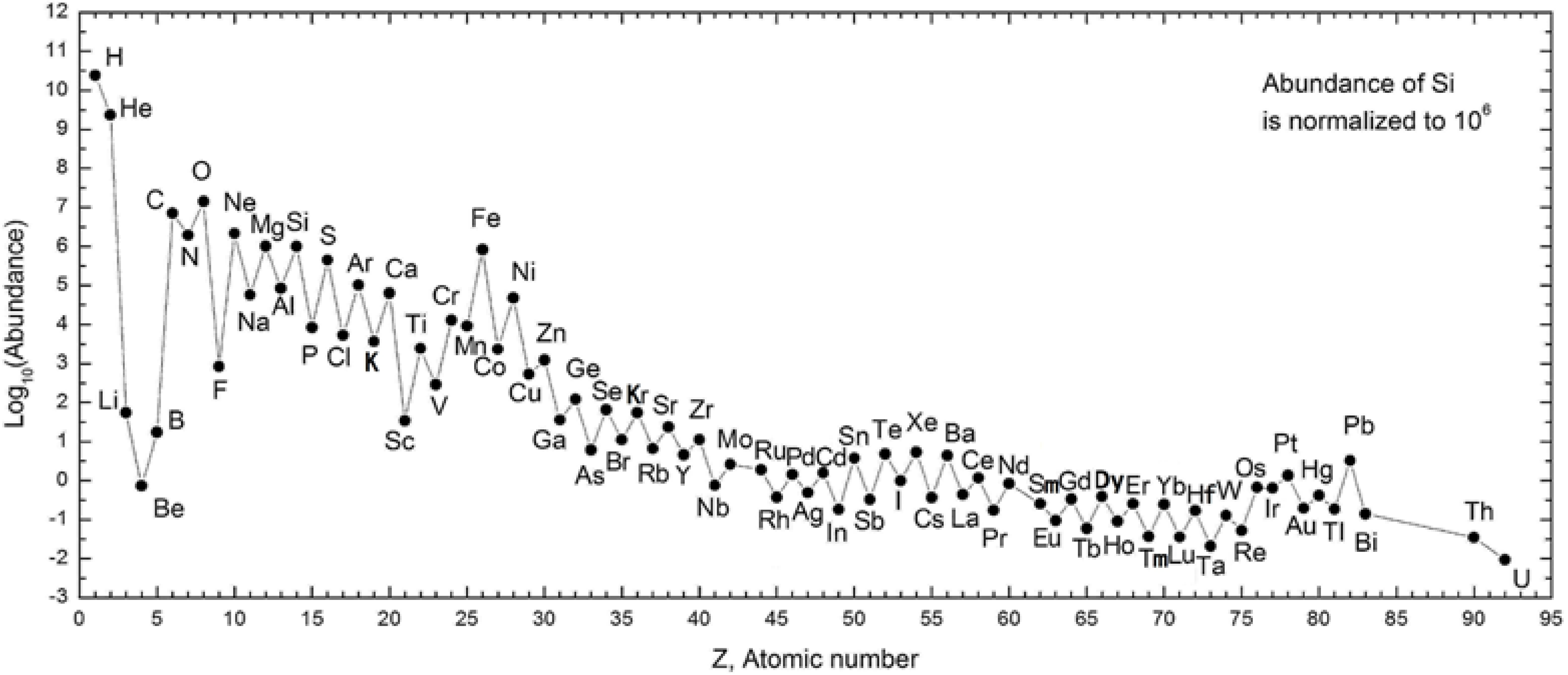
Lecture 2: Making the elements

1. Chemical composition of the solar system
    A. Making the elements
2. Condensation from the nebula
    A. Thermodynamics

We acknowledge and respect the lək̓ʷəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.



Abundance of Si
is normalized to 10^6
Log10(Abundance)
Z, Atomic number
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
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Why is a nucleus stable?

electrostatic

$\oplus \longleftrightarrow \oplus$

force

Mass of:

(P) Proton: 1.007276u

(N) Neutron: 1.008664u

(e) Electron: 0.00054858u

u is unified atomic mass unit $\sim 10^{-27}$ kg

Consider:

$$^{2}H + {}^{2}H \rightarrow {}^{4}He$$

$$2(P+N+e) \neq 2(P+N+e)$$

Mass ^{4}He < Mass $2 \times (P+N+e)$

mass decrement, δ, related to energy

$e = \delta c^2$

the **strong** force

10^2 times stronger than electromagnetic

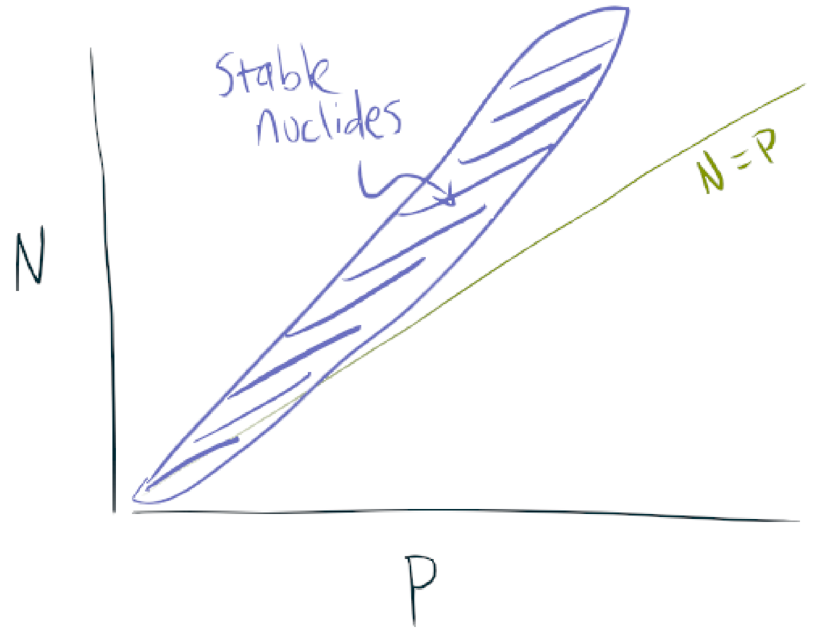
10^{39} times stronger than gravity

– falls off w/ distance rapidly

at > 10^{-14} m weaker than electromagnetic

$$E_b = \frac{\delta}{A} c^2$$

binding energy per nucleon



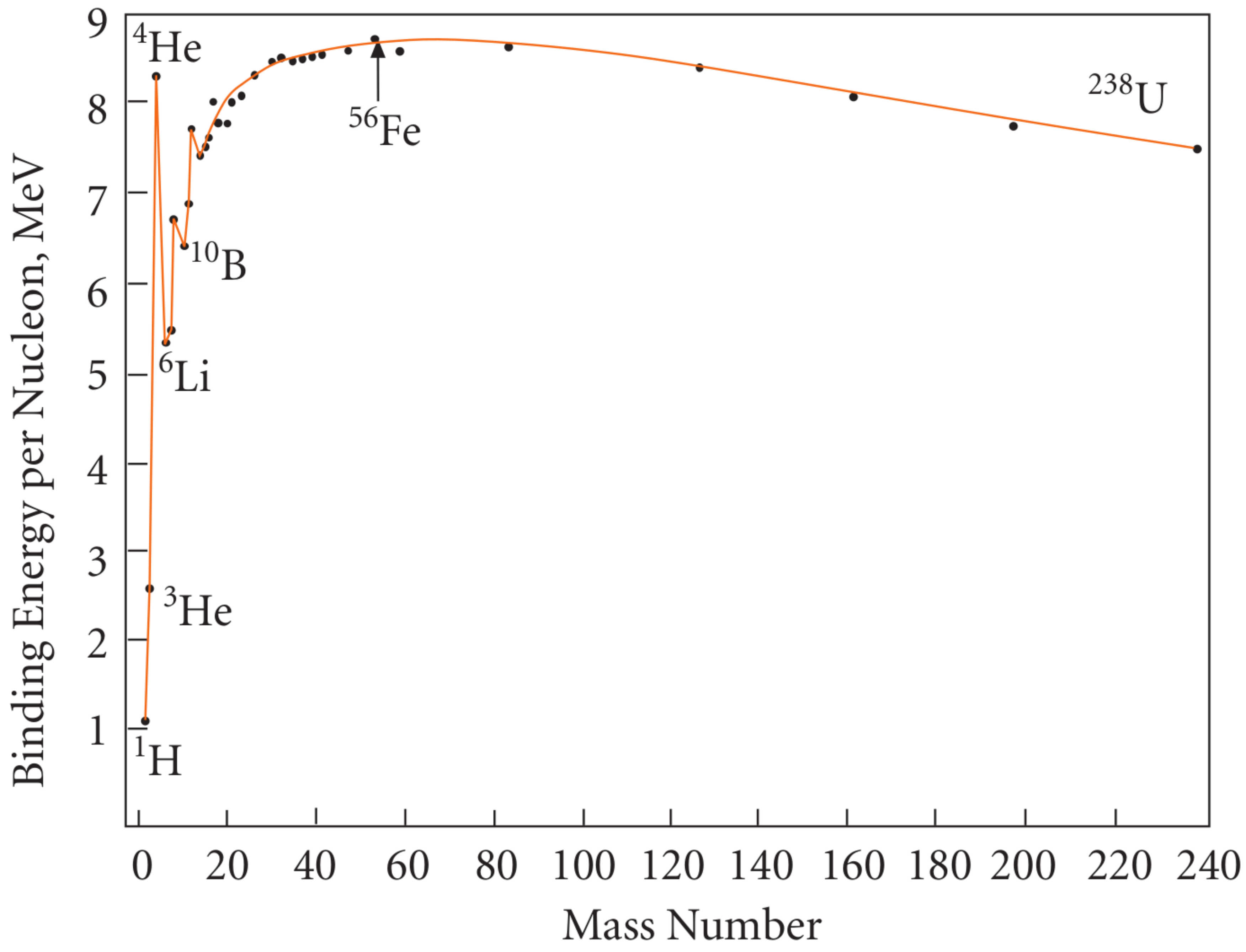
more N needed to counter $\oplus \leftrightarrow \oplus$

(A = P + N)

More stable nuclei with even A

even : 169

odd : 105



Binding Energy per Nucleon, MeV
Mass Number
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
140
160
180
200
220
240
4He
56Fe
238U
10B
6Li
3He
1H

$$E_b = \frac{\delta}{A} c^2$$

binding energy per nucleon

^{56}Fe most stable

$$H + H \rightarrow He + \text{energy}$$

Fusion to a more stable nucleus releases energy

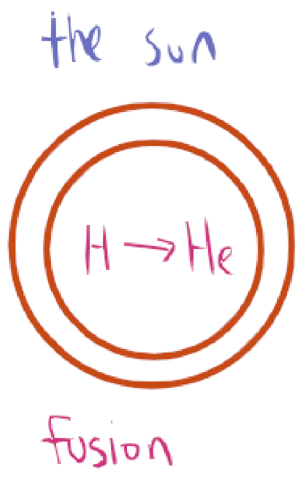
Favorable*

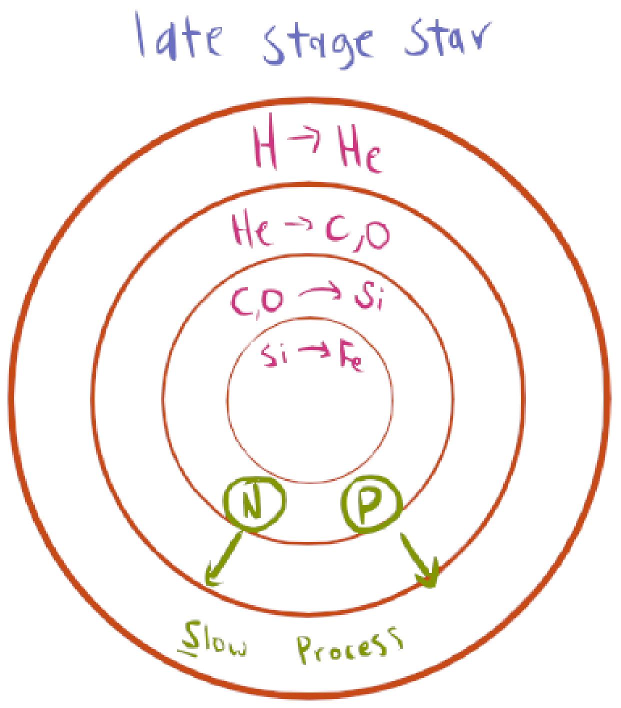
*Why doesn't it always happen?

activation E needed to overcome ⊖ ↔ ⊖

H and He produced in Big Bang ~ $\overset{H}{75} : \overset{He}{25}$

heavier elements form in Stars





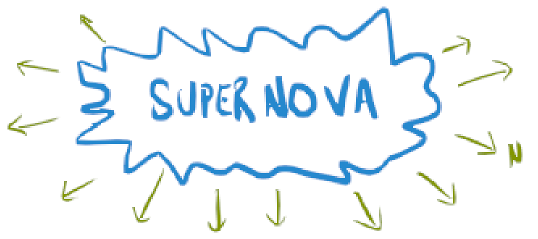
S process

→ if unstable will decay* before another capture

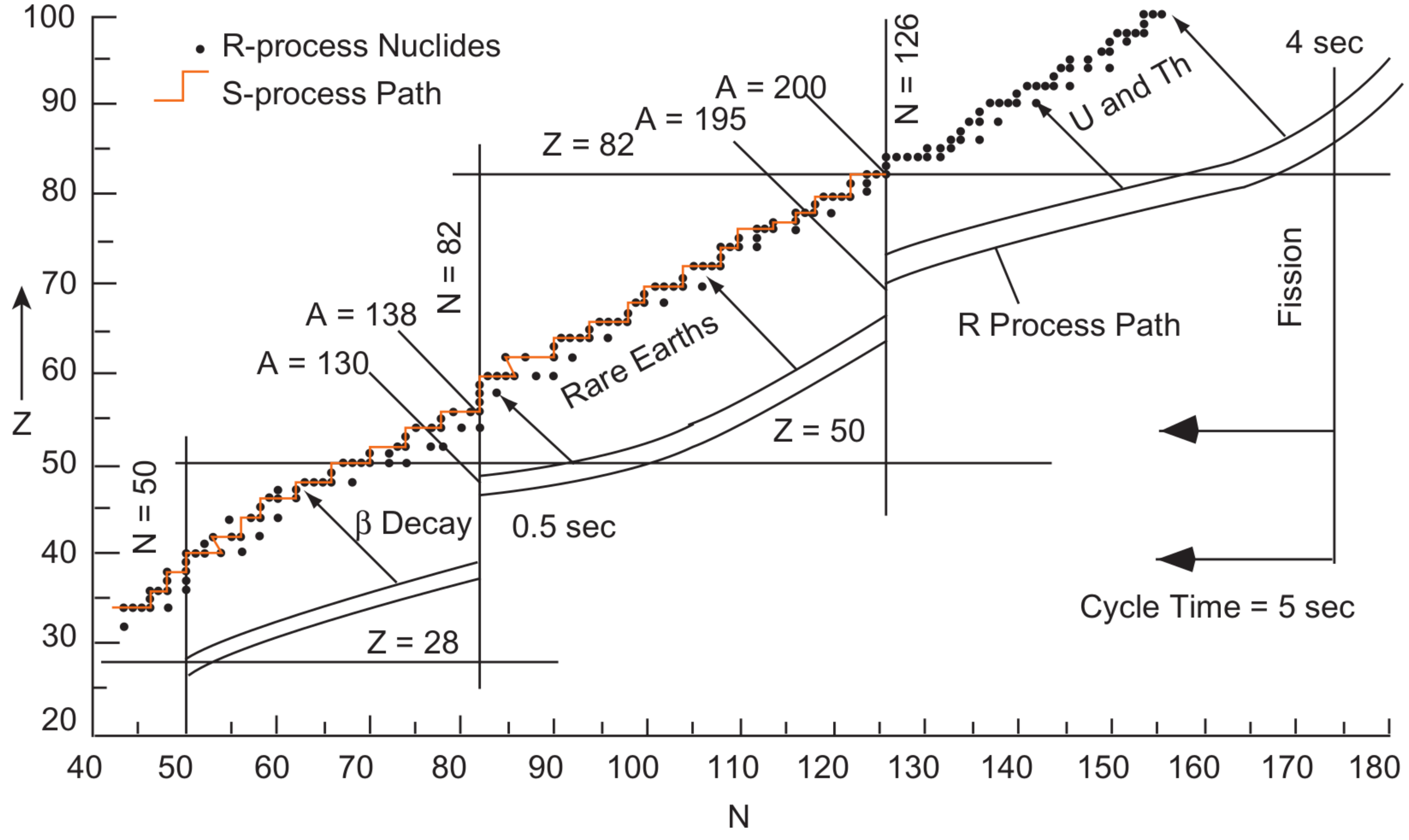
We will learn more about β- decay later N → P

What happens when there's no fuel left for fusion?

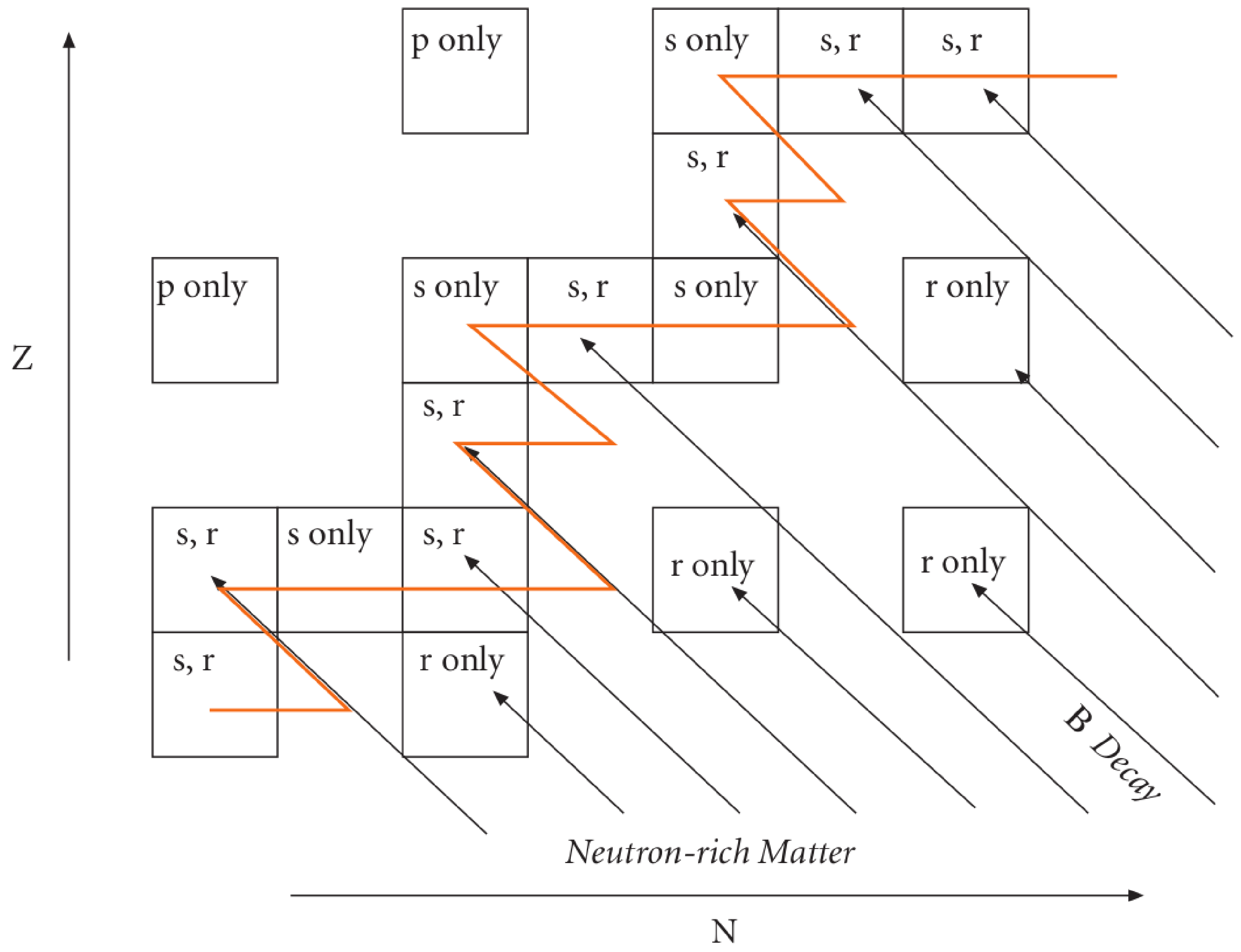
thermal expansion < gravity



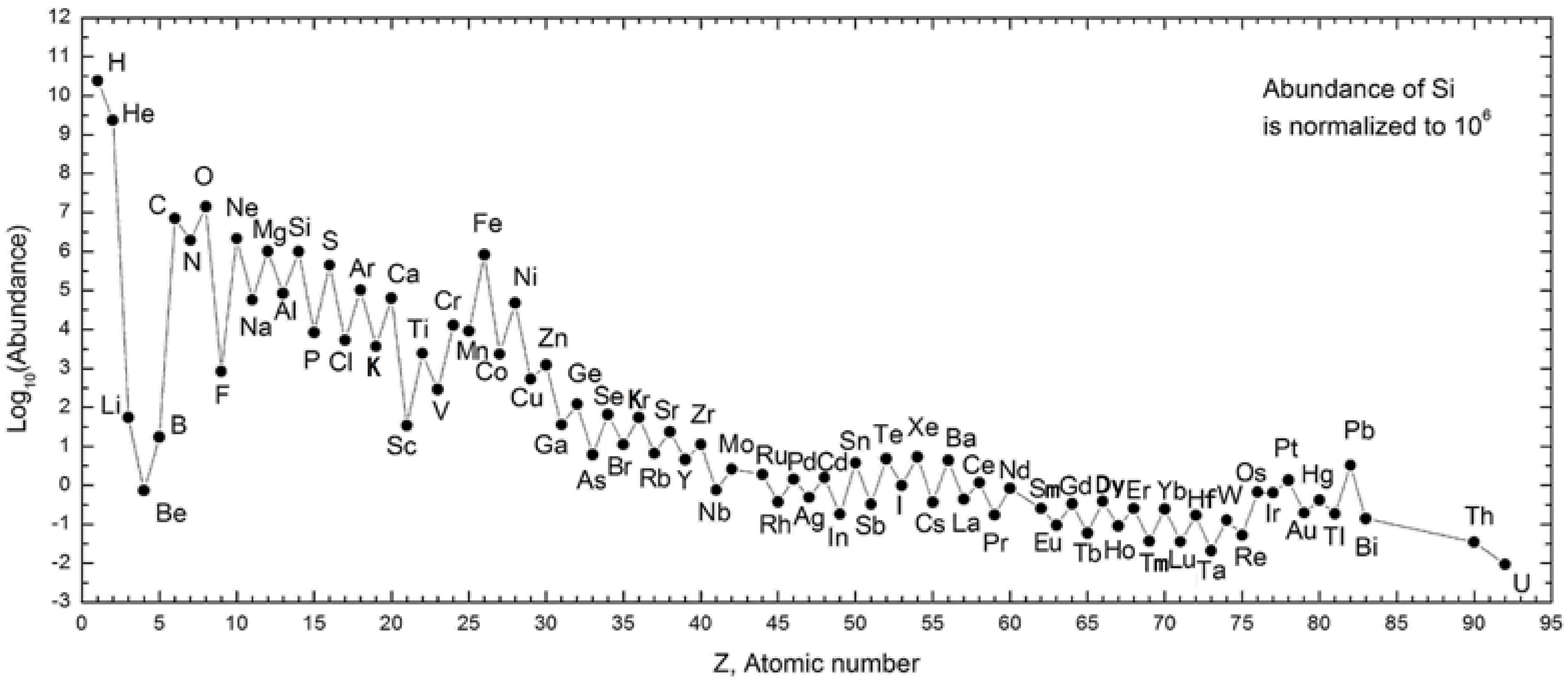
rapid process: N capture faster than β decay



R-process Nuclides
S-process Path
100
90
80
70
60
50
40
30
20
Z
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
N
N = 50
N = 82
N = 126
Z = 28
Z = 50
Z = 82
A = 130
A = 138
A = 195
A = 200
β Decay
Rare Earths
U and Th
0.5 sec
4 sec
R Process Path
Fission
Cycle Time = 5 sec

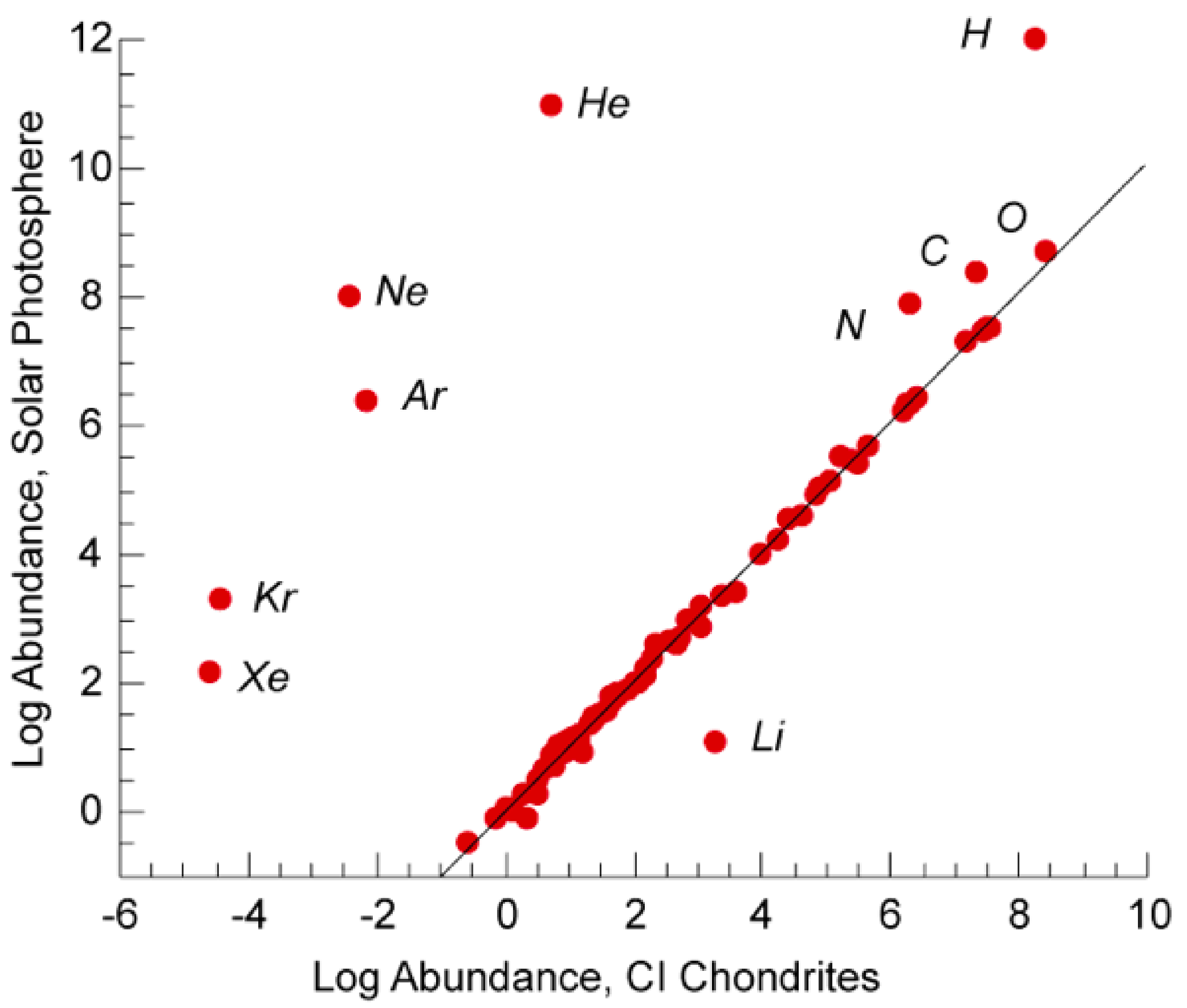


Z
p only
s only
s, r
s, r
s, r
p only
s only
s, r
s only
r only
s, r
s, r
s only
s, r
r only
r only
s, r
r only
B Decay
Neutron-rich Matter
N



Should the Sun and Earth have the same chemistry? What about Earth and Jupiter?

Do the planets share a common origin with the Sun?



Condensation sequence

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- Condensation: as a gaseous material cools, it will condense into solid or liquid form
- Some questions we will consider:
  - Starting with a hot gas with the composition of the sun/nebula, what solids condense first? (These solids are the building blocks of planets)
  - When does all of a specific element finish condensing?

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- To answer these questions, will need to use **thermodynamics**

What is energy?

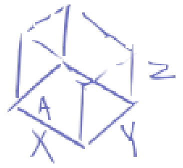
- capacity to produce $\boxed{\text{change}}$

What forms does it take? work, thermal, chemical, etc

equilibrium: no more change, so energy minimized

1st Law of Thermodynamics: $\Delta U = Q + W$

Δ energy = heat + work



$A = xy$

$V = xyz$

Work

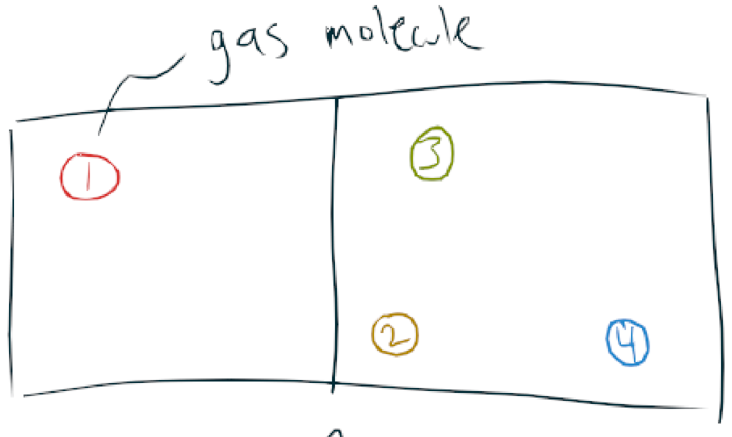
$W = \int_{x_0}^{x} F\,dx \qquad F = m \cdot \frac{dv}{dt} \qquad P = \frac{F}{A}$

P–V work

$W = \int_{z_0}^{z} \frac{F}{A} A\,dz = -\int_{V_0}^{V} P\,dV$

convention defines work the system does as negative

Q or heat: related to T but must also capture that there is a natural direction which reactions proceed



remove partition

What happens?

What are the possible distributions?

$2^4 = 16$ options

$\frac{6}{16}$ options with 2:2

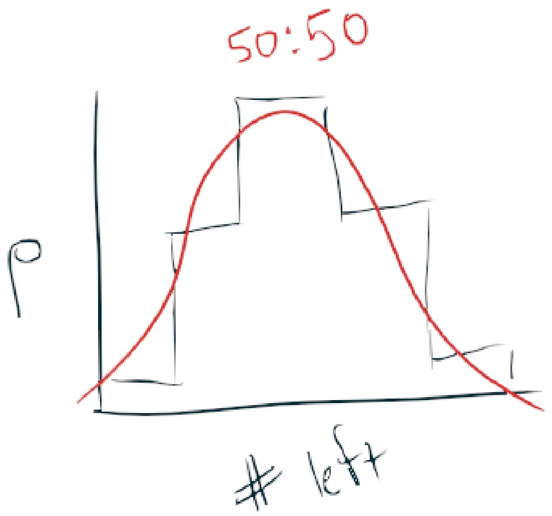
most probable state

2nd law says

$$dS = \frac{dQ}{T}$$

So

$$\Delta U = TdS - PdV$$



entropy is minimized when a system is at the most probable state

causes change towards max p