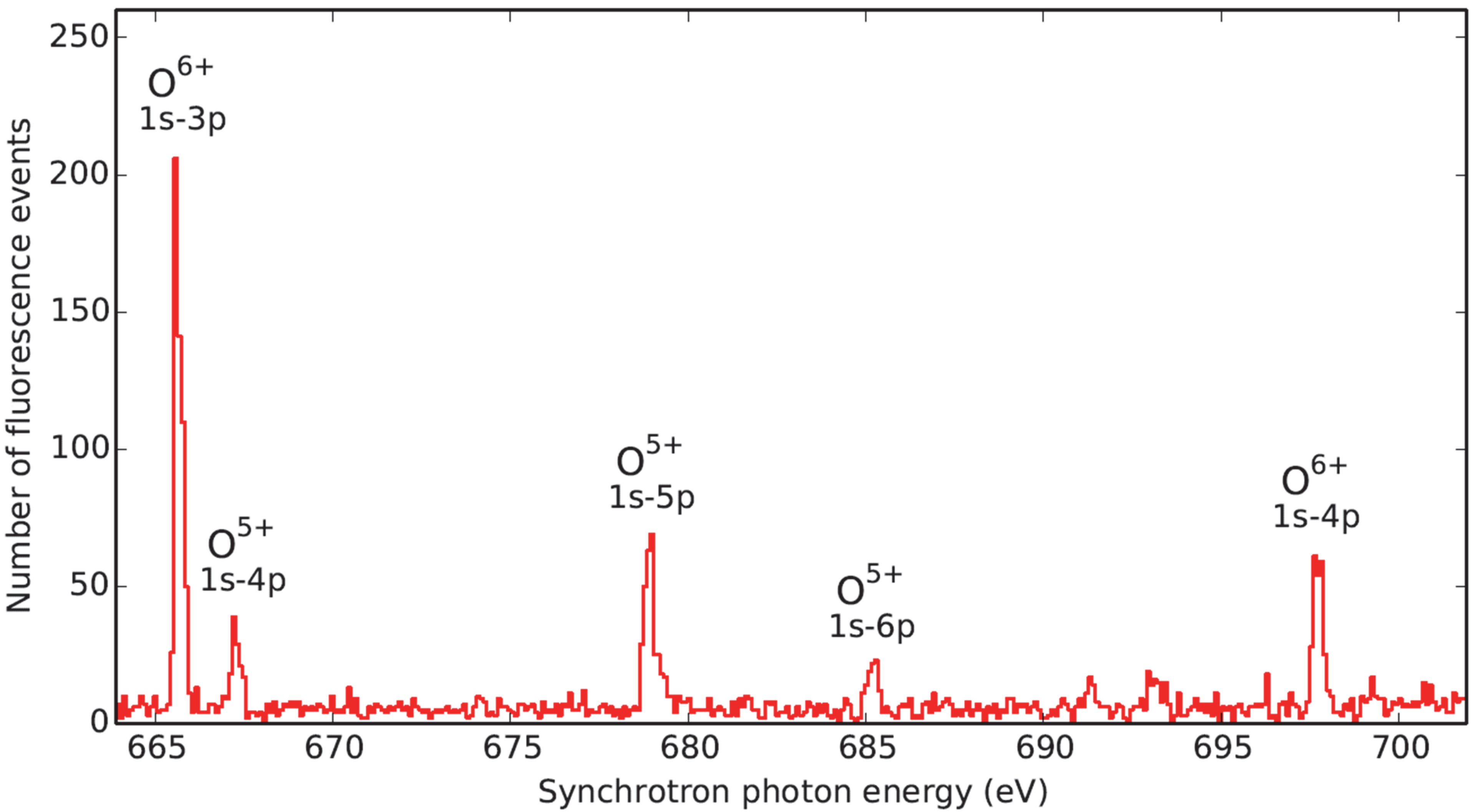
He-like O^{5+} 1s-2p (line *q*)



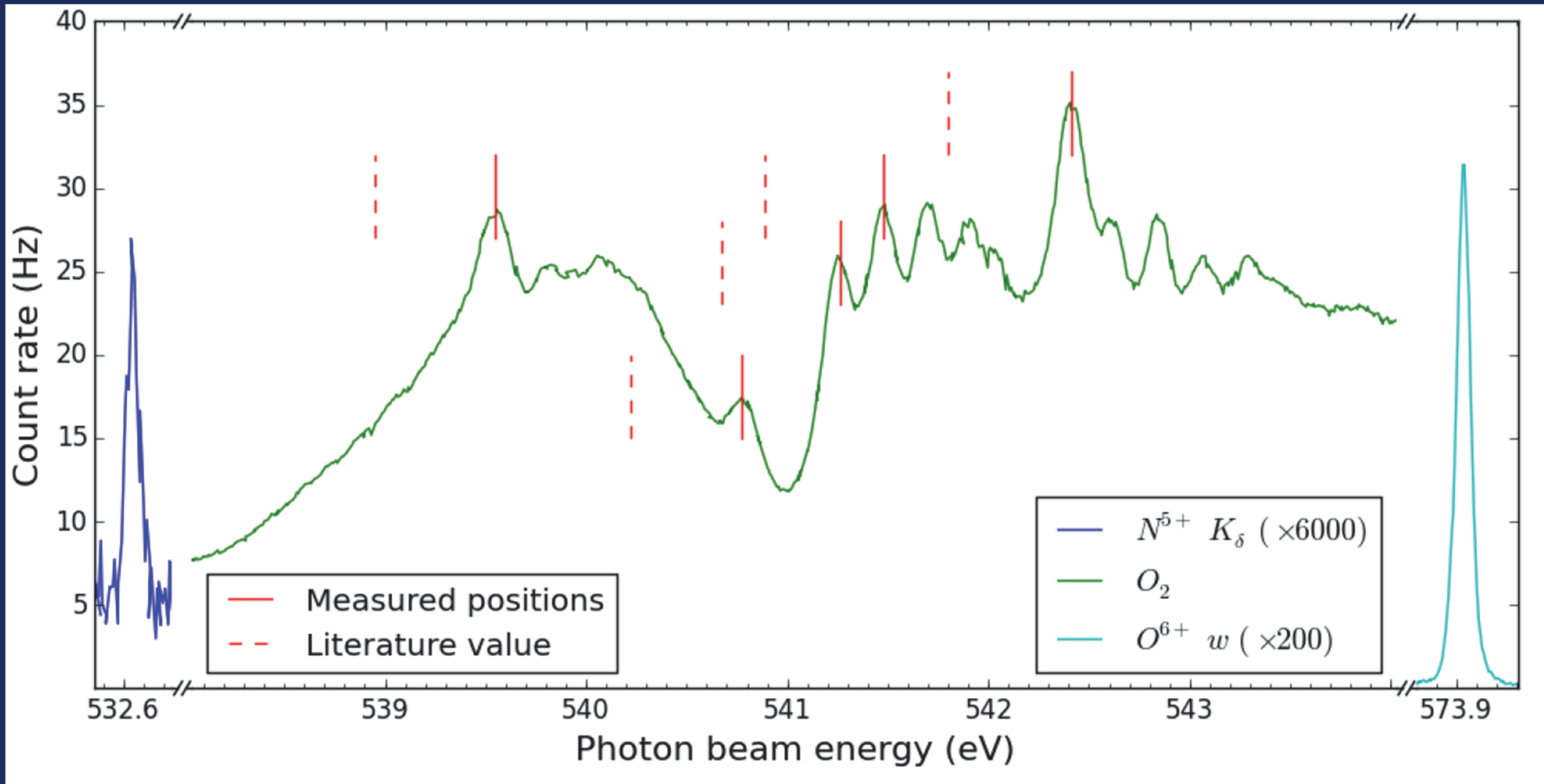
O_2 absorption edges



Overview spectrum at low resolution and statistics



≈500 meV offset relative to old calibration!



G.V. Brown, P. Beiersdorfer, T. Lockard (LLNL); R. Kelley, C.A. Kilbourne, M.A. Leutenegger, F.S. Porter (GSFC); J. Wilms (FAU)

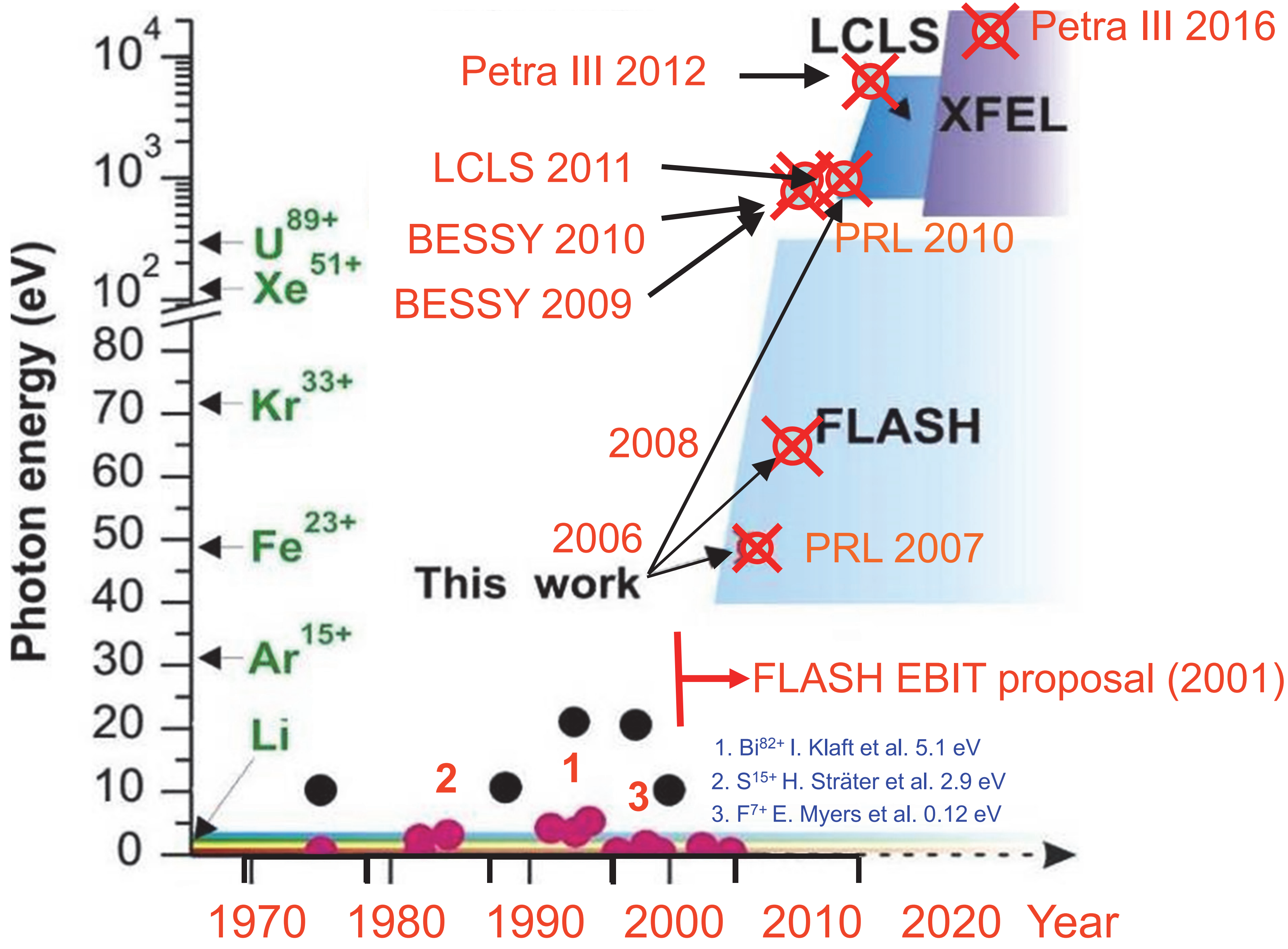
Lawrence Livermore National Laboratory

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Photon energy range accessed



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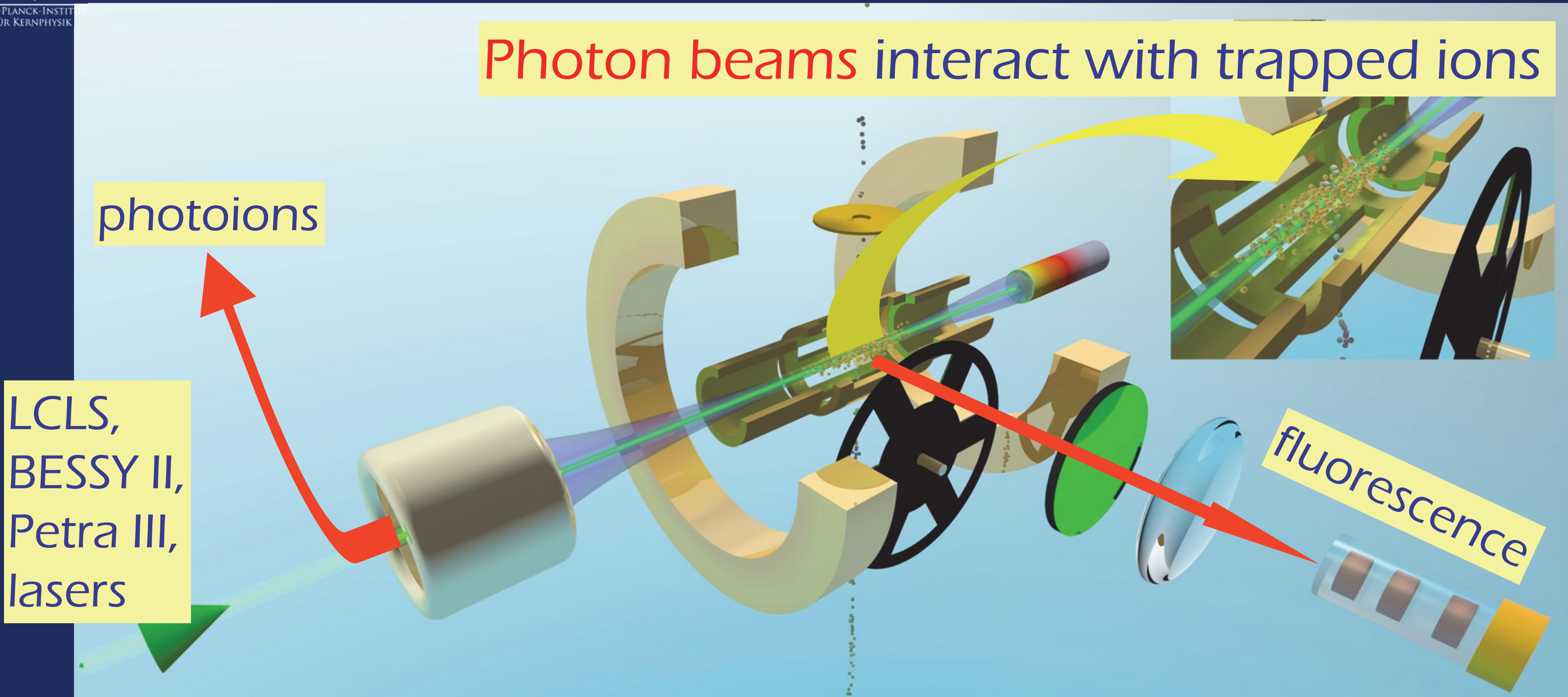
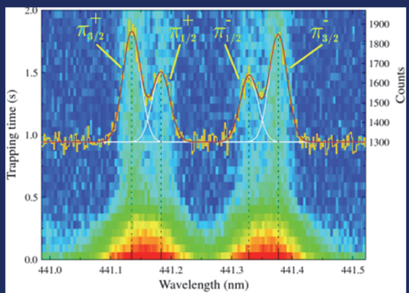
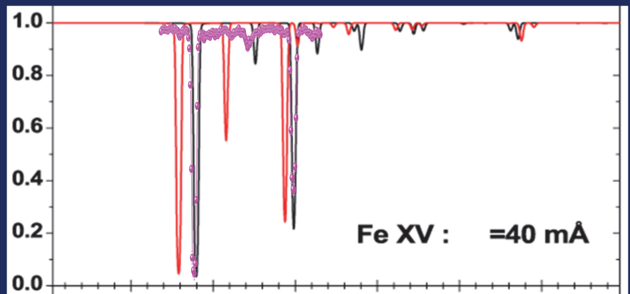
Resonant photon excitation in EBITs



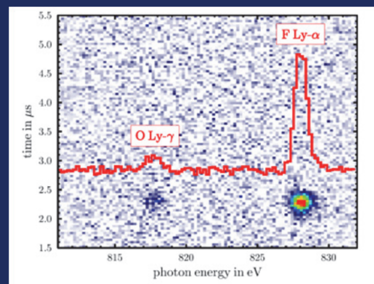
Visible M1 Ar^{13+}	Soft X-ray photoionization Fe^{14+}	FEL 800 eV Fe^{16+}	Synchrotron 6 keV Fe^{24+}, 13 keV Kr^{34+}



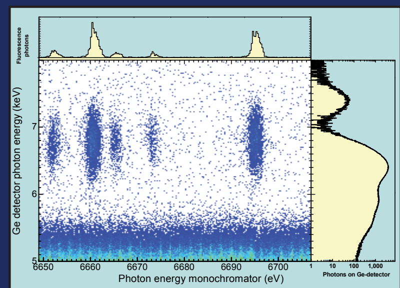
V. Mäckel et al., PRL **107** 143002 (2011)



M. C. Simon et al., PRL **105** 183001 (2010)

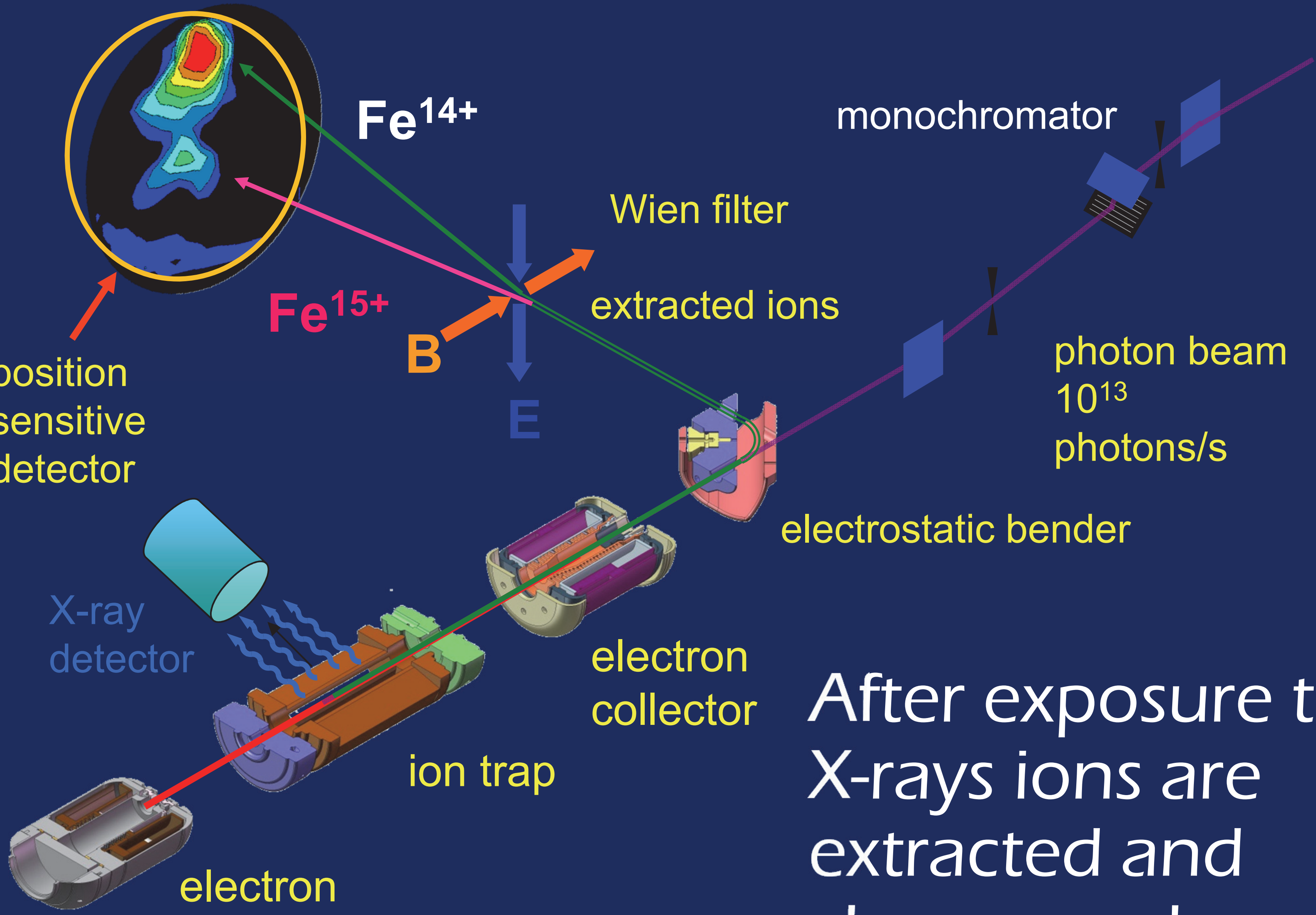


S. Bernitt et al., Nature **492**, 225 (2012)



J. Rudolph et al., PRL **111**, 103002 (2013)

Photoionization studies



After exposure to X-rays ions are extracted and charge analyzed

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Ar^{12+} : ionization potential 684 eV

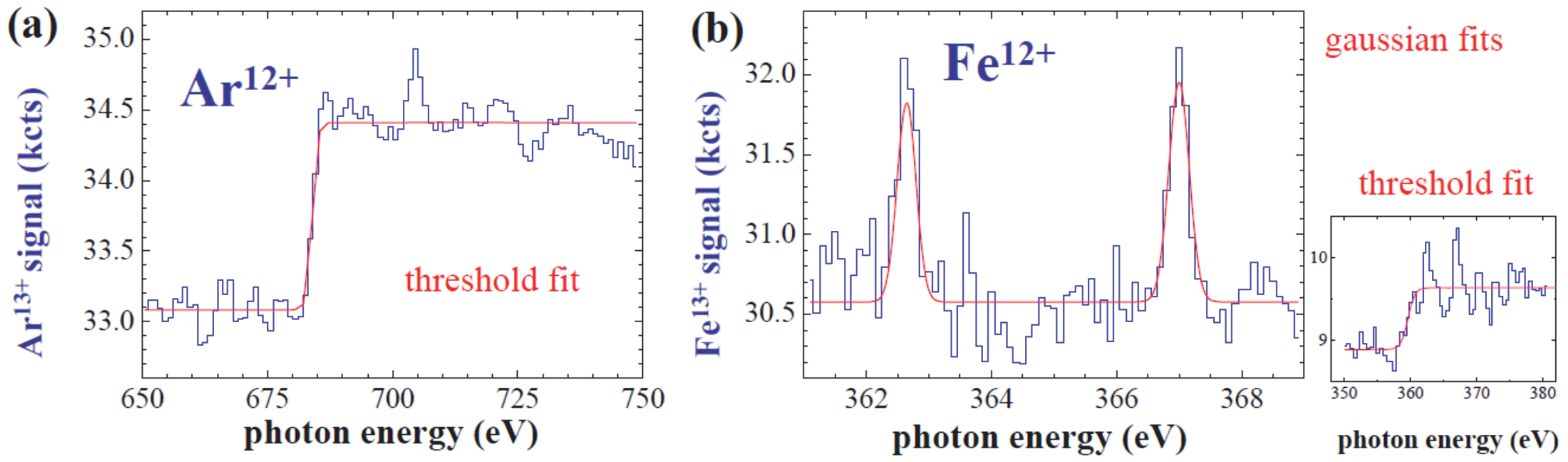
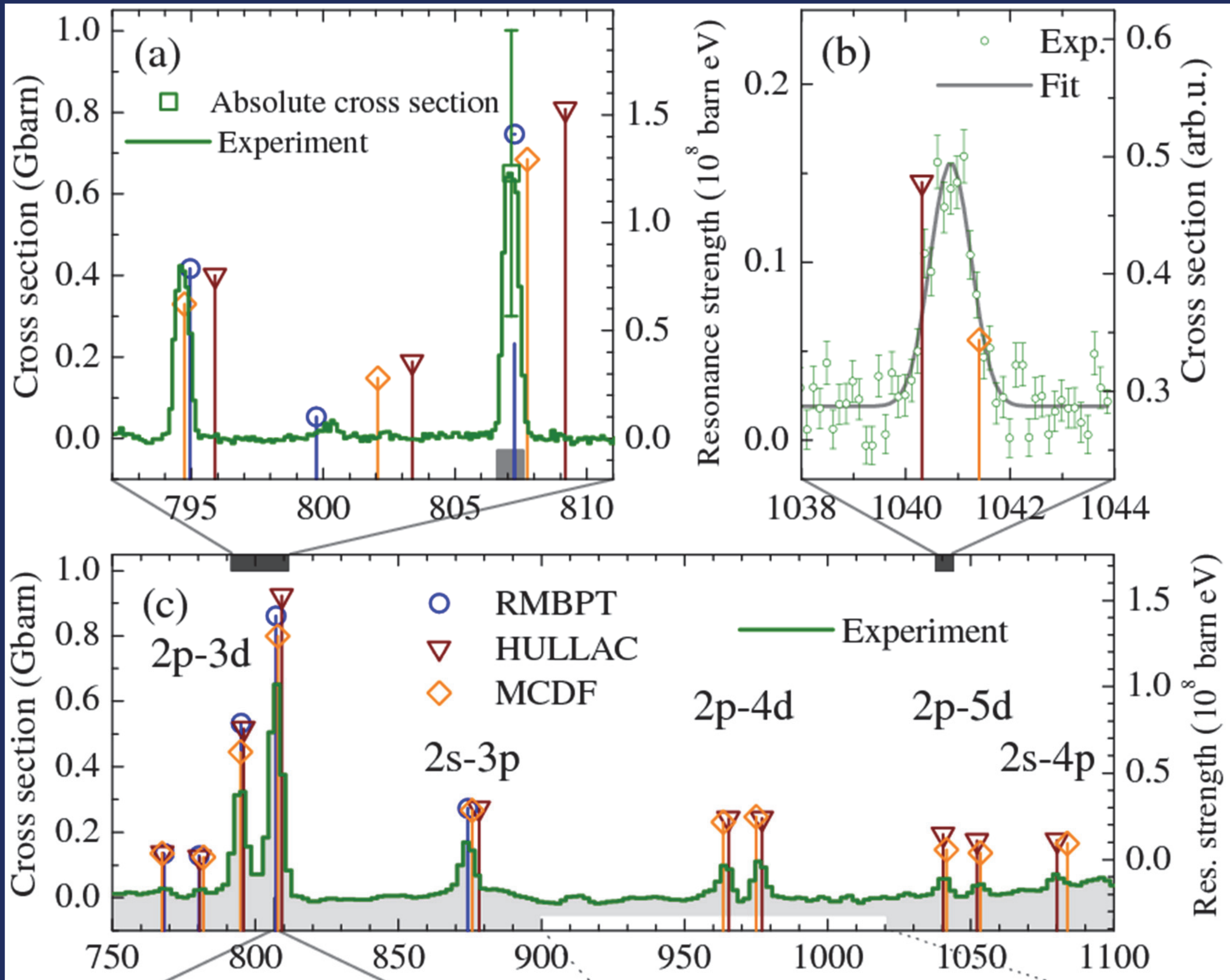


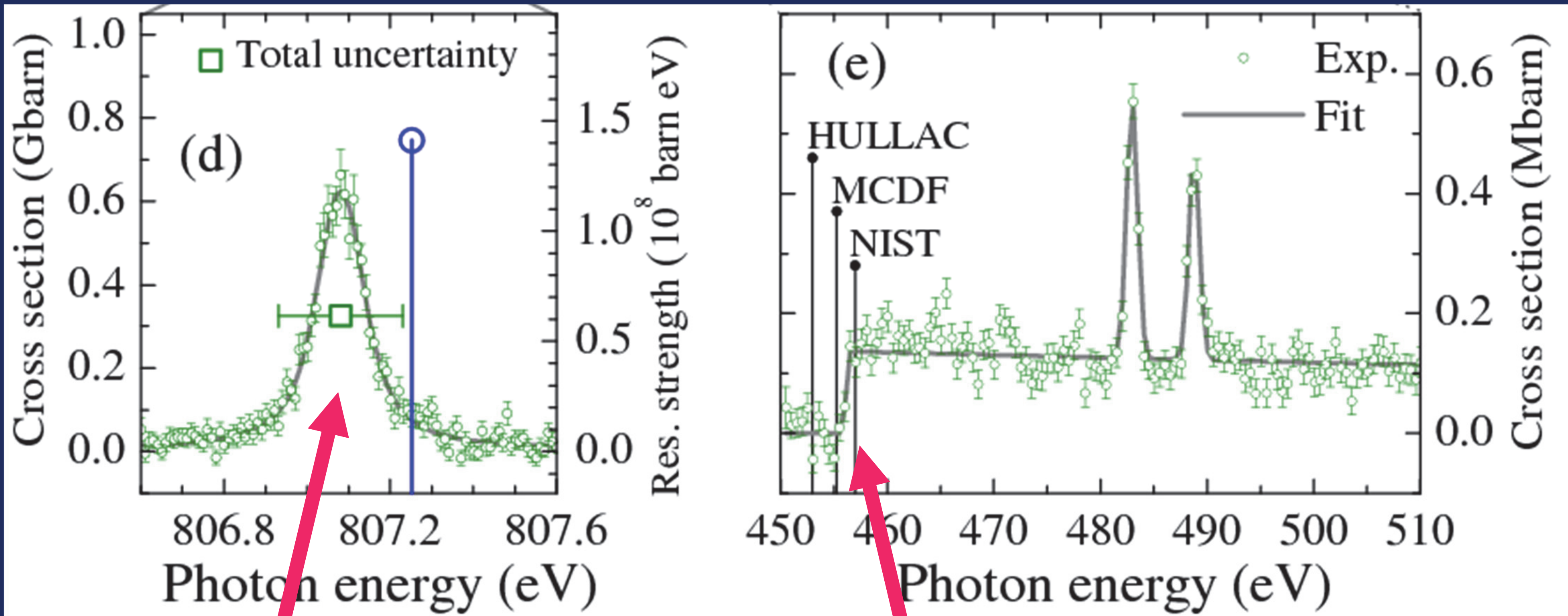
Figure 4. (color online) PI of ions in charge state q=12 demonstrate the ability to access HCIs by the EBIT based method. (a) PI threshold of Ar^{12+} at 683.93 eV, obtained by a fit to the Ar^{13+}-signal. The strong background signal below the ionization edge is mainly caused by residual gas ions with close lying charge-to-mass ratios (O^{5+}, C^{4+}). (b) Near-threshold PI of Fe^{12+} revealing two significant resonances at 362.6 eV and 370.0 eV.

Fe^{14+} photoionization



M. C. Simon et al., PRL 105 (2010) 183001

Fe^{14+} photoionization

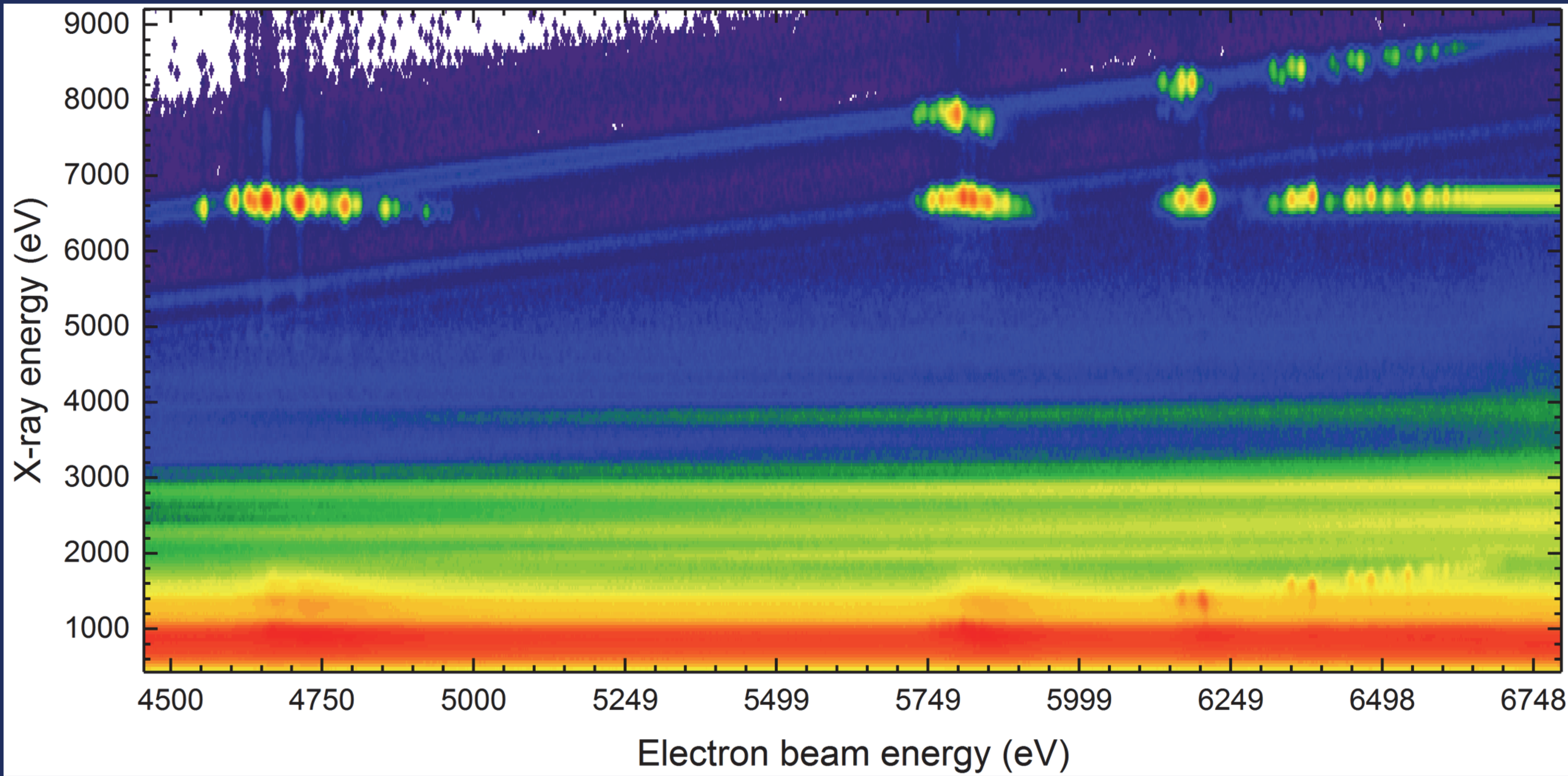


Strong resonances allow high resolution nearly reaching natural line width

Current sensitivity for non-resonant photoionization around 20 kbarn

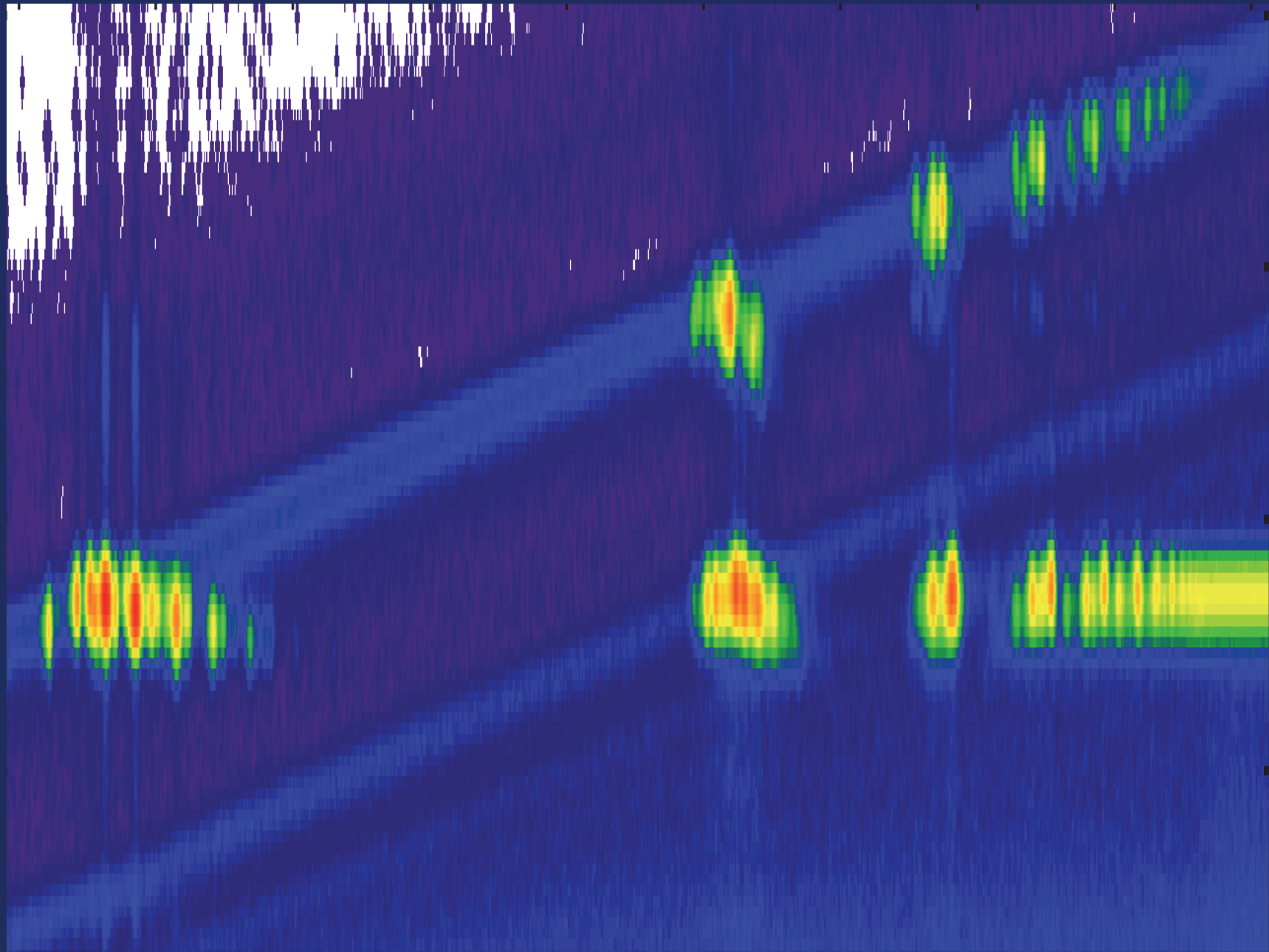
Electron-driven resonant processes

X-ray data depending on electron energy



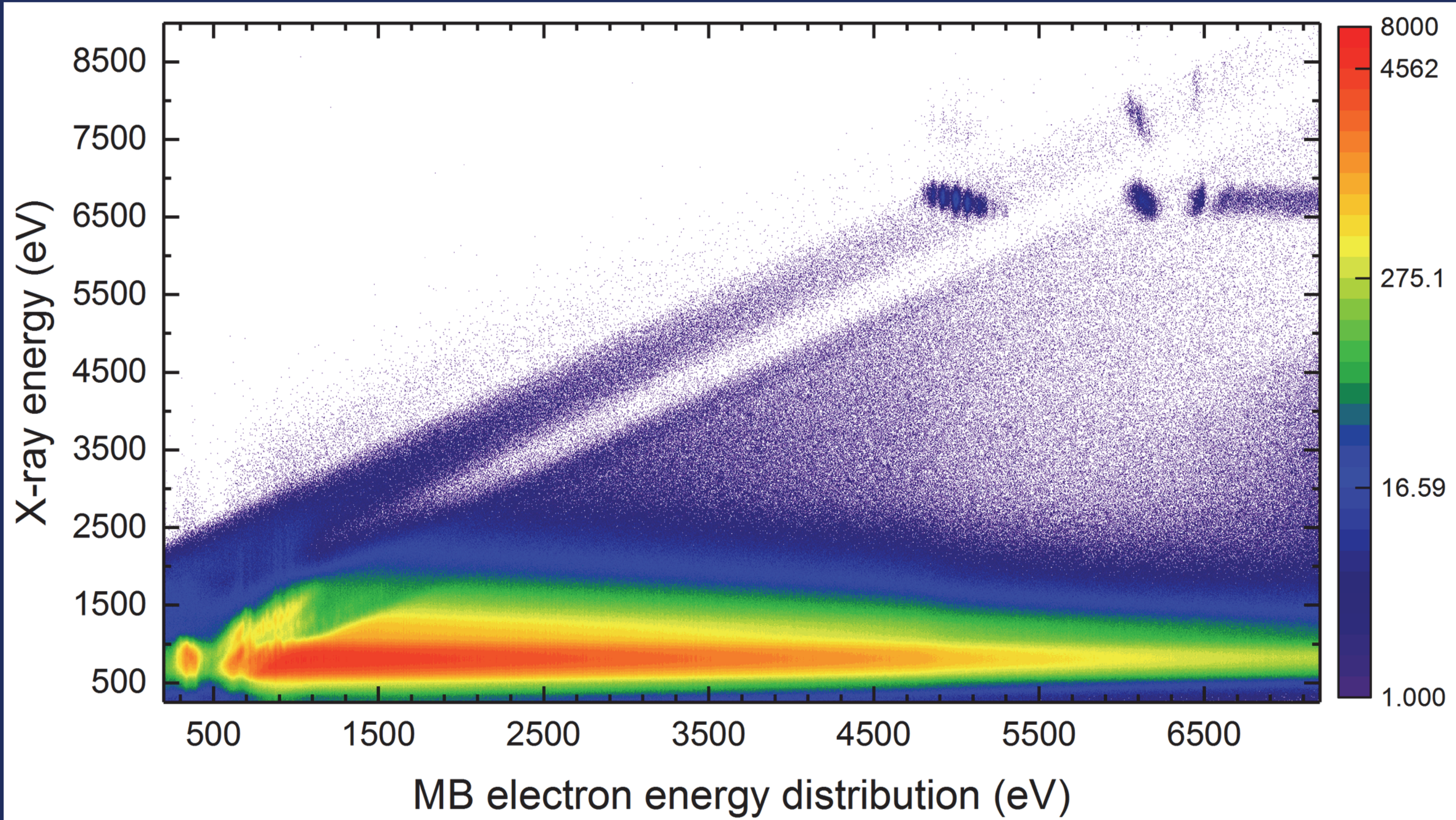
- Fe photorecombination studies
- Slow scans at high electron energy resolution

X-ray data depending on electron energy



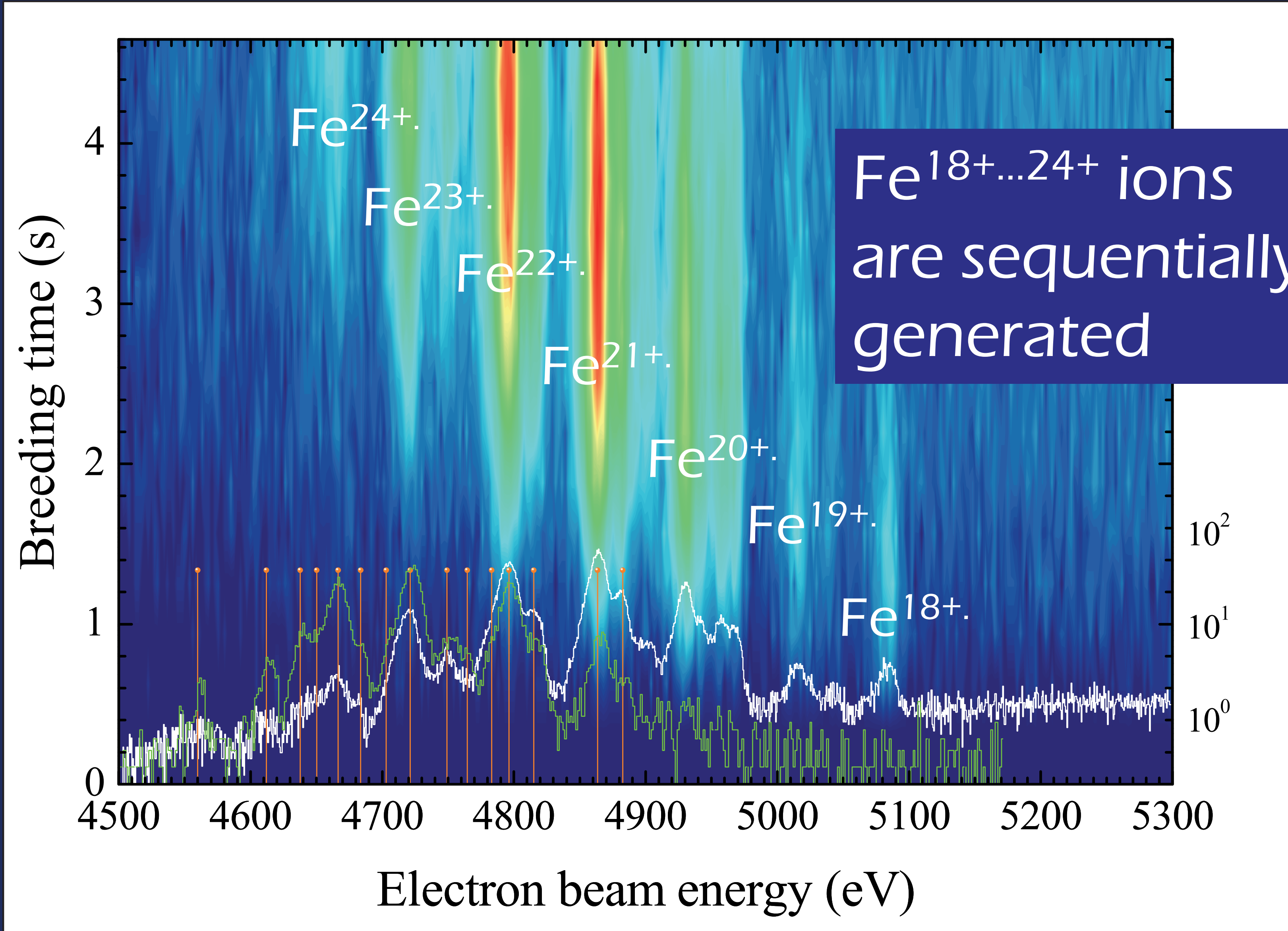
- High energy resolution
- High statistics

X-ray data depending on electron energy



- Fast Fe photorecombination studies
- Maxwellian electron energy distribution

X-ray data depending on electron energy



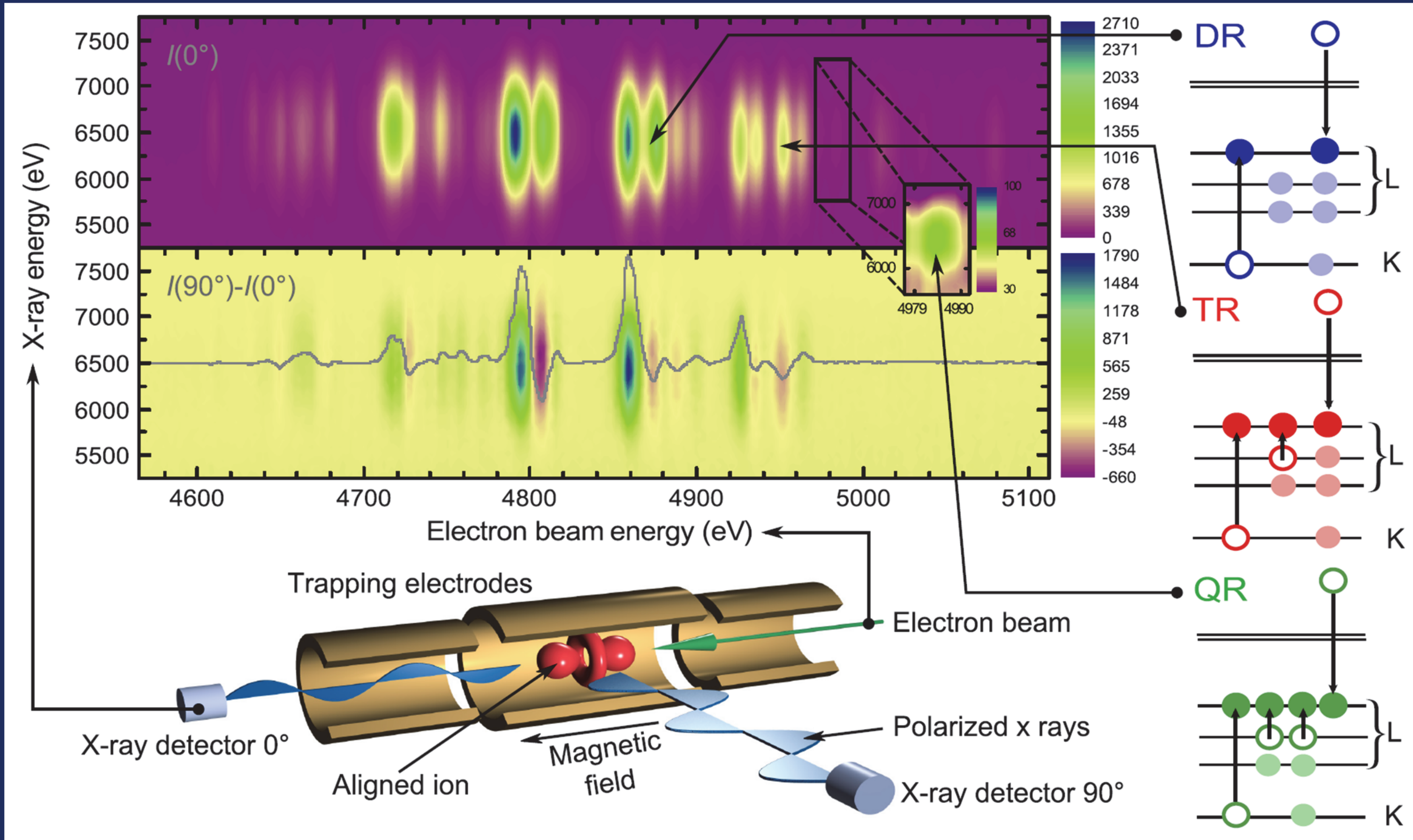
interaction time

$Fe^{18+...24+}$ ions are sequentially generated

Ions in any desired charge state can be prepared, stored and spectroscopically studied

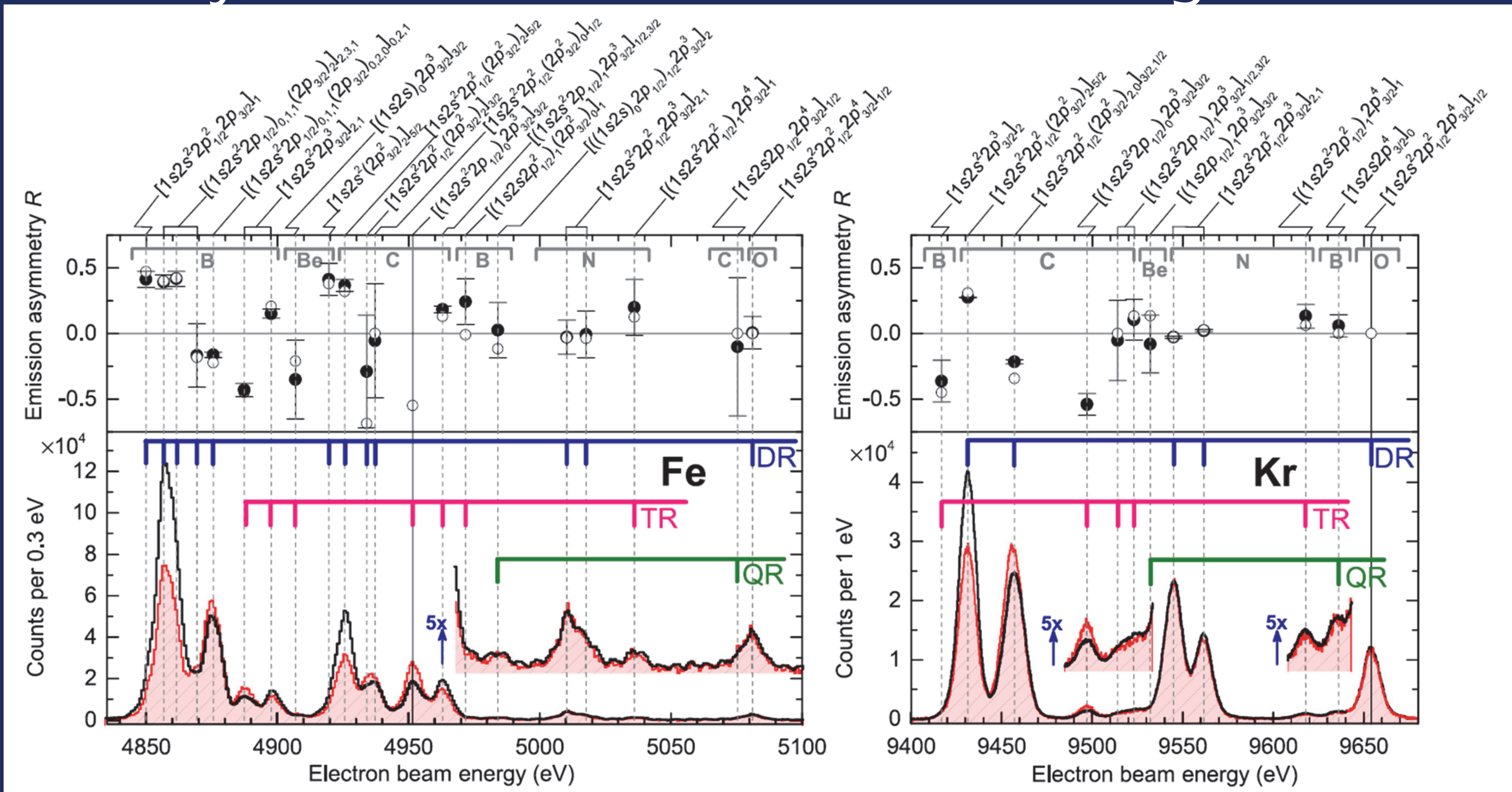
T. M. Bauman et al., PRA **90**, 052704 (2014)

Unexpected, strong contributions by many-electron resonant excitation at high resolution



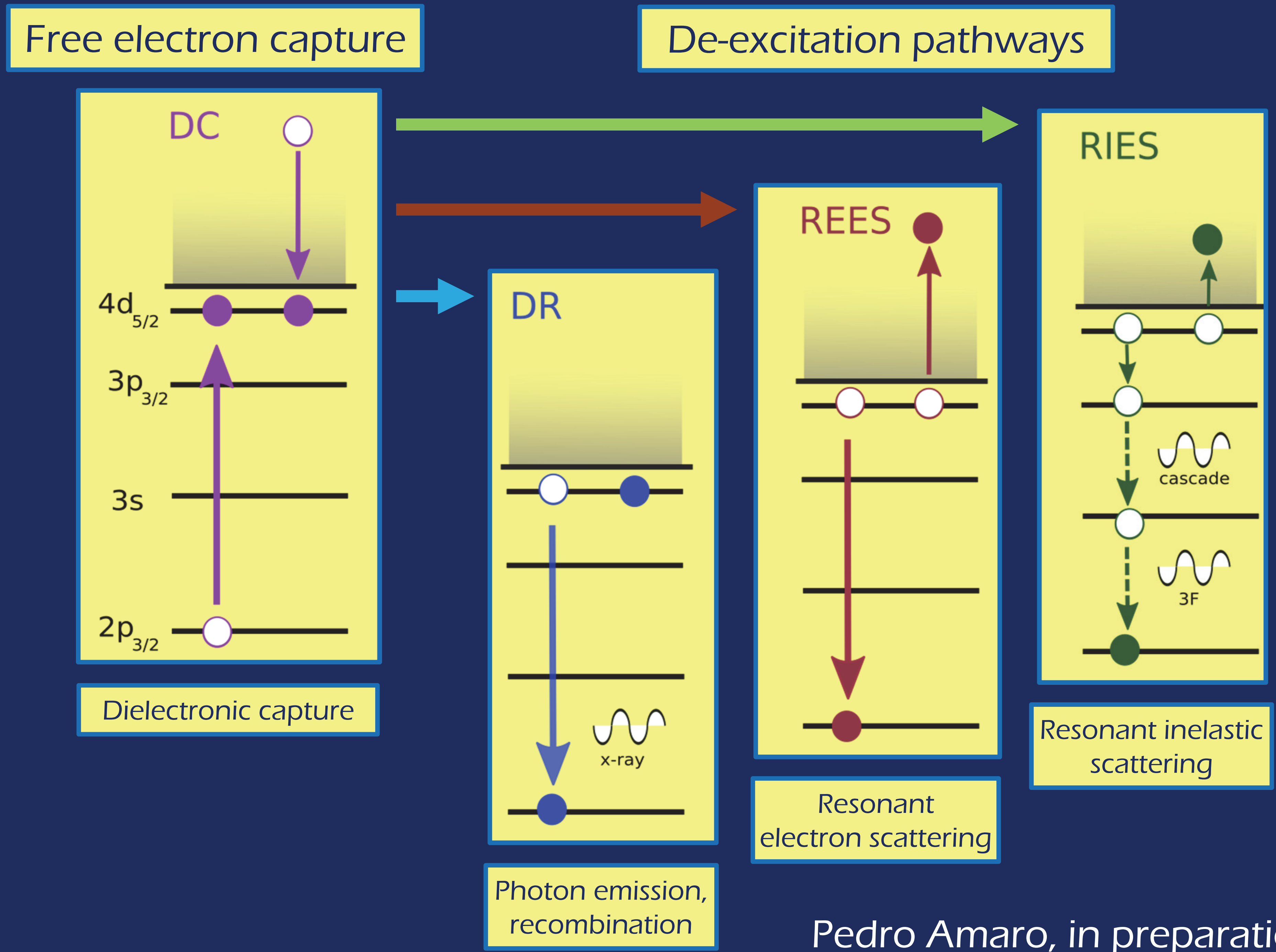
C. Shah et al., Phys. Rev. E **93**, 061201(R) (2016)
C. Beilmann et al., Phys. Rev. Lett **107**, 143201 (2011)
C. Beilmann et al., Phys. Rev. A **88**, 062706 (2013)

Unexpected, strong contributions by many-electron resonant excitation at high resolution



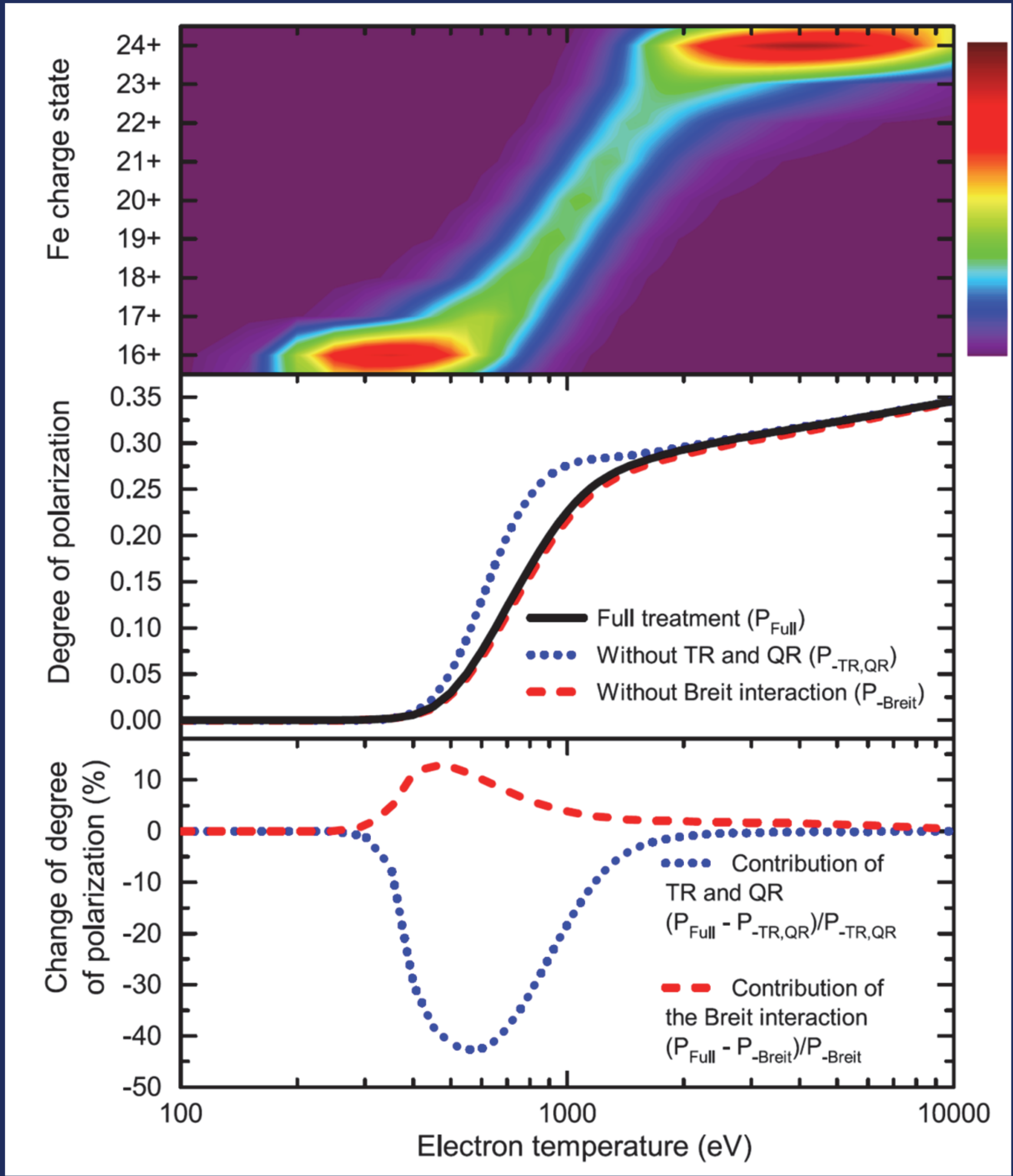
C. Shah et al., Phys. Rev. E **93**, 061201(R) (2016)
C. Beilmann et al., Phys. Rev. Lett **107**, 143201 (2011)
C. Beilmann et al., Phys. Rev. A **88**, 062706 (2013)

L-shell resonant excitation



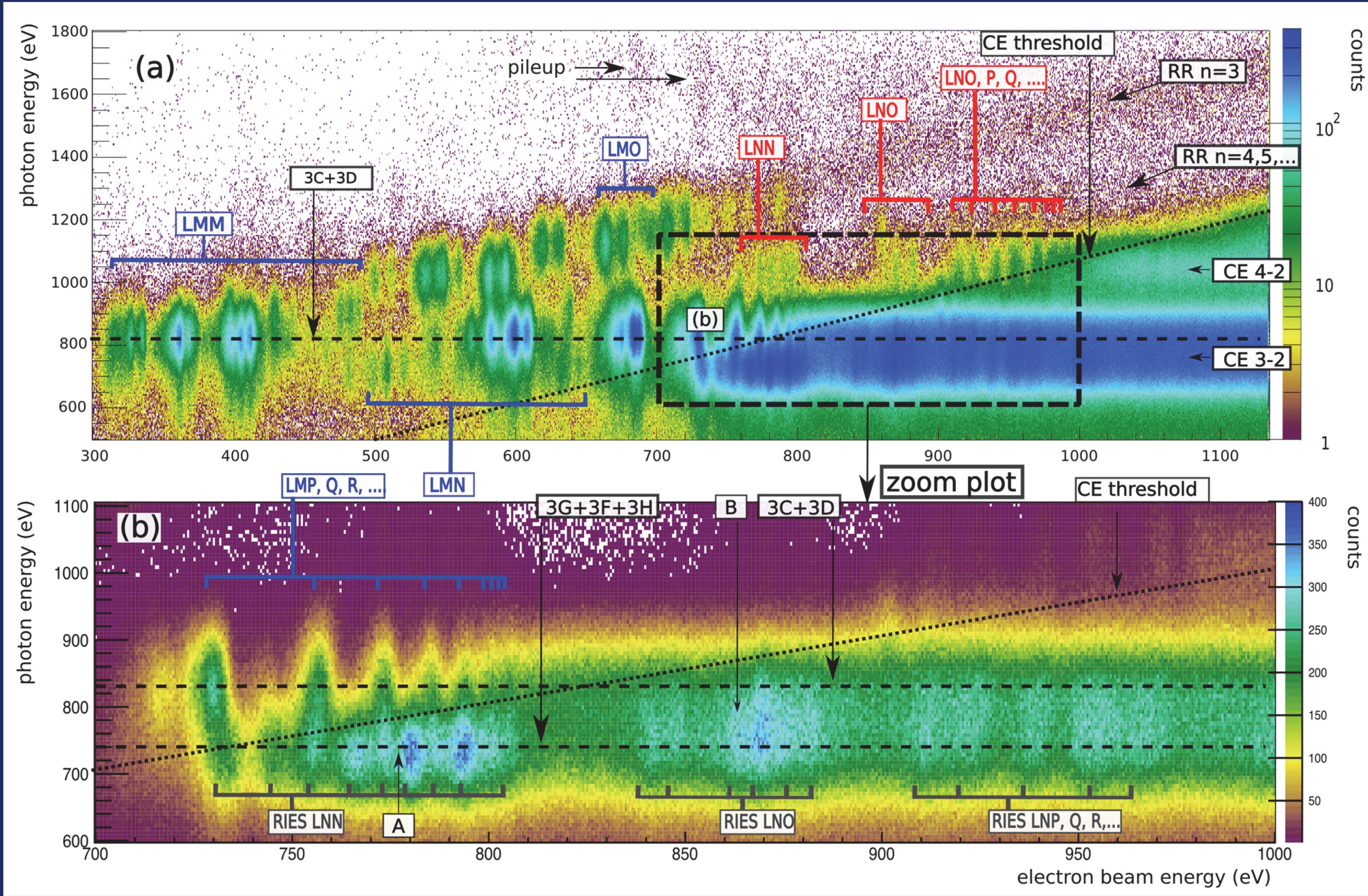
Pedro Amaro, in preparation

Mean charge state of plasmas changed by many-electron resonant excitation



C. Shah et al., Phys. Rev. E 93, 061201(R) (2016)

Fe L-shell resonant excitation



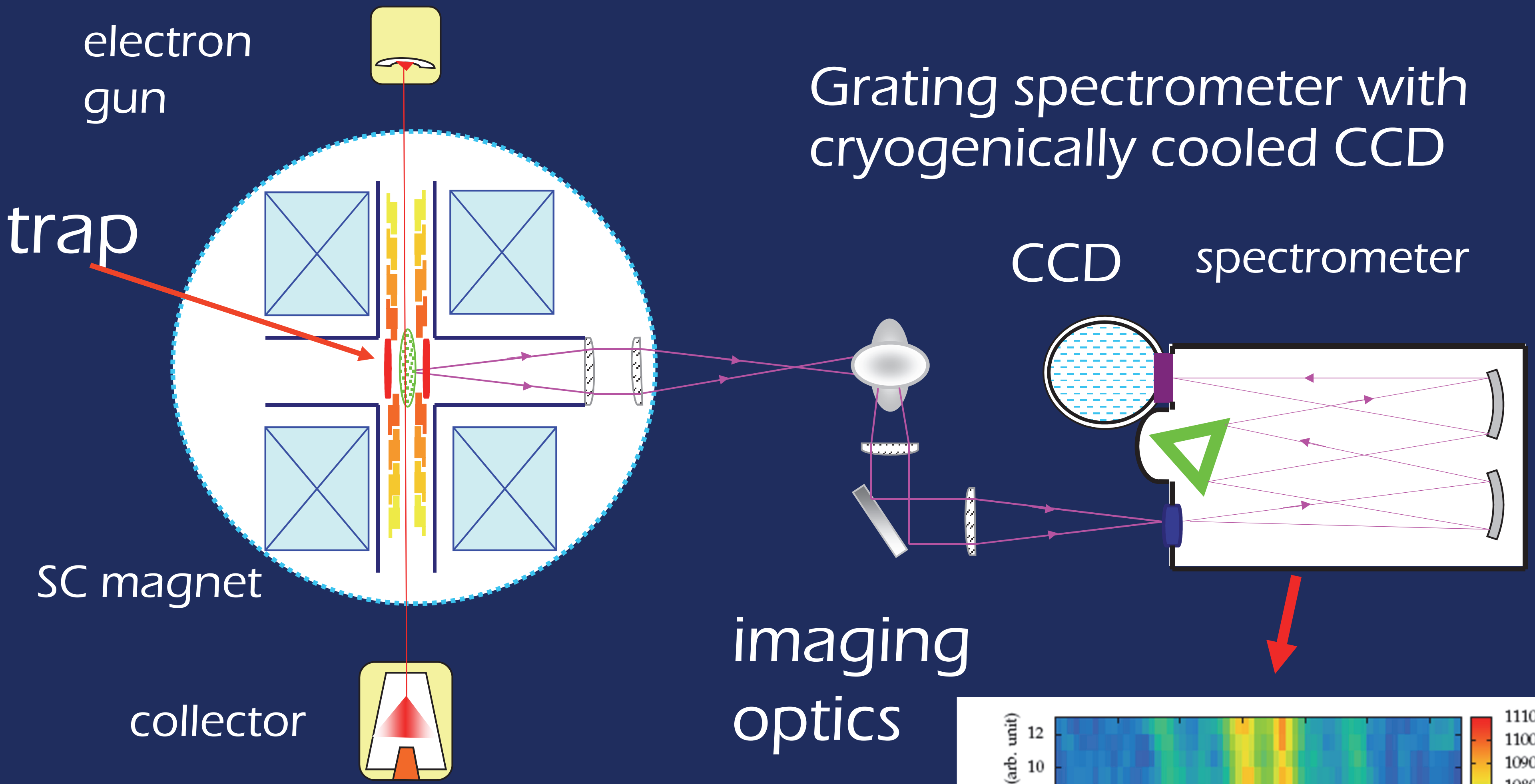
Pedro Amaro, in preparation

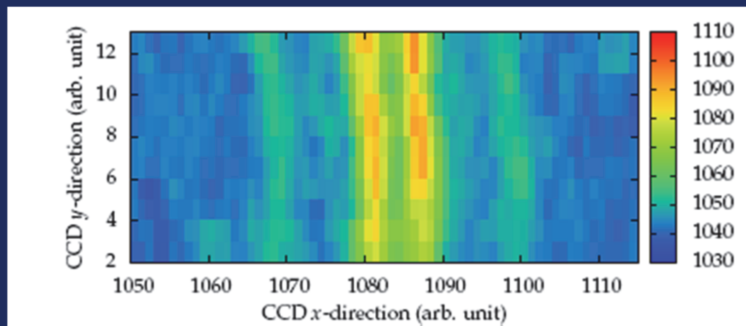
Conclusions from FEL, synchrotron and photorecombination studies

- Previously known but neglected complex multielectron processes have experimentally shown unexpectedly strong contributions to both photrecombination and photoionization
- Inclusion of those channels in calculations is necessary to achieve agreement with existing experimental data
- Even the most advanced theoretical methods are not as accurate as the experiments
- Achieving agreement at the 1% (energies) respectively 5% (cross sections) levels will require more dedicated theoretical work and benchmarking experimental data

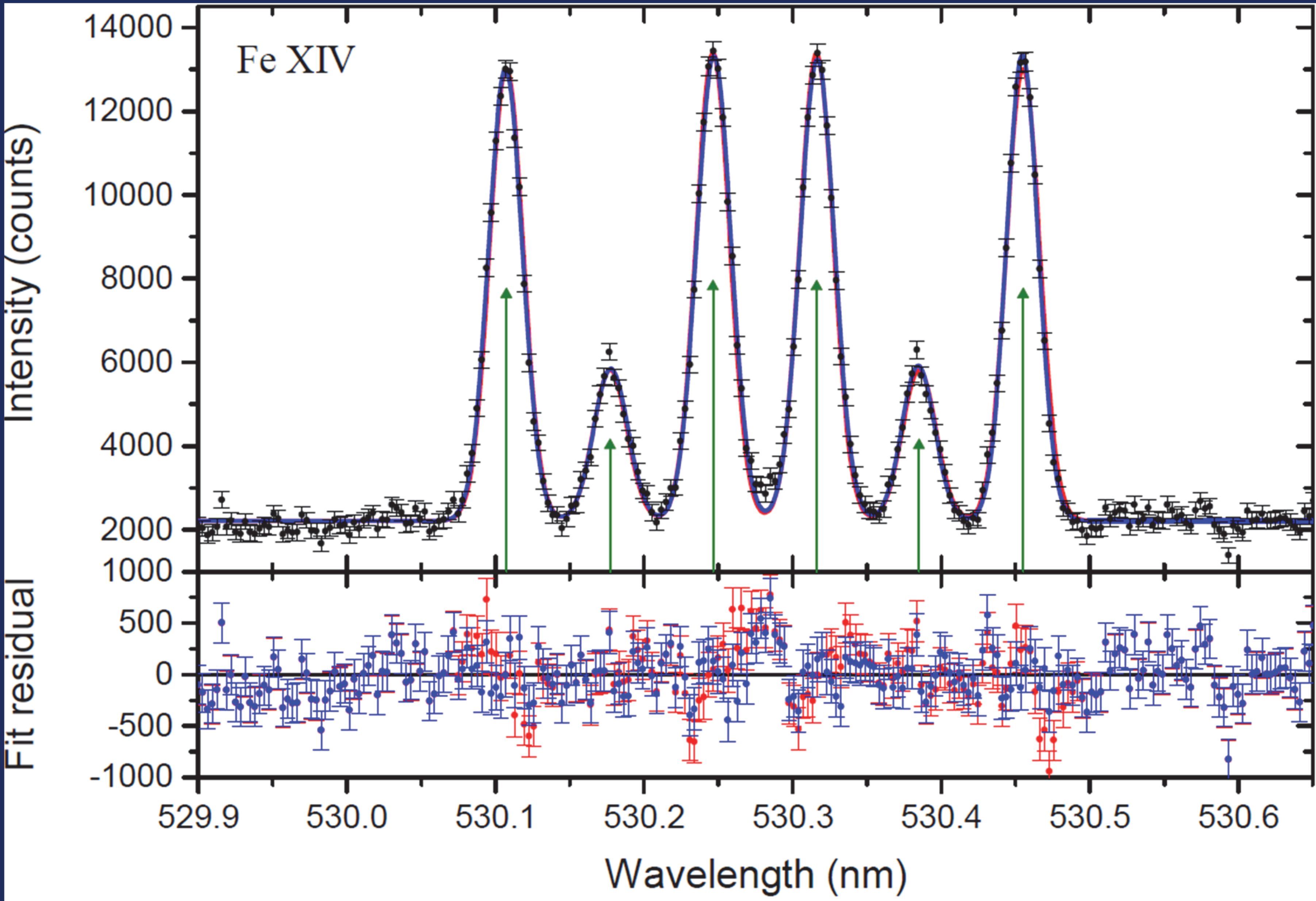
Optical and EUV spectroscopy with EBITs

Spectroscopy of few-electron ions in the visible range



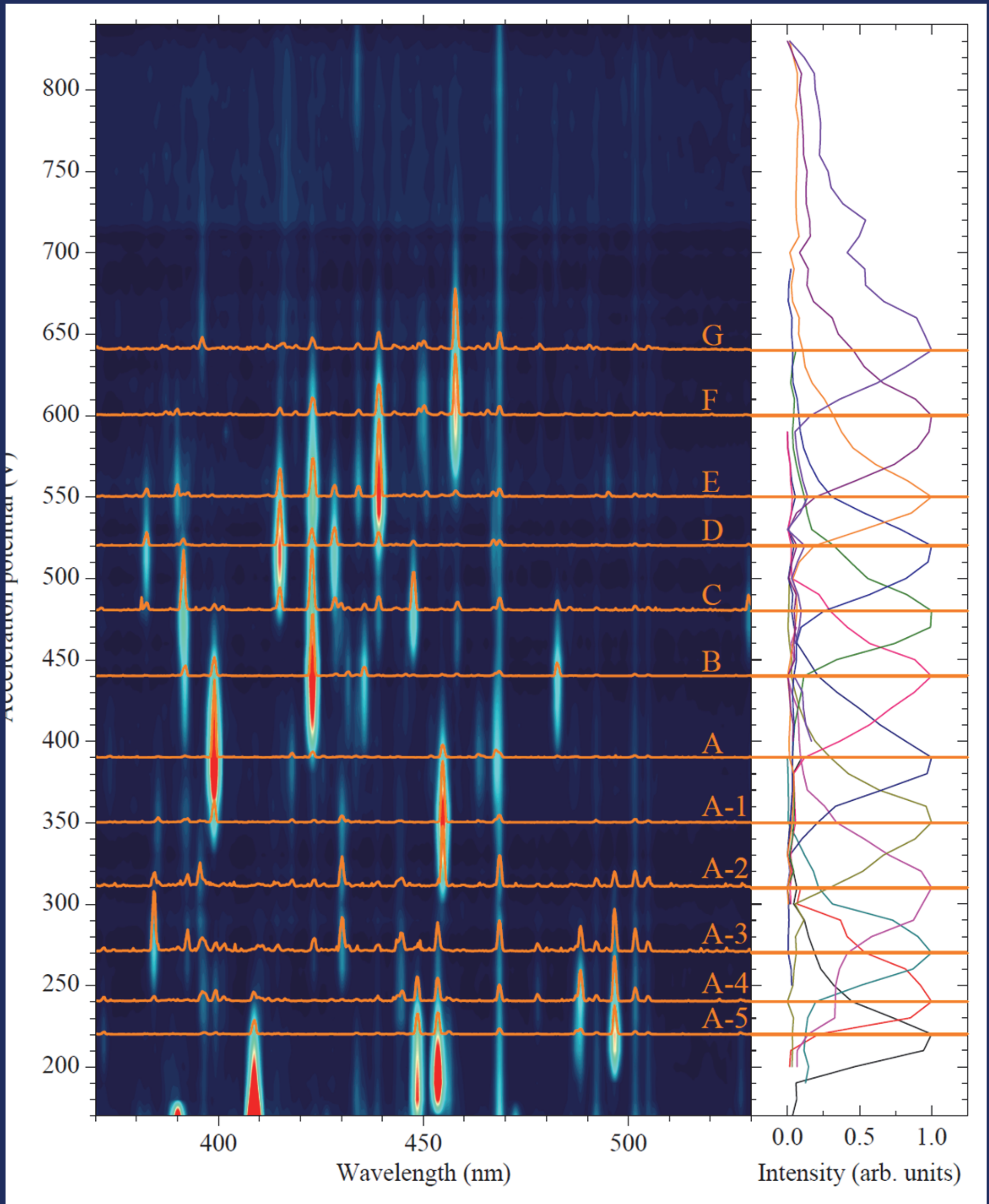


Fe^{13+} (Fe XIV): the *"green coronal line"*



Hendrik Bekker, accepted PRA 2018

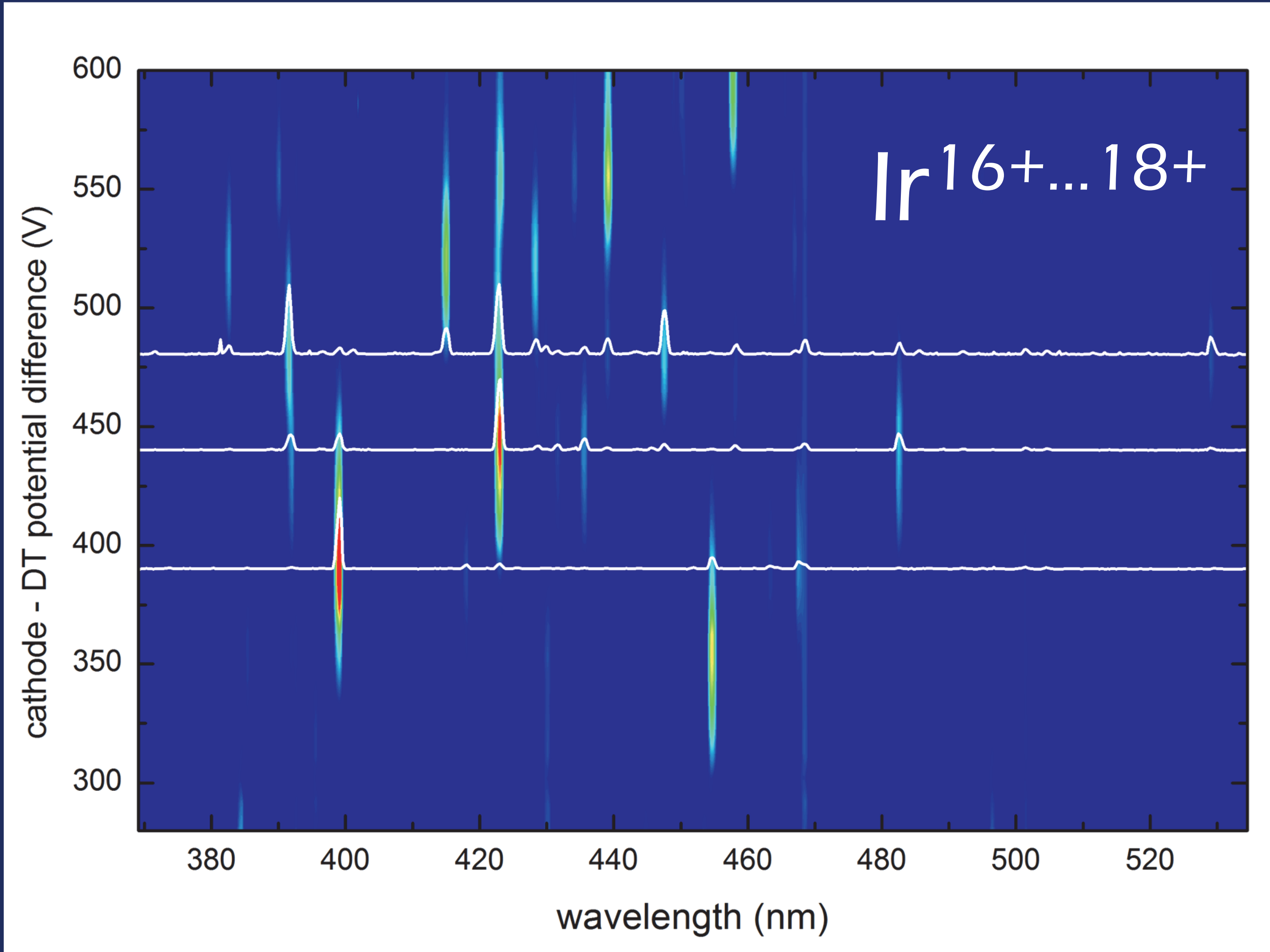
Level crossings at Ir^{17+} provide α sensitivity



- At certain charge state levels change order
- *4f* goes below *5s* in Ir^{17+}
- Opposite parities degenerate: *$4f^{12}\,5s^2$, $4f^{13}\,5s$, $4f^{14}$*
- Many slow M1, E1, E2, M2, M3 transitions become possible
- Several long lived „ground states" available

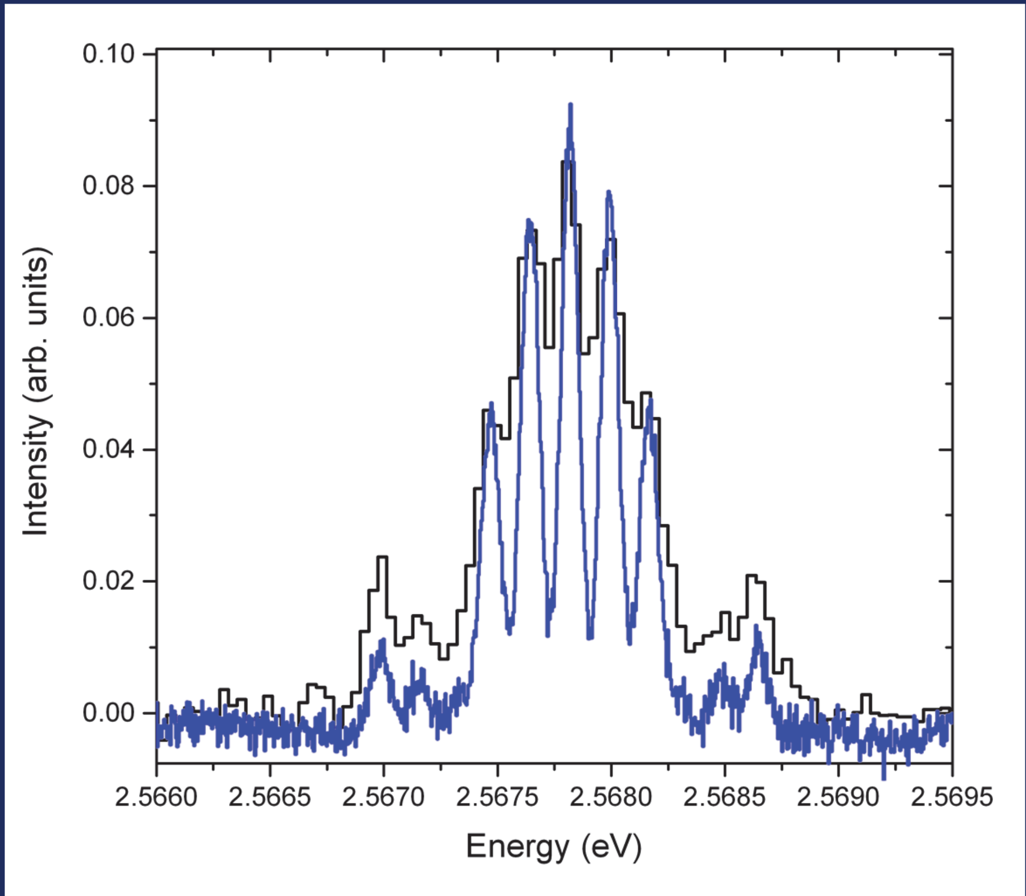
Windberger et al., PRL **114**, 150801 (2015)

Visible spectra of M1 lines in Ir ions



First observations; line identification difficult

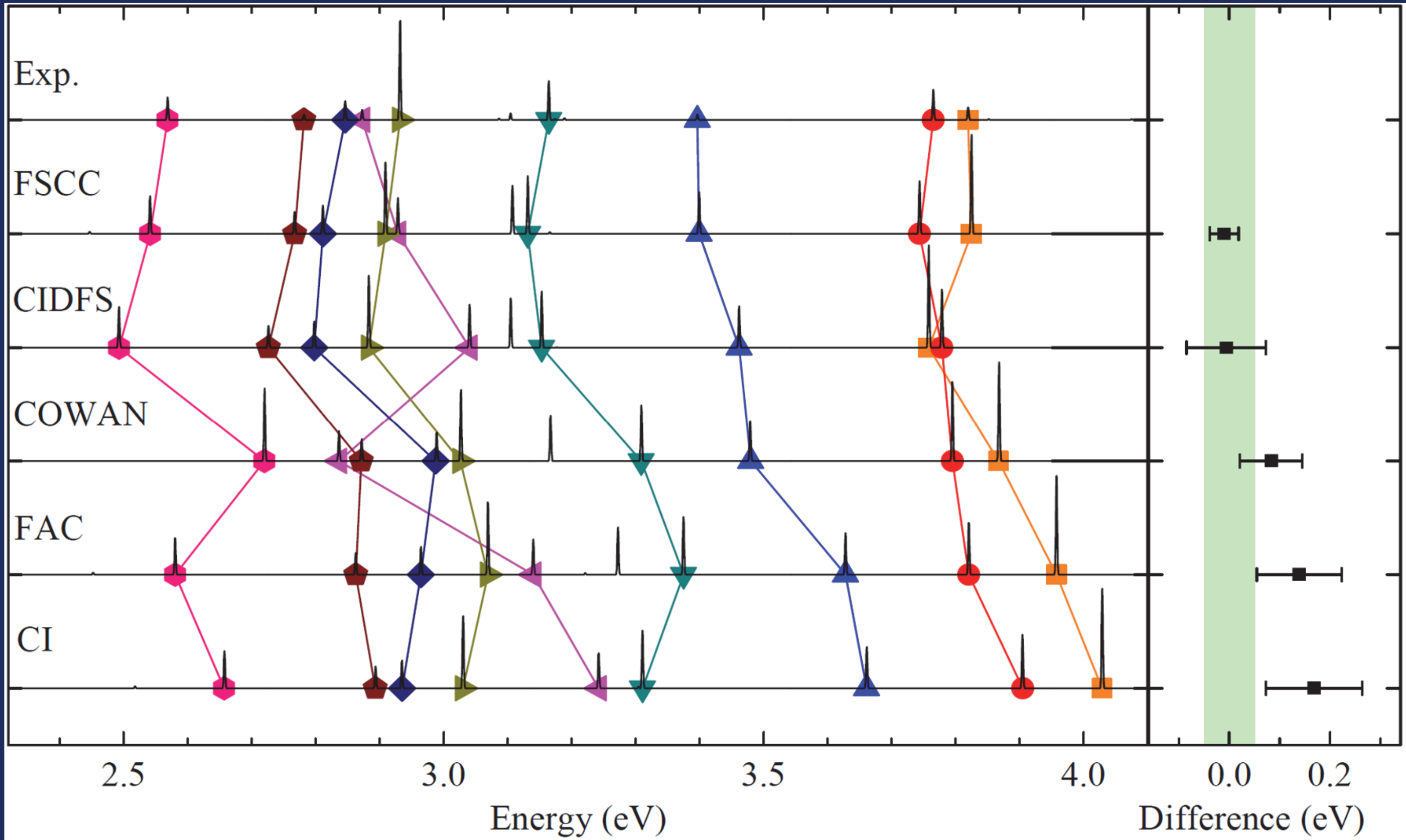
Improved resolving power



Transition	Wavelength (nm)	Updated
$^3P_1 - {}^3F_2$	226.63(2)	
$^3F_3 - {}^3F_3^o$	240.098(1)	
$^1G_4 - {}^3F_3^o$	255.8684(3)	
$^3H_4 - {}^3H_5$	324.6113(4)	
$^1F_3^o - {}^3F_4^o$	329.3025(4)	329.3028 (2)
$^1D_2 - {}^3F_2$	365.0318(10)	365.03230(14)
$^1F_3^o - {}^3F_3^o$	390.7408(9)	
$^3F_3 - {}^3F_4$	391.8220(3)	391.82393(16)
$^3P_2 - {}^1D_2$	399.4702(3)	
$^3H_5 - {}^3H_6$	422.8950(3)	422.89512(17)
$^1D_2 - {}^3F_3$	431.6044(3)	431.60376(8)
$^1G_4 - {}^3F_4$	435.6348(5)	435.7595 (2)
$^3H_4 - {}^1G_4$	445.7057(9)	445.70825(17)
$^3F_2^o - {}^3F_3^o$	482.7039(7)	482.70386(8)
$^3H_4 - {}^3F_3$	503.423(2)	
$^3P_1 - {}^1D_2$	597.65(2)	

H. Bekker et al., in preparation

Comparison between theories



*

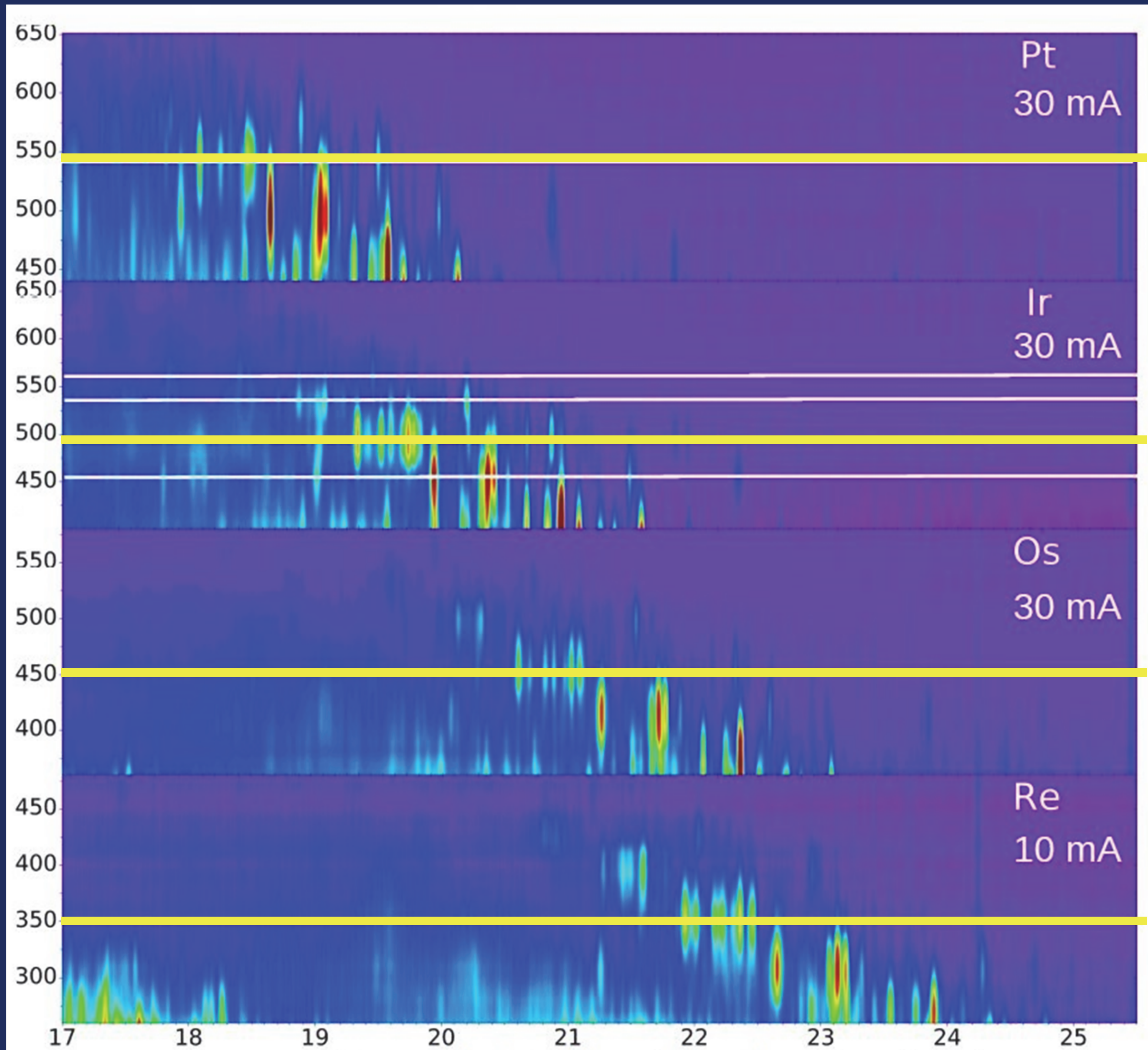
- Fock-space coupled cluster calculation (A. Borschevski) shows agreement with experimental result at a level suitable for identification.
- Its deviations from experiment are smaller than the average separation between spectral lines (as given by the green band).

* Berengut *et al.*, PRL **106**, (2011)

Windberger et al., PRL **114**, 150801 (2015)

Pm-like (61electrons) isoelectronic sequence

Electron beam energy (eV)



Wavelength (nm)

Pt^{17+}

Ir^{16+}

Os^{15+}

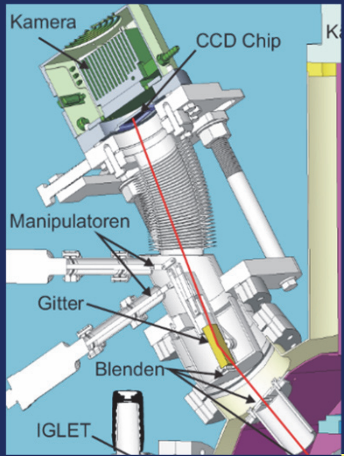
Re^{14+}

Ce (Z=58)
Pr (Z=59)
Nd (Z=60)
Pm (Z=61)
Sm (Z=62)

Isoelectronic sequence studied in detail to find analogies

Electron beam ion trap diagnostics

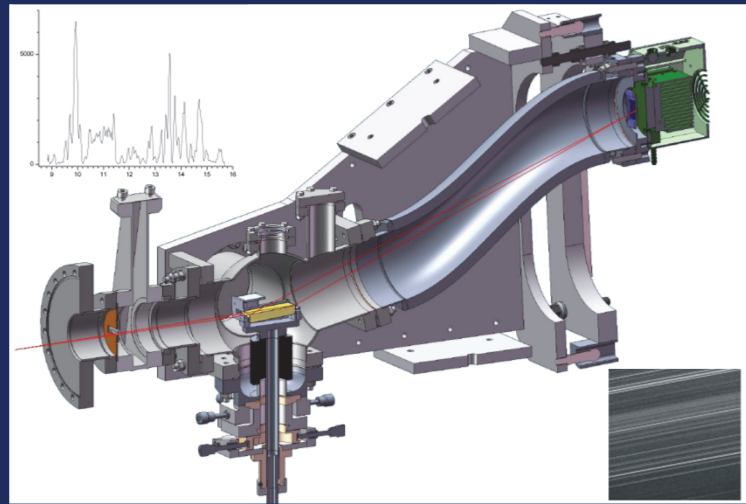
EUV grating spectrometer 1



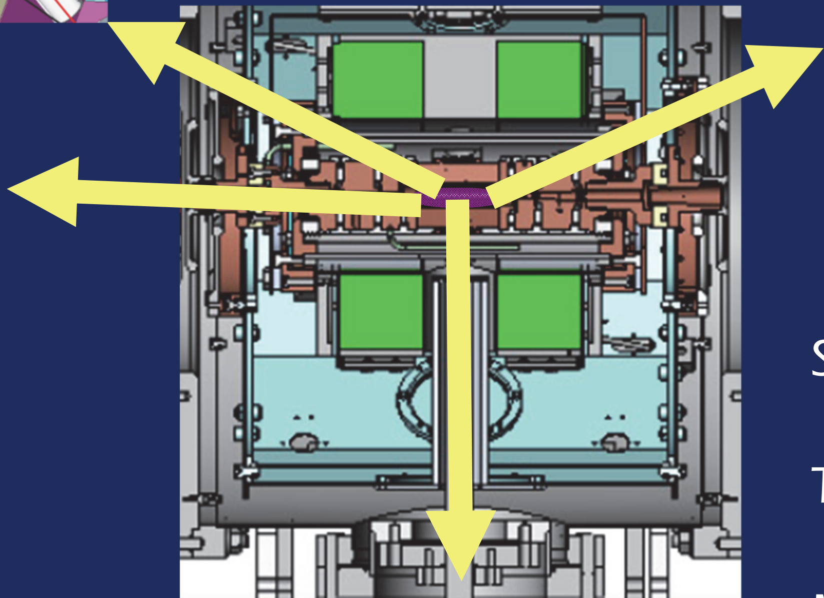
EUV to soft X-ray

EUV grating spectrometer 2

EUV



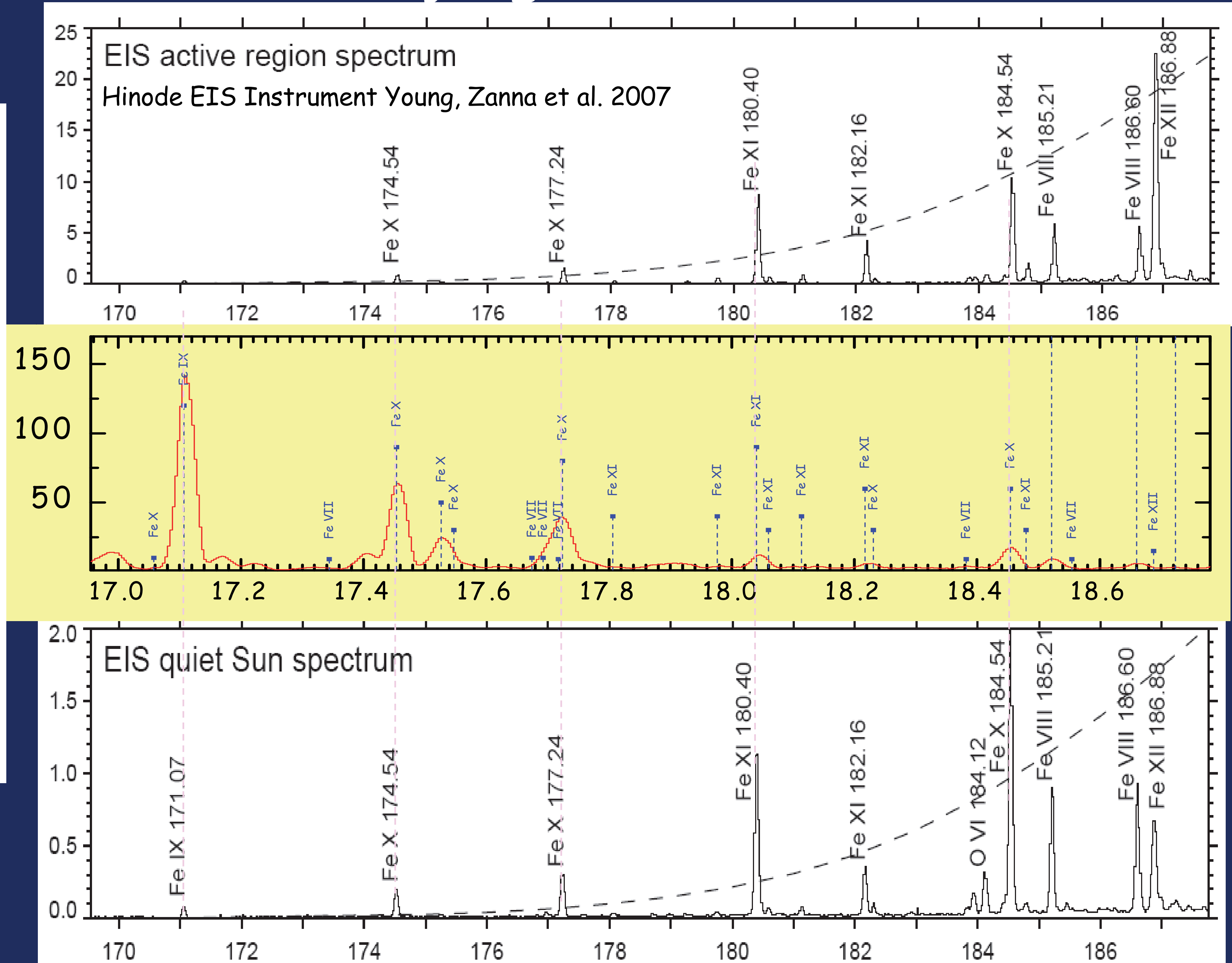
X-ray



X-ray
Silicon drift detector
Germanium detector

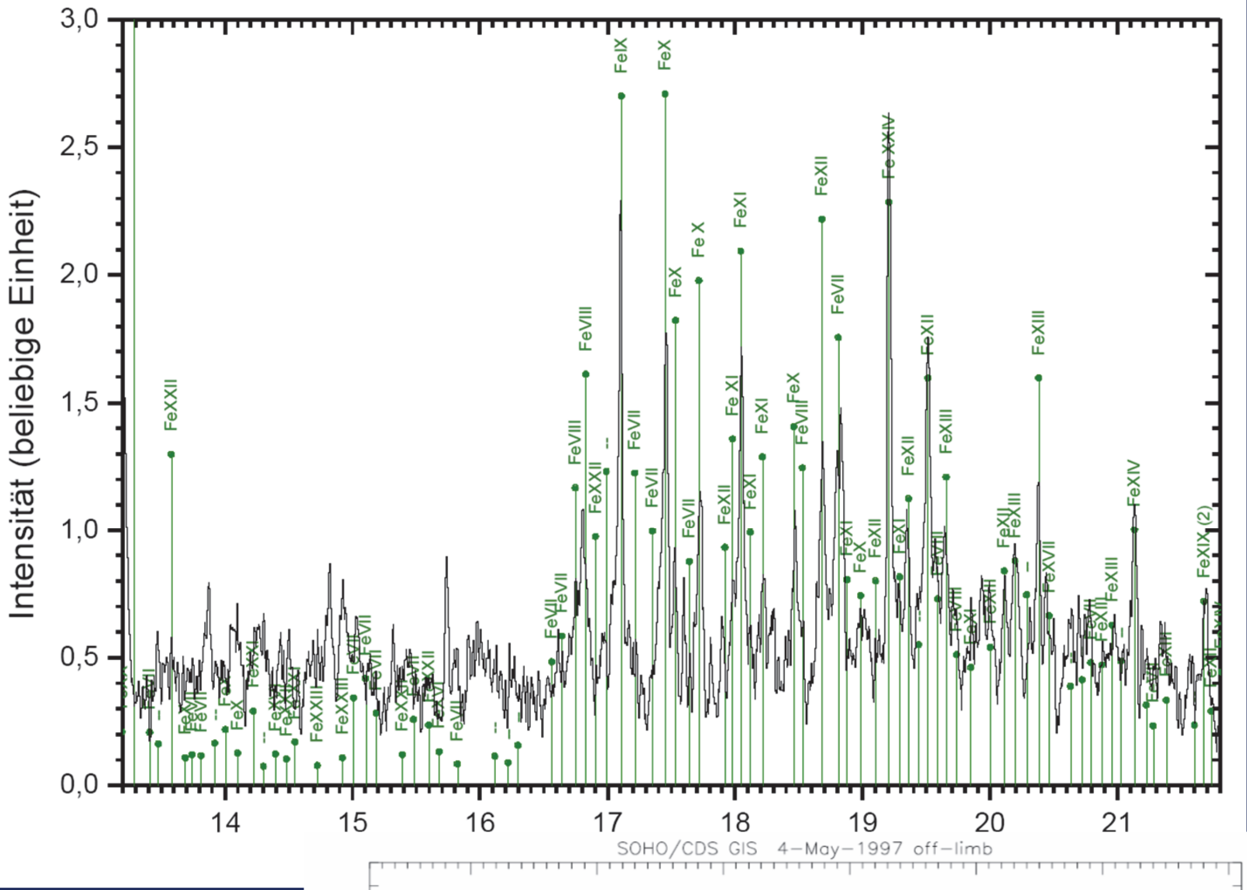
Si drift detector, Ge detector
X-ray photons 1 to 30 keV
Two grating spectrometers
EUV photons 40 eV to 1 keV
Metallic magnetic microcalorimeter
X-ray photons 2 to 8 keV

Hinode ("sunrise"): space telescope (2006) studying the solar corona



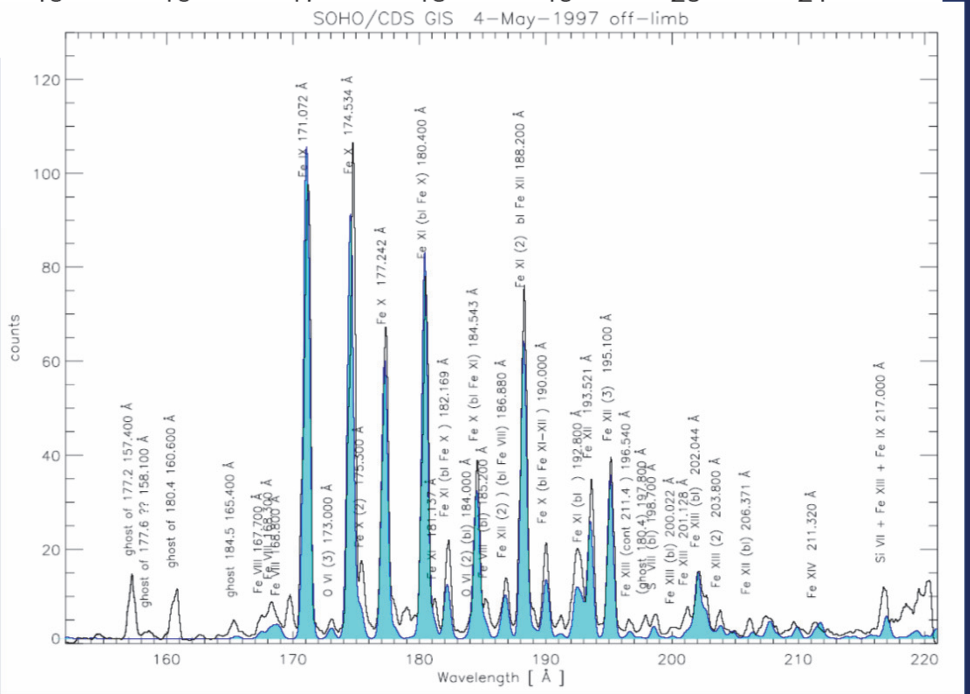
Comparison

of new data



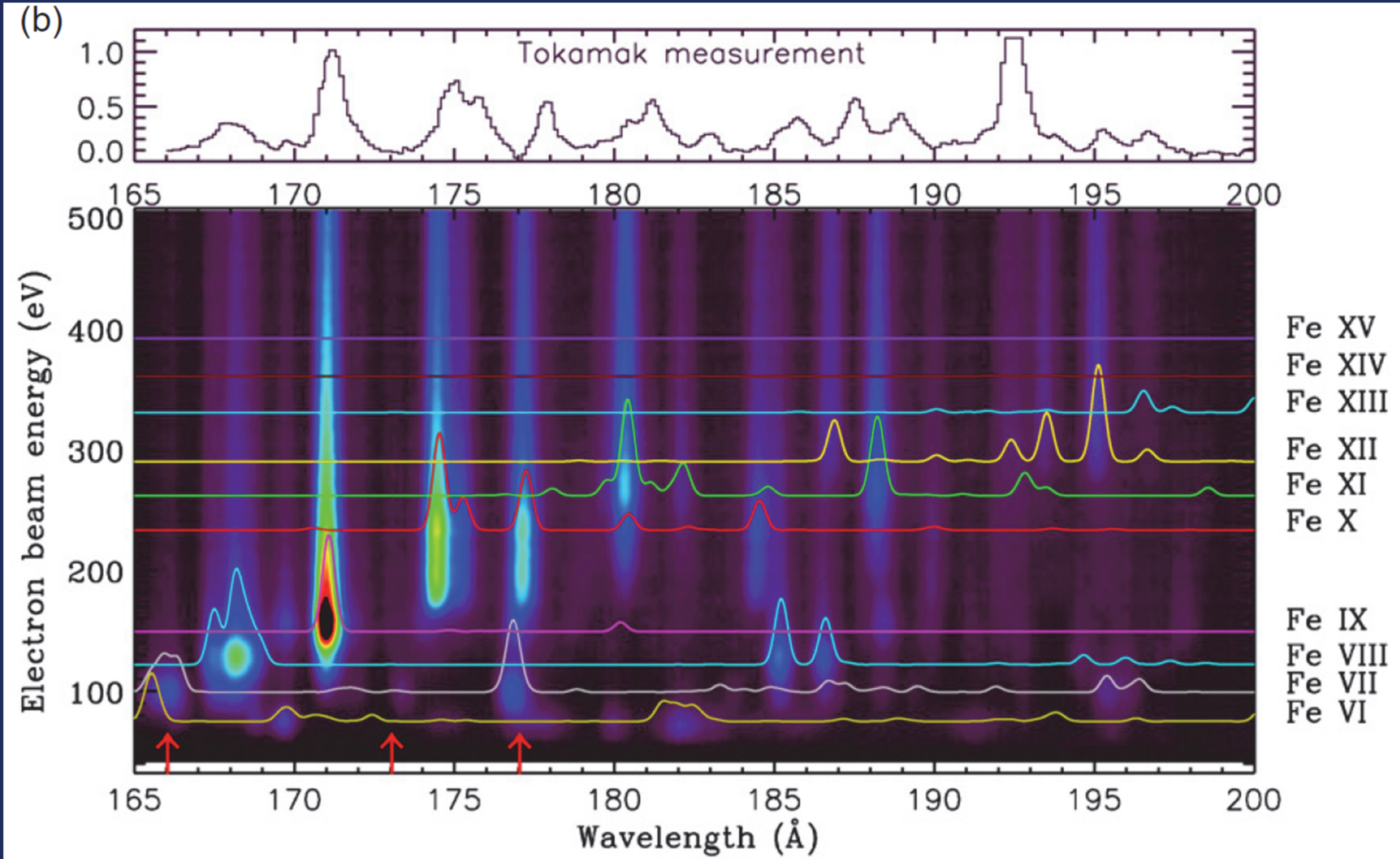
with

SOHO



SOHO: Solar Heliospheric Observatory

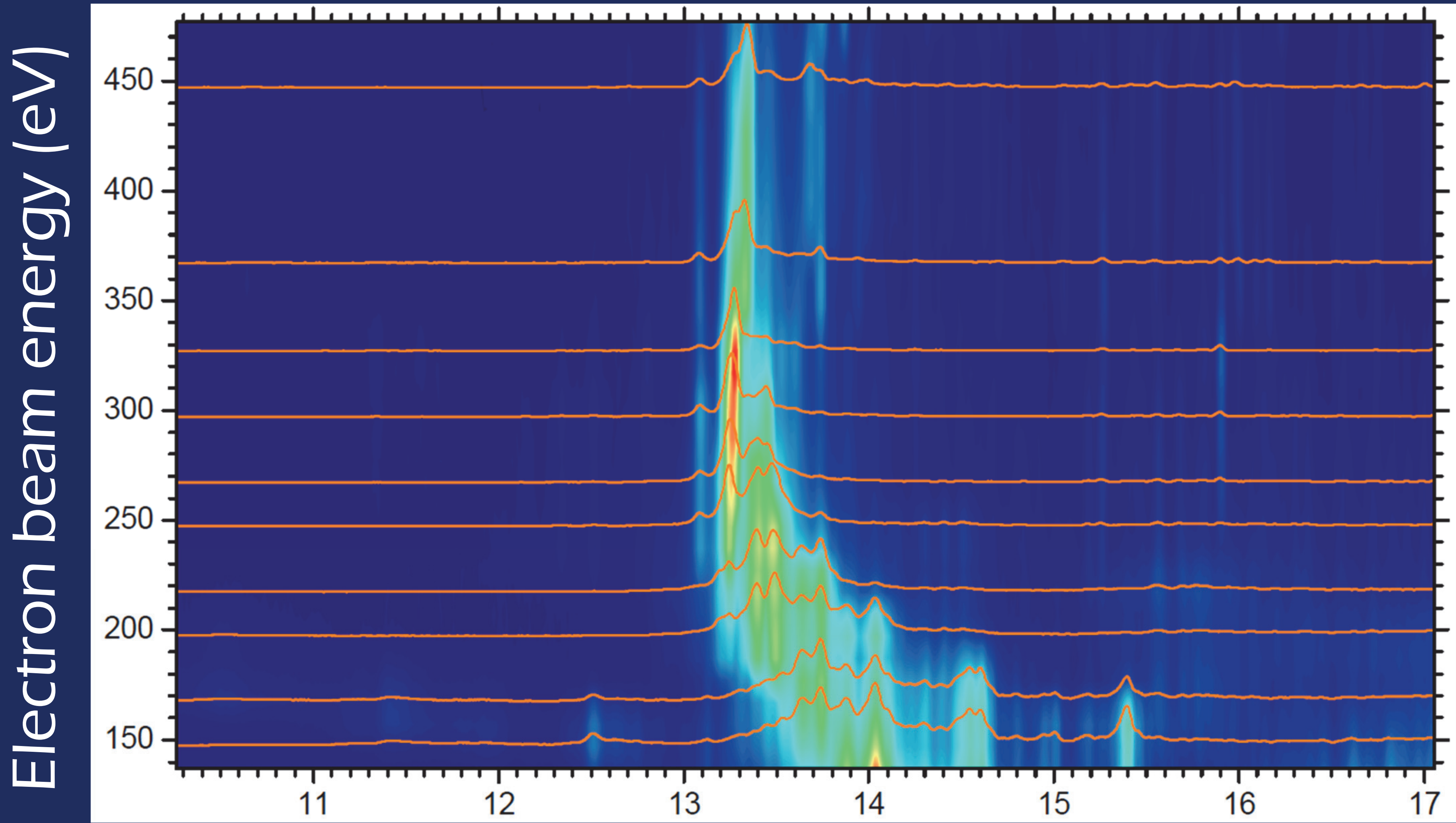
Studies of Fe HCI with charge-state resolution



Gu et al., Astrophys. J. 696, 2275 (2009)

Understanding optical and EUV spectra of Sn ions

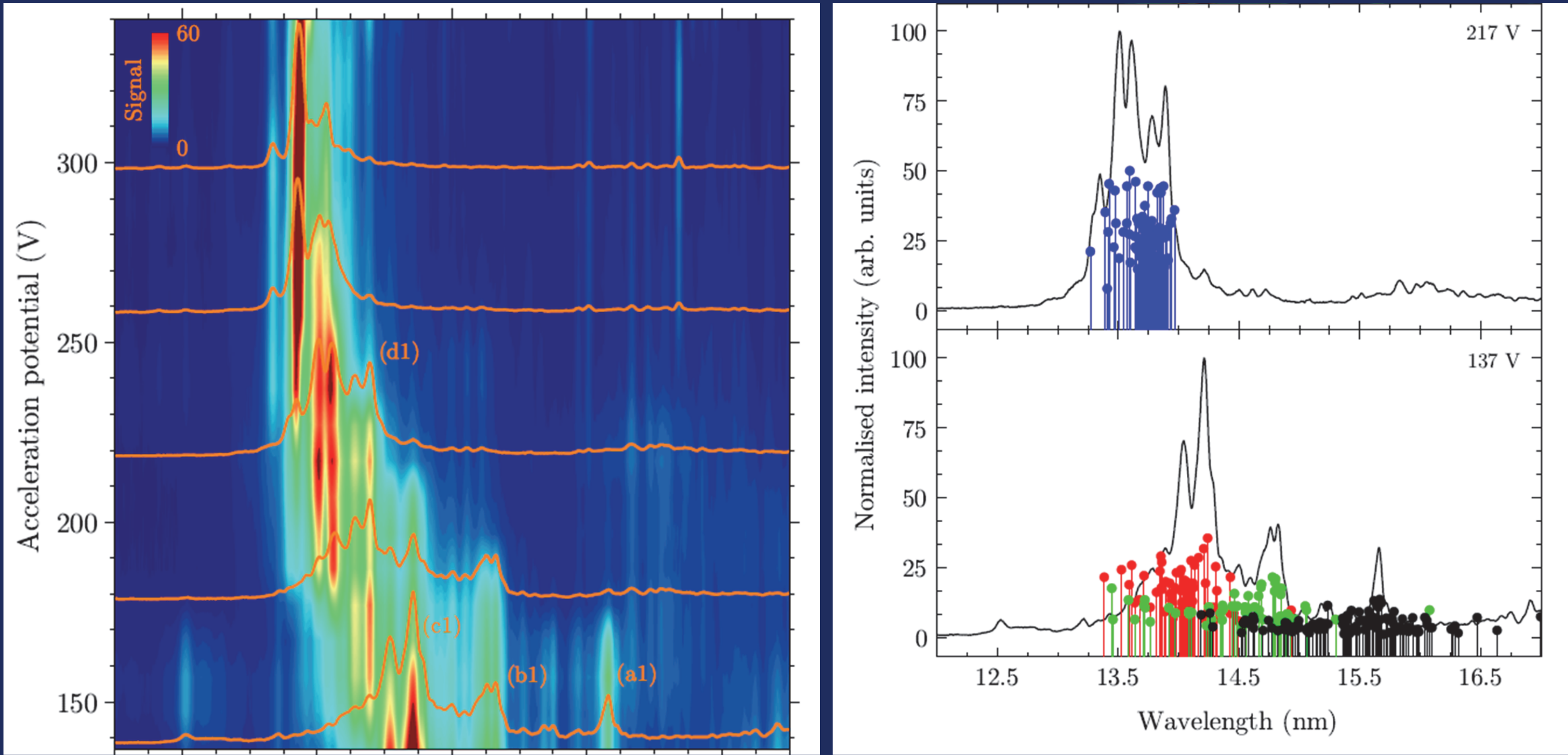
Understanding Sn spectra



Wavelength (nm)

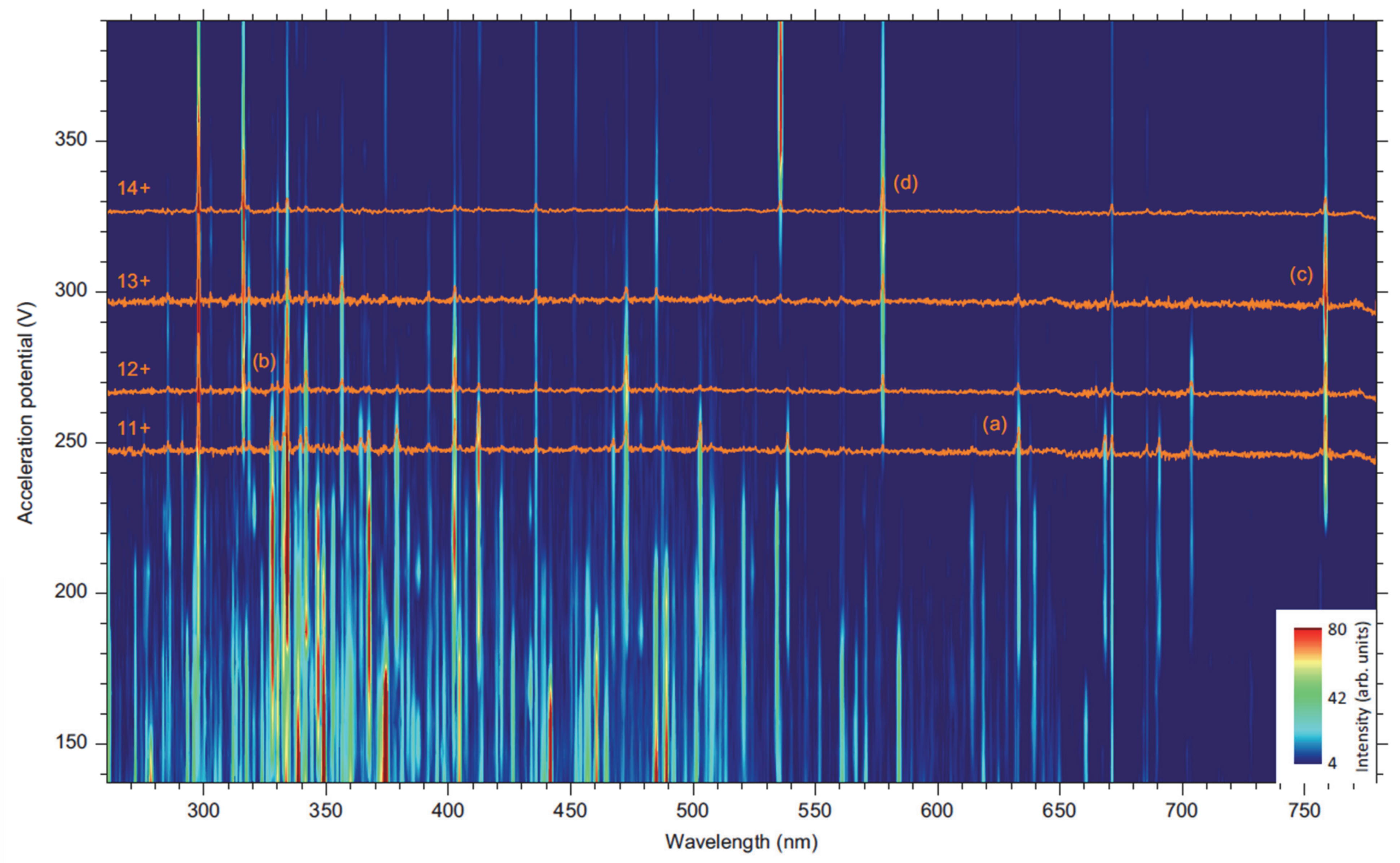
H. Bekker et al., J. Phys. B **48**, 144018 (2015)

Understanding Sn spectra



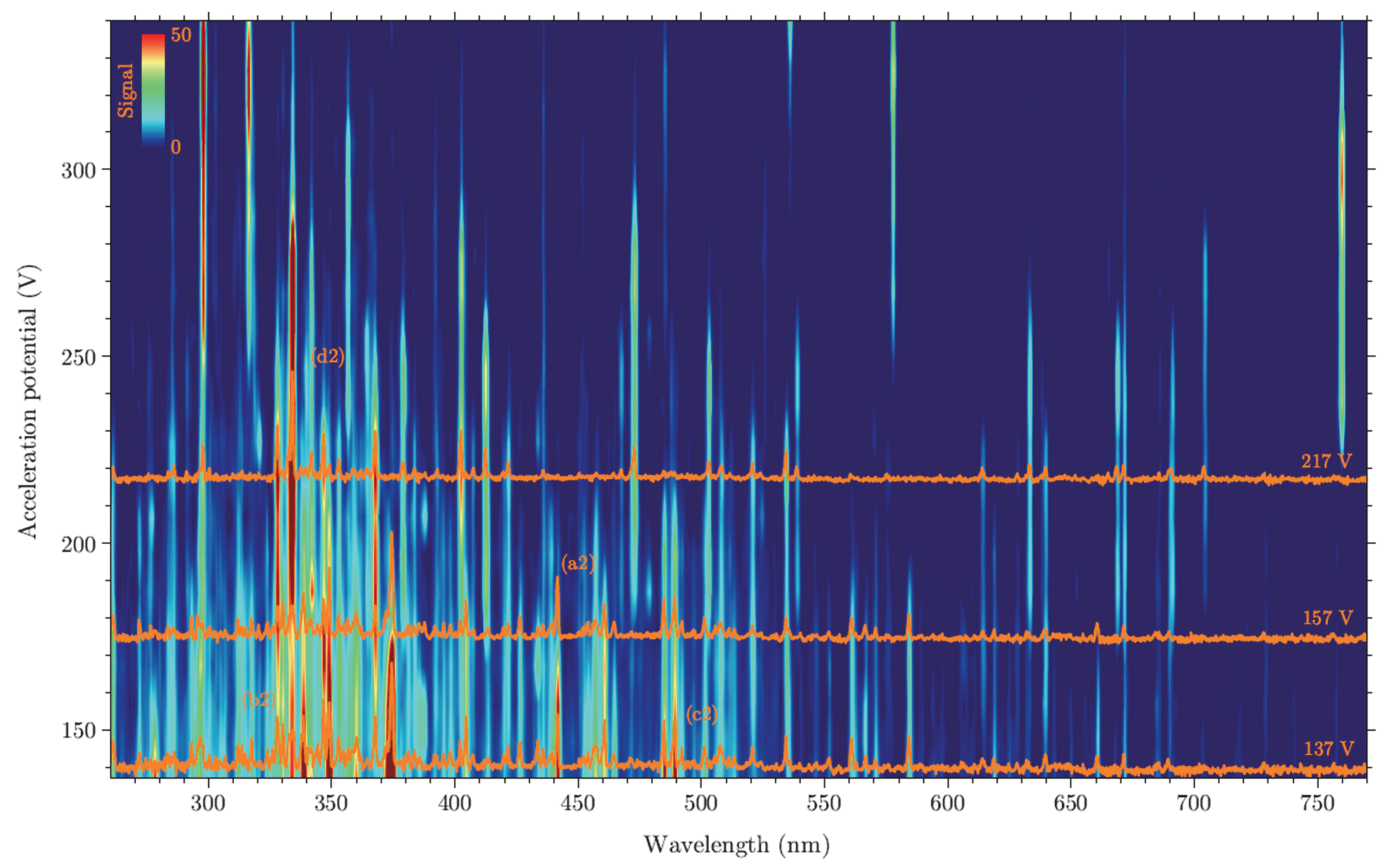
F. Torretti, ARCNL, PRA (2017)

Understanding Sn spectra



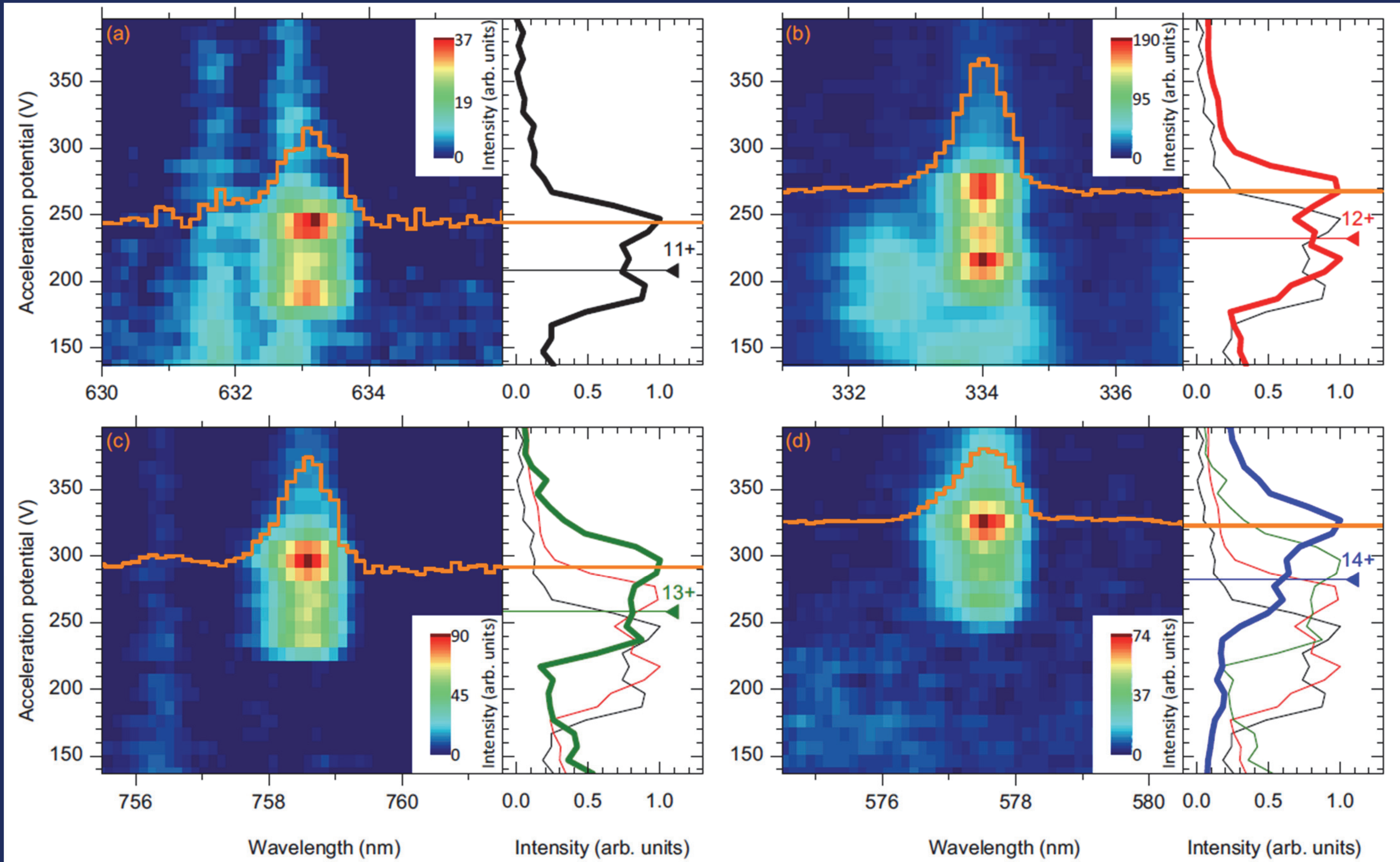
A. Windberger et al., Phys. Rev A **94**, 012506 (2016)

Understanding Sn spectra



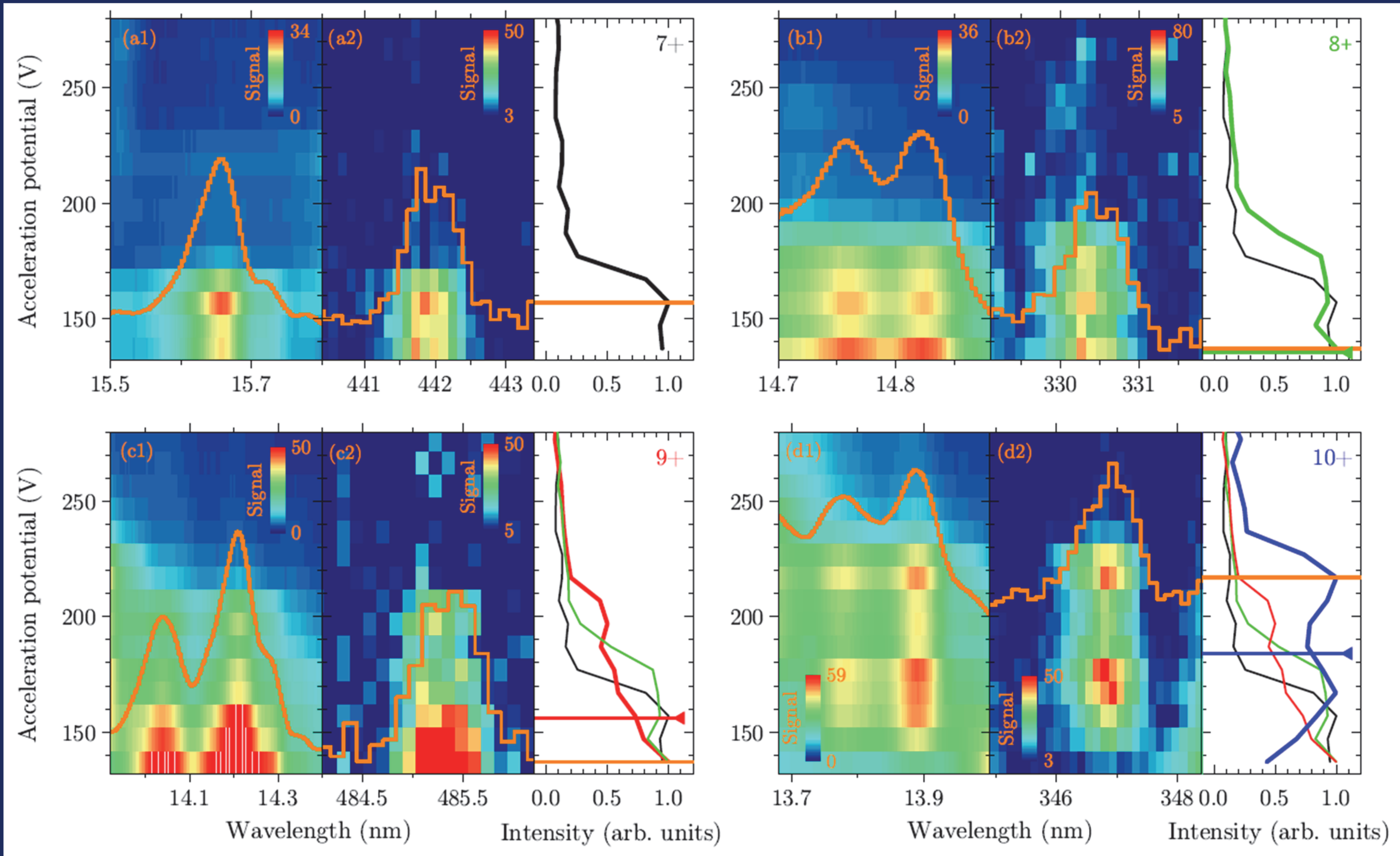
F. Torretti, ARCNL, PRA (2017)

Understanding Sn spectra



A. Windberger et al., Phys. Rev A 94, 012506 (2016)

Understanding Sn spectra

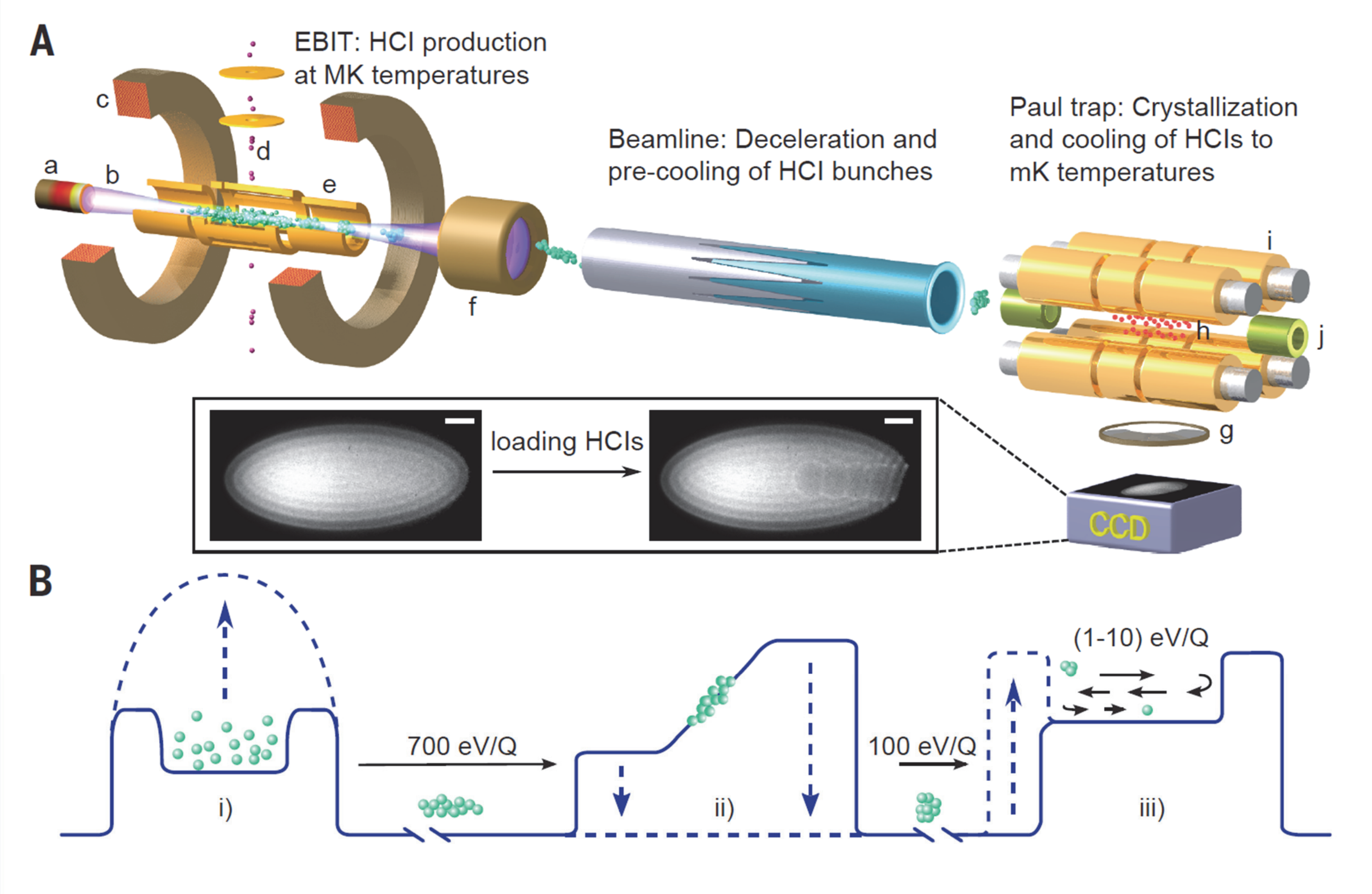


F. Torretti, ARCNL, PRA (2017)

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

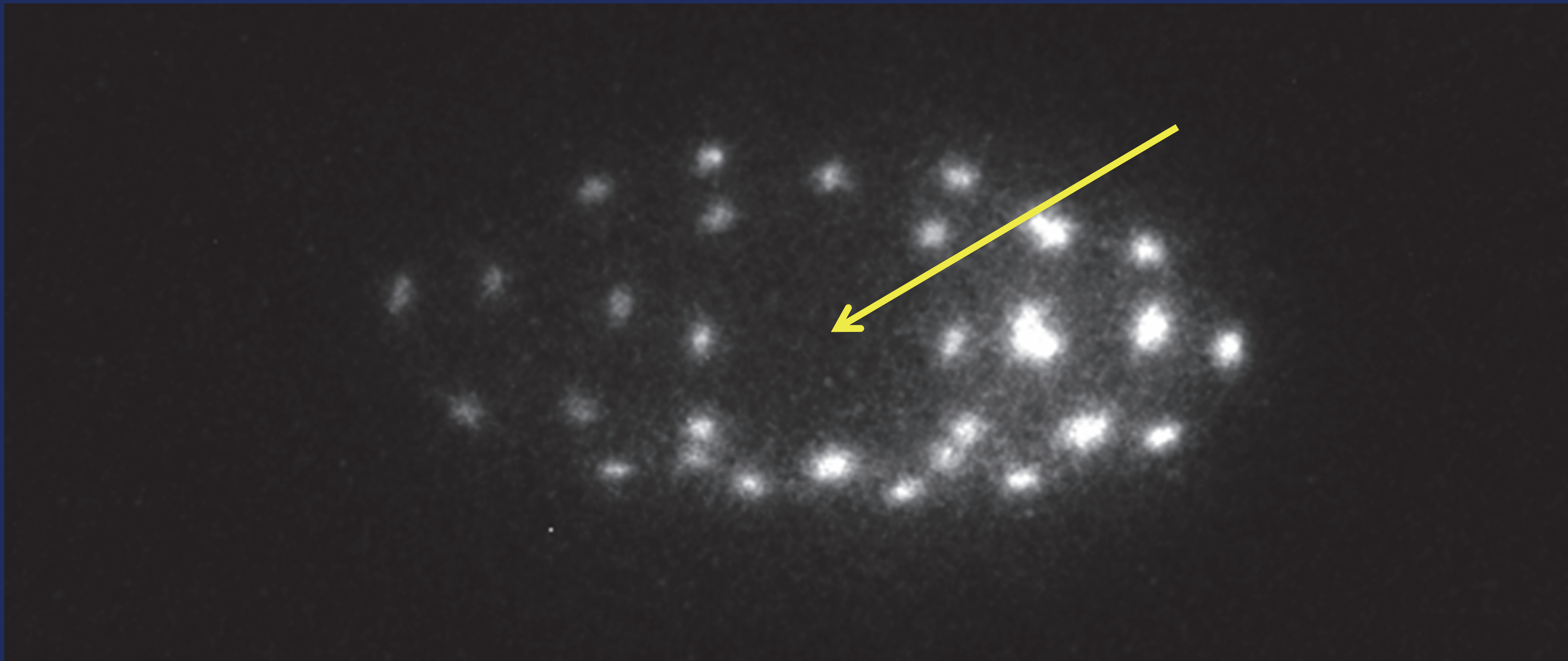
Optical frequnecy metrology with HCI stabilization

Production, deceleration, implantation of HCI



Lisa Schmöger et al., Science **347**, 1233 (2015)

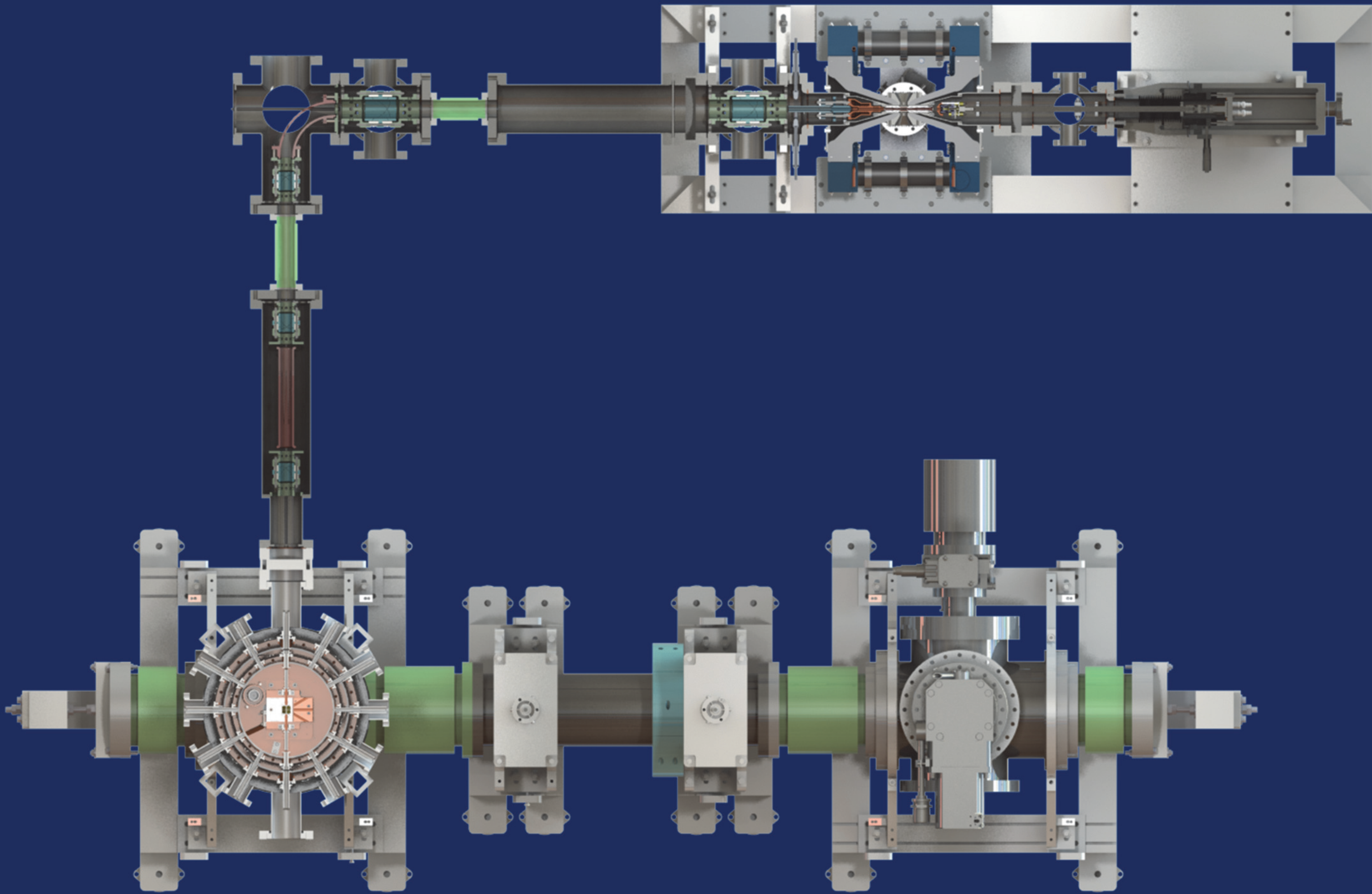
HCl identification by image analysis



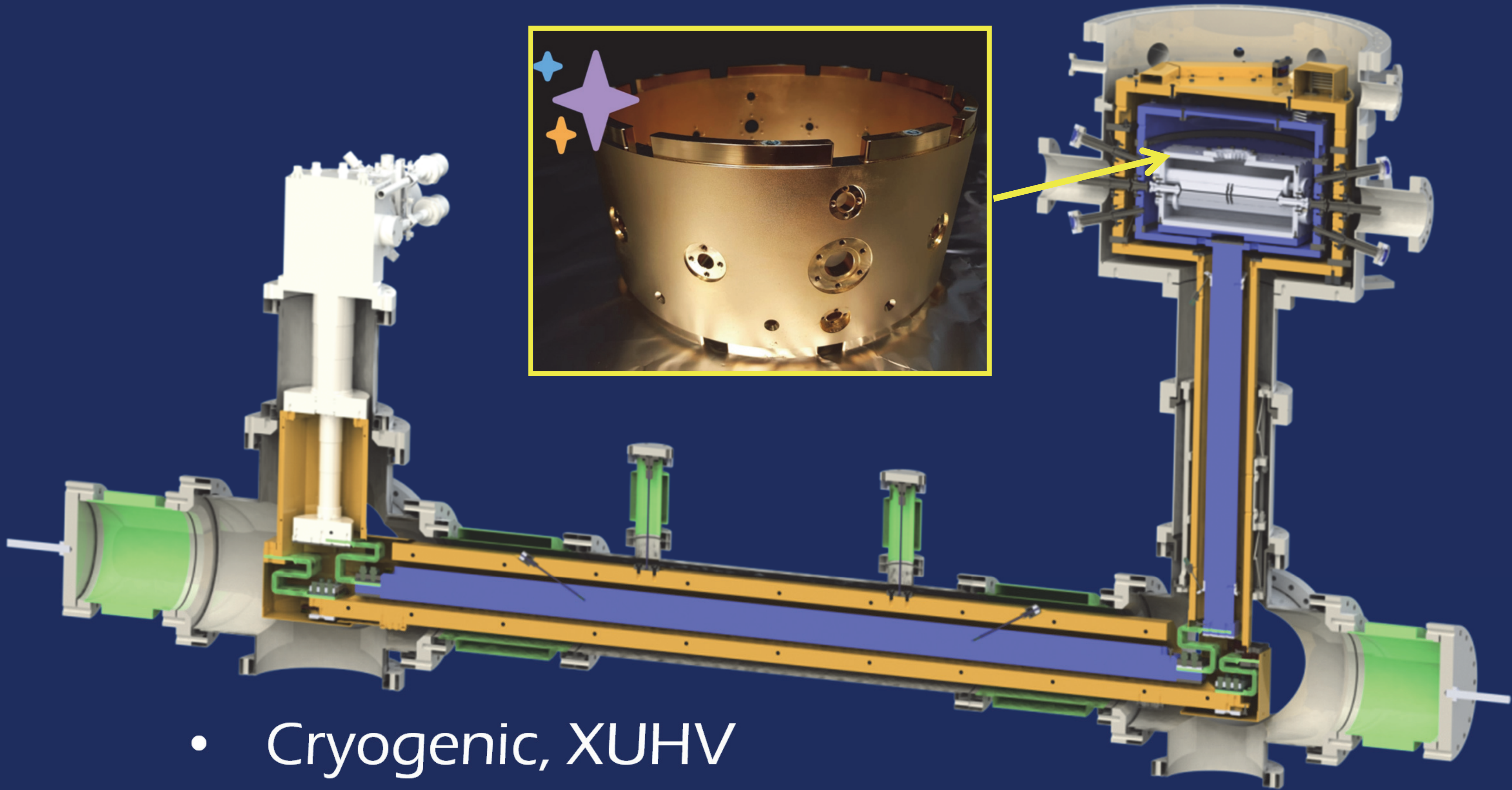
- The single HCI (here Ar^{13+}) repels Be^{+} ions and produces a hole in the Coulomb crystal
- Addressing a single ion in the trap with a focused beam is possible due to large separation.

Lisa Schmöger et al., Science **347**, 1233 (2015)

Setup at PTB

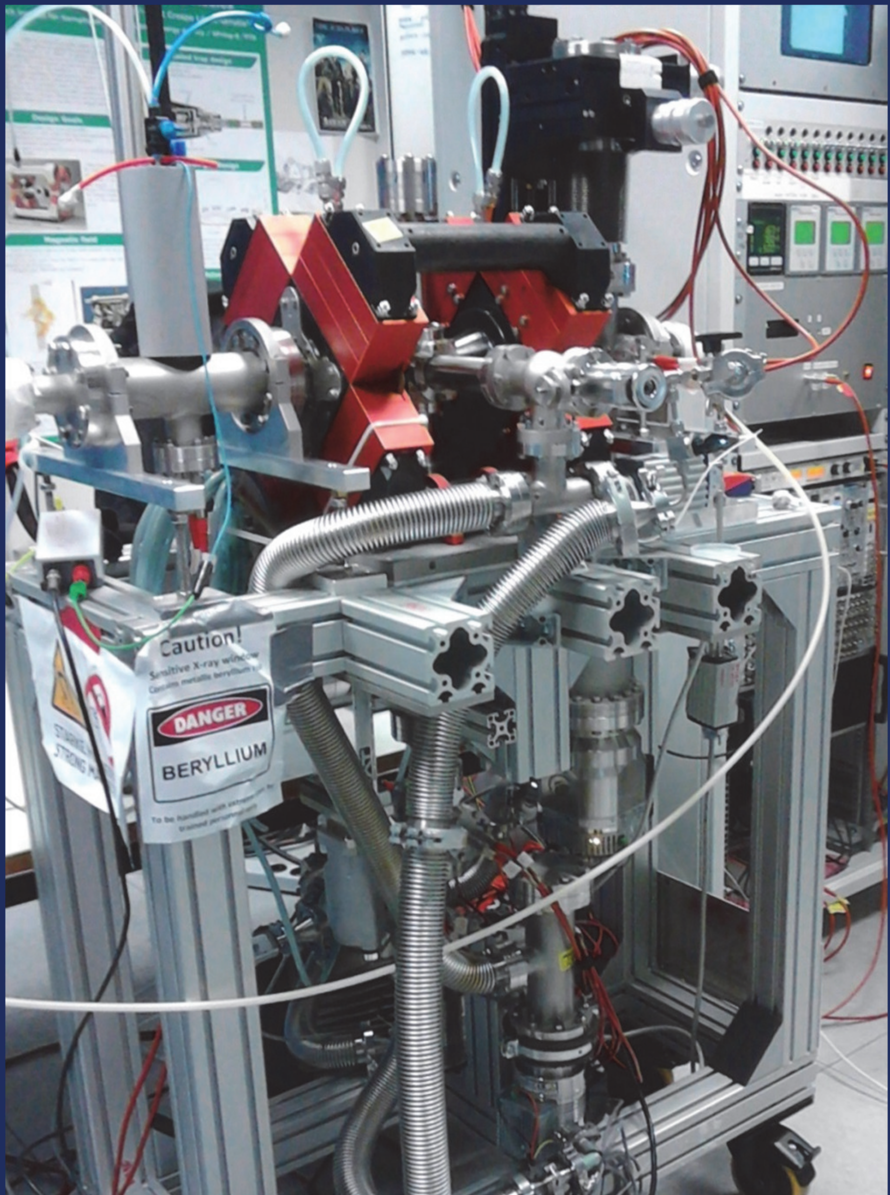


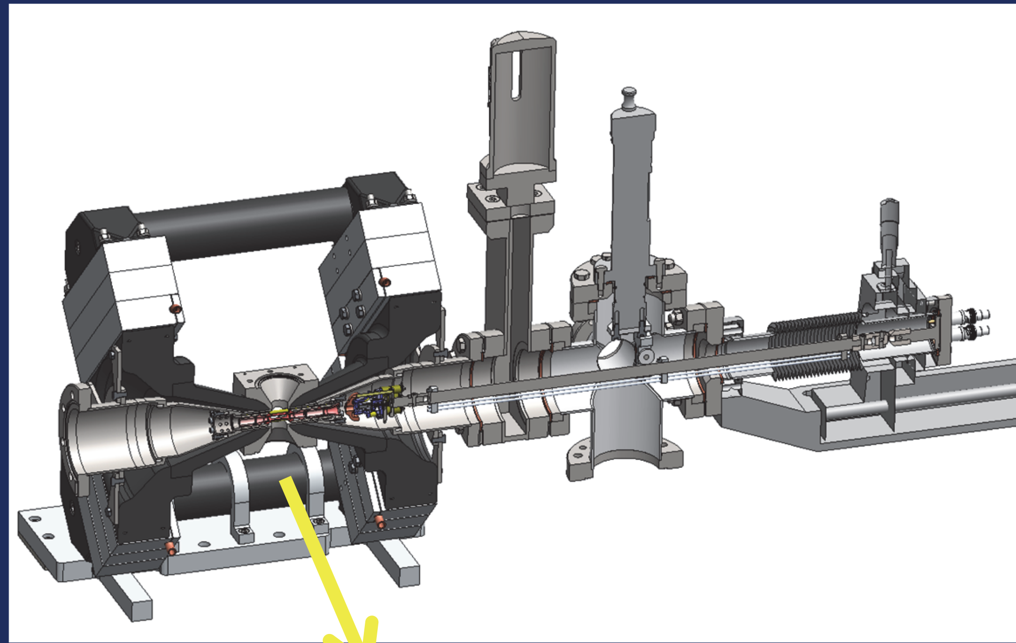
Next generation cryogenic trap

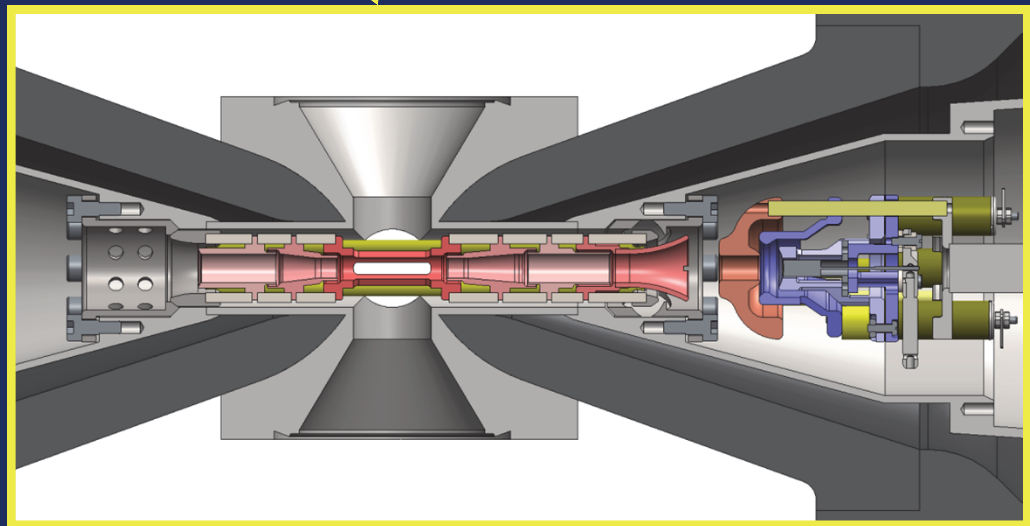


- Cryogenic, XUHV
- Ultra-low vibration
- Superconducting high-Q RF resonator

Table-top EBITs for PTB, Petra-III, Blaum division







Peter Micke et al., RSI (2018)

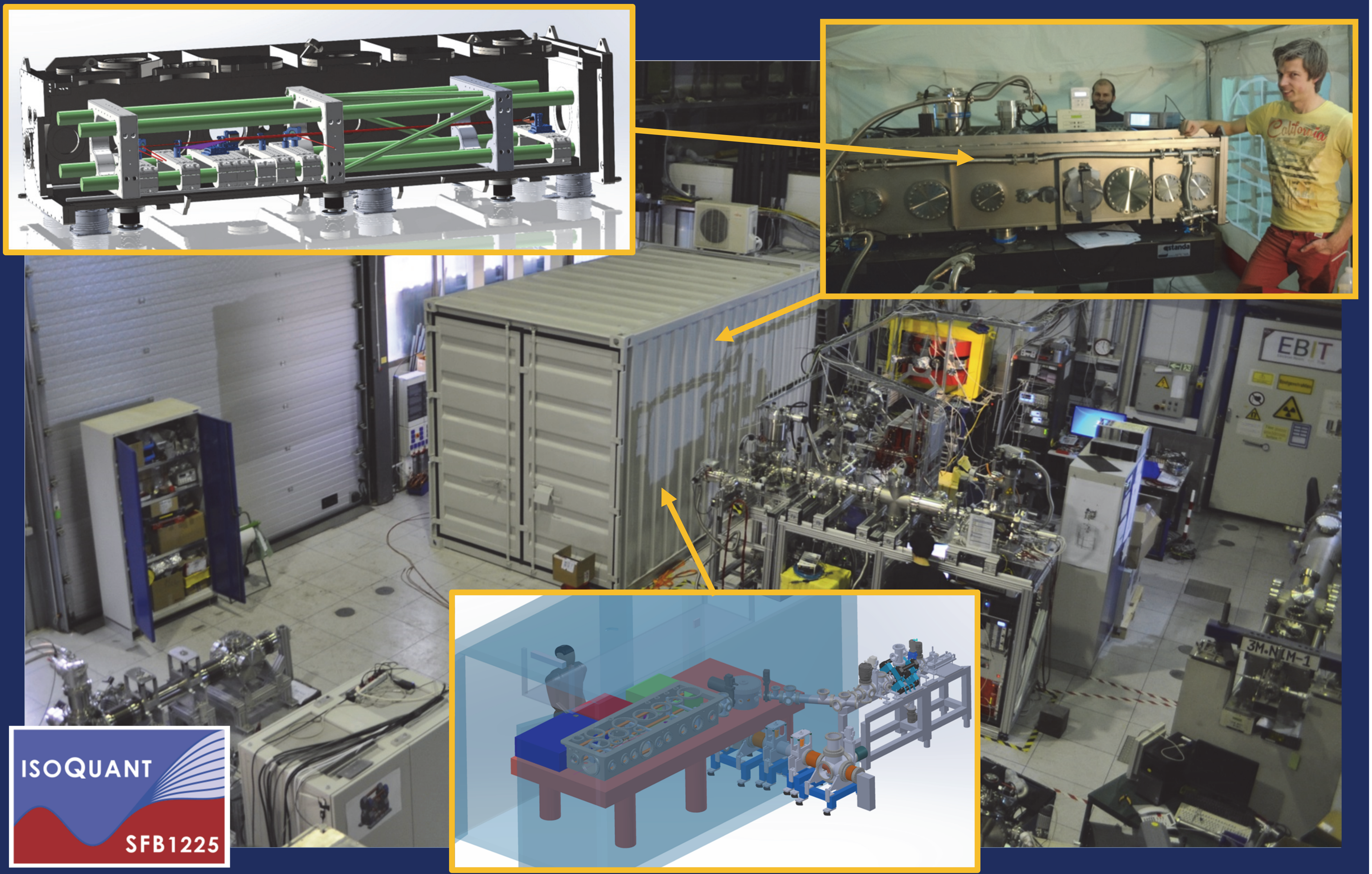
Possibilities through frequency metrology

- Whole new class of laser-accessible targets, with *Z* and ionic charge as parameters
- Great variety of optical and EUV lines from fine and hyperfine transitions up to the highest charge states
- Stable up to X-ray region
- Forbidden transitions suitable as frequency standards
- Low sensitivity to DC, AC Stark, Zeeman and blackbody shifts
- Highest sensitivity to fine-structure constant α in atomic systems

A laser high harmonic frequency comb in the VUV

Max-Planck-Institut für Kernphysik

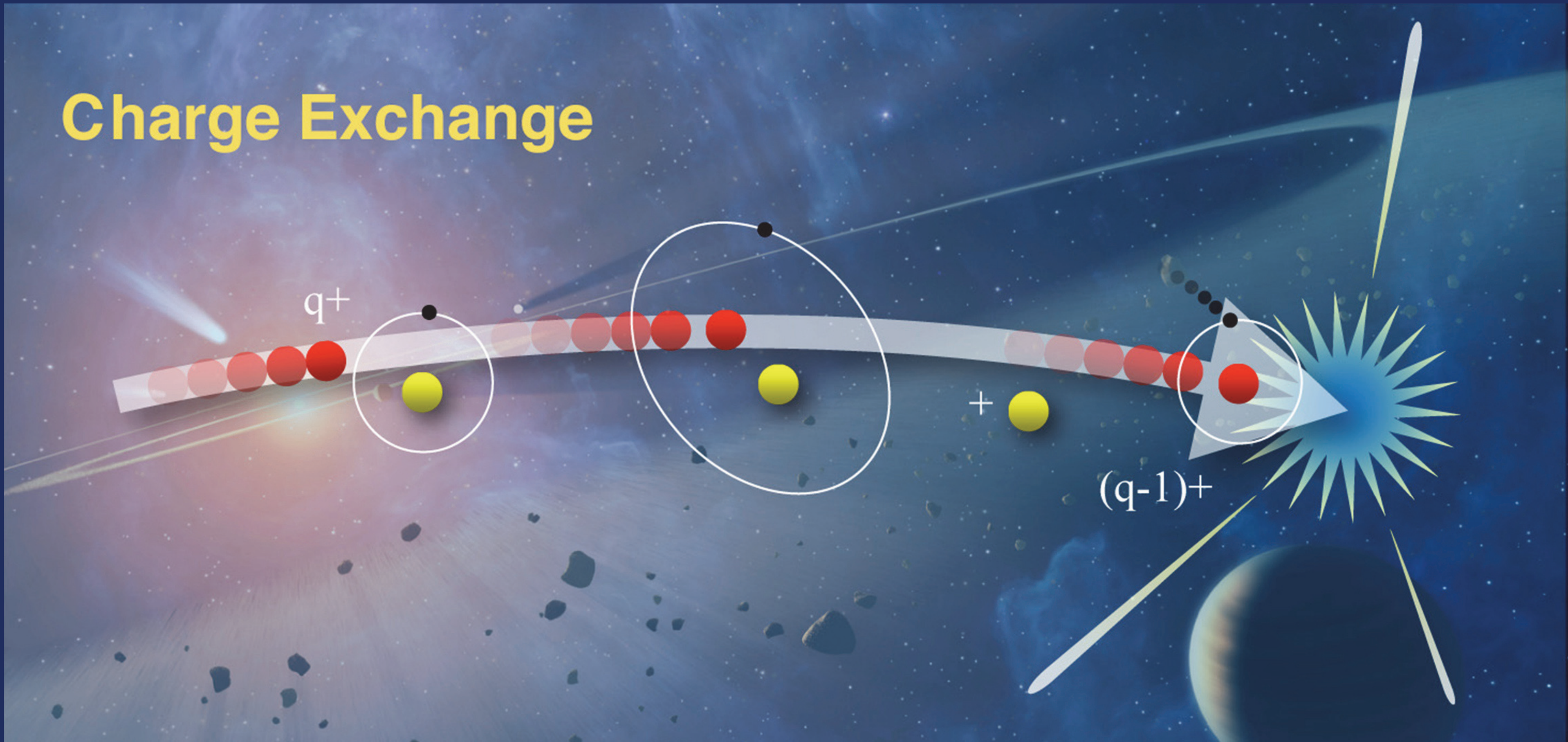
Temperature-controlled container for HHG-frequency comb



ISOQUANT SFB1225

Charge exchange studies with photon emission

Charge exchange from neutrals to HCI



Solar wind:

Beiersdorfer, P., Boyce, K. R., Brown, G. V., et al. 2003, Science, **300**, 1558 (2003)
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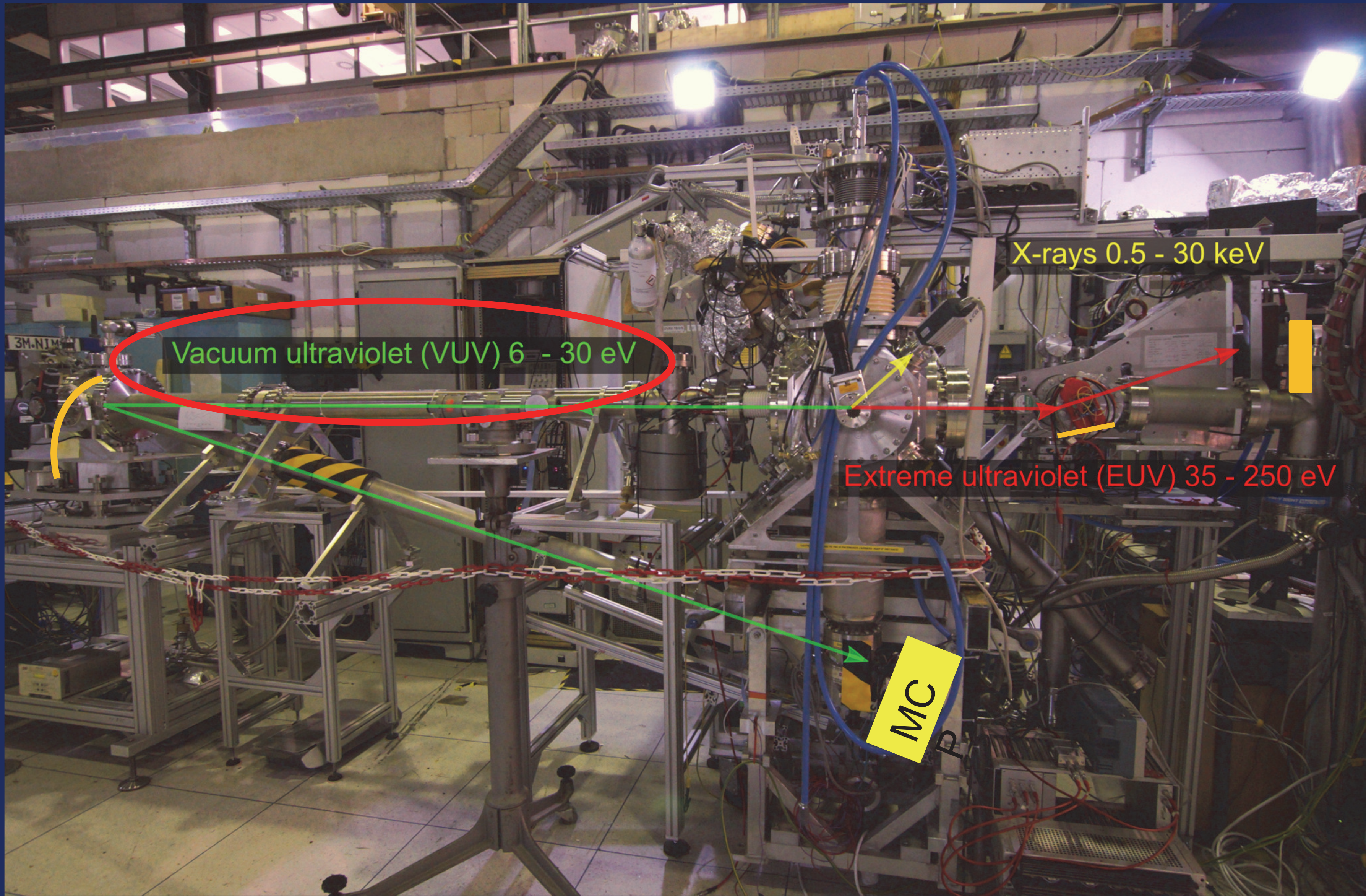
Charge exchange in the laboratory



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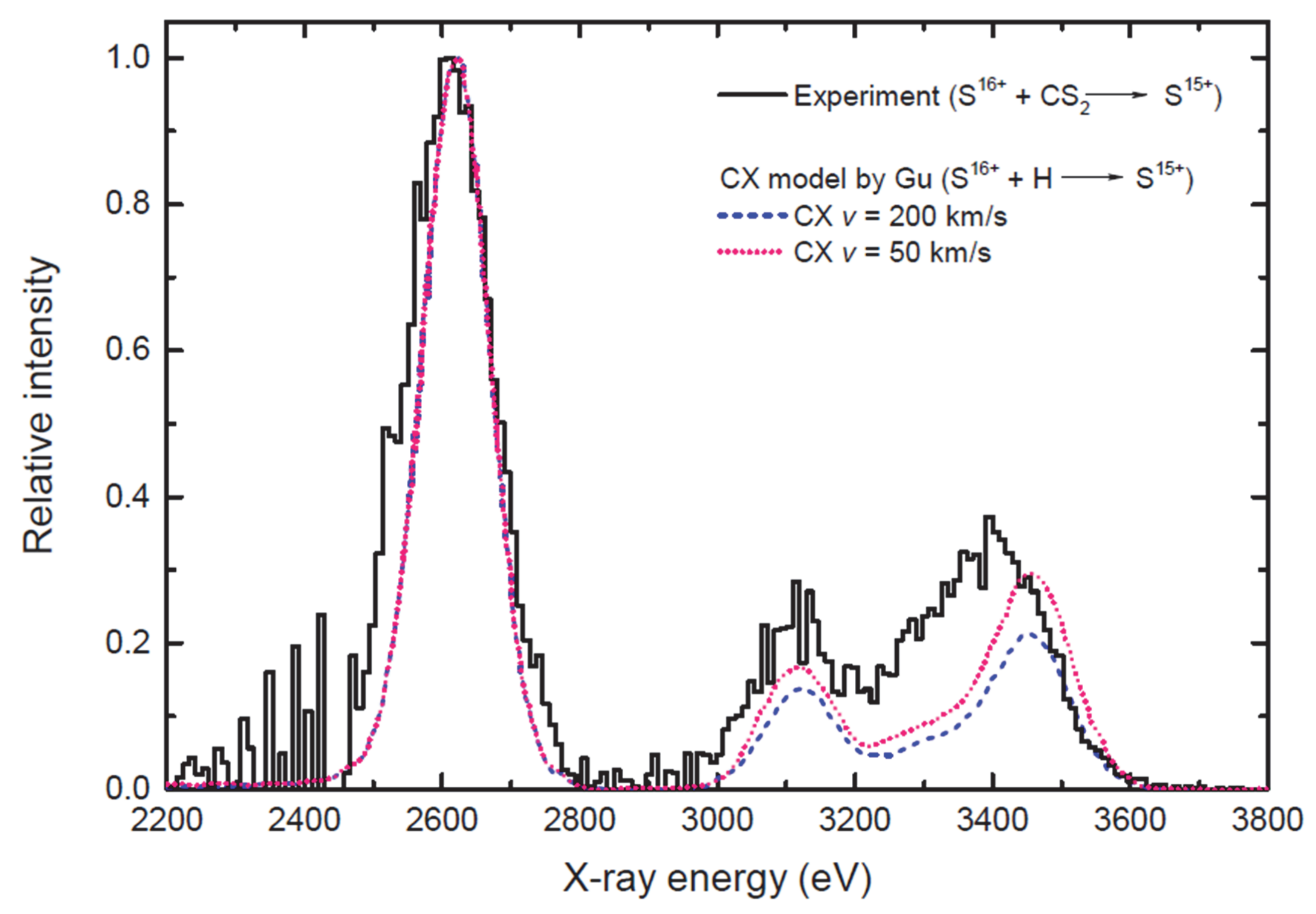
3.5 keV line (a.k.a. Dark Matter annihilation signal) is produced in the laboratory with recombining S^{16+} ions



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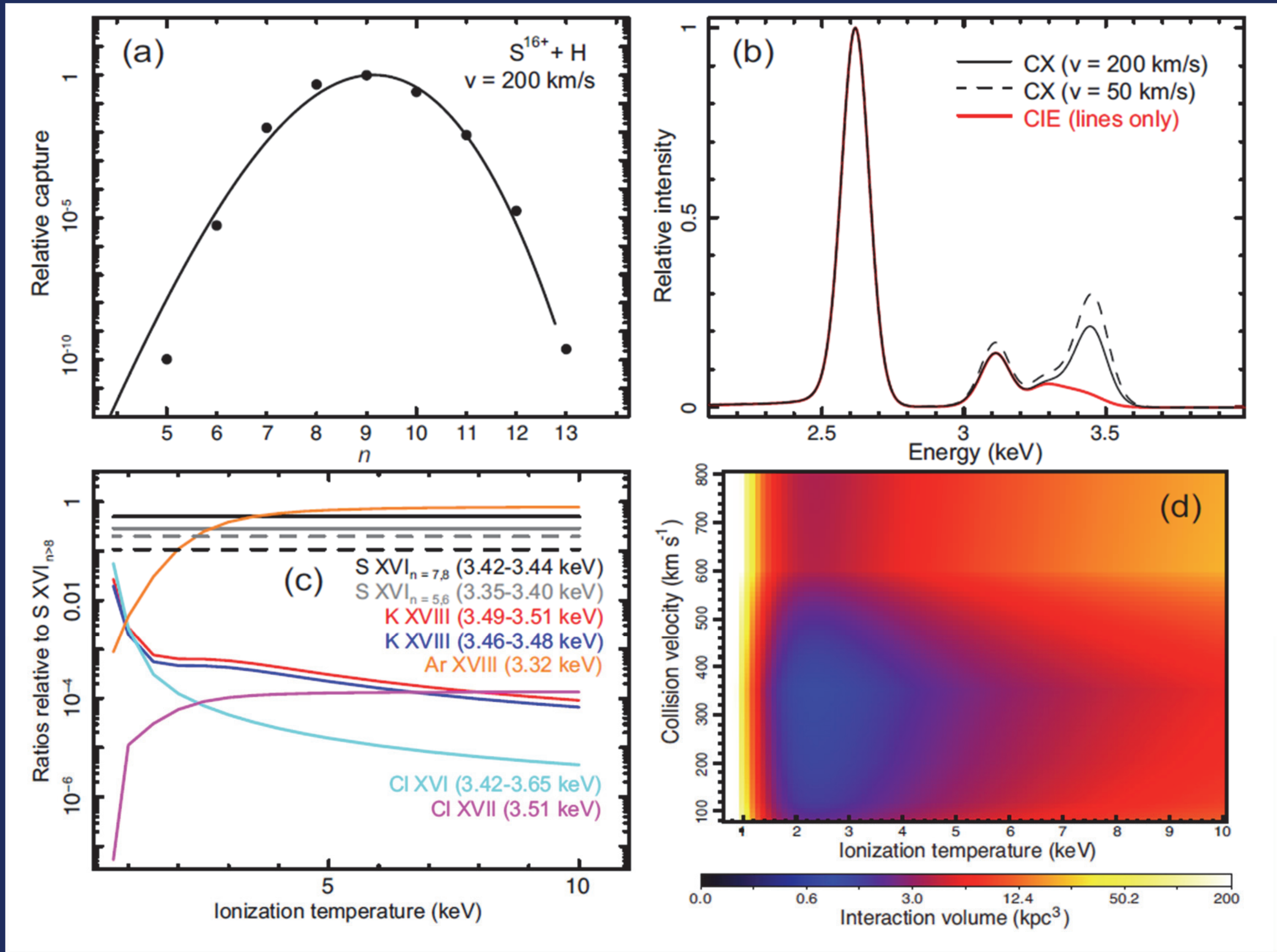

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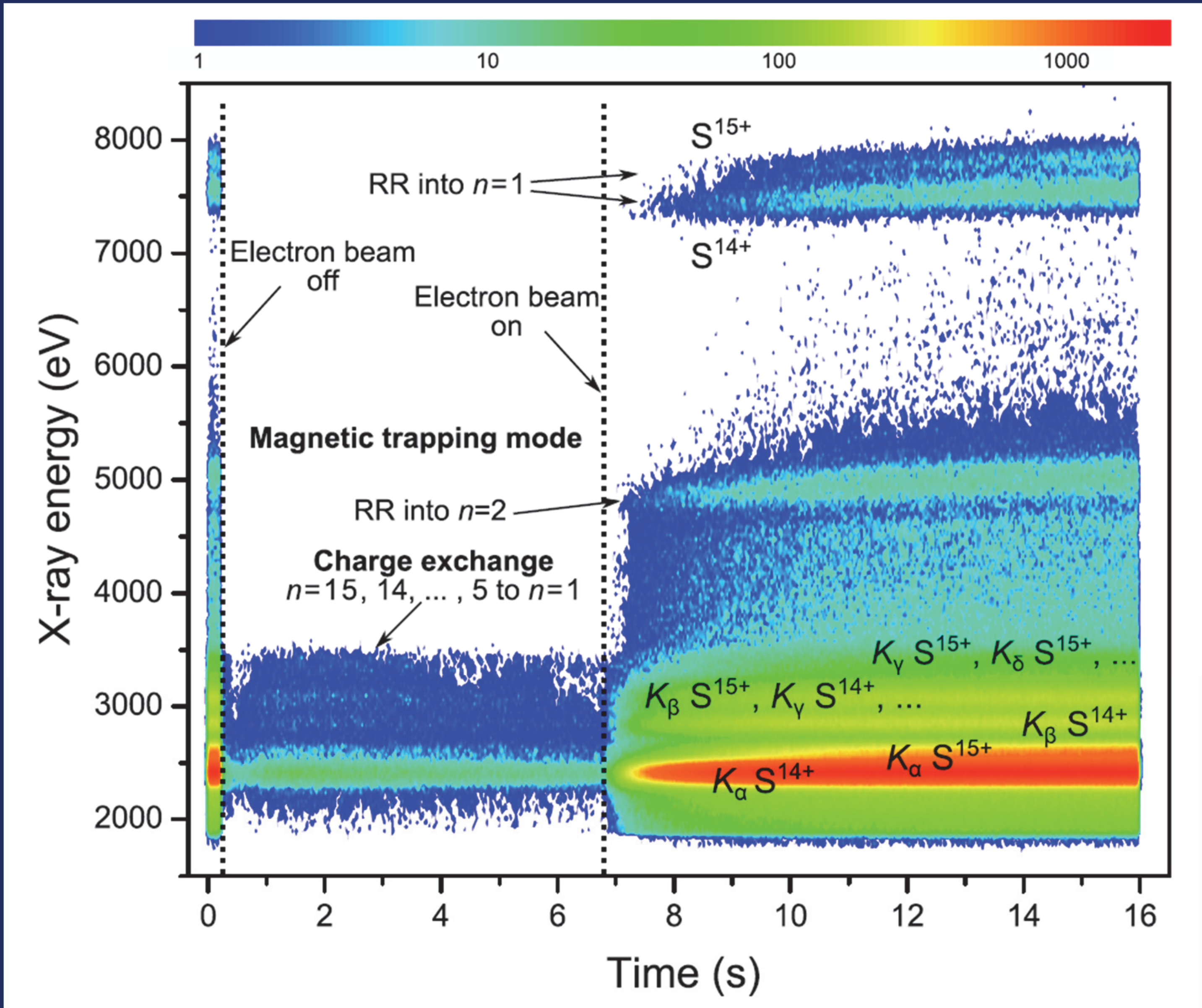

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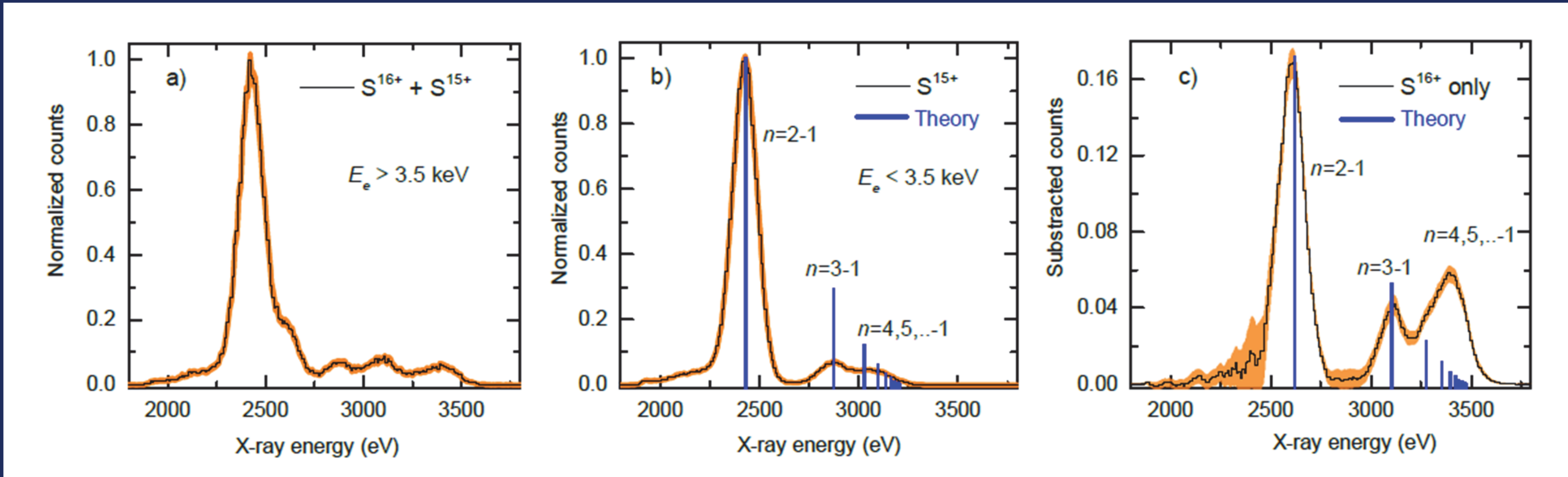

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Summary

- X-ray Lyman-α and He-like studies with ppm accuracy
- EUV, VUV studies with ppm accuracy
- Photoionization studies from N^{3+} to Fe^{23+}
- X-ray laser spectroscopy demonstrated:
  - $Fe^{15+...17+}$ resonance transitions at ~800 eV
  - Ly-series lines of F^{8+} and O^{7+} at ~800 eV
  - Fe Kα in $Fe^{21+...24+}$ ions excited at 6.7 keV
  - Kr^{34+}, Br^{33+} high-resolution studies up to 14 keV
  - Soft x-ray calibrations with $\Delta E \approx 20$ meV
- Oscillator strengths, line widths, cross sections determinations
- Charge exchange with photon emission
- VUV frequency comb in preparation
- Optical clock tests at PTB already running in collaboration

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