String theory: has Einstein's dream come true?

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Introduction

In the second half of his scientific life Einstein struggled with the problem of how to combine in a single framework two beautiful, successful -and not disconnected- theories:

1. Maxwell's Electromagnetism (that had led him to Special Relativity) and its quantum developments, from his own analysis of the photo-electric effect to QED;
2. His classical theory of Gravitation, General Relativity

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 who forever buries its head in the relativistic sand in order not to face the evil quanta" (Einstein, 1954)

What has become of Einstein's dream 50 years later?

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*) Cf. Kaluza (1921) and Klein (1926) serious attempts

Outline

- An exercise in «meta-theory»
- Classical cosmology: successes & puzzles
- Inflationary cosmology: successes & limitations
- Classical and quantum patologies of Einstein's gravity
- A lesson from the Electroweak Theory
- String Theory and its quantum miracles
- Physical applications: black holes, cosmology
- Conclusion

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

«infinitely» small

with that of the

«infinitely» large

More quantitatively:

Minimal (quantum) length/time scale:

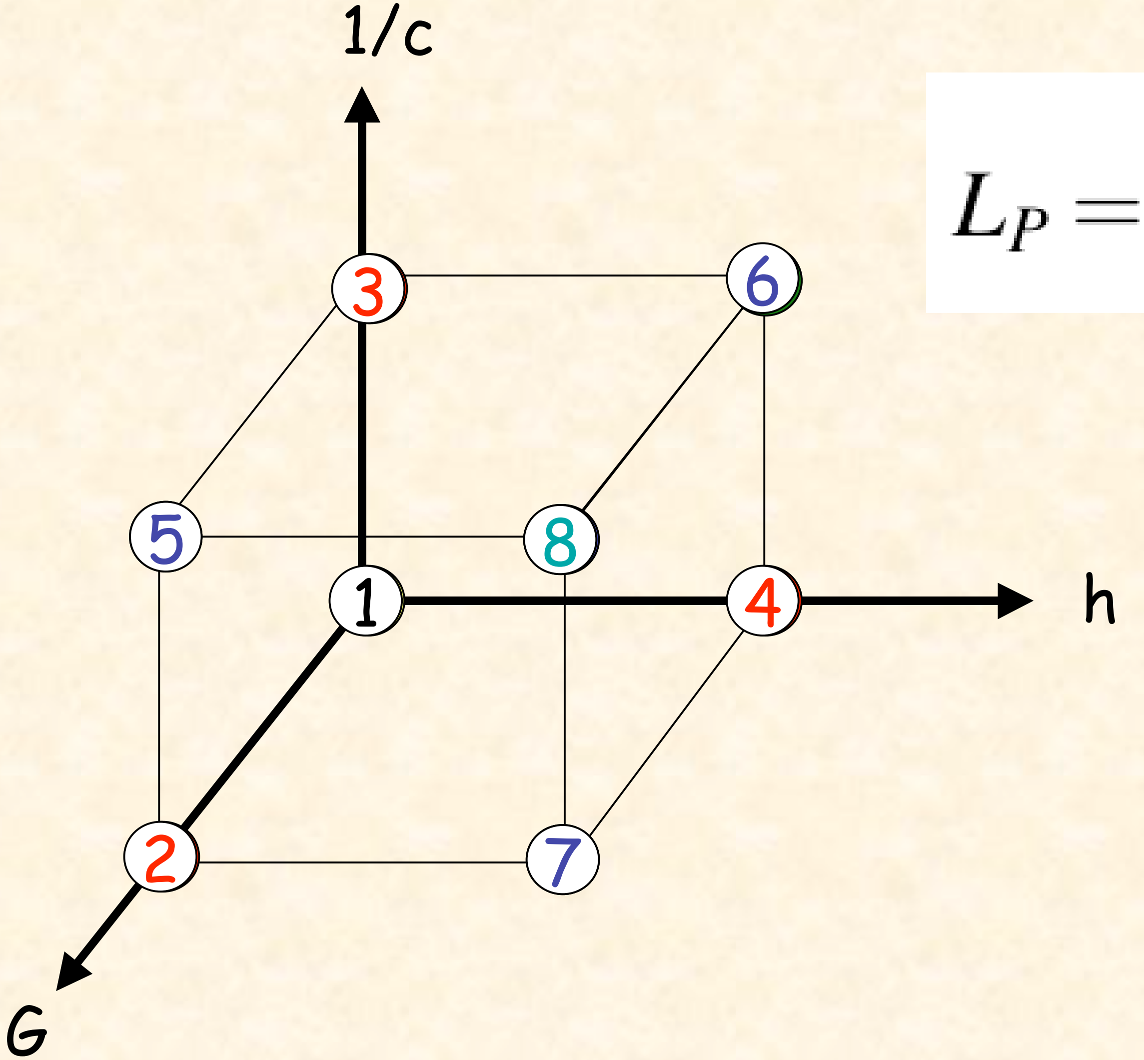
$$L_P = \sqrt{\frac{Gh}{c^3}} \sim 10^{-33} cm \qquad T_P = \frac{L_P}{c} \sim 10^{-43} s$$

Maximal (classical) length/time scale:

$$\Delta\lambda = \frac{d\,\lambda}{L_H} \qquad L_H \sim 10^{28} cm\,,\ T_H \sim 10^{18} s$$

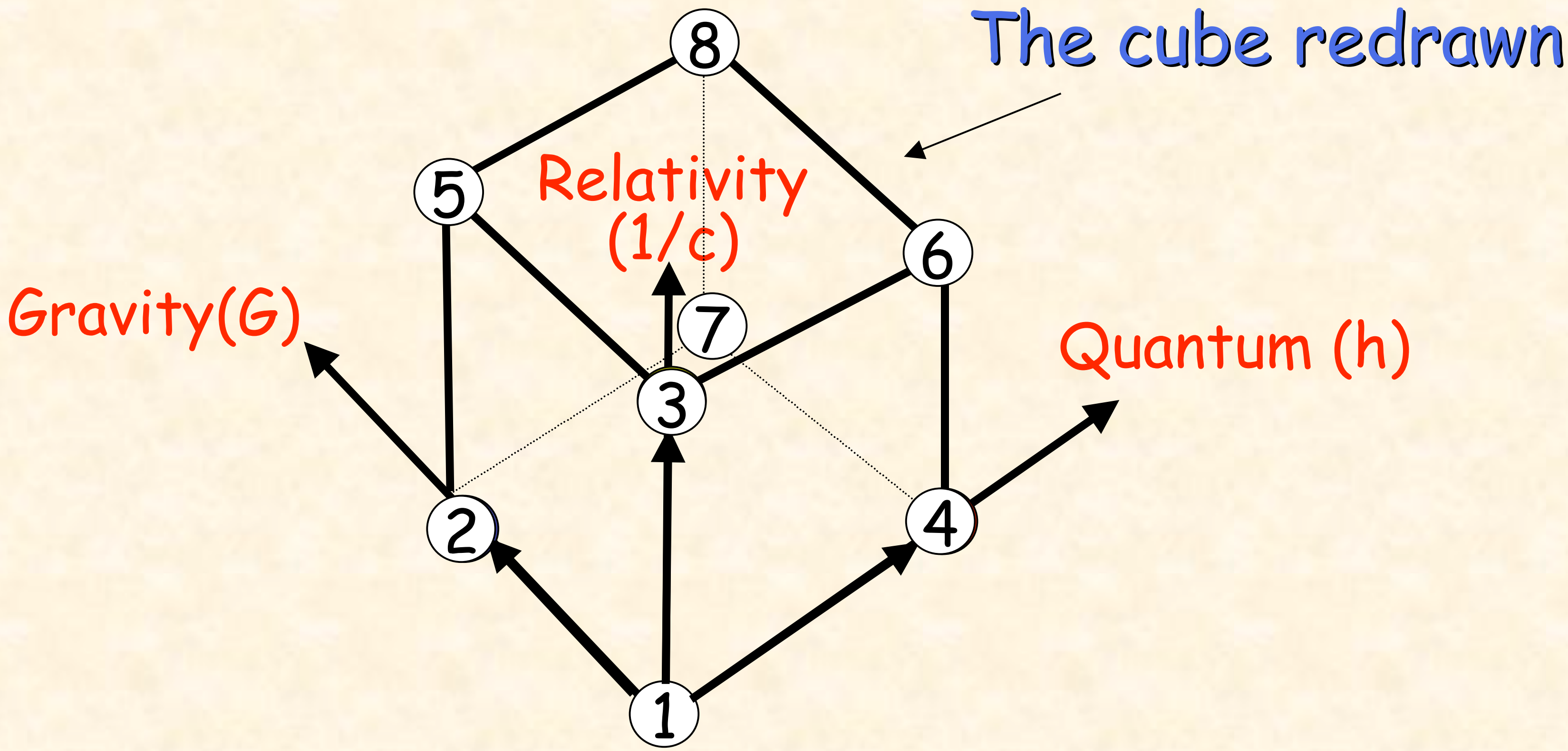
$$\frac{L_H}{L_P} = \frac{T_H}{T_P} \sim 10^{61}$$

A « russian cube » (from Landau to Okun)

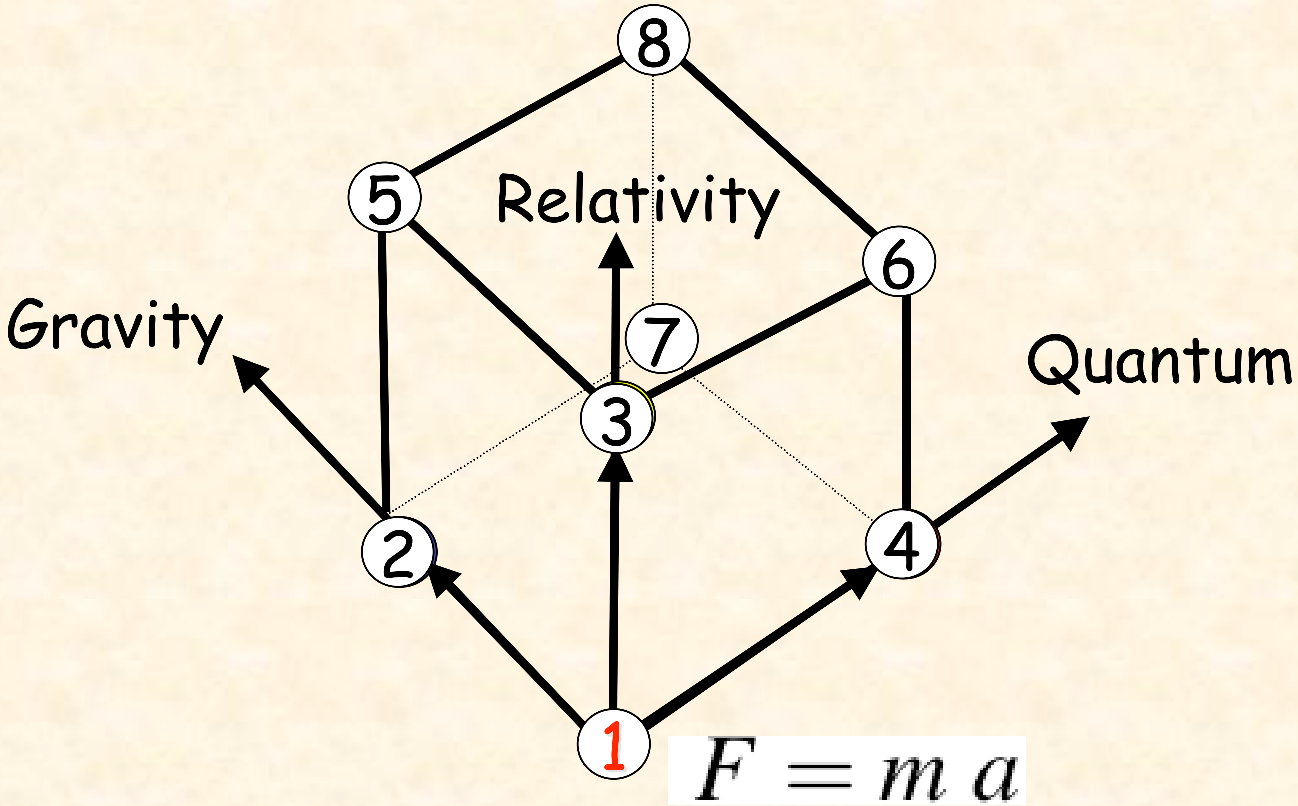


$$L_P = \sqrt{\frac{Gh}{c^3}}$$

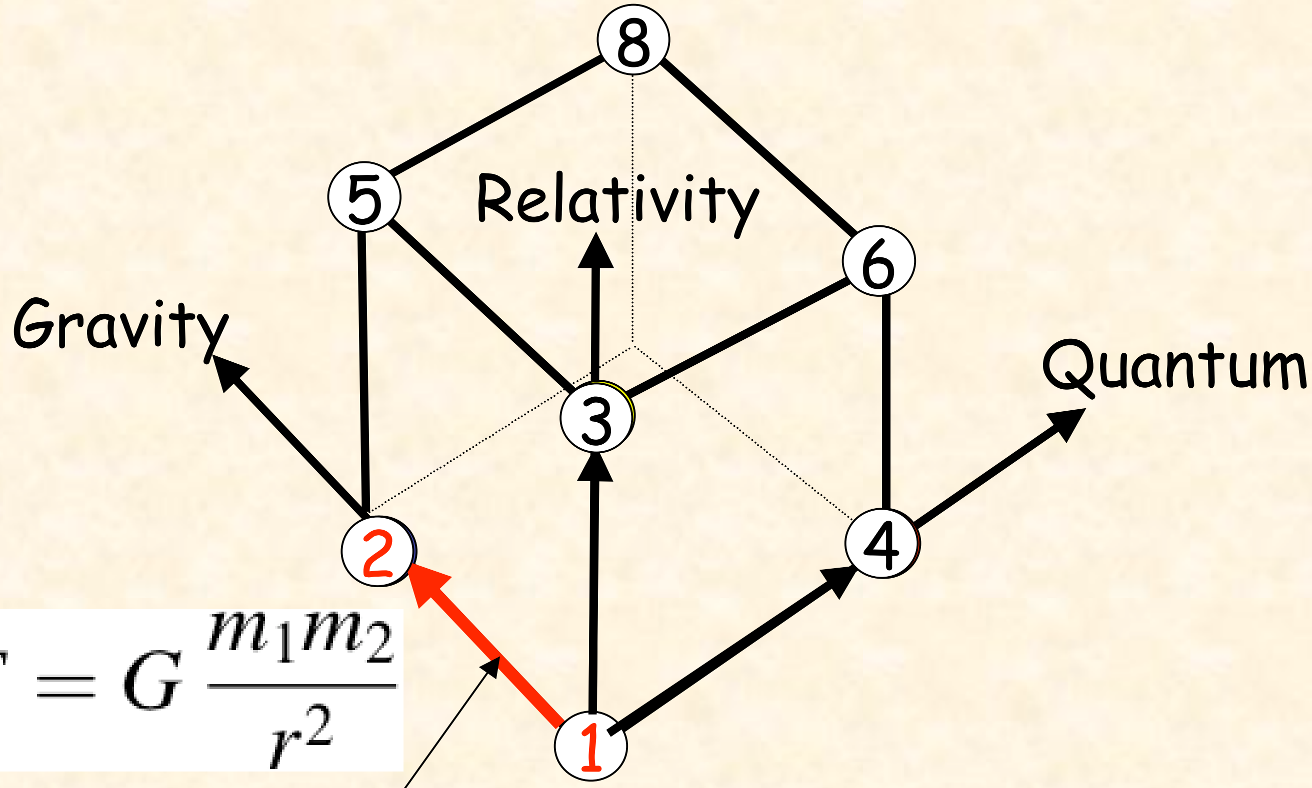
A «Theory of Theories»



The trivial vertex



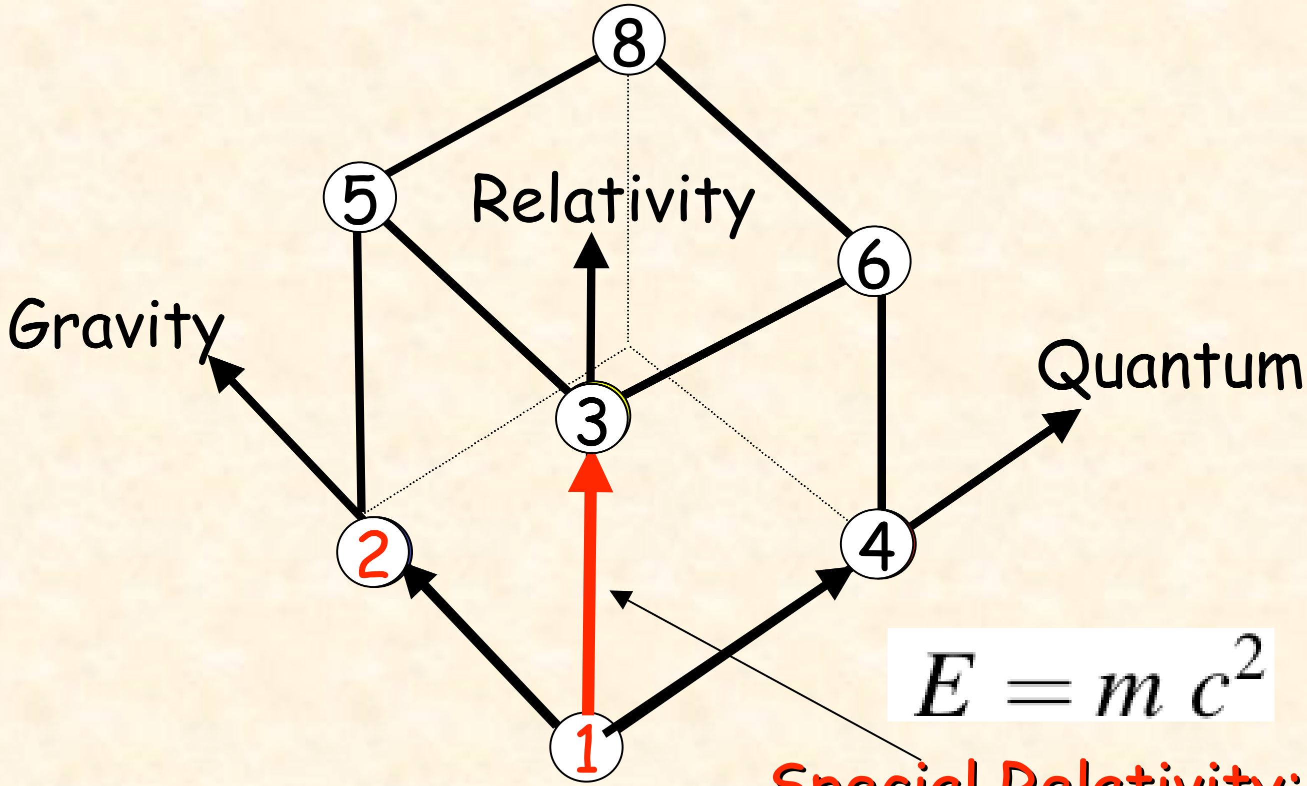
The simplest edges: I



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

Newtonian Gravity: e.g. the solar system

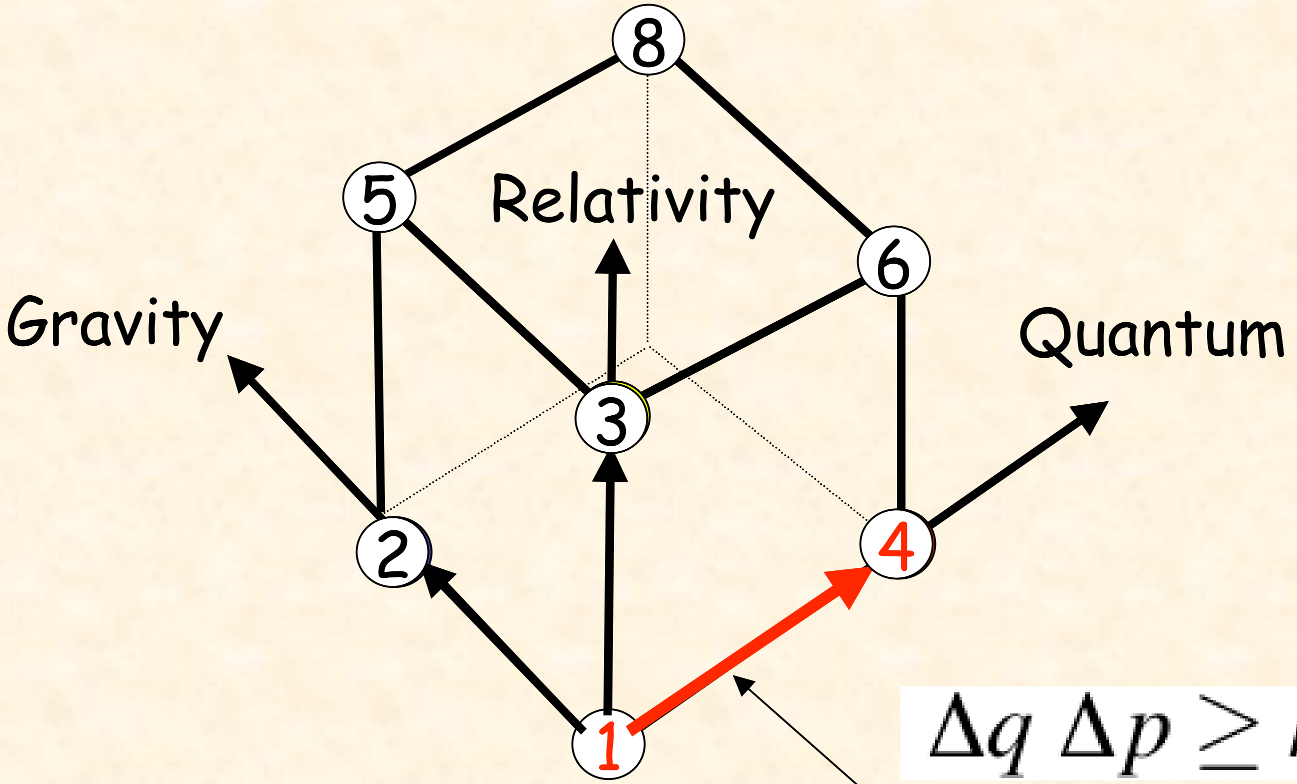
The simplest edges: II



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

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

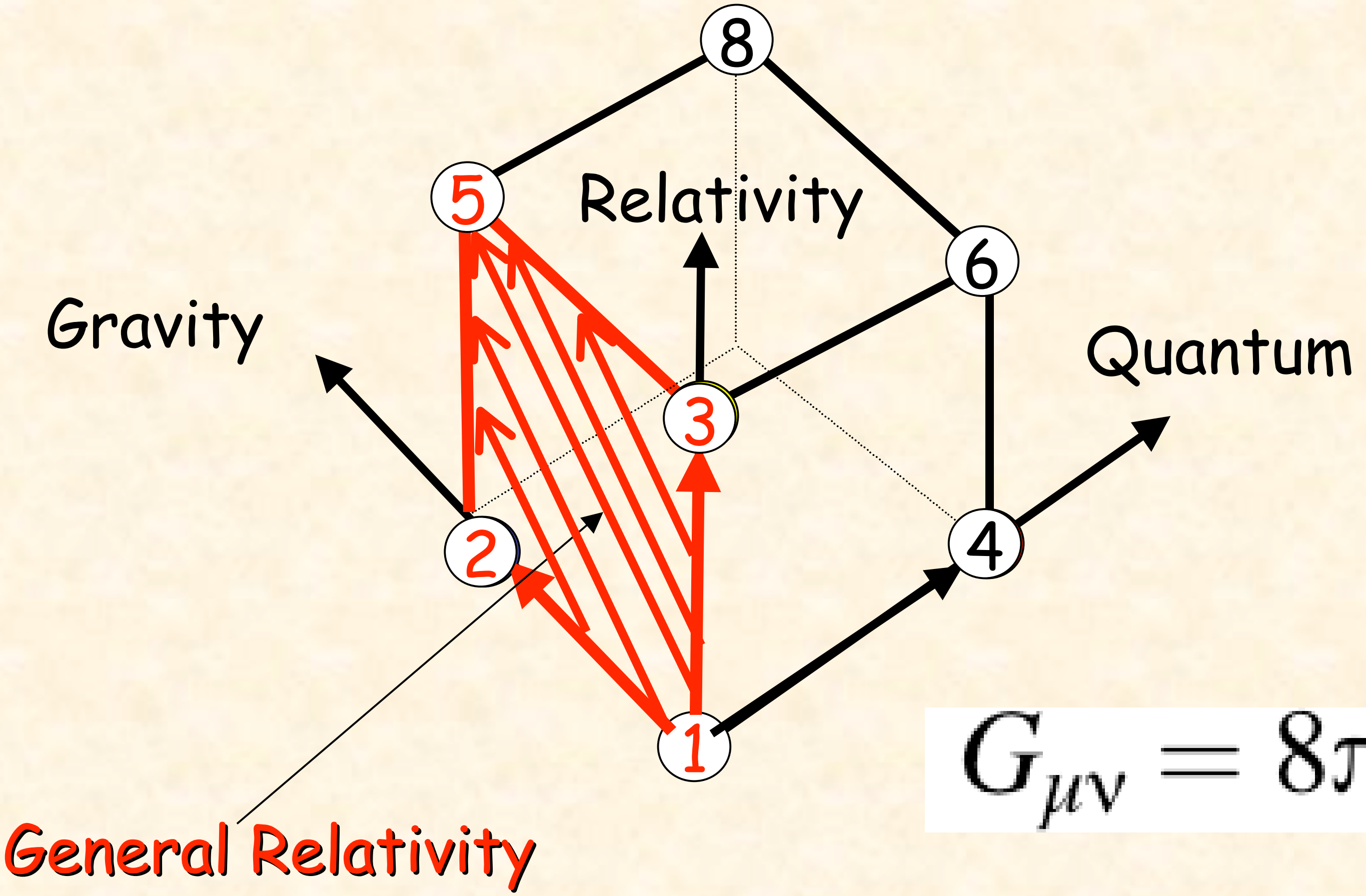
The simplest edges: III



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

Quantum Mechanics: e.g. H-atom

The most relevant faces: I



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

General Relativity (GR)

NG + SR = GR

Our «Standard Model» of classical gravity

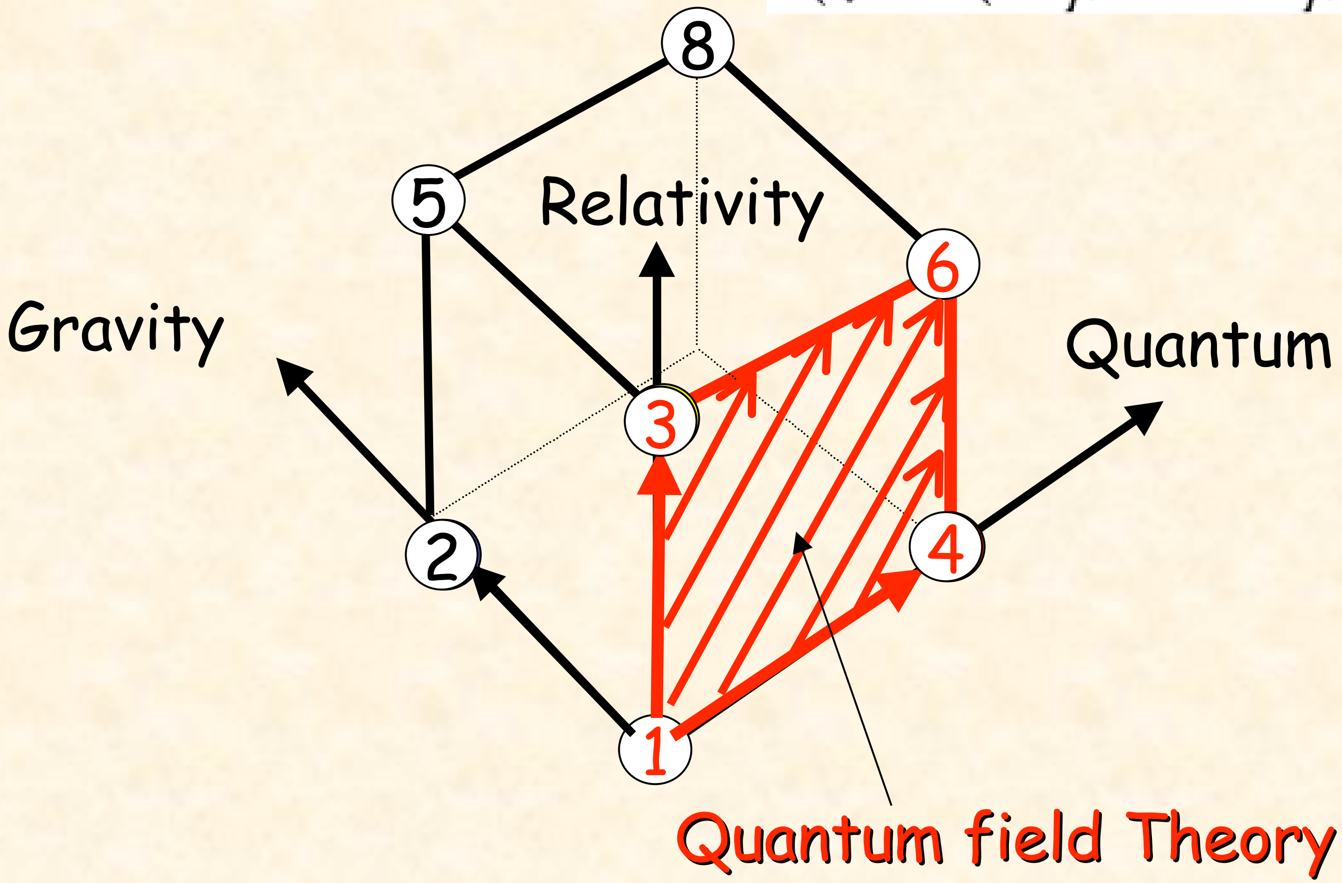
Corrections to NG better and better tested

New predictions

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

The most relevant faces: II

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



SR + QM = QFT

«Standard Model» of elementary particles

(verified to high precision, LEP..)

The quantum-relativistic nature of the SM manifests itself through real and virtual particle production

Radiative corrections are essential for agreement!

Summarizing so far:

NG + SR = GR = SMCG

SR + QM = SMEP

Both work wonders…but

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

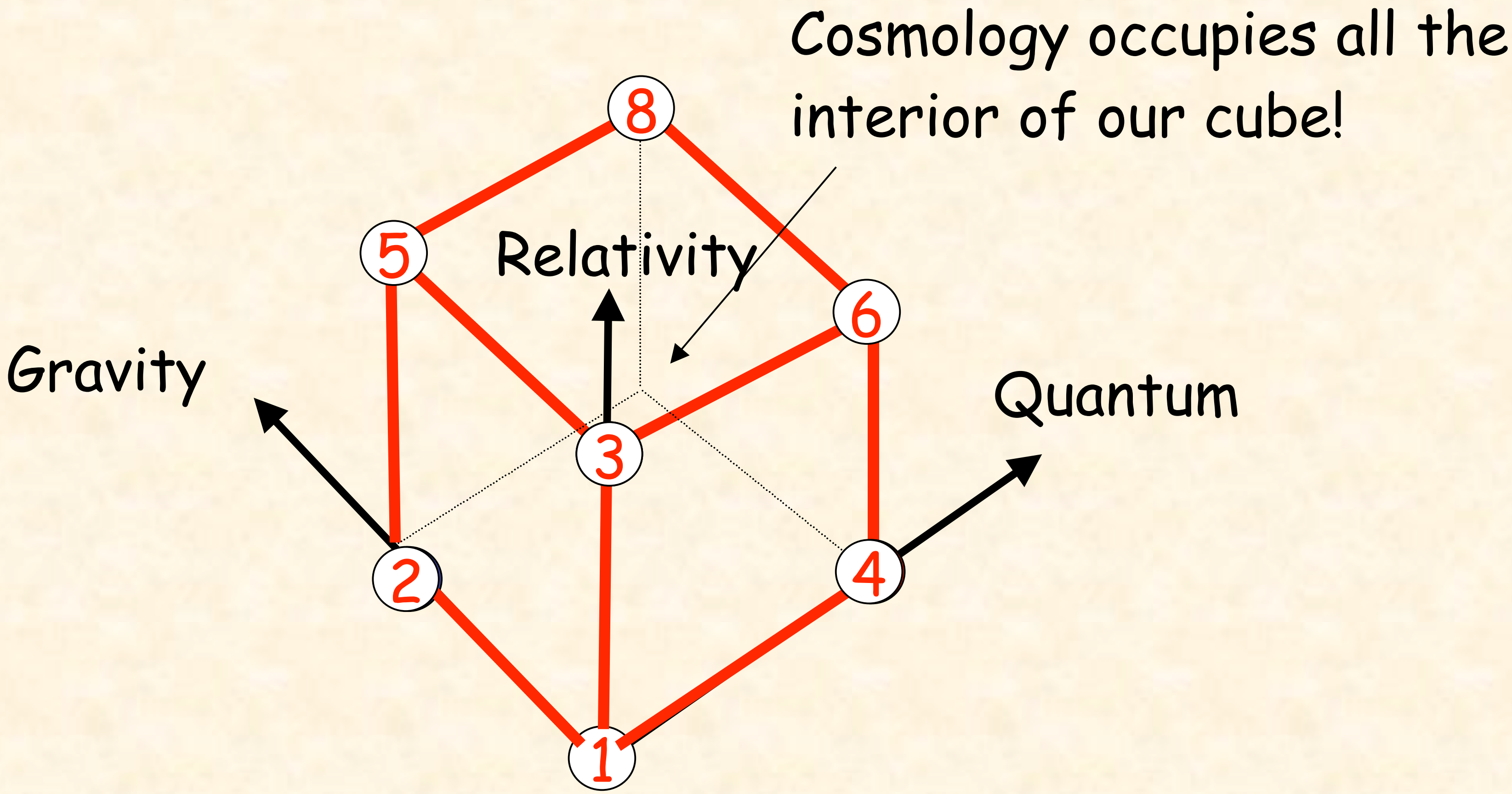
L.H.S. : Classical Geometry
R.H.S. : Quantum Matter

Sounds inconsistent. E.g.:

- A classical cosmological constant or the quantum-corrected potential energy of a scalar field?
- And what about today's generally accepted quantum origin of Large-Scale Structure in the Universe?

An impossible marriage?

The issue is not just a conceptual one: it becomes physically relevant in a cosmological context



Cosmology occupies all the interior of our cube!
8
5
Relativity
6
Gravity
Quantum
3
2
4
1

Expansion of the Universe

Far past ⇒ Very hot and dense Universe

Very hot Universe ⇒ Very high energies (R)

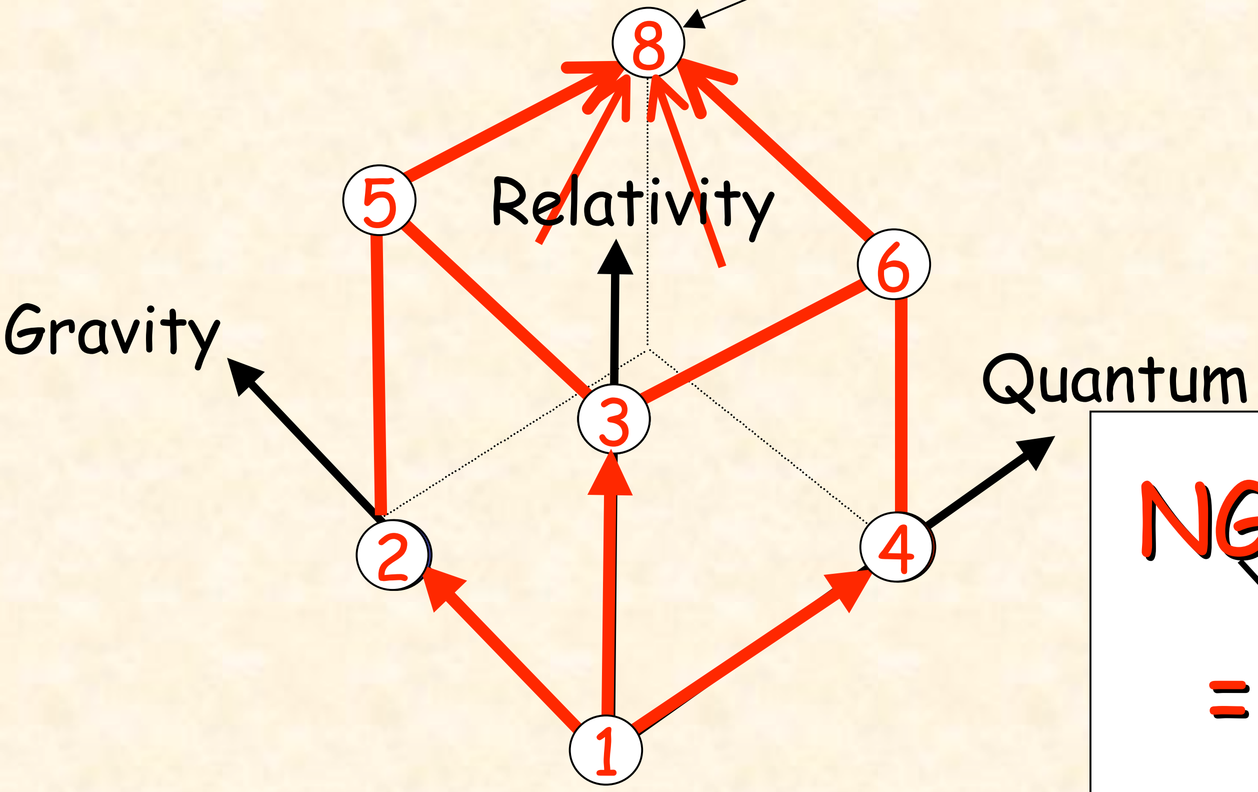
Very dense Univers ⇒ Very high curvature (G)

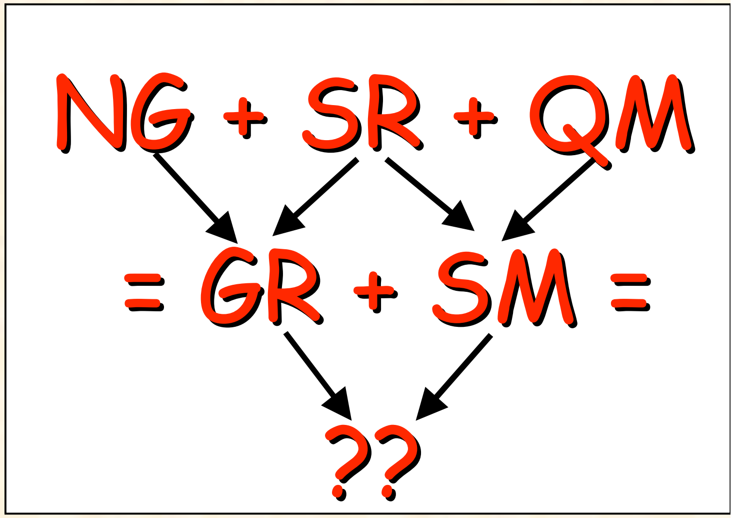
Very high curvature ⇒ Quantum processes (Q)

Far away in space ⇔ Far 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!





Conventional Cosmology

I: Successes

1. Cosmic microwave Background (CMB)
2. Structure Formation
3. Big-bang nucleosynthesis
4. Star formation & evolution

Conventional Cosmology

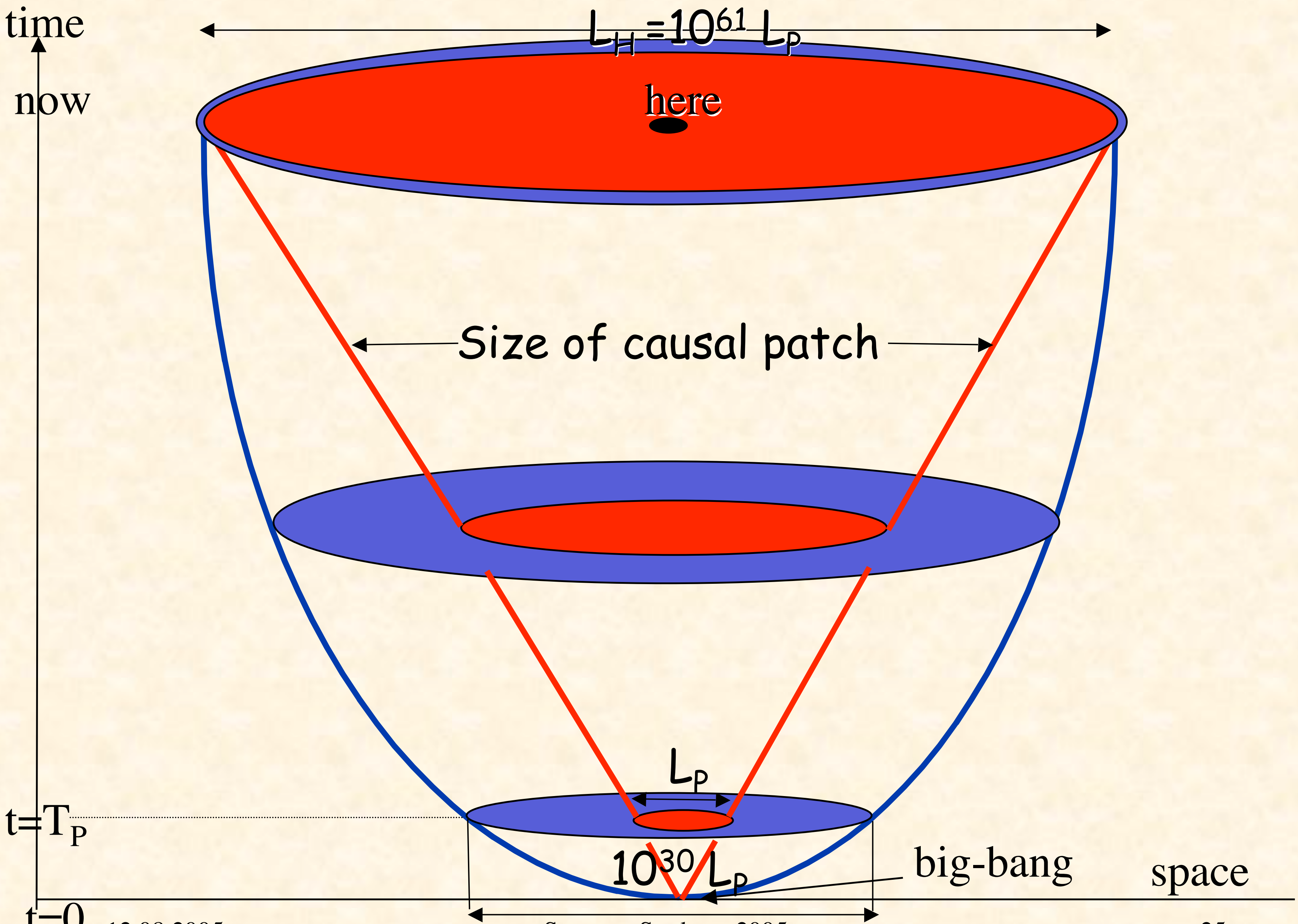
IIa: Problems on the Particle side

1. Matter-antimatter asymmetry (~5% vs. 0%)
2. Dark Matter (~25%)
3. Dark Energy (~70%)

Conventional Cosmology

IIb: Problems on the Gravity side

1. Large-scale homogeneity, flatness
2. Origin of LSS
3. Dark Energy (particle or gravity side?)

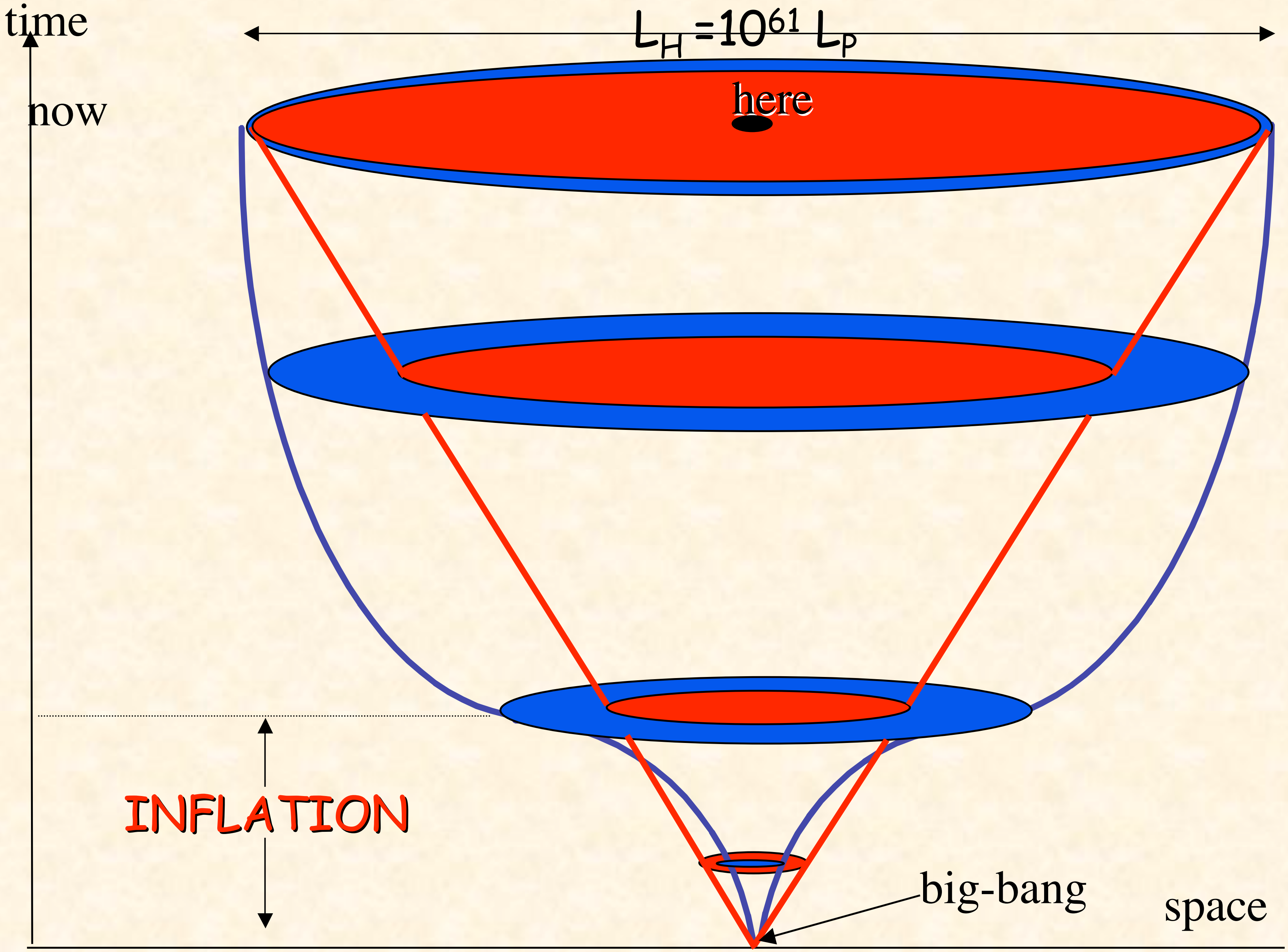


time
$L_H = 10^{61} L_P$
now
here
Size of causal patch
L_P
$t=T_P$
$10^{30} L_P$
big-bang
space
t=0

Inflationary Cosmology

Successes:

1. Thanks to the potential energy of a scalar field (the inflaton) the early expansion can be such that today's observable Universe was once within a single causal patch (figure)
2. Initial inhomogeneities stretched, washed out
3. They are replaced by calculable quantum fluctuations that get amplified and brought to cosmologically-relevant scales by inflation


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

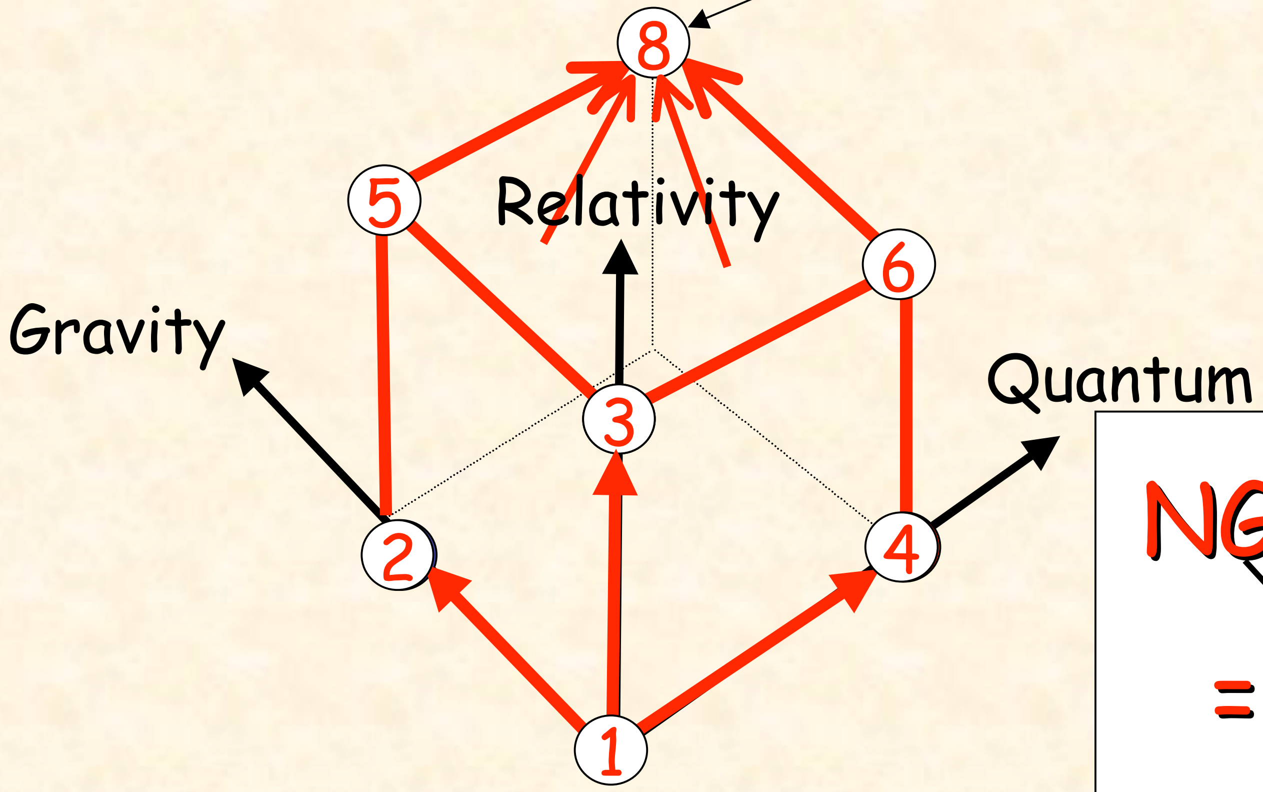
Inflationary Cosmology

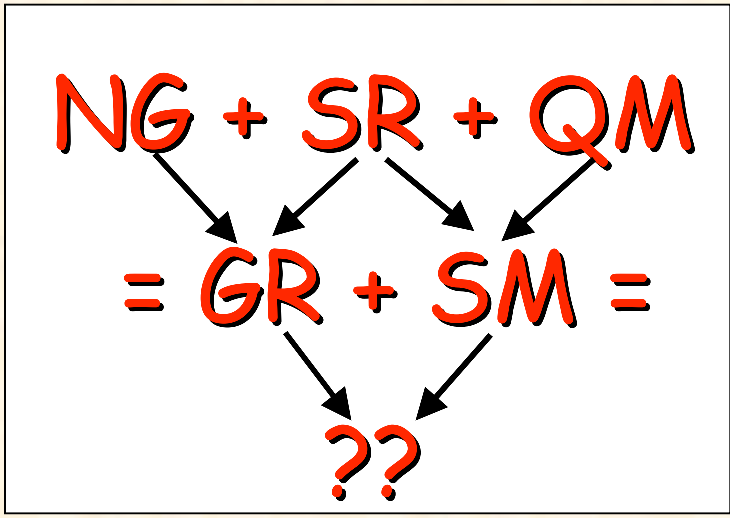
New Questions:

1. What's the inflaton? It doesn't look like any of the scalar fields of the SM
2. Where does its flat potential come from?
3. What determines the initial conditions that can turn on the inflationary epoch?

In order to answer this crucial last question we have to understand pre-inflation physics i.e. the Big Bang itself!

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





Patologies in Classical General Relativity

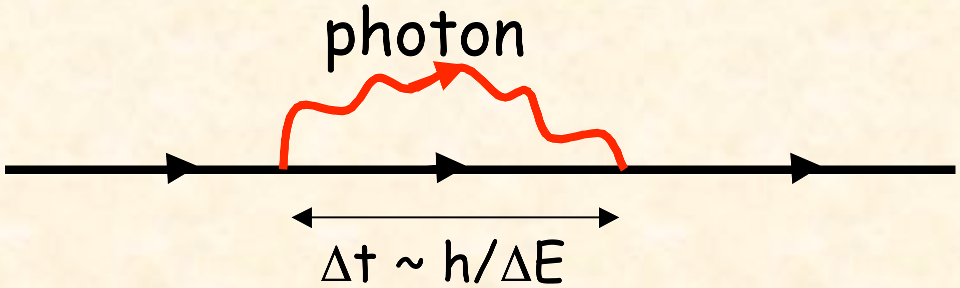
Theorems due to Hawking and Penrose imply that, under quite general conditions, perfectly smooth « initial » conditions lead eventually to space-time singularities

However, near curvature singularities quantum corrections to CGR cannot be neglected

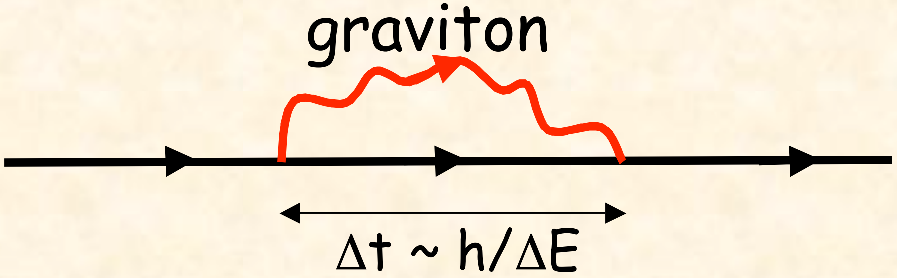
Q: Can QM remove the singularities of CGR, like it did with other infinities a century ago..?
A: QM appears to worsen the situation. Why?

Patologies in Quantum General Relativity

(the «evil quanta» are back!)



= **Calculable** corrections



= **Uncalculable** corrections

Patologies in Quantum Field Theories

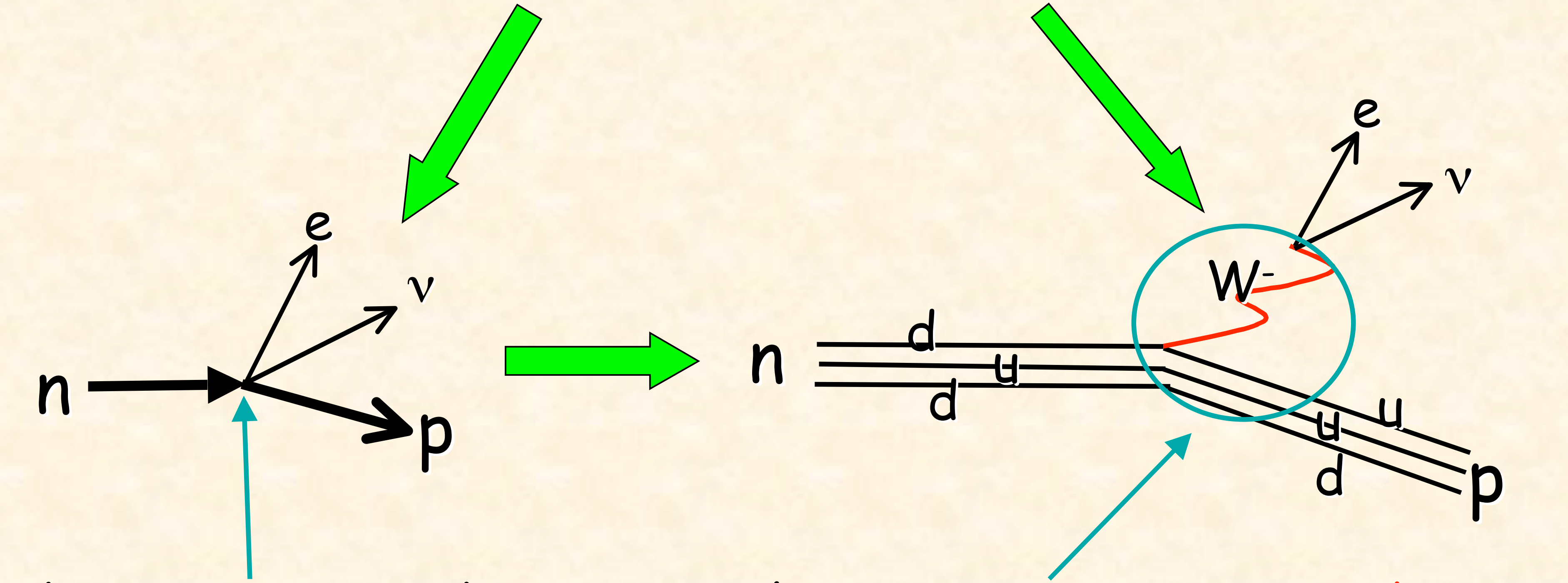
Even in the SM there are UV infinities. The difference is that we can tame them (renormalization)

Today even QFTs and the SM are viewed as «effective theories», approximately valid below (above) a certain energy (distance) scale

The difference between renormalizable and non-renormalizable theories is just in the price to be payed for our ignorance on the physics above that energy scale!

An instructive example: Fermi vs. GSW

From Fermi (1934) to EWT (~1973)



The interaction takes place in 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:
it does so through what we may call a number of
«Quantum Miracles»

What is String Theory?

« String Theory is the theory of strings »

What does that mean?

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

Relativistic Quantum Strings

Strings + SR + QM = Grand Synthesis

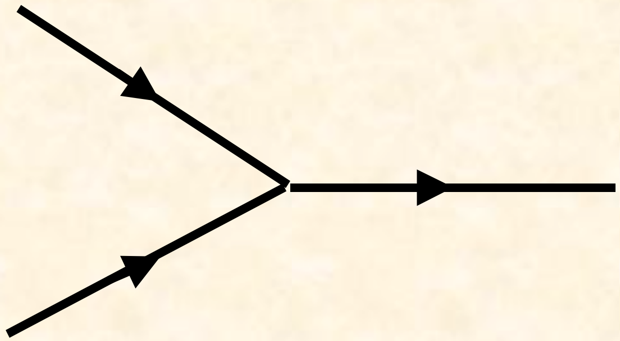
Quantum miracles: I

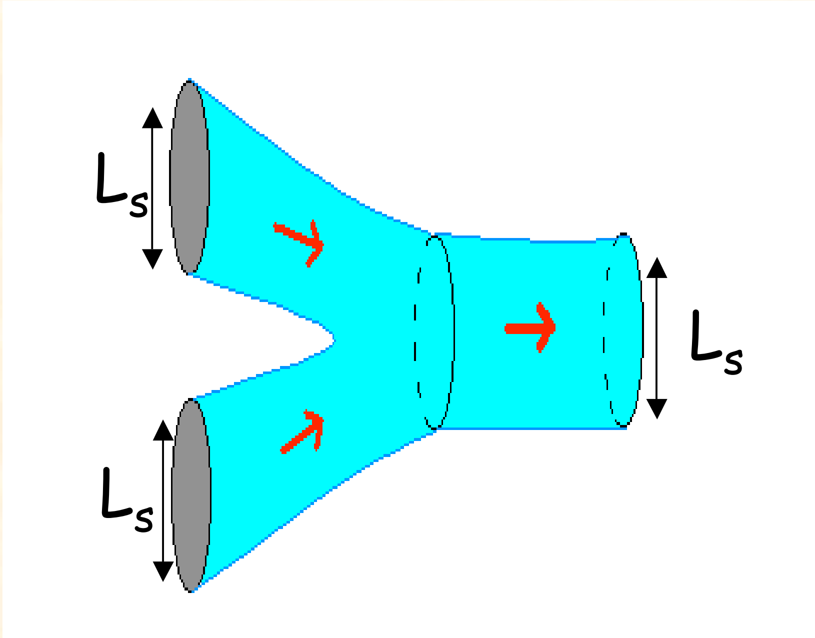
While classical relatistic strings with tension T may have any size L (and therefore any mass $Mc^2 \sim T\,L$), quantum strings have a minimal (optimal) size L_s (Cf. Bohr radius), given by $L_s^2 = hc/T$ *). This length appears naturally in the (dimensionless, quantum) action of a string:

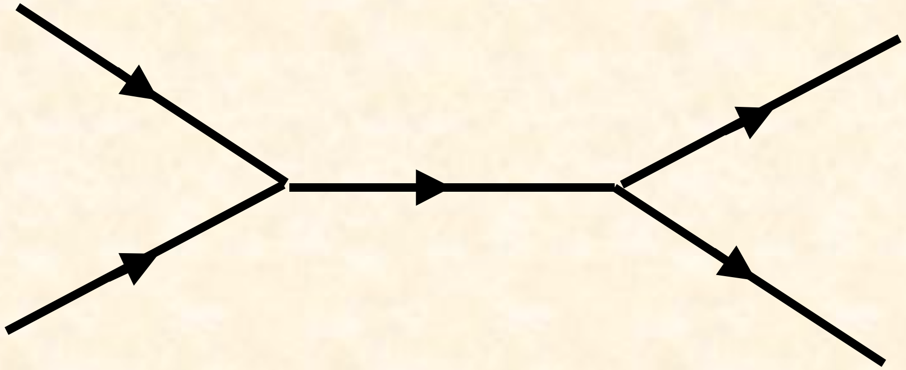
$$S_{class.} = -T(Area\ swept) \Rightarrow \frac{1}{\hbar} S_{class.} = -\frac{1}{L_s^2}(Area\ swept)$$

*) Cf. analogy with $L_P^2 = hG/c^3$ (if G-->1/T)

The finite string size L_s, is responsible for the smearing







becomes

Quantum miracles: II

While classical string cannot have angular momentum without also having a finite size/mass, quantum strings may have up to 2 units of J without acquiring a mass:

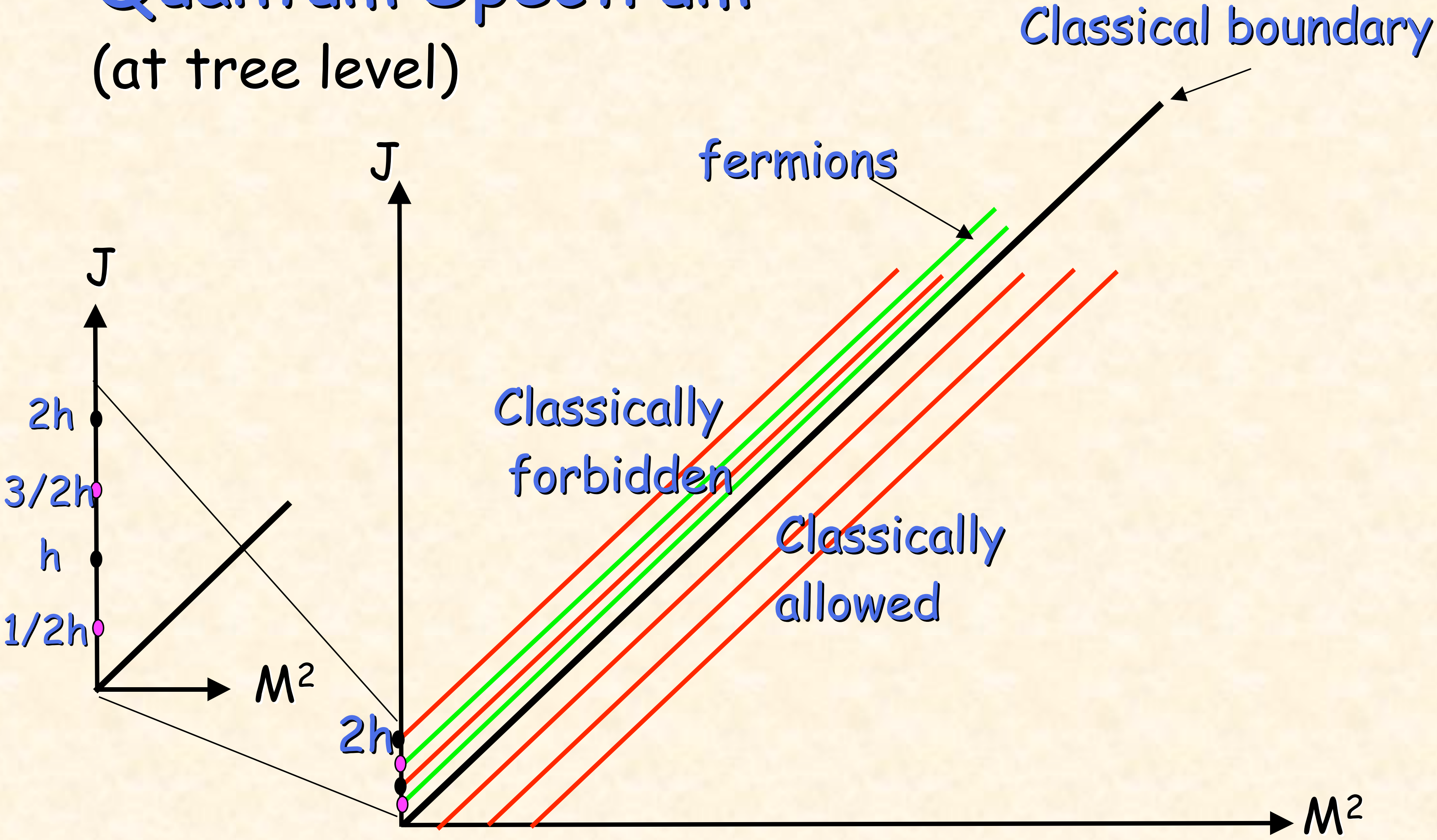
$$\frac{M^2}{T} \geq J + \hbar \sum_{1}^{\infty} \frac{n}{2} = J - \alpha_0 \hbar$$

$$\alpha_0 = 1/2, 1, 3/2, 2.$$

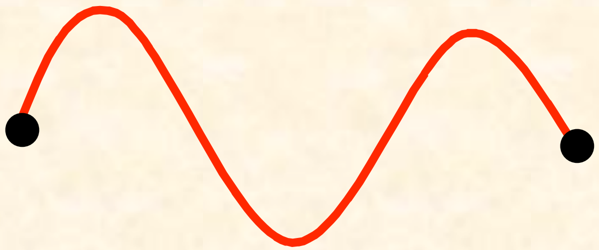
Cf. Casimir effect

Quantum Spectrum

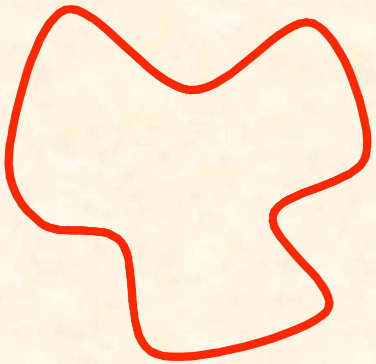
(at tree level)



In particular..



=> m=0, J = 1 => photon and other gauge bosons (other can originate from a stringy version of the KK mechanism)



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

$\Rightarrow$ m=0, J = 0 => dilaton

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

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!

Other quantum news

1. While classical strings can move consistently in any ambient space-time, quantum strings require particular «target» space-times in order to avoid letal anomalies. A Minkowskian space-time, e.g., must have 1 time and 9 space dimensions, 6 of which must be compact & small
2. A symmetry, called target-space duality, implies that a compactification radius R_c is equivalent to L_s^2/R_c
3. A web of dualities unifies conceptually all known consistent string theories (M-theory)

4. There are no free parameters: these are replaced by scalar fields whose ground-state values provide (dynamically?) the «Constants of Nature». For instance, the fine-structure constant α and $G_N T$ are fixed by the above-mentioned dilaton and by the various radii.

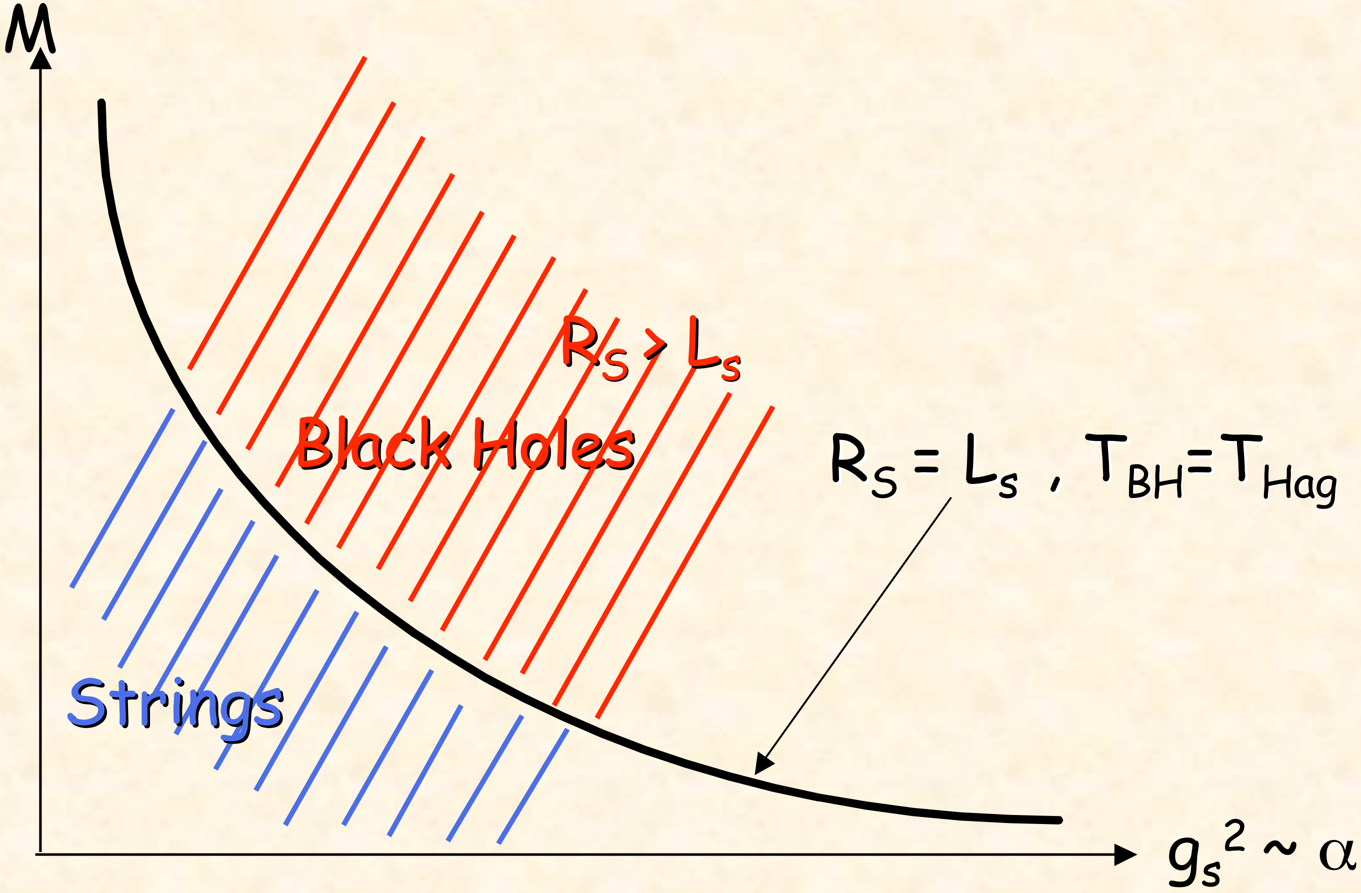
All these scalar fields have vanishing perturbative mass, because of SUSY. If they remain light (at NP level after SUSY breaking), they may induce «short-distance» modifications of gravity, threaten the equivalence principle and universality of free-fall, induce space-time variations of the above «constants»,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

⇨ A very active field of experimental and theoretical research

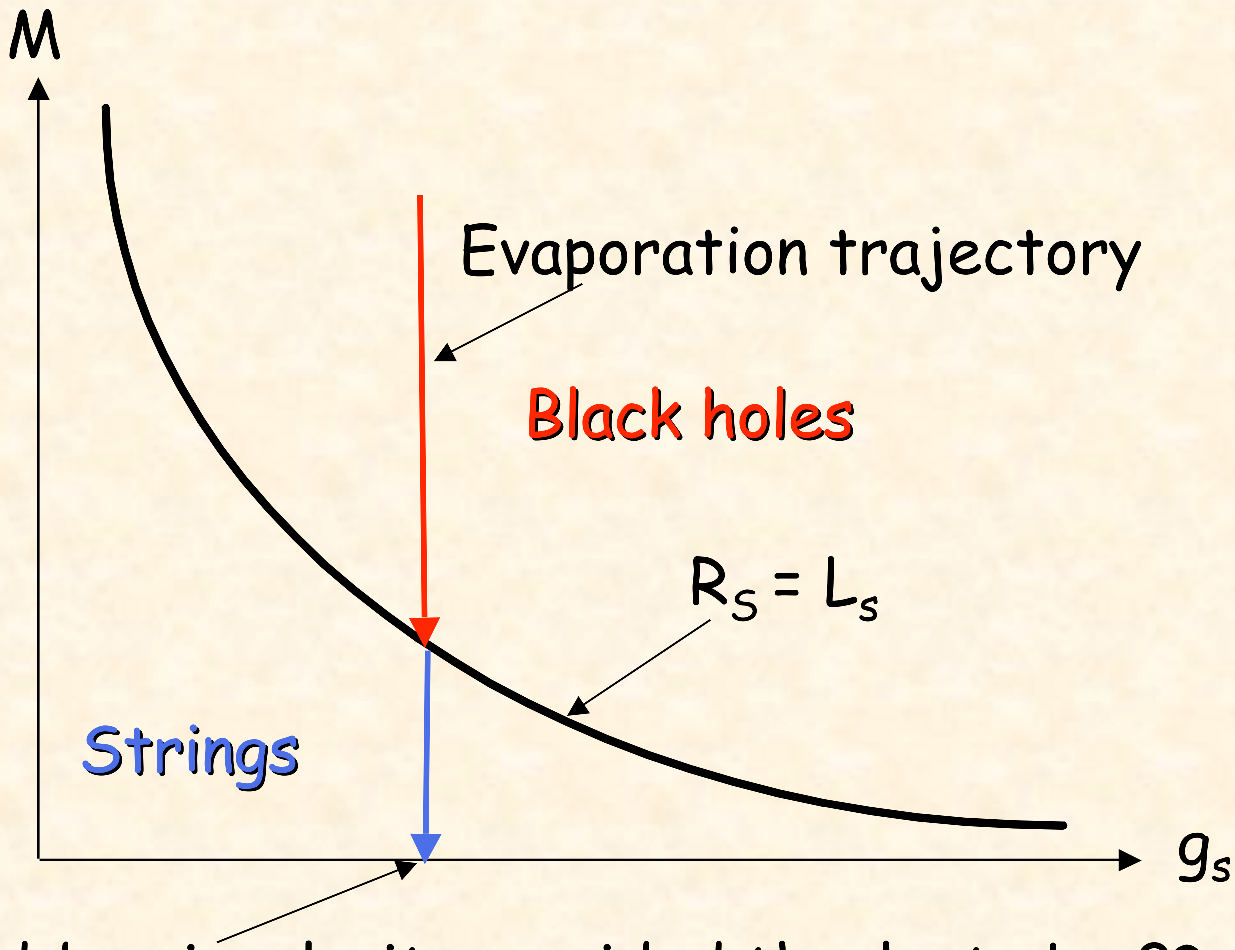
Possible physical applications

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

String/Black Hole phase diagram



Evolution of evaporating Black Hole (via Hawking's process)



would-be singularity: avoided thanks to $L_s \neq 0$?

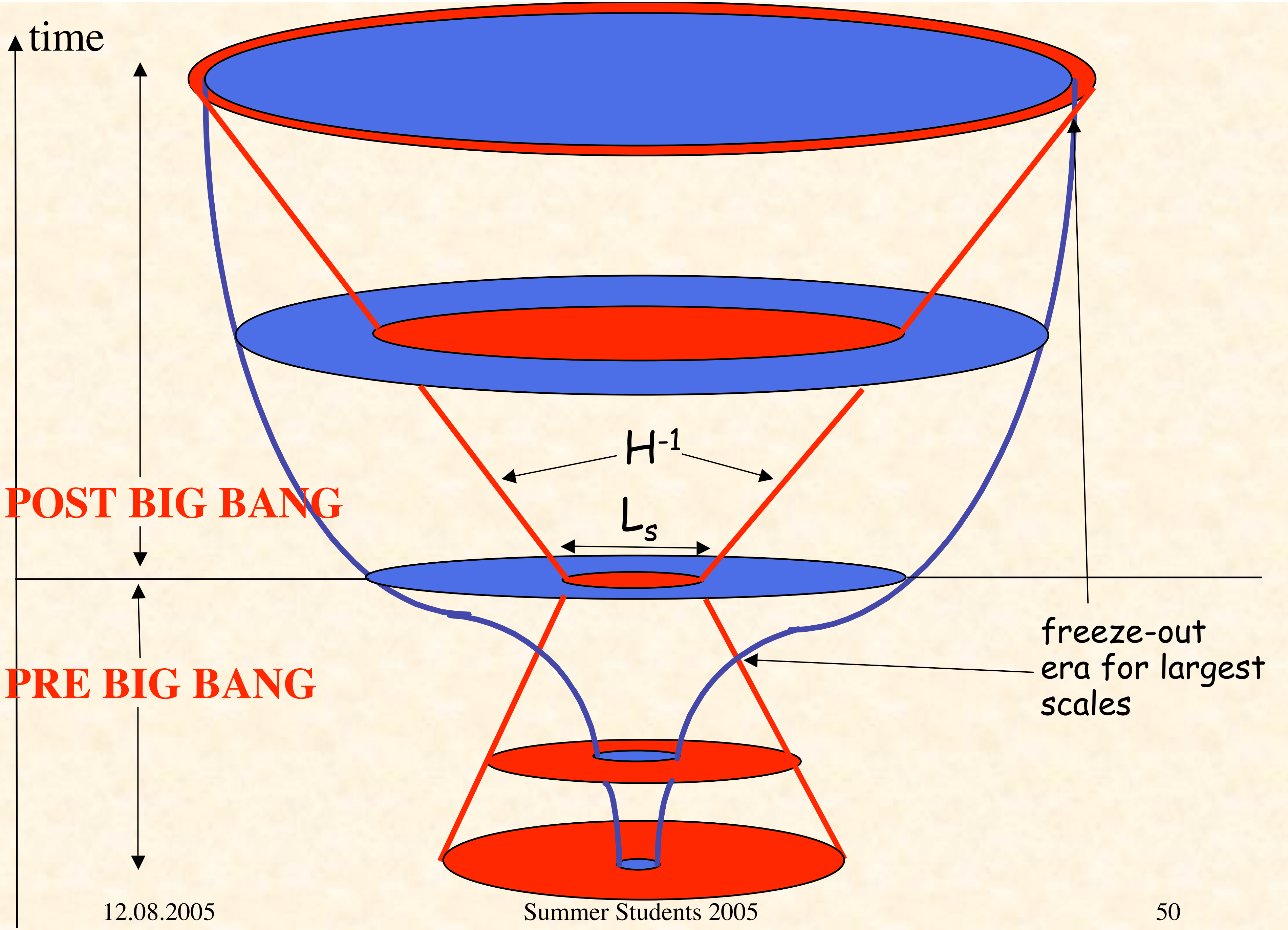
BH entropy and the information paradox

- In some favourable cases, string theory provides a statistical interpretation of the thermodynamic (Bekenstein-Hawking) entropy of a black hole, $S_{BH} = A/4L_P^2$
- String theory offers convincing arguments (e.g. through the holographic correspondence between gravity and gauge theories) against any loss of quantum coherence in processes where a black hole is formed from a pure state and then undergoes Hawking evaporation.
- Hawking himself has taken back (Dublin talk 2004, and recent paper) his previous claims to the contrary

Cosmological Applications

- String theory «resolves» some singularities of GR
- Those associated with cosmology (big bang) are harder to deal with (SUSY breaking), but are also likely to be eliminated/reinterpreted (new d.o.f.)
- If so, we may conceive new scenarios in which the big bang, rather than representing the beginning of time, is the result of a previous phase in which space-time curvature (~ Hubble parameter H) grew
- String effects would then force the Universe to «bounce» after going through a high-curvature «string phase»
- The Big Bang becomes a «Big Bounce»

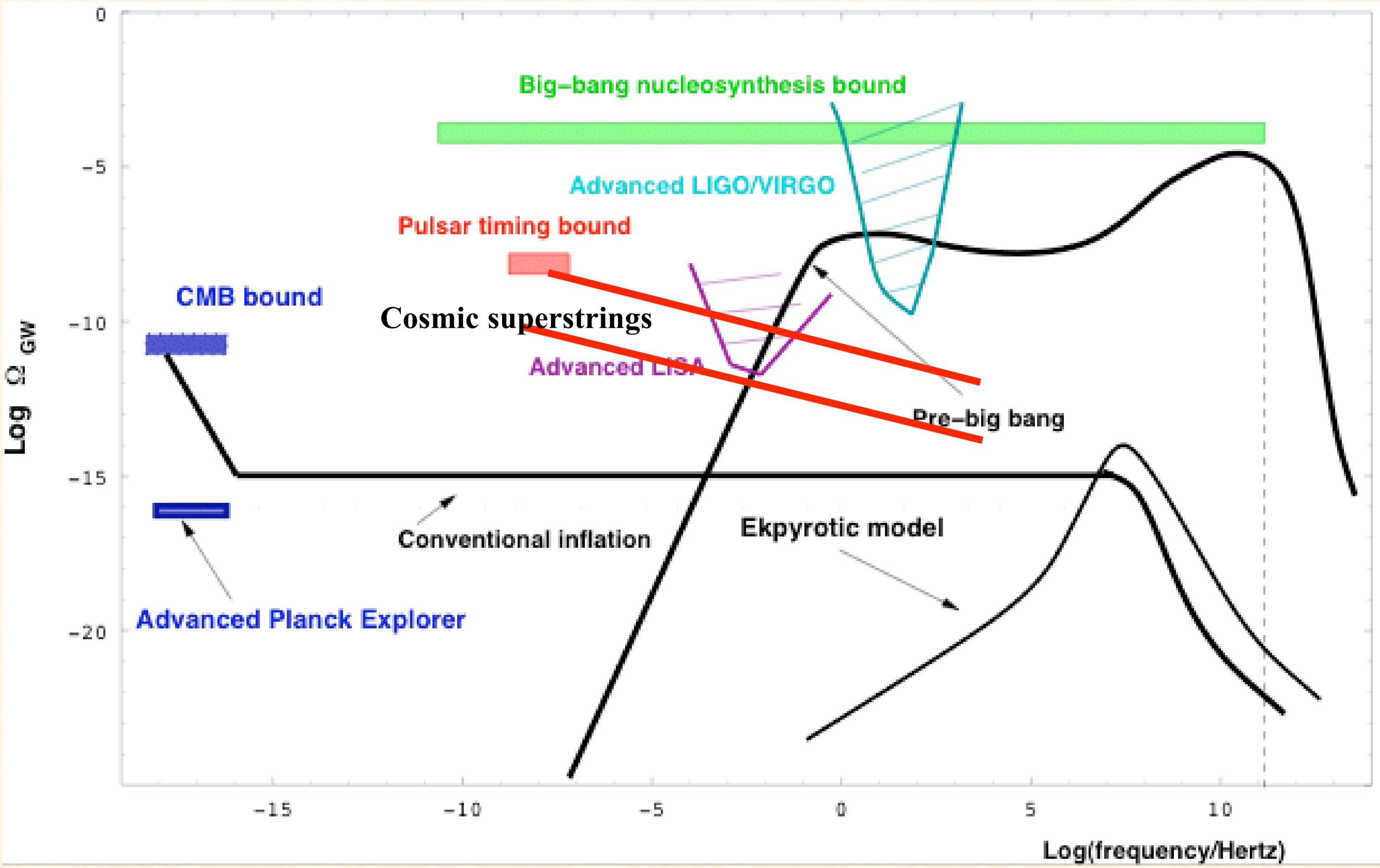
➡ New ways to solve the problems of standard cosmology (an older, rather than a smaller Universe)


time
POST BIG BANG
PRE BIG BANG
H^{-1}
L_s
freeze-out
era for largest
scales

- Such «pre big bang» cosmologies have observable consequences, i.e. can be tested in principle
- The reason is the one invoked for «observing» the inflationary epoch today: the freeze-out of perturbations while their wavelength exceeds the Hubble radius H^{-1}.

Examples:

1. A stochastic background of GW (see figure)
2. Cosmic (F and D) strings that can possibly provide interesting GW sources (see figure)
3. Seeds for cosmic magnetic fields due to an evolving dilaton and/or internal dimensions during the pre-bounce phase
4. A «curvaton» mechanism for generating CMB anisotropies and LSS (w/out tensor contribution, B-polarization)



Big–bang nucleosynthesis bound
Advanced LIGO/VIRGO
Pulsar timing bound
CMB bound
Cosmic superstrings
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

Conclusion

- 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 came about in late sixties because in QCD (and apparently in Nature) there are string-like excitations as a consequence of confinement
- The true QCD string is yet to be constructed, while the old string found an application that no-one could have forseen at the time.

Sergio Fubini used to say (~ 1970):

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

- Its starting point is not a classical field theory (Maxwell + GR) that we then quantize with much pain, if at all.
- Without QM strings do not give a photon or a graviton and thus, a fortiori, an electromagnetic or a gravitational field: these only emerge as semiclassical (large distances, large occupation number) limits of a fundamentally quantum theory of extended objects.
- Einstein's dream comes true (at a theoretical level, so far) thanks to (and not against) QM, hence in a way that is quite opposite to the one he was pursuing.
- I am afraid he could have reacted to String Theory, like he did to QM, by saying:

God does not play strings!

Let's find out whether Nature does!