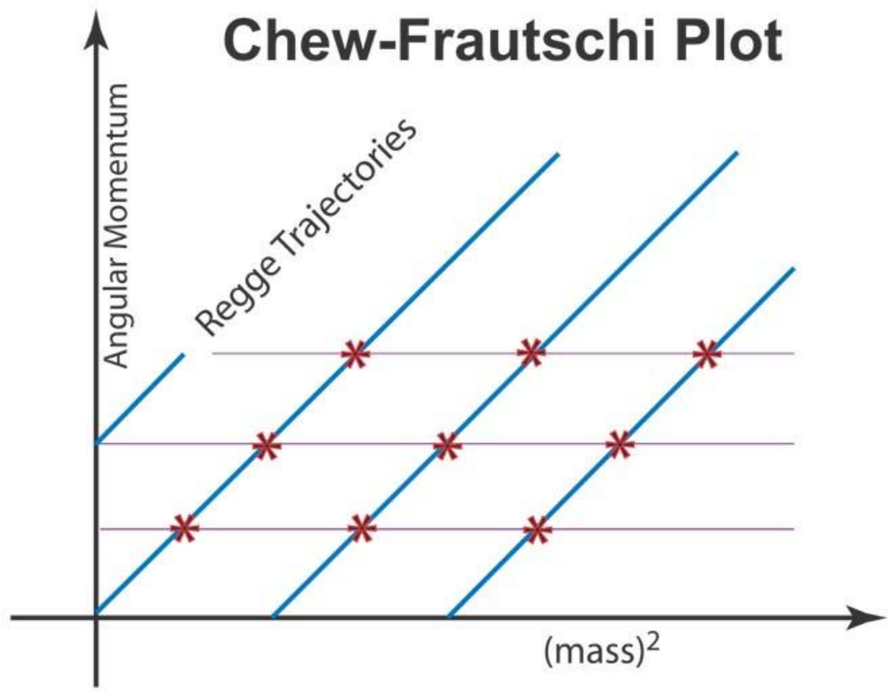
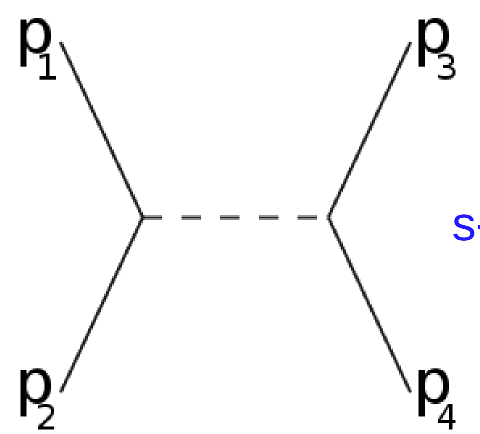
What is String Theory?

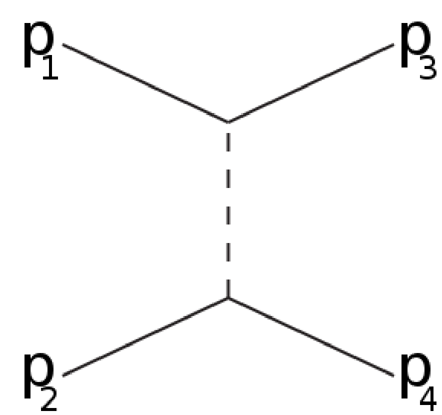
A theory in search of its principles

Hadronic origin of Strings

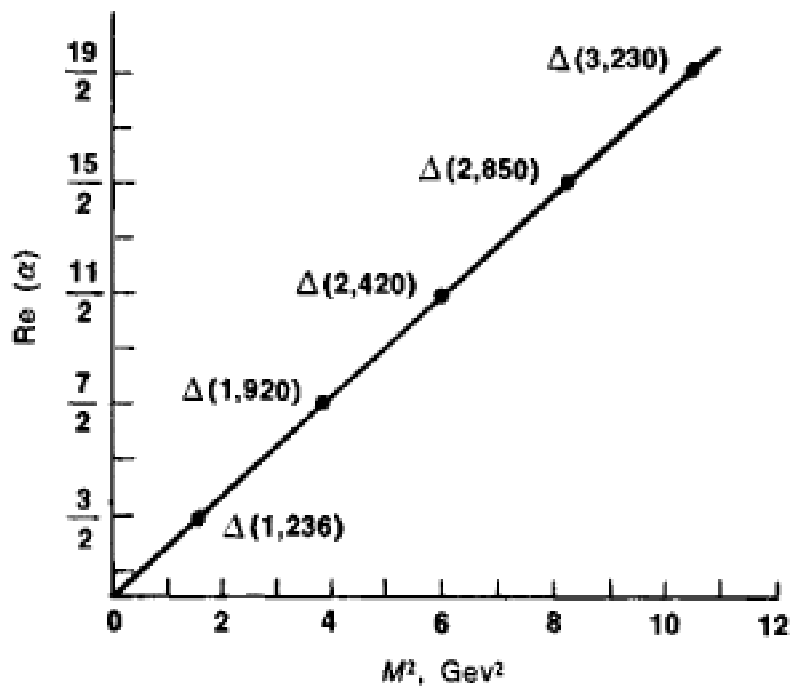




s-channel exchange of resonances



t-channel exchange of resonances



$$A(s,t) = \frac{\Gamma(-\alpha(s))\,\Gamma(-\alpha(t))}{\Gamma(-\alpha(s)-\alpha(t))}$$

$$\alpha(x) = \alpha(0) + \alpha' x$$

Not possible in QFT

Think string...

Fundamental 1-dimensional objects have very remarkable properties, they come in two varieties, open and closed

The Veneziano amplitude can be reproduced

They admit a field theory limit

There is a single interaction vertex

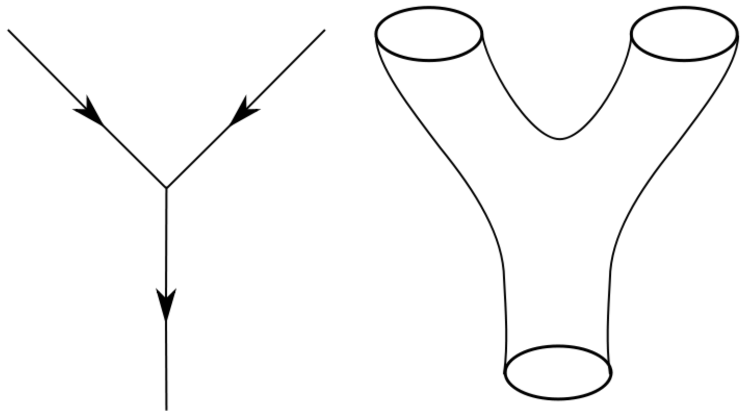
Consistency puts stringent constraints

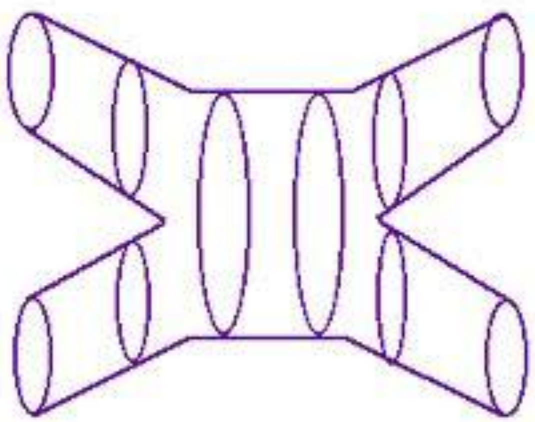
String Theory is the origin of supersymmetry

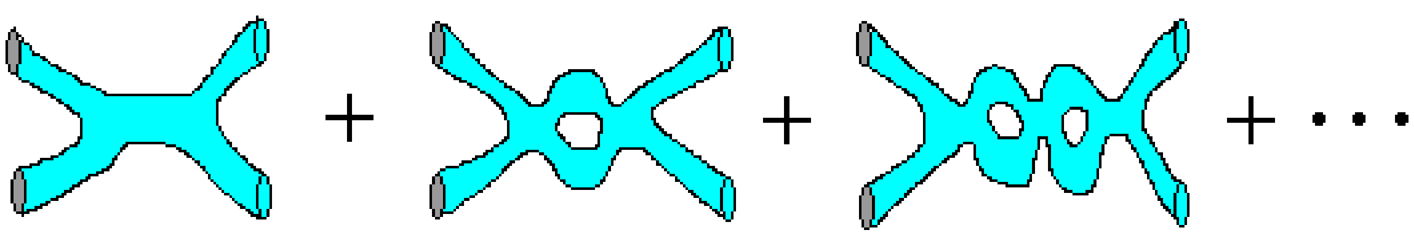
Space-time has dimension= 10 !!

Gravity and gauge symmetry are not unified, they are inseparable

Only known fundamental origin of general covariance and gauge invariance.



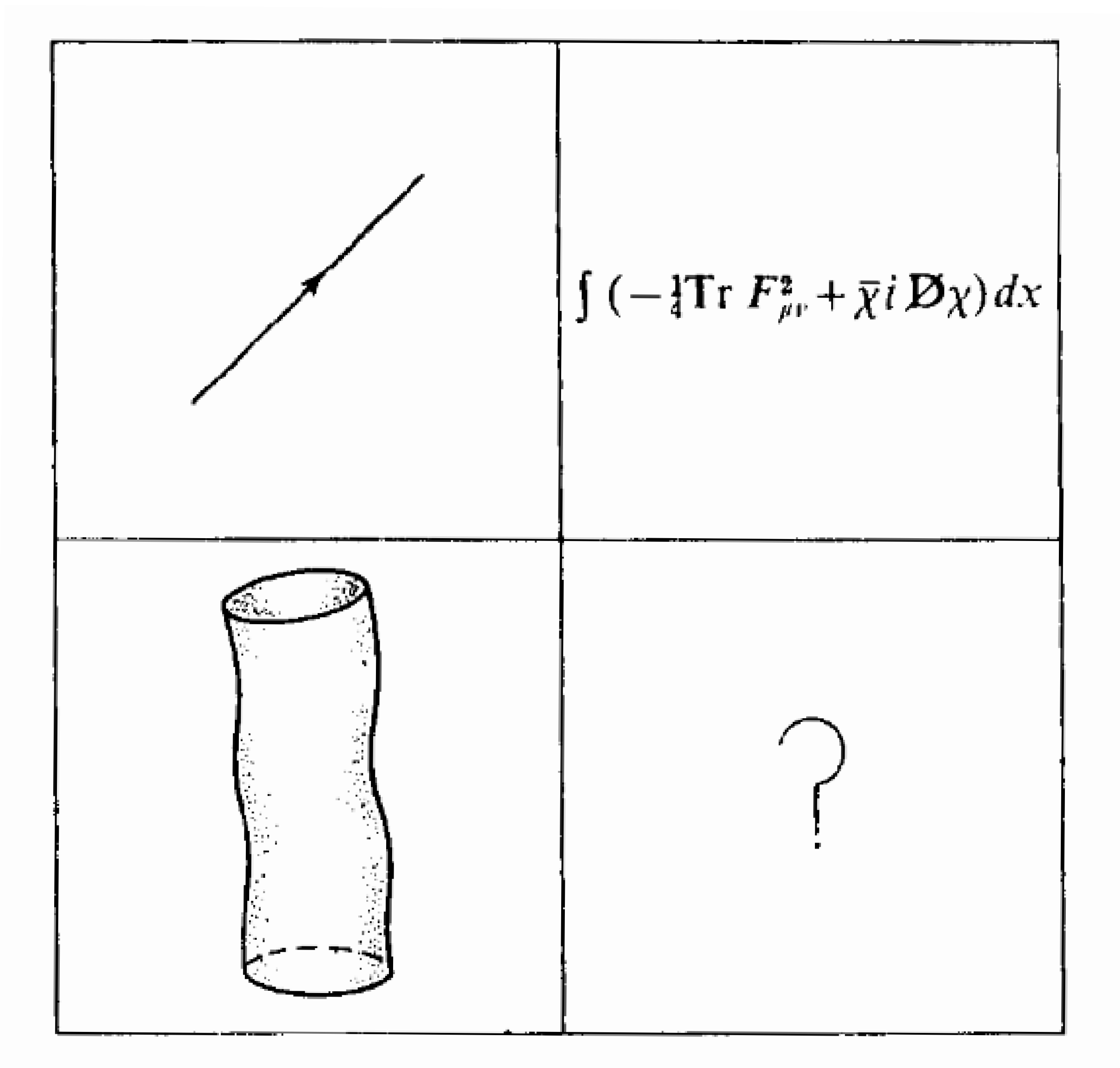




$$S = m\,L(x, x')$$

$$S = T\,A(\gamma, \gamma') \qquad T = 1/l_s^2$$

Particles versus strings



Courtesy of Green Schwarz and Witten

Ultraviolet completion of General Relativity

Strings cannot live in any space-time, only those satisfying a generalised form of Einstein's equations. This is a consequence of the two-dimensional conformal symmetry

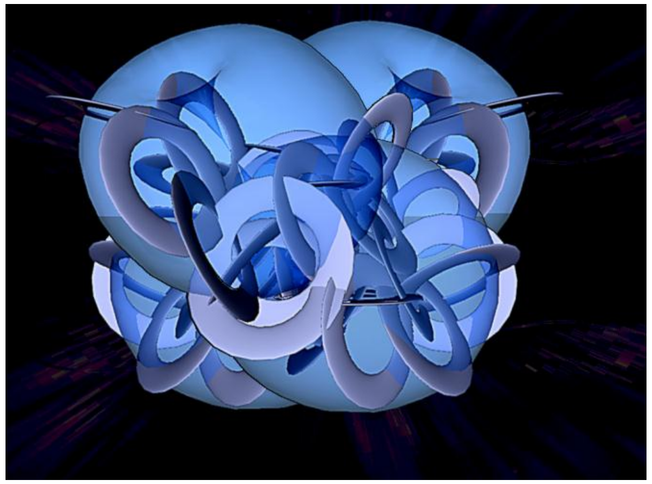
The quantum numbers of quarks leptons etc may have a geometrical or topological origin

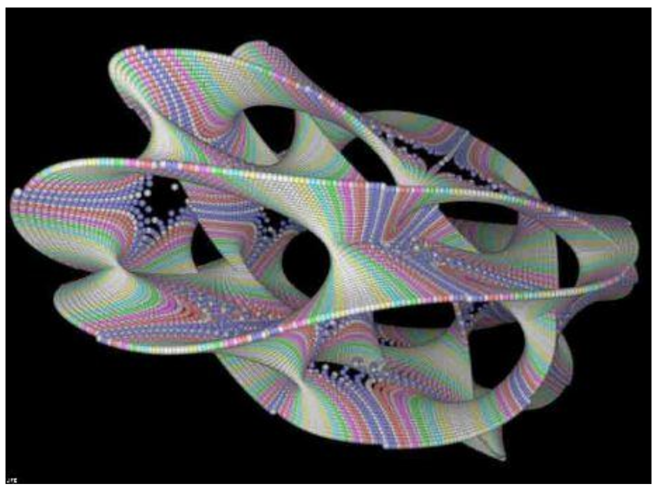
UV-IR connection: a new form of the uncertainty principle

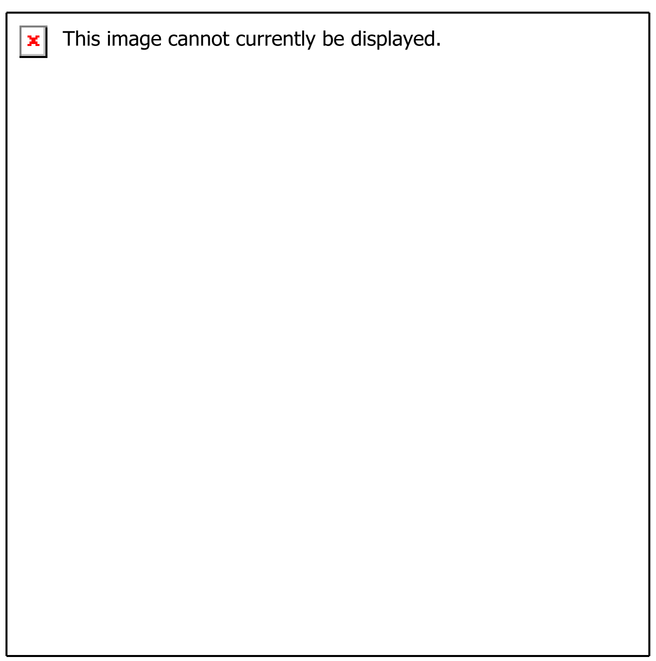
$$R_{\mu\nu} + \ldots = 0$$

$$\Delta x \sim \frac{\hbar}{E} + l_s^2 E$$

Calabi-Yau compactifications





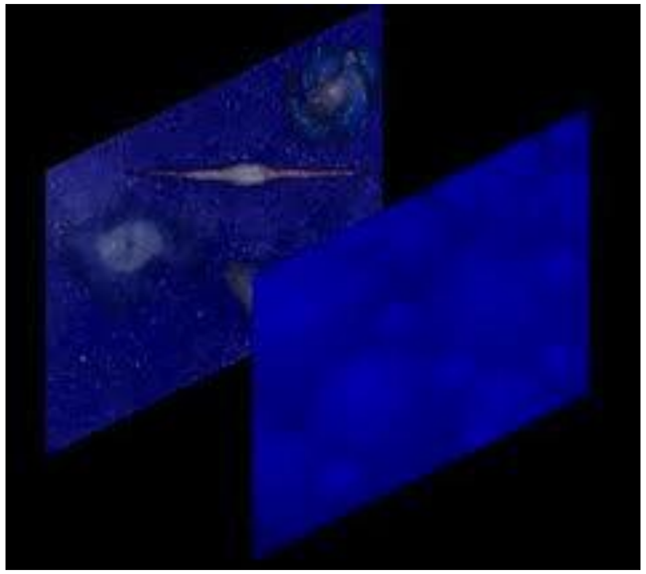


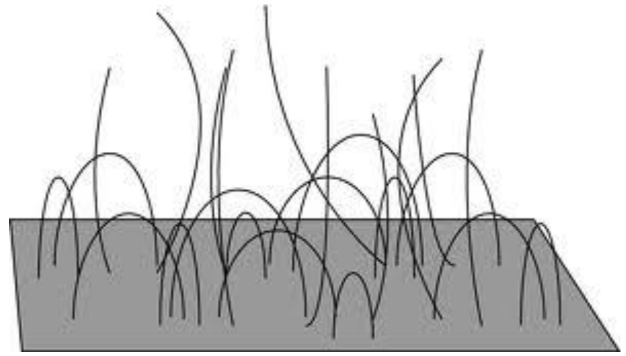
Since we live in 4 dimensions, the extra 6 have to be curled up into closed manifolds. Not any manifold qualifies, the simplest are CY-folds.

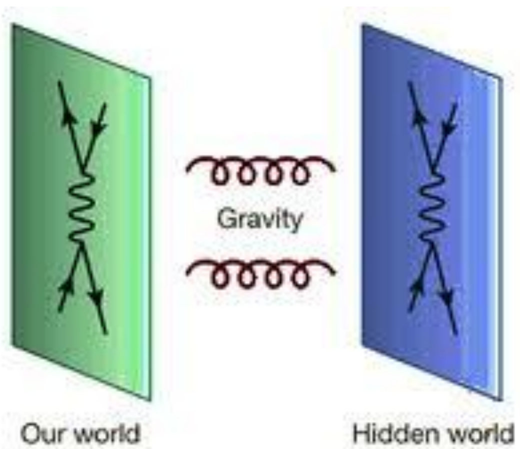
The extra dimensions have to be curled up into interesting algebro-geometric structures, Calabi-Yau manifolds and their generalisations once branes and other objects are included.

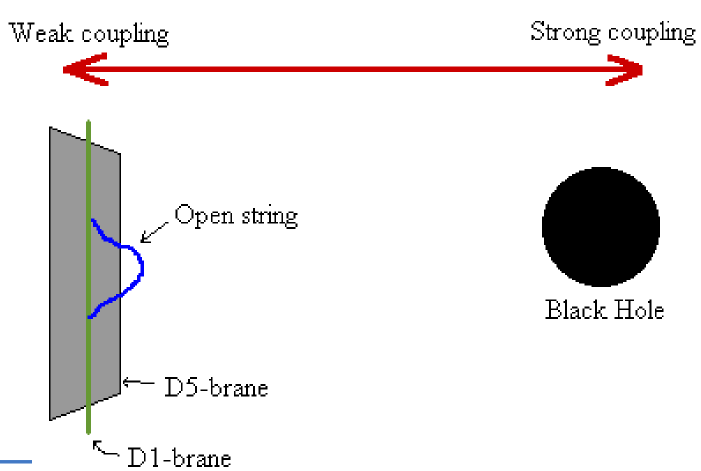
Exotic objects to say the least, that could populate the extra dimensions to determine the basic quantum numbers of the particles we observe at low energies, as well as their numbers.

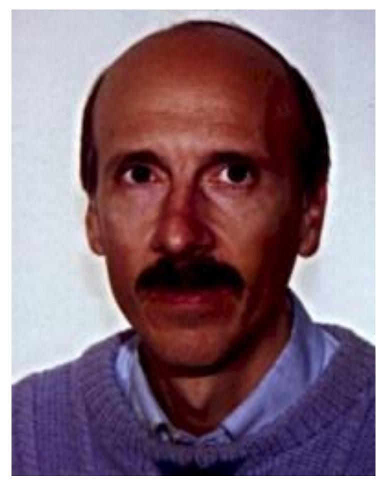
Brane new worlds



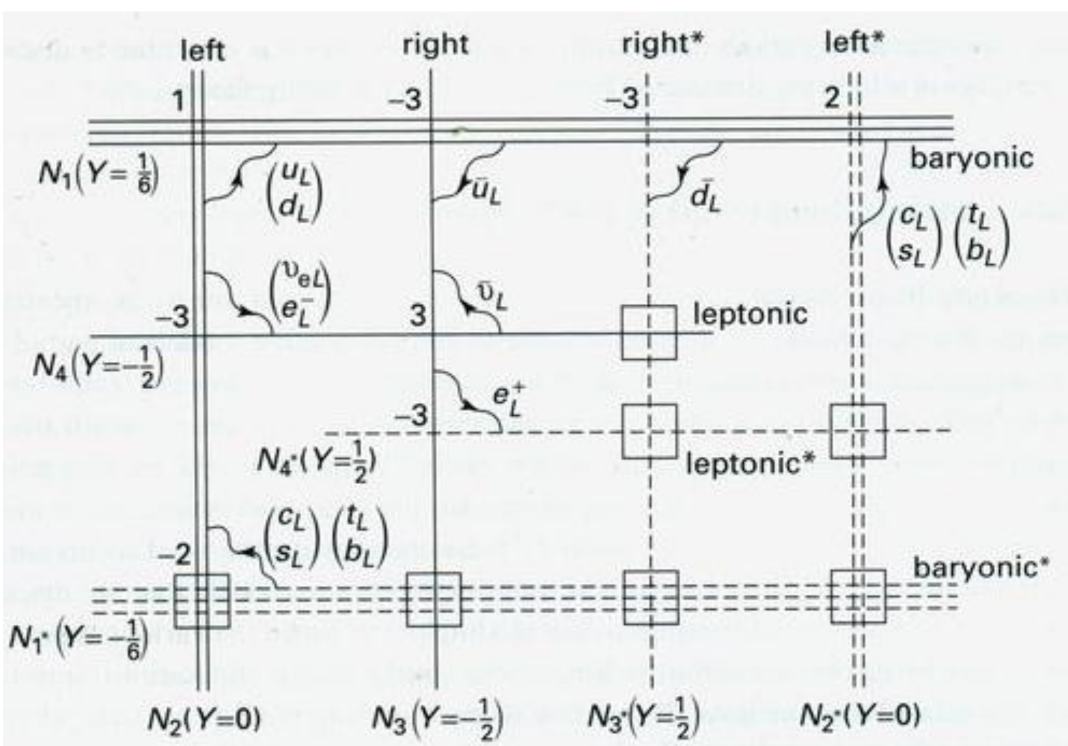








Brane intersection theories



The proliferation of models is staggering. They come with many scalar fields whose expectation values have to be stabilised. They provide models compatible with the SM but also with many of its extensions. It is not known how to choose among them. There is no selection principle. This makes String Theory very hard to test. Low energy supersymmetry is not a prediction of the theory.

Perhaps this proliferation of universes has a deep meaning… there are fundamental things we do not understand, and perhaps we will never understand in the usual meaning of explanation…

Perhaps this is the only way to cope with the Dark Energy...

The dark side of the Universe

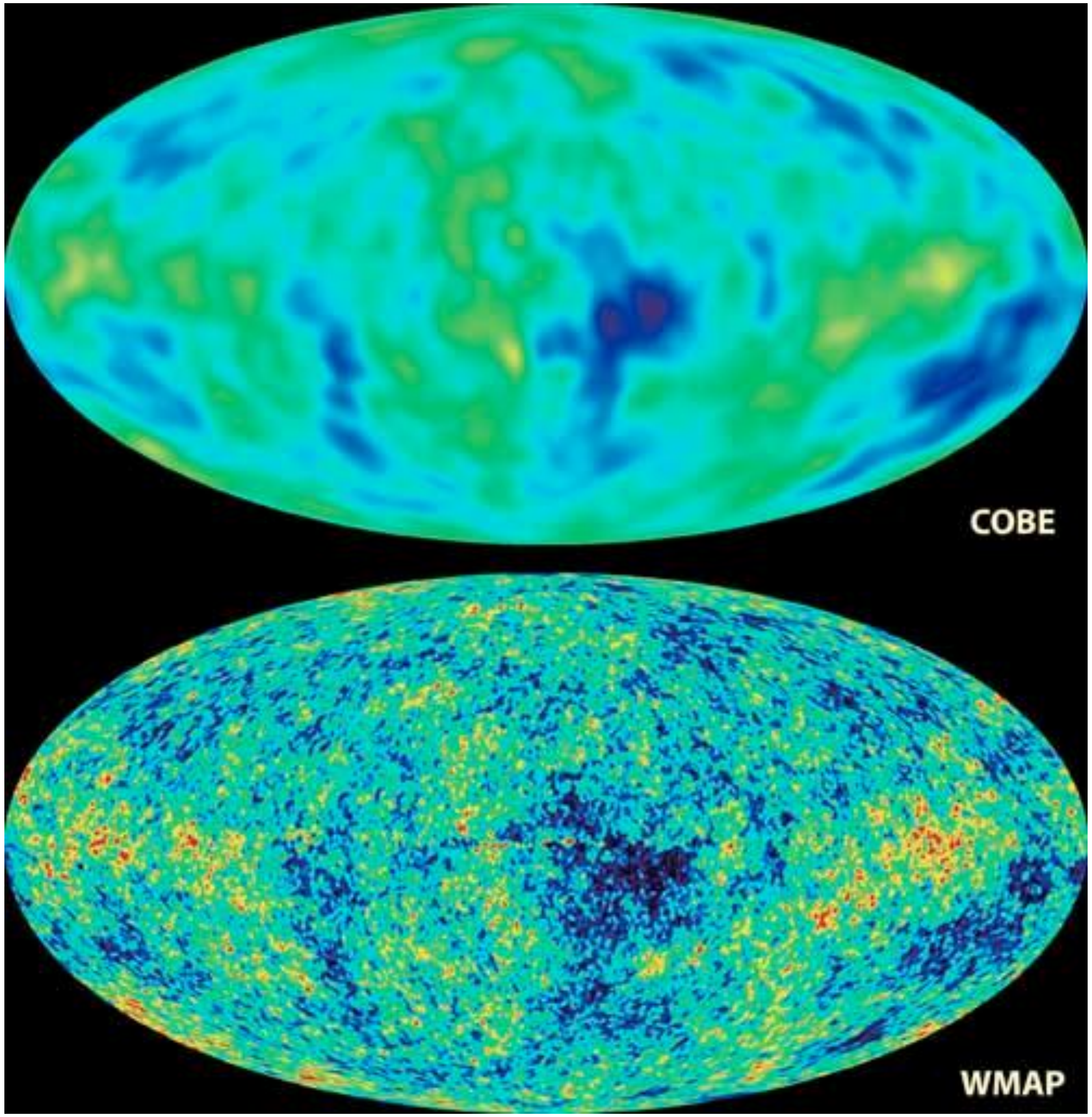
- There is no preferred ST candidate for DM apart from those of SUSY

- Interesting perspective on the DE question

- Black Hole properties

Why should we be afraid of the dark?

The Mona Lisa of modern cosmology



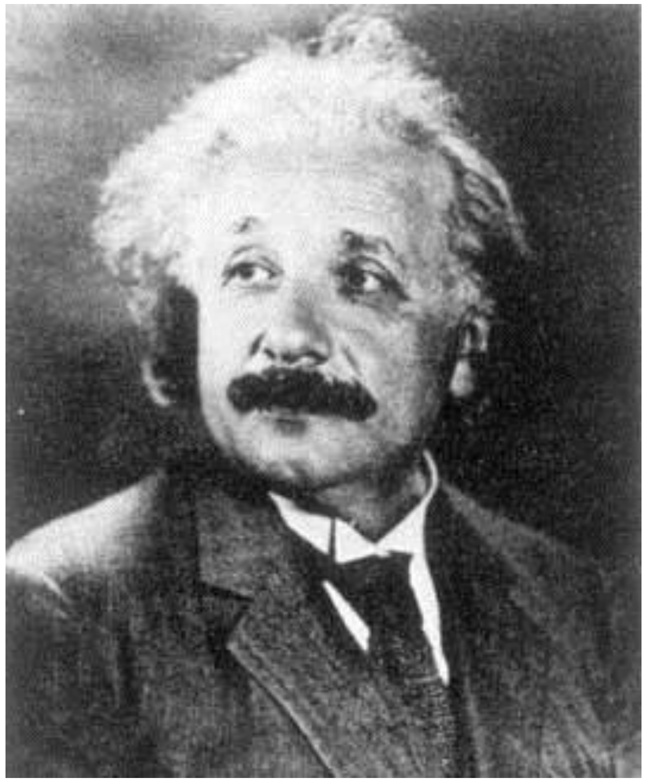
The Universe when it had 300 000 years, just like the first week in a 100 year human life

Luis Alvarez-Gaume CERN July 29th 2011

Dr. Einstein gets in...

Einstein's first equation allows us to compute (weigh) the mass of the different components in the Universe

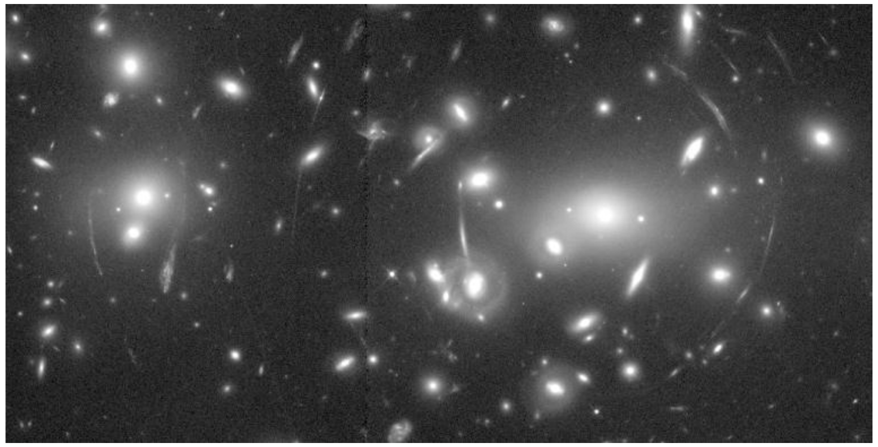
After revealing a deep secret, the Universe came back with a vengeance.



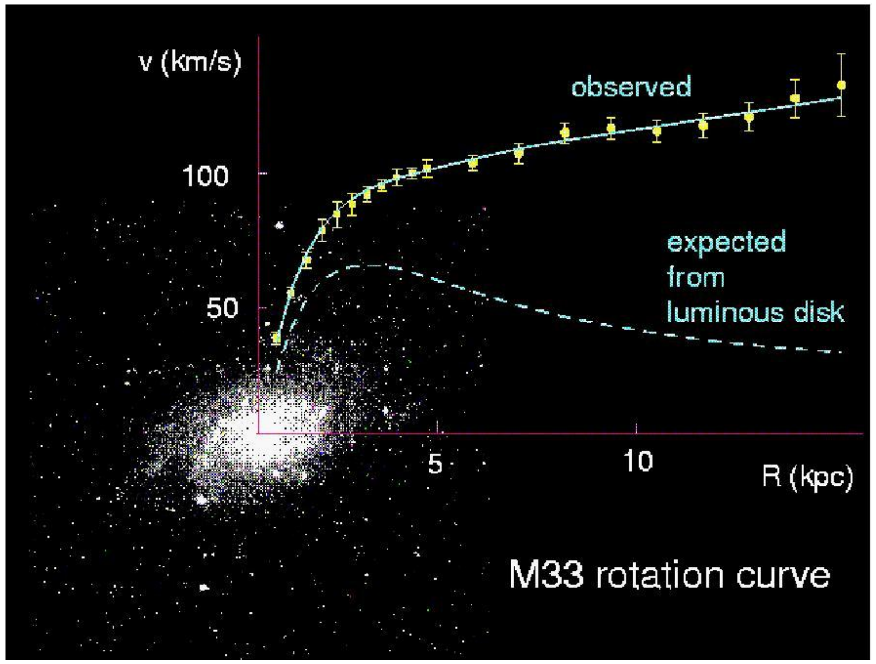
$$\Omega_\Lambda + \Omega_{DM} + \Omega_B = 1$$
$$73\% + 22.6\% + 4.4\% = 100\%$$

We can safely say that out of 100% we do not understand 100% !!

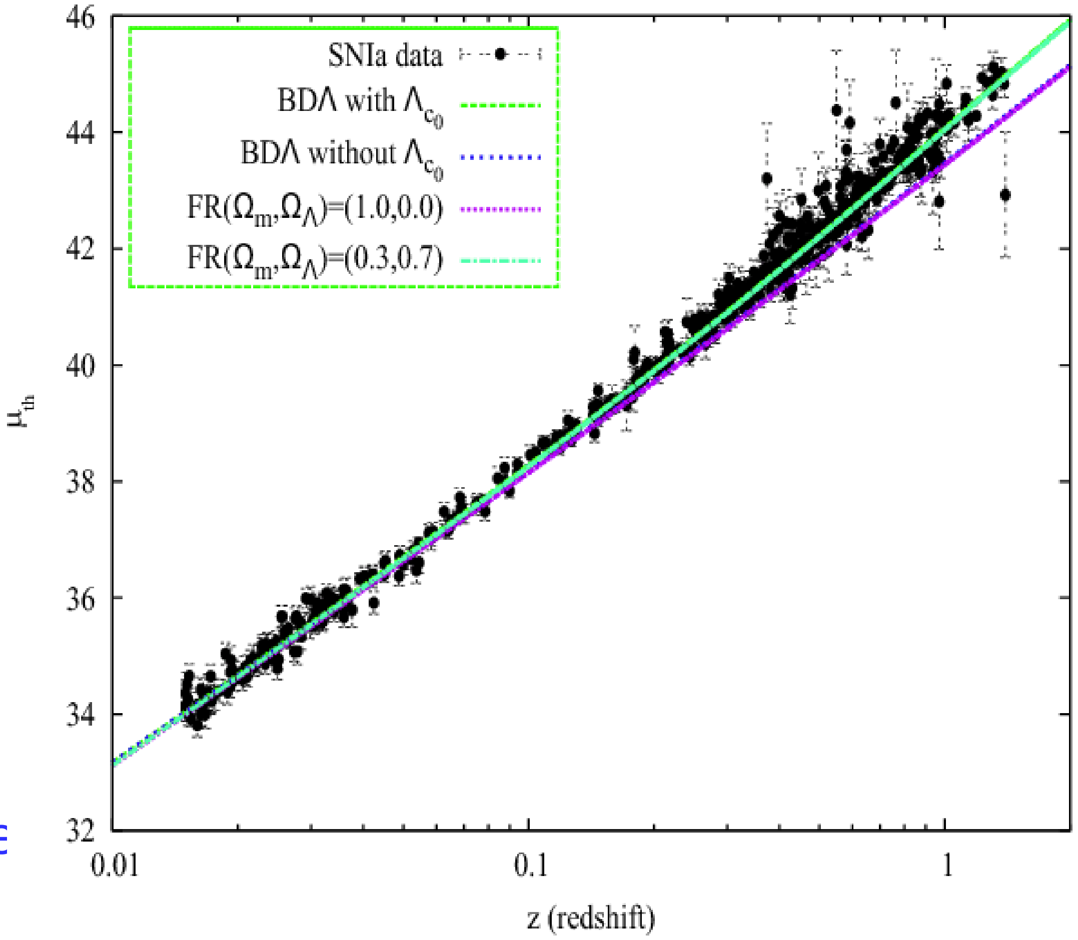
Observations



Einstein rings



Rotation curve



Redshift supernova project

Luis Alvarez-Gaume CERN July 29th 2011

Black hole in action...

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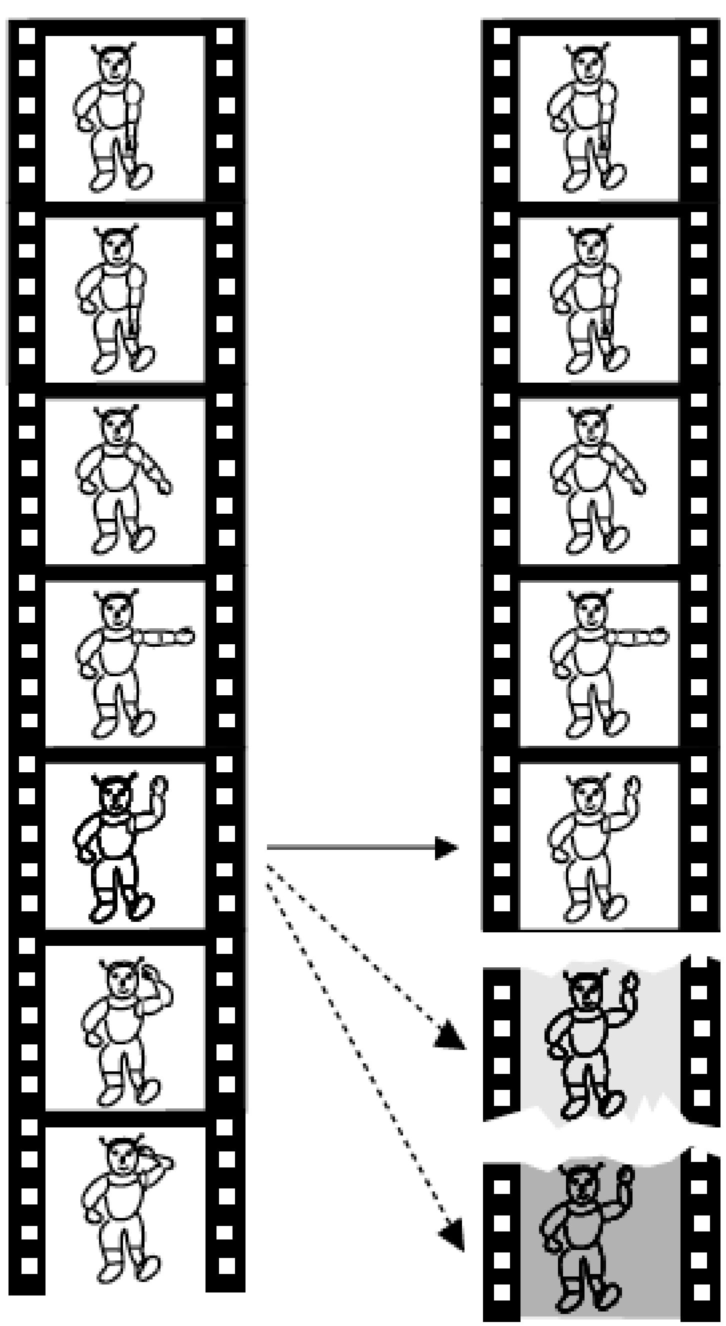
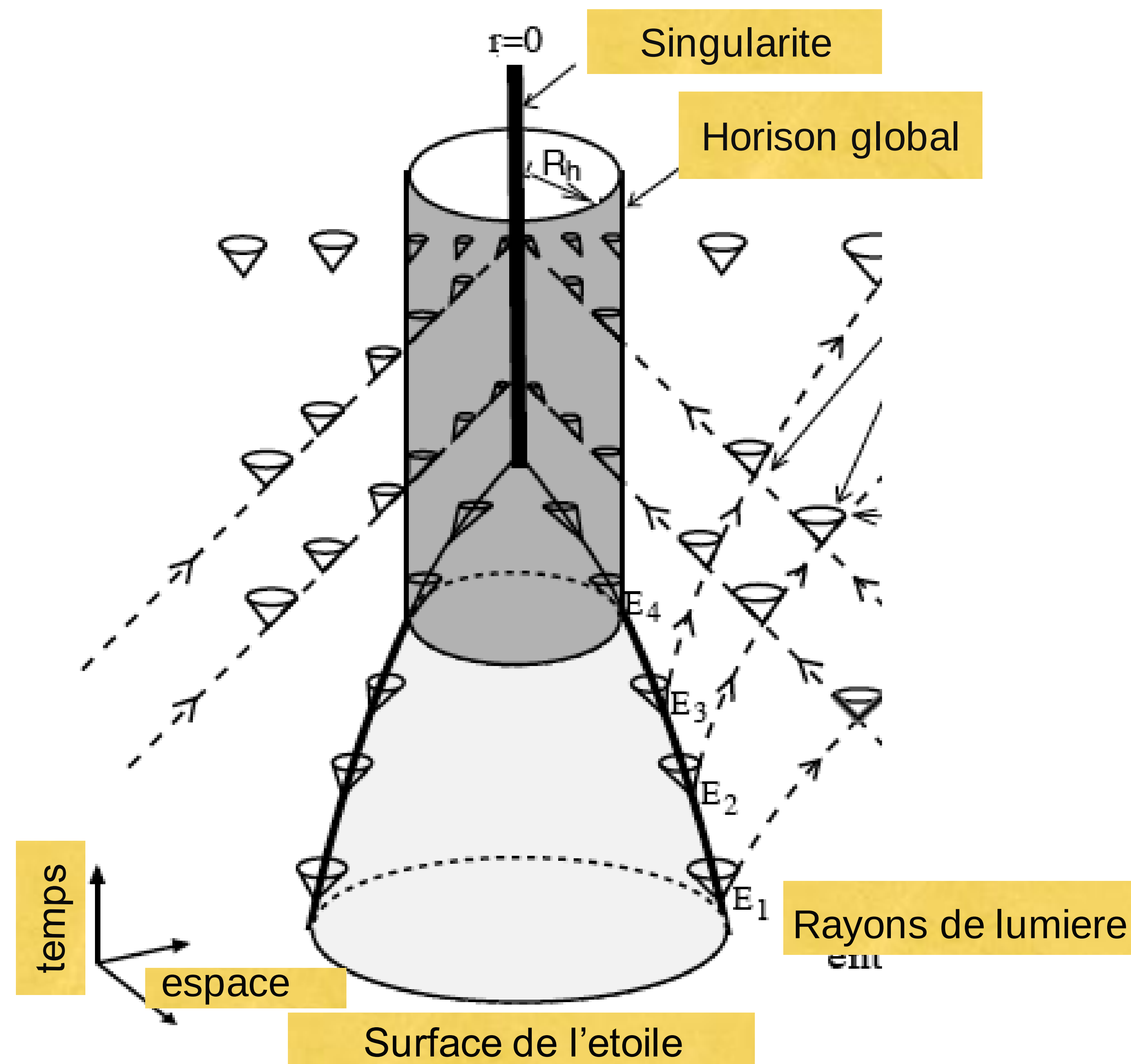
The monster in the center of our galaxy: 3.6 Million solar masses

Courtesy of Bernard Schutz

Dr. Who's planet

Falling into a black hole





Classical BH properties

$$R_{ab} - \frac{1}{2} g_{ab} R = 8\pi G T_{ab}$$

Black holes have no hair. The general BH solution in d=4 is characterised by M, J, Q, the Kerr-Newman solution.

There is more than meets the eye in this statement. It is a purely classical statement, and it is also not fully satisfied in dimensions d>4. Do BH have quantum hair?

$$dM = \frac{\kappa}{8\pi} dA + \Omega dJ + \Phi dQ$$

$$\delta A = \sum_n \delta A_n \geq 0$$

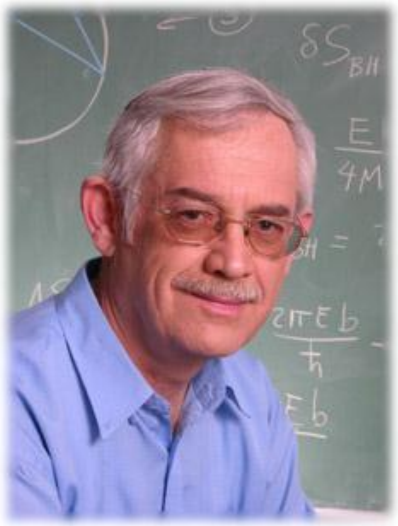
For a stationary BH, the surface gravity on the horizon is constant

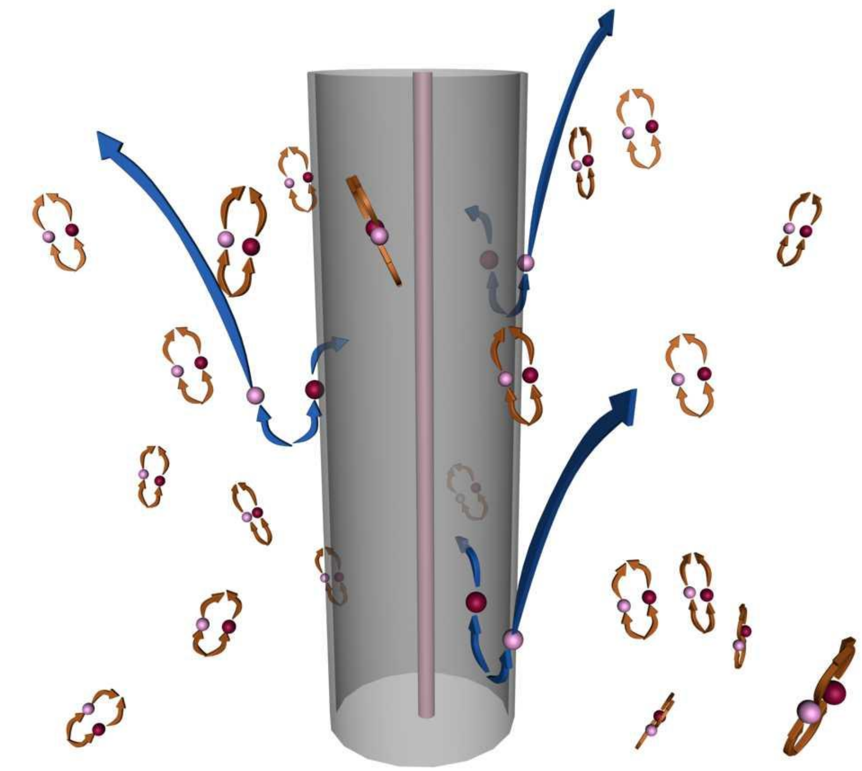
Under small variation of the parameters of a stationary BH, we have the analogue of the 1st law of thermodynamics

Given a system with various BHs, each with area A_n, the total horizon area does not decrease with time

A stationary BH with zero surface gravity, is not accessible by a finite number of steps.

Hawking radiation





$$T_H = \frac{\hbar c^3}{8\pi G M k} \qquad S = \frac{A_h}{4A_P} \qquad A_P = \frac{\hbar G_N}{c^3}$$

BHs emit thermal radiation at a temperature that depends on their mass

$$A_P = \frac{\hbar G_N}{c^3} \sim (10^{-33}\,\mathrm{cm})^2$$

The associated entropy is normalised (1/4 in Planck units)

This is a huge entropy. This is larger than you might think

$$S = \log \Omega(M, J, Q)$$

No-hair theorems tell that the final BH state depends on 3 parameters

$$\Omega = e^S$$

Where are the missing states? One bit per Planck area

$$T = 10^{-8}\,K\,\left(\frac{M_{Sun}}{M}\right) \qquad \tau = \tau_{Univ}\left(\frac{M}{10^{12}\mathrm{Kg}}\right)^3$$

Violating QM?

In QM pure states do not evolve to mixtures.

Can entanglement disappear down a BH drain?

Is quantum information fundamentally lost?

Is gravity incompatible with QMs?

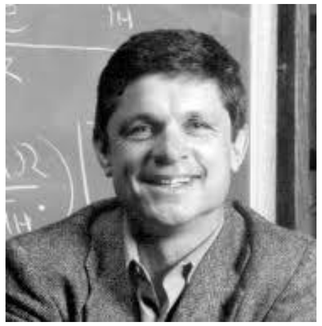
Some non-locality and a new uncertainly principle is lurking in the background, some fundamental non-locality has to enter physics when quantum gravity is taken into account, AdS/CFT does not solve the problem straightforwardly. How does information escape, or how it leaks out into remnants. Just saying that QM is unitary is not enough to understand what is going on.

$$Tr\rho^2 = 1 \;\rightarrow\; Tr\rho^2 < 1$$

$$\rho_{out} = \$\,\rho_{in} \qquad \$ \neq S \otimes S^\dagger$$

$$\Delta x \sim \frac{\hbar}{E} + l_s^2\, E$$

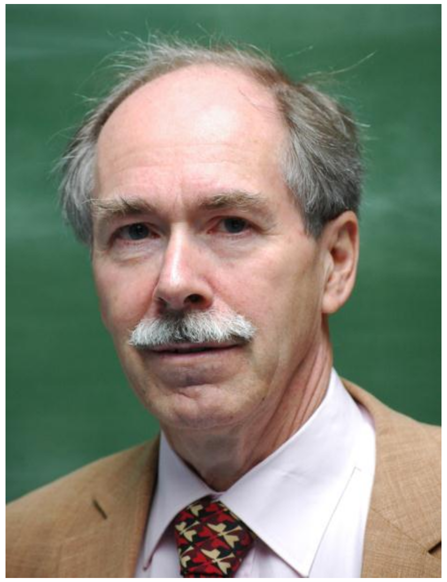
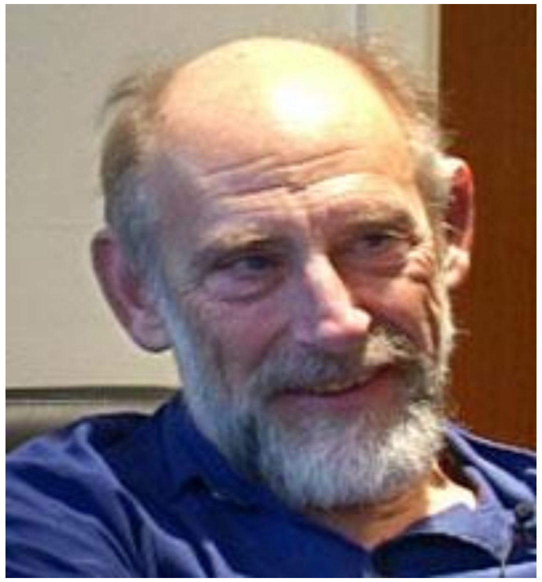
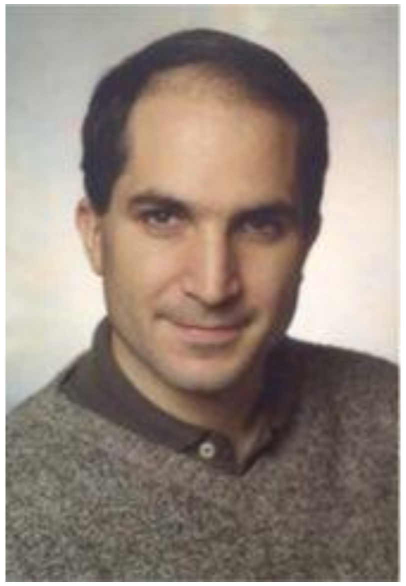
String count of BH states



One of the major theoretical achievements of String Theory has been to provide a way of reproducing the BH entropy formula in terms of a genuine state count, a la Boltzmann. They in fact provide Wald's generalisation.

The count works for some special BHs, not yet for all types, but this is likely to be a purely technical issue. It is based on general properties of brane worlds and of the conformal properties of the two dimensional theory on
the world sheet.

Holographic principle

'tHooft's entropy bound

In QFT suppose we have a system with energy E, volume V and area A. How many states would a QFT allow under these conditions, rather what is the largest number of states? The most probable state would be a gas at some temperature T, with energy and entropy:

$$E \sim n_{d.o.f.} T^4 \qquad S \sim n_{d.o.f.} T^3$$

To avoid falling inside its Schwarzschild horizon, we need to require:

$$2\,E \,<\, (V/\tfrac{4}{3}\pi)^{1/3}$$

The maximal entropy however is the one given by the BH area law S=A/4!

$$S \,<\, n^{1/4} A^{3/4}$$

AdS/CFT Maldacena conjecture

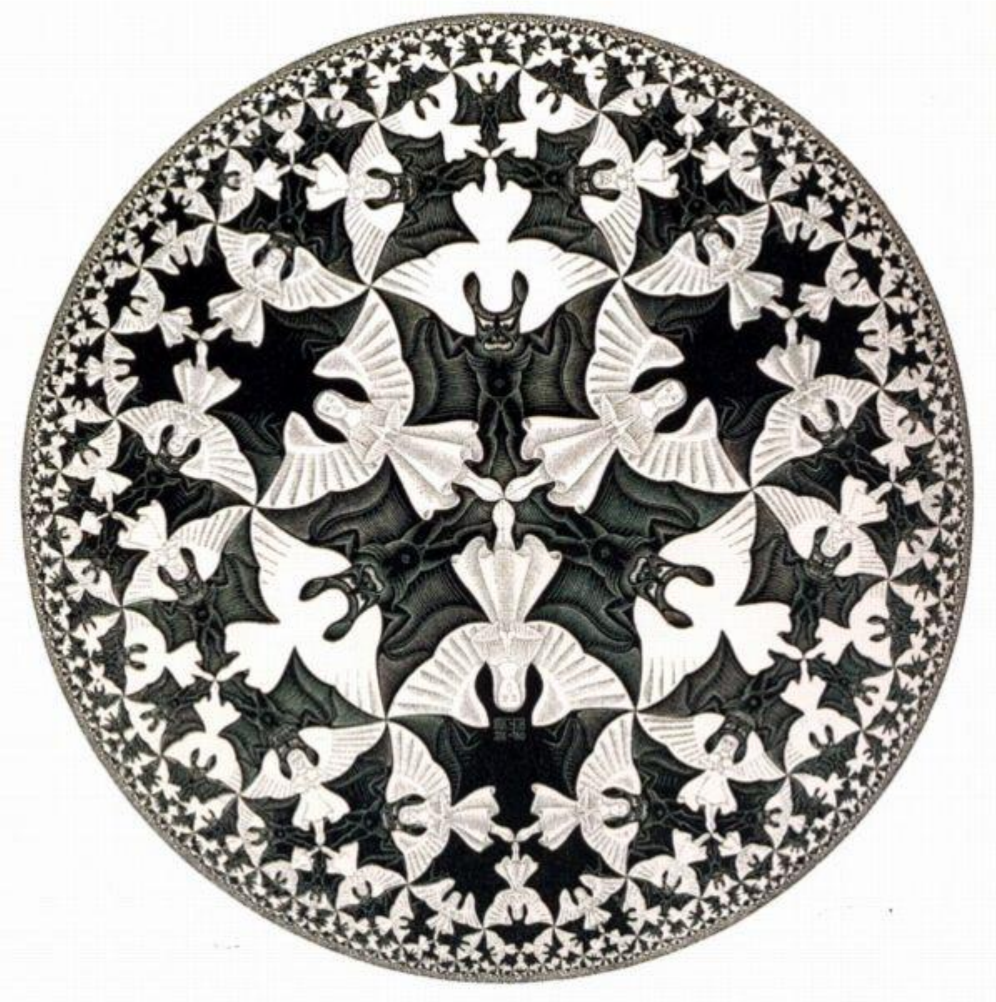
In gravity there are no local observables, hence it makes sense to parametrize the quantum state of gravity in a given volume in terms of degrees of freedom on the boundary of the bulk region.

Non-locality at the horizon appears always one way or another in solving the puzzle

$$-X_0^2 + X_1^2 + \ldots + X_d = R^2$$

$$-X_{-1}^2 - X_0^2 + X_1^2 + \ldots + X_{d-1} = -R^2$$

$SU(N)$ $\qquad g_{YM}$ $\qquad \left(\frac{R}{l_s}\right)^4 = g_{YM}^2 N$



Gravitational processes in the bulk can be represented in terms of gauge states in the boundary. Since gauge theories represent well defined unitary gauge theories, the process of BH formation and evaporation should be described. So far however, there are too many details missing…

GAUGE----GRAVITY DUALITY

The String Landscape. Anthropic reasoning?

The number of possible ground states in ST is incredibly large, each can produce a different universe, with different physical laws. In each one the cosmological constant has a different value, but the value 0 is sufficiently populated to allow for an anthropic "explanation" of why it is so small. Bousso and Polchinski provided a consistent argument based on the proliferation of the possible String Universes. This combined with eternal inflation makes it reasonable to have as small a cc as it is observed.

Are the laws of our universe given by a bar code like in a supermarket product? Is there anything to explain? Are there fundamental laws and environmental laws?

Will this decade see the dawning of new understanding?

Farewell

Many believe that String Theory contains some of the basic ingredients of the next revolution.

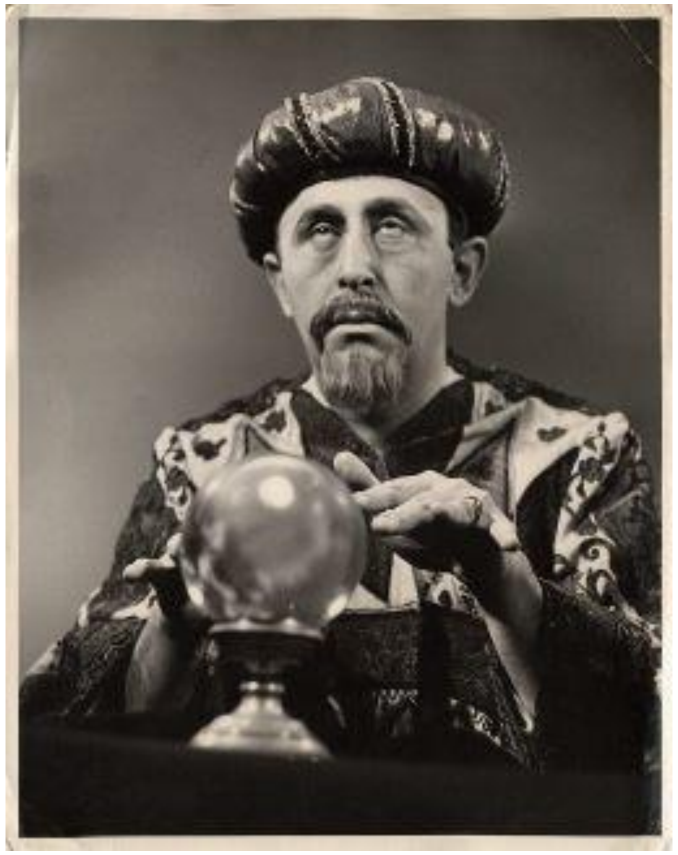
Holography or Supersymmetry?

Is the landscape here to stay? Together with anthropic arguments and/or eternal inflation?

Have we reached the limit of the symmetry paradigm to explain the basic laws of Nature?

Why should our local laws apply globally?

There is certainly an elephant in the room and we just don't see it ...



Who knows what the future will bring!

Thank you