Teaching the Universe, 10 July, 2018

Gravity and the primordial Universe

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Προλεγόμενα

- Gravity is very different from the other three interactions we know today.

- When we see in high school Coulomb's law and Newton's law, they look invariably VERY similar.

- But this is an illusion. This is only because Electro-Magnetism (EM) and Gravity have (apparently) massless force carriers (photon and graviton).

Actually: $m_\gamma \lesssim 10^{-14}\ \ eV$, $m_g \lesssim 10^{-34}\ \ eV$.

- But the similarities between GR and EM stop there:

- EM has both negative and positive charges. Different charges attract, same repel.

- Overall most of the bodies are approximately neutral. No major macroscopic forces are observed in EM.

- The charges of gravity (energies) are all ”positive”. Gravity forces are always attractive.

- This is the reason that although gravity is extremely weak,it dominates all other forces at large distances.

- The strength of gravity (the Newton’s constant G) has a different dimension than that of EM.

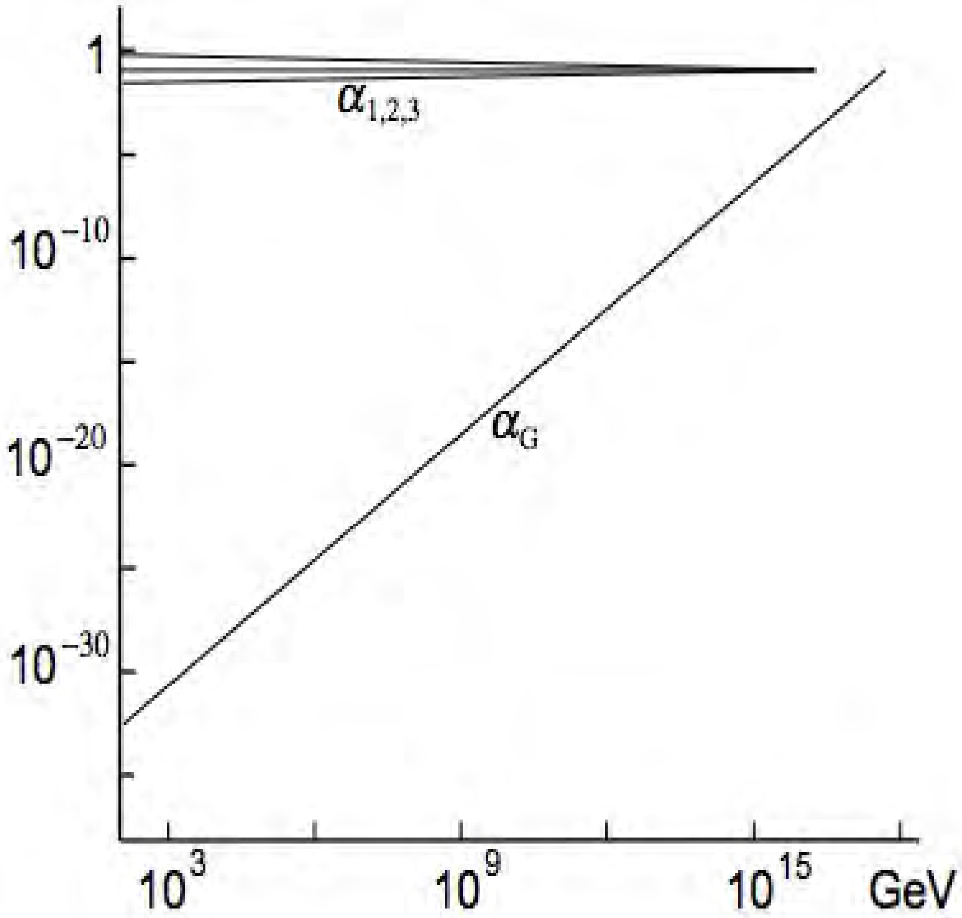

Figure 1: The three gauge couplings and the dimensionless gravitational coupling as functions of the energy. Here $\alpha_G = G_N E^2/8\pi$.

The quantum theory

- Einstein's gravity is a theory that defies a quantum treatment at arbitrarily high energies.

- If one tries to define the quantum theory, he finds that at high energies (ie larger than the Planck scale):

$$M_P^2 = \frac{1}{16\pi G} \quad \sim \quad (10^{19}\ GeV)^2$$

the relevant physics is ambiguous.

- This is not true for the weak and the strong force.

- But this is also true for EM: however here the theory breaks down at much higher energies:

$$E \sim e^{\frac{1}{\alpha_{EM}}}\ m_e \quad \sim \quad e^{137}\ m_e \quad \sim \quad 10^{57}\ GeV$$

- But for EM we can comfortably live without knowing what happens at $E > 10^{57}\ GeV$

- Why do we have to care about quantum gravity?

The big-bang revisited

- The conventional cosmological story we hear (since the times of Lemaître) is as follows:

- The universe expands and cools down.

- Therefore it must have been hot in the past.

- If we extrapolate in the past, at some point the density becomes infinite, and the theory (and time) stops: we can not move further back.

- This is the initial singularity: It is predicted by the cosmological equations (Freedman equations) of general relativity (GR).

- It is a breakdown of the classical GR equations.

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- This is a "naked" (uncensored) singularity: everyone is affected by it!

- This is the conventional meaning of the big-bang singularity.

- The classical GR equations lead to unpredictable situations.

- It is believed that one needs the quantum theory to resolve the initial singularity.

The novel big-bang

- As you have already heard, we now have good reasons to believe that the physics of the primordial universe is somewhat different.

- At some point in our past "inflation" happened.

- This is a very fast (almost exponential) expansion of the universe.

- This was advocated by several authors to solve several "fine tuning problems" of cosmology: the horizon problem, the flatness problem, the monopole problem etc.

- It did so at the expense of a new fine tuning: the potential of the inflaton must be very flat...

- or the theory must be in the quantum regime where we do not trust it.

- Inflation on the other hand produced one of the most interesting avatars in cosmology: a highly plausible theory of cosmological perturbations.

- This is in other words the beginning of the formation of structure in the universe.

- But during inflation the universe is cold and empty, very far from our usual picture of the hot universe.

- Almost all of the energy is vacuum energy during inflation.

- But at the end of inflation, we believe that this energy was reconverted into many different types of particles (including those of the Standard Model).

- The universe become hot again and continued to expand ”normally”.

- This process is known as reheating at the end of inflation.

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- This is the new "big-bang"

- It comes with the primordial perturbations frozen (until much later) in the largest strands of the fabric of space-time.

- Despite all the impressive successes of the inflationary idea, there are still many dark points:

♠Reheating (or the new big-bang) is poorly understood.

♠It is not known how inflation is incorporated into the fundamental theory (gravity+SM), and why there is a lot of fine tuning.

Before the "big-bang"

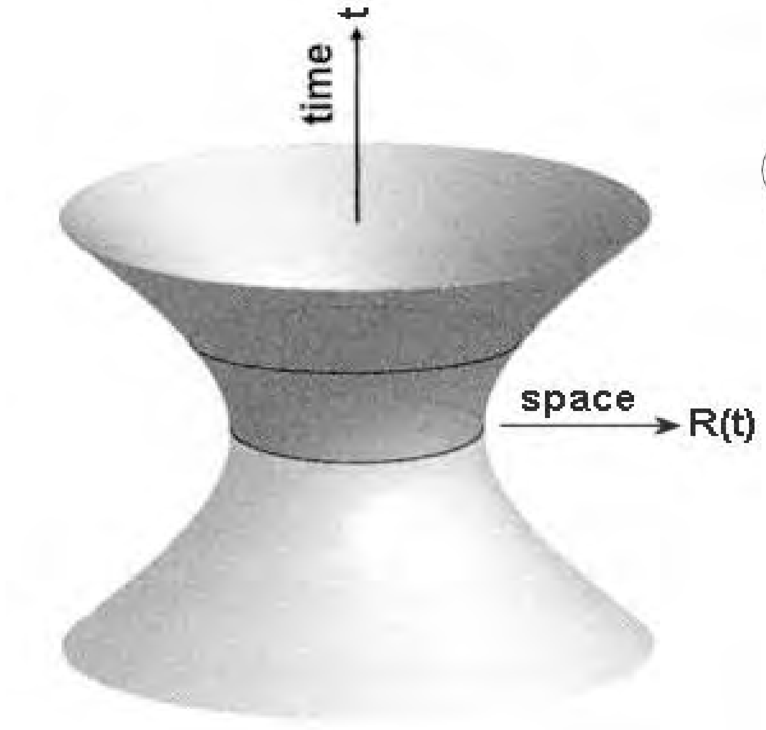
- According to the new story, the period before the "big bang" is the period of cosmological inflation and anything else before it.

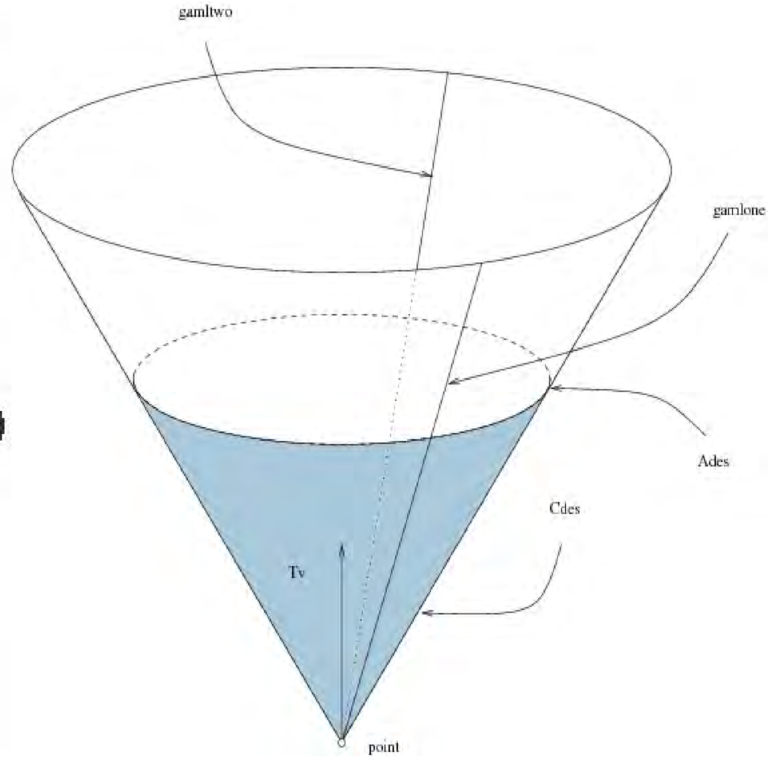
- How important is to know what happened before?

- It is much less than before: inflation dilutes by more than 10^{60} any previous energy, structure, density, features etc.

- However, the initial singularity problem remains: for generic configurations of the fields in the universe, there is still an initial singularity.

- But now a special option exists: for a specially tuned configuration of the fields in the universe the initial singularity disappears.





- This is known as de Sitter space and is a highly symmetric space.

- The behavior of quantum fields on this space is not well understood.

- The "big-bang" singularity is now a coordinate singularity (ie. a mirage).

- The infinite past, is an infinitely large 3-sphere exactly as the infinite future.

Dark energy and the Cosmological constant

- **Observations indicate that today the expansion of the universe is accelerating.**

- All known forms of matter produce a deceleration of the expansion

- Therefore, there must exist a source of antigravity)

- Such a source of antigravity is known since 1916: **It is the "energy of the vacuum"** (or the cosmological constant)

- It is known that Einstein changed after two years his gravity theory, when he learned that it did not have static cosmological solutions.

- For the scientists of 1916-1930 the observable universe appeared static at large scales

- Einstein found that if he added a cosmological constant in his theory there was a static cosmological solution.

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-\det(g)}\,[R-\Lambda]$$

- Since the 40's, there were indications that the universe expands and the cosmological constant was abandoned.

- Until 2000, when the observations indicated the presence of a small positive cosmological constant.

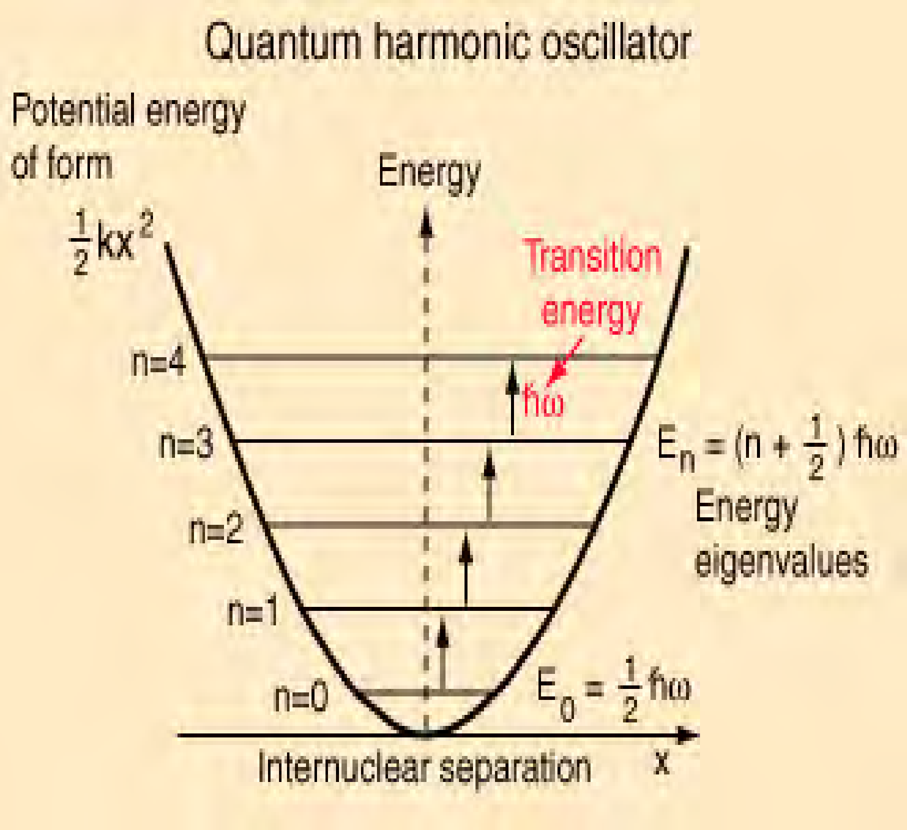
The quantum theory and the vacuum energy

- If we exclude gravity, all other interactions measure only energy differences.

- In quantum mechanics it is typical that the ground state has non-trivial energy and is ALWAYS above the minimum of the classical potential.

- The reason is the uncertainty principle: to localise a system costs momentum and therefore energy.

- Let us look at the simplest bound quantum mechanical system: a particle in the harmonic oscillator potential.



- The energy eigenvalues are

$$E_n = \hbar\omega\left(n + \frac{1}{2}\right)$$

- In the ground state the energy is non-zero:

$$E_0 = \frac{\hbar\omega}{2}$$

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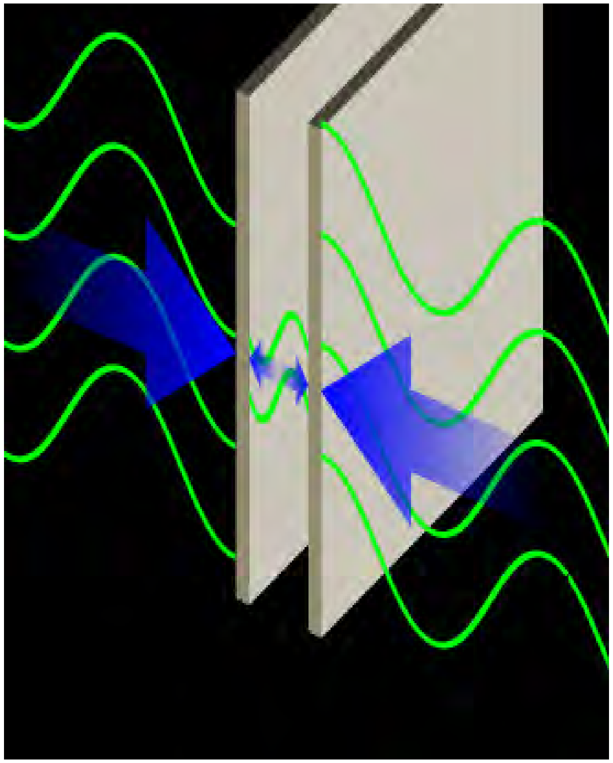
- In the quantum theory of fields, a free field theory is a collection of an infinite number of harmonic oscillators.

- Therefore the vacuum in quantum field theory has non-zero energy, and this has been measured in several cases.

The Casimir effect



- Casimir in 1948 predicted that the energy of the vacuum between two parallel metallic plates creates a force between the plates:

$$Force = \frac{\text{d Energy}}{\text{d Length}}$$

- This force was measured for the first time in 1997 by S. Lamoreaux in Los Alamos and found to agree with the quantum field theory calculations with an accuracy better than 1%.

- So the quantum mechanical energy of the vacuum is a reality.

- But does this energy interact with gravity? Do quantum mechanical corrections to energies interact gravitationally?

- The naive expectation is that all energies interact gravitationally. But as there were problems with this idea , experimental checks were needed.

- It is well known that about a few percent of the mass of the proton and neutron is due to quantum corrections due to the EM interaction. This has been verified by measurement.

- It is also well known that this quantum contribution to the mass (energy) gravitates (other wise the equivalence principle that is measured to very high accuracy would have failed).

- Therefore, quantum contributions to the energy gravitate with an accuracy of better than 1/1000.

- **Corollary:** The quantum field theories that describe the three (non-gravitational interactions) give us the opportunity to calculate the vacuum energy.

The Big Fiasco

- A calculation of the vacuum energy in the known theories of interactions (the Standard Model) gives the ratio of vacuum energy density (Λ_{QFT} to the Planck scale to be e'inai

$$\frac{\Lambda_{QFT}}{M_P^2} \quad \simeq \quad 1 \quad , \quad M_P^2 = \frac{\hbar \; c}{G}$$

- However the recent cosmological measurements give:

$$\frac{\Lambda_{cosmo}}{M_P^2} \quad \simeq \quad 10^{-60}$$

- The QFT calculation is wrong by sixty orders of magnitude!

- Even if we substitute the theory of matter, at higher energies with the best behaved QFT, we will get at best

$$\frac{\Lambda_{QFT}}{M_P^2} \quad \simeq \quad 10^{-30}$$

- This is the biggest error ever made in physics!

- **Gravity and Quantum Mechanics are not well behaved together**

- There are many things that have been tried (reviewed by Prof. Georgantopoulos).

- So far NONE has worked.

Black Holes

- One of the strangest predictions of GR is that of black holes.

- The Schwarzchild solution was found a year after GR appeared.

- It took 40 years for physicists to understand the full meaning of this solution:

♠Far away it describes the gravitational field of a mass M particle.

♠But close to the "center" it has a horizon at $R \sim M$.

♠In the original Schwarzchild coordinates the horizon is a singular surface. But this is only a coordinate singularity. This is a "censored" singularity.

♠Classically, the horizon is a semipermeable surface (hence the name black hole).

♠The solution has a single parameter: M.

♠The horizon hides a "singularity" at the center.

♠This is again one of the recurring features of classical gravity: predictability breaks down and the theory "cries from help".

- For years, it looked like black holes are mythical beasts confined to the phantasy world.

- As you have heard, this is no longer true.

Black holes and thermodynamics

In a period of 3 years, it was discovered that black holes follow the laws of thermodynamics

Christodoulou, Carter, Bekenstein, Hawking, 1970-72

- In particular, they have entropy that is larger (by far) than any other physical system of the same volume.

- Moreover, the entropy, instead of scaling as the volume of the BH, it scales like the area of the horizon:

$$S \quad \sim \quad R^2 \quad \sim \quad M^2 \quad , \quad G = \hbar = c = 1$$

- In 1974, Hawking showed that if treat matter around the black hole quantum mechanically, then the black hole evaporates by emitting black body radiation with a temperature equal to that calculated from the thermodynamic laws.

- In physics, thermodynamics emerges as the collective description of many-body systems at finite energy/temperature.

- Entropy is the measure of the many microstates of matter that make the many-body system.

- But in gravity there is no substructure in the black hole solution.

- Where are the microstates that explain the thermodynamics?

- And this leads to a theoretical paradox:

♠Take matter in a pure quantum mechanical state to collapse and form a black hole.

♠Wait long enough until the black hole evaporates.

♠Now the final state is Hawking radiation. It is thermal, and therefore is in a mixed state.

♠A pure state evolving in a mixed state is NOT allowed by the laws of quantum mechanics.

- Today we (theoretically) understand some of the mysteries posed by the black hole paradox, (thanks to string theory) but not all.

- The thermodynamic connection suggested that maybe the gravitational field is not a fundamental field but a collective field (like pressure, or temperature in thermodynamics).

- If that is the case, trying to quantize it directly, is not a good approach.

- In standard thermodynamics, we do not quantize pressure or temperature.

- Rather, we must find the microscopic degrees of freedom (atoms, molecules, protons etc) and implement the rules of quantum mechanics on these.

A parallel for the strong interactions

• In hadronic physics, in the 60's, the theory appeared complex: many particles (pions, nucleons), and strong non-renormalizable* interactions among pions and nucleons.

• The nature of hadronic interactions, had the same problems as that of gravity.

• But in late 60's, experiments at SLAC suggested a novel possibility:

♠That hadrons are composites of more elementary constituents (quarks, gluons)

♠The interactions of quarks and gluons are simple at high energy, but complicated at low energy (forming bound states with complicated interactions that behave badly at high-energy).

• The bad behavior of low-energy hadronic interactions when extrapolated to high energy, could be now explained:

♠The fundamental degrees of freedom at high energy where quarks and gluons, not hadrons.

♠Therefore, the extrapolation to high energy of the low-energy theory fails.

♠The theory that describes the strong interactions is now known as Quantum Chromodynamics (QCD), its elementary fields are quarks and gluons, and it is well behaved at all energies.

♠But it is strongly-coupled at low energy and any attempt to describe low-energy physics using quarks and gluons is messy.

• Therefore: at high energy the simple description is in terms of quarks and gluons.

♠Low energy physics is best described by interacting hadrons.

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♠If the pions of QCD were massless, then their interactions would be almost like gravity:

- The interaction would have infinite range, it will be very weak at low energies and strong at higher energy. The analogue of the Planck scale is the pion decay constant $f_\pi \simeq 190 MeV$.

- The only difference is that that the spin of the carriers is zero, and there are nine of them.

Emergent gravitons

- What if something similar happened for gravity:

♠At low energy, the theory is classical and weakly coupled. The relevant field is the space-time metric.

♠But at high energies the space-time metric is a bound state of more fundamental ingredients, making the theory well behaved.

♠May be also this would explain the microscopic degrees of freedom needed to explain the entropy of black holes.

- Efforts in that direction, started soon after the advent of QCD, in the mid-seventies.

- But it was very difficult to make spin-two bound states (like the graviton) with zero mass.

- In 1980, Weinberg and Witten proved a theorem:

♠"It is impossible a 4d Lorentz invariant QFT in flat space, to contain a state that has spin two and is massless"

- The theoretical efforts ceased.

- But already in 1976, Schwarz and Scherk and Yoneya, suggested that a good quantum theory of gravity would be given by a string theory (as those proposed in late 60s to describe the strong interactions).

- It was indeed true, that closed string theories were quantum theories and always contained a massless graviton.

- This was one of the basic reasons that such theories were studied intensely in the eighties and nineties.

- In 1997, the two ideas, string theory and emergent/composite gravitons met again in an unexpected fashion.

The holographic correspondance of gravity and QFT

- In 1997, J. Maldacena suggested that a 10-dimensional string theory, that contains among other things, 10-dimensional gravity, is equivalent to a four-dimensional strongly coupled gauge theory (a bit like QCD).

- The gravitons could be thought as "bound-states" of gluons.

- This is a case of a "duality": the same theory has two equivalent (but very different-looking) descriptions.

- A black hole in this 10-dimensional string/gravity theory was equivalent to the canonical ensemble of the dual gauge theory, with the same temperature.

- The microscopic states of this black hole where the states of the dual quantum field theory.

- Gravity emerged like magic from the quantum gauge theory.

- It is now clear that ANY quantum field theory has a dual string theory/ gravitational description.

- But few QFTs have a dual theory of only gravity and few other fields, that is weakly coupled.

- This opens the way for understanding the fundamental degrees of freedom of observable gravity.

- We can now try to understand the point of clash between gravity and the quantum theory we mentioned already.

- But most interestingly we can also study other gravity theories.

QCD revisited

- Could be that QCD be described as a theory of gravity?

- The answer is yes, but:

- At high energies (when the gluons interact weakly) one needs the full string theory associated to QCD

- At low energies the graviton is massive. Its mass is about 1.7 GeV (it is known as the 2^{++} glueball).

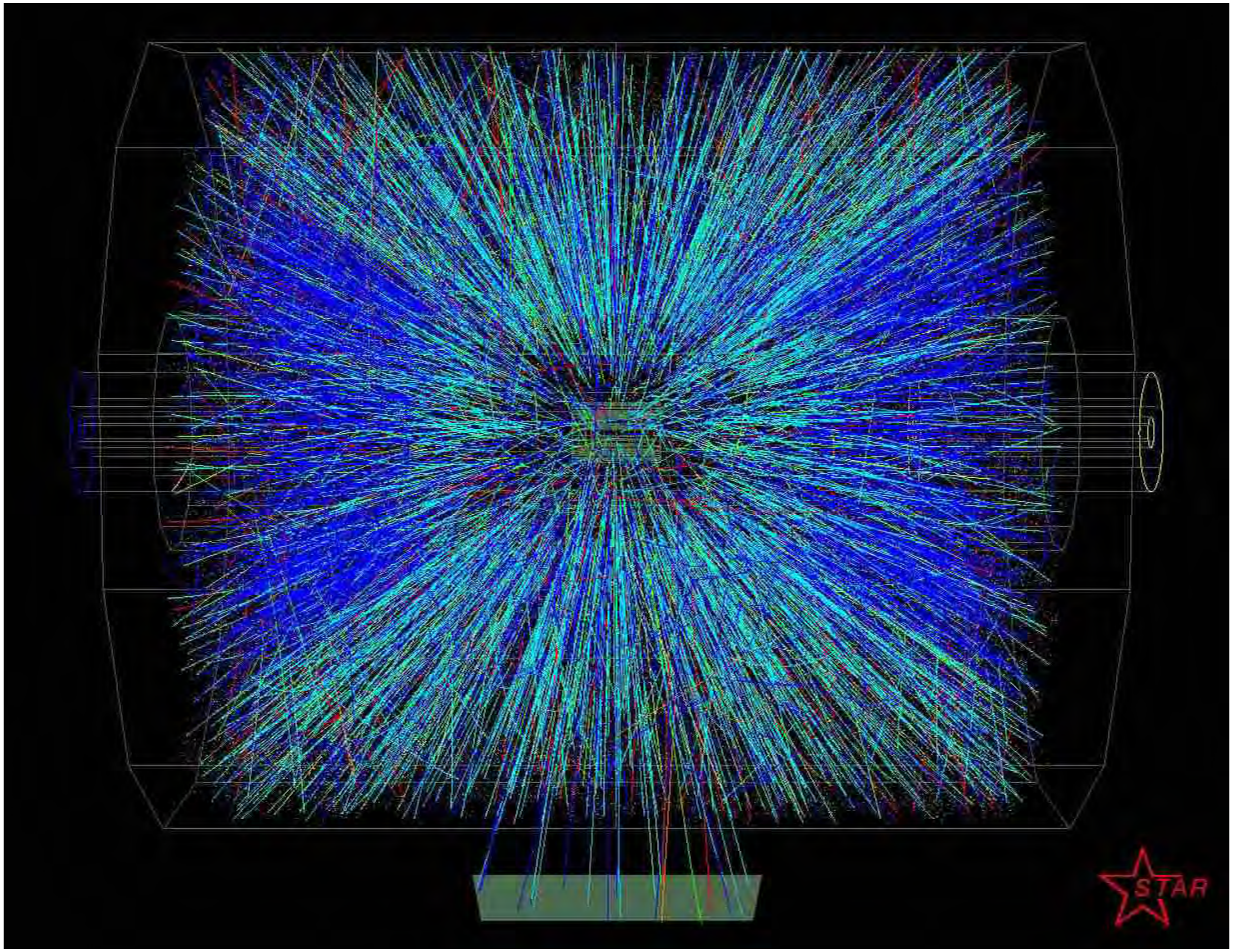
- Moreover it is unstable: it decays fast into pions.

- However, the theory has "black holes": They are different from the standard Schwarzschild black holes, but they can be created in the laboratory.

- They have been created in the RHIC and CERN accelerators now for 15 years, in heavy ion collisions, but it is only now that we start understanding this picture.

- The heavy ion collisions, involve heavy ions at very high energy.

- In each such collision about 10000 particles are eventually created.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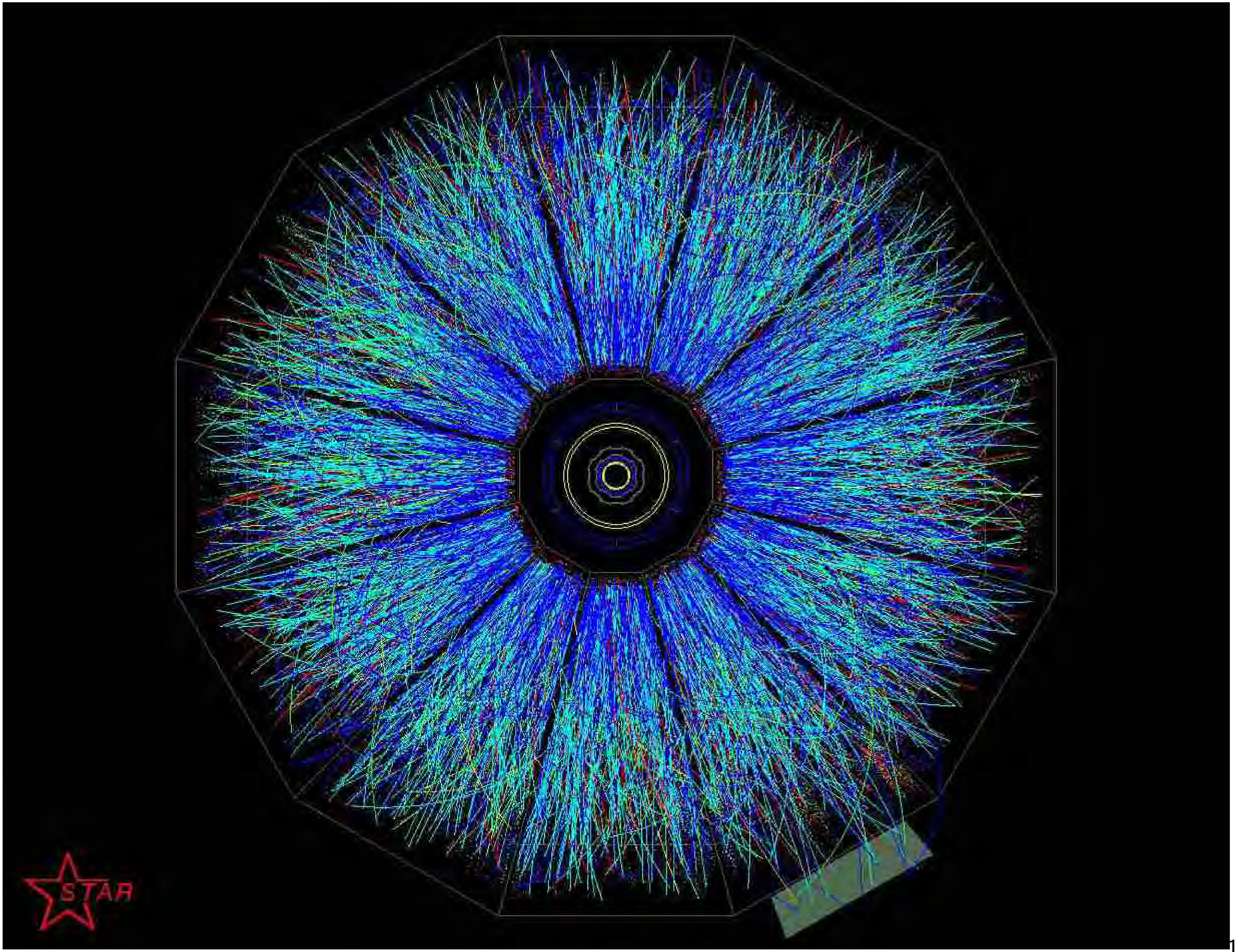

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- The gravitational description of such a collisions involves the making of a (QCD) black hole that subsequently Hawking evaporates to many particles.

- We do hope that such experiments will also boost our understanding of conventional gravity.

Επίλογος

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- Cosmology has made impressive strides in the last 30 years.
- There are however many fundamental questions we still do not understand.
- This is why the effort is continuing, and we count on the contribution of the young generations.
- Your role is important in this direction.

THANK YOU

Presentation map