Title: The Hidden Phase Space of our Universe

Date: Jun 22, 2011 09:00 AM

URL: http://pirsa.org/11060065

Abstract: By combining insights from black holes and string theory we argue for the existence of a hidden phase space associated with an underlying fast dynamical system, which is largely invisible from a macroscopic point of view. The dynamical system is influenced by slow macroscopic observables, such as positions of objects. This leads to a collection of reaction forces, whose leading order Born Oppenheimer force is determined by the general principle that the phase space volume of the underlying system is preserved. We propose that this adiabatic force is responsible for inertia and gravity. This fact allows us to calculate the hidden phase space volume from the known laws of inertia and gravity. We find that in a cosmological setting the appearance of dark energy is naturally explained by the finite temperature of the underlying system. The adiabatic approximation that leads to the usual laws of inertia and gravity breaks down in the neighborhood of horizons. In this regime the reaction force degenerates into an entropic force, and the laws of inertia and gravity receive corrections due to thermal effects. A simple estimate of these effects leads to the conclusion that they coincide with observed phenomena attributed to dark matter.

Introduction:

Gravity is a macroscopic force that dominates in IR.

Yet it knows about microscopic information (UV).

But why? Is it a UV/IR conspiracy?

Or is it due to a principle?

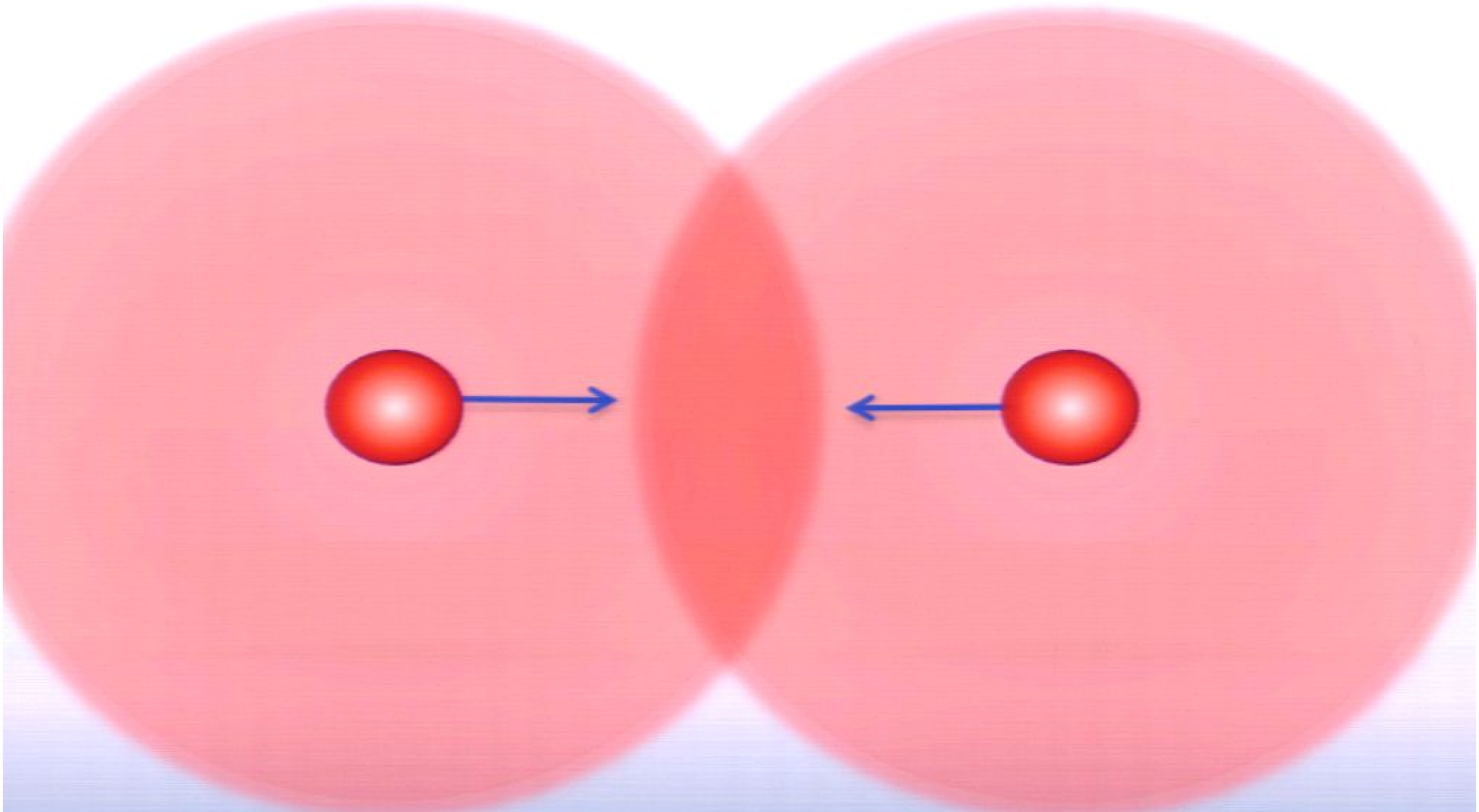
Basic idea:

To arrive at our paradigm in terms of space time, matter, and forces we ignore (non-local) UV DOF.

This requires a separation of time scales: breaks down near horizons and in cosmology.

The distinction between matter and space time will disappear and forces should be seen as emergent.

Gravity, and the other forces, are reaction forces due to the fast microscopic dynamics of the underlying dynamical system.

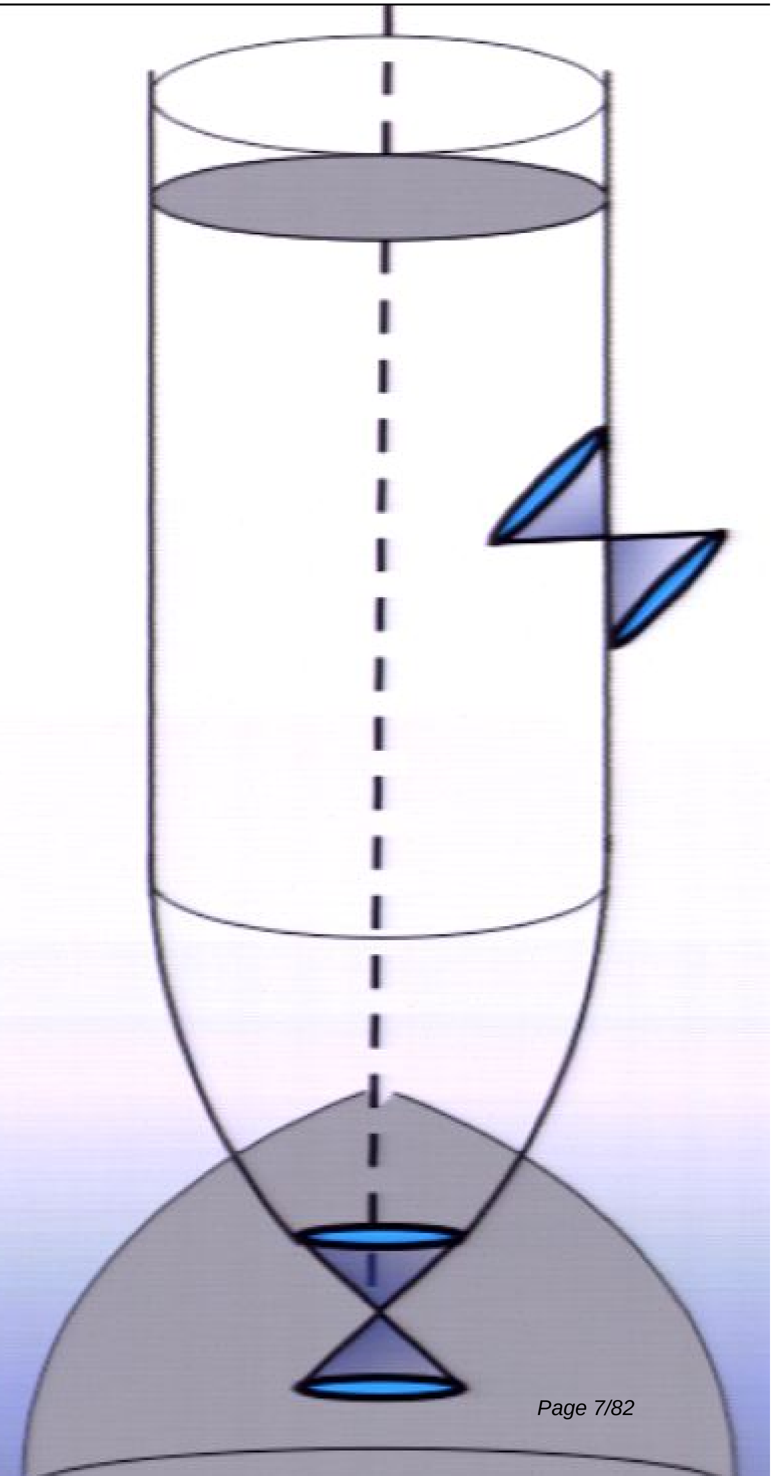


Outline:

- Motivation: BH’s + String-/matrix theory.
- Adiabatic reaction forces.
- Hidden phase space: proposal.
- Inertia/gravity as adiabatic reaction force.
- Speculations about dark energy/dark matter.

GRAVITATIONAL COLLAPSE:

What happens to the phase space occupied by the fermions?



NEUTRON STAR

Degenerate Fermions

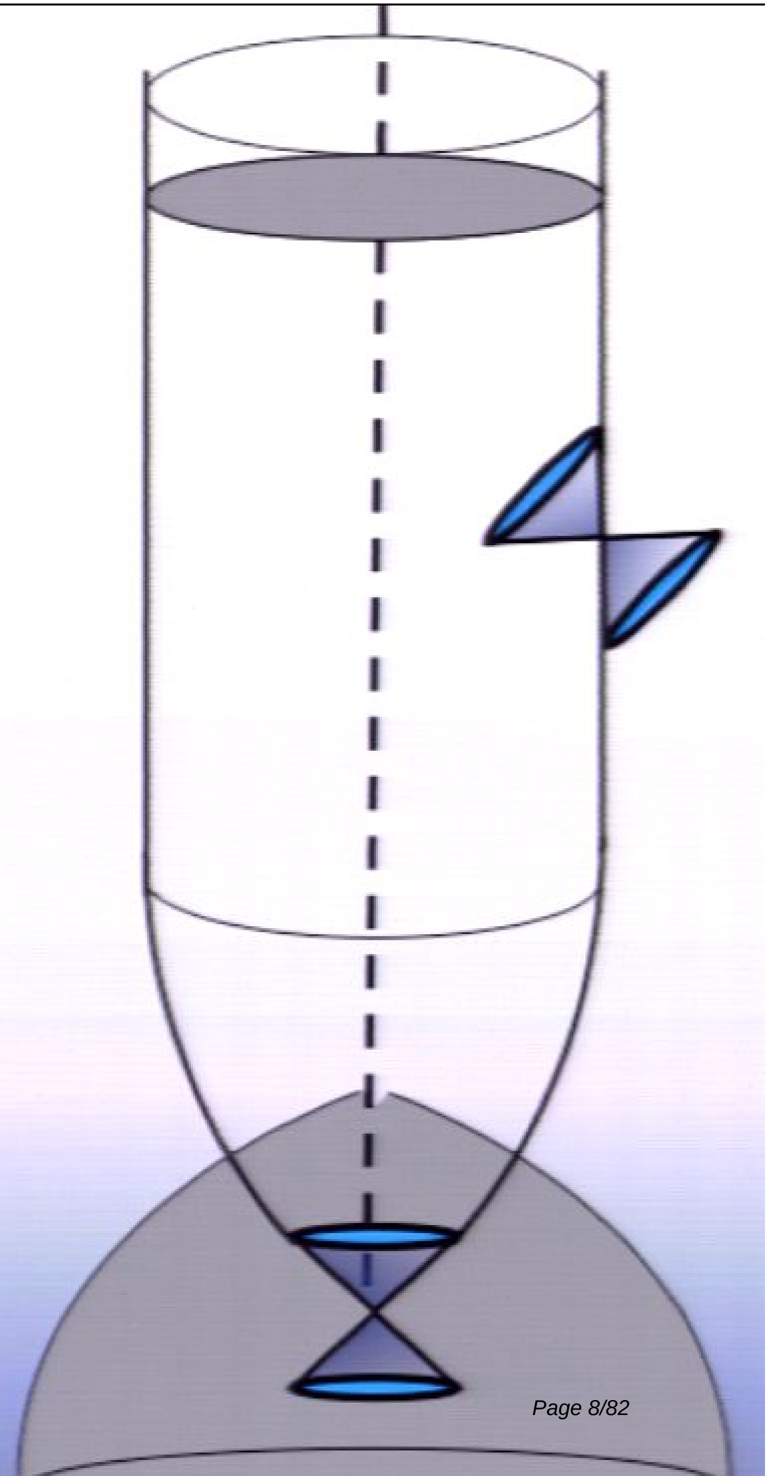
GRAVITATIONAL COLLAPSE:

What happens to the phase space occupied by the fermions?

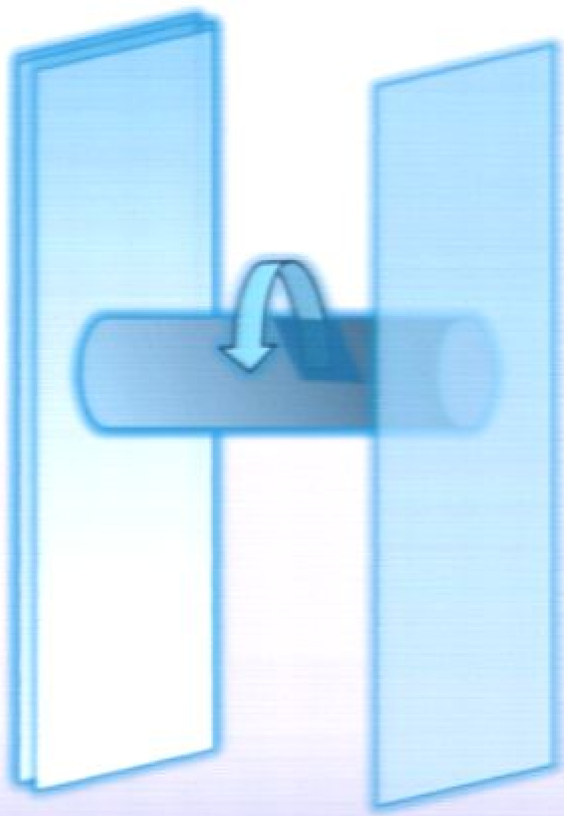
String theory/ AdS-CFT:

$$\Psi(x) \leftrightarrow \mathrm{tr}(X^n)$$

Bulk fields correspond to (short) traces of boundary fields.



Gravity results from integrating out DOF, associated with the emergence of space-time



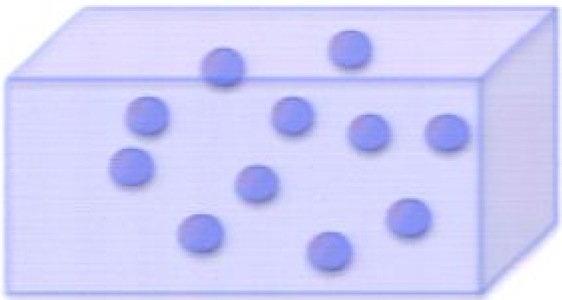
Coordinates are matrices

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdot\cdot & x_{1N} \\ x_{21} & x_{22} & \vdots & \vdots \\ \vdots & \vdots & \vdots & x_{N-1N} \\ x_{N1} & \cdot\cdot & x_{NN-1} & x_{NN} \end{pmatrix}$$

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

Eigenvalues: describe position of matter

Off-diagonal DOF induce forces.



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The off diagonal modes carry a **positive** gravitational energy

$$E_g = \frac{1}{8\pi G}\int \left|\nabla\Phi\right|^2$$

GRAVITATIONAL COLLAPSE:

The phase space occupied by the fermions goes into the "off diagonal" modes.

Eigenvalues and off diagonal modes equilibrate and together form a thermal state describing the black hole.

Space-time in its usual sense ceases to exist.

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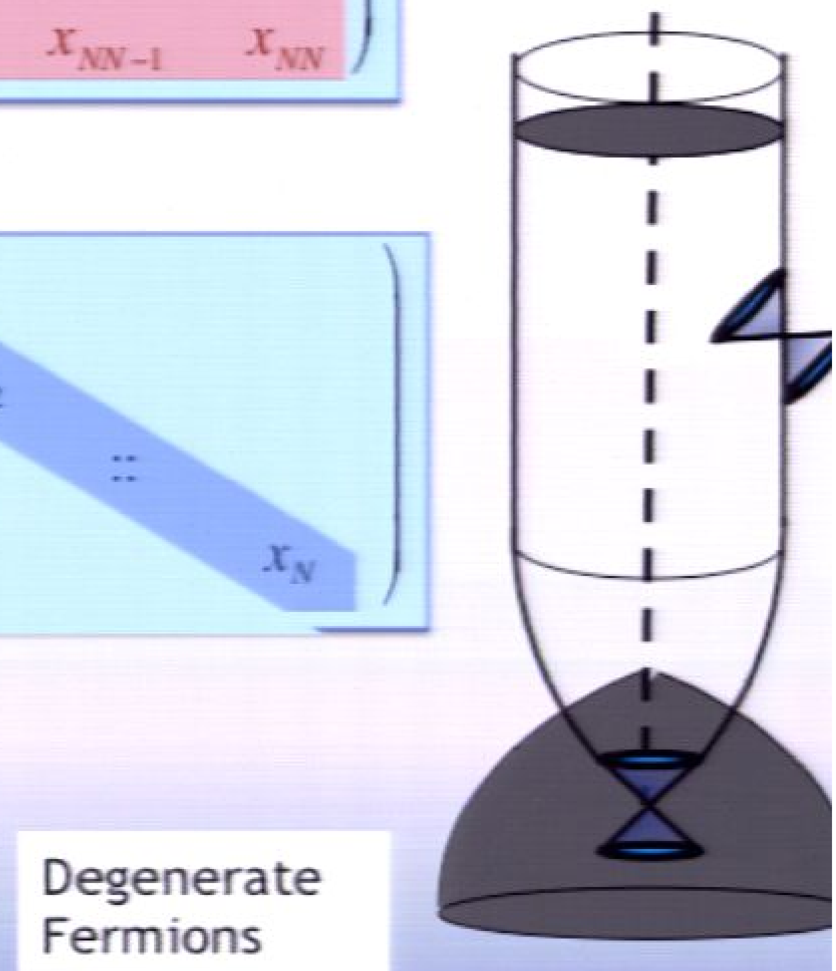

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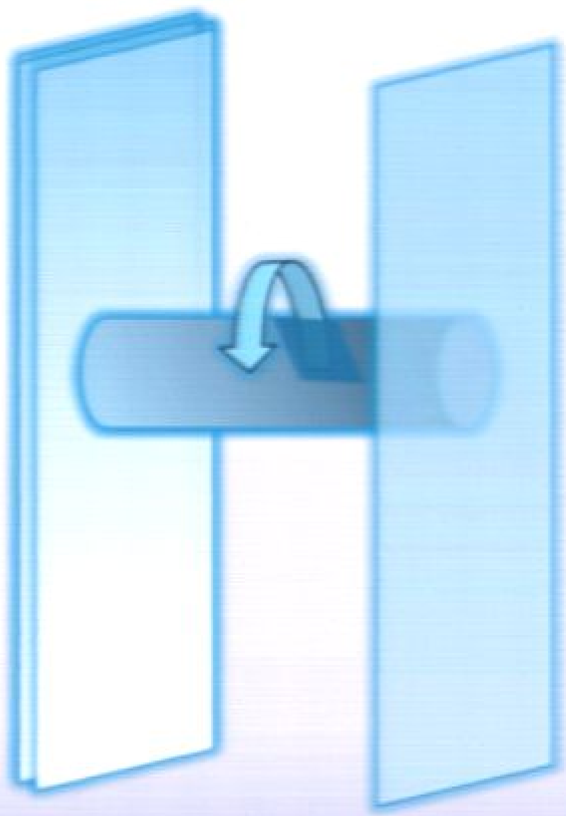

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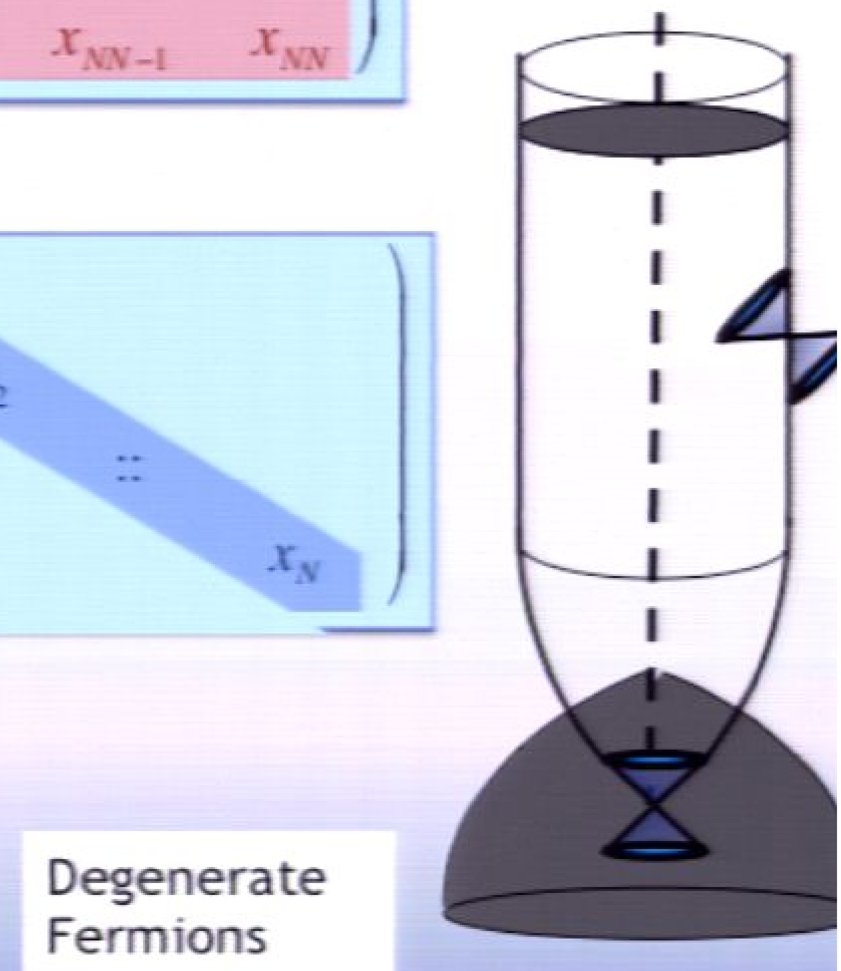

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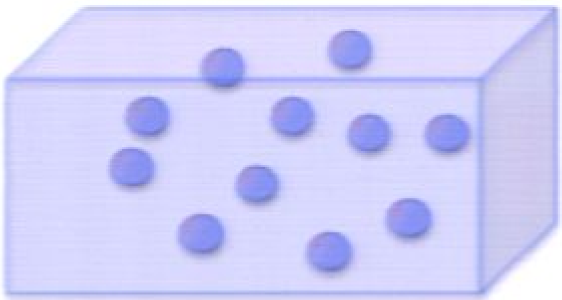

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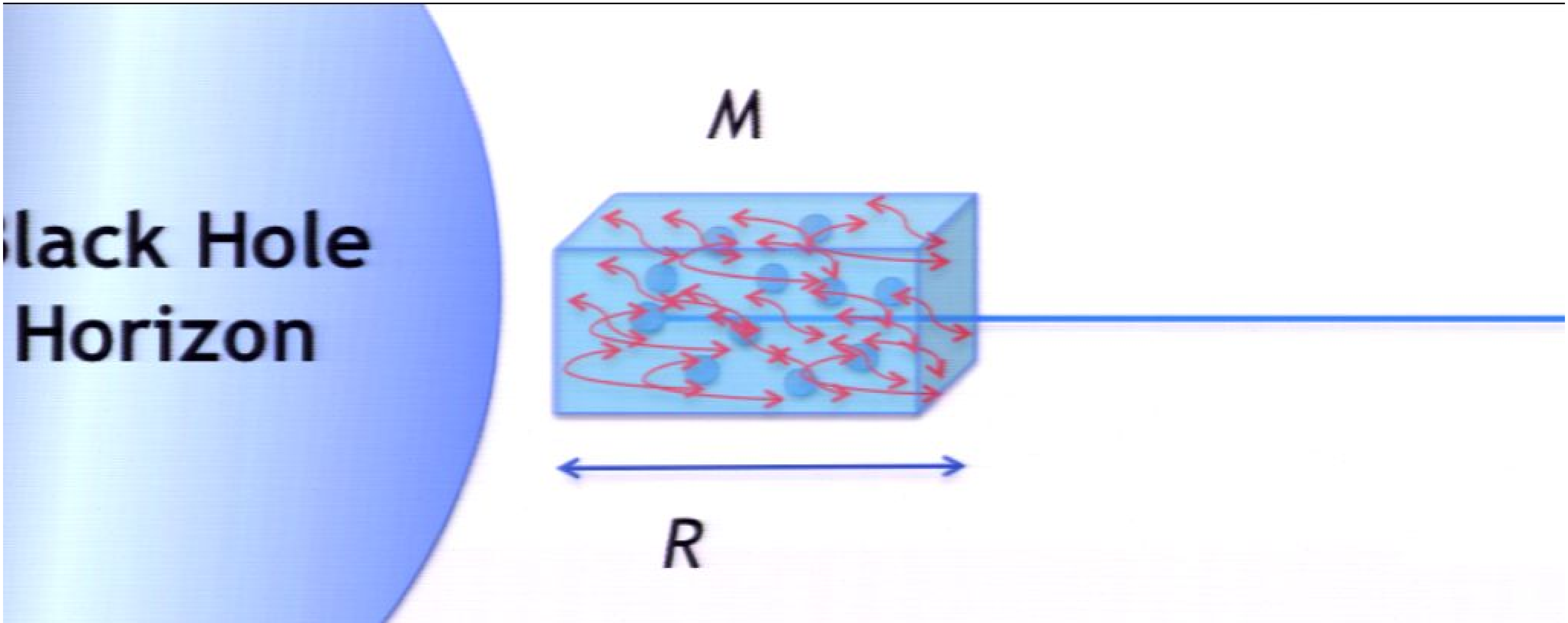
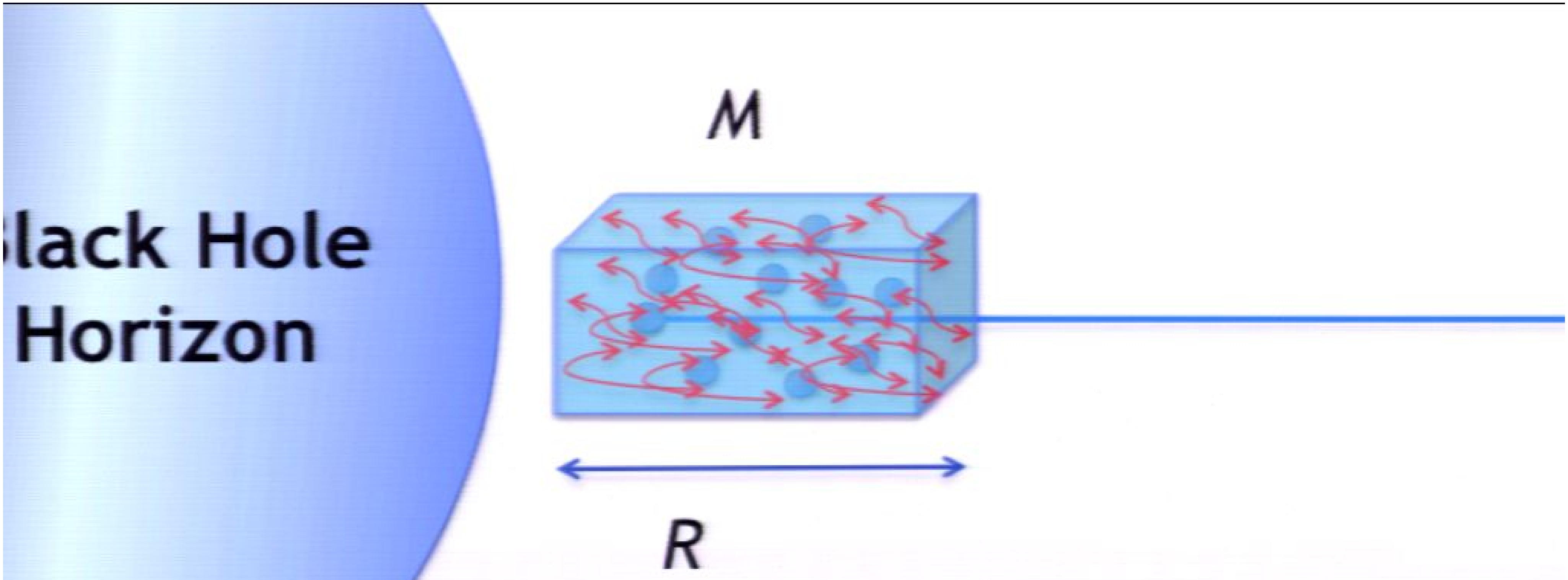


Box with a gas of particles.

What is the maximal entropy inside the box?



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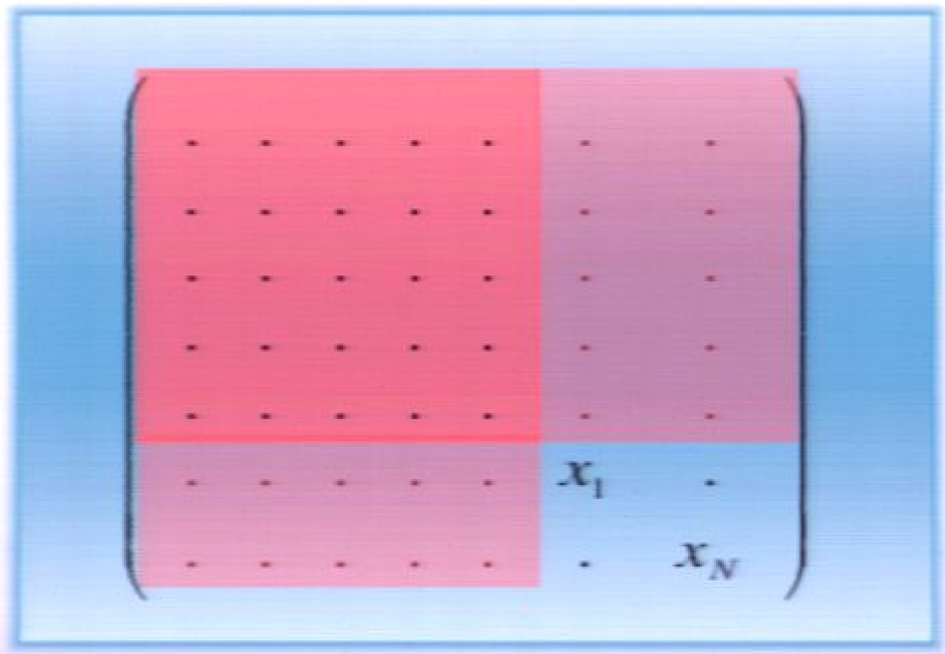
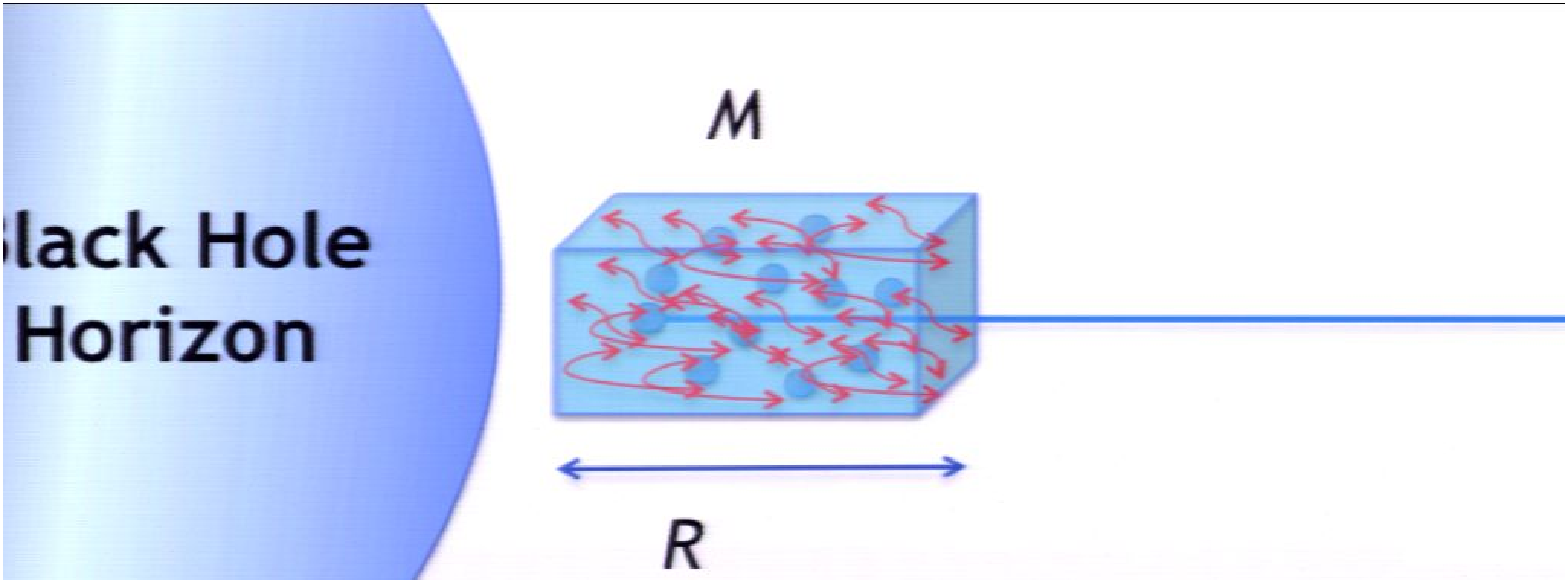
$$T = \frac{\hbar g}{2\pi} \Rightarrow \Delta S = 2\pi \frac{McR}{\hbar}$$

$$N = \frac{McR}{\hbar}$$





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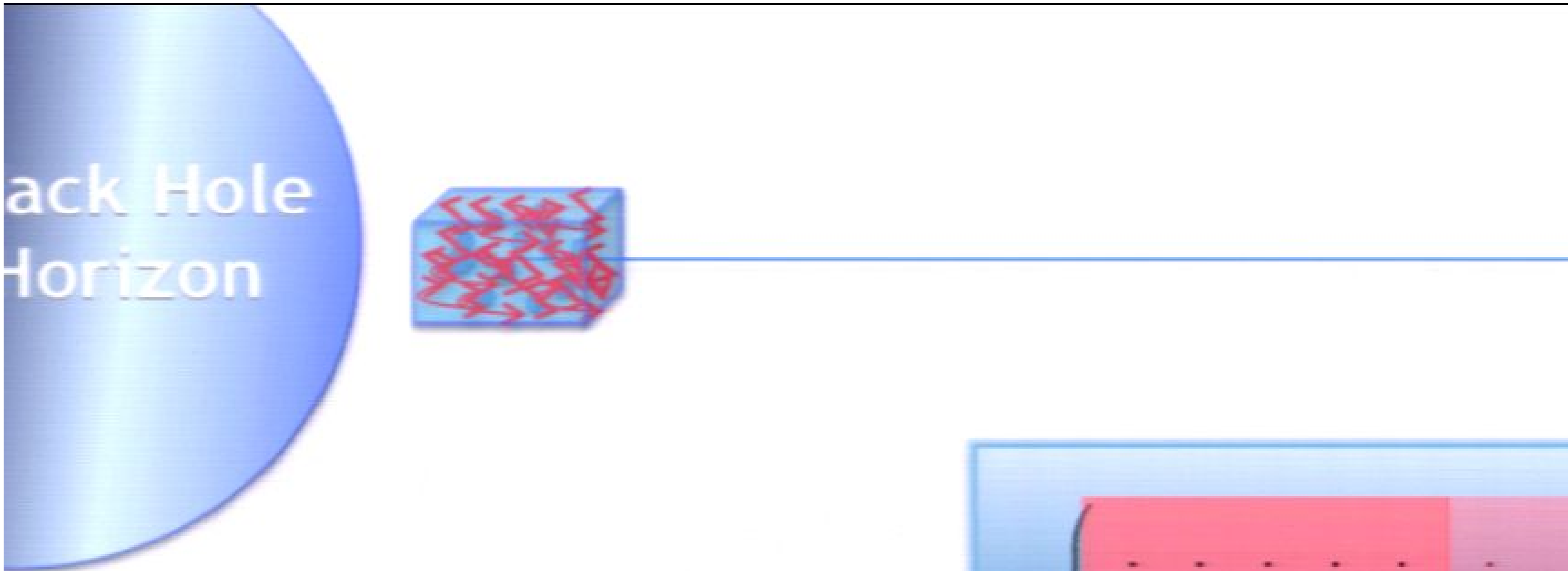

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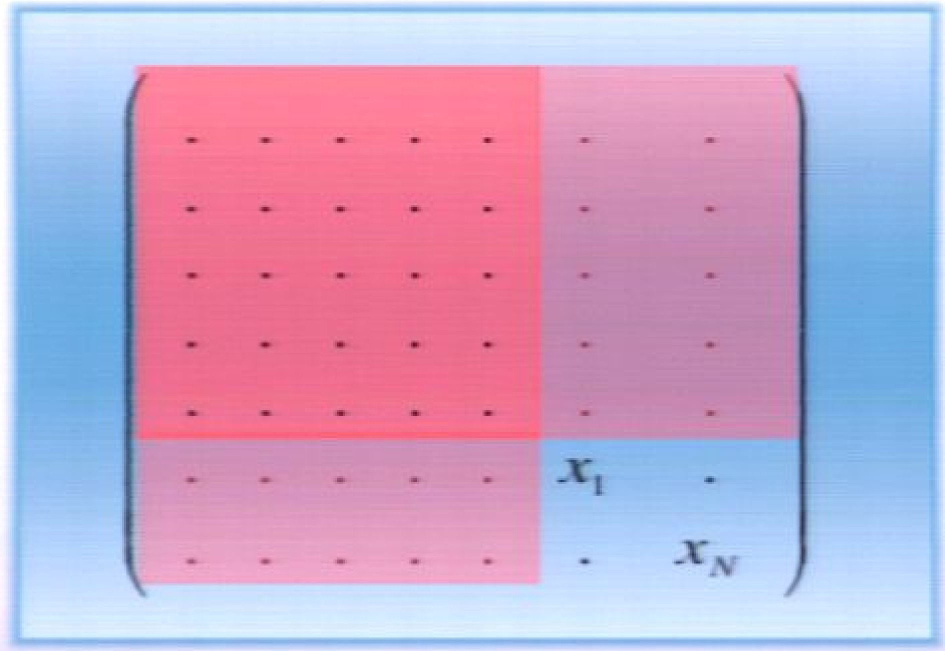
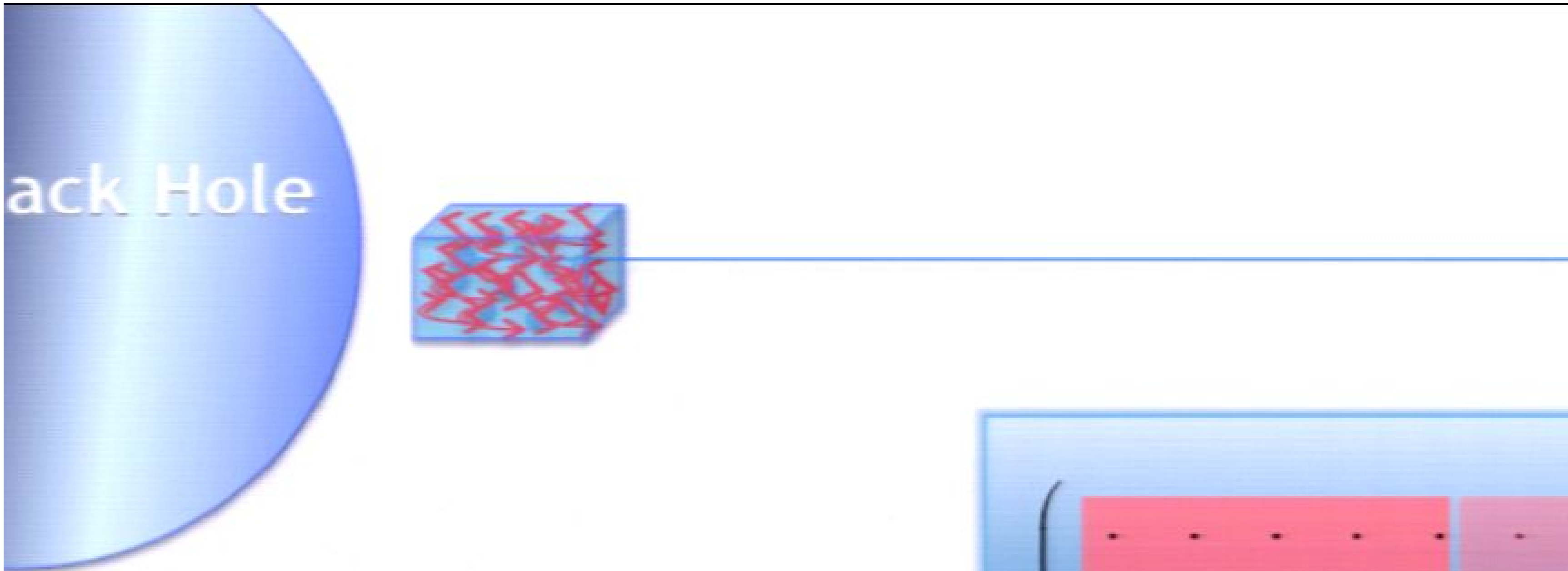
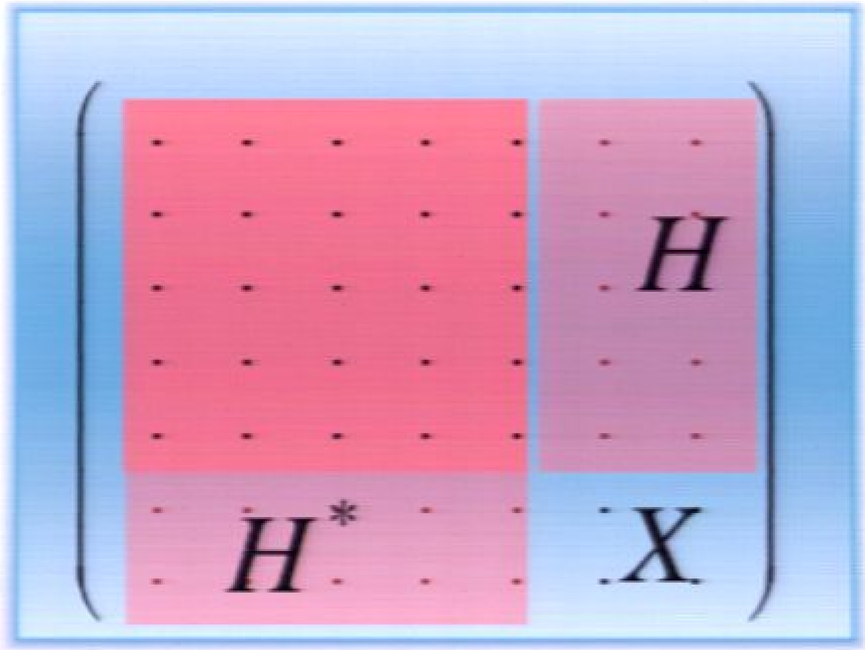
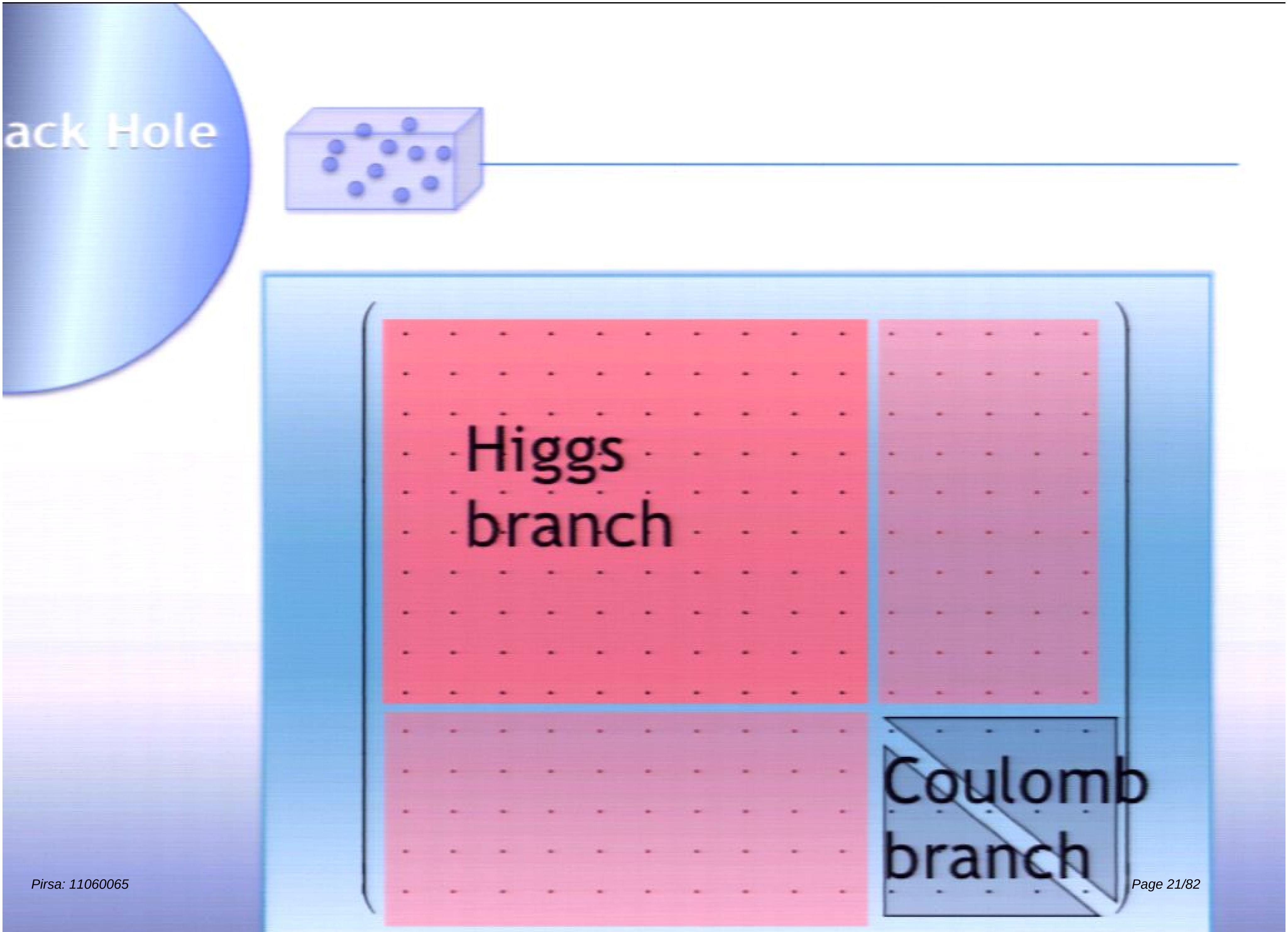




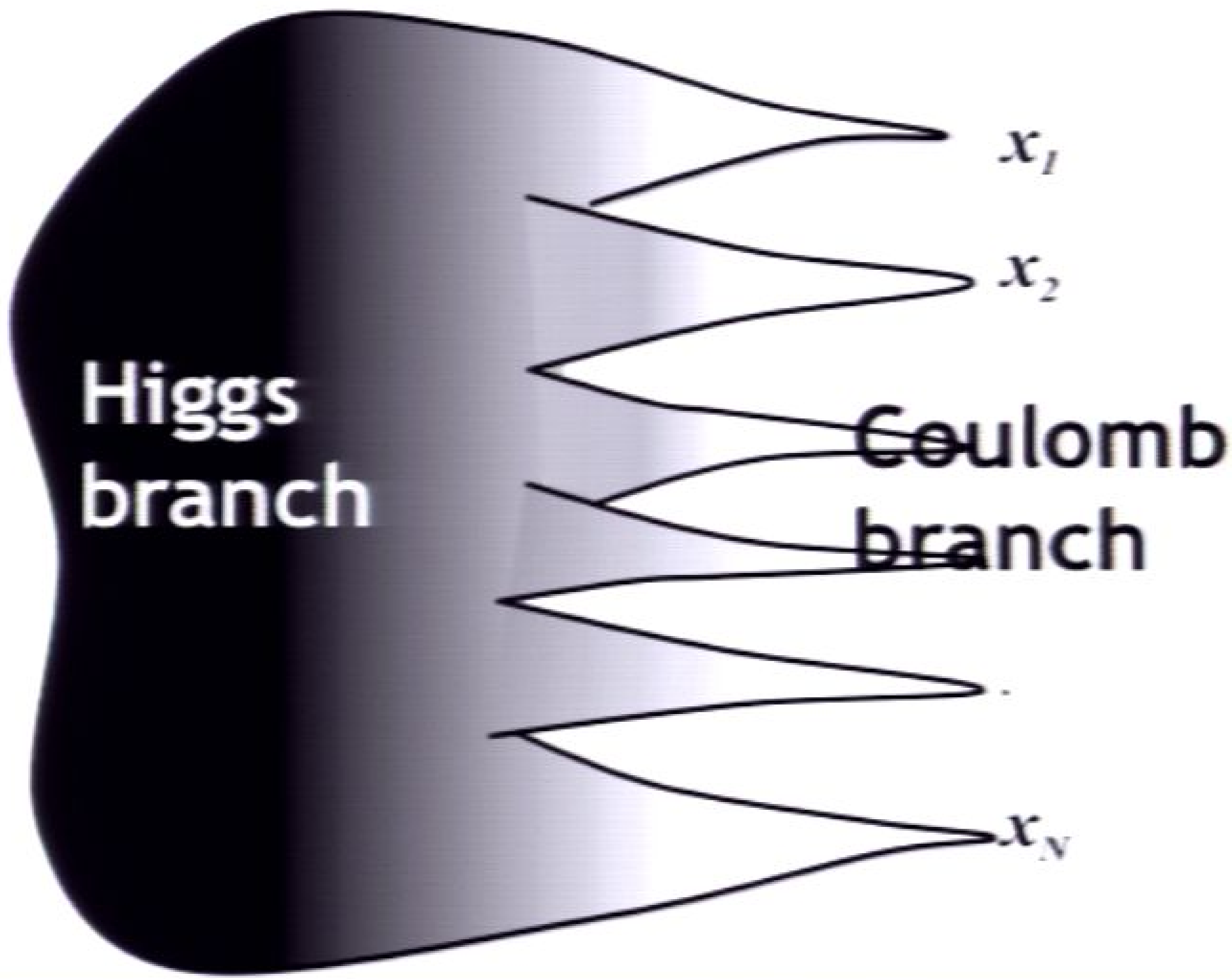
$$|X \cdot H|^2$$



Matrices gets "Higgsed"
Eigenvalues disappear as flat directions
Coulomb branch goes over into Higgs branch

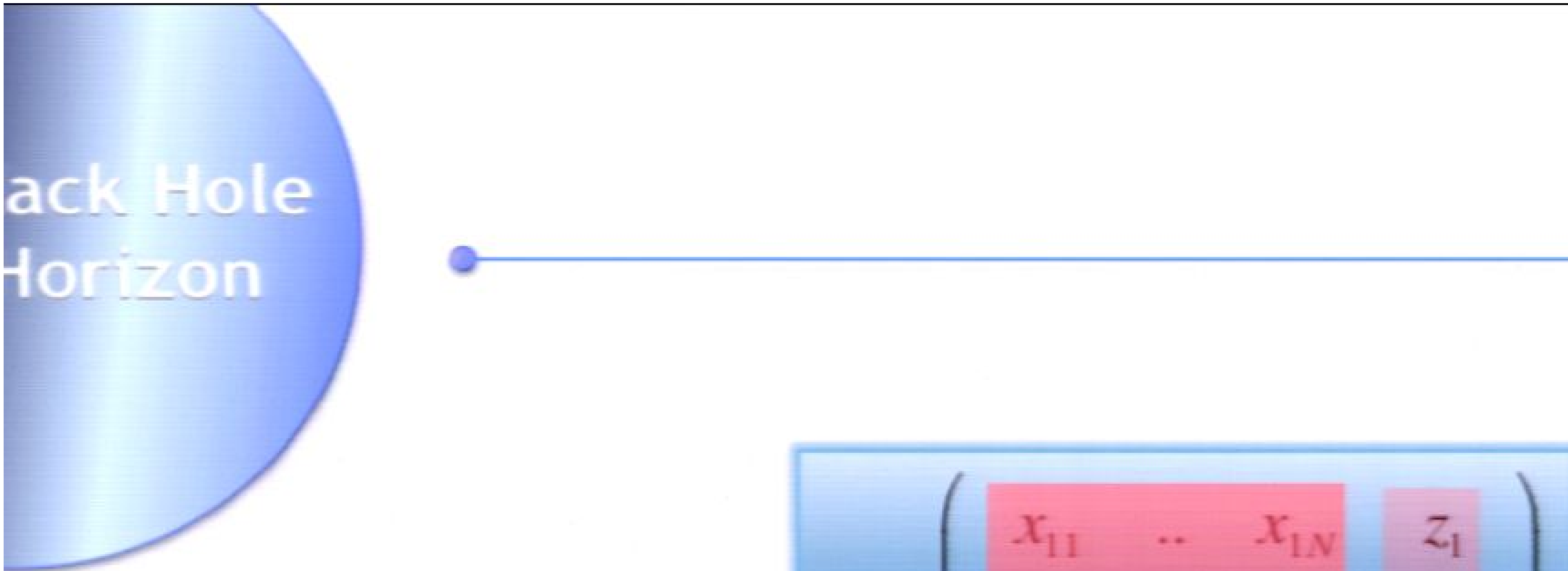

ack Hole
Higgs branch
Coulomb branch

PHASE SPACE



ack Hole
Horizon

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1N} & z_1 \\ \vdots & \vdots & \vdots & \vdots \\ x_{N1} & \cdots & x_{NN} & z_N \\ z_1^* & \cdots & z_N^* & xI \end{pmatrix}$$



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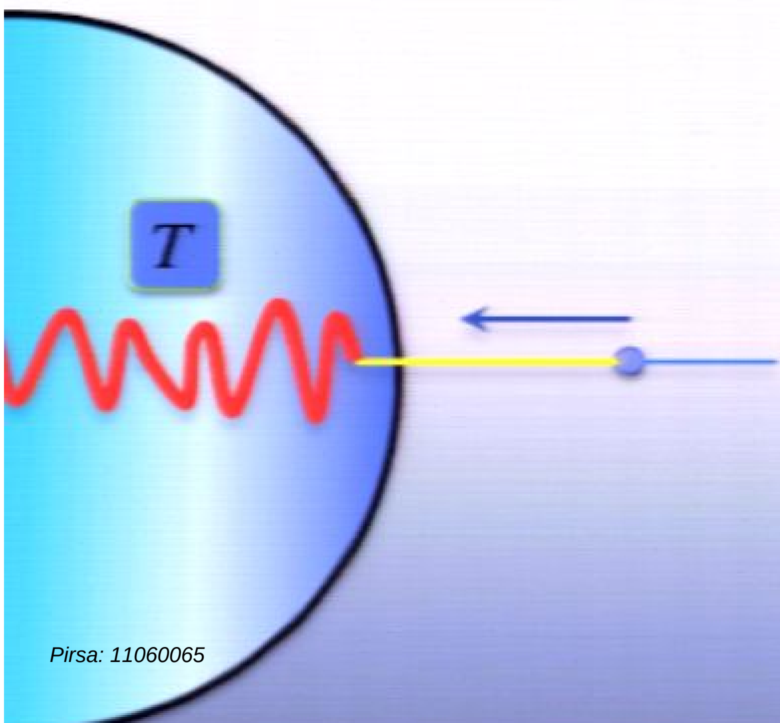

$$F = mg$$

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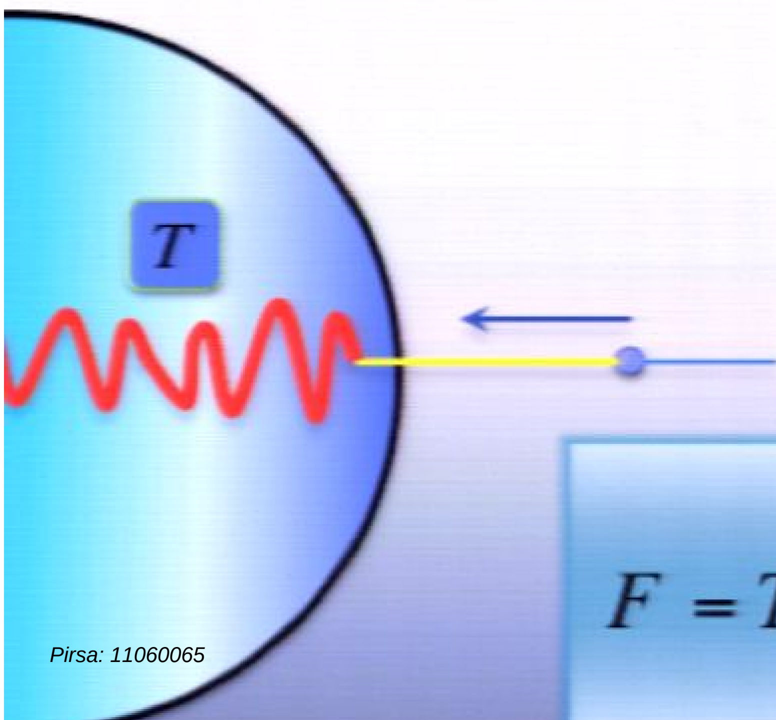


$$F = T\frac{\partial S}{\partial x}$$

$$T = \frac{\hbar g}{2\pi} \Rightarrow \frac{\partial S}{\partial x} = 2\pi\frac{mc}{\hbar}$$

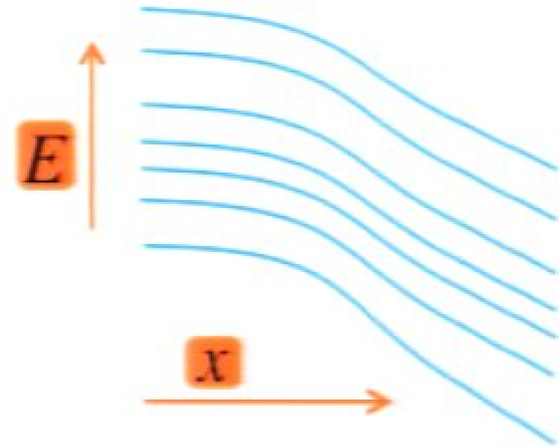
Adiabatic reaction forces:

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.

Adiabatic Reaction Force



Harmonic oscillator with slowly varying frequency

$$H(p,q;x) = \tfrac{1}{2}\left(p^2 + \omega^2(x)q^2\right)$$

Bohr-Sommerfeld action integral satisfies the basic identiy

$$J \equiv \frac{1}{2\pi}\oint p\,dq$$

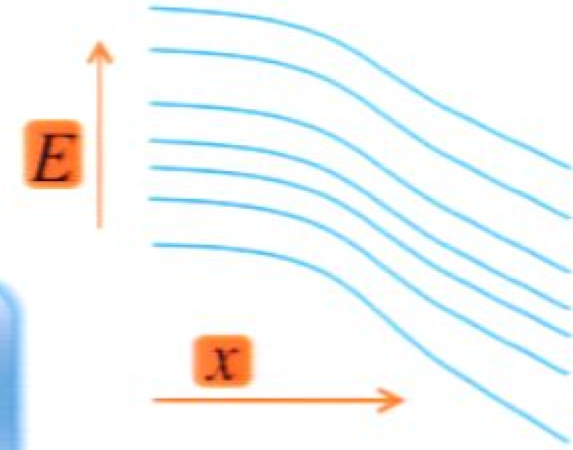
$$dE = \omega\; dJ - F dx$$

Adiabatic reaction force:

$$F = -\left(\frac{\partial E}{\partial x}\right)_J = \omega\left(\frac{\partial J}{\partial x}\right)_E$$

$$\frac{1}{\omega} = \left(\frac{\partial J}{\partial E}\right)_x$$

Adiabatic Reaction Force



For a (chaotic/ergodic) system with many DOF

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

the phase space volume is an adiabatic invariant. Formally it defines an entropy

$$S = k_B \log \Omega$$

$$dE = T\, dS - F dx$$

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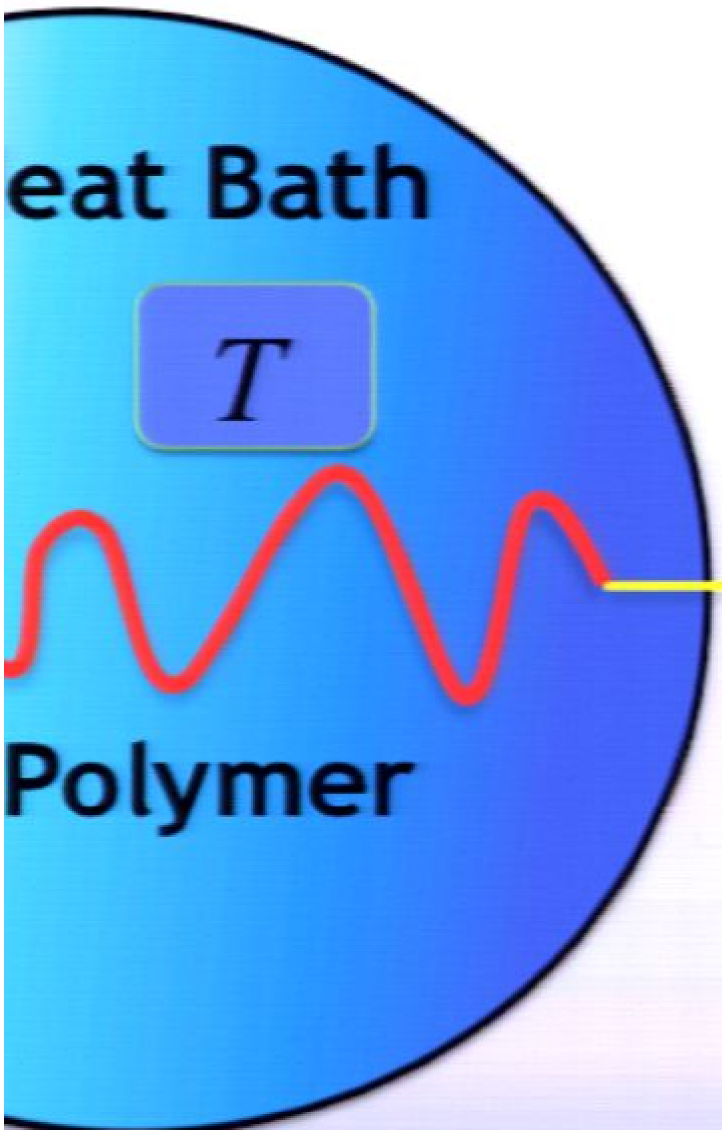
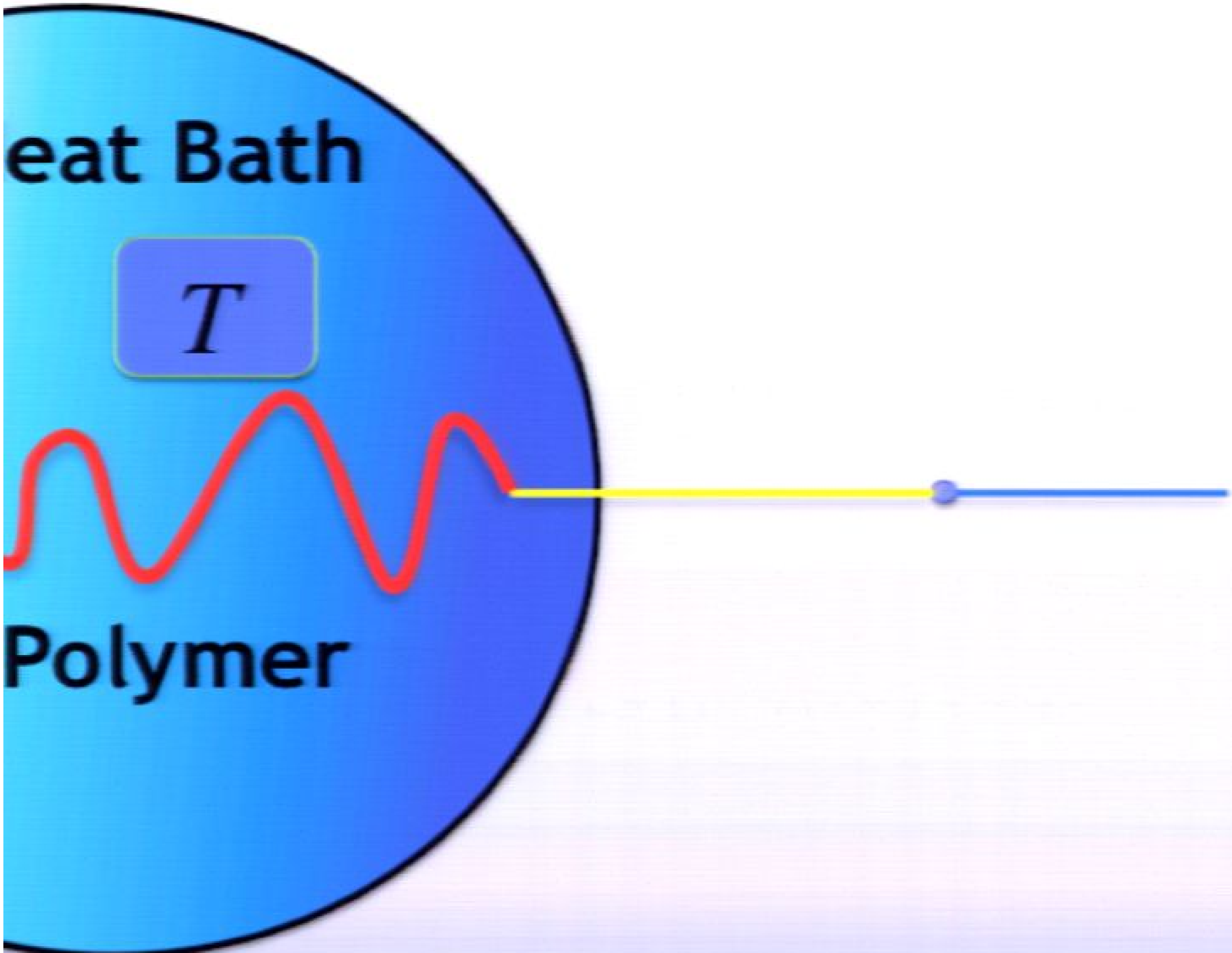
$$\frac{1}{T} = \left(\frac{\partial S}{\partial E}\right)_x$$



Entropic Force in Canonical Ensemble


eat Bath
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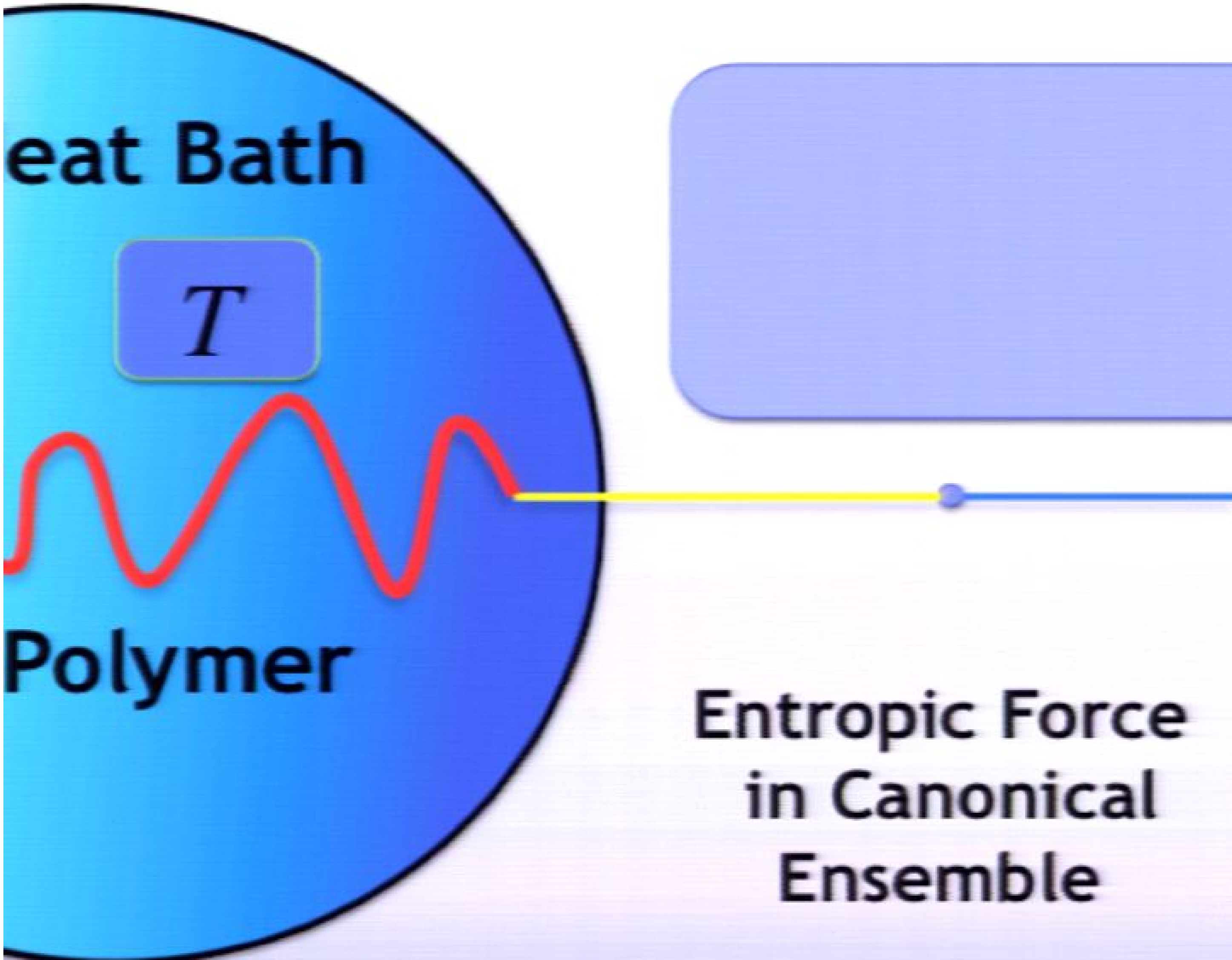

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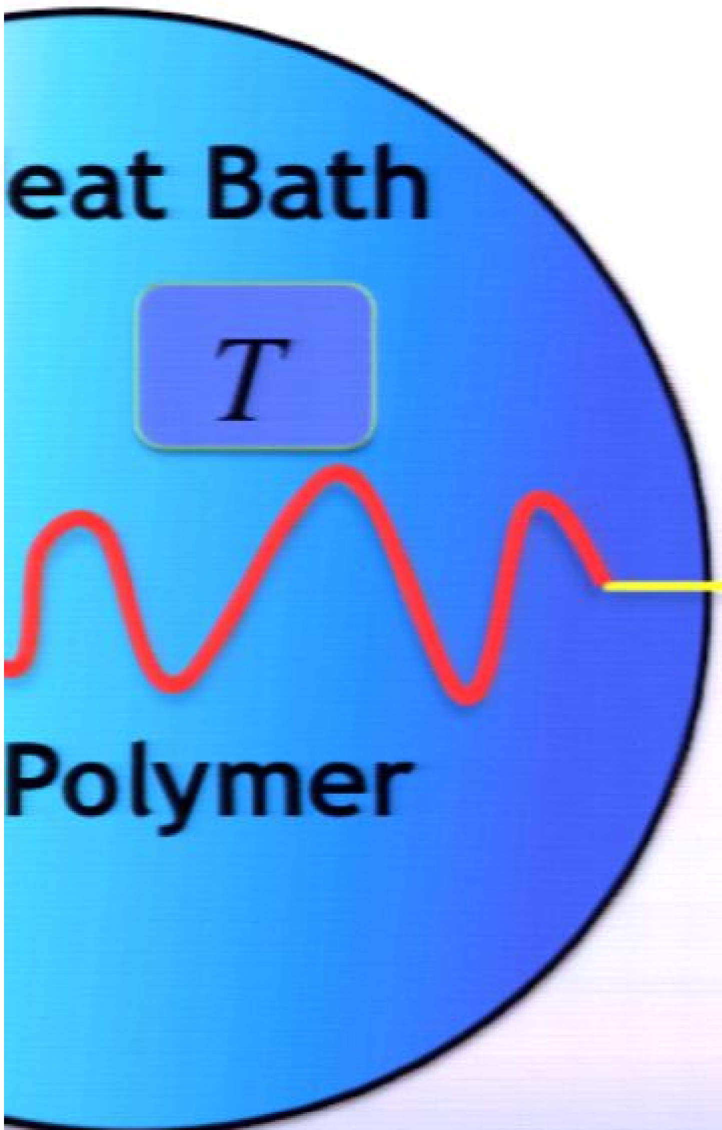

$$1/T = \partial_E S(E,x)$$

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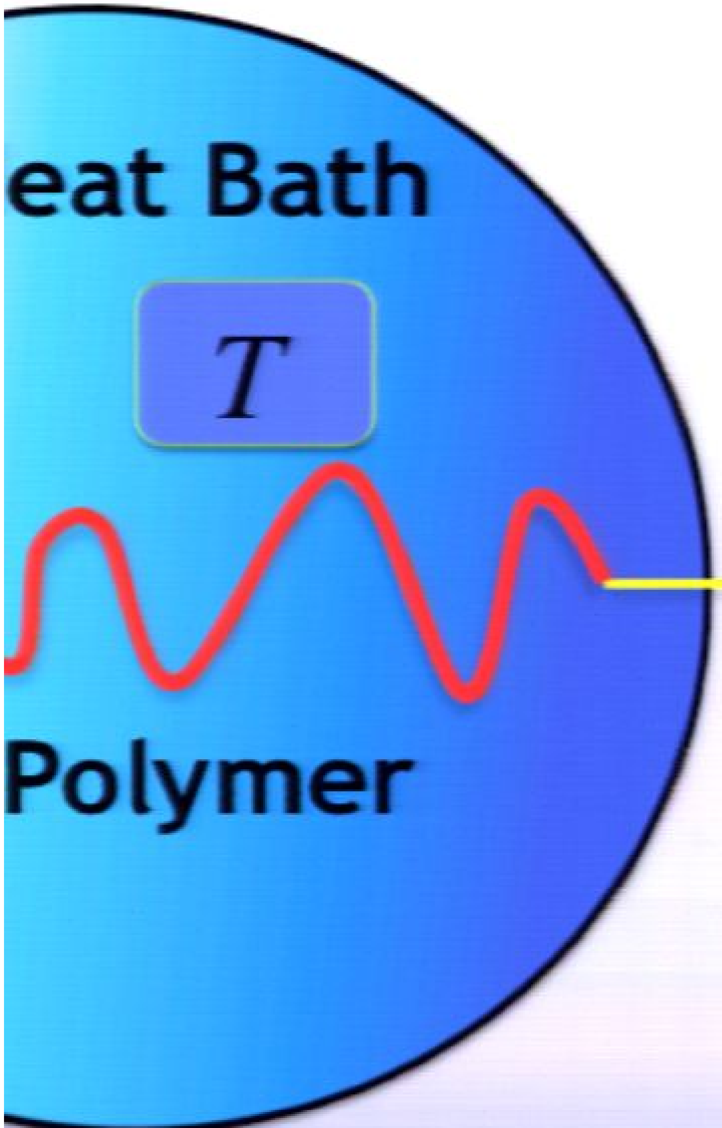

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Saddle point equations

Entropic Force in Canonical Ensemble

$$Z(T,F) = \int dE dx\ \Omega(E,x)\ e^{-(E+Fx)/kT}$$

Consider a fast system with phase space volume

$$\Omega(E, x)$$

but we want to integrate out its DOF and describe it effectively by a small number of degrees of freedom .

How would we do it?

We have to make sure that the reaction forces remain the same

Replace all degrees of freedom by just one

$$\int \Omega(E,x)\, e^{-E/T} = \int [dp\, dq] e^{I[p,q;x]/\hbar}$$

$$I[p,q;] = \oint \left(p dq - H(p,q;x) dt \right)$$

Action/Entropy correspondence

$$S = 2\pi \frac{J}{\hbar}$$

$$T = \frac{\hbar\omega}{2\pi}$$

Action/Entropy correspondence in Gravity

$$S = 2\pi \frac{J}{\hbar}$$

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Gibbons-Hawking-Wald formalism

$$I = 2\pi(J - E/\omega) = S - E/T$$

$$I = \frac{2\pi}{\omega}\left[\int_{hor} Q - \int_{\infty} Q\right]$$

Brown Henneaux => Kerr/CFT

Conjecture:

Gravity is an adiabatic reaction force

Due to a fast dynamical system underlying our universe.

Inertia (gravity) is the leading order reaction force.

The separation of time scales breaks down at horizons.

Other forces arise from higher order corrections

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In this regime the fast system serves as a heat bath

This leads to thermal fluctuations in inertial frame

Dark energy and dark matter are associated with these thermal effects.

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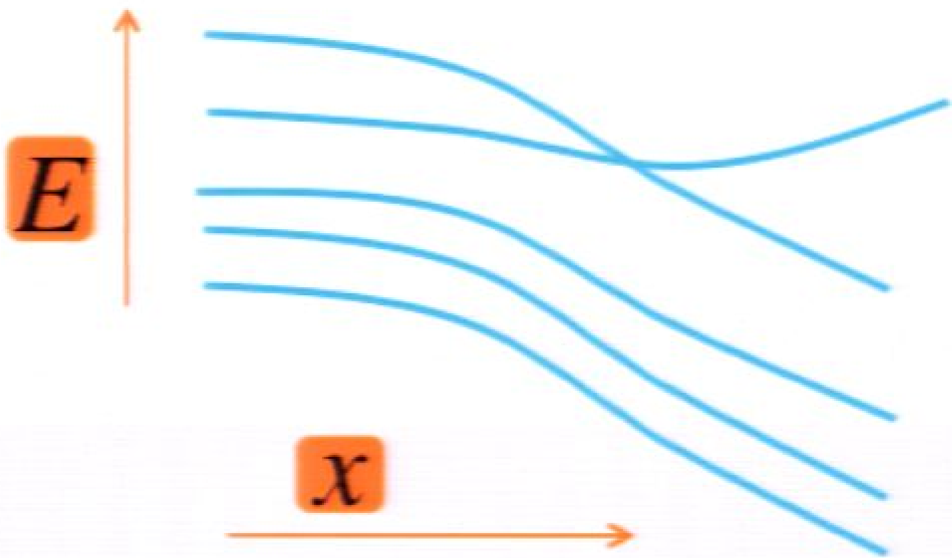
Berry Phase and Crossing Eigenvalues



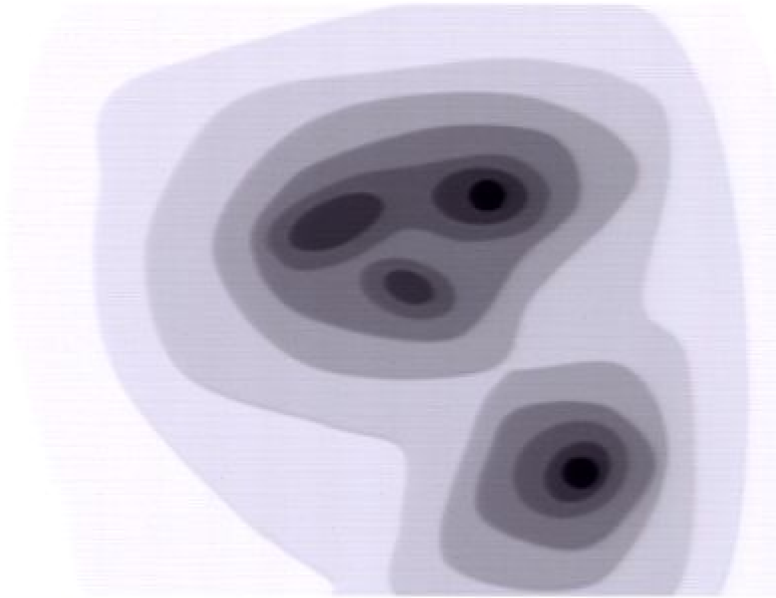
$$H = \begin{pmatrix} z & x+iy \\ x-iy & -z \end{pmatrix} = \vec{x}\cdot\vec{\sigma}$$

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

Dirac monopool

At the locus of coinciding eigenvalues one can construct a non-abelian Berry connection.

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

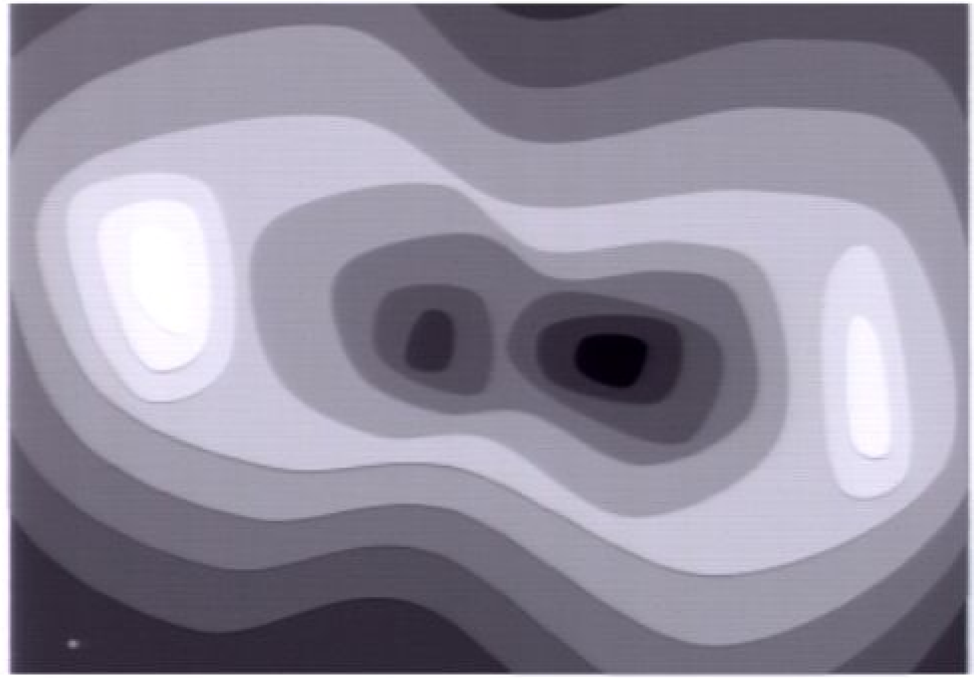


Question:

What is the total phase space volume associated with a region of space contained within a particular surface given the amount of energy inside of it?

Assumption:

We consider a quasi static situation and a region that is surrounded by an equipotential surface.



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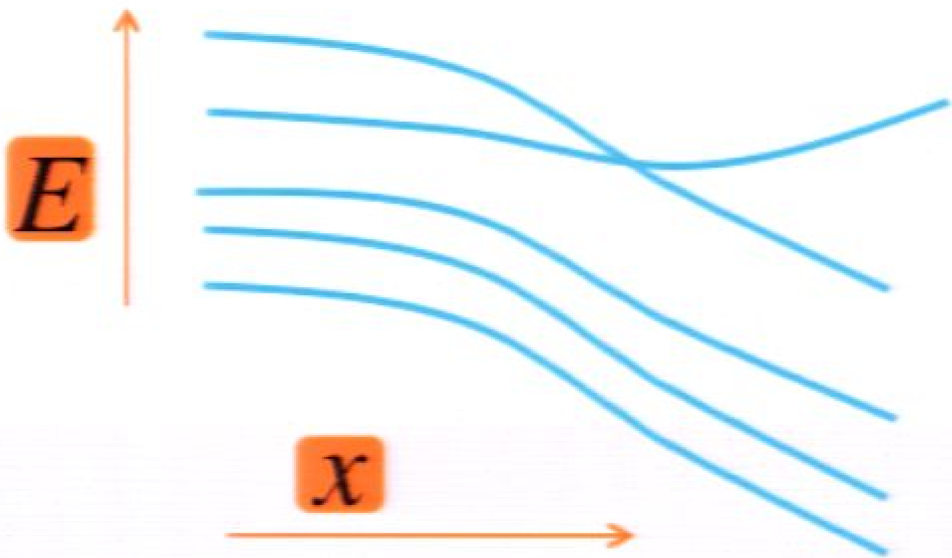

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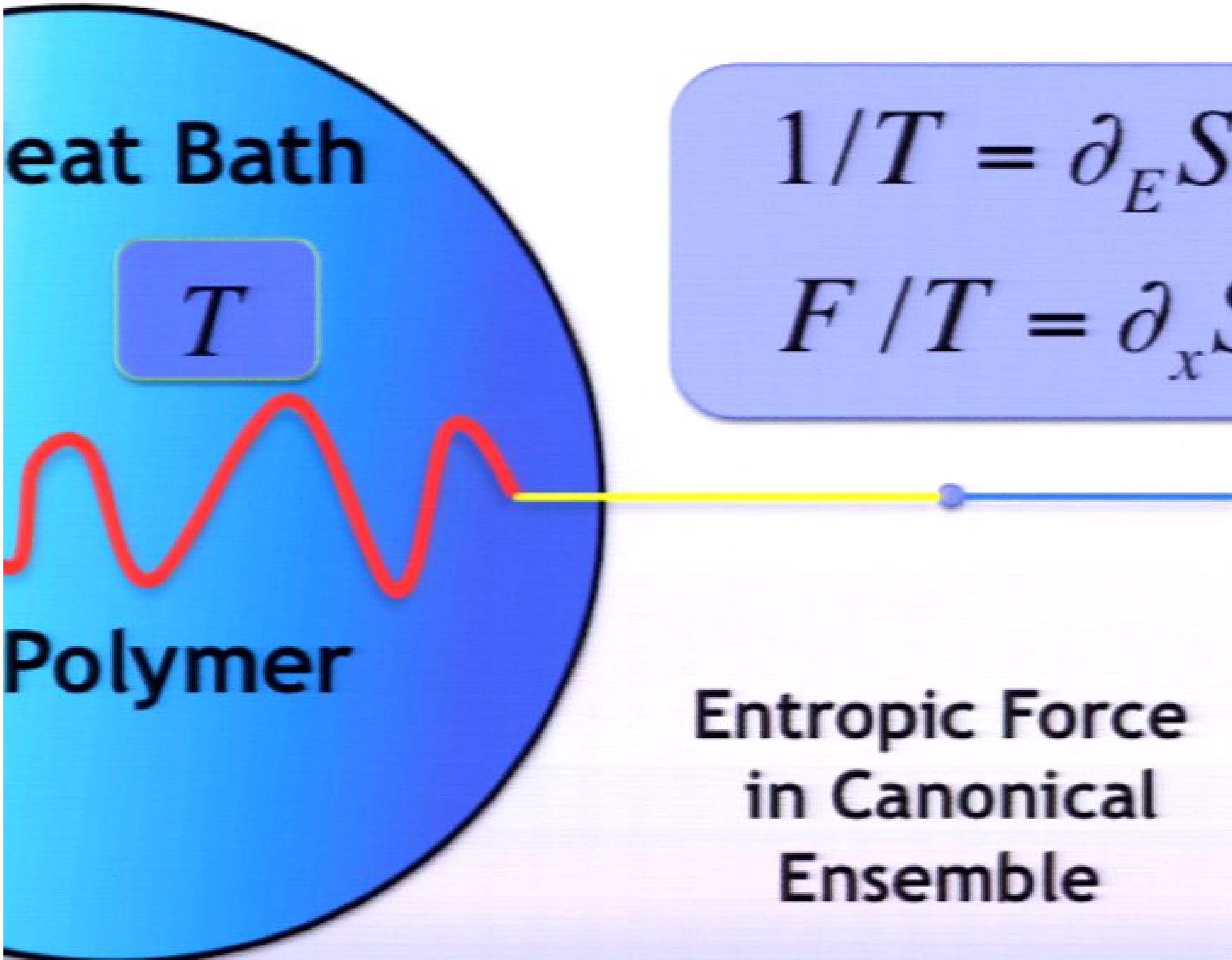

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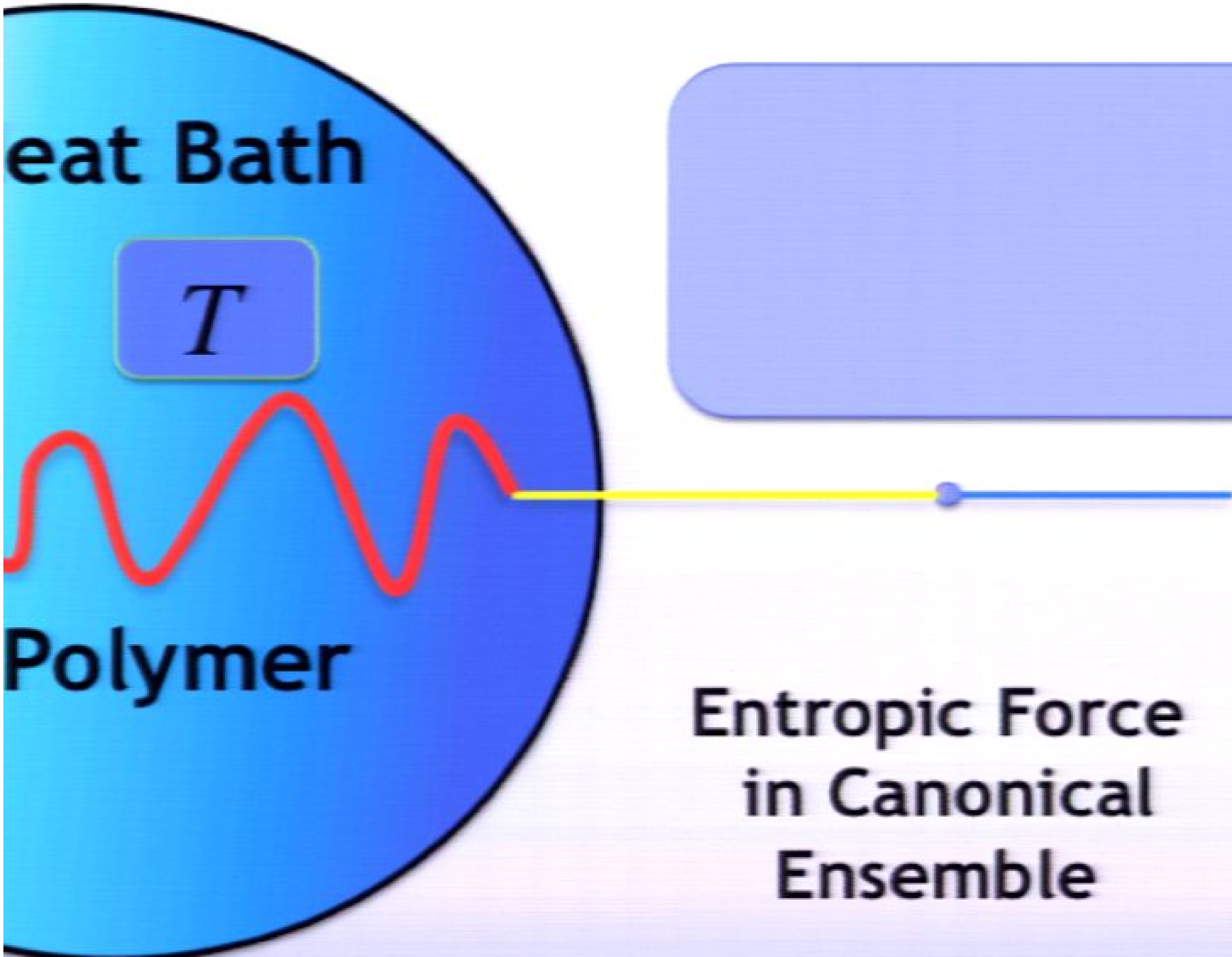

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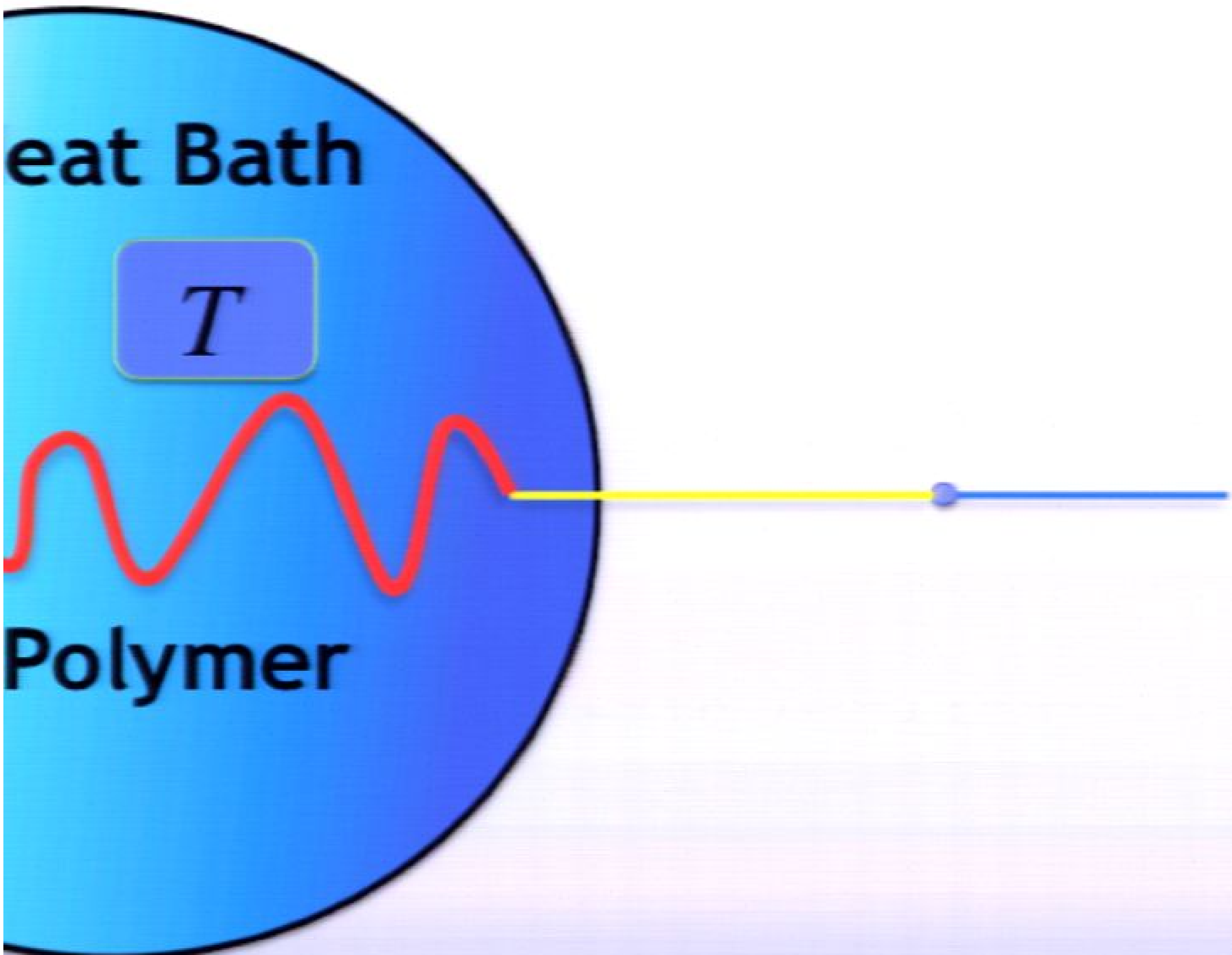
eat Bath
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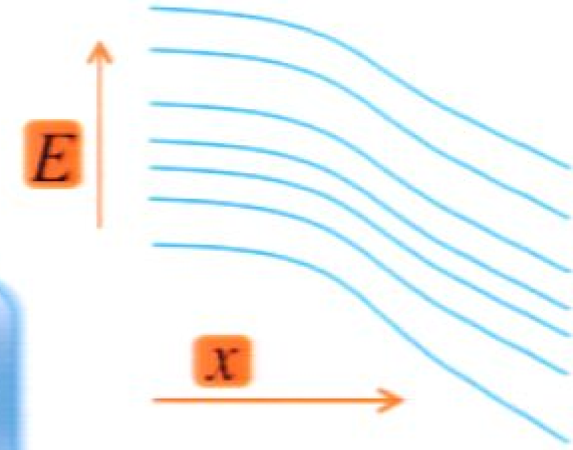
Adiabatic Reaction Force



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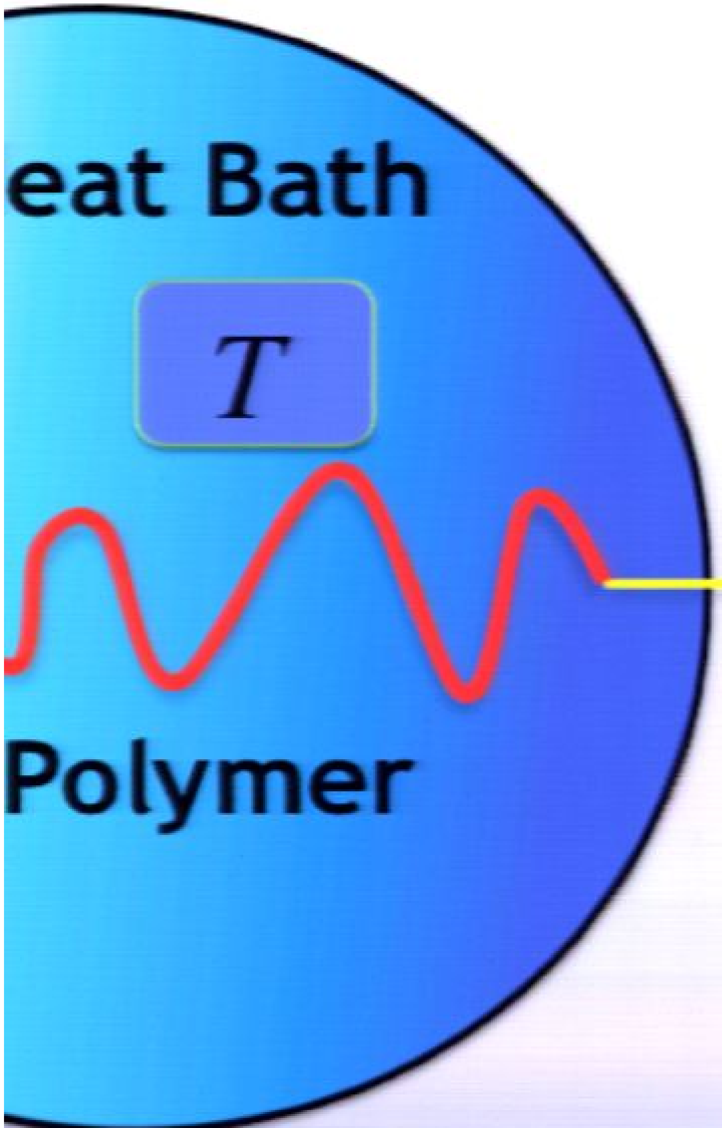


$$1/T = \partial_E S(E,x)$$

$$F/T = \partial_x S(E,x)$$

Saddle point equations

Entropic Force in Canonical Ensemble

$$Z(T,F) = \int dE dx \; \Omega(E,x) \; e^{-(E+Fx)/kT}$$

Consider a fast system with phase space volume

$$\Omega(E,x)$$

but we want to integrate out its DOF and describe it effectively by a small number of degrees of freedom .

How would we do it?

We have to make sure that the reaction forces remain the same

Conjecture:

Gravity is an adiabatic reaction force

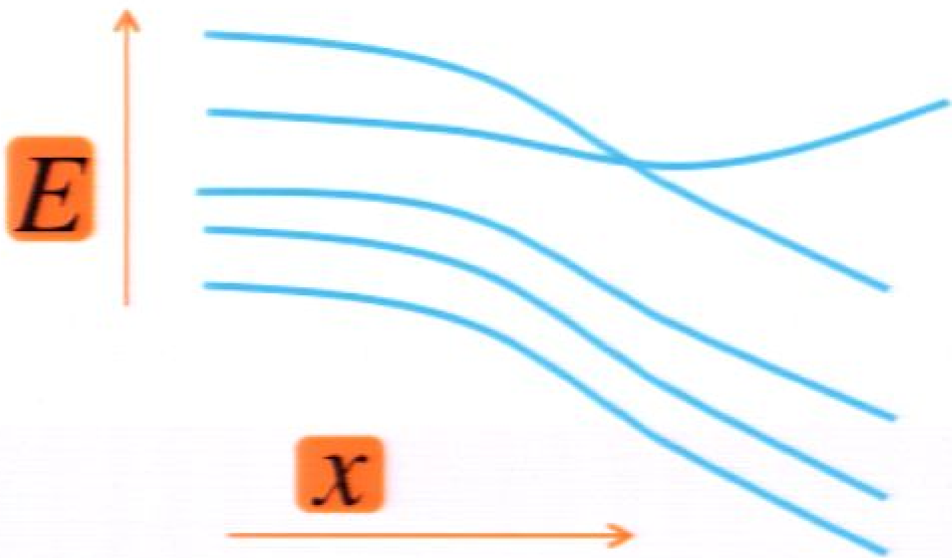
Due to a fast dynamical system underlying our universe.

Inertia (gravity) is the leading order reaction force.

The separation of time scales breaks down at horizons.

Other forces arise from higher order corrections

Berry Phase and Crossing Eigenvalues



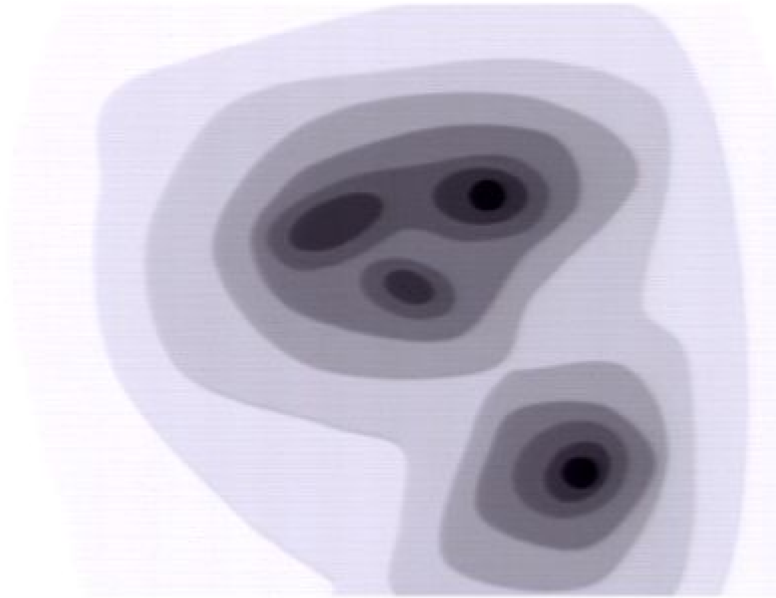
$$H = \begin{pmatrix} z & x+iy \\ x-iy & -z \end{pmatrix} = \vec{x}\cdot\vec{\sigma}$$

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

Dirac monopool

At the locus of coinciding eigenvalues one can construct a non-abelian Berry connection.

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

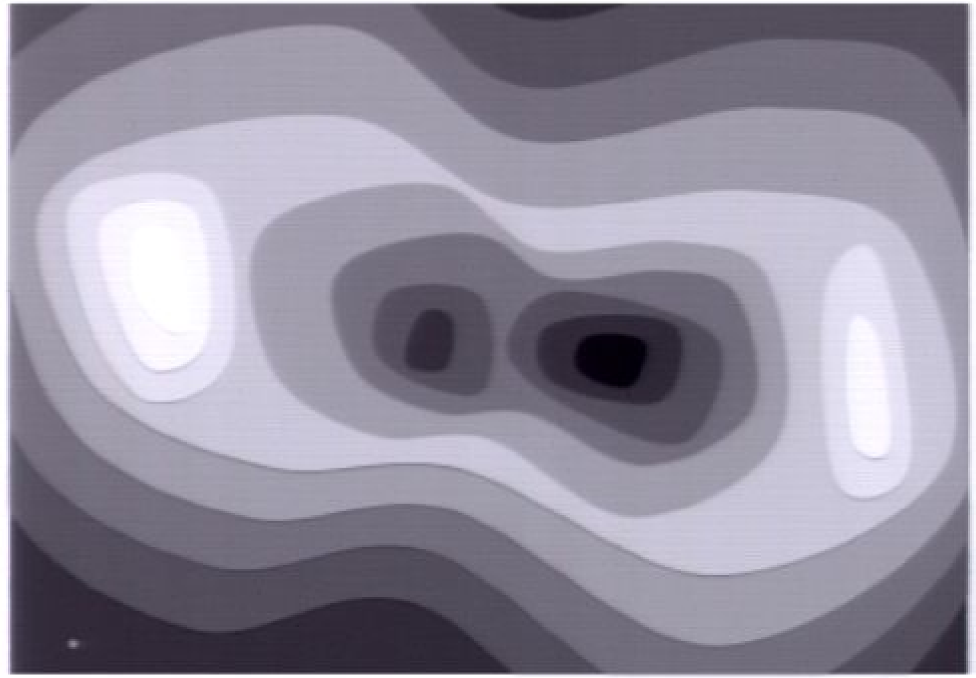


Question:

What is the total phase space volume associated with a region of space contained within a particular surface given the amount of energy inside of it?

Assumption:
We consider a quasi static situation and a region that is surrounded by an equipotential surface.

Question:



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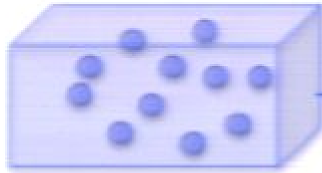
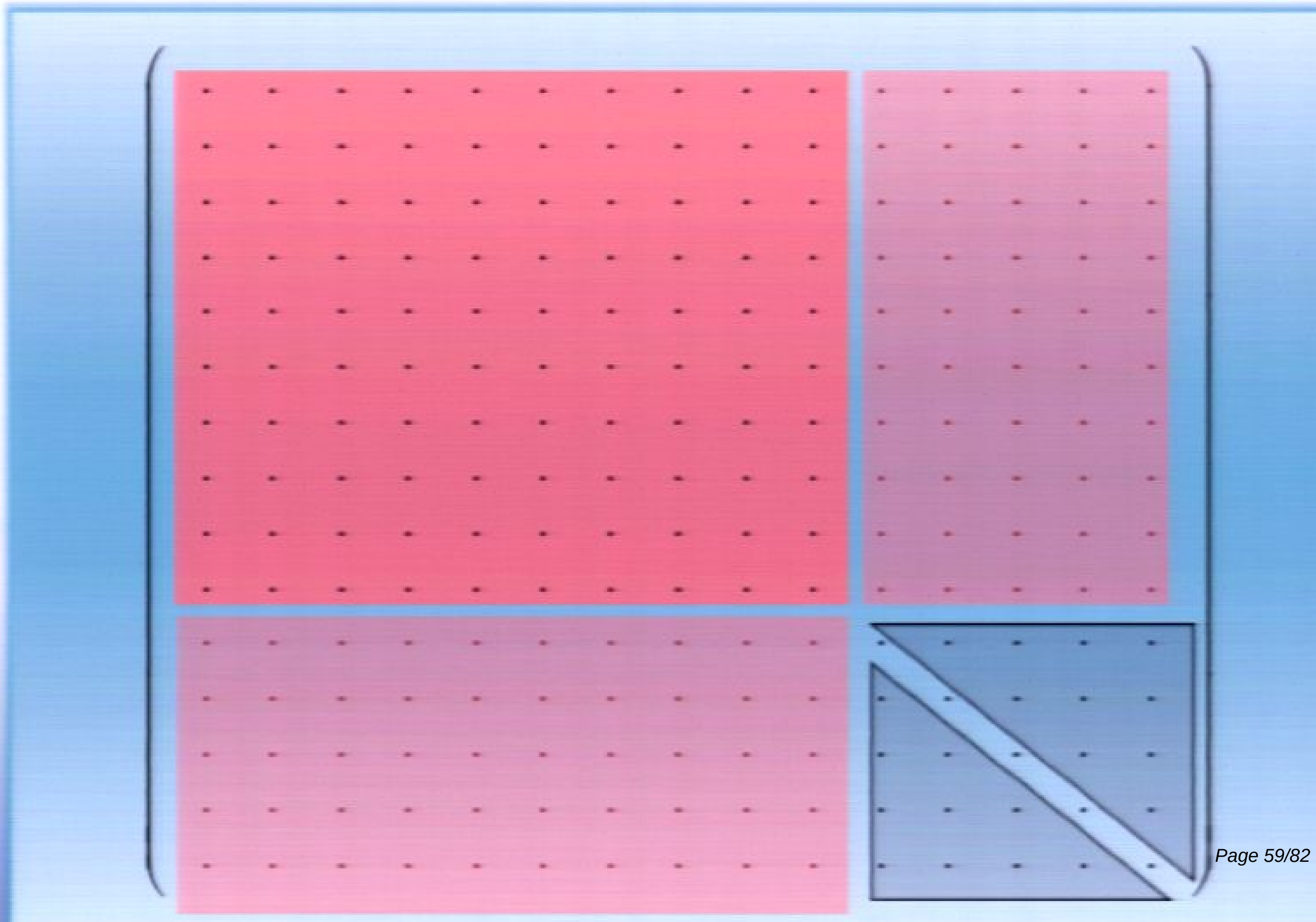
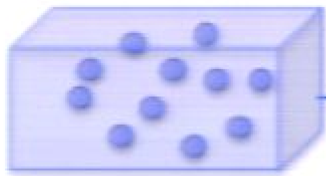
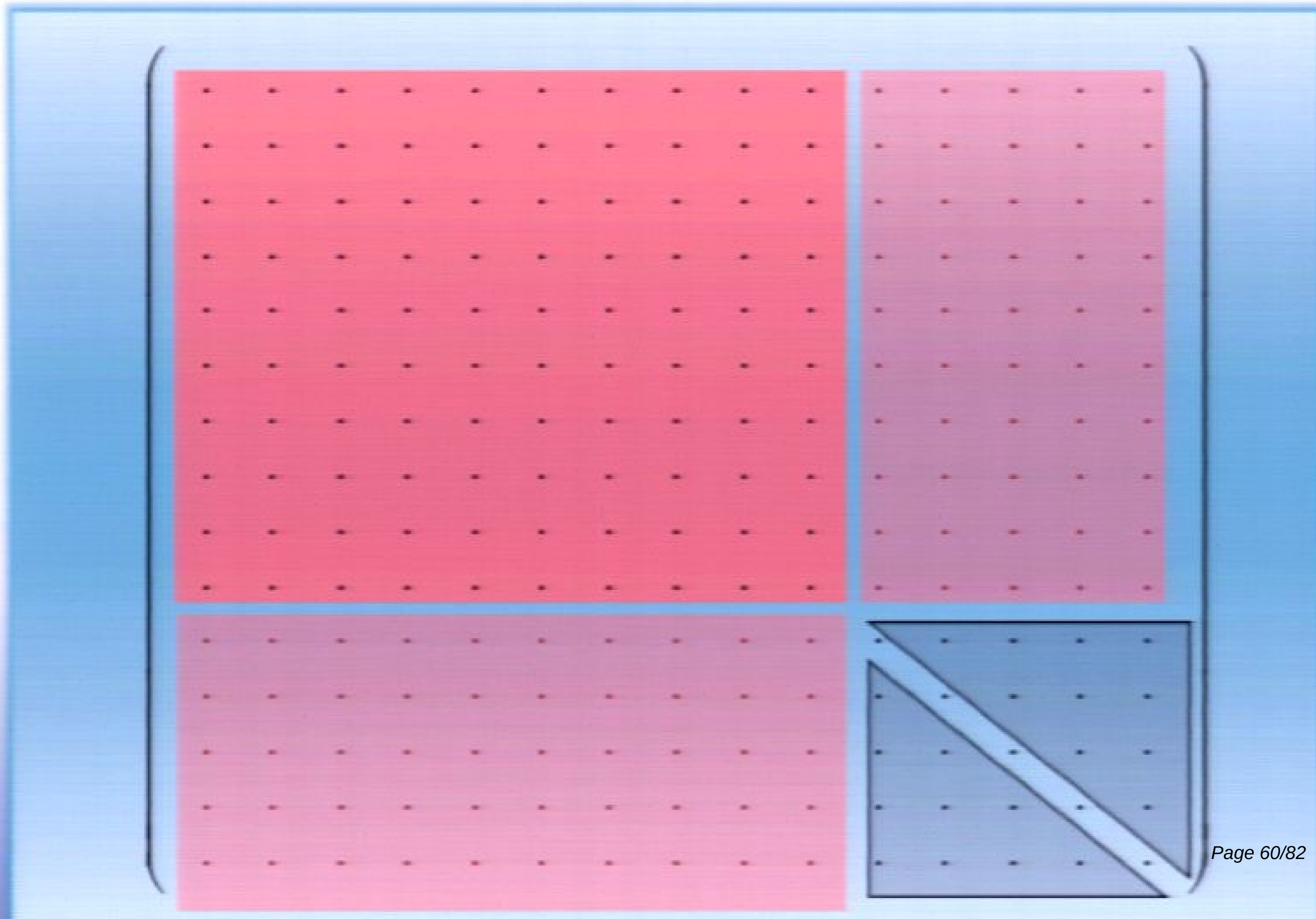
ack Hole





ack Hole





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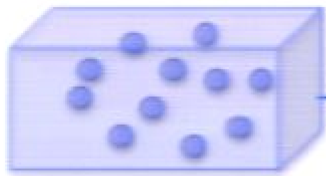

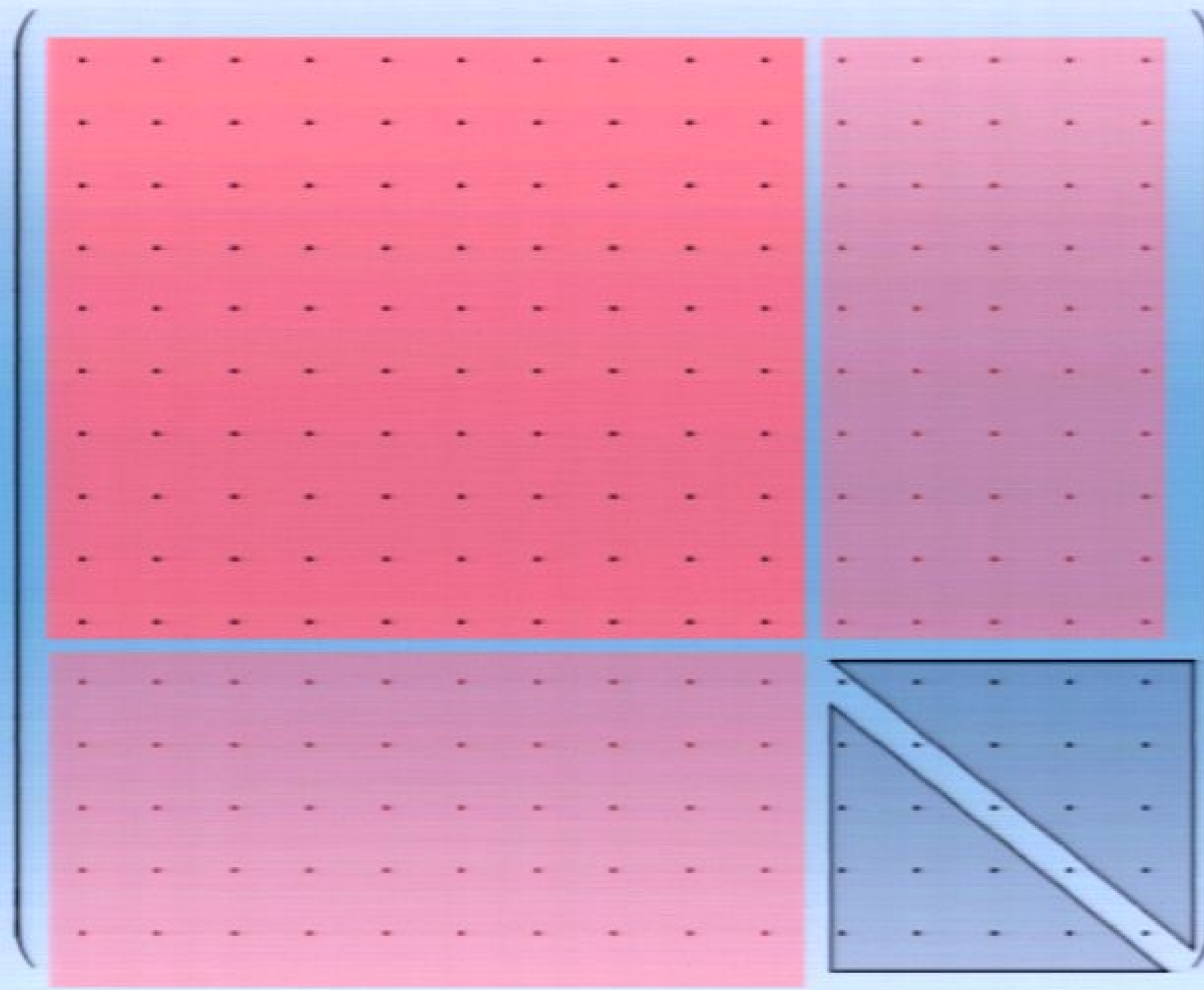

Proposal for phase space volume

$$MR \to 2L_0$$

$$\frac{A}{4G} \to 2\pi \frac{c}{12}$$

(Brown Hennaux)

Take Cardy formula

$$S = 2\pi\sqrt{\frac{c}{6}L_0}$$

Proposal

$$\frac{24L_0}{c} = \frac{16\pi GMR}{A} = 2\Phi$$

For equipotential surfaces (= constant redshift)

$$S = \frac{A}{4G}v$$

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Cosmological Horizon

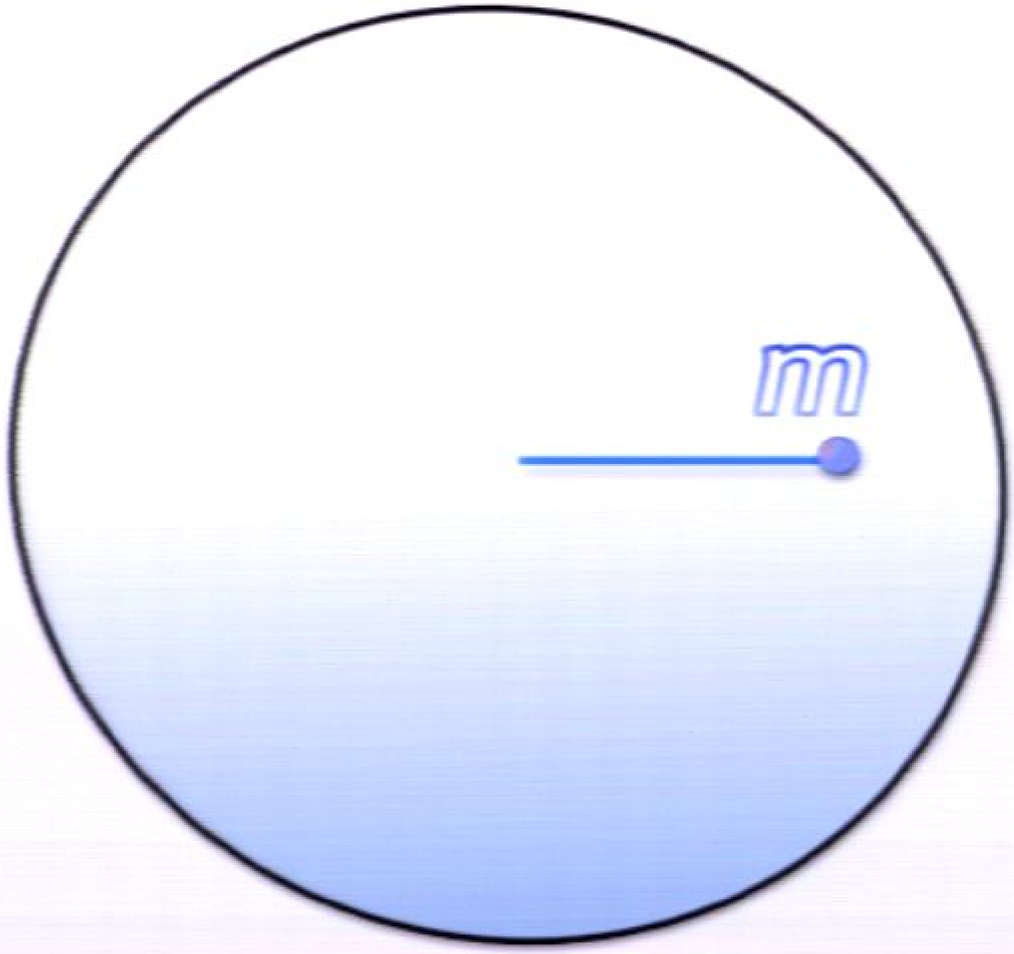
De Sitter Space

$$T = \frac{H_0}{2\pi}$$

$$S = \frac{A}{4G} v$$

$$v = H_0 R$$

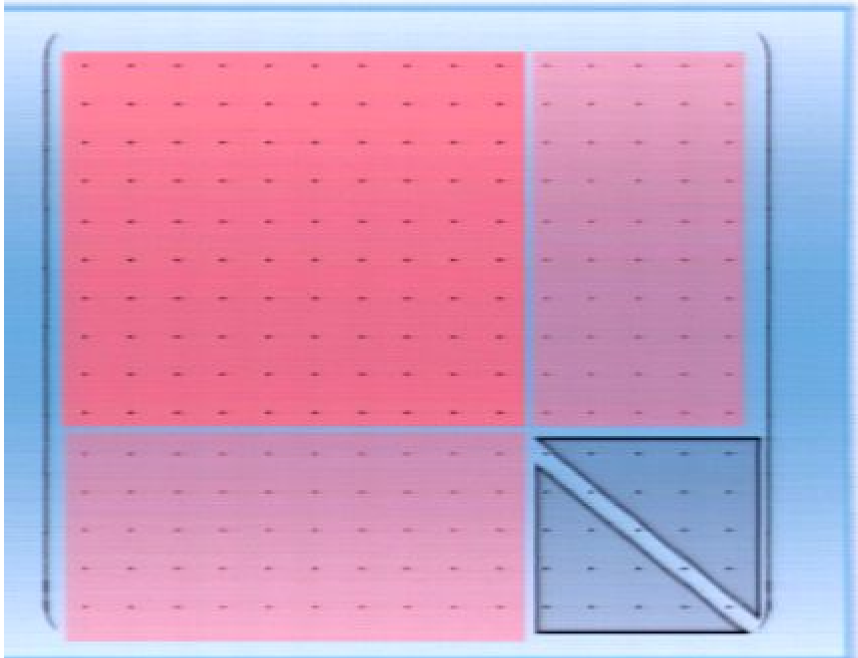
$$X = \begin{pmatrix} x_{11} & .. & x_{1N} & z_1 \\ \vdots & \vdots\vdots & \vdots & \vdots \\ x_{N1} & .. & x_{NN} & z_N \\ z_1^* & .. & z_N^* & xI \end{pmatrix}$$

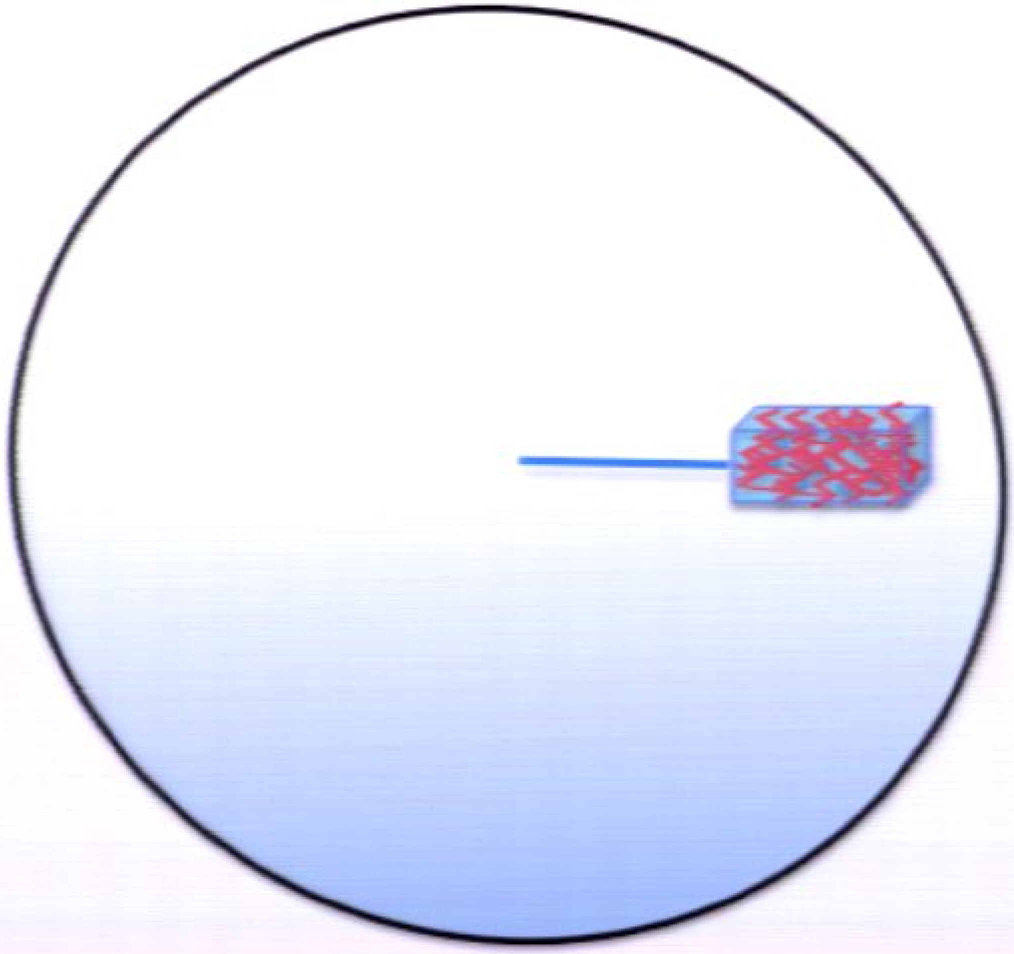


$$F = T\frac{\partial S}{\partial x}$$

$$T = \frac{\hbar H_0}{2\pi} \Rightarrow \frac{\partial S}{\partial x} = 2\pi\frac{mv}{\hbar}$$

$$v = H_0 r$$



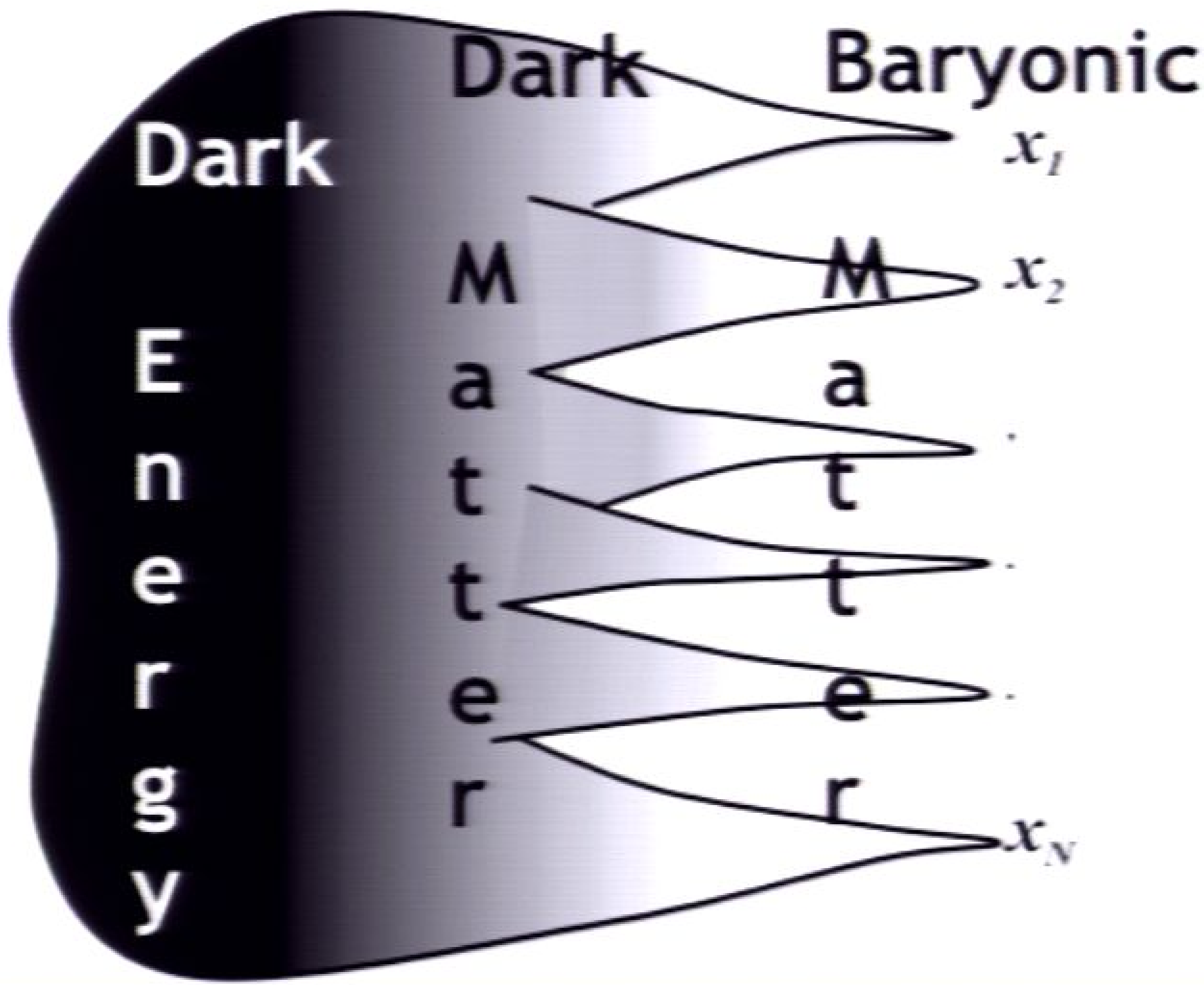


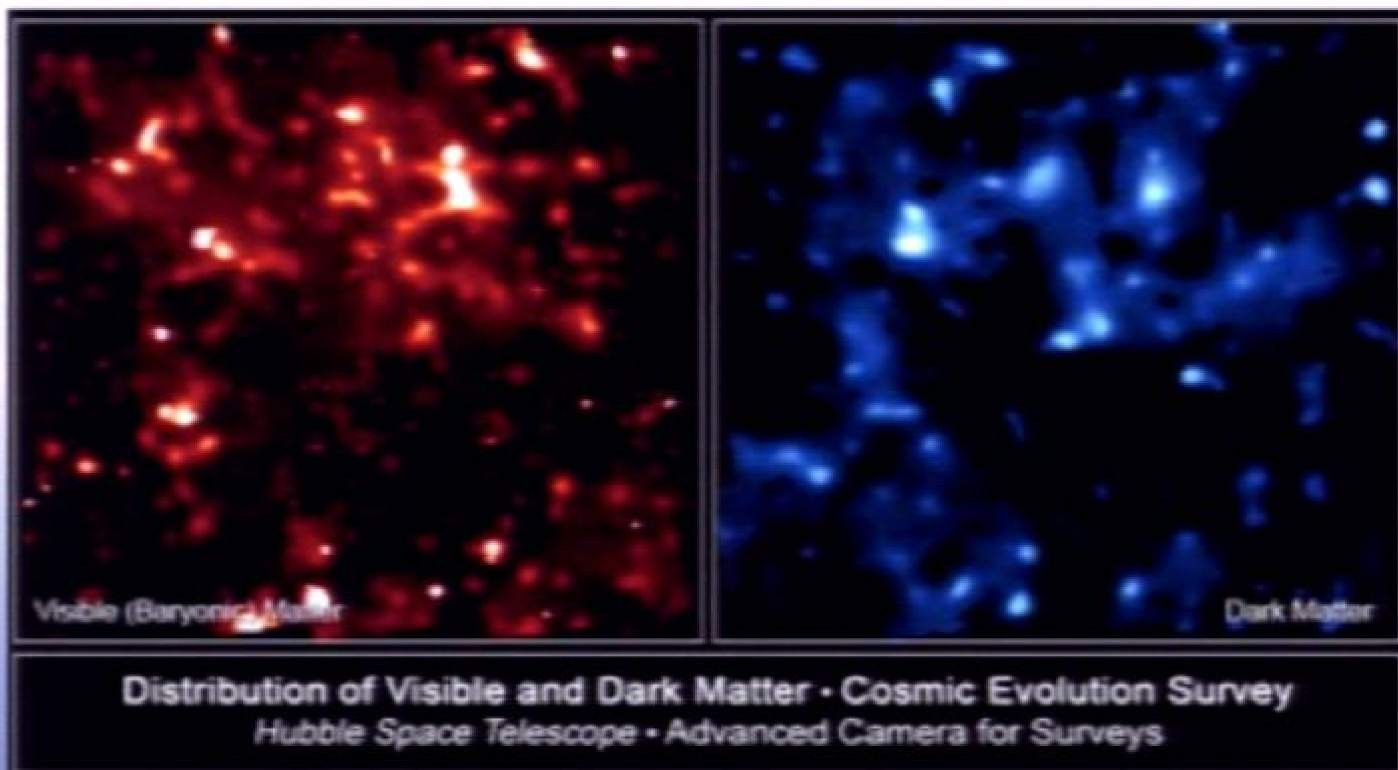
$$N = \frac{McR}{\hbar}$$

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

At horizons space and time dissappear.

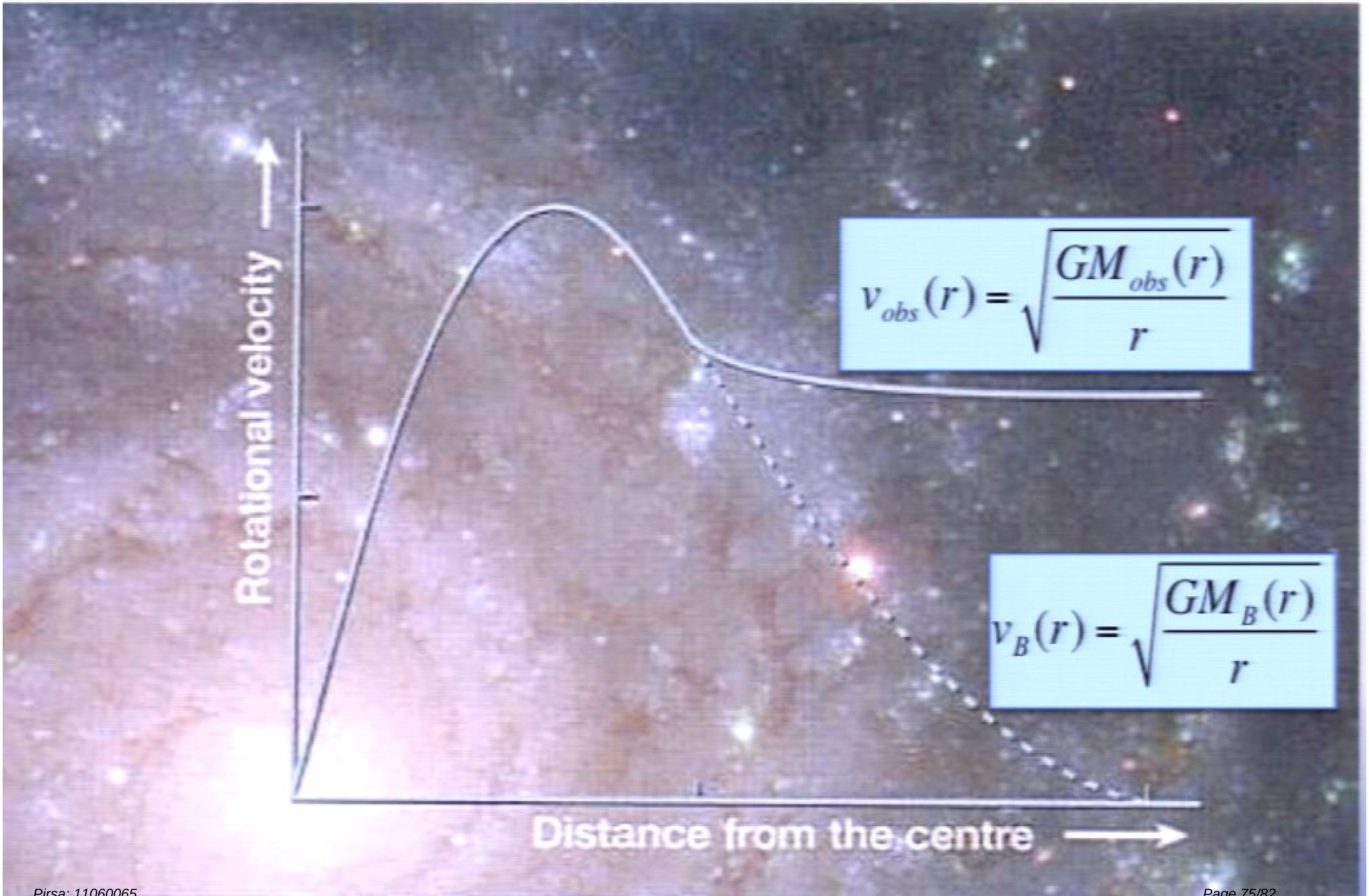
PHASE SPACE



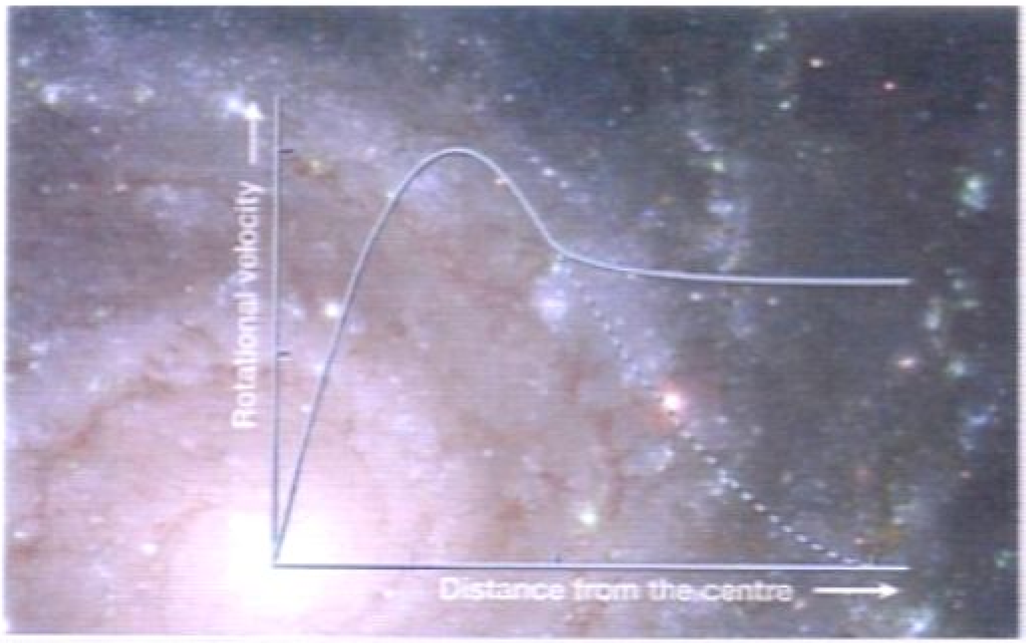

Visible (Baryonic) Matter
Dark Matter
Distribution of Visible and Dark Matter • Cosmic Evolution Survey
Hubble Space Telescope • Advanced Camera for Surveys

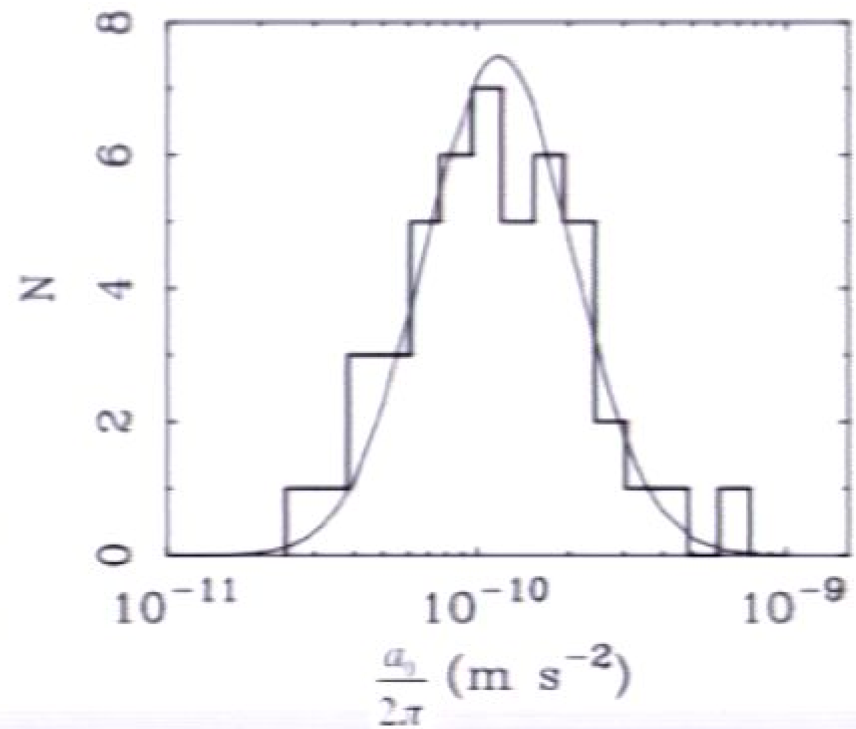
Galaxy rotation curves

$$\frac{v(r)^2}{r} = \frac{GM(r)}{r^2}$$


Rotational velocity
$v_{obs}(r) = \sqrt{\frac{GM_{obs}(r)}{r}}$
$v_B(r) = \sqrt{\frac{GM_B(r)}{r}}$
Distance from the centre

Baryonic Tully-Fisher relation



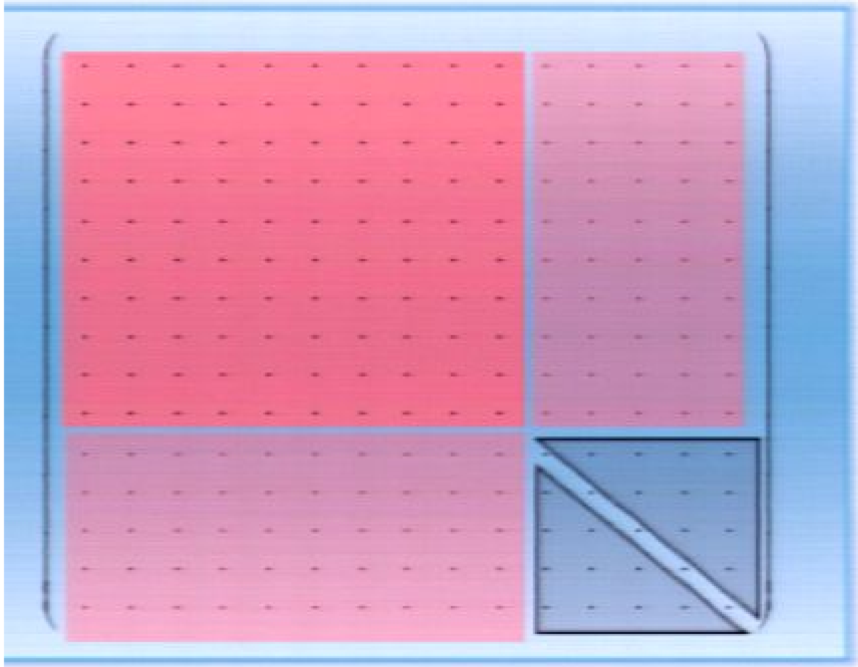


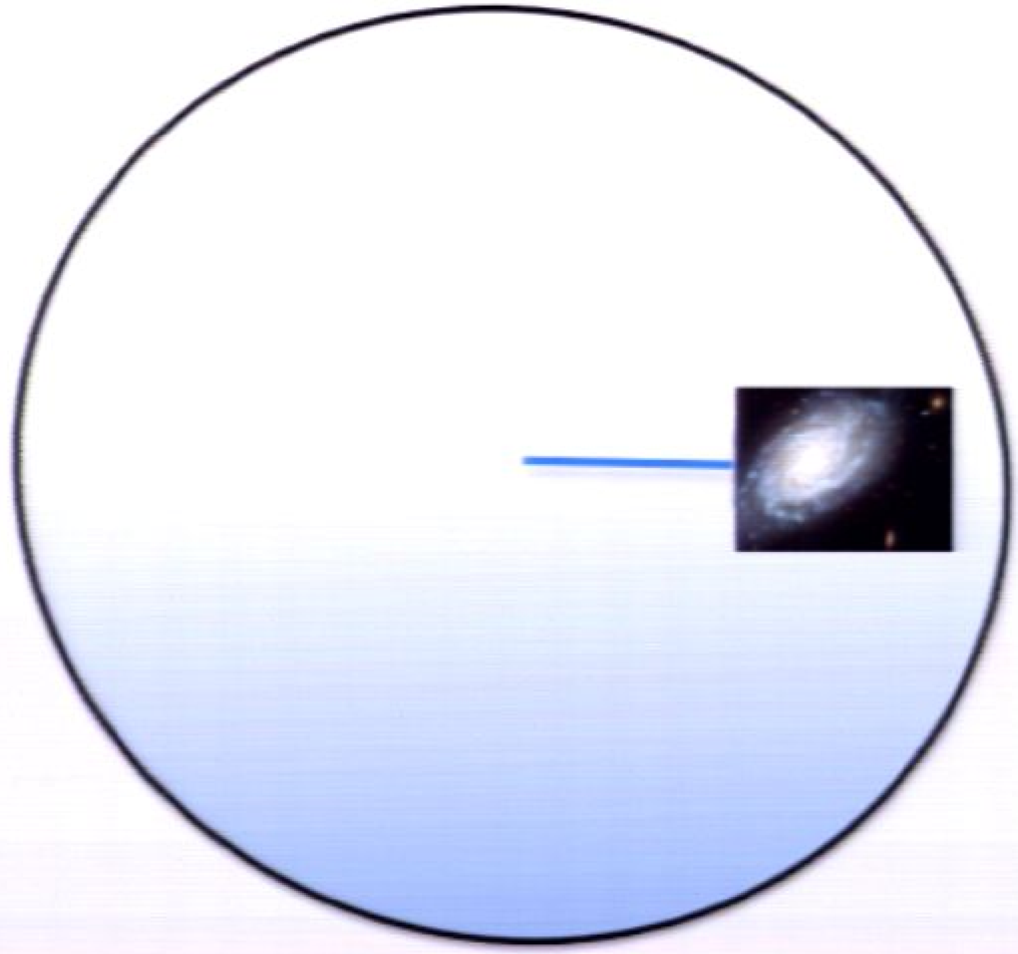
$$\frac{a_0}{2\pi} = 1.24 \pm 0.14 \cdot 10^{-10} \text{ m/s}$$

$$V_{obs}^4 = GM_B \frac{a_0}{2\pi}$$

$$a_0 \approx cH_0$$

Why?





$$N = \frac{McR}{\hbar}$$

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

Fluctuations in the gravitational field

$$E_{grav} = \frac{1}{8\pi G}\int |\nabla\Phi|^2$$

$$\langle \nabla\Phi\nabla\Phi \rangle = \int [d\Phi] e^{-\frac{1}{8\pi GkT}\int |\nabla\Phi|^2} \nabla\Phi\nabla\Phi$$

$$\langle \nabla\Phi\nabla\Phi \rangle = \frac{GkT}{d^3}$$

d = short distance cut off

Fluctuations in the gravitational field

$$\langle \nabla\Phi\nabla\Phi \rangle = \frac{GkT}{d^3}$$

d = short distance cut off

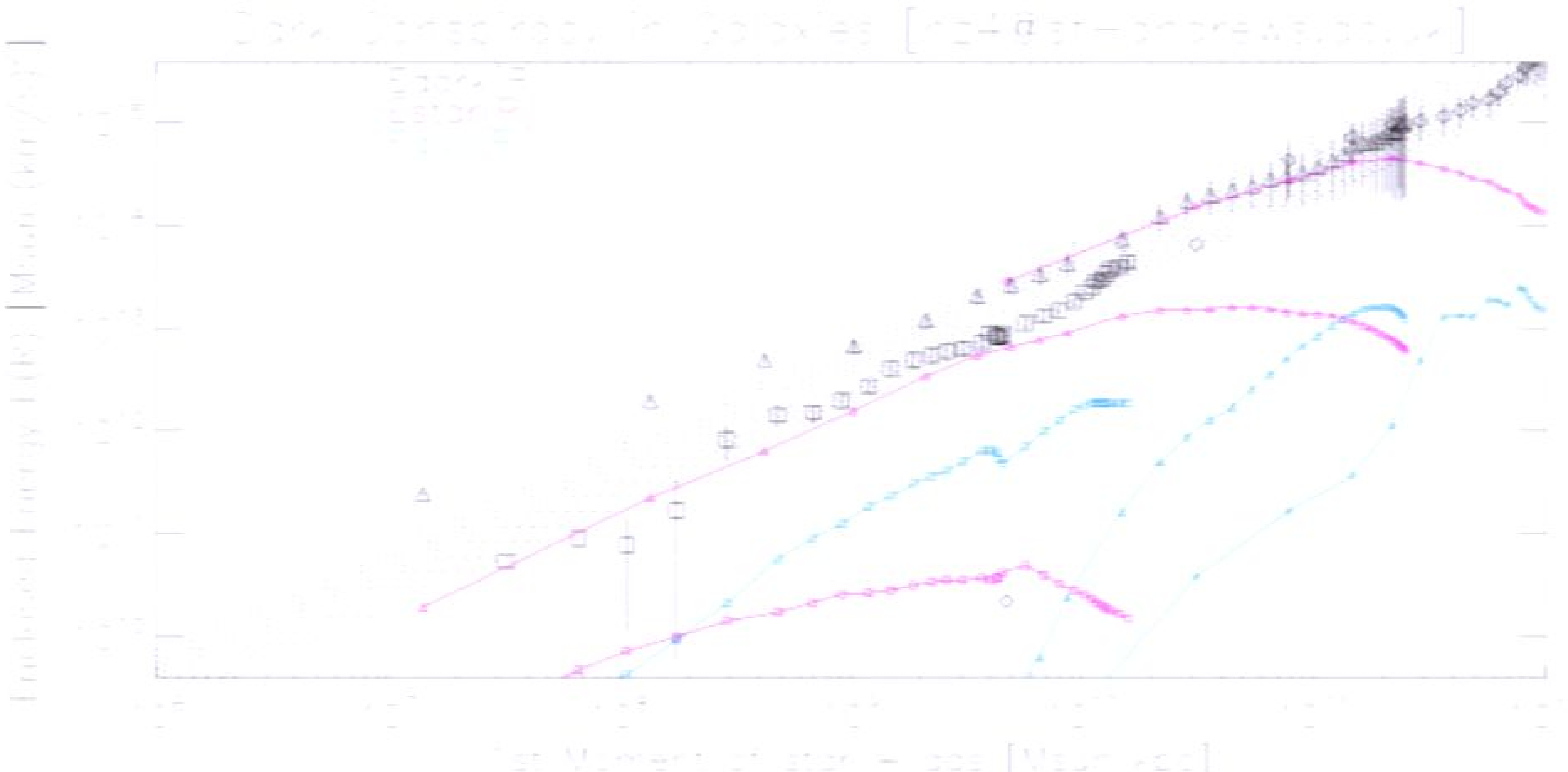
$$N = \frac{R^3}{d^3}$$

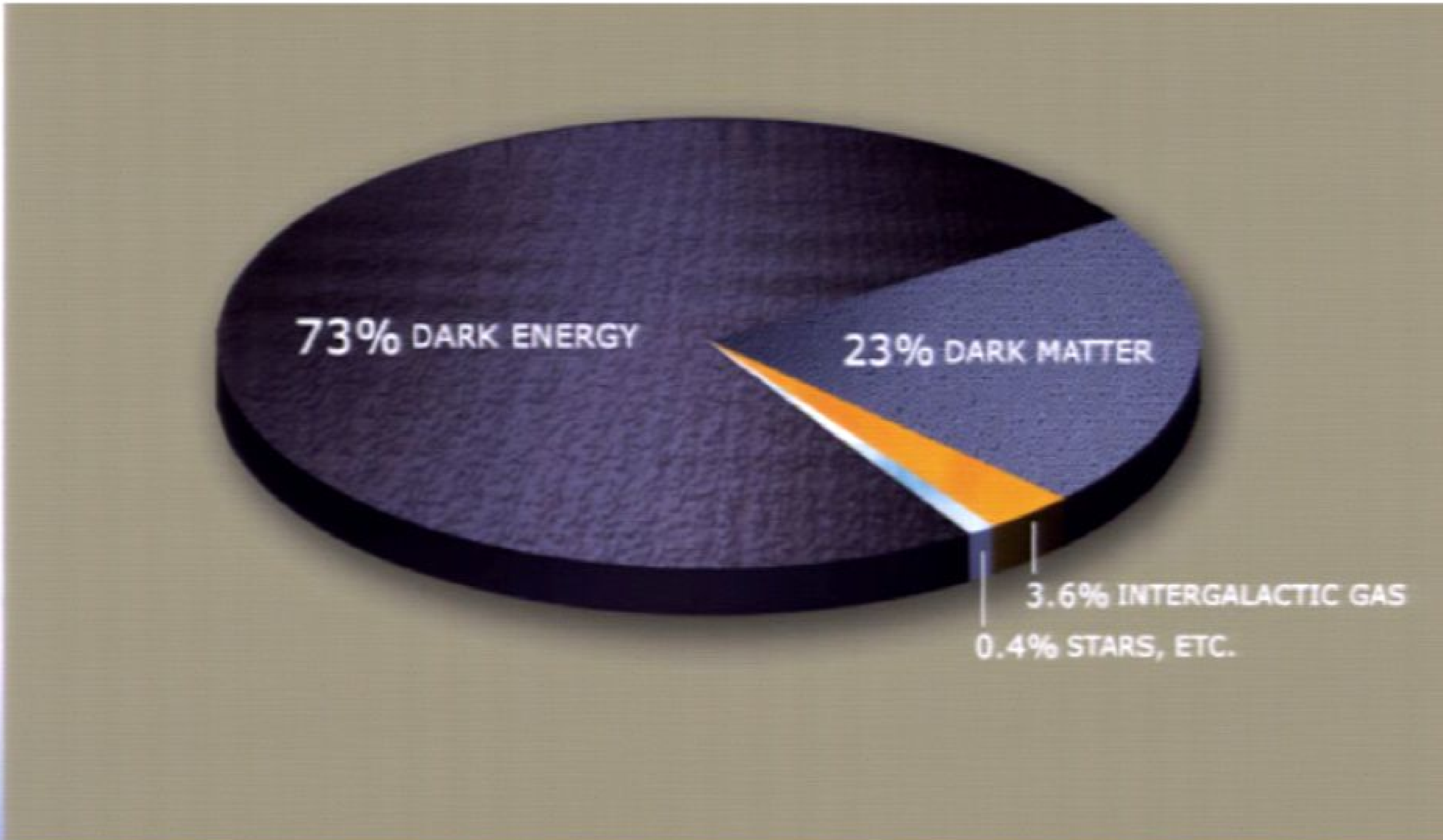
N= maximum number of degrees

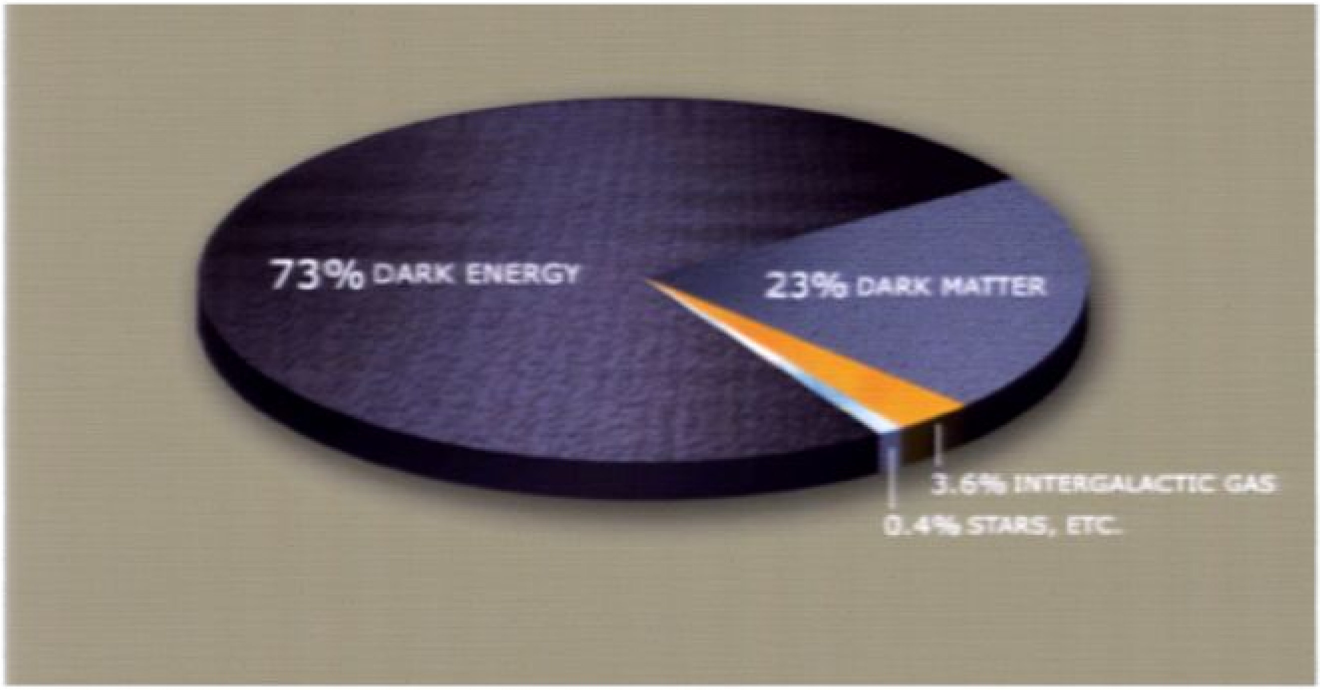
Take N = Bekenstein bound

$$N = \frac{McR}{\hbar}$$

$$\langle \nabla\Phi\nabla\Phi \rangle = \frac{GMkT}{\hbar R^2}$$




73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.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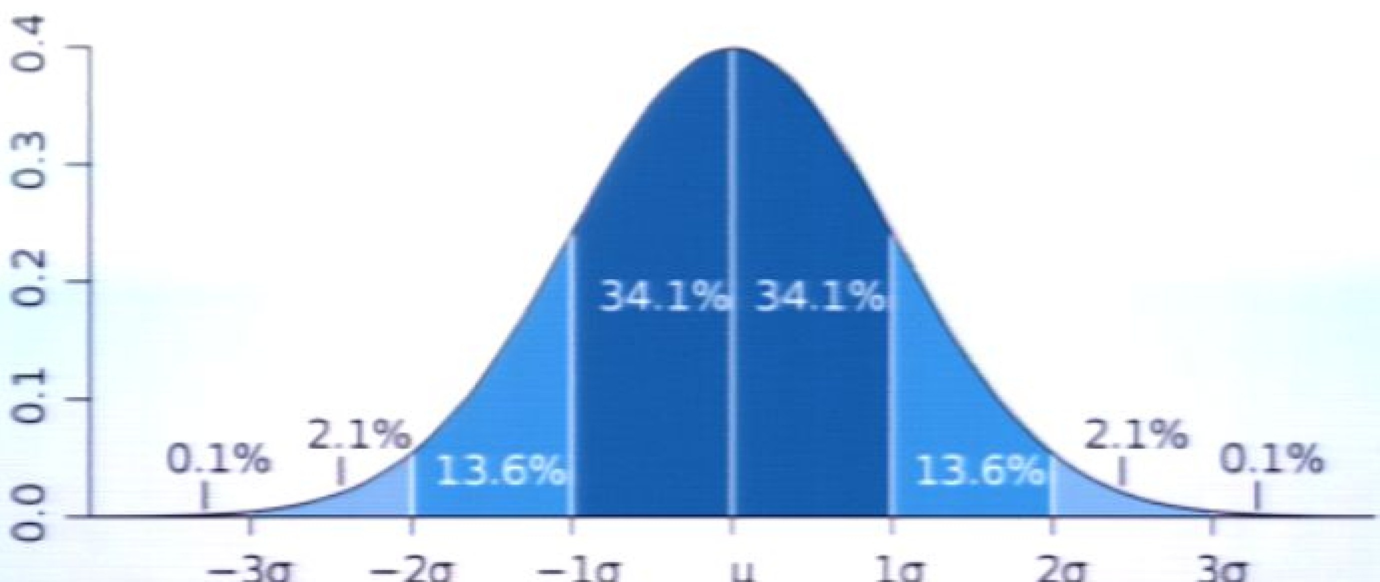
0.0
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1σ
2σ
3σ