Laser Resonance Ionisation for Isotope Separator Facilities

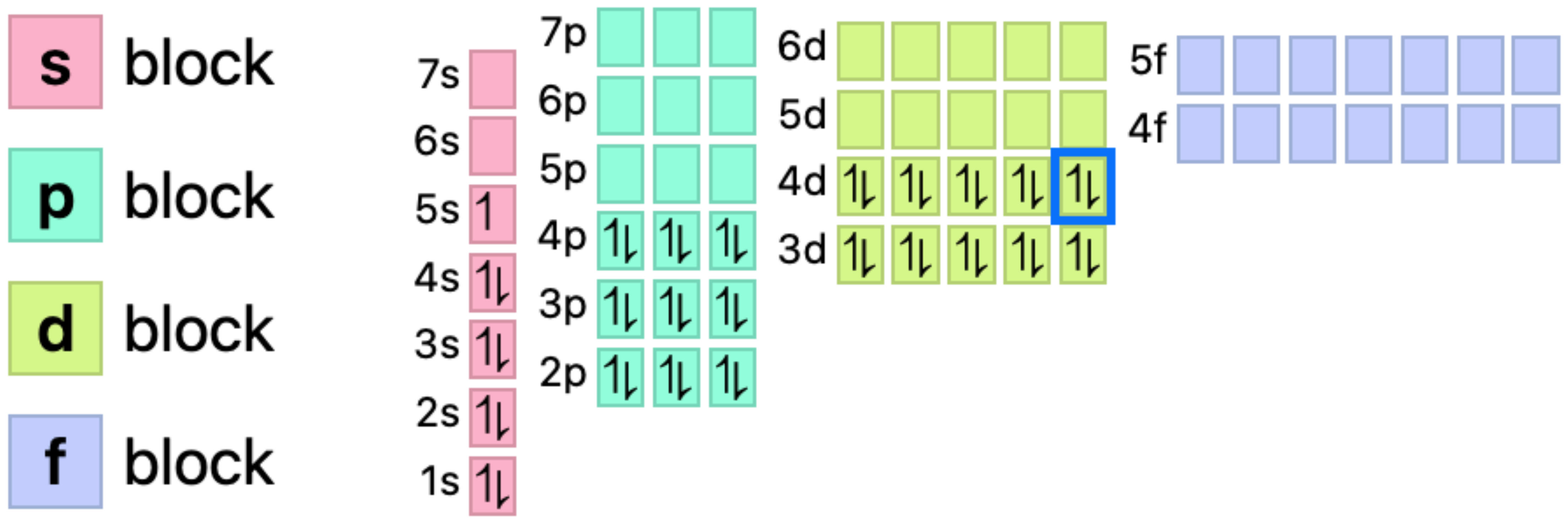
Bruce Marsh
SY-STI-LP

http://cds.cern.ch/record/2207615?ln=es

Overview

- Introduction to ISOLDE and the motivation for a Resonance Ionisation Laser Ion Source (RILIS)
- Atomic physics fundamentals relevant to achieving resonance ionisation
- Considerations for the implementation of a laser ion source
- The ISOLDE RILIS
- The RILIS as part of the array of ISOLDE Experiments

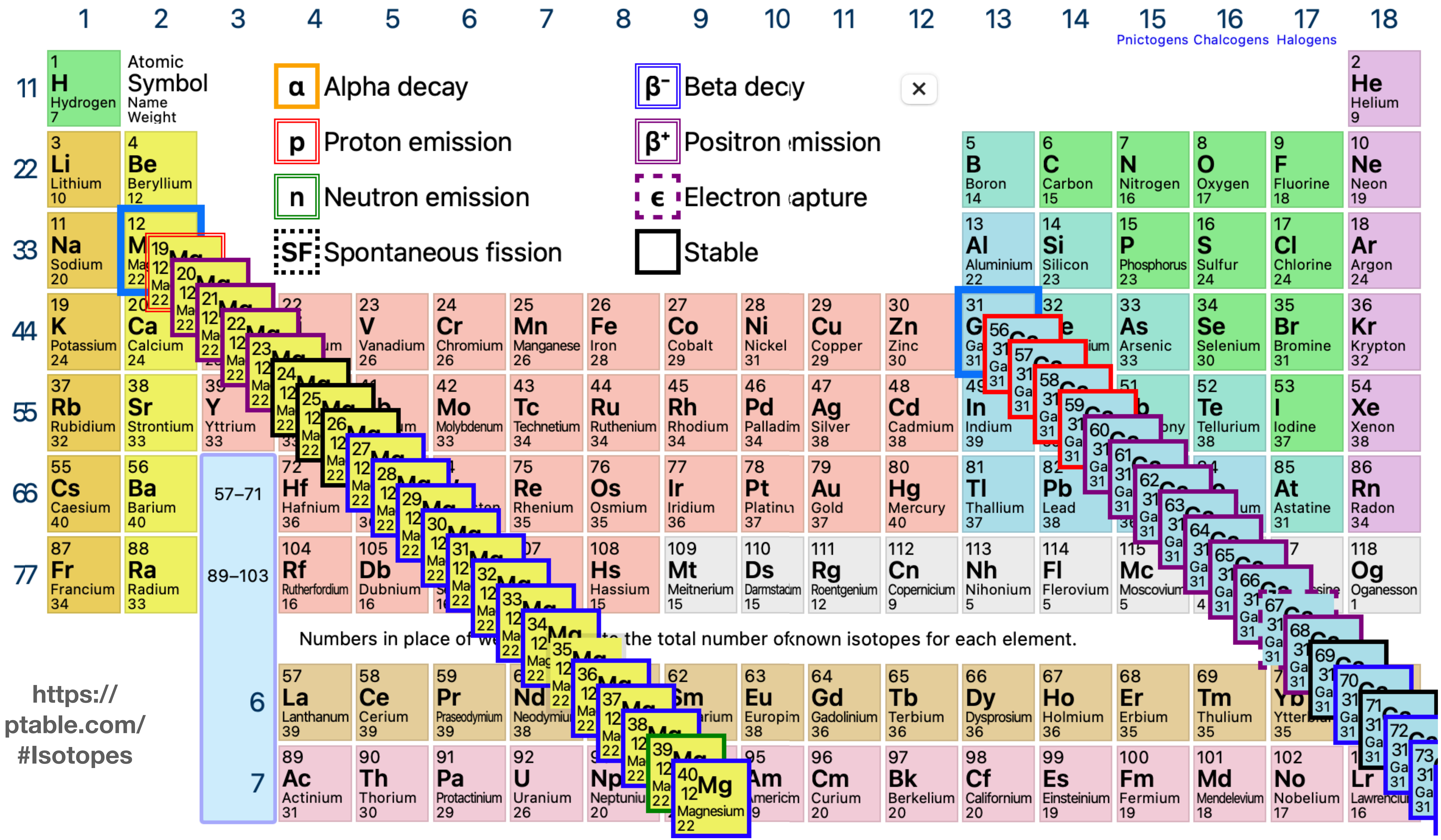
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15 Pnictogens	16 Chalcogens	17 Halogens	18
1	1 **H** Hydrogen -1 1	2 **He** Helium																Atomic **Symbol** Name Weight
2	3 **Li** Lithium 1	4 **Be** Beryllium 2											5 **B** Boron 3	6 **C** Carbon -4 4	7 **N** Nitrogen -3 3 5	8 **O** Oxygen -2	9 **F** Fluorine -1	10 **Ne** Neon
3	11 **Na** Sodium 1	12 **Mg** Magnesium 2											13 **Al** Aluminium 3	14 **Si** Silicon -4 4	15 **P** Phosphorus -3 3 5	16 **S** Sulfur -2 2 4 6	17 **Cl** Chlorine -1 1 3 5 7	18 **Ar** Argon
4	19 **K** Potassium 1	20 **Ca** Calcium 2	21 **Sc** Scandium 3	22 **Ti** Titanium 4	23 **V** Vanadium 5	24 **Cr** Chromium 3 6	25 **Mn** Manganese 2 4 7	26 **Fe** Iron 2 3	27 **Co** Cobalt 2 3	28 **Ni** Nickel 2	29 **Cu** Copper 2	30 **Zn** Zinc 2	31 **Ga** Gallium 3	32 **Ge** Germanium -4 2 4	33 **As** Arsenic -3 3 5	34 **Se** Selenium -2 2 4 6	35 **Br** Bromine -1 1 3 5	36 **Kr** Krypton 2
5	37 **Rb** Rubidium 1	38 **Sr** Strontium 2	39 **Y** Yttrium 3	40 **Zr** Zirconium 4	41 **Nb** Niobium 5	42 **Mo** Molybdenum 4 6	43 **Tc** Technetium 4 7	44 **Ru** Ruthenium 3 4	45 **Rh** Rhodium 3	46 **Pd** Palladium 2 4	47 **Ag** Silver 1	48 **Cd** Cadmium 2	49 **In** Indium 3	50 **Sn** Tin -4 2 4	51 **Sb** Antimony -3 3 5	52 **Te** Tellurium -2 2 4 6	53 **I** Iodine -1 1 3 5 7	54 **Xe** Xenon 2 4 6
6	55 **Cs** Caesium 1	56 **Ba** Barium 2	57–71	72 **Hf** Hafnium 4	73 **Ta** Tantalum 5	74 **W** Tungsten 4 6	75 **Re** Rhenium 4	76 **Os** Osmium 4	77 **Ir** Iridium 3 4	78 **Pt** Platinum 2 4	79 **Au** Gold 3	80 **Hg** Mercury 1 2	81 **Tl** Thallium 1 3	82 **Pb** Lead 2 4	83 **Bi** Bismuth 3	84 **Po** Polonium -2 2 4	85 **At** Astatine -1 1	86 **Rn** Radon 2
7	87 **Fr** Francium 1	88 **Ra** Radium 2	89–103	104 **Rf** Rutherfordium 4	105 **Db** Dubnium 5	106 **Sg** Seaborgium 6	107 **Bh** Bohrium 7	108 **Hs** Hassium 8	109 **Mt** Meitnerium	110 **Ds** Darmstadtium	111 **Rg** Roentgenium	112 **Cn** Copernicium	113 **Nh** Nihonium	114 **Fl** Flerovium	115 **Mc** Moscovium	116 **Lv** Livermorium	117 **Ts** Tennessine	118 **Og** Oganesson



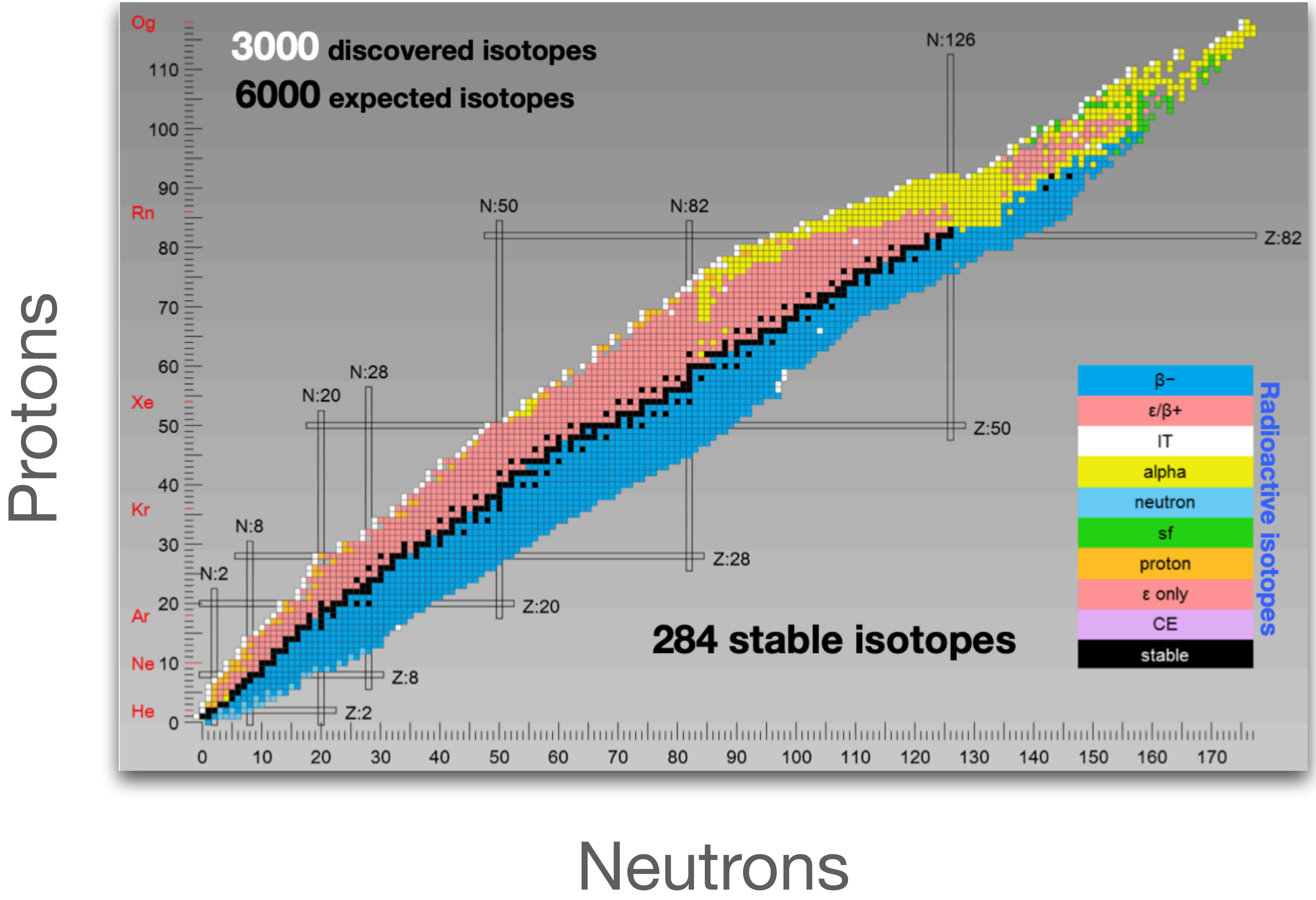
Oxidation states are the number of electrons added to or removed from an element when it forms a chemical compound.

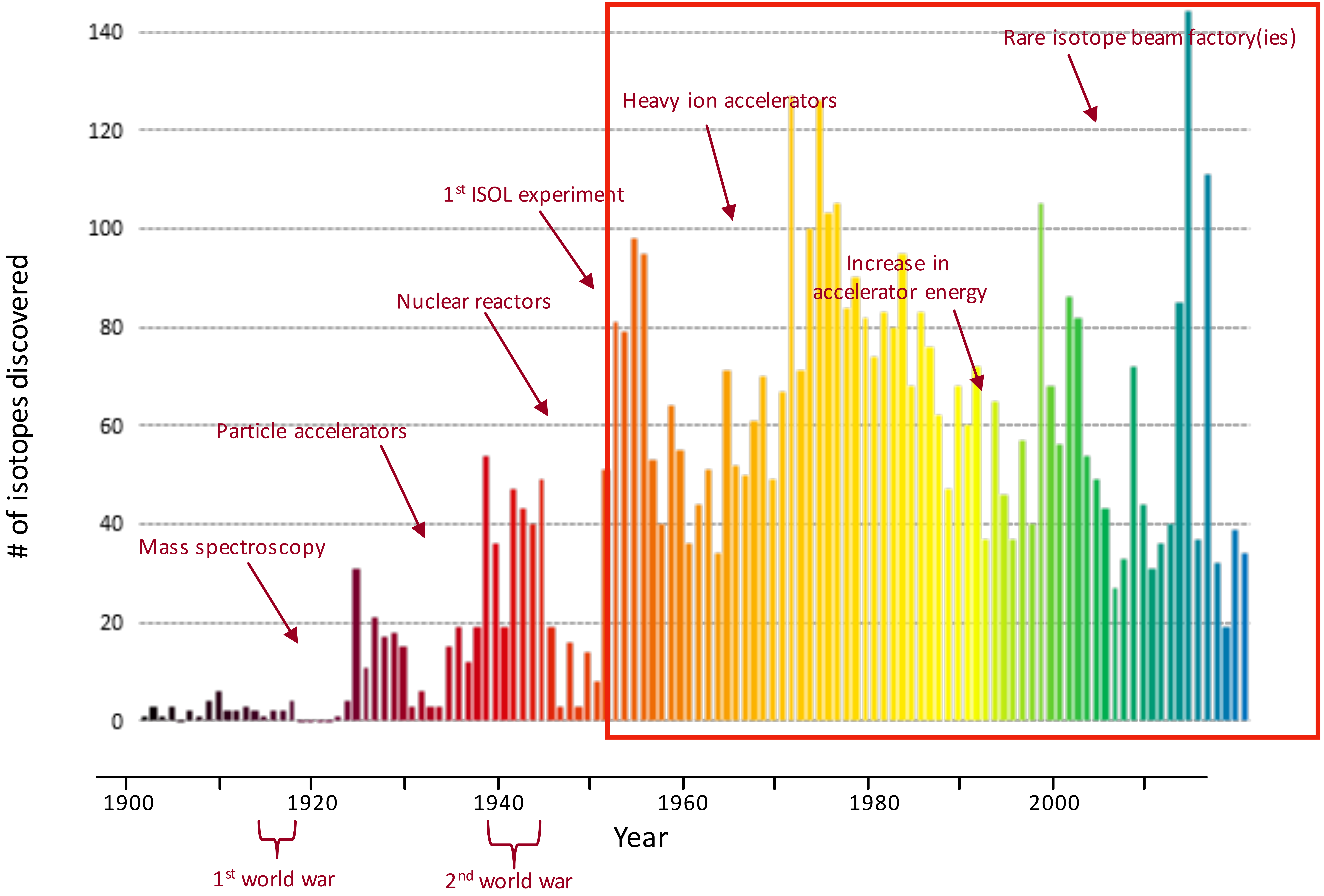
6	57 **La** Lanthanum 3	58 **Ce** Cerium 3 4	59 **Pr** Praseodymium 3	60 **Nd** Neodymium 3	61 **Pm** Promethium 3	62 **Sm** Samarium 3	63 **Eu** Europium 2 3	64 **Gd** Gadolinium 3	65 **Tb** Terbium 3	66 **Dy** Dysprosium 3	67 **Ho** Holmium 3	68 **Er** Erbium 3	69 **Tm** Thulium 3	70 **Yb** Ytterbium 3	71 **Lu** Lutetium 3
7	89 **Ac** Actinium 3	90 **Th** Thorium 4	91 **Pa** Protactinium 5	92 **U** Uranium 6	93 **Np** Neptunium 5	94 **Pu** Plutonium 4	95 **Am** Americium 3	96 **Cm** Curium 3	97 **Bk** Berkelium 3	98 **Cf** Californium 3	99 **Es** Einsteinium 3	100 **Fm** Fermium 3	101 **Md** Mendelevium 3	102 **No** Nobelium 2	103 **Lr** Lawrencium 3

https://ptable.com/



Pnictogens Chalcogens Halogens
Atomic
Symbol
Name
Weight
α Alpha decay
p Proton emission
n Neutron emission
SF Spontaneous fission
β⁻ Beta decy
β⁺ Positron mission
ϵ Electron apture
Stable
57–71
89–103
Numbers in place of we te the total number ofknown isotopes for each element.
40 Mg Magnesium 22
https://
ptable.com/
#Isotopes


3000 discovered isotopes
6000 expected isotopes
284 stable isotopes
Radioactive isotopes
β−
ε/β+
IT
alpha
neutron
sf
proton
ε only
CE
stable
Og
Rn
Xe
Kr
Ar
Ne
He
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
Protons
Neutrons

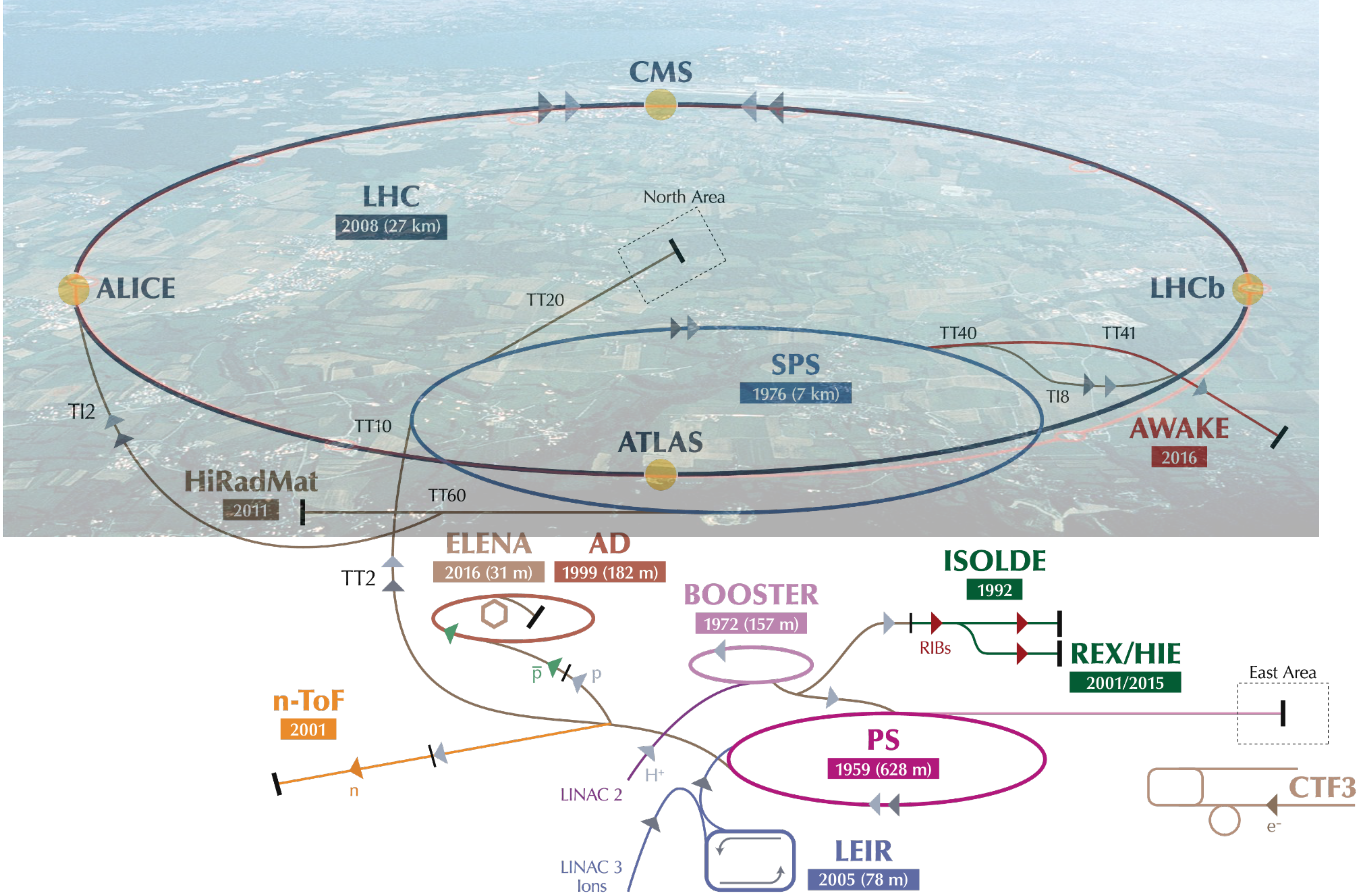


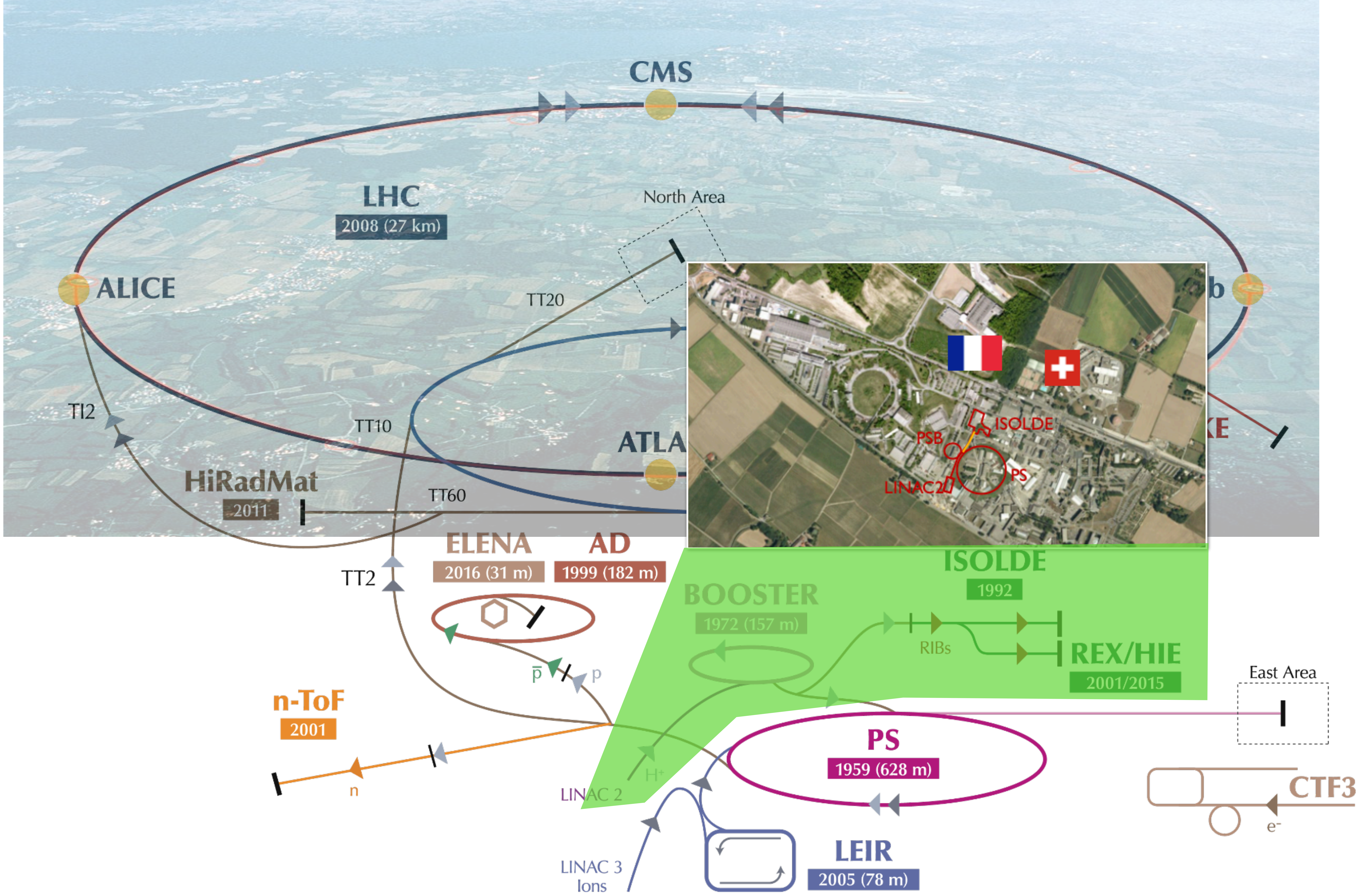
# of isotopes discovered
140
120
100
80
60
40
20
0
Rare isotope beam factory(ies)
Heavy ion accelerators
1st ISOL experiment
Increase in accelerator energy
Nuclear reactors
Particle accelerators
Mass spectroscopy
1900
1920
1940
1960
1980
2000
Year
1st world war
2nd world war

“Isotope Separator On-Line”

radioisotope production, selection and transport to an experiment in one machine

$T_{1/2}$ > 5 ms


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
ISOLDE
1992
TT2
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
p̄
p
East Area
n-ToF
2001
PS
1959 (628 m)
H+
CTF3
n
LINAC 2
e−
LINAC 3
Ions
LEIR
2005 (78 m)

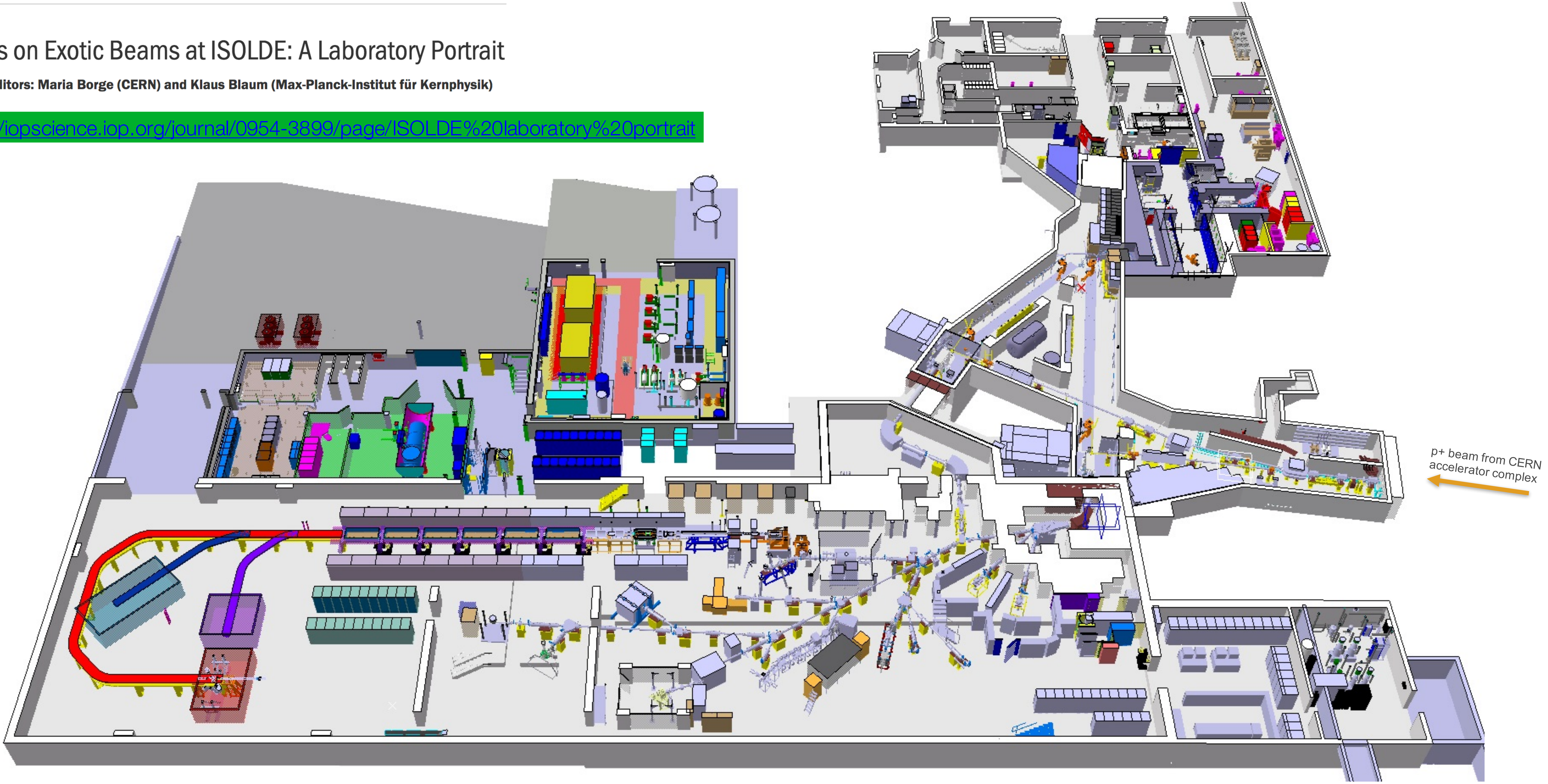

CMS
LHC
2008 (27 km)
North Area
ALICE
TT20
TI2
TT10
ATLA
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
ISOLDE
PSB
LINAC2
PS
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
TT2
p̄
p
n-ToF
2001
n
East Area
PS
1959 (628 m)
CTF3
e⁻
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)

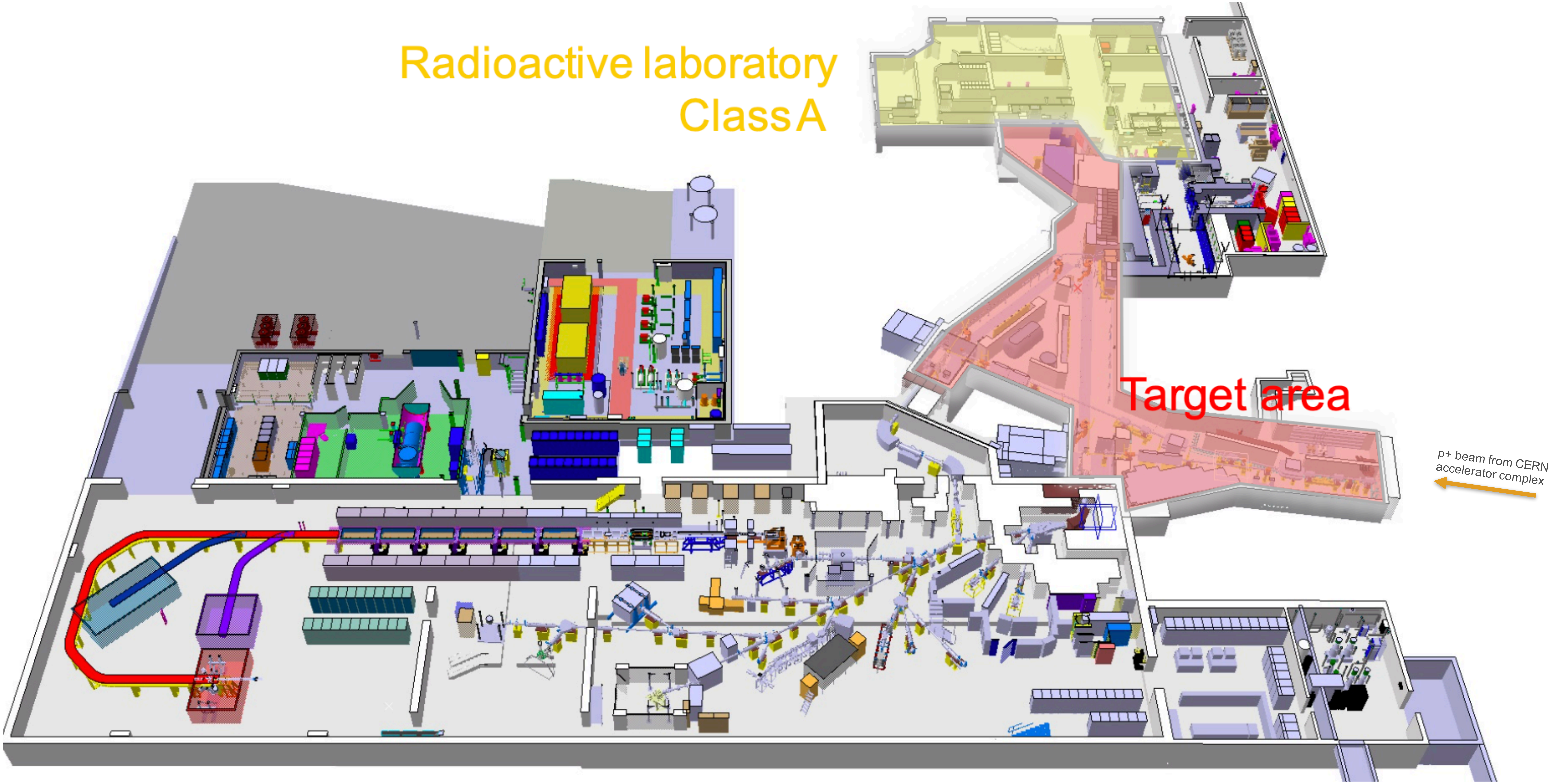
Journal of Physics G: Nuclear and Particle Physics

Focus on Exotic Beams at ISOLDE: A Laboratory Portrait

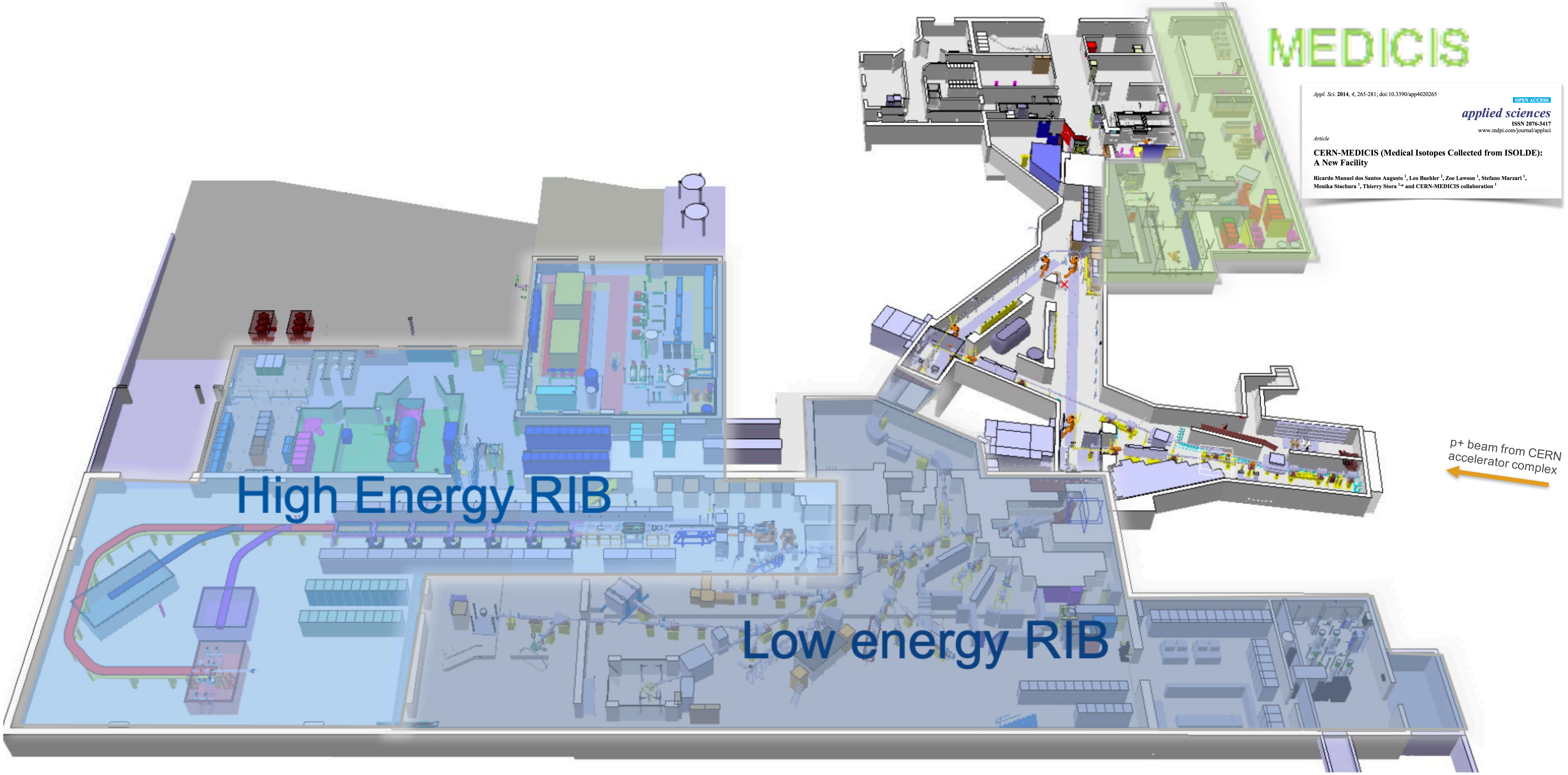
Guest Editors: Maria Borge (CERN) and Klaus Blaum (Max-Planck-Institut für Kernphysik)

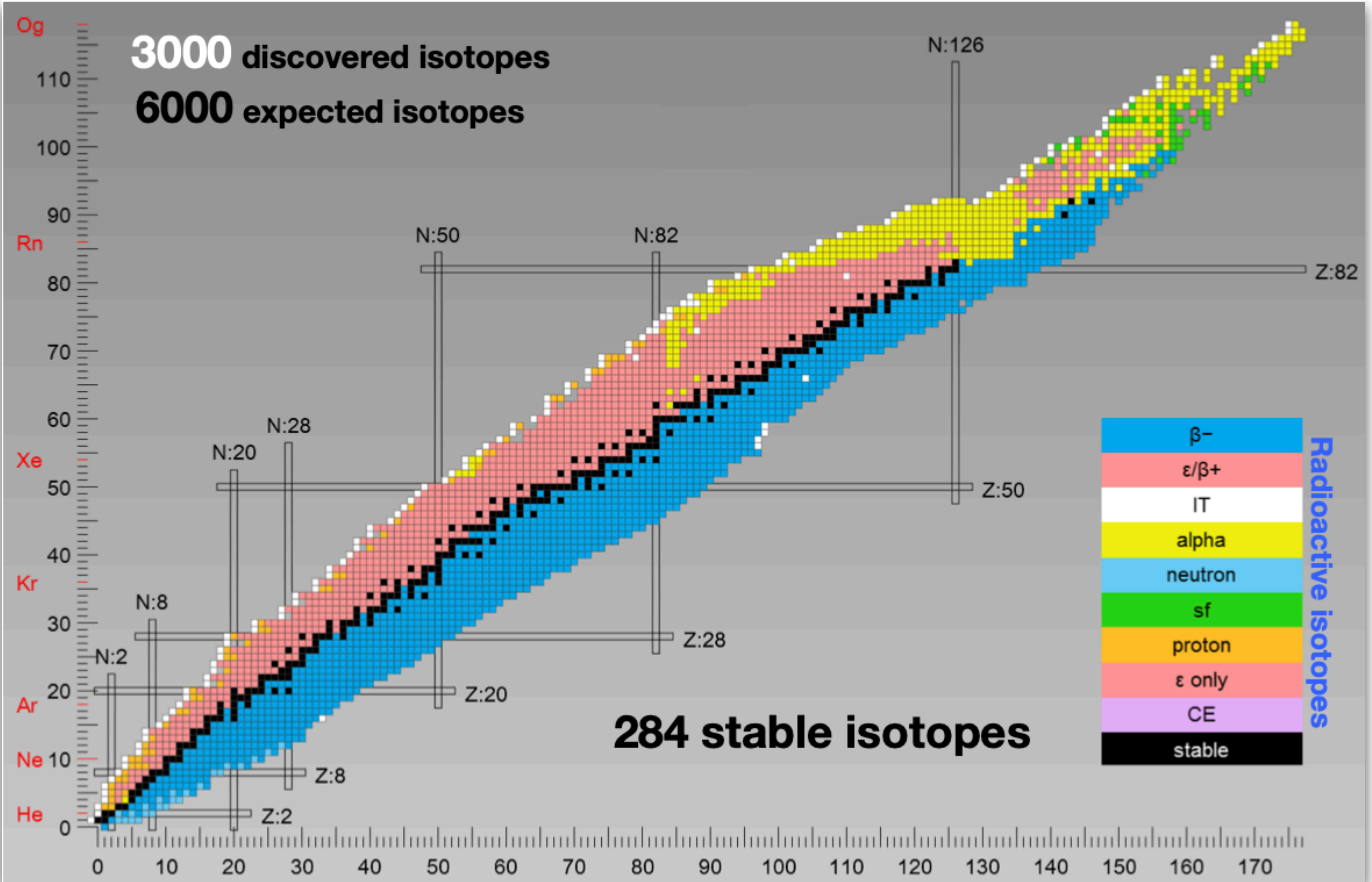
http://iopscience.iop.org/journal/0954-3899/page/ISOLDE%20laboratory%20portrait





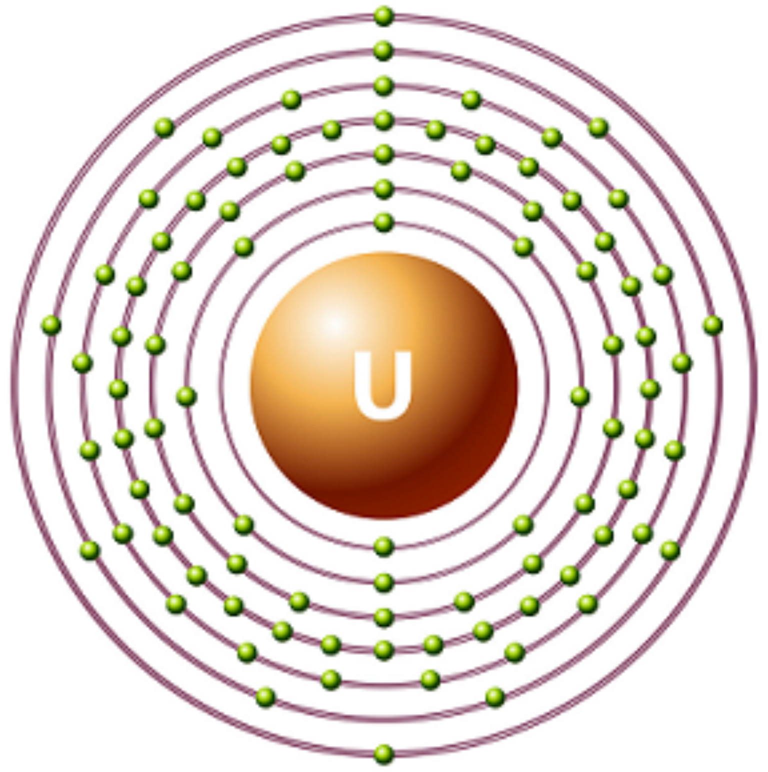
Radioactive laboratory
Class A
Target area
p+ beam from CERN
accelerator complex

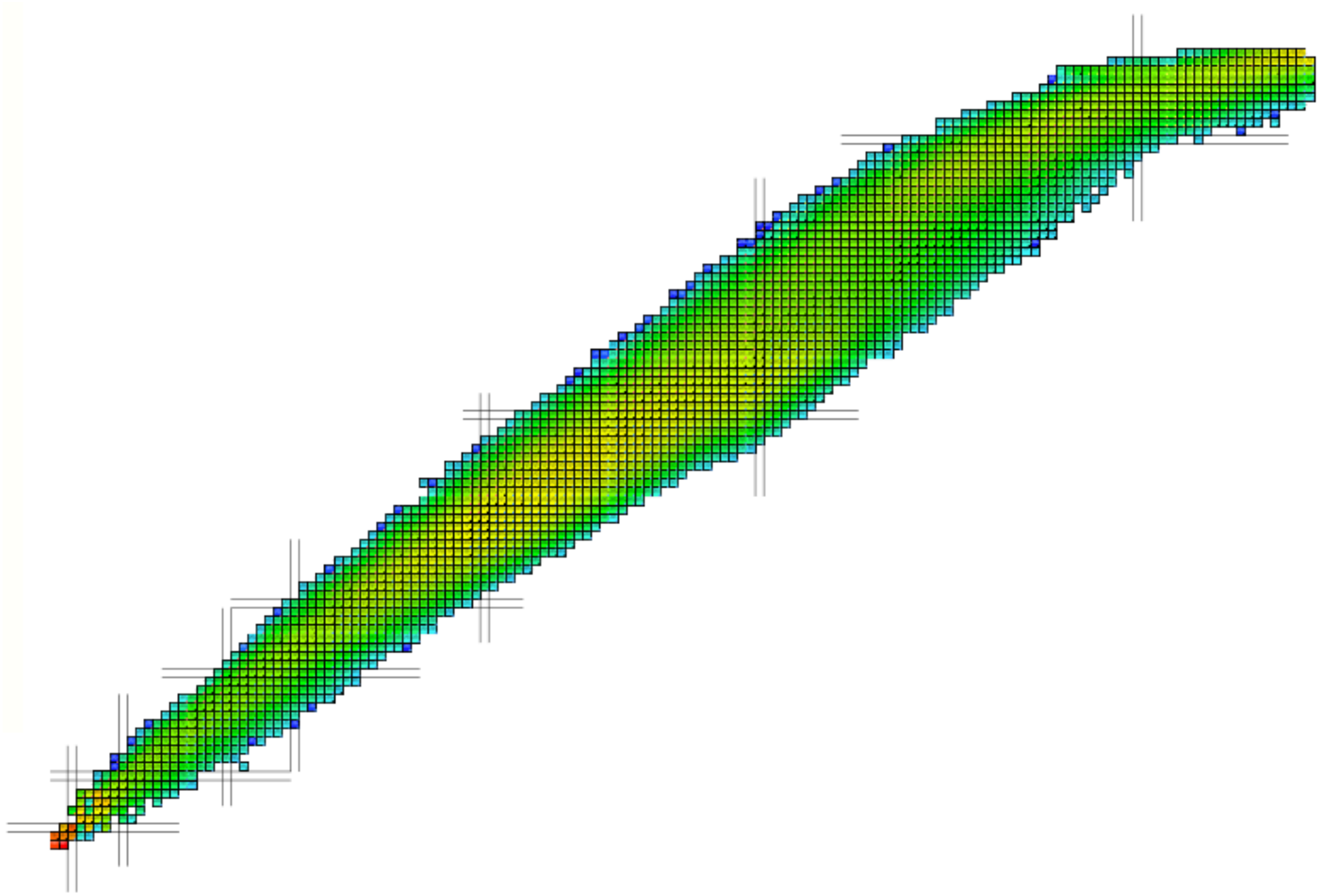

MEDICIS
Appl. Sci. 2014, 4, 265-281; doi:10.3390/app4020265
OPEN ACCESS
applied sciences
ISSN 2076-3417
www.mdpi.com/journal/applsci
Article
CERN-MEDICIS (Medical Isotopes Collected from ISOLDE): A New Facility
Ricardo Manuel dos Santos Augusto [1], Leo Buehler [2], Zoe Lawson [1], Stefano Marzari [1], Monika Stachura [1], Thierry Stora [1,*] and CERN-MEDICIS collaboration [1]
High Energy RIB
Low energy RIB
p+ beam from CERN accelerator complex

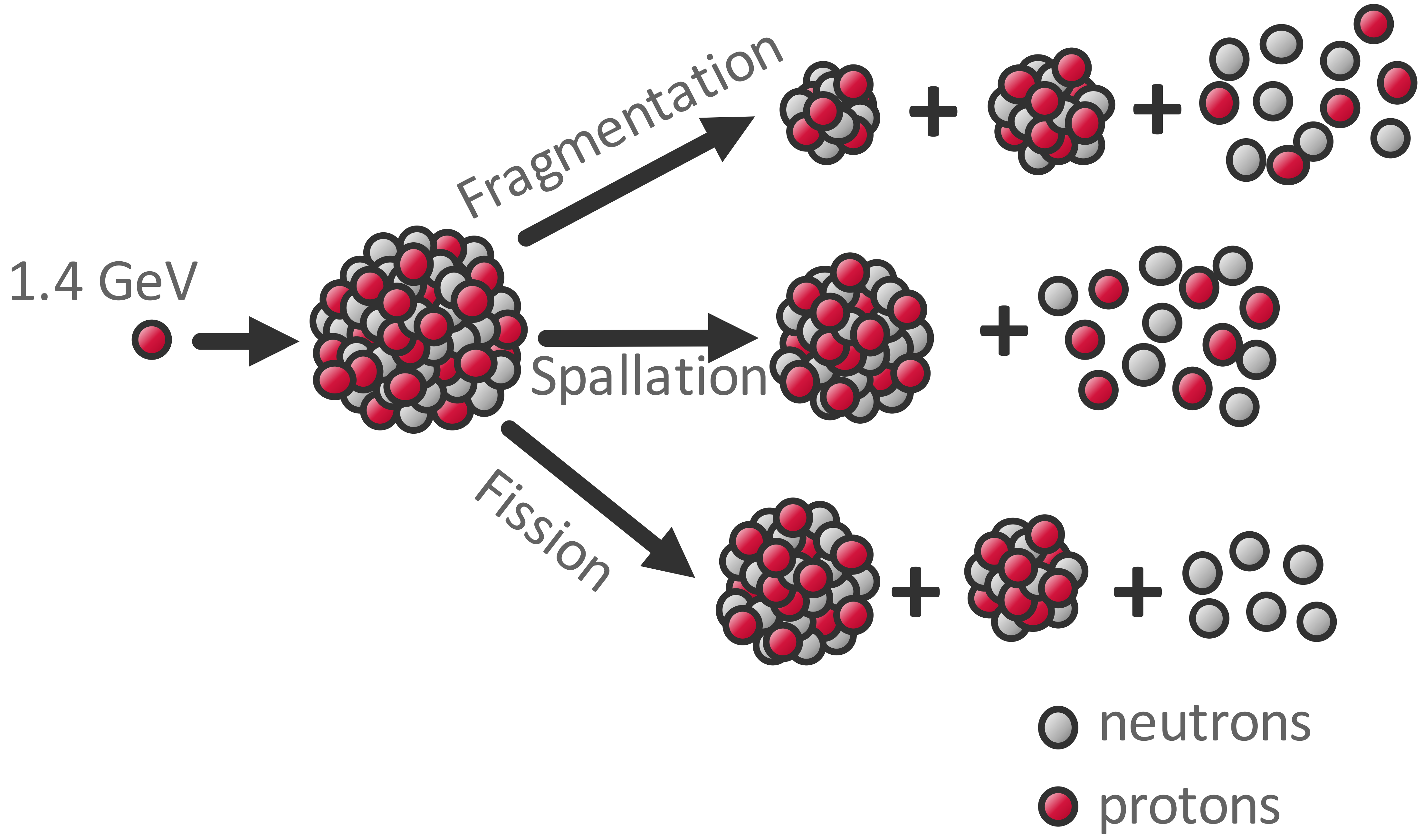


3000 discovered isotopes
6000 expected isotopes
284 stable isotopes
Radioactive isotopes
β−
ε/β+
IT
alpha
neutron
sf
proton
ε only
CE
stable
N:2
N:8
N:20
N:28
N:50
N:82
N:126
Z:2
Z:8
Z:20
Z:28
Z:50
Z:82
Og
Rn
Xe
Kr
Ar
Ne
He

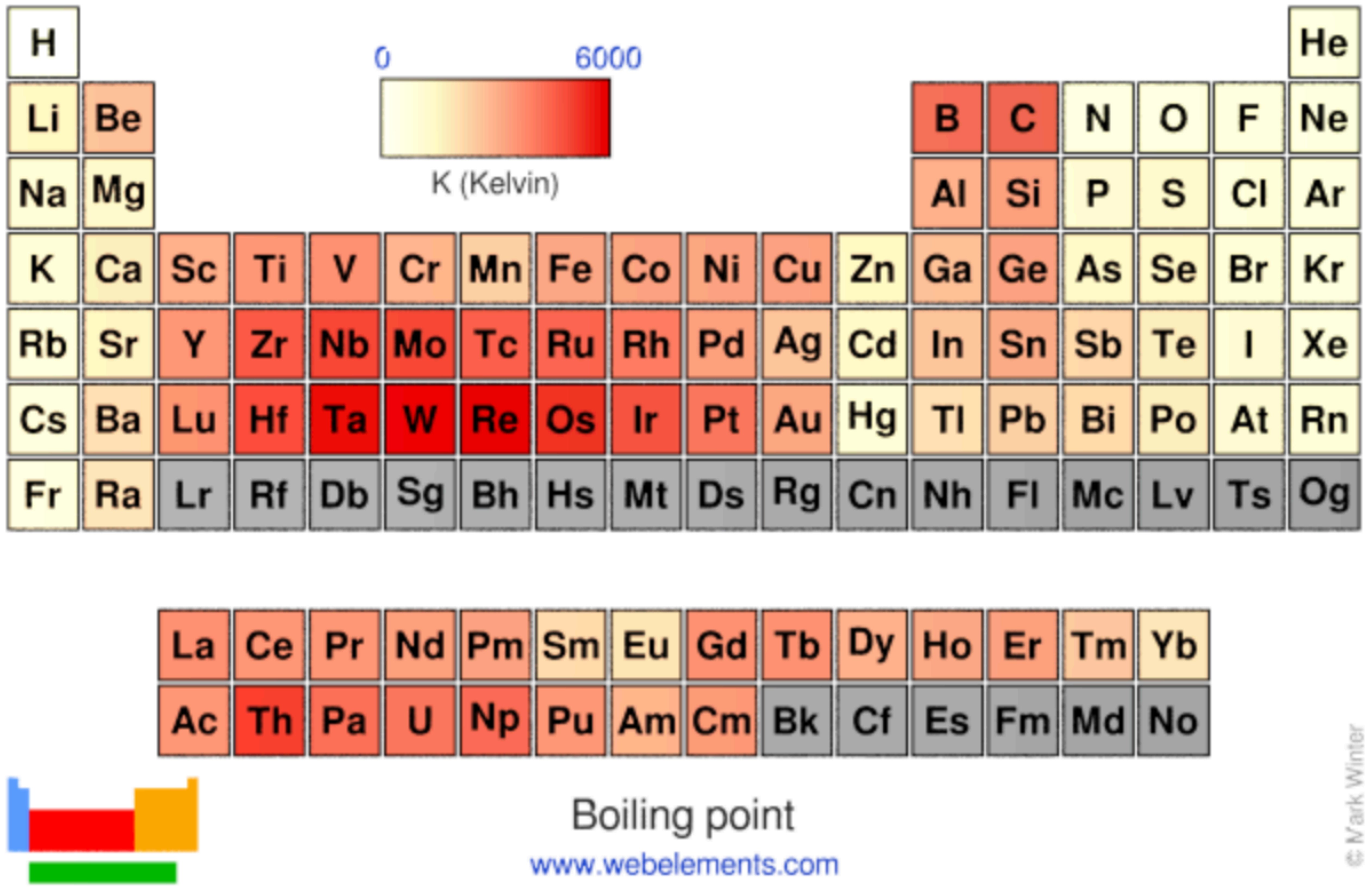
• Create the isotope



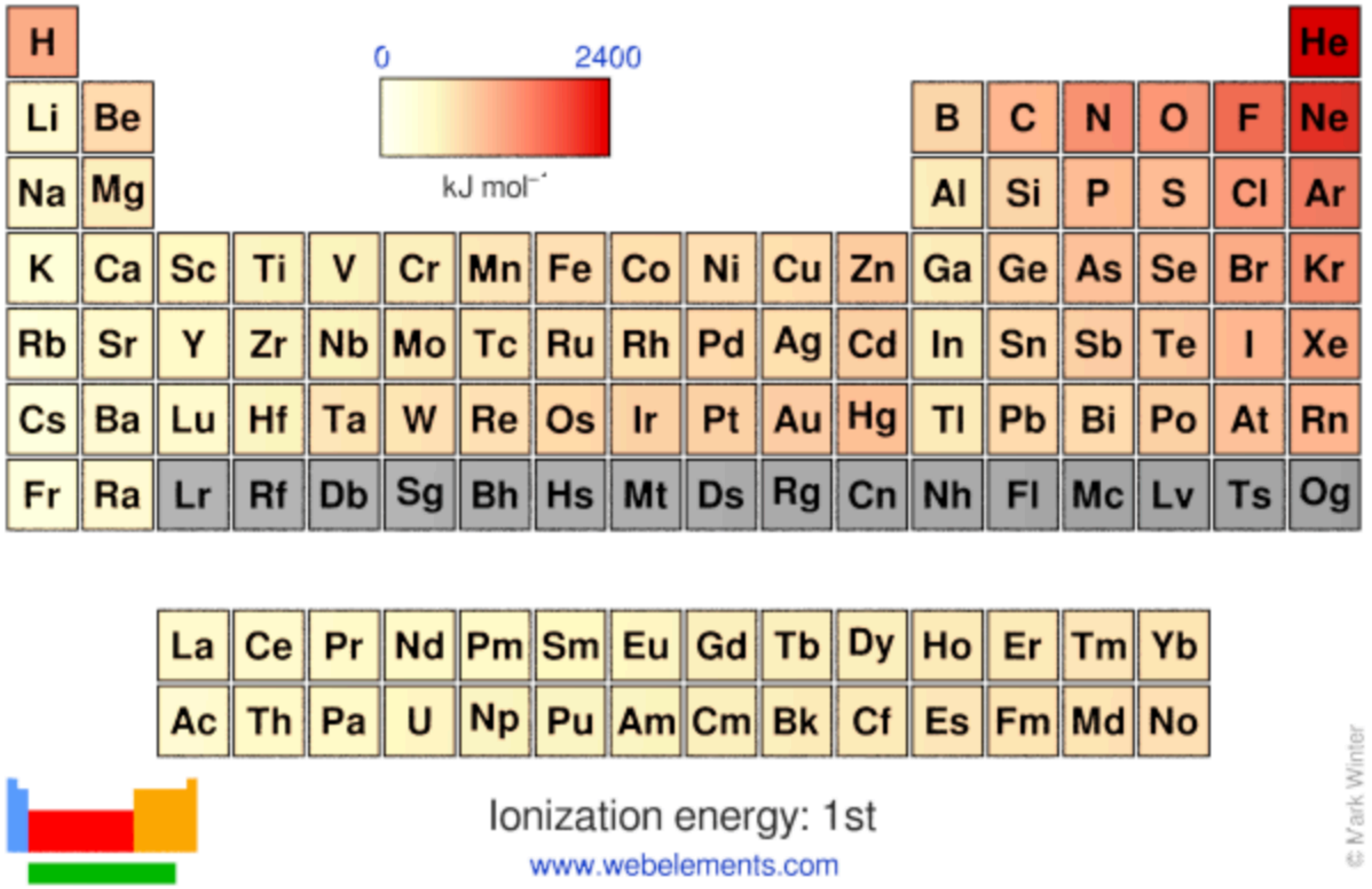




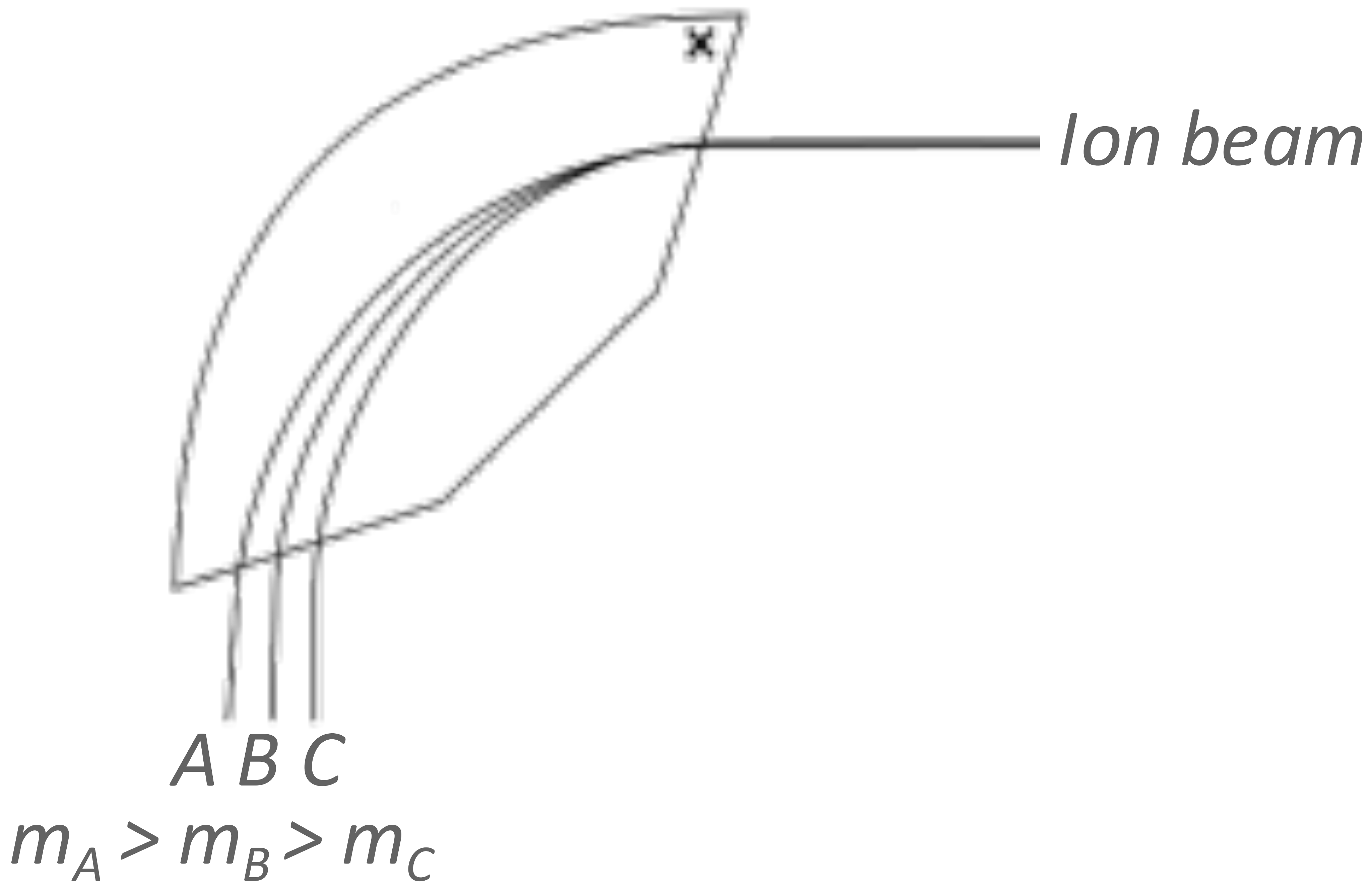
- Create the isotope
- Release the isotope from the target

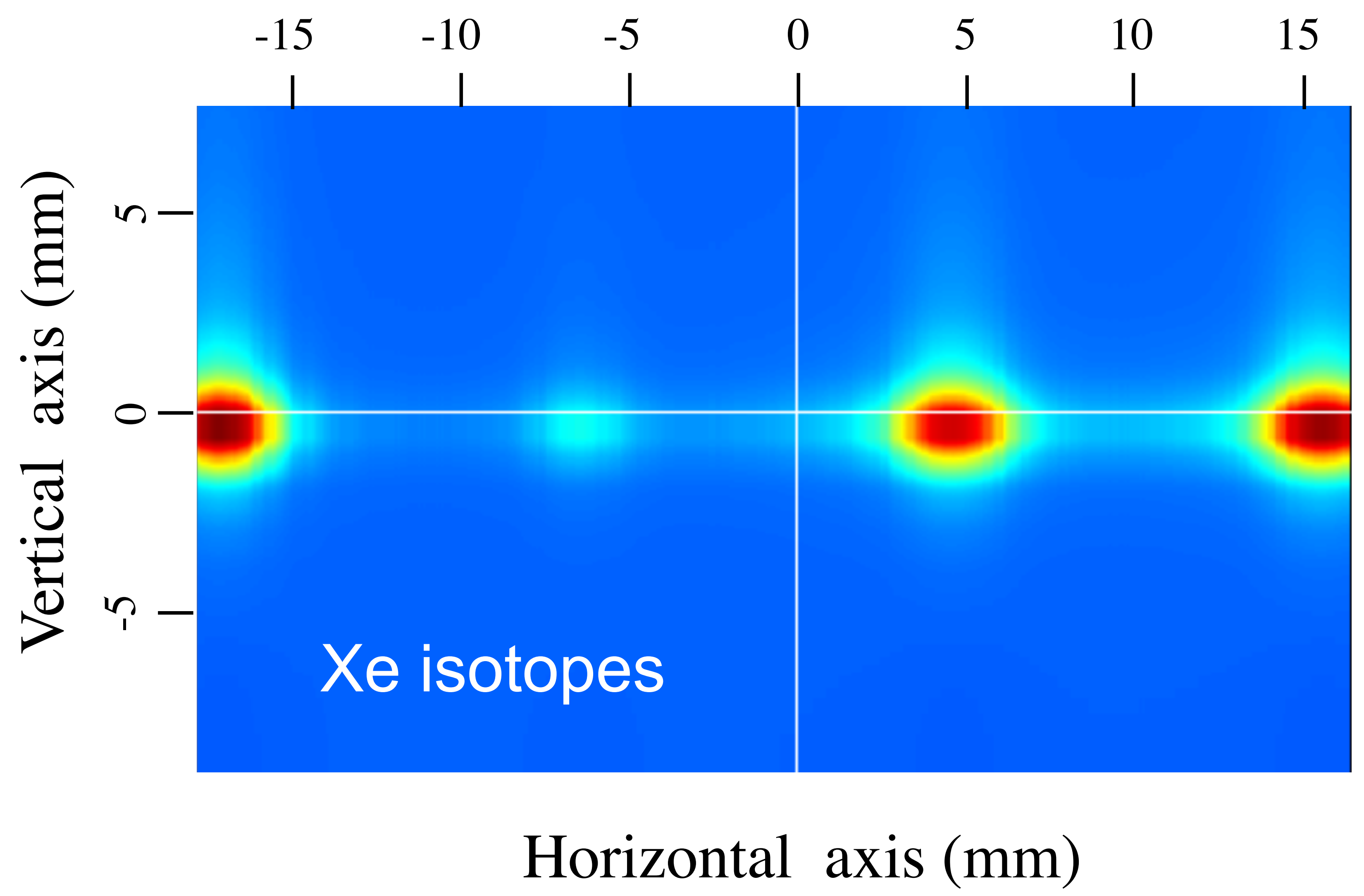


- Create the isotope
- Release the isotope from the target
- Ionise the isotope

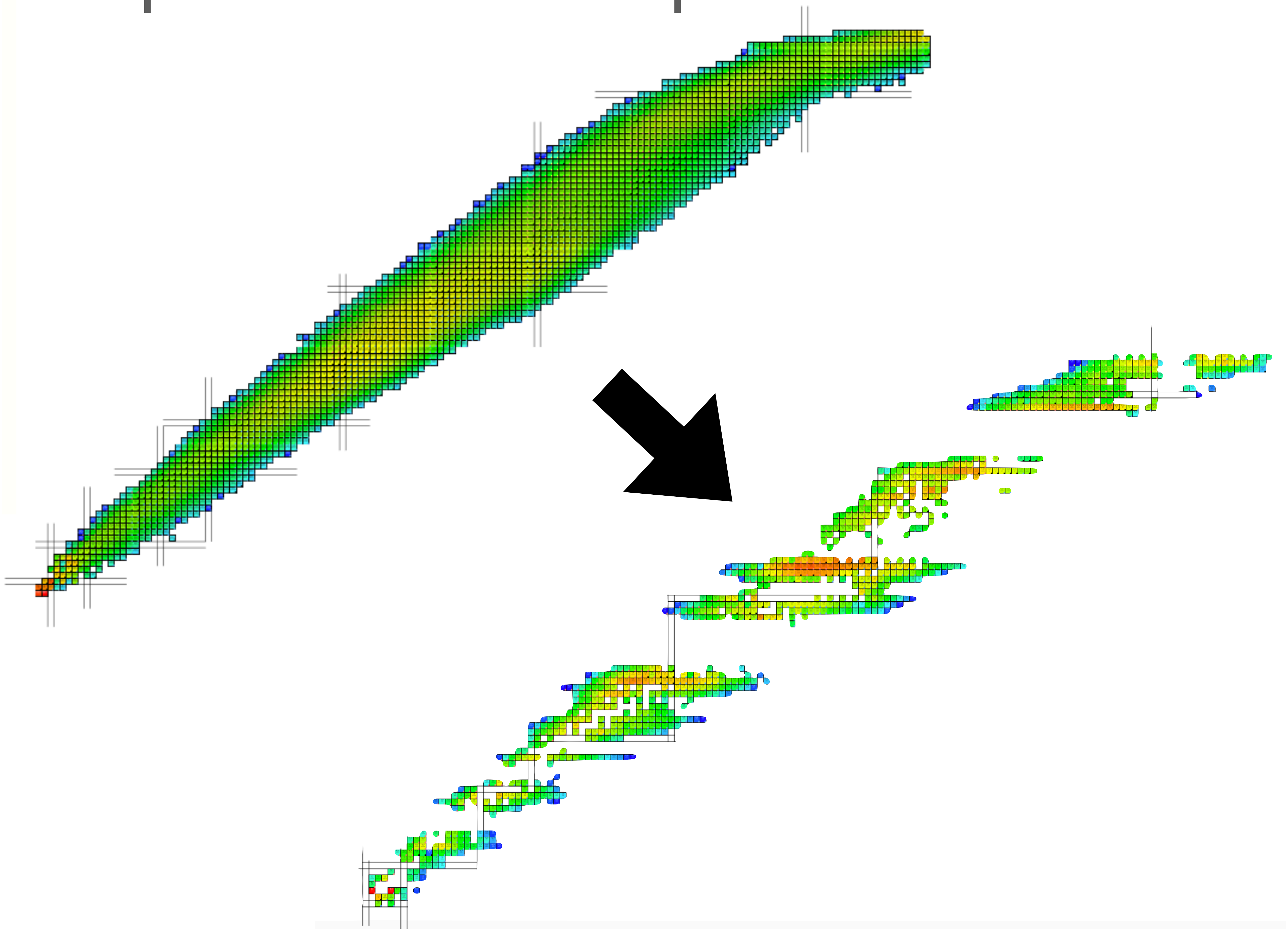


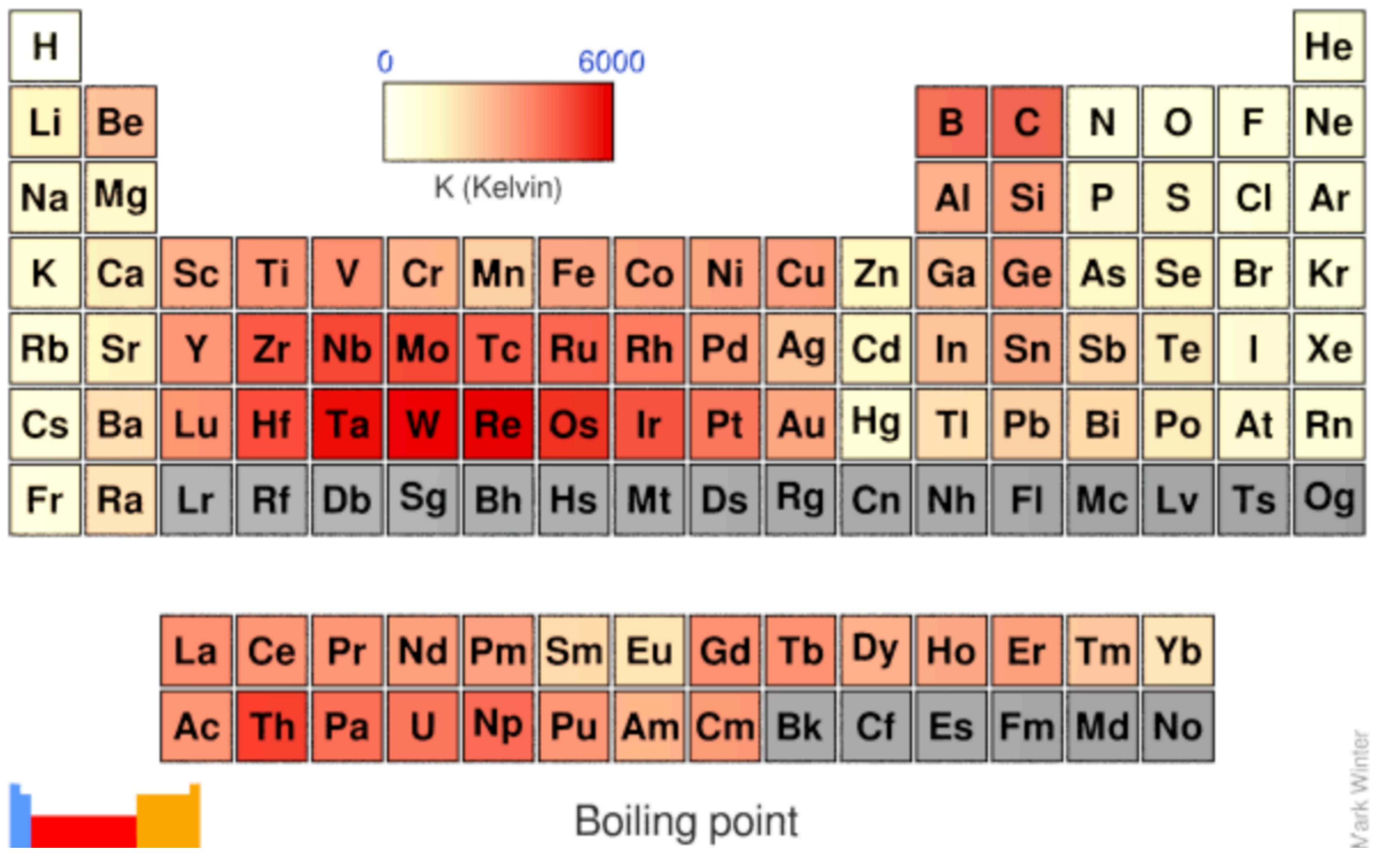
- Create the isotope
- Release the isotope from the target
- Ionise the isotope
- Separate the isotope from contaminants

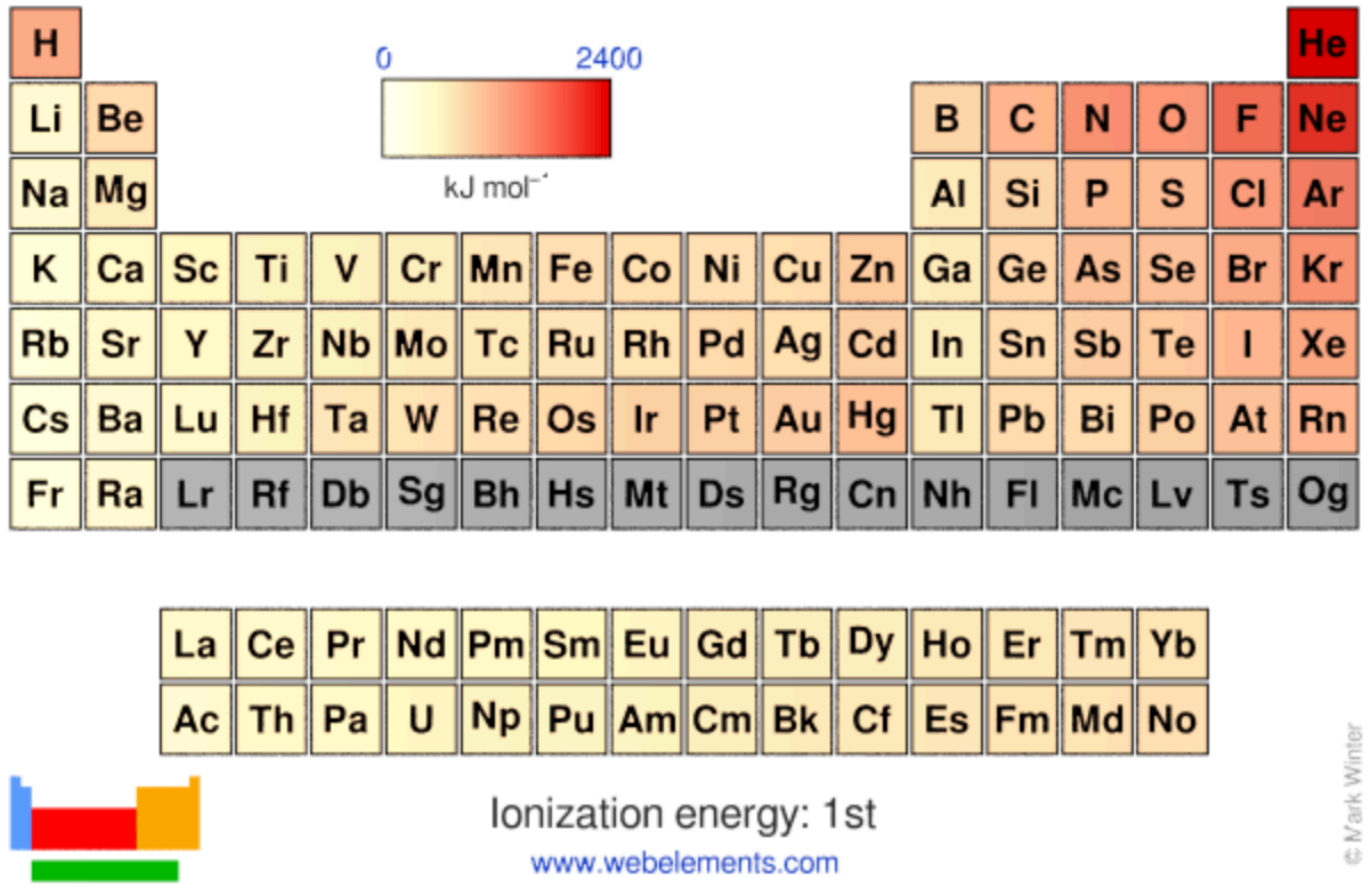


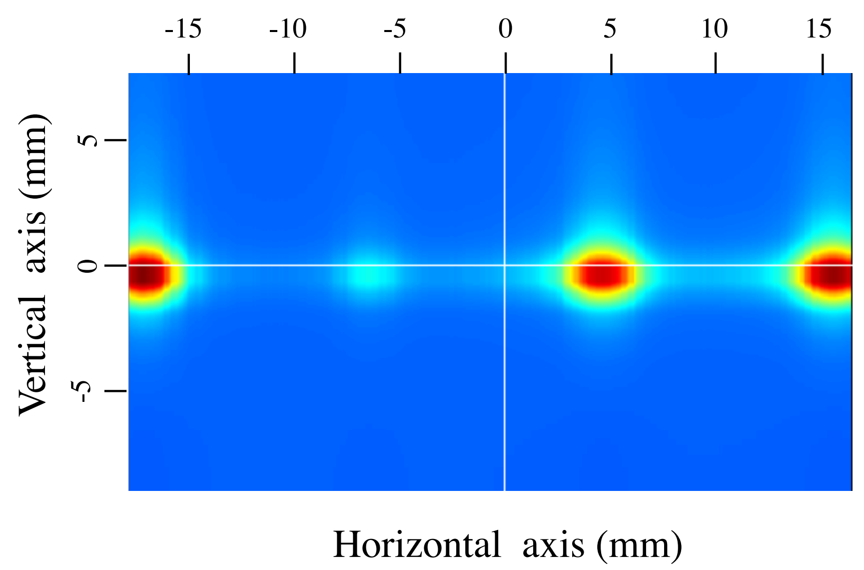


- Create the isotope
- Release the isotope from the target
- Ionise the isotope
- Separate the isotope from contaminants

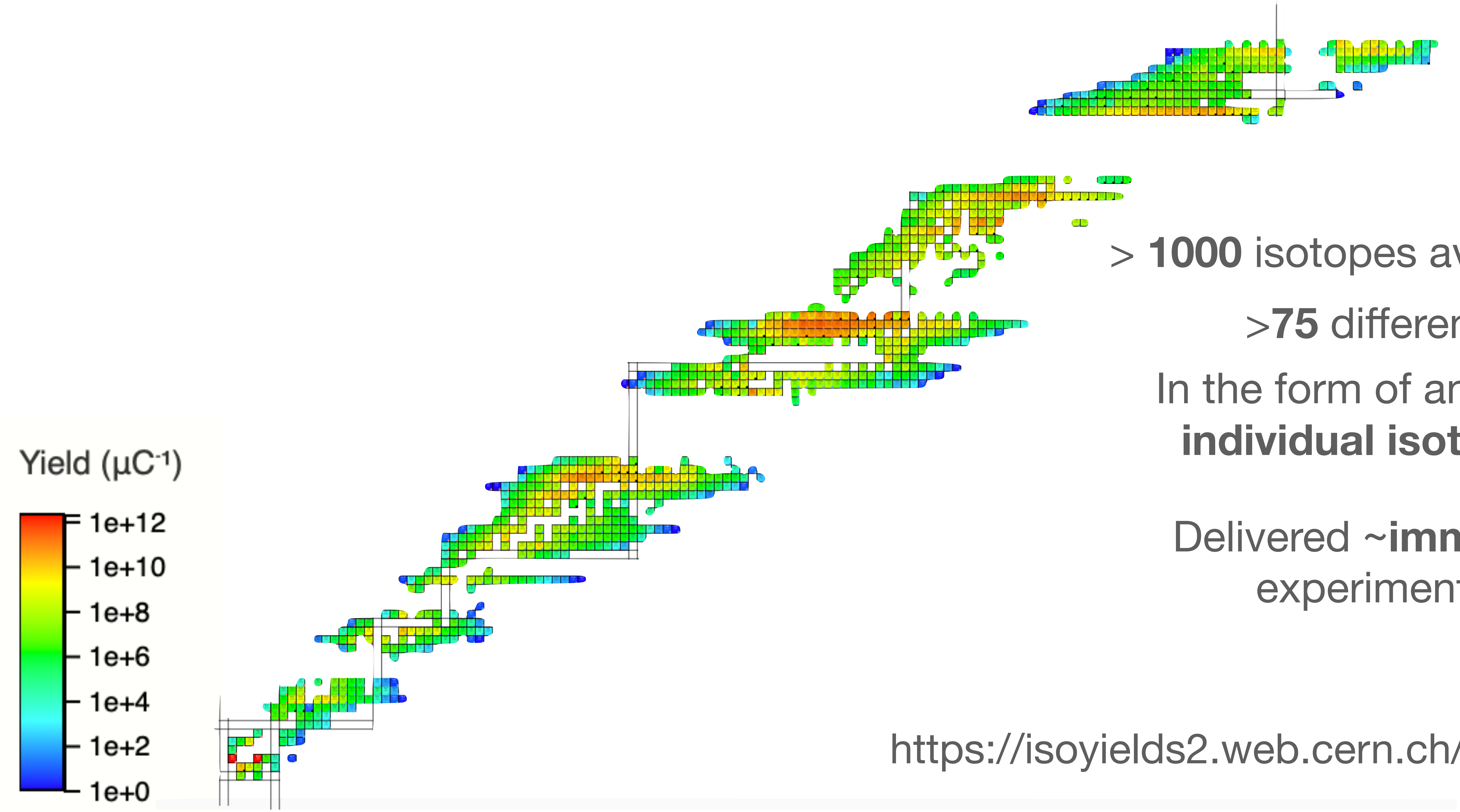








ISOLDE beams: available for experiments



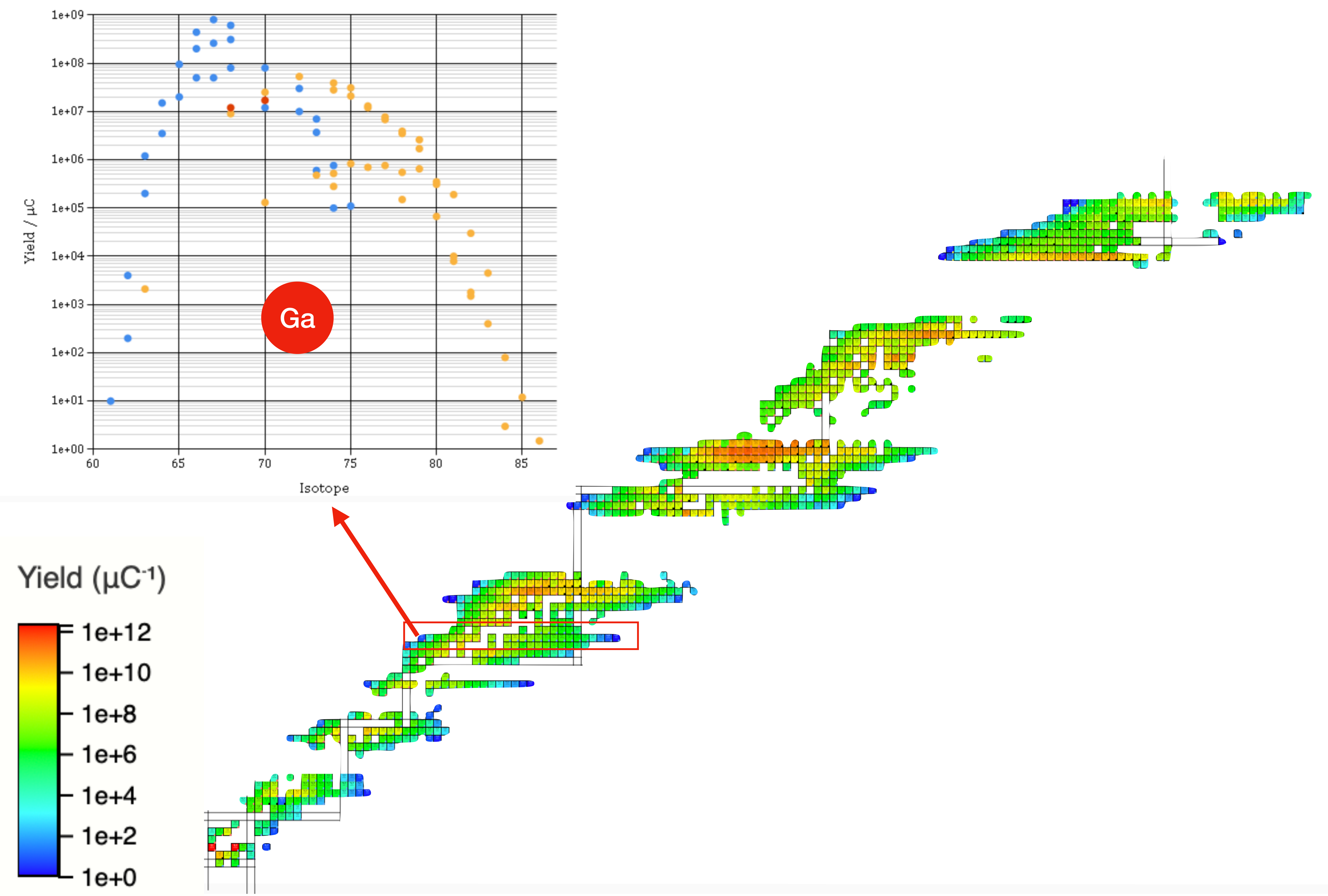
> **1000** isotopes available at ISOLDE

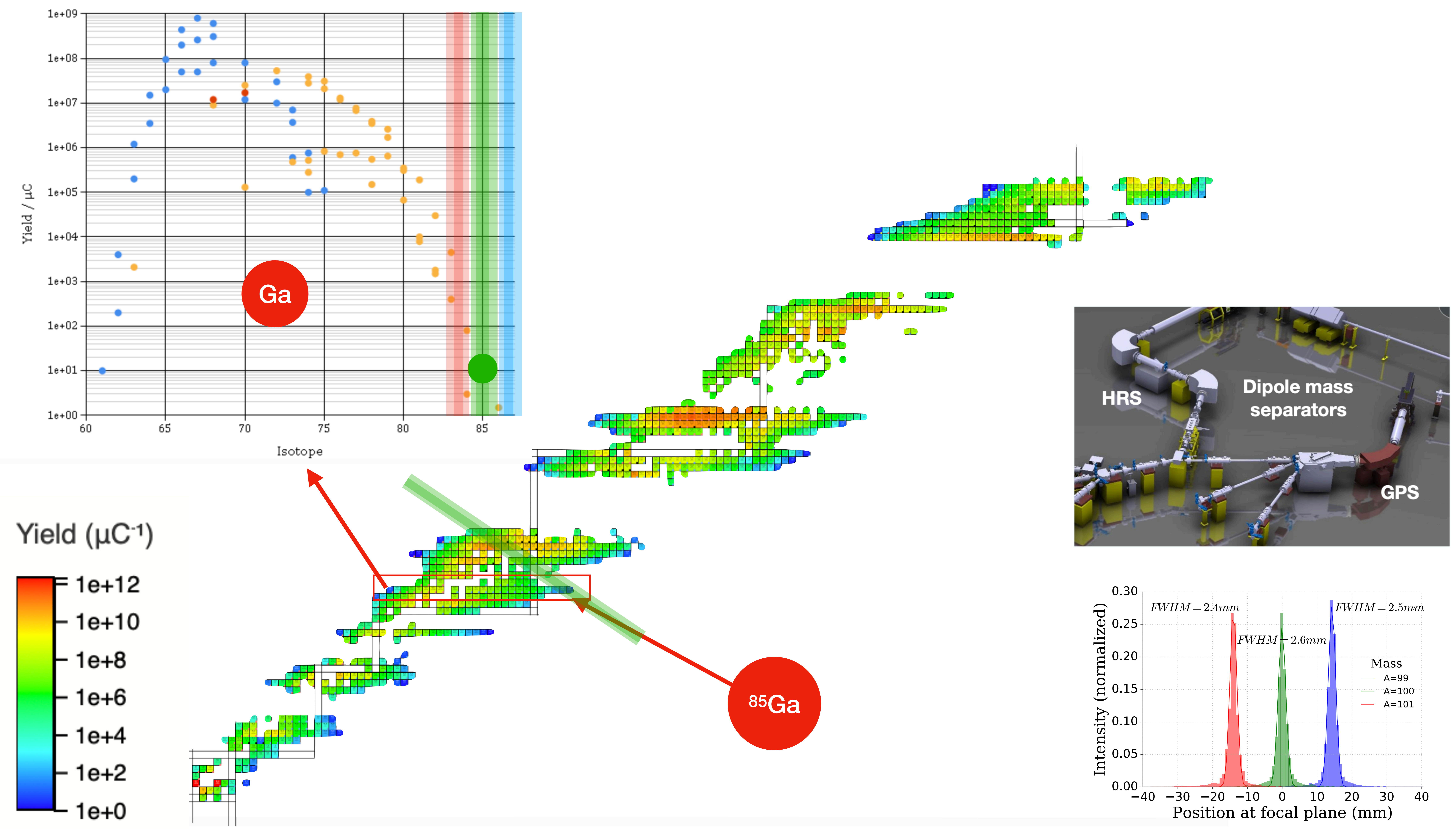
>**75** different elements

In the form of an **ion beam** with **individual isotope selection**

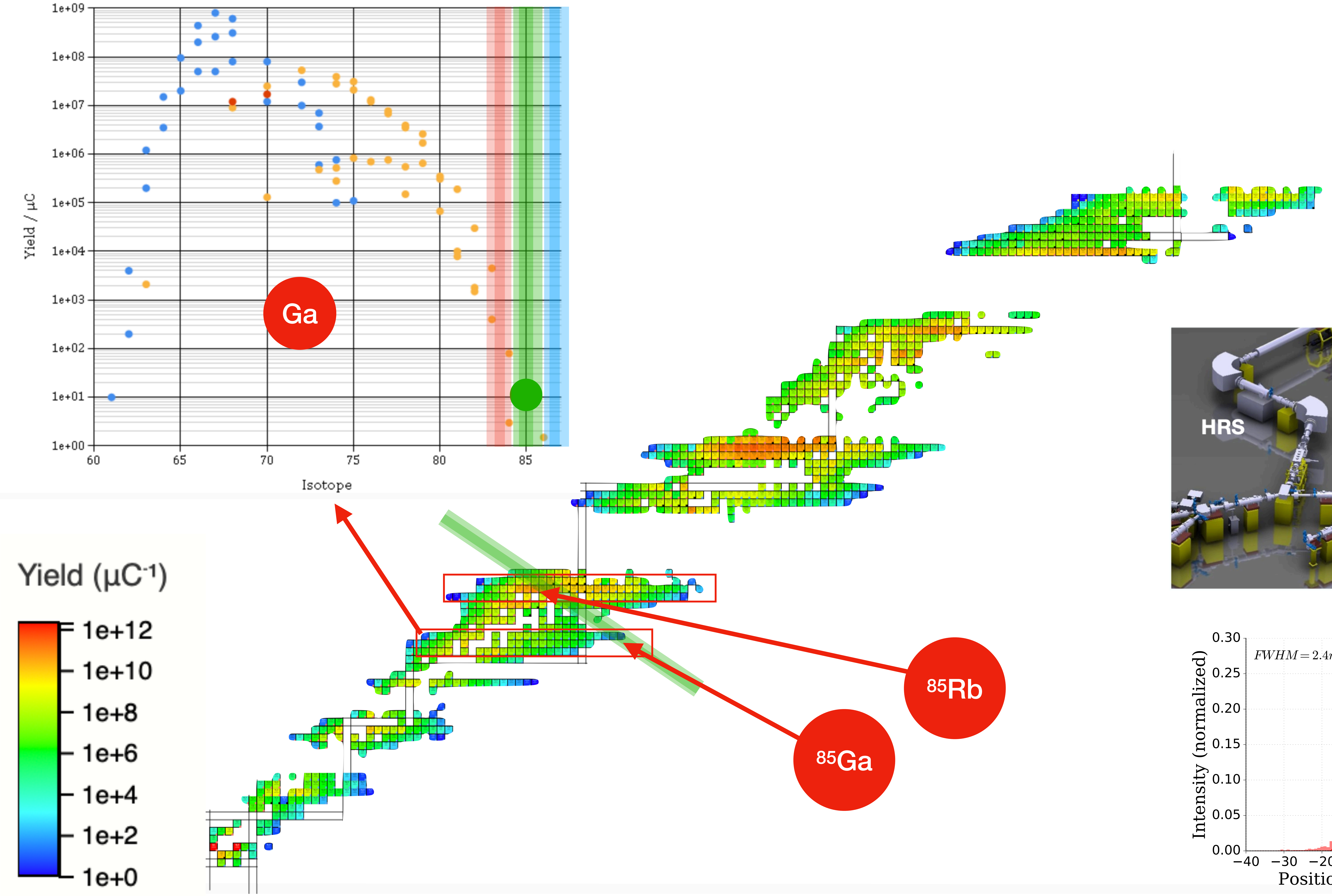
Delivered ~**immediately** to an experiment for study!

https://isoyields2.web.cern.ch/Yield_Home.aspx

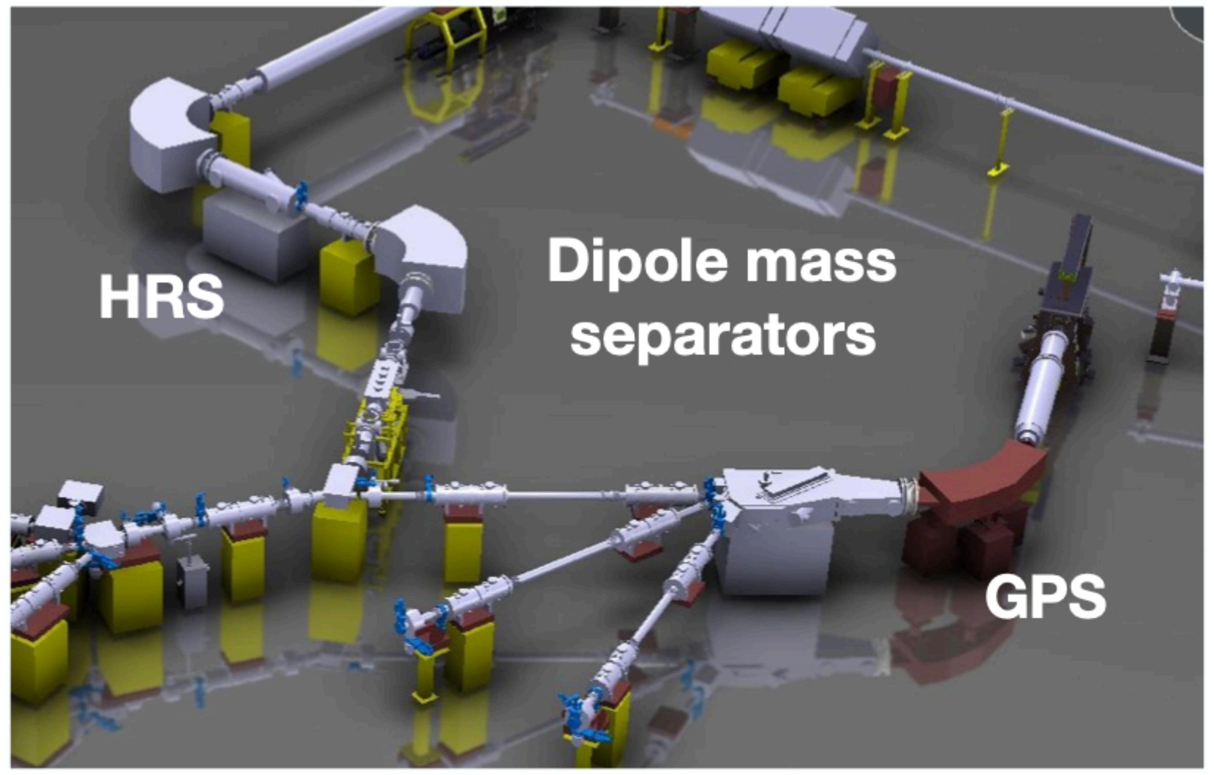

1e+09
1e+08
1e+07
1e+06
1e+05
1e+04
1e+03
1e+02
1e+01
1e+00
60
65
70
75
80
85
Yield / µC
Isotope
Ga
Yield (µC⁻¹)
1e+12
1e+10
1e+8
1e+6
1e+4
1e+2
1e+0



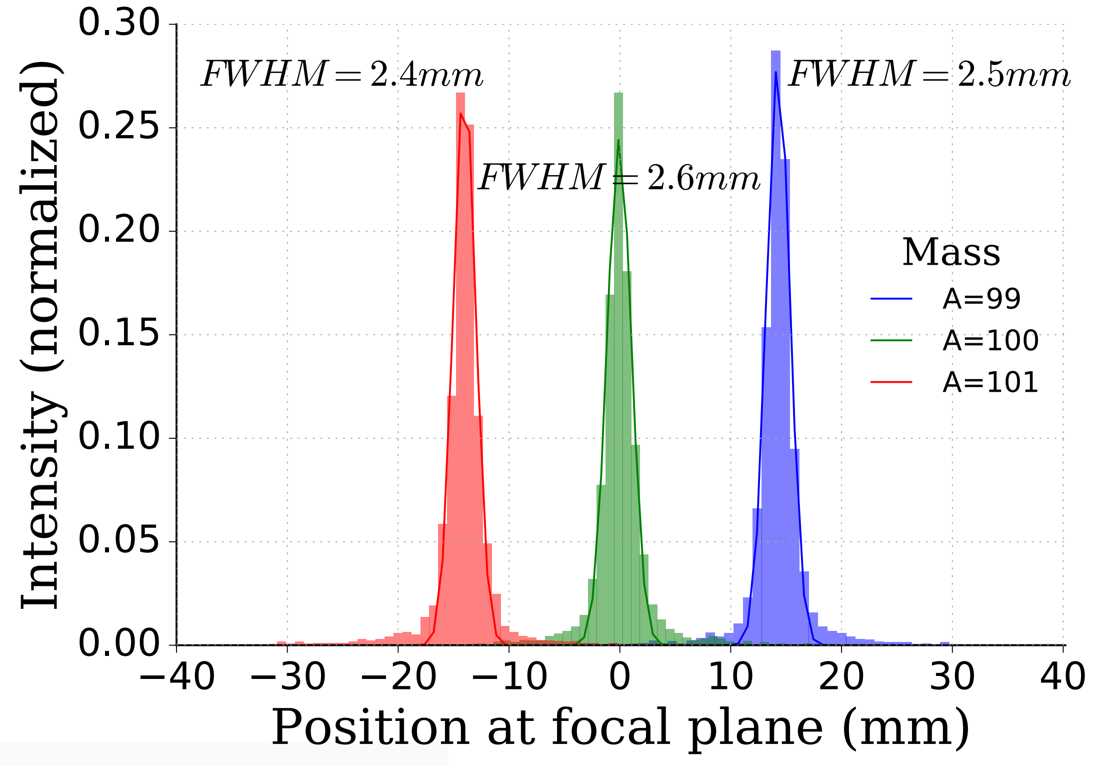
Yield / µC
1e+09
1e+08
1e+07
1e+06
1e+05
1e+04
1e+03
1e+02
1e+01
1e+00
60
65
70
75
80
85
Isotope
Ga
Yield (µC-1)
1e+12
1e+10
1e+8
1e+6
1e+4
1e+2
1e+0
85Ga
HRS
Dipole mass separators
GPS
FWHM = 2.4mm
FWHM = 2.6mm
FWHM = 2.5mm
Mass
A=99
A=100
A=101
Intensity (normalized)
Position at focal plane (mm)



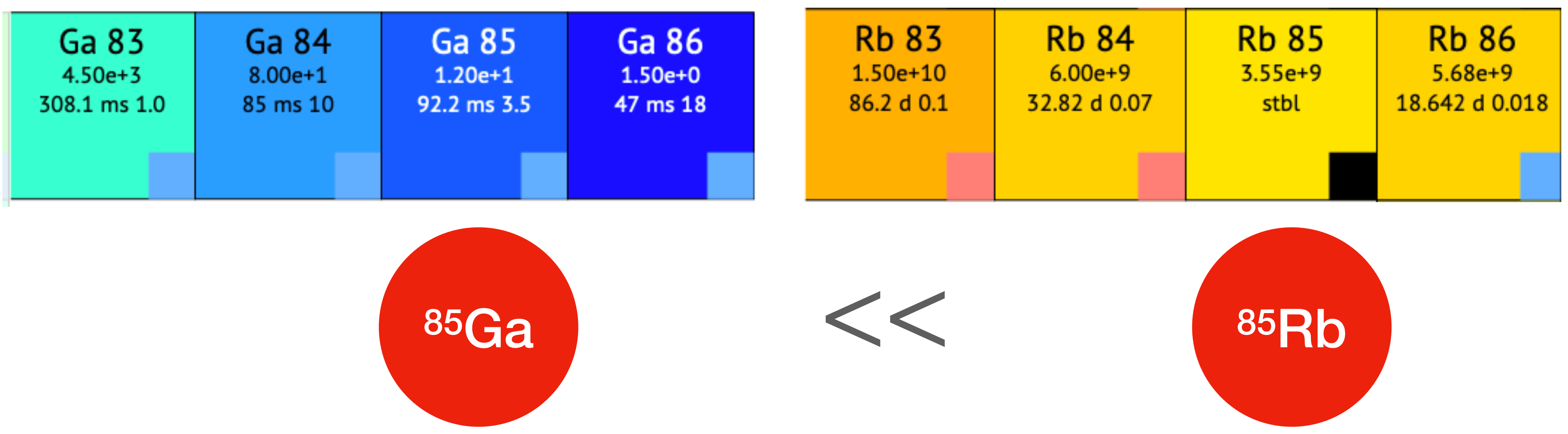
Yield / µC
Isotope
Ga
Yield (µC-1)
1e+12
1e+10
1e+8
1e+6
1e+4
1e+2
1e+0
85Rb
85Ga

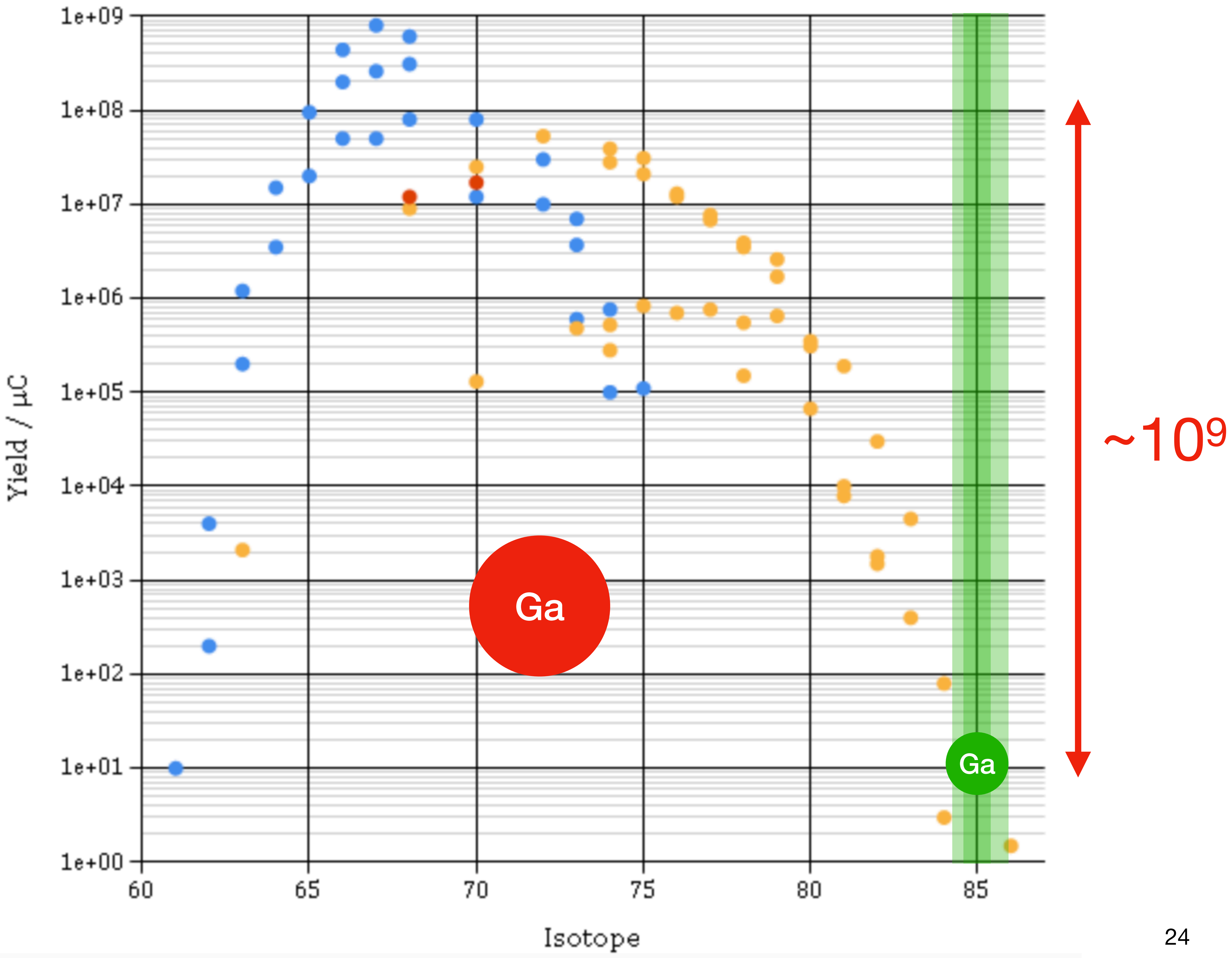


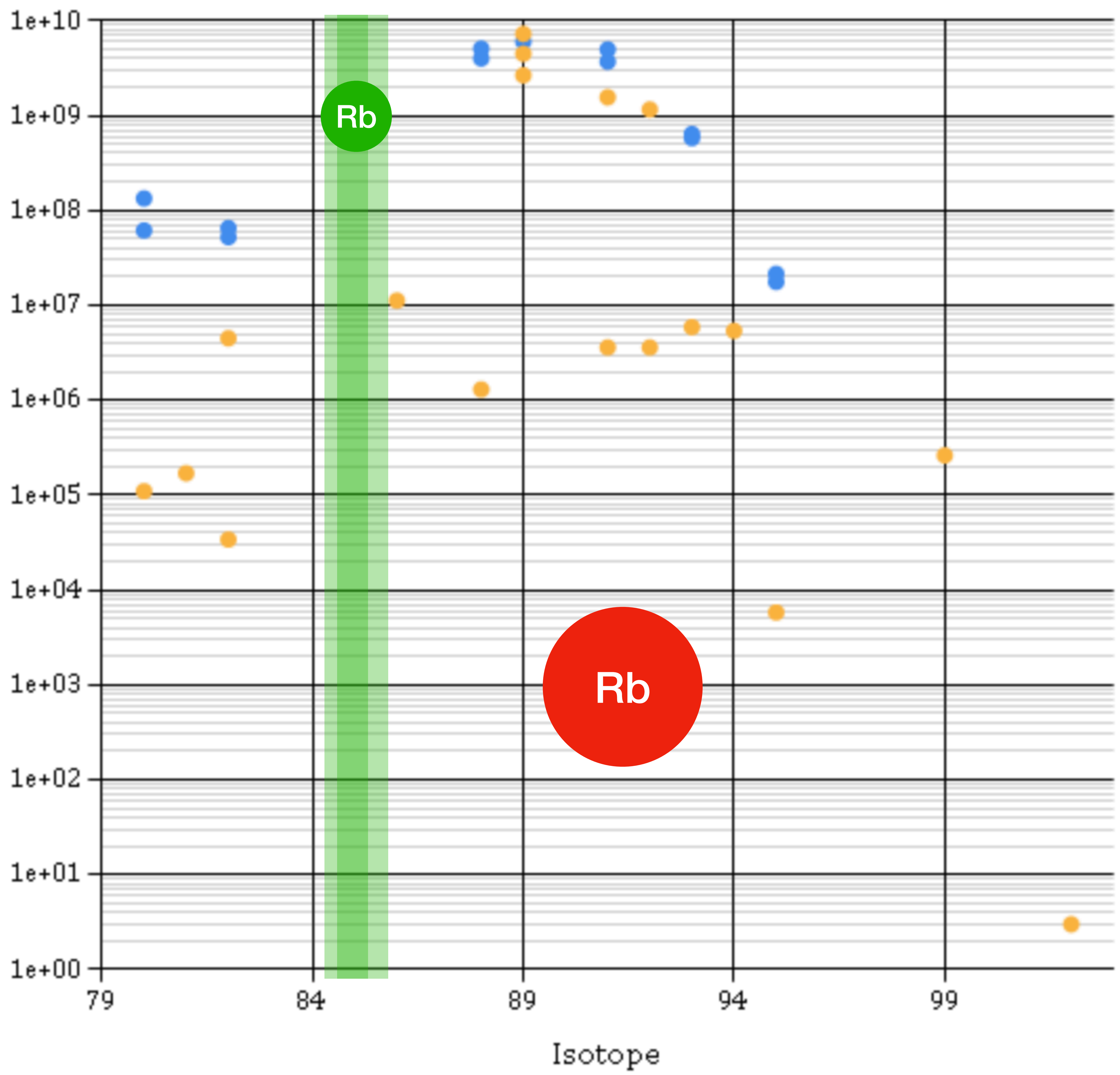
HRS
Dipole mass separators
GPS

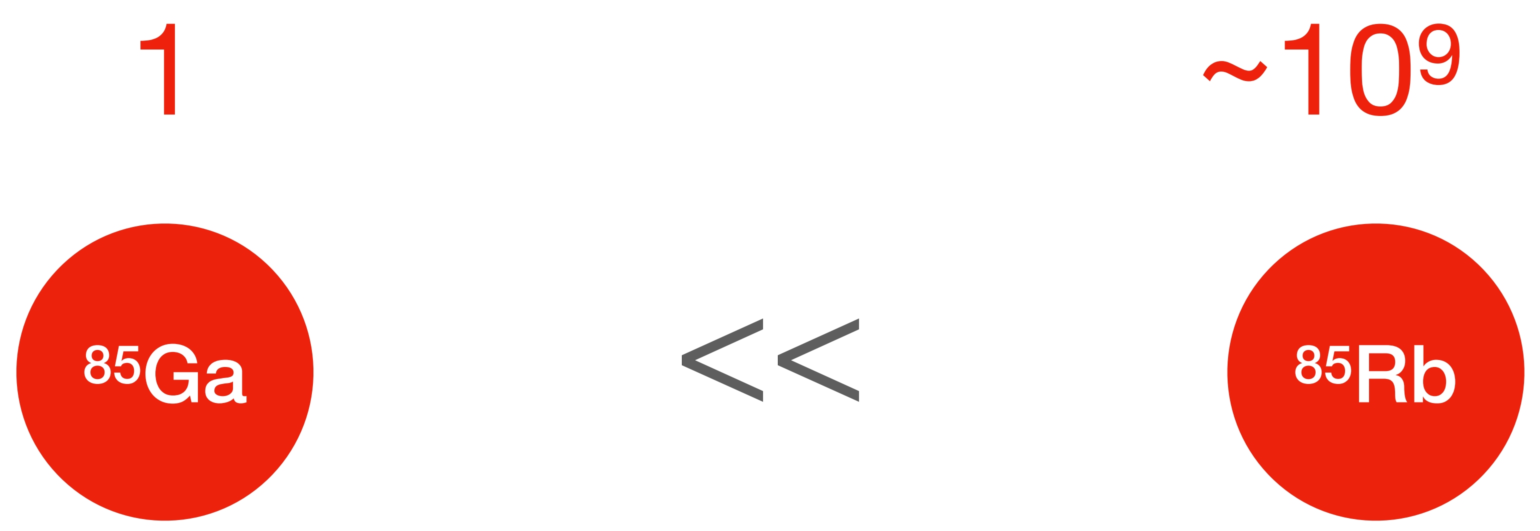


FWHM = 2.4mm
FWHM = 2.6mm
FWHM = 2.5mm
Mass
A=99
A=100
A=101
Intensity (normalized)
Position at focal plane (mm)


Ga 83
4.50e+3
308.1 ms 1.0
Ga 84
8.00e+1
85 ms 10
Ga 85
1.20e+1
92.2 ms 3.5
Ga 86
1.50e+0
47 ms 18
Rb 83
1.50e+10
86.2 d 0.1
Rb 84
6.00e+9
32.82 d 0.07
Rb 85
3.55e+9
stbl
Rb 86
5.68e+9
18.642 d 0.018
85Ga
<<
85Rb


Yield / μC
Isotope
Ga
Ga
~10^9


Isotope
Rb
Rb

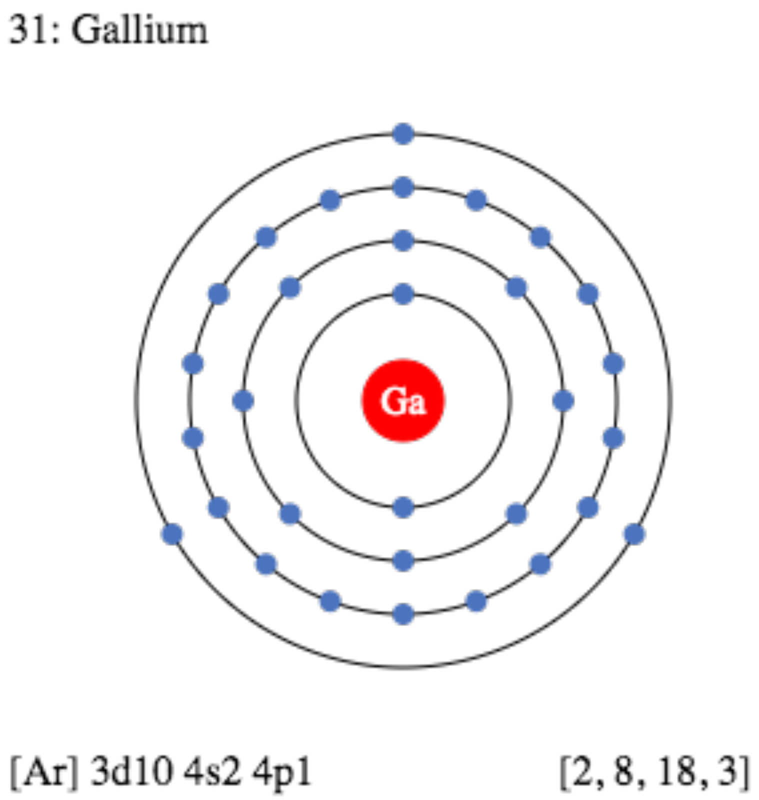

1
~10^9
85Ga
<<
85Rb

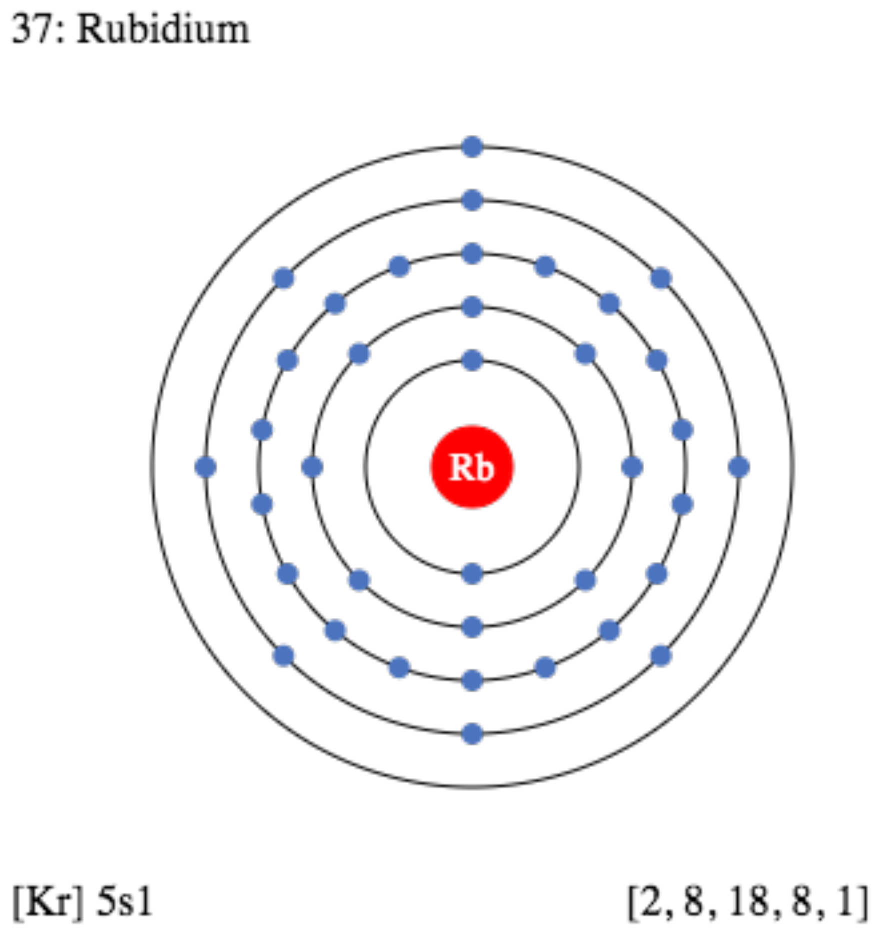
1 $\ll$ $\sim 10^{9}$

^{85}Ga << ^{85}Rb

Different number of **protons**

Different **electron configuration**



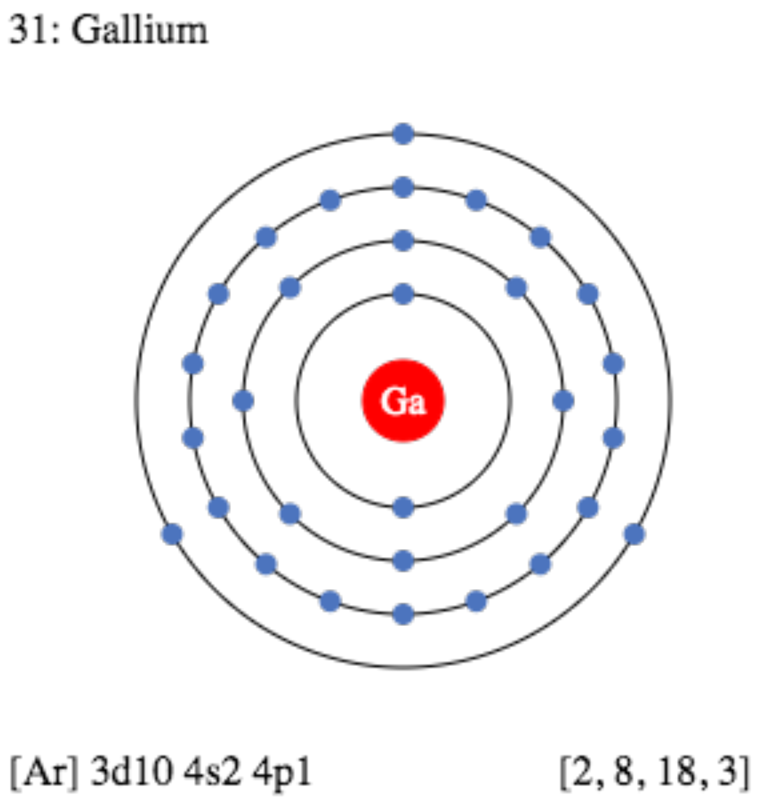


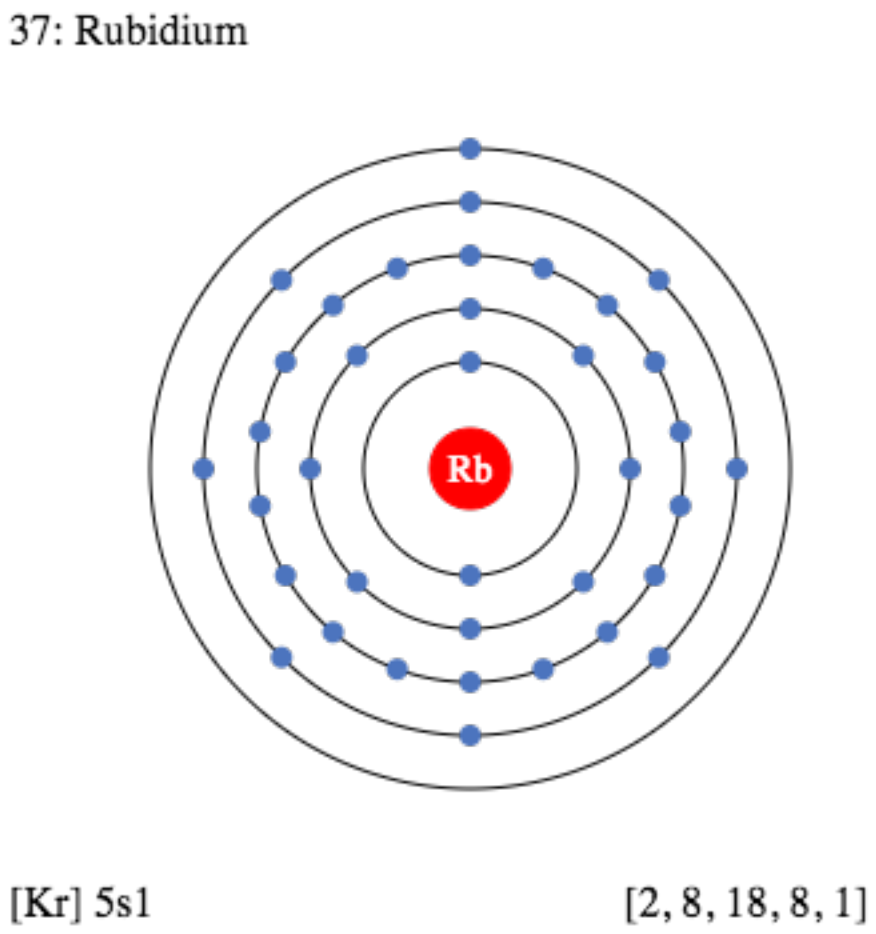
1

<<

$\sim 10^9$

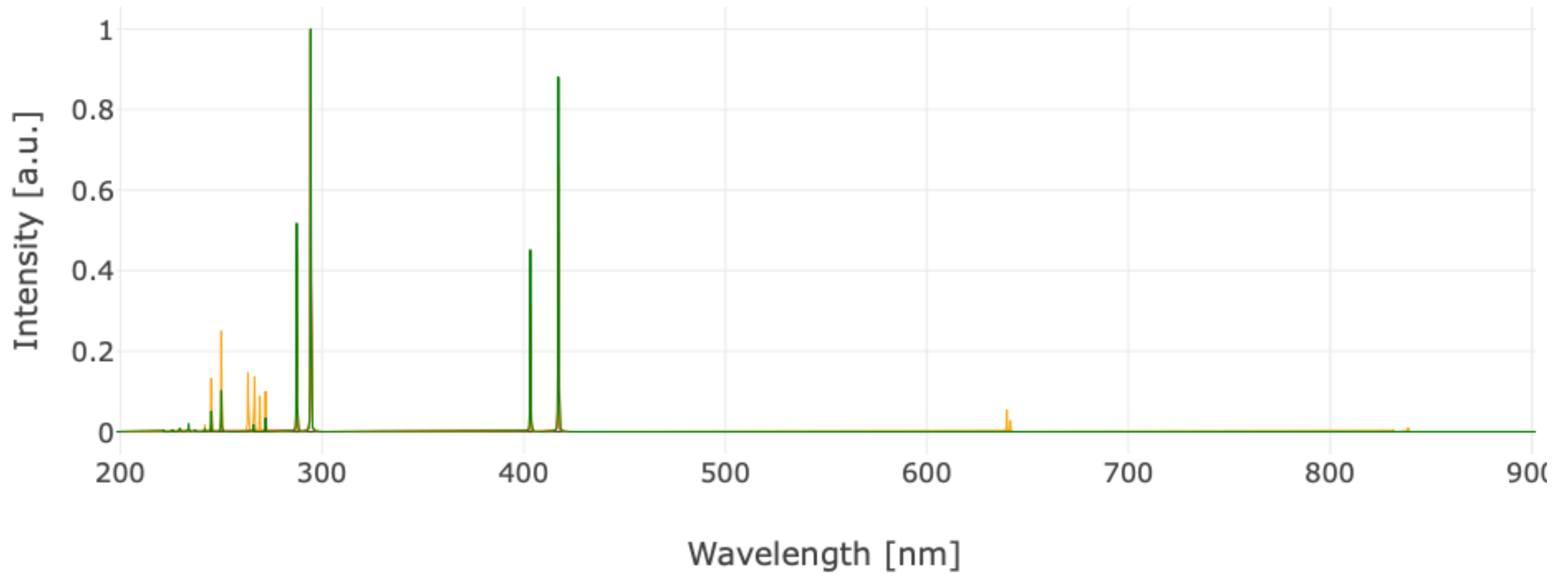
Different number of **protons**

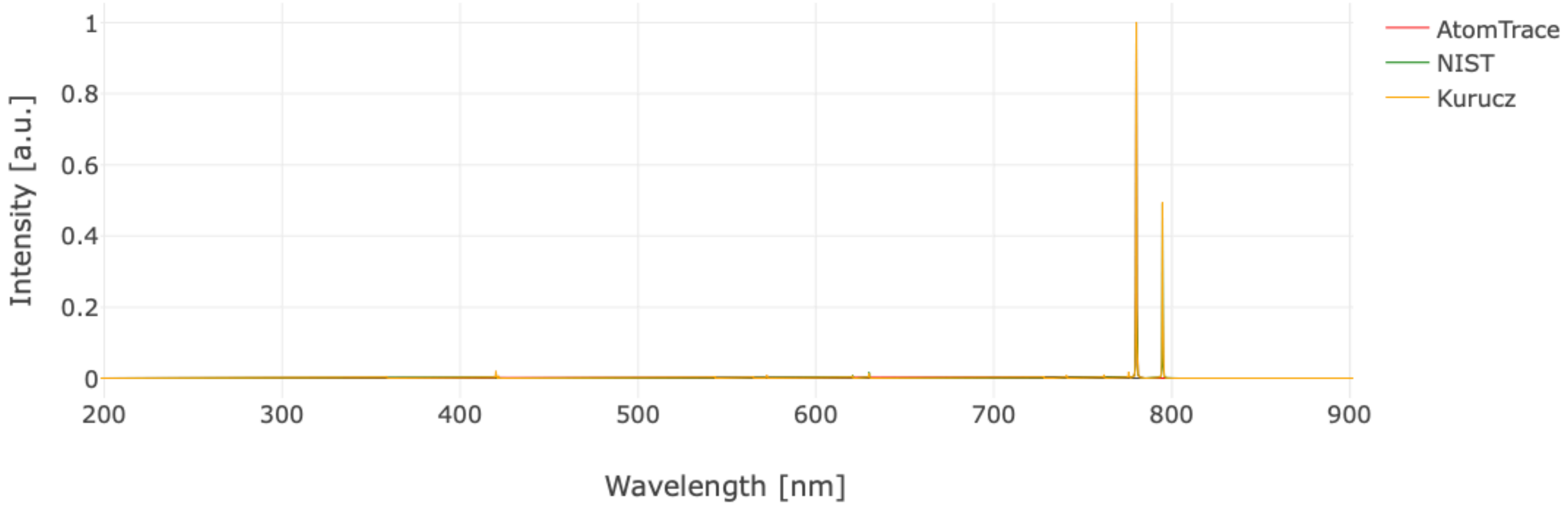


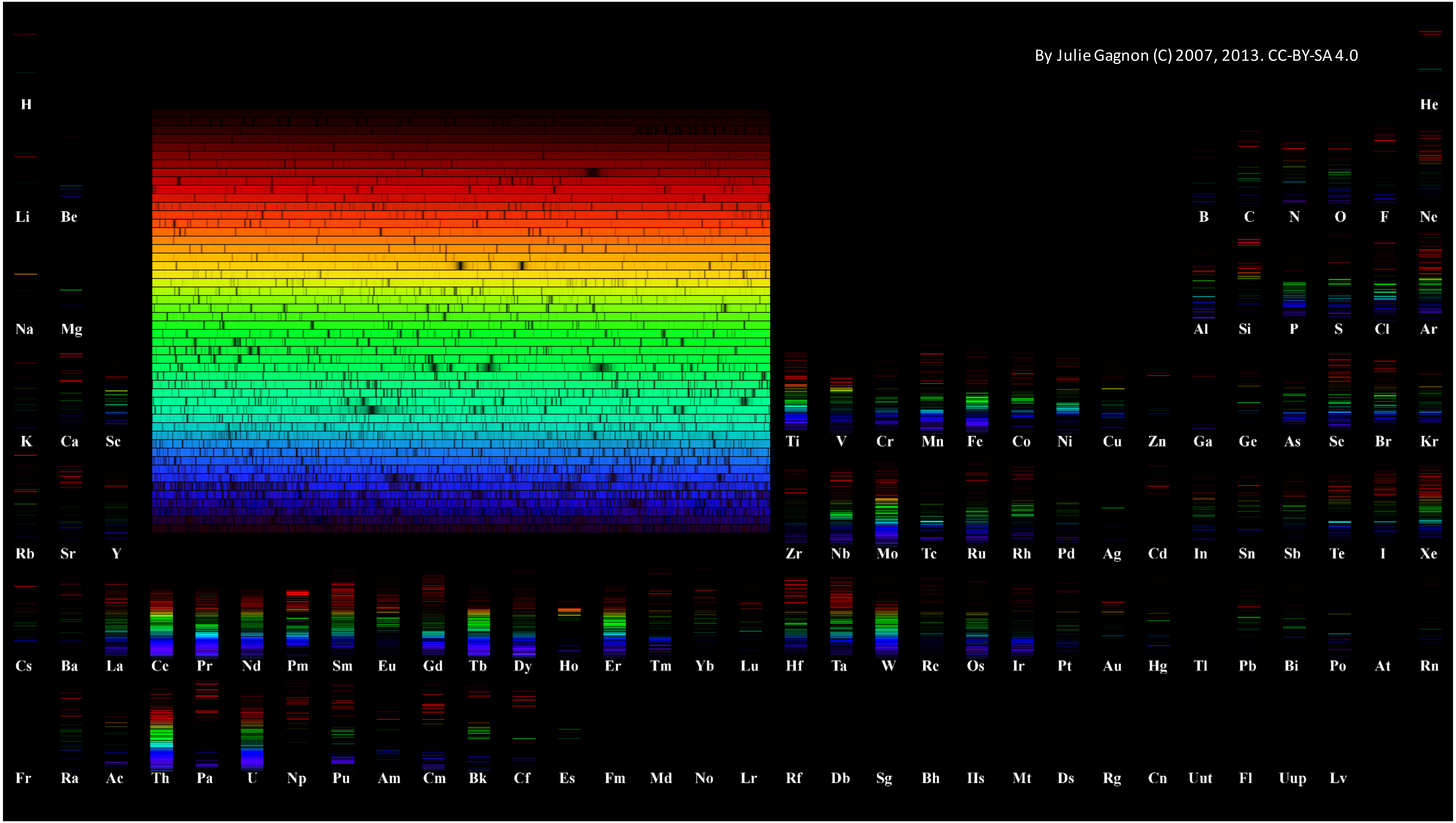


Different **electron configuration**

Different **spectral properties**

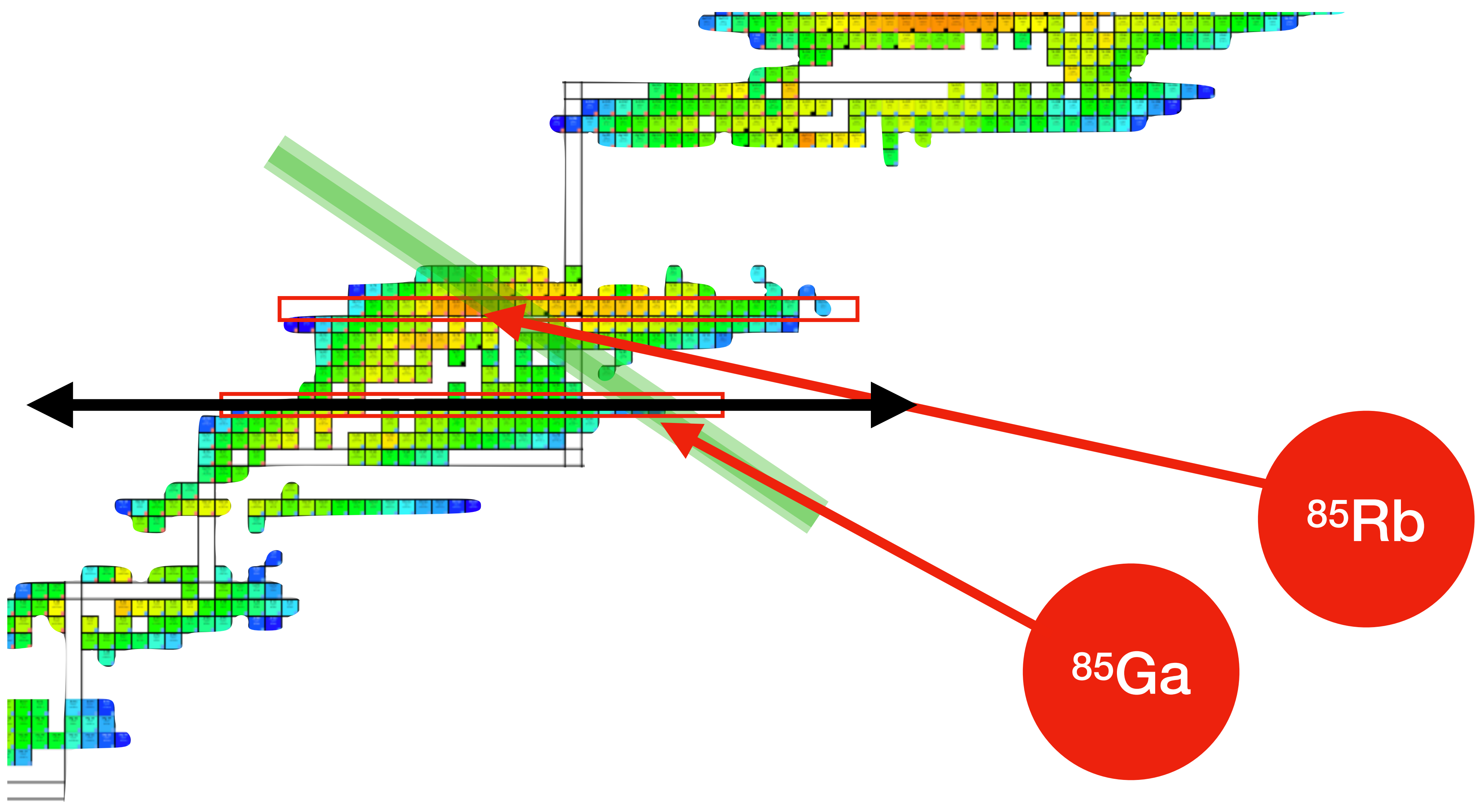


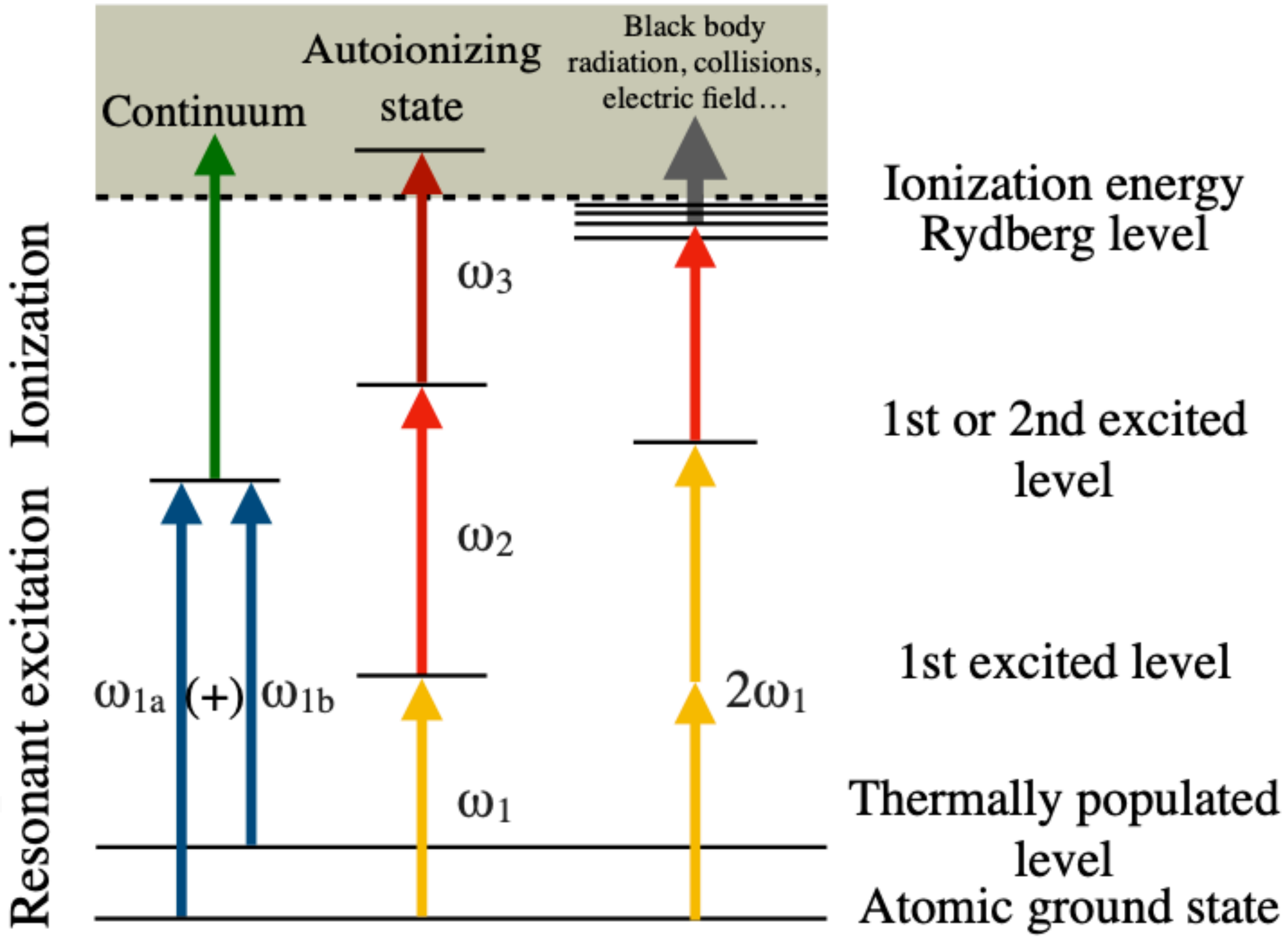



By Julie Gagnon (C) 2007, 2013. CC-BY-SA 4.0
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv

Stepwise Resonance Photo-ionization

An element-selective ionisation method!





History of the RILIS method

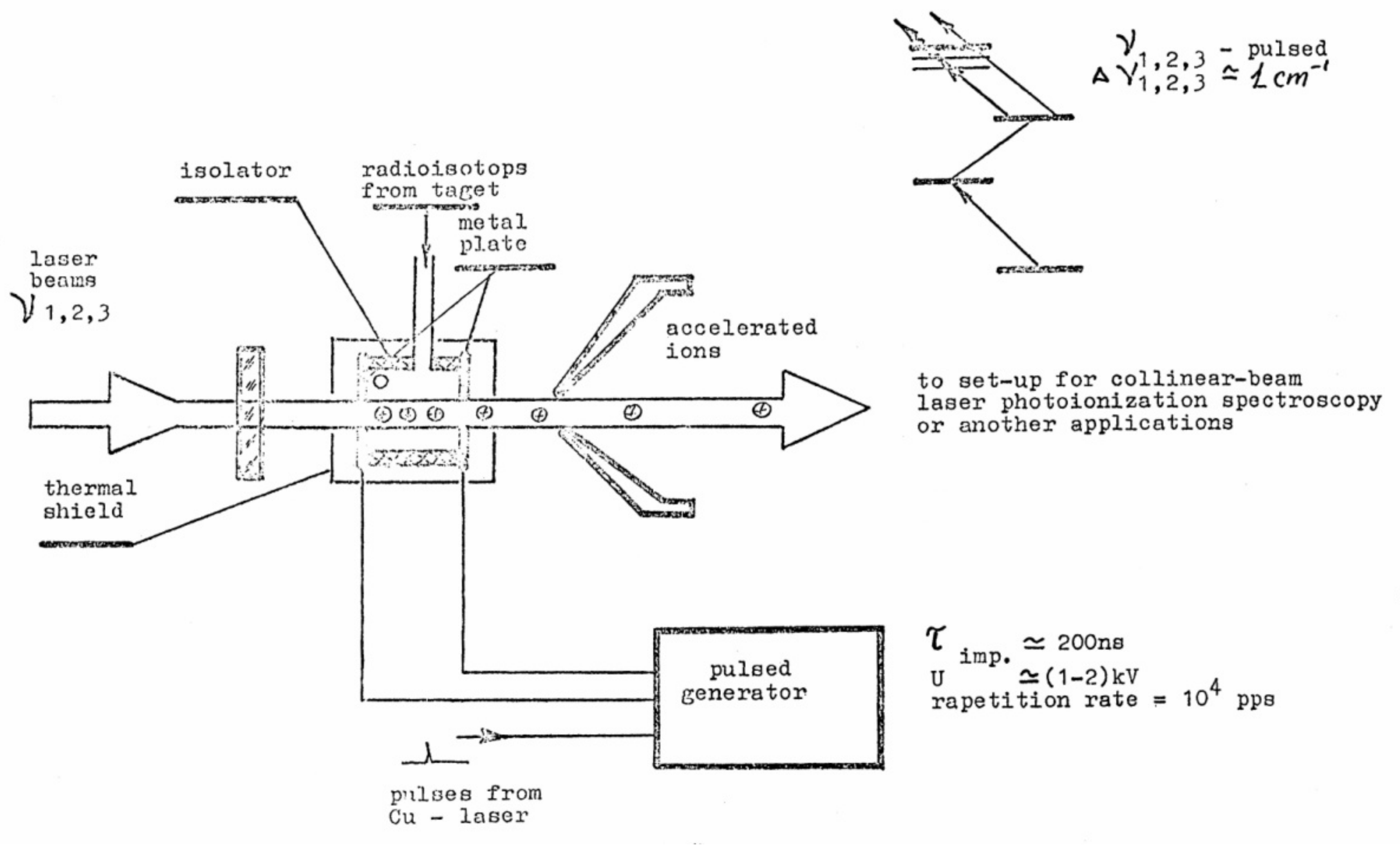
Early proposals: 1988

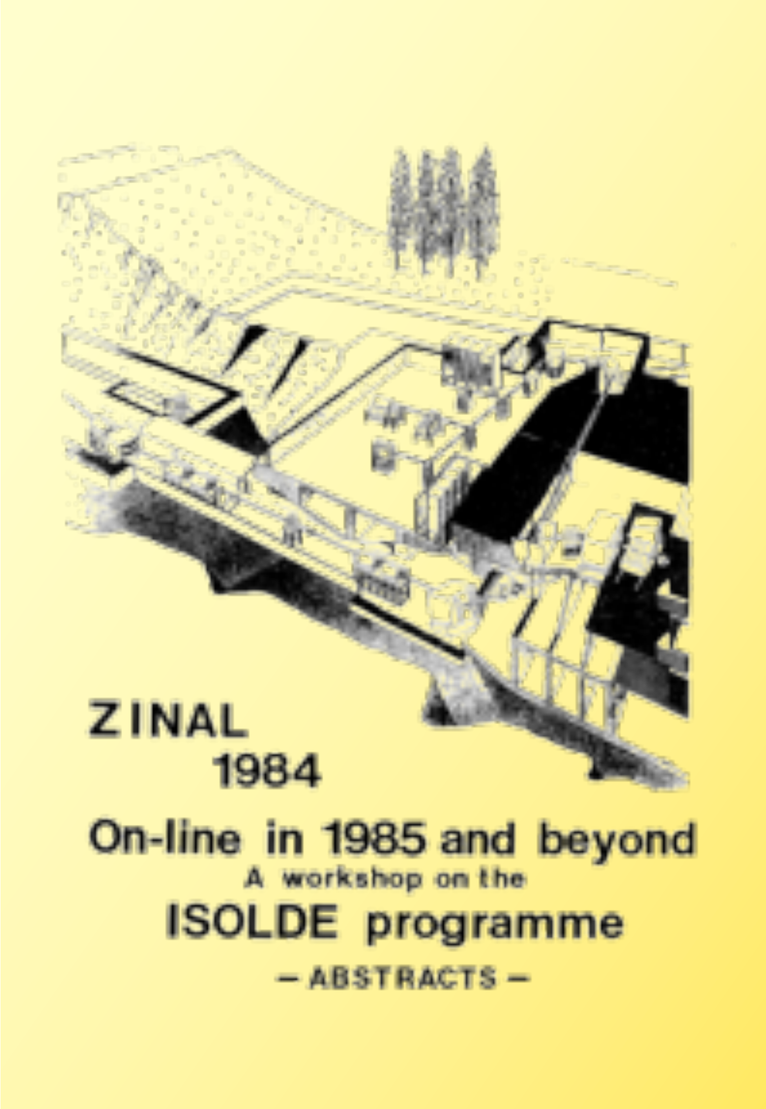
PROPOSAL
of the Institute of Spectroscopy, Acad.Sci. USSR
for experiments with ISOLDE-CERN Facility
(V. S. Letokhov and V. I. Mishin)

LASER PHOTOIONIZATION PULSED SOURCE OF
RADIOACTIVE ATOMS

1984

I. Purpose The development of a pulsed isobar-selective effective source of ions at the mass-separator inlet on the basis of the method of laser resonant atomic photoionization.





EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/ISOLDE
IP 50

PROPOSAL TO THE ISOLDE COMMITTEE

DEVELOPMENT OF A LASER ION SOURCE

F. Ames, E. Arnold, H.J. Kluge, Y.A. Kudryavtsev,
V.S. Letokhov, V.I. Mishin, E.W. Otten, H. Ravn,
W. Ruster, S. Sundell and K. Wendt

University of Mainz, F.R.G.,
Institute of Spectroscopy, Troitzk, USSR
and the ISOLDE Collaboration, CERN, Switzerland

Spokesman: K. Wendt
Contactman: E. Arnold

SUMMARY

Test experiments at Troitzk and Mainz have demonstrated the feasibility of step-wise multi-photon excitation and final ionisation by pulsed lasers as a selective and efficient tool for the production of isobarically pure ion beams. The development of a new type of ion source based on this concept is proposed. In combination with existing targets, this will open up the way to a further extension in respect to purity and availability for a number of elements at on-line mass separator facilities. The collaboration proposes to use the CERN-ISOLDE off-line separator for tests of appropriate target ion source configurations with respect to efficiency and purity. After succesful development the laser ion source shall be installed as an additional facility at the IS-3 separator.

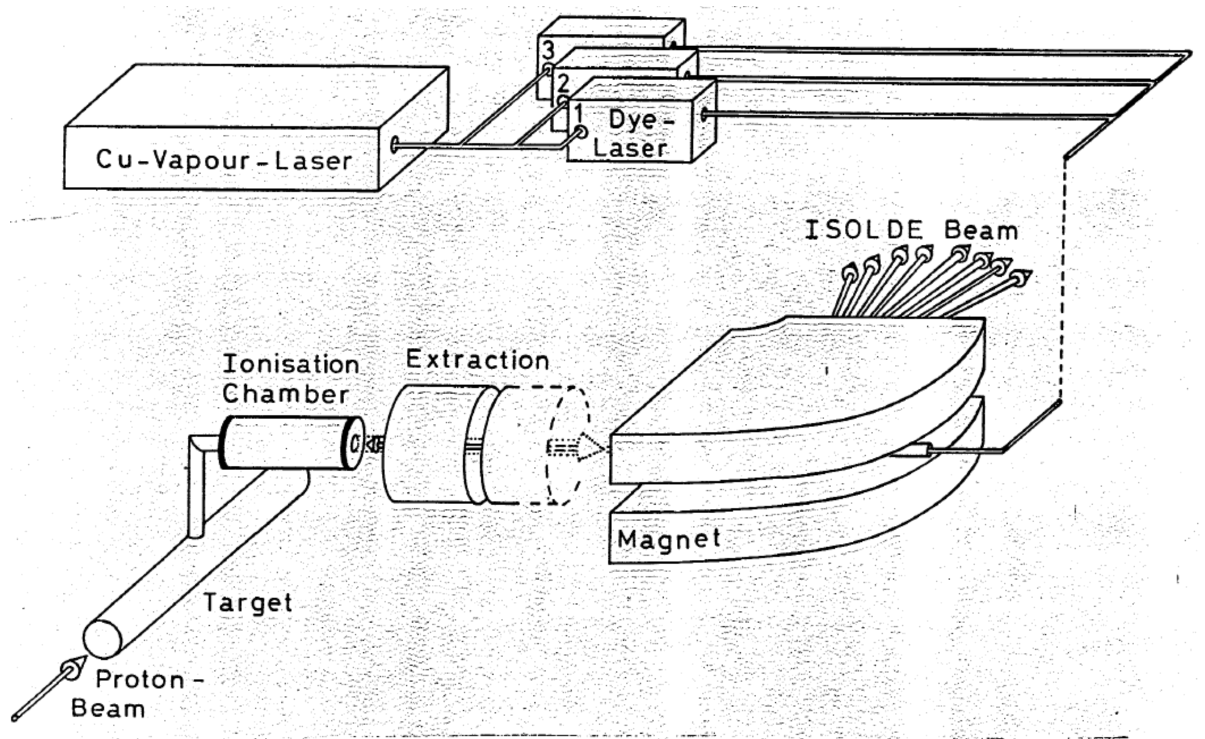
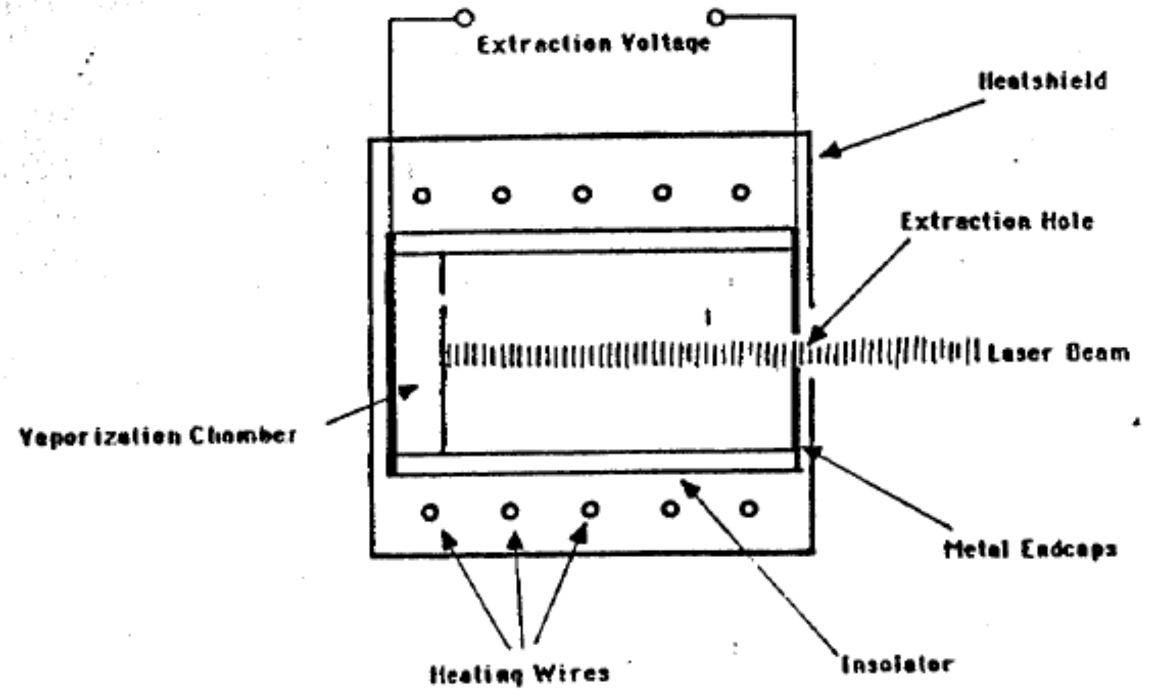
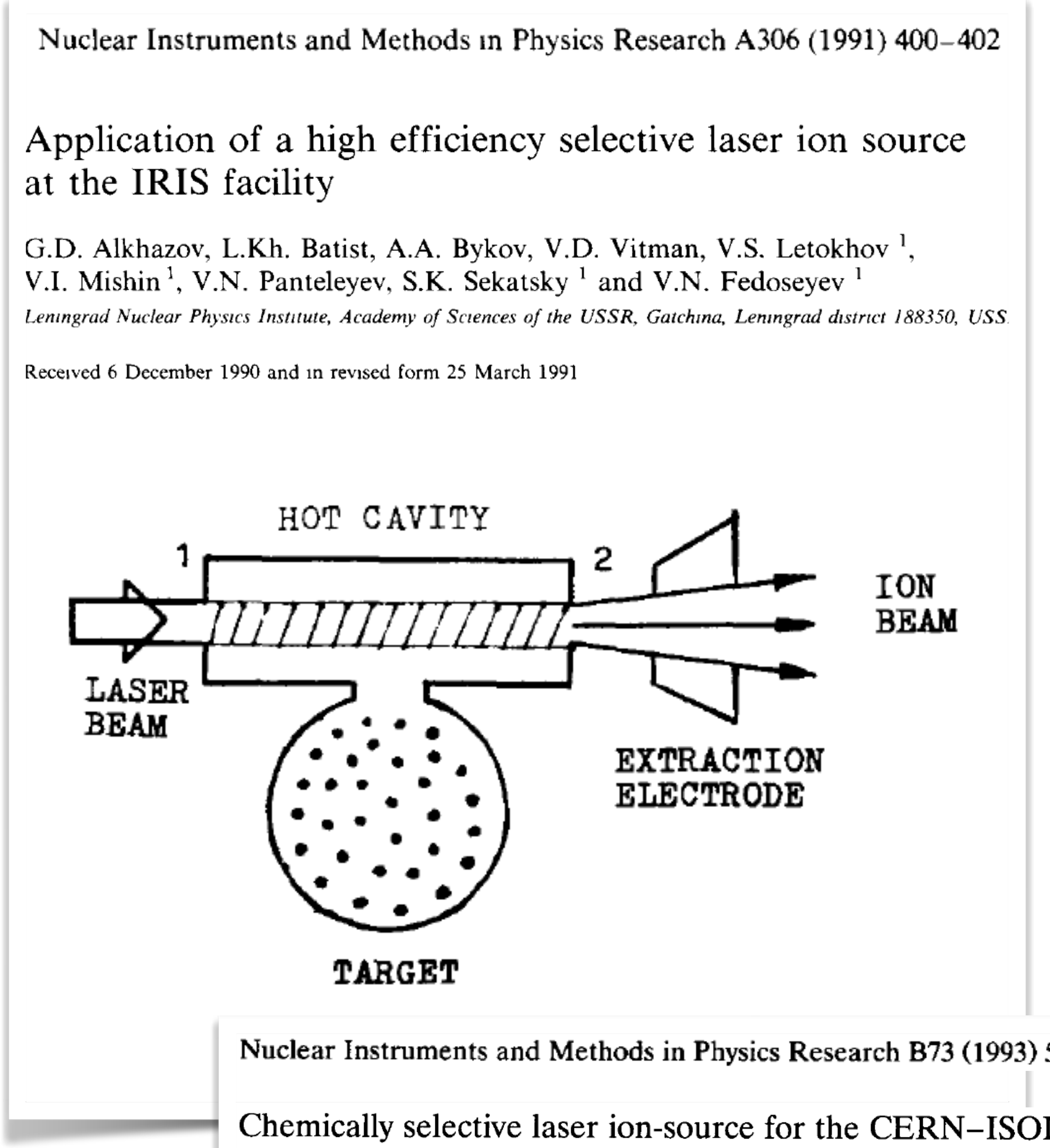


Fig. 5: General layout of the experimental set-up at the off-line separator



History of RILIS at ISOLDE

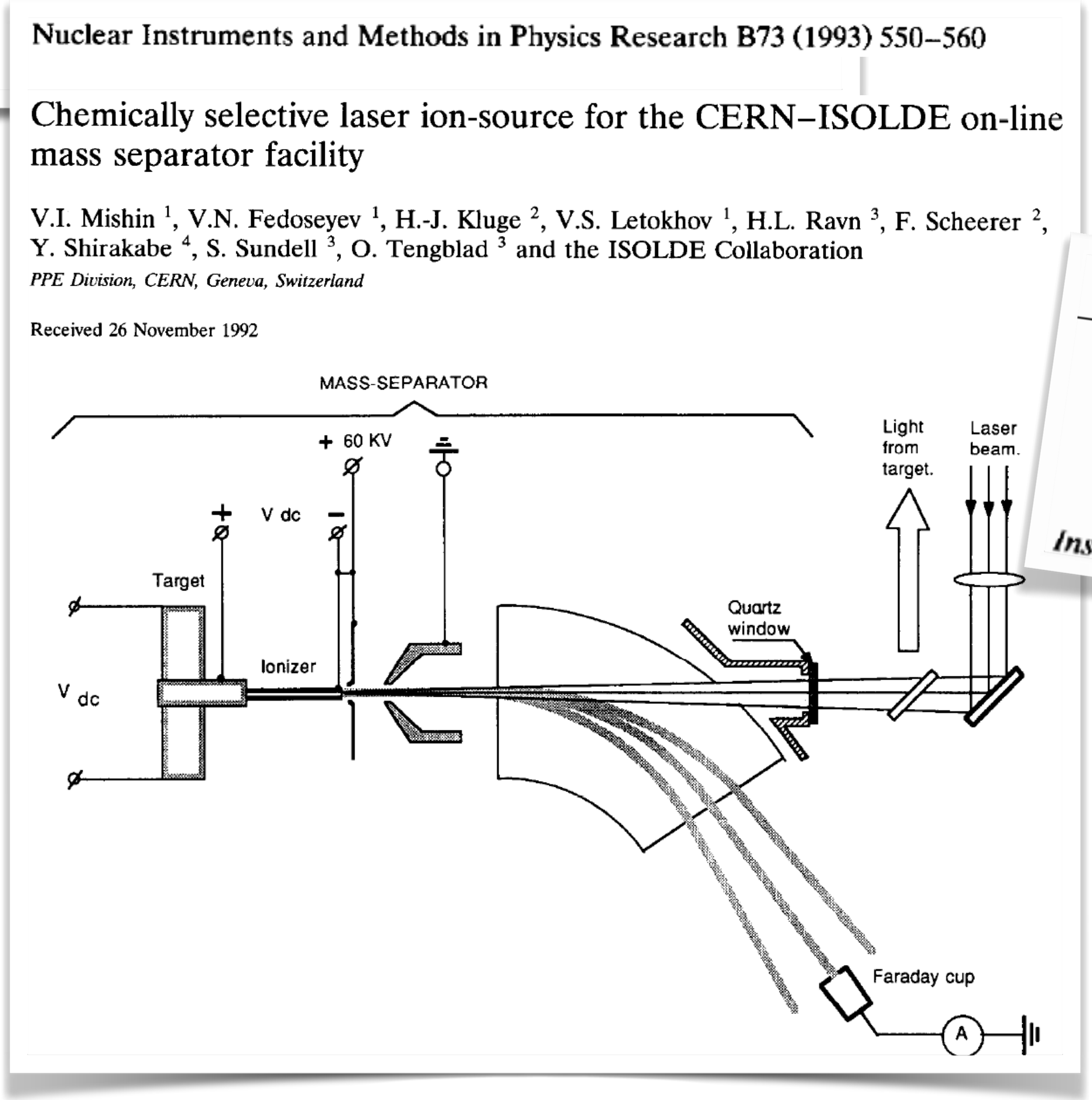


Nuclear Instruments and Methods in Physics Research A306 (1991) 400–402

Application of a high efficiency selective laser ion source at the IRIS facility

G.D. Alkhazov, L.Kh. Batist, A.A. Bykov, V.D. Vitman, V.S. Letokhov [1], V.I. Mishin [1], V.N. Panteleyev, S.K. Sekatsky [1] and V.N. Fedoseyev [1]
Leningrad Nuclear Physics Institute, Academy of Sciences of the USSR, Gatchina, Leningrad district 188350, USS

Received 6 December 1990 and in revised form 25 March 1991

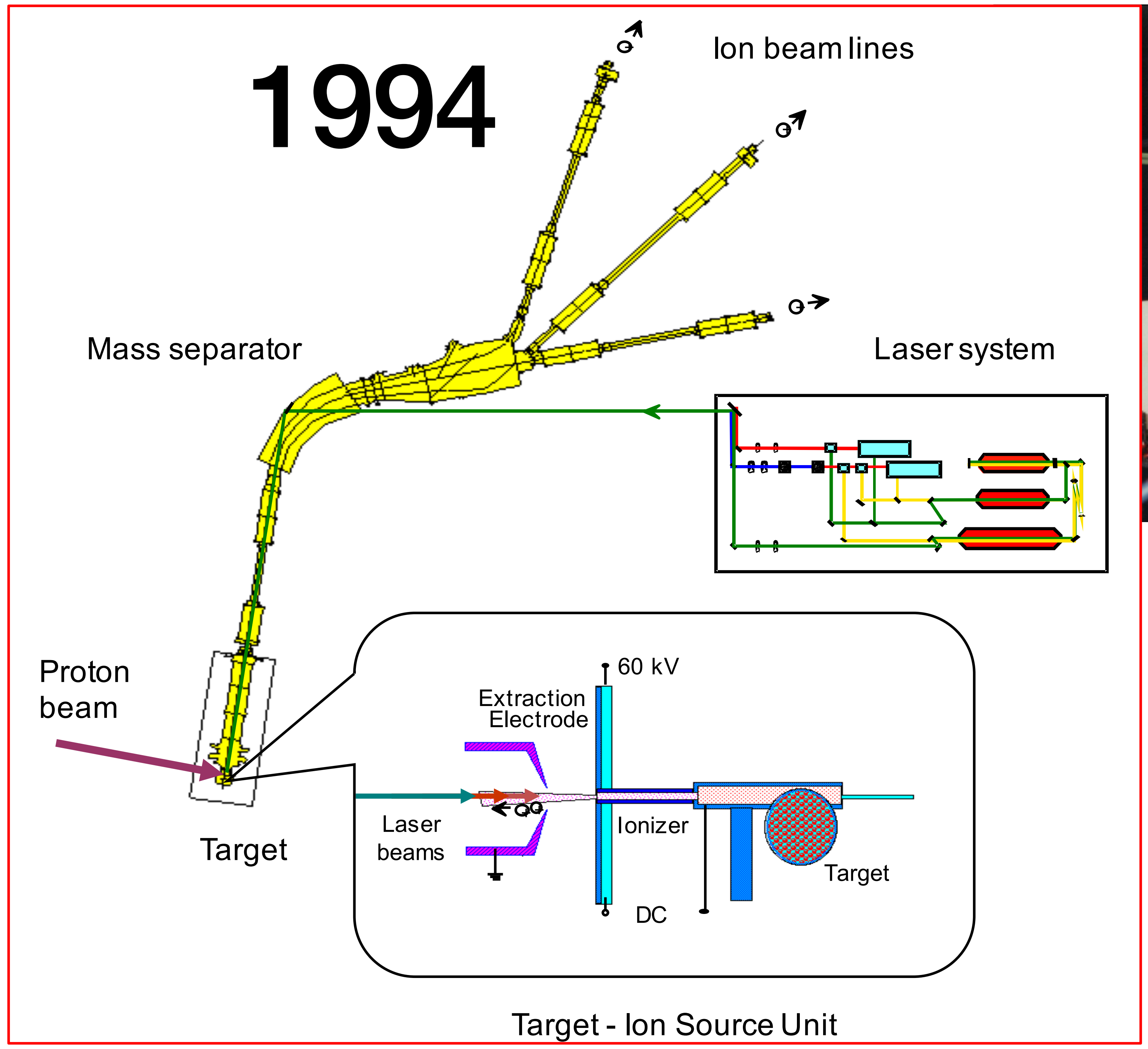


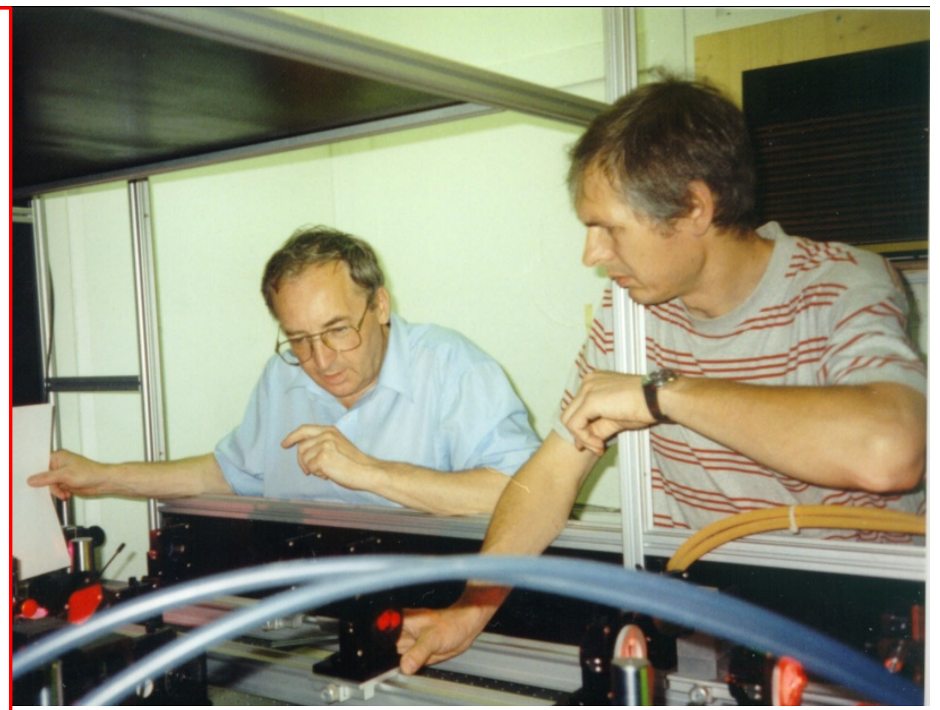
Nuclear Instruments and Methods in Physics Research B73 (1993) 550–560

Chemically selective laser ion-source for the CERN–ISOLDE on-line mass separator facility

V.I. Mishin [1], V.N. Fedoseyev [1], H.-J. Kluge [2], V.S. Letokhov [1], H.L. Ravn [3], F. Scheerer [2], Y. Shirakabe [4], S. Sundell [3], O. Tengblad [3] and the ISOLDE Collaboration
PPE Division, CERN, Geneva, Switzerland

Received 26 November 1992

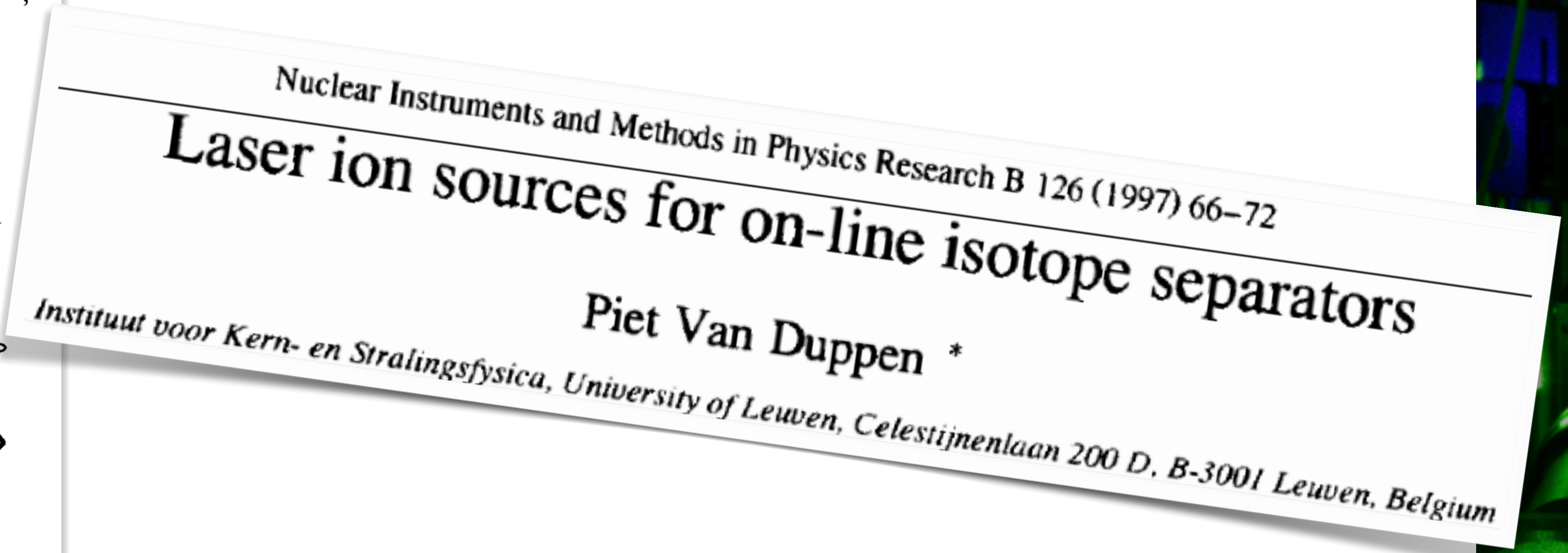




V. Mishin — Institute of Spectroscopy of the Russian Academy of Sciences

Valentin Fedosseev
(Former section leader of SY-STI-LP), now a Contributing Retiree @ CERN

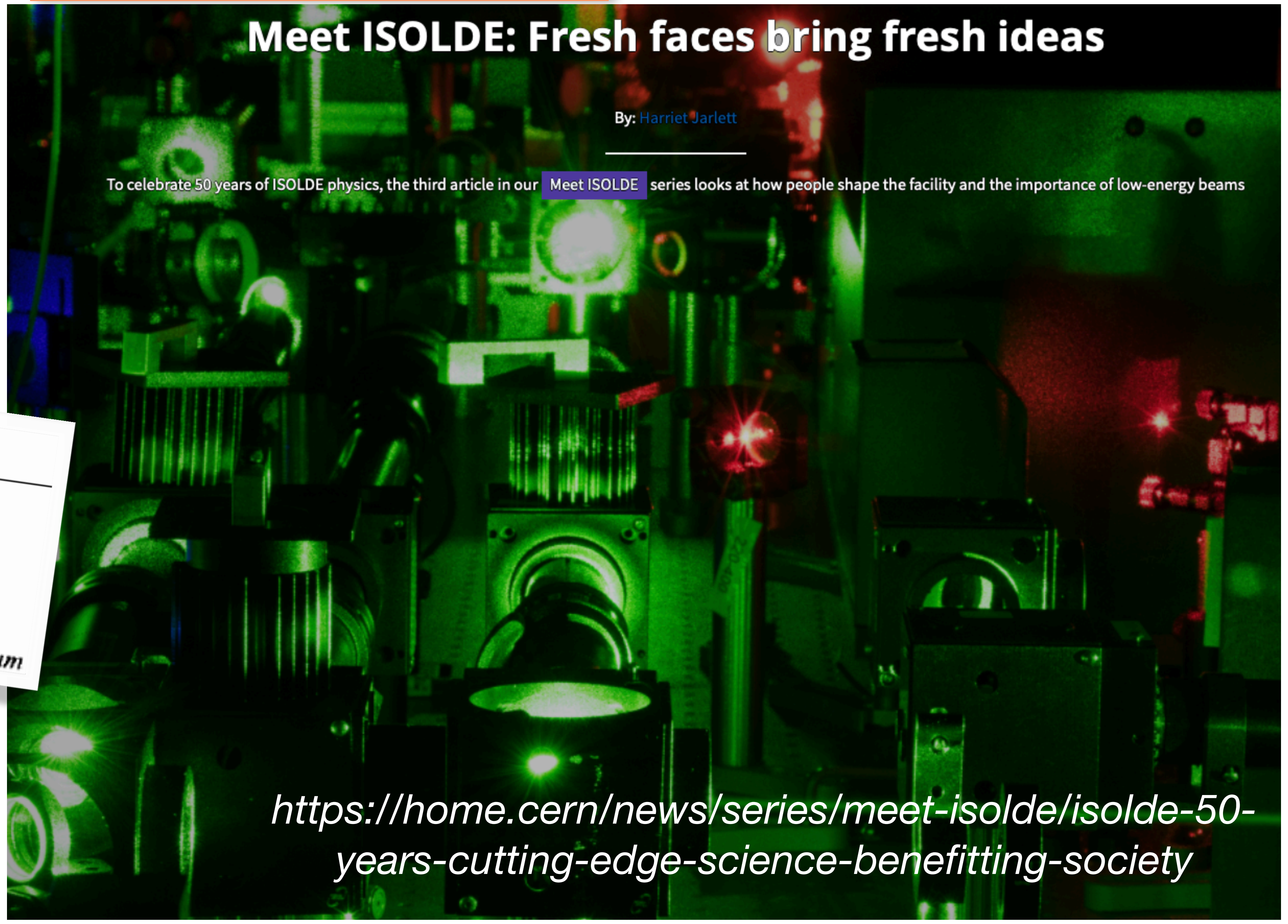
CVL lasers: ν_{rep}=11.000 Hz
Oscillator + 2 amplifiers
2-3 dye lasers with amplifiers,
nonlinear crystals BBO:



Nuclear Instruments and Methods in Physics Research B 126 (1997) 66–72

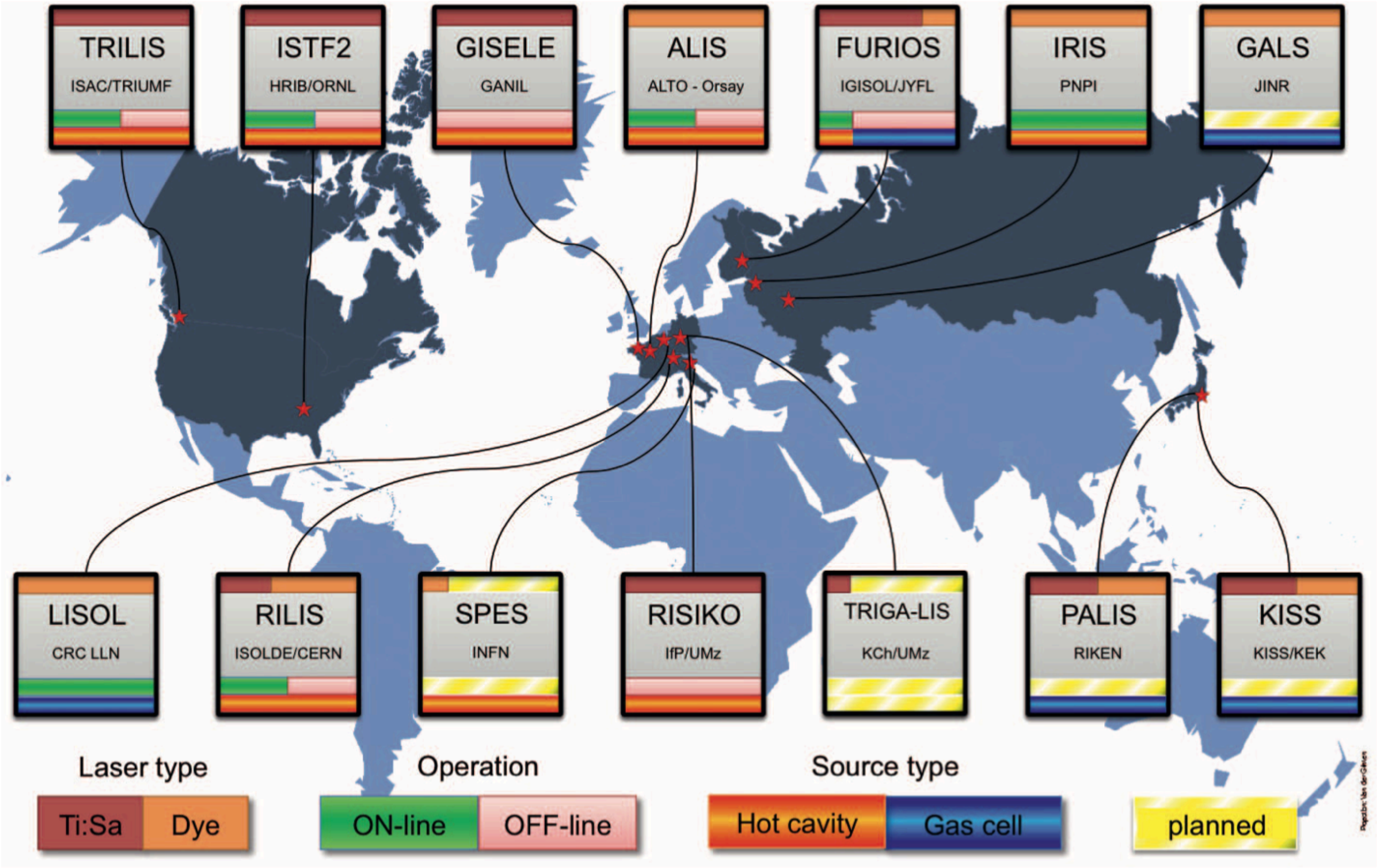
Laser ion sources for on-line isotope separators

Piet Van Duppen *
Instituut voor Kern- en Stralingsfysica, University of Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium



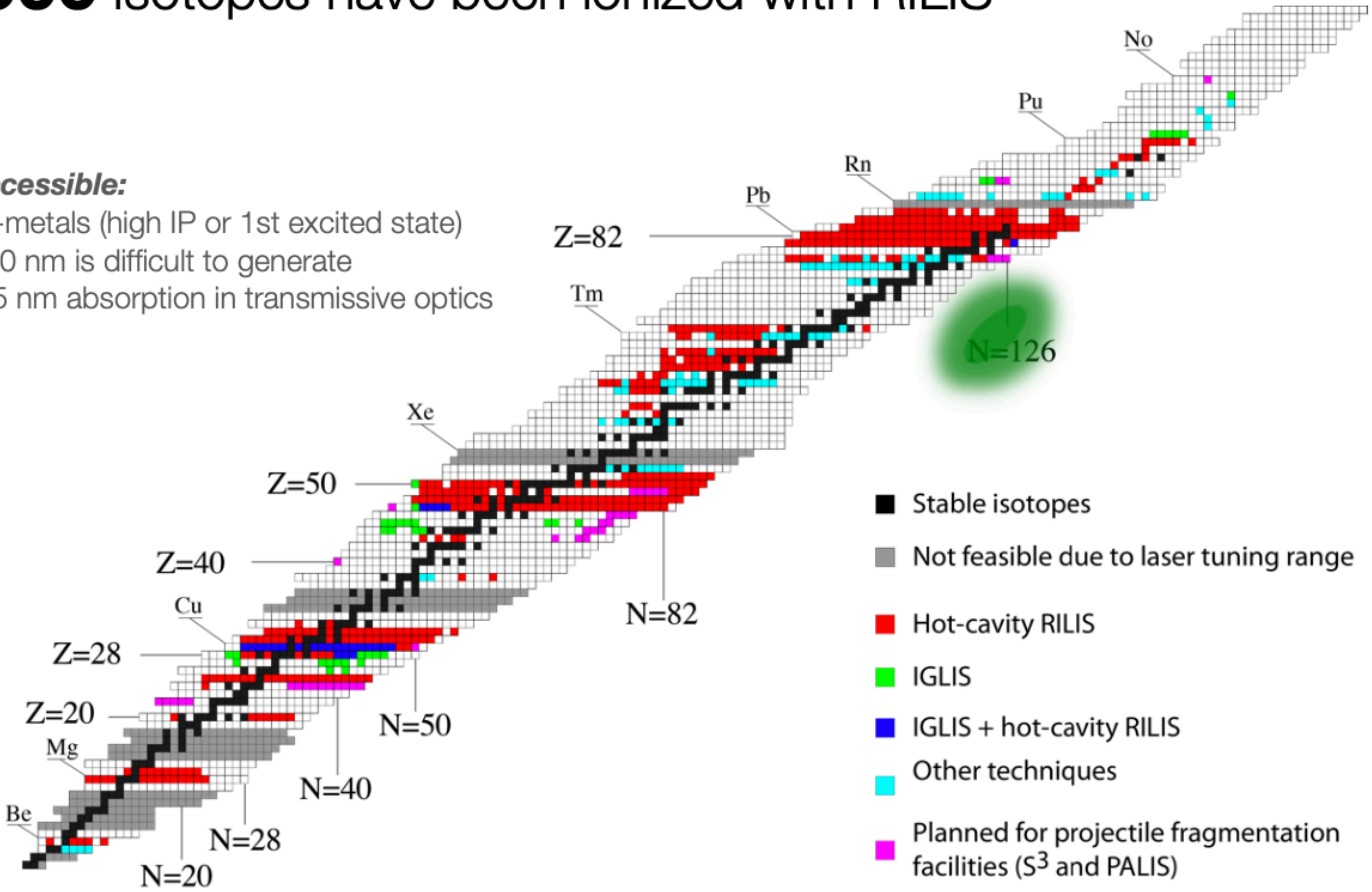
https://home.cern/news/series/meet-isolde/isolde-50-years-cutting-edge-science-benefitting-society

Laser ion sources worldwide



>600 isotopes have been ionized with RILIS

Inaccessible:
Non-metals (high IP or 1st excited state)
< 210 nm is difficult to generate
<205 nm absorption in transmissive optics



B. A. Marsh, Resonance ionization laser ion sources for on-line isotope separators http://dx.doi.org/10.1063/1.4858015

Now for some atomic physics fundamentals..

Some terminology

Energy, eV

$$E = \frac{h \cdot c}{\lambda}$$

h - Planck's constant, **6.6261 x 10-34 J·s or 4.1357 x 10-15 eV·s**

Some terminology

Energy, eV

$$E = \frac{h \cdot c}{\lambda}$$

h - Planck's constant, **6.6261 x 10-34 J·s or 4.1357 x 10-15 eV·s**

Wavelength, nm

A 500 nm photon is ~2.5 eV

Some terminology

Energy, eV

$$E = \frac{h \cdot c}{\lambda}$$

h - Planck's constant, **6.6261 x 10-34 J·s or 4.1357 x 10-15 eV·s**

Wavelength, nm

A 500 nm photon is ~2.5 eV

Wavenumber, cm^{-1}

Number or wavelengths per unit distance (cm)

Proportional to energy (and to frequency)…. Very convenient

1 cm^{-1} x 30 (speed of light in in cm per nanosecond) = 30 GHz

500 nm = 20000 cm^{-1}

Some terminology

Energy, eV

$$E = \frac{h \cdot c}{\lambda}$$

h - Planck's constant, **6.6261 x 10-34 J·s or 4.1357 x 10-15 eV·s**

Wavelength, nm

A 500 nm photon is ~2.5 eV

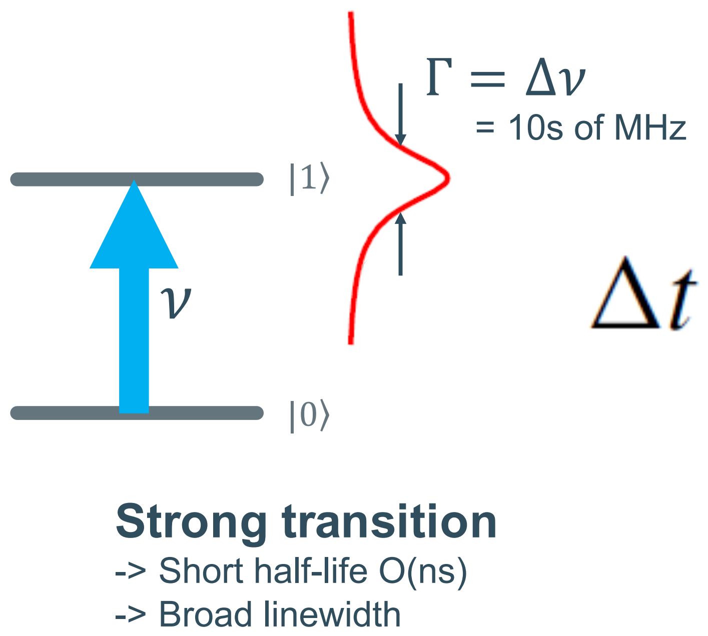
Wavenumber, cm^{-1}

Number or wavelengths per unit distance (cm)
Proportional to energy (and to frequency)…. Very convenient

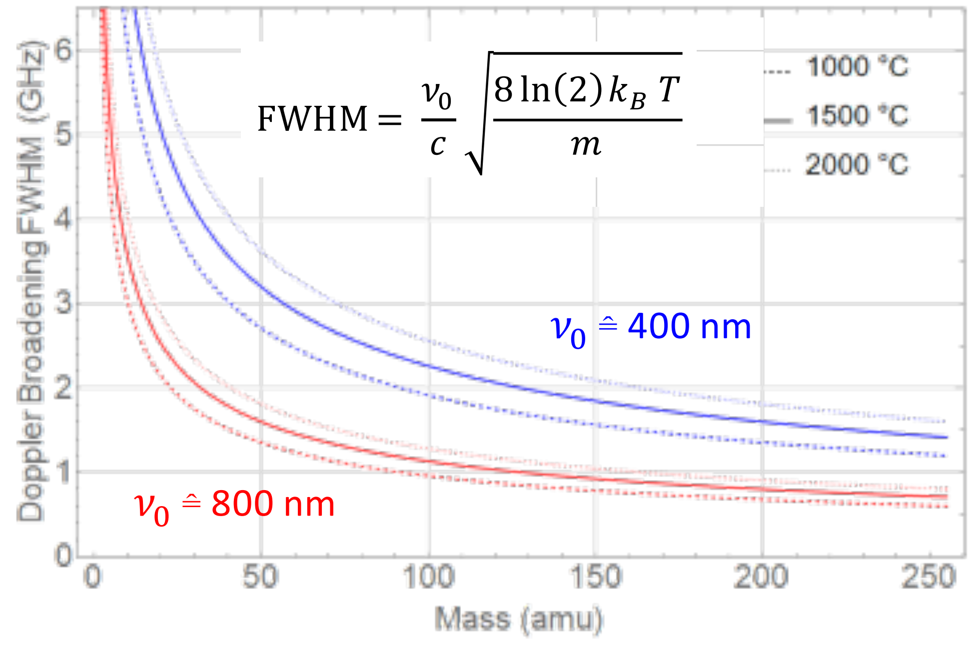
1 cm^{-1} x 30 (speed of light in in cm per nanosecond) = 30 GHz

500 nm = 20000 cm^{-1}

Linewidth, MHz, GHz



$$\Delta t \, \Delta E \geq \frac{\hbar}{2}$$



Some terminology

Energy, eV

$$E = \frac{h \cdot c}{\lambda}$$

h - Planck's constant, **6.6261 x 10-34 J·s or 4.1357 x 10-15 eV·s**

Wavelength, nm

A 500 nm photon is ~2.5 eV

Wavenumber, cm^{-1}

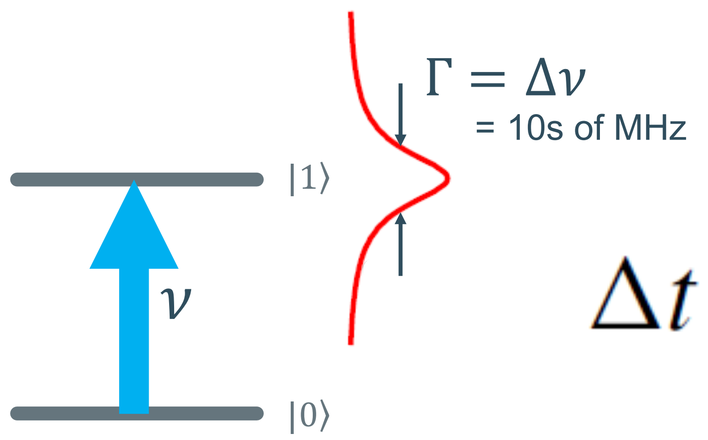
Number or wavelengths per unit distance (cm)

Proportional to energy (and to frequency)…. Very convenient

$1\ cm^{-1}$ x 30 (speed of light in in cm per nanosecond) = 30 GHz

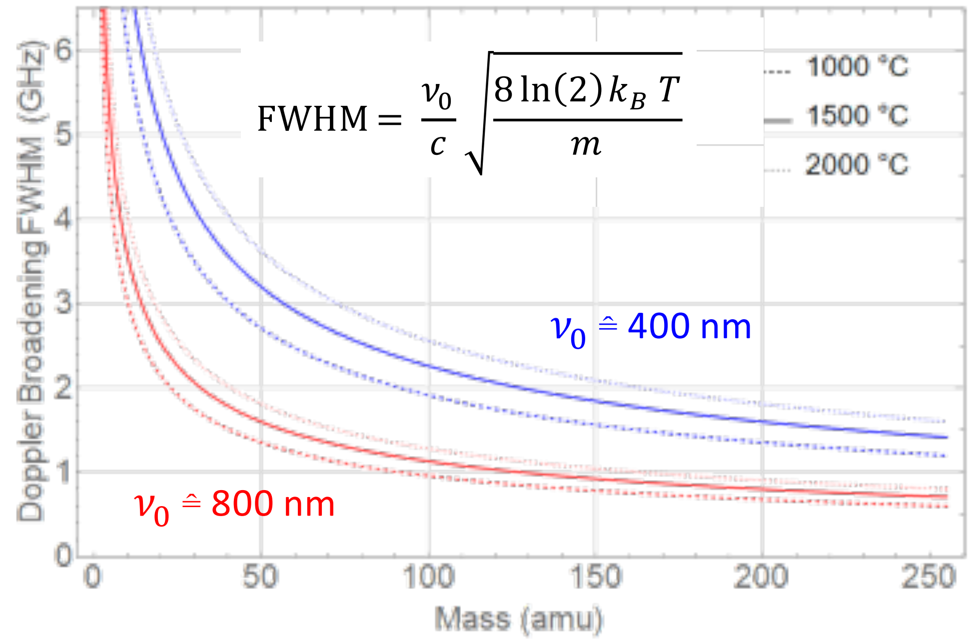
500 nm = 20000 cm^{-1}

Linewidth, MHz, GHz



Strong transition
-> Short half-life O(ns)
-> Broad linewidth

$$\Delta t\ \Delta E \geq \frac{\hbar}{2}$$



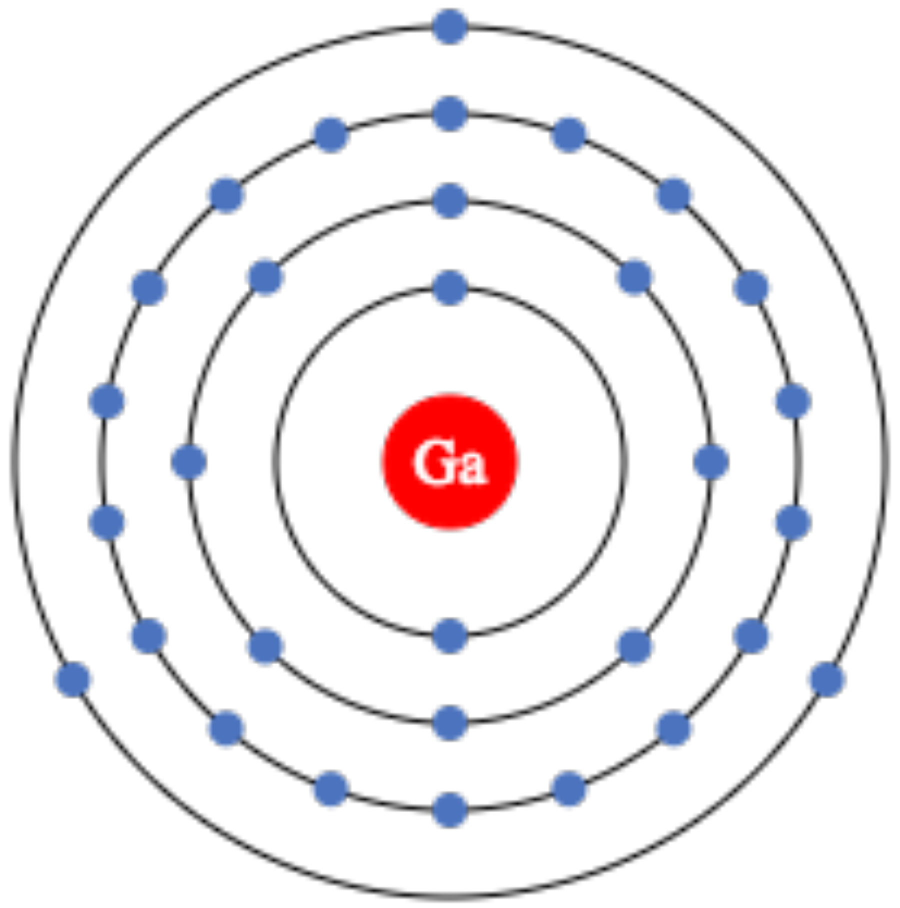
Timescales, ns

Light travels ~1m in 3 ns

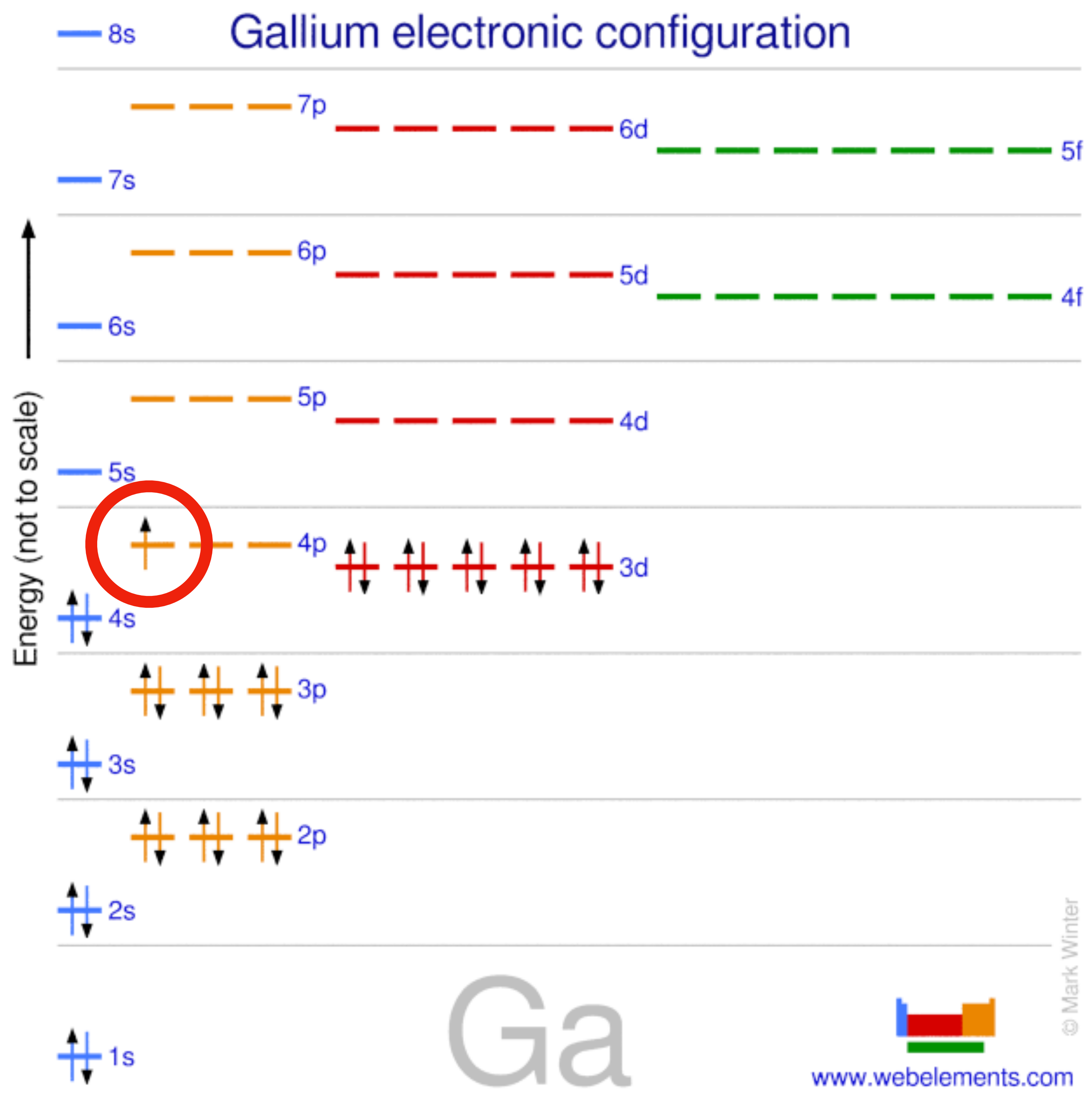
Lifetime of a strong atomic transition = 10 ns

Some atomic structure terminology: spectroscopic notation

31: Gallium

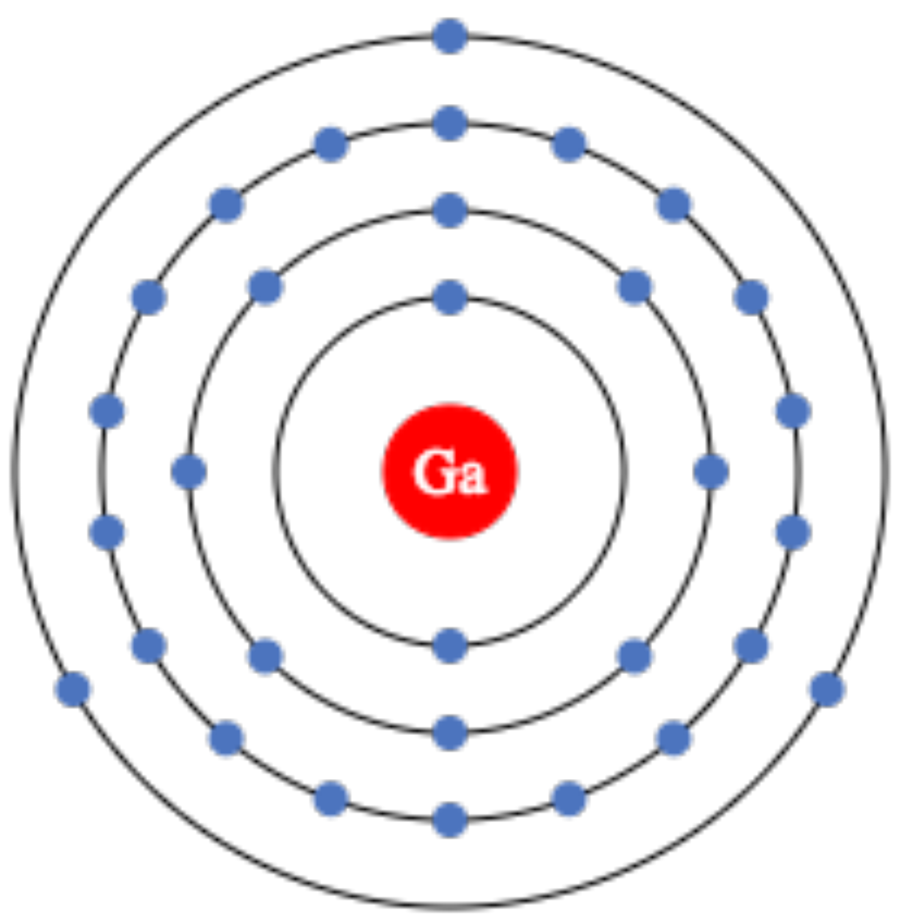


[Ar] 3d10 4s2 4p1 [2, 8, 18, 3]

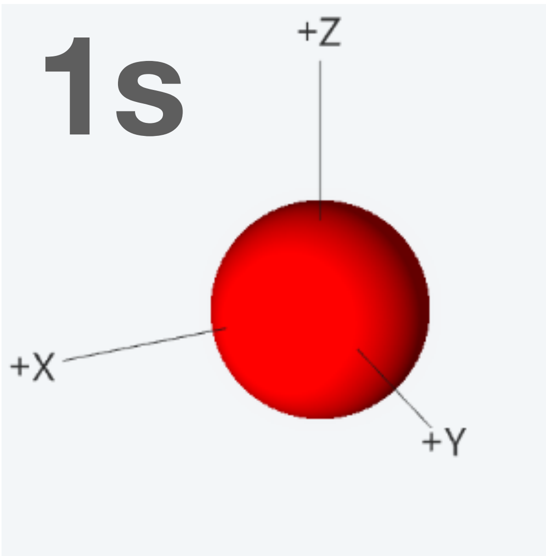


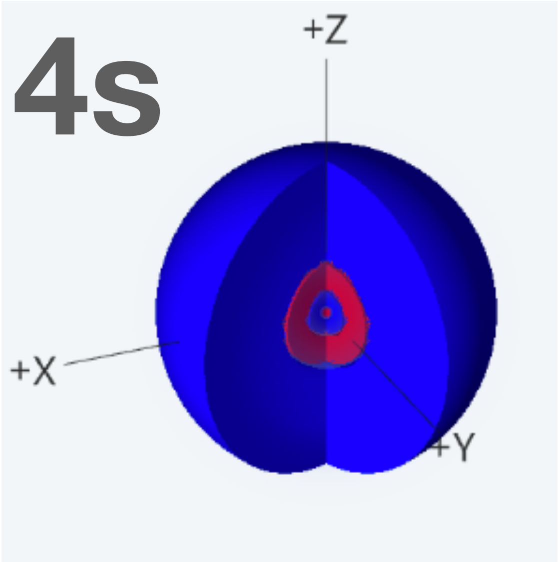
Some atomic structure terminology: spectroscopic notation

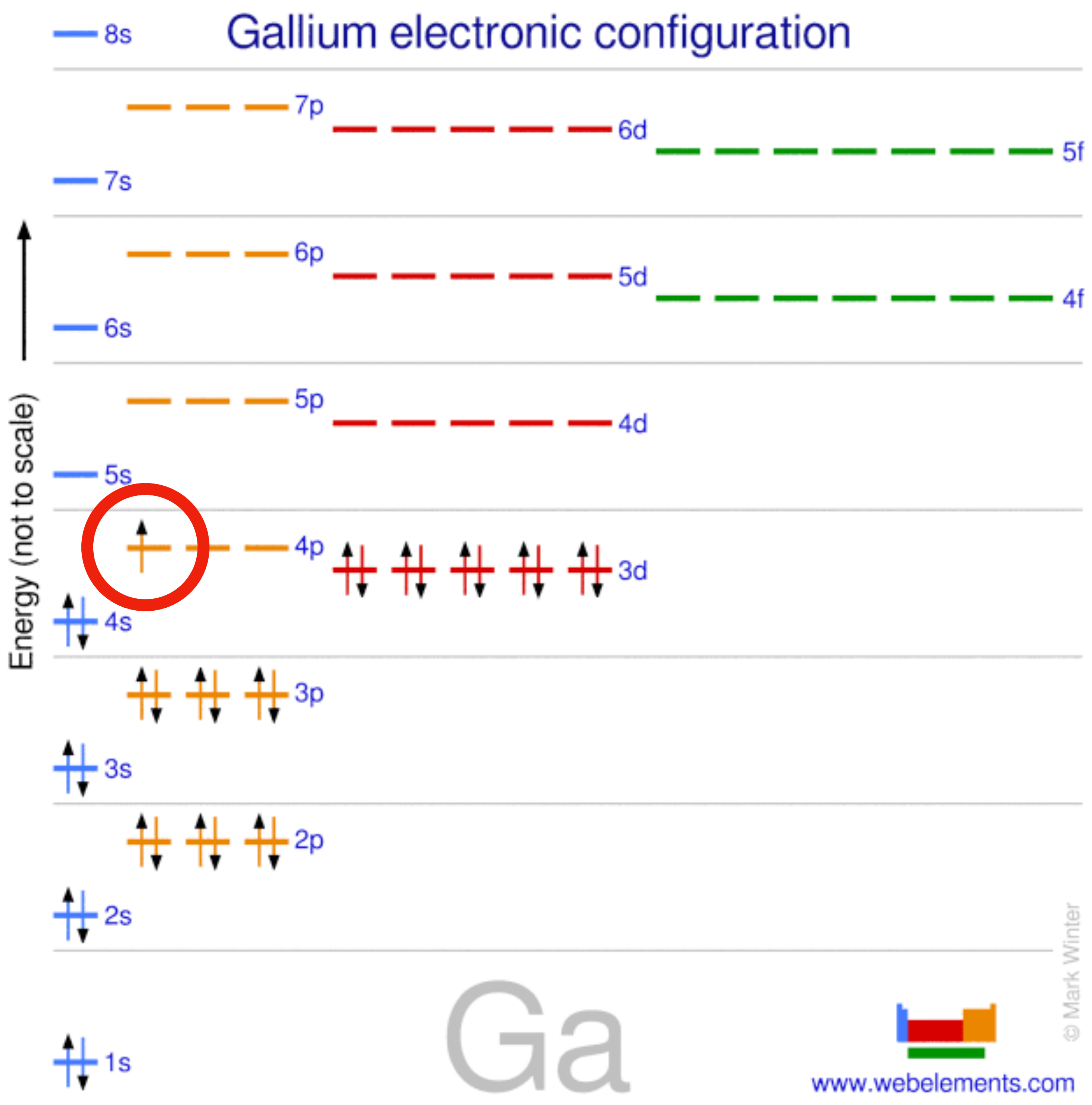
31: Gallium



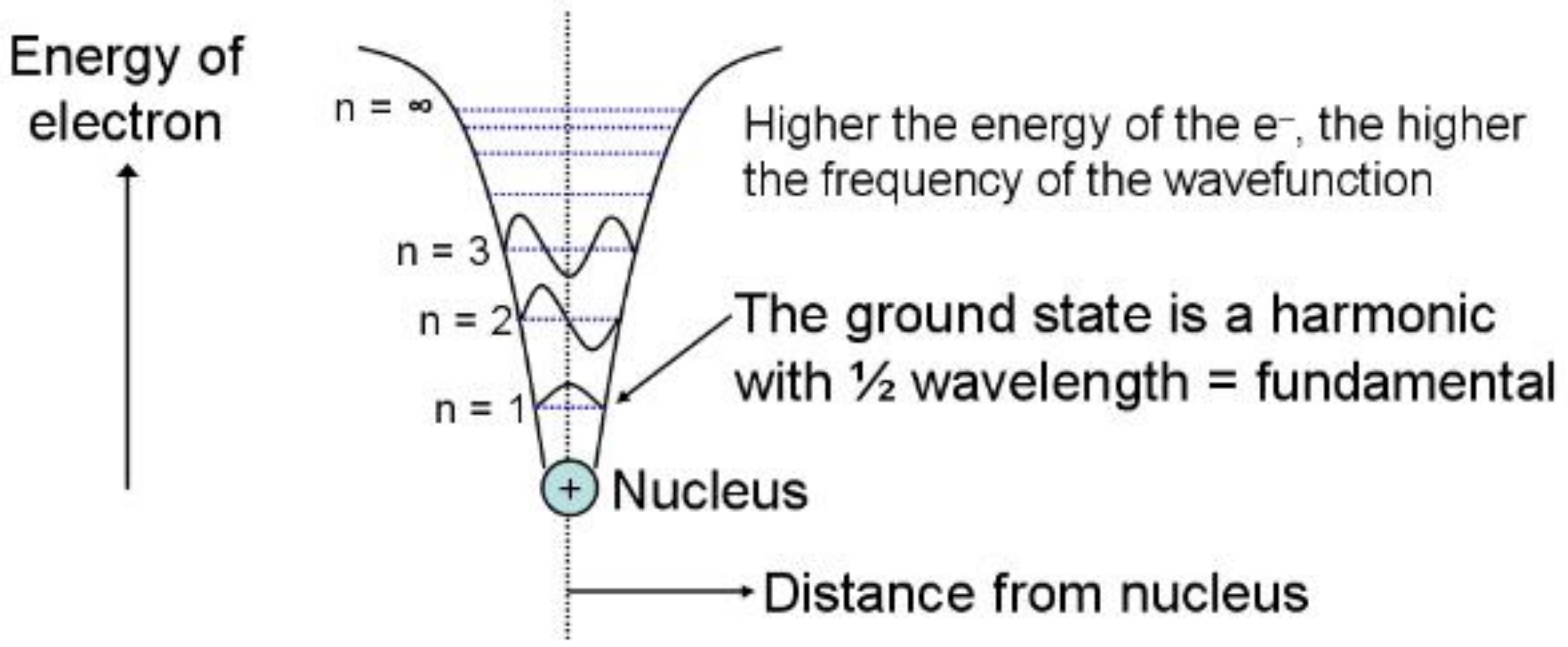
[Ar] 3d10 4s2 4p1 [2, 8, 18, 3]





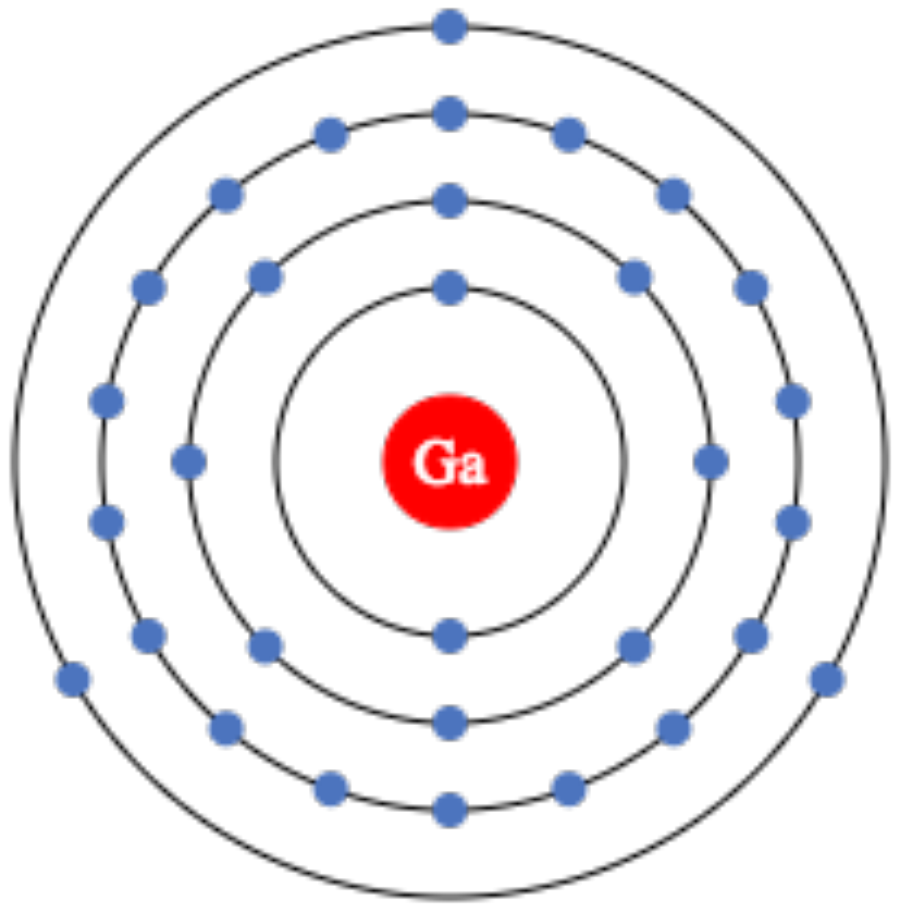


Principal quantum number, n



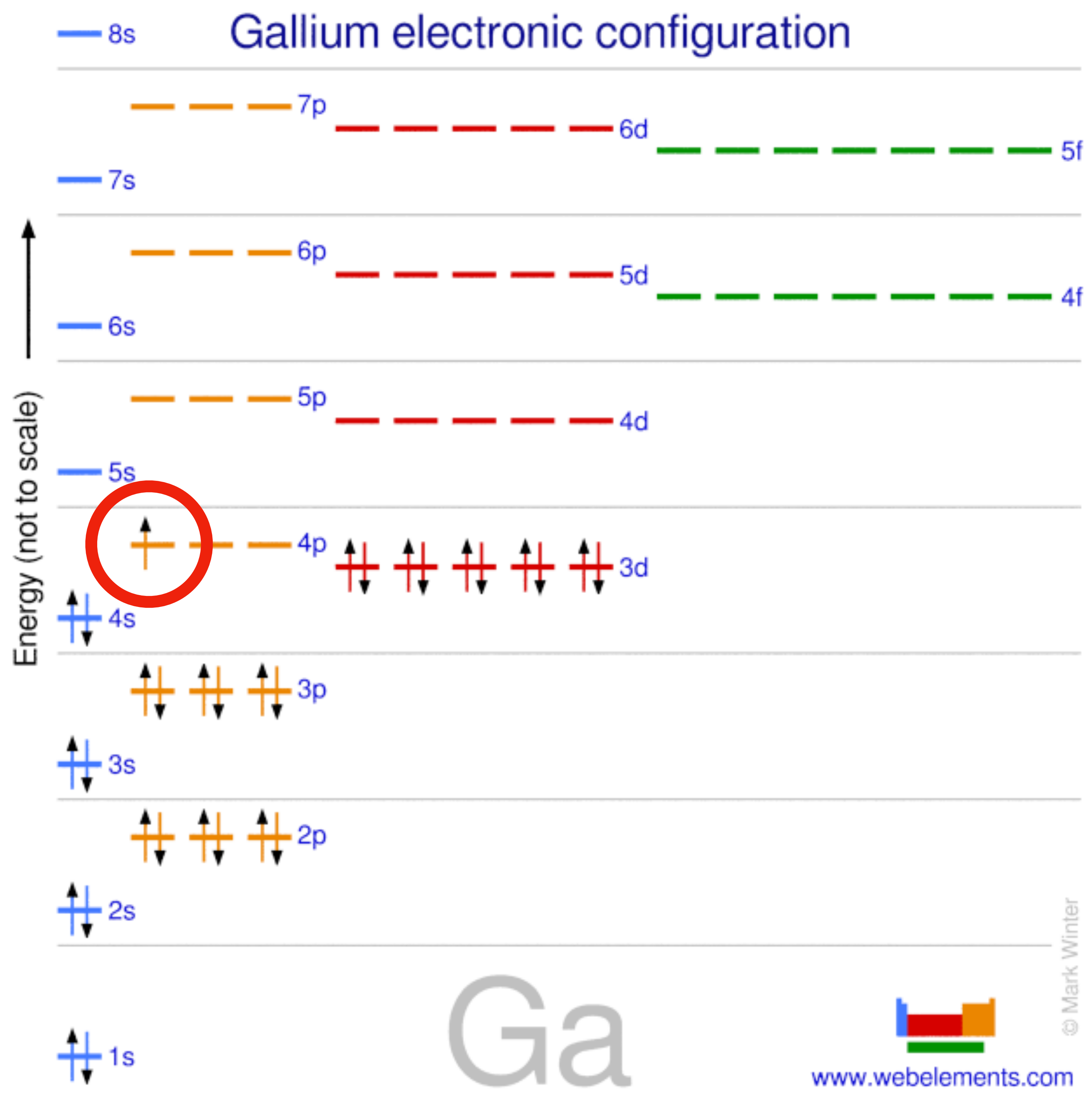
Some atomic structure terminology: spectroscopic notation

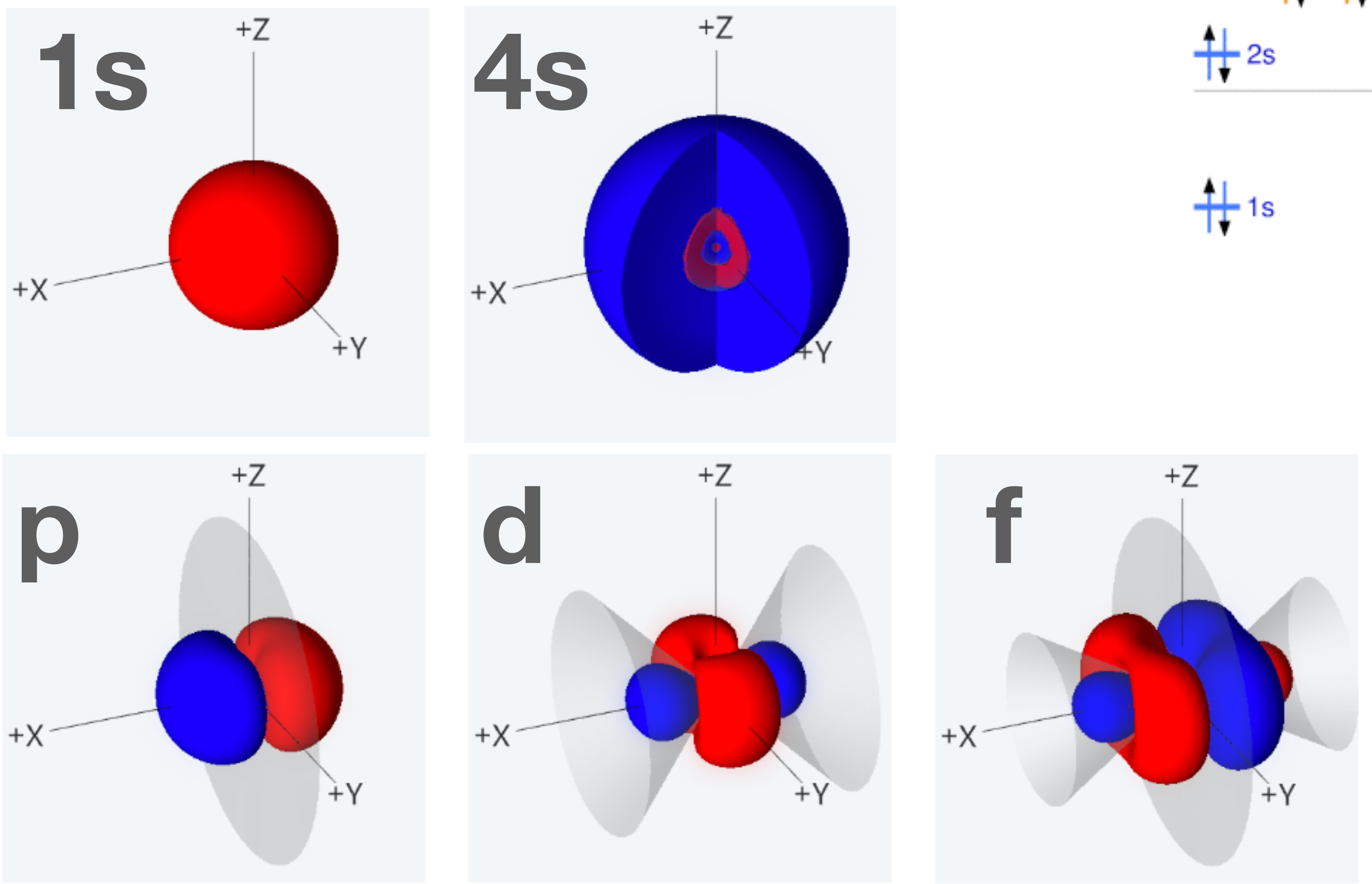
31: Gallium



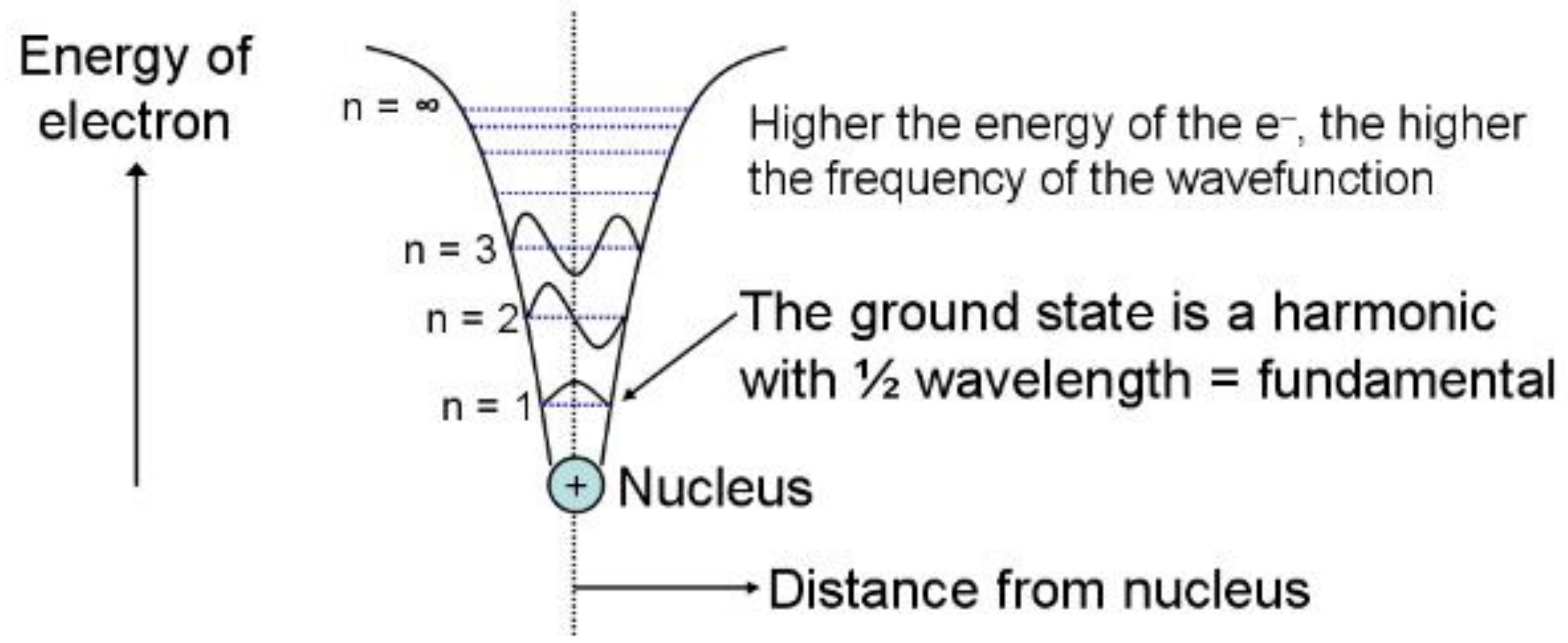
[Ar] 3d10 4s2 4p1

[2, 8, 18, 3]





Principal quantum number, n



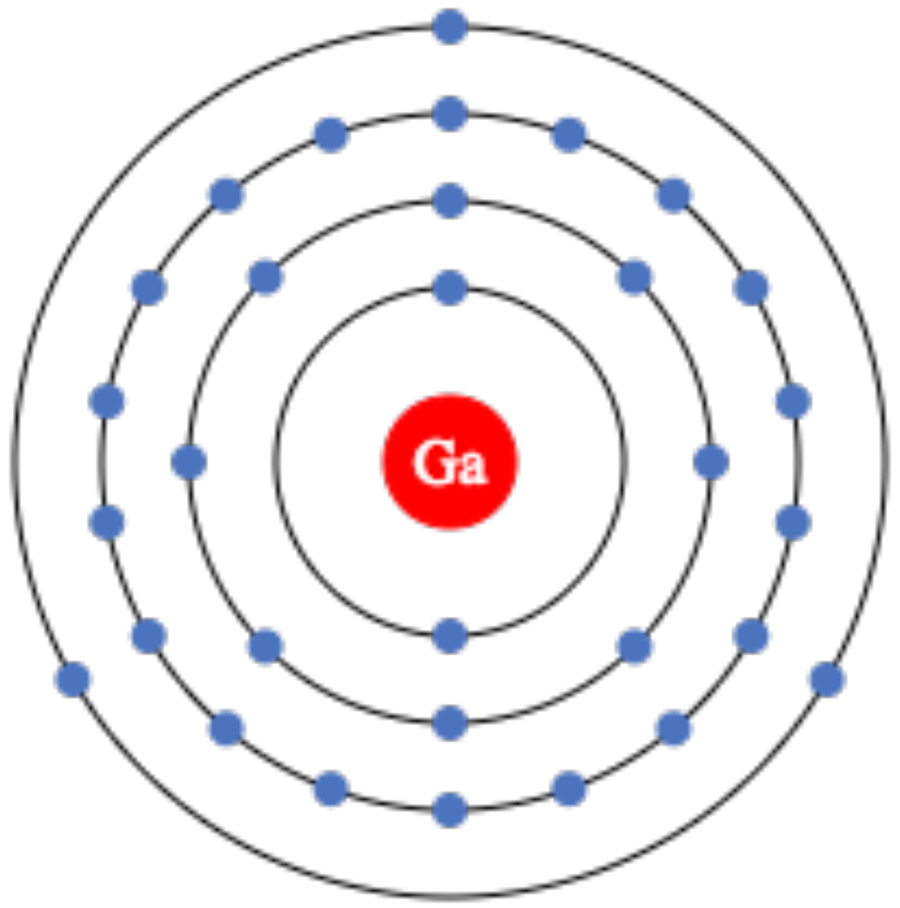
Orbital angular momentum, **L**

(s,p,d,f) = (0,1,2,3)

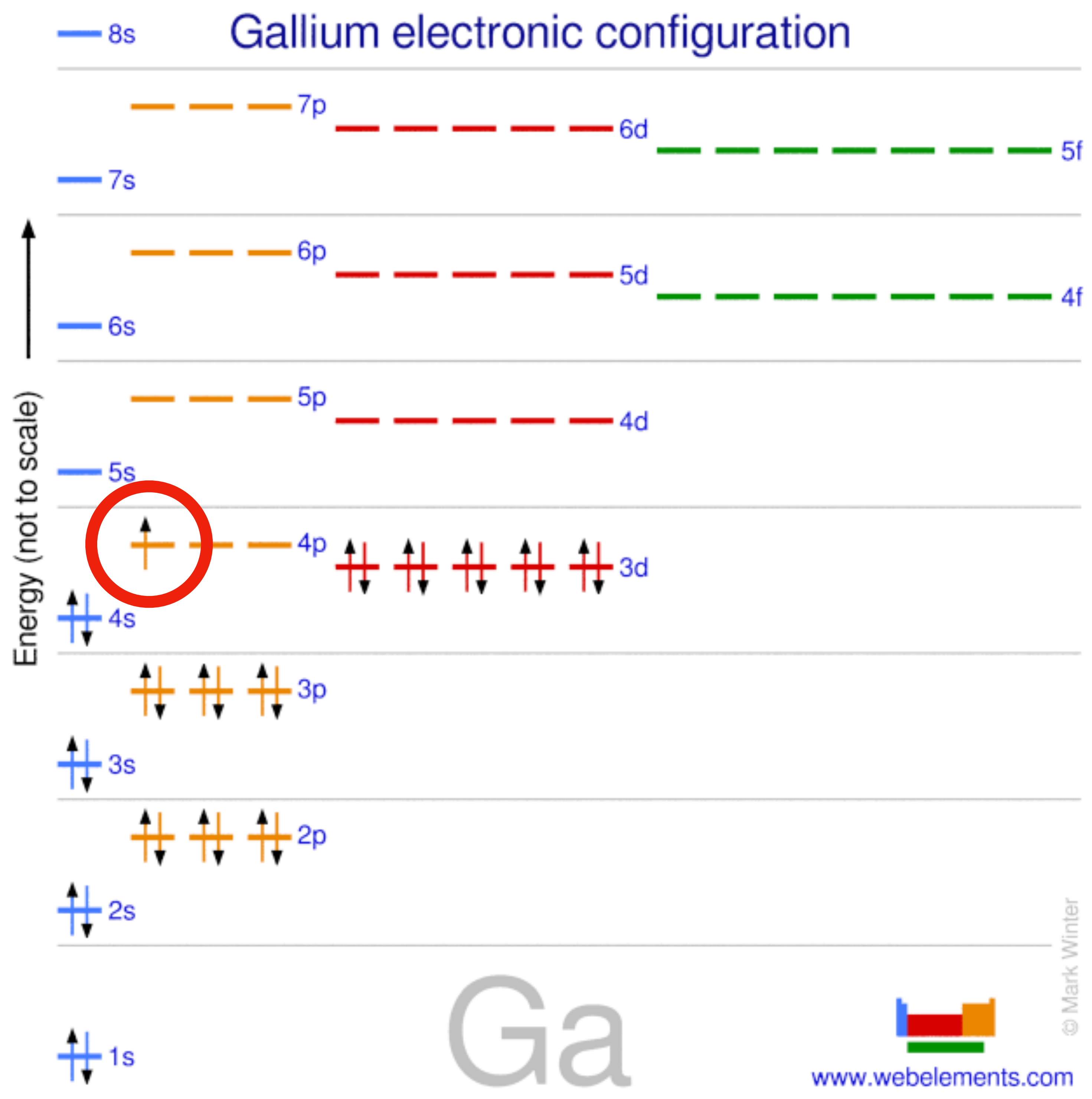
Related to the electron's motion in space, around the atom

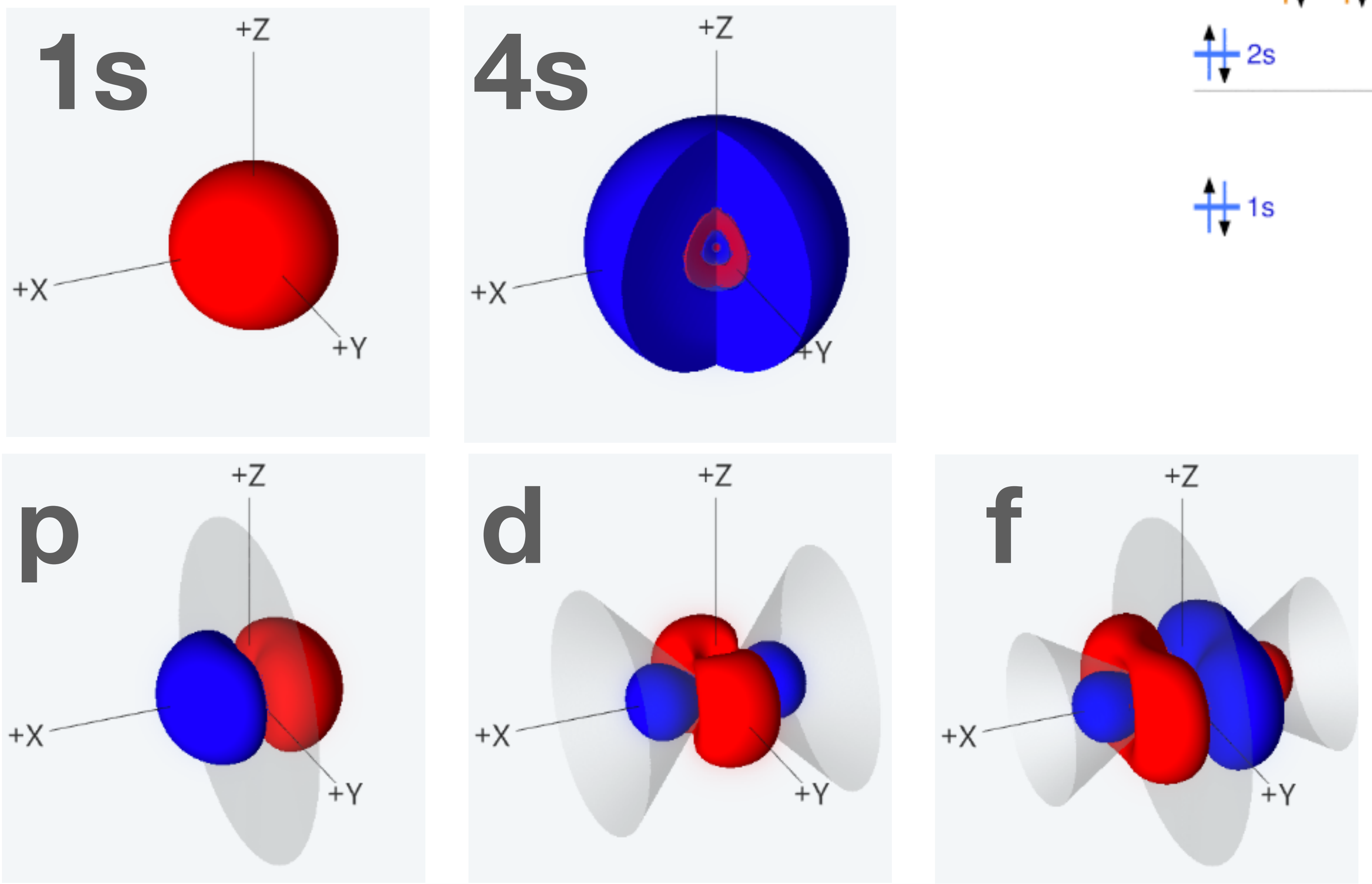
Some atomic structure terminology: spectroscopic notation

31: Gallium

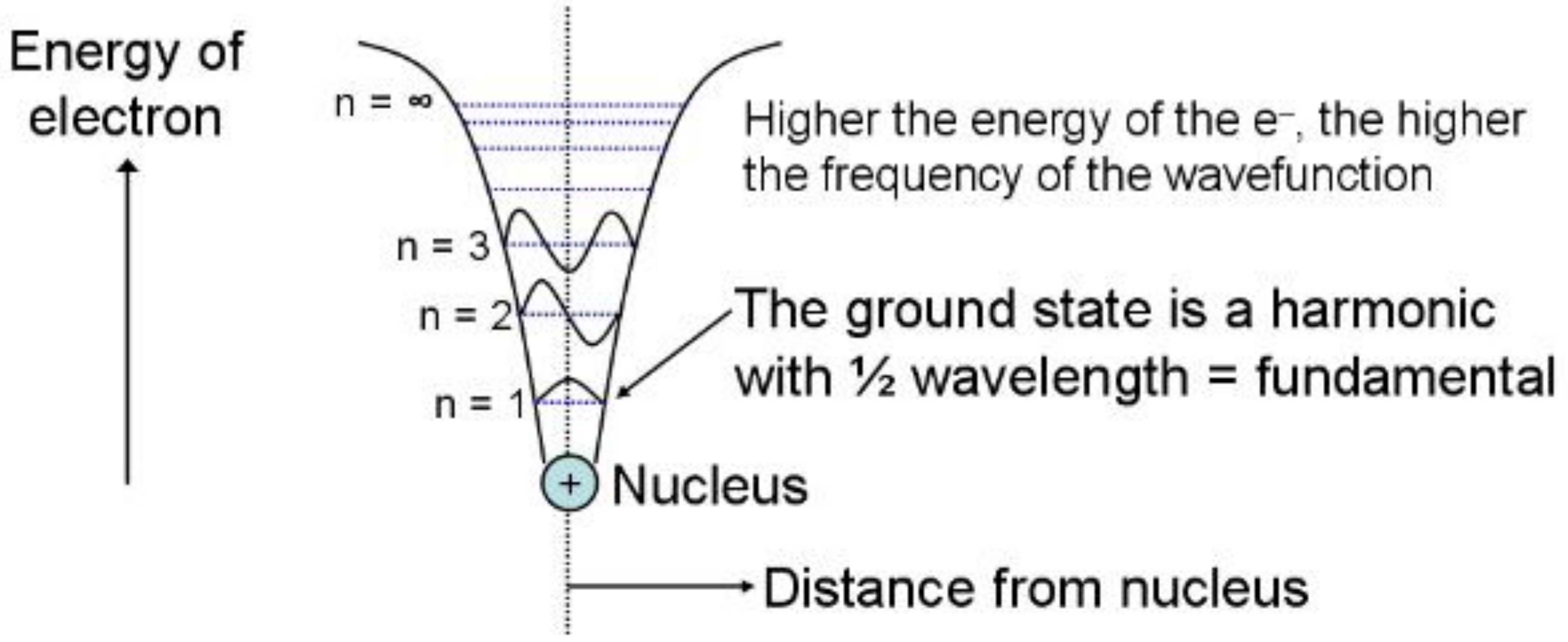


[Ar] 3d10 4s2 4p1 [2, 8, 18, 3]





Principal quantum number, n



Orbital angular momentum, **L**

(s,p,d,f) = (0,1,2,3)

Related to the electron's motion in space, around the atom

Spin angular momentum **S**

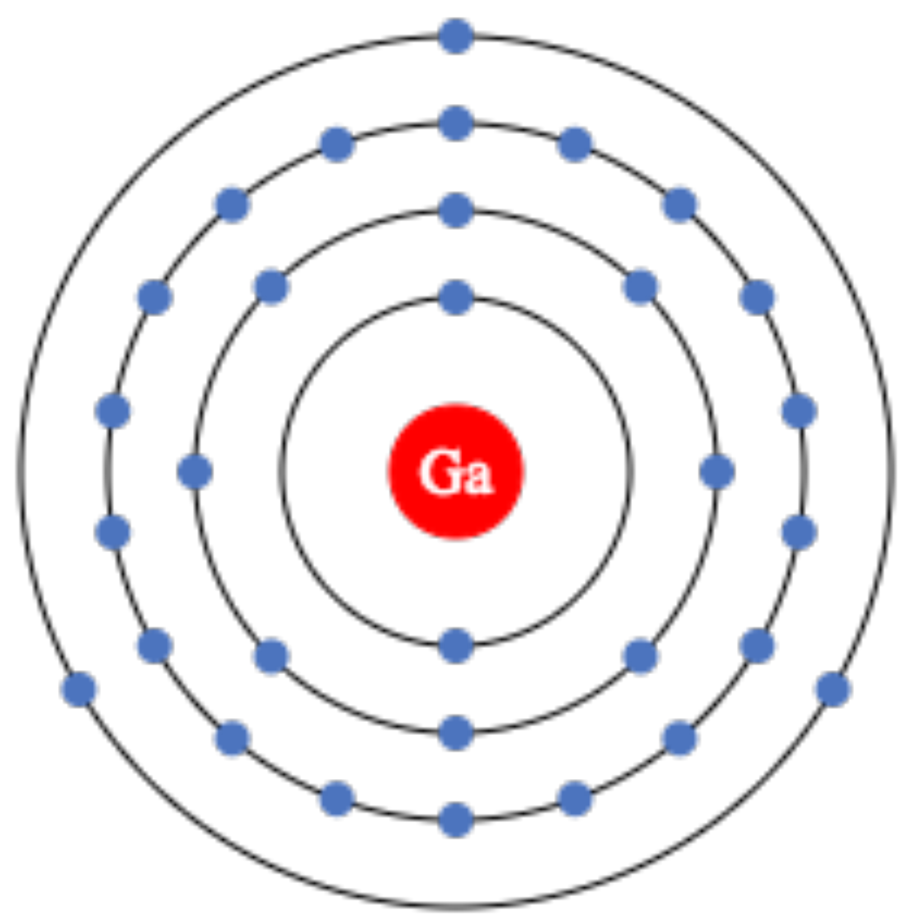
Intrinsic motion (rotation) of the electron around its own axis

'Up' or 'down'

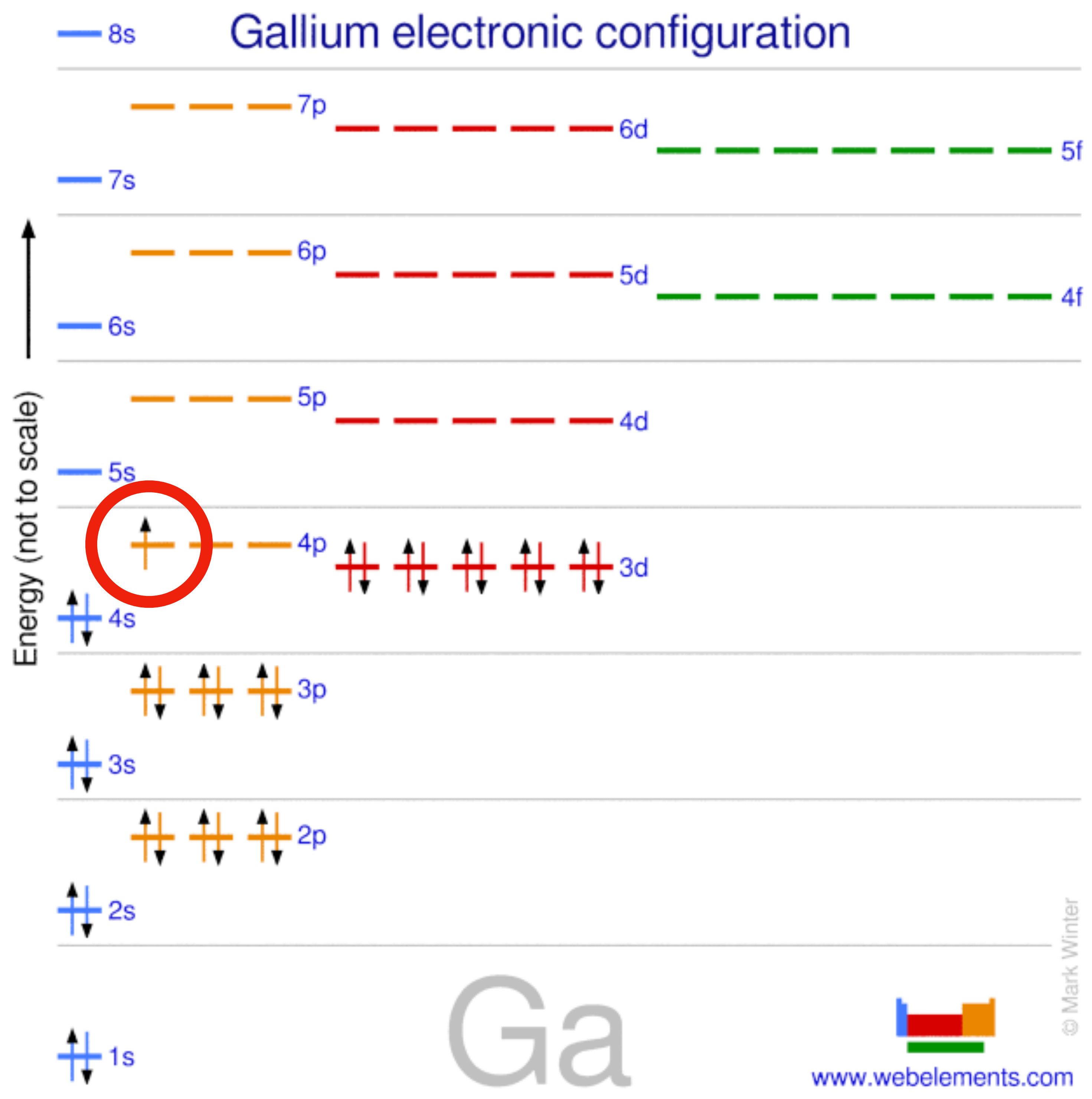
+1/2 *or* **-1/2**

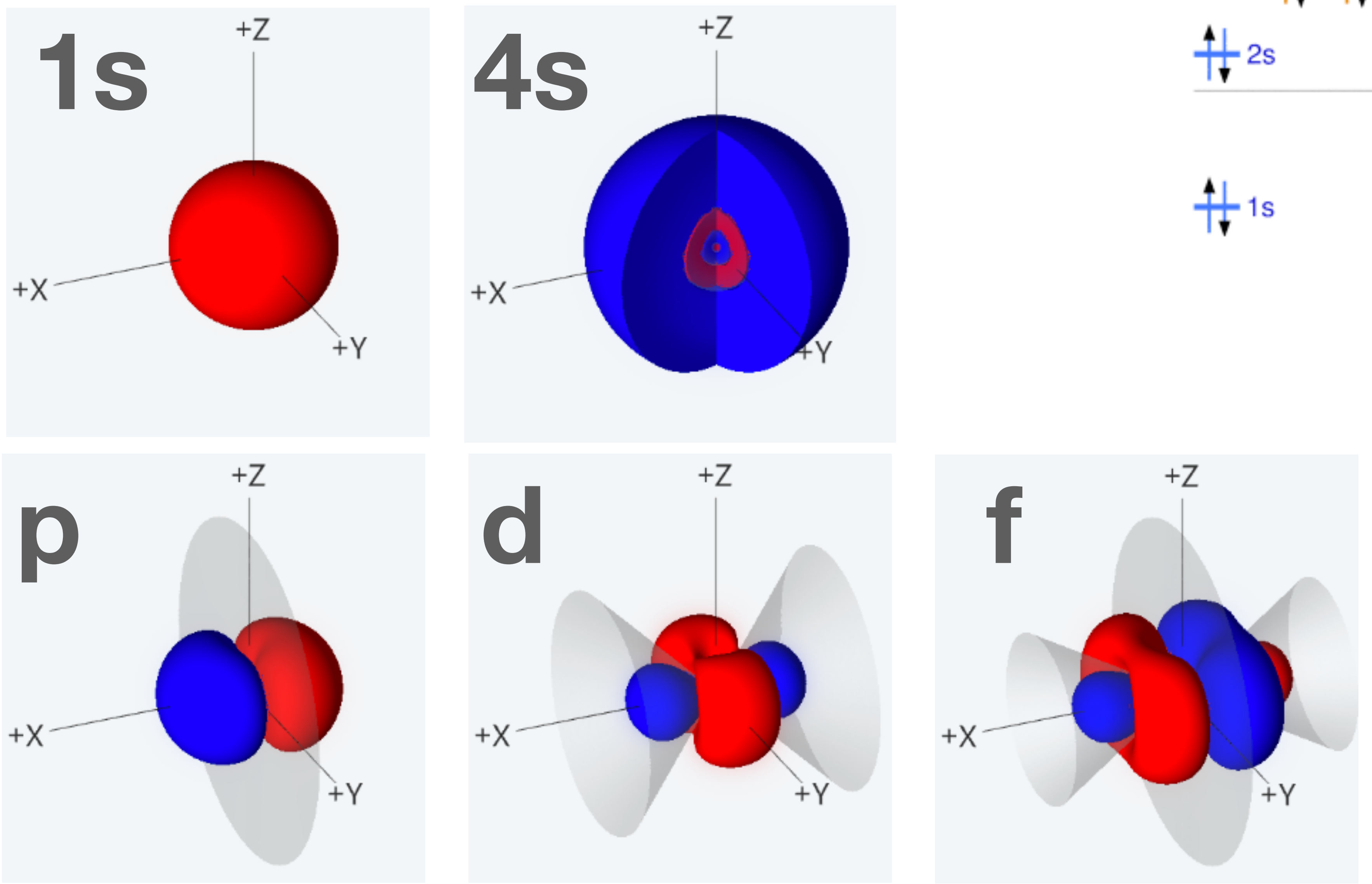
Some atomic structure terminology: spectroscopic notation

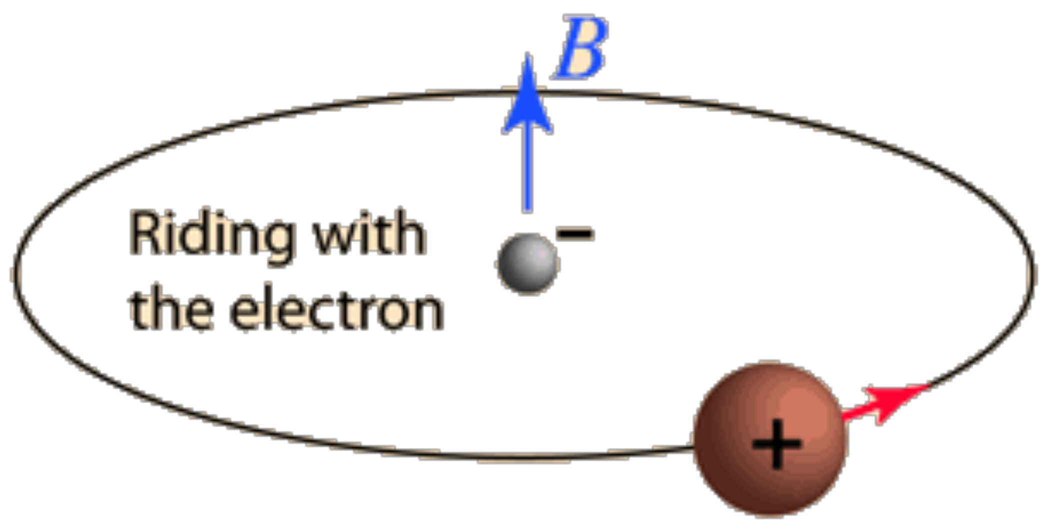
31: Gallium



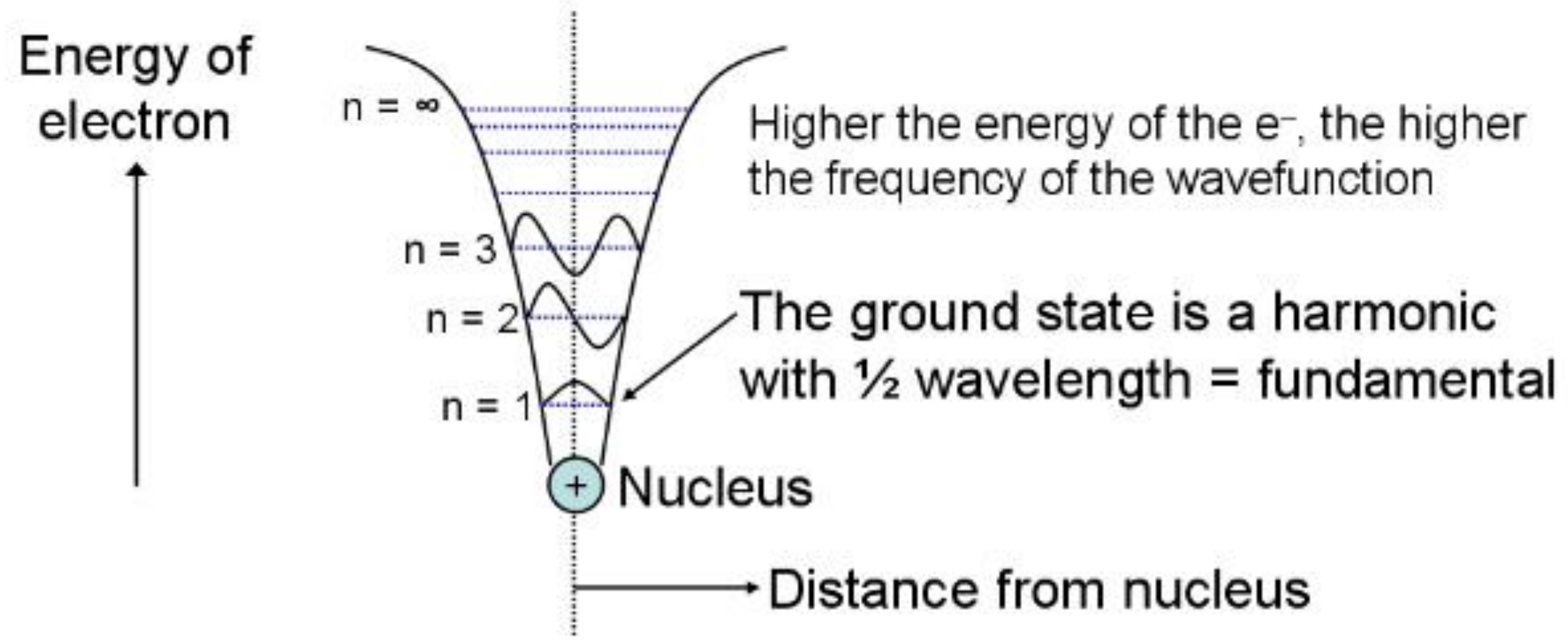
[Ar] 3d10 4s2 4p1 [2, 8, 18, 3]







Principal quantum number, n



Orbital angular momentum, **L**

(s,p,d,f) = (0,1,2,3)

Related to the electron's motion in space, around the atom

Spin angular momentum **S**

Intrinsic motion (rotation) of the electron around its own axis

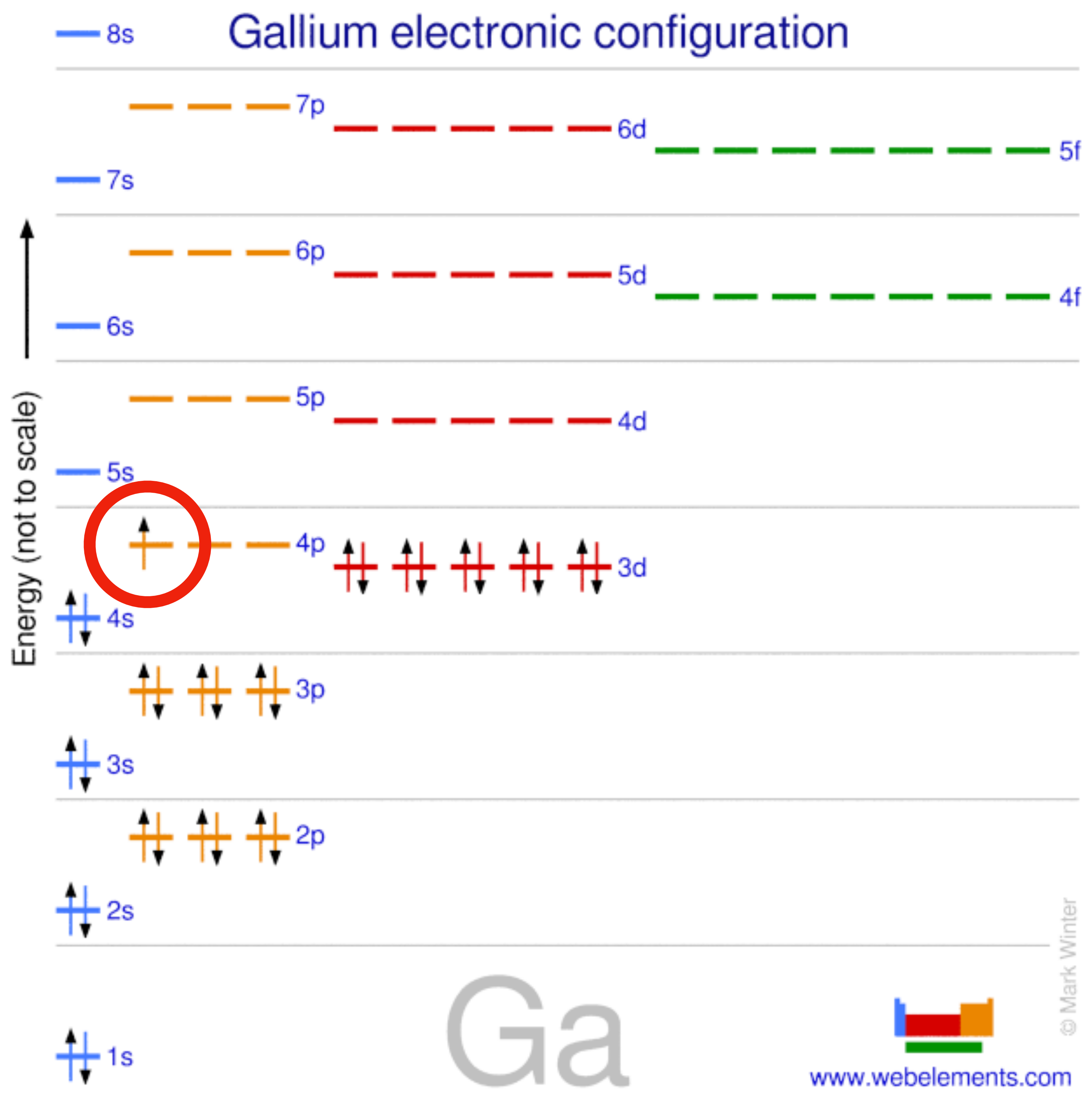
'Up' or 'down'

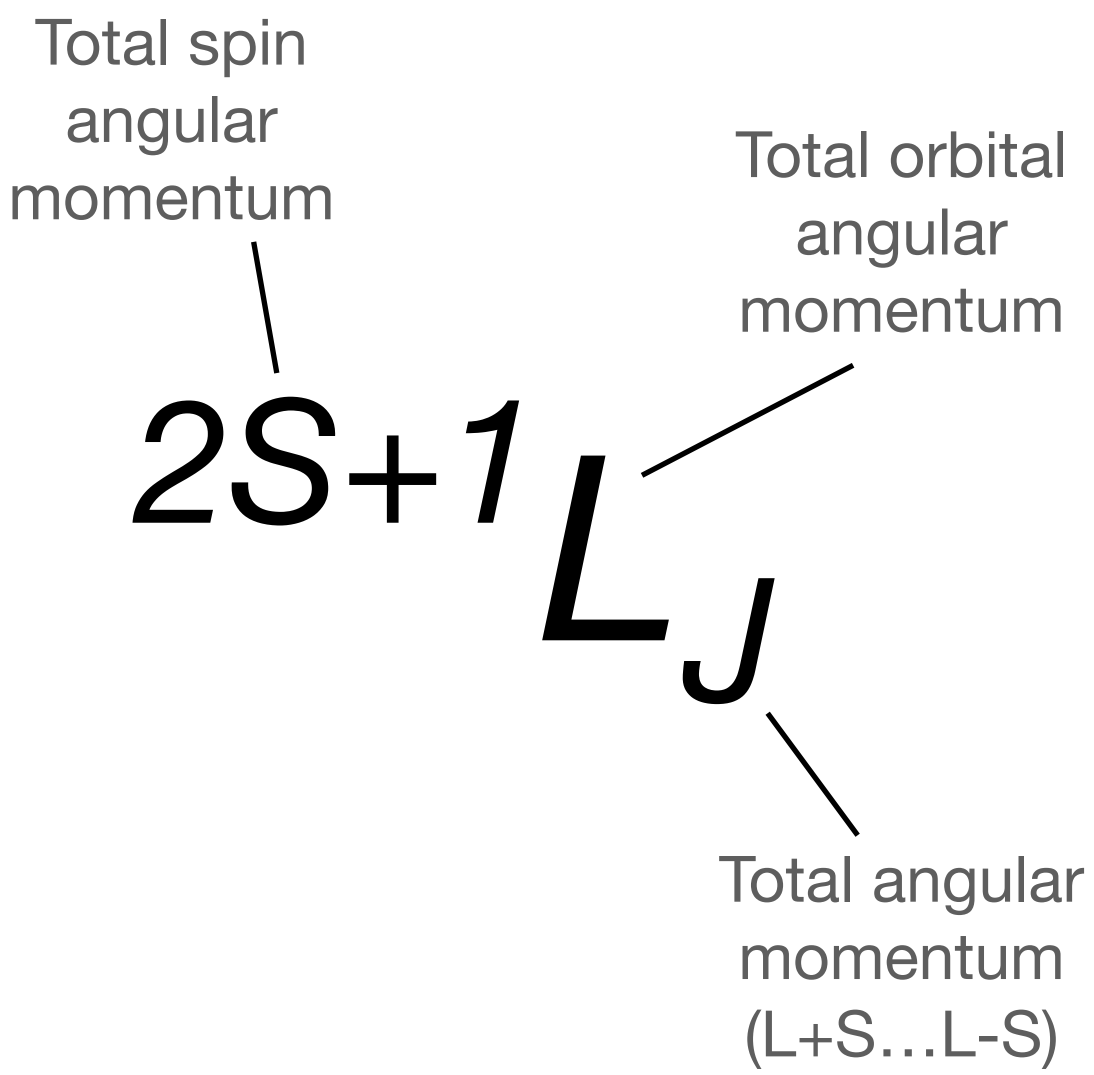
+1/2 *or* **-1/2**

Total angular momentum, **J**

$J = L + S$ to $|L - S|$

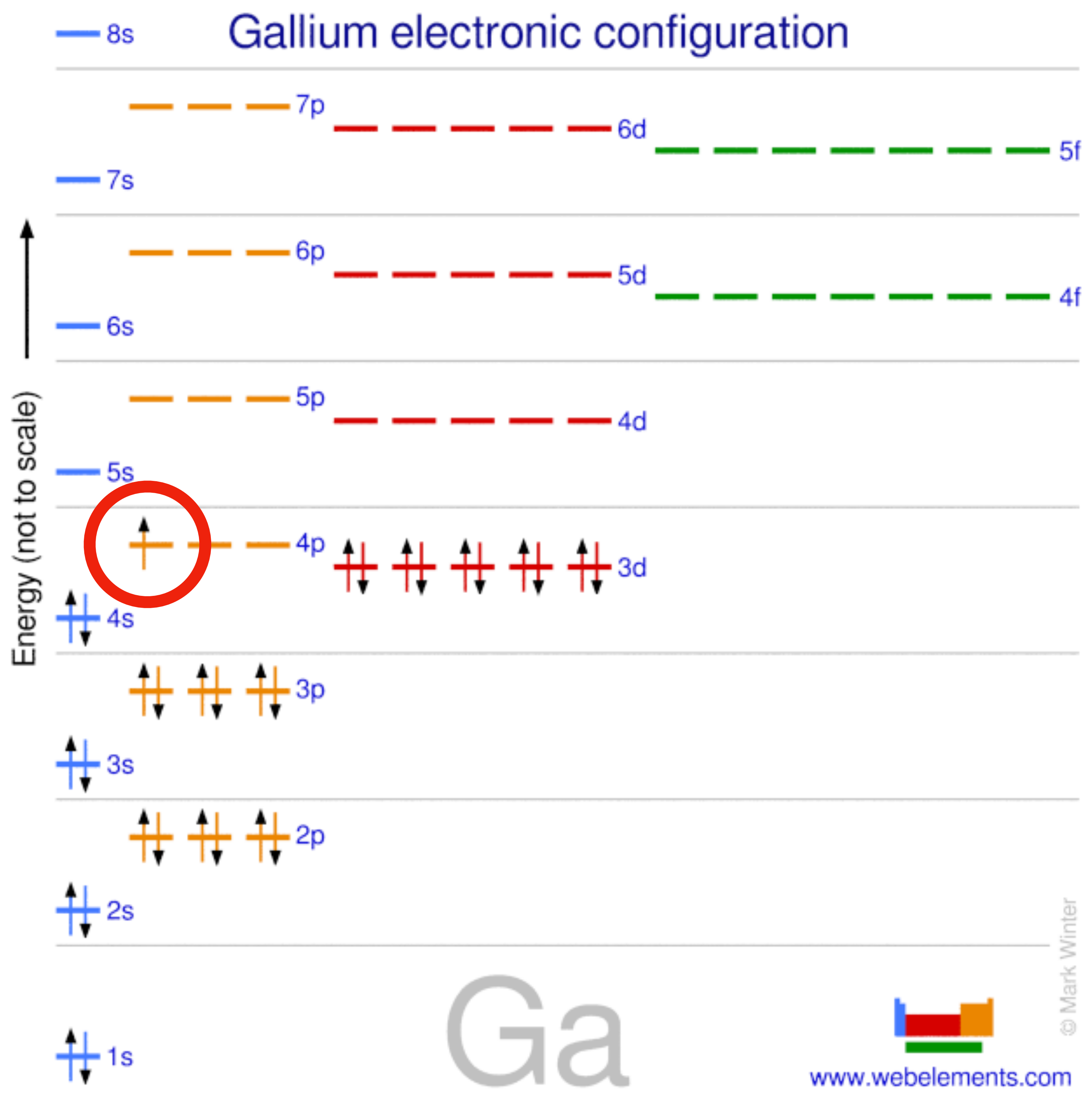
The Term Symbol, to describe the (excited) state of the atom





$$^{2S+1}L_J$$

The Term Symbol, to describe the (excited) state of the atom



Total spin angular momentum

Total orbital angular momentum

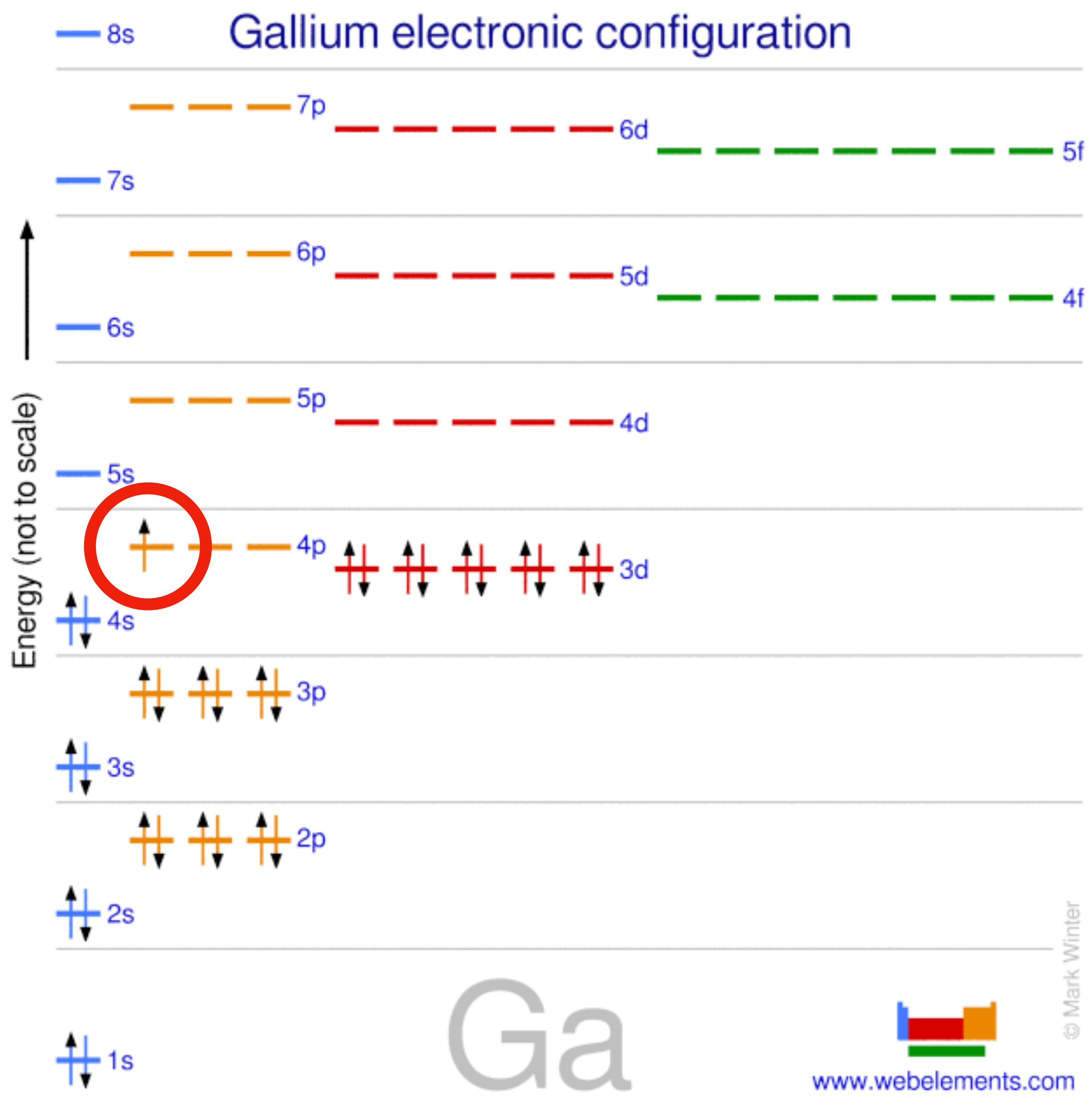
$$^{2S+1}L_J$$

Total angular momentum (L+S…L-S)

Ground state = 0 eV

$$^{2*(1/2)+1}P_{(1/2)+1} \quad ^{2}P_{3/2}$$

The Term Symbol, to describe the (excited) state of the atom



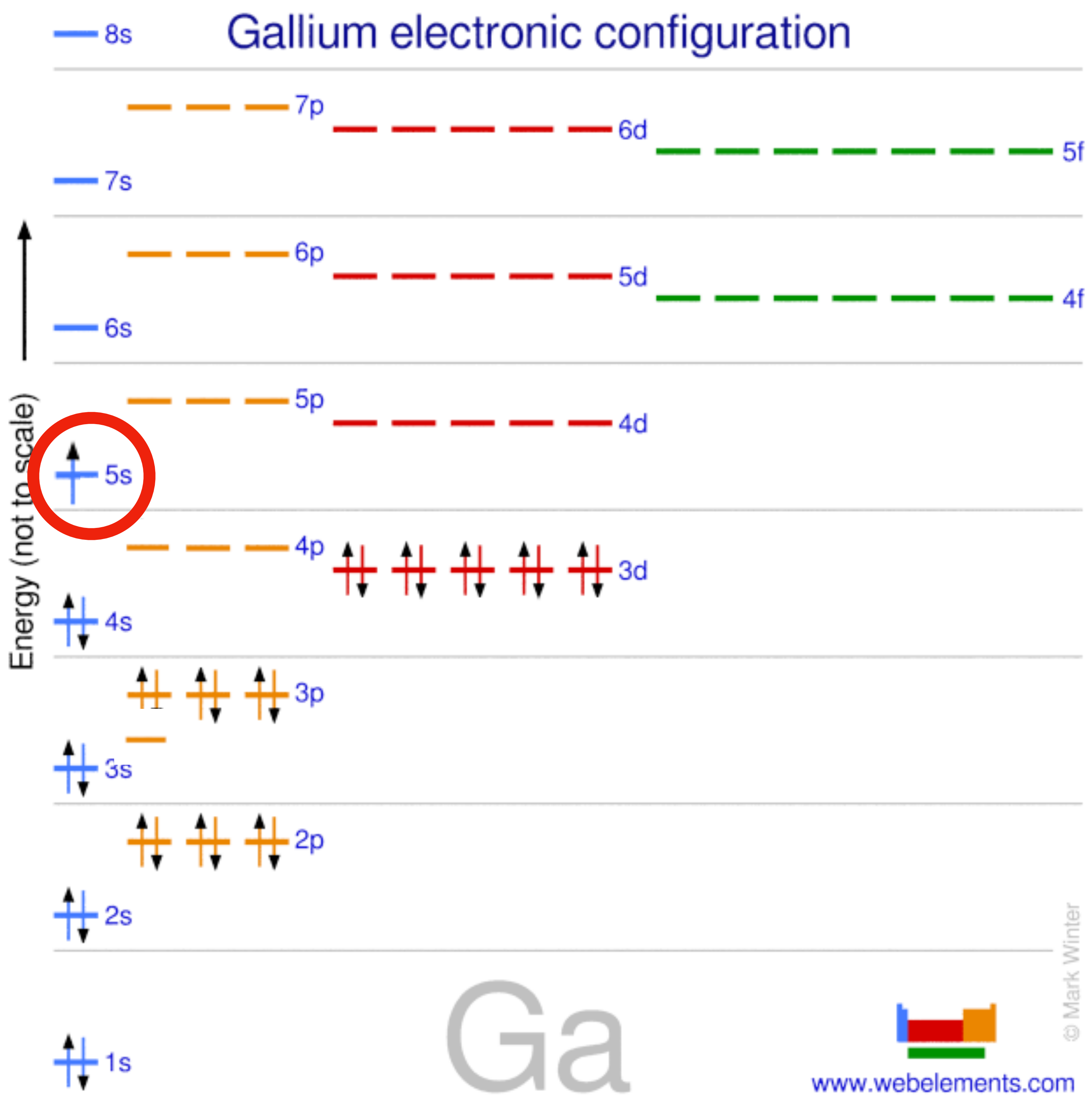
Ground state = 0 eV

Total spin angular momentum

Total orbital angular momentum

$$^{2S+1}L_J$$

Total angular momentum (L+S…L-S)



First excited state = 3.07 eV

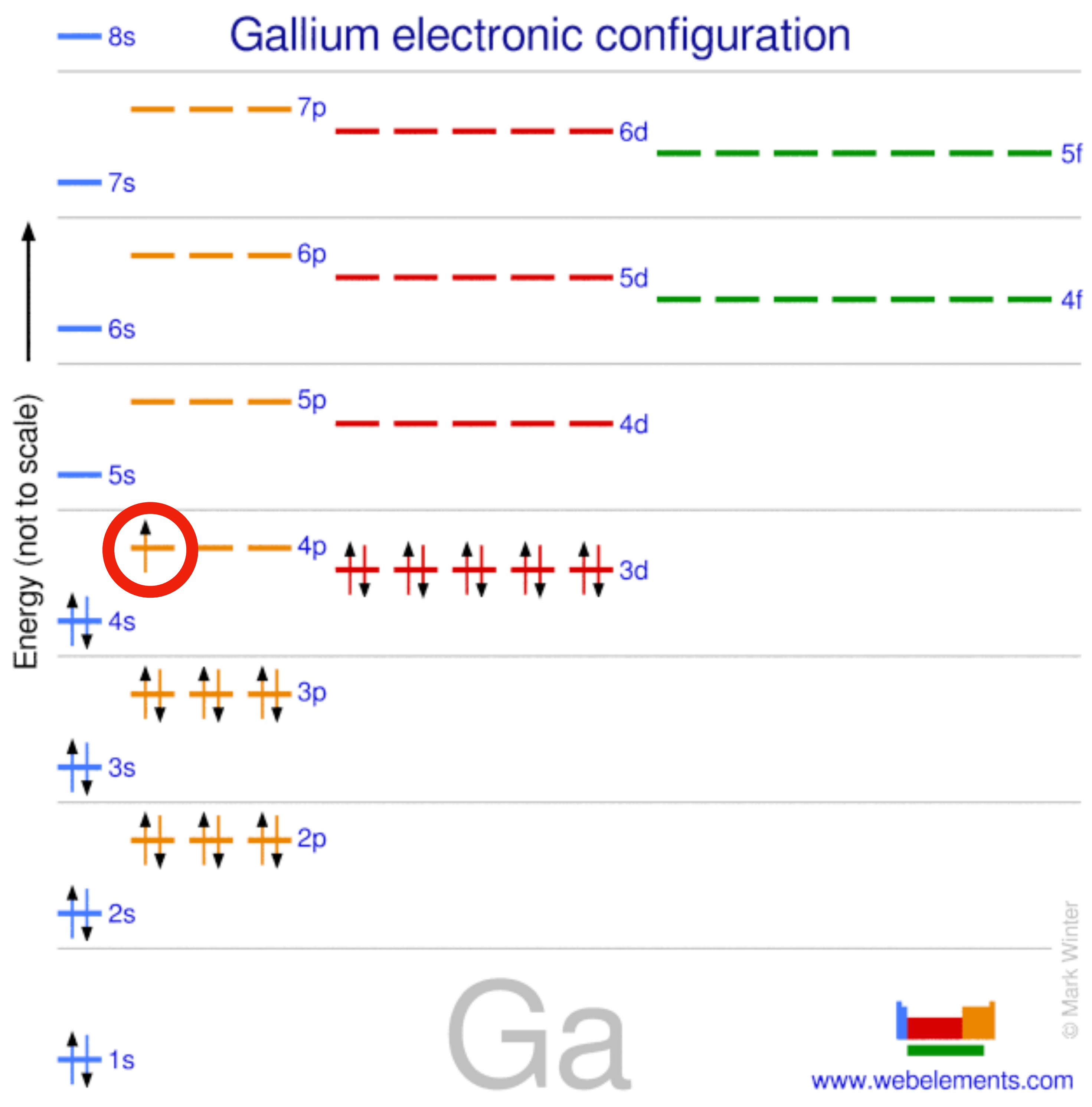
24788.530 cm-1

$$^{2*(1/2)+1}P_{(1/2)+1} \quad ^{2}P_{3/2}$$

$$^{2*(1/2)+1}S_{(1/2)+0} \quad ^{2}S_{1/2}$$

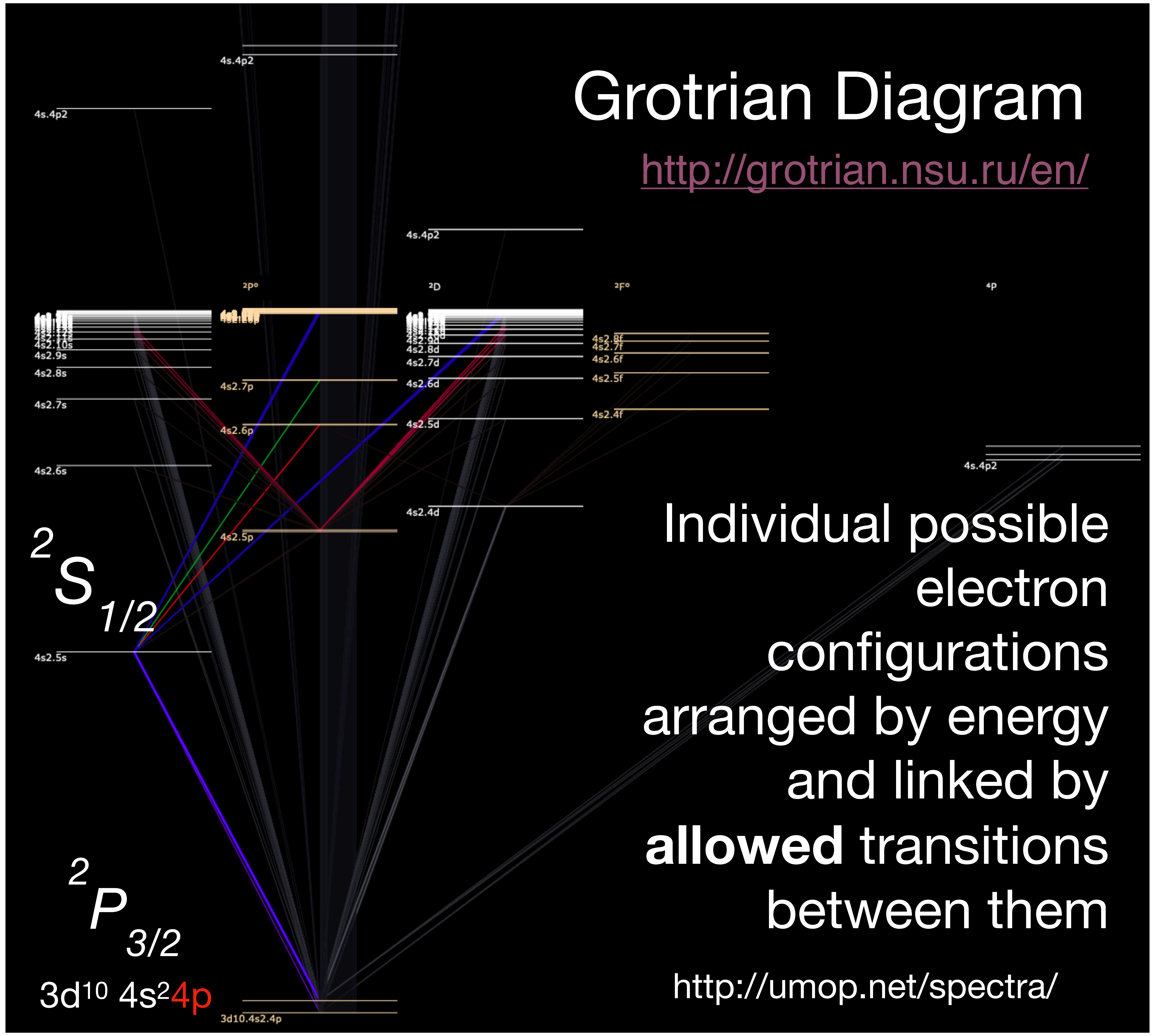
Building up an ionization scheme

Ionization energy



Energy

Ground state (lowest energy electron configuration)

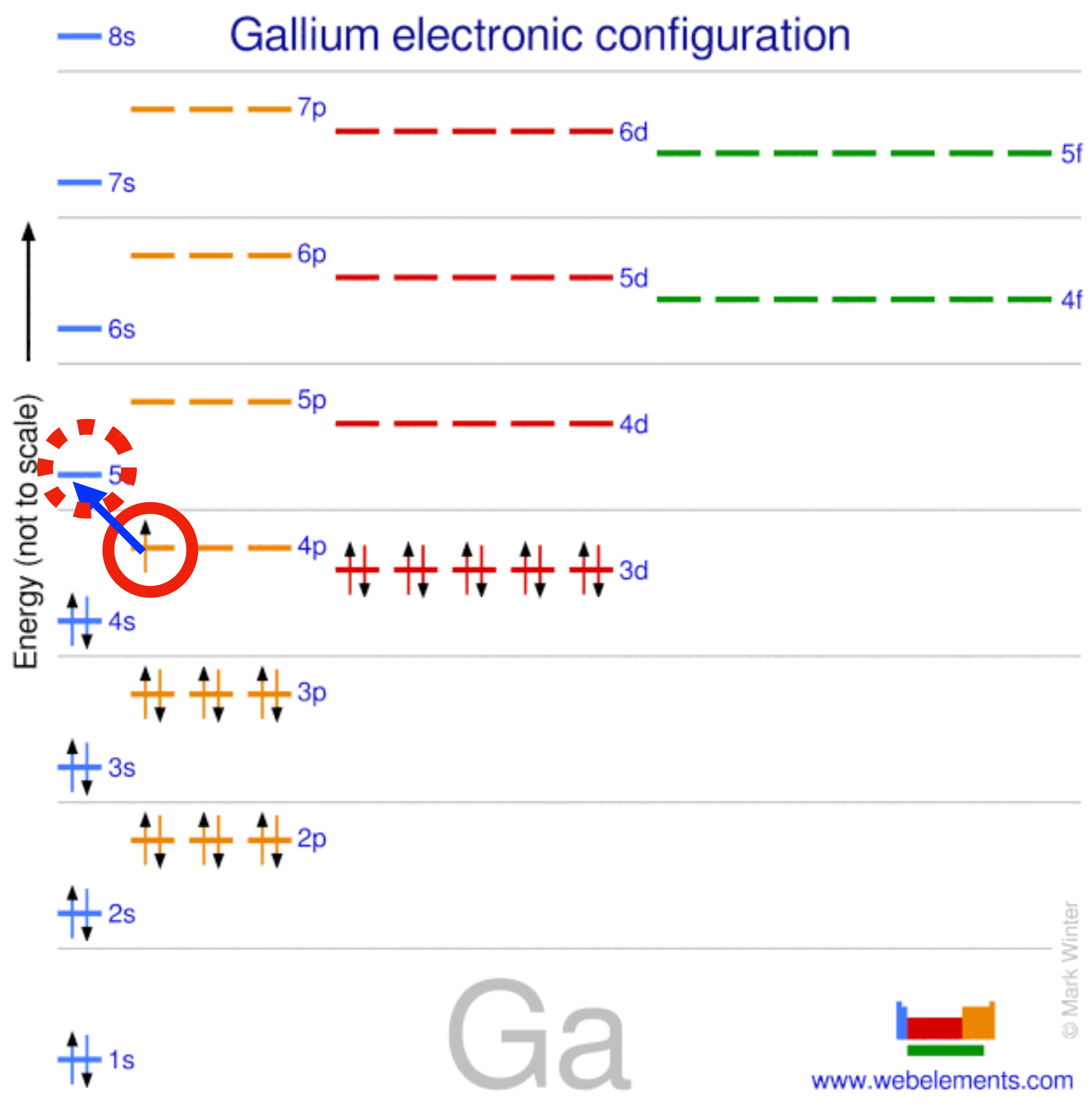


https://physics.nist.gov/PhysRefData/ASD/levels_form.html

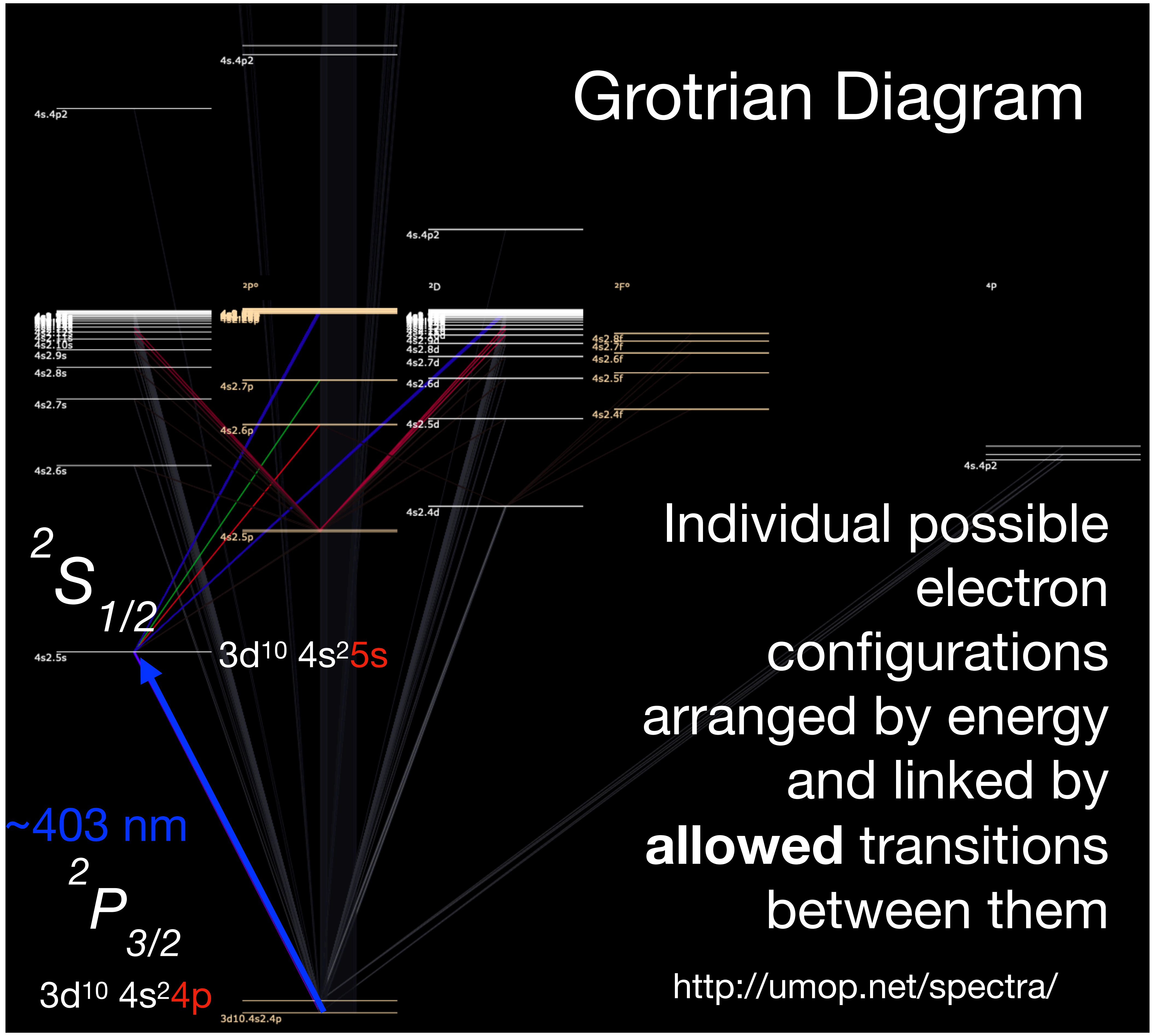
Building up an ionization scheme

Ionization energy

Energy

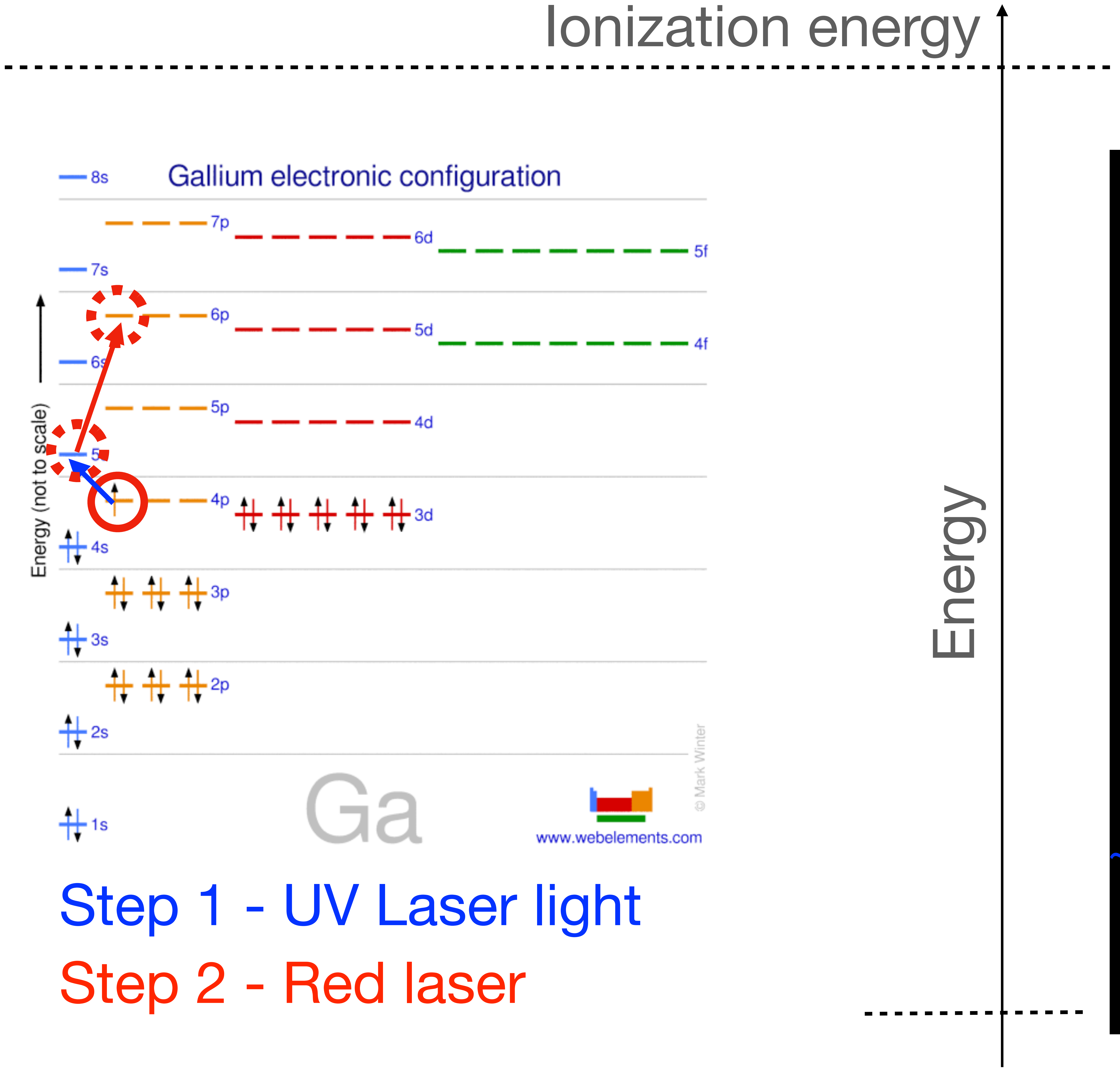


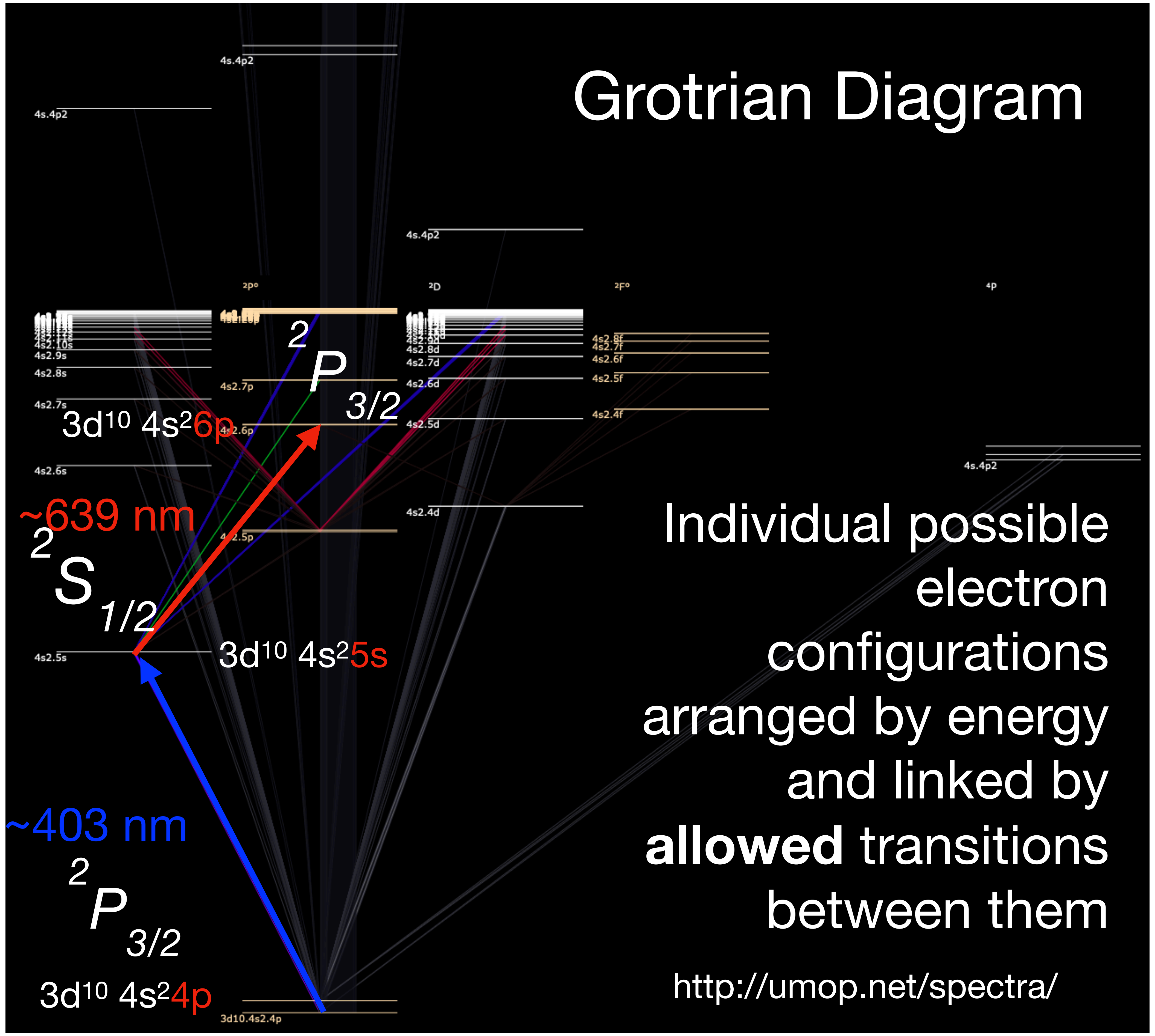
Step 1 - Blue Laser light



https://physics.nist.gov/PhysRefData/ASD/levels_form.html

Building up an ionization scheme



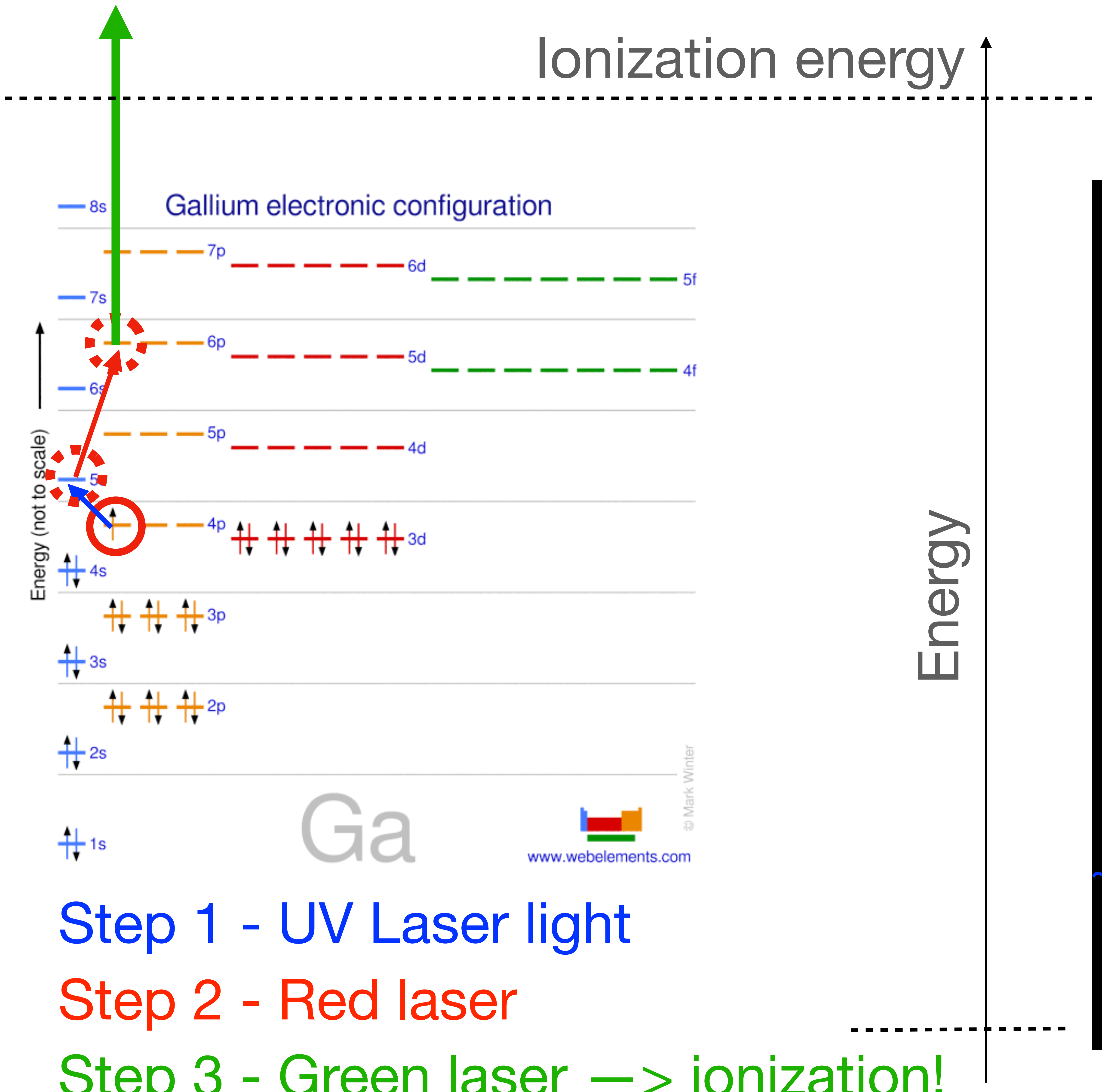


Step 1 - UV Laser light

Step 2 - Red laser

https://physics.nist.gov/PhysRefData/ASD/levels_form.html

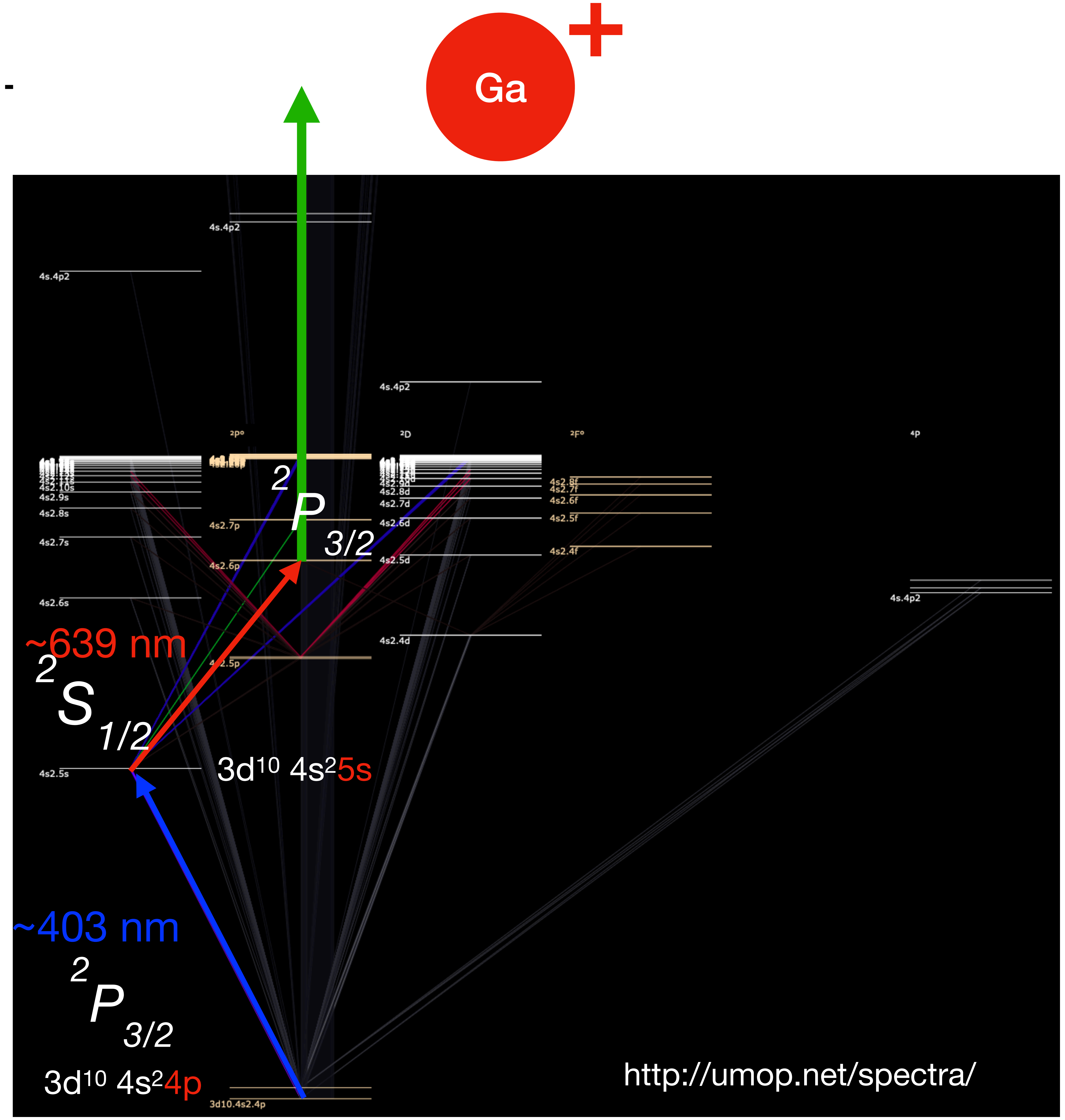
Building up an ionization scheme



Step 1 - UV Laser light

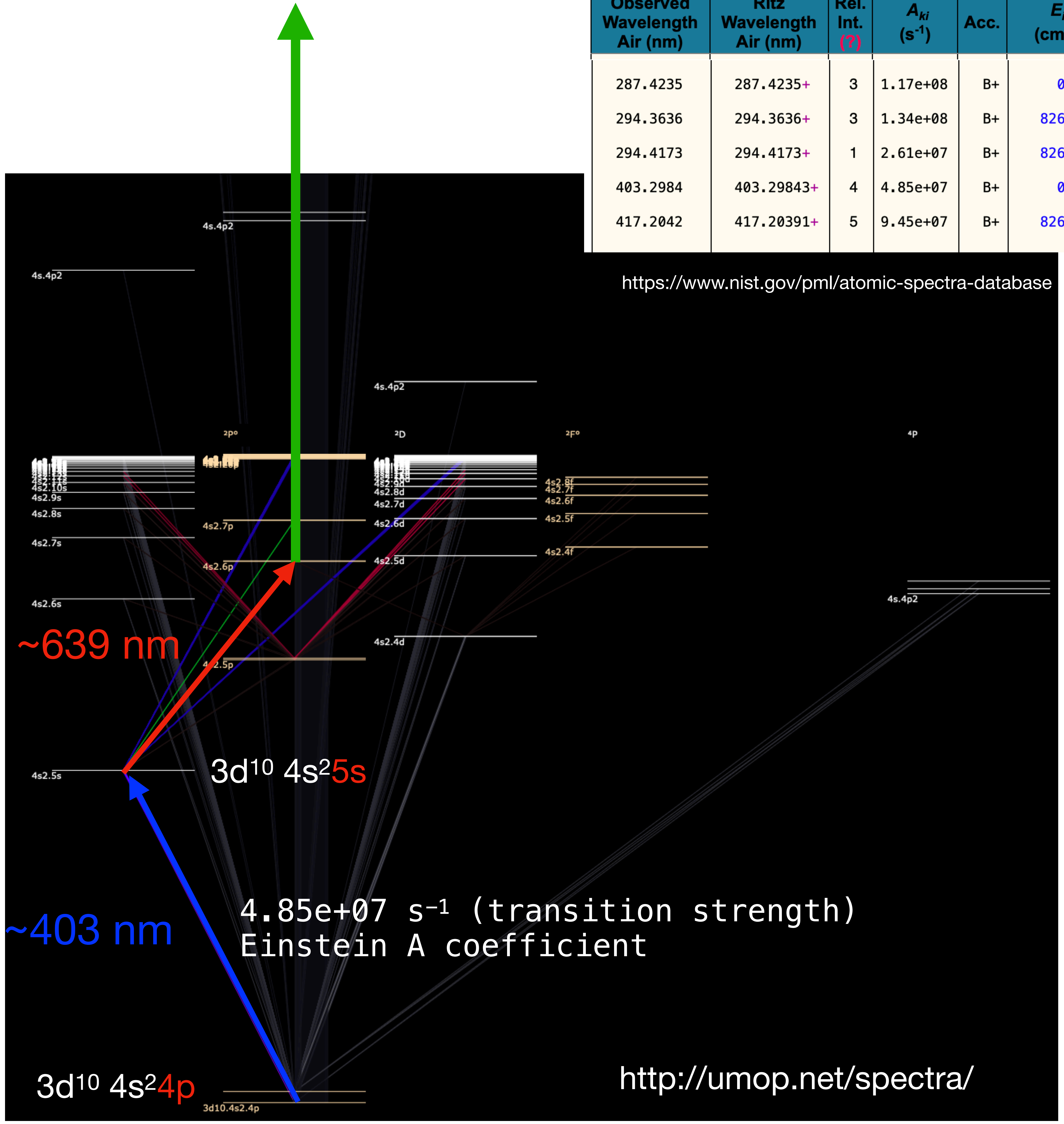
Step 2 - Red laser

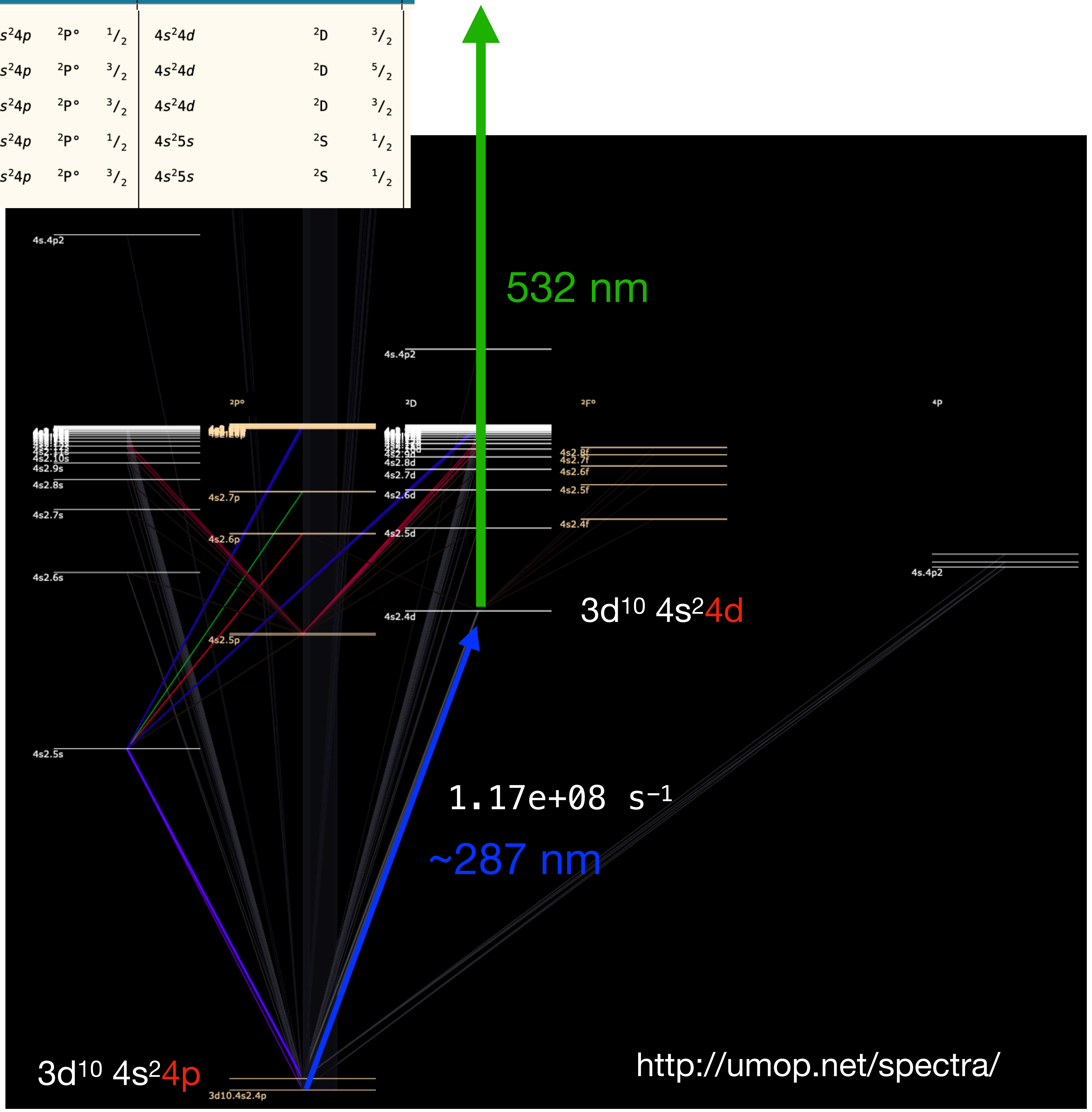
Step 3 - Green laser —> ionization!



https://physics.nist.gov/PhysRefData/ASD/levels_form.html

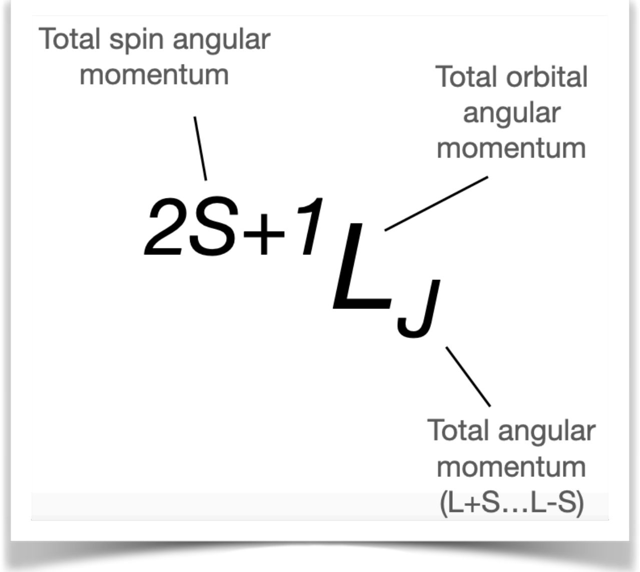
Observed Wavelength Air (nm)	Ritz Wavelength Air (nm)	Rel. Int. (?)	A_{ki} (s^{-1})	Acc.	E_i (cm^{-1})		E_k (cm^{-1})	Lower Level Conf., Term, J			Upper Level Conf., Term, J		
287.4235	287.4235+	3	1.17e+08	B+	0.000	-	34 781.66	$3d^{10}4s^24p$	$^2P°$	1/2	$4s^24d$	^2D	3/2
294.3636	294.3636+	3	1.34e+08	B+	826.190	-	34 787.85	$3d^{10}4s^24p$	$^2P°$	3/2	$4s^24d$	^2D	5/2
294.4173	294.4173+	1	2.61e+07	B+	826.190	-	34 781.66	$3d^{10}4s^24p$	$^2P°$	3/2	$4s^24d$	^2D	3/2
403.2984	403.29843+	4	4.85e+07	B+	0.000	-	24 788.530	$3d^{10}4s^24p$	$^2P°$	1/2	$4s^25s$	^2S	1/2
417.2042	417.20391+	5	9.45e+07	B+	826.190	-	24 788.530	$3d^{10}4s^24p$	$^2P°$	3/2	$4s^25s$	^2S	1/2

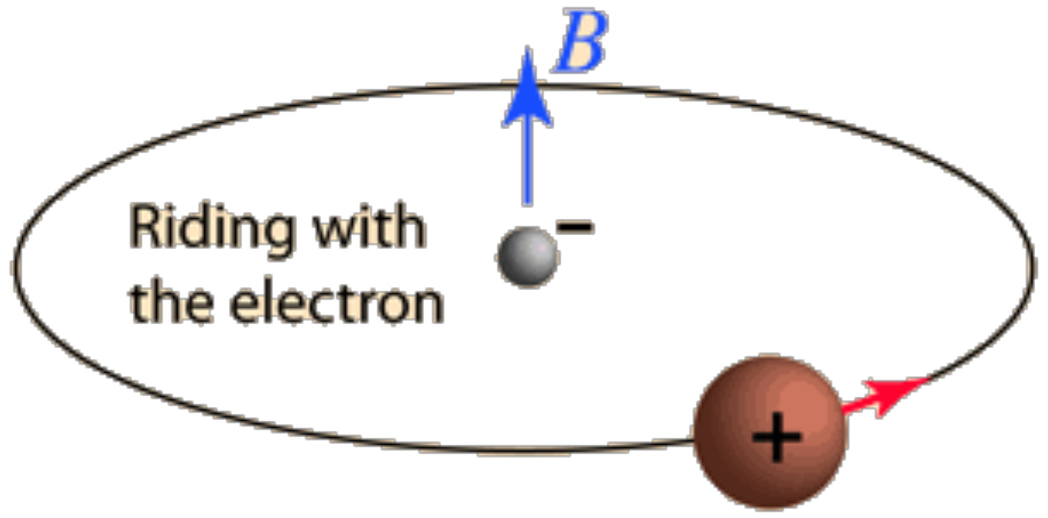




Simpler, 2 step scheme, higher efficiency, reduced complexity

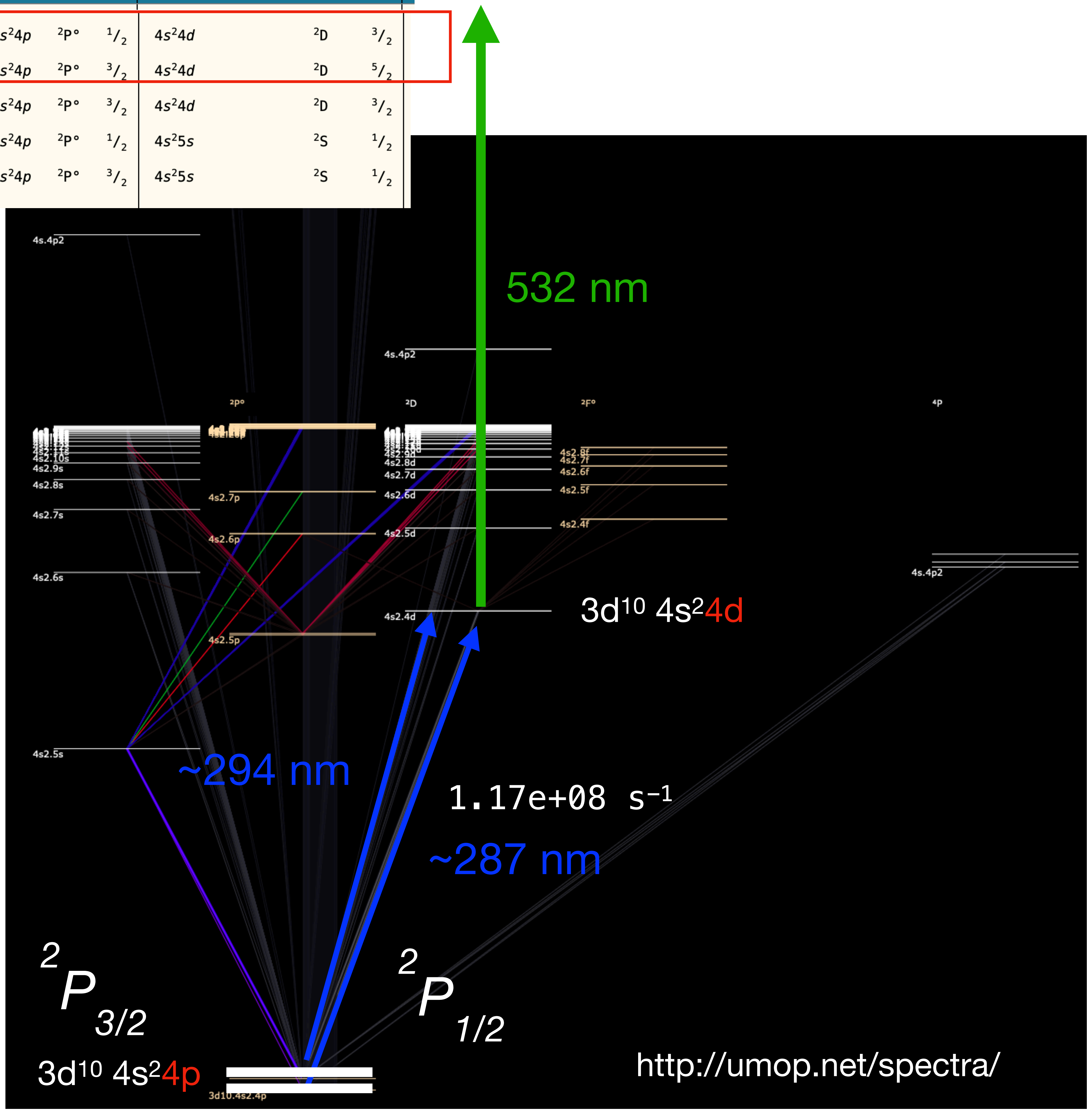
Observed Wavelength Air (nm)	Ritz Wavelength Air (nm)	Rel. Int. (?)	A_{ki} (s^{-1})	Acc.	E_i (cm^{-1})		E_k (cm^{-1})	Lower Level Conf., Term, J			Upper Level Conf., Term, J		
287.4235	287.4235+	3	1.17e+08	B+	0.000	-	34 781.66	$3d^{10}4s^24p$	$^2P°$	1/2	$4s^24d$	^2D	3/2
294.3636	294.3636+	3	1.34e+08	B+	826.190	-	34 787.85	$3d^{10}4s^24p$	$^2P°$	3/2	$4s^24d$	^2D	5/2
294.4173	294.4173+	1	2.61e+07	B+	826.190	-	34 781.66	$3d^{10}4s^24p$	$^2P°$	3/2	$4s^24d$	^2D	3/2
403.2984	403.29843+	4	4.85e+07	B+	0.000	-	24 788.530	$3d^{10}4s^24p$	$^2P°$	1/2	$4s^25s$	^2S	1/2
417.2042	417.20391+	5	9.45e+07	B+	826.190	-	24 788.530	$3d^{10}4s^24p$	$^2P°$	3/2	$4s^25s$	^2S	1/2





Fine Structure splitting

Spin-orbit interaction



Total angular momentum, J

J= L-S = 1/2 826.19 cm−1
L+S = 3/2 0 cm−1

Boltzmann formula to calculate thermal population of fine-structure levels

$$\frac{N_j}{N_1} = \frac{g_j}{g_1} e^{-(E_j-E_1)/k_B T}$$

55 % @ 2200 C

Use a second laser @ 294 nm to also excite from 826.12 cm-1 thermally populated level!

Some ionization scheme considerations

Transition strength

Is it possible to saturate the transition with available laser?

Some ionization scheme considerations

Transition strength

Is it possible to saturate the transition with available laser?

Wavelength
(< 200 nm is difficult to generate and transport)

Is the wavelength convenient (or possible) to produce?

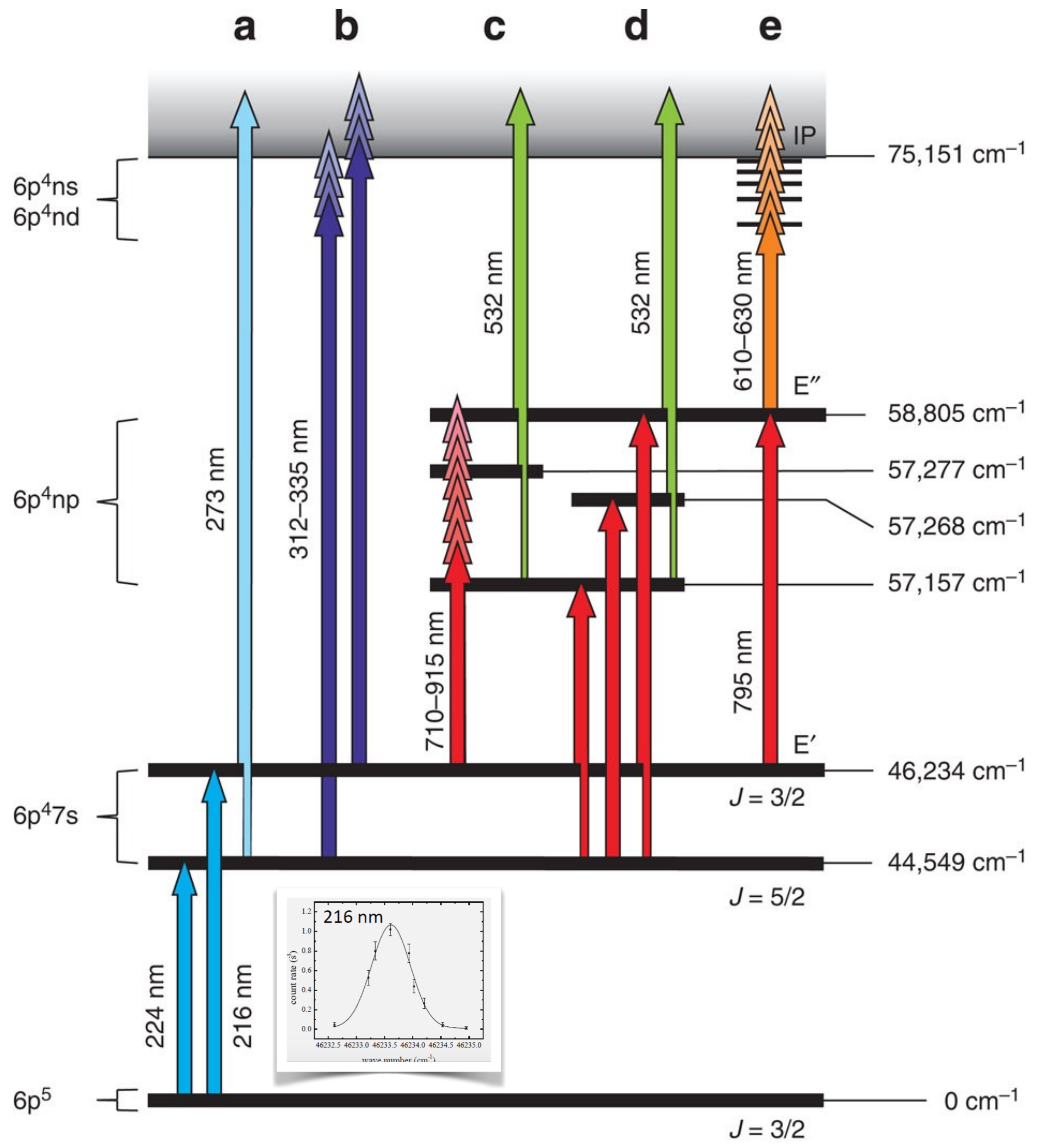
Some ionization scheme considerations

Transition strength	Is it possible to saturate the transition with available laser?
Wavelength (< 200 nm is difficult to generate and transport)	Is the wavelength convenient (or possible) to produce?
Radiative decay paths	Does the excited state decay to a level that will render the atom 'invisible'?

Some ionization scheme considerations

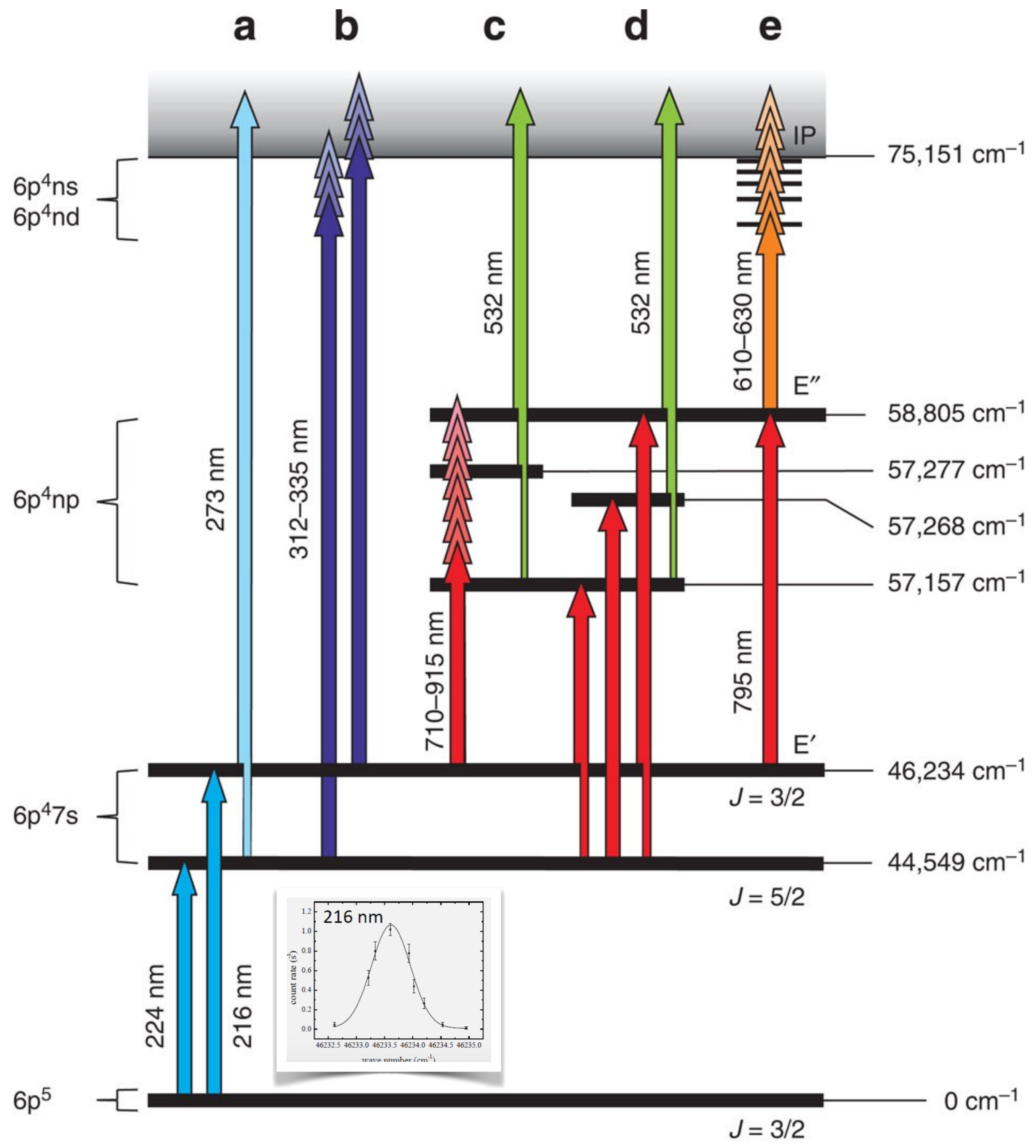
Transition strength	Is it possible to saturate the transition with available laser?
Wavelength (< 200 nm is difficult to generate and transport)	Is the wavelength convenient (or possible) to produce?
Radiative decay paths	Does the excited state decay to a level that will render the atom 'invisible'?
Suitability / existence of subsequent transitions	We may compromise on the above considerations if it makes subsequent steps more convenient or efficient

Developing an ionisation scheme for astatine



PhD work
Sebastian Rothe

Developing an ionisation scheme for astatine



PhD work
Sebastian Rothe

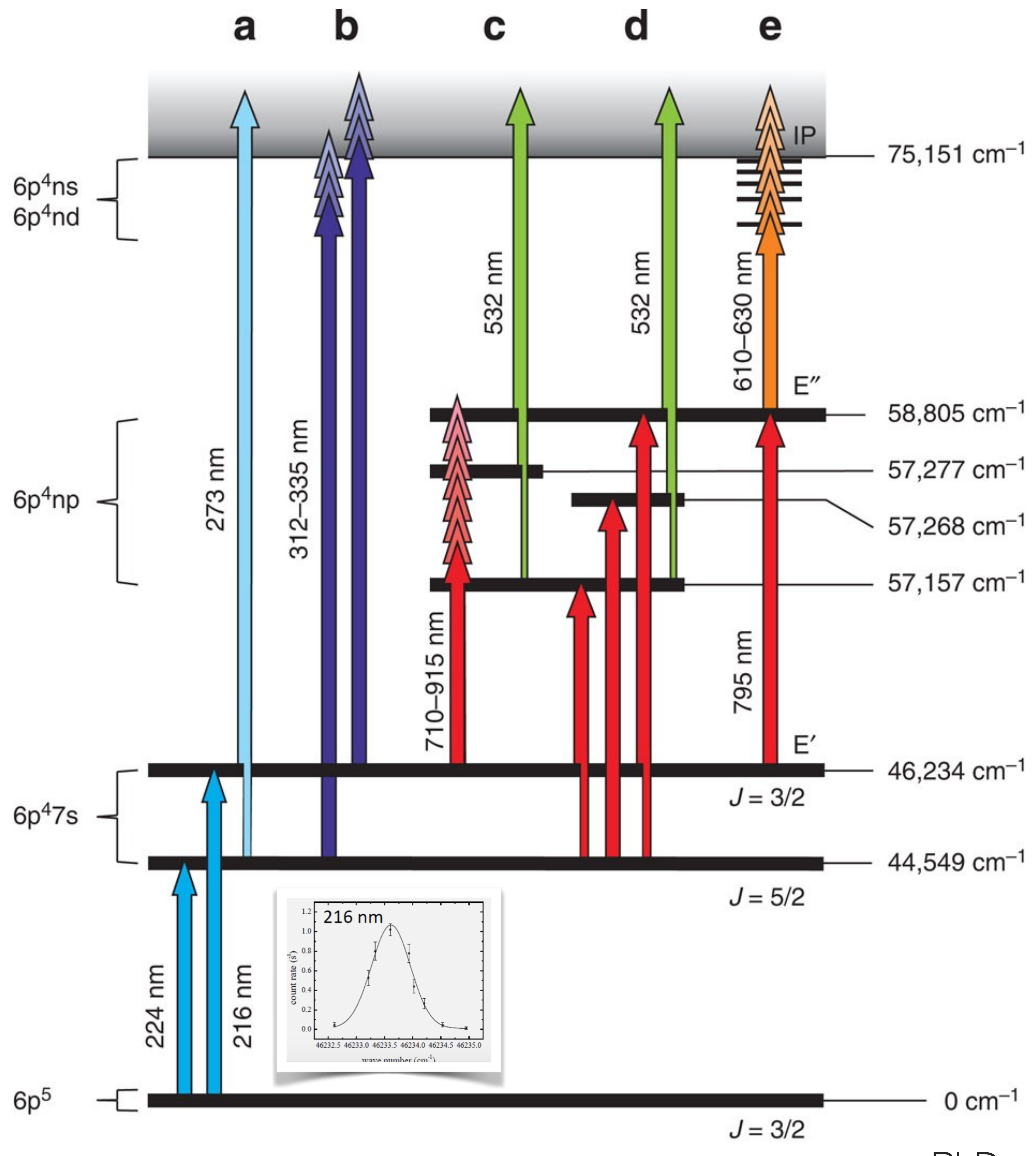
a Initial exploration - confirm existence of 1st steps

b Search for on-set of ionization (ionization energy)

c Search for second steps that would allow the use of the high power green laser for ionization

d Carefully compare best second steps

Developing an ionisation scheme for astatine



PhD work
Sebastian Rothe

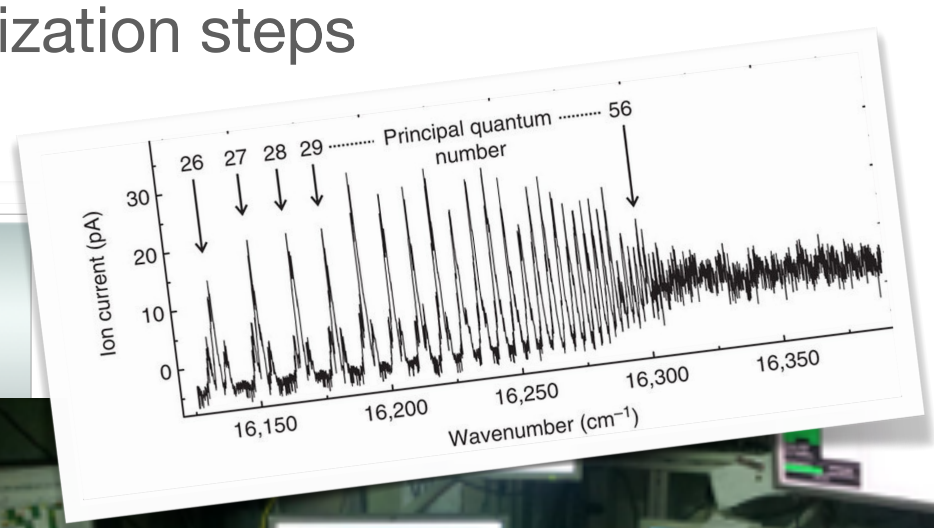
a Initial exploration - confirm existence of 1st steps

b Search for on-set of ionization (ionization energy)

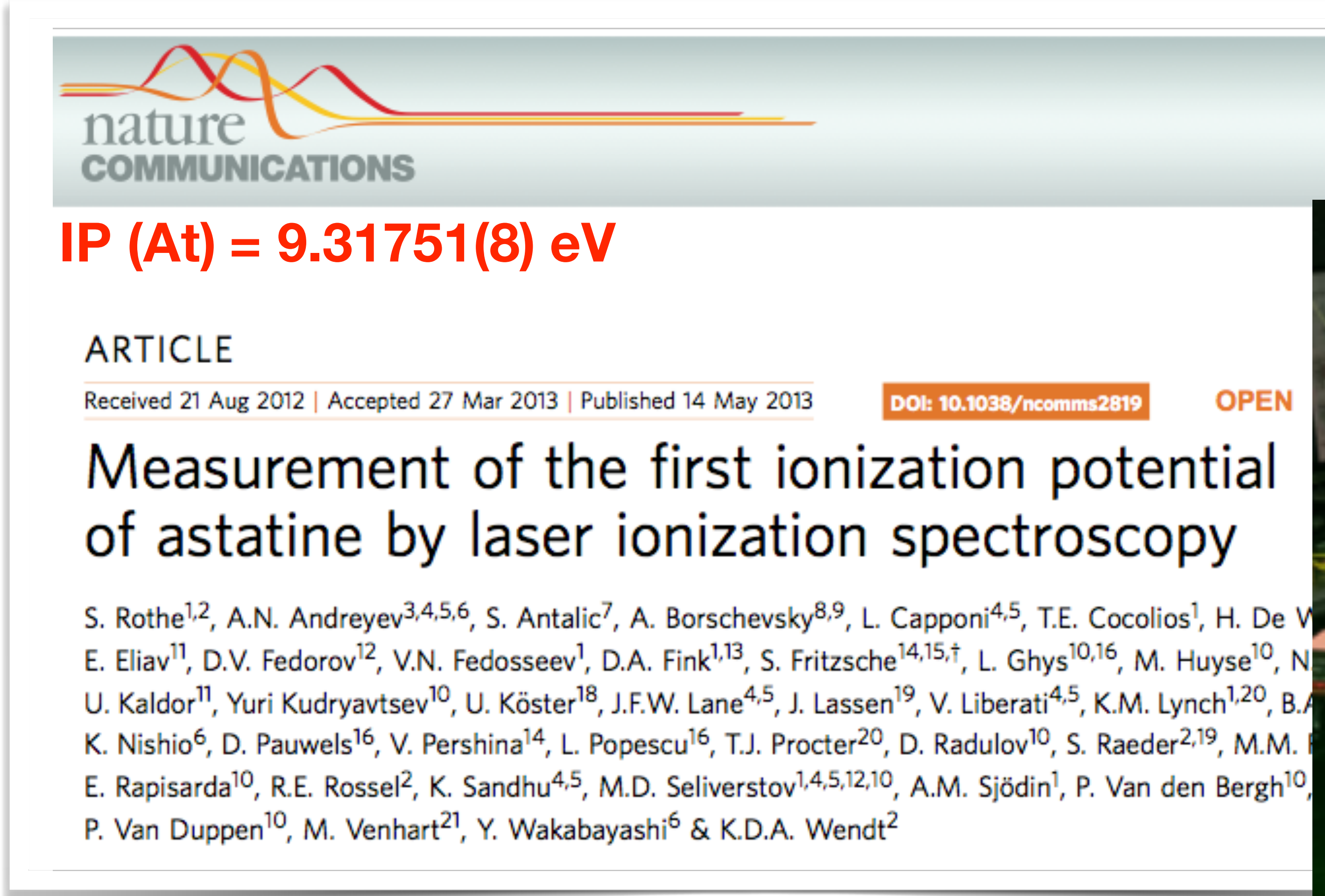
c Search for second steps that would allow the use of the high power green laser for ionization

d Carefully compare best second steps

e Careful scan across the ionization continuum - to precisely measure ionization energy and look for more efficient ionization steps



IP (At) = 9.31751(8) eV

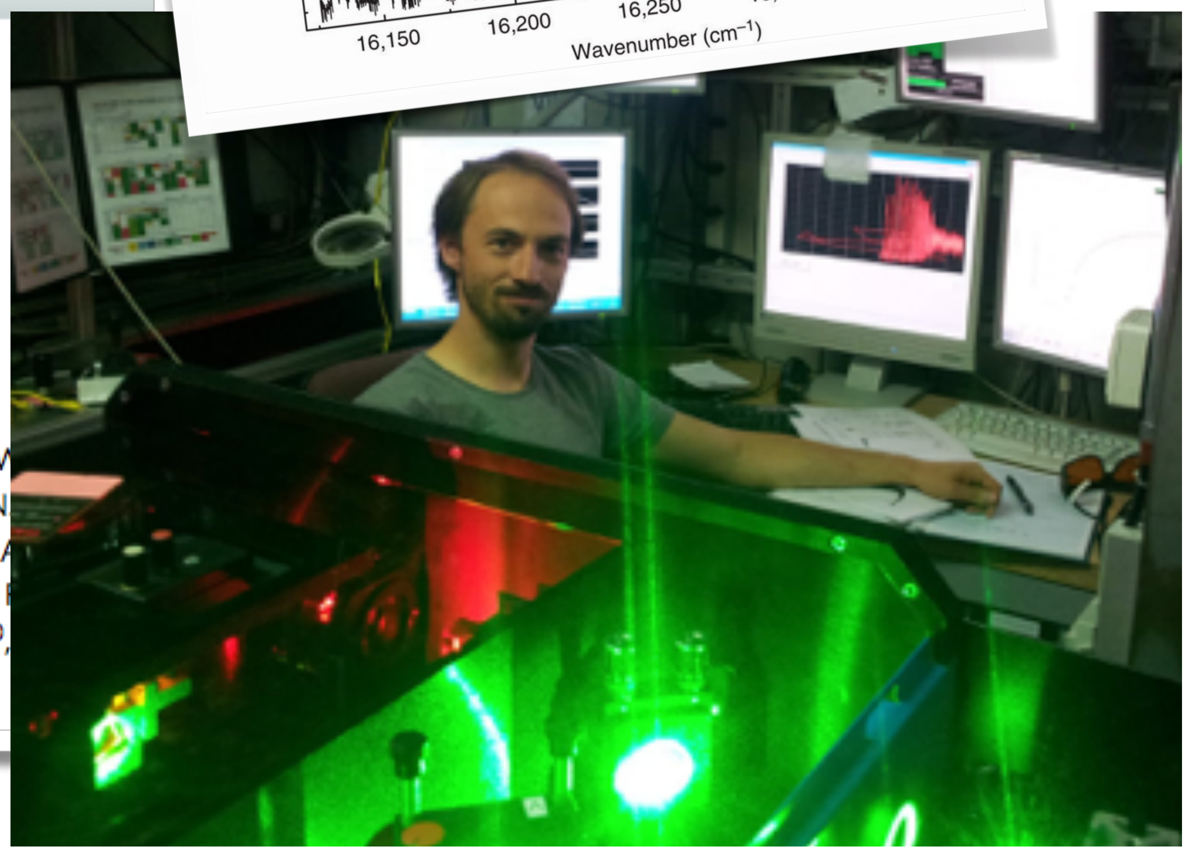

nature COMMUNICATIONS

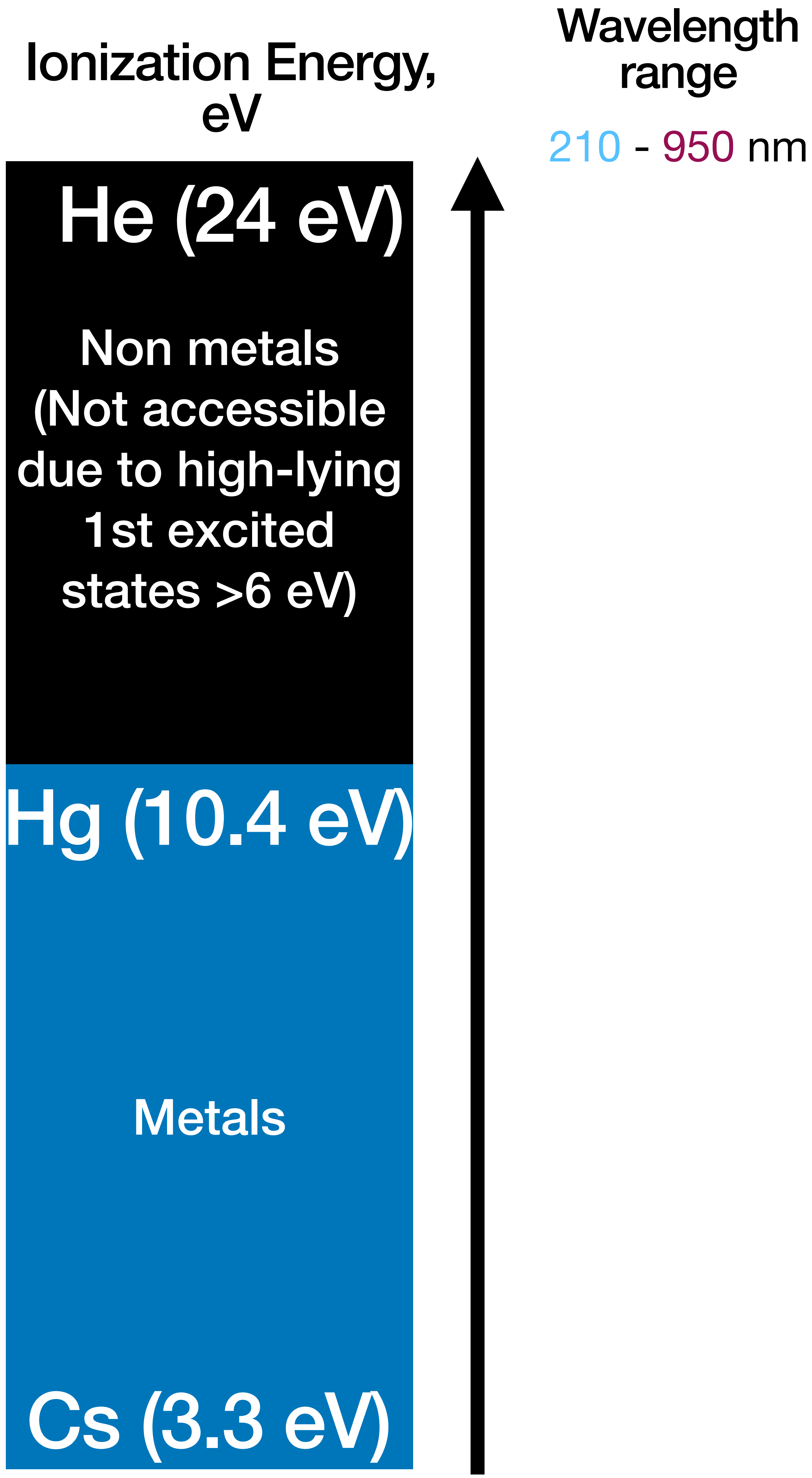
ARTICLE

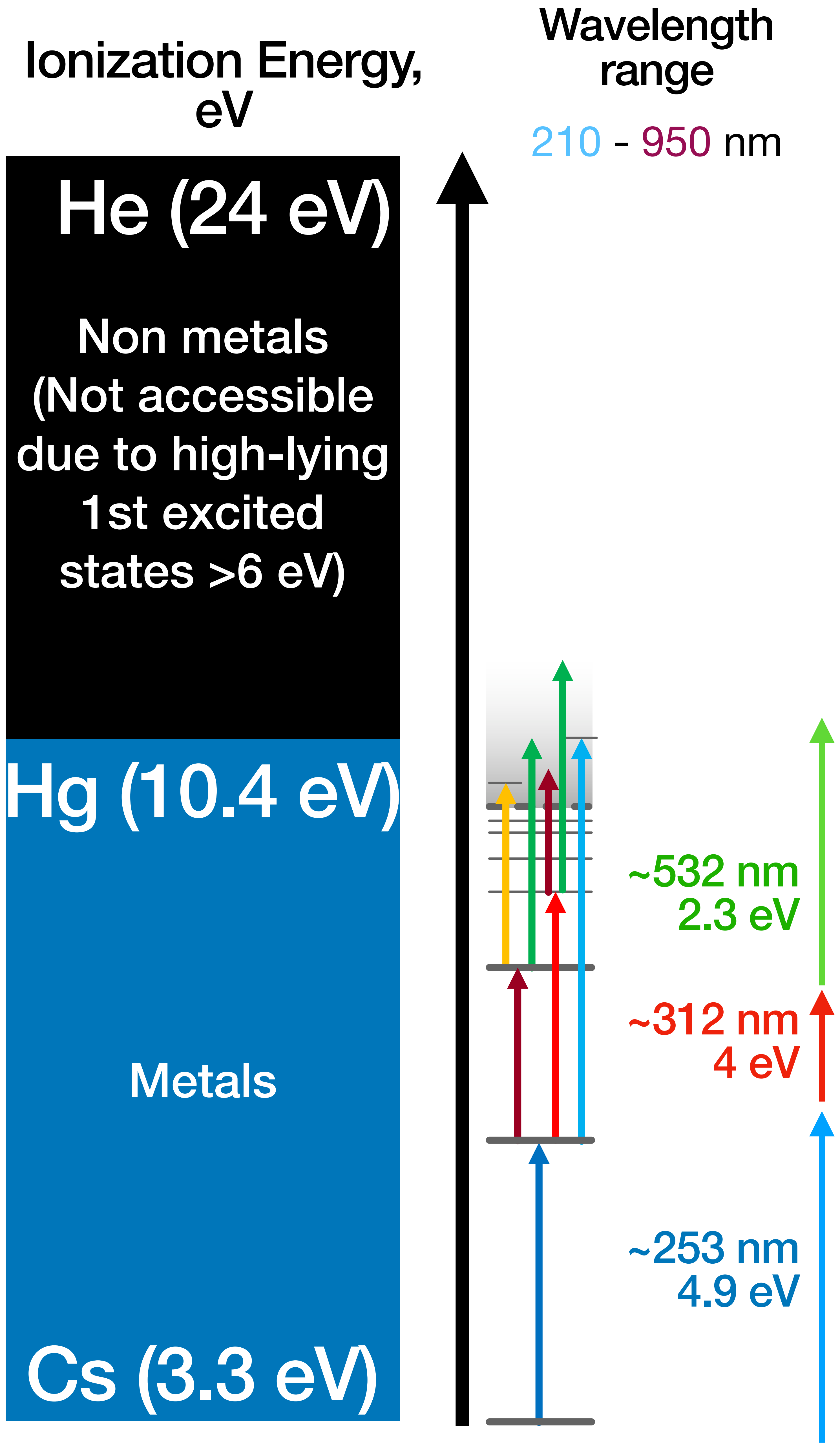
Received 21 Aug 2012 | Accepted 27 Mar 2013 | Published 14 May 2013 | DOI: 10.1038/ncomms2819 | OPEN

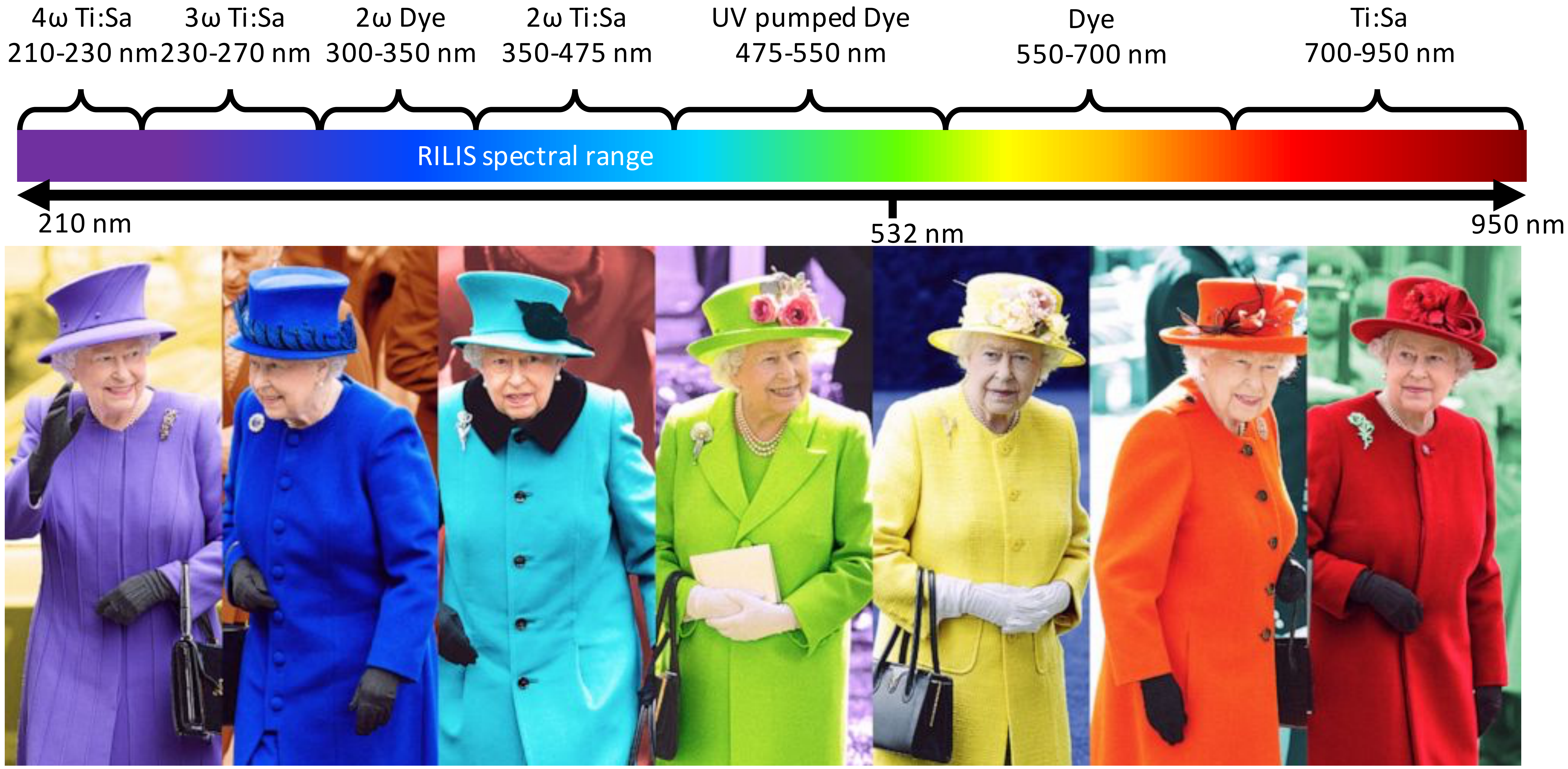
Measurement of the first ionization potential of astatine by laser ionization spectroscopy

S. Rothe[1,2], A.N. Andreyev[3,4,5,6], S. Antalic[7], A. Borschevsky[8,9], L. Capponi[4,5], T.E. Cocolios[1], H. De W… E. Eliav[11], D.V. Fedorov[12], V.N. Fedosseev[1], D.A. Fink[1,13], S. Fritzsche[14,15,†], L. Ghys[10,16], M. Huyse[10], N… U. Kaldor[11], Yuri Kudryavtsev[10], U. Köster[18], J.F.W. Lane[4,5], J. Lassen[19], V. Liberati[4,5], K.M. Lynch[1,20], B.A… K. Nishio[6], D. Pauwels[16], V. Pershina[14], L. Popescu[16], T.J. Procter[20], D. Radulov[10], S. Raeder[2,19], M.M… E. Rapisarda[10], R.E. Rossel[2], K. Sandhu[4,5], M.D. Seliverstov[1,4,5,12,10], A.M. Sjödin[1], P. Van den Bergh[10]… P. Van Duppen[10], M. Venhart[21], Y. Wakabayashi[6] & K.D.A. Wendt[2]




Ionization Energy, eV
Wavelength range
210 - 950 nm
He (24 eV)
Non metals (Not accessible due to high-lying 1st excited states >6 eV)
Hg (10.4 eV)
Metals
Cs (3.3 eV)

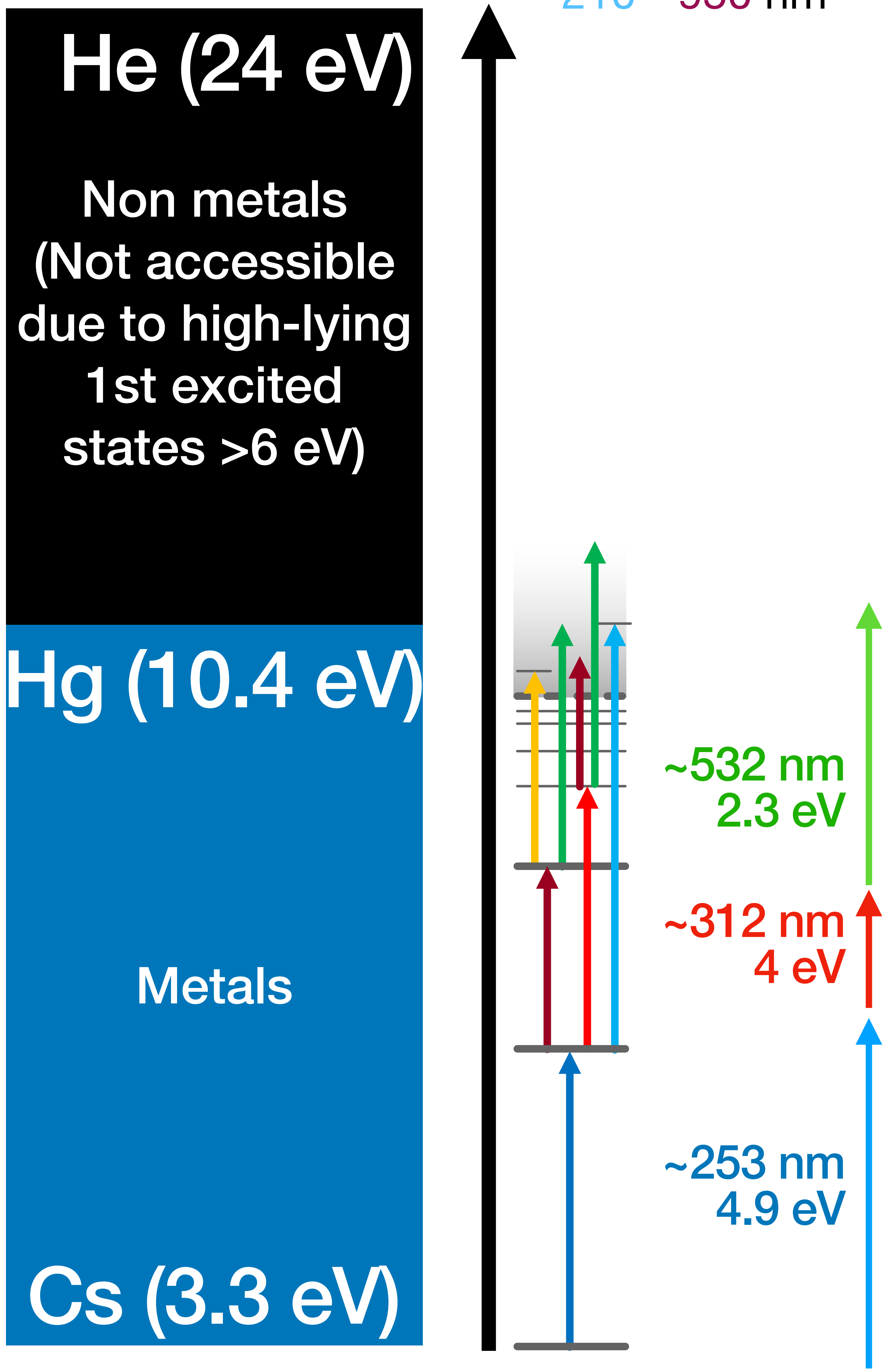

Ionization Energy, eV
Wavelength range
210 - 950 nm
He (24 eV)
Non metals (Not accessible due to high-lying 1st excited states >6 eV)
Hg (10.4 eV)
Metals
Cs (3.3 eV)
~532 nm
2.3 eV
~312 nm
4 eV
~253 nm
4.9 eV


4ω Ti:Sa
210-230 nm
3ω Ti:Sa
230-270 nm
2ω Dye
300-350 nm
2ω Ti:Sa
350-475 nm
UV pumped Dye
475-550 nm
Dye
550-700 nm
Ti:Sa
700-950 nm
RILIS spectral range
210 nm
532 nm
950 nm

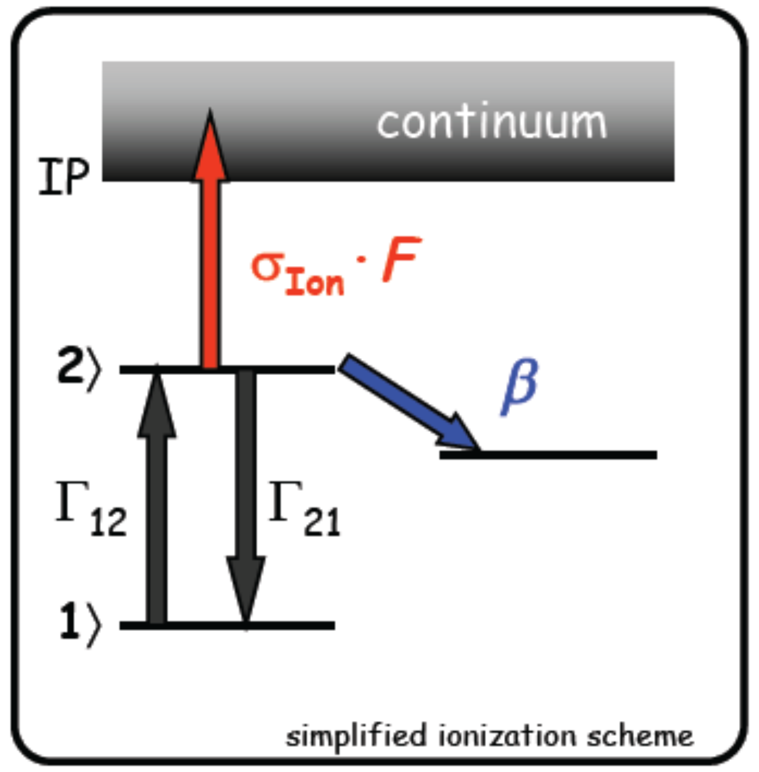
Ionization Energy, eV

Wavelength range

210 - 950 nm



Laser power (CW)



Cross section for photon absorption

$$\sigma_{ab} = \frac{g_a}{g_b} \frac{\lambda_{ab}^2}{4\pi^2} \frac{A_{ba}}{\Delta\nu_t^{ab}}$$

$\sigma_{ion} \longrightarrow 10^{-17}$ cm^2

$\beta \longrightarrow 10^{6}$ s^{-1}

Flux (F) condition

$$\sigma_{Ion} \cdot F \gg \beta$$

~10^{21} photons/s

>0.5 kW @ 500 nm

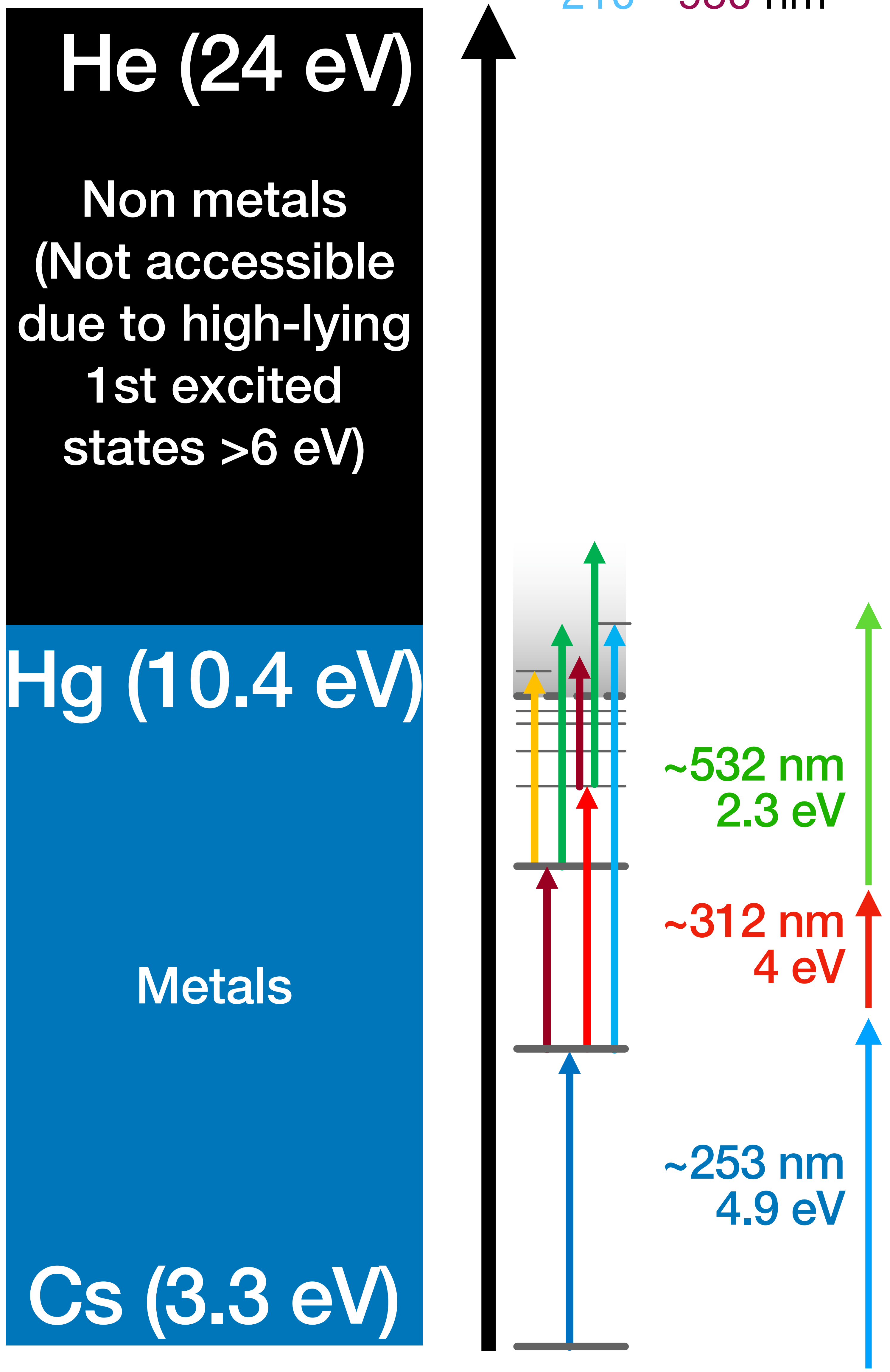
But may be < 1W/ cm^2

For strong transitions

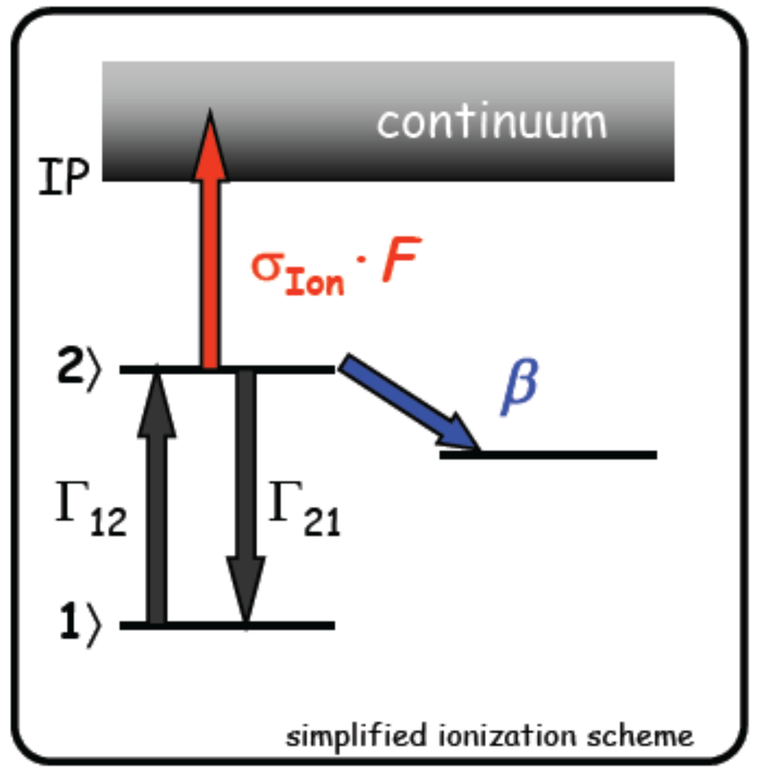
Ionization Energy, eV

Wavelength range

210 - 950 nm



Laser power (CW)



Cross section for photon absorption

$$\sigma_{ab} = \frac{g_a}{g_b} \frac{\lambda_{ab}^2}{4\pi^2} \frac{A_{ba}}{\Delta\nu_t^{ab}}$$

$\sigma_{ion} \longrightarrow 10^{-17}\ cm^2$

$\beta \longrightarrow 10^{6}\ s^{-1}$

Flux (F) condition

$$\sigma_{Ion} \cdot F \gg \beta$$

~10^{21} photons/s

>0.5 kW @ 500 nm

But may be < 1W/ cm^2

For strong transitions

Pulse energy (ns pulse)

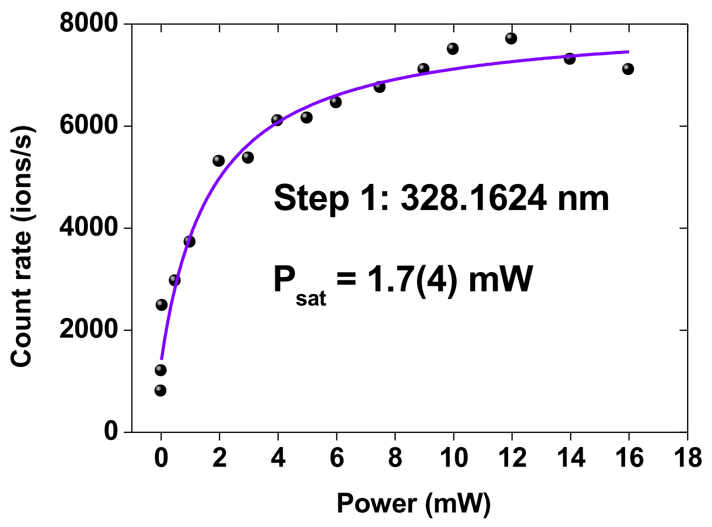
For a 10W laser with 10 ns pulses @ 10kHz

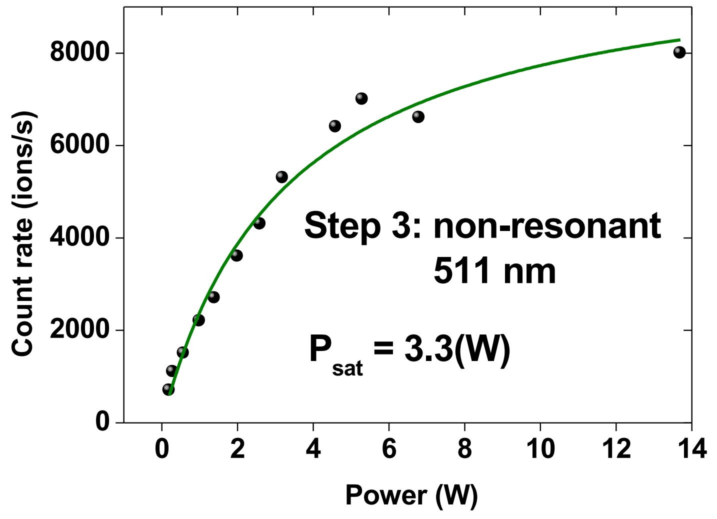
Peak power is ~100kW

<10 mJ

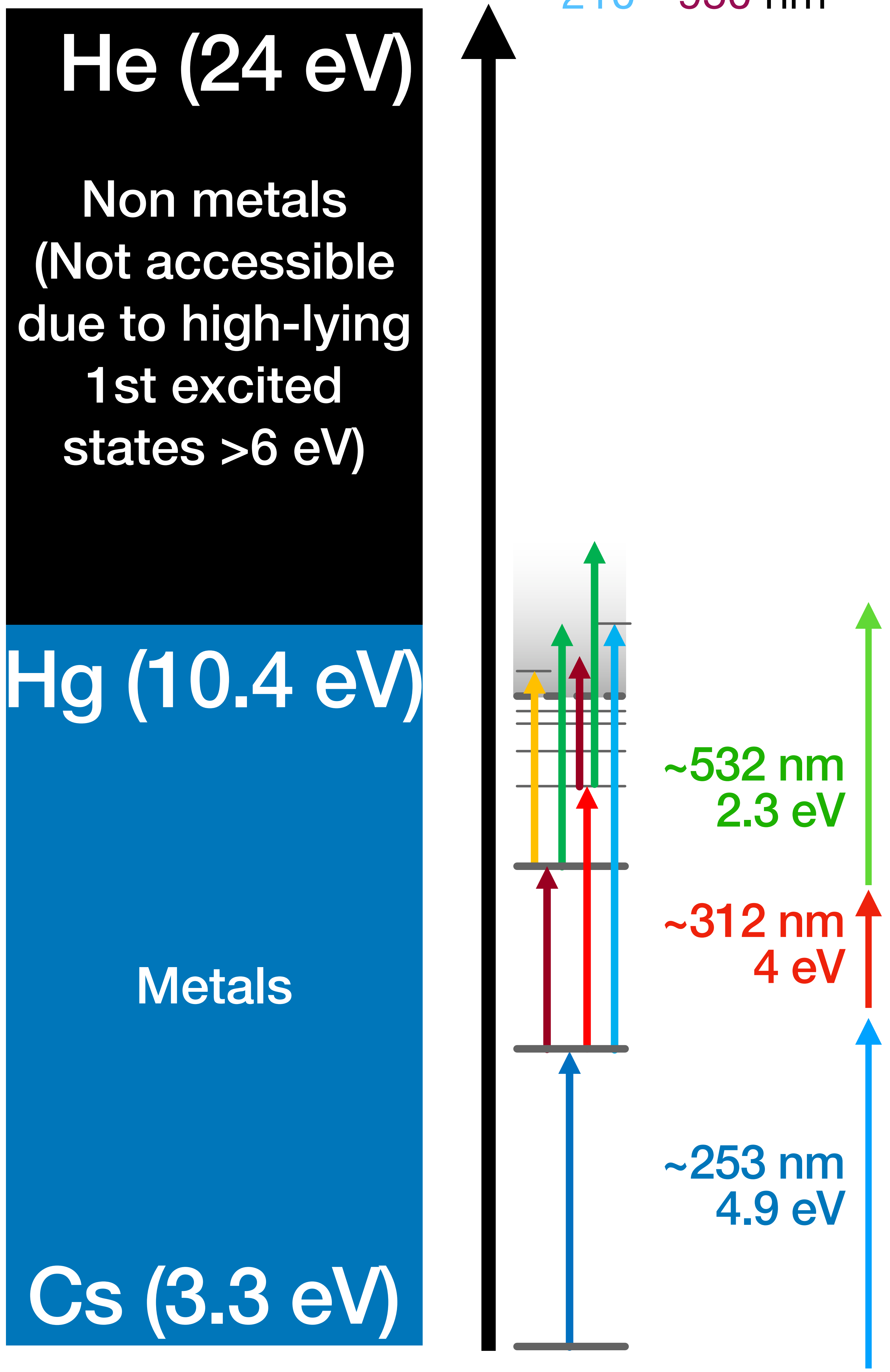
Fluence condition φ

$$\sigma_{Ion} \cdot \varphi > 1$$





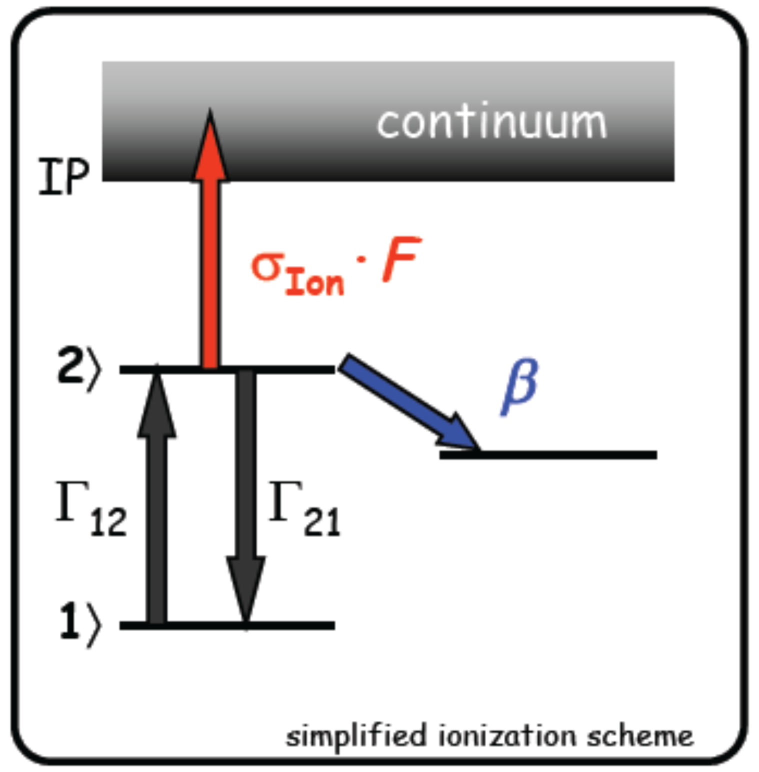
Ionization Energy, eV



Wavelength range

210 - 950 nm

Laser power (CW)



Cross section for photon absorption

$$\sigma_{ab} = \frac{g_a}{g_b}\frac{\lambda_{ab}^2}{4\pi^2}\frac{A_{ba}}{\Delta\nu_t^{ab}}$$

σ_{ion} ⟶ 10^{-17} cm²

β ⟶ 10^{6} s^{-1}

Flux (F) condition

$$\sigma_{Ion} \cdot F \gg \beta$$

~10^{21} photons/s

>0.5 kW @ 500 nm

But may be < 1W/ cm²

For strong transitions

Pulse energy (ns pulse)

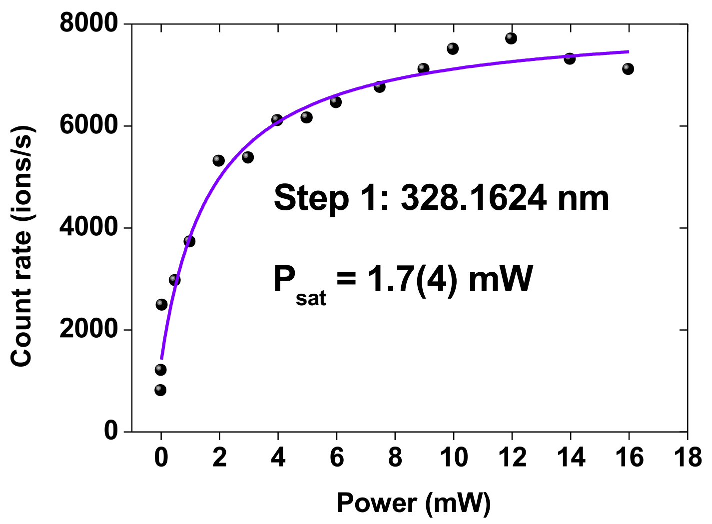
For a 10W laser with 10 ns pulses @ 10kHz

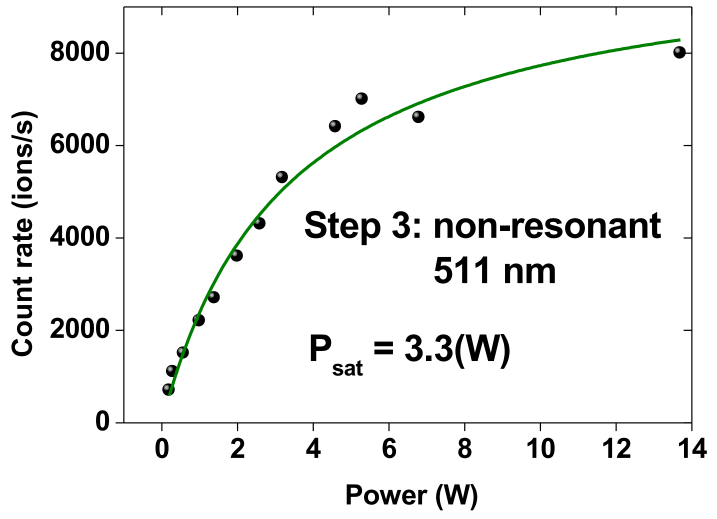
Peak power is ~100kW

<10 mJ

Fluence condition φ

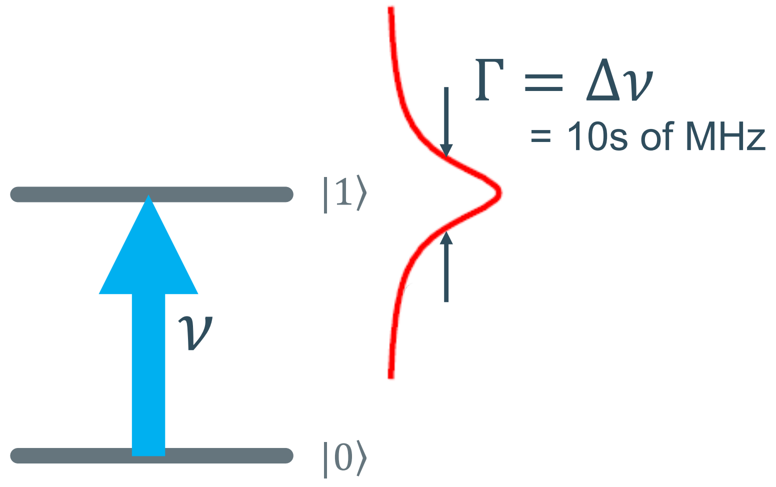
$$\sigma_{Ion} \cdot \varphi > 1$$





Linewidth (@ 2000 C)

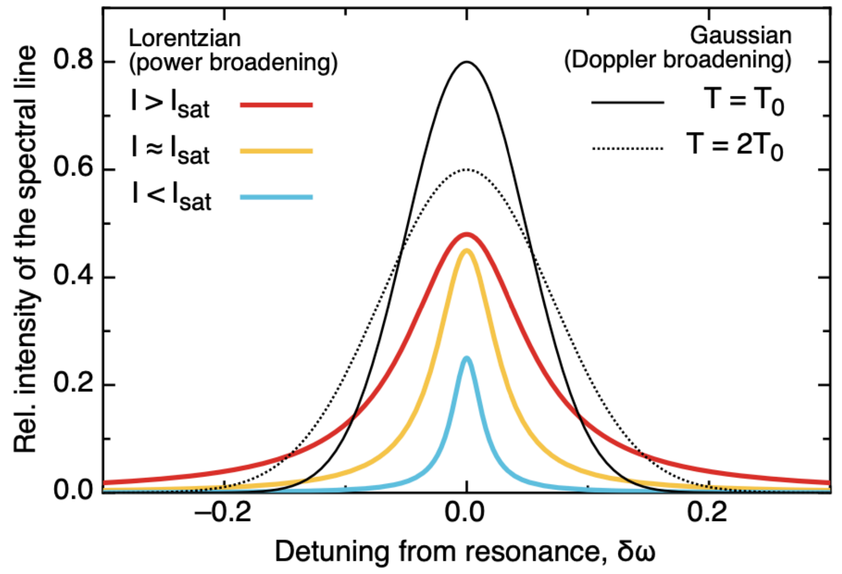
$$\Delta t\ \Delta E \geq \frac{\hbar}{2}$$

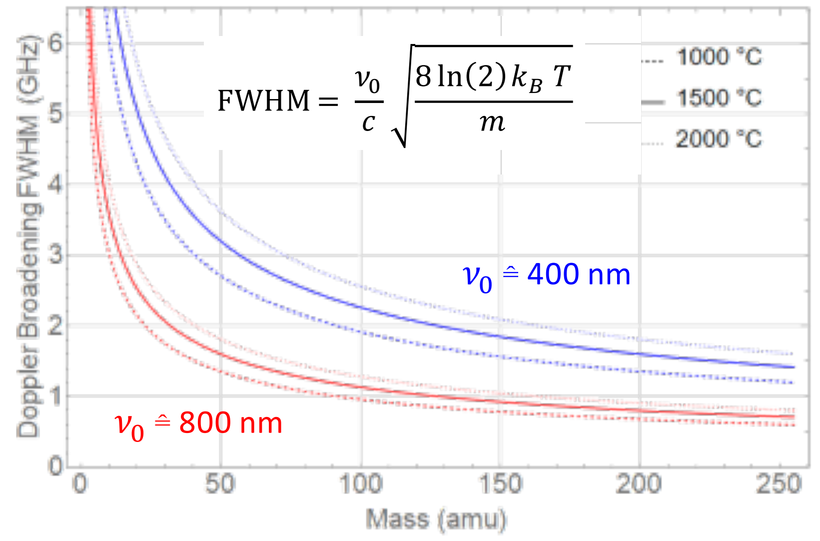


Strong transition

-> Short half-life O(ns)

-> Broad linewidth





1-10 GHz

Ionization Energy, eV

He (24 eV)

Non metals (Not accessible due to high-lying 1st excited states >6 eV)

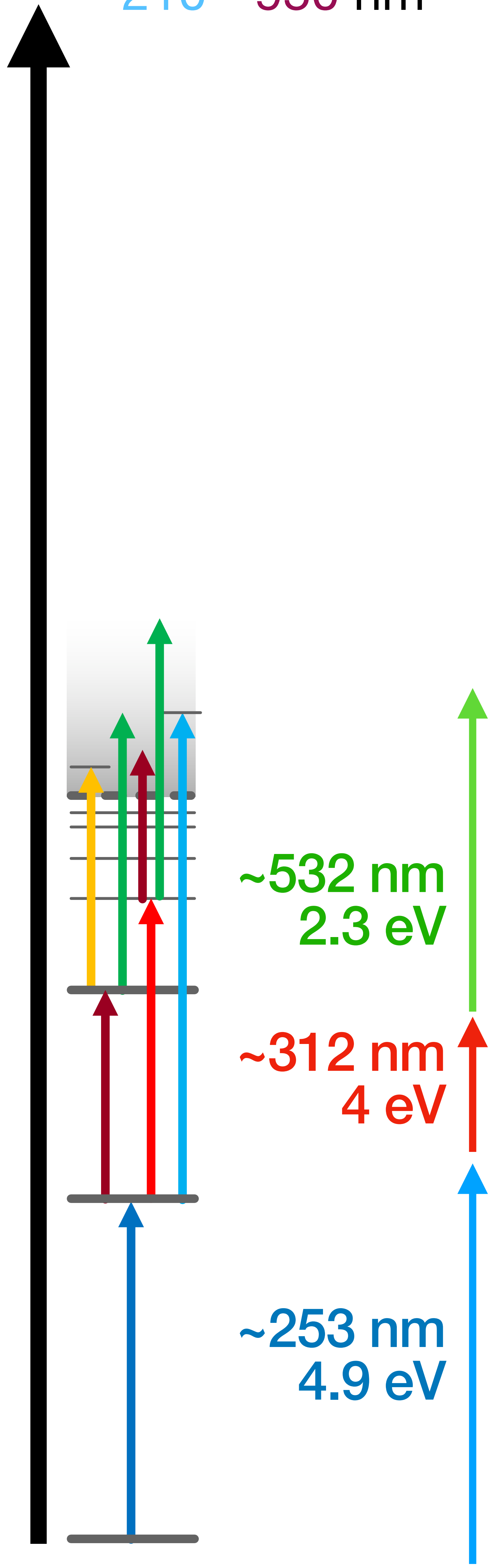
Hg (10.4 eV)

Metals

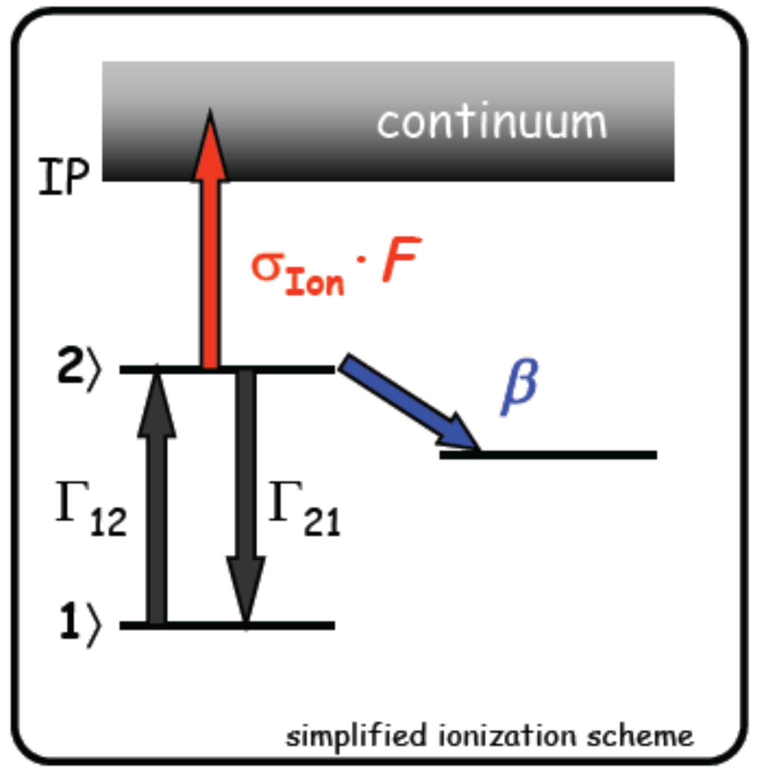
Cs (3.3 eV)

Wavelength range

210 - 950 nm



Laser power (CW)



Cross section for photon absorption

$$\sigma_{ab} = \frac{g_a}{g_b}\frac{\lambda_{ab}^2}{4\pi^2}\frac{A_{ba}}{\Delta\nu_t^{ab}}$$

$\sigma_{ion} \longrightarrow 10^{-17}$ cm^2

$\beta \longrightarrow 10^6$ s^{-1}

Flux (F) condition

$$\sigma_{Ion} \cdot F \gg \beta$$

~10^{21} photons/s

>0.5 kW @ 500 nm

But may be < 1W/ cm^2

For strong transitions

Pulse energy (ns pulse)

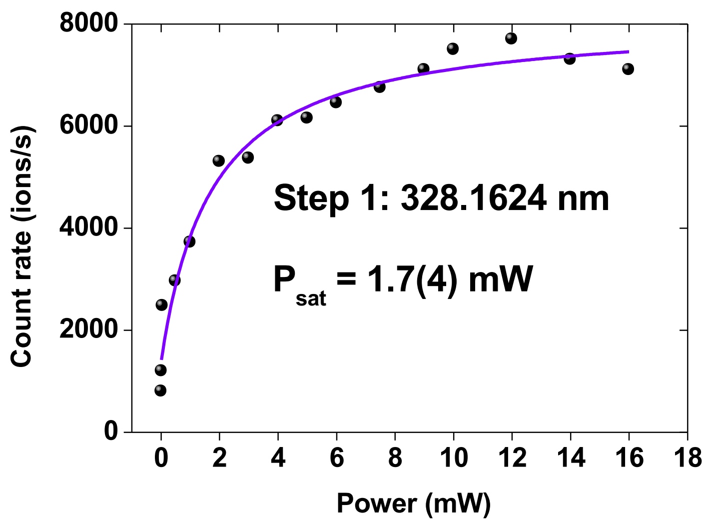
For a 10W laser with 10 ns pulses @ 10kHz

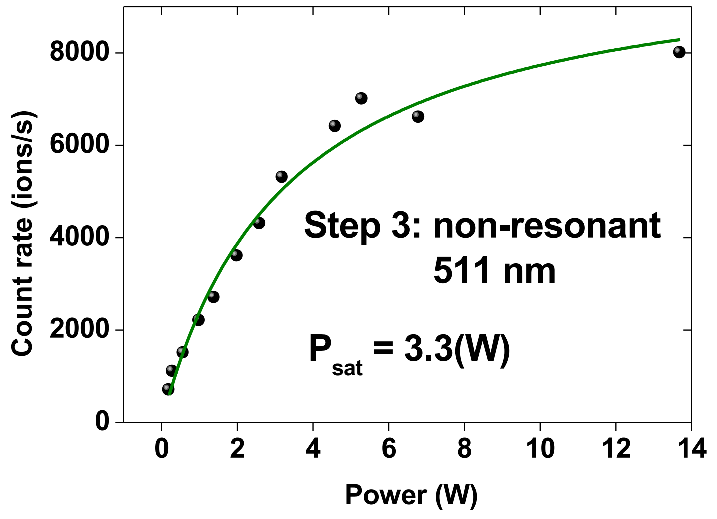
Peak power is ~100kW

<10 mJ

Fluence condition φ

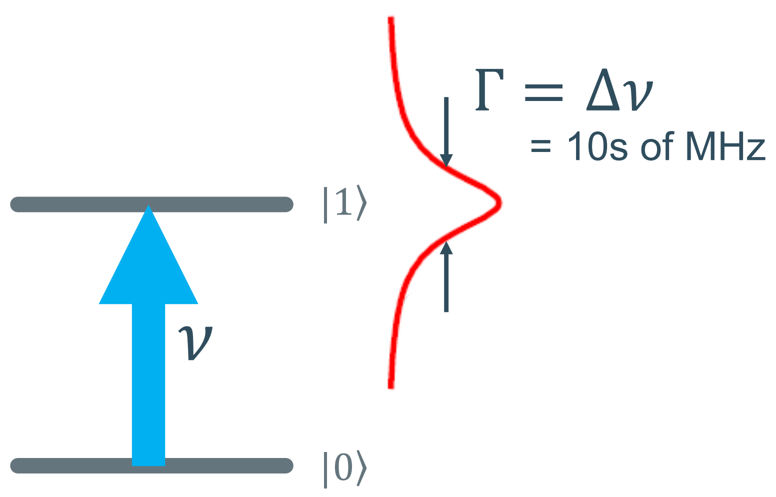
$$\sigma_{Ion} \cdot \varphi > 1$$





Linewidth (@ 2000 C)

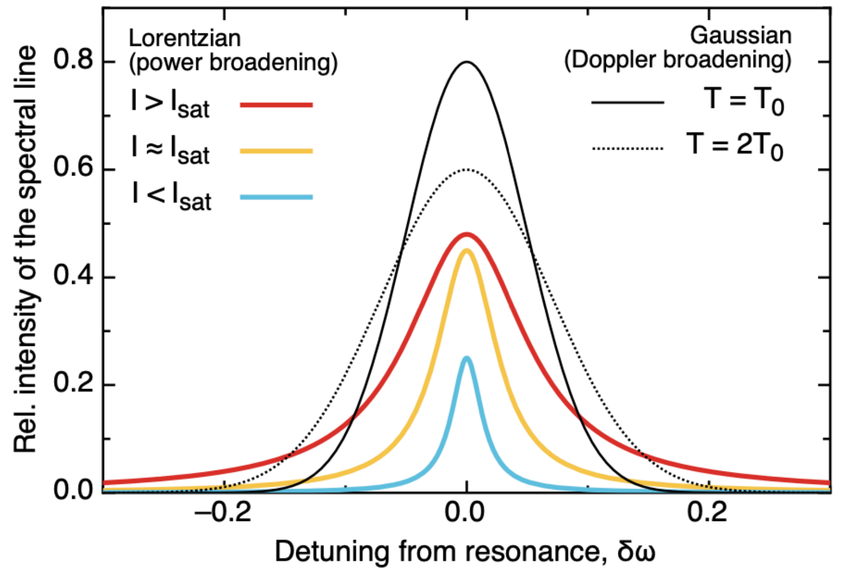
$$\Delta t \, \Delta E \geq \frac{\hbar}{2}$$

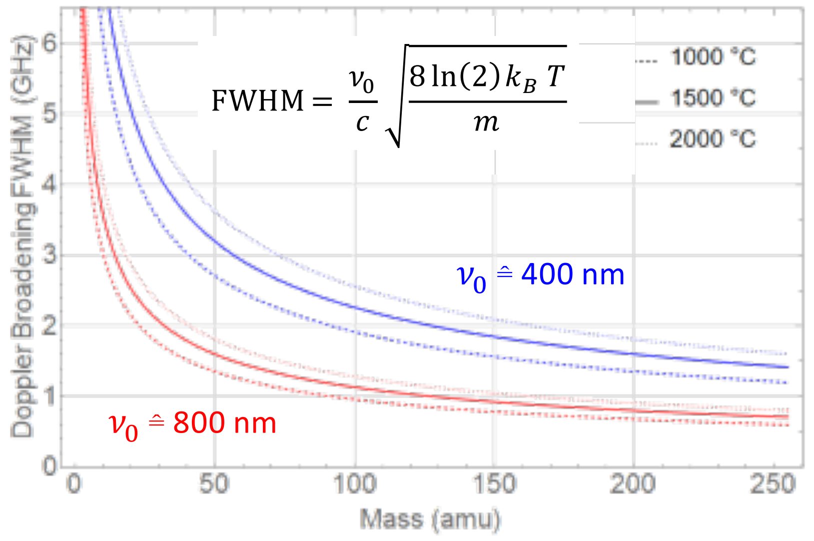


Strong transition

-> Short half-life O(ns)

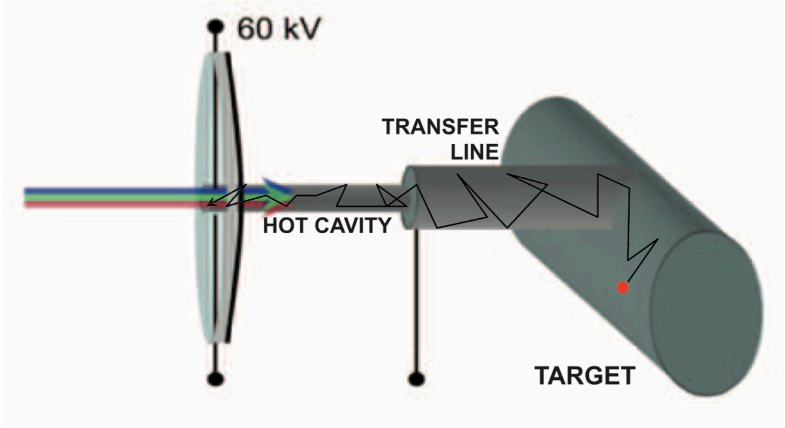
-> Broad linewidth





1-10 GHz

Repetition Rate

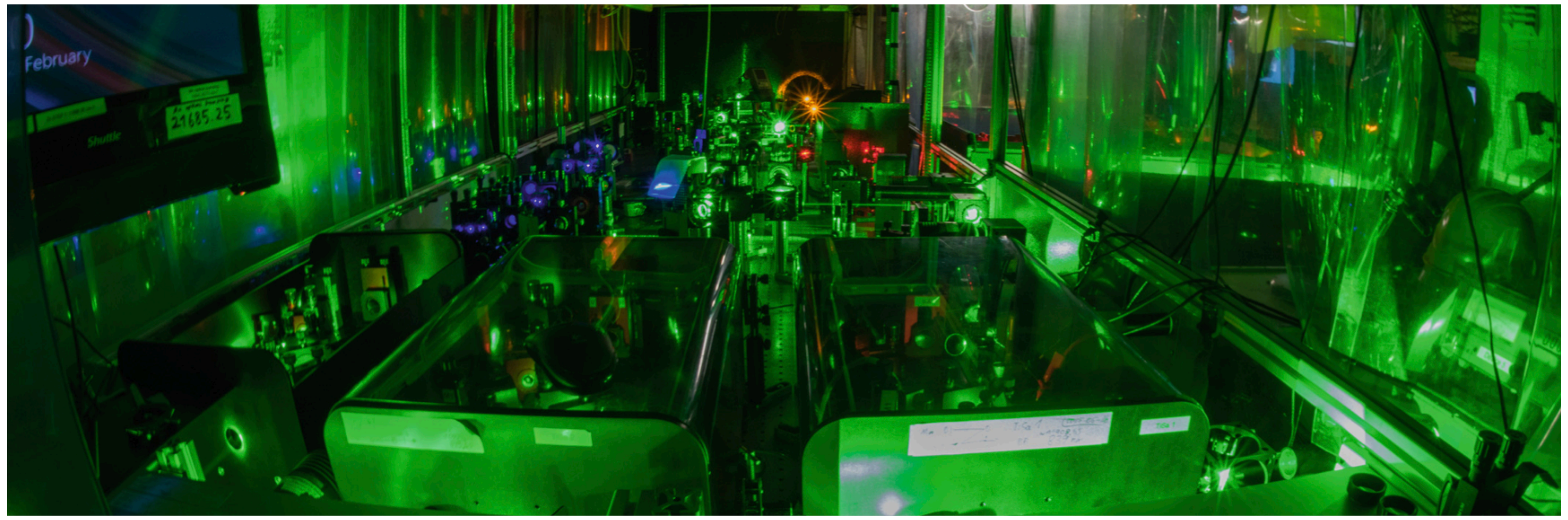


Each atom should be exposed to at least 1 laser pulse

1/repetition < atom residency time within the laser/atom interaction region

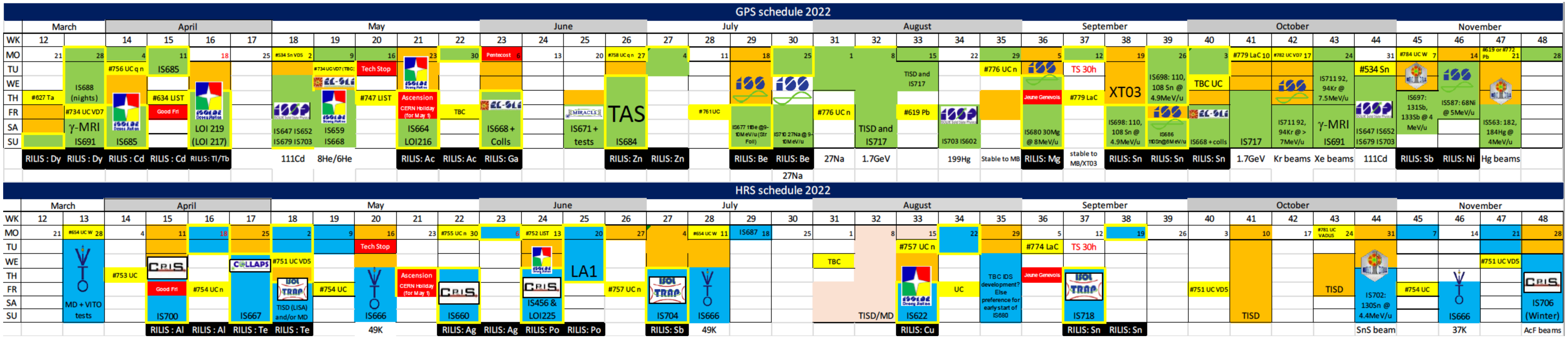
Repetition rate / average power trade-off

10 kHz @ 10mJ = 100 W



Now how is this actually done practically..

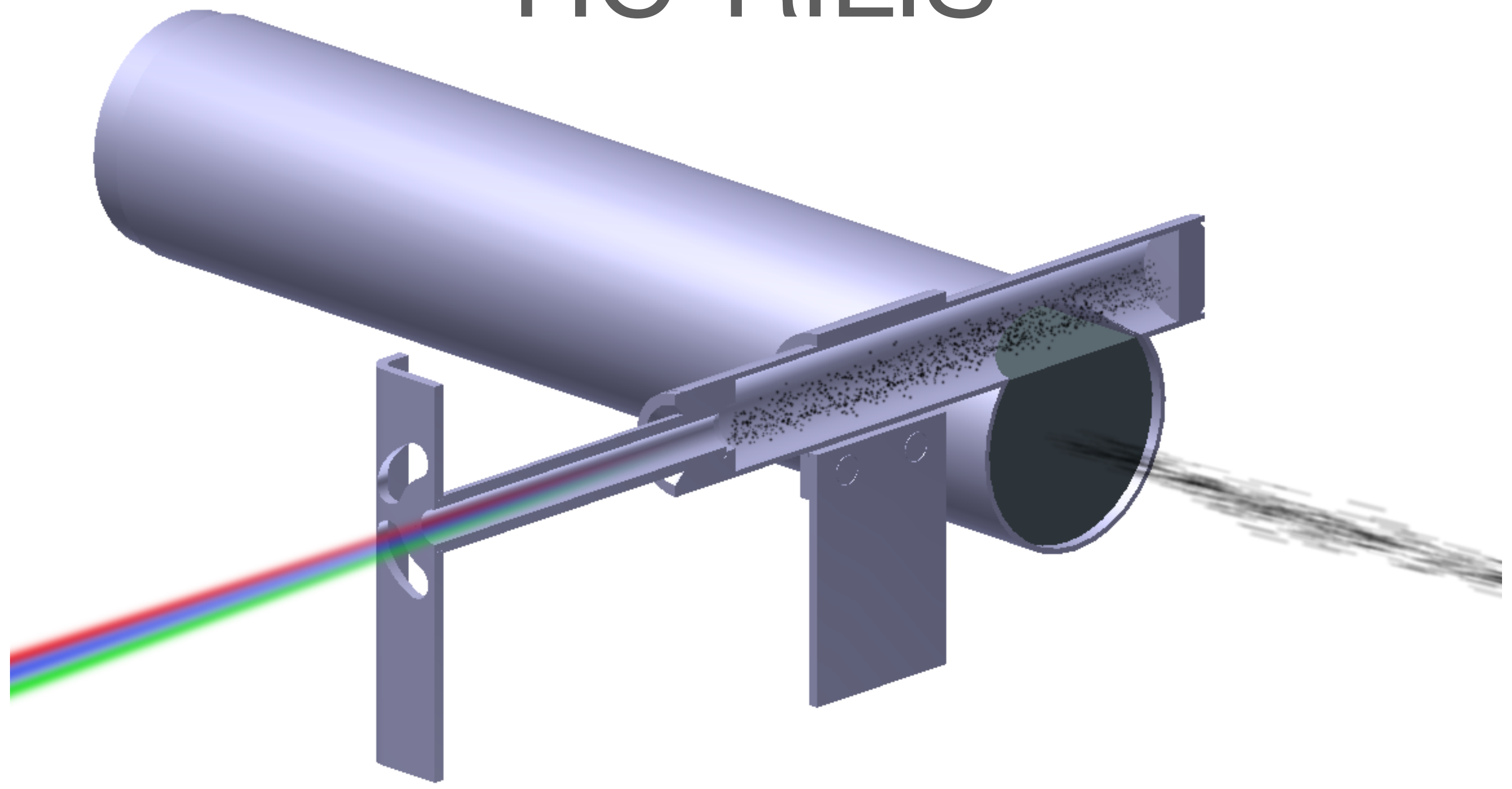
ISOLDE operation in 2022….



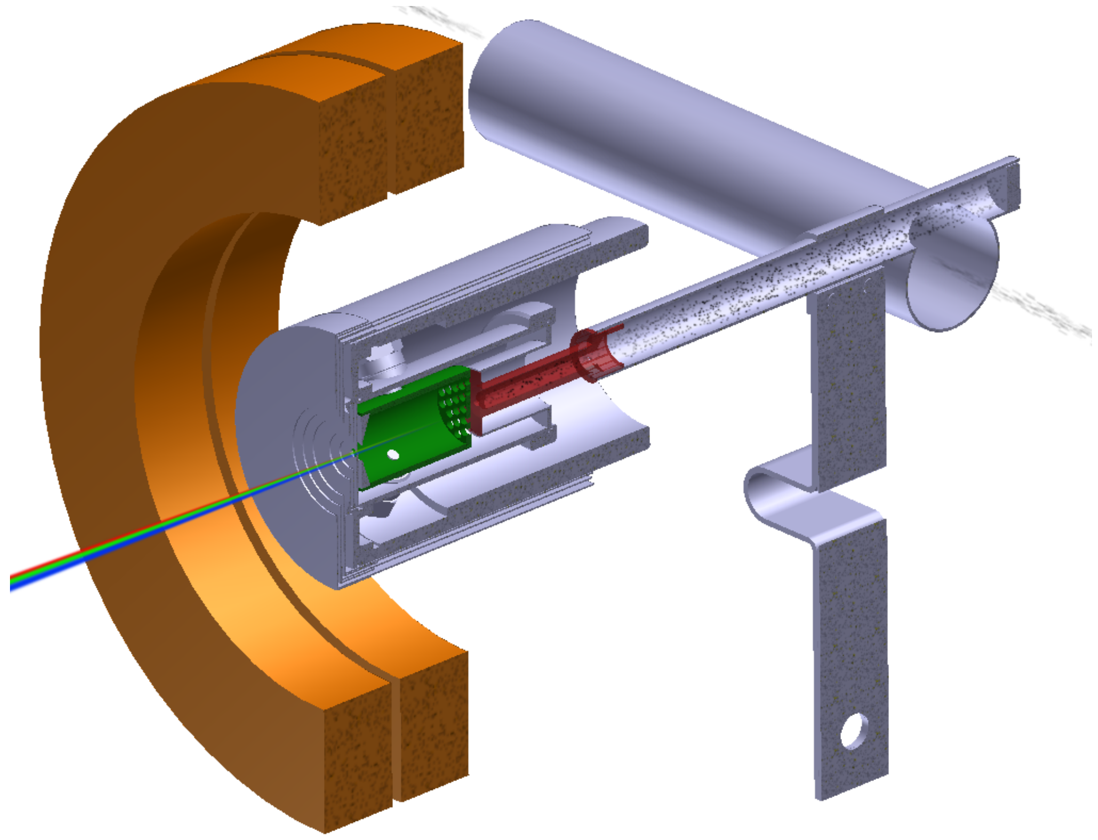
RILIS overview

3 ion source types:

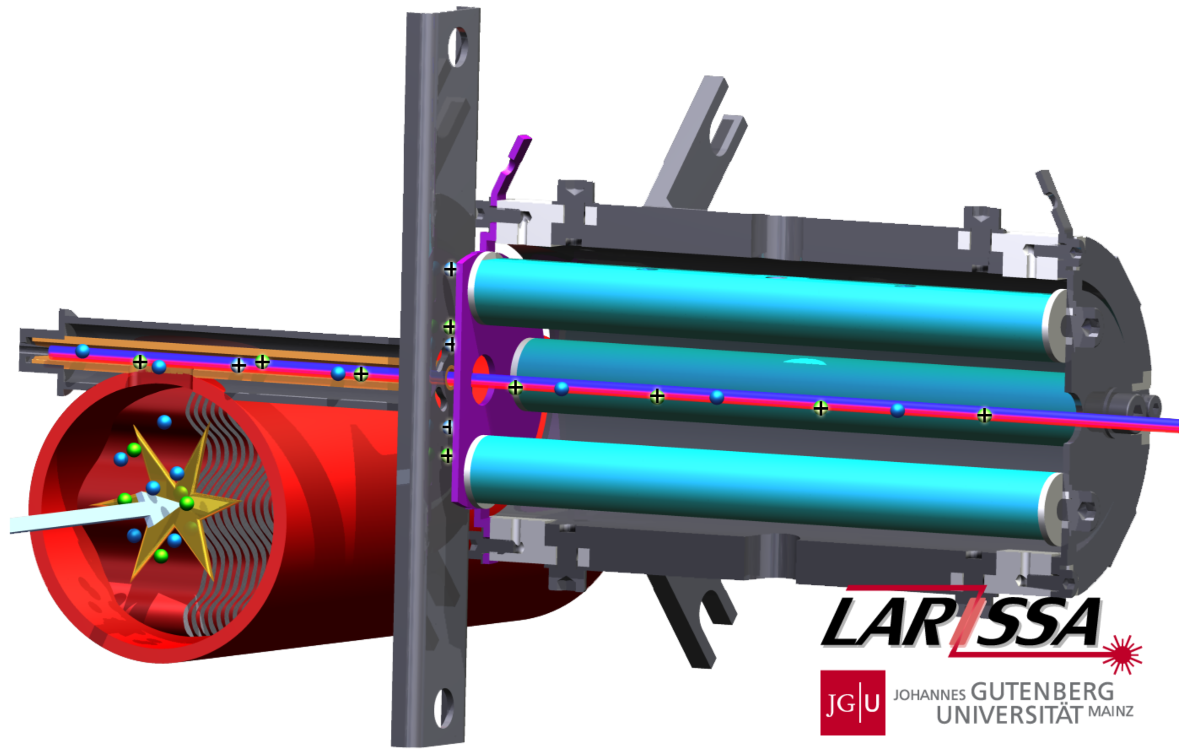
HC-RILIS

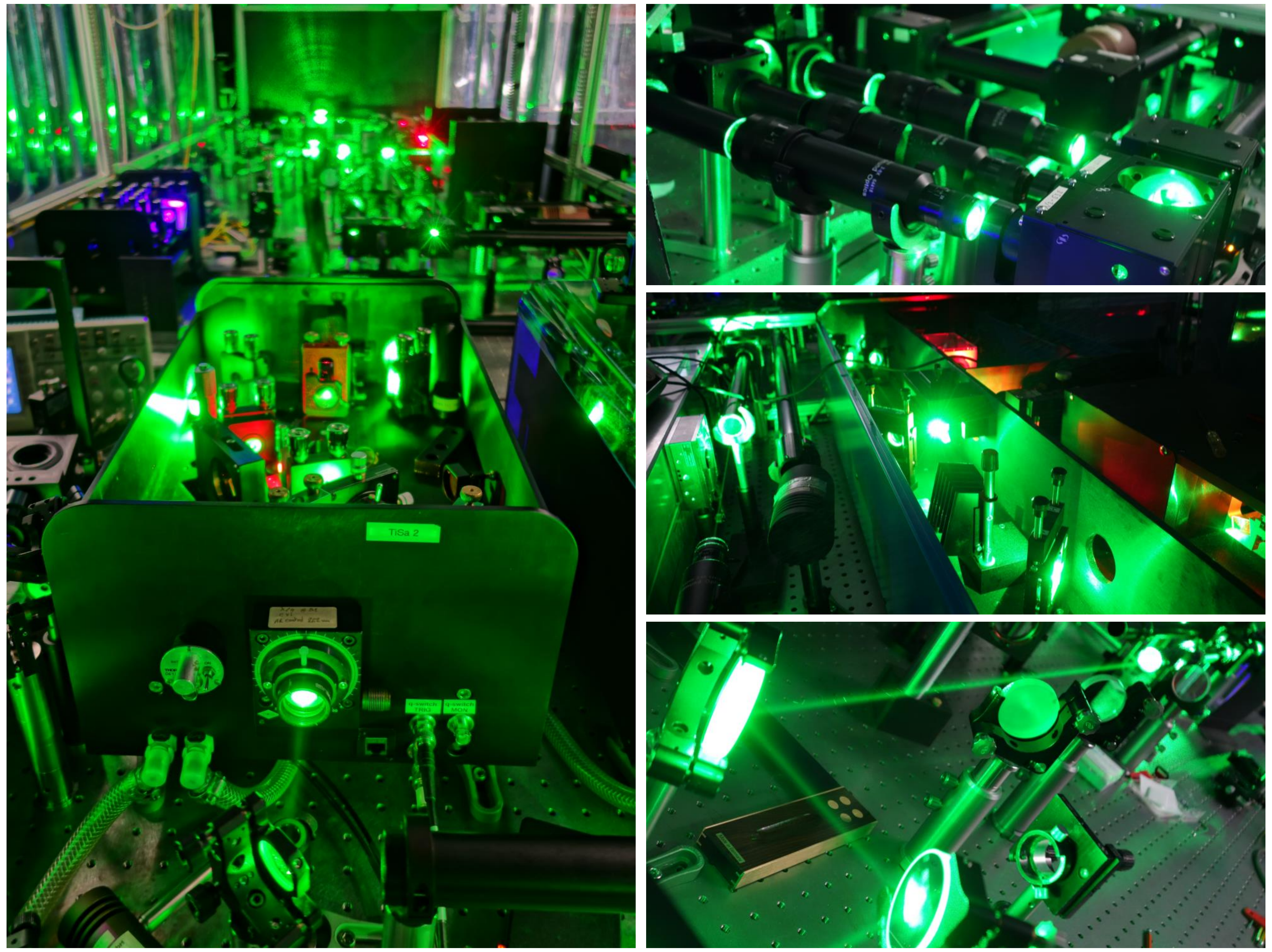


VADLIS



LIST

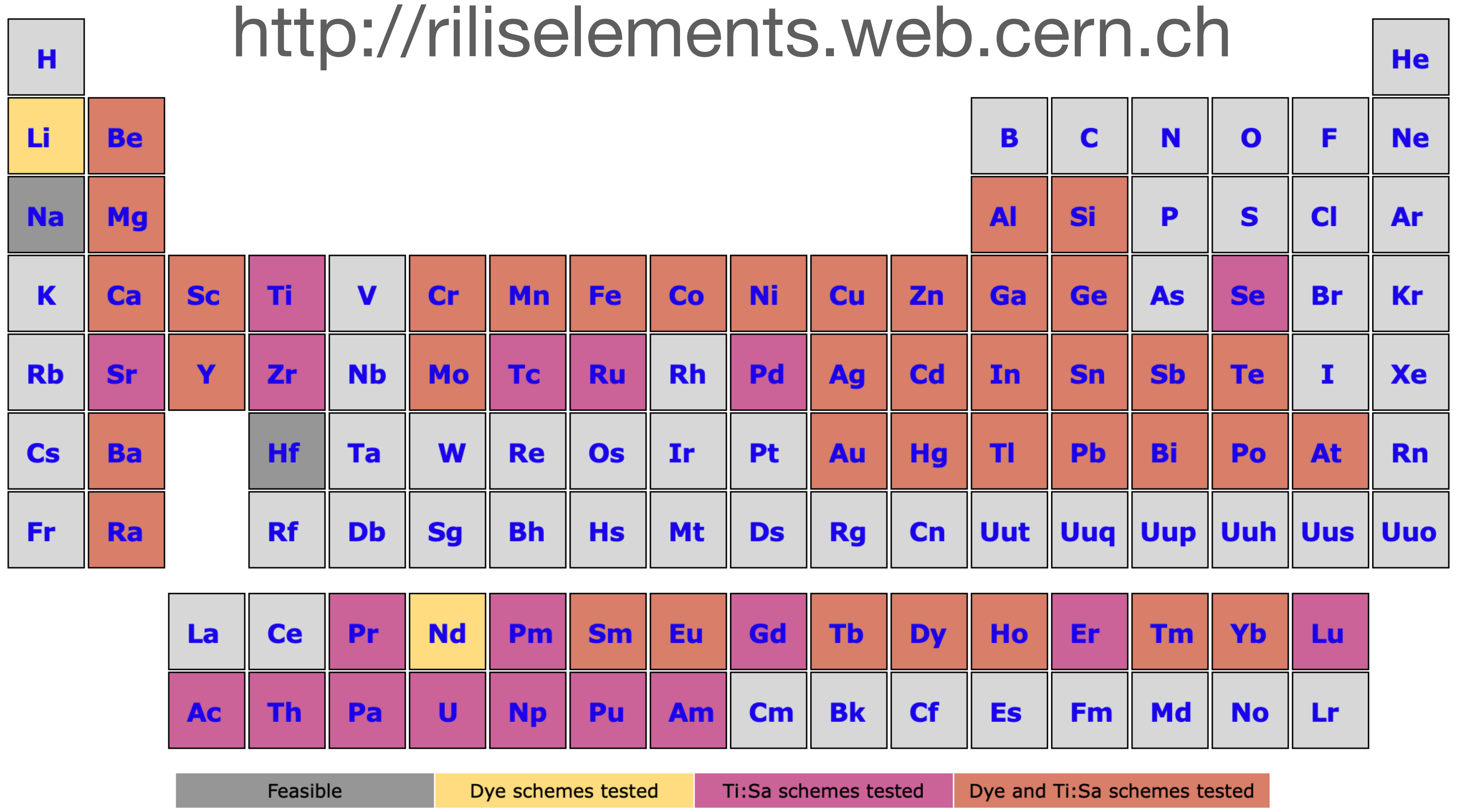




6 tuneable lasers

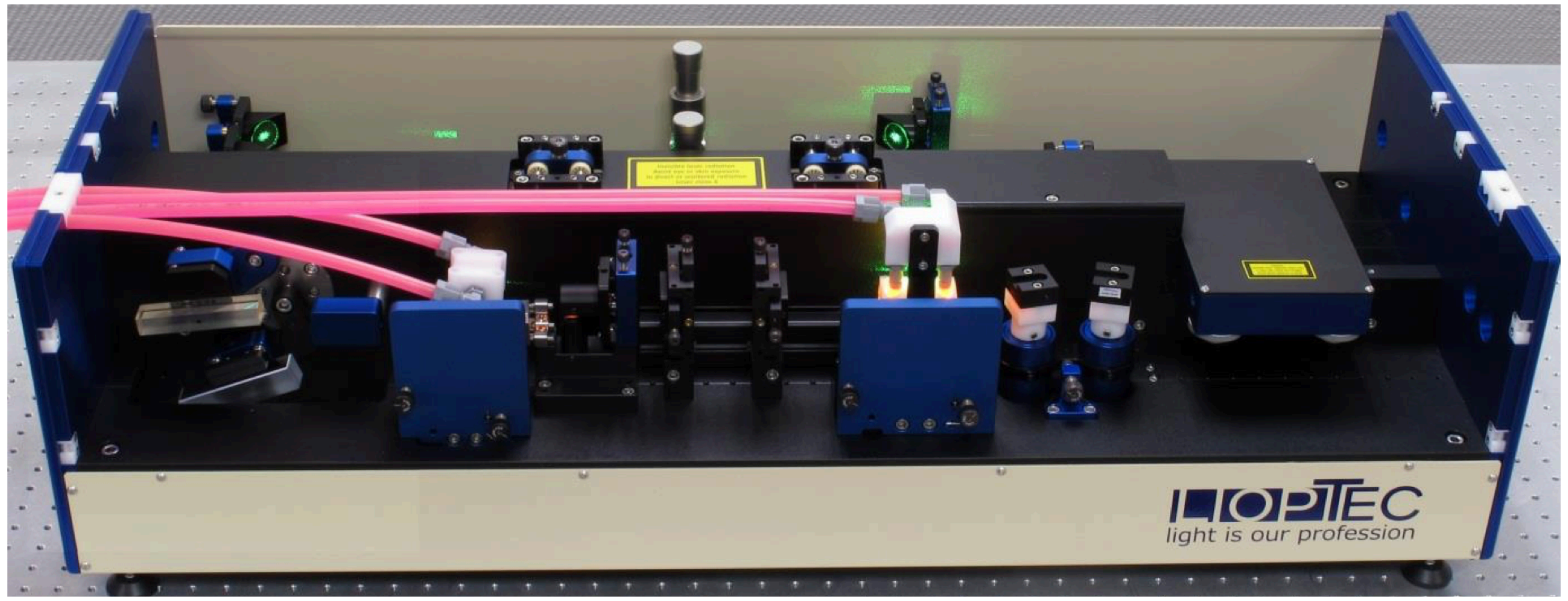
40 ionisation schemes

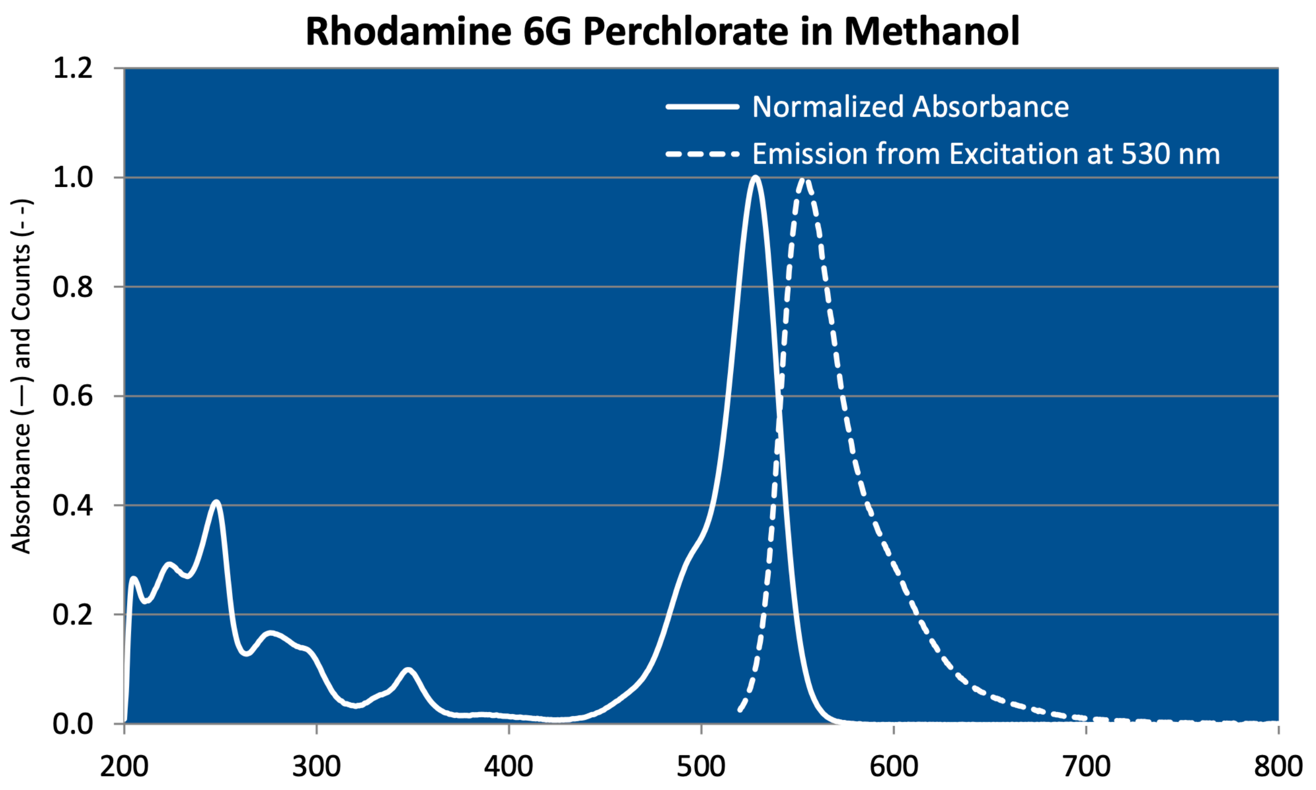
http://riliselements.web.cern.ch

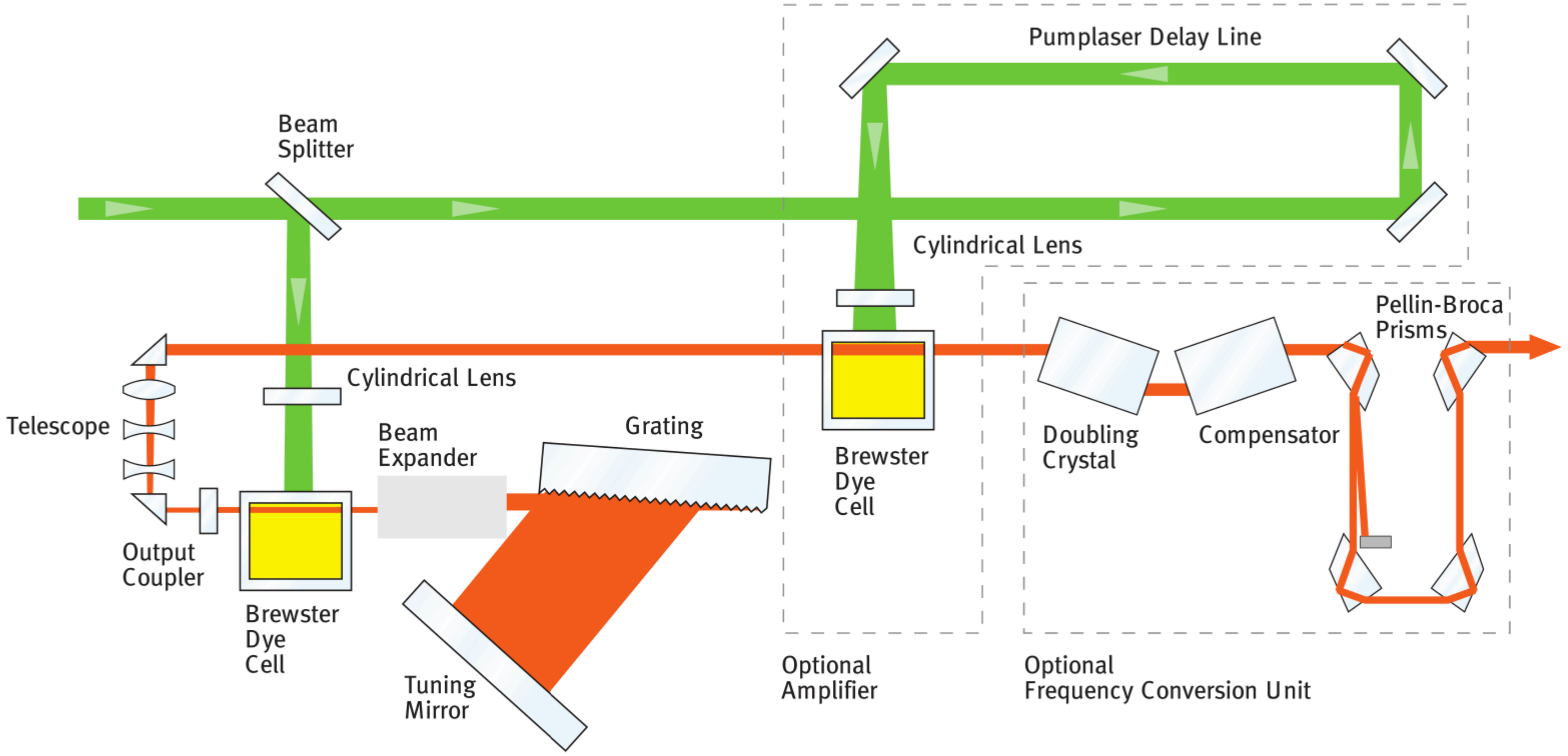


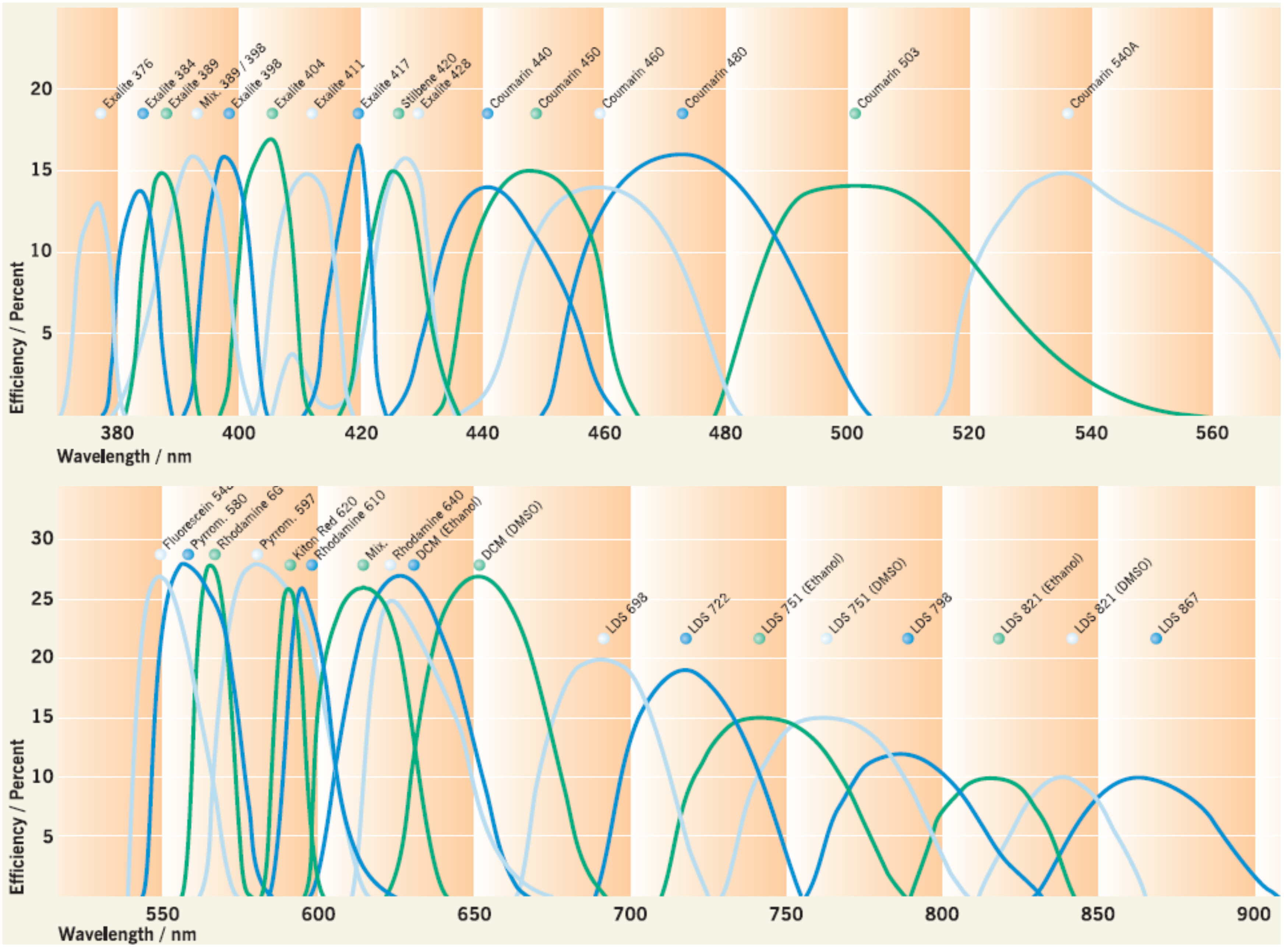
+ MEDICIS (MELISSA), Offline 2 , LARIS

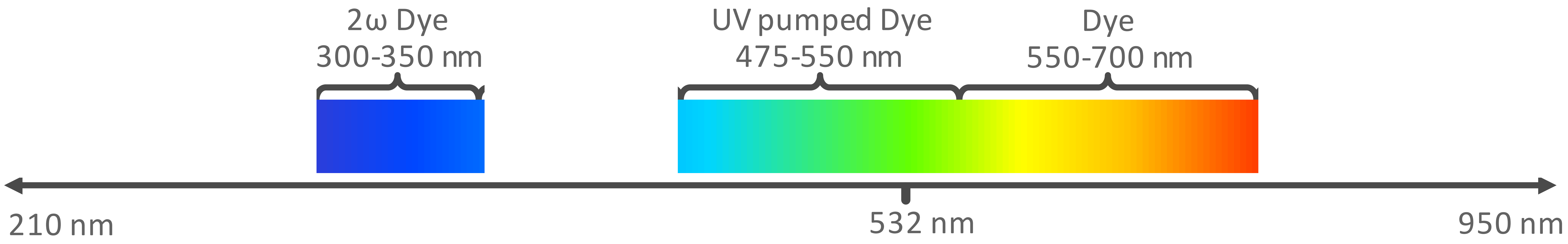
Dye laser


LIOPTEC
light is our profession

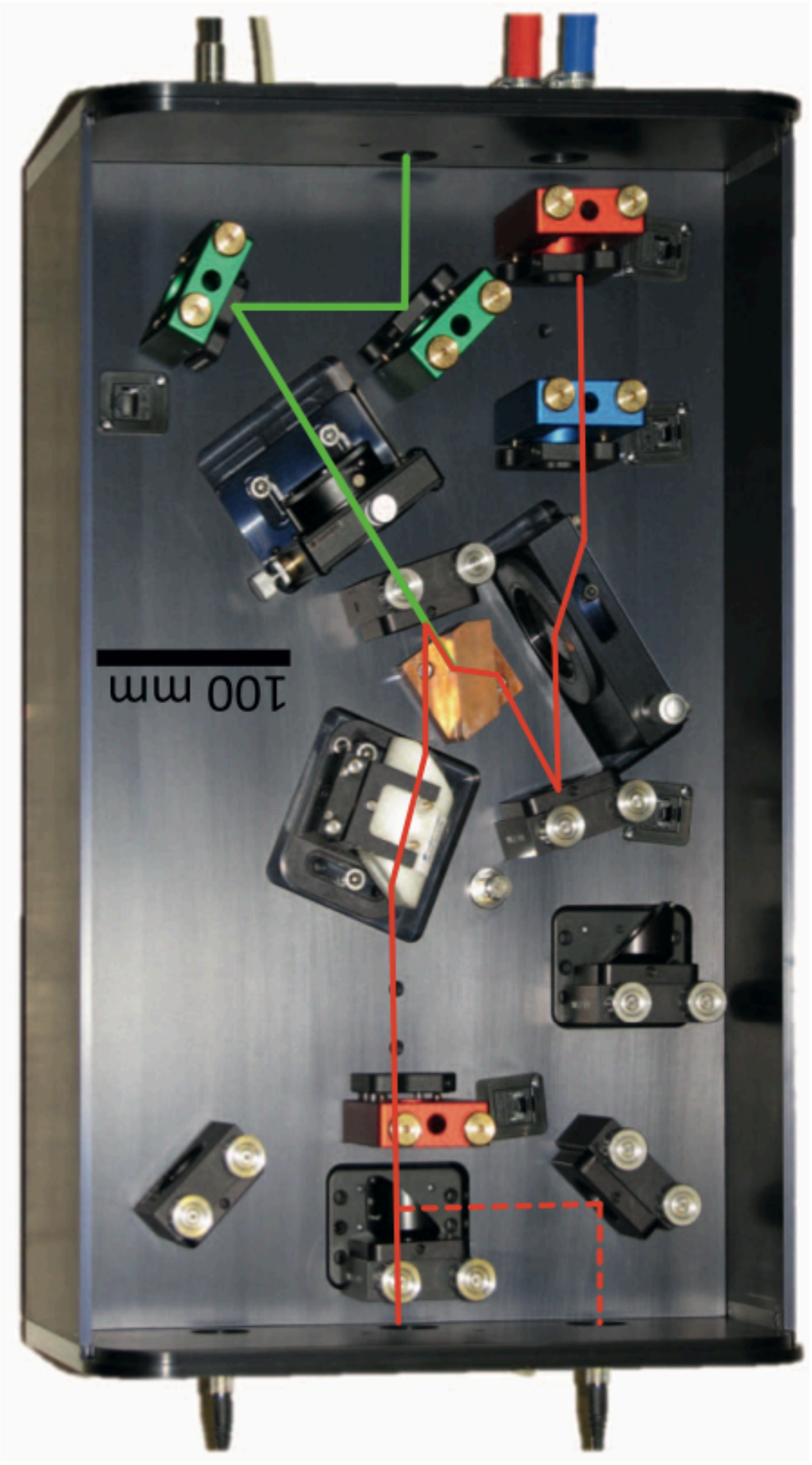

Rhodamine 6G Perchlorate in Methanol
Normalized Absorbance
Emission from Excitation at 530 nm
Absorbance (—) and Counts (- -)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
200
300
400
500
600
700
800

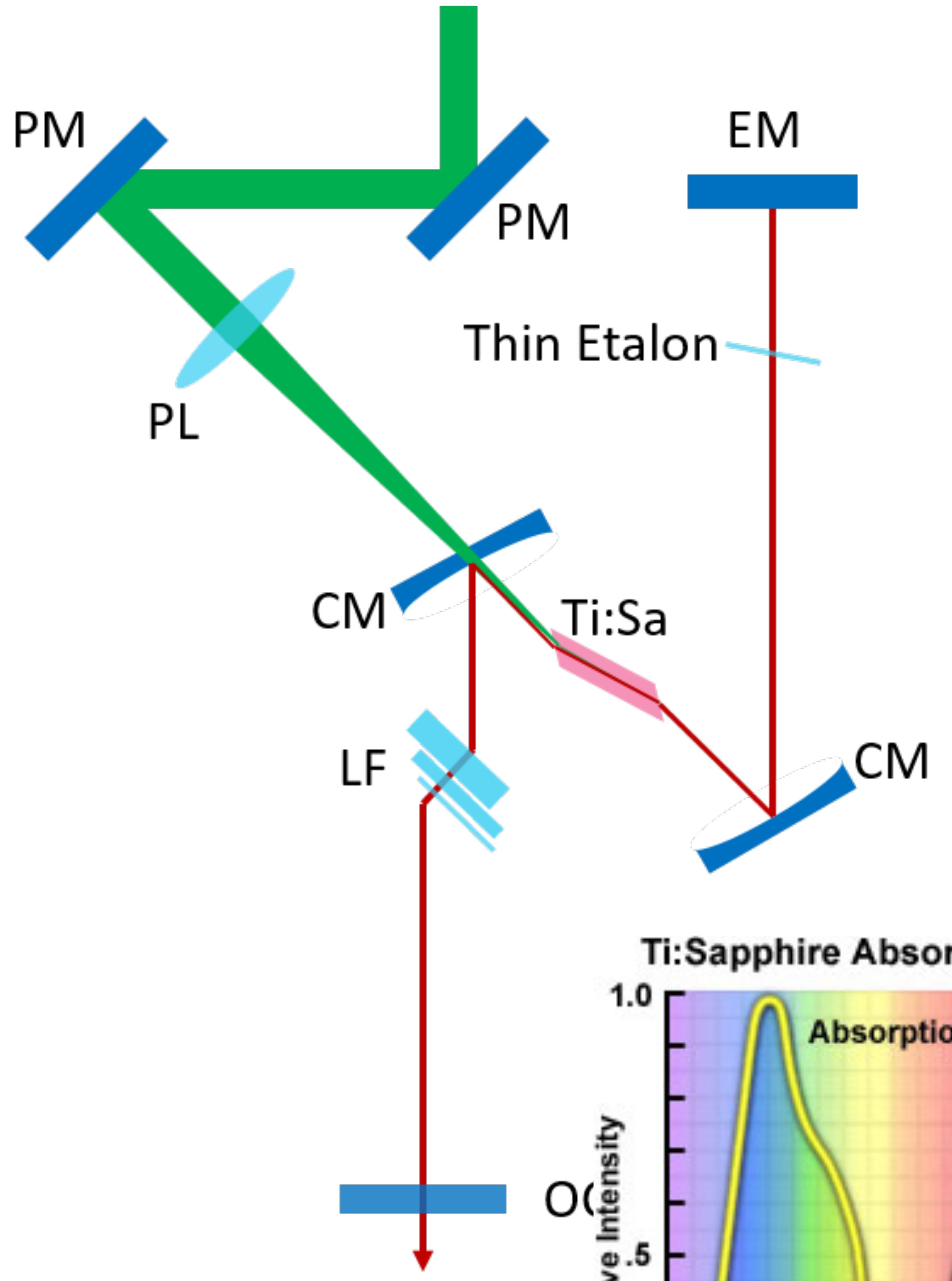

Pumplaser Delay Line
Beam Splitter
Cylindrical Lens
Cylindrical Lens
Pellin-Broca Prisms
Telescope
Beam Expander
Grating
Brewster Dye Cell
Doubling Crystal
Compensator
Output Coupler
Brewster Dye Cell
Tuning Mirror
Optional Amplifier
Optional Frequency Conversion Unit

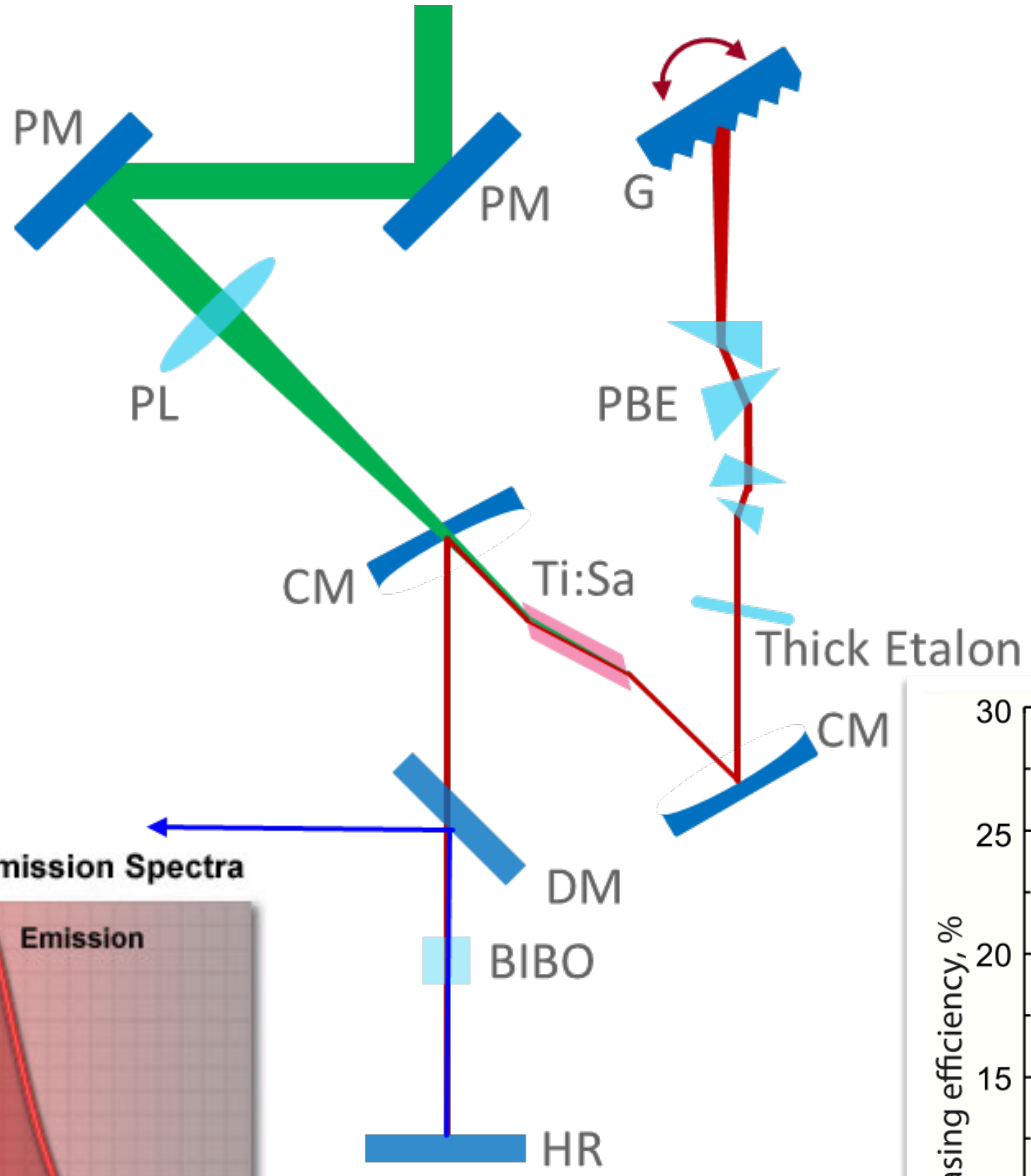

Efficiency / Percent
Wavelength / nm
380
400
420
440
460
480
500
520
540
560
Efficiency / Percent
Wavelength / nm
550
600
650
700
750
800
850
900

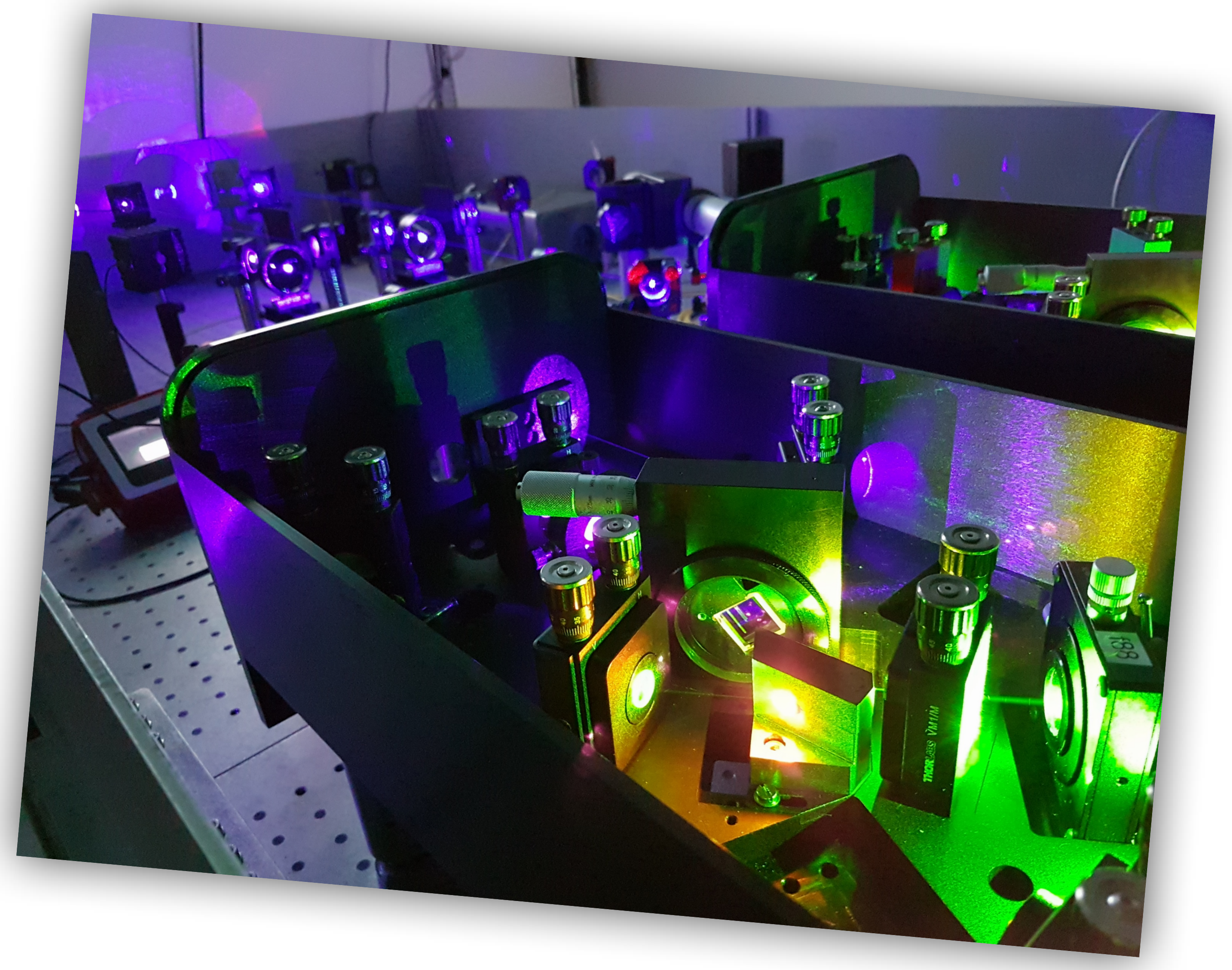

2ω Dye
300-350 nm
UV pumped Dye
475-550 nm
Dye
550-700 nm
210 nm
532 nm
950 nm

Ti:Sapphire laser









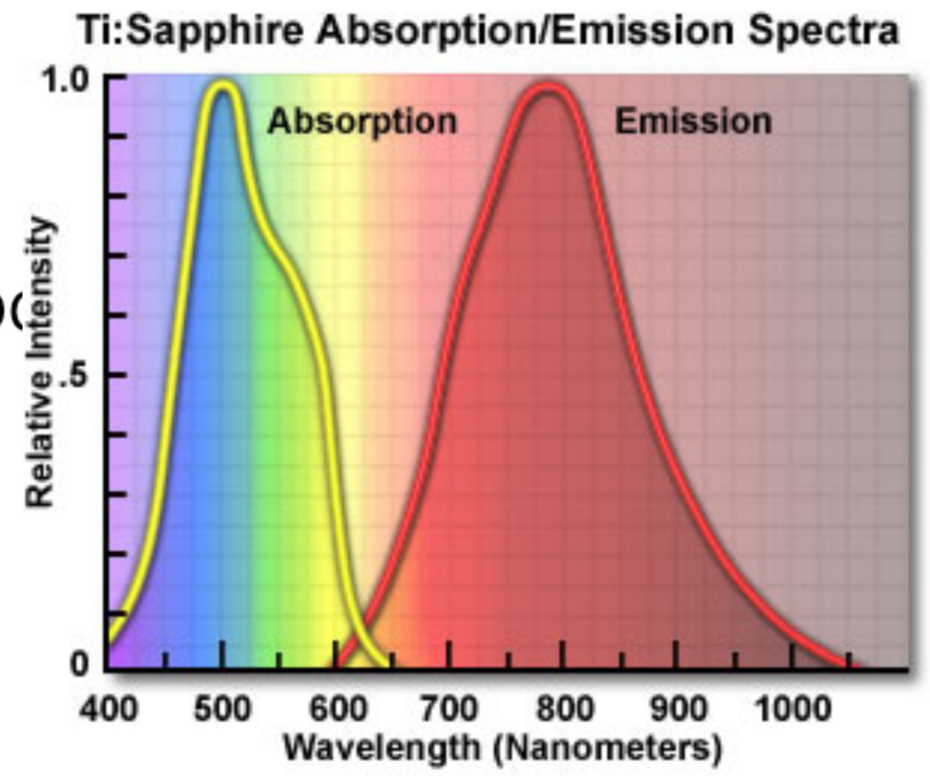
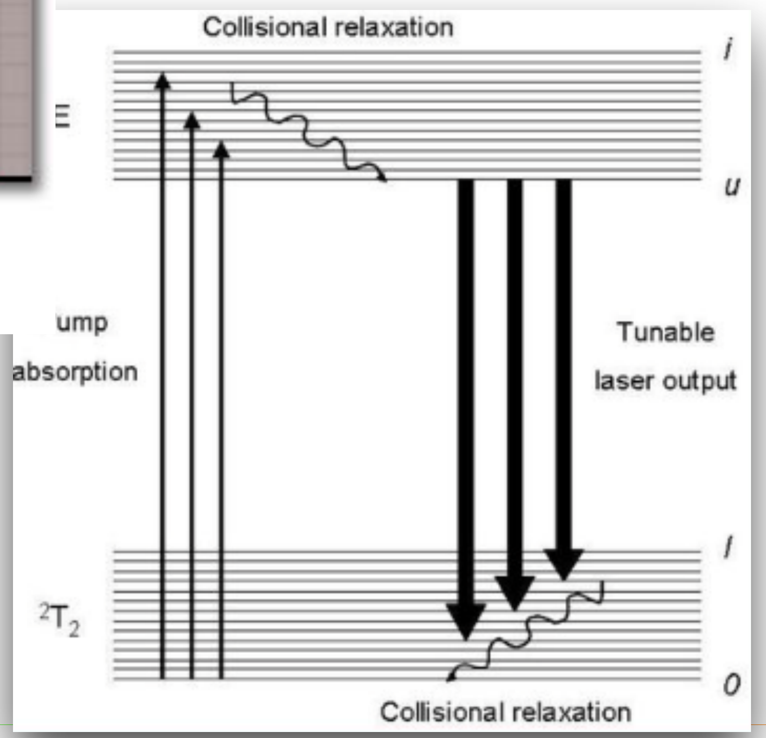
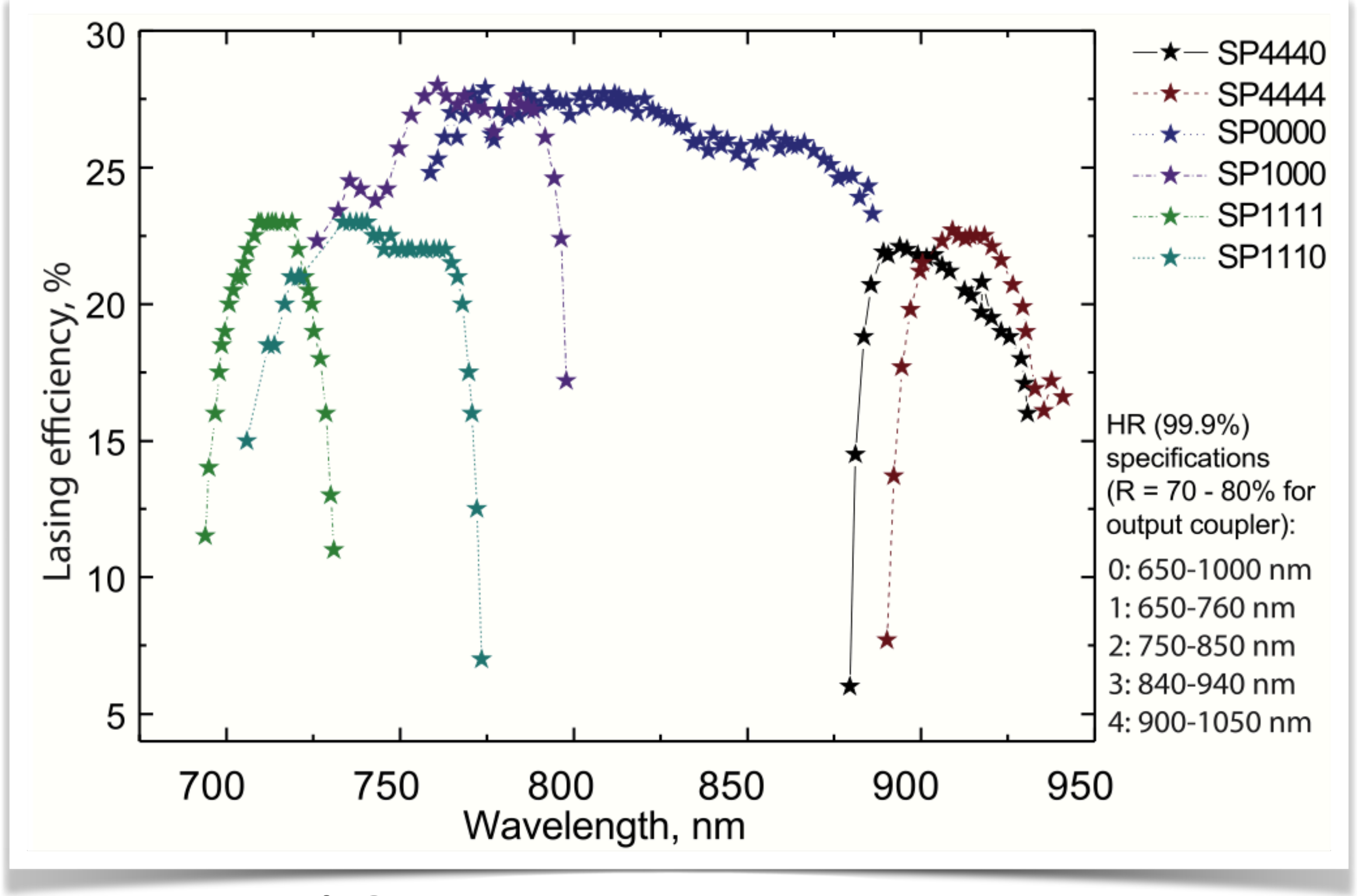
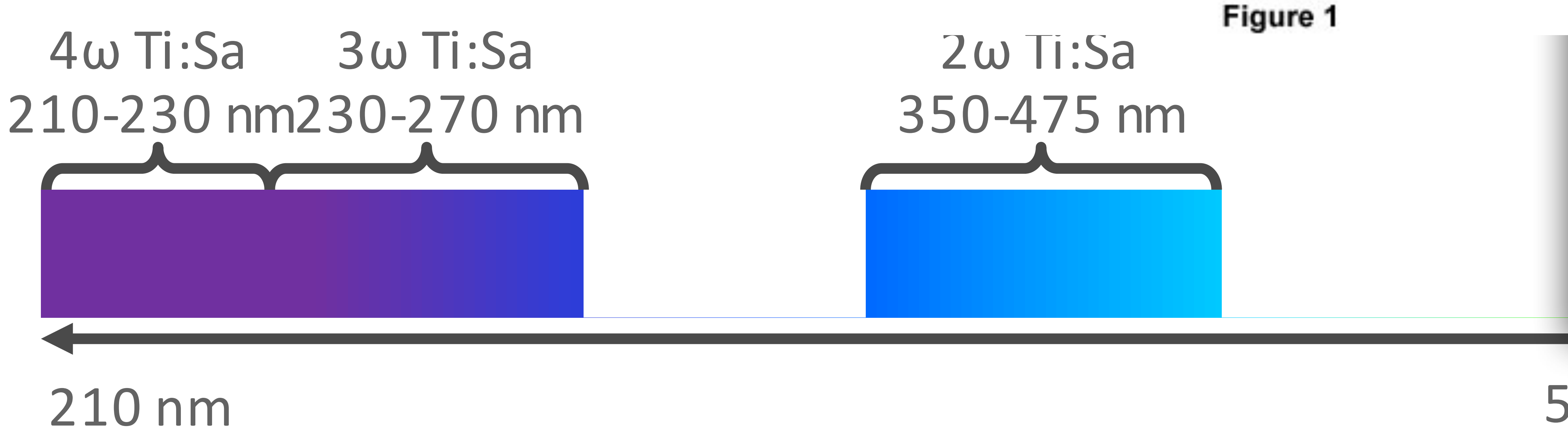
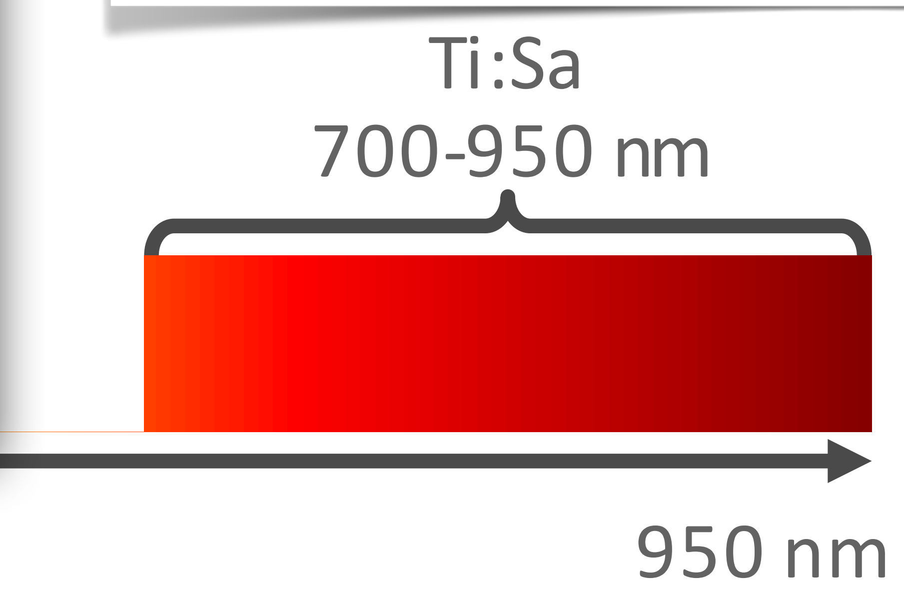


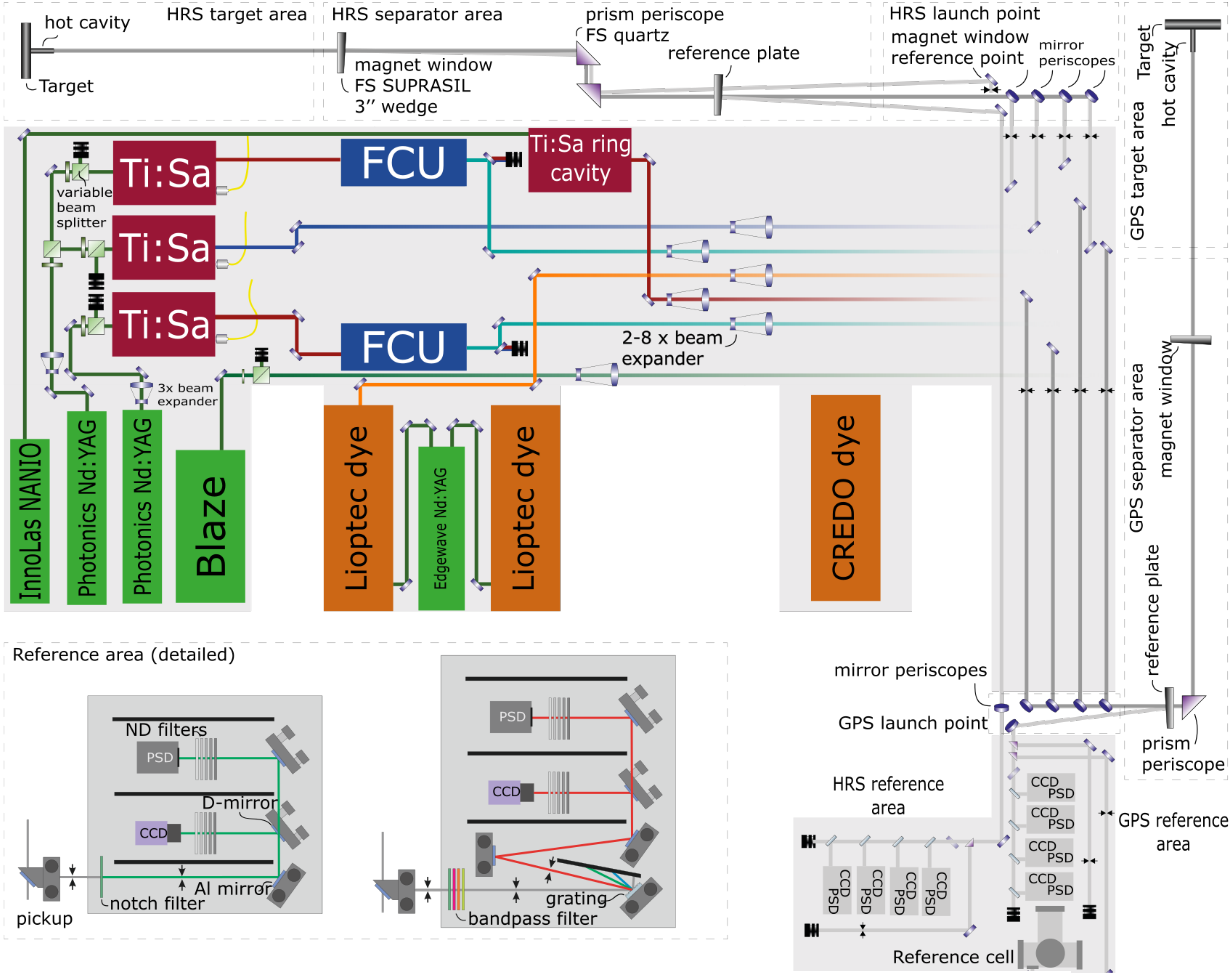
Figure 1





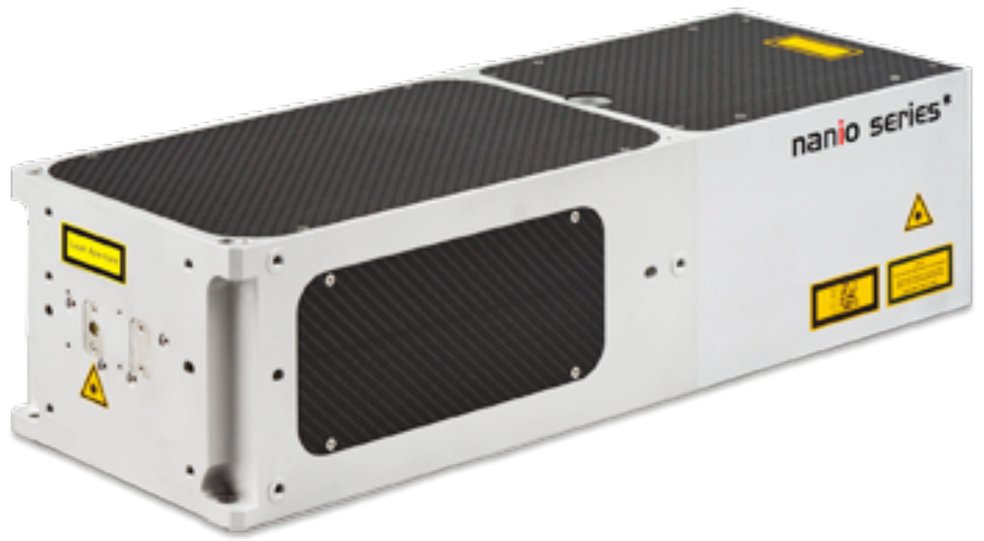






S. Rothe et al. Nuclear Instruments and Methods in Physics Research B 376 (2016) 91–96

TiSa pump lasers

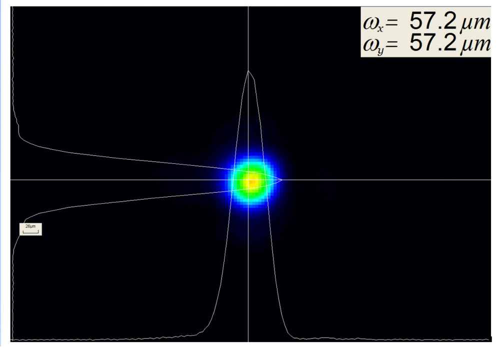


18 W, 40 ns, 532 nm

60 W, 150 ns, 532 nm

Dye pump laser

10 kHz (9 ns), 100 W @ 532 nm

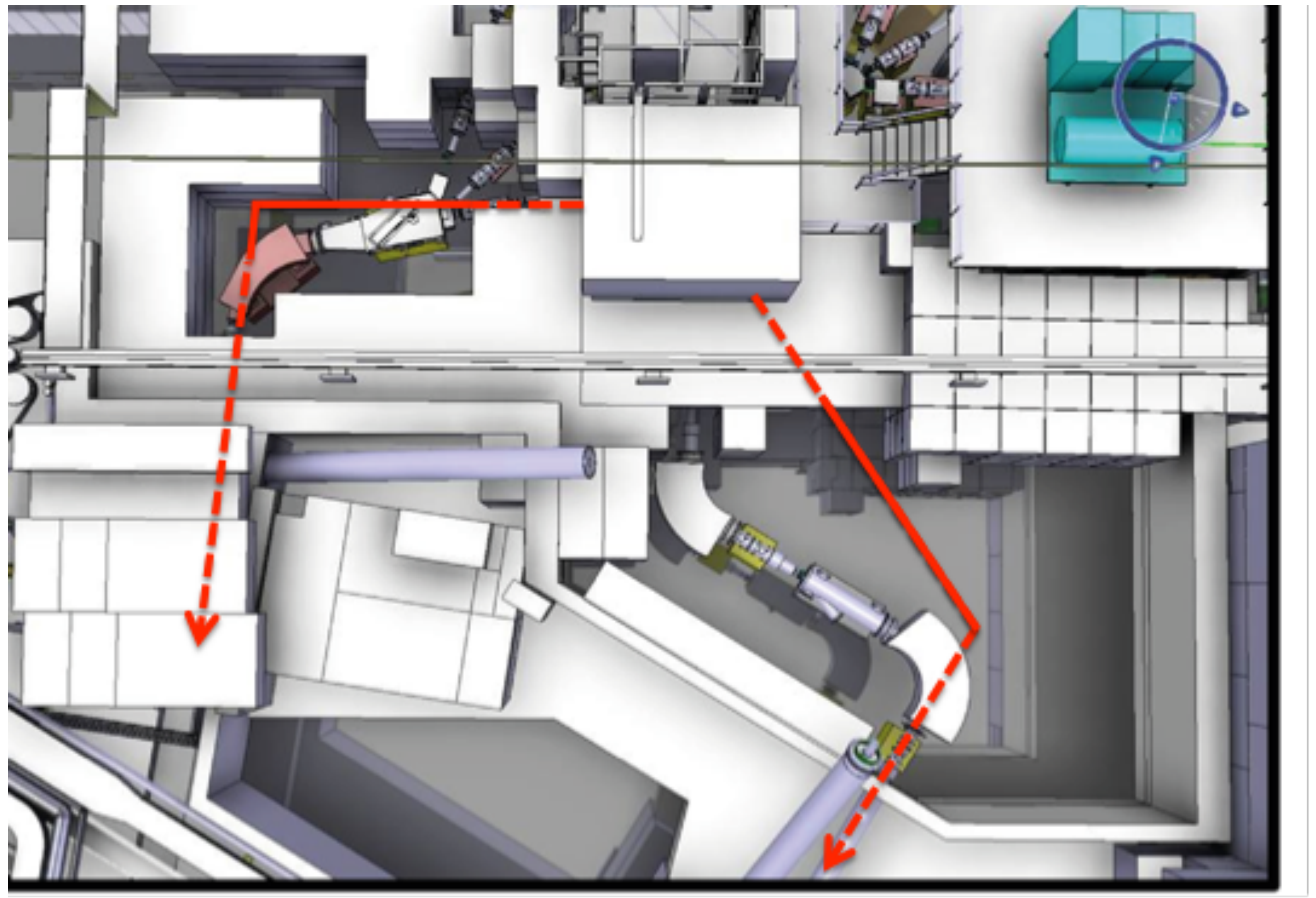


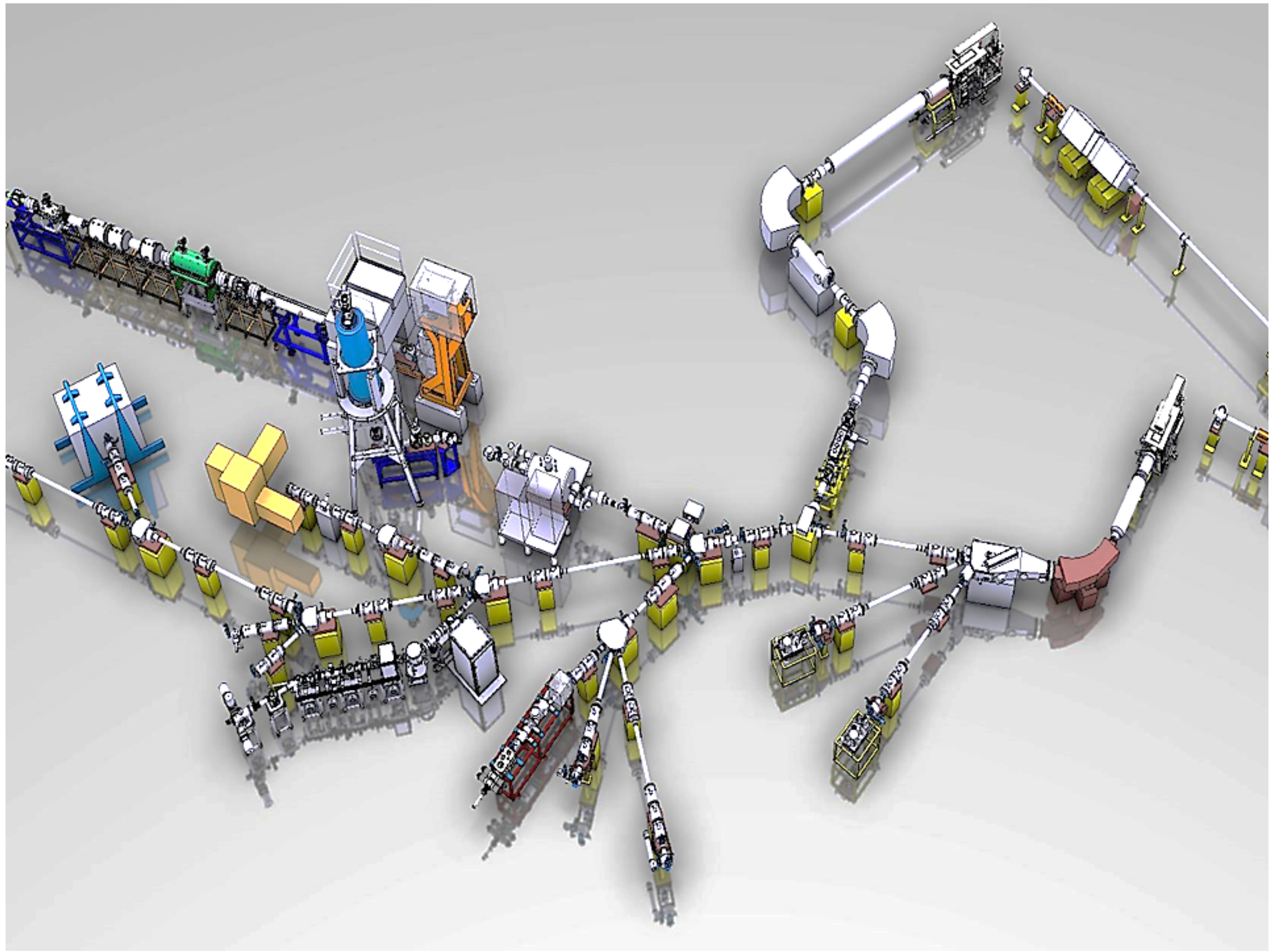
TEM 00
$M^2 = 1.1$
Circular, gaussian beam

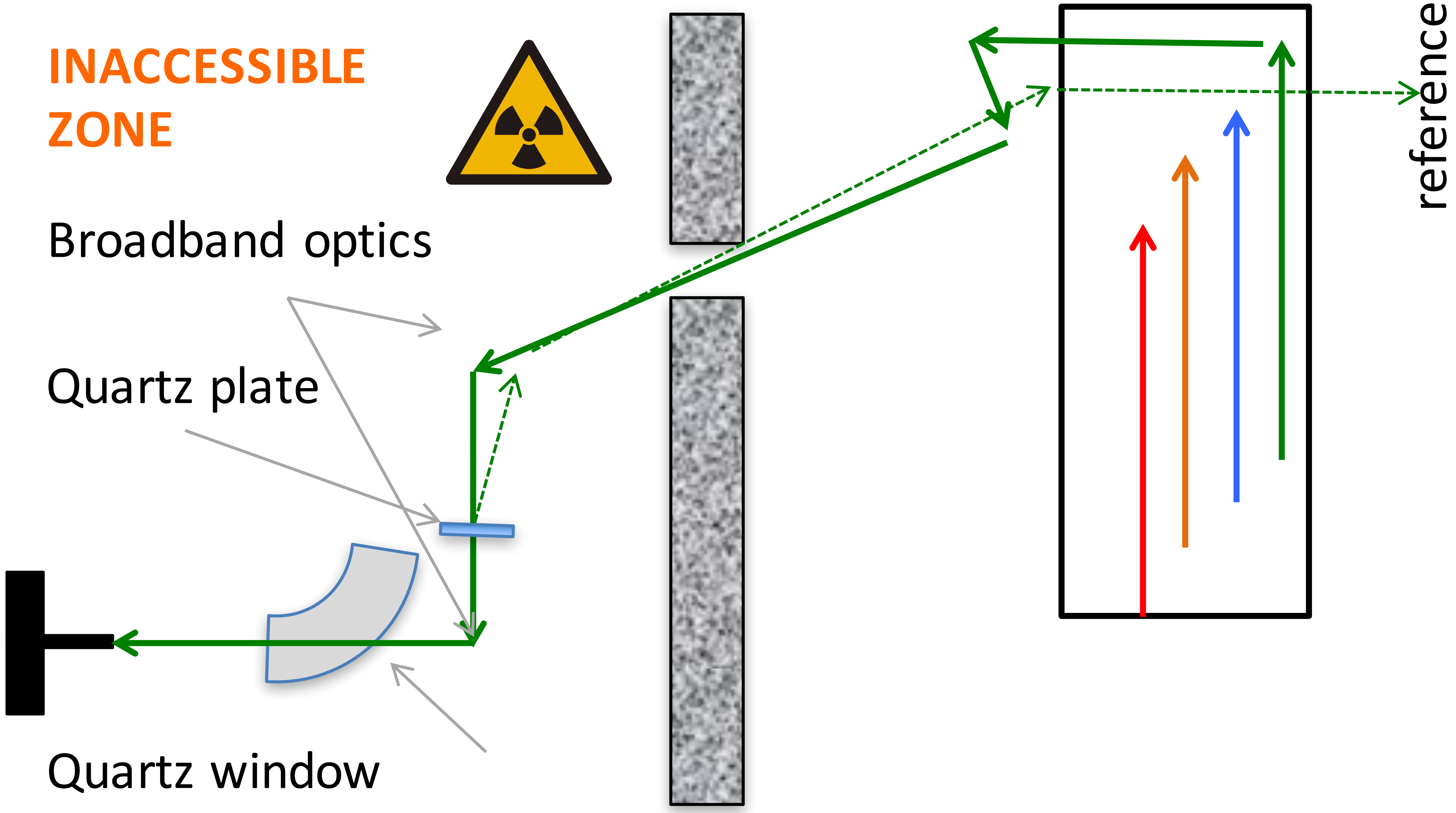
Non-resonant ionisation

40 W, 17 ns, 532 nm

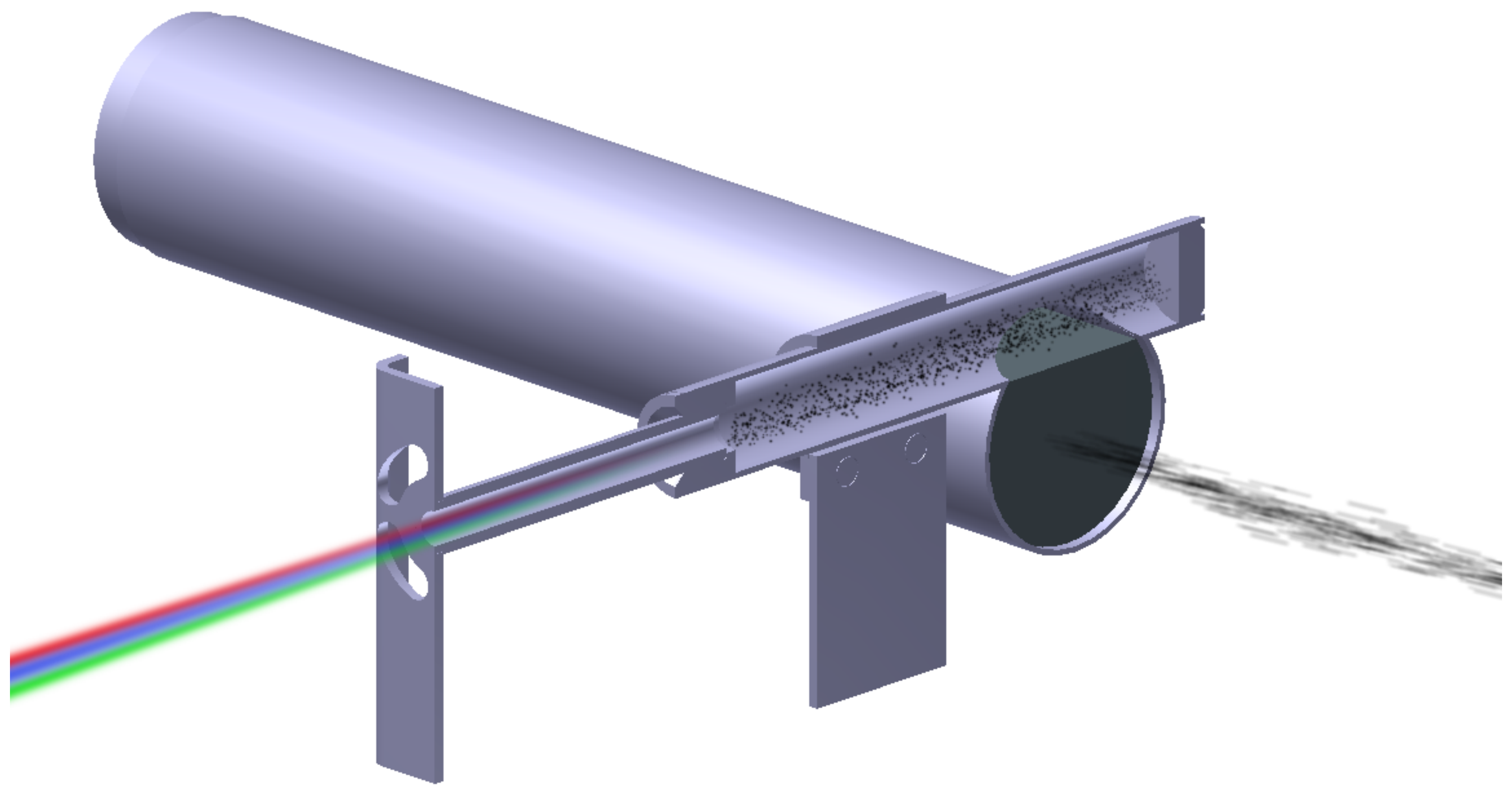
Beam transport to targets

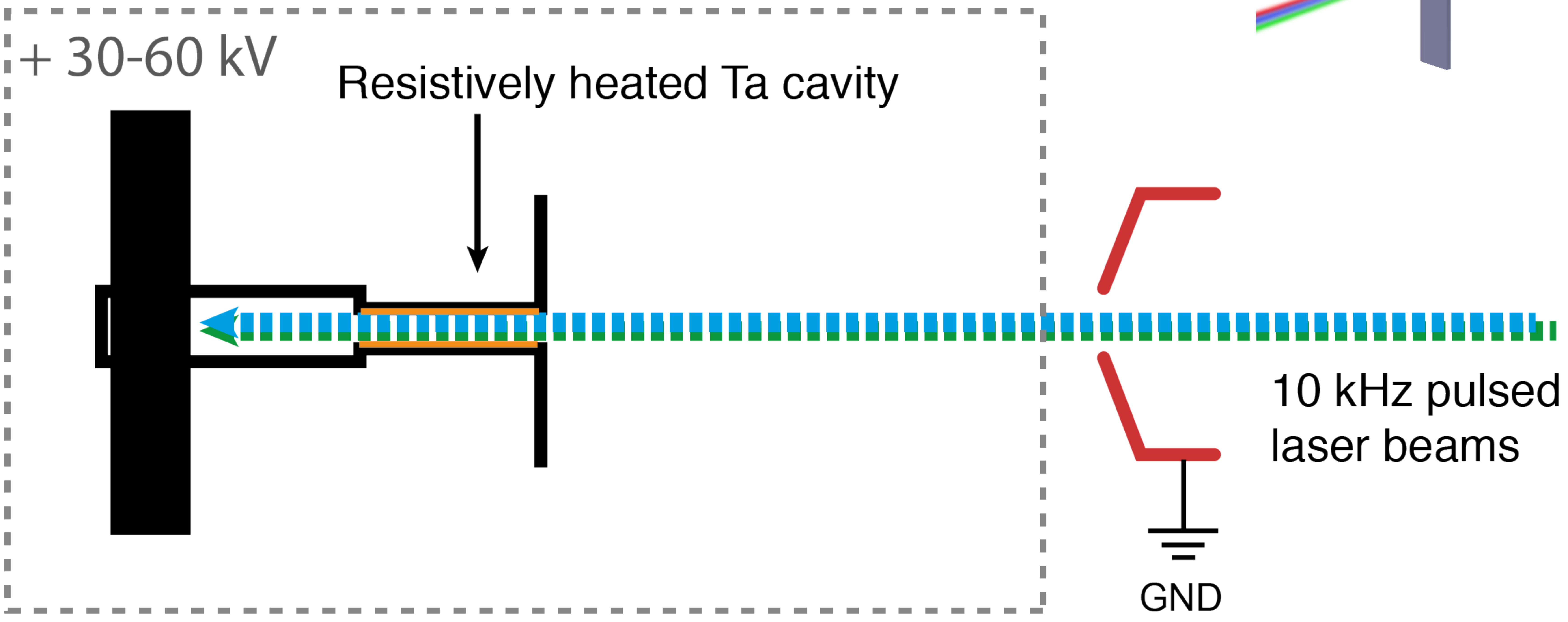






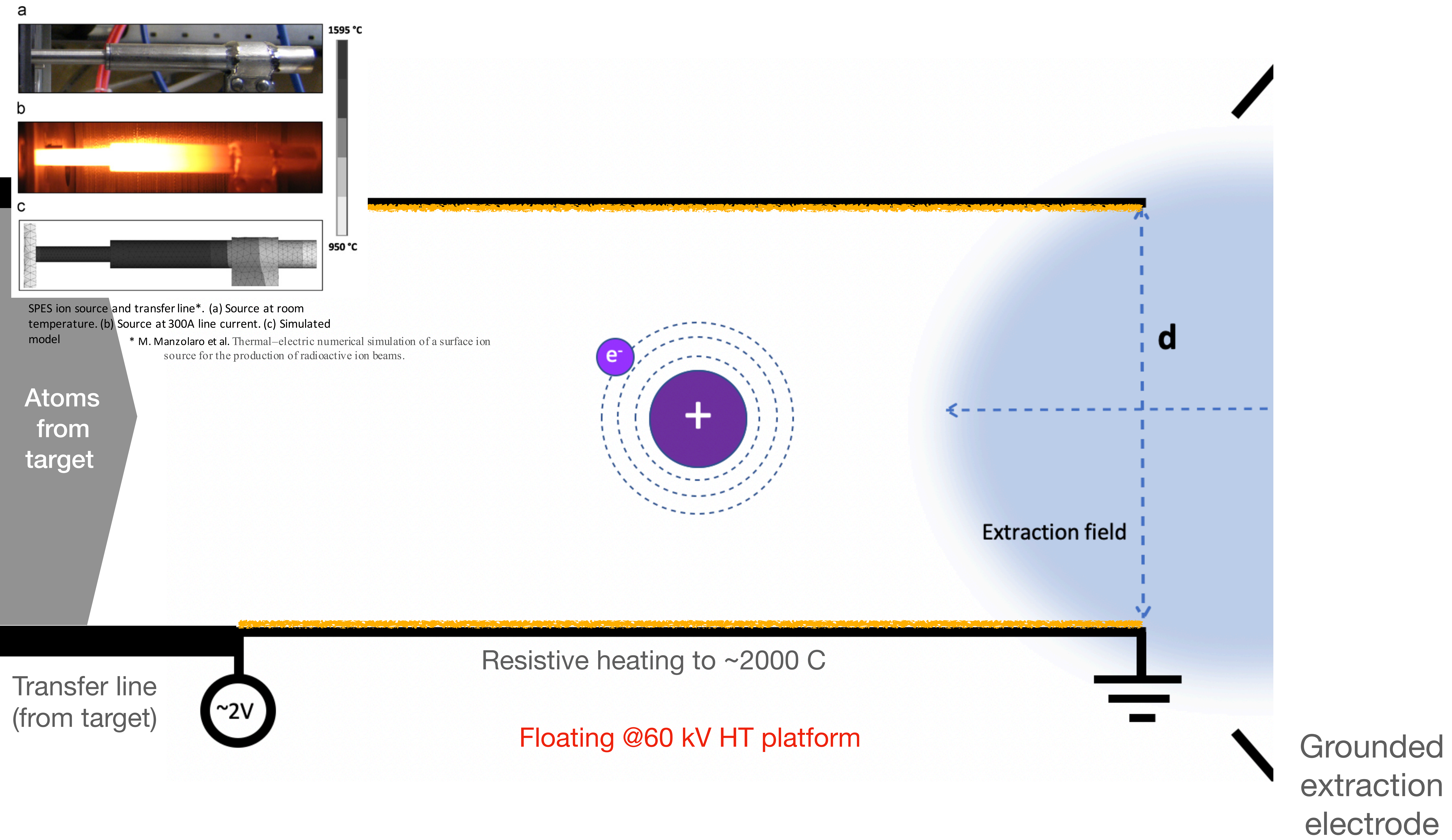
Hot-cavity RILIS





- Simple, robust, reliable
- Problem with surface-ionised isobars
- Ion capacity limit in the range of 10-100 nA


Atoms
from
target
e-
+
d
Extraction field
Transfer line
(from target)
~2V
Floating @60 kV HT platform
Grounded
extraction
electrode



SPES ion source and transfer line*. (a) Source at room temperature. (b) Source at 300A line current. (c) Simulated model

* M. Manzolaro et al. Thermal–electric numerical simulation of a surface ion source for the production of radioactive ion beams.

* V. Panteleev et al. Enhancement of ionization efficiency of surface, electron bombardment and laser ion sources by axial magnetic field application

** R. Kirchner. Progress in ion source development for on-line separators.

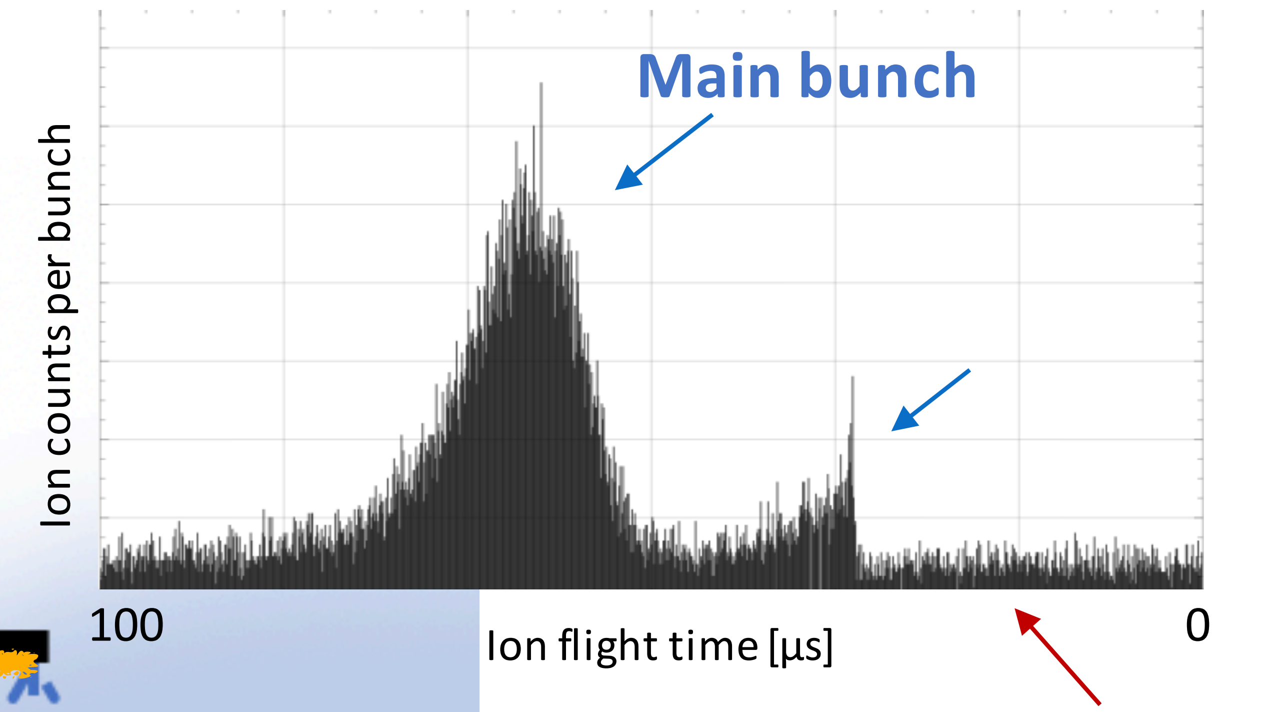

Surface ionization efficiency
Ion density
Work function
Ionization potential
$\frac{n_i}{n_0} = \frac{g_i}{g_0} \exp\left(\frac{\Phi - E_{IP}}{k_B T}\right)$
Neutral density
Statistical weights
Boltzmann constant
Temperature
Surface ionization
Main bunch
Ion counts per bunch
100
Ion flight time [µs]
0
Surface ions
Z
e
Z+
e-
e-
+
d
Confining potential**
Plasma potential with respect to plasma enclosure
Ion density
$\Phi_p = \frac{k_B T}{e} \ln\left[\frac{n_i}{n_e}\right]$
Electron charge
Electron density
e-
Extraction field
Thermionic emission
Resistive heating to ~2000 C
~2V
Floating @60 kV HT platform
Grounded extraction electrode

Ralitsa Mancheva

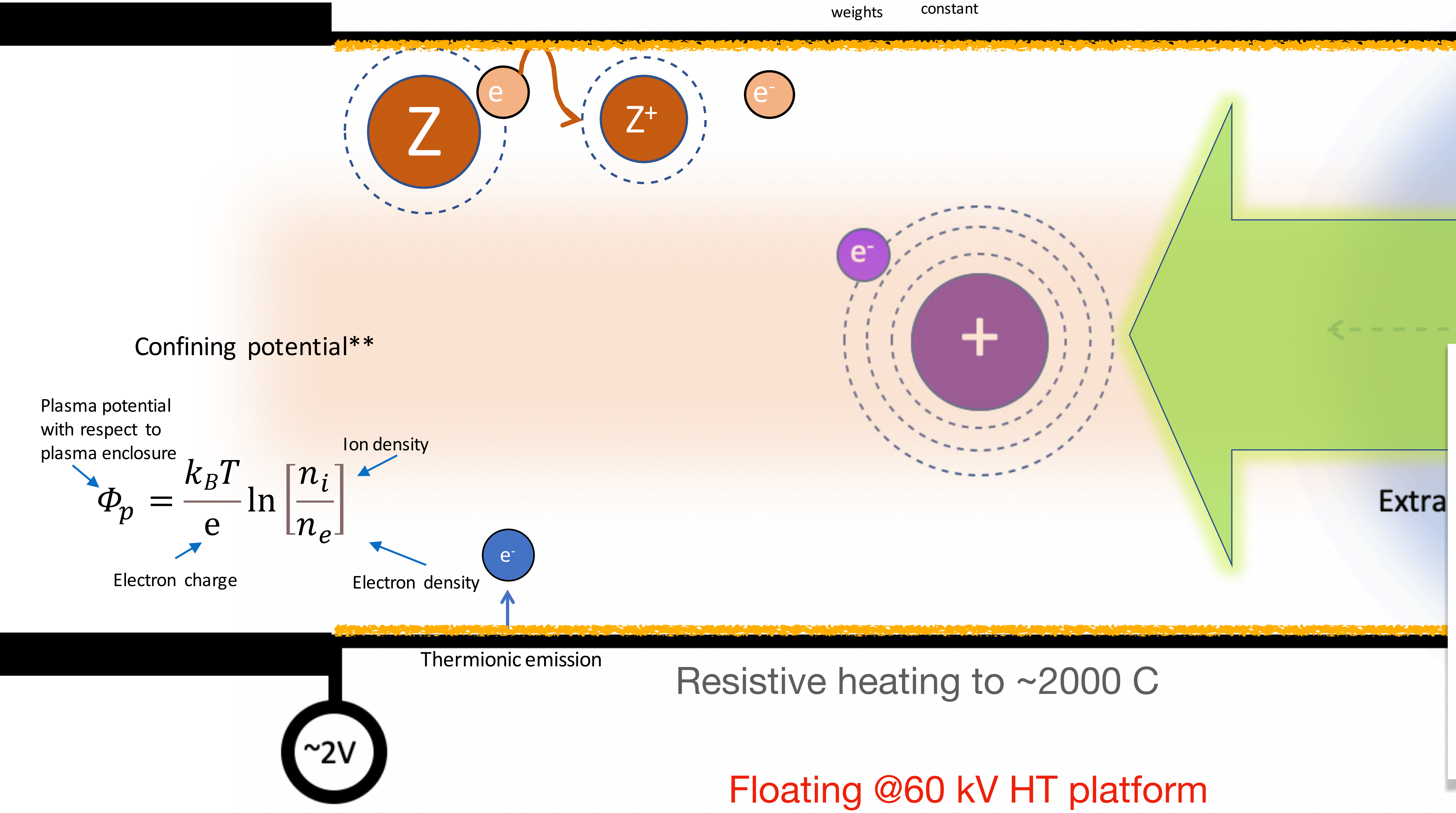
Surface ionization efficiency

Ion density, Neutral density, Statistical weights, Work function, Ionization potential, Boltzmann constant, Temperature

$$\frac{n_i}{n_0} = \frac{g_i}{g_0} \exp\left(\frac{\Phi - E_{IP}}{k_B T}\right)$$



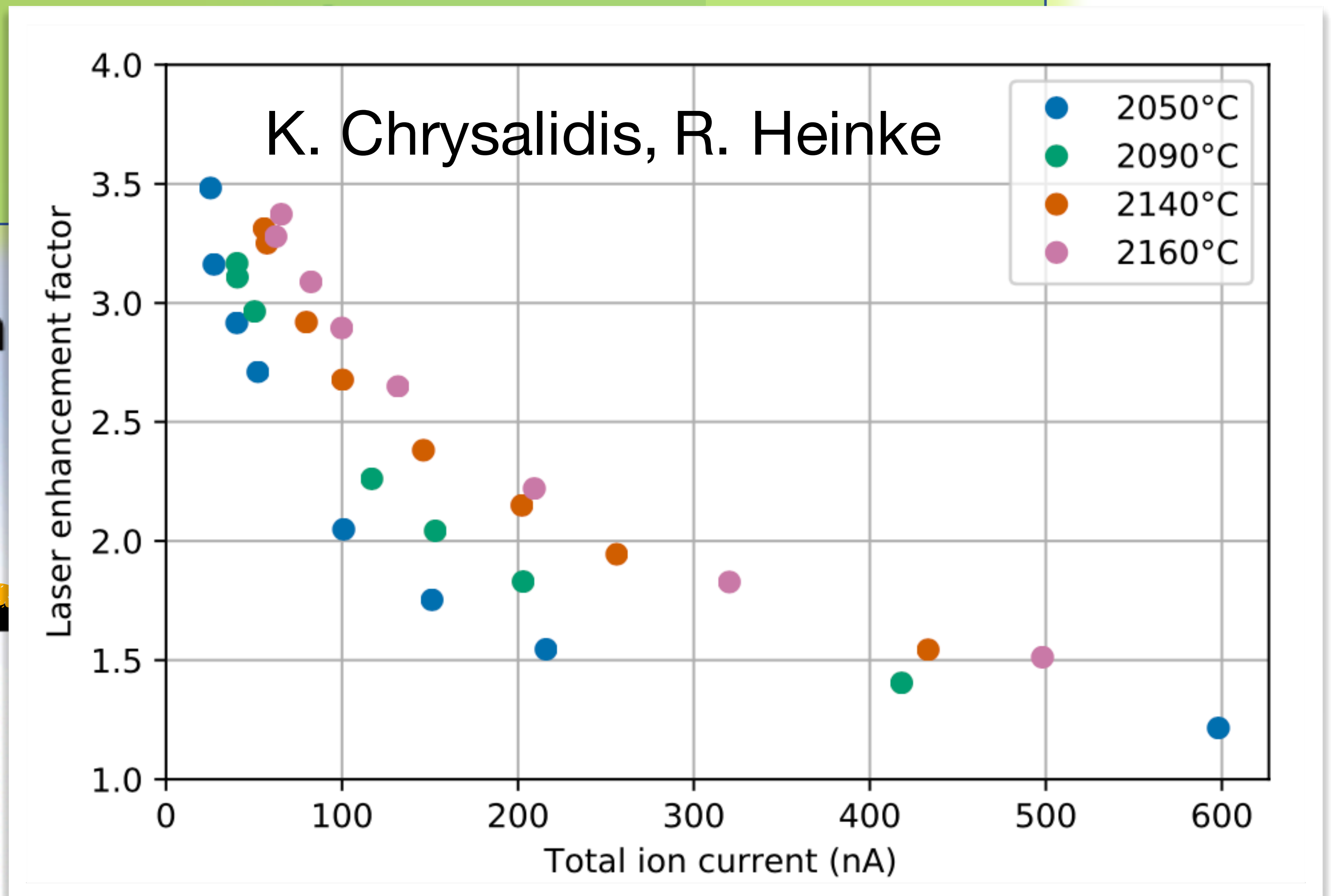
Surface ionization



Confining potential**

Plasma potential with respect to plasma enclosure, Ion density, Electron charge, Electron density

$$\Phi_p = \frac{k_B T}{e} \ln\left[\frac{n_i}{n_e}\right]$$



Resistive heating to ~2000 C

Floating @60 kV HT platform

Low work function cavity material

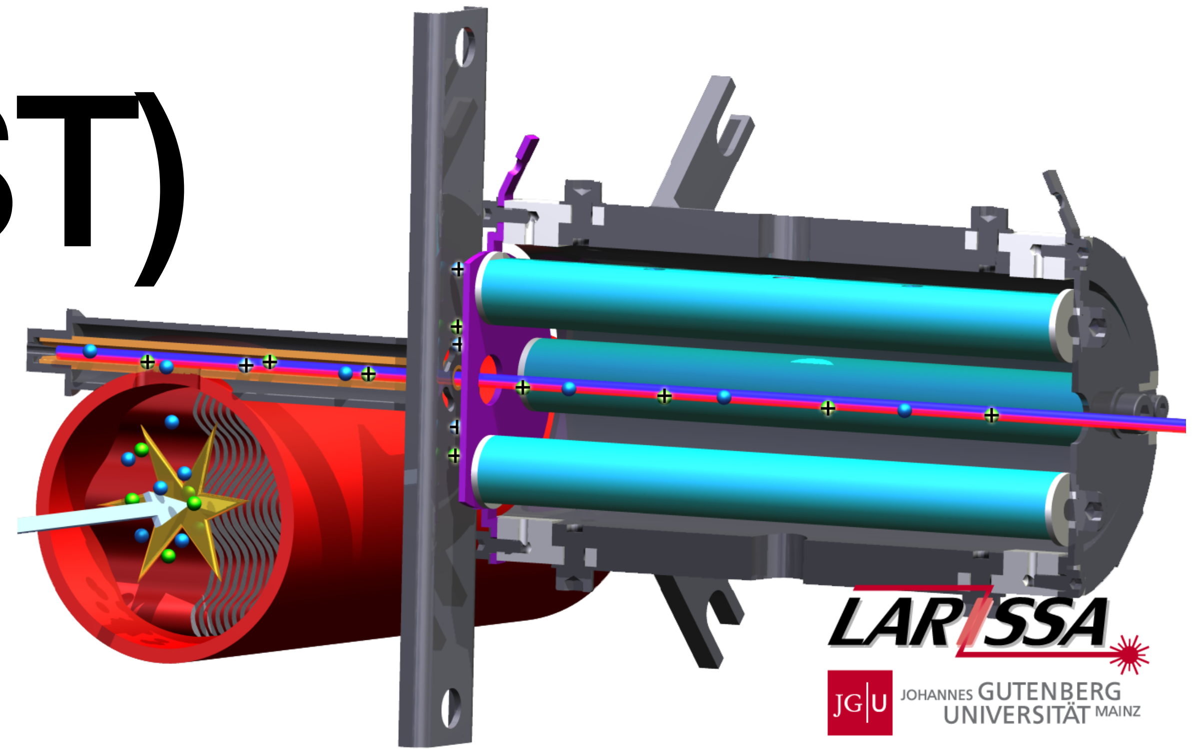
Higher electron emission (better laser ion

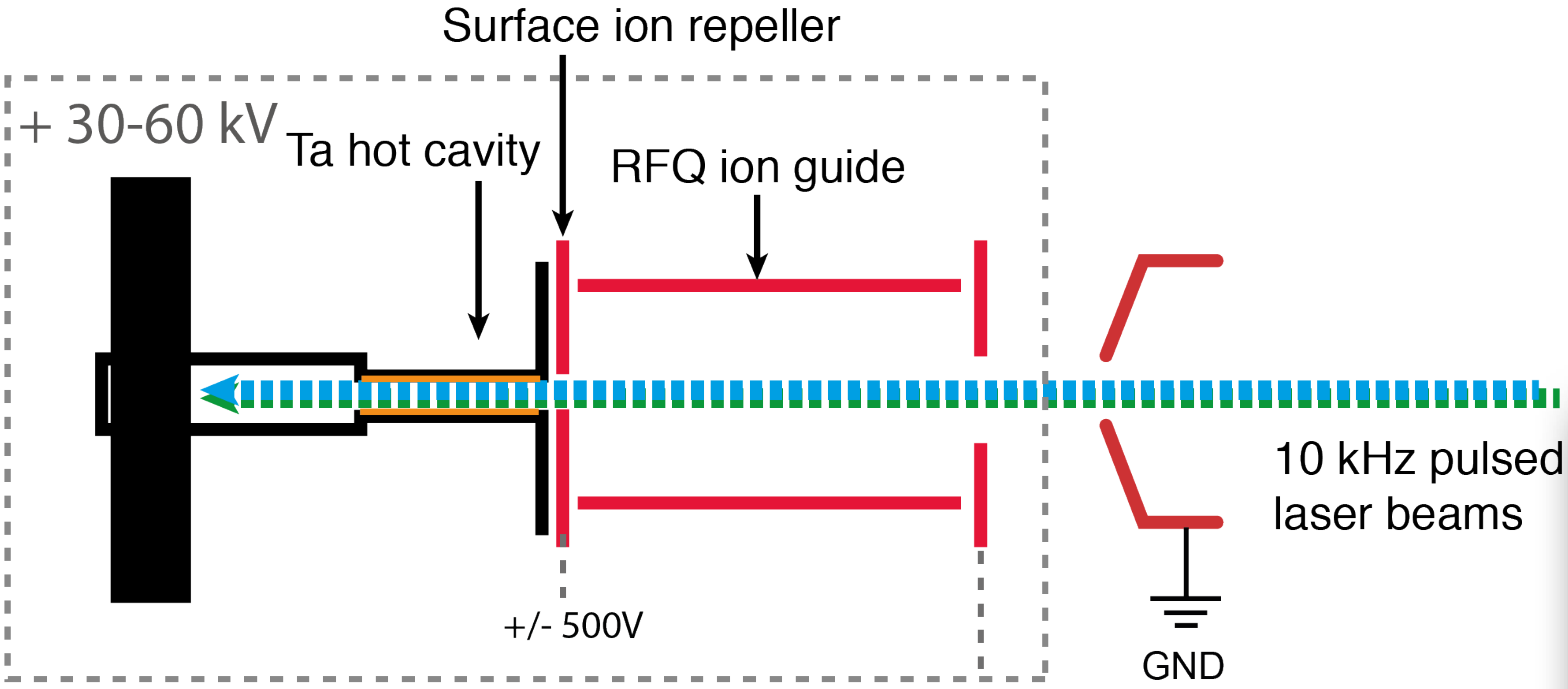
Lower surface ion rate (less contamination, lower ion

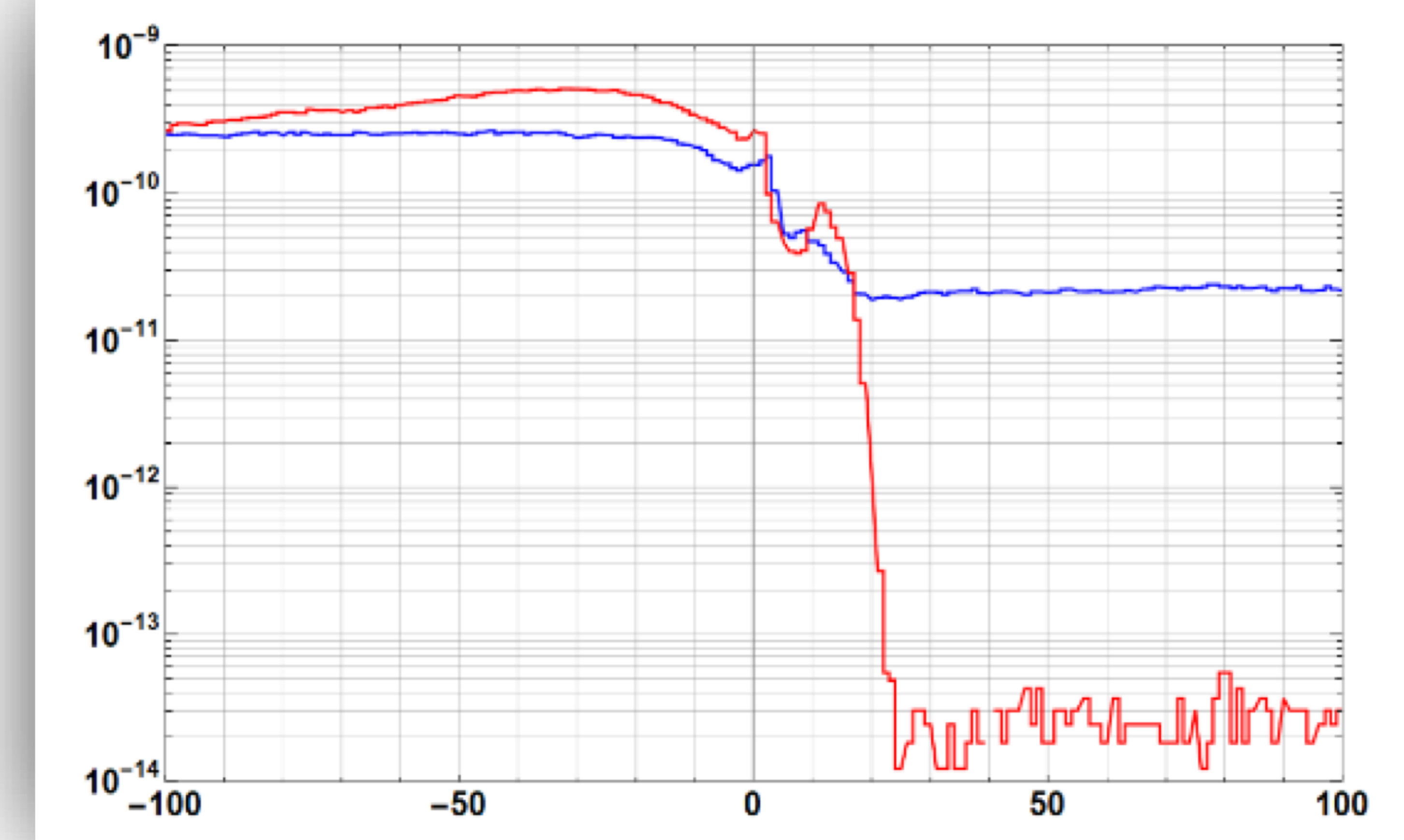
High temperature operation, material compatibility

Tantalum is standard choice

Laser Ion Source Trap (LIST)







- >5 orders of magnitude surface ion suppression in LIST mode
- Efficiency loss factor of ~20-50

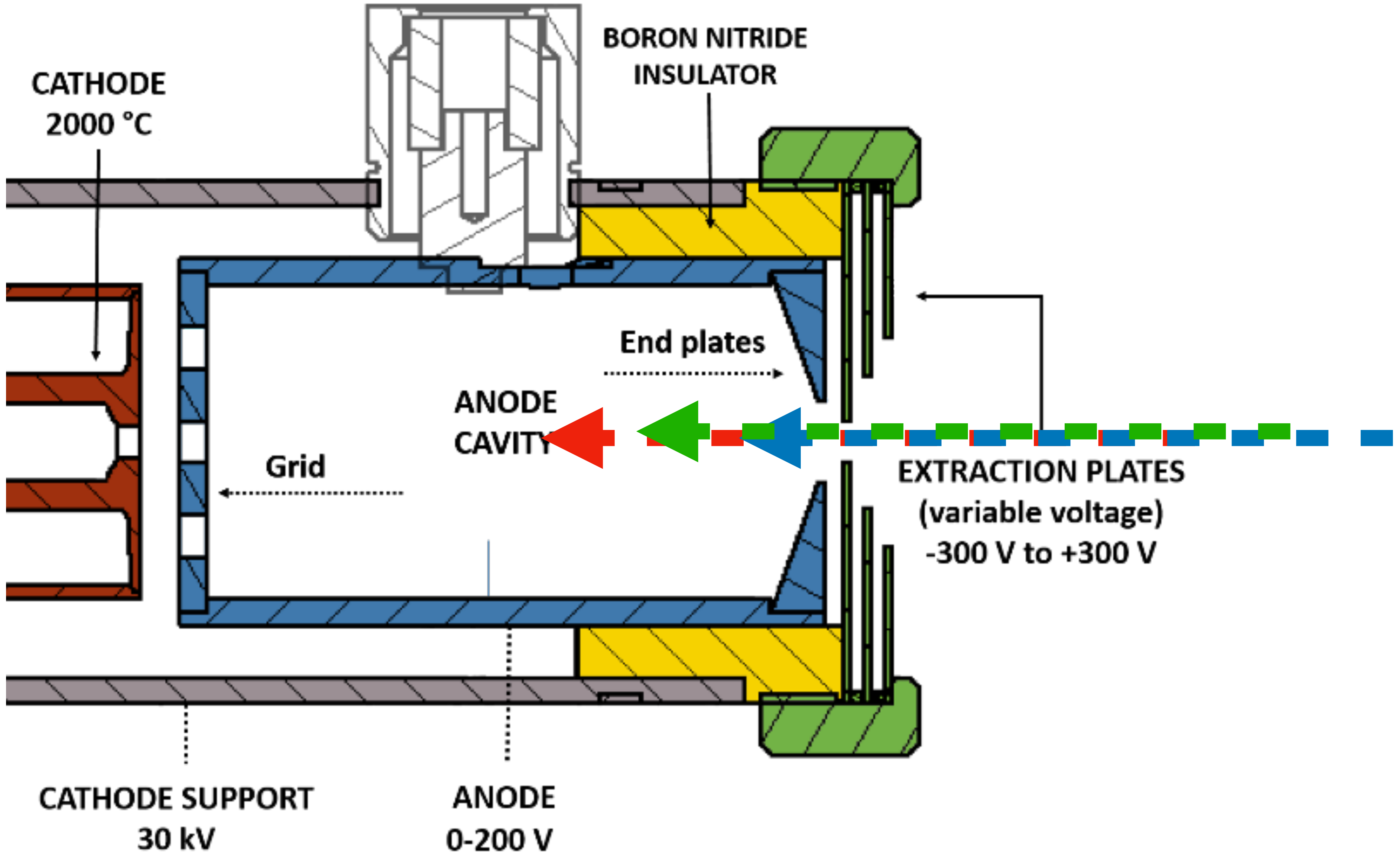
http://dx.doi.org/10.1103/PhysRevX.5.011018

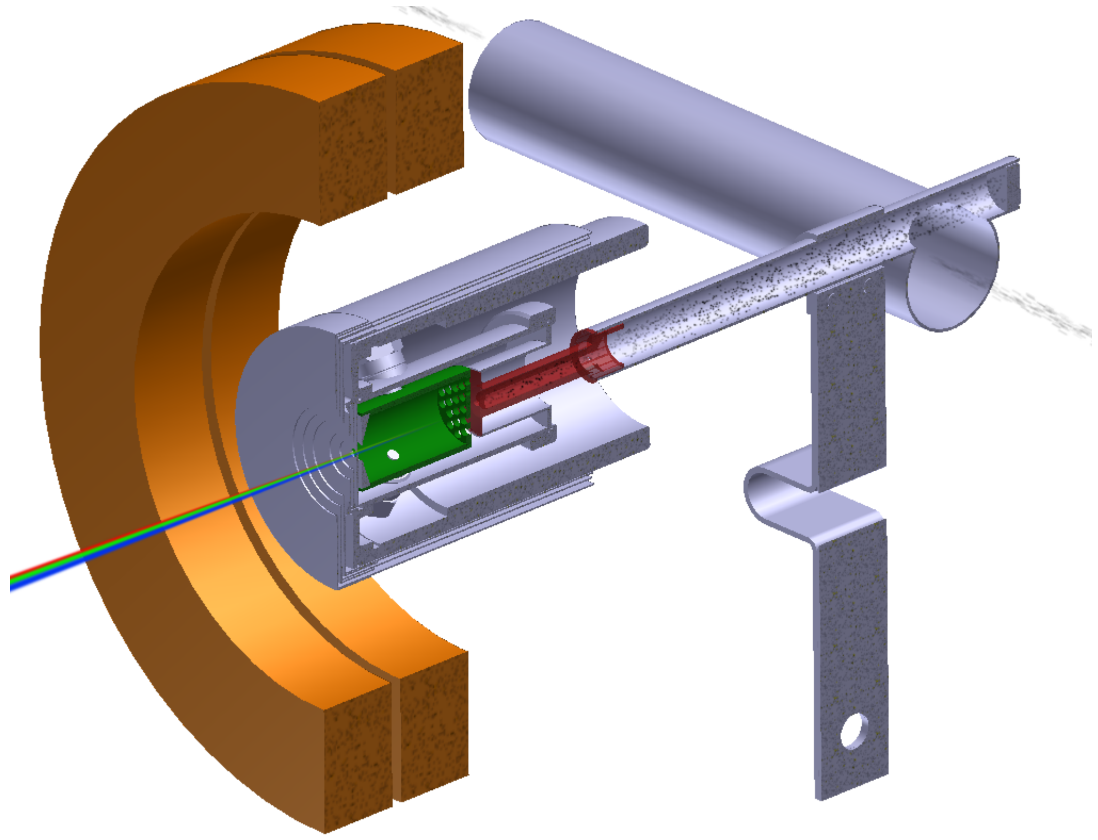
http://dx.doi.org/10.1016/j.nimb.2013.06.039

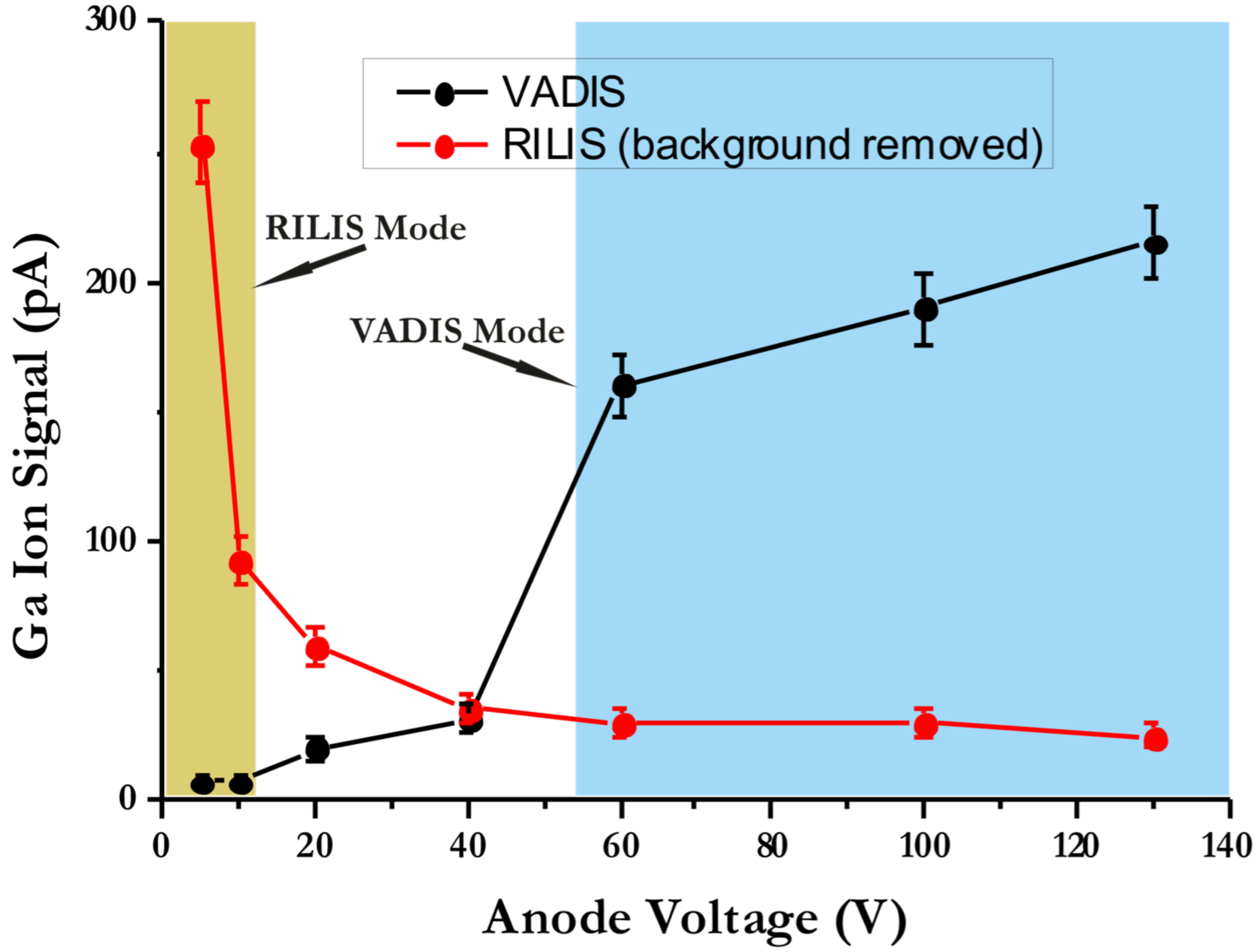
http://www.ub.uni-heidelberg.de/archiv/16725

Reinhard Heinke Daniel Fink Sven Richter

Versatile Arc Discharge and Laser Ion Source (VADLIS)







- Modified version of the standard FEBIAD source at ISOLDE
- Ability to turn on/off non selective electron impact ionization
- Molecular breakup with electrons or lasers
- Adjustable extraction voltage and larger volume may improve ion capacity limit to 10 uA range

Yisel Martinez Tom Day Goodacre

OPTimizing **ION** Sources for medical applications

https://www.prismap.eu

The challenge

Maintain efficiency at high evaporation rates

The goal

Maximum specific activity BEFORE chemical treatment

Solutions

High ion capacity and /or **Selectivity**

Modified VADLIS with variable extraction Voltage

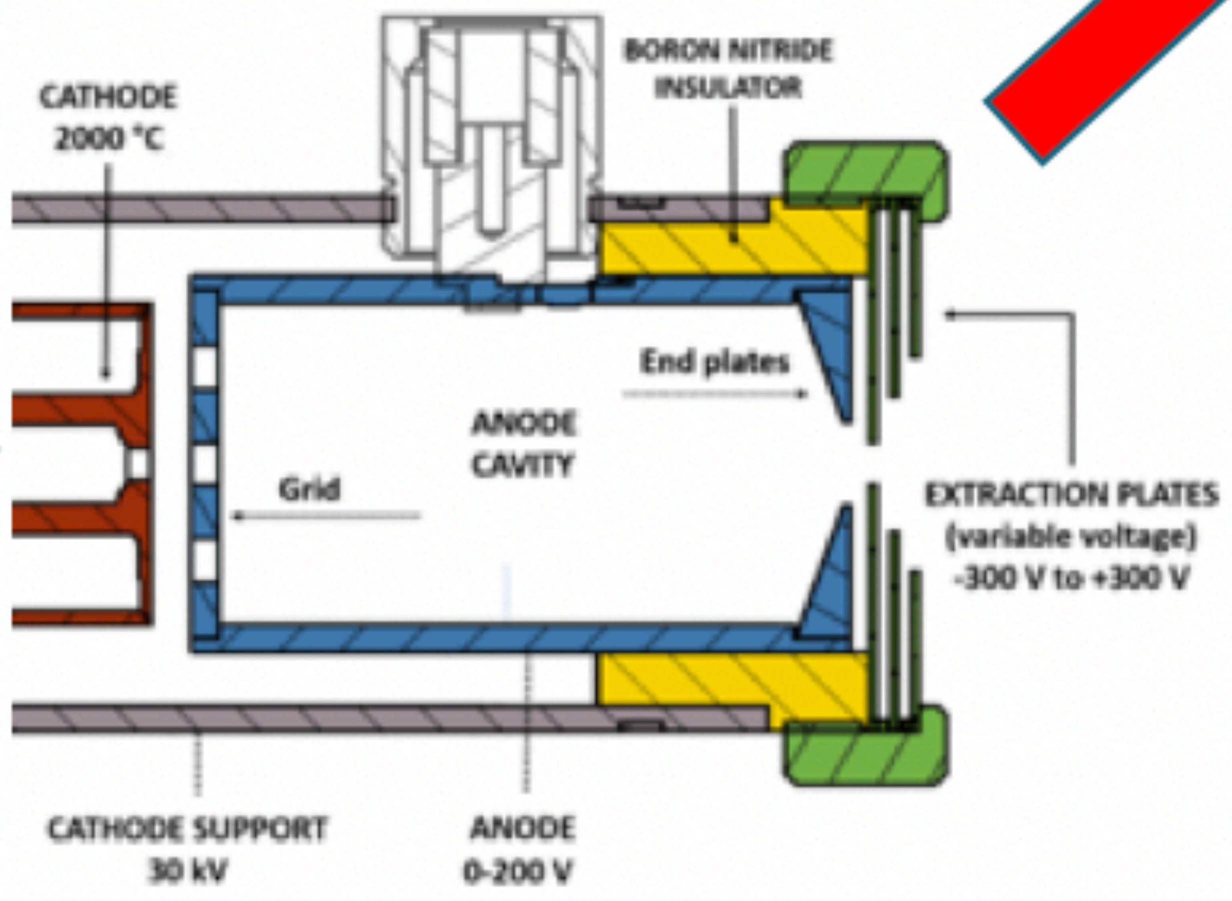
Surface Ion Source
-new materials
-optimize geometry

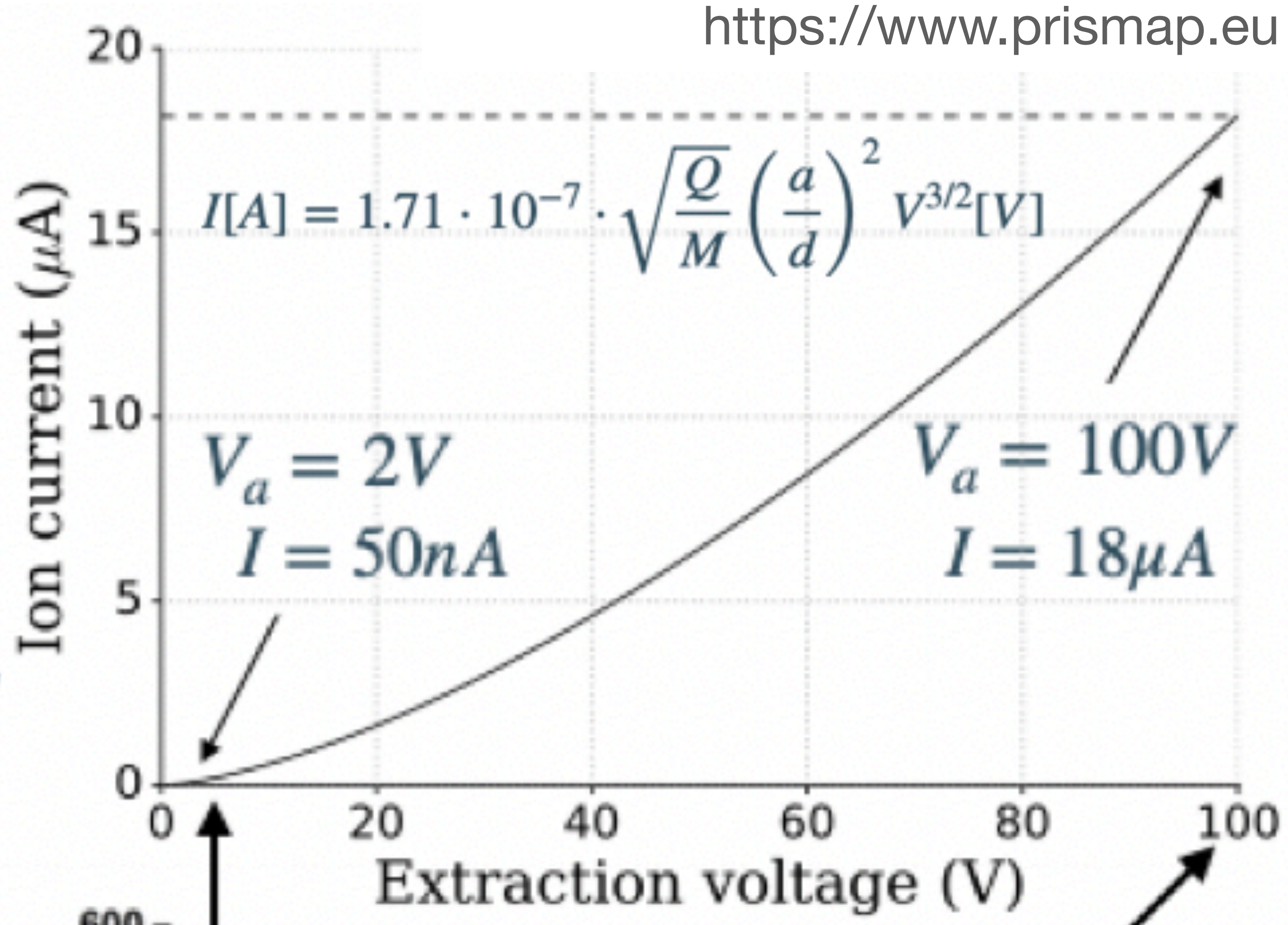
Laser Ionisation schemes

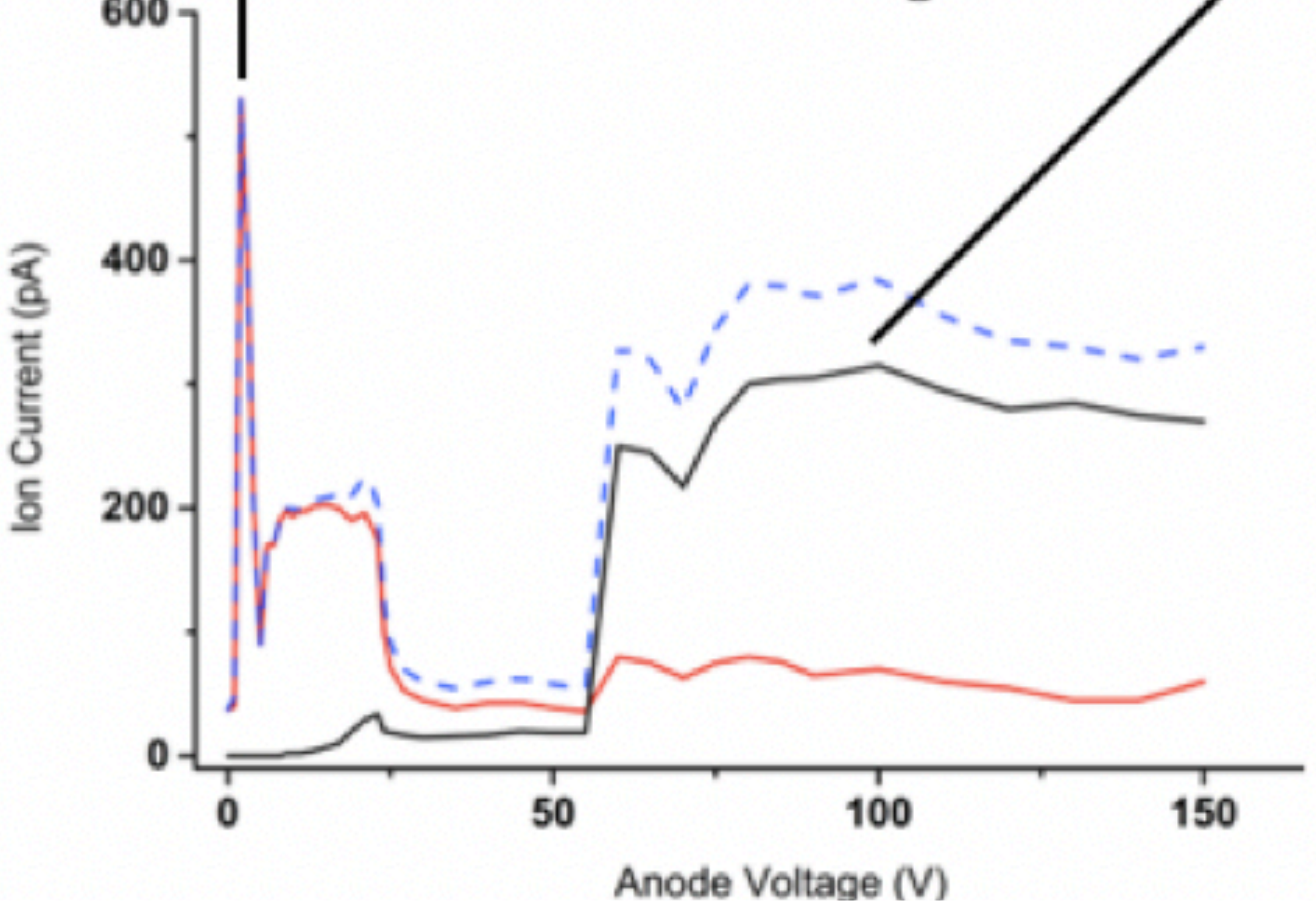
High-voltage laser ion source

Time-of-flight laser ion source

FEBIAD/EBIS optimisation





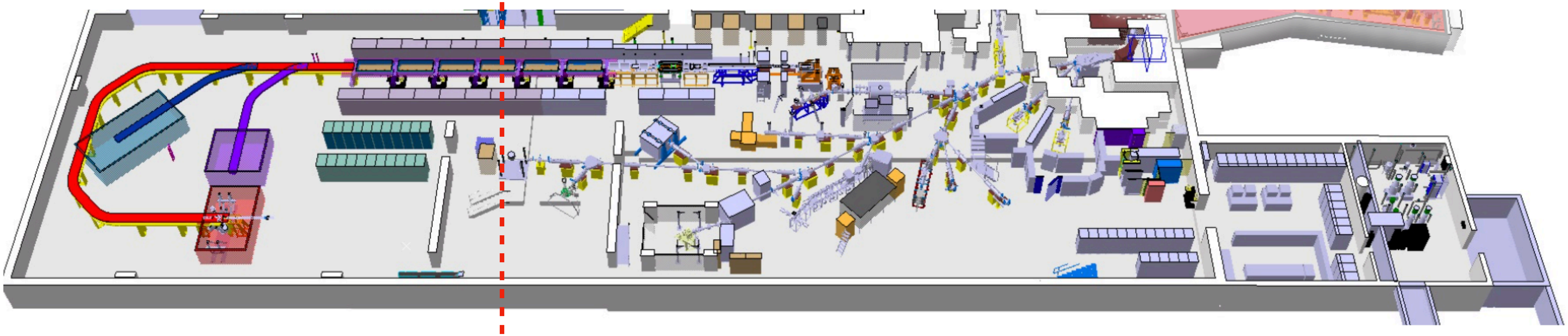


Yisel Martinez

PhD Topic Ralitsa Mancheva, KU Leuven / CERN

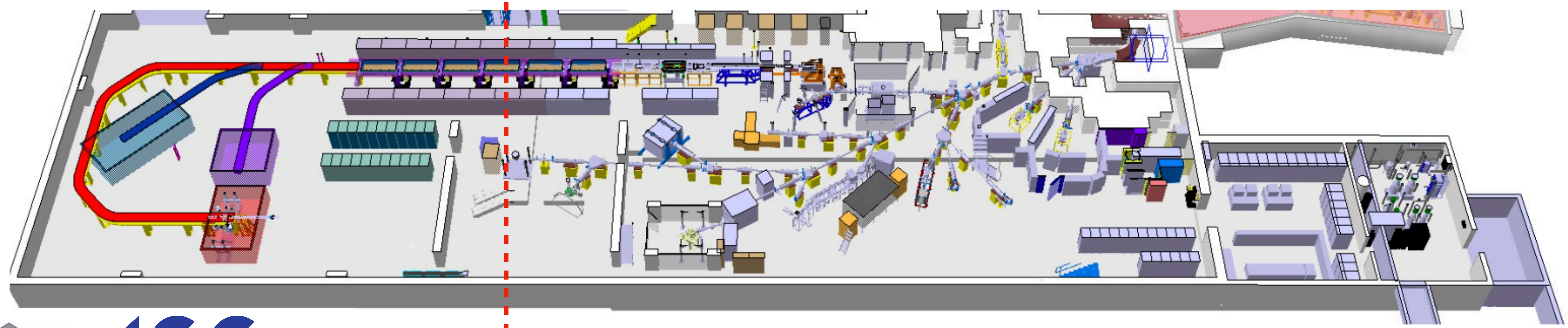
RILIS as one of the ISOLDE experiments

Low energy nuclear physics (nuclear ground / isomer state properties)



High energy nuclear physics (excited states, nuclear reactions, astrophysics)

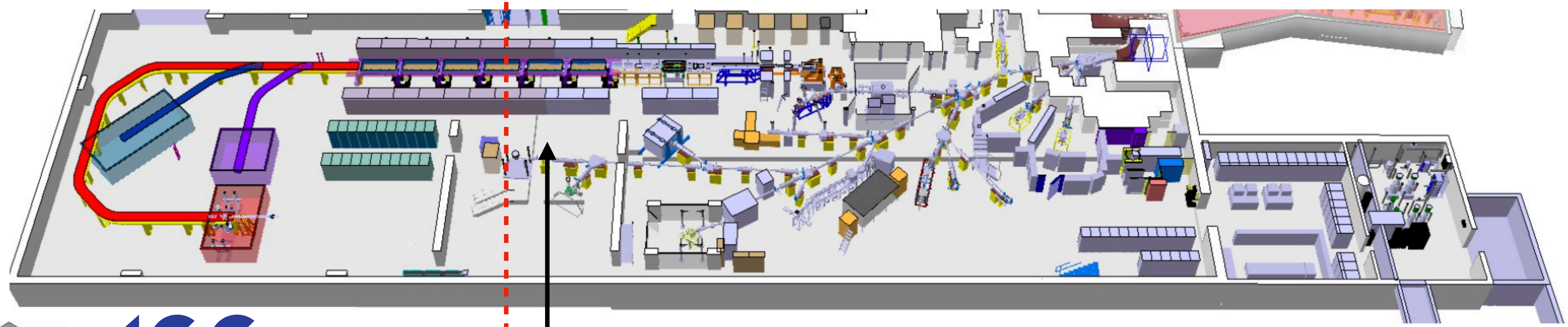
Low energy nuclear physics (nuclear ground / isomer state properties)



ISOLDE Solenoidal Spectrometer

High energy nuclear physics (excited states, nuclear reactions, astrophysics)

Low energy nuclear physics (nuclear ground / isomer state properties)



MINIBALL

ISS

ISOLDE Solenoidal Spectrometer

ISOLDE Decay Station

Decay modes

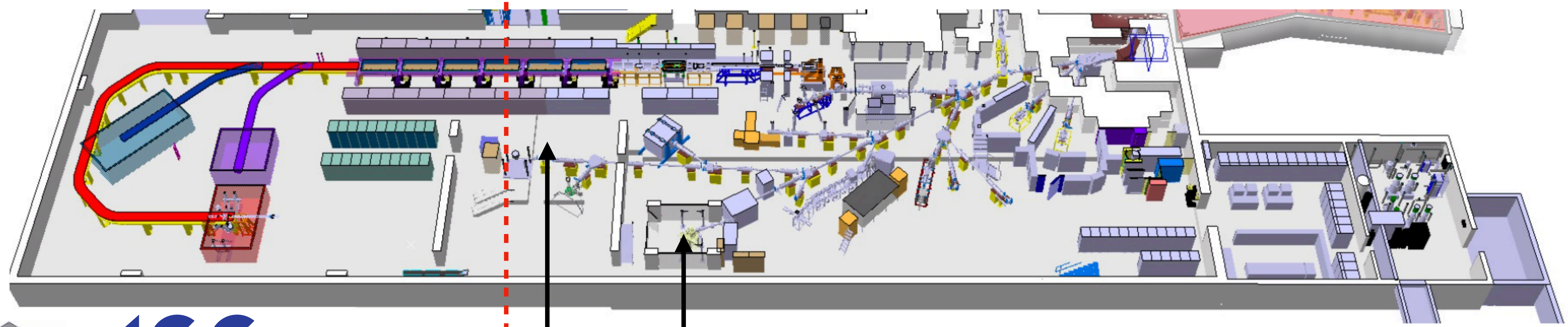
Half life

Decay energies

Branching ratios

High energy nuclear physics (excited states, nuclear reactions, astrophysics)

Low energy nuclear physics (nuclear ground / isomer state properties)



MINIBALL

ISS
ISOLDE Solenoidal Spectrometer

ISOLTRAP

Nuclear Masses

ISOLDE Decay Station

Decay modes

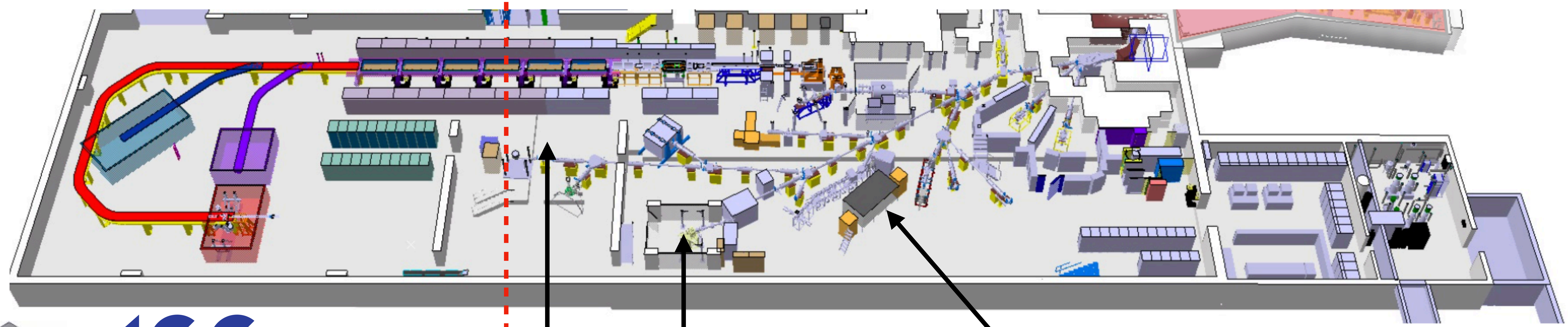
Half life

Decay energies

Branching ratios

High energy nuclear physics (excited states, nuclear reactions, astrophysics)

Low energy nuclear physics (nuclear ground / isomer state properties)



MINIBALL

ISOLDE Solenoidal Spectrometer

ISOLTRAP

COLLAPS

High resolution

ISOLDE Decay Station

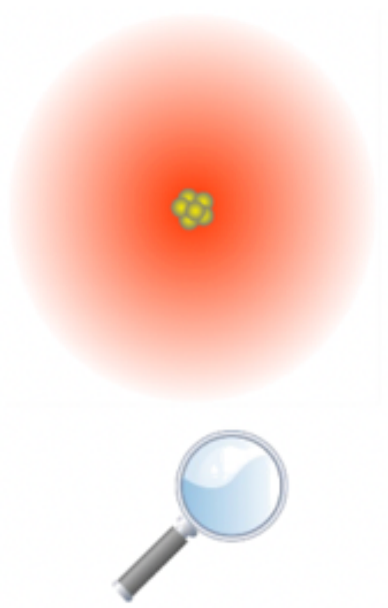
Nuclear Masses

Decay modes

Half life

Decay energies

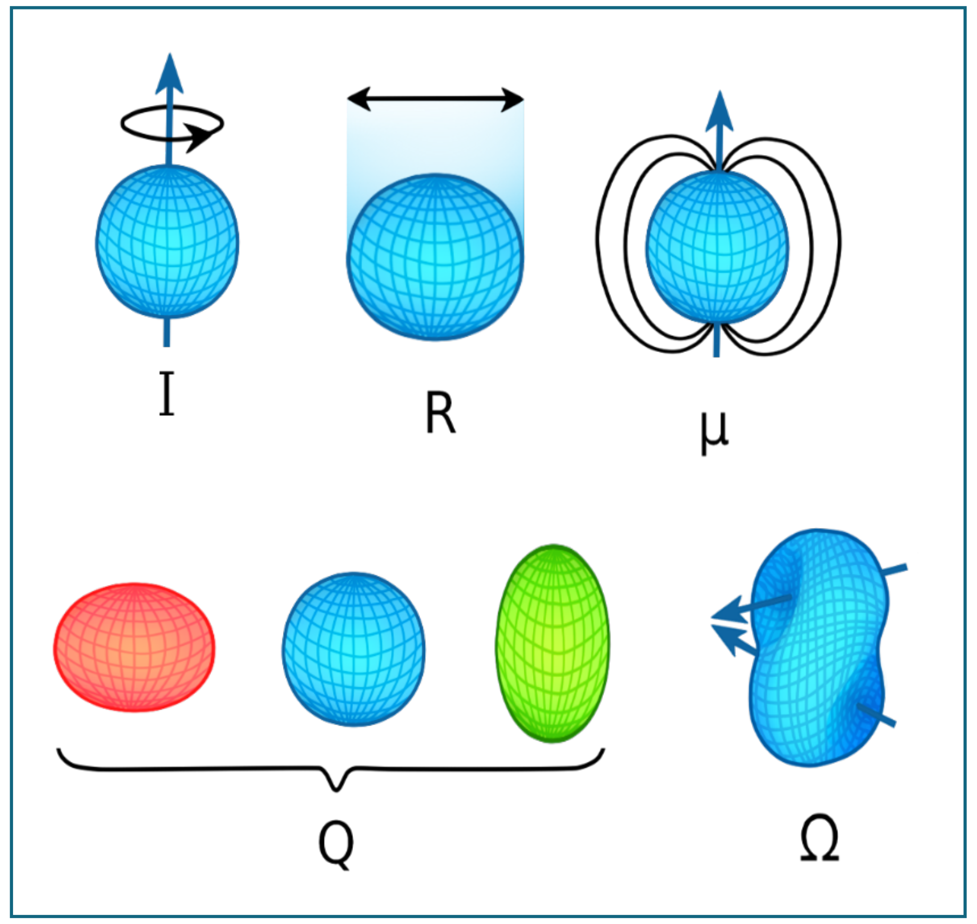
Branching ratios



x 10^5

Nuclear sizes, shapes, dynamic properties

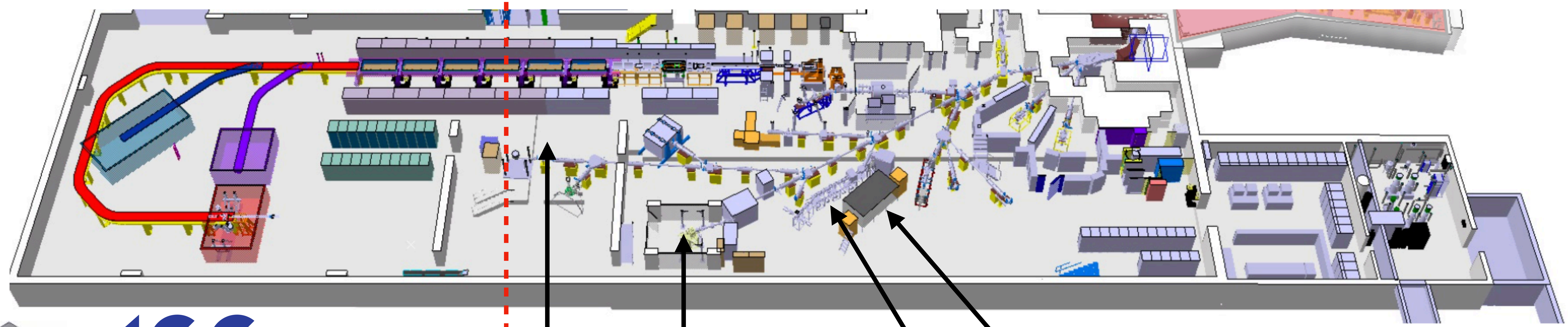
Moments : SPIN, magnetic dipole, electric quadrupole




High energy nuclear physics (excited states, nuclear reactions, astrophysics)
Low energy nuclear physics (nuclear ground / isomer state properties)
MINIBALL
ISS
ISOLDE Solenoidal Spectrometer
ISOLTRAP
Nuclear Masses
COLLAPS
High resolution
CRIS
High resolution + ν sensitive
Nuclear sizes, shapes, dynamic properties
Moments : SPIN, magnetic dipole, electric quadrupole
I
R
μ
Q
Ω
ISOLDE Decay Station
Decay modes
Half life
Decay energies
Branching ratios
x 10^5

High energy nuclear physics (excited states, nuclear reactions, astrophysics)

Low energy nuclear physics (nuclear ground / isomer state properties)



MINIBALL

ISS — ISOLDE Solenoidal Spectrometer

ISOLTRAP

Nuclear Masses

COLLAPS

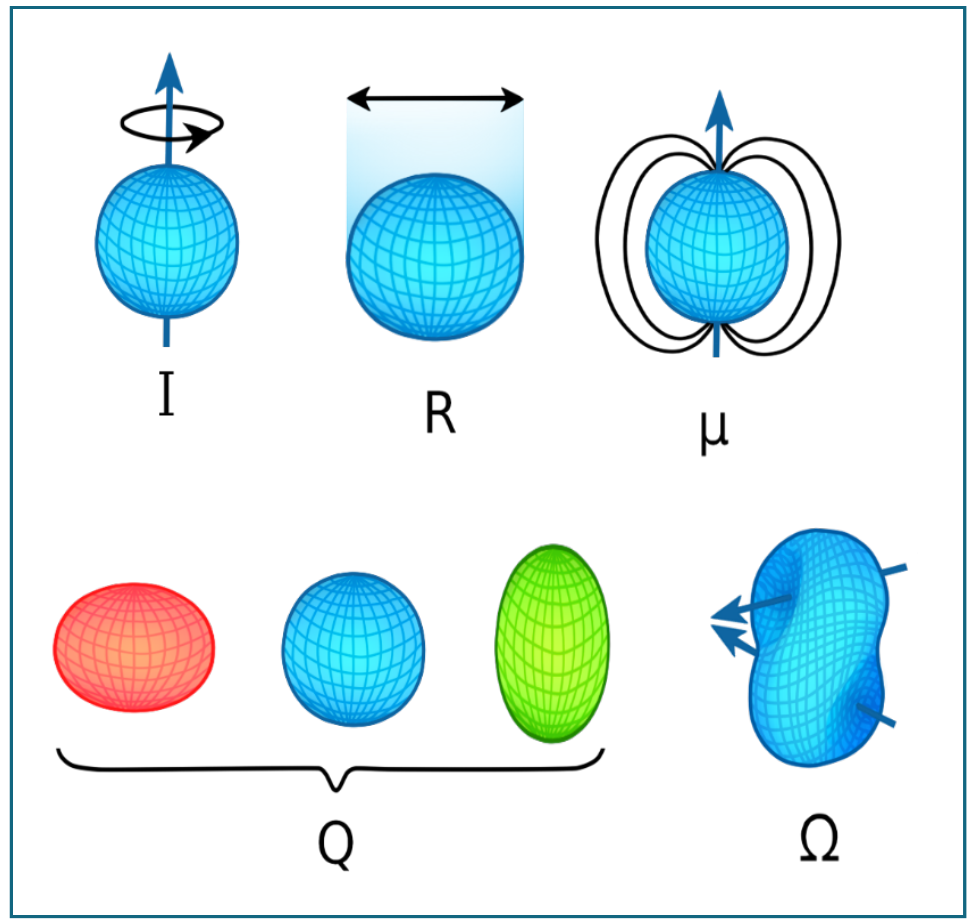
High resolution

CRIS

High resolution + ν sensitive

Nuclear sizes, shapes, dynamic properties

Moments : SPIN, magnetic dipole, electric quadrupole



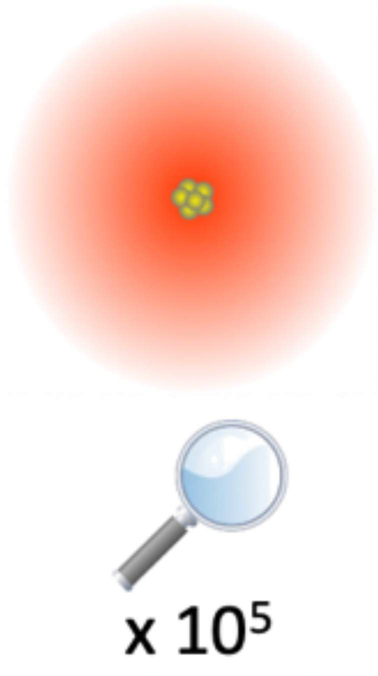
ISOLDE Decay Station

Decay modes

Half life

Decay energies

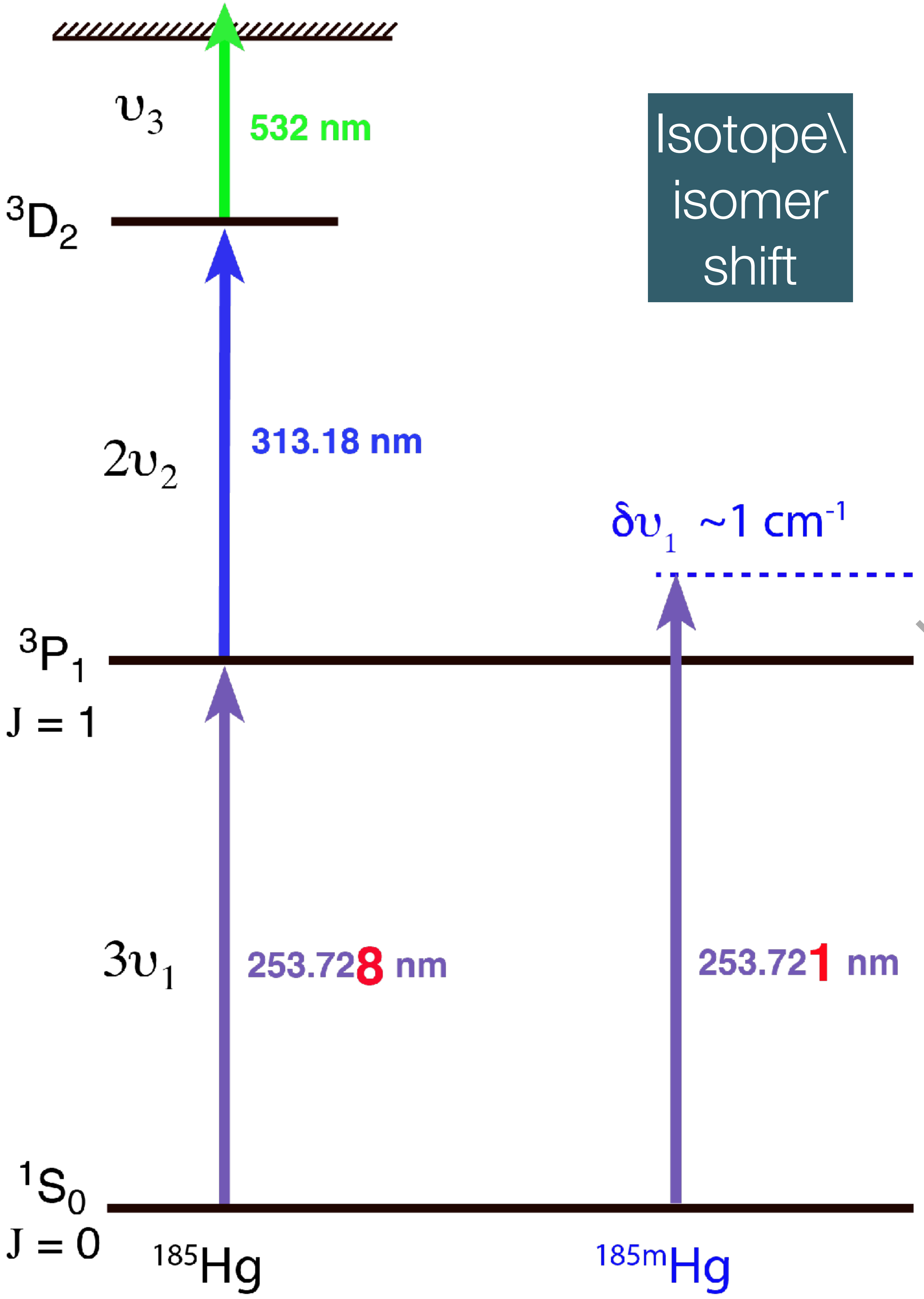
Branching ratios

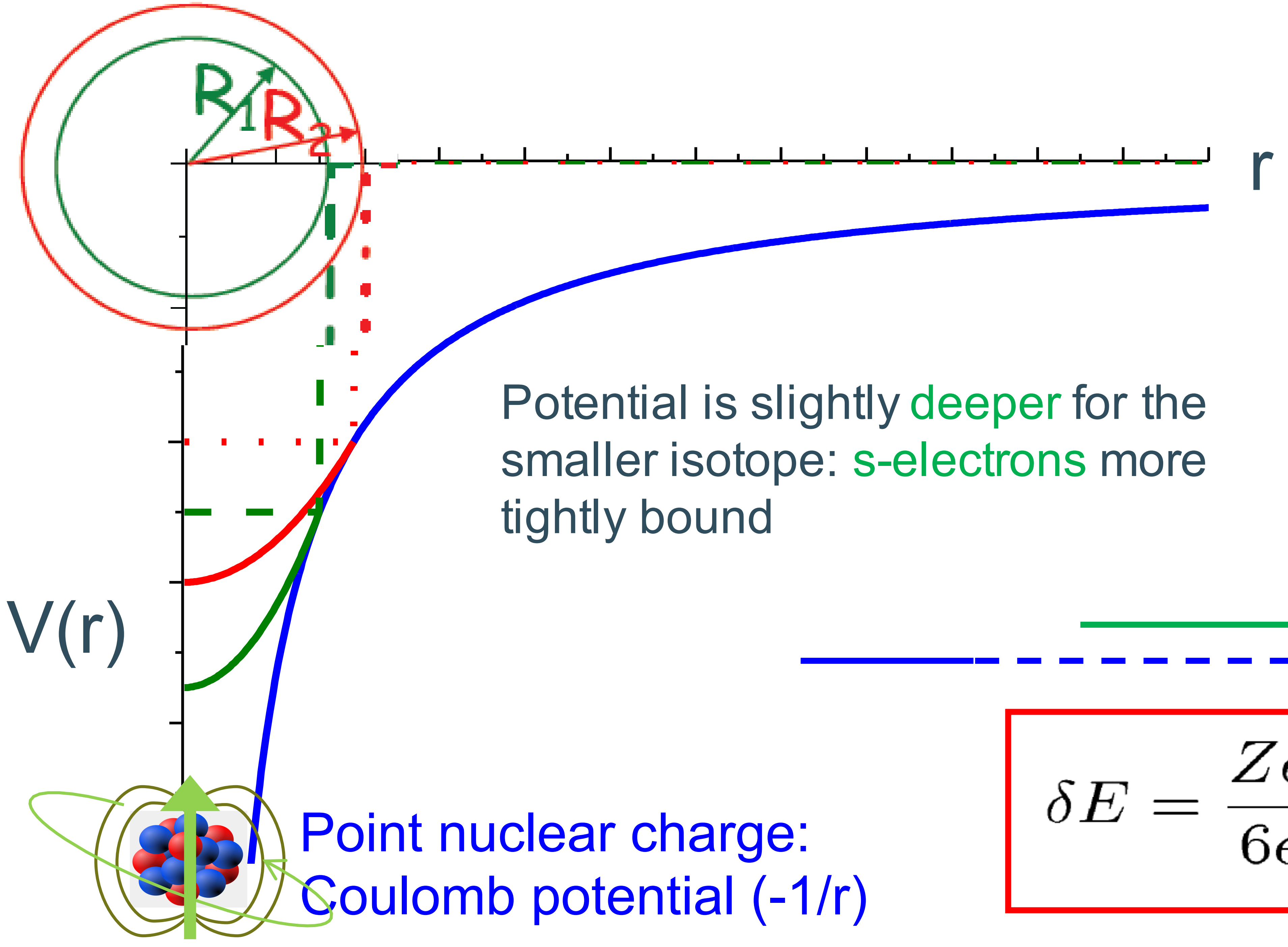


Unmatched Sensitivity Low resolution

RILIS

Measuring the charge radius systematics: isotope shifts





Nuclear radius: few × 10^{-15} m
Atomic radius: few × 10^{-10} m

Isotope shift of atomic level

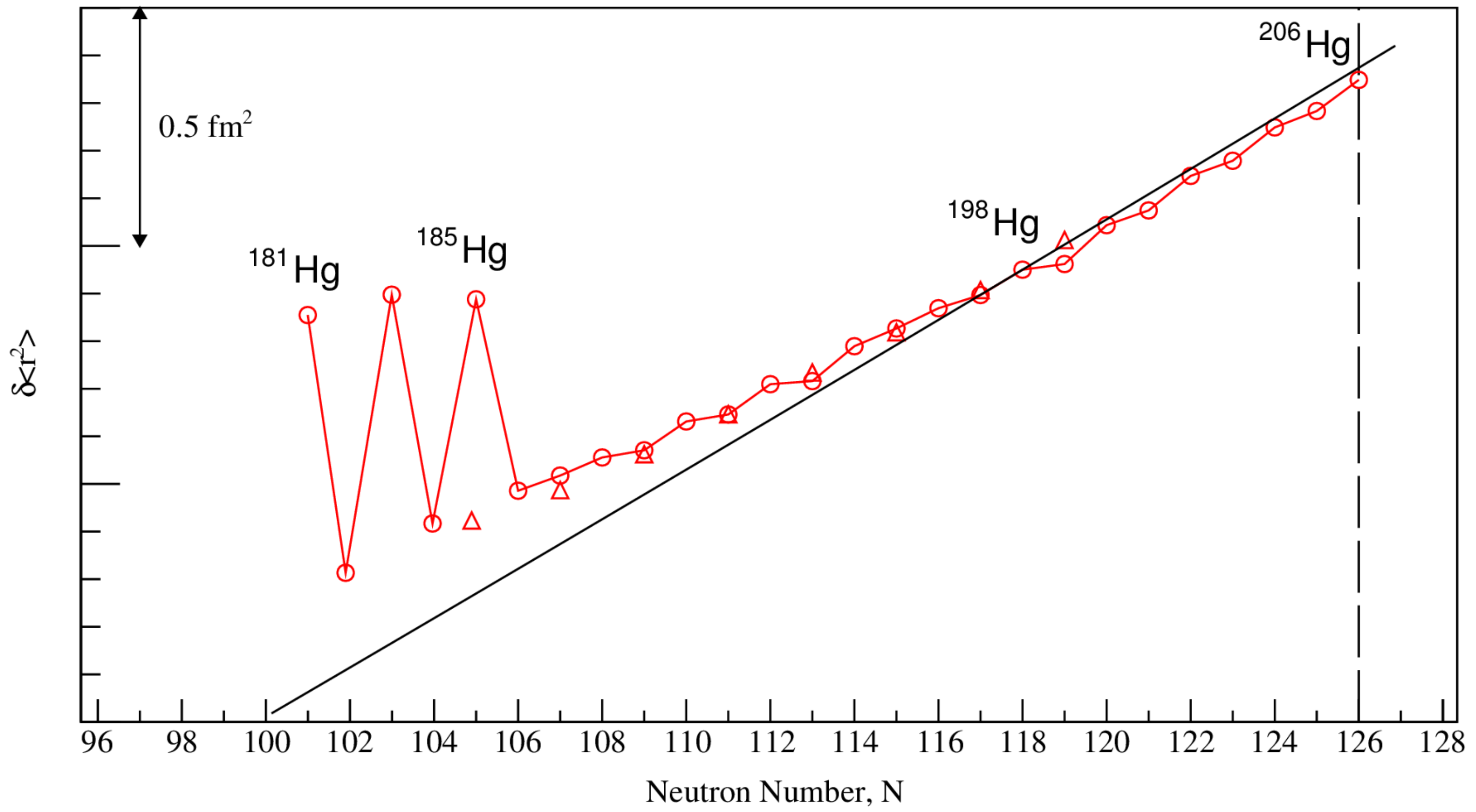
$$\delta E = \frac{Ze^2}{6\epsilon_0} \mid \psi(0) \mid^2 \delta\langle r^2\rangle^{A,A'}$$

$$\delta\nu_{IS} = \delta\nu_{MS} + \delta\nu_{FS}$$

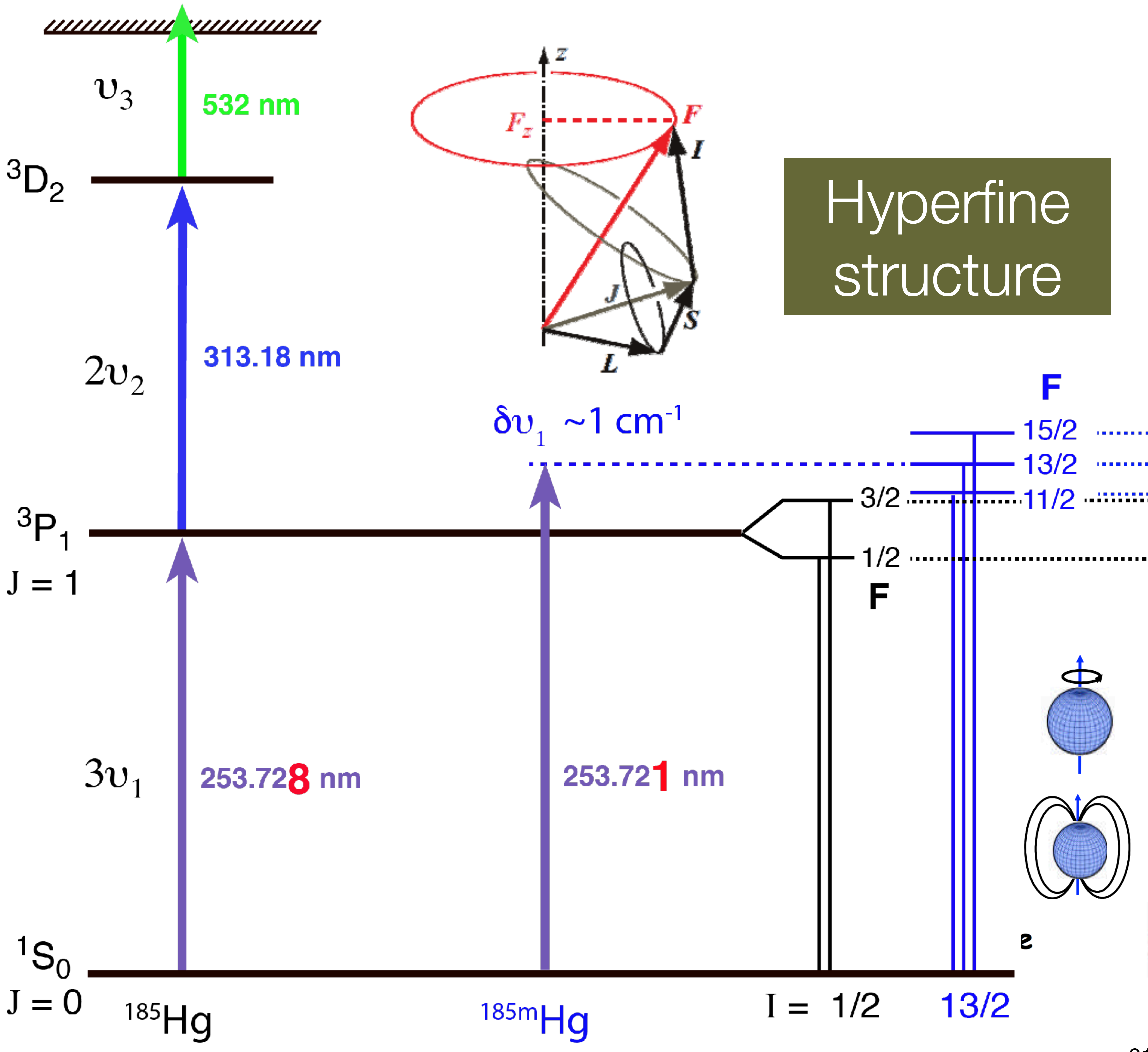
$$\frac{Ze^2}{6h\varepsilon_0}\Delta|\psi_e(0)|^2 \quad \delta\langle r^2\rangle$$

EXPERIMENT | THEORY

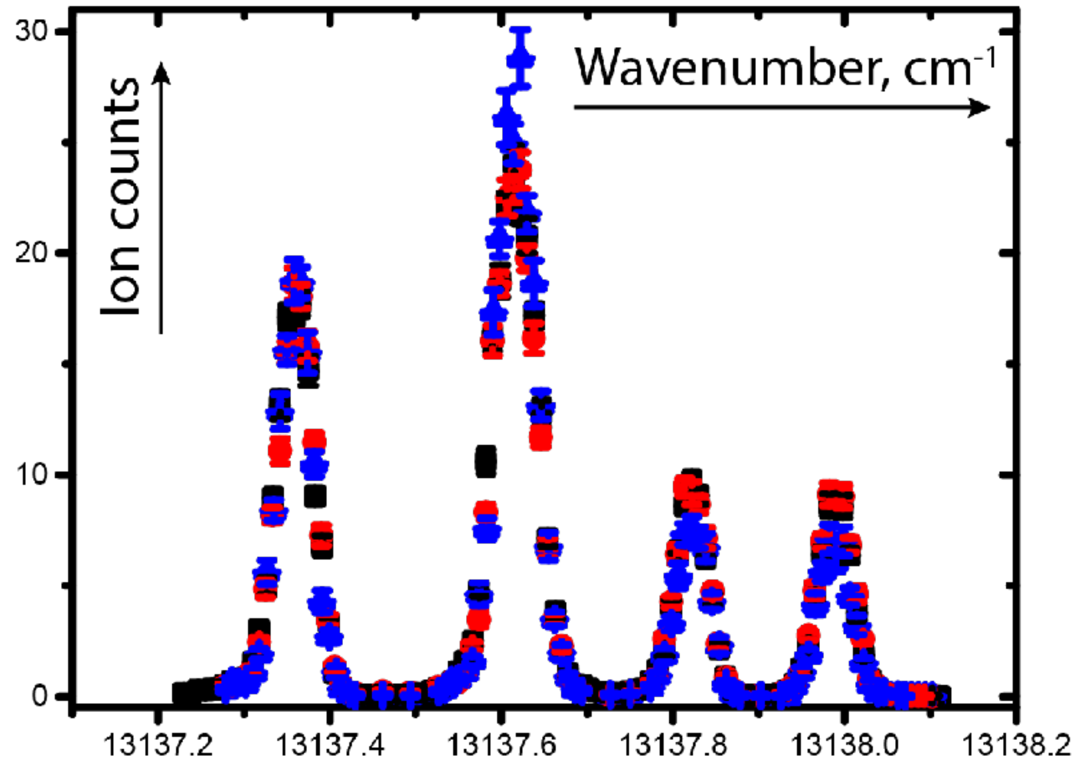
Change in nuclear mean-squared **charge radius**



Measuring shape and nuclear moments: The Hyperfine Structure

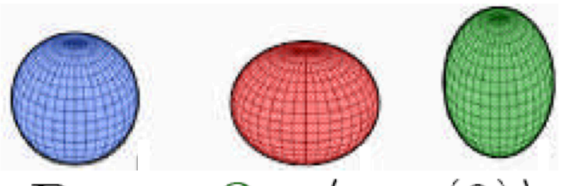


Hyperfine structure



$$\mathbf{F} = \mathbf{I} + \mathbf{J}$$

$$A = \mu_I \frac{\langle B(0) \rangle}{\mathbf{I} \cdot \mathbf{J}}$$



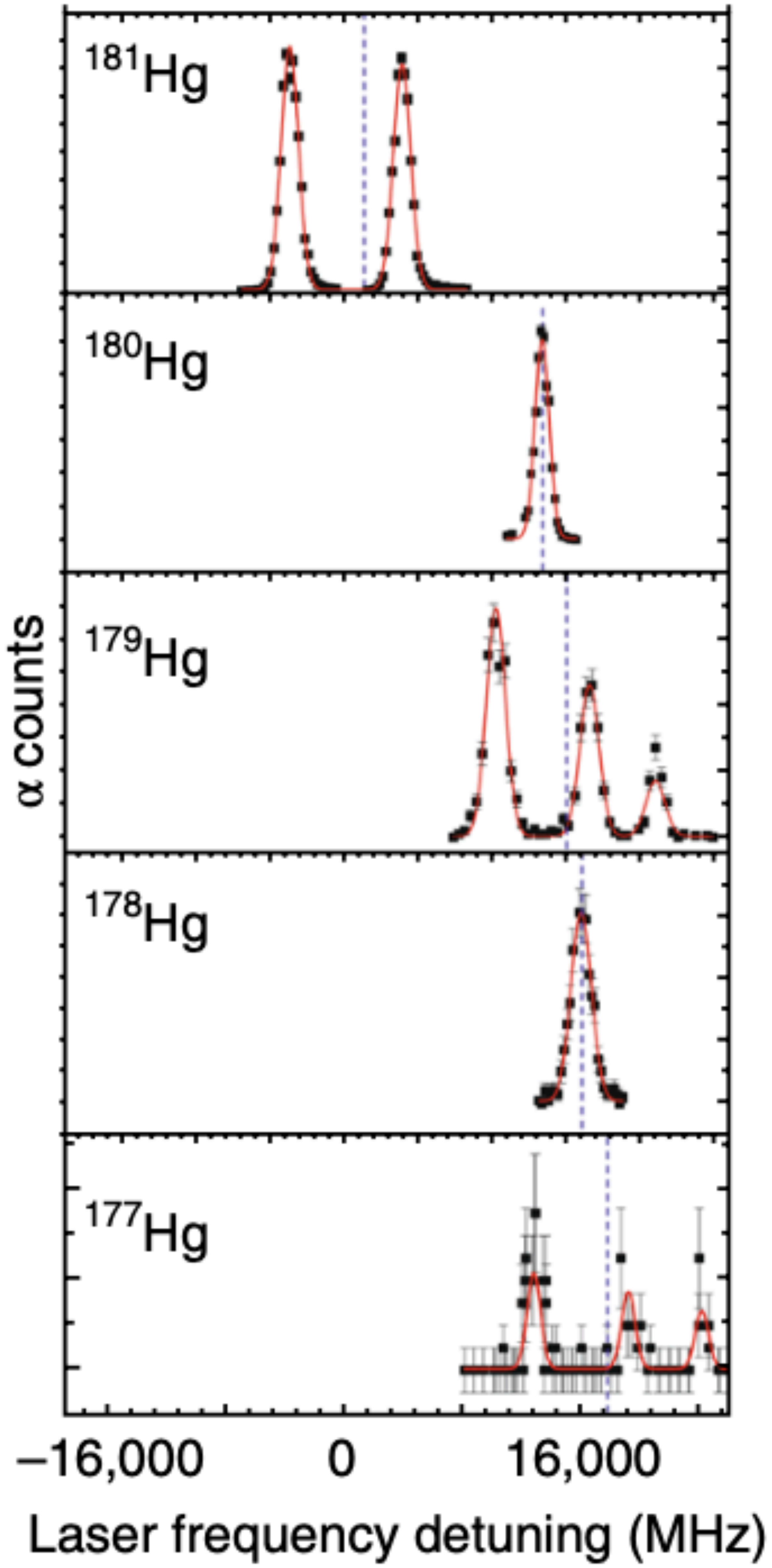
$$B = e\, Q_S\, \langle \varphi_{zz}(0) \rangle$$

Spin

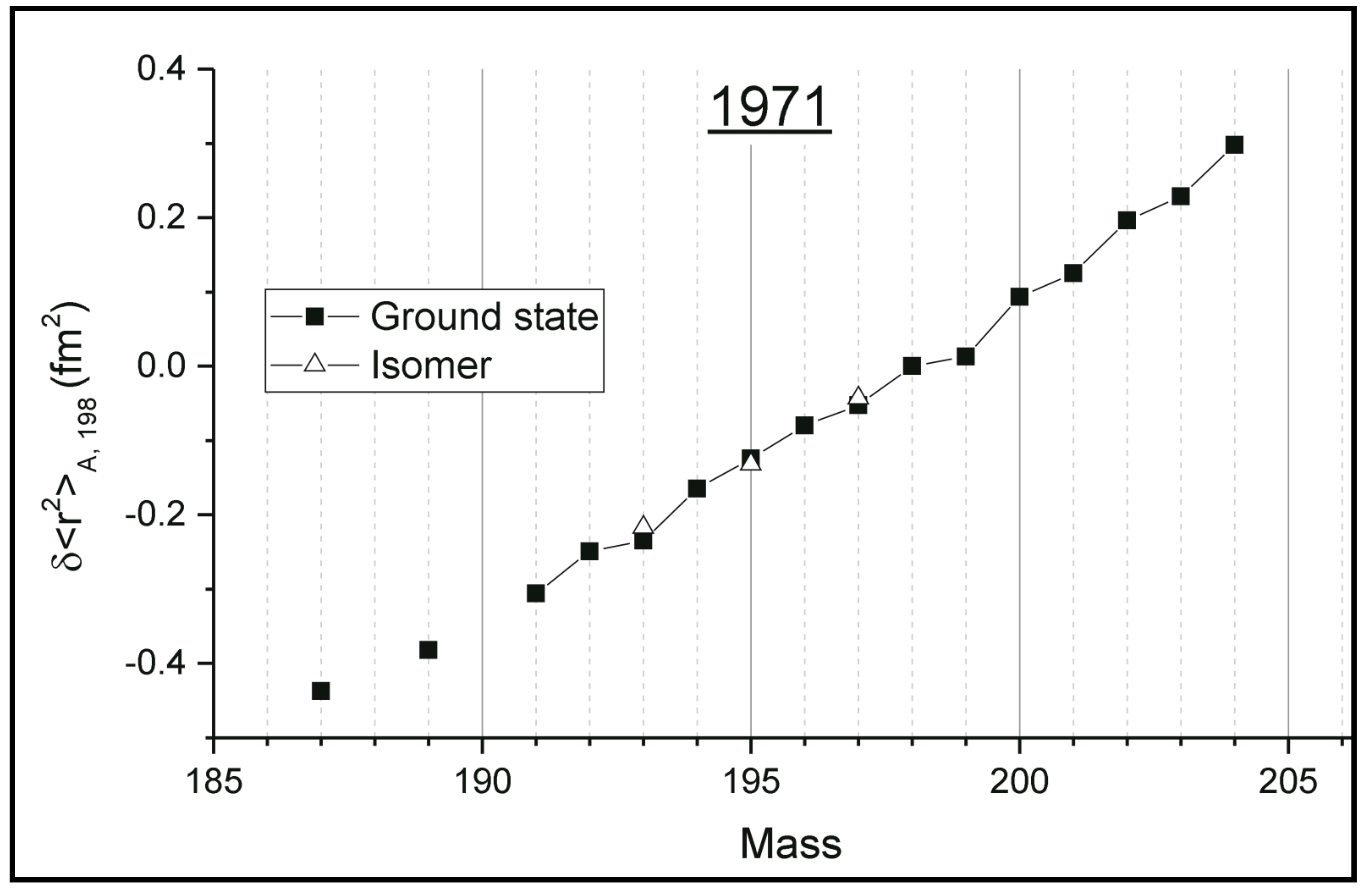
Quadrupole

Dipole

Shapes,

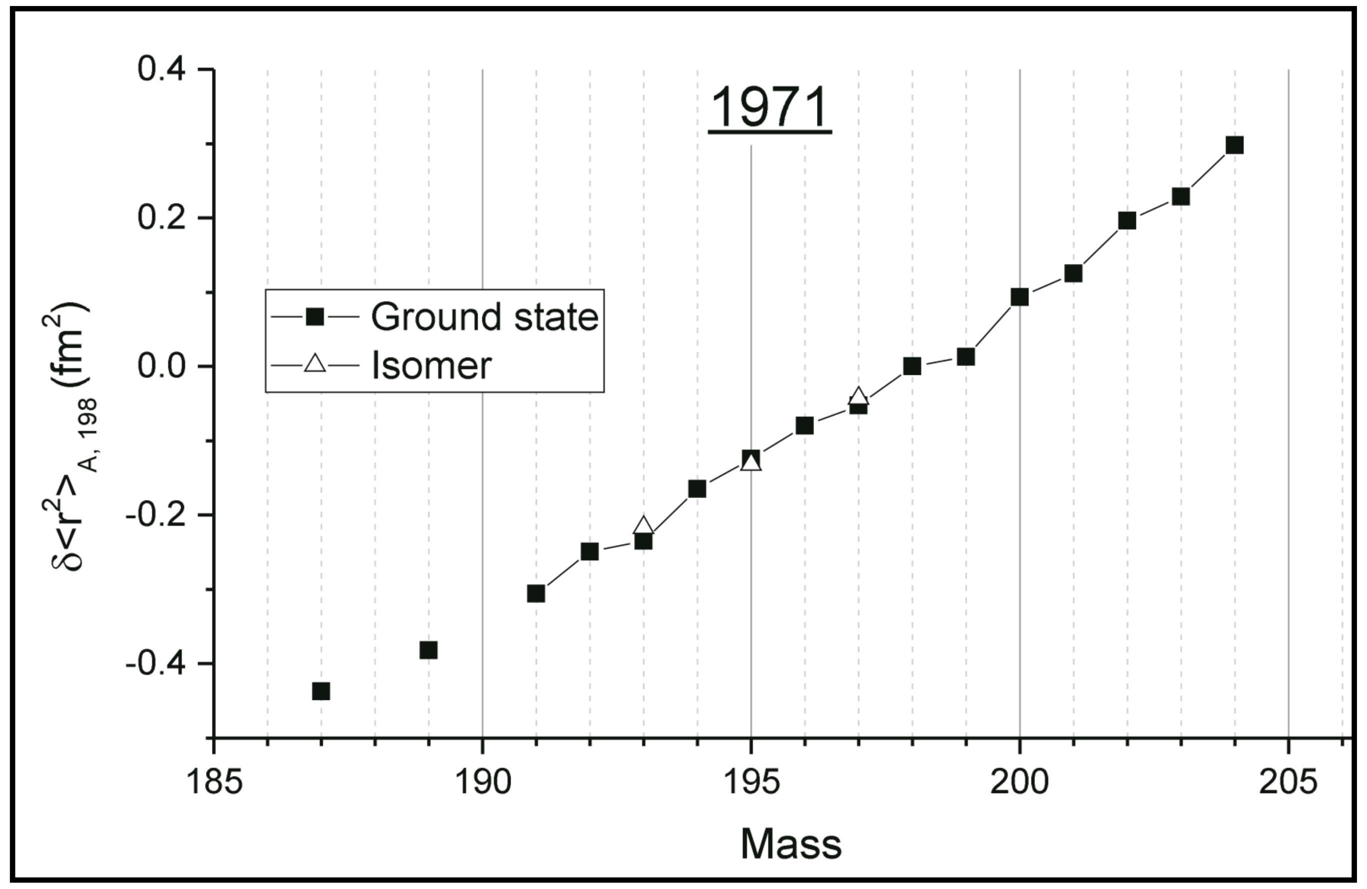


1971



1971
Ground state
Isomer
$\delta\langle r^2\rangle_{A,198}$ (fm^2)
Mass
0.4
0.2
0.0
-0.2
-0.4
185
190
195
200
205

1971

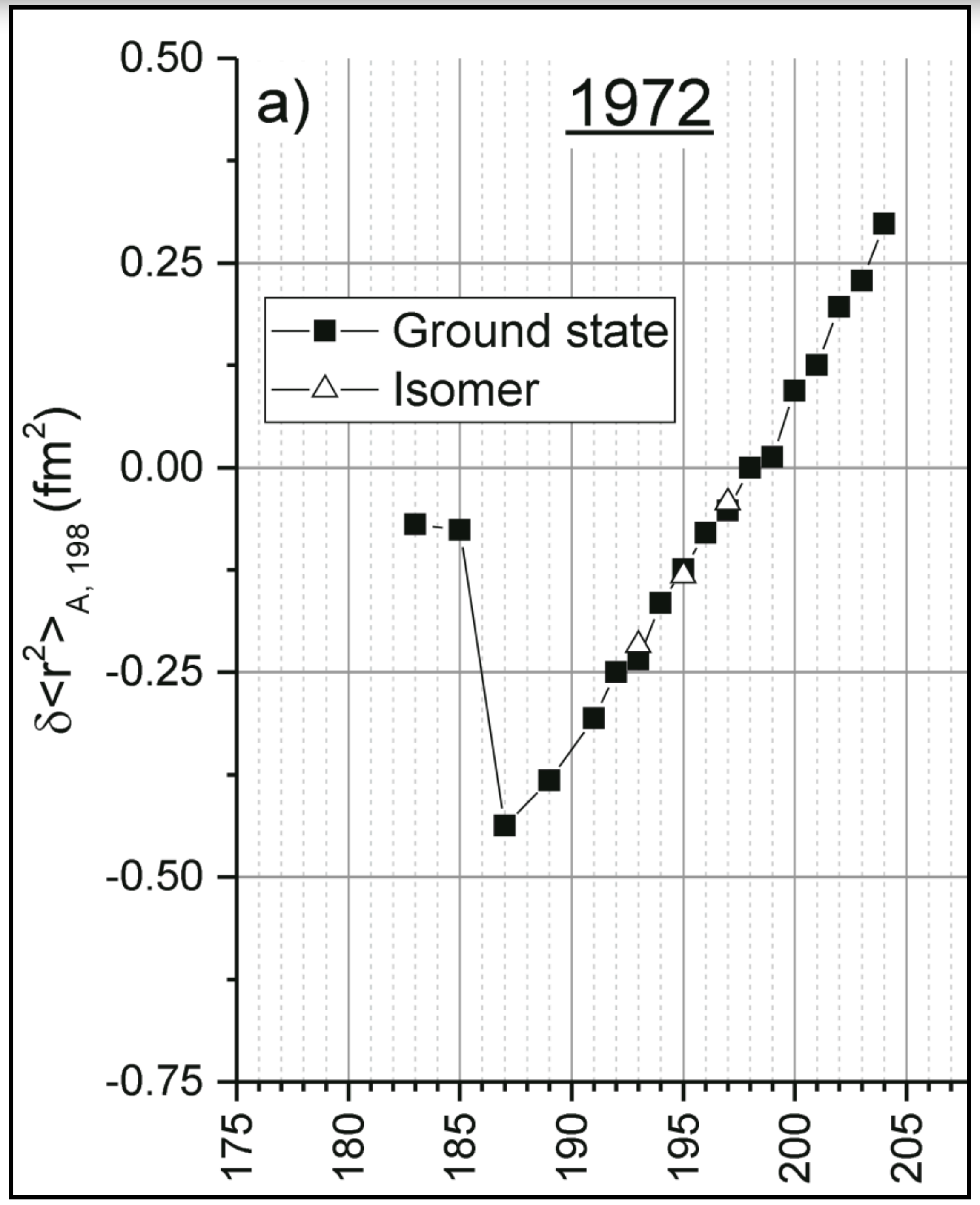


1972

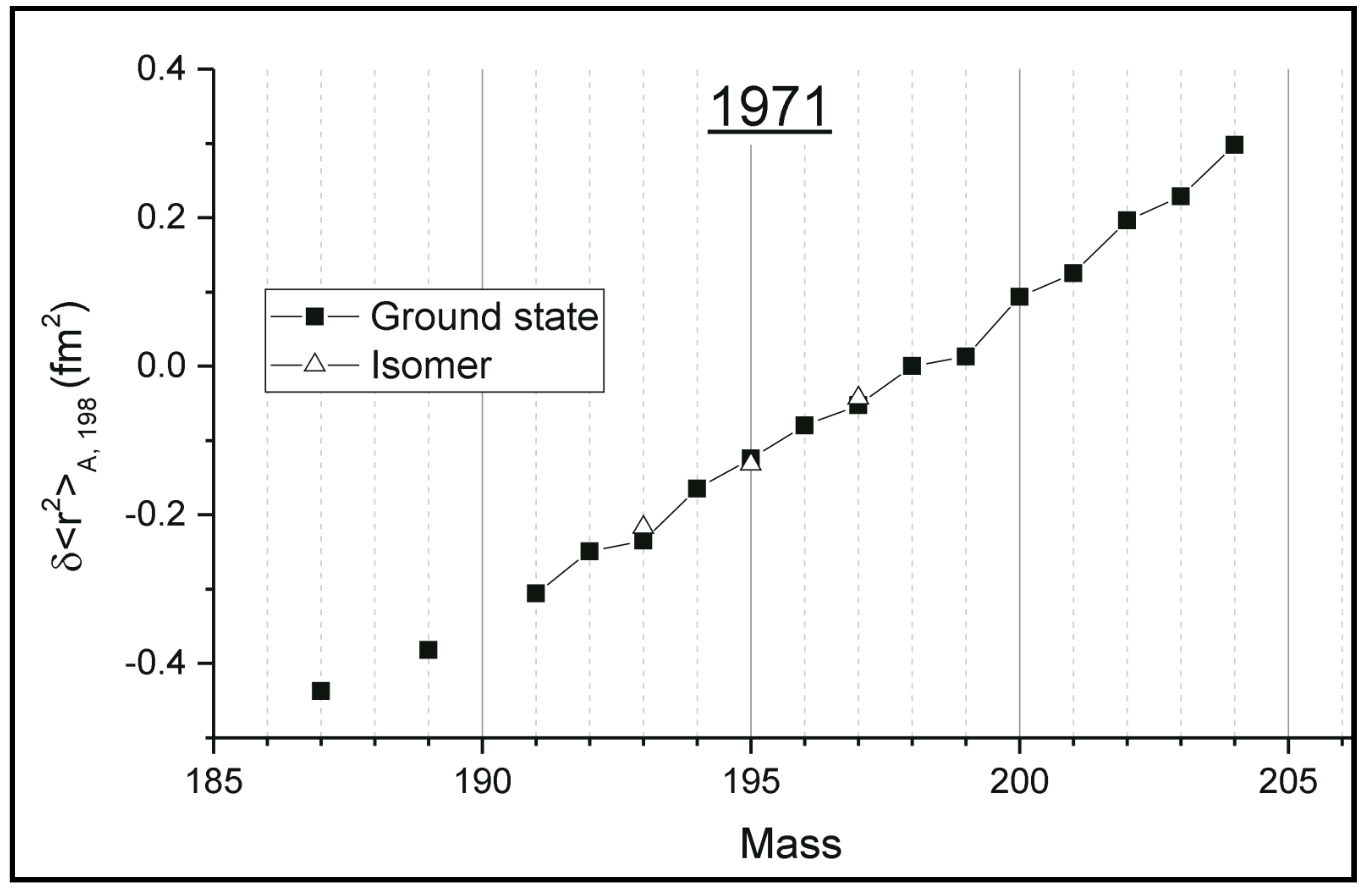
Physics Letters B
8, Issue 5, 6 March 1972, Pages 308-311

Sudden change in the nuclear charge distribution of very light mercury isotopes

J. Bonn [a, b], G. Huber [a, b], H.-J. Kluge [a, b], L. Kugler [a, b], E.W. Otten [a, b]



1971

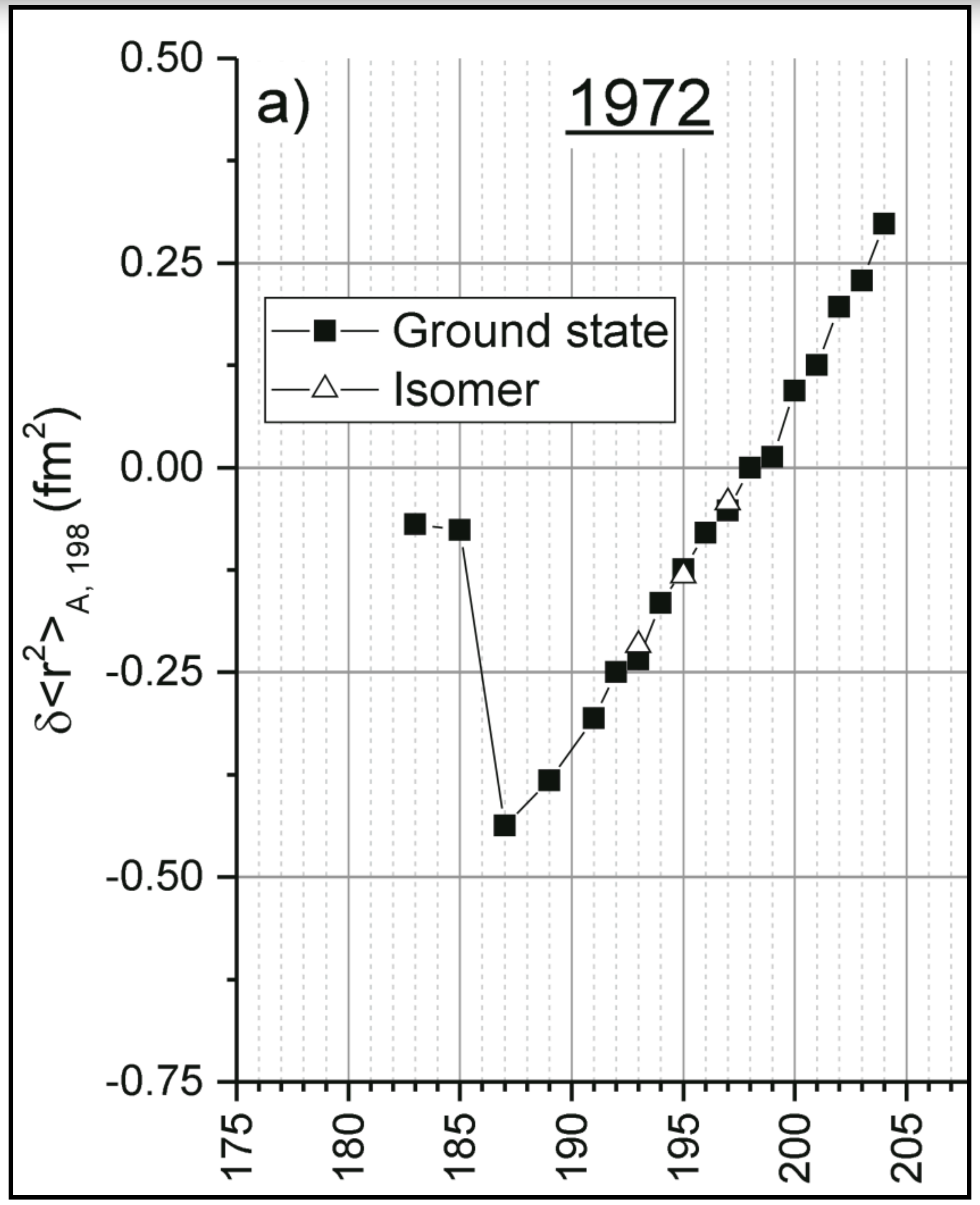


1972

Physics Letters B
8, Issue 5, 6 March 1972, Pages 308-311

Sudden change in the nuclear charge distribution of very light mercury isotopes

J. Bonn [a, b], G. Huber [a, b], H.-J. Kluge [a, b], L. Kugler [a, b], E.W. Otten [a, b]



Z. Phys. A – Atomic Nuclei 325, 247–259 (1986)

Zeitschrift für Physik A
Atomic Nuclei

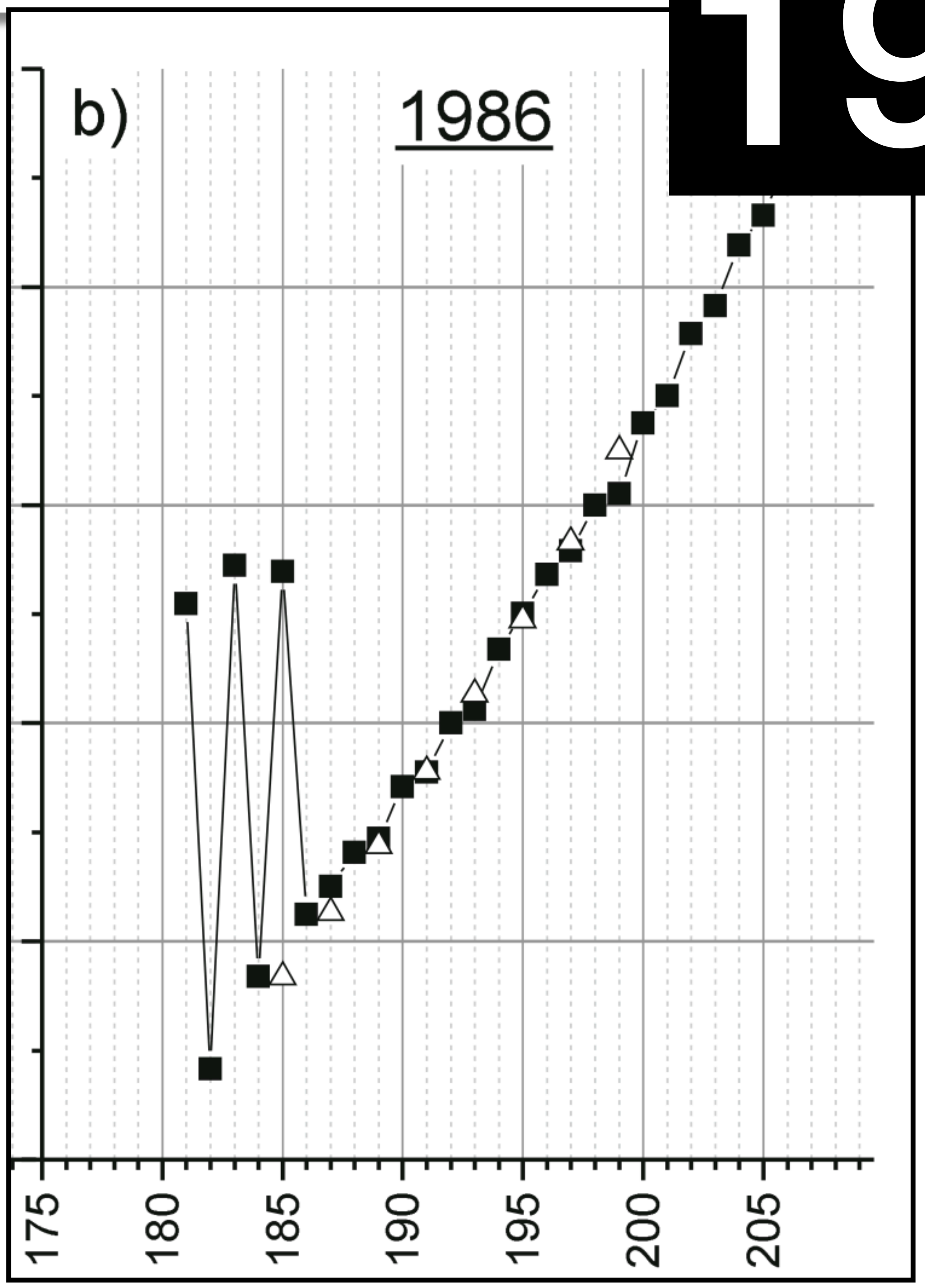
Isotope Shift of ^{182}Hg and an Update of Nuclear Moments and Charge Radii in the Isotope Range ^{181}Hg – ^{206}Hg

G. Ulm[1], S.K. Bhattacherjee[2], P. Dabkiewicz[3], G. Huber, H.-J. Kluge[1], T. Kühl[4], H. Lochmann[5], E.-W. Otten, and K. Wendt
Institut für Physik, Universität Mainz, Federal Republic of Germany

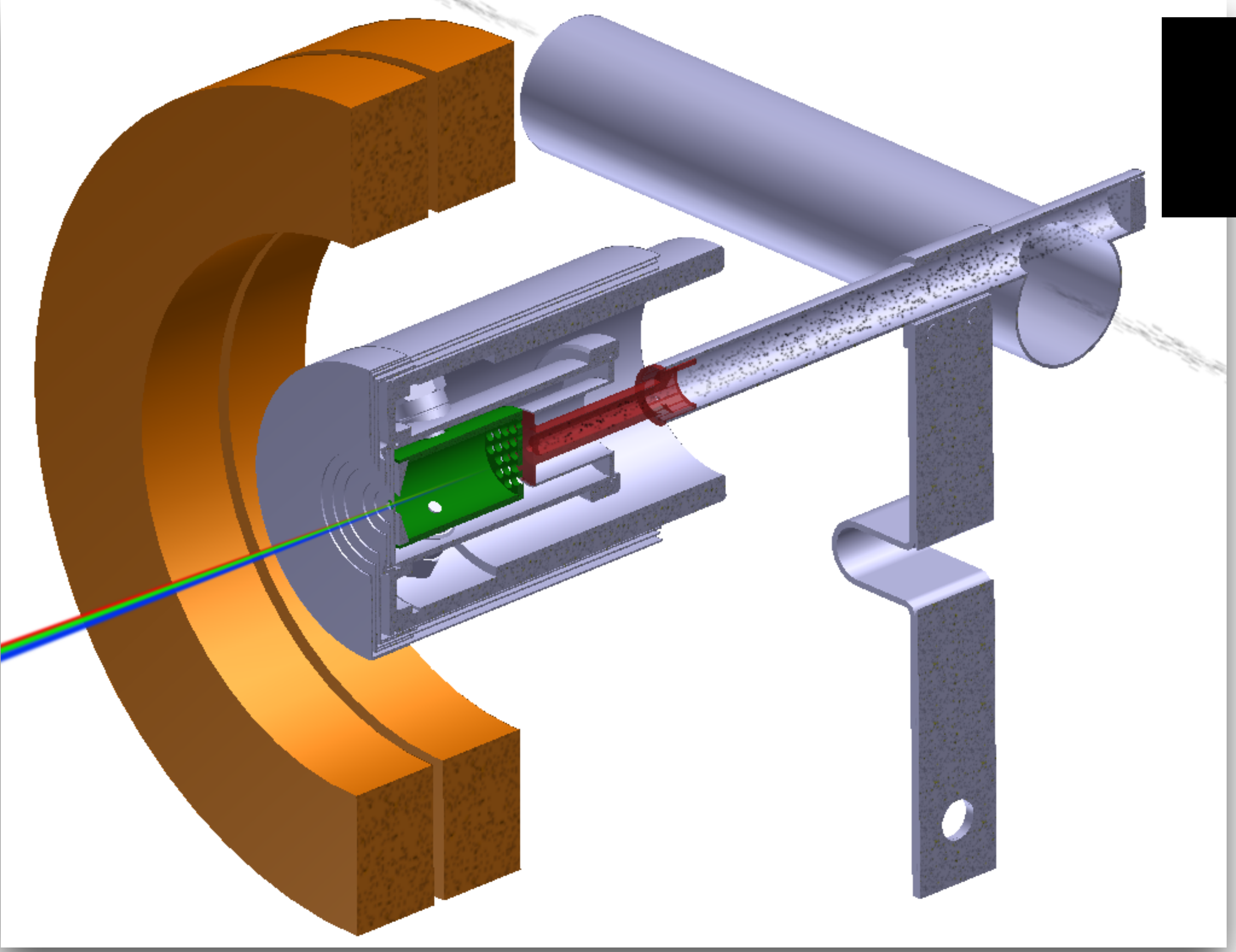
S.A. Ahmad[6], W. Klempt, R. Neugart[7], and the ISOLDE Collaboration
CERN, Geneva, Switzerland

Received July 15, 1986

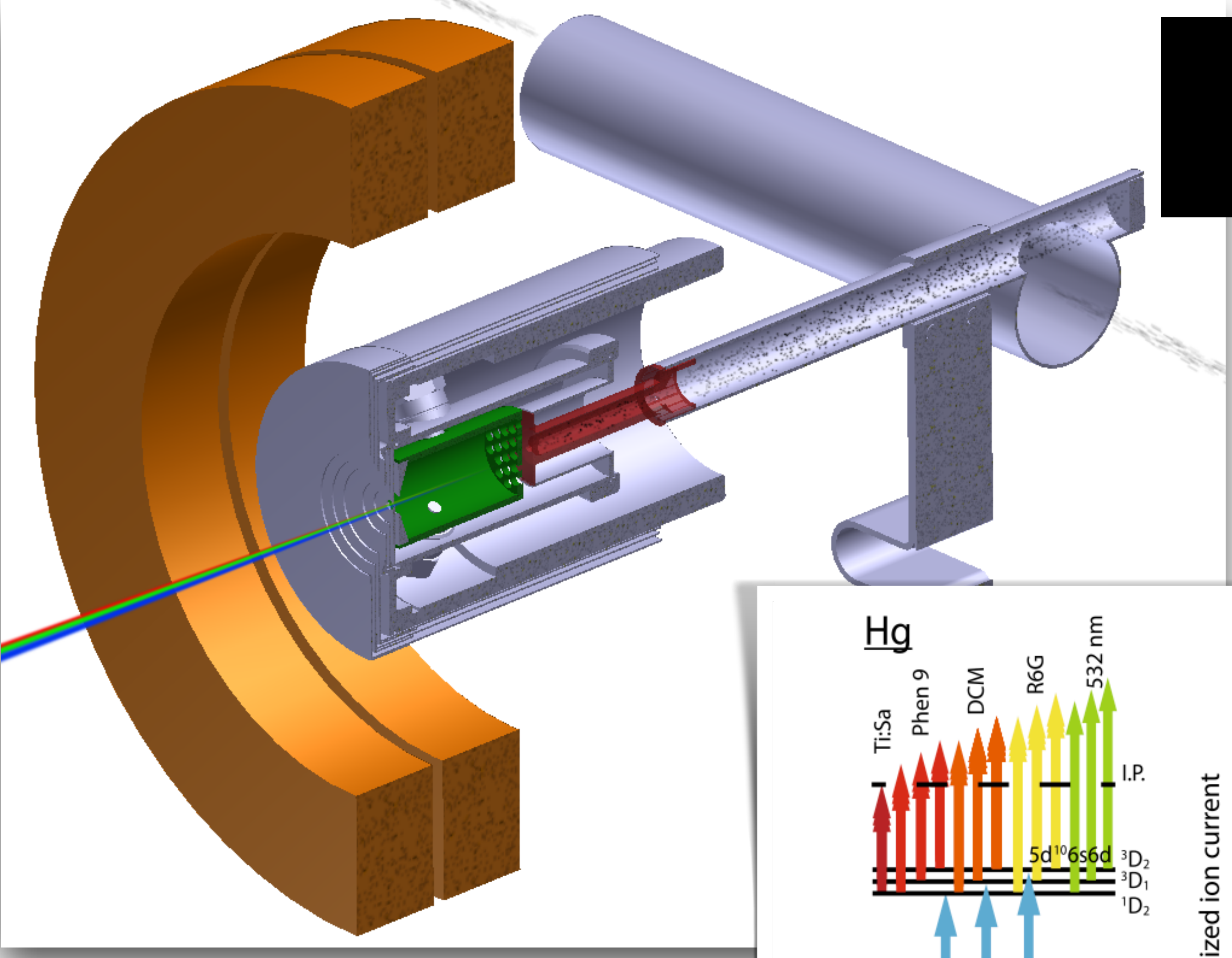
1986



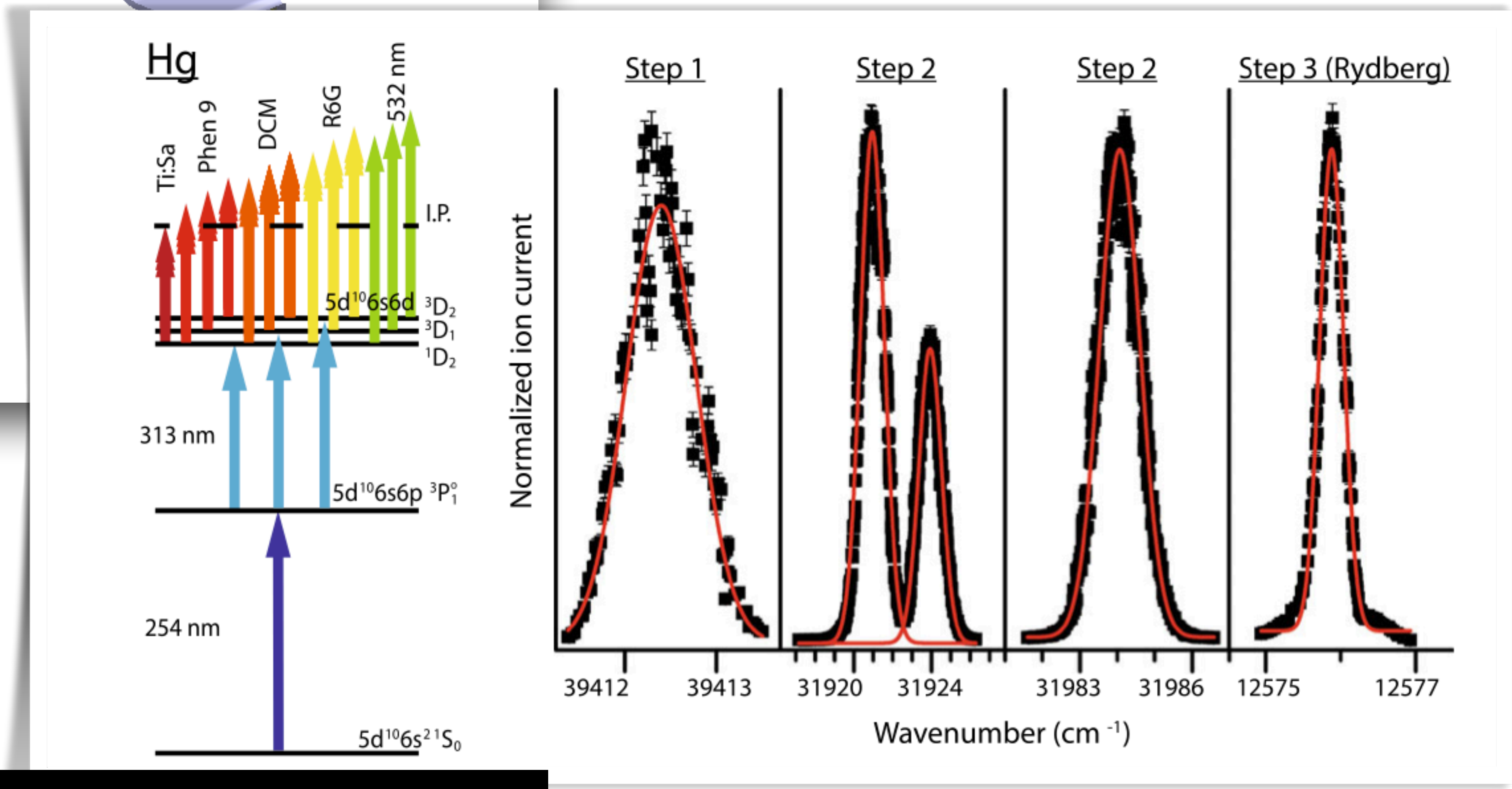
Incredible results for the time, but limited by low production rates and low sensitivity of the method



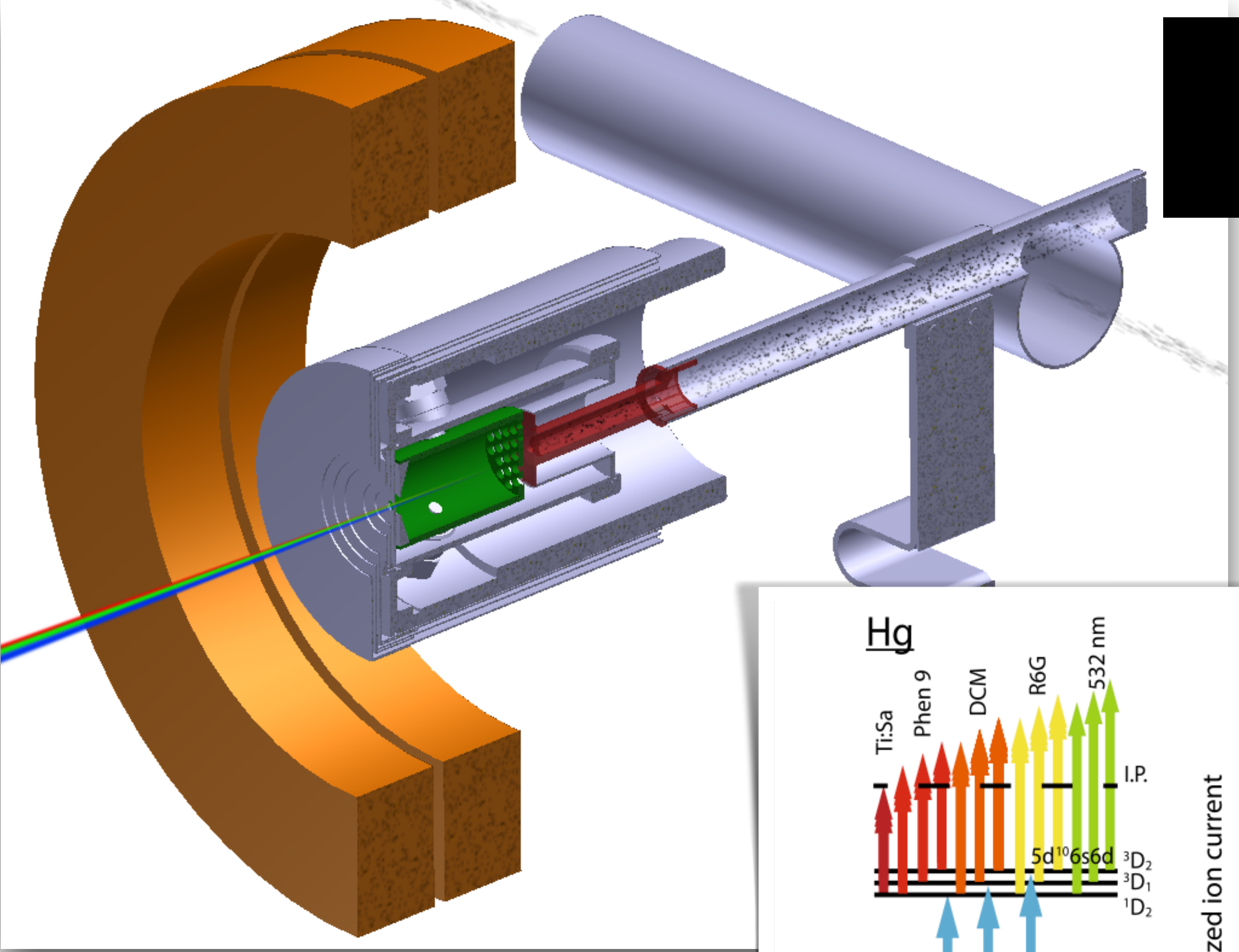
Ion source development



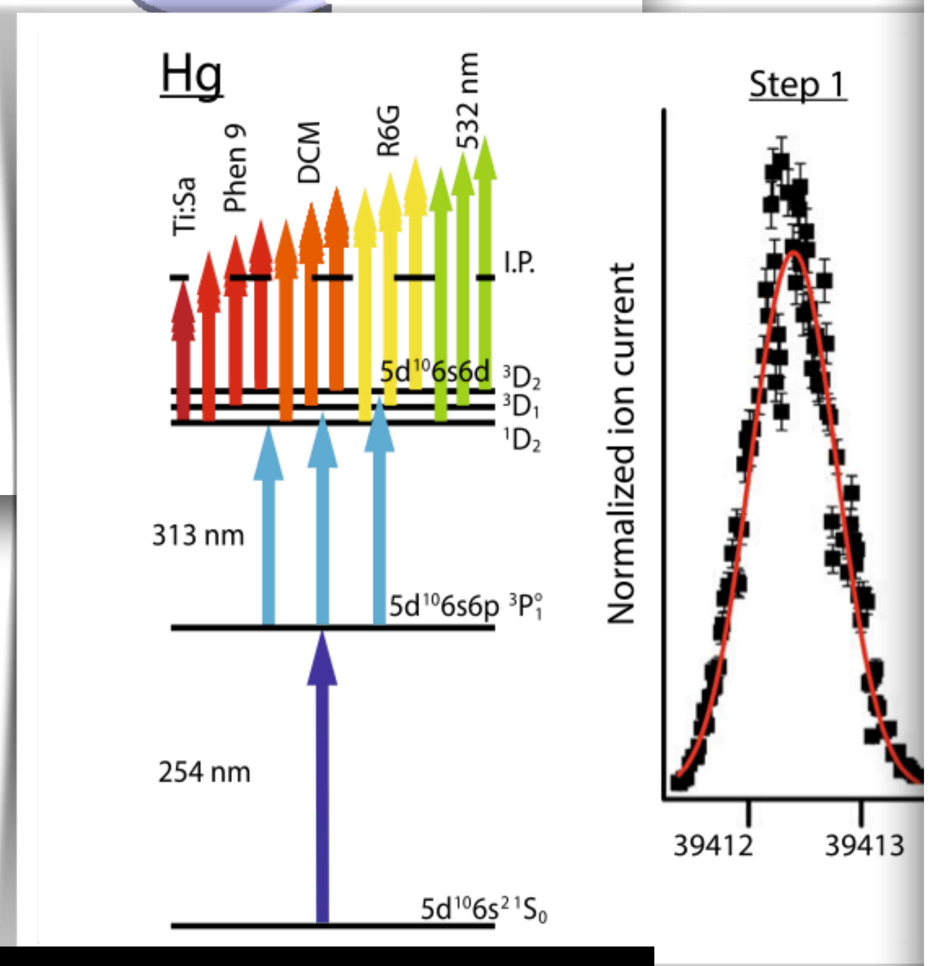
Ion source development



New ionization scheme for Hg (10 x efficiency improvement)

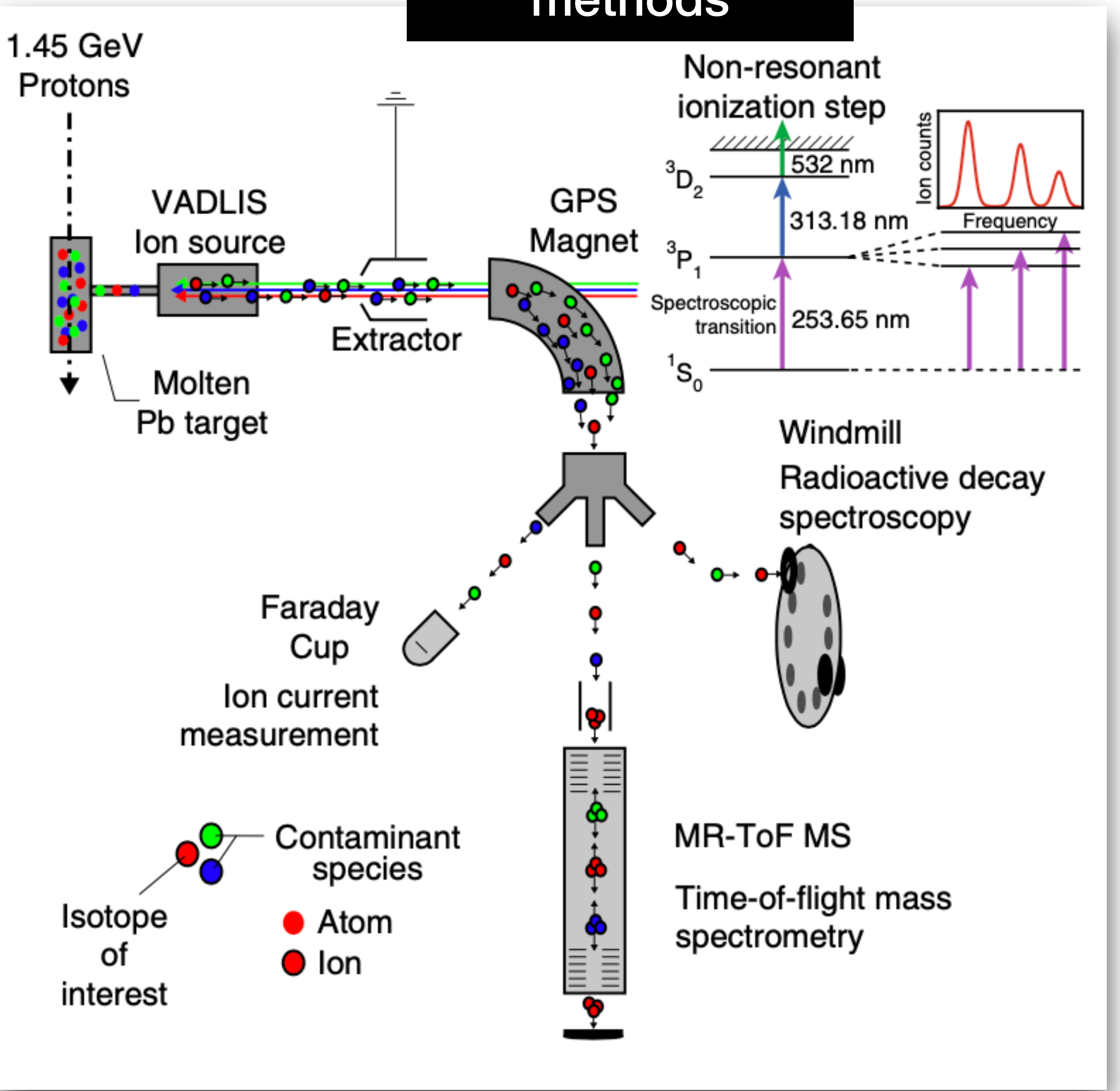


Ion source development



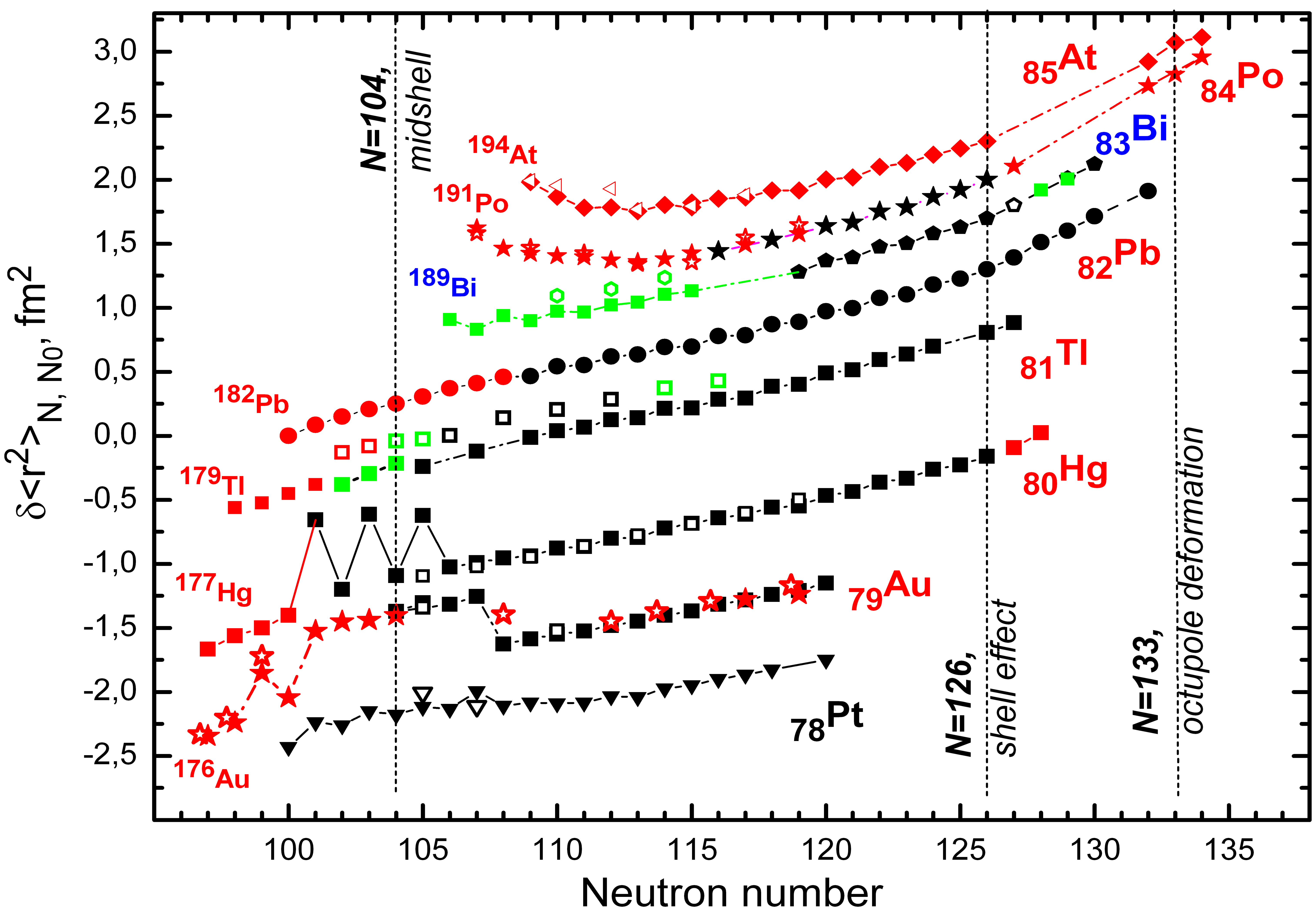
New ionization scheme for Hg (10 x efficiency improvement)

State-of -the art ISOLDE detection methods



Ion source development
State-of -the art ISOLDE detection methods
New ionization scheme for Hg (10 x efficiency improvement)
Completing the 40 year old study of Hg!
New theoretical approaches to explain this effect
Hg
Ti:Sa
Phen 9
DCM
R6G
532 nm
I.P.
313 nm
254 nm
Step 1
Normalized ion current
39412
39413
1.45 GeV Protons
VADLIS Ion source
Molten Pb target
Extractor
GPS Magnet
Non-resonant ionization step
532 nm
313.18 nm
253.65 nm
Spectroscopic transition
Ion counts
Windmill Radioactive spectroscop
Faraday Cup
Ion current measurement
Contaminant species
Isotope of interest
Atom
Ion
MR-T
Time- spect
^{181}Hg: $\langle\beta_2^2\rangle^{1/2}$= 0.313
^{190}Hg: $\langle\beta_2^2\rangle^{1/2}$= 0.174
$\delta\langle r^2\rangle^{A-198}$ (fm^2)
This work, gs/is
Previous work, gs/is
Neutron number
Mass number
Previous work gs/is
This work gs/is
MCSM
MCSM with $\mu_{th} \neq \mu_{exp}$
Small deformation
Large deformation
MCSM ground-state occupation numbers
Neutron
Proton
Energy (MeV)

Ion source development
State-of -the art ISOLDE detection methods
Completing the 40 year old study of Hg!
New theoretical approaches to explain this effect
1.45 GeV Protons
VADLIS Ion source
Molten Pb target
Extractor
GPS Magnet
Non-resonant ionization step
532 nm
313.18 nm
Spectroscopic transition
253.65 nm
Windmill Radioactive spectroscop
Faraday Cup
n current surement
Contaminant species
Atom
Ion
MR-T
Time- spect
Hg
Step 1
Normalized ion current
313 nm
181Hg: ⟨β2²⟩1/2 = 0.313
190Hg: ⟨β2²⟩1/2 = 0.174
This work, gs/is
Previous work, gs/is
nature physics
LETTERS
https://doi.org/10.1038/s41567-018-0292-8
Characterization of the shape-staggering effect in mercury nuclei
B.A.Marsh1*, T.Day Goodacre1,2,18, S.Sels3,18, Y.Tsunoda4, B.Andel5, A.N.A
N.A.Althubiti2, D.Atanasov8, A.E.Barzakh9, J.Billowes2, K.Blaum8, T.E.Cocolios
J.Dobaczewski6, G.J.Farooq-Smith2,3, D.V.Fedorov9, V.N.Fedosseev1, K.T.Fl
L.Ghys3, M.Huyse3, S.Kreim8, D.Lunney11, K.M.Lynch1, V.Manea8, Y.Martinez P
T.Otsuka3,4,12,13,14, A.Pastore6, M.Rosenbusch13,15, R.E.Rossel1, S.Rothe1,2, L.Schwe
P.Spagnoletti10, C.Van Beveren3, P.Van Duppen3, M.Veinhard1, E.Verstraelen3, A
F.Wienholtz15, R.N.Wolf8, A.Zadvornaya3 and K.Zuber16
Springer Theses
Recognizing Outstanding Ph.D. Research
Thomas Day Goodacre
Applied Laser Spectroscopy for Nuclear Physics
Isotope Shifts in the Mercury Isotopic Chain and Laser Ion Source Development
Springer
Neutron number
Mass number
Previous work gs/is
This work gs/is
MCSM
Small deformation
Large deformation



δ<r2>N, N0, fm2
Neutron number
N=104, midshell
N=126, shell effect
N=133, octupole deformation
85At
84Po
83Bi
82Pb
81Tl
80Hg
79Au
78Pt
194At
191Po
189Bi
182Pb
179Tl
177Hg
176Au


Editors' Suggestion
Open Access
Shape staggering of midshell mercury isotopes from in-source laser spectroscopy compared with density-functional-theory and Monte Carlo shell-model calculations
S. Sels et al.
Phys. Rev. C 99, 044306 – Published 12 April 2019
Open Access
In-Source Laser Spectroscopy with the Laser Ion Source and Trap: First Direct Study of the Ground-State Properties of ^{217,219}Po
D. A. Fink et al.
Phys. Rev. X 5, 011018 – Published 20 February 2015
Open Access
Laser Spectroscopy of Neutron-Rich ^{207,208}Hg Isotopes: Illuminating the Kink and Odd-Even Staggering in Charge Radii across the $N = 126$ Shell Closure
T. Day Goodacre et al.
Phys. Rev. Lett. 126, 032502 – Published 22 January 2021
Open Access
Charge radii and electromagnetic moments of $^{195-211}$At
J. G. Cubiss et al.
Phys. Rev. C 97, 054327 – Published 29 May 2018
Physics Letters B
Volume 786, 10 November 2018, Pages 355-363
ELSEVIER
Change in structure between the $I = 1/2$ states in ^{181}Tl and ^{177,179}Au
Open Access
Shape coexistence in ^{187}Au studied by laser spectroscopy
A. E. Barzakh et al.
Phys. Rev. C 101, 064321 – Published 25 June 2020
Physics Letters B
Volume 719, Issues 4–5, 26 February 2013, Pages 362-366
ELSEVIER
Charge radii of odd-A $^{191-211}$Po isotopes
Early Onset of Ground State Deformation in Neutron Deficient Polonium Isotopes
T. E. Cocolios et al.
Phys. Rev. Lett. 106, 052503 – Published 2 February 2011
Nuclear Charge Radii of Neutron-Deficient Lead Isotopes Beyond $N = 104$ Midshell Investigated by In-Source Laser Spectroscopy
H. De Witte et al.
Phys. Rev. Lett. 98, 112502 – Published 16 March 2007
PRL 98, 112502 (2007)
PHYSICAL REVIEW LETTERS
week ending 16 MARCH 2007
Nuclear Charge Radii of Neutron-Deficient Lead Isotopes Beyond $N = 104$ Midshell Investigated by In-Source Laser Spectroscopy
nature physics
LETTERS
Characterization of the shape-staggering effect in mercury nuclei
Open Access
Large Shape Staggering in Neutron-Deficient Bi Isotopes
A. Barzakh et al.
Phys. Rev. Lett. 127, 192501 – Published 2 November 2021
Open Access
Inverse odd-even staggering in nuclear charge radii and possible octupole collectivity in ^{217,218,219}At revealed by in-source laser spectroscopy
A. E. Barzakh et al.
Phys. Rev. C 99, 054317 – Published 14 May 2019
N=104, midshell
N=126, shell effect
N=133, octupole defor
194At
191Po
189Bi
84Po
83Bi
82Pb
81Tl
80Hg
79Au
78Pt
-0,5
105

In-source spectroscopy ‘niche’

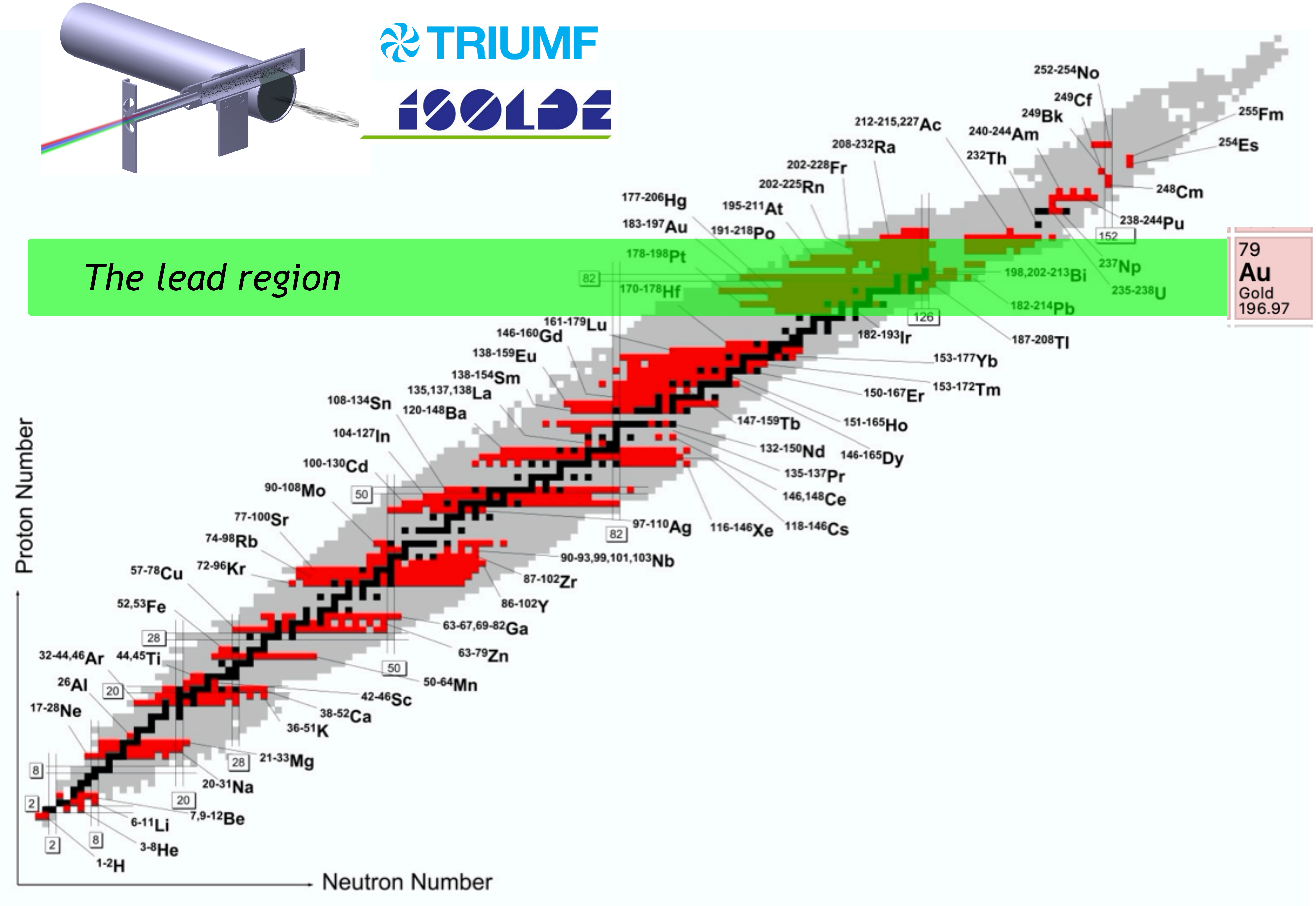
TRIUMF

ISOLDE

Sensitivity is unmatched!

0.01 ions per second!

Half life < 50 ms



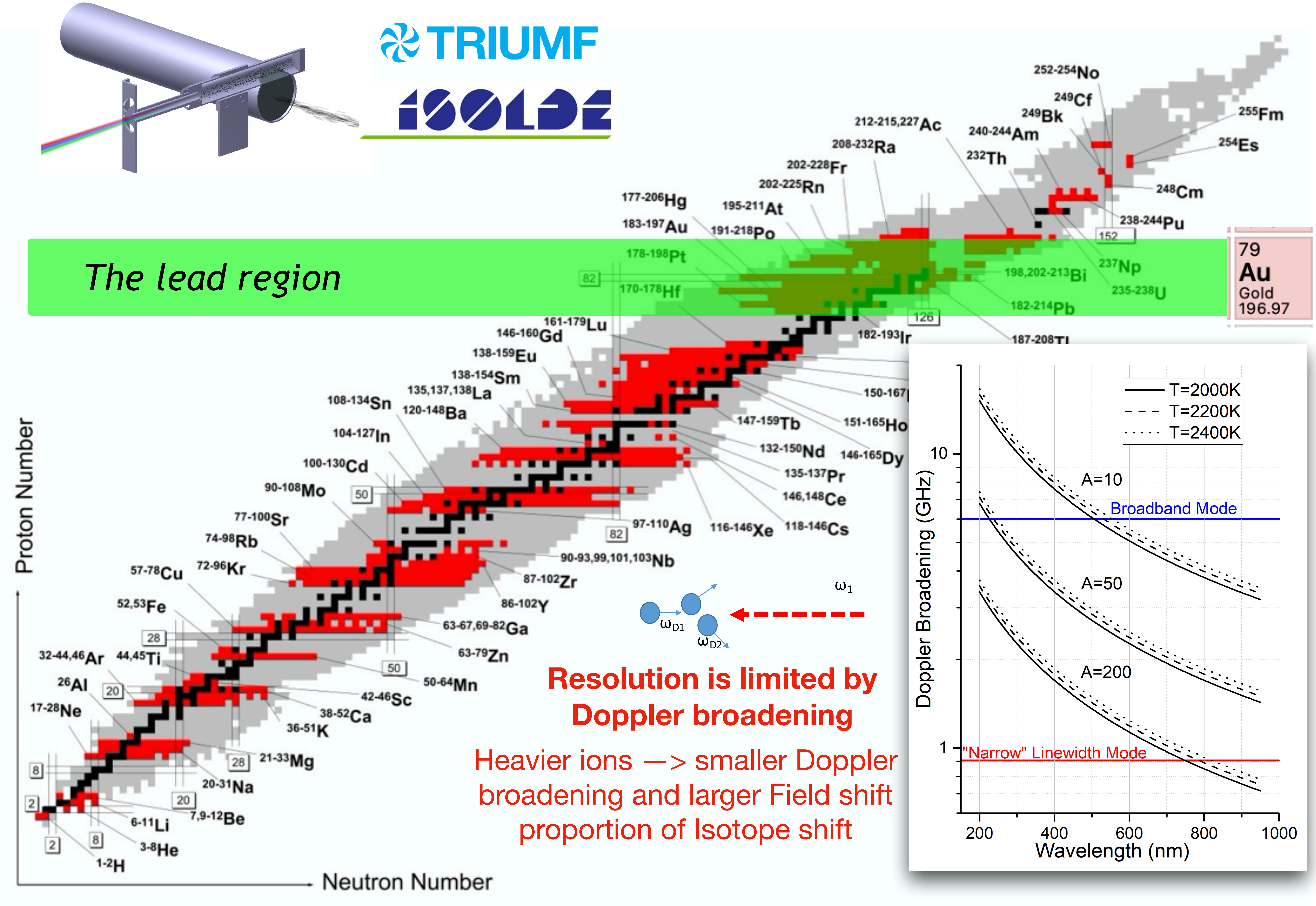
79	80	81	82	83	84	85
Au	Hg	Tl	Pb	Bi	Po	At
Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine
196.97	200.59	204.38	207.2	208.98	(209)	(210)

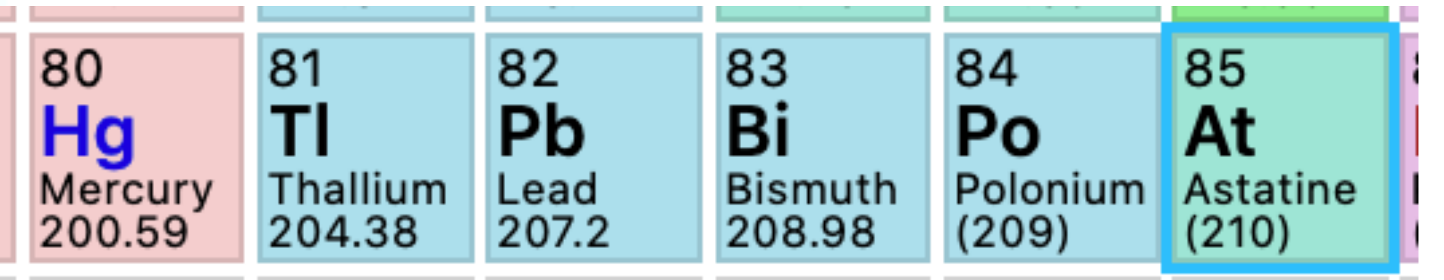
In-source spectroscopy ‘niche’

Sensitivity is unmatched!

0.01 ions per second!

Half life < 50 ms

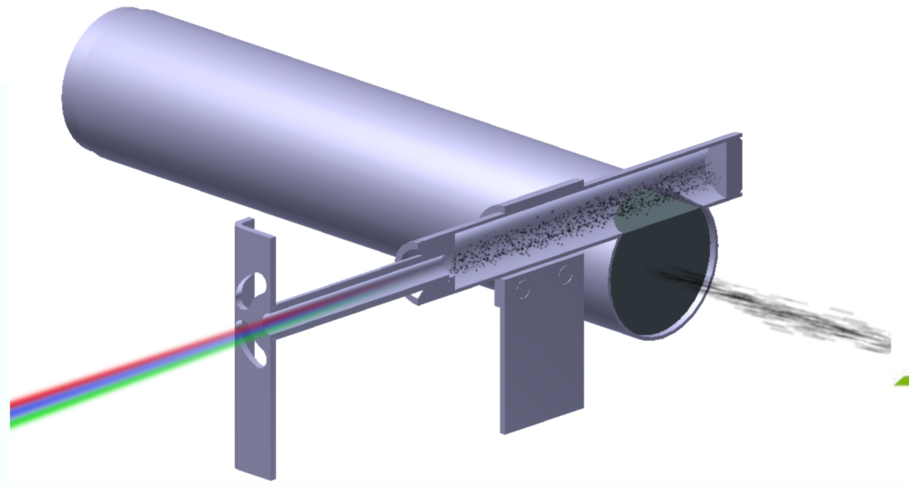




Resolution is limited by Doppler broadening

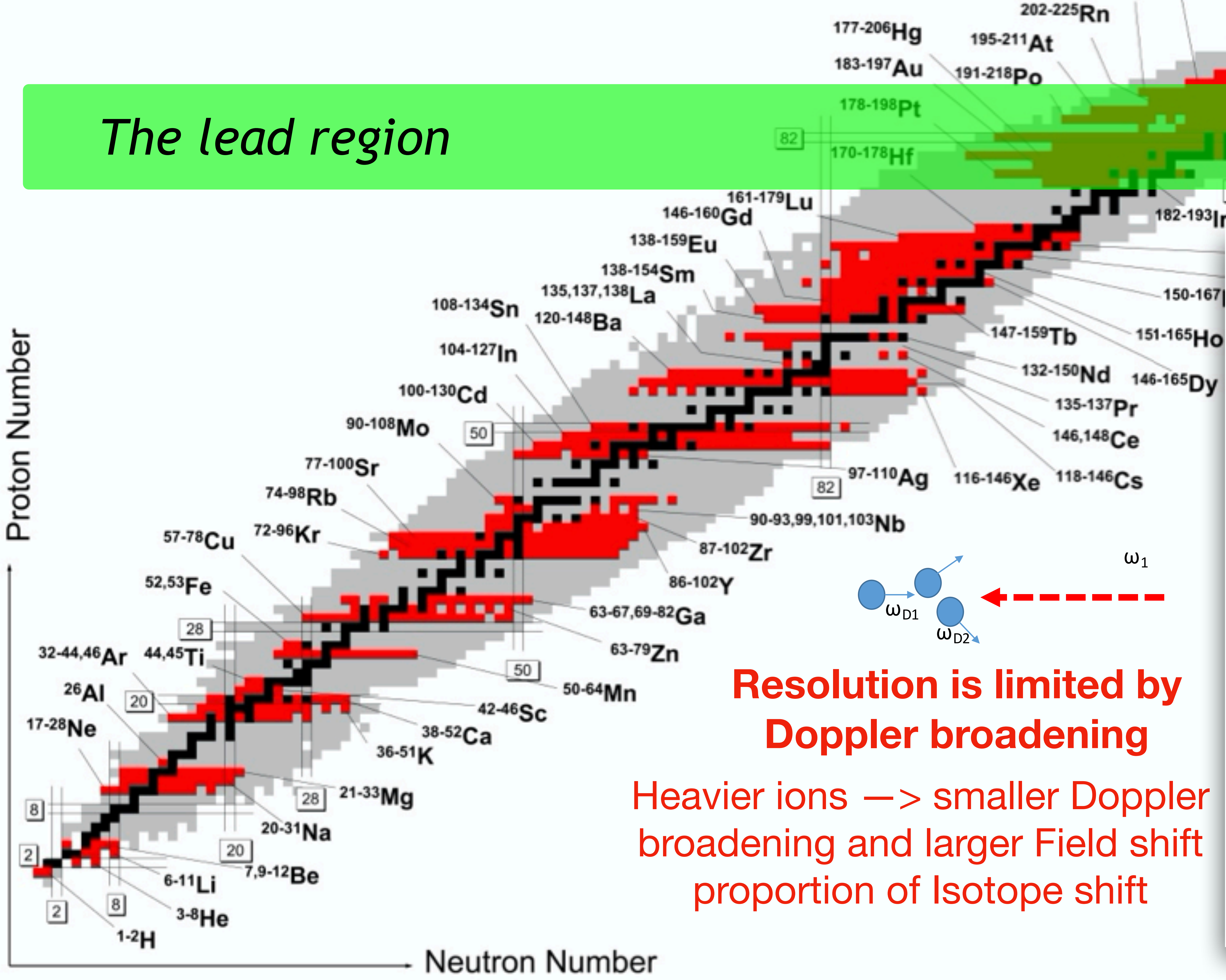
Heavier ions —> smaller Doppler broadening and larger Field shift proportion of Isotope shift

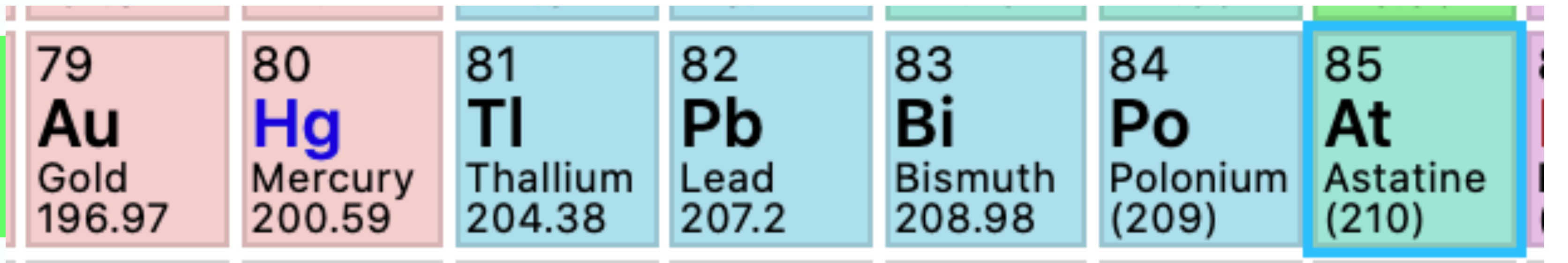
In-source spectroscopy ‘niche’



TRIUMF

ISOLDE





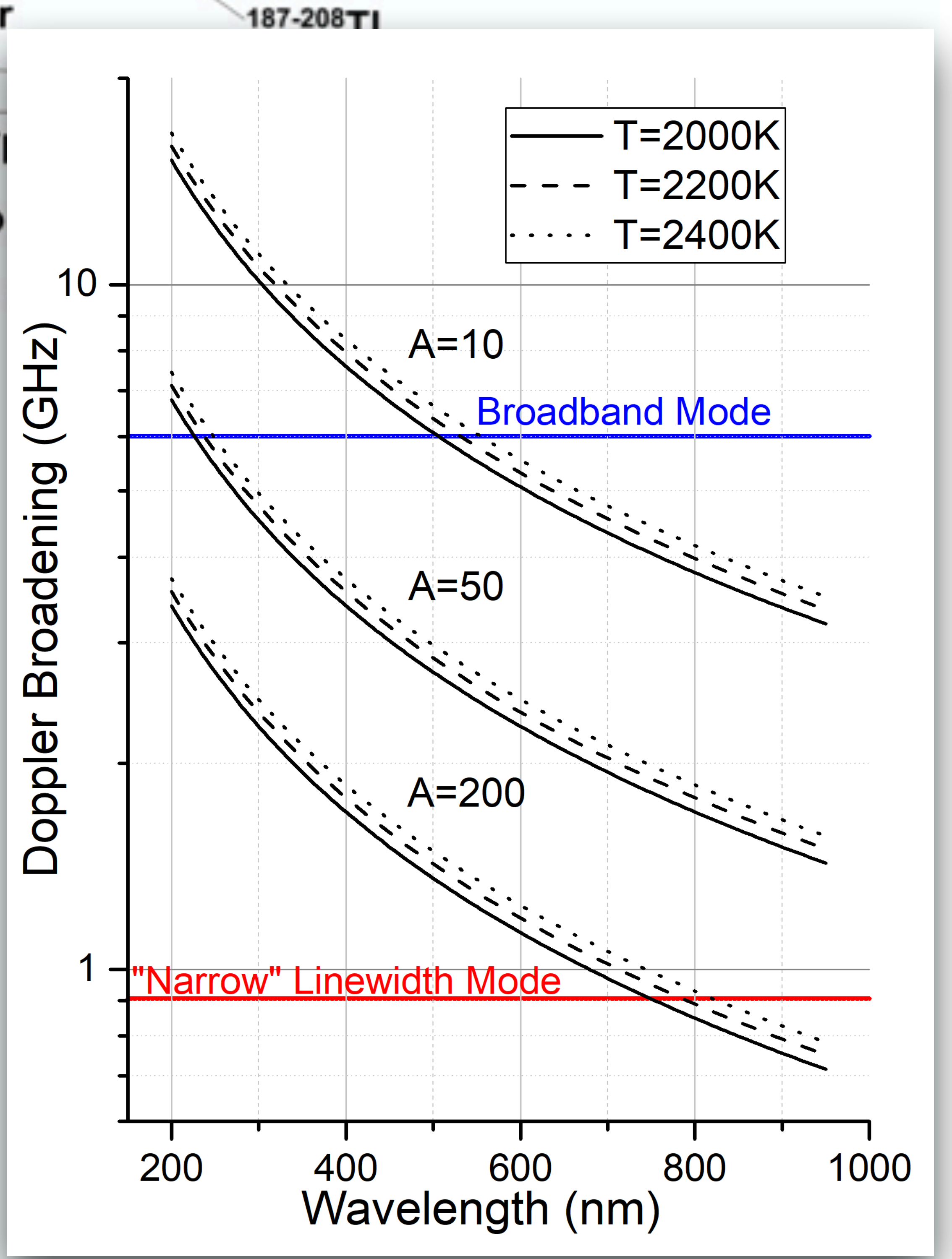
Sensitivity is unmatched!

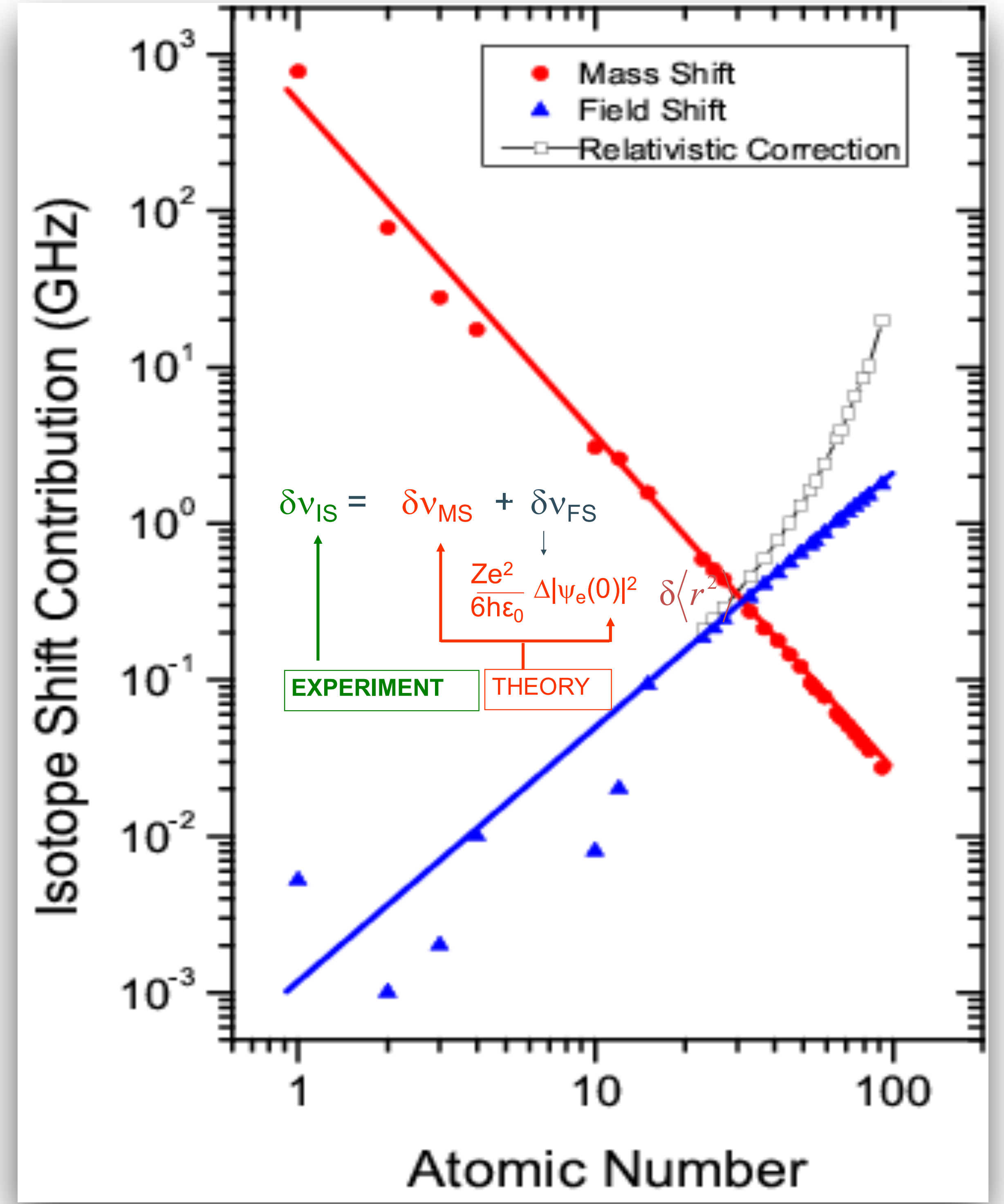
0.01 ions per second!

Half life < 50 ms

Resolution is limited by Doppler broadening

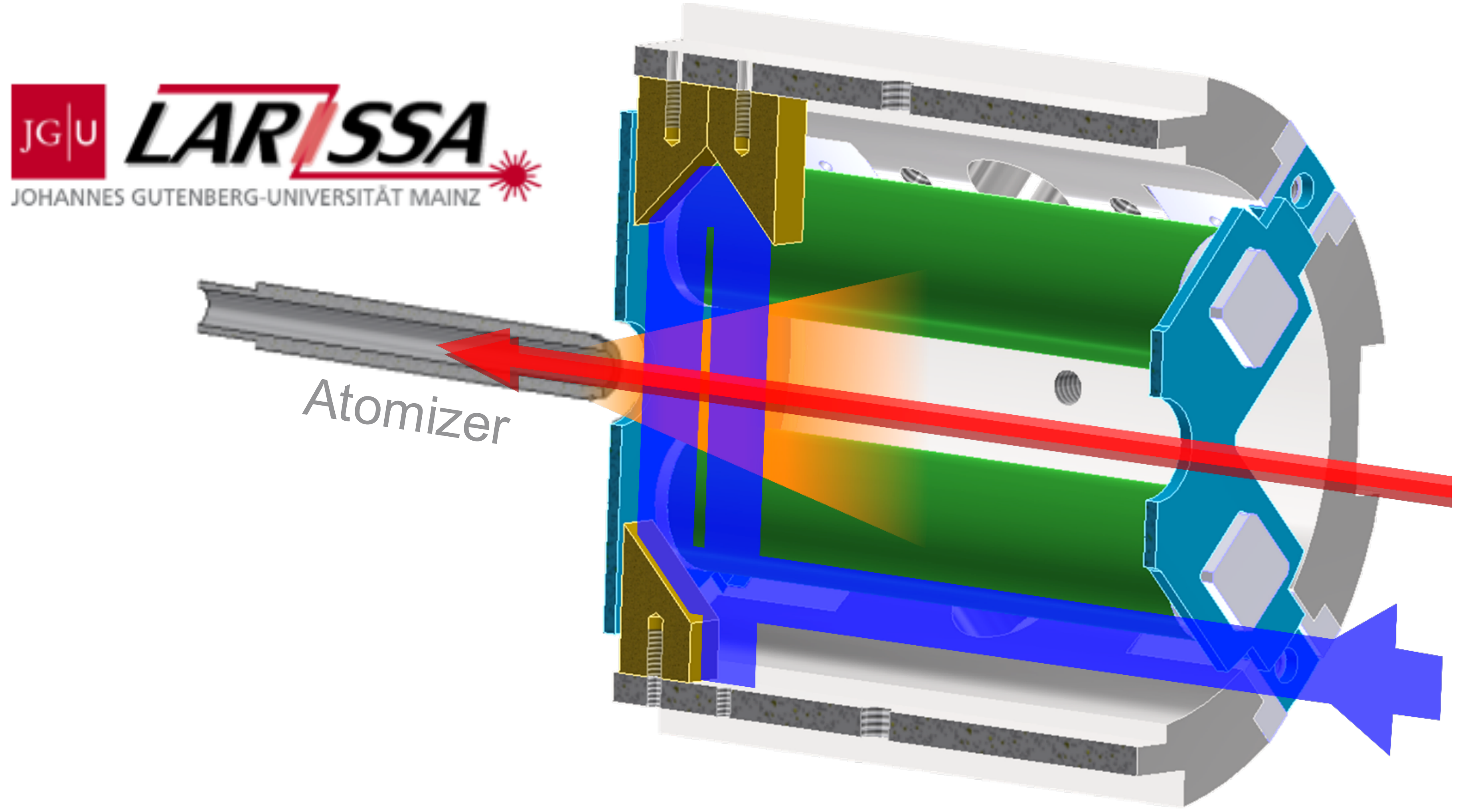
Heavier ions —> smaller Doppler broadening and larger Field shift proportion of Isotope shift

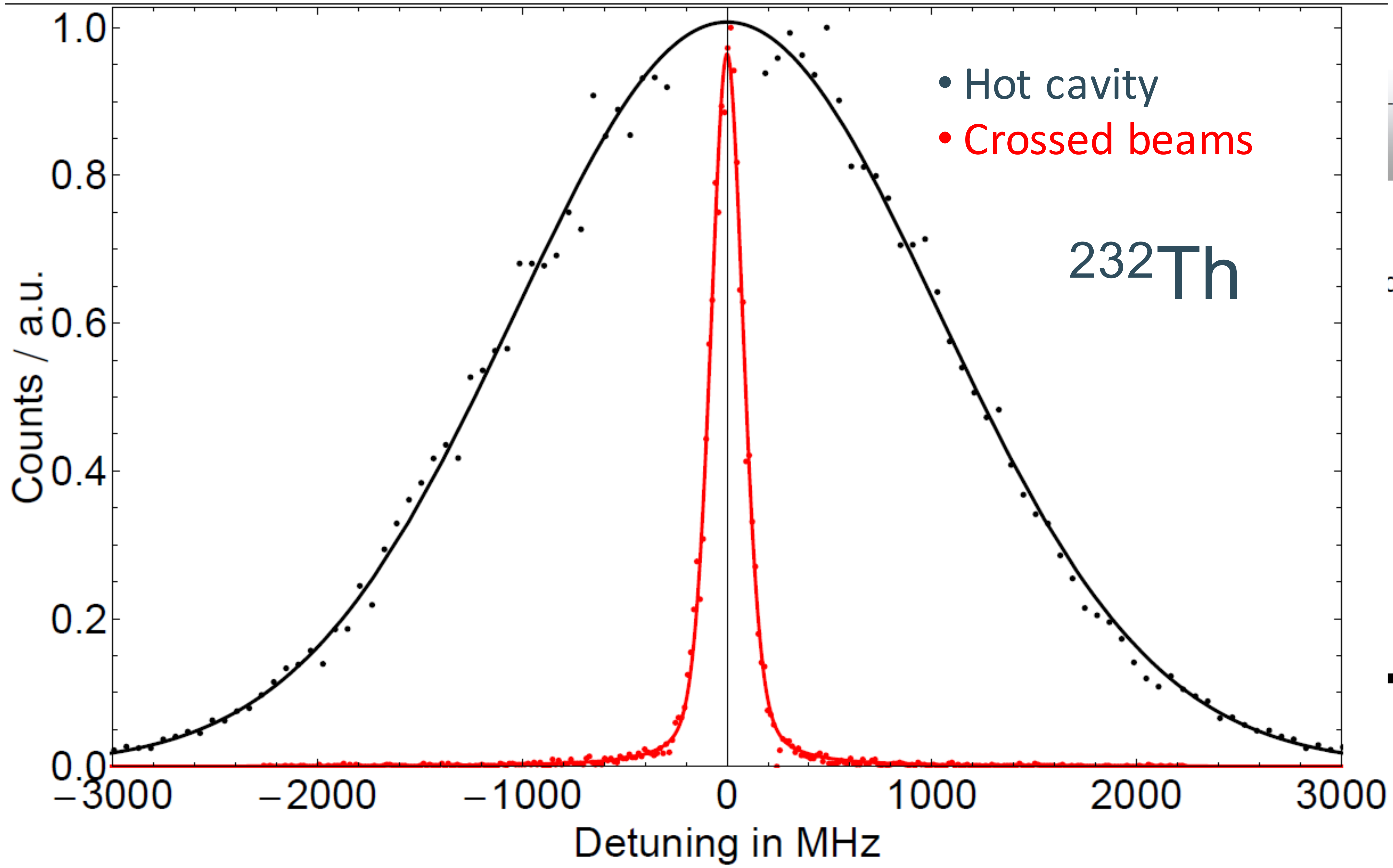


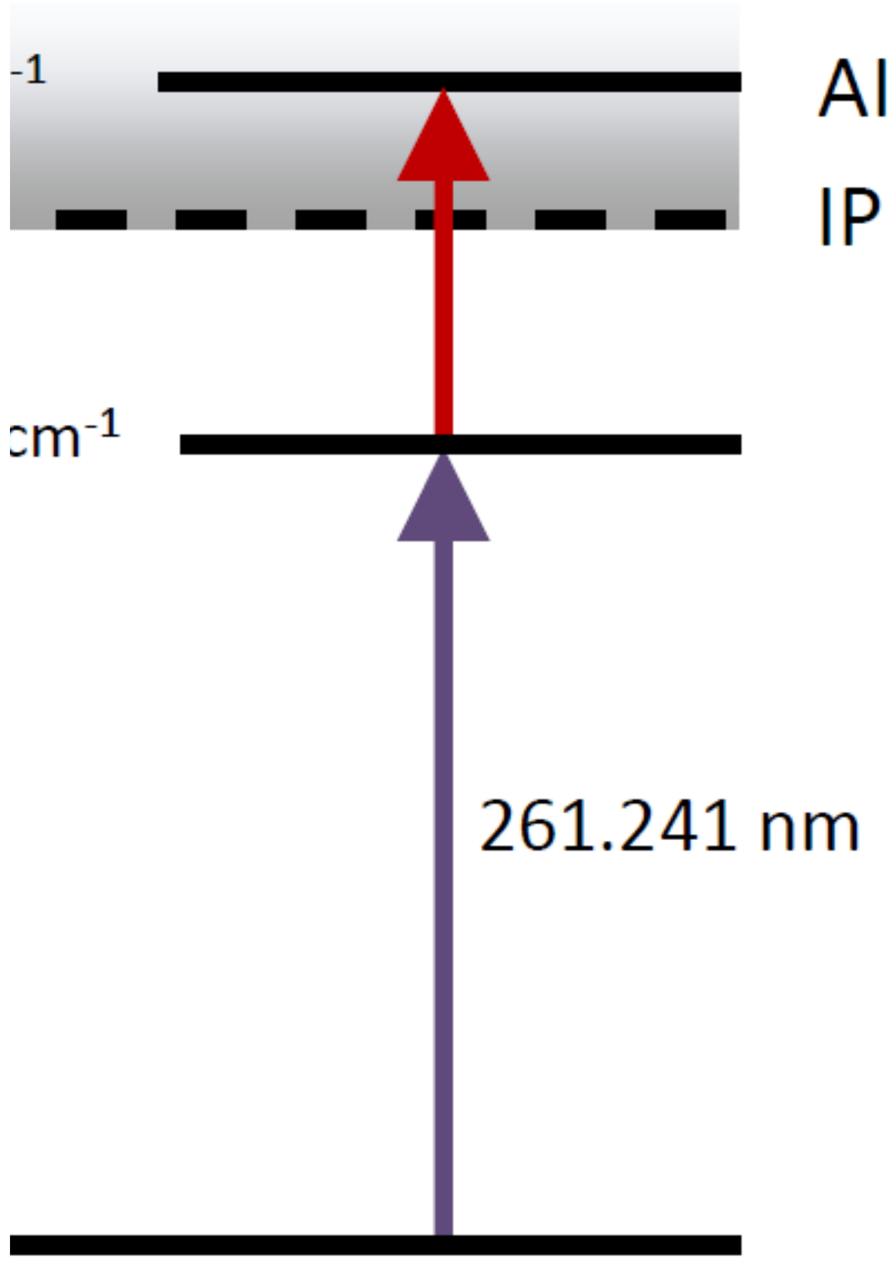


The PI-LIST

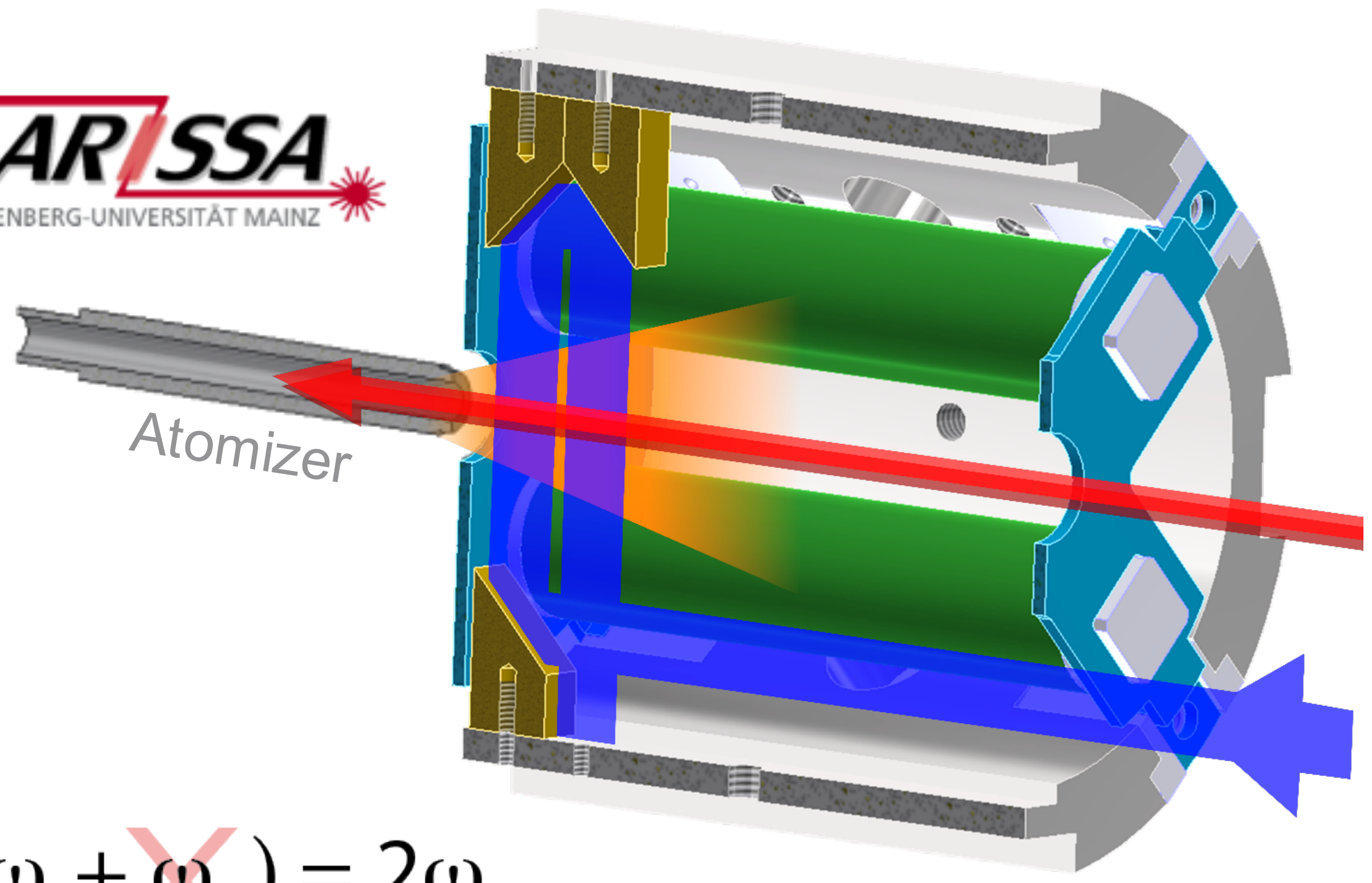
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES



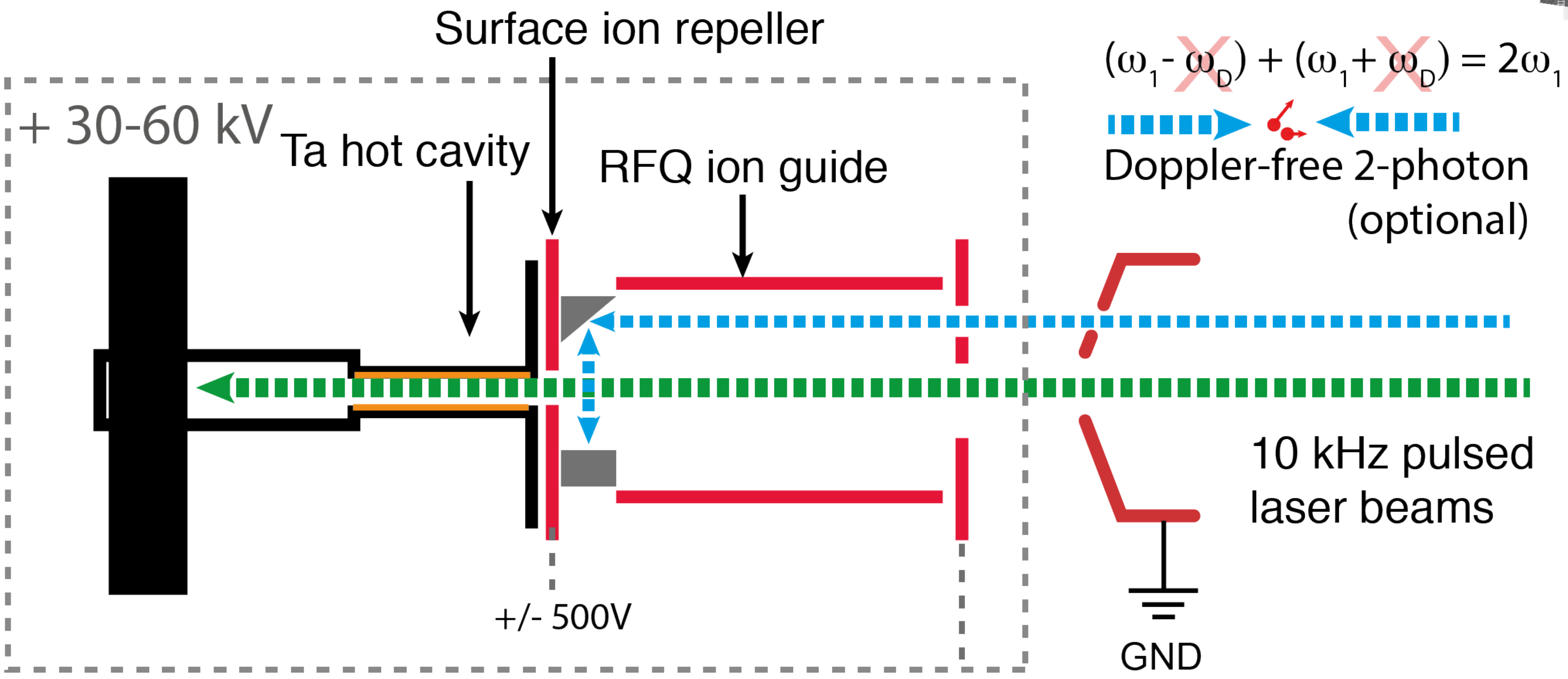




The PI-LIST

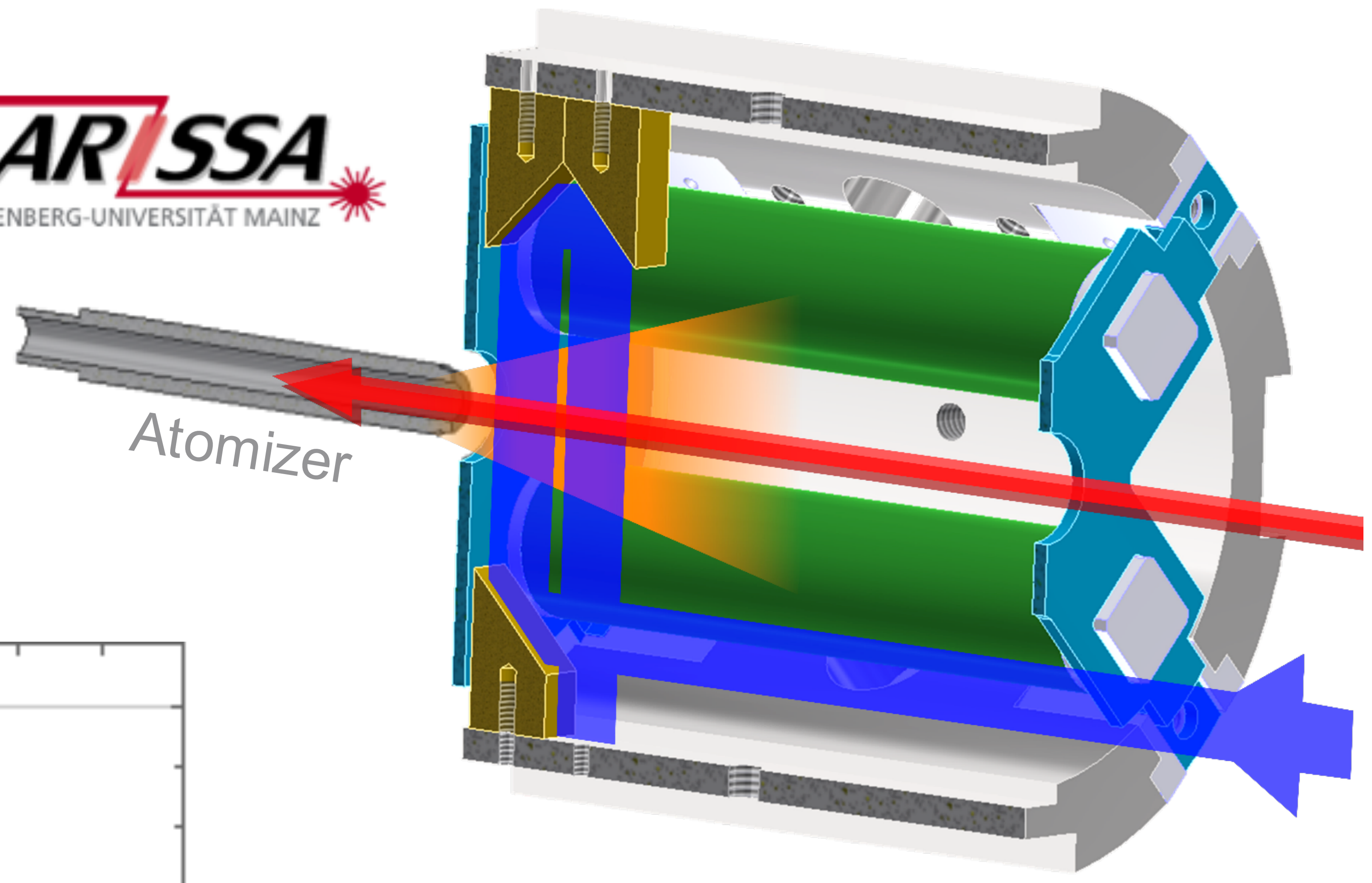


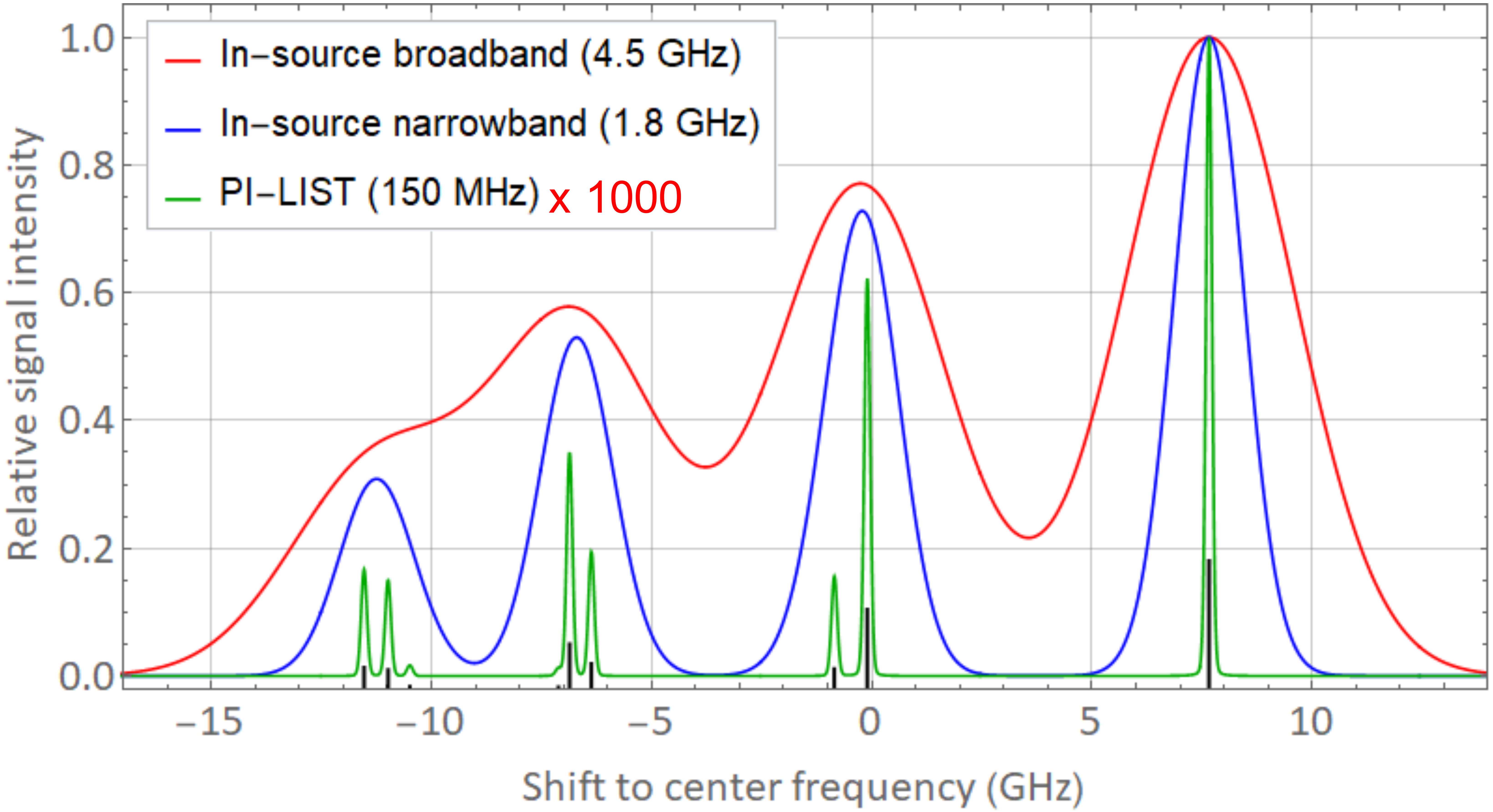
Atomizer



Surface ion repeller
+ 30-60 kV
Ta hot cavity
RFQ ion guide
+/- 500V
$(\omega_1 - \omega_D) + (\omega_1 + \omega_D) = 2\omega_1$
Doppler-free 2-photon
(optional)
10 kHz pulsed
laser beams
GND

The PI-LIST





Loss factors

RILIS → LIST ~ 30

LIST → PI-LIST ~ 4

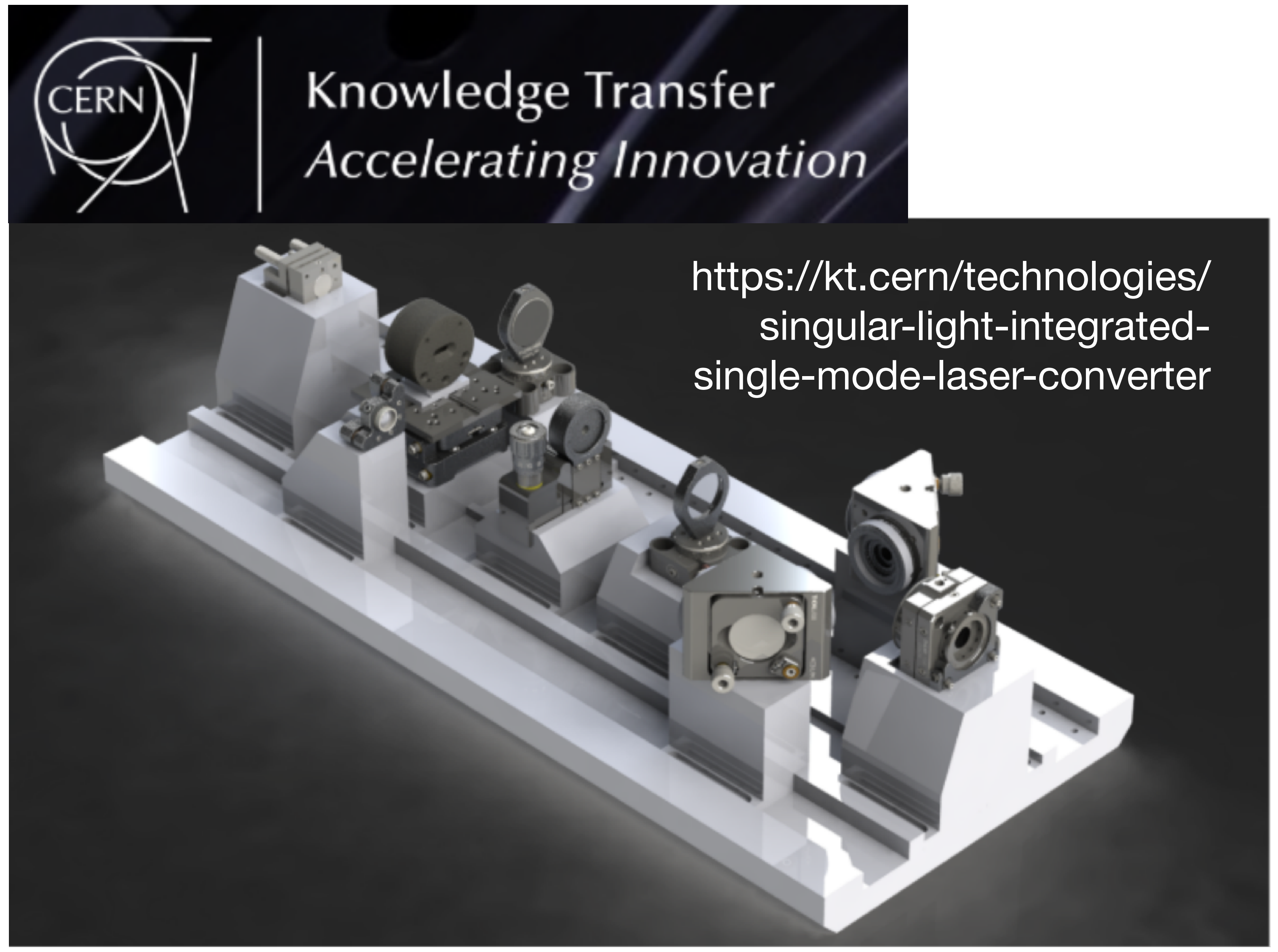
PI-LIST opt. ~ 10

~ 1,000

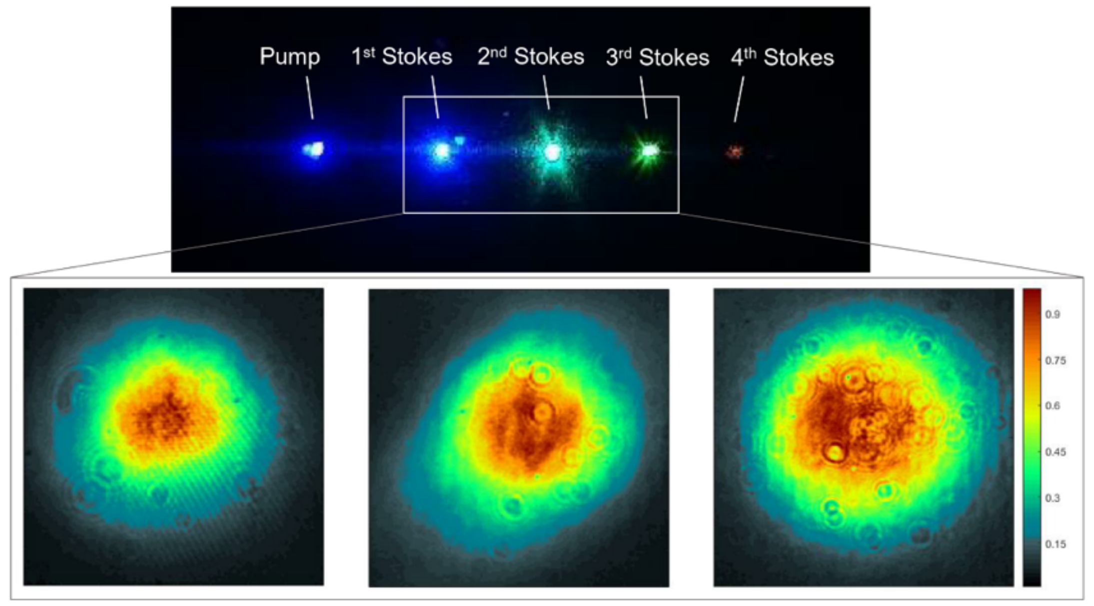
Reinhard Heinke

Asar Jaradat

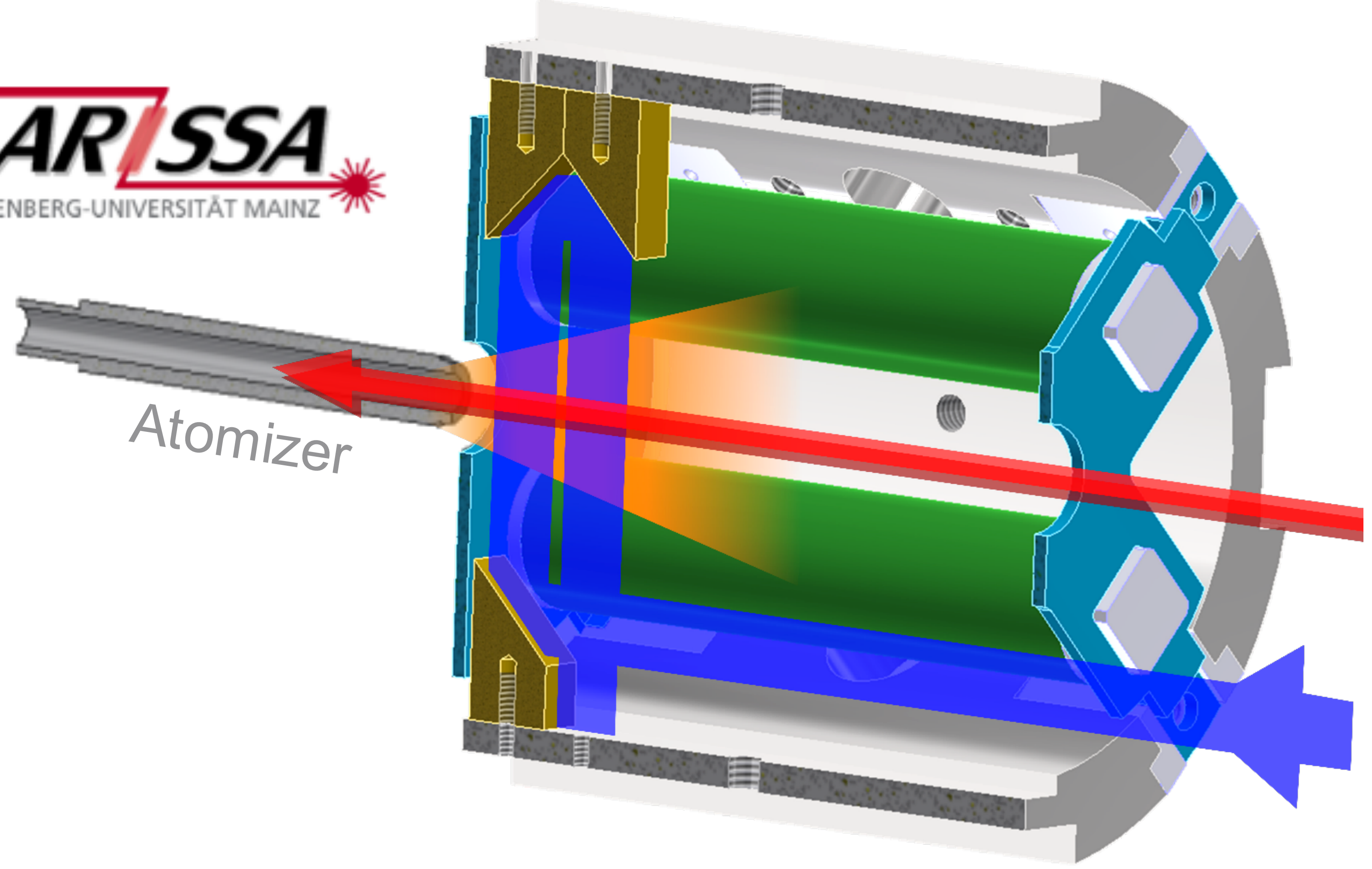
The single-mode diamond Raman laser

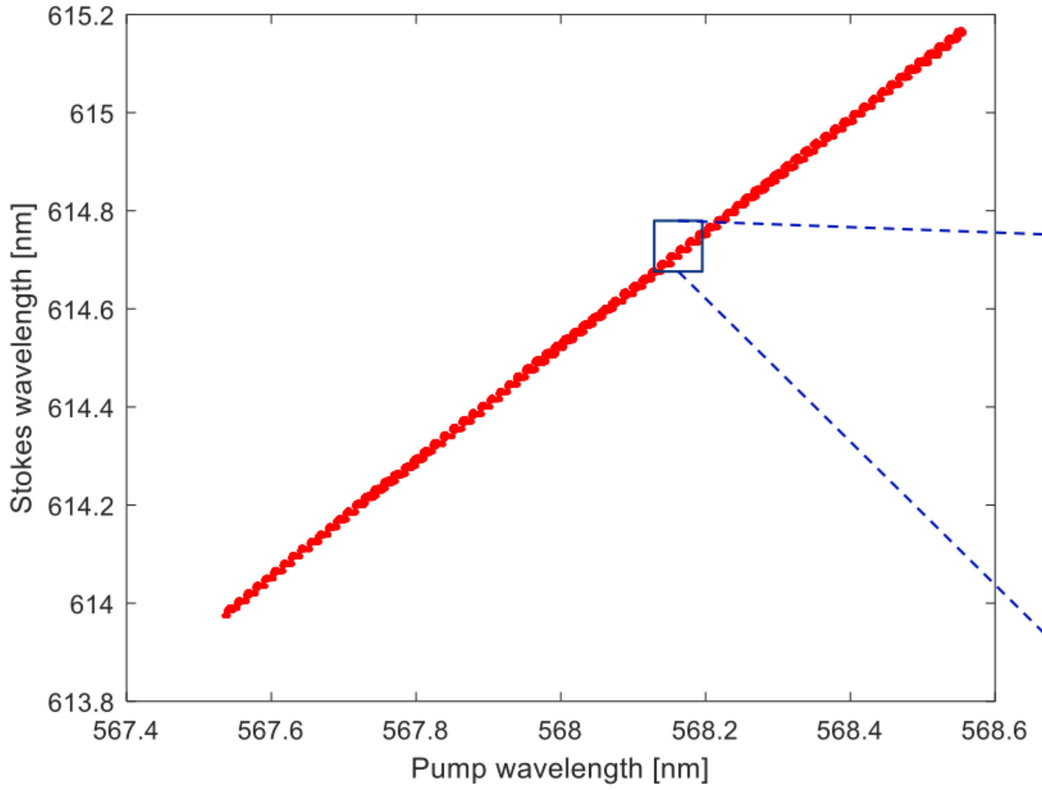


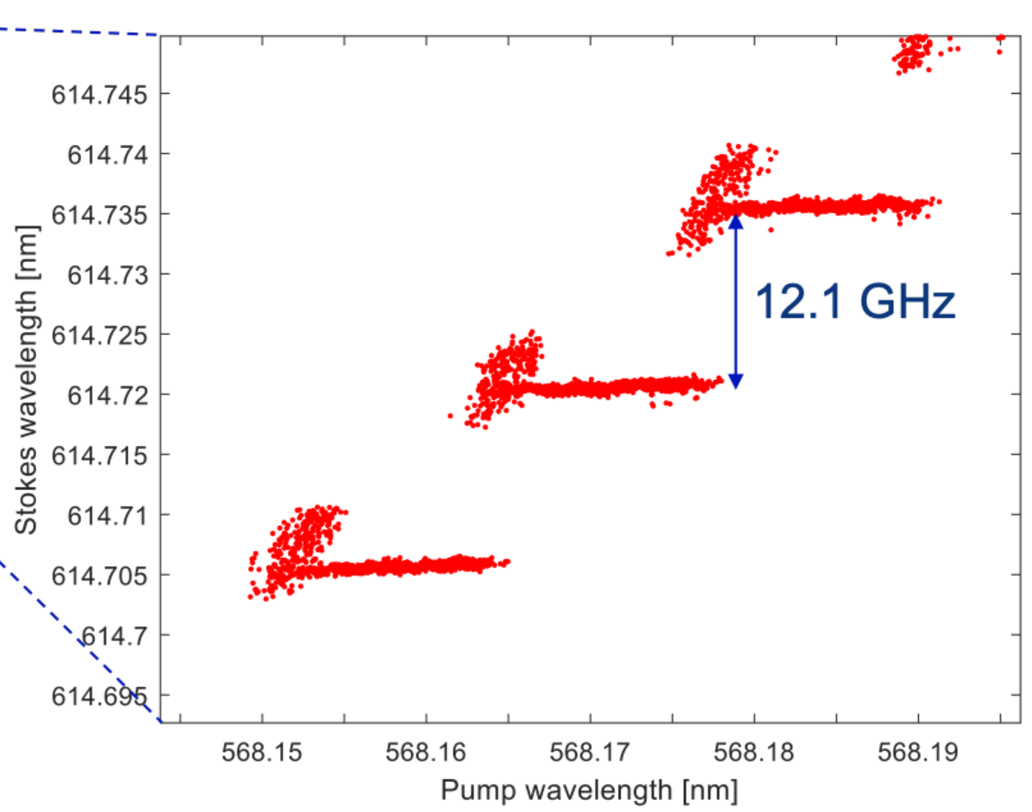
Courtesy D. Talan

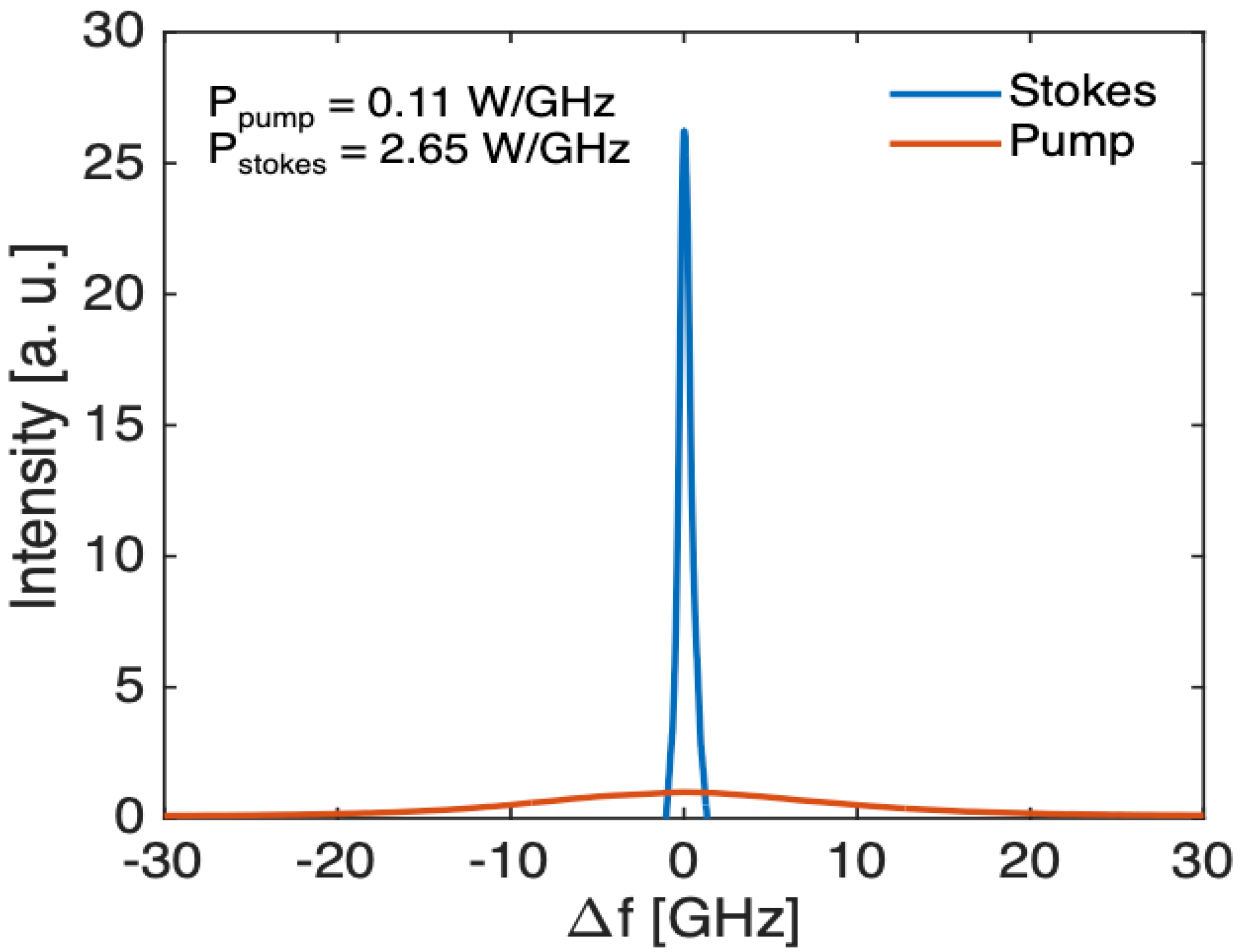


JG|U LARISSA
JOHANNES GUTENBERG-UNIVERSITÄT MAINZ





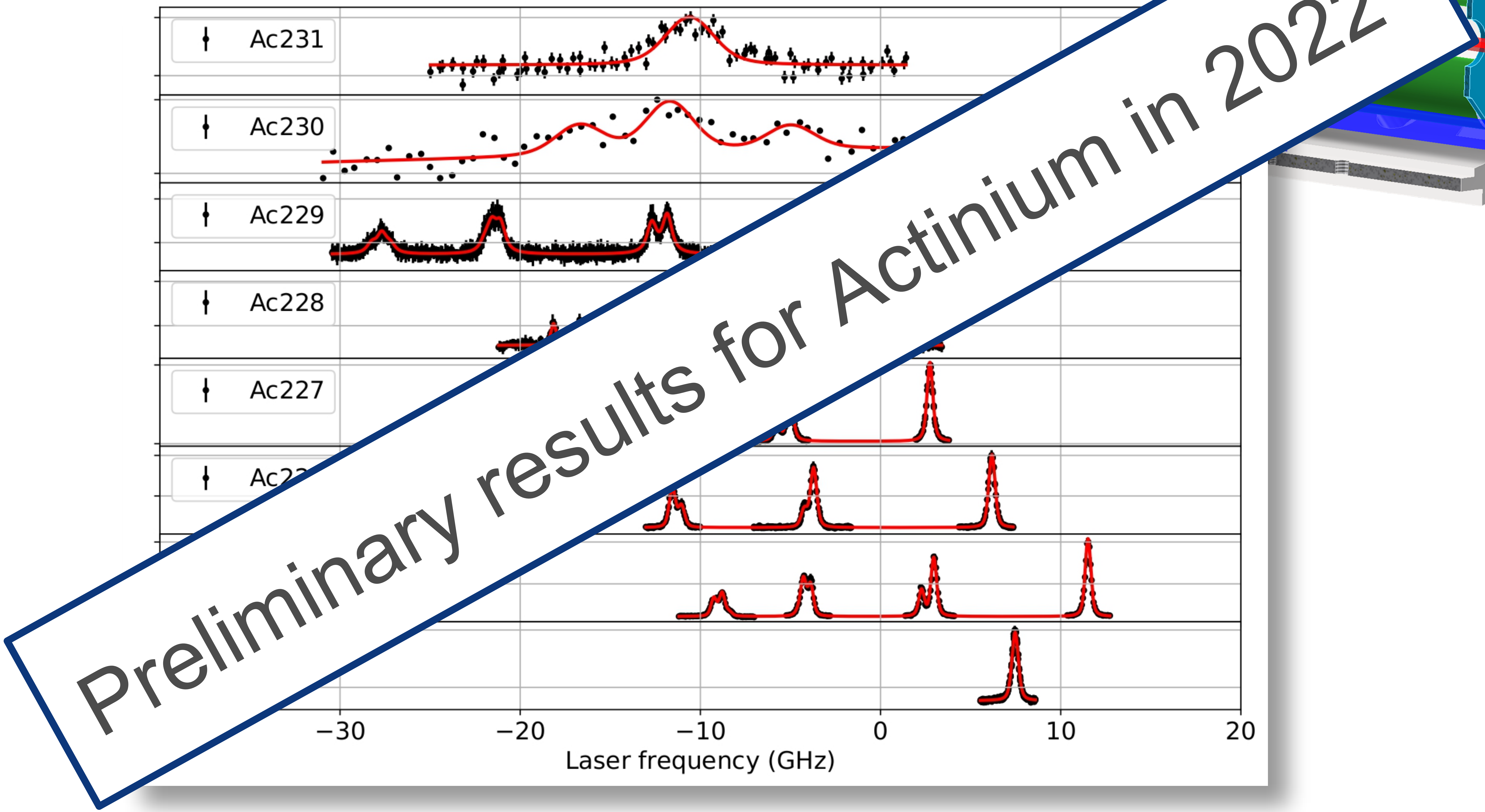




[1] https://doi.org/10.1364/OL.44.003924
[2] https://doi.org/10.1364/OE.384630

Daniel Talan Echarri
George Stoikos
Eduardo Granados
Katerina Chrysalidis

The PI-LIST

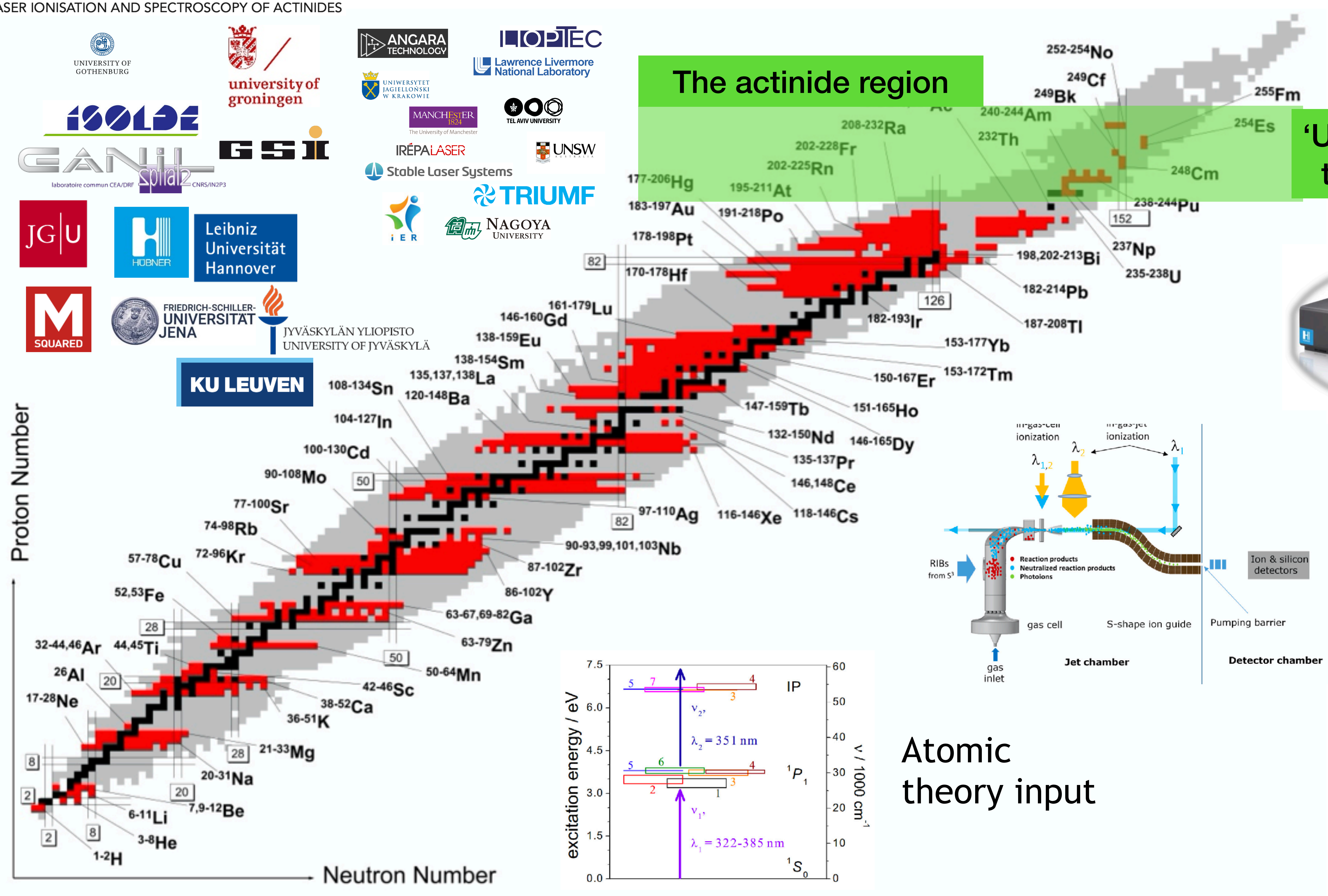


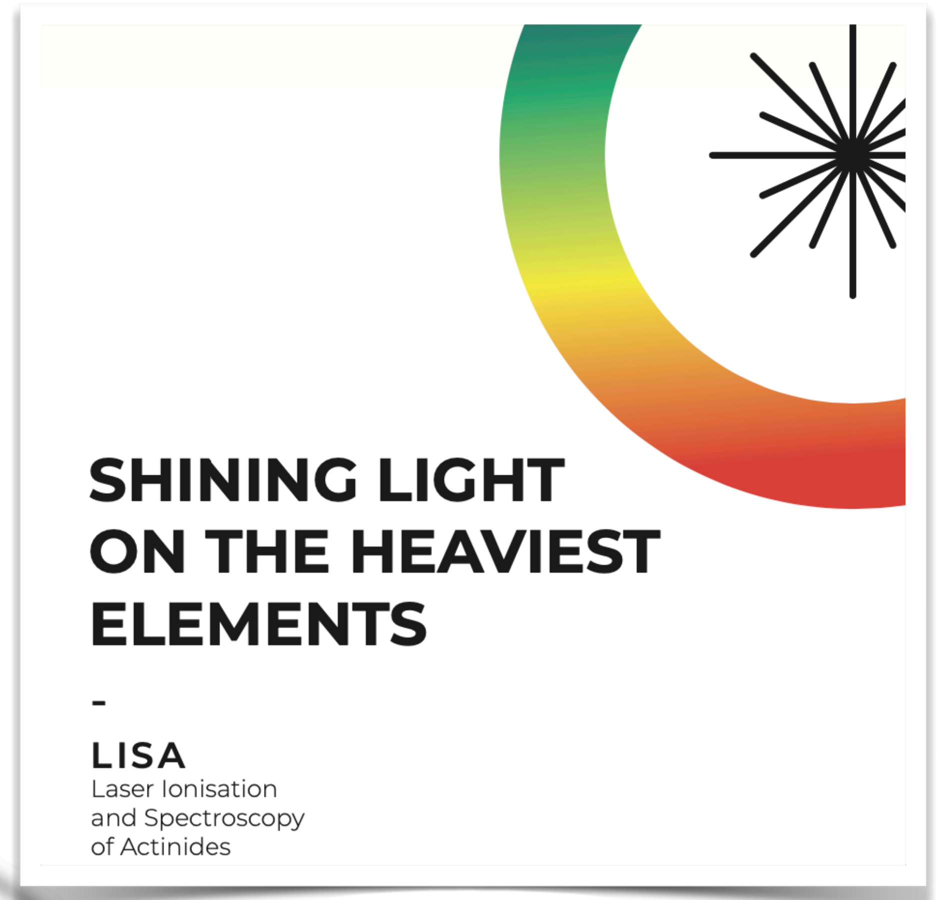
Reinhard Heinke

LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

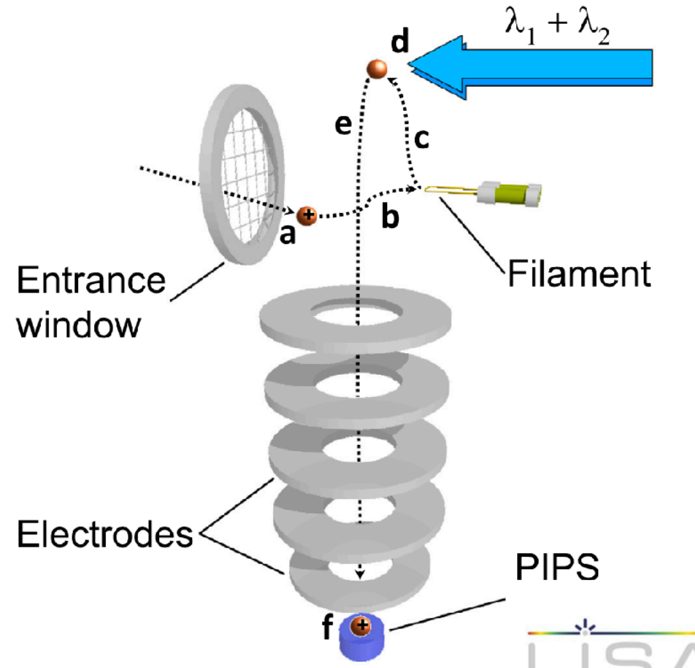
An **innovative training network** for laser ionisation and spectroscopy of the actinide elements

89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium
Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide	Actinide





New laser technologies



Advances in experimental methods

Atomic theory input

15 new young researchers in the field

A significant experimental challenge ! e.g Fm, Md, No, Lr

LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

Follow us:

https://lisa-itn.web.cern.ch

@LISA_ITN

@lisa_itn

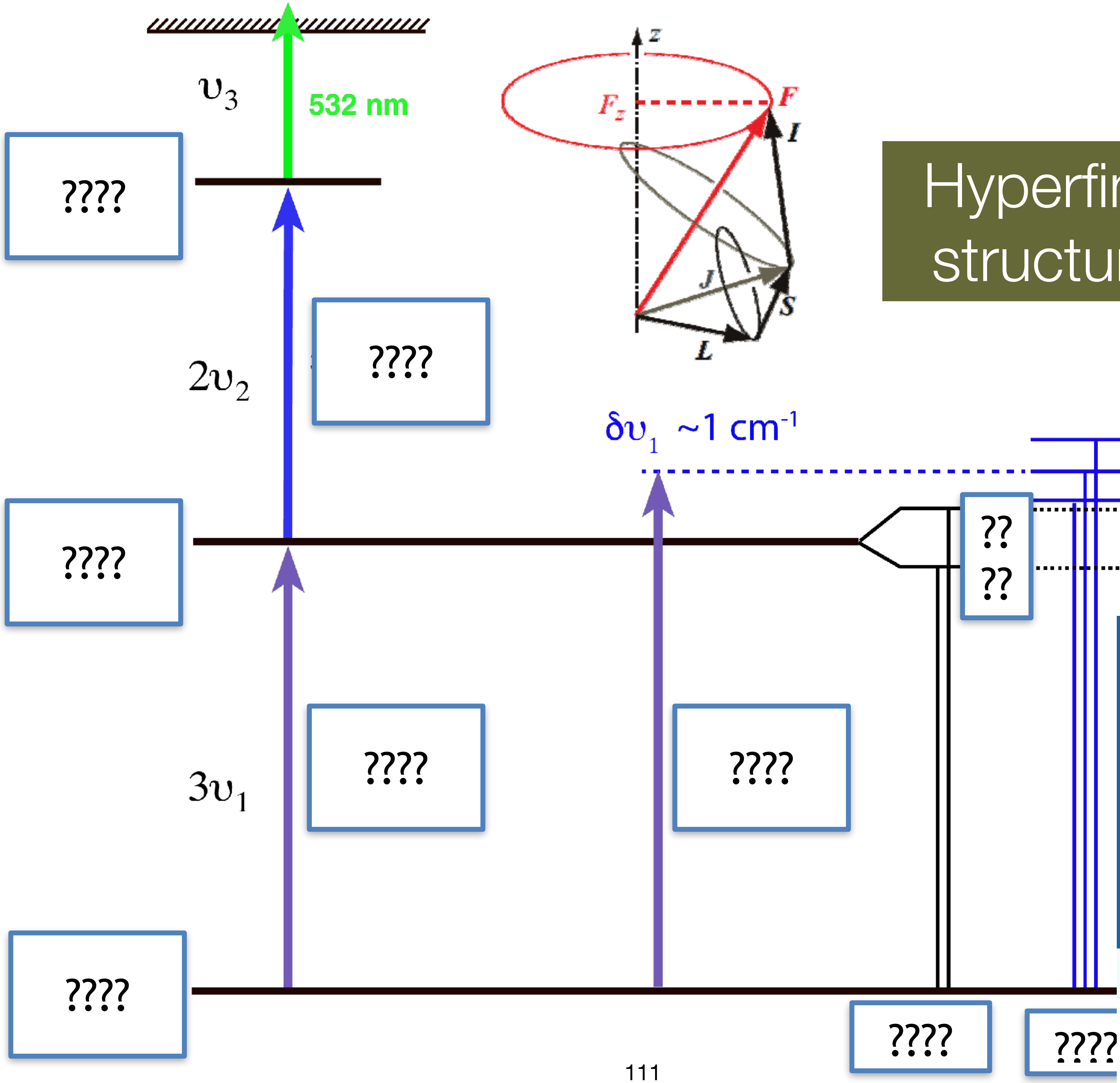
LISA ITN

LISA ITN

LISA.ITN

zenodo communities/lisa-itn

This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN) receives funding from the European Union's H2020 Framework Programme under grant agreement no. 861198



https://indico.cern.ch/event/1231547/

Thanks to contributors

Valentin Fedosseev

Ralitsa Mancheva

Eduardo Granados

Cyril Bernerd

Katerina Chrysalidis

Reinhard Heinke

Ruben de Groote

Asar Jaradat

Isa Hendriks

If you are interested in a PhD, Masters (technical studentship) or internship in the RILIS team..
Let me know!

bruce.marsh@cern.ch