ICHEP conference, Paris , 22/07/10

GRAVITY AS AN EMERGENT FORCE

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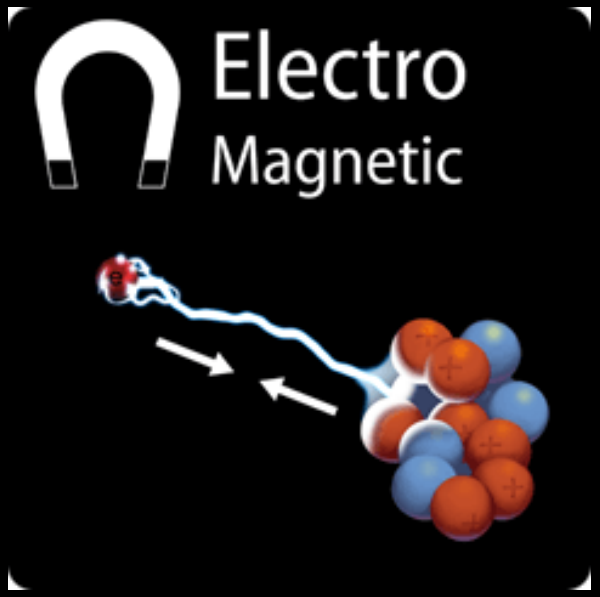
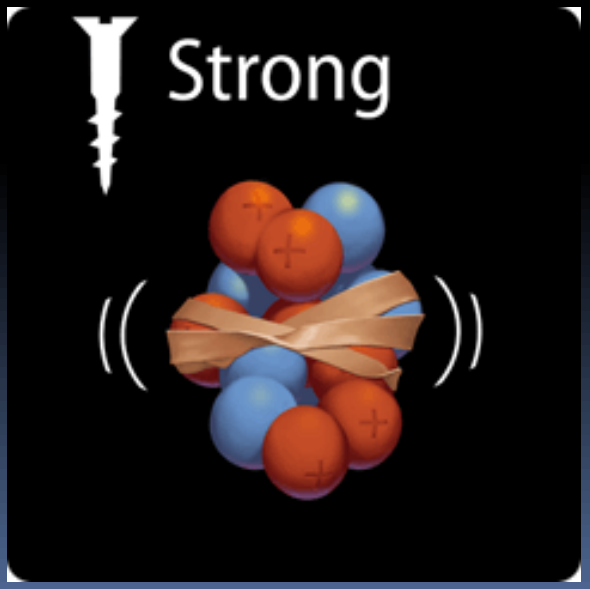
University of Amsterdam

Emergence

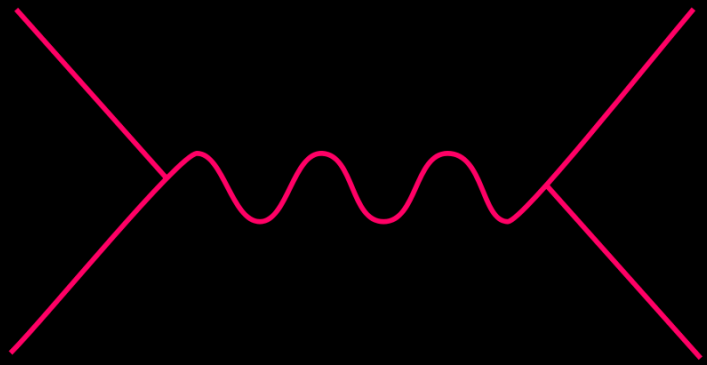

Electro
Magnetic


Gravity

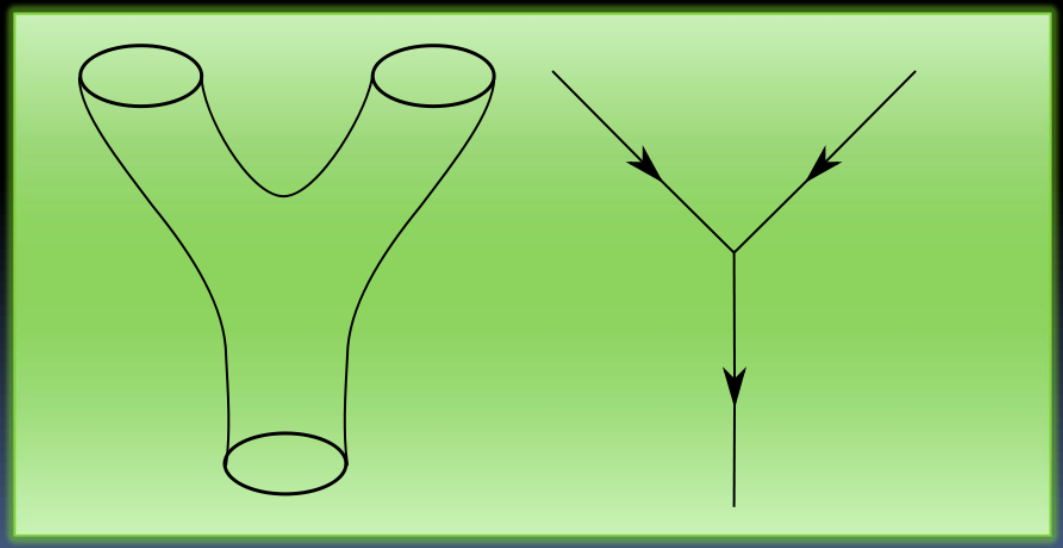

Weak


Strong

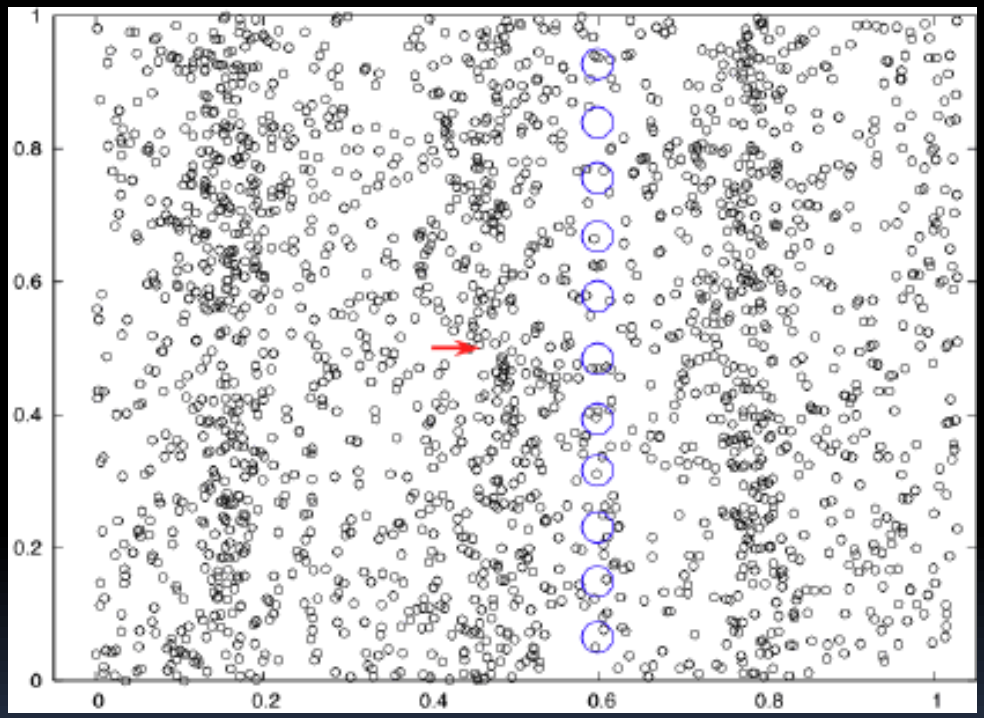
Current Paradigm

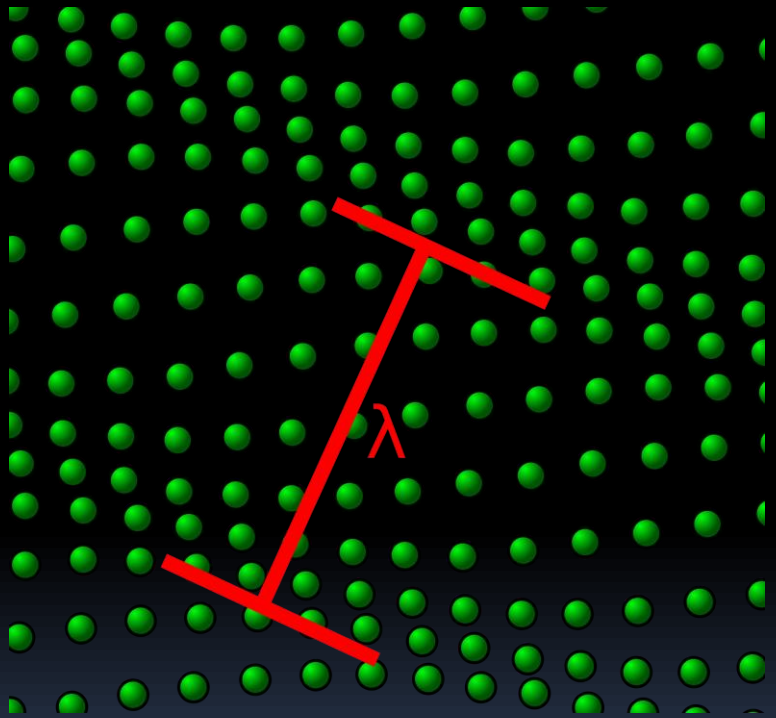


FUNDAMENTAL FORCES: carried by elementary particles



Emergence of Particles and Forces



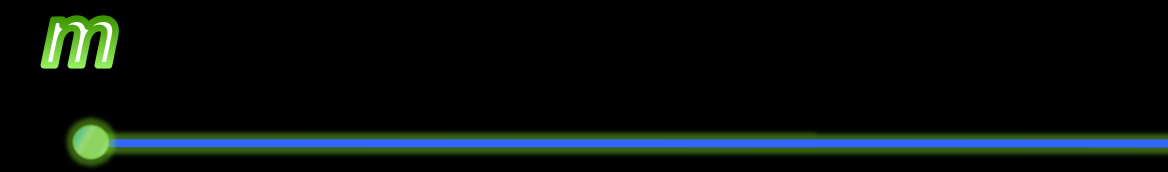


Gravity as an Emergent Force

- At a microscopic scale Nature is described by many degrees of freedom, most of which are invisible and at first sight irrelevant for the observed macroscopic physics.

- Gravity arises due to the fact that the amount of phase space volume ("information") occupied by these microscopic degrees of freedom is influenced by the observable macroscopic variables, like the positions of material objects.

Black Hole Horizon



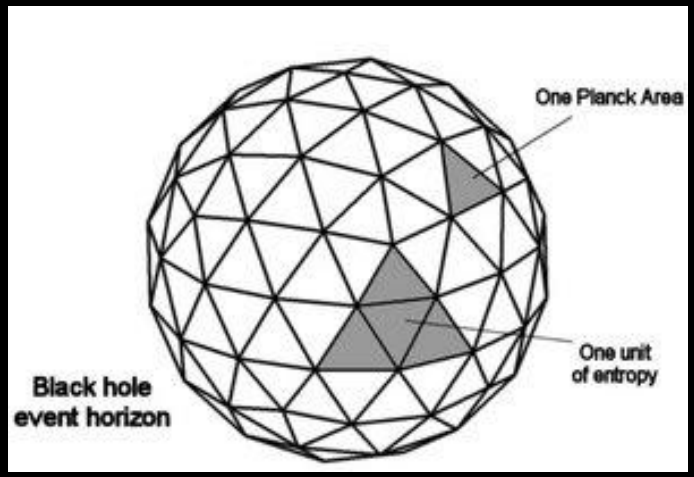
- **Black hole thought experiments.**

Consider a particle gradually lowered in to a black hole.

Classically, the energy associated with the particle gets redshifted, and vanishes when the particle is at the horizon.

Penrose
Christodoulou
Bekenstein
Hawking

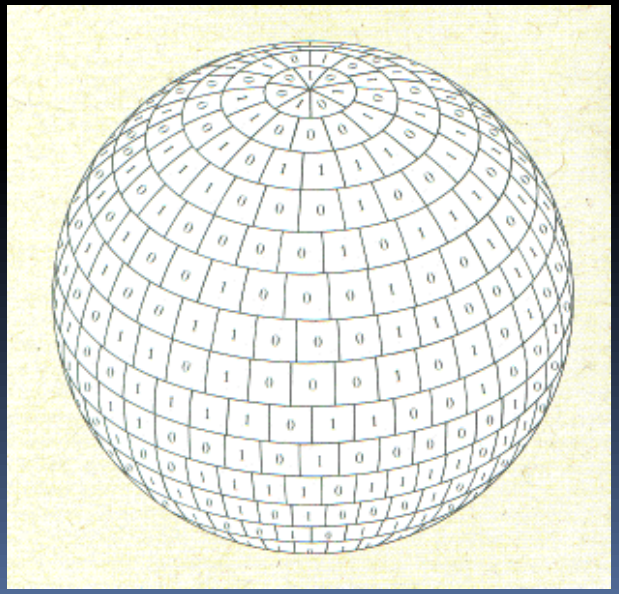
Black Hole Entropy



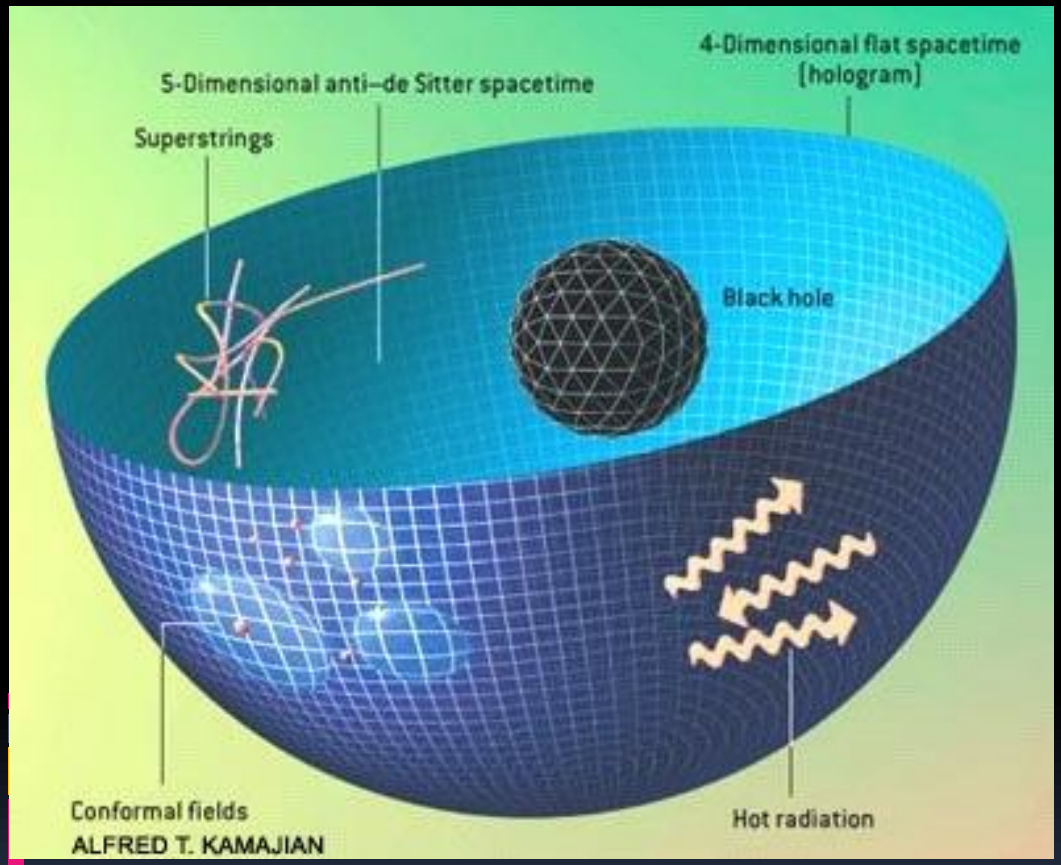
$$S_{BH} = k_B \frac{Ac^3}{4Gh}$$

=> Holographic Principle

Maximal information associated with a part of space can be encoded in a # of bits equal to the area in Planck units



ADS/CFT CORRESPONDENCE



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

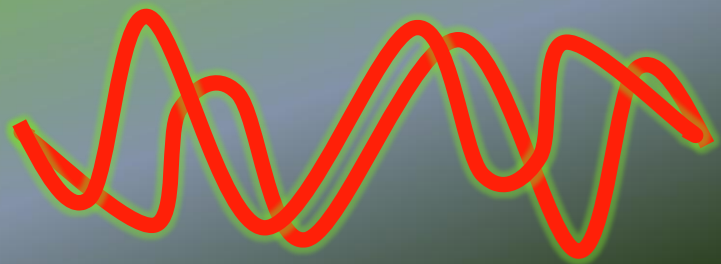
ONE SPACE DIMENSION EMERGES CORRESPONDING TO THE "SCALE" OF THE BOUNDARY THEORY. RADIAL EVOLUTION IS LIKE RENORMALIZATION GROUP FLOW.

Black Hole In AdS space

Bulk description

Particle gets lowered in to black hole

Hot CFT



Thermal Heat Bath

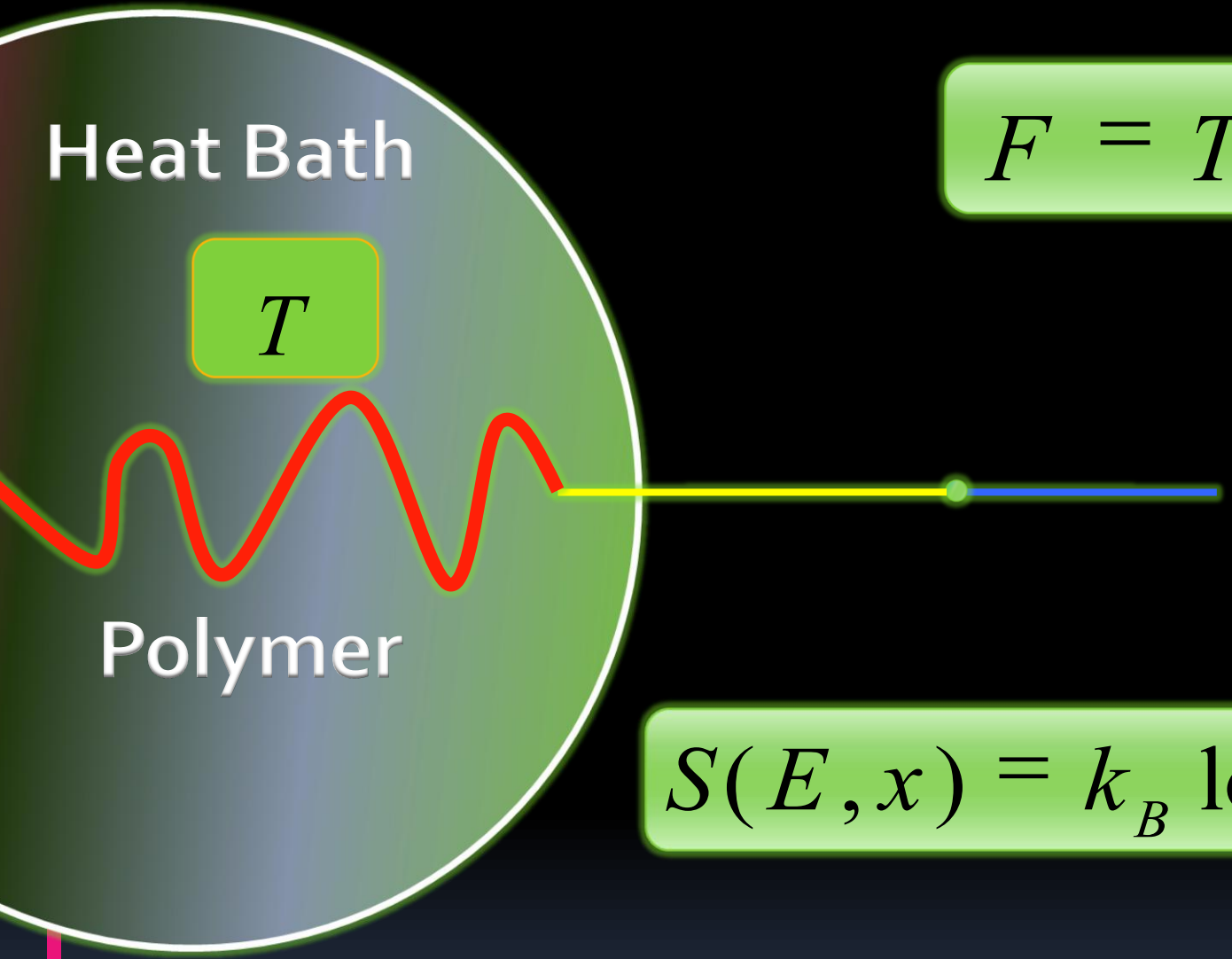
T

Boundary description:

Delocalized state gets thermalized by heath bath

Entropic force (wikipedia)

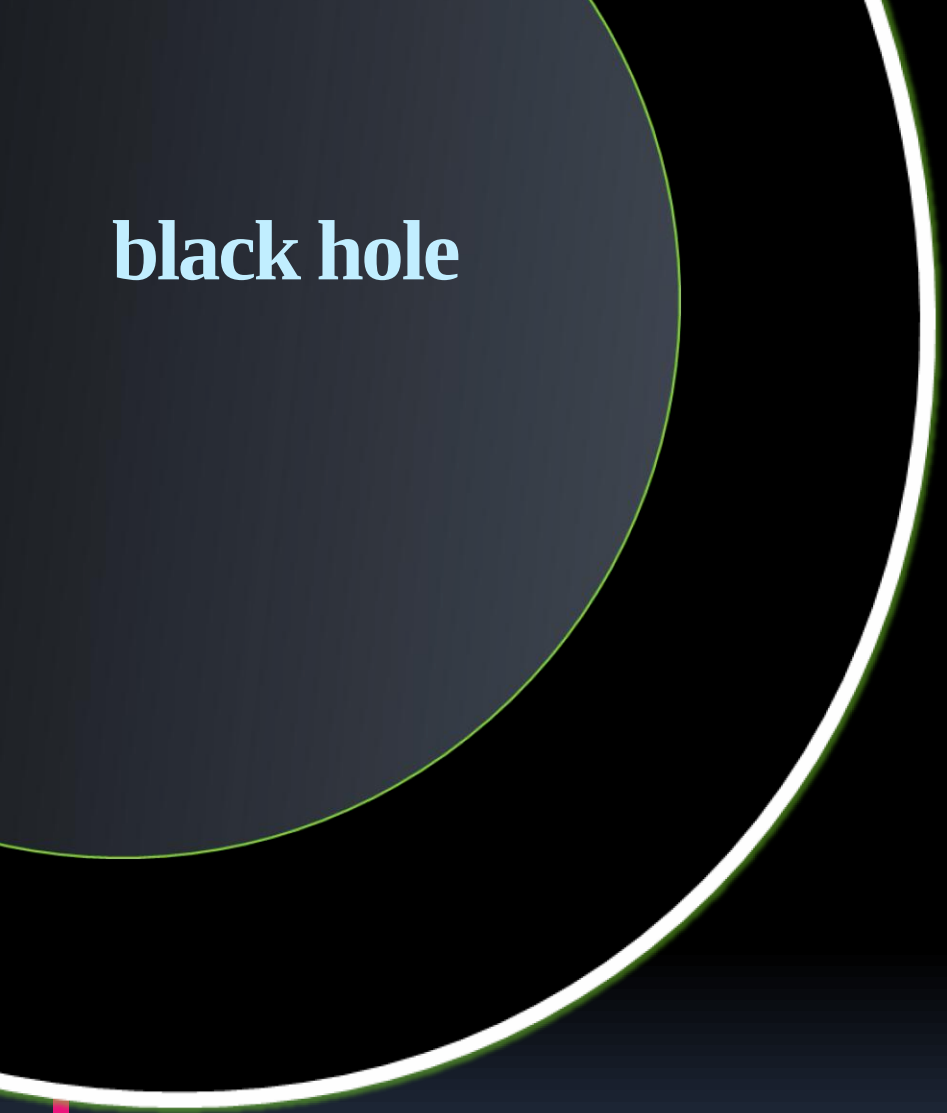
An entropic force is a macroscopic force whose properties are determined not by the character of an underlying microscopic force, but by the whole system's statistical tendency to increase its entropy.



$$F = T \nabla_x S$$

Entropic Force

$$S(E,x) = k_B \log \Omega(E,x)$$



- Thought experiment

m

$$dx = \frac{dr}{\sqrt{1 - 2GM/r}}$$

$$E = m\sqrt{1 - 2GM/r}$$

$$F = \frac{dE}{dx} = \frac{GMm}{r^2}$$

“stretched horizon”

- **Consistency with black hole thermodynamics implies**

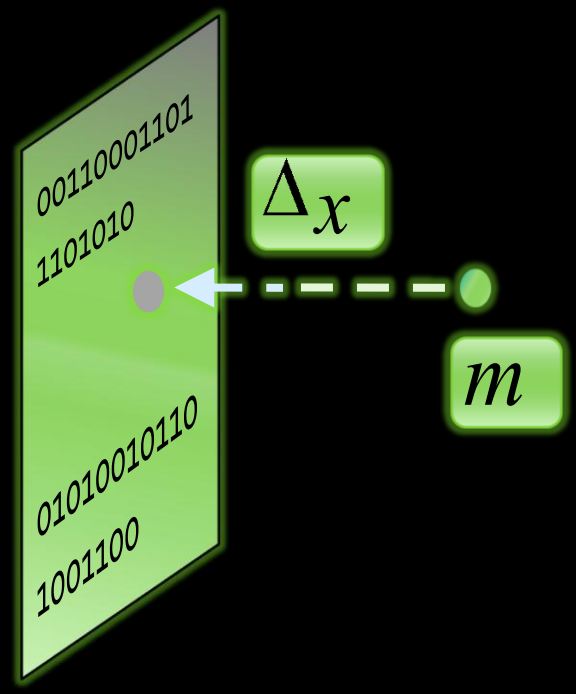
$$F\Delta x = T_H \Delta S_{BH}$$

$$T_H = \frac{g}{2\pi}$$

$$\Delta S_{BH} = 2\pi m \Delta x$$

A HEURISTIC DERIVATION

OF GRAVITY

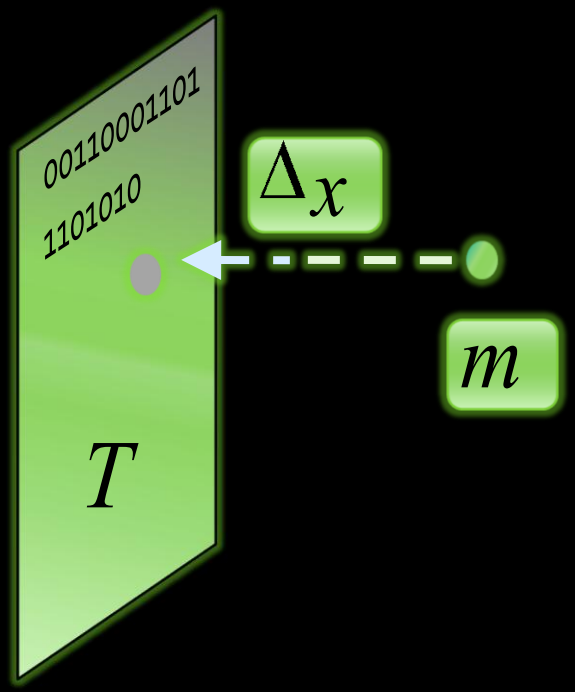


information is stored on holographic screens
moving a particle over one Compton wavelength
leads to one more bit of information

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

$$\Delta x = \frac{\mathrm{h}}{mc}$$

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

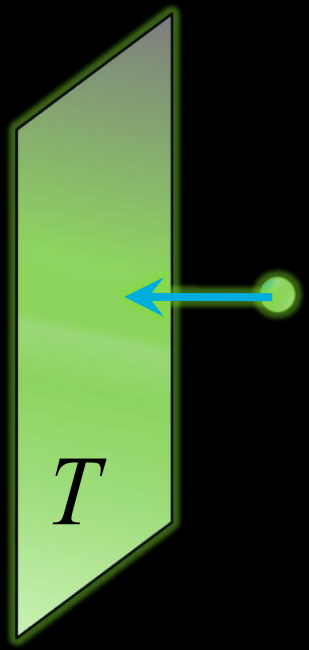


To get a force one needs a temperature.
By taking that temperature to be the Unruh temperature one finds Newton's law of inertia

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

$$F = ma$$

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



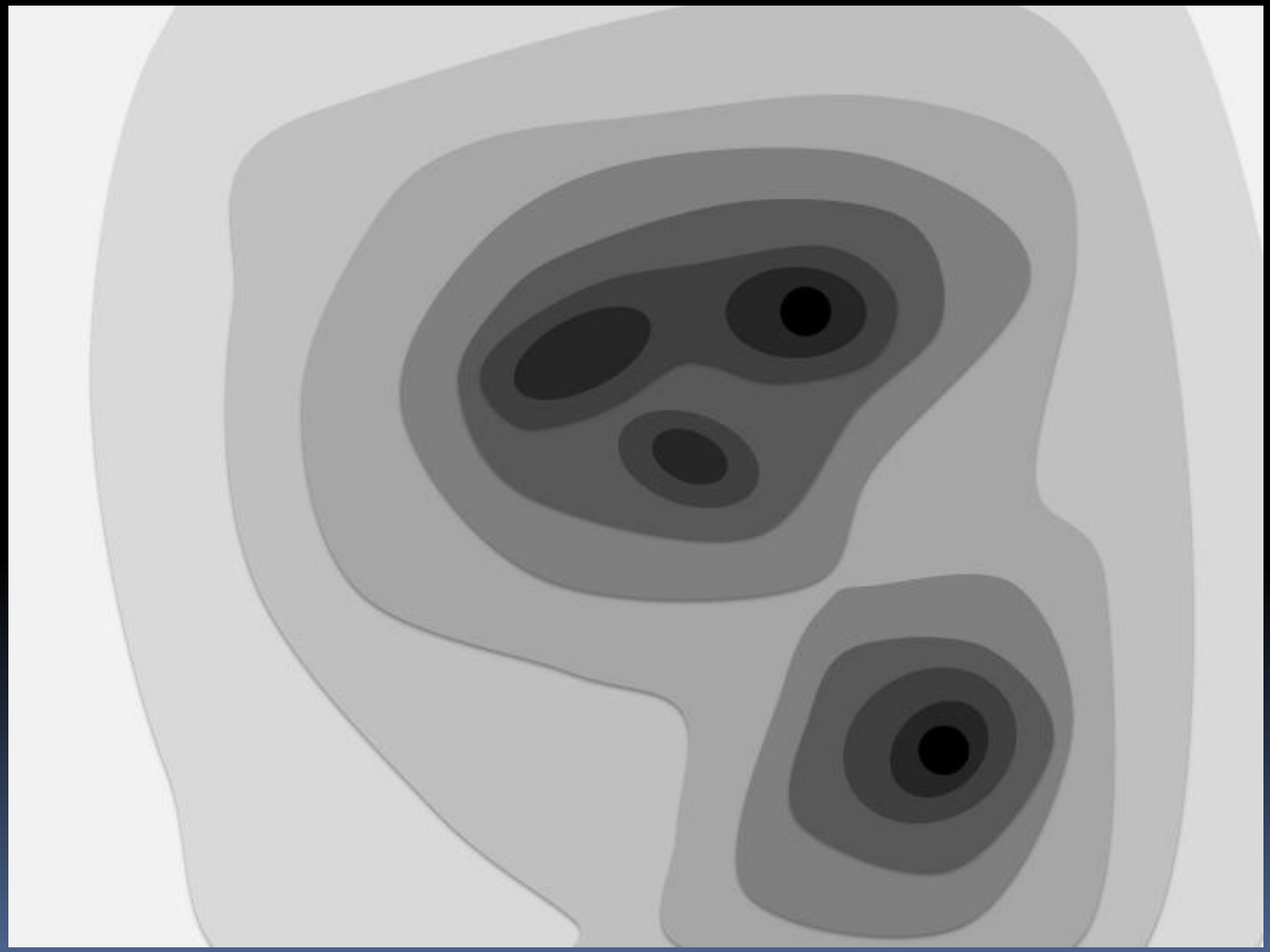
In order to get an entropic force I need a temperature

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

$$E = Mc^2$$

$$\# bits = \frac{Ac^3}{G\hbar}$$

Holographic screens at equipotential (= equal redshift) surfaces

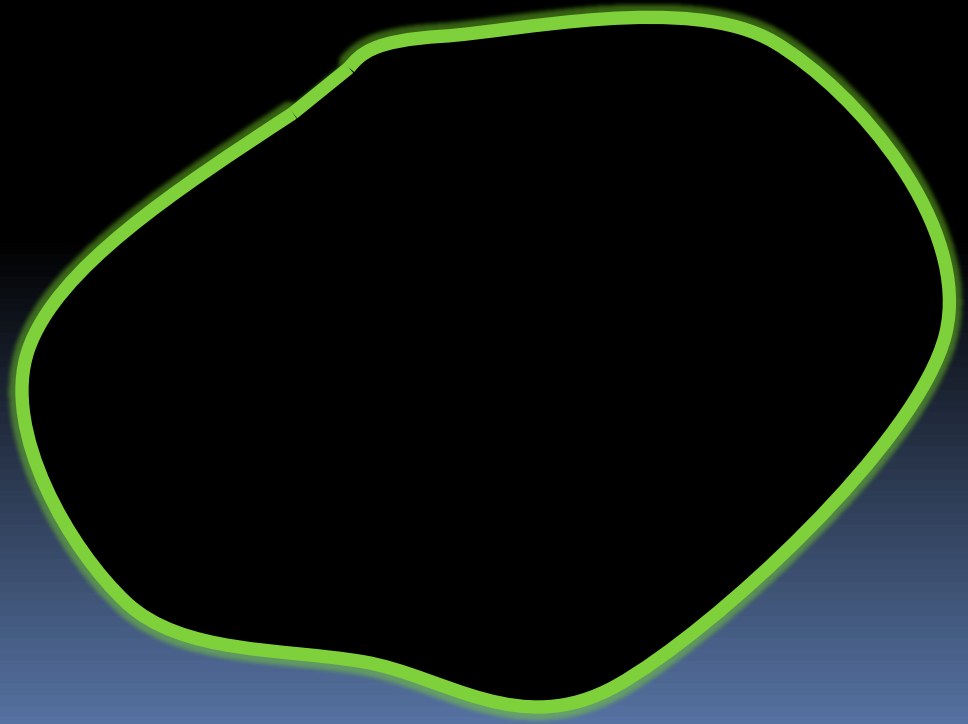


What about General Relativity?

$$\Phi = \log \xi^a \xi_a$$

ξ^a = timelike Killing vector

Surface of constant redshift



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

$$dn = \frac{c^3}{G\hbar} dA$$

$$\int \nabla \Phi \, dA = 8\pi GM$$

Komar mass

=> Einstein equation

Rindler Horizon

$$F = T\nabla_x S = ma$$

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

$$\frac{\hbar}{2\pi k_B}\nabla_x S = mc$$

Suggestive link with QM:

$$c \to v$$

What is this velocity v ?

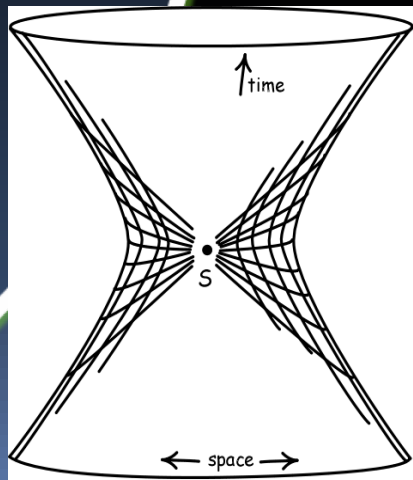
Cosmological Horizon

De Sitter Space

$$T = \frac{\mathrm{h}}{2\pi k_B}\frac{a_0}{c}$$

m

$$a_0 = c^2\sqrt{\Lambda}$$



Cosmological Horizon

$$T = \frac{\mathrm{h}}{2\pi k_B} \frac{\sqrt{a^2 + a_0^2}}{c}$$

m

Cosmological Horizon

$$T = \frac{\mathrm{h}}{2\pi k_B} \frac{\sqrt{a^2 + a_0^2}}{c}$$

$$\frac{\mathrm{h}}{2\pi k_B} \frac{dS}{dx} = mc \frac{a}{\sqrt{a^2 + a_0^2}}$$

Equipotential surface

$$\Phi = \frac{v^2}{2}$$

$$T = \frac{\mathrm{h}}{2\pi k_B}\frac{dv}{dx}$$

m

$$\frac{\mathrm{h}}{2\pi k_B}\nabla_x S = mv$$

v = escape velocity

Born-Oppenheimer & Adiabatic theorem

Schroedinger eqn with H depending on infinitely slow variable

$$i\frac{\partial}{\partial_t}\left|\psi(t)\right\rangle = H\left(x(t)\right)\left|\psi(t)\right\rangle$$

Instantaneous eigenstates

$$H\left(x\right)\left|\psi_n(x)\right\rangle = E_n(x)\left|\psi_n(x)\right\rangle$$

Adiabatic Reaction Force

$$F = \frac{dE_n}{dx}(x)$$

Semiclassically

$$F = \frac{dE}{dJ}\frac{dJ}{dx}$$

$$J = \oint pdq = 2\pi n\mathrm{h}$$

Born-Oppenheimer & Entropic Force

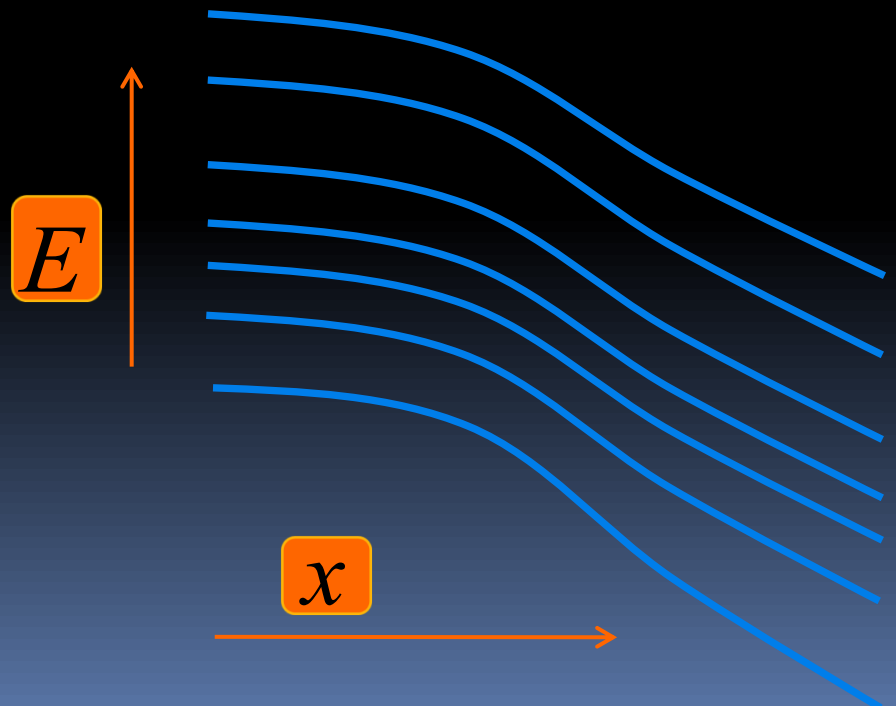
Microscopic
Fast Variables

ζ

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

x

Macroscopic
Slow Variables

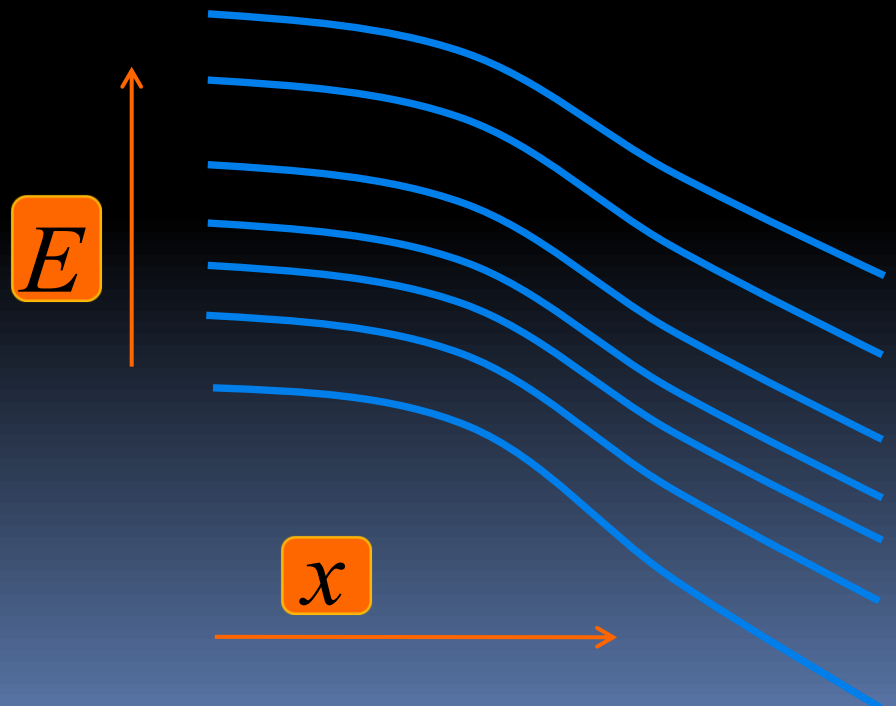


Born-Oppenheimer & Entropic Force

Assuming eigenvalues don't cross, the energy follows from

$$\Omega(E,x) = \int d\zeta\, \Theta\big(E - H(\zeta,x)\big)$$

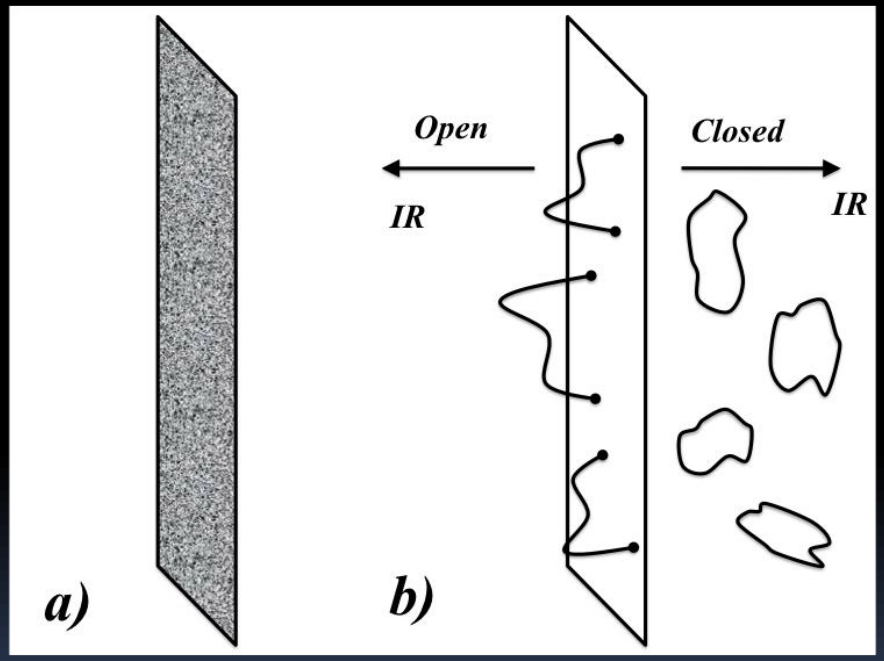
$$\frac{d}{dx}\log \Omega\big(E(x),x\big) = 0$$



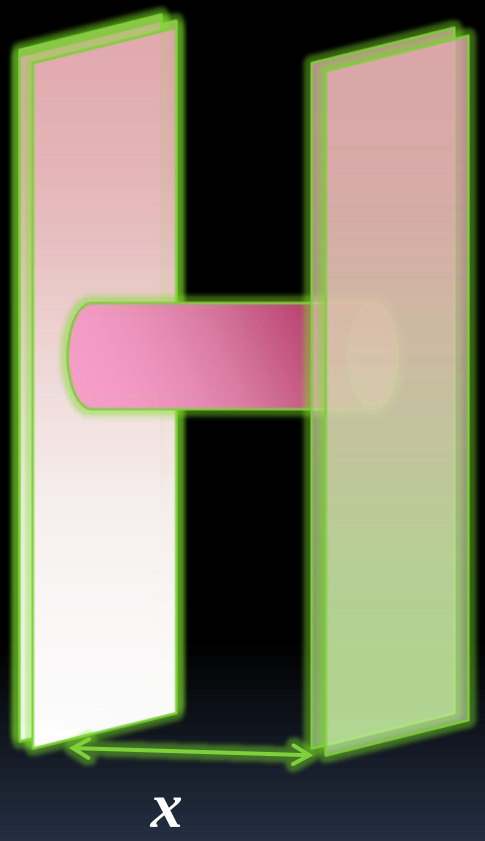
What lives on the screens?

According to string theory: open strings.

Integrating out the UV open strings produces closed strings in the emerged space.



Open closed string duality



$$\sum_i (-1)^F \int_0^\infty \frac{ds}{s^{3/2}} \exp\ -s(m_i^2 + x^2)$$

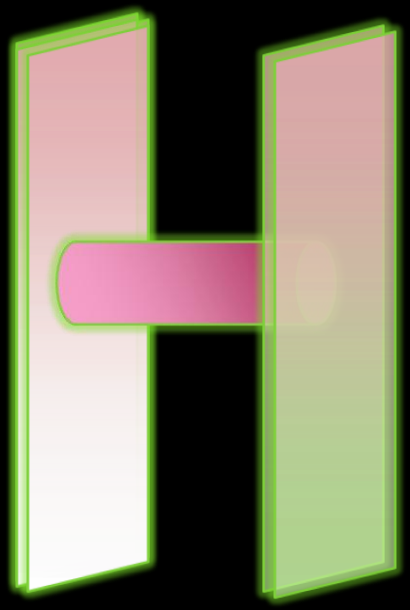
Open string one loop diagram

$$\sum_i (-1)^F m_i^{d-2} \int_0^\infty \frac{ds}{s^{(5-d)/2}} \exp\ -sx^2$$

Massless pole in dual channel

$$\sum_i (-1)^F m_i^{d-2} \int_0^\infty d\tilde{s} \int dk \exp\ \left(ikx - \tilde{s}k^2\right)$$

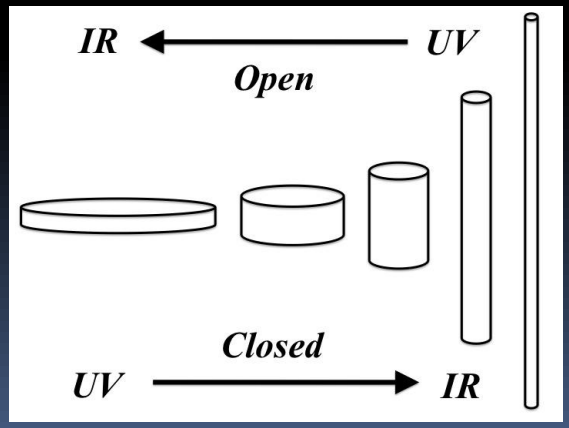
UV/IR correspondence



$$\sum_i (-1)^F \int_{\frac{1}{\Lambda}}^{\infty} \frac{ds}{s^{3/2}} \exp\left(-s(m_i^2 + x^2)\right)$$

Open string with UV cut off

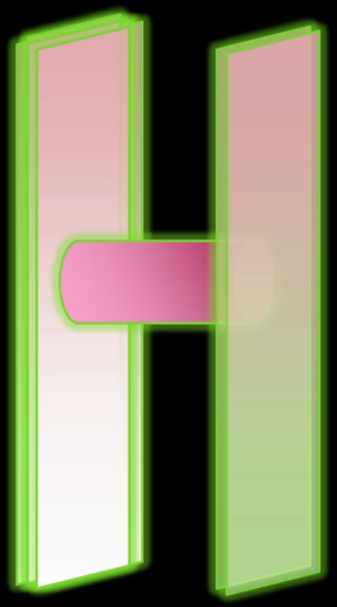
$$\sum_i (-1)^F \int_{0}^{\frac{1}{\Lambda}} \frac{ds}{s^{3/2}} \exp\left(-s(m_i^2 + x^2)\right)$$



$$\sum_i (-1)^F m_i^{d-2} \int_{\Lambda}^{\infty} d\tilde{s} \int dk \exp\left(ikx - \tilde{s}k^2\right)$$

Closed string / gravity with UV cut off

Matrix description of gravity.

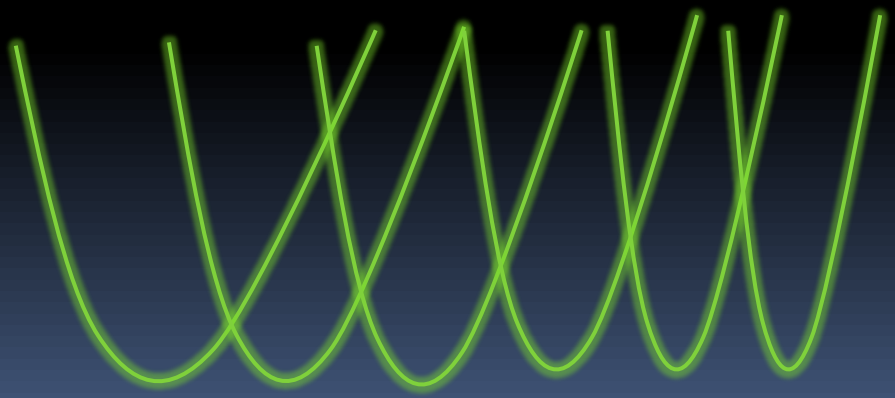


$$X = \begin{pmatrix} x_{11} & .. & x_{1N} & z_1 \\ : & :: & : & : \\ x_{N1} & .. & x_{NN} & z_N \\ z_1^* & .. & z_N^* & yI \end{pmatrix}$$

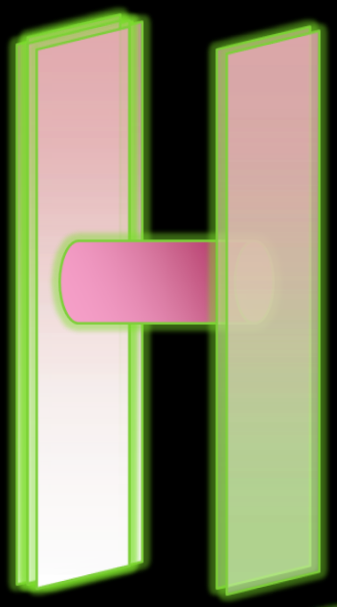
$$\mathrm{tr}\left(\dot{X}_I^2\right) + \mathrm{tr}\left([X_I, X_J]^2\right)$$

$$\Rightarrow$$

$$\|\dot{z}\|^2 + (x-y)^2\|z\|^2$$



Matrix description of gravity.



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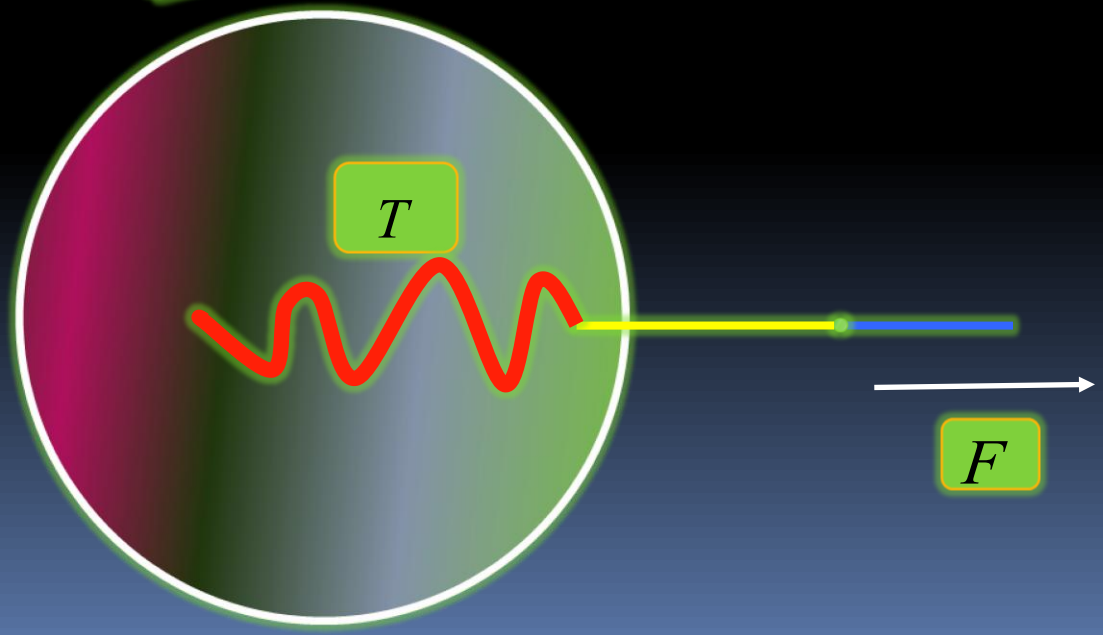

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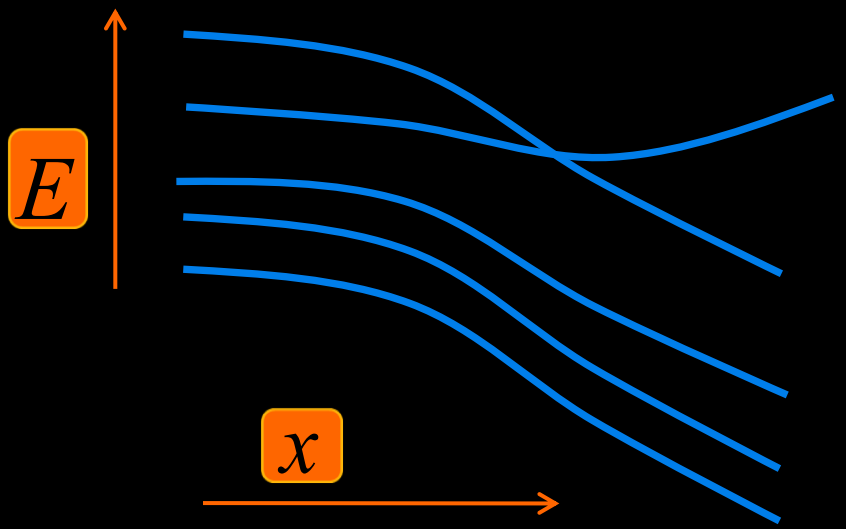
Berry Phase and Crossing Eigenvalues



$$H = \begin{pmatrix} z & x+iy \\ x-iy & -z \end{pmatrix} = \vec{x}\cdot\vec{\sigma}$$

$$\vec{B} = \frac{\hat{x}}{4\pi|\vec{x}|^2}$$

Dirac monopool

At the locus of coinciding eigenvalues one can construct

Non-abelian Berry

$$A_{ij} = \langle \psi_i | d\psi_j \rangle$$