AMO Physics: its diversity and specialty to bridge the gap between physics, biology and medical science

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RIKEN

Two lessons

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Lesson I : Physics and Medical Science

Lesson II : Interdiscplinary Science

one year before ….

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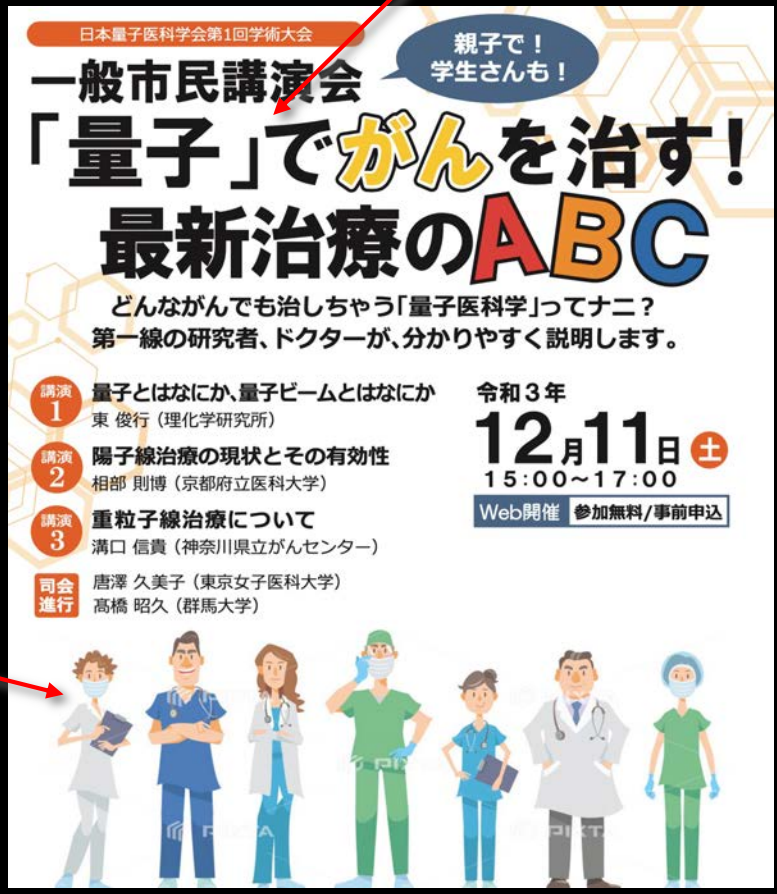
requested from Japanese Quatum Medical Science Society
to provide a public lecture:

the title was
“what is quantum, and
what is quantum beam?”

curing cancer by “quantum”



expected audience ?

Quiz

Is the electron a wave or a particle?

1) wave

2) particle

3) both

4) neither

HIMAC: heavy ion medical accelerator

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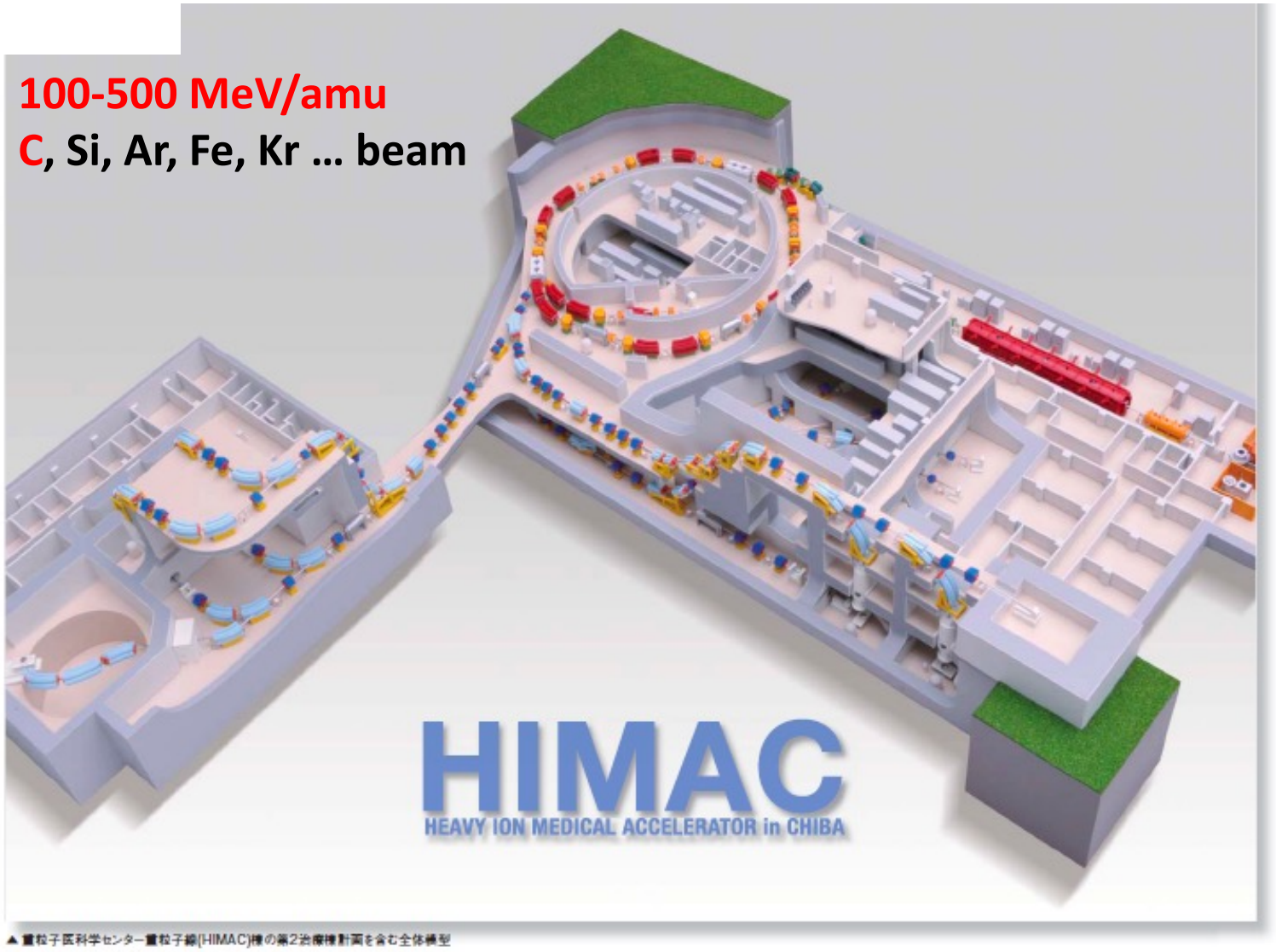
Dedicated for cancer therapy
at National Institute of Radiological Science @Chiba



▲重粒子医科学センター重粒子線(HIMAC)棟の第2治療棟計画を含む全体模型

Cancer irradiation

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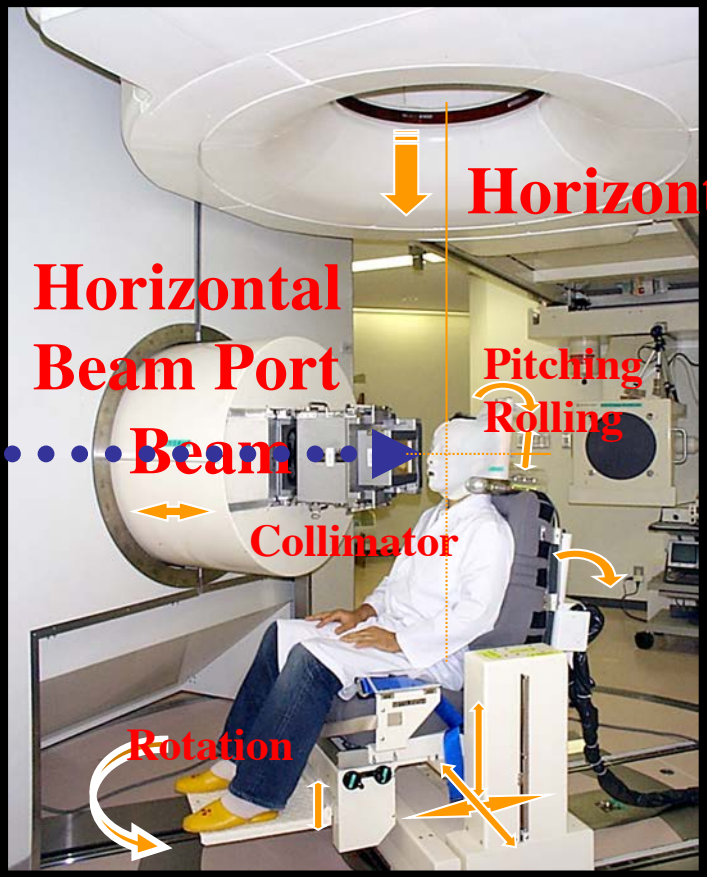
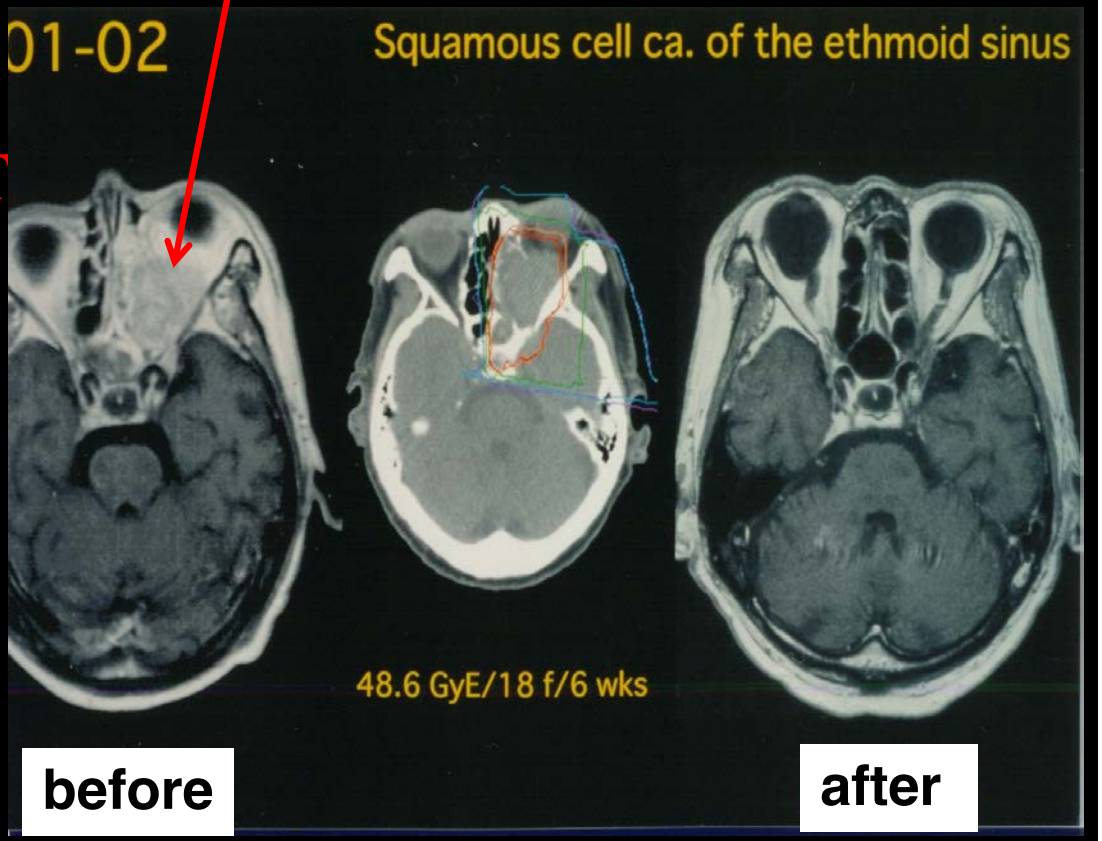


Cancer behind eye

(before / treatment planning / after)



HIMAC: heavy ion medical accelerator

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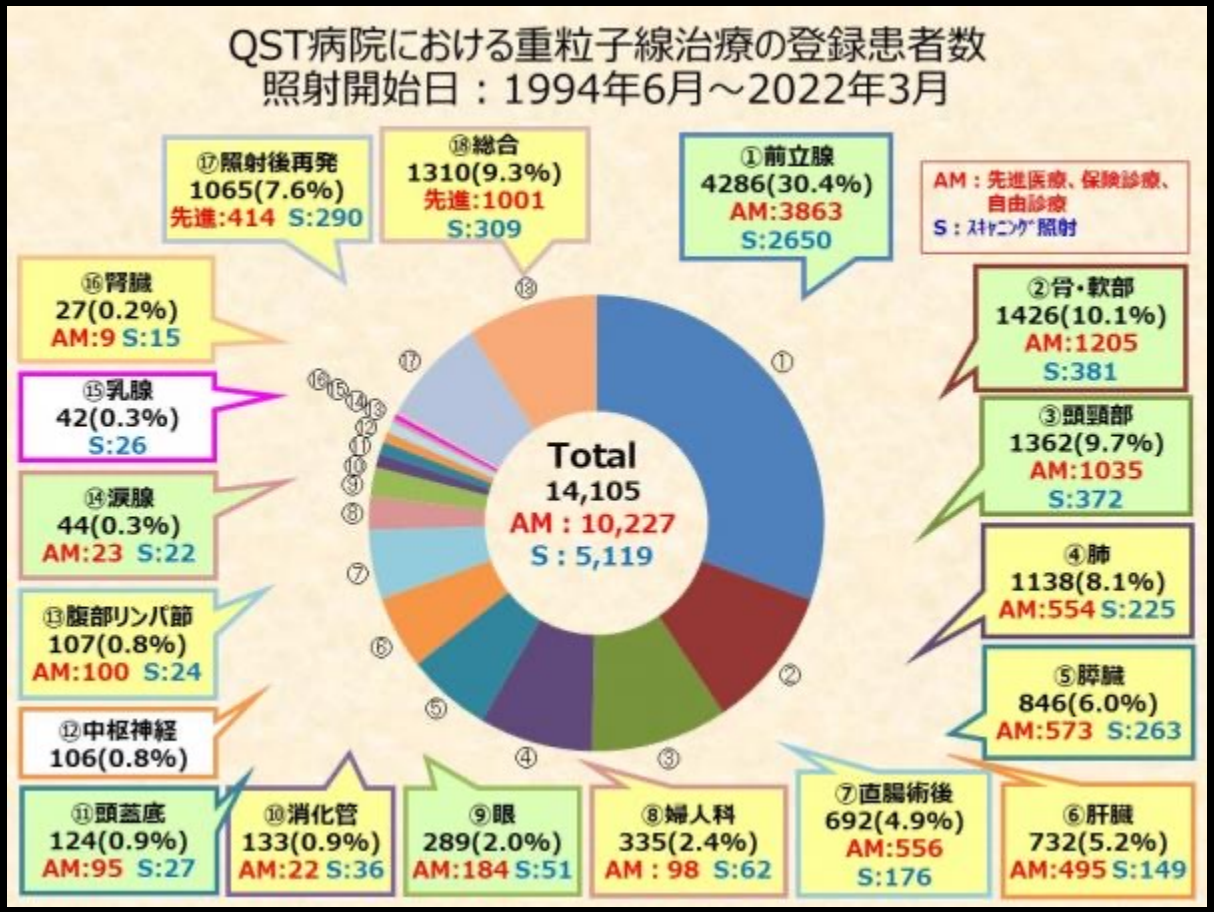
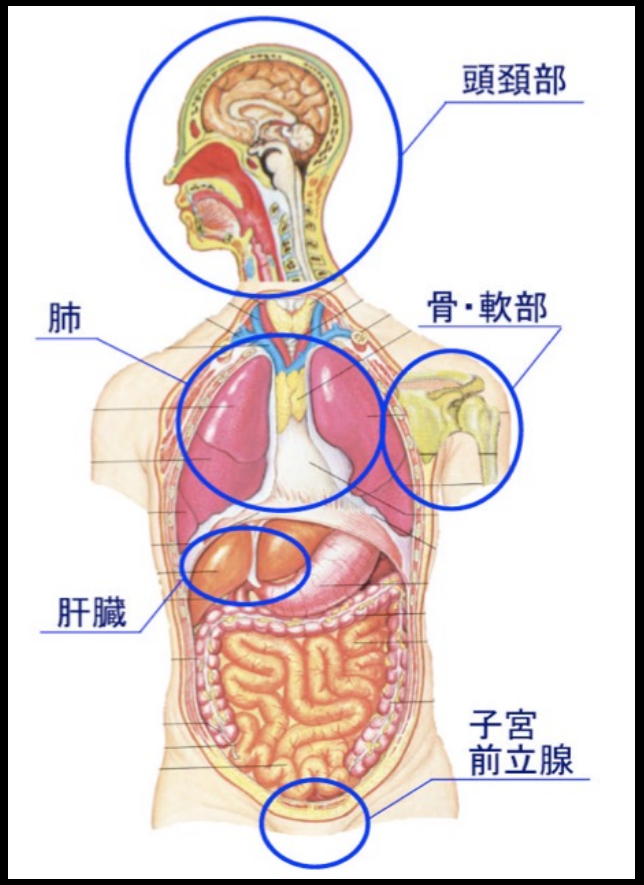
14,000 patients @2022.3





HIMAC: heavy ion medical accelerator

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Ion beams at HIMAC are fast and heavy.
Are they “quantum beam” ?

290 MeV/amu (65% of the speed of light)

Carbon beam (炭素)

so... total energy is 3.5 GeV

de Broglie wavelength = 3.2×10^{-16} m

$$\lambda = \frac{h}{mv}$$

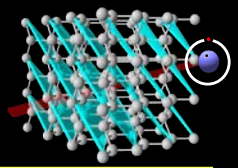
λ : wavelength of wave

m : mass of particle

h : Planck constant

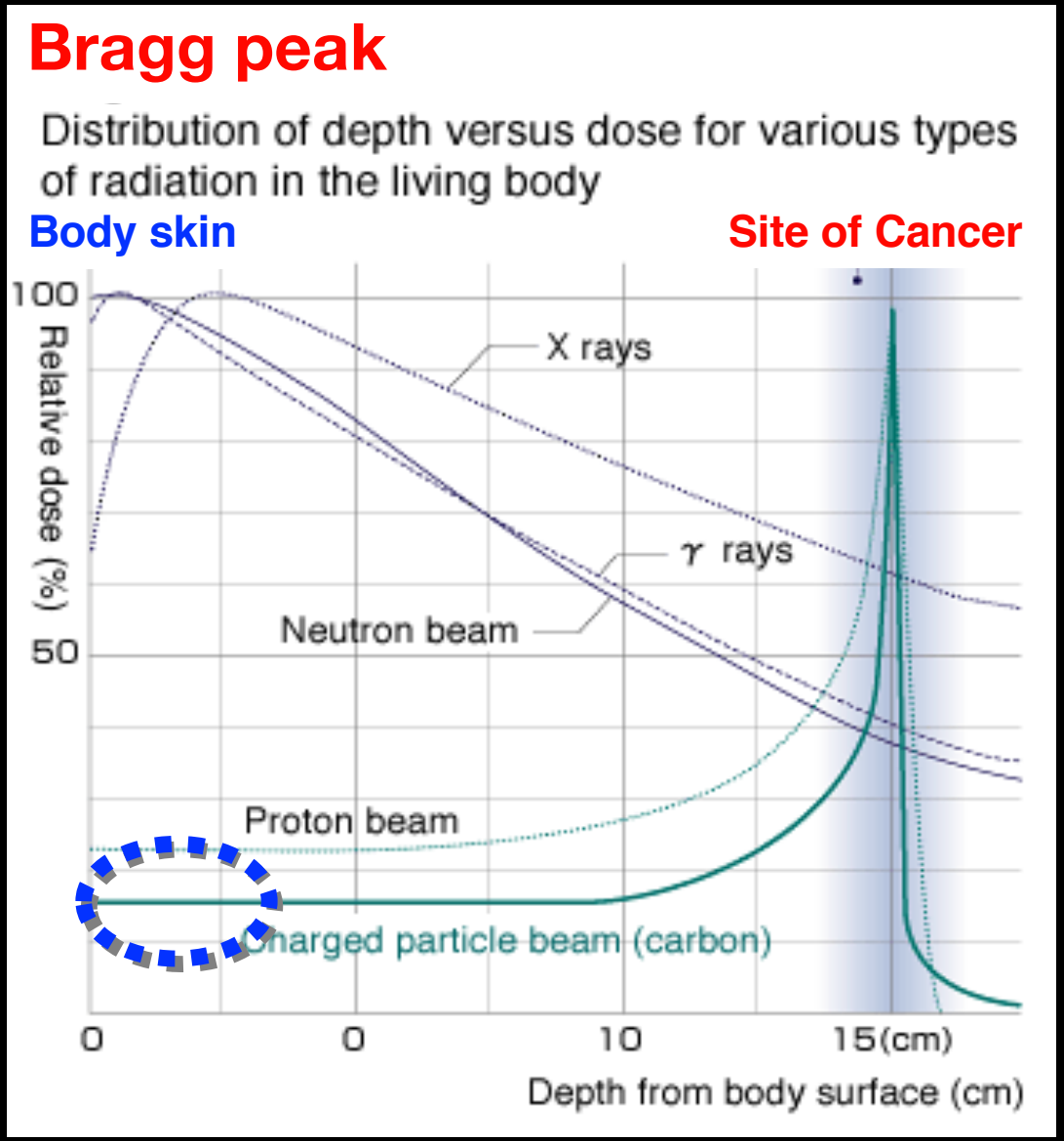
v : velocity of particle

fast ion - matter interaction



Bragg peak

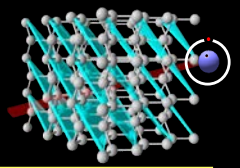
Distribution of depth versus dose for various types of radiation in the living body



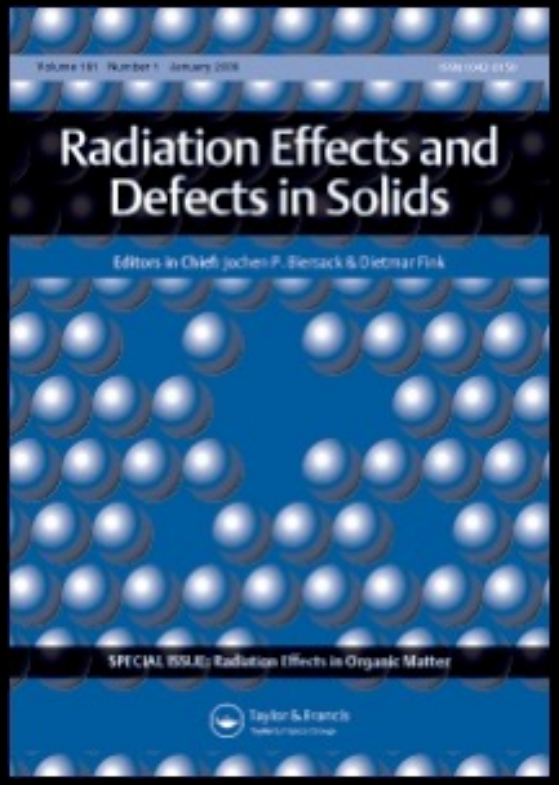
Doses are concentrated at the end point

Small effect at the entrance point

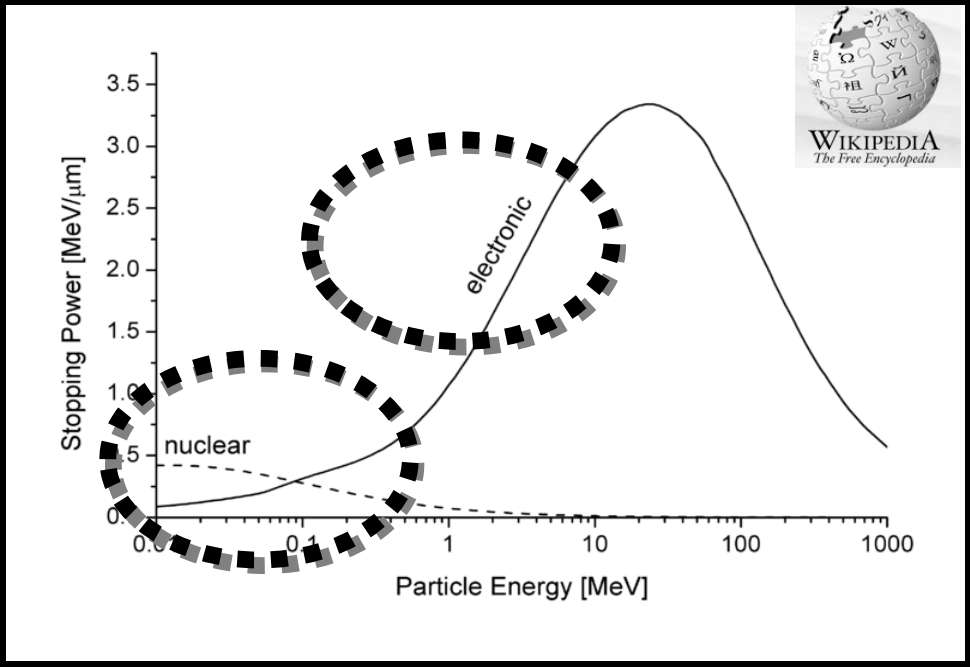
fast ion - matter interaction



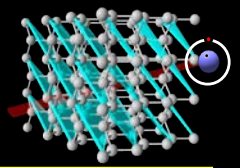
Complicated issues on radiation damage ?



Electronic and nuclear stopping power for Al ions in Al

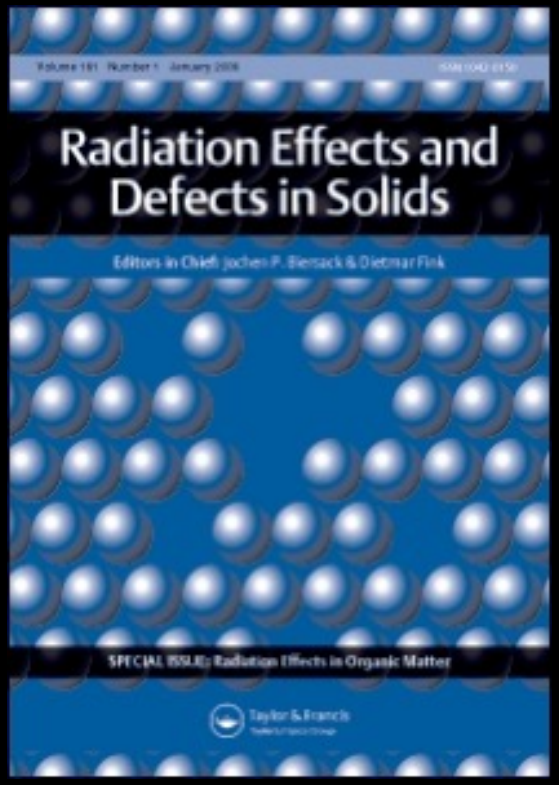


fast ion - matter interaction



Complicated issues on radiation damage ?

NO ! at the higher energy regions



Electronic and nuclear stopping power
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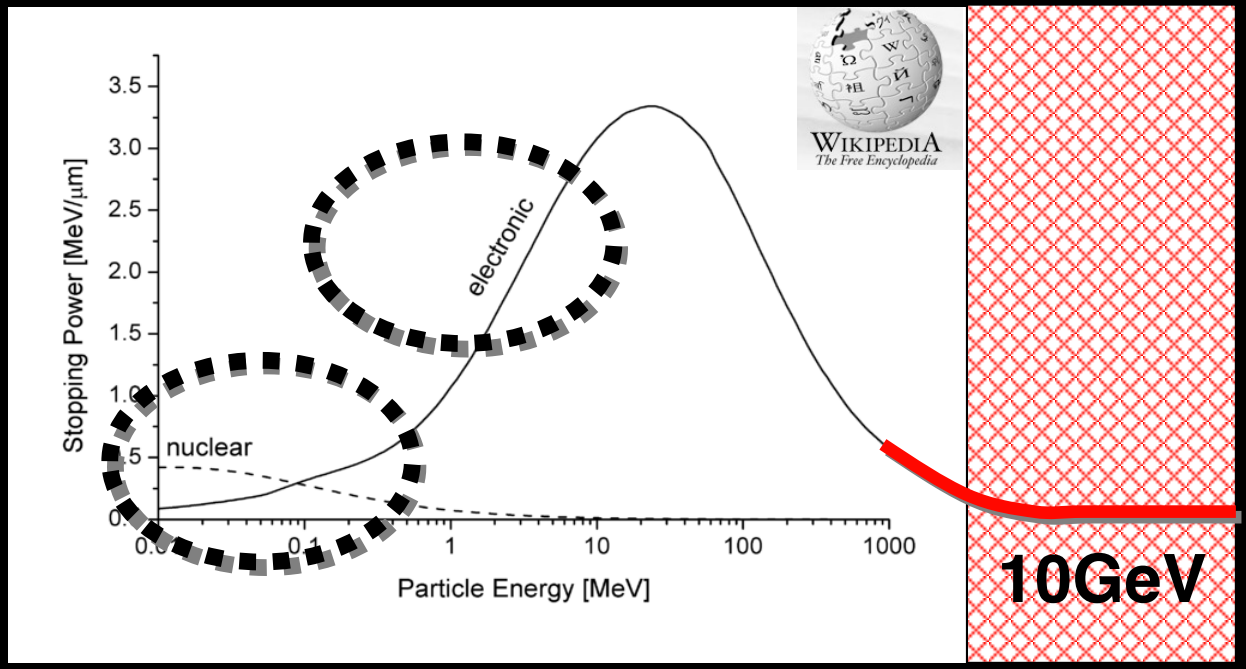
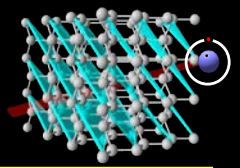


fast ion - matter interaction



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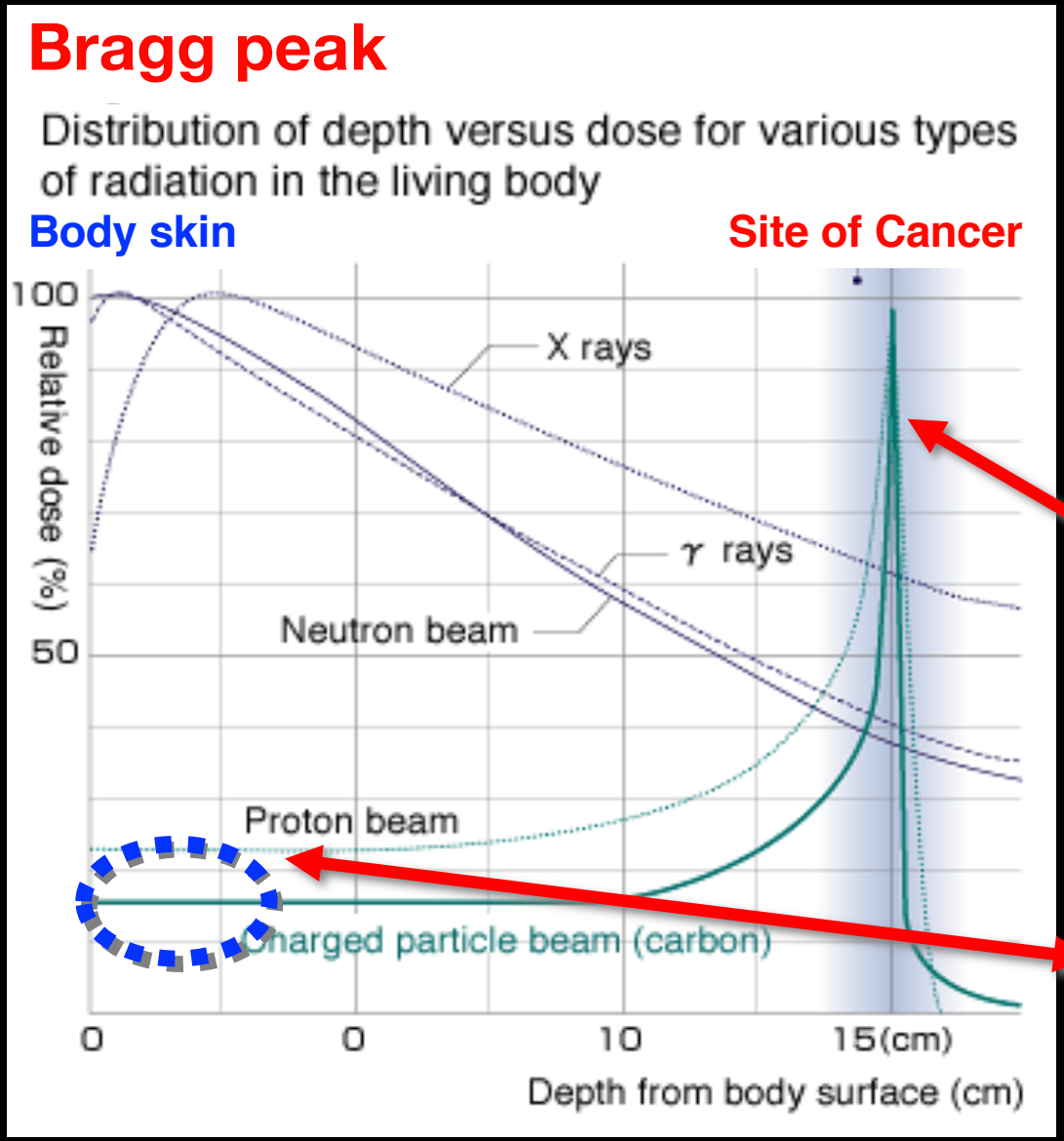
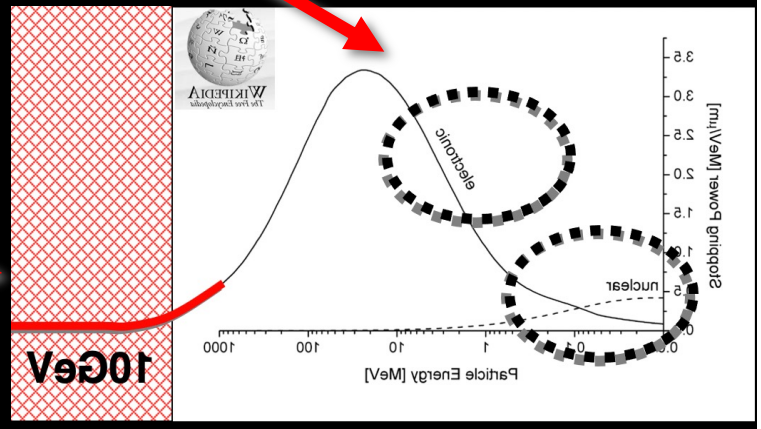
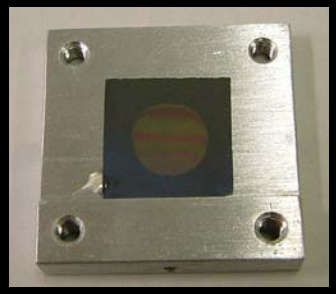




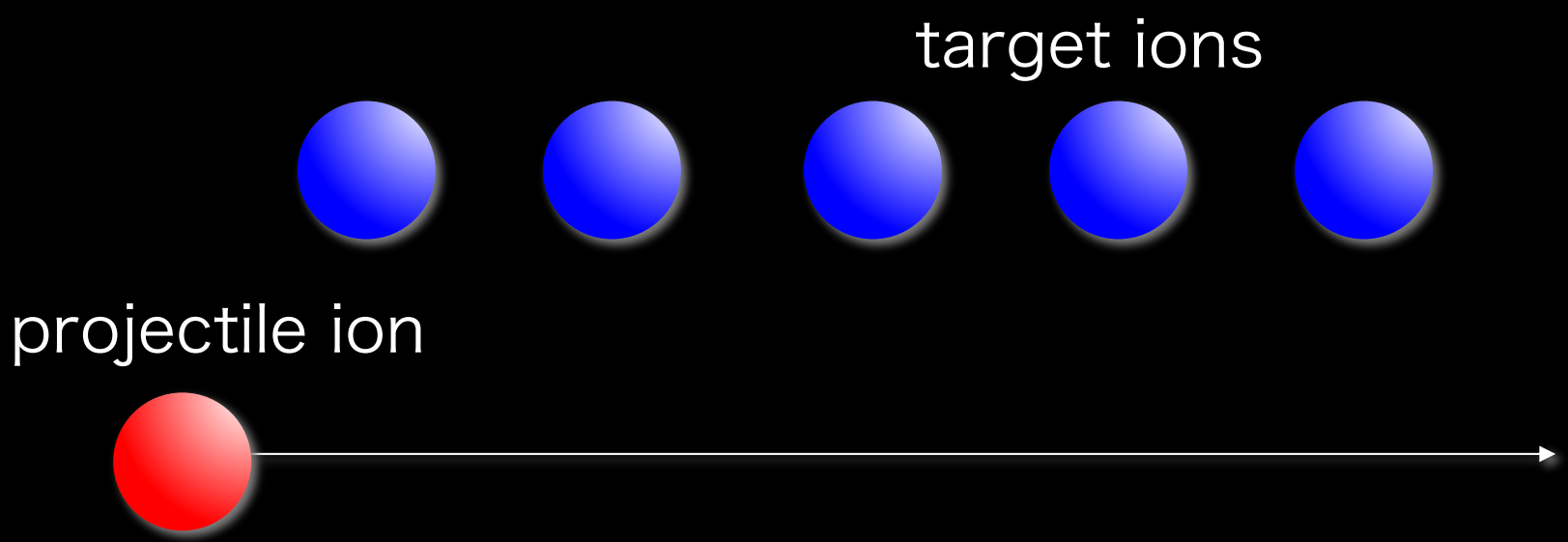
Let's replace the body skin with

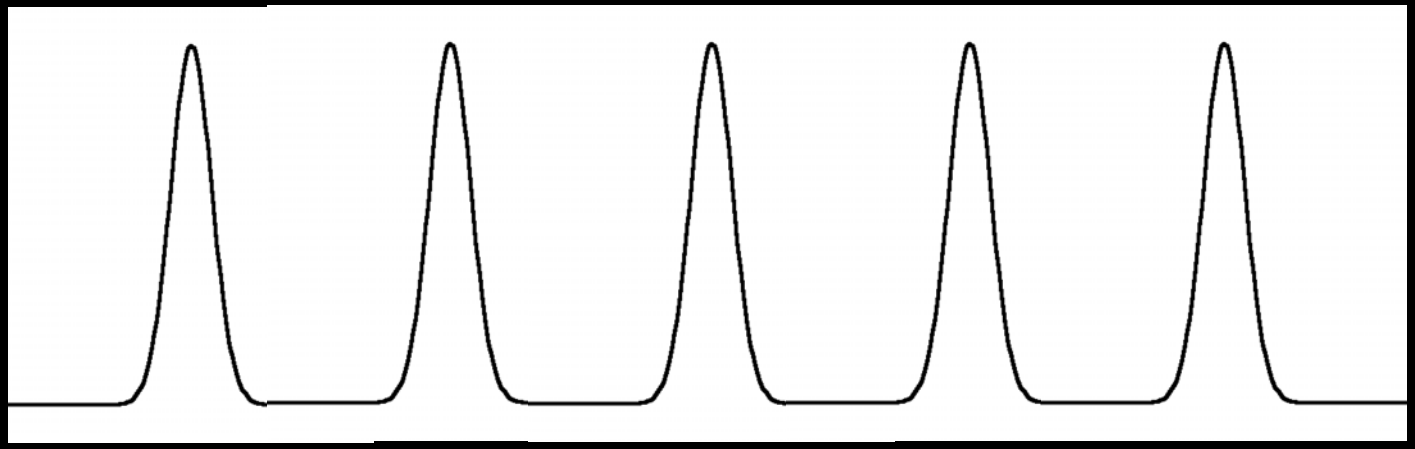
a tiny thin Si crystal



1 micron-thick
10mm diameter

Virtual photon picture in high energy ion collision





Resonant Coherent Excitation (RCE)

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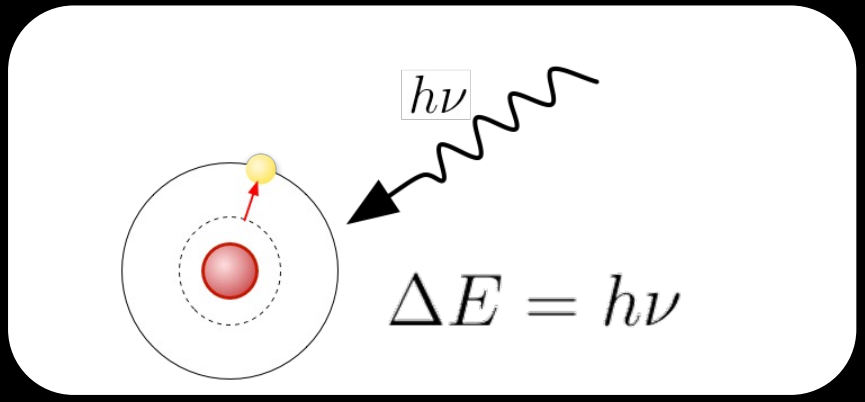
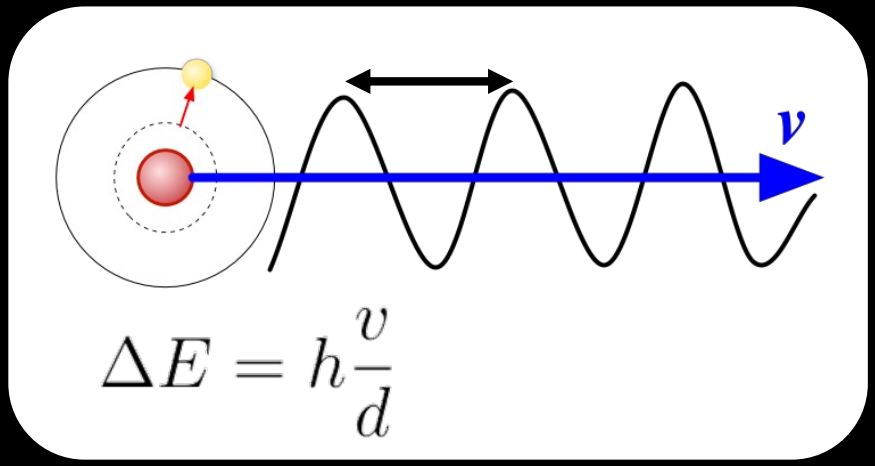
- **atom/ion irradiated by photon** **oscillating electric field**



Photon energy
→ Atomic internal energy

- **ion moving in the periodic potential** **projectile-flame: oscillating electric field**



Atomic translational energy
→ Atomic internal energy

Crystal irradiation

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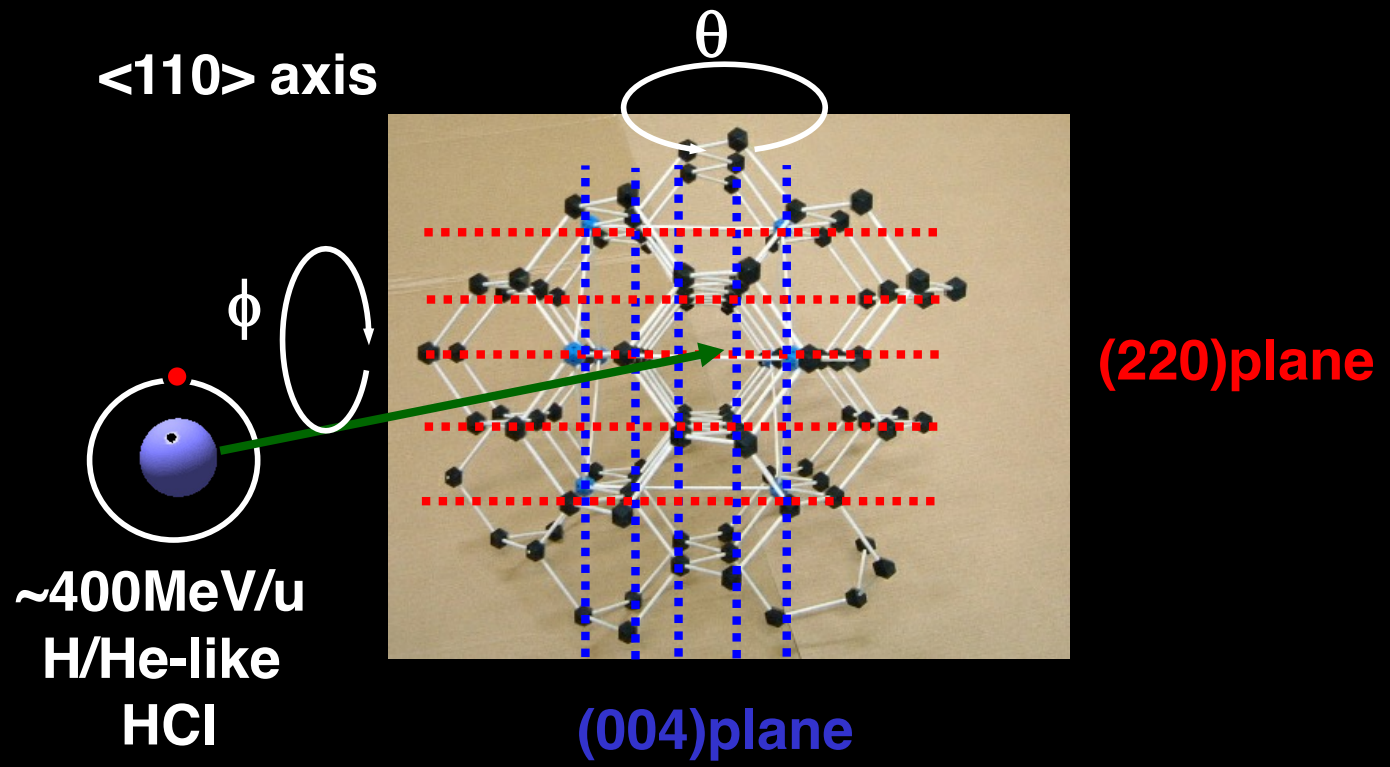
Silicon crystal

- “virtual photon” source
- spectrometer
- strong electric field

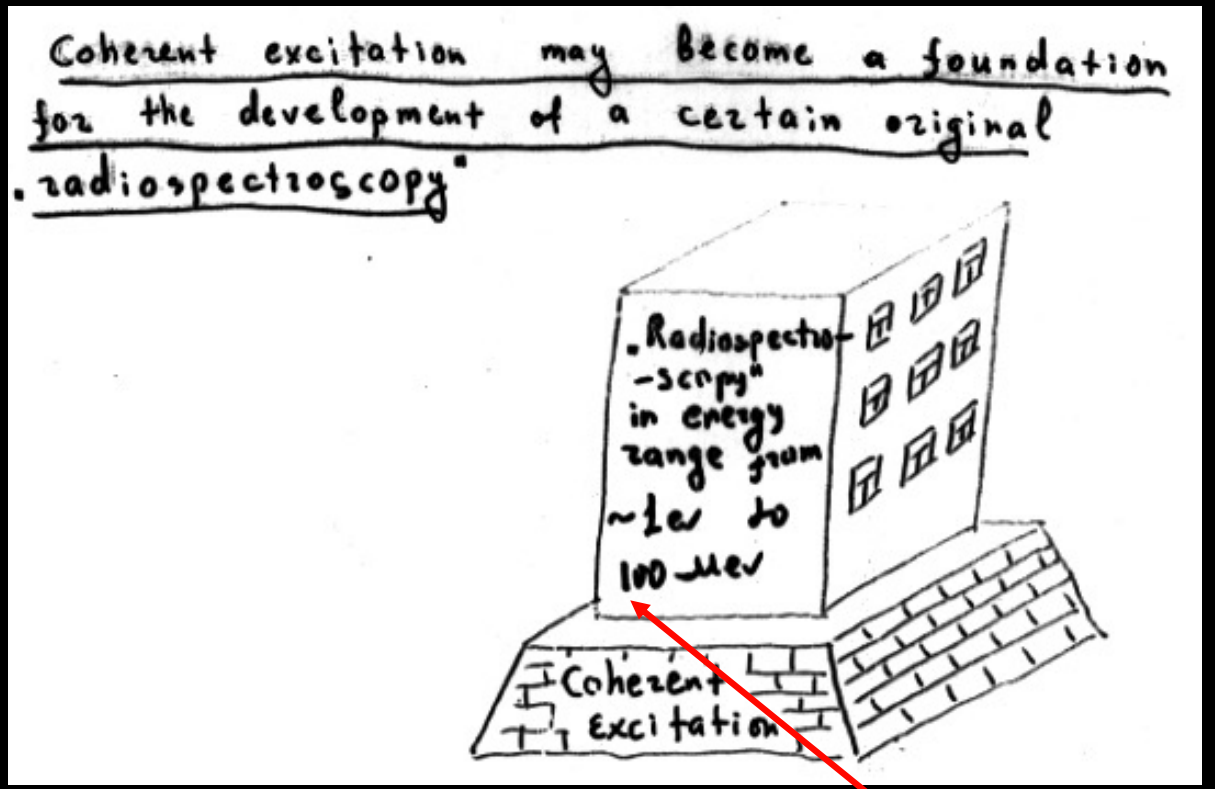


Okorokov-effect *vs*. resonant coherent excitation

Okorokov effect

JETP Lett. 2, 111(1965)

V. V. Okorokov (Russia)



from 1 eV to 100 MeV

Radiospectroscopy

predicted

Resonant coherent excitation *vs*. Okorokov-effect

J. Kondo (JAPAN)

described

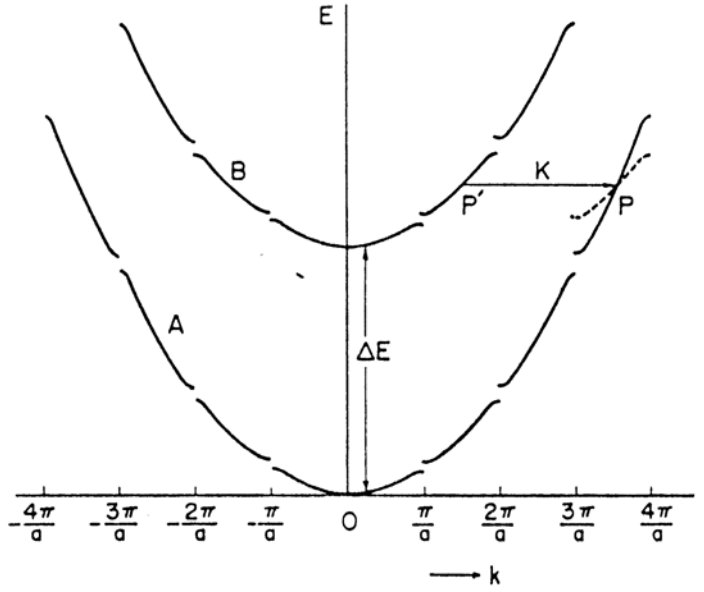
Motion of a Fast Ion in Periodic Potentials

J. Phys. Soc. Japan 36, 1406(1974)

Motion of a Fast Ion in Periodic Potentials

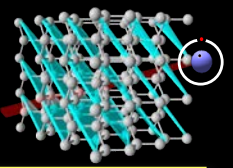
Jun KONDO
Electrotechnical Laboratory, Tanashi, Tokyo

(Received December 7, 1973)

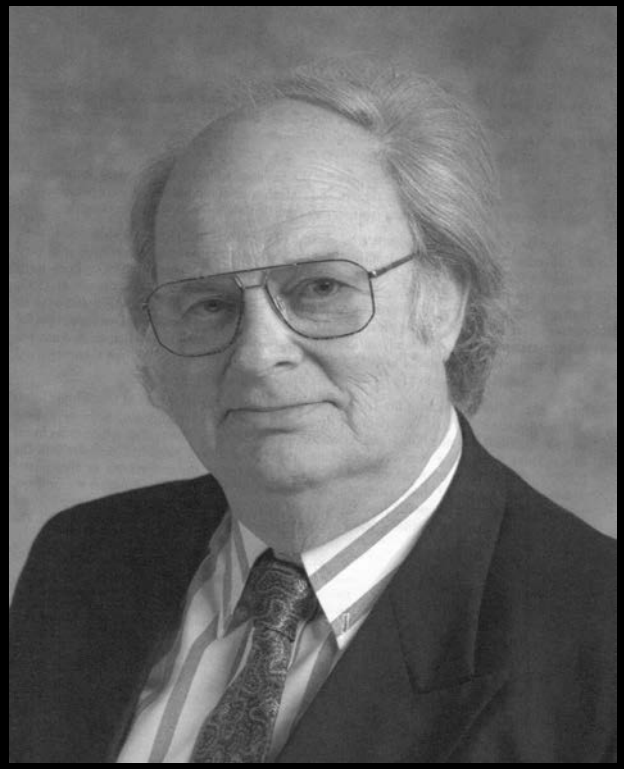


avoided level crossing behavior

resonant coherent excitation *vs*. Okorokov-effect



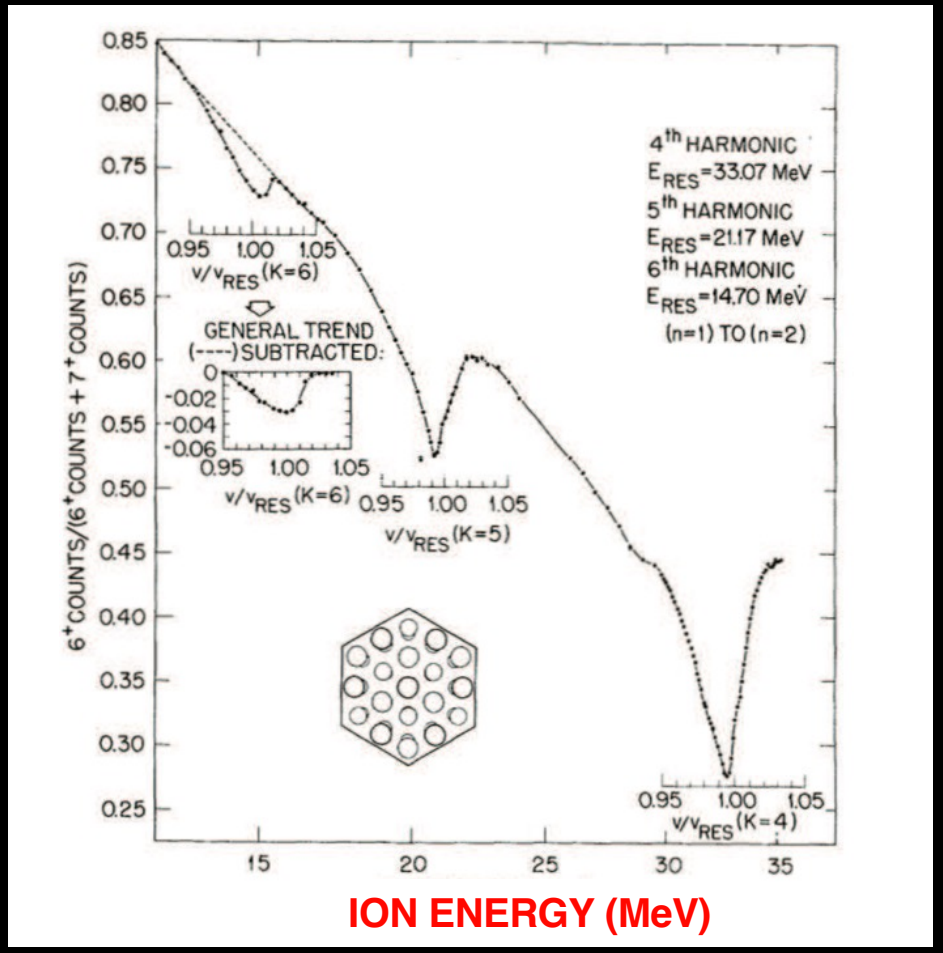
RCE



S. Datz
(US)

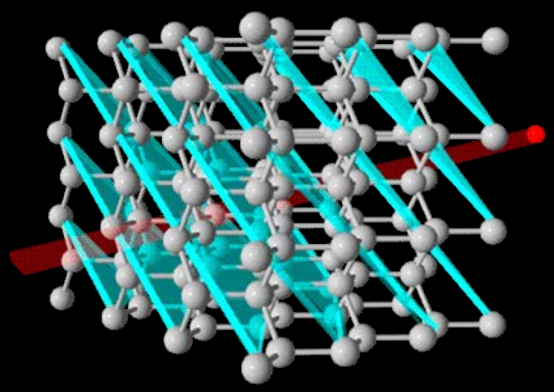
measured

N^{6+} through Au crystal under axial channeling



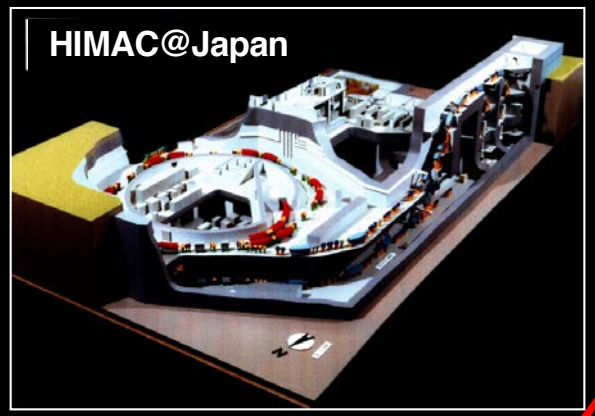
Phys. Rev. Lett. 40, 843(1978)

RCE of high energy ions



Si crystal
(d ~ 1Å)

E ~ 400 MeV/u, β ~ 0.7

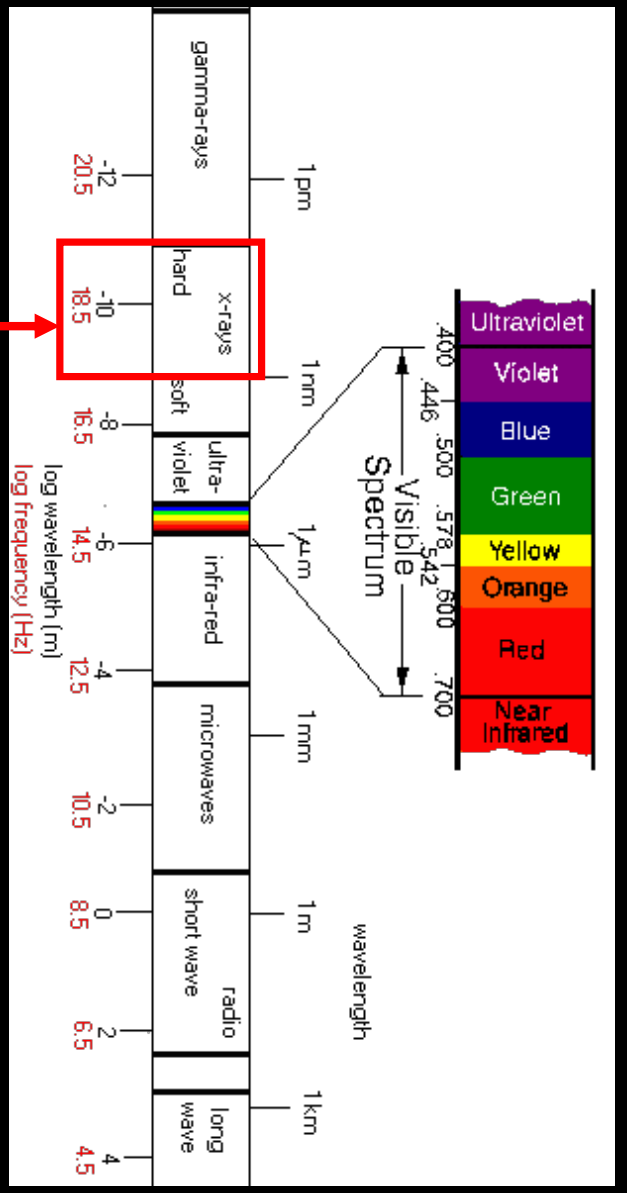


high-energy ion
(v ~ 10^8 m/s)

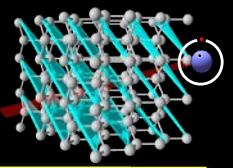
frequency

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

light source in the x-ray region



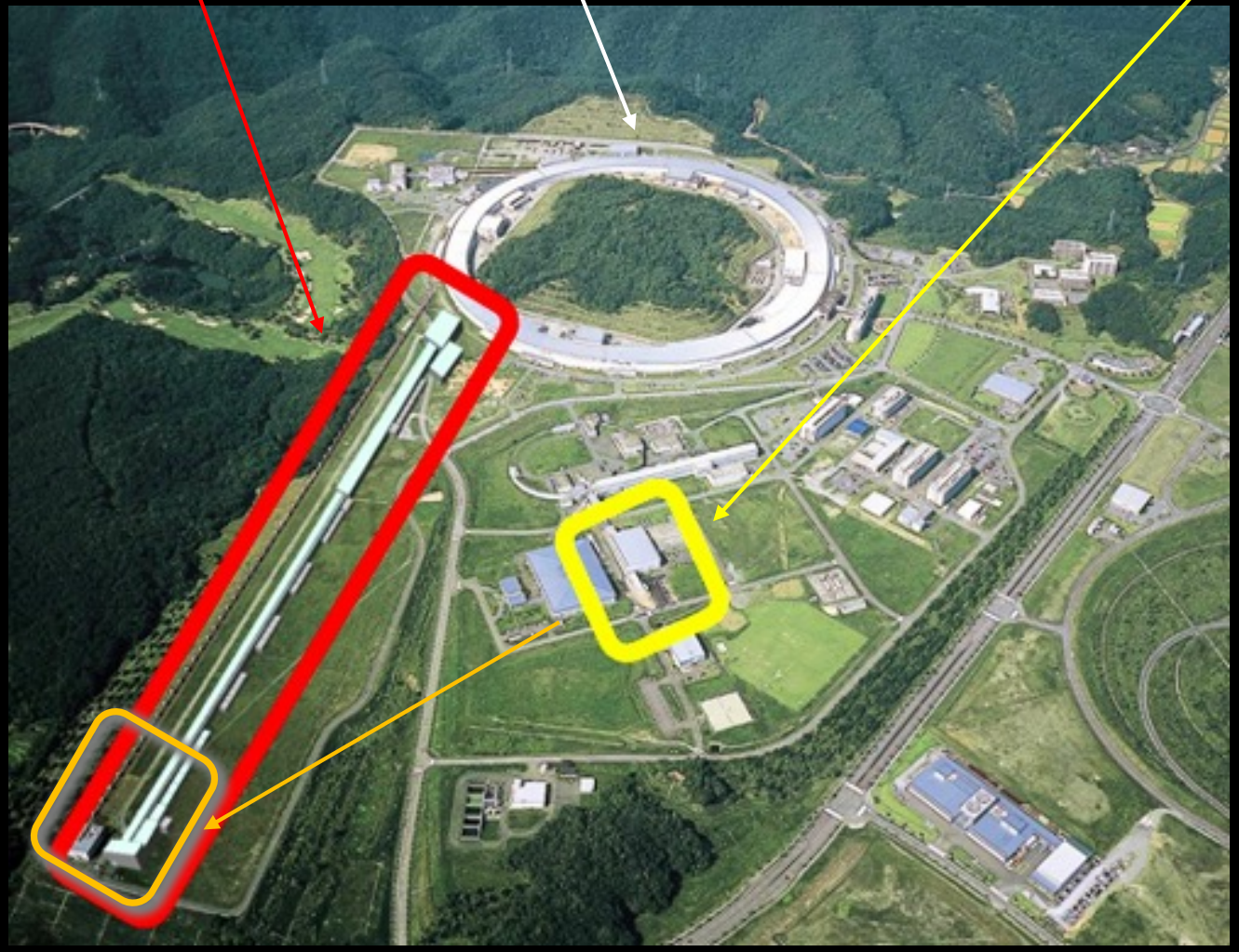
XFEL in Japan



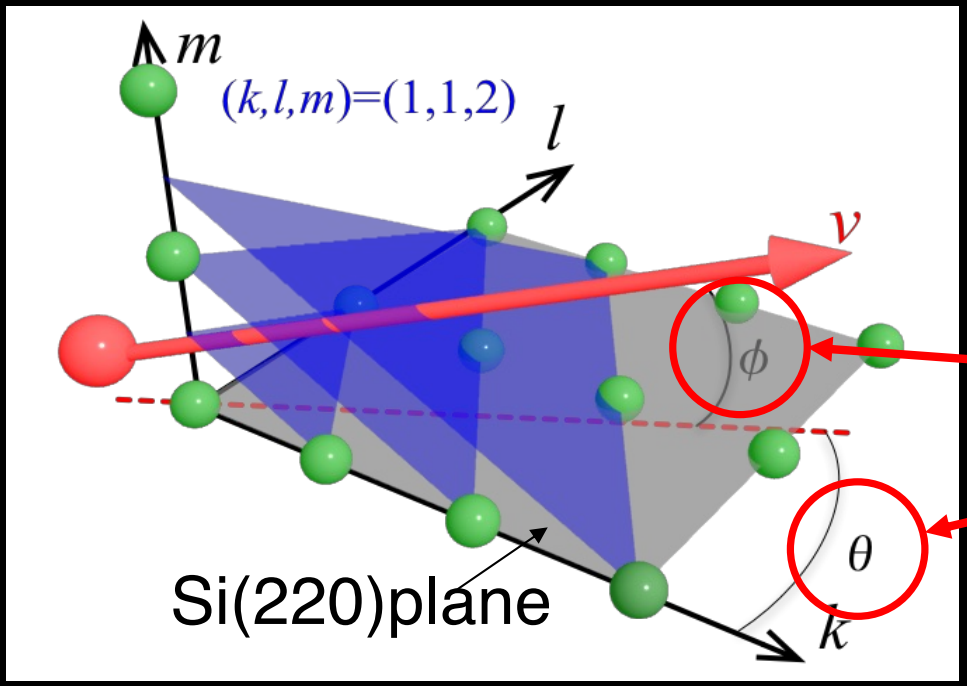
SACLA
1-10keV XFEL

SOR: Spring-8

25eV proto-type FEL
40-150eV FEL



3D-RCE



2 parameters to vary the interaction frequency keeping ion velocity

3D-RCE	v, θ, Φ

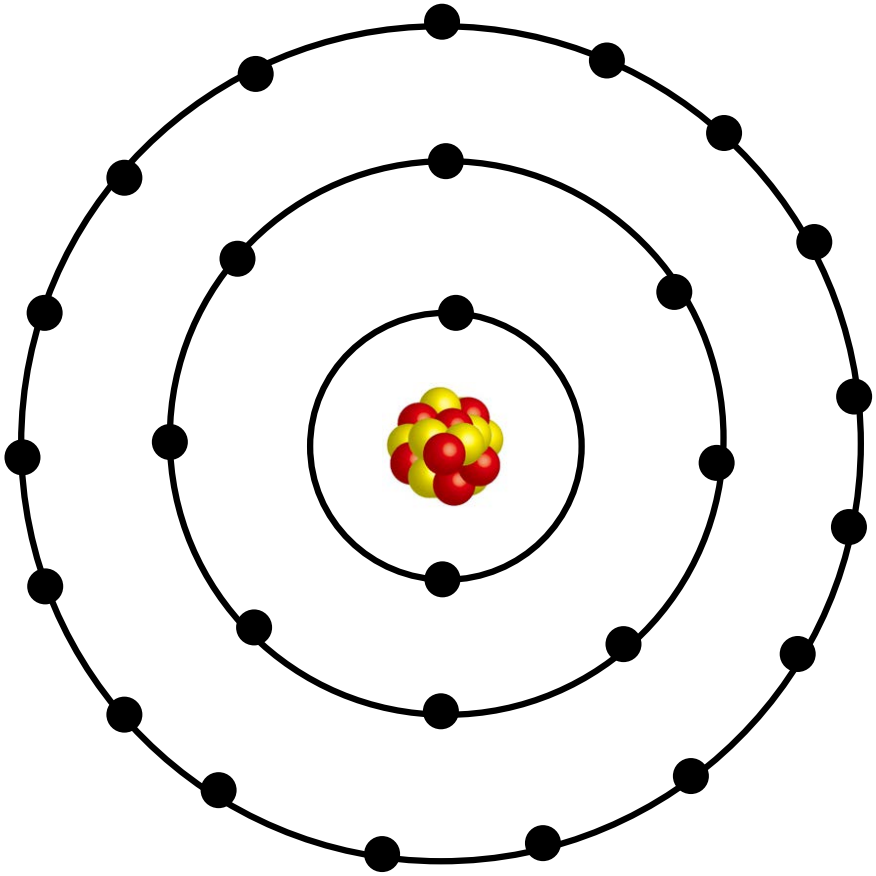
interaction frequency in 3D-RCE

→ frequency traversing the atomic planes

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

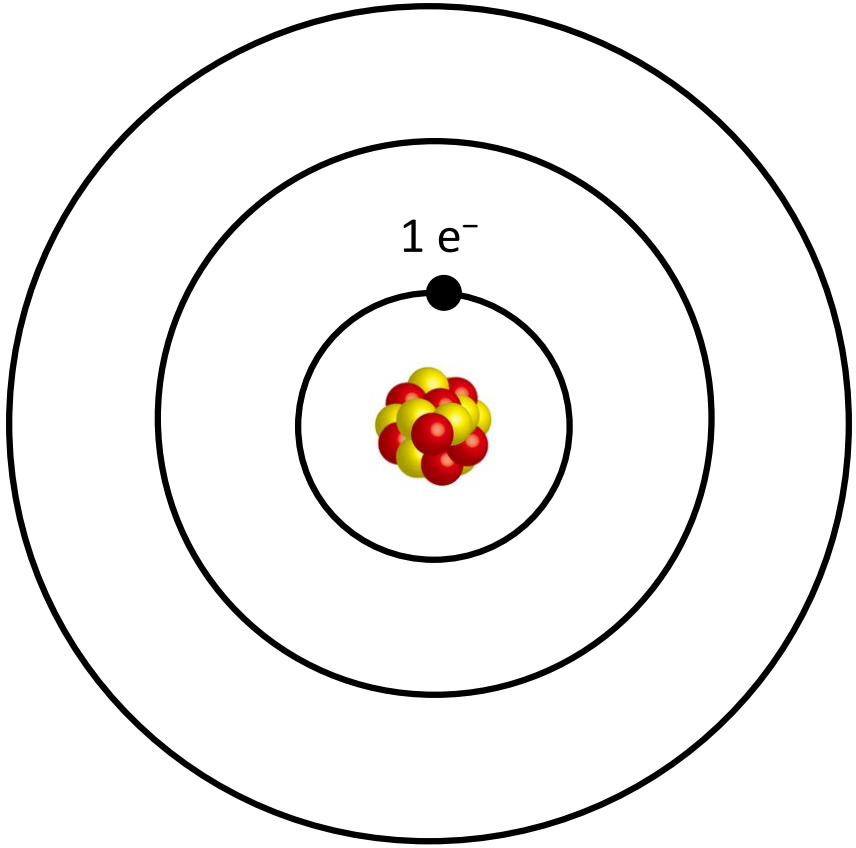
$$\vec{g}_{klm} = k\vec{A}^* + l\vec{B}^* + m\vec{C}^*$$

Atom



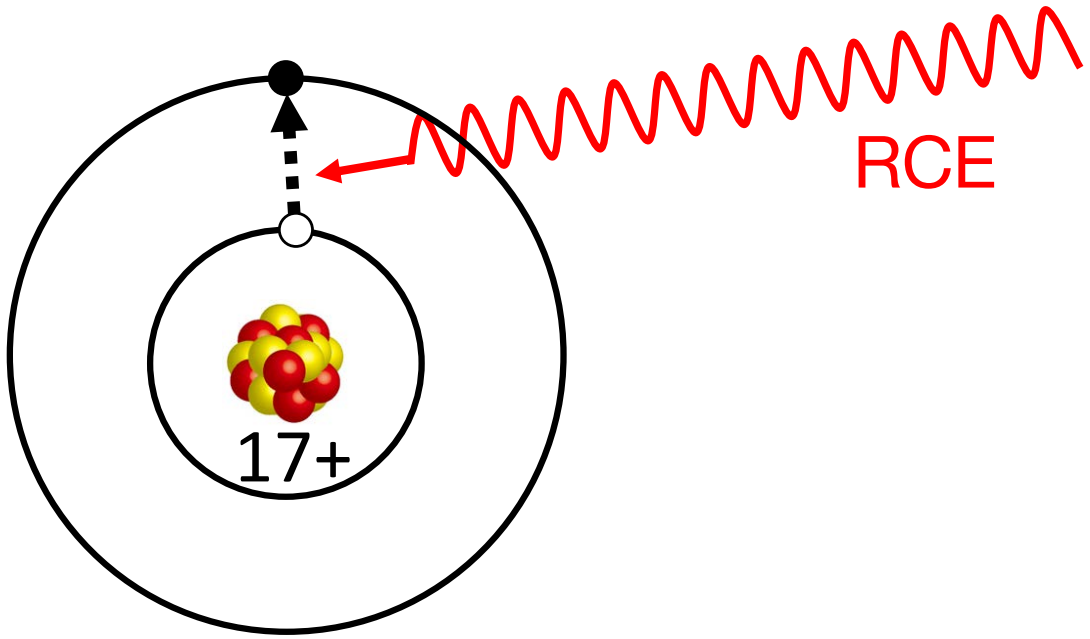
Highly charged atomic ion

after stripping most of the bound electrons,

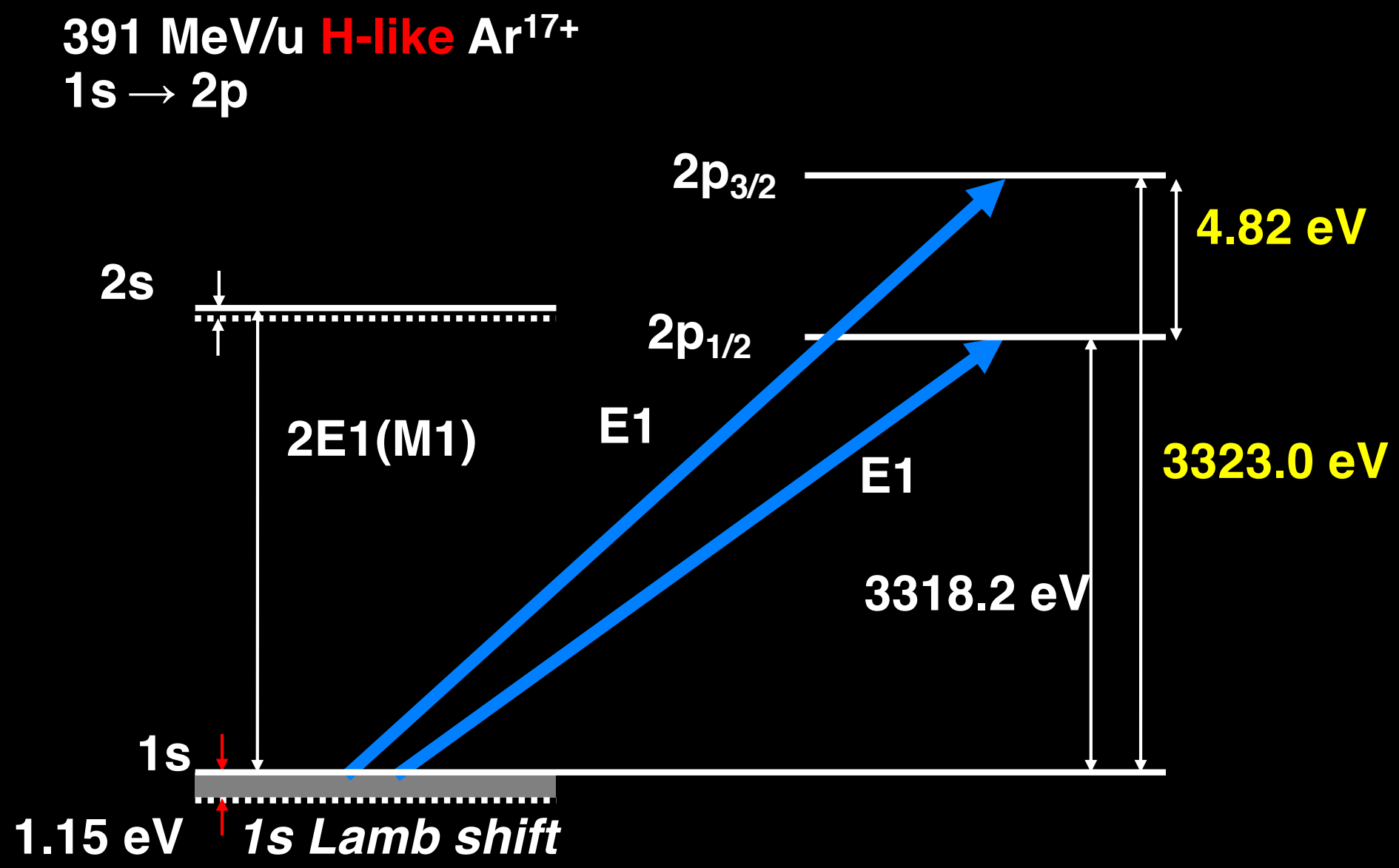


Hydrogen-like Ar^{17+}

Excitation of n=1(1s) electron to n=2 states

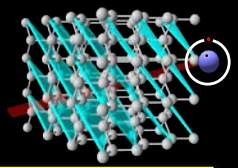


Energy levels of hydrogen-like system

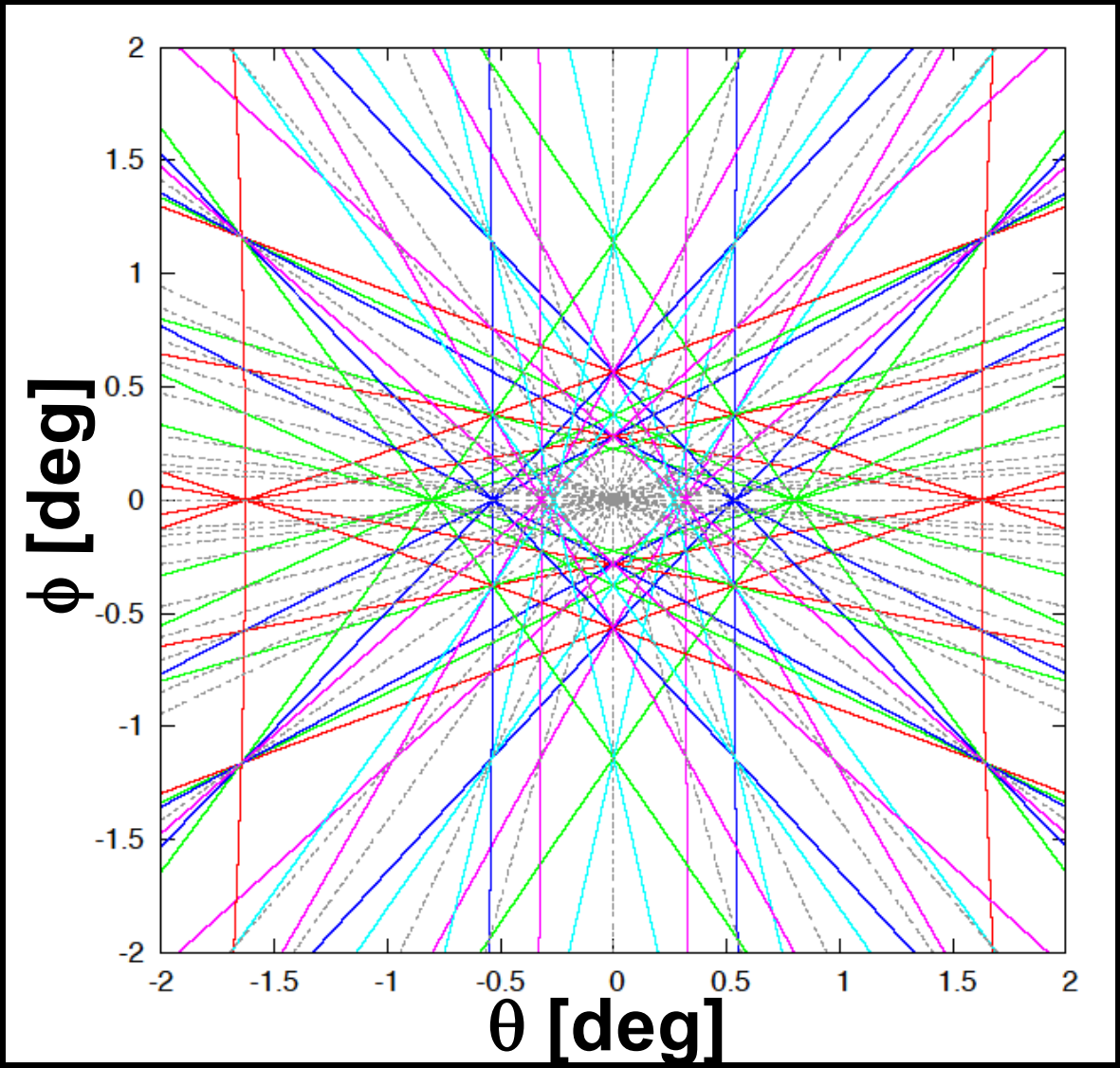


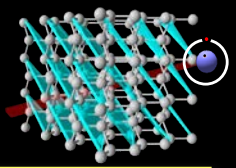
3D-RCE conditions

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

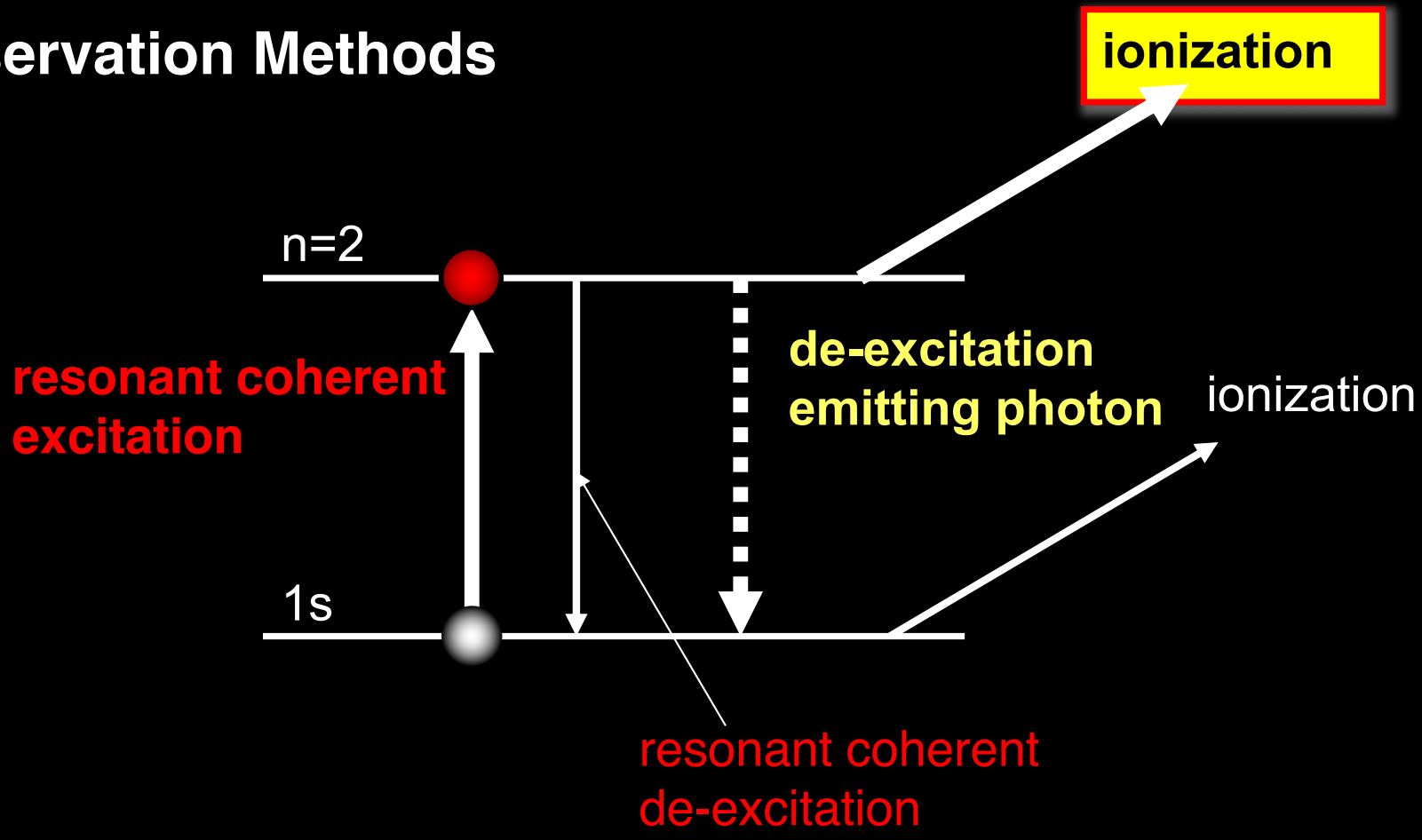


So many resonance conditions in random incidence !

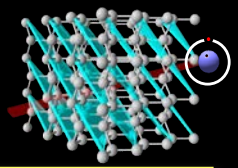




Observation Methods



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



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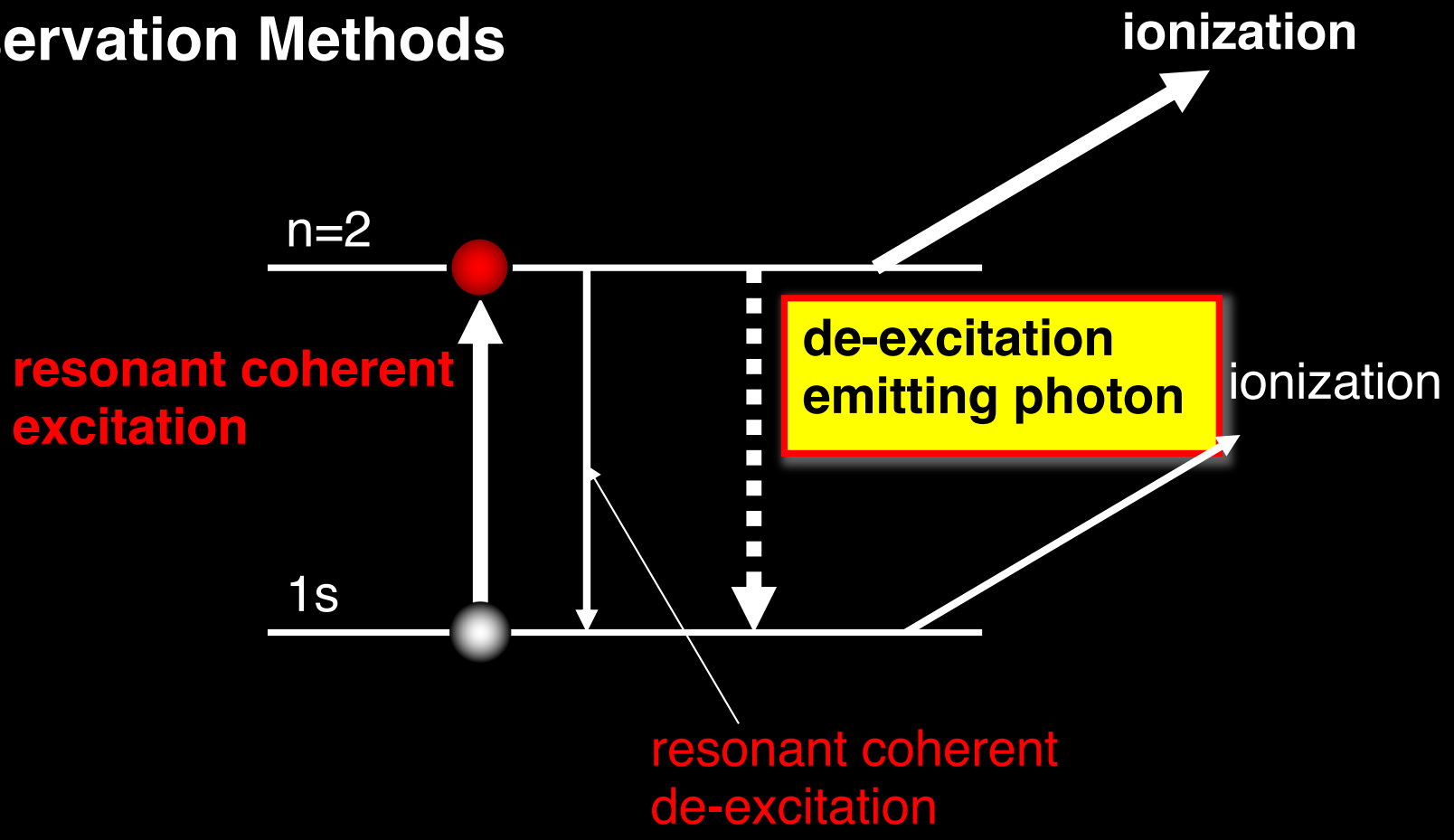
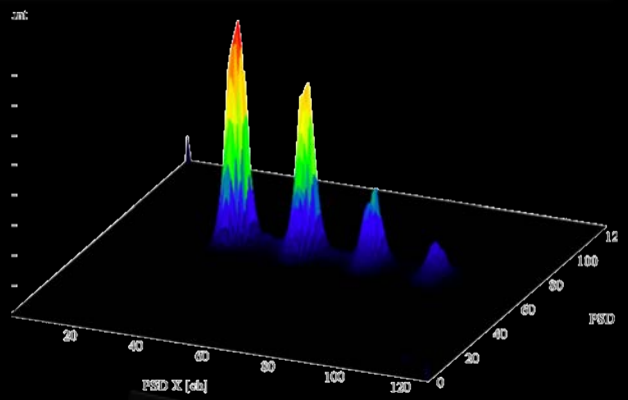


Scanning the crystal angle with respect to the beam, de-excitation X-ray yields are monitored

experimental set up

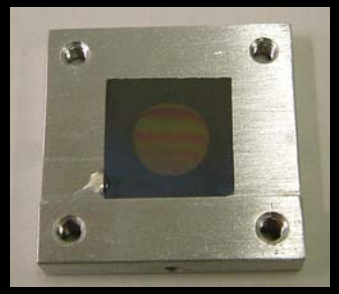
scan:
incident angle θ

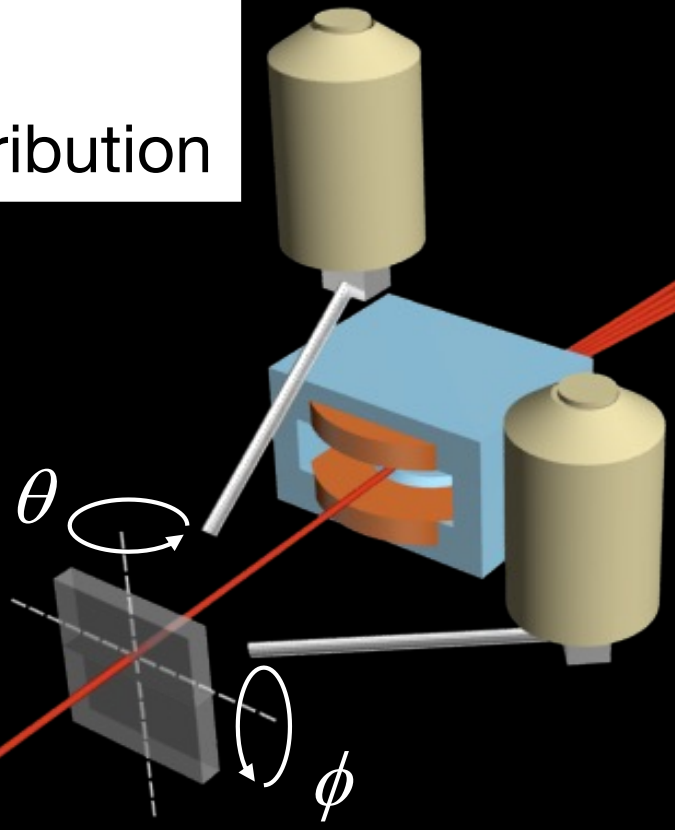
observation:
x-ray yields
charge state distribution



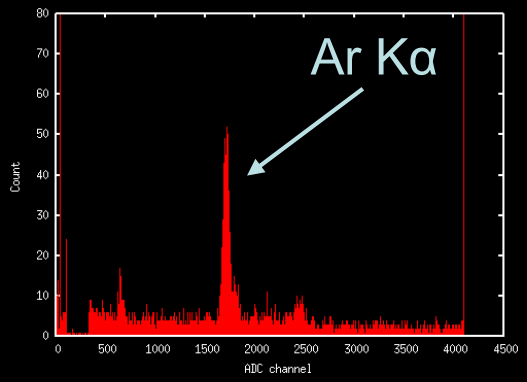
2D PSD

Si crystal





Si(Li) x-ray detector

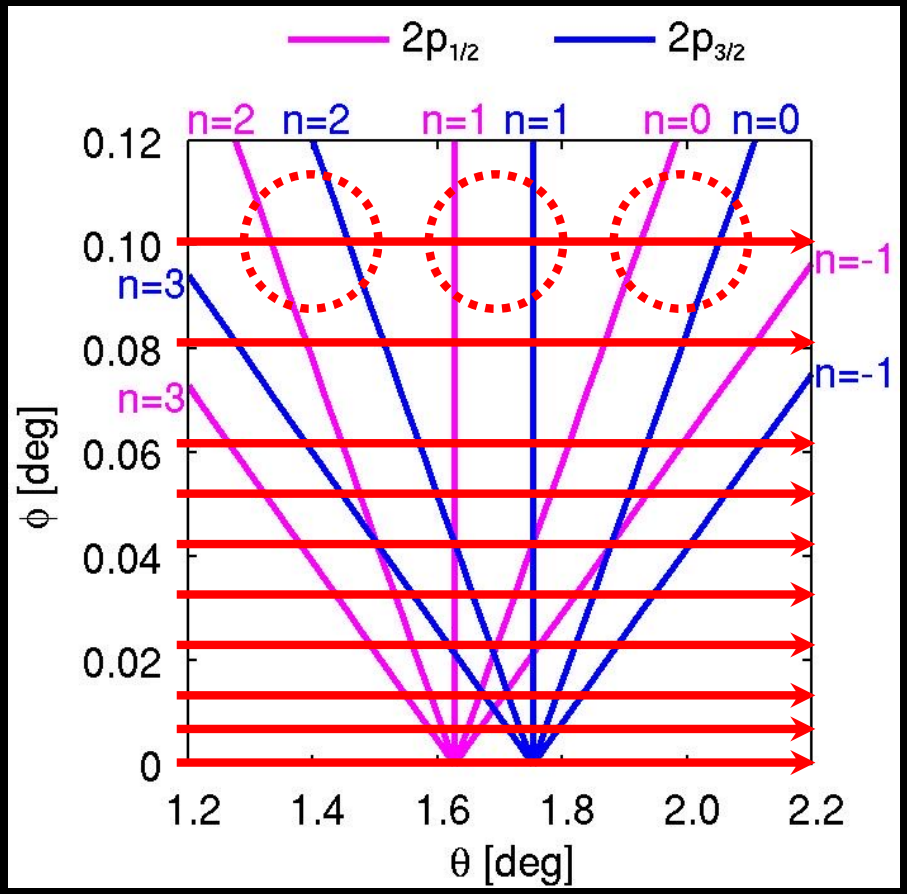


x-ray spectrum

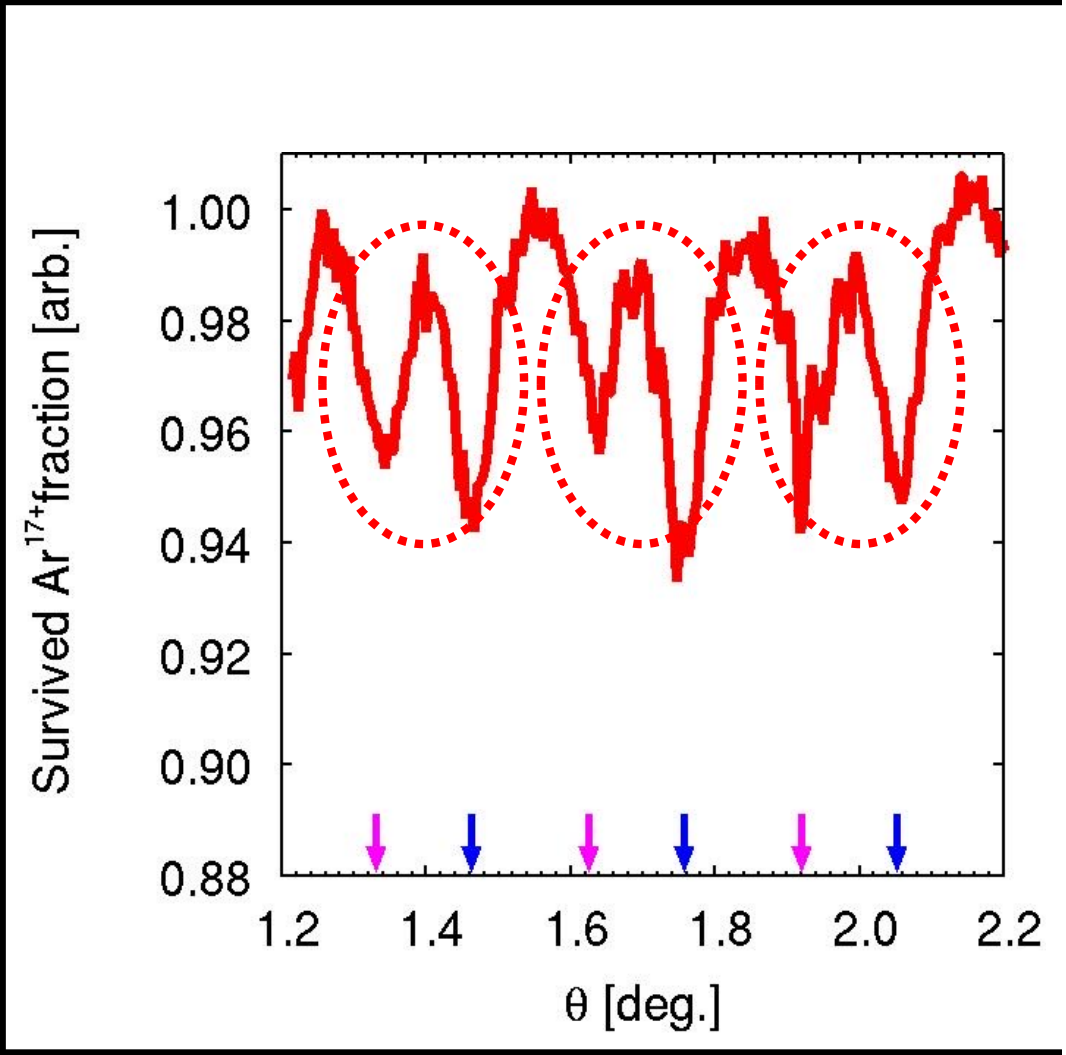
@ HIMAC
416 MeV/u Ar^{16+}

3D-RCE resonance profile

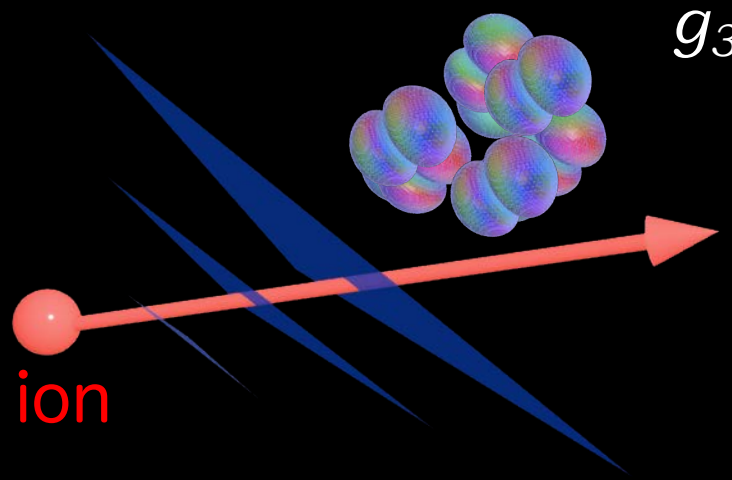
391MeV/u H-like Ar^{17+}



channeling critical angle
（quasi-channeling）



oscillating field by crystal periodic field



$$\mathbf{F}'(t') = \sum_{\mathbf{g}} 2\pi i V_{\mathbf{g}} \begin{pmatrix} \gamma \mathrm{g}_x \\ \gamma \mathrm{g}_y \\ \mathrm{g}_z \end{pmatrix} \exp(-2\pi i \gamma \mathbf{g} \cdot \mathbf{v}t)$$

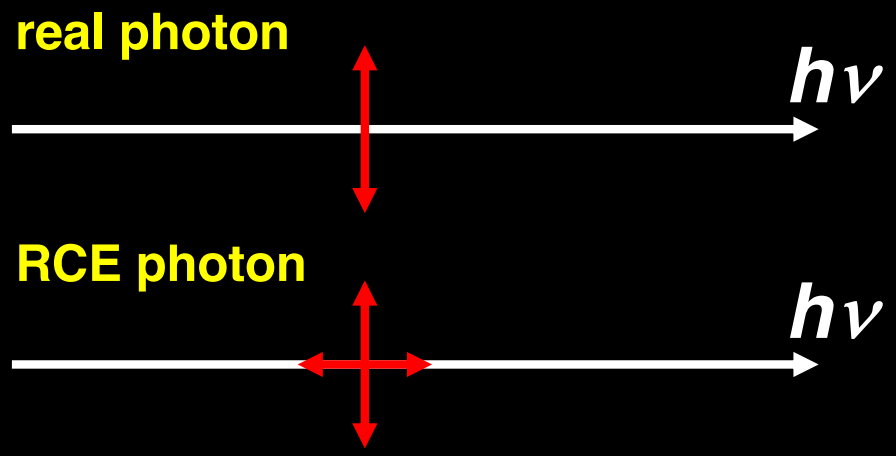
Pol. Freq.

Multi-color Light

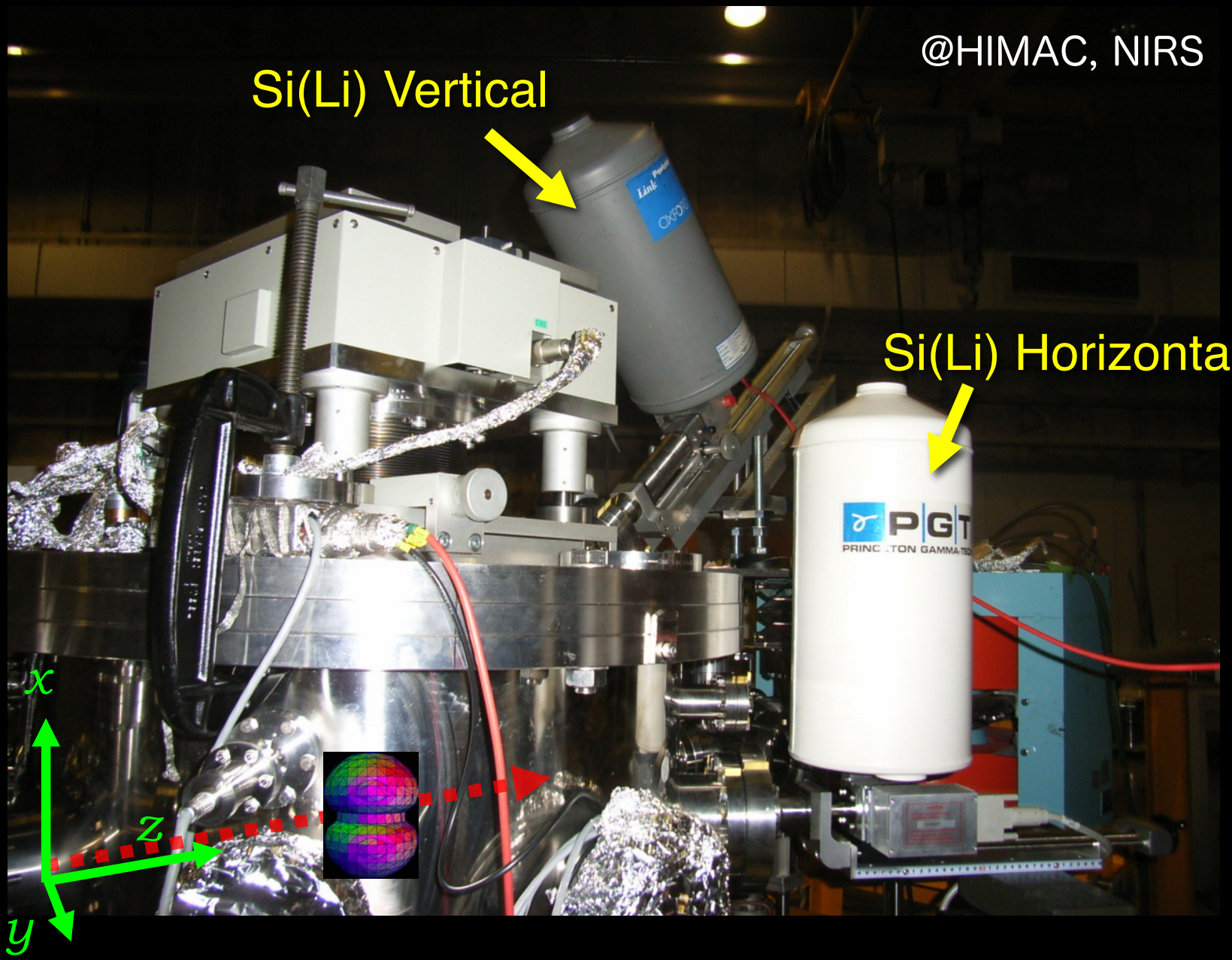
Linearly-polarized Light

***g*: reciprocal vector**

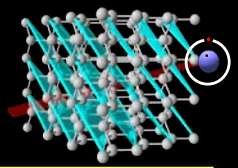
PLANE WAVE
No trajectory-dependence



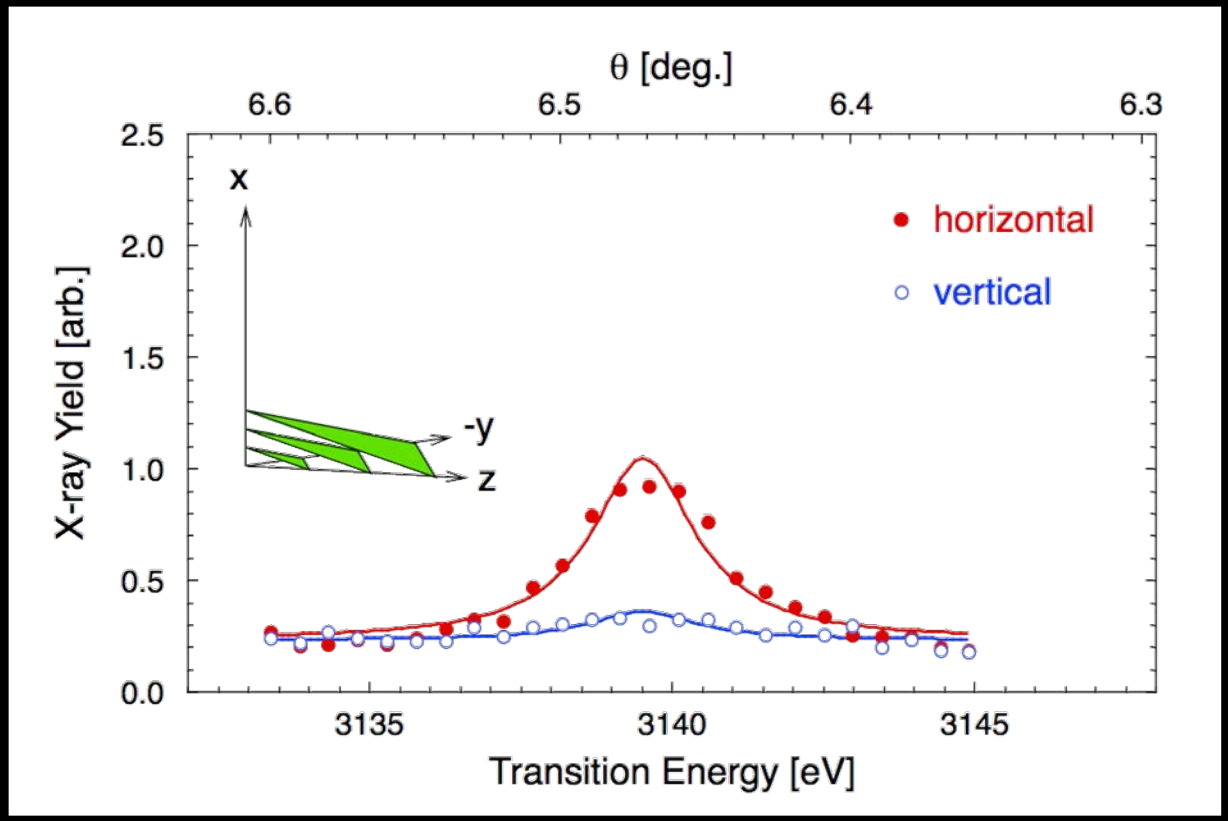
experimental setup



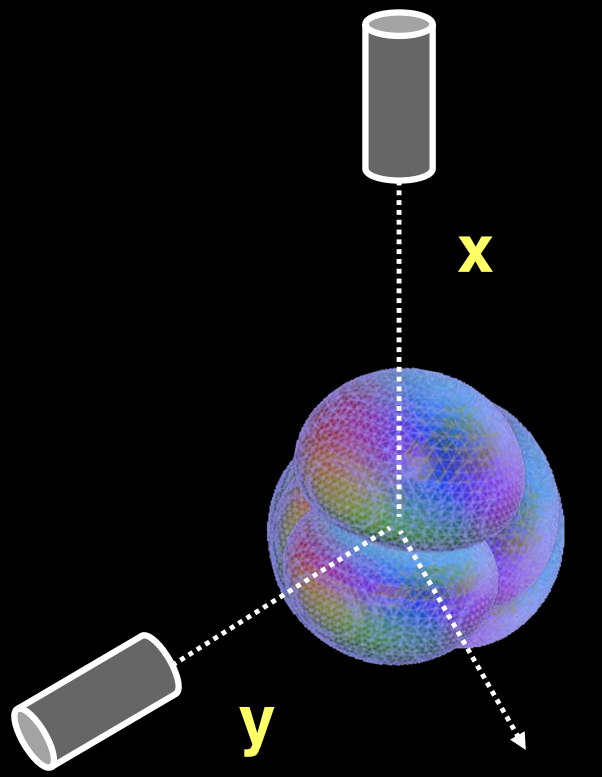
anisotropic x-ray emission depending on polarization

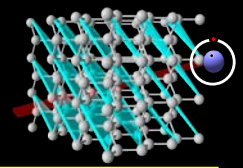


He-like Ar^{16+} ions (^1P): Large anisotropy !

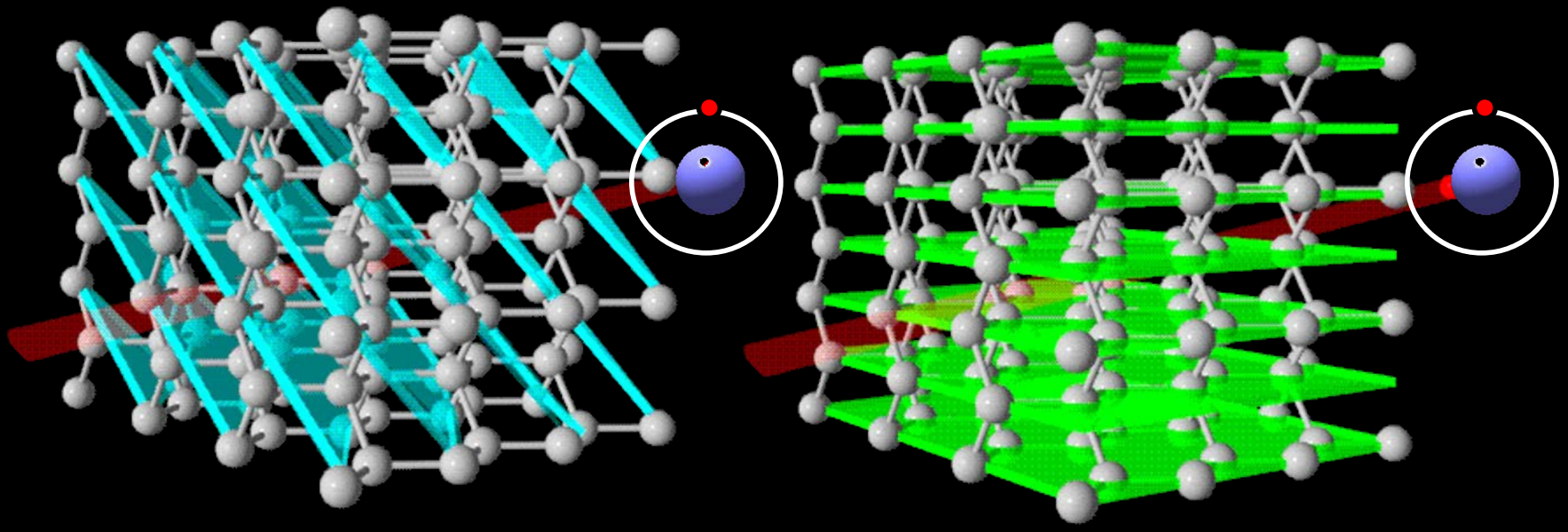


reflecting polarization direction of oscillating fields





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

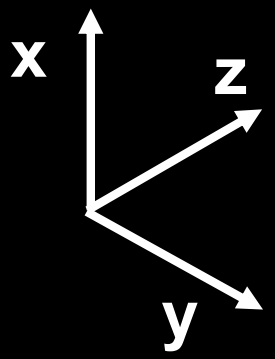


(k,l,m)= (1,-1,2)

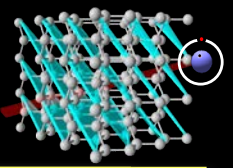
x,y,z

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

x



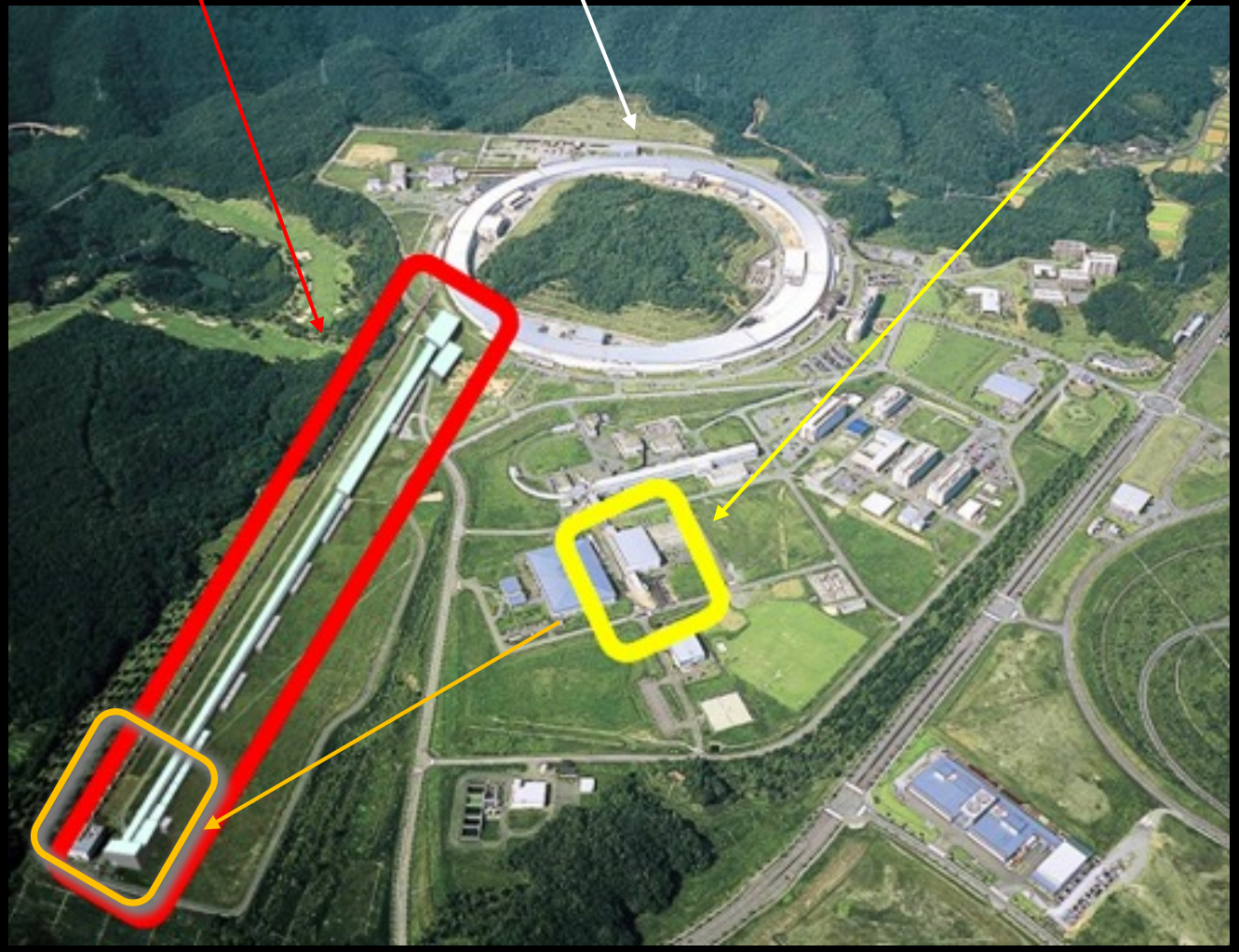
XFEL in Japan



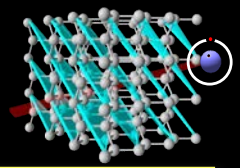
SACLA
1-10keV XFEL

SOR: Spring-8

25eV proto-type FEL
40-150eV FEL

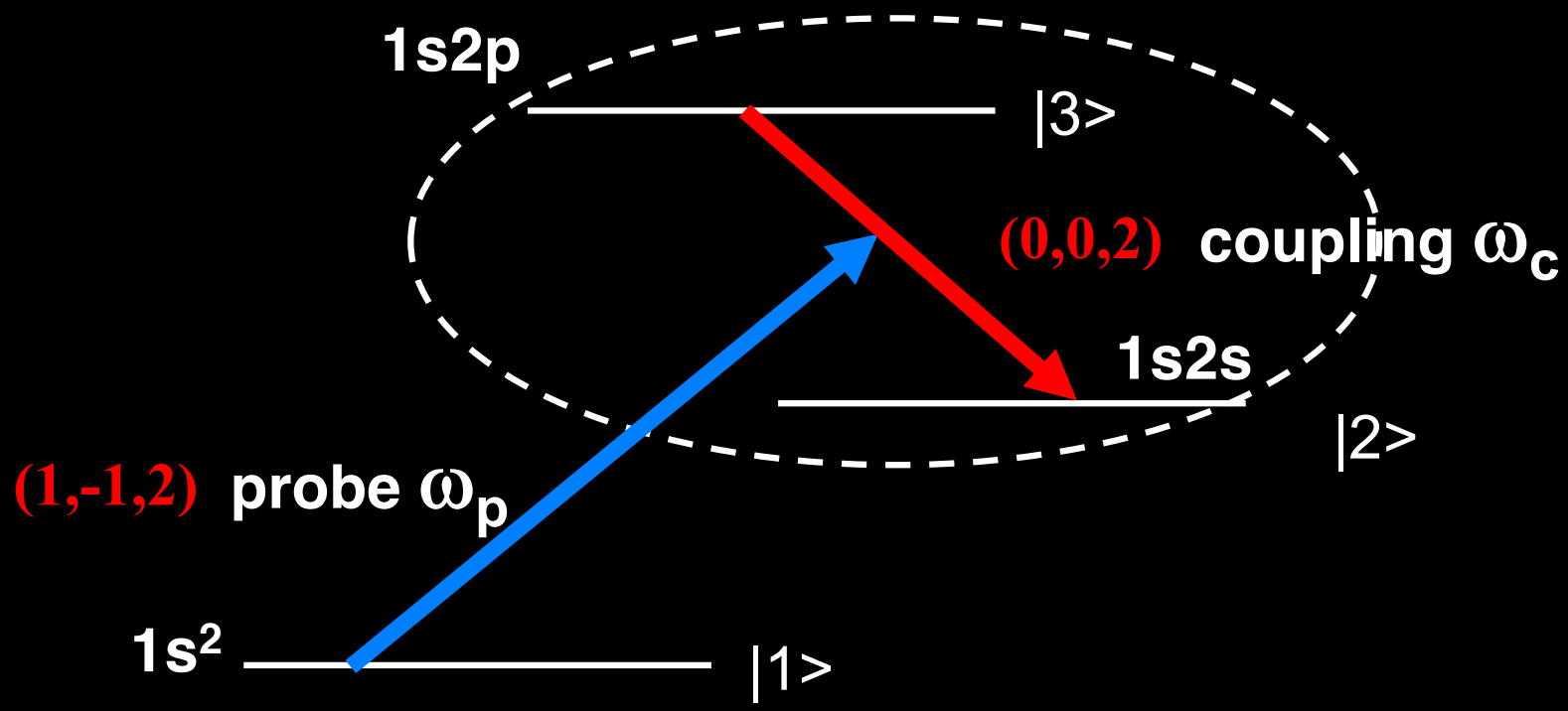


Double resonance: dressed-atom picture



Consider Λ system (3 level atom): Ar^{16+}

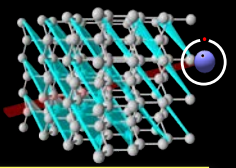
Si crystal

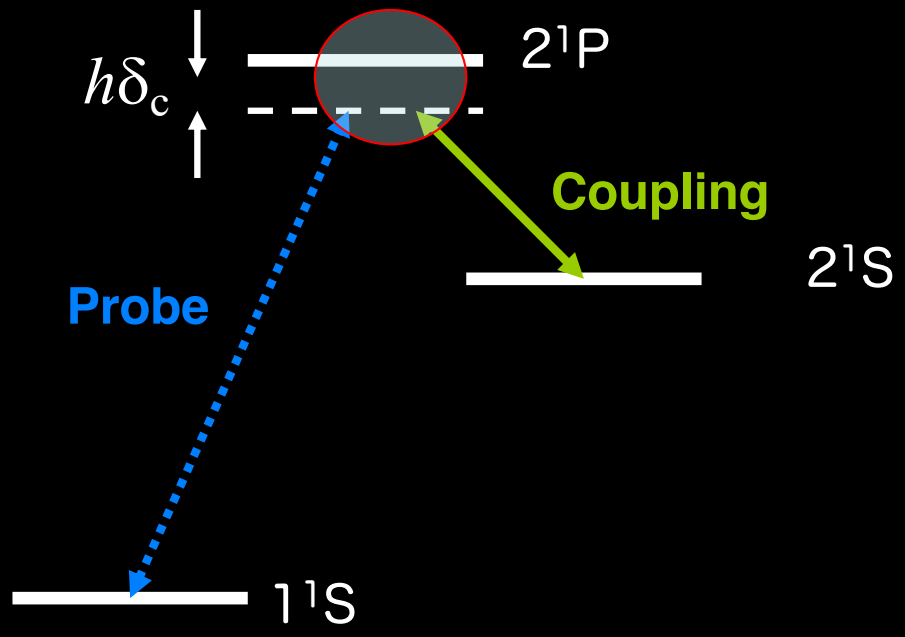


2s-2p: for coupling

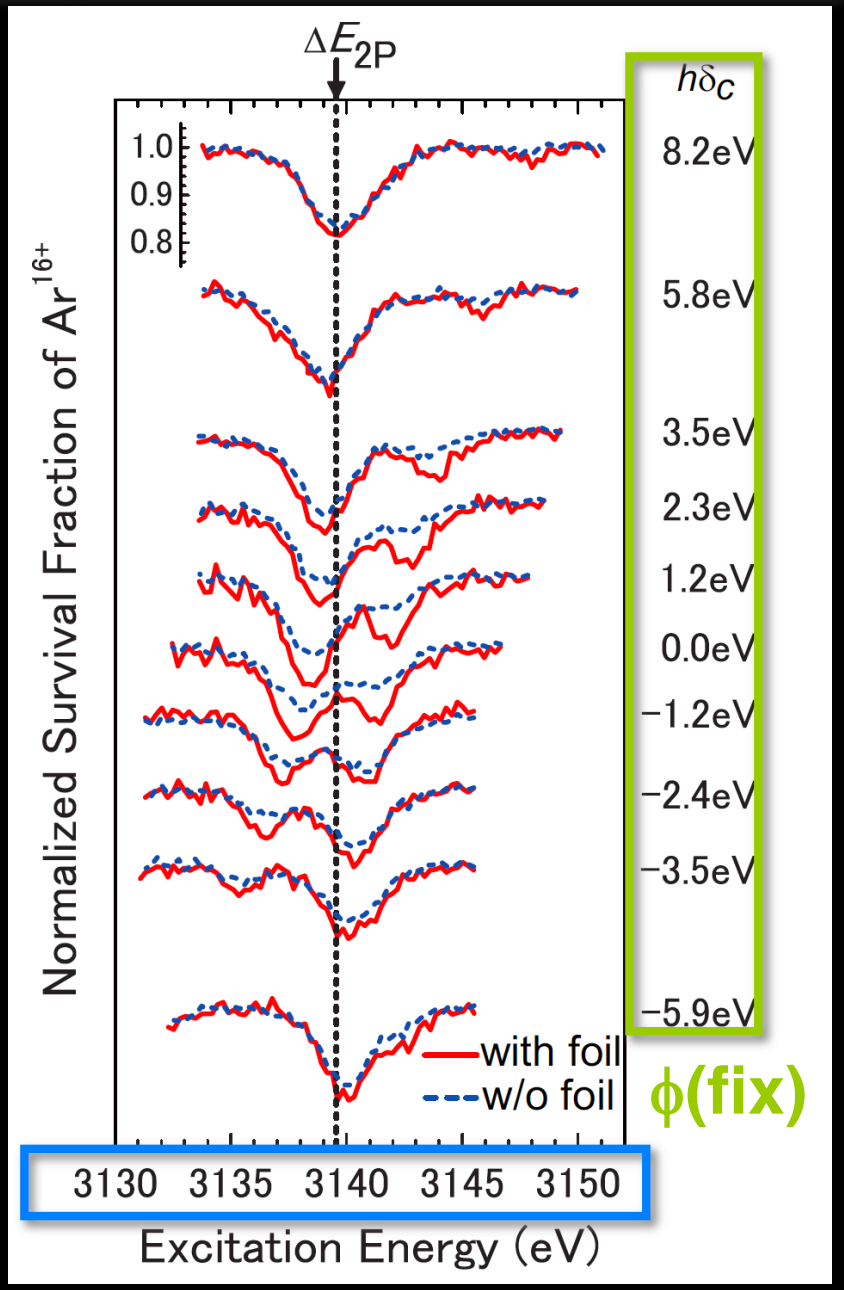
1s-2p: for probe

Avoided level crossing (charge state)

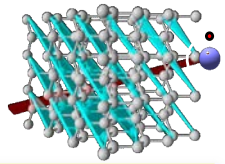


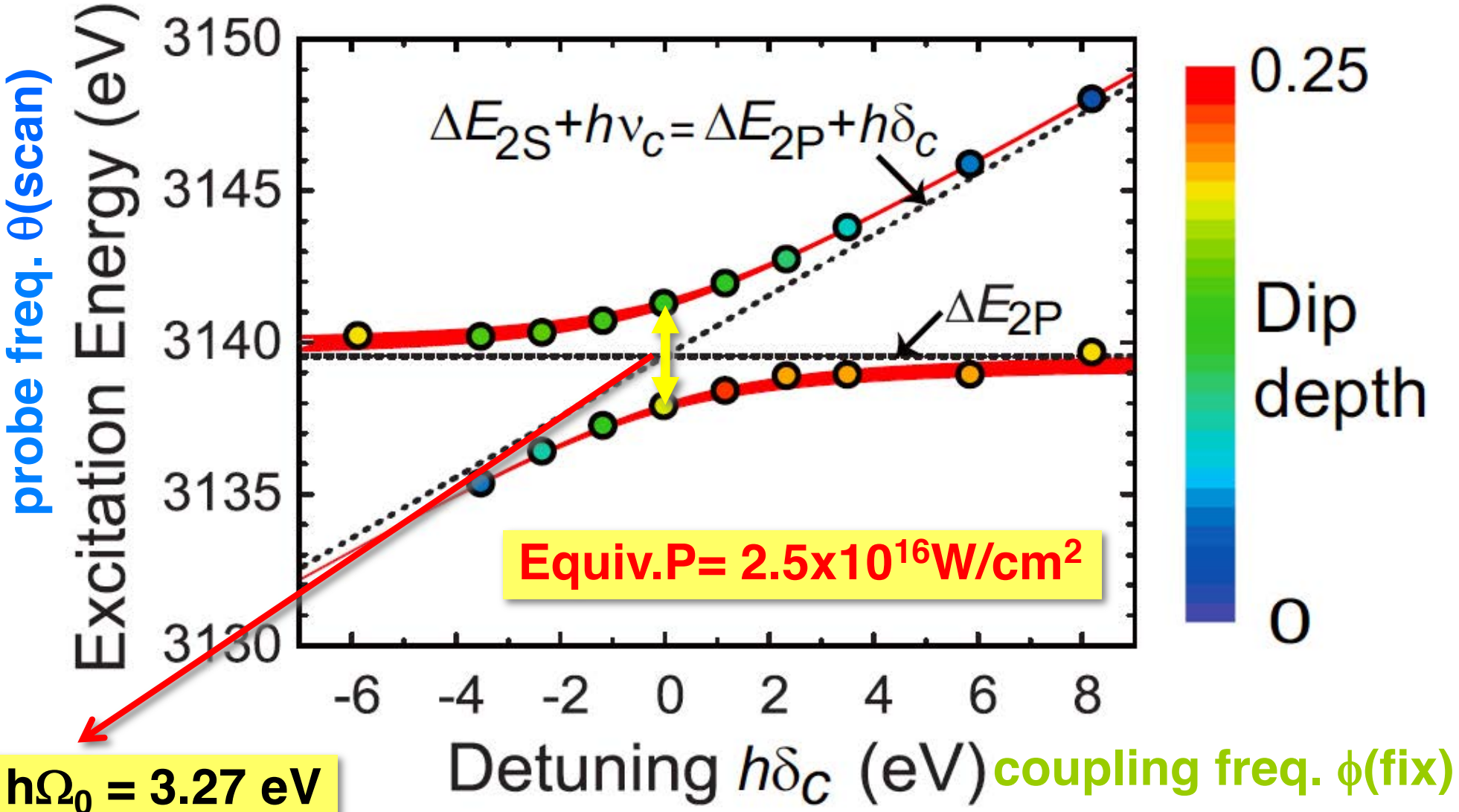


θ(scan)



Avoided level crossing (charge state)

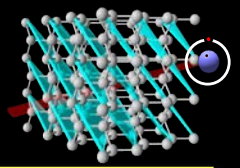




$h\Omega_0$ = 3.27 eV

Rabi frequency = 8.2 x10^{14} Hz

Asymmetric doublets

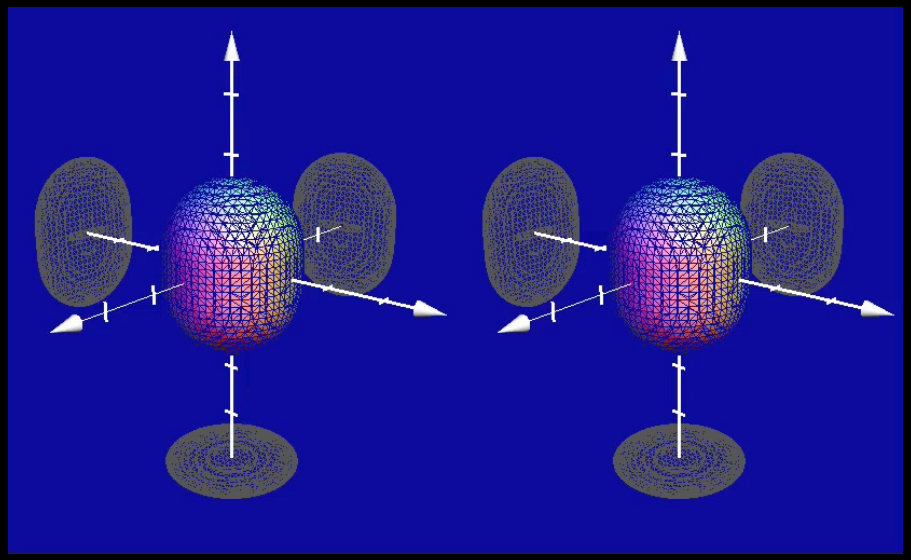


dressed state

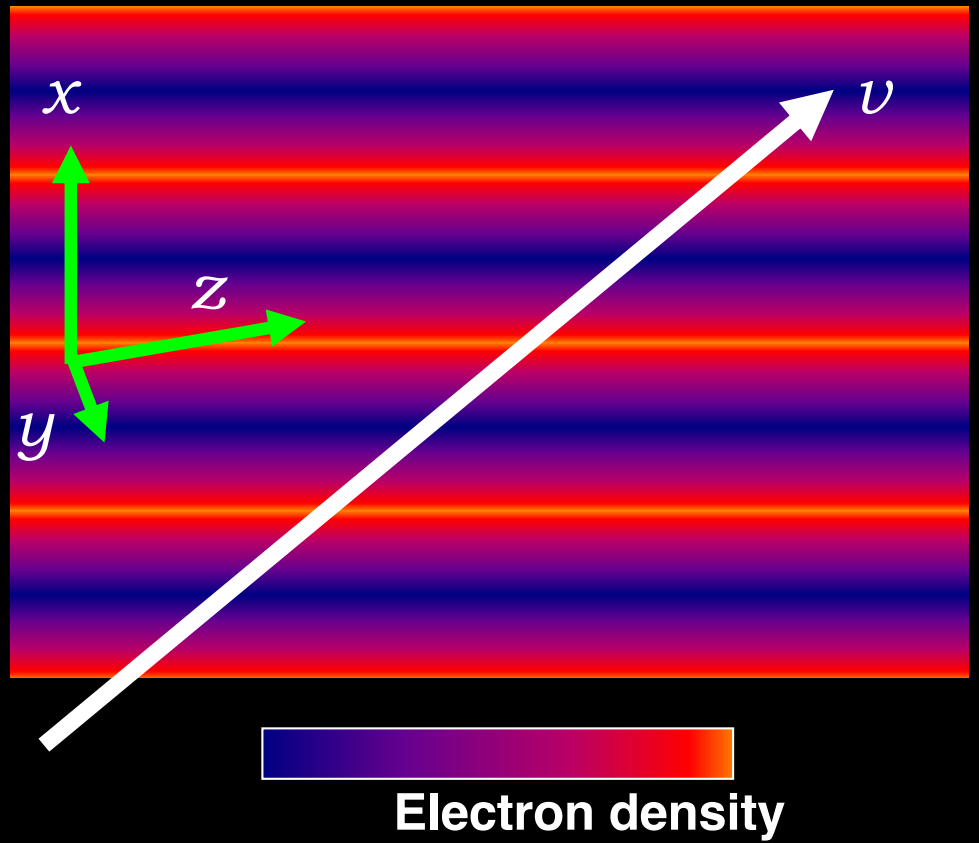
$$|+\rangle = \cos\theta\,|{}^1\mathrm{S}\rangle + \sin\theta\,|{}^1\mathrm{P}\rangle$$

$$|-\rangle = -\sin\theta\,|{}^1\mathrm{S}\rangle + \cos\theta\,|{}^1\mathrm{P}\rangle$$

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

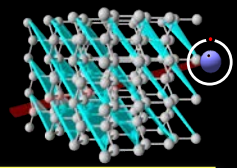


Periodic potential of (k,l,m)=(0,0,2)

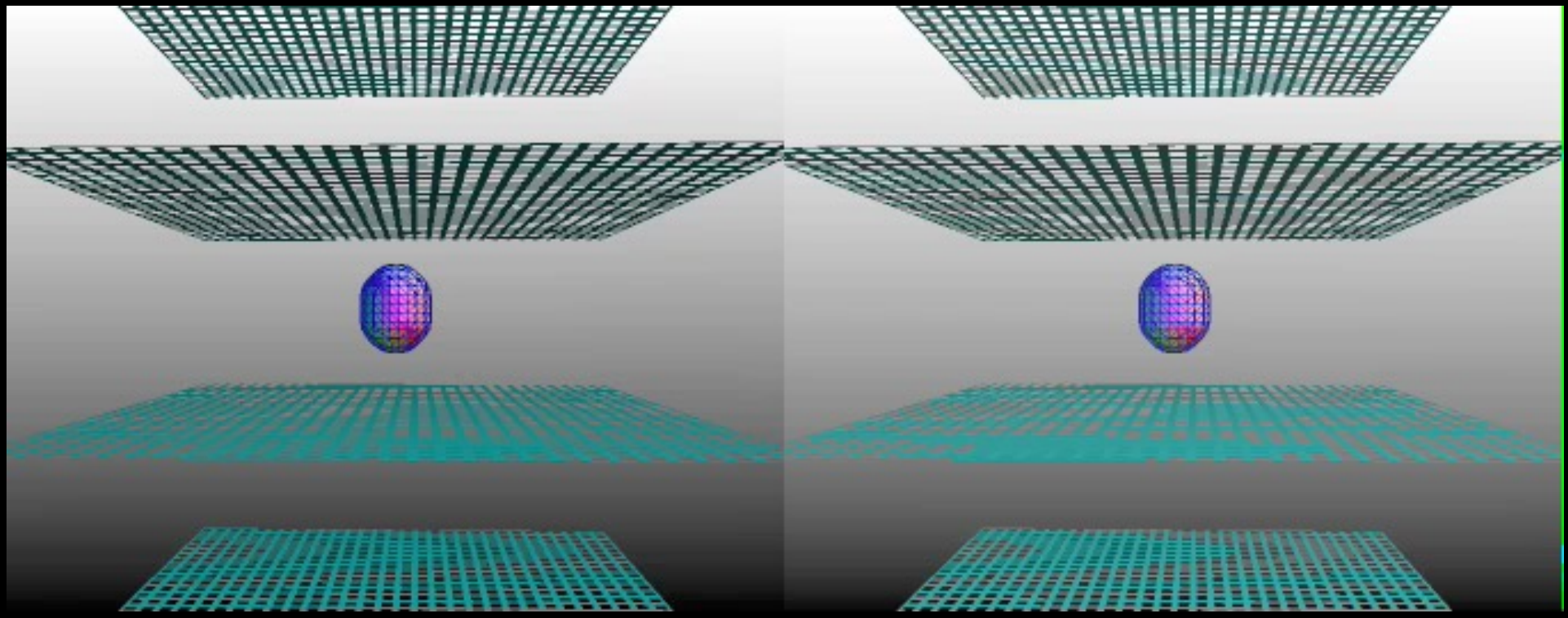


Oscillation of wave functions at frequency of coupling field

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

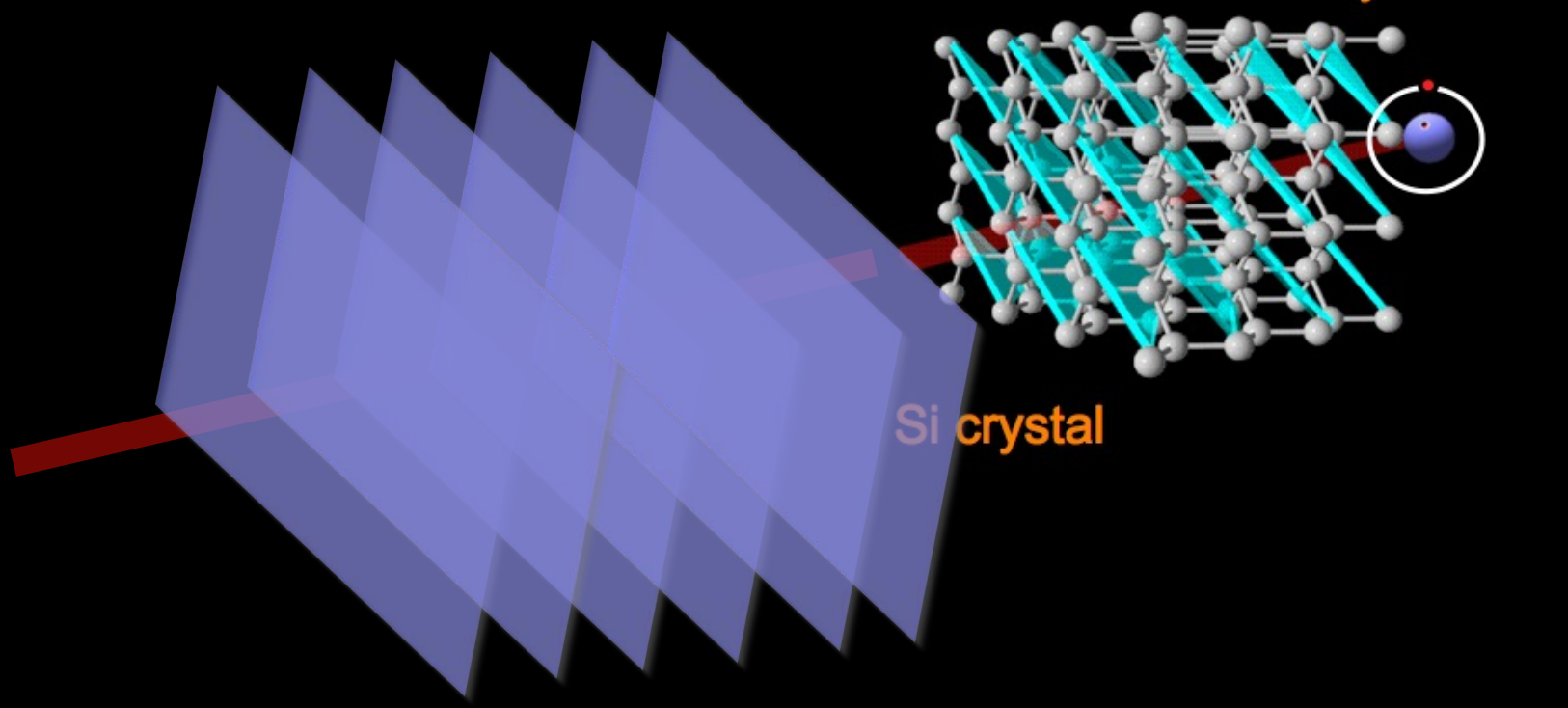
ionization： increase ⇧
deexitation: decrease ⇩

HIMAC: heavy ion medical accelerator

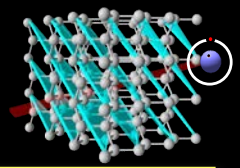
AMO physics
RIKEN

Ion beams at HIMAC are fast and heavy.
Are they “quantum beam” ? Yes !

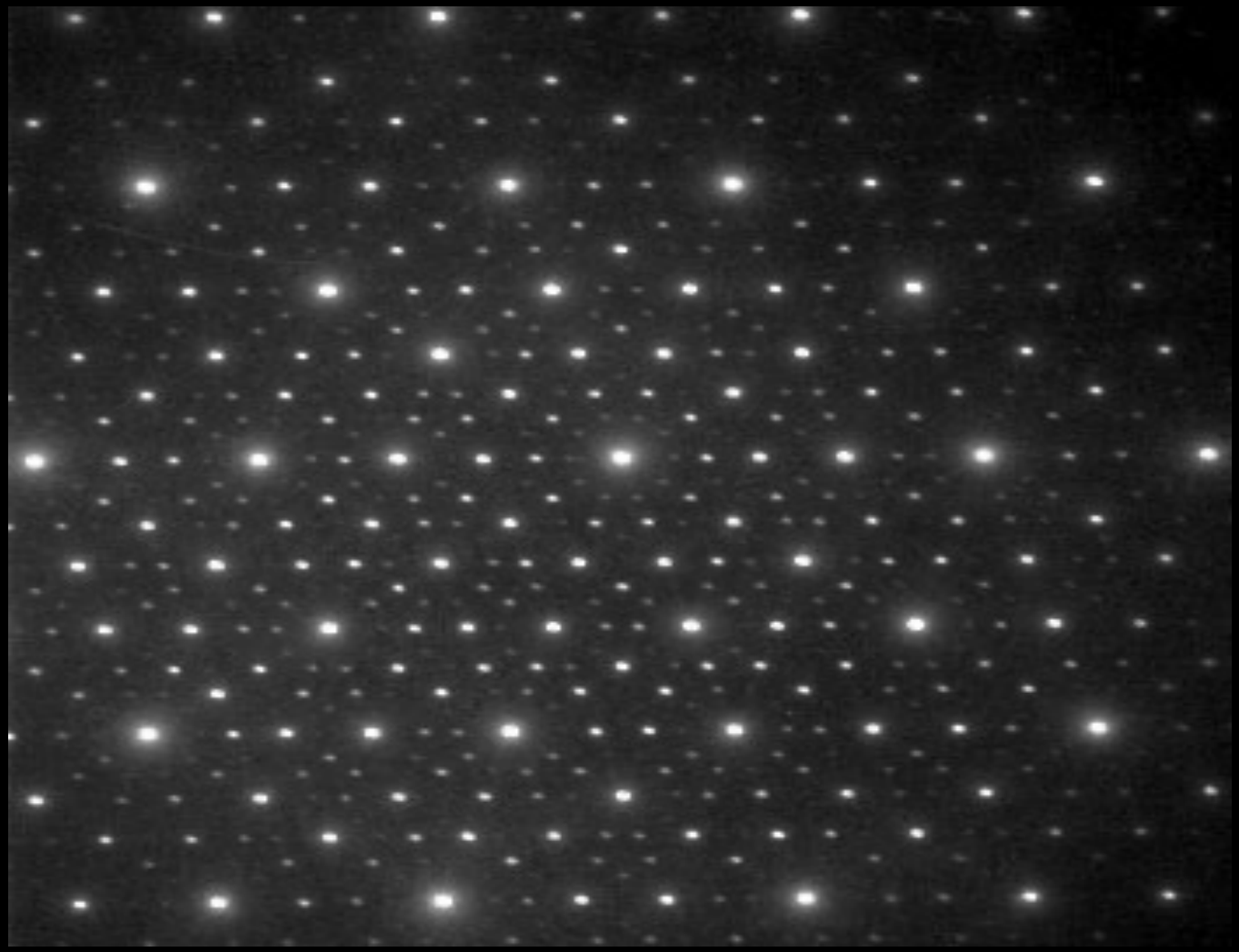
heavy ions are described by the plane-wave,
and experience diffraction by a crystal.



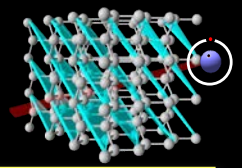
inelastic ion diffraction



Can we observe diffraction of high-energy heavy ions ?



inelastic ion diffraction



Can we observe diffraction of high-energy heavy ions ?

70% of the speed of light and ^{40}Ar

de Broglie wave length of the ion : 10^{-17} m

crystal periodicity : 10^{-10} m

↓

diffraction angle : 10^{-7} rad …. hard to be detected !

RCE: inelastic ion diffraction with internal excitation

with a momentum transfer *hg*

Using the high-energy heavy ions,

in the day-time of the week days, medical doctors enjoy cancer therapy

in the night and the week end, physisists enjoy quantum physics.

Physics and Medical Science coexist happily .

Two lessons

AMO physics
RIKEN

Lesson I : Physics and Medical Science

Lesson II : Interdisciplinary Science

astrophysics vs atomic physics

Grand-in-Aid for Scientific Research on Innovative Areas (2018-2022)

Toward new frontiers :
Encounter and synergy of state-of-the-art astronomical detectors and exotic quantum beams

Area manager : T. Takahashi (髙橋忠幸)

Encounter and Synergy of different fields

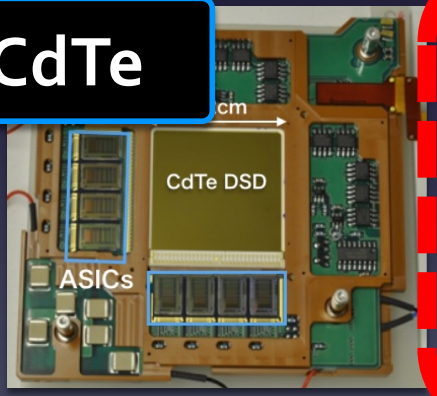
State-of-the-art astronomical detectors

×

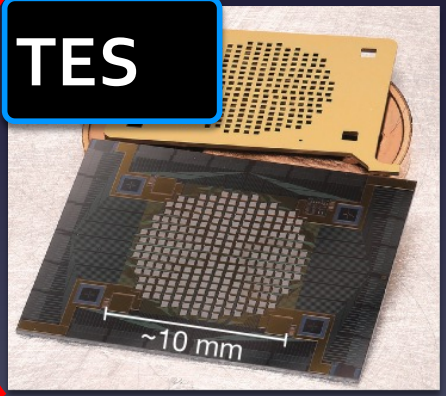
μ- (J-PARC)
e- (JLAB etc.)
RI (RIKEN)

Quantum beam

CdTe

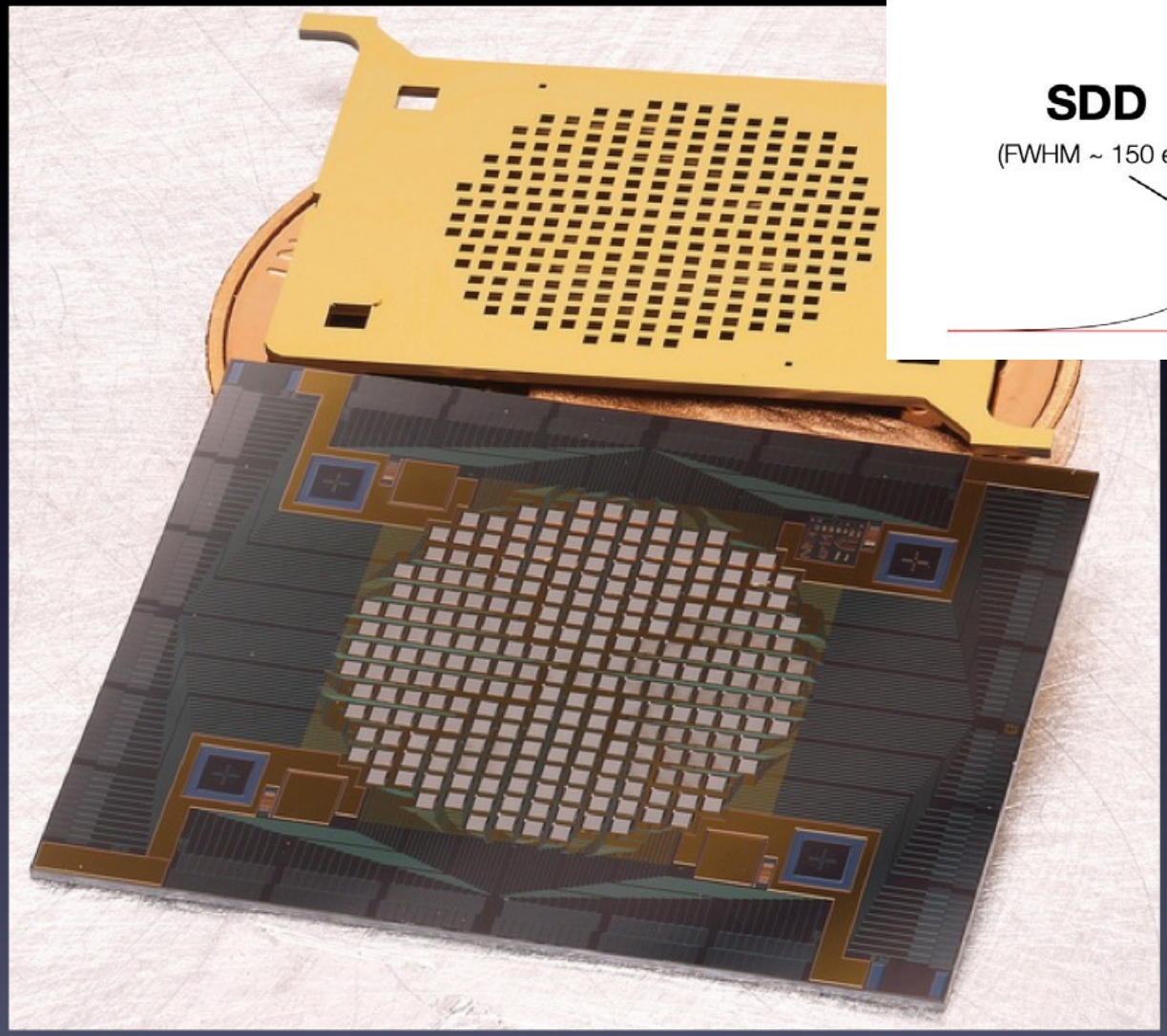


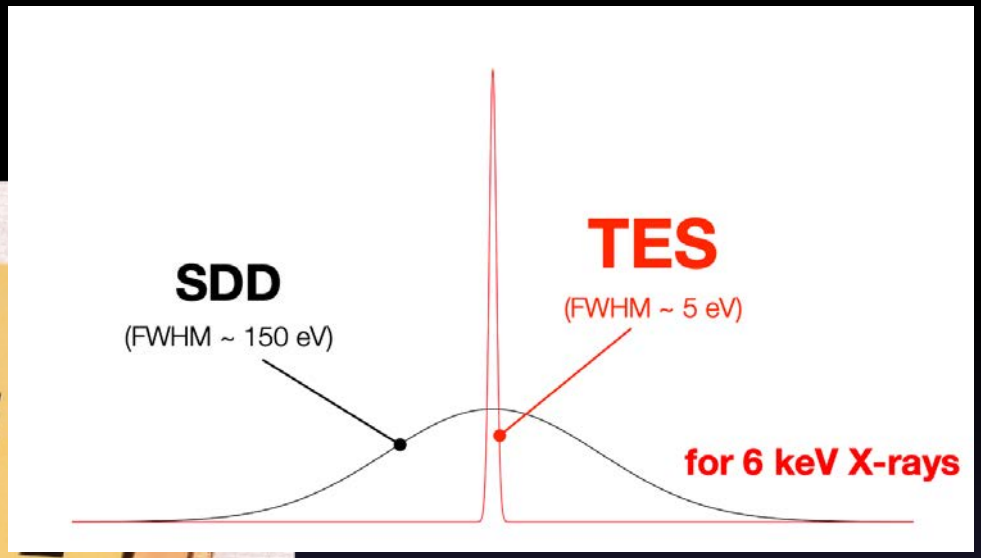
TES



to break barriers between disciplines

Superconducting Transition-Edge-Sensor (TES) calorimeter

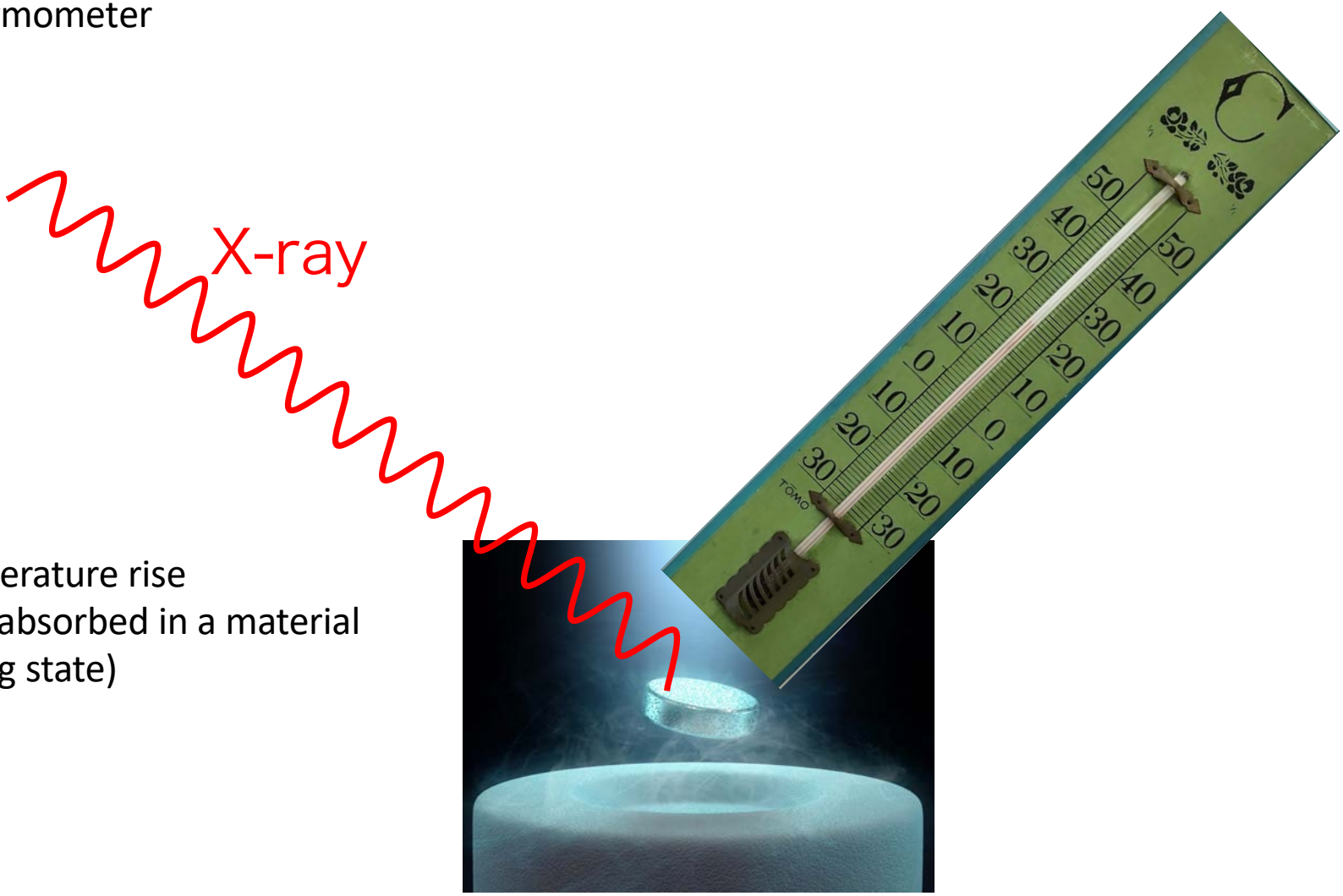




Transition-Edge-Sensor microcalorimeter

Microcalorimeter

tiny thermometer



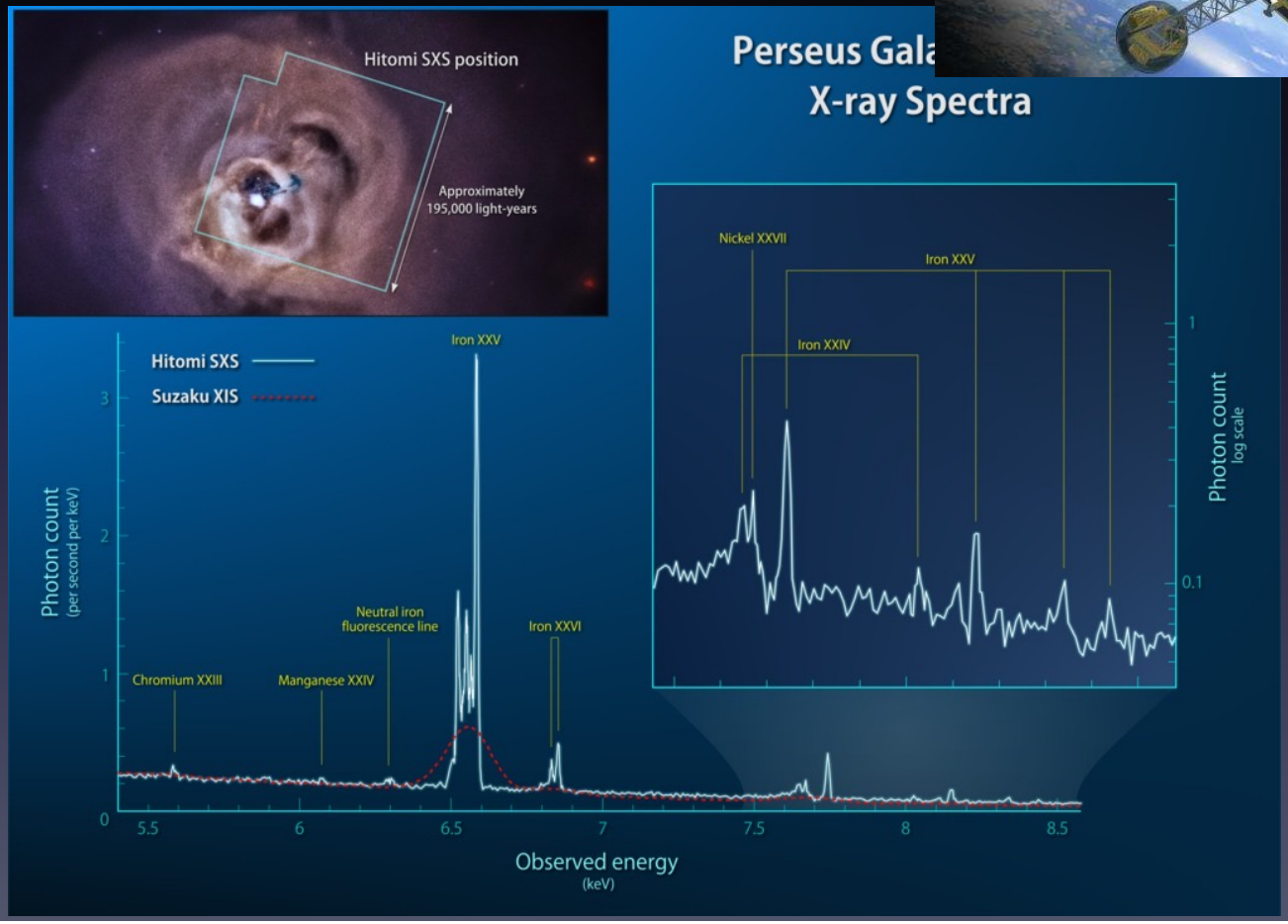
measuring temperature rise
when x-rays are absorbed in a material
(superconducting state)

AMO Physics and Astrophysics

X-ray satellite HITOMI

Electronic spectra of atoms (Fe) clarified

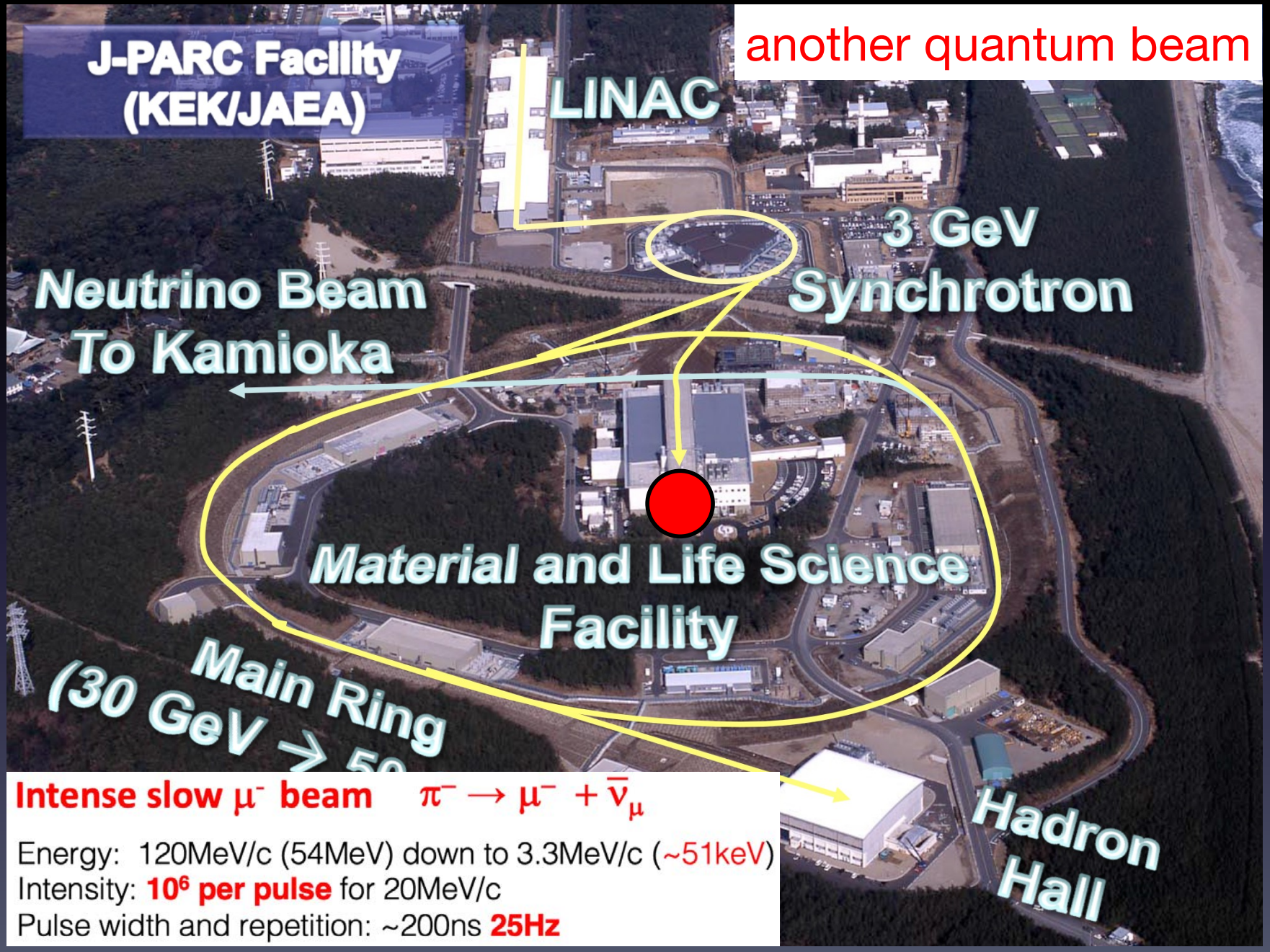
"Gentle" Winds of a Galaxy Cluster



The Hitomi collaboration
Nature **535,** 117–121 (2016)

X rays from
Highly charged Fe ions

intense muon beam at J-PARC

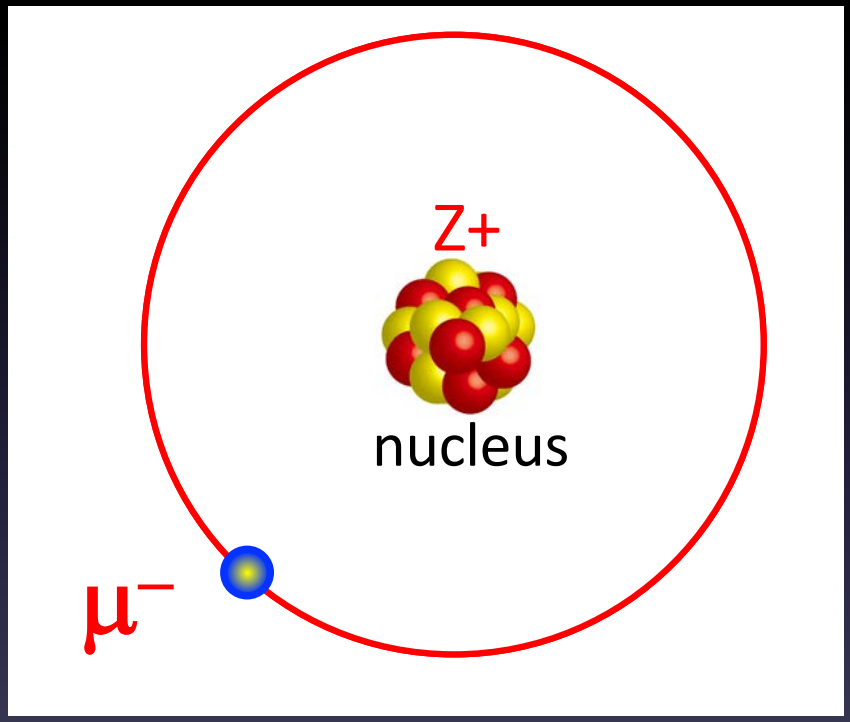


another quantum beam

Intense slow μ^- beam $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

Energy: 120MeV/c (54MeV) down to 3.3MeV/c (~51keV)
Intensity: **10^6 per pulse** for 20MeV/c
Pulse width and repetition: ~200ns **25Hz**

Muonic Atom



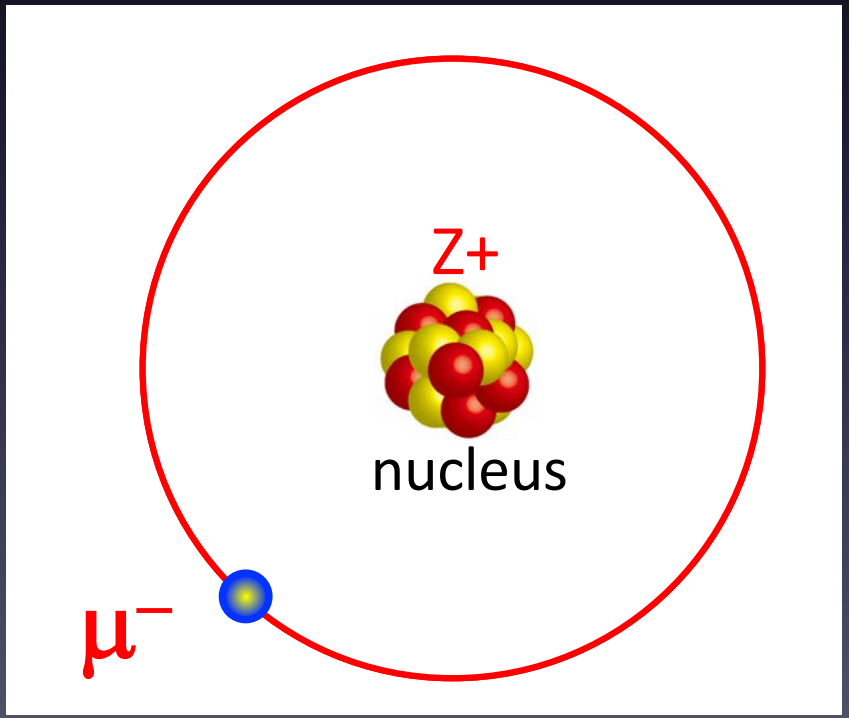
Muonic Atom

negative muon = “Heavy“ electron

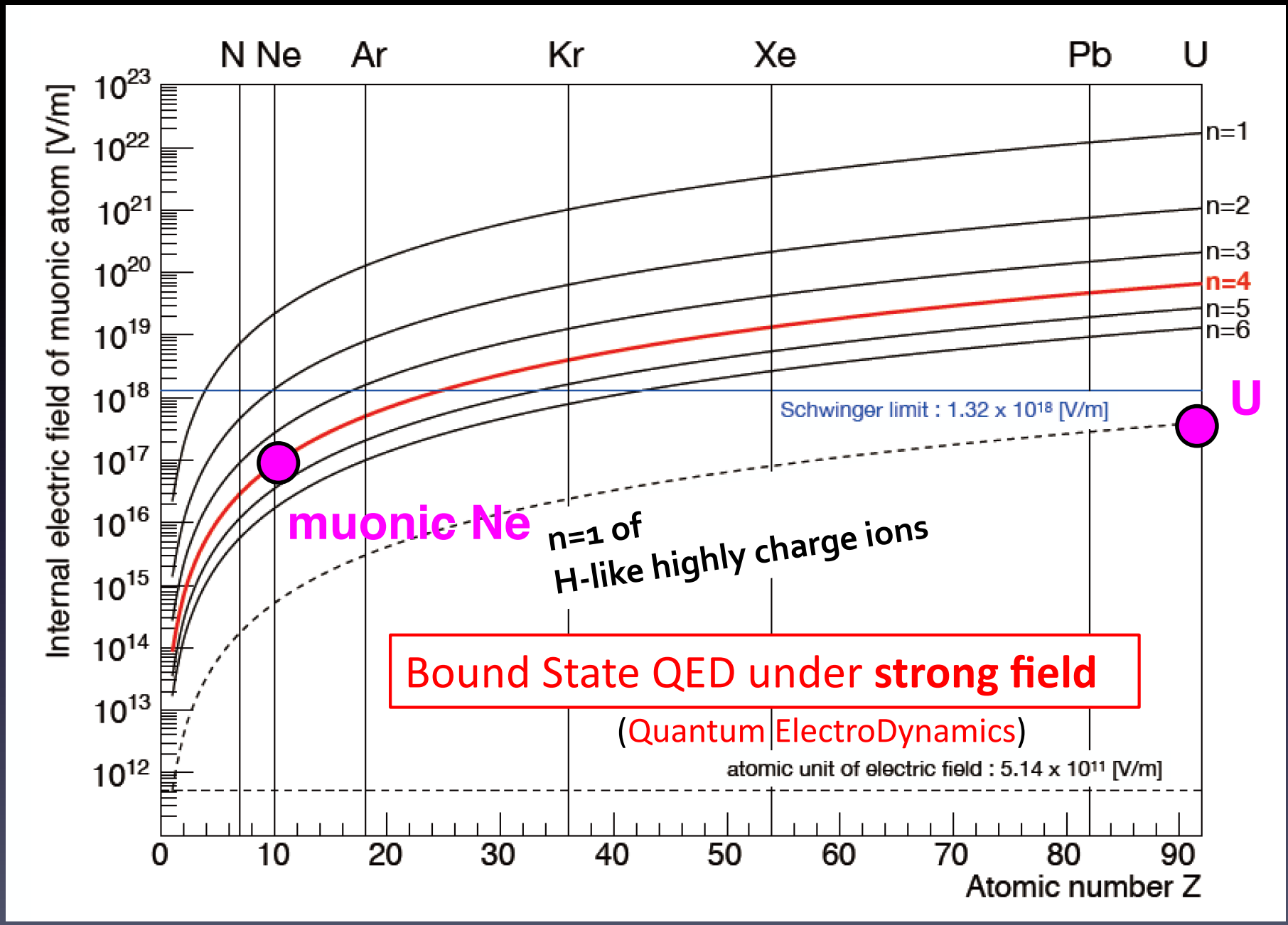
compared with normal atoms;

- a Bohr radius: **207 times smaller**
- transition energies: **207 times larger**
- muonic X-ray energies: **207 times larger**

cf.
H atom 1s-2p 122nm = 10eV
vs.
muonic hydrogen = 2keV



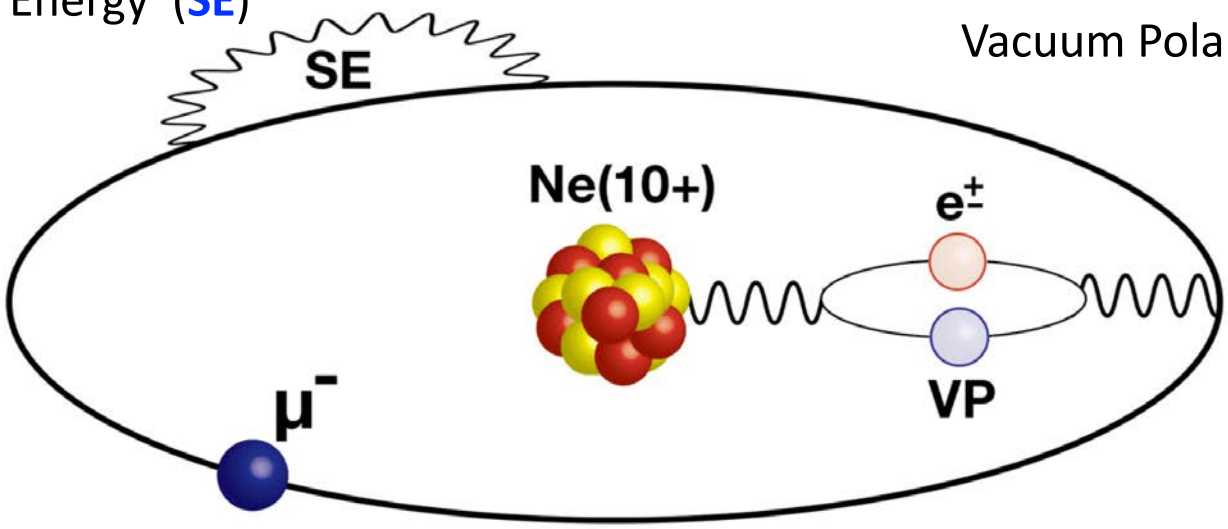
Bohr model : muonic atom *vs* highly charged ion



Bound State QED (Quantum ElectroDynamics)

Self Energy (**SE**)

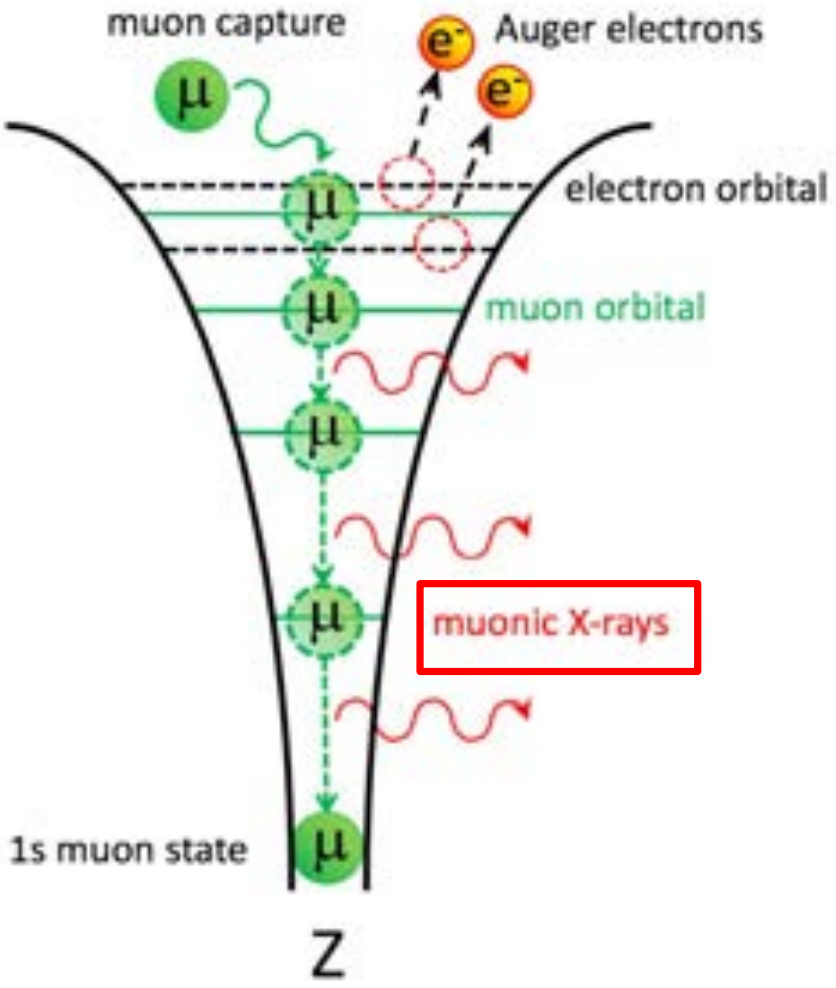
Vacuum Polarization (**VP**)



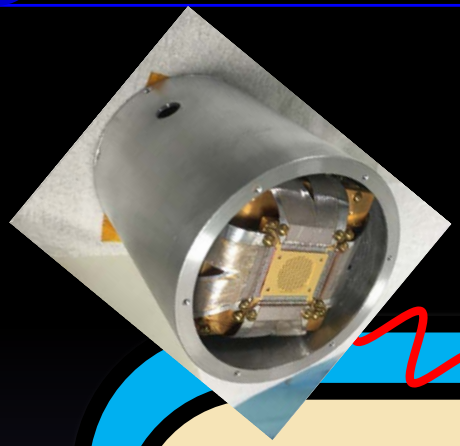
muonic atom

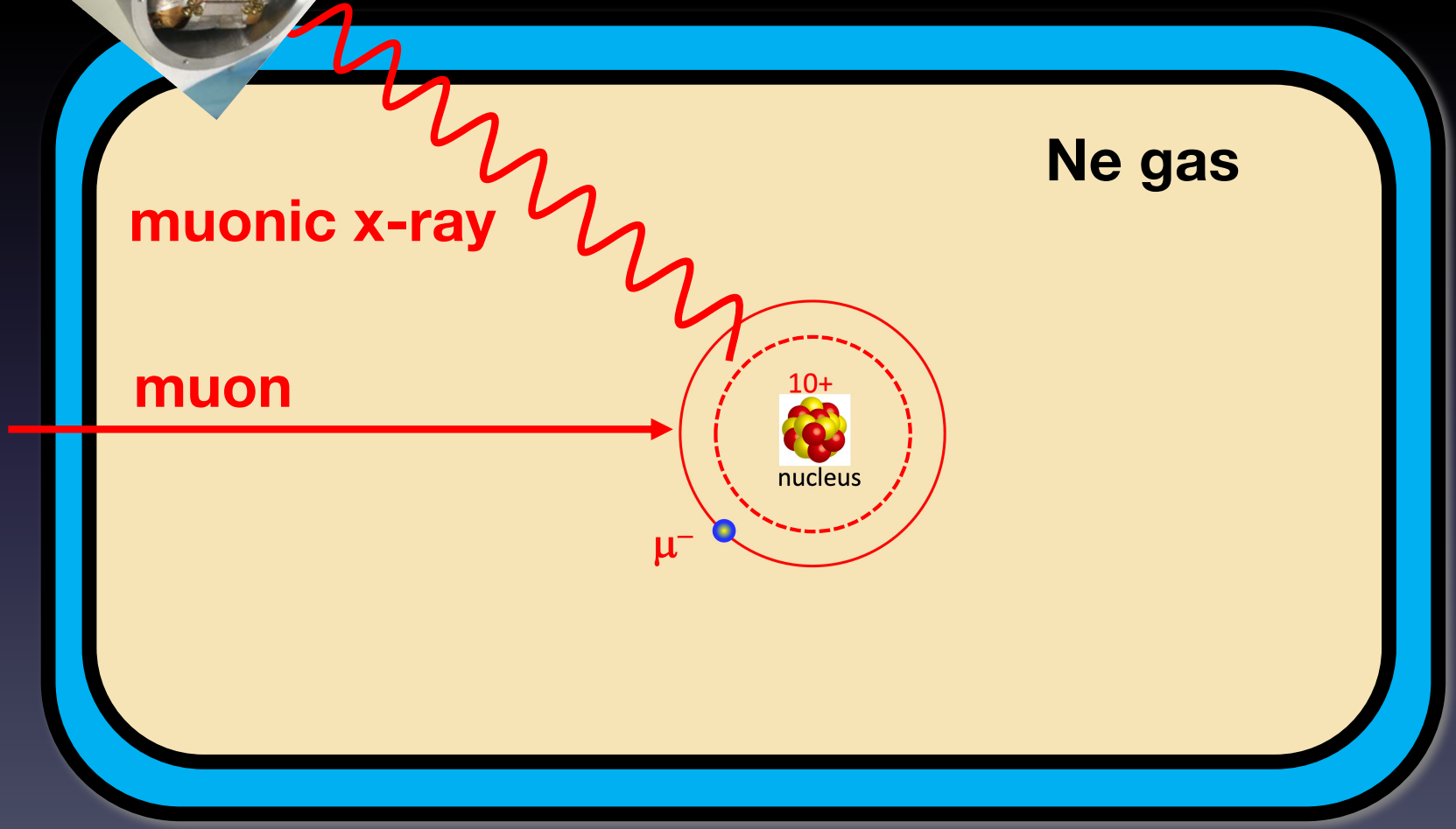
VP > **SE**

muon and electron dynamics in muonic atom



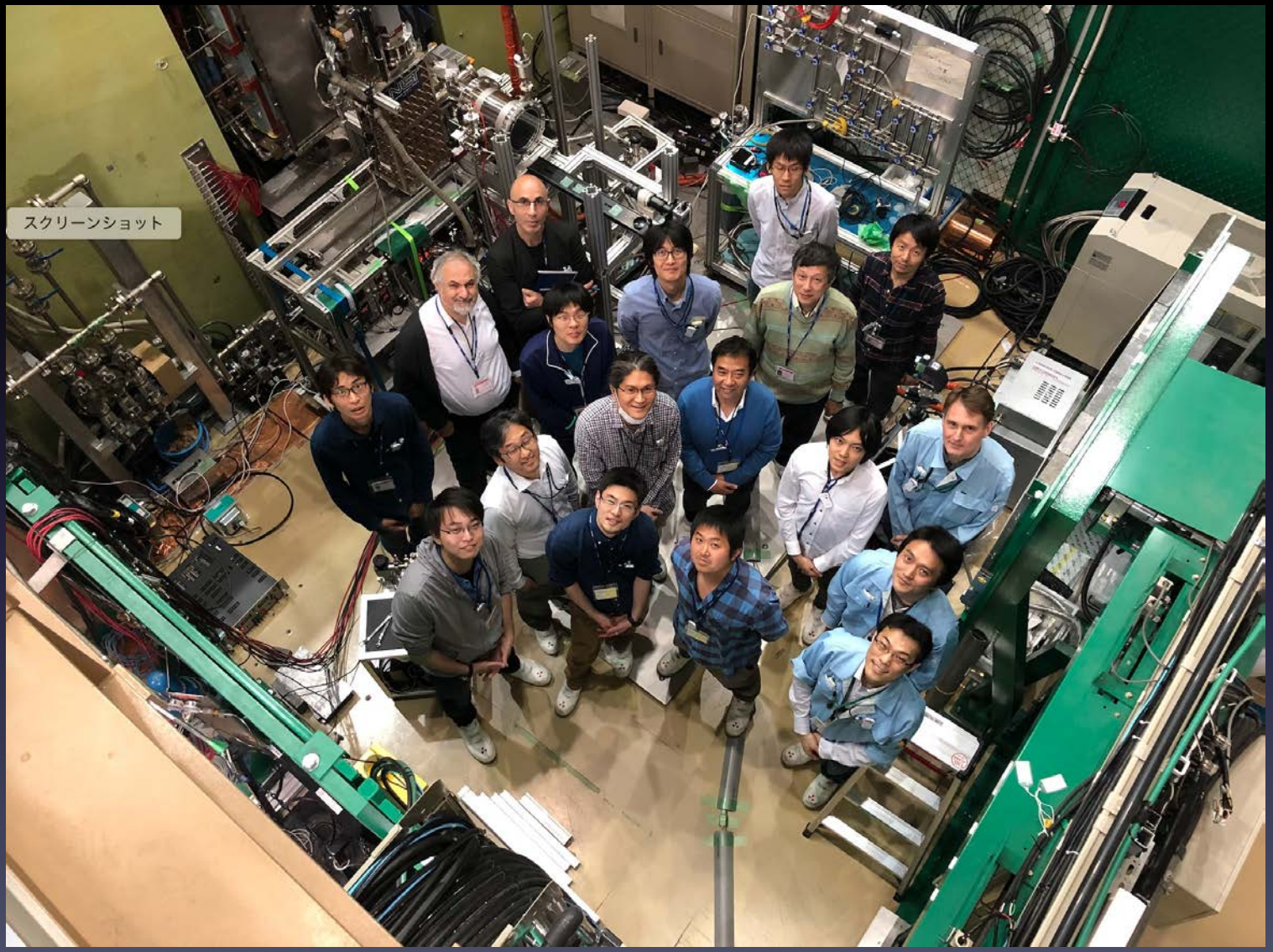
Muonic Atom





Members: total 26 researchers from different fields

from Atomic Physics, Nuclear Physics, Astro Physics, Muon Physics



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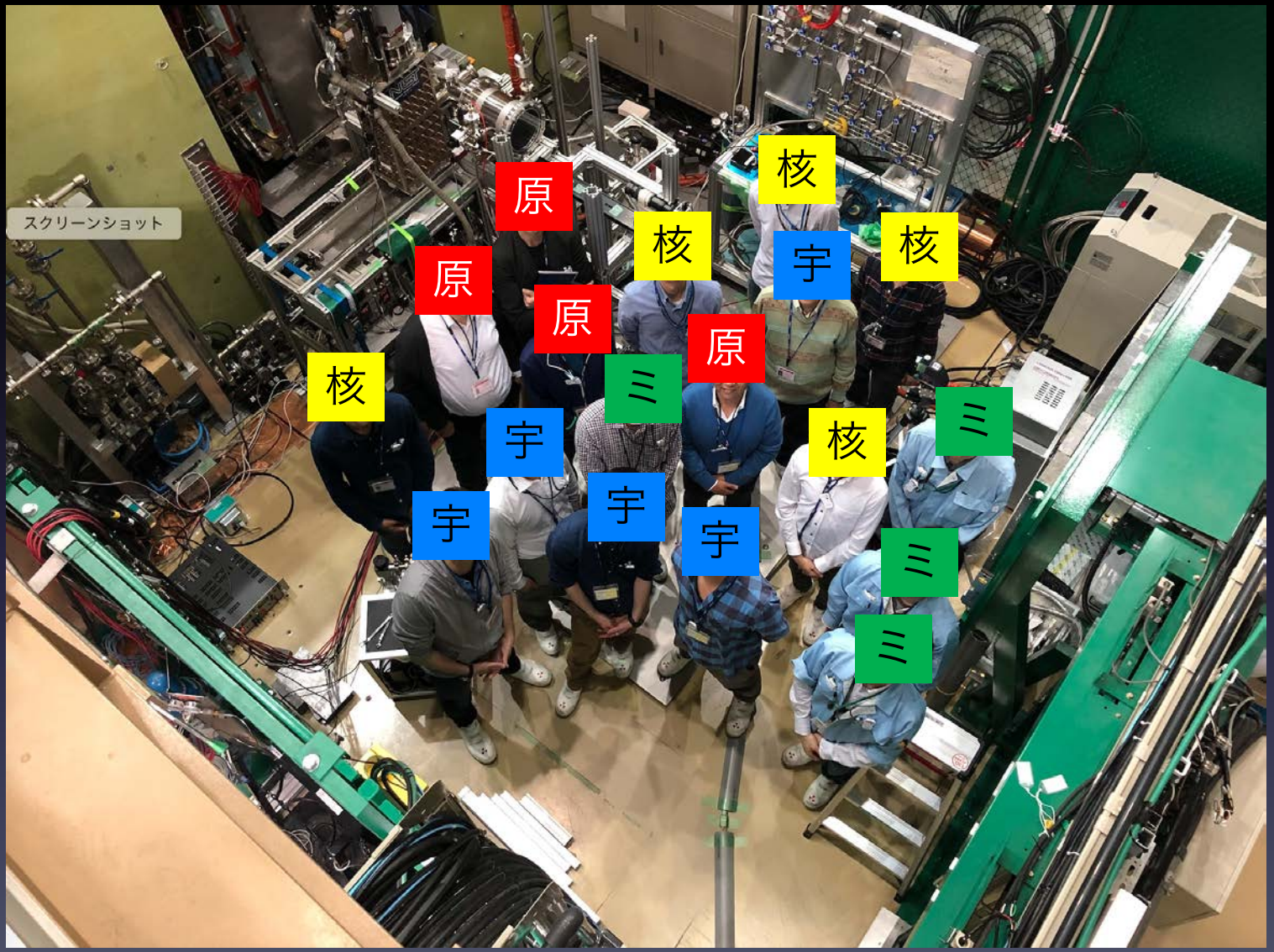
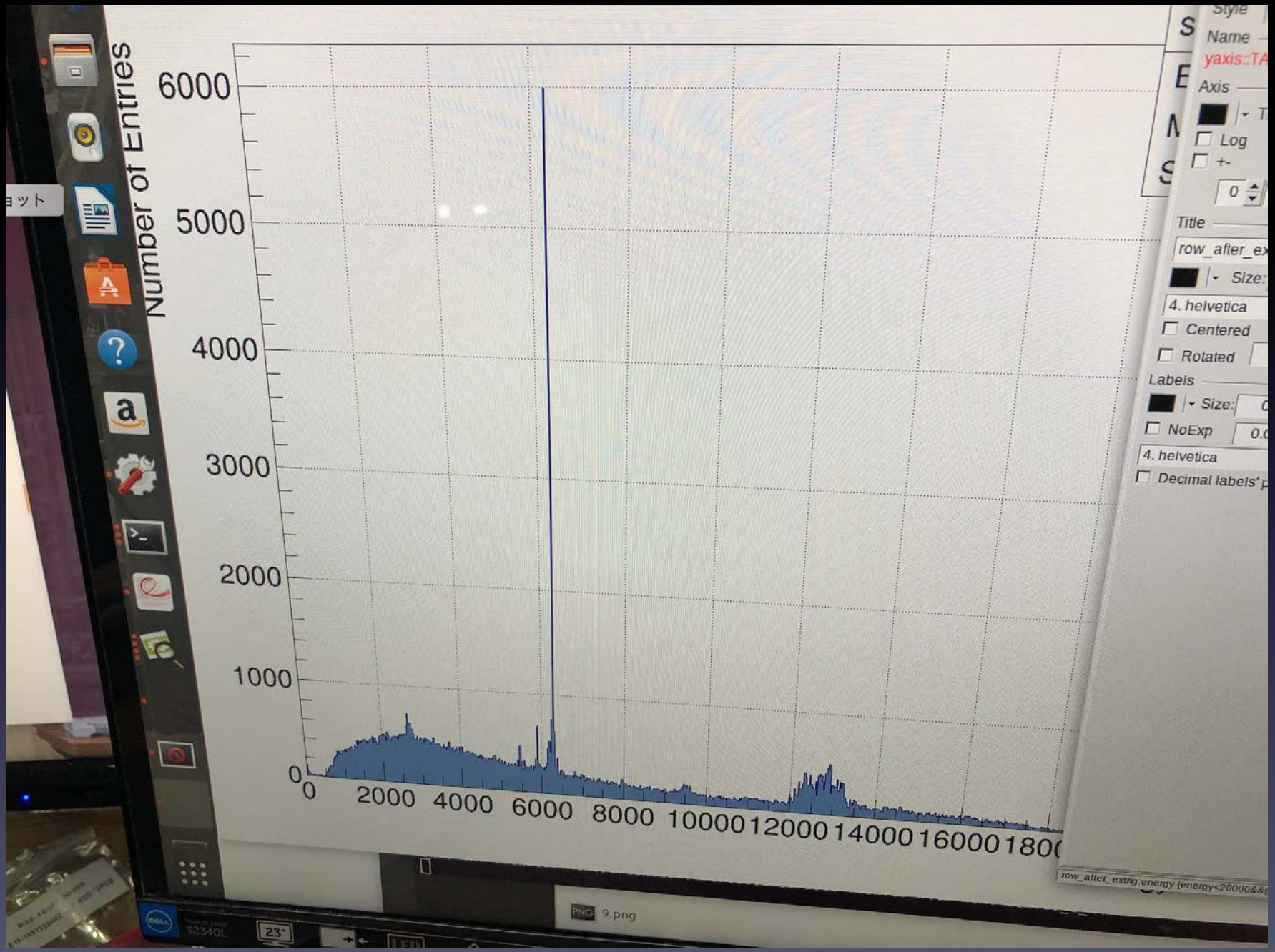


10 min. measurement setup (present version)

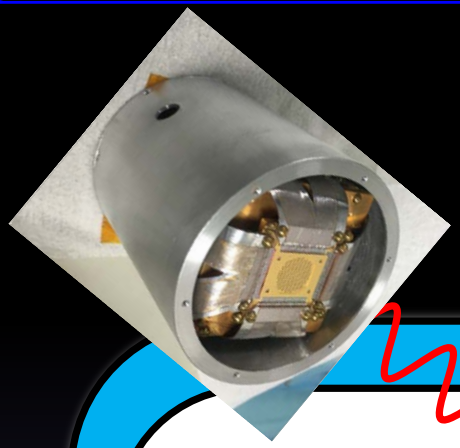


But the story never ends

...

more interdisciplenary finding

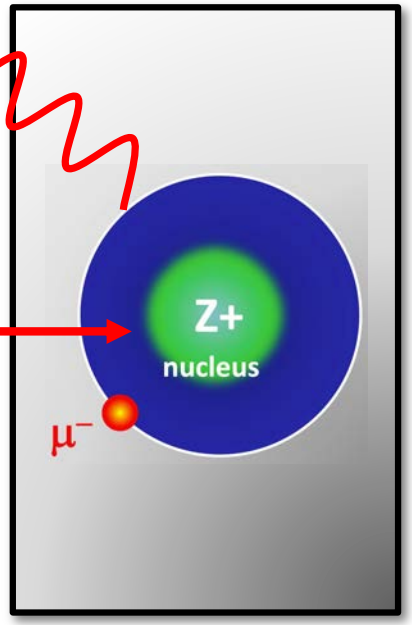
Muonic Atom



Serendipity !!

????? x-ray

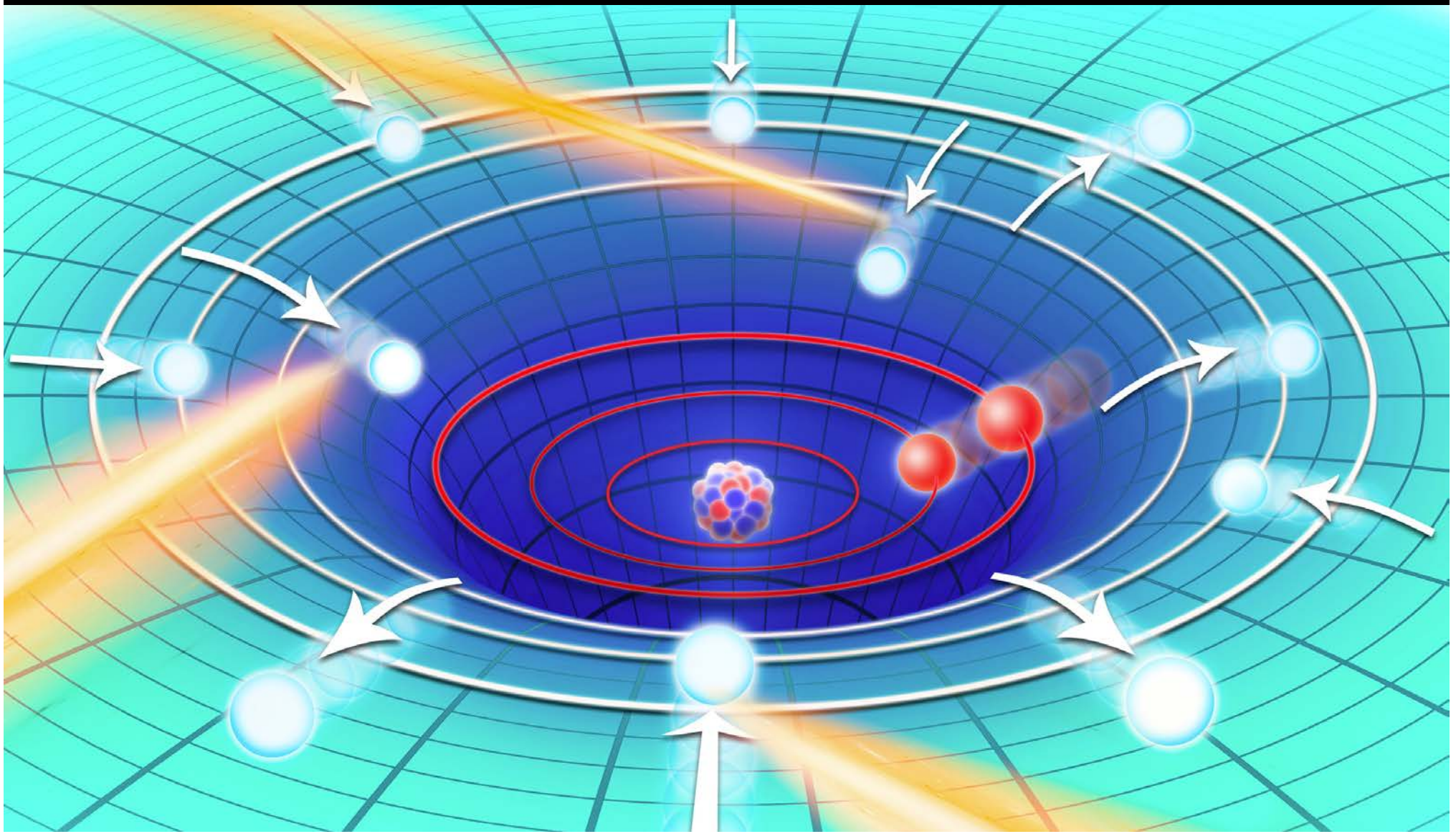
muon



Cu / Fe
metal foil

electronic x rays from muonic atom

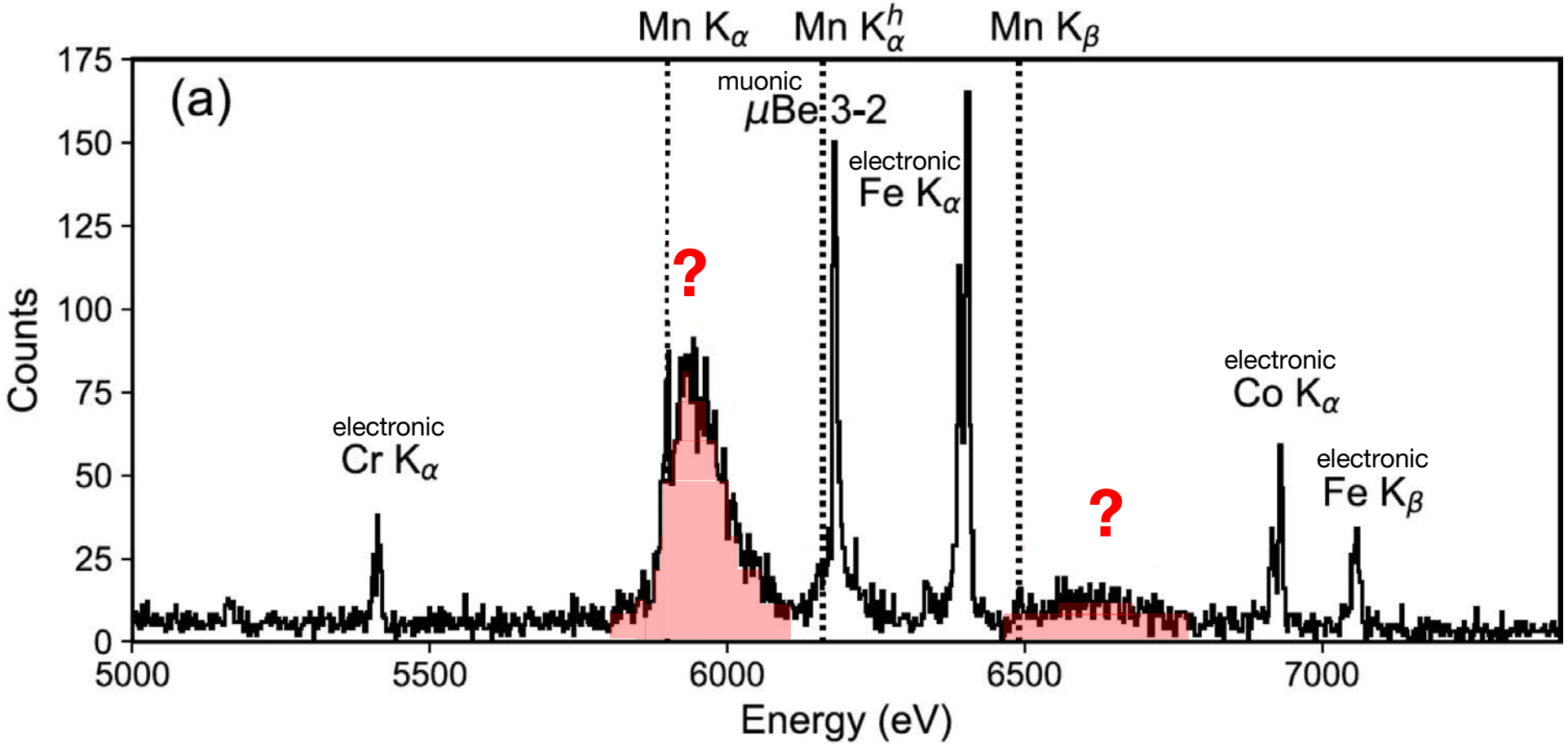
red: negative muon
white: electron



X ray energy spectrum for negative muon / Fe

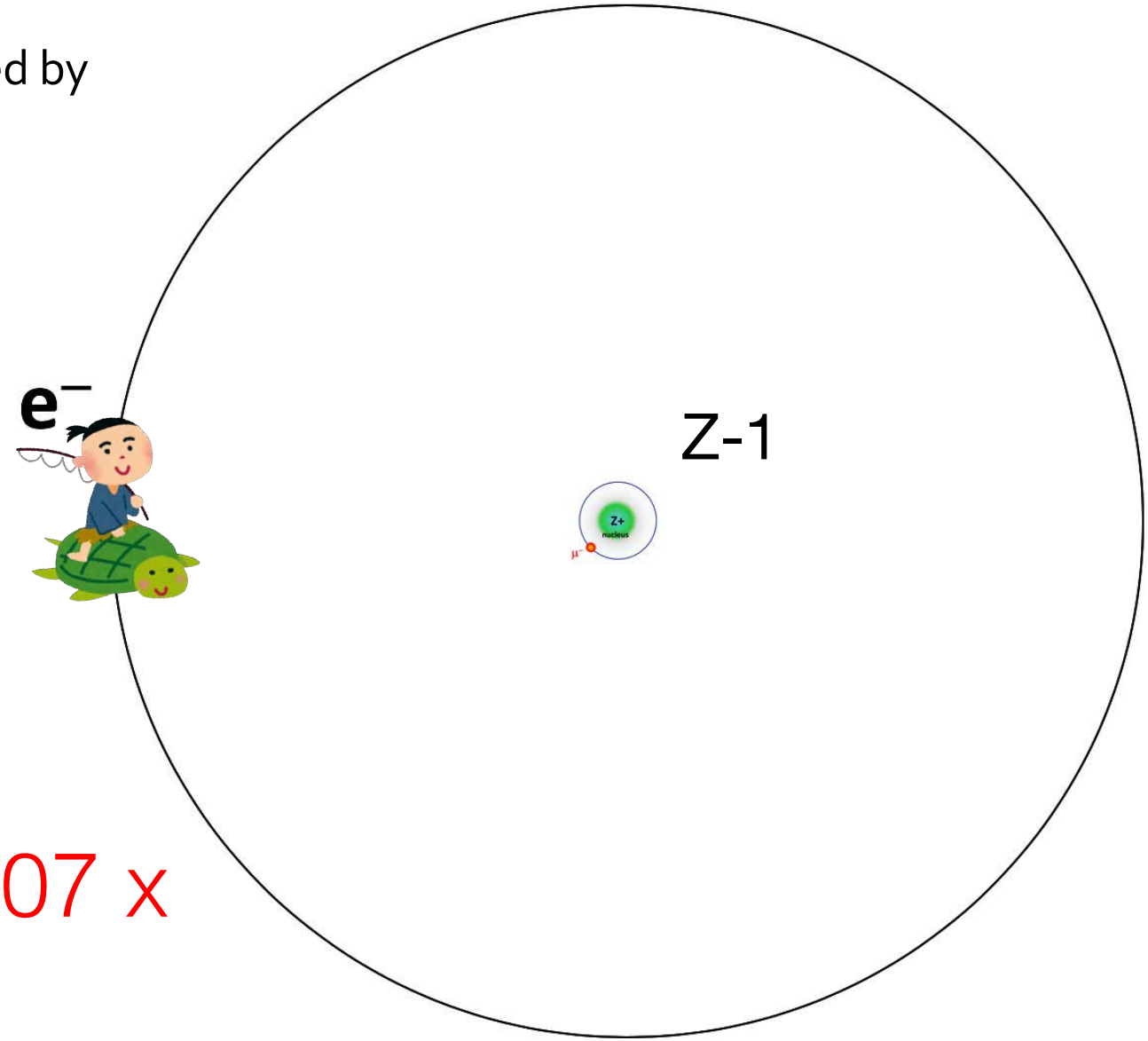
20.5 MeV/c negative muon

atomic number
Fe: 26
Mn: 25



Muonic Atom

For electron,
nucleus is screened by
negative muon

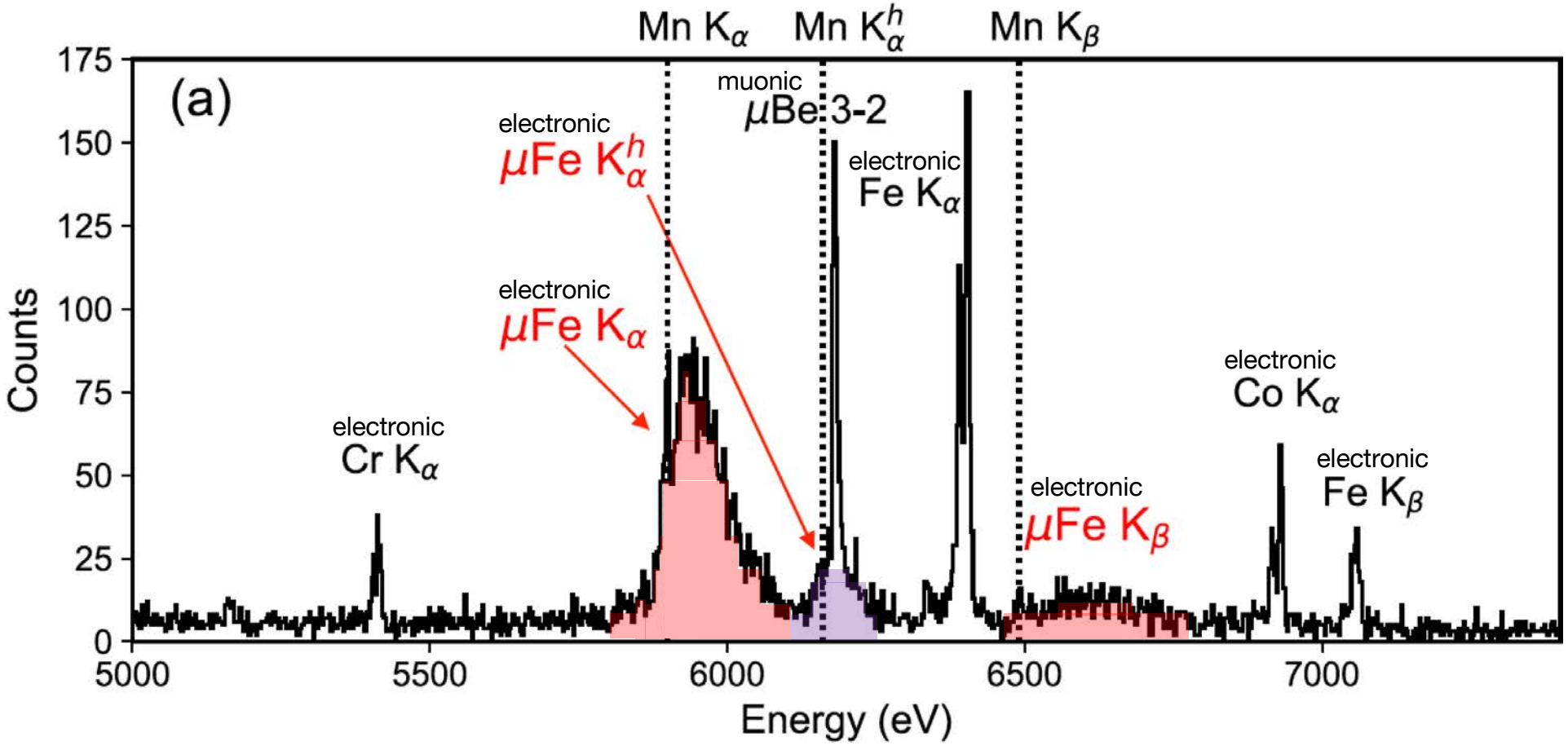


207 x

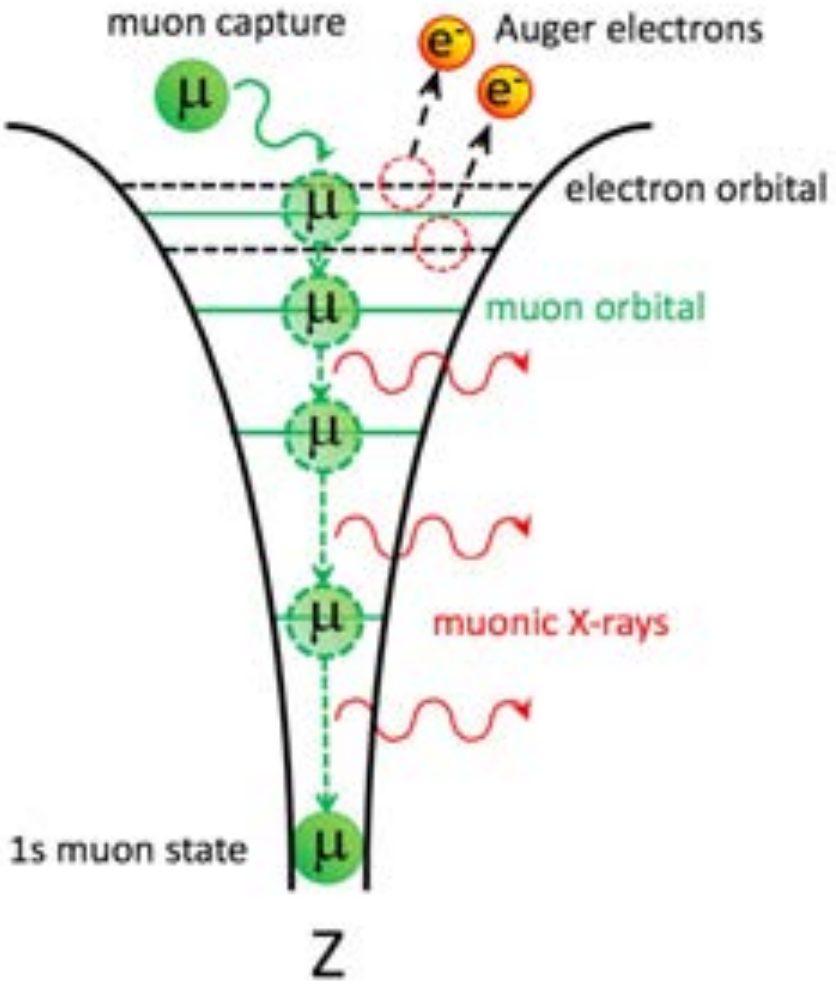
X ray energy spectrum for negative muon / Fe

20.5 MeV/c negative muon

atomic number
Fe: 26
Mn: 25

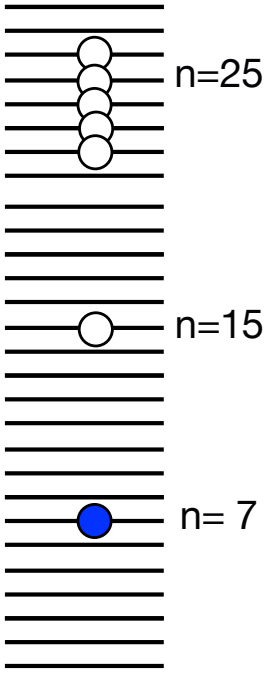


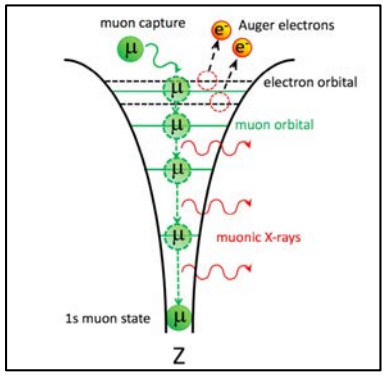
muon and electron dynamics in muonic atom



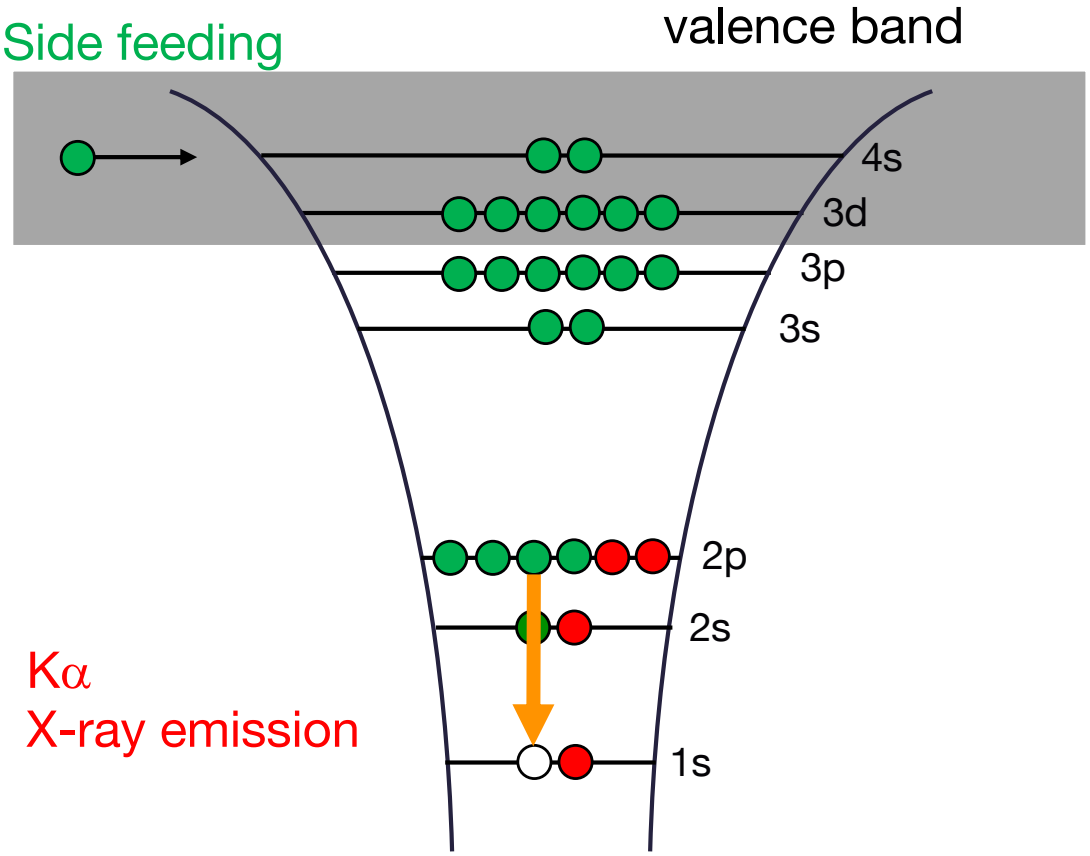
muon and electron dynamics in muonic atom

negative muon



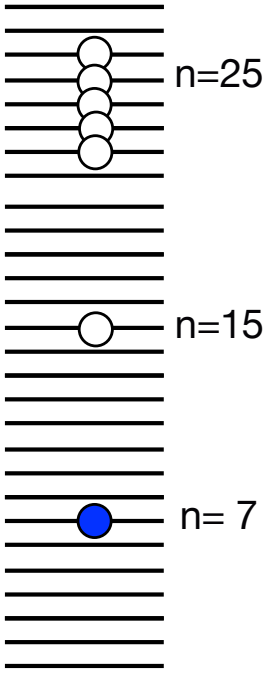


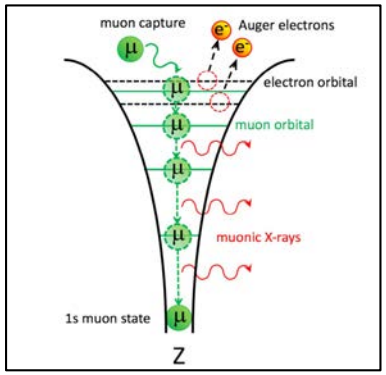
Fe metal



muon and electron dynamics in muonic atom

negative muon

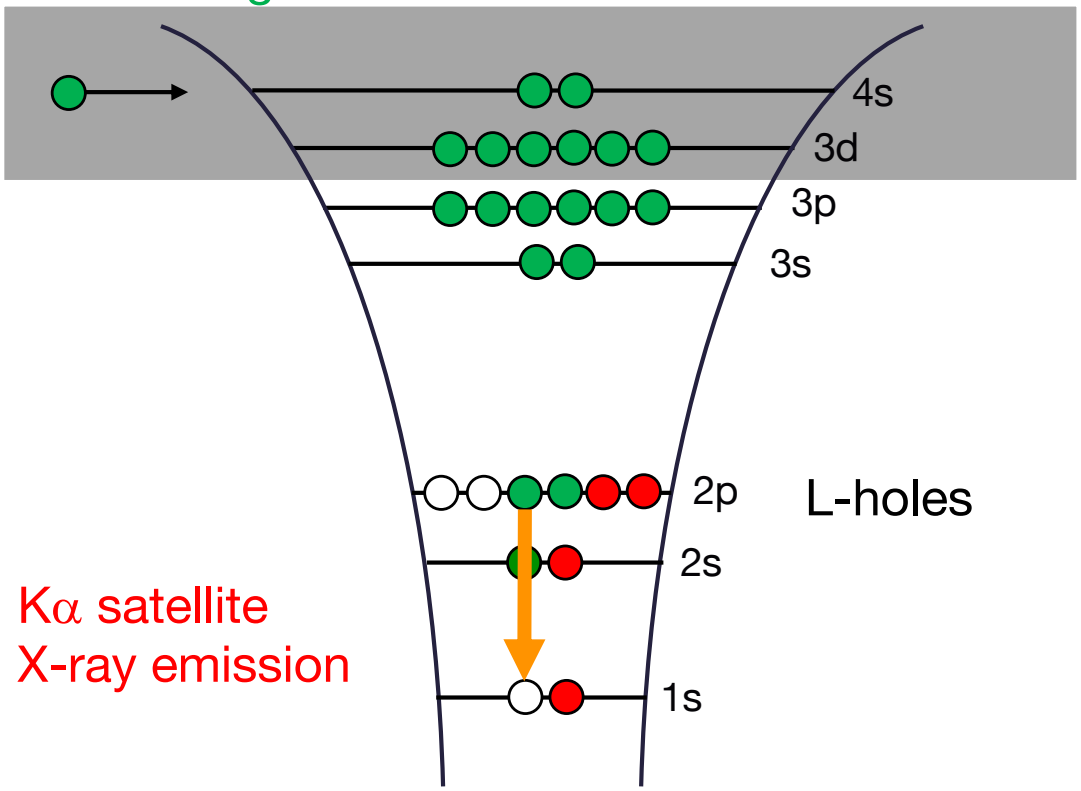




Fe metal

Side feeding

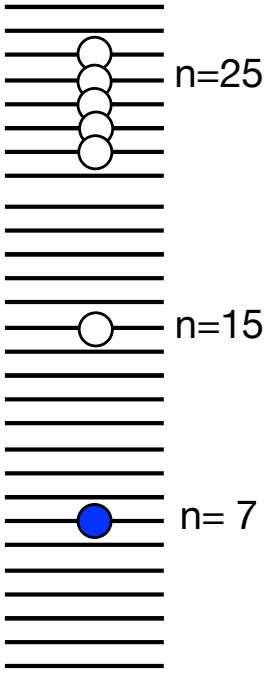
valence band

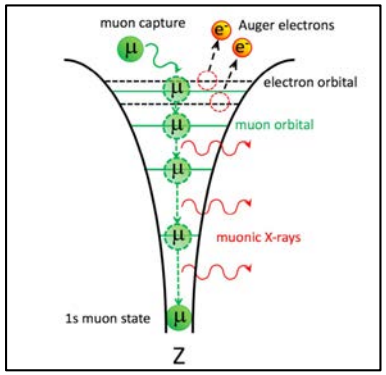


Kα satellite
X-ray emission

muon and electron dynamics in muonic atom

negative muon

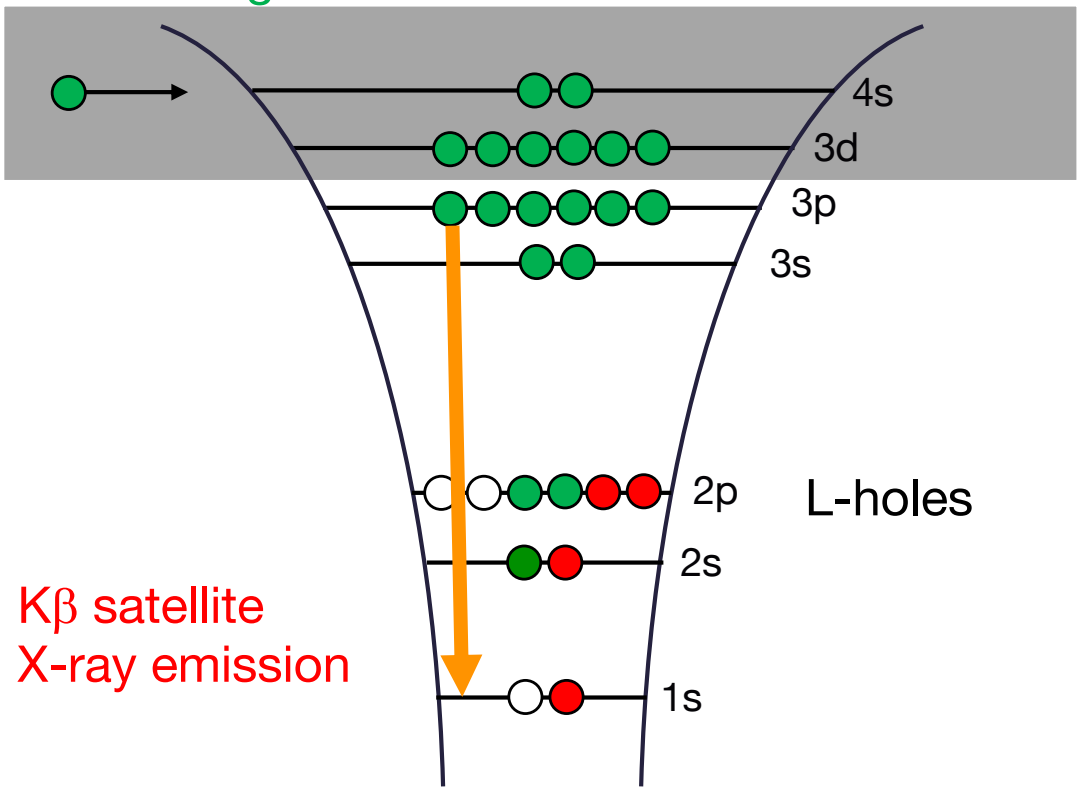




Fe metal

Side feeding

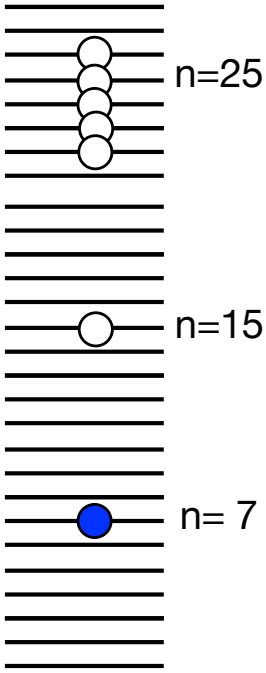
valence band

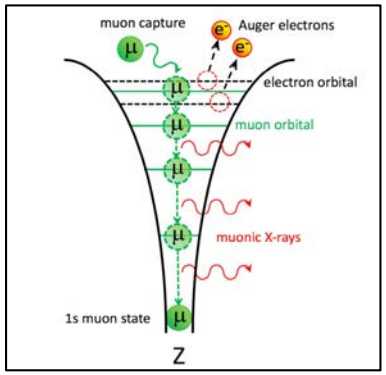


Kβ satellite
X-ray emission

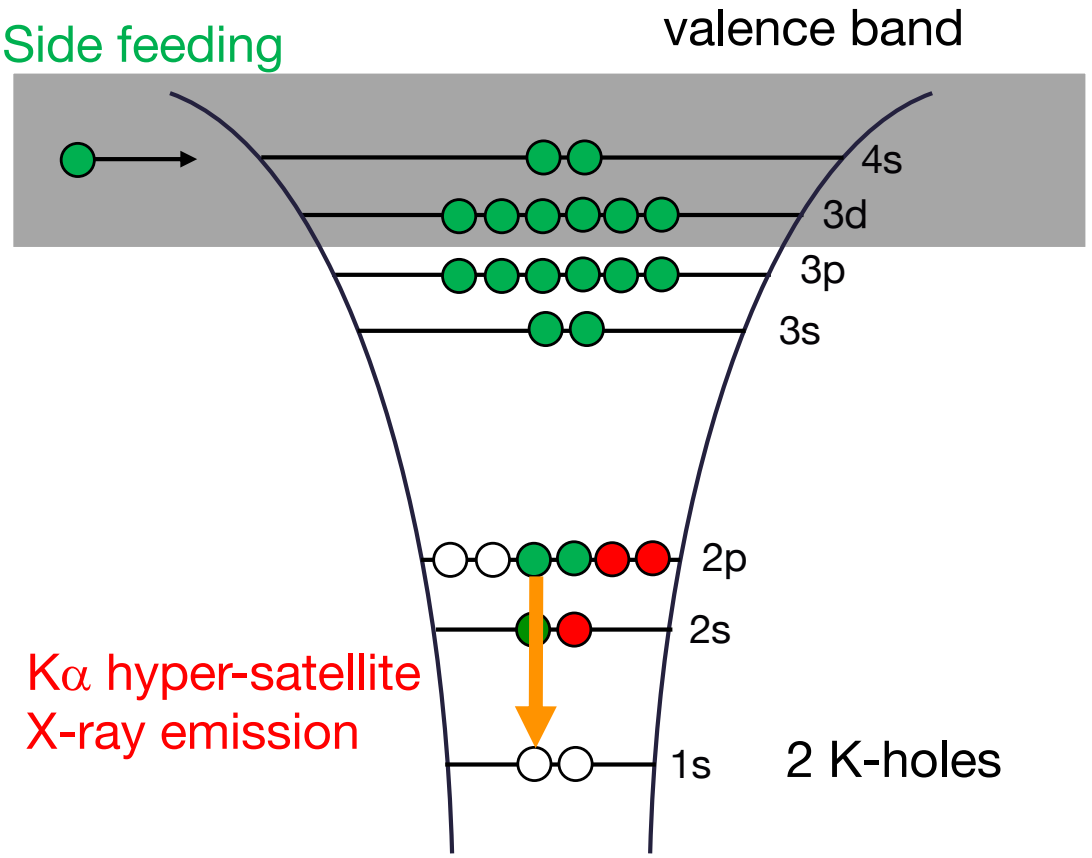
muon and electron dynamics in muonic atom

negative muon



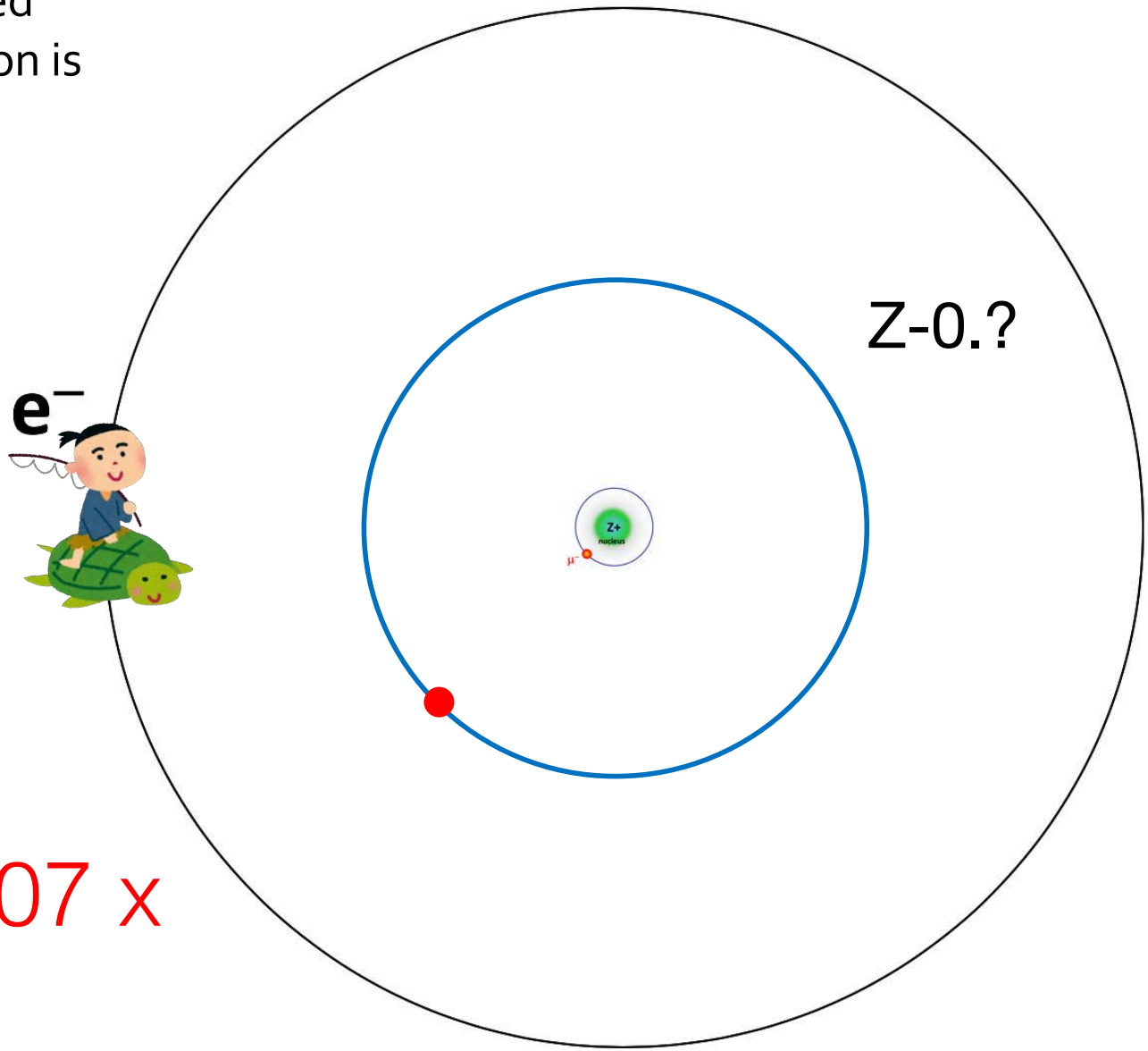


Fe metal



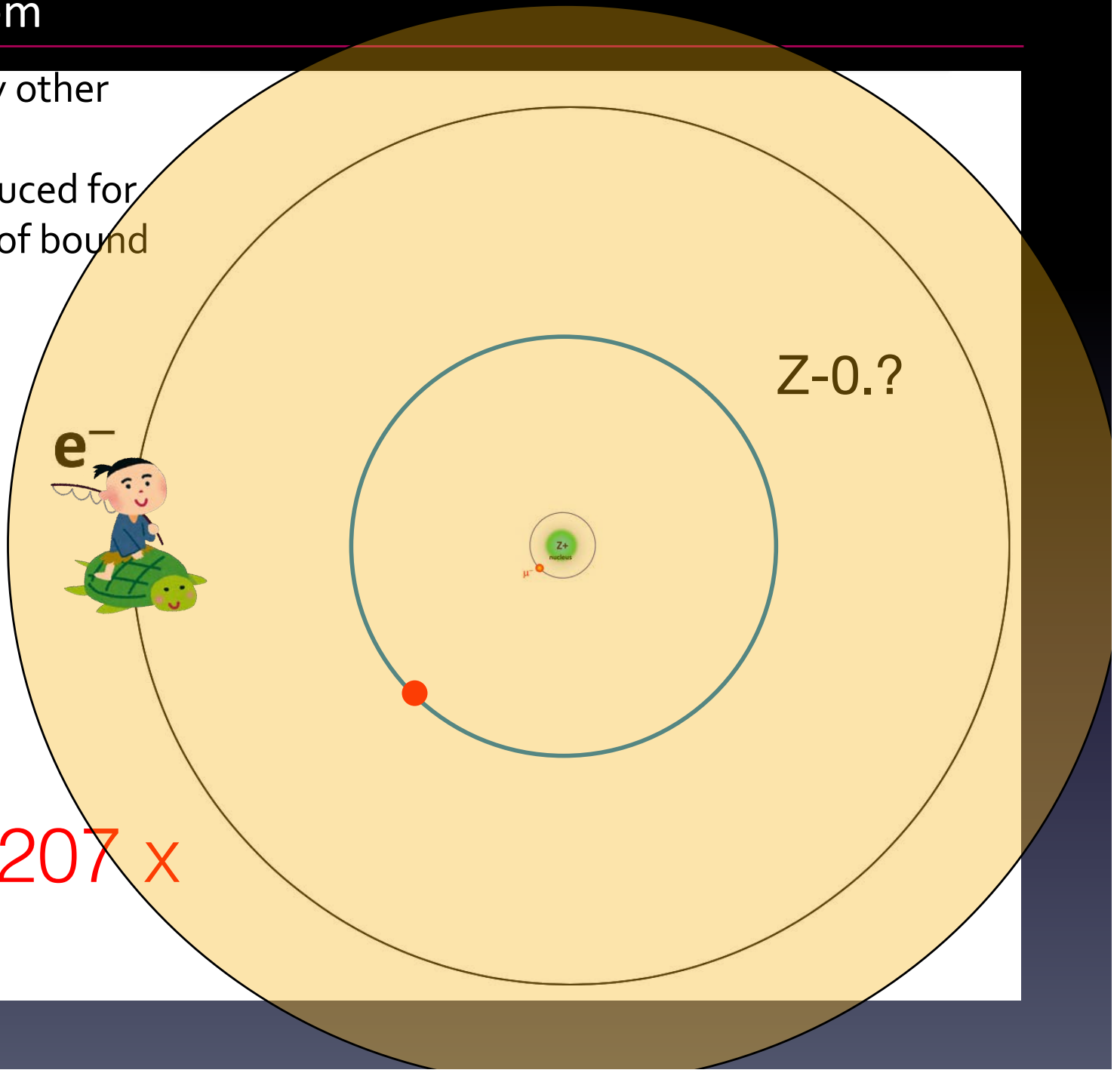
Muonic Atom

Screening is reduced when negative muon is away from nucleus



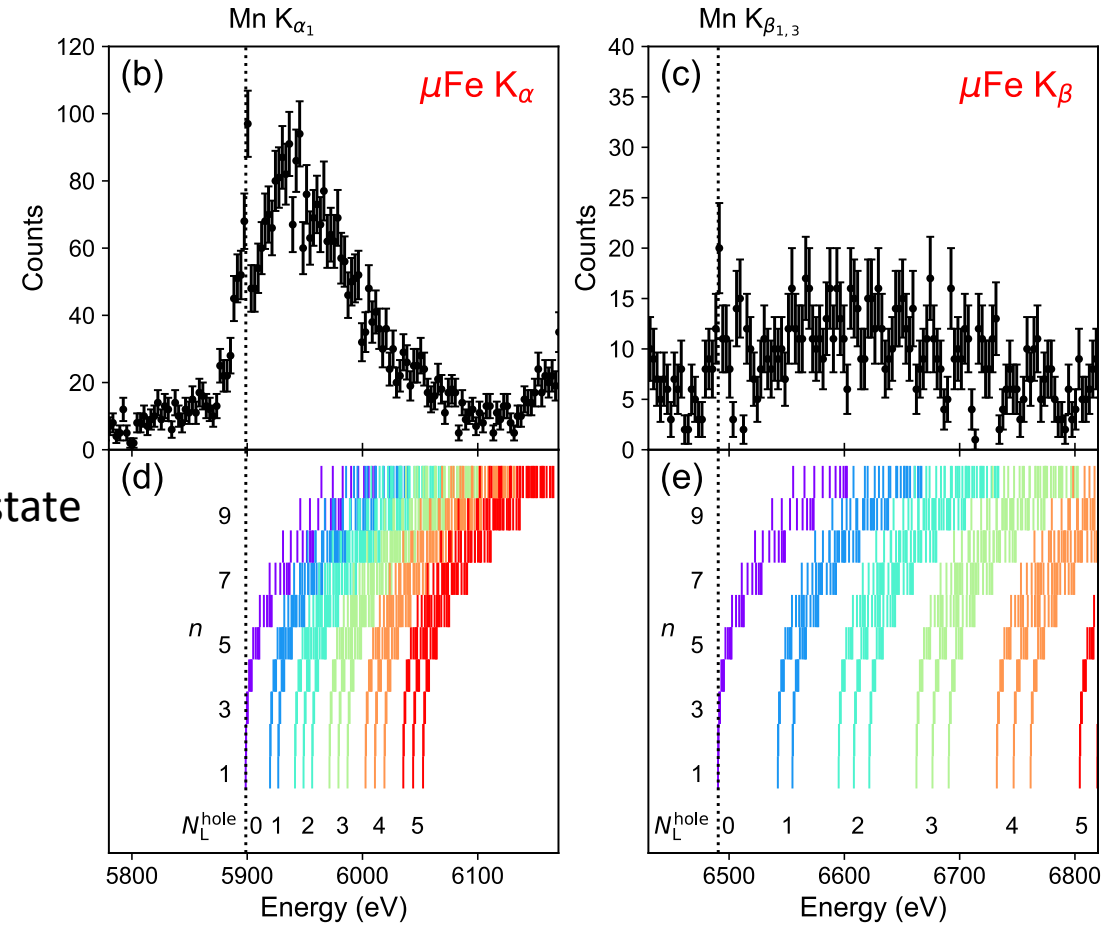
Muonic Atom

Screened also by other bound electrons (screening is reduced for smaller number of bound electrons)



energy levels of electron K X-ray lines of μFe

n: muon state



muon stataes ~ 30,000

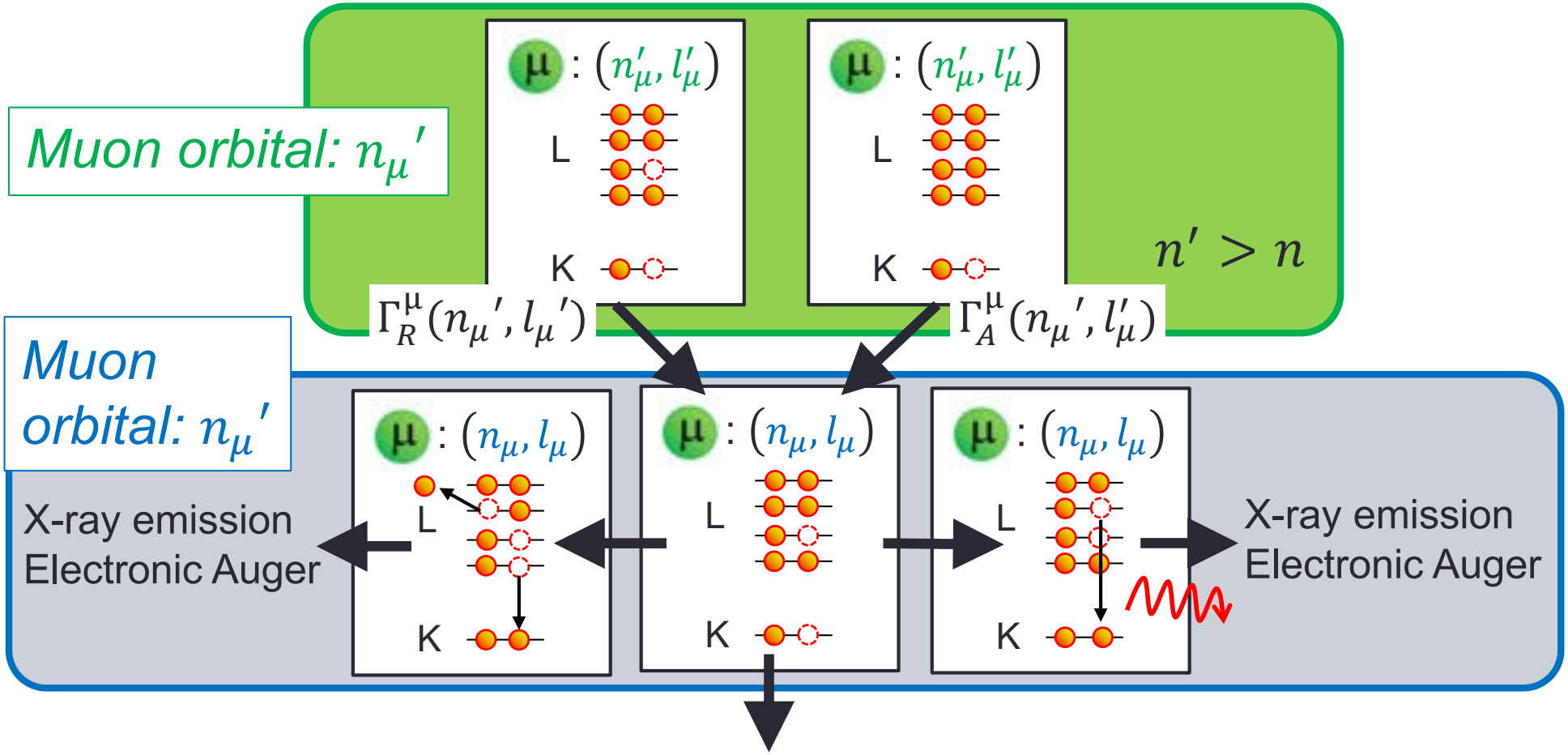
(shown only fot the case of $l = n\text{-}1$)

We understand levels, and dynamics are simutated

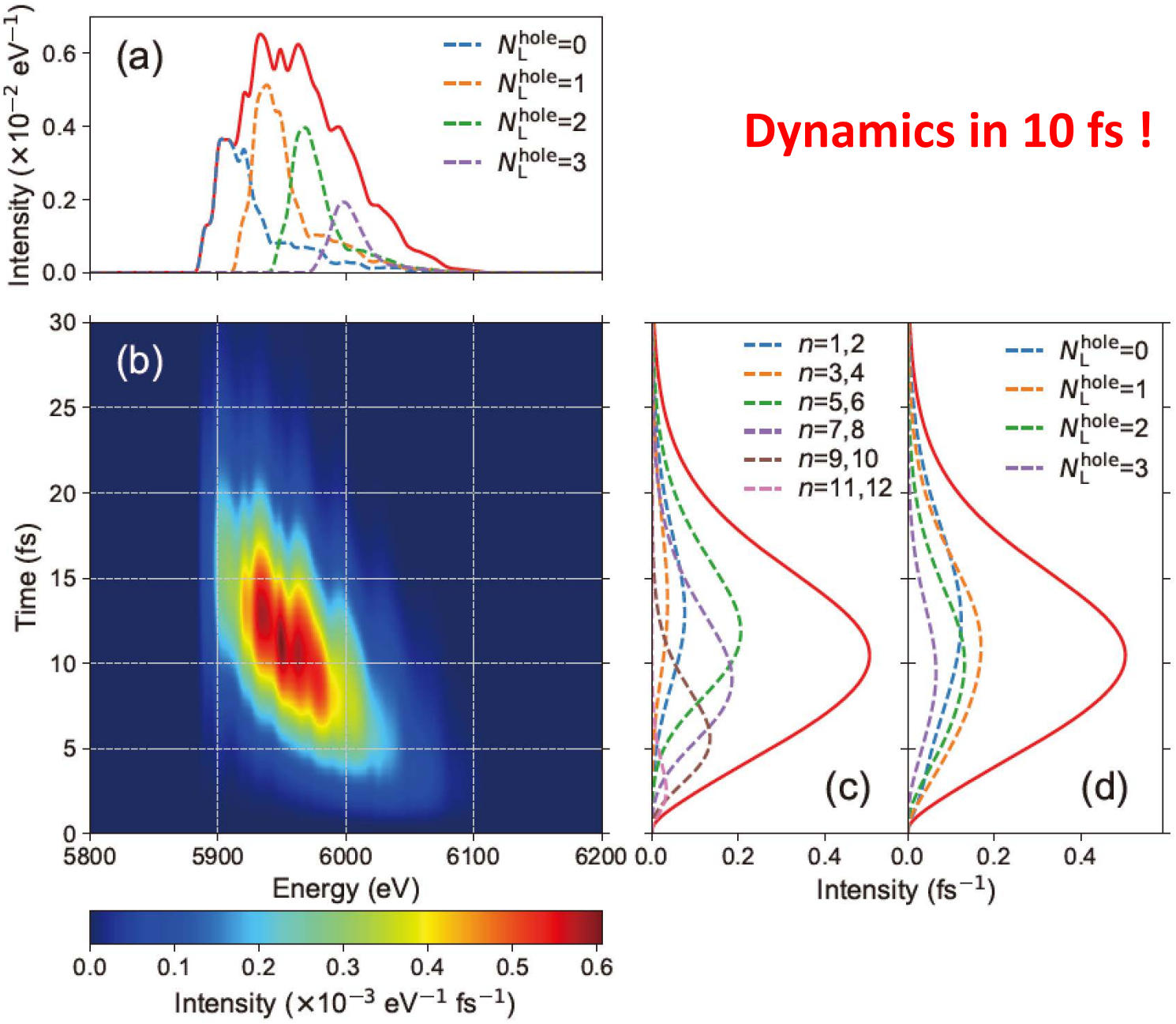
Simulation of muon cascade process

Assuming an unchanged number of M-shell electrons.

Infinitely fast M-shell refilling from metal band



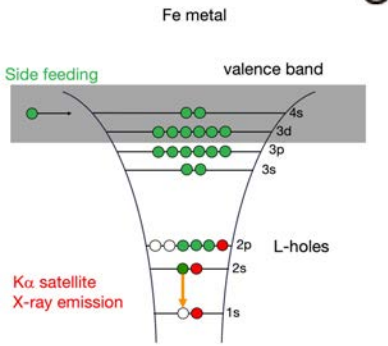
simulated dynamics of energy distribution of K X-rays

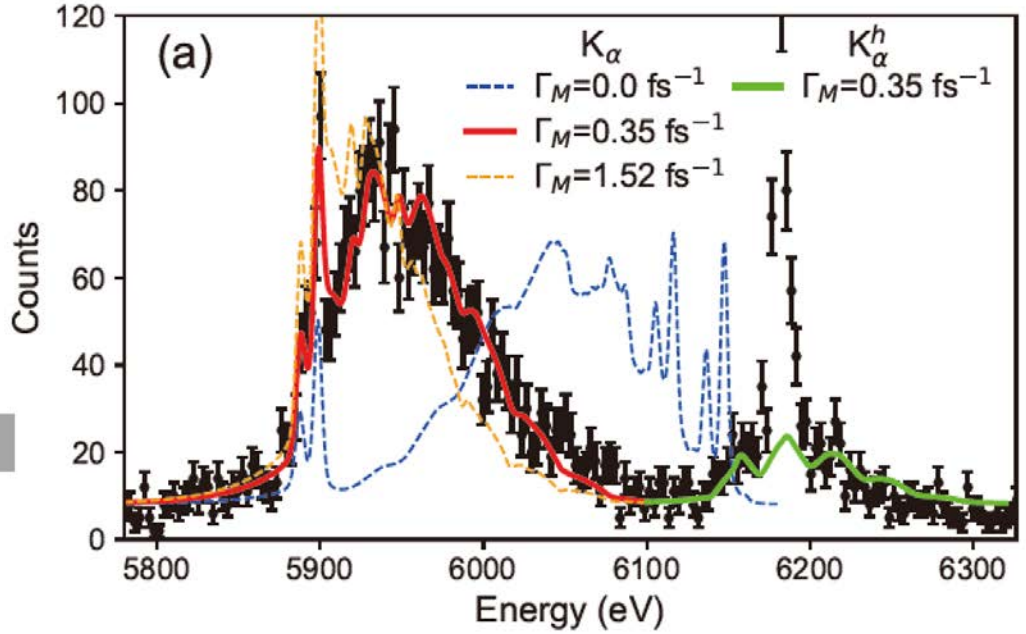


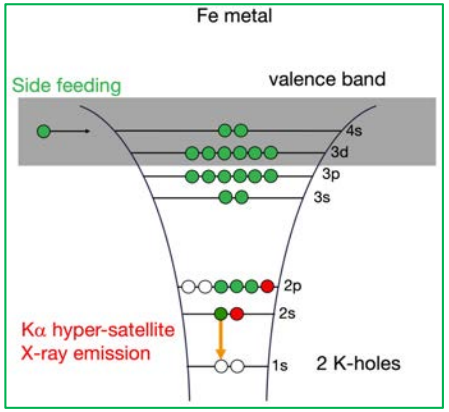
Dynamics in 10 fs !

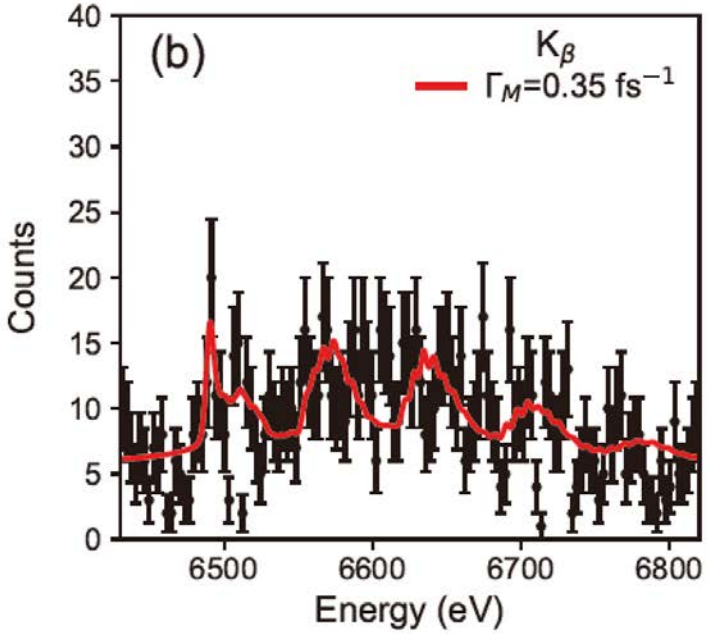
comparison: experimental data vs simulation

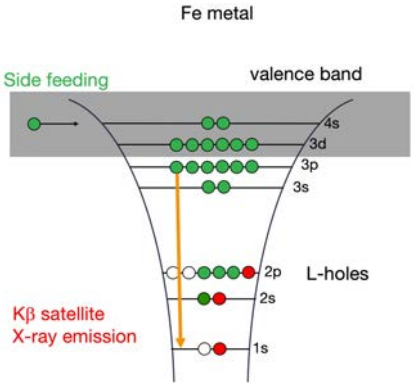
side-feeding
Γ_M











Summary from two lessons

AMO physics RIKEN

Lesson I : Physics and Medical Science

Lesson II : Interdisciplinary Science

astrophysics vs atomic physics

We can find something new and exciting
by encounter of different fields of science