


Memorial Lecture, 19 June 2007

# String Theory, Gravity, and Cosmology

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(CERN & CdF)

# Introduction

At the turn of the XIX$^{th}$ century, about 100 years ago, two revolutions had just shaken two sacred scientific beliefs:

1. The belief in absolute determinism when Max Planck, in 1900, puzzled by an UV divergence in the black-body spectrum, introduced h and started the quantum revolution.

2. The belief in absolute time when Albert Einstein, in 1905, building on the invariance of the speed of light, c, arrived at the theory of Special Relativity.

In 1915 Einstein set off yet another revolution:

Starting from the Galileian universality of free-fall, he arrived at a geometric theory of gravity, General Relativity, in which even the concept of an absolute (Euclidean) geometry is abandoned

In General Relativity Newton's constant, G, fixes the overall amount of space (and/or time)-curvature induced by the presence of matter/energy.

| |
|---|
| h => no absolute determinism<br>c => no absolute time<br>G => no absolute geometry |

In the later part of his scientific life Einstein tried to combine in a single conceptual framework all these great developments and, in particular, tried to unify Gravity and Electromagnetism

Neither Einstein, nor others succeeded

With hindsight, we can say that the most serious attempts were those initiated by Kaluza & Klein (KK) in the twenties. According to their theory, pure-gravity in the presence of one compact extra dimension of space (say a circle of radius R) gives rise to a unified theory of gravity and electromagnetism at distances much larger than R. Furthermore, electric charge is automatically quantized in units of 1/R ($\alpha \sim l_P^2/R^2$).

Thus $R \sim 10\, l_P \sim 10^{-32}$ cm

Einstein very much appreciated the potentialities of KK theory but got frustrated by his unsuccessful attempts (~ 1940) to exorcise it from its (essential) quantum aspects

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

**What has become of Einstein's unification dream and of the KK idea some 50 years later?**

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: what do we mean by «infinitely»?

# 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

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

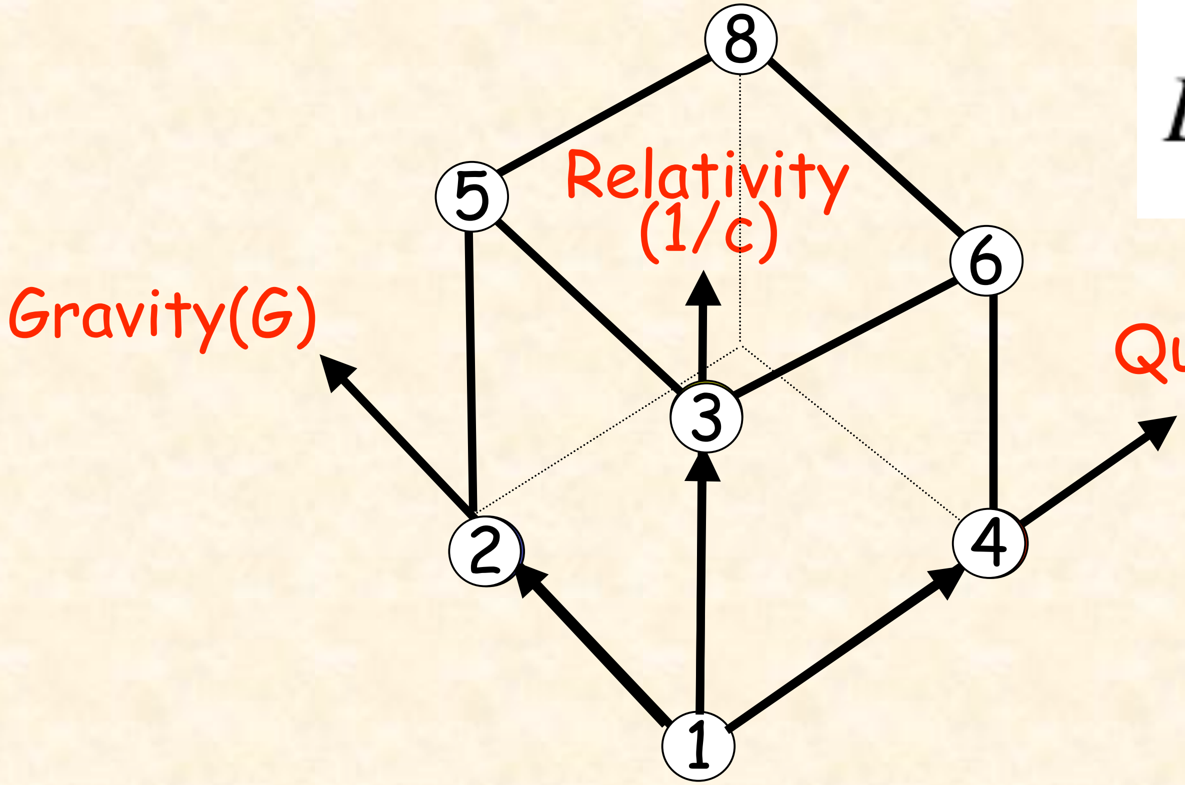
$$L_H \sim 10^{28} cm\,,\ T_H \sim 10^{18} s$$

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

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

# An exercise in «meta-theory»

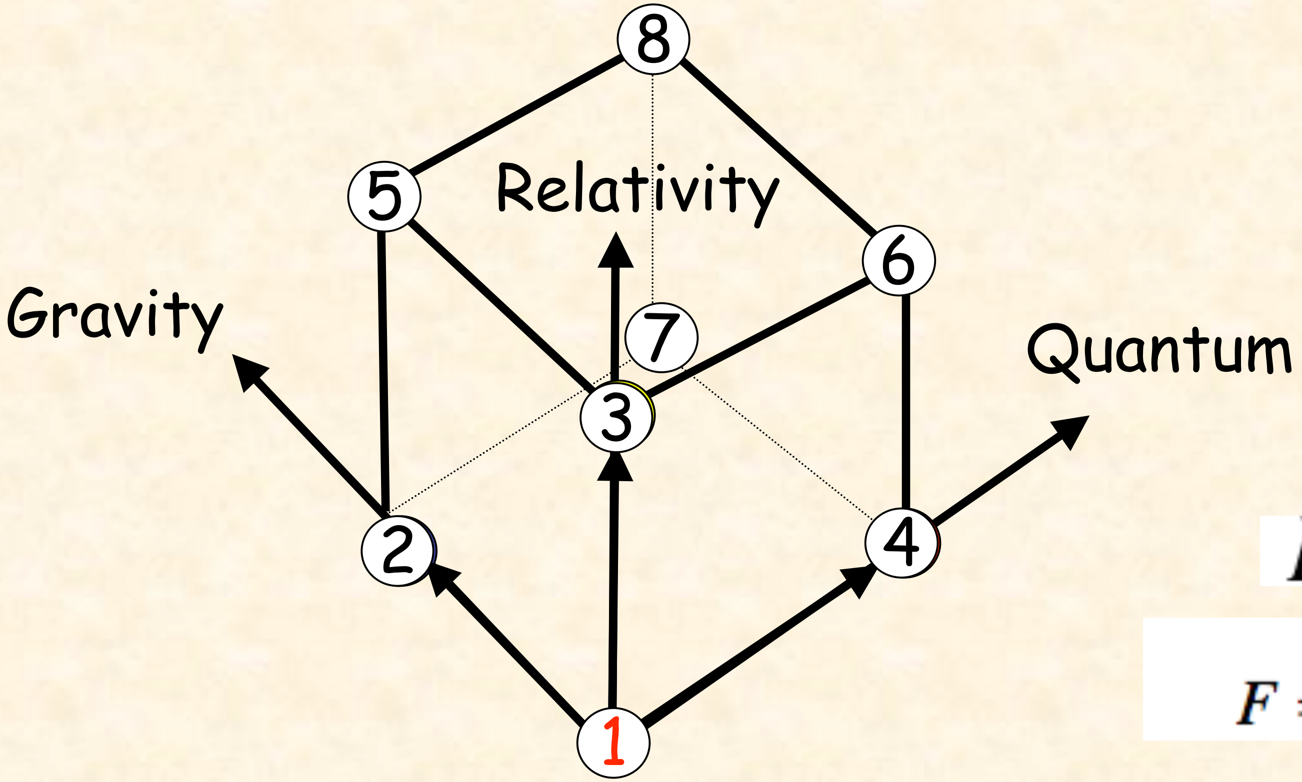
(a Russian cube: from L. Landau to L. Okun)




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

A guided tour follows…

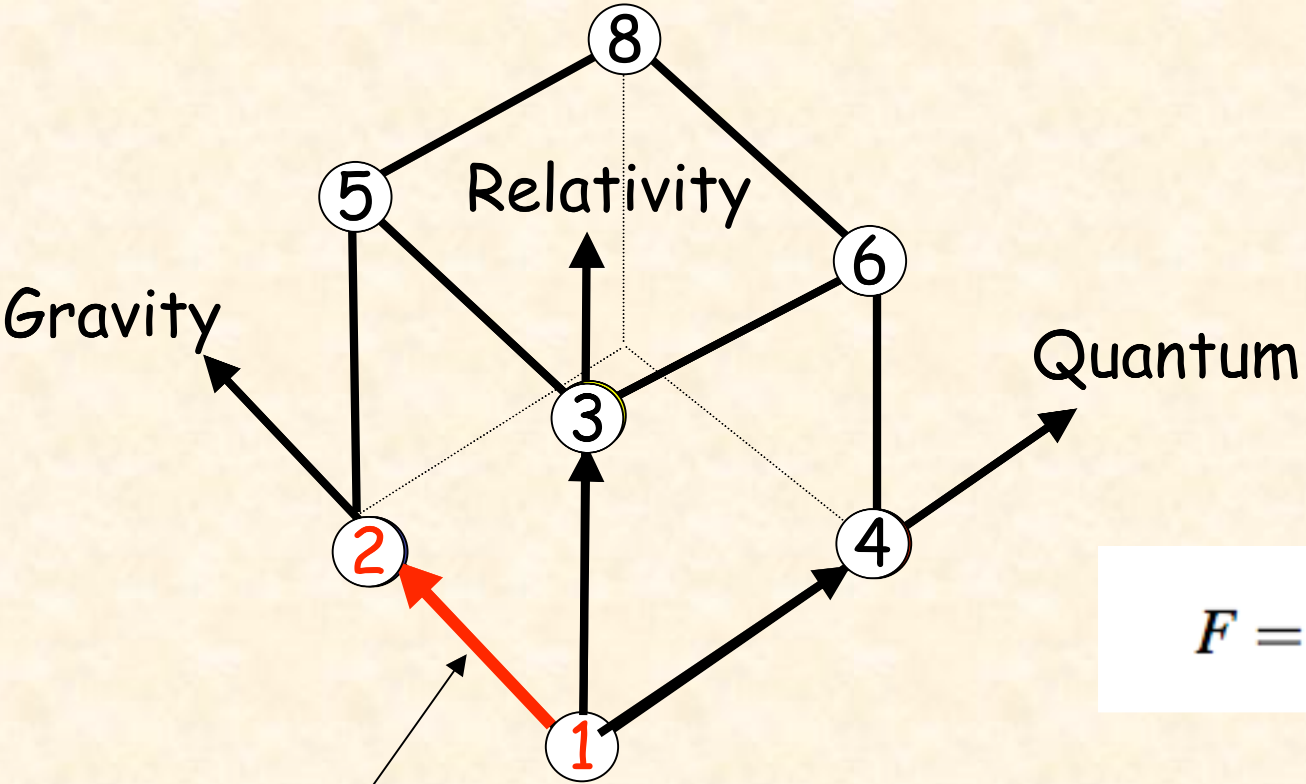
# The trivial vertex




$$F = m\,a$$

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

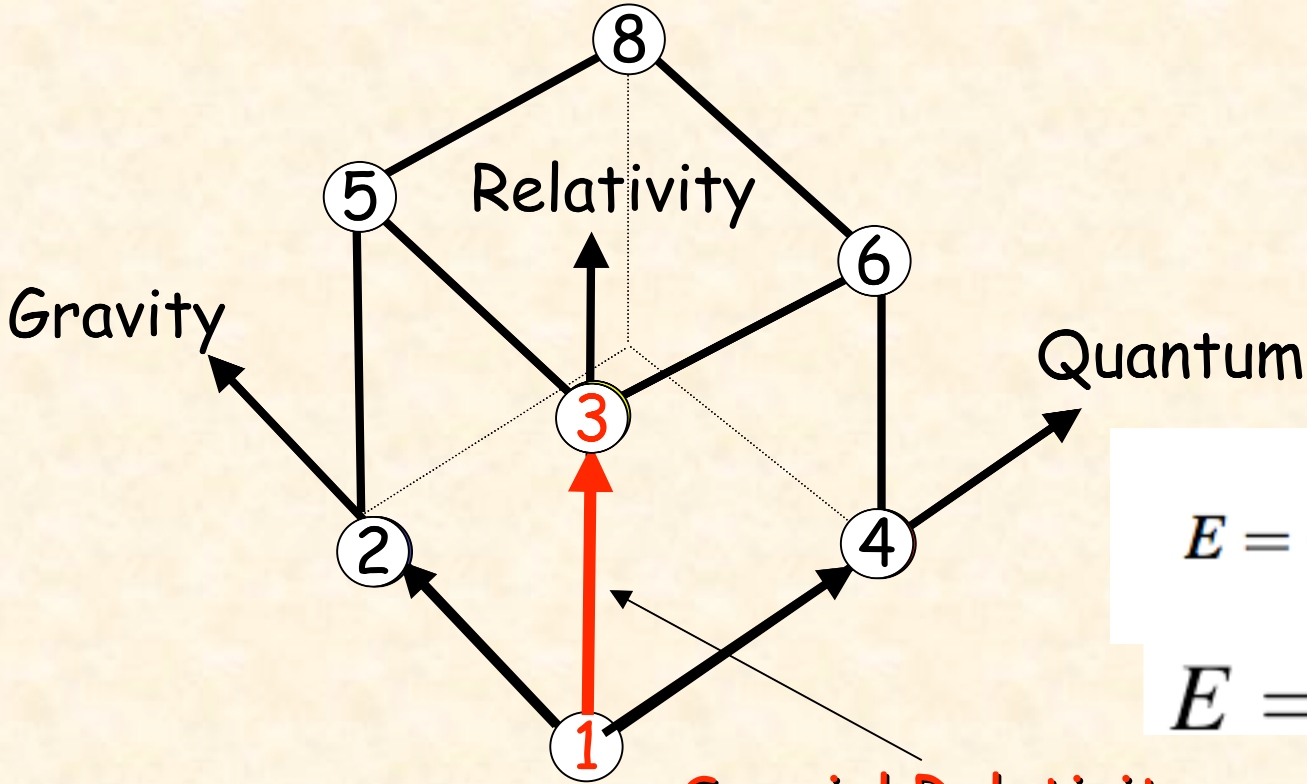
# The simplest edges: I




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

Newtonian Gravity: e.g. the solar system

# The simplest edges: II

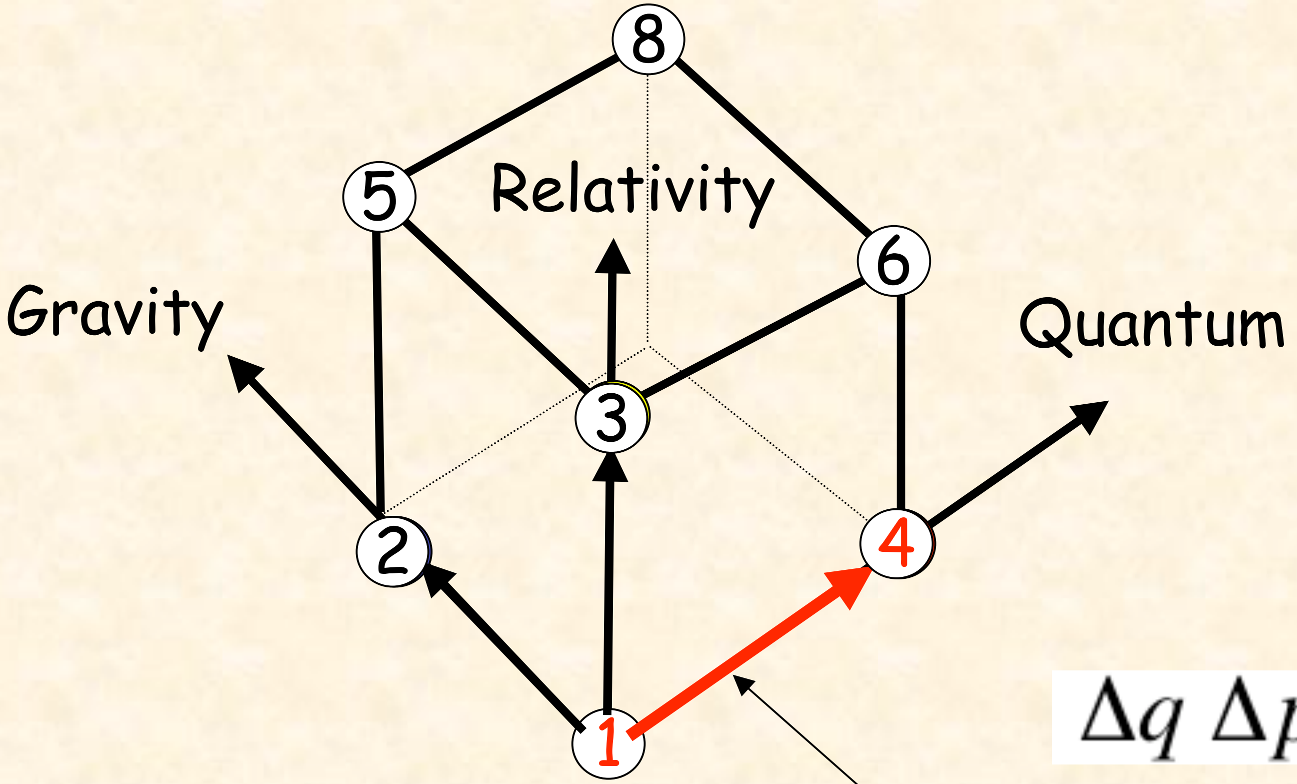



$$E = \frac{mc^2}{\sqrt{1 - v^2/c^2}}$$

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

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

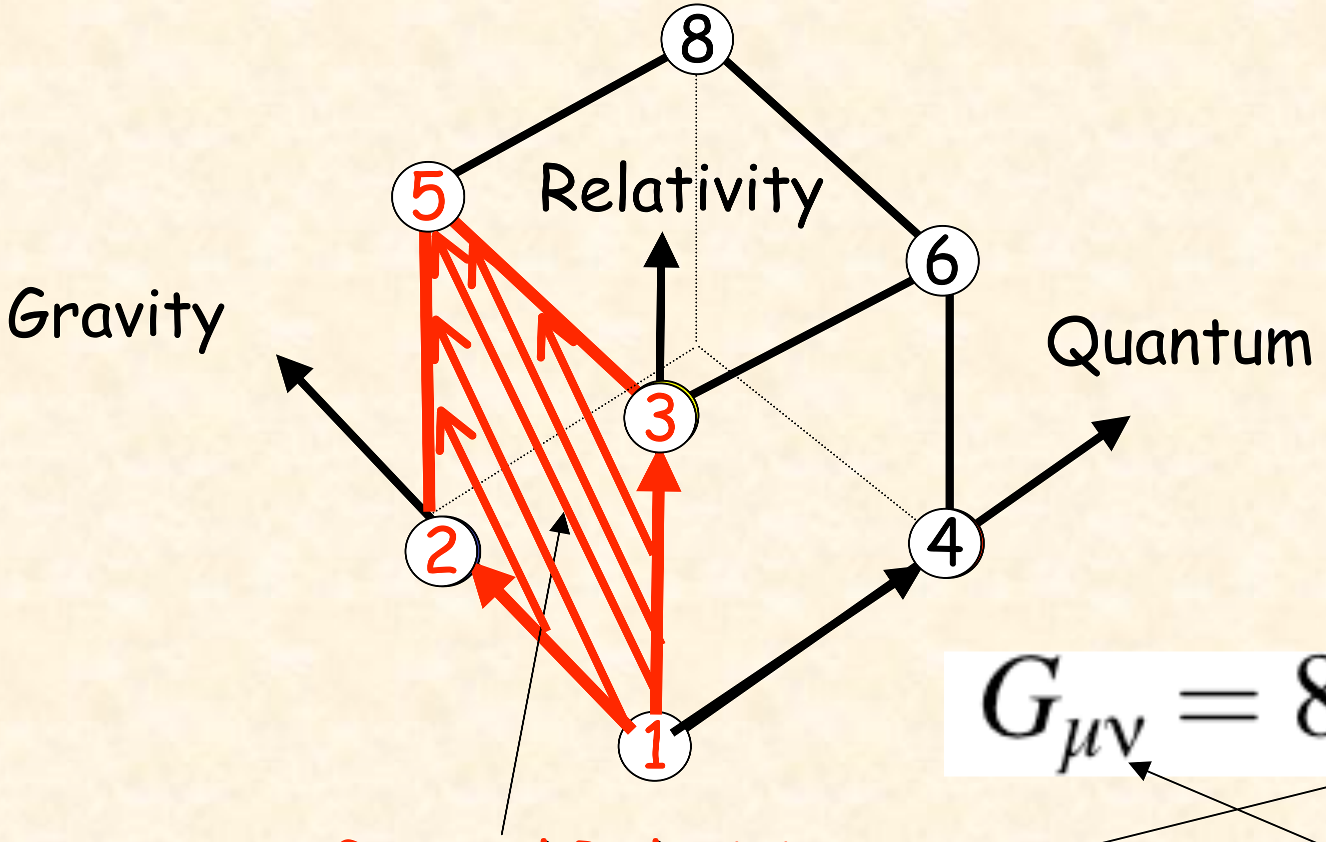
# The simplest edges: III




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

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)

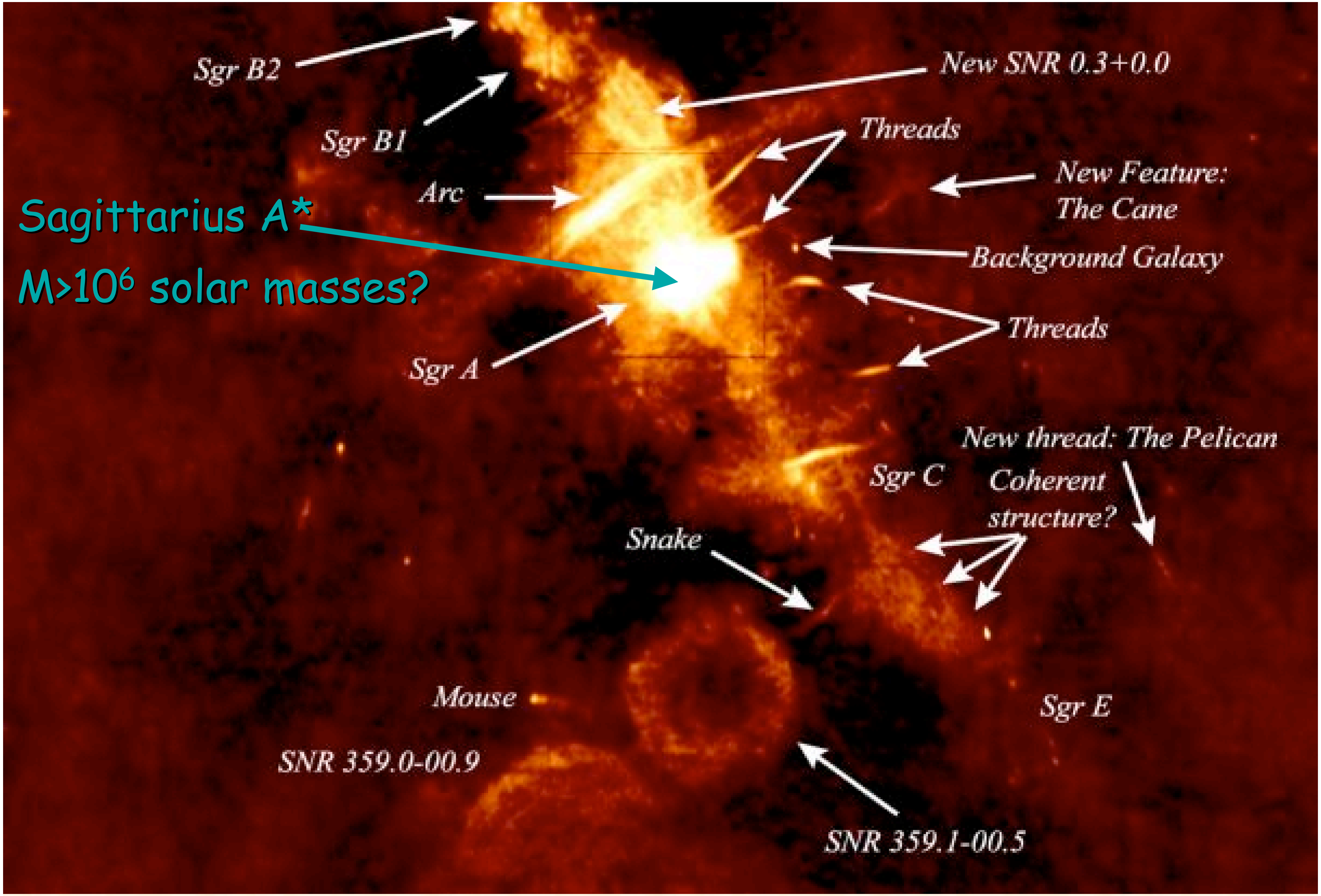
$\boxed{NG + SR = GR}$

Our «Standard Model» of classical gravity

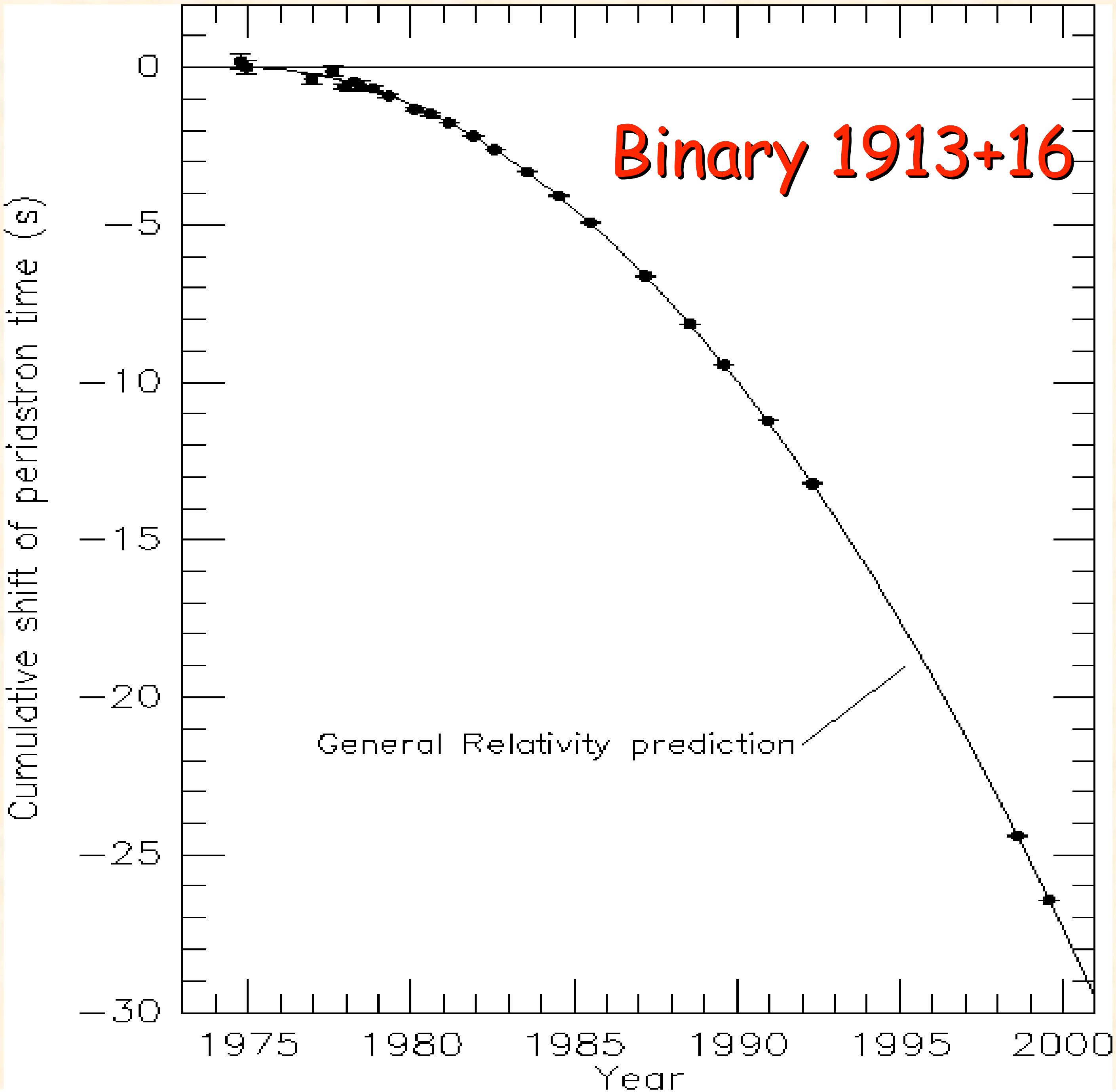
Corrections to NG better and better tested

New predictions

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

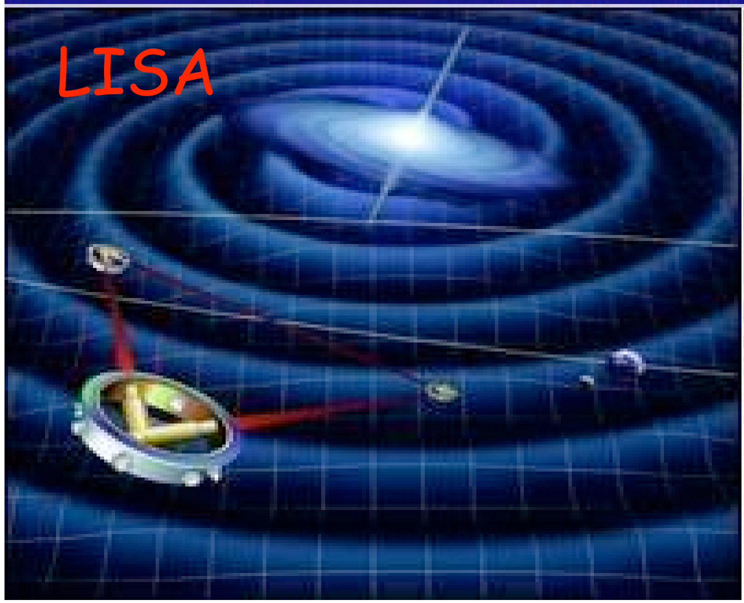


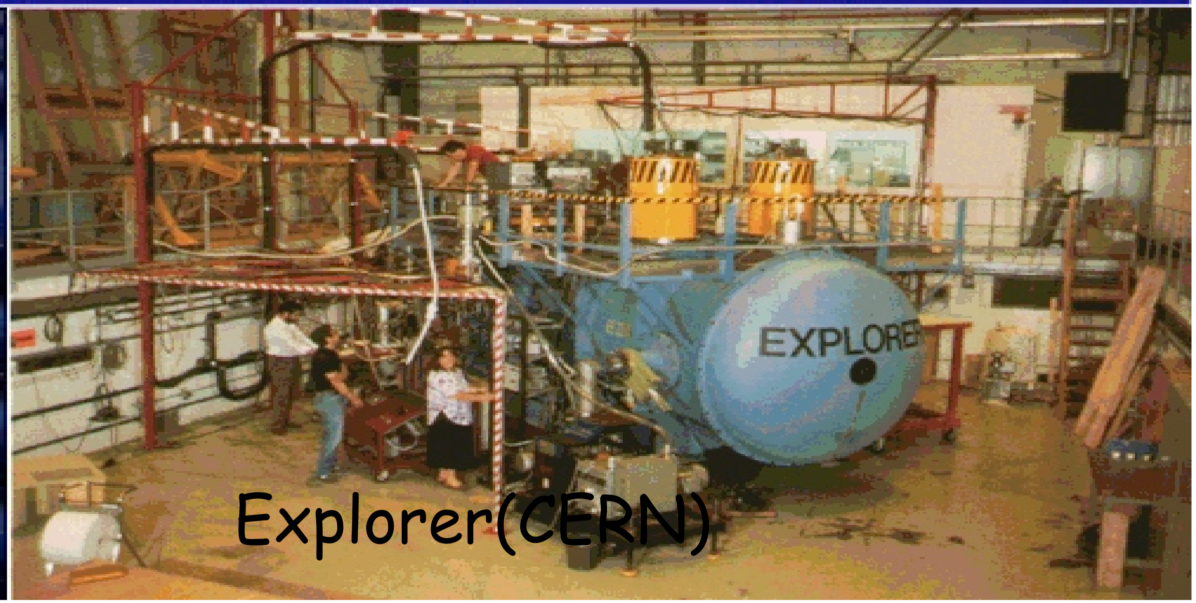
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature:
The Cane
Arc
Sagittarius A*
M>10⁶ solar masses?
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent
structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5


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)

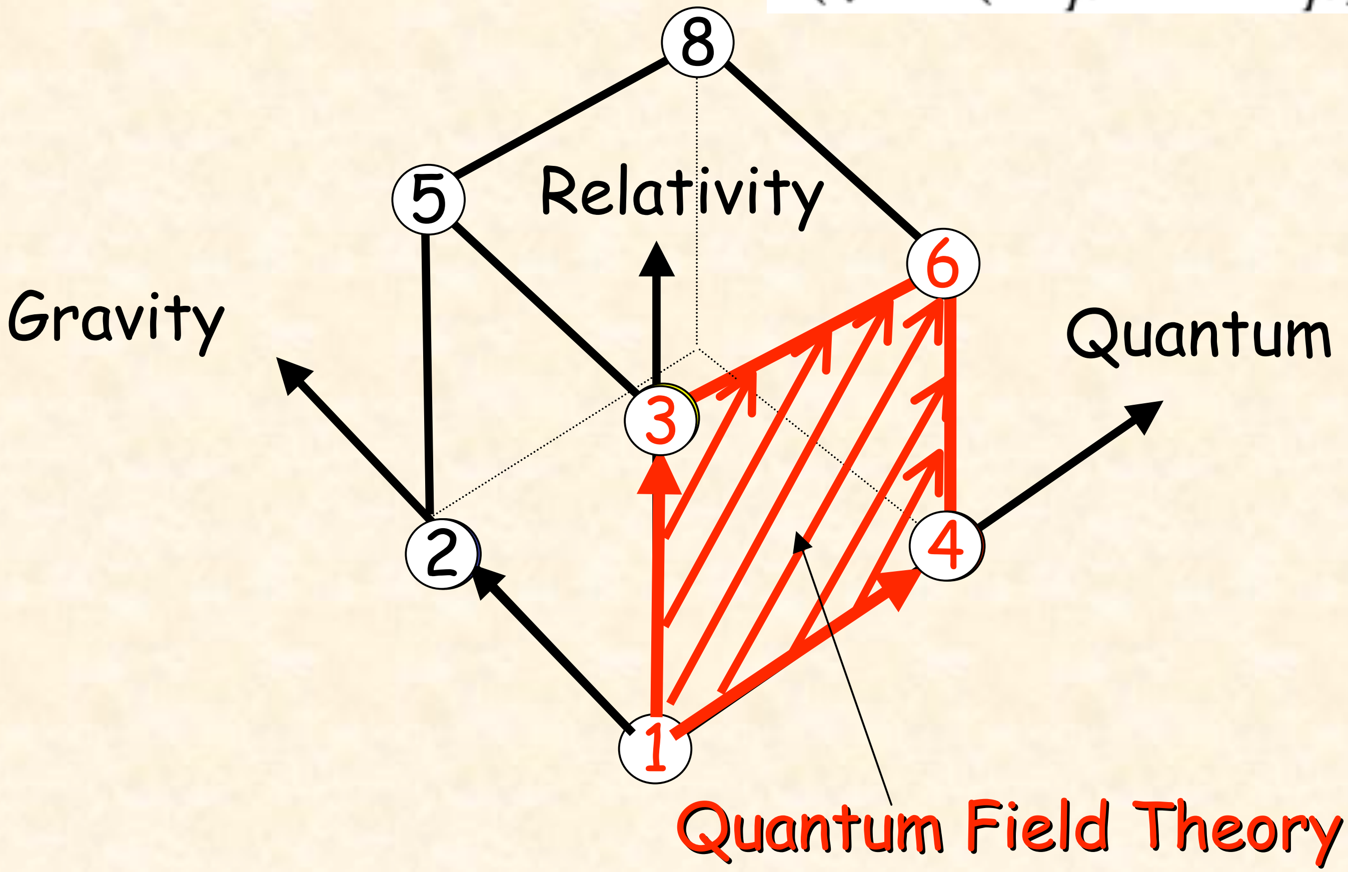

VIRGO(Cascina)


LISA


Explorer(CERN)

# The most relevant faces: II

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

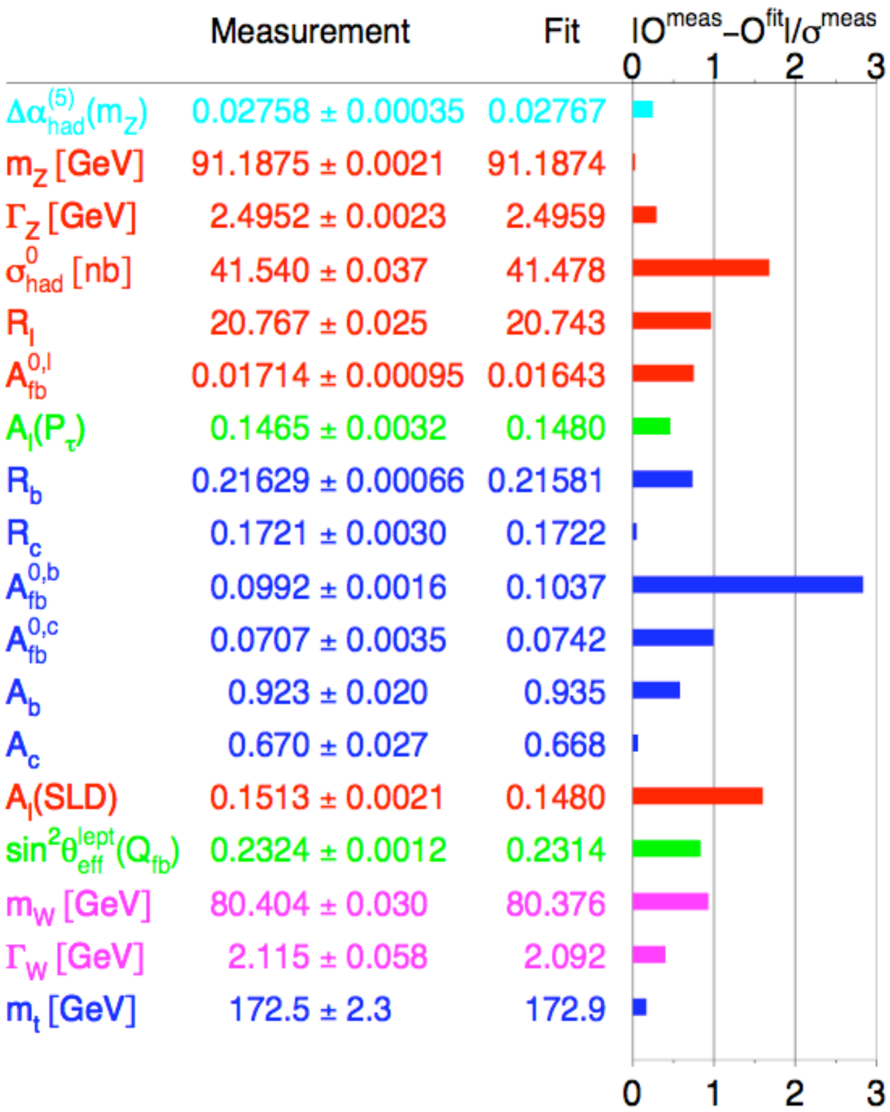


SR + QM = QFT

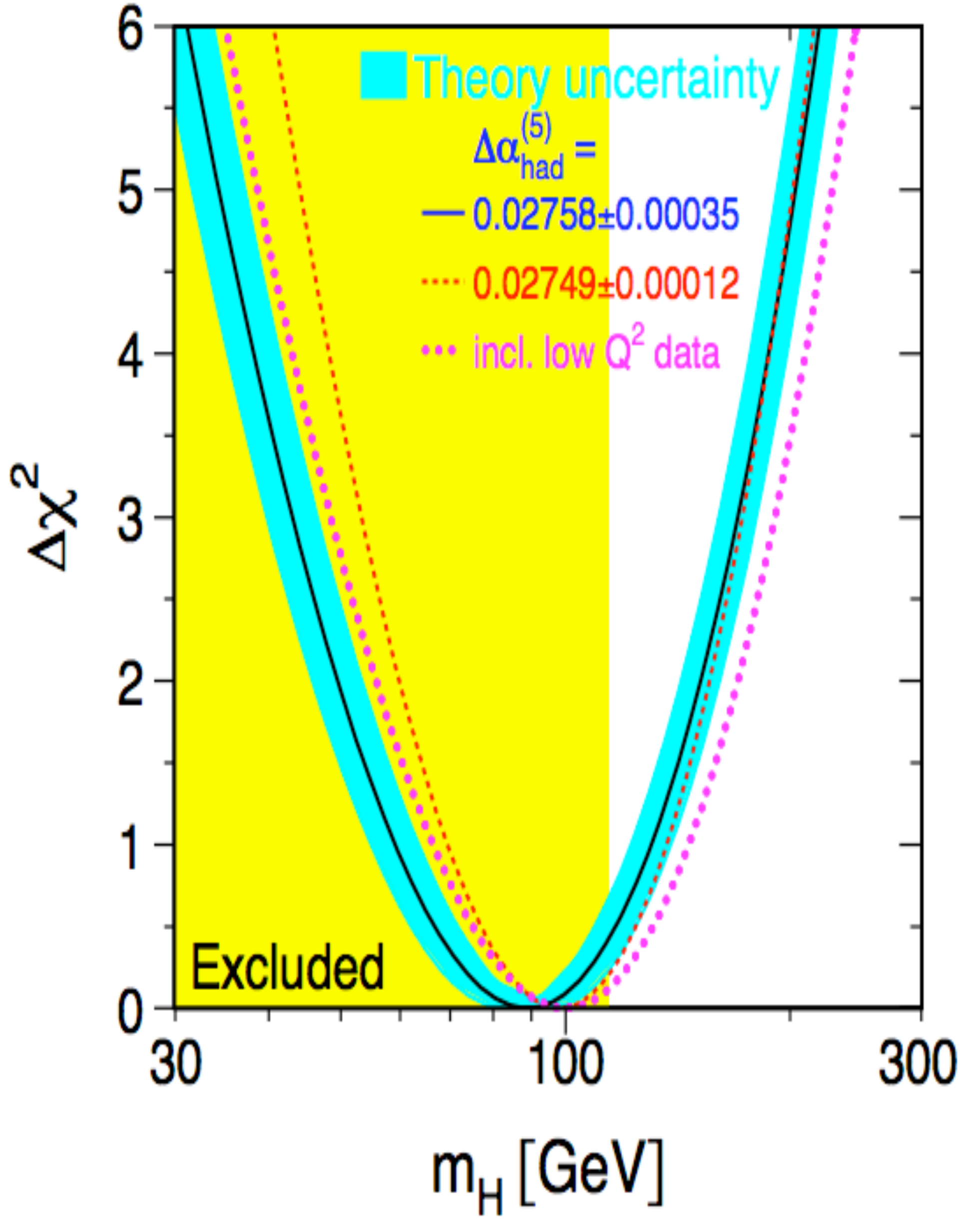
in particular the celebrated

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

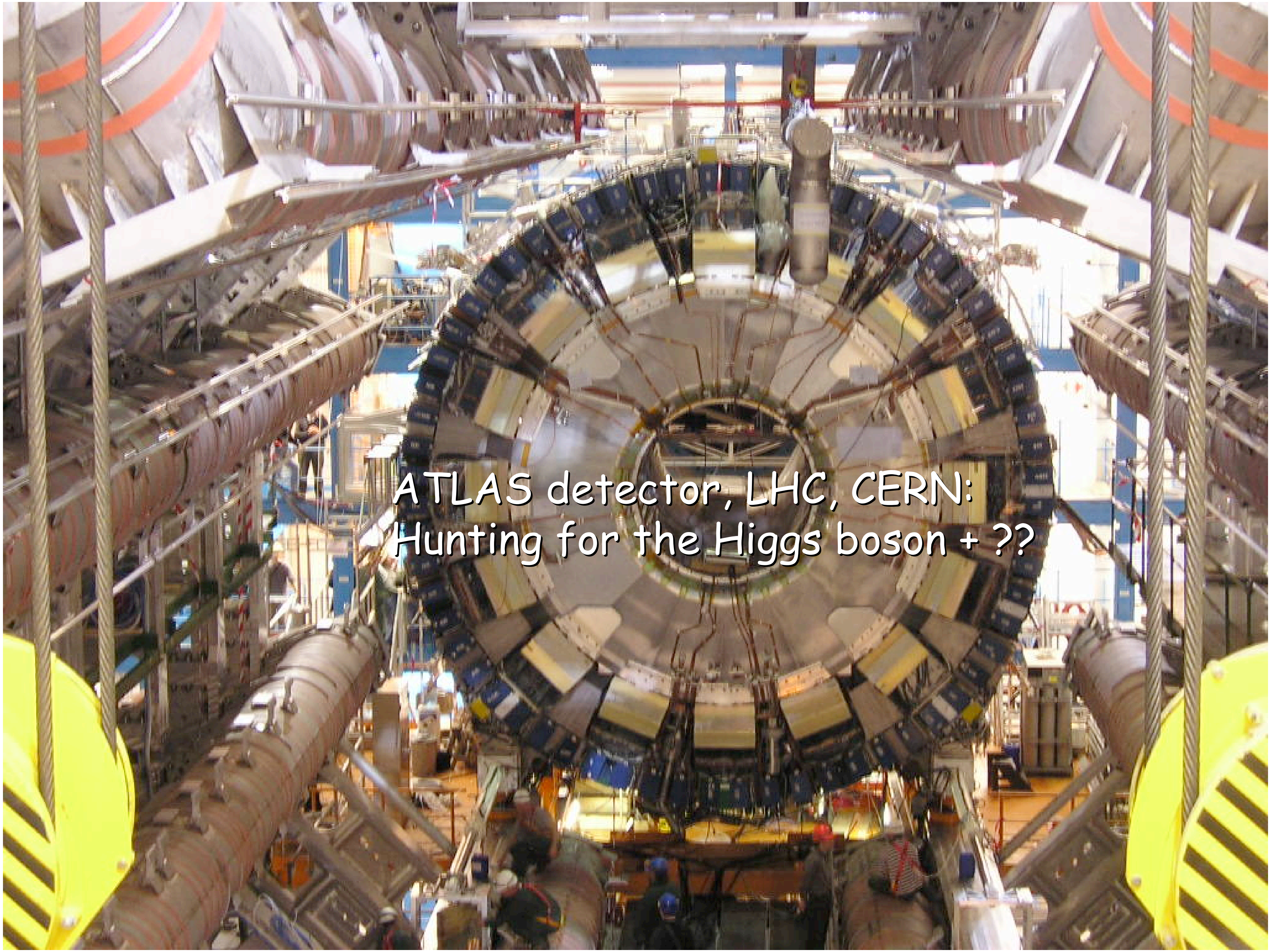
The quantum-relativistic nature of the SM manifests itself through real and virtual particle production
Taking these effects into account is essential for agreement between theory and experiment



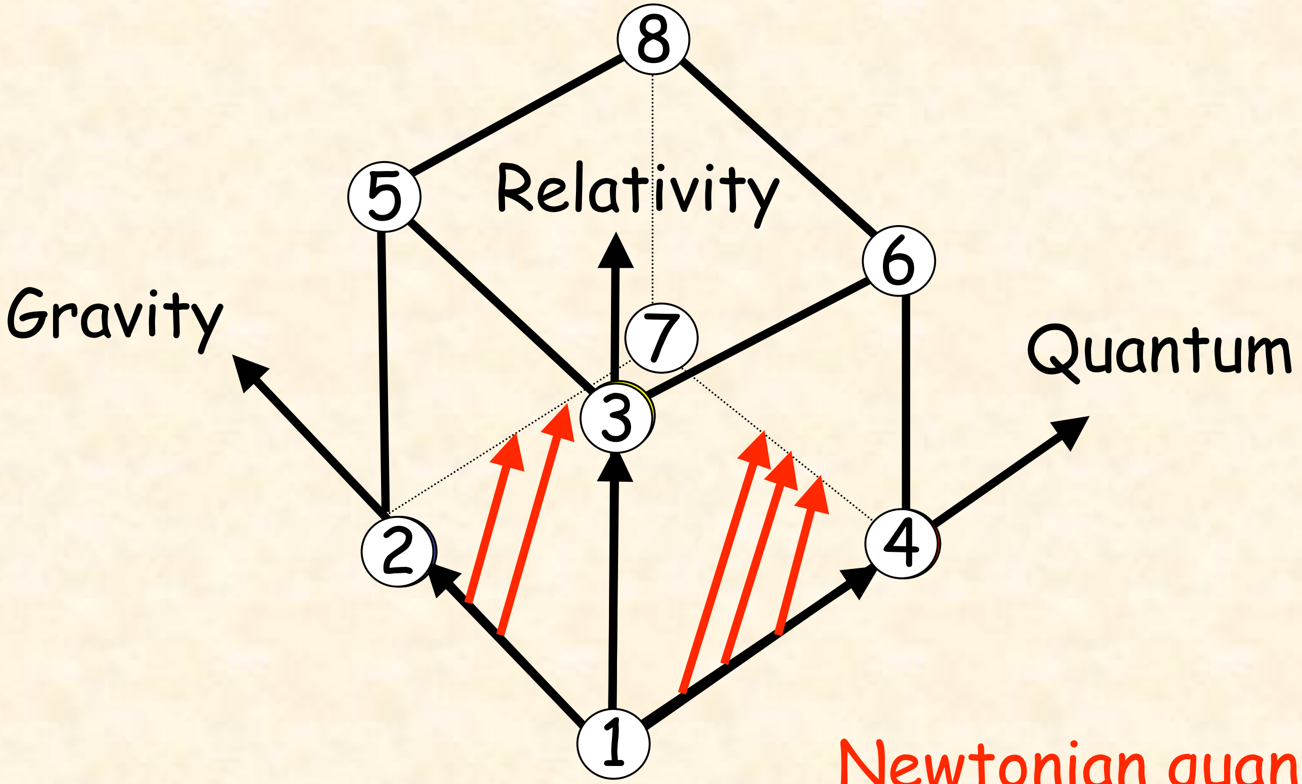
Measurement
Fit
$|O^{meas}-O^{fit}|/\sigma^{meas}$
0 1 2 3
$\Delta\alpha_{had}^{(5)}(m_Z)$ 0.02758 ± 0.00035 0.02767
$m_Z$ [GeV] 91.1875 ± 0.0021 91.1874
$\Gamma_Z$ [GeV] 2.4952 ± 0.0023 2.4959
$\sigma_{had}^0$ [nb] 41.540 ± 0.037 41.478
$R_l$ 20.767 ± 0.025 20.743
$A_{fb}^{0,l}$ 0.01714 ± 0.00095 0.01643
$A_l(P_\tau)$ 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
$\Gamma_W$ [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 for 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:

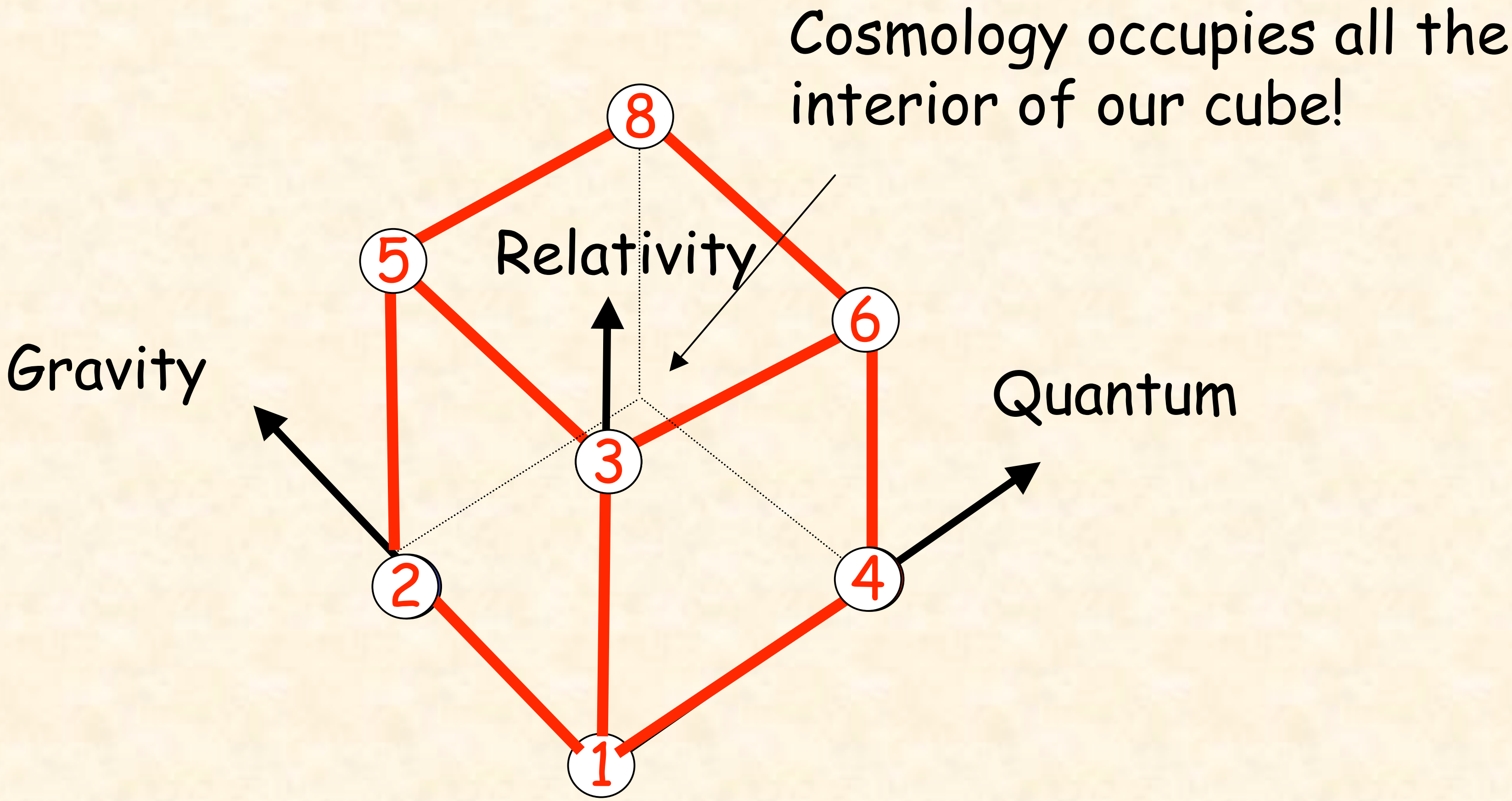
**Newtonian Gravity + Special Relativity =**

**Standard Model of Classical Gravity (GR)**

**Special Relativity + Quantum Mechanics =**
**Standard Model of Elementary Particles**

Both work wonders…but again the question arises of how we combine all three

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!
8
5
Relativity
6
Gravity
Quantum
3
2
4
1

# Expansion of the Universe

Far past $\Rightarrow$ Very hot and dense Universe

Very hot Universe $\Rightarrow$ Very high energies (R)

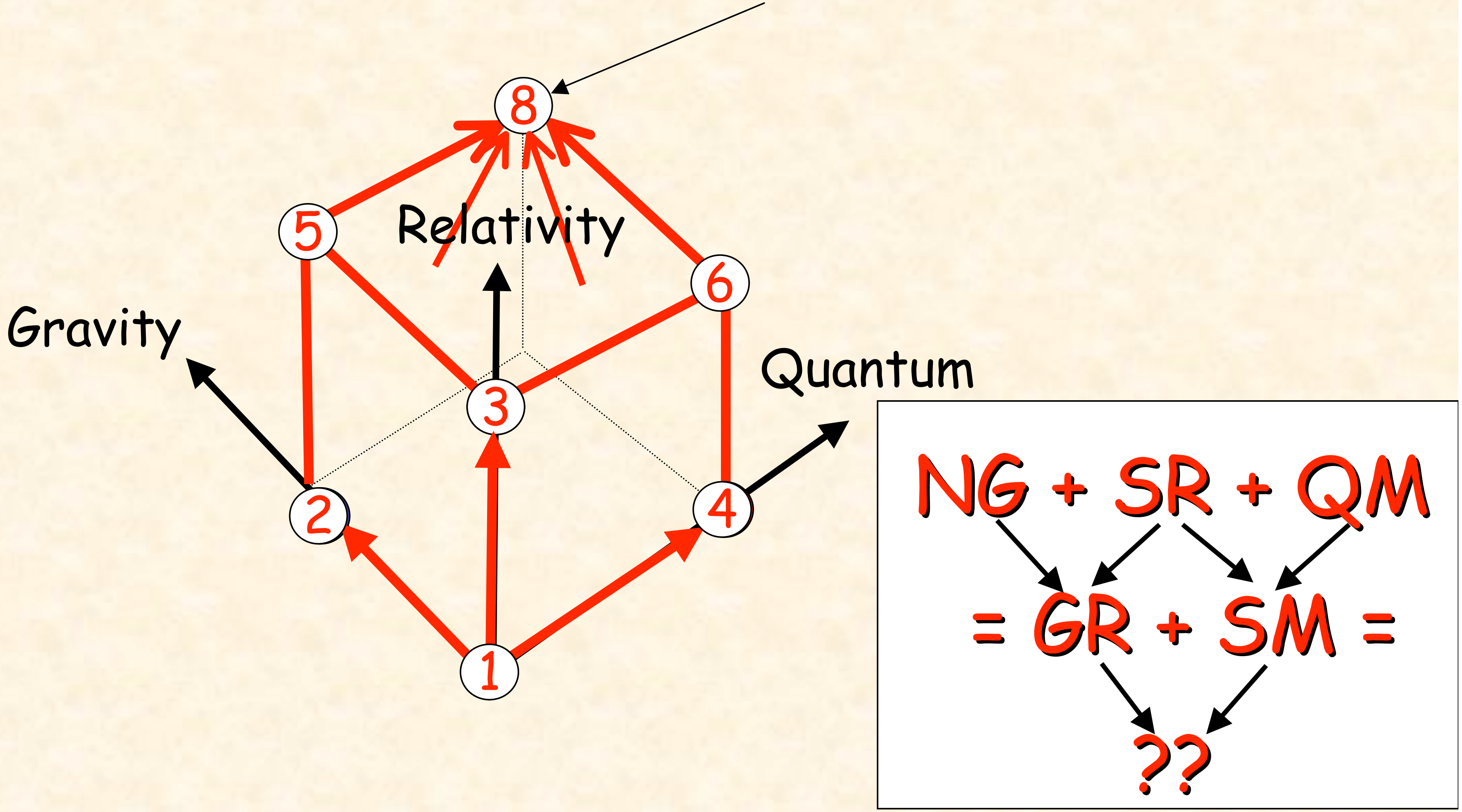
Very dense Univers $\Rightarrow$ Very high curvature (G)

Very high curvature $\Rightarrow$ Quantum processes (Q)

Far in space $\Leftrightarrow$ 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

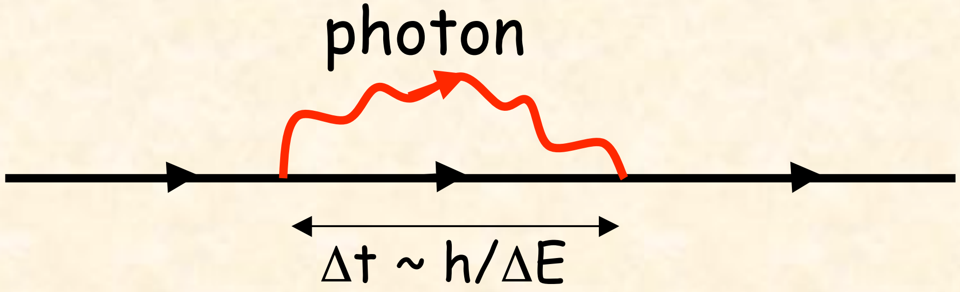
Near curvature singularities quantum corrections to GR cannot be neglected.

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

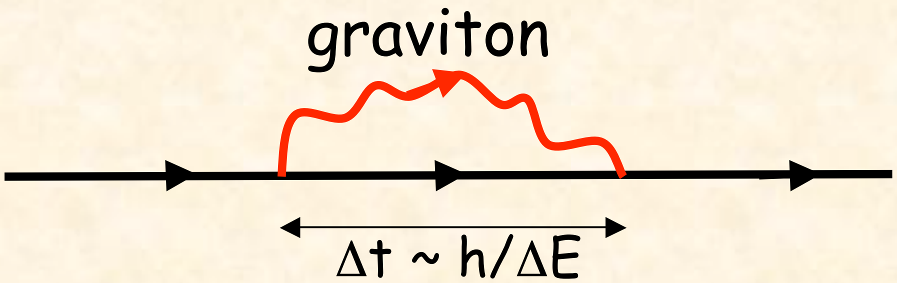
A: QM appears to worsen the situation. Why?

# Patologies in Quantum General Relativity

## ( the «evil quanta» are back!)




= **Calculable** (and essential) corrections




= **Uncalculable** corrections

# Patologies in Quantum Field Theories

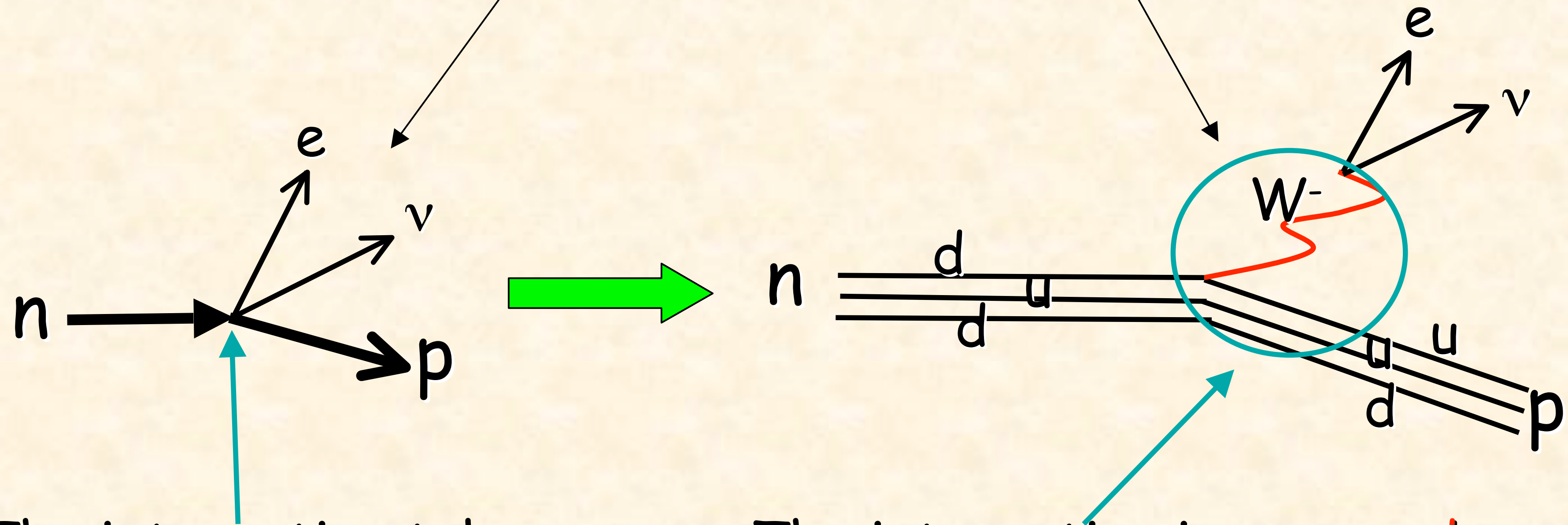
Even in QFTs there are infinities. The difference is that we can tame them and thus keep predictivity

[Actually, if following KK we increase the number of spatial dimensions, QFTs start having the same bad UV problems as Quantum Gravity in 4-D spacetime:
not at all unexpected, of course, because of KK unification!]

An instructive example of taming:

Weak interactions, from Fermi to the SM

# 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

The EW theory has infinities, hence uncalculable parameters: yet, as we have seen, 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 String 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 |
| --- |

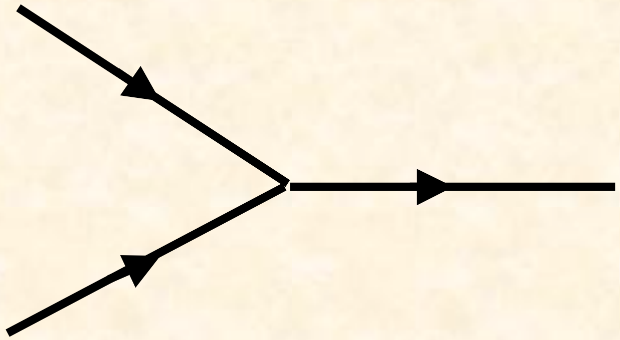
A magic 3-ingredient cocktail!

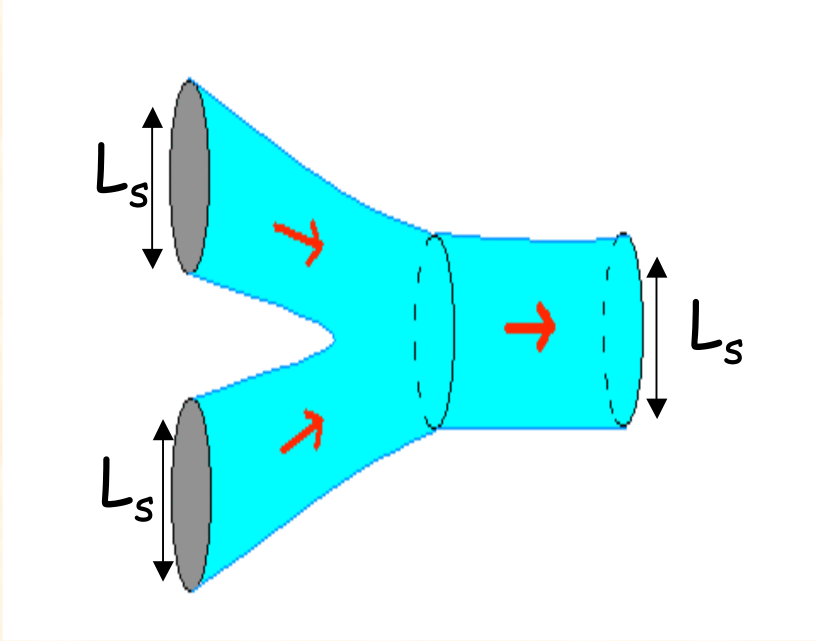
# Quantum magic I

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

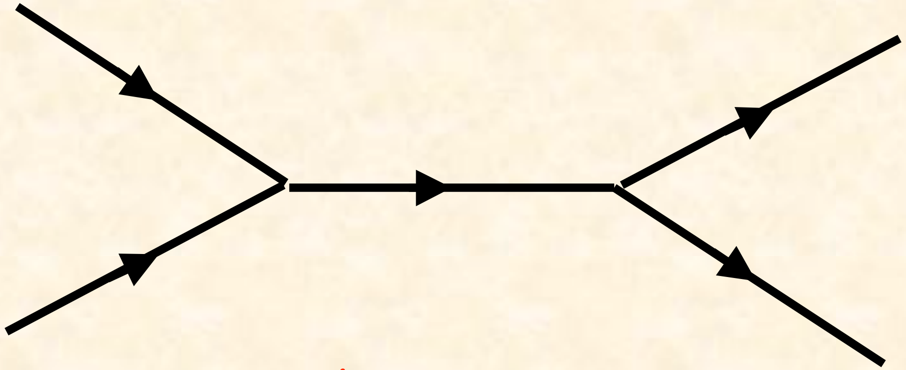
Quantum strings have a minimal (optimal) size $L_s$ (Cf. Bohr radius, h.osc.), given by $L^2_s = h/T$ . This length appears naturally in the (quantum) action of a string:

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

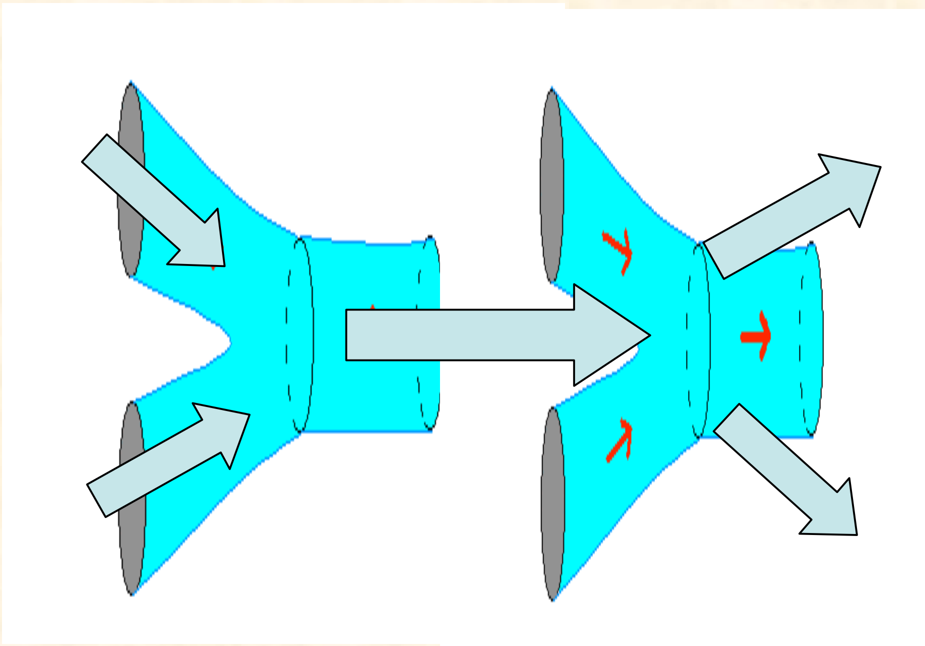




$L_s$
$L_s$
$L_s$



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:

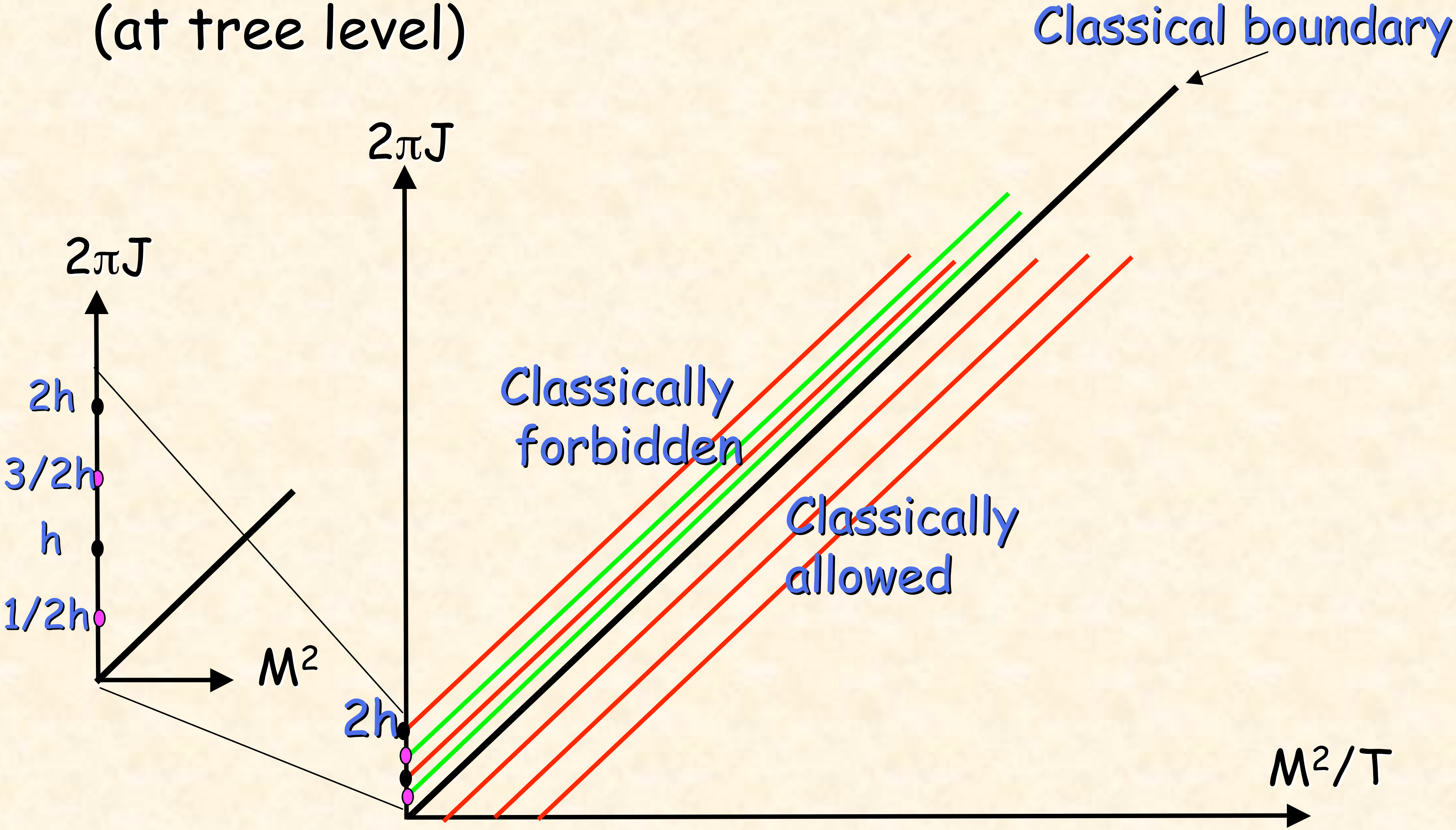
once regularized

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

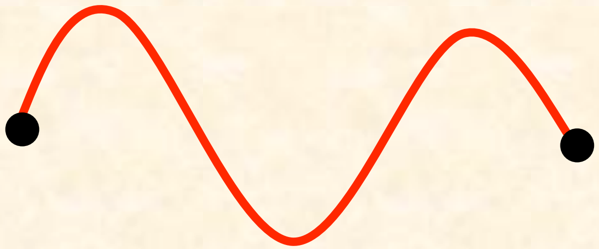
where

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

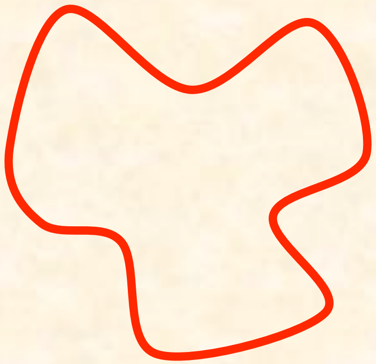
# Quantum Spectrum
(at tree level)



In particular..



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



$\Rightarrow$m=0, J = 2 => graviton,

Integer J(> 0) 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 $$E_s \sim E_P/10 \sim 10^{17} GeV$$

NB: This is reminiscent of KK unification of electromagnetism and gravity at the energy scale corresponding to $R_{KK}$

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 upon, Quantum Mechanics!

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

# More quantum magic

1. While classical strings can move consistently in any ambient space-time, quantum strings require particular «target» space-times in order to avoid lethal anomalies. Spacetime must have 9 space and 1 time dimensions, vindicating, some 50 years later, the KK idea! Six of them must be compact & small..
2. But how small? A symmetry, called T-duality, guaranties that compactification radii $R$ and $L_s^2/R$ are equivalent. This effectively introduces a minimal KK radius, $R = L_s$. In this special case new non abelian gauge interactions (needed for the full SM!) emerge through a stringy version of the KK mechanism!

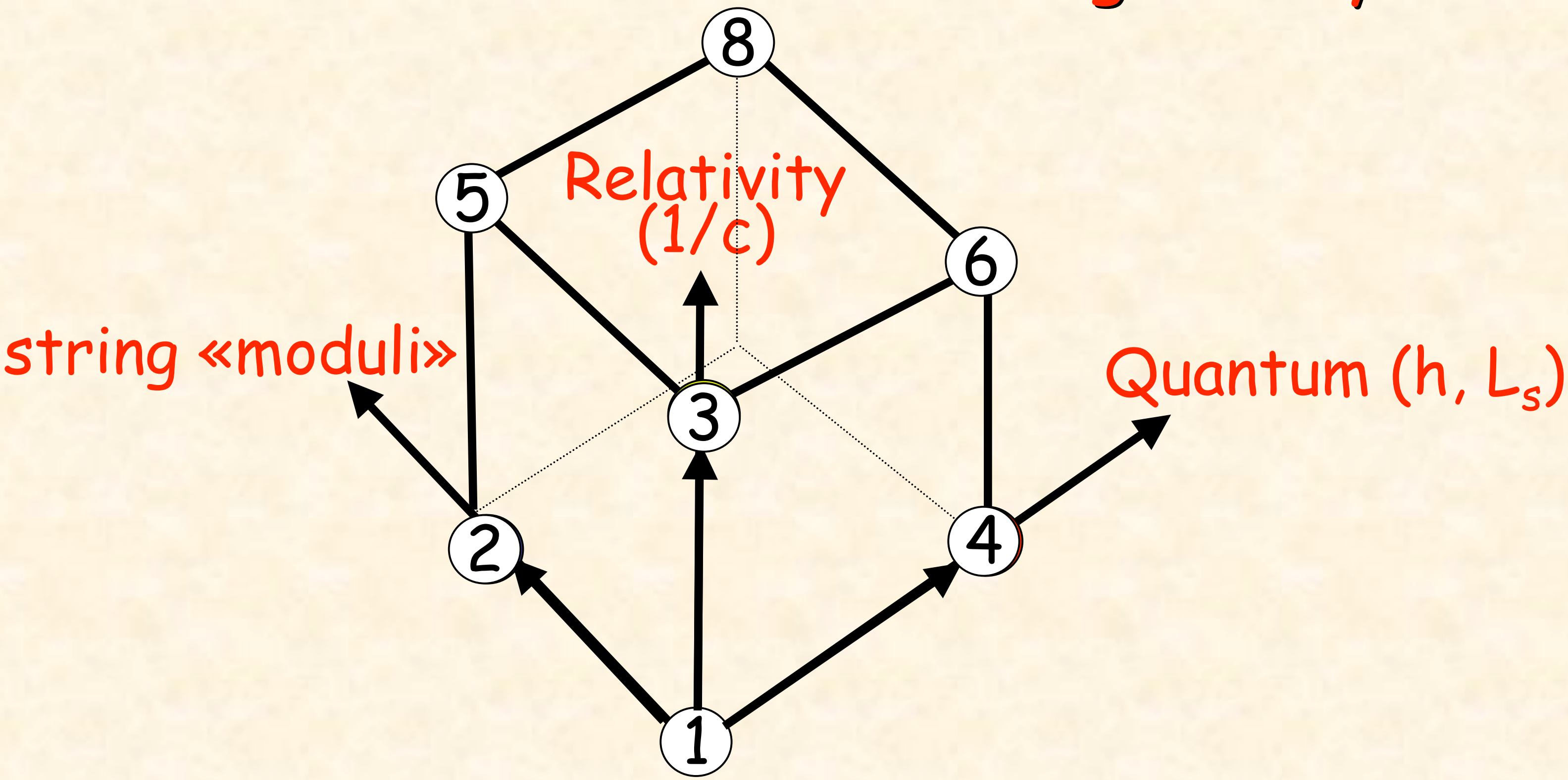
3. There are no free parameters: these are replaced by scalar (J=0) fields whose values provide (dynamically?) the «Constants of Nature», e.g. the fine-structure constant

- These fields have vanishing perturbative mass, because of SUSY. If they remain light at the NP level, they may induce «short-distance» modifications of gravity, space-time variations of the above «constants», threaten the equivalence principle and universality of free-fall.

➪ A very active field of experimental and theoretical research

➪ String theory is, in principle, falsifiable!

# string theory's «cube»?




The "moduli" determine all dimensionless parameters. Are they fixed, or free (discrete or continuous) parameters? At some level of approximation some are dangerously free…making microphysics not absolute either (unlike with the EP of GR!).
Difficult questions limiting today's 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:

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

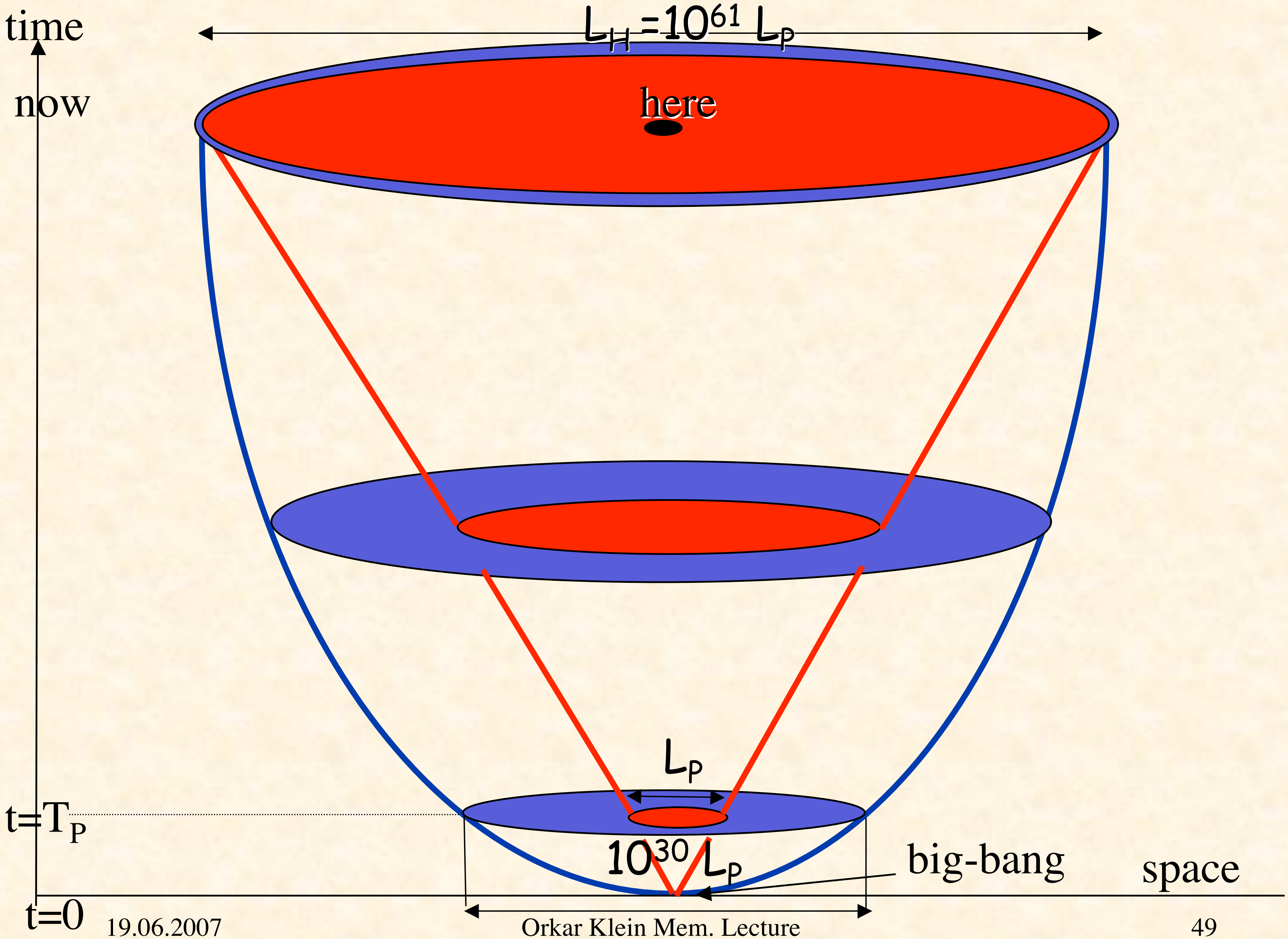
- Microscopic quantum states counting gives precisely (for large $S_{BH}$) $\ln N = S_{BH}$.

- 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

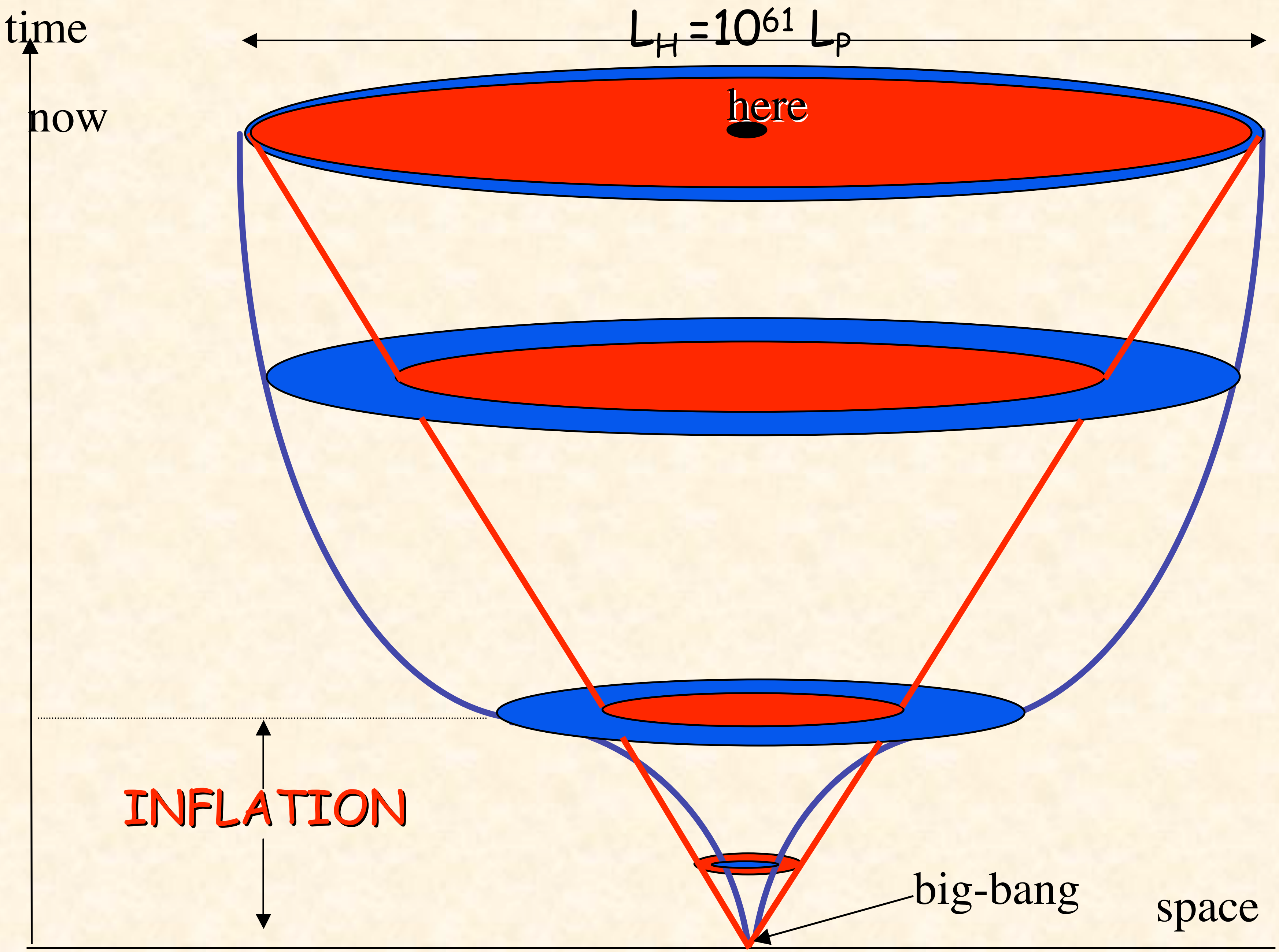
# Cosmology

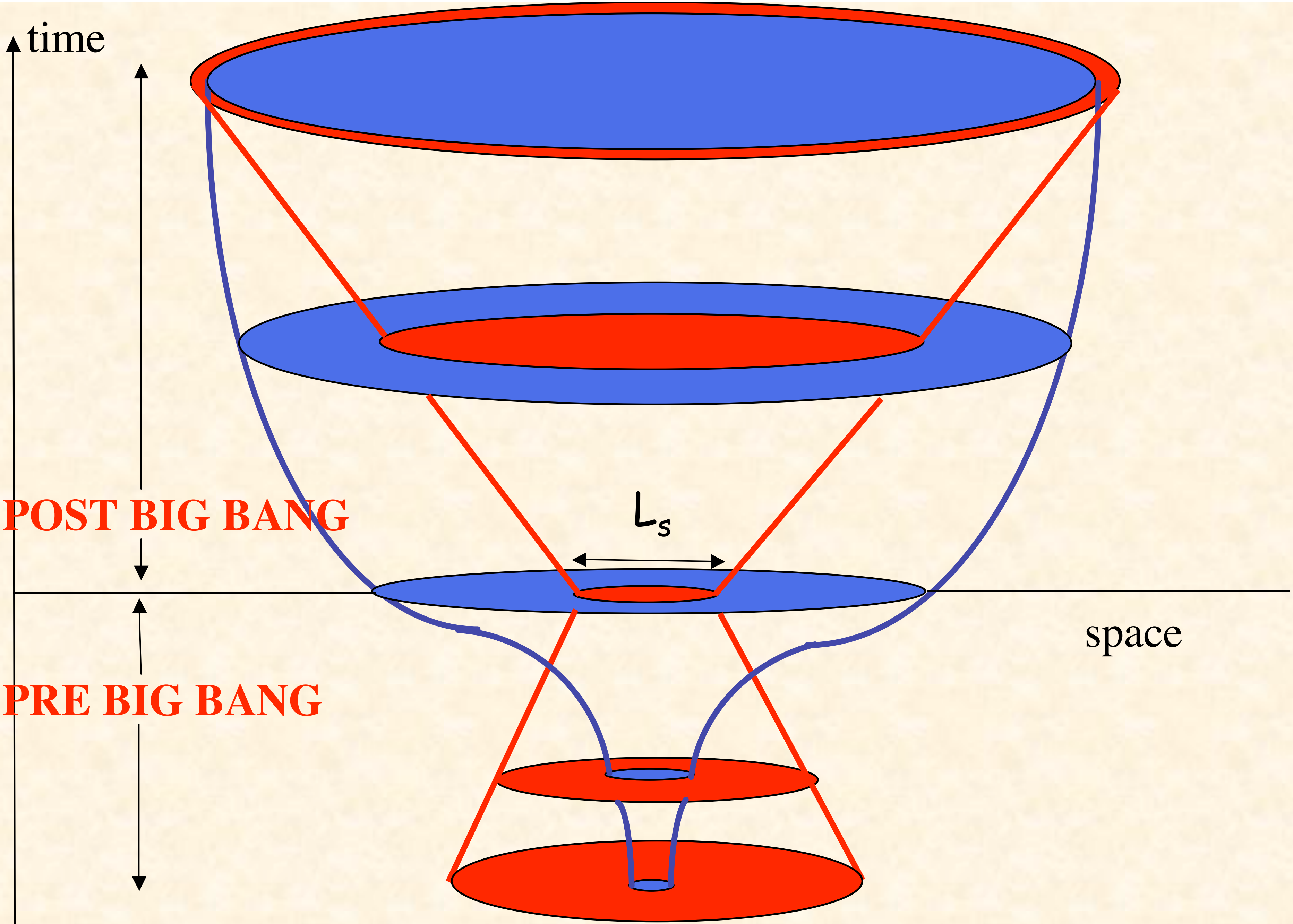
- String theory «resolves» certain singularities of CGR
- Those associated with cosmology (big bang) are harder to deal with, but very likely they are also eliminated or reinterpreted (new degrees of freedom needed for a non-singular description?)
- If so, we may conceive new cosmological scenarios in which the big bang, rather than representing the beginning of time, is the result of a previous phase during which the space-time curvature (~ the Hubble parameter H) grew until it reached a maximal value (~ $c/L_s$?), and, perhaps, the extra dimensions shrank down to a well-defined value (~ $L_s$ ?)

- 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.
- Or just generate the initial conditions that conventional inflation badly needs.



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

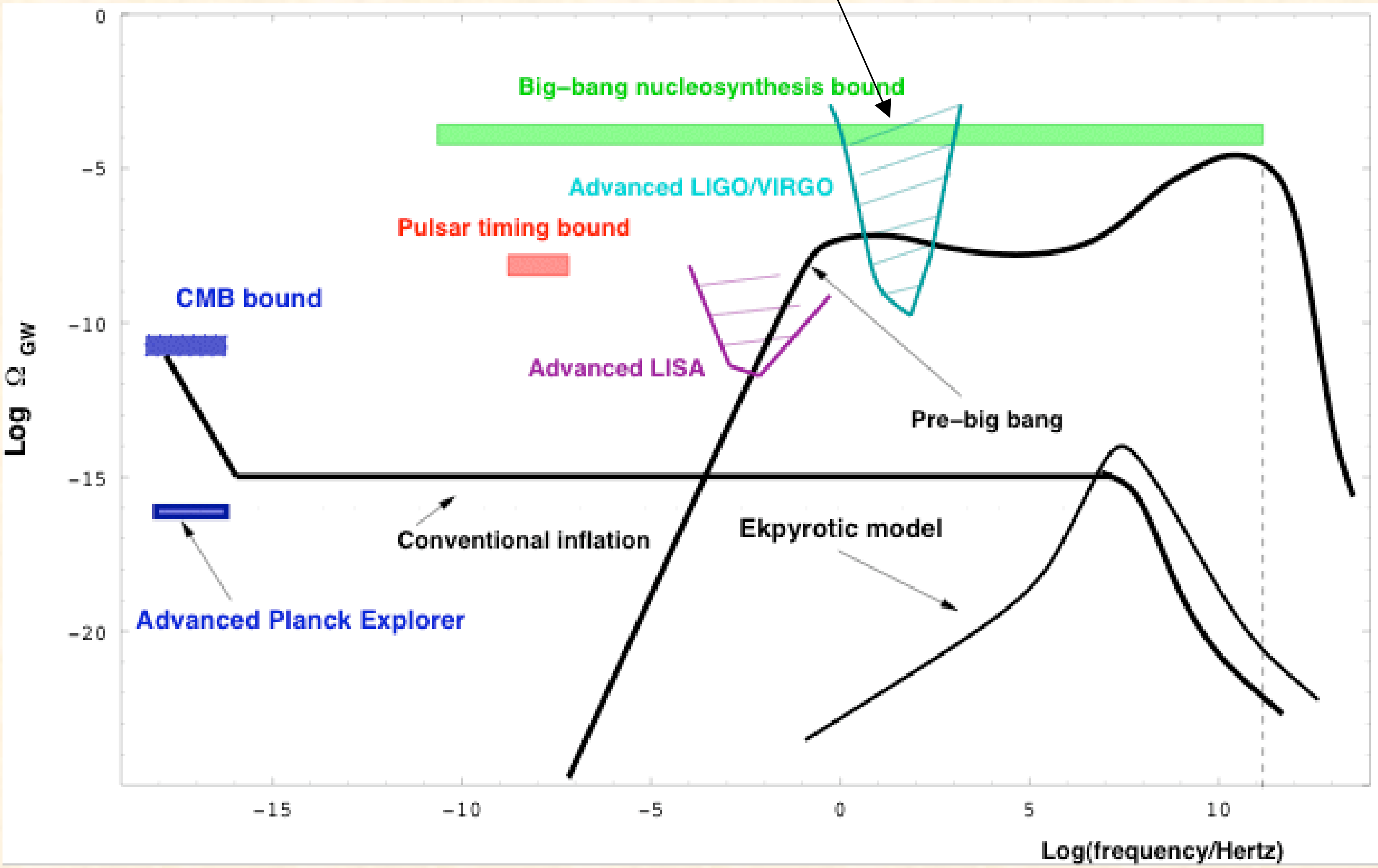

time
$L_H = 10^{61} L_P$
now
here
INFLATION
big-bang
space


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 (also here the extra dimensions play a crucial role in providing a scale-invariant spectrum via the « curvaton » mechanism)

# Present LIGO bound



# Conclusion

- Einstein's unification dream appears to be realized in string theory, but in a way that he could have hardly imagined
- With hindsight we can say that string theory was born in the late sixties (through the bottom-up approach of ARVV) because there exist, in the hadronic world, string-like structures (QCD's string tension..)
- That «hadronic» string theory is still waiting to be discovered, while the original one has found a possible application that no-one could have foreseen at the time:

«A piece of XXI$^{st}$ century physics that fell too early on us!»

(D. Amati and/or S. 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. It is more like an improvement (and an even more quantum version) of KK theory!
- Would he have reacted to String Theory, like he did to QM, by saying, instead of his famous:

**God doesn't play dice!**

# God doesn't play strings!

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

So far, during the last 50 years, there has been ever mounting evidence (Cf. testing Bell's inequalities) that He does play dice after all!

However, we could be disappointed once more.

Will massless particles be again the killers?

Does string theory really apply to the particles we consider today as being elementary?

Even then, I think that string theory is too beautiful to have no place in Nature. Quoting again from AE:

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

(letter to Besso, 1954)