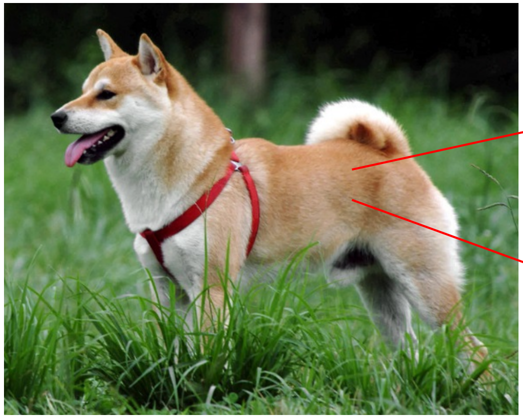
Physics of superheavy elements

Kouichi Hagino

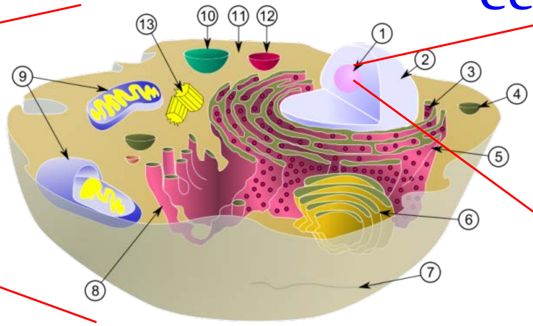
Tohoku University, Sendai, Japan

- What are elements?
- What are superheavy elements?
- How to create superheavy elements?
- What are chemical properties of superheavy elements?

Introduction: atoms and atomic nuclei

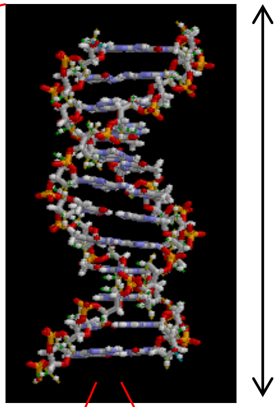


~ 50 cm



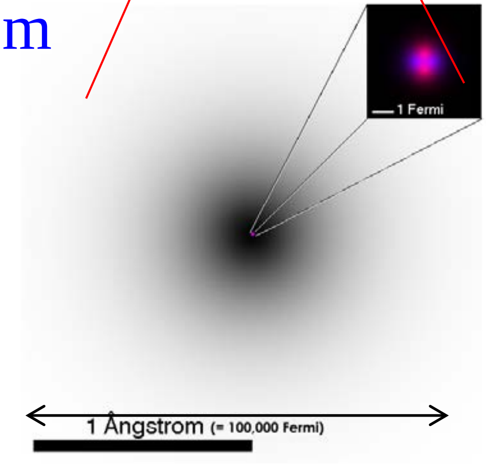
cells

DNA



~ 10^{-8} m

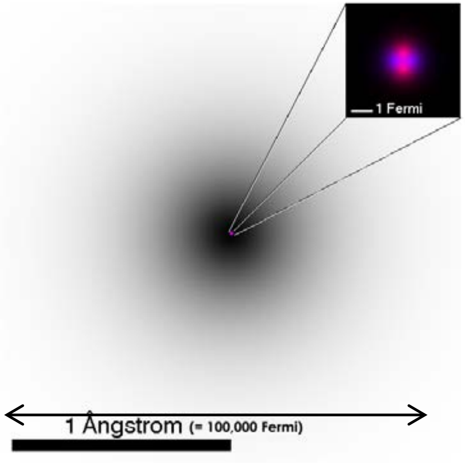
atom



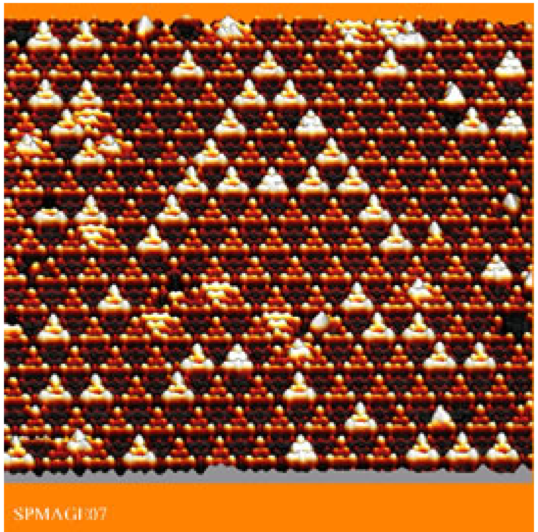
~ 10^{-10} m

Everything is made of atoms.

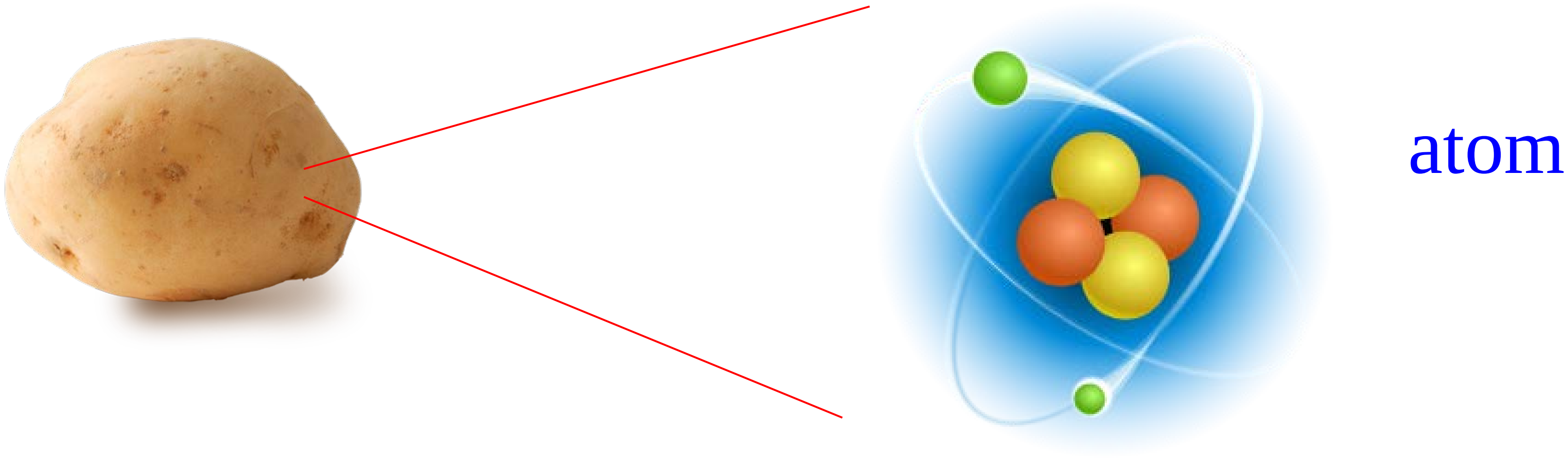
- Thales, Democritus (ancient Greek)
- Dalton (chemist, 19th century)
- Boltzmann(19th century)
- Einstein (1905)



~ 10^{-10} m



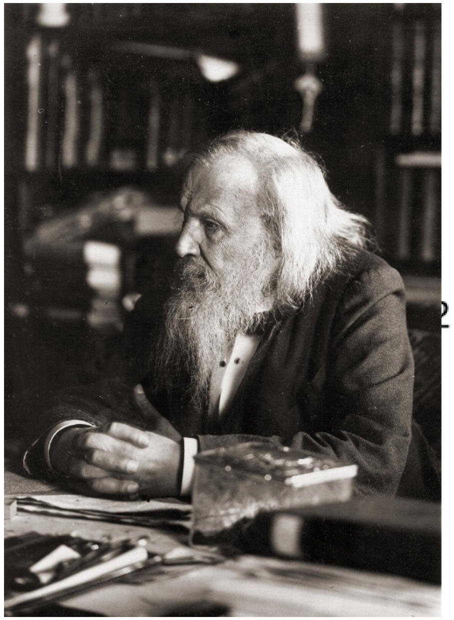
STM image
(surface physics group,
Tohoku university)



Several kinds of atoms = elements

- Hydrogen
- Oxygen
- Carbon
- Calcium
- Magnesium
- Sulfer etc.

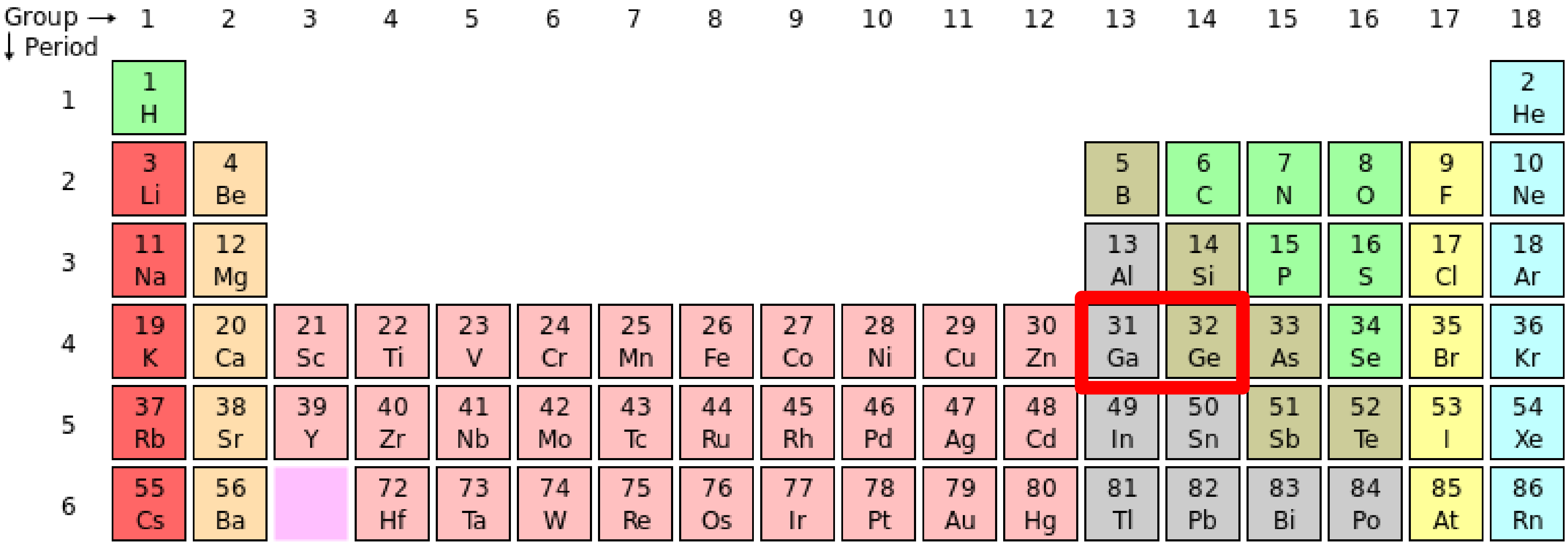
Periodic Table of elements



Mendeleev
(1834-1907)

Group → Period ↓	1	2	3		4	5	6	7					2	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Periodic Table of elements



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn

Each column: elements with the same chemical properties (Mendeleev, 1869)

→ Prediction of the properties of unknown atoms

Discovery of Ga (1874)

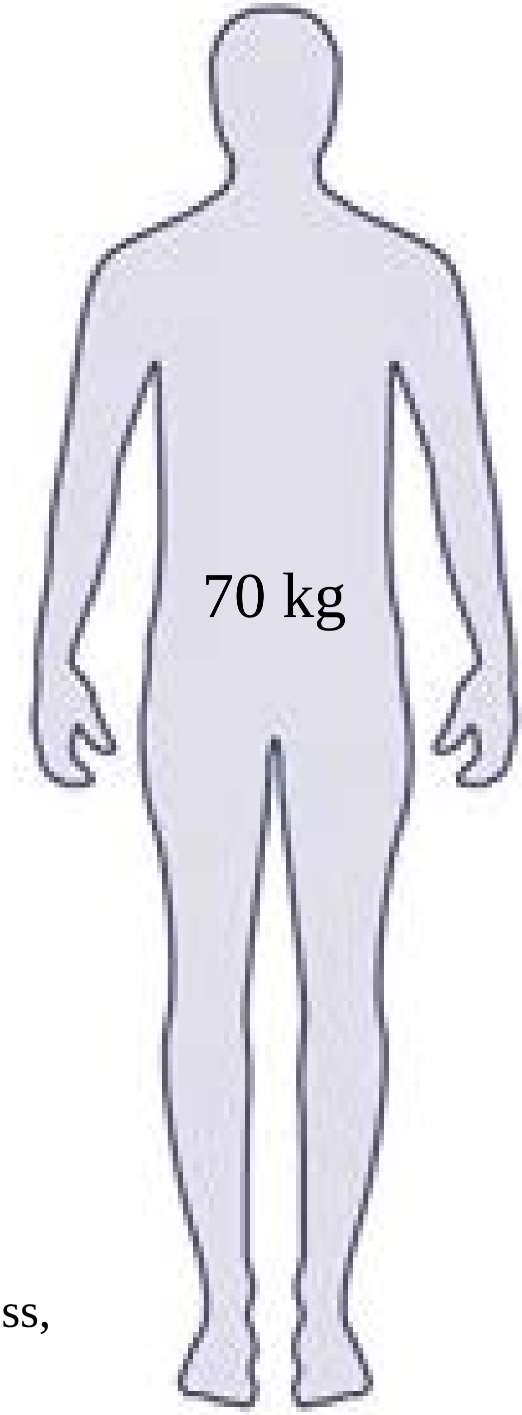
Dicsovery of Ge (1879)

What are we made of ?

oxygen 43 kg
carbon 16 kg
hydrogen 7 kg
nitrogen 1.8 kg
calcium 1.0 kg
phosphorus 780 g
potassium 140 g
sulphur 140 g
sodium 100 g
chlorine 95 g
magnesium 19 g
iron 4.2 g
fluorine 2.6 g
zinc 2.3 g
silicon 1.0 g
rubidium 0.68 g
strontium 0.32 g
bromine 0.26 g
lead 0.12 g
copper 72 mg
aluminium 60 mg
cadmium 50 mg

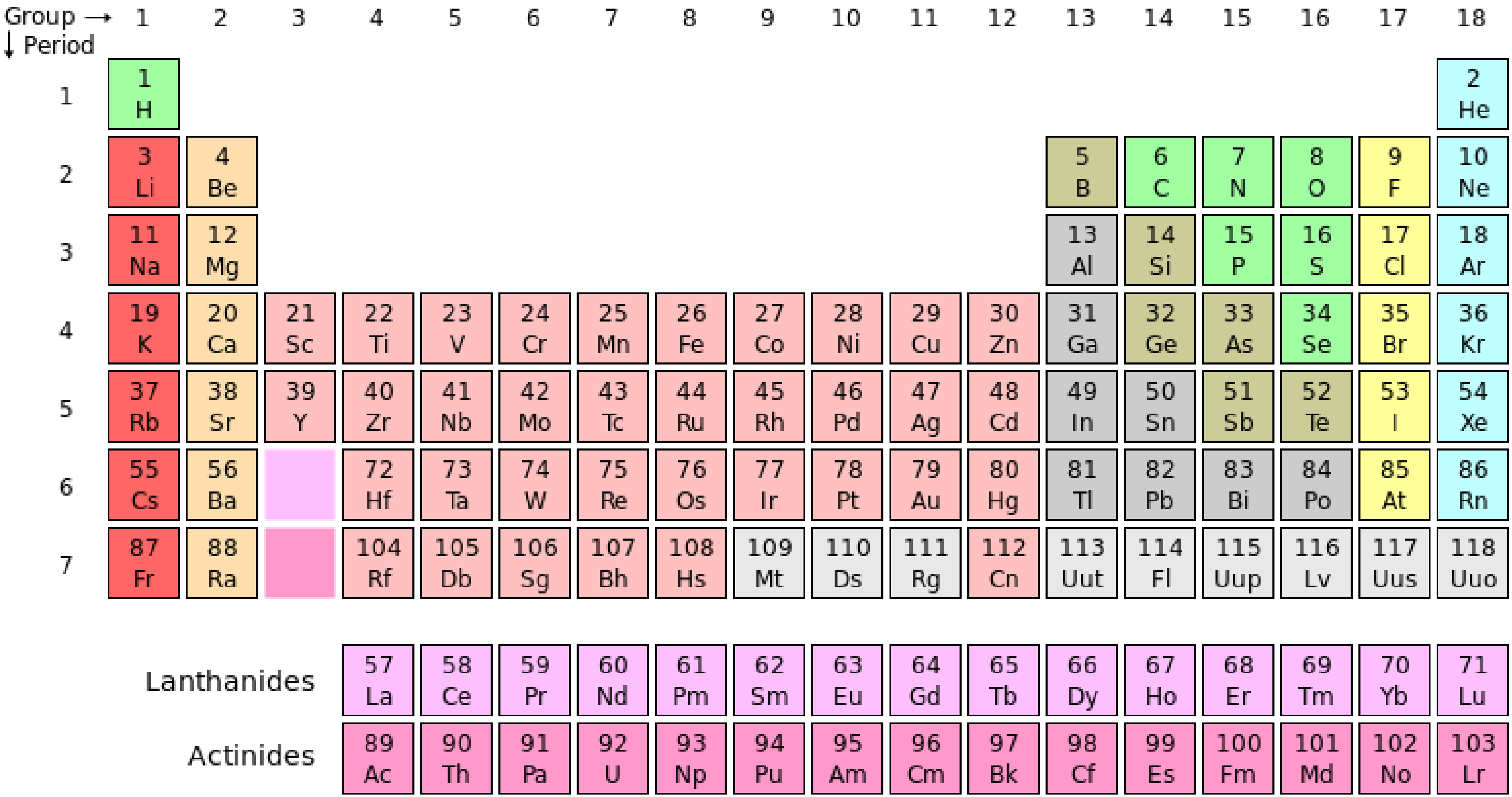
cerium 40 mg
barium 22 mg
iodine 20 mg
tin 20 mg
titanium 20 mg
boron 18 mg
nickel 15 mg
selenium 15 mg
chromium 14 mg
manganese 12 mg
arsenic 7 mg
lithium 7 mg
caesium 6 mg
mercury 6 mg
germanium 5 mg
molybdenum 5 mg
cobalt 3 mg
antimony 2 mg
silver 2 mg
niobium 1.5 mg
zirconium 1 mg
lanthanum 0.8 mg

gallium 0.7 mg
tellurium 0.7 mg
yttrium 0.6 mg
bismuth 0.5 mg
thallium 0.5 mg
indium 0.4 mg
gold 0.2 mg
scandium 0.2 mg
tantalum 0.2 mg
vanadium 0.11 mg
thorium 0.1 mg
uranium 0.1 mg
samarium 50 µg
beryllium 36 µg
tungsten 20 µg



John Emsley,
“The Elements”,
3rd ed. Clarendon Press,
Oxford, 1998

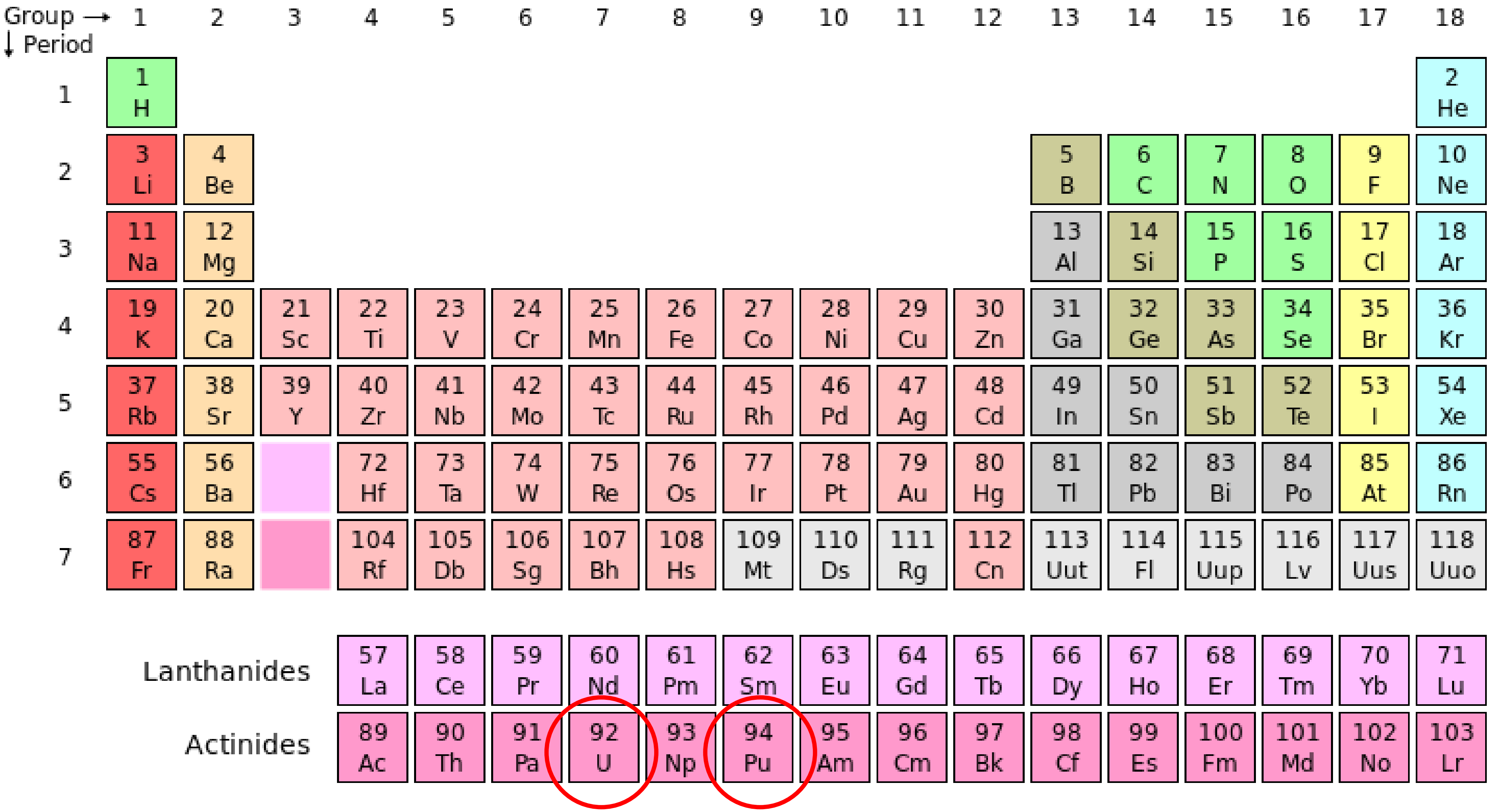
Periodic table of chemical elements



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

What is the heaviest element?

Periodic table of chemical elements



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

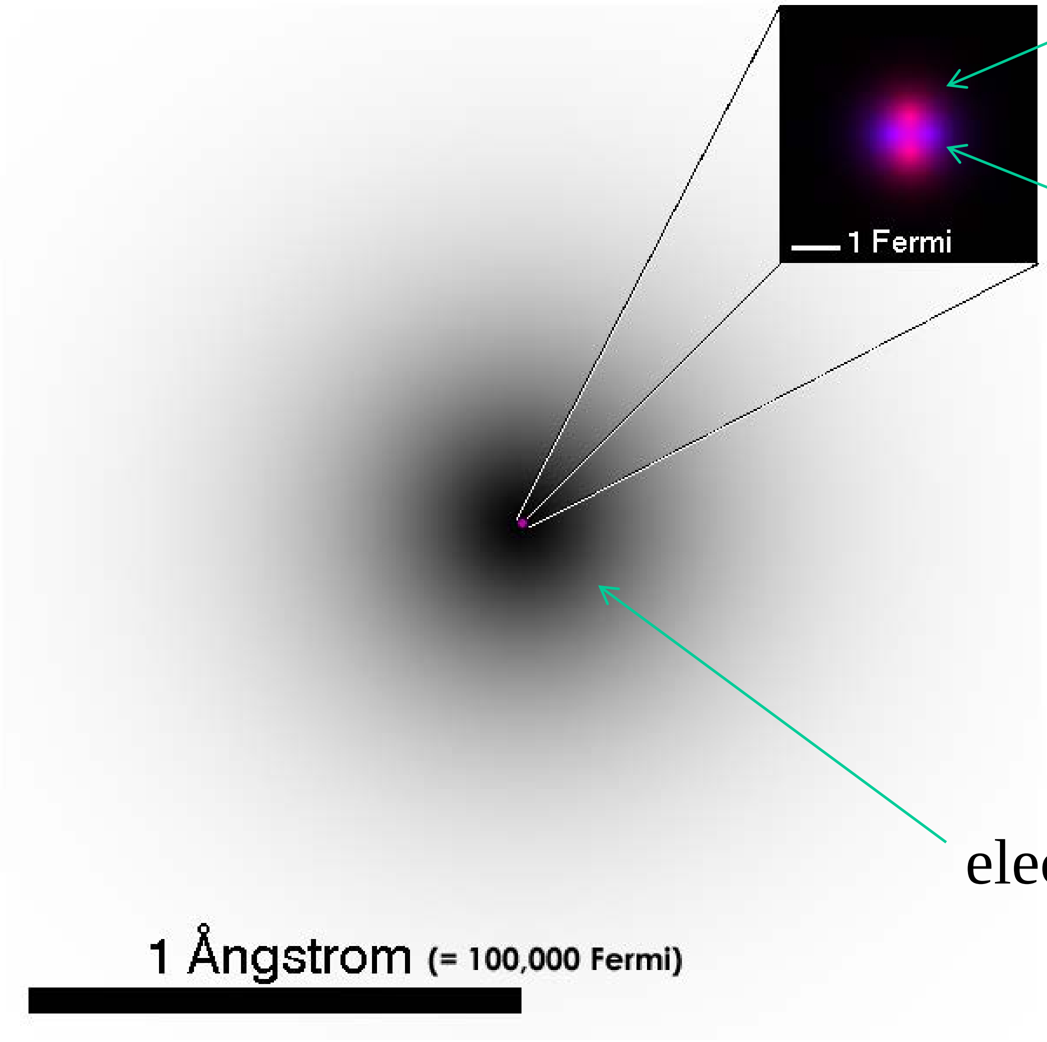
What is the heaviest element?

natural elements: **Pu** (Z=94) ⟶ a tiny amount in nature

U (Z=92)

What determines these numbers??

Atomic Nucleus



proton (+e)

neutron (no charge)

electron cloud (-e)

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

What is the heaviest element?

natural elements: Pu (Z=94) → a tiny amount in nature

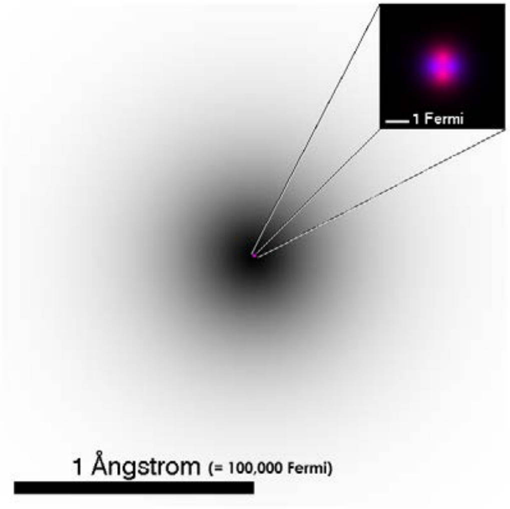
U (Z=92)

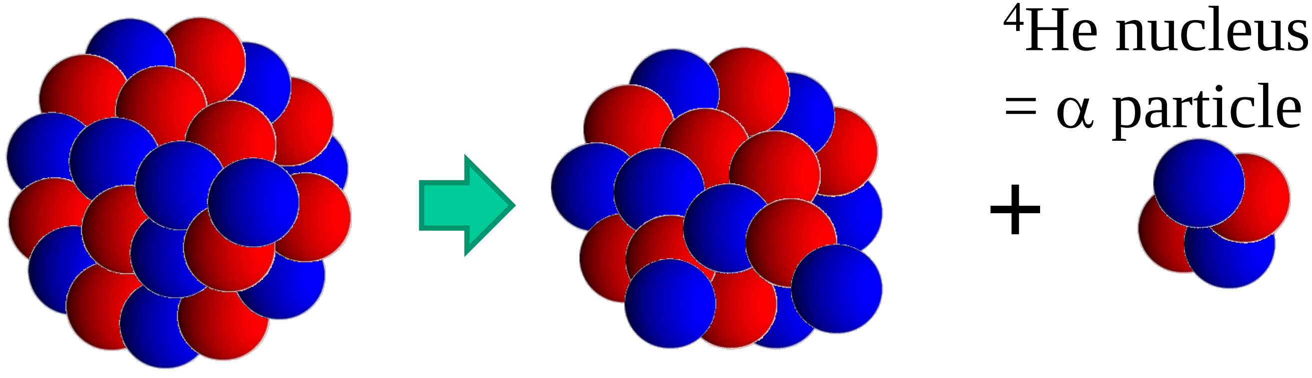
What determines these numbers?

heavy nuclei → large Coulomb repulsion

↓

unstable against α decay



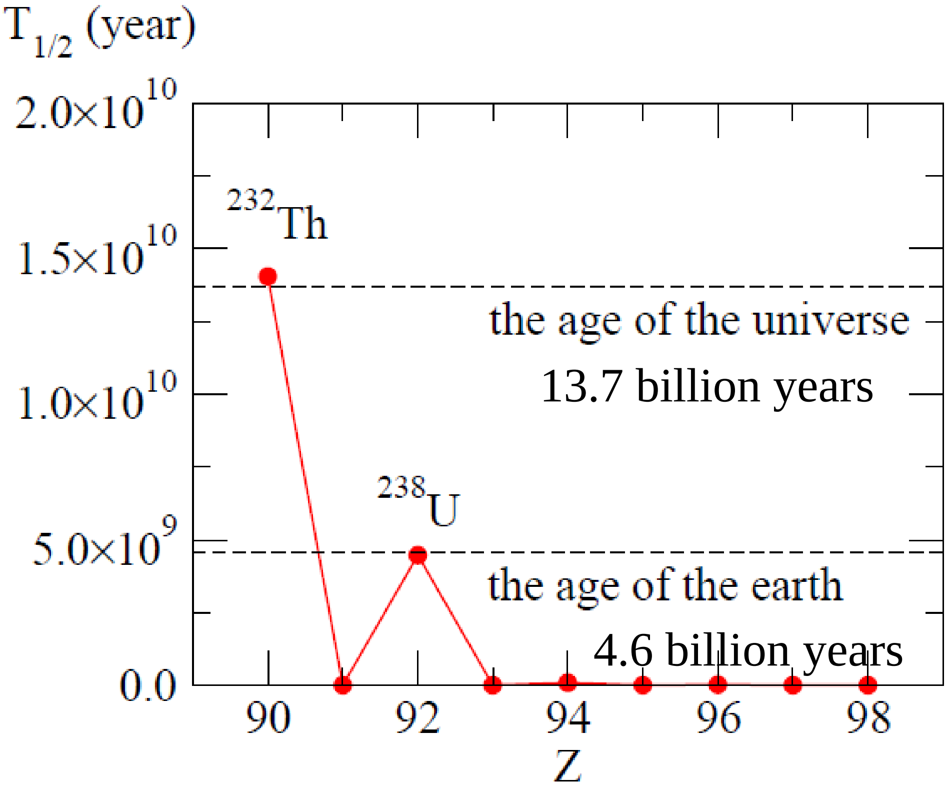


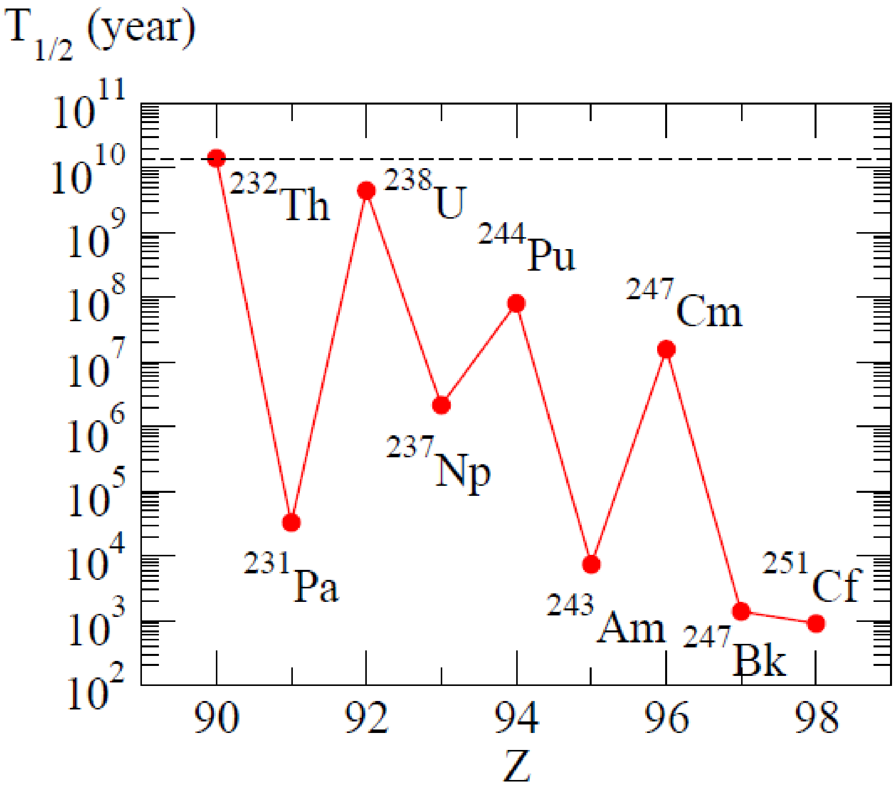
^{4}He nucleus

= α particle

(Z,N) (Z-2,N-2) + (Z=2,N=2)

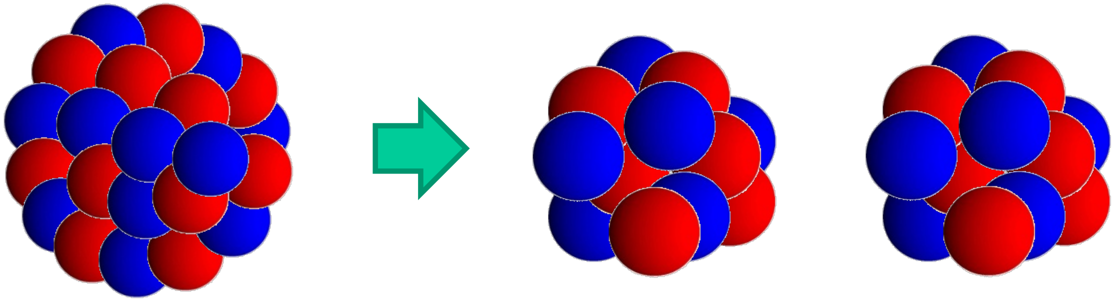
Decay half-lives of heavy nuclei



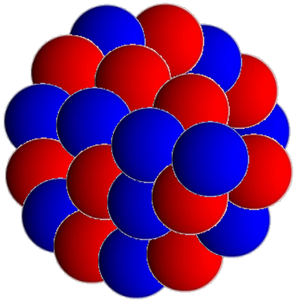


^{232}Th 1.405 x 10^{10} years
^{238}U 4.468 x 10^{9} years
^{244}Pu 8.08 x 10^{7} years
^{247}Cm 1.56 x 10^{7} years

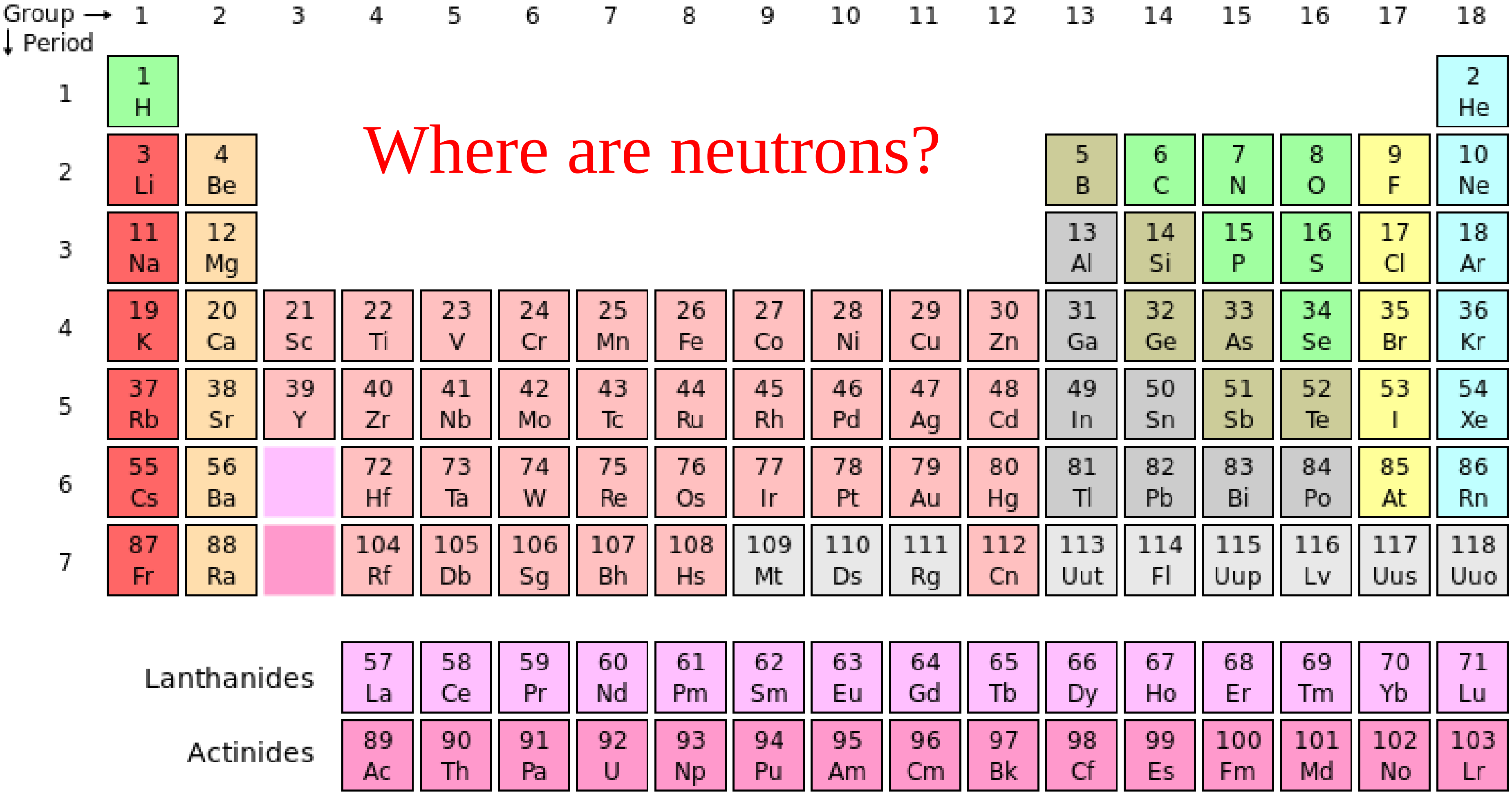
Heavier nuclei: unstable against fission



Nuclei : protons + neutrons

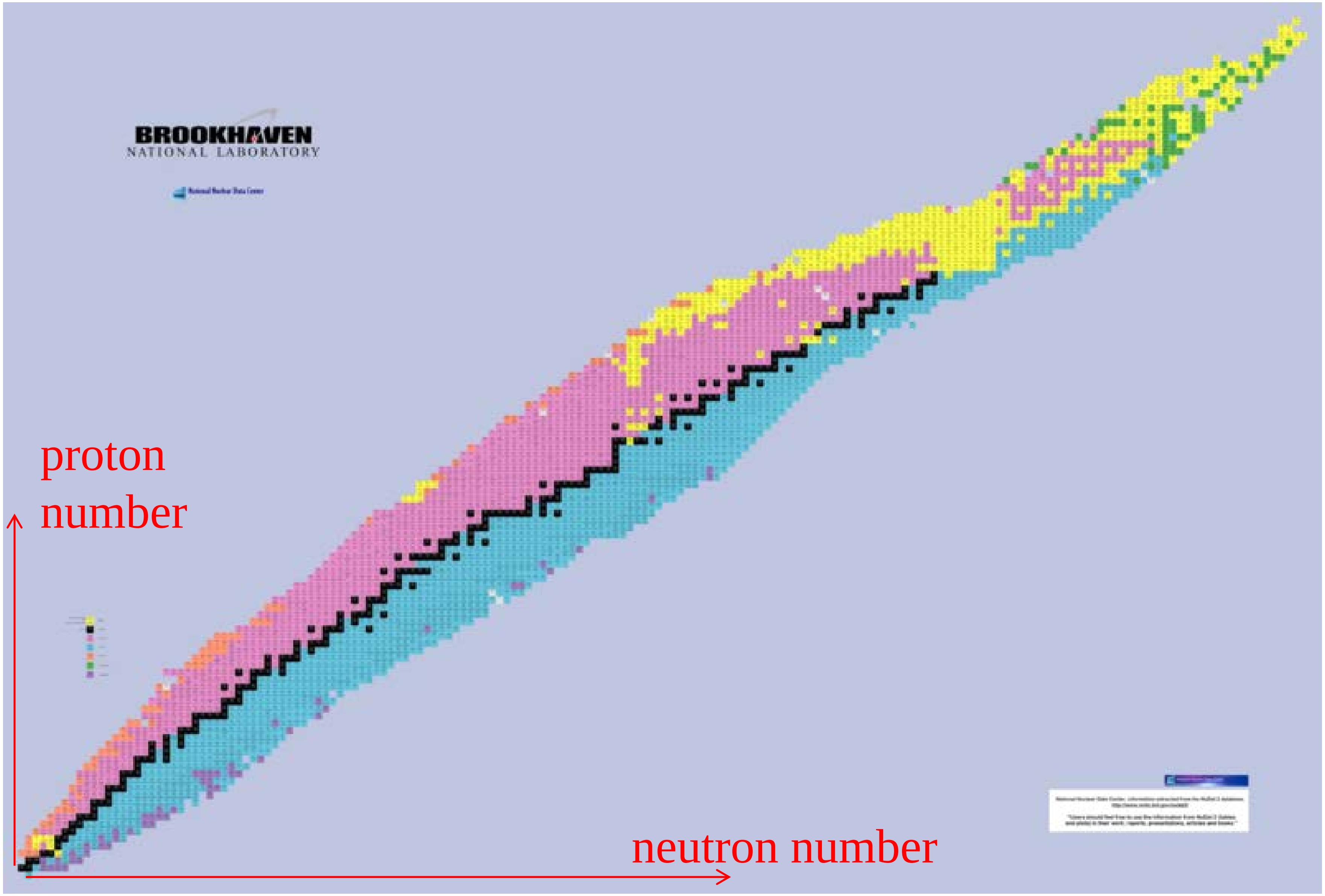


Where are neutrons?

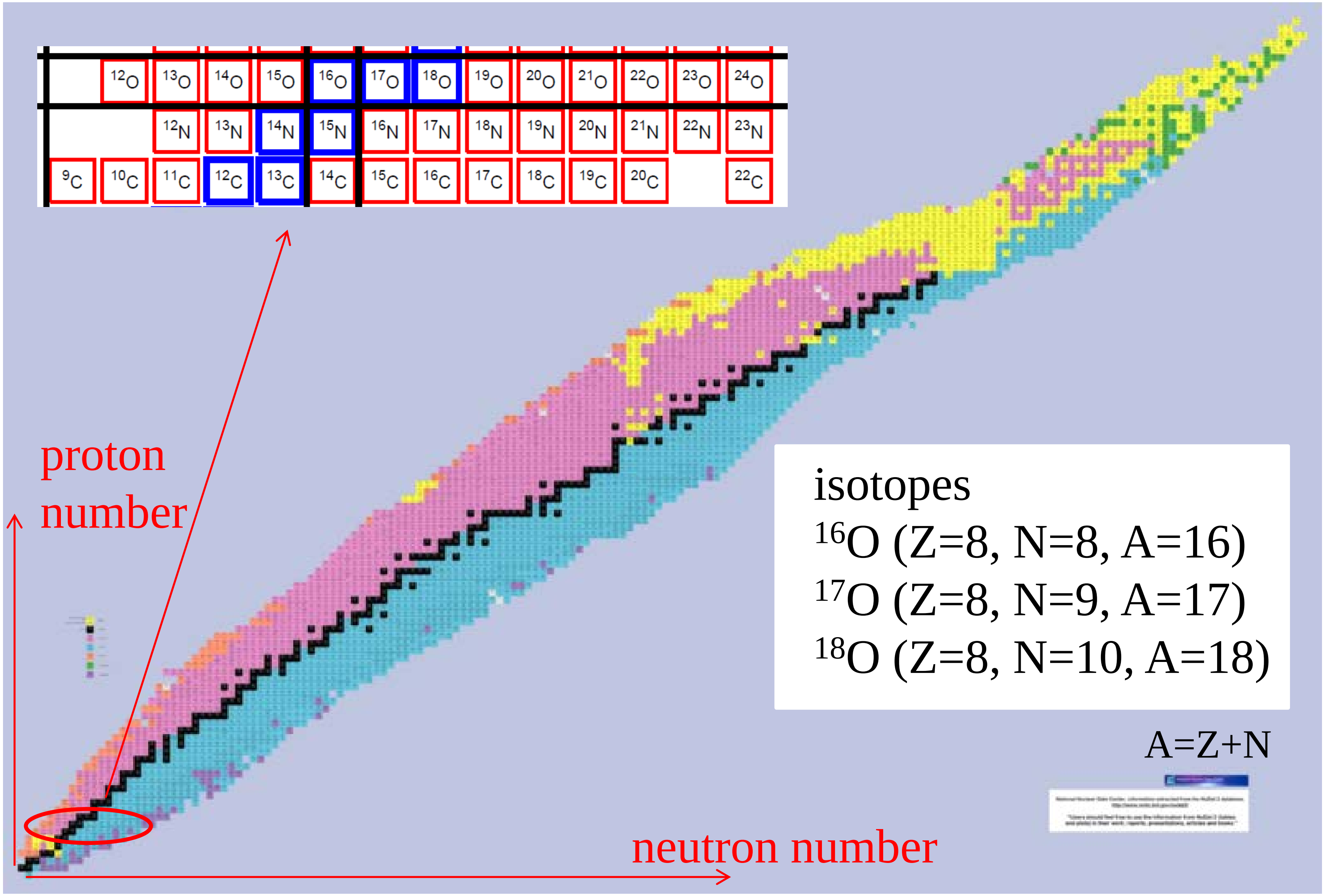


Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Extension of Periodic table: Nuclear Chart ~2D map of atomic nuclei~



Extension of Periodic table: Nuclear Chart ~2D map of atomic nuclei~



isotopes

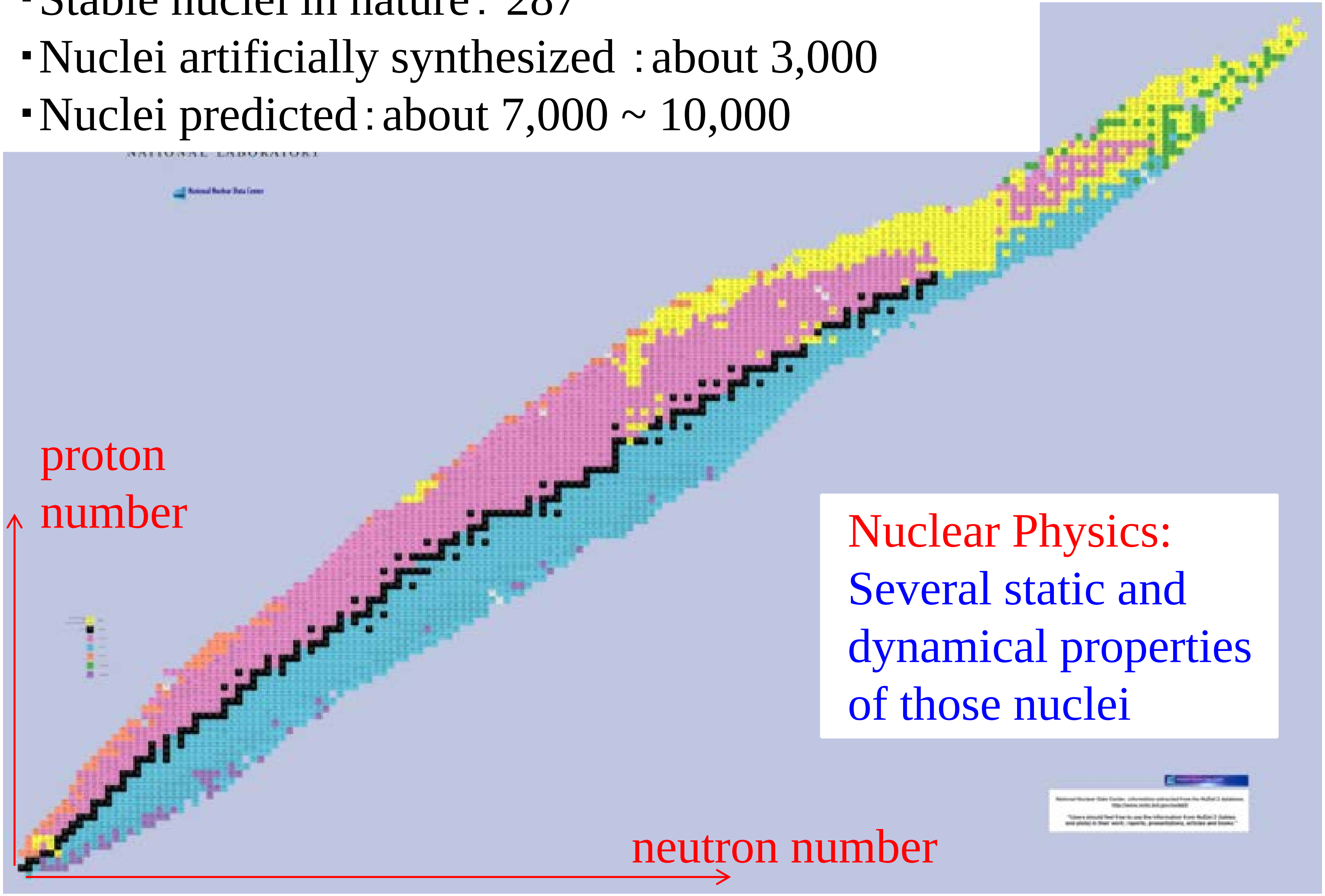
^{16}O (Z=8, N=8, A=16)

^{17}O (Z=8, N=9, A=17)

^{18}O (Z=8, N=10, A=18)

A=Z+N

- Stable nuclei in nature： 287
- Nuclei artificially synthesized ：about 3,000
- Nuclei predicted：about 7,000 ~ 10,000



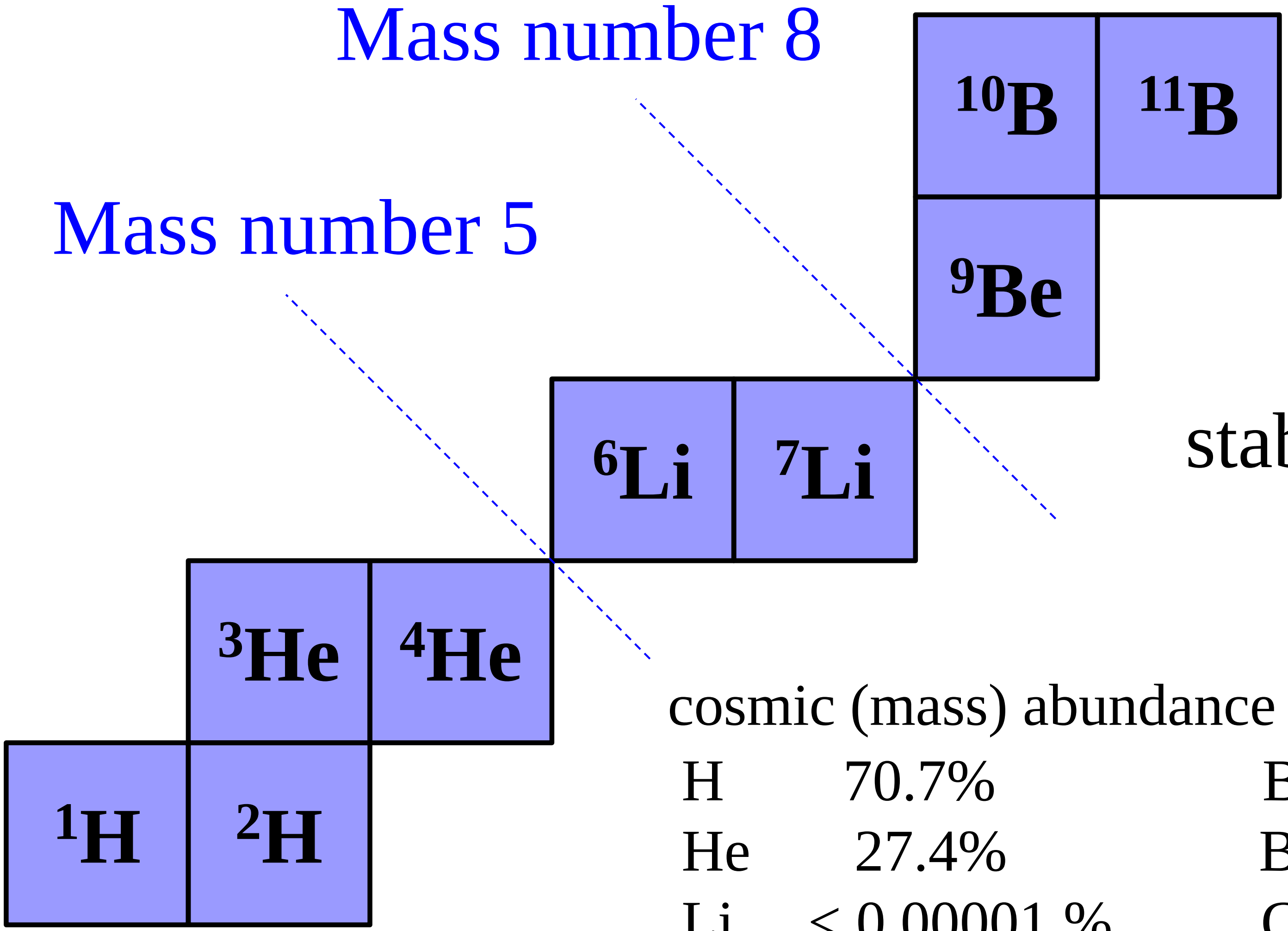
Nuclear Physics:
Several static and dynamical properties of those nuclei

How were elements created?

→ in the universe

Big bang
(13.8 billion years ago)

the reason why only little amount of Li was created



a big wall at A=5 and 8

stable isotopes

cosmic (mass) abundance of elements

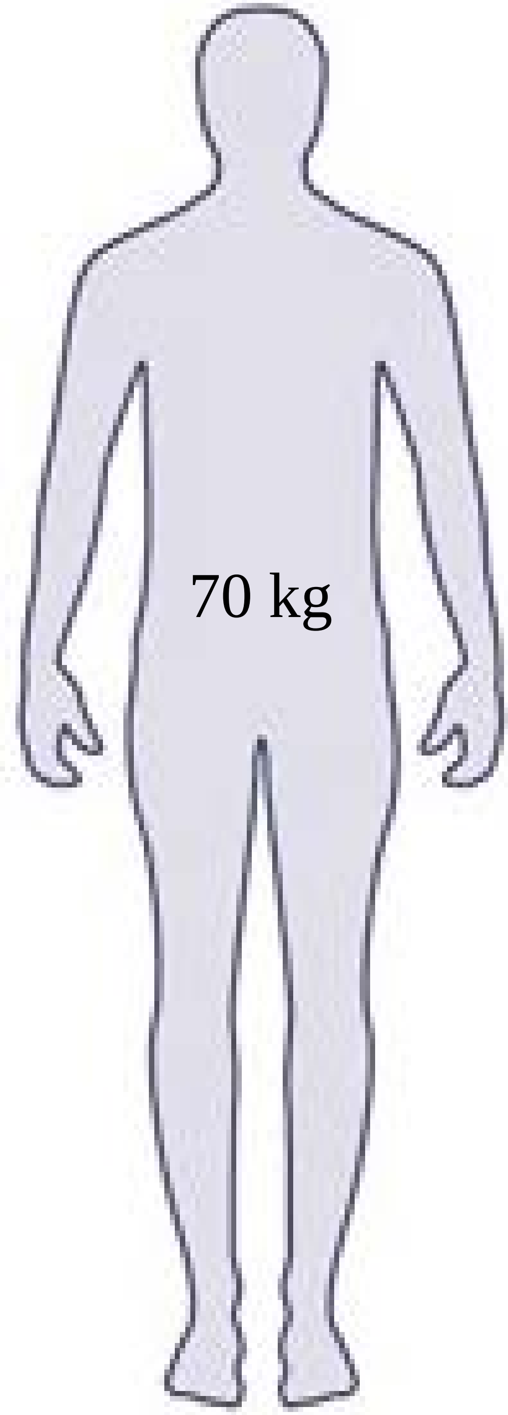
H	70.7%	Be	< 0.00001%
He	27.4%	B	< 0.00001%
Li	< 0.00001 %	C	0.3 %

What are we made of ?

oxygen 43 kg
carbon 16 kg
hydrogen 7 kg
nitrogen 1.8 kg
calcium 1.0 kg
phosphorus 780 g
potassium 140 g
sulphur 140 g
sodium 100 g
chlorine 95 g
magnesium 19 g
iron 4.2 g
fluorine 2.6 g
zinc 2.3 g
silicon 1.0 g
rubidium 0.68 g
strontium 0.32 g
bromine 0.26 g
lead 0.12 g
copper 72 mg
aluminium 60 mg
cadmium 50 mg

these hydrongens were created 13.8 billion years ago!!

Big bang
(13.8 billion years ago)



How were elements up to Fe created?

The origin of elements up to Fe

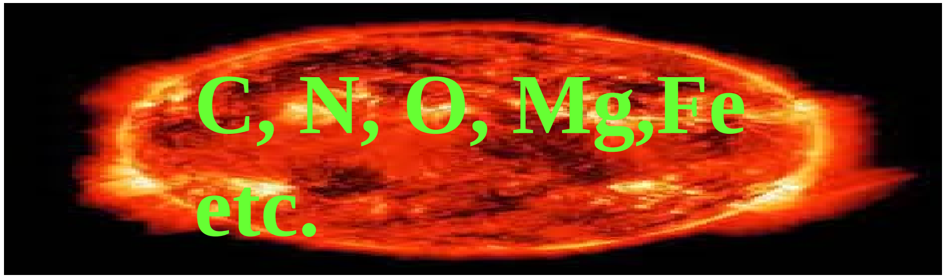
C, N, O, Mg,Fe etc.

Nuclear fusion inside (massive) stars

⟶ the reason why stars are shining

Why up to Fe?

The origin of elements up to Fe



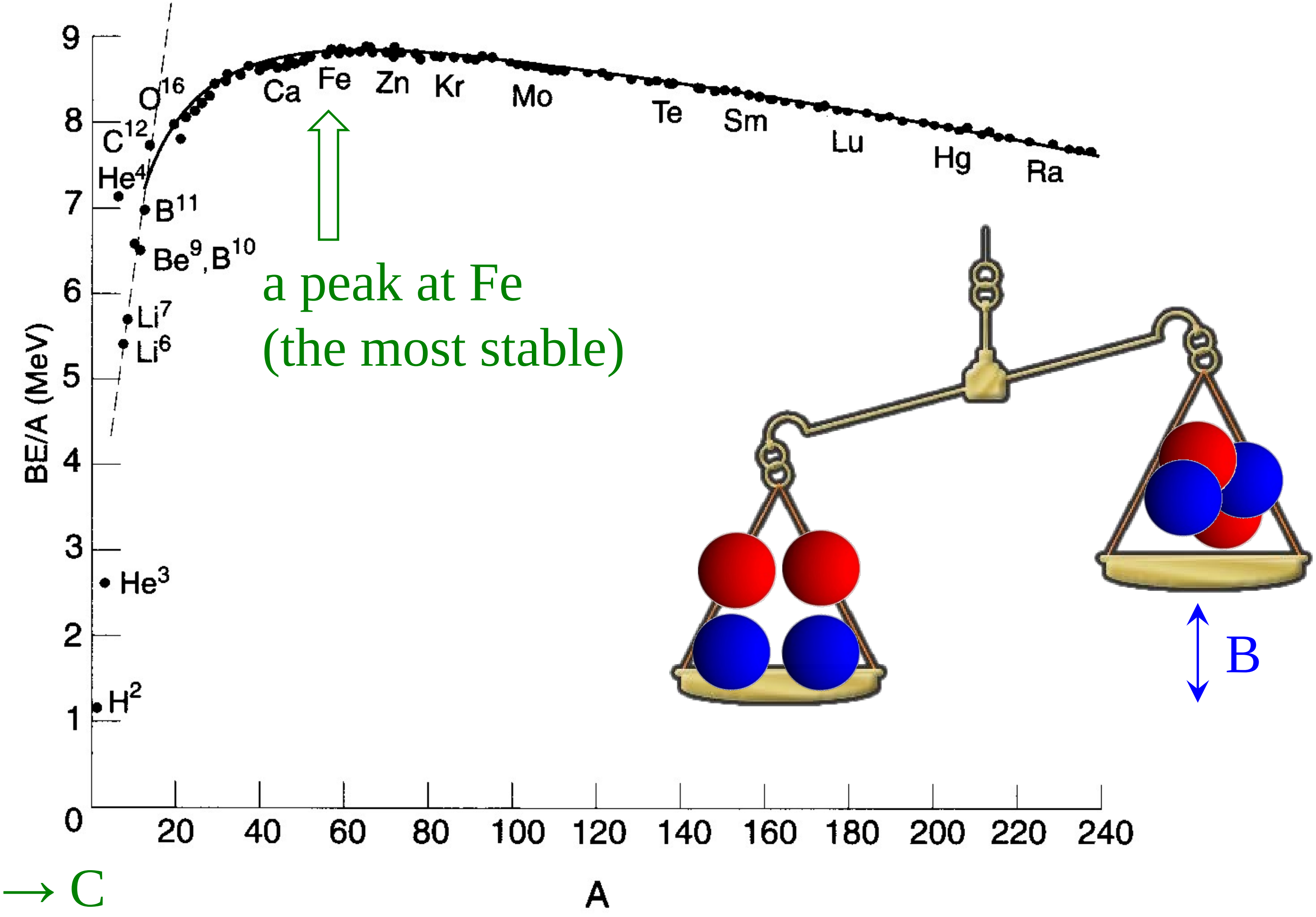
Nuclear fusion inside (massive) stars

→ the reason why stars are shining

- up to Fe: exothermal reactions
- from Fe: endothermal reactions

→ fusion stops at Fe

Binding energy of atomic nuclei



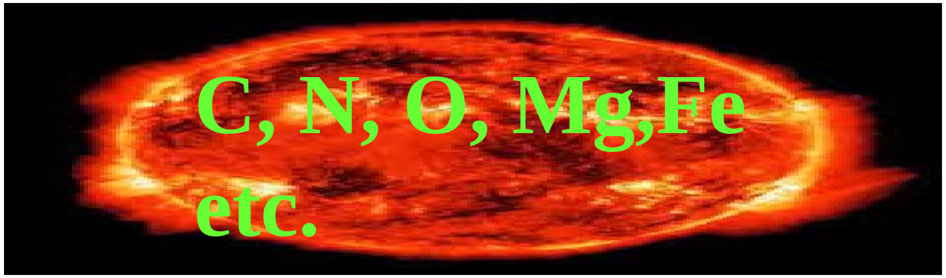
a peak at Fe
(the most stable)

$A + B \rightarrow C$

- up to Fe: $m_A + m_B > m_C$ (exothermal) creation of energy
- from Fe: $m_A + m_B < m_C$ (endothermal) extra energy required

Why up to Fe?

The origin of elements up to Fe



Nuclear fusion inside (massive) stars

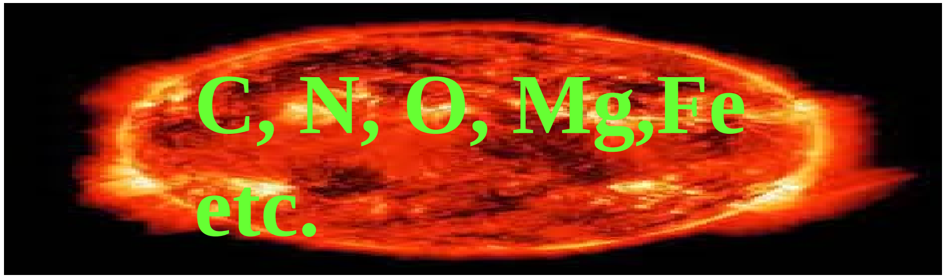
→ the reason why stars are shining

- up to Fe: exothermal reactions
- from Fe: endothermal reactions

→ fusion stops at Fe

How to create heavier elements (e.g., Pb and U)?

a life of stars



C, N, O, Mg,Fe etc.

Nuclear fusion inside (massive) stars

⇒

when fuels for fusion are exhausted:

- ✓ shrinkage due to the gravitational force
- ✓ then, explosion (supernova explosion)

O

Mg

Ti

N

Ca

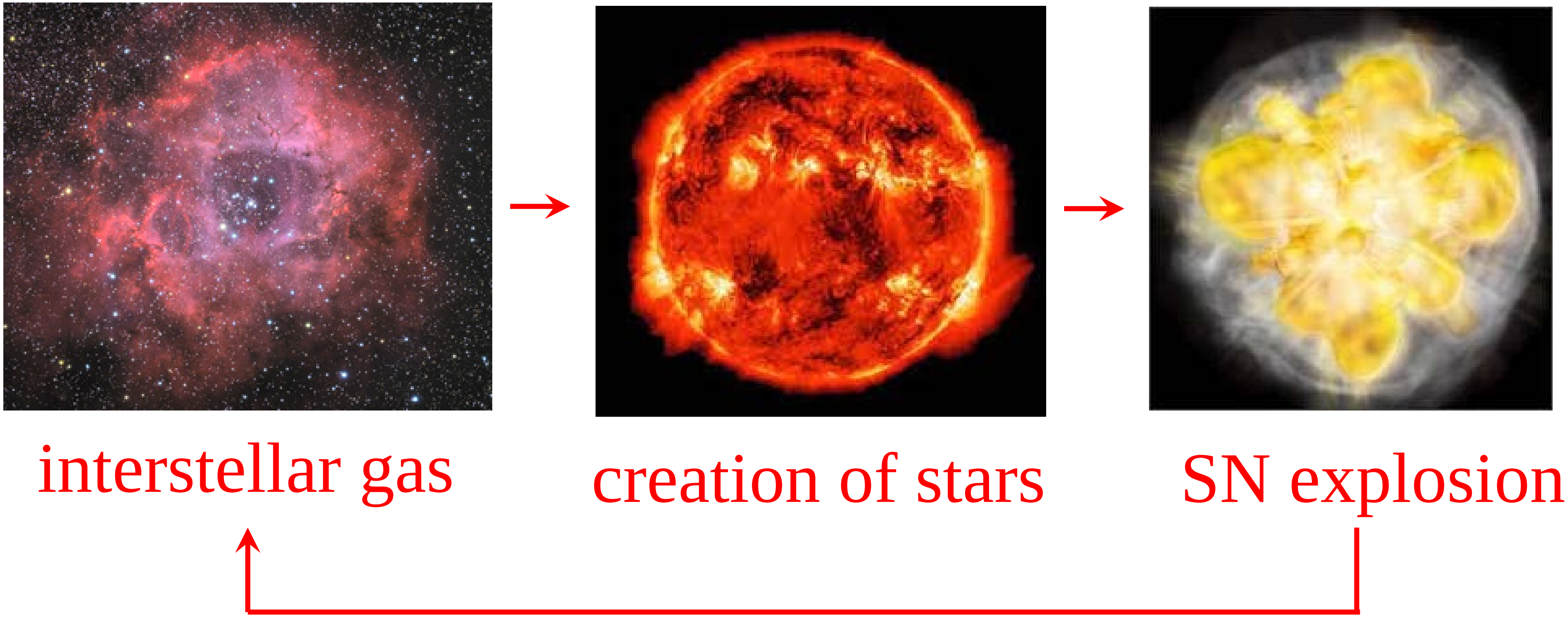
Fe

C

Si

SN explosions distribute elements into the universe.

repetition of a cycle



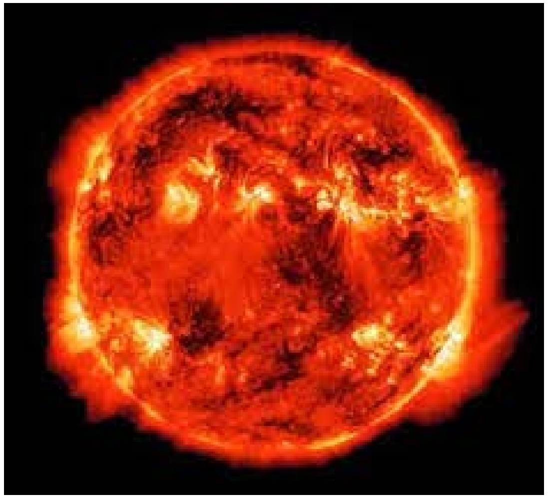
interstellar gas

creation of stars

SN explosion

How to create heavier elements than Fe?

Neutron captures

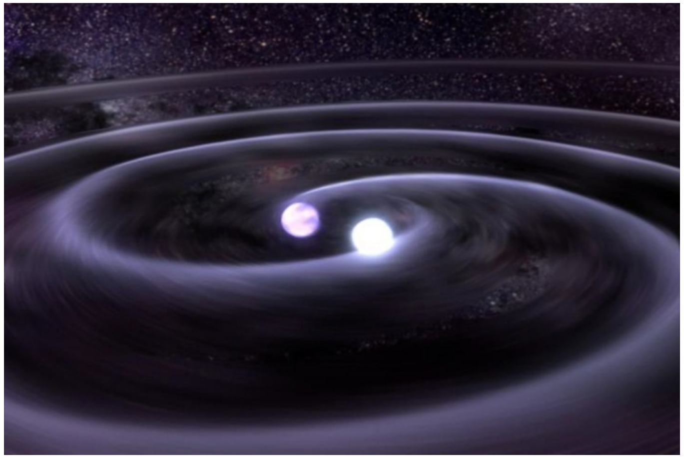


red giant

↓

s-process

Ba, La, Pb, Bi etc.

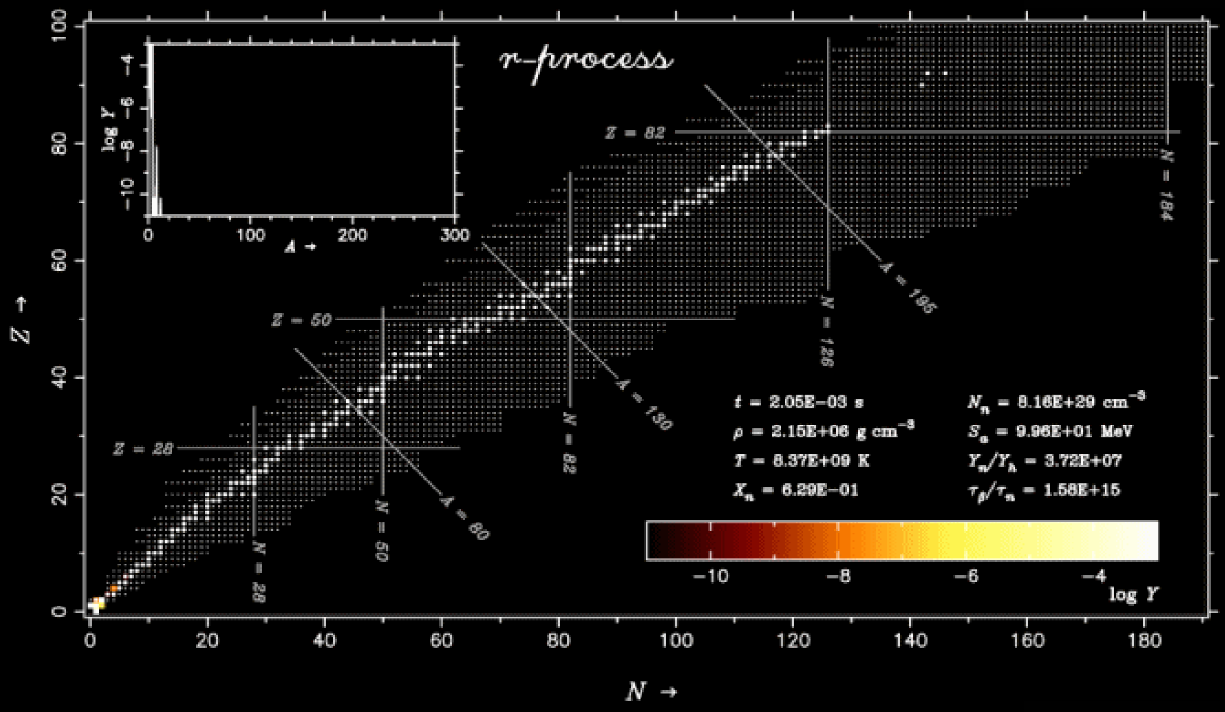


neutron star merger

↓

r-process

Th, Eu, U etc.

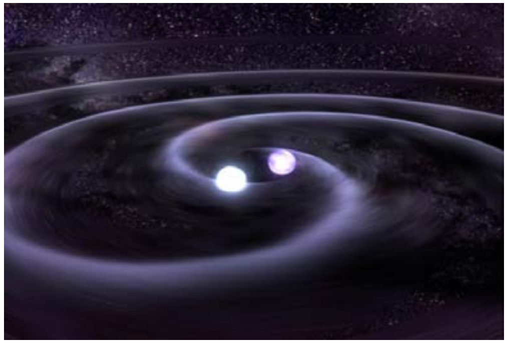


As a matter of fact, it is not known well how Au and U were created….

Open issues in r-process nucleosyntehsis

- where is the main site?

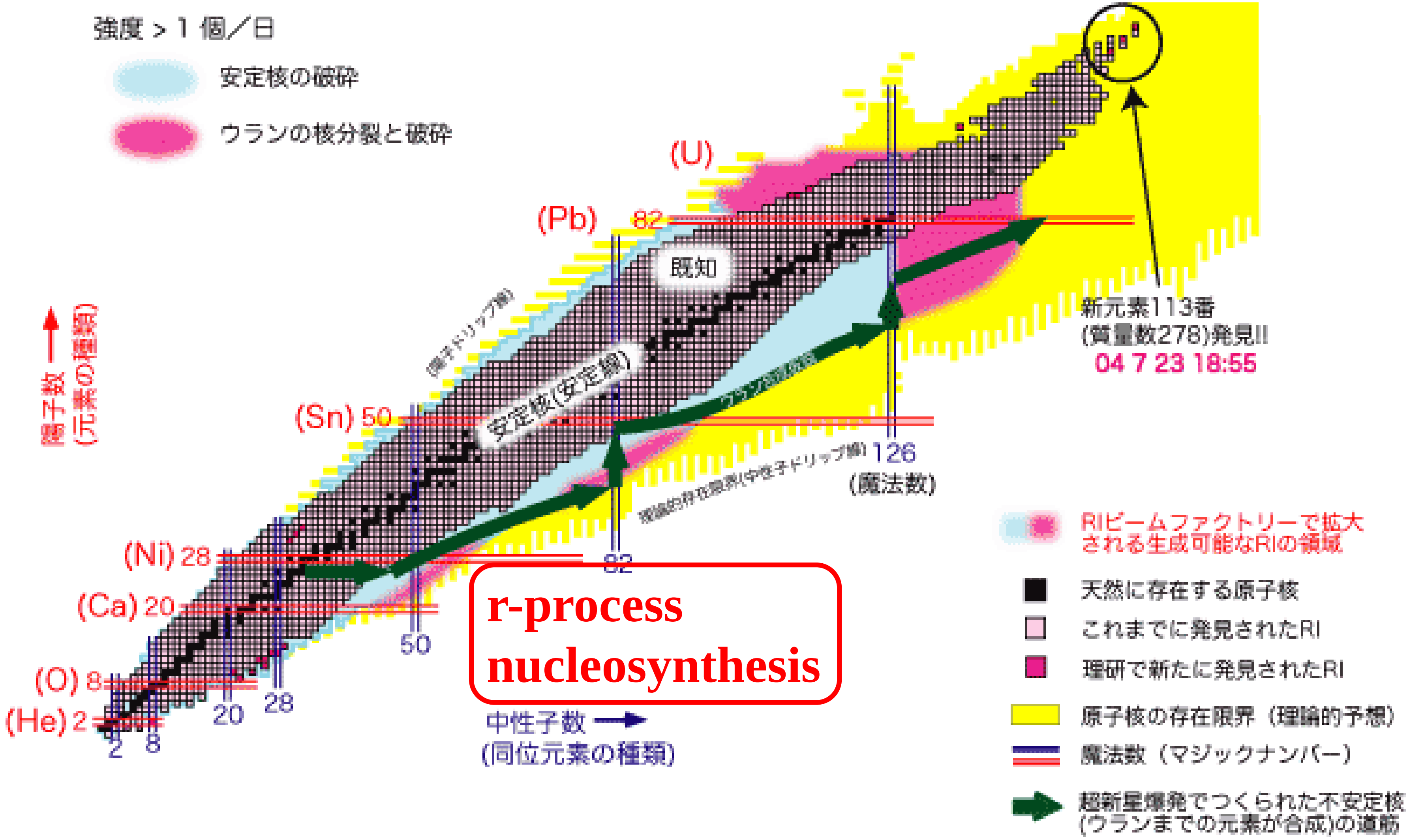
SN explosion



Neutron star merger

- how well do we know the properties of neutron-rich nuclei?
  - mass
  - β-decay (life-time)
  - magic numbers
- role of fission?
  - spontaneous and neutron-induced fissions
  - β-delayed fission

Neutron-rich nuclei (RIBF at RIKEN)



r-process nucleosynthesis

Lucky accident for the origin of lie

Atomic magic numbers

electron #: 2, 10, 18, 36, 54, 86

元素の周期表

	1A	2A	3A	4A	5A	6A	7A	8			1B	2B	3B	4B	5B	6B	7B	0
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	L	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	A															
		L	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		A	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

🟧 典型金属元素
🟩 半金属元素
🟦 非金属元素
🟨 遷移金属元素
🟥 希ガス

inert gas：He, Ne, Ar, Kr, Xe, Rn

Nuclear magic numbers

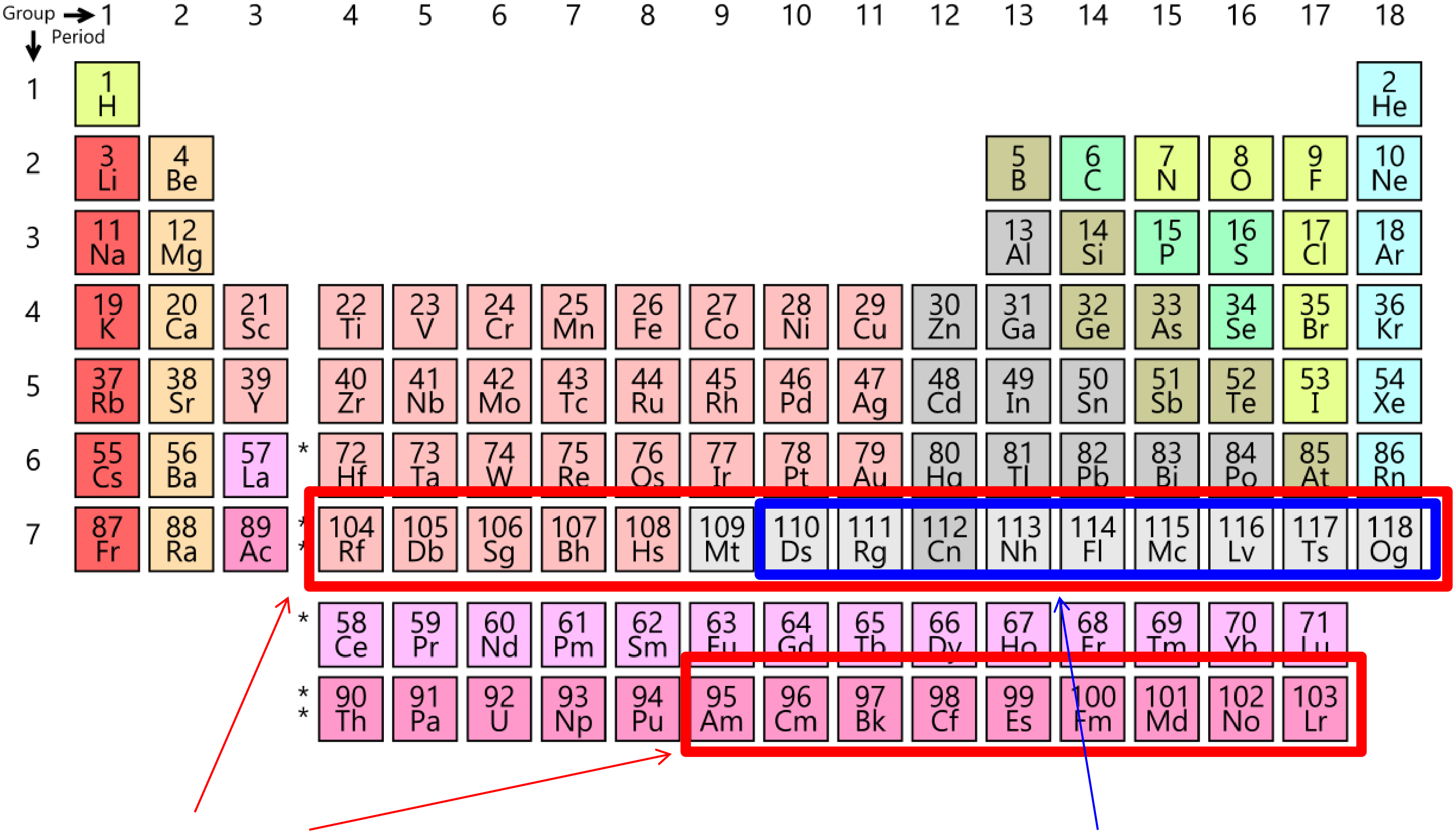
proton # or neutron #

2, 8, 20, 28, 50, 82, 126

- e.g., $^{16}_{8}\mathrm{O}_{8}$ (double magic)
- many oxygen nuclei: produced during nucleosynthesis
- oxygen: chemically active
- several complex chemical reactions, leading to the birth of life

参考：望月優子　ビデオ「元素誕生の謎にせまる」　http://rarfaxp.riken.go.jp/~motizuki/contents/genso.html

Elements heavier than U and Pu



Group → Period ↓	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

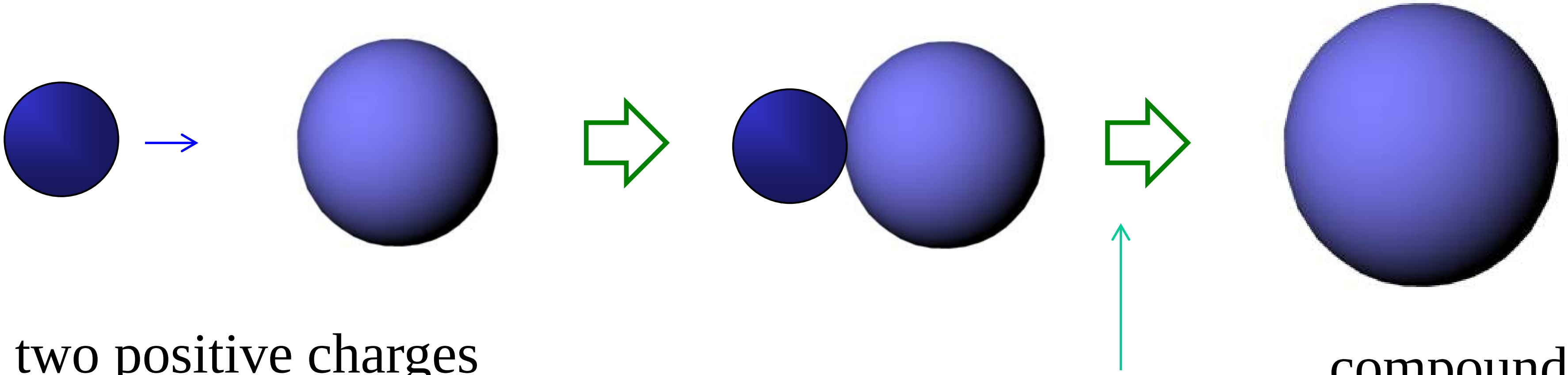
artificially synthesized (‘man-made’)

← nuclear reactions

superheavy elements (SHE)

How to synthesize SHE?

Nuclear fusion reactions



two positive charges
repel each other

↓

accelerate a projectile
nucleus to overcome the barrier

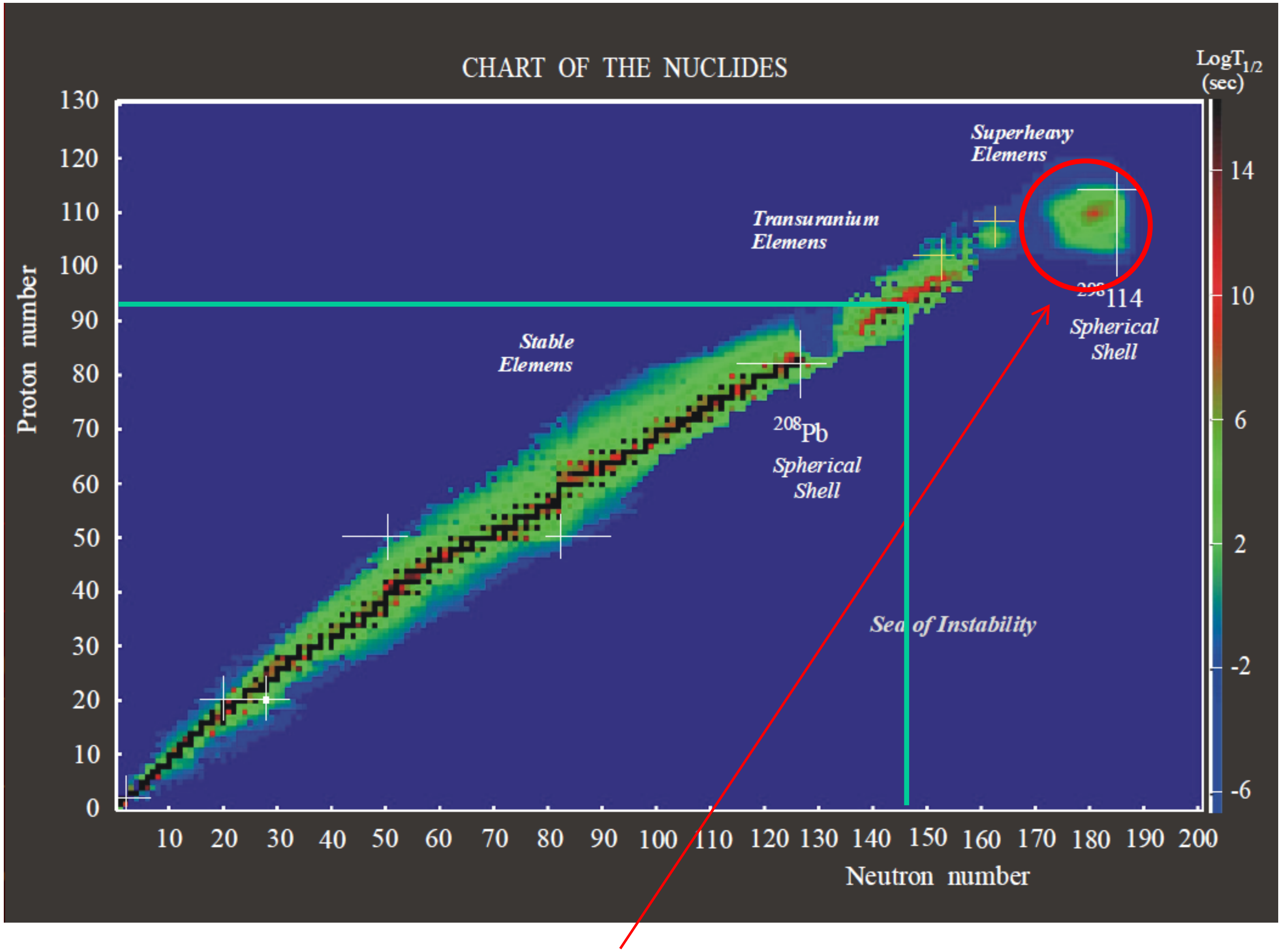
nuclear *attractive*
intraction

compound
nucleus

e.g.,

$^{70}_{30}Zn + ^{209}_{83}Bi \longrightarrow ^{279}_{113}Nh$

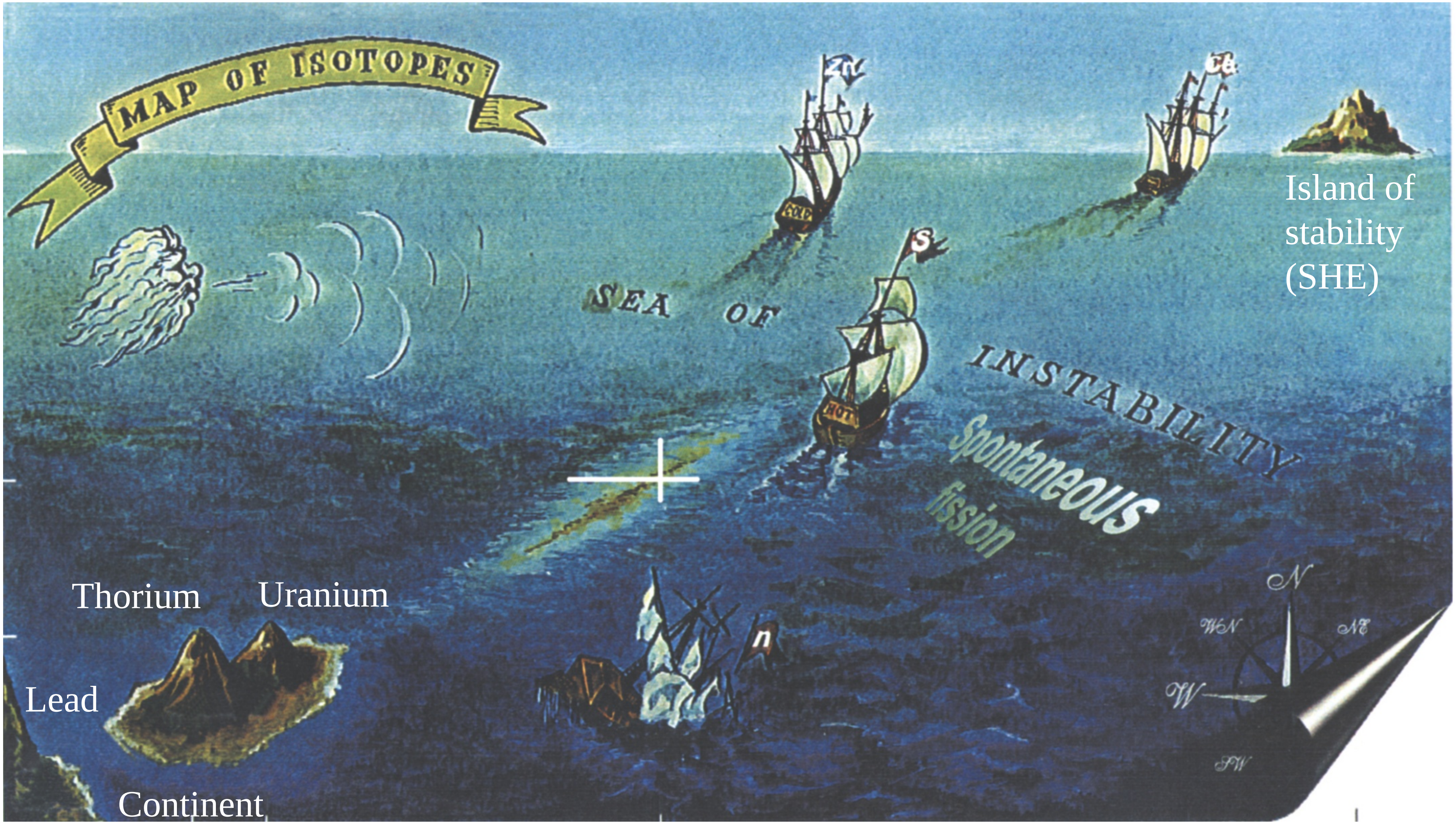
Prediction of island of stability: an important motivation of SHE study



Yuri Oganessian

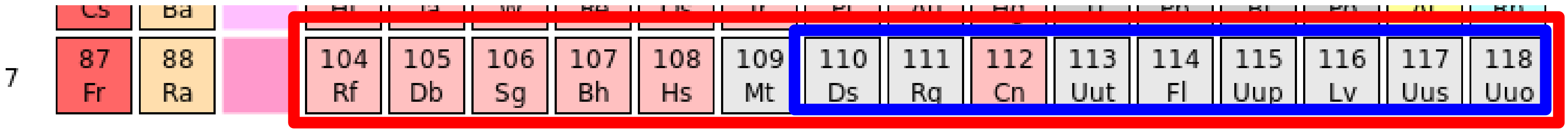
island of stability around Z=114, N=184

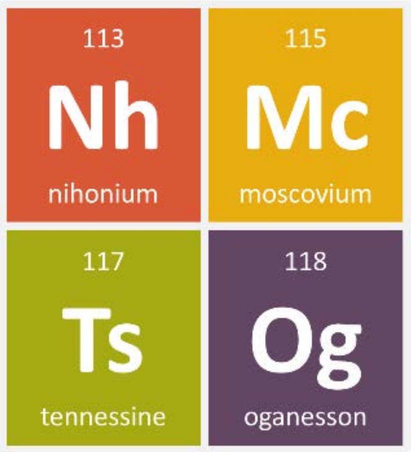
W.D. Myers and W.J. Swiatecki (1966), A. Sobiczewski et al. (1966)



Yuri Oganessian

who is she?

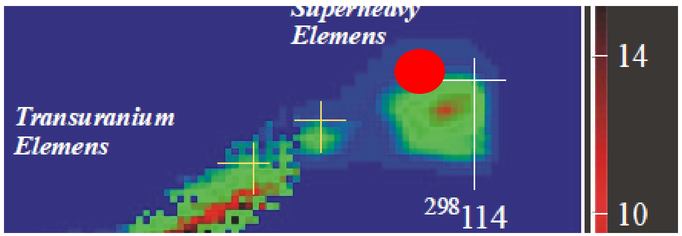




Nov., 2016

Z=110	Darmstadtium (Ds)	1994 Germany
Z=111	Roentgenium (Rg)	1994 Germany
Z=112	Copernicium (Cn)	1996 Germany
Z=113	Nihonium (Nh)	2003 Russia / 2004 Japan
Z=114	Flerovium (Fl)	1999 Russia (*)
Z=115	Moscovium (Mc)	2003 Russia
Z=116	Livermoriun (Lv)	2000 Russia
Z=117	Tennessine (Ts)	2010 Russia
Z=118	Oganesson (Og)	2002 Russia

(*)



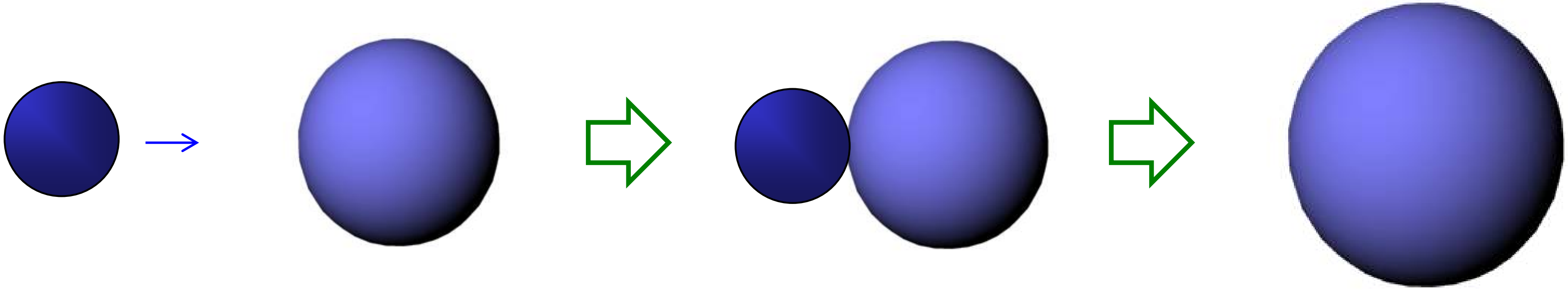
island of stability: Z=114, N=184

Fl discovered: Z=114, N=174-175

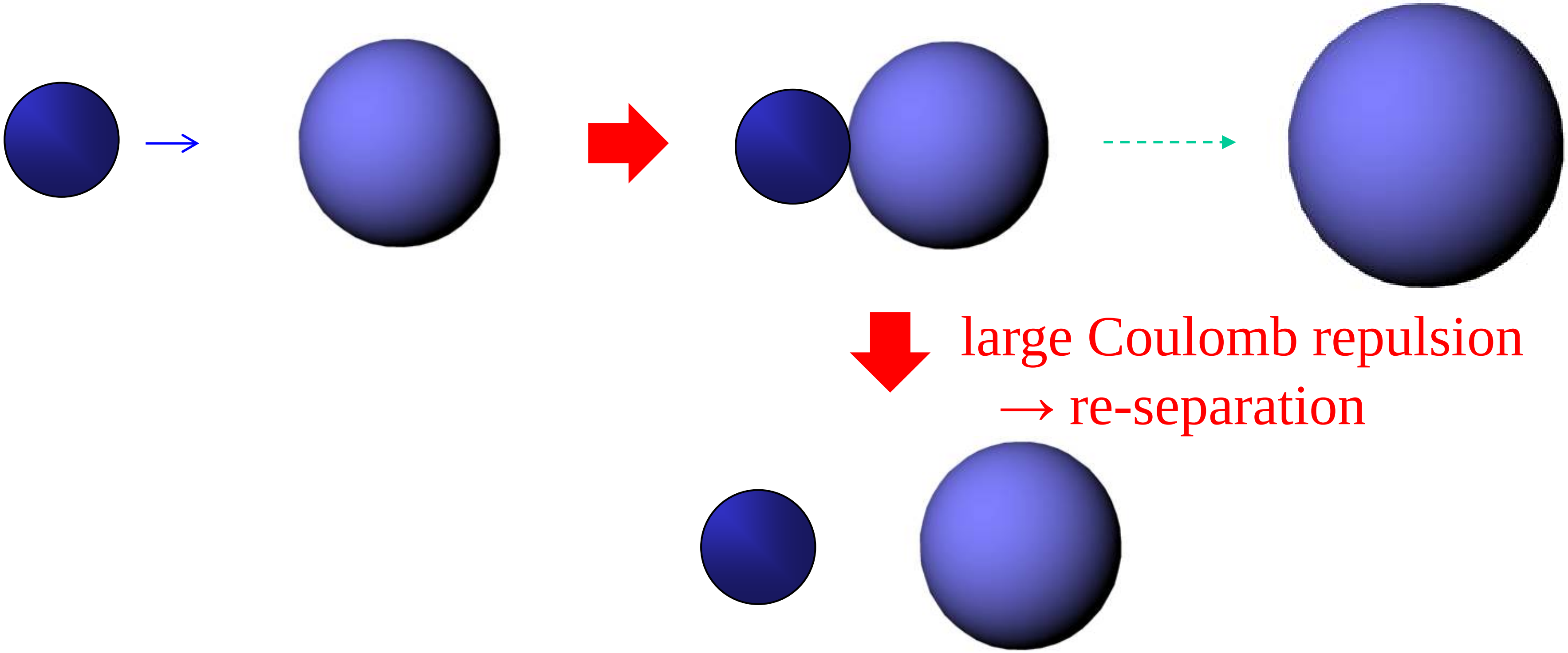
→ island not yet confirmed

A complication

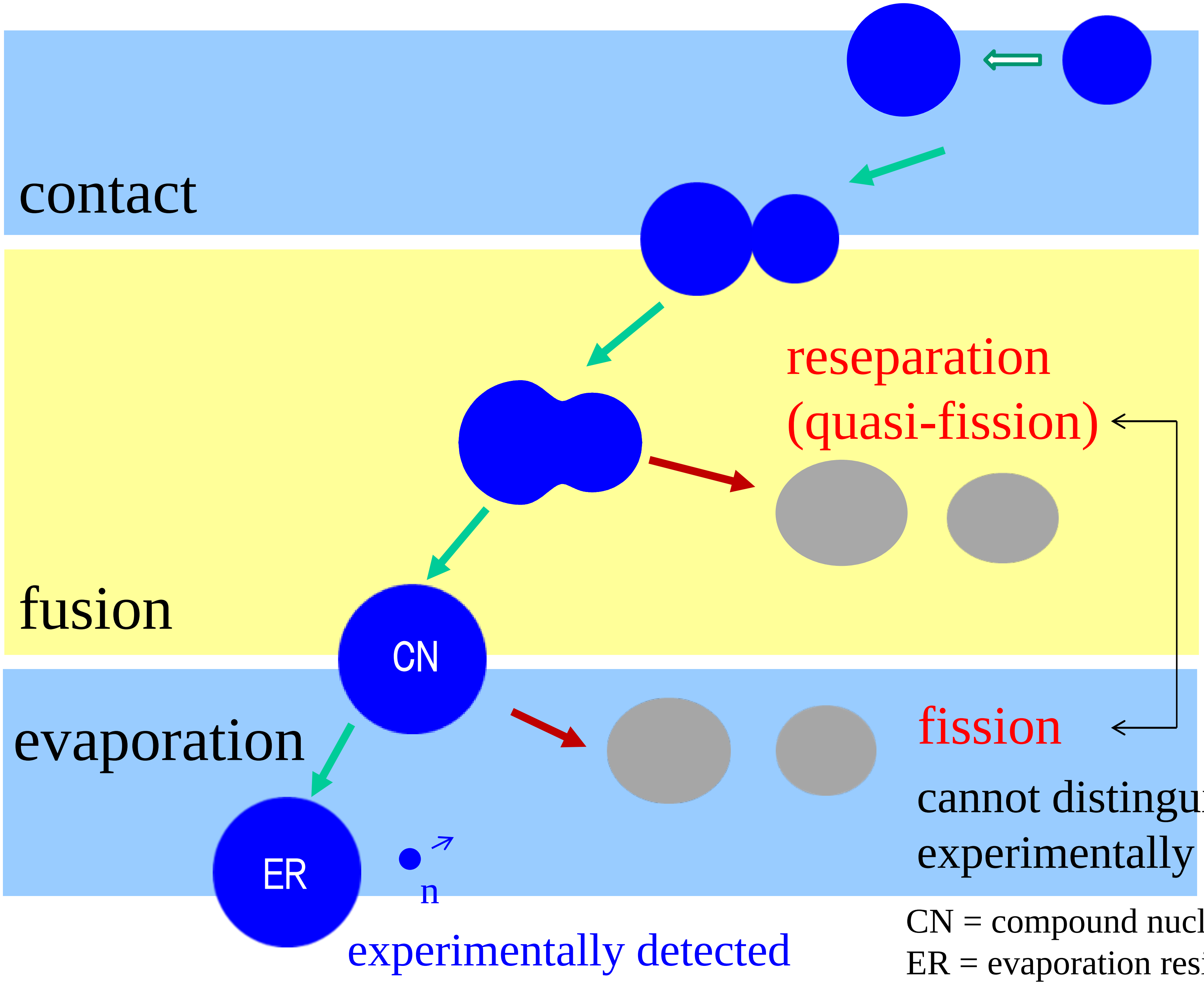
- Fusion of medium-heavy systems:



- Fusion of heavy and super-heavy systems:



large Coulomb repulsion
→ re-separation



contact

fusion

reseparation
(quasi-fission)

CN

evaporation

fission

cannot distinguish
experimentally

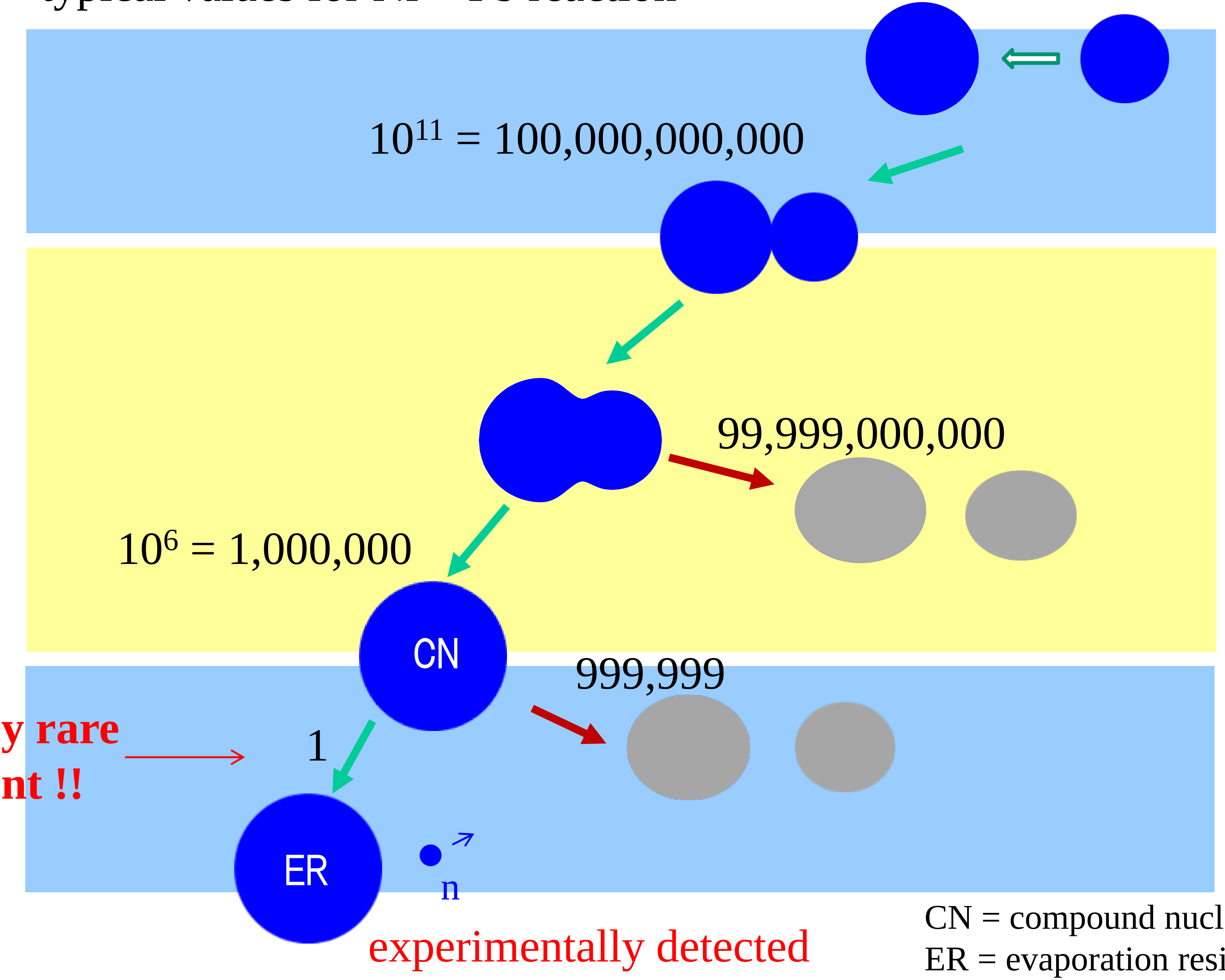
ER

n

experimentally detected

CN = compound nucleus
ER = evaporation residue

typical values for Ni + Pb reaction



$10^{11} = 100,000,000,000$

99,999,000,000

$10^{6} = 1,000,000$

CN

999,999

very rare event !! →

1

ER

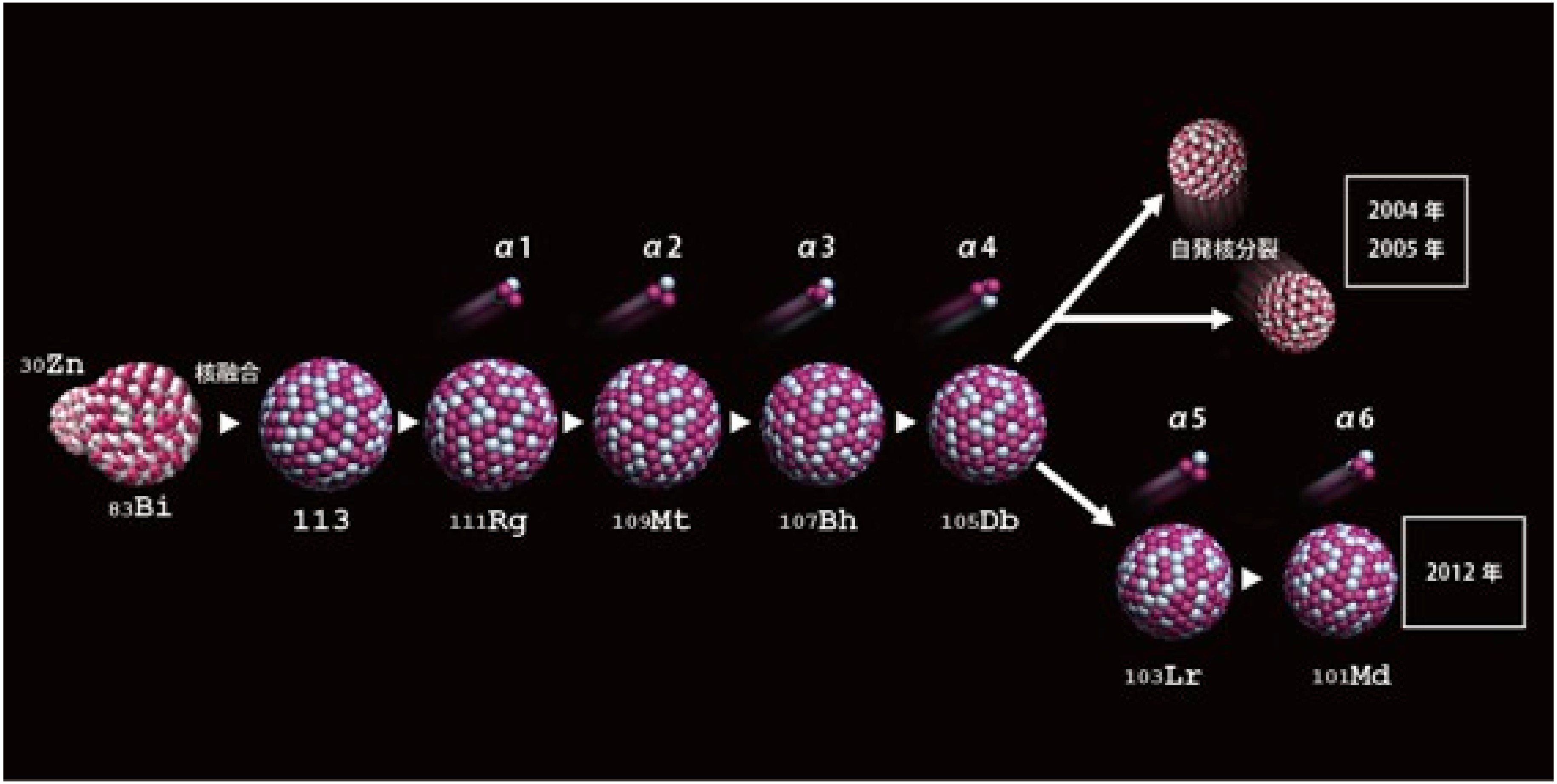
n

experimentally detected

CN = compound nucleus
ER = evaporation residue

Element 113 (RIKEN, K. Morita et al.)

$$^{70}\mathrm{Zn}\ (Z=30) + {}^{209}\mathrm{Bi}\ (Z=83) \longrightarrow {}^{278}\mathrm{Nh}\ (Z=113) + n$$



K. Morita et al., J. Phys. Soc. Jpn. 81(‘12)103201

only 3 events for 553 days experiment

Z=113: Nihonium (Nh)

Ni ppon

日本

Ni hon

Ancient Chinese: “Jippon”
→ Japan

→ Nihonium

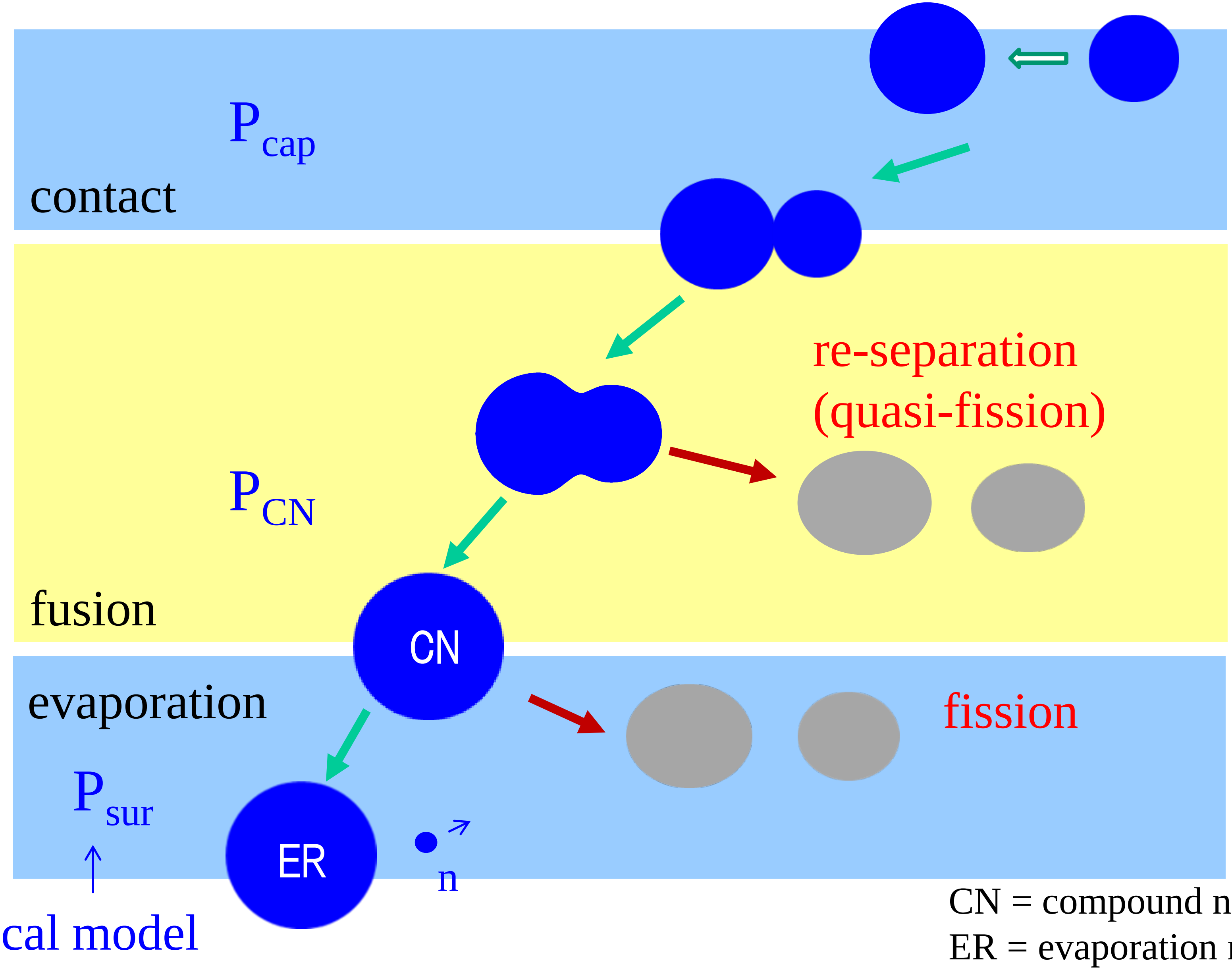
cf.

日本

Sun origin

Theoretical treatment

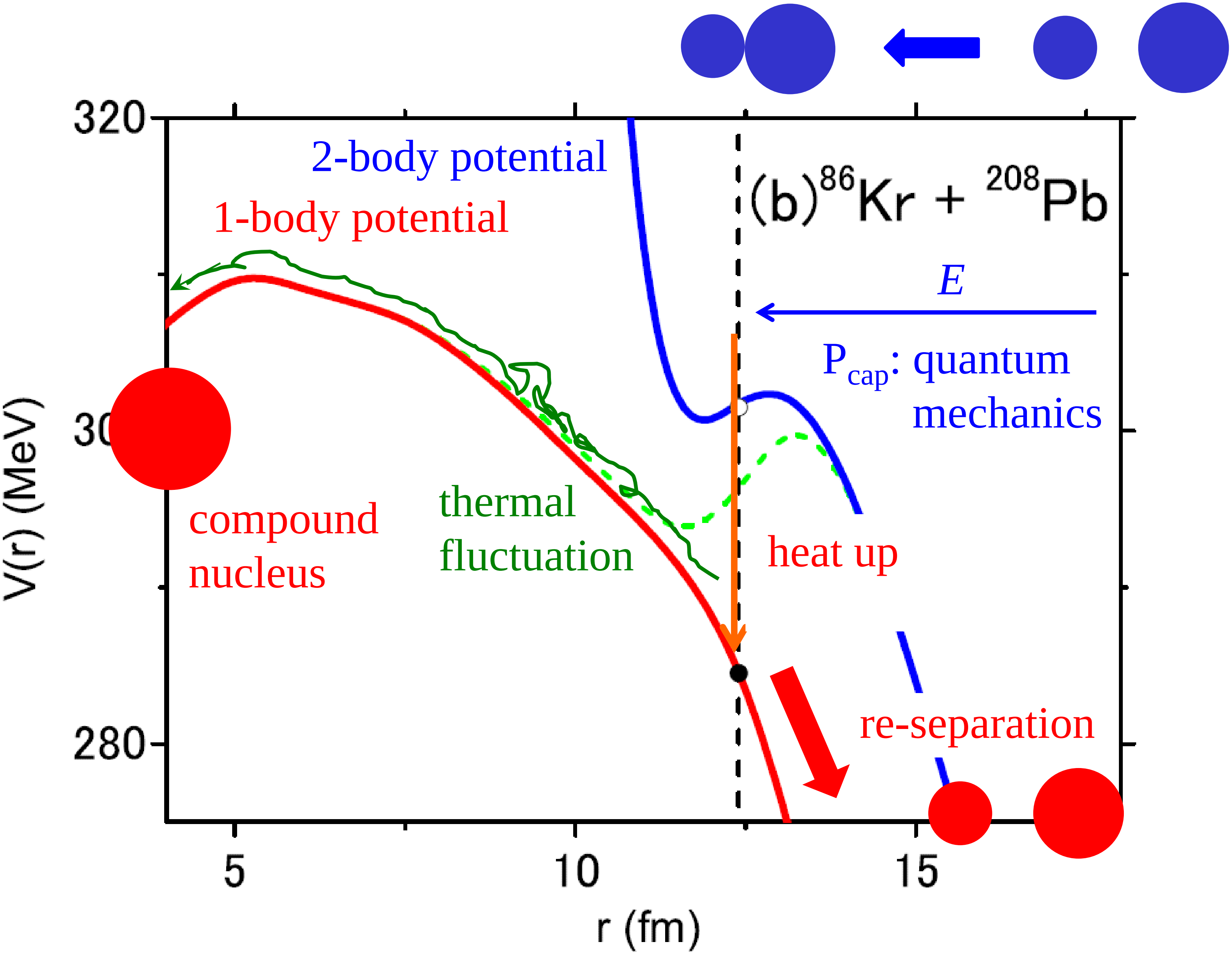
$$\boxed{P_{\mathrm{ER}} = P_{\mathrm{cap}} \cdot P_{\mathrm{CN}} \cdot P_{\mathrm{sur}}}$$



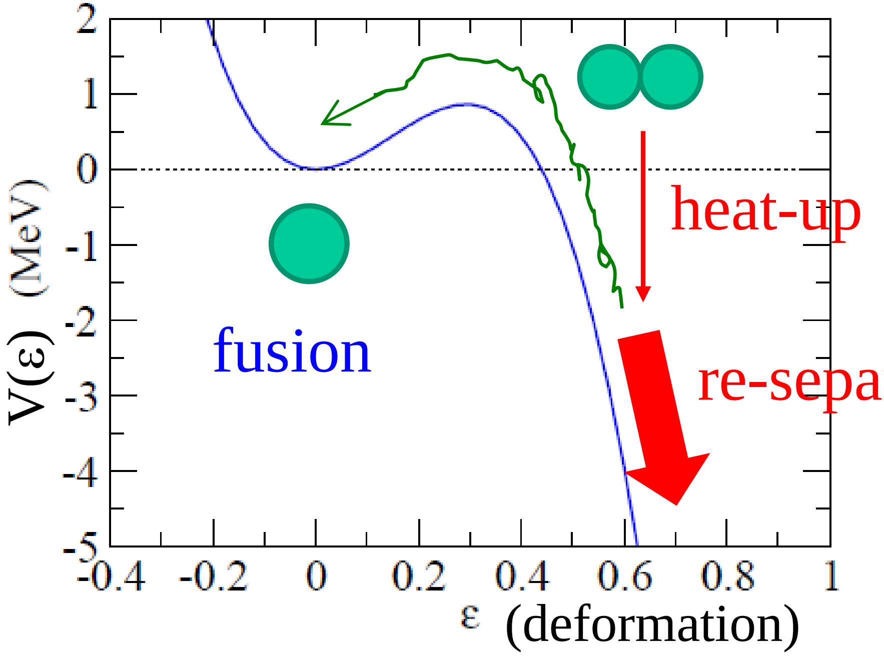
↑

statistical model

CN = compound nucleus
ER = evaporation residue


2-body potential
1-body potential
(b) ^{86}Kr + ^{208}Pb
E
P_{cap}: quantum mechanics
compound nucleus
thermal fluctuation
heat up
re-separation
320
300
280
V(r) (MeV)
5
10
15
r (fm)

Langevin approach



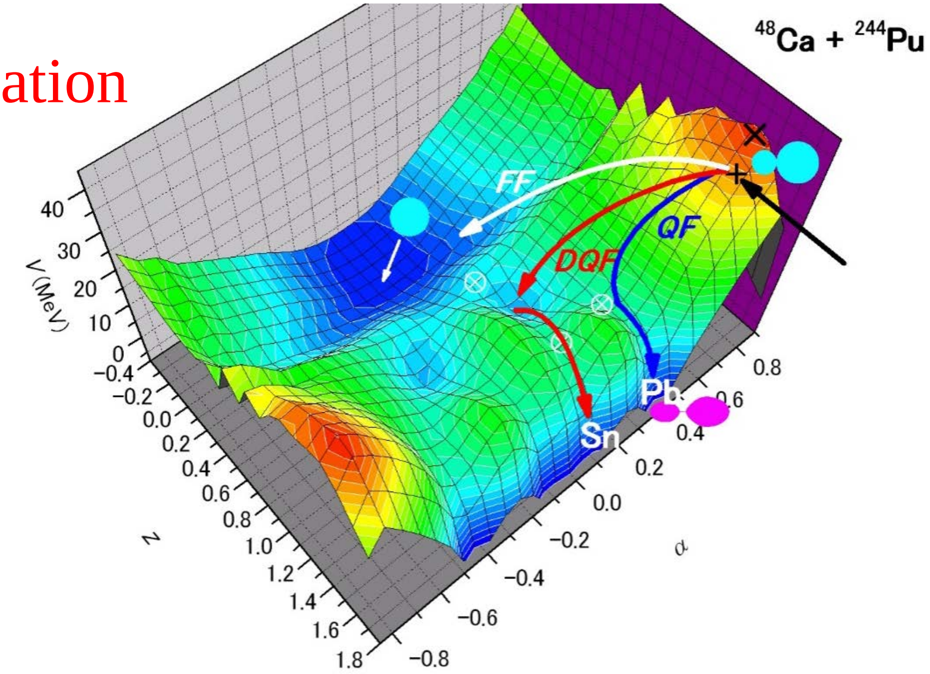
thermal fluctuation

⟶ Langevin method
(Brownian method)

$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

multi-dimensional extention

q: ▪internuclear separation,
▪deformation,
▪asymmetry of the two fragments



γ: friction coefficient
R(*t*): random force

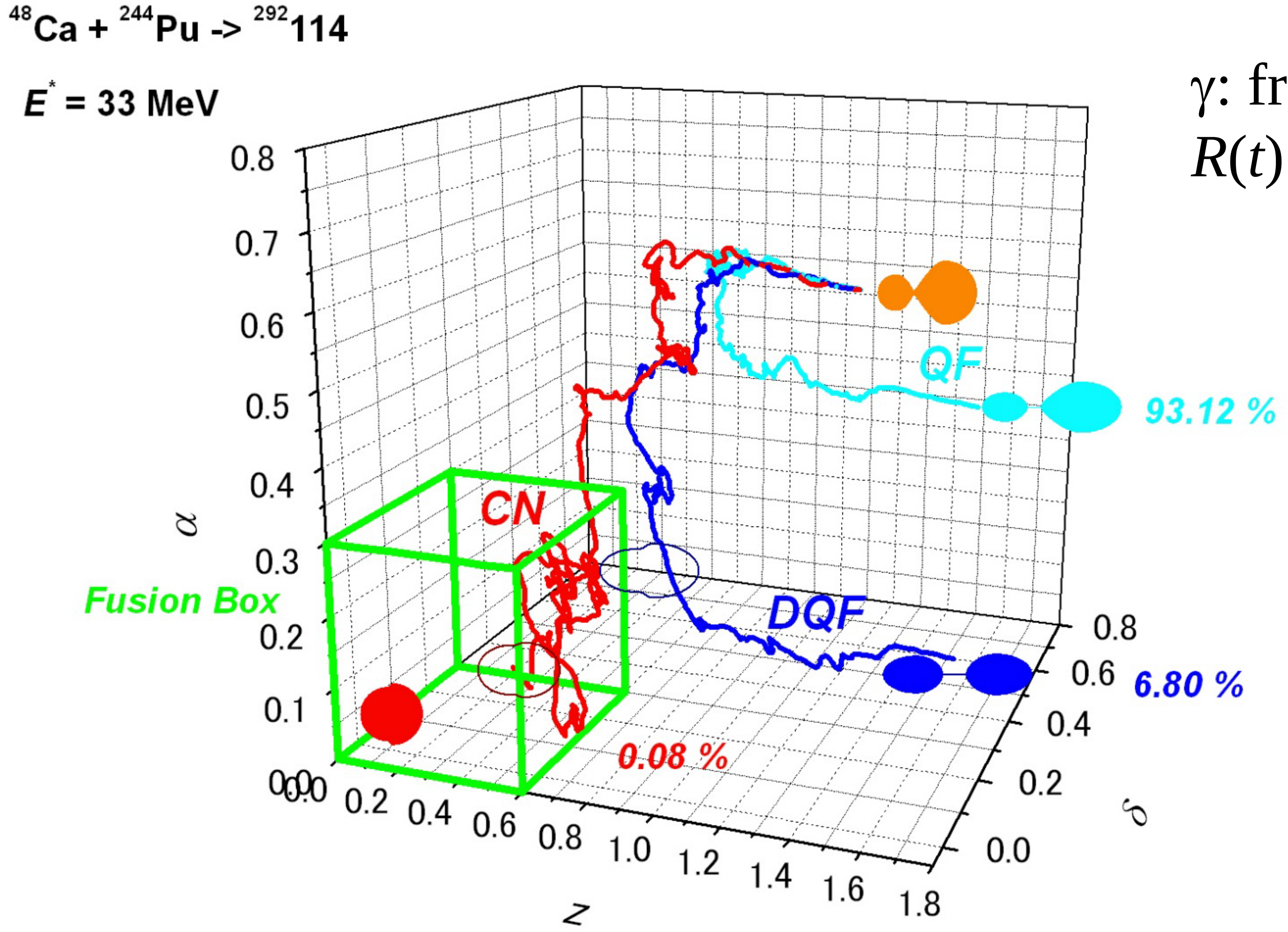
Theory: Lagenvin approach

multi-dimensional extension of:

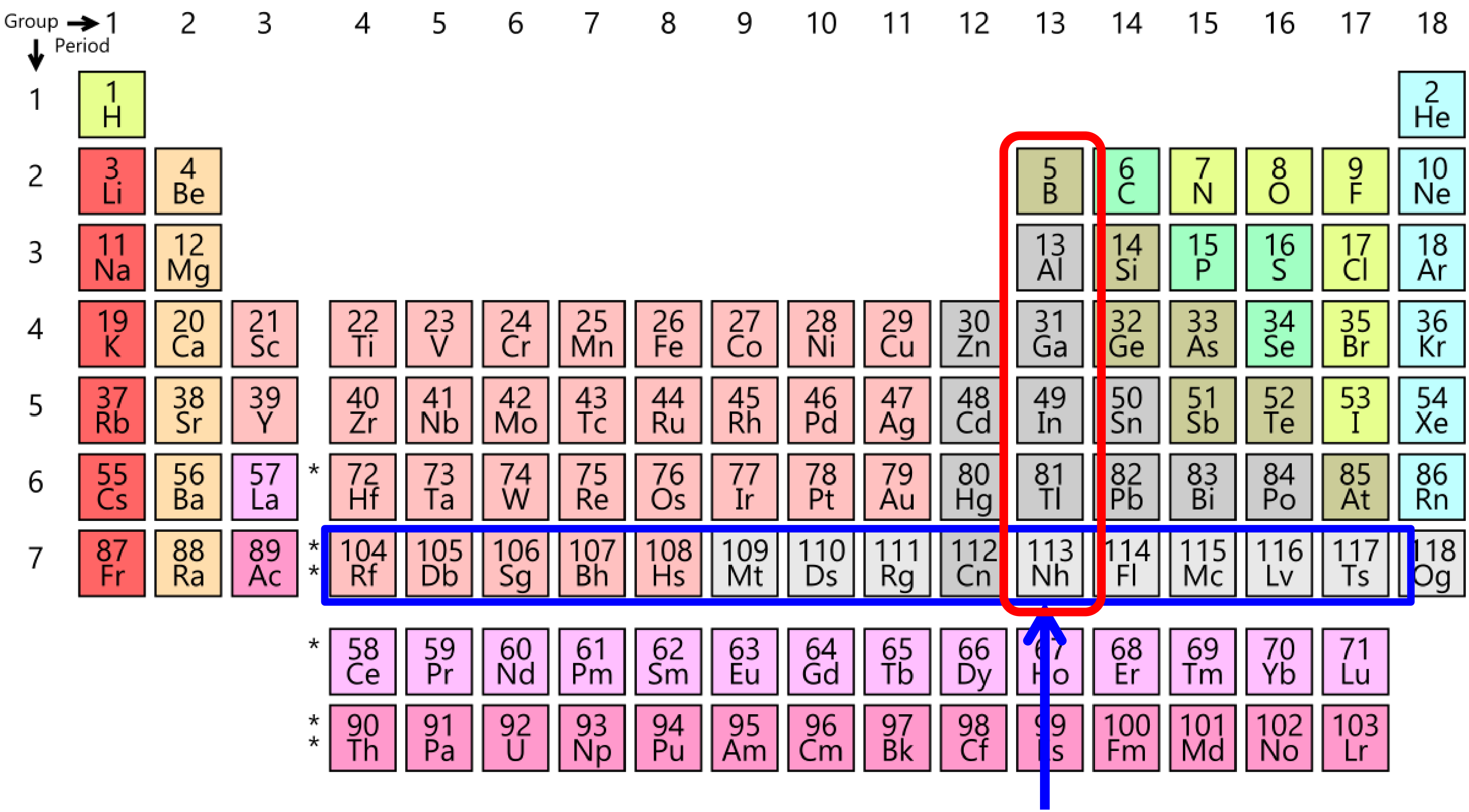
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

γ: friction coefficient

$R(t)$: random force



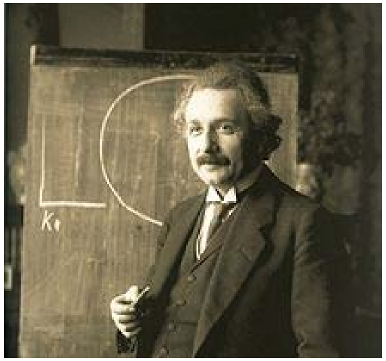
Chemistry of superheavy elements



- ➢Are they here in the periodic table?
- ➢Does Nh show the same chemical properties as B, Al, Ga, In, and Tl?

relativistic effect : important for large Z

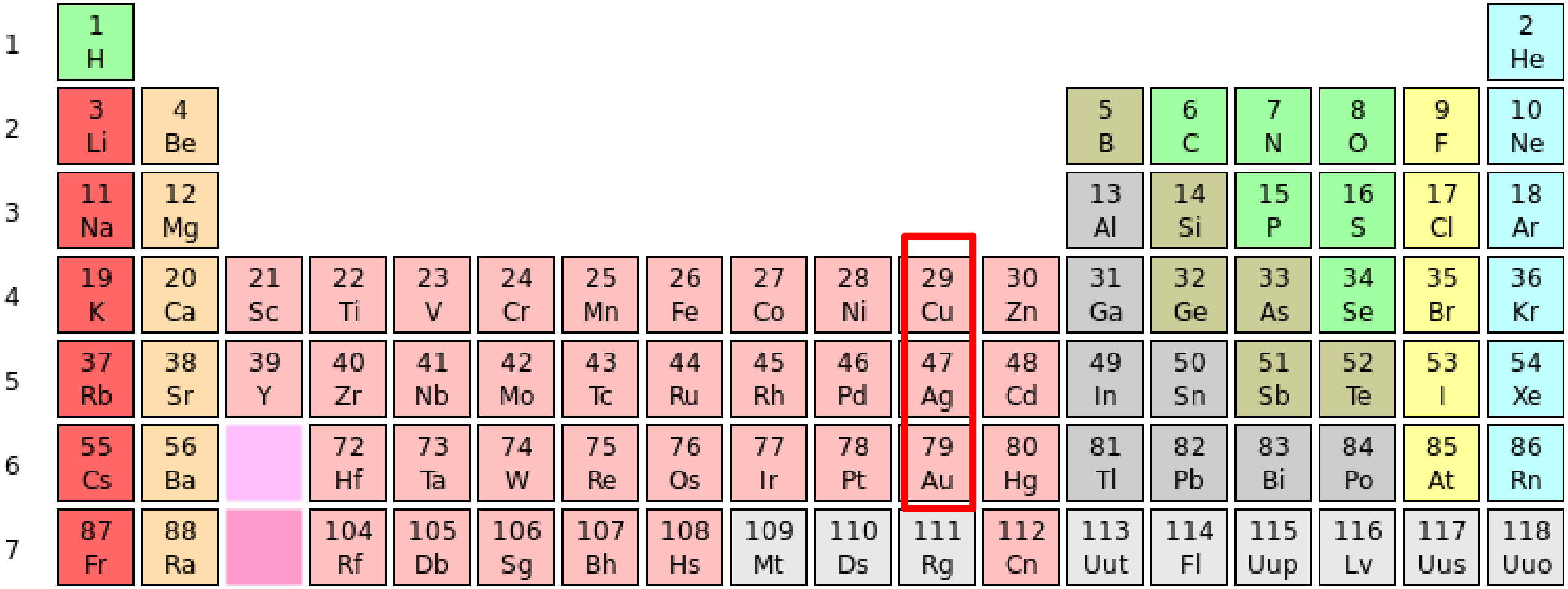
$$E = mc^2$$



Solution of the Dirac equation (relativistic quantum mechanics) for a hydrogen-like atom:

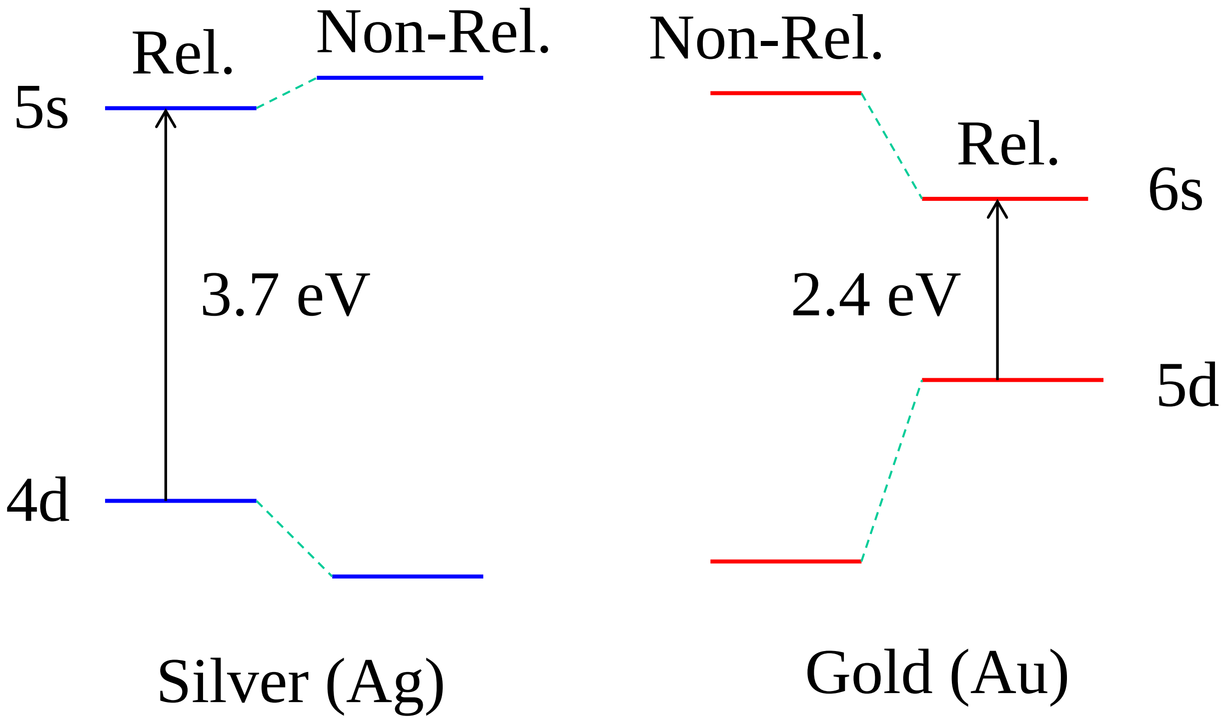
$$E_{1S} = mc^2\sqrt{1-(Z\alpha)^2} \sim mc^2\left(1 - \frac{(Z\alpha)^2}{2} \underbrace{- \frac{(Z\alpha)^4}{8} + \cdots}_{\text{relativistic effect}}\right)$$

Famous example of relativistic effects: the color of gold

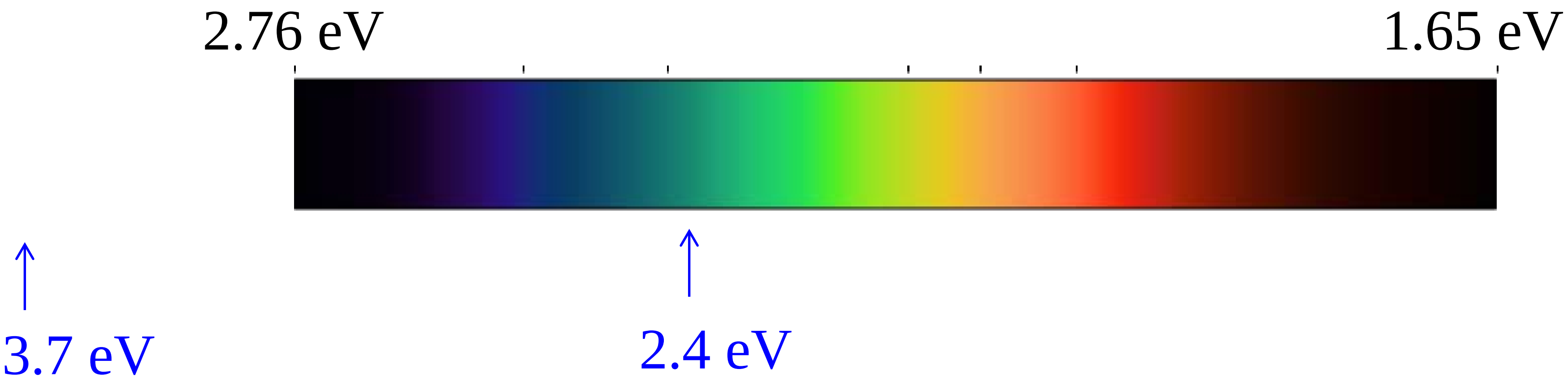


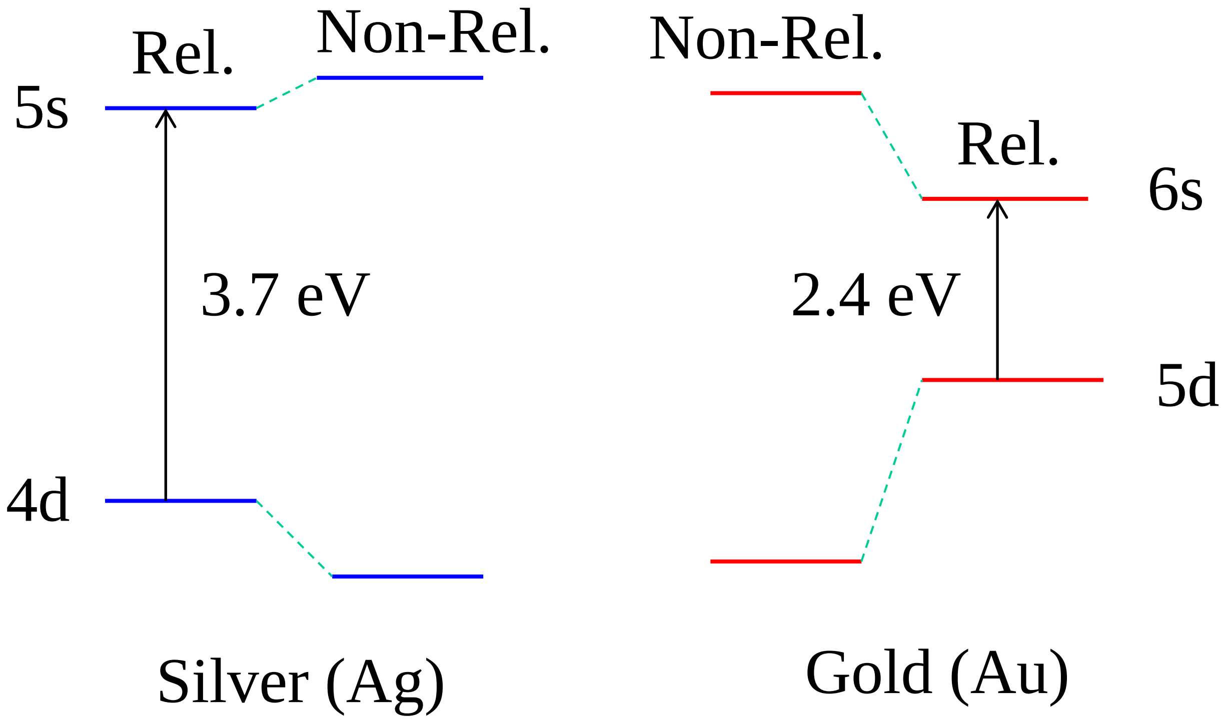
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

Gold looked like silver if there was no relativistic effects!



cf. visible spectrum





Rel.

Non-Rel.

5s

4d

3.7 eV

Silver (Ag)

Non-Rel.

Rel.

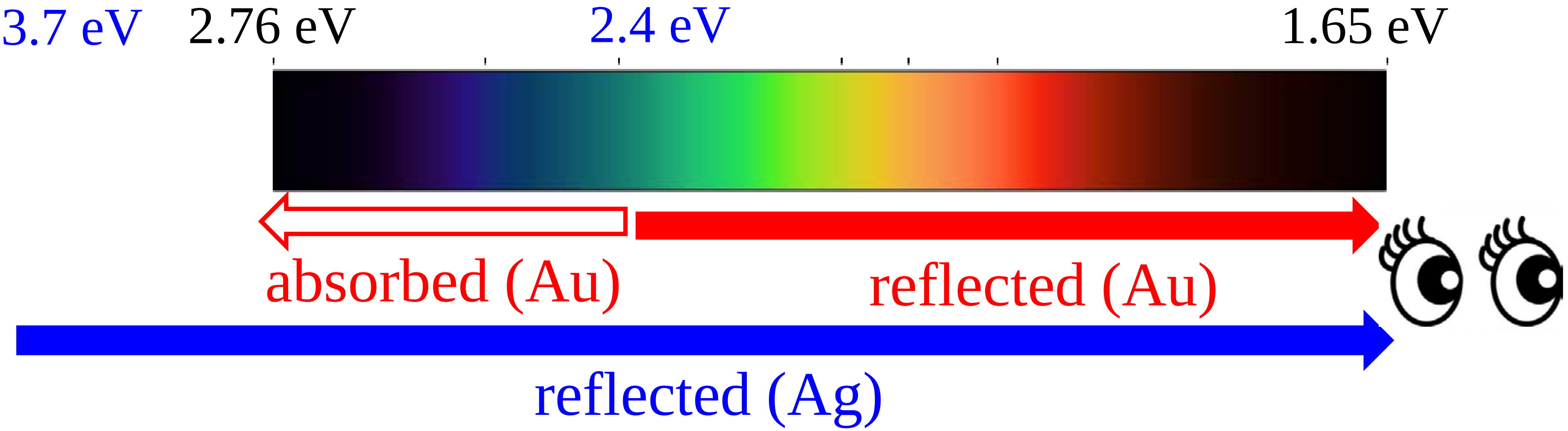
6s

2.4 eV

5d

Gold (Au)

cf. visible spectrum



3.7 eV

2.76 eV

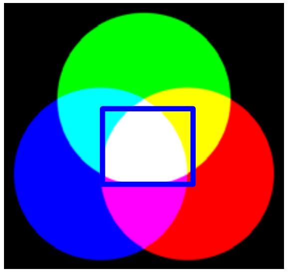
2.4 eV

1.65 eV

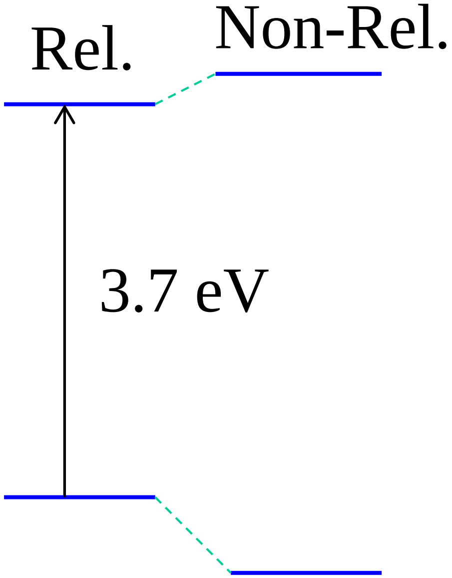
absorbed (Au)

reflected (Au)

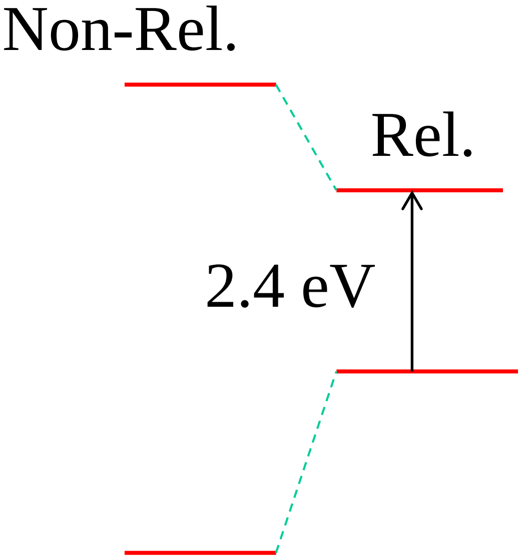
reflected (Ag)



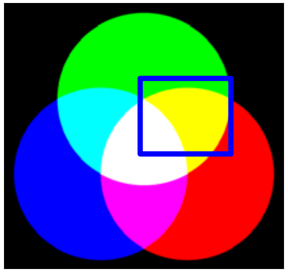
no color
absorbed



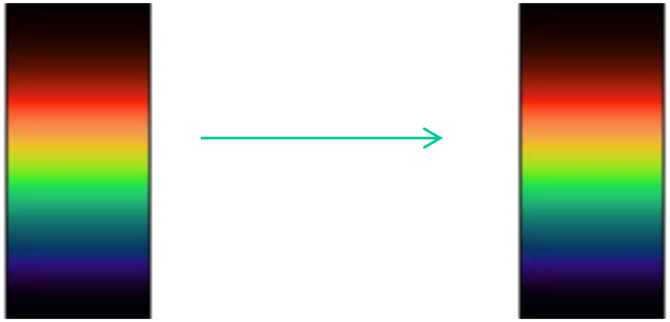
Silver (Ag)

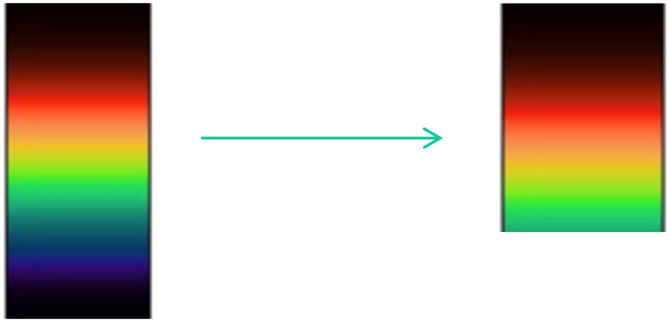


Gold (Au)



blue: absorbed





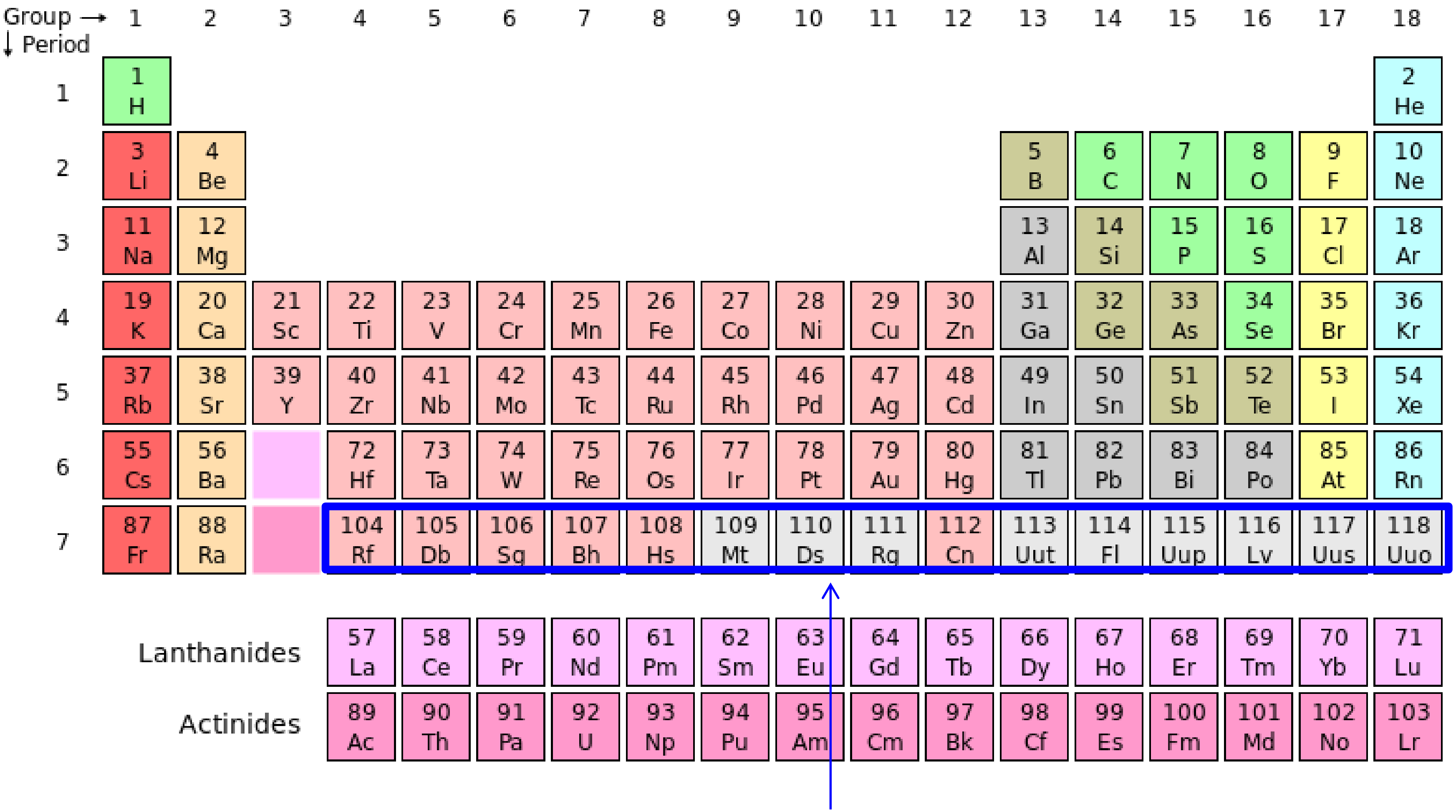
Ag

47th element

Au

79th element

Chemistry of superheavy elements



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

How do the relativistic effects alter the periodic table for SHE?

⟶ a big open question

Summary

- ➢ **Everything is made from atoms.**

- ➢ **The heaviest natural elements are U/Pu.**
- ➢ **r-process nucleosynthesis (elements heavier than U)**
- ➢ **Prediction: the island of stability**
- ➢ **Superheavy elements (SHE) up to Z=118 have been synthesized with nuclear fusion reactions.**
- ➢ **The fusion probability for SHE is extremely small.**
- ➢ **The element 113: Nihonium (Nh)**
- ➢ **Chemistry of SHE: relativistic effects?**