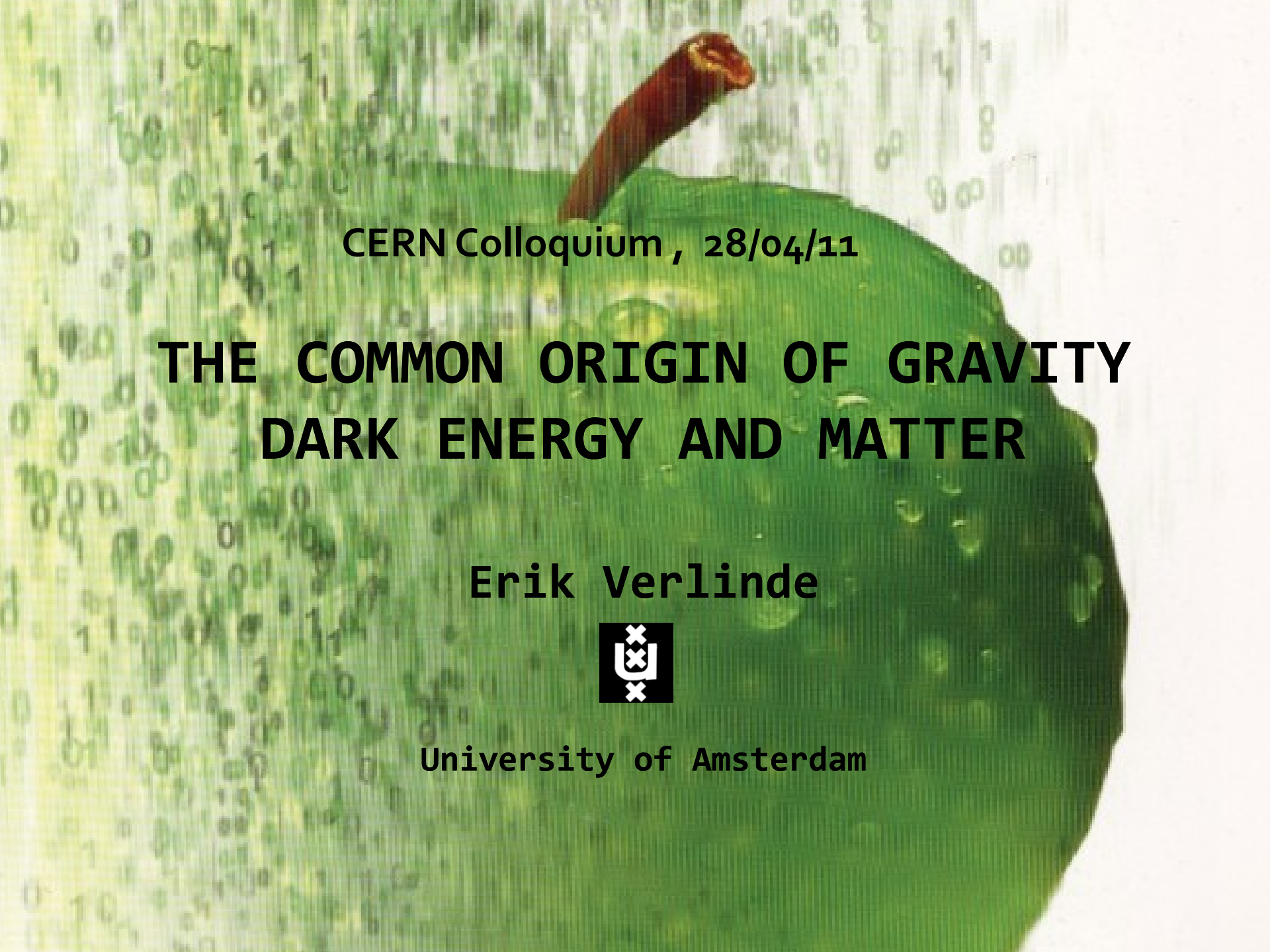


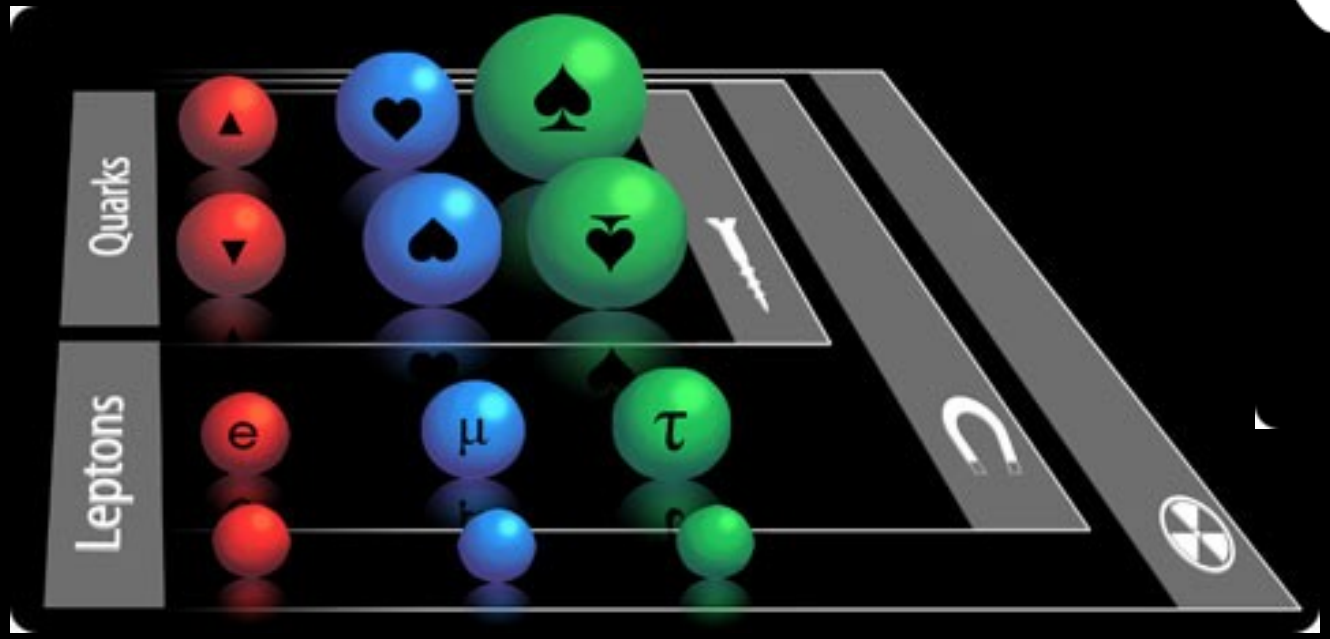
CERN Colloquium , 28/04/11

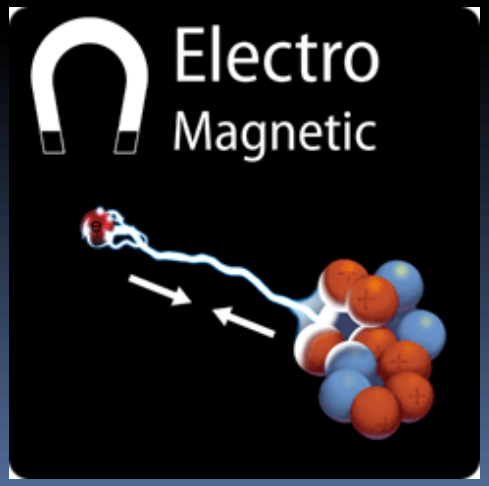
THE COMMON ORIGIN OF GRAVITY DARK ENERGY AND MATTER

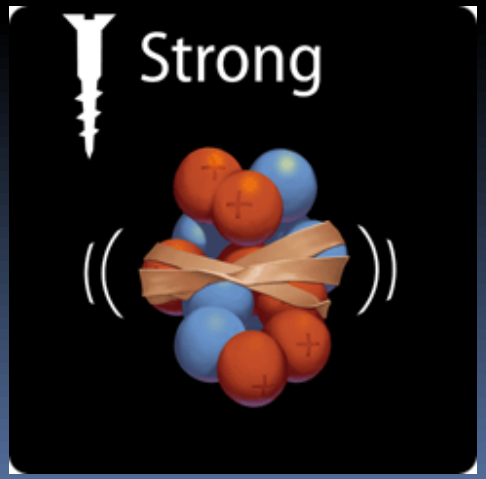
Erik Verlinde

University of Amsterdam

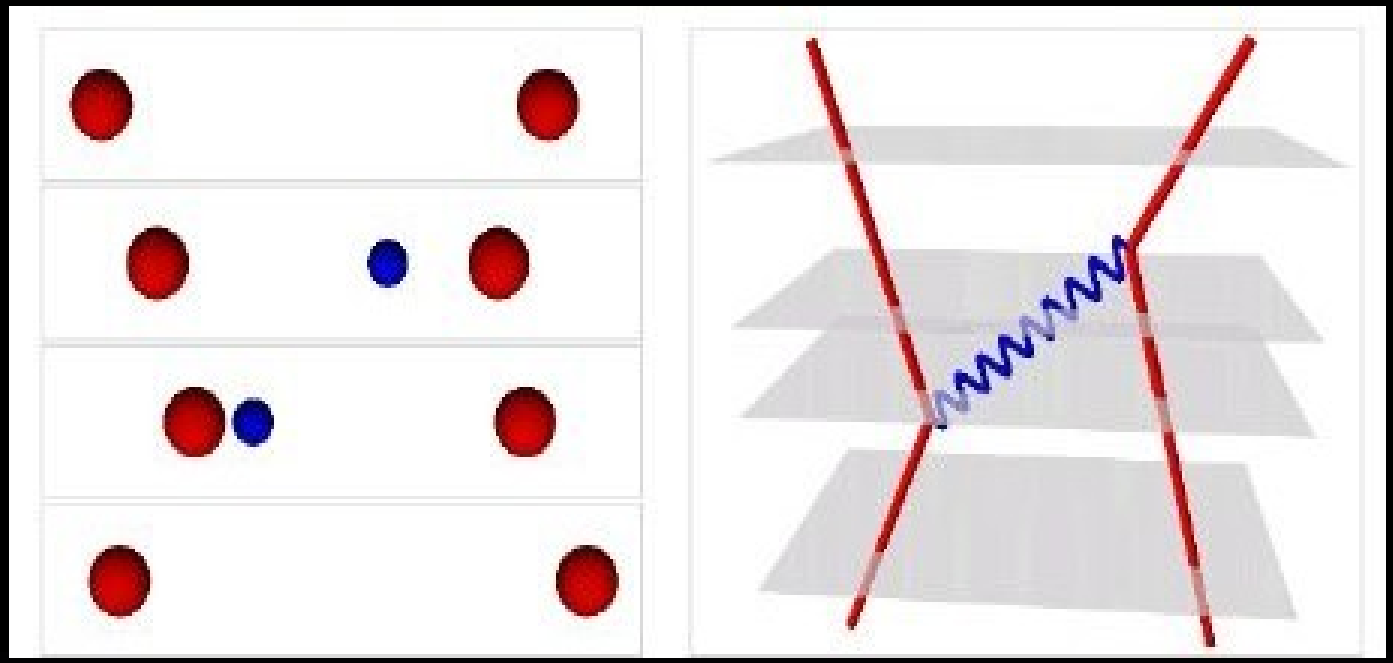
Matter and Forces





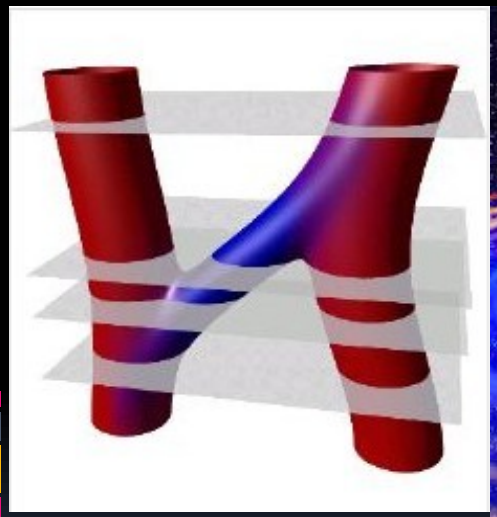


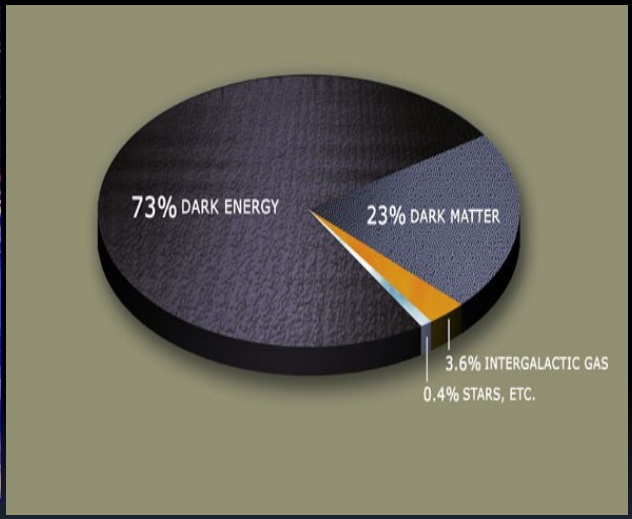
Current Paradigm



FUNDAMENTAL FORCES: carried by elementary particles

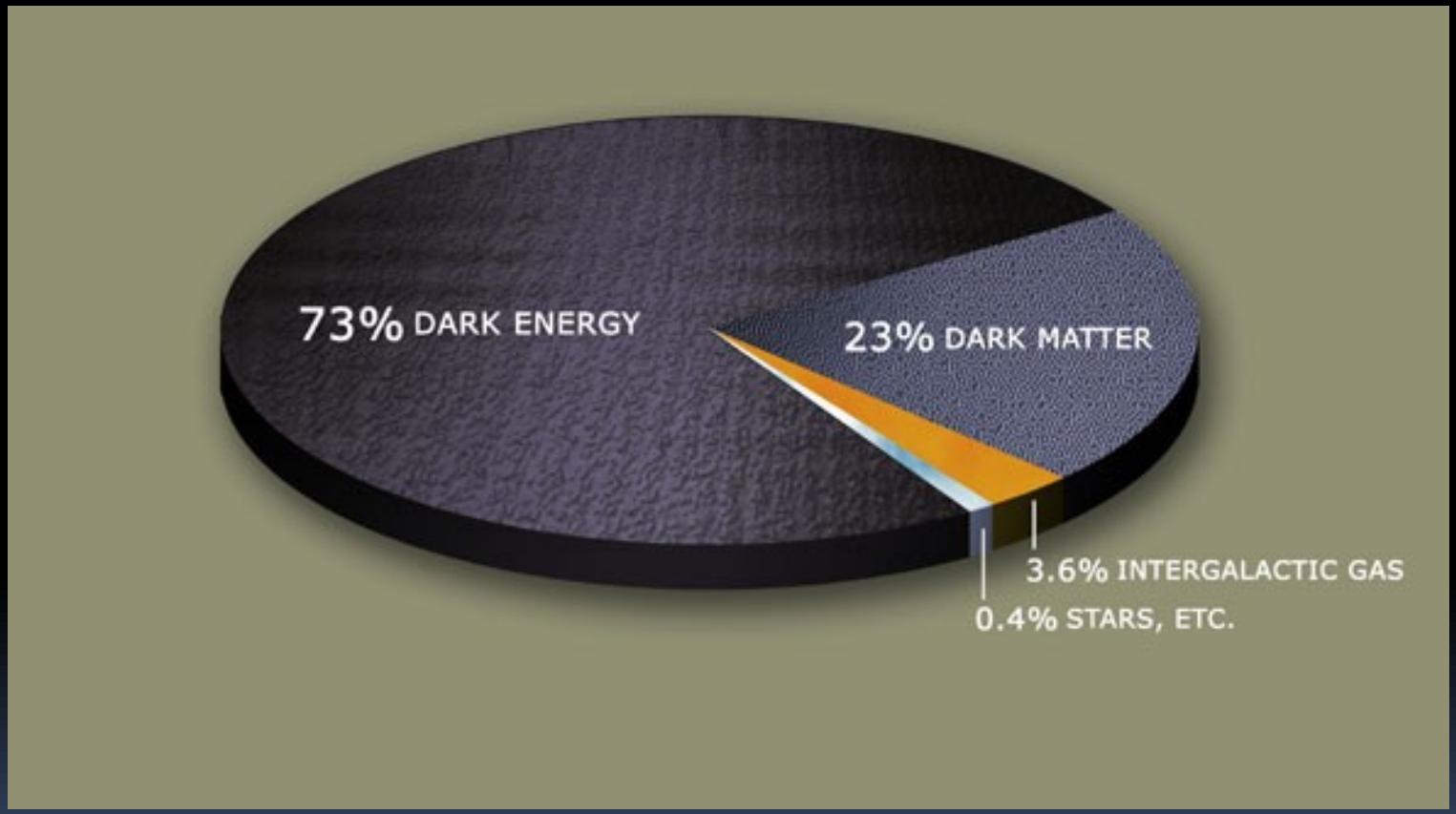
We may need to reconsider our current paradigms



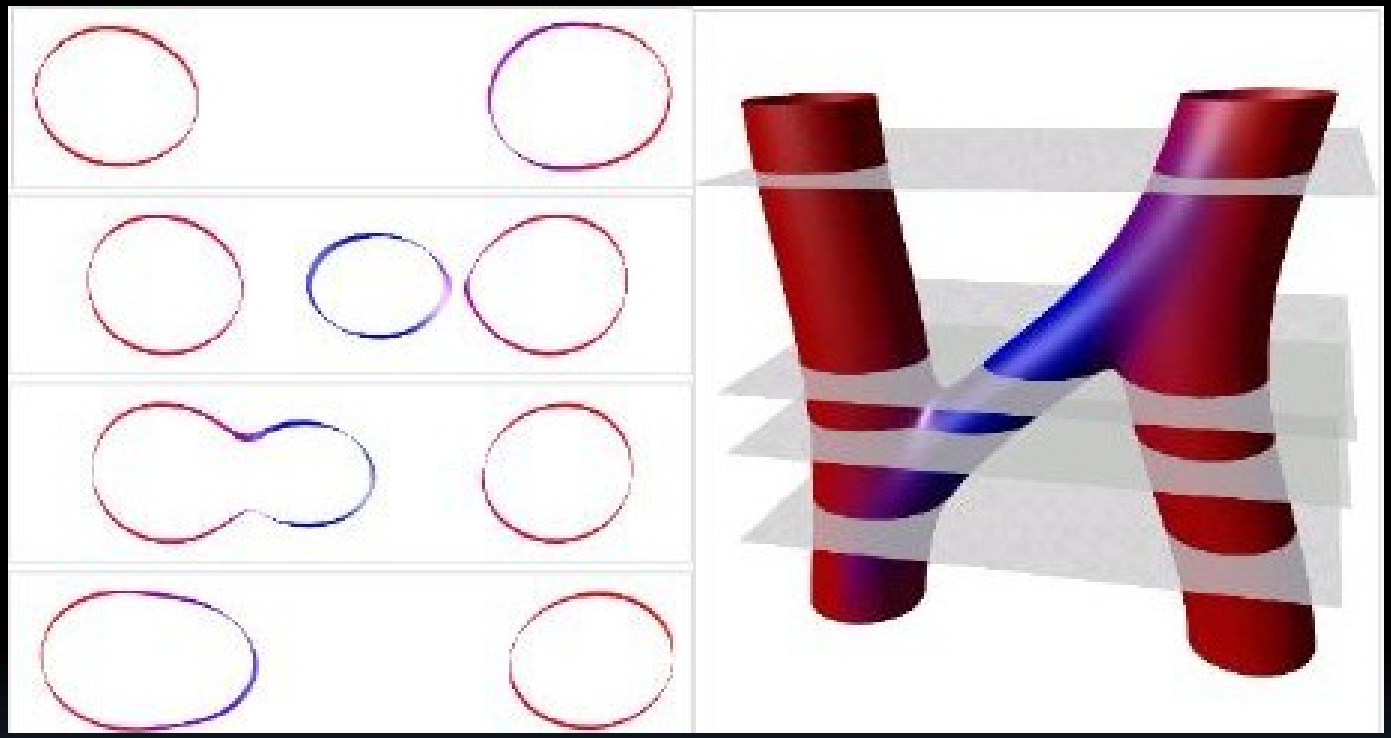


theory & observation

96% of the Energy in our Universe is not understood!

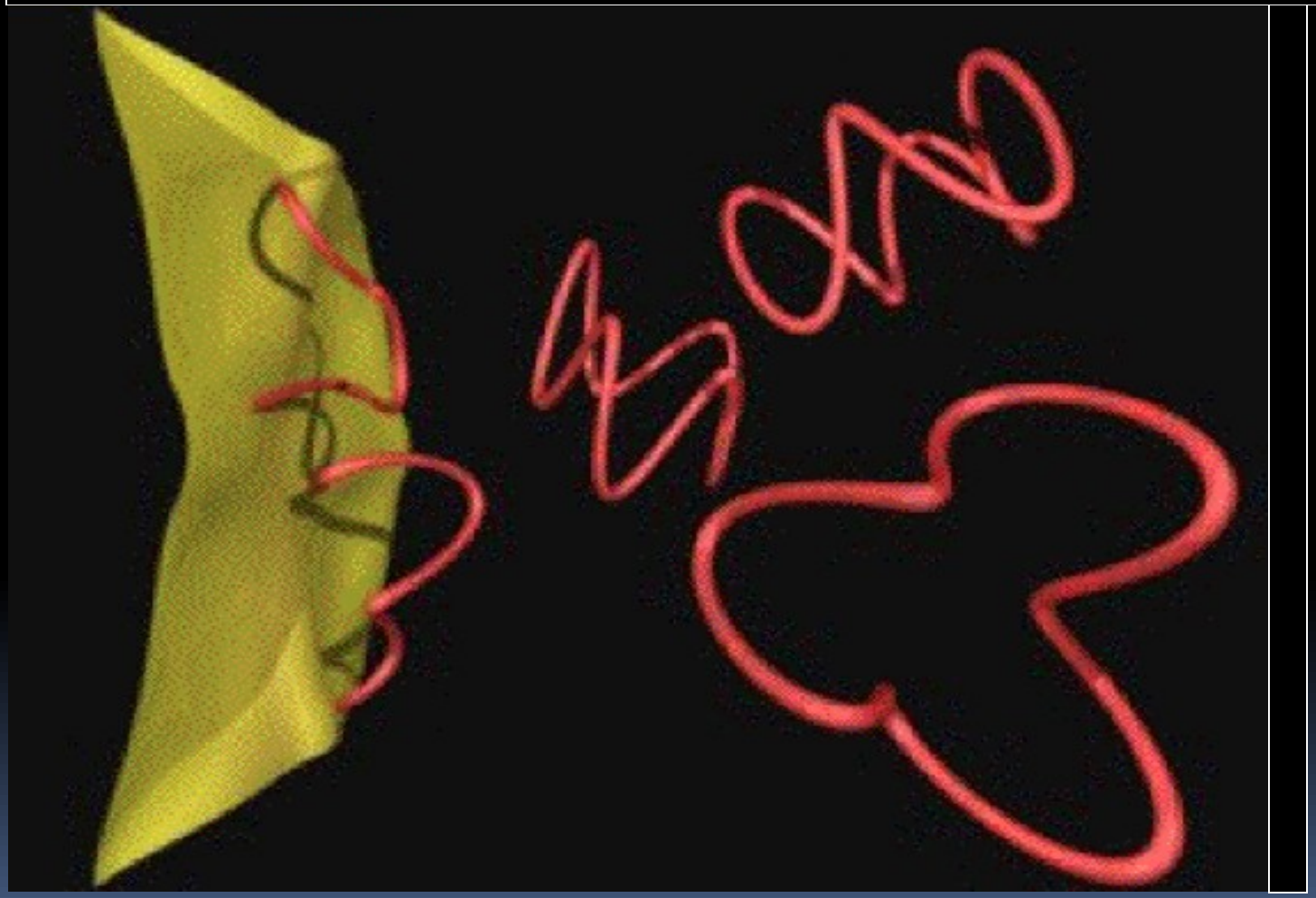


String Theory



FUNDAMENTAL FORCES: carried by vibrating strings

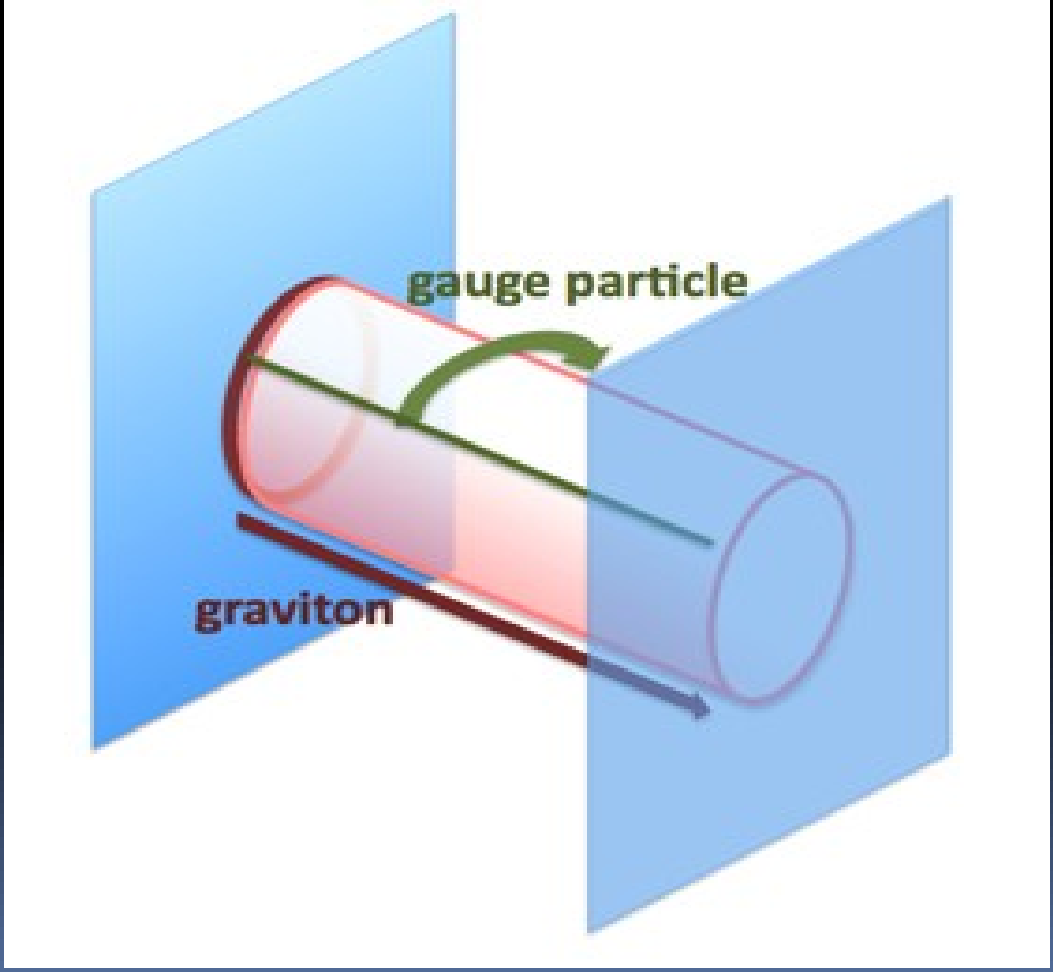
D-branes



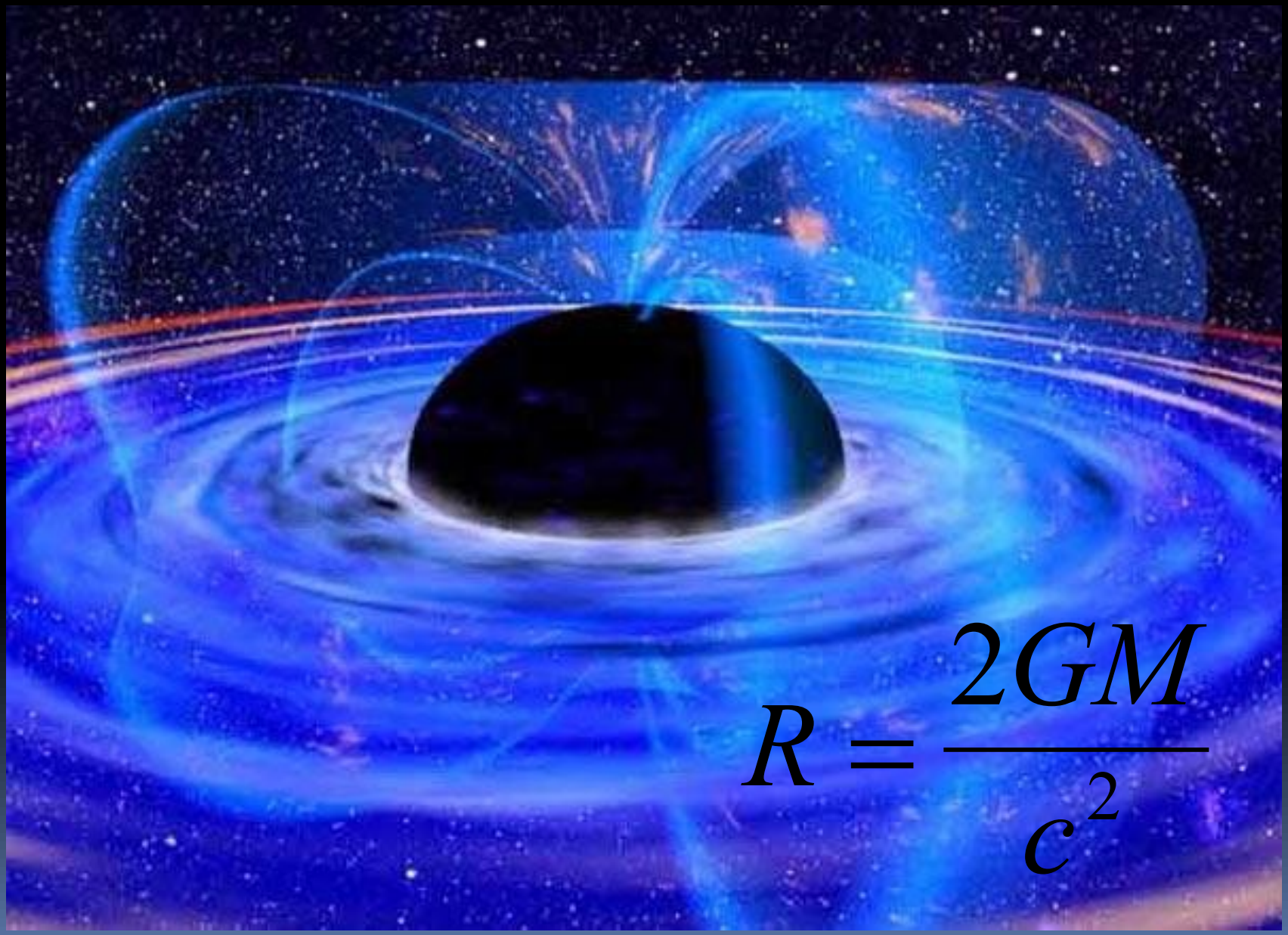
EMERGENCE

We use concepts and observe phenomena at a macroscopic scale, which are derived from a microscopic scale where they have no a priori meaning

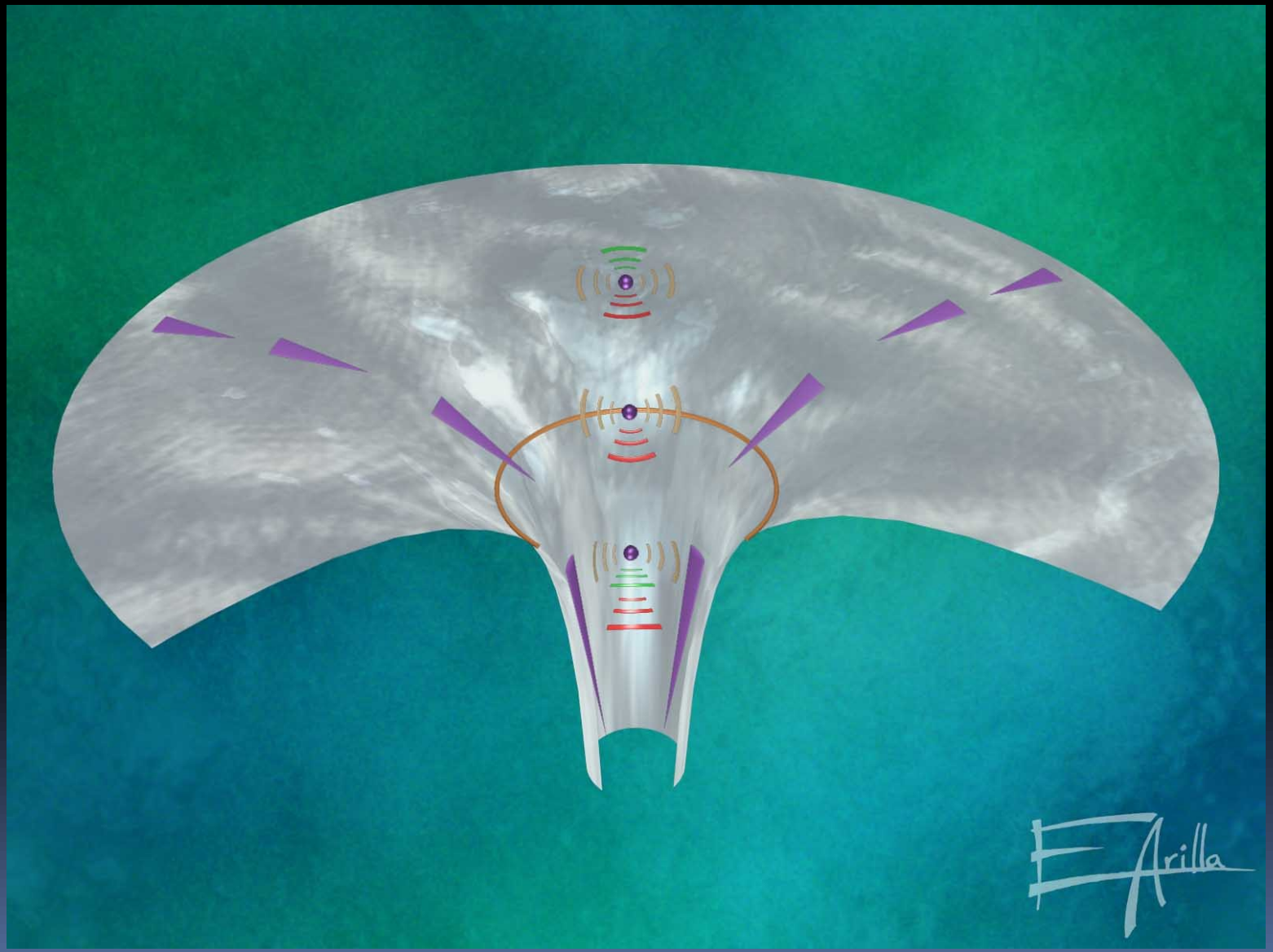
Open/closed string
or
gauge theory/gravity duality



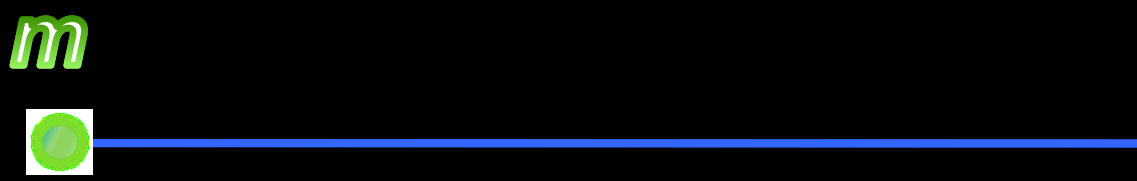
Black Holes



Black Holes



Black Hole Horizon



Bekenstein

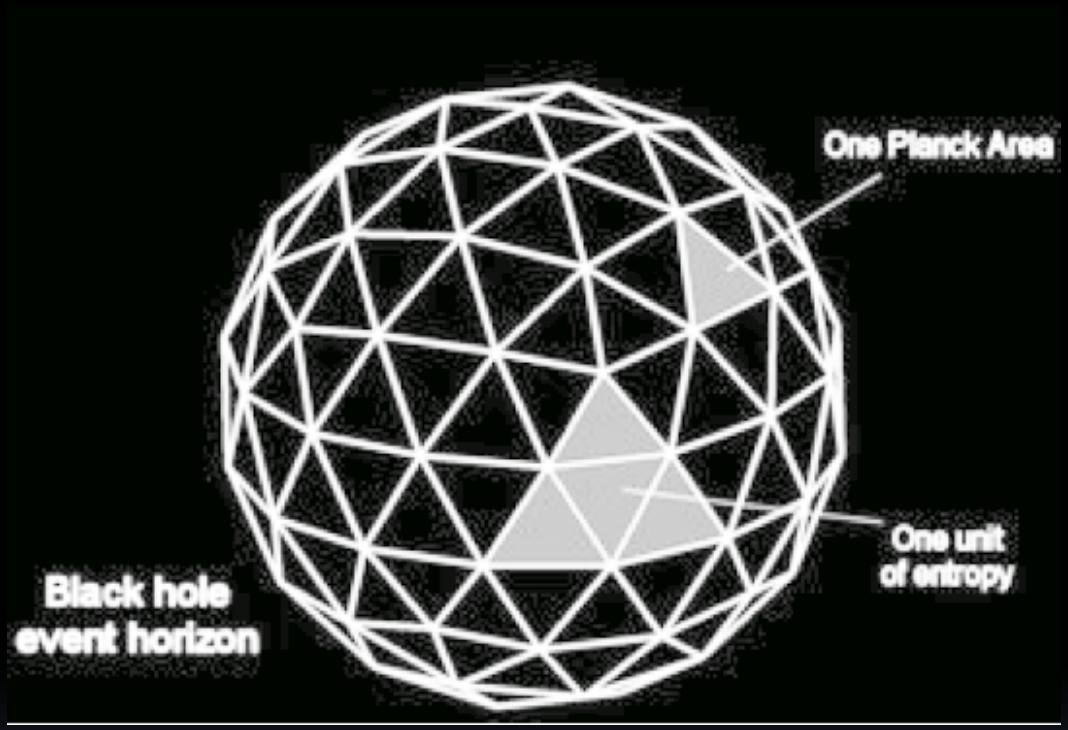
Consider a particle gradually lowered into a black hole. Classically, the energy associated with the particle gets redshifted, and vanishes when the particle is at the horizon.

Black Hole Horizon

Now take a gas of particles lowered in to a black hole. What happens to the entropy?

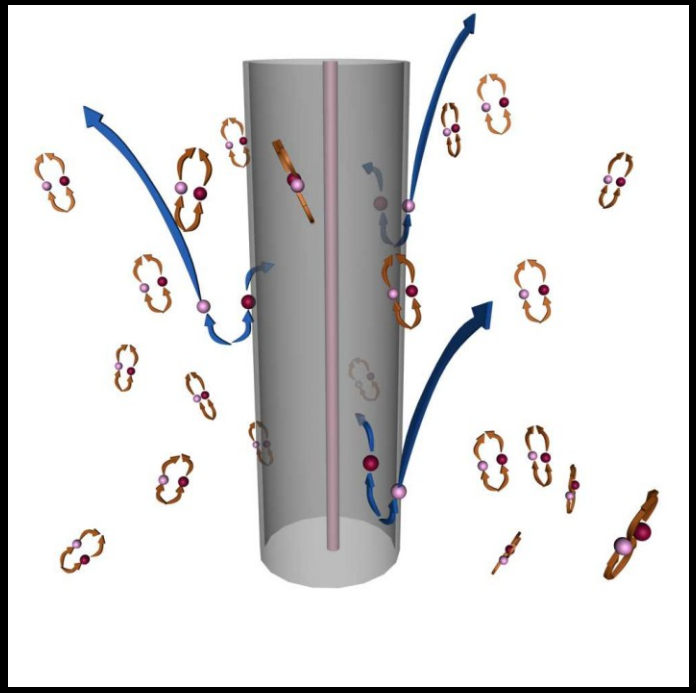
Bekenstein
Hawking

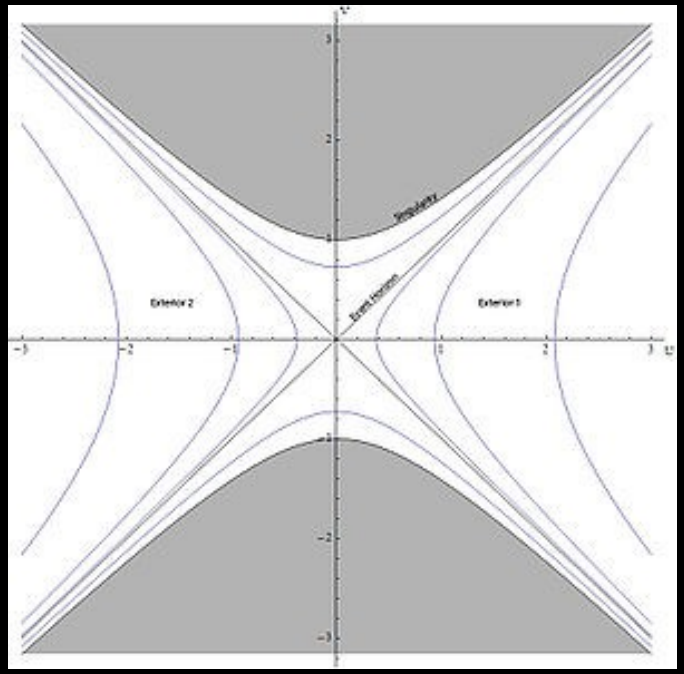
Black Hole Entropy



$$S_{BH} = k_B \frac{Ac^3}{4G\hbar}$$

Hawking Temperature

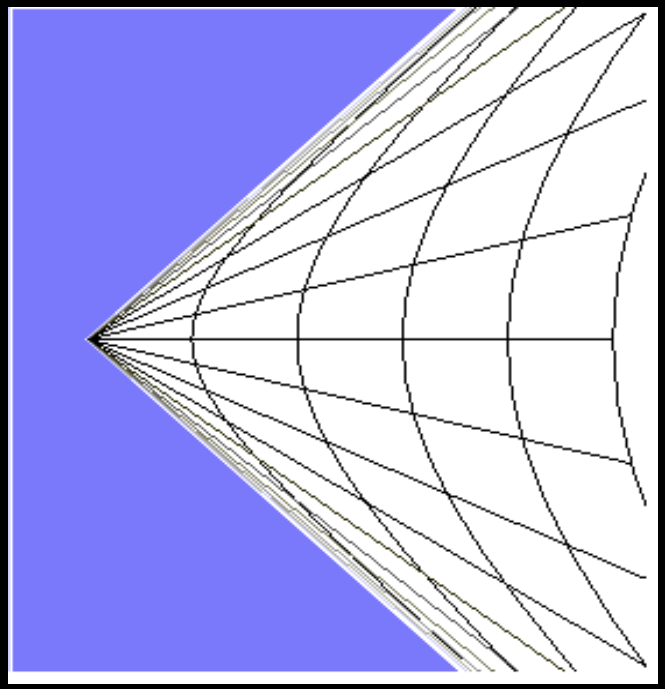


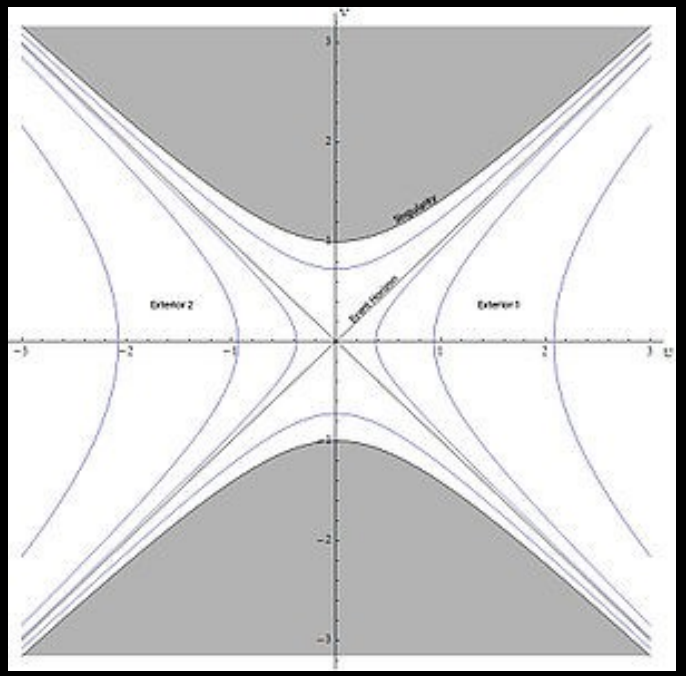


$$T = \frac{1}{2\pi} \frac{\hbar g}{k_B c}$$

$$g = \frac{GM}{R^2}$$

Unruh Temperature



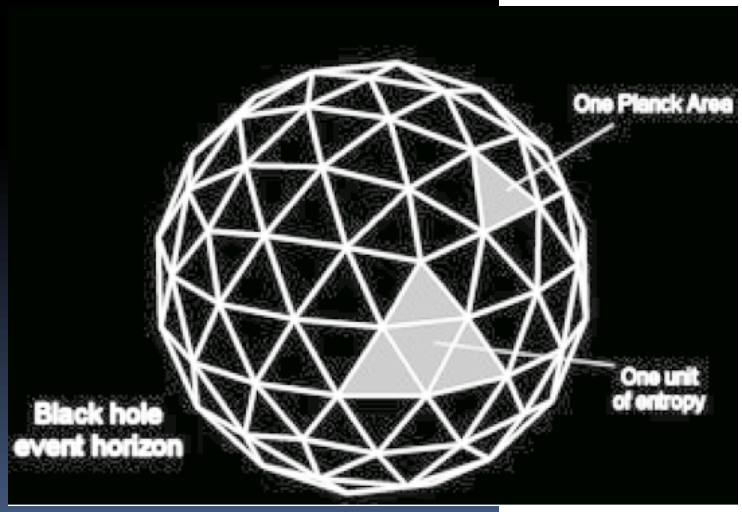


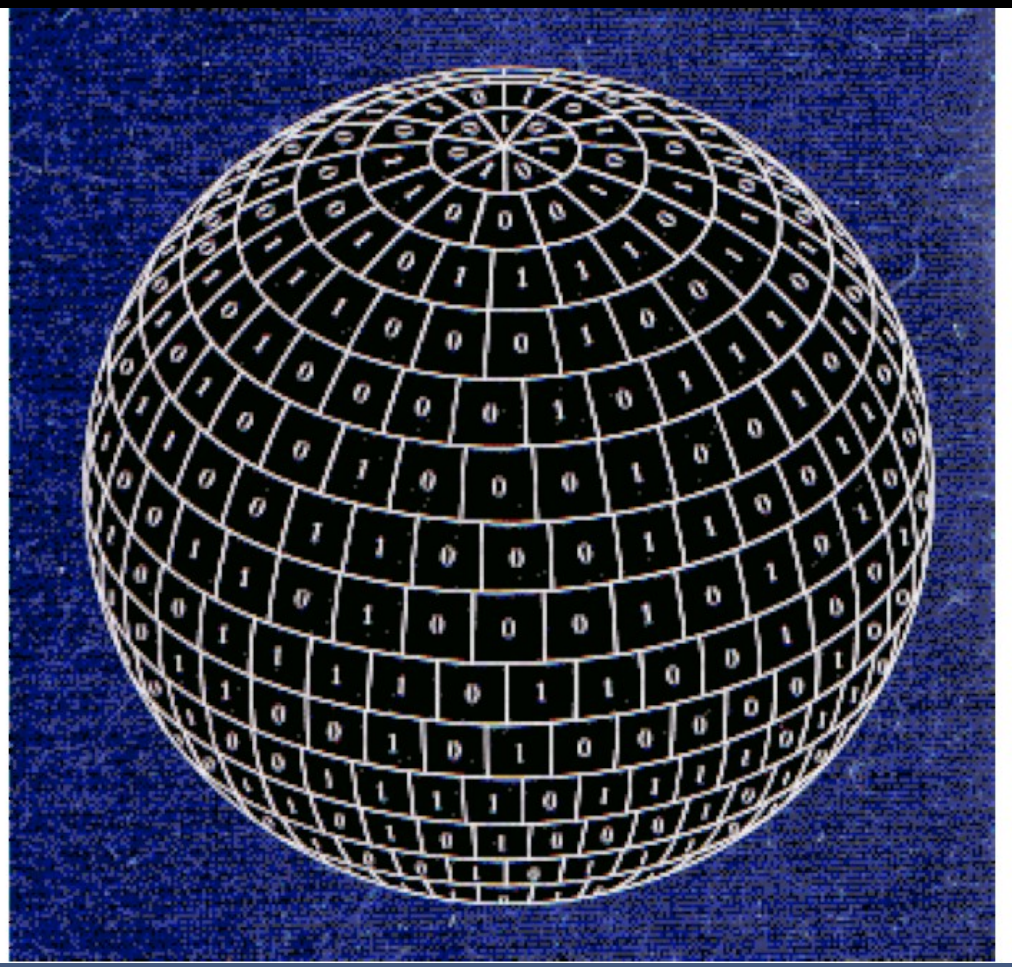
$$T = \frac{1}{2\pi} \frac{\hbar a}{k_B c}$$

in accelerated frame

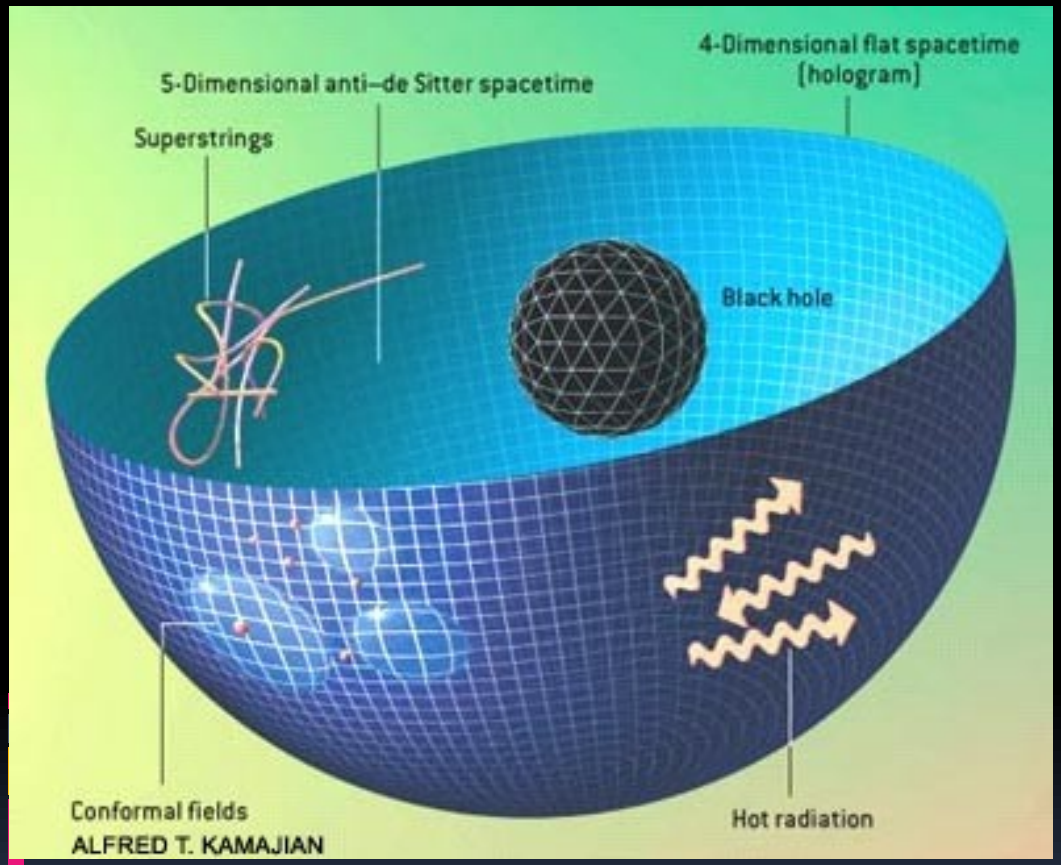
Holographic principle

The information associated with a certain part o may be (heuristicall represented as bits surface surroundin

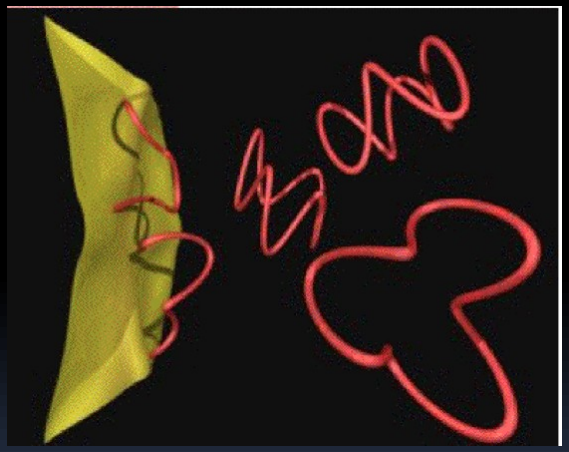




ADS/CFT CORRESPONDENCE



EQUIVALENCE BETWEEN FIELD THEORY ON THE "BOUNDARY" AND GRAVITY IN THE "BULK"



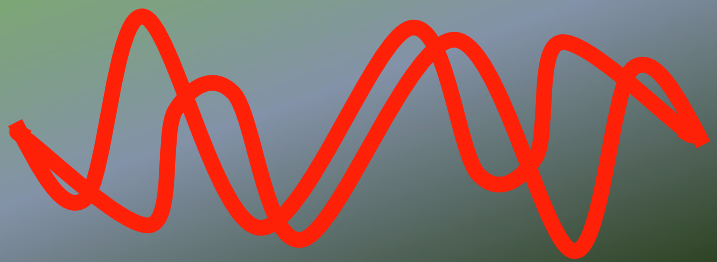
ONE SPACE DIMENSION EMERGES CORRESPONDING TO THE "SCALE" OF THE BOUNDARY THEORY. RADIAL EVOLUTION IS LIKE RENORMALIZATION GROUP FLOW.

Black Hole In AdS space

Bulk description

Particle gets lowered in to black hole

Hot CFT



Thermal Heat Bath

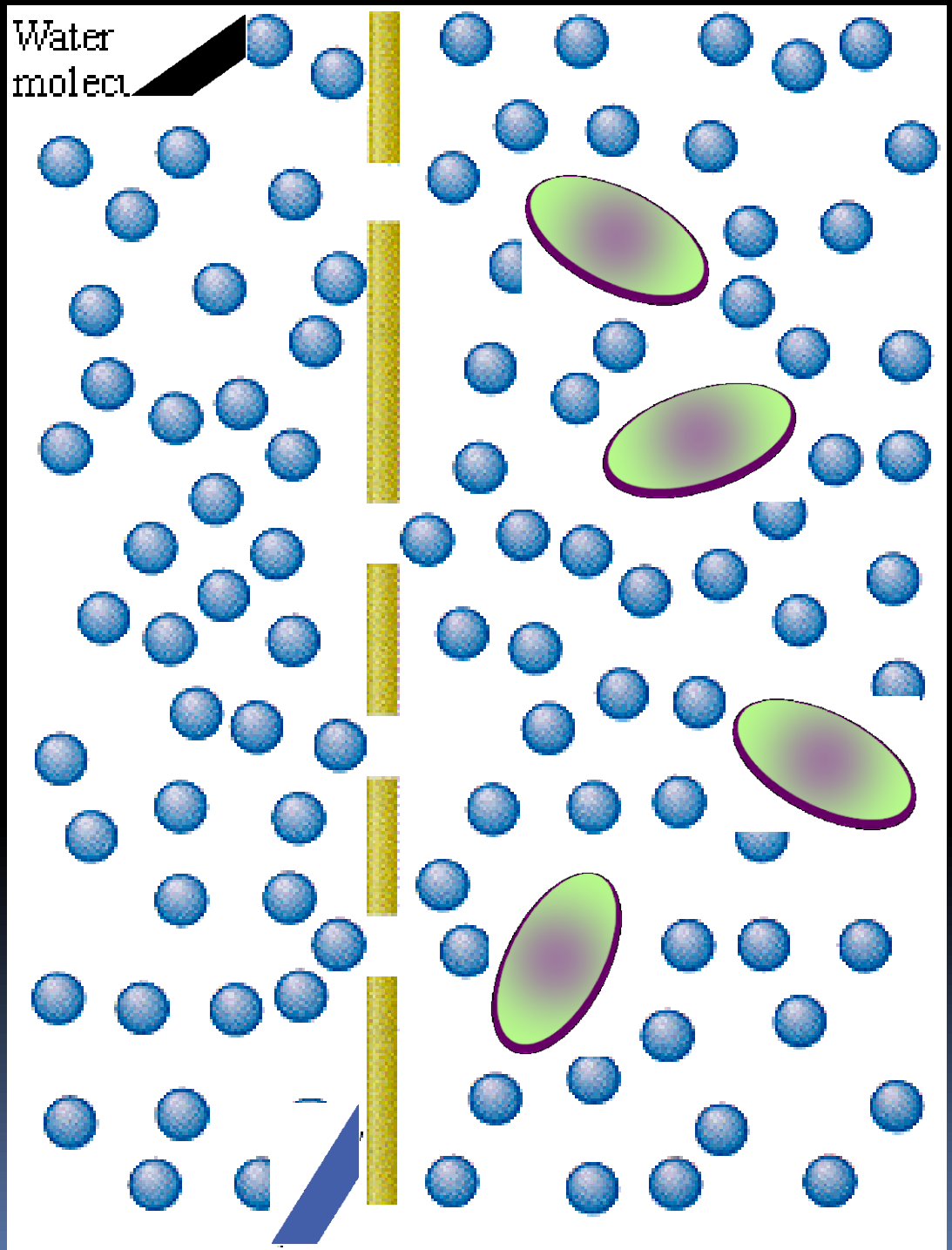
T

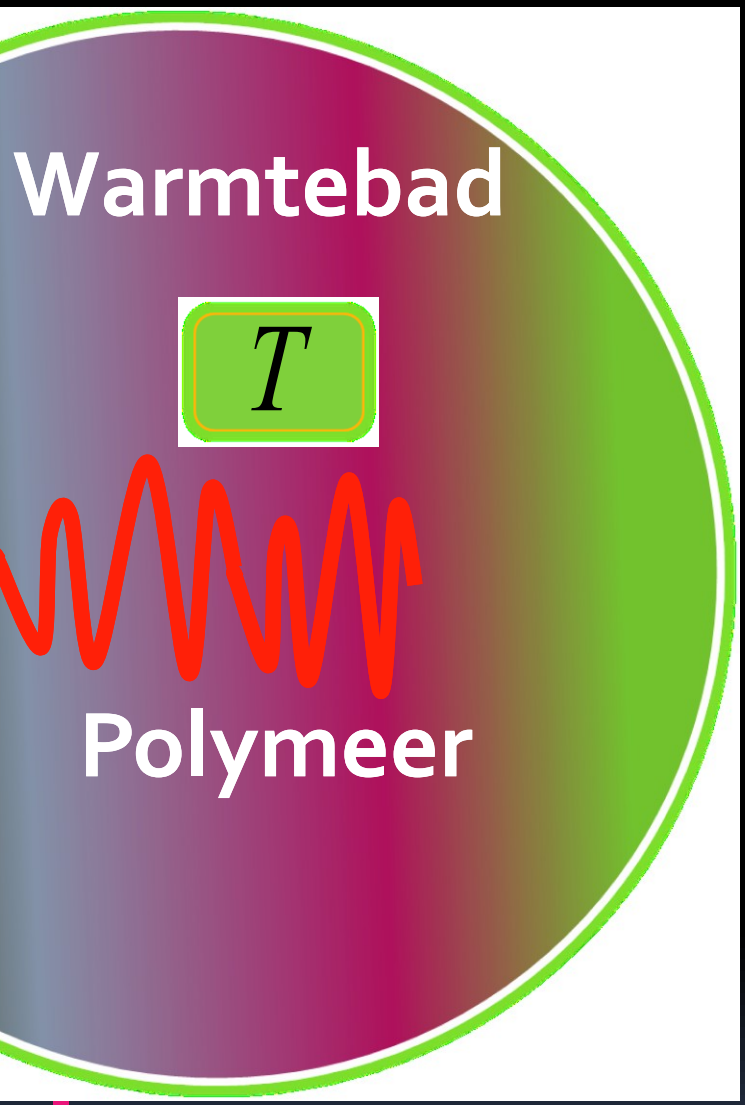
Boundary description:

Delocalized state gets thermalized by heath bath

Entropic force (wikipedia)

An entropic force is a macroscopic force whose properties are determined not by the character of an underlying microscopic force, but by the whole system's statistical tendency to increase its entropy.


Water
molecu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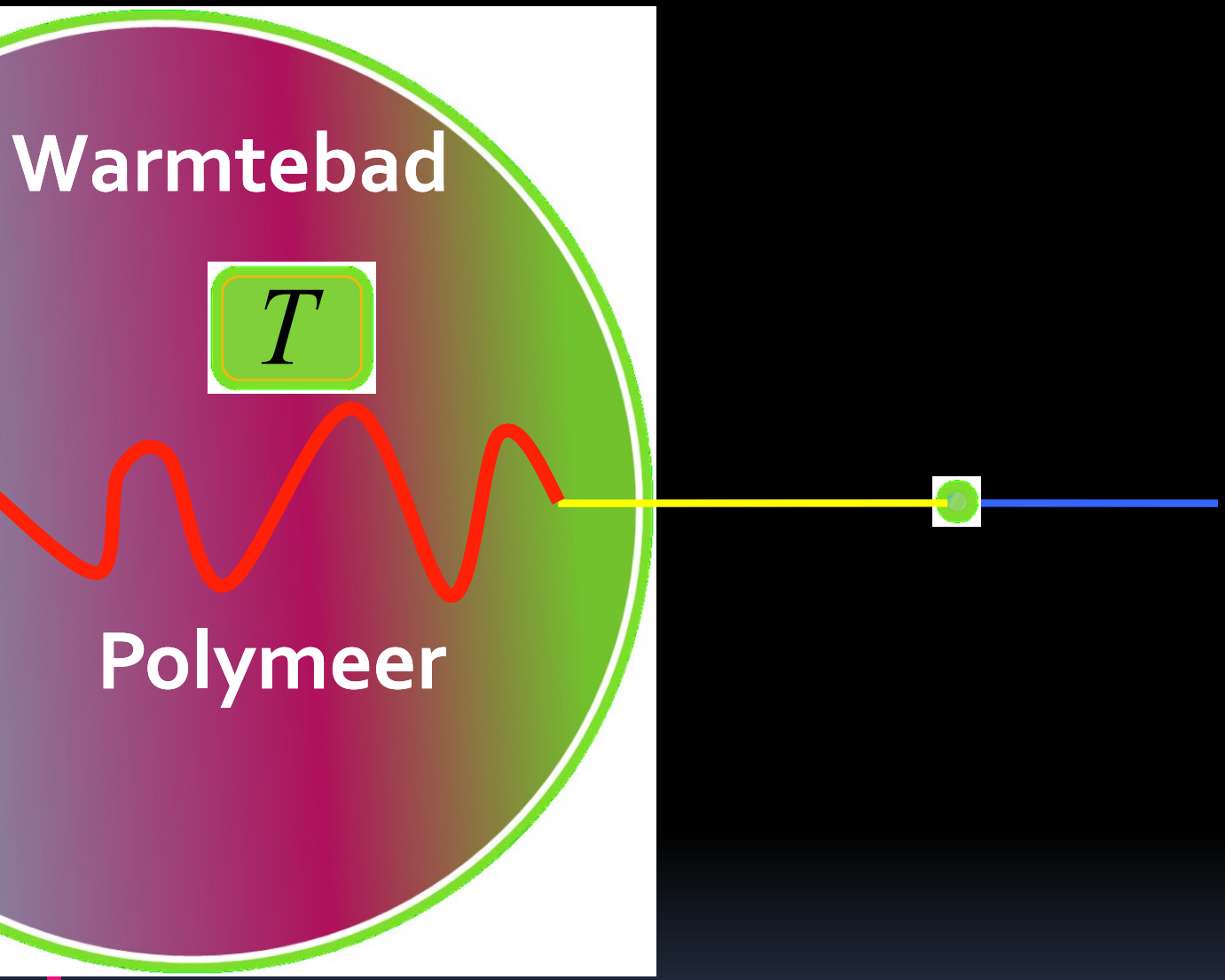
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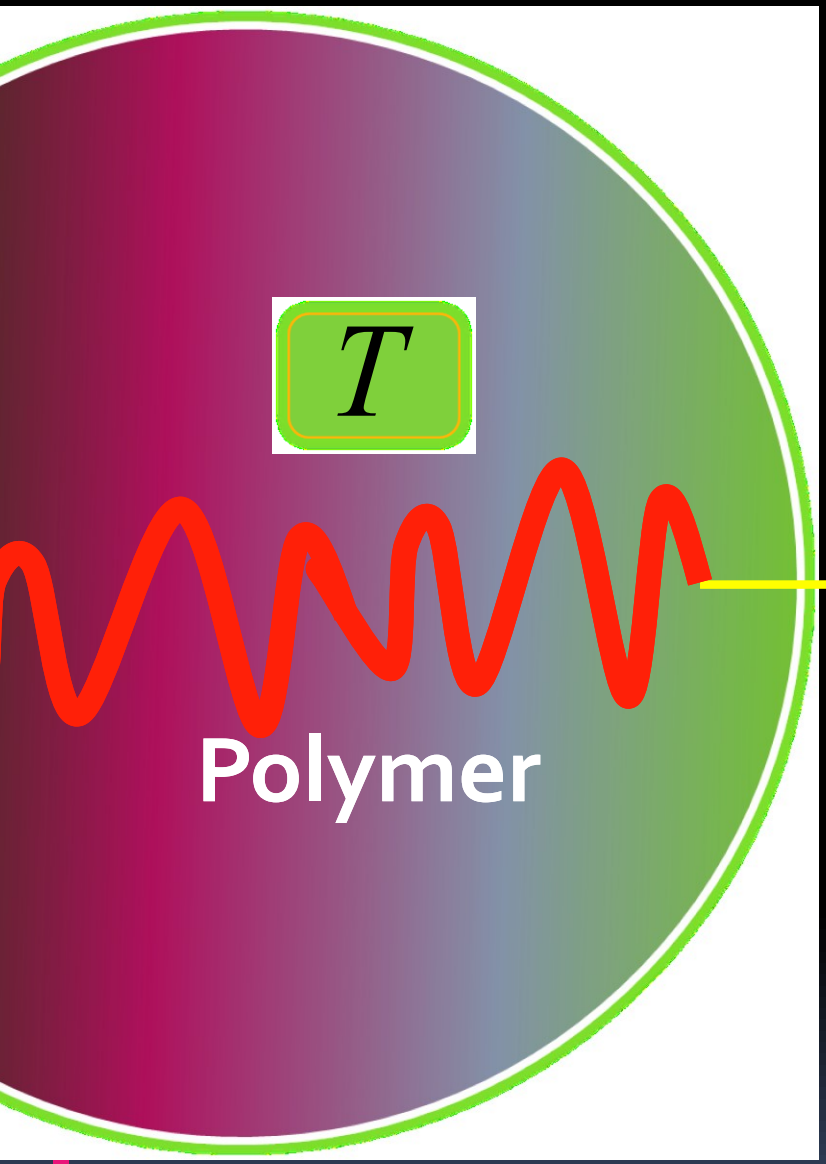
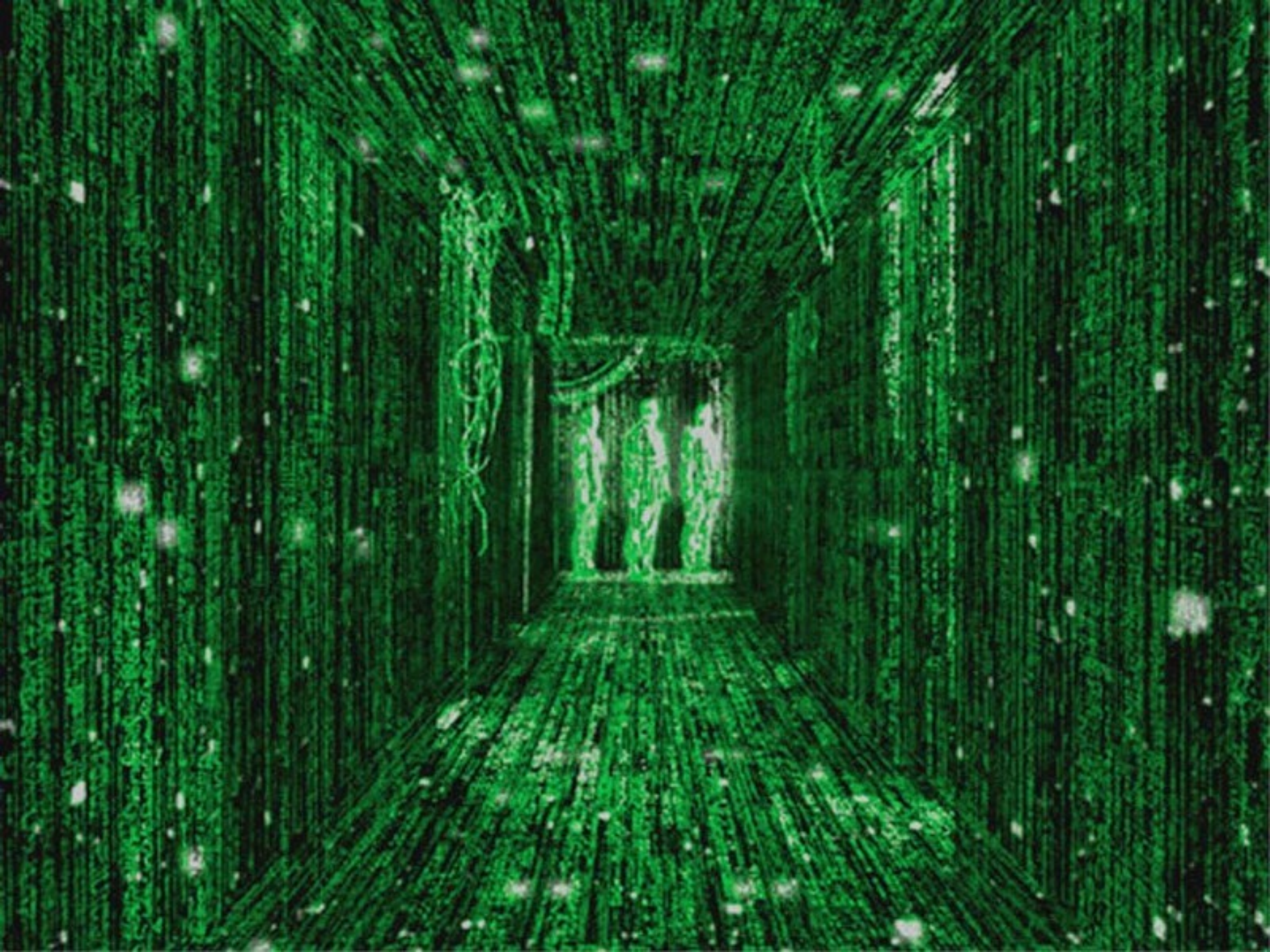


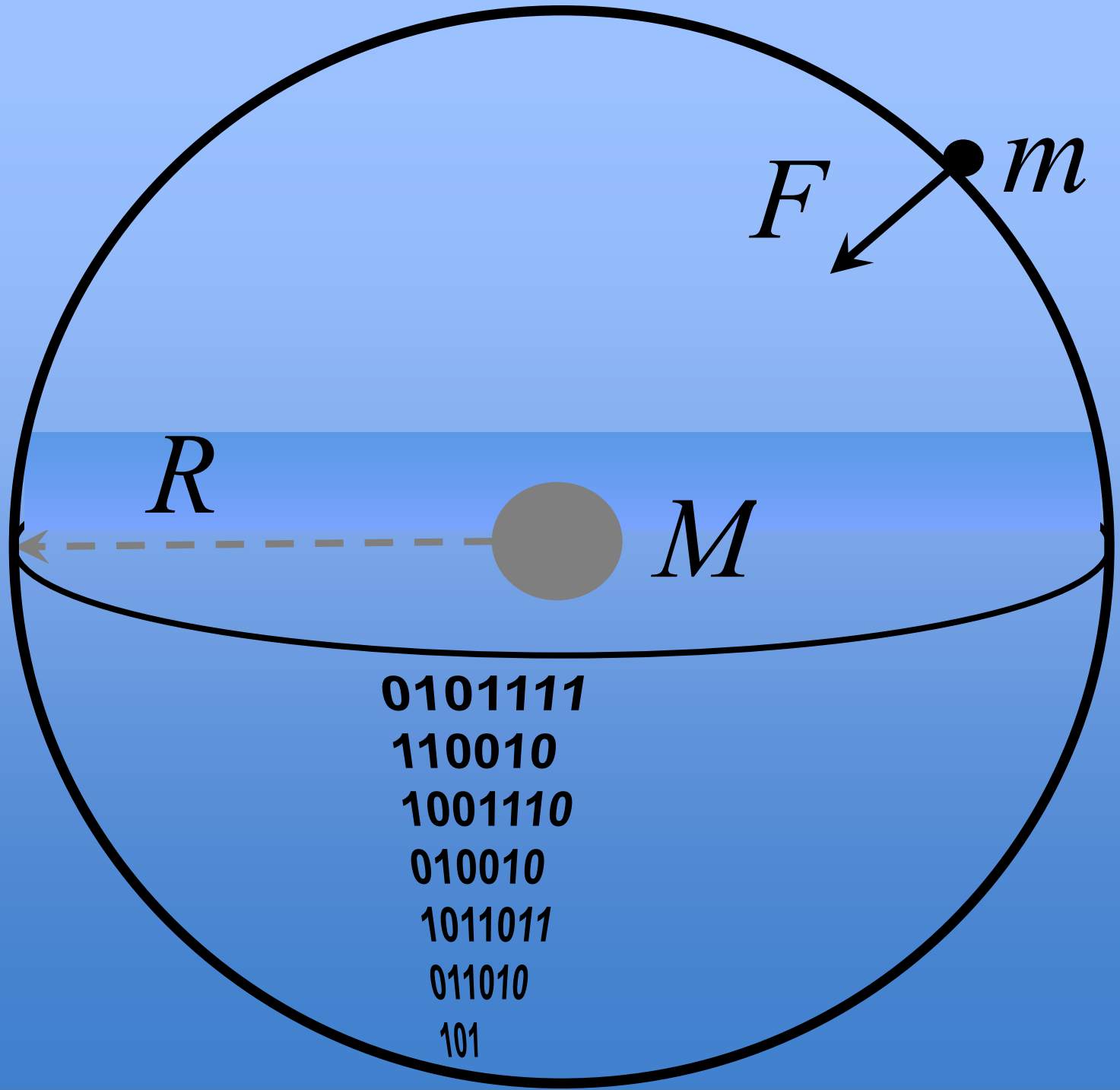
$$F\Delta x = T\Delta S$$

Entropic Force

Gravity as an Emergent Force

- At a fundamental scale our notions of space and time and matter cease to exist: they are derived concepts.
- In describing Nature in terms of space-time and matter, we ignore many degrees of freedom.
- Gravity arises because the amount of phase space (information) available for these degrees of freedom is influenced by the location of matter in space and time.

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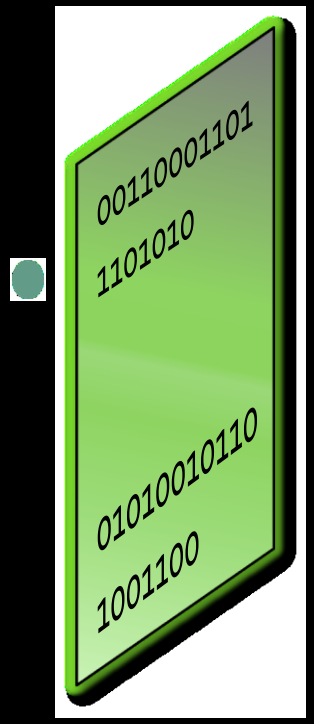
101

A HEURISTIC ARGUMENT



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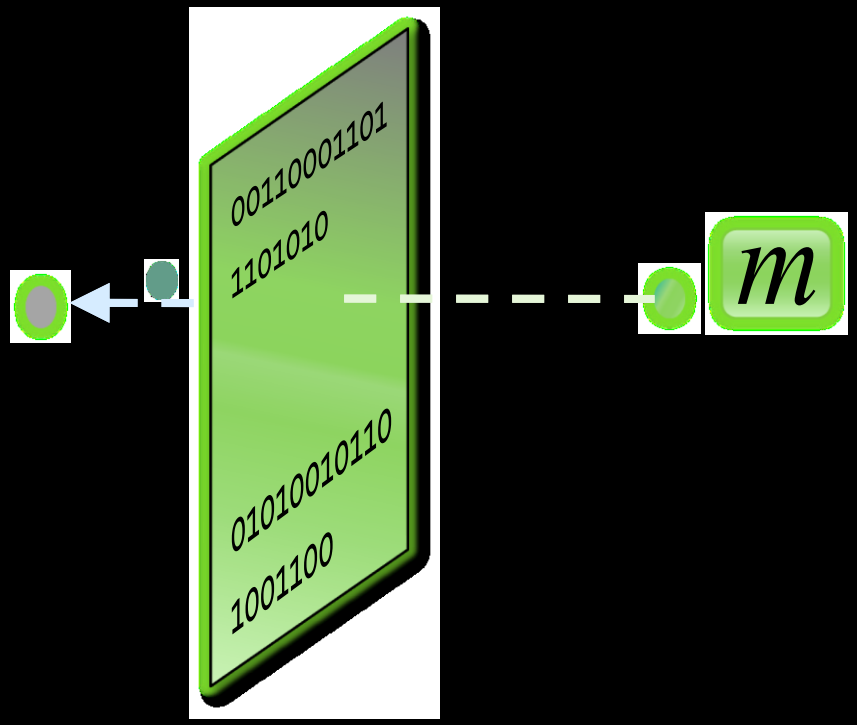

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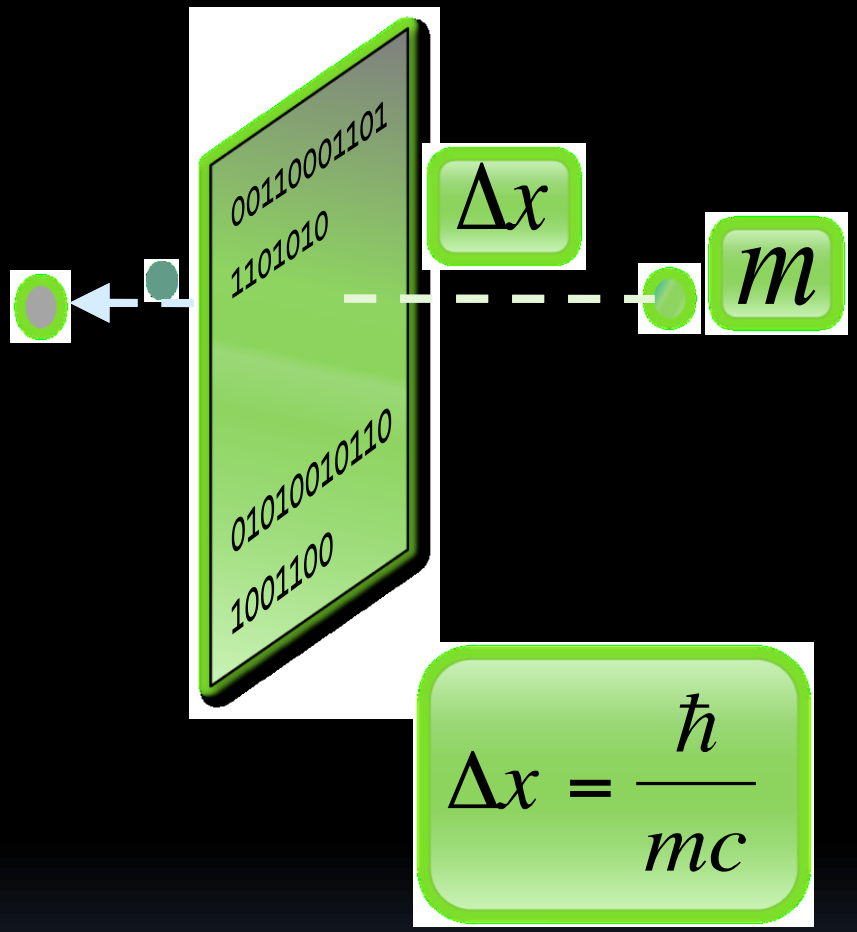

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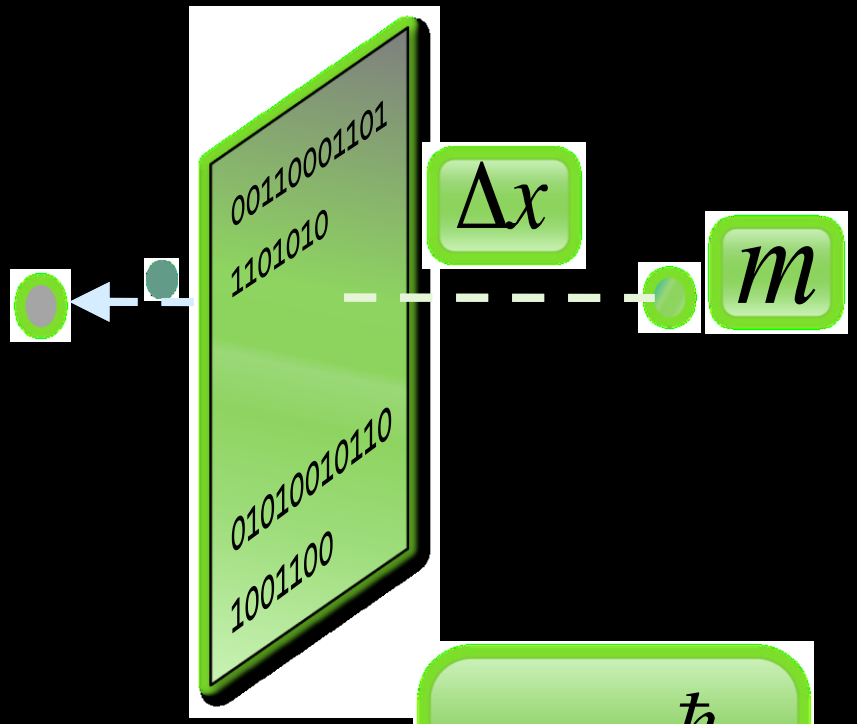
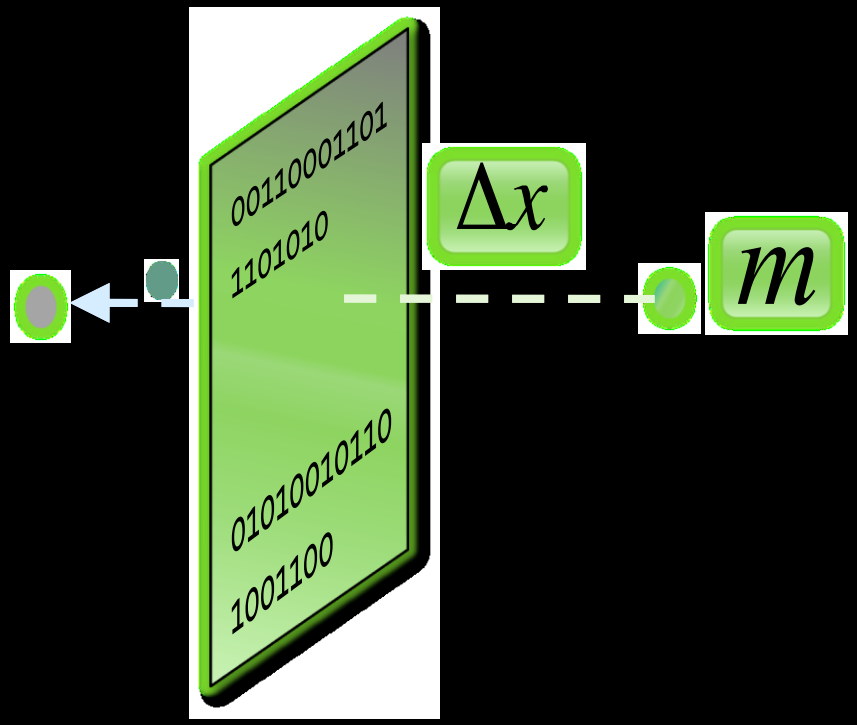


$$\Delta x = \frac{\hbar}{mc}$$

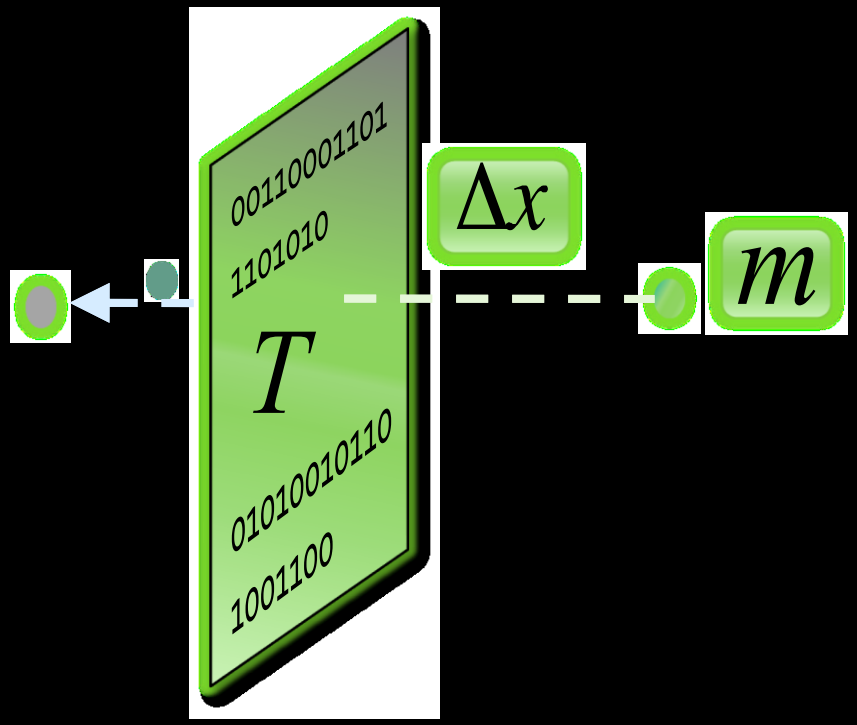
$$\Delta S = 2\pi\, k_B$$

A HEURISTIC ARGUMENT



$$\Delta S = 2\pi\, k_B \frac{mc}{\hbar} \Delta x$$

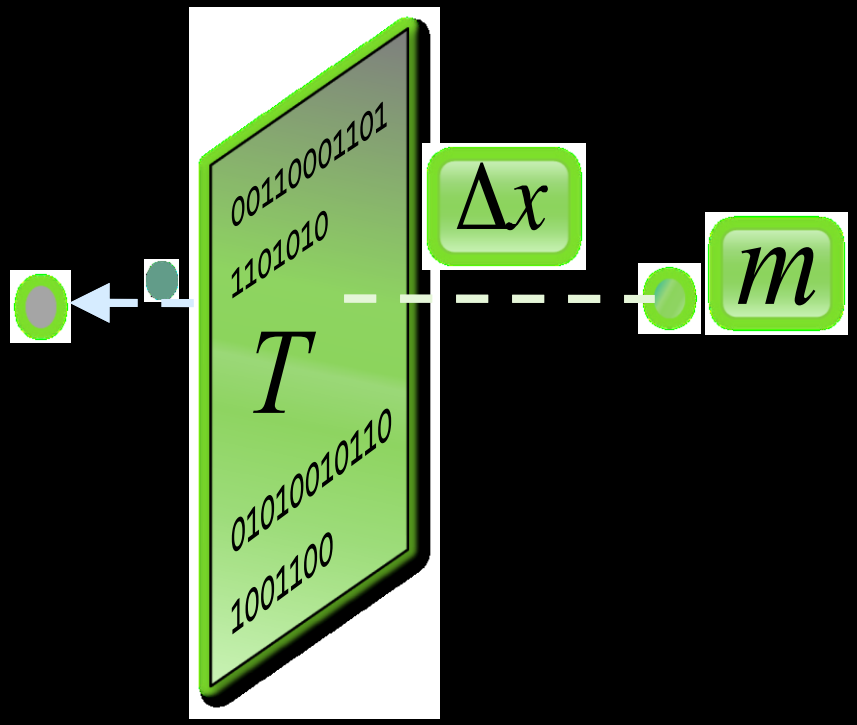
A HEURISTIC ARGUMENT



$$\Delta S = 2\pi\, k_B \frac{mc}{\hbar} \Delta x$$

A HEURISTIC ARGUMENT

$$F\Delta x = T\Delta S$$



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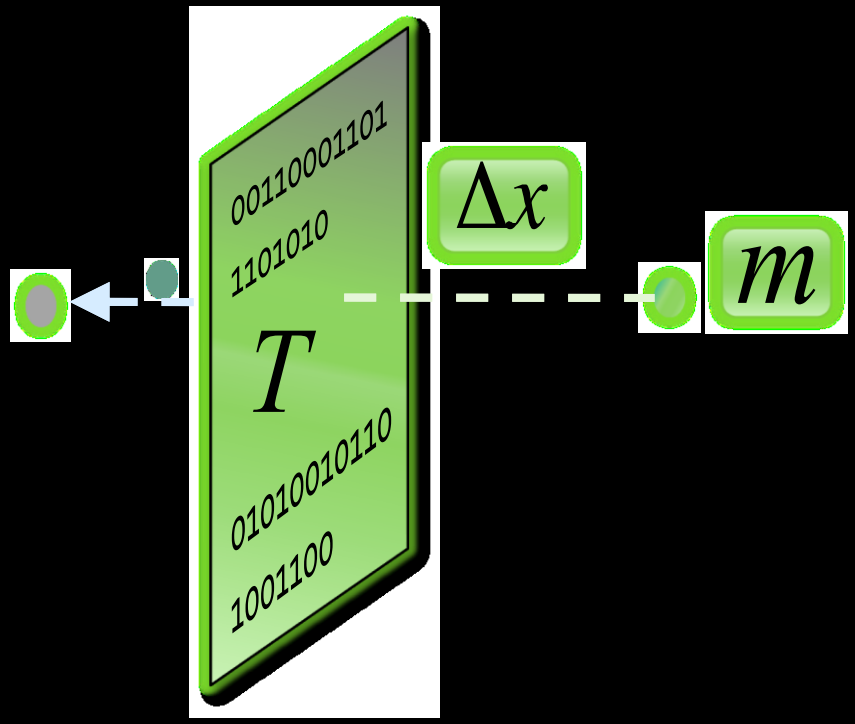
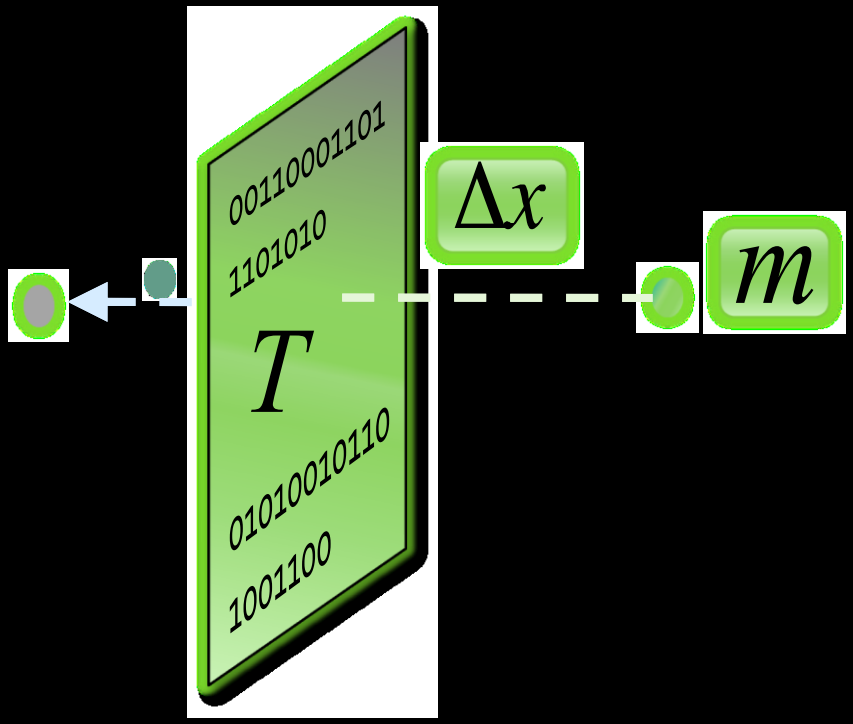


$$k_B T = \frac{\hbar a}{2\pi c}$$

$$\Delta S = 2\pi\, k_B \frac{mc}{\hbar} \Delta x$$

A HEURISTIC ARGUMENT

$$F\Delta x = T\Delta S$$

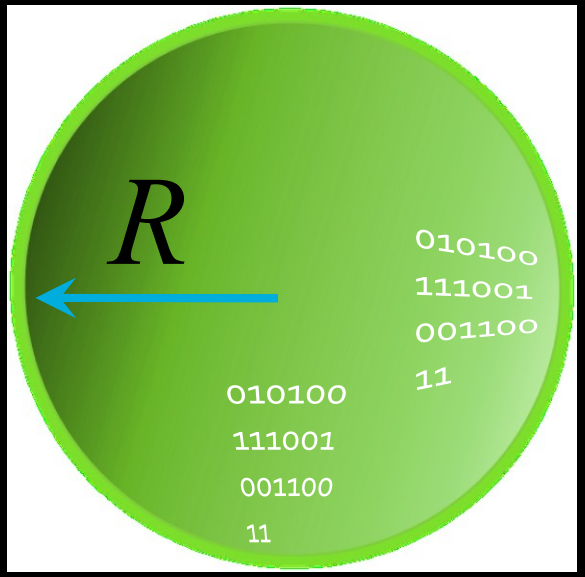


$$k_B T = \frac{\hbar a}{2\pi c}$$

$$F = ma$$

$$\Delta S = 2\pi\, k_B \frac{mc}{\hbar}\Delta x$$

A HEURISTIC ARGUMENT



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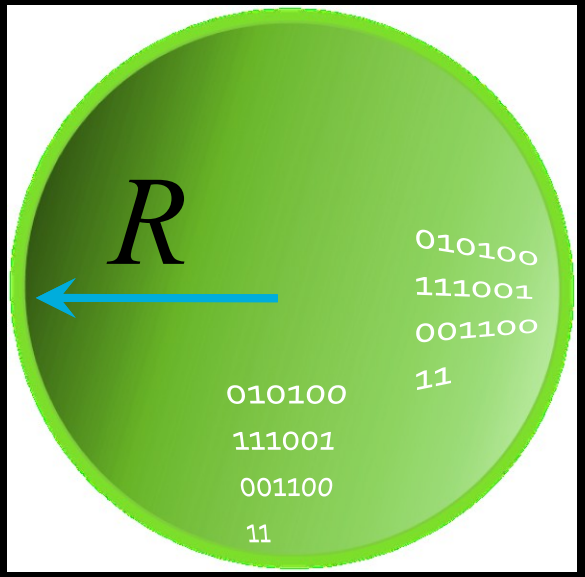
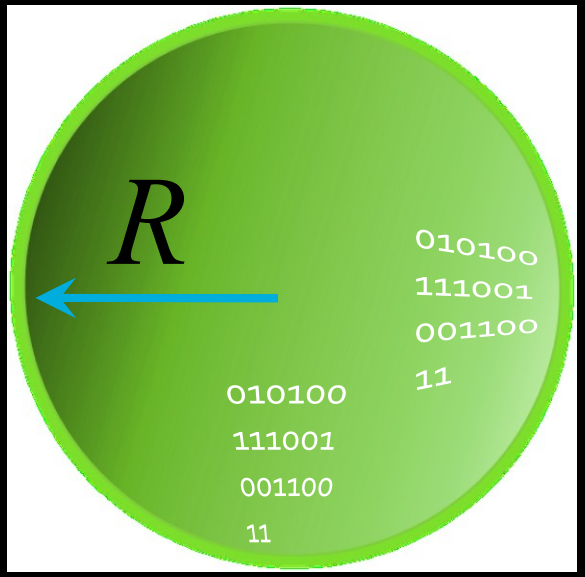


$$\#\ bits = \frac{4\pi R^2}{\ell^2}$$

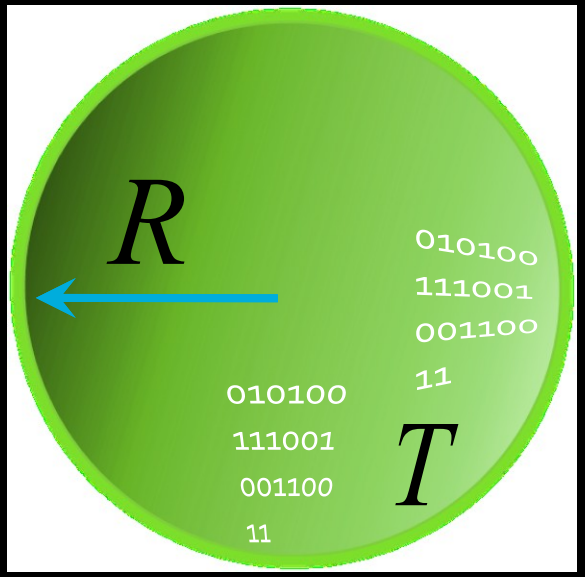
A HEURISTIC ARGUMENT



$$\#\ bits = \frac{4\pi R^2}{\ell^2}$$

$$\ell^2 = \frac{G\hbar}{c^3}$$

A HEURISTIC ARGUMENT



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$$\ell^2 = \frac{G\hbar}{c^3}$$

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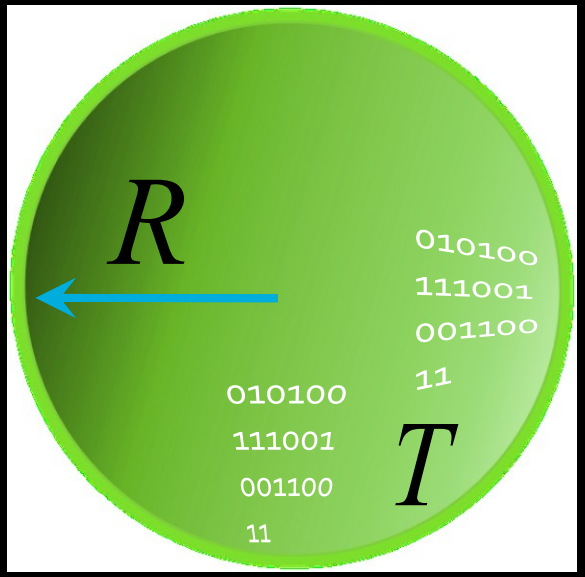
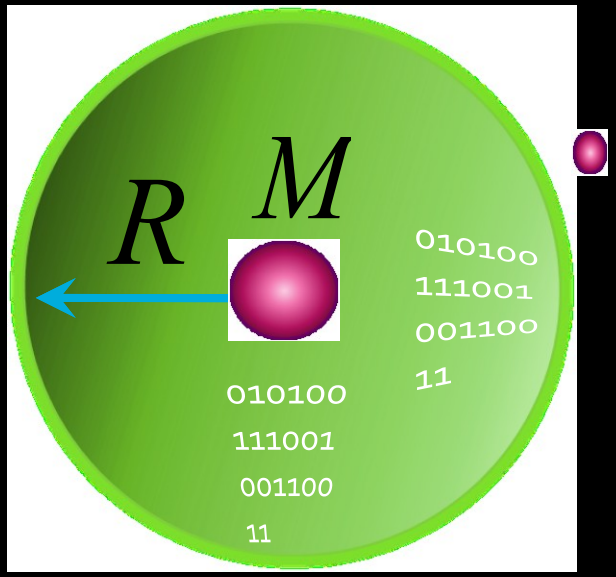


$$\#\ bits = \frac{4\pi R^2}{\ell^2}$$

$$\ell^2 = \frac{G\hbar}{c^3}$$

$$\frac{1}{2} k_B T = E / \#bits$$

A HEURISTIC ARGUMENT



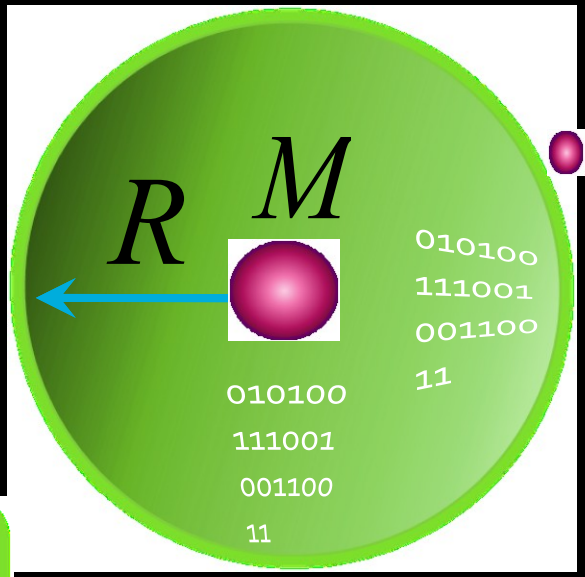
$$\#\ bits = \frac{4\pi R^2}{\ell^2}$$

$$\ell^2 = \frac{G\hbar}{c^3}$$

$$\frac{1}{2}k_B T = E / \#bits$$

$$E = Mc^2$$

A HEURISTIC ARGUMENT



$$\# \ bits = \frac{4\pi R^2}{\ell^2}$$

$$F\Delta x = T\Delta S$$

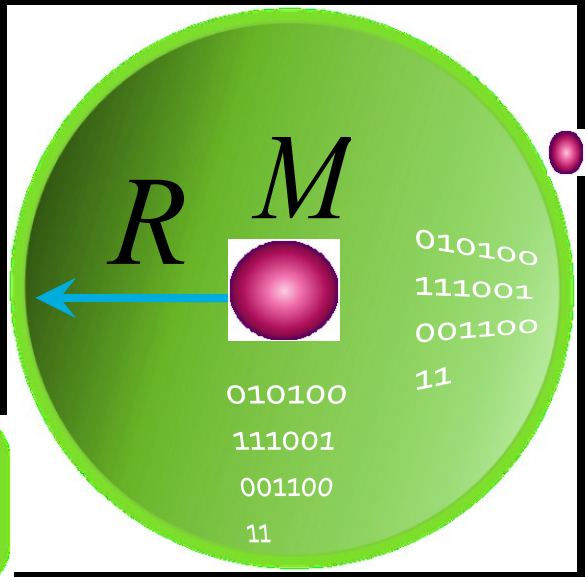
$$\ell^2 = \frac{G\hbar}{c^3}$$

$$\Delta S = 2\pi \, k_B \frac{mc}{\hbar} \Delta x$$

$$\frac{1}{2} k_B T = E / \ \#bits$$

$$E = Mc^2$$

A HEURISTIC ARGUMENT



$$F\Delta x = T\Delta S$$

$$\Delta S = 2\pi\, k_B \frac{mc}{\hbar}\Delta x$$

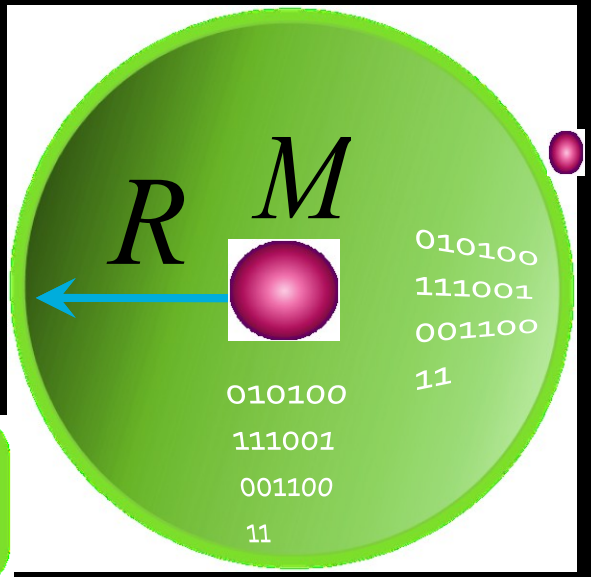
$$\#\ bits = \frac{4\pi R^2}{\ell^2}$$

$$\ell^2 = \frac{G\hbar}{c^3}$$

$$\tfrac{1}{2} k_B T = E / \#bits$$

$$E = Mc^2$$

A HEURISTIC ARGUMENT



$$\#\ bits = \frac{4\pi R^2}{\ell^2}$$

$$F\Delta x = T\Delta S$$

$$\ell^2 = \frac{G\hbar}{c^3}$$

$$\Delta S = 2\pi\, k_B \frac{mc}{\hbar}\Delta x$$

$$\tfrac{1}{2} k_B T = E / \#bits$$

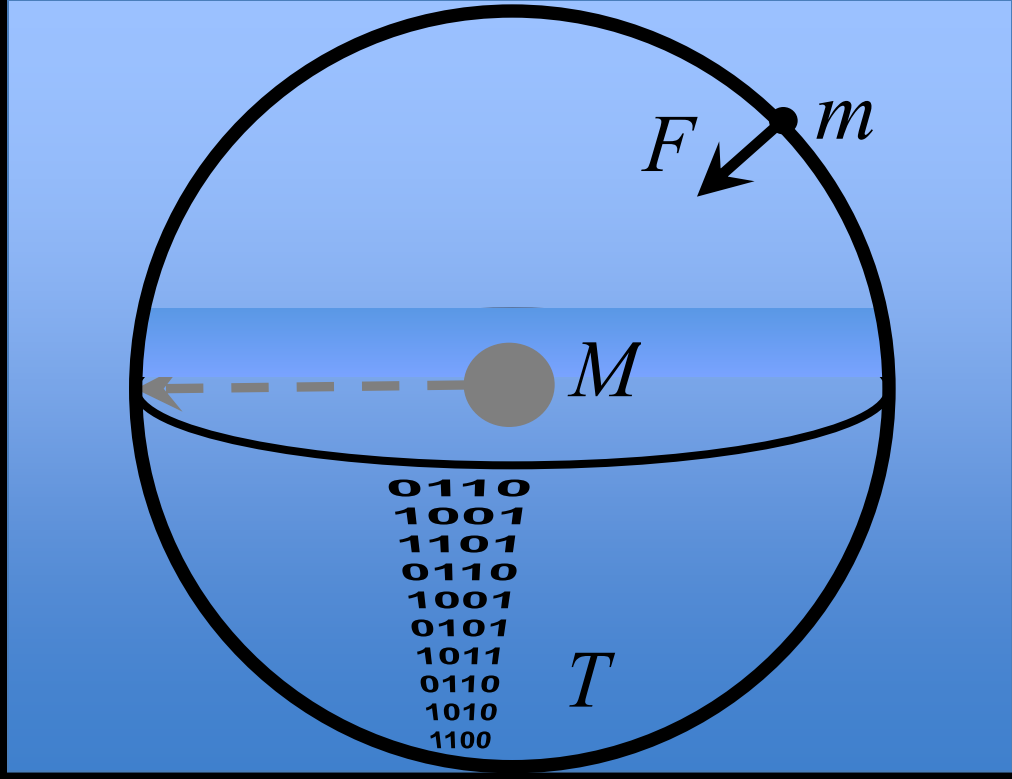
$$F = \frac{GMm}{R^2}$$

$$E = Mc^2$$

This is heuristic, so far…

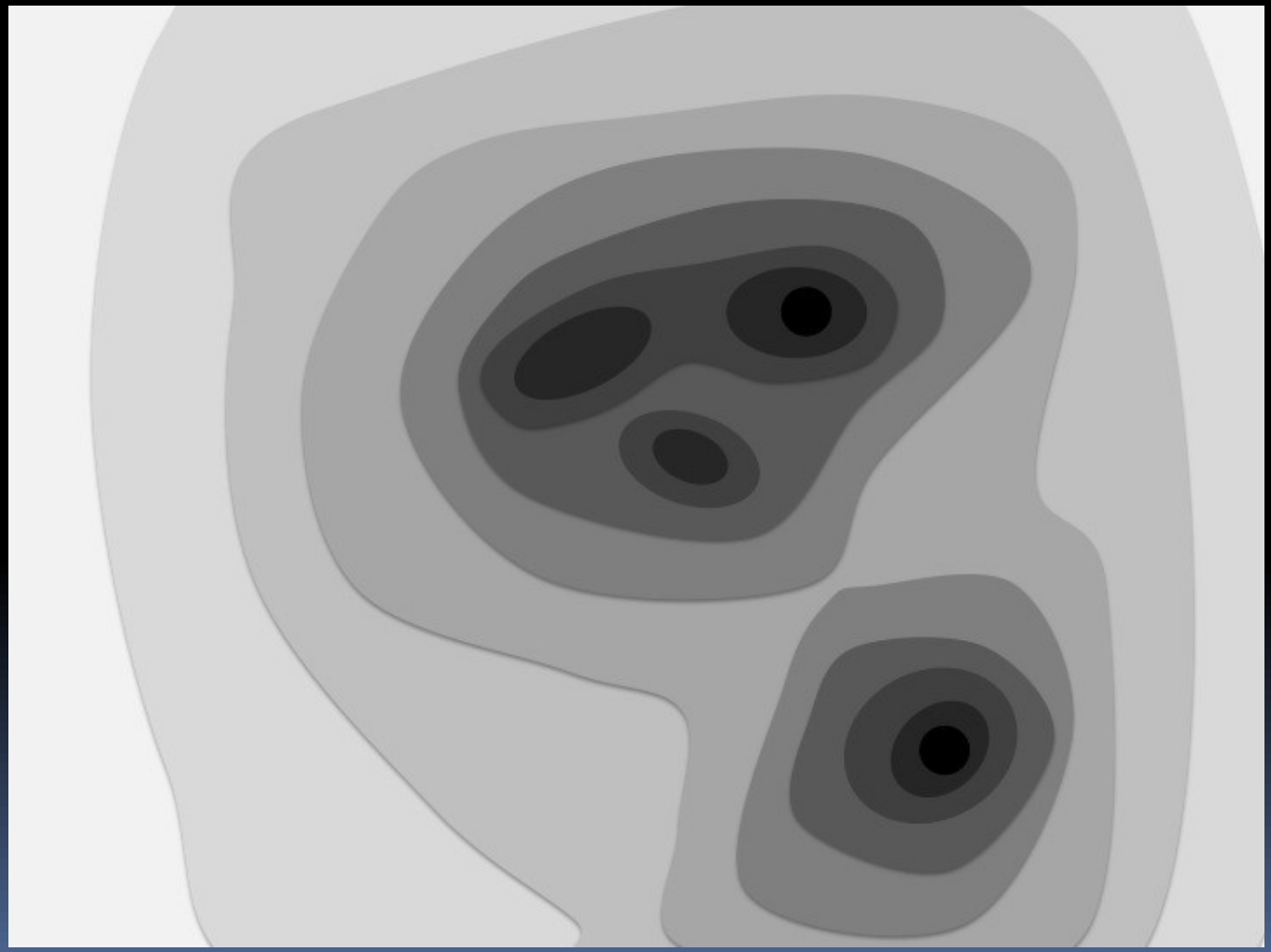
It is bit of a “swindle”
but it catches the essence.

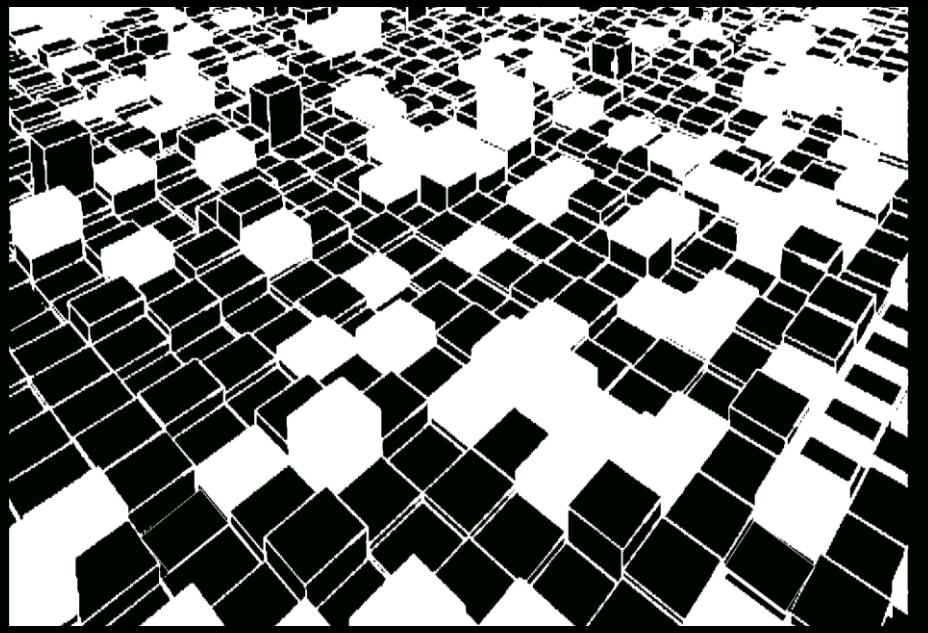
It should be seen as a
metaphore. But of what?



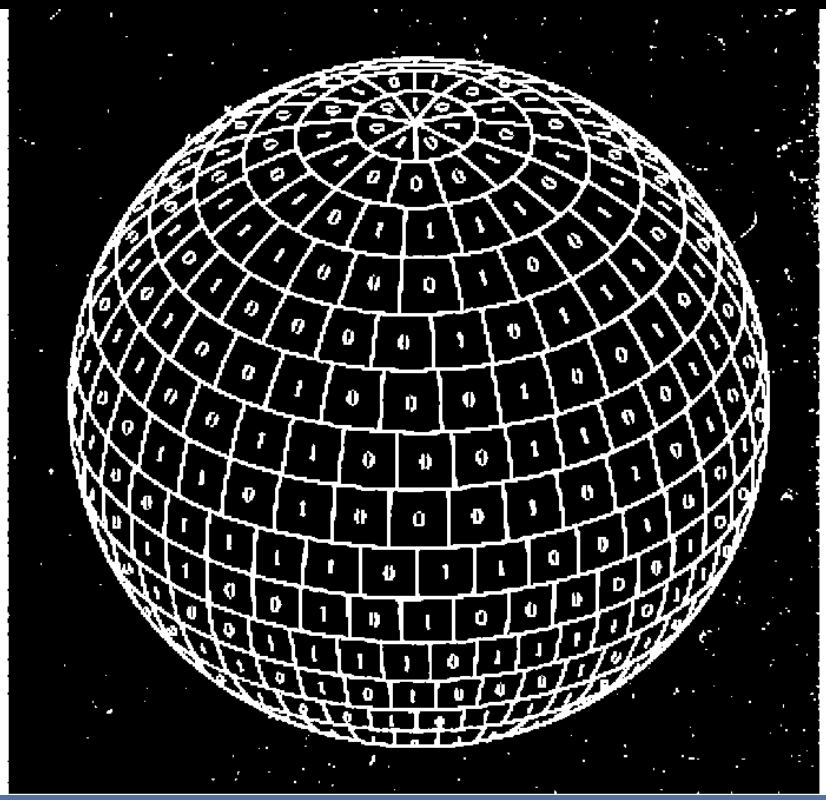
- Why does it work?
- What is the meaning of the temperature?
- What is the nature of this information?
- Why is it stored on screens? Can this be derived?
- Why is gravity attractive?
- What about the other forces?
- Are there observable consequences?

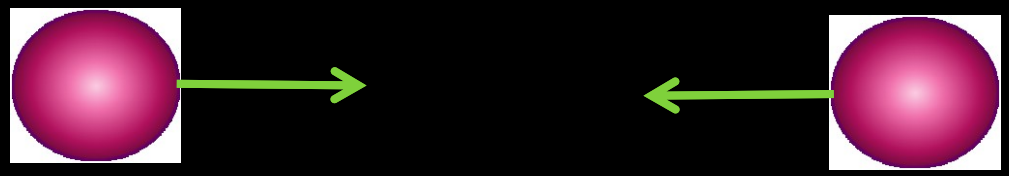
Holographic screens at equipotential (= equal redshift) surfaces

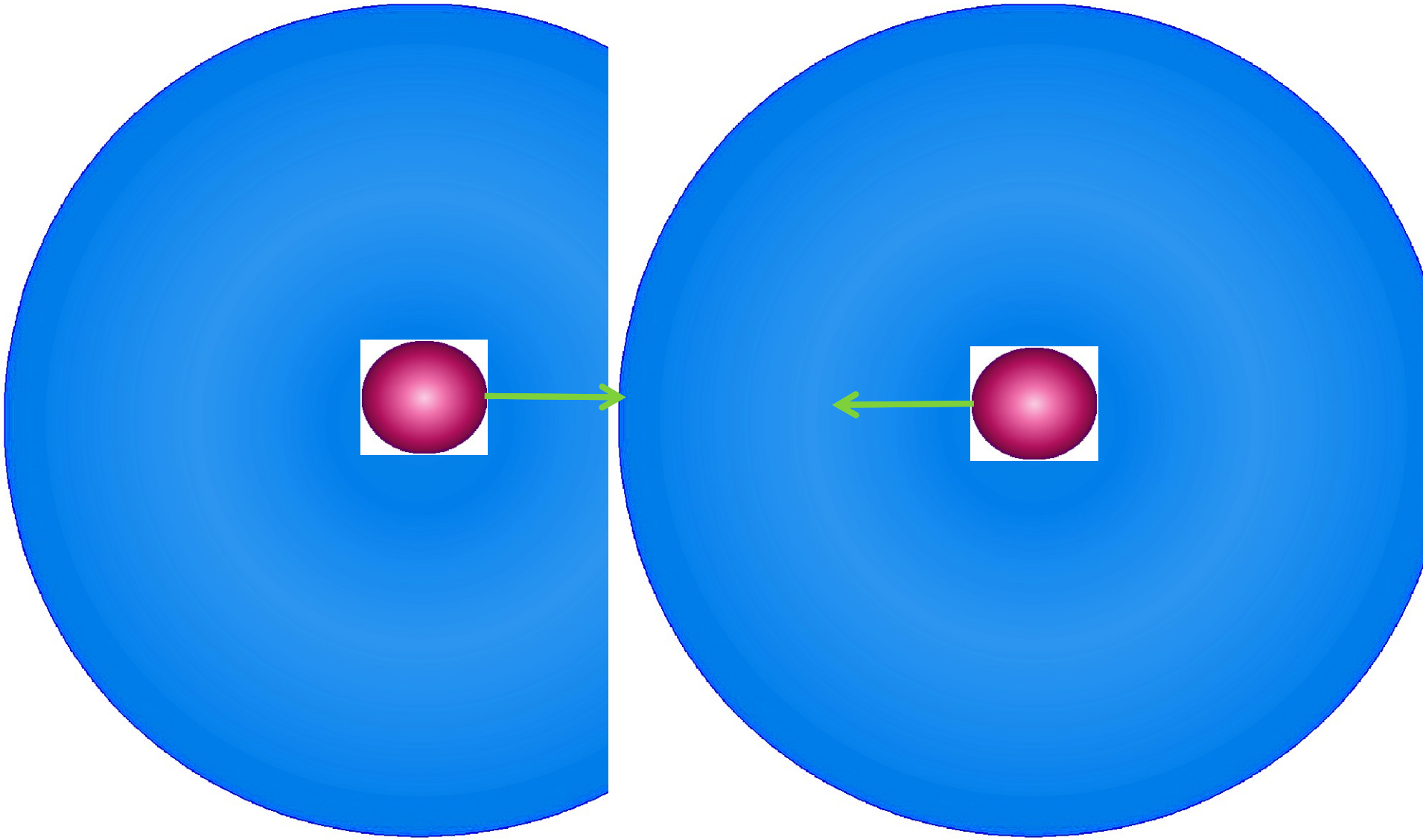




The phase space can b
described by counting
ways in which the ener
can be distributed over
cells on the boundary







Adiabatic principle:

When a fast dynamical system is driven by a slow system the fast reacts back on the slow and creates a reaction force.

When the time scales are widely separated the force is determined by the principle that the phase space volume is preserved.

In quantum mechanics this is a consequence of the Born-Oppenheimer approximation.

rn-Oppenheimer & Entropic Force

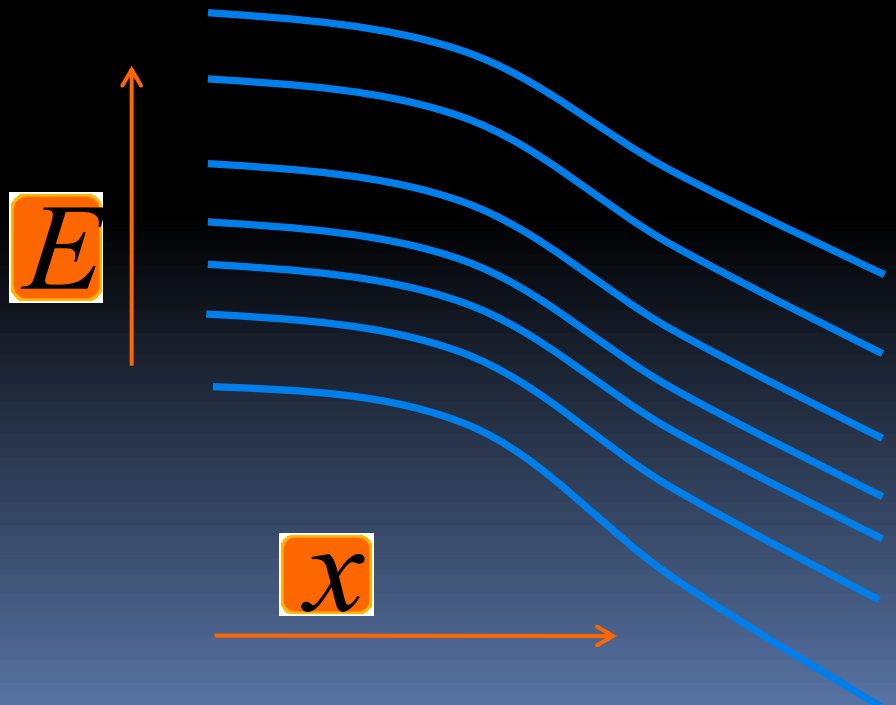
Microscopic
Fast Variables

$H(p,q;x)$

The system stays in an energy eigenstate of the fast variables(**adiabatic theorem).**

x

Macroscopic
Slow Variables

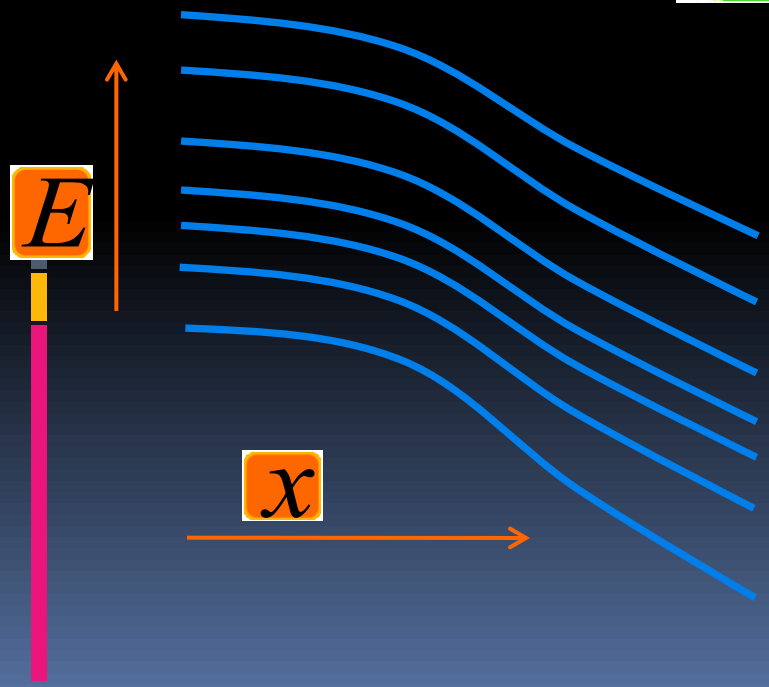


Adiabatic Reaction Force

Assuming eigenvalues don't cross, the force follows from an adiabatic argument

$$\Omega(E,x) = \int d^N p\, d^N q \,\Big|_{H(p,q;x) \le E}$$

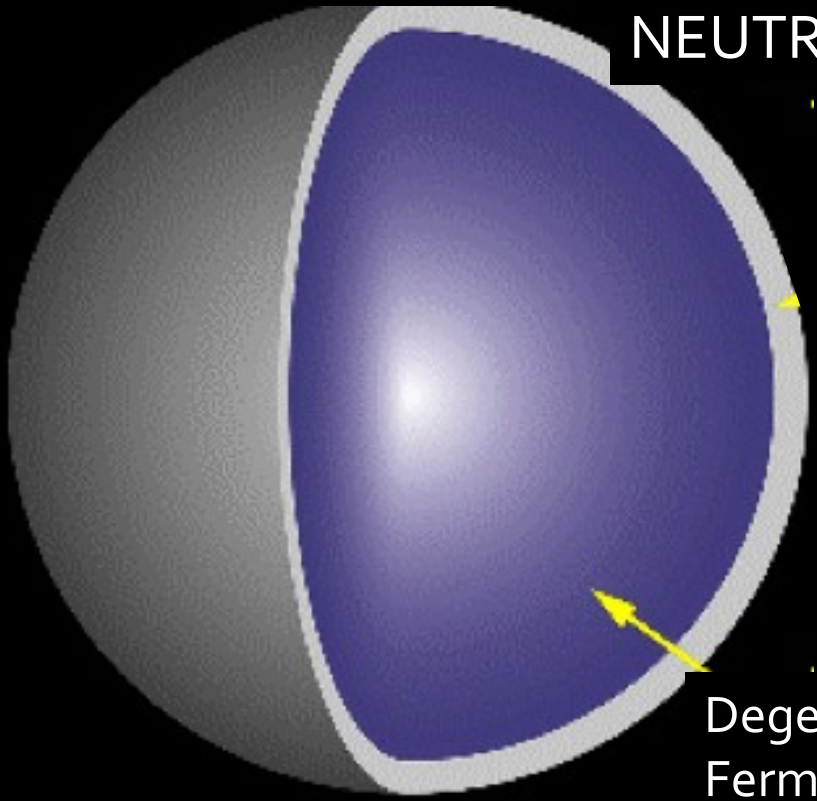
$$S(E,x) = k_B \log \Omega(E,x) = \text{const}$$



$$F = -\left(\frac{\partial E}{\partial x}\right)_S = T\left(\frac{\partial S}{\partial x}\right)_E$$

$$\frac{1}{k_B T} = \left(\frac{\partial S}{\partial E}\right)_x$$

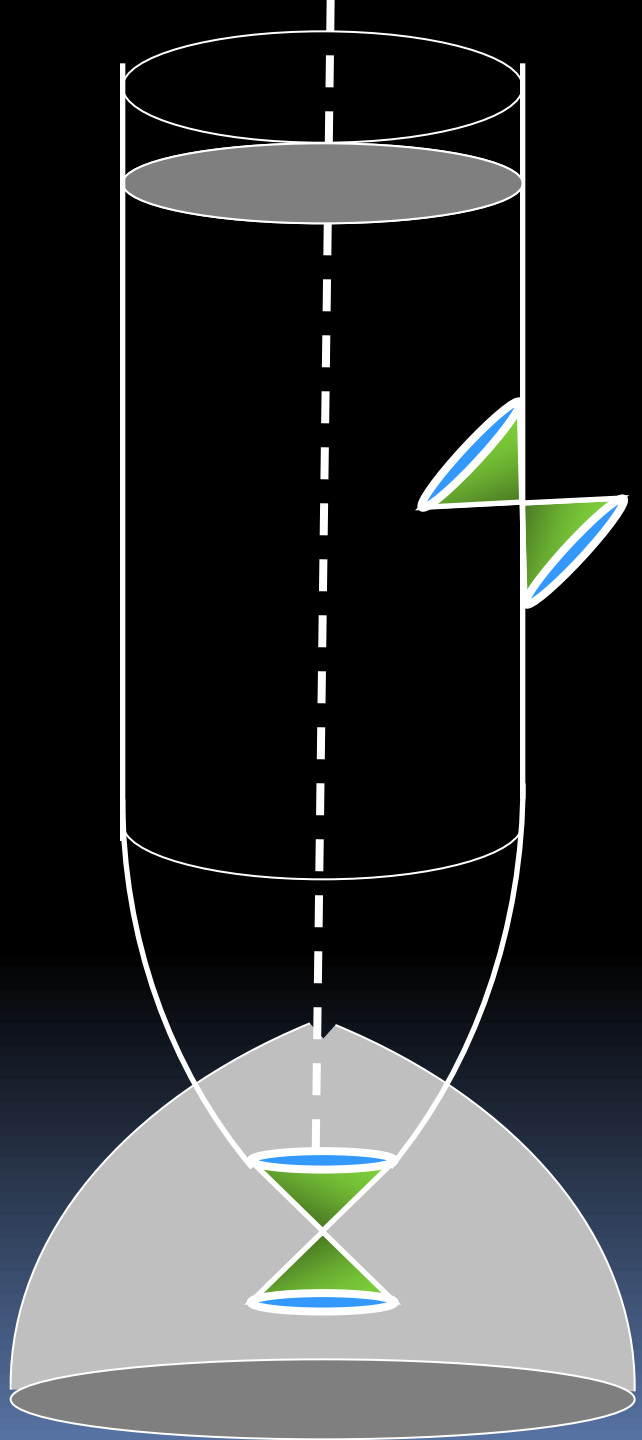
NEUTRON STAR



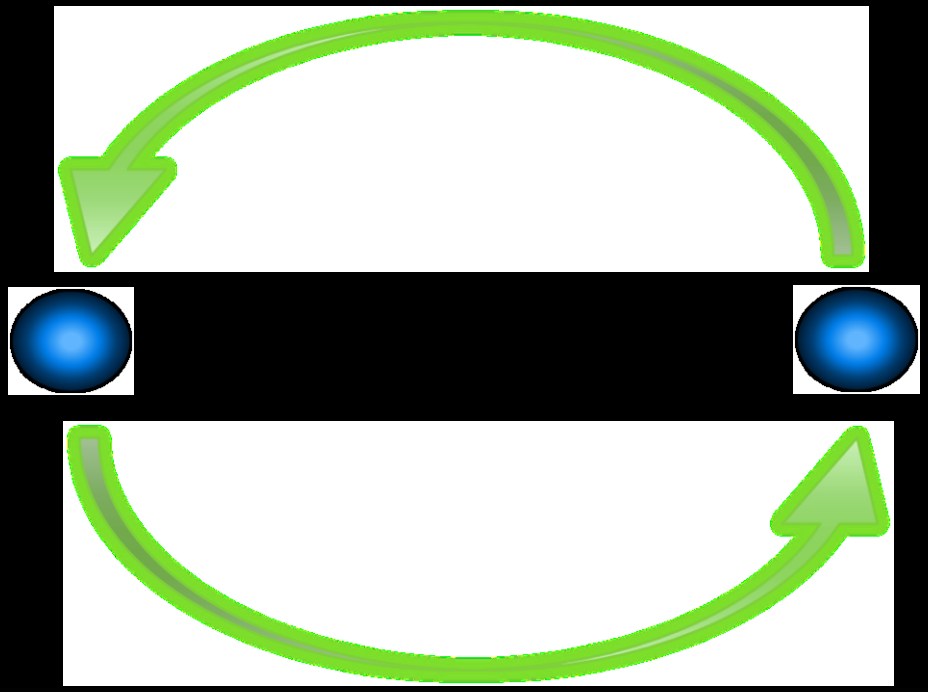
Degenerate
Fermions

GRAVITATIONAL COLLAPSE:

What happens to the phase space occupied by the fermions? What about the fermi statistics?

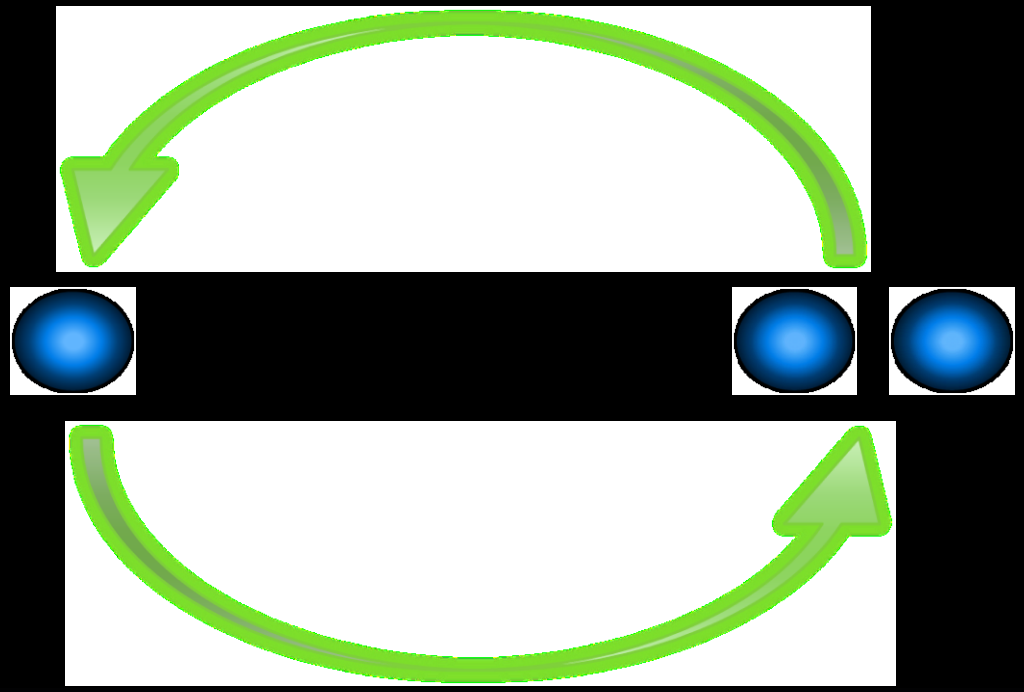


Statistics operation: discrete



$$|\Psi\rangle_{\text{particle 1}} \Leftrightarrow |\Psi\rangle_{\text{particle 2}}$$

Statistics operation: why not continuous?

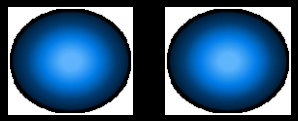


$$|\Psi\rangle_{\text{particle 1}} \not\rightarrow \alpha\,|\Psi\rangle_{\text{particle 1}} + \beta\,|\Psi\rangle_{\text{particle 2}}$$

Positions get ambiguous

$$\langle \Psi |_1 \hat{x} | \Psi \rangle_2 \neq 0$$

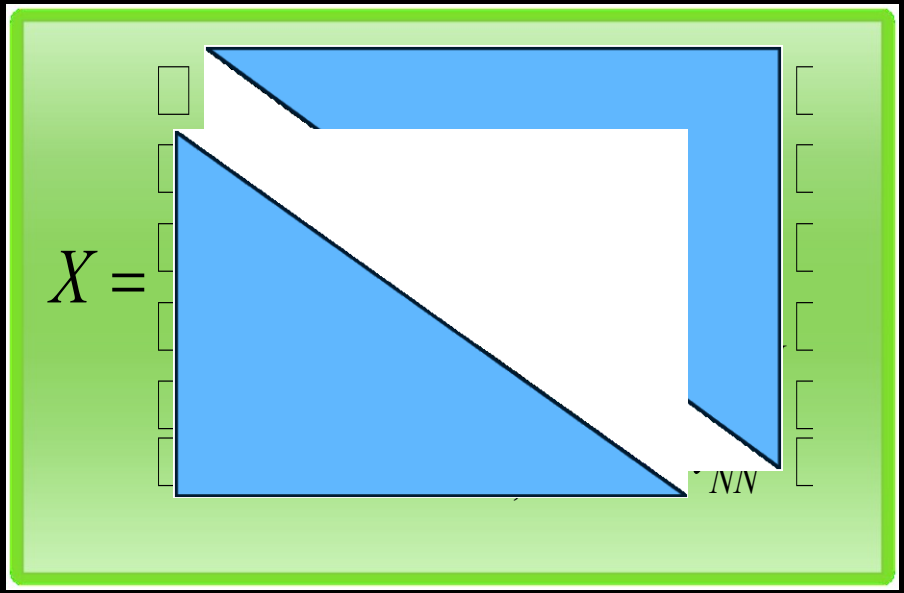
$$x_1, x_2 \neq \begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{bmatrix}$$

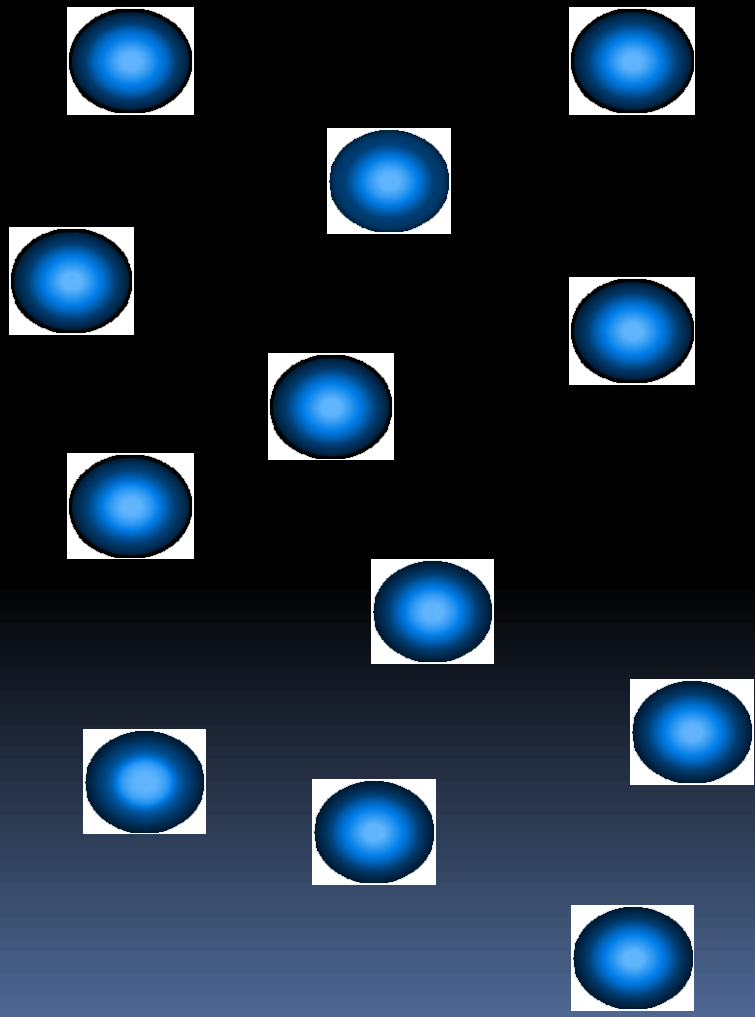


$$x_{ij} = \langle \Psi |_i \hat{x} | \Psi \rangle_j$$

Coordinates turn into matrices

At horizons space and time dissappear.





At horizons the separation of time scales between the eigenvalues and the “off diagonal modes” breaks down and the coordinates become non commuting matrices.

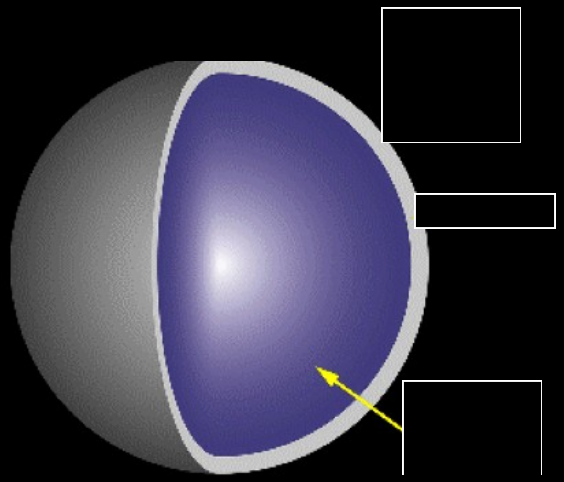
GRAVITATIONAL COLLAPSE:

What happens to the phase space occupied by the fermions?

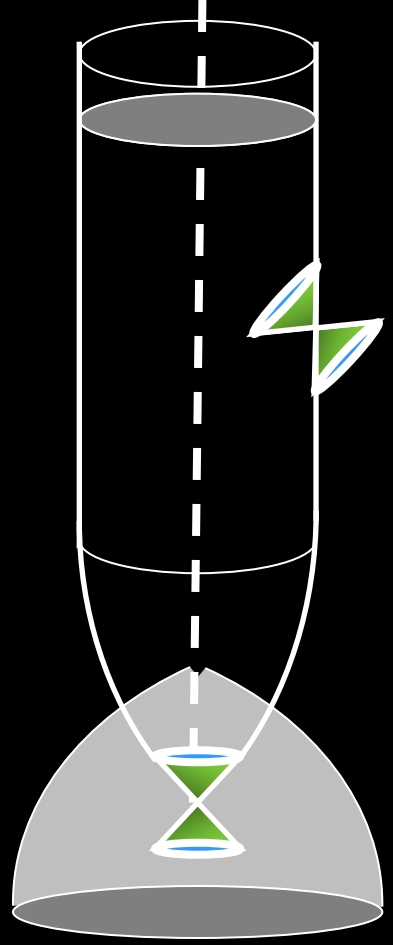
Answer: It goes into the off diagonal phase phase. Not of gravity!

After collapse one can no longer integrate out the off diagonal modes!!

Eigenvalues and off diagonal modes equilibrate and together form “black hole stuff”.



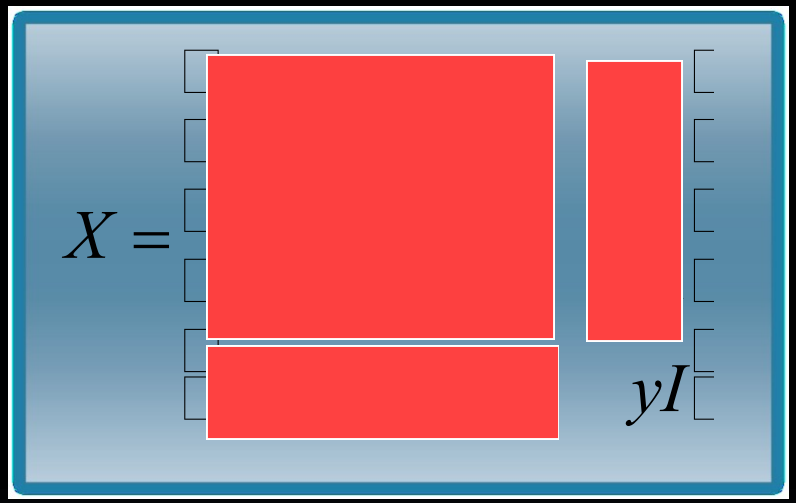
Degenerate Fermions

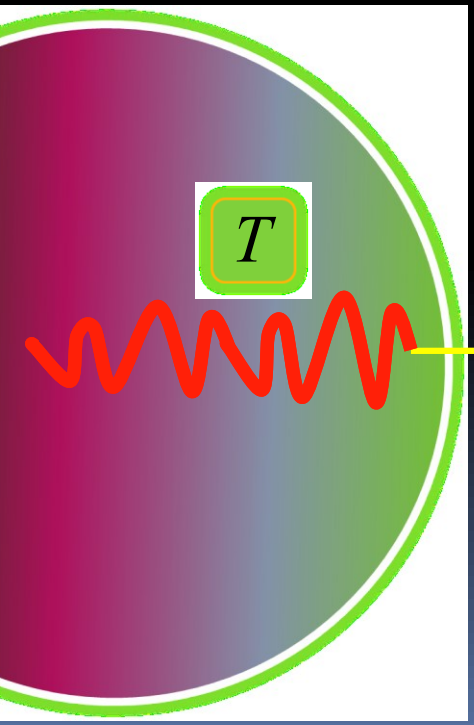


$$X = \begin{bmatrix} & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \end{bmatrix}$$

Black Hole Horizon

Thought experiment



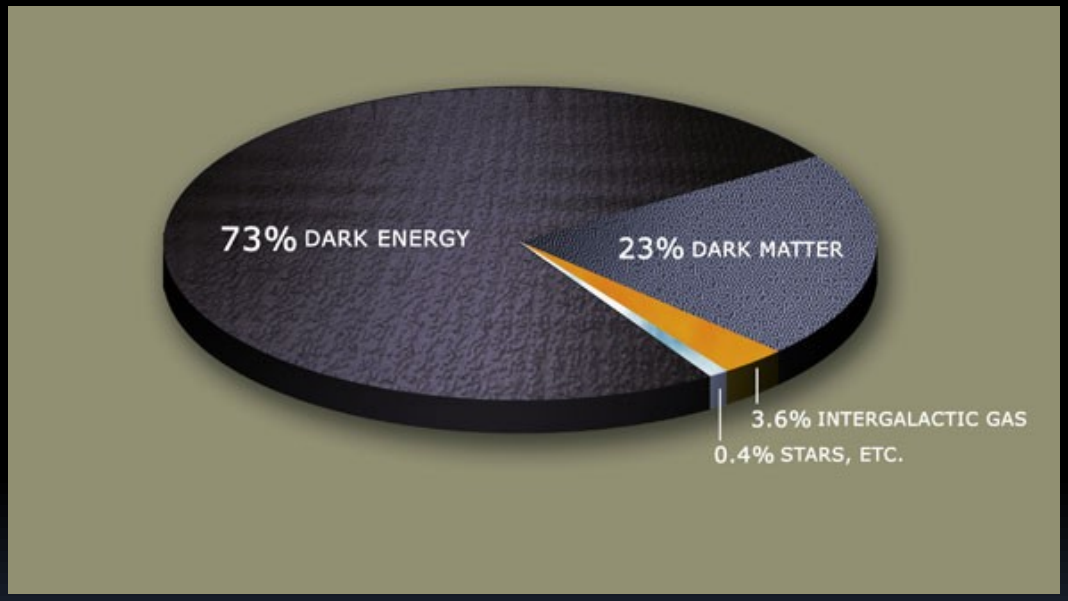


$$F = T\frac{\Delta S}{\Delta x}$$

Entropic force

Why do we need to reconsider the origin of gravity and change our current paradigms?

96% of our Universe is not understood!



What went wrong?

Our current paradigms ignore a lot of information (phase space).

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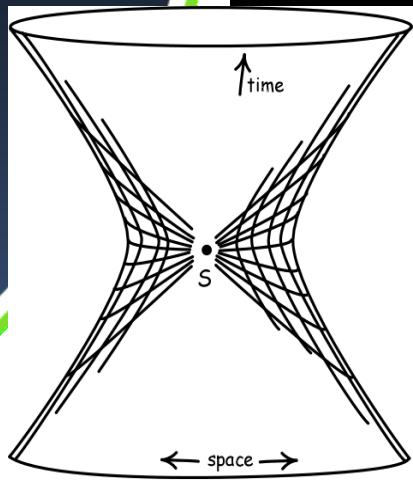
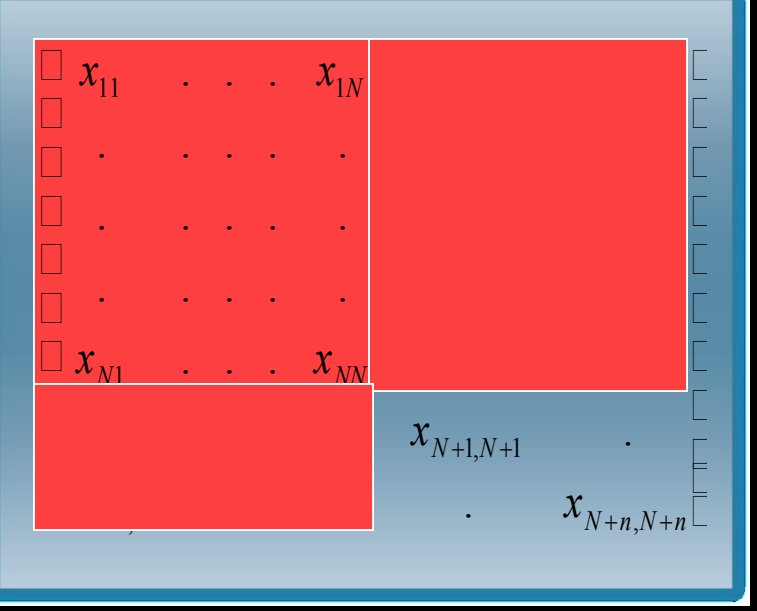
Cosm ter
Hori

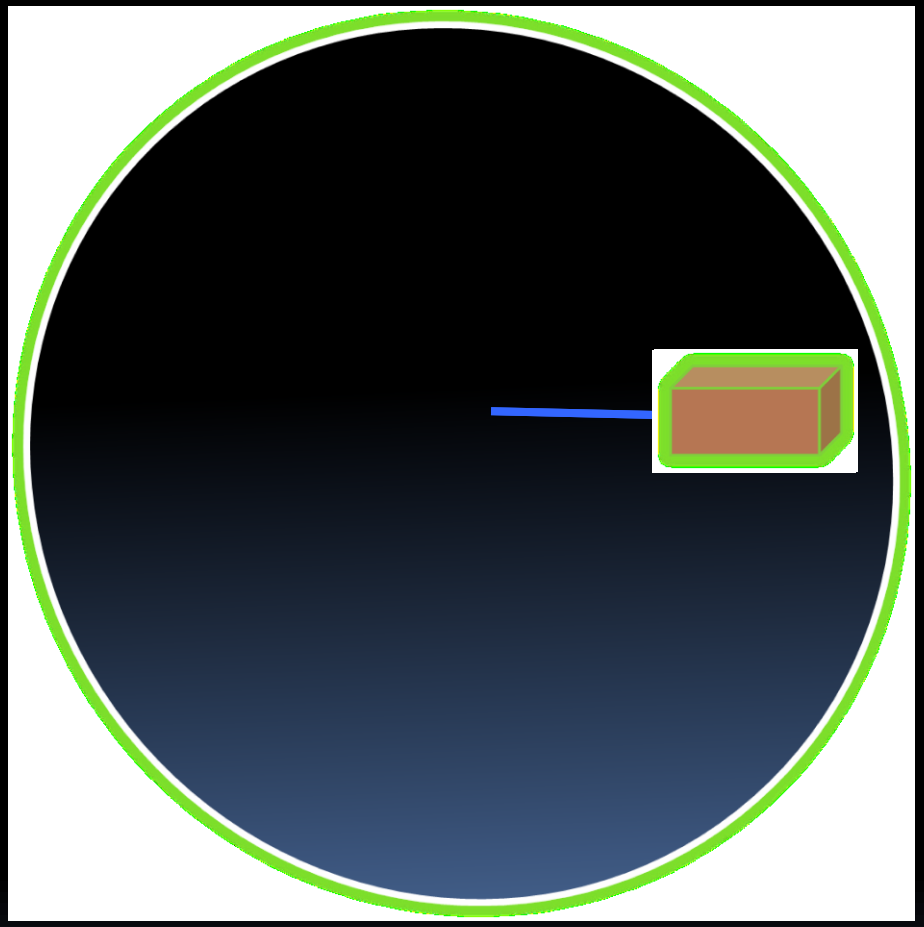
$$kT = \frac{\hbar H_0}{2\pi}$$

m

$$H_0^2 = c^2 \Lambda$$







These ideas can be applied to our universe

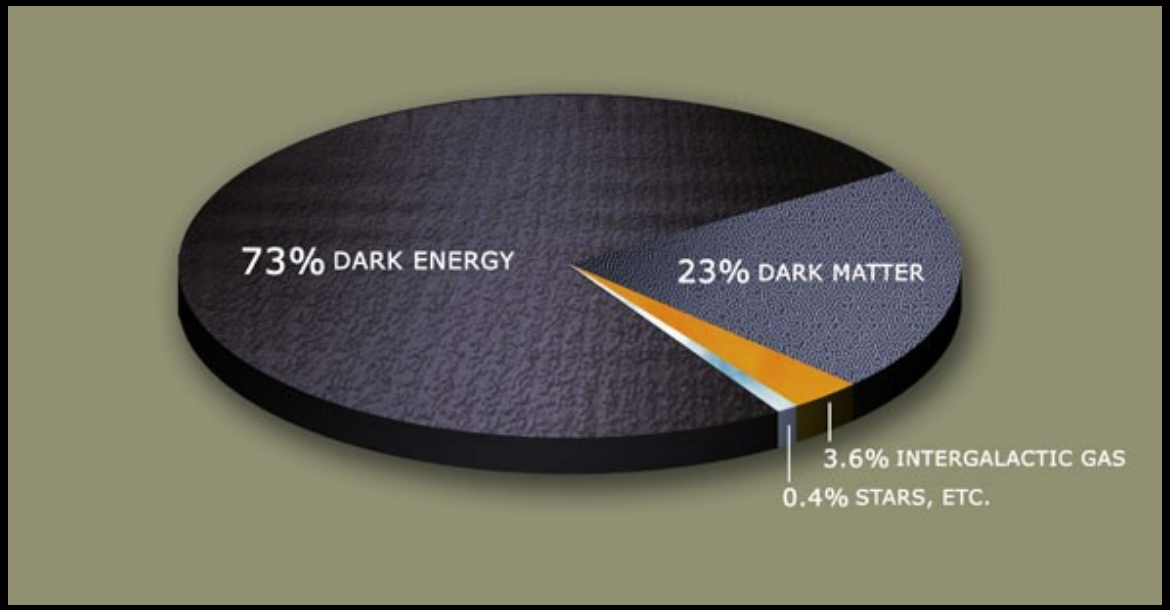
$$kT = \frac{\hbar H_0}{2\pi}$$

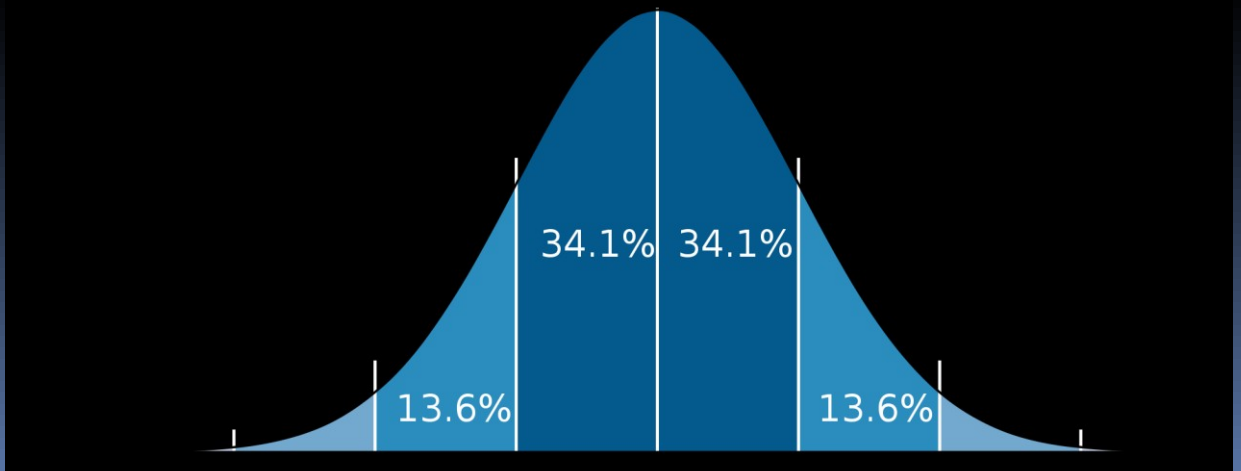
$$S = \frac{c^2 H_0 V}{4G\hbar}$$

Dark energy and matter are made of the same stuff

At horizons space and time dissappear.

Dark Energy and Dark Matter

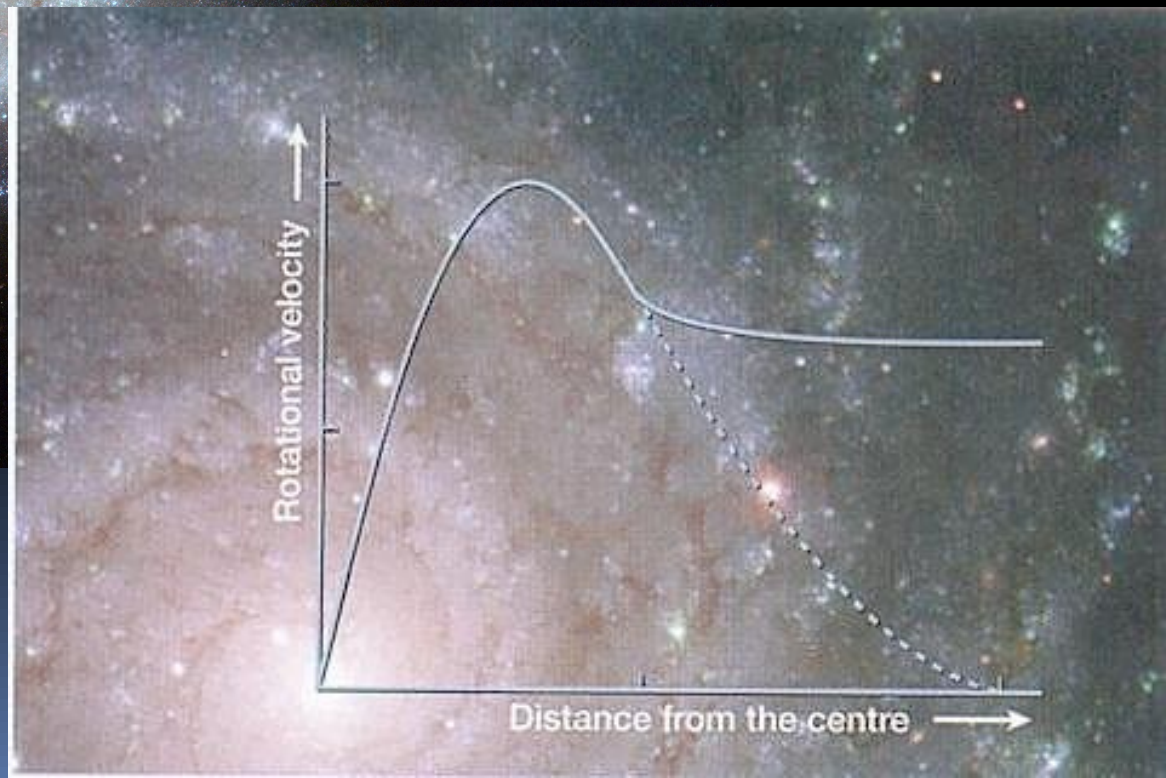




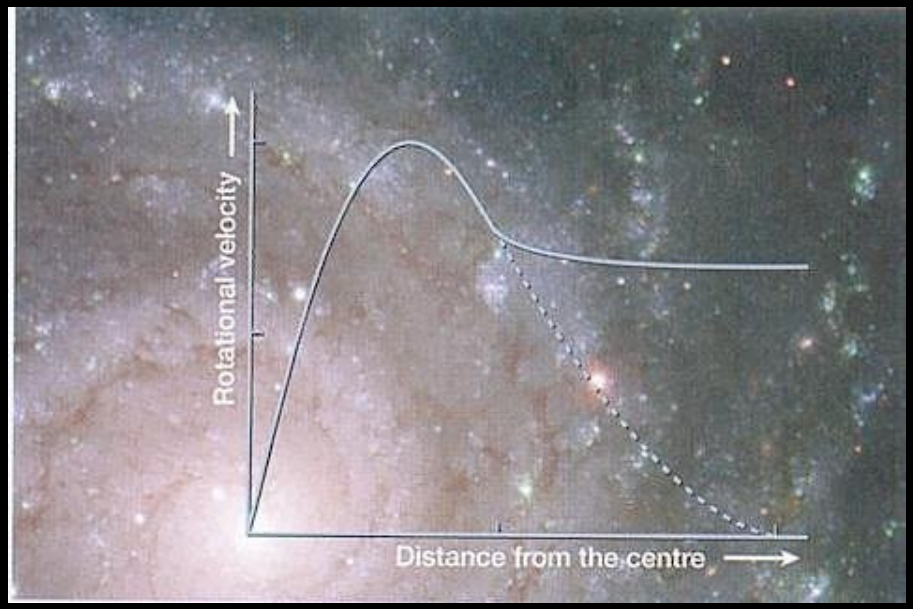
Clusters

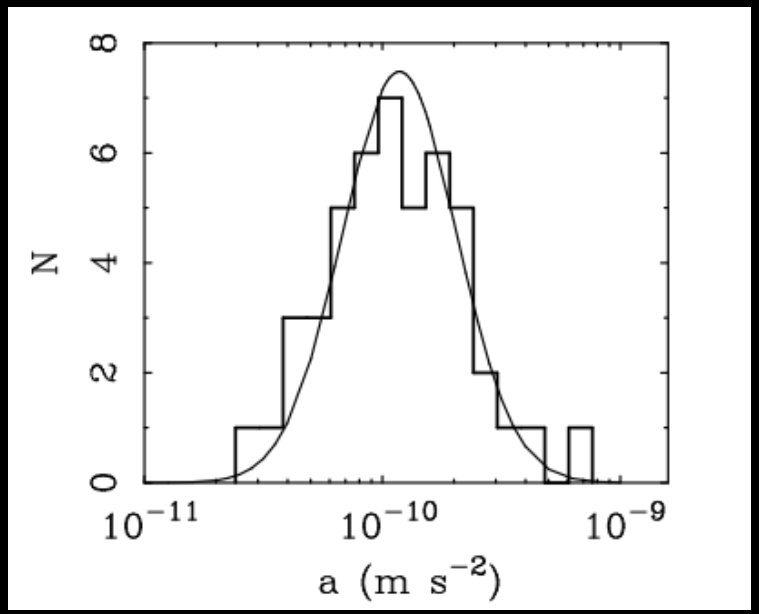
Galaxies

Flattening of rotation curves



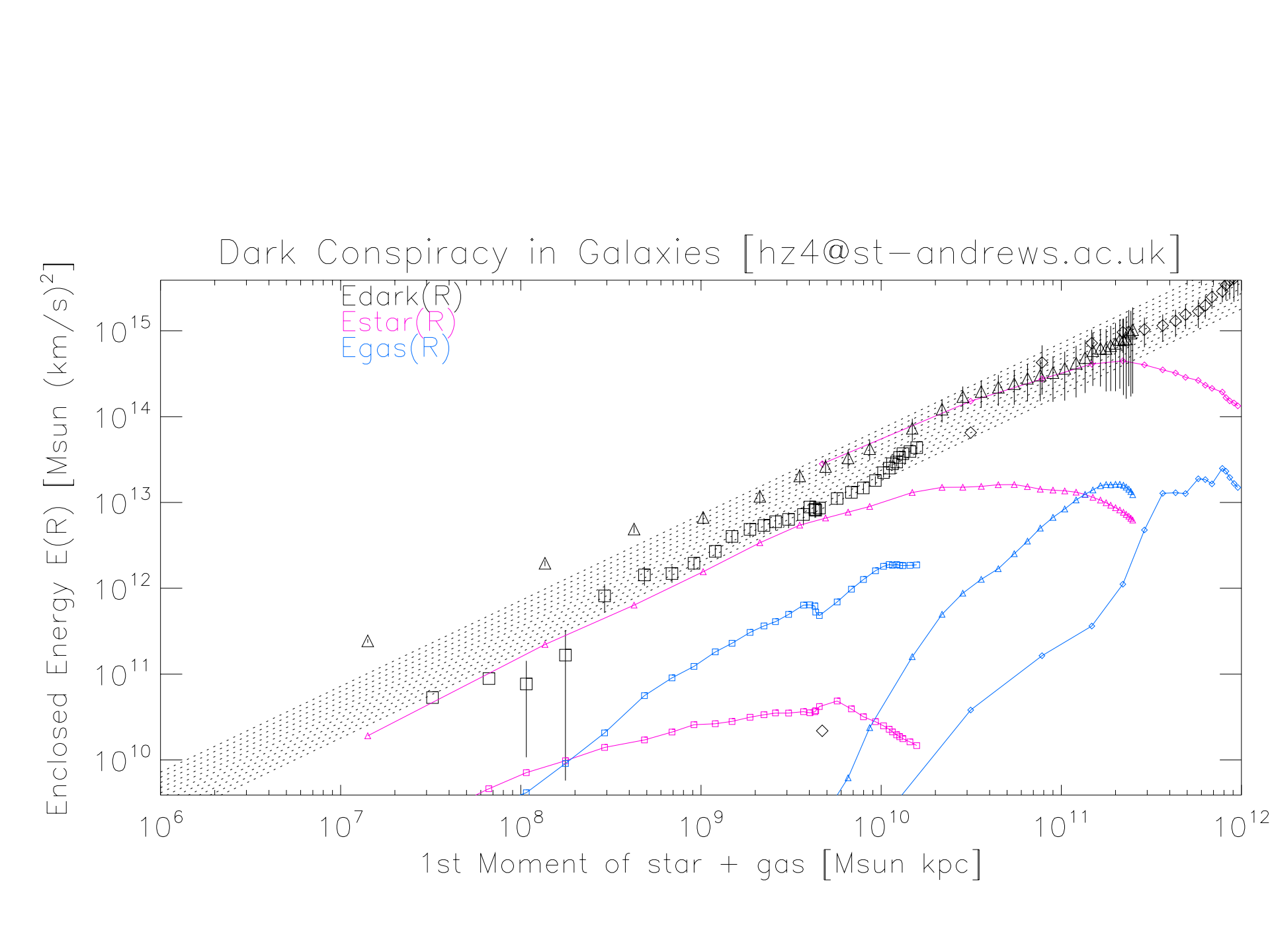
Flattening of rotation curves





$$V^4 = GM_B a_0$$

$a_0 = 1.24 \pm 0.14 \times 10^{-10}\ m/s^2$


Dark Conspiracy in Galaxies [hz4@st-andrews.ac.uk]
Edark(R)
Estar(R)
Egas(R)
Enclosed Energy E(R) [Msun (km/s)^2]
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
1st Moment of star + gas [Msun kpc]