Title: From Emergent Gravity to Dark Energy and Dark Matter

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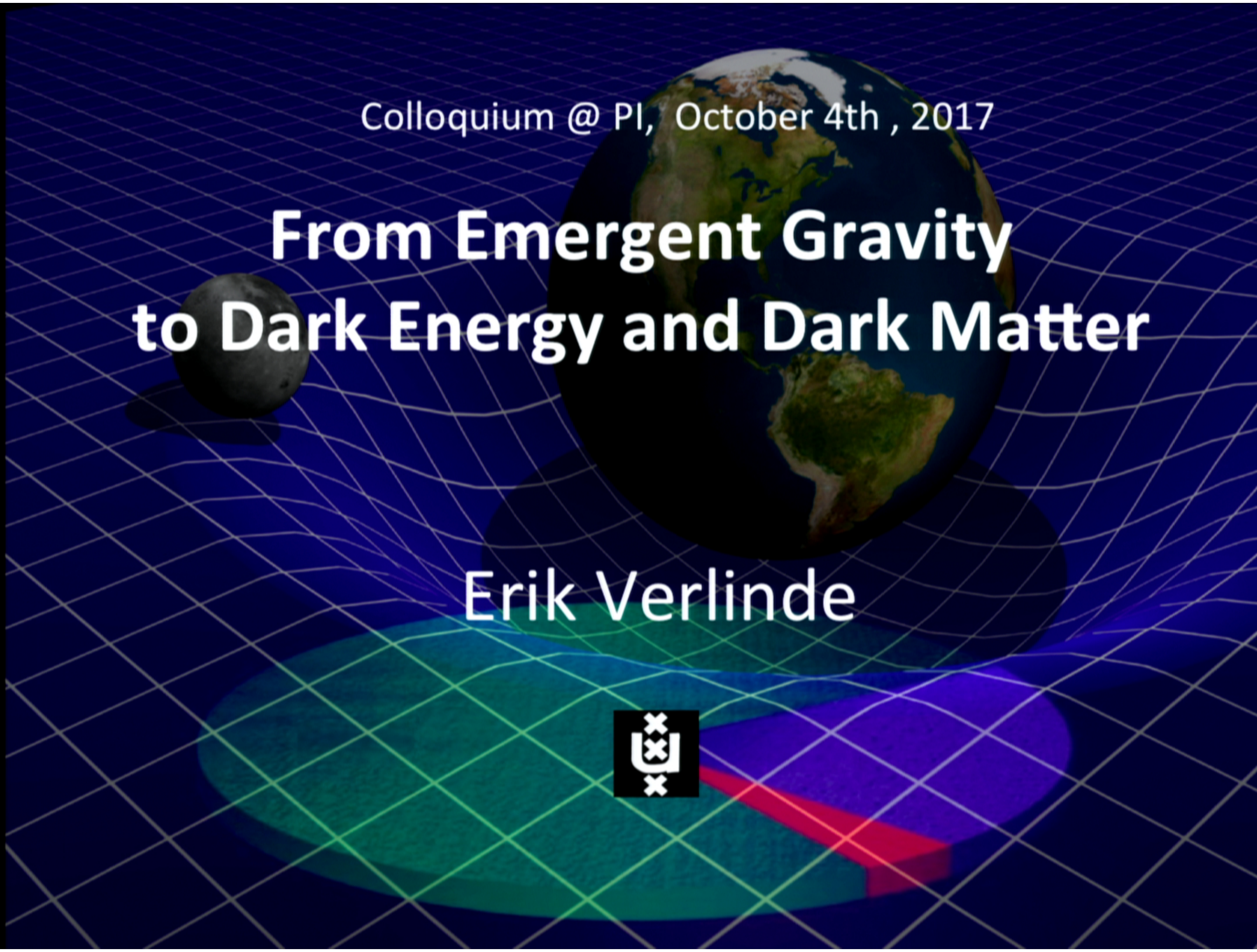
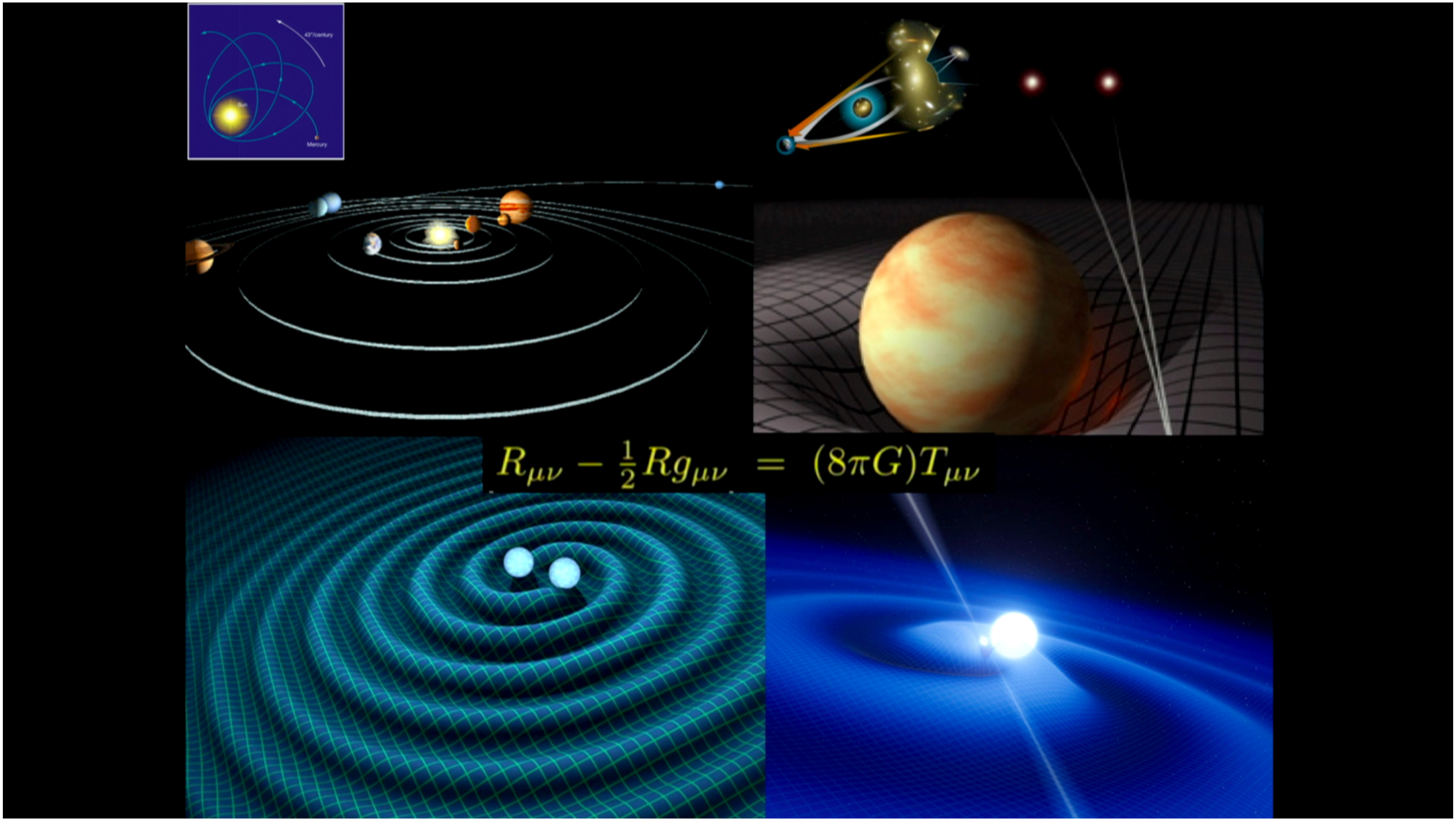
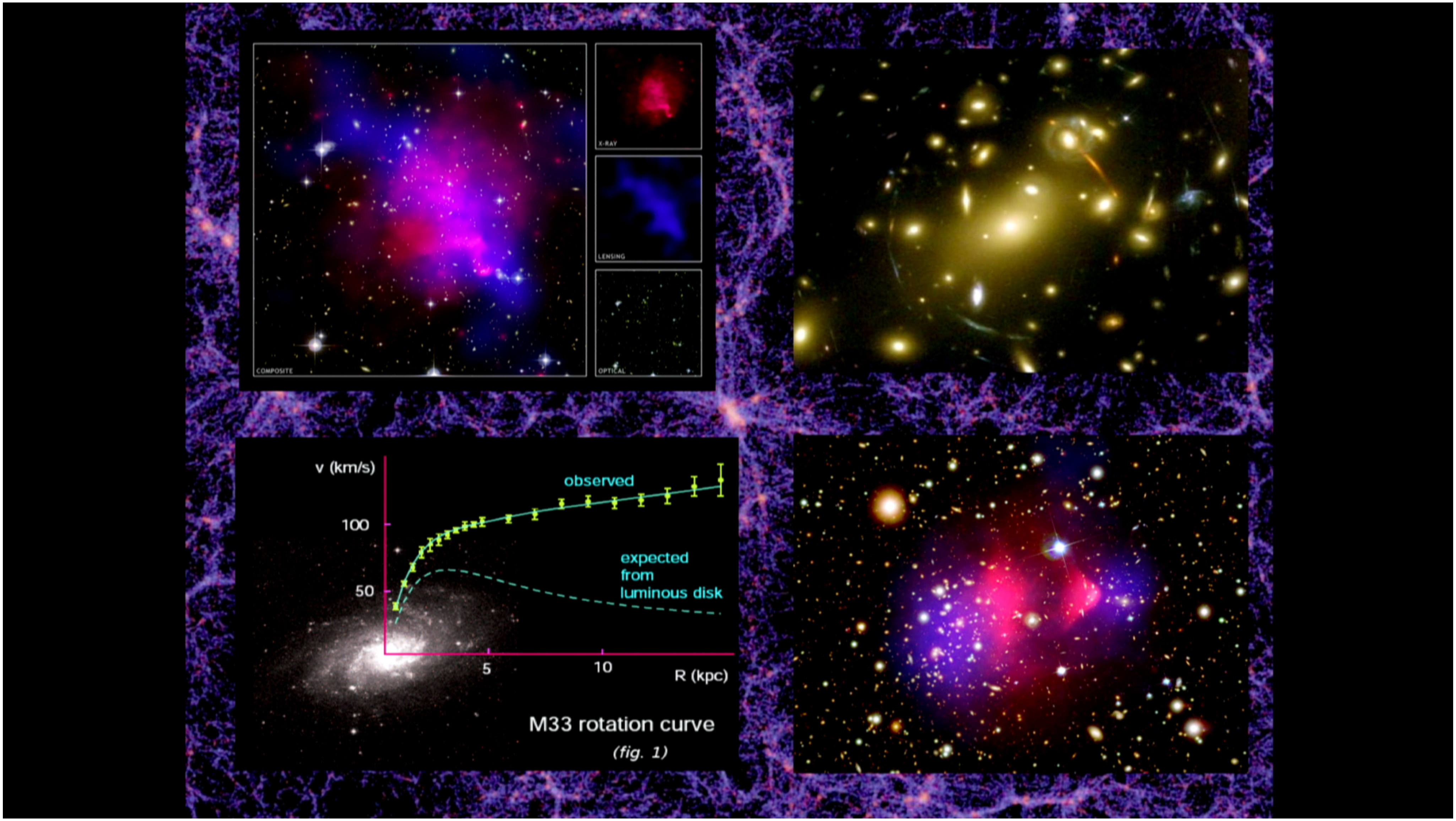
Abstract: <p>The observed deviations from the laws of gravity of Newton and Einstein in galaxies and clusters can logically speaking be either due to the presence of unseen dark matter particles or due to a change in the way gravity works in these situations. Until recently there was little reason to doubt that general relativity correctly describes gravity in all circumstances. In the past few years insights from black hole physics and string theory have lead to a new theoretical framework in which the gravitational laws are derived from the quantum entanglement of the microscopic information that is underlying space-time. An essential ingredient in the derivation is of the Einstein equations is that the vacuum entanglement obeys an area law, a condition that is known to hold in Anti-de Sitter space due to the work of Ryu and Takayanagi. We will argue that in de Sitter space due to the positive dark energy, that the microscopic entanglement entropy also contains also a volume law contribution in addition to the area law. This volume law contribution is related to the thermal properties of de Sitter space and leads to a total entropy that precisely matches the Bekenstein-Hawking formula for the cosmological horizon. We study the effect of this extra contribution on the emergent laws of gravity, and argue that it leads to a modification compared to Einstein gravity. We provide evidence for the fact that this modification explains the observed phenomena in galaxies and clusters currently attributed to dark matter.</p>

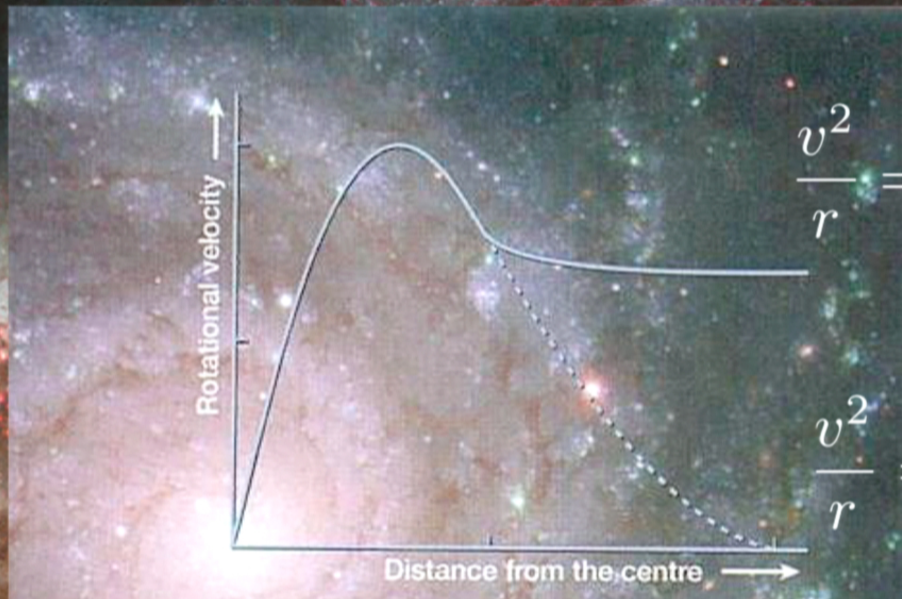


Colloquium @ PI, October 4th , 2017
From Emergent Gravity
to Dark Energy and Dark Matter
Erik Verlinde



$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \;=\; (8\pi G) T_{\mu\nu}$$


COMPOSITE
X-RAY
LENSING
OPTICAL
v (km/s)
100
50
5
10
R (kpc)
observed
expected
from
luminous disk
M33 rotation curve
(fig. 1)



$$\frac{v^2}{r} = \frac{GM_B}{r^2} + \frac{GM_D}{r^2}$$

$$\frac{v^2}{r} = \frac{GM_B}{r^2}$$

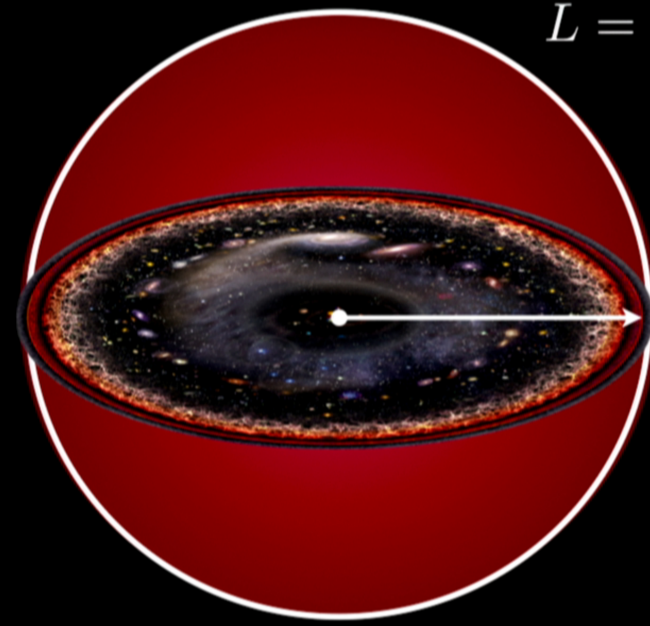
Empirically DM-effects appear when

$$\frac{GM_B}{r^2} < \frac{cH_0}{2}$$

de Sitter Space

cosmological horizon

$$L = \frac{c}{H_0}$$



$$ds^2 = -\left(1 - R^2/L^2\right) dt^2 + \frac{dR^2}{1 - R^2/L^2} + R^2 d\Omega^2$$

Black Hole Thermodynamics

The Laws of Gravity take the form of the Laws of Thermodynamcics

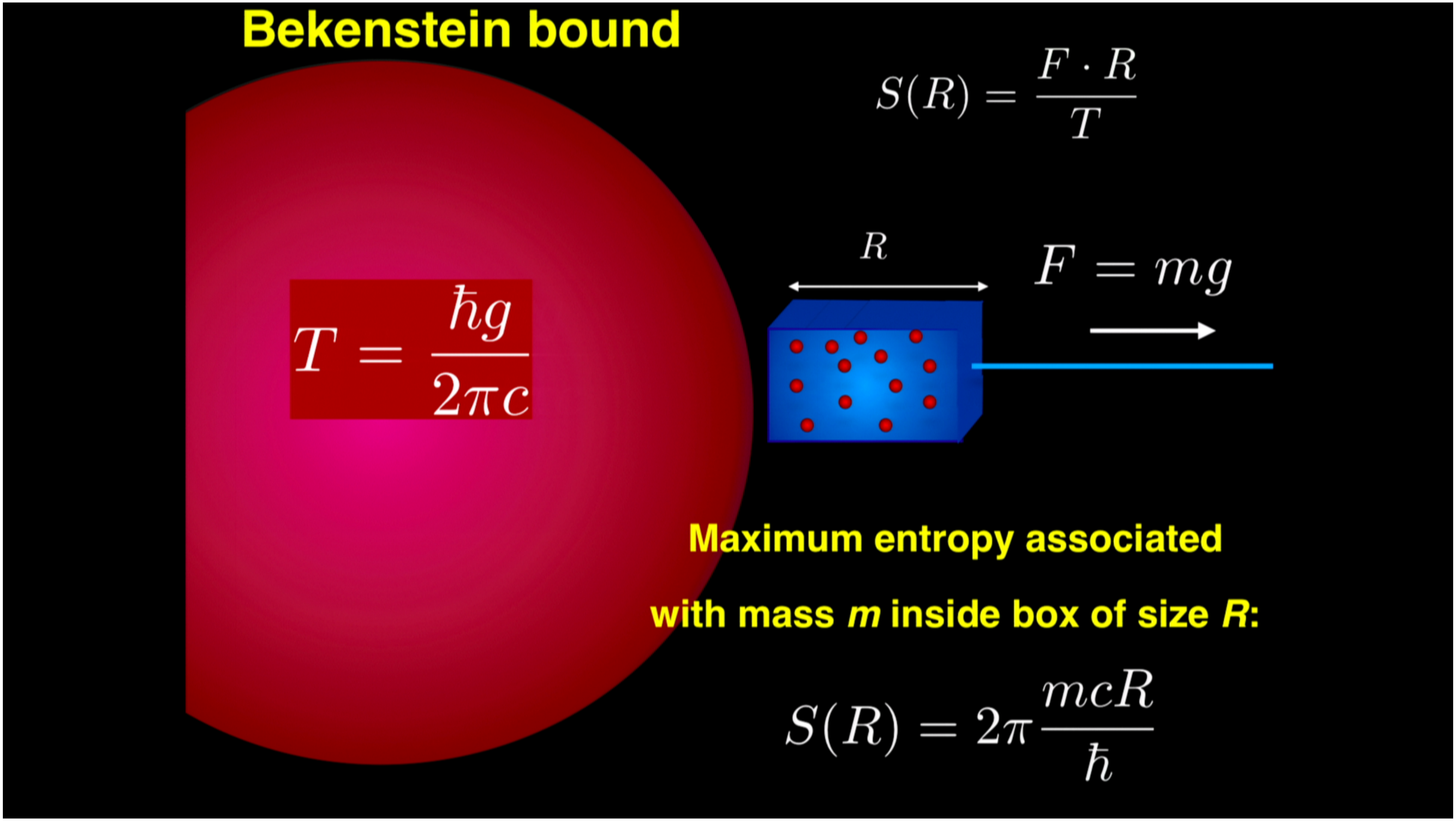
1st Law

$$dM = \frac{g}{2\pi}\frac{dA}{4G}$$

$$dE = T dS$$

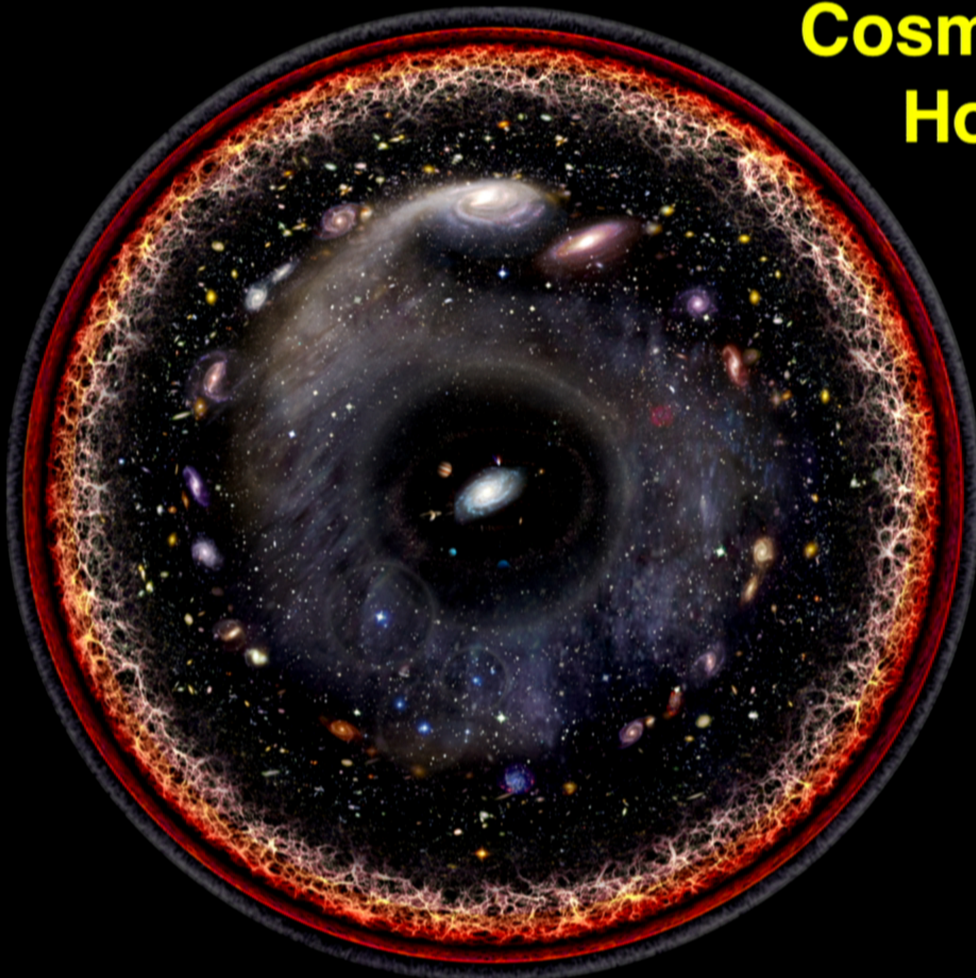
$$S = k_B \frac{A c^3}{4G\hbar}$$

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


Bekenstein bound
$S(R) = \frac{F \cdot R}{T}$
$T = \frac{\hbar g}{2\pi c}$
R
$F = mg$
Maximum entropy associated
with mass *m* inside box of size *R*:
$S(R) = 2\pi \frac{mcR}{\hbar}$

Cosmological Horizon

$$L = \frac{c}{H_0}$$



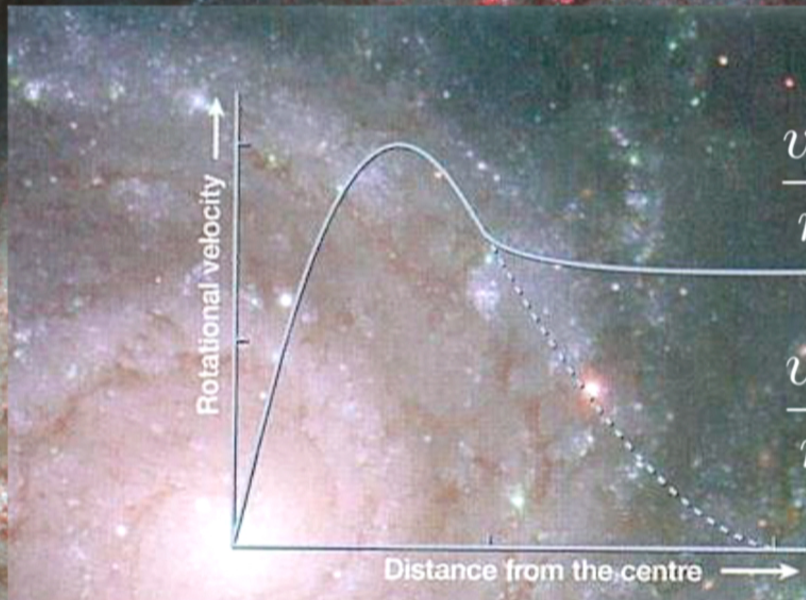
Total Entropy

$$S(L) = k_B \frac{A(L)c^3}{4G\hbar}$$

Temperature

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

Entropy and Temperature are due to positive dark energy.



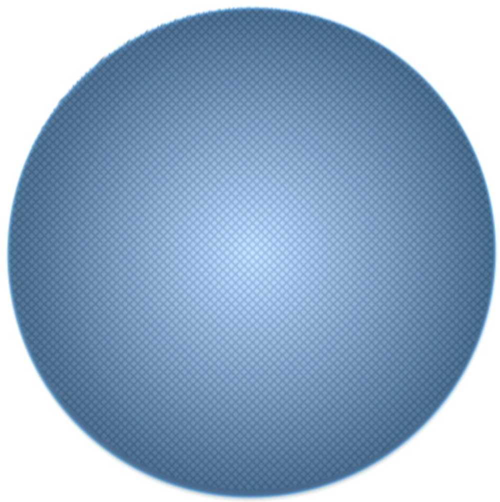
$$\frac{v^2}{r} = \frac{GM_B}{r^2} + \frac{GM_D}{r^2}$$

$$\frac{v^2}{r} = \frac{GM_B}{r^2}$$

Empirically DM-effects appear when

$$\frac{GM}{r^2} < \frac{cH_0}{2} \qquad \frac{Mc^2}{\hbar H_0/2\pi} < \frac{Ac^3}{4G\hbar}$$

Black hole horizon



Bekenstein-Hawking Entropy

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

Hawking temperature

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

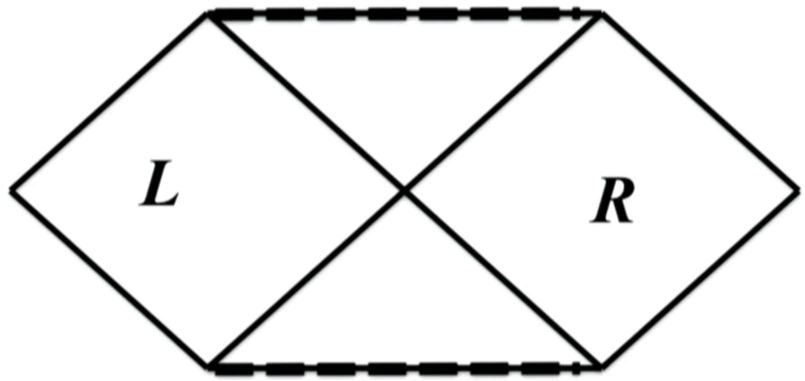
$\kappa = \text{surface gravity}$

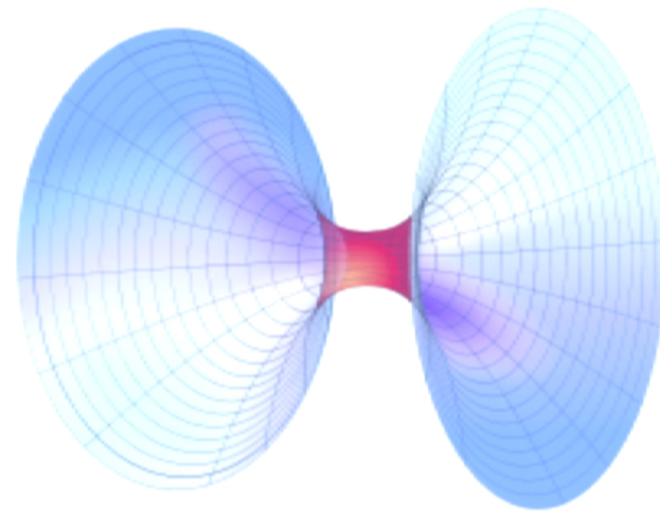
Two possible interpretations

S = log(# black hole microstates)

S = entanglement entropy of spacetime vacuum

EPR=ER: for two-sided horizon





Microscopic state:

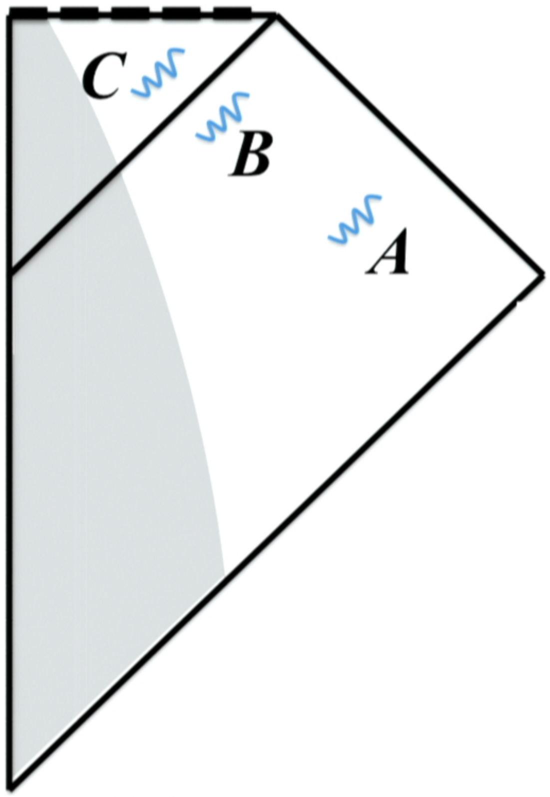
$$|vac\rangle_{BH} = \frac{1}{\sqrt{Z}} \sum_i |E_i\rangle_L |E_i\rangle_R e^{-\beta E_i/2}$$

Entanglement ⇔ Connectivity of spacetime:

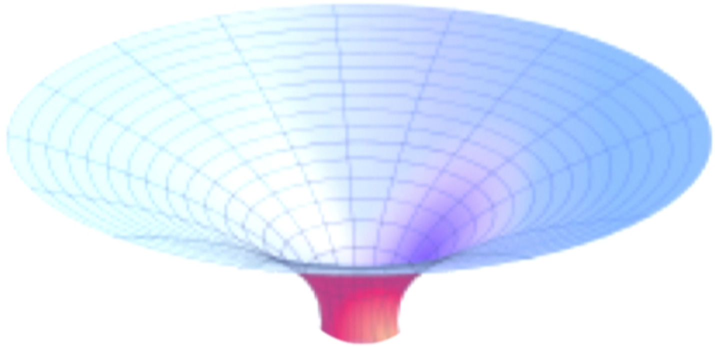
$$S_{ent} = \frac{A}{4G\hbar}$$

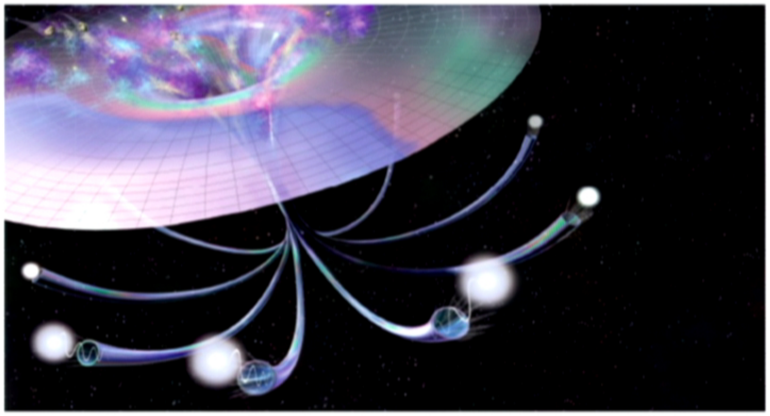
Van Raamsdonk
Maldacena-Susskind

EPR=ER: for one-sided horizon



Maldacena
Susskind

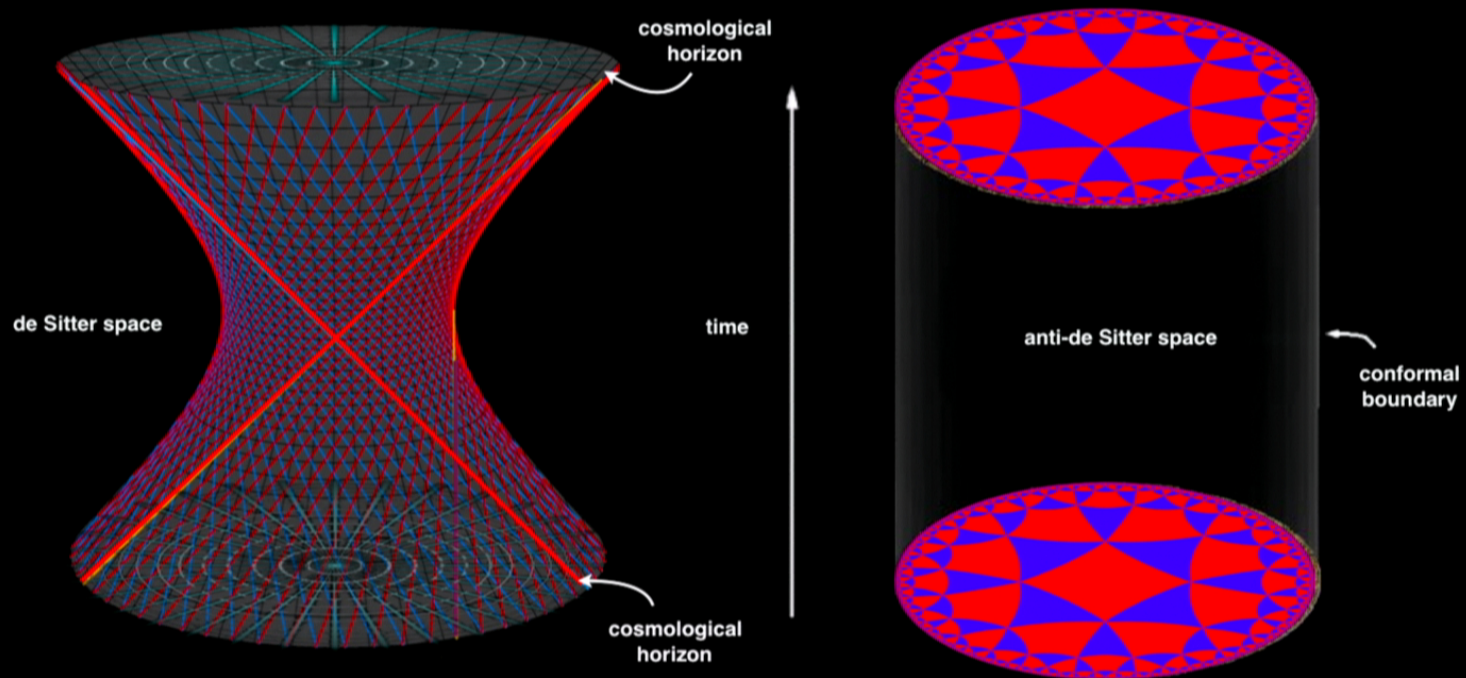




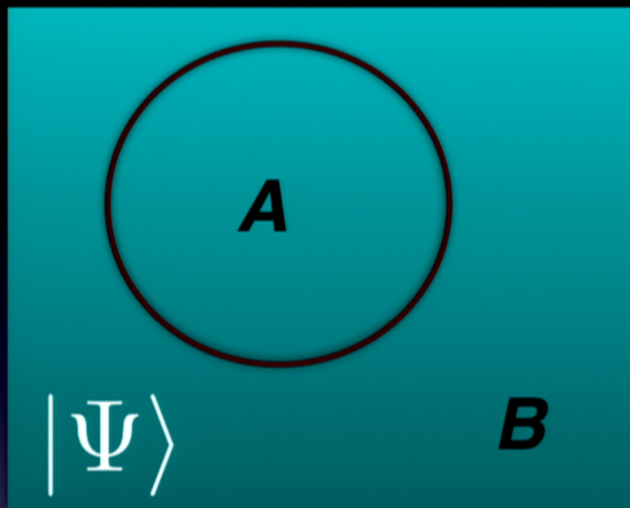
horizon of physical black hole:
Thermalization => long range
Entanglement.

(Anti-) de Sitter space

$$ds^2 = -(1 \pm R^2/L^2)dt^2 + \frac{dR^2}{1 \pm R^2/L^2} + R^2 d\Omega^2$$



Entanglement entropy

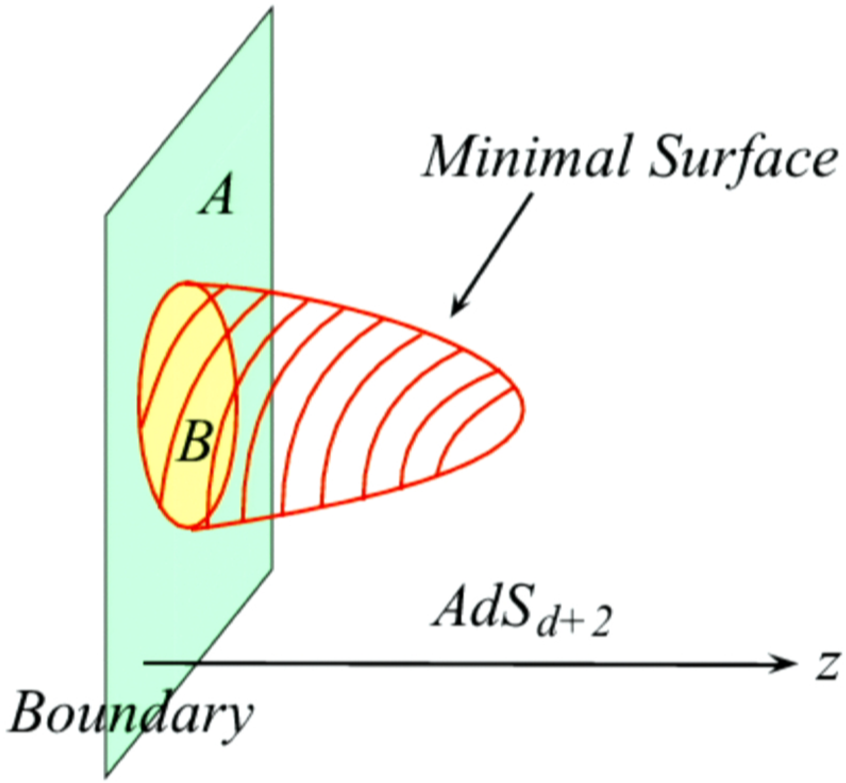


$$\rho_A = \mathrm{tr}_{\mathcal{H}_B}\big(|\Psi\rangle\langle\Psi|\big)$$

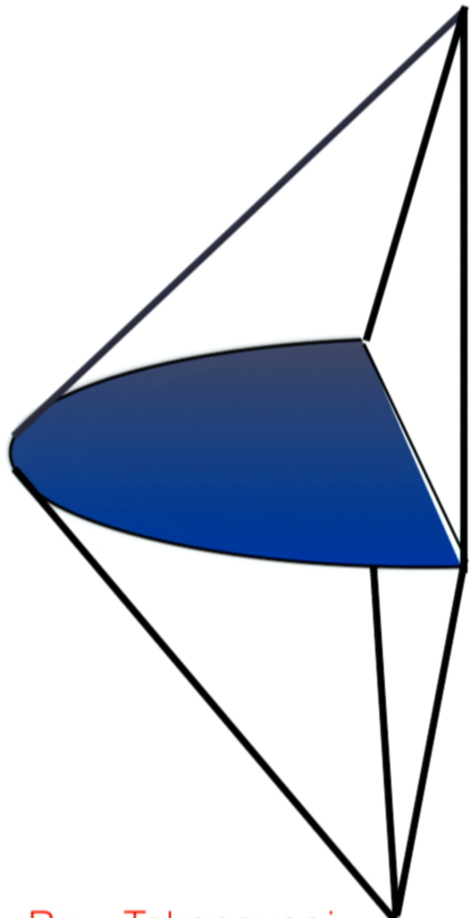
$$S_A = -\mathrm{tr}_{\mathcal{H}_A}(\rho_A \log \rho_A)$$

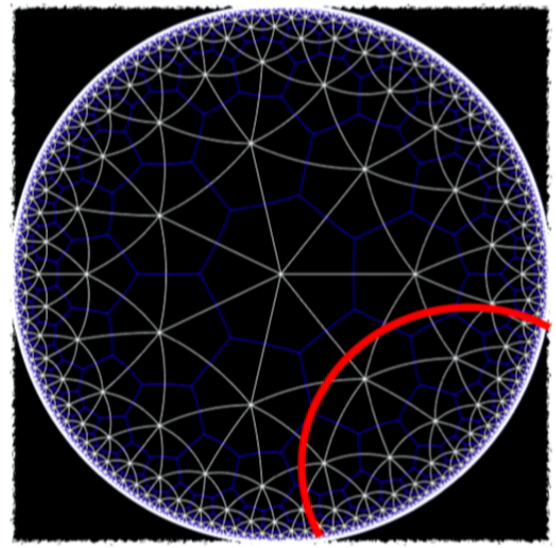
The entanglement entropy measures the number of "entangled Bell pairs" that connect the regions *A* en *B*. One has

$$S_A = S_B$$



$$S_{ent} = \frac{Area}{4G\hbar}$$

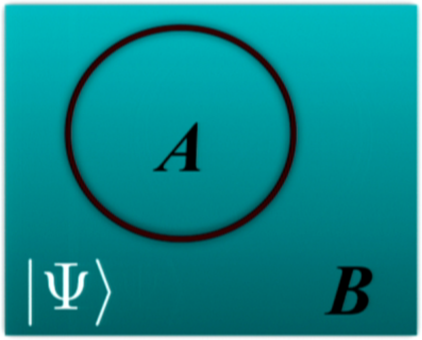




Anti-de Sitter space
Entanglement entropy equals area of minimal surface.

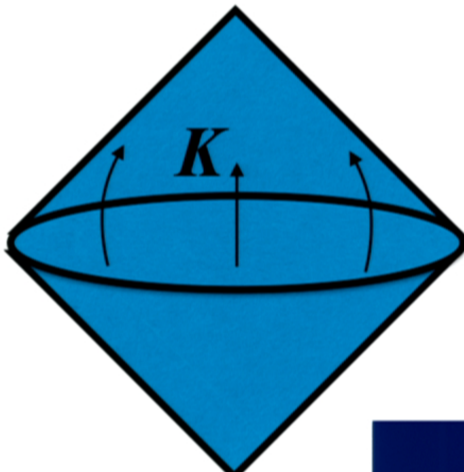
Ryu, Takanayagi
van Raamsdonk
Myers, Casini etal.

Entanglement entropy and Modular Hamiltonian



$$\rho_A = \mathrm{tr}_{\mathcal{H}_B}\big(|\Psi\rangle\langle\Psi|\big)$$

$$S_A = -\mathrm{tr}(\rho_A \log \rho_A)$$



$$\rho = \frac{e^{-K}}{Z} \qquad Z = \mathrm{tr}\left(e^{-K}\right)$$

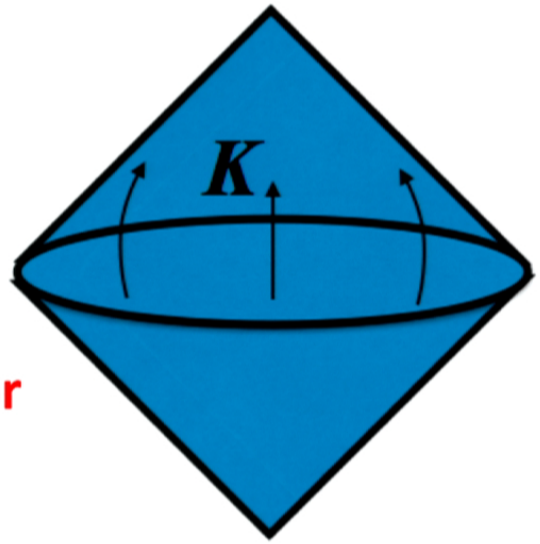
K = Modular Hamiltonian

1st law of entanglement entropy

$$\delta S = \langle \delta K \rangle \qquad \langle \delta K \rangle = \mathrm{tr}(\delta\rho K)$$

Modular Hamiltonian for a ball shaped region with radius *r*

$$K = \int \xi^a n^b T_{ab}$$



Here ξ is a **conformal Killing vector**

On the t=0 slice it takes the form

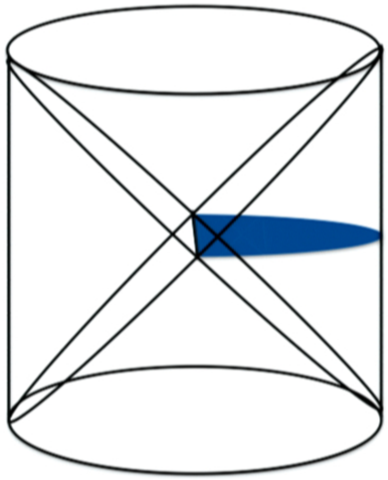
$$K = \int d^n x \left(\frac{r^2 - |x|^2}{2r} \right) T_{00}(x)$$

Casini.

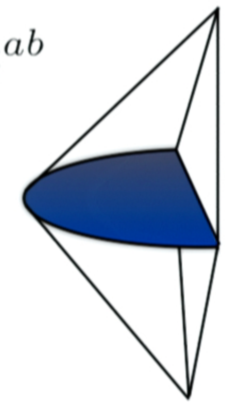
$n = d - 1$

Generates time flow in **causal diamond** constructed on the ball shaped region.

General Relativity from Area law of Entanglement



$$\frac{\hbar}{2\pi}S = \frac{A}{8\pi G} = \frac{1}{8\pi G}\int_{hor}\nabla_a\xi_b d\Sigma^{ab}$$



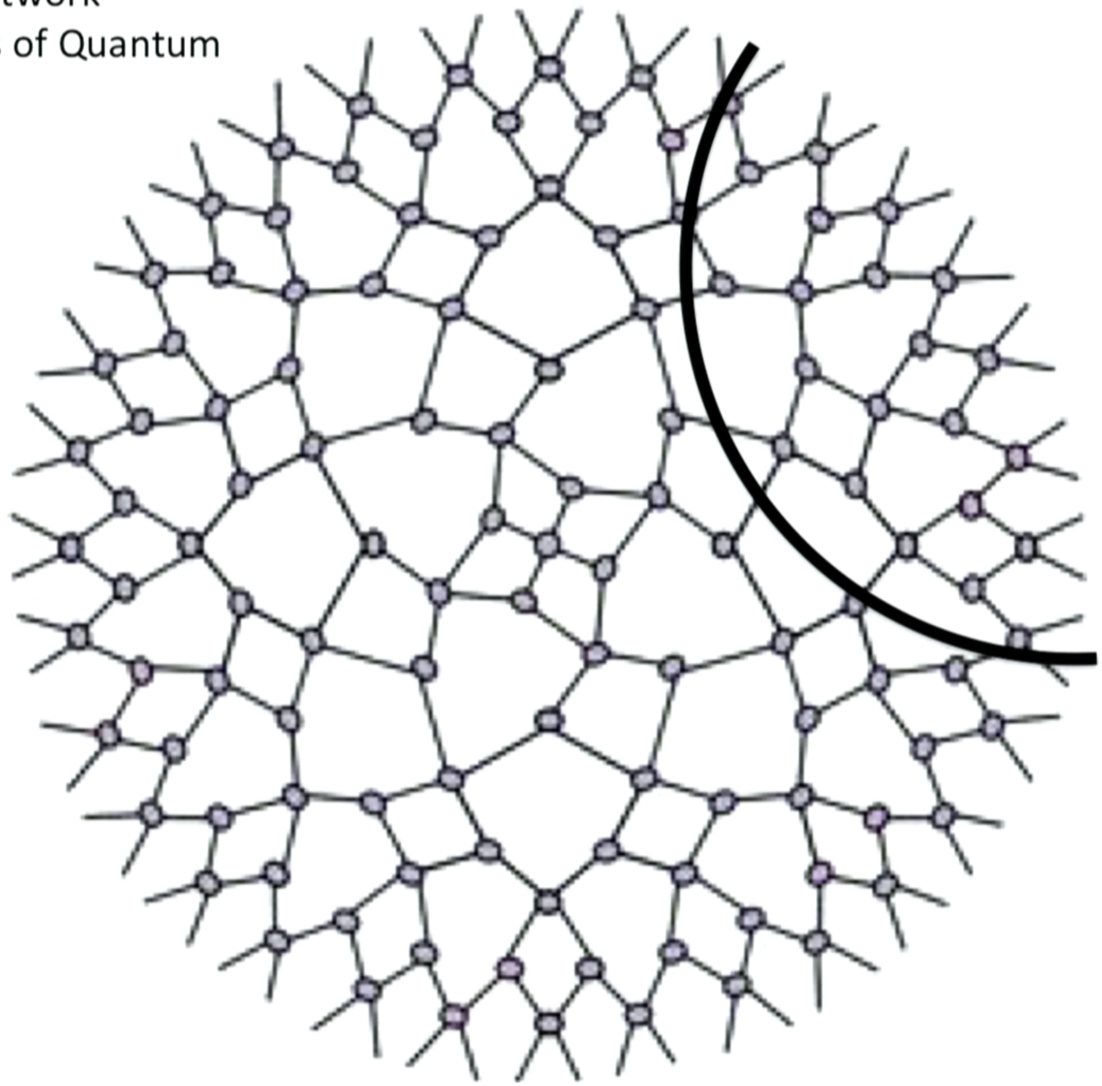
$$\langle\delta K\rangle = \int_{\infty}\xi^a n^b \langle T_{ab}\rangle_{CFT}$$

Imposing the first law $$\frac{\hbar}{2\pi}\delta S = \langle\delta K\rangle$$

van Raamsdonk
Myers, Faulkner
Guica.

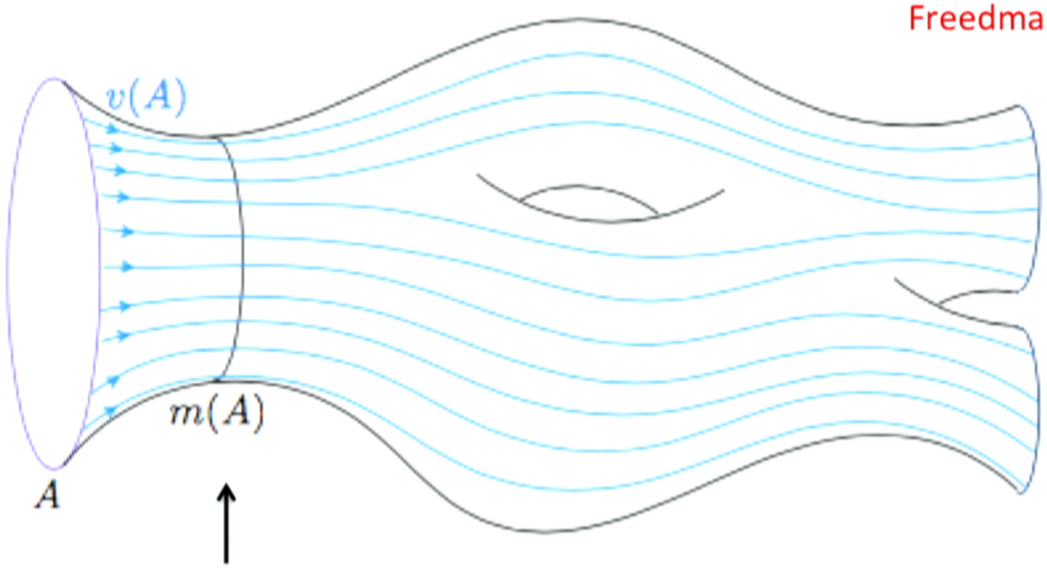
implies the linearised (vacuum) Einstein equations for pertrubations around the vacuum AdS background.

Spacetime as a Network
of Entangled Units of Quantum
Information



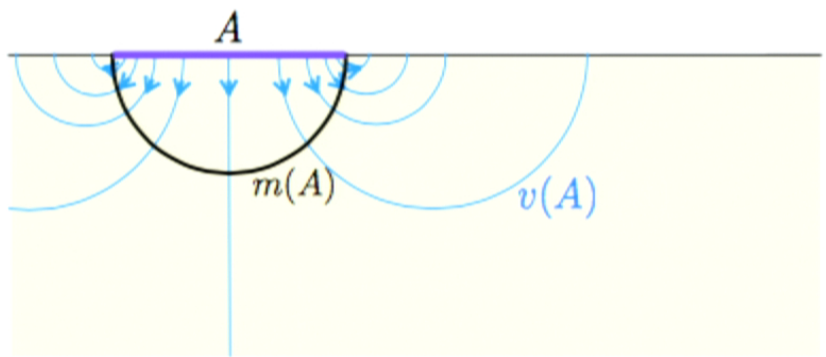
Bit threads: describe flow of entanglement

Freedman& Headrick



Max flow- min cut

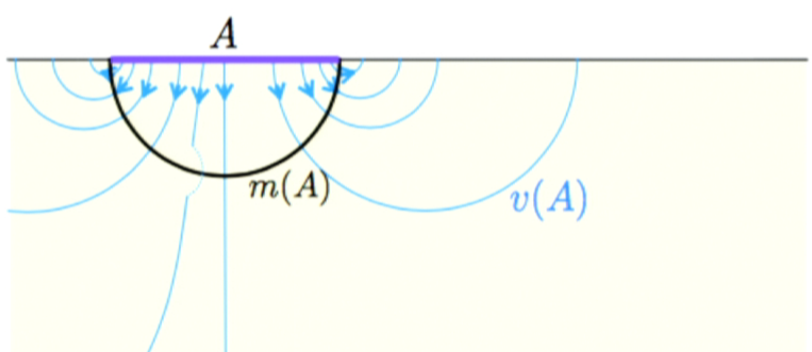
RT-formula from bit threads



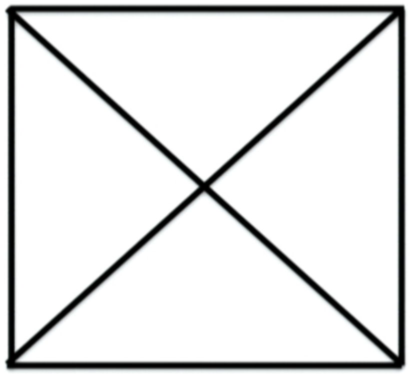
Freedman& Headrick

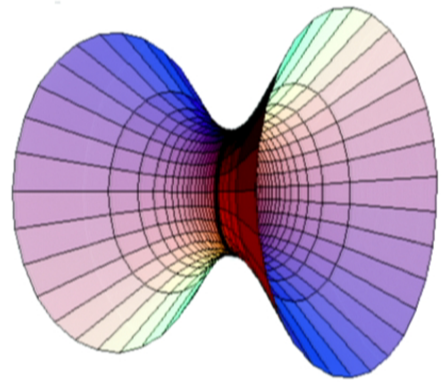
Max flow- min cut
=> Minimal area

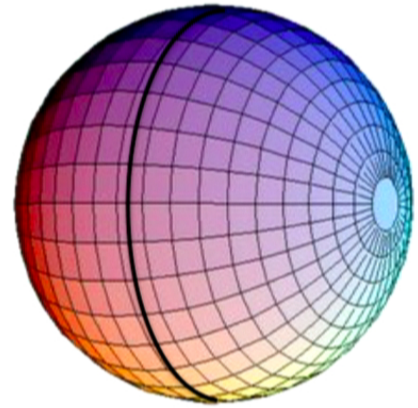
1/N corrections: bit threads that leave the space.



AdS-BH versus dS







Microscopic state:

$$|vac\rangle_{BH} = \frac{1}{\sqrt{Z}} \sum_i |E_i\rangle_L |E_i\rangle_R e^{-\beta E_i/2}$$

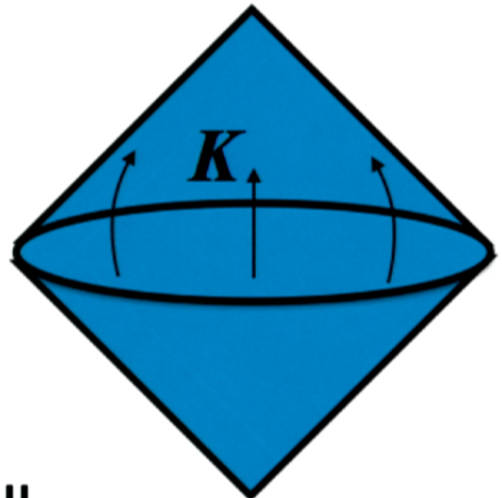
Entanglement entropy:

$$S_{ent} = \frac{A}{4G\hbar}$$

What is its interpretation?

For any ball shaped region in a maximally symmetric space the modular Hamiltonian is given by

$$K = \int d^n x \left(\frac{r^2 - |x|^2}{2r} \right) T_{00}(x)$$



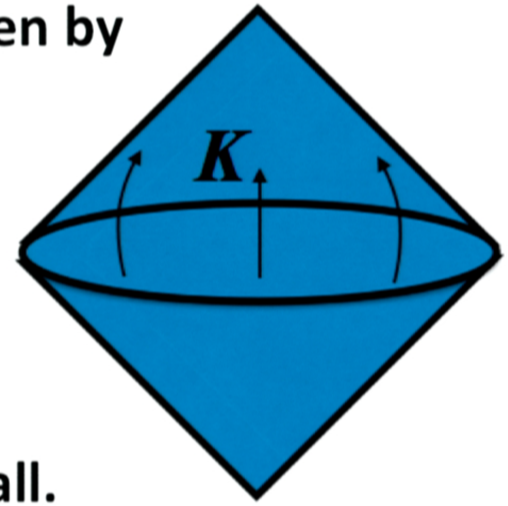
in conformally flat coordinates.
Here *r* determines the area *A* of the ball.
The Einstein equations are equivalent to the following 1st law

$$\delta K = -\frac{\delta A_{|V}}{8\pi G}$$

Jacobson

Here the volume *V* is kept fixed under the variation

For any ball shaped region in a maximally symmetric space consider the modular Hamiltonian given by



$$K = \int d^n x \left(\frac{r^2 - |x|^2}{2r} \right) T_{00}(x)$$

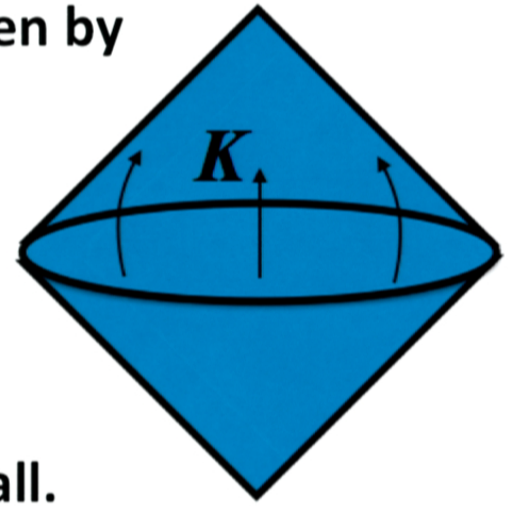
in conformally flat coordinates.
Here *r* determines the area *A* of the ball.
Using the Hollands-Wald formalism one shows that alternatively

$$\delta K = \frac{d-2}{r} \frac{\delta V_{|A}}{8\pi G}$$

Jacobson,
Manus Visser,
(to appear)

Here the area *A* is kept fixed under the variation

For any ball shaped region in a maximally symmetric space consider the modular Hamiltonian given by



$$K = \int d^n x \left(\frac{r^2 - |x|^2}{2r} \right) T_{00}(x)$$

in conformally flat coordinates.
Here *r* determines the area *A* of the ball.
More generally the Einsteins equations imply

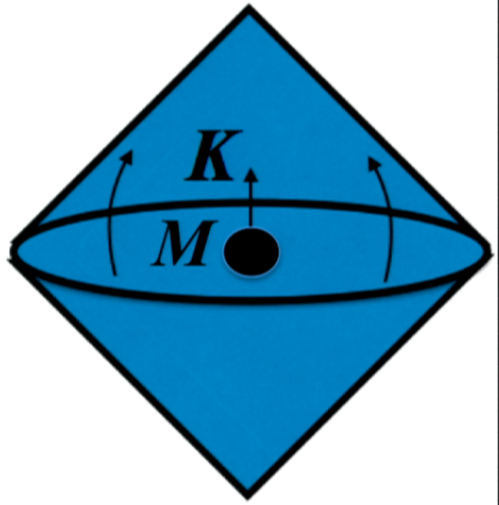
$$\delta K = -\frac{\delta A}{8\pi G} + \frac{d-2}{r} \frac{\delta V}{8\pi G}$$

Jacobson,
Manus Visser,
(to appear)

when both the area *A* and volume *V* are varied.

In terms of the modular Hamiltonian

$$K = \int d^n x \left(\frac{r^2 - |x|^2}{2r} \right) T_{00}(x)$$



the added volume due a mass equals

$$V_M(r) = \frac{8\pi G r}{d-2} K$$

It obeys

$$\frac{d}{dr} V_M(r) = \frac{8\pi G r}{d-2} M(r)$$

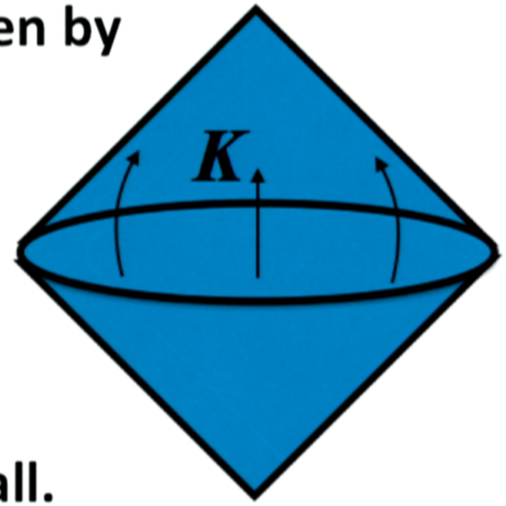
where

$$M(r) = \int d^n x \, T_{00}(x)$$

Is the enclosed mass inside the ball of radius *r*

For any ball shaped region in a maximally symmetric space consider the modular Hamiltonian given by

$$K = \int d^n x \left(\frac{r^2 - |x|^2}{2r} \right) T_{00}(x)$$



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Jacobson,
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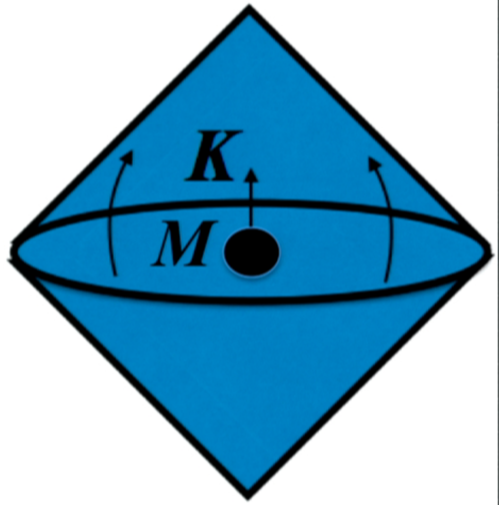

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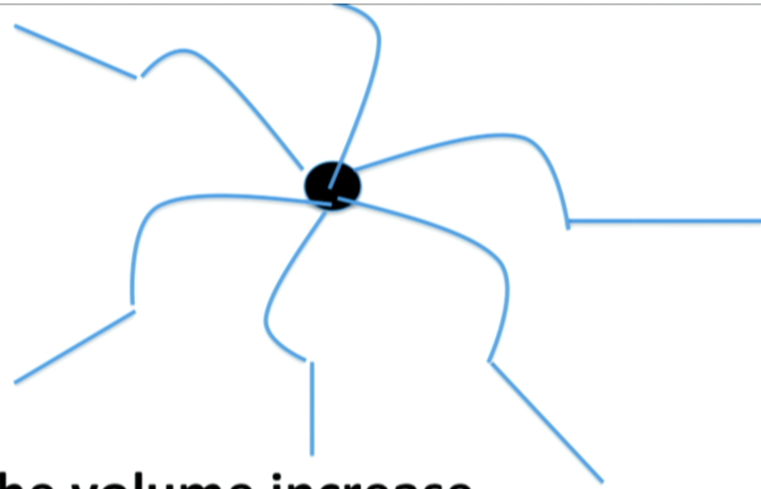
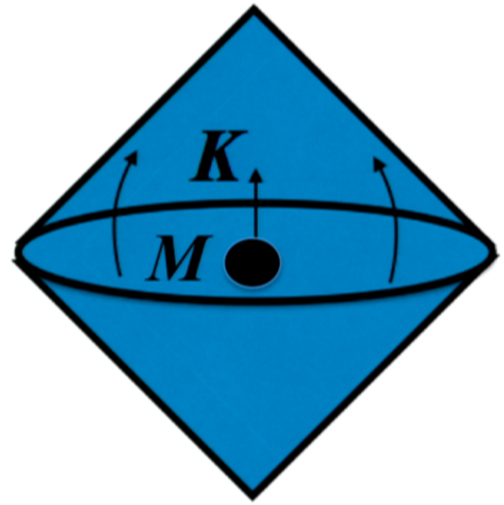




The volume increase

$$\frac{d}{dr}V_M(r) = \frac{8\pi G r}{d-2}M(r)$$

Interpreted as an increase of the `complexity' due to the extra 'bit threads' associated with the mass *M* => geometrically this causes the curvature due to matter. In AdS and flat space this continues till infinity.

The same can be done for the static patch of de Sitter space.

$$ds^2 = -\left(1 - \frac{R^2}{L^2}\right) dt^2 + \frac{dR^2}{1 - R^2/L^2} + R^2 d\Omega^2$$

In this case the conformal killing vector is

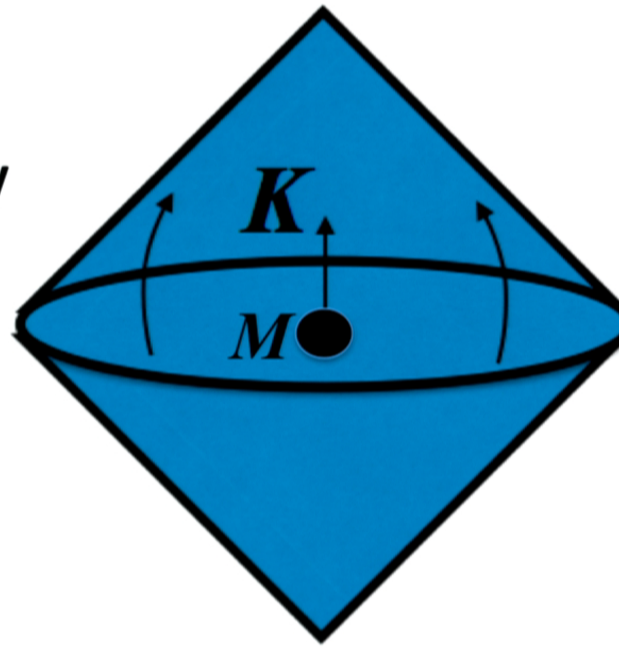
$$\xi^a \partial_a = L\partial_t$$

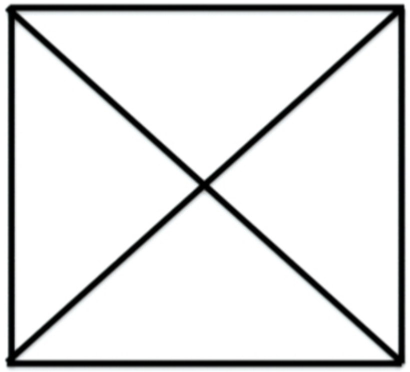
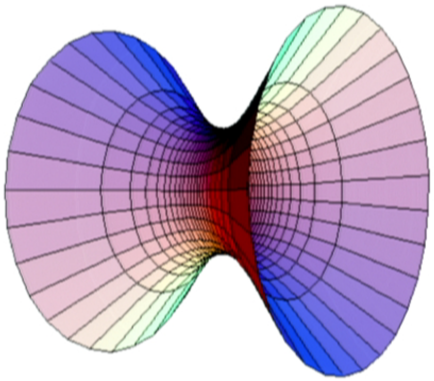
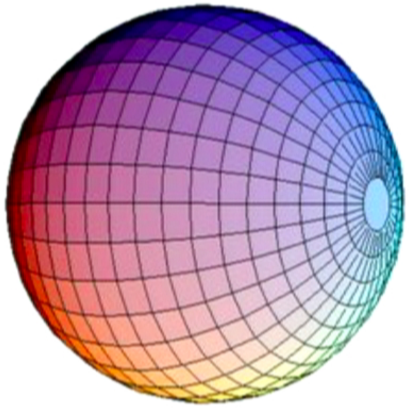
Hence the Einstein equations imply

$$\frac{\delta A_{|V}}{8\pi G} = -ML$$

or alternatively

$$\delta V_{|A} = \frac{8\pi G M L^2}{d-2}$$

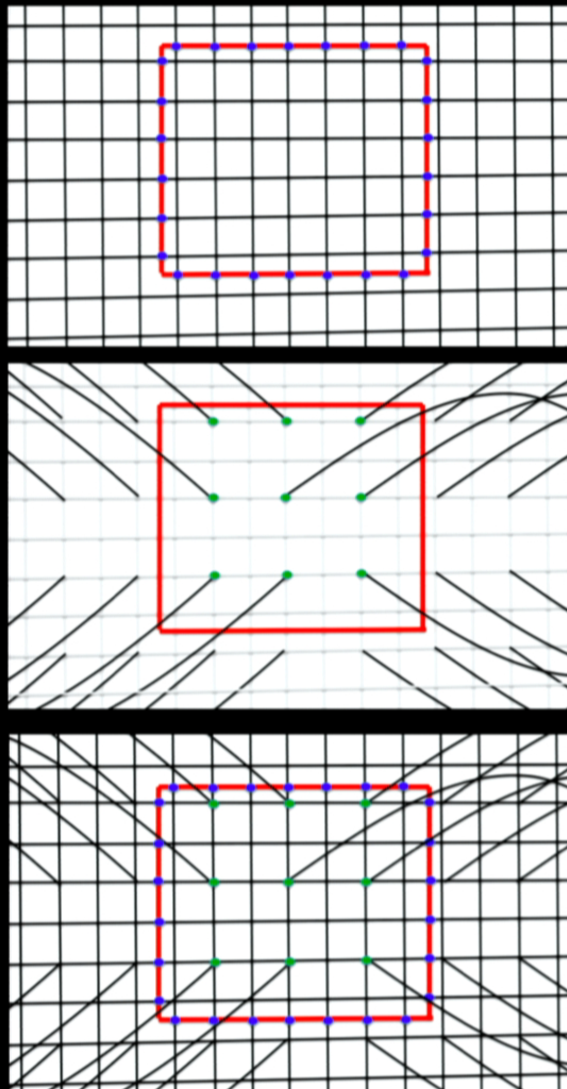


The bit threads must exit the de Sitter spacetime inside the static patch => A thermal state with entropy equal to

$$\frac{\hbar}{2\pi} S_{ent} = \frac{A(L)}{4G} = \frac{d-1}{L}\frac{V(L)}{4G}$$

describes the entanglement accros the horizon as well the thermal entropy in the bulk.



Area law entanglement

Ground state with
short range entanglement

Volume law entanglement

Quantum state with
long range entanglement

Area+volume law entanglement

Quantum state with mostly short
but also long range entanglement

de Sitter Horizon

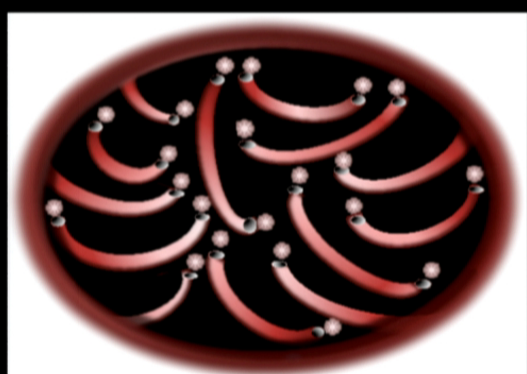
$$L = \frac{c}{H_0}$$

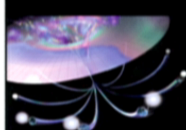
$$S(L) = \frac{A(L)}{4G\hbar} \qquad T = \frac{\hbar H_0}{2\pi}$$

Hypothesis:

de Sitter entropy + temperature are due to positive dark energy.

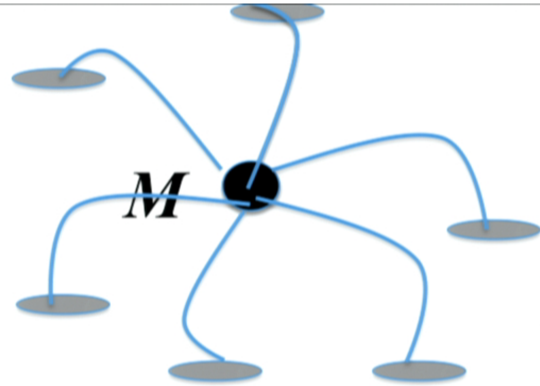
The entanglement entropy contains volume law contribution





$$S(R) = \frac{A(R)}{4G\hbar}\,\frac{R}{L}$$

$$R < L$$

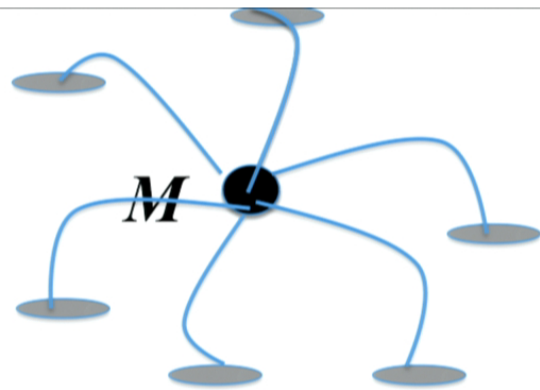


$$\frac{d}{dr}V_M(r) = \frac{8\pi G r}{d-2}M(r)$$

The volume occupied by the dark energy excitations that are entangled with the mass M obeys approximately

$$\frac{d}{dr}V_{DE}(r) \sim \frac{8\pi G L}{d-2}M(r)$$

This leads to an elastic strain and stress that can be



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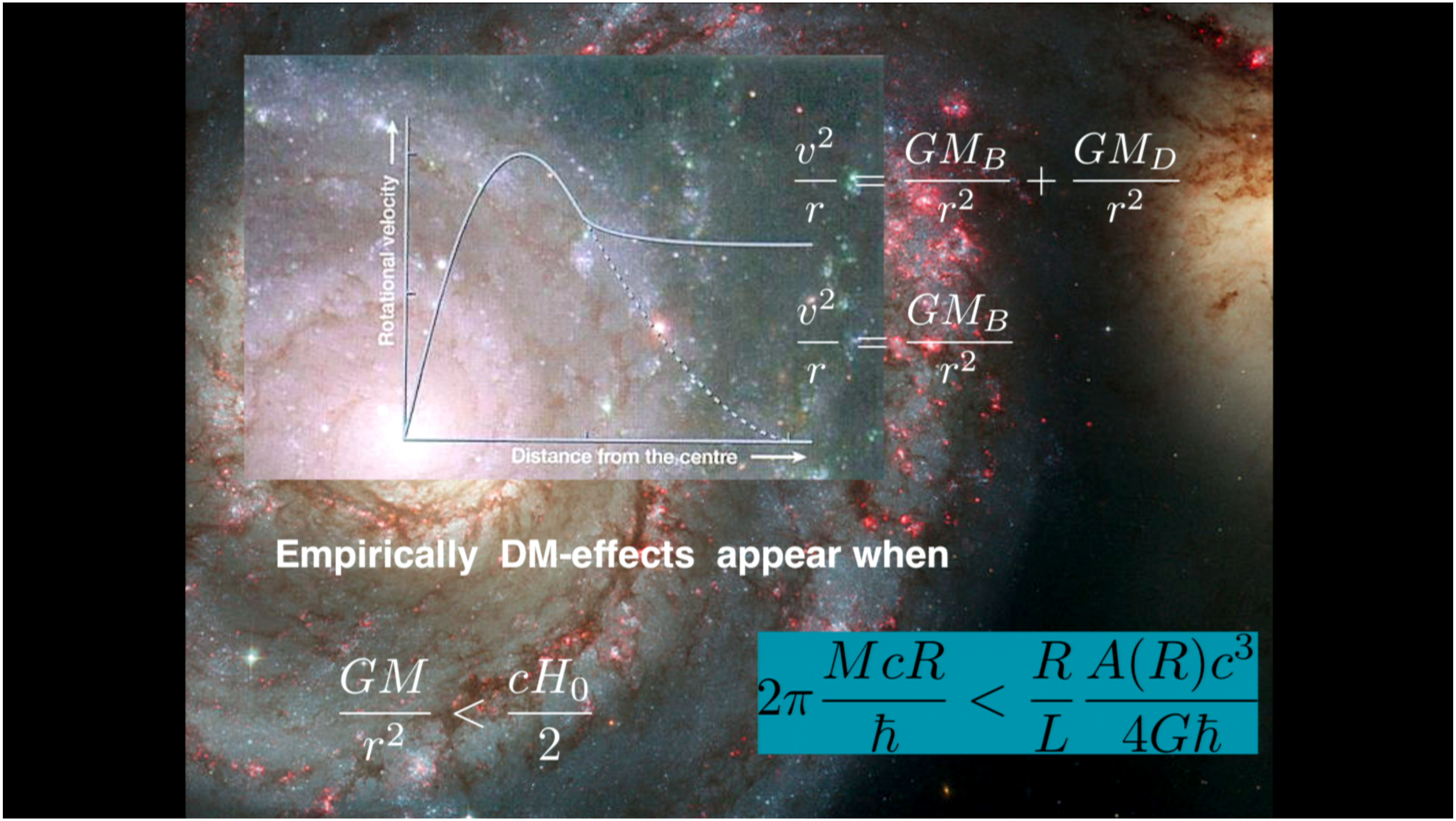
Rotational velocity
Distance from the centre
$\frac{v^2}{r} = \frac{GM_B}{r^2} + \frac{GM_D}{r^2}$
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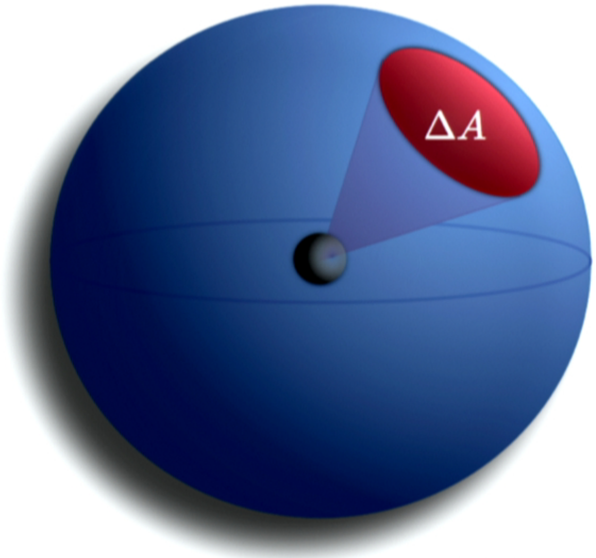
Empirically DM-effects appear when
$\frac{GM}{r^2} < \frac{cH_0}{2}$
$2\pi \frac{McR}{\hbar} < \frac{R}{L} \frac{A(R)c^3}{4G\hbar}$



Matter influences the growth of the Area as a function of the geodesic distance.

$$ds = \frac{dr}{\sqrt{1+2\Phi}}$$

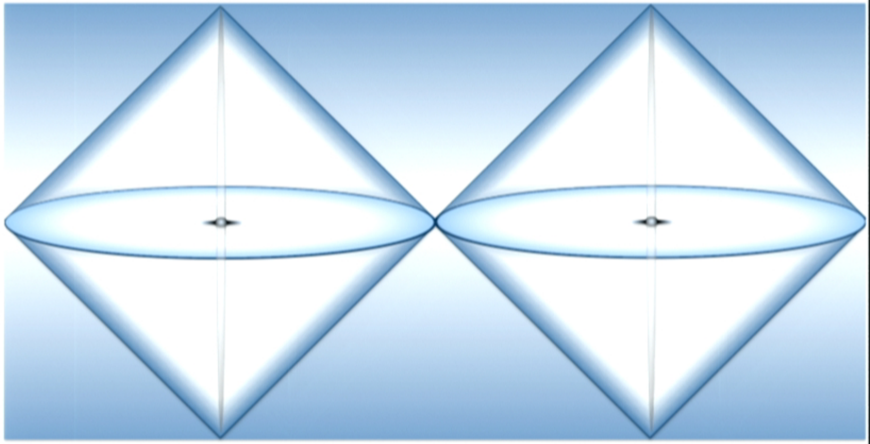
Mass <=> Area deficit

$$\frac{d}{ds}\left(\frac{A(r)}{4G\hbar}\right)\Bigg|_{M=0}^{M\neq 0} = \Phi(r)\frac{d}{dr}\left(\frac{A(r)}{4G\hbar}\right) = -\frac{2\pi M}{\hbar}$$

Interpretation: Matter reduces the entanglement by an amount

$$S_M(r) = -\frac{2\pi M r}{\hbar} \qquad \frac{dS_M(r)}{dr} = -\frac{2\pi M}{\hbar}$$

De Sitter-Schwarzschild:



$$f(r) = 1 - \frac{r^2}{L^2} + 2\Phi(r)$$

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2$$

$$\Phi(r) = -\frac{8\pi GM}{(d-2)\Omega_{d-2}\, r^{d-3}}.$$

Mass reduces horizon area

$$L \to L + u(L)$$

$$u(L)\frac{d}{dL}\left(\frac{A(L)}{4G\hbar}\right) = -\frac{2\pi ML}{\hbar}.$$

$$u(L) = \Phi(L)L$$

$$\Delta\left(\frac{Area}{4G\hbar}\right) = -\frac{2\pi ML}{\hbar}$$

Dark Energy as Elastic Medium

The entropy density of DE equals

$$s = \frac{c^2 H_0}{2G\hbar}$$

Mass reduces the entropy by

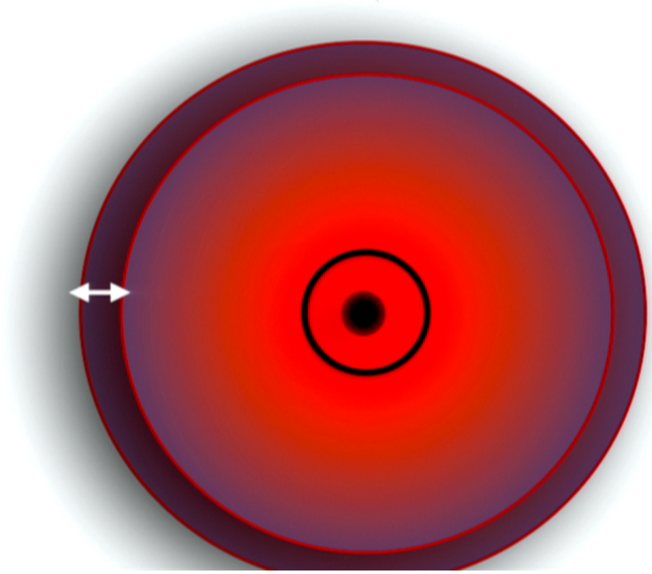
$$\Delta S = \frac{2\pi M c R}{\hbar}$$

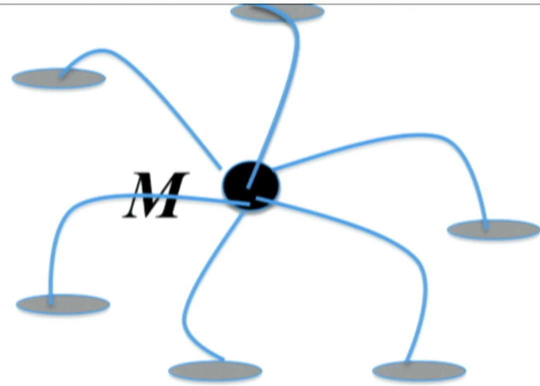
and removes a corresponding volume from the medium

$$\Delta V = \frac{4\pi G M R}{c H_0}$$

This creates an elastic response

$$\Delta S = s \Delta V$$





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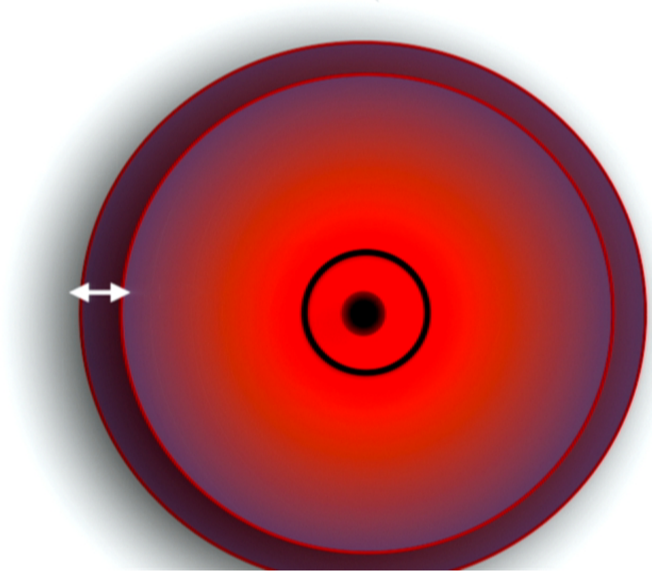
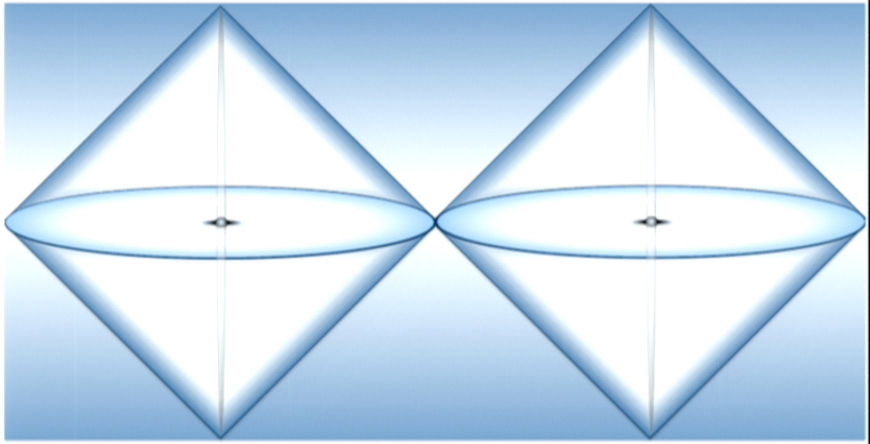


De Sitter-Schwarzschild:



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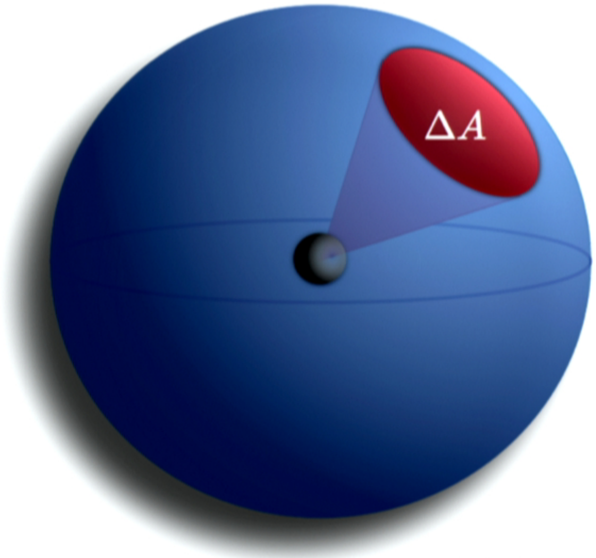

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Interpretation: Matter reduces the entanglement by an amount

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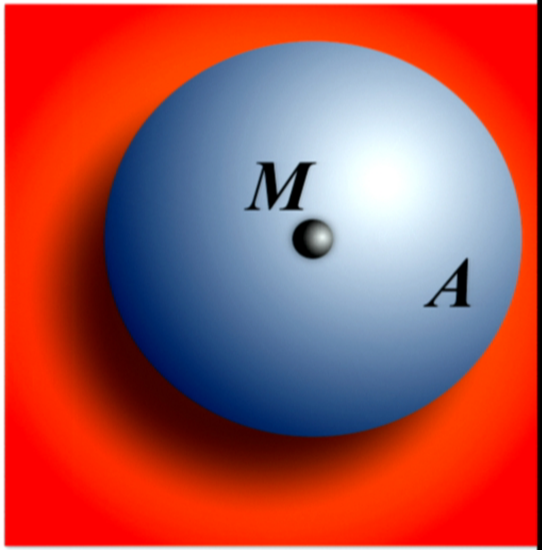
Matter entangles with Dark Energy

- The empirical fact

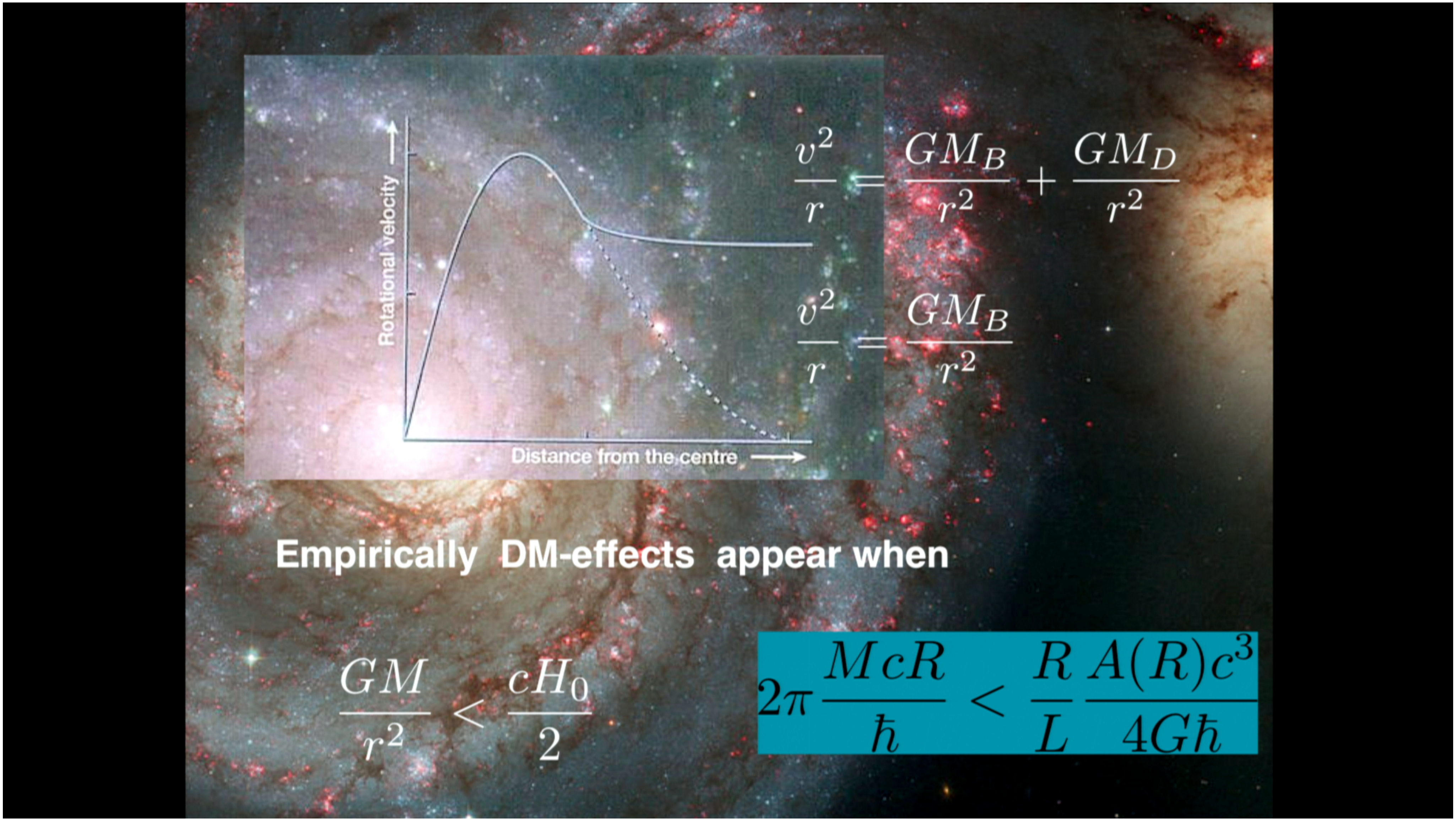
$$2\pi \frac{M\,L}{\hbar} < \frac{A}{4G\hbar}$$



- implies that DM-effects appear when

$$2\pi \frac{M\,R}{\hbar} < \frac{A}{4G\hbar}\frac{R}{L}$$

- The left hand side is the entanglement entropy of matter.
- The right hand side represents the entropy contained in DE.



Rotational velocity
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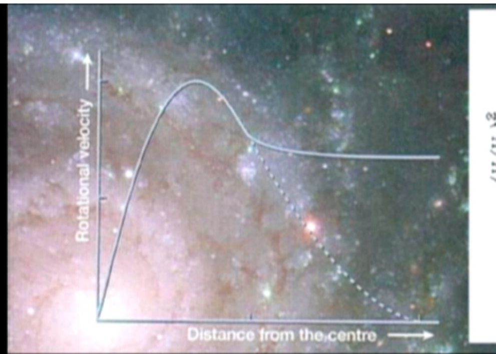
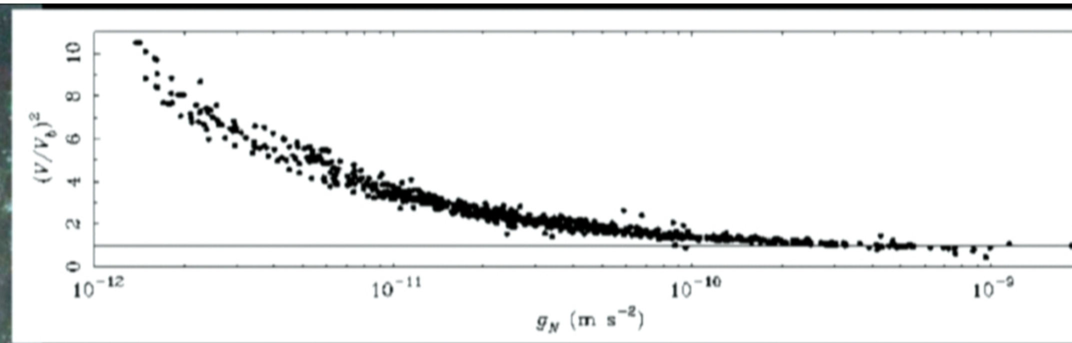




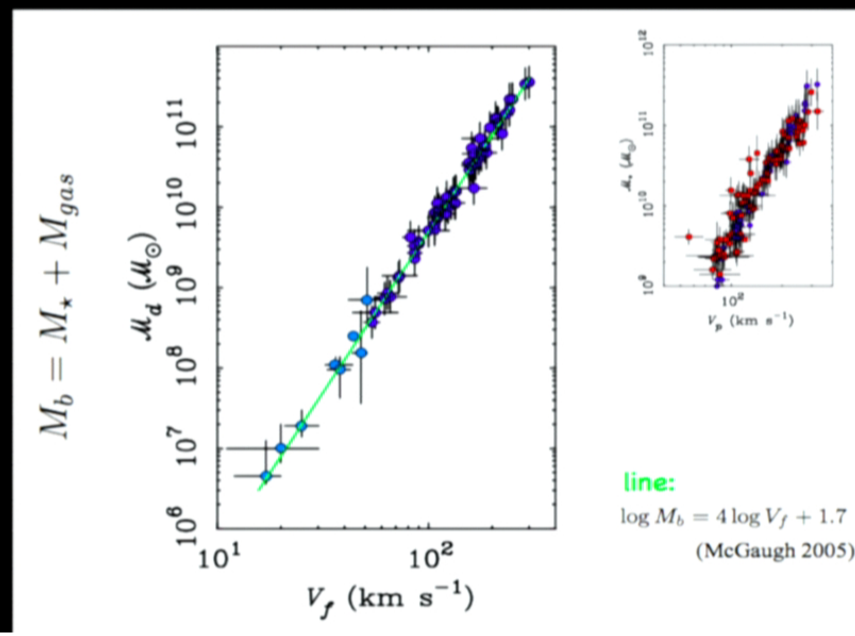
Baryonic Tully-Fisher relation

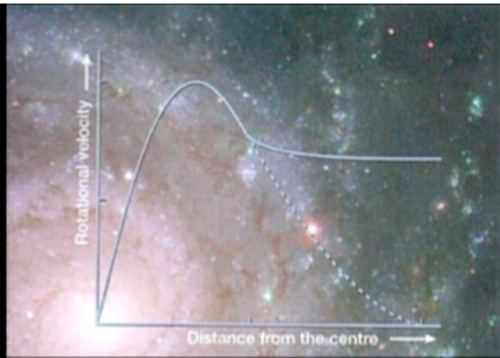
$$g_{obs} = \frac{v^2}{r}$$

$$g_{bar} = \frac{GM_B}{r^2}$$

for large ***r*** :

$$g^2_{obs}(r) \approx g_{bar}(r)cH_0/6$$



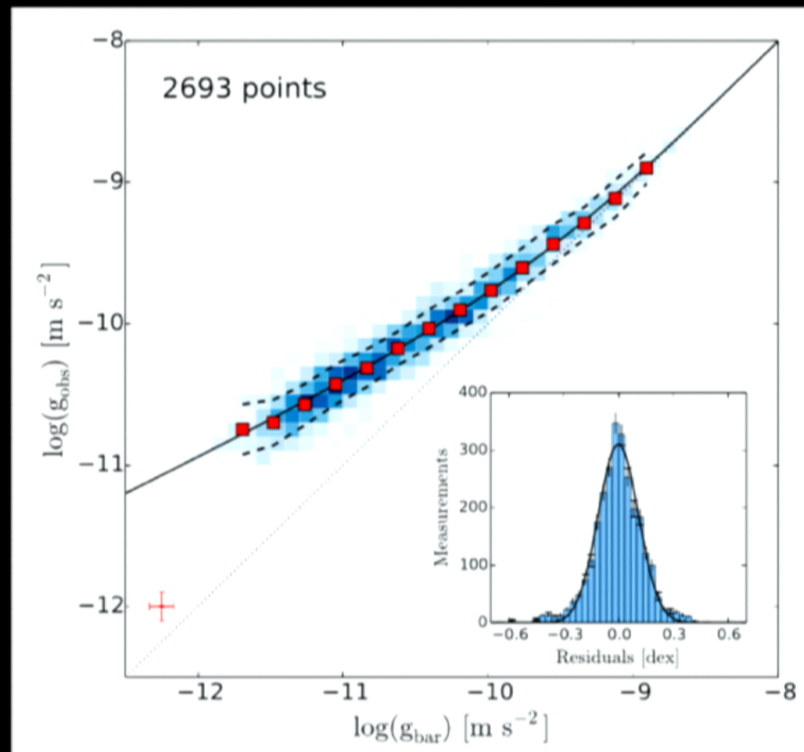


$$g_{obs}(r) = \frac{GM_B(r)}{r^2} + \frac{GM_D(r)}{r^2}$$

$$g_{bar}(r) = \frac{GM_B(r)}{r^2}$$

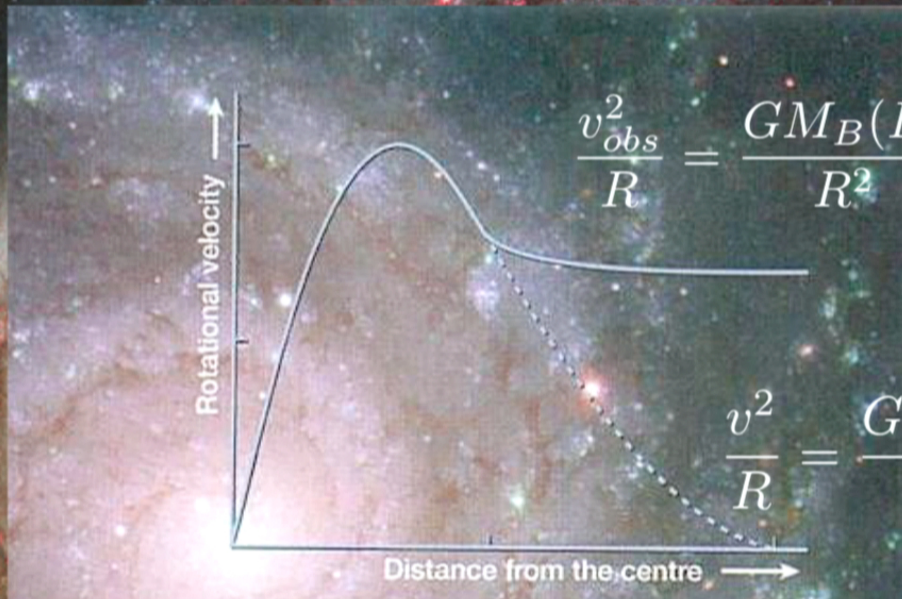
Mass discrepancy–acceleration relation

McGaugh, Lelli, Schombert (2016)
(see also Navarro, Frenk, etal.)



for large $\boldsymbol{r}$:

$$g_{obs}^2(r) \approx g_{bar}(r) c H_0 / 6$$



$$\frac{v_{obs}^2}{R} = \frac{GM_B(R)}{R^2} + \frac{GM_D(R)}{R^2}$$

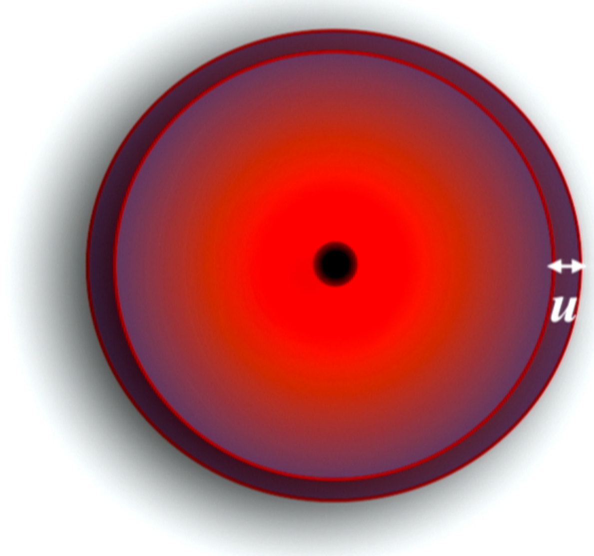
$$\frac{v^2}{R} = \frac{GM_B(R)}{R^2}$$

$$\frac{1}{8\pi G}\int_{r\leq R} g_i^2\, dV = \frac{M_B c R}{\hbar}\,\frac{\hbar H_0}{6}$$

Mass => change in de Sitter entropy

$$1 - \frac{r^2}{L^2} + 2\Phi(r) = 0$$

$$\Phi(r) = -\frac{8\pi G M}{(d-2)\Omega_{d-2} r^{d-3}}$$



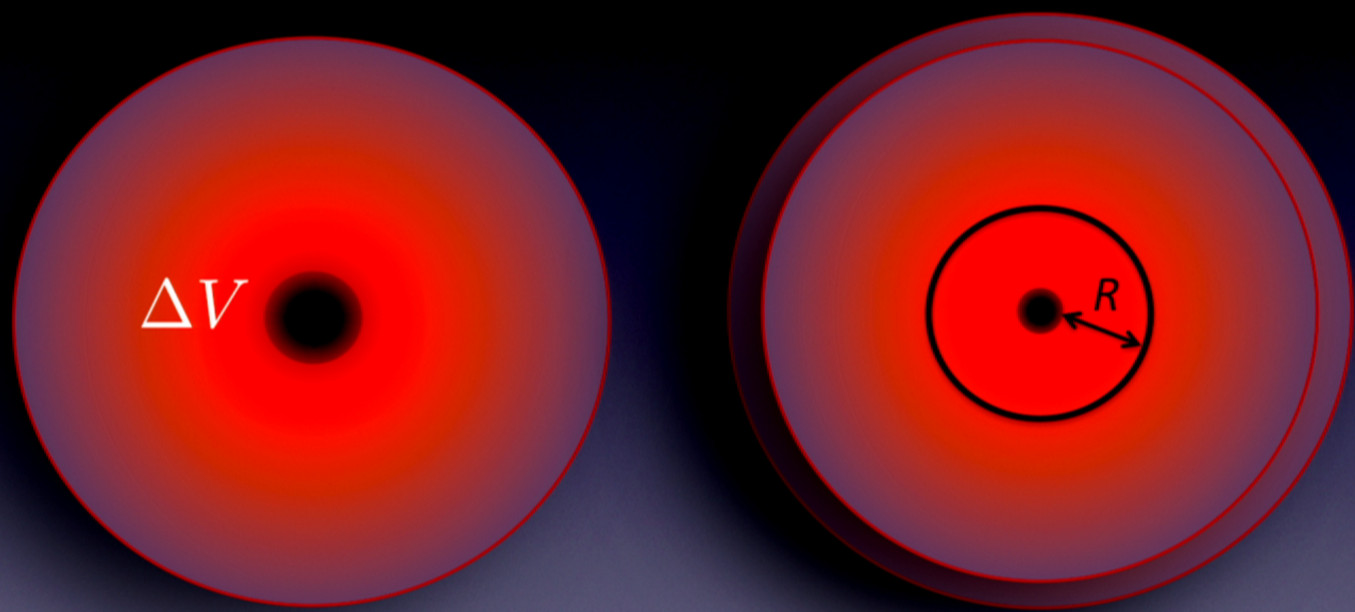
- Adding mass to de Sitter space reduces its horizon entropy by an amount

$$\frac{\Delta A}{4G\hbar} = \frac{2\pi M L}{\hbar}$$

- The cosmological horizon is displaced by

$$u_i(L) = \Phi(L) L n_i$$

Removing information/entropy from a volume leads to an elastic respons.



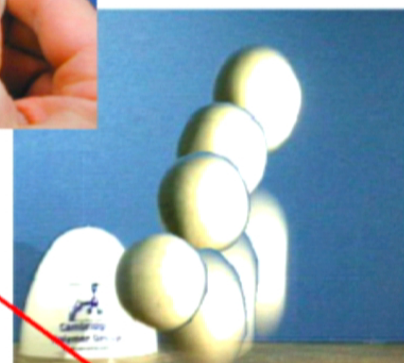
$$\Delta V = \frac{4\pi G M L}{c^2} R$$

$$\int \vec{u} \cdot dA = \Delta V$$

On that same timescale we have observed the Universe for only a fraction of a second.

At very long times the material behaves like a liquid spreading out onto a flat surface

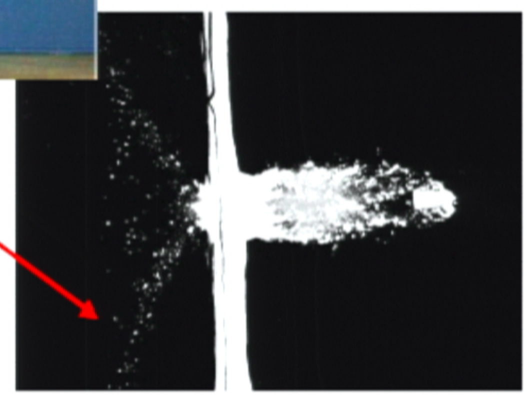
At moderate times the Silly Putty™ stretches like a plastic solid



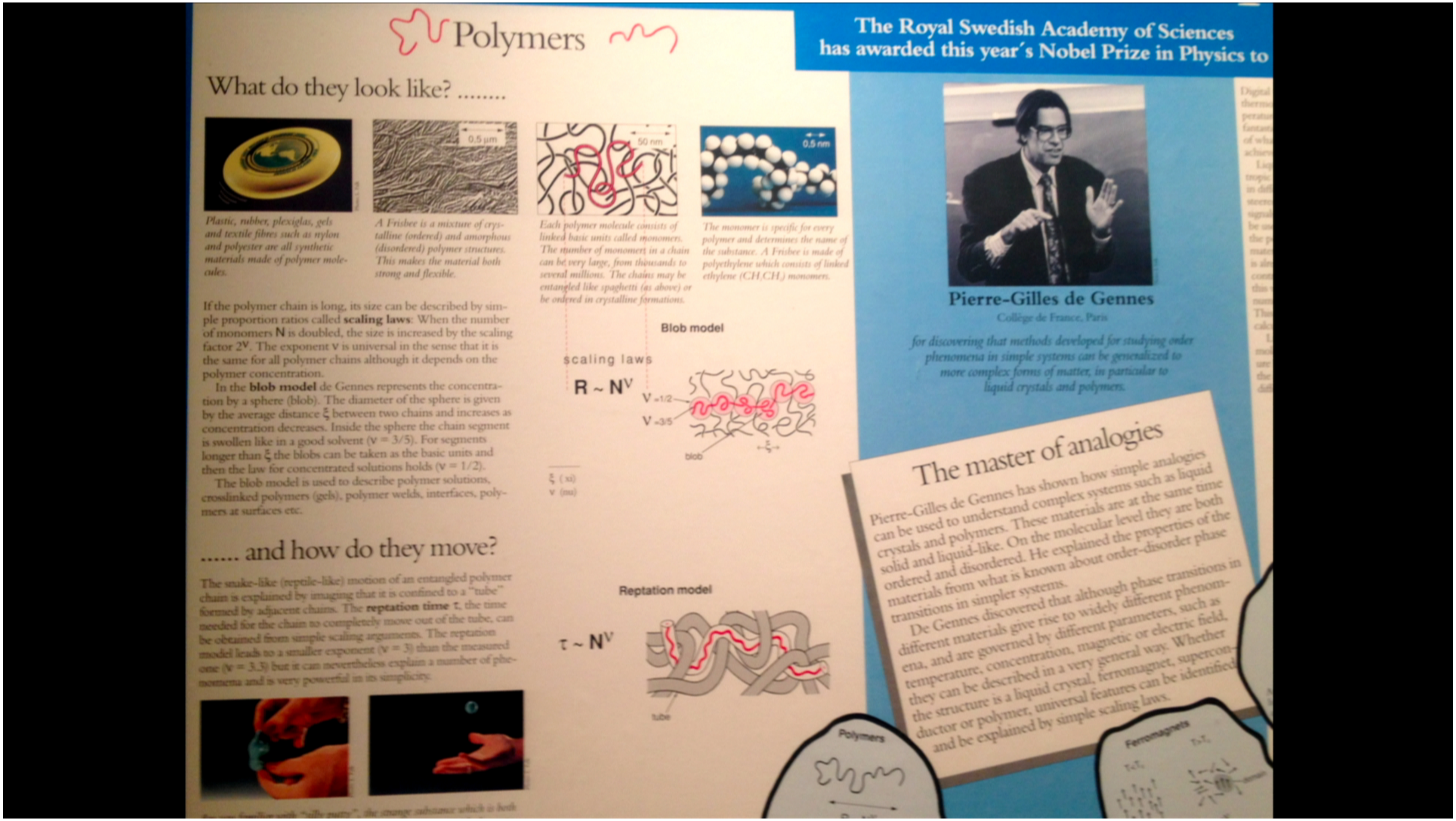
At short times the Silly Putty™ bounces like an elastic solid

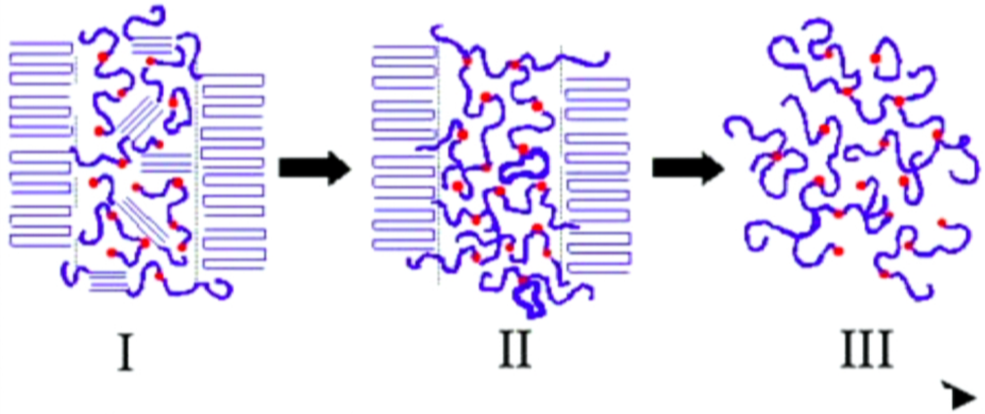
Increasing Deborah Number

$$De = \frac{\lambda_{material}}{t_{flow}}$$

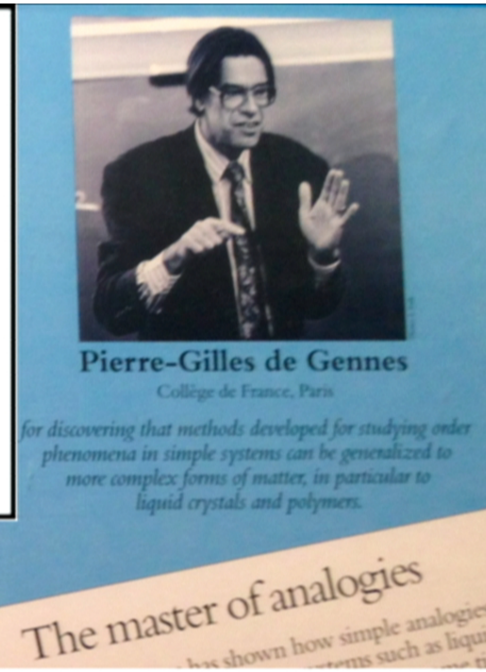


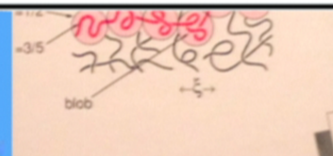
At very short times (the impact of a bullet) the Silly Putty™ shatters (courtesy MIT Edgerton Strobe Laboratories).


Polymers
What do they look like? ....
Plastic, rubber, plexiglas, gels and textile fibres such as nylon and polyester are all synthetic materials made of polymer molecules.
A Frisbee is a mixture of crystalline (ordered) and amorphous (disordered) polymer structures. This makes the material both strong and flexible.
Each polymer molecule consists of linked basic units called monomers. The number of monomers in a chain can be very large, from thousands to several millions. The chains may be entangled like spaghetti (as above) or be ordered in crystalline formations.
The monomer is specific for every polymer and determines the name of the substance. A Frisbee is made of polyethylene which consists of linked ethylene (CH2CH2) monomers.
0,5 µm
50 nm
0,5 nm
If the polymer chain is long, its size can be described by simple proportion ratios called scaling laws: When the number of monomers N is doubled, the size is increased by the scaling factor 2ν. The exponent ν is universal in the sense that it is the same for all polymer chains although it depends on the polymer concentration.
In the blob model de Gennes represents the concentration by a sphere (blob). The diameter of the sphere is given by the average distance ξ between two chains and increases as concentration decreases. Inside the sphere the chain segment is swollen like in a good solvent (ν = 3/5). For segments longer than ξ the blobs can be taken as the basic units and then the law for concentrated solutions holds (ν = 1/2).
The blob model is used to describe polymer solutions, crosslinked polymers (gels), polymer welds, interfaces, polymers at surfaces etc.
Blob model
scaling laws
R ~ Nν
ν =1/2
ν =3/5
blob
ξ (xi)
ν (nu)
...... and how do they move?
The snake-like (reptile-like) motion of an entangled polymer chain is explained by imaging that it is confined to a "tube" formed by adjacent chains. The reptation time τ, the time needed for the chain to completely move out of the tube, can be obtained from simple scaling arguments. The reptation model leads to a smaller exponent (ν = 3) than the measured one (ν = 3.3) but it can nevertheless explain a number of phenomena and is very powerful in its simplicity.
Reptation model
τ ~ Nν
tube
The Royal Swedish Academy of Sciences
has awarded this year's Nobel Prize in Physics to
Pierre-Gilles de Gennes
Collège de France, Paris
for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers.
The master of analogies
Pierre-Gilles de Gennes has shown how simple analogies can be used to understand complex systems such as liquid crystals and polymers. These materials are at the same time solid and liquid-like. On the molecular level they are both ordered and disordered. He explained the properties of the materials from what is known about order-disorder phase transitions in simpler systems.
De Gennes discovered that although phase transitions in different materials give rise to widely different phenomena, and are governed by different parameters, such as temperature, concentration, magnetic or electric field, they can be described in a very general way. Whether the structure is a liquid crystal, ferromagnet, supercon-ductor or polymer, universal features can be identified and be explained by simple scaling laws.
Polymers
Ferromagnets

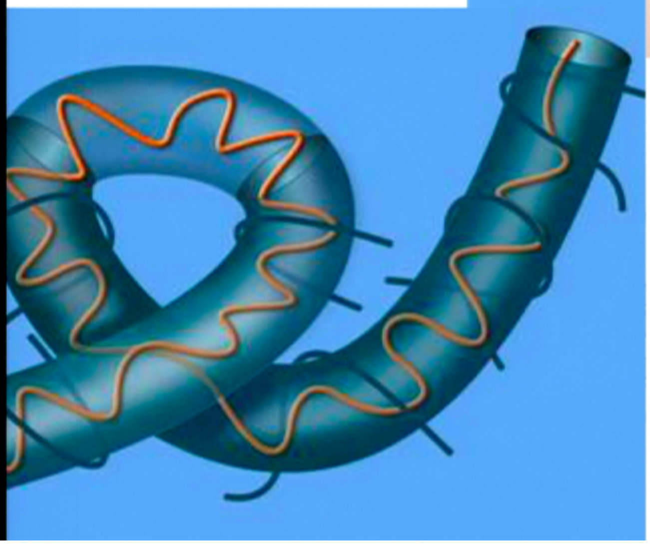


Polymer Melts





Reptation Model



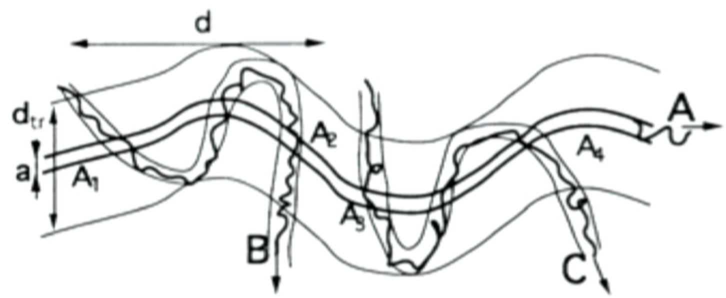


FIG. 1. As chain *A* reptates out of its tube, the neighbori chains *B* and *C* move into the region and partially recover t memory left by the chain *A* in the form of elastic distortions the entanglement net.

PHYSICAL REVIEW LETTERS 20 SEPTEMBER 1993

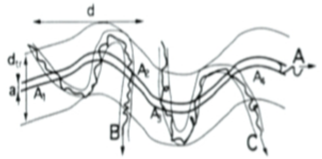
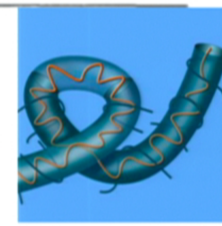


FIG. 1. As chain A reptates out of its tube, the neighboring chains B and C move into the region and partially recover the memory left by the chain A in the form of elastic distortions of the entanglement net.

Memory Effects in Entangled Polymer Melts

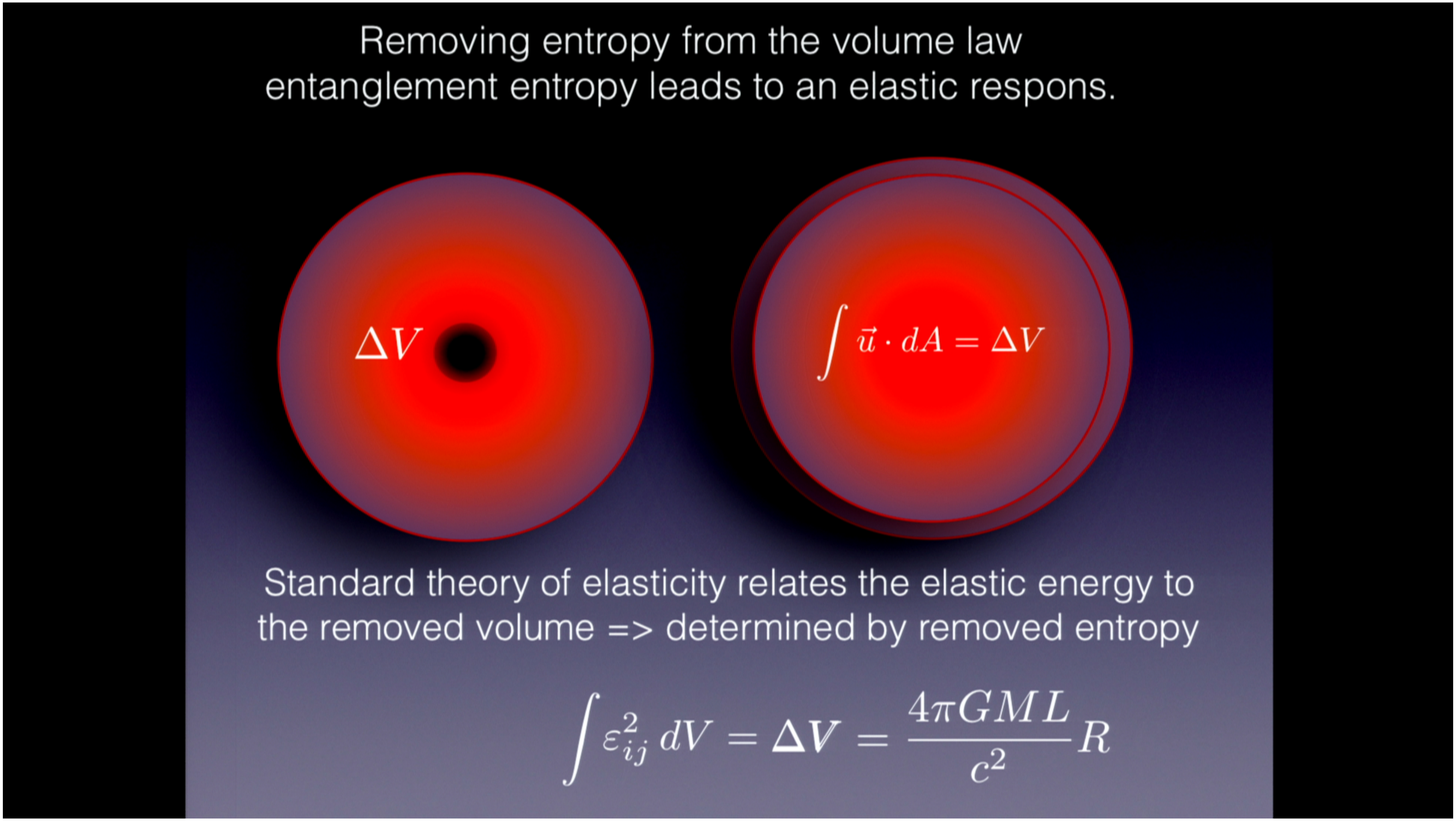
Michael Rubinstein
ch Laboratories, Eastman Kodak Company, Rochester, New York 14650-2110

S. P. Obukhov

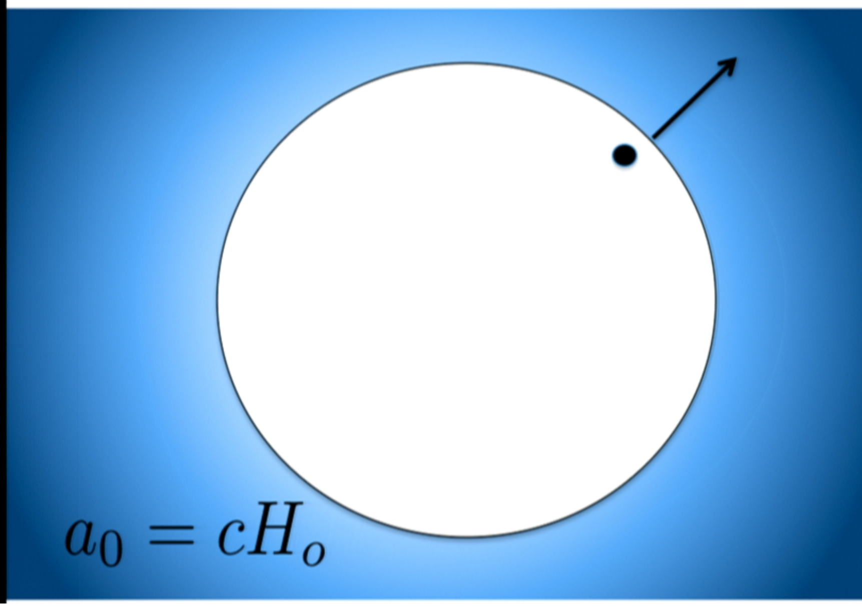


A simple estimate of the energy of elastic deformation of an entanglement network with modulus $G \sim kT/N_e v_0$ due to displacement of N_e monomers from one end of the tube to the other can be made. Here N_e is the degree of polymerization between entanglements and v_0 is the volume of a monomer. The extra volume V_e appearing at the end of the tube is proportional to the number N_e of displaced monomers $V_e = N_e v_0$. This results in the displacement δr_e of elastic media distance r away from the tube end $\delta r_e \approx V_e/4\pi r^2$, leading to the strain ε_e in the neighborhood of the tube end of the order of $\varepsilon_e = \partial(\delta r_e)/\partial r \approx -V_e/2\pi r^3$. The elastic energy can be estimated as

$$E_e \approx \int (G\varepsilon_e^2/2) d^3 r \approx G V_e^2/a^3 \approx kT v_0 N_e/a^3 . \qquad (1)$$

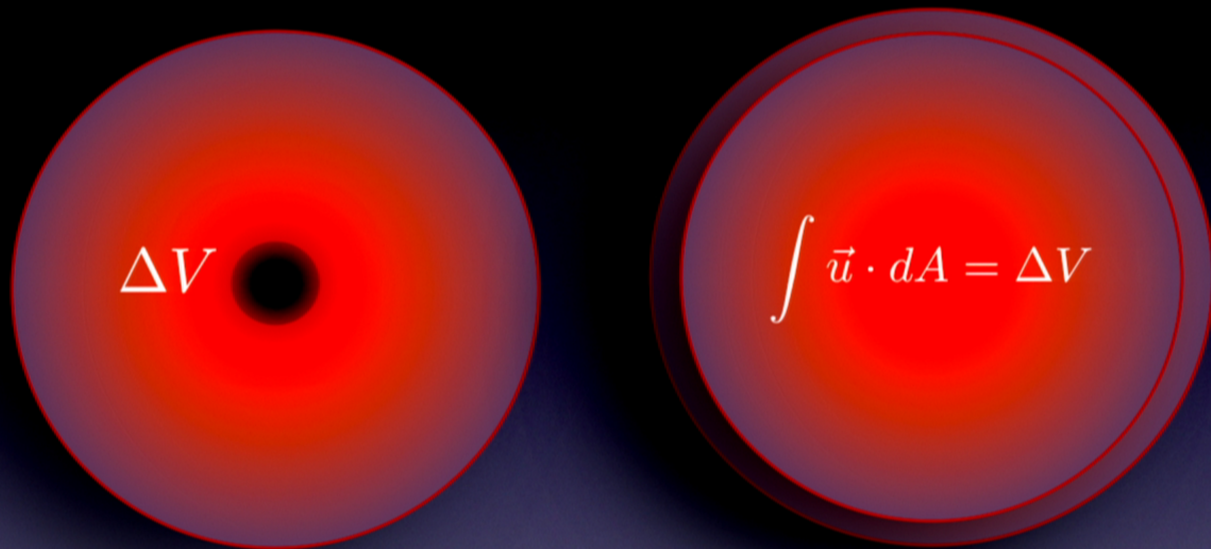

Removing entropy from the volume law
entanglement entropy leads to an elastic respons.
ΔV
$\int \vec{u} \cdot dA = \Delta V$
Standard theory of elasticity relates the elastic energy to
the removed volume => determined by removed entropy
$\int \varepsilon_{ij}^2 \, dV = \Delta V = \frac{4\pi GML}{c^2} R$

Gravitational quantity		Elastic quantity	
Newtonian potential	Φ	displacement field	u_i
gravitational acceleration	g_i	strain tensor	ε_{ij}
surface mass density	Σ_i	stress tensor	σ_{ij}
mass density	ρ	body force	b_i
point mass	m	point force	f_i



Correspondence		
$\Phi\, n_i$	$=$	$a_0 u_i$
g_i / a_0	$=$	$\varepsilon_{ij} n_j$
$\Sigma_i a_0$	$=$	$\sigma_{ij} n_j$
$\rho\, n_i$	$=$	b_i / a_0
$m\, n_i$	$=$	f_i / a_0

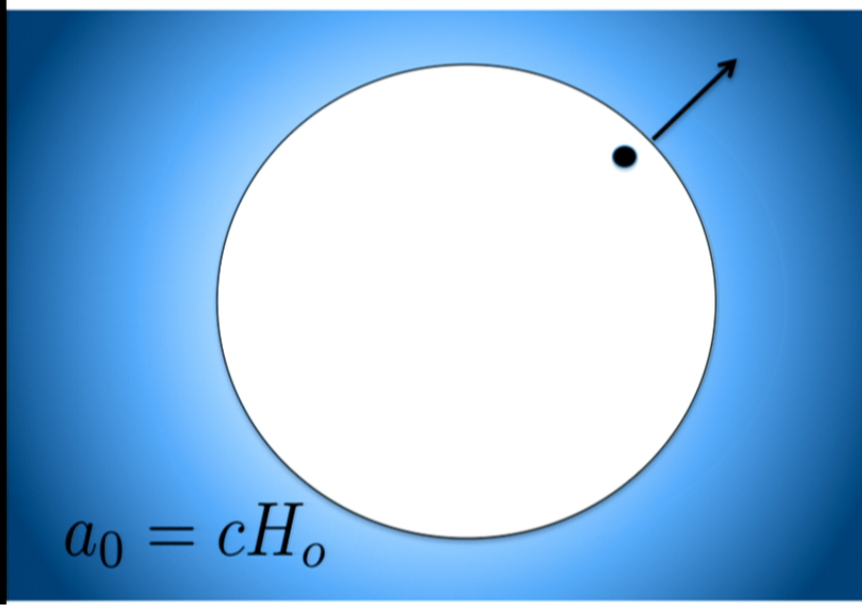
Removing entropy from the volume law entanglement entropy leads to an elastic respons.



Standard theory of elasticity relates the elastic energy to the removed volume => determined by removed entropy

$$\int \varepsilon_{ij}^2 \, dV = \Delta V = \frac{4\pi G M L}{c^2} R$$

Gravitational quantity		Elastic quantity	
Newtonian potential	Φ	displacement field	u_i
gravitational acceleration	g_i	strain tensor	ε_{ij}
surface mass density	Σ_i	stress tensor	σ_{ij}
mass density	ρ	body force	b_i
point mass	m	point force	f_i



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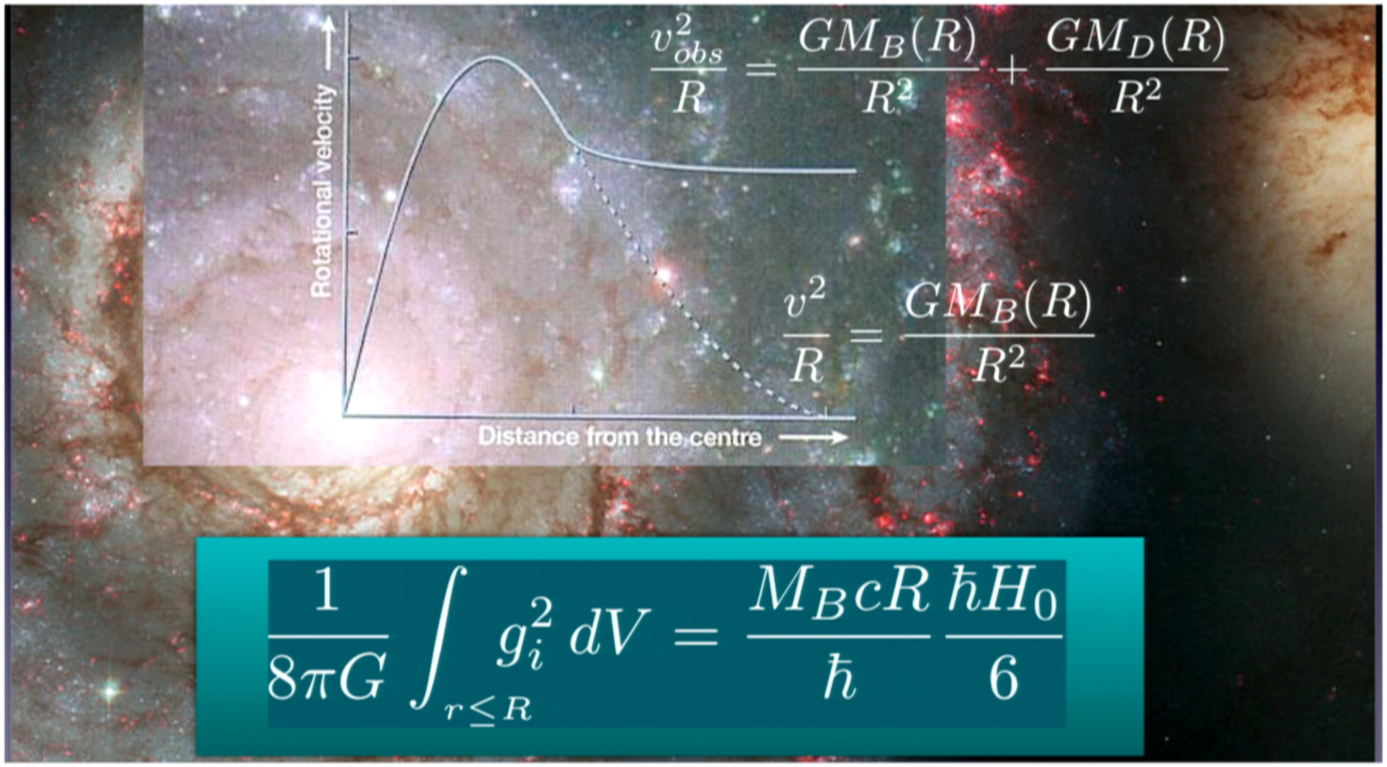
$m\, n_i$	$=$	f_i / a_0



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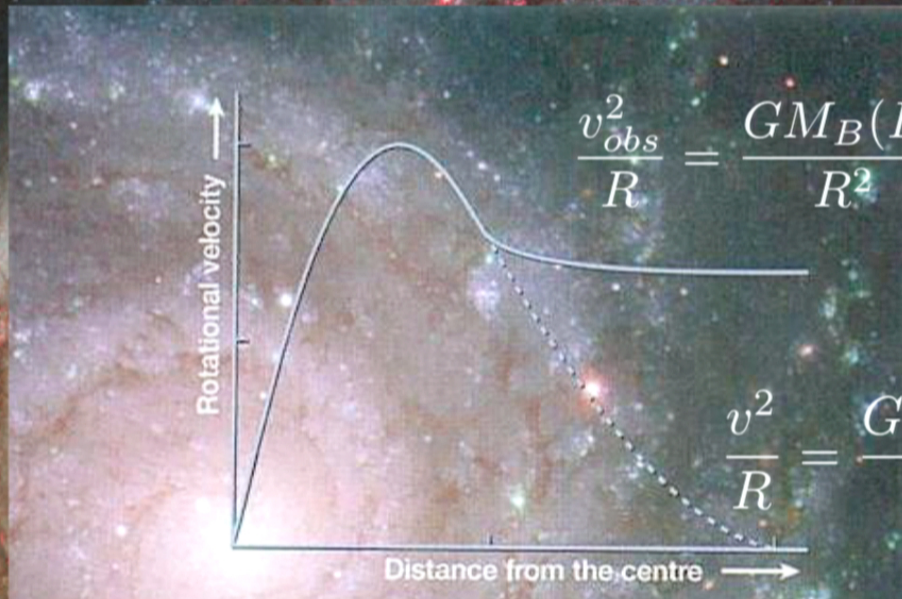
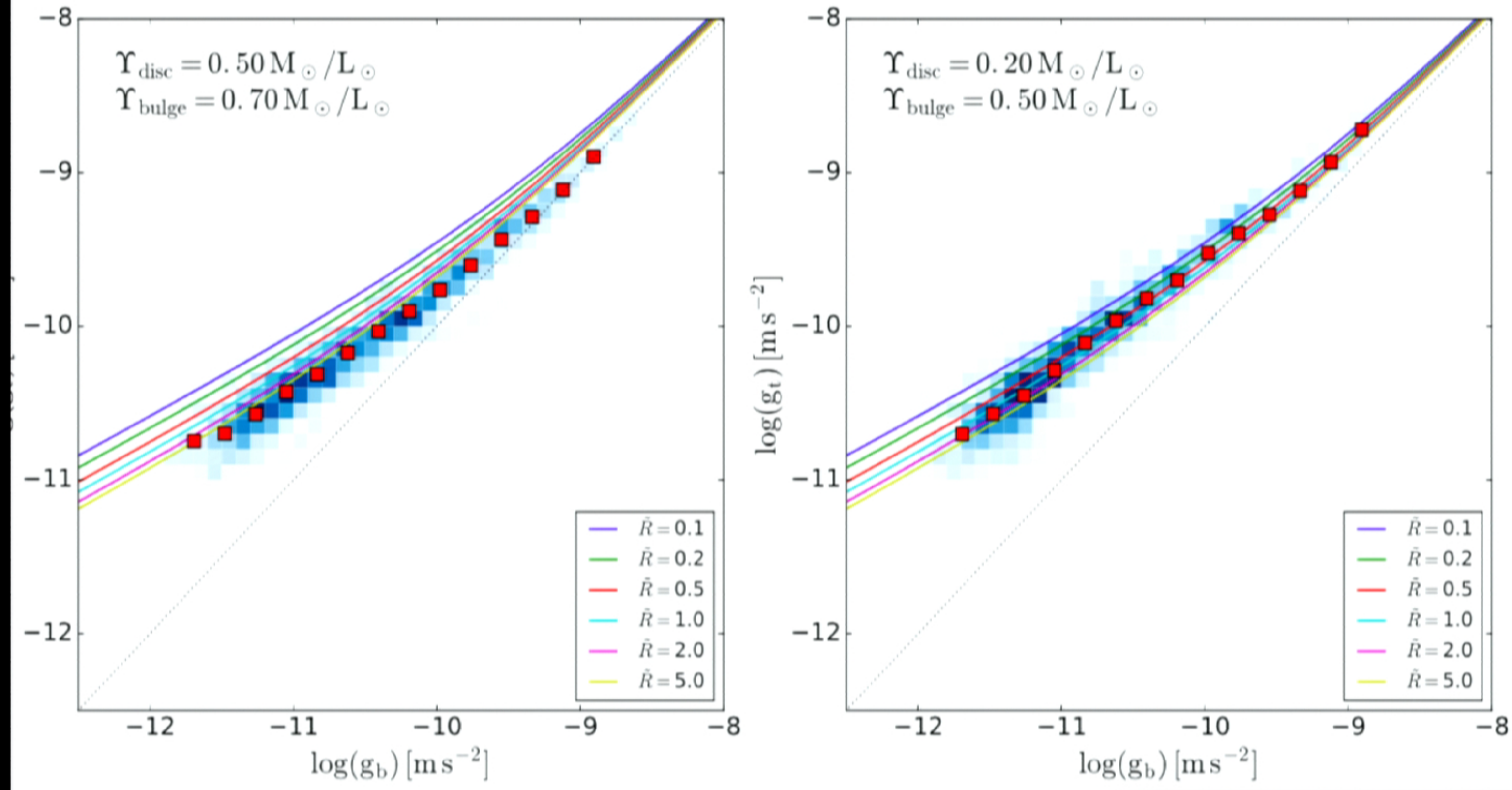
Distance from the centre
$\frac{1}{8\pi G}\int_{r\leq R} g_i^2\, dV = \frac{M_B c R}{\hbar}\frac{\hbar H_0}{6}$



$$\frac{v_{obs}^2}{R} = \frac{GM_B(R)}{R^2} + \frac{GM_D(R)}{R^2}$$

$$\frac{v^2}{R} = \frac{GM_B(R)}{R^2}$$

$$\int_0^R \frac{GM_D(r)^2}{r^2} dr = \frac{M_B(R) c H_0 R}{6}$$



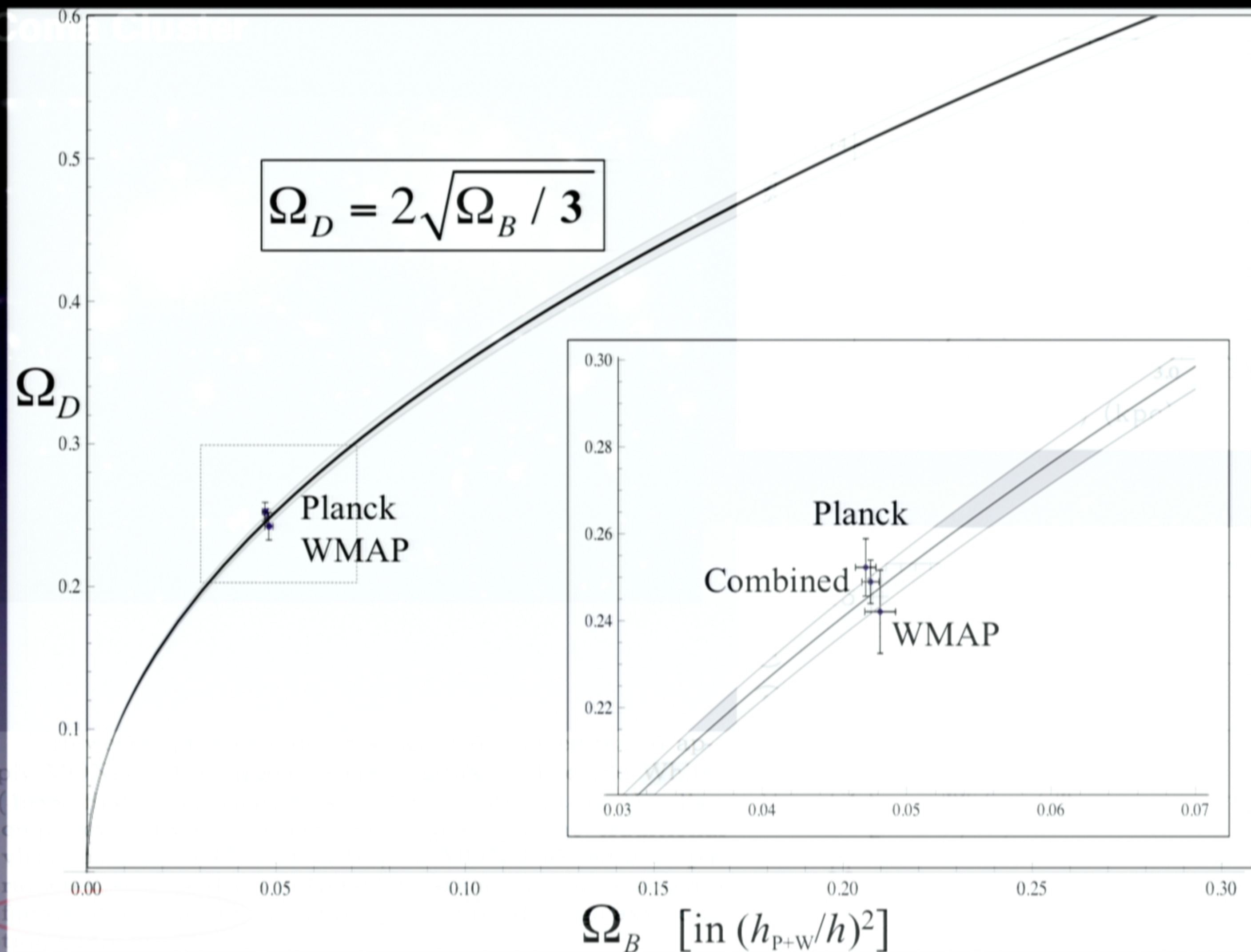
$\Upsilon_{\rm disc} = 0.50\,{\rm M}_\odot/{\rm L}_\odot$
$\Upsilon_{\rm bulge} = 0.70\,{\rm M}_\odot/{\rm L}_\odot$
$\Upsilon_{\rm disc} = 0.20\,{\rm M}_\odot/{\rm L}_\odot$
$\Upsilon_{\rm bulge} = 0.50\,{\rm M}_\odot/{\rm L}_\odot$
$\log(g_t)\,[{\rm m\,s^{-2}}]$
$\log(g_b)\,[{\rm m\,s^{-2}}]$
$\hat{R} = 0.1$
$\hat{R} = 0.2$
$\hat{R} = 0.5$
$\hat{R} = 1.0$
$\hat{R} = 2.0$
$\hat{R} = 5.0$

Universal formula for equivalent dark matter density

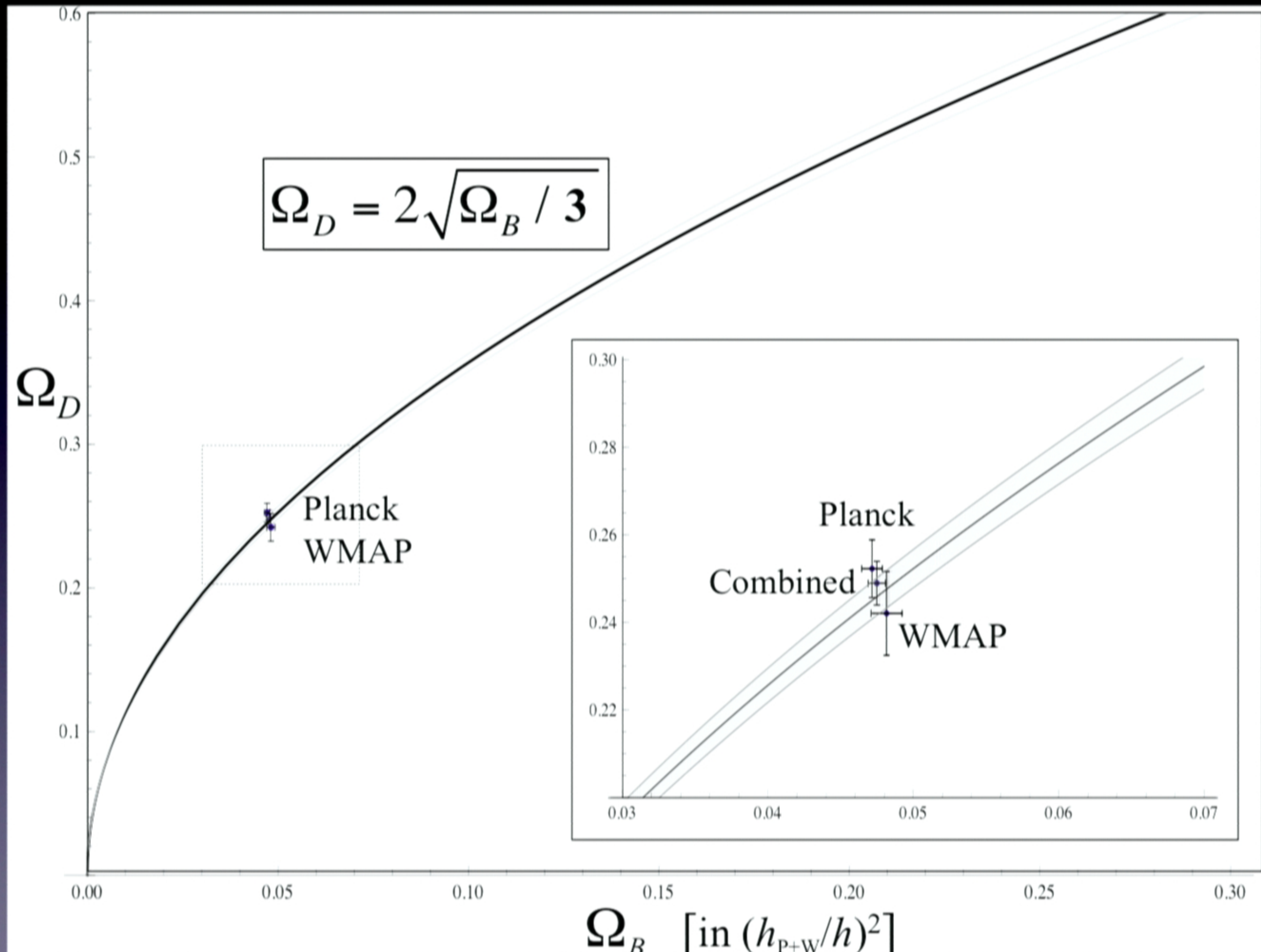
$$\frac{\overline{\rho}_B(R)\overline{\rho}_{crit}}{\overline{\rho}_D^2(R)} = \frac{3H_0R}{4+\alpha_B(R)}$$

$$M(R) = \frac{4\pi\overline{\rho}(R)R^3}{3}$$

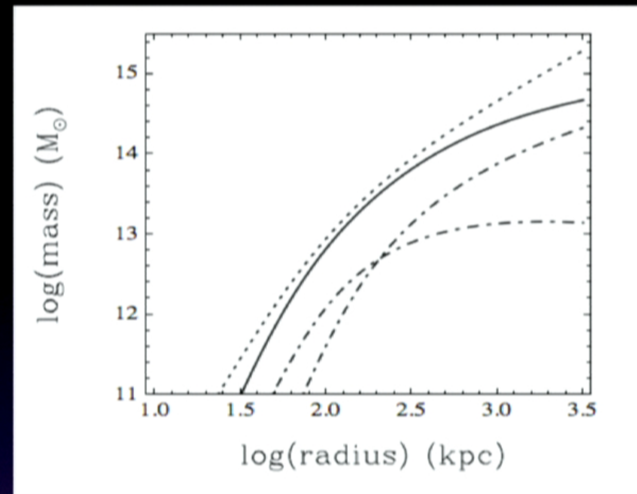
$$\alpha_B(R) = \frac{d\log\overline{\rho}_B(R)}{d\log R}$$



$\Omega_D = 2\sqrt{\Omega_B / 3}$
Ω_D
Planck
WMAP
Combined
Ω_B [in $(h_{P+W}/h)^2$]
0.6
0.5
0.4
0.3
0.2
0.1
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.22
0.24
0.26
0.28
0.03
0.04
0.06
0.07


$\Omega_D = 2\sqrt{\Omega_B / 3}$
Ω_D
Planck
WMAP
Combined
Ω_B [in $(h_{P+W}/h)^2$]
0.00 0.05 0.10 0.15 0.20 0.25 0.30
0.1 0.2 0.3 0.4 0.5 0.6
0.03 0.04 0.05 0.06 0.07
0.22 0.24 0.26 0.28 0.30

Coma Cluster



However, problems do arise when one attempts to apply MOND to the large clusters of galaxies. The and White (1988) first noted that, to successfully account for the discrepancy between the observed mass and the traditional virial mass in the Coma Cluster, the MOND acceleration parameter, supposedly a universal constant, should be about a factor of four larger than the value implied by galaxy rotation curves.