→ Don't be afraid to interrupt

→ Signal any problem

→ General introduction — Easy

Two-nucleon system

Three-nucleon system ] dry (difficult)

Nuclear models

→ Geared towards theoreticians

Experimentalist ⇒ concentrate on the conceptual level (ideas, etc)

techniques, formalism

→ Evaluation → Exercises (presentation)

Exercise ~~sheets~~ sets → choose (extra points)

15 points → lenient correction

↳ no copying

You can ask

2–3 minutes break now

(first, some questions)

→ begin the $1^{st}$ lesson

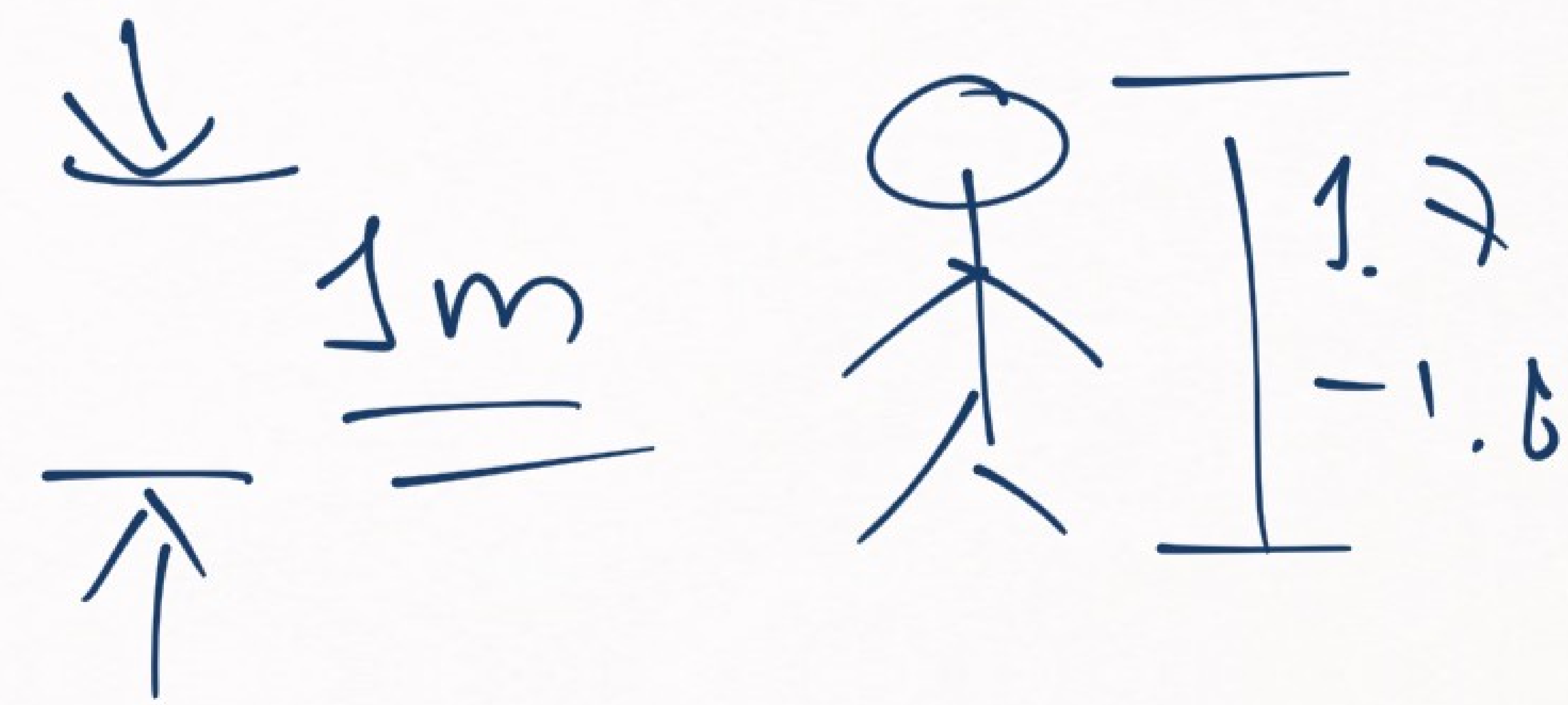
# NUCLEAR PHYSICS ①

"a matter of scales"

↓

what are "scales" in physics
how to use them to understand physics

Scale (尺度) →




How we view physics depends on the scale

Scales → from very big to very small

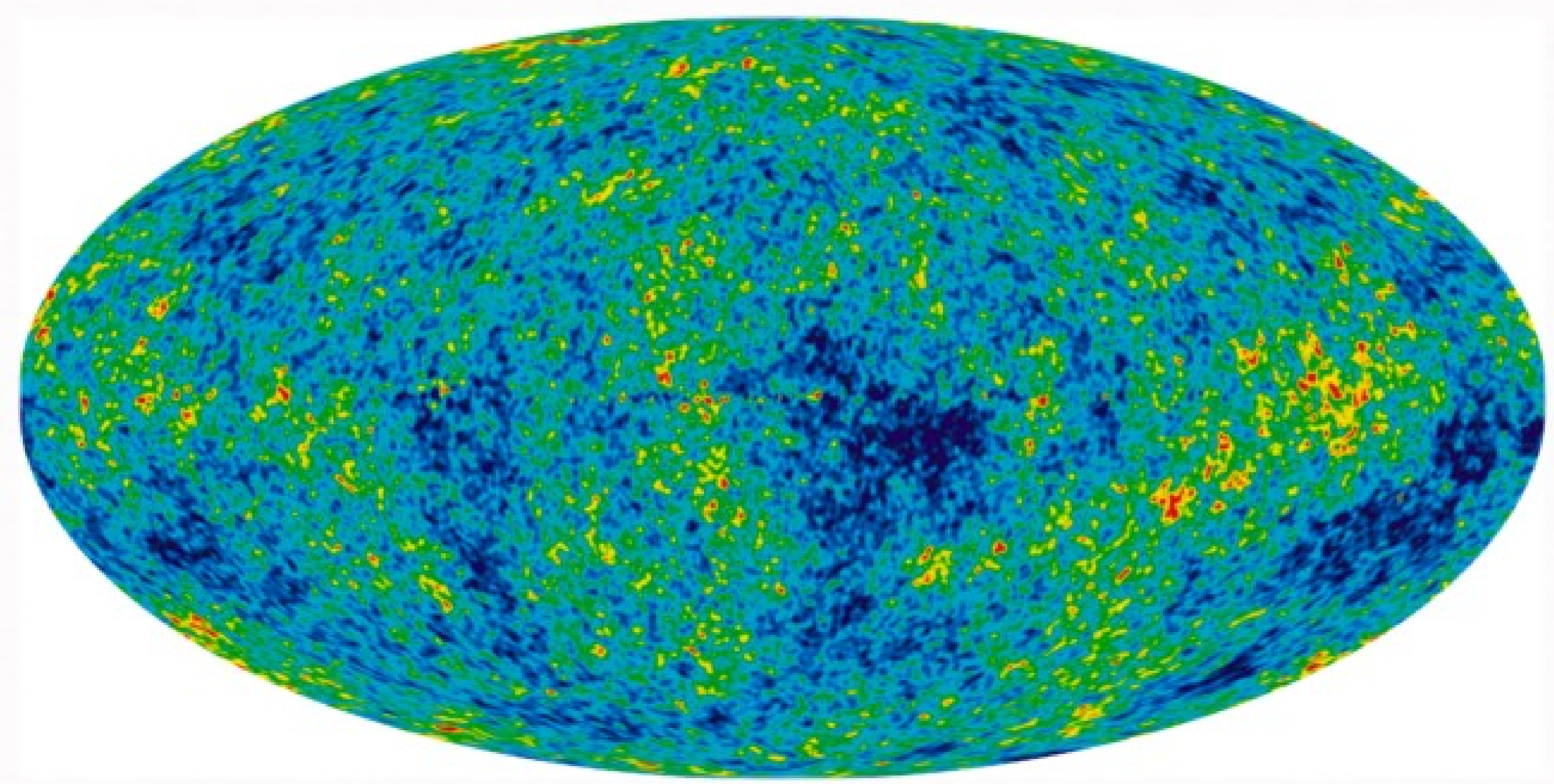
Each scale → different understanding of physics

metaphysics

"εν το παν" (all is one)

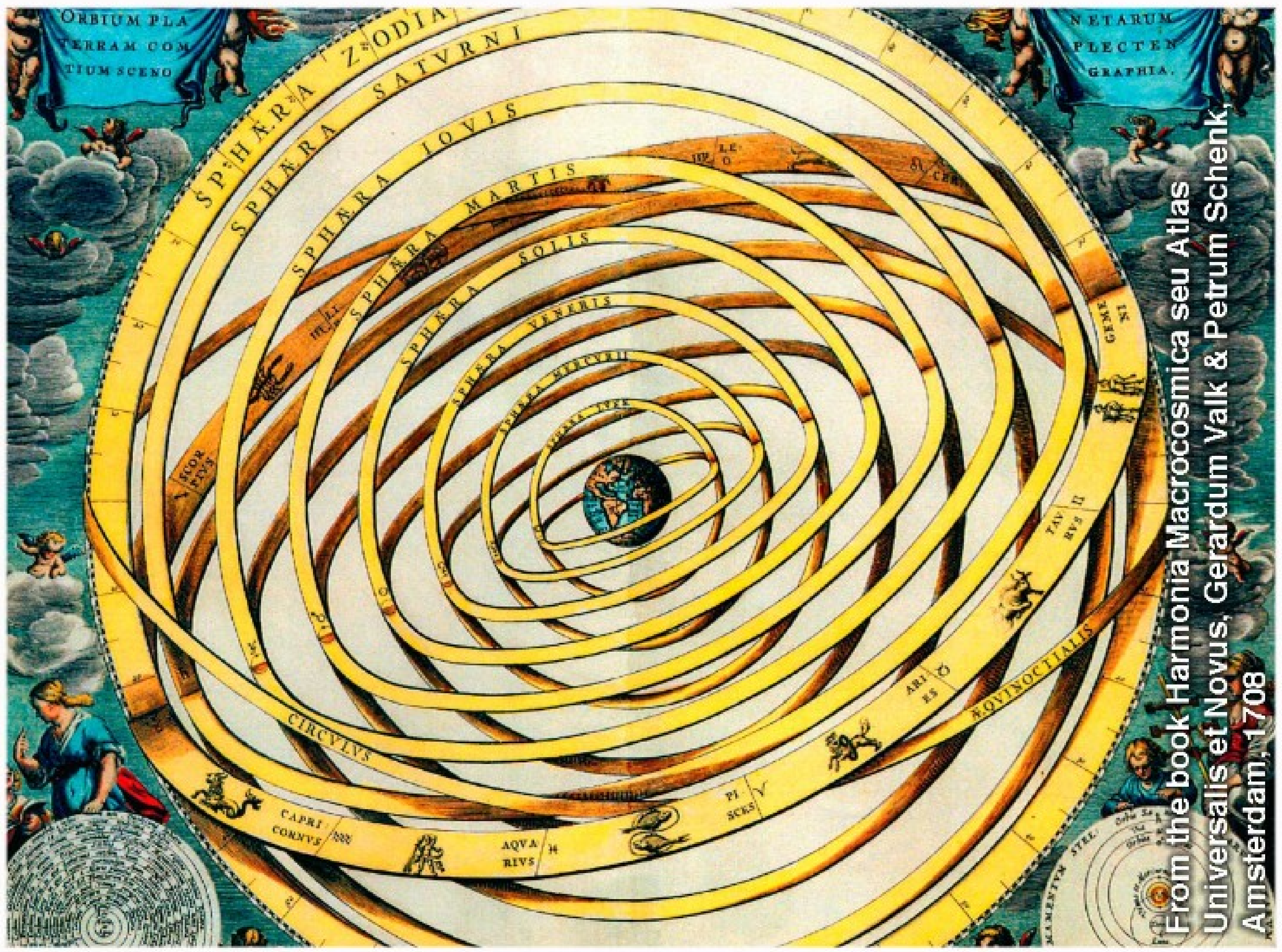
$\infty$

$10^9$ light years → cosmology



$10^3 - 10^5$ light years → astrophysics

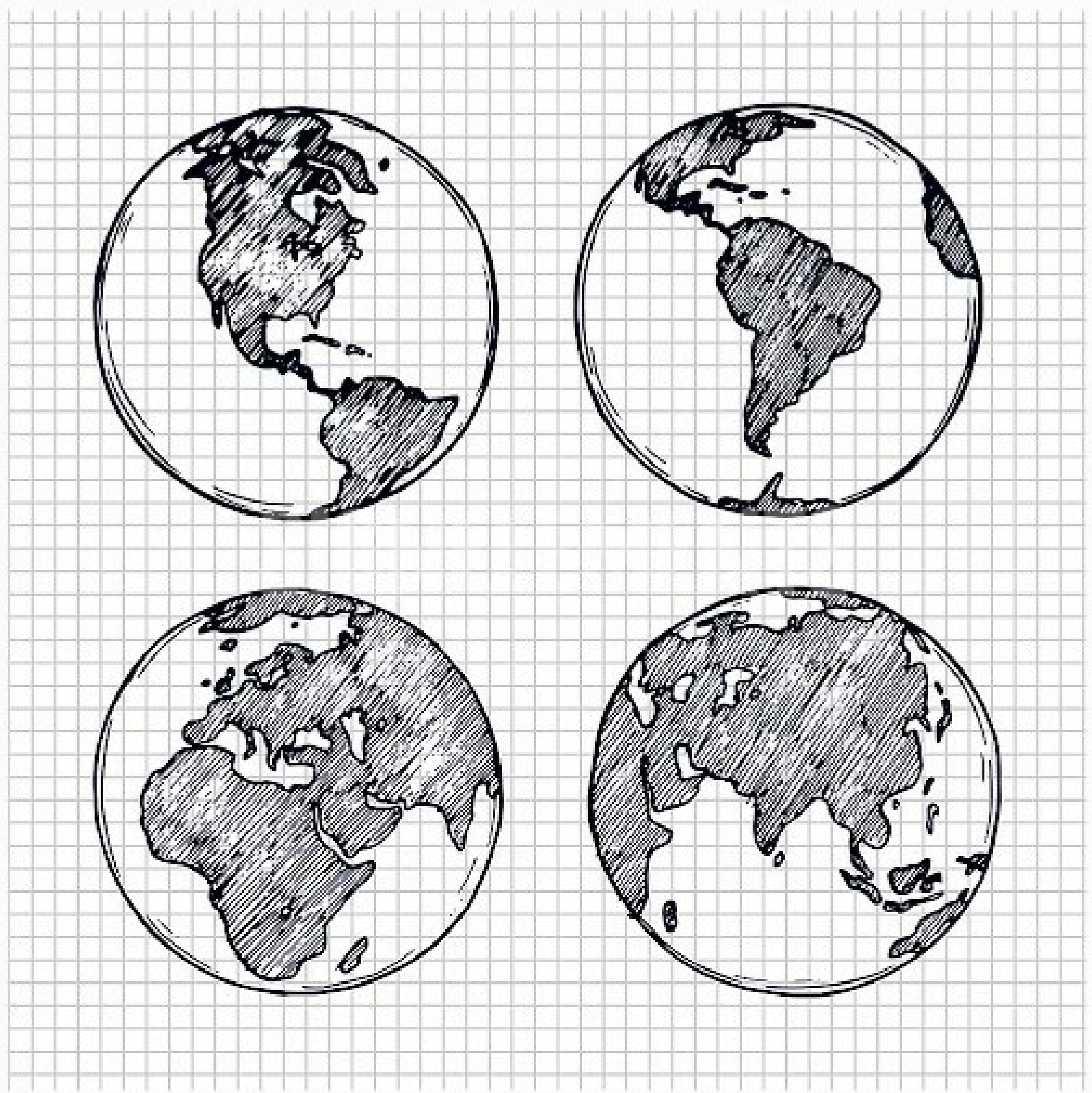
100 a.u. (astronomical units)




→ solar system

classical mechanics

$10^4$ km → geography,
ecology,
climate

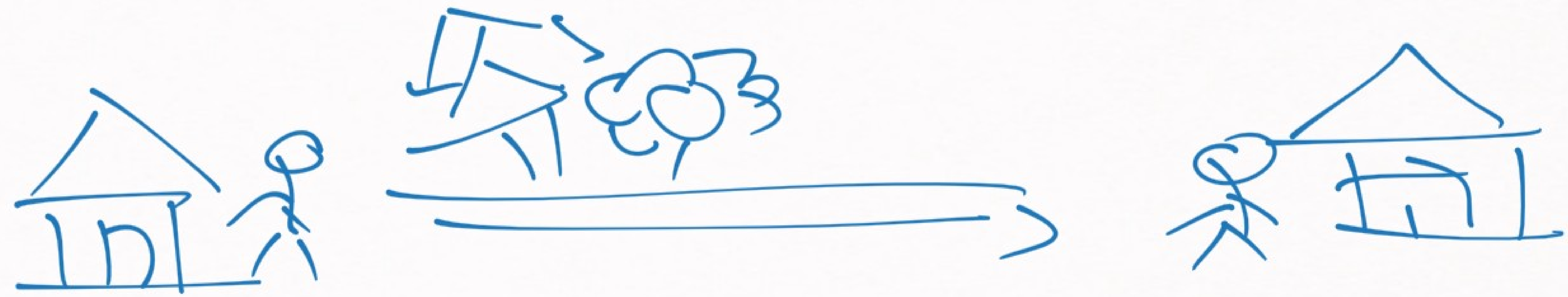


$10^3$ km →

→ countries
economy
sociology

concepts change
w/ the scale

1km



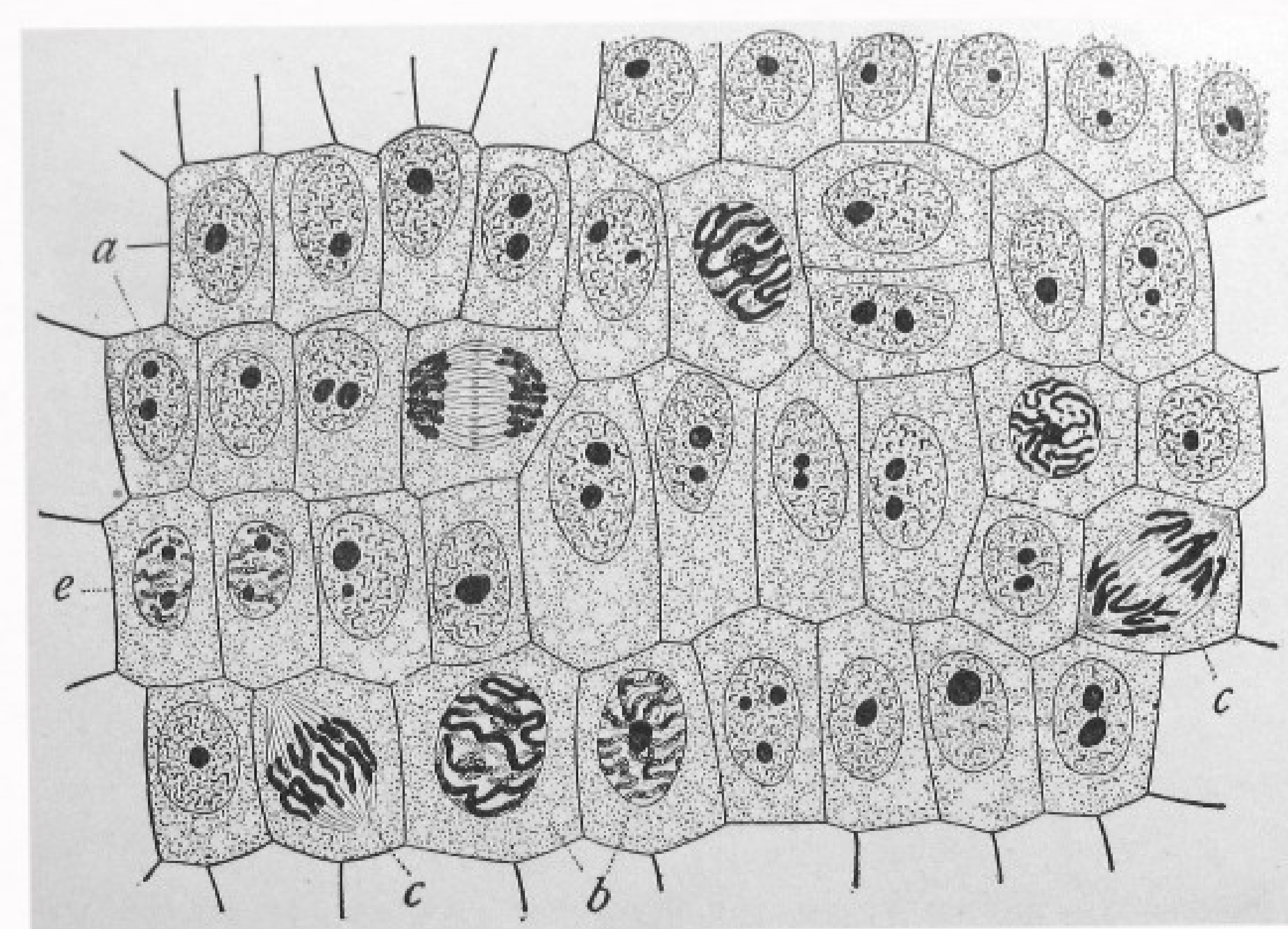
social life

Beihang campus size

1m → classical mechanics
people

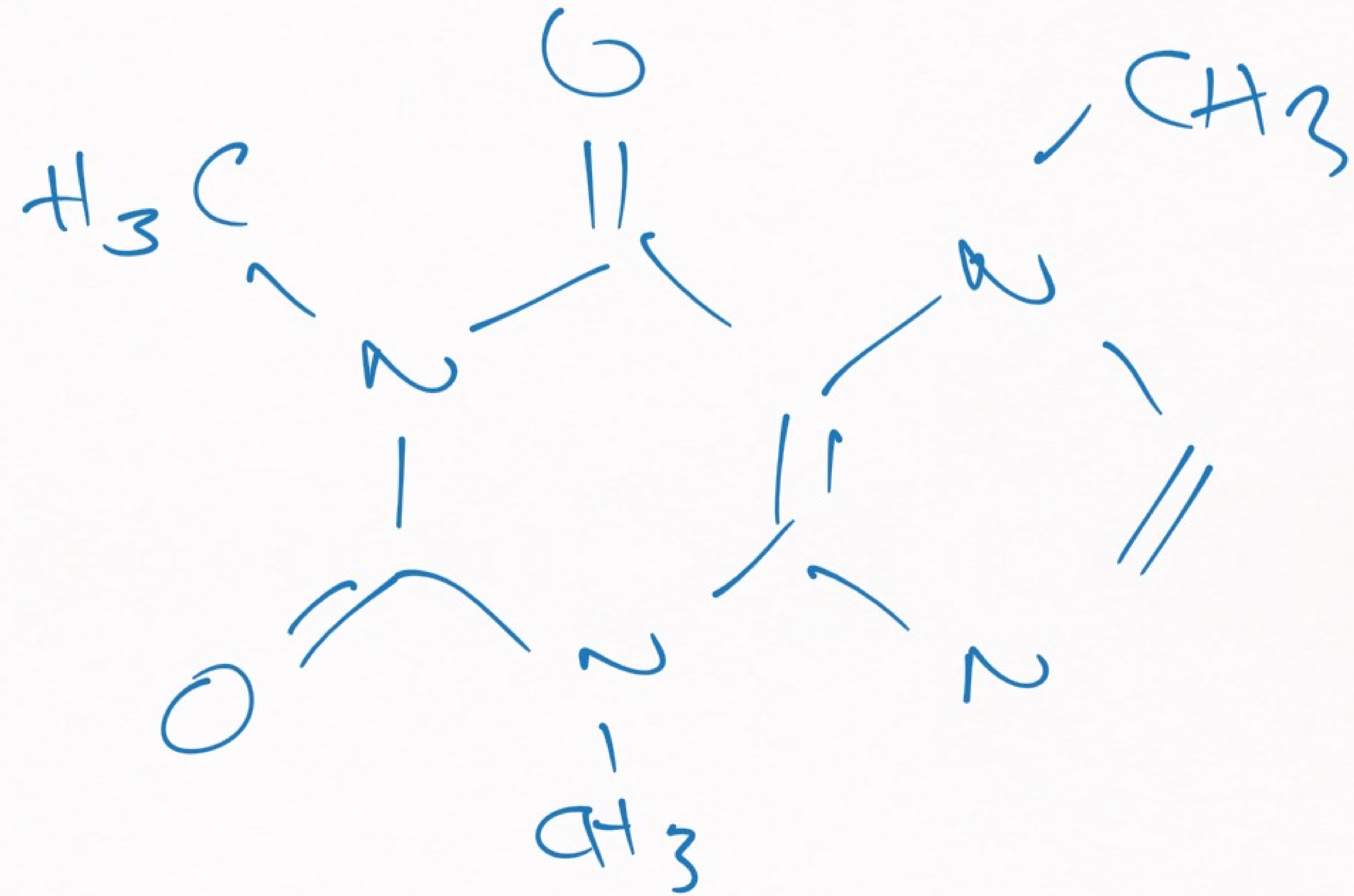
⇓

$10^{-5}$ m → biology



$10^{-9}$ m y Å

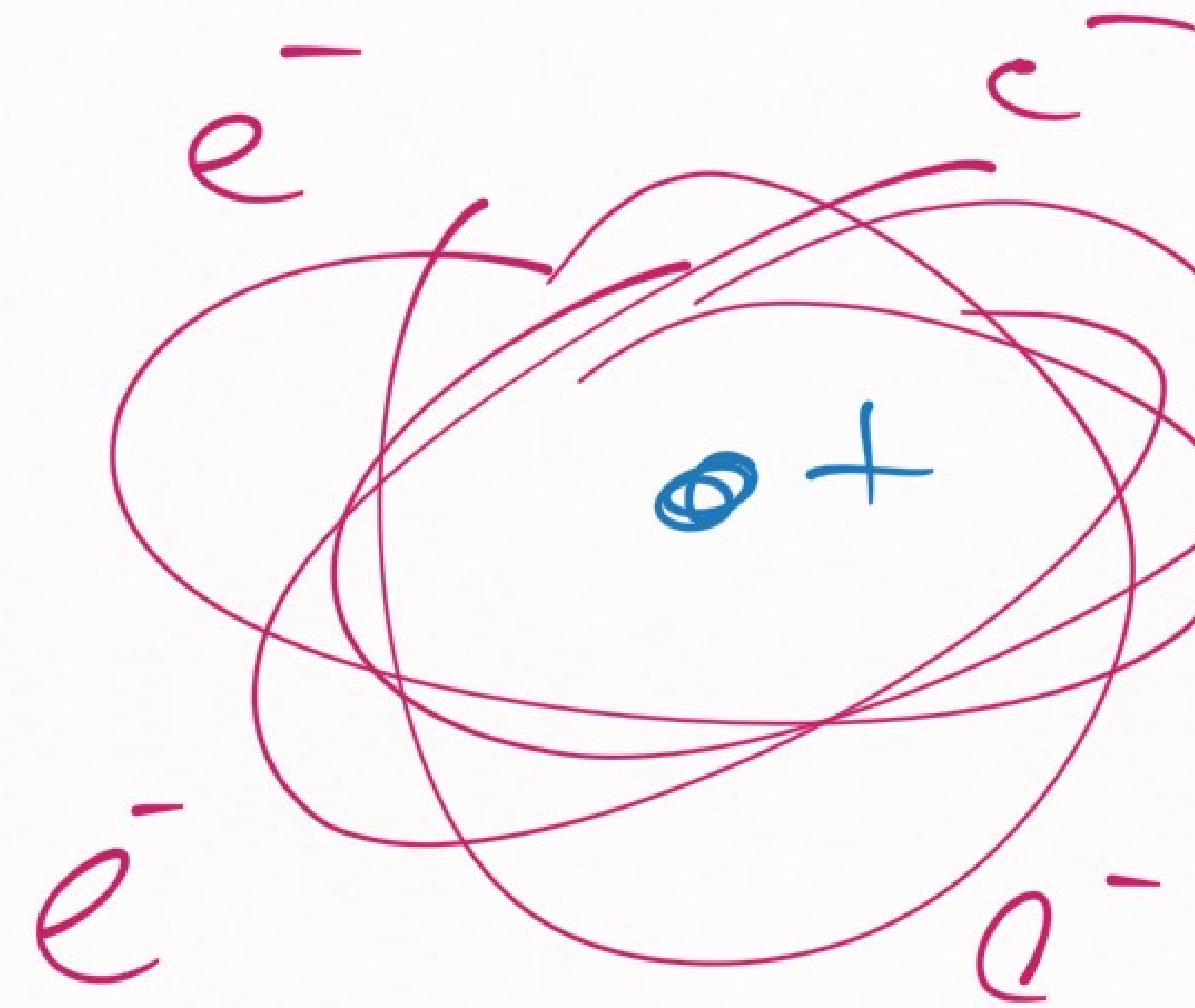
chemistry




(caffeine)

→ useful for physics

$10^{-10}$ m



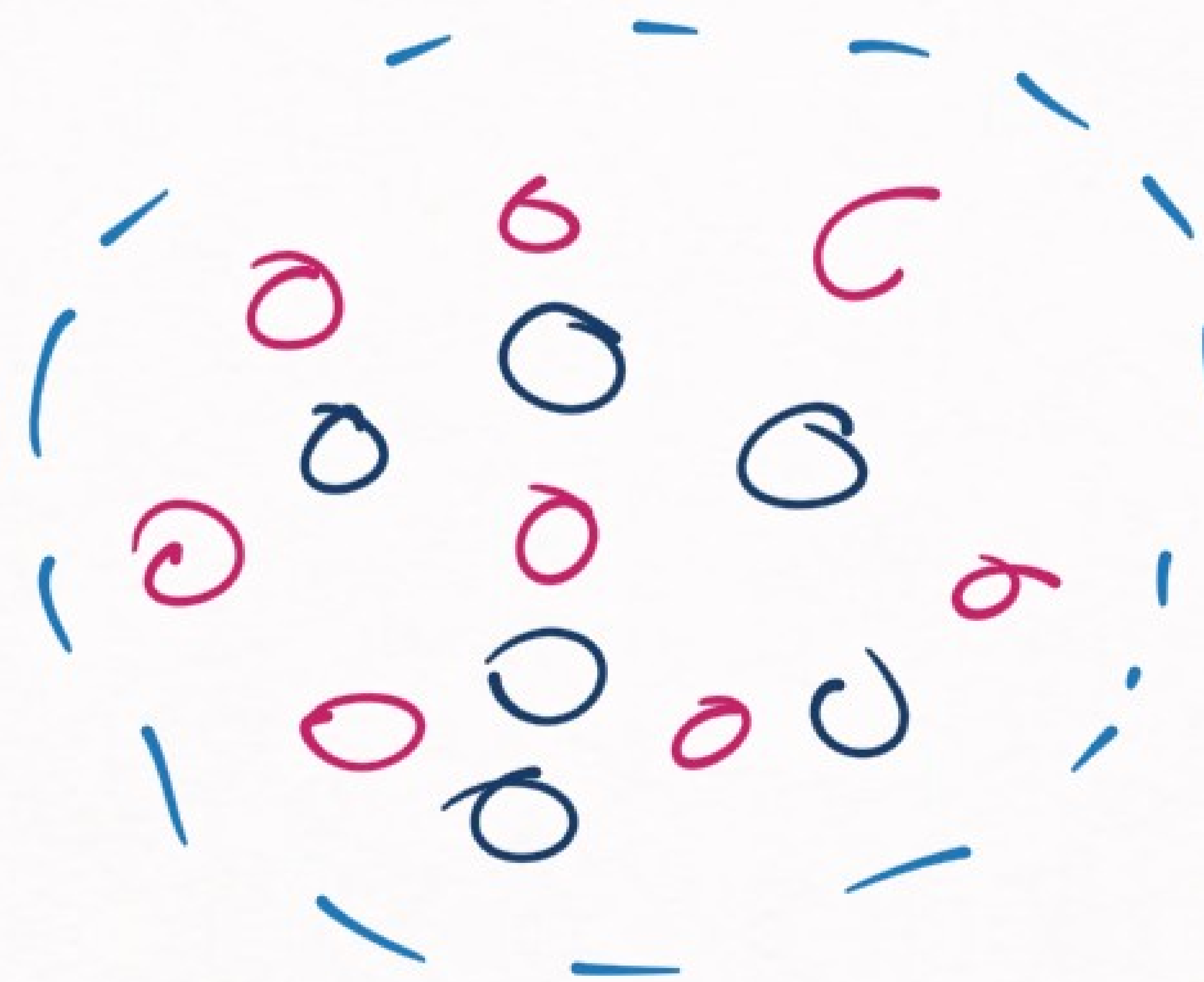

atomic physics

different scales → different world-views

$10^{-15}$ m

↓

units of fm



nucleus

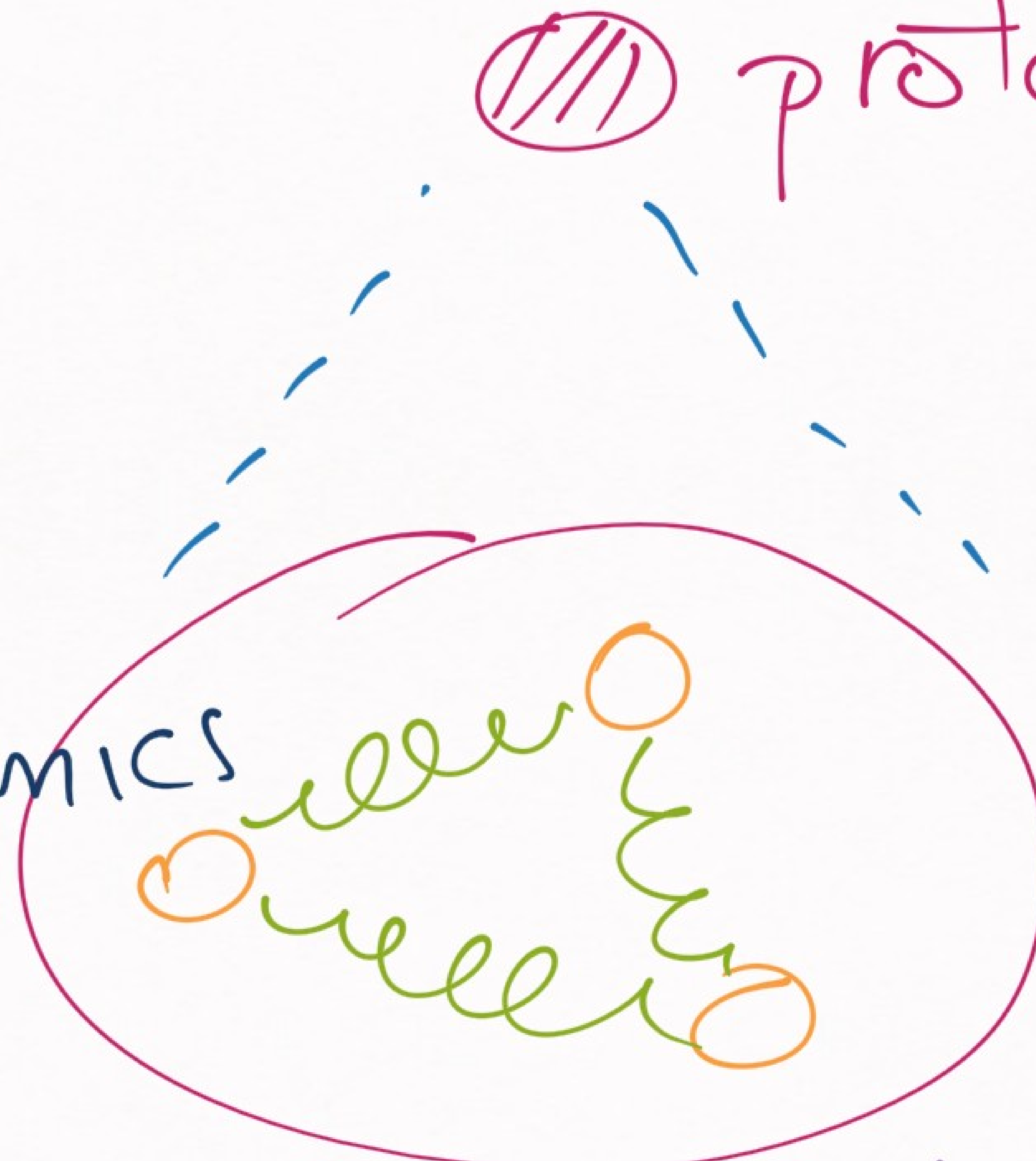
nuclear physis

↓

our course

$10^{-16}$ m

proton



Quantum chromodynamics (QCD)

→ very important

quarks & gluons

$10^{-35}$ m $\longrightarrow$ Planck scale

(quantum gravity)

(nobody knows how it works, yet)

O → metaphysics


physics

[only O/∞ do not have ents]

→ Here we are interested in

$10^{-(15-16)}$ m scales

(nuclear physics & QCD)

→ Back to atomic physics (to understand scale)

→ Question (you guys are shy, but don't be afraid)

→ Rest a pair of minutes before going for atomic physics

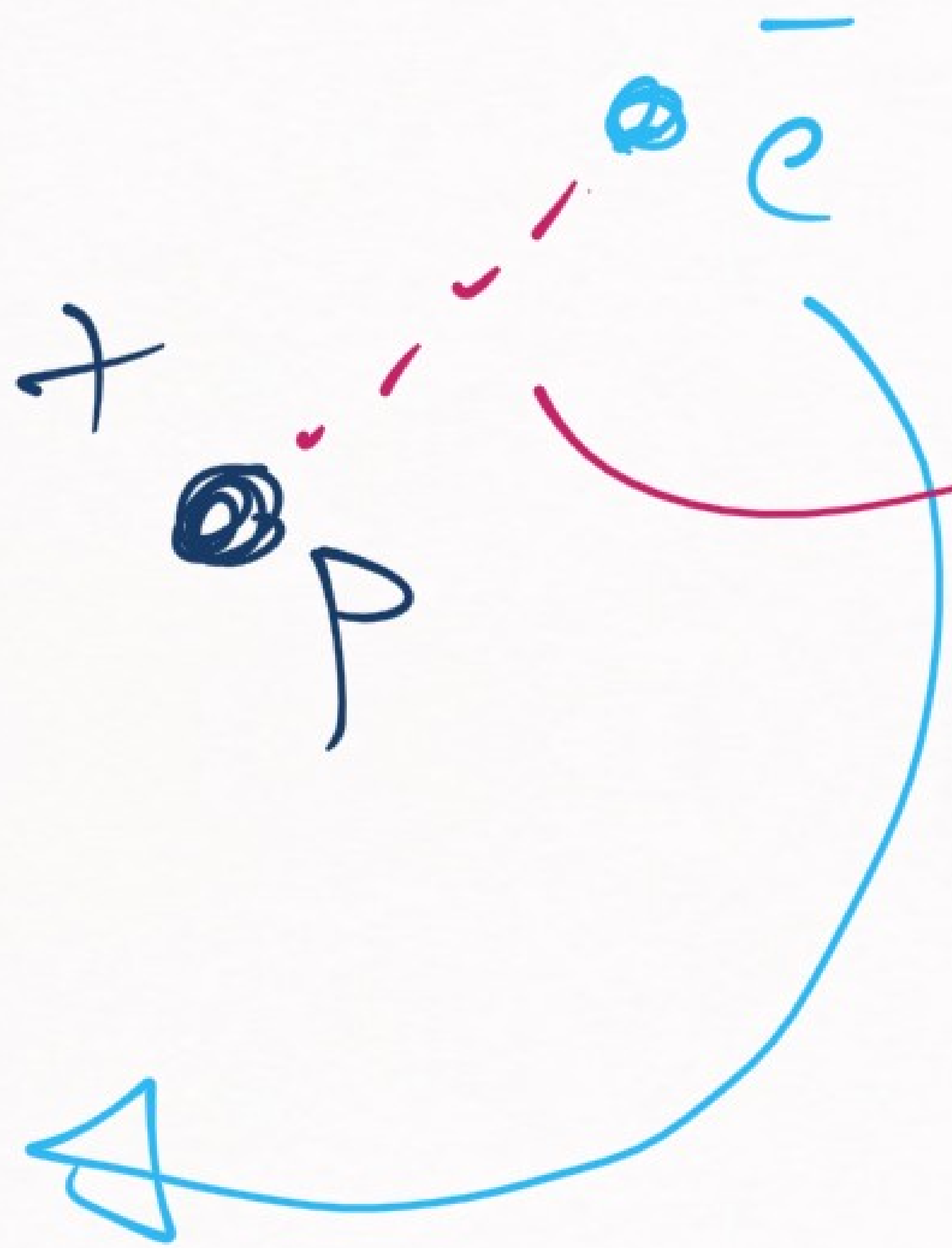
# ATOMIC PHYSICS

→ THE HYDROGEN ATOM

(FROM THE SCALE VIEWPOINT)

↓

why scales are important




Coulomb force

$$V(r) = -\frac{\alpha}{r}$$

$\alpha \simeq \frac{1}{137}$ (fine structure constant)

$r$ → radius

Use the Schrödinger equation:

$$\left[-\frac{1}{2\mu}\vec{\nabla}^2 + V(\vec{r})\right]\psi(\vec{r}) = E_B\,\psi(\vec{r})$$

- $\frac{1}{2\mu}$ → reduced mass ⇒ $\frac{1}{\mu} = \frac{1}{m_e} + \frac{1}{m_p}$ (electron & proton mass)
- $V(\vec{r})$ → Coulomb potential
- $\psi(\vec{r})$ → wave function
- $E_B$ → binding energy

$$E_B = -\frac{\gamma_B^2}{2\mu}$$

$\gamma_B$ → wave number

$\mu$ → reduced mass

Rewrite the equation:

$$\left[-\nabla^2 - \frac{2\mu a}{r}\right]\psi(\vec{r}) = -\gamma_B^2\,\psi(\vec{r})$$

INPUT → OUTPUT (prediction)

$$\left[-\nabla^2 - \frac{2\mu\alpha}{r}\right]\psi(\vec{r}) = -\gamma_B^2\,\psi(\vec{r})$$

$$\mu\alpha = \frac{1}{a_B} \longrightarrow a_B = \underline{\text{Bohr radius}}$$

(length scale)

$\alpha = \frac{1}{137}$ (pure number)

$\mu$ (mass) $\longrightarrow [E] = [L]^{-1}$

$\Delta x \Delta p \sim \hbar/2 \qquad \Delta E \Delta t \sim \hbar/2$

$[E]^{-1} = [L]$ → conversion factor

$\hbar c = 197.3$ MeV.fm

Example: $m_\pi \simeq 140$ MeV → $\frac{e^{-m r}}{r}$

$$\frac{1}{m_\pi} \simeq \frac{\hbar c}{m_\pi} \simeq \frac{200 \text{ MeV fm}}{140 \text{ MeV}} \simeq 1.4 \text{ fm}$$

WE USE IT ALL THE TIME

$$M_{scale} \rightarrow a_{scale} = \frac{1}{M_{scale}} \left( \frac{\hbar c}{M_{scale}} \right)$$

Planck energy → Planck legth

$1.2 \cdot 10^{19}$ GeV $\qquad 10^{-35}$ m

$1.2 \cdot 10^{22}$ MeV

$$\left[-\nabla^2 - \frac{2}{a_B r}\right]\psi(\vec{r}) = -\gamma_B^2 \psi(\vec{r})$$

$a_B$ : Bohr radius $\rightarrow$ $\left[ a_B = \frac{1}{\mu\alpha} \simeq \frac{137}{0.5} MeV^{-1} \right]$

$\simeq 270\, MeV^{-1} \times (\hbar c)$

$\simeq 5.4 \cdot 10^{4}$ $\left[\, fm \,\right]$

$\frac{1}{\mu} = \frac{1}{m_e} + \frac{1}{m_p} \simeq \frac{1}{m_e}$

$m_e \ll m_p$ $(0{,}5\, GeV \ll 940\, MeV)$

$\left[\, 0{,}54\, \mathring{A} \,\right]$

$$\left[-\nabla^2 - \frac{2}{a_B r}\right]\psi(\vec{r}) = -\gamma_B^2\,\psi(\vec{r})$$

INPUT → OUTPUT : $\gamma_B$

$([E] \sim [L]^{-1})$

SCALES: $a_B$ → $\gamma_B \propto \frac{1}{a_B}$

ONLY POSSIBILITY

SCALES → hydrogen atom only has

one scale

$A$ $a_B$

→ every property of the hydrogen atom will only depend on $a_B$

$$\gamma_B = \frac{c}{a_B}$$

$$\left(-\nabla^2 - \frac{2}{a_B r}\right)\psi = -\gamma_B^2 \psi$$

no $\mu$ (explicitly)

$$E_B = -\frac{1}{2\mu}\left(\frac{c}{a_B}\right)^2$$

$\rightarrow$ inert scale

$$\sqrt{\langle r^2 \rangle} = \sqrt{\langle \psi | r^2 | \psi \rangle} = d\, a_B$$

$r_B = \frac{c}{a_B}$ $\sqrt{\langle r^2 \rangle} = d\, a_B$

<u>Poll</u>: how large are $c$ & $d$?

$c \sim \mathcal{O}(1)$

$d \sim \mathcal{O}(1)$

} naturalness

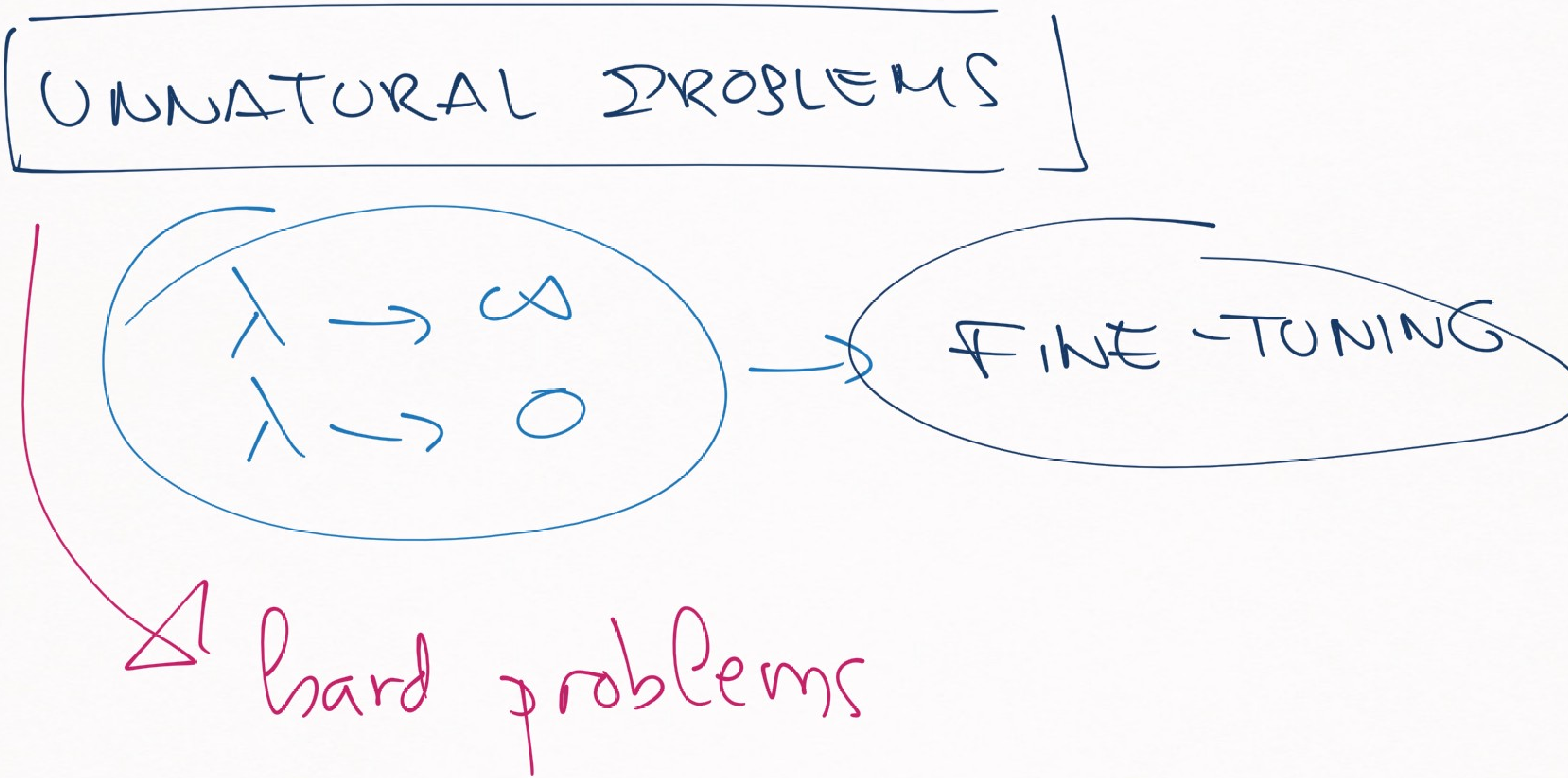
NATURAL PROBLEM → easy problems

$\exists$

SYSTEM → A SCALE $(a_s)$

Observable $\hat{O}$ $[\hat{O}] = [L]^d$

$\langle \hat{O} \rangle = \lambda \, a_s^d \Rightarrow \lambda \sim O(1)$


UNNATURAL PROBLEMS
λ → ∞
λ → 0
FINE-TUNING
hard problems

$$r_B = \frac{1}{a_B}$$

$$\sqrt{\langle r^2 \rangle} = \sqrt{3}\, a_B$$

→ atomic physics

natural

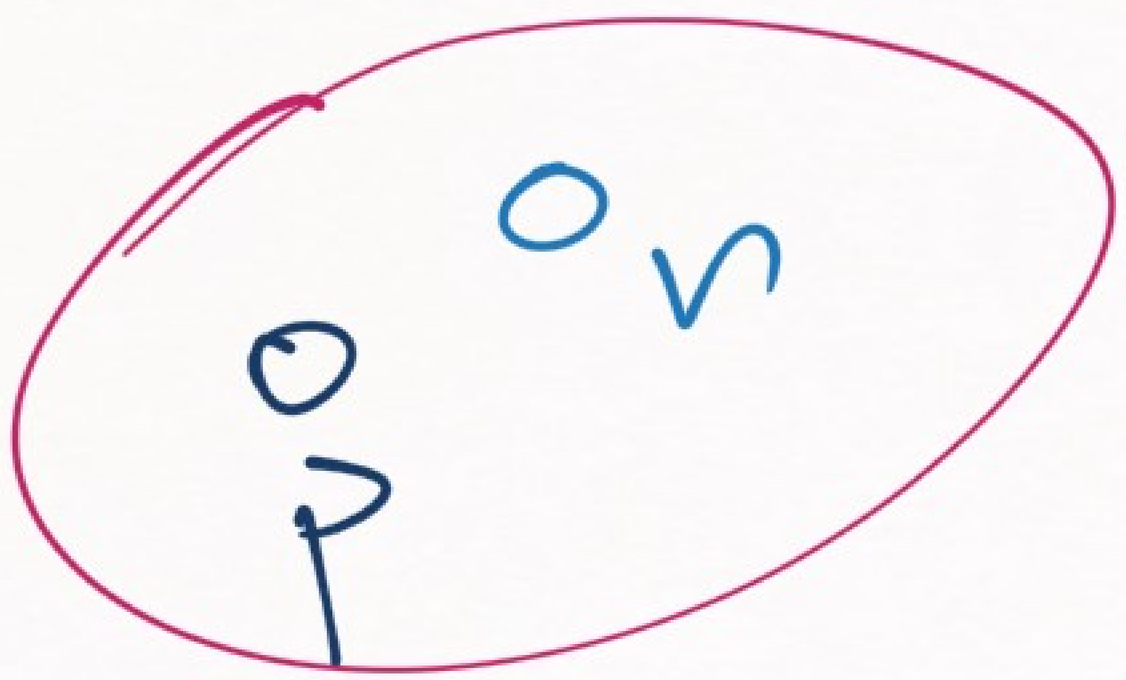
↓

easy

undergraduates → atomic properties w/ a precision of $\frac{1}{10^4} - \frac{1}{10^6}$

# NUCLEAR PHYSICS

$$\frac{1}{m_\pi} \simeq 1.4 \text{ fm}$$




$^3S_1$

$$\gamma \simeq 0.23 \text{ fm}^{-1}$$

$$\frac{1}{\gamma} \simeq 5.4 \text{ fm} \quad \left(\frac{3}{m_\pi}\right)$$

(explained better next lesson)

p → n

(s=0) → singlet state

virtual state : $\gamma \sim 0.04$ → fine-tuning

$$\frac{1}{\gamma} \simeq 8 \text{ MeV}$$

$\ll 140$ MeV

virtual state (np) → reason why thermal neutrons are bad for your health

$\Sigma$

EXTRA ; $\left[-\nabla^2 - \frac{2}{a_B r}\right]\psi(\vec{r}) = -\gamma_B^2\,\psi(\vec{r})$

RESULT

$\gamma_B = \gamma_B(\ldots\ldots)$ $a_B$ , $\nabla^2$

$\nabla^2 \to \frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr} + \ldots$

part of the equation

$$\left(-\frac{d^2}{dr^2} - \frac{2}{a_B r}\right) u(r) = -\gamma_B^2 u(r)$$

(S-wave)

$$\frac{u(r)}{r} = \psi(\vec{r})$$

$$\gamma_B^2 = \gamma_B^2(a_B) \rightarrow f(x)$$

$$f^2(x) \quad f(x) \quad f(x,y)$$

$$\gamma_B = \gamma_B(a_B)$$

$$r_B^2 = \frac{c^2}{a_B^2}$$