



Time is a great teacher, but unfortunately it
kills all its pupils.

Hector Berlioz
(French Composer)

On the nature of
TIME

WHAT IS TIME?



In your groups, discuss for
a few minutes (5 min).

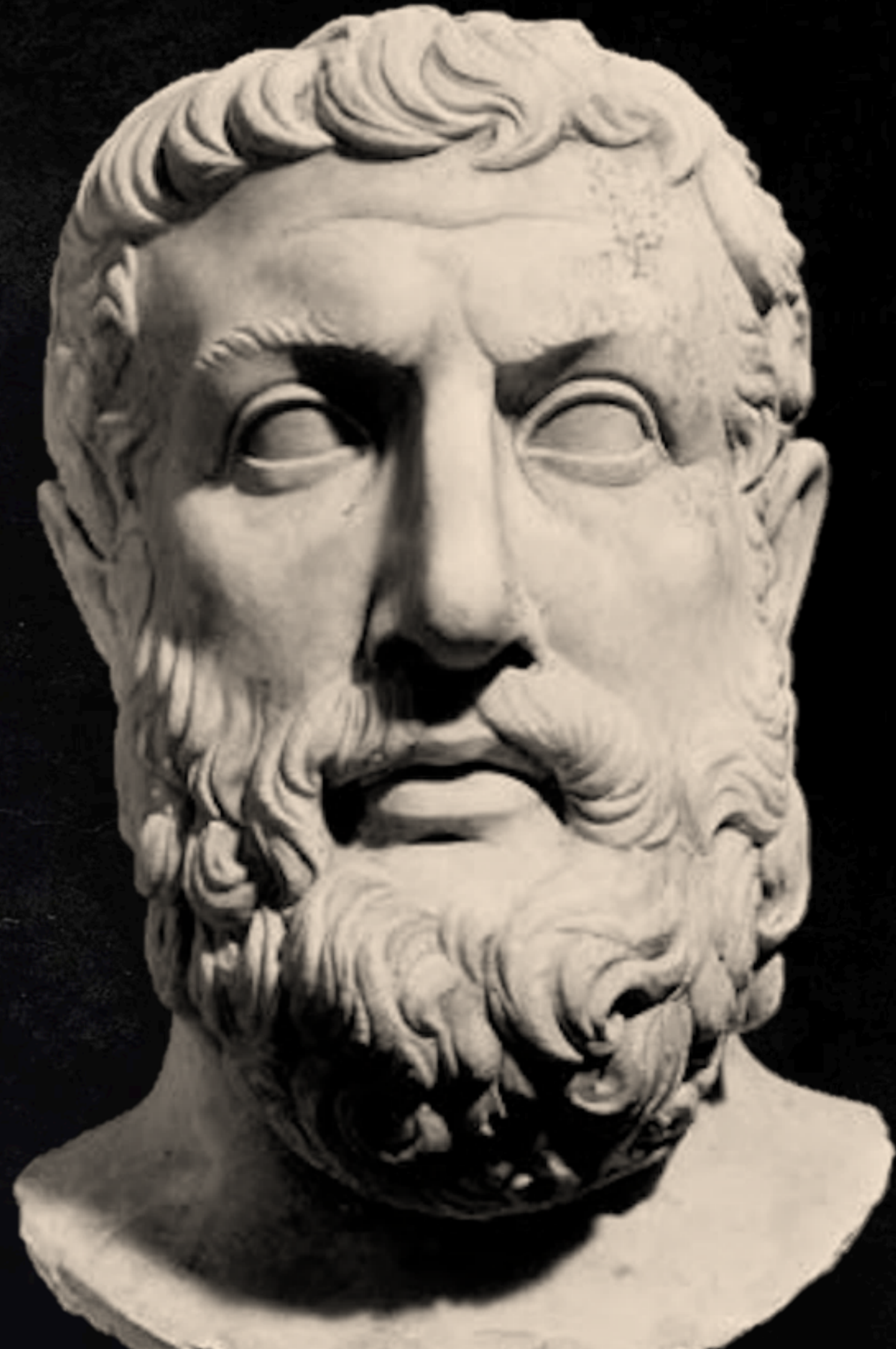


**TIME IS NATURE'S WAY OF KEEPING
EVERYTHING FROM HAPPENING AT ONCE.**

**JOHN WHEELER
(PHYSICIST)**



Philosophy

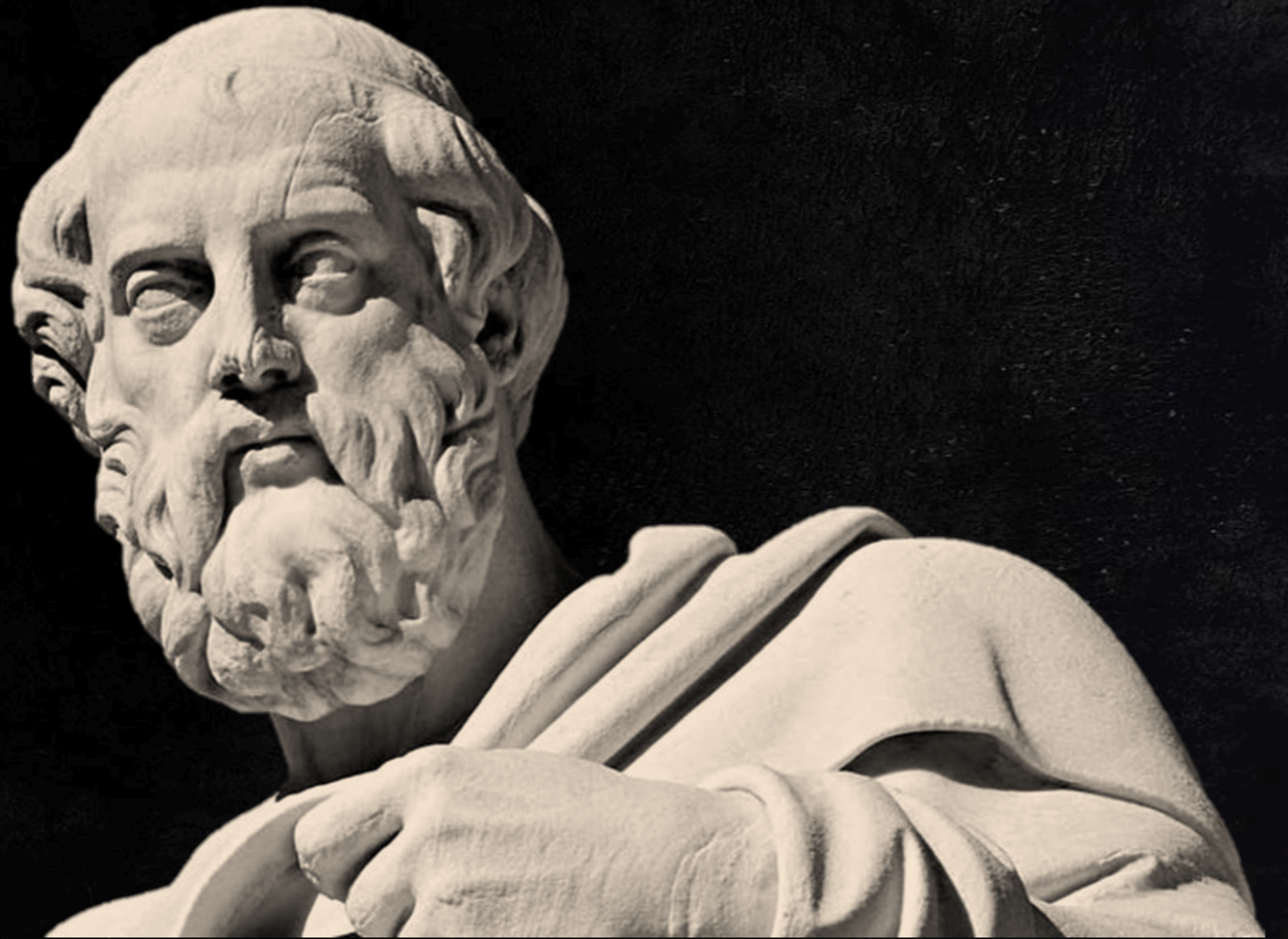


Parmenides



Heraclitus

Plato

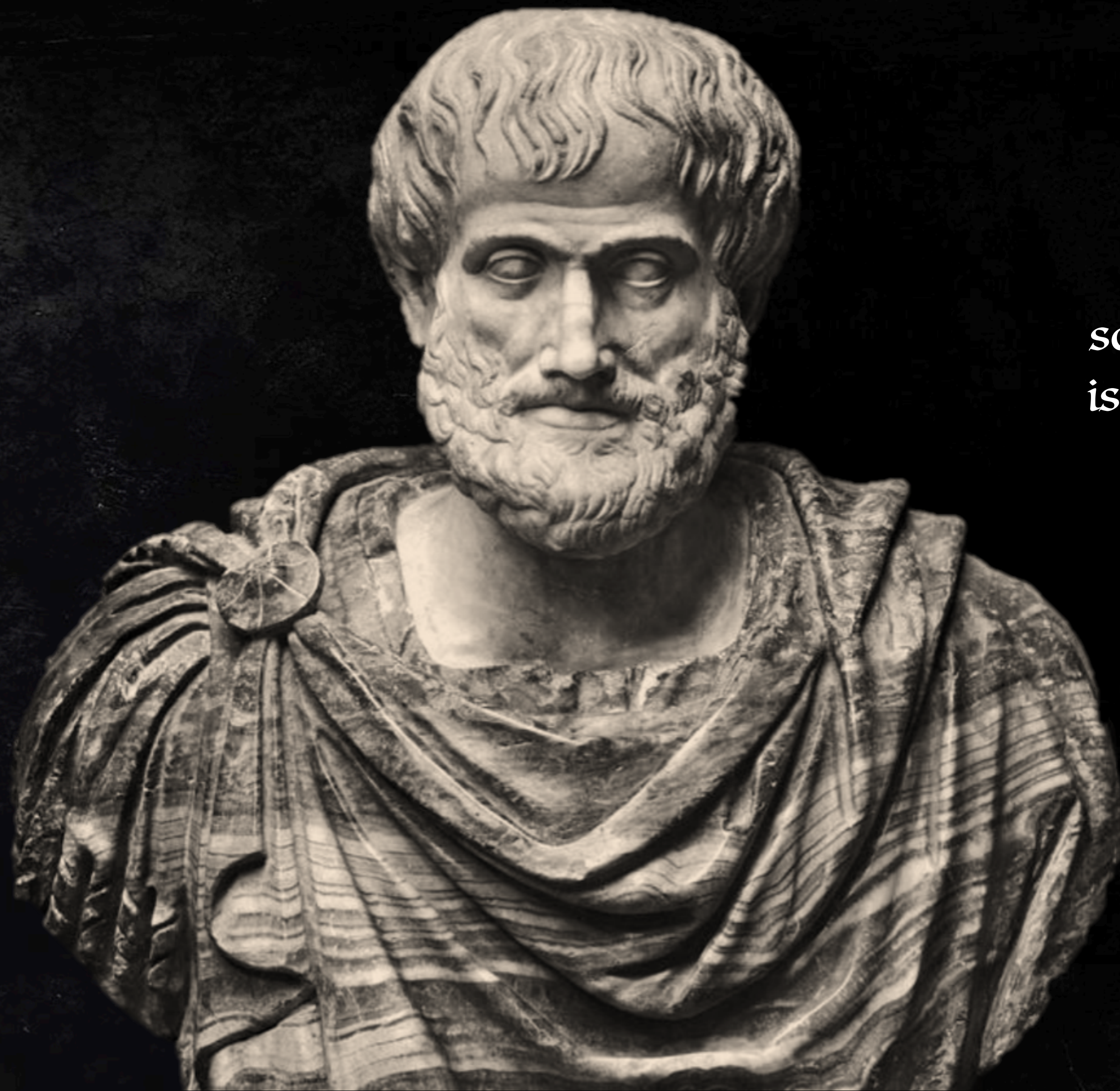






Aristotle

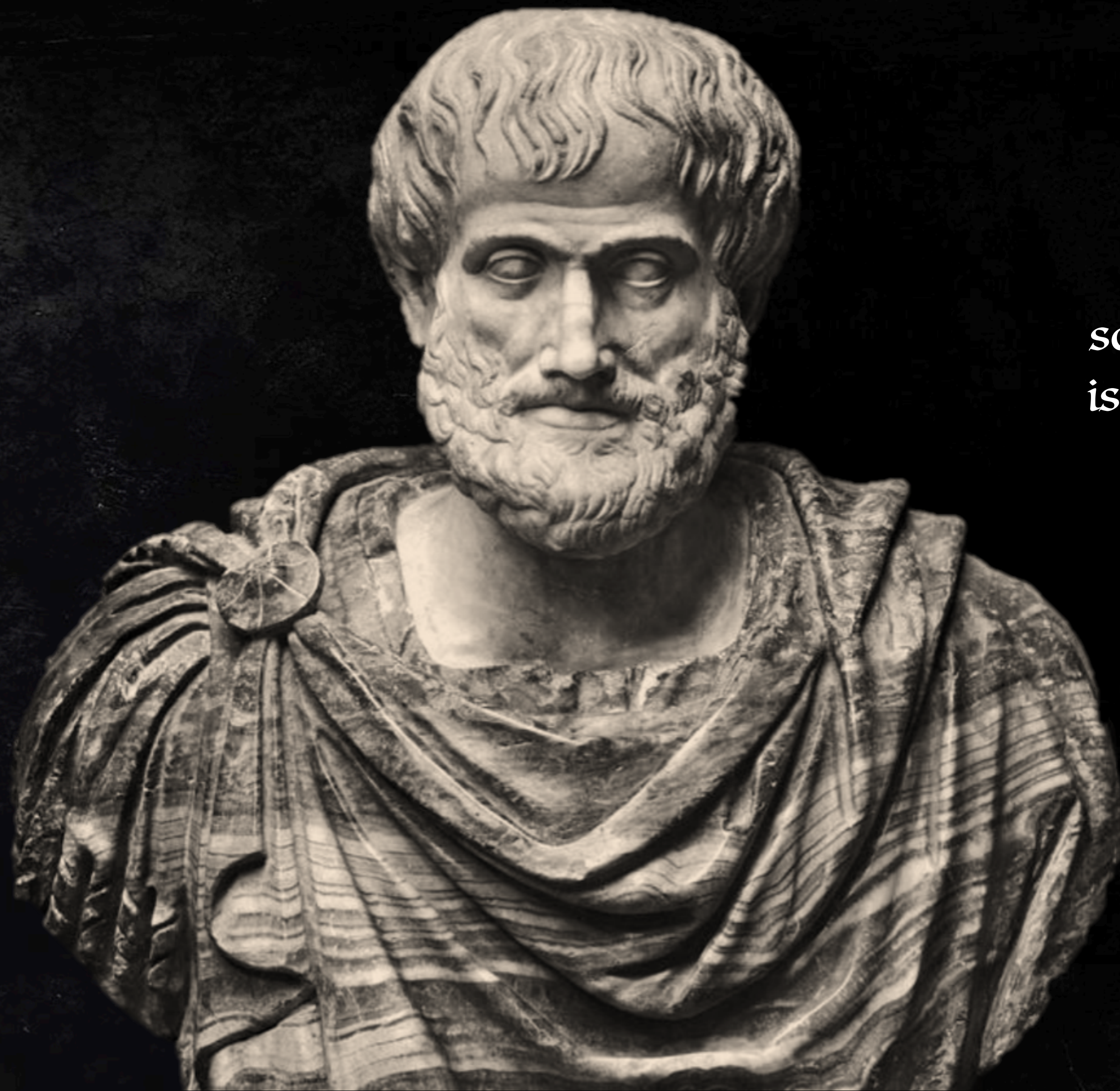
(Physics, book IV)



Aristotle

(Physics, book IV)

"... of number... sometimes there is a minimum,
sometimes not: e.g. of a 'line' ... in respect of size there
is no minimum: *for every line is divided ad infinitum.*
Hence it is so with time."



Aristotle

(Physics, book IV)

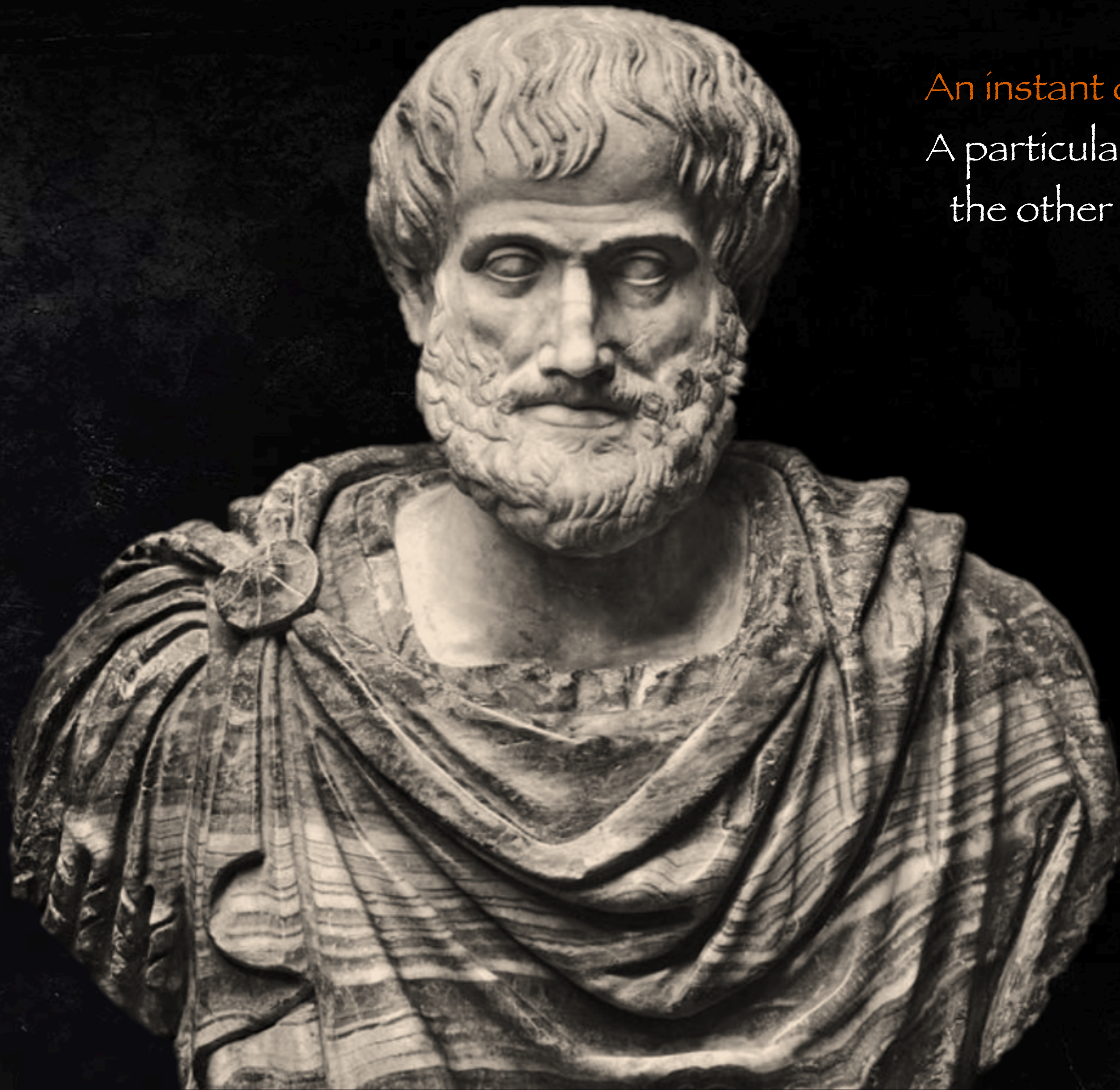
"... of number... sometimes there is a minimum, sometimes not: e.g. of a 'line' ... in respect of size there is no minimum: **for every line is divided ad infinitum.**
Hence it is so with time."

"Further, **there is the same time everywhere at once**, but not the same time before and after."

Aristotle's *Aporia* on Time

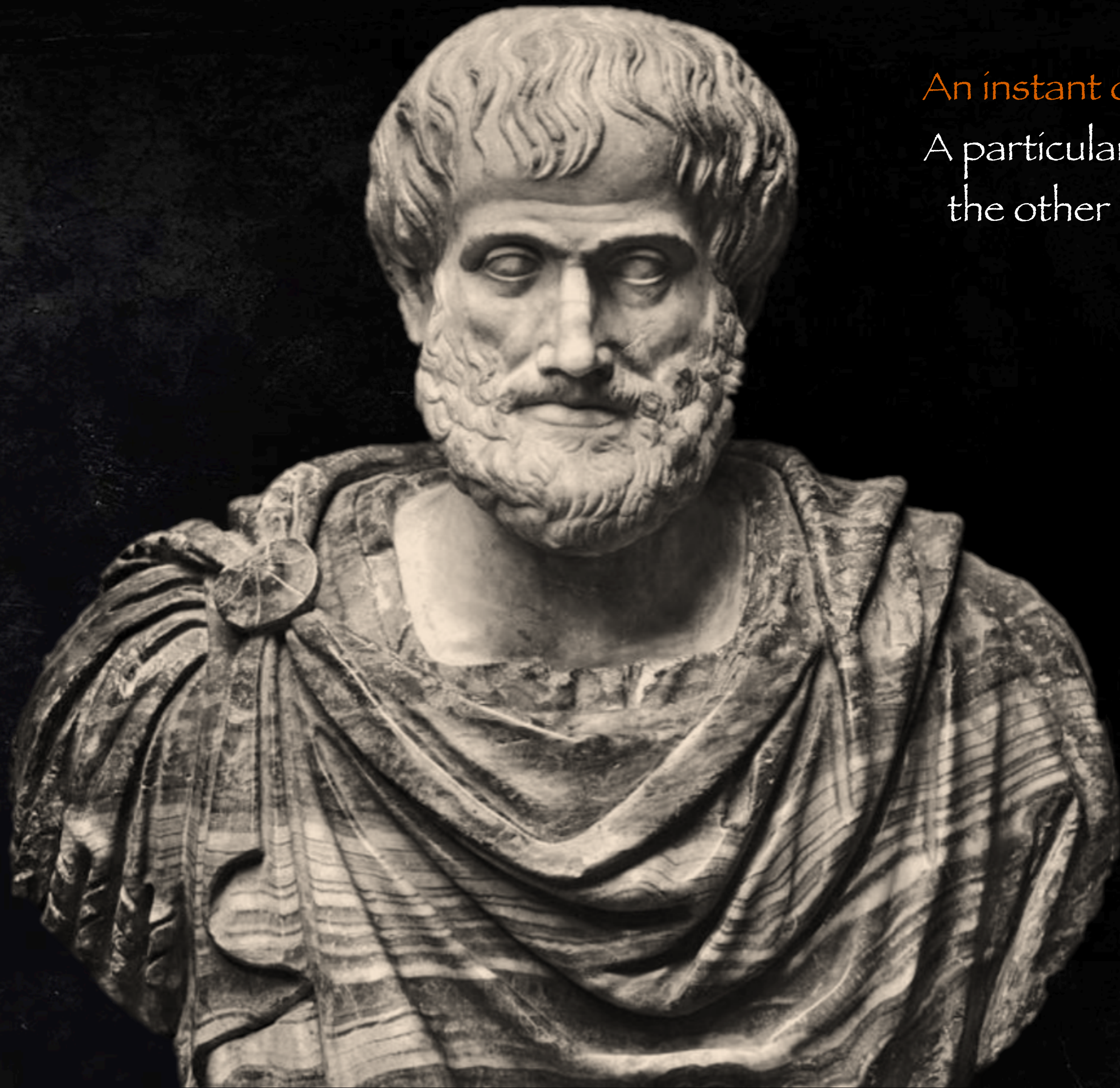


Aristotle's *Aporia* on Time



An instant of time is defined as the exclusion of any other instant of time. A particular case is the current instant (now/present), which excludes all the other instants to be (future) and the ones which were (past). Then,

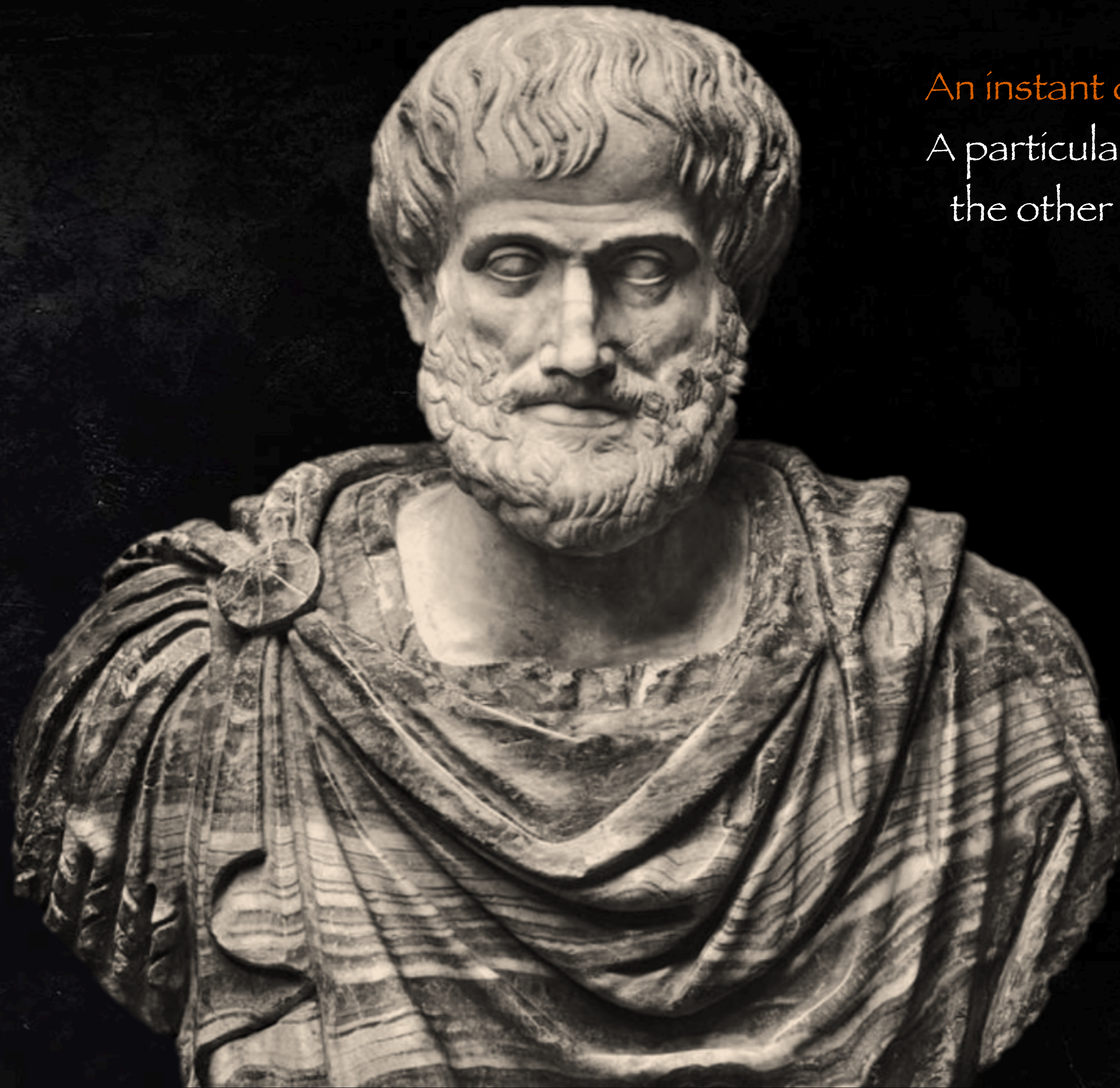
Aristotle's *Aporia* on Time



An instant of time is defined as the exclusion of any other instant of time. A particular case is the current instant (now/present), which excludes all the other instants to be (future) and the ones which were (past). Then,

Either the instant remains, and when an instant remains the now does not become past, and when the now does not become past it is eternal. But we are talking about time, not eternity. Therefore, the instant needs to cease;

Aristotle's *Aporia* on Time

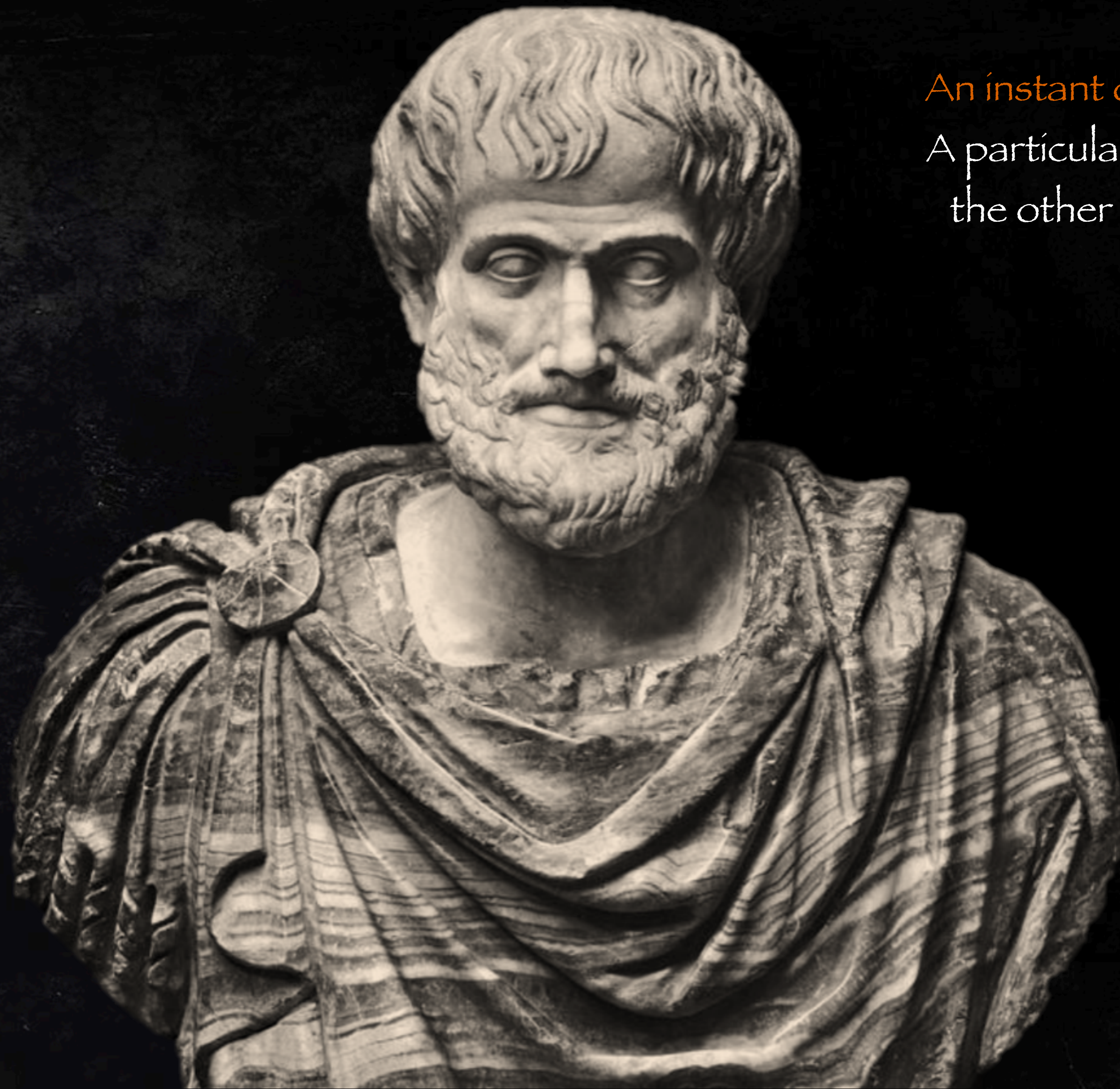


An instant of time is defined as the exclusion of any other instant of time. A particular case is the current instant (now/present), which excludes all the other instants to be (future) and the ones which were (past). Then,

Either the instant remains, and when an instant remains the now does not become past, and when the now does not become past it is eternal. But we are talking about time, not eternity. *Therefore, the instant needs to cease;*

Or the instant ceases to be, but that cannot happen by itself since it is overthrown by another instant. *But nothing destroys anything without a certain temporal coexistence.* That implies some overlapping between the instants, which contradicts the definition of an instant.

Aristotle's *Aporia* on Time



An instant of time is defined as the exclusion of any other instant of time. A particular case is the current instant (now/present), which excludes all the other instants to be (future) and the ones which were (past). Then,

Either the instant remains, and when an instant remains the now does not become past, and when the now does not become past it is eternal. But we are talking about time, not eternity. Therefore, the instant needs to cease;

Or the instant ceases to be, but that cannot happen by itself since it is overthrown by another instant. But nothing destroys anything without a certain temporal coexistence. That implies some overlapping between the instants, which contradicts the definition of an instant.

Time is absurd!



Questions or
thoughts?

Augustine of Hippo

(Confessions, book XI)

"When we talk of it, we comprehend what we say. We also understand what others talk of it. What is, then, time? **If no one asks me, I know**; if I want to explain it to whom asked me the question, then I do not."



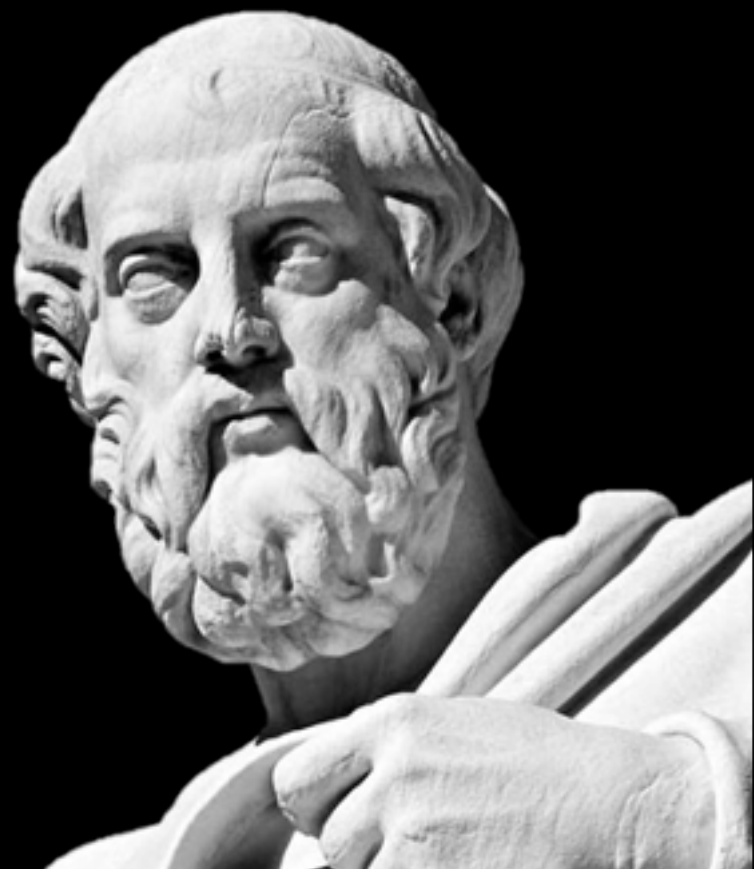
"I dare to declare... that, if nothing survives,
there would not be future time, and *if*
nothing exists now, there would not be
present time."



"I dare to declare... that, if nothing survives,
there would not be future time, and *if
nothing exists now, there would not be
present time.*"

"About the present, if it was always present, and if
it did not become past, it would not be time
anymore, but eternity. *But if the present, in order
to be time, needs to become past, how we can say it
exists, since the cause of its existence is the same
cause for its nonexistence?"*





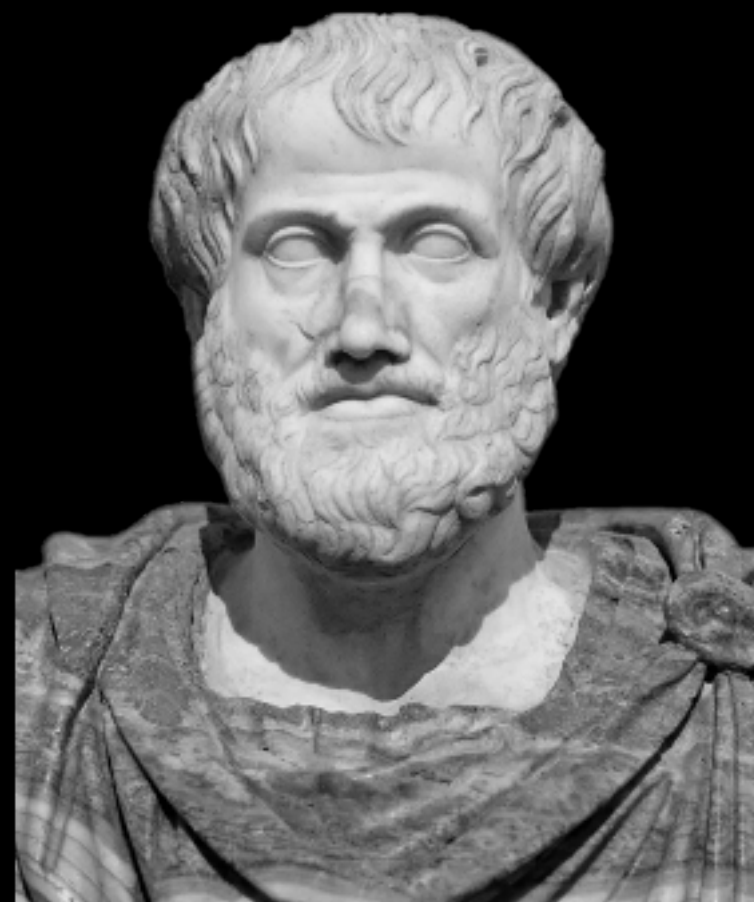
Plato



Augustine of
Hippo



George
Berkely



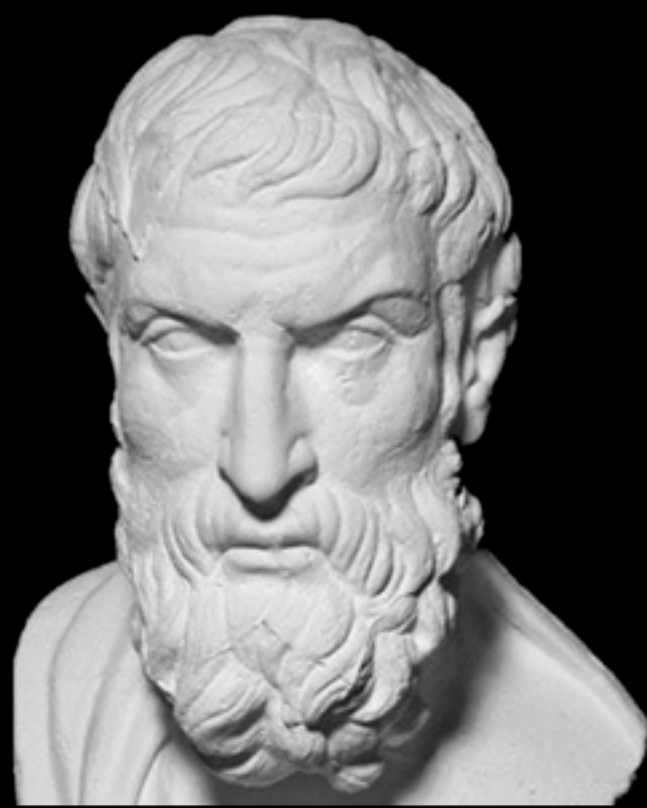
Aristotle



Émilie du
Châtelet



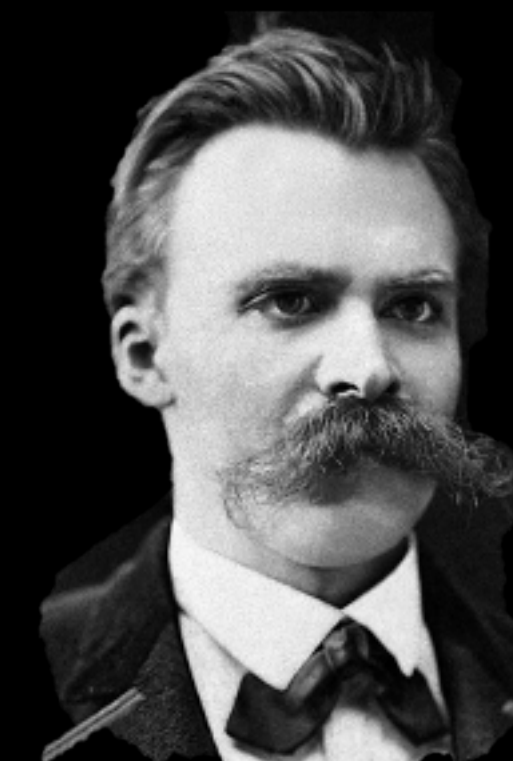
Immanuel
Kant



Epicurus



David
Hume

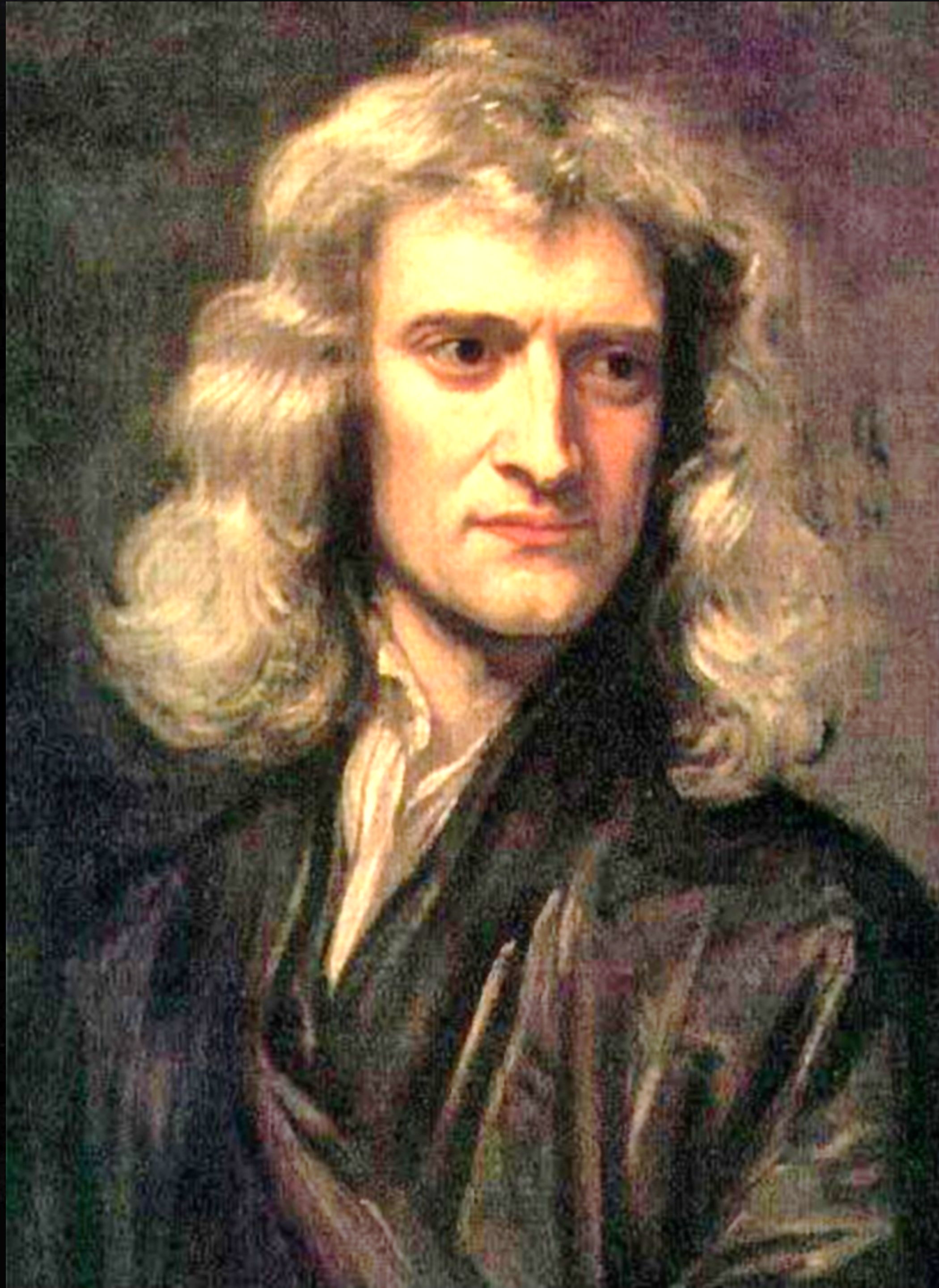


Friedrich
Nietzsche



PHYSICS

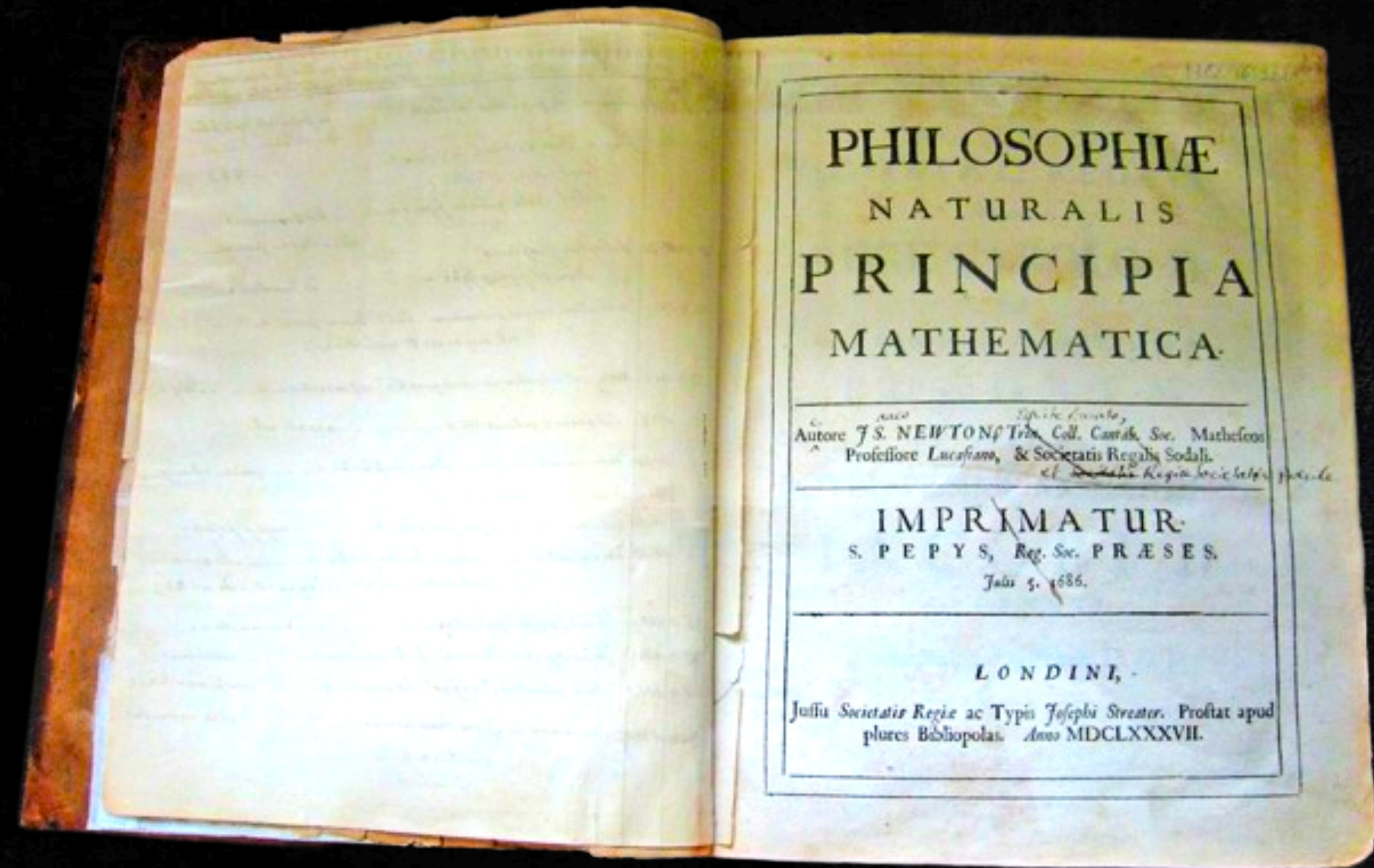
**ISAAC
NEWTON**



(BOOK I)

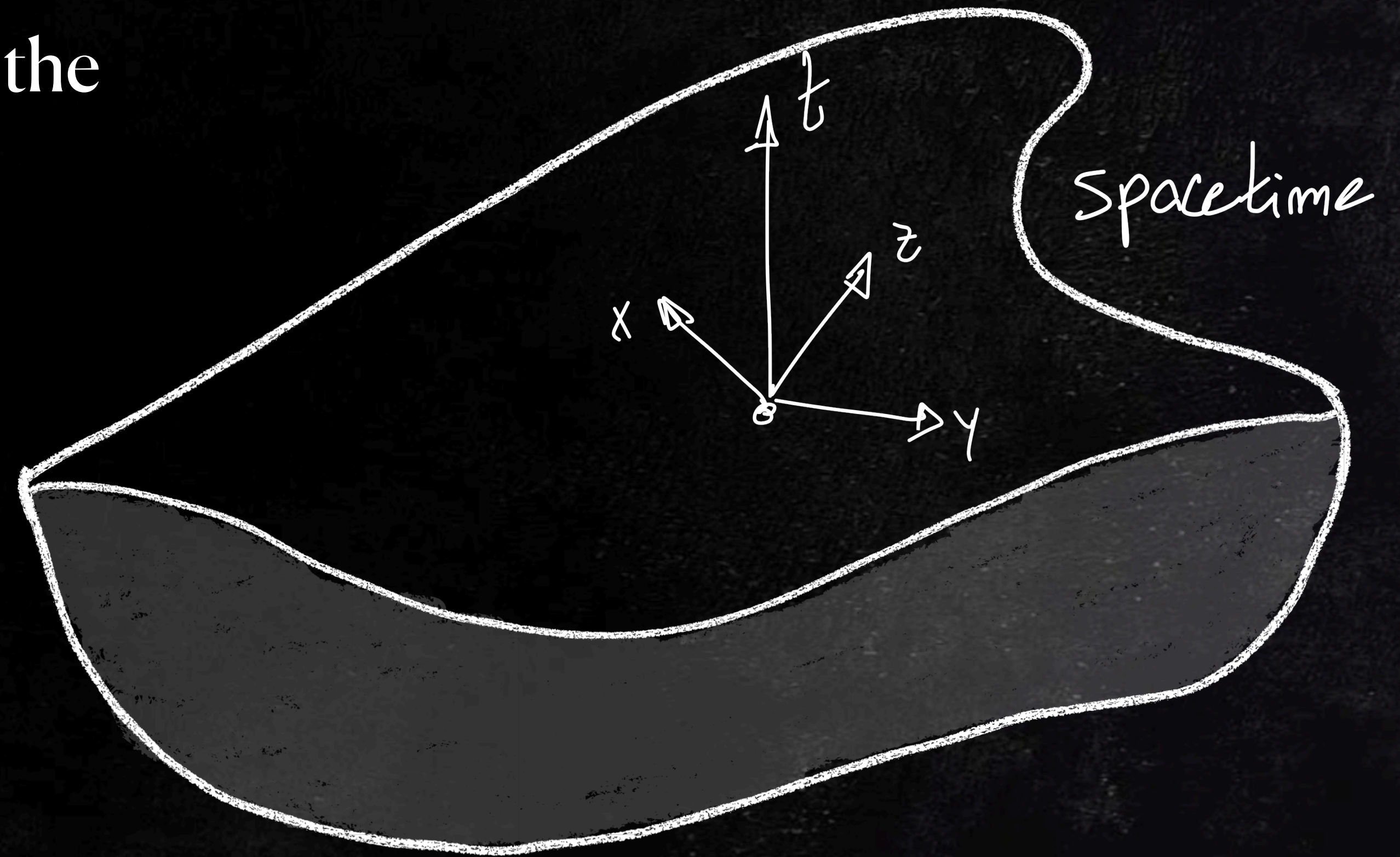
"I. **Absolute**, true, and mathematical **time**, of itself, and from its own nature, flows equably *without* relation to anything external."

"II. **Absolute space**, in its own nature, *without* regard to anything external, remains always similar and immovable."



Substantivalism:

Space and time **exist** as *independent* substances, i.e., **independently** of the material content of the universe.



GOTTFRIED WILHELM LEIBNIZ

(I) Time is relational: not itself a physical entity, but a relation of such entities;

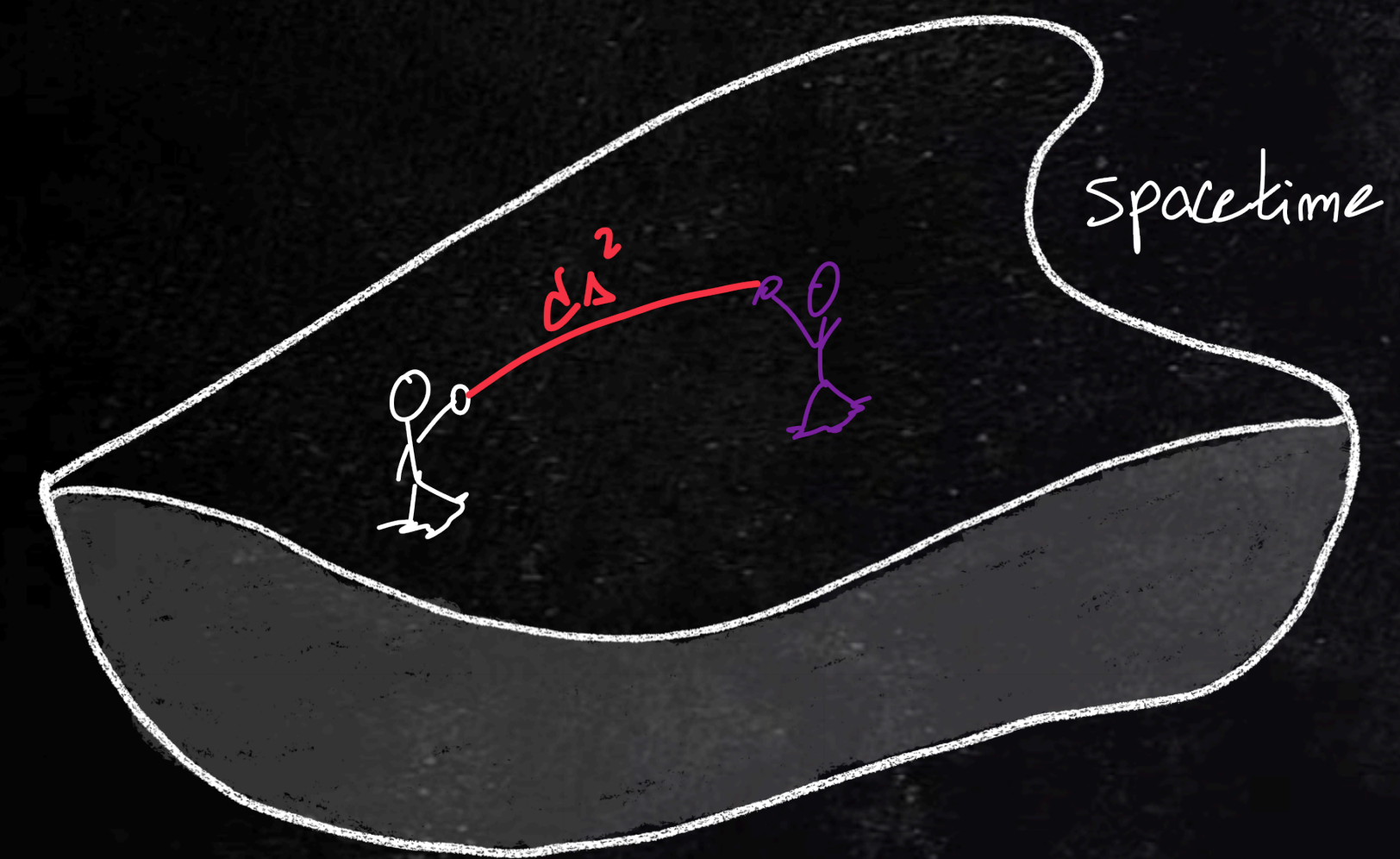
•
(II) Time is ideal. Being relational, time has no existence apart from the things it relates;

(III) Time is a continuous quantity.

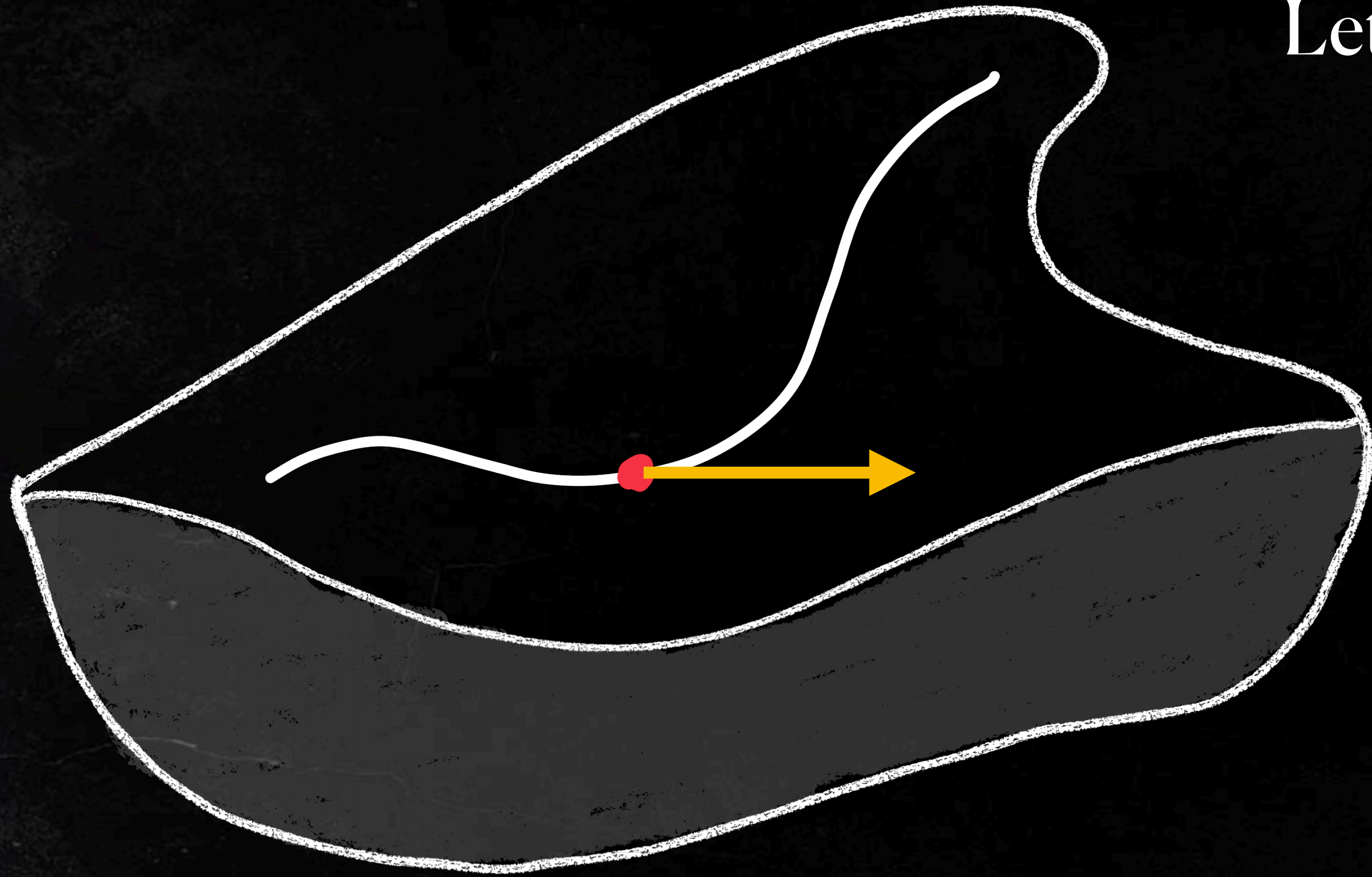


Relationalism:

Space and time *do not exist* as independent substances, *there is only the material content of the universe*. Space and time are merely defined through spatiotemporal relations among the material objects in the universe (and their parts). Spacetime is thus a (constructed) relational complex of relative positions of material objects.



But so there is also material content!
Let's consider a particle:

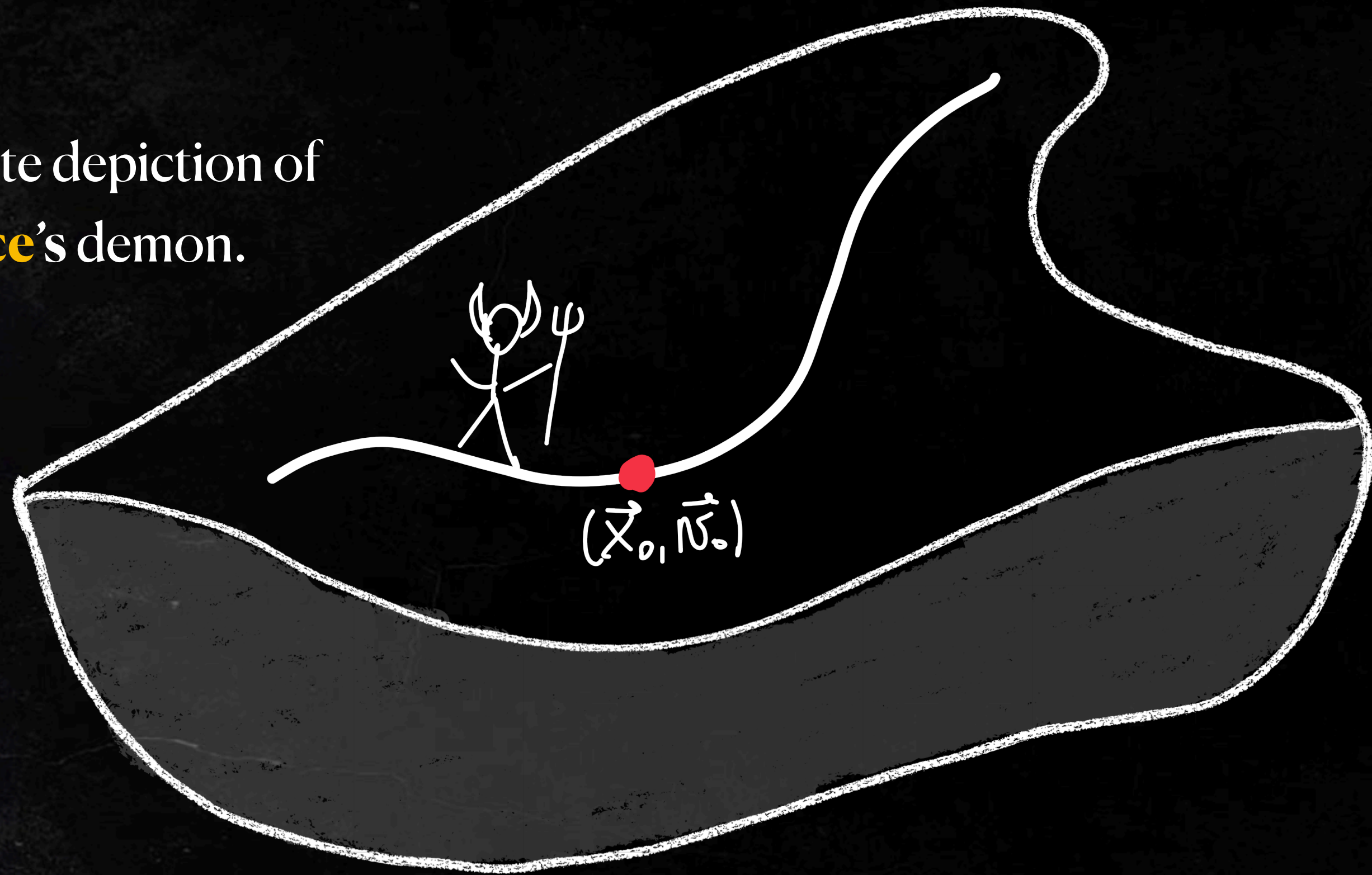


a) A state: $(\vec{x}, \vec{p})$

b) An evolution equation:

$$\vec{F}(\vec{x}) = m \frac{d^2 \vec{x}}{dt^2}$$

Accurate depiction of
Laplace's demon.



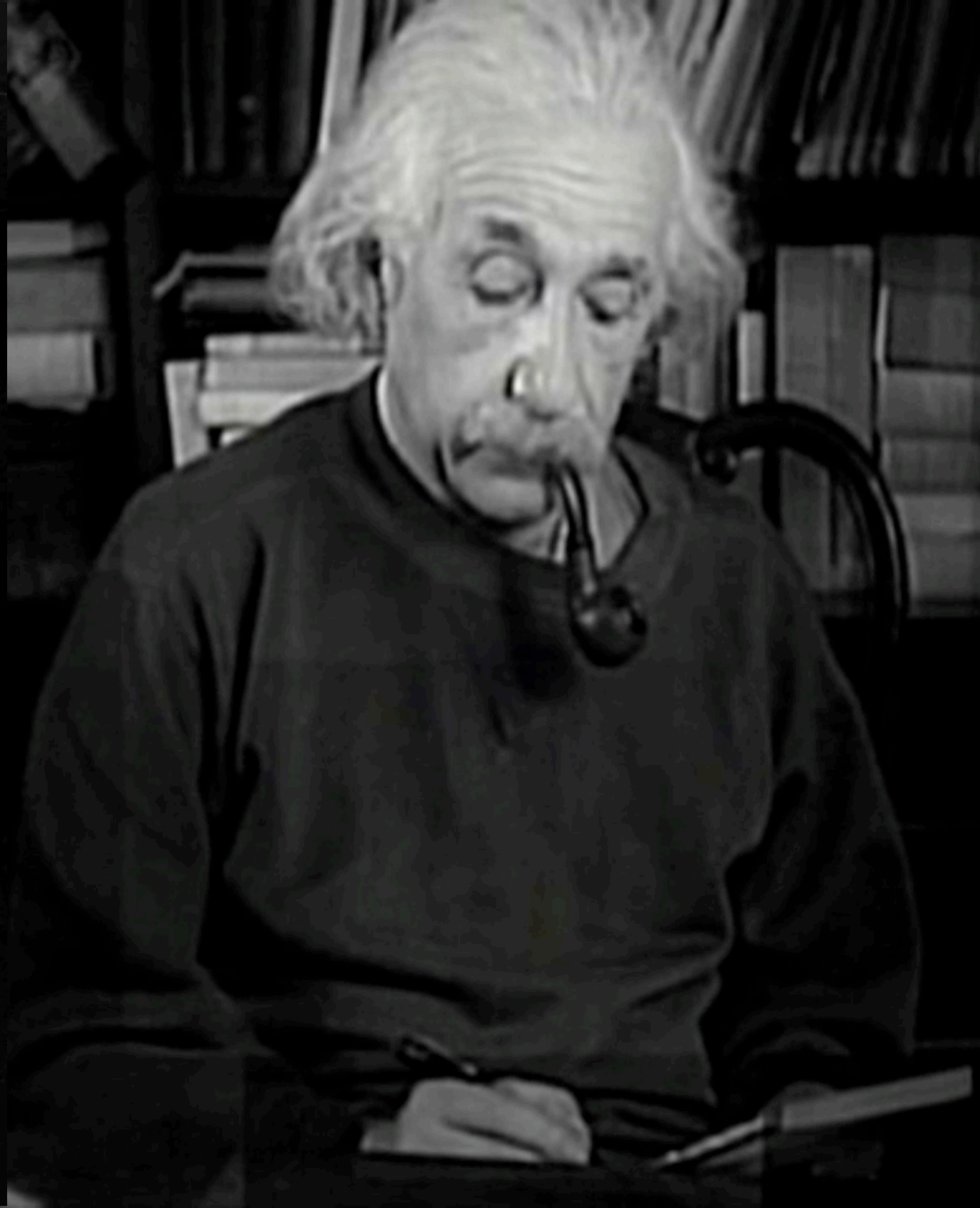
Classical mechanics is deterministic!



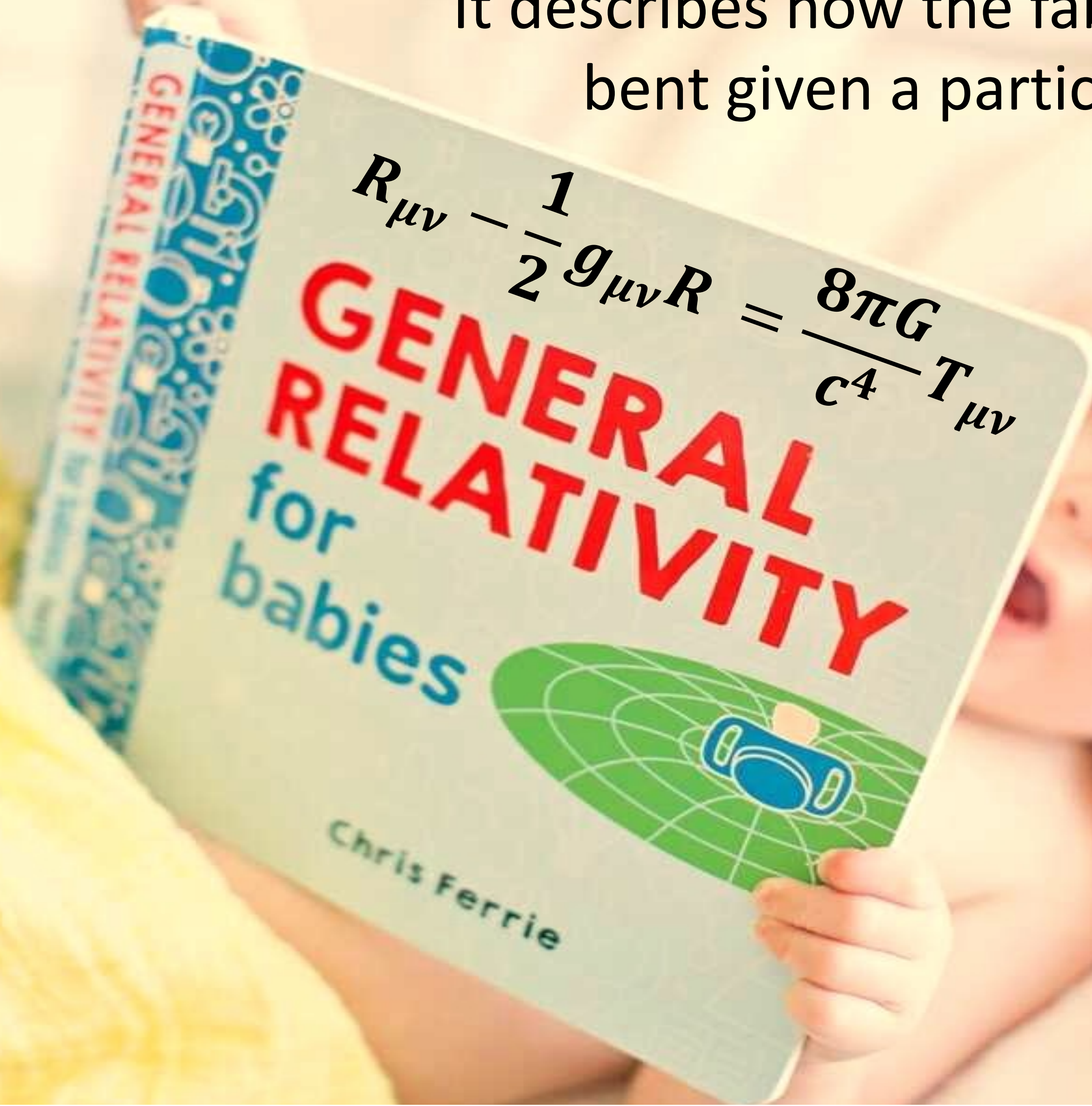


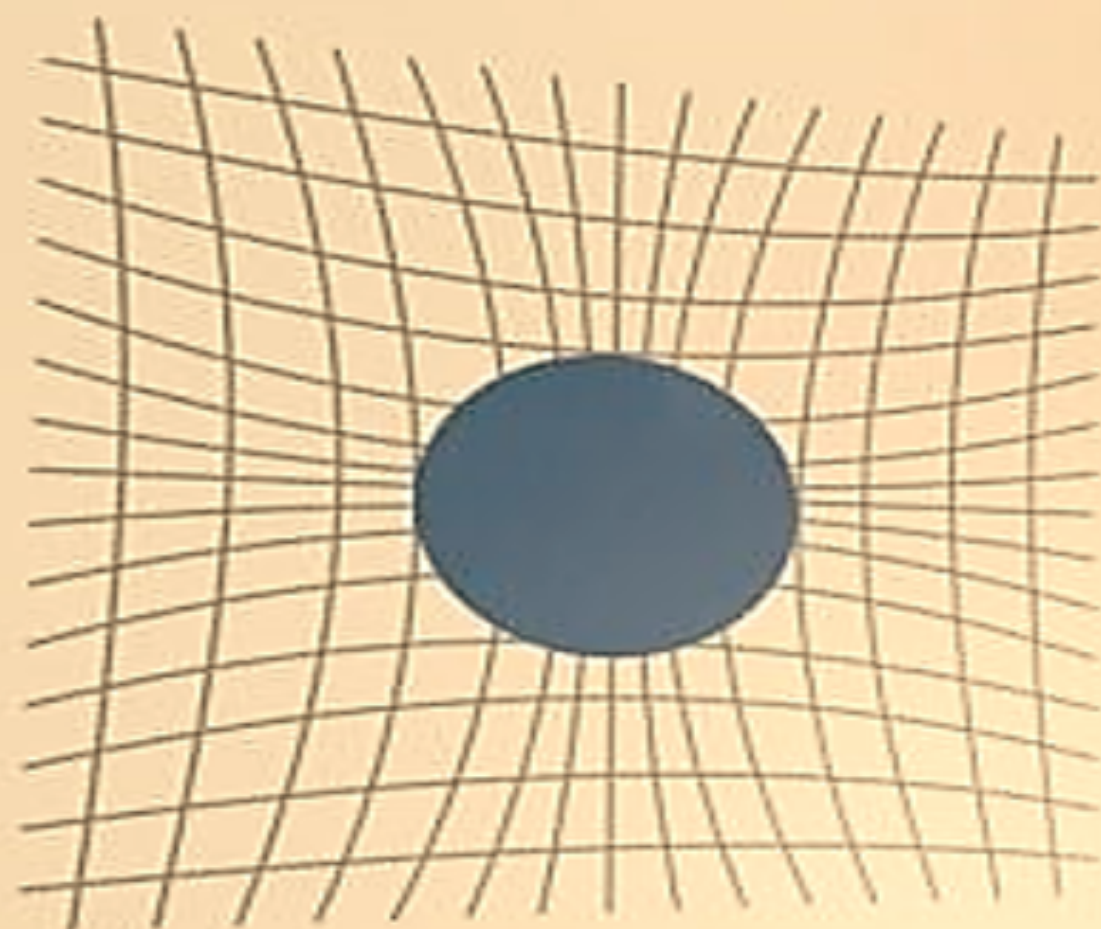
Questions or
thoughts?

**ALBERT
EINSTEIN**

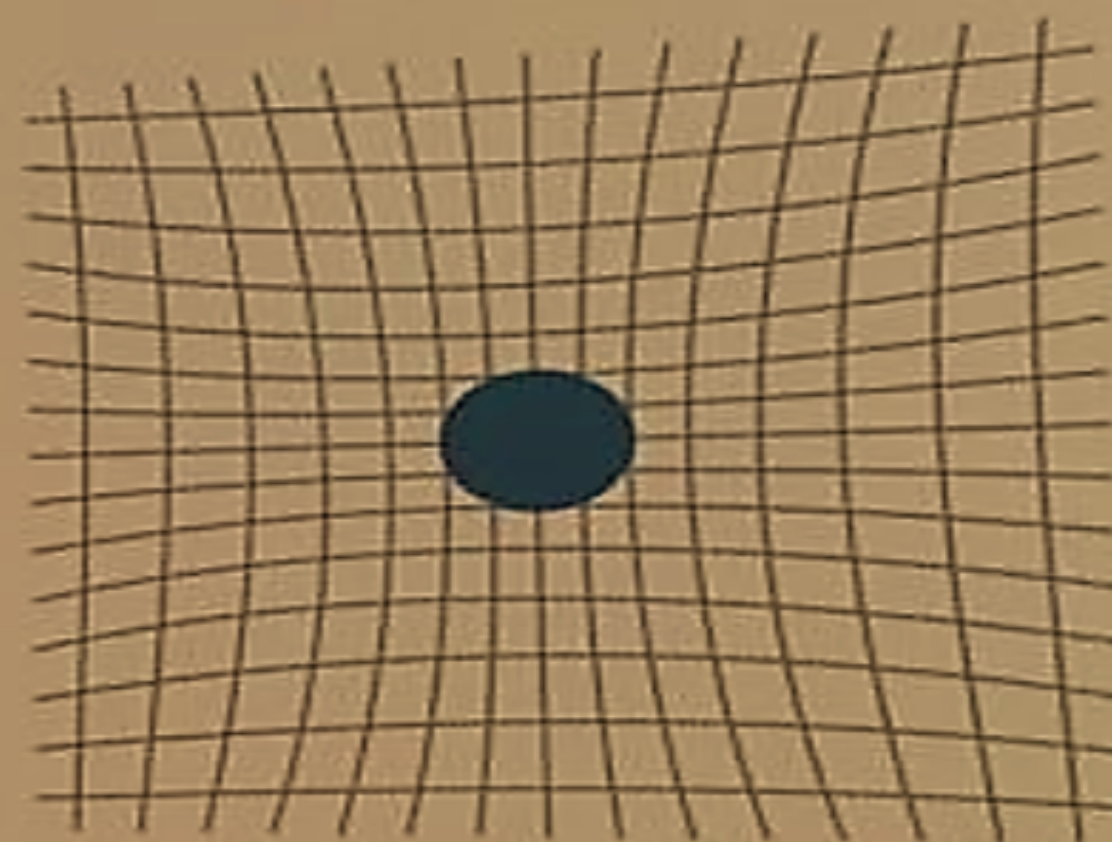


It describes how the fabric of spacetime is bent given a particular distribution of matter and energy.

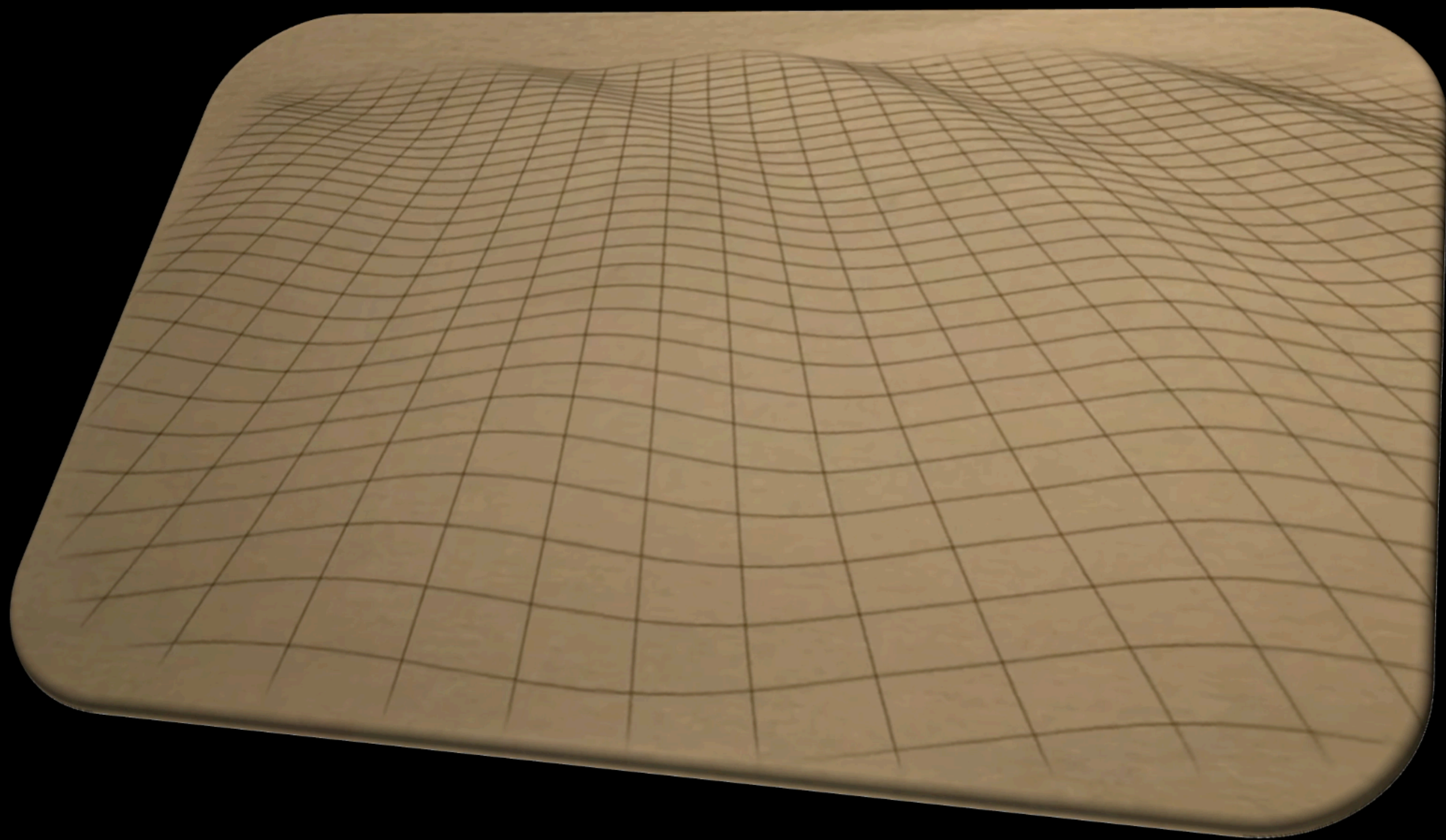




Mass warps space.

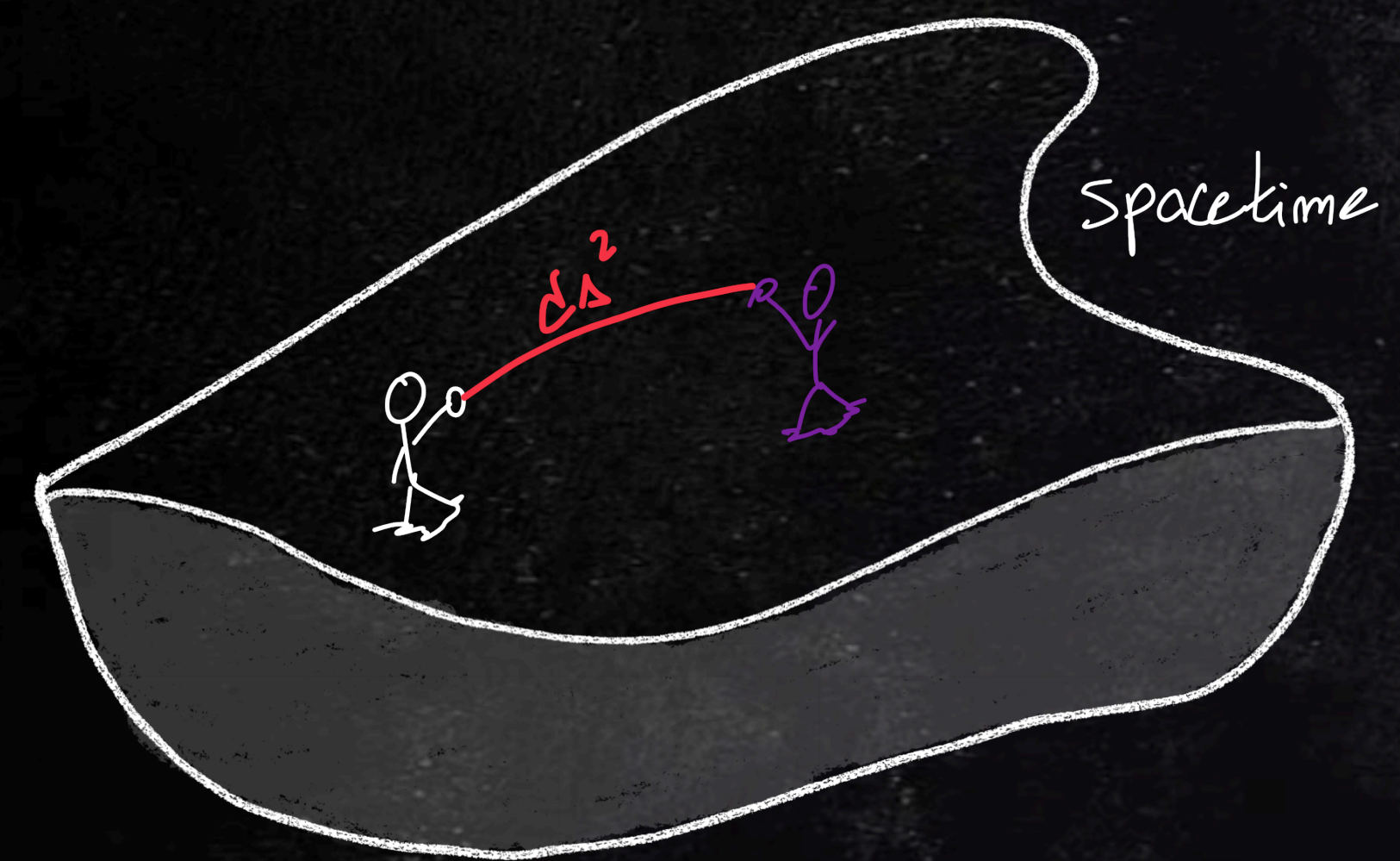


Less mass, less warp.



The relationalist dream?

$$\left. \begin{aligned} R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} &= \frac{8\pi G}{c^4}T_{\mu\nu} \\ \frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\rho\sigma}\frac{dx^\rho}{d\lambda}\frac{dx^\sigma}{d\lambda} &= 0 \end{aligned} \right\}$$

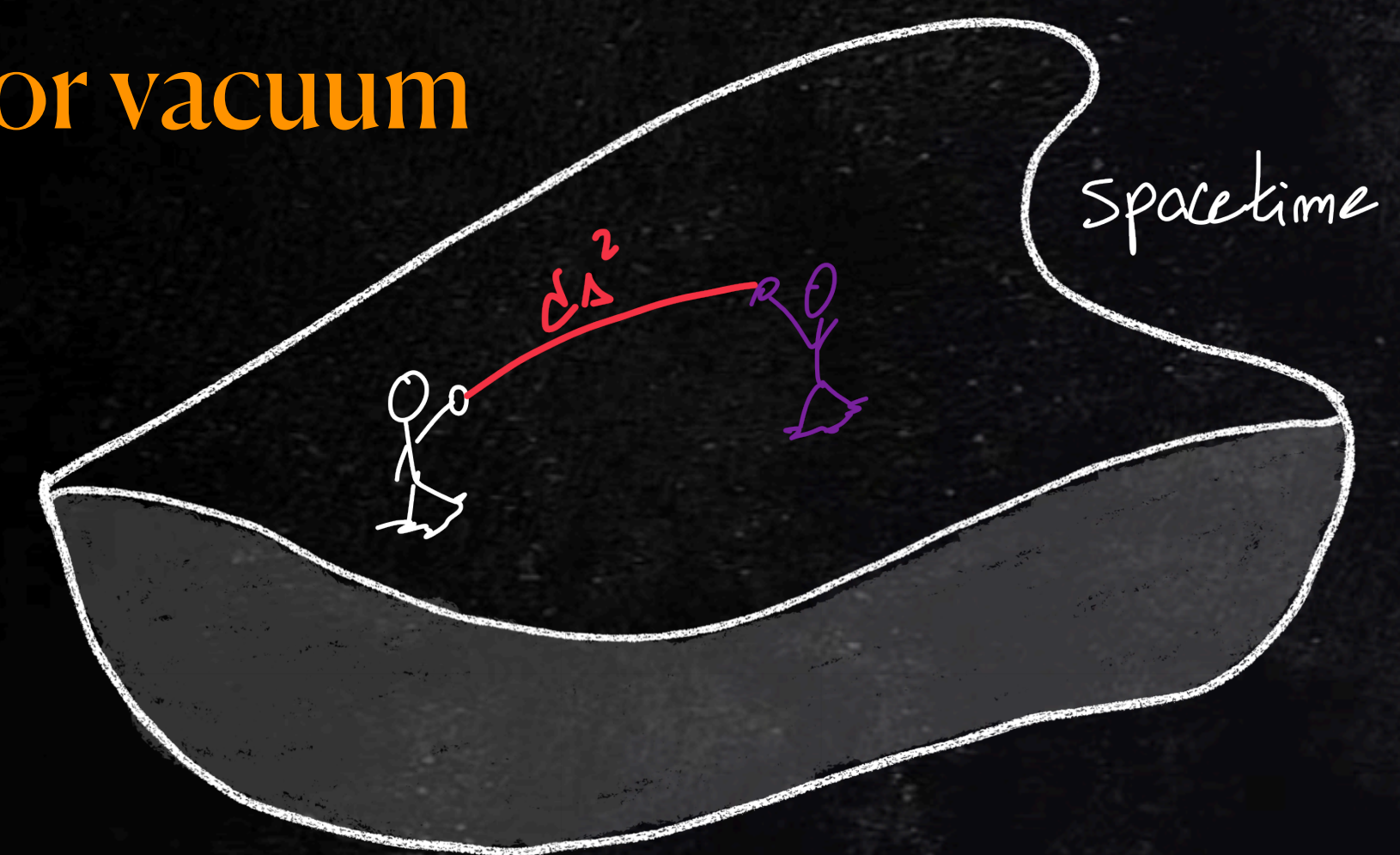


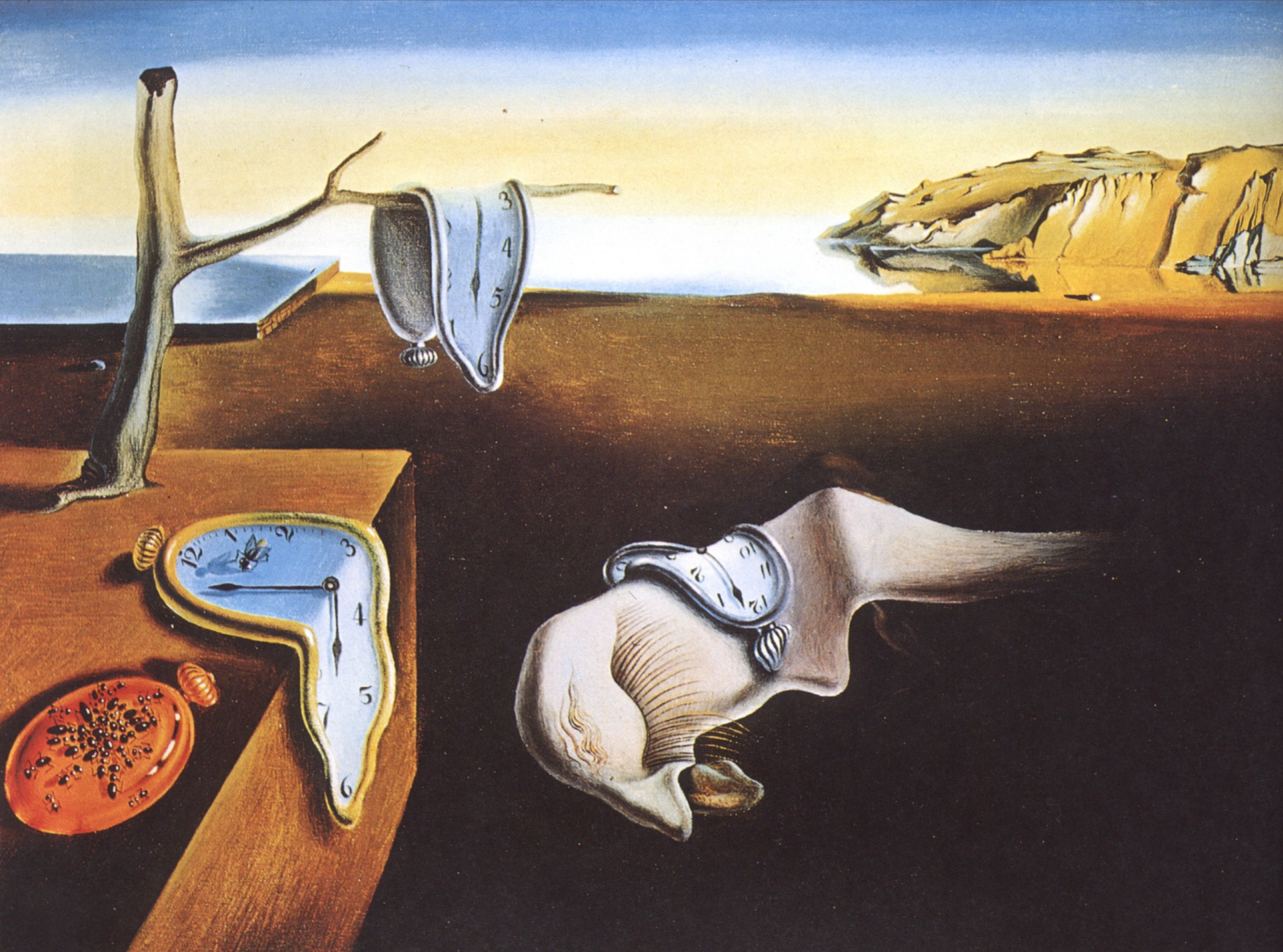
The relationalist dream?

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\rho\sigma}\frac{dx^\rho}{d\lambda}\frac{dx^\sigma}{d\lambda} = 0$$

It doesn't quite fully realize relationalism, and overall Einstein's project, as it still **allows for vacuum (no matter) solutions.**





The Persistence of Memory

- Salvador Dalí, 1931

“...Dalí replied that the soft watches were not inspired by the theory of relativity, but by the surrealist perception of a Camembert melting in the sun.”





So, now we understood
the nature of time?!



Time...

- labels moments in the universe (coordinate)



Time...

- labels moments in the universe (coordinate)
- measures the duration elapsed between events (observable)



Time...

Just like space!

- labels moments in the universe (coordinate)
- measures the duration elapsed between events (observable)



Time...

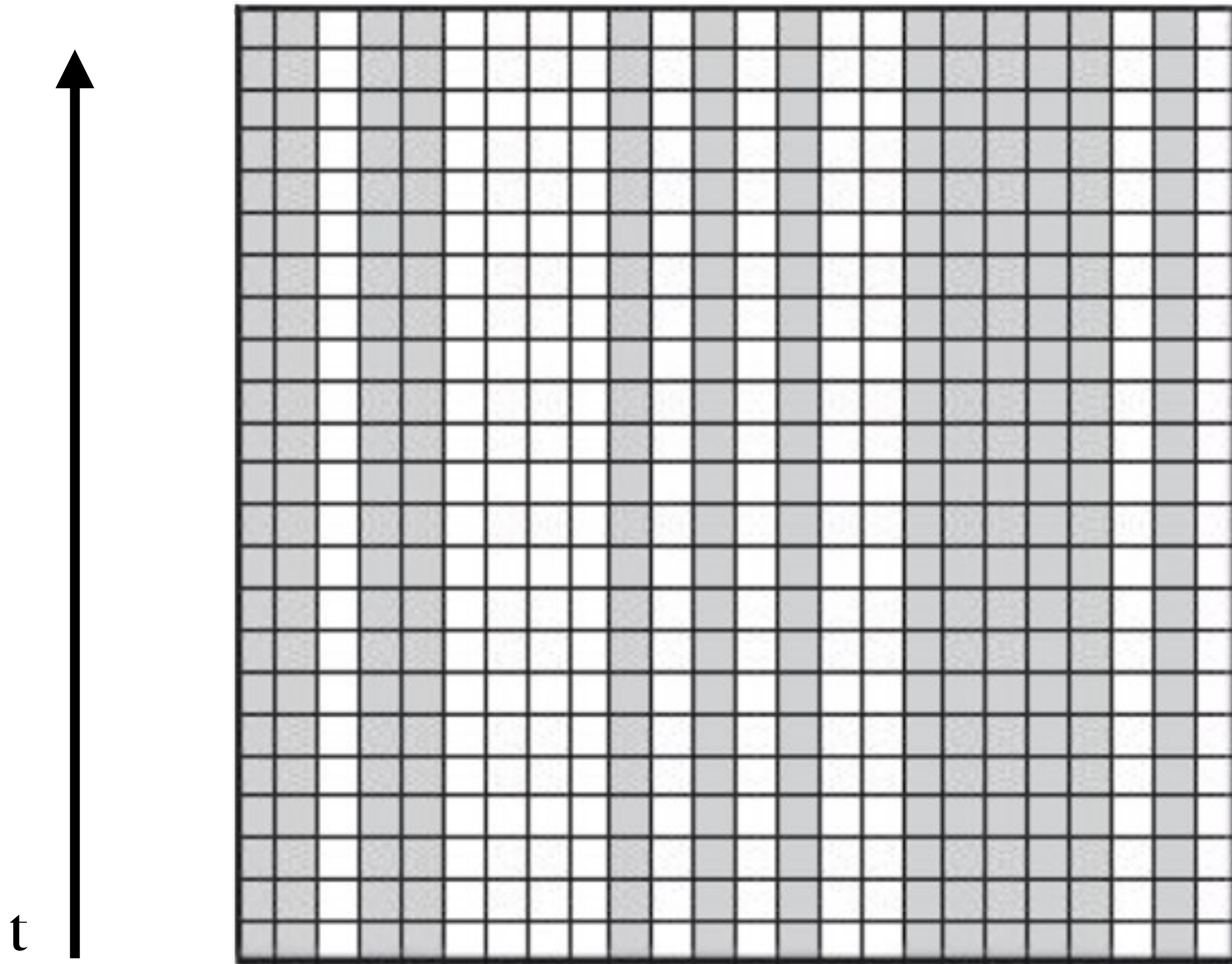
Just like space!

- labels moments in the universe (coordinate)
- measures the duration elapsed between events (observable)
- is a medium through which we move (direction and evolution)

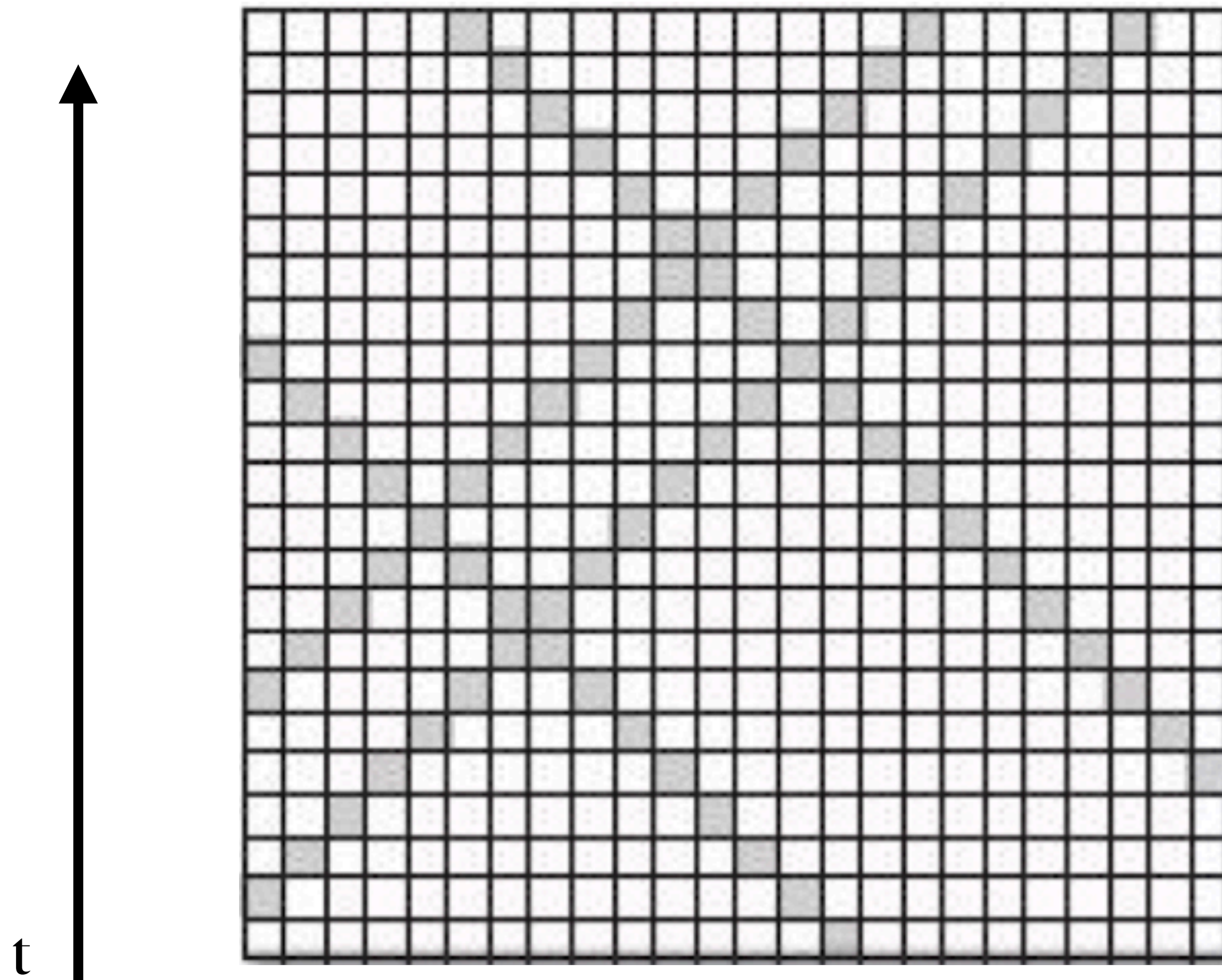
Fundamental Laws of Physics are time reversible!



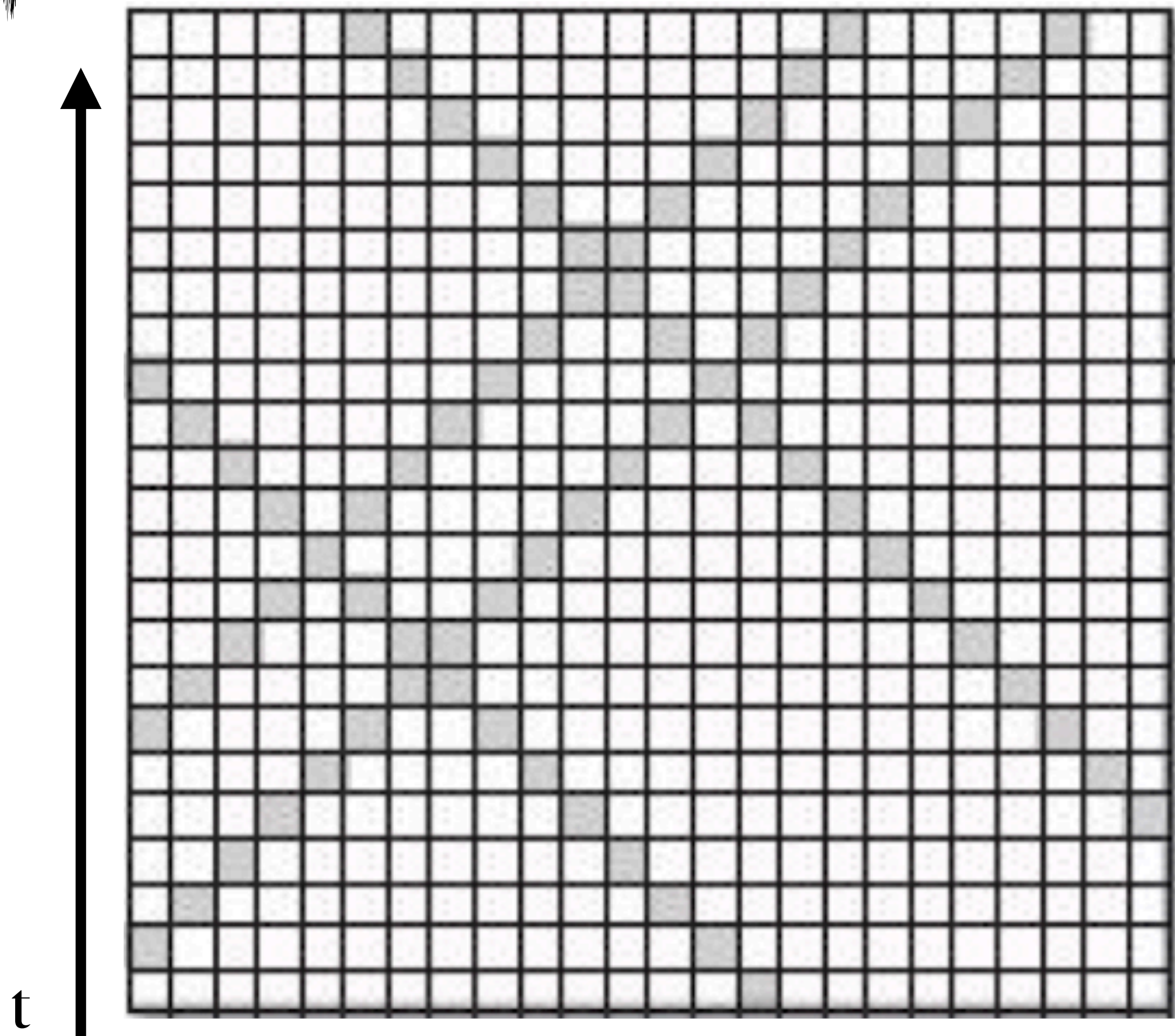
ON REVERSIBILITY



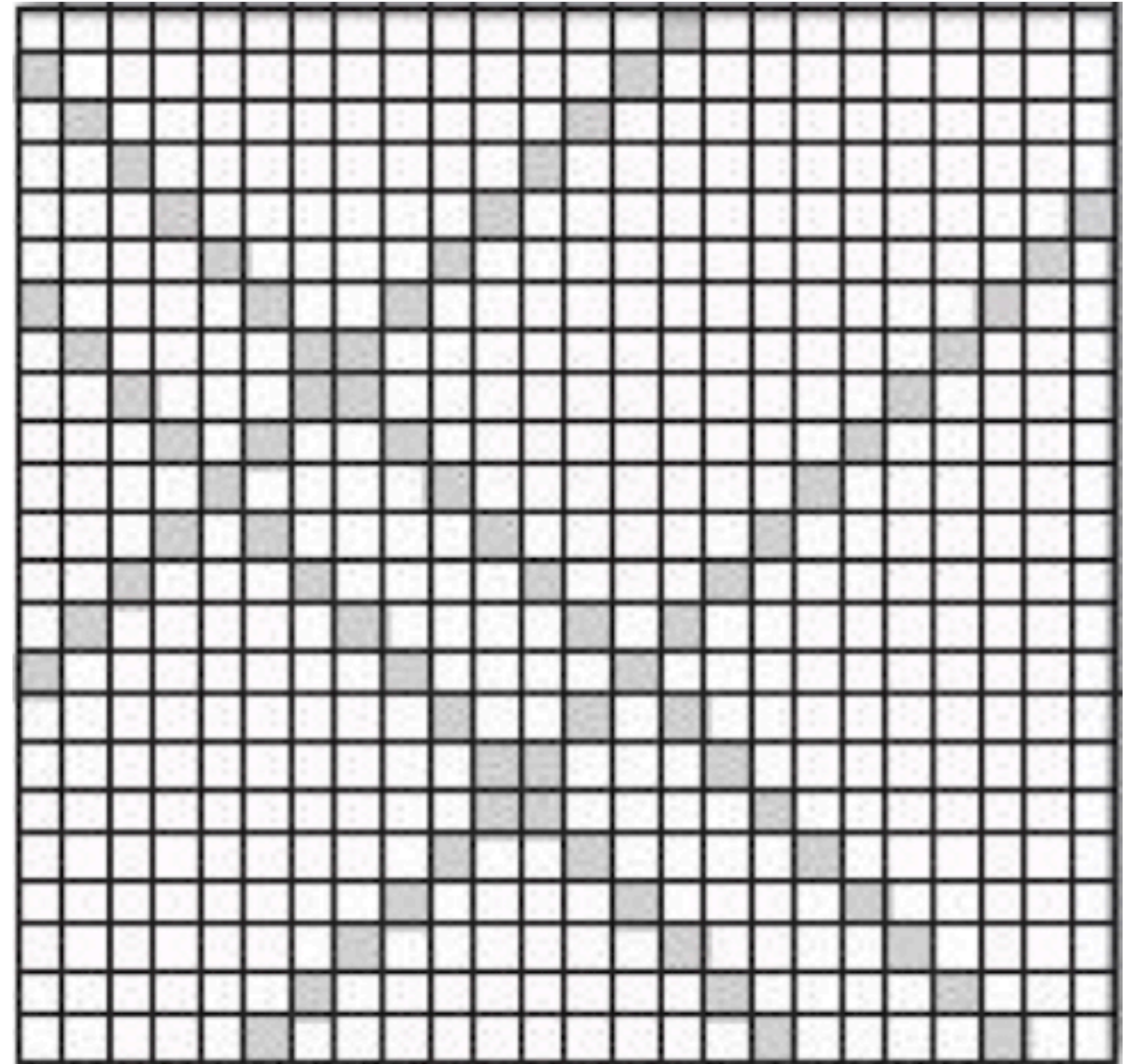
ON REVERSIBILITY



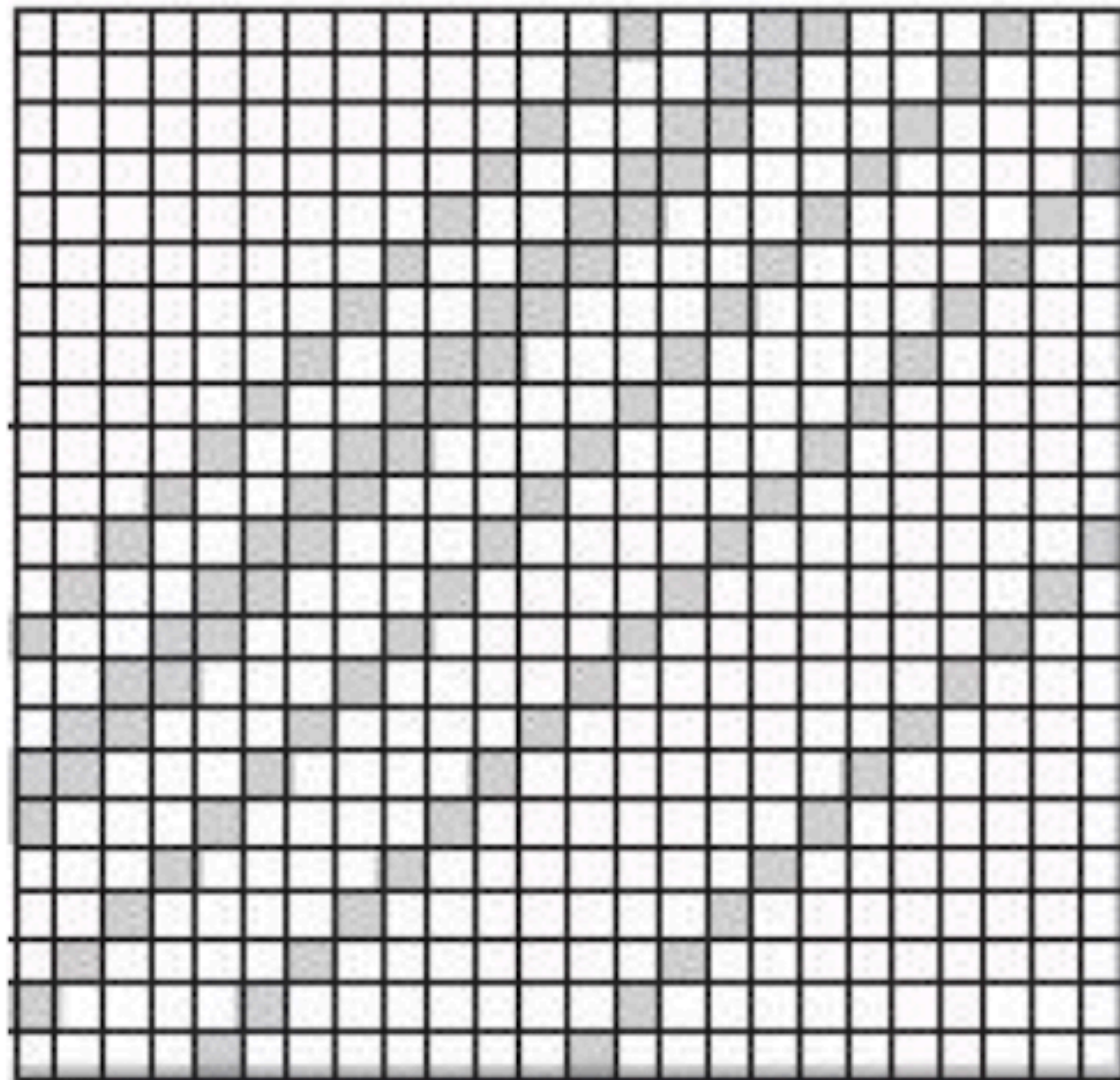
ON REVERSIBILITY



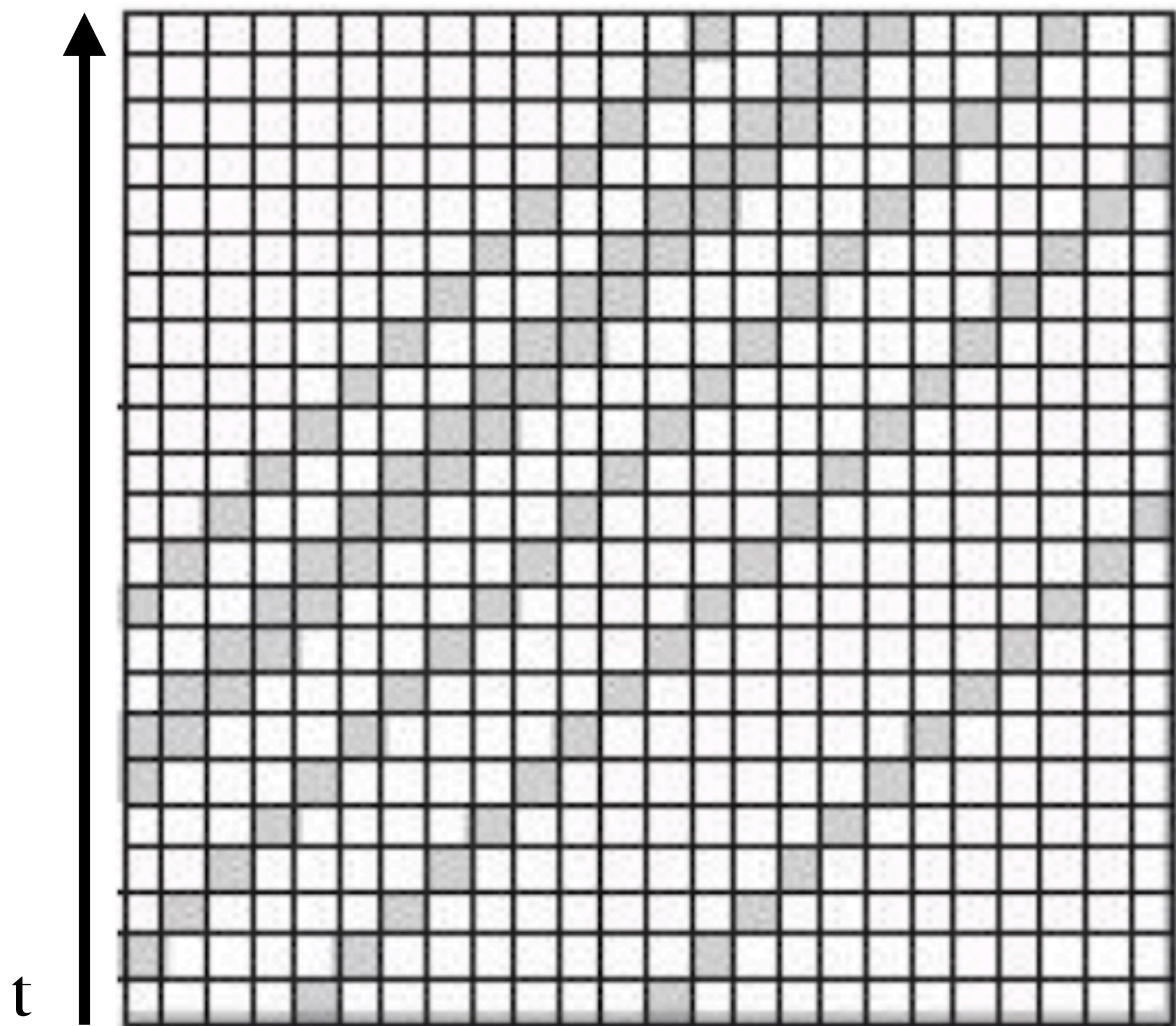
$$T : t \rightarrow -t$$



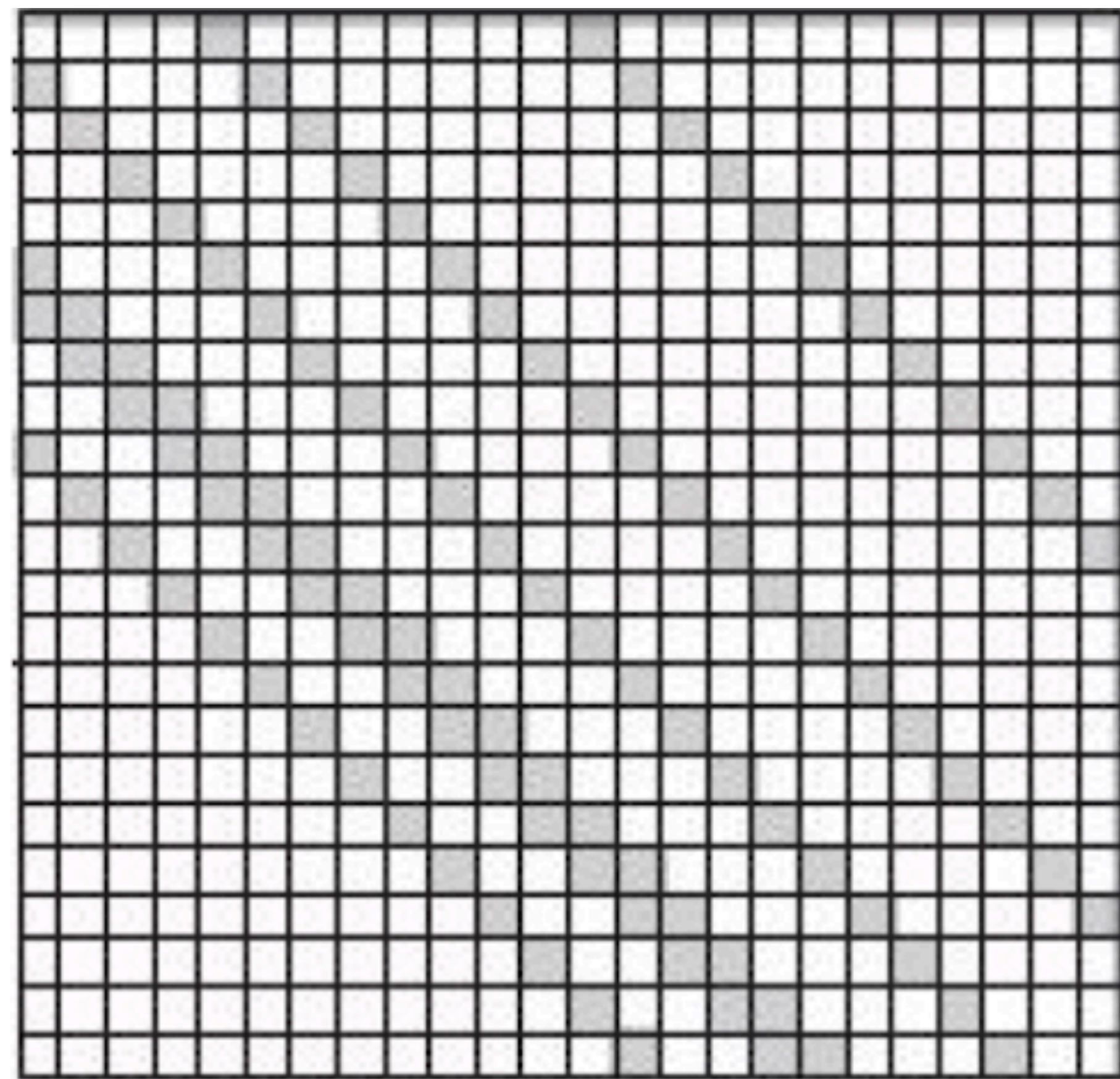
ON REVERSIBILITY



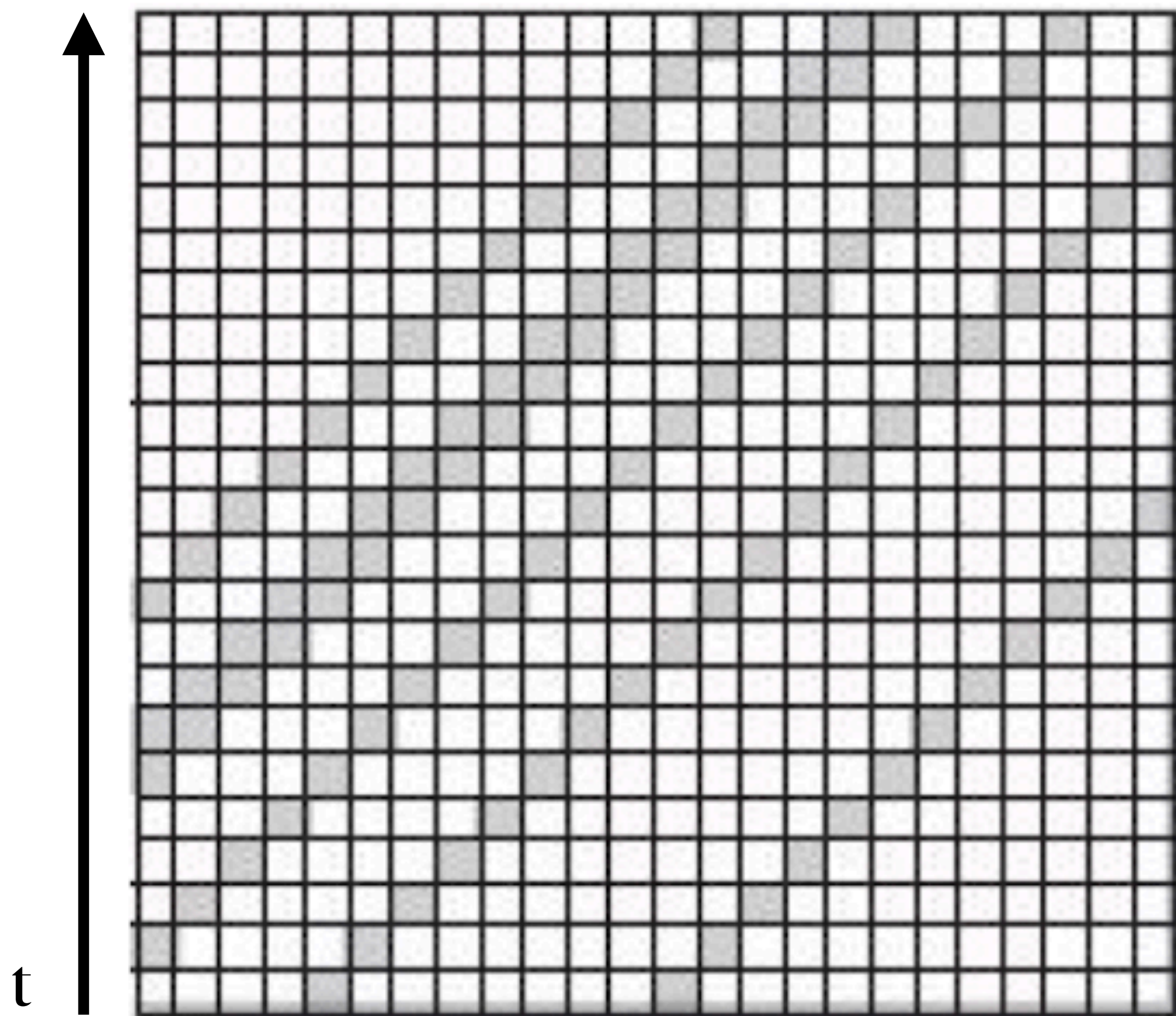
ON REVERSIBILITY



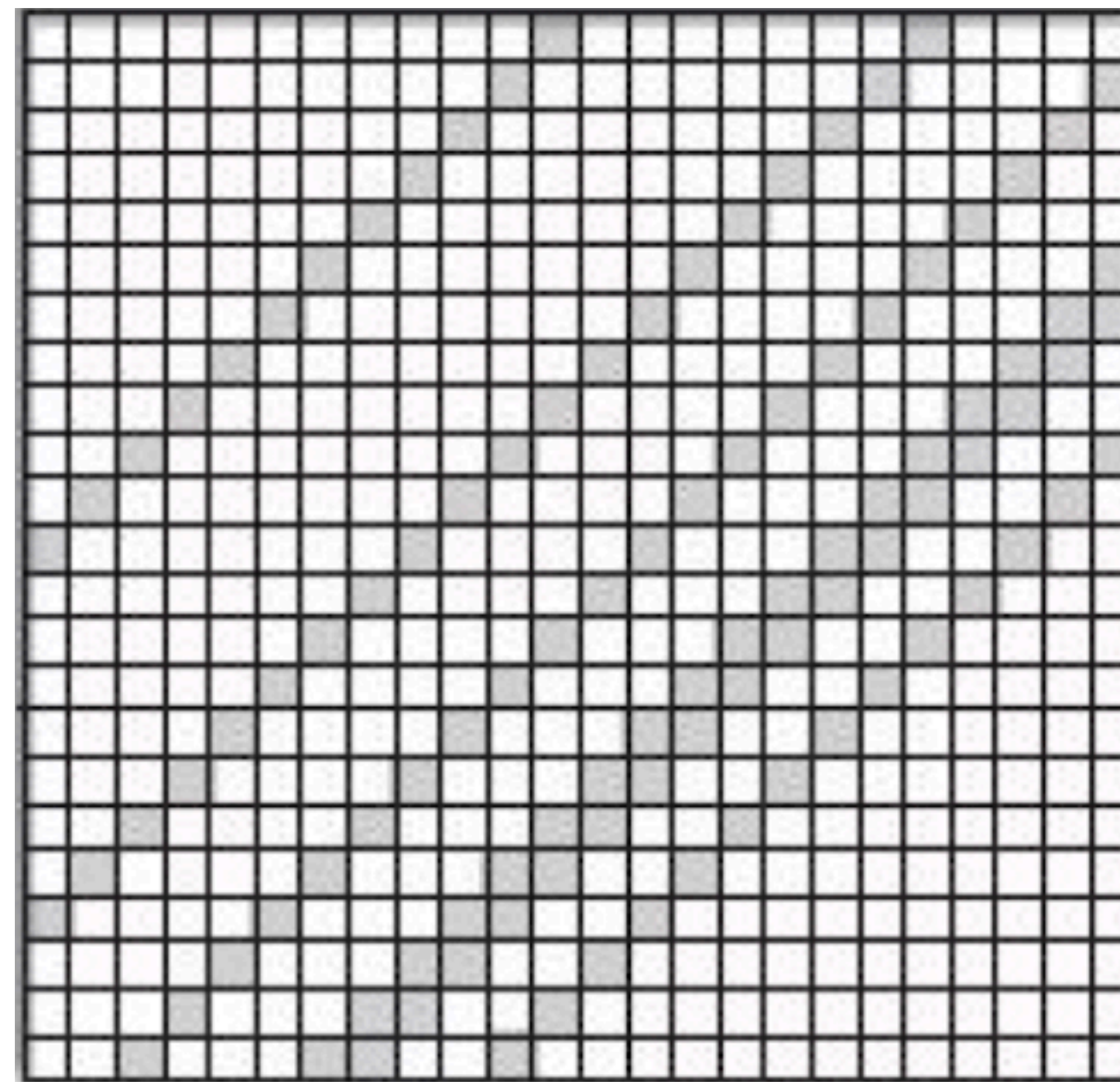
$$T : t \rightarrow -t$$



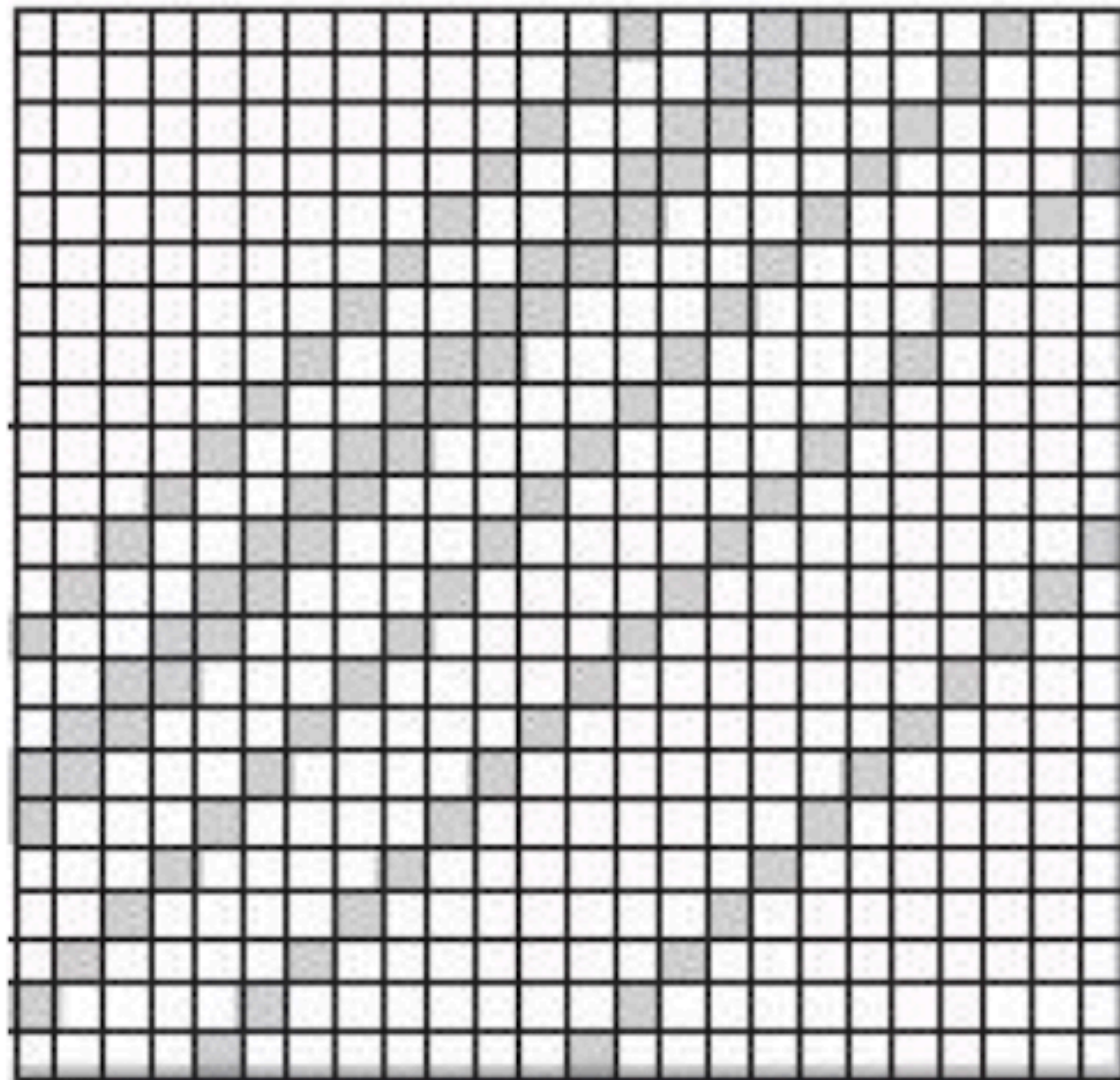
ON REVERSIBILITY



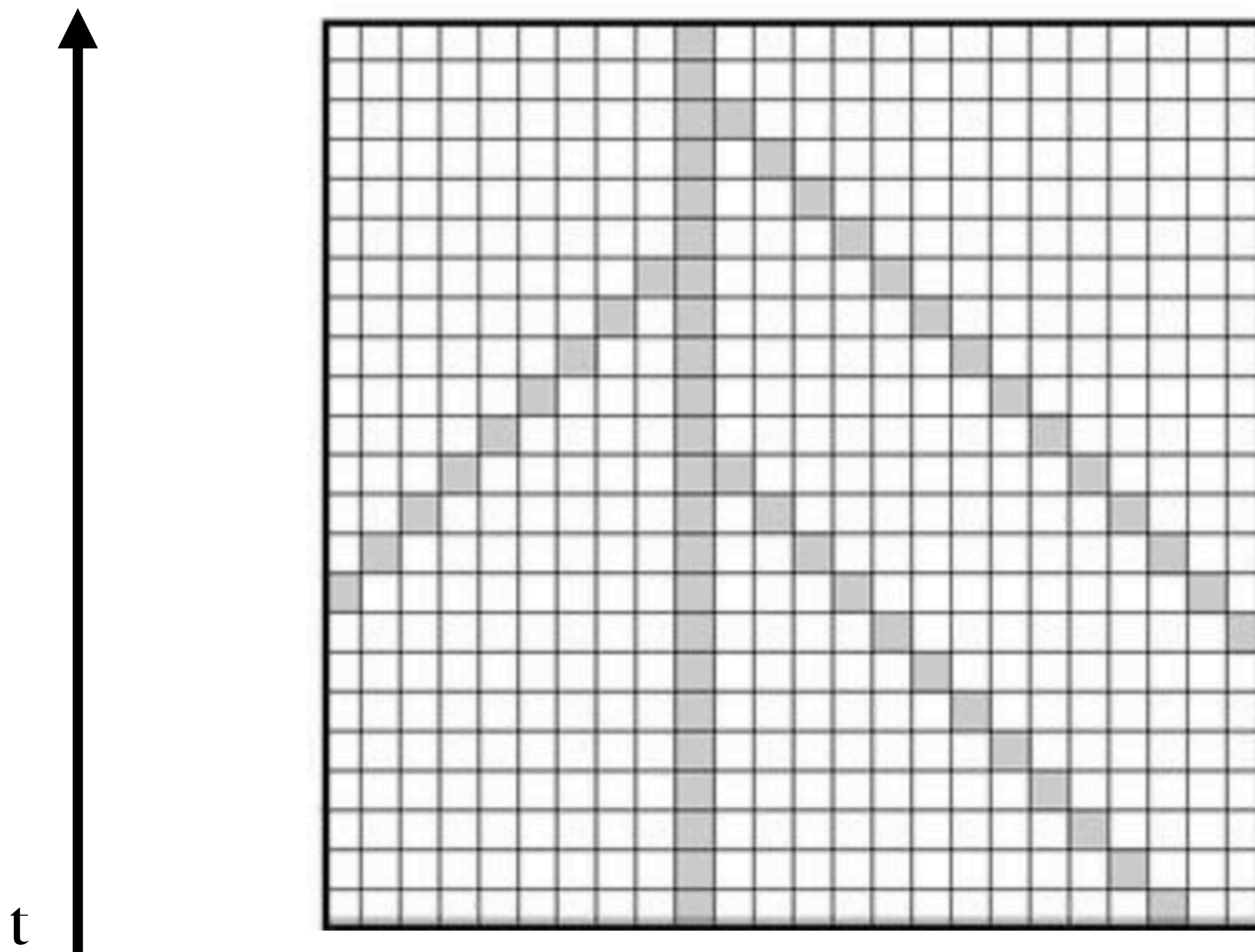
$$T : t \rightarrow -t$$
$$P : x \rightarrow -x$$



ON REVERSIBILITY



ON REVERSIBILITY





Questions or
thoughts?

Fundamental Laws of Physics are time reversible!

Fundamental interactions are described by **time-reversible laws**:

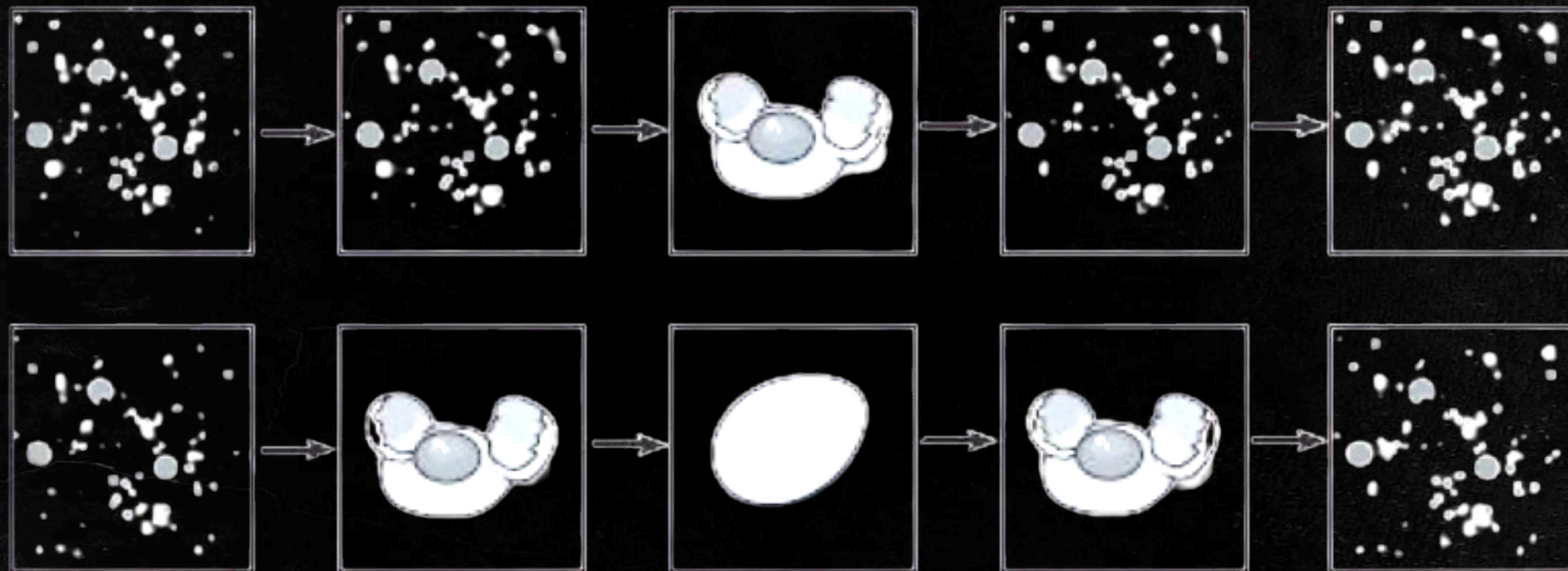
- o Electromagnetism
- o Weak nuclear force
- o Strong nuclear force
- o Gravity



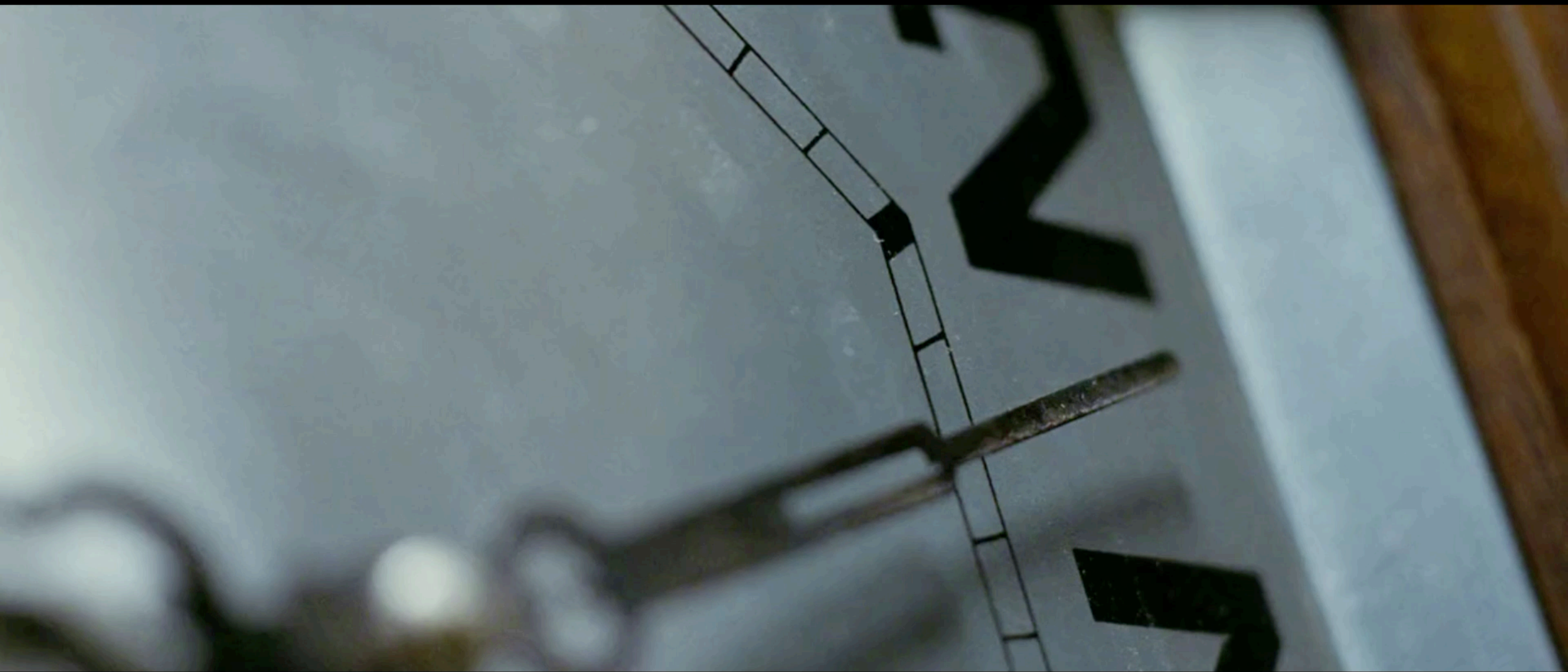
Scientific Realism - case study 1

Who does identify as a
scientific realist here?

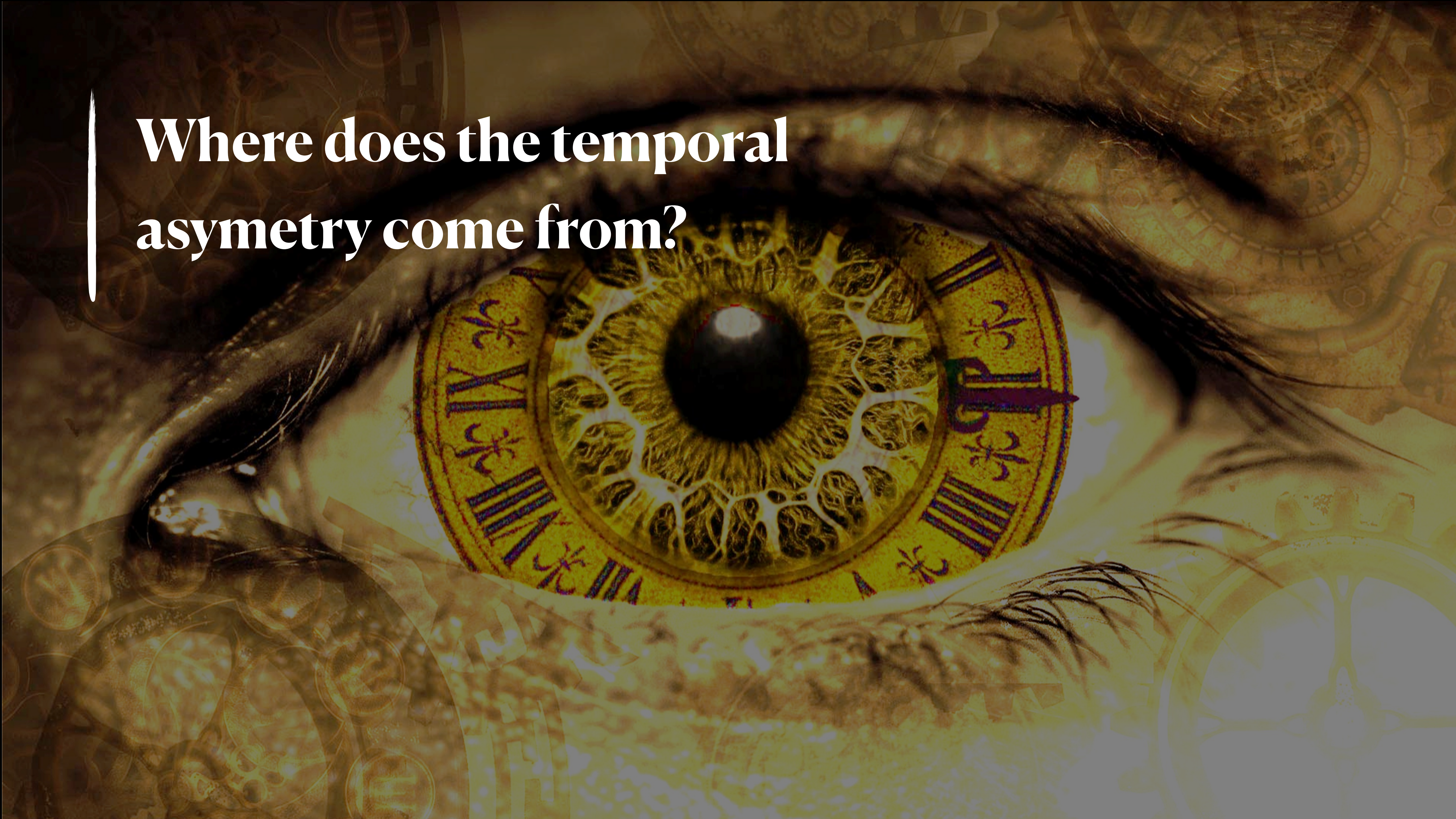
Scientific Realism - case study 1



In your groups, discuss for a few minutes whether the broken egg in the box ever gets back to its unbroken form (~7 min).



**Where does the temporal
asymmetry come from?**

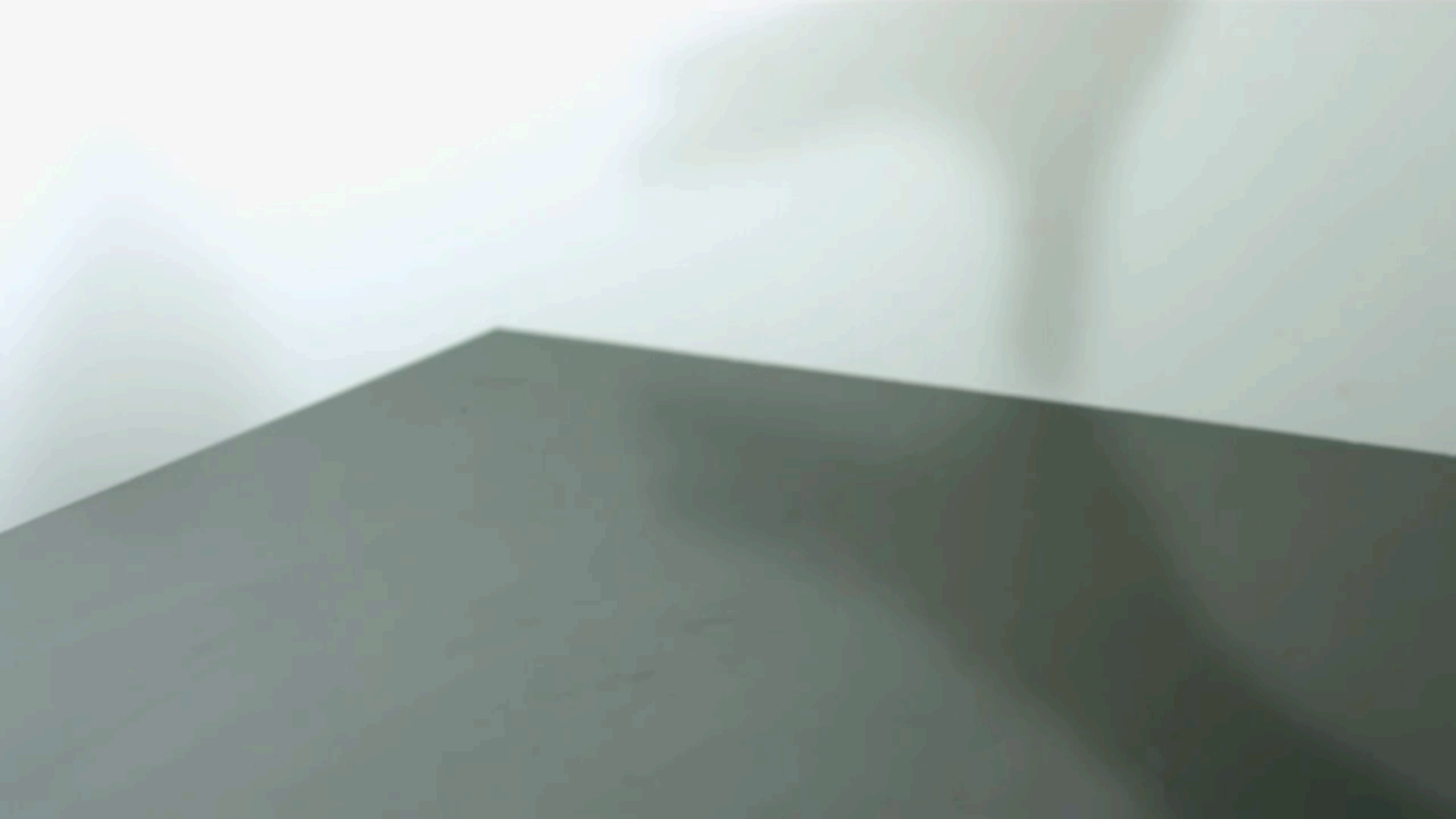


Thermodynamics

101

- 1st law: the **total energy is conserved**





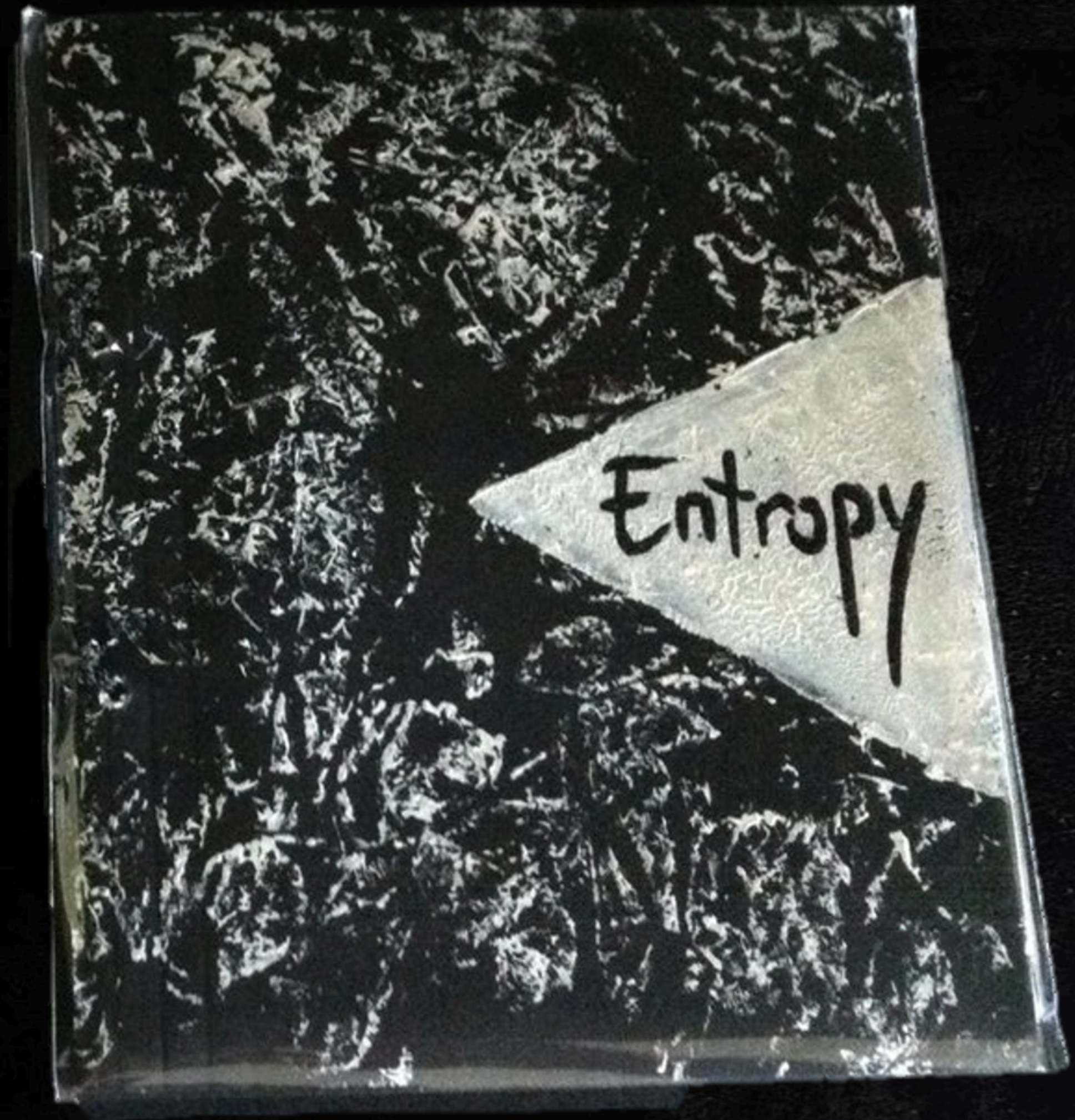


Thermodynamics 101

- 1st law: the **total energy is conserved**
- 2nd law: the **total entropy never decreases**



**The entropy of a system is a
measure of its manifest disorder.**





Entropy is a measure of the number of particular microscopic arrangements of atoms that appear **indistinguishable from a macroscopic perspective.**

Ludwig Boltzmann

(Physicist)

Center of Mass Motion

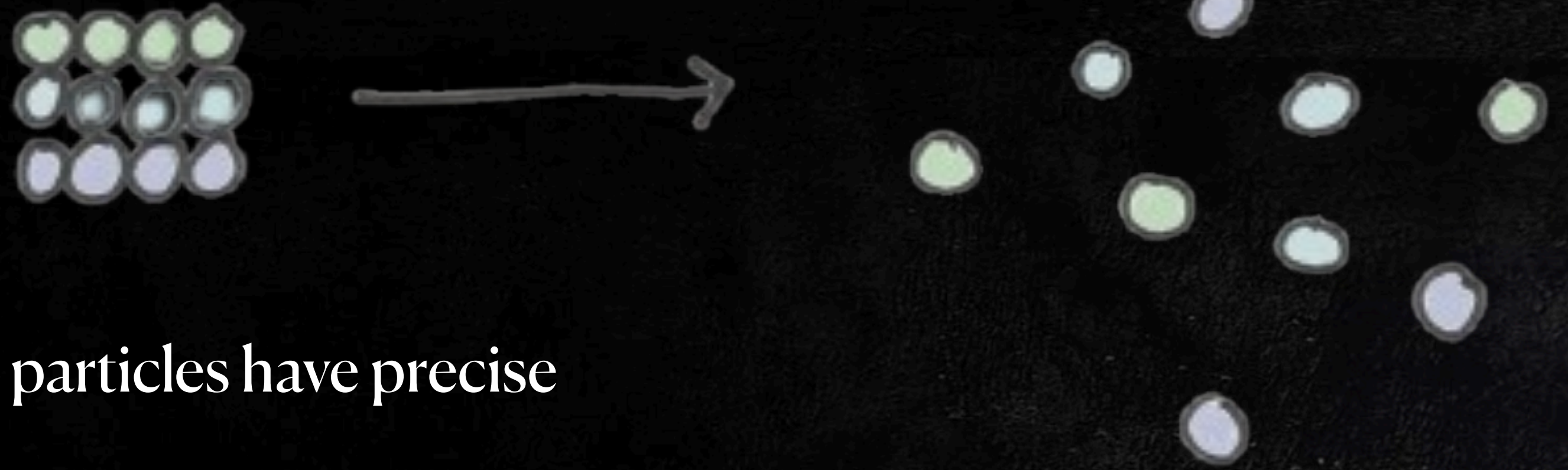
10^{50} particles in the Earth $\rightarrow$ positions and velocities
for each of them

But, the center of mass has only 6 “degrees of
freedom”: its $\vec{3}$ -*position* and $\vec{3}$ -*velocity*!

And still satisfies the *same* equations of motion!



Entropy



Classical mechanics is deterministic, and all particles have precise momenta and positions. **But we don't know all that data!** So, instead, we **coarse-grain the system: states with nearly identical momenta and locations are grouped together.**

Microstates: specific configurations of momenta and locations

Macrostates: sets of microstates with identical macroscopic properties

Entropy

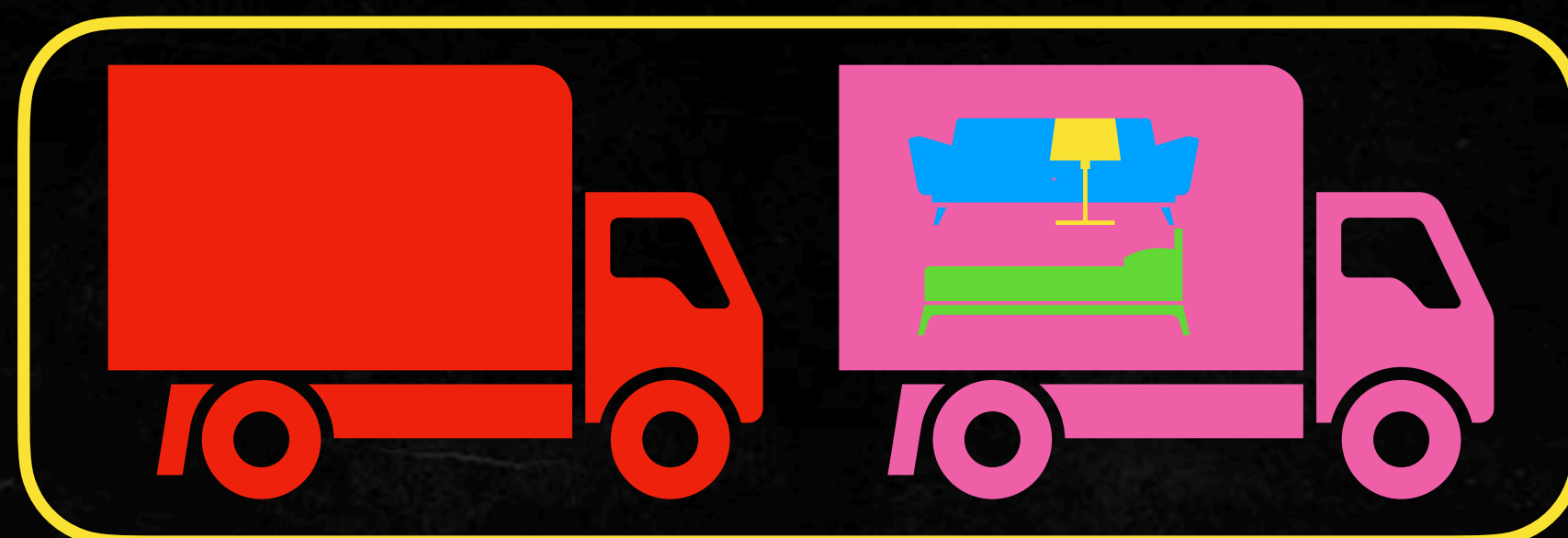
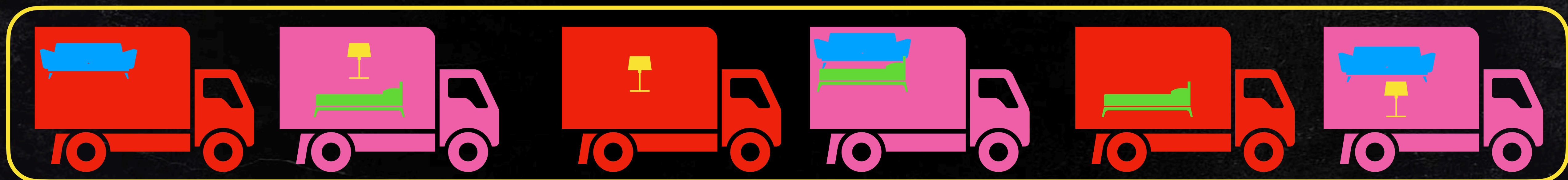
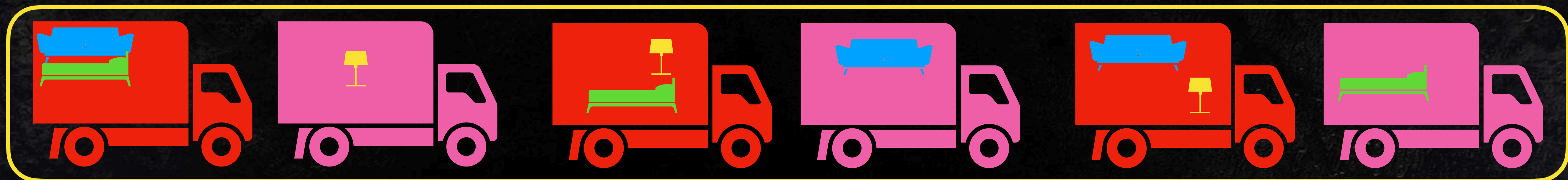
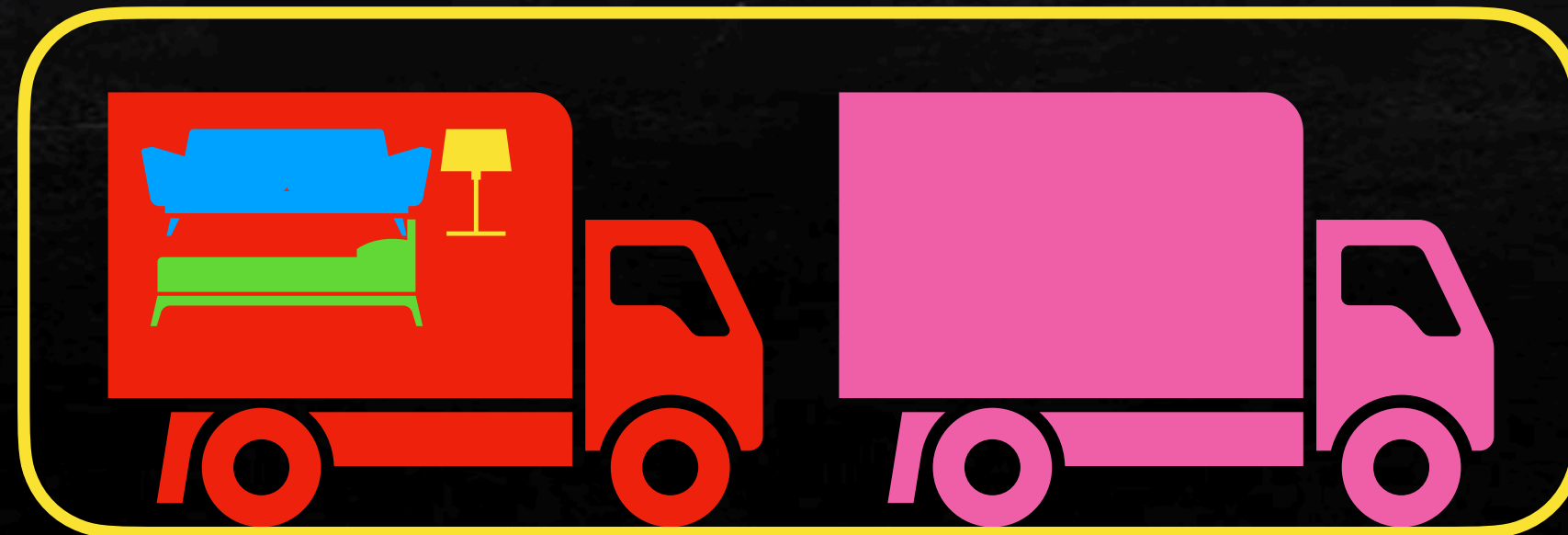
$$S = k_B \ln \Omega$$

Entropy

$$S = k_B \ln \Omega$$

Example:





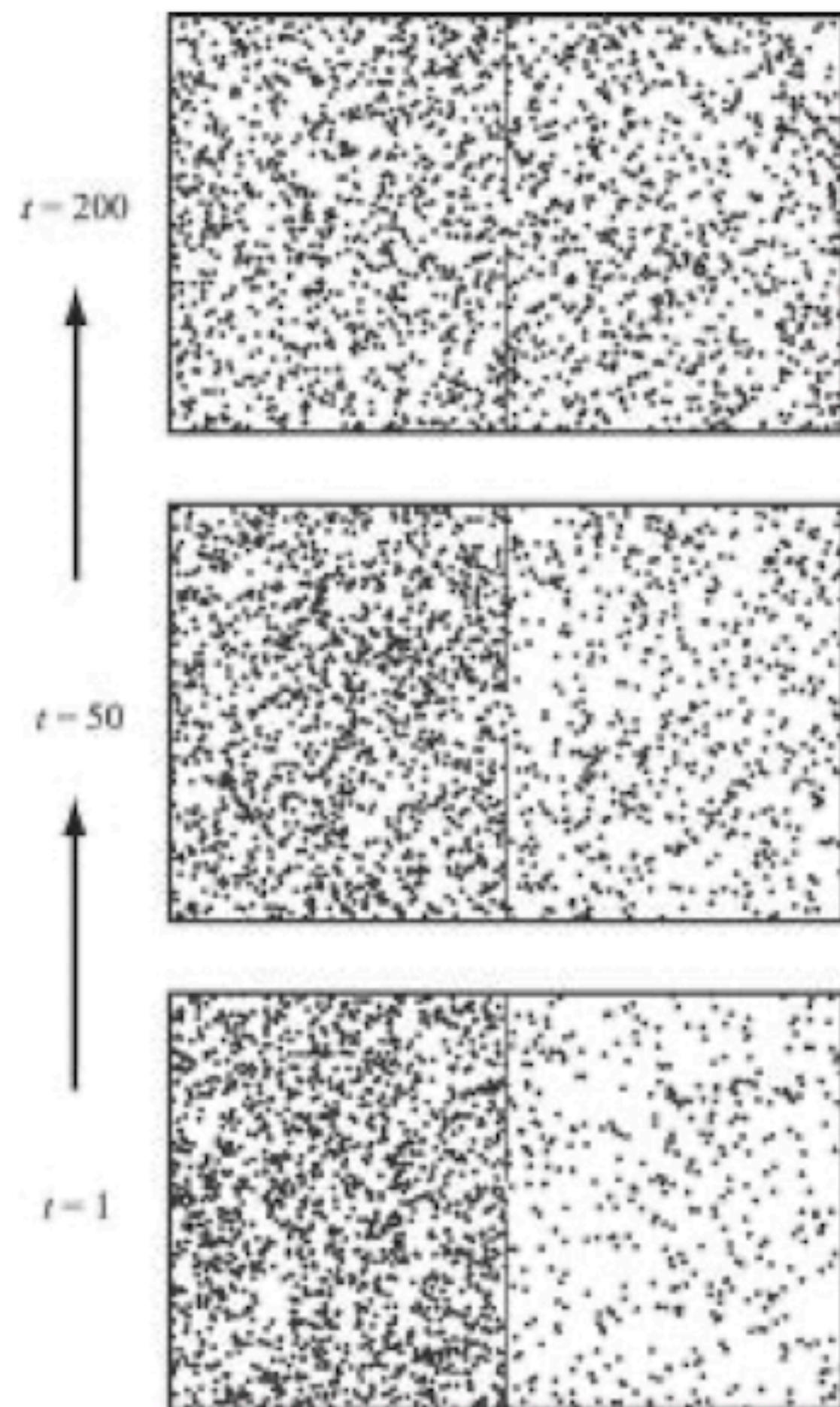
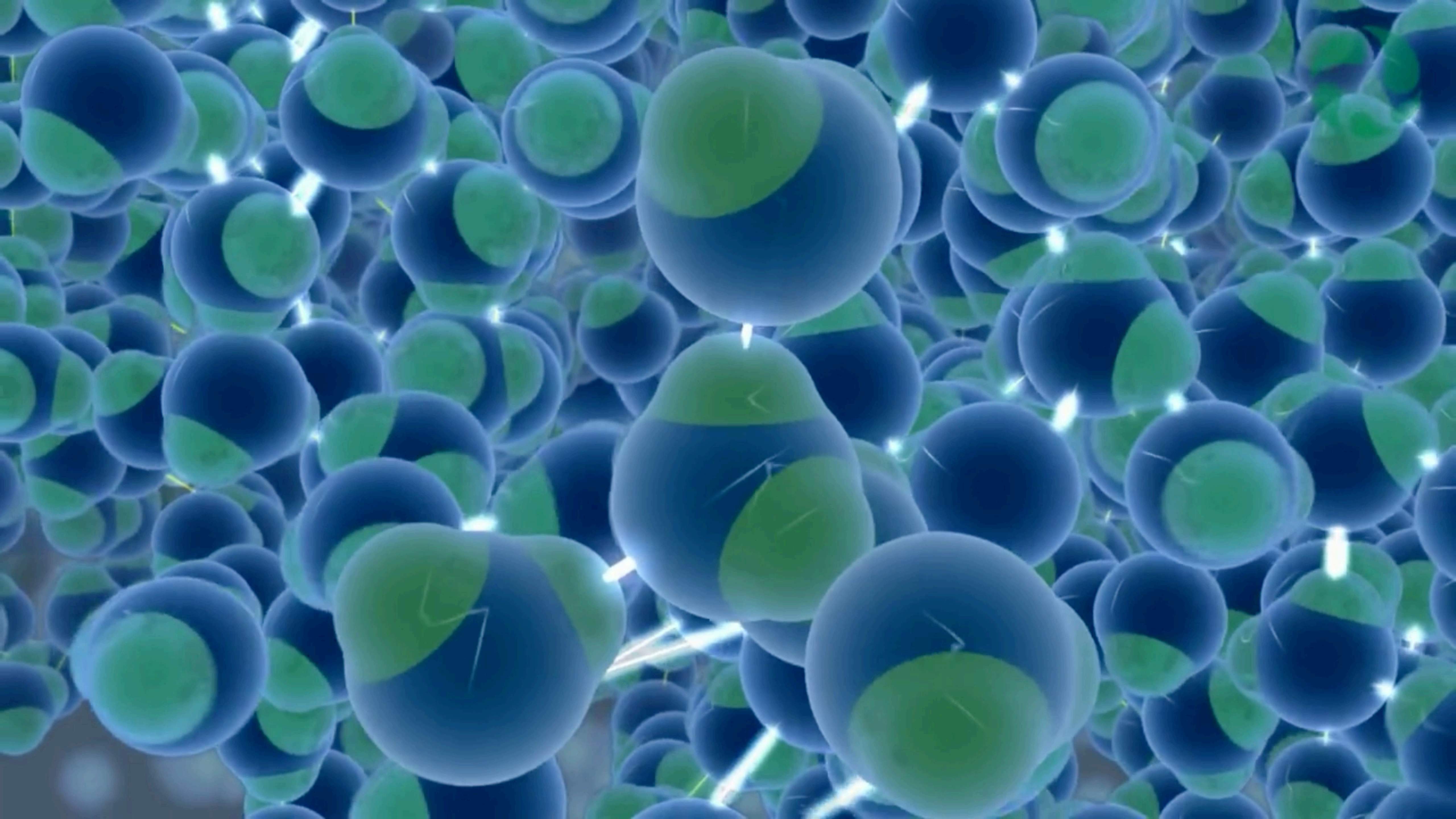


Figure 42: Evolution of 2,000 molecules in a divided box of gas. We start with 1,600 molecules on the left, 400 on the right. After 50 seconds, there are about 1,400 on the left and 600 on the right; by the time 200 seconds have passed, the molecules are distributed equally between the two sides.

Particles on Left, Right Sides	W	Log W
2000, 0	1	0
1999, 1	2000	3.3
1998, 2	1999000	6.3
1997, 3	1331334000	9.1
...	...	...
1000, 1000	2×10^{600}	600.3
...	...	...
3, 1997	1331334000	9.1
2, 1998	1999000	6.3
1, 1999	2000	3.3





Particles to Gases

From 10^{24} degrees of freedom to three variables (P, V, T) satisfying a different equation:

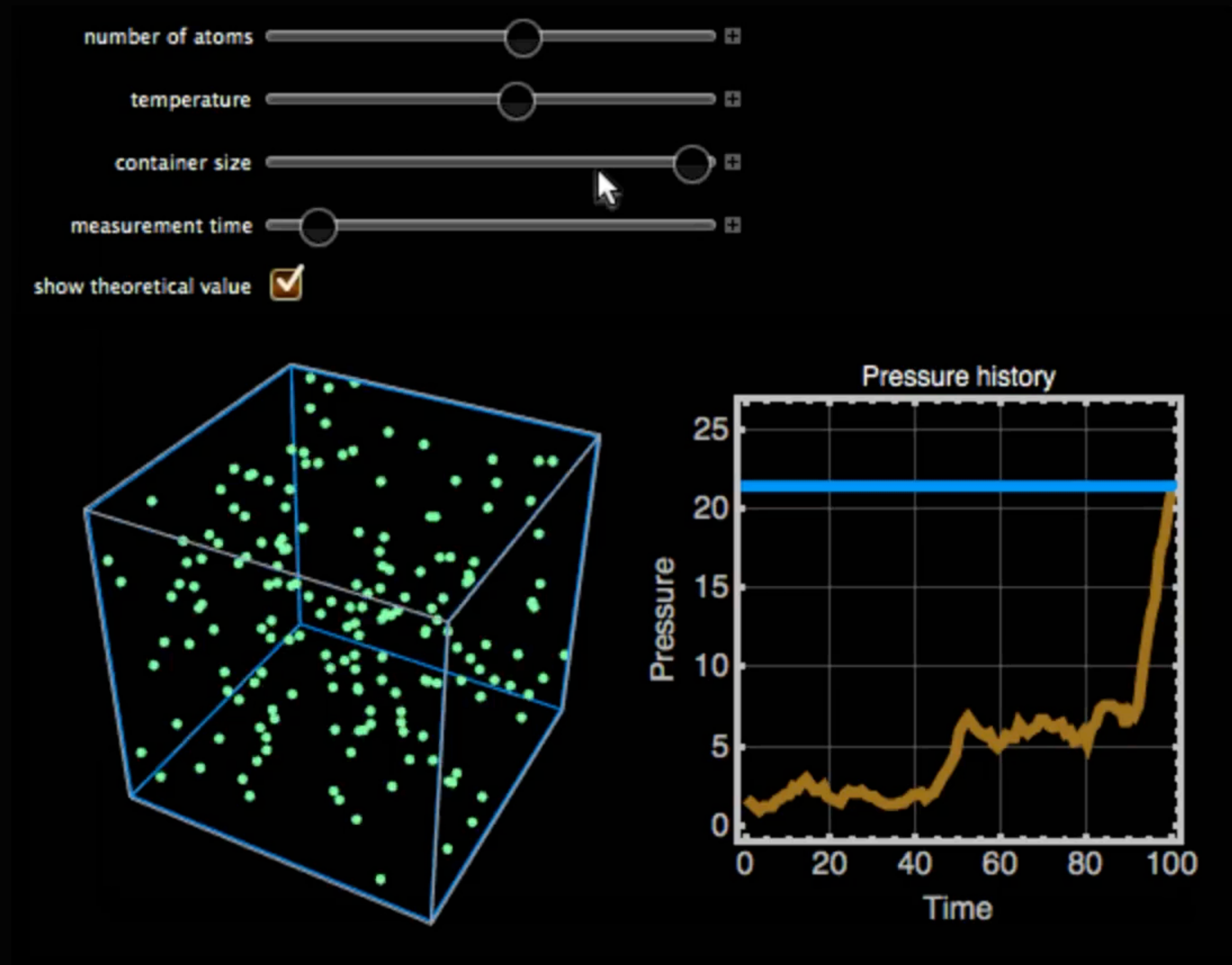
10^{24} of $(\vec{x}, \vec{p})$'s →

$$T = \frac{m\bar{v}^2}{3k_B}$$

$$P = \frac{Nm\bar{v}^2}{3V}$$

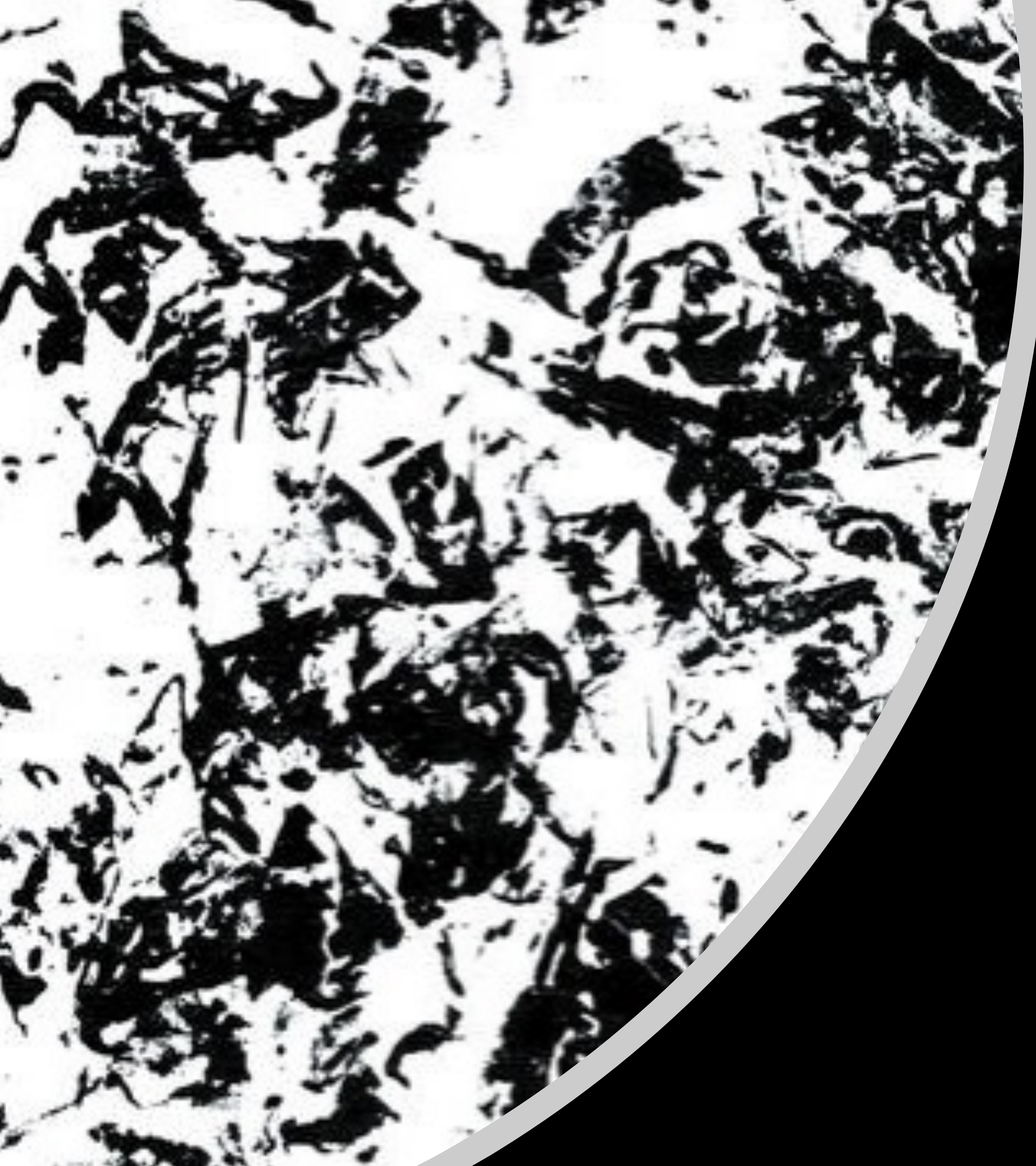
$\vec{F}(\vec{x}_I) = m_I \frac{d\vec{v}_I}{dt}$ → (Equilibrium*)

$$PV = k_B NT$$





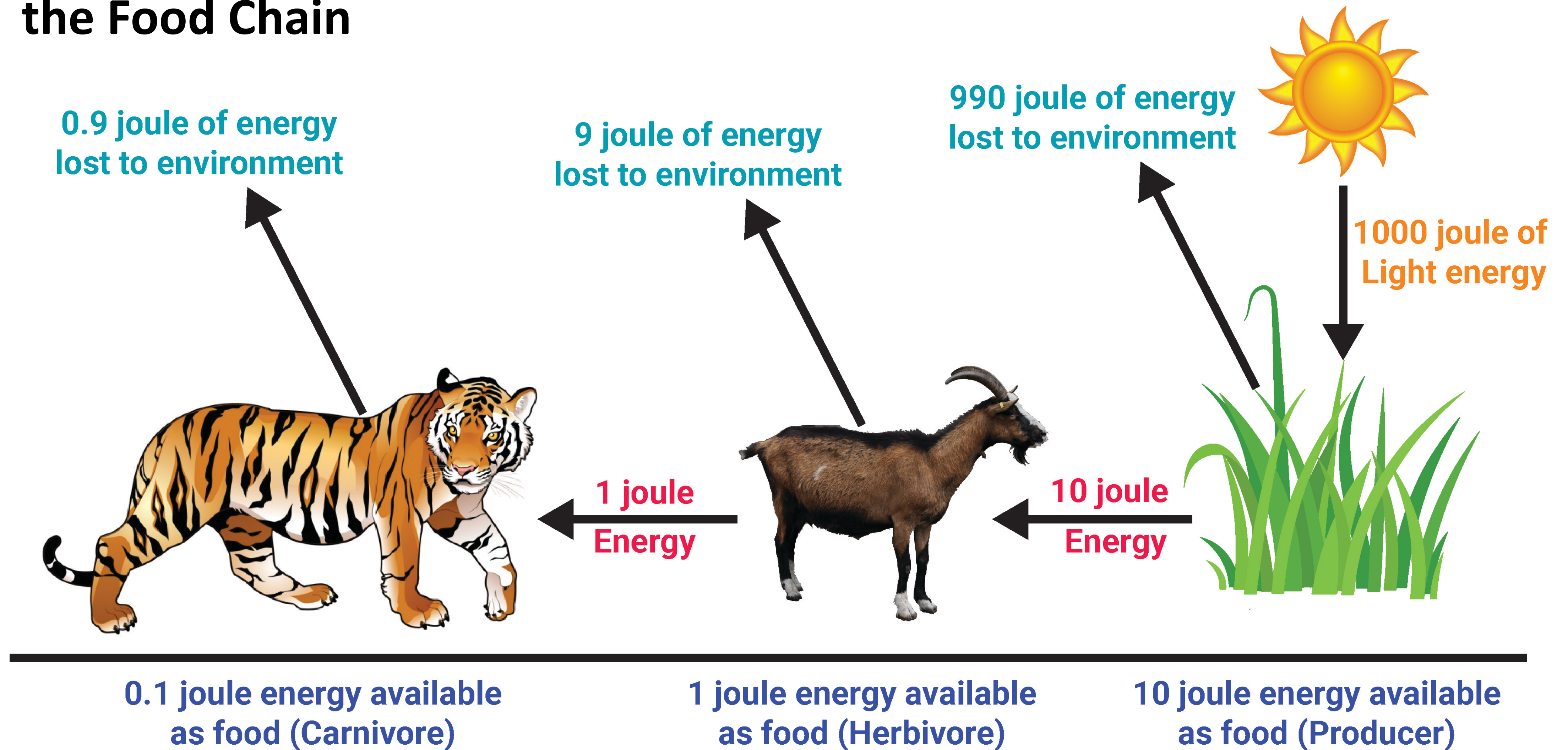
Questions or
thoughts?

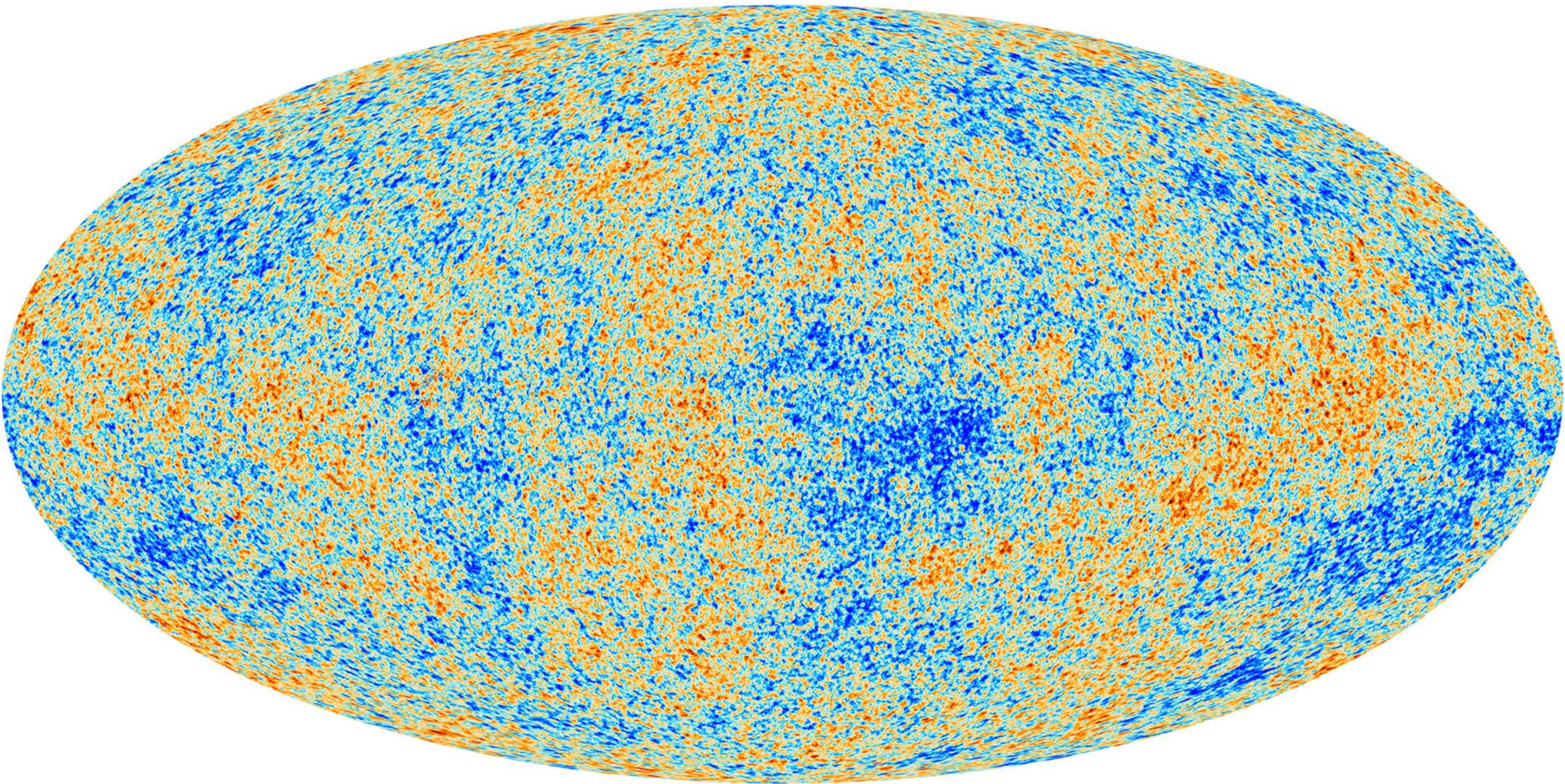


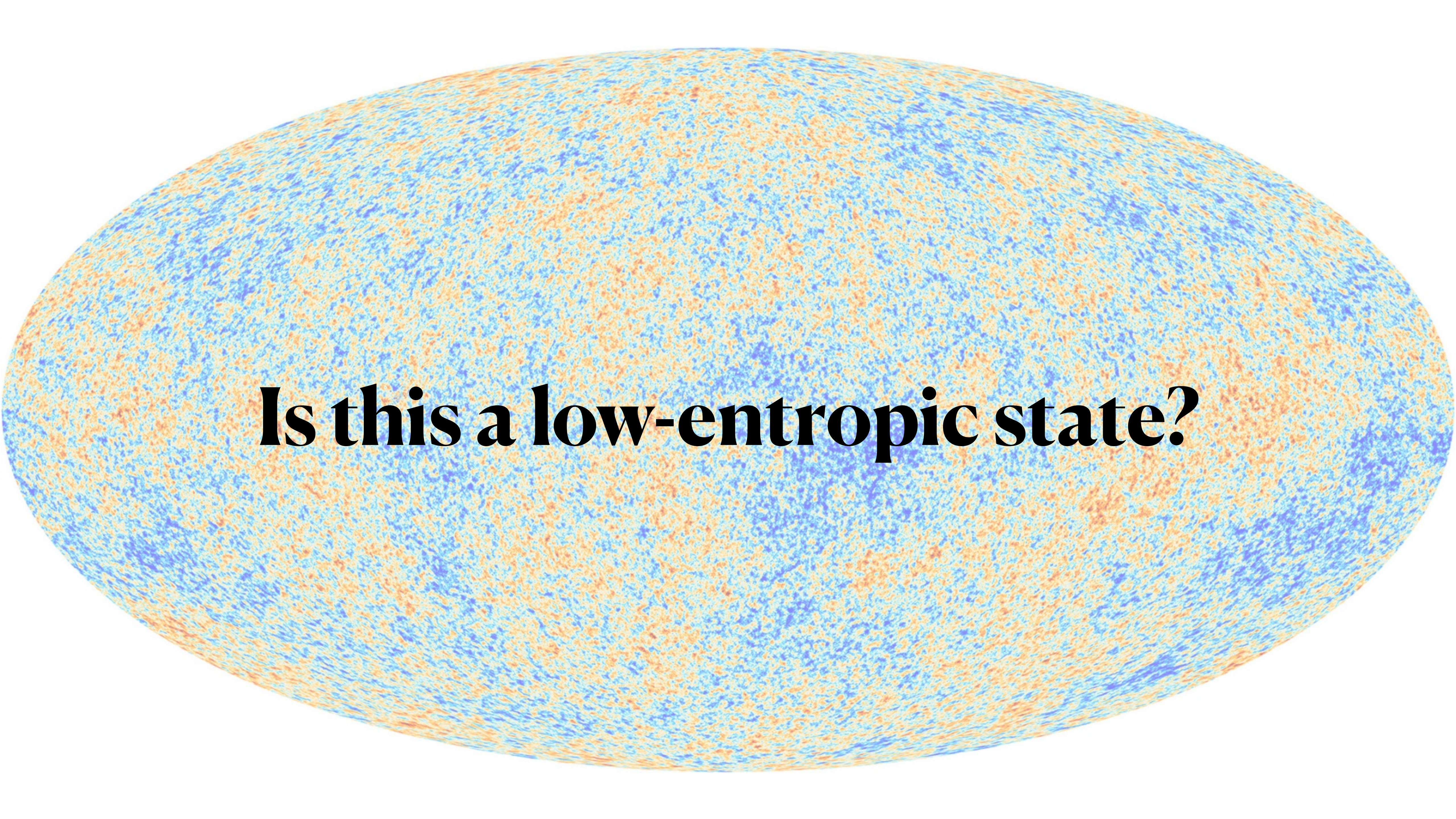
**Where does the low
entropy come from?**



Progressive Loss of Energy in the Food Chain

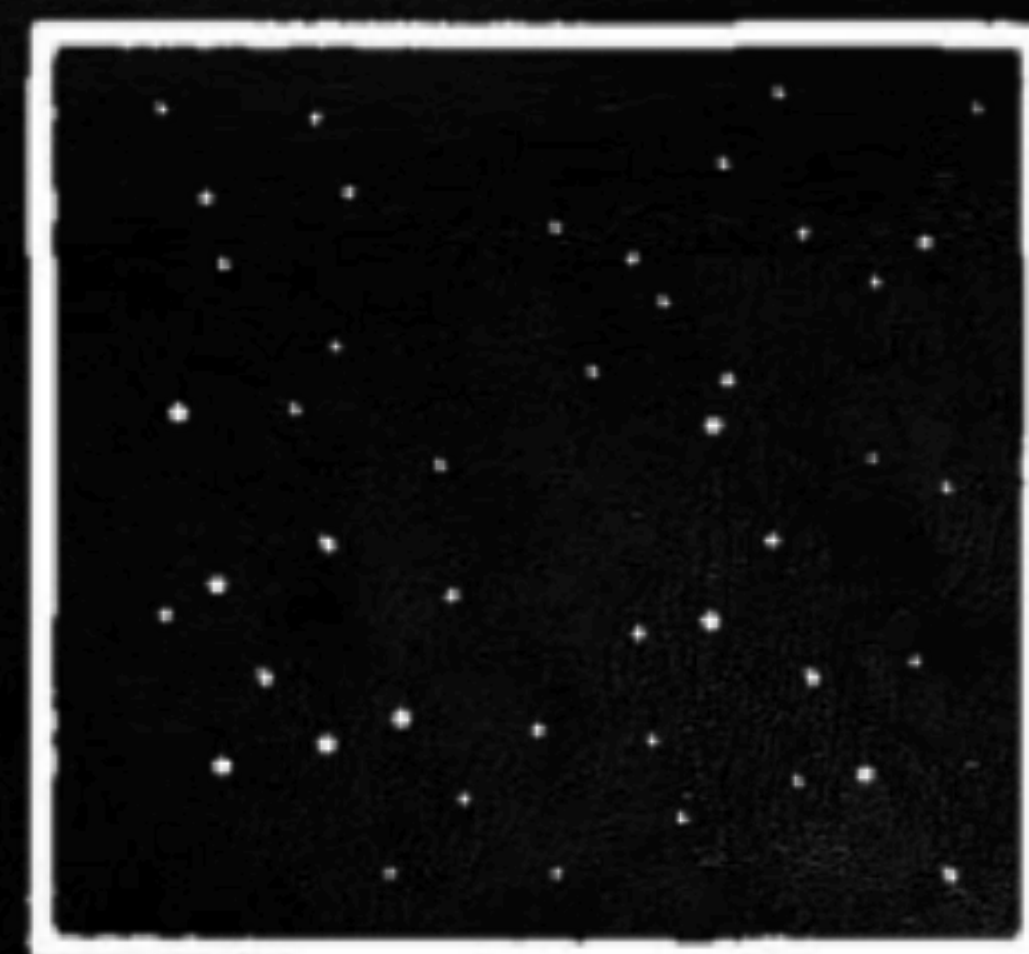
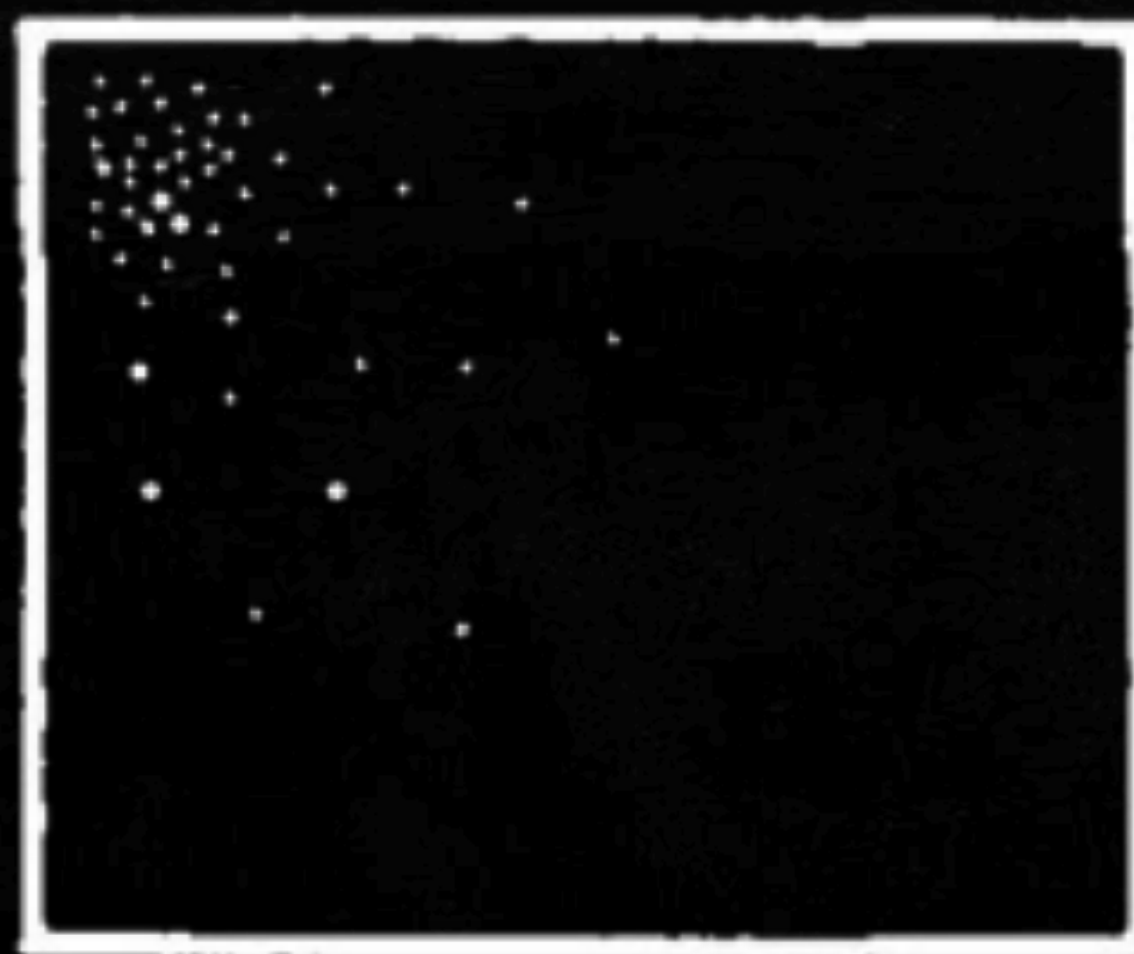




The image is a Cosmic Microwave Background (CMB) fluctuation map, often called a "Mandelbrot map". It shows a noisy, grainy pattern of blue and orange colors, representing temperature variations across the sky. The pattern is roughly circular, with a slight gradient from top to bottom. The text "Is this a low-entropic state?" is centered over the map.

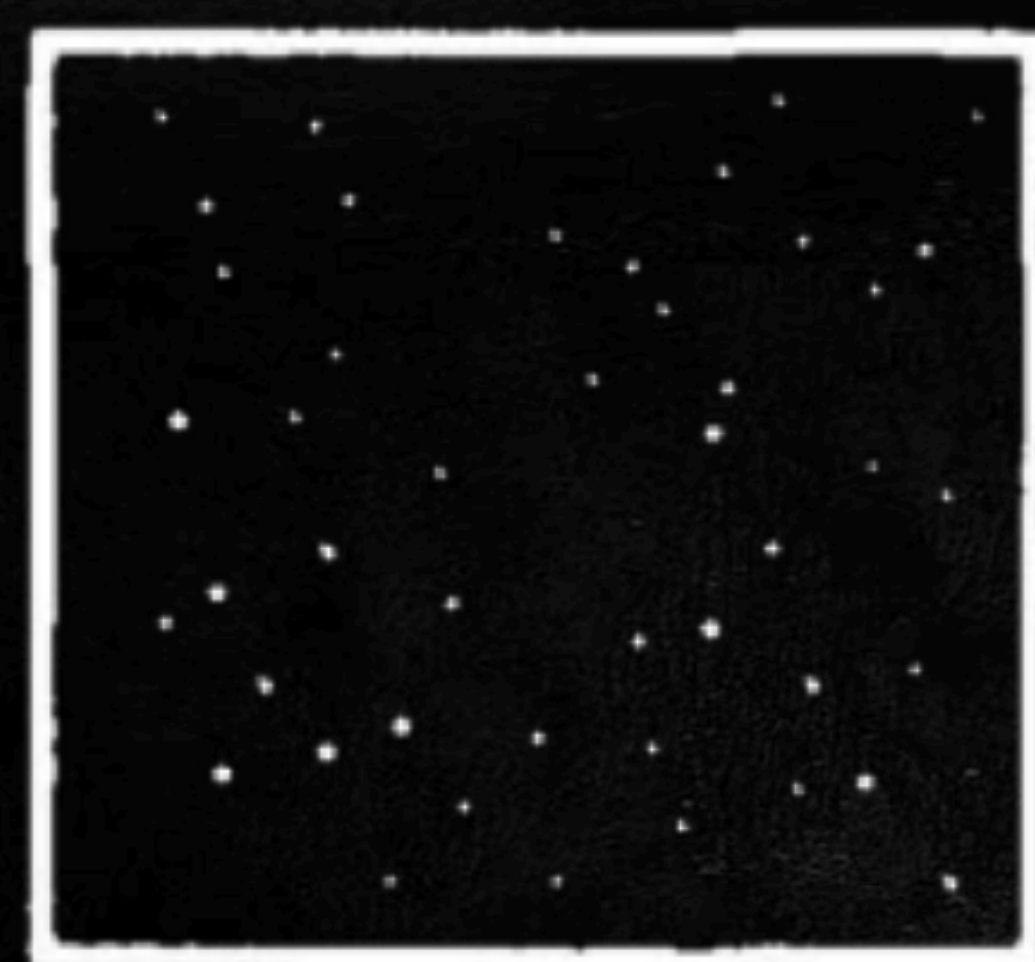
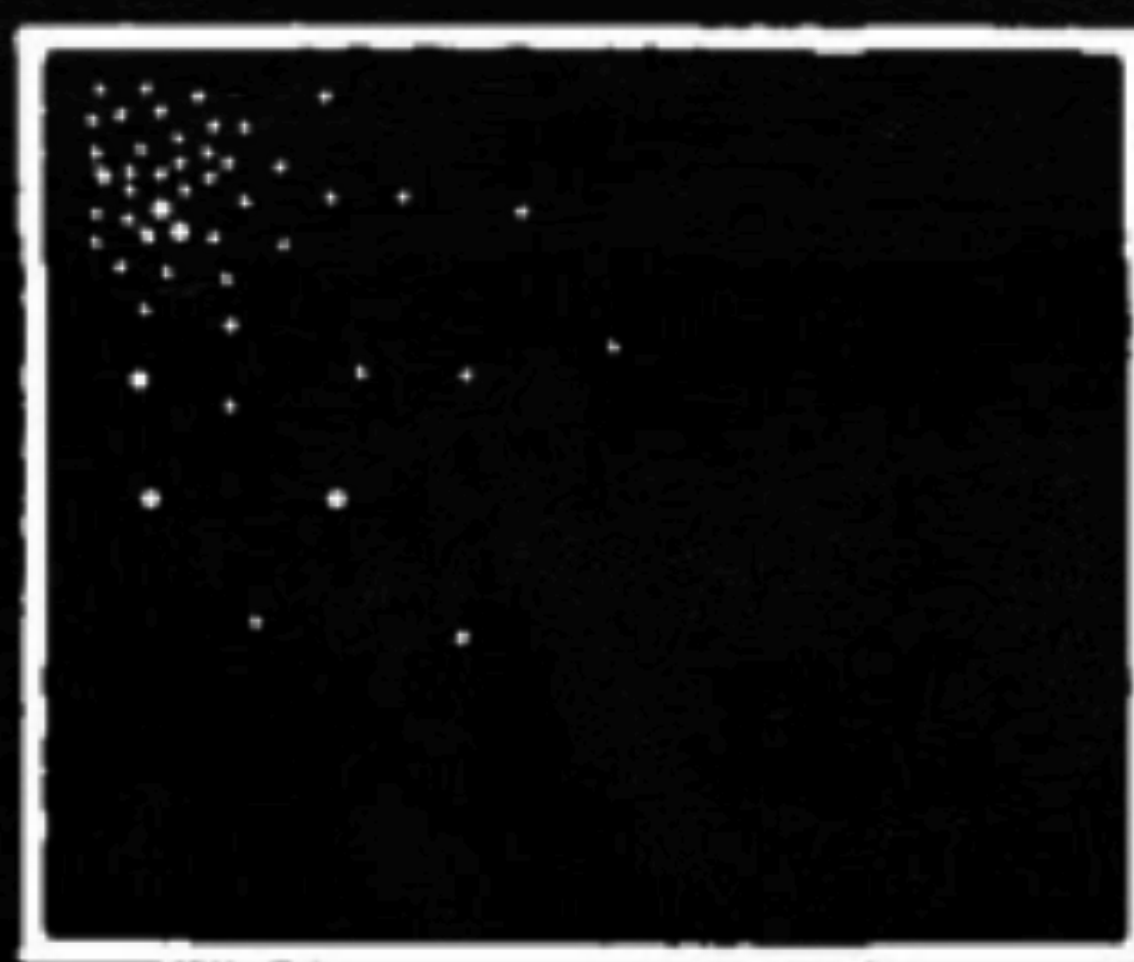
Is this a low-entropic state?

Gas

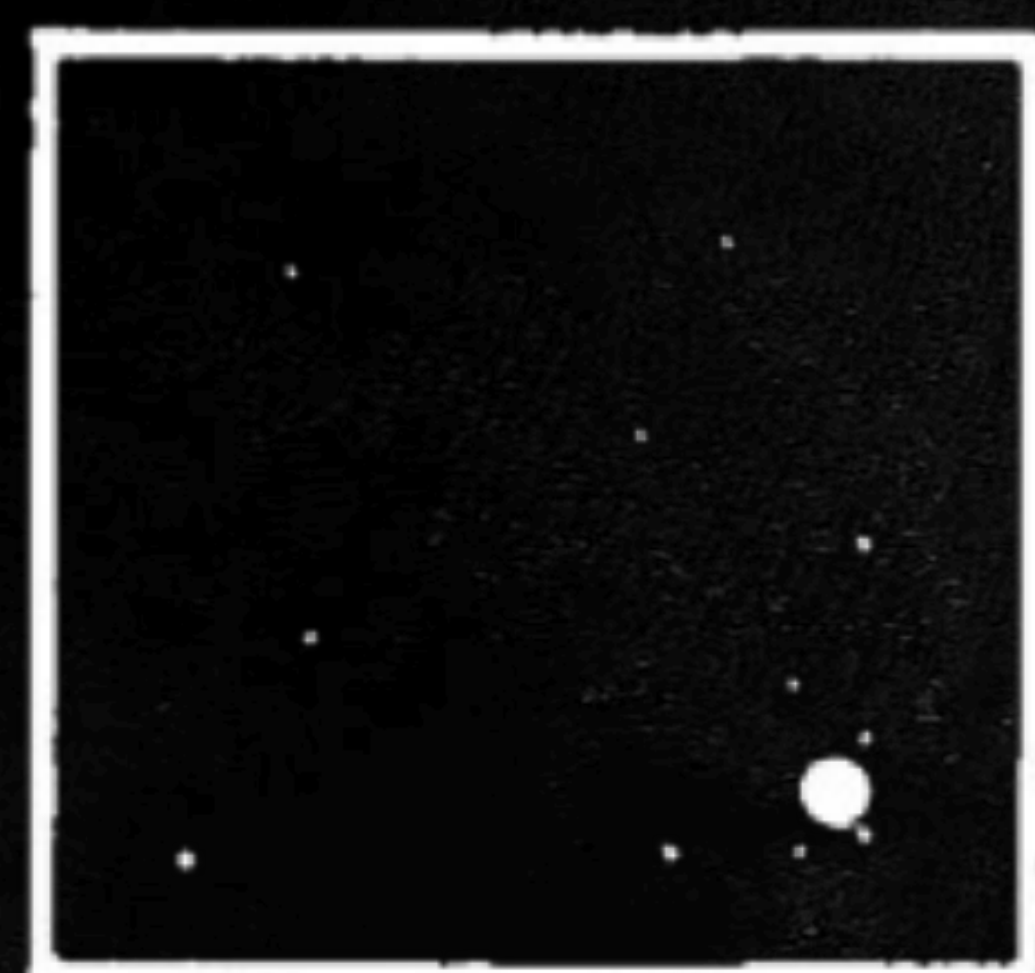


Increasing entropy

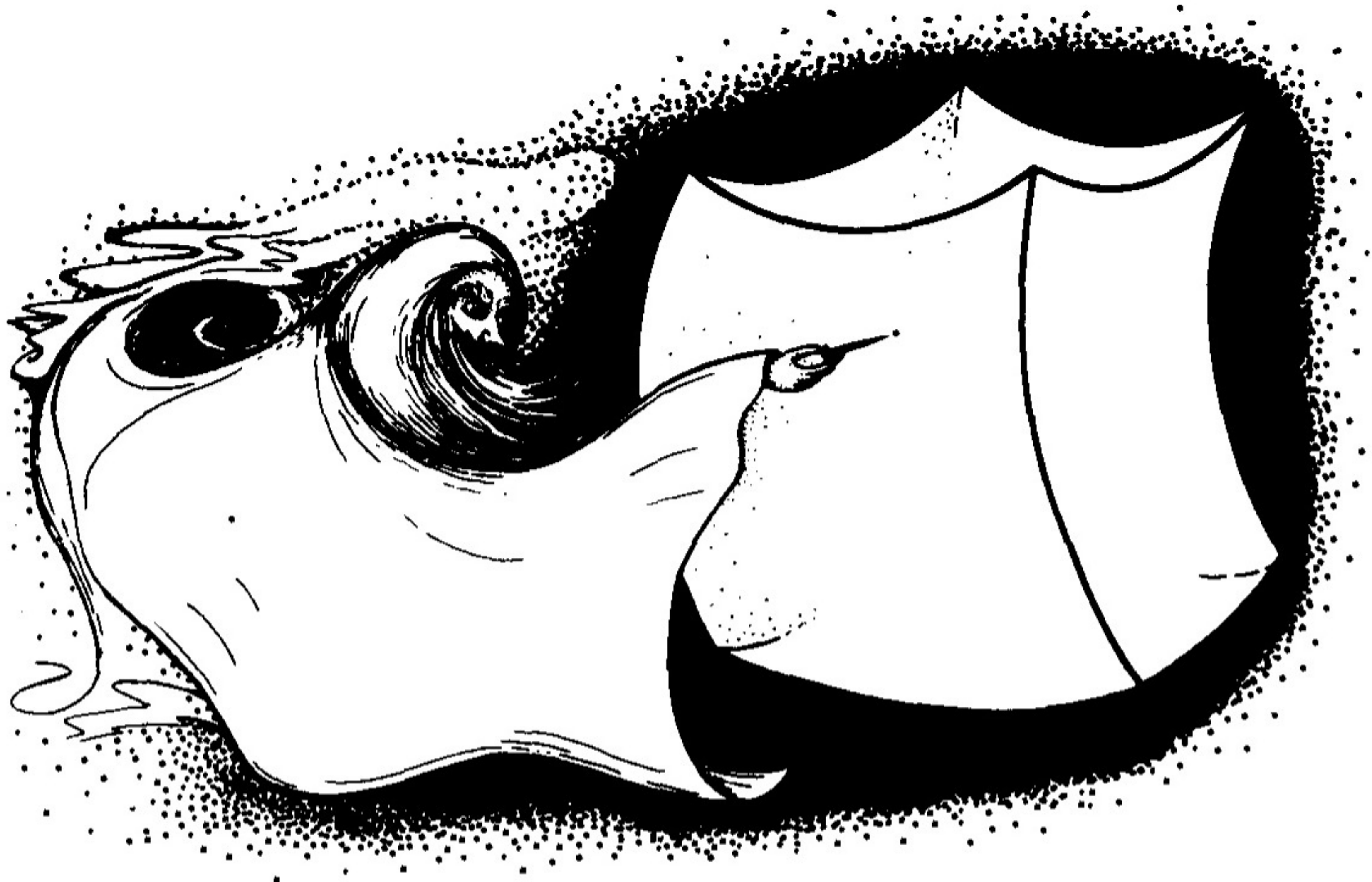
Gas



Increasing entropy



Gravitating bodies



God picking out the special (low-entropy) initial conditions of our universe.

- Penrose (1999)

Let's just call it
Past Hypothesis
;)

David Albert
(Philosopher of Physics)





How weird is this move?

“Up” = “away from Earth”

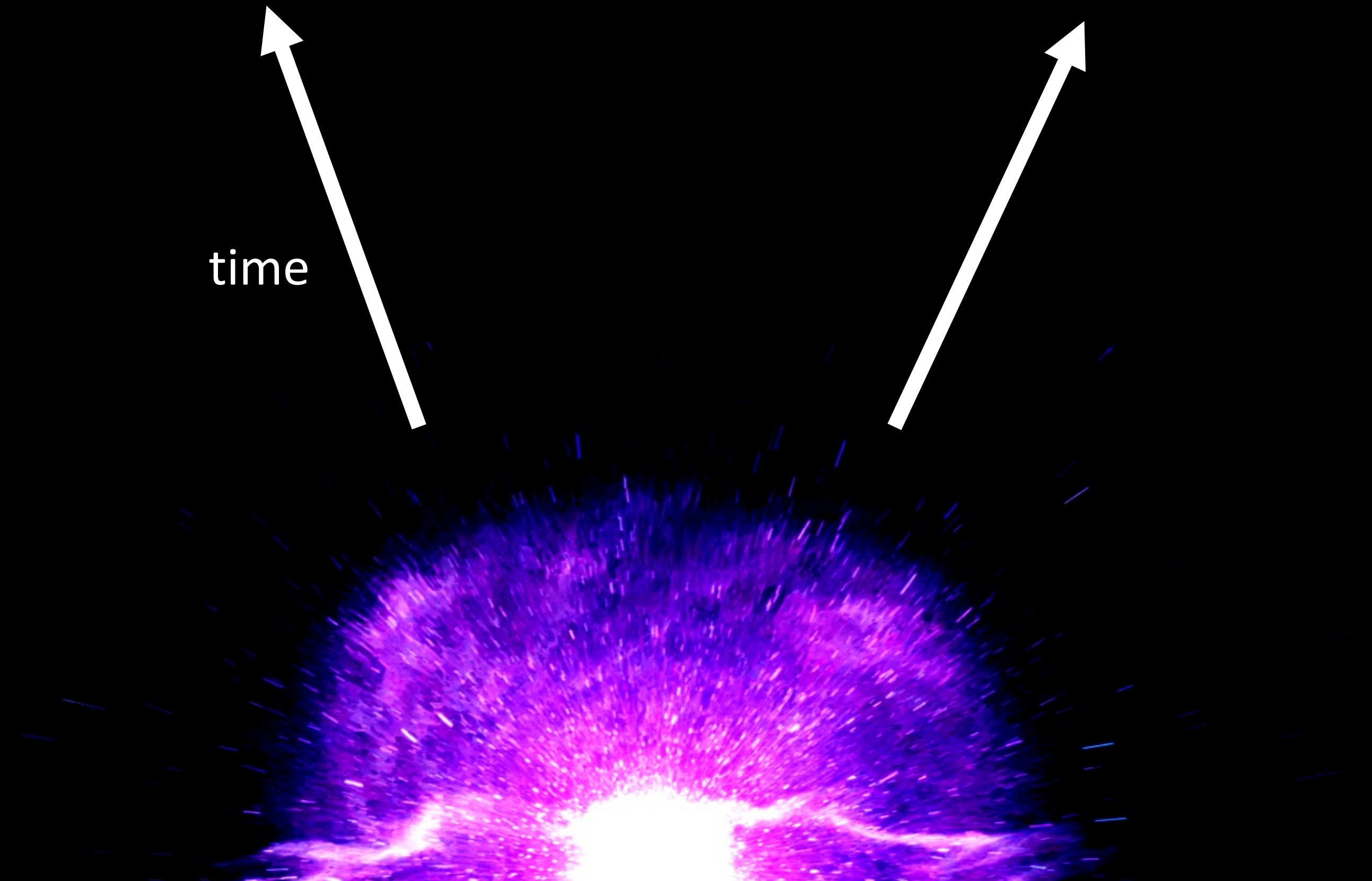
“Future” = “away from the Big Bang”

space

time



surface of the Earth



moment of the Big Bang



“The arrow of time connects the early universe to something we experience literally every moment of our lives... the arrow of time is the reason why time seems to flow around us... it's why we remember the past, but not the future. It's why we evolve and metabolize and eventually die. It's why we believe in cause and effect, and is crucial to our notions of free will.

And it's all because of the Big Bang.”

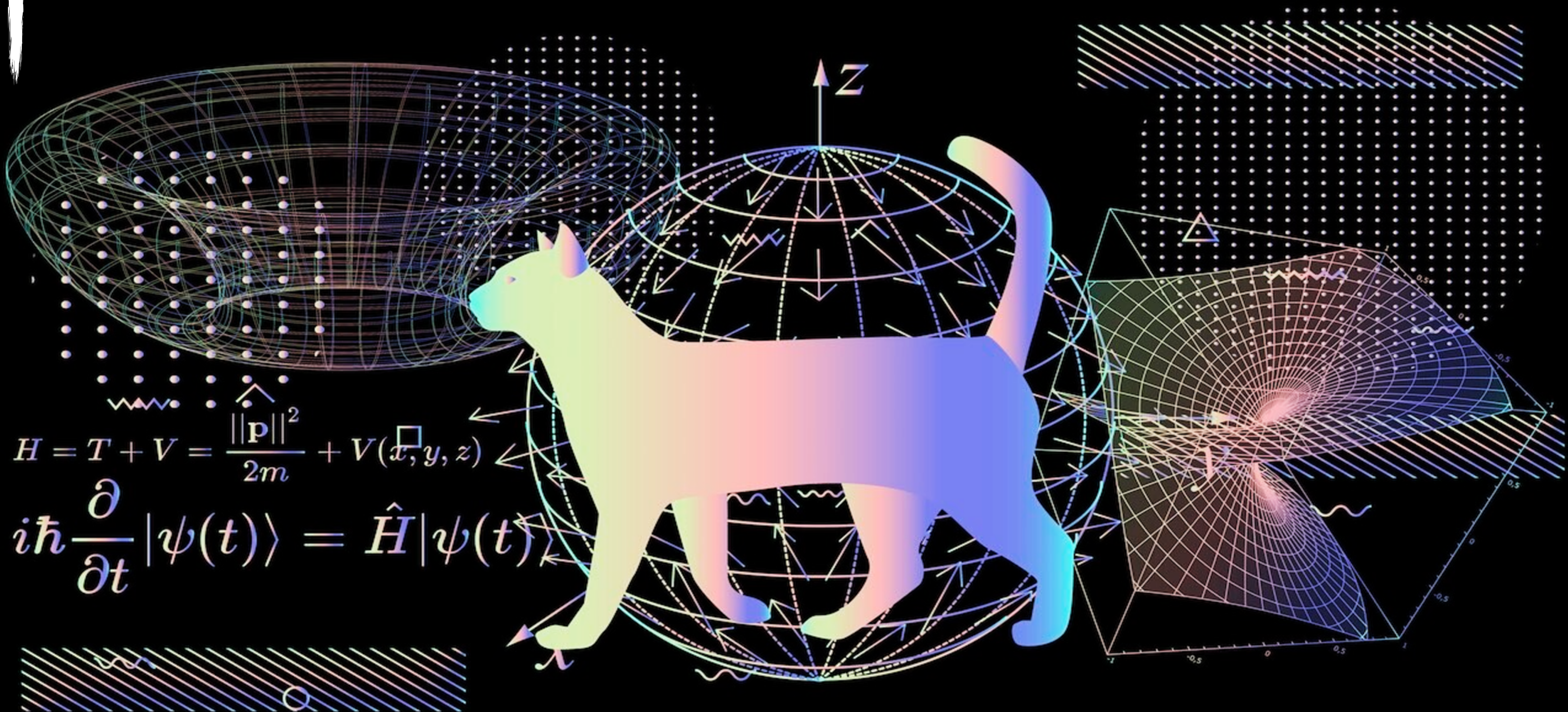
Sean Carroll

(Physicist)



Questions or
thoughts?

WHAT ABOUT QUANTUM MECHANICS?





(Solvay Conference, '27 - Belgium)

a) A new space: **Hilbert space, $\mathcal{H}$ - quantum space!**

b) A state: **$|\psi\rangle \in \mathcal{H}$ - the state-vector!**

c) An evolution (Schrödinger) equation*:

$$i\hbar \frac{d}{dt} |\psi\rangle = \hat{H} |\psi\rangle$$



(Solvay Conference, '27 - Belgium)

a) A new space: **Hilbert space, $\mathcal{H}$ - quantum space!**

b) A state: **$|\psi\rangle \in \mathcal{H}$ - the state-vector!**

c) An evolution (Schrödinger) equation*:

$$i\hbar \frac{d}{dt} |\psi\rangle = \hat{H} |\psi\rangle$$

?) Born rule: Prob = $|\psi_n|^2$

??) “collapse”: $|\psi\rangle \rightarrow |\psi_n\rangle$

The collapse of the wave function is irreversible, defining **an intrinsic arrow of time**. But is that what really happens in nature?

If we just accept the Schrödinger equation, everything is reversible!

But then you need to deal with the idea of branching of the wavefunction and existence of many worlds!

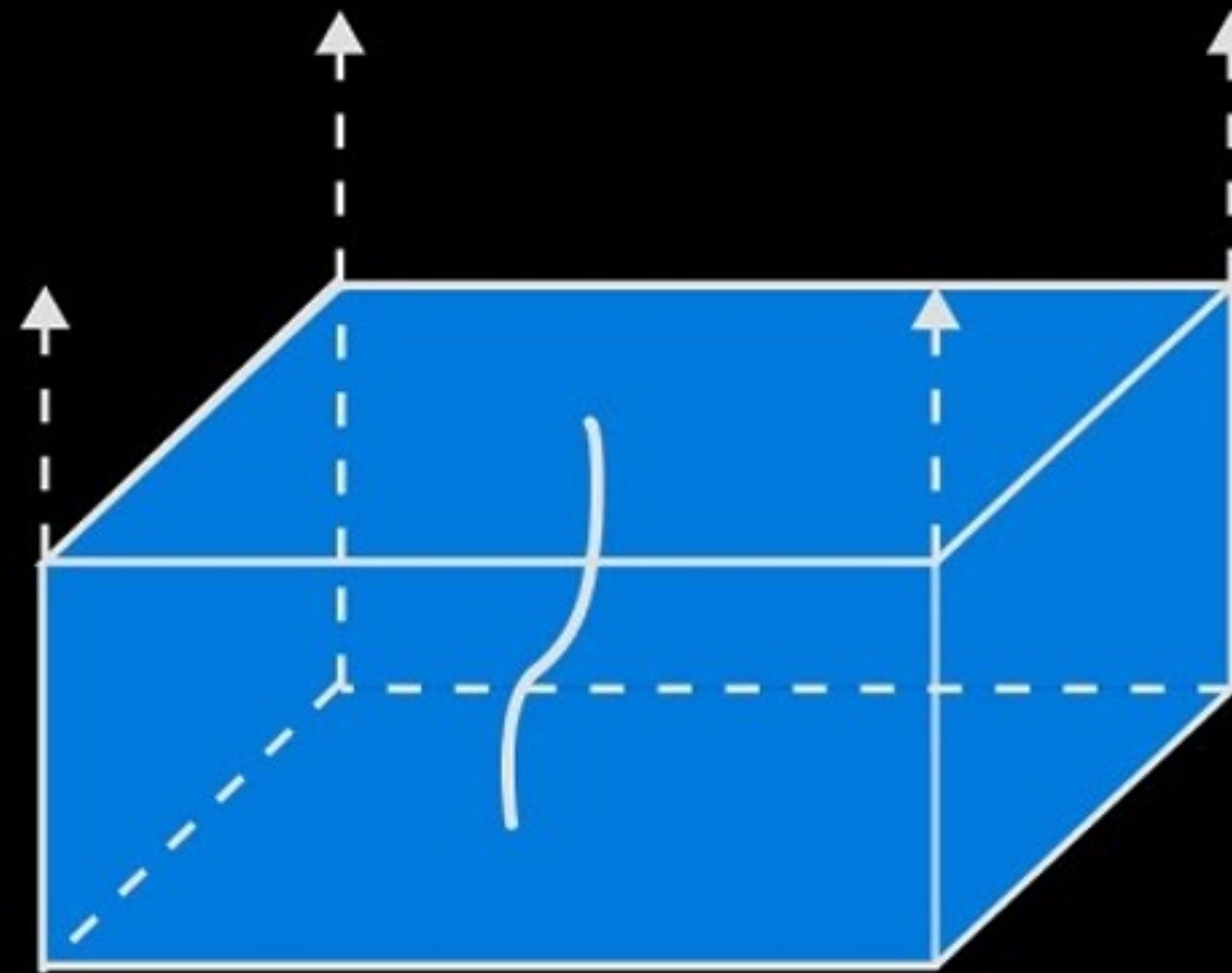


Scientific Realism - case study 2

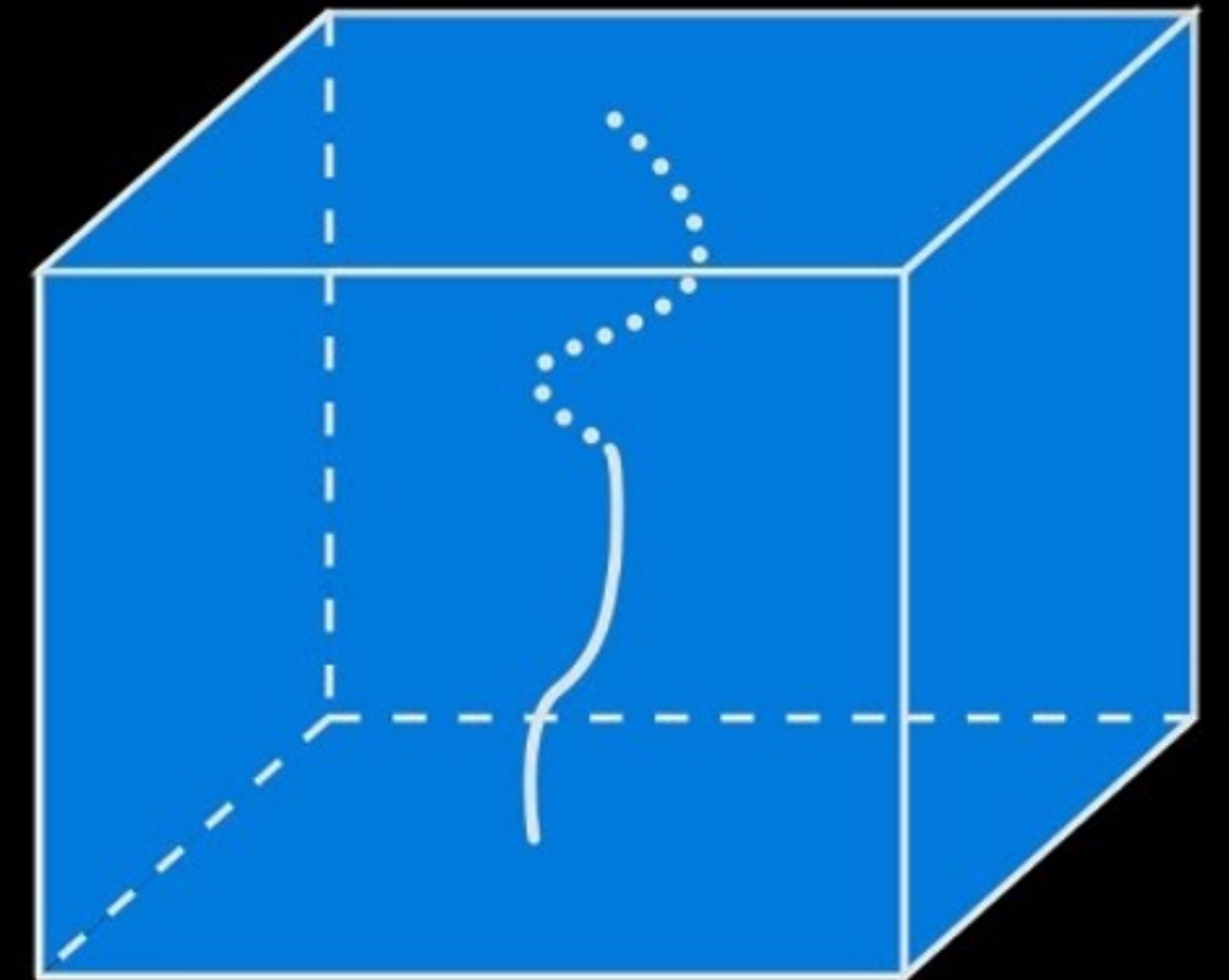
PRESENTISM (BEING)



GROWING PAST (BECOMING)



ETERNALISM (BLOCK UNIVERSE)



In your groups, discuss for a few minutes whether the broken egg in the box ever gets back to its unbroken form (~5 min).

Mathematical Aporia

(Aristotle's Physics, book II)

Mathematical Aporia

- How does a mathematician differ from the student of nature?

(Aristotle's Physics, book II)

Mathematical Aporia

- How does a mathematician differ from the student of nature?
- Mathematics extrapolates objects of the world to the realm of abstractions (forms)

(Aristotle's Physics, book II)

Mathematical Aporia

- How does a mathematician differ from the student of nature?
- Mathematics extrapolates objects of the world to the realm of abstractions (forms)
- The world of forms, as Plato discussed, is eternal, not temporal

(Aristotle's Physics, book II)

Mathematical Aporia

- How does a mathematician differ from the student of nature?
- Mathematics extrapolates objects of the world to the realm of abstractions (forms)
- The world of forms, as Plato discussed, is eternal, not temporal
- Is it reasonable, then, to expect mathematics to describe completely the world of passage?

(Aristotle's Physics, book II)

Evolutionary Aporia



Evolutionary Aporia

Our intuition and understanding is limited by
what we are: primates.



Evolutionary Aporia

Our intuition and understanding is limited by
what we are: primates.

We evolved being used to very important notions,
as cause&effect and finiteness.



Evolutionary Aporia

Our intuition and understanding is limited by what we are: primates.

We evolved being used to very important notions, as cause&effect and finiteness.

Concerning the “beginning” of the universe, there are two options: **spontaneous appearance or eternity.**



Evolutionary Aporia

Our intuition and understanding is limited by what we are: primates.

We evolved being used to very important notions, as cause&effect and finiteness.

Concerning the “beginning” of the universe, there are two options: **spontaneous appearance** or **eternality**.

Neither is fulfilling given our intuitions.



Next Time (Nov 29th) - Einstein comes along, and now space and time are relative

To read:

- S. Carroll, Space, Time and Motion: Ch. 6
- D. Wallace, Philosophy of Physics: Ch. 3