Physics of superheavy elements

Kouichi Hagino

Nuclear Theory Group,
Department of Physics,
Tohoku University

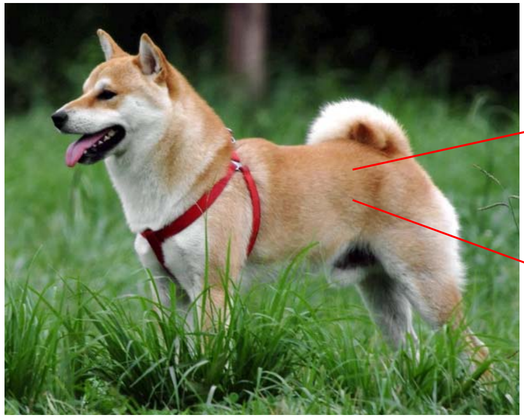
- What is nuclear physics?
- What are superheavy elements?
- How to create superheavy elements?
- What are chemical properties of superheavy elements?

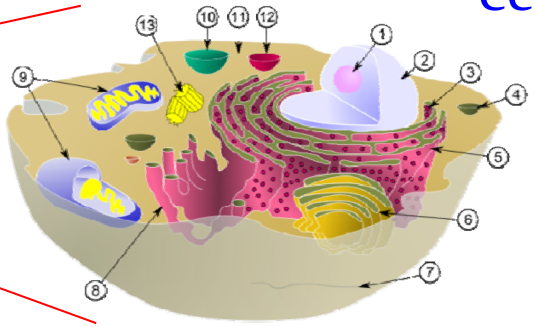
Introduction: atoms and atomic nuclei

~ 50 cm

What would you see if you magnified the dog?

Introduction: atoms and atomic nuclei



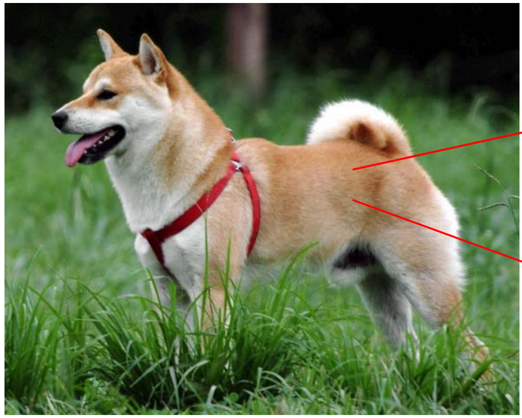


cells

~ 50 cm

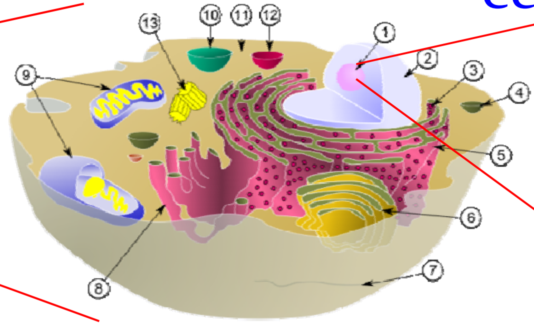
~ μm = 10^{-6} m

Introduction: atoms and atomic nuclei



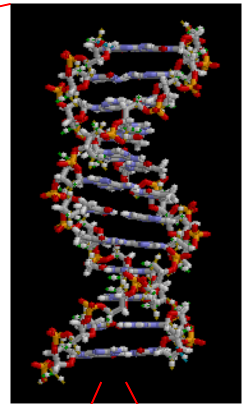
~ 50 cm

cells



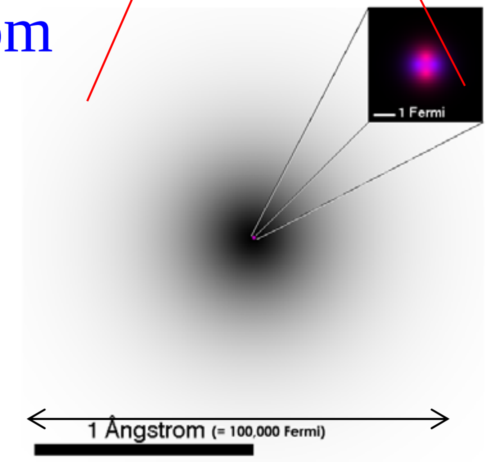
~ µm = 10^{-6} m

DNA



~ 10^{-8} m

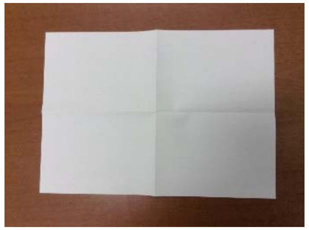
atom



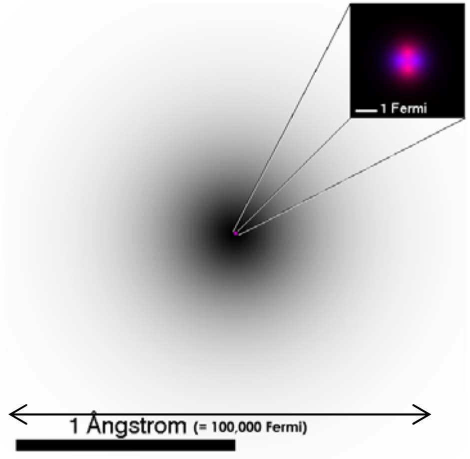
~ 10^{-10} m

All things are made of atoms.

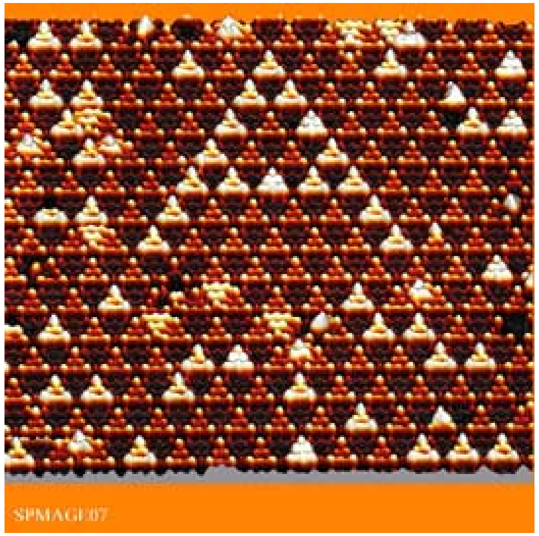
All things are made of atoms.

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

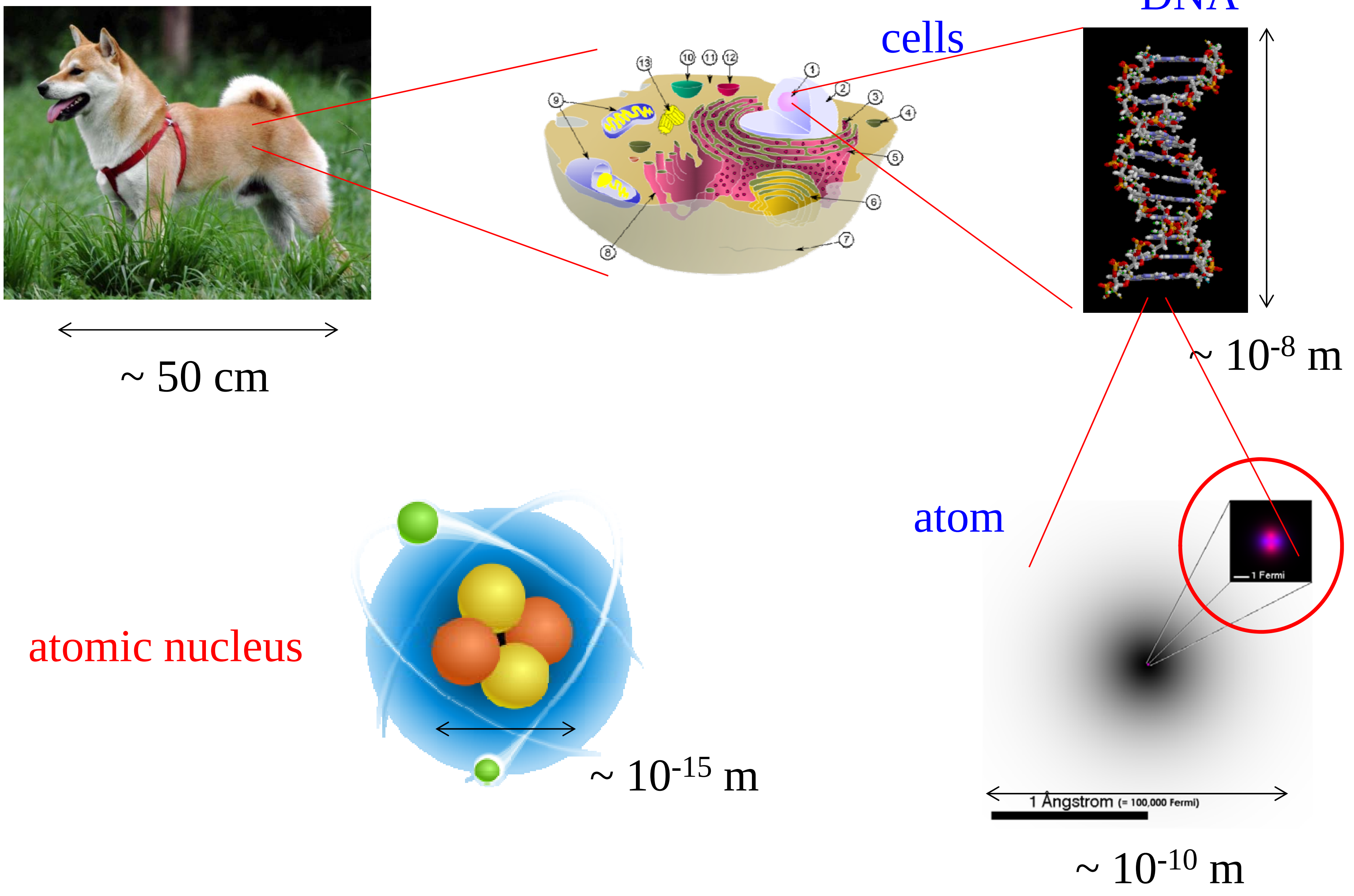


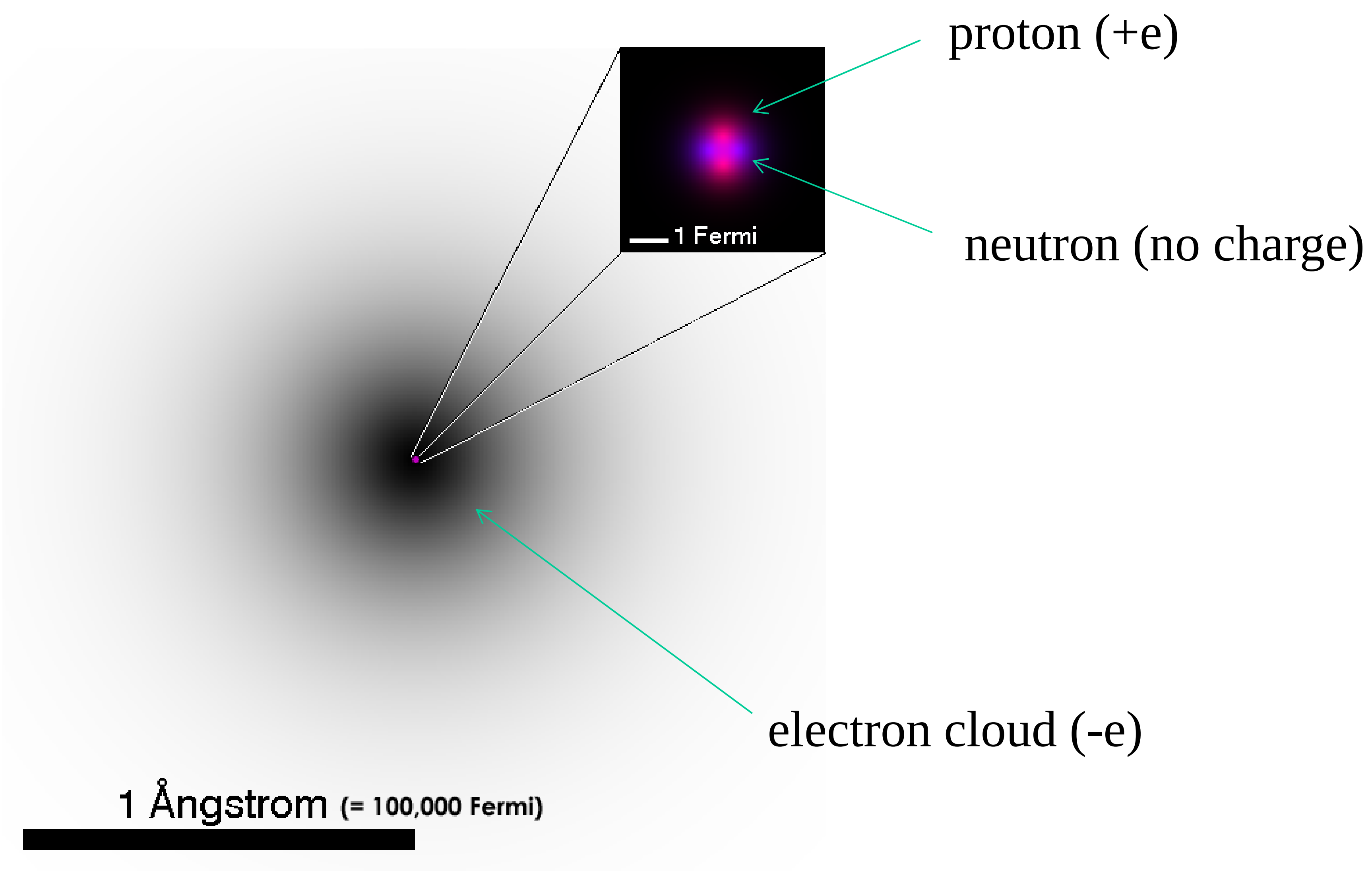
~ 10^{-10} m



STM image
(surface physics group,
Tohoku university)

Introduction: atoms and atomic nuclei





- Neutral atoms: # of protons = # of electrons
- Chemical properties of atoms ⟶ # of electrons
- $M_p \sim M_n \sim 2000\ M_e$ ⟶ the mass of atom ~ the mass of nucleus

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
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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

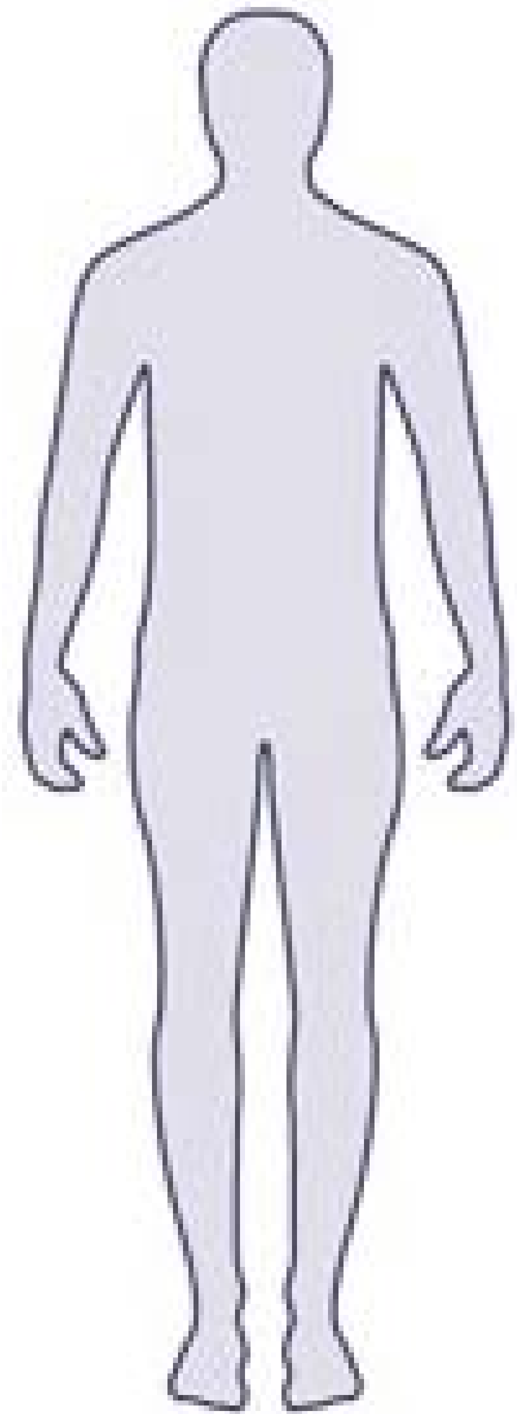
tabular arrangement of chemical elements based on the atomic numbers (= # of electrons = # of protons)

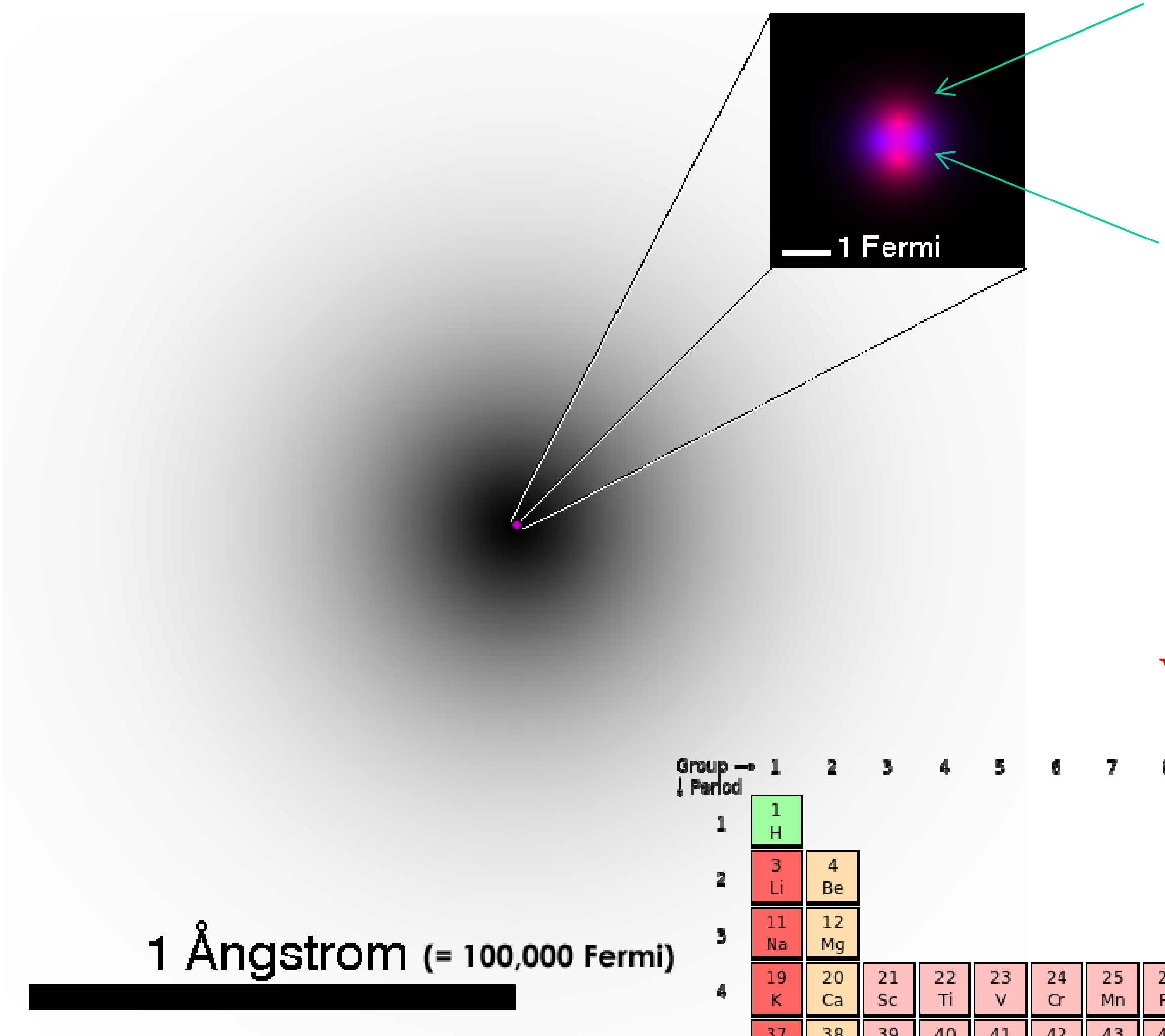
What are we made of ?

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





Where are neutrons?

Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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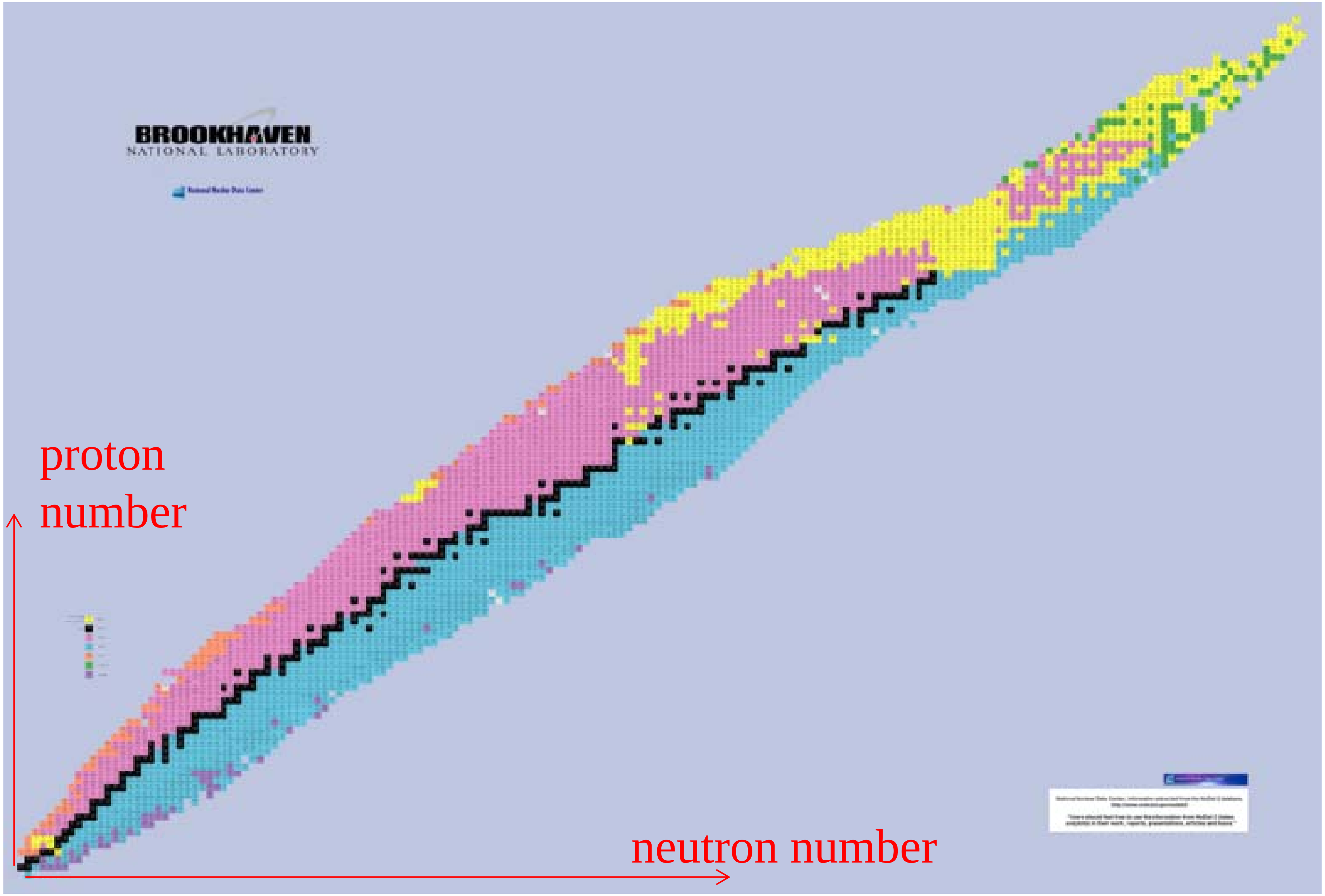
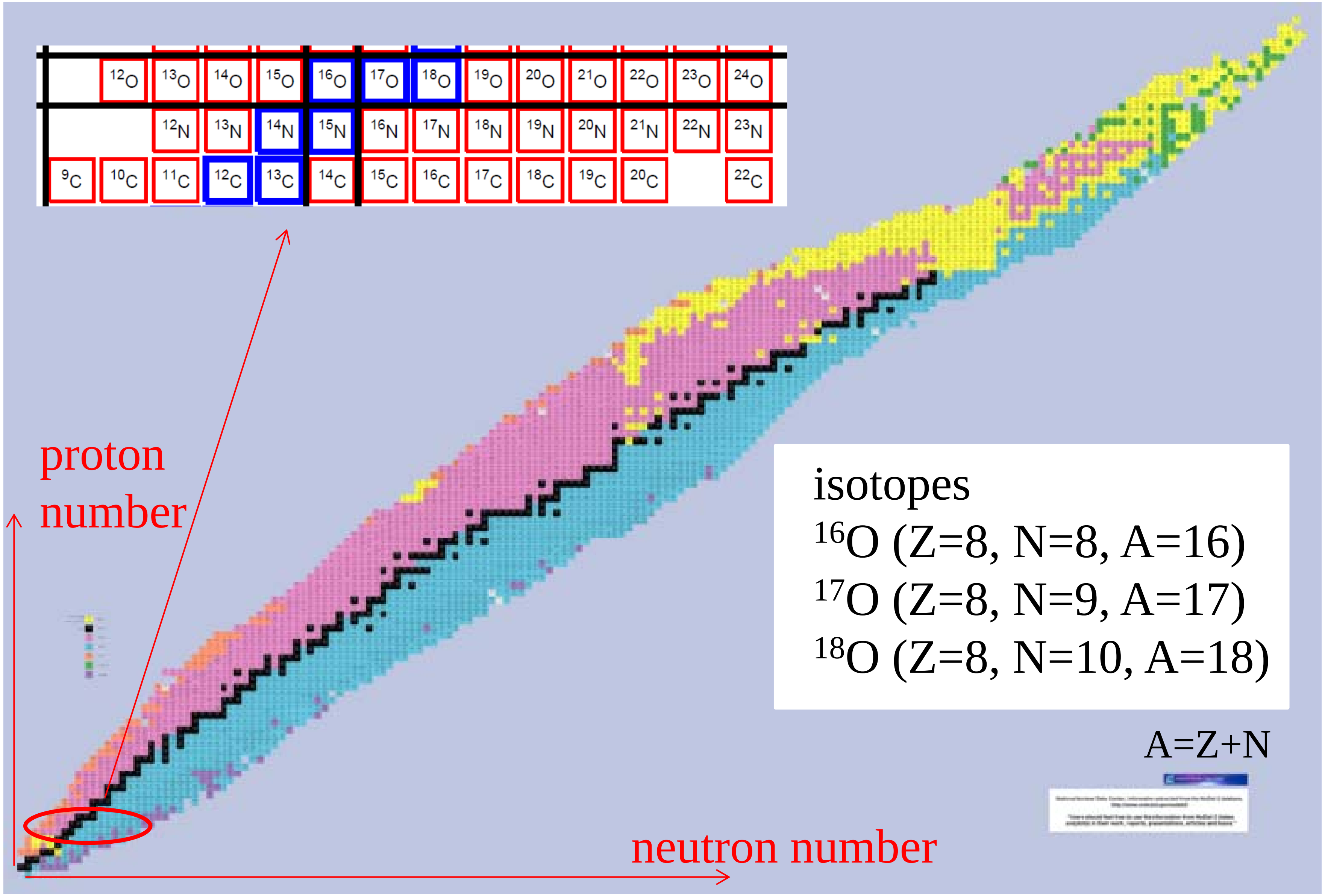
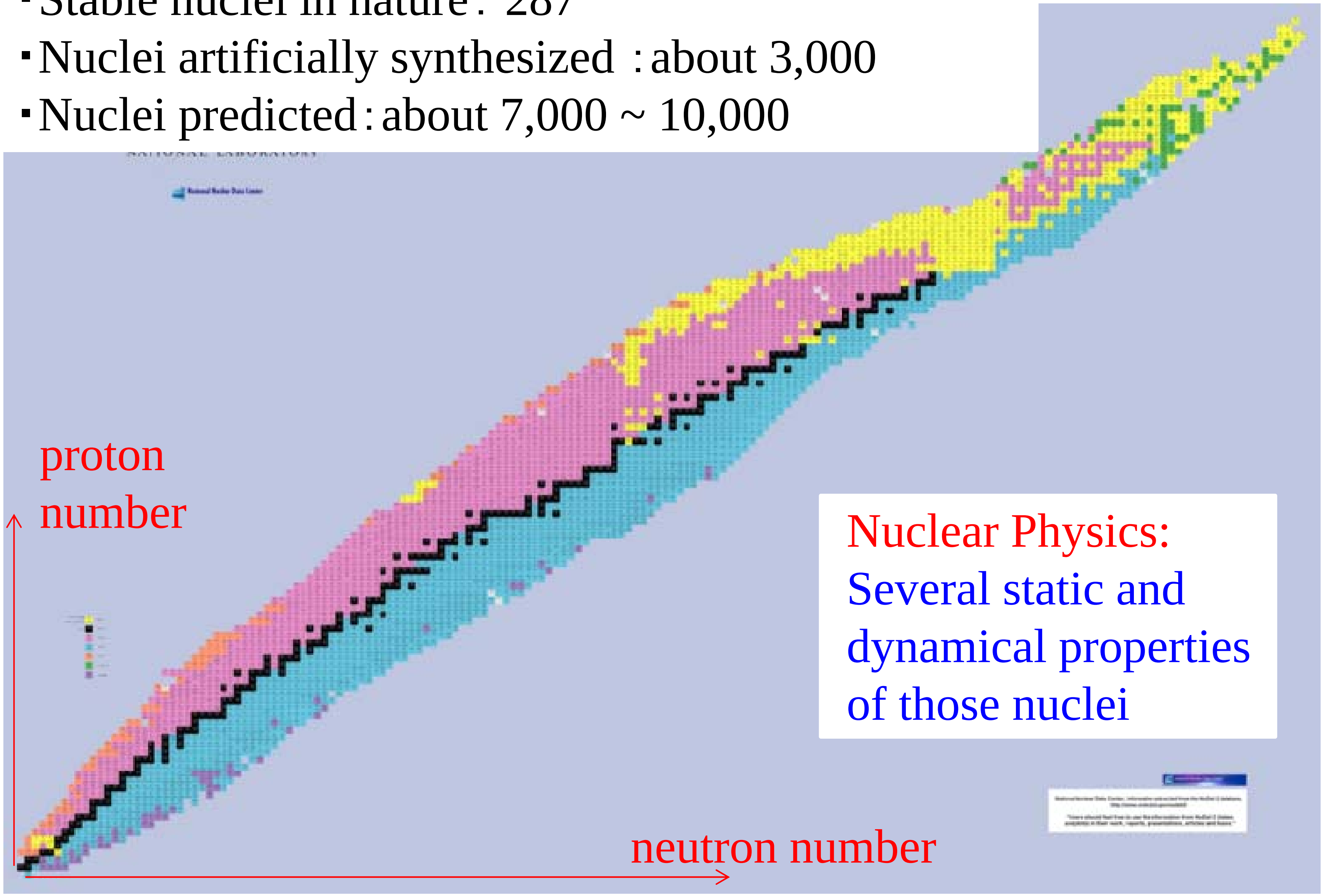
Nuclear Chart: 2D map of atomic nuclei



Nuclear Chart: 2D map of atomic nuclei

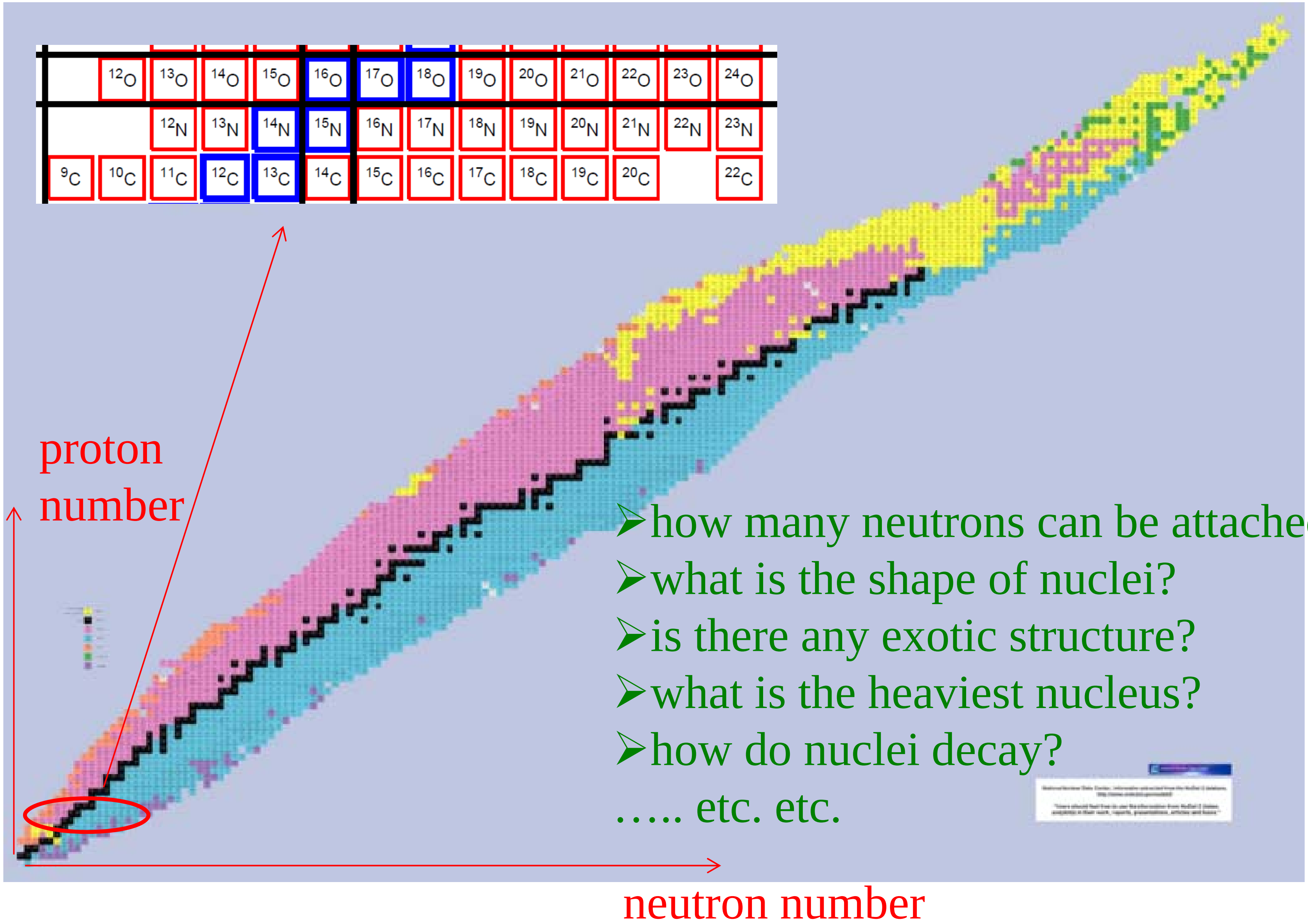


- Stable nuclei in nature： 287
- Nuclei artificially synthesized ：about 3,000
- Nuclei predicted：about 7,000 ~ 10,000



Nuclear Physics:
Several static and dynamical properties of those nuclei

Nuclear Chart: 2D map of atomic nuclei

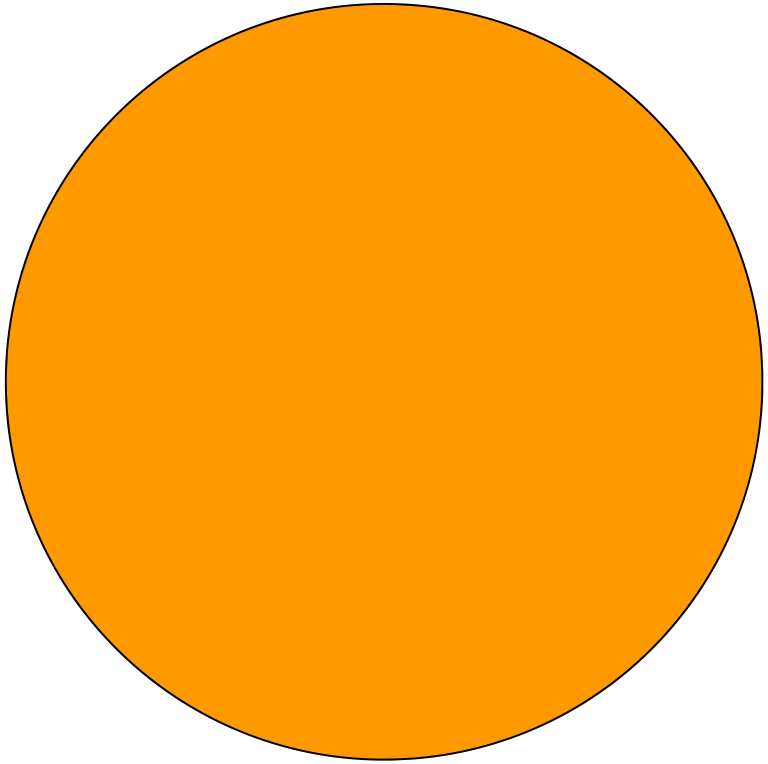


- ➢how many neutrons can be attached?
- ➢what is the shape of nuclei?
- ➢is there any exotic structure?
- ➢what is the heaviest nucleus?
- ➢how do nuclei decay?

….. etc. etc.

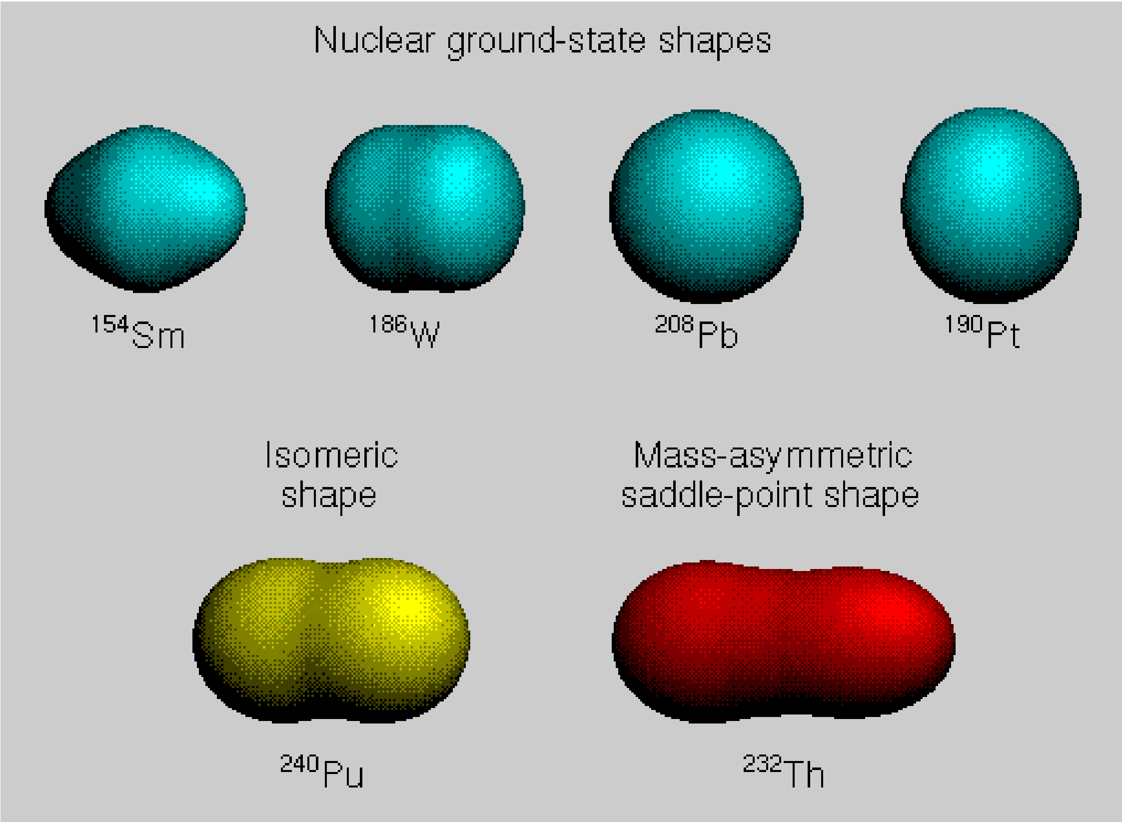
An example of what we investigate in nuclear physics

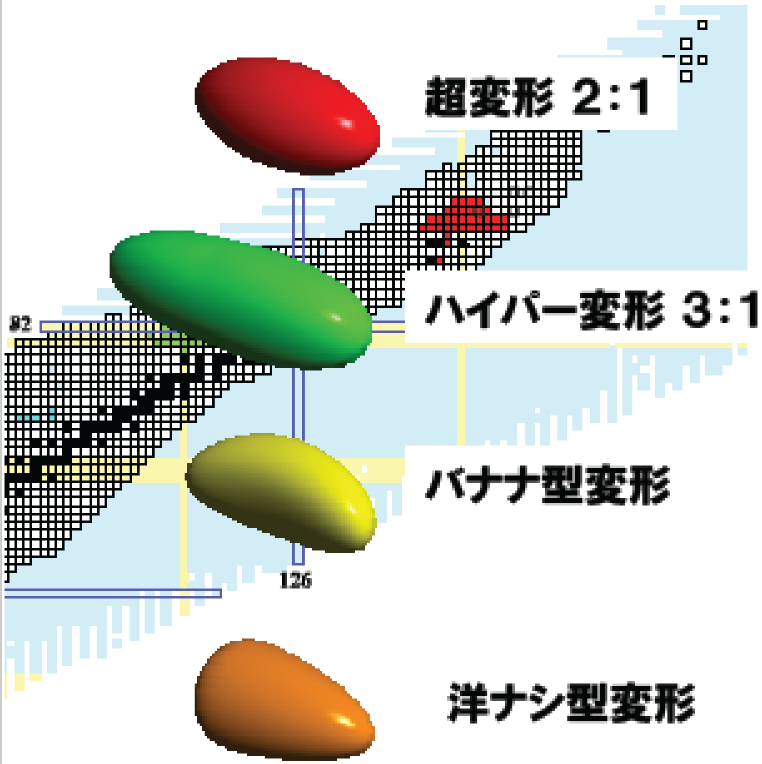
- what is the shape of a nucleus?



Are nuclei all spherical?

➢what is the shape of nucleus?





http://t2.lanl.gov/tour/sch001.html

Some nuclei are deformed in the ground state!

what are combinations of (Z,N) which yield a deformation?

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What is the heaviest element?

Periodic table of chemical elements

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What is the heaviest element?

natural elements: **Pu** (Z=94) ⟶ a tiny amount in nature
U (Z=92)

What determines these numbers??

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What is the heaviest element?

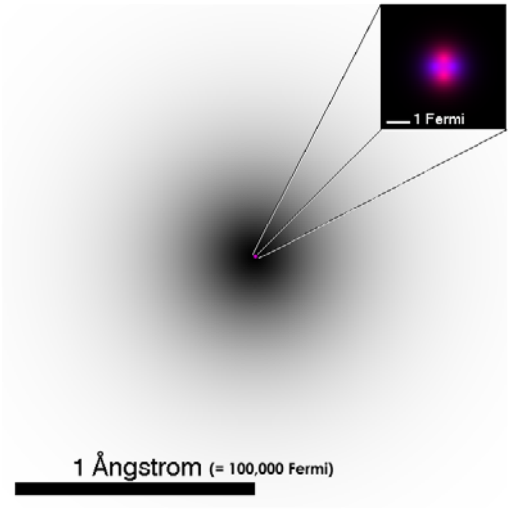
natural elements: **Pu** (Z=94) ⟶ a tiny amount in nature
U (Z=92)

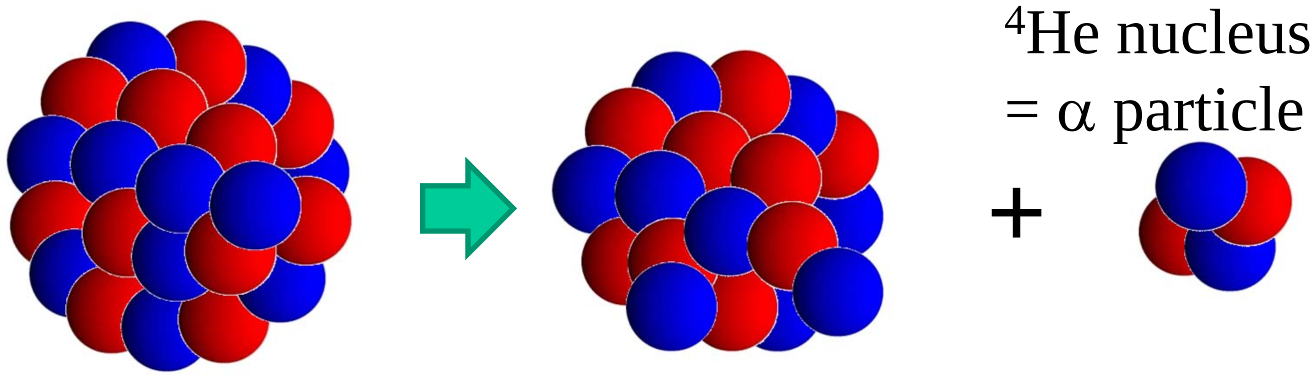
What determines these numbers??

heavy nuclei ⟶ large Coulomb repulsion

↓

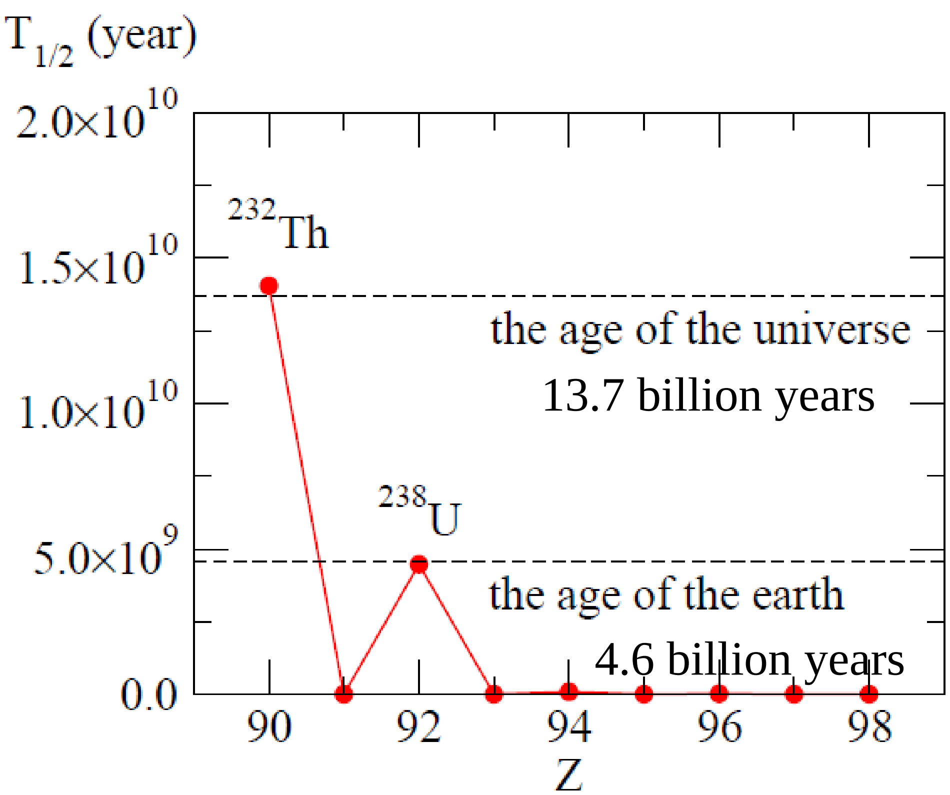
unstable against α decay

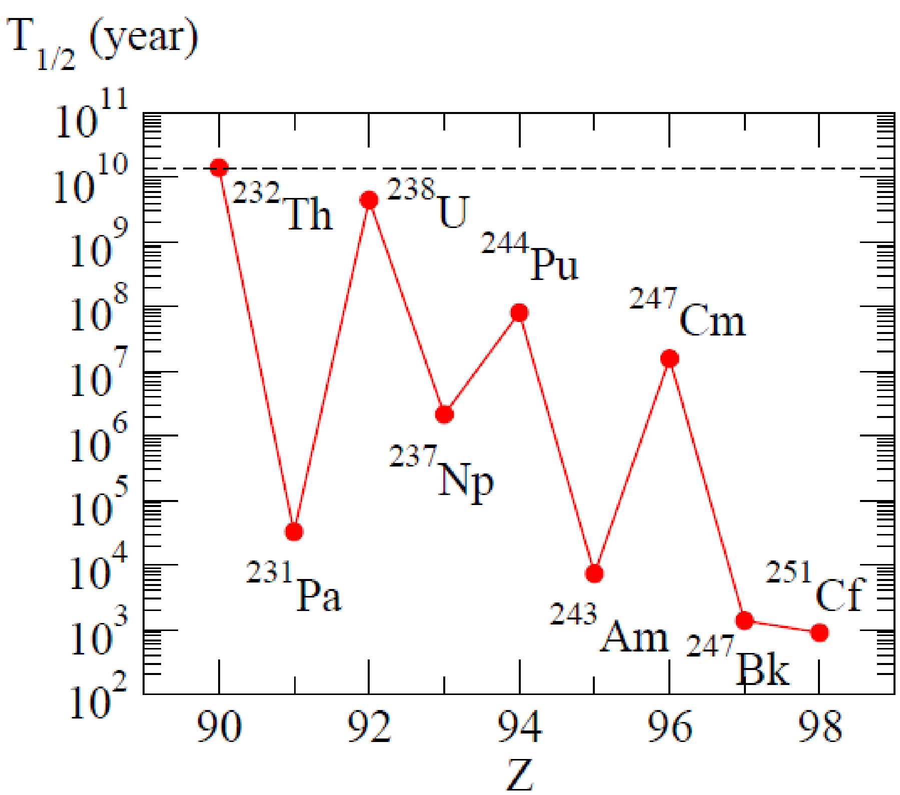




(Z,N) (Z-2,N-2) (Z=2,N=2)

Decay half-lives of heavy nuclei





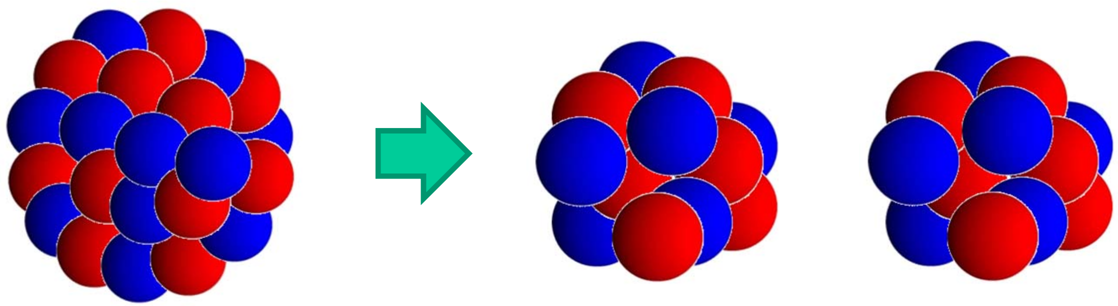
^{232}Th 1.405 x 10^{10} years

^{238}U 4.468 x 10^{9} years

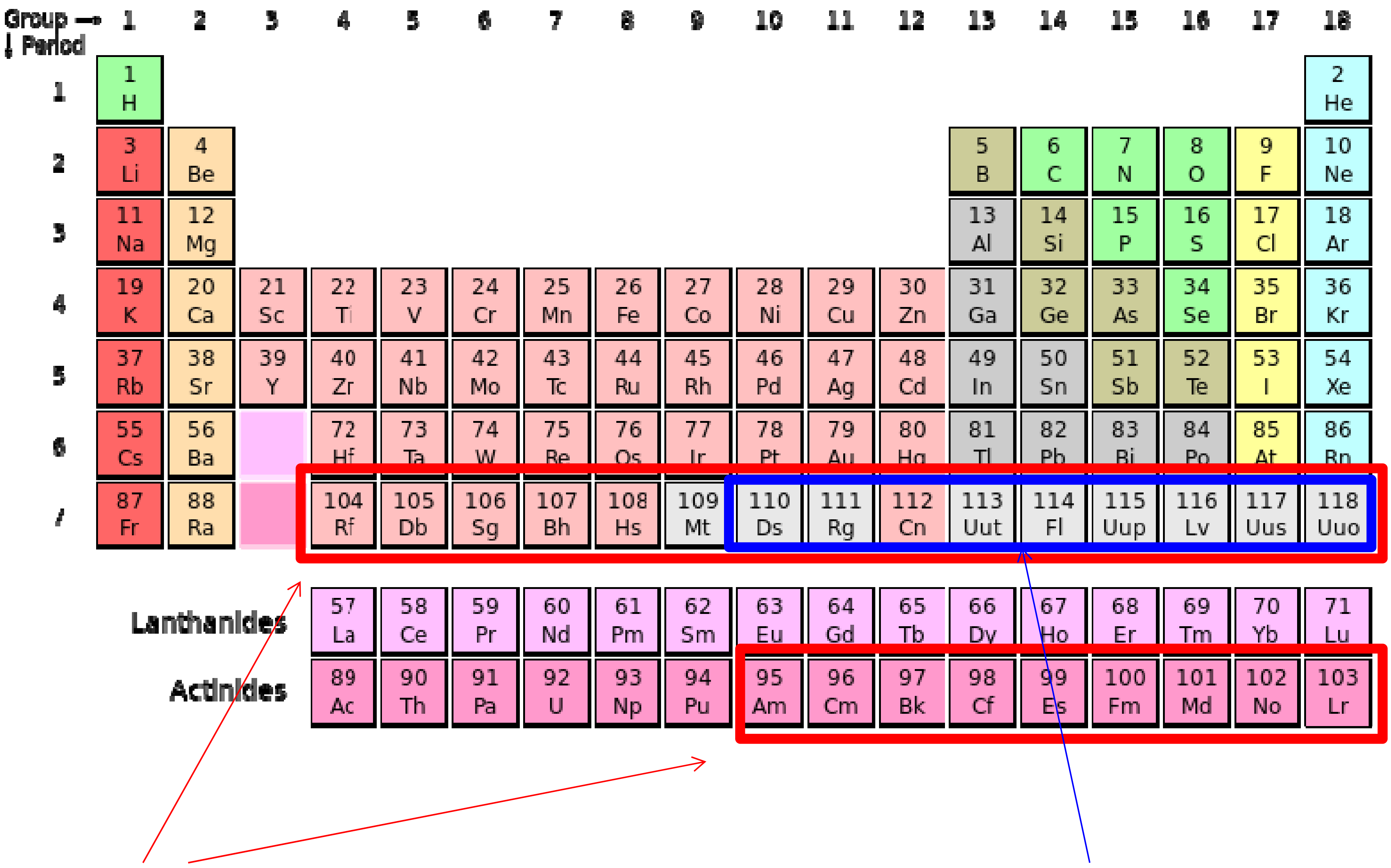
^{244}Pu 8.08 x 10^{7} years

^{247}Cm 1.56 x 10^{7} years

Heavier nuclei: unstable against fission



Periodic table of chemical elements

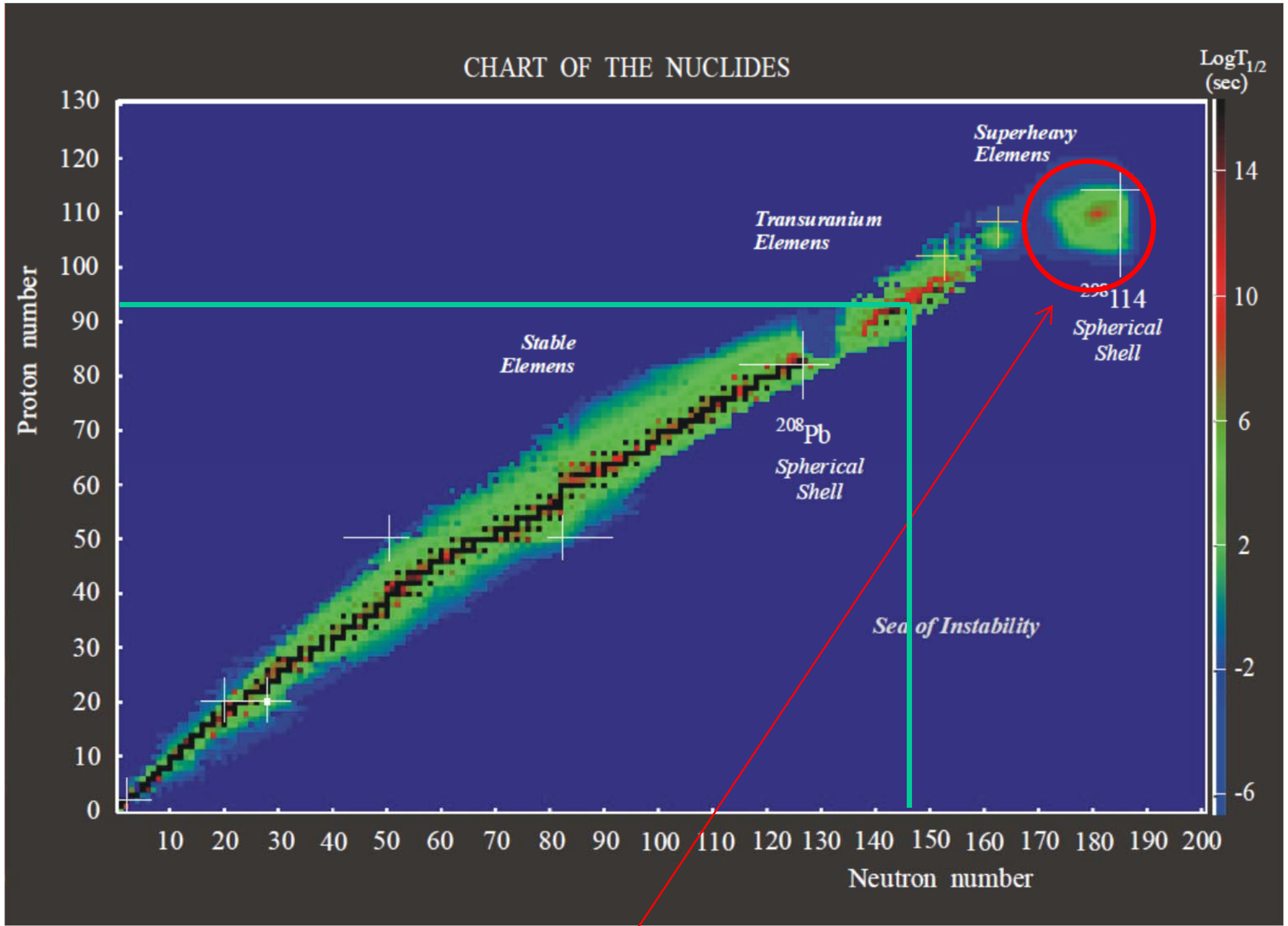


artificially synthesized (‘man-made’)

superheavy elements (SHE)

⟵ nuclear reactions

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



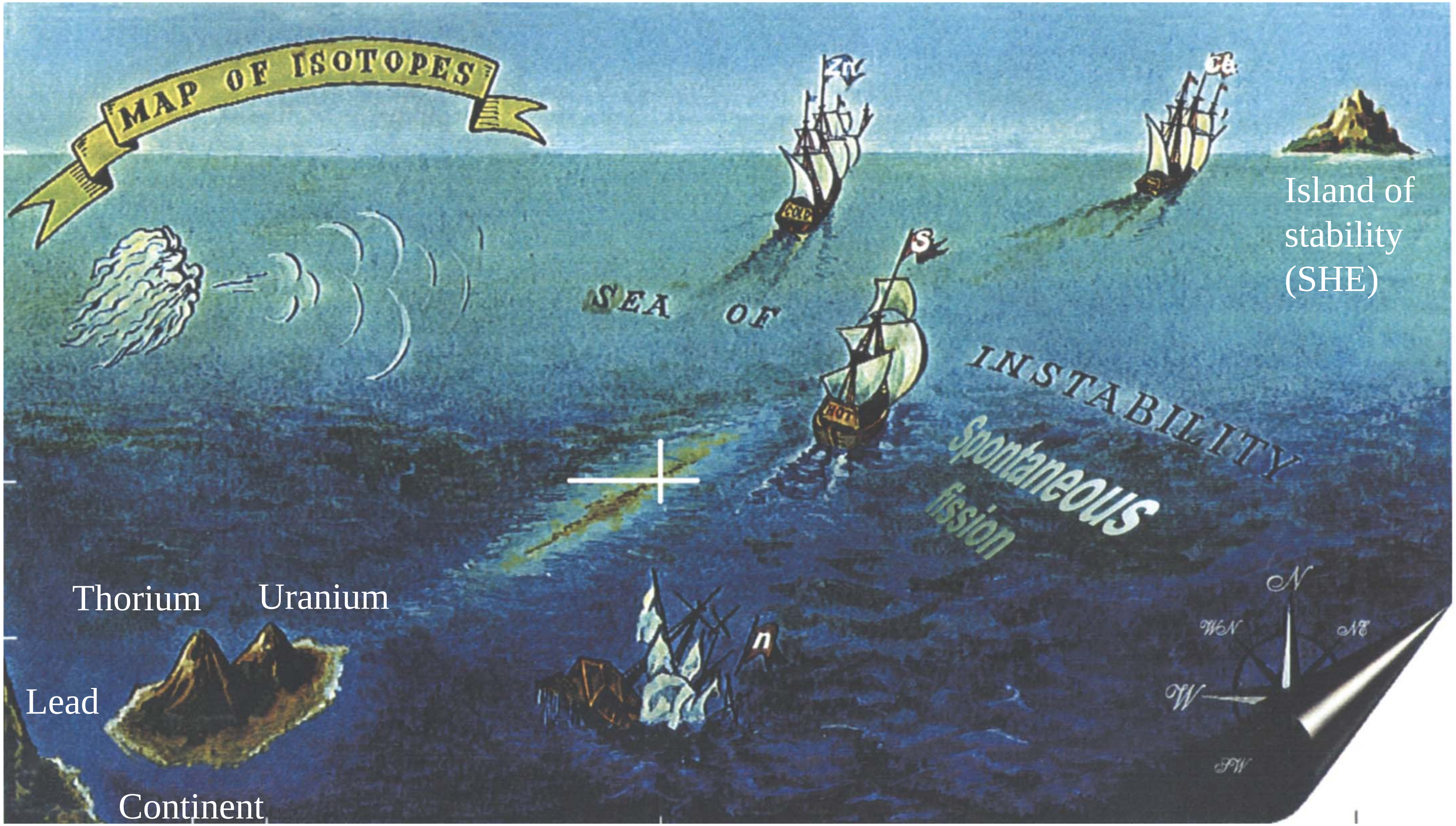
Yuri Oganessian

island of stability around Z=114, N=184

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

→ modern calculations: Z=114,120, or 126, N=184

e.g., H. Koura et al. (2005)

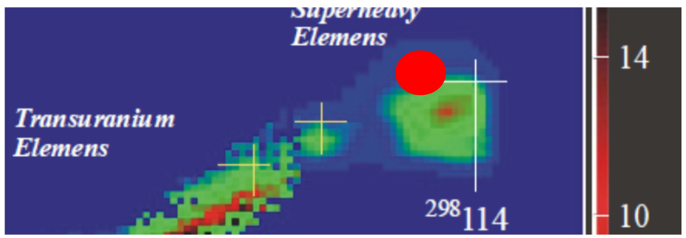


Yuri Oganessian

who is she?

Z=110	Darmstadtium (Ds)	1994 Germany
Z=111	Roentgenium (Rg)	1994 Germany
Z=112	Copernicium (Cn)	1996 Germany
Z=113	No name yet	2003 Russia / 2004 Japan
Z=114	Flerovium (Fl)	1999 Russia (*)
Z=115	No name yet	2003 Russia
Z=116	Livermoriun (Lv)	2000 Russia
Z=117	No name yet	2010 Russia
Z=118	No name yet	2002 Russia

(*)



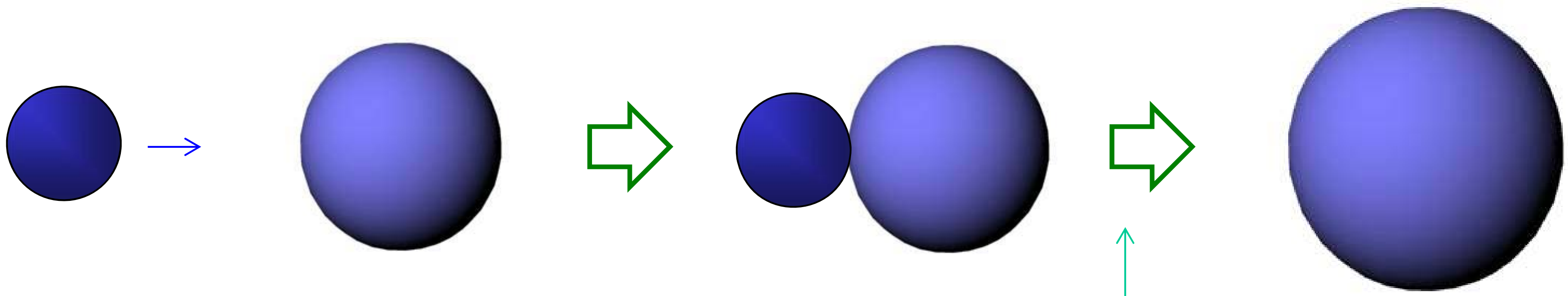
island of stability: Z=114, N=184

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

⟶ island not yet confirmed

How to synthesize SHE?

Nuclear fusion reactions

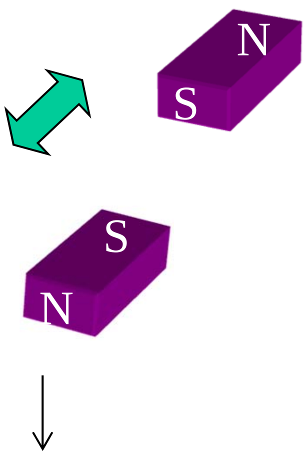


two positive charges
repel each other

nuclear *attractive*
intraction

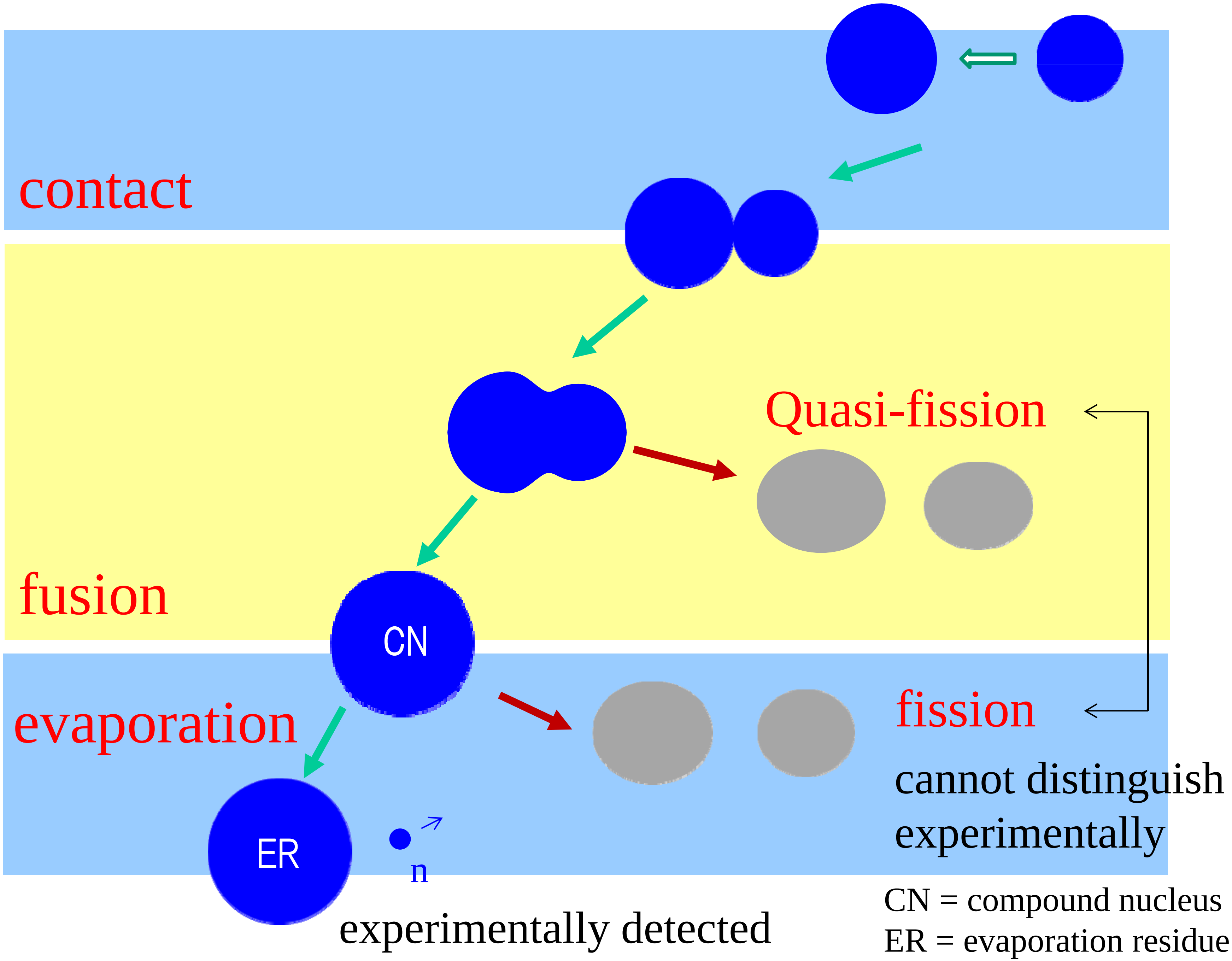
compound
nucleus

cf.

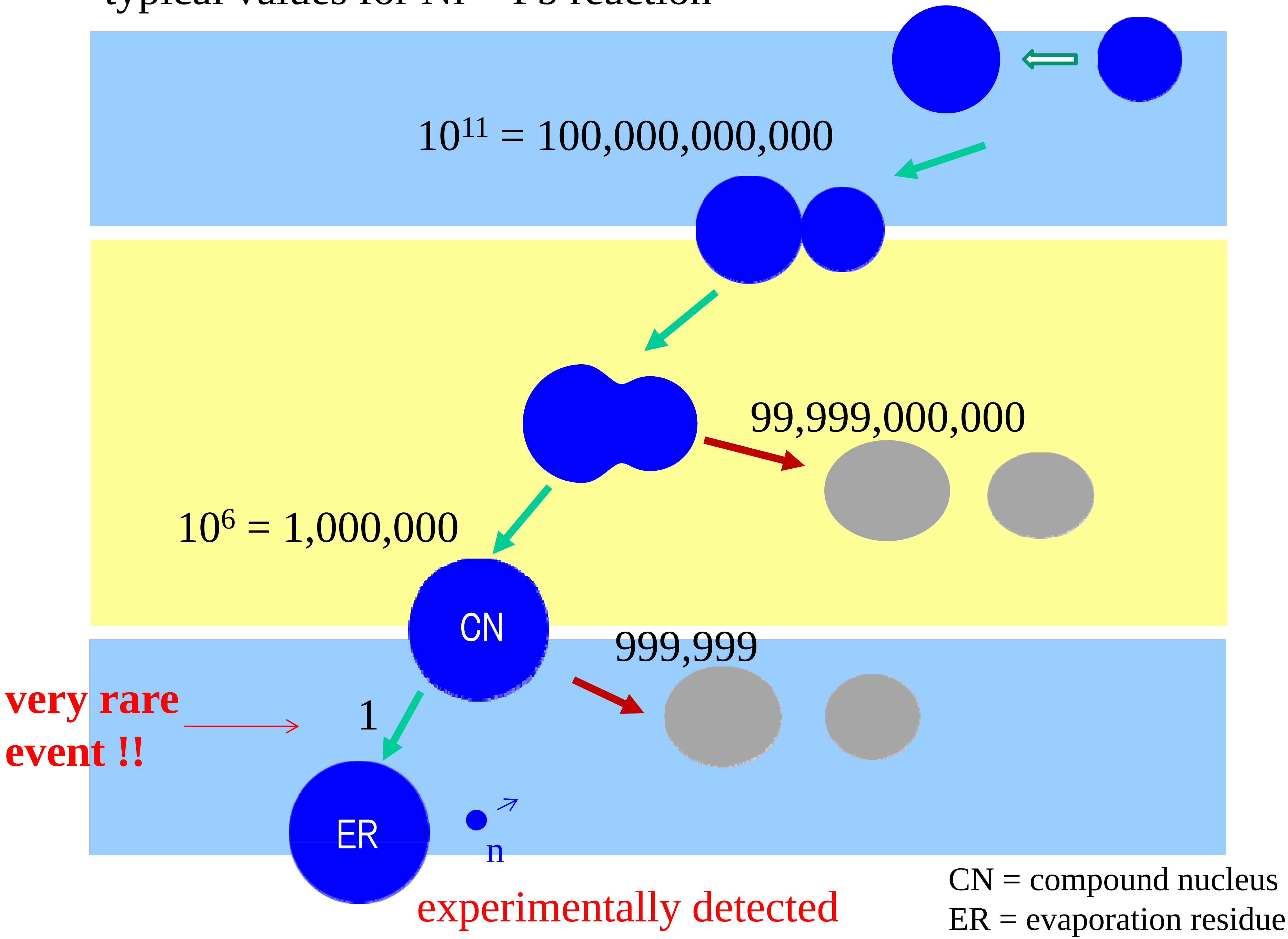


accelerate a projectile
nucleus to overcome the barrier

e.g.,
$^{70}Zn + ^{209}Bi \longrightarrow ^{279}113$

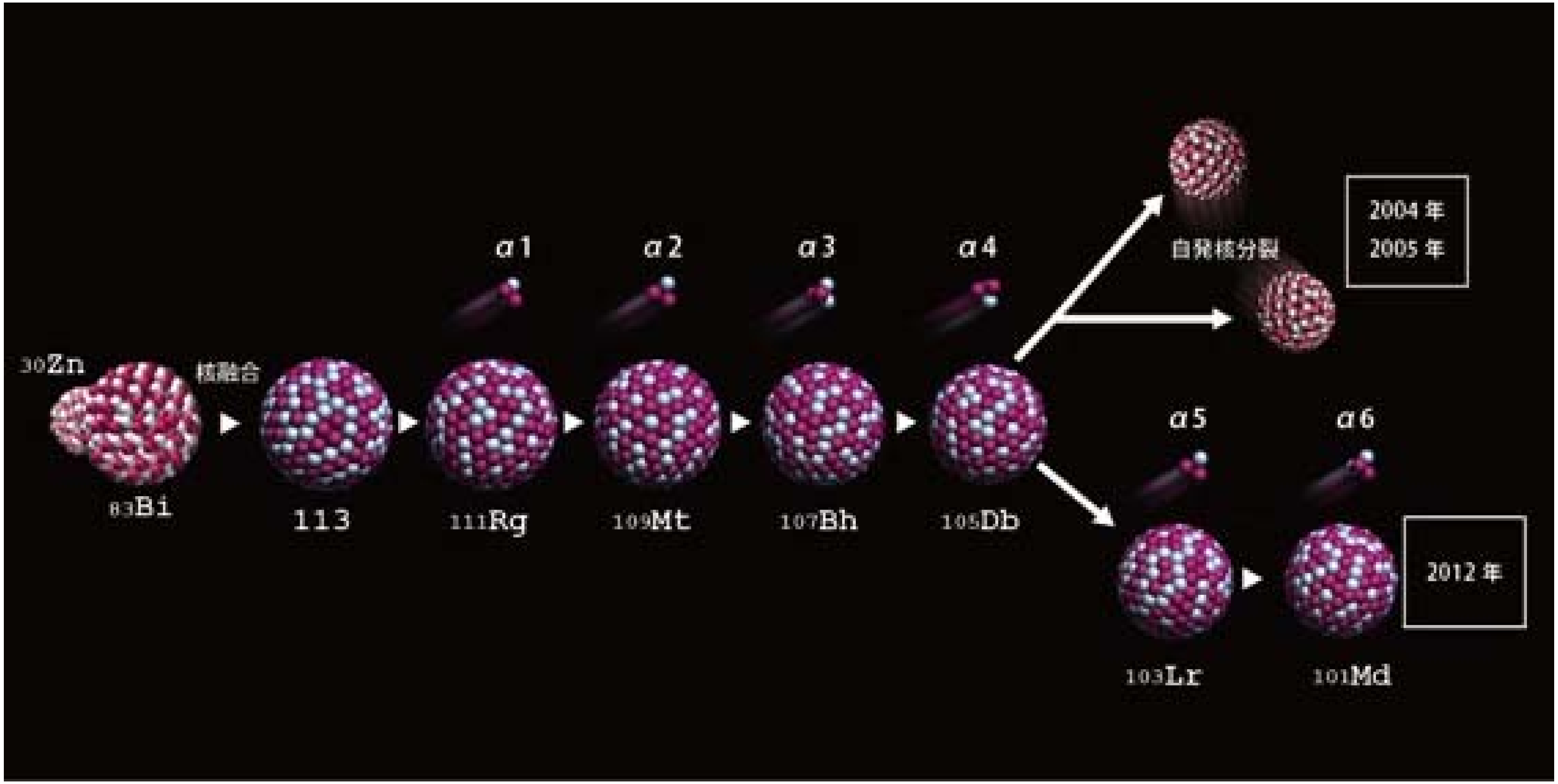

contact
Quasi-fission
fusion
CN
evaporation
fission
cannot distinguish experimentally
ER
n
experimentally detected
CN = compound nucleus
ER = evaporation residue

typical values for Ni + Pb reaction



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

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

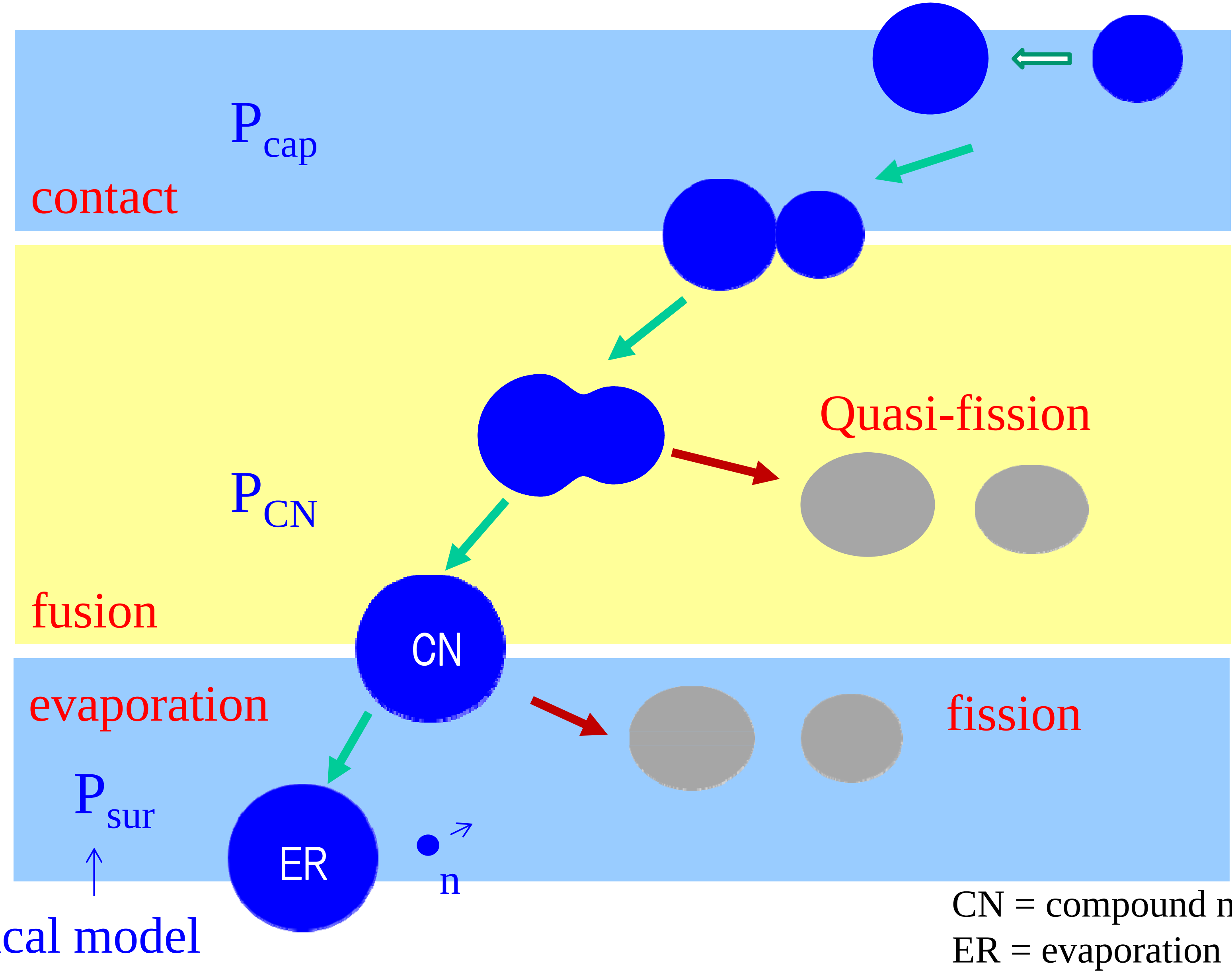


K. Morita et al., J. Phys. Soc. Jpn. 81(‘12)103201

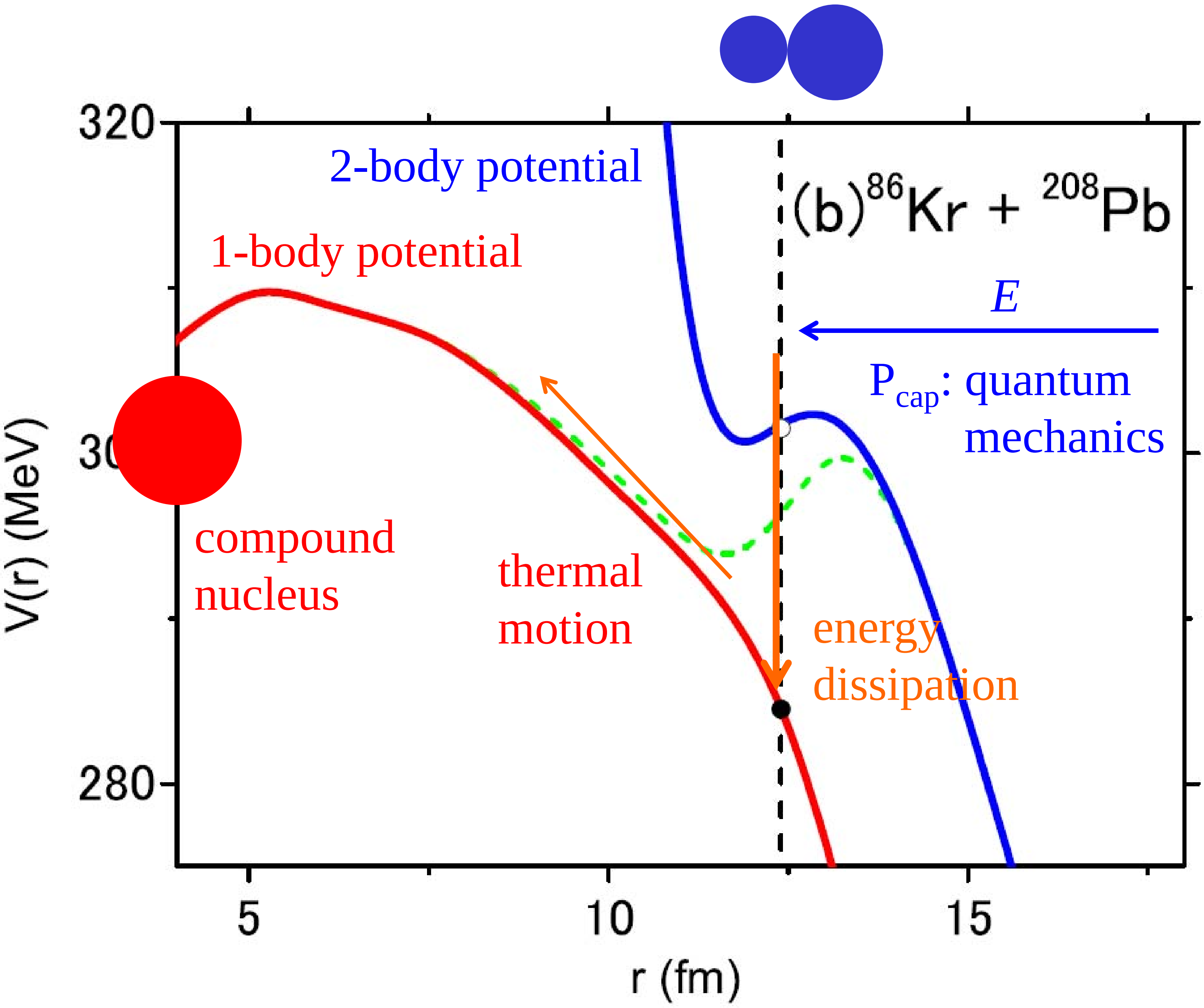
only 3 events for 553 days experiment

Theoretical treatment

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

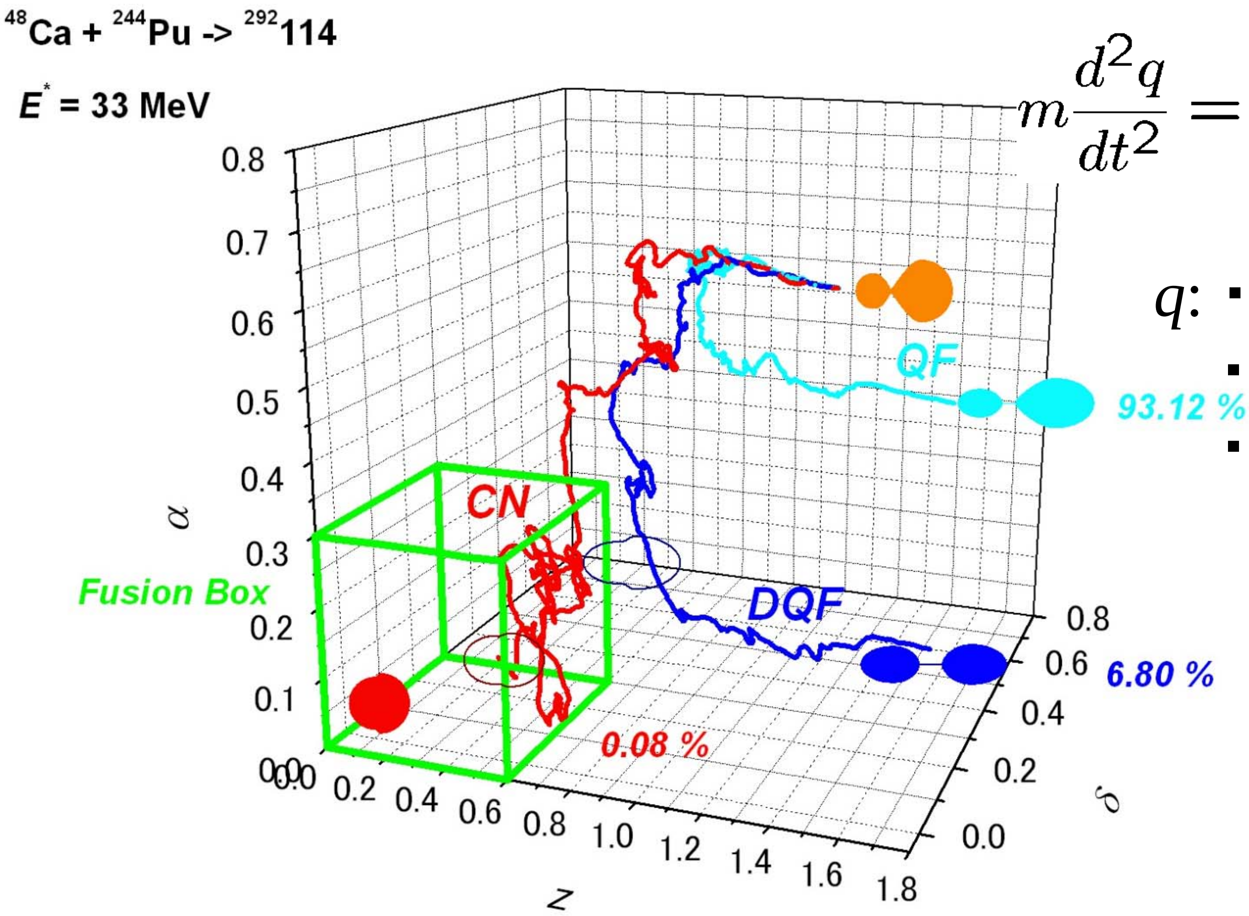


CN = compound nucleus
ER = evaporation residue



2-body potential
(b) 86Kr + 208Pb
1-body potential
E
Pcap: quantum mechanics
compound nucleus
thermal motion
energy dissipation
320
280
V(r) (MeV)
5
10
15
r (fm)

Theory: Lagenvin approach



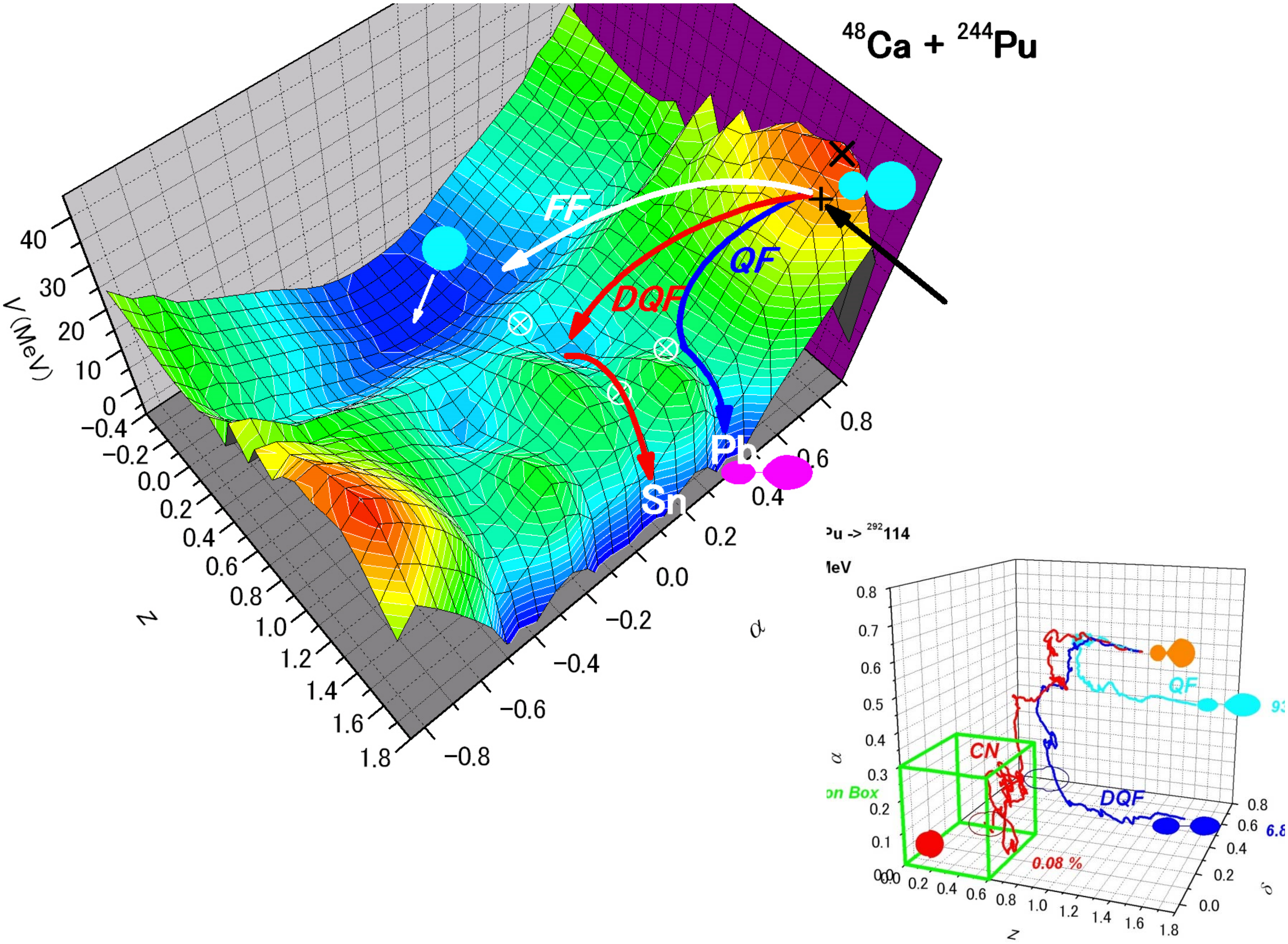
multi-dimensional extension of:

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

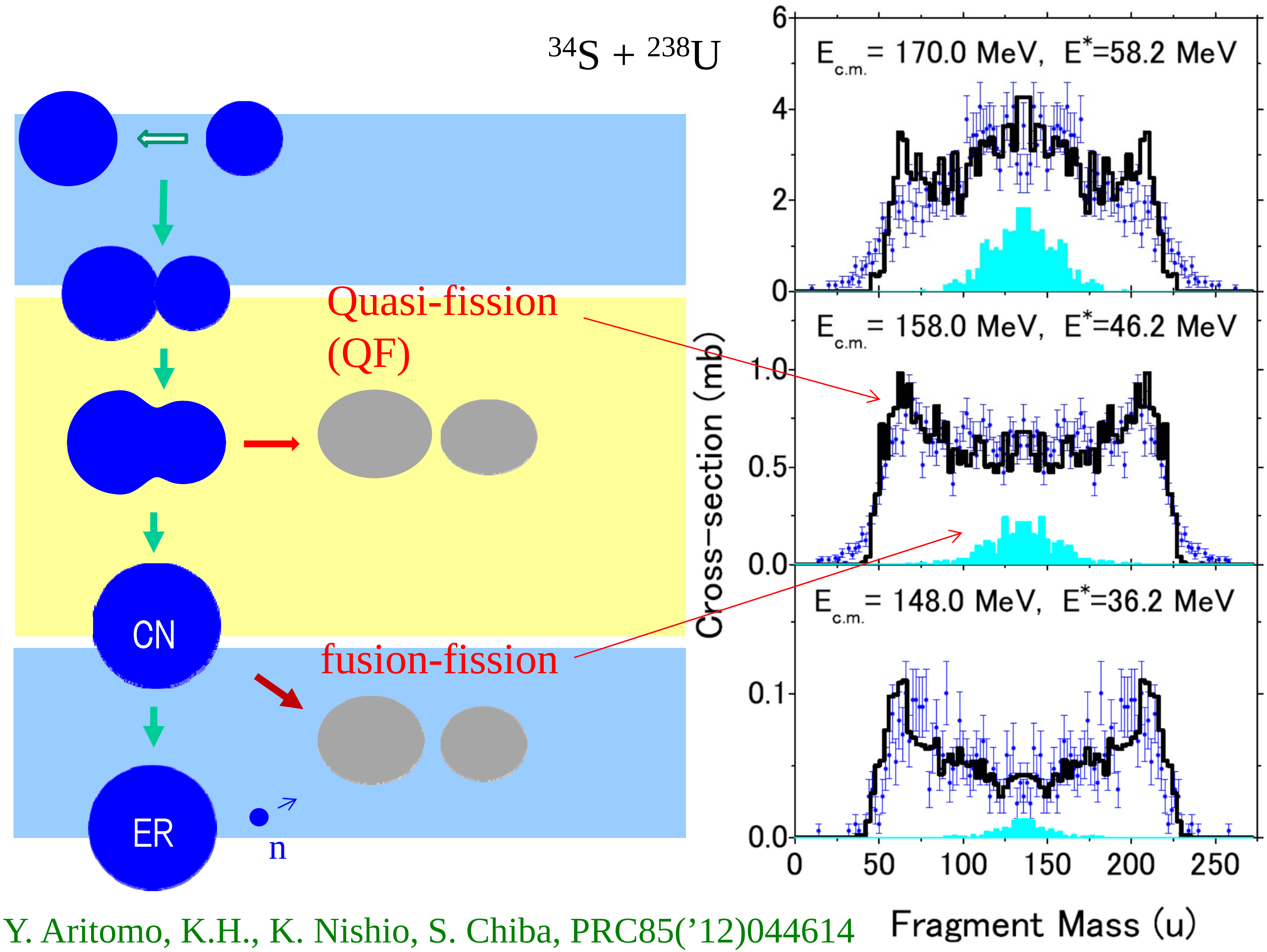
q:
- internuclear separation,
- deformation,
- asymmetry of the two fragments

γ: friction coefficient

R(*t*): random force



$^{48}Ca + ^{244}Pu$
FF
QF
DQF
Pb
Sn
V (MeV)
z
α
CN
QF
DQF
0.08 %
δ



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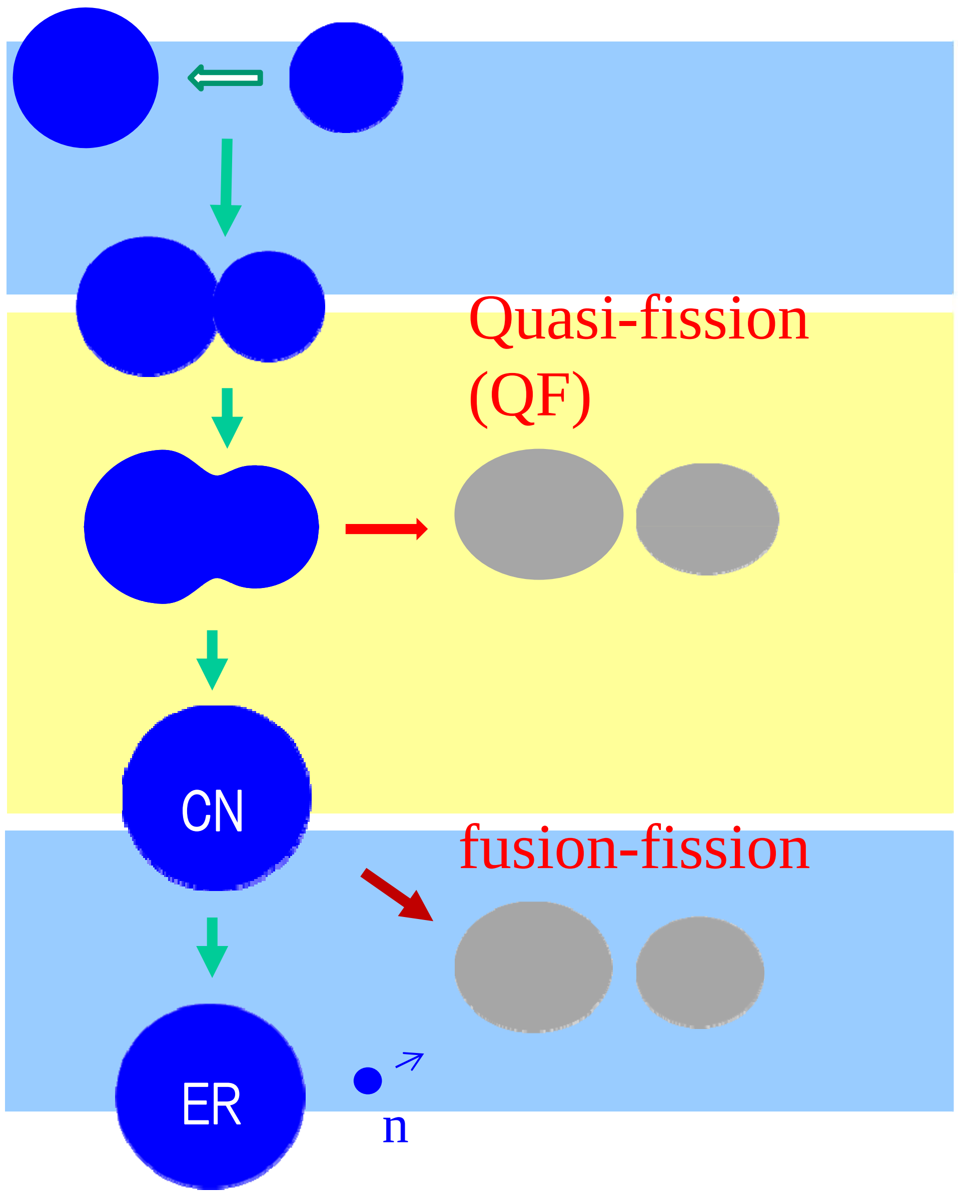
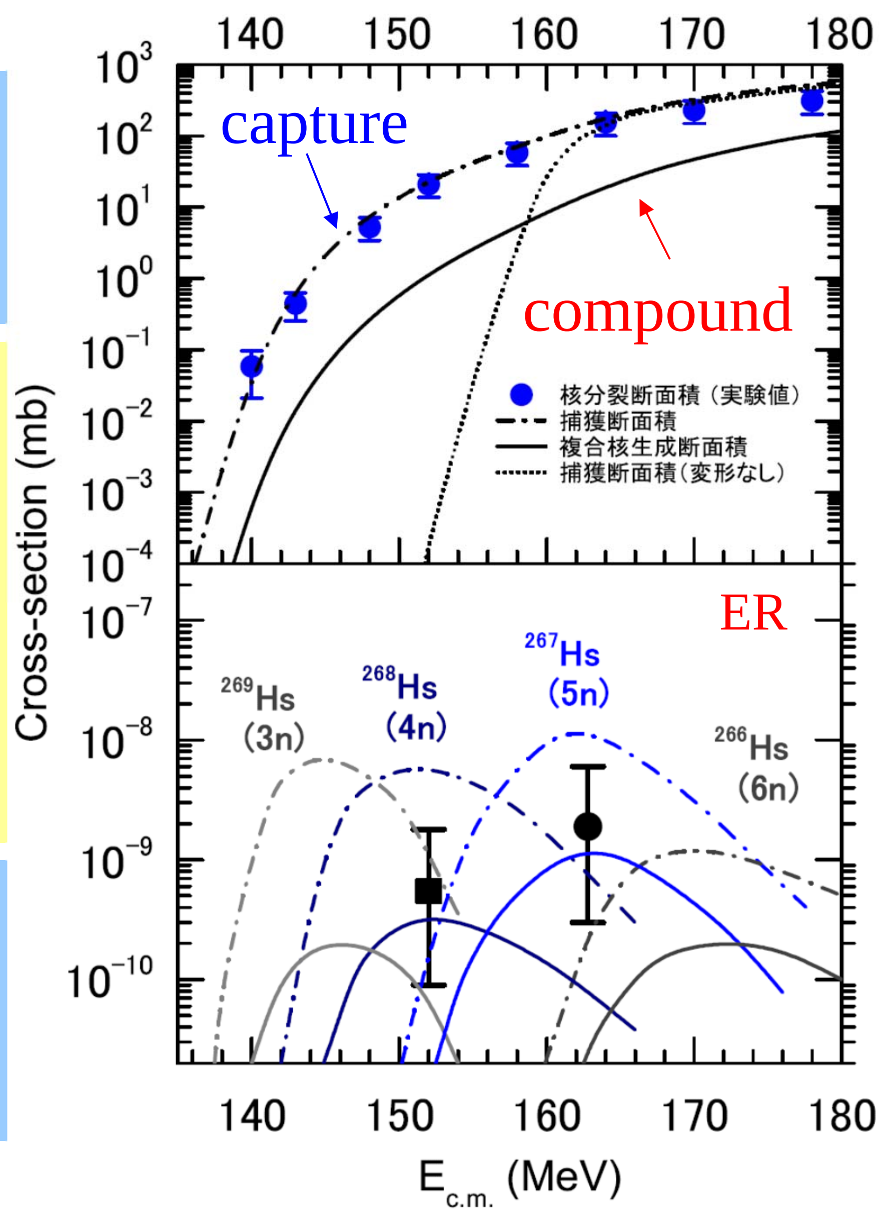


$^{34}S + ^{238}U$



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Element 113

- Dubuna

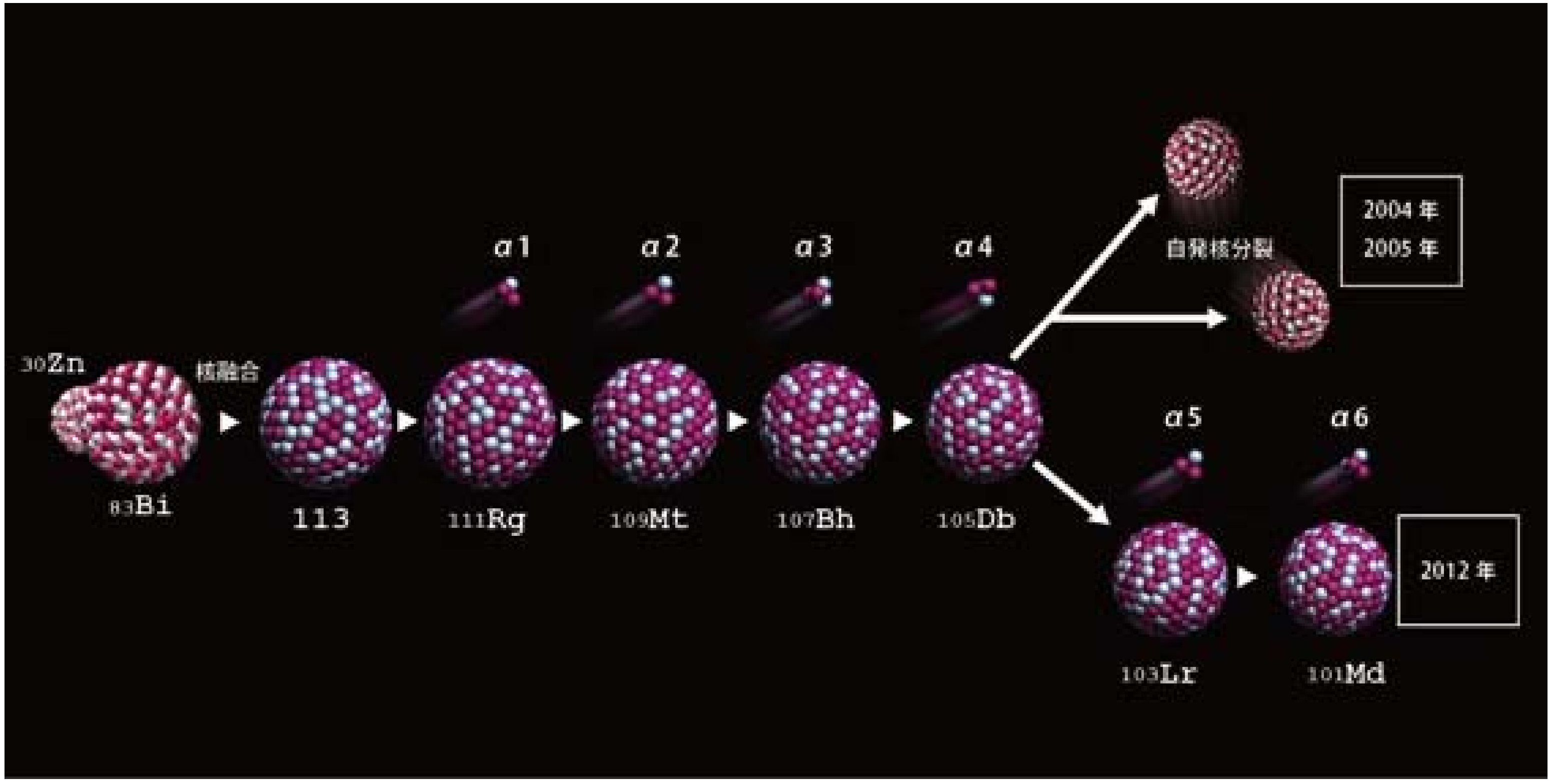
  $^{48}\mathrm{Ca} + {}^{243}\mathrm{Am} \rightarrow {}^{288}115 + 3n \rightarrow {}^{284}113 + \alpha$ (2003)

  $^{48}\mathrm{Ca} + {}^{249}\mathrm{Bk} \rightarrow {}^{293}117 + 4n \rightarrow {}^{189}115 + \alpha \rightarrow {}^{285}113 + \alpha$ (2010)

  etc. Hot Fusion: ^{48}Ca projectile

- RIKEN

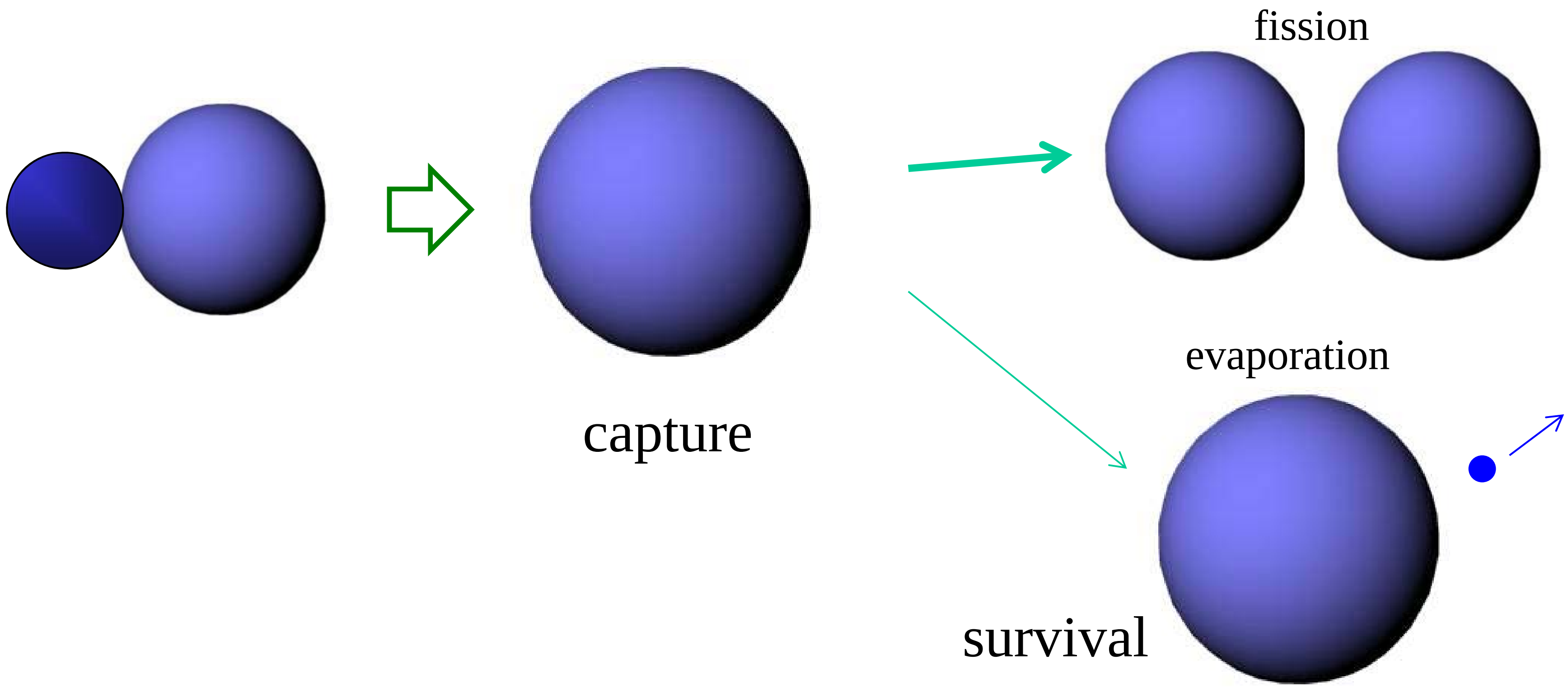
  $^{70}\mathrm{Zn} + {}^{209}\mathrm{Bi} \rightarrow {}^{278}113 + n$ (2004) Cold Fusion: ^{208}Pb or ^{209}Bi target



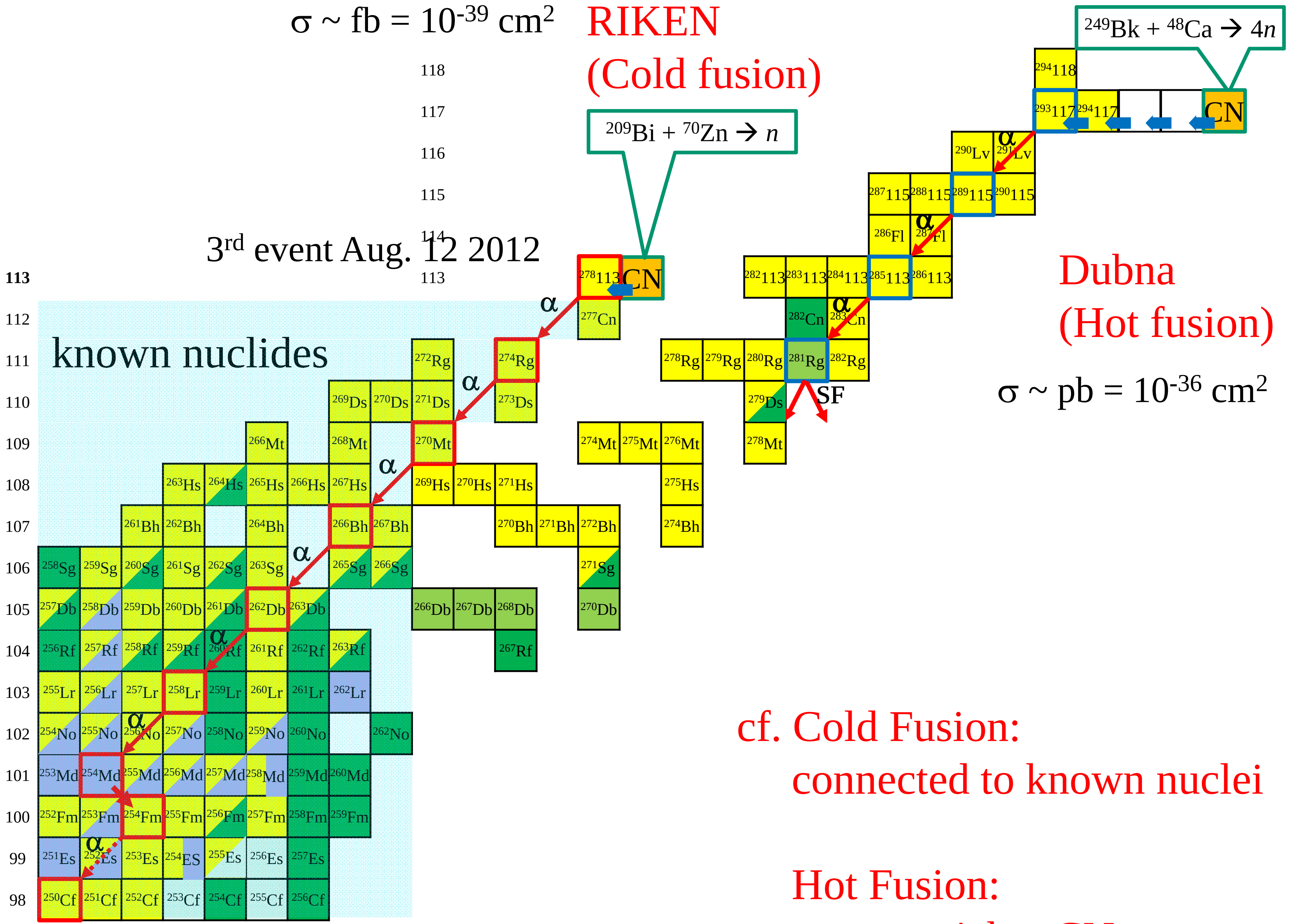
Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia

about 120 km north of Moscow

$_{105}$Db (Dubnium)



	Hot Fusion	Cold Fusion
Example	$^{48}Ca + ^{243}Am \rightarrow 4n$	$^{70}Zn + ^{209}Bi \rightarrow 1n$
asymmetry	large	small
Capture	large	small
Survival	small	large



cf. Cold Fusion:
connected to known nuclei

Hot Fusion:
neutron-richer CN

Naming rights?

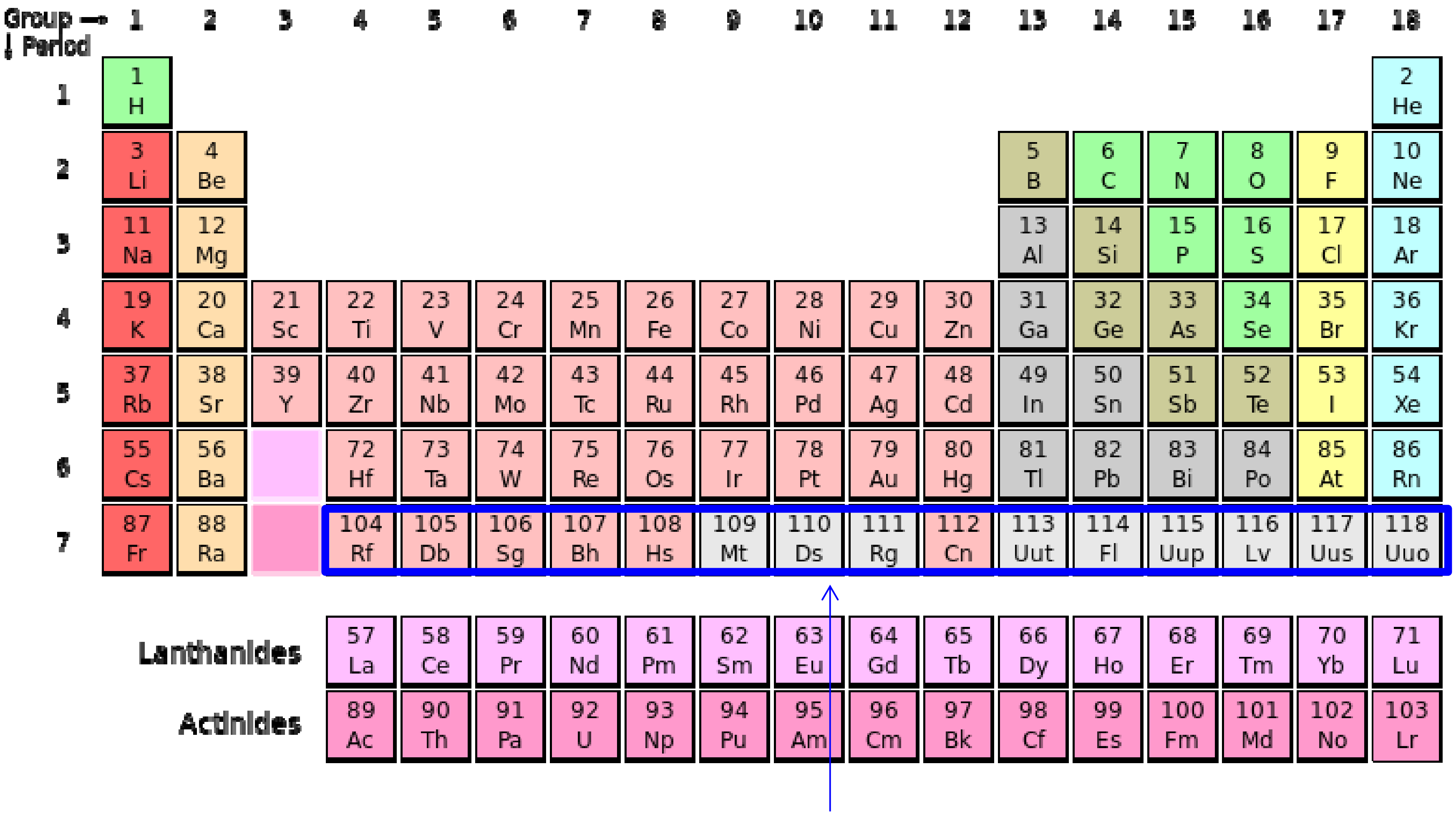
Under discussions in the joint IUPAC/IUPAP Joint Working Party

IUPAC = International Union of Pure and Applied Chemistry
IUPAP = International Union of Pure and Applied Physics

- RIKEN (Japan)
  much less ambiguity with cold fusion

- Dubna (Russia)
  much larger number of events

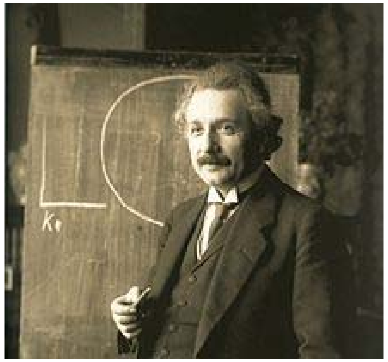
Chemistry of superheavy elements



- Are they here in the periodic table?
- That is, does e.g., Lv show the same chemical properties as O, S, Se, Te, and Po?

relativistic effect : important for large Z

$E = mc^2$



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

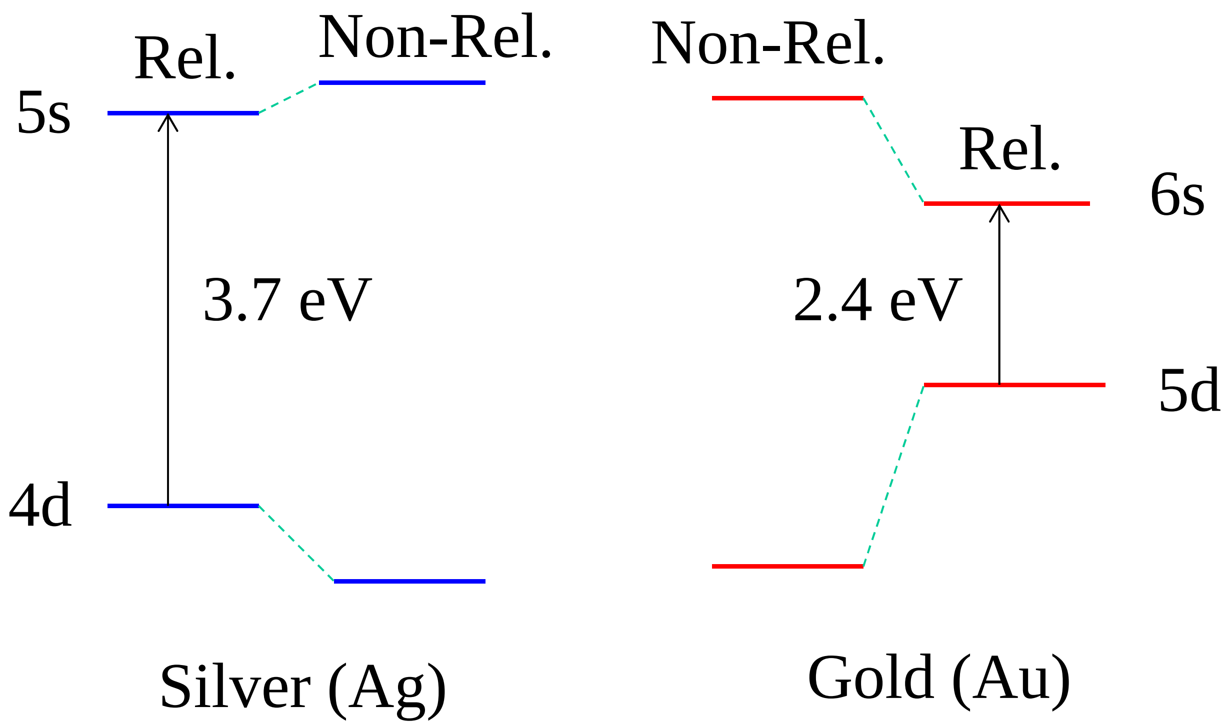
$$E_{1S} = mc^2\sqrt{1-(Z\alpha)^2} \sim mc^2\left(1 - \frac{(Z\alpha)^2}{2} \underbrace{- \frac{(Z\alpha)^4}{8} + \cdots}\right)$$

relativistic effect

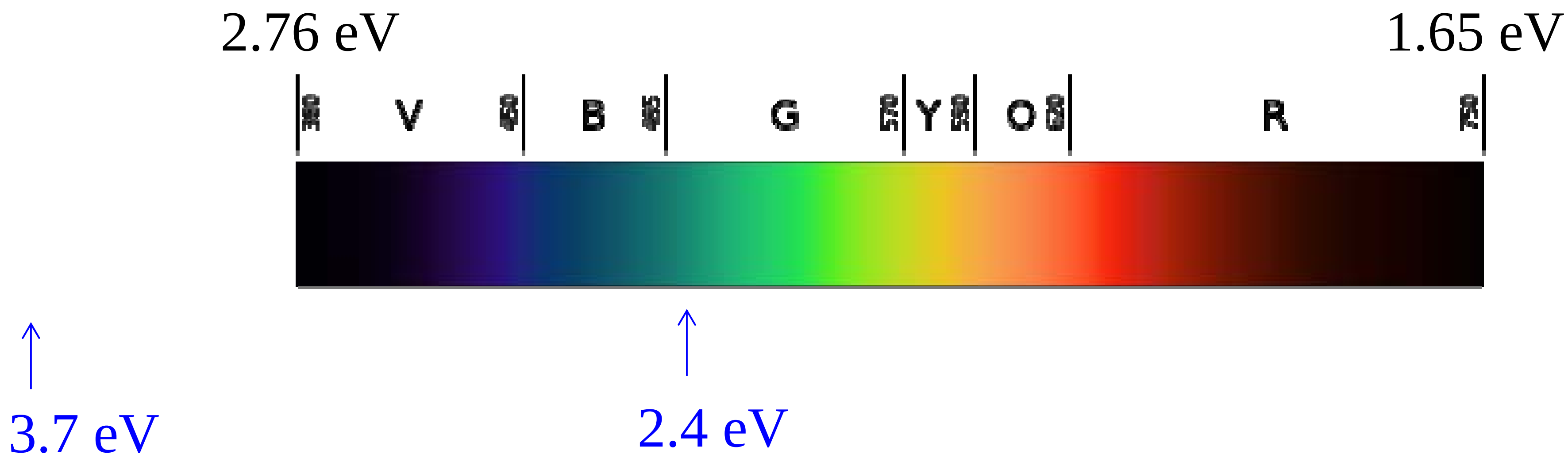
Famous example of relativistic effects: the color of gold

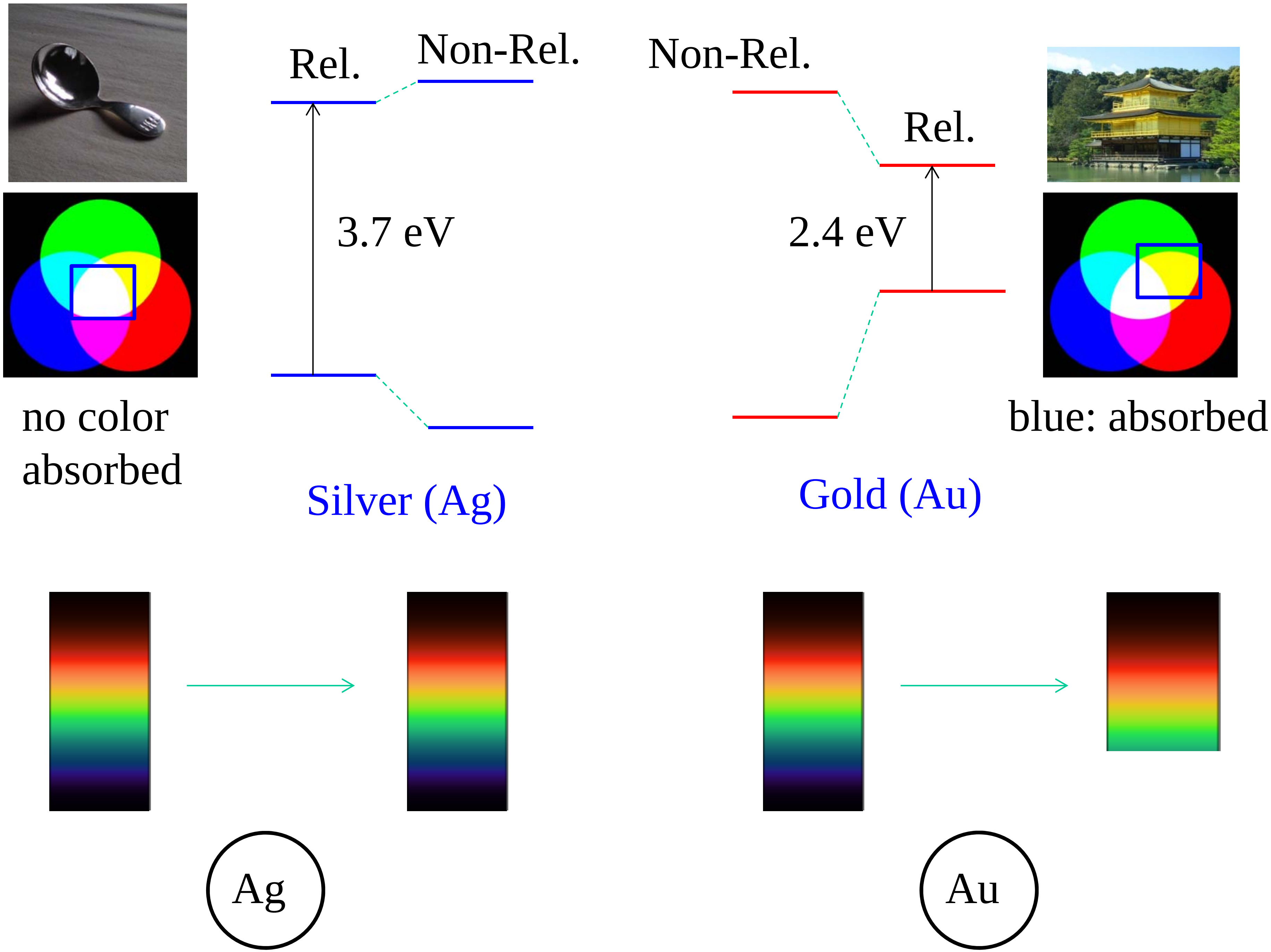
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	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!

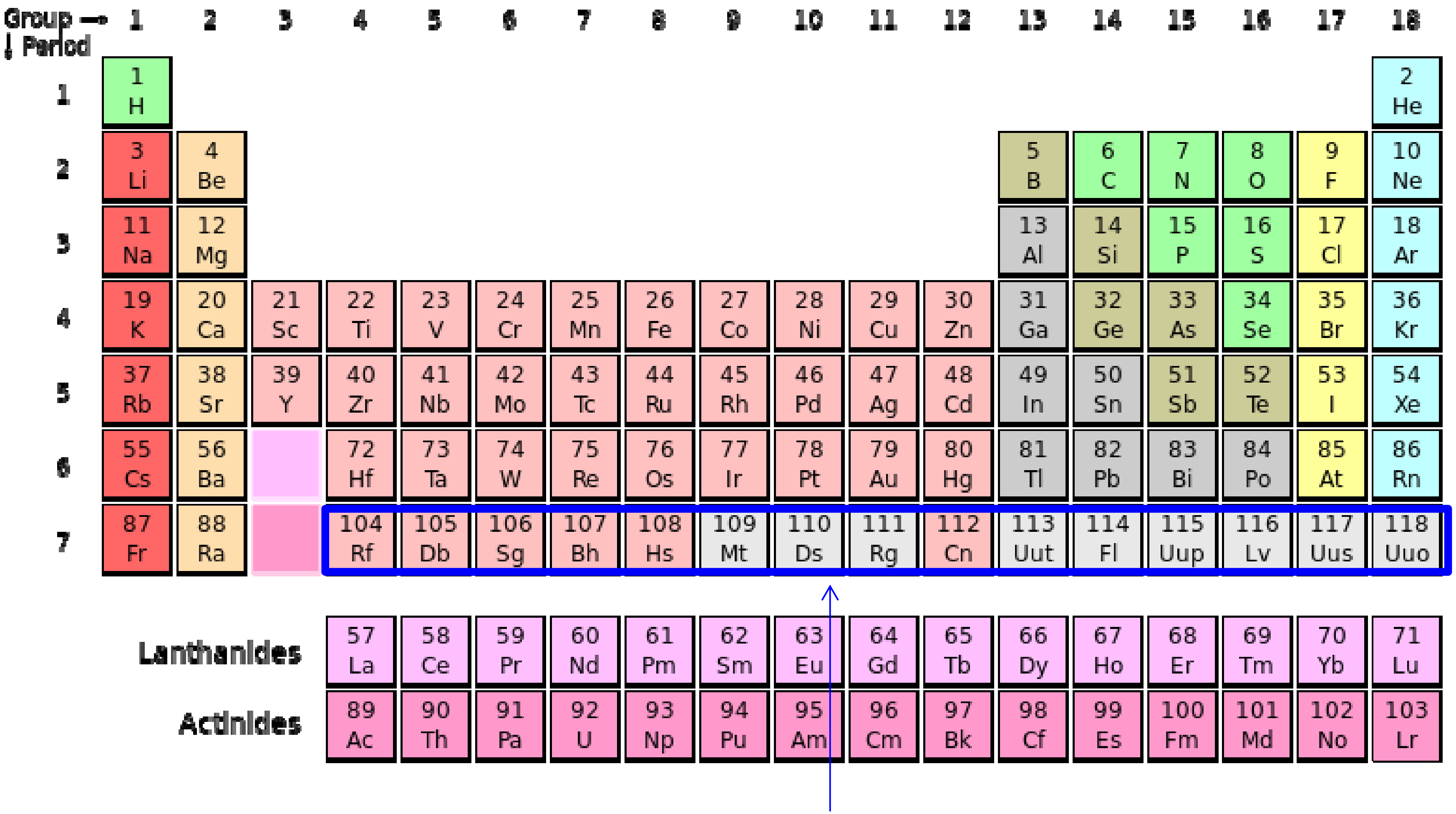


cf. visible spectrum




Rel.
Non-Rel.
3.7 eV
no color
absorbed
Silver (Ag)
Non-Rel.
Rel.
2.4 eV
blue: absorbed
Gold (Au)
Ag
Au

Chemistry of superheavy elements



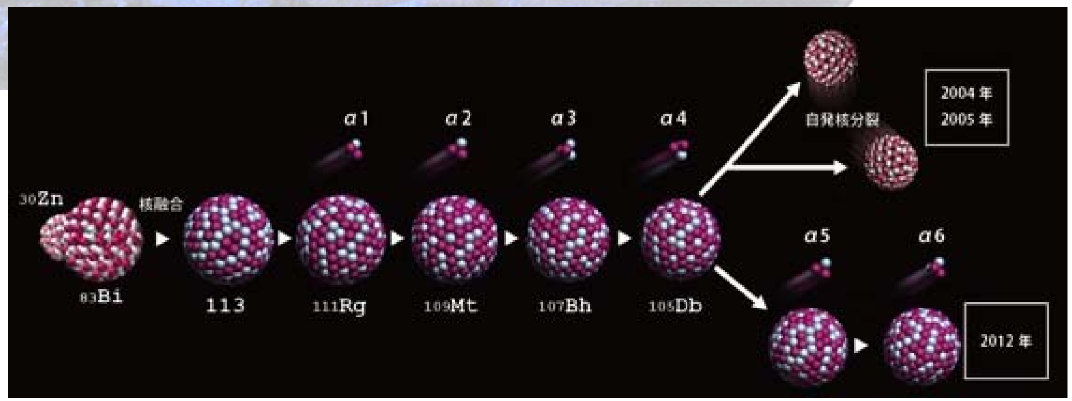
How do the relativistic effects alter the periodic table for SHE?

⟶ a big open question

<u>Summary</u>

- **All things are made from atoms.**

- **The heaviest natural elements are U/Pu.**
- **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 naming rights for Z=113: RIKEN or Dubna?**
- **Chemistry of SHE: relativistic effects?**



Homework

- Deadline: Wednesday, Nov. 13, 2013
- Submit the homework inside an envelope at #1047 (10th floor, Hagino's office) in the Science Complex B building
  or send it by e-mail to hagino@nucl.phys.tohoku.ac.jp.

1. Explain why it is so difficult to synthesize a superheavy element.
2. Write what you thought about the physics and chemistry of superheavy elements and/or your impression on this lecture.