MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

Spectroscopy of Highly Charged Ions with Free Electron Lasers

Sascha Epp
MPI-K Heidelberg & ASG within CFEL Hamburg
@ PSAS 2008

People involved in this work

MPI-K

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Support by Max-Planck Gesellschaft: Advanced Study Group (ASG) at the Center for Free Electron Laser Physics (CFEL)

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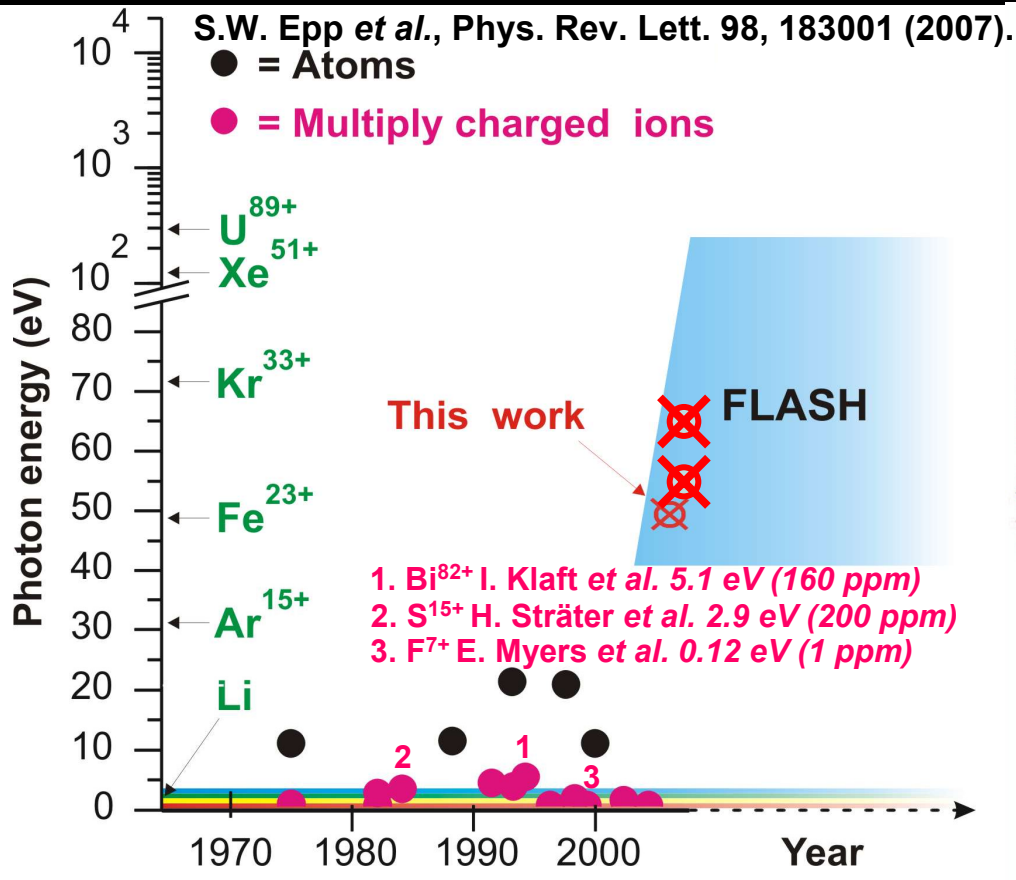
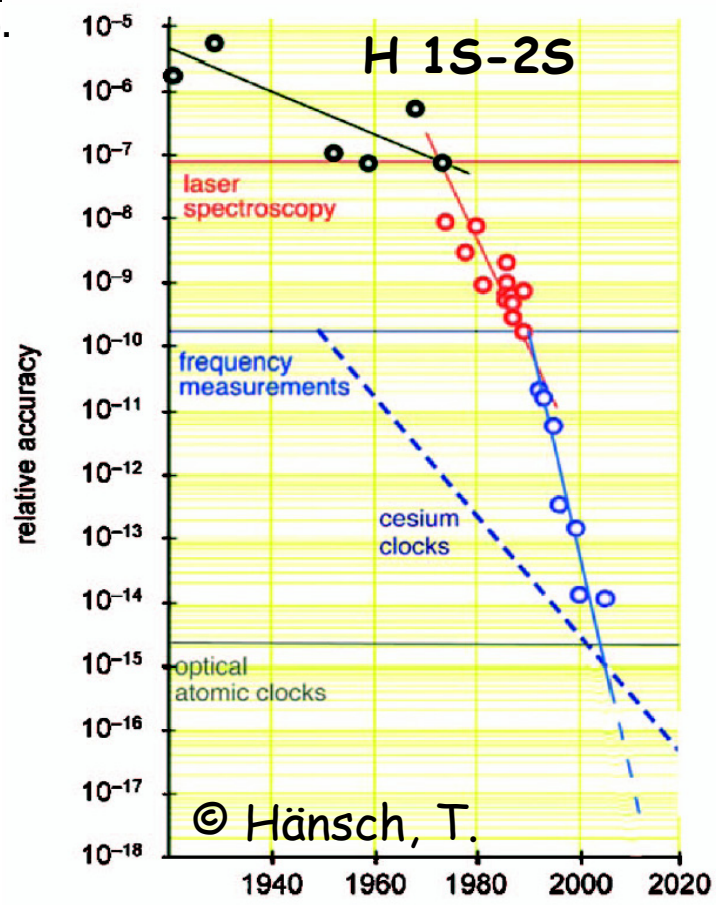
a. Motivation
- Laser spectroscopy -





- First demonstration of resonant laser spectroscopy (l. s.) of a bound transition in the soft x-ray regime.
- Extending l. s. to a new class of targets — ground state transitions in Highly Charged Ions (HCI) — where most transitions lay in the (soft) x-ray regime.

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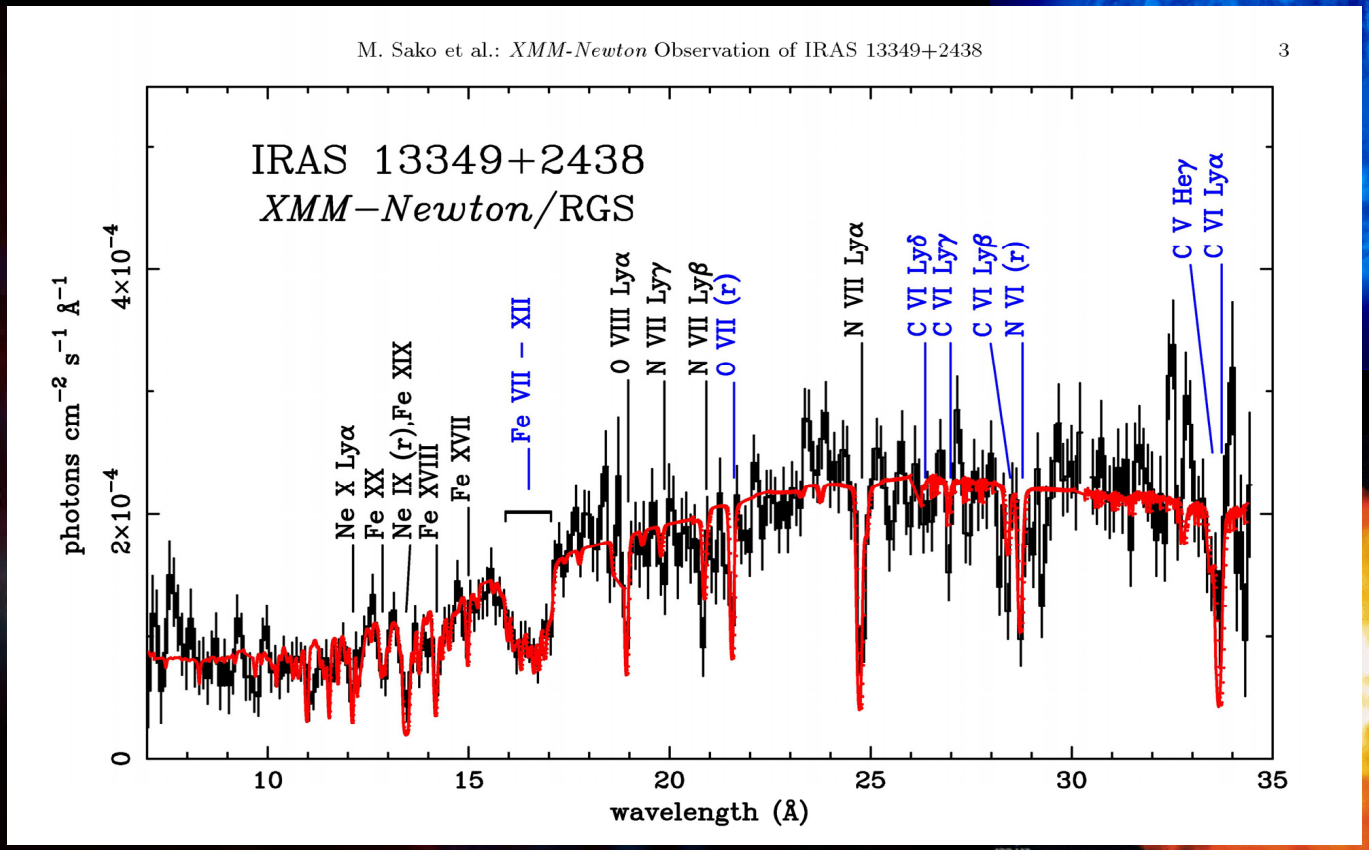
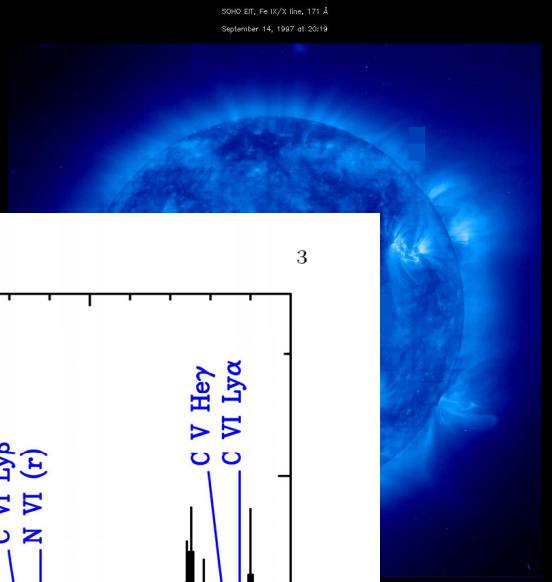
a. Motivation
- Astrophysics -

HCIs constitute a dominant fraction of the visible matter in the universe !





Active Galactic Nuclei

Comets

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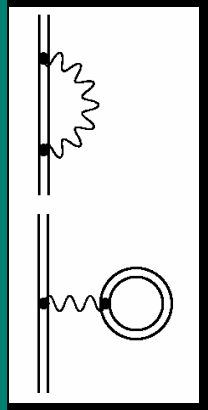
MAX-PLANCK-GESELLSCHAFT

a. Motivation

- Atomic structure theory -

Relativistic corrections (Dirac)

$\propto Z^4$



QED corrections

$\propto Z^4$

Electron correlations

$\propto Z^{-1}$

- Corrections are boosted in HCIs compared to neutral systems.
  → scaling laws
- Electron correlations are suppressed.

HCIs are an ideal testing ground for theory.

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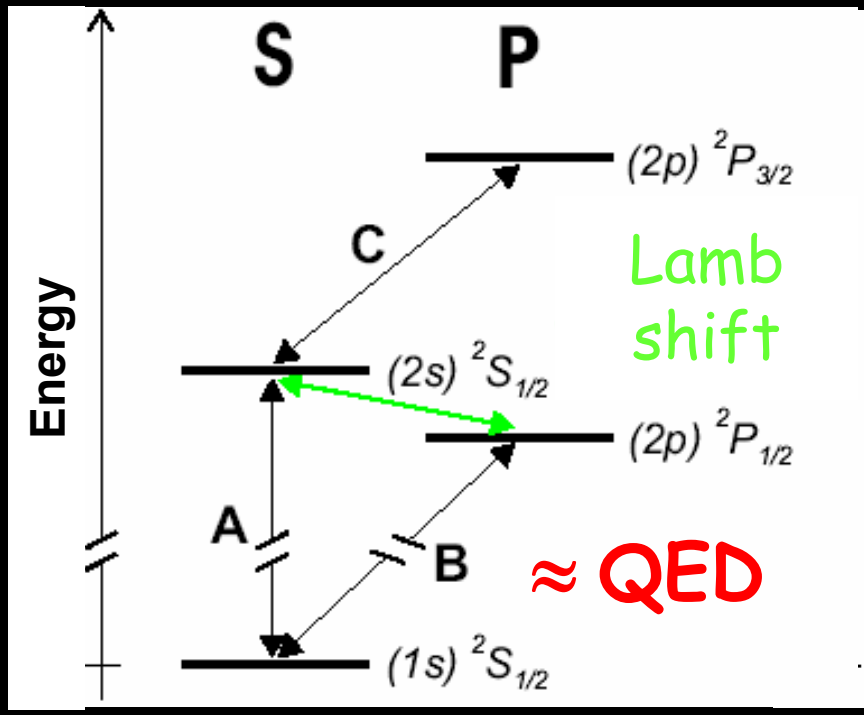
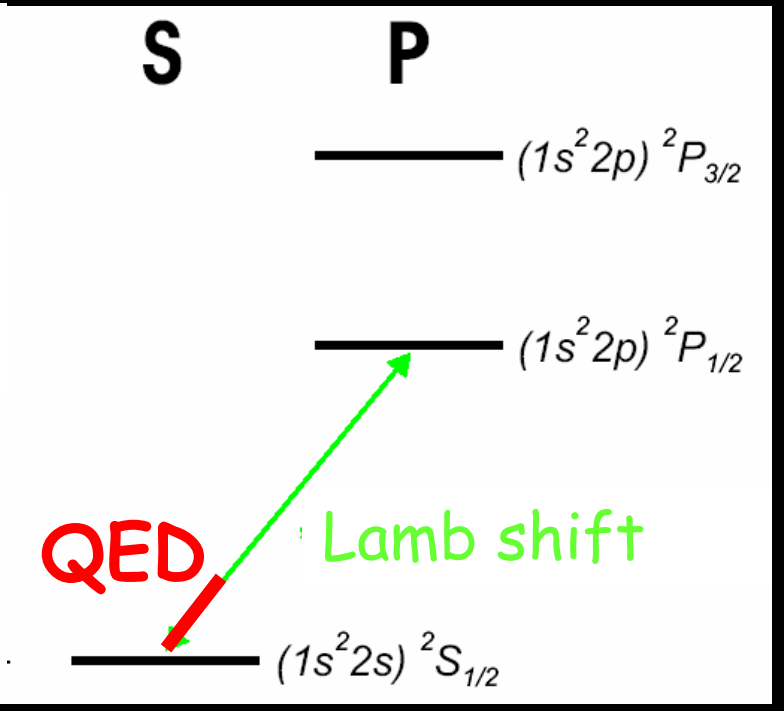
a. Motivation

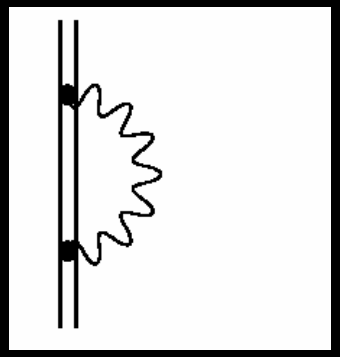
- Atomic structure theory -

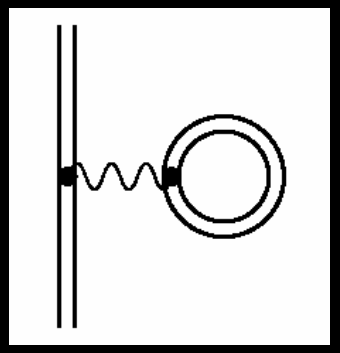
H-like



Li-like







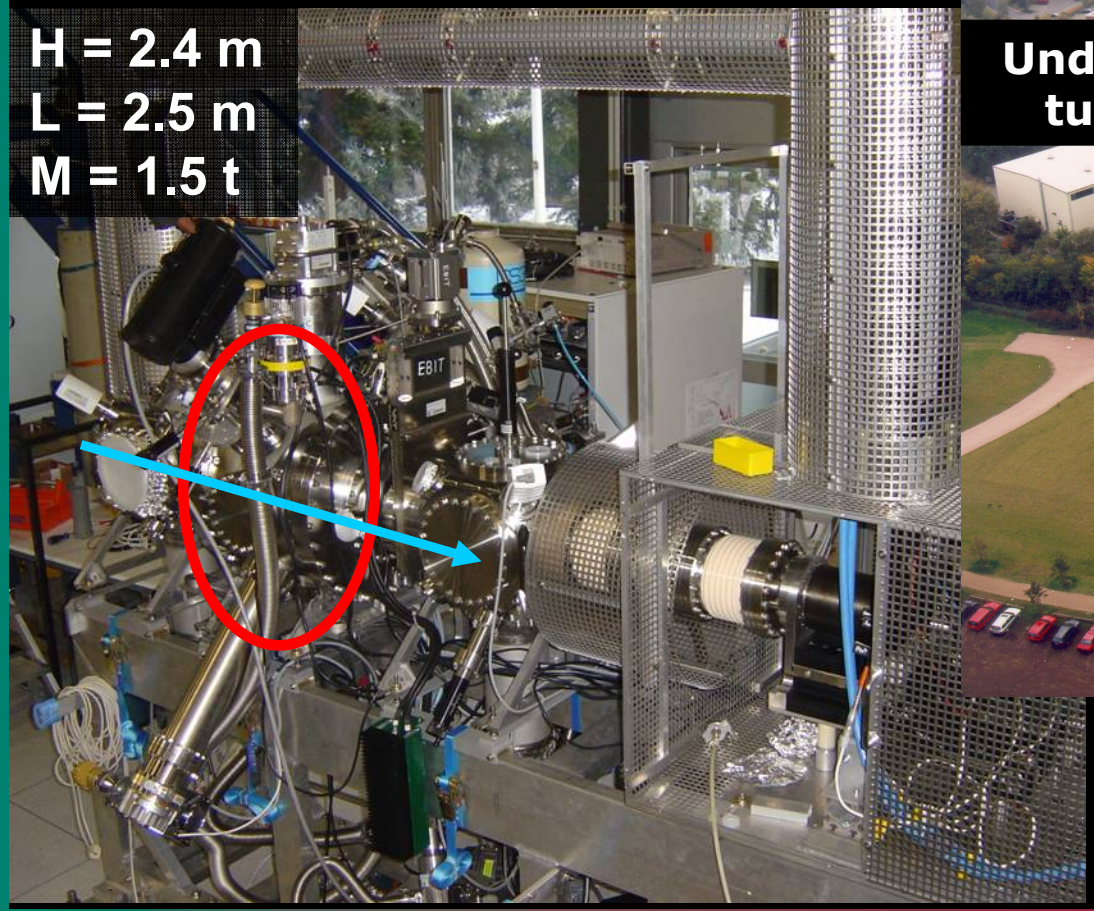
QED contributions

Li:	0.002% of 1.85 eV
Fe^{23+}:	1% of 48.6 eV
U^{89+}:	15% of 280 eV

β. Experimental setup

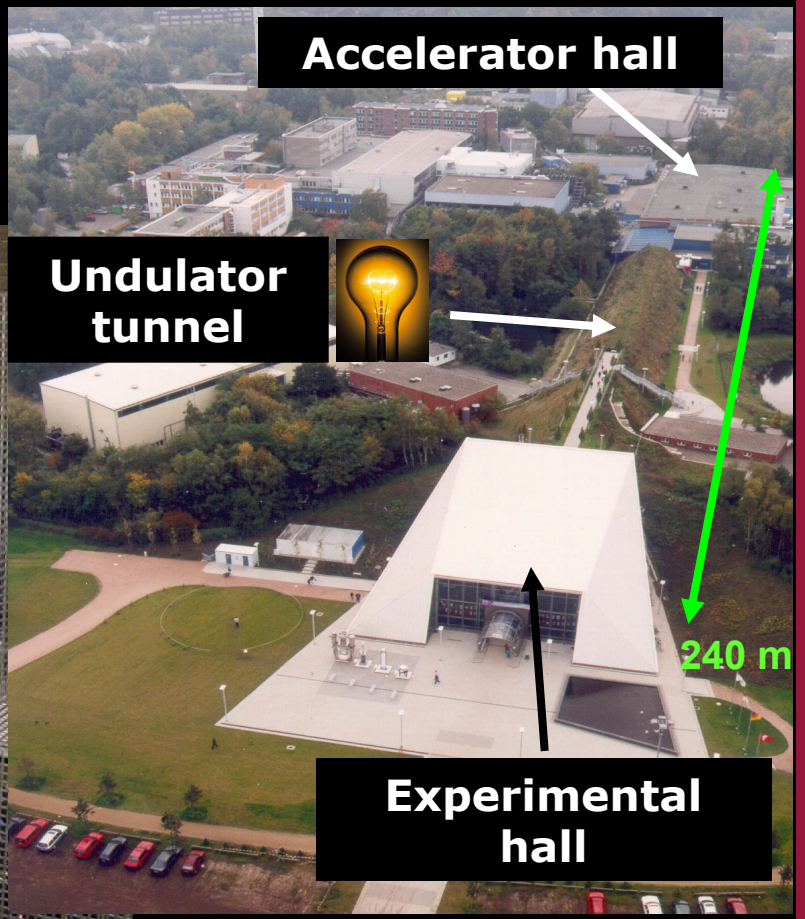
FLASH-EBIT

(electron beam ion trap)



FLASH

(Free electron LASer in Hamburg)



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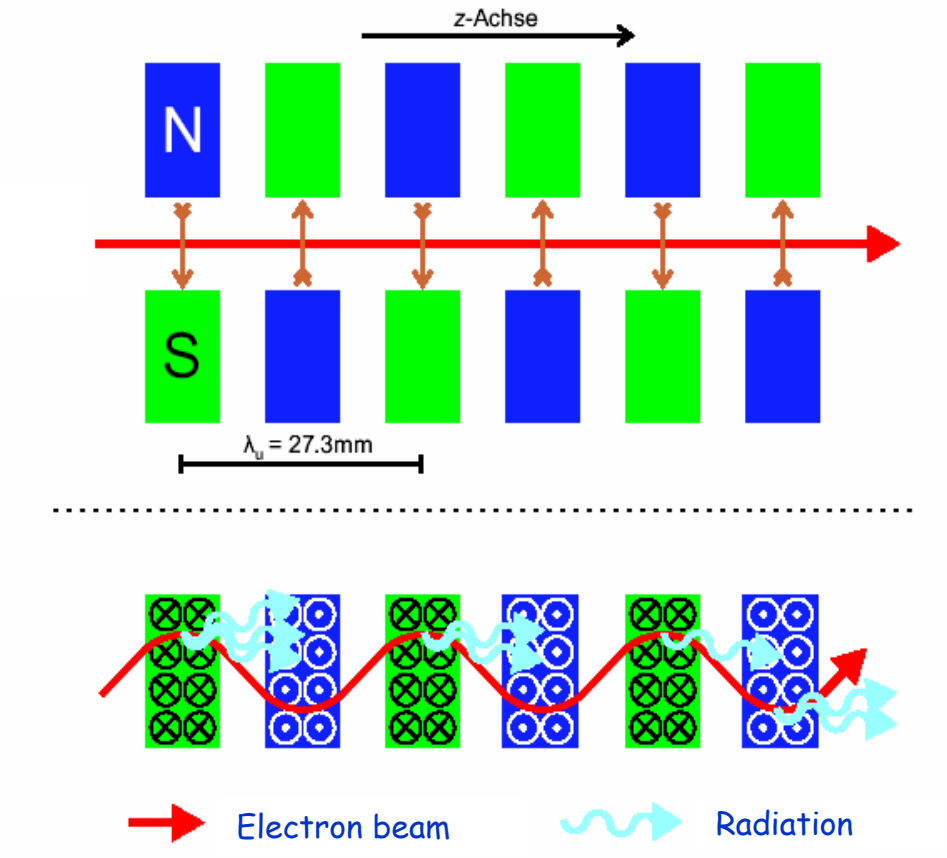
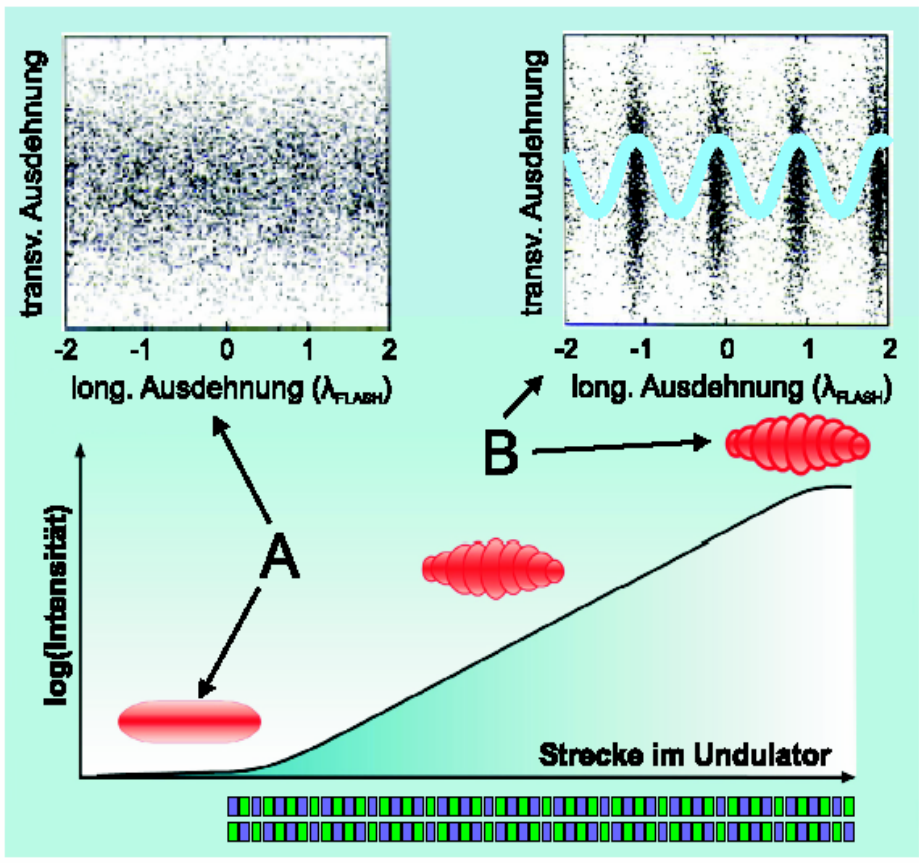
β. Experimental setup
- FEL principle -

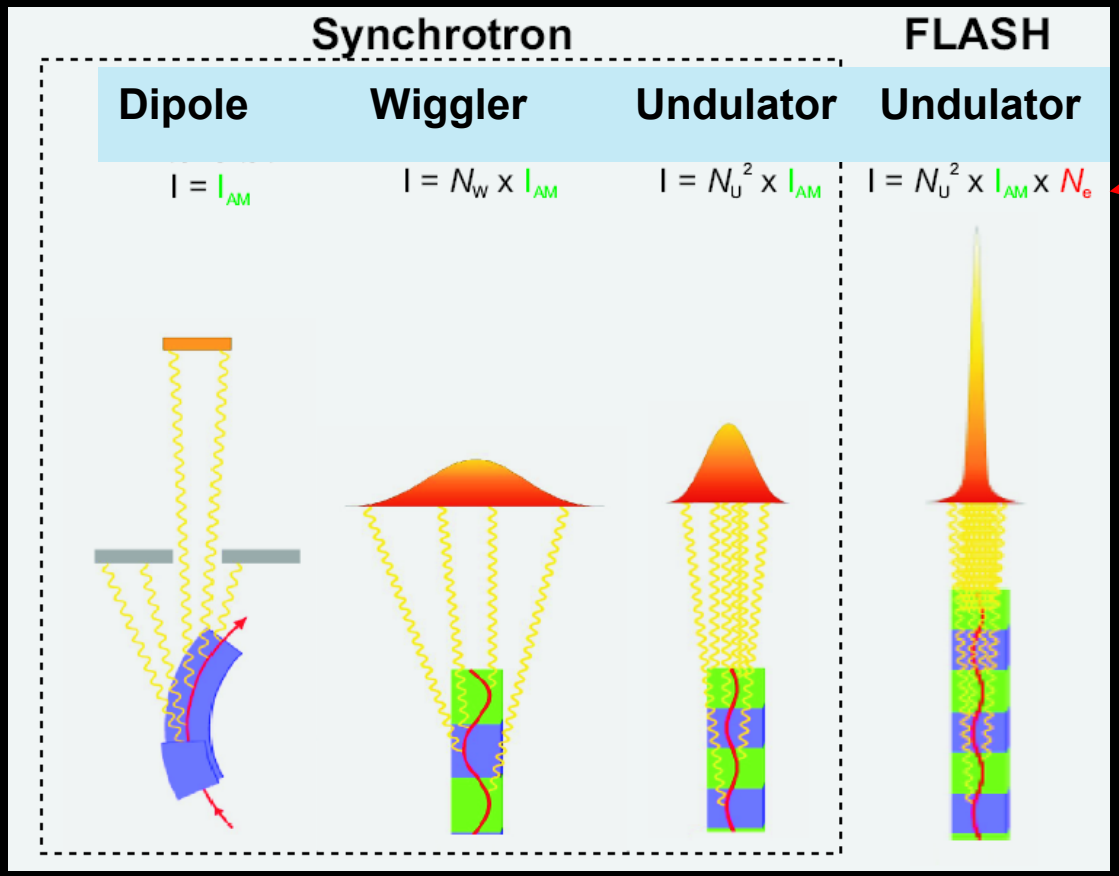
Radiation field interacts with electron bunch and structures it





β. Experimental setup
- FEL principle -

Coherent superposition enhances intensity by a factor proportional to the number of charges in the bunch N_e



Brilliance increases by many orders of magnitude

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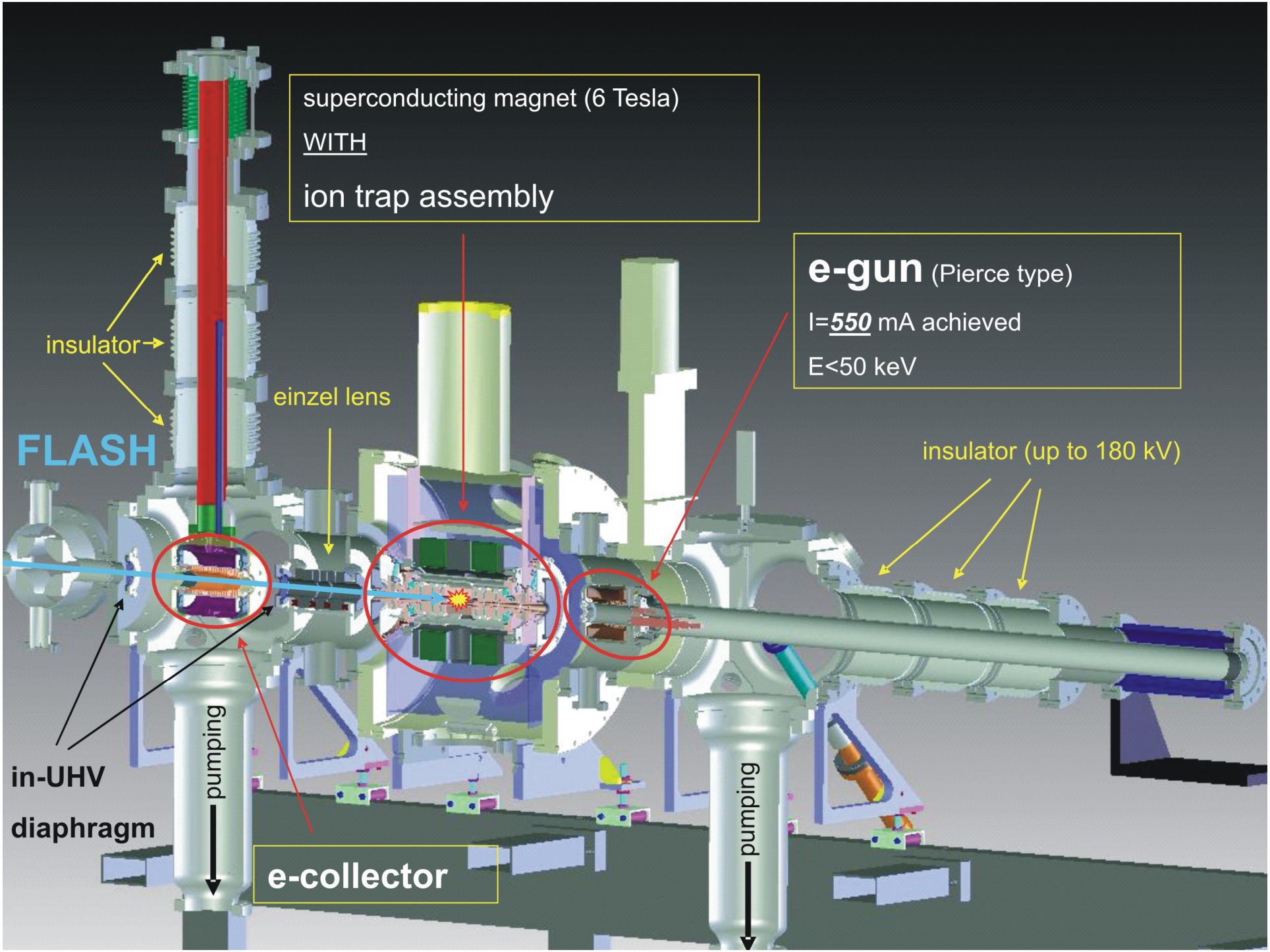
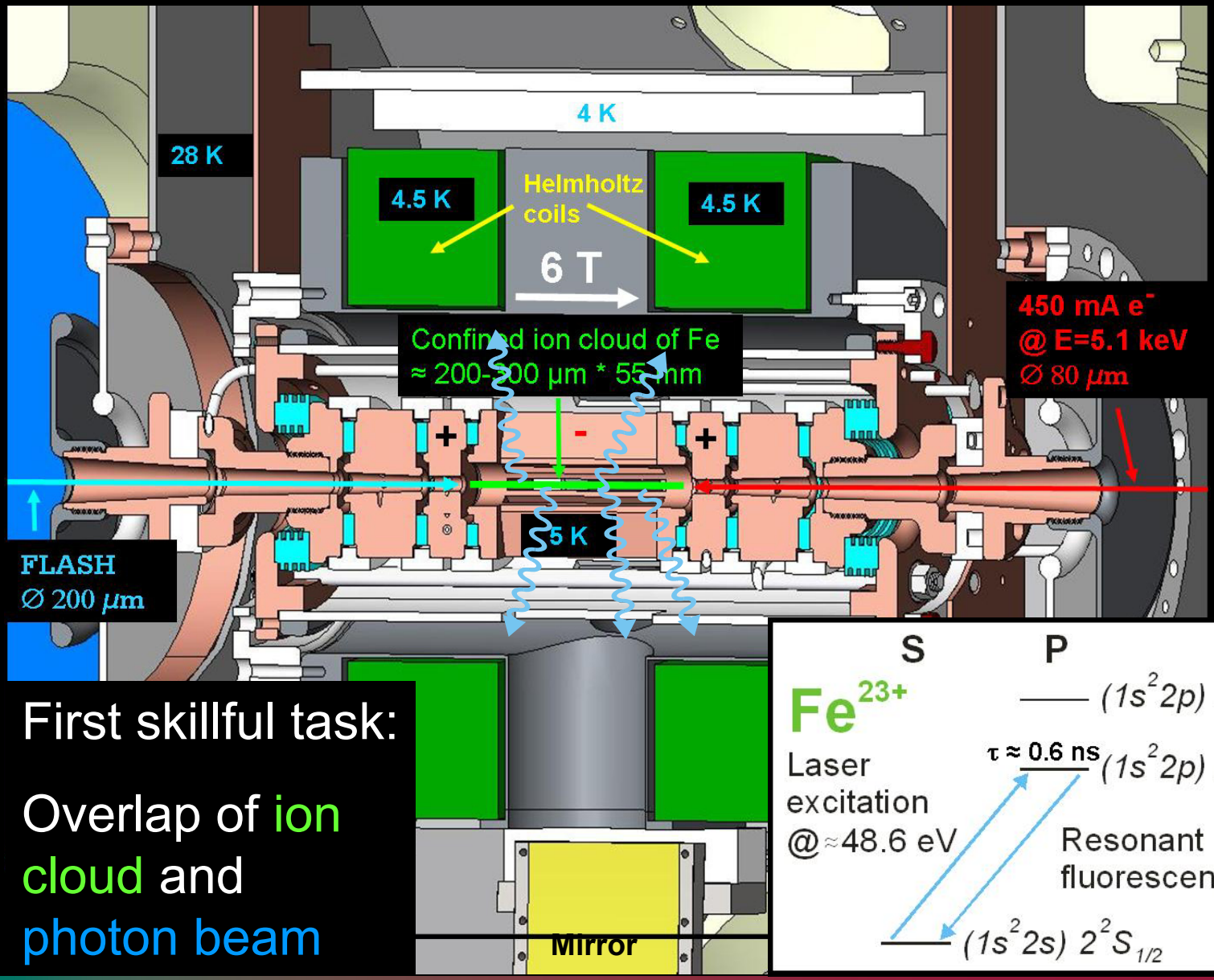

superconducting magnet (6 Tesla)
WITH
ion trap assembly
e-gun (Pierce type)
I=550 mA achieved
E<50 keV
insulator
einzel lens
FLASH
insulator (up to 180 kV)
in-UHV
diaphragm
pumping
pumping
e-collector

β. Experimental setup
- FLASH-EBIT -



First skillful task:

Overlap of ion cloud and photon beam

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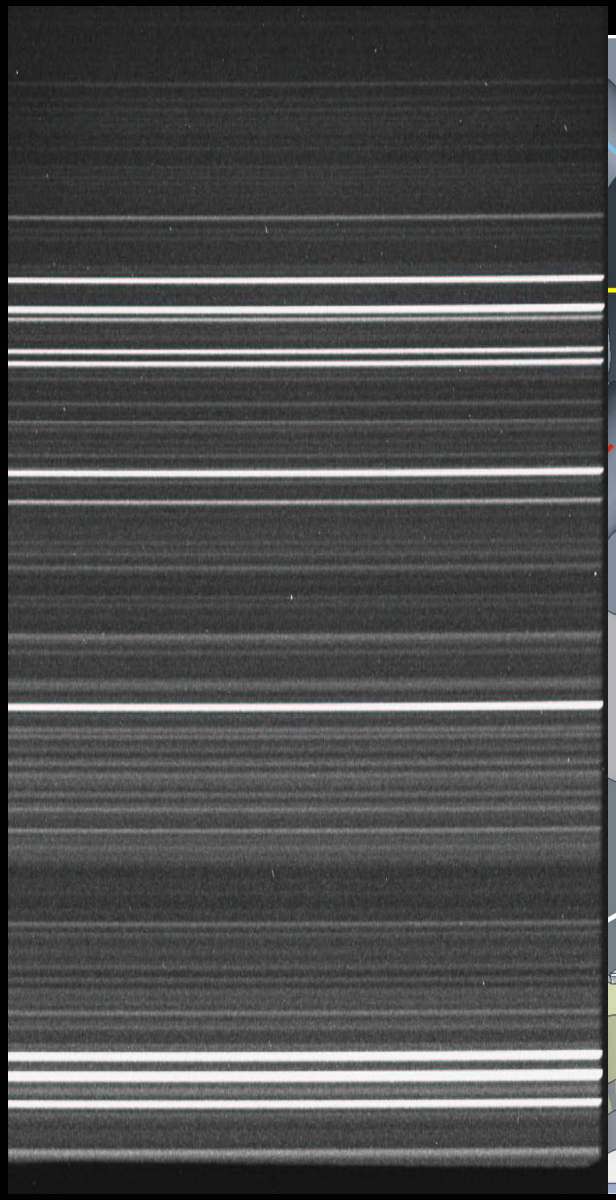
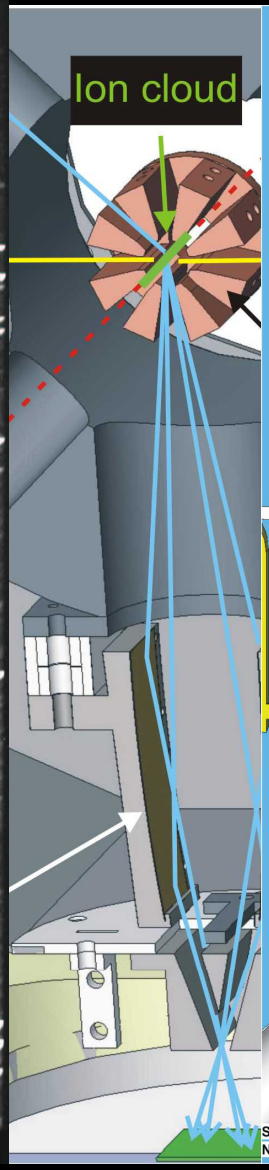
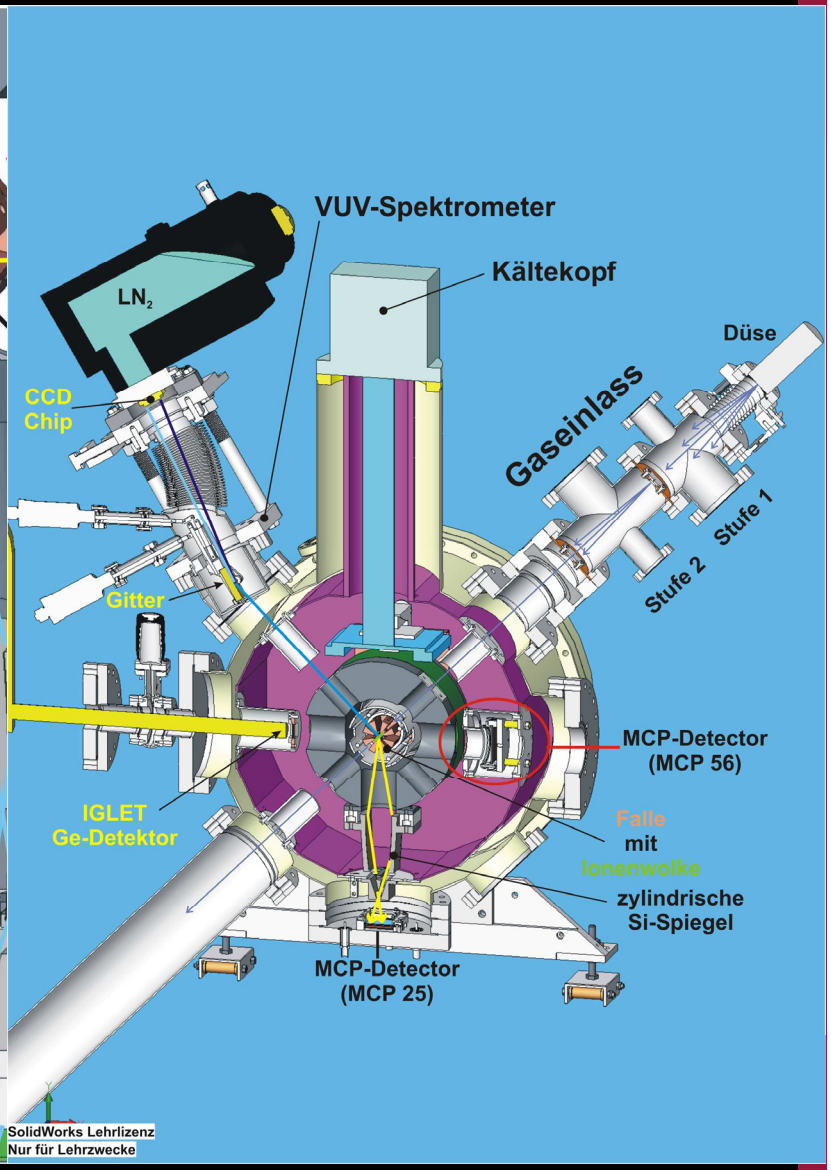
β. Experimental setup
- FLASH-EBIT -







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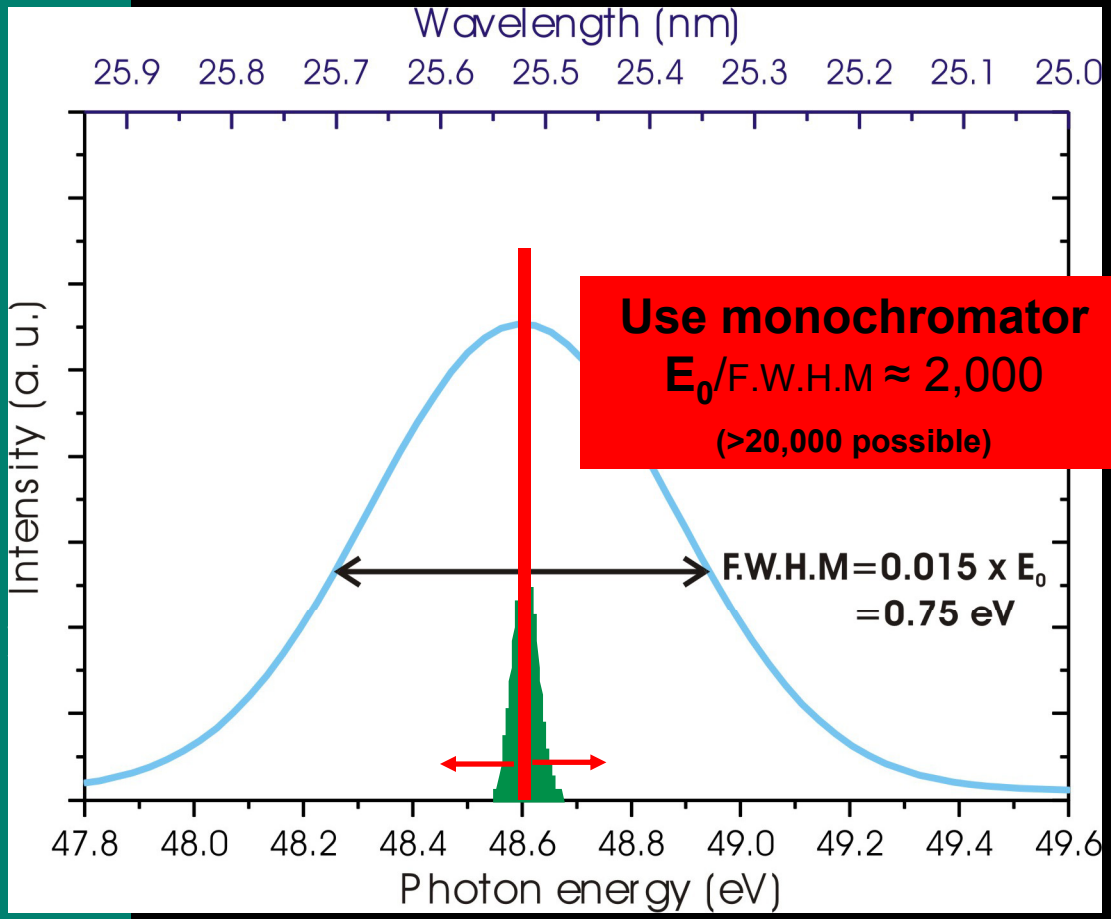
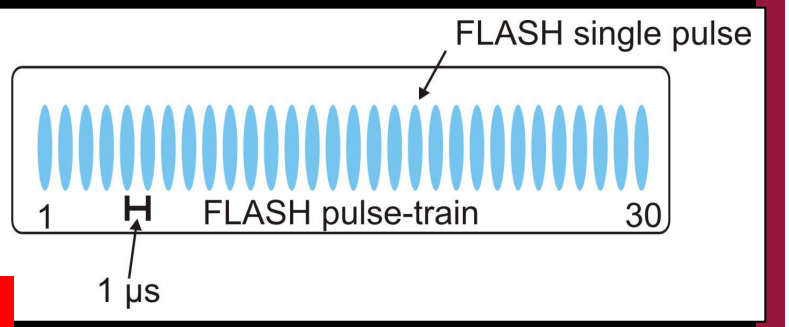
γ.Experiment & Results
- Laser spectroscopy -

FLASH: Ava. spectral distribution



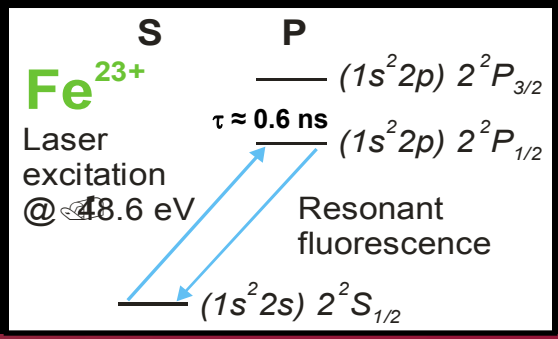
Use monochromator
E_0/F.W.H.M ≈ 2,000
(>20,000 possible)

FLASH: Repetition structure



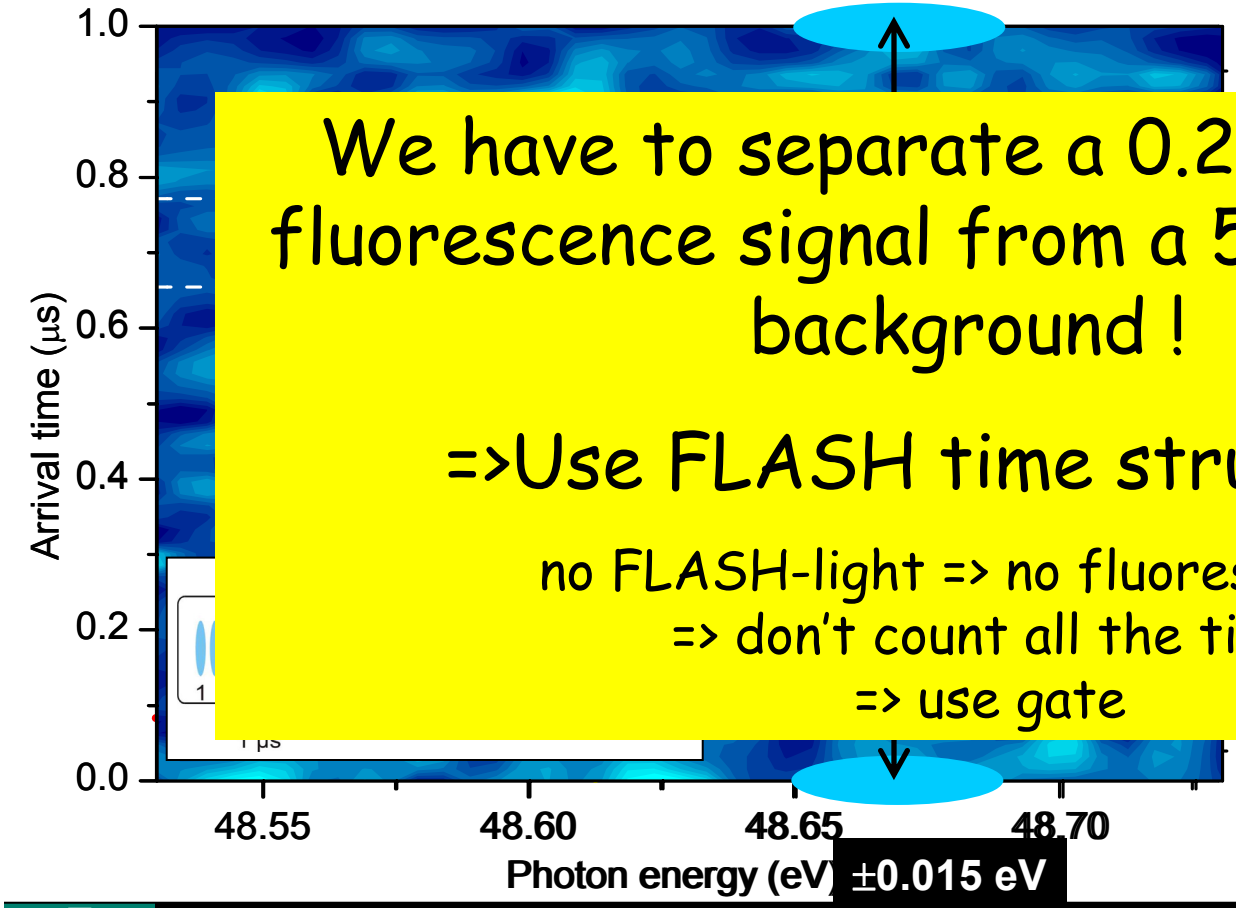
- 5 Hz repetition rate
  =>150 single pulses/s
- Average power†:
  up to 10 mW (laser pointer 4 mW)

†at time of experiment



γ.Experiment & Results
- Results 2007 (1st run) -

Fe^{23+} $2^2S_{1/2}$-$2^2P_{1/2}$



- 33 minutes acquisition time
- different colour

counts

5σ with
on

750 ppm)

011) eV

$\delta = \frac{}{48.6127} - 23$ ppm

We have to separate a 0.2 cts/s true fluorescence signal from a 50 000 cts/s background !

=>Use FLASH time structure !

no FLASH-light => no fluorescence
=> don't count all the time
=> use gate

Systematic shift due preliminary calibration of monochromator unit !

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

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γ. Experiment & Results

- Calibration parenthesis -

How much is e.g. 48.0001 eV?

- equivalent to 11606.375 THz
- defined by the second:

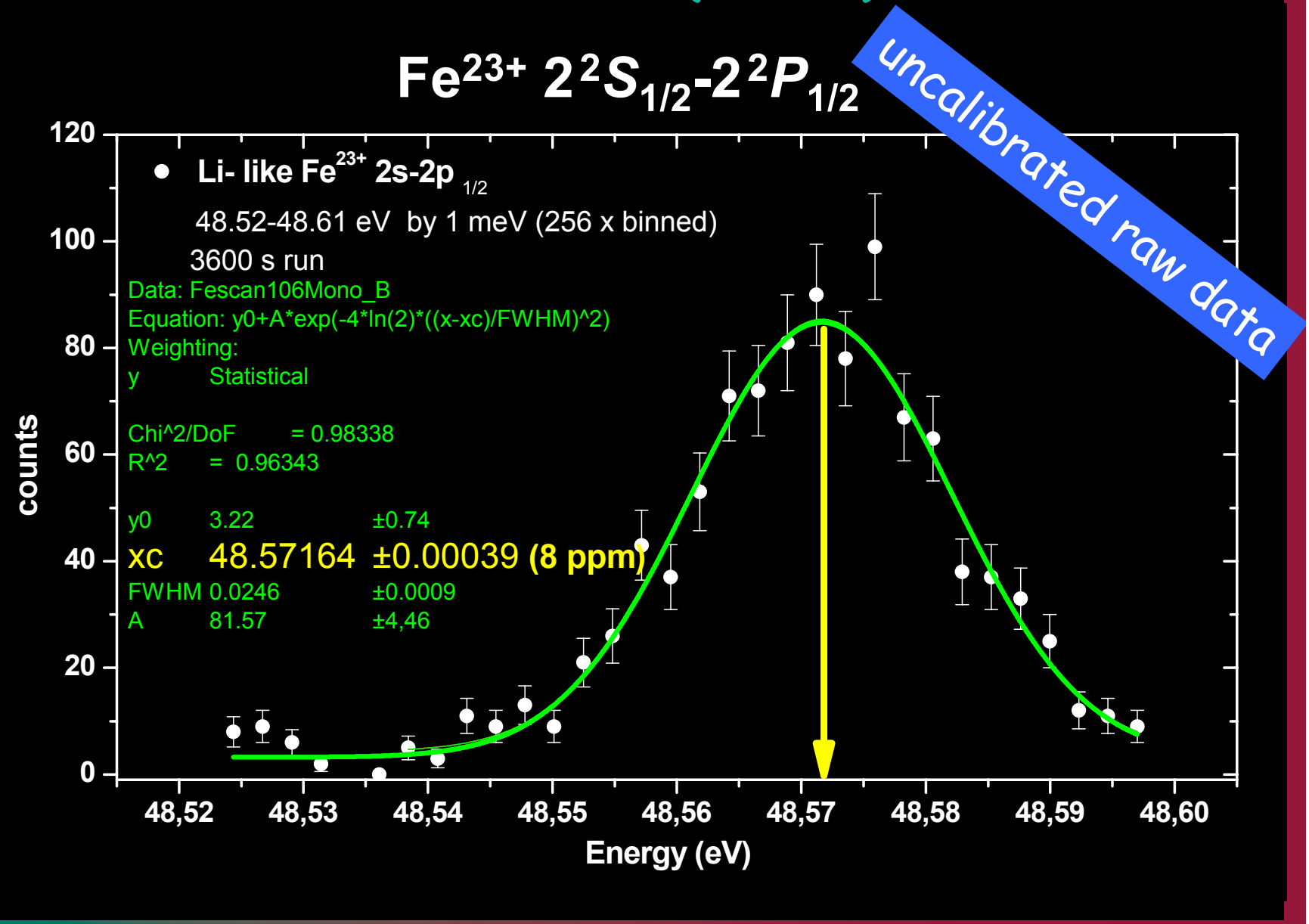
"The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom."

- no frequency chain goes into the deep VUV, soft x-ray range
- frequency comb recently extended to 60 nm (20.7 eV)

A. Ozawa *et. al.* PRL **100** (2008)

- calibration is a challenging task !
- photo-ionization resonances of noble gases
- desirable: highly accurate theoretical data of light hydrogen- and helium-like ions. (B, C, N, O, F)
  => wavelength standard in the soft x-ray

γ.Experiment & Results
- Results 2008 (2nd run) -



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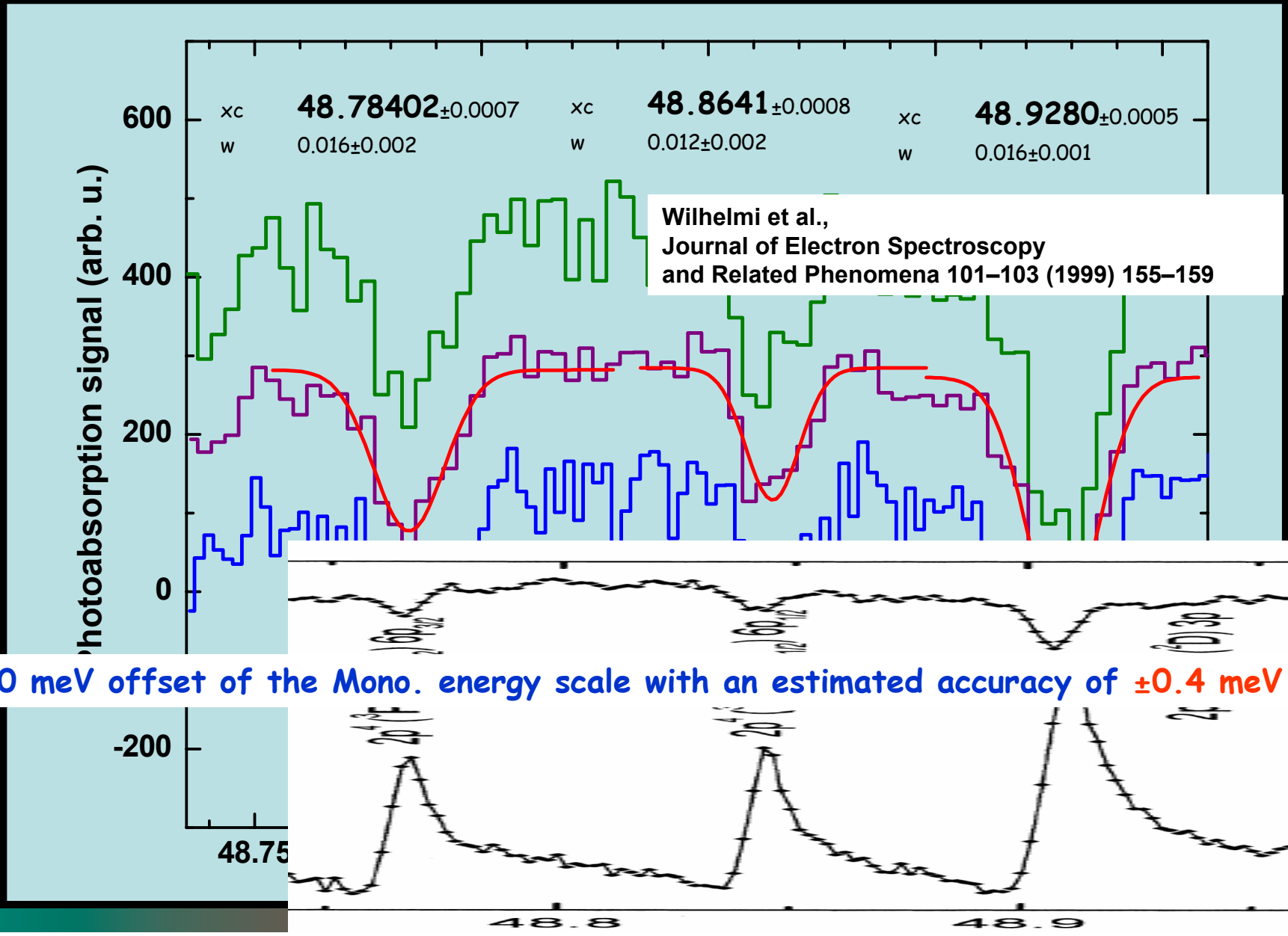
γ. Experiment & Results
- Neon Calibration -



Wilhelmi et al.,
Journal of Electron Spectroscopy
and Related Phenomena 101–103 (1999) 155–159

20 meV offset of the Mono. energy scale with an estimated accuracy of ±0.4 meV

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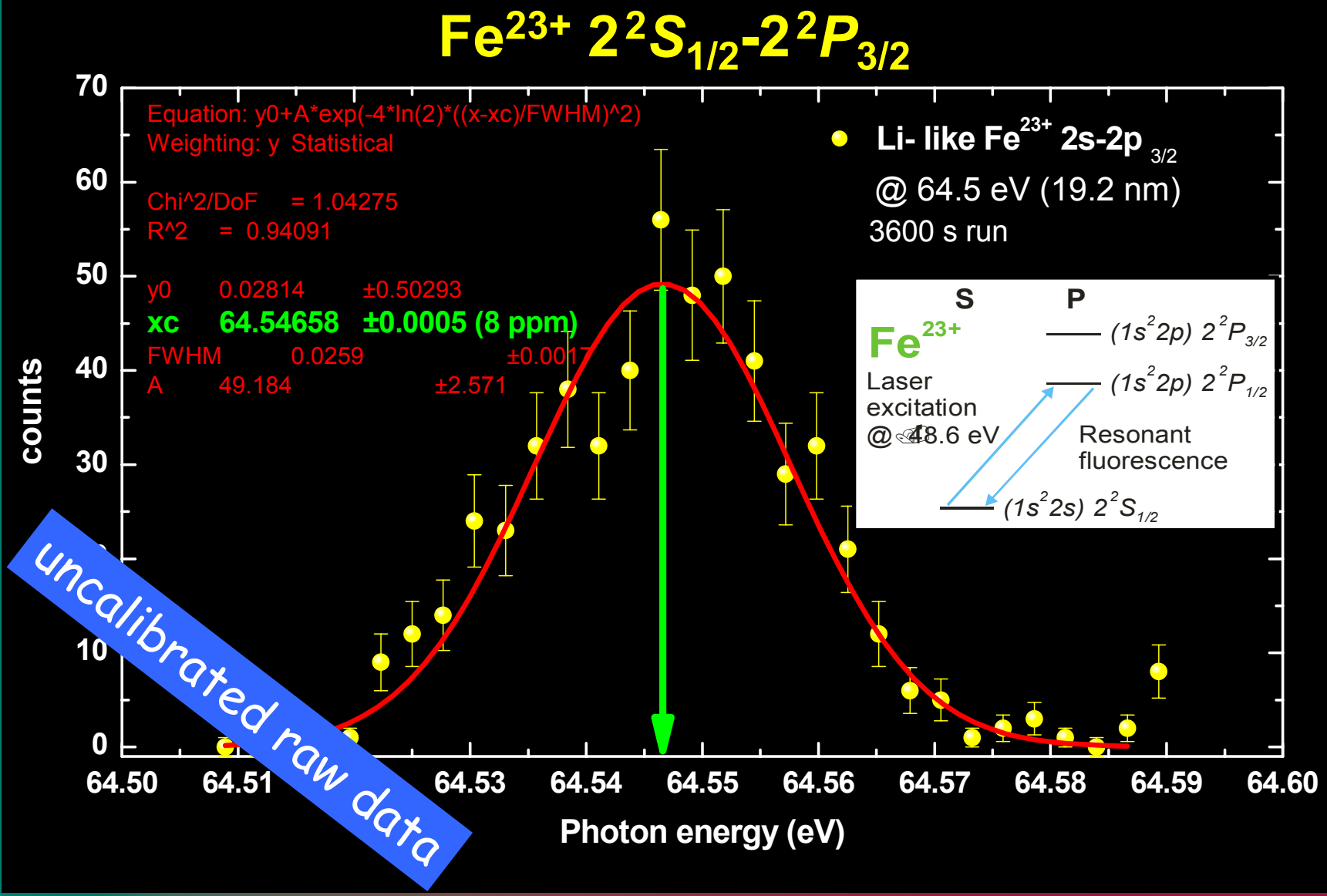
γ.Experiment & Results
- Results 2008 (2nd run) -



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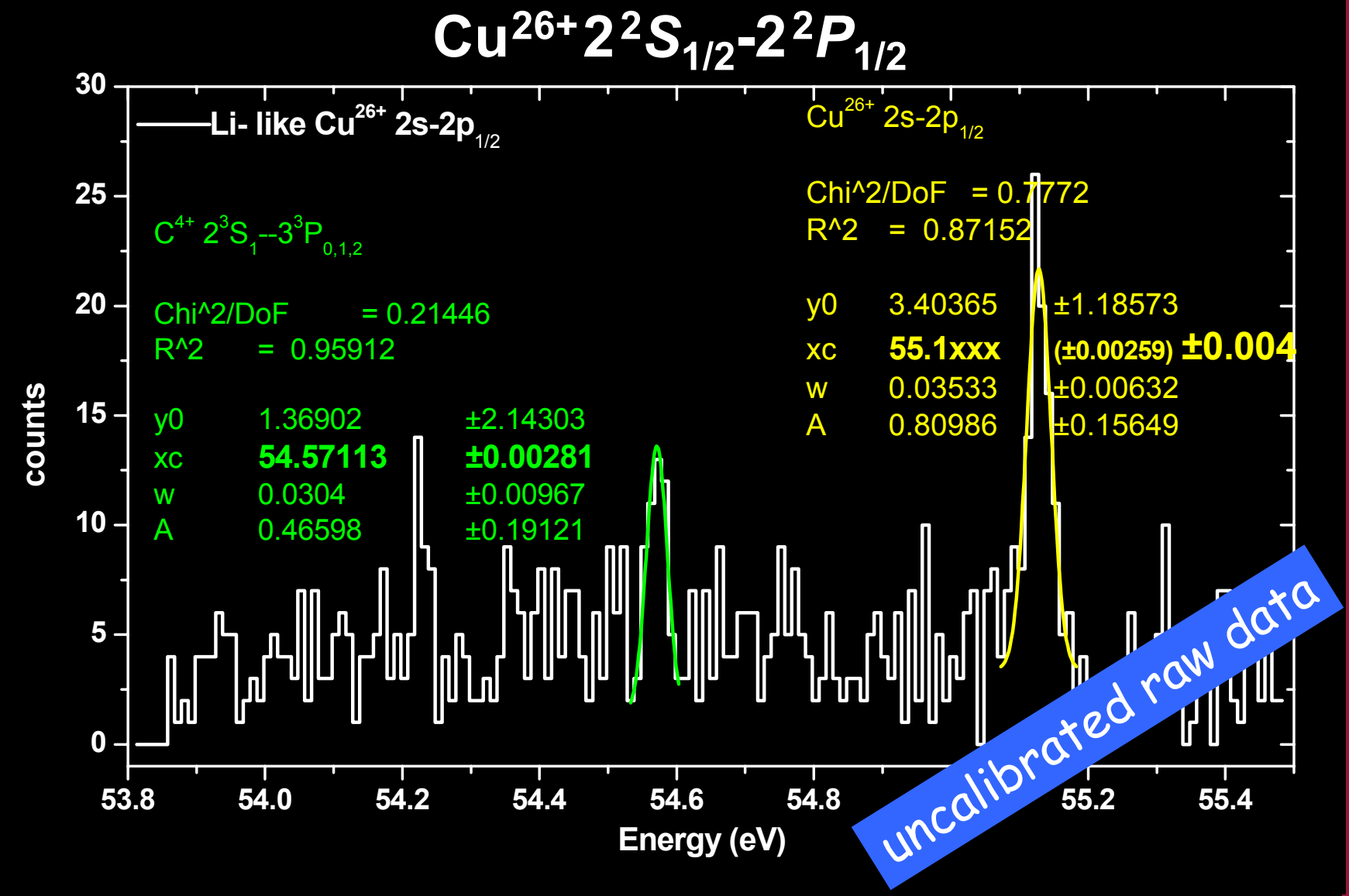
γ.Experiment & Results
- Results 2008 (2nd run) -



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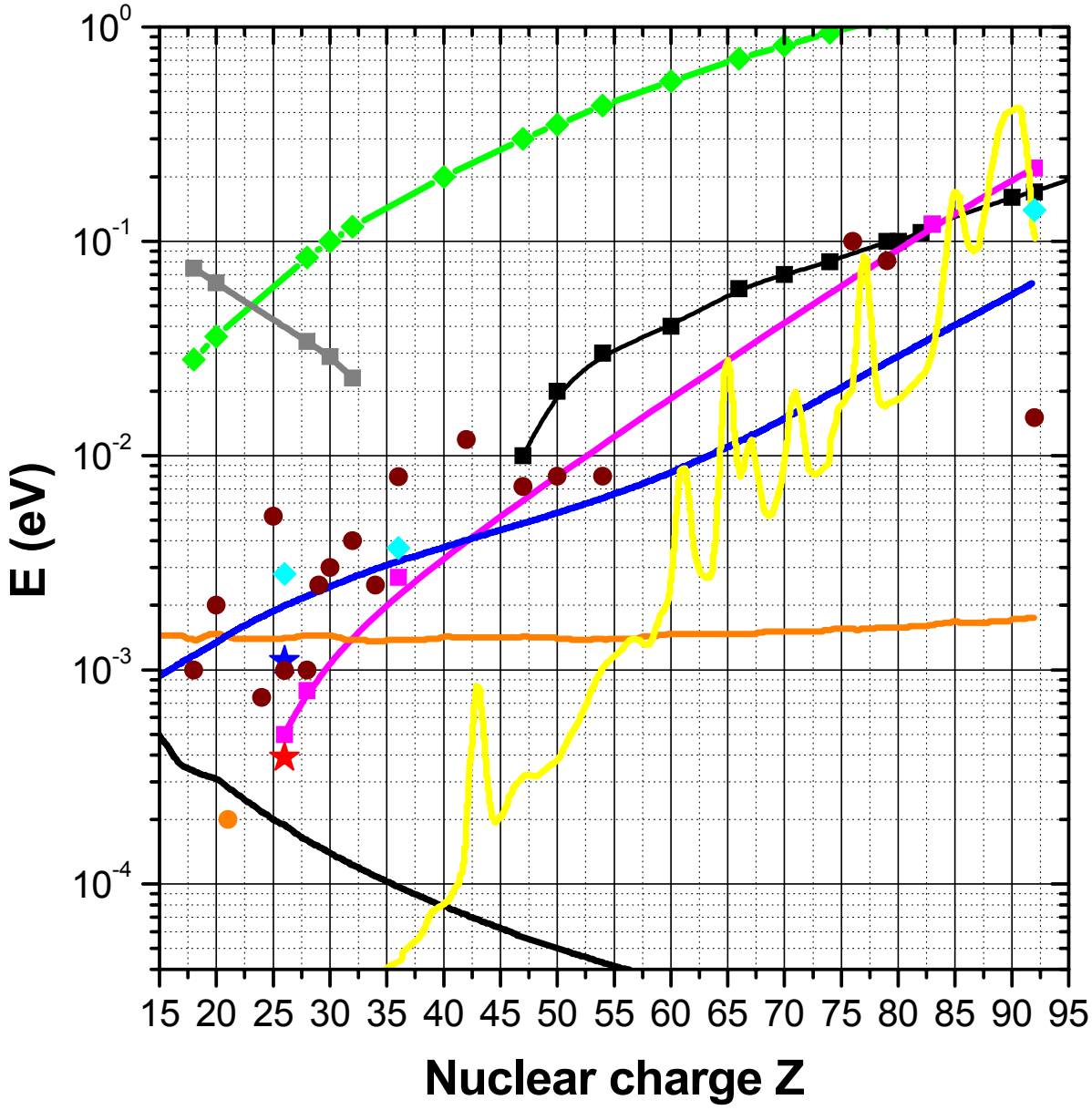
γ. Experiment & Results



Contributions

- Screening SE $O(\alpha^2)$
- SE + VP $O(\alpha^2)$
- 3 photon inter-electron
- 3 photon inter-electron

Source of main error

- Nuclear size
- Recoil
- Screening SE + VP $O(\alpha^3)$
- 3 & more photons inter-elec.

Theory

- Yerokhin et. al. '08

Experiment

- Other
- Lestinsky et. al. $2s\text{-}2p_{3/2}$
- This work '07 (laser spec.)
- This work '08 (laser spec.)
  8 ppm in 3600 s

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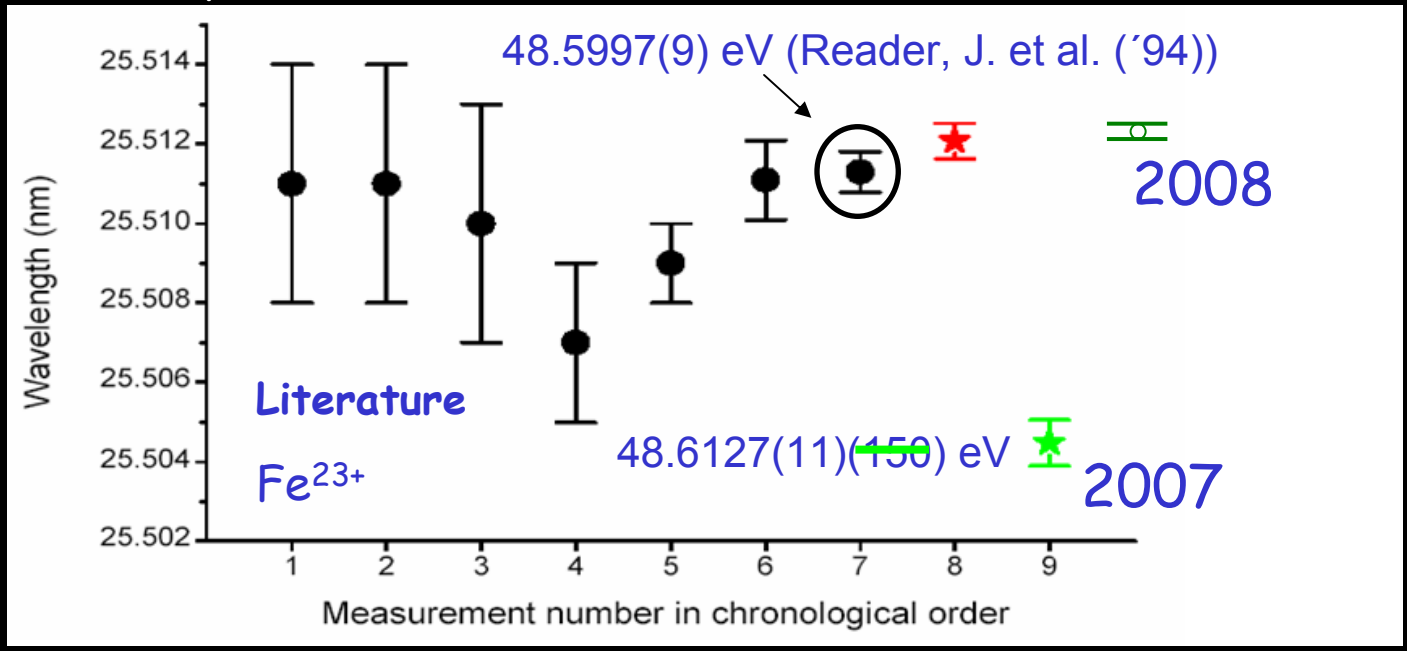
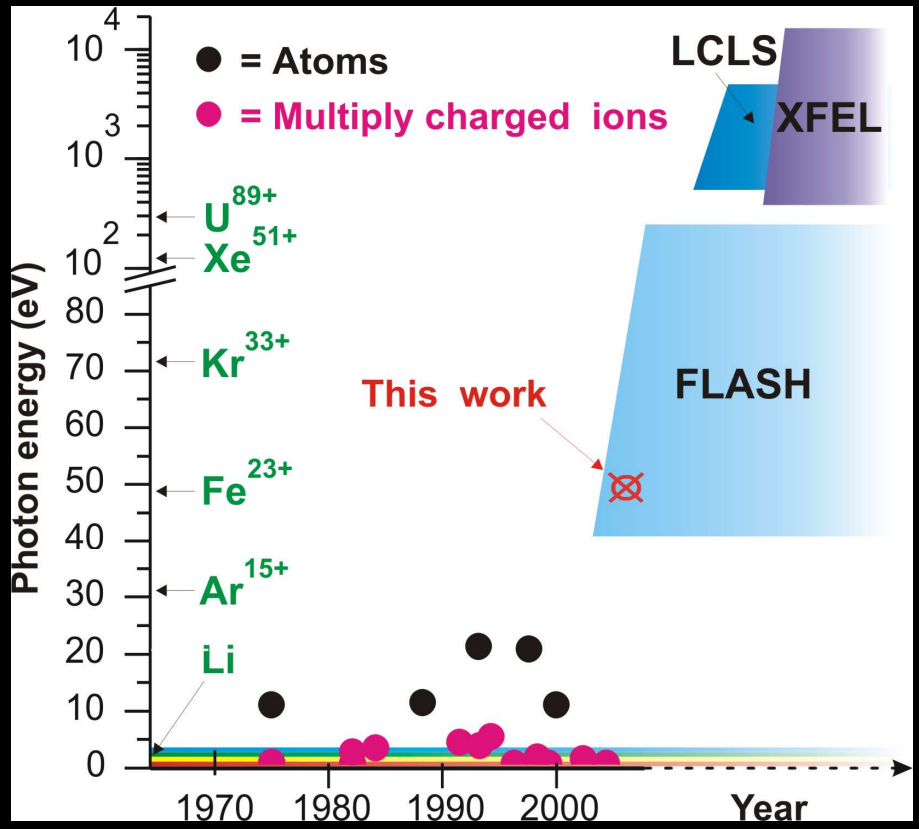
δ. Summary

- demonstration of resonant laser spectroscopy of HCI in an EBIT with soft x-rays at photon energies as high as 65 eV using FELs
  - *advantage: selective, resonant excitation @ huge cross sections*
- nearly routinely 8 ppm statistical precision in 1 h of D.A.Q.
  -> unprecedented accuracy is expectable
- working on calibration to convert precision in absolute accuracy
  - photo-absorption in noble gases
  - comparison with transitions in He- & H-like ions (Cu^{26+})



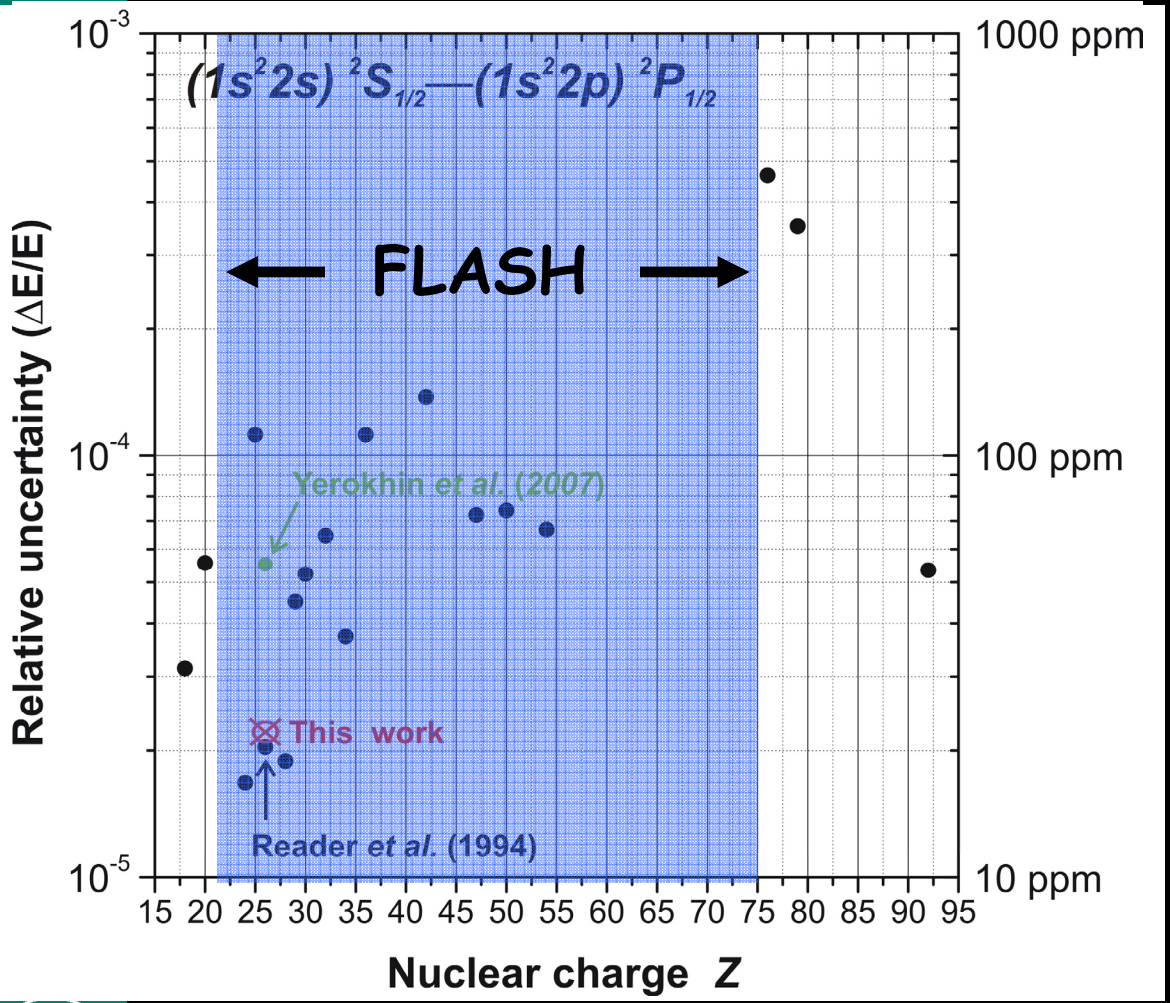
δ. Outlook

- FLASH
- laser spectroscopy @ synchrotron light sources
- LCLS (Lin. Collider Light Source) @ SLAC Stanford
- European X-FEL in Hamburg



FLASH	30-200 eV	15-400 eV 10-1000 eV	BESSY ALS	intra-shell (n=n') transitions
LCLS (SXR)	800-8000 eV (800-2000 eV)	10-1000 eV	ALS	inter-shell (n<n') t. photo-ionization
X-FEL	200-15000 eV	300-100 000 eV 200-100 000 eV 400-100 000 eV	APS ESRF PETRA III	inter-shell (n<n') t. photo-ionization

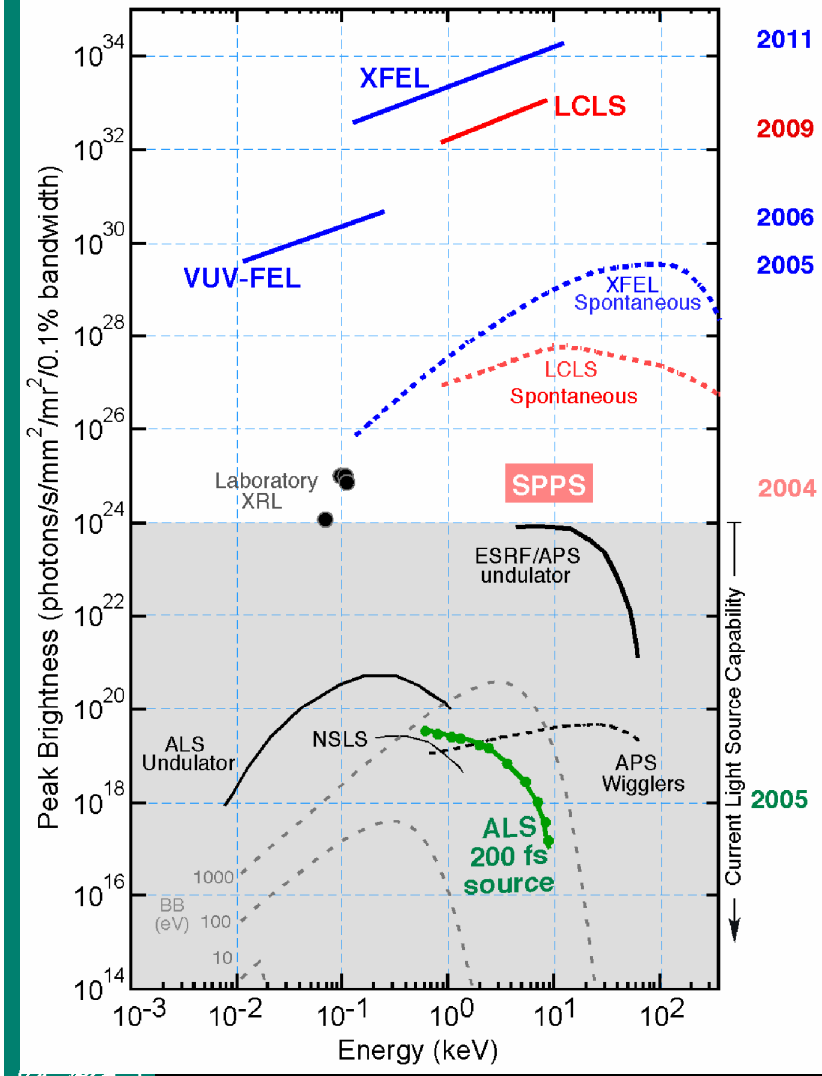
δ. Outlook
- @ FLASH -

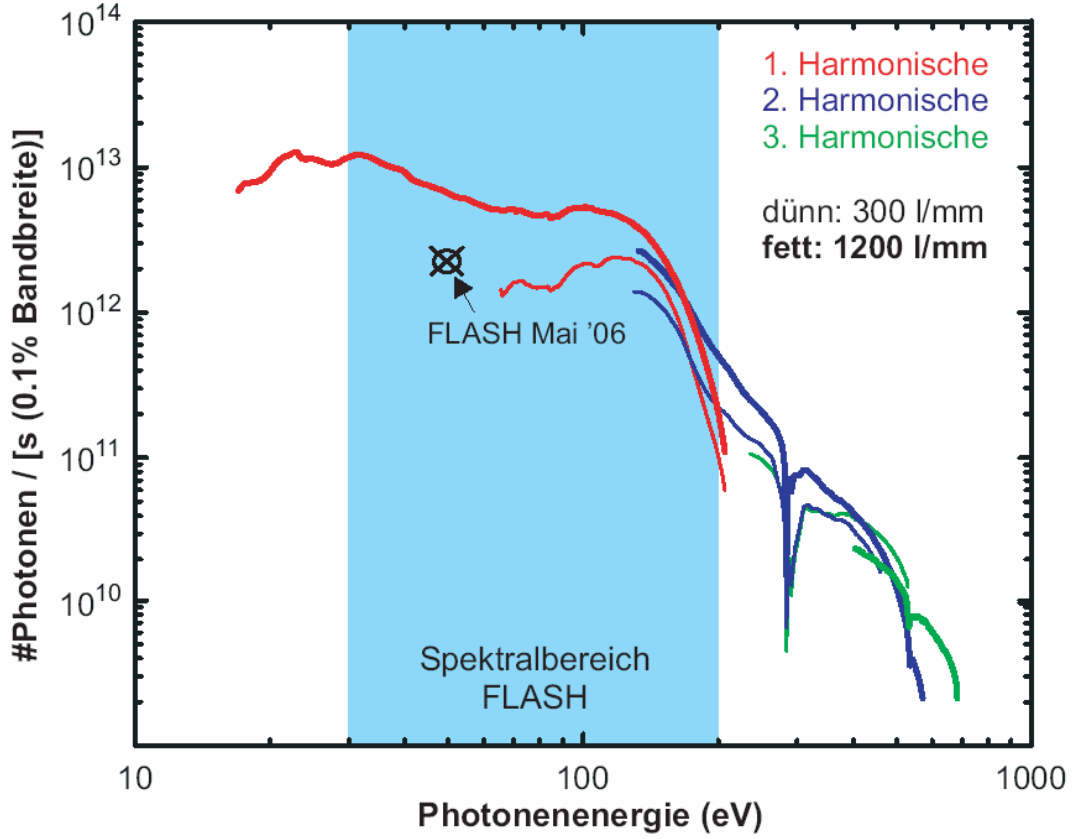


- FLASH still misses 2-3 orders of flux compared to design values -> more STATISTICS
- one order of mag. more resolution power possible 2k->20k Monochromator with up to 150k exist
- Seeding of FLASH will enhance #photons/eV B.W.
- systematic studies of Li- or Be-like HCIs over a wide Z-range, including isotopes

=> a consistent body of data to resolve nuclear and QED effects

δ. Outlook
- @ synchrotron light sources -





Problem: Time structure !

Synchrotrons are approx. c.w.

δ. Outlook
- @ synchrotron light sources -

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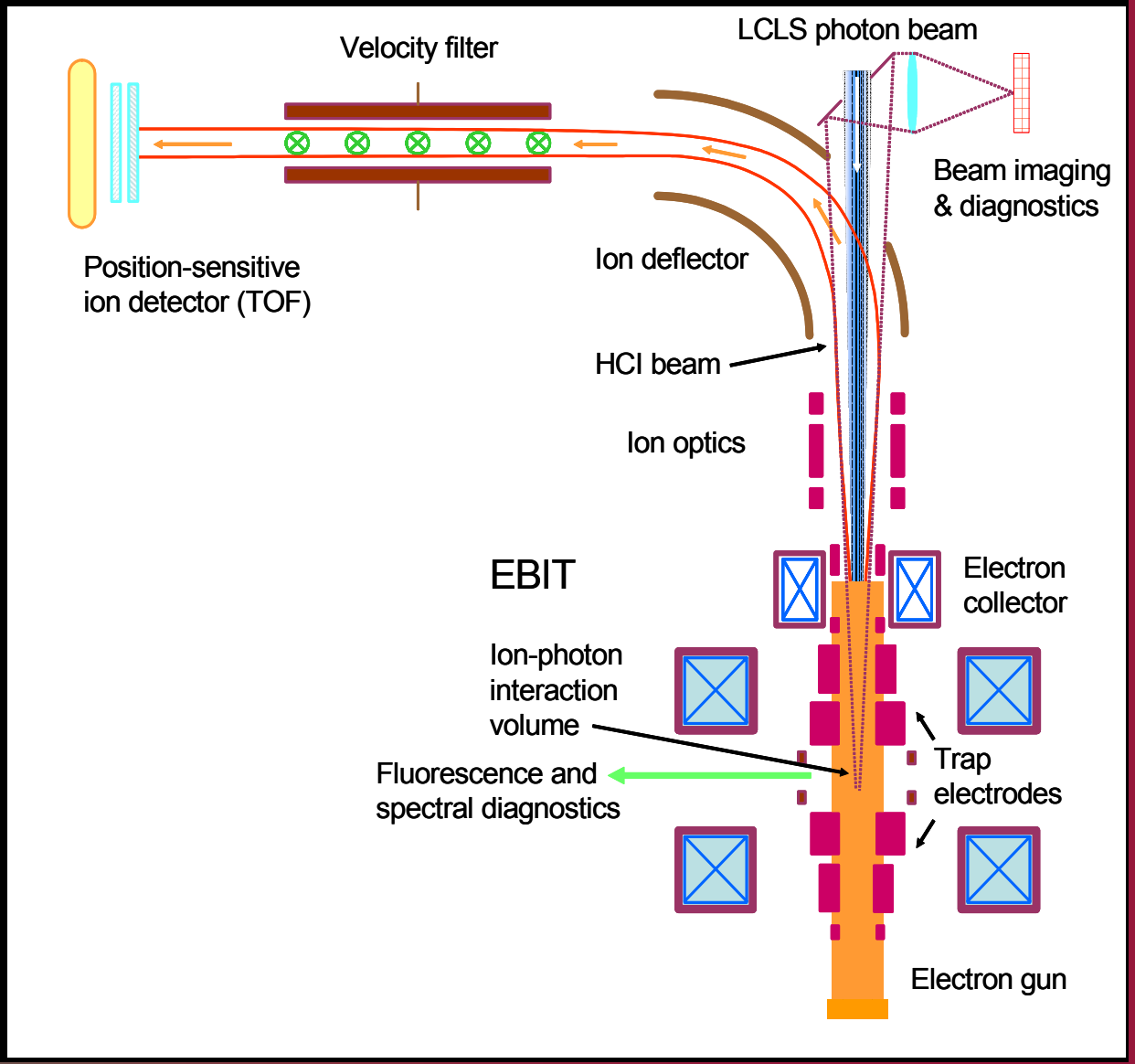
What we do:

Photoionization meassurements

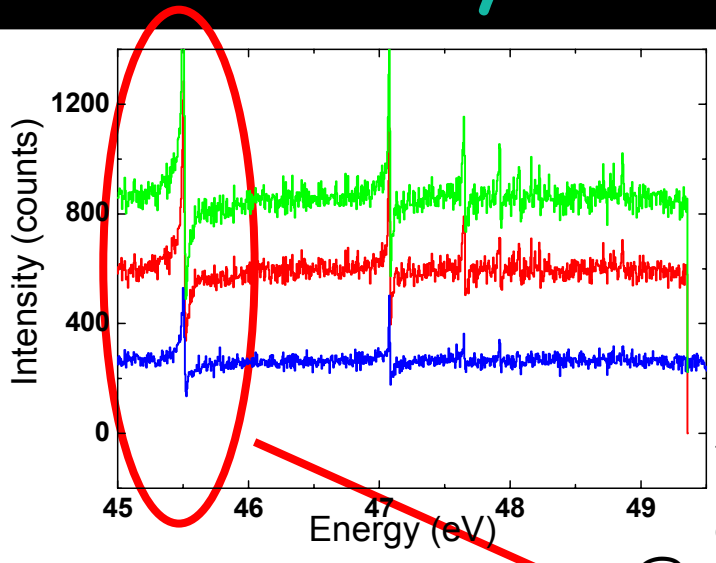
Last week:

N^{3+}-> N^{4+} resonances

@ BESSY, Berlin

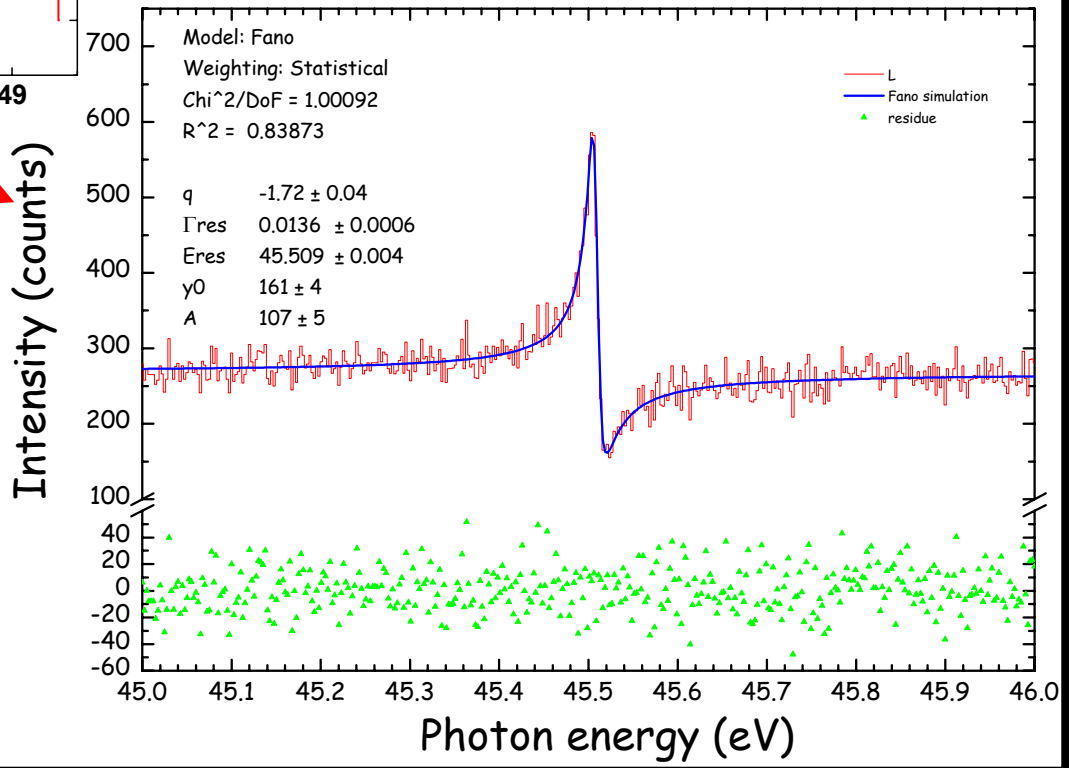


δ. Outlook
- @ synchrotron light sources -



The use of narrow photoionization resonances of Ne (He) etc. can provide calculable standards in the region up to 80 eV

EBIT<-> PHOBIS



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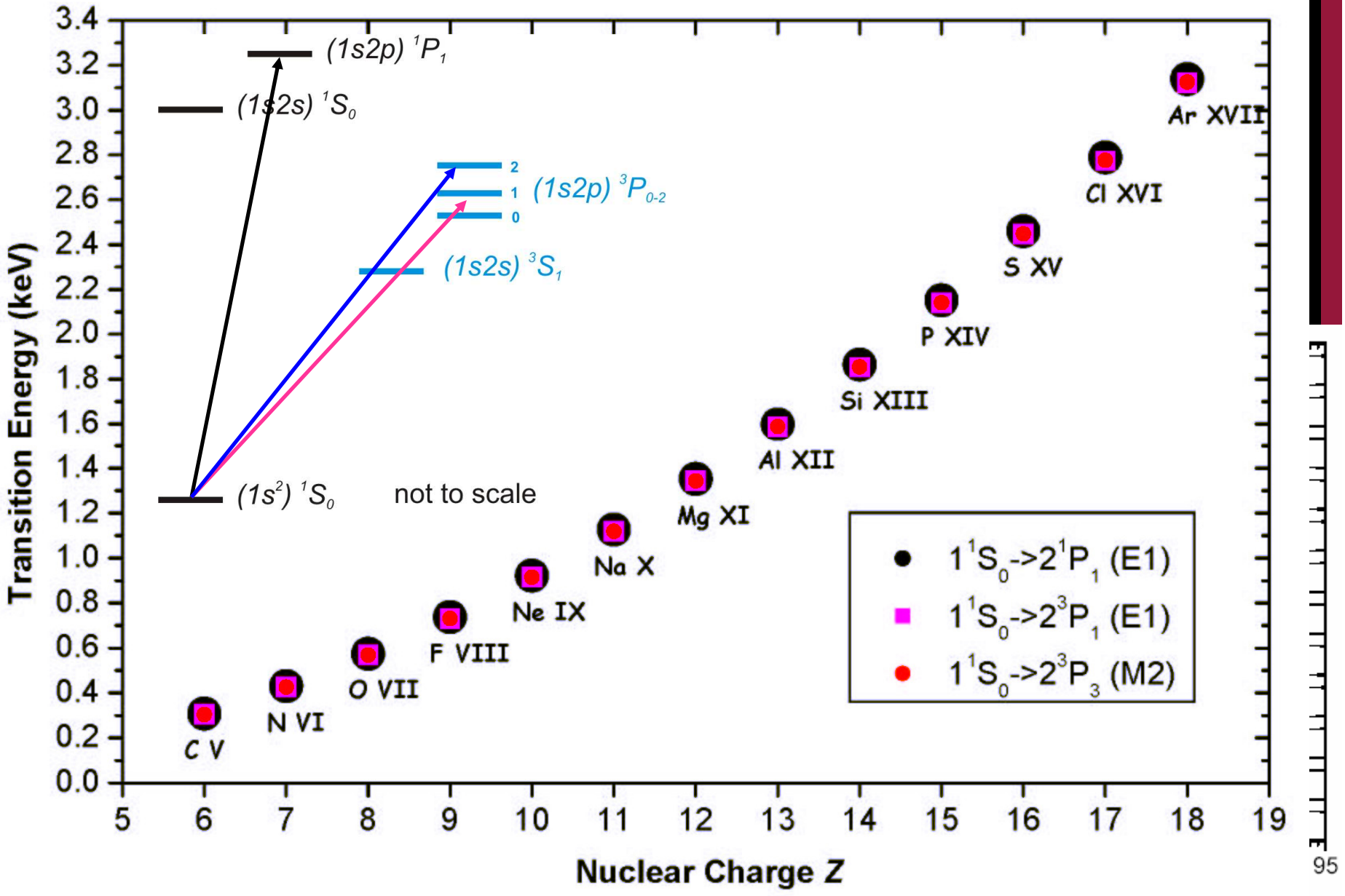
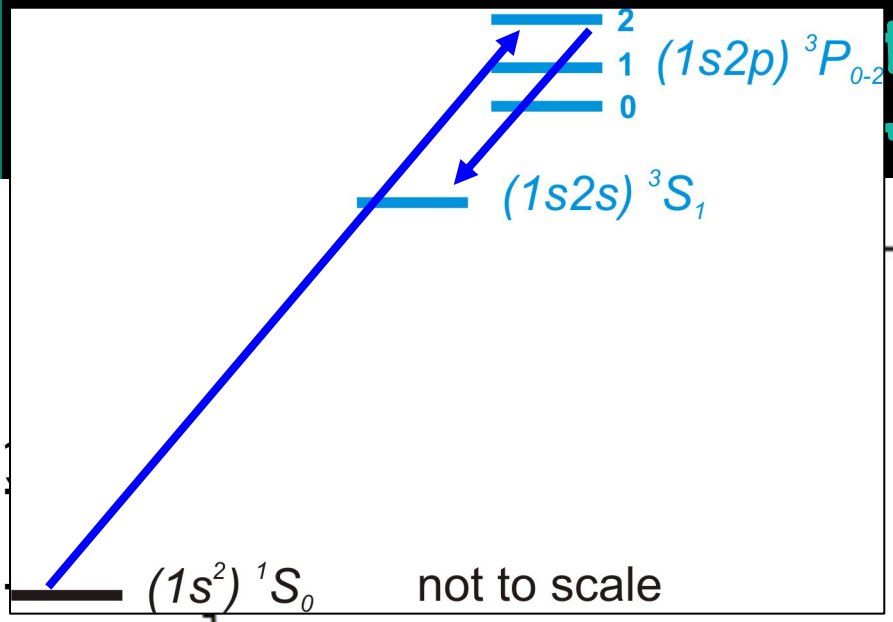
δ. Outlook


(1s2p) $^1P_1$
(1s2s) $^1S_0$
2
1
0
(1s2p) $^3P_{0-2}$
(1s2s) $^3S_1$
(1s^2) $^1S_0$
not to scale
Transition Energy (keV)
Nuclear Charge Z
C V
N VI
O VII
F VIII
Ne IX
Na X
Mg XI
Al XII
Si XIII
P XIV
S XV
Cl XVI
Ar XVII
1^1S_0->2^1P_1 (E1)
1^1S_0->2^3P_1 (E1)
1^1S_0->2^3P_3 (M2)

tlook
rom 2009 -



only few measurements, not better than 10% acc.

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δ. Outlook
- @ X-FEL from 2015 -

- Possibilities increase even more for transitions mentioned and not mentioned in this talk
- H-like 1s-nP etc. full accessible for lot of HCIs
  Targeting 1s Lamb-shift by laser spectroscopy
- Wavelength standard by HCIs?

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δ. Outlook
- @ LCLS from 2009 -