Elements and Nuclear Physics 2
元素和核物理 2

Kouichi Hagino
Tohoku University, Sendai, Japan

TOHOKU UNIVERSITY

- How were elements created?
- Physics and chemistry of superheavy elements

Everything is made of atoms.




Group → 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period ↓																	
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		

How were elements created?

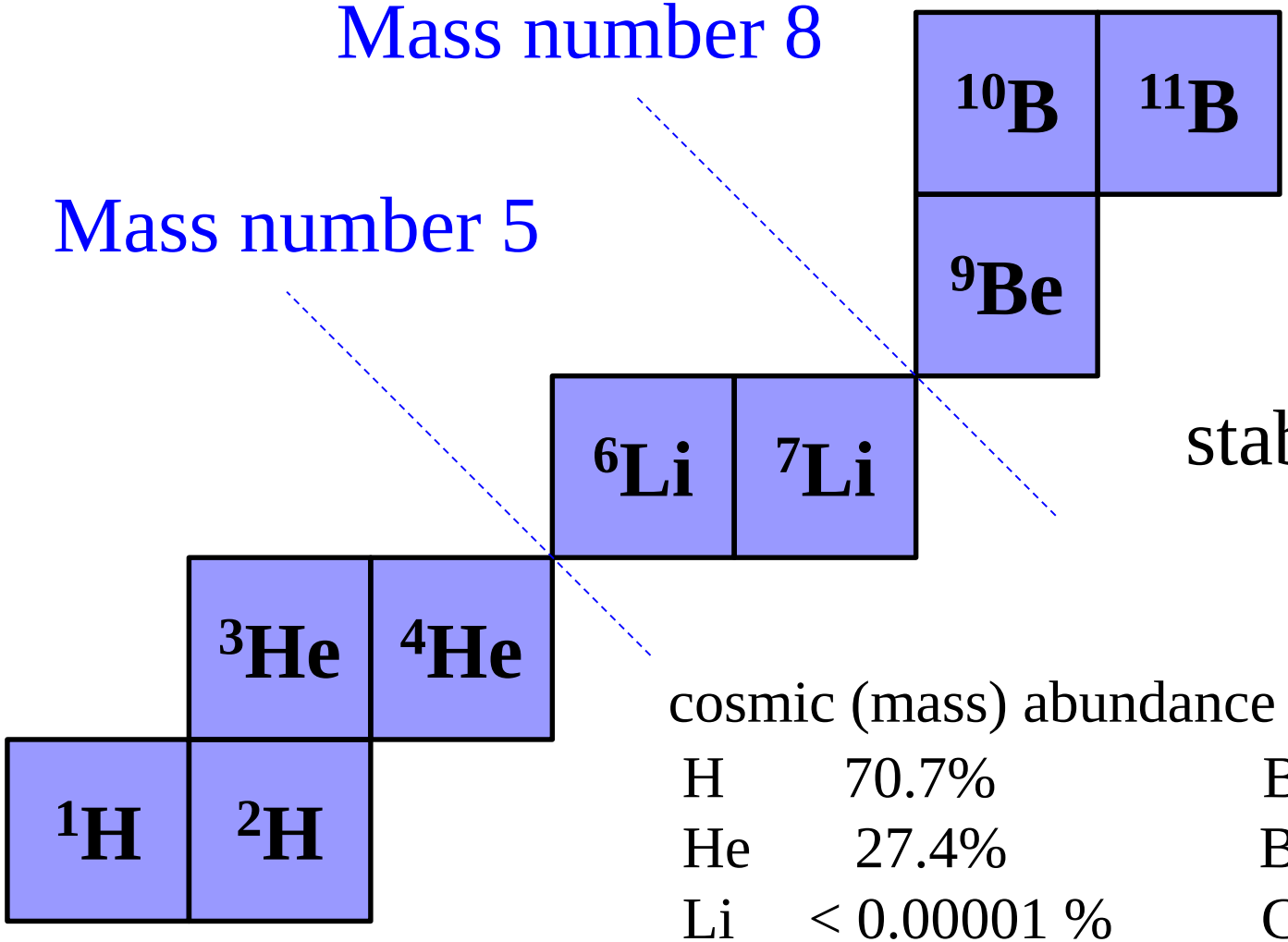
⟶ in the universe

Big bang
(13.8 billion years ago)

Li

the reason why only little amount of Li was created

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

more is different

these hydrongens were created 13.8 billion years ago!!

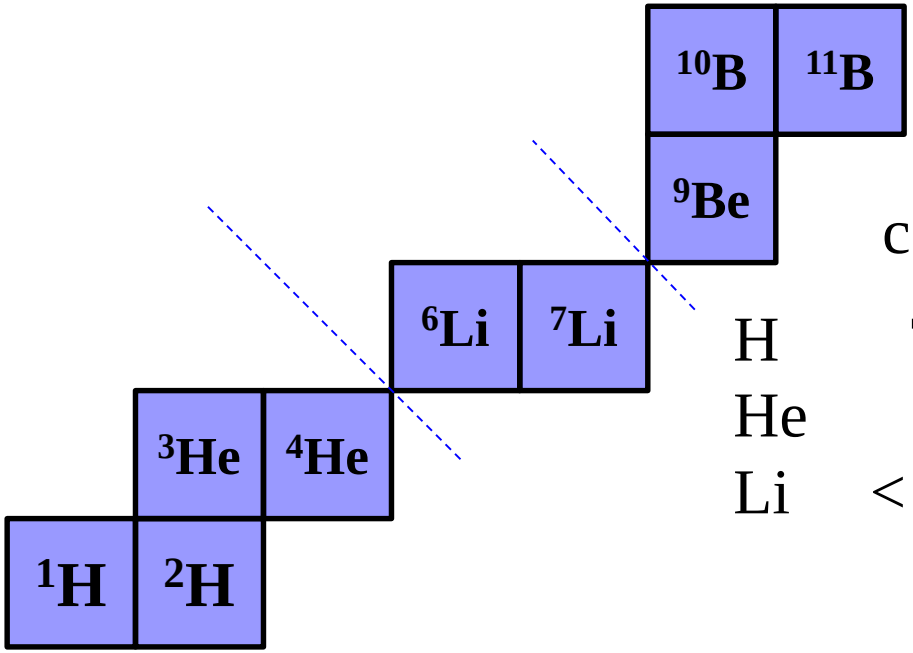
Big bang (13.8 billion years ago)

How were elements up to Fe created?

The origin of elements up to Fe

Nuclear fusion inside (massive) stars

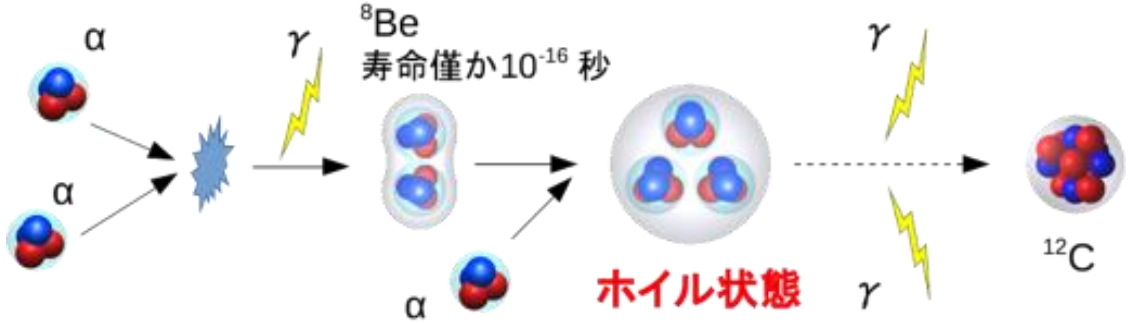
⟶ the reason why stars are shining



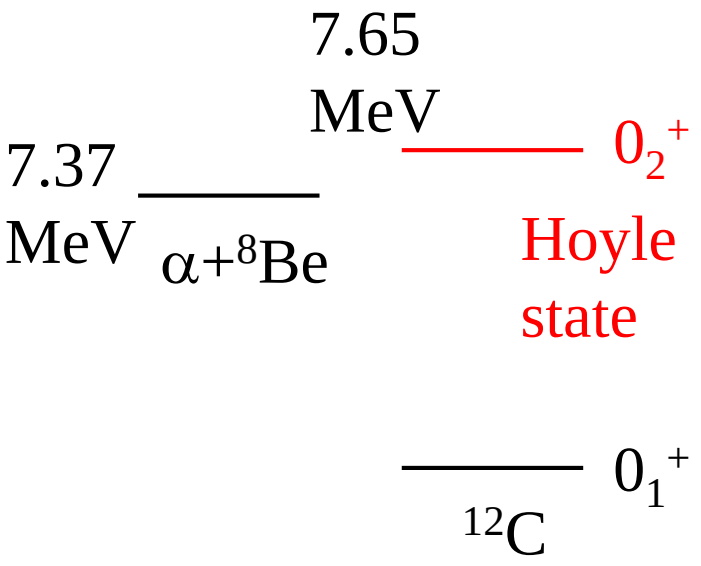
cosmic (mass) abundance of elements

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

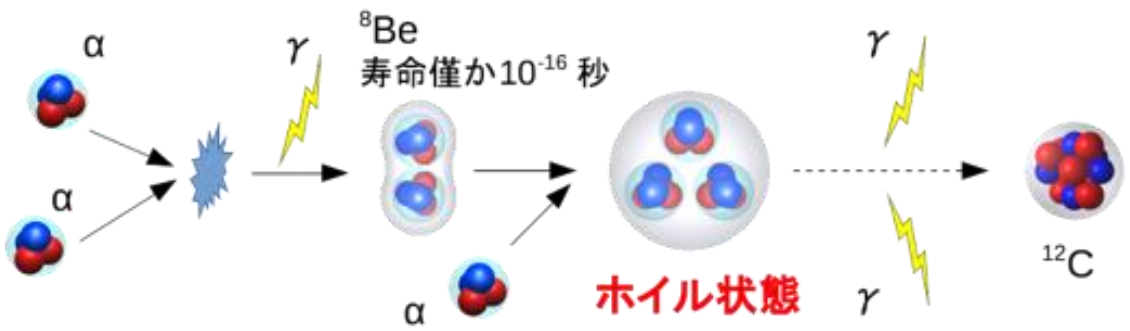
Triple alpha reactions

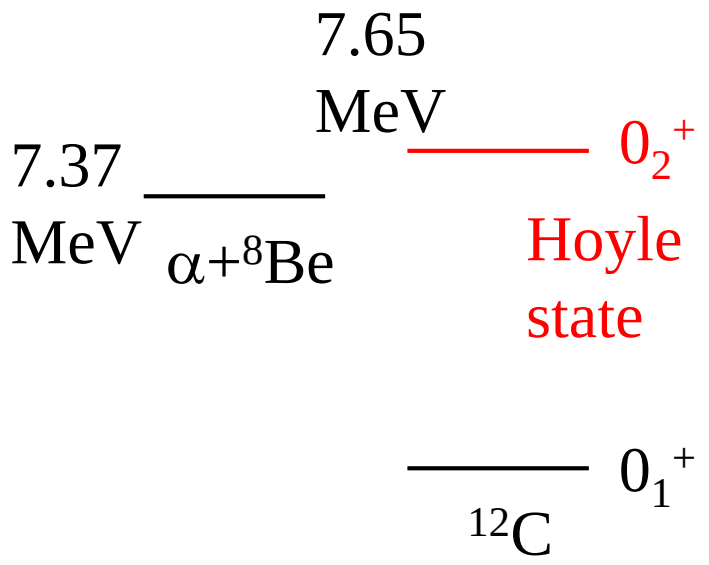


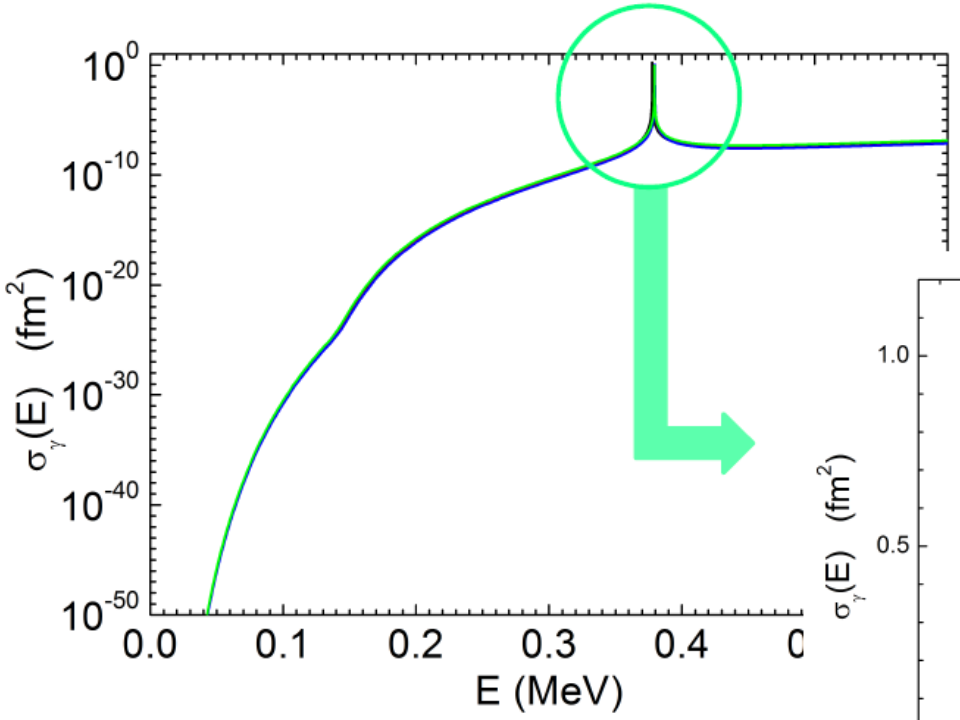
http://www.phys.tohoku.ac.jp/topics/topics-2052/



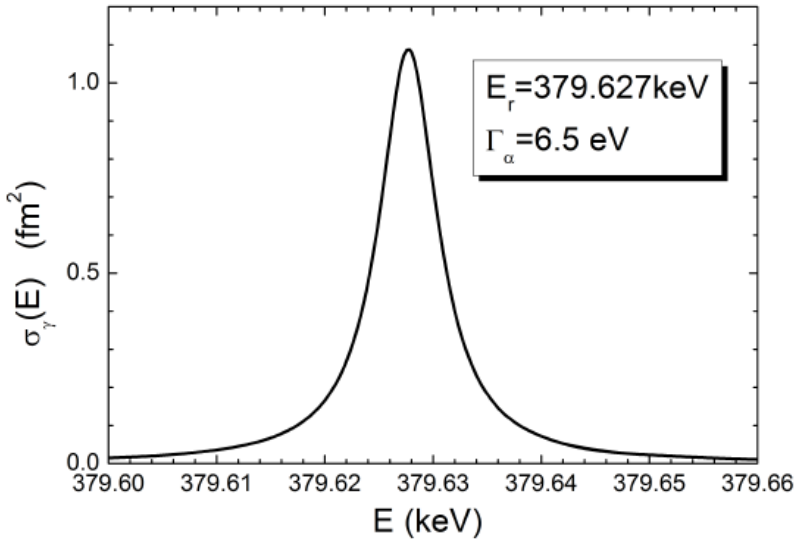
Triple alpha reaction







F. Hoyle: a prediction for a resonance state in ^{12}C (1952)



S. Ishikawa, PRC87 (‘13) 055804

Quantum Mechanics（量子力学）

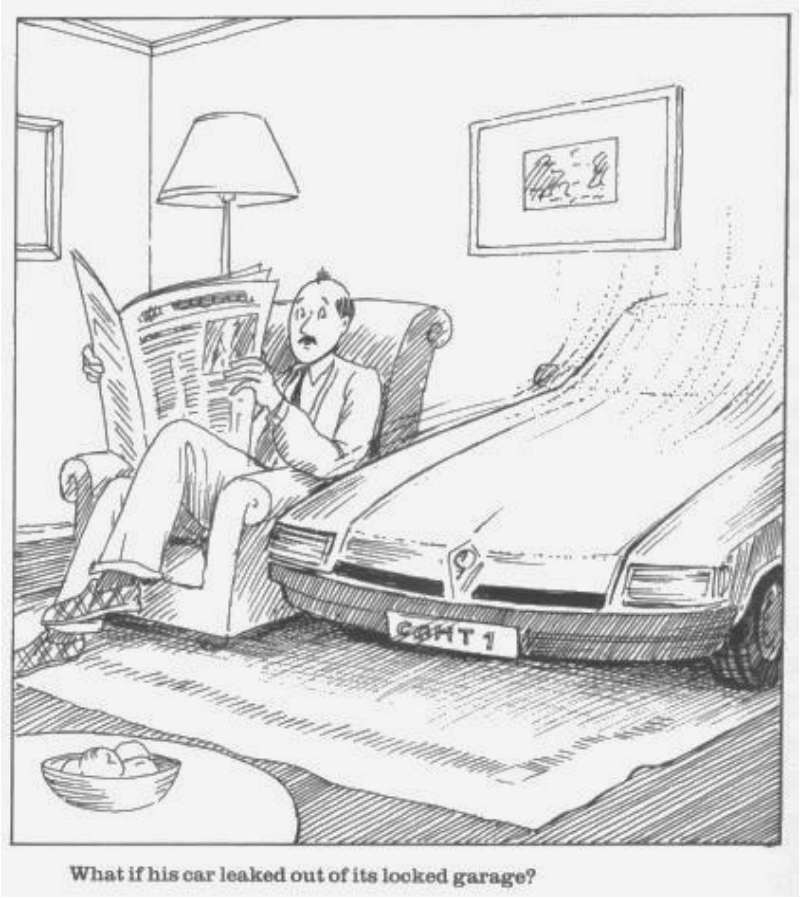
a particle also has a wave property = de Bloglie wave

Uncertainty principle of Heisenberg

$$\Delta p \cdot \Delta x \geq 10^{-34} \quad \text{J s}$$

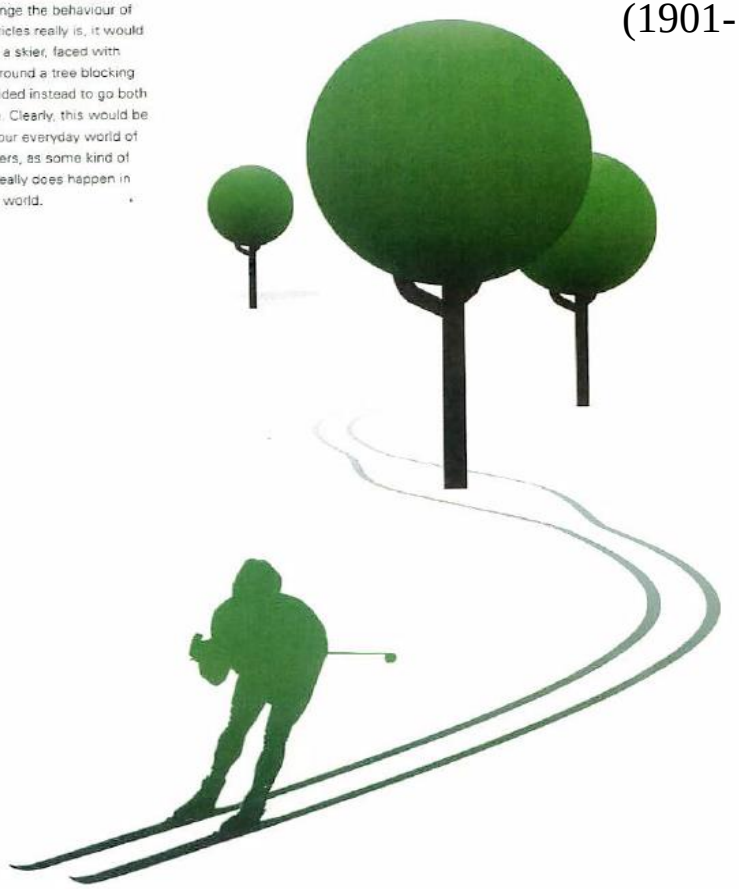
one cannot determine the position and the momentum of a particle at the same time

W. Heisenberg
(1901-1976)



What if his car leaked out of its locked garage?

just how strange the behaviour of quantum particles really is, it would be as though a skier, faced with having to go round a tree blocking his path, decided instead to go both ways at once. Clearly, this would be regarded, in our everyday world of trees and skiers, as some kind of hoax. But it really does happen in the quantum world.

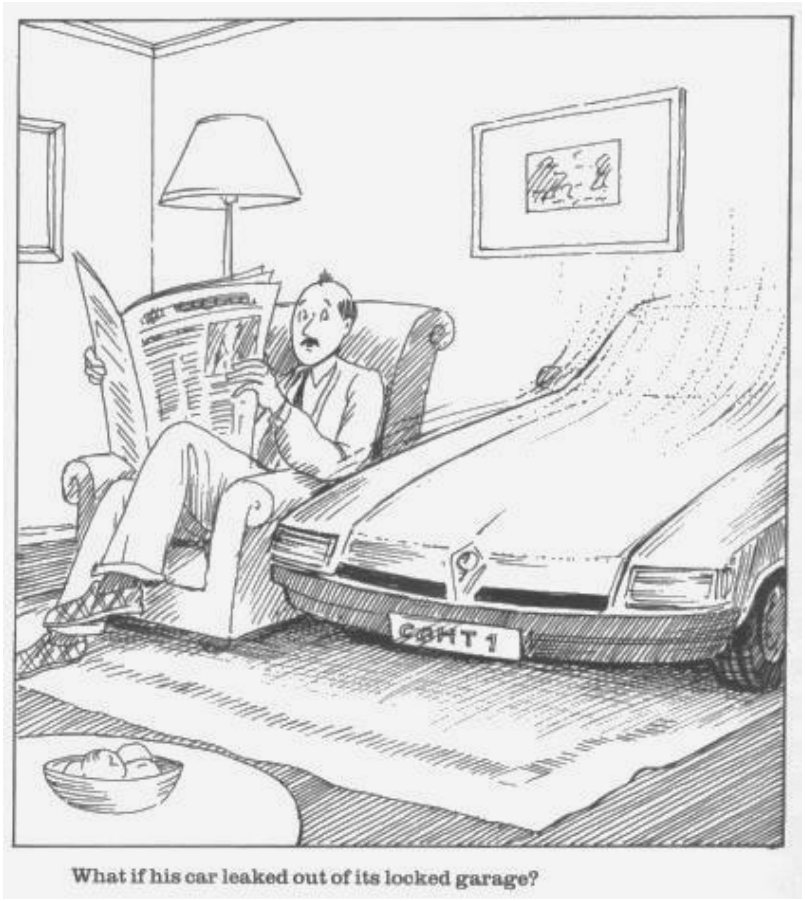


Uncertainty principle of Heisenberg

$$\Delta p \cdot \Delta x \geq 10^{-34} \quad \text{J s}$$

W. Heisenberg
(1901-1976)

…..what happens if $\Delta p \cdot \Delta x \geq 10$ J s …?



What if his car leaked out of its locked garage?

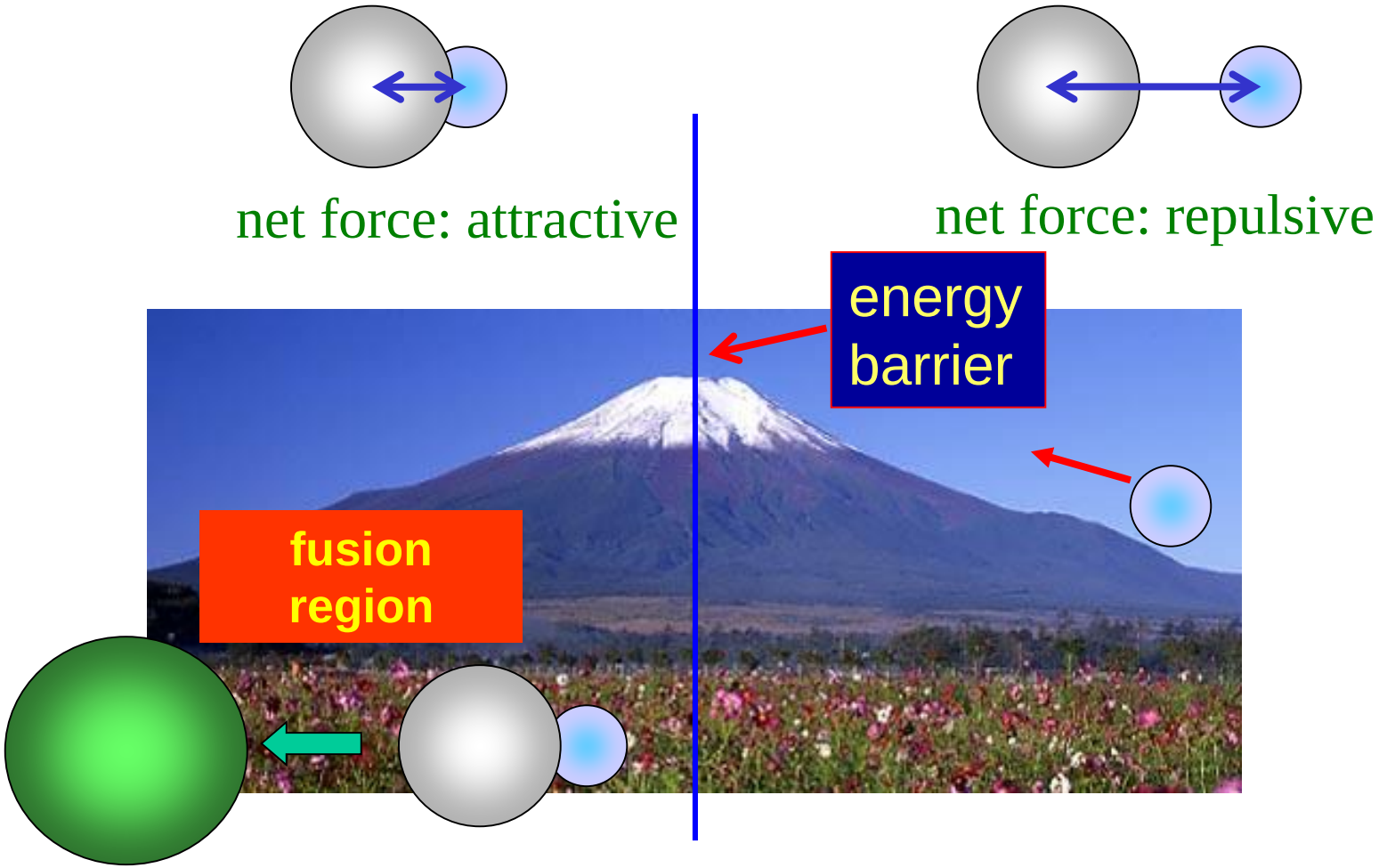
a car may come in through the wall !?

in reality, this happens only when the mass is very light

the mass of electron:~10^{-27} g
the mass of proton: ~10^{-24} g

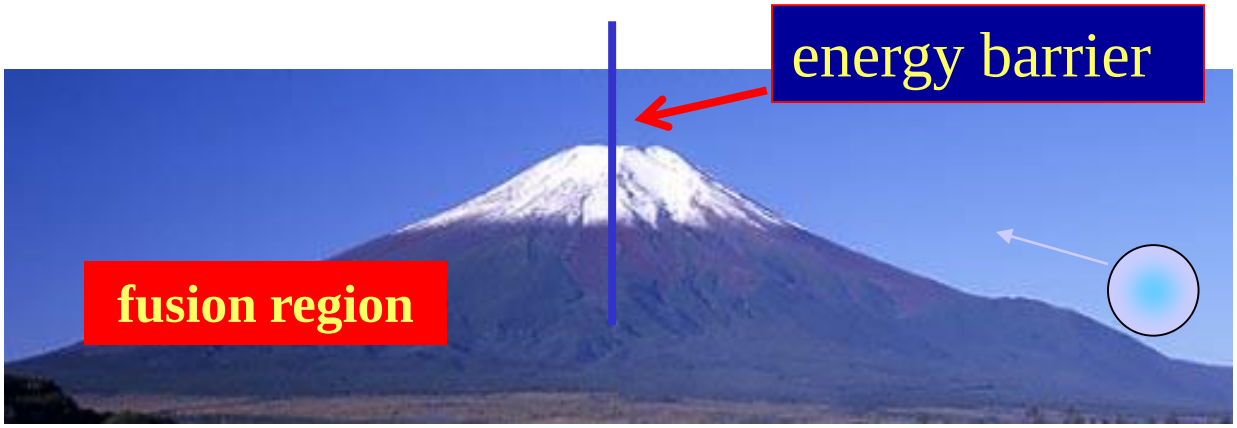
Nuclear Fusion in stars

Strong force (attractive) vs EM force (repulsive)



if two nuclei collide with a large energy

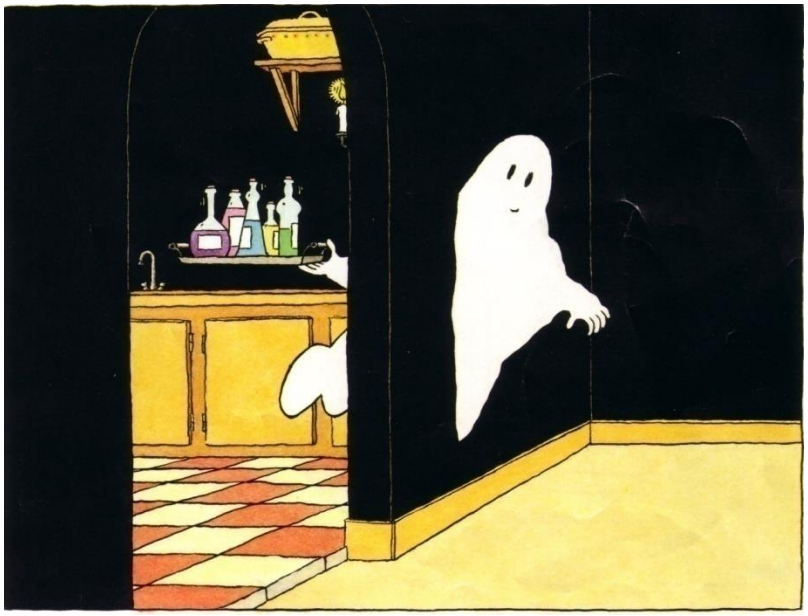
→ fusion by overcoming the barrier



fusion if the energy is large

….but, the energy is not large enough in stars (such as the sun)

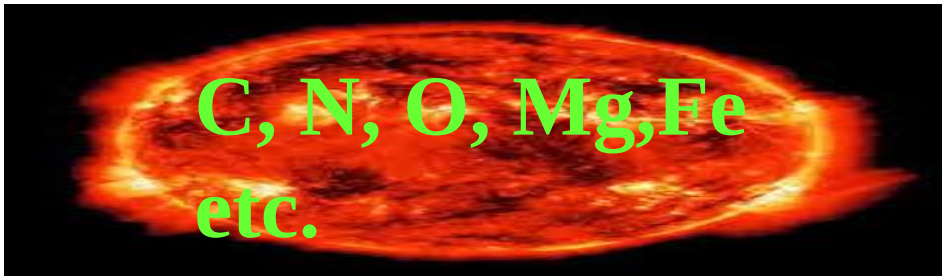
→ stars are shining by Quantum Tunneling



"Ghost party" by Jacques Duquennoy

Why up to Fe?

The origin of elements up to Fe



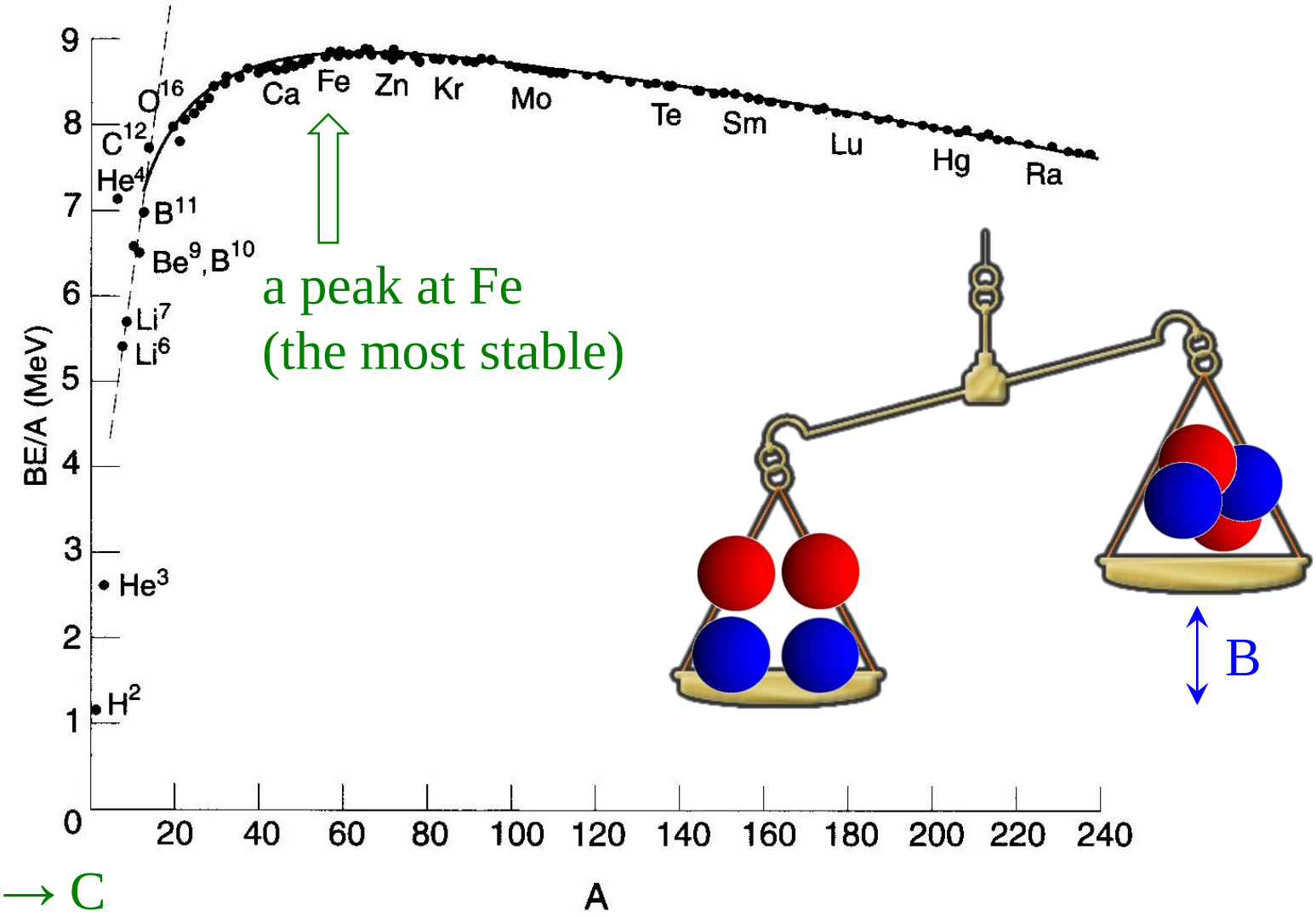
Nuclear fusion inside (massive) stars

⟶ the reason why stars are shining

- up to Fe: exothermal reactions 発熱反応
- from Fe: endothermal reactions 吸熱反応

⟶ fusion stops at Fe

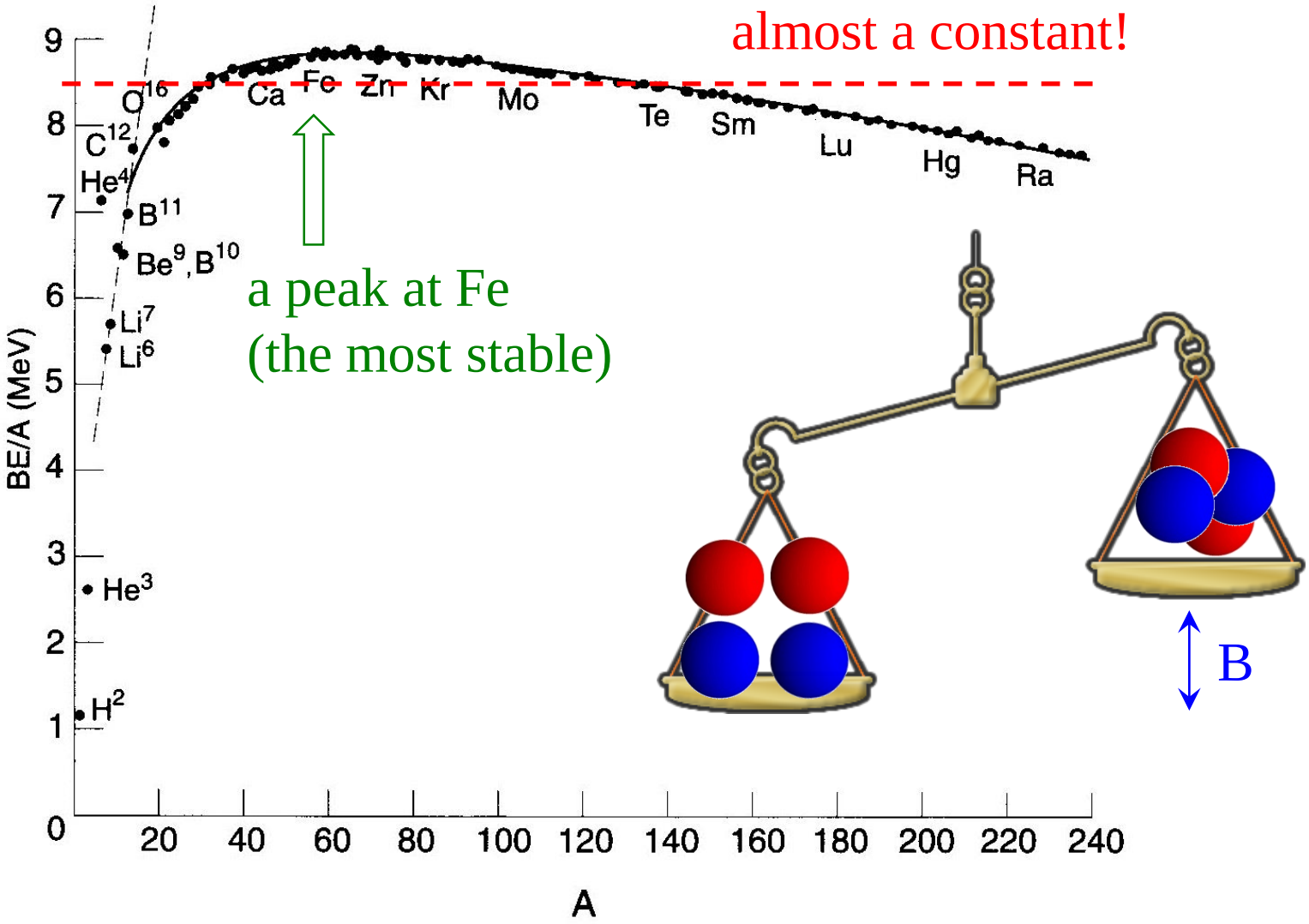
Binding energy of atomic nuclei



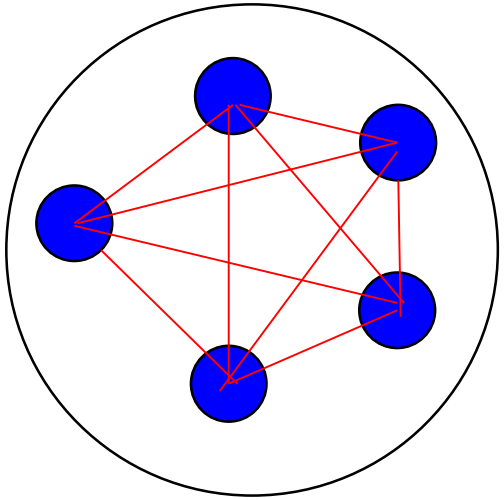
$A + B \rightarrow C$

- 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

the origin of the peak



the origin of the peak

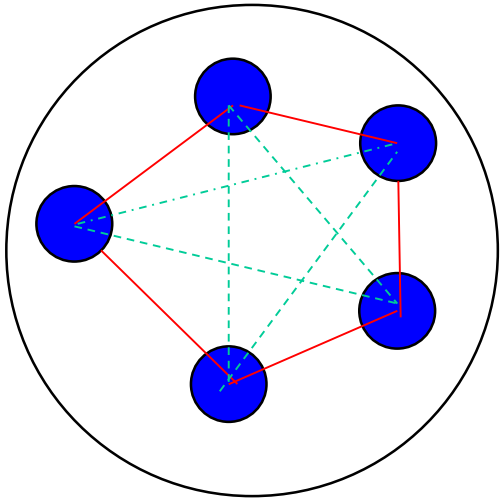


if all the nucleons are interacting with each other inside a nucleus:

$$B \sim vA(A-1)/2$$

$$\rightarrow B/A \propto A - 1 \sim A$$

inconsistent with the data



if one nucleon can interact only a definite number of nucleons close by:

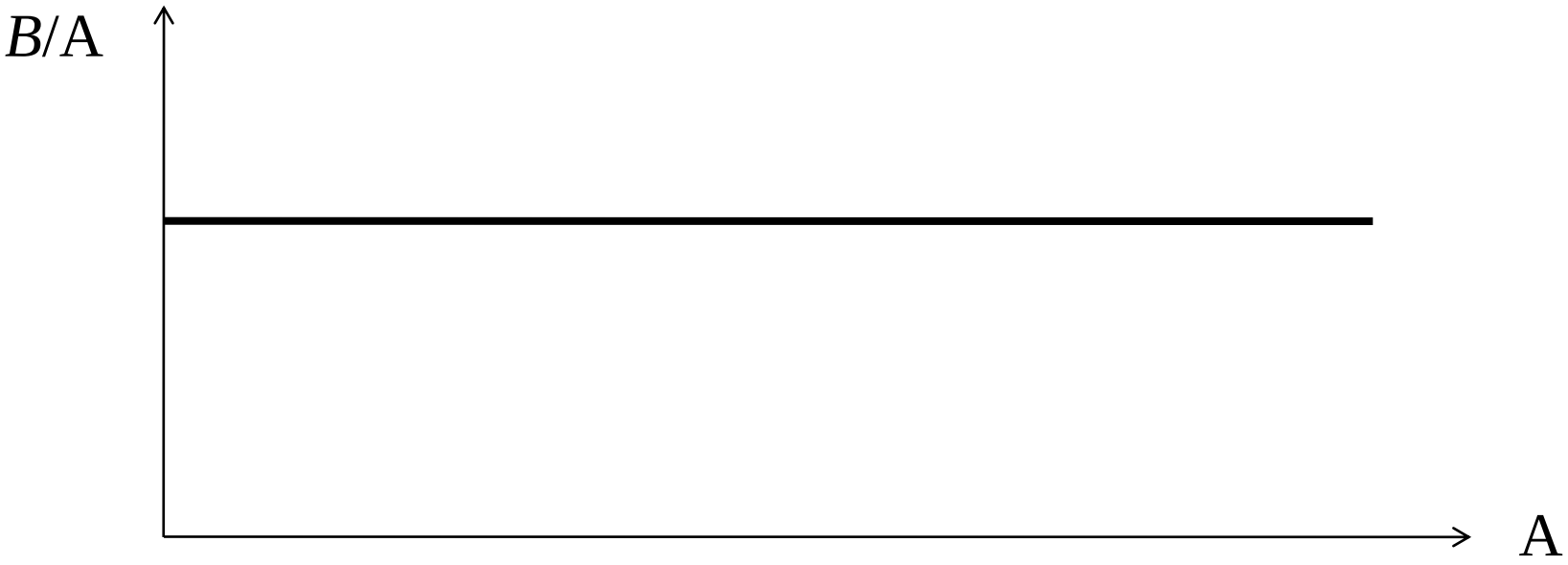
$$B \sim v\alpha A/2$$

$$\rightarrow B/A = const.$$

consistent with the data!

if each nucleon can interact only α-nucleons close by:

$$B \sim \alpha\, A/2 \longrightarrow B/A \sim \alpha/2 \text{ (const.)}$$

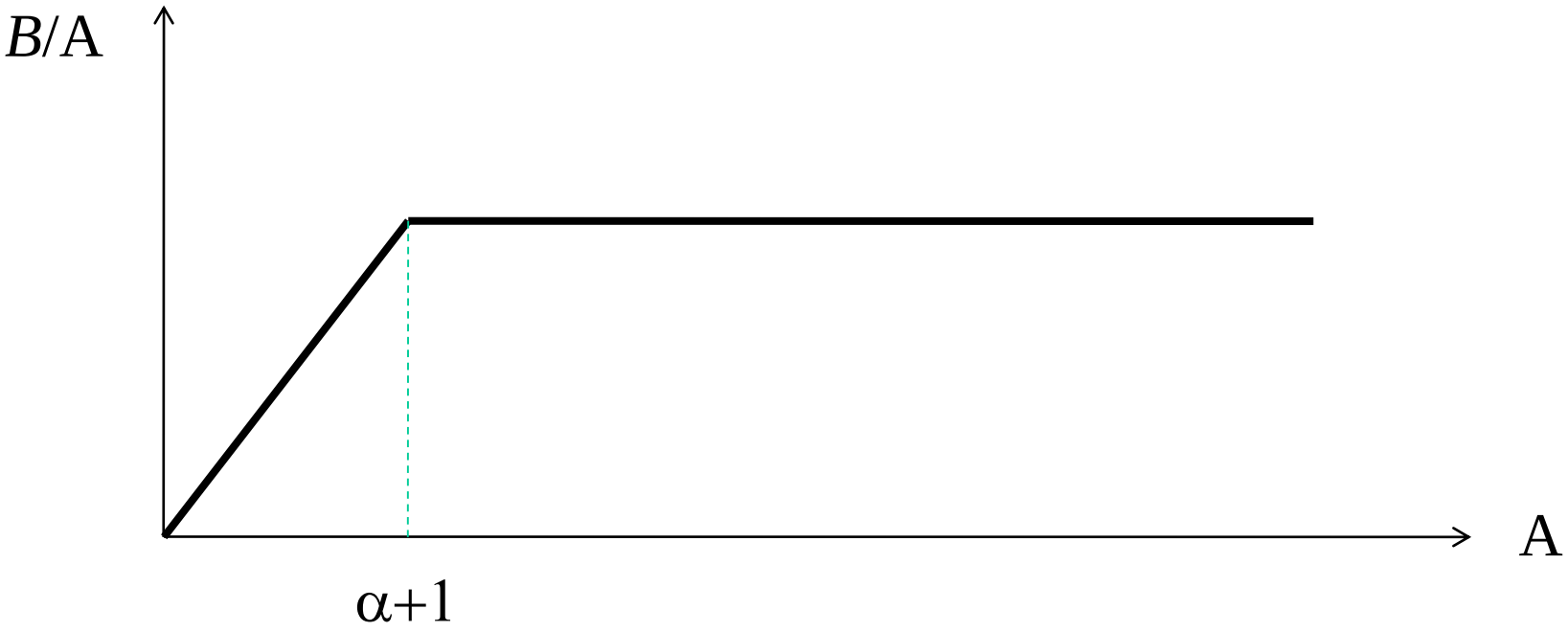


if each nucleon can interact only α-nucleons close by:

$B \sim \alpha\, A/2 \longrightarrow B/A \sim \alpha/2$ (const.)

* for A < α+1, all the nucleons can interact with each other

$$\rightarrow\ B/A \propto A$$



if each nucleon can interact only α-nucleons close by:

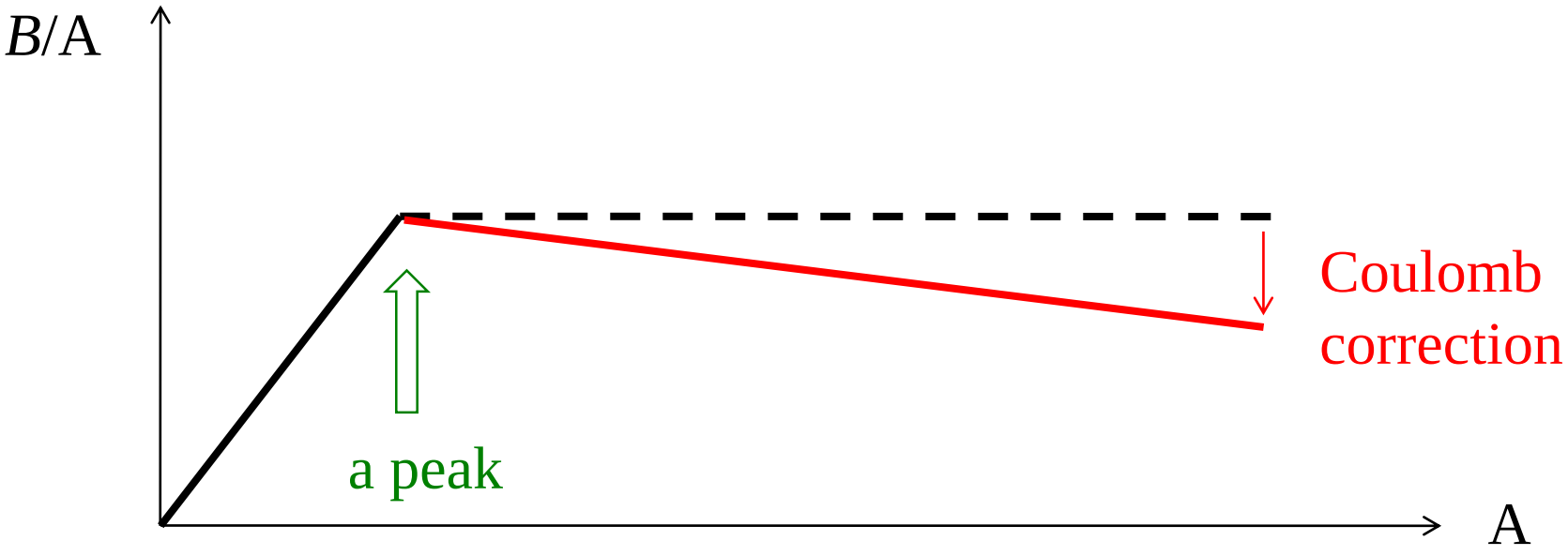
$B \sim \alpha\, A/2 \longrightarrow B/A \sim \alpha/2$ (const.)

* for A < α+1, all the nucleons can interact with each other

$$\rightarrow B/A \propto A$$

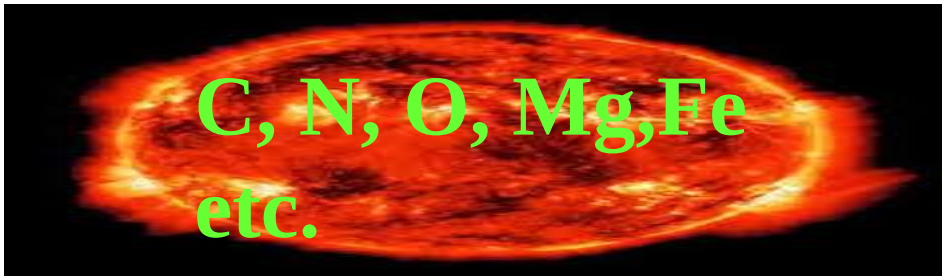
Coulomb interaction (a long range interaction)

$$\rightarrow B/A \propto A$$



Why up to Fe?

The origin of elements up to Fe



Nuclear fusion inside (massive) stars

$\longrightarrow$ the reason why stars are shining

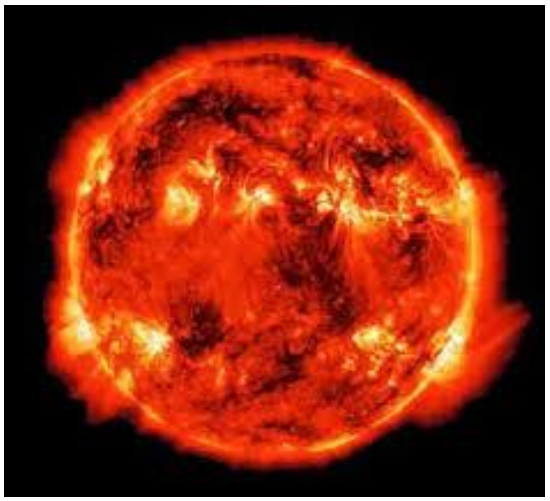
- up to Fe: exothermal reactions
- from Fe: endothermal reactions

$\longrightarrow$ fusion stops at Fe

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

How to create heavier elements than Fe?

Neutron captures (neutrons: no charge)

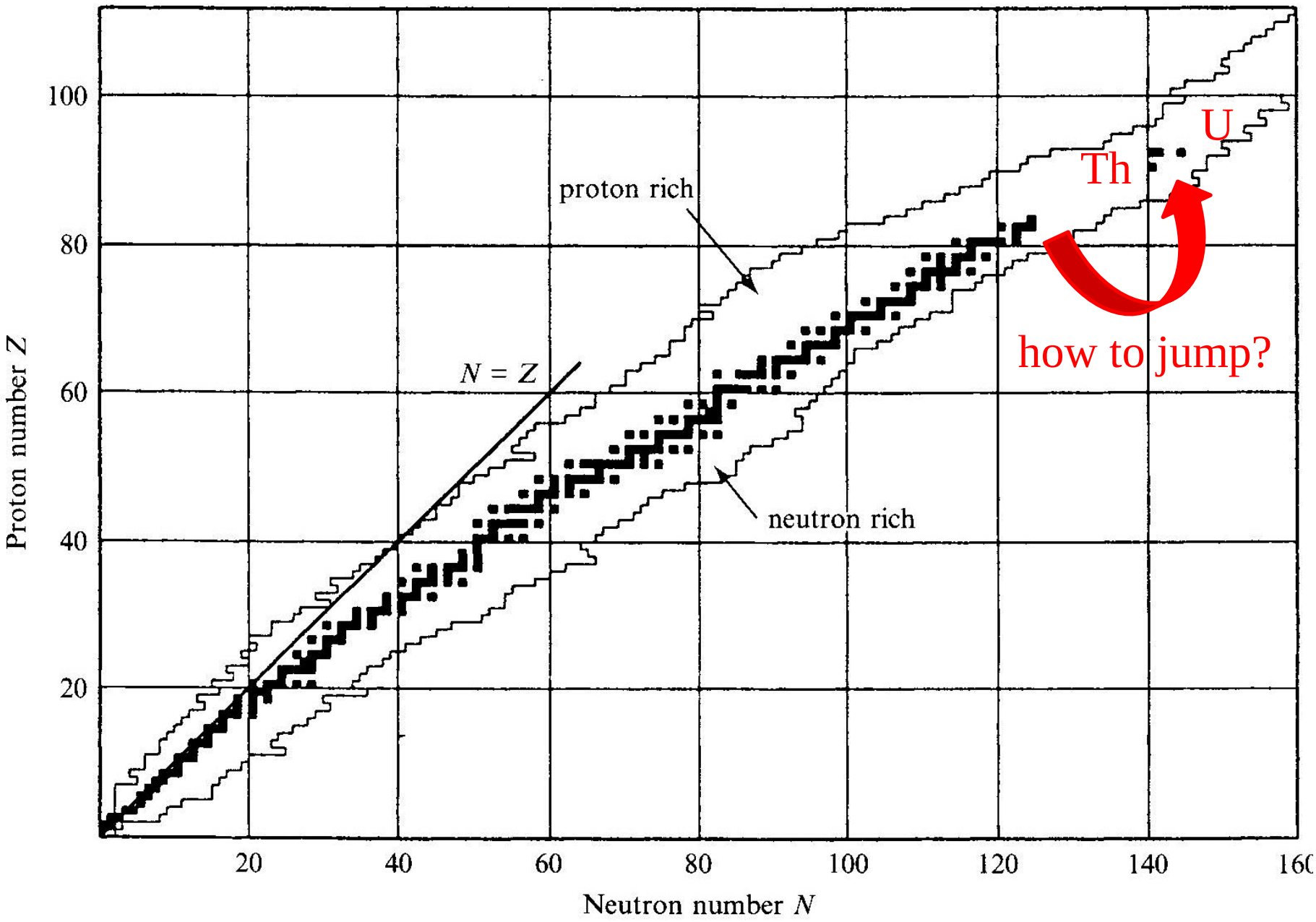


red giant

↓

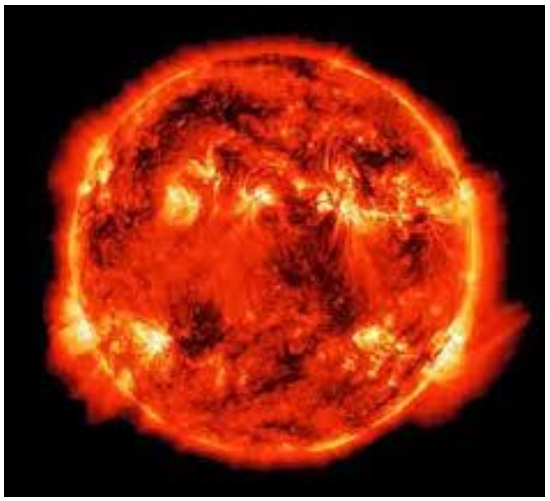
s-process

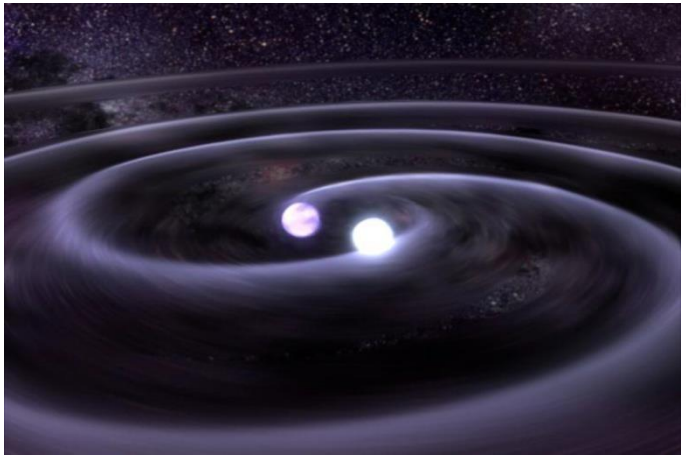
Ba, La, Pb, Bi etc.


Proton number Z
Neutron number N
100
80
60
40
20
20
40
60
80
100
120
140
160
proton rich
neutron rich
N = Z
U
Th
how to jump?

How to create heavier elements than Fe?

Neutron captures (neutrons: no charge)





red giant

↓

s-process

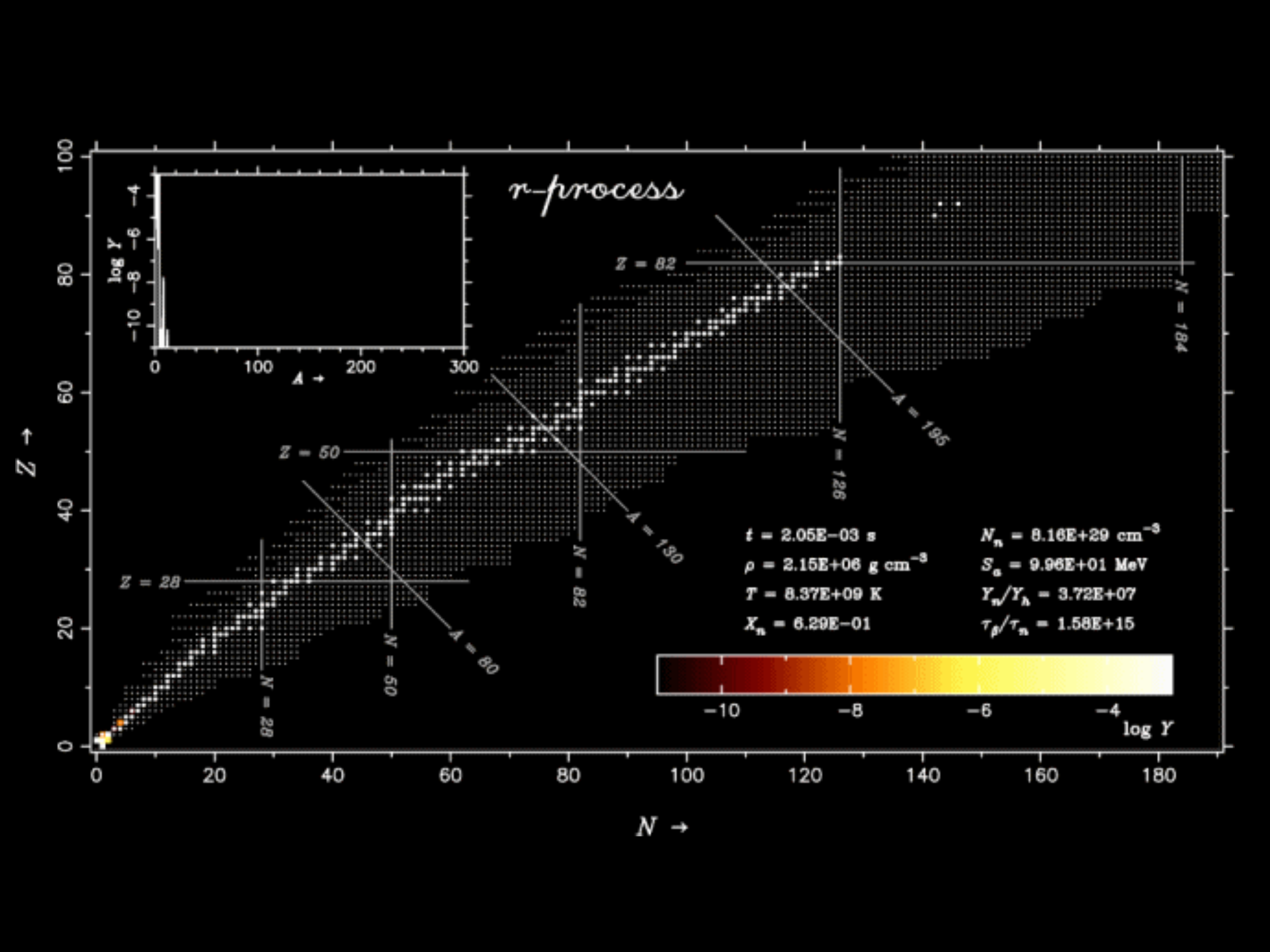
Ba, La, Pb, Bi etc.

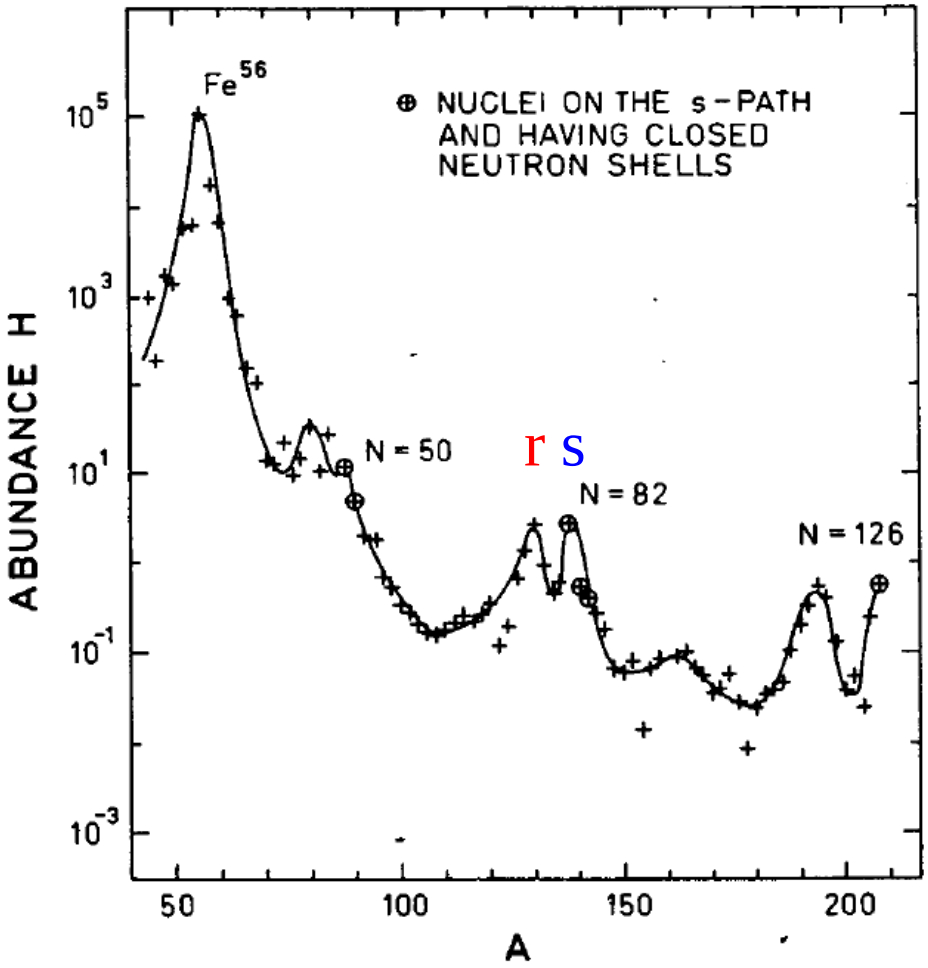
neutron star merger

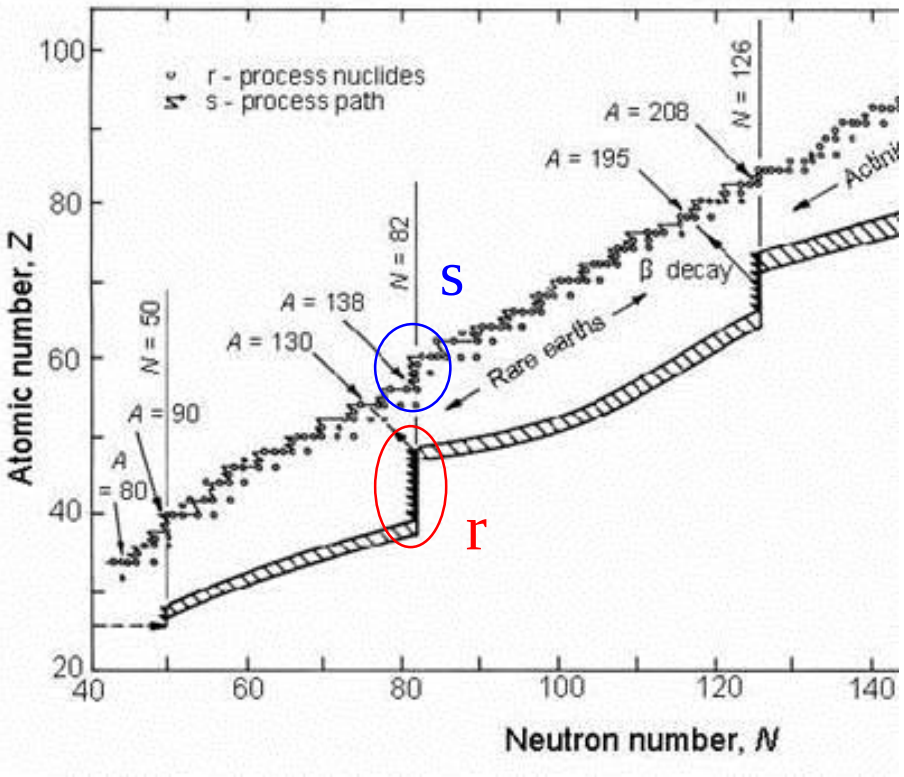
↓

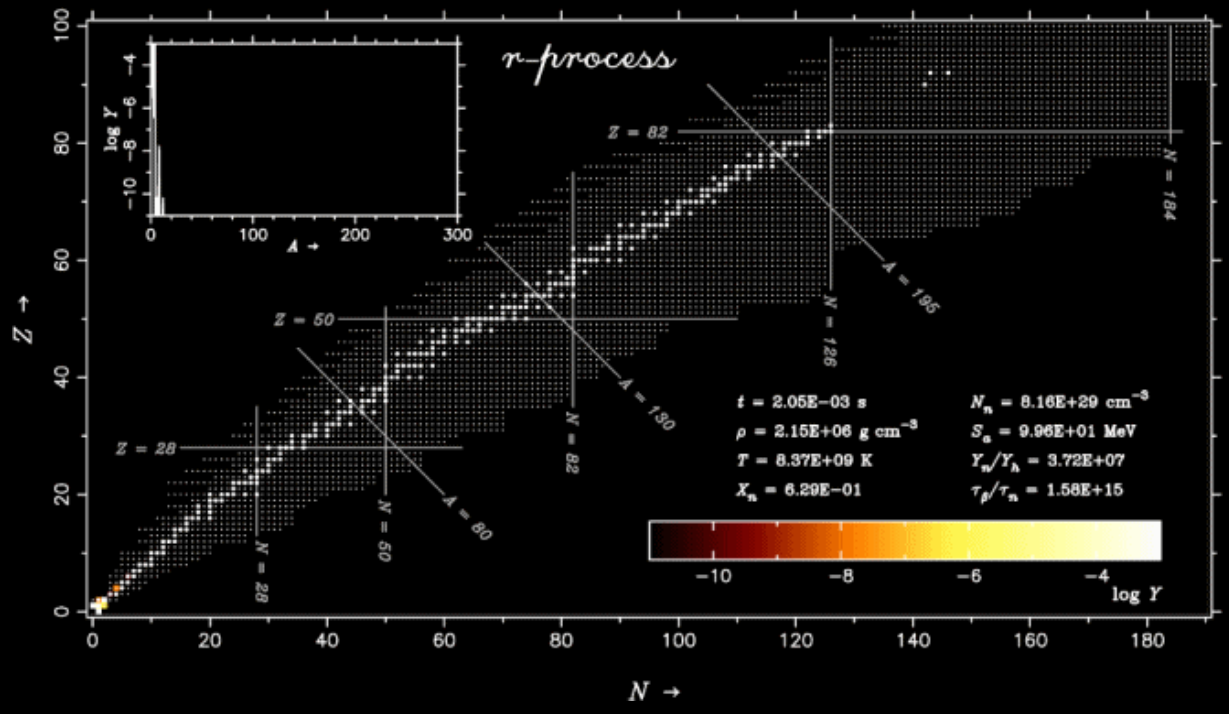
r-process

Th, Eu, U etc.


r-process
log Y
A →
Z →
N →
Z = 82
Z = 50
Z = 28
N = 184
N = 126
N = 82
N = 50
N = 28
A = 195
A = 130
A = 80
t = 2.05E−03 s
ρ = 2.15E+06 g cm⁻³
T = 8.37E+09 K
X_n = 6.29E−01
N_n = 8.16E+29 cm⁻³
S_n = 9.96E+01 MeV
Y_n/Y_h = 3.72E+07
τ_β/τ_n = 1.58E+15
log Y


ABUNDANCE H
10^5
10^3
10^1
10^{-1}
10^{-3}
Fe^{56}
⊕ NUCLEI ON THE s-PATH AND HAVING CLOSED NEUTRON SHELLS
N = 50
N = 82
N = 126
r s
50
100
150
200
A

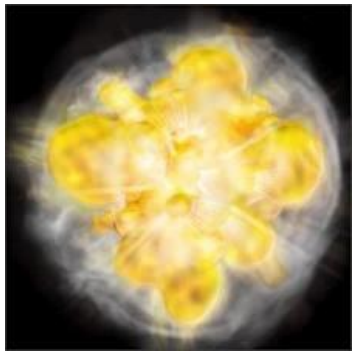

r - process nuclides
s - process path
Atomic number, Z
Neutron number, N
100
80
60
40
20
40
60
80
100
120
140
N = 50
N = 82
N = 126
A = 80
A = 90
A = 130
A = 138
A = 195
A = 208
β decay
Rare earths
Actinides
s
r



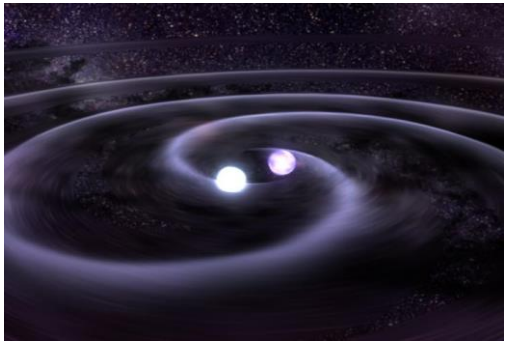
As a matter of fact, it is not known well how Au and U were created….

Open issues in r-process nucleosyntehsis

- where is the main site?

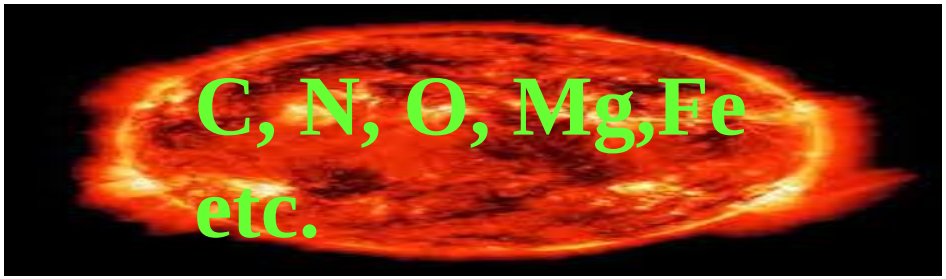


SN explosion



Neutron star merger

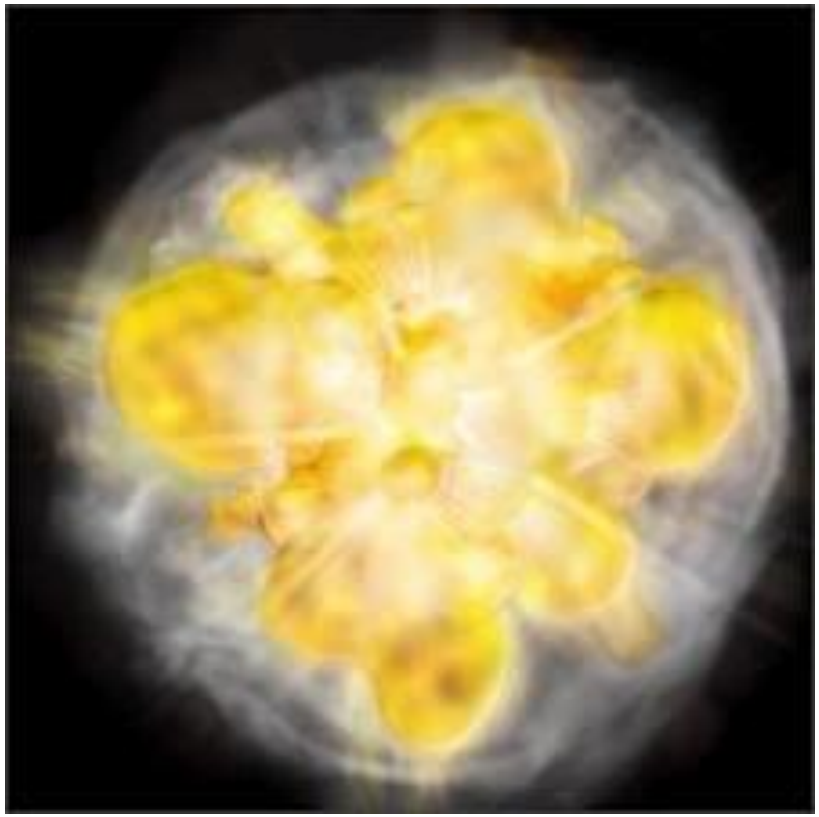
a life of stars



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

H

Fe

C

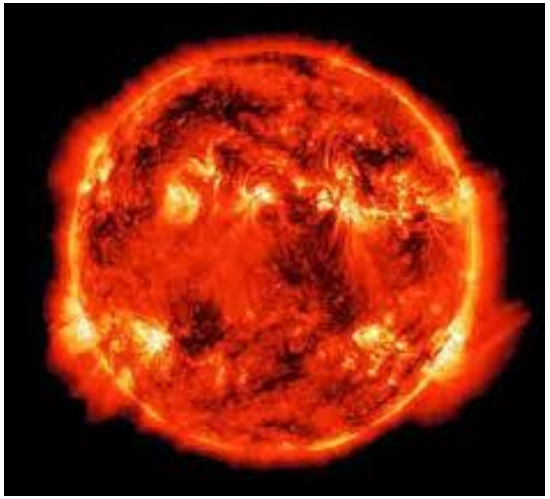
Li

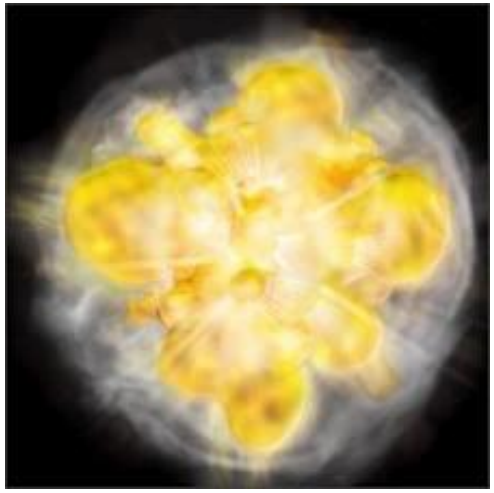
Si

He

SN explosions distribute elements into the universe.

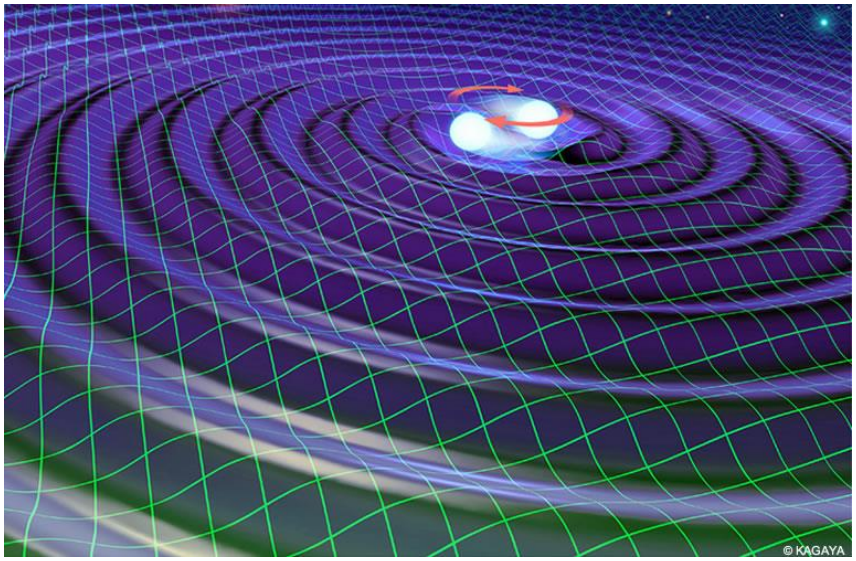
repetition of a cycle



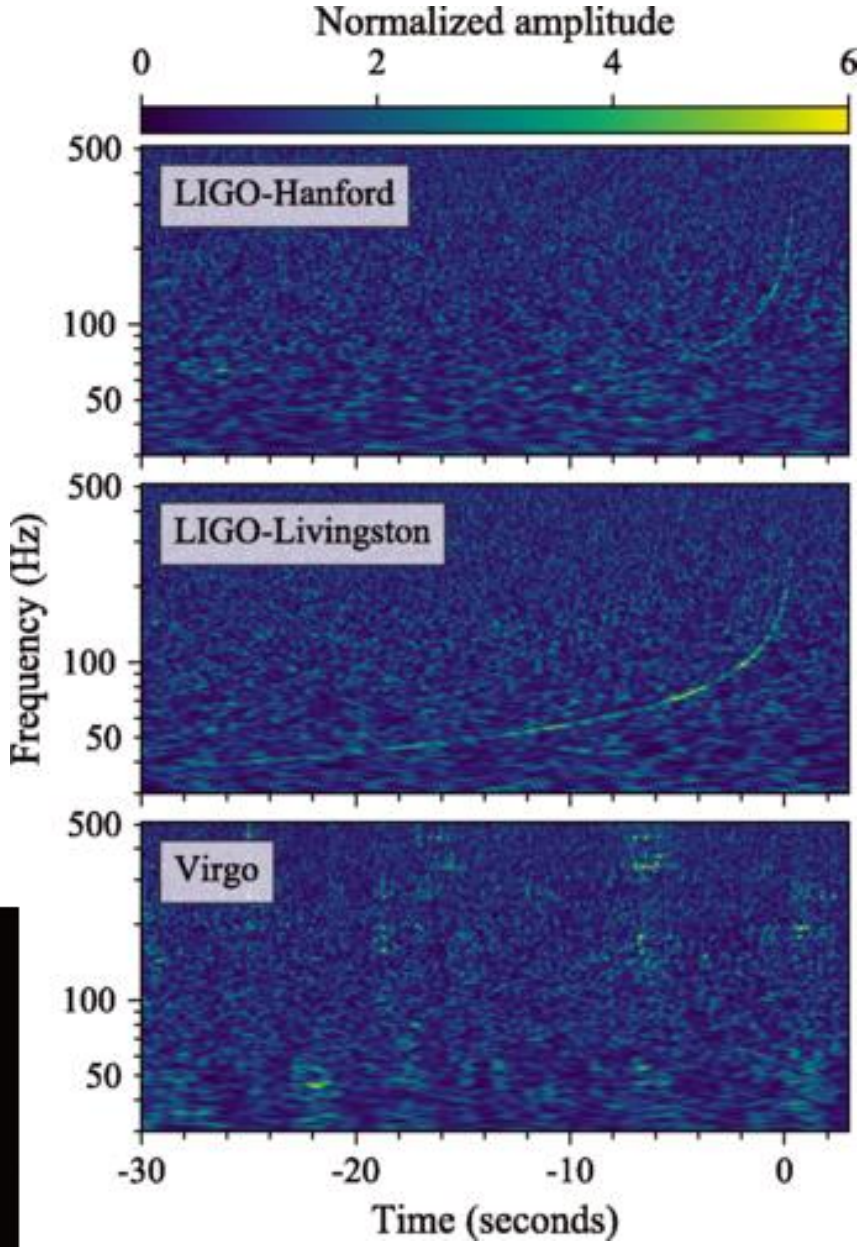


interstellar gas → creation of stars → SN explosion

gravitational wave due to
a neutron star merger



NAOJ



B.P. Abbott et al., PRL119 (‘17) 161101

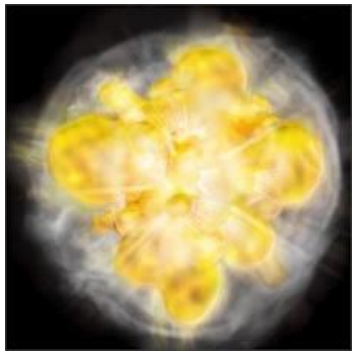
photons from r-process

2017.08.18–19

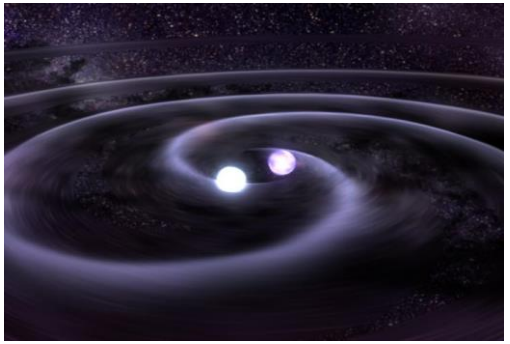
2017.08.24–25

Open issues in r-process nucleosyntehsis

- where is the main site?



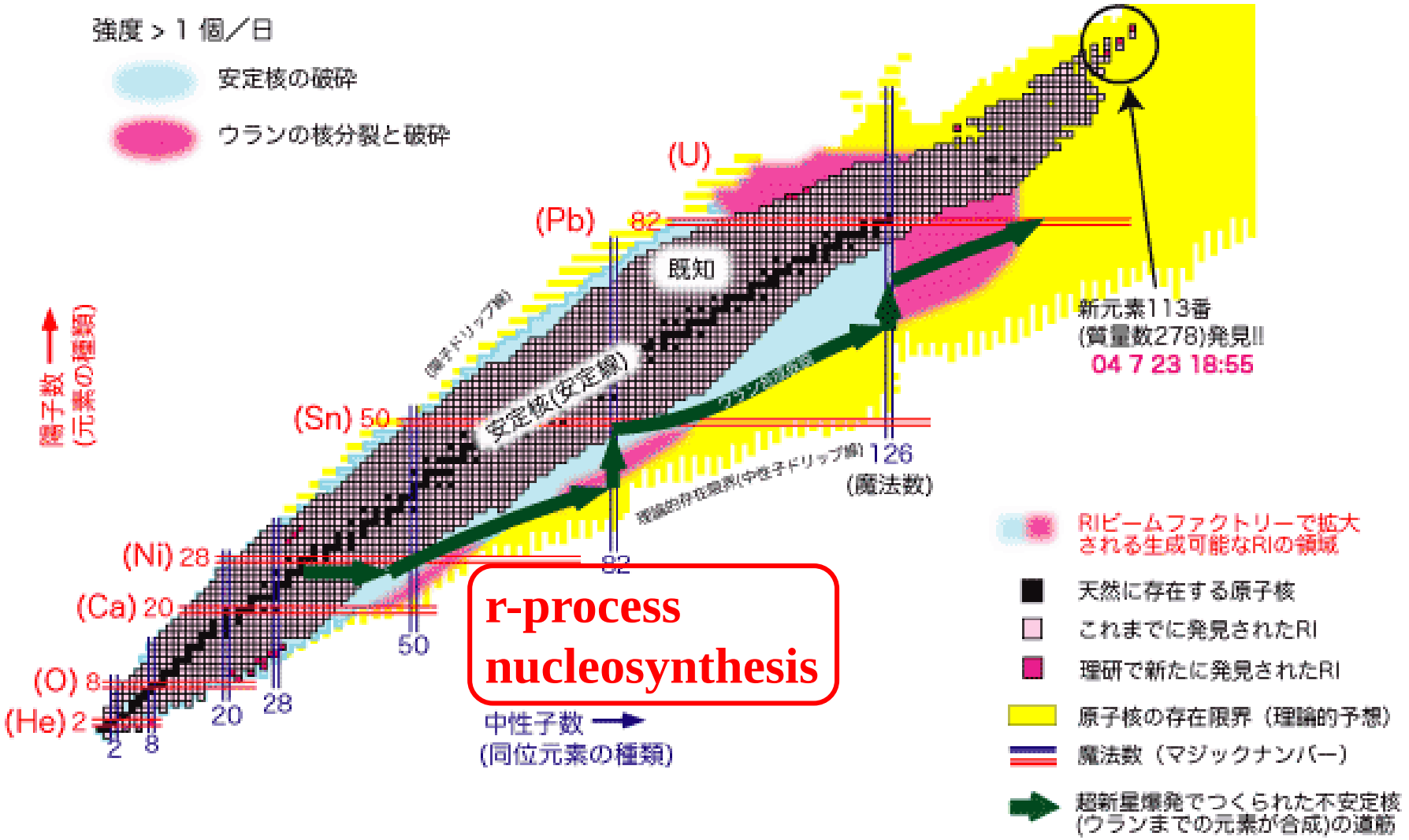
SN explosion



Neutron star merger

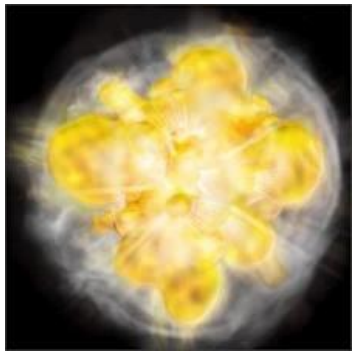
- how well do we know the properties of neutron-rich nuclei?
  - mass
  - β-decay (life-time)
  - magic numbers

Neutron-rich nuclei (RIBF at RIKEN)

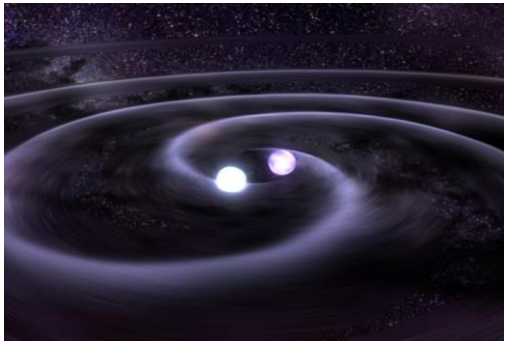


Open issues in r-process nucleosyntehsis

- where is the main site?

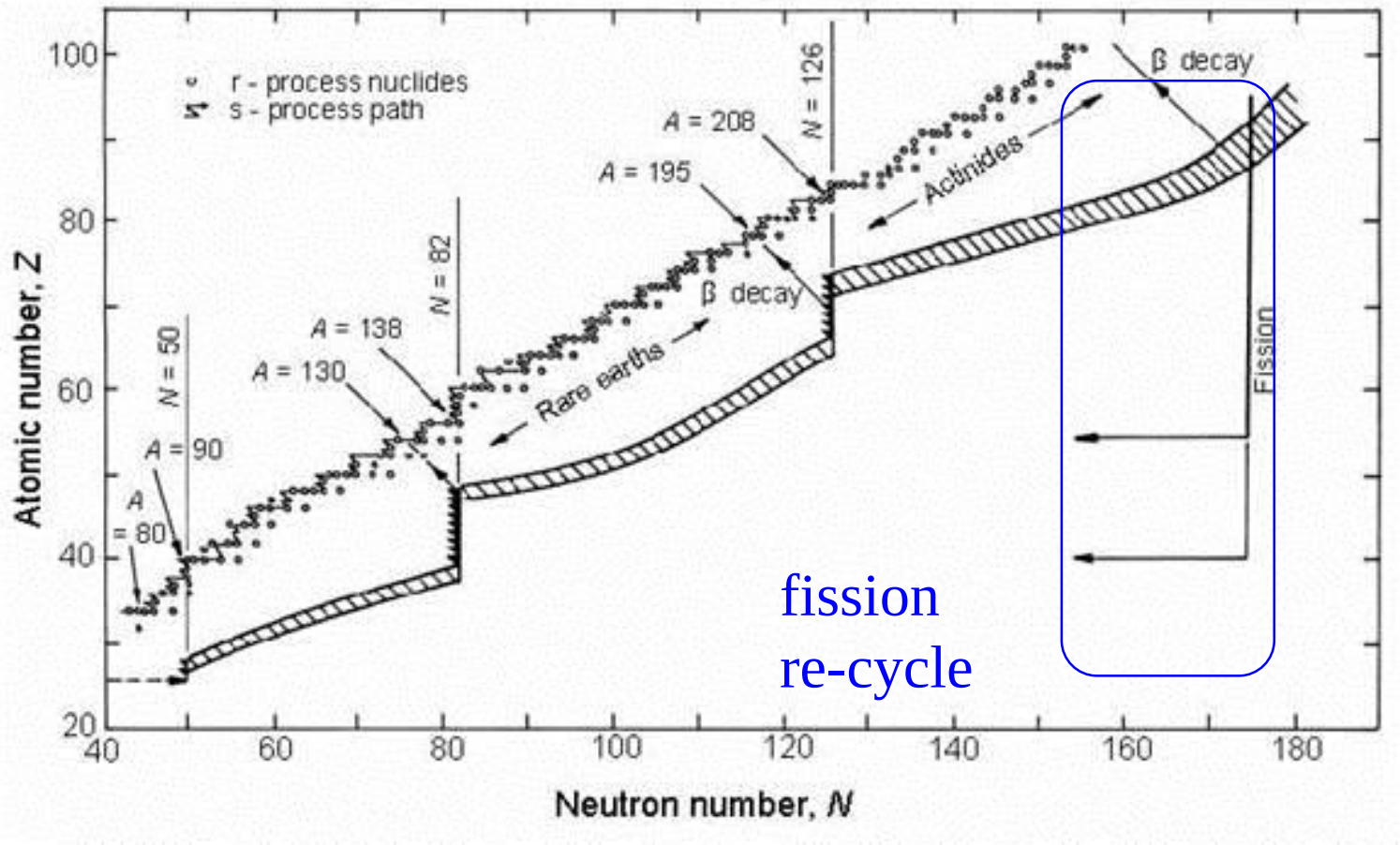


SN explosion



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


r - process nuclides
s - process path
N = 50
N = 82
N = 126
A = 80
A = 90
A = 130
A = 138
A = 195
A = 208
β decay
β decay
Rare earths
Actinides
Fission
fission
re-cycle
Atomic number, Z
Neutron number, N
20
40
60
80
100
40
60
80
100
120
140
160
180