Who is afraid of big bad Λ ?

carlo rovelli
Toulouse, November 2013

- ***Critics of on current ideas on the dark energy problem***

Bianchi, CR: “Is dark energy really a mystery?", Nature (2010)
Bianchi, CR: “Why all these prejudices against a constant?", arXiv:1002.3966

- ***Λ in quantum gravity***

Noui-Roche 2003, Han 2012, Fairbairn-Meusburger 2012, Riello 2013,…

“ To be a scientist is
to be open to novelty ,
not to trust current theories,
to be ready to speculate. ”

The scientific history of my life: when I entered physics, in the ’70,
there were three fundamental theories:

- General Relativity, but nobody expected it to be truly correct.
- Quantum mechanics, but few believed its long distance entanglement and similar.
- The particle physics standard model, but nobody expected it to last more of a couple of years.

- *SU(5)*
- *Proton decay*
- *Low-energy supersymmetry*
- *Validity of Bell inequalities and violation of QM*
- *Violations of Lorentz invariance*
- *Brans Dick theory, alternative theories to GR*
- *Low-energy Planck constant and black hole production at CERN*
- *Fifth force*
- *Violations of GR at the millimetre scale*
- *Pioneer anomaly as an indication of violation of GR*
- *Beyond the standard model physics at LEP*
- *Beyond the standard model physics as soon as the LHC is turned on*
- *PLANK data discrepancies with the cosmological standard model*
- *Neutrinos that run faster than light*
- …
- …

What an impressive list of bad ideas!!!

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The scientific history of my life has been witnessing a long shooting down of speculations!

Something does not fit

We have empirical evidence:

- since the early ’30 that the universe is expanding,
- since the late ’90 that the universe accelerating.

“Arguably the greatest mystery of humanity today is the prospect that 75% of the universe is made up of a substance known as ‘dark energy’ about which we have almost no knowledge at all.”

Great mystery?

No knowledge at all?

This is the theory of gravity I learned at school:.

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\,T_{\mu\nu}$$

It is based on spectacular beautiful ideas.

It is highly constrained (at least at large scale): it cannot be simply modified without spoiling some of its features.

It predicts black holes, gravitation waves, the expansion of the universe (but not its rate), gravitation lensing…. all phenomena that were not observed when I studied it.

It also predicts an accelerated expansion (but not its rate).

Where is the mystery?

Well, well, which is Einstein theory?

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

In all relativity books the Einstein equations are derived from a certain number of basic assumptions. These single out the theory with the cosmological constant.

The natural geometrical theory of gravity depends on two parameters, not one.

The beauty of GR spoiled?

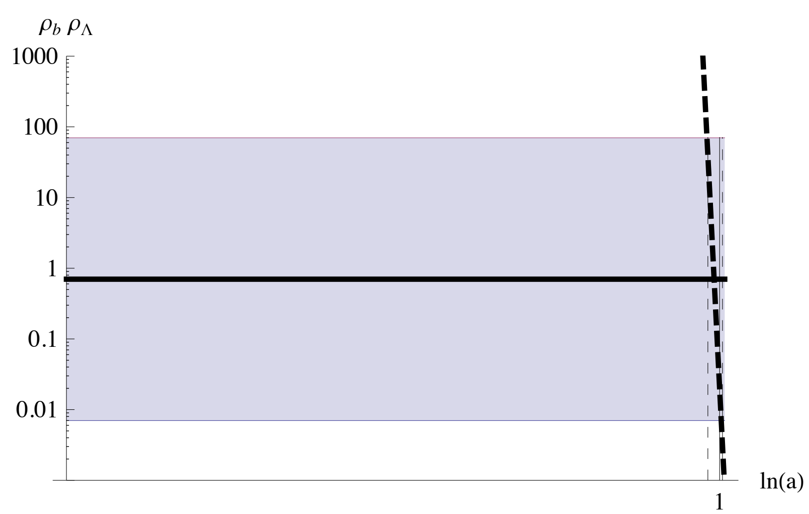
Einstein blunder, the real story.

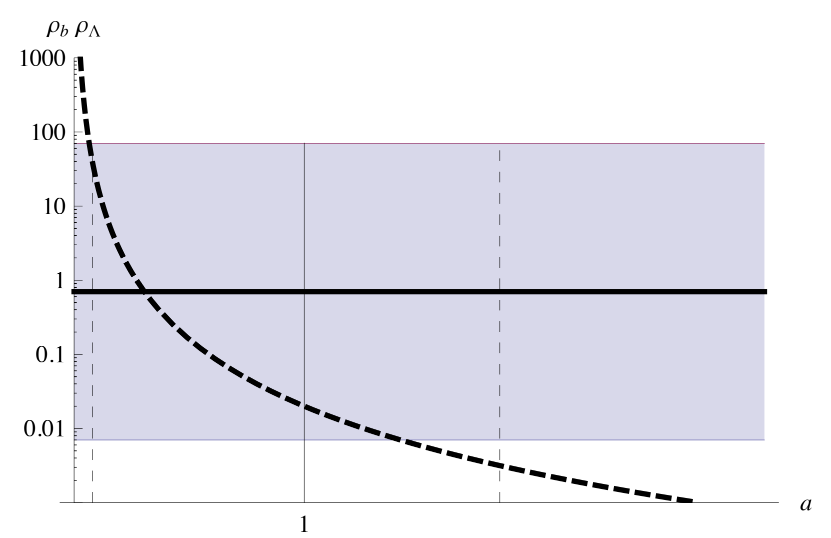
1) Einstein believes the Universe to be static.
2) His equations (without Λ) predict it is expanding. He has a **great prediction** in his hands!!
3) Einstein could predict the expansion of the universe, but makes a **blunder**:
   tries to adjust the equations to be compatible with a stable universe: he reconsiders the Λ term.
4) Einstein makes a second **blunder**: fails to realise that his solution is unstable, therefore
   even with Λ the equations predicts expansion.
5) Therefore Einstein still fails to predict expansion, in spite of having it under his nose.
6) Lemaître and Hubble see the expansion in the data.
7) Einstein has plenty of good reasons to furious to himself!

Moral: Einstein blunder is truly shameful,
it has nothing to do with Λ being zero or not.

Well, well, if the acceleration is due to Λ is very strange coincidence that the matter energy density is within two order of magnitude to the dark energy density.

Cosmological coincidence (error in probability).





Well, well, OK, but Λ is a completely unnatural number! It is too small!

There cannot be so small number sin the foundation of nature.!

Naturalness, in the sense of a strange number.

Naturalness arguments of this kind have been used other times in the history of science:

Here are two typical examples:

- In the III century a.e.v, Aristarchus measures the distance of the Sun. He finds out that the Sun is very distant, hence very large. He speculates that it is the Sun and not the Earth at center of the scholar system. Why the idea is dismissed at that time?

ARCHIMEDES, *Psammites (Sand-reckoner)*, c. 1, 1–10.

But Aristarchus of Samos brought out a book consisting of certain hypotheses, in which the premisses lead to the conclusion that the universe is many times greater than that now so called. His hypotheses are that the fixed stars and the sun remain motionless, that the earth revolves about the sun in the circumference of a circle, the sun lying in the middle of the orbit, and that the sphere of the fixed stars, situated about the same centre as the sun, is so great that the circle in which he supposes the earth to revolve bears such a proportion to the distance of the fixed stars as the centre of the sphere bears to its surface.

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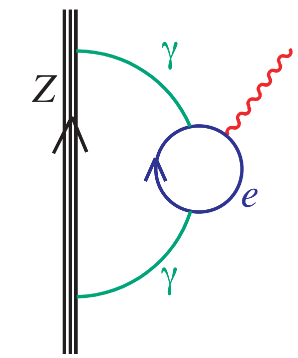
- All the way until the end of the XIX century the *atomic hypothesis* is dismissed by many physicists and philosophers (Mach, and Ostwald, among many others), also on the simple ground that the number of atoms in a normal portion of matter is too big a number and the seize of an atom too small a number to be realistic.

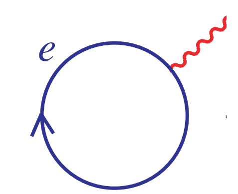
There are plenty of small and large numbers in physics (the ratio of the electric and gravitational forces between two electrons, for instance)

But Λ is vacuum energy!!! And this would be to large! 10^{120}

Cosmological constant and vacuum energy



- In quantum field theory, some quantities are affected by radiative corrections.
- Examples: charge of the electron, mass of the Higgs, cosmological constant.
- In current theories, these radiative corrections are infinite (missing physics? else?)
- Since we do not know the "uncorrected" quantity, we can immagine that this is infinite, and we only see the difference, which is finite. Examples: charge of the electron, mass of the Higgs, cosmological constant. What is special about Λ?
- Radiative corrections affect also differences of energies. These can be computed, are finite, and measurable. (Examples: Lamb shift, Casimir effect.)
- The fact that differences are measurable does not imply that the terms of the difference has individual meaning. (Examples: distance versus position, Potential difference versus absolute potential…)



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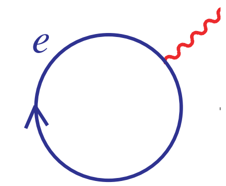


Confusing the Λ with the vacuum energy is a serious mistake:

it is like confusing e with its radiative corrections.

the charge of the electron is NOT made by its radiative corrections
(which are infinite, or at the cut off scale)

Λ is not vacuum energy

The strange logic of the identification of the cosmological constant with vacuum energy:

- Universe accelerates.
- We don't like having a second constant in the EE.
- Ah! But there is vacuum energy that makes the Universe accelerate! So we have solved the problem!
- No, in fact, if it was vacuum energy it would be too large.
- Therefore we have a mystery.

Compare with:

- Somebody has eaten the chocolate cake.
- Little Alain was the only one in the kitchen. But we do not like to blame him.
- Ah! But maybe there was a bear who got it. So, we have solved the problem!
- No, in fact, the bear is too big to enter in our small door.
- Therefore we have a mystery.
- (The fact that Little Alain has chocolate on his mouth is to be considered irrelevant…)

Well, well, wait a minute. Naturalness is a more subtle business than just the fact that a number in the theory is large or small.

Naturalness is the idea that because of radiative corrections physical quantities go to the physical cutoff scale unless there is some symmetry that protects them.

So, why don't the radiative corrections to Λ move it up to the cut off?

This is a good question! And we do not know the answer.

But we have the same question for the Higgs mass, and in fact for all the masses.

This is a question about the physics at the Planck scale, namely quantum gravity.

We do not yet have a consensual theory of quantum gravity, so, the problem is not the cosmological constant, from this perspective: it is just what is the theory at the Planck scale. That is, the problem is what is quantum gravity.

But we do no have a theory of quantum fields on curved spacetime!
What does this say?

Vacuum energy can be computed and has be computed using QFT on curved spacetime

And the result is …..
(Wald 2013, Hollands 2011, Fredenhagen 2012 …).

Λ is determined by a free constant in the theory, and can be small.

Exactly like the charge of the electron.

Wait a minute. There are many alternatives to the EE with Λ!
Aren't they better?

If you like an alternative theory, <u>first</u> ask:

- Does it solve the problem that the radiative corrections are large?
- Also: is it more predictive than the standard EE?
- Does it has less parameters?

Of course:

- Studying alternative theories or alternative explanations is always interesting.
- Testing with observations a theory against alternatives is always essential.
- Exploring the unknown and speculating…. Why not? After all we already have permanent salary.

But testing a good theory, it is profoundly different from claiming loud and strong that we do not have a decent theory, we know nothing and there is the greatest of all mysteries!

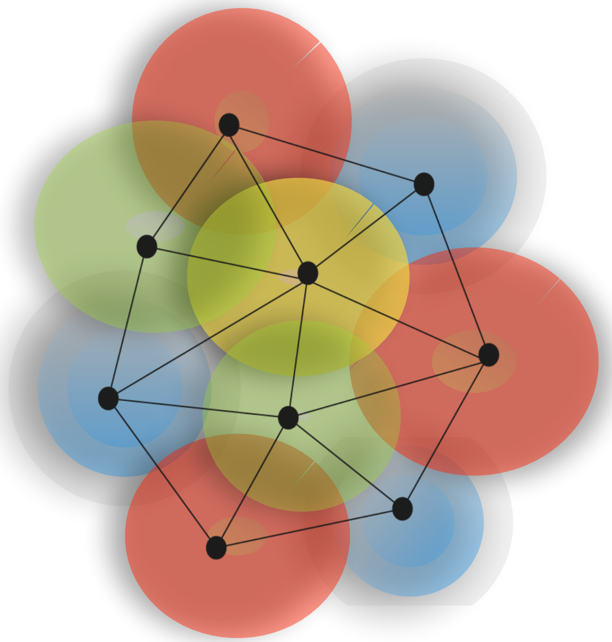
Does quantum gravity have anything to say about the cosmological constant?

Loop quantum gravity

$(\mathcal{H}, \mathcal{A}, \mathcal{W})$ defines a background independent quantum field theory

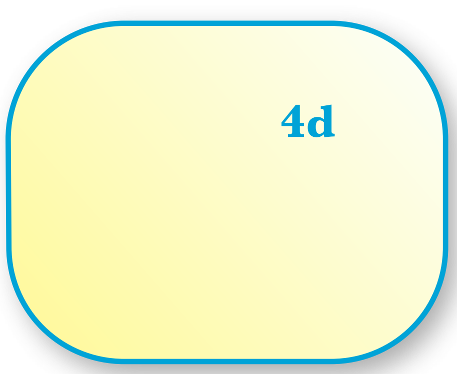
- Hilbert Space: $\mathcal{H}_\Gamma = L_2[SU(2)^L/SU(2)^N]$
- Operator Algebra: $\left[L_a^i, L_b^j\right] = i\delta_{ab}\ell^2\epsilon^{ij}_k L_a^k$
- Transition Amplitude: $W_v = (P_{SL(2,\mathbb{C})} \circ Y_\gamma\ \psi_v)(\mathbb{1})$

$$Y_\gamma : \quad \mathcal{H}_j \quad \to \mathcal{H}_{j,\gamma j}$$
$$|j;m\rangle \mapsto |(j,\gamma(j+1))\,;\ j,m\rangle$$

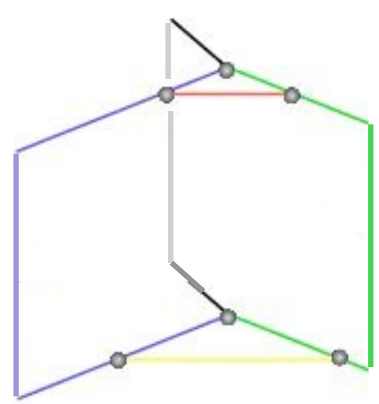


Geometry is quantized

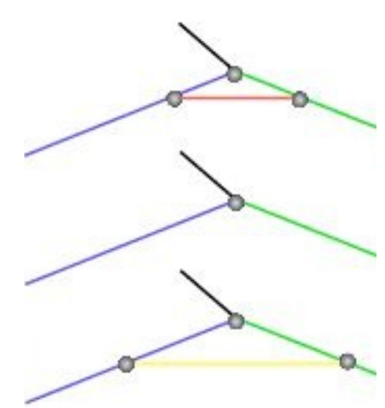
- eigenvalues are discrete
- the operators do not commute
- quantum superposition



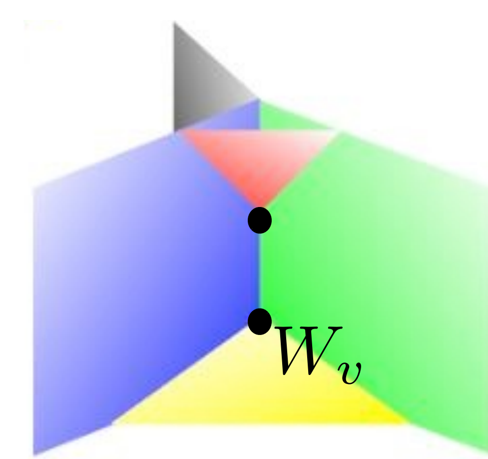
3d boundary



boundary graph



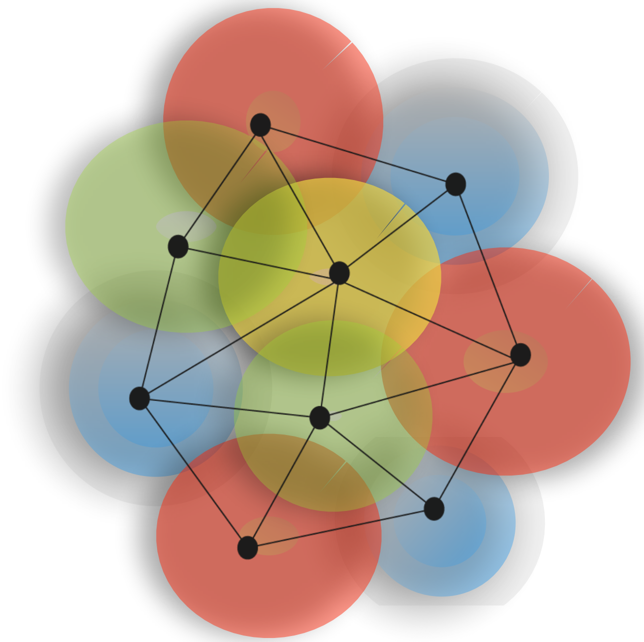
a spin network history

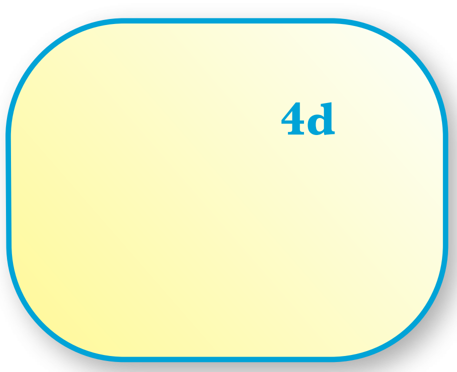


σ : spinfoam

Loop quantum gravity (main results)

- Black hole thermodynamics.
- Early Universe (bounce).
- UV finite. n-point functions.
- Quantum gravity correction to the CMB spectrum.





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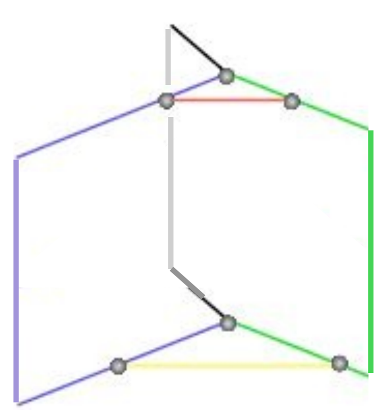

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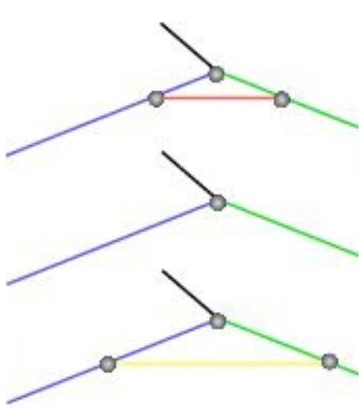

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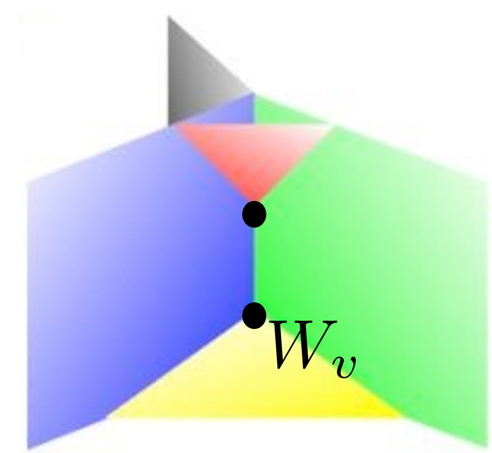


σ : spinfoam

- Transition amplitudes are *finite* in the UV, but they diverge in the IR.
- The divergence come from summing over large spins.
- There is a simple solution to fix the theory: cut on high spins: j_{max} .
- This can be done covariantly, saving all symmetries, by replacing

$$SU(2) \longrightarrow SU(2)_q$$

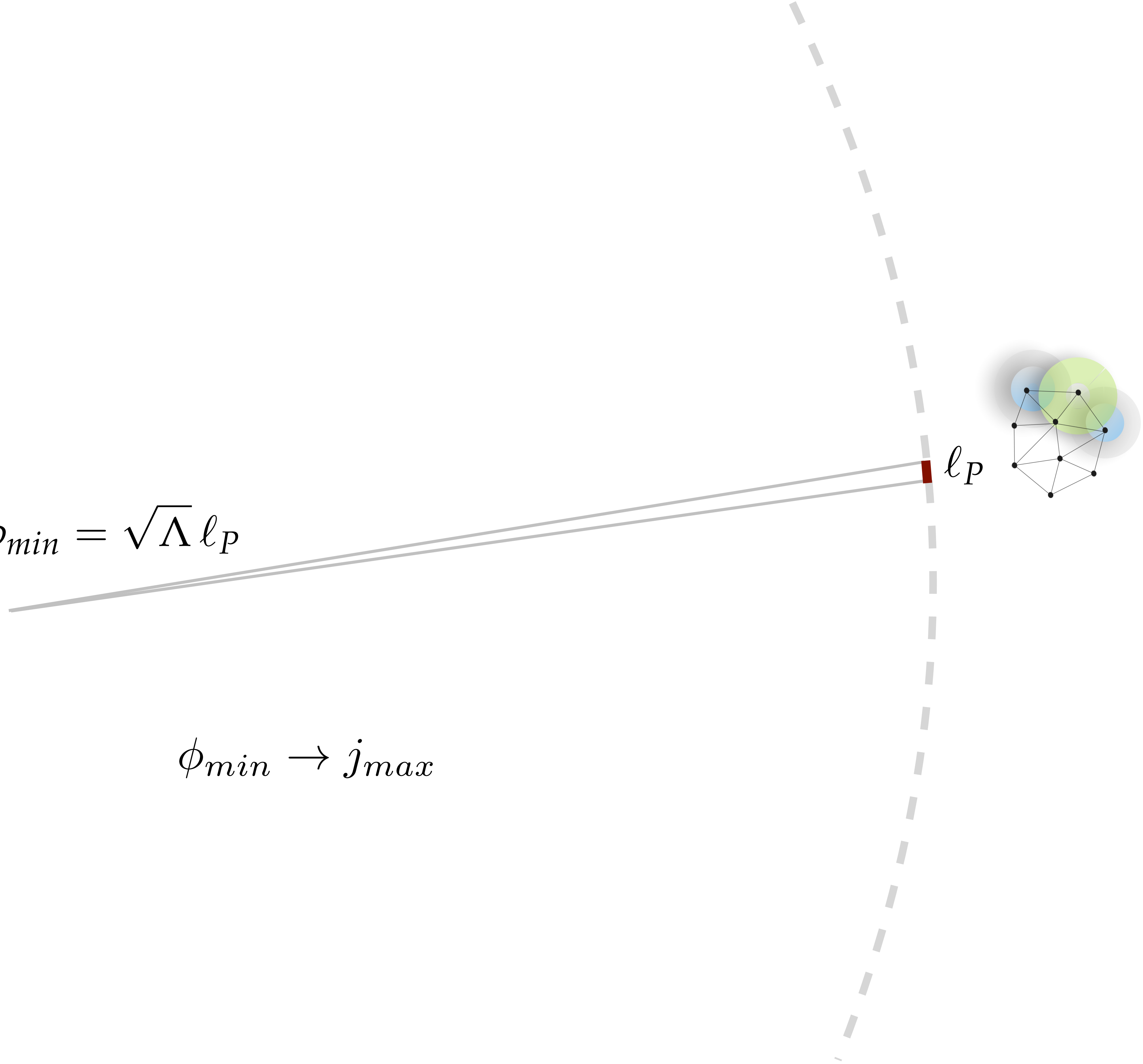
- This defines a very good theory of quantum gravity: all amplitudes are finite!
- This introduces a new parameter in the theory.

$$q = e^{i2\pi/k} \qquad k = 2j_{max}$$

- One can study the limit of the classical of the resulting amplitudes.
- One obtains the Einstein equations with cosmological constant, where

$$q = e^{i\Lambda l_P^2} \qquad j_{max} \sim \frac{1}{l_P^2\,\Lambda}$$

Noui-Roche 2003, Han 2012, Fairbairn-Meusburger 2012, Han 2013



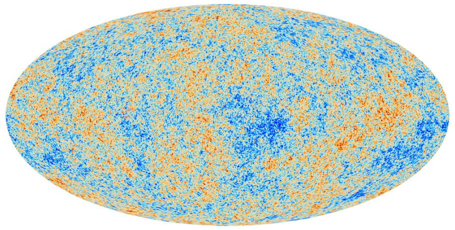
$$\phi_{min} = \sqrt{\Lambda}\,\ell_P$$

$$\phi_{min} \to j_{max}$$

Quantum gravity demands the existence of a small positive cosmological constant.

How does the renormalisation of the vacuum energy appears in the context of this theory?

See hints in the talk by Aldo Riello



Planck data (*Planck 2013 results. XVI. Cosmological parameters)*

The dark energy density is known to 3.7% precision.

"Our overall conclusion is that the Planck data are remarkably consistent with the predictions of the base ΛCDM cosmology."

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

"We still have no good theory to explain this value"

Nor we have a good theory for any of the other very numerous fundamental constants and initial value parameters in our fundamental physics.

The 6 parameter ΛCDM

- **ΩΛ = 0.692 ± 0.010;**
- **baryon density = 0.416 ± 0.0045 yoctograms per cubic meter;**
- **cold dark matter density = 2.23 ± 0.032 yoctograms per cubic meter;**
- **baryon density ratio = 5.36 ± 0.10;**
- **dark energy density = 3352 ± 125 eV/cc; (2.25 meV)4**
- **H0 = 67.80 ± 0.77 km/sec/Mpc**
- **→age of the Universe = 13.798 ± 0.037 Gyr.**

"The Lambda-Cold Dark Matter (ΛCDM) model is today the standard model in cosmology, it assumes the presence of the cosmological term in the Einstein's equations. It is the best description of the present data. It is the best theoretical construction we have so far, up to the open problem of quantum gravity.

By the way is the Earth flat?

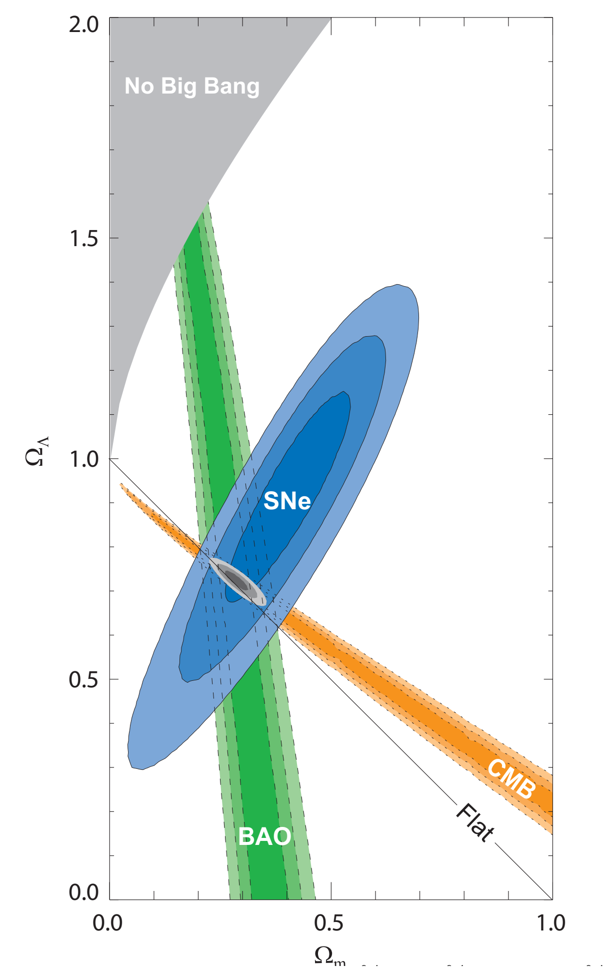
This is wrong: *(from everywhere)*

$\Omega = 0.9995 \pm 0.0034$ *so the Universe is flat*

This is right: *(from Planck papers)*

"In summary, there is no evidence from Planck for any departure from a spatially flat geometry.

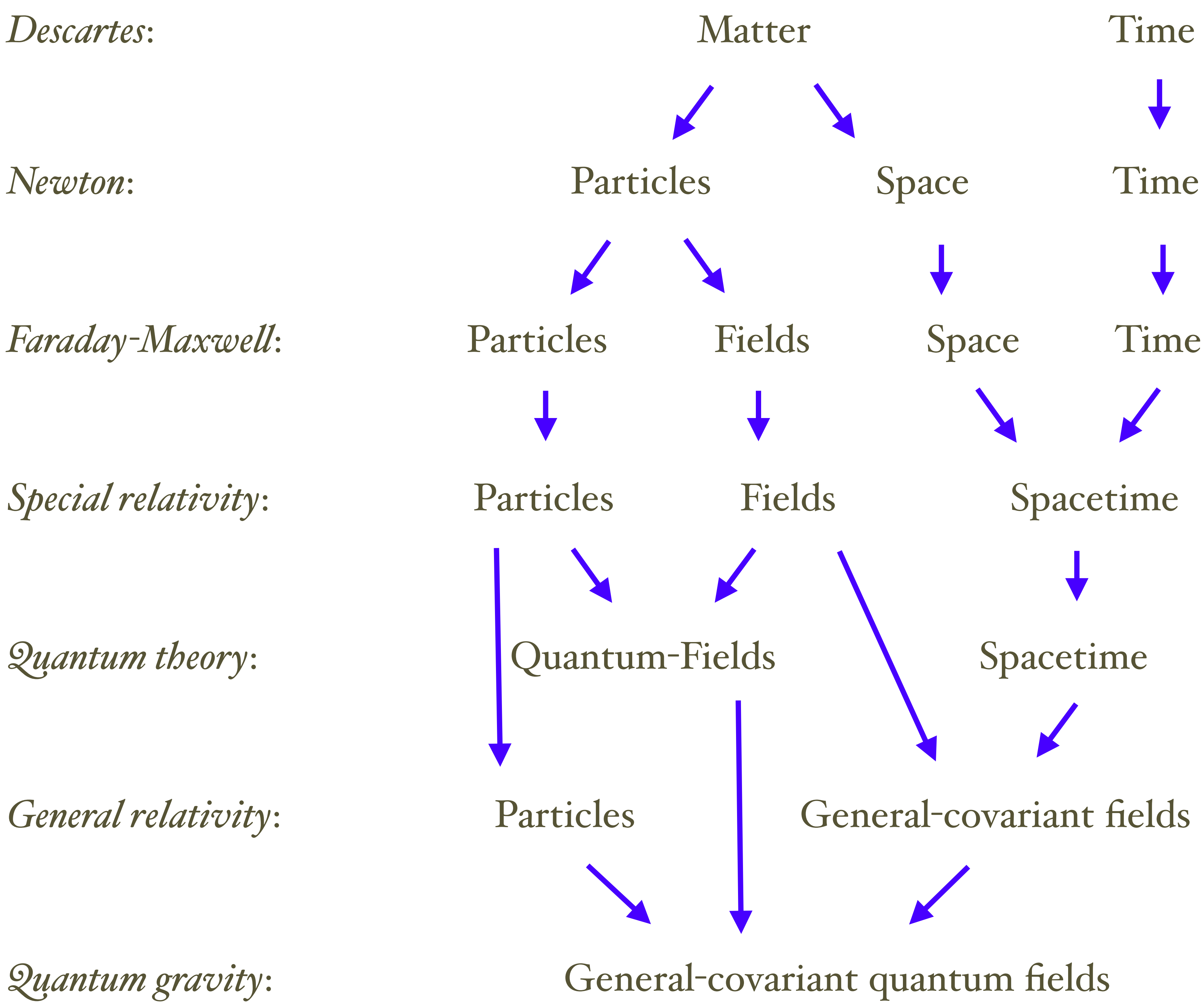
The results of Eqs. (68a) and (68b) suggest that our Universe is spatially flat to an accuracy of better than a percent."



If 1% accuracy in measuring vanishing curvature implied flatness,
one could easily prove that the Earth is flat
using a road map of France !

Summary

- There is ***no "dark energy mystery"*** at all.
- ***We have a good theory*** of the large scale behaviour of the universe, which
    - is theoretically very compelling and
    - fit the data extraordinary well.
- Like all good theories, it need to be tested, and alternatives and extensions explored.
- But:
    - Λ does not "spoil the beauty" of the Einstein theory at all.
    - It has nothing to do with "Einstein" blunder.
    - There is no coincidence mystery if probabilities are used right.
    - There is nothing strange in the fact that it is a large number.
    - Its renormalisation is no more questionable than for other constants.
    - It is not large if one uses QFT in curved spacetime.
    - There are alternative theories, but all have this same QFT difficulty.
- ***Do not confuse Λ with vacuum energy***: they are very different things!
- ***Λ (positive) is required in loop quantum gravity*** to make the theory finite. It is an integral part of the theory. It appears as the parameter of $SU(2)_q$.
- I think that current theoretical physics suffers for excess of speculation. *Einstein, Copernicus, Heisenberg, Newton, Maxwell,* were ***not driven by trying funny ideas***: they were moved by strict requirements of internal consistency, or by new data. In the absence of new data (like dark matter, which *is* a real mystery), and internal inconsistencies (like quantum versus gravity): do not despise the simplest explanation! ***Trust current theory!***


Descartes:
Matter
Time
Newton:
Particles
Space
Time
Faraday-Maxwell:
Particles
Fields
Space
Time
Special relativity:
Particles
Fields
Spacetime
Quantum theory:
Quantum-Fields
Spacetime
General relativity:
Particles
General-covariant fields
Quantum gravity:
General-covariant quantum fields