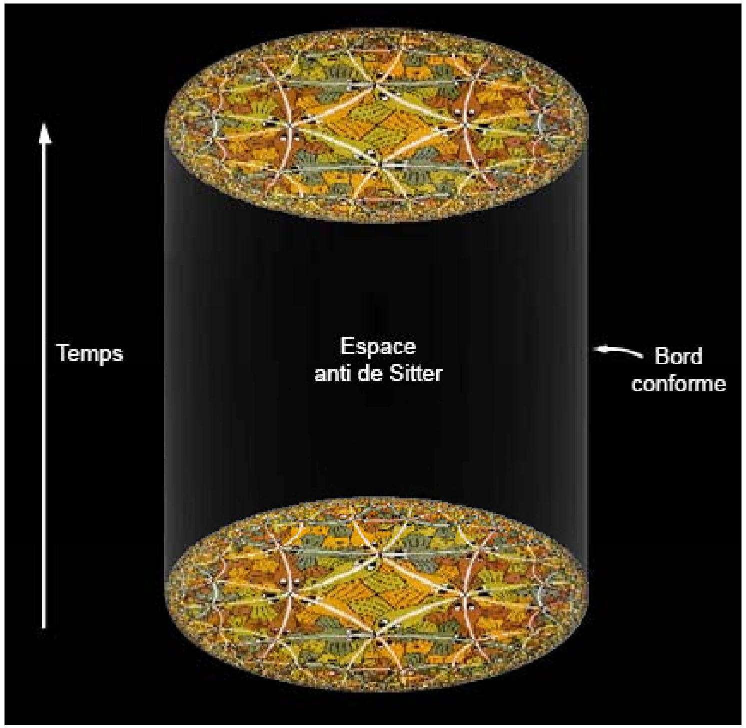
COLLÈGE DE FRANCE 1530

Chaire Galaxies et Cosmologie

Dark energy and new physics



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Outline

- Modified gravity: **why?** (Quantum physics + dark sector)
- F(R), Tensor-scalar-vectorial TeVeS, MOND
- Holographic theory of gravity, superstrings
  Correspondance AdS/CFT, duality gauge/gravity
- Emergent gravity, entropic theory of gravity
- Loop quantum gravity

Limits at Planck scale

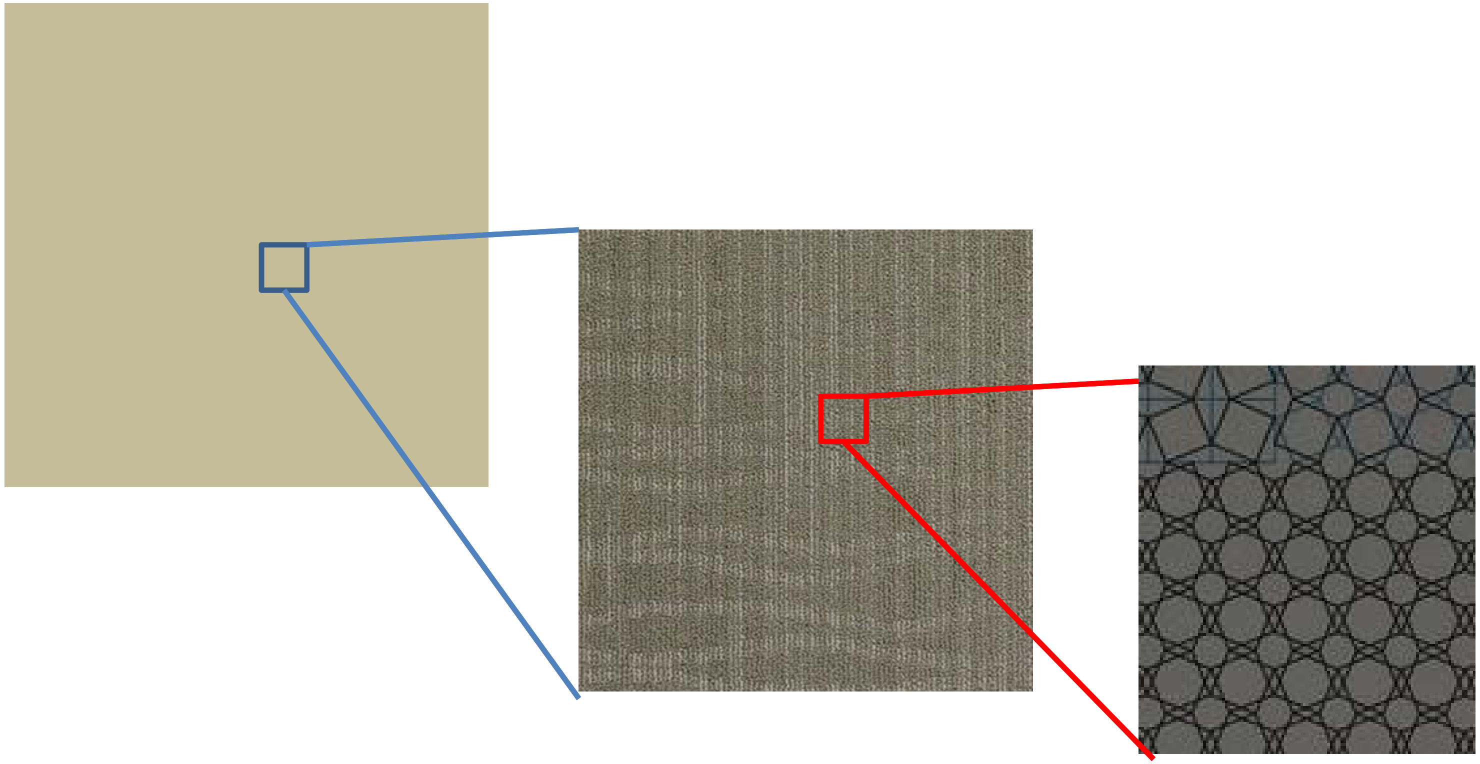
- Heisenberg uncertainty relations
- $\Delta x \, \Delta p > \hbar$ To precise the position of a particle $\Delta x < L$, a large energy is required $p^2 > \Delta p^2 > (\hbar/L)^2$ so large that $E \sim pc$
- But this energy is equivalent to a mass $Mc^2 = E$, and this mass deflects light rays by gravitational lensing
- This leads to a black hole, when light cannot escape any more

  $R \sim GM/c^2$
- When R = L, one obtains the Planck scale
- $L = GM/c^2 = EG/c^4 = pG/c^3 = \hbar G/Lc^3$

$$L_{\text{Planck}} = \sqrt{\frac{\hbar G}{c^3}}$$

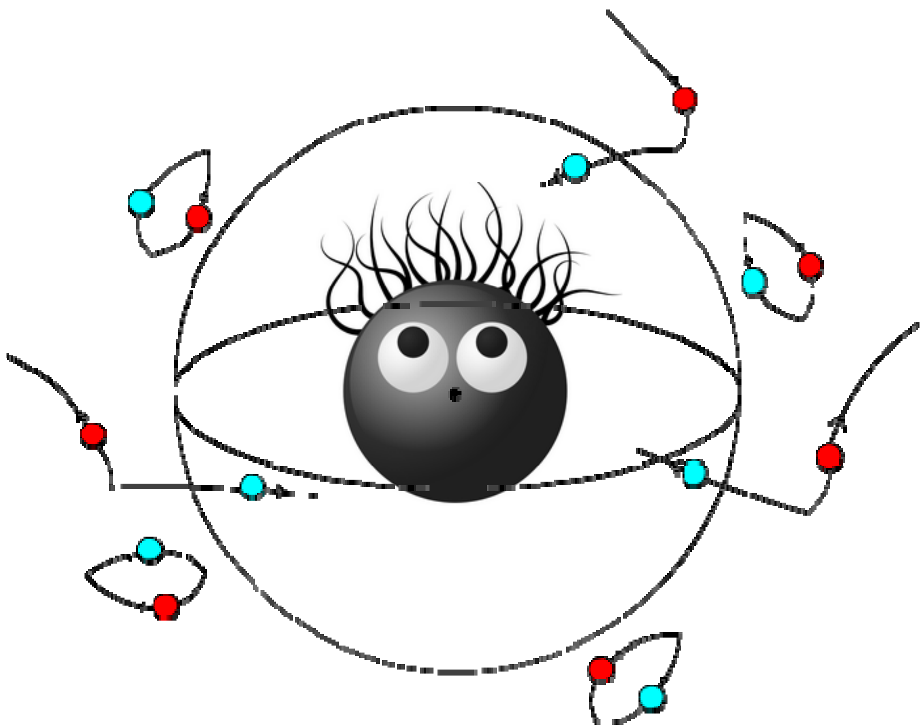
Quantum space

At Planck scale, the idea of smooth space is no longer valid
Mini-black hole, hidden inside its horizon



Links with black holes

- Black holes, as singularities of space-time, considered as the solitons of Einstein theory
- Horizon at $R = 2GM/c^2$ (3 km for 1 $M_\odot$)
- Thermodynamics: Temperature ~1/M, Entropy ~Area A ~M^2
- (Bekenstein, 1973, Hawking, 1974) **$S/k = A/(4L_p^2)$**

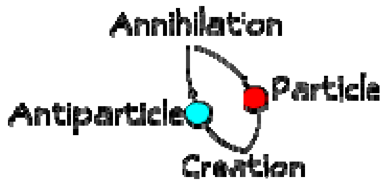


Black holes can evaporate

The life time of a black hole of $M < 10^{-19}\ M_\odot$ is smaller than Hubble time

$T = 10^{-7}$K for 1 $M_\odot$

$S \sim 10^{76}$ bytes



Black holes and entropy

Entropy related to the number of degrees of freedom

$S = k \log \Omega(E)$ Number of quantum states for a given energy E

How to compute them for a black hole?

It is possible to represent a black hole with an ensemble of strings and D-branes (Strominger & Vafa 1996), and count the different micro-states

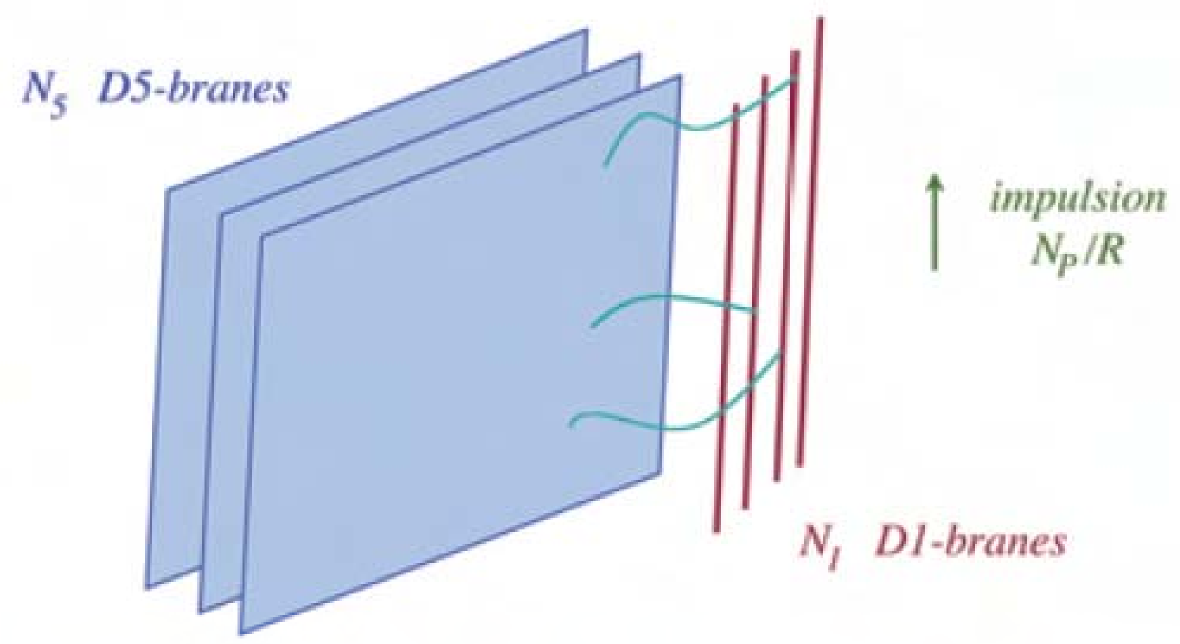
➔ The string theory can give a representation of quantum gravity, and justify the microscopic origin of the Bekenstein-Hawking entropy

One of the simplest descriptions

- The entropy writes $S = k\, 2\pi \sqrt{(N_1 N_5 N_p)}$
- With 1-branes (strings) of charge Q_1, and 5-branes of Q_5
- Impulsion is quantified in the compact dimensions, N_p integer

Hypothesis of supergravity : Supersymmetry

The states are half bosons & half fermions



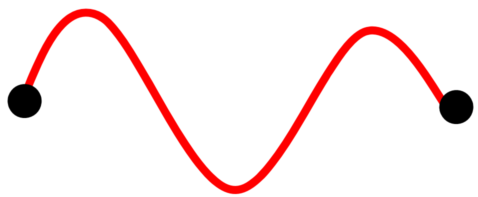
The black hole of Strominger-Vafa

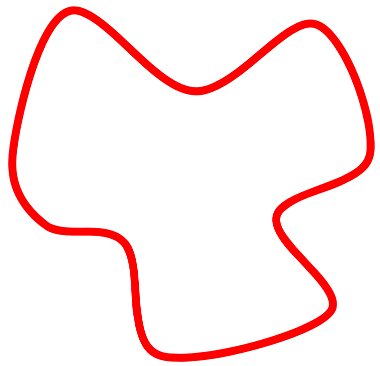
Black holes and superstrings

- However, one must assume an electric charge $Q + Q_M$ axion
  (if $Q=Q_M=0$, degenerate solution, with zero surface)
- A theory at **5 non compact dimensions, + 4 dimensions**

- **Unbroken supersymmetry** (simplifies the computation! No quantum corrections) in natural units, one must have Q=M
- Superposition of solitons D-branes, and supersymmetric states

➔ A solution is found, but with conditions very different from the reality of black holes





Theories of modified gravity

The problem of dark energy can be solved:

- Either in modifying the right hand side $\boldsymbol{T\mu\nu}$, **the quintessence**

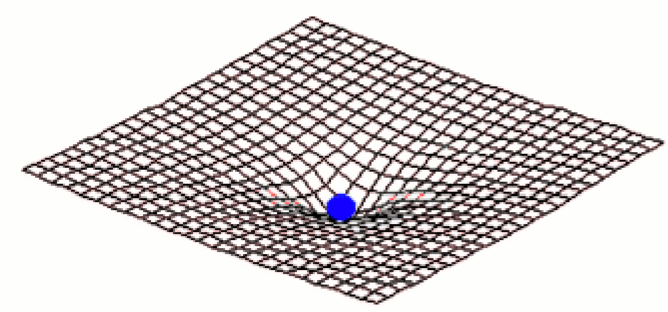
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Or in modifying the left hand side, **the gravity/geometry**

f(R) models of gravity, Tensor-scalar models, brane world, inhomogeneities, etc.

$\boldsymbol{R_{\mu\nu}}$ Ricci Tensor

$\boldsymbol{R}$ scalar curvature



What can be changed

***The gravity is universal, infinite range, without screening**

➔ Could have a massive mediator, or be non-universal at Ndim

***Is responsible of the space-time structure**

*Solution of Einstein equation, remarkably tested
in the solar system R ➔ f(R)

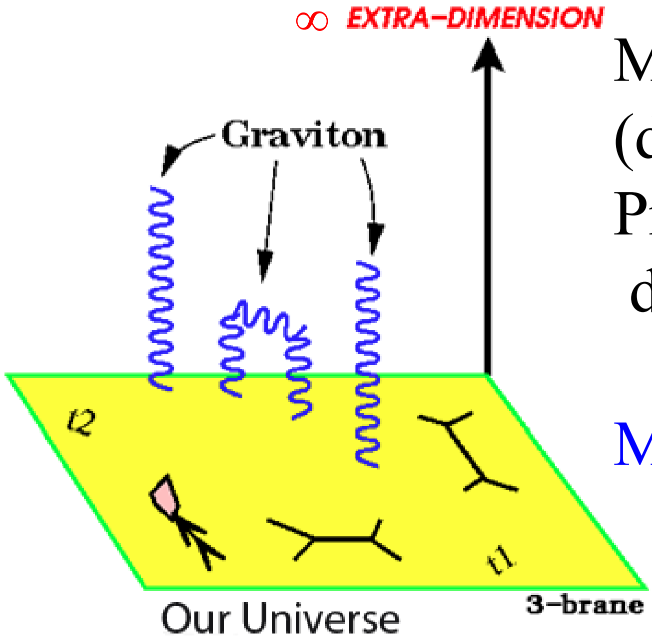
*Interaction with a mediator particule : the graviton, boson without mass
With spin 2 (tensor) ➔ tensor+scalar, +vectorial fields

***Coupled in a universal way at all other fields**

➔ Coupled to mass

Extra-Dimensions, DGP

Dvali, Gabadadze, Porrati (2000)



Model at 5 dimensions, only one extra (different from superstrings)
Proposed to accelerate the expansion, without dark energy

Model already ruled out by observations (besides, has problems of internal coherence, ghosts)

$\mathbf{S} = \int d^5x \sqrt{-g^{(5)}}\, R^{(5)} + \mathbf{L}\int d^4x \sqrt{-g}\, R$

$\mathbf{H^2 - H/L = 8\pi G\rho /3}$

$\mathbf{r \ll L \rightarrow V \propto 1/r}$

$\mathbf{r \gg L \rightarrow V \propto 1/r^2}$

L = transition scale

- 5D gravity dominates at low energy/long times/large scales
- 4D gravity at high energy/primordial universe/small scales

Changing gravity

Dark energy could be only a manifestation of a modified gravity beyond Einstein:

Gravity f(R), scalar-tensor models,
Brane models

The simplest model

gravity f(R)

$$S = \int d^4x \sqrt{-g}\left[f(R)/2 \; + L_m \right]$$

R: Ricci scalar

Model ΛCDM: $f(R) = R - \Lambda$

Starobinsky model **of inflation** :
Useful in the primordial Universe

$$f(R) = R + \alpha R^2$$

How could these f(R) models represent dark energy ?

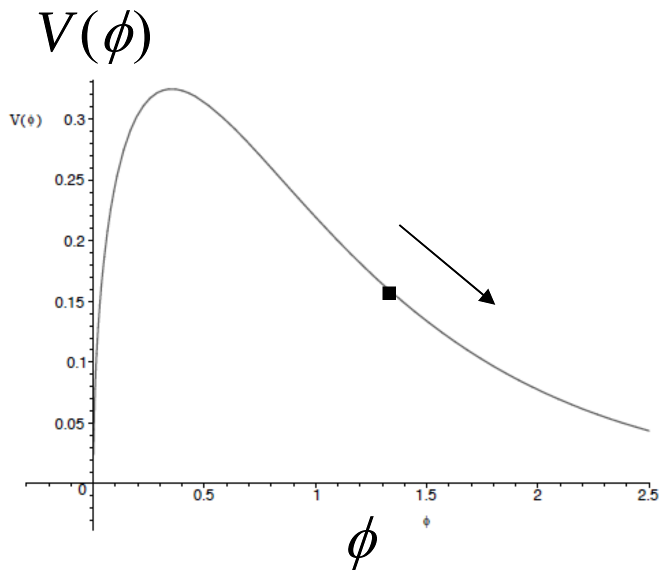
Example of a model

Caroll et al 2003

$$f(R) = R - \frac{\mu^{2(n+1)}}{R^n} \quad (n>0)$$

The potential is

$$V(\phi) = Ae^{-2\sqrt{6}\phi/3}(e^{\sqrt{6}\phi/3} - 1)^{n/(n+1)}$$



For large values of the field

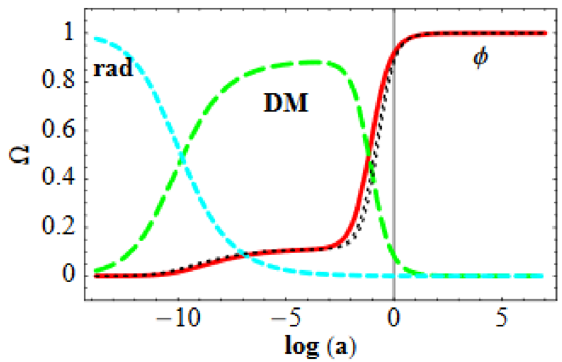
$$V(\phi) \propto e^{-\lambda\phi}$$

$$\lambda = \frac{\sqrt{6}}{3}\frac{n+2}{n+1}$$

➔Quintessence coupled to an exponential potential

The matter era then becomes matter +ϕ with

$$\mathbf{w_{DE} = -2/3, \;\; a \propto t^{1/2}}$$



➔ Incompatible with observations $\mathbf{a \propto t^{2/3}}$

Amendola et al (2007)

Conditions for a viable f(R) model

Amendola et al 2008

$$S = \int d^4x \sqrt{-g}\left[f(R)/2\kappa^2 + L_m + L_{rad}\right]$$

$$\kappa^2 = 8\pi G$$

For an FRW metric with a scale factor "a"

$$3FH^2 = \kappa^2(\rho_{\rm m} + \rho_{\rm rad}) + \frac{1}{2}(FR - f) - 3H\dot{F},$$

$$-2F\dot{H} = \kappa^2\left(\rho_{\rm m} + \frac{4}{3}\rho_{\rm rad}\right) + \ddot{F} - H\dot{F},$$

$$F \equiv \frac{{\rm d}f}{{\rm d}R}.$$

Matter, no pressure $\dot{\rho}_{\rm m} + 3H\rho_{\rm m} = 0,$

Radiation $\dot{\rho}_{\rm rad} + 4H\rho_{\rm rad} = 0.$

➔ A **general study,** without specifying the form of f(R)

The parameter $m(r) = \frac{Rf_{,RR}}{f_{,R}}$ **characterises the deviation** from the standard model ΛCDM

➔ **Cases where m is negative are ruled out,** as shown in:

Viable models

1) ΛCDM m =0

2) $f(R) = (R^b - \Lambda)^c$ bc~1

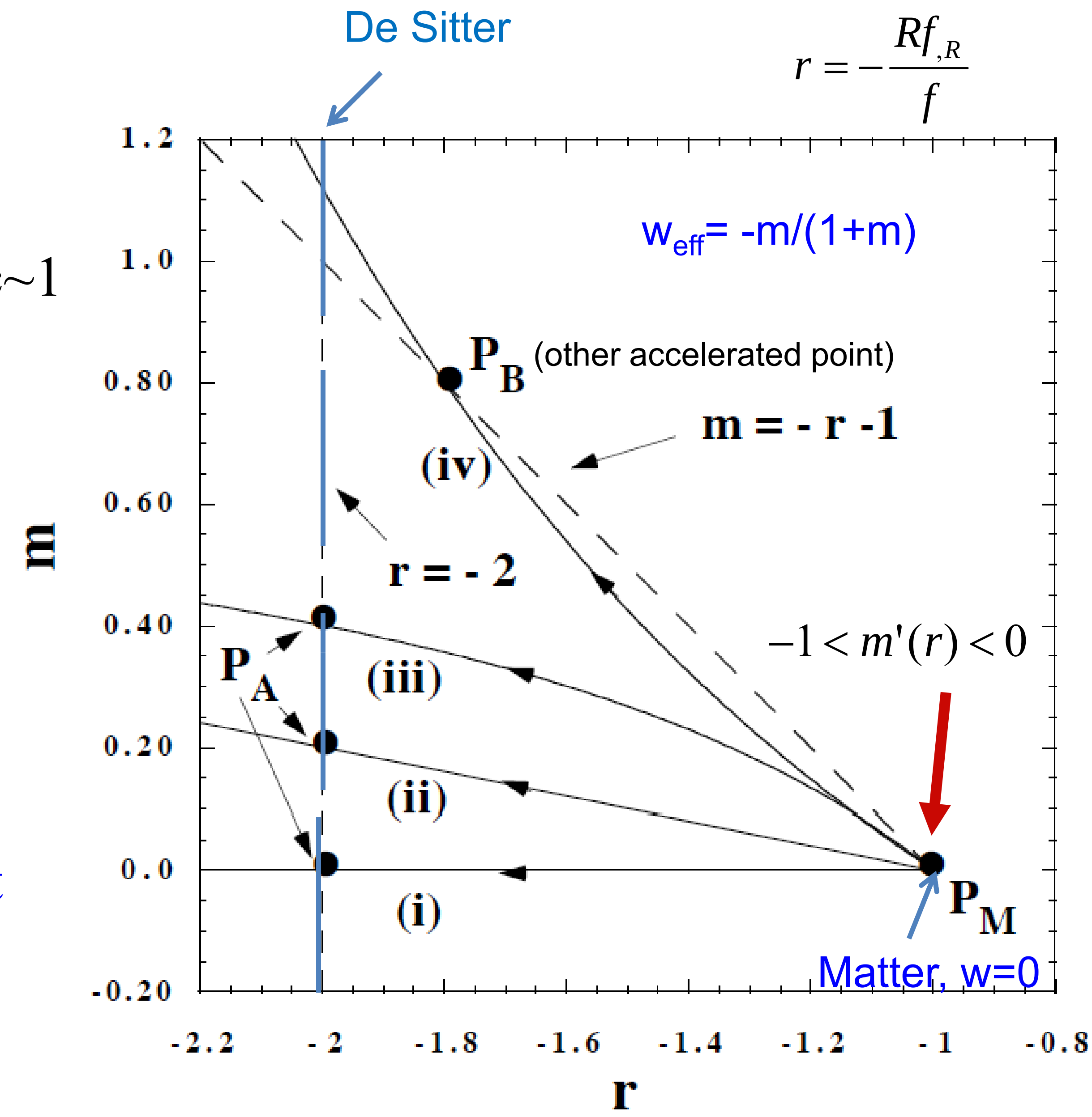
3) $f(R) = R - \alpha R^n$
with $\alpha > 0$, $0 < n < 1$

4) m(r) = -C(r+1)(r2+ar+b)

Model with m constant
$f(R) = R^{1+m} - \Lambda$

Amendola & Tsujikawa (2008)

$$r = -\frac{Rf_{,R}}{f}$$



Generalization to tensor-scalar models
More generic: Horndeski

Action $$\int dx^4 \sqrt{-g} \left[\sum_i L_i + L_{matter} \right]$$

Theory of 4D scalar fields, the most general
but complex equations

Horndeski (1975), Deffayet et al. (2011)
Modified gravity without ghost, nor instability

Can include f(R), Brans-Dicke, k-essence, Galileons, etc
Invariant by conformal transformation

MOND and TeVeS

MOND proposed in 1983 by M. Milgrom to solve the dark matter problem: **modification in weak field limit** $a < a_0 = 10^{-11} g$

At low acceleration

$a \ll a_0$ MOND regime $a = (a_0 a_N)^{1/2}$

$a \gg a_0$ Newtonian $a = a_N$

Asymptotically

$a_N \sim 1/r^2$ ➔ $a \sim 1/r$

➔ $V^2 = cste$

➔Lorentz covariant theory, **TeVeS** (Bekenstein 2004)

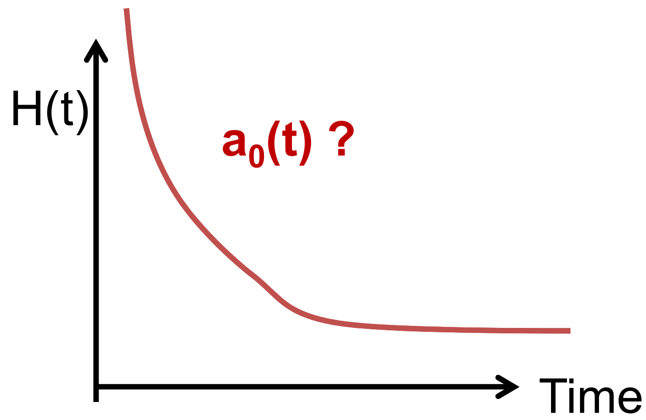
Contains two scalar fields plus a vectorial field + metric

According to the free parameters, can also account for dark energy

Does the critical acceleration vary?

$\mathbf{a_0 \sim c\, H_0}$, **or also** $\mathbf{a_0 \sim c\, (\Lambda/3)^{1/2}}$

(Extensions GEA, BSTV, Bimond..)



Massive gravity

Quadratic action of Pauli-Fierz (1939):
the only one exempt from ghost, at the linear level, with a massive graviton of spin 2

But this theory has **problems**:

(1) Its non-linear extension contains ghosts

(2) The limit $m \rightarrow 0$ does not lead to the standard model (discontinuity vDVZ)

The massive graviton propagates 3 extra degrees of freedom (vector, scalar), and within a Vainshtein radius, it was necessary to renormalize to retrieve normal gravity. This renormalization reduces the value of the force at the limit $m \rightarrow 0$

Vainshtein radius

Rv~800kpc!

The effects of massive gravity around sources is non-linear inside the Vainshtein (1972) radius

$$R_V = \left(\frac{M_{source}}{m^4 M_P^2} \right)^{1/5}$$

m graviton
M_p Planck

The discontinuity vDVZ is not necessarily a problem
Indeed, it comes from the extrapolation of the linear theory, which is wrong

For the Sun, the Vainshtein radius includes all the solar system!
This phenomenon, called **Vainshtein screening**, applies also for a certain number of modifieed theories, which must conform to the standard model in the solar system

Massive gravity and Bi-gravity

The ghost problem preventing a reliable non-linear theory of massive gravity was solved by de Rham, Gabadadze, Tolley (2010),
by summing all terms of superior order

$$S = \int d^4x \sqrt{-g}\left(-\frac{M_{\rm Pl}^2}{2}R + m^2 M_{\rm Pl}^2 \sum_{n=0}^{4} \alpha_n e_n(\mathbb{K}) + \mathcal{L}_{\rm m}(g, \Phi_i)\right)$$

The new term is in m^2, where m is the graviton mass
(natural units)

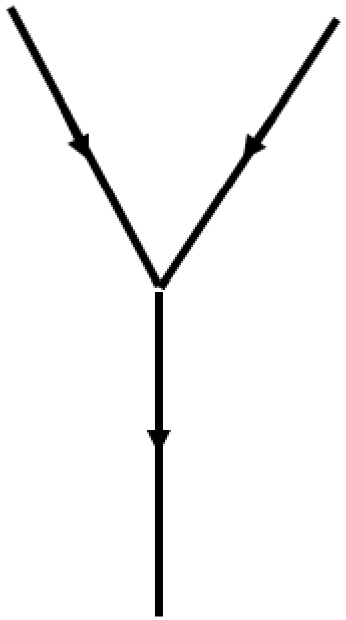
If $mc^2 \sim \hbar H_0$ (10^{-68}kg) **the present acceleration** of expansion is explained
But there is no metric for a flat universe, in this formalism

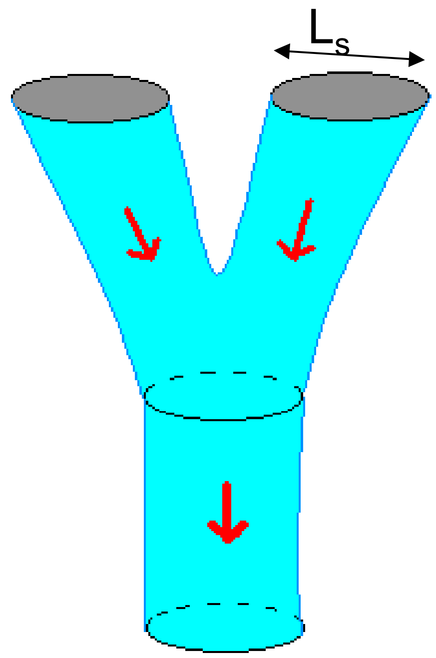
➔One has then to invoke a bi-gravity model, with two metrics
one for the high energies (Hassan & Rosen 2012)

→Instability just shifted earlier!!

Gravity and string theory

At the level of infinitely small ➔ strings of finite size





Size of the string L_s

T tension of the string

$$L_s = \sqrt{\frac{h\,c}{T}}$$

Goals: Unified theory of gravity and other interactions,
Based on quantum mechanics, and supersymmetry
➔Requires to have at least 10 dimensions

Limit at low energy in **Supergravity at 11 dimensions**

Existence of a field of zero mass and spin 2, the graviton

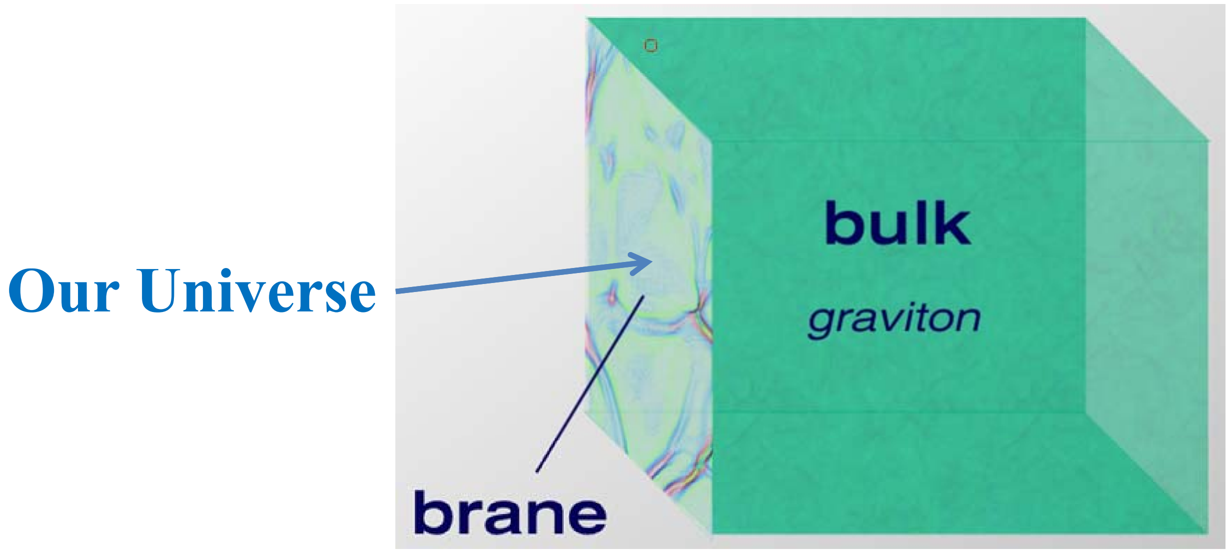
Dimensions of all sizes

➔Either a microscopic size ($\sim L_s$) ➔ with $L_s \sim 10 L_P$
compact dimensions, impulsions quantified

➔Either an intermediate size (~ micron?)

➔Or even a macroscopic size (and even infinite)

Only the gravitational force «sees» the extra dimensions,
and gravity is modified at small distance



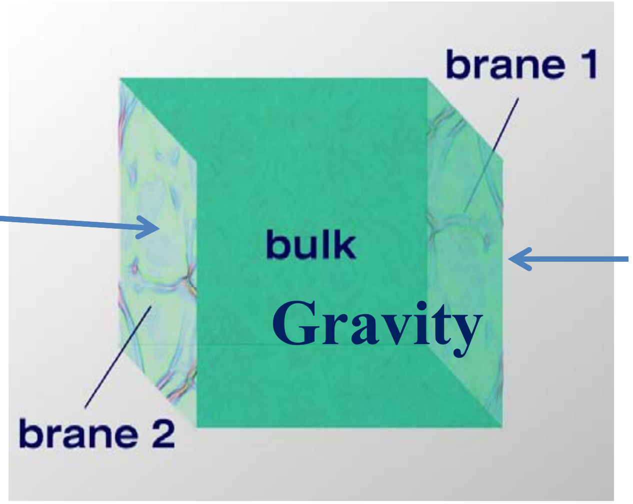
Infinite dimensions, with 2 branes

- The gravity is a property of space, it is the only one present in all dimensions

  The matter is confined in the (3+1) visible dimensions

  The other dimensions can be infinite (Randall & Sundrum 1999)

Our Universe



Hidden Universe at high gravity

- The 5^{th} dimension is not factorisable in the metric, but interacts with an exponential factor
- ➔ predicts TeV resonances at LHC

Implications

- To preserve Poincare invariance, the space curvature between the two 3-branes must be negative. In fact they are slices of **Anti-de-Sitter universe AdS5**

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

- Assuming another 3-brane, at distance r_c, then the bound states of graviton **are quantified** (continuum if the dimension is infinite)

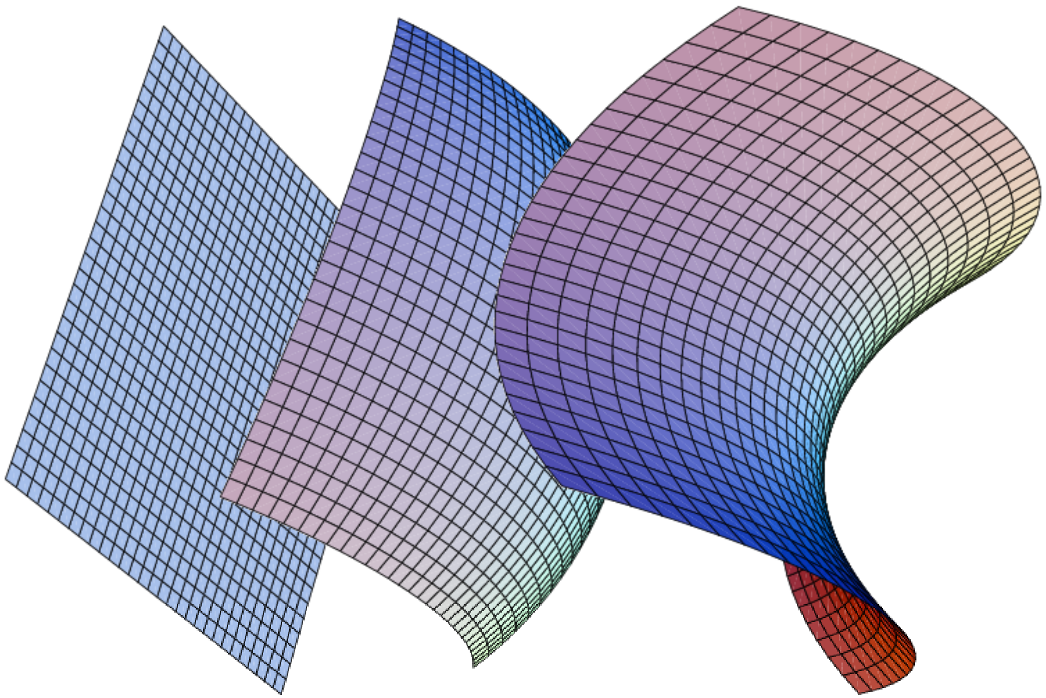
$$V(r) = G_N \frac{m_1 m_2}{r}\left(1 + \frac{1}{r^2k^2}\right)$$

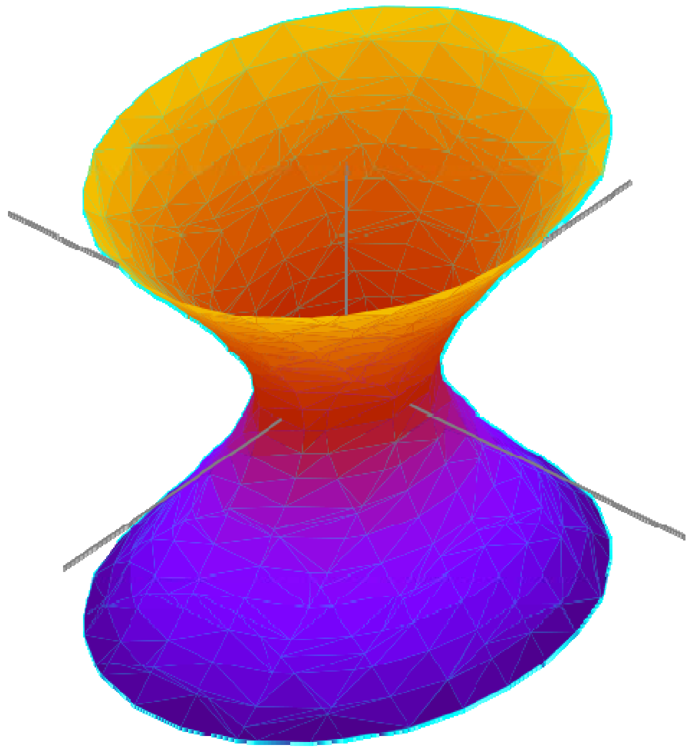
- The corresponding gravitational potential, introduces an extra weak term (k ~1/L_P)

(Randall & Sundrum 1999)

Anti-de-Sitter (AdS) space

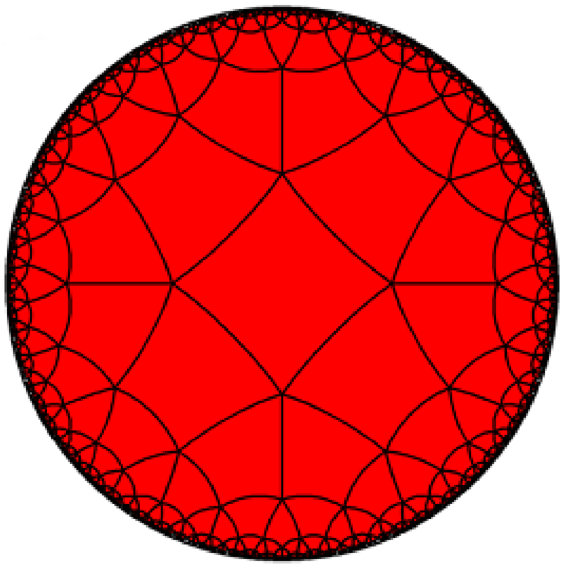
- This is a quasi-static universe, without mass, with only **a negative cosmological constant**
- Negative curvature (hyperbolic space, saddle shape)
- with n dimensions ➔AdSn

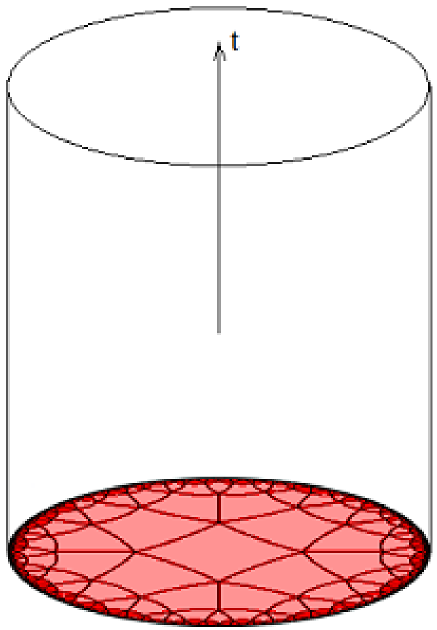


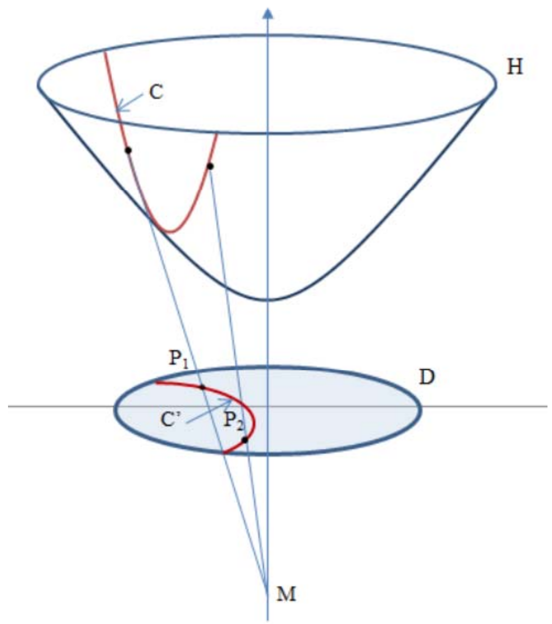


Representation of the surface

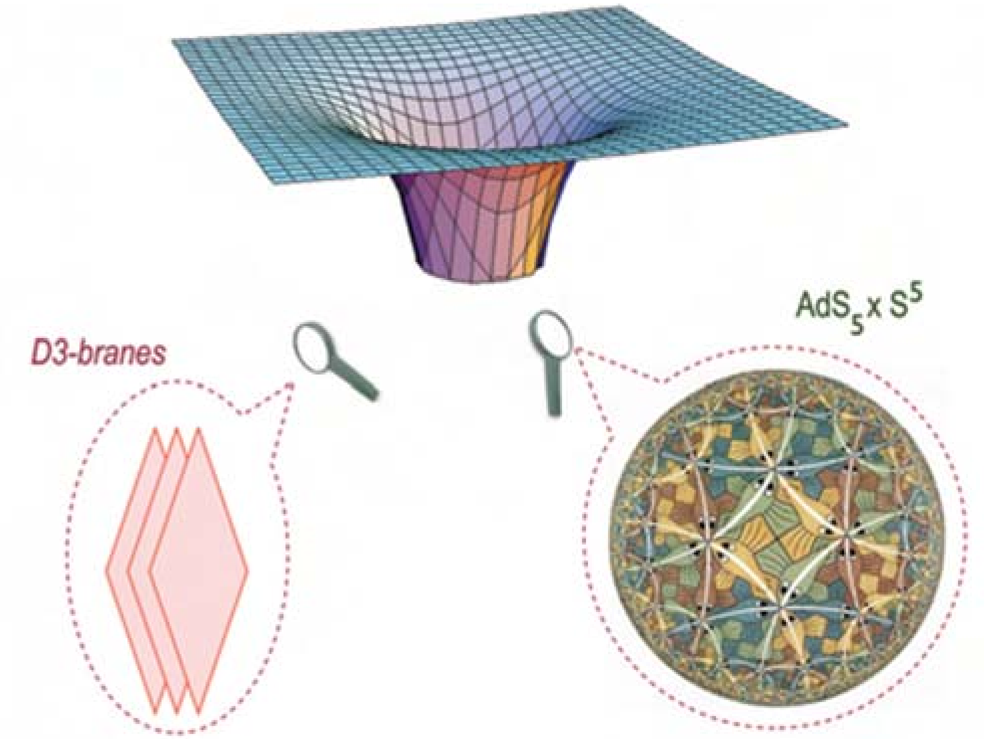
- The Poincaré disk is a conformal representation of an hyperbolic sheet (a 2-surface of negative constant curvature). While stacking Poincaré disks, one obtains the conformal representation of an Anti-de-Sitter space of dimension 3 (X,Y,t)
- AdS of dimension 4 is an hyper-cylinder of such type. Its boarder has the same properties as the Minkowski space-time of dimension n-1.







Duality with AdS_5



- An ensemble of N D3-branes is equivalent to AdS_5 x S^5

A curved Anti-de-Sitter space
 (Λ negative)

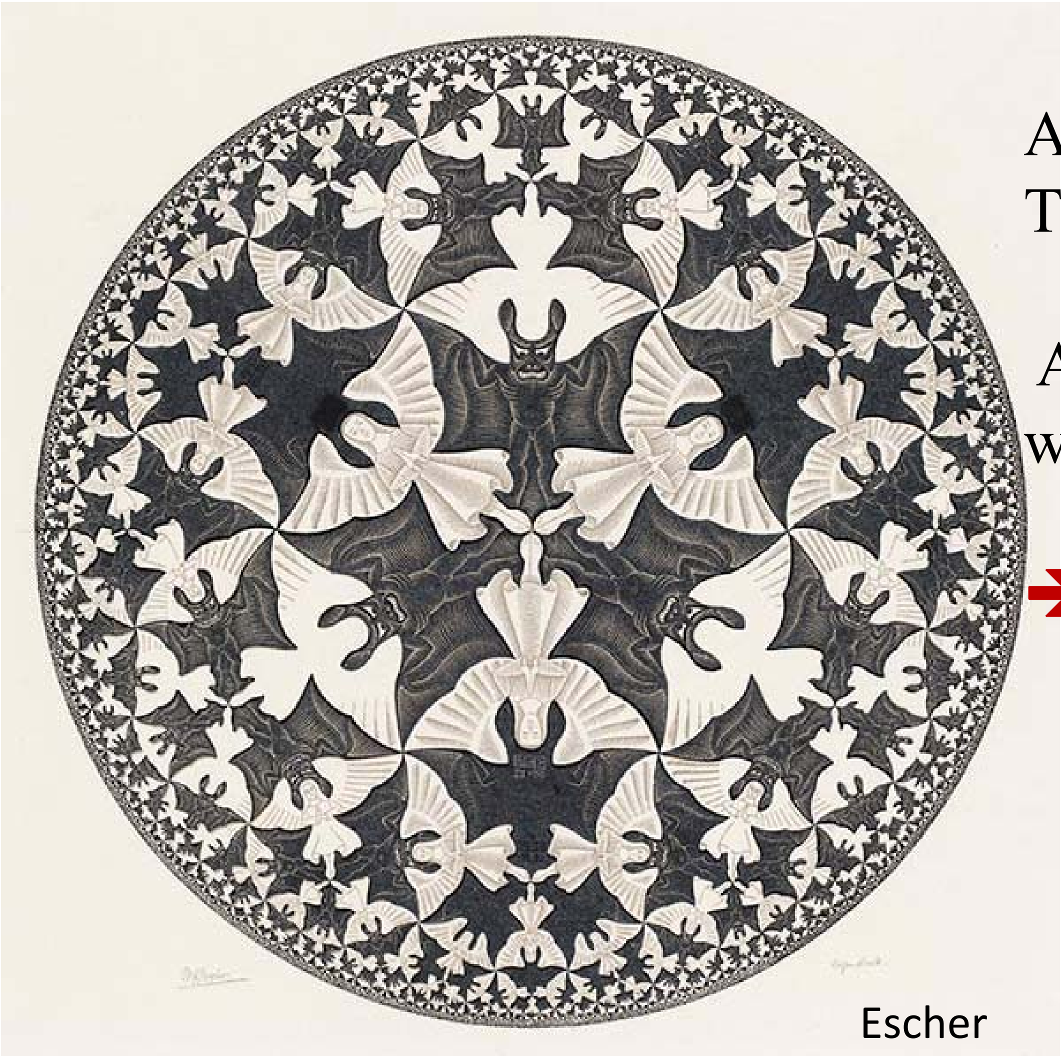
Gravity can then be equivalent to a field theory

Conjecture of equivalence **AdS/CFT** (conformal field theory)

Correspondence between quantum field theory and AdS string theory, holographic duality (Maldacena 1997)

Holographic theory

- Example of a tessellation, where objects are smaller and smaller when going to the boarder: scale invariance illustrating an AdS space



Escher

AdS spaces have negative Λ
Their geometry is hyperbolic

At the opposite, our universe is dS with positive Λ, and an horizon

➔ **More difficult to compute**

Hyperbolic space

Representation of AdS (3D) space

Escher disk

Pour la Science, 2006

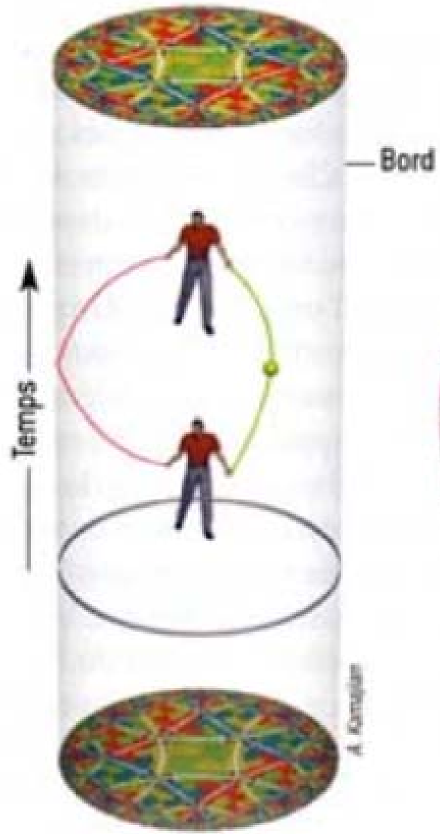
Particularities of the AdS (4D) space

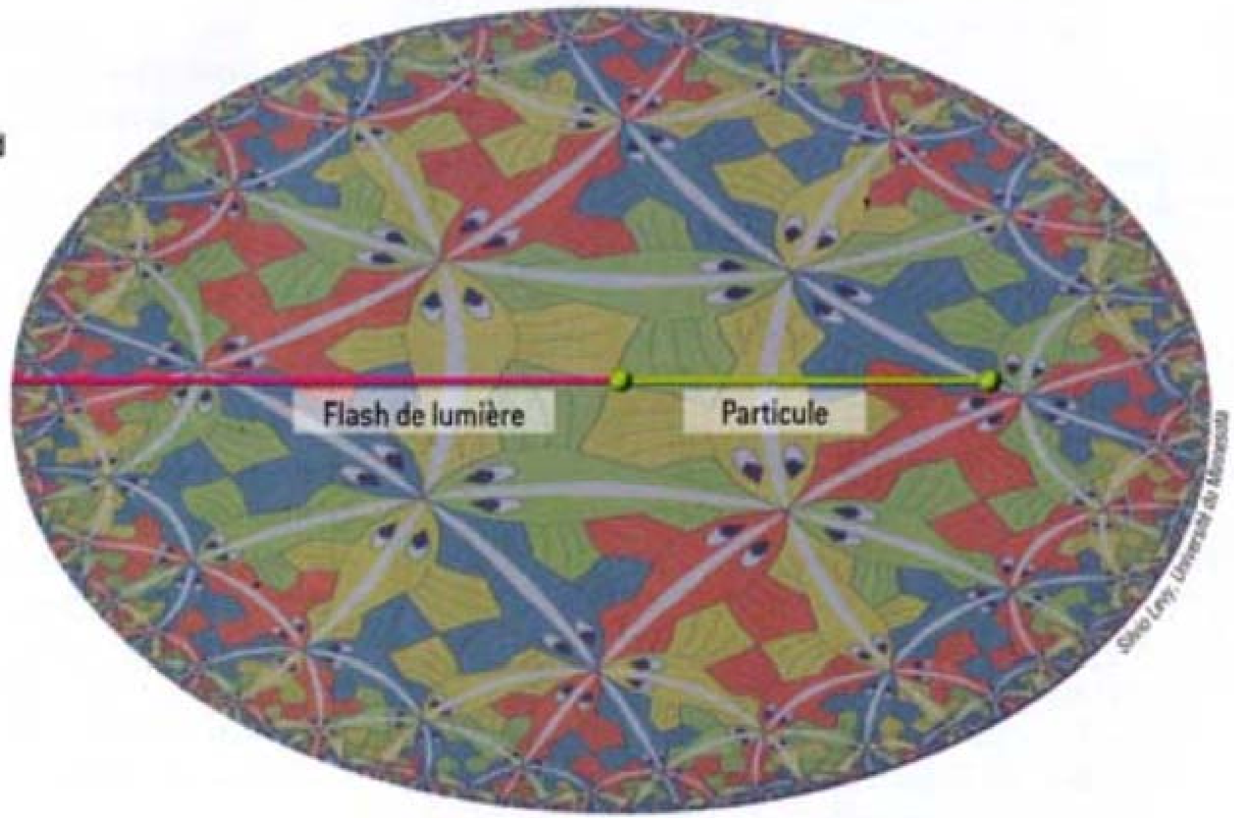
Negative curvature (k=-1, hyperpolic space), but negative Λ

$a(t) = a_0 \cos(At)$ $A = (-\Lambda/3)^{1/2}$

Representation of the cylinder: a space dim is wound around the cylinder
the other, time-like, is vertical

An object thrown up comes back at its start point (a light flash goes to ∞ and comes back in a finite time)





Emergent gravity

The gravity is not a fundamental force, but a
maximisation of entropy

Entropy and thermodynamics of horizon (Bekenstein-Hawking)
Thermodynamic paradigm and nature of gravity (Padmanabhan)

Holographic theory (Gerard ‘t Hooft)
Acceleration and temperature (Unruh)

Verlinde E.: 2010, On the origin of gravity and Newton laws
Verlinde E., Verlinde H: 2013, Intrication of black holes and quantum corrections
Verlinde E.: 2016, Emergent gravity and the dark Universe

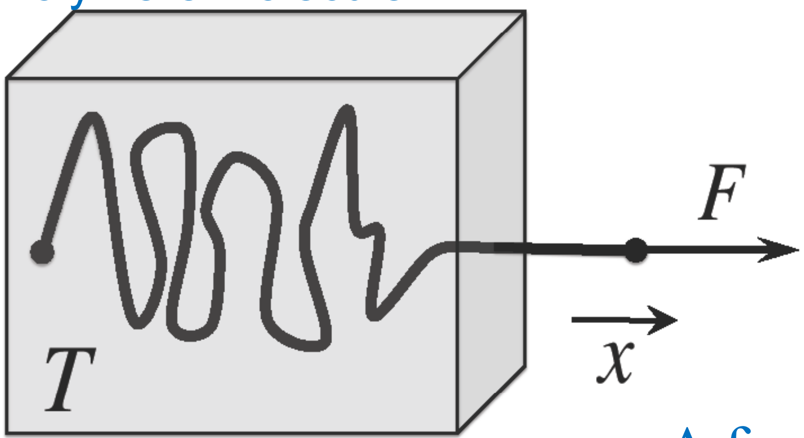
Gravity as an entropic force

At the microscopic level: a large number of degrees of freedom
They are not visible, but relevant for the macroscopic physics

Gravity would come automatically from the fact that space occupied by this information, these microscopic degrees of freedom, depend on macroscopic variables, such as the position of massive objects

➔ emergent gravity

Polymere molecule



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

A force occurs since the system tends to icrease its entropy *(Verlinde 2011)*

The Unruh temperature

Temperature and acceleration are linked
Unruh (1976) shows than an accelerated observer with **a** sees a black-body temperature T

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

The phenomenon comes from the vacuum energy and is related to the black hole thermodynamics

In the Hawking theory, black holes have a temperature

$$T = \frac{1}{8\pi k_{\mathrm{B}}}\frac{\hbar c^3}{GM}$$

which coincides with the Unruh temperature, if one considers the surface acceleration GM/R^2, at the horizon $R = 2\ GM/c^2$

For the acceleration on Earth $g \sim 10 m/s^2$, T is $4\ 10^{-20}$K

Emergent force

When a mass m approaches the black hole horizon, $R = 2GM/c^2$

The entropy $S/k = A/(4L_p^2)$ increases, $A = 4\pi R^2$

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

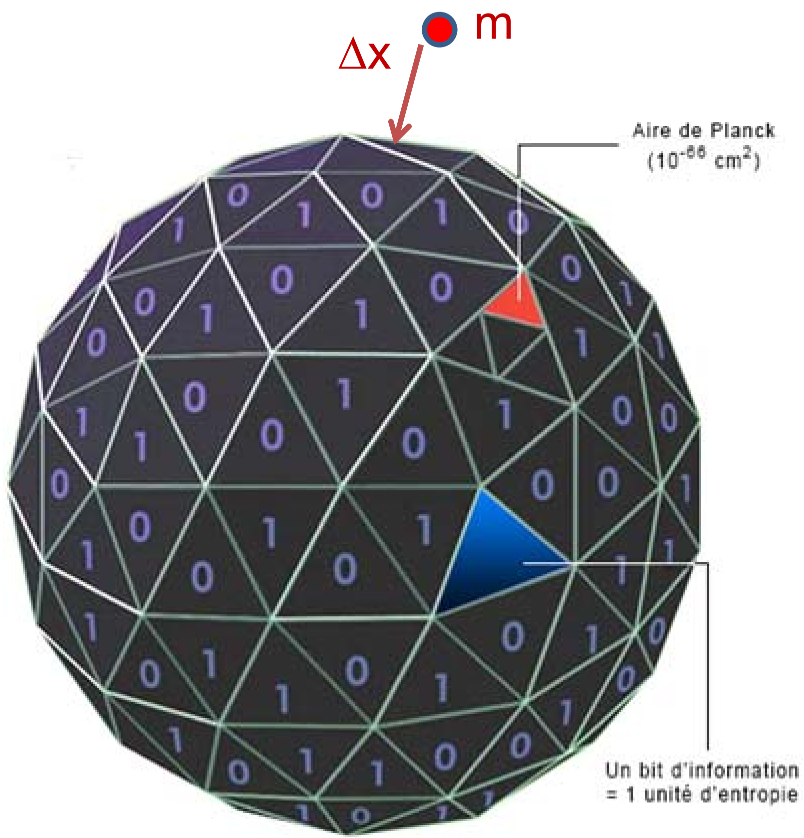
$\Delta S = 2\pi k\, mc/\hbar \;\; \Delta x$ $\qquad F\Delta x = T\Delta S = ma$

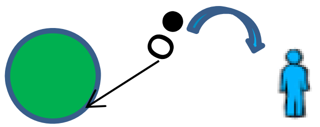
Energy equipartition

$Mc^2 = E = \frac{1}{2} kT N$

$S/k = N = A/(4L_p^2) = Ac^3/G\hbar$

$$T = \frac{2Mc^2}{kN} = \frac{GM}{R^2}\frac{\hbar}{2\pi kc}$$





Quantum intrication

Intricated entropy of quantum vacuum

At the black hole horizon: Bekenstein-Hawking entropy

$$S_{BH} = \frac{kc^3}{4\hbar G} A.$$

Intrication for two systems A, B, when their wave function is mixed: a measure on one system will automatically reduce the other, whatever their mutual distance (EPR paradox)

One can define the max of intrication entropy: maximum when systems are completely mixed (ex p-antip in the neighborhood of the black hole, but also at the Universe horizon?)

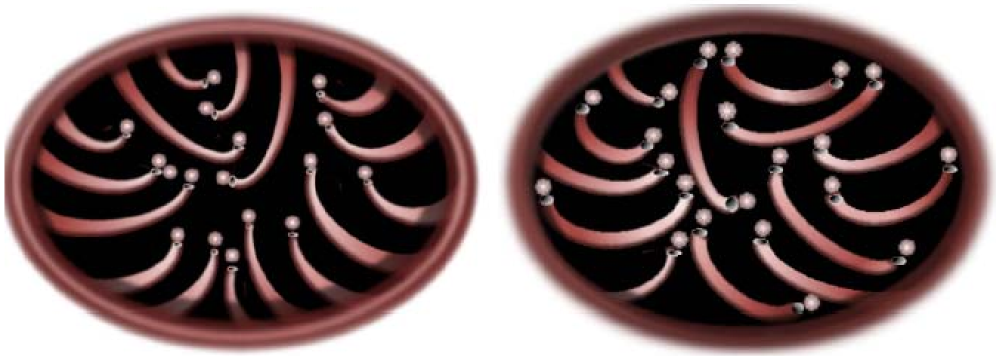
The variations of intrication entropy, due to the presence of matter can explain the emergence of gravity ***(Verlinde 2016)***

The space-time geometry represents the structure of the intrication at the microscopic level *(Maldacena and Susskind, 2013 Van Raamsdonk 2010)*

de Sitter space, dominated by Λ

Approximation, H_0 is constant, the horizon is $L = ct_0 = c/H_0$
The temperature T is proportional to the surface acceleration

$a_0 = c\, H_0 = c^2/L \Rightarrow T = \frac{\hbar\, a_0}{2\pi c k}$



Two possible schemes of quantum intrication
***Left**: particle-horizon:*
***Right:** particles with each other*

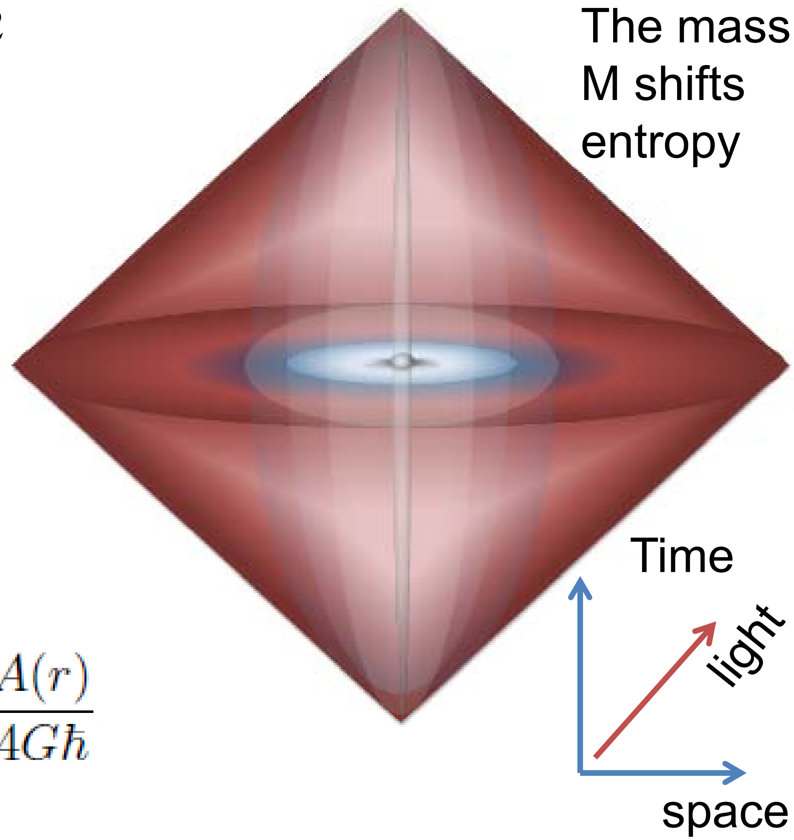
The case particule/horizon applies to dS, the intrication entropy produces states of thermal excitation responsible of dark energy.

Dark energy and accelerated expansion are due to the slow thermalisation of the emergence of space-time

Implication for dark matter

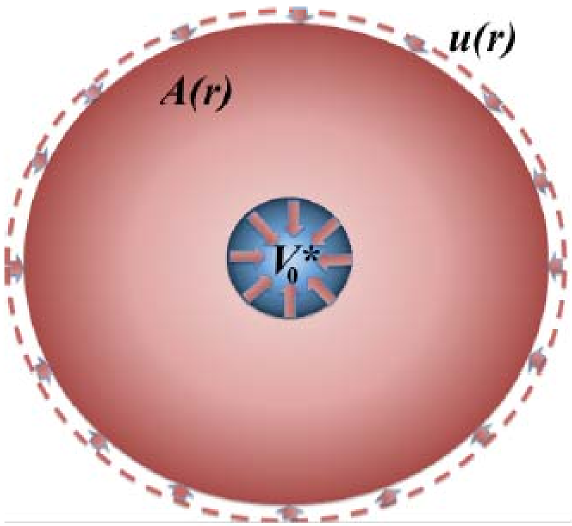
Mass M included in a sphere, $A(r) = 4\pi r^2$
Surface density $\Sigma = M/4\pi r^2$

The observations show that when
$\Sigma < a_0/8\pi G$, there exists dark matter
a_0 is the critical acceleration of MOND



One can write the entropy change S_M
brought by mass M

$$S_M = \frac{2\pi M}{\hbar a_0} < \frac{A(r)}{4G\hbar}$$



Suppression of V_0^* from the elastic and
incompressible medium
➔Shift $u(r) = -V_0^*/A(r)$
A mass M reduces the intrication entropy

Space-time elasticity

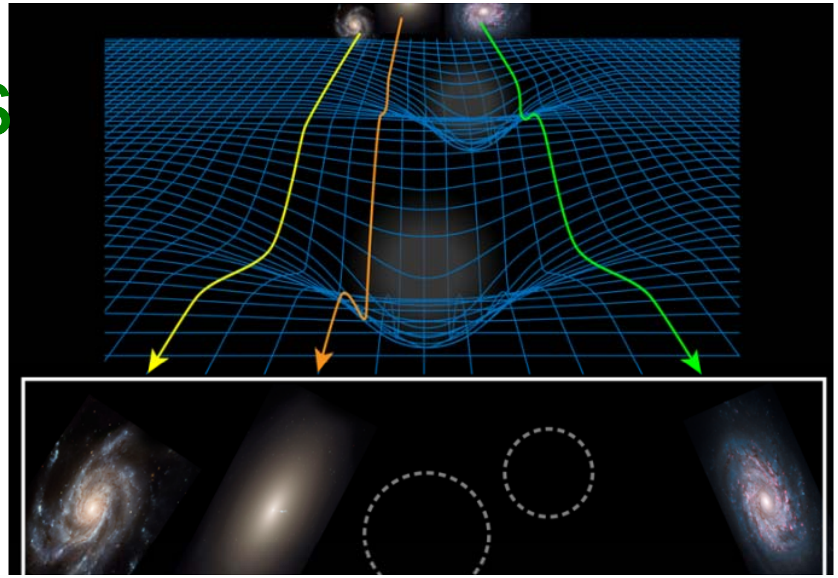
The entropy spread in universe under the form of dark energy, makes space more elastic, and creates an extra emergent gravity:
A dark matter, when $\Sigma < a_0/8\pi G$, the apparent dark matter is

$$\frac{2\pi}{\hbar a_0} M_D^2 = \frac{A(r)}{4G\hbar}\frac{M_B}{d-1} \qquad \text{ou} \qquad \Sigma_D^2(r) = \frac{a_0}{8\pi G}\frac{\Sigma_B(r)}{d-1}. \qquad d=4$$

Or $g_D{}^2 = g_N\, a_0/6$, which is the MOND relation *(Milgrom 1983)*

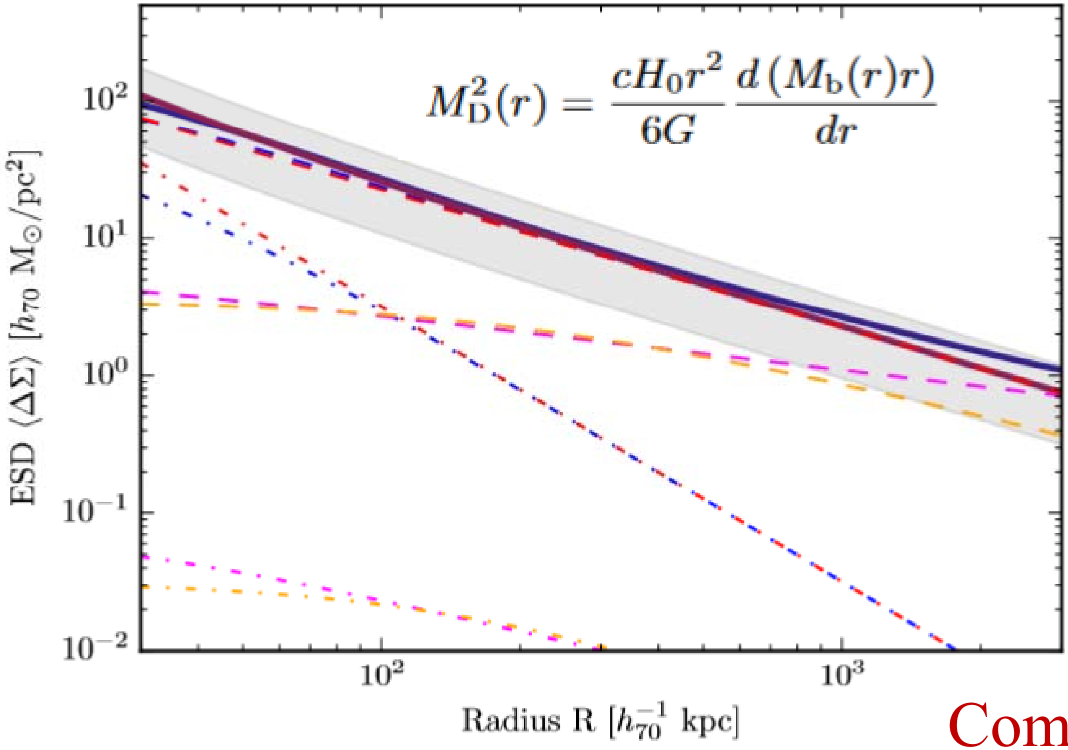
The elastic response is due to the intrication of matter with entropy DE contained in the volume r^3. The intrication entropy increases with r
This increase of gravity (dark matter) occurs when the intrication entropy of the matter falls below the dark energy entropy

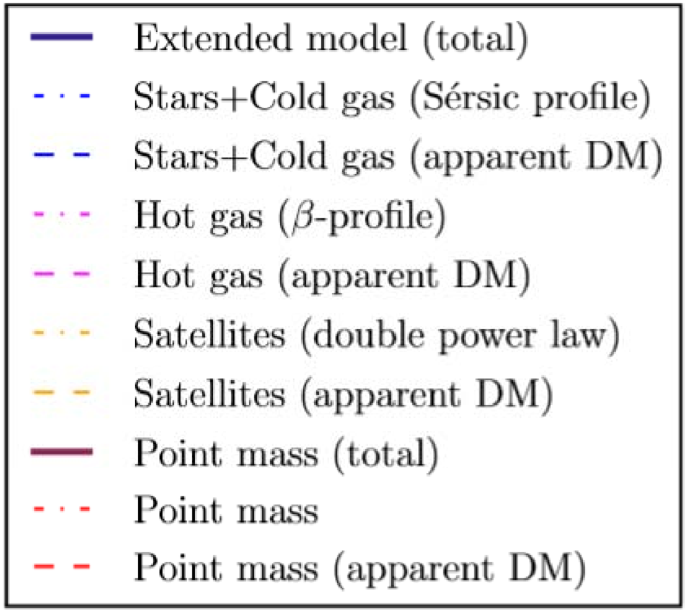
Test of gravitationnal lenses



KIDS: VST-ESO KiloDegree Survey
+ GAMA spectro survey
33 000 galaxies

ESD=Excess surface density (R)

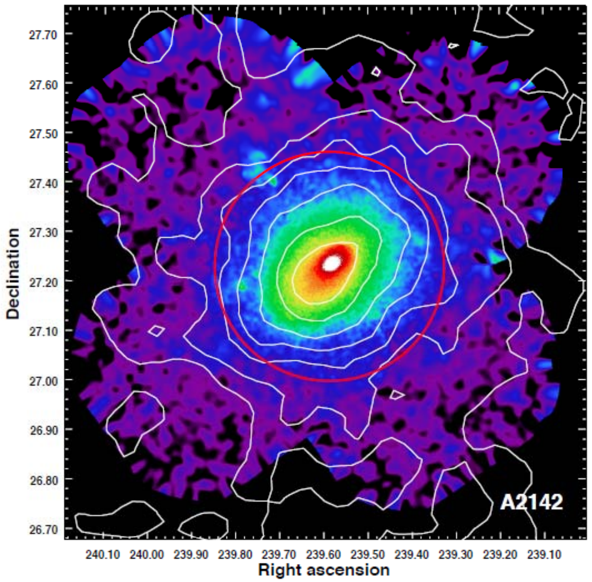


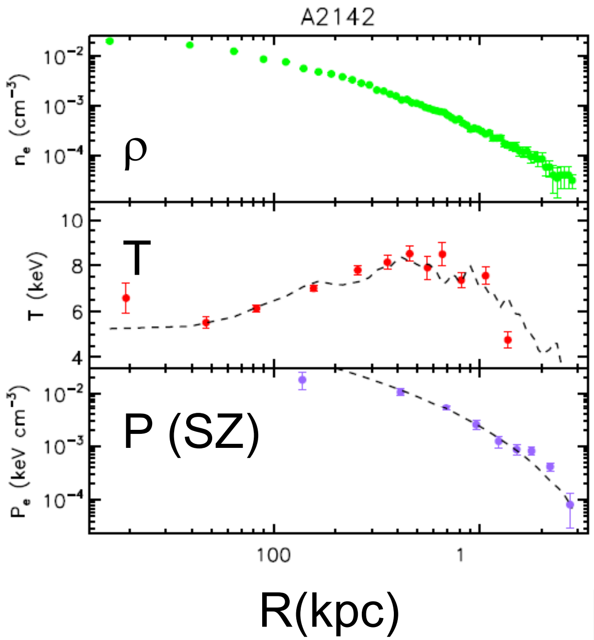


Brouwer et al 2016

Compatible with apparent DM
due to emergent gravity

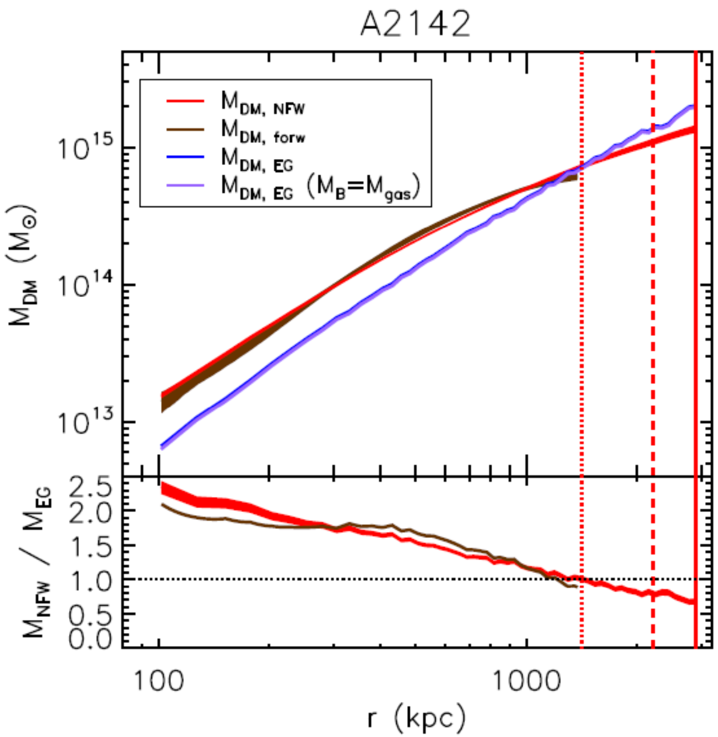
Emergent gravity : test on galaxy clusters





Radial distribution of mass in A2142 and A2319 X-Rays and SZ effect

Ettori et al 2016



In the theory of emergent gravity (Verlinde 2016), dark matter is a manifestation of the elastic force due the entropy shift

$$\int_0^r \frac{G\,M^2_{\mathrm{DM,EG}}(r')}{r'^2}\,dr' = \frac{M_{\mathrm{B}}(r)\,cH_0\,r}{6}.$$

Other problems?

Main plus: propose a microscopic interpretation of the MOND hypothesis

Problems in galaxy clusters?

More exact formula for extended masses

$$\overline{\rho}_D^2(r) = \left(4 - \overline{\beta}_B(r)\right) \frac{a_0}{8\pi G} \frac{\overline{\rho}_B(r)}{r}.$$

Bullet collision, separation of two masses? No problem in this hypothesis

The DE effect is different from baryons

$$\rho_{crit} = \frac{3H_0^2}{8\pi G} = \frac{3a_0}{8\pi G}\frac{1}{L}.$$

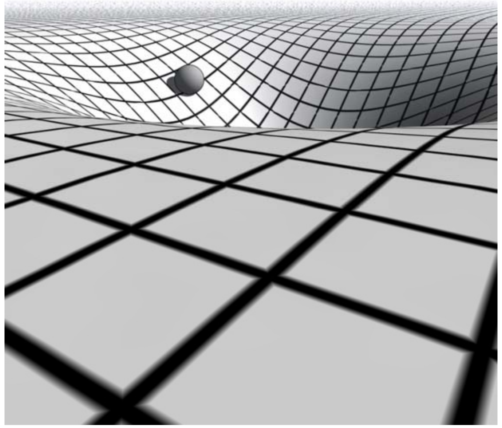
➔Problem of the cosmic background anisotropies: 2nd peak

$\Omega_D{}^2 = 4/3\ \Omega b$

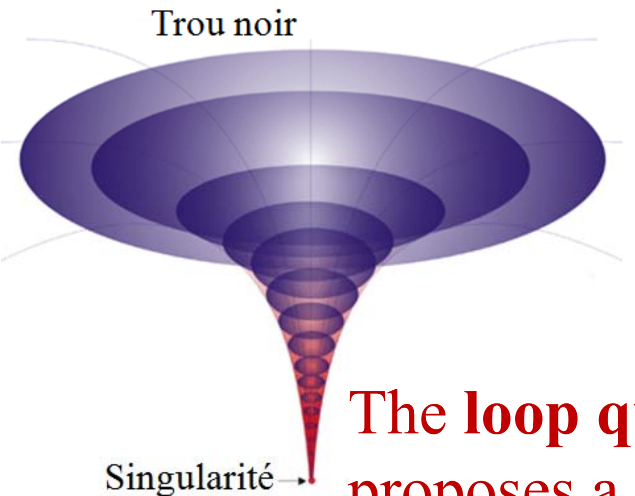
Not yet known: what role DE plays in the early Universe?

But not impossible

Space-time depending on mass



Space-time is created at the
Big-Bang
Blakc holes tear off space-time
in a singularity



At Planck scale $\ell_P = \sqrt{\frac{\hbar G}{c^3}}$ $\sim 10^{-35}$m
$M_p = 5\mu g$, $\rho \sim 10^{94}$ g/cm^3
Space is no longer continuous

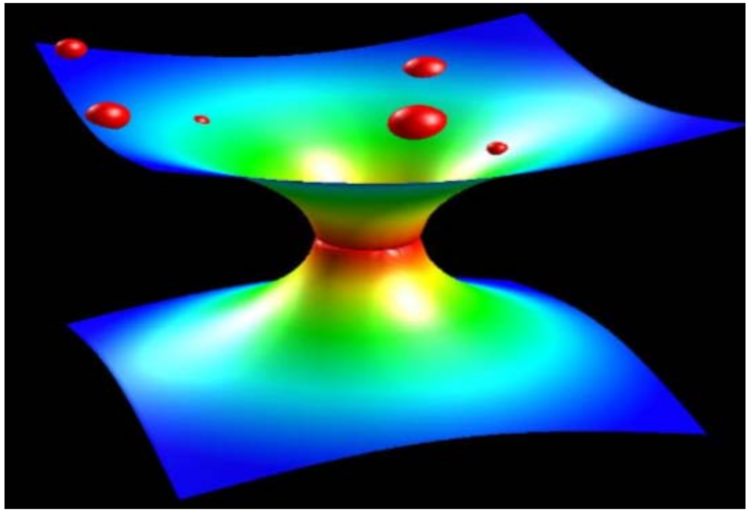
The **loop quantum gravity** theory
proposes a scheme to get rid of the background space
Based on transformations or « connections » between spins
where fields analogous to **(E, A)** define the orthonormal
Structure (**E** distances, **A** curvature)
➔ covariant equations

Loop quantum gravity

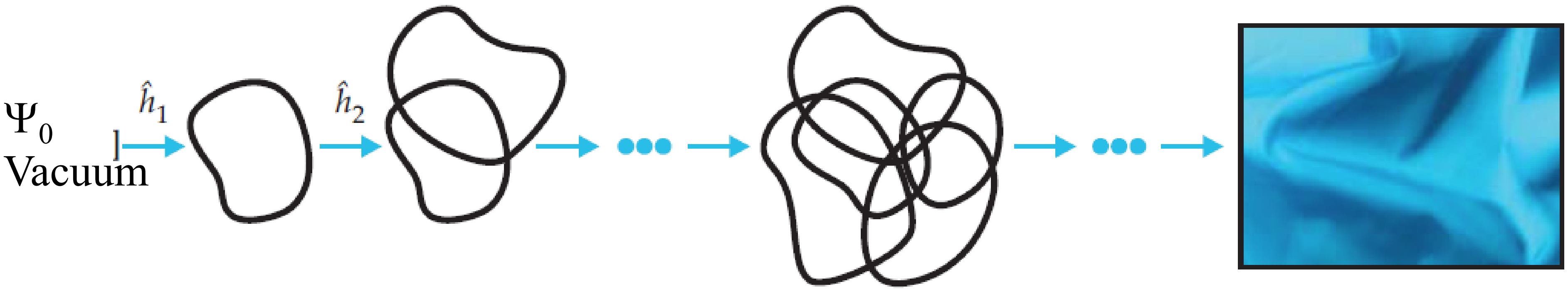
Holonomy operators, to quantify the Riemann space
Operators represent lengths, surfaces, volumes,
and have all discrete eigen values
Creation/annihilation operators (analogous â, â+ for oscillators)
to deal with geometry excitation *(L. Smolin, C. Rovelli)*

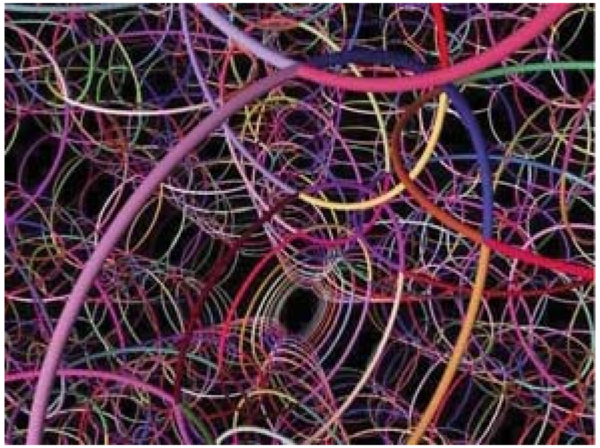
The quantum geometry introduces a negative pressure at small scale
➔Gravity becomes a repulsive force at Planck scale
The Big-Bang singularity transforms in rebound

Model different from cyclic models
Time does not exist any more at Big-Bang
Problem of entropy increase?



Creation of space



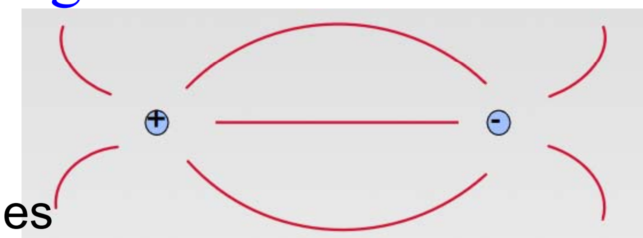


Spin network, different degrees of excitation are in different colors

The operator ĥ creates a geometry quantum, and space is randomly assembled as a polymer

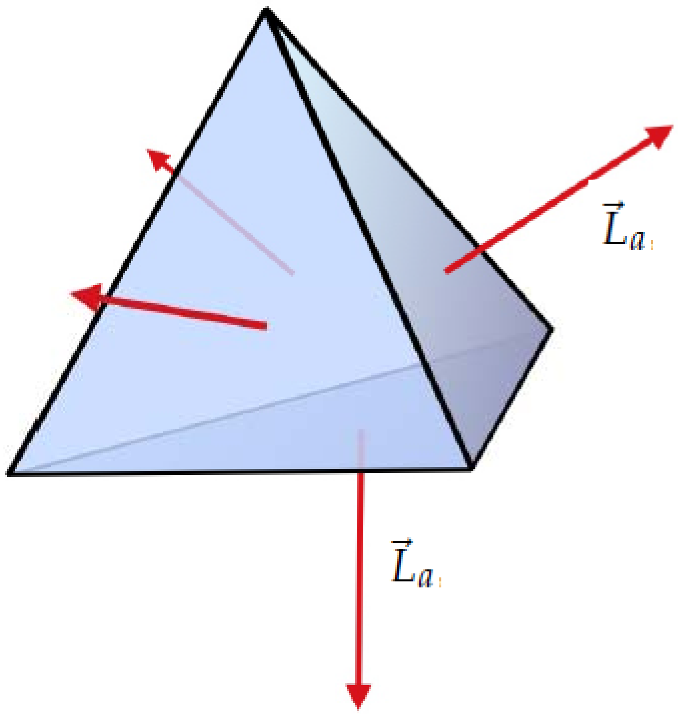
At large scales ➔continuous aspect of space

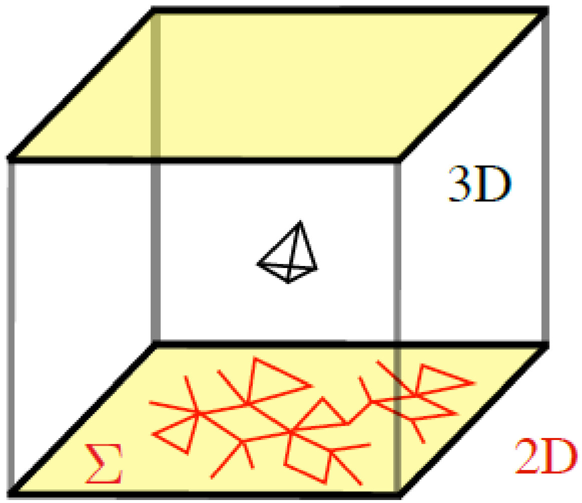
Analogy **(E, A),** a surface has an area proportionnal to the crossing flux



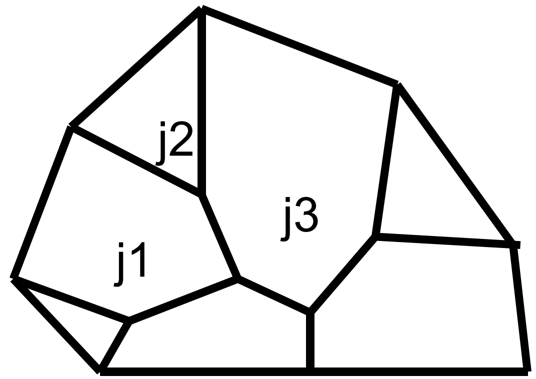
Faraday lines

Theory based on spins





Quantification of space by tetraedrons



Divergences suppressed at small scale by the cut-off at Lp
At large scale, the introduction of a small cosmological constant Λ solves the problem

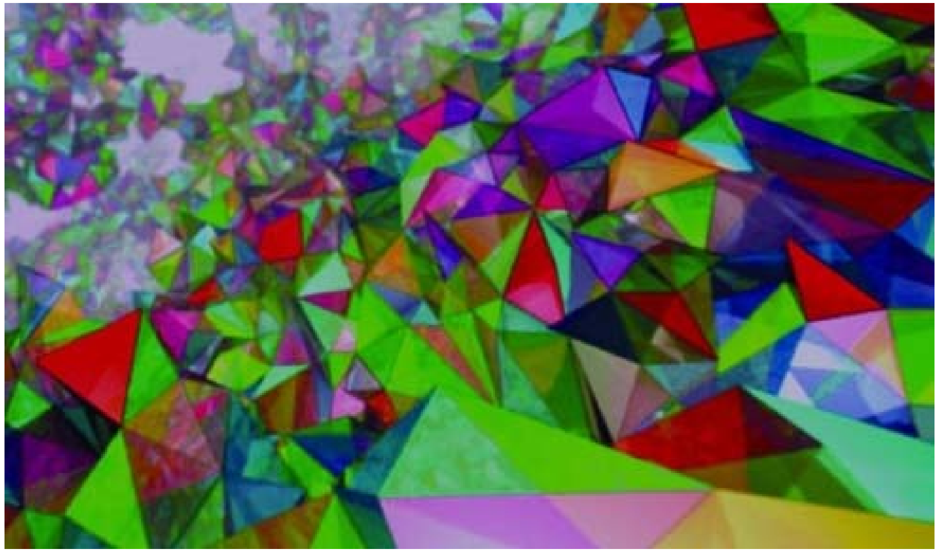
Loop quantum gravity

Initial state Ψ_0 Infinite temperature, maximum entropy,
But no space-time

How to probe this structure at small scale?
Only by its implications. The Universe amplifies these structures in the inflation ➔ ideal laboratory

Effects are expected of the order of ρ/ρ_P,
thus extremely weak!

Also effects at scales L,
of order of (L/L_p)



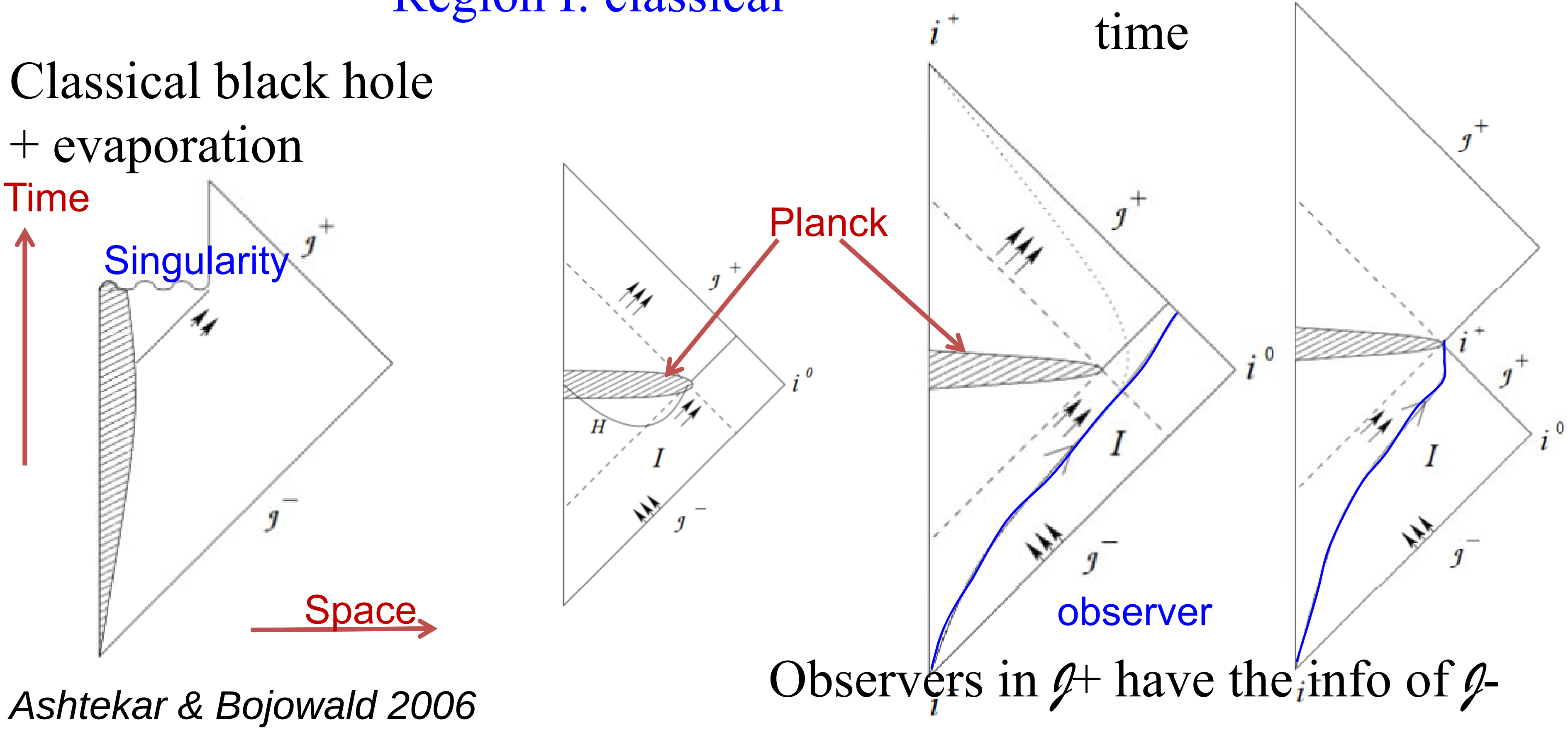
Black hole singularity

No loss of information: no singularity either
Quantum gravity plays a role in the region of Planck density, and produces a rebound

In loop quantum gravity
Region I: classical

Classical black hole
+ evaporation

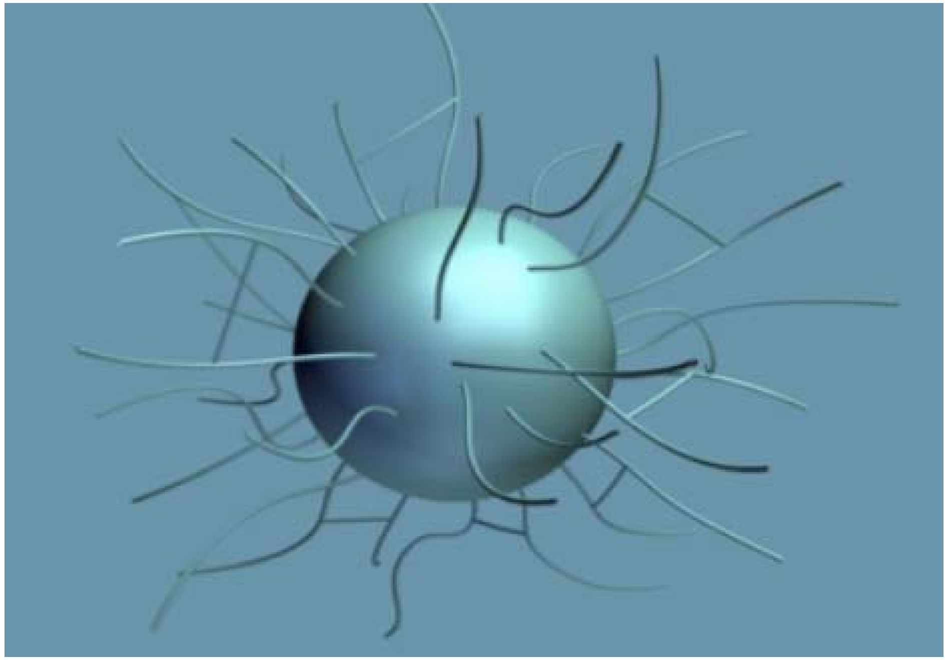
Infinite evaporation time



Observers in $\mathscr{I}$+ have the info of $\mathscr{I}$-

Ashtekar & Bojowald 2006

Black hole entropy



Black hole horizon
and its spin network
(Rovelli 2014)

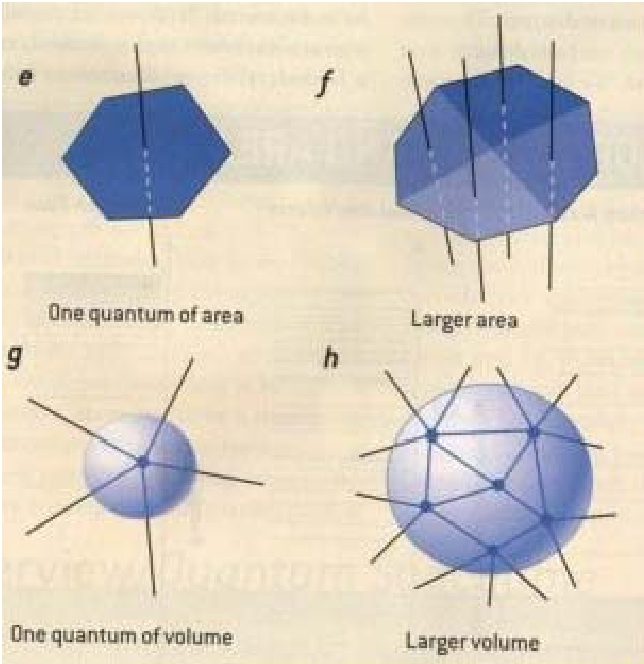
➔The entropy converges to that of Bekenstein-Hawking

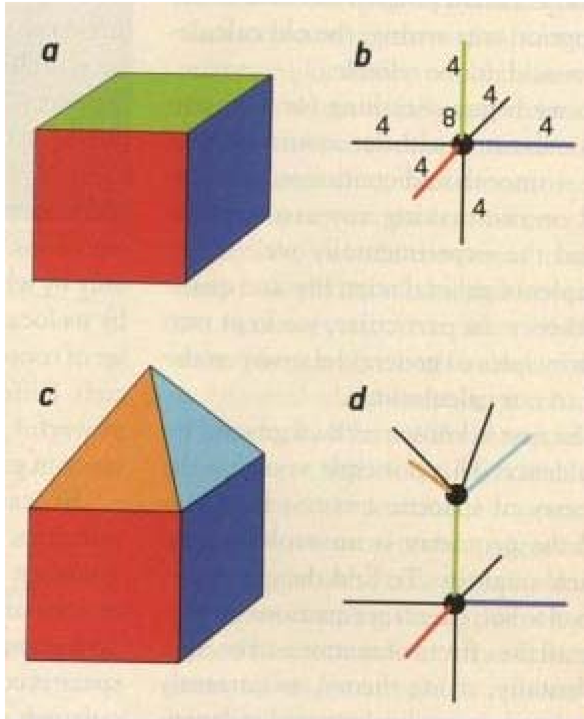
$$S_{BH} = \frac{kc^3}{4\hbar G} A.$$

➔The black hole has a physical representation (contrary to string theory)

➔No singularity in r=0

Spin network, spin foam





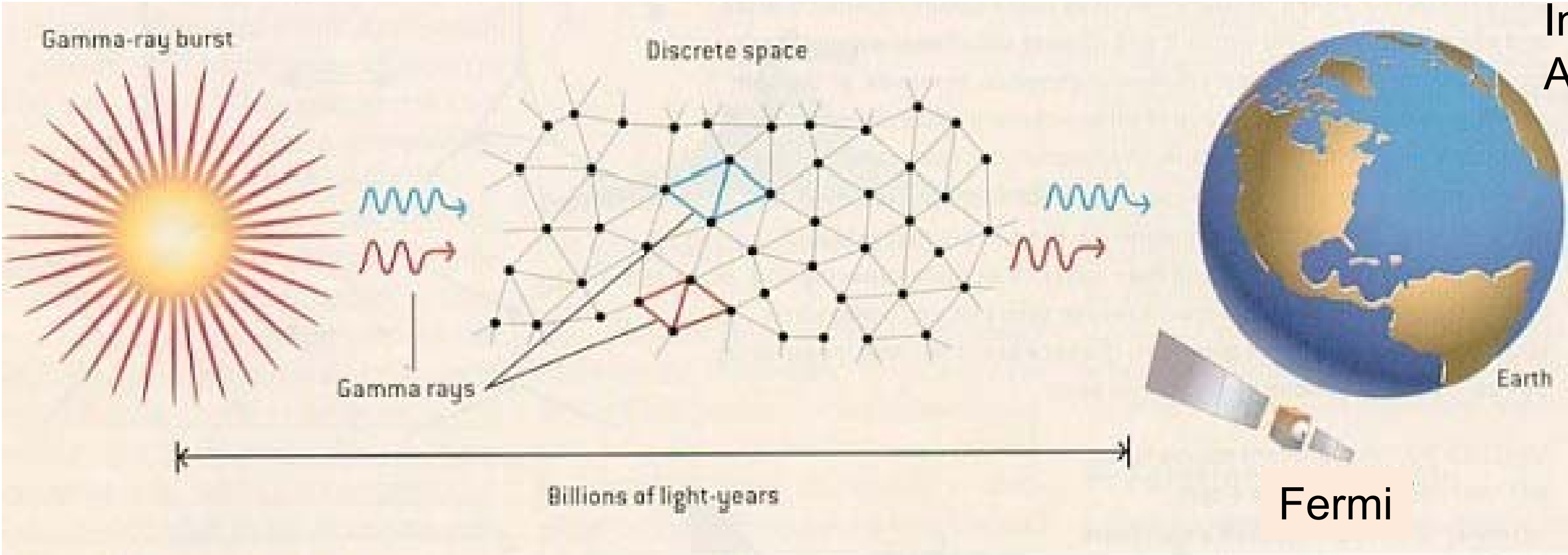
Surface= a line
Volume= a node

3D: spin network (polyedrons)
+ 1D the time: spin foam

A covariant version of spin foam has been demonstrated (2008-11)
Engle, Perini, Rovelli, Livine, Freidel, Krasnov

Test by gamma-ray bursts

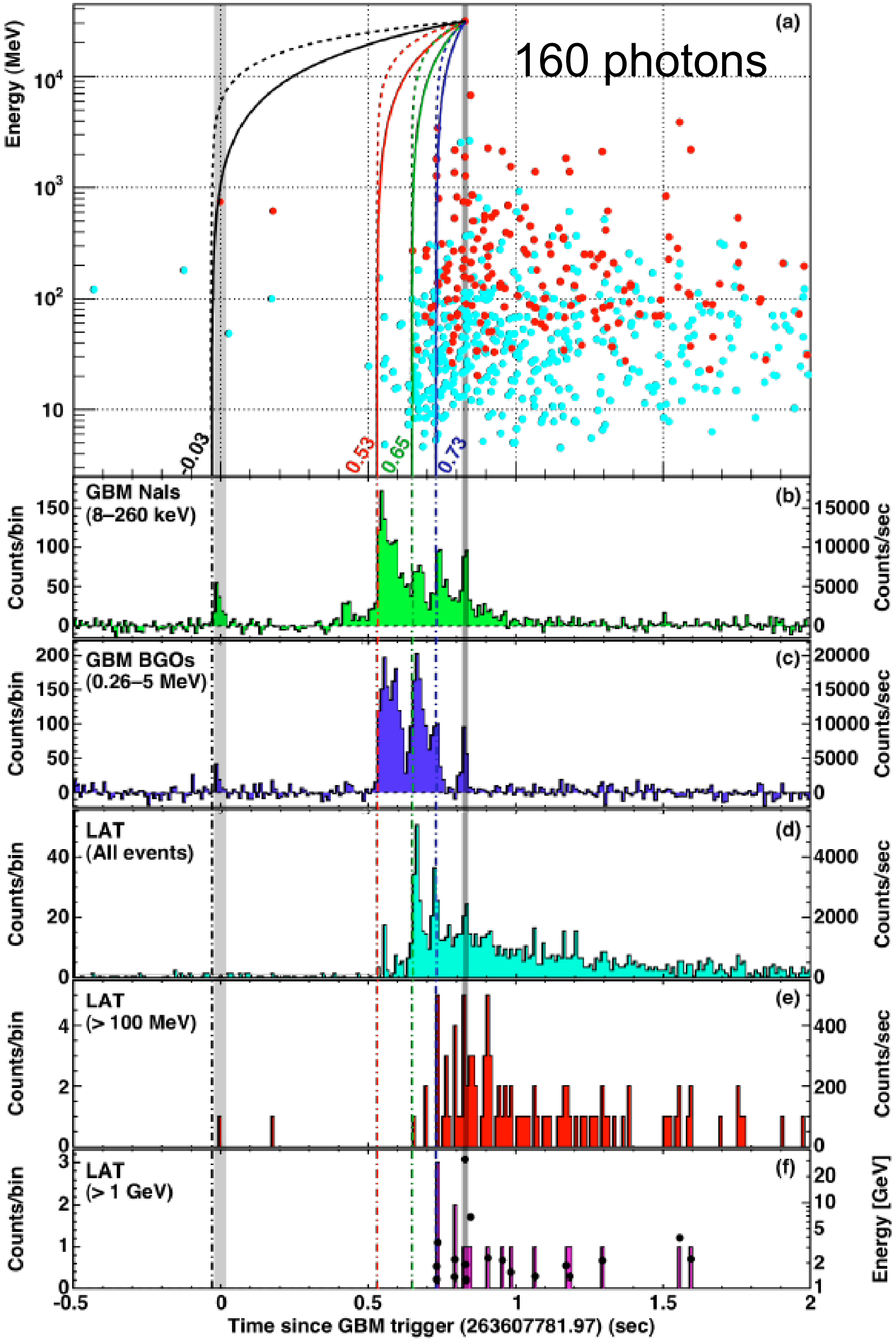
Swift
Suzaku
Integral
Agile



Detection of very high energy emission from a short GRB: GRB090510
2 distinct componants, synchroton emission, + self-Compton
31 Gev in the first second (z=0.9)
Lorentz factor $\gamma > 1200$ ➔ constraints on a possible linear energy dependency of the photon speed (violation of Lorentz invariance)

Requires a mass scale for quantum gravity >> Mp

Fermi collaboration 2009



GRB090510

Relation between photon energy and their arrival time

—— Full line n=1 linear

---- Dash n=2 quadratic

Colors: starting time

Black -30ms Red 530ms Green 648 Blue 730ms

First soft componant

10keV-10MeV: synchrotron

2nd self-Compton, 01-0.2 s delay

➔ Starting time is constrained

The test of GRB090510

The quantum gravity theories predict that the photon speed could depend on their energy E_{ph}, at Planck scale of E_{ph}~M_pc2

The difference is very small, and very remote sources, with large difference in energy (keV – 31GeV) are required at z=0.9 in the first half of the Universe

$(v/c - 1) \sim (E_{ph}/M_{QG}c^2)^n \sim (M_p/M_{QG})^n$

n=1 linear

No Lorentz violation has yet be detected, v=c, and $\mathbf{M_{QG} >> M_p}$

In other words, quantum scale < Planck scale

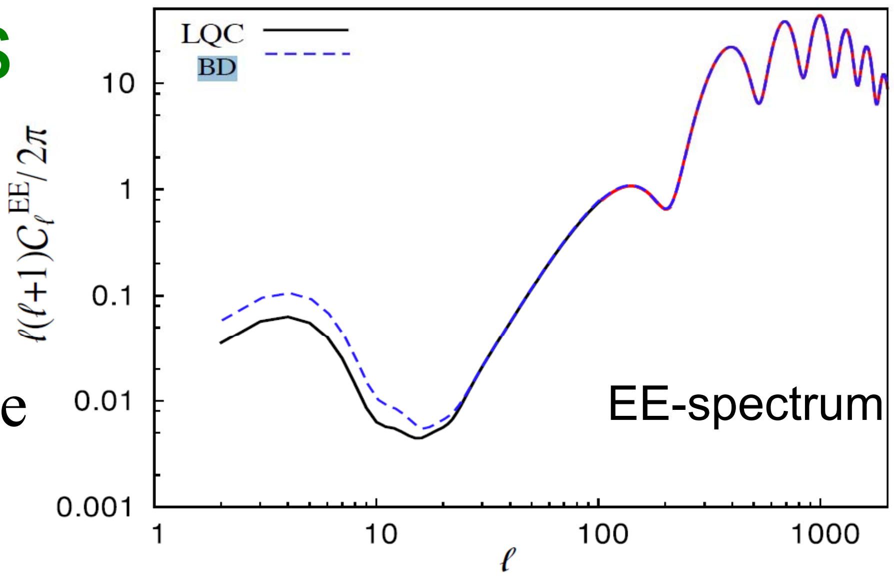
Or $n \neq 1$

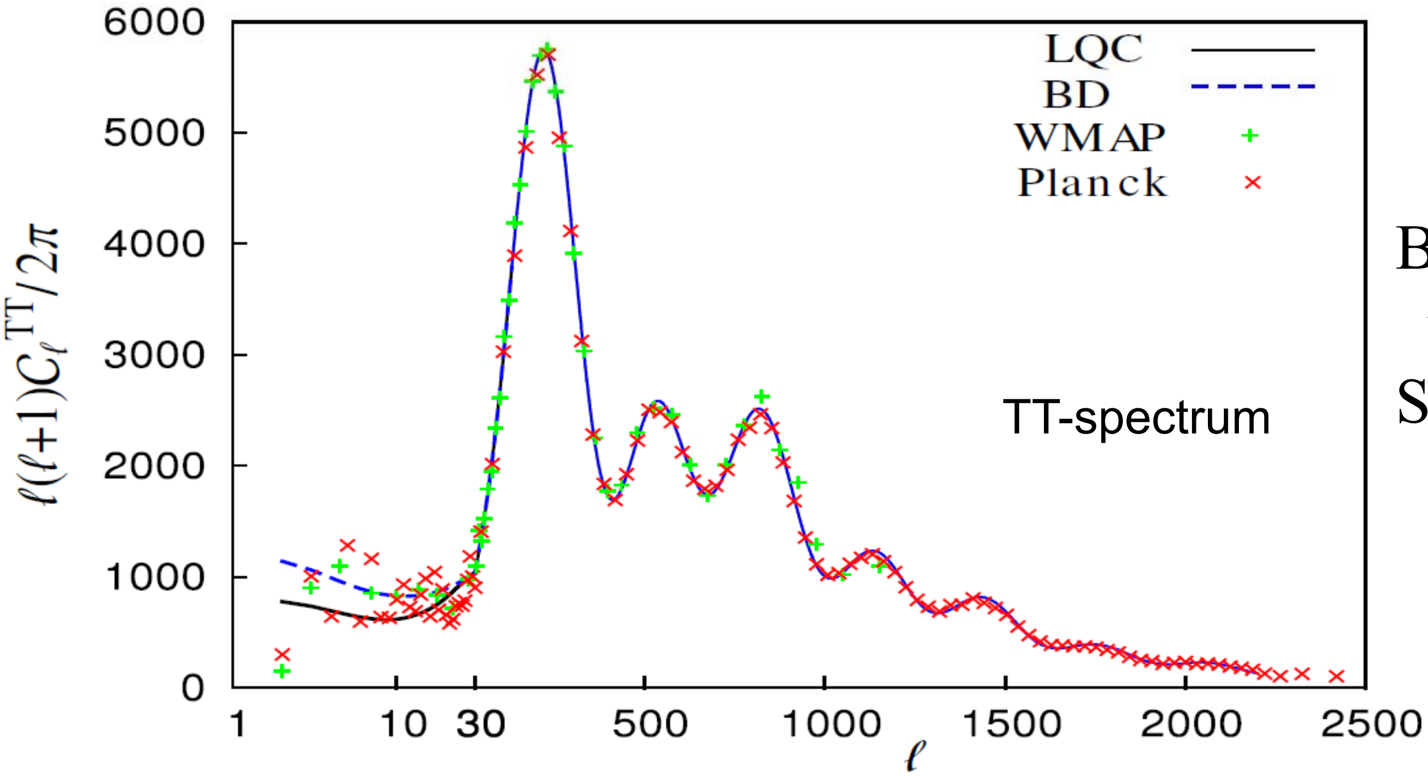
Cosmologic predictions

CMB anisotropies: power suppressed at $\ell < 30$

(Ashtekar & Gupt 2017)

These scales are the consequence of the different pre-inflation physics





BD Bunch-Davies vacuum = Standard model

Non-local effects

Visible at cosmologic scale : power suppressed at $\ell < 30$

Effects characterised by the scale of cosmological constant

$L = \Lambda^{-1/2}$

The neutrino masses are at scale L: $m \sim \rho^{1/4} \sim \ell_P^{-1/2}\,\Lambda^{1/4} \sim 0.1$ eV

Anomalies are expected for accelerations at scale

$a_0 = c^2/L = 10^{-10}$ m/s^2

This is the MOND acceleration, which reproduces remarkably rotation curves of galaxies

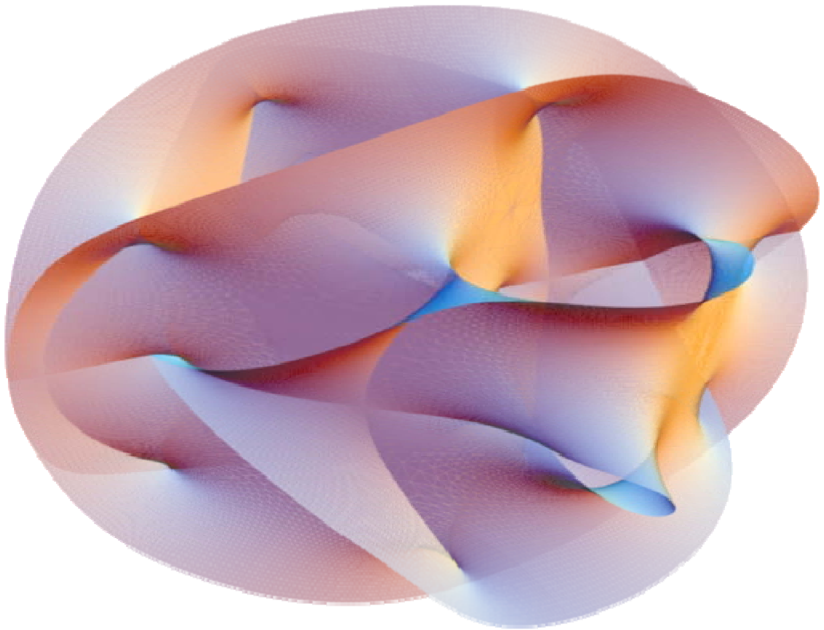
And fully satisfies the Tully-Fisher relation $V_{rot}^4 \sim M_b$

As the gravity force varies in $1/r$ instead of $1/r^2$

when $a < a_0$, there is **non-locality**

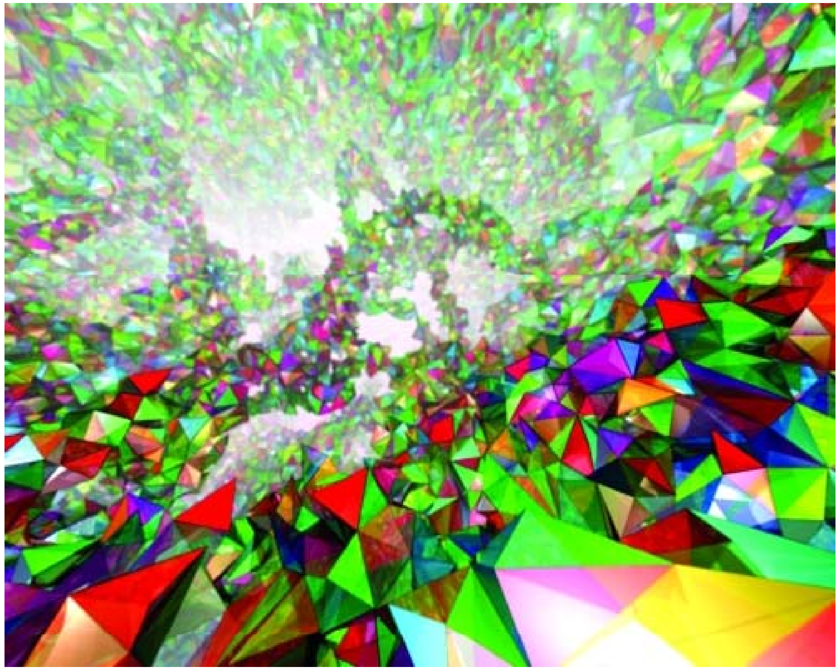
Quantum gravity : two theories

➔ Superstring theory



➔Space smooth and flat at large distance

➔Loop quantum Gravity



➔Fractal structure, in clumps

(1) String theory

- Gravity as other quantum fields: Graviton like an exchange boson
- All elementary particles are string excitations
- Requires 26 dimensions, or 10 in super-symmetry (superstrings)
- Gets rid of infinite divergences in computations (no point-like particles, infinitely small)
- Supersymmetry- a parallel world, where each fermion has a corresponding boson and vice-versa
- Reduced number of degrees of freedom: the string theory satisfies the **holographic principle**, the entropy in a volume is limited to the nbre of Planck bits on its surface

(2) Loop quantum gravity

- Succeeds in quantifying gravity

  Space-time has holes, constituted of connected pieces

  There exists a “true vacuum”, without space-time (no background)

- Number of degrees of freedom is limited (cut-off L_p), entropy increases as the volume however
- The theory violates the local Lorentz symmetry (while the string theory preserves it)

  The test of Fermi rules out all theories violating this symmetry – But it is not sure that LQG is strongly violating..

- Question of other forces, link to other quantum fields, other particles

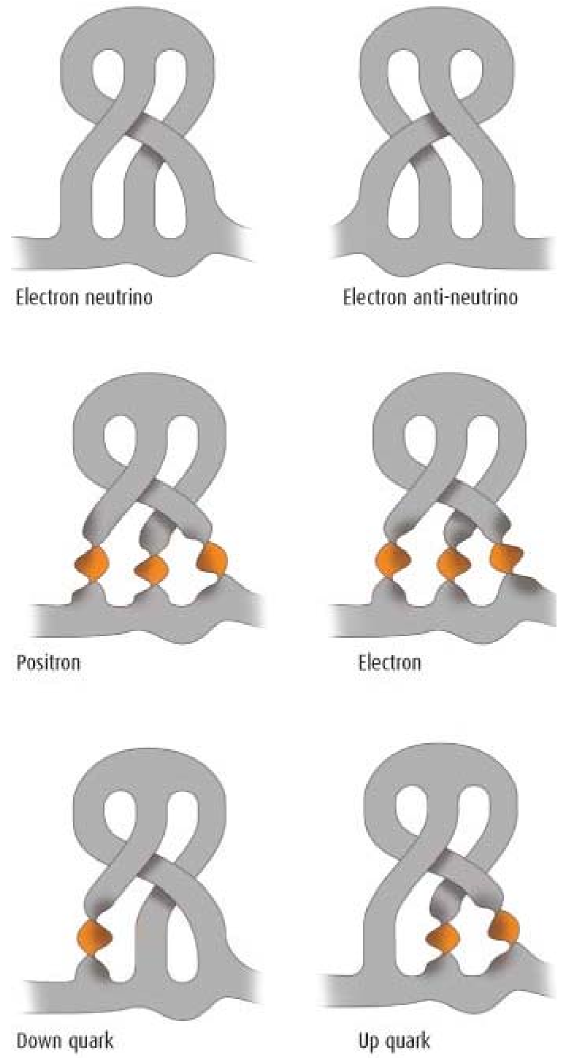
Representation of particles

The connections form braided loops

These are elementary particles

The twists determine the charge

Each twist 1/3 of electronic charge
Negative in the retrograde sense
Positive in the direct sense
Electron: 3 retrograde twists
Positron: 3 direct twists



Difficulties of string theory

- Supersymmetry: not yet discovered at LHC
- The large number of extra dimensions, even compactified, have never been detected
- The number of degrees of freedom is even larer with N dimensions
- Is not yet able to provide precise predictions

Always has to adapt to new discoveries (as dark energy)

- The theory is not independent of the background: assumes a pre-existing space-time – contrary to the loop quantum gravity, which creates space. While space-time is emergent in general relativity

Conclusions

Theories of modified gravity, to account for the dark energy problem, are multiple!
f(R), Tensor-scalar Tensor-vector (even TeVeS..)
Horndeski formalism for a generalization

➔ Superstring theory, with supersymmetry?
Including holographic theory, coming from the information problem around black holes
AdS/CFT correspondance, gauge/gravity duality

➔ Emergent gravity, entropic theory of gravity, microscopic phenomena of entropy intrication -- could explain also the dark matter (MOND)

➔ Loop quantum gravity, which creates its space-time