Colloquio Galileiano, Pisa, 22 March 2007

String theory: is Einstein's dream being realized?

Gabriele Veneziano
(CERN & Collège de France)

Introduction

During the second half of his scientific life Einstein struggled with the problem of how to combine in a single, consistent framework two beautiful and successful theories to which he had so much contributed:

1. Maxwell's Electromagnetism*) and its quantum developments, from the photo-electric effect**) to Quantum Electro-Dynamics (QED);
2. His theory of Gravitation: Classical General Relativity (CGR)

*) that had led him, in 1905, to Special Relativity

**) 1905, for which he had received the Nobel prize

Neither Einstein, nor others succeeded

Somehow the big obstacle was in the clash between the Quantum of QED and the Classical*) of CGR

"I must seem like an ostrich which buries its head in the relativistic sand in order not to face the evil quanta"
(Einstein, 1954)

What has become of Einstein's dream half a century later?

*) Here and below « classical » means « non quantum »

In essence, Einstein's dream was to unify our theoretical understanding of the quantum world of the

« infinitely » small

with the classical world of the

« infinitely » large

More quantitatively:

Planck's minimal length/time scale

$$L_P = \sqrt{\frac{Gh}{c^3}} \sim 10^{-33} cm$$

$$T_P = \frac{L_P}{c} \sim 10^{-43} s$$

Hubble's maximal length/time scale

$$\Delta\lambda = \frac{d\,\lambda}{L_H}$$

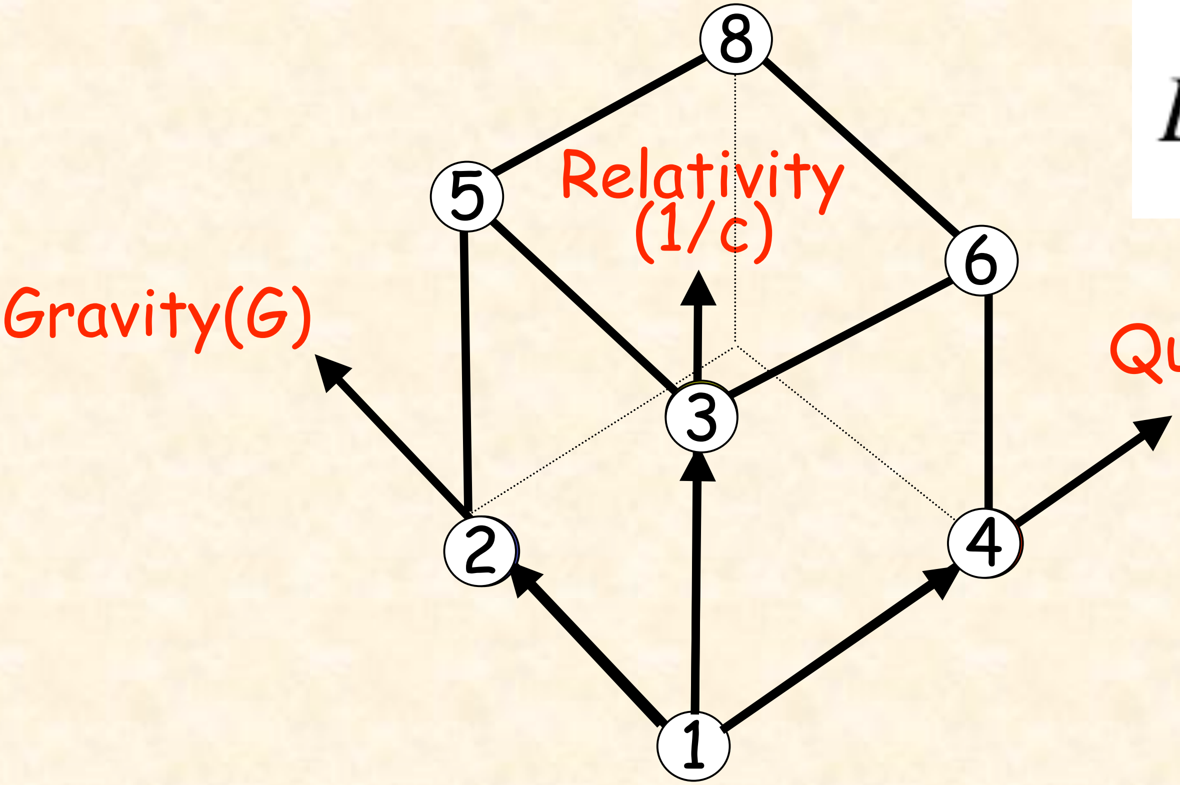
$$L_H \sim 10^{28} cm\,,\ T_H \sim 10^{18} s$$

$$\frac{L_H}{L_P} = \frac{T_H}{T_P} \sim 10^{61}$$

To cope with this huge hierarchy of scales we will use a tool

An exercise in «meta-theory»

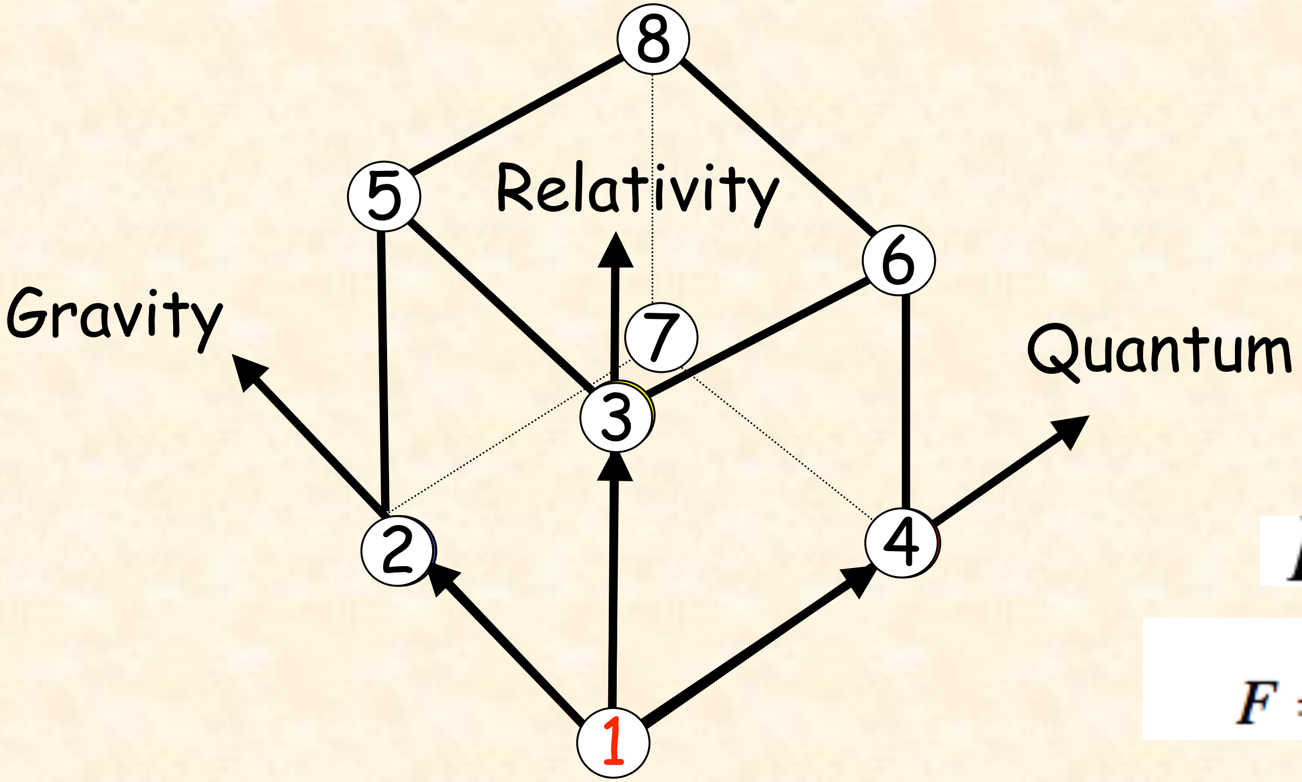
(a Russian cube: from L. Landau to L. Okun)



$$L_P = \sqrt{\frac{Gh}{c^3}}$$

A guided tour follows…

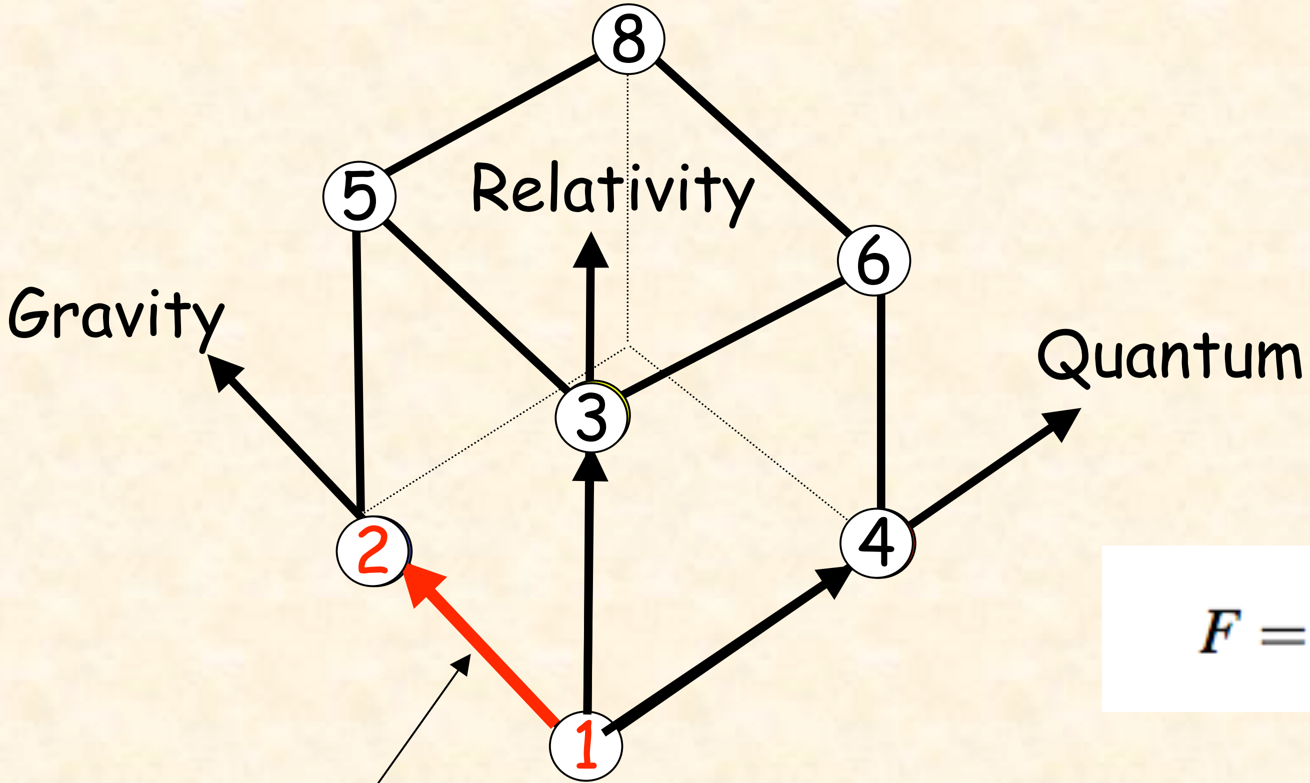
The trivial vertex



$$F = m\,a$$

$$F = 0 \Rightarrow a = 0$$

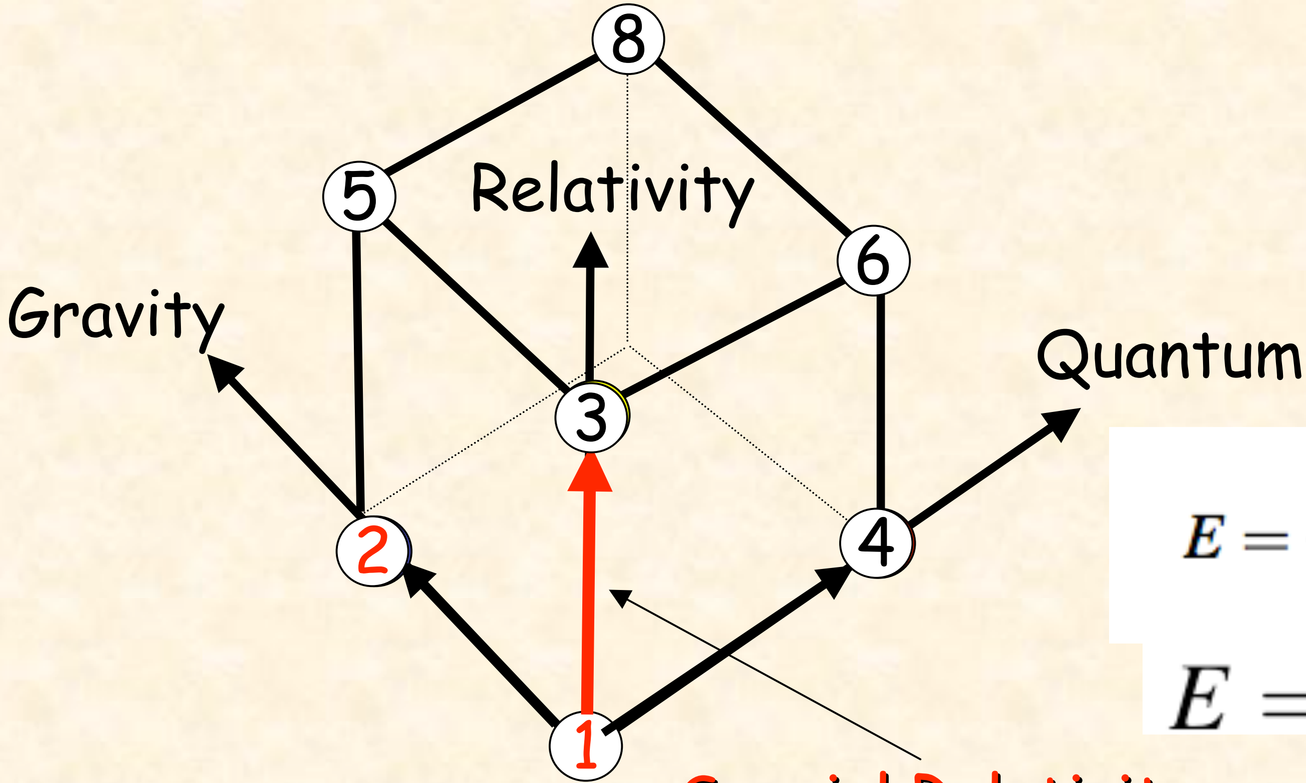
The simplest edges: I



$$F = -G\,\frac{m_1 m_2}{r^2}$$

Newtonian Gravity: e.g. the solar system

The simplest edges: II

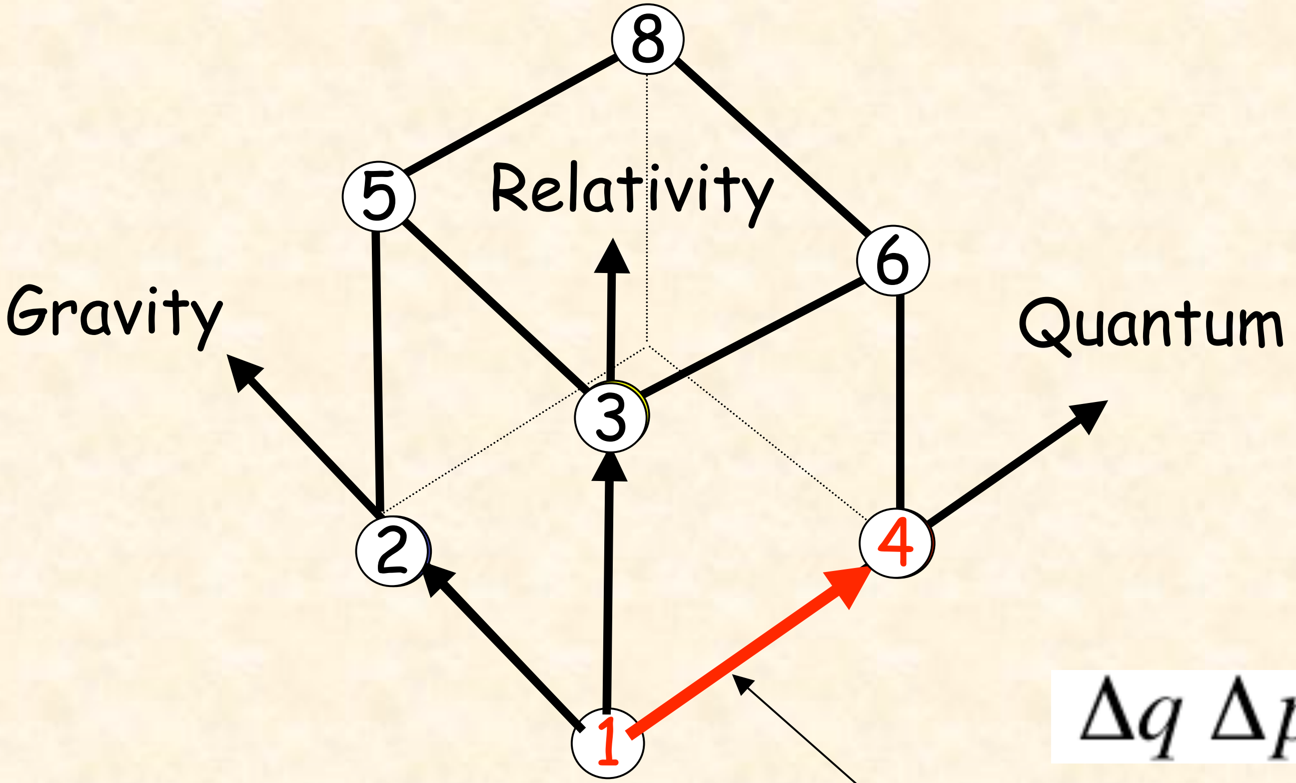


$$E = \frac{mc^2}{\sqrt{1 - v^2/c^2}}$$

$$E = m\, c^2$$

Special Relativity: e.g. particle moving in an accelerator ring

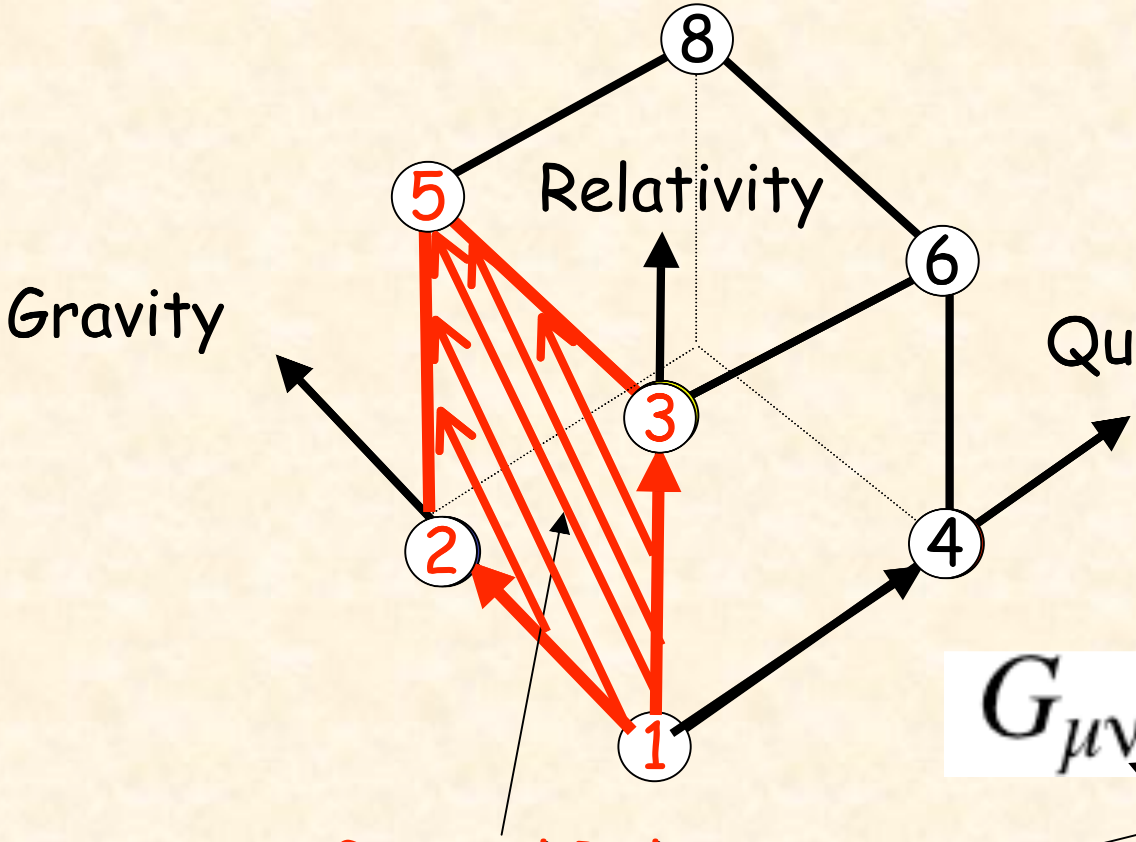
The simplest edges: III



$$\Delta q \, \Delta p \geq h$$

Quantum Mechanics: e.g. H-atom

The most relevant faces: I



$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

General Relativity: matter curves spacetime!

General Relativity (GR)

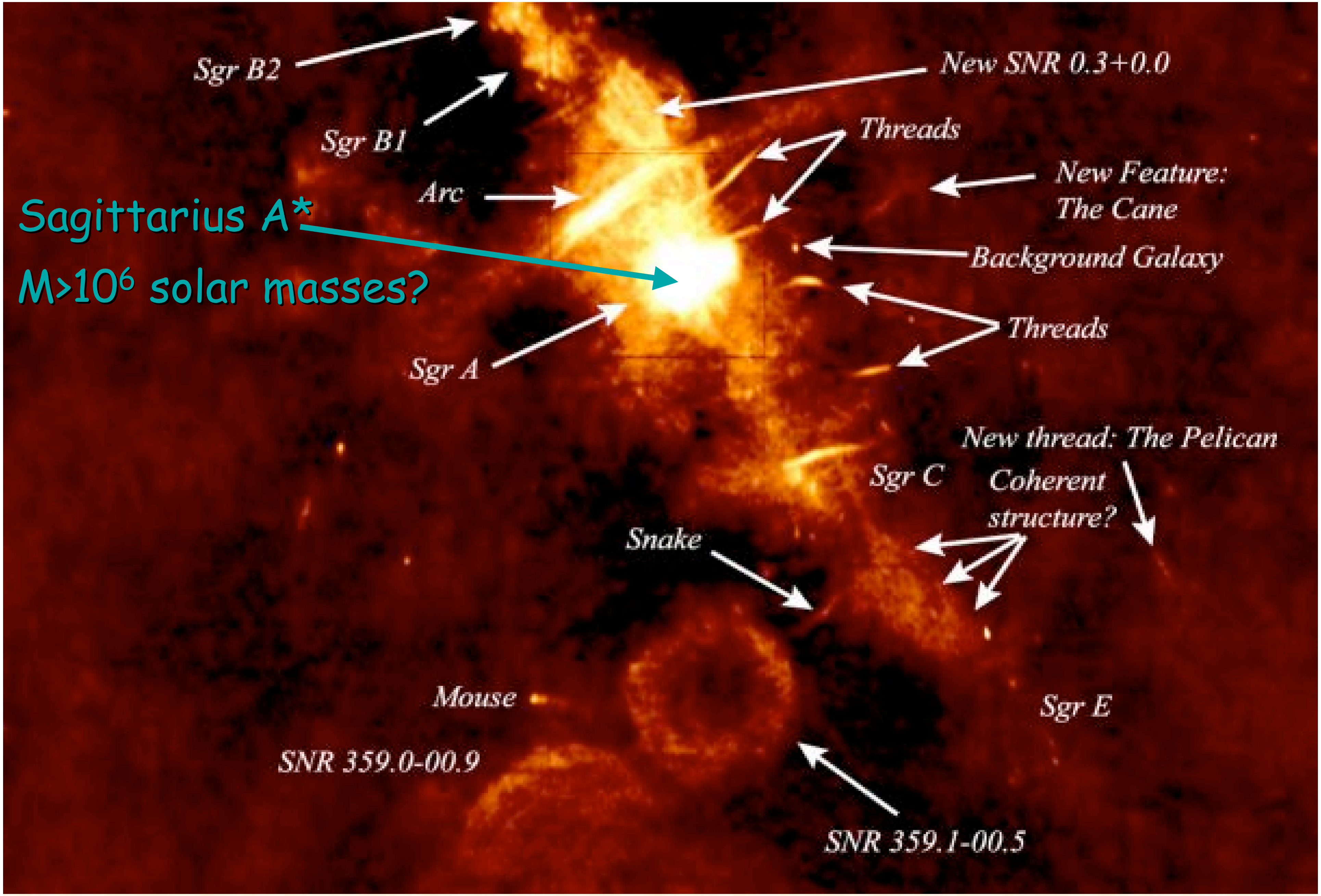
$$\boxed{NG + SR = GR}$$

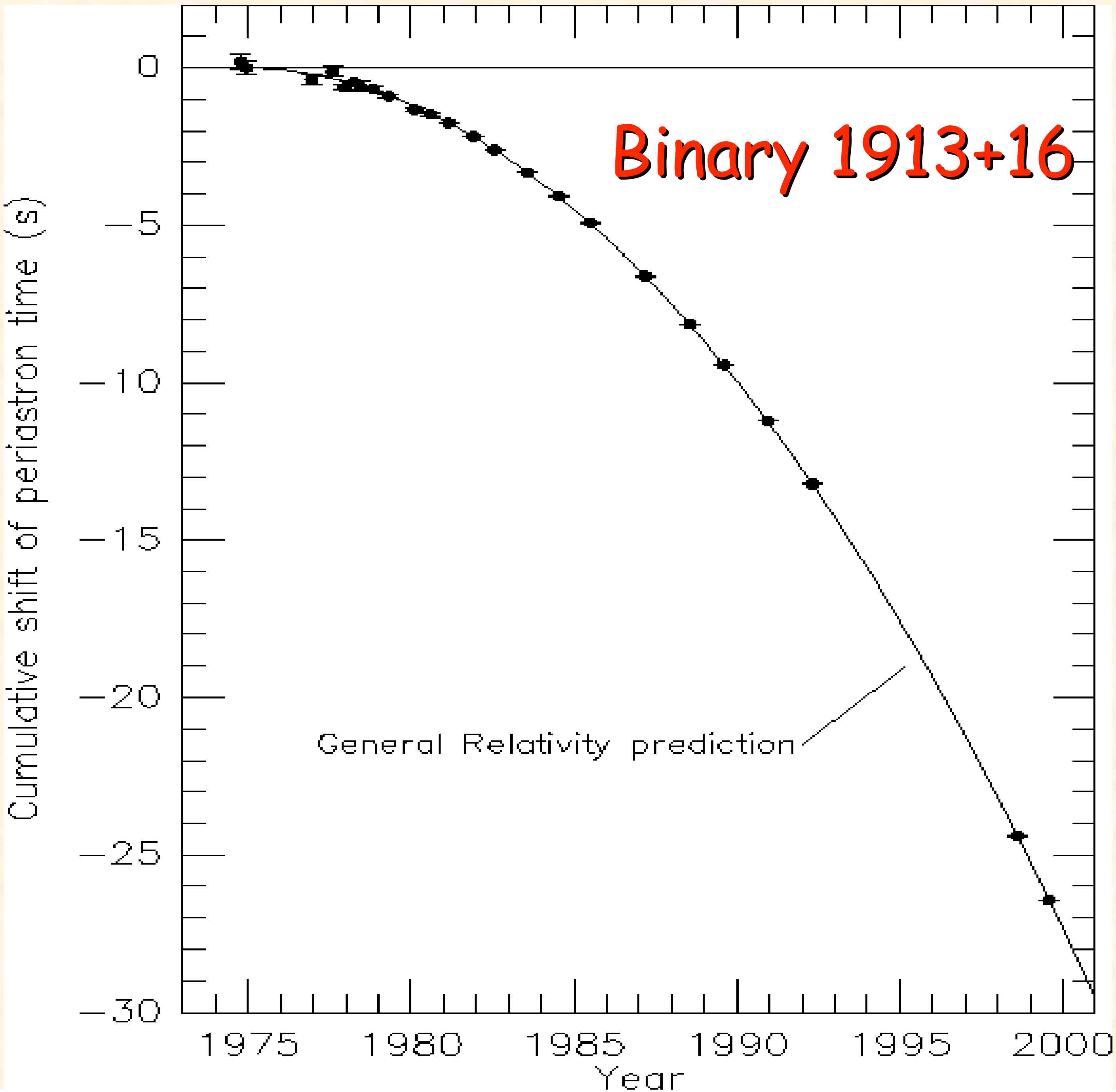
Our «Standard Model» of classical gravity

Corrections to NG better and better tested

New predictions

1. Black holes (overwhelming evidence)
2. Gravitational waves (indirect evidence)

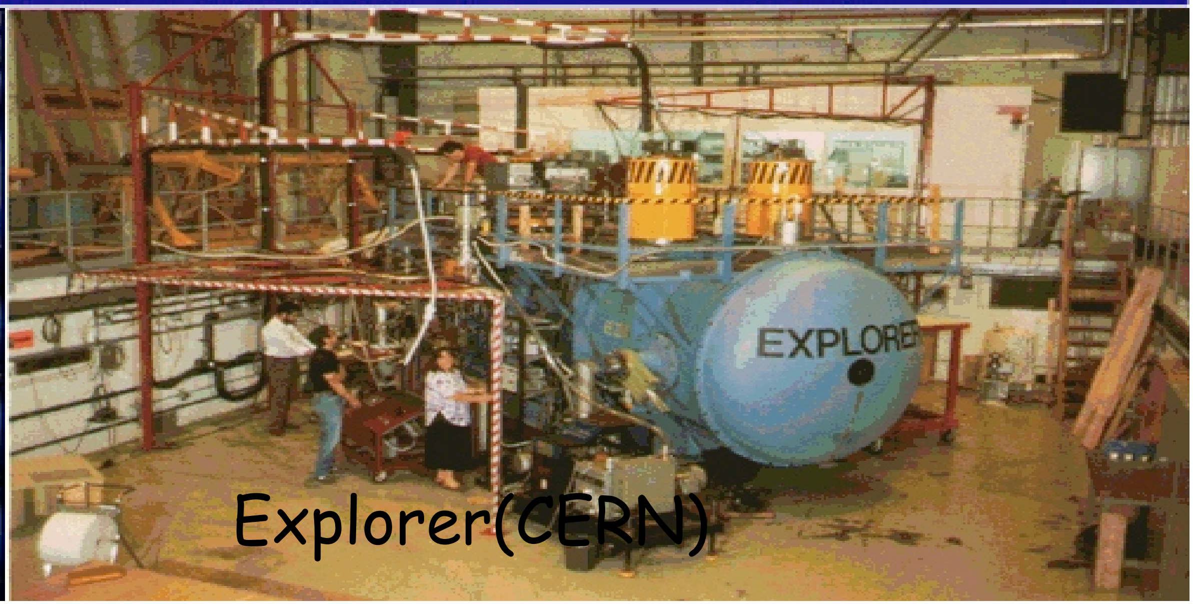

Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature:
The Cane
Arc
Sagittarius A*
M>10^6 solar masses?
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent
structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5


Binary 1913+16
Cumulative shift of periastron time (s)
0
−5
−10
−15
−20
−25
−30
General Relativity prediction
1975
1980
1985
1990
1995
2000
Year


LIGO (USA)

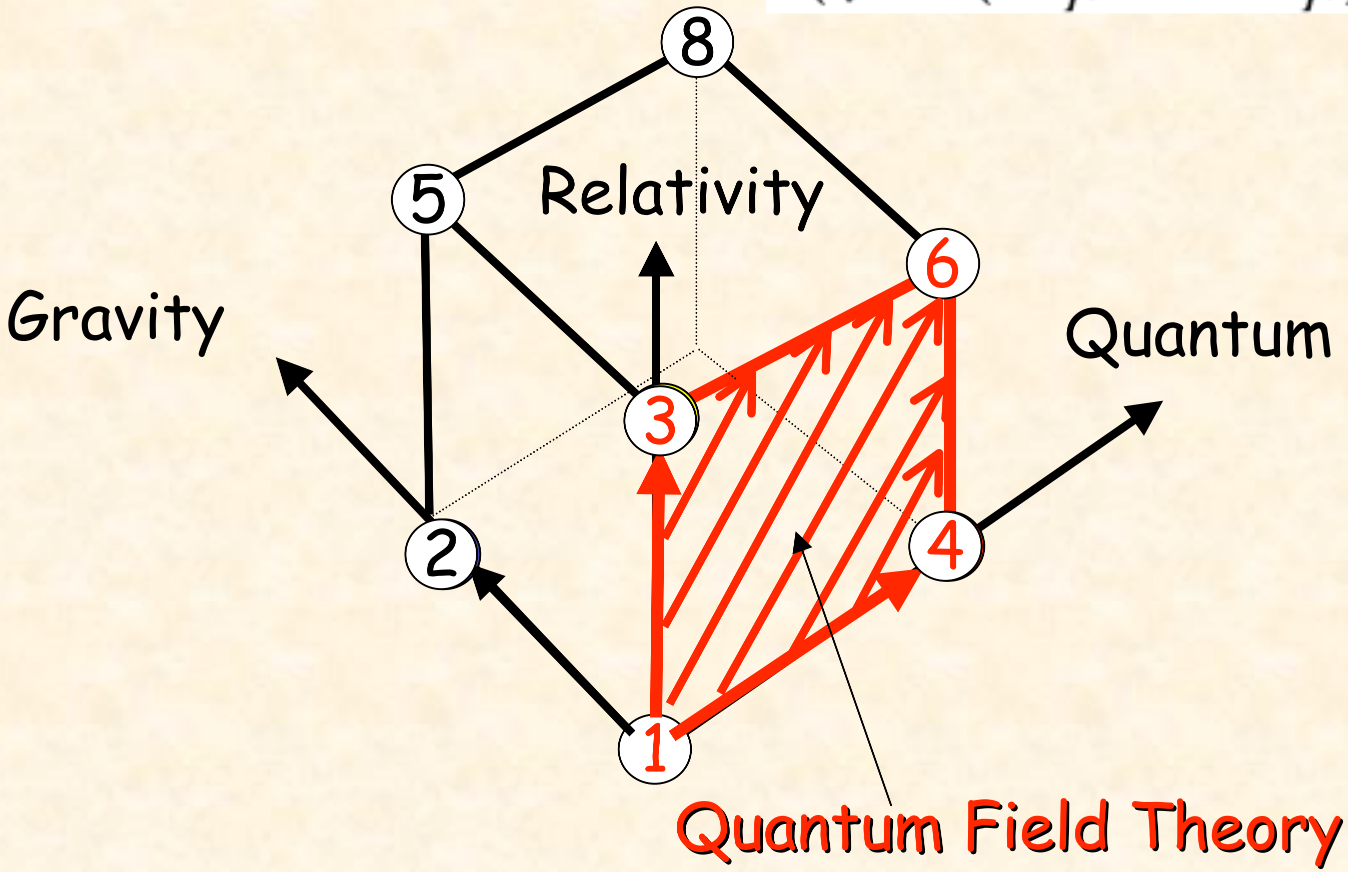

VIRGO(Cascina)


LISA


EXPLORER
Explorer(CERN)

The most relevant faces: II

$$(\gamma^{\mu} \cdot (i\partial_{\mu} - eA_{\mu}) + m)\psi = 0$$

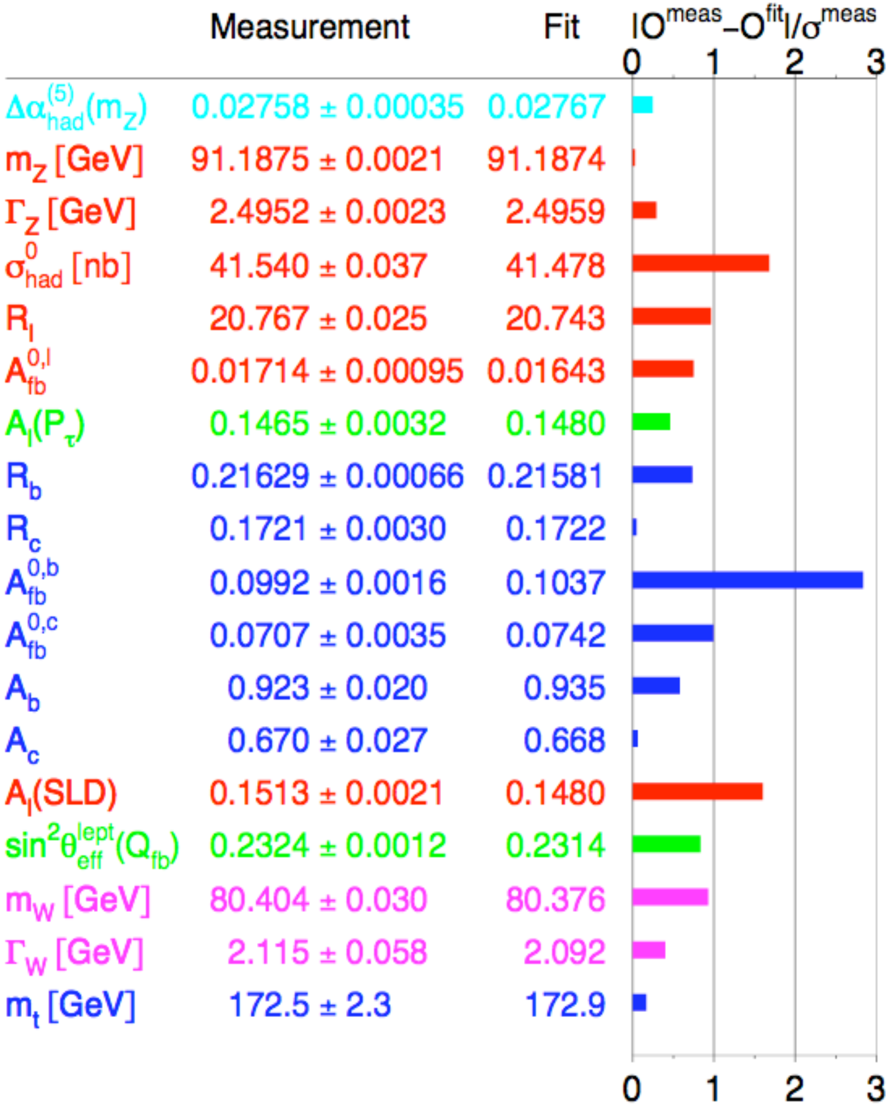


SR + QM = QFT

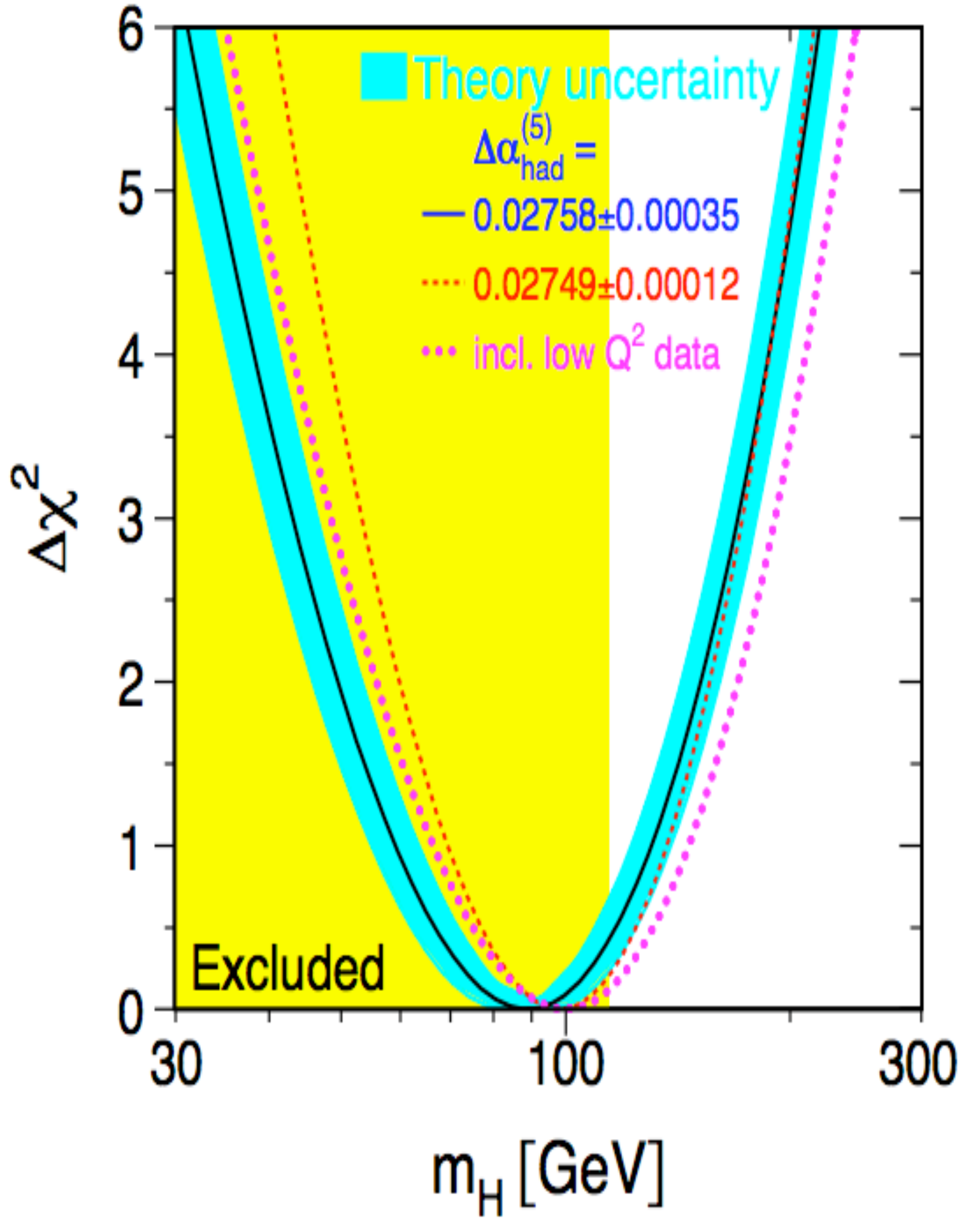
in particular the celebrated

Standard Model (SM) of elementary particles
verified to high precision, e.g. @ LEP (CERN)

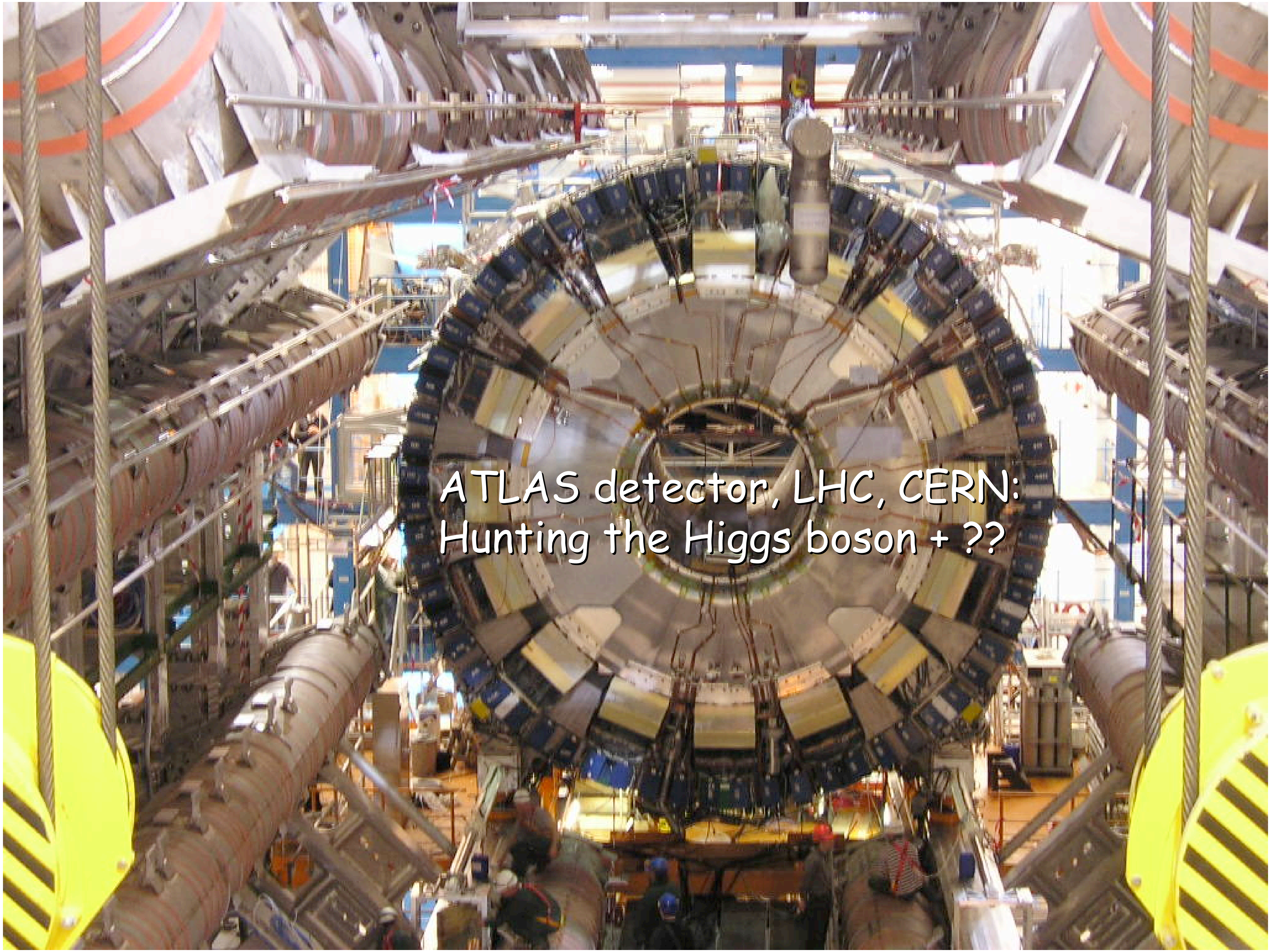
The quantum-relativistic nature of the SM manifests itself through real and virtual particle production
Taking these effects into account is essential for agreement between theory and experiment



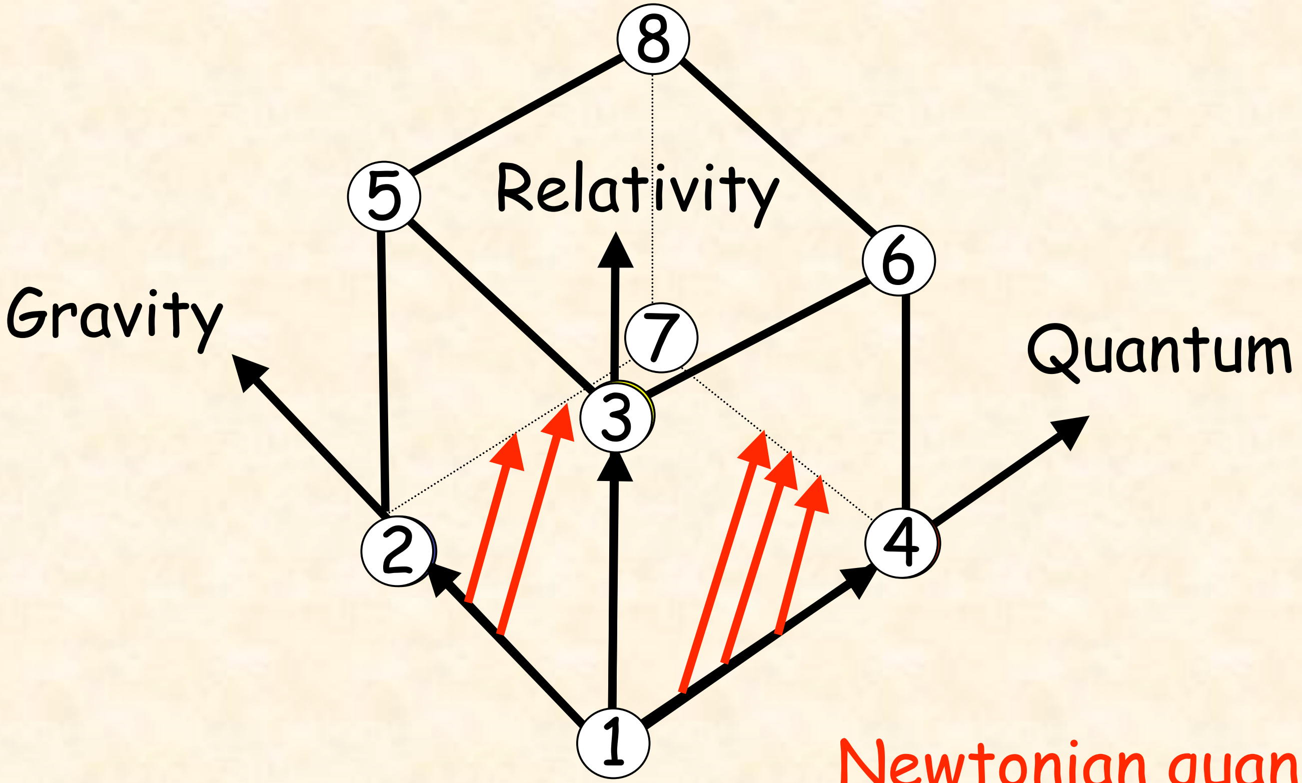
Measurement
Fit
$|O^{meas}-O^{fit}|/\sigma^{meas}$
0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$ 0.02758 ± 0.00035 0.02767
m_Z [GeV] 91.1875 ± 0.0021 91.1874
Γ_Z [GeV] 2.4952 ± 0.0023 2.4959
σ_{had}^{0} [nb] 41.540 ± 0.037 41.478
R_l 20.767 ± 0.025 20.743
$A_{fb}^{0,l}$ 0.01714 ± 0.00095 0.01643
$A_l(P_\tau)$ 0.1465 ± 0.0032 0.1480
R_b 0.21629 ± 0.00066 0.21581
R_c 0.1721 ± 0.0030 0.1722
$A_{fb}^{0,b}$ 0.0992 ± 0.0016 0.1037
$A_{fb}^{0,c}$ 0.0707 ± 0.0035 0.0742
A_b 0.923 ± 0.020 0.935
A_c 0.670 ± 0.027 0.668
A_l(SLD) 0.1513 ± 0.0021 0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$ 0.2324 ± 0.0012 0.2314
m_W [GeV] 80.404 ± 0.030 80.376
Γ_W [GeV] 2.115 ± 0.058 2.092
m_t [GeV] 172.5 ± 2.3 172.9
0 1 2 3



Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
$\Delta\chi^2$
0 1 2 3 4 5 6
30 100 300
m_H [GeV]


ATLAS detector, LHC, CERN:
Hunting the Higgs boson + ??

What about face III?



Newtonian quantum gravity?
Yes, it's possible!

Gravitationally bound quantum states of neutrons: applications and perspectives

H.Abele, S.Bassler, H.G.Borner, A.M.Gagarski, V.V.Nesvizhevsky, A.K.Petoukhov, K.V.Protasov, A.Yu.Voronin and A.Westphal

Gravitationally bound quantum states of matter were observed recently due to unique properties of ultracold neutrons. We discuss here the actual status and possible improvements in this experiment. This phenomenon could be useful for various domains ranging from the physics of elementary particles and fields, to surface studies, or to foundations of quantum mechanics.

http://www.panic05.lanl.gov/abstracts/250/proc_Nesvizhevsky_250.pdf

Summarizing so far:

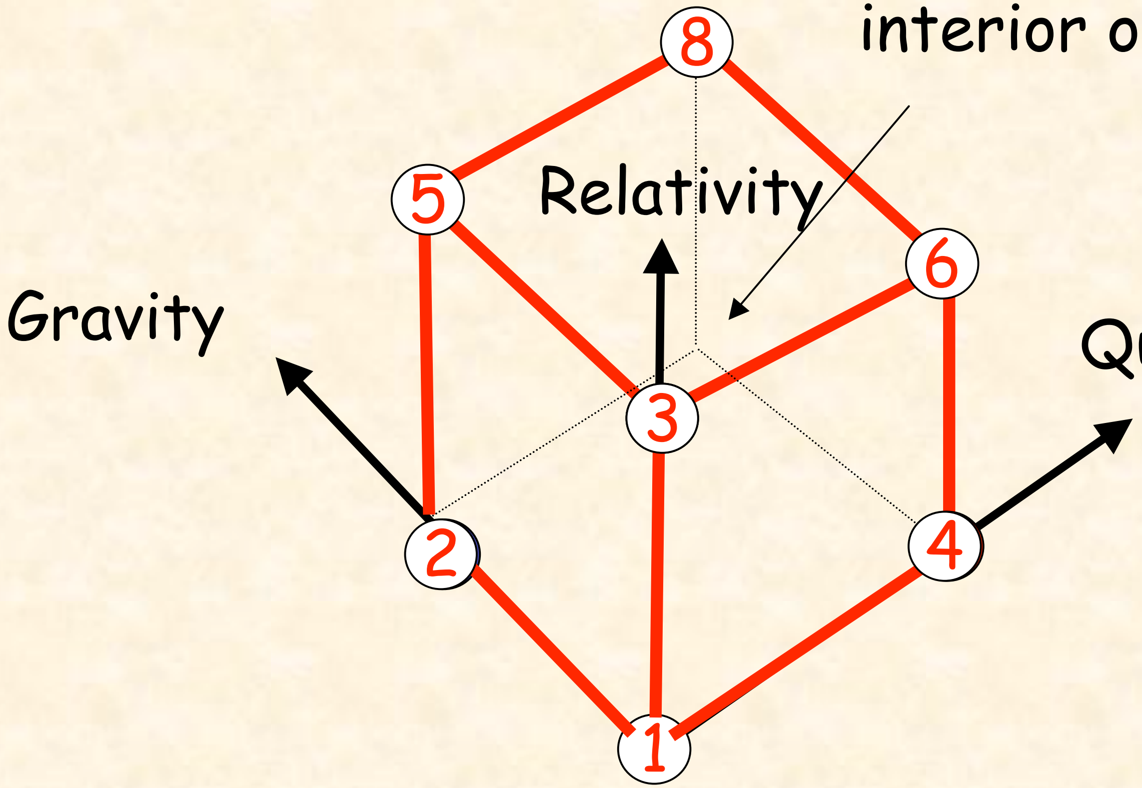
NG + SR = GR = SMCG

SR + QM = SMEP

Both work wonders…but again the question arises of how we combine the classical and the quantum

The issue is not just a conceptual one: it becomes physically relevant in the context of cosmology

Cosmology occupies all the interior of our cube!



Expansion of the Universe

Far past → Very hot and dense Universe

Very hot Universe → Very high energies (R)

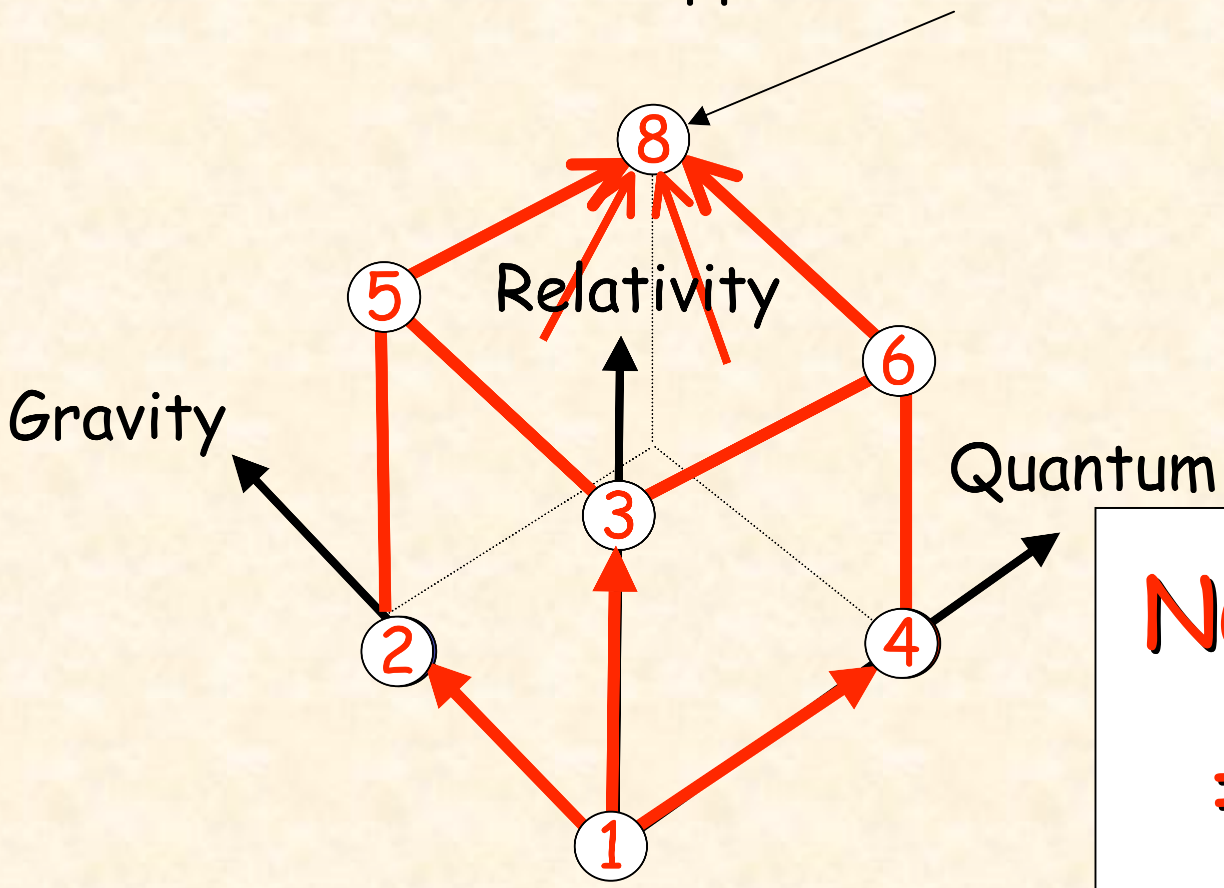
Very dense Univers → Very high curvature (G)

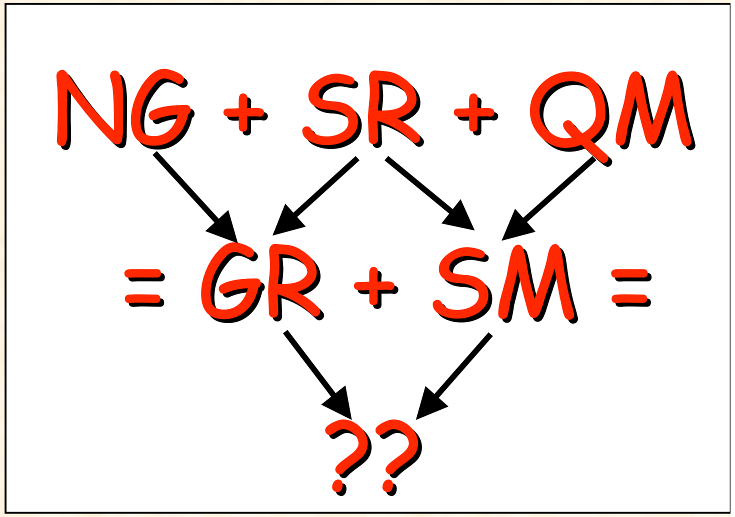
Very high curvature → Quantum processes (Q)

Far in space ⟷ Back in time (c finite)

Deep connection between L_H and T_P

The more we go towards the past the more we approach vertex no. 8!





Patologies of Classical General Relativity

Theorems due to Hawking and Penrose imply that, under quite general conditions, perfectly smooth initial data lead to space-time singularities

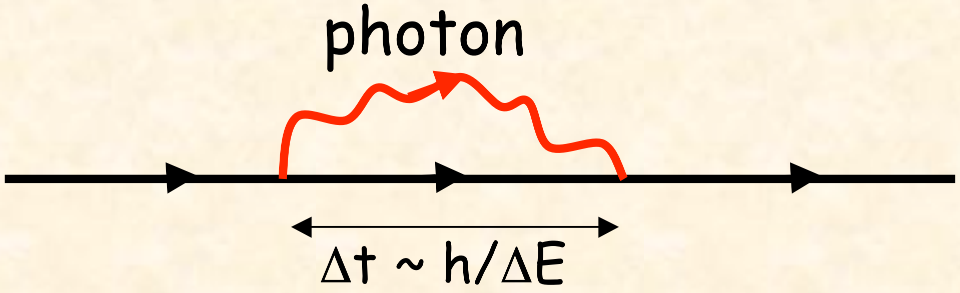
Near curvature singularities quantum corrections to GR cannot be neglected.

Q: Can QM remove the singularities of GR, like it did with other infinities a century ago..?

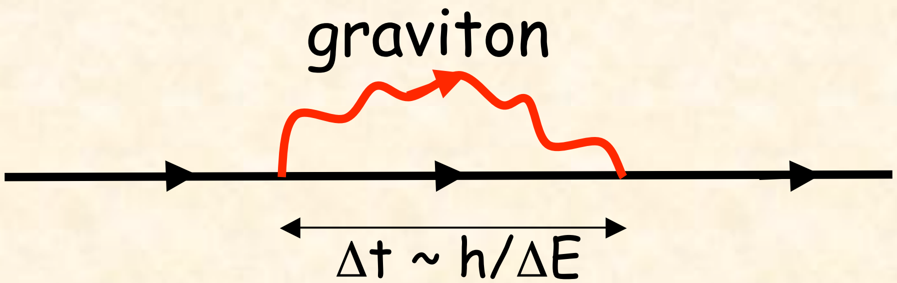
A: QM appears to worsen the situation. Why?

Patologies in Quantum General Relativity

(the «evil quanta» are back!)



= **Calculable** (and essential) corrections



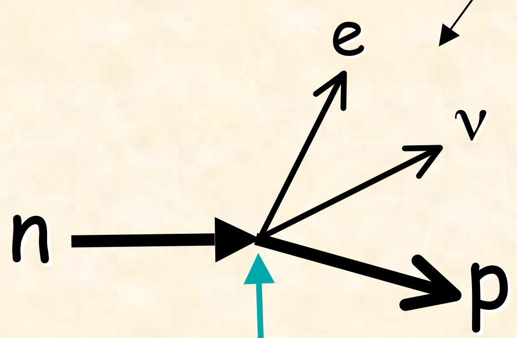
= **Uncalculable** corrections

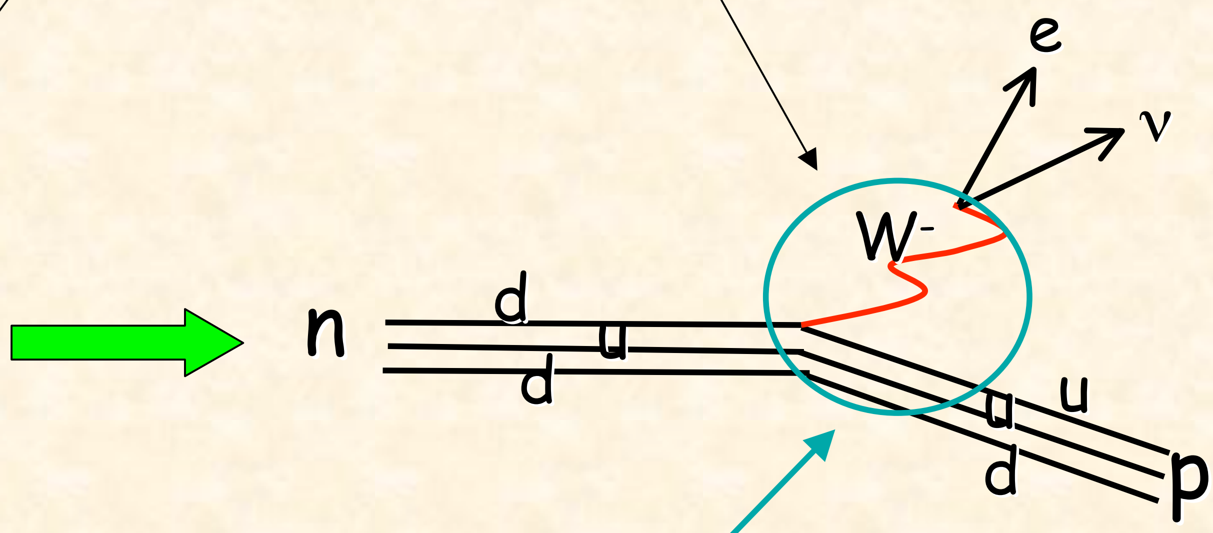
Patologies in Quantum Field Theories

Even in the SM there are infinities. The difference is that we can tame them and keep much predictivity

An instructive example: weak interactions

From Fermi (1934) to EWT (~1973)





The interaction takes place at a single point in space-time

The interaction is smeared over a finite region of space-time

Even the EW theory of GSW has infinities, hence uncalculable parameters: yet it's much more predictive than Fermi's!

Is it possible to do something similar in GR?

A priori looks like an impossible dream since GR is based in an essential way on a space-time continuum where coincidences of events can be defined

Yet string theory seems capable of realizing that dream through what we may call
«Quantum Magic»

String Theory: what's that?

« String Theory is the theory of strings »

Replace some grand principles (Equivalence, Gauge) by «just» the assumption that everything is made of

Relativistic Quantum Strings

Strings + SR + QM = Grand Synthesis

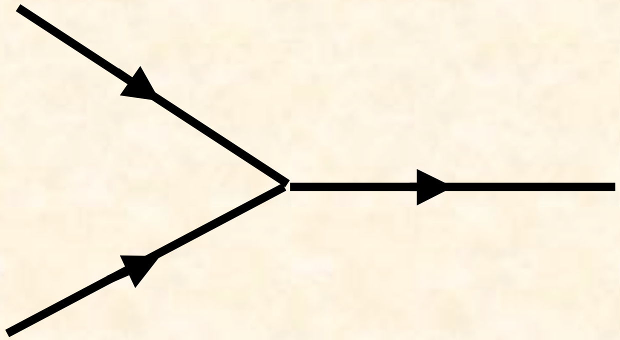
A magic 3-ingredient cocktail!

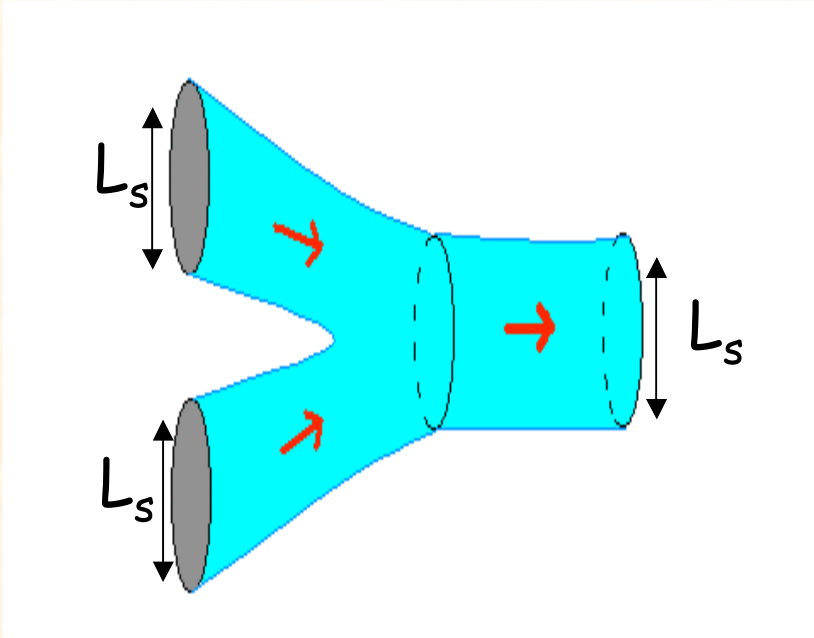
Quantum magic I

Classical relativistic strings with tension T may have any size L, and therefore any mass M~T L;

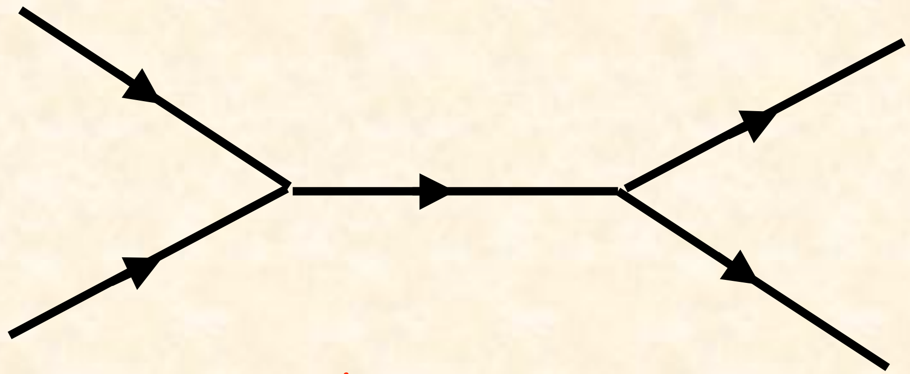
Quantum strings have a minimal (optimal) size L_s (Cf. Bohr radius, h.osc.), given by $L^2{}_s = h/T$. This length appears naturally in the (quantum) action of a string:

$$S_{class.} = T(Area\ swept) \Rightarrow \frac{1}{\hbar} S_{class.} = \frac{1}{L_s^2}(Area\ swept)$$

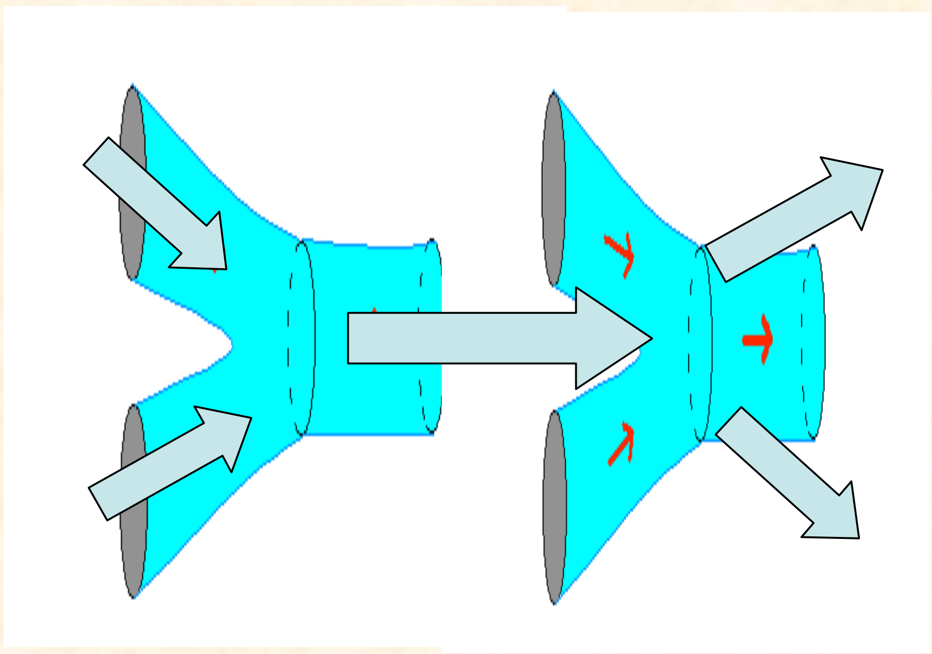




L_s
L_s
L_s



becomes



Quantum magic II

Classical string cannot have angular momentum without also having a finite size, and thus a finite mass;

Quantum strings may have up to 2 units of J without acquiring mass:

once regularized

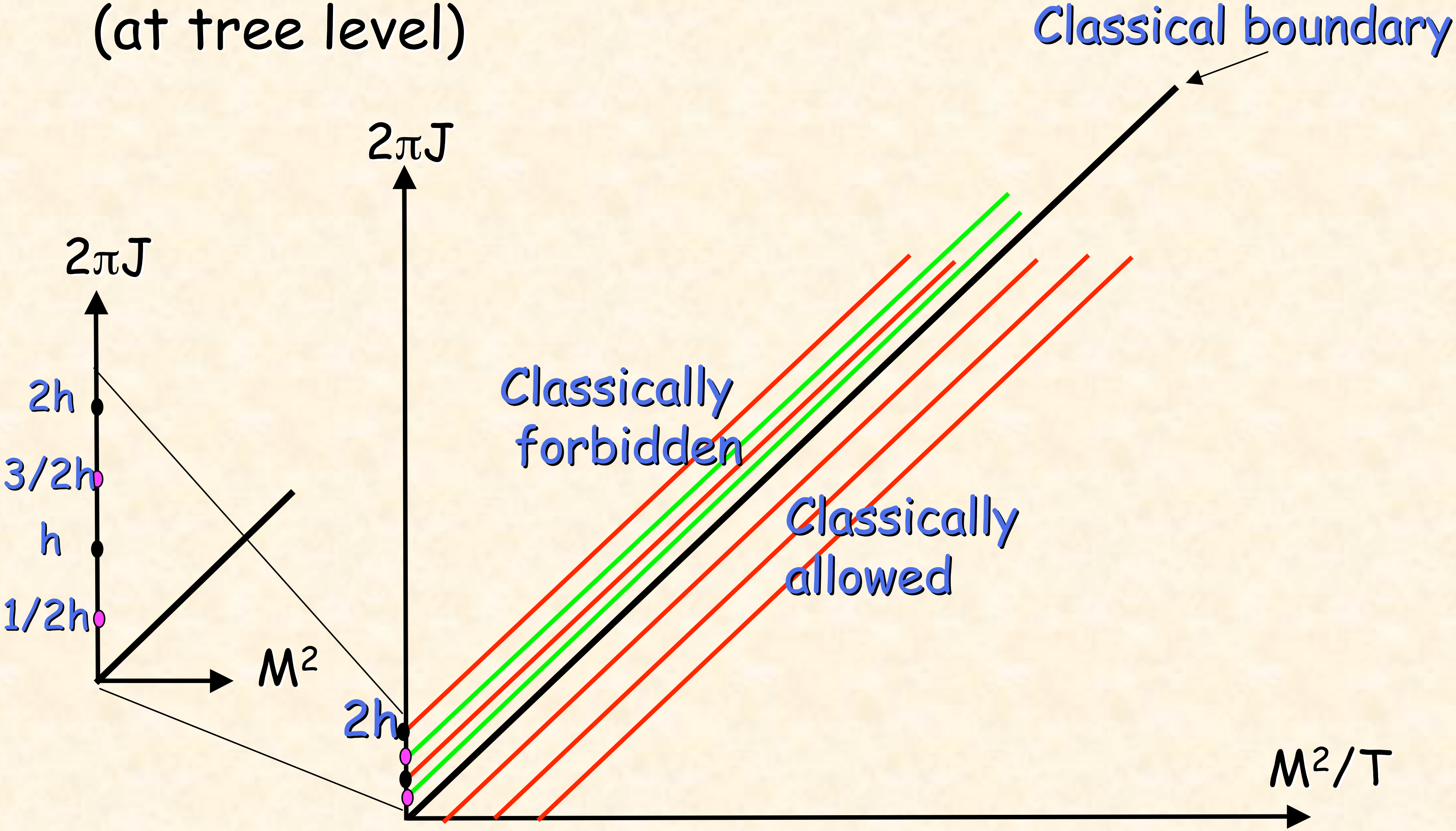
$$\frac{M^2}{2\pi T} \geq J + \hbar \sum_{1}^{\infty} \frac{n}{2} = J - \alpha_0 \hbar$$

where

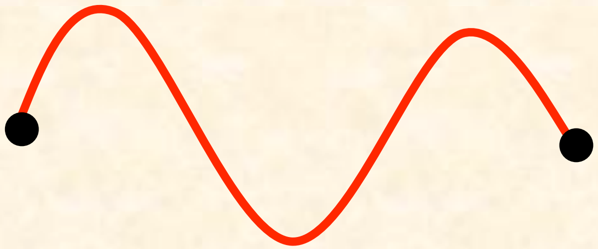
$$\alpha_0 = 0,\ \frac{1}{2},\ 1,\ \frac{3}{2},\ 2.$$

Quantum Spectrum

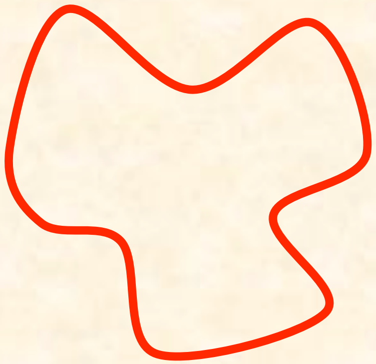
(at tree level)



In particular..



=> m=0, J = 1 => photon and other gauge bosons



⇒m=0, J = 2 => graviton,

Integer J massless states => carriers of interactions;
1/2-integer J massless (light) states => constituents of matter

This common stringy origin of photons and gravitons implies a quantitative unification of all forces at very high energies.

The string length parameter L_s can be converted into an energy scale via the UP:

$$E_s \equiv \frac{\hbar c}{L_s} = c\sqrt{\hbar T}$$

At these energies gravitational and electromagnetic interactions become comparable. In turn this implies that

$$L_s^2 \sim \frac{1}{\alpha} L_P^2 \Rightarrow L_s \sim 10 L_P \sim 10^{-32} cm$$ or $$E_s \sim E_P/10 \sim 10^{17} GeV$$

Thus, combining both miracles provides

A unified and finite theory of elementary particles, and of their gauge and gravitational interactions, not just compatible with, but based on, Quantum Mechanics!

«Relativistic sand» and «evil quanta» happily coexist in string theory!

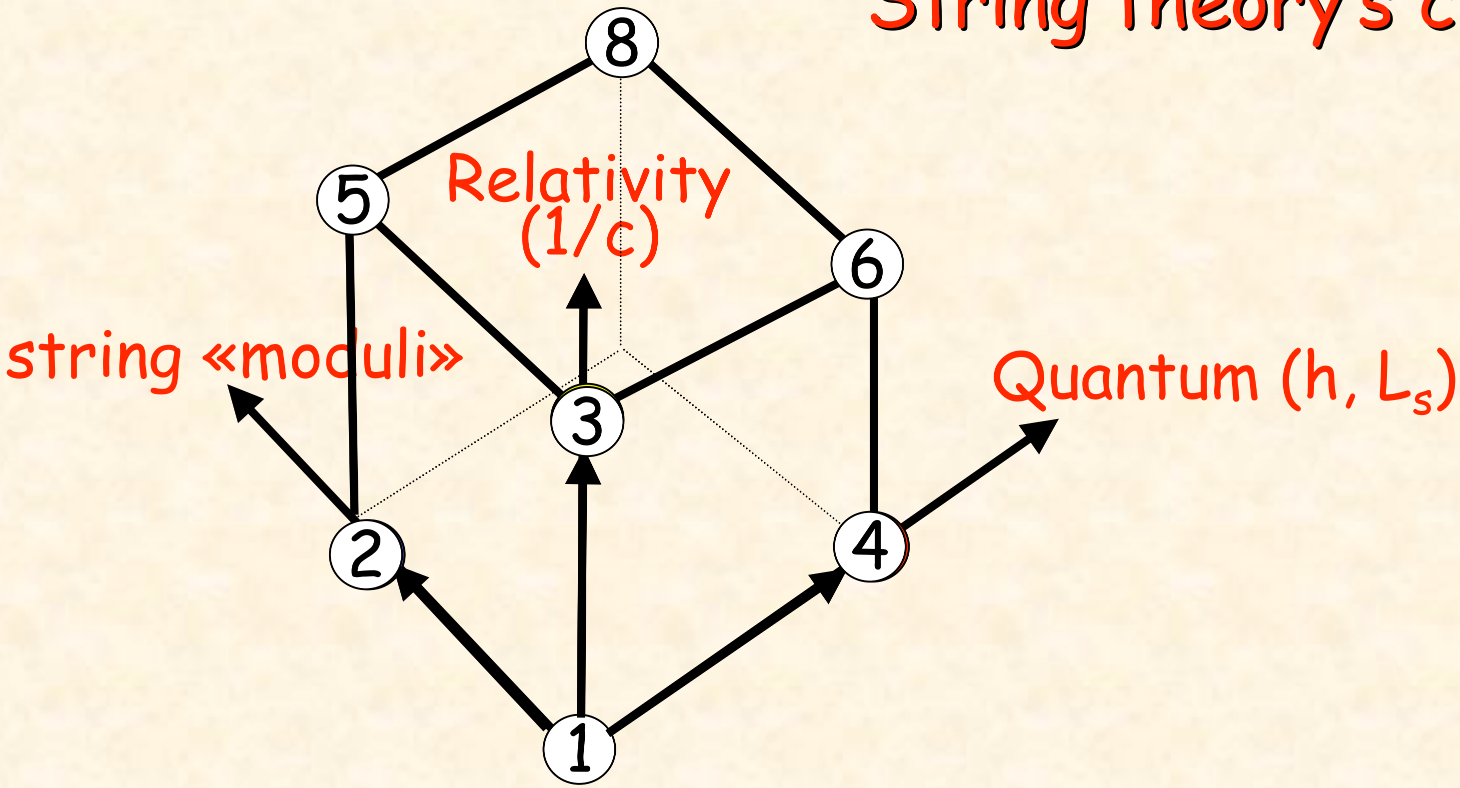
More quantum magic (incomplete list)

- While classical strings can move consistently in any ambient space-time, quantum strings are more fussy.
- Unless we accept a Universe of size L_s, space must have 6 (well hidden!) extra dimensions, themselves probably of size L_s.
- If these are instead «mesoscopic» (say micron-size), they may induce short-distance modifications of Newton’s law.

- There are no free parameters: these are replaced by (scalar) fields whose values provide the «Constants of Nature», e.g. the fine-structure constant. Are these values determined dynamically?
- While today these « constants » look indeed to be space and time-independent, their variations may have played an important role in early cosmology.
- The possibility that they vary slightly even today is all but excluded. Furthermore, those scalar fields could provide new long-range forces and induce tiny violations of the equivalence principle (e.g. of universality of free-fall).

➪ A very active field of experimental and theoretical research

String theory's cube?



The moduli determine, in principle, all dimensionless parameters. Are they fixed, discrete, continuous parameters? At some level of approximation some are dangerously free… A major problem limiting today string theory's predictivity.

Possible physical applications

1. Black holes, strings and QM
2. Primordial cosmology

BH entropy and the information paradox

•In favourable cases string theory allows for a stat mech interpretation of the thermodynamic entropy of a black hole as given by the Hawking-Bekenstein formula:

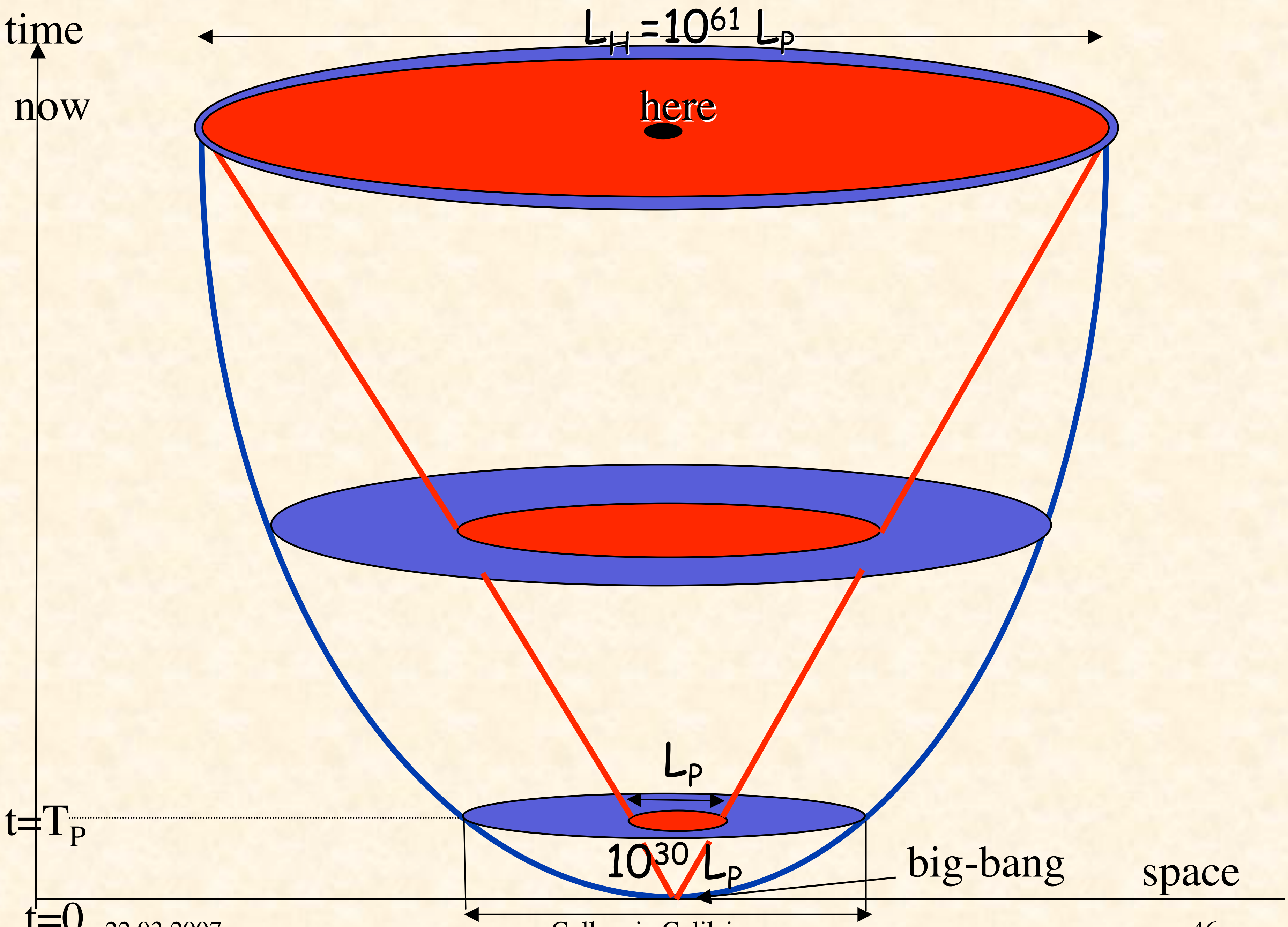
$$S_{BH} = \frac{Horizon\ Area}{4L_P^2}$$

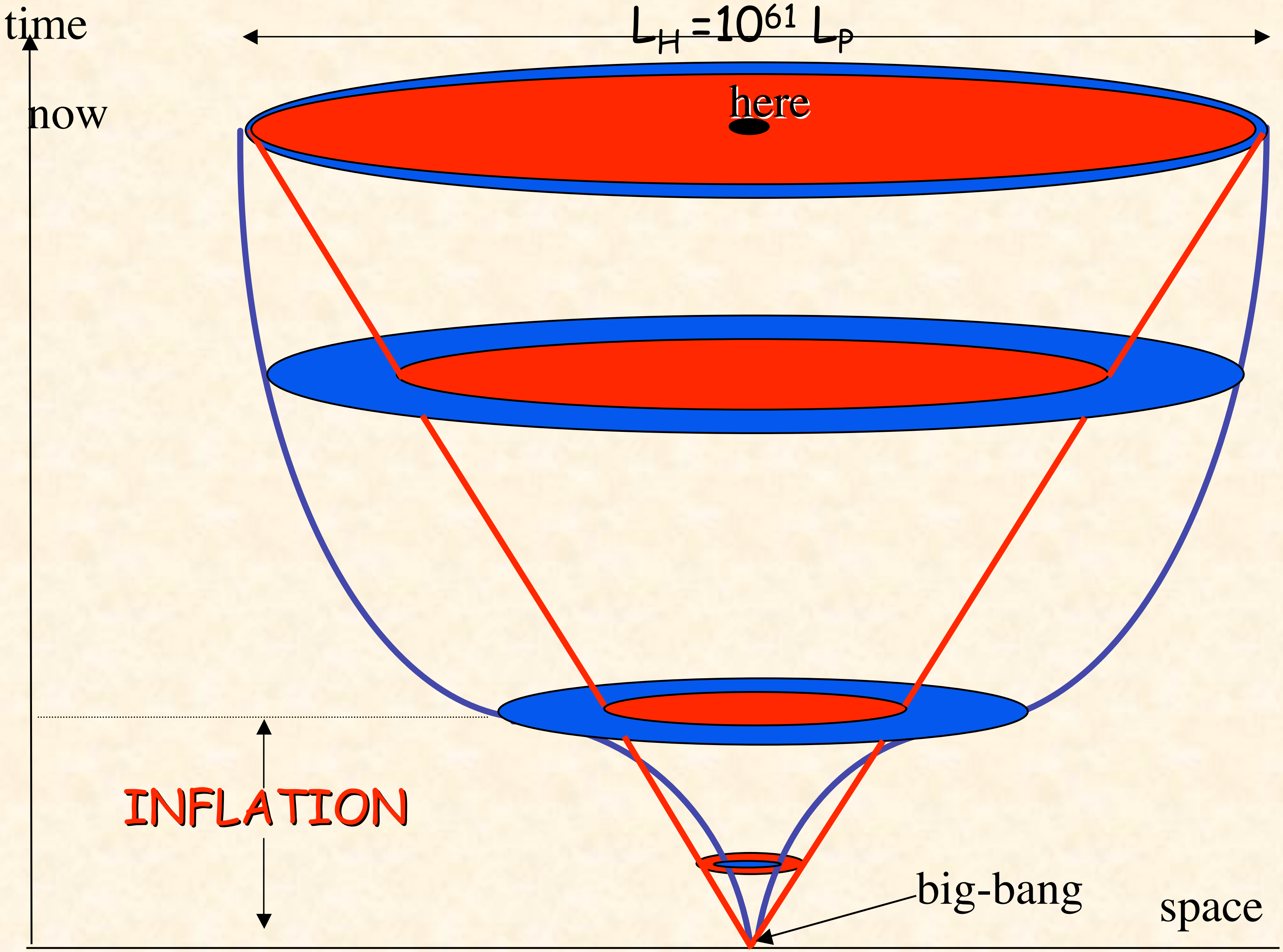
•Microscopic quantum states counting gives precisely (for large S_{BH}) ln N = S_{BH}.

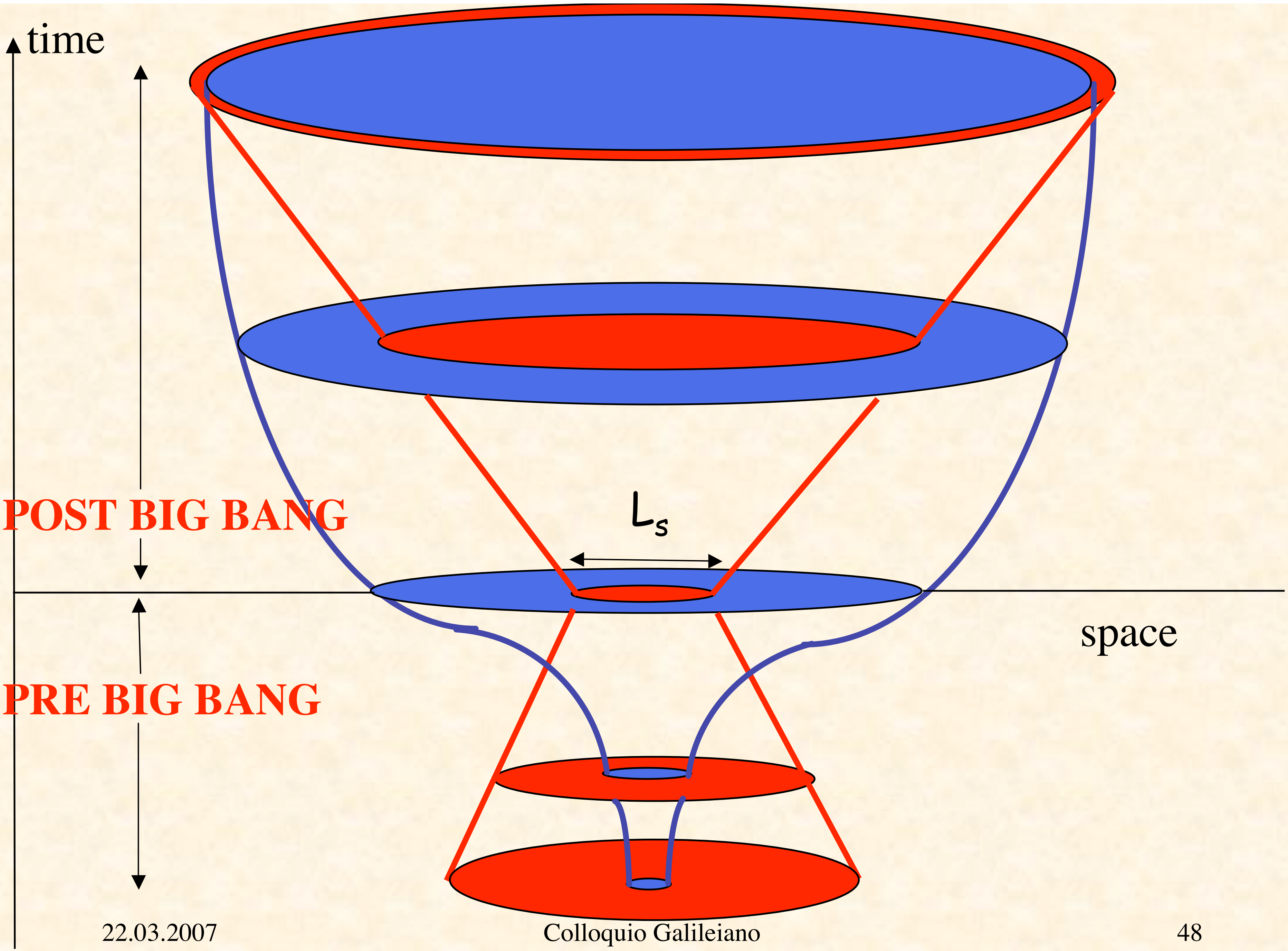
•String theory also provides arguments against loss of quantum coherence in processes where a black hole is formed from a pure initial state and then undergoes Hawking evaporation. Hawking himself has taken back (Dublin, 2004) his previous claims to the contrary

Cosmology

- String theory «resolves» certain singularities of CGR
- Those associated with cosmology (big bang) are harder to deal with but very likely they are also eliminated or reinterpreted (new degrees of freedom needed)
- If so we may conceive new cosmological scenarios in which the big bang, rather than representing the beginning of time, is the result of a previous phase in which the space-time curvature scale (in particular the Hubble parameter H) grows until it reaches values of order L_s^{-1}
- A «string phase» would then make the Universe «bounce». The Big Bang becomes a «Big Bounce»
- These scenarios can provide new solutions to the problems of standard cosmology: an older Universe, rather than the smaller one of the inflationary paradigm.

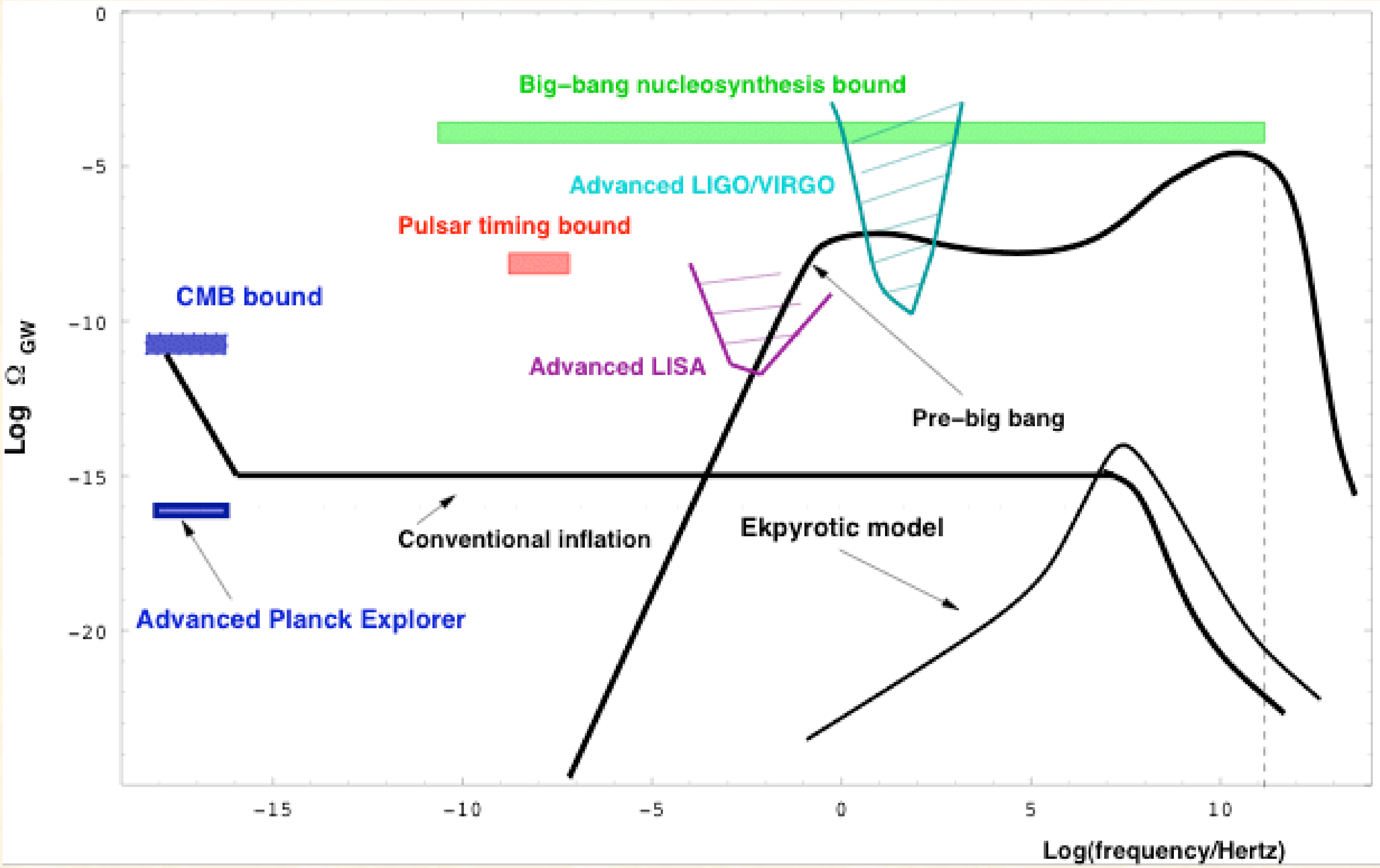

time
$L_H = 10^{61} L_P$
now
here
L_P
$t = T_P$
$10^{30} L_P$
big-bang
space
t=0


time
$L_H = 10^{61} L_P$
now
here
INFLATION
big-bang
space


time
POST BIG BANG
L_s
space
PRE BIG BANG

These «pre big bang» cosmologies have observable consequences, can be tested in principle. Examples:

1. A stochastic background of GW
2. Seeds for cosmic magnetic fields due to an evolving fine-structure constant and/or size of internal dimensions during pre-bounce phase
3. Some characteristic features of CMB anisotropies



Big–bang nucleosynthesis bound
Advanced LIGO/VIRGO
Pulsar timing bound
CMB bound
Advanced LISA
Pre–big bang
Conventional inflation
Ekpyrotic model
Advanced Planck Explorer
Log Ω GW
Log(frequency/Hertz)
0
-5
-10
-15
-20
-15
-10
-5
0
5
10

Strings and Einstein's dream

- Einstein's dream appears to be realized in string theory, but in a way that could have been hardly imagined 50 years ago
- String theory was born «accidentally» in the late sixties because (as a consequence of quark confinement) there are, in the physics of strong interactions, string-like structures
- That «hadronic» string is still to be understood, while the original strings have found an application that no-one could have forseen at the time:

«A piece of XXIst century physics that fell too early on us!»

(Sergio Fubini ~ 1970)

- The dream is realized thanks to (and not against) QM.
- Without QM strings do not provide photons or gravitons, and, a fortiori, an electromagnetic or a gravitational field: these only emerge as semiclassical limits of a fundamentally quantum theory of extended objects.
- Einstein's dream comes true (at a theoretical level, at least), but in a way that is quite opposite to the one he was pursuing.
- Would he react today to String Theory, like he did to QM, by saying, instead of his famous:

God does not play dice!

God does not play strings!

or would he have accepted that
He can play dice and strings at the same time?

So far, during the last 50 years, there has been mounting evidence (e.g. via tests of Bell's inequalities) that He does play dice after all!

However, like with the old hadronic string, we could be disappointed once more. Quite possibly, the objects to which string theory applies are not the particles we consider today as elementary. But I do believe that string theory is too beautiful for having no place in Nature. Quoting again Albert Einstein:

« Subtle is the Lord, but malicious He is not »

(letter to Besso, 1954)