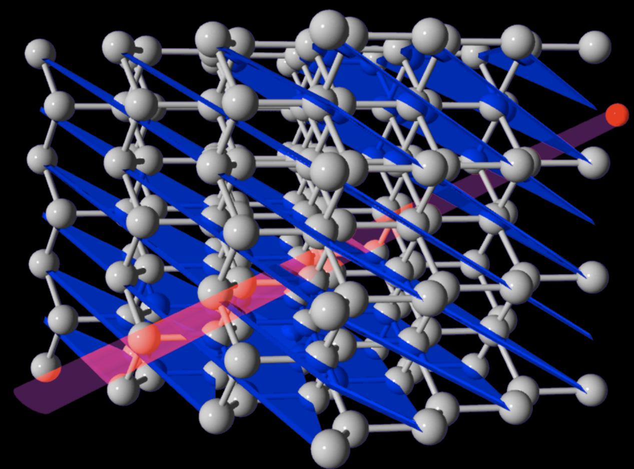
Oct.15, 2014 FAIR-conference@Worms

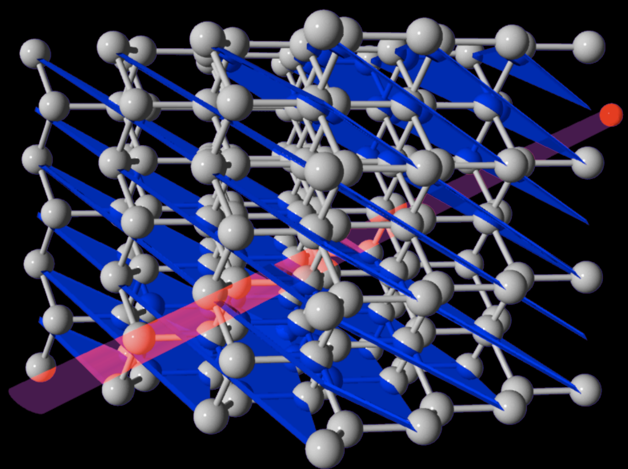
Resonant coherent excitation of heavy ions in a crystal at relativistic energies

Toshiyuki Azuma
AMO Physics Lab., RIKEN, JAPAN



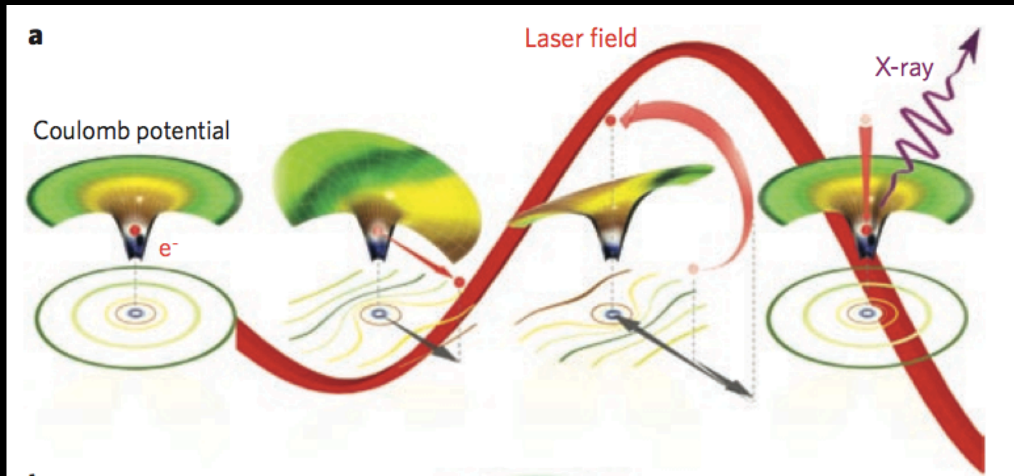
Alternative to X-ray laser

Toshiyuki Azuma
AMO Physics Lab., RIKEN, JAPAN



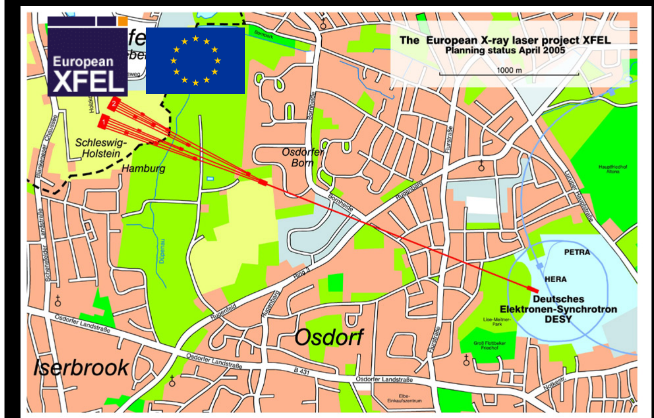
REAL X-RAY PHOTON: HHG / XFEL

High harmonics generation



X-ray FEL

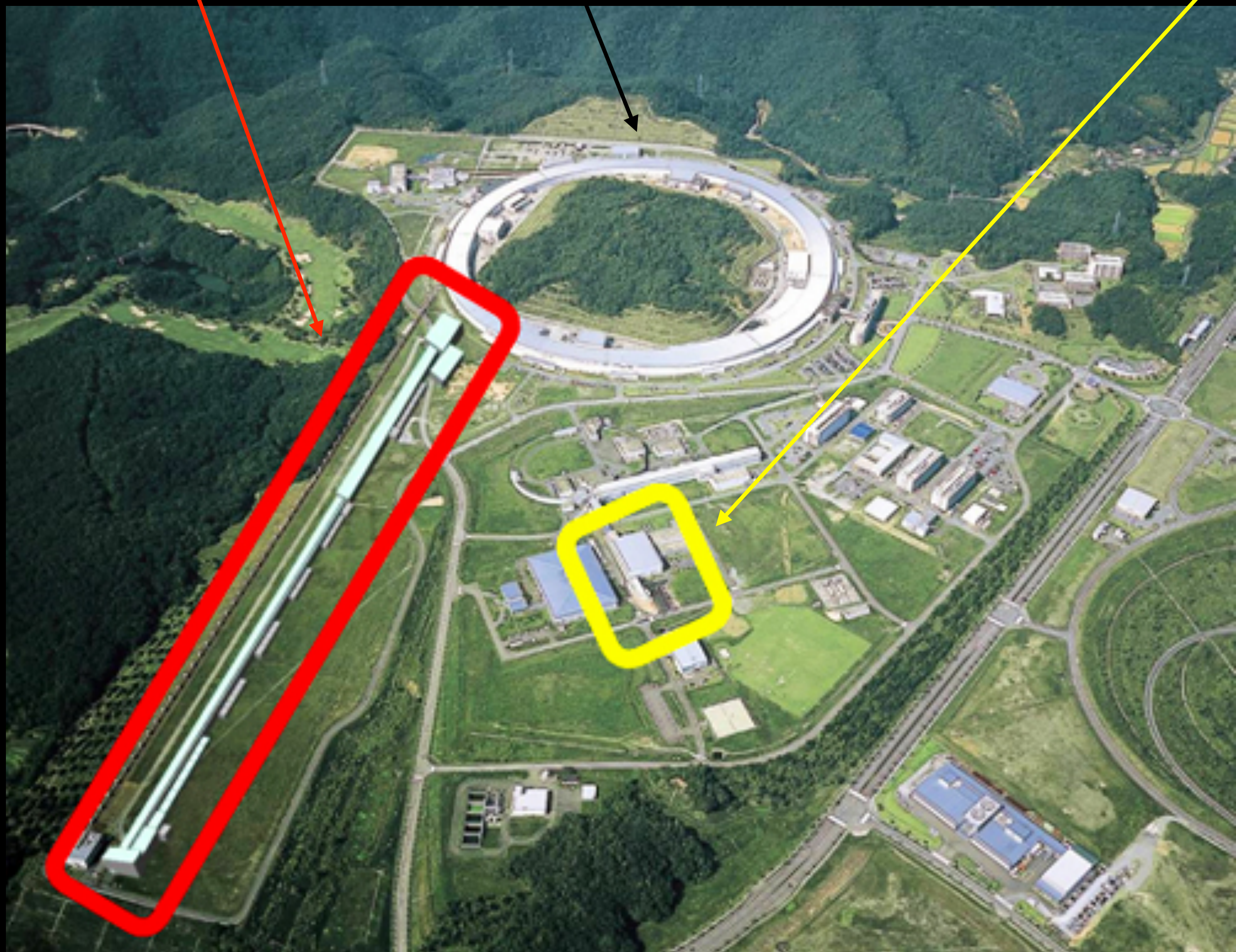
SACLA



REAL X-RAY LASER

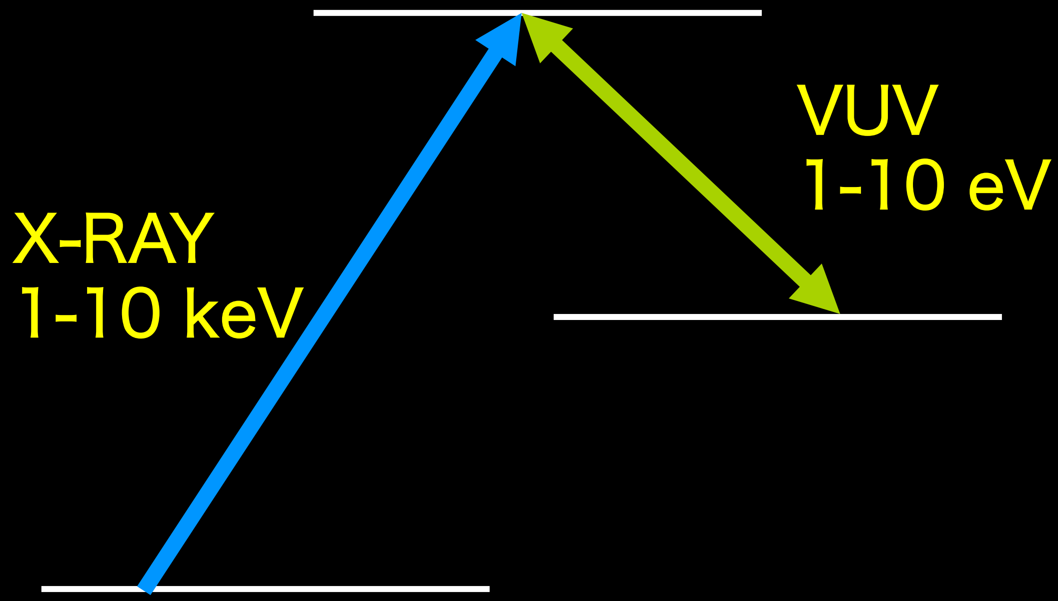
1-10keV XFEL

25eV proto-type FEL



dream or reality ?

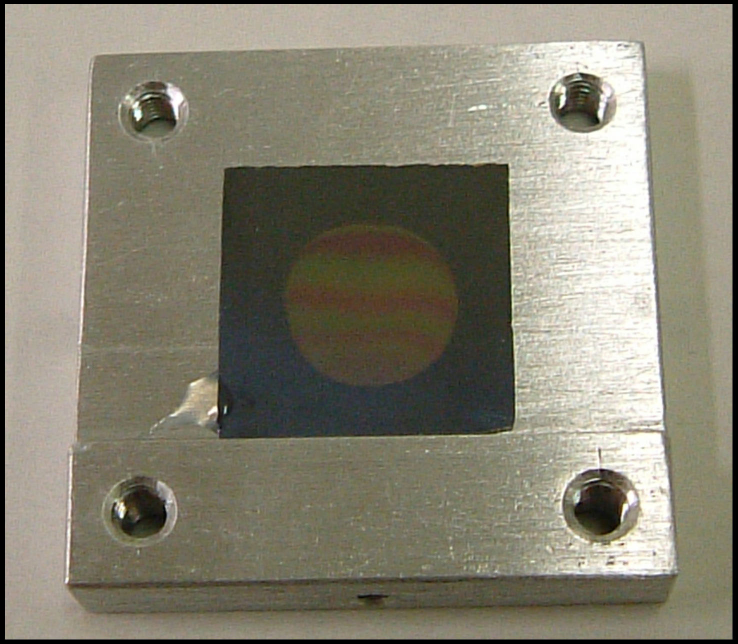
Pump and Probe experiments of highly-charged ions



But, it's not a dream !

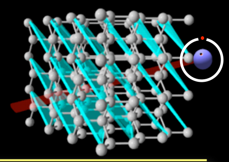
VIRTUAL X-RAY PHOTON SOURCE

a tiny thin Si crystal



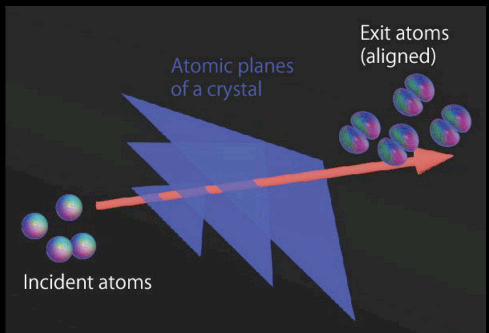
1 -10 μm thick
10 mm diameter

What can we do for highly charged heavy ions ?



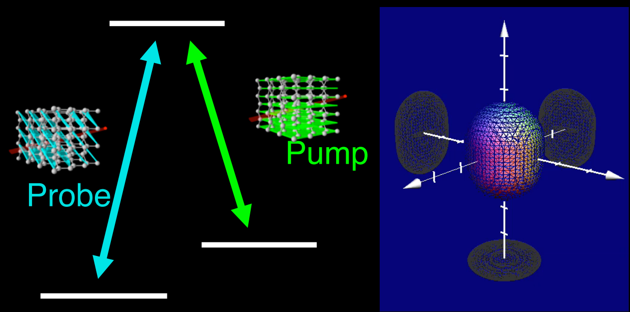
@HIMAC: Population manipulation in the X-ray domain

Alignment of *m*-state



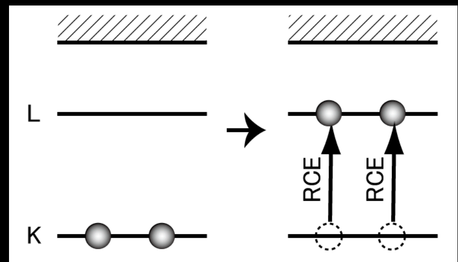
Y. Nakano et al.,
PRL 102, 085502 (2009)

Pump-probe experiment



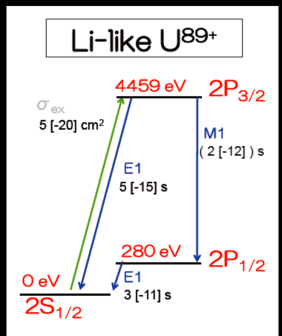
Y. Nakai et al.,
PRL 101, 113201 (2008)

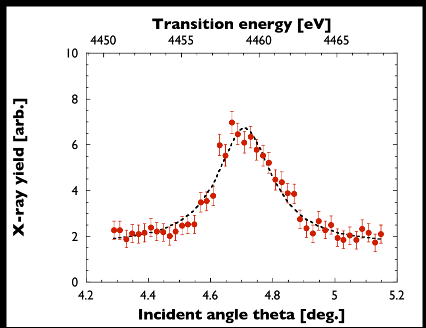
Double excitation



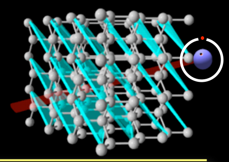
Y. Nakano et al.
PRA 85, 020701(R) (2012)

@GSI: High-resolution spectroscopy





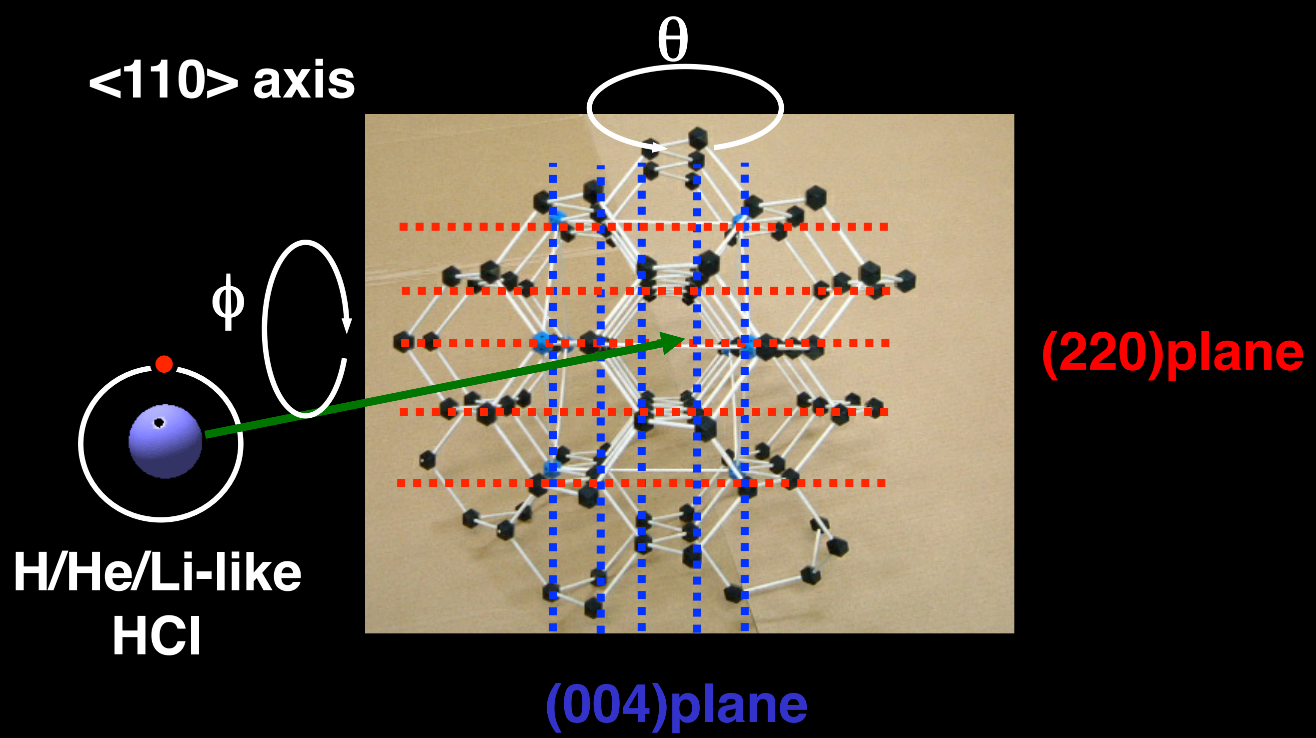
Y. Nakano et al.
PRA 87 060501(R) (2013)



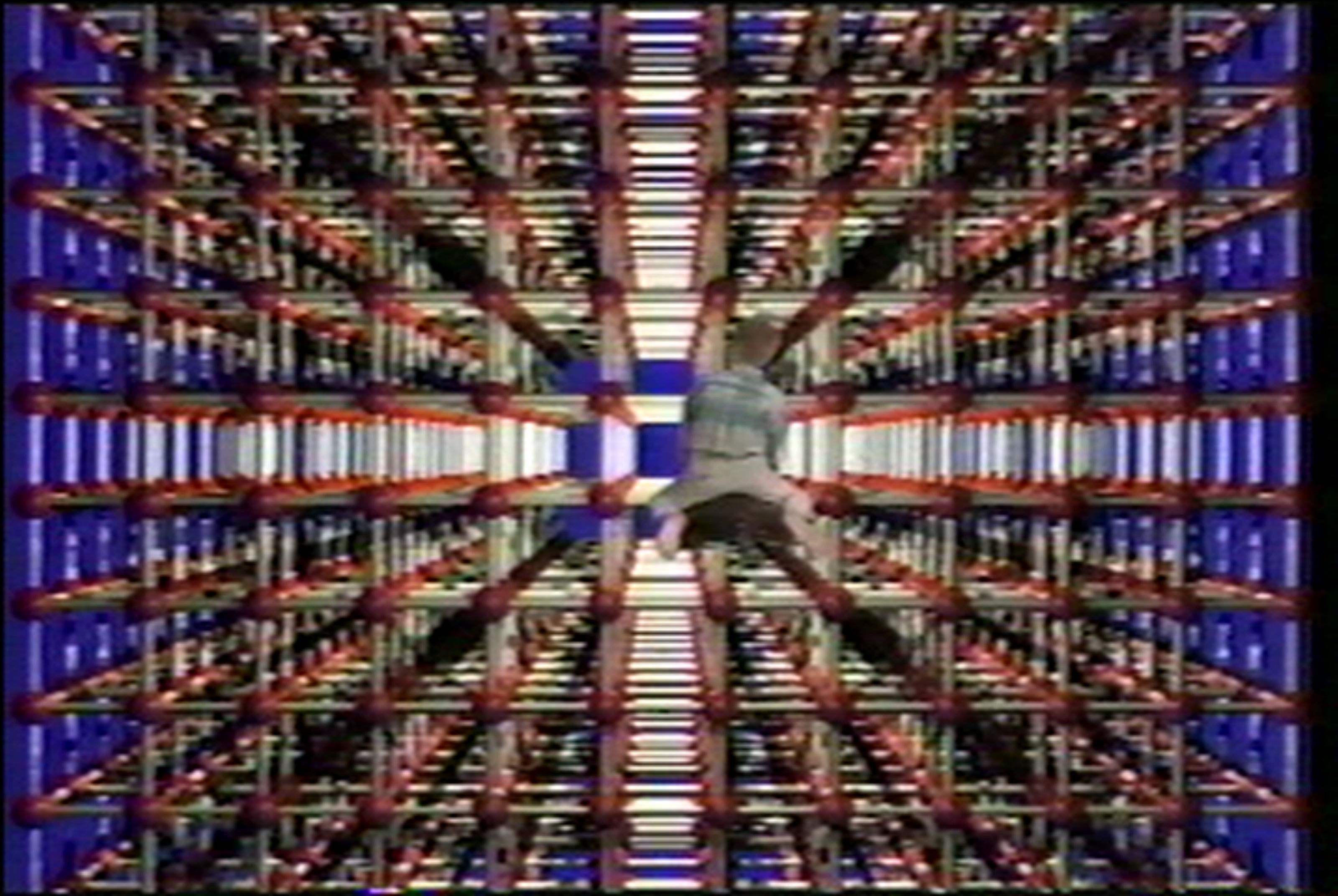
Crystal irradiation

Silicon crystal

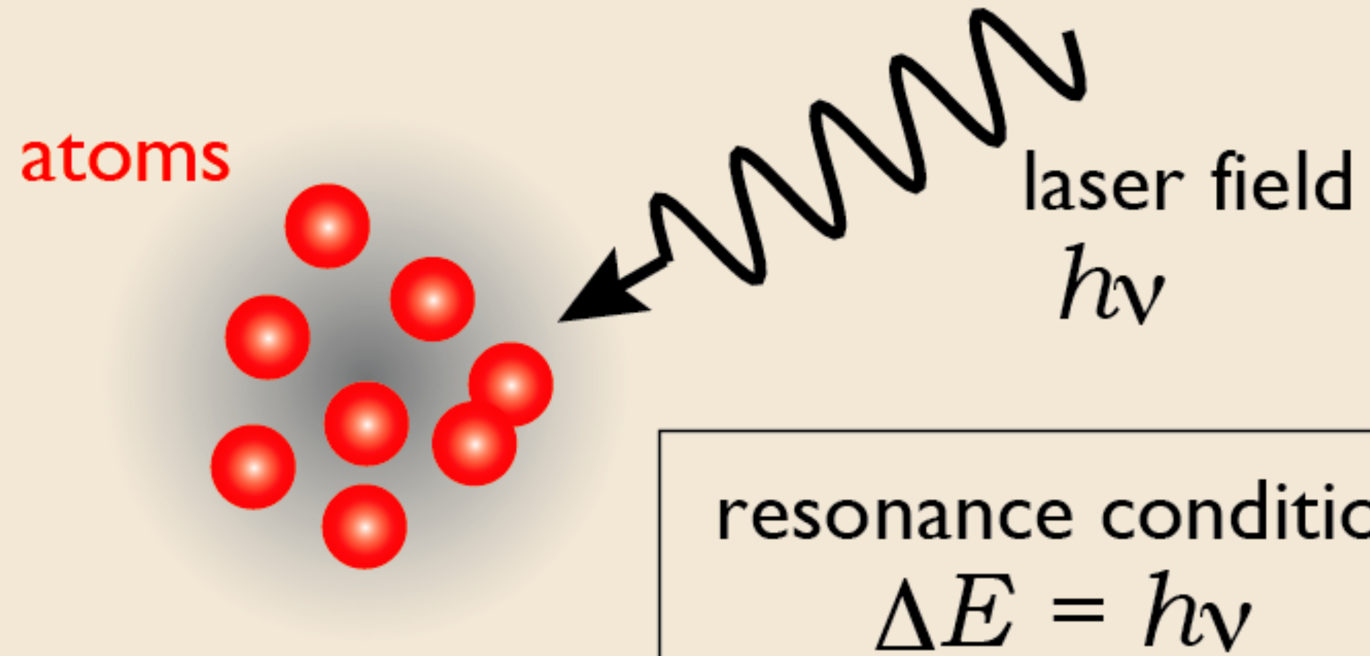
- “virtual photon” source
- spectrometer



Boy's adventure



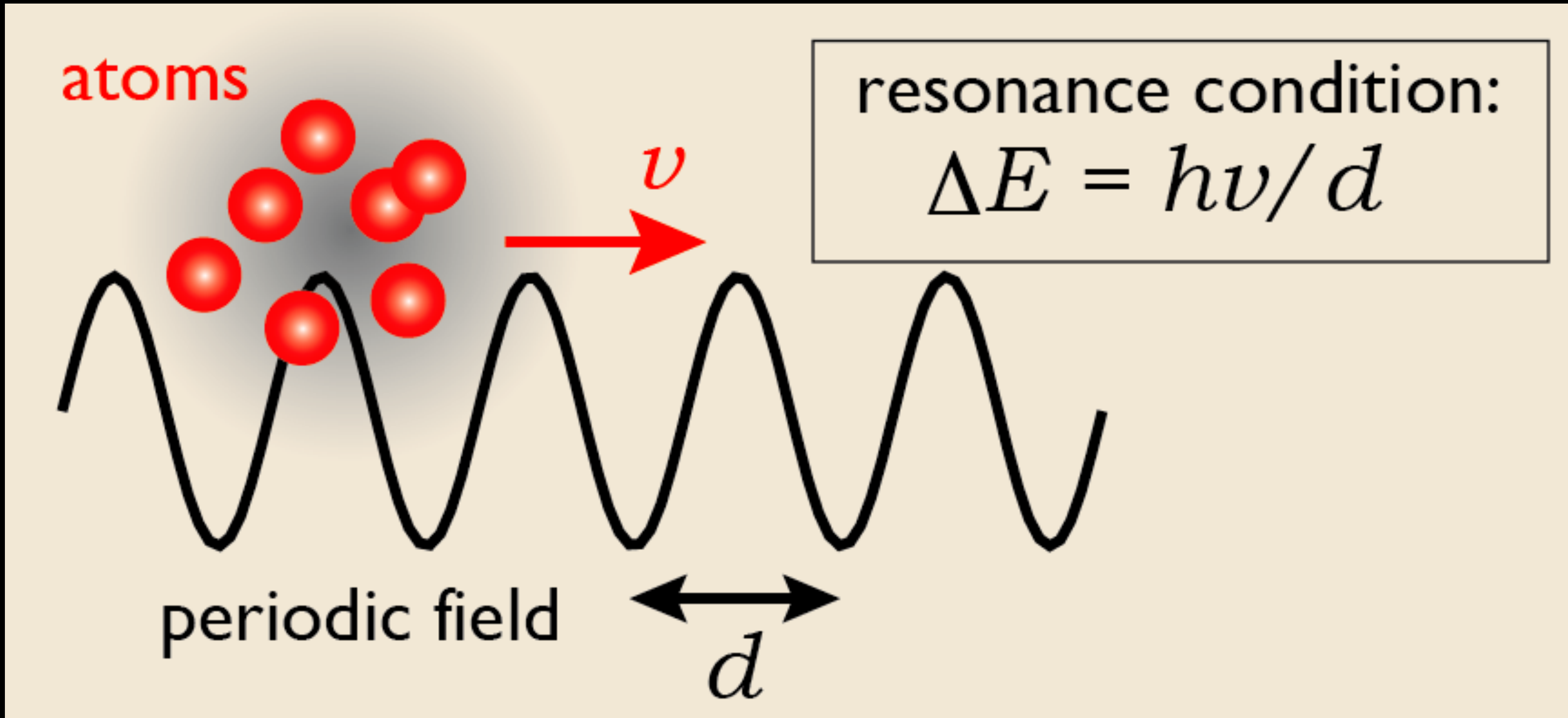
Laser excitation



resonance condition:

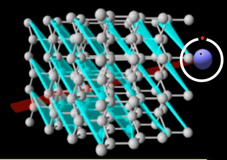
$$\Delta E = h\nu$$

Resonant coherent excitation (RCE)



1965
V.V.Okorokov

Oscillating electric field felt by the ion



1. Derivative of the periodical potential
   $\rightarrow$ spatially periodic field

$$\begin{aligned}\mathbf{F}(\mathbf{r}) &= -\nabla\mathbf{V}(\mathbf{r}) \\ &= \sum_{\mathbf{g}} 2\pi i \mathbf{g} V_{\mathbf{g}} \exp\left(-2\pi i \mathbf{g}\cdot\mathbf{r}\right)\end{aligned}$$

2. Lorentz transformation into the projectile frame
   $\rightarrow$ temporally oscillating field

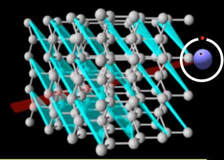
$$\mathbf{F}'(t') = \sum_{\mathbf{g}} 2\pi i V_{\mathbf{g}} \boxed{\begin{pmatrix}\gamma g_x \\ \gamma g_y \\ g_z\end{pmatrix}} \boxed{\exp(-2\pi i \gamma \mathbf{g}\cdot\mathbf{v}t)}$$

Freq.

Pol.

typical amplitude $|F'(t')| = 10^{11}$ V/m
$\rightarrow$ 10^{15} W/cm^2 of photon irradiation

Oscillating electric field felt by the ion



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$$\begin{aligned}\mathbf{F}(\mathbf{r}) &= -\nabla \mathbf{V}(\mathbf{r}) \\ &= \sum_{\mathbf{g}} 2\pi i \mathbf{g} V_{\mathbf{g}} \exp\left(-2\pi i \mathbf{g}\cdot\mathbf{r}\right)\end{aligned}$$

2. Lorentz transformation into the projectile frame
   $\rightarrow$ temporally oscillating field

Lorentz Contraction

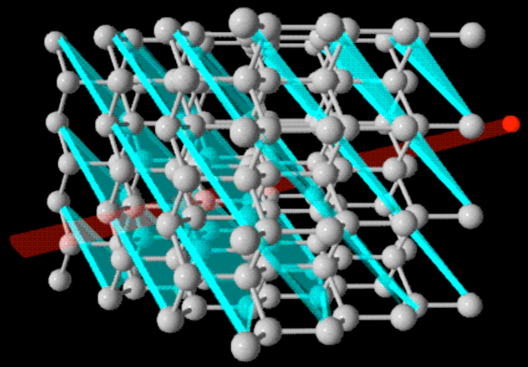
$$\mathbf{F}'(t') = \sum_{\mathbf{g}} 2\pi i V_{\mathbf{g}} \begin{pmatrix} \gamma g_x \\ \gamma g_y \\ g_z \end{pmatrix} \exp(-2\pi i \gamma \mathbf{g}\cdot\mathbf{v}t)$$

Freq.

Pol.

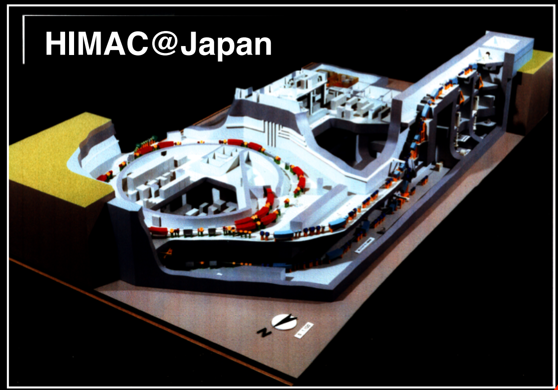
typical amplitude |F'(t')| = 10^{11} V/m
$\rightarrow$ 10^{15} W/cm^2 of photon irradiation

RCE of high energy ions



Si crystal
($d \sim 1$Å)

E ~ 400 MeV/u, $\beta \sim 0.7$

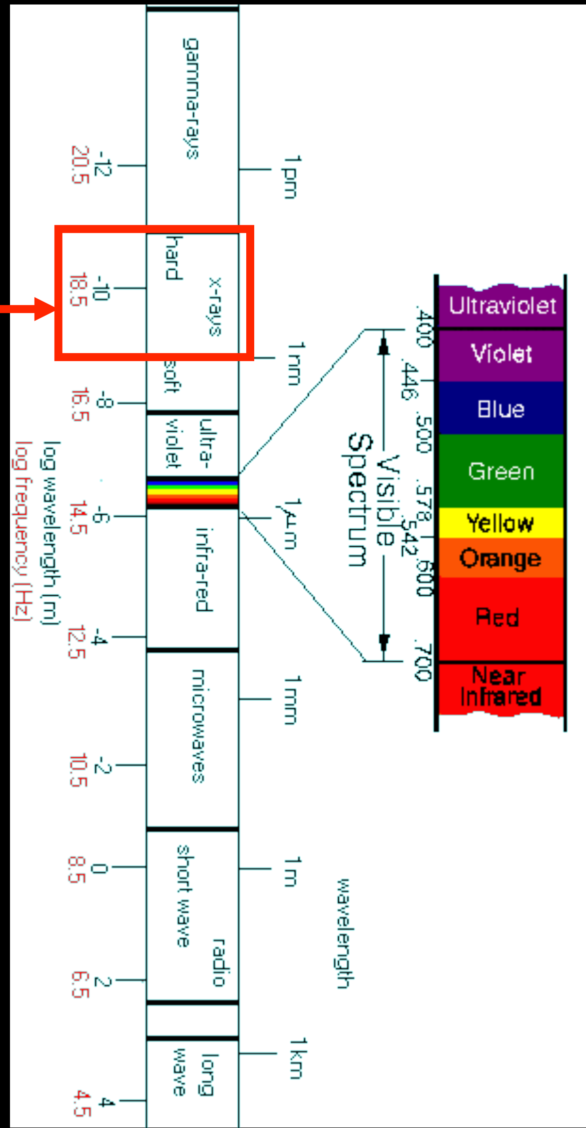


high-energy ion
($v \sim 10^8$ m/s)

frequency

$$\nu = \frac{v}{d} \sim 10^{18}\ \mathrm{Hz}$$

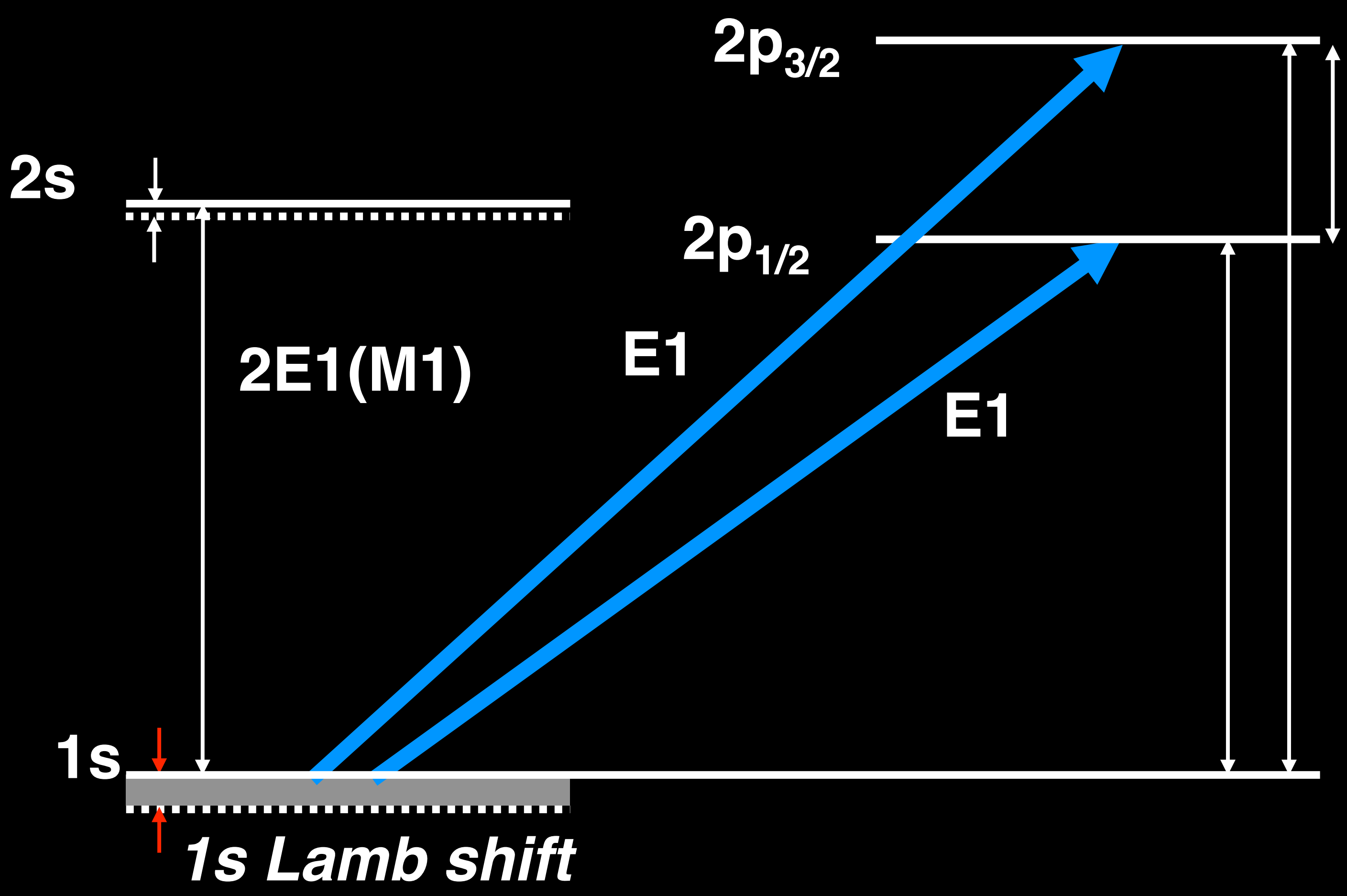
coherent light in the x-ray region



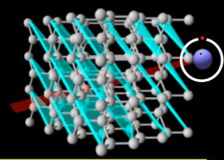
Energy levels of hydrogen-like system

H-like system

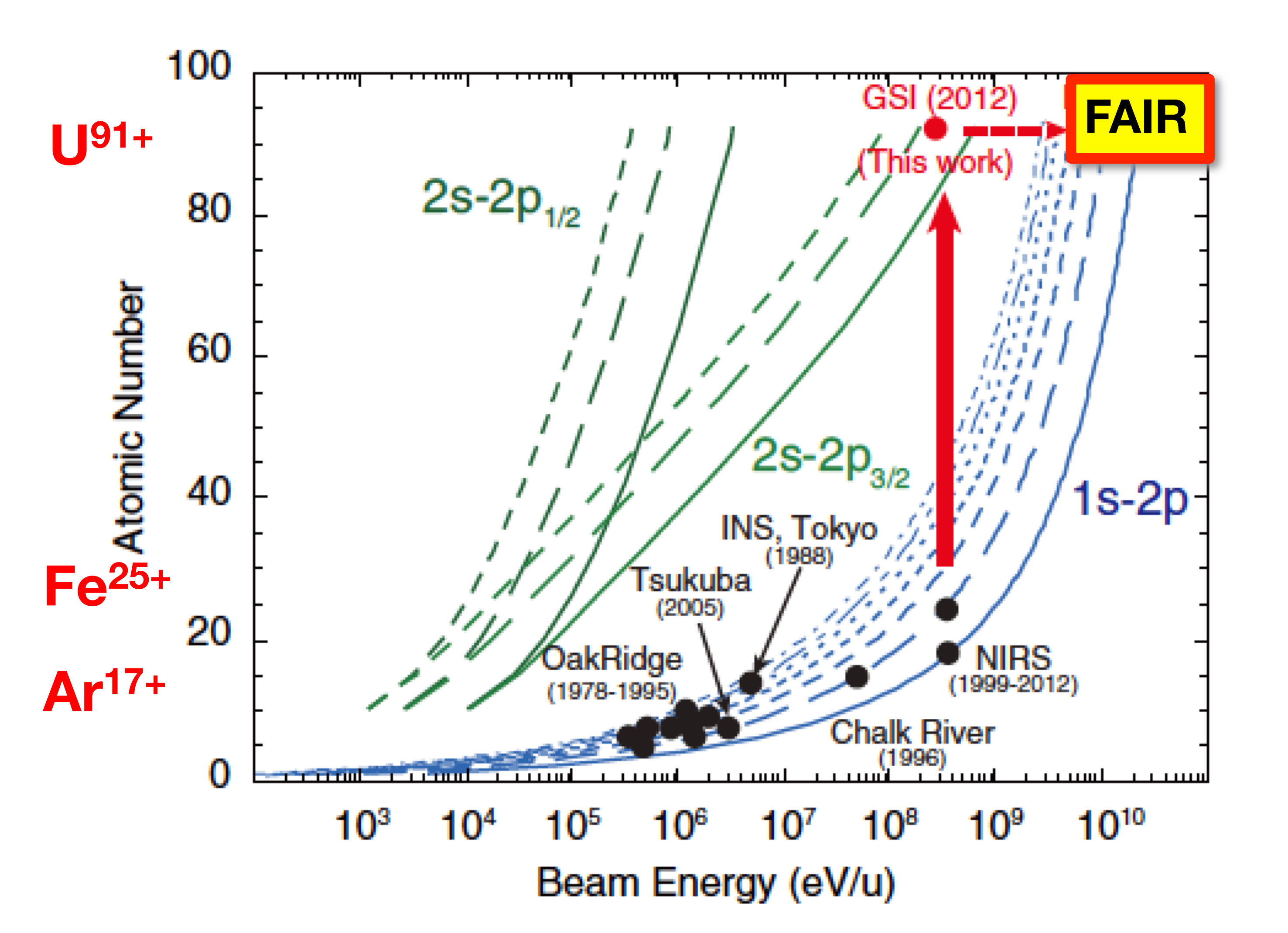
1s → 2p

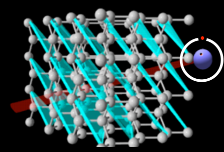


Transition energy

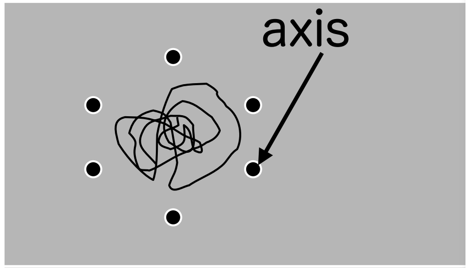
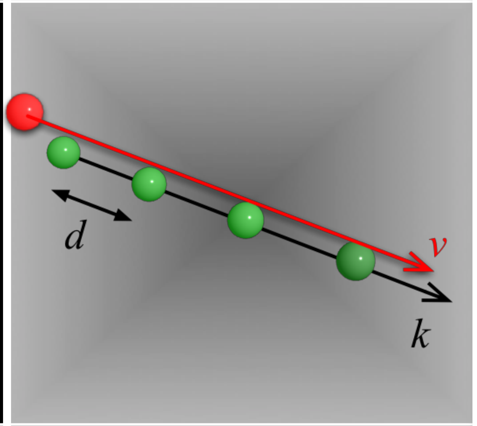


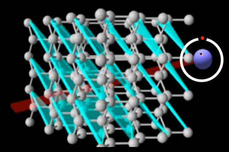
In principle ANY energy for RCE-photon is available



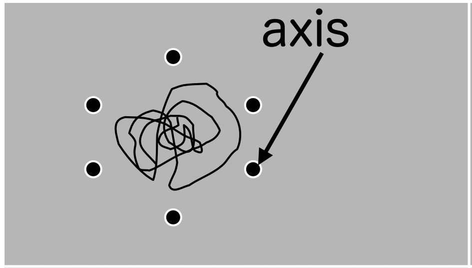
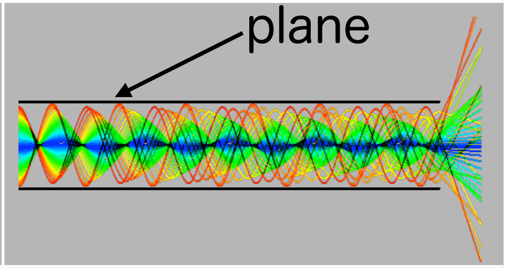
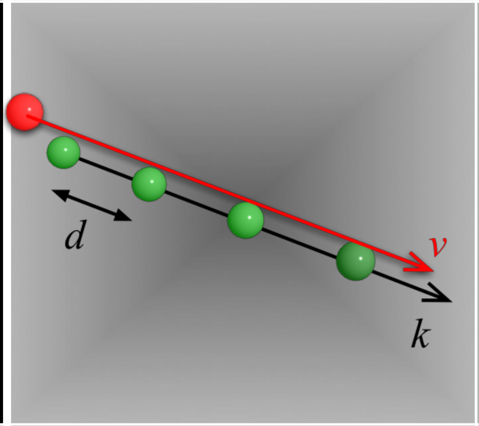
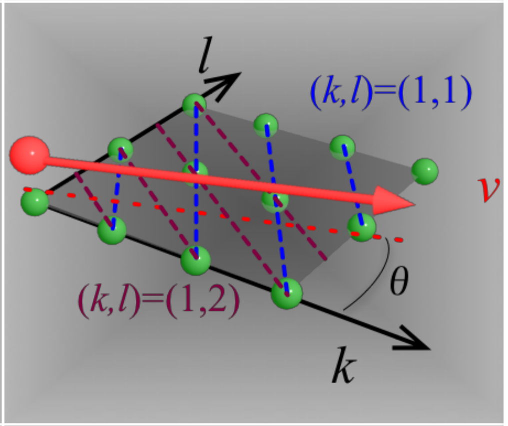


1D-RCE

	Axial-channeling (1D-RCE)
trajectory	
periodic potential	
continuum potential	Axial potential
impact parameter dep.	Yes

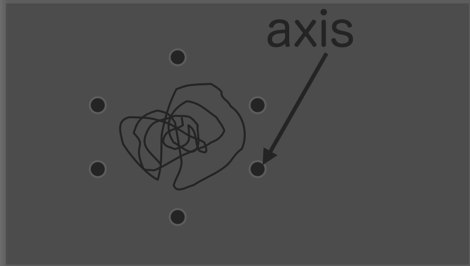
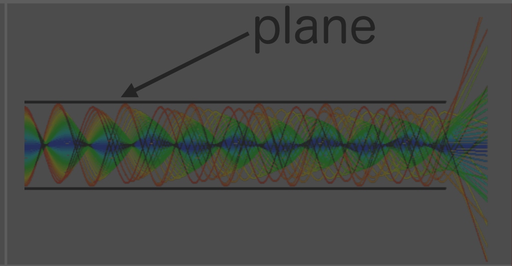
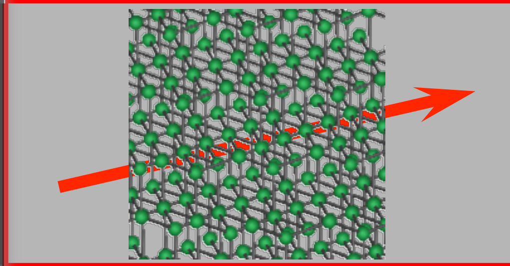
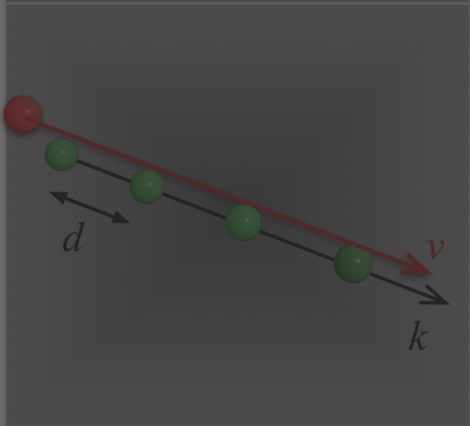
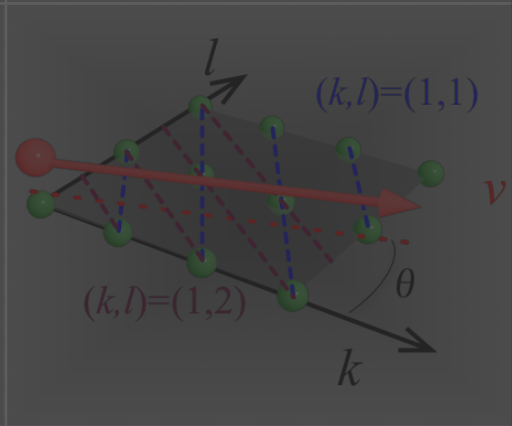
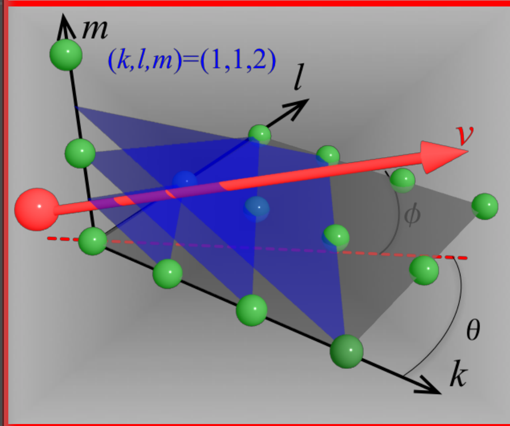


2D-RCE

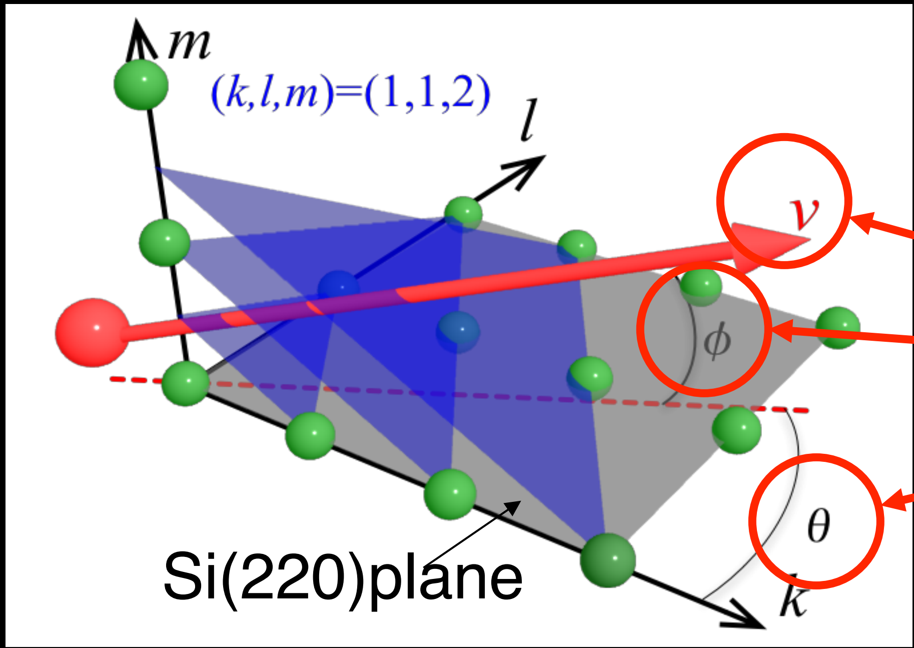
	Axial-channeling (1D-RCE)	Planar-channeling (2D-RCE)
trajectory		
periodic potential		
continuum potential	Axial potential	Planar potential
impact parameter dep.	Yes	Yes

3D-RCE

C. Kondo at al, PRL 97 135503(2006)

	Axial-channeling (1D-RCE)	Planar-channeling (2D-RCE)	Random (3D-RCE)
trajectory			
periodic potential			
continuum potential	Axial potential	Planar potential	
impact parameter dep.	Yes	Yes	No

3D-RCE



Axis (1D)	v
Plane (2D)	v , θ
Random (3D)	v, θ, Φ

2 parameters to vary the interaction frequency keeping ion velocity

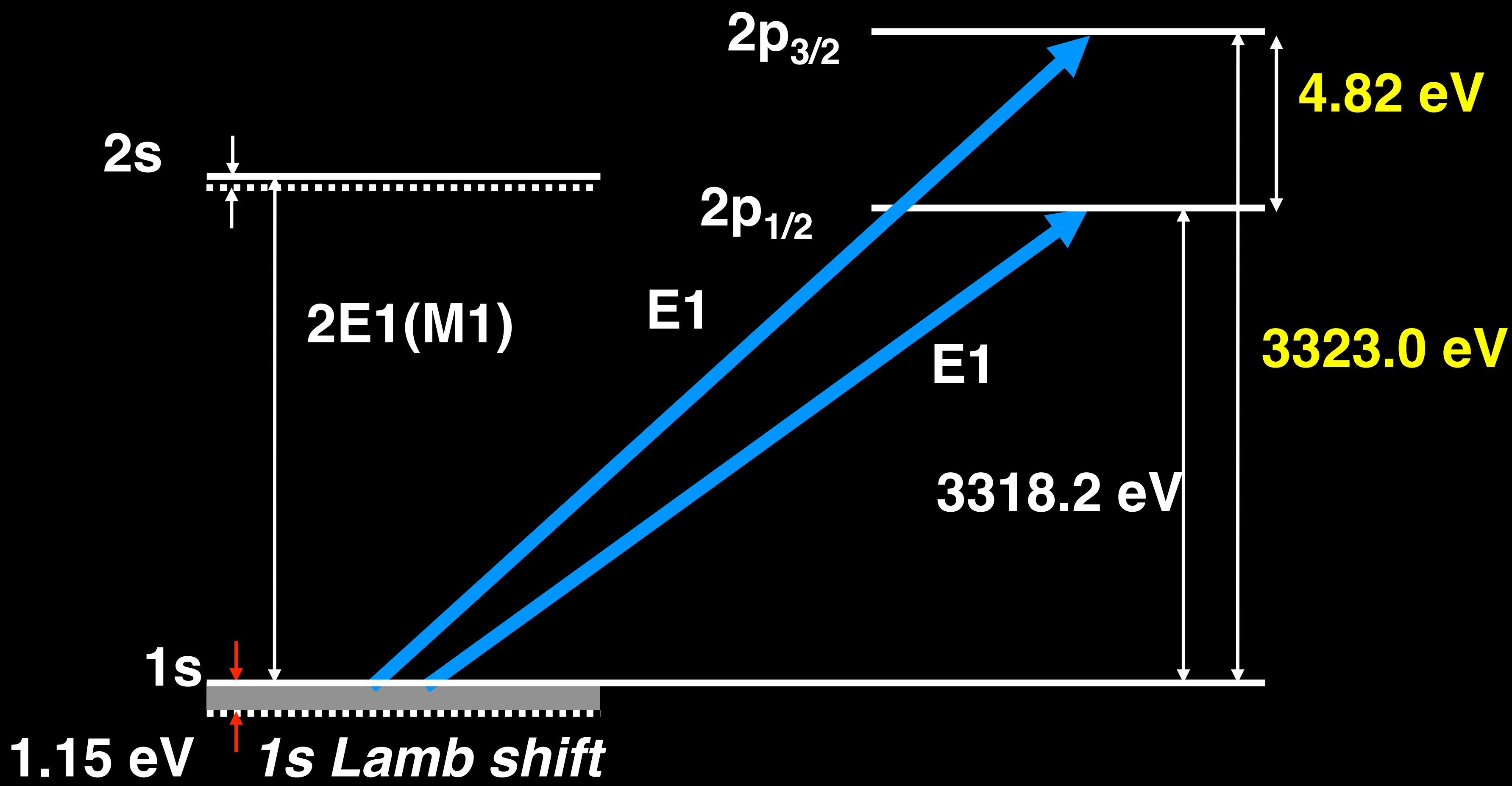
interaction frequency in 3D-RCE
→ frequency traversing the atomic planes

the atomic planes are specified by corresponding to reciprocal vector of with Miller Index (*k,l,m*)

$$\vec{g}_{klm} = k\vec{A}^* + l\vec{B}^* + m\vec{C}^*$$

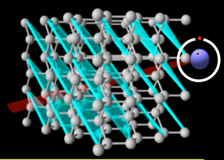
Energy levels of hydrogen-like system

391 MeV/u H-like Ar^{17+}
1s → 2p

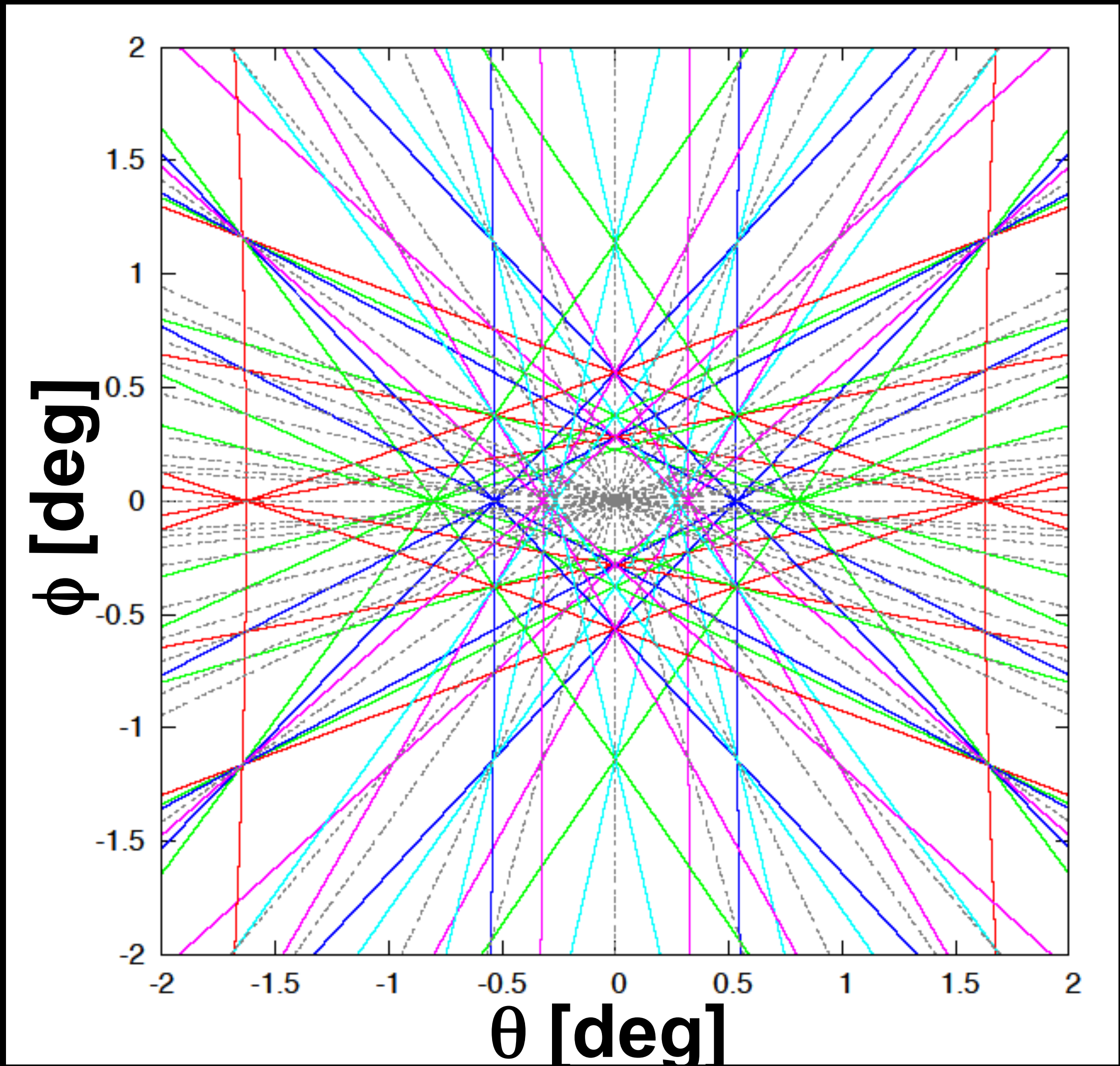


3D-RCE conditions

$$E_{trans} = h\nu_{k,l,n}(\theta,\phi)$$

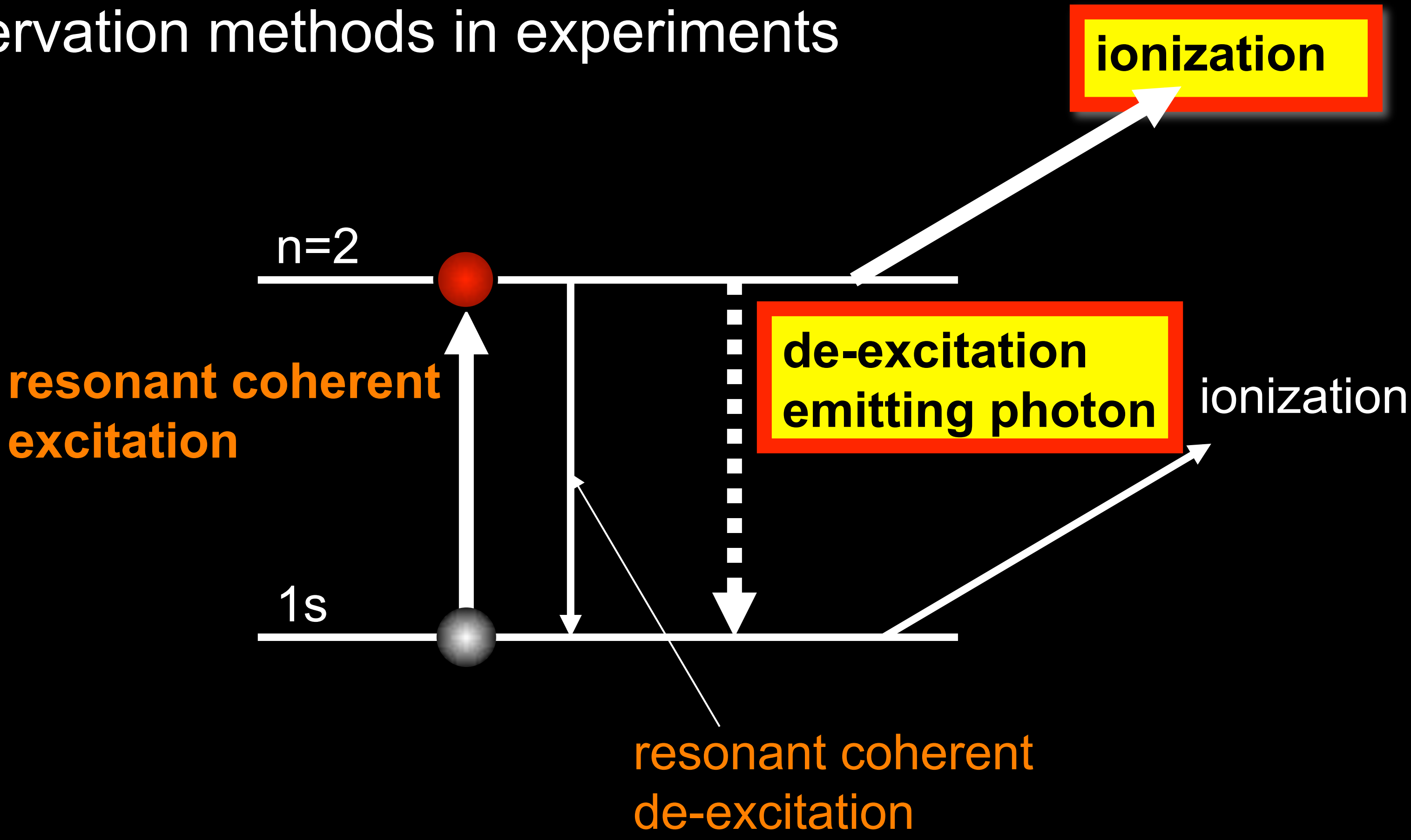


So many resonance conditions in random incidence !



Electronic excitation process

observation methods in experiments

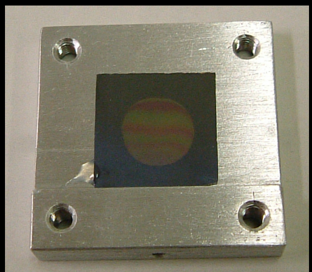


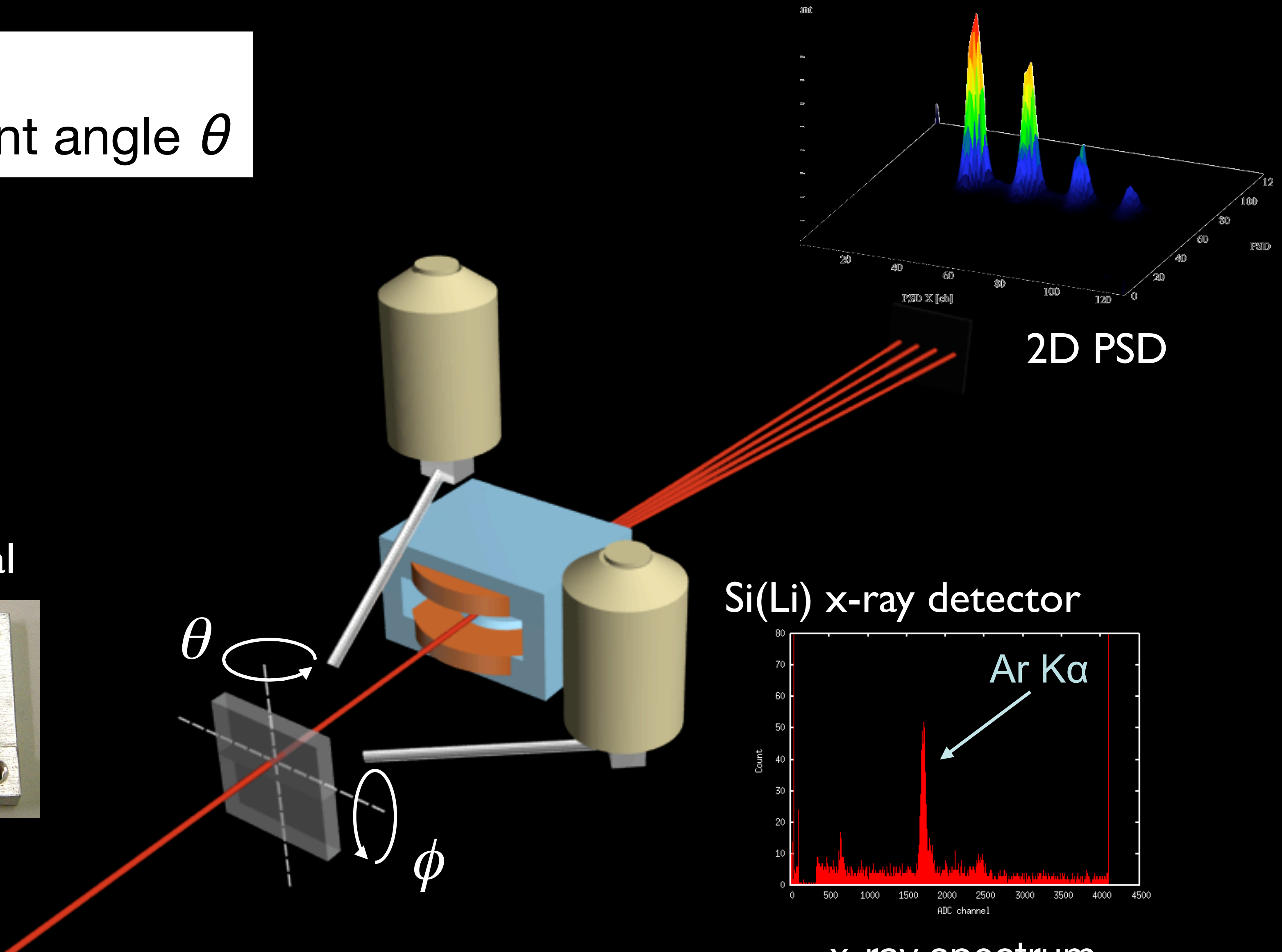
Scanning the crystal angle with respect to the beam,
charge state distribution of ions are monitored

Experimental set up

scan:
incident angle θ

Si crystal





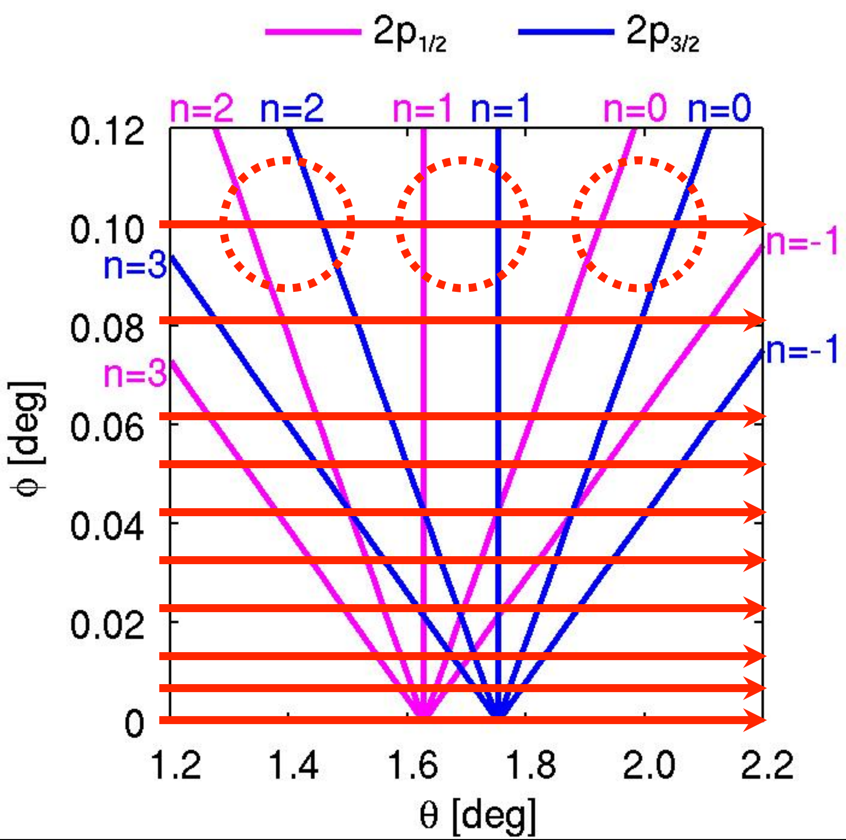
x-ray spectrum

@ HIMAC
416 MeV/u Ar^{16+}

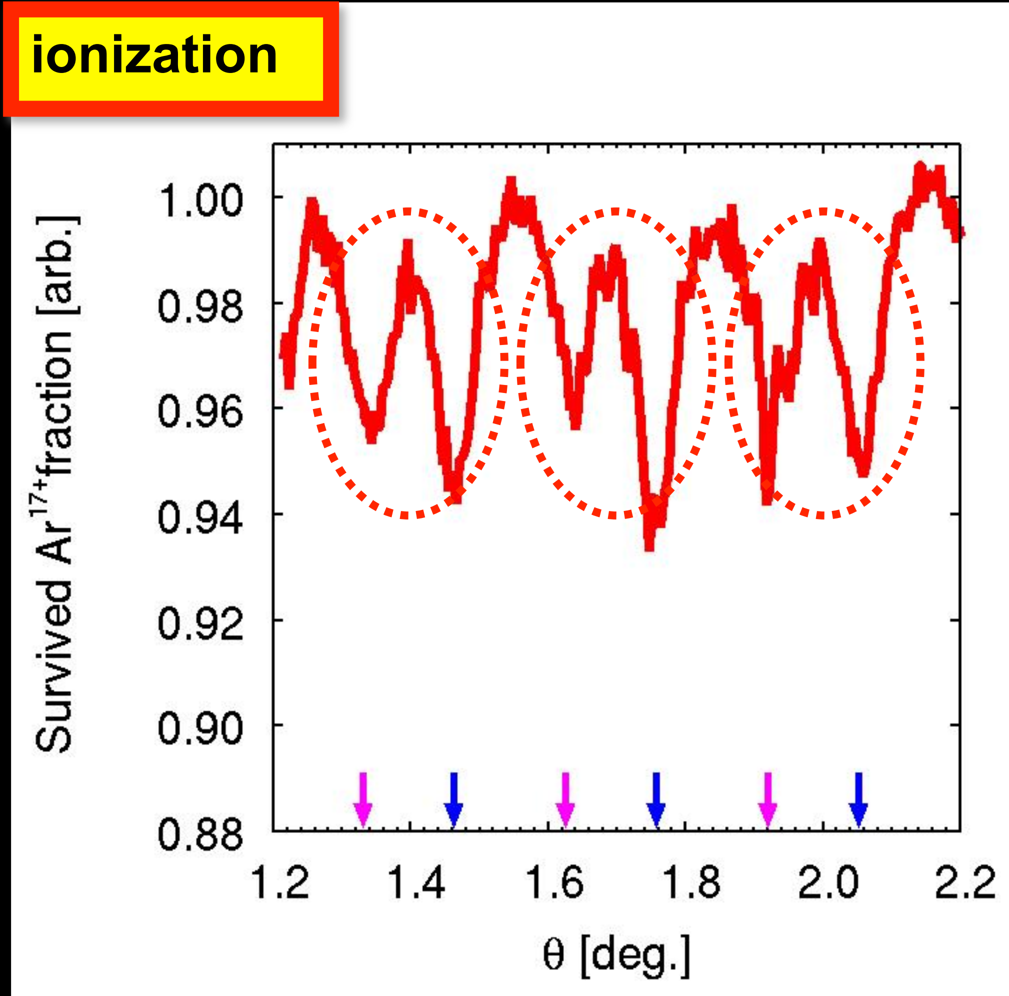
3D-RCE resonance profile

391MeV/u H-like Ar^{17+}

C. Kondo at al, PRL 97 135503(2006)



channeling critical angle
(quasi-channeling)

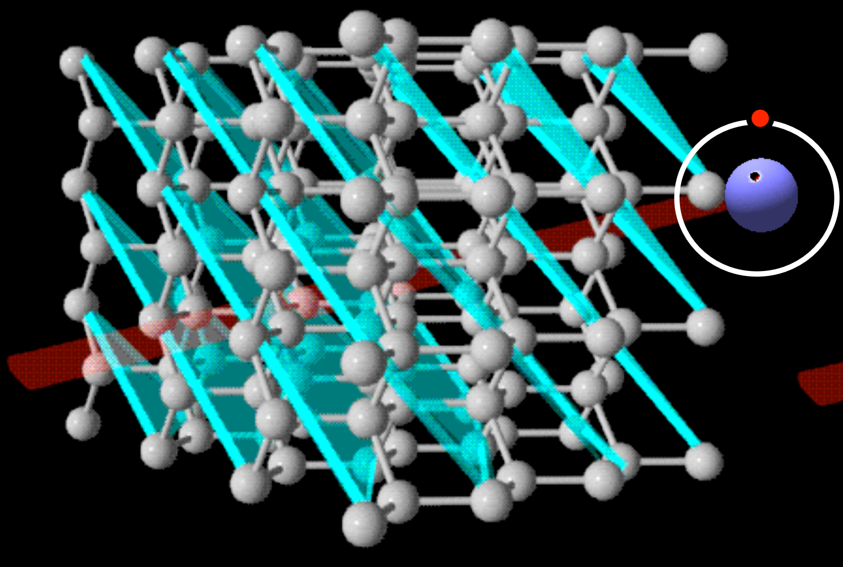


Population Control

Double Resonance

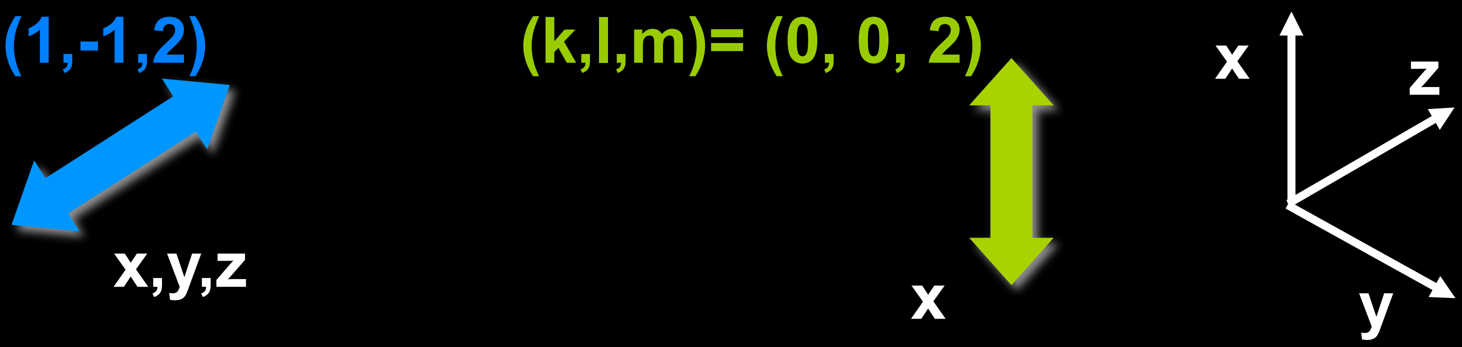
Double resonance / 3D-RCE

Simultaneously, 2 oscillating fields of different frequencies are applied for 2 transitions



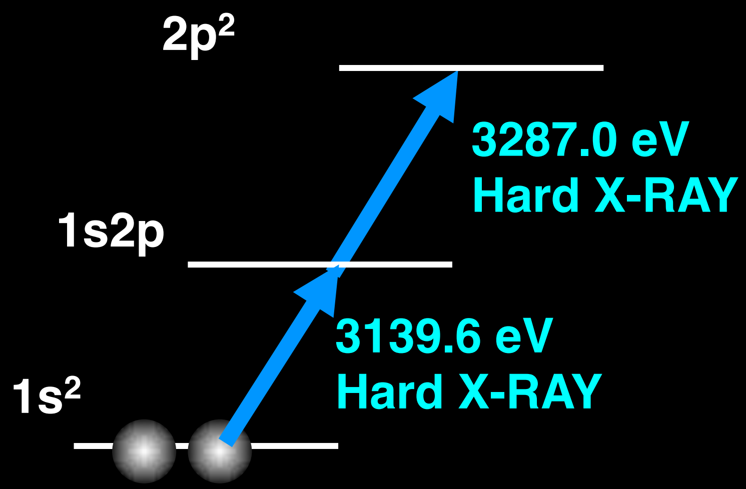
(k,l,m)= (1,-1,2)

(k,l,m)= (0, 0, 2)

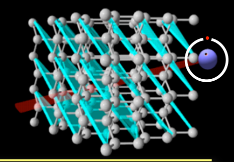


Double Resonance (3 level system in atom)

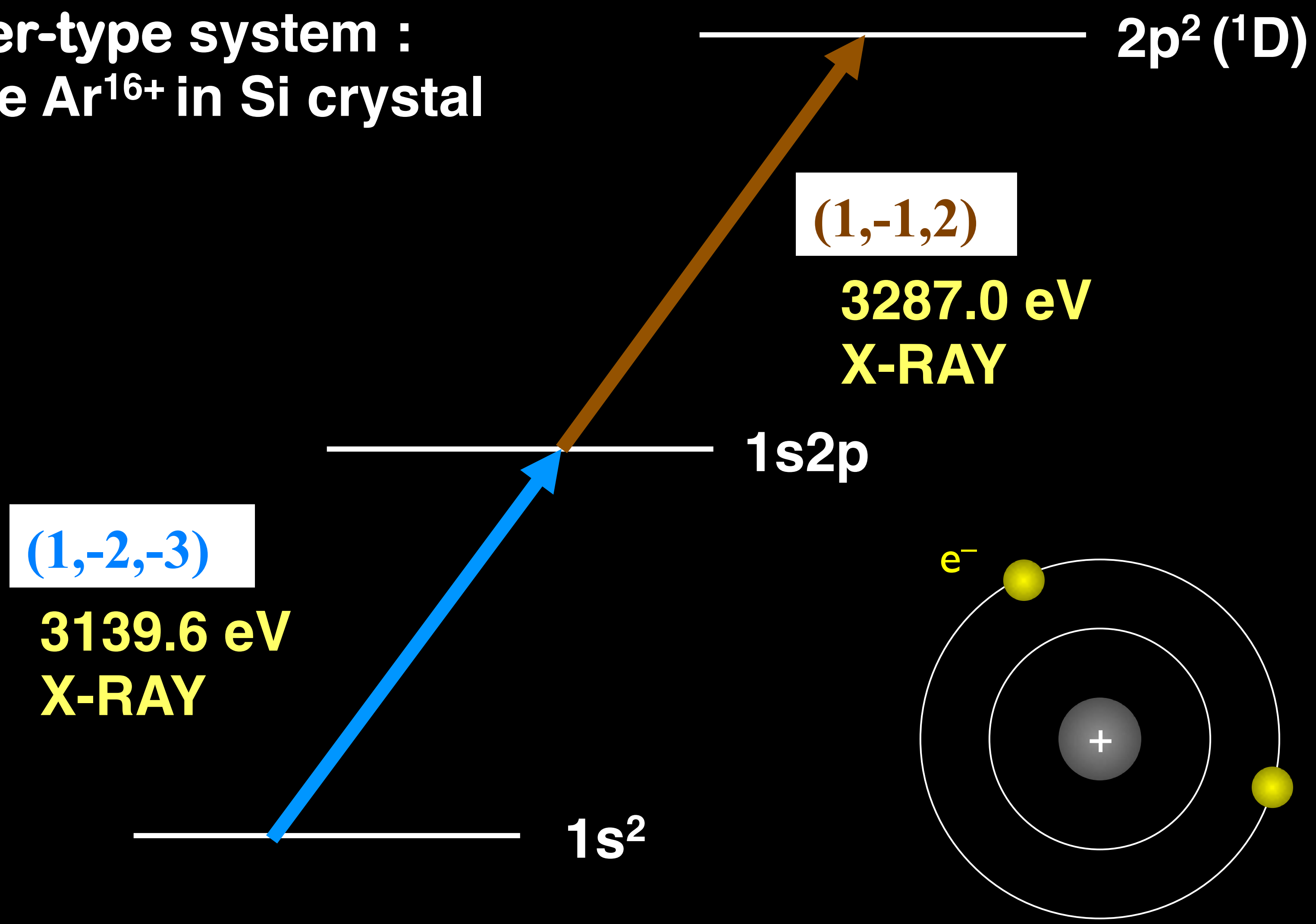
Ladder: doubly excited Ar^{16+}



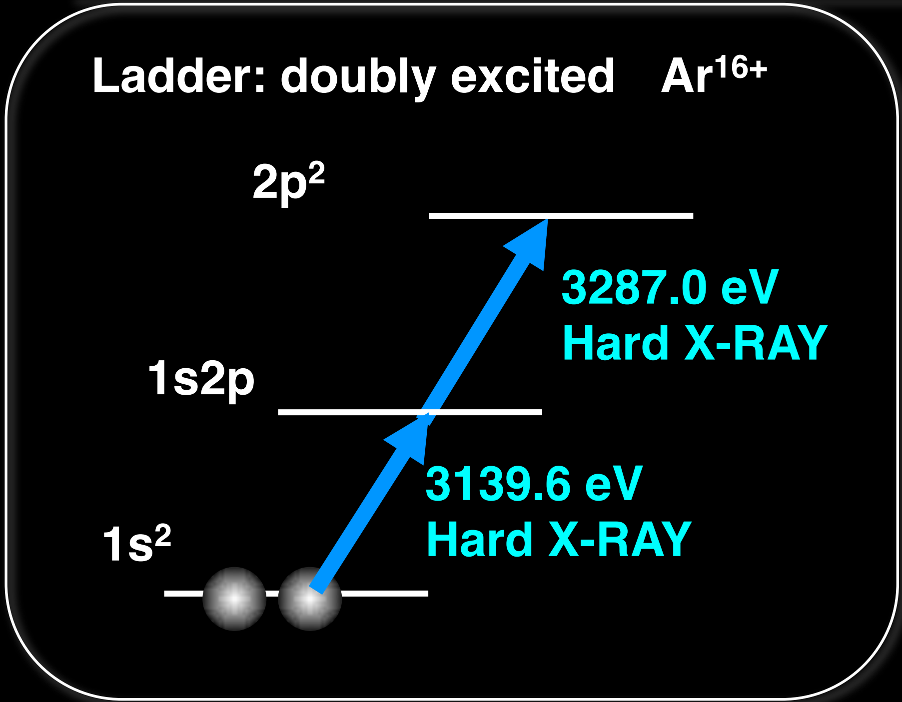
Doubly excited state formation

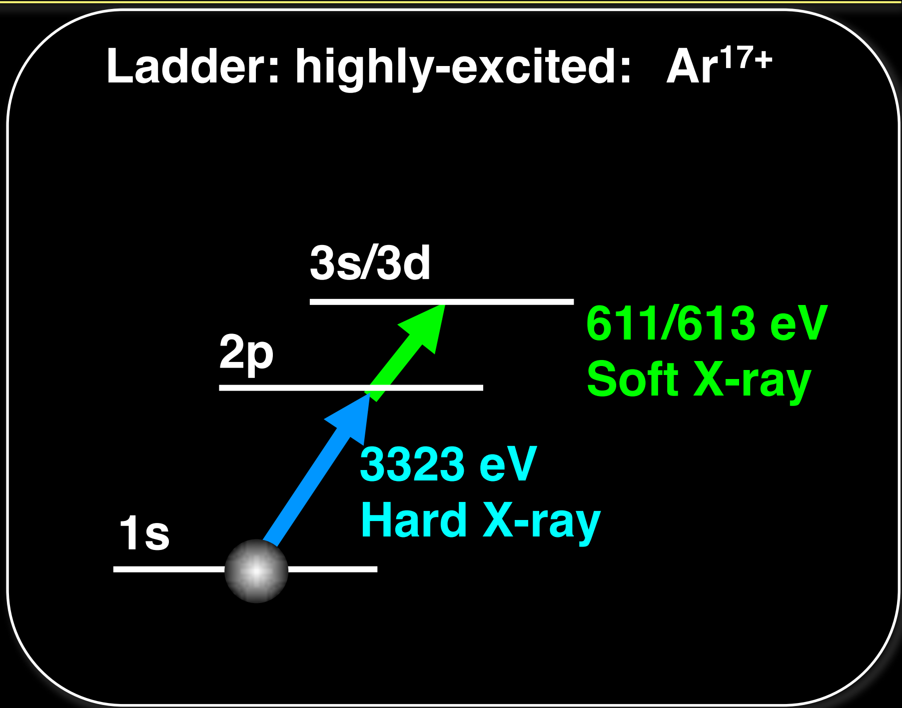


Ladder-type system :
He-like Ar^{16+} in Si crystal

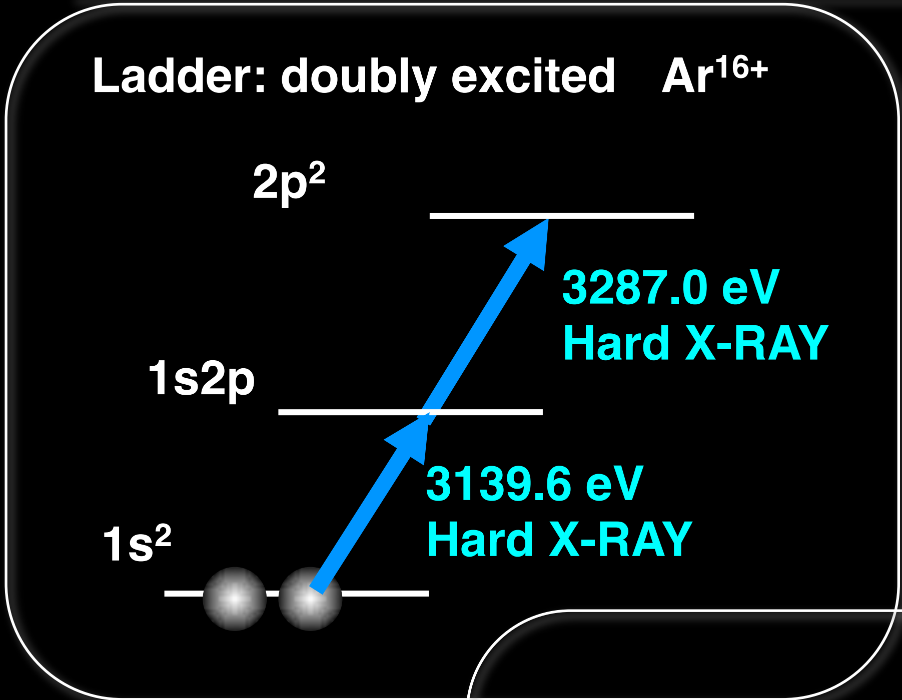


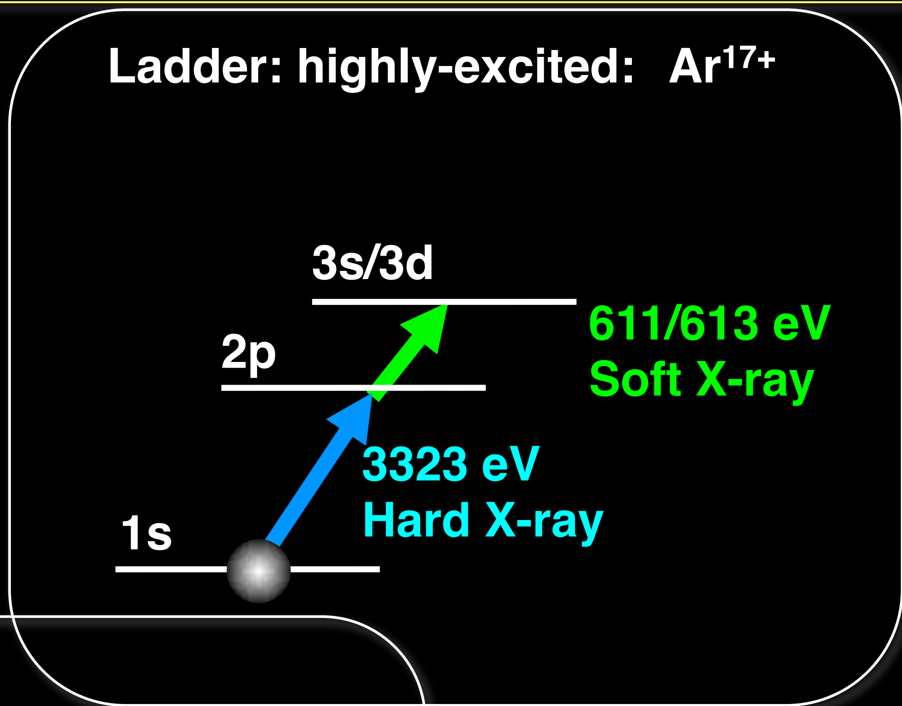
Double Resonance (3 level system in atom)

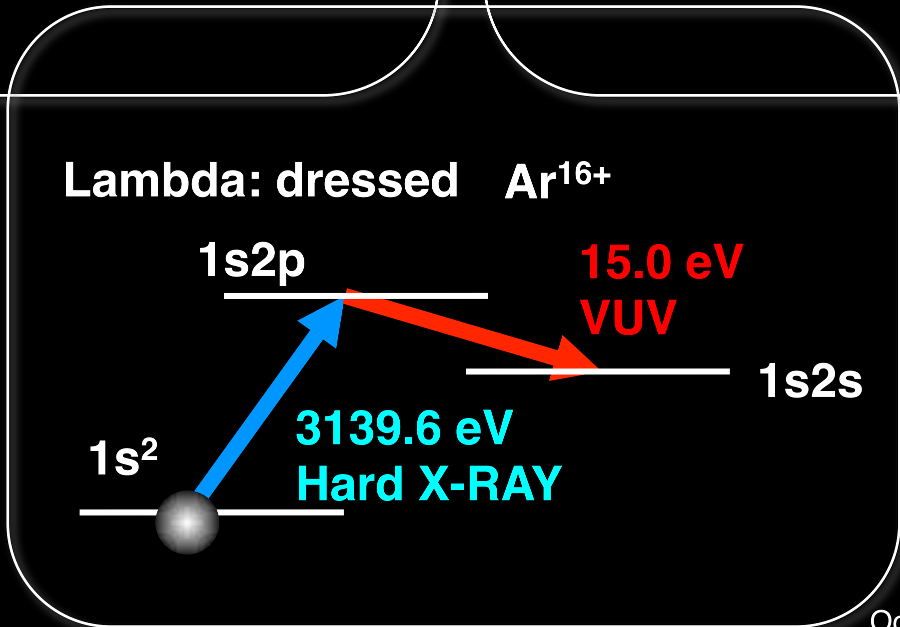




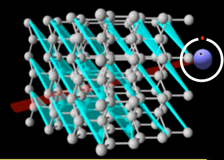
Double Resonance (3 level system in atom)



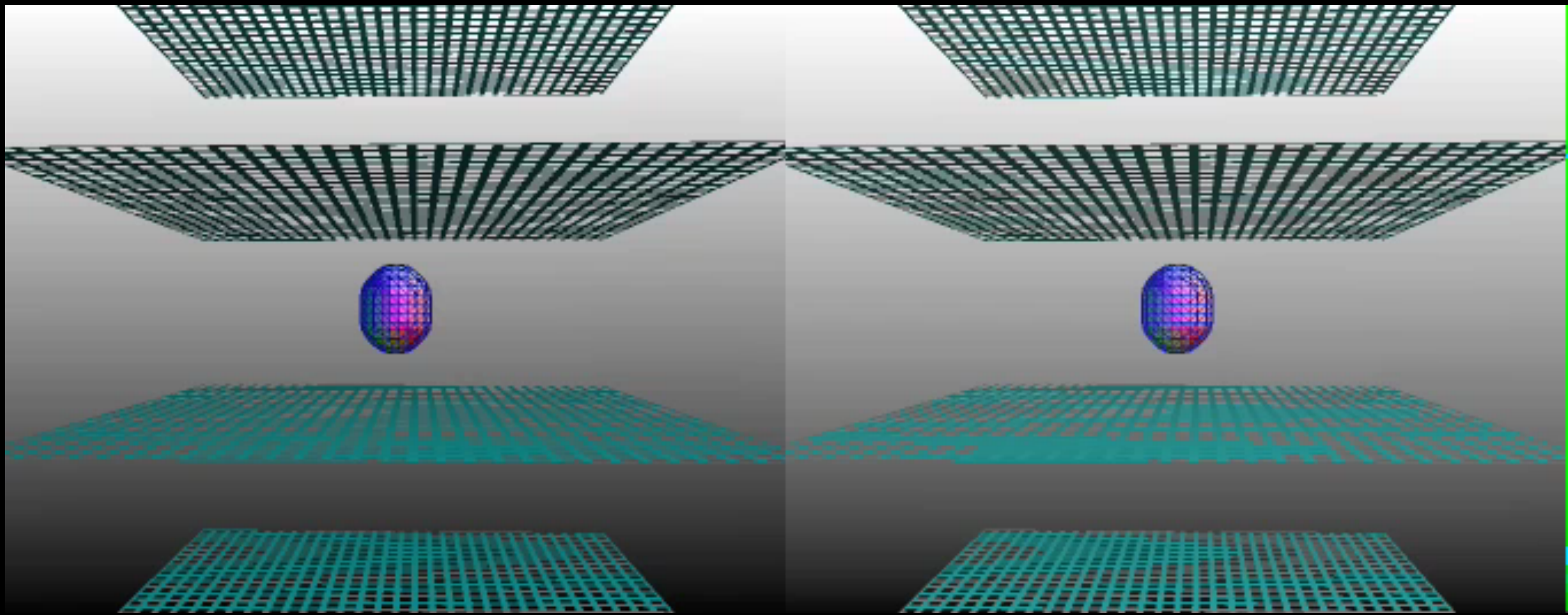




Asymmetric doublets



$|+\rangle$ $|-\rangle$

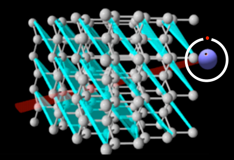


low electron density in the neighborhood of atomic planes

ionization : decrease ⇩
deexcitation: increase ⇧

high electron density in the neighborhood of atomic planes

ionization : increase ⇧
deexitation: decrease ⇩



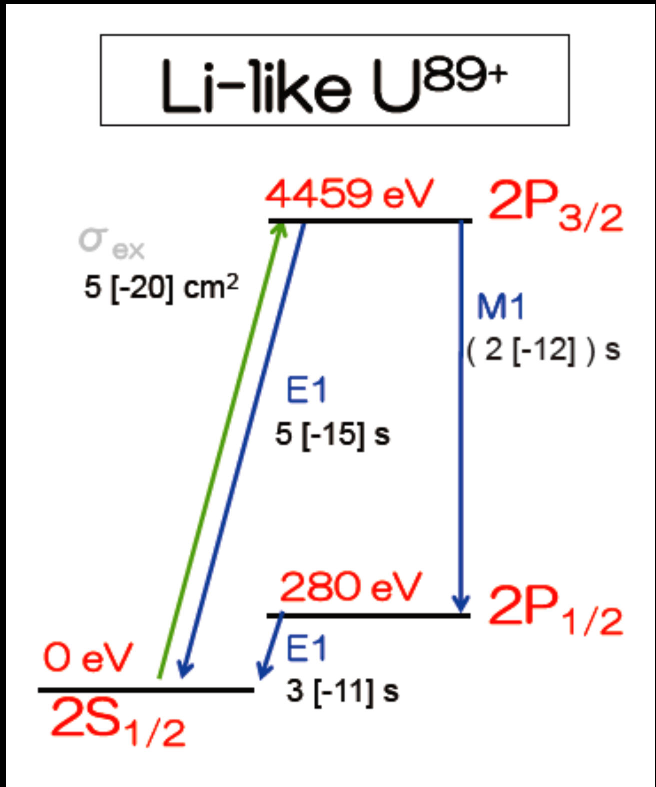
High precision spectroscopy

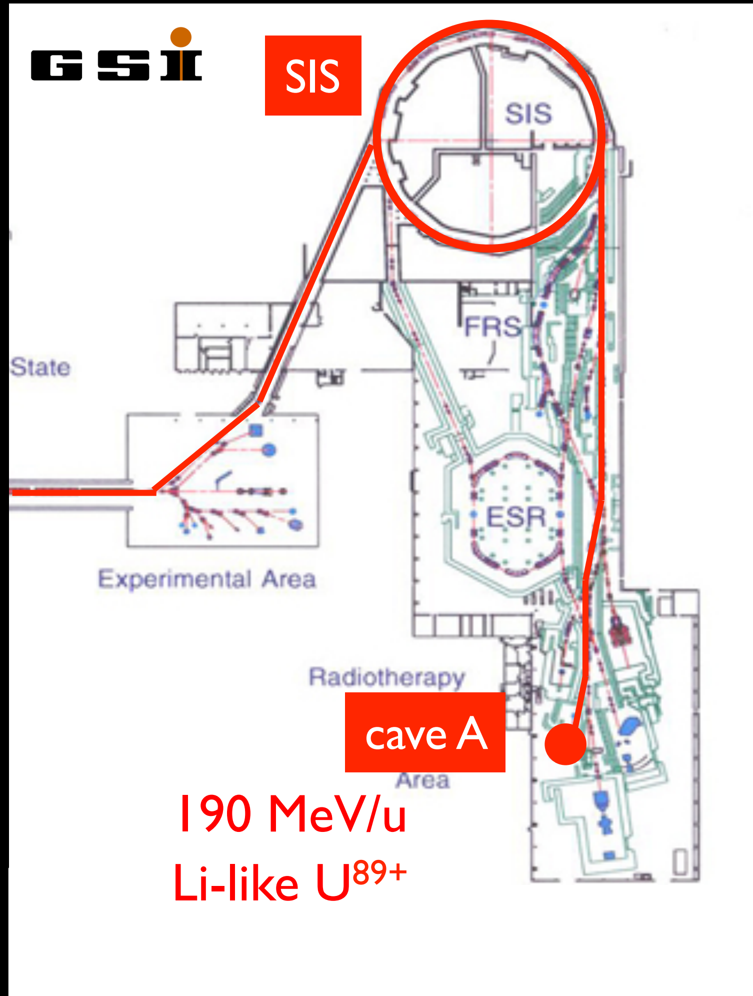
@GSI

2s-2p$_{3/2}$ transition of Li-like U^{89+}

$$\Delta E = 4459.37(21)\ \text{eV}$$

(Beiersdörfer *et al.*)

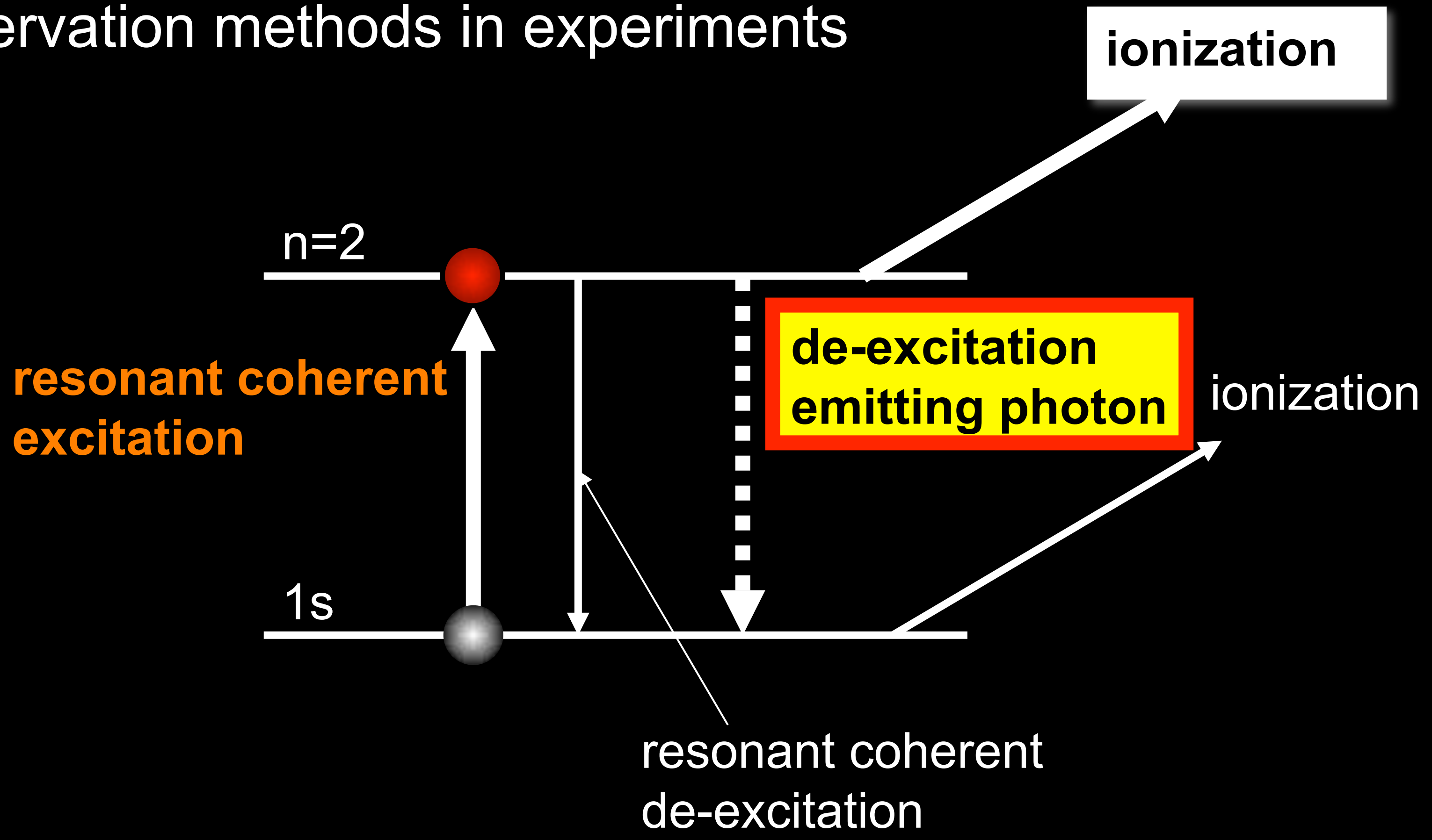




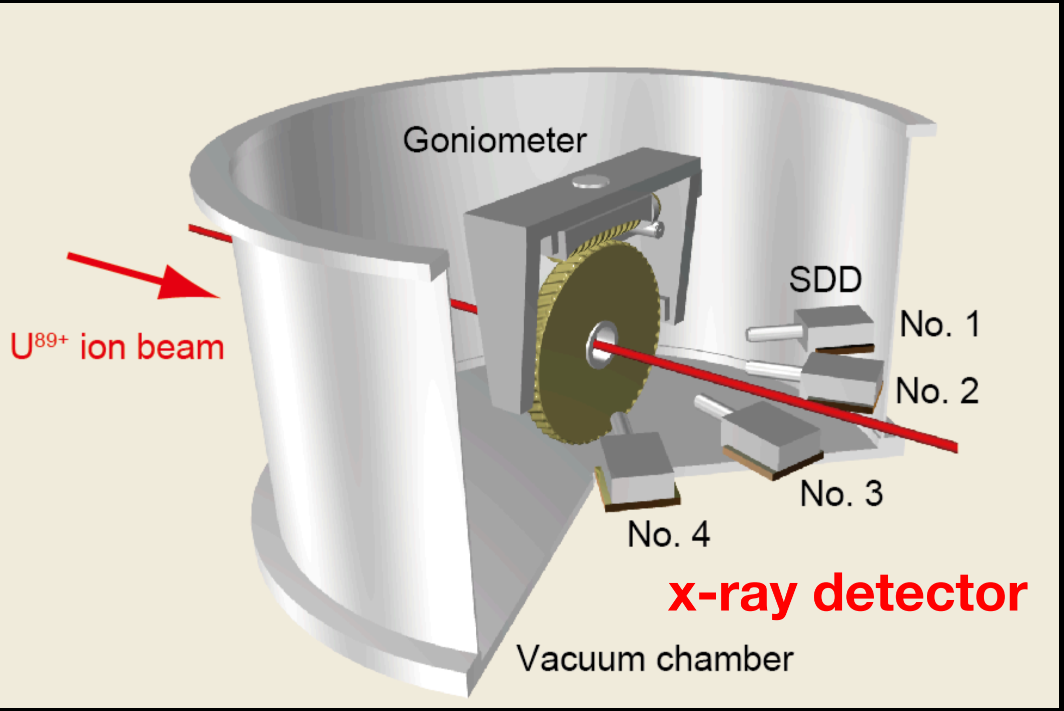
e$^-$ - e$^-$ correlation

Electronic excitation process

observation methods in experiments

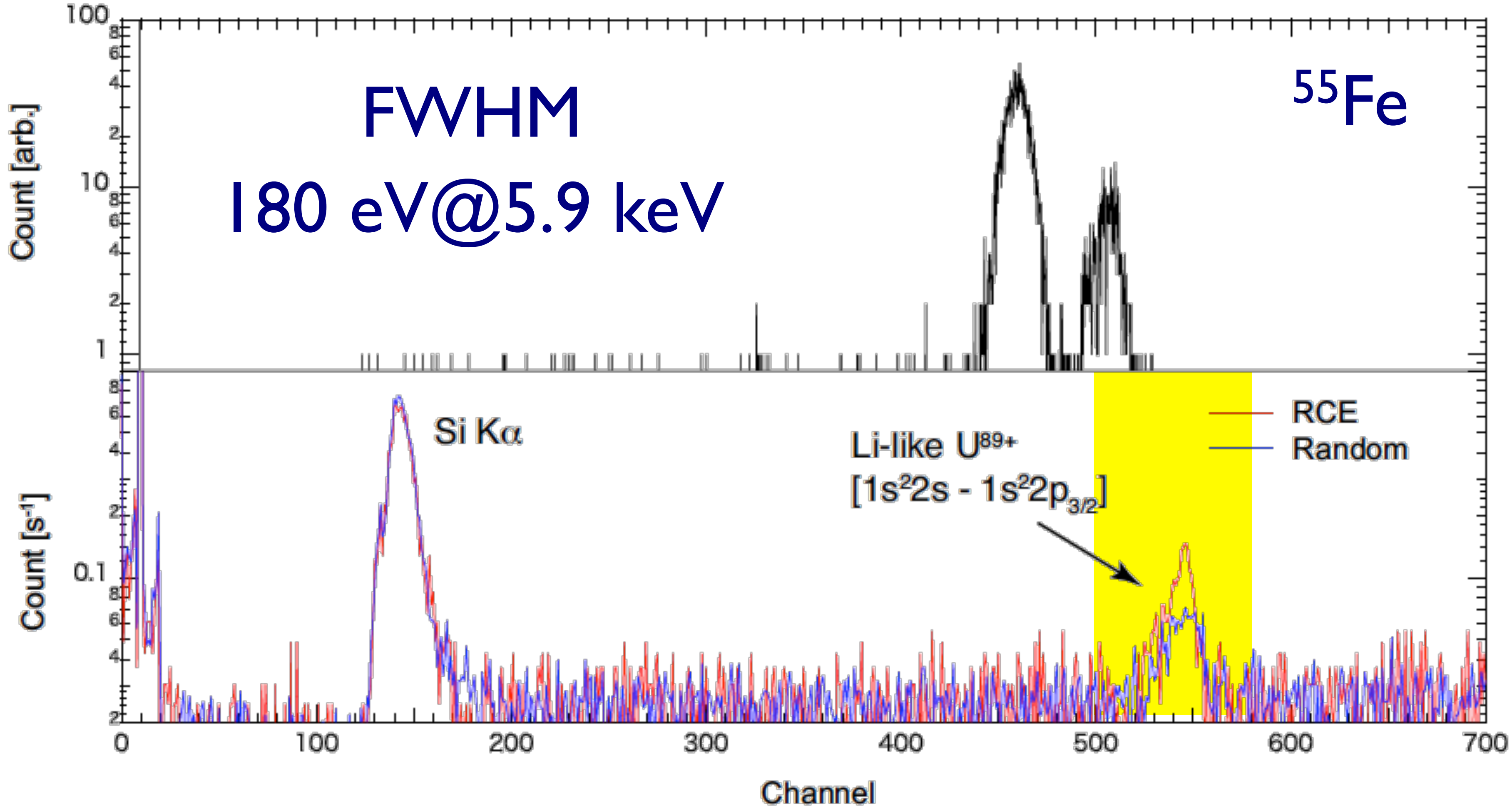


Experimental set up

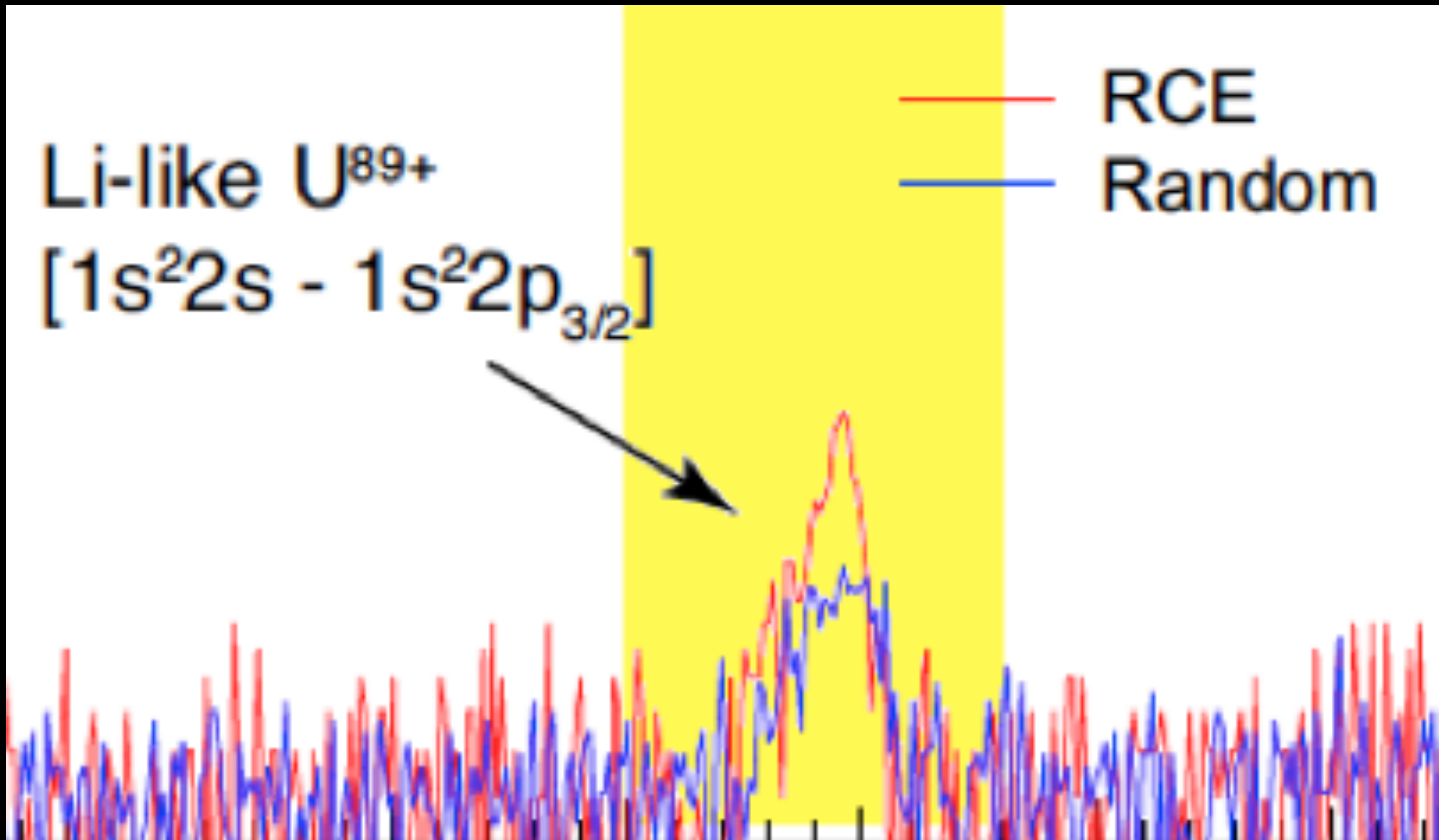


7 μm-thick Si crystal
High-resolution goniometer (μrad)
Four sets of x-ray detectors

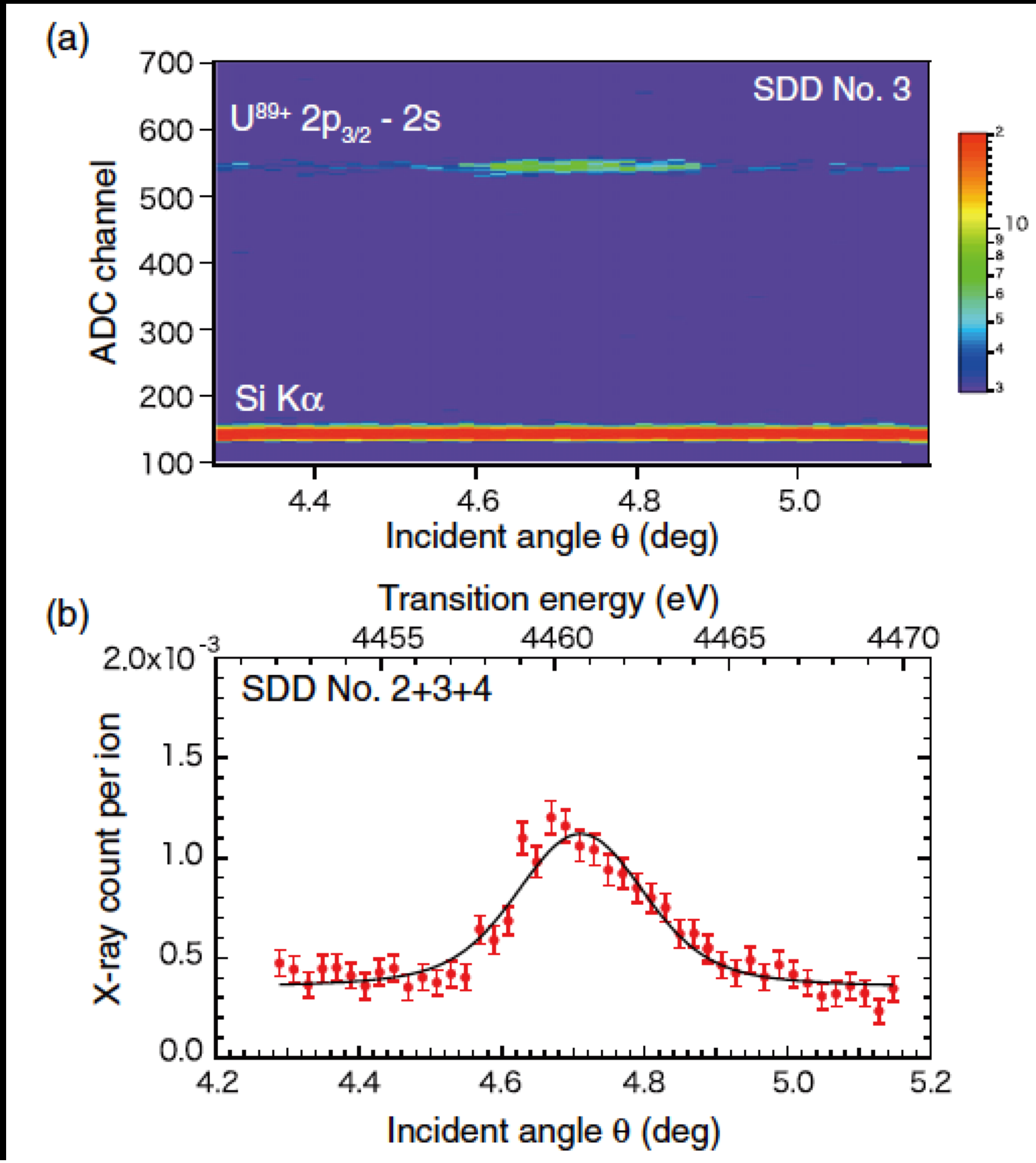
Raw X-ray spectra



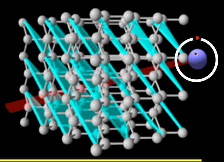
X-ray spectra

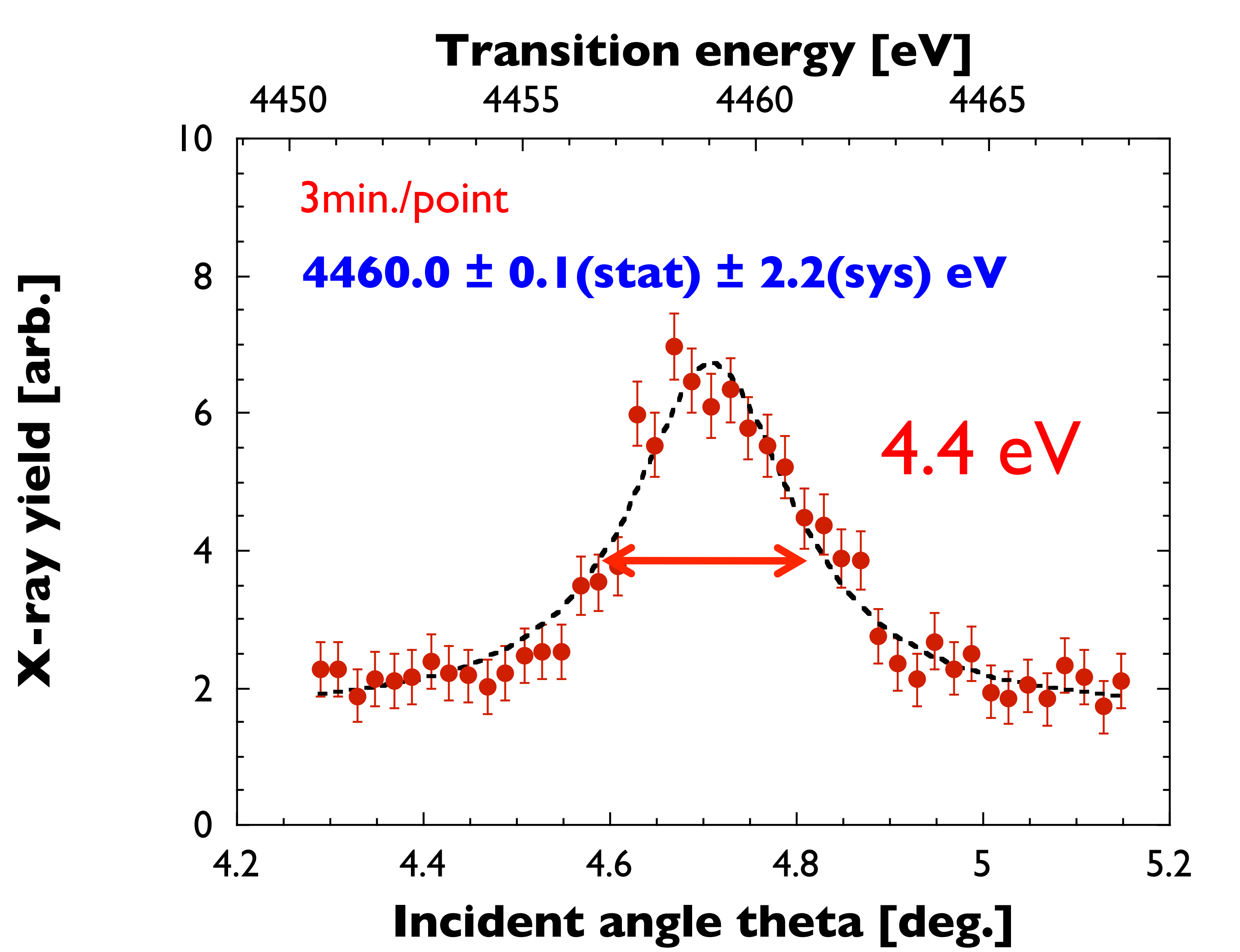


RCE spectra


(a)
SDD No. 3
U89+ 2p3/2 - 2s
Si Kα
ADC channel
Incident angle θ (deg)
(b)
Transition energy (eV)
SDD No. 2+3+4
X-ray count per ion
Incident angle θ (deg)

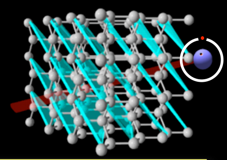
RCE spectra





Transition energy [eV]
4450
4455
4460
4465
3min./point
4460.0 ± 0.1(stat) ± 2.2(sys) eV
4.4 eV
X-ray yield [arb.]
0
2
4
6
8
10
4.2
4.4
4.6
4.8
5
5.2
Incident angle theta [deg.]

Our progress



Exp. 2007: crystaline coherence (published in 2008)

Physics
spotlighting exceptional research

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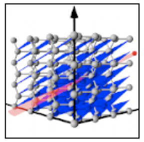
APS » Journals » Physics » Synopses » Crystalline coherence

Crystalline coherence



Dressed Atoms in Flight through a Periodic Crystal Field: X-VUV Double Resonance
Y. Nakai, Y. Nakano, T. Azuma, A. Hatakeyama, C. Kondo, K. Komaki, Y. Yamazaki, E. Takada, and T. Murakami
Phys. Rev. Lett. 101, 113201 (Published September 8, 2008)

ShareThis ShareThis • Atomic and Molecular Physics

Exp. 2009: 2s-2p$_{3/2}$ in Li-like U^{89+} (publised in 2013)

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **87**, 060501(R) (2013)

Resonant coherent excitation of the lithiumlike uranium ion: A scheme for heavy-ion spectroscopy

Y. Nakano,[1,2,*] Y. Takano,[1,3] T. Ikeda,[1] Y. Kanai,[1] S. Suda,[1,2] T. Azuma,[1,2] H. Bräuning,[4] A. Bräuning-Demian,[4] D. Dauvergne,[5] Th. Stöhlker,[4,6,7] and Y. Yamazaki[1,3]
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(Received 7 September 2012; published 7 June 2013)

Next week (20.Oct.2014 -)

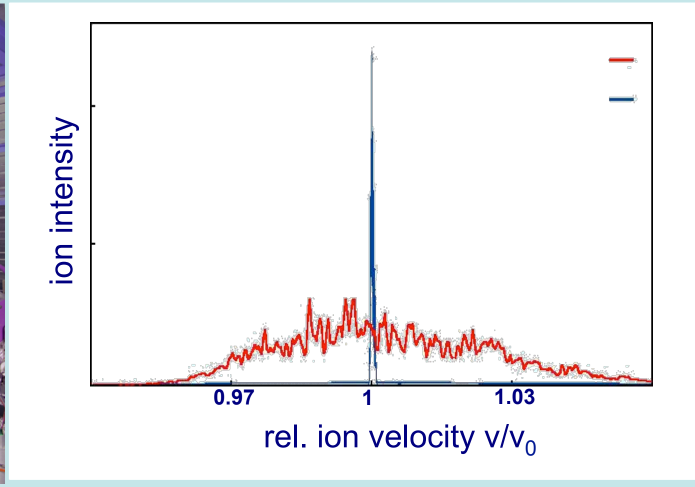
Resonance width

Energy Resolution: 4.4 eV (1.1×10^{-3})

$\Delta P/P$	7×10^{-4}
Energy loss	5×10^{-4}
Divergence	1×10^{-4}
Stripper	9×10^{-5}
Collision	1×10^{-13}
Natural width	1×10^{-14}

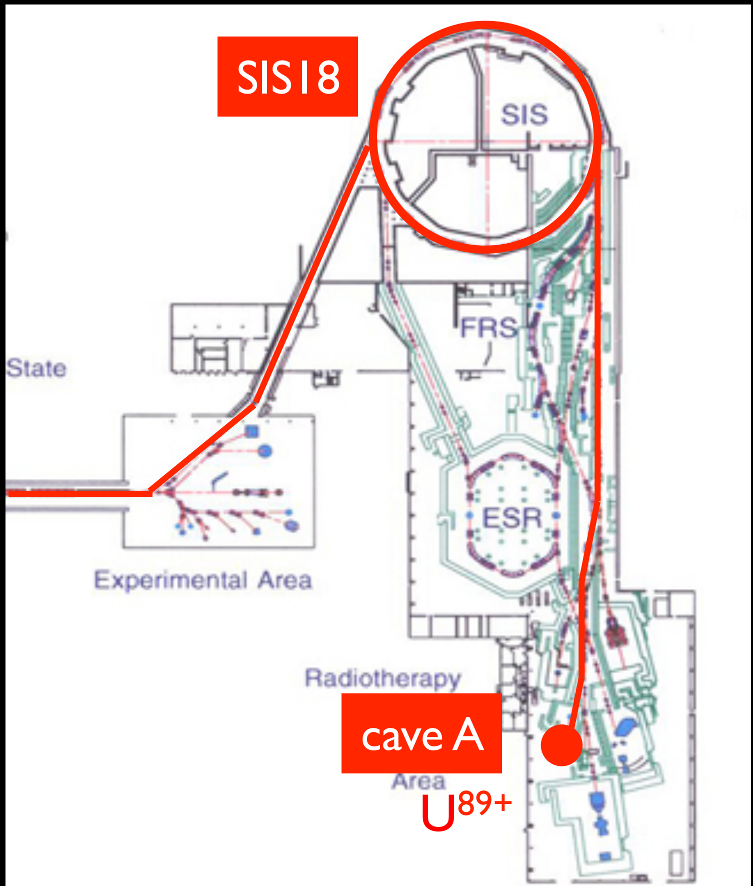
$< 10^{-4}$

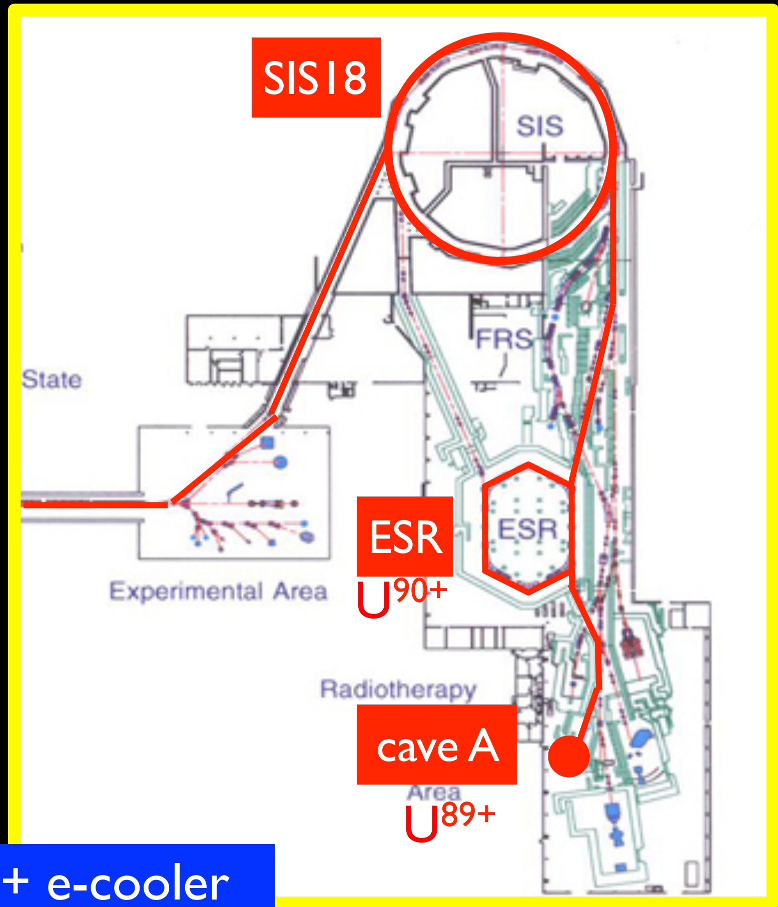
Electron cooling of the beam



2009

NEXT-WEEK





ESR + e-cooler
$\Delta p/p < 1.0 \times 10^{-4}$

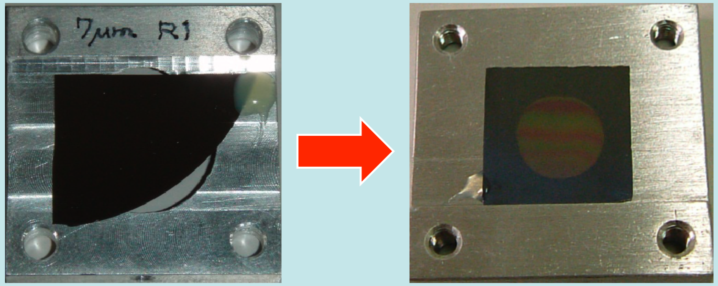
Radiative Recombination
$U^{90+} + e^{-} \rightarrow U^{89+}$

NEXT STEP: Resonance width

Energy Resolution: 4.4 eV (1.1 x 10^{-3})

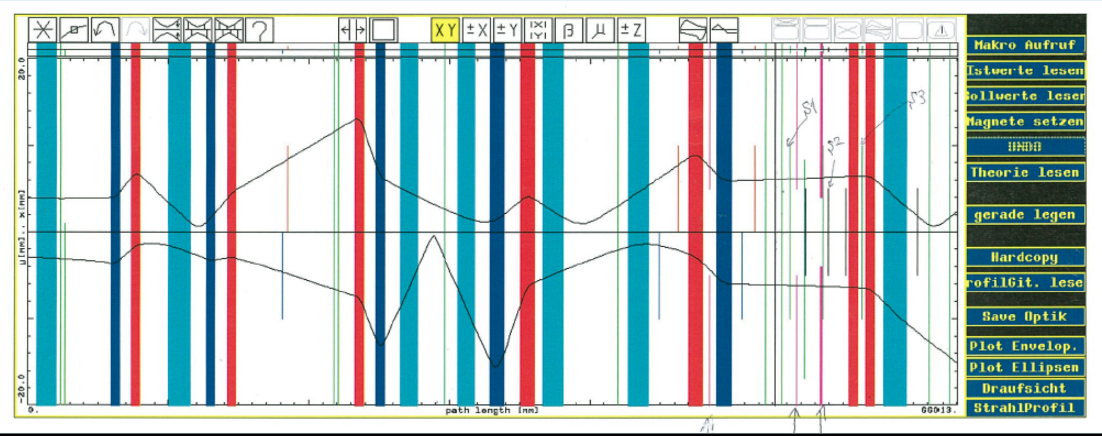
$\Delta P/P$	7 x 10^{-4}	< 10^{-4}
Energy loss	5 x 10^{-4}	5 x 10^{-5}
Divergence	1 x 10^{-4}	
Stripper	9 x 10^{-5}	
Collision	1 x 10^{-13}	
Natural width	1 x 10^{-14}	

Use of thinner target

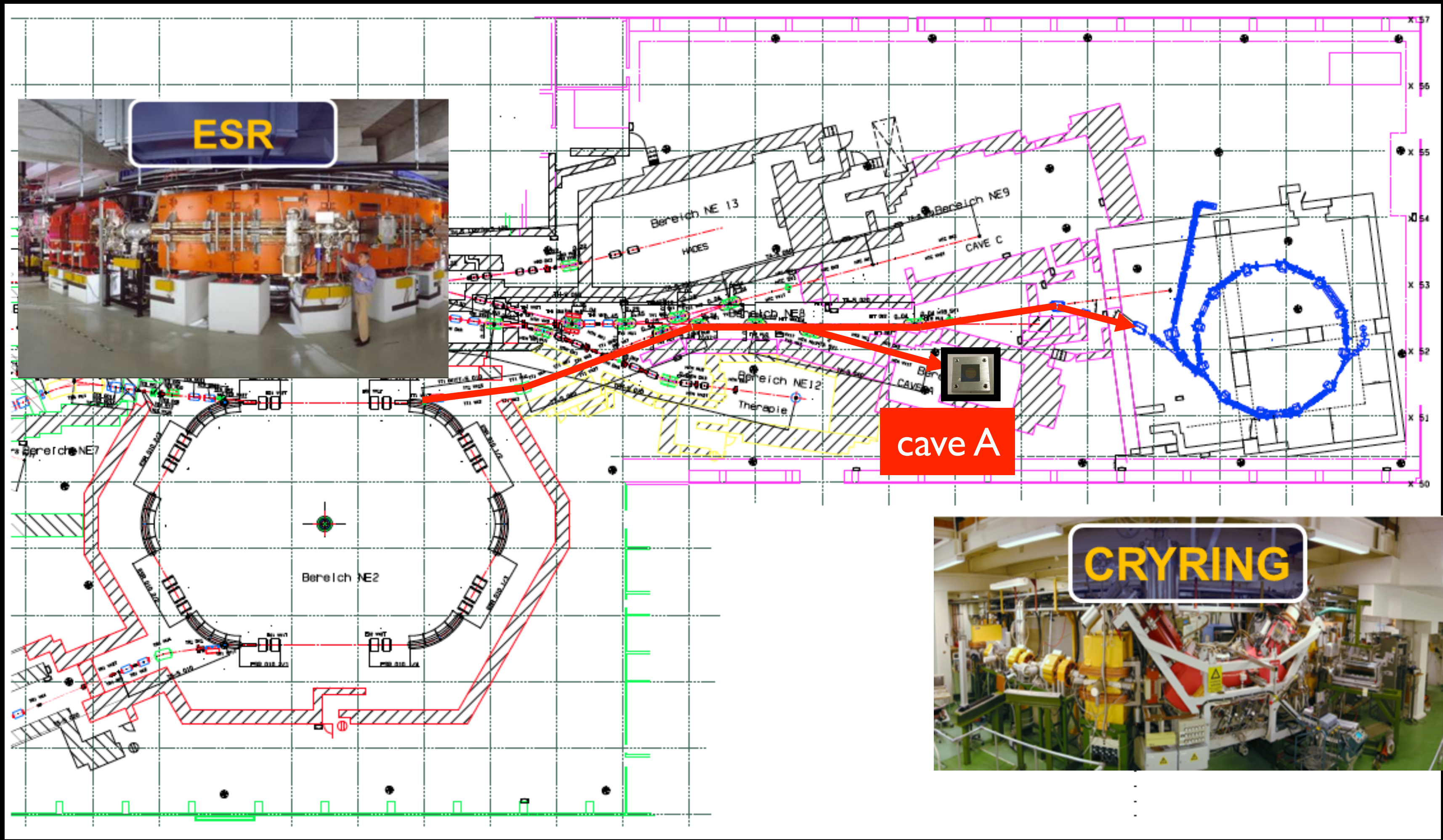


7 µm 0.7 µm

Better beam transporttation from ESR



Better beam transportation from ESR

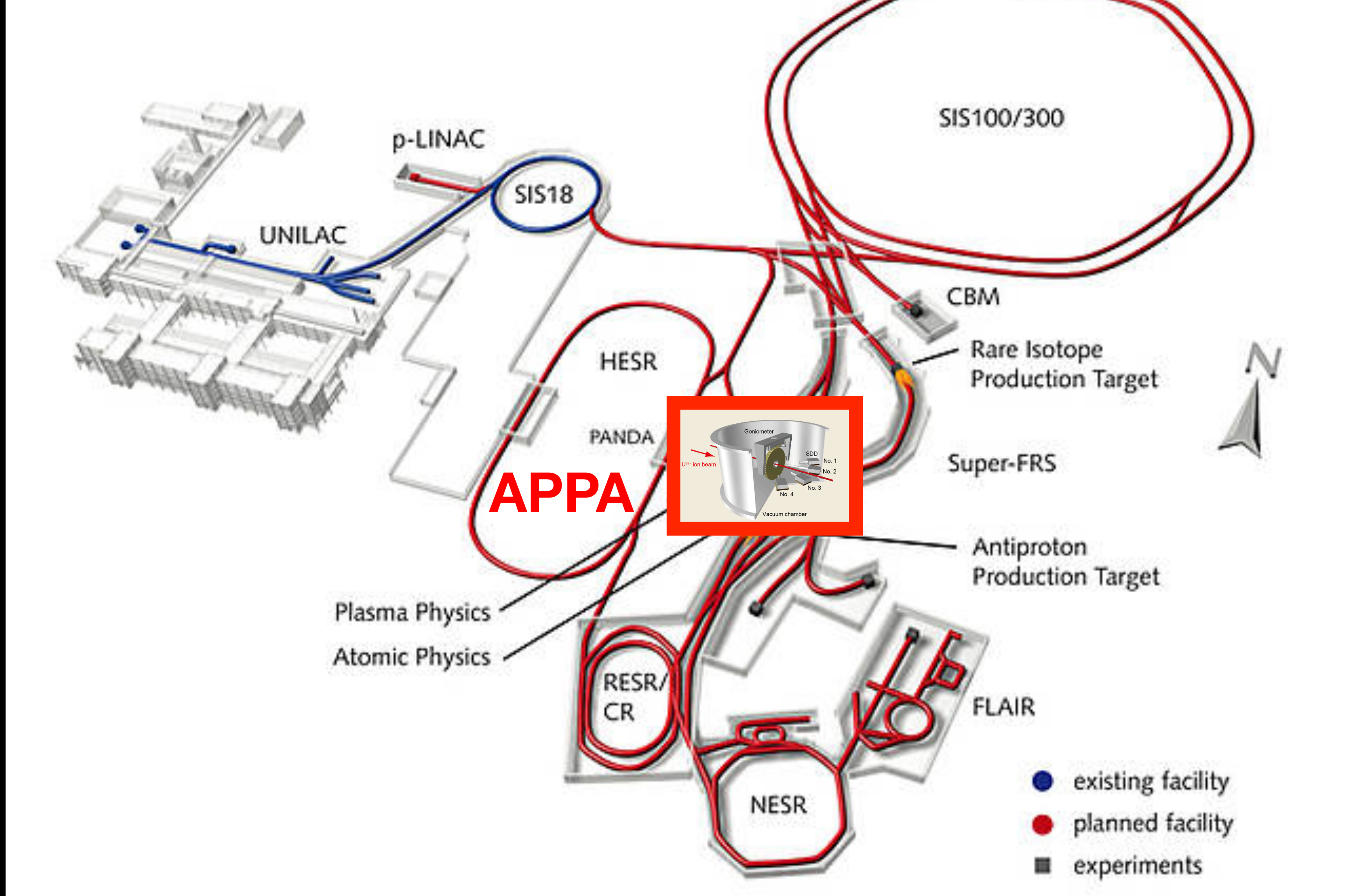


CRYRING moved from Manne-Siegbahn to GSI in 2013.
Injection of ions at highest charge state from ESR into CRYRING.

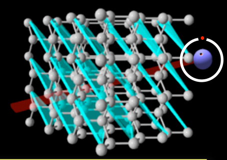
FAIR

NEXT STEP: SIS100 / APPA

1s->2p H-like U^{91+}



ADVANTAGES of RCE technique



RCE channeling is excelent

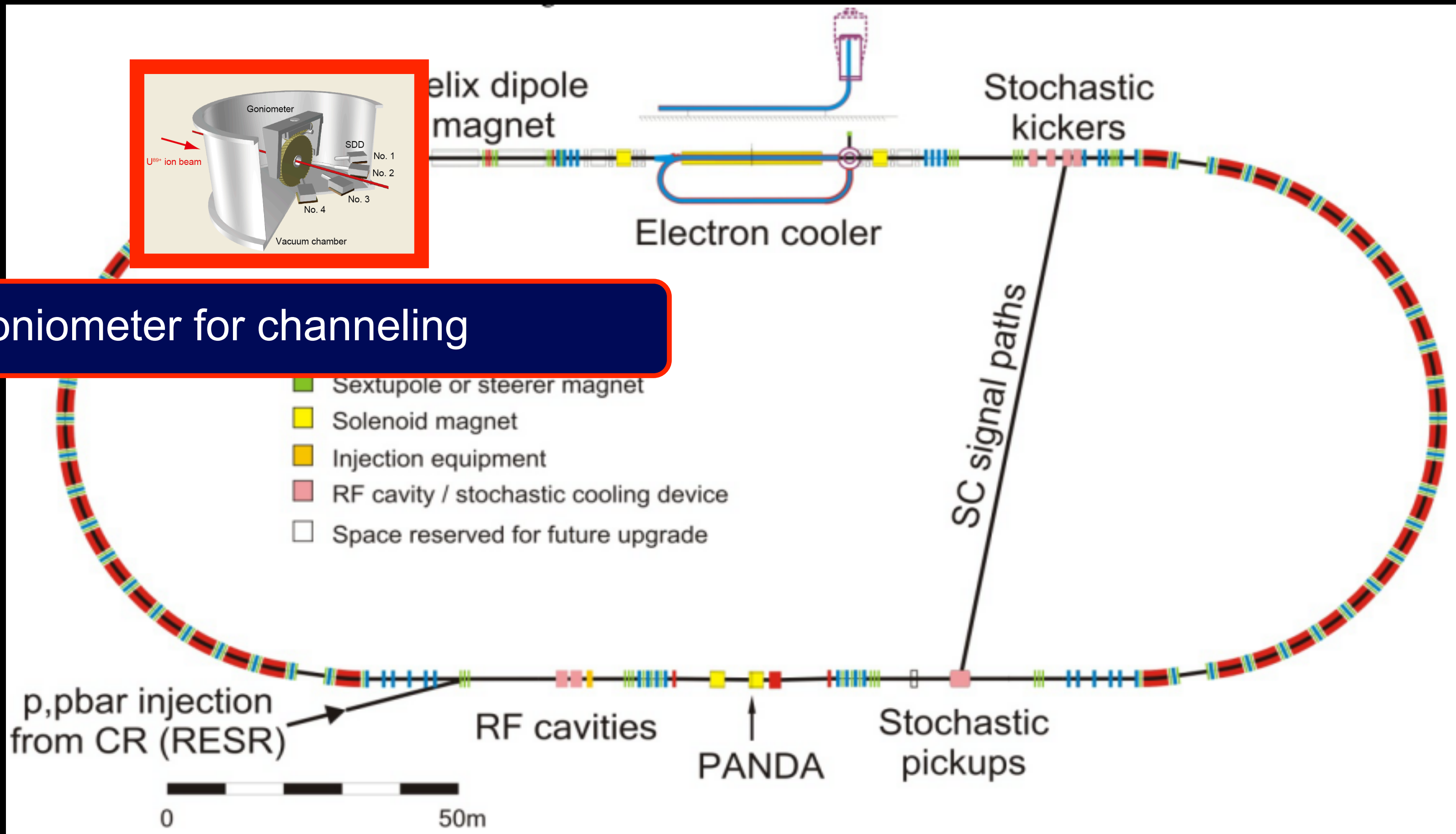
- **Any energy is achievable (wave-length tunable)**
- **Quite high efficiency (good for rare ions)**
- **High resolution (not limited by the detecotr)**
- **Two color experiments are possible**

However, RCE channeling requires

- **Low emittance/small divergence**

(cooling)

NEXT STEP: HESR



goniometer for channeling

A tiny thin crystal is almost nothing for the beams

HESR

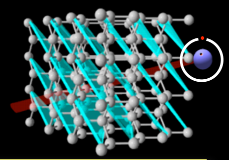
RCE is good for

- **monitoring absolute beam-energy**
- **monitoring beam-luminocity**

- **atomic transition: U^{91+}**

- **nulcear transition: stable-lived nuclei**
- **nulcear transition: short-lived nuclei**

Summary



[Dynamics]

Coherent control of the level population of the heavy ions in the x-ray region

[Spectroscopy]

New novel technique for high precision spectroscopy

Alternative to optical technique