Title: Searching for the Quantum Origins of Space and Time

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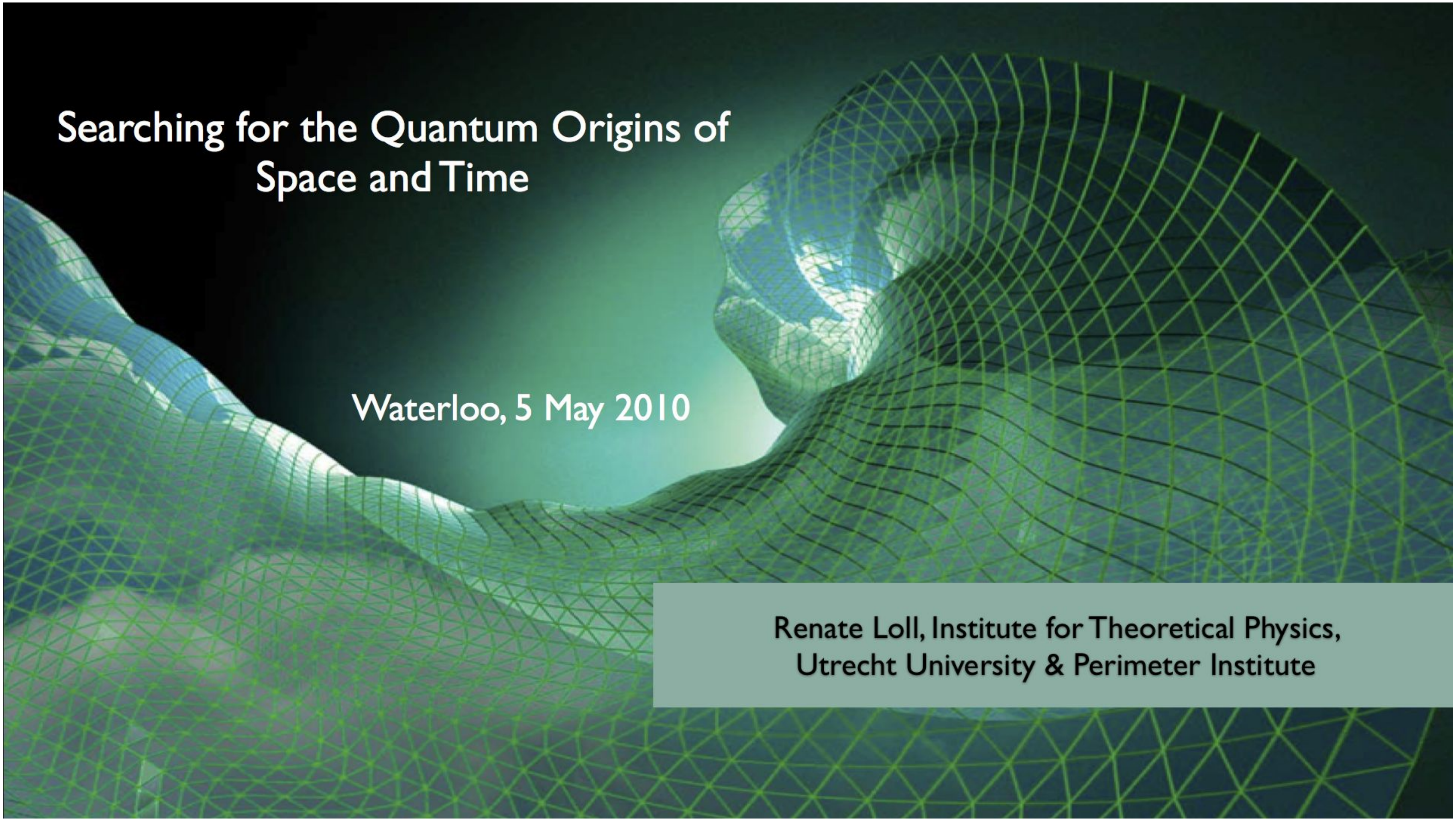
Abstract: Einstein's theory of General Relativity has taught us that empty space (or, more precisely, spacetime) is in itself a dynamical and wonderfully rich entity for both theoretical physicists and science fiction authors alike. Although it may stretch our imagination, astrophysical observations leave little doubt that spacetime can bend, move and vibrate. If we want to explain these phenomena from an underlying microscopic and more fundamental structure, we need to bring in quantum theory, leading to even more exotic possibilities such as spacetime foam and wormholes. Do they really exist? How would we know? Are they in conflict with known physics? At least some of these questions may already be within the reach of our fundamental physical theories, not just qualitatively, but also quantitatively. In this talk, Professor Loll will share her insights into how much we know and how much we can still hope to learn about quantum gravity - the elusive quantum theory of space and time.


Searching for the Quantum Origins of Space and Time
Waterloo, 5 May 2010
Renate Loll, Institute for Theoretical Physics, Utrecht University & Perimeter Institute

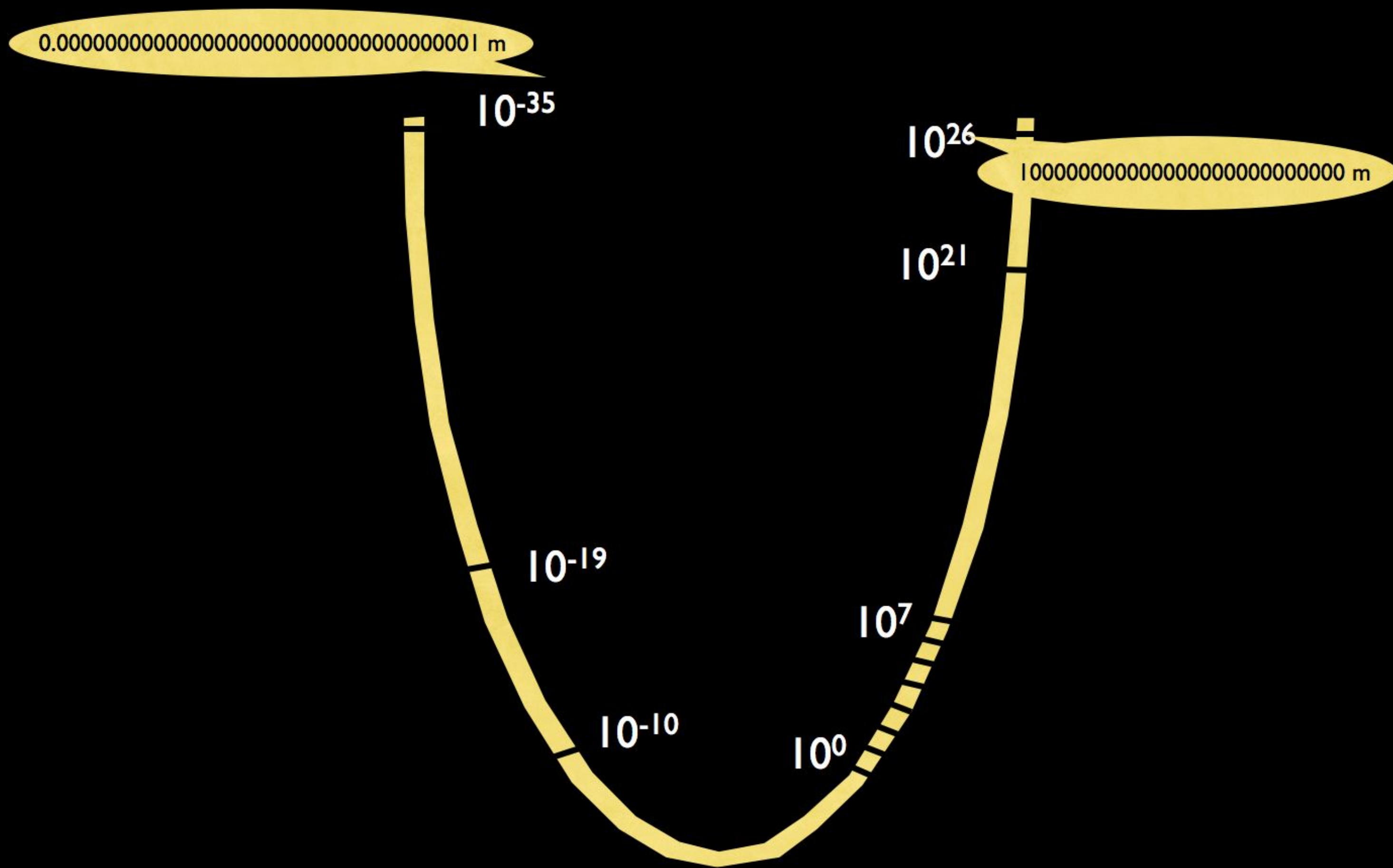
Things to take away from this lecture

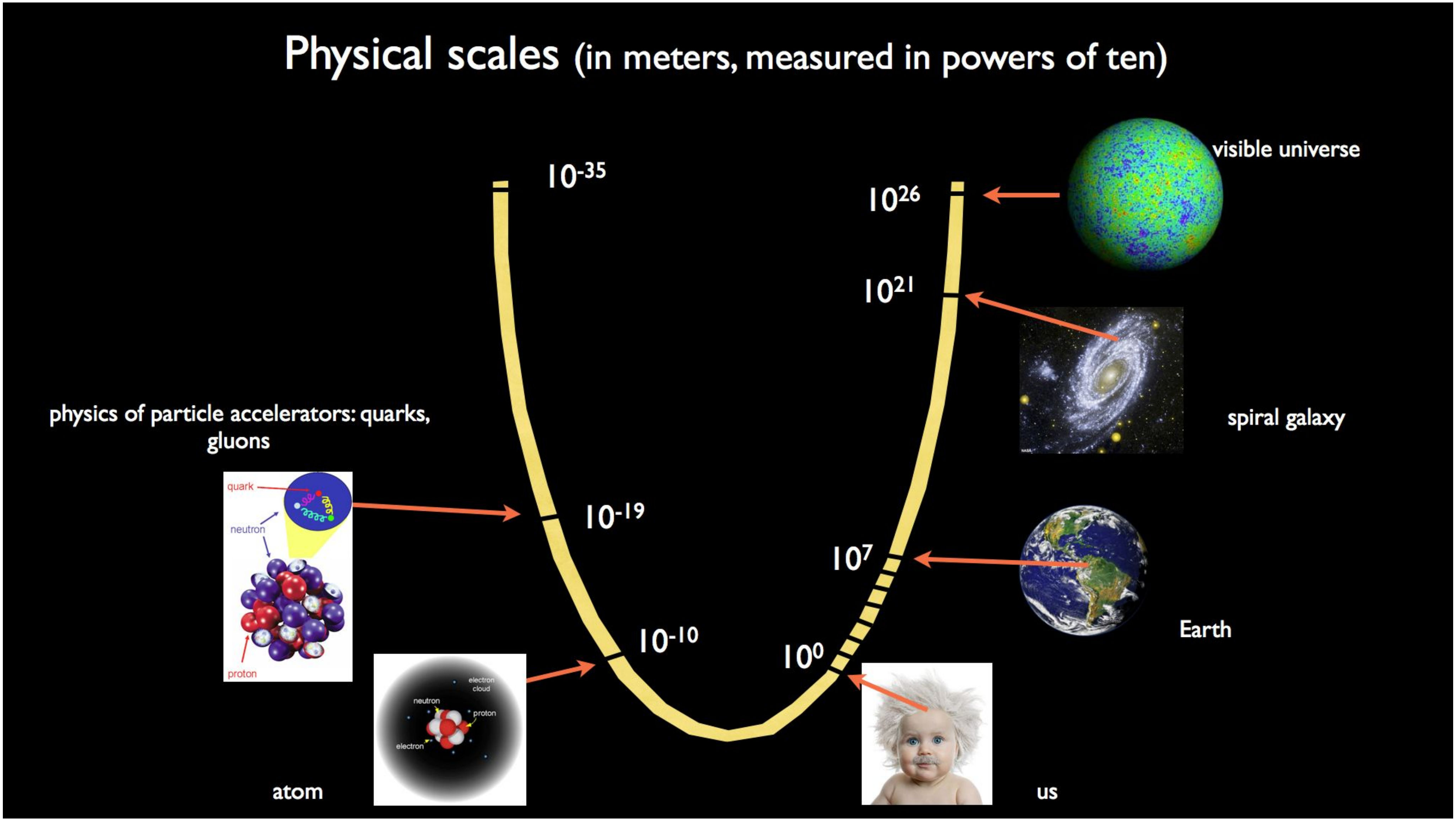
★ "Why there is something rather than nothing" - why physicists are interested in empty space and time.

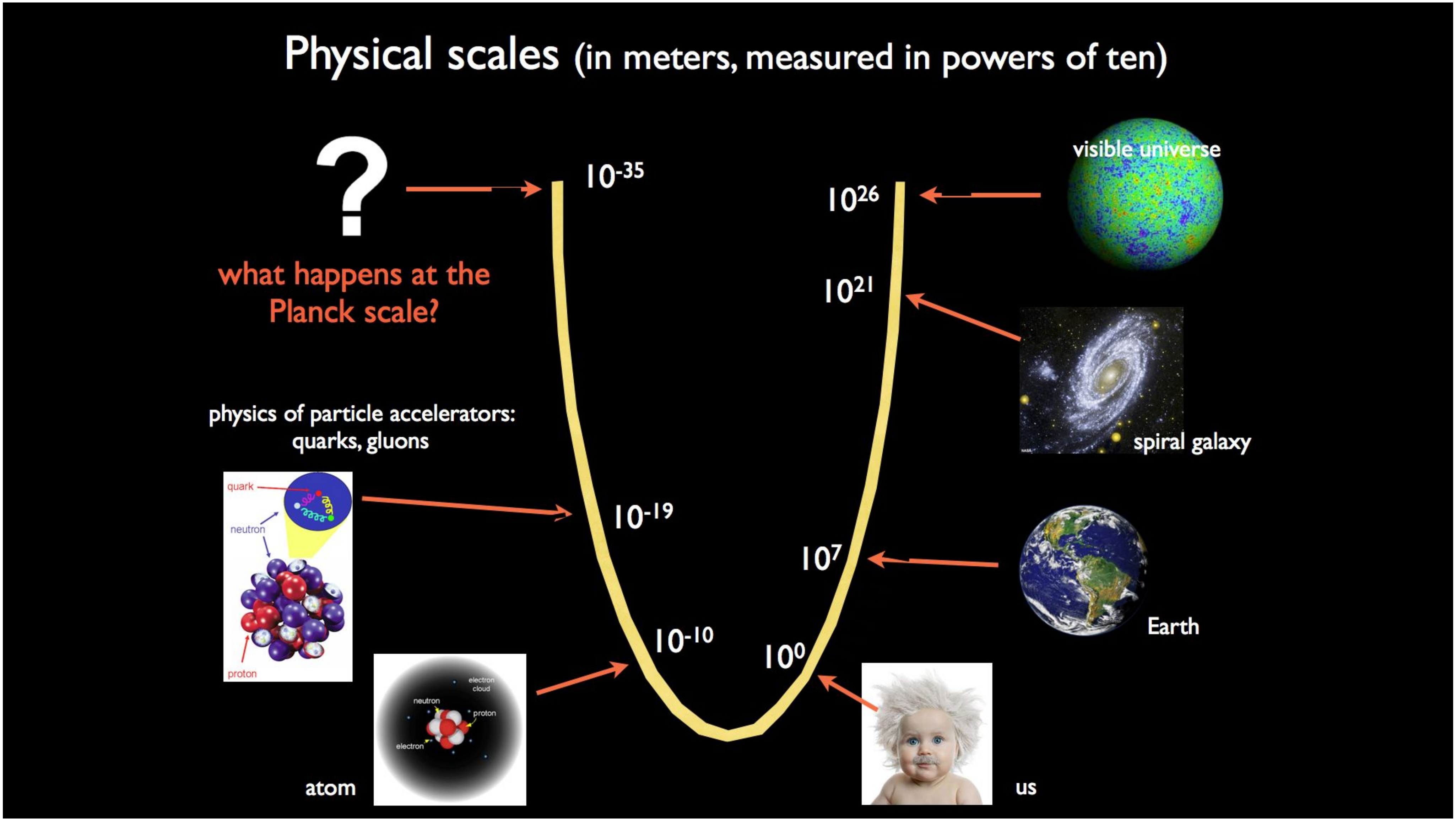
★ The uses of 'applied space-time science' (including a trip down the wormhole) and why we need a *quantum* theory of space and time.

★ What new candidate theories of Quantum Gravity can tell us about the microstructure of spacetime and its macroscopic consequences.

Physical scales (in meters, measured in powers of ten)




Physical scales (in meters, measured in powers of ten)
visible universe
10-35
10-19
10-10
10^0
10^7
10^21
10^26
spiral galaxy
Earth
us
atom
physics of particle accelerators: quarks, gluons
quark
neutron
proton
electron cloud
neutron
proton
electron



Physical scales (in meters, measured in powers of ten)
?
what happens at the Planck scale?
10^{-35}
10^{26}
visible universe
10^{21}
spiral galaxy
physics of particle accelerators: quarks, gluons
quark
neutron
proton
10^{-19}
10^{7}
Earth
10^{-10}
10^{0}
electron cloud
neutron
proton
electron
atom
us

?

What is in the space between the smallest elementary particles?

Nothing?

20^{th}-century physics tells us that there is much more than meets the eye ...

Why we are interested in "nothing":

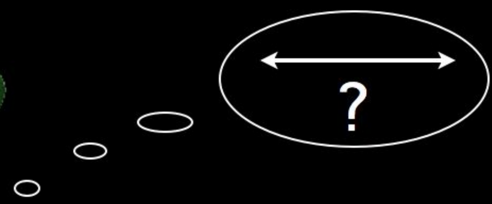
A *very* brief history of space and time

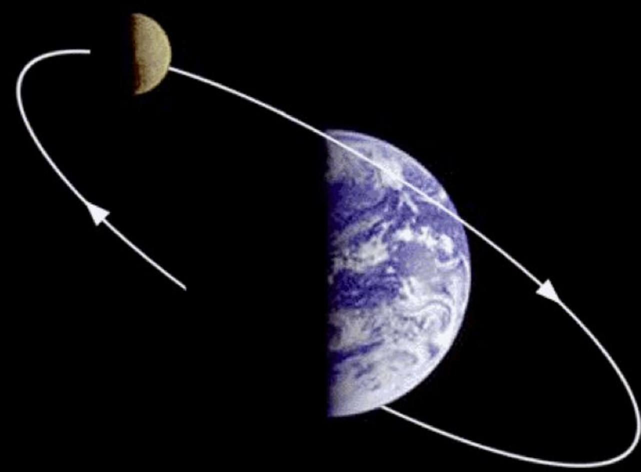
empty space =
"the vacuum"

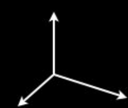
Physicists are in hot pursuit of a theory describing the quantum structure of empty space on the smallest scales, a so-called *theory of quantum gravity.*

The world view of classical physics

Isaac Newton 1666







Universe = Space + Time + Gravity

Space ↑ forever unchanging (three-dimensional)

Time ↑ universal

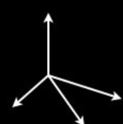
Gravity ↑ dynamical

Einstein’s double revolution

1905:

~~Space + Time~~

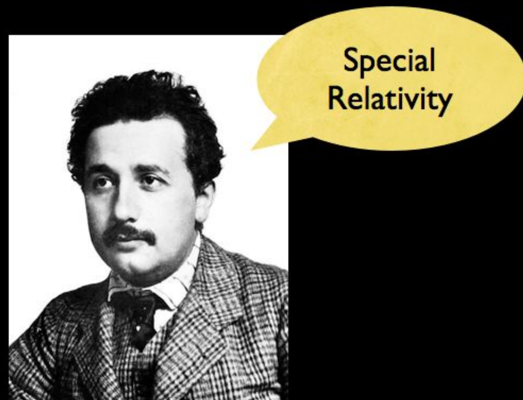
Spacetime



forever unchanging,
uniform, structureless
(four-dimensional)

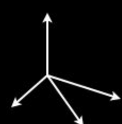
Einstein's double revolution

1905:



~~Space + Time~~

Spacetime



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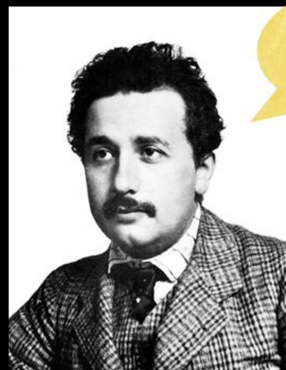
Einstein's double revolution

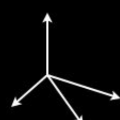
1905:



Special Relativity

~~Space + Time~~

Spacetime



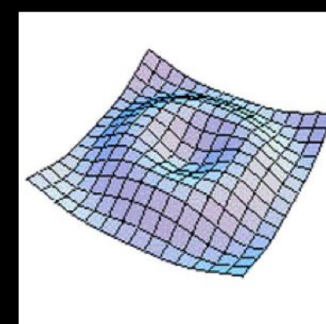
forever unchanging,
uniform, structureless
(four-dimensional)

1915:

~~Space + Time + Gravity~~

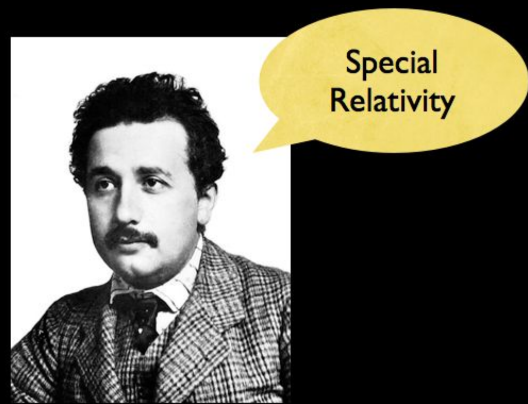
Curved Spacetime

(empty) spacetime itself is the interesting quantity: it can bend, move and vibrate!



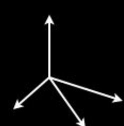
Einstein's double revolution

1905:



~~Space + Time~~

Spacetime



forever unchanging,
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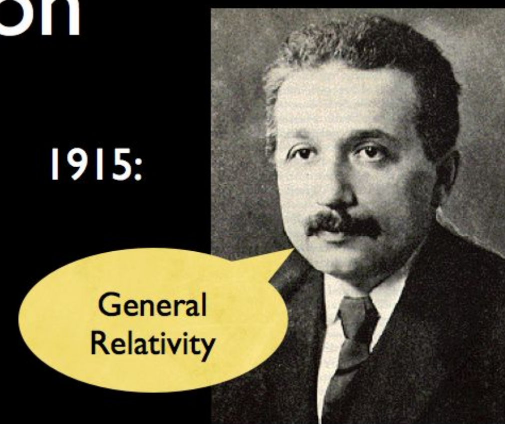
1915:



~~Space + Time + Gravity~~

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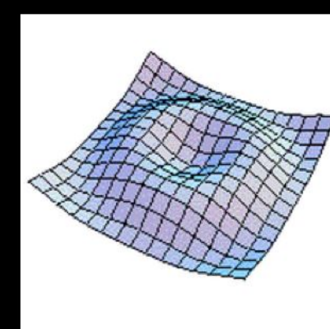
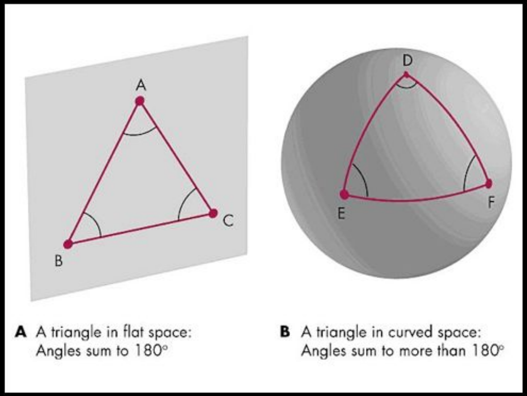
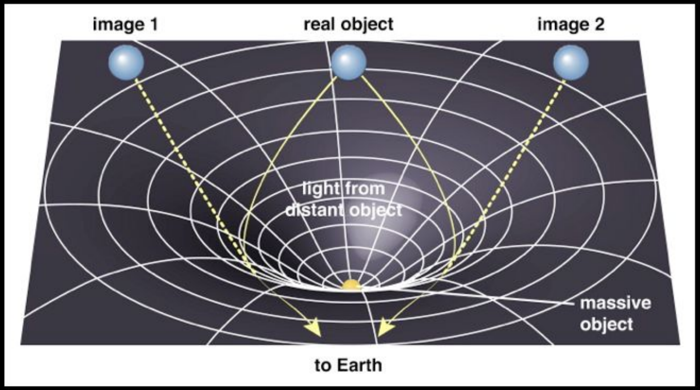


How do we know that spacetime is curved?

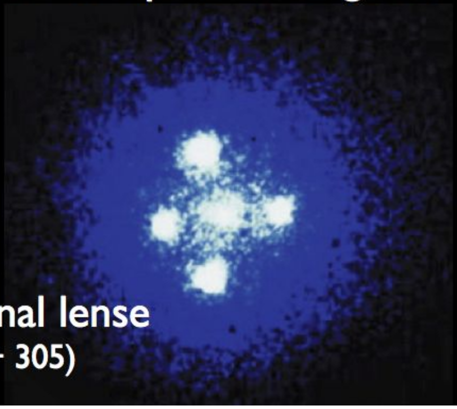
imagine living in two dimensions:



flat space   curved space



Empty, curved spacetime can bend light rays which pass through it.



a gravitational lense
(G2237 + 305)

curved spacetime geometry = gravitational forces

To summarize:

Contrary to what our everyday intuition may suggest, empty spacetime is in itself an interesting (albeit invisible and immaterial) entity with intricate local properties.

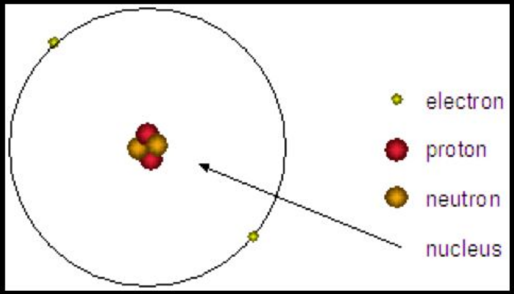
How a piece of spacetime curves and moves, depending on what kind of matter and energy is inside it, is described quantitatively by General Relativity, the "classical theory of gravity".

ripples in space: gravitational wave, generated by two rotating stars (source: GWDAW-2)

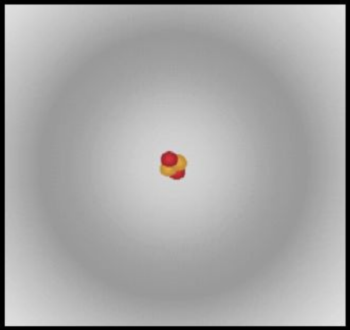
But this is not the end of it ...

Einstein's classical theory of General Relativity cannot answer all questions we may ask about empty spacetime - it is incomplete!

- It is well tested from cosmological scales down to the millimeter range.
- On atomic/nuclear scales gravity appears to be completely unimportant.
- On even smaller scales, eventually reaching the Planck scale, spacetime must be described by *quantum*, and not by *classical* equations of motion.



classical model of a helium atom, with two orbiting electrons

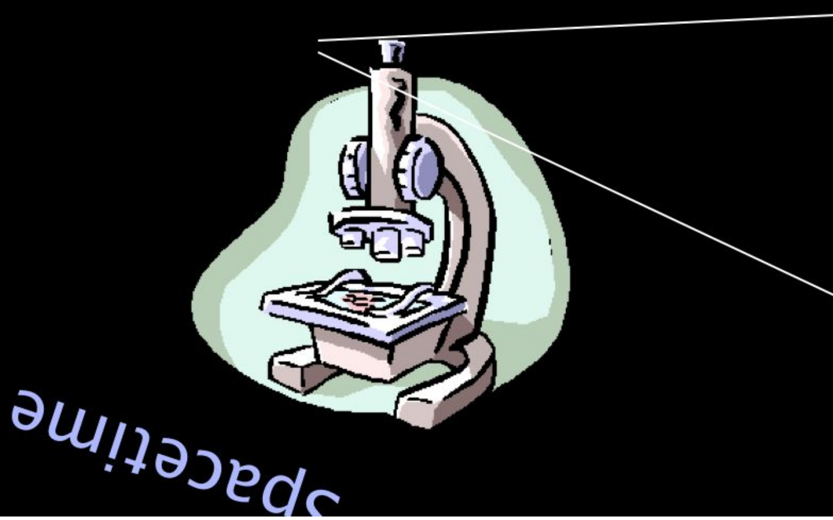


correct, quantum-mechanical model, with a probability cloud of the two orbiting electrons

We need a theory of Quantum Gravity!

The smaller the scale, the larger the “quantum fuzziness” of the spacetime geometry, due to Heisenberg’s famous Uncertainty Relations.

Combining general arguments from quantum theory and general relativity, we expect that the microstructure of spacetime near the Planck scale is completely dominated by quantum fluctuations.



Spacetime Foam?

Which questions could quantum gravity help us answer?

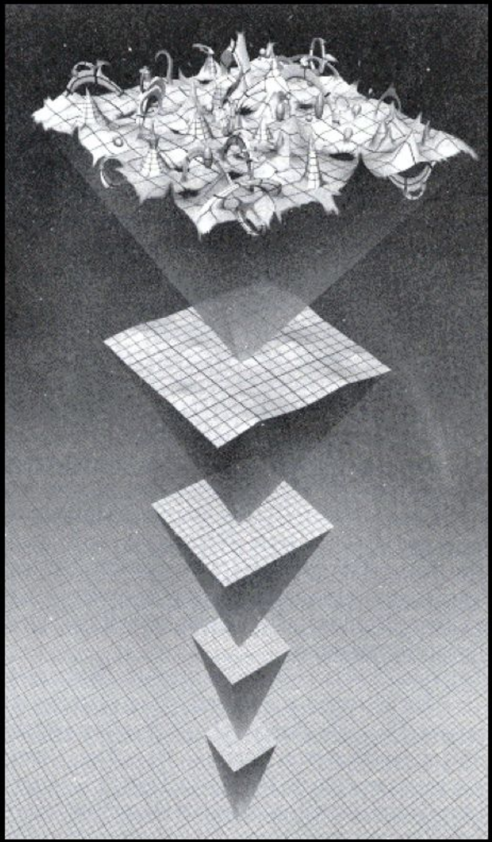
• What are the quantum origins of space, time and our universe?

• What is the microstructure of spacetime, and what are its fundamental constituents?

• Can their dynamics *explain* the observed large-scale structure of our own universe, that of an approximate de Sitter space?

• Are 'space', 'time' and 'causality' ("cause precedes effect") still meaningful notions at the Planck scale?

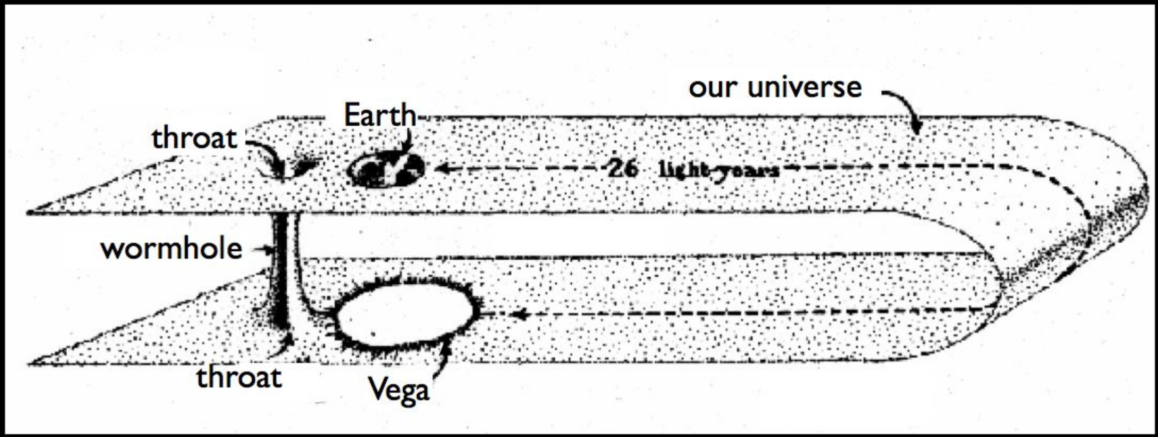
• Do quantum laws permit 'exotic' physics, related to *wormholes* and *spacetime foam*?



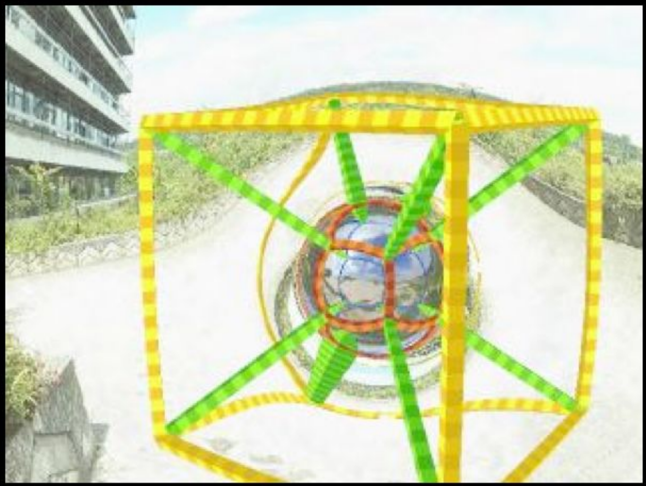
zooming in on the Planck scale

Wormhole (definition):
(a) a solution to the classical Einstein equations, allowing for a 'shortcut' in space and time
(b) preferred mode of transport for today's fashionable time traveller

imagine you were a flat, two-dimensional creature living in flatland, travelling from Earth to Vega:



A promotional video says more than a thousand words ...



- the edges of the coloured grid represent the straightest possible lines (in the curved space near and in the "throat")
- we pass three nested cubes (yellow, orange, blue) as we traverse the wormhole, linked by the straight green lines
- the green lines get defocused as they pass through the wormhole

A lunchtime trip from Tübingen to Boulogne-sur-Mer:

What is fact and what is fiction?

The geometry of space shown in the movie is rendered strictly according to Einstein's theory of General Relativity, *however,*

(i) classical GR does not allow for the 'birth' of wormholes,

(ii) to keep the wormhole open we would need 'exotic matter' with negative energy and a density a billion times that of a neutron star!

THE REALLY IMPORTANT QUESTION: Can we use a wormhole to build a time machine for travelling *backwards* in time? (This would violate our most cherished principle of causality.)

Is there anything in the nature of space and time that would forbid this to happen?

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To answer this question, the classical theory is insufficient. One needs to understand the quantum behaviour of spacetime at ultrashort, distances, given by a theory of ***quantum gravity***.

What do we know about 'Quantum Gravity'?

It has proved difficult to come up with a consistent, quantitative theory, not least because of the absence of direct experiment.

→ a free ride at the Planck scale?

... only as long as we don't have the tools to establish the macroscopic consequences of our microscopic assumptions

powerful computational tools have become available in recent times

→ 'new conservatism' in quantum gravity, leading to surprising and radical results

How can we possibly understand what is going on at the Planck scale of 10^{-35} meters?

★ We *extrapolate* from best current knowledge of quantum (field) theory and General Relativity.

★ We try to *build quantitative models* of Planck-scale spacetime which are *robust* (i.e. rely on few fundamental physical principles and symmetries, and are not sensitive to arbitrary model details).

★ A necessary condition is to *verify the classical limit*, i.e. to show that the model theory does not contradict already established large-scale (=classical) physics.

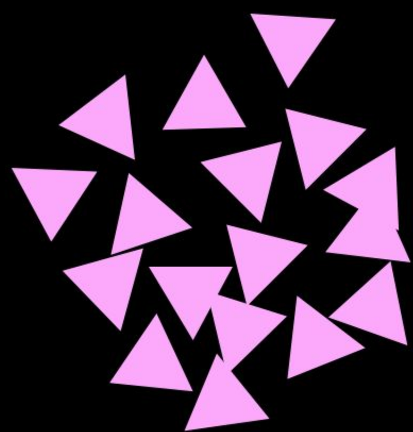
This is difficult, but *not* impossible.

How to concretely construct such a theory?

(building on the experience of ~50 years of quantum gravity research ...)

My collaborators and I have developed *and tested* a new, causal theory of the quantum microstructure of spacetime,

Quantum Gravity from Causal Dynamical Triangulation.



sub-Planckian, triangular building blocks

glue together & let them quantum-interact

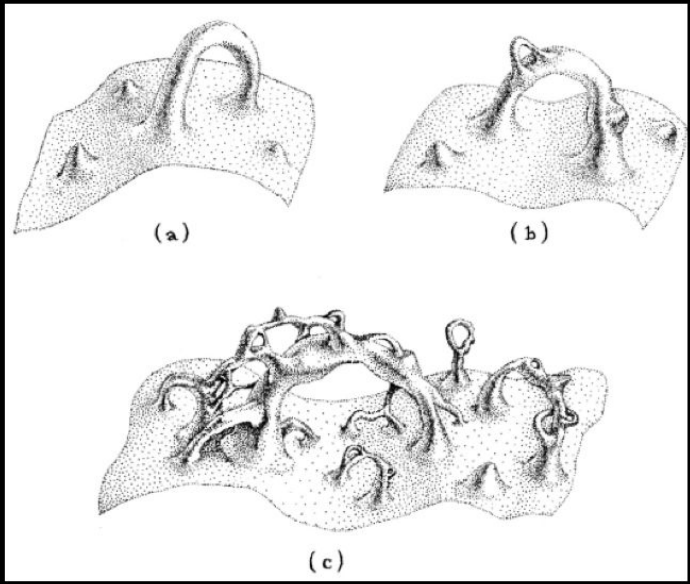
(with help from the computer)

do we obtain a realistic quantum universe?

In this setting, we can run two distinct numerical "experiments":

(a) use microscopic building rules which allow for the existence and formation of wormholes (of any size)

(b) use microscopic building rules which do *not* allow for such wormholes

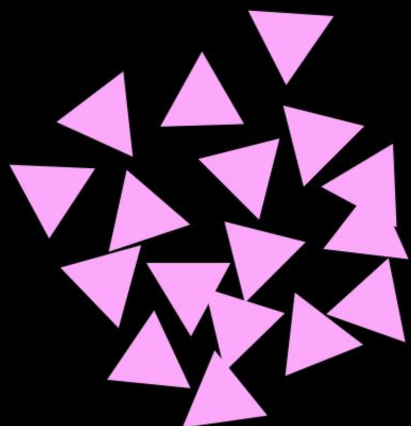


spacetimes with wormholes, case (a)

→ let the system quantum-fluctuate and ...

... a big surprise

Only in case (b) - no wormholes allowed - does the resulting quantum spacetime have a good classical limit on large scales!



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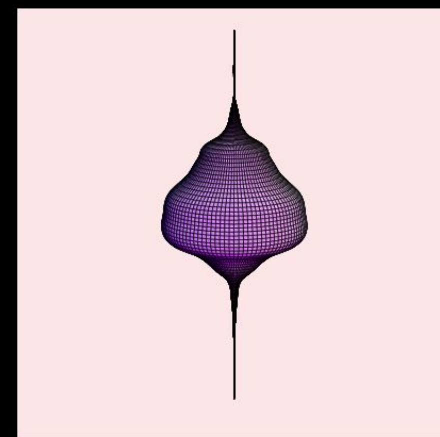
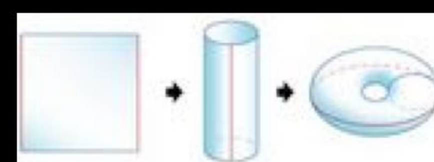


a *four*-dimensional quantum universe

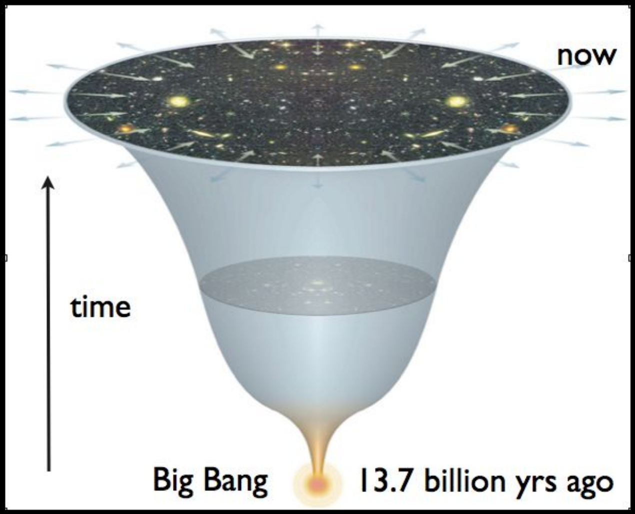
Why? - in case (a), each tiny piece of spacetime wants to form its own little wormhole, instead of contributing to the growth of the "mother universe"



→ the quantum gravity theory corresponding to (a) is ruled out!

What *is* the 'self-organized' quantum universe that emerges in case (b)?

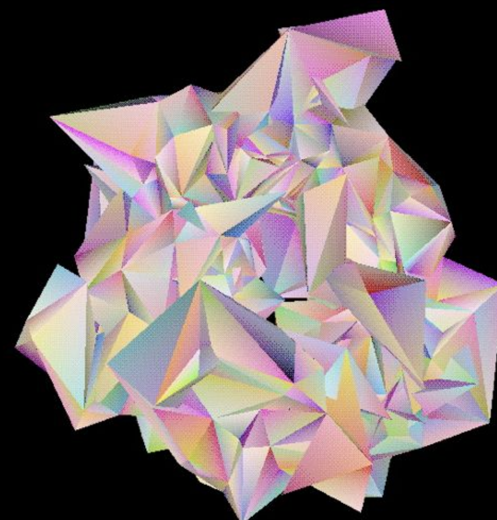
On large scales it is a well-known solution to the *classical* equations of Einstein's General Relativity: *de Sitter spacetime*



De Sitter spacetime has a *cosmological constant*, or 'dark energy', so that everything contained in it flies apart at an ever increasing rate - a well-known feature of both the early and late universe.

Now that we have recreated a macroscopic quantum universe from first principles, we can investigate its properties on short, Planckian scales - our computer experiments tell us that is a bizarre, wildly curved and effectively *two*-dimensional spacetime foam, ...

Einstein would never have believed it!



Work is ongoing on a more detailed, quantitative understanding of the quantum structure of spacetime and predicting from it measurable consequences which are not already contained in General Relativity.

Some final thoughts

What is perhaps most surprising is that we are beginning to get a quantitative handle on Planck scale physics, with computer simulations acting as "experimental lab".

This has a bearing on whether phenomena like wormholes or time travel exist. (The way things look, they don't!)

All theories of quantum gravity are <u>*tentative*</u> - apart from fitting in with what is already known, their predictions must still be corroborated by observation/experiment.

The theory obtained from *Causal Dynamical Triangulation* is the only one where a realistic, macroscopic universe emerges from pure quantum dynamics. Some of its findings have in the meantime been corroborated in other approaches to quantum gravity.

Where to learn more

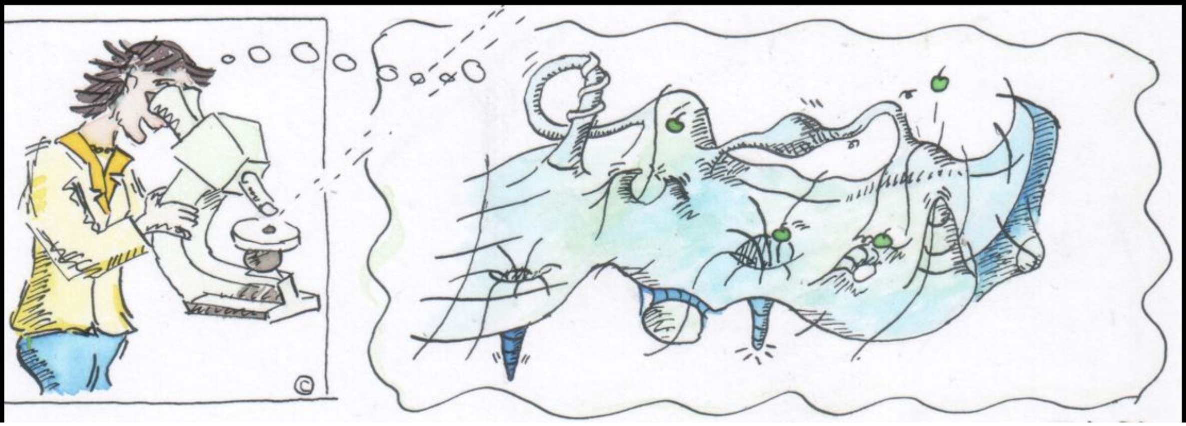
• popular account of Causal Dynamical Triangulation: "The self-organizing quantum universe", by J. Ambjorn, J. Jurkiewicz, R. Loll (Scientific American, July 2008)

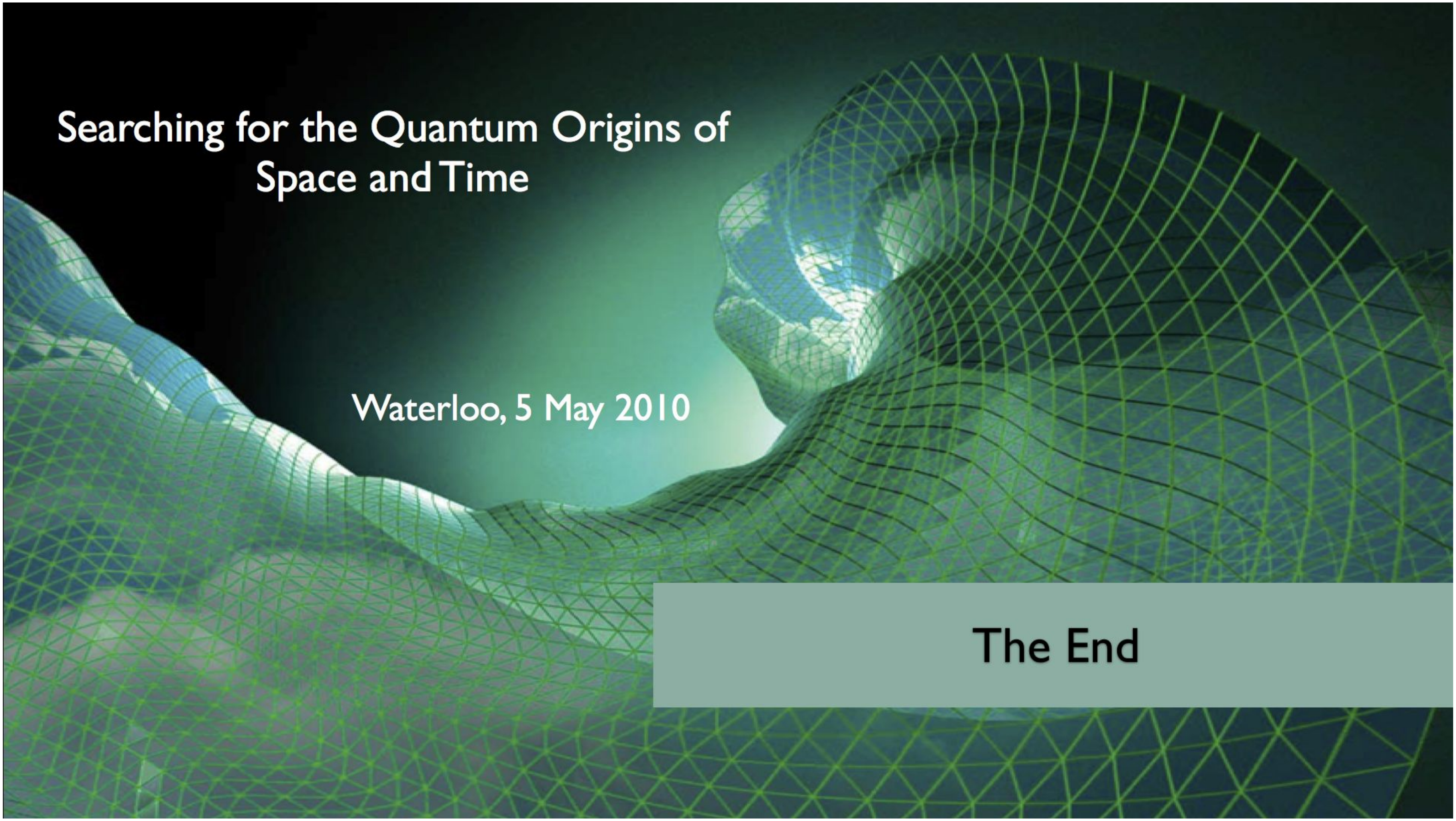
• both review and popular science material on my homepage

http://www.phys.uu.nl/~loll

• beautiful visualizations of Special/General Relativity:

http://www.spacetimetravel.org

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The End