Title: Black Holes and the Foundations of Quantum Mechanics

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Abstract: The theory of Quantum Mechanics requires \'completeness\', that is, we need to know the complete set of physically allowed states before we can reliably compute quantum mechanical amplitudes. Among these possible states are microscopic black holes, since they are valid solutions to Einstein\'s equations for the gravitational force. However, a quantum description of black holes requires a drastic revision of our notions of space and time, in particular if we were to accept the interpretation of their microstates as given by superstring theories. The logical foundations of our physical world view are touched upon here. A natural sounding solution of our problems here could come from a re-interpretation of what quantum mechanics really is. The first thing to dispose of should be all references to \'magic\' and \'mystery\' when dealing with quantum mechanics or string theory.

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BLACK HOLES

and the Foundations of

QUANTUM MECHANICS

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The Standard Model

Leptons

ν_e e ν_μ μ

Quarks

u u u

d d d s s s

Z^0 W^+ W^- γ

The Standard Model

Leptons

ν_e e ν_μ μ

Quarks

u u u

d d d

s s s

Gauge Bosons

Z^0 W^+ W^- γ

g

Higgs

The Standard Model

	Generation I	Generation II
Leptons	ν_e e	ν_μ μ
Quarks	u u u / d d d	c c c / s s s
Gauge Bosons	Z^0 W^+ W^- γ	g
Higgs		

The Standard Model

	Generation I	Generation II	Generation III
Leptons	ν_e e	ν_μ μ	ν_τ τ
Quarks	u u u / d d d	c c c / s s s	t t t / b b b
Gauge Bosons	Z^0 W^+ W^- γ	g	Higgs

The Standard Model

	Generation I	Generation II	Generation III
Leptons	ν_e e	ν_μ μ	ν_τ τ
Quarks	u u u d d d	c c c s s s	t t t b b b
Gauge Bosons	Z^0 W^+ W^- γ	g	

Higgs

Graviton

All fundamental particles must have

spin 0 (scalar fields, Klein-Gordon Eq.),
spin ½ (spinor fields, Dirac Eq.),

or

spin 1 (vector fields, Yang-Mills Eq.)

All fundamental particles must have

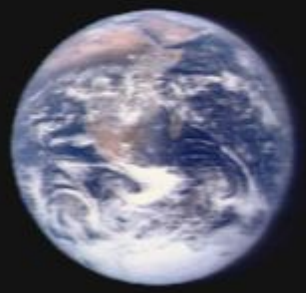
spin 0 (scalar fields, Klein-Gordon Eq.),
spin ½ (spinor fields, Dirac Eq.),

or

spin 1 (vector fields, Yang-Mills Eq.)

otherwise, their interactions
are *non-renormalizable*

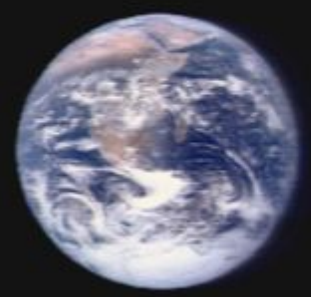
Force and spin



Earth

Force and spin

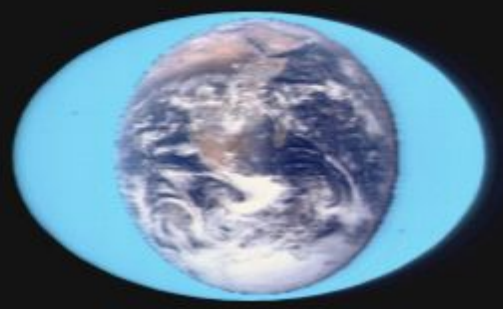
Moon



Earth

Force and spin

Moon



Earth

Force and spin

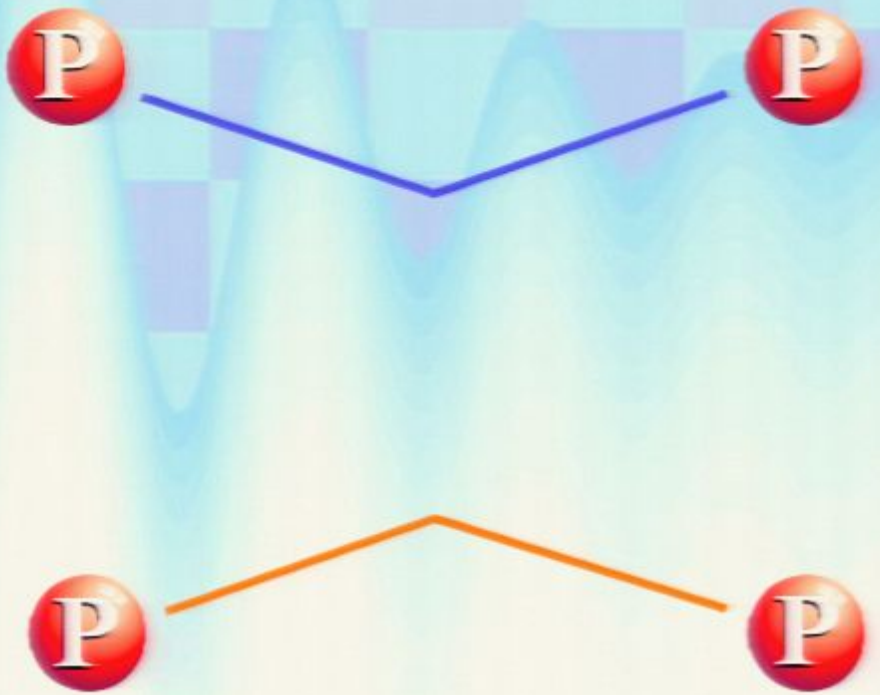
Earth

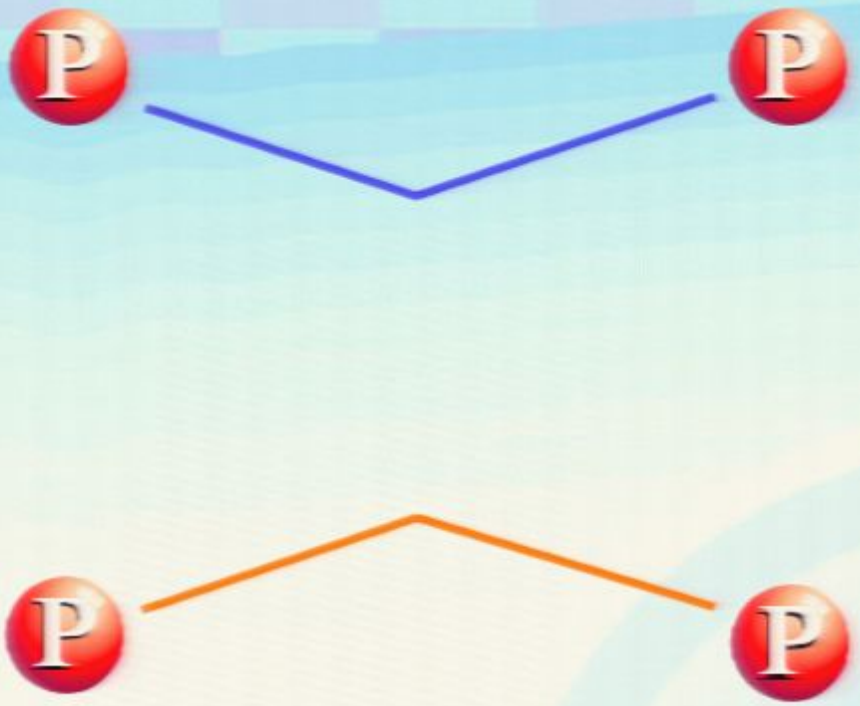
Moon

Sun

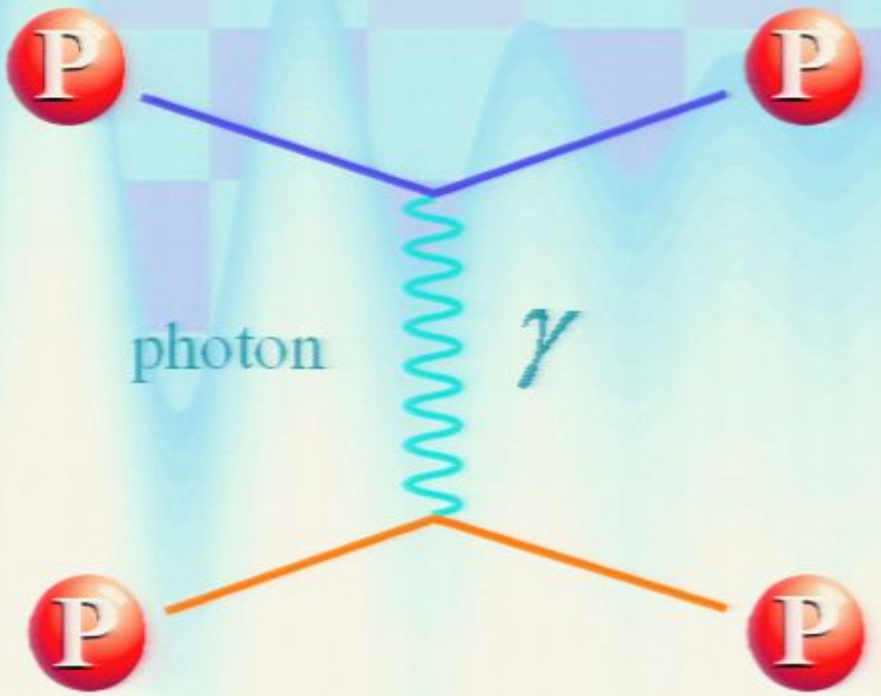
The Photon

The Graviton

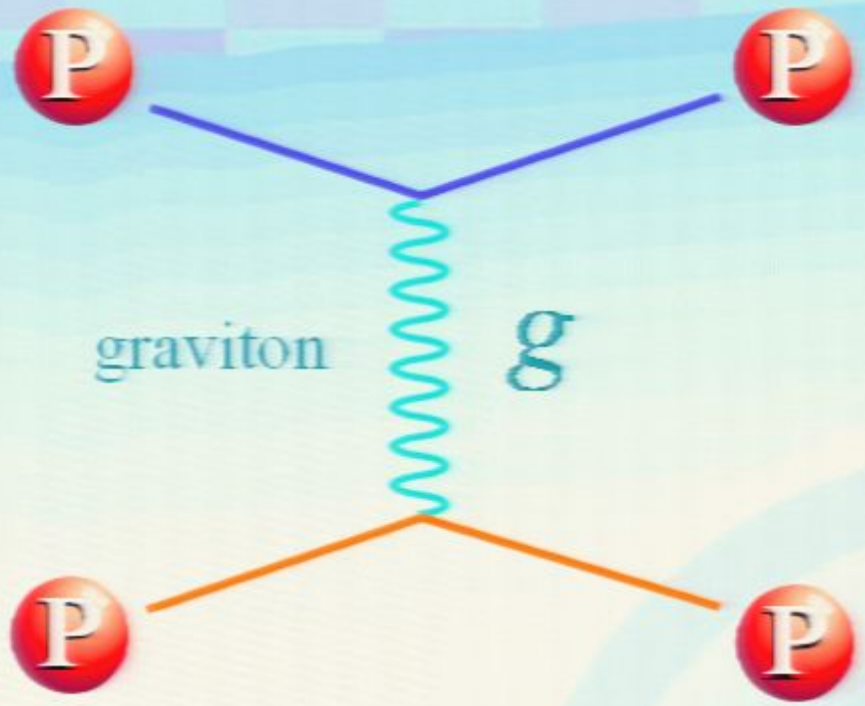




The Photon



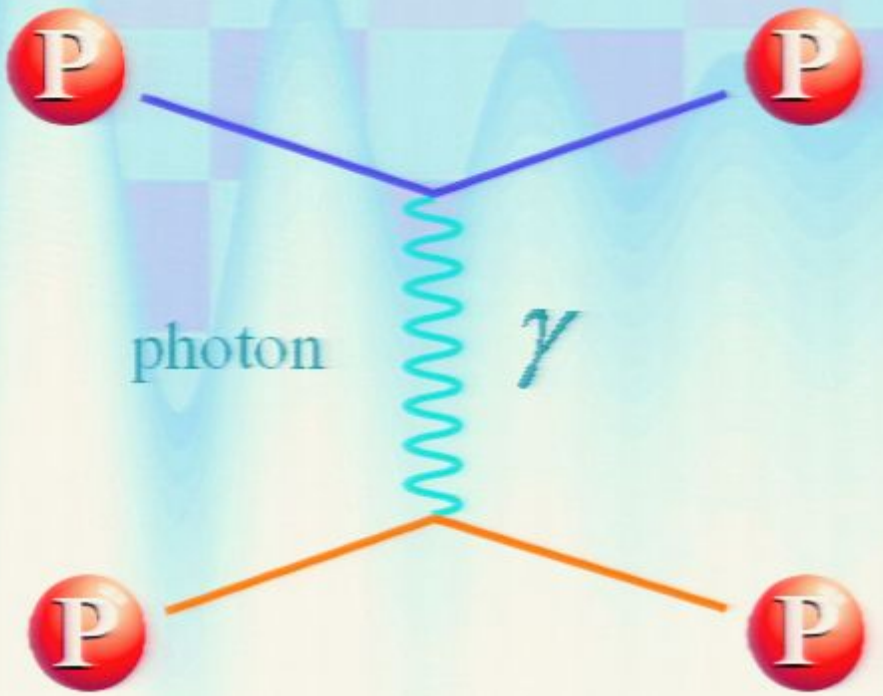
The Graviton



The Photon

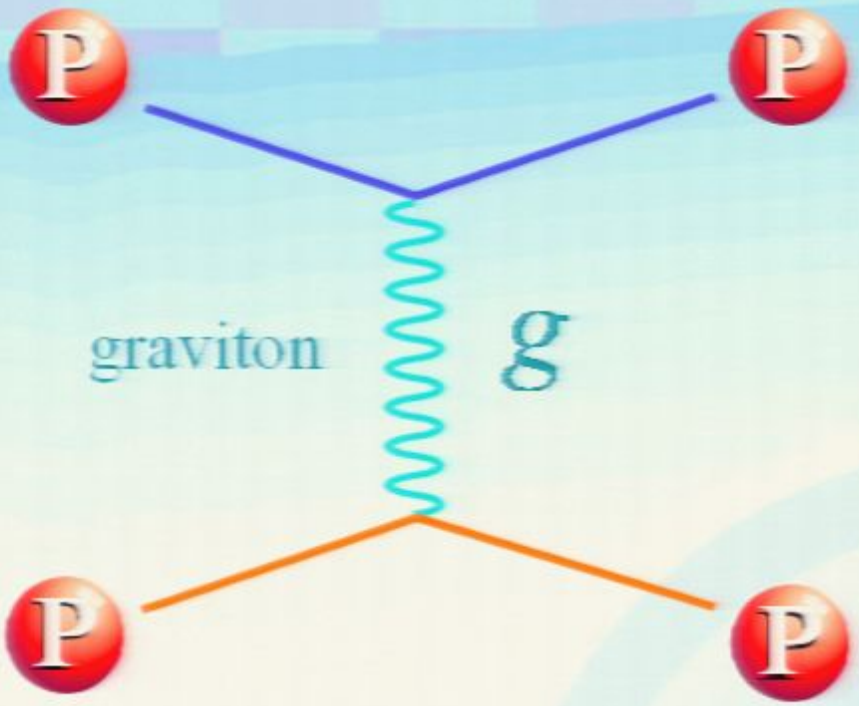
Spin = 1

Equal charges repel one another ...



The Graviton

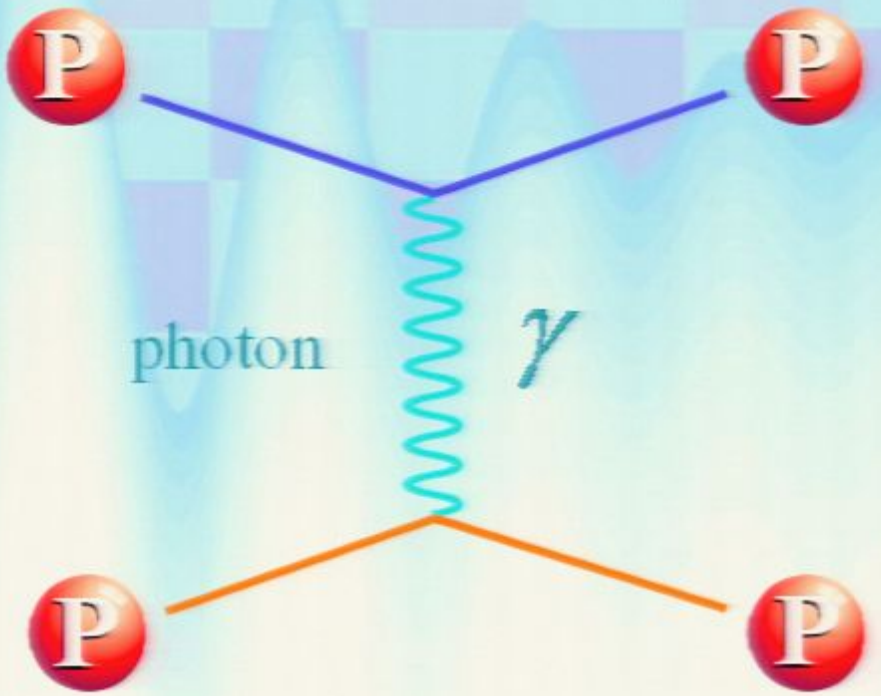
Spin = 2



The Photon

Spin = 1

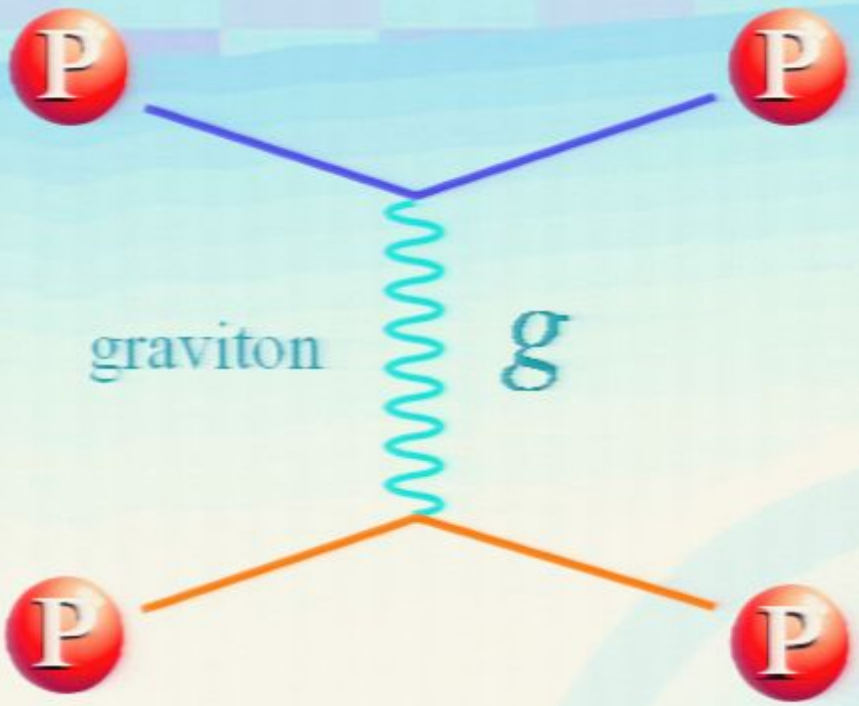
Equal charges repel one another ...



The Graviton

Spin = 2

Equal masses attract one another ...



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The Cosmological Constant Problem

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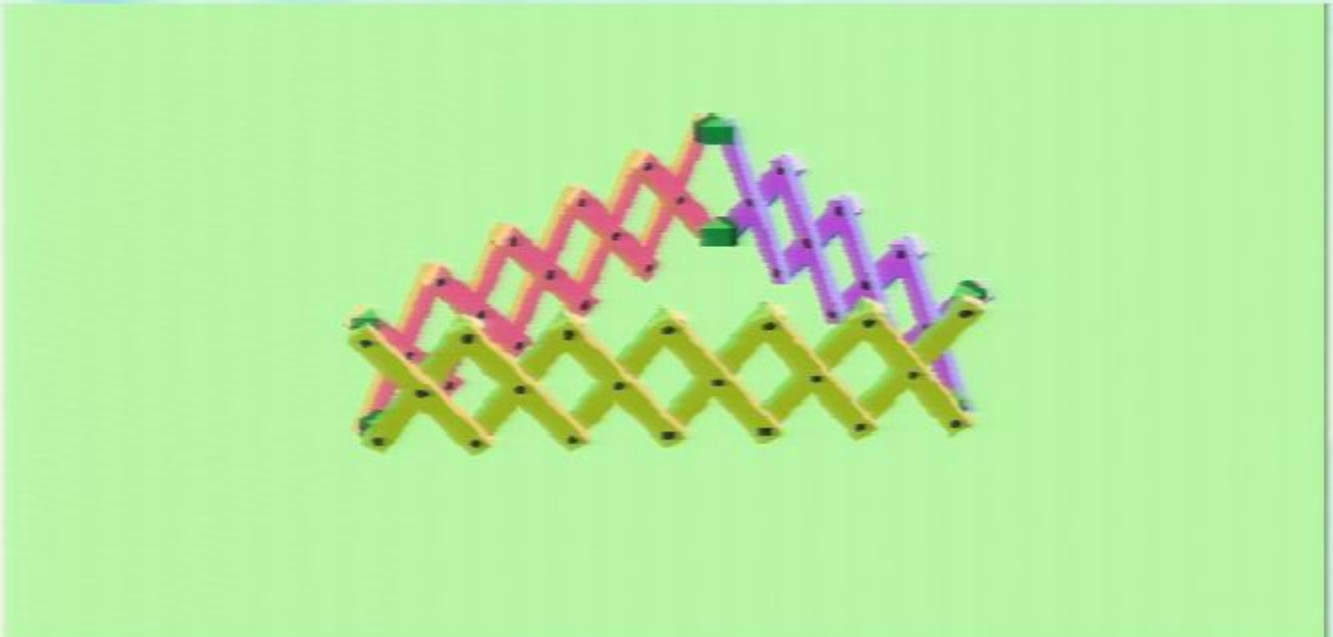

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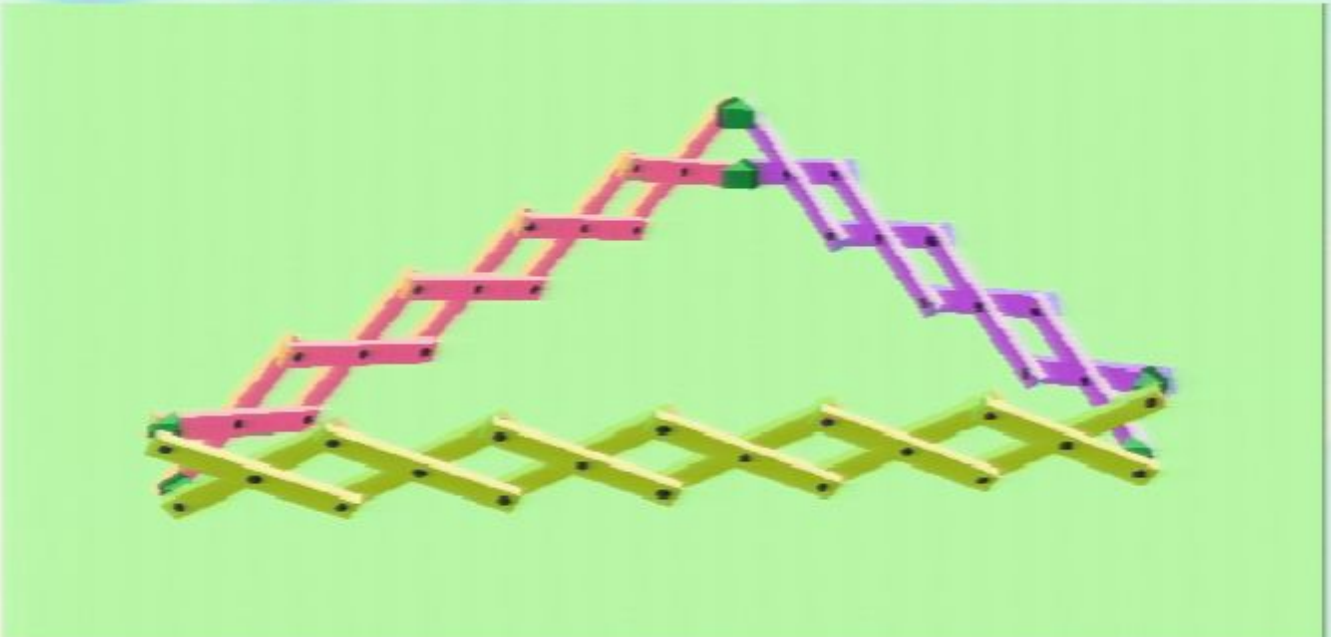

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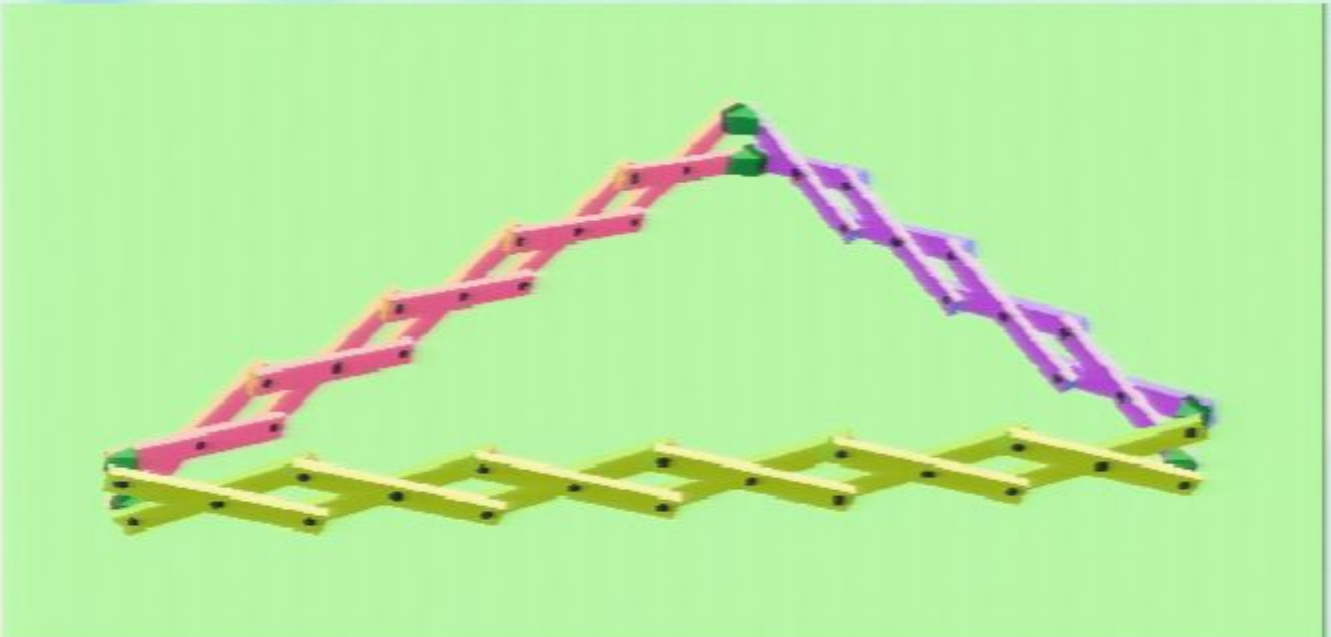

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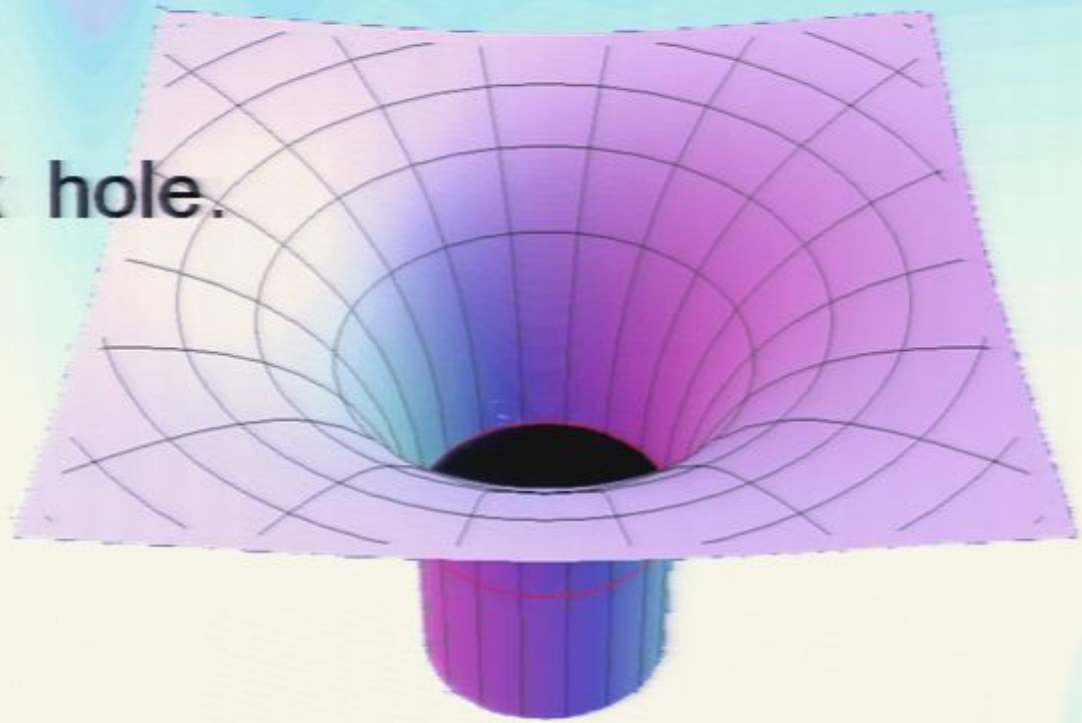

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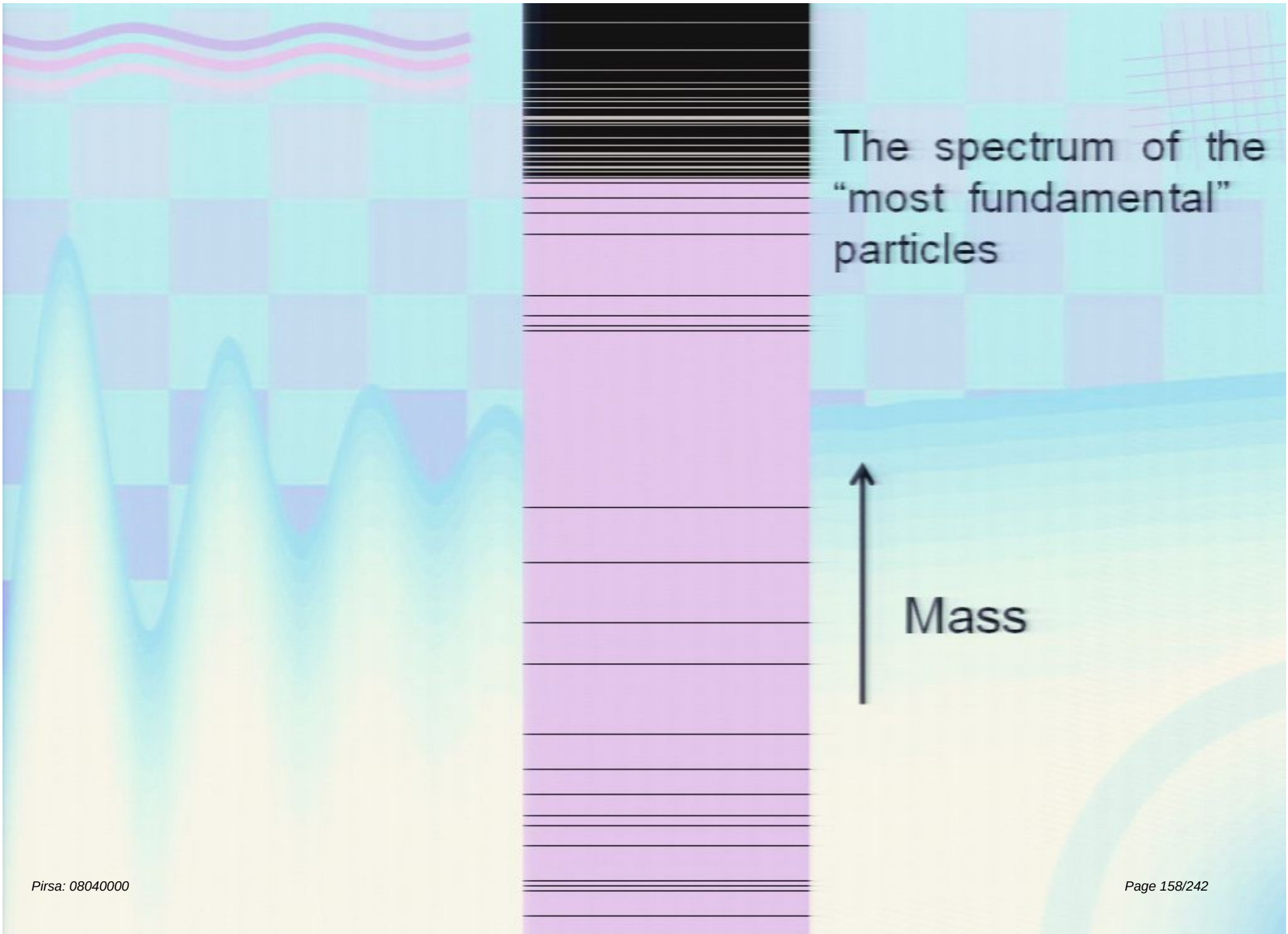
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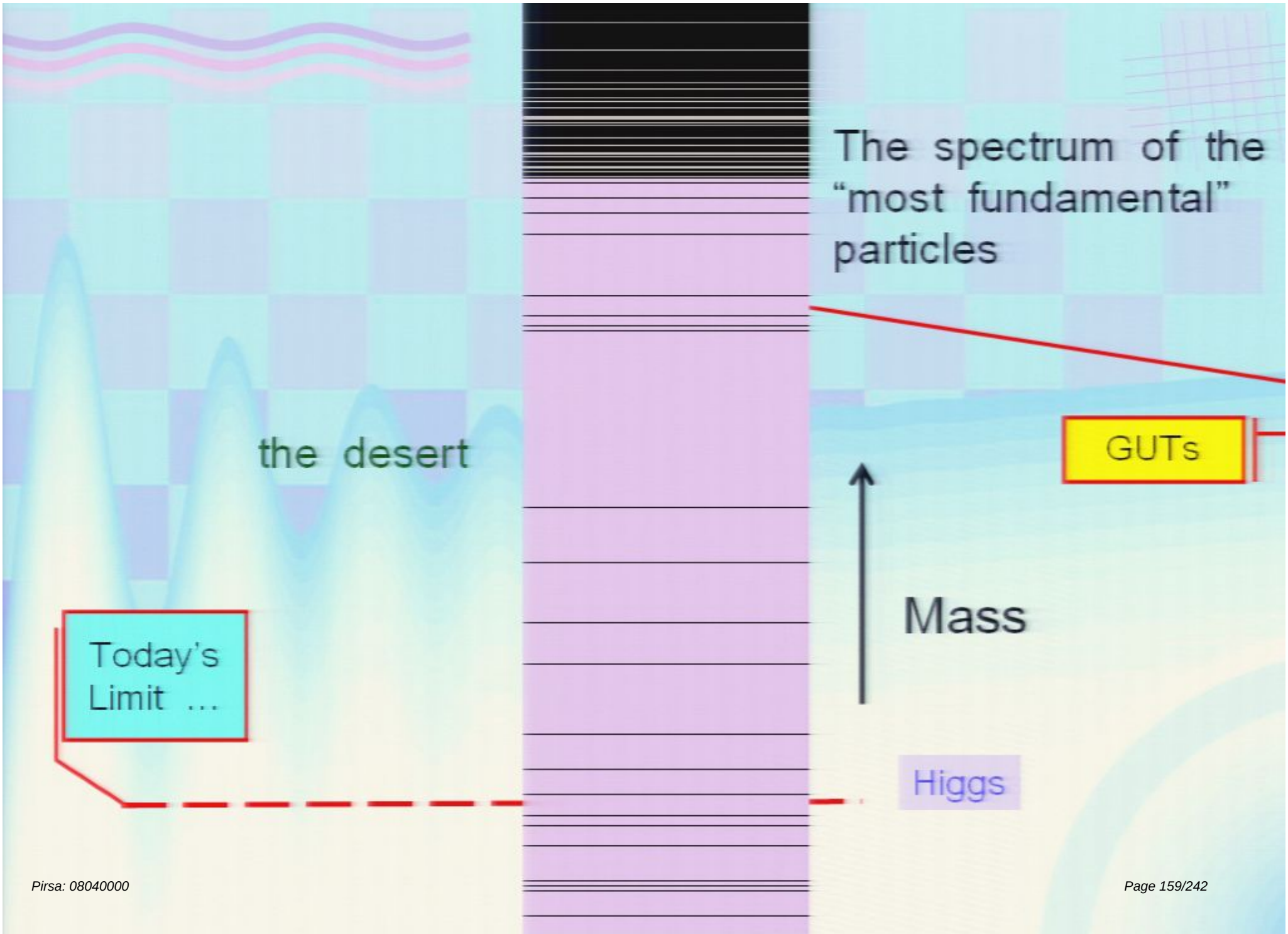
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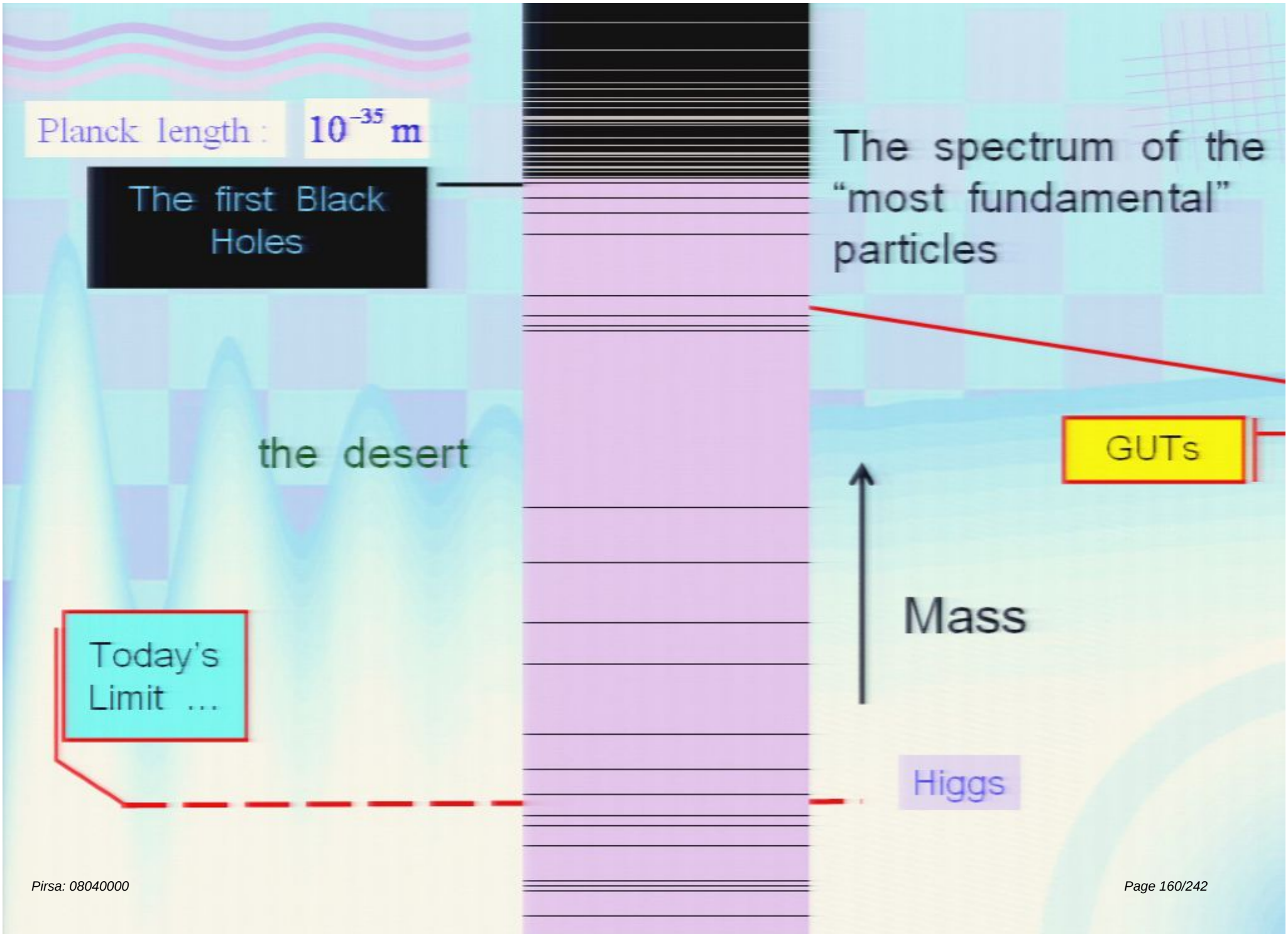
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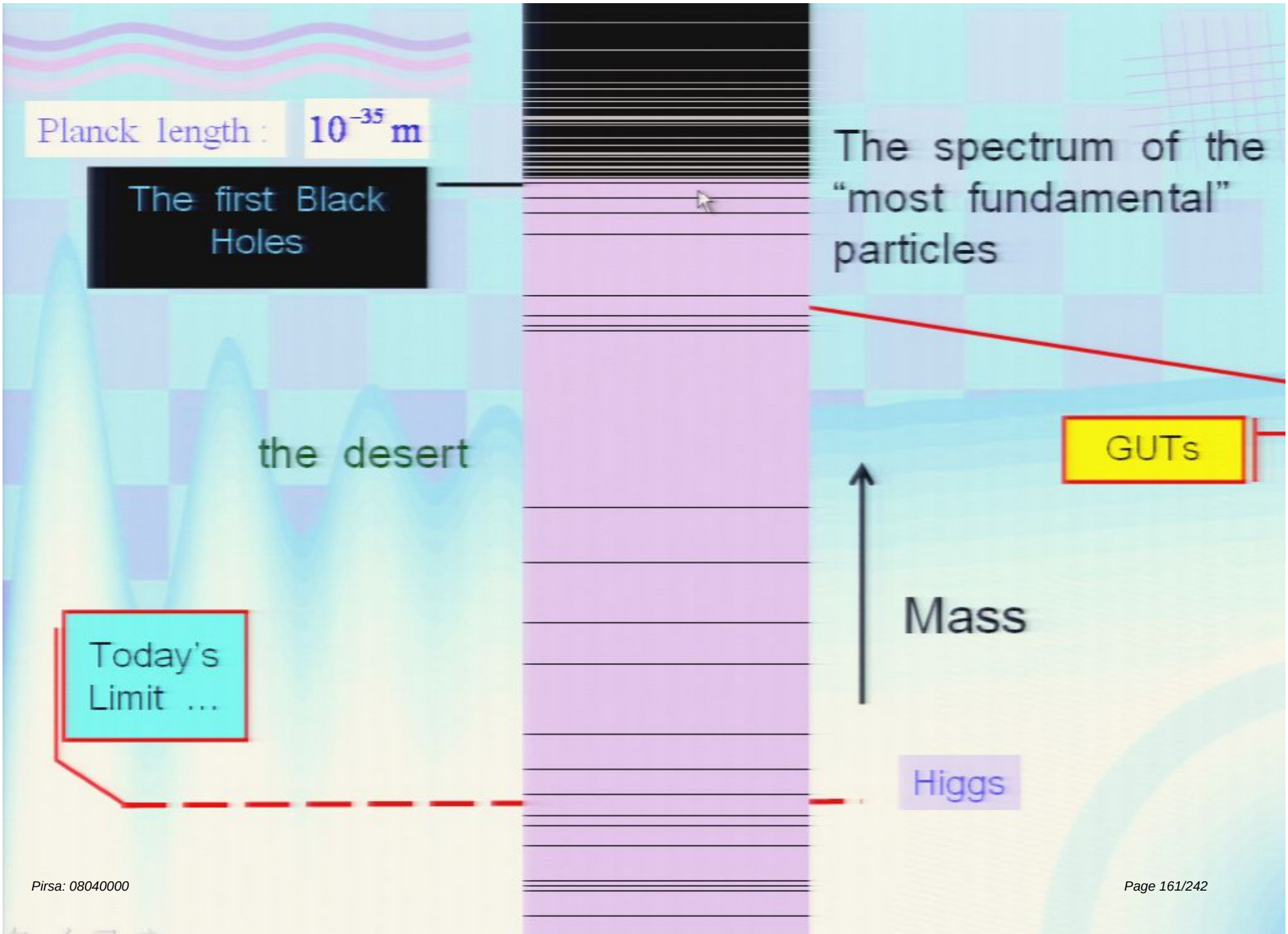
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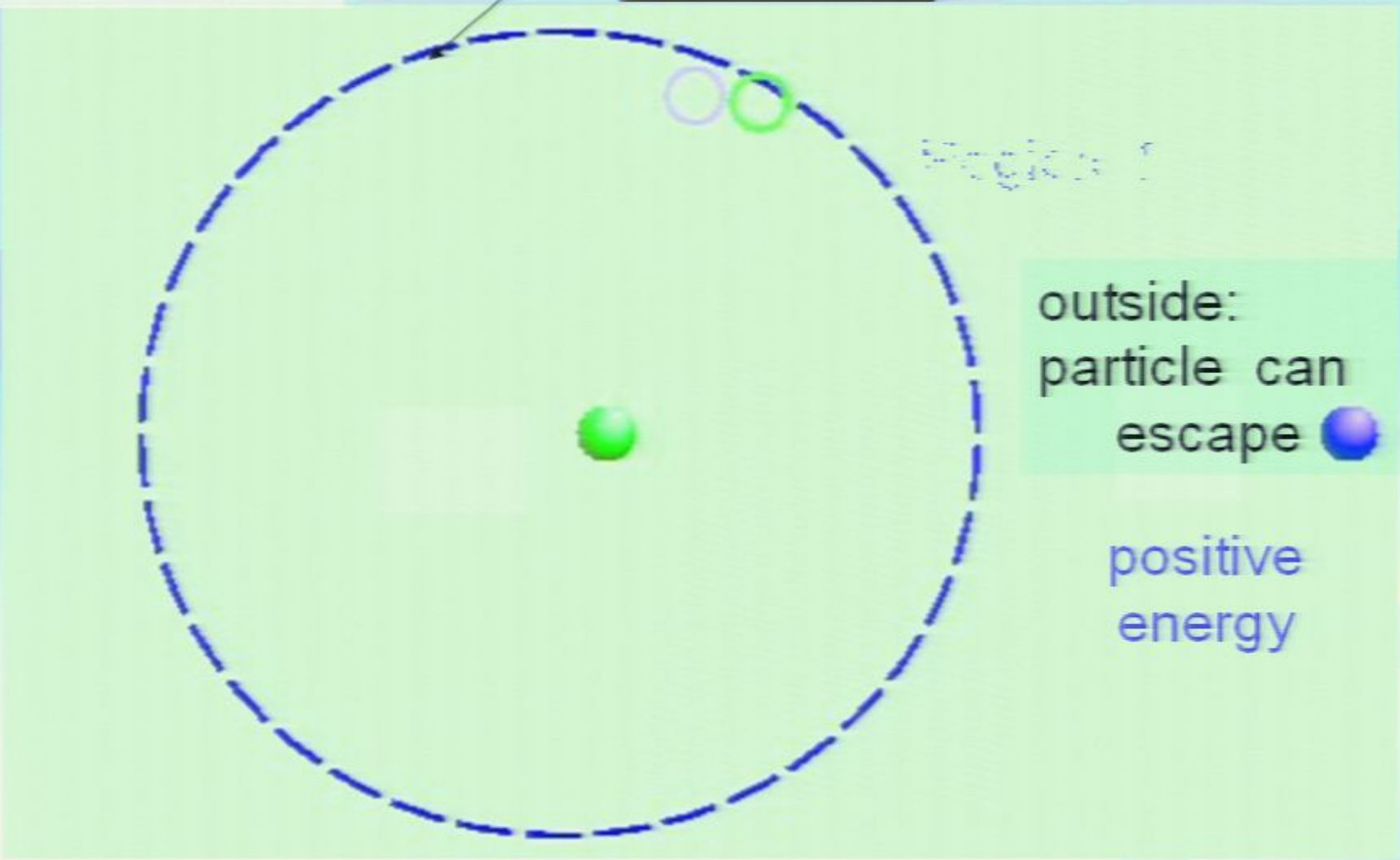

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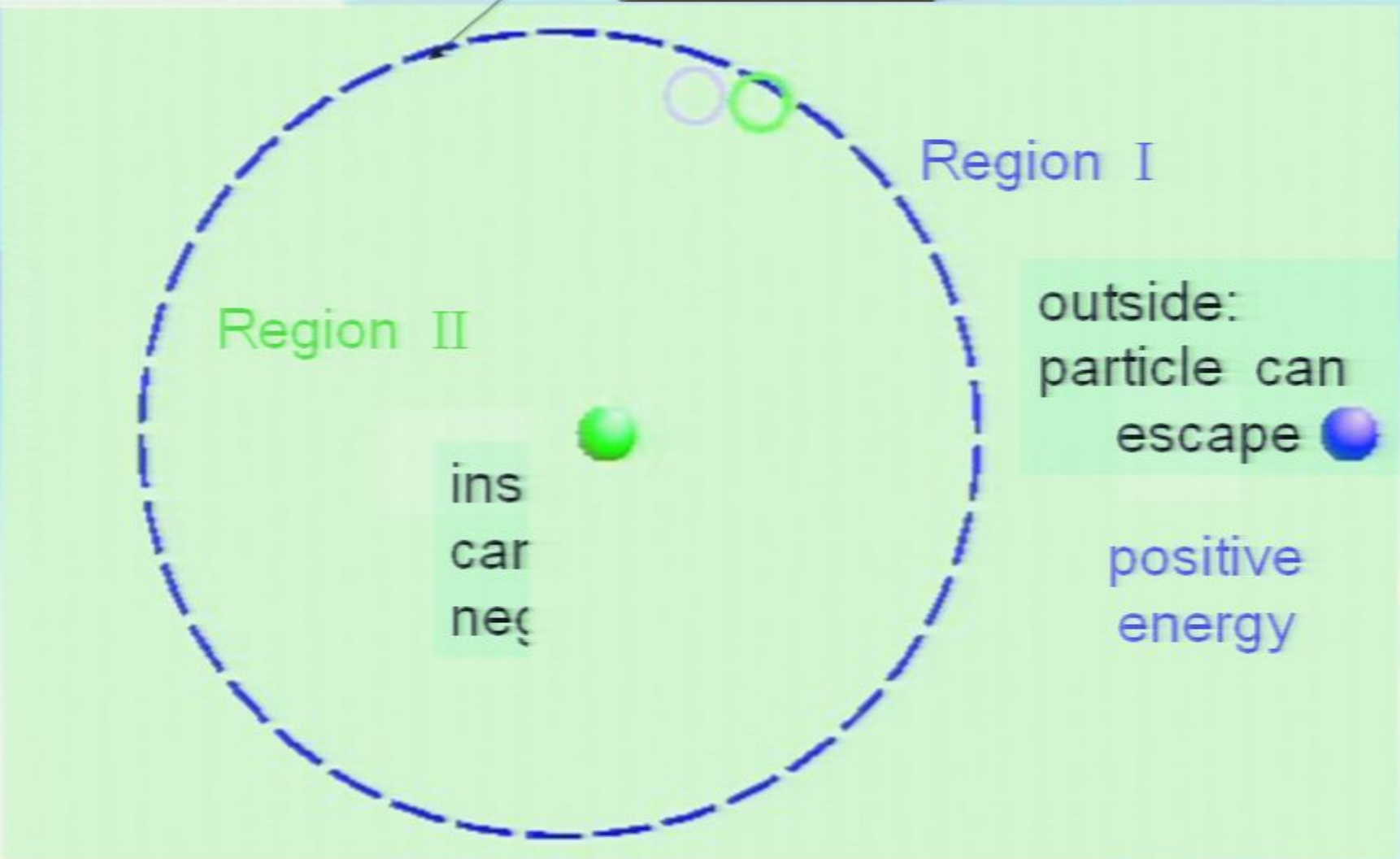

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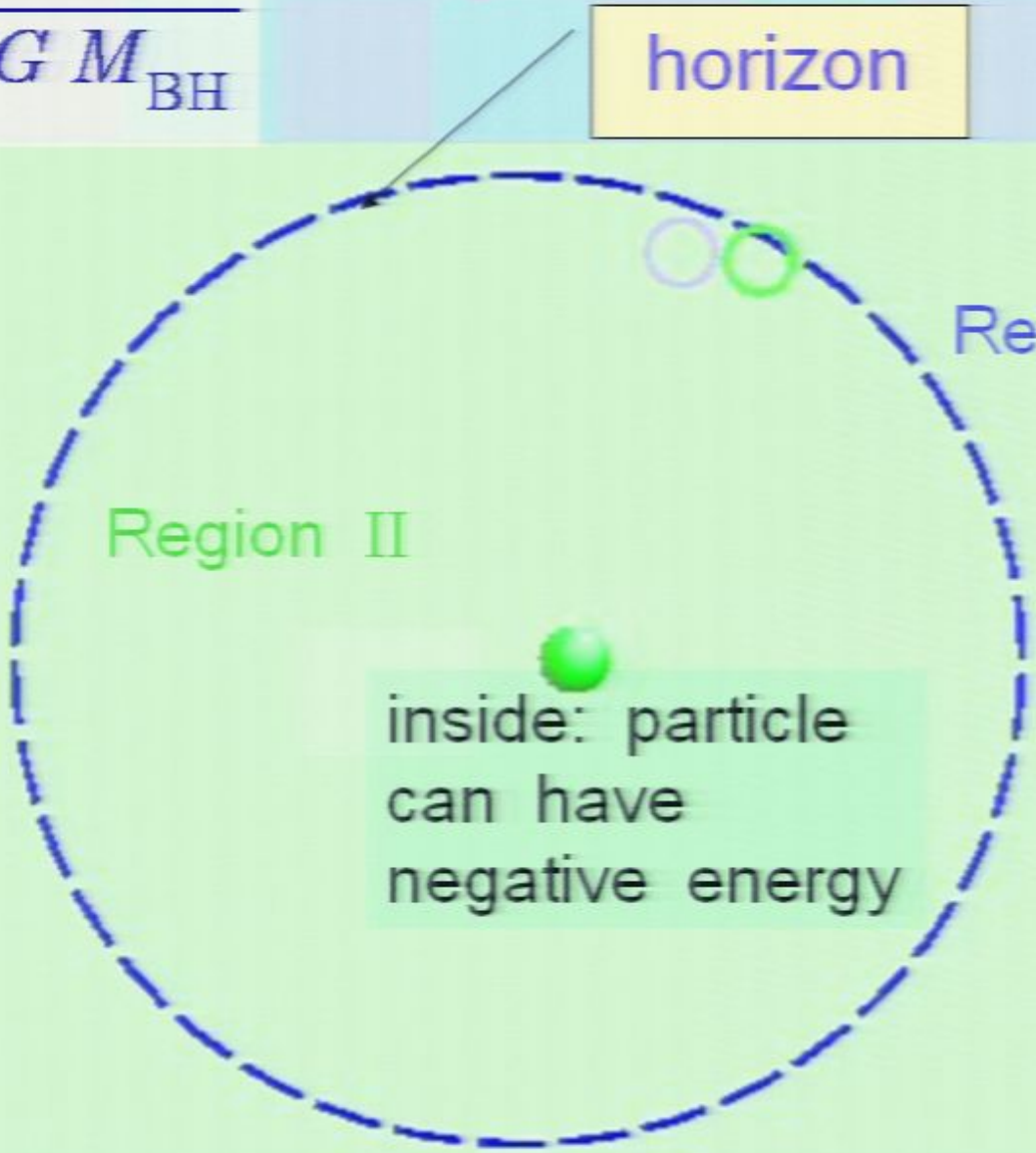

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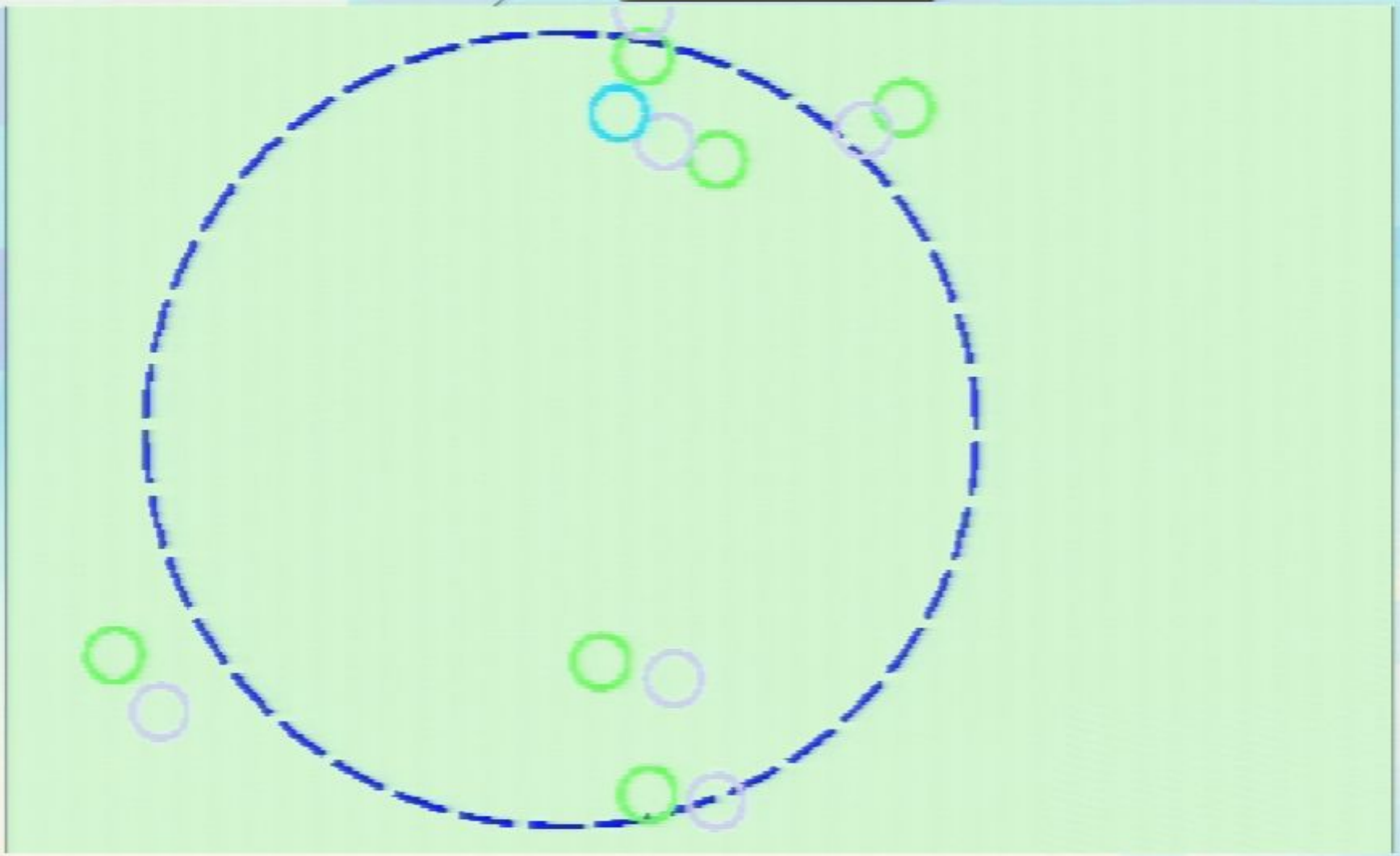

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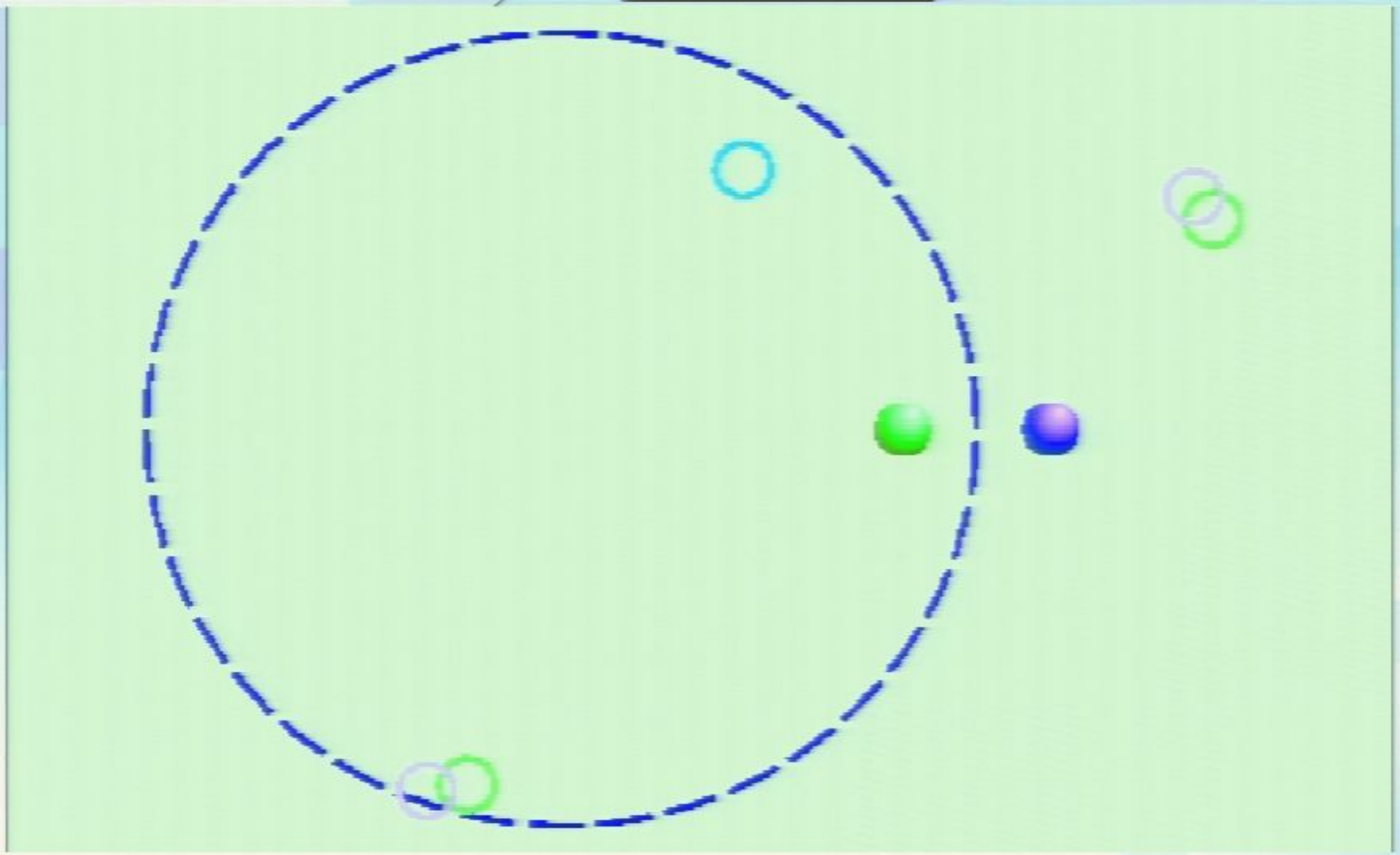

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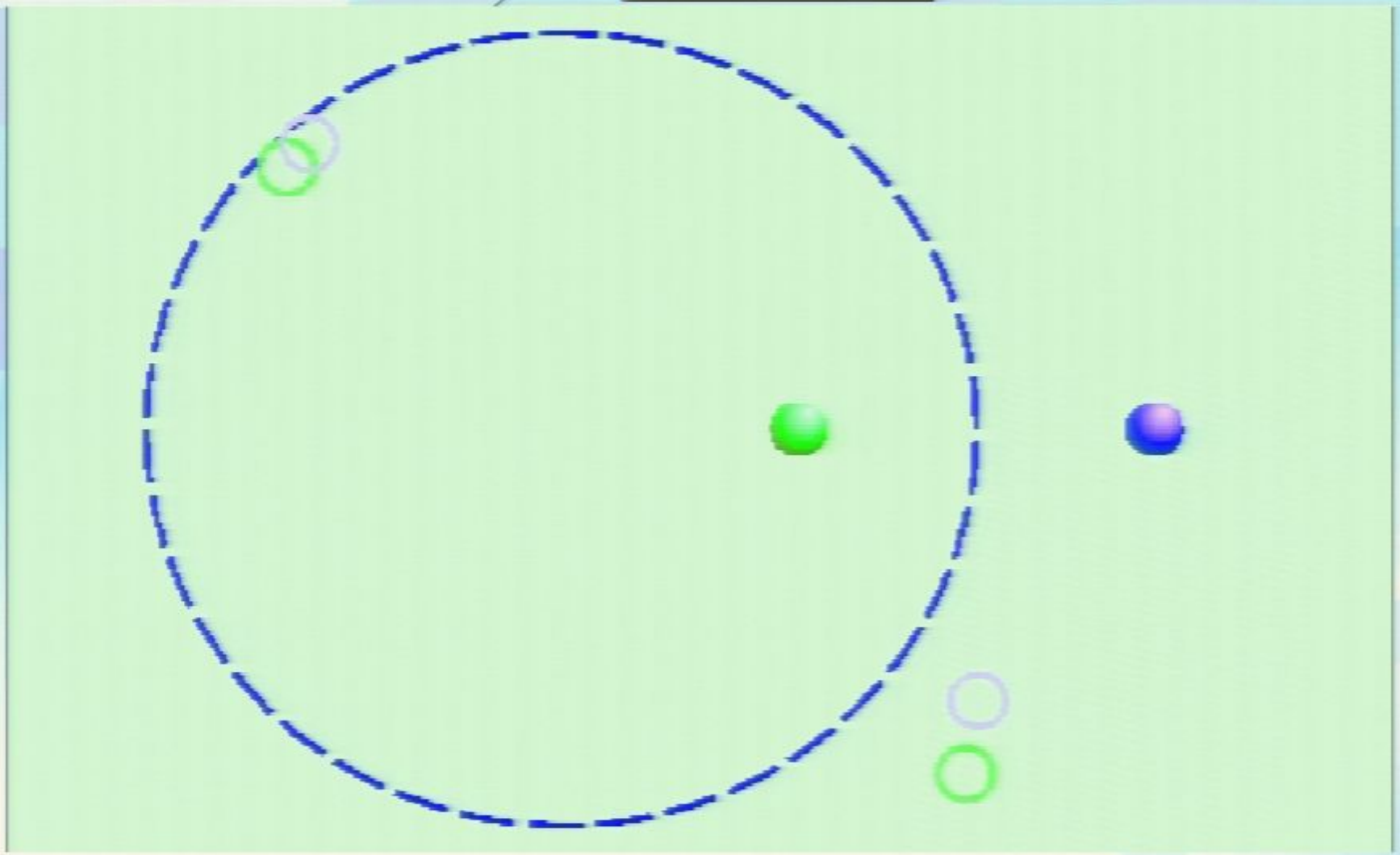

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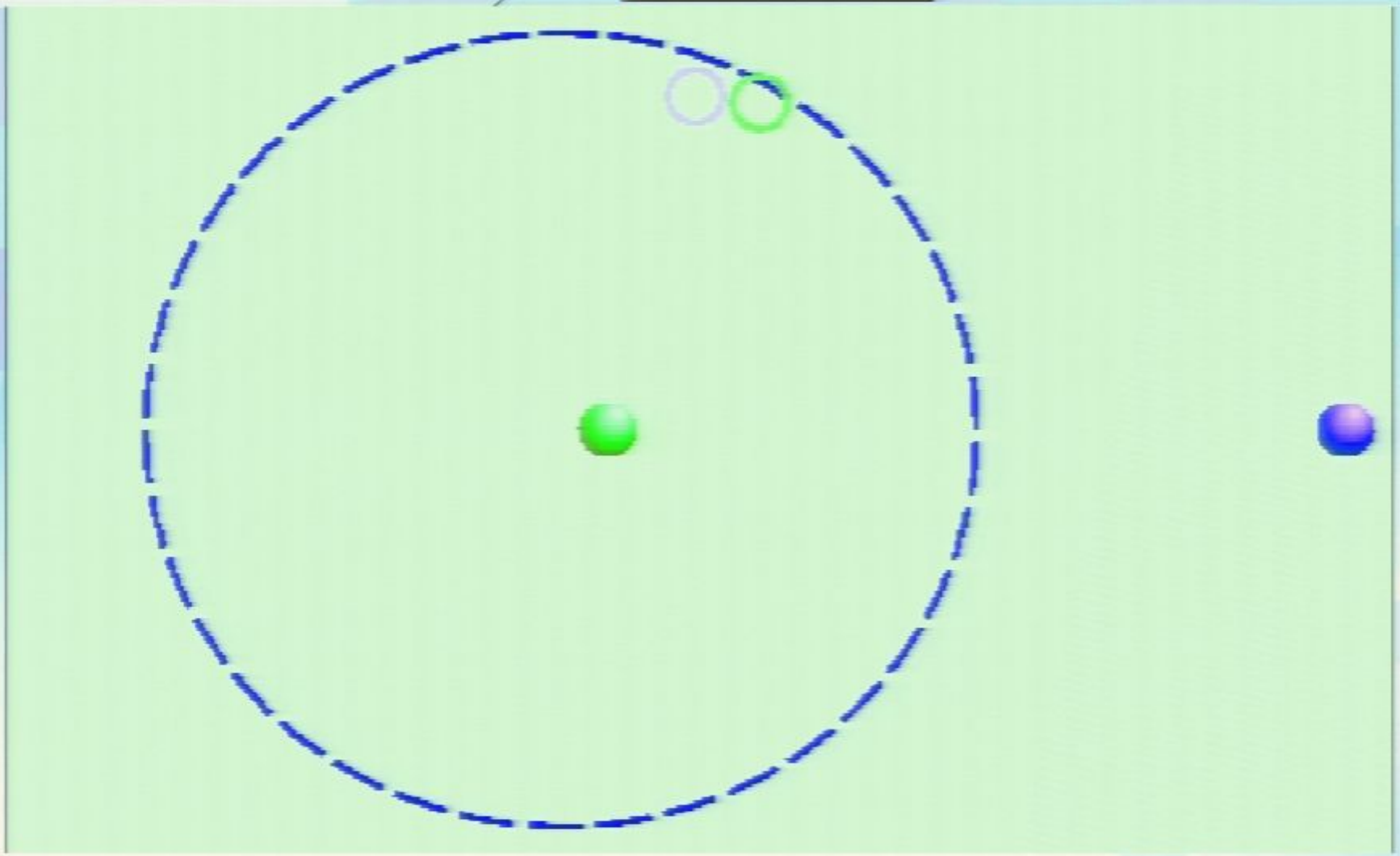

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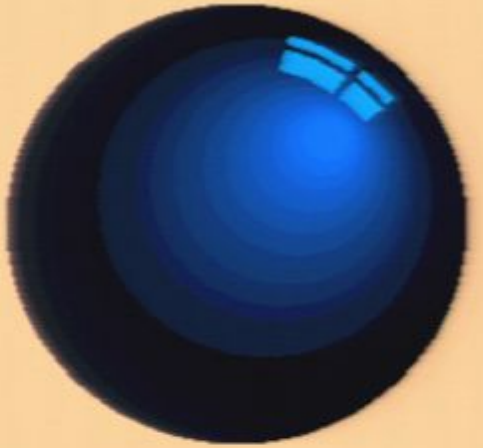

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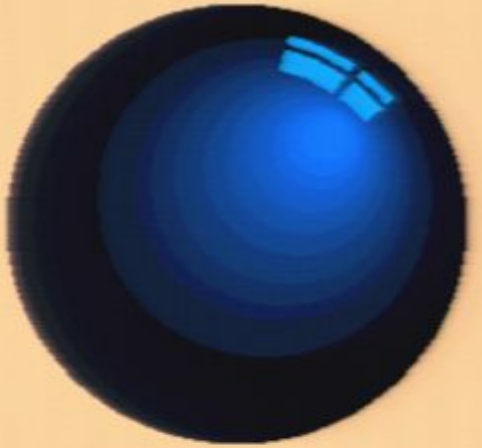

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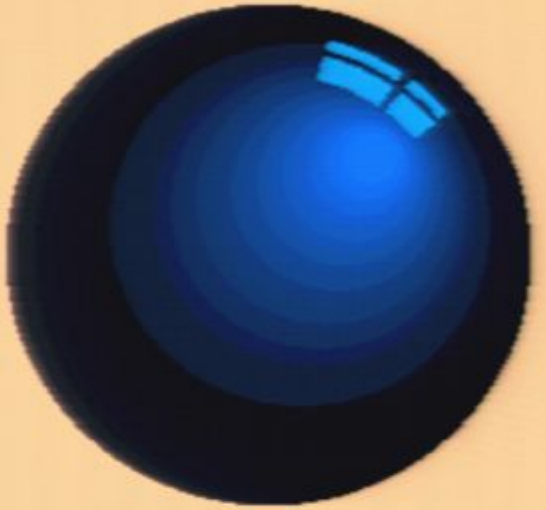

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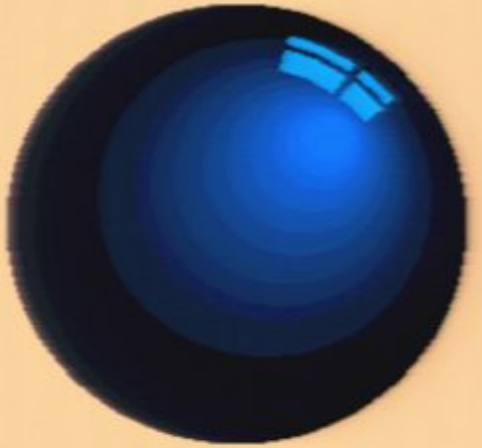

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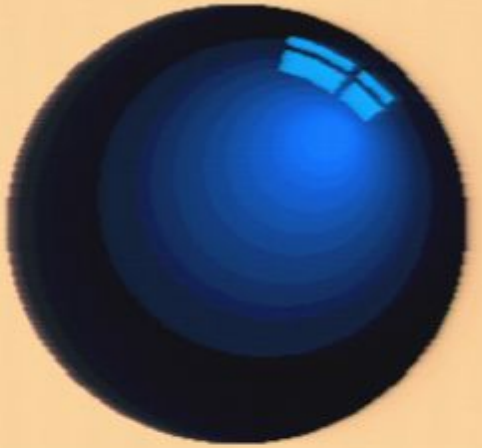

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Comparing the probabilities of these two processes, gives us the number of quantum states !

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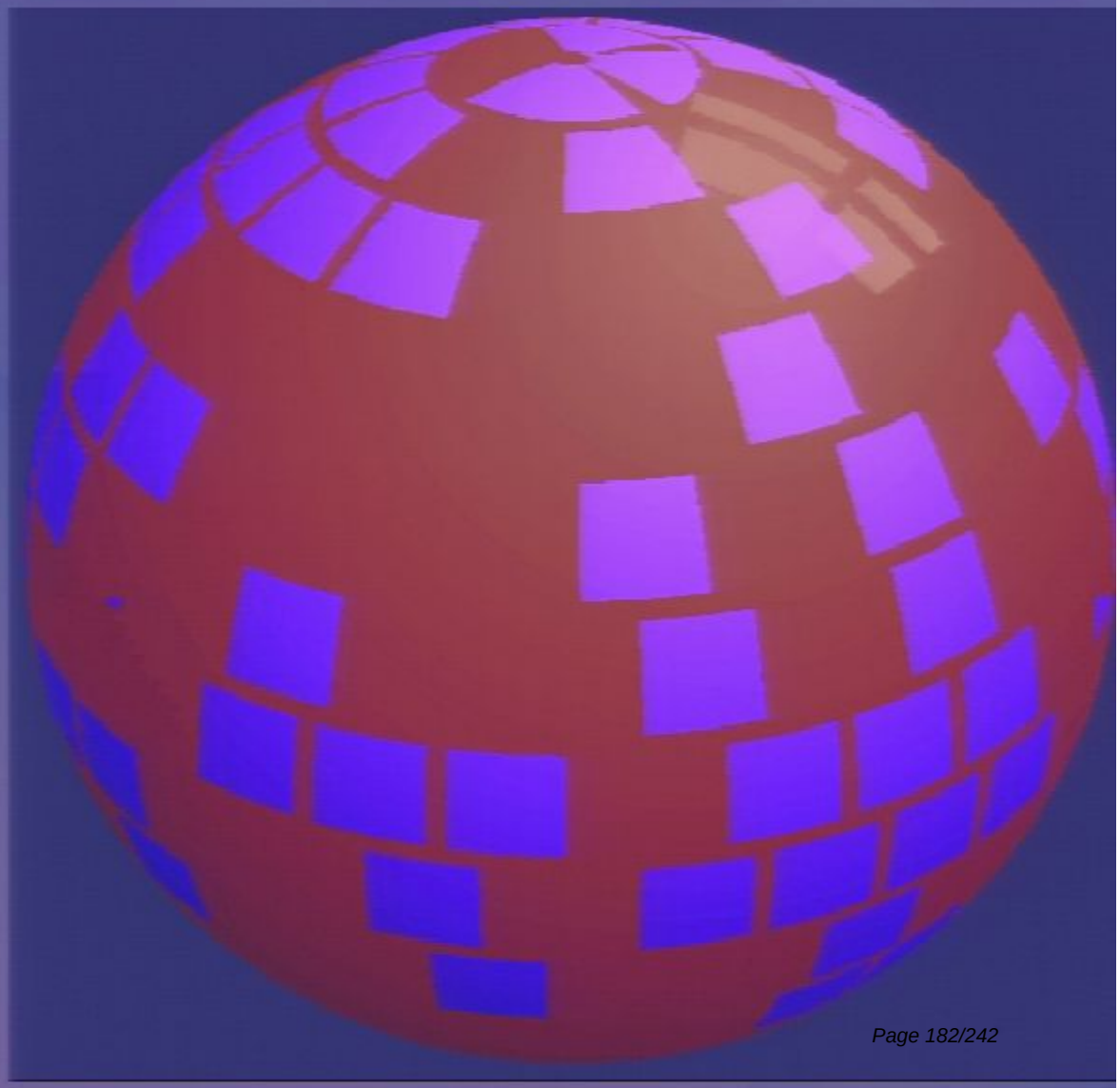
The black hole as an information processing machine

One bit of information on every 0.724×10^{-65} cm^2



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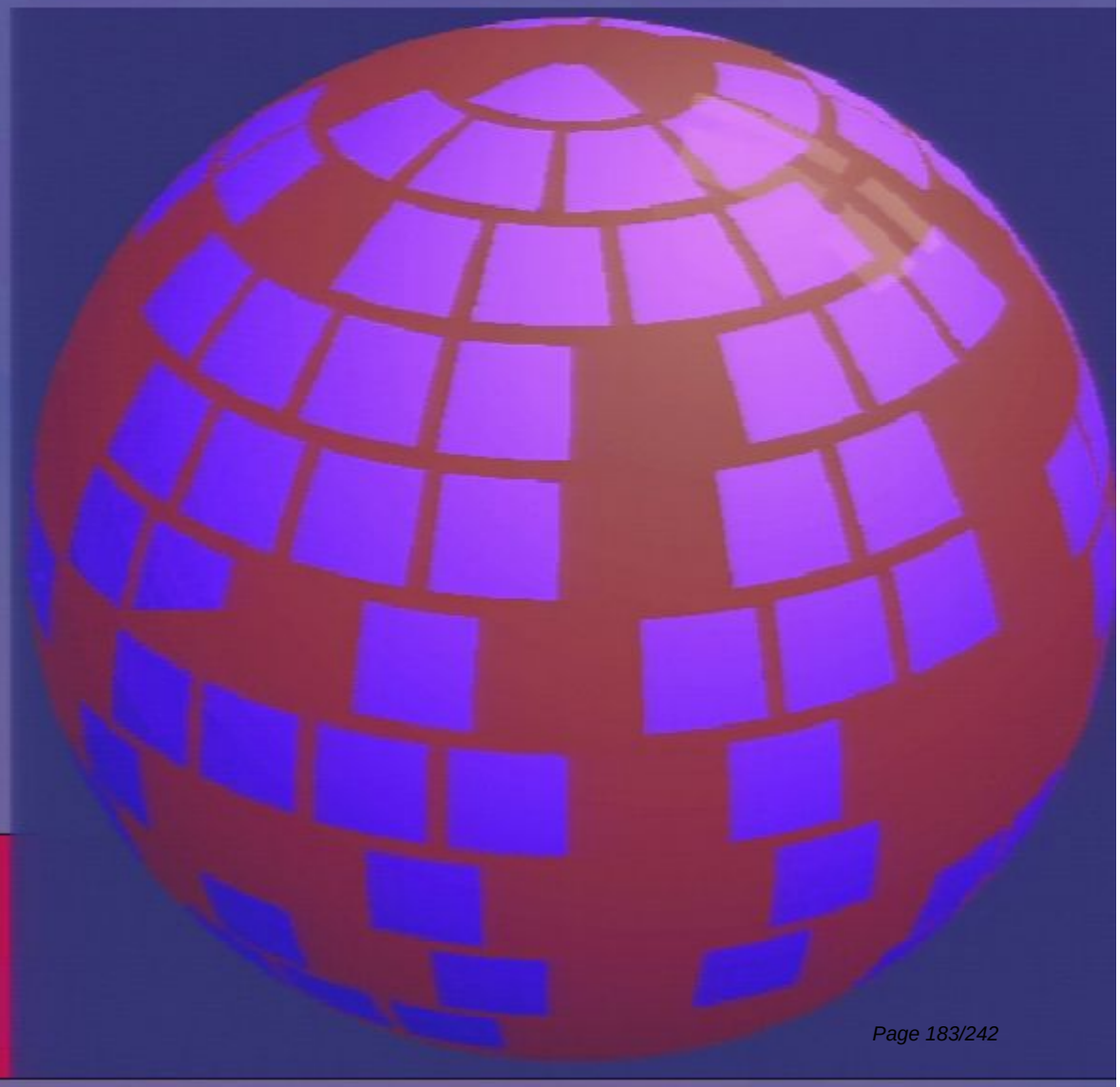

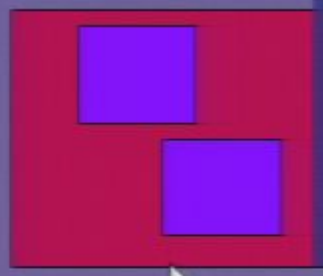

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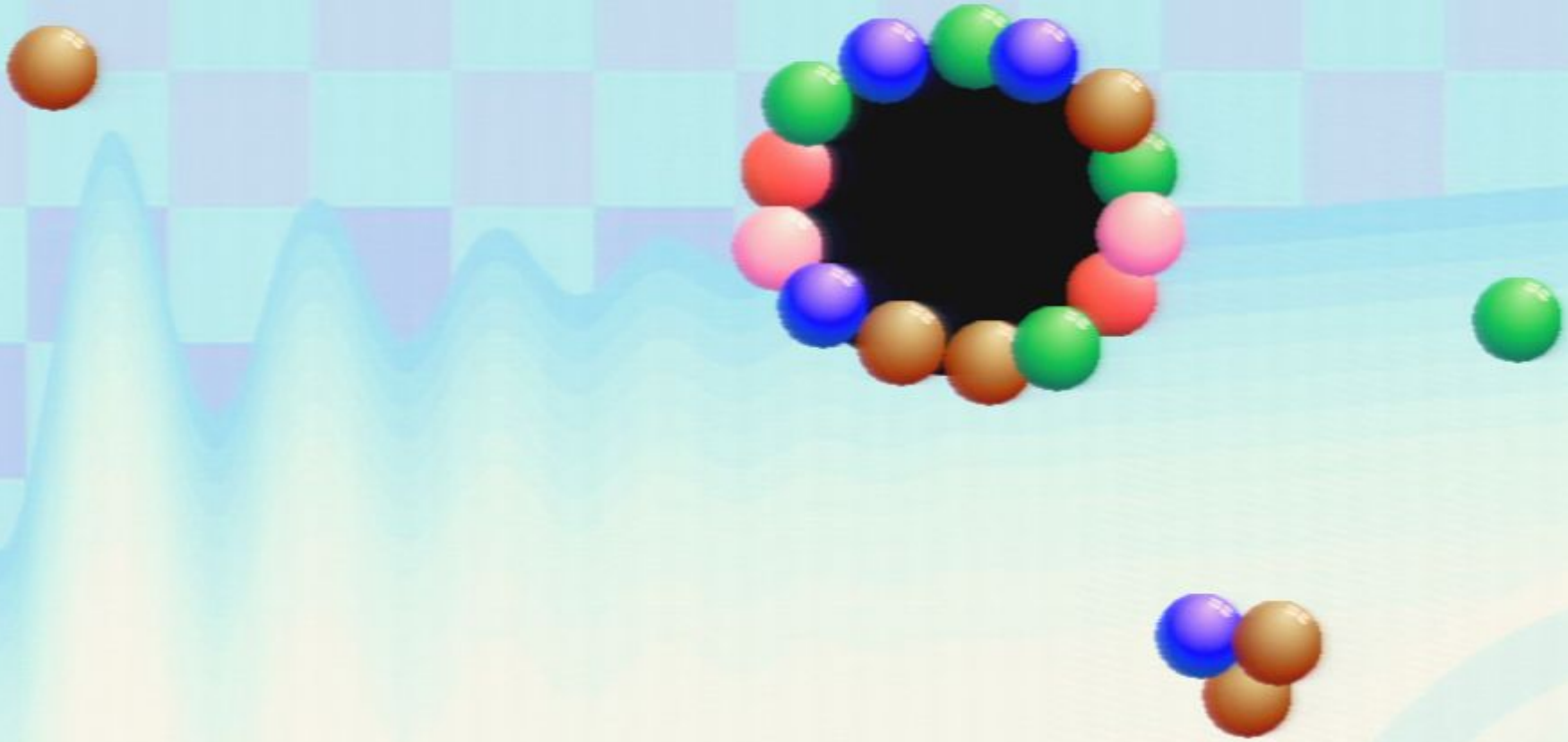

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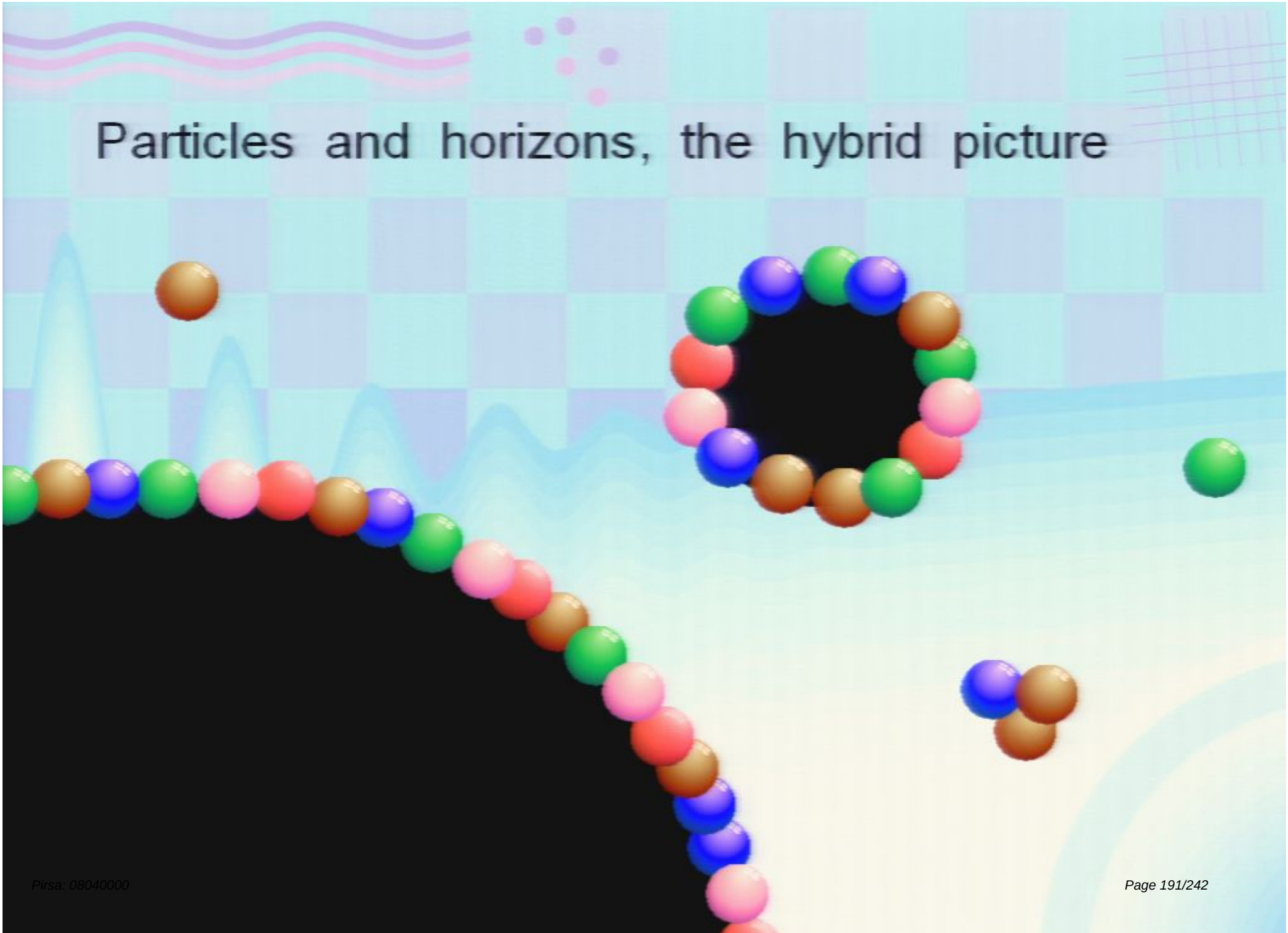
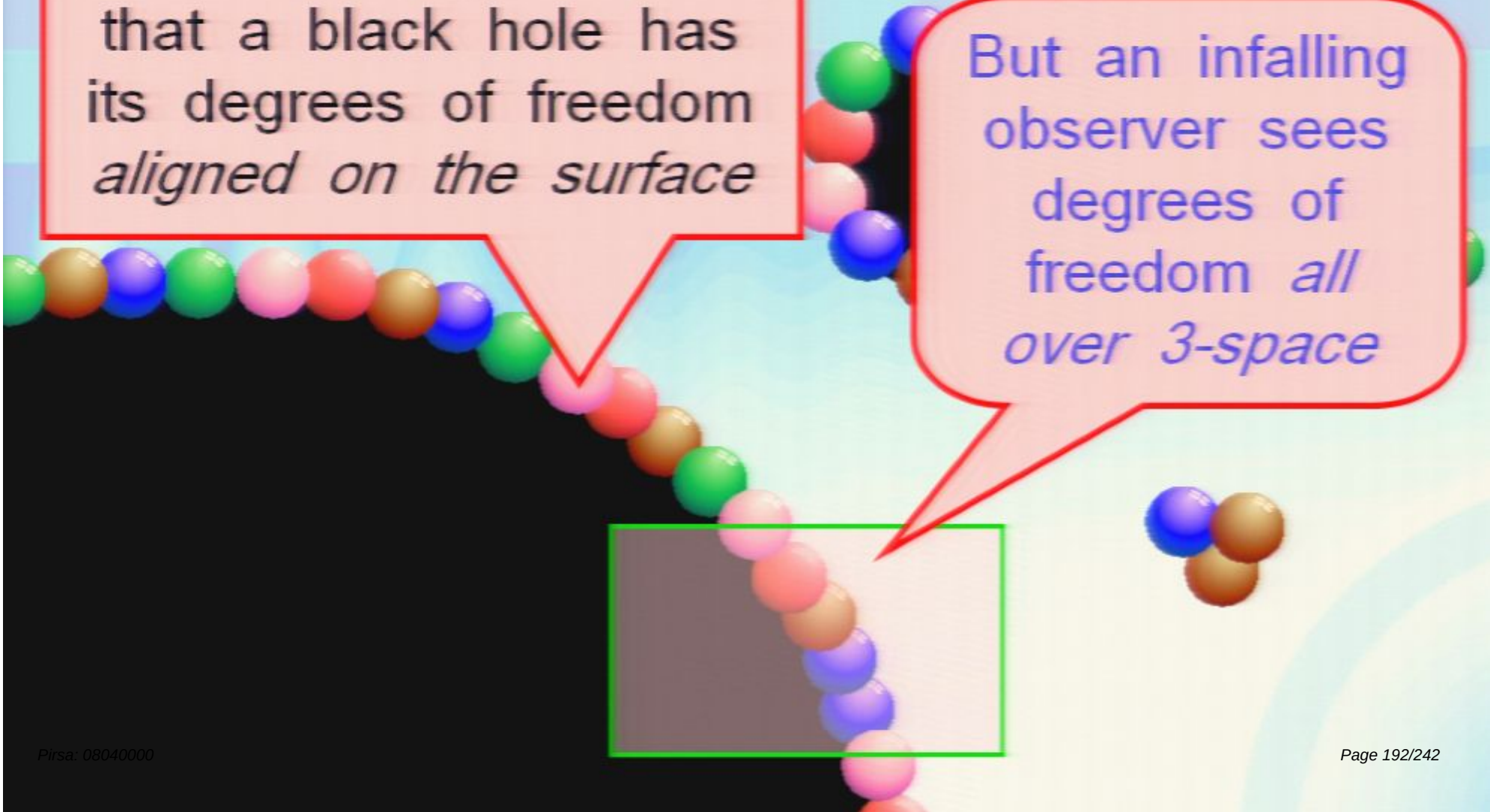


Particles and horizons, the hybrid picture

State-counting tells us that a black hole has its degrees of freedom *aligned on the surface*



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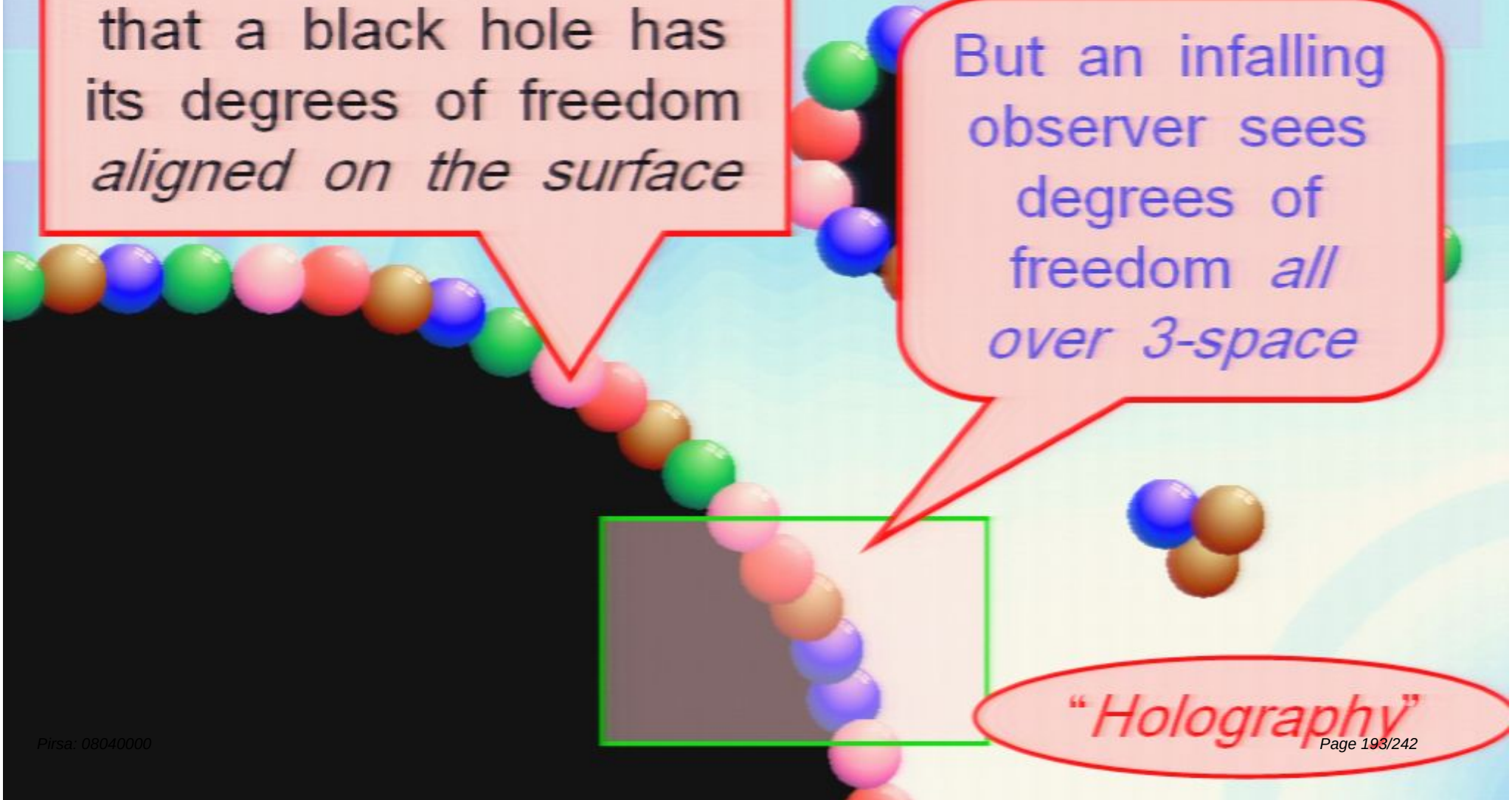

"*Holography*"

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... and why should these issues NOT be related to the question of the foundation of quantum mechanics ?

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The Planck distance is the smallest distance ...


HOW
DOES
GOD
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DICE ?

The use of **Hilbert Space Techniques** as technical devices for the treatment of the statistics of chaos ..

A "state" of the universe:

$\{\vec{x}, \ldots, \vec{p}, \ldots, i, \ldots,$  $, \text{anything} \ldots\}$

A simple model universe: $\{1\} \rightarrow \{2\} \rightarrow \{3\} \rightarrow \{1\}$

$$U = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

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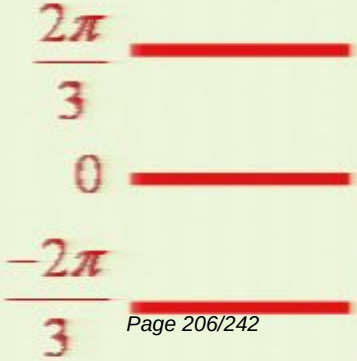

Emergent quantum mechanics in a deterministic system

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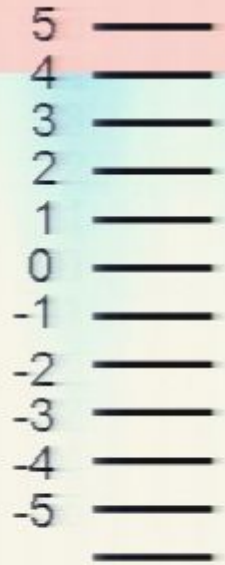

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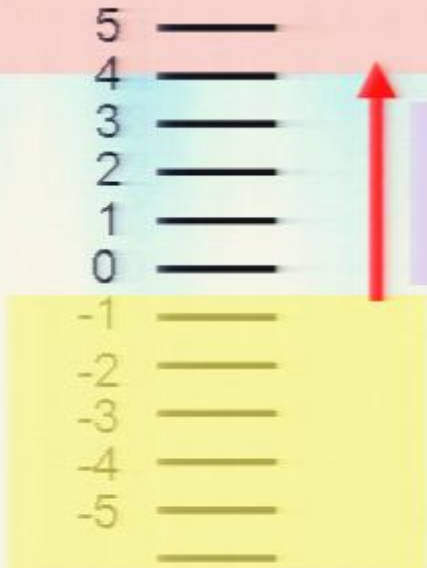

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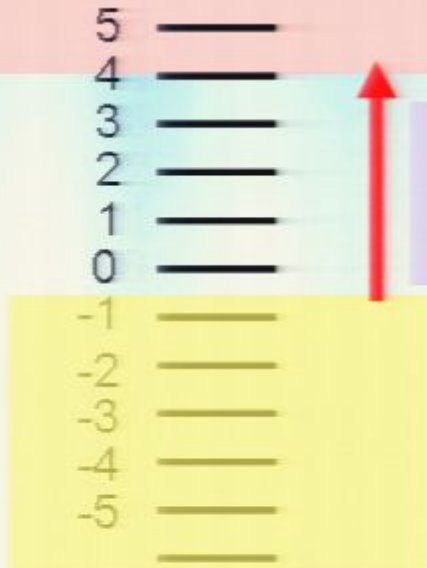

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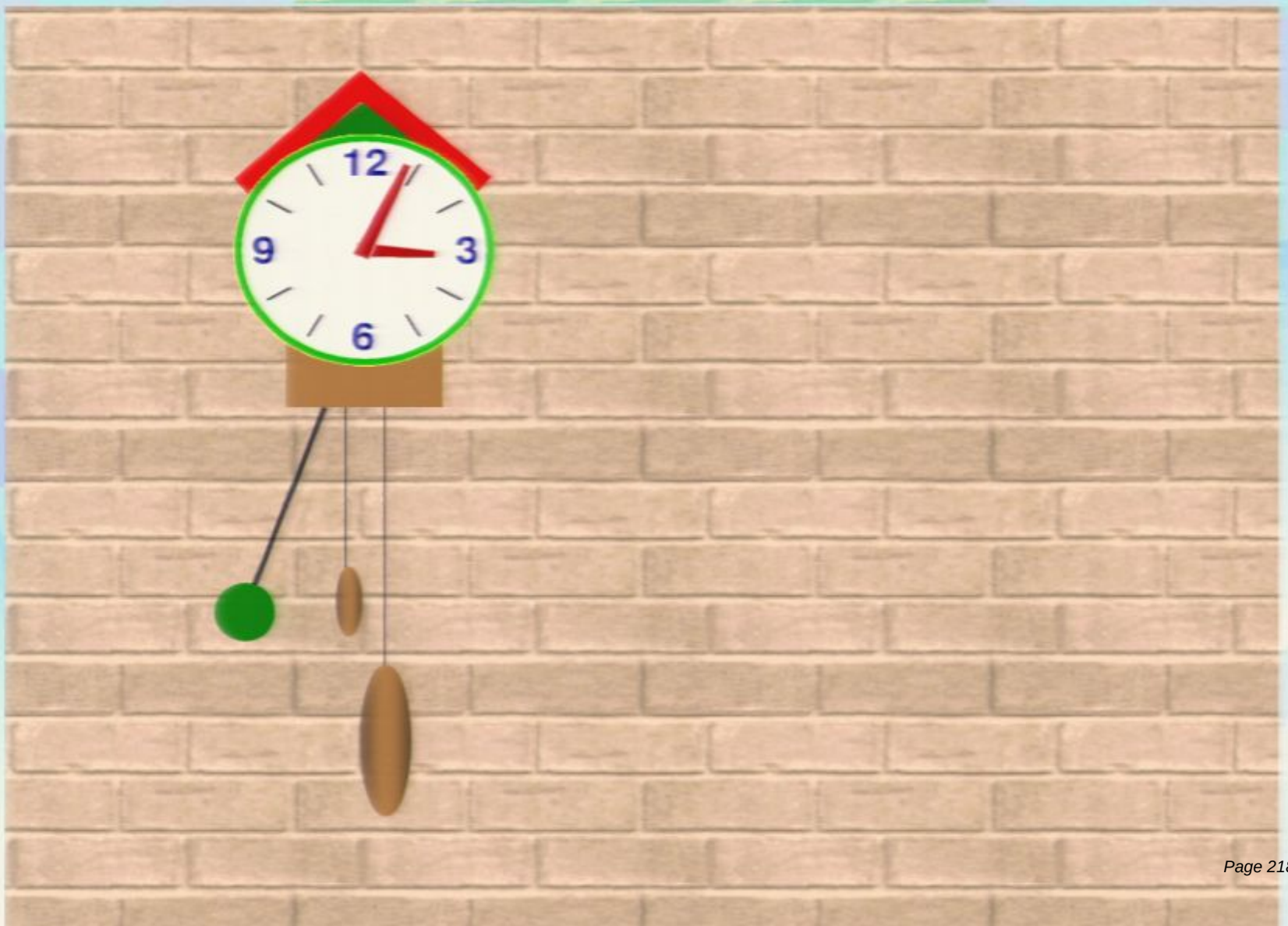

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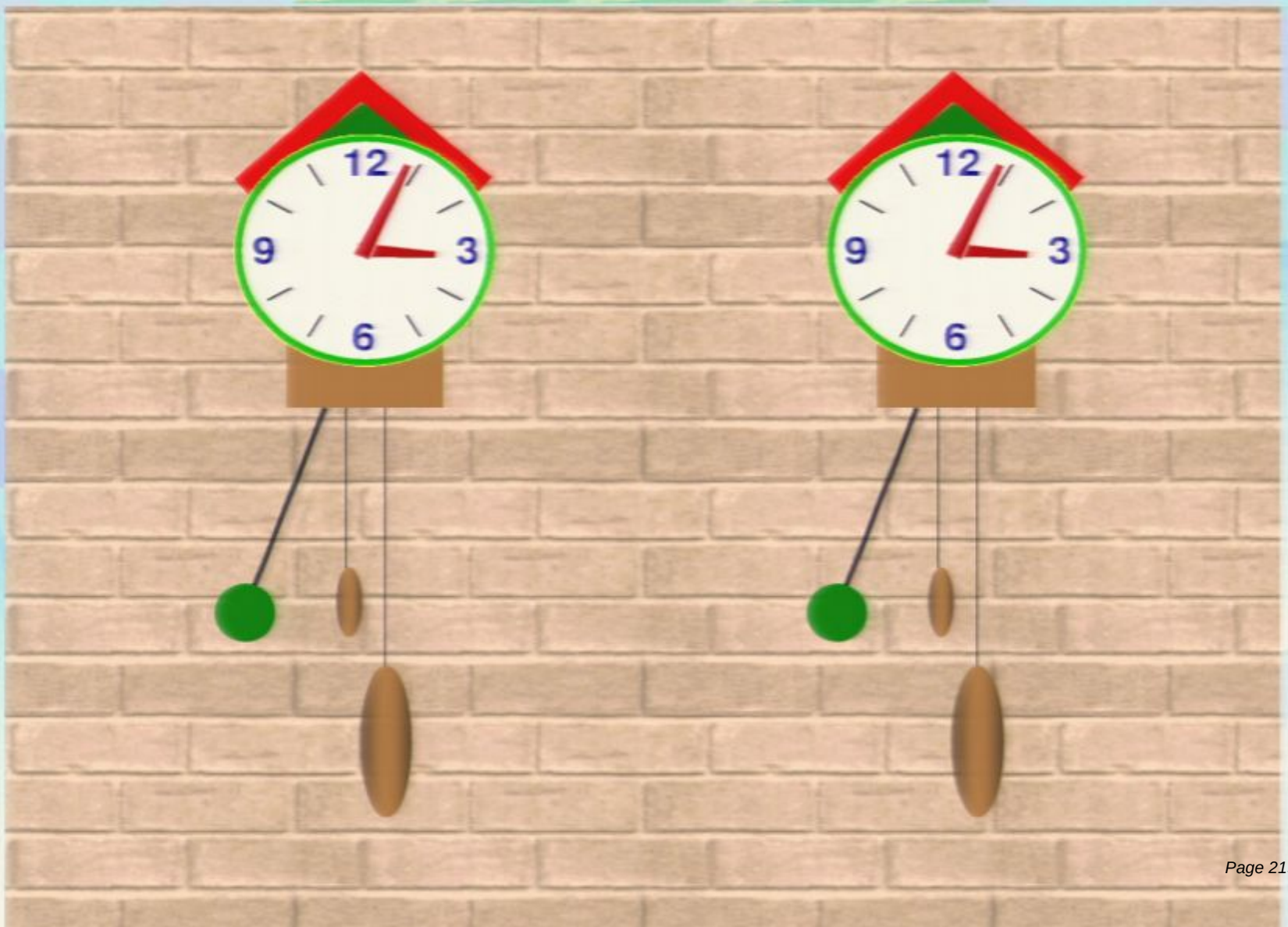

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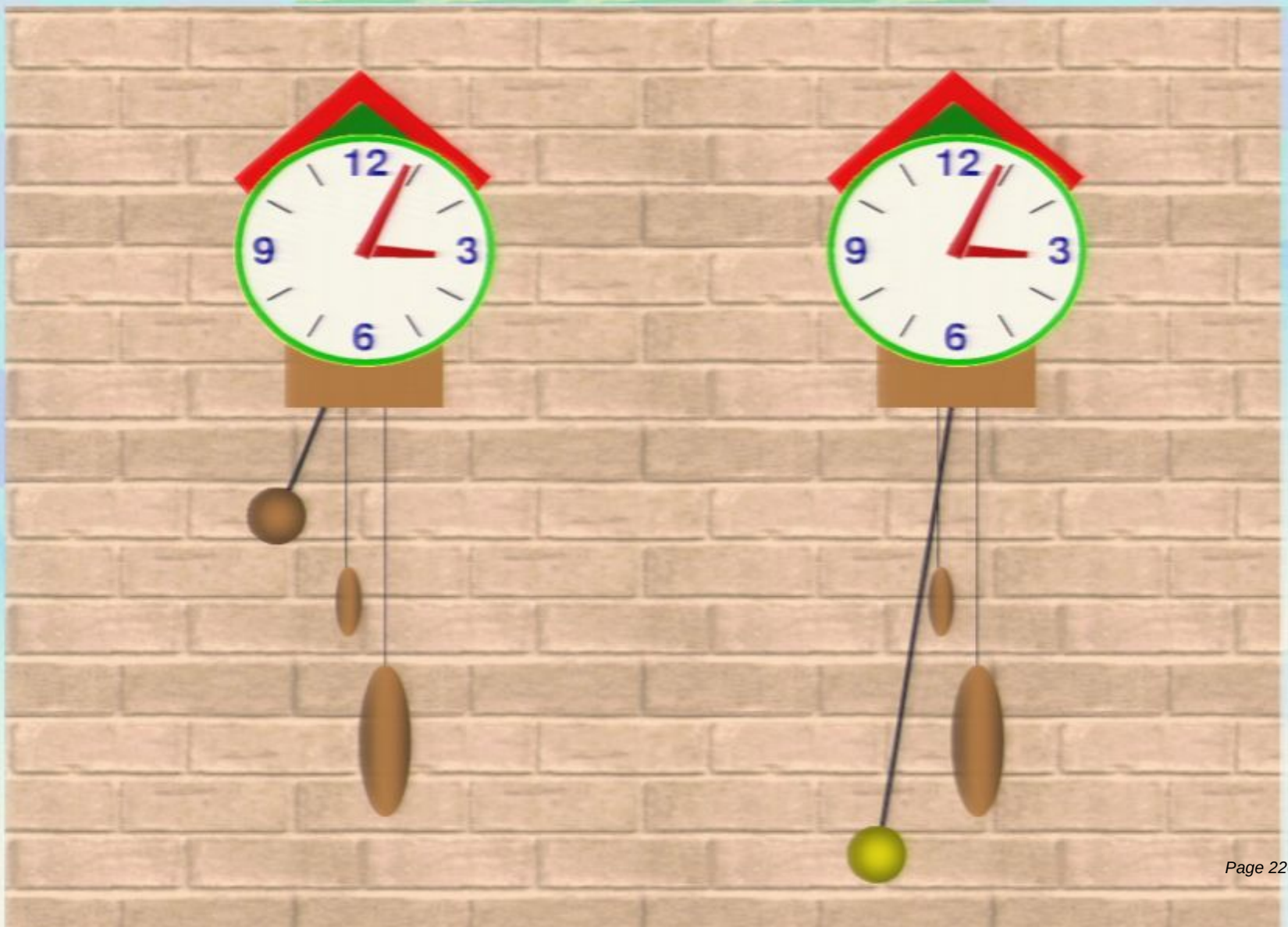

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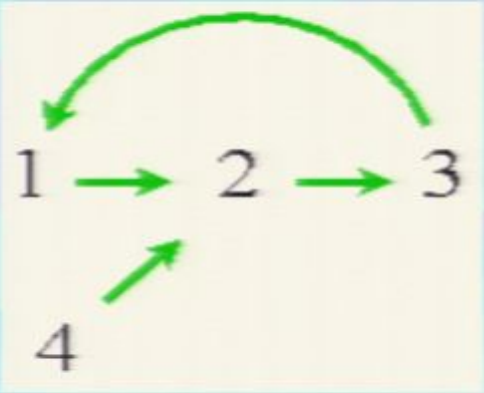
Limit ourselves to states where N and H are locked in:

$$(H - N)|\psi\rangle = 0, \qquad H|\psi\rangle = N|\psi\rangle \; ;$$

$$N \geq 0 \;\; \Rightarrow \;\; H \geq 0$$

A key ingredient for an ontological theory:

Information loss



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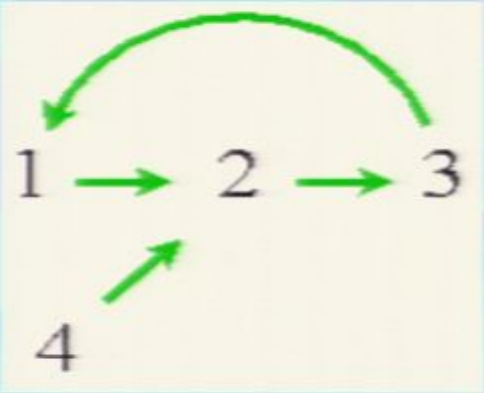

Introduce equivalence classes

$$\left|\{1\},\{4\}\right\rangle \rightarrow \left|\{2\}\right\rangle \rightarrow \left|\{3\}\right\rangle$$

With (virtual) **black holes**, information loss will be very large!

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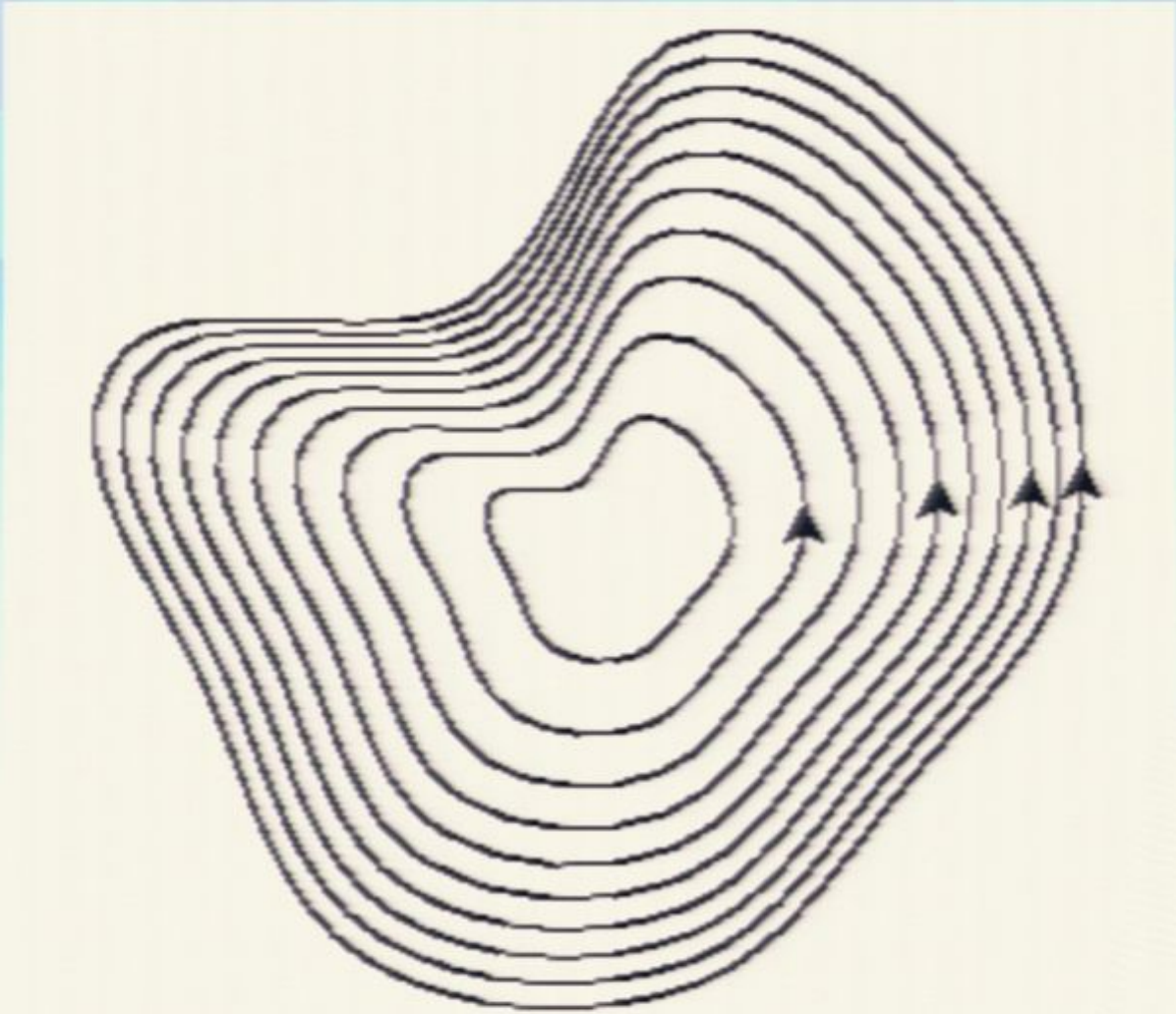
The (perturbed) oscillator has discretized stable orbits. This is what causes quantization.



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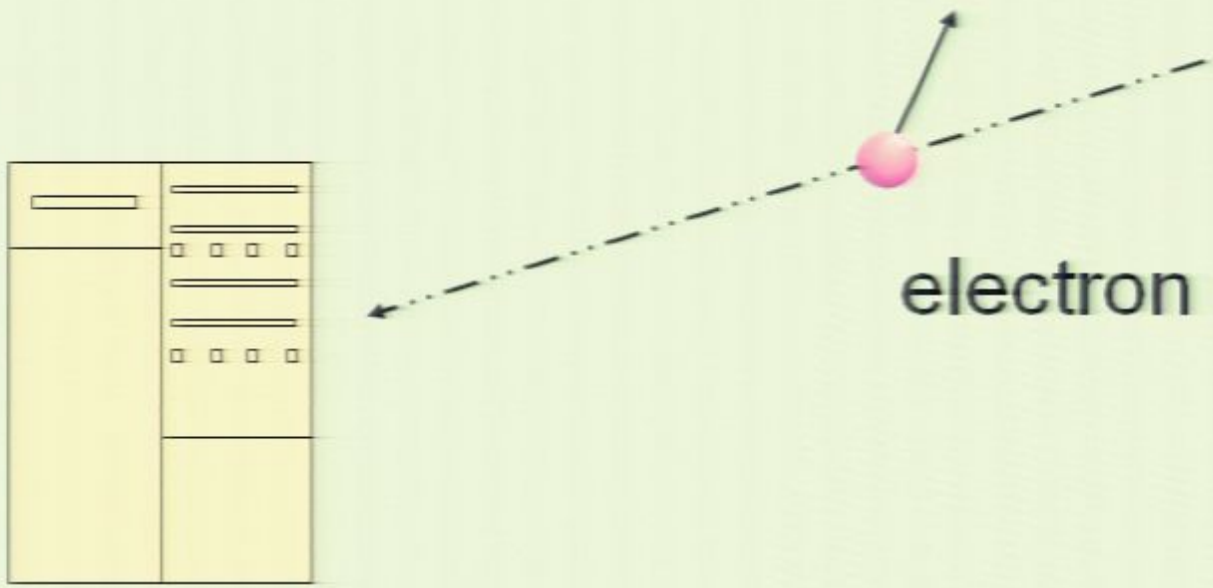

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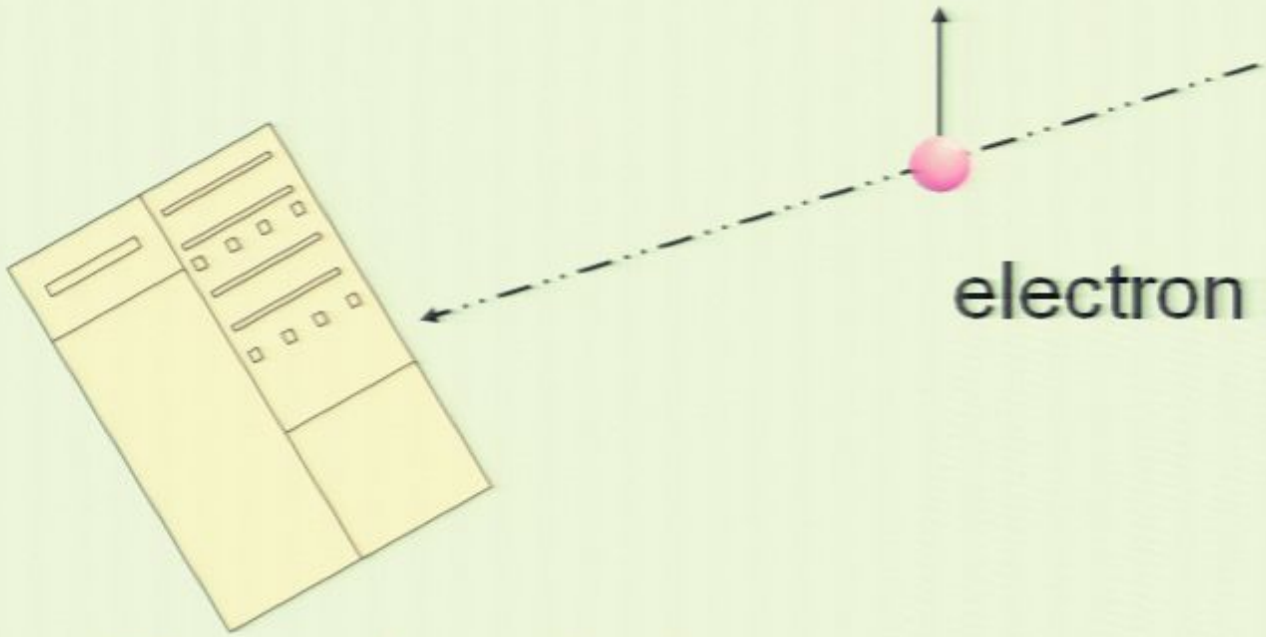

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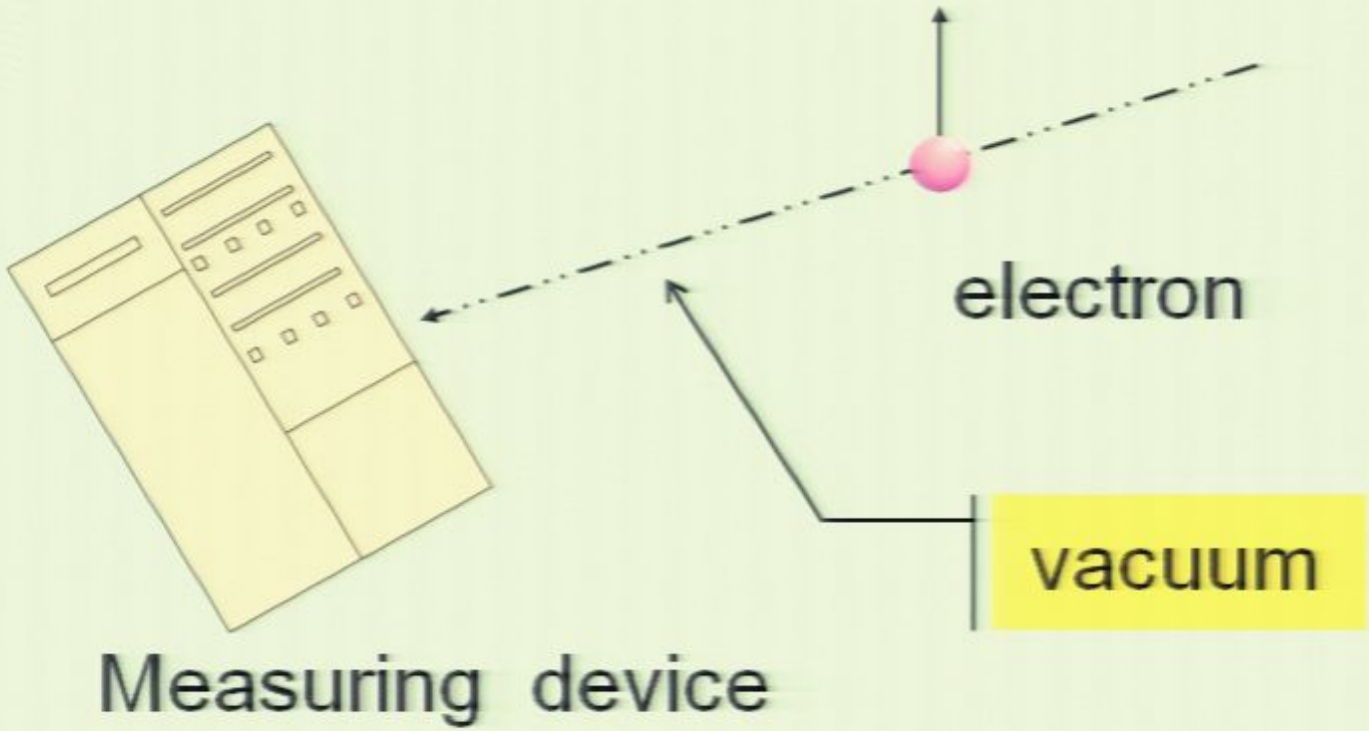

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These correlation laws describe at the same time how small changes tend to evolve:
non-commuting operators

At the Planck scale, observables ("beables") are very different from operators that bring about small changes ("changeables")

The renormalization group allows us to make the scale transformation from Planck scale to SM scale.

The renormalization group however mixes the beables with the changeables, which is why we, today, are unable to keep them apart.
These non-commuting operators then violate Bell's inequalitis, as they should.

Conclusions

At the Planck scale, Quantum Mechanics is *not* wrong, but its interpretation may have to be revised, *not* for philosophical reasons, but to enable us to construct more concise theories, recovering e.g. locality

The "random numbers", inherent in the usual statistical interpretation of the wave functions, may well find their origins at the Planck scale, so that, there, we have an ontological (deterministic) mechanics

For this to work, this deterministic system must feature *information loss* at a vast scale

Utrecht University

BLACK HOLES

and the Foundations of

QUANTUM MECHANICS

The End

A key ingredient for an ontological theory:

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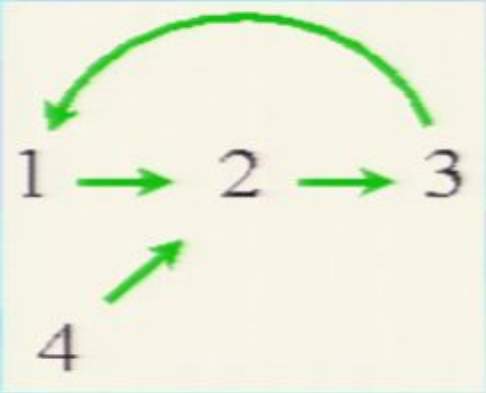

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The use of **Hilbert Space Techniques** as technical devices for the treatment of the statistics of chaos ..

A "state" of the universe:

$\{\vec{x}, \ldots, \vec{p}, \ldots, i, \ldots,$  $, \text{anything} \ldots\}$

A simple model universe: $\{1\} \rightarrow \{2\} \rightarrow \{3\} \rightarrow \{1\}$

$$U = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

$$|\Psi\rangle = \alpha|1\rangle + \beta|2\rangle + \gamma|3\rangle;$$

$$P_1 = |\alpha|^2, \quad P_2 = |\beta|^2, \quad P_3 = |\gamma|^2$$

Diagonalize: $U \rightarrow \begin{pmatrix} 1 & & \\ & e^{2\pi i/3} & \\ & & e^{-2\pi i/3} \end{pmatrix} = e^{-iH}$