

Highlights in physics
today:
100 years after the
birth of
Beppo Occhialini
(Milano, 16 February 2007)

**String Theory: a unified description of
elementary particles & interactions?**
(Gabriele Veneziano, CERN & CdF)

Introduction

100 years ago, when G.O. was born, **two** revolutions had already shaken **two** sacred XIXth century beliefs:

1. The belief in **absolute determinism** when Max Planck, in **1900**, introduced the constant **h** and started the **quantum revolution**.
2. The belief in **absolute time** when Albert Einstein, in **1905**, starting from the invariance of the speed of light in the vacuum, **c**, arrived at his theory of **Special Relativity**.

In that same year AE also gave an important contribution to **quantum** theory by explaining the photoelectric effect as due to light **quanta** (photons) of energy **$E = h f$**

In **1915** Einstein made yet another ground-shaking proposal:

Starting from the universality of free-fall, he arrived at a geometric theory of gravity, **General Relativity**, whereby Newton's constant, **G** , determines the amount by which matter (energy) bends spacetime.

In the second half of his scientific life Einstein tried to combine in a single conceptual framework all these beautiful developments (embodied in h , c and G)

Meanwhile, thanks to the effort of many physicists, including G.O., the panorama of elementary particles and fundamental interactions had drastically changed

It had grown more and more complicated with the discovery of the **nuclear** and **weak** forces, and of a host of new particles endowed with one and/or the other interaction, besides electromagnetism

Einstein's search for **unification** looked more and more like a remote, impossible **dream**

When I started entering elementary particle physics, in the late sixties, G.O. and the physicists of his generation had already collected an incredible amount of exciting data, but a theoretical synthesis looked as remote as ever. Yet, some kind of revolution was boiling....

It came to completion within a « golden decade » (1965-1974) that culminated in the construction of the **Standard Model** of elementary particles. I have been very lucky to enter PP just at that time...

Such diverse phenomena as atomic levels, nuclear reactions, radioactivity, were understood, in the standard model, as different realizations of a single theoretical structure, known as a gauge theory. Its three possible realizations:

- A **Coulomb** phase with a **massless** gauge boson
- A **Higgs** phase with **massive** gauge bosons
- A **confining** phase with a dynamically generated **mass-gap**

represented, respectively, the **electromagnetic, weak** and **strong** force, 3 of the 4 known basic interactions

It is hard to overestimate the importance of such an achievement. I am sure it will remain in the books of physics like Maxwell's or Einstein's equations did (do).

But, once more, Einstein's dream was as far as ever from being realized. There was no way to bring his General Relativity (GR) to terms with QM. GR remained, obstinately, a completely **classical, deterministic** theory.

"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)

Outline

- A huge hierarchy of scales
- Travel on a «meta-theoretical» cube
- Cosmology needs unification
- Classical and quantum pathologies of Einstein's gravity
- A lesson from the Electro-Weak theory
- String Theory: a 3-ingredient cocktail
- Quantum magic and Einstein's dream
- String's cube and problems ahead
- Conclusion

Einstein's dream was to unify our
understanding of the
« infinitely » small
& the
« infinitely » large

More quantitatively:

Minimal (quantum) length/time scale

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

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

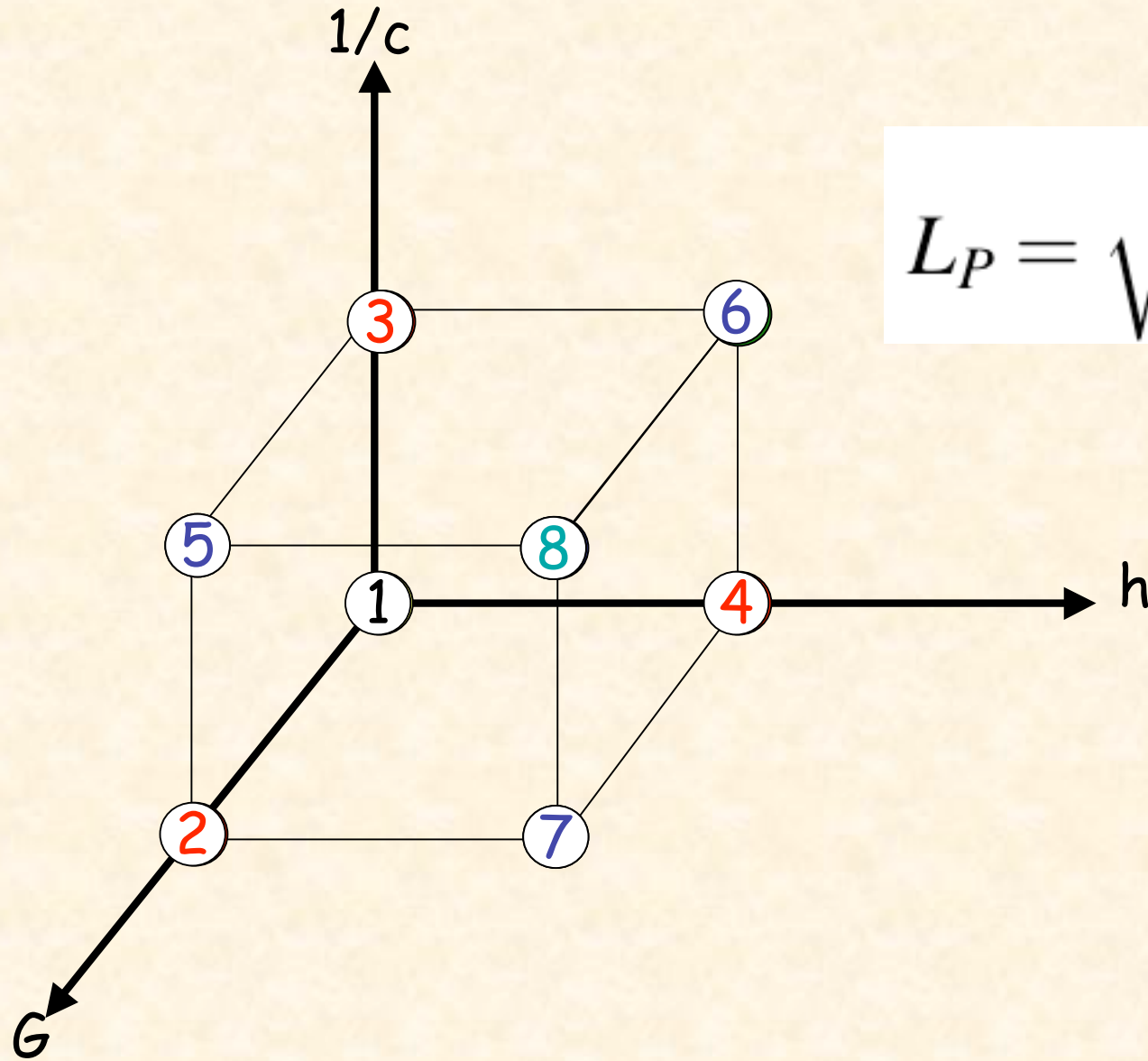
Maximal (classical) length/time scale

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

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

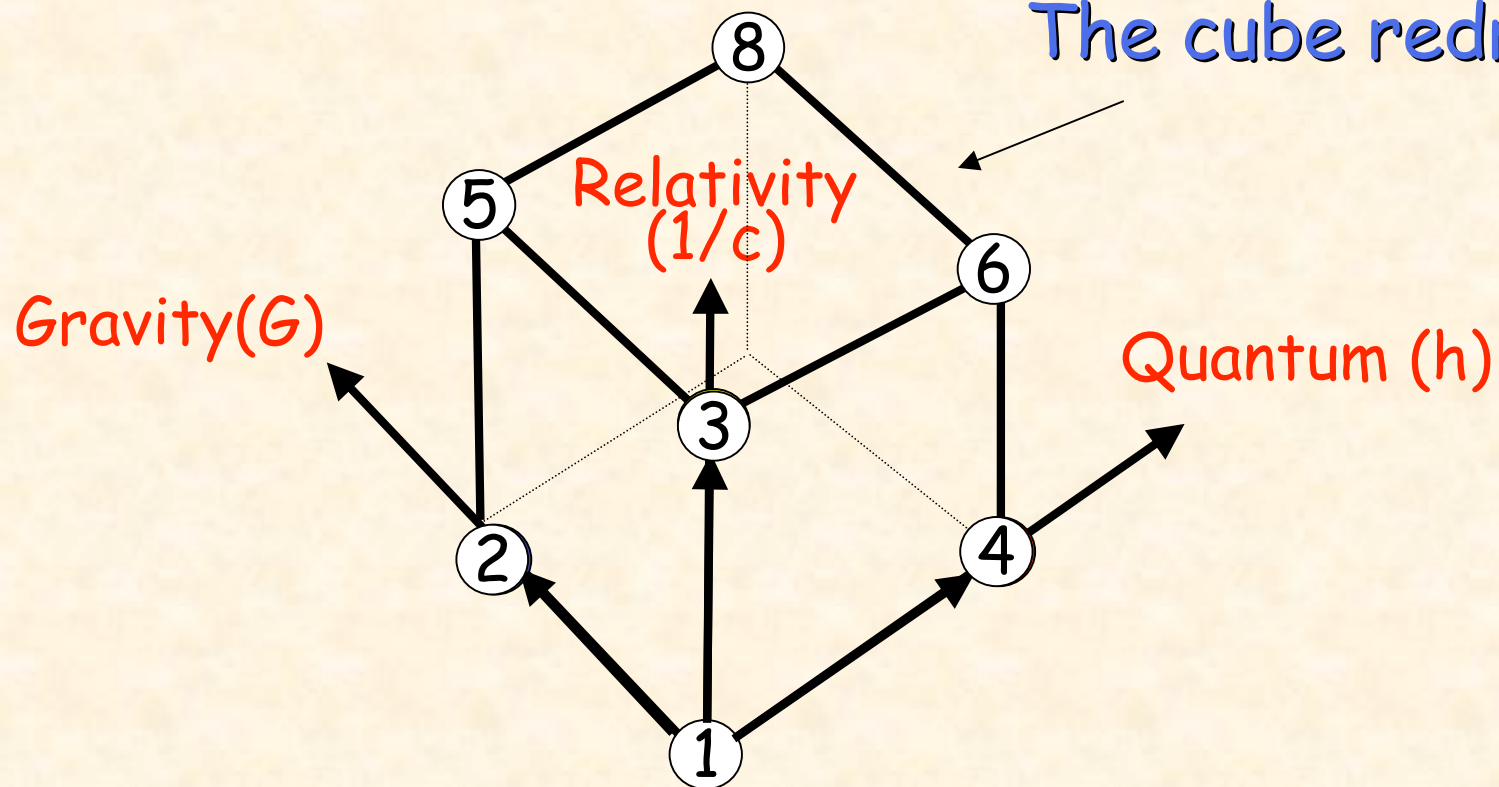
$$\frac{L_H}{L_P} = \frac{T_H}{T_P} \sim 10^{61}$$

Travel on a meta-theoretical cube

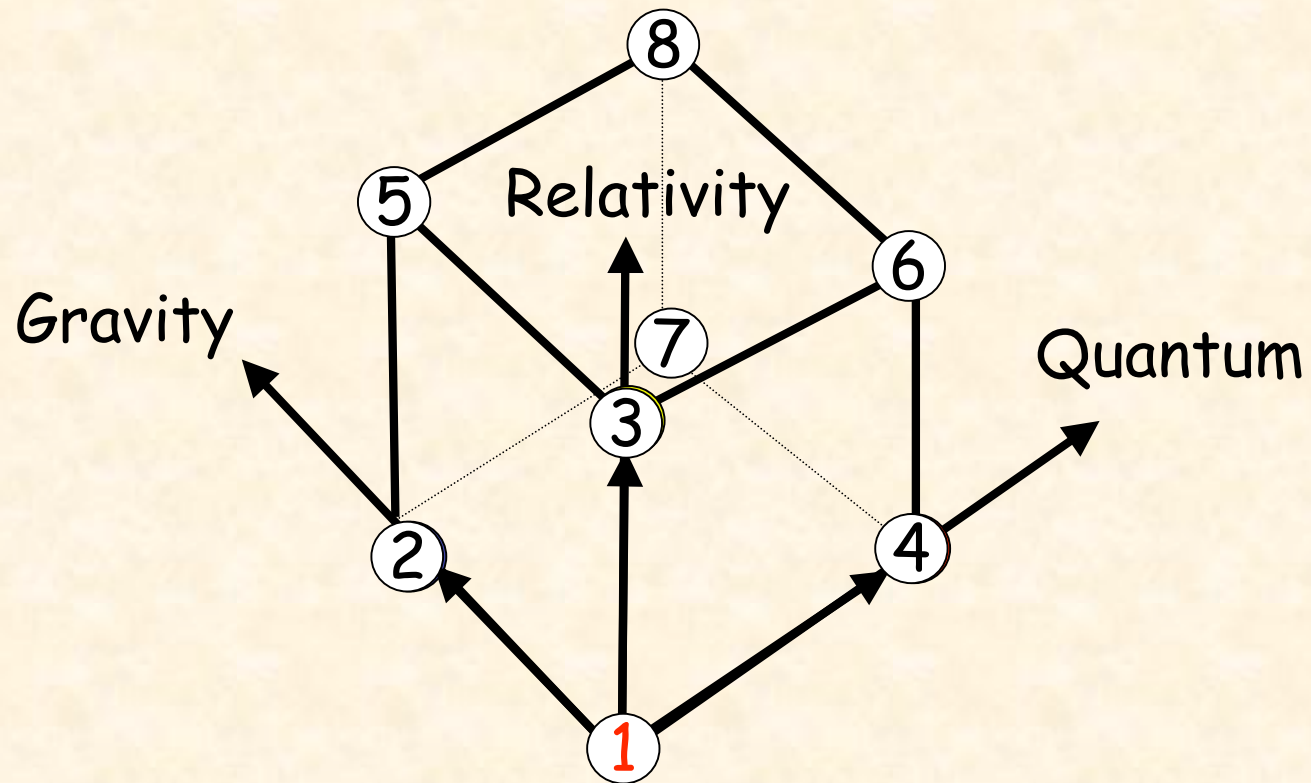


$$L_P = \sqrt{\frac{Gh}{c^3}}$$

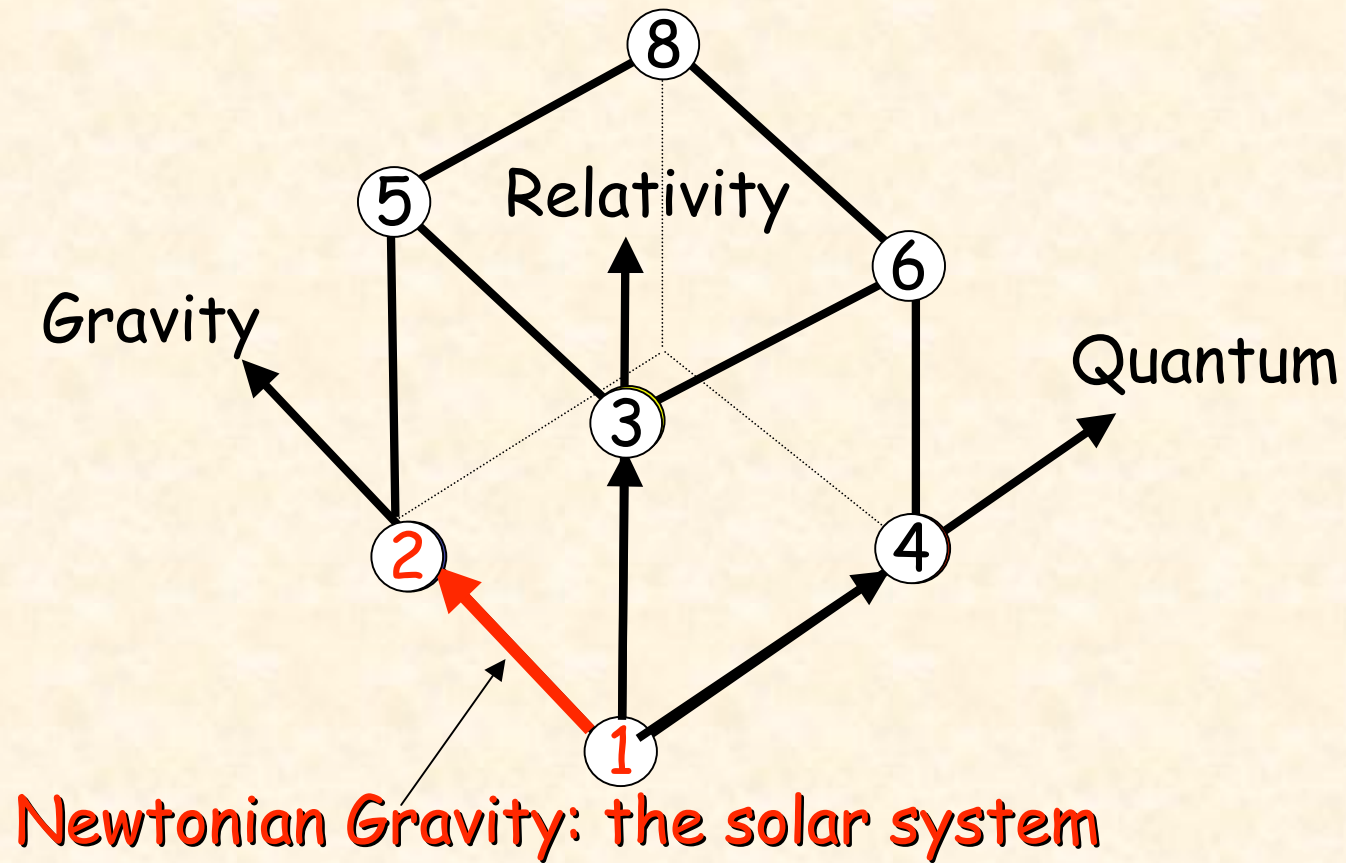
The cube redrawn



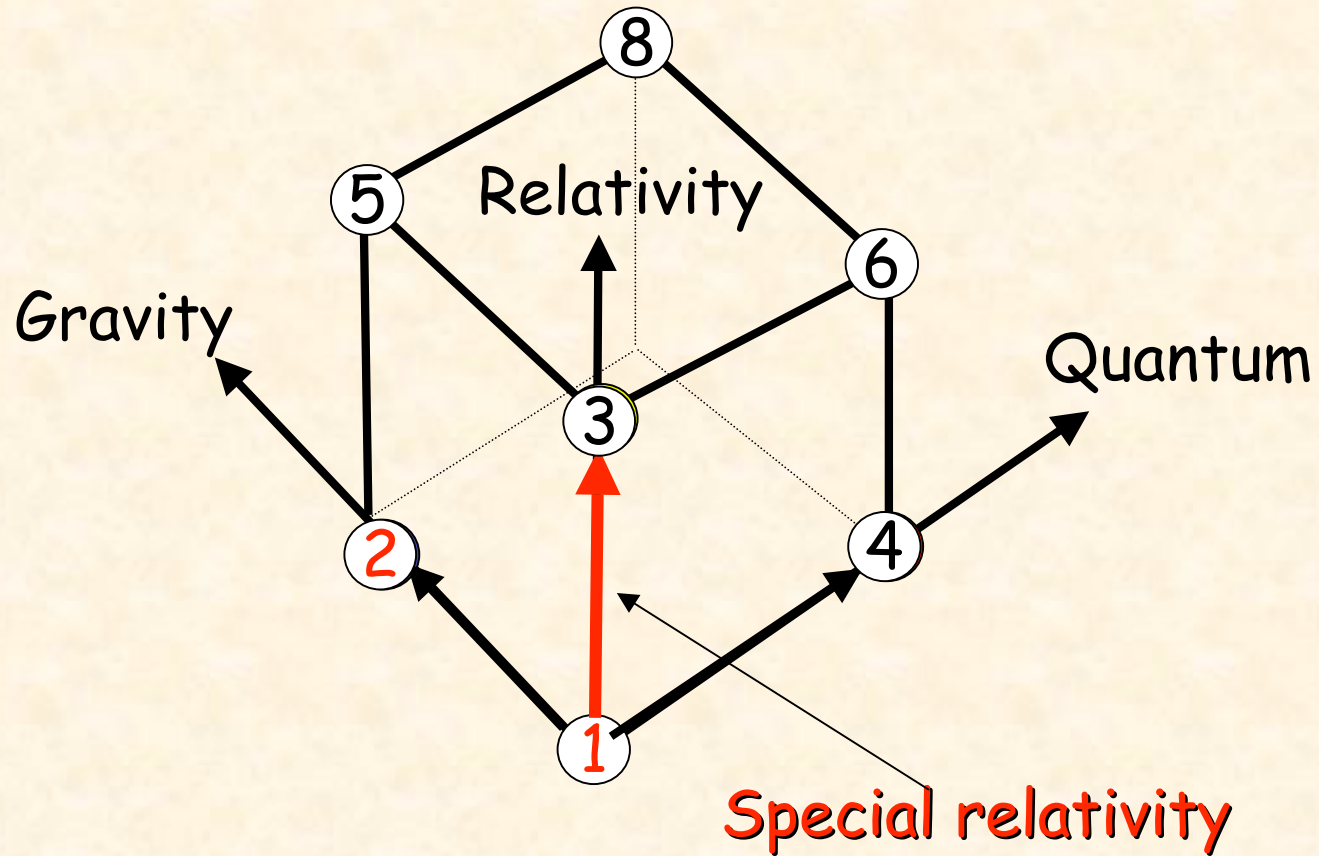
The trivial vertex



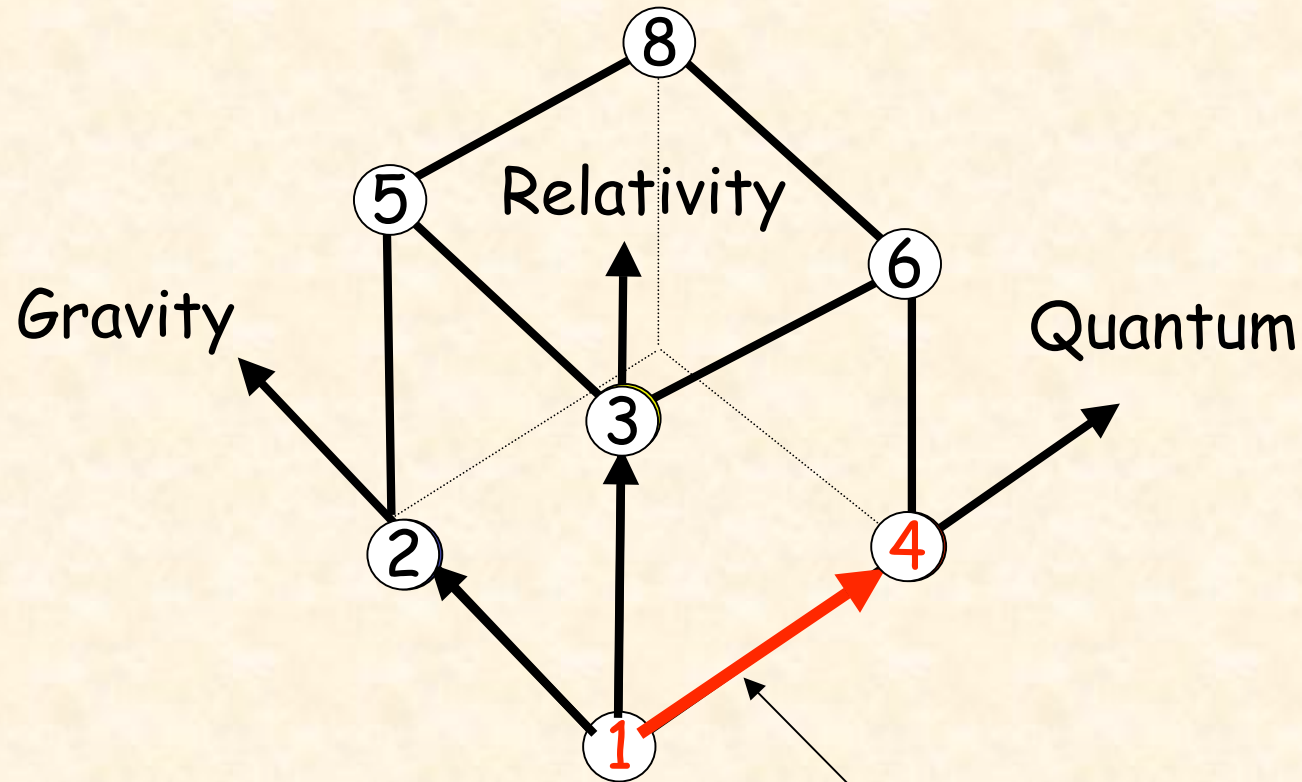
The simplest edges: I



The simplest edges: II

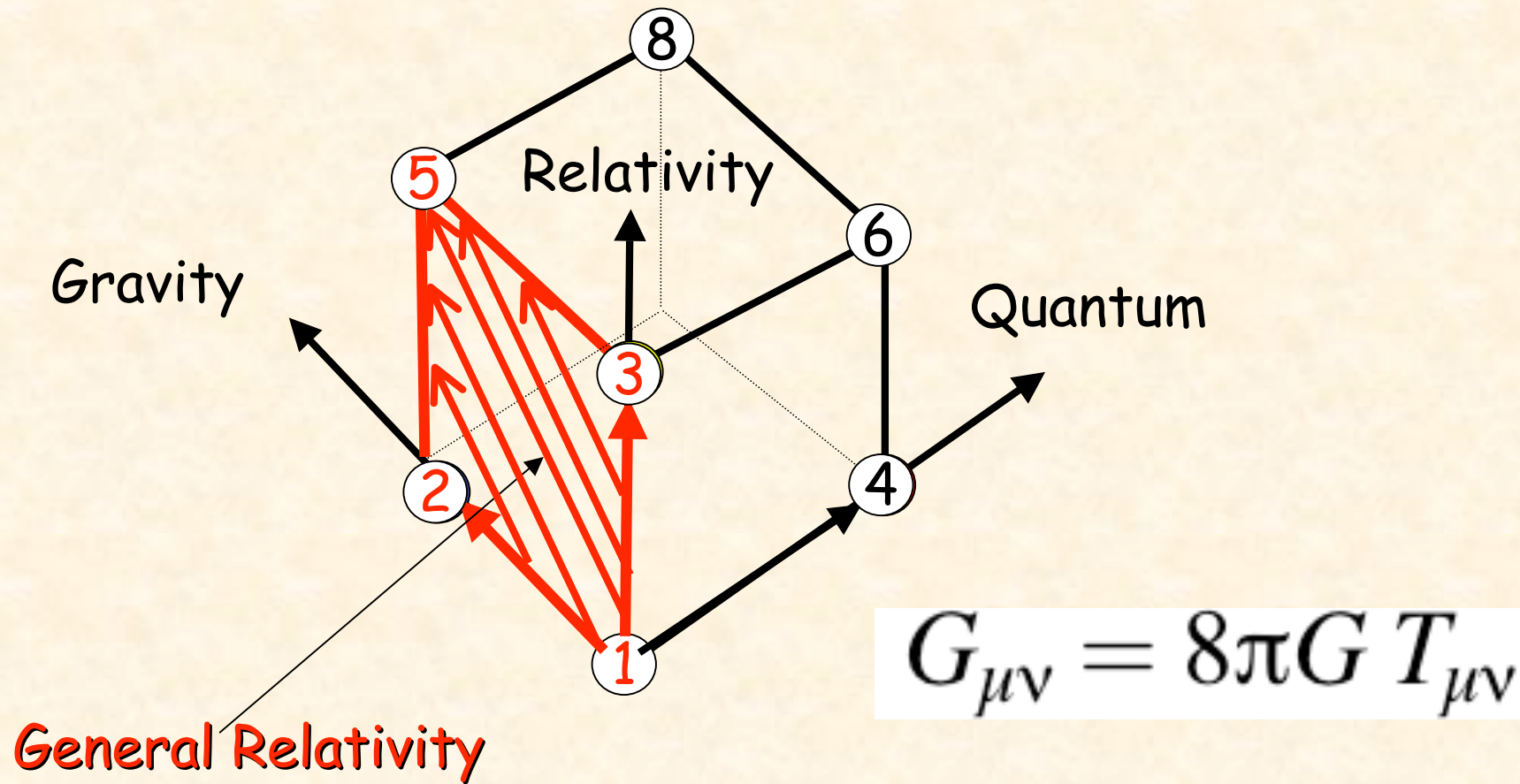


The simplest edges: III



Non-relativistic Quantum Mechanics: H-atom

The most relevant faces: I



$$NG + SR = GR$$

General Relativity (GR)

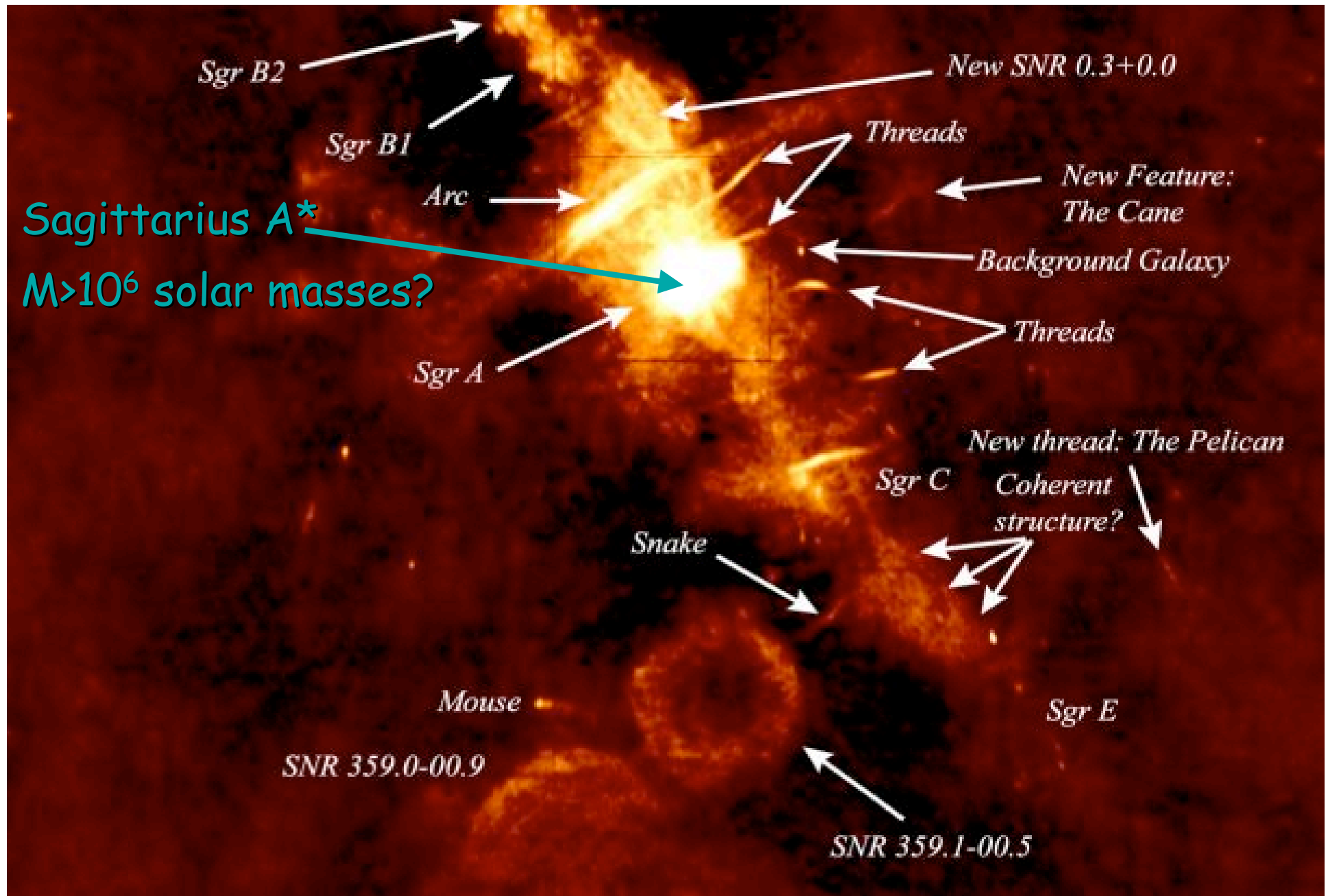
Our «Standard Model» of classical gravity

Corrections to NG better and better tested

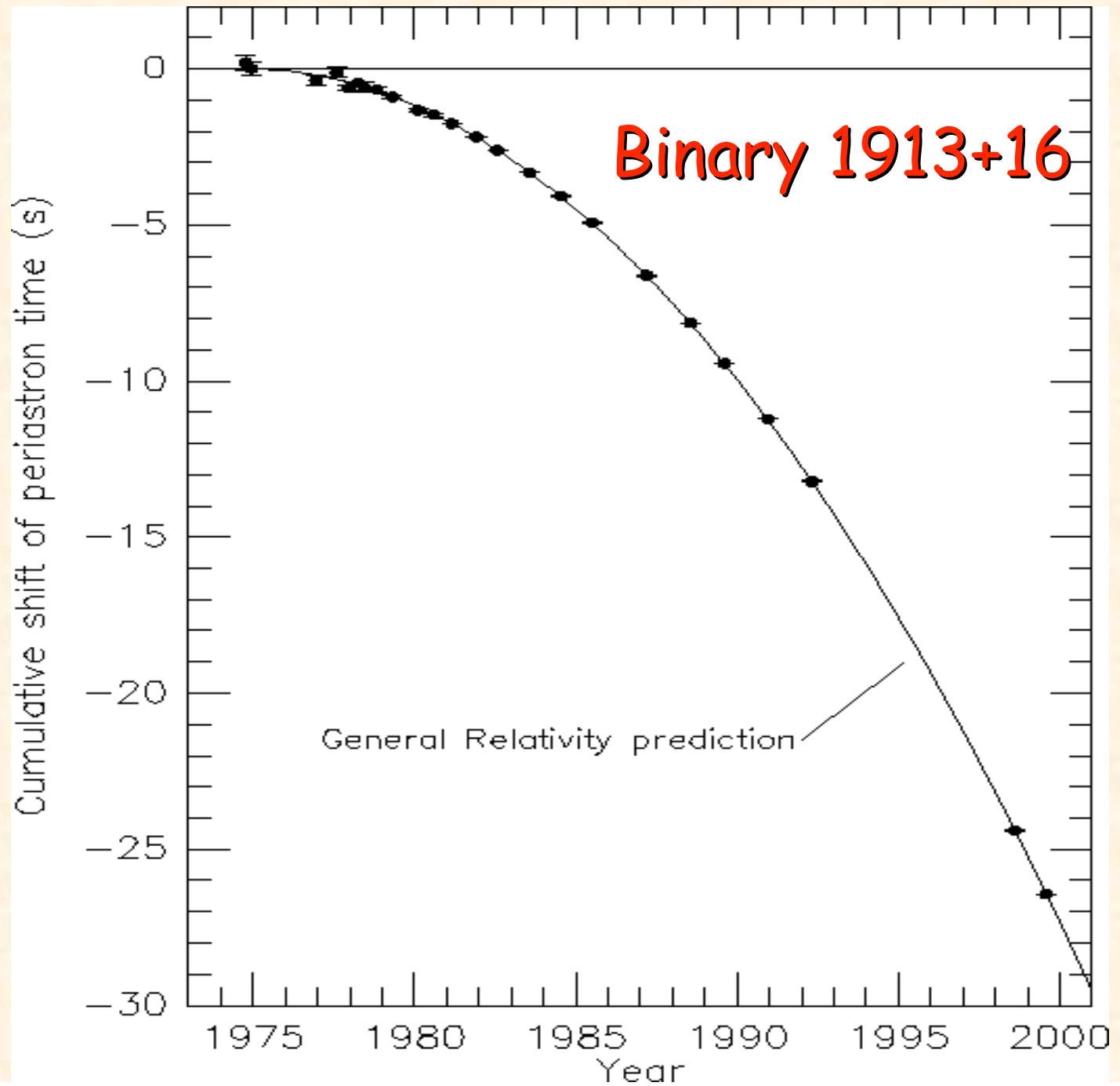
New predictions

1. **Black holes** (direct evidence)
2. **Gravitational waves** (indirect evidence)

Sagittarius A*
 $M > 10^6$ solar masses?



16.02.2007





LIGO (USA)



VIRGO(Cascina)

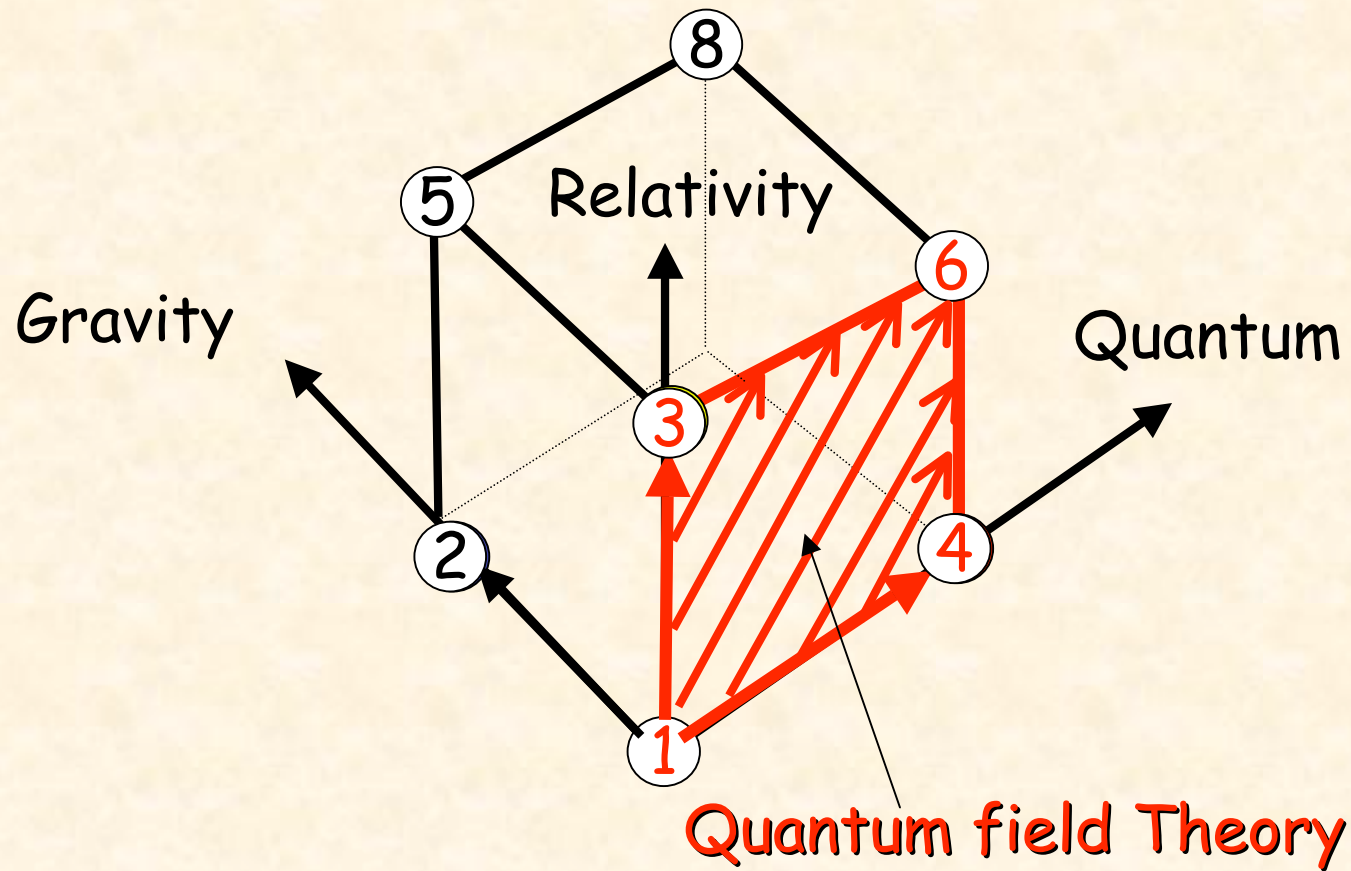


LISA



Explorer(CERN)

The most relevant faces: II



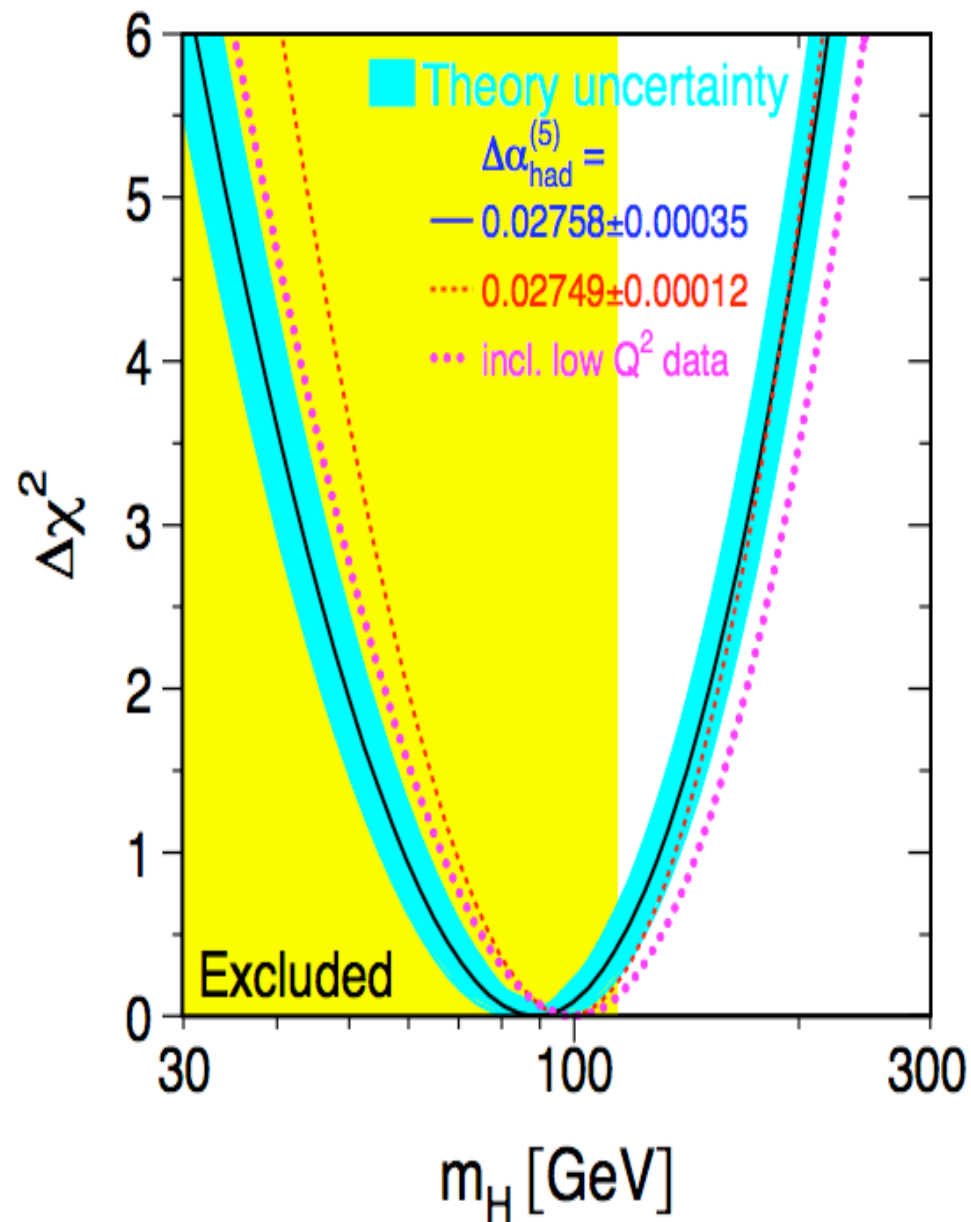
$$SR + QM = QFT$$

«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 with the
data:

The **SM** is **not** a **semiclassical** theory!

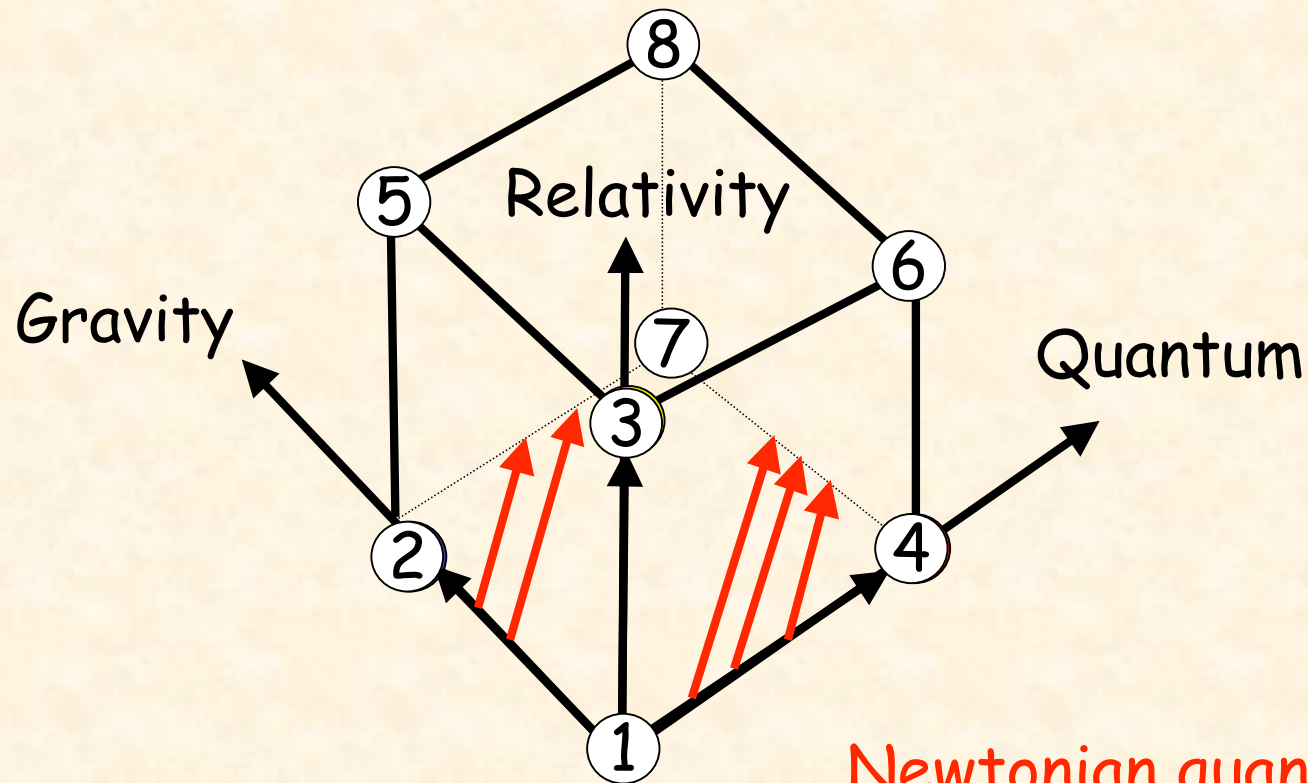
	Measurement	Fit	$10^{\text{meas}} - 0^{\text{fit}} / \sigma^{\text{meas}}$
			0 1 2 3
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.478	
R_1	20.767 ± 0.025	20.743	
$A_{\text{fb}}^{0,l}$	0.01714 ± 0.00095	0.01643	
$A_1(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21581	
R_c	0.1721 ± 0.0030	0.1722	
$A_{\text{fb}}^{0,b}$	0.0992 ± 0.0016	0.1037	
$A_{\text{fb}}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
$A_1(\text{SLD})$	0.1513 ± 0.0021	0.1480	
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$	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	



A photograph of the ATLAS detector at CERN, showing its complex, cylindrical structure with various layers and components. The detector is surrounded by support structures and cables. The text "ATLAS detector, LHC, CERN: Hunting the Higgs boson + ??" is overlaid on the image.

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

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

L.H.S. : Classical Geometry

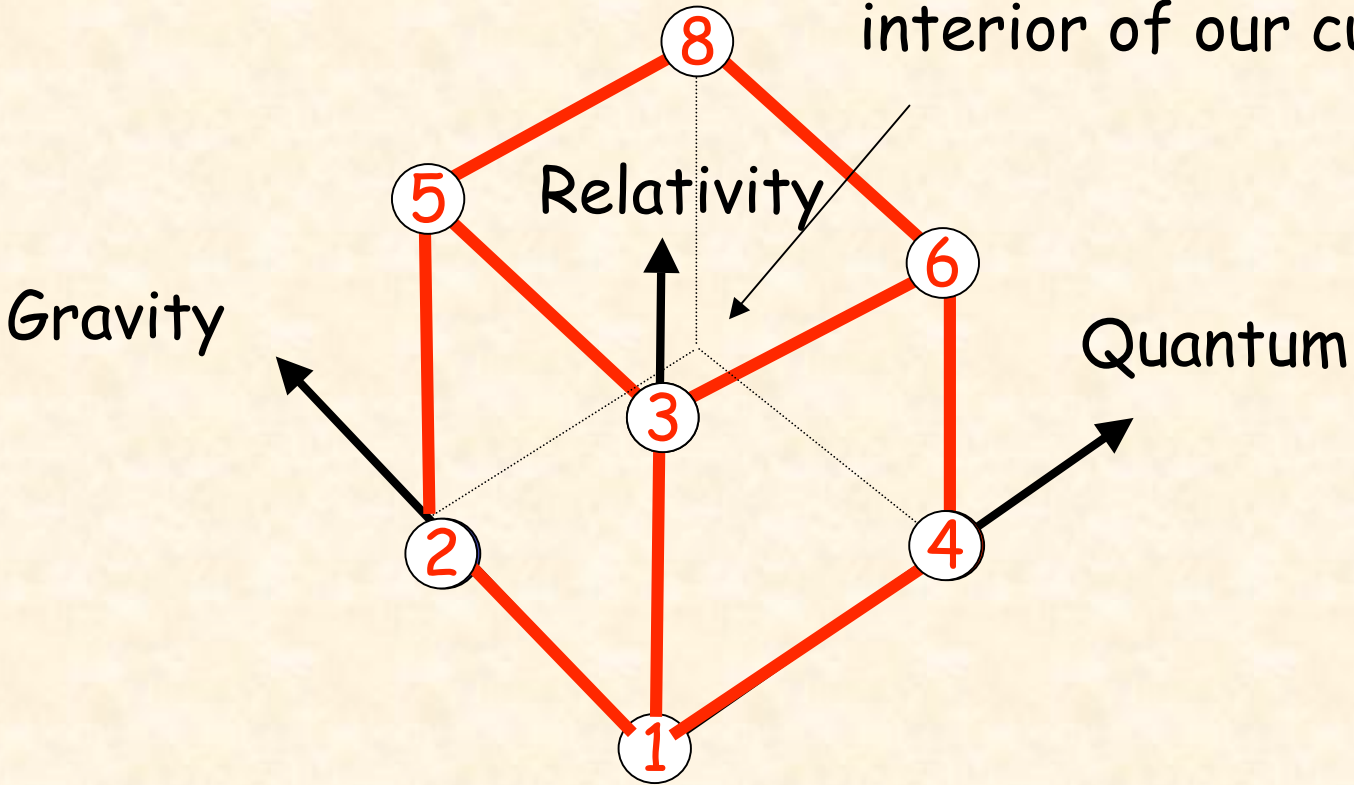
R.H.S. : Quantum Matter

Sounds inconsistent. E.g.: Classical cosmological constant or quantum-corrected potential energy of a scalar field? And what about the supposed quantum origin of LSS 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!



Expansion of the Universe

Far past \Rightarrow Very hot and dense Universe

Very hot Universe \Rightarrow Very high energies (R)

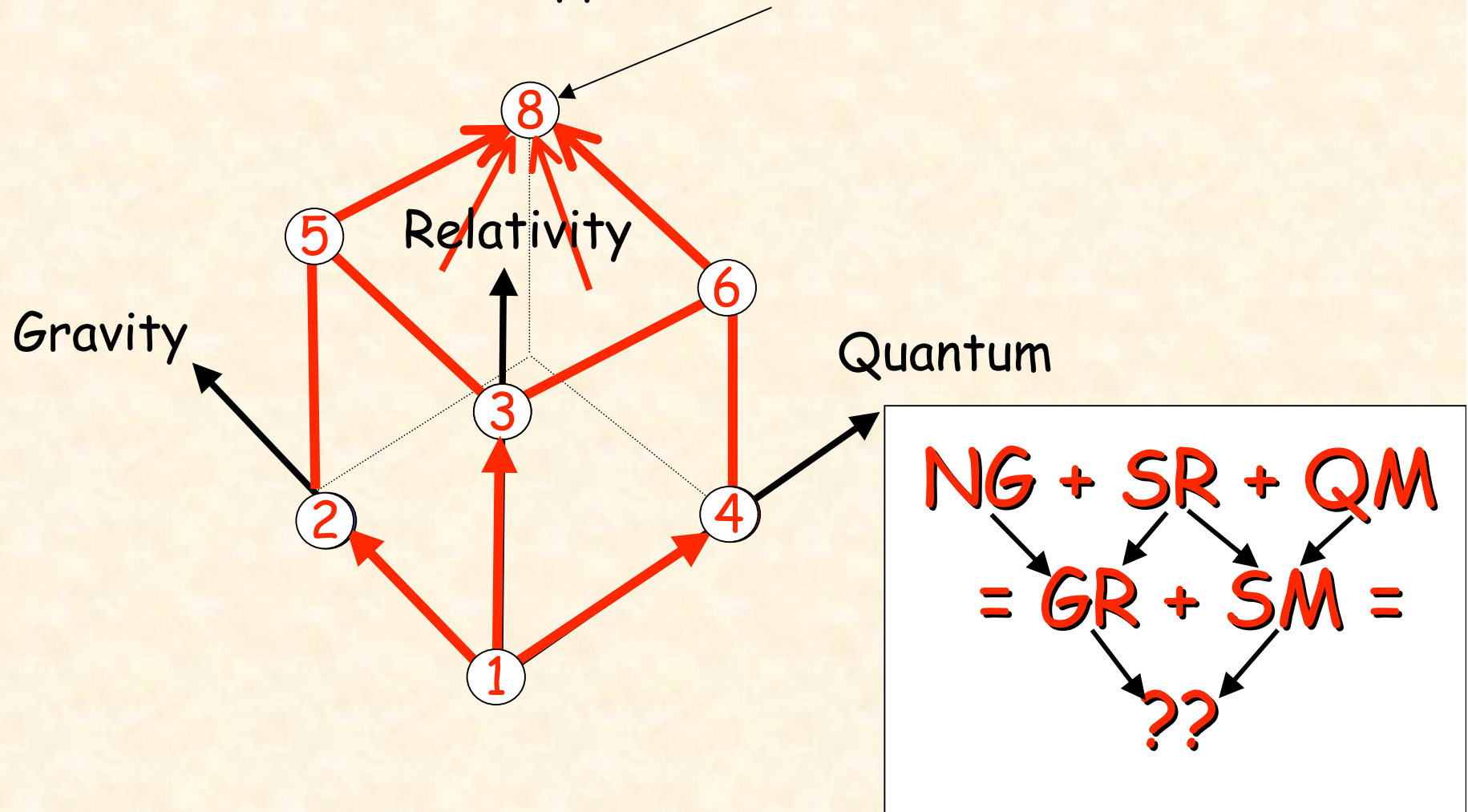
Very dense Univers \Rightarrow Very high curvature (G)

Very high curvature \Rightarrow Quantum processes (Q)

Far in space \longleftrightarrow 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**

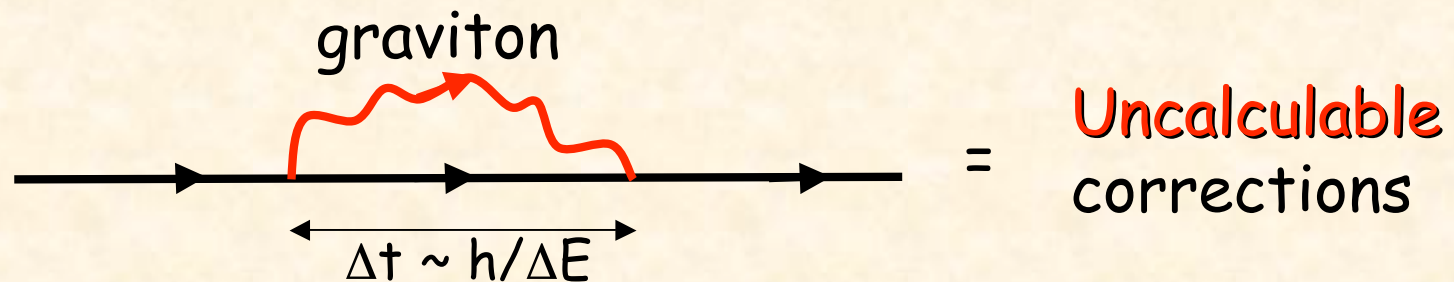
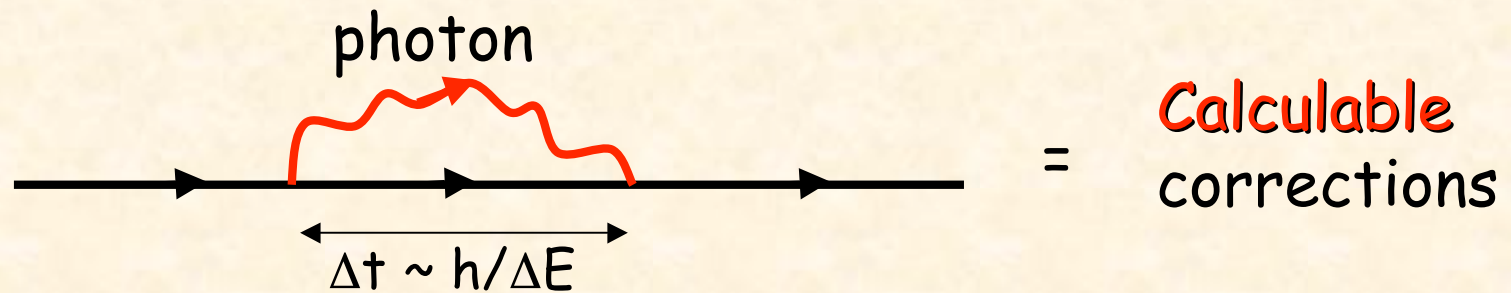
Near curvature singularities **quantum** corrections to GR cannot be neglected.

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!)



UV infinities even propagate down to low energies

Patologies in Quantum Field Theories

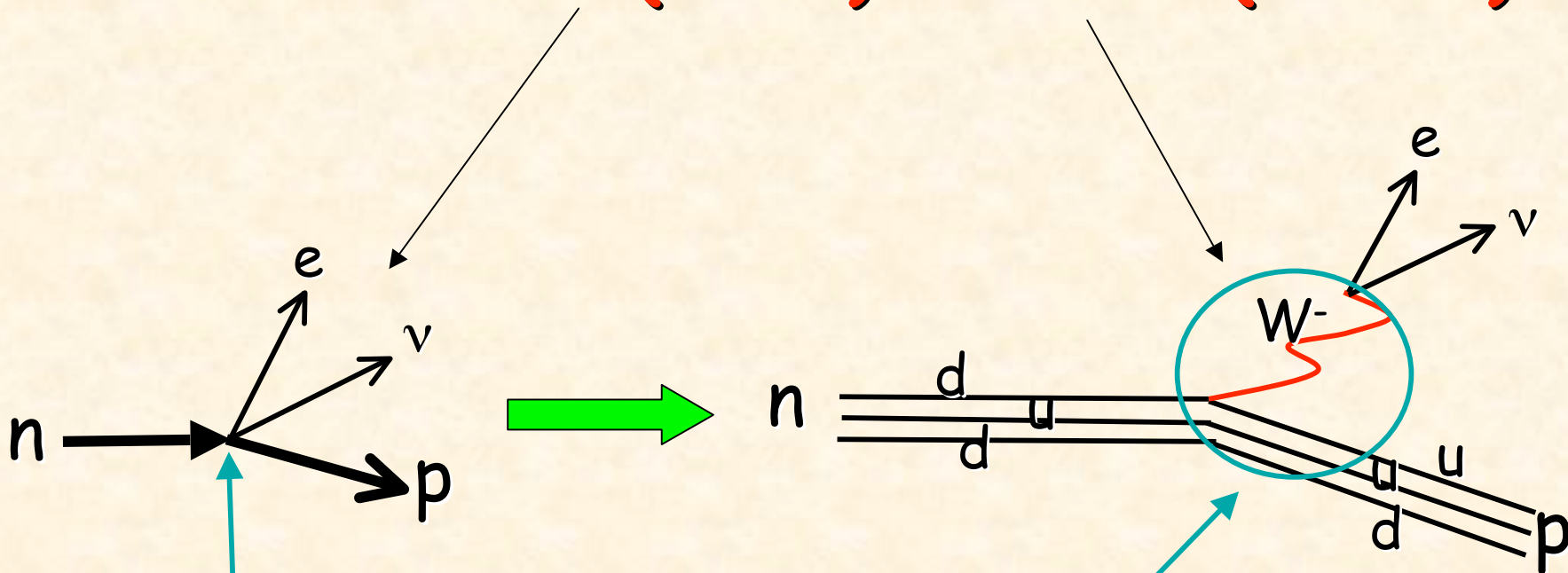
Even in the SM there are infinities. The difference is that we can tame them (renormalization)

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 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 »

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

Relativistic Quantum Strings

Strings + SR + QM = Grand Synthesis

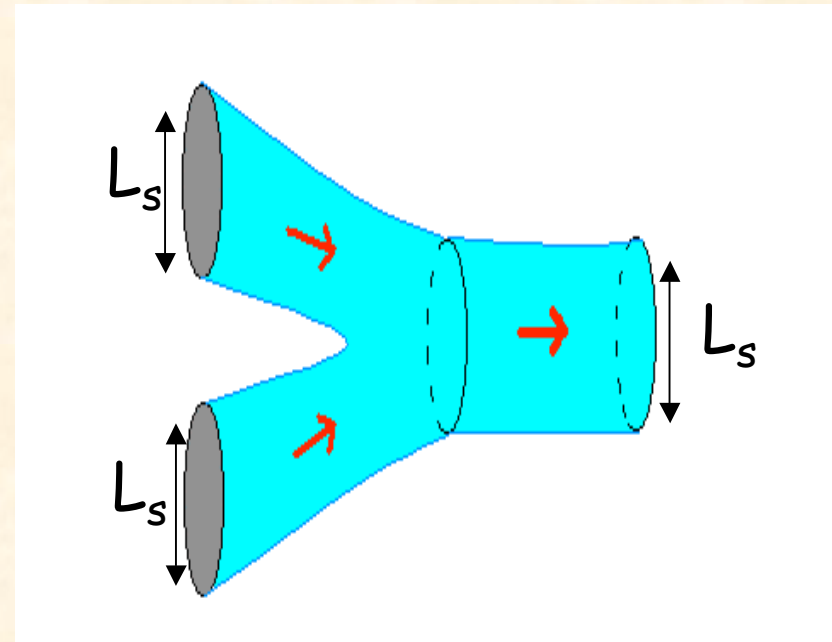
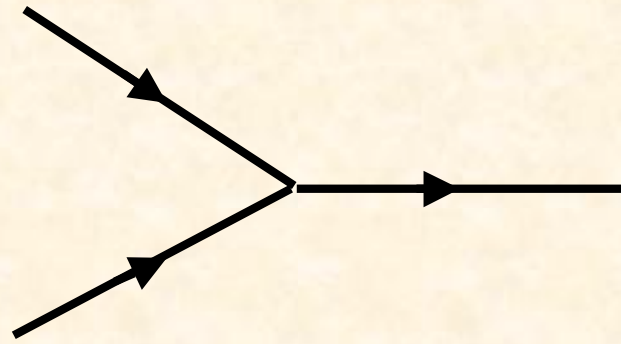
A magic 3-ingredient cocktail!

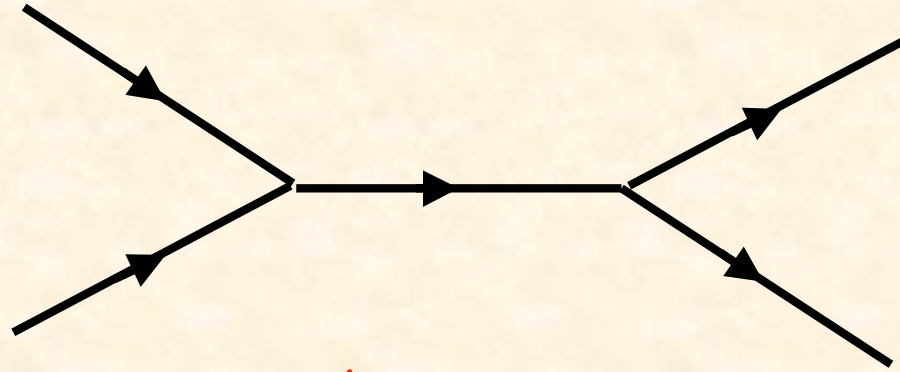
Quantum magic I

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

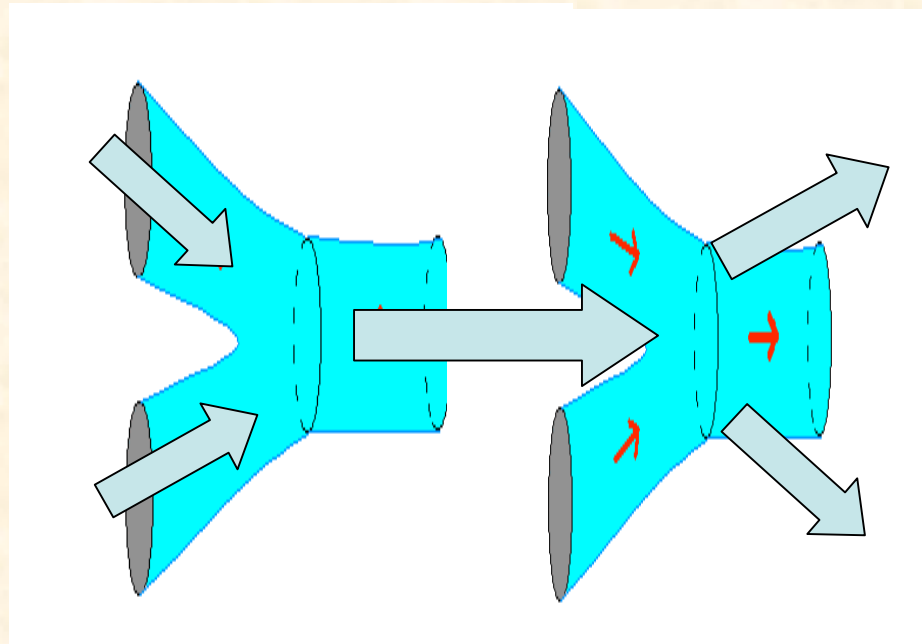
Quantum strings have a minimal (optimal) size L_s (Cf. Bohr radius, h.osc.), given by $L_s^2 = \hbar/T$. This length appears naturally in the (quantum) action of a string:

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





becomes



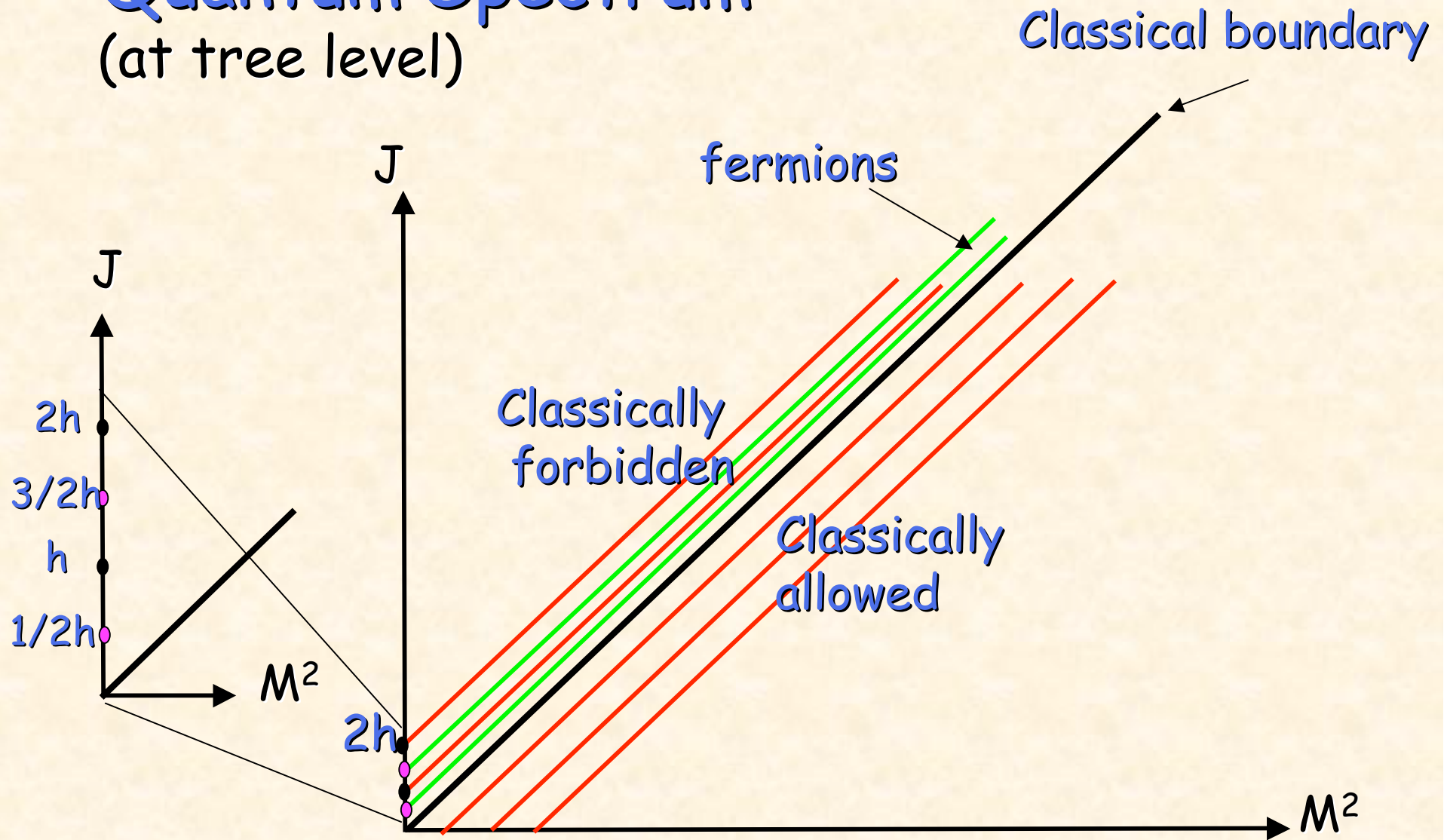
Quantum magic II

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

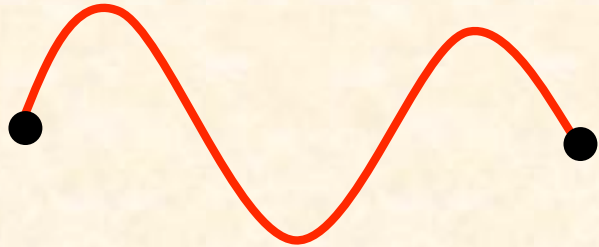
Quantum strings may have up to 2 units of J without acquiring mass:

$$\frac{M^2}{T} \geq J + \hbar \sum_1^{\infty} \frac{n}{2} = J - \alpha_0 \hbar \quad \alpha_0 = 1/2, 1, 3/2, 2.$$

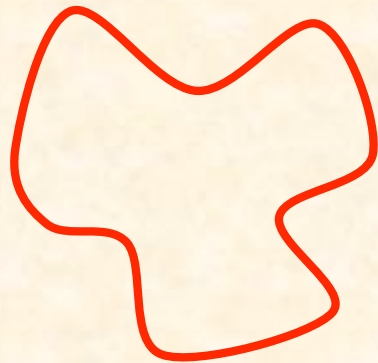
Quantum Spectrum (at tree level)



In particular..



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



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

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

Integer J massless states \Rightarrow **carriers of interactions;**
1/2-integer J massless (light) states \Rightarrow **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!

More quantum magic

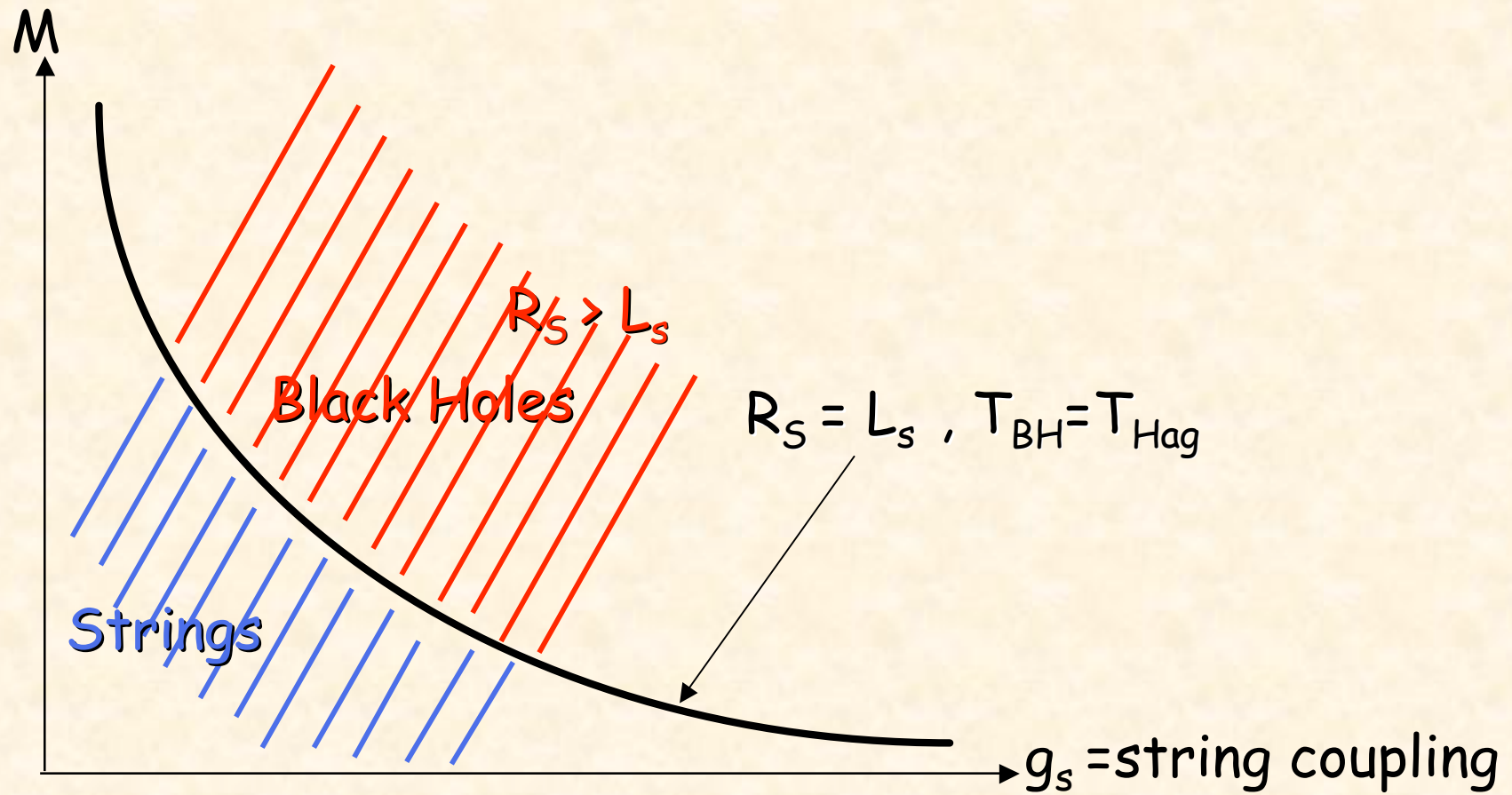
1. While classical strings can move consistently in any ambient space-time, quantum strings require **particular** «target» **space-times** in order to avoid lethal anomalies. A Minkowskian space-time must have 9 space and 1 time dimensions. Six of them must be compact & small..
2. But how small? A symmetry, called target-space **duality**, guaranties that compactification radii R_c and L_s^2/R_c are equivalent. At the fixed point of T-duality, $R_c = L_s$, new non abelian gauge interactions emerge through a stringy version of the Kaluza-Klein mechanism
3. This and other (strong-weak) dualities **unify conceptually** all known consistent quantum string theories (**M-theory**)

4. There are **no free parameters**: these are replaced by scalar fields whose VEVs 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**, threaten the **equivalence principle** and **universality of free-fall**, and induce space-time **variations** of the above «constants».
- ⇒ A very active field of experimental and theoretical research

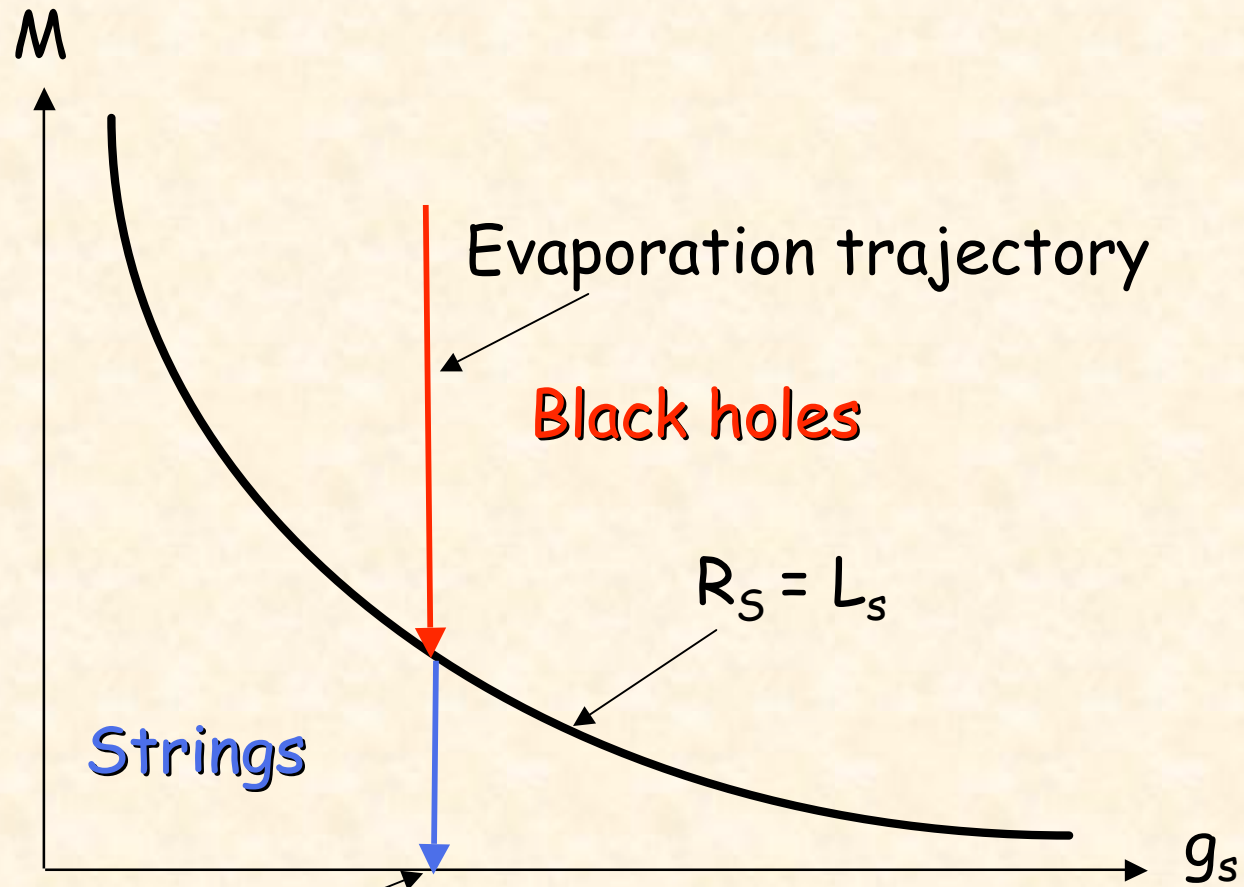
Other physical applications

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

String/Black Hole phase diagram



Evolution of evaporating Black Hole



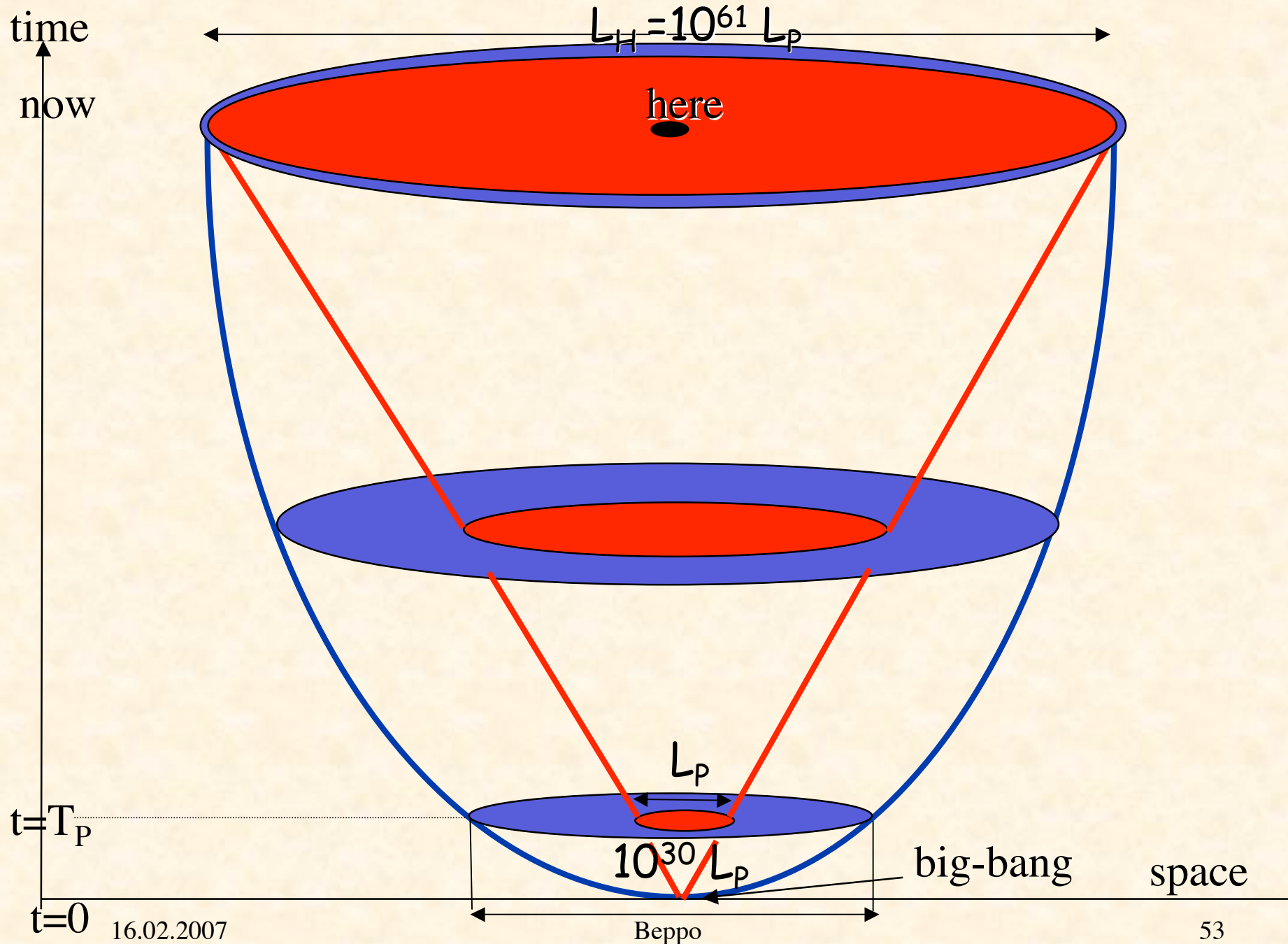
Would-be singularity: avoided thanks to $L_s \neq 0?$

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,
 $S_{\text{BH}} = A/4L_p^2$
- It also provides 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 initial state and then undergoes Hawking evaporation. Hawking himself has taken back (Dublin, 2004) his previous claims to the contrary
- An explicitly unitary S-matrix can be constructed for superstring collisions **up to** BH threshold

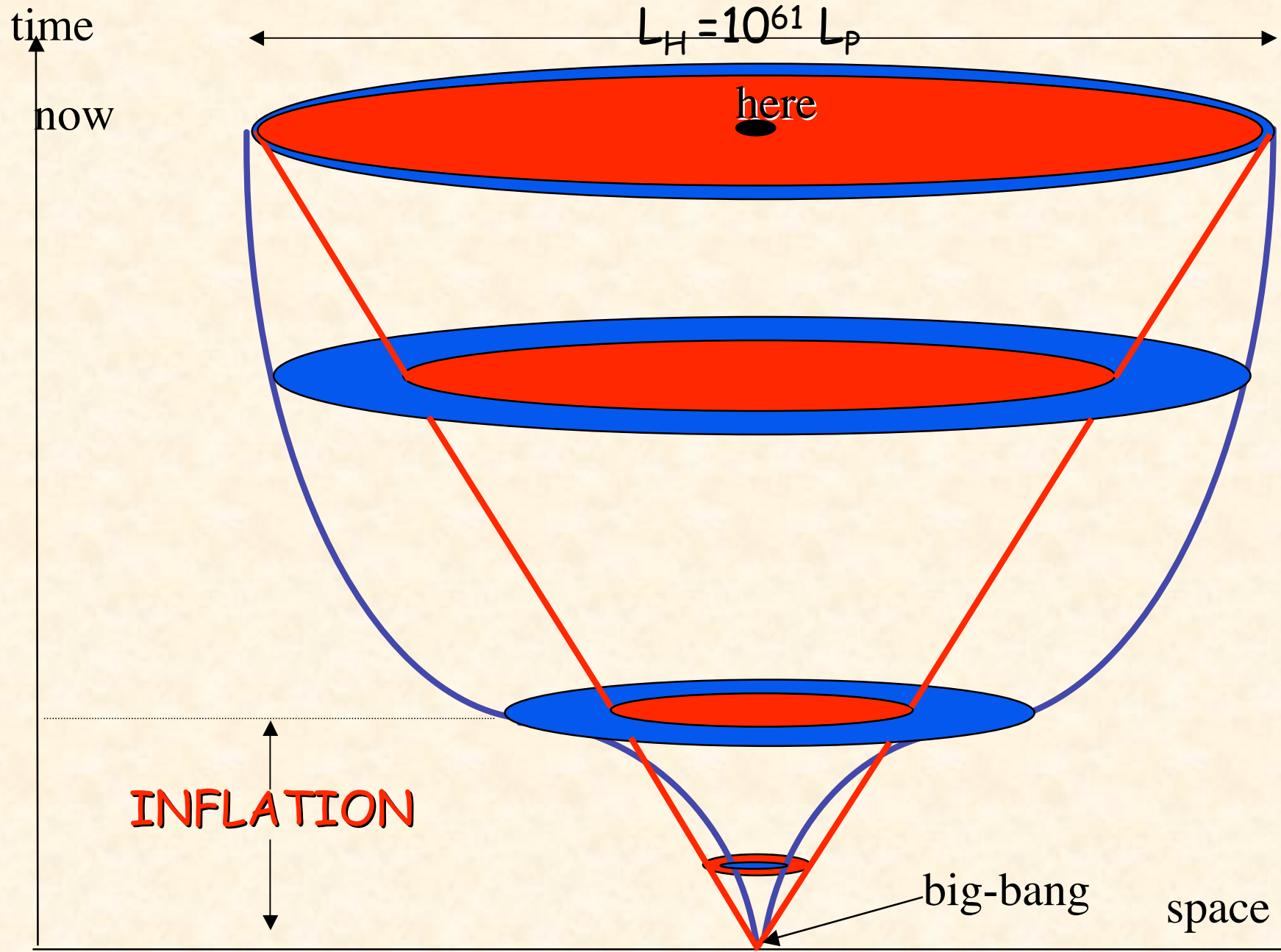
Cosmology

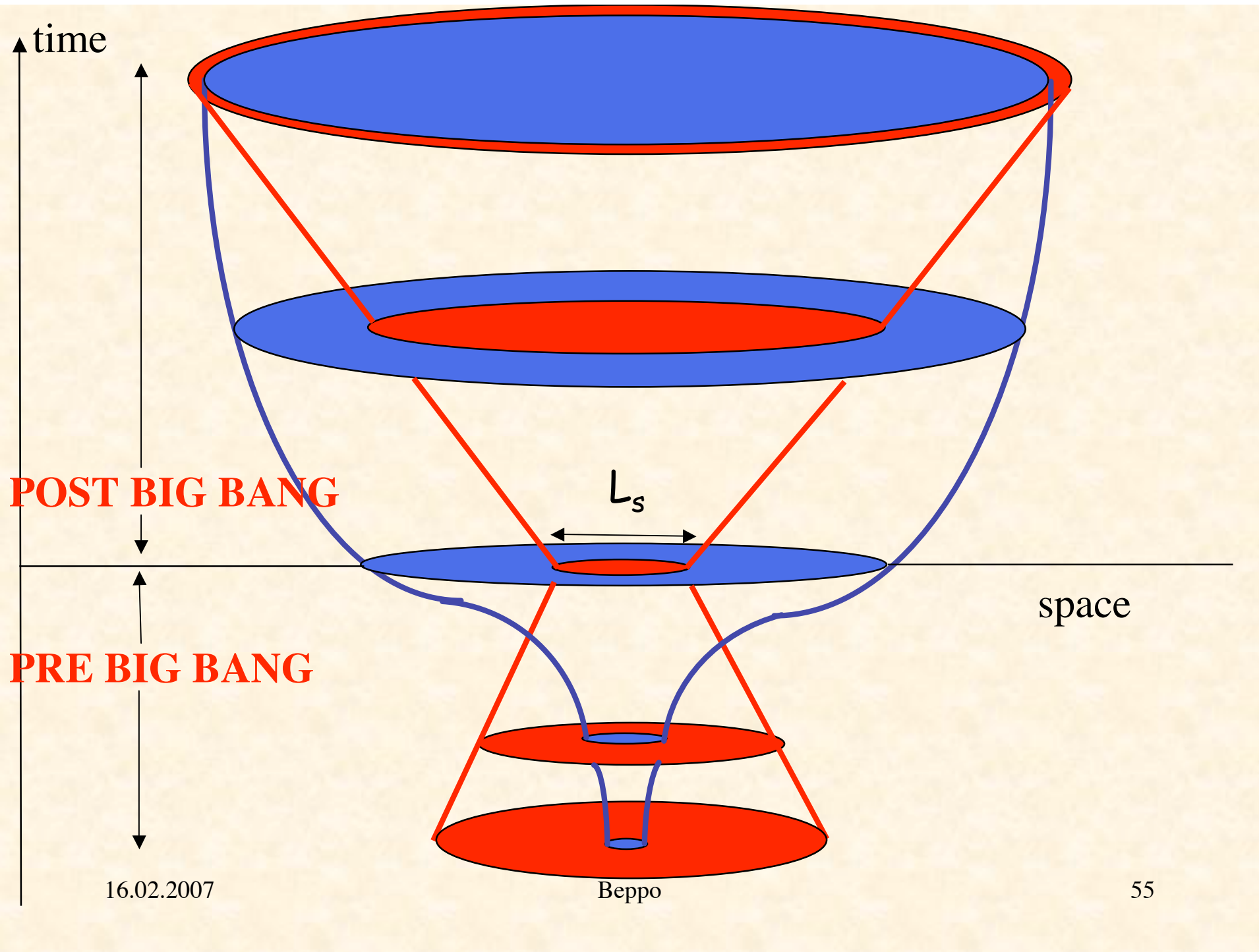
- String theory «**resolves**» certain **singularities** of GR
- Those associated with **cosmology** (big bang) are **harder** to deal with but it is likely that also there the singularity is eliminated/reinterpreted (new d.o.f.)
- If so we may conceive new cosmological scenarios in which the big bang, rather than representing the beginning of time, is the **result of a previous phase** in which space-time curvature (in particular the Hubble parameter H) grows
- A «string phase» would then make the Universe «bounce». The Big Bang becomes the «**Big Bounce**»
- These scenarios can solve in new ways the problems of standard cosmology: an **older**, rather than the smaller **Universe** of the inflationary paradigm.



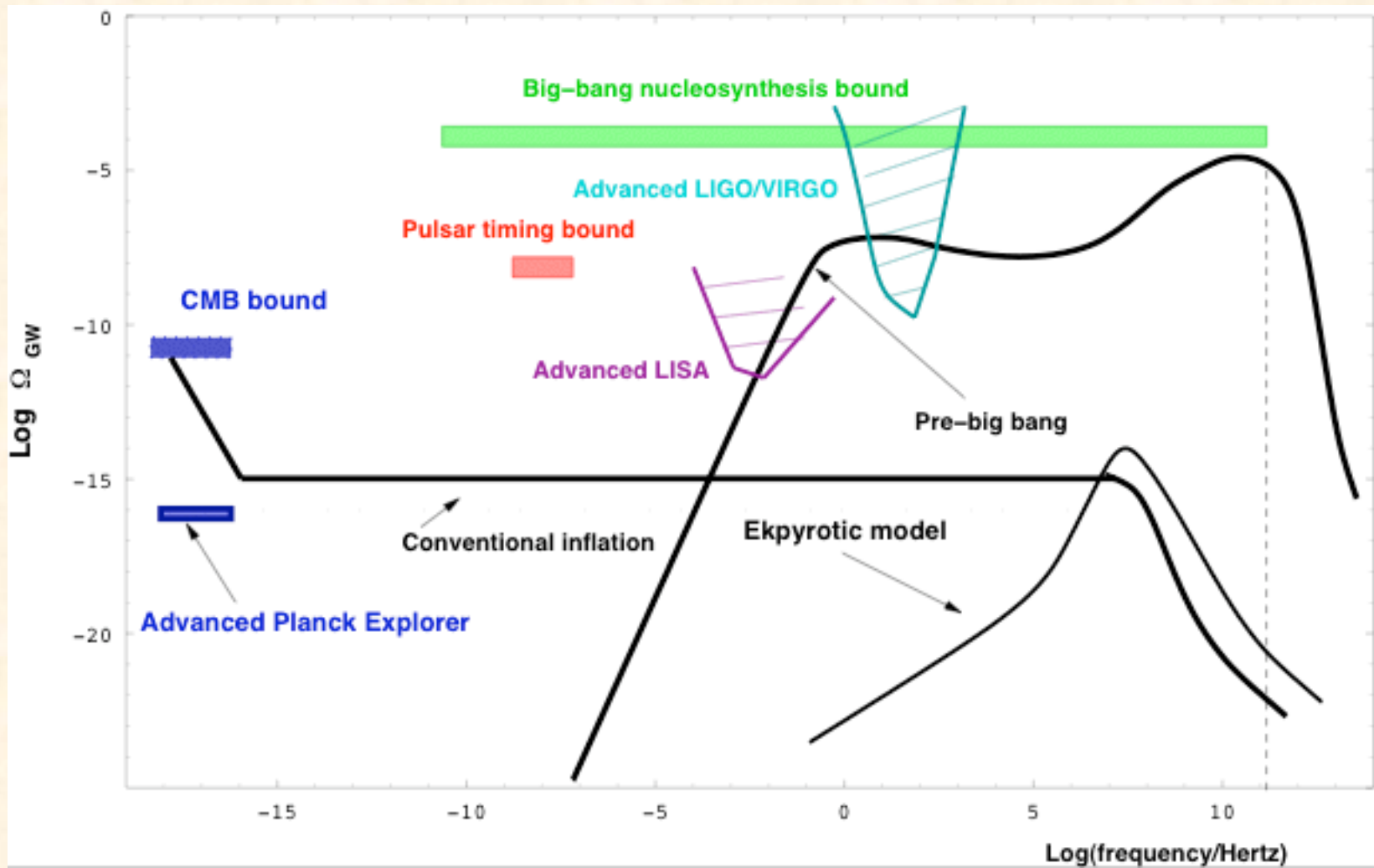
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Beppo

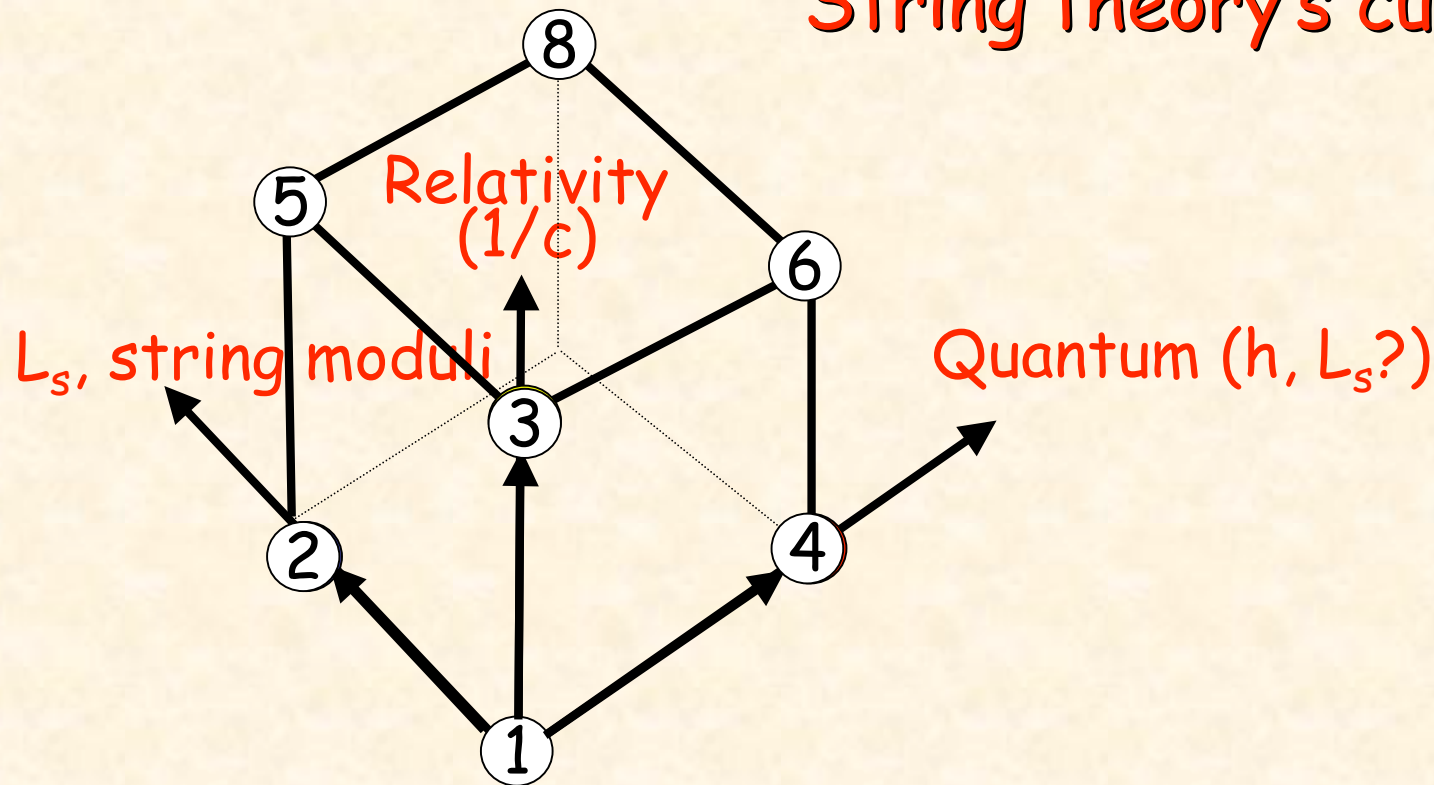




- These «pre big bang» cosmologies have observable consequences, can be tested in principle
- The reason is the one invoked for «observing» the inflationary epoch today: the **freeze-out** of perturbations while their wavelength exceeds the Hubble radius H^{-1} .
Examples:
 1. A **stochastic** background of **GW**
 2. Seeds for cosmic **magnetic fields** due to an evolving dilaton and/or internal dimensions during pre-bang phase
 3. A « curvaton » mechanism for generating **CMB** anisotropies and **LSS** (w/out tensor contribution)



String theory's cube?



Moduli determine, in principle, all dimensionless parameters.
Are they fixed, discrete, continuous?
The other major unsolved question in string theory!

Conclusion

- Einstein's dream appears to be **realized** in string theory, but in a way that could have been **hardly imagined** 50 years ago
- It gets realized **thanks to** (and **not against**) QM.
- Its starting point is **not** a classical field theory (Maxwell + GR) to be quantized with much pain, if at all.
- Without QM strings do not give a photon or a graviton, an electromagnetic or a gravitational field: these only emerge as semiclassical (large distance, large occupation number) limits of a **fundamentally quantum theory**.
- Einstein's dream comes true, but in a way that is opposite to the one he had been pursuing.

May be he would have reacted to String Theory, like he did to QM, by saying:

God does not play strings!

Or maybe he would have reconciled himself with QM

We will never know...

Instead, we can try to find out what Nature does!