Quantum Gravity made simple, but not too simple

Pisa, 24 Oct 2019

Renate Loll
Radboud University, Nijmegen

Preview

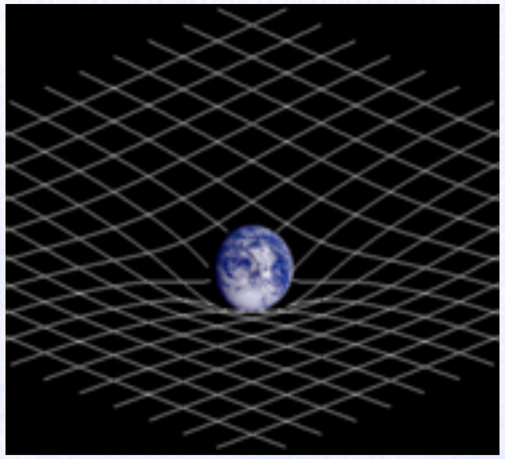
The context of my talk is the search for a ***theory of quantum gravity beyond perturbation theory*** and the ongoing research program of Causal Dynamical Triangulations (CDT) addressing the problem. My main message is that the *dynamical character of spacetime geometry* and the *absence of an a priori fixed background*, combined with otherwise standard tools from QFT, have led and are still leading to completely new insights on the possible nature of quantum gravity.

My presentation will address

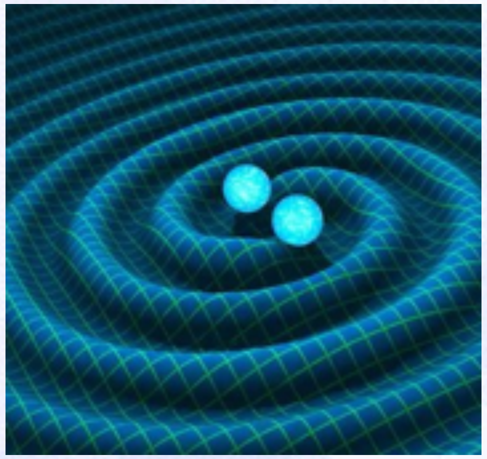
- motivation and context (is it all “speculative physics”?)
- lattice gravity and CDT in a nutshell (“simple but not too simple”)
- incorporating coordinate invariance and causal structure
- quantum signatures and recovery/emergence of classicality

Life in the *Century of Gravity*

- **urgent**: complete our quantum gravity theories to make reliable predictions, minimizing free parameters and ad hoc assumptions
- **my route**: tackle quantum gravity and geometry *directly* in a non-perturbative, Planckian regime (no appeal to duality/dictionaries)
- the beauty of classical GR: "theory ***of*** spacetime", captured by its curvature properties
- given the central role of **curvature** classically, is it also true that



(©User:Johnstone, Wikipedia)



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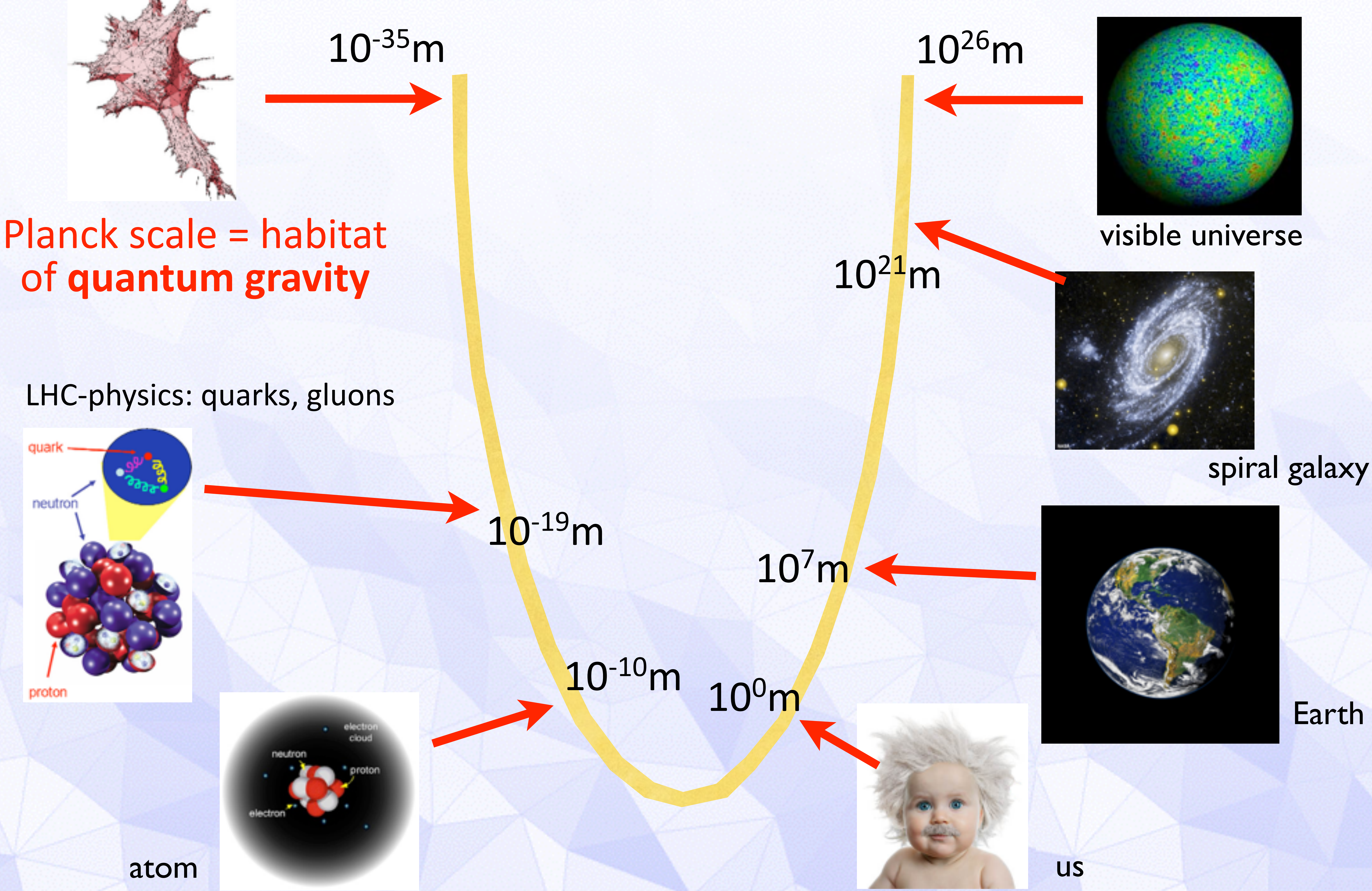
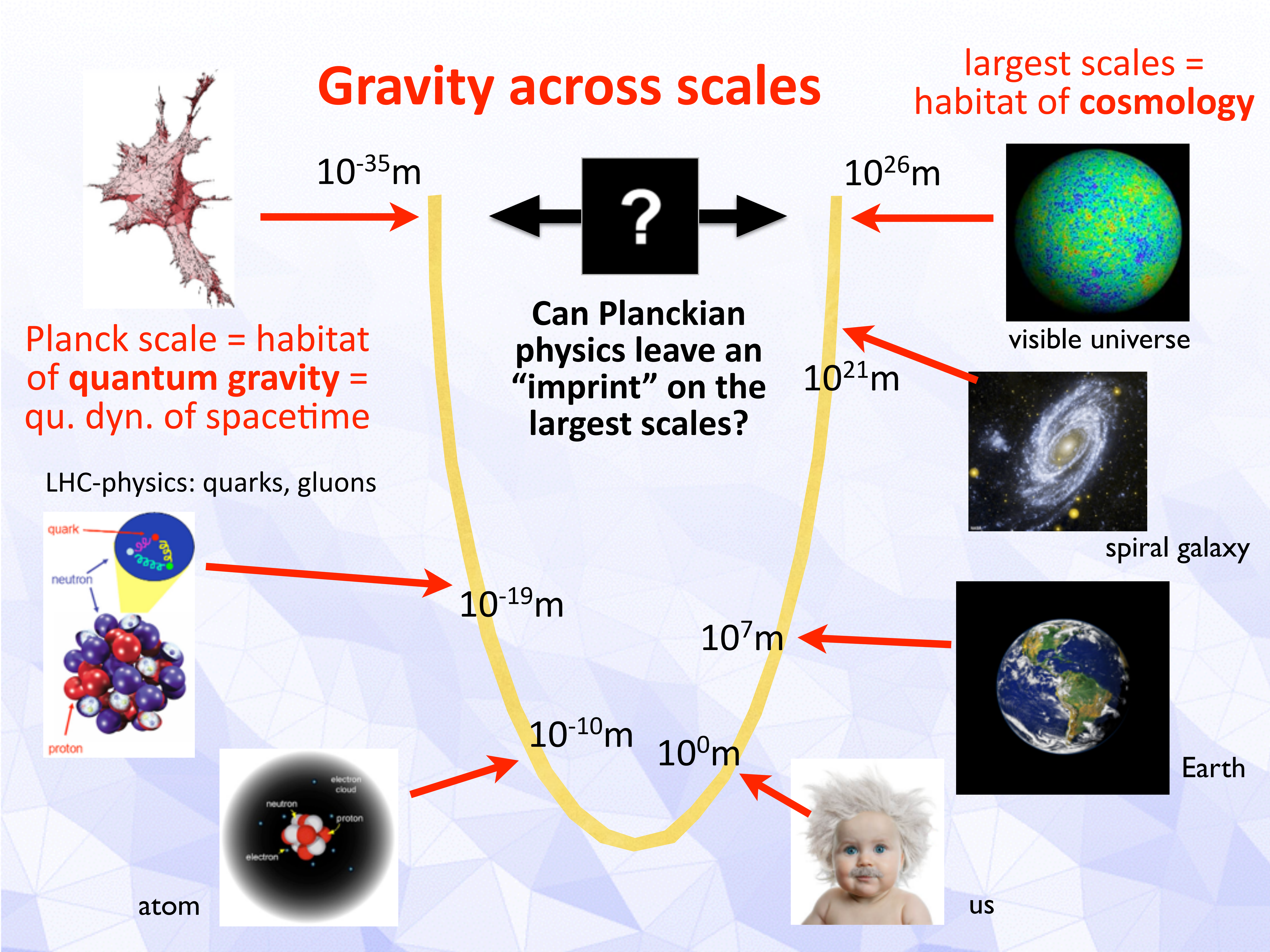
nonperturb. quantum gravity = theory of quantum curvature?

- It is unclear a priori whether one can make much sense of such a proposition. However, we have recently demonstrated how one may define and measure *quantum Ricci curvature* in quantum gravity.

Gravity across scales

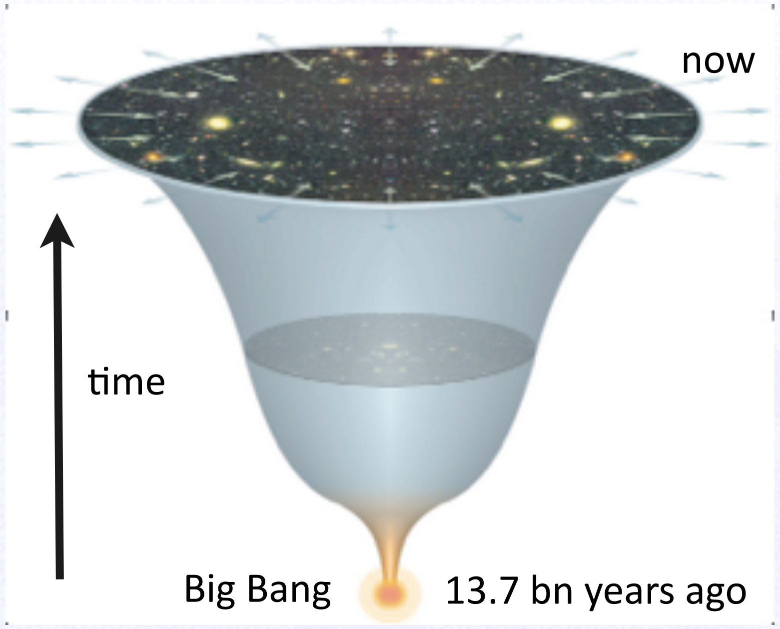


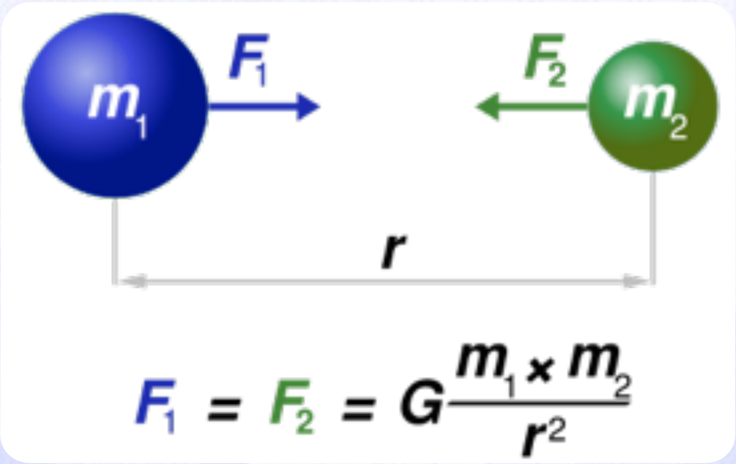


Gravity across scales
largest scales = habitat of cosmology
10-35m
10²⁶m
?
Can Planckian physics leave an “imprint” on the largest scales?
visible universe
Planck scale = habitat of quantum gravity = qu. dyn. of spacetime
10²¹m
spiral galaxy
LHC-physics: quarks, gluons
quark
neutron
proton
10-19m
10⁷m
Earth
10-10m
10⁰m
electron cloud
neutron
proton
electron
atom
us

Some questions for quantum gravity

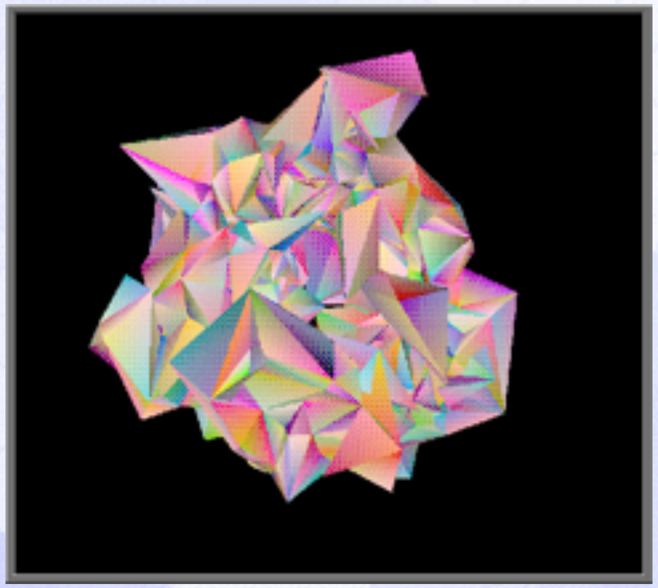
- What was the quantum behaviour of spacetime in the "even earlier" universe?
- Are space and time, and principles like causality or locality fundamental or merely emergent on macroscopic scales?





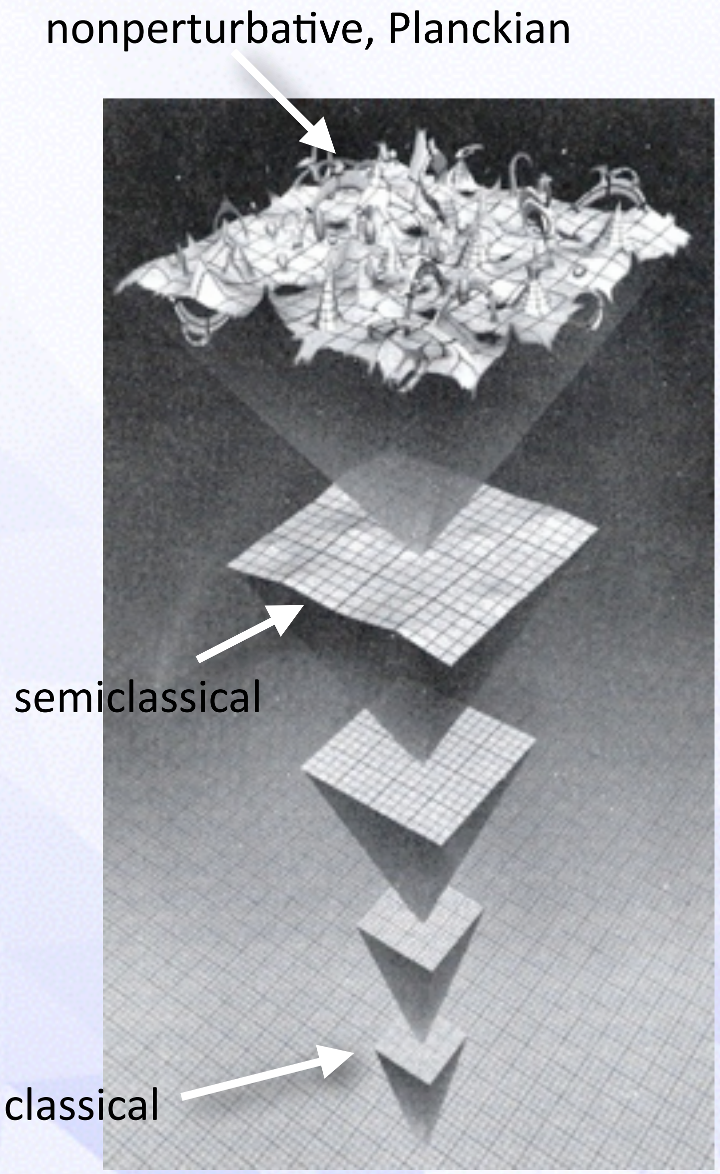
- Can we *derive* gravitational attraction from first-principles quantum dynamics @ ℓ_{Pl}?

- What is the quantum microstructure of spacetime? Can we use it to *explain* the observed large-scale de Sitter nature of our universe, or perhaps the origin of dark energy?



triangulated model of quantum space

Going beyond classical and perturbative gravity



zooming in on a piece of empty spacetime

classical: $g_{\mu\nu}(x) \approx \eta_{\mu\nu}$, i.e. flat Minkowski metric on sufficiently small scales ($g_{\mu\nu}$ is a Lorentzian metric)

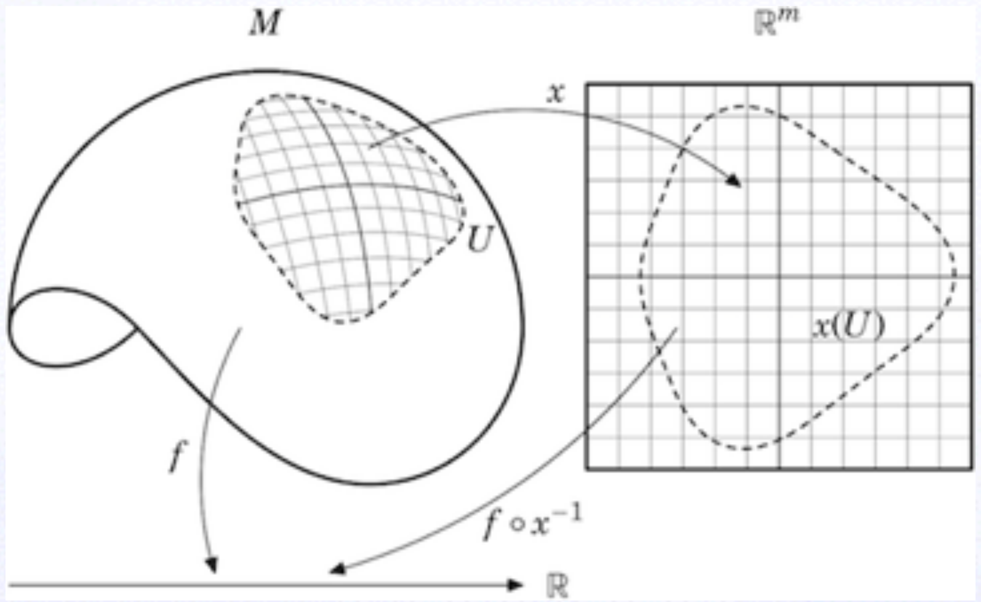
classical, linearized: $g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x)$, $|h_{\mu\nu}| \ll 1$, e.g. gravitational waves far away from source

perturbative quantum gravity: $\hat{g}_{\mu\nu}(x) = \eta_{\mu\nu} + \hat{h}_{\mu\nu}(x)$, but this theory is non-renormalizable, i.e. not useful near the Planck scale ℓ_{Pl}.

nonperturbative quantum gravity: what becomes of spacetime and the degrees of freedom of gravity at ℓ_{Pl} ?: quantum foam, worm holes? Unlike in $d=2$, nonperturbative systems of quantum geometry in higher dimensions are largely uncharted territory. Our classical geometric intuition is ***not*** a good guide. Unexpected things can and do happen!

Which aspects of class. geometry/gravity survive? How to explore this regime?

Getting rid of local "gauge" degrees of freedom



differentiable manifold *M* and a coordinate chart

- Classically, smooth manifolds $(M,g_{\mu\nu})$ provide powerful and extremely convenient models of spacetime.
- geometric properties encoded in the Riemann curvature tensor $R^{\kappa}{}_{\lambda\mu\nu}(x)$

- However, this description comes with an enormous redundancy, the "freedom to choose coordinates" without affecting the physics.
- The "gauge" group of GR is the infinite-dim. group of coordinate transformations (diffeomorphisms) on *M*. **The key challenges of quantum gravity are how to implement this symmetry and describe physics in terms of coordinate-invariant *quantum observables*.**
- In terms of implementing local gauge symmetry, CDT for quantum gravity is the analogue of lattice gauge FT for QCD, but even better!

Putting gravity on the lattice, but correctly

- following the extremely successful example of QCD, we explore the nonperturbative regime quantitatively by **"lattice quantum gravity"**
- lattice gauge field configurations à la Wilson (PRD 10 (1974) 2445) are replaced by piecewise flat geometries (triangulations) à la Regge (Nuovo Cim. 19 (1961) 558)

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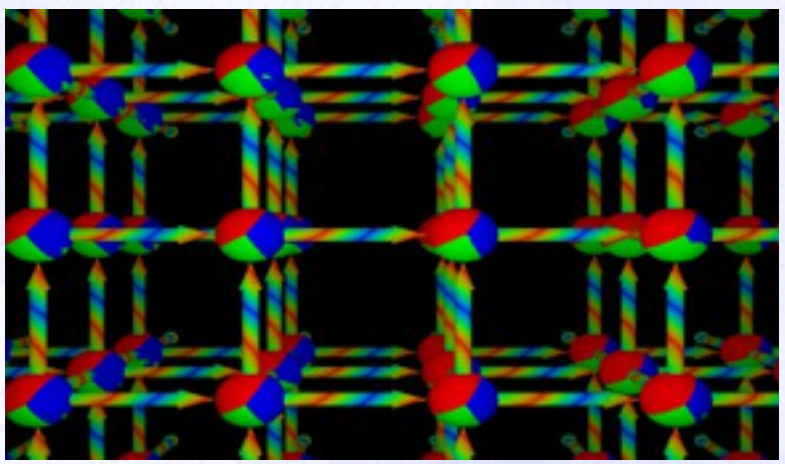
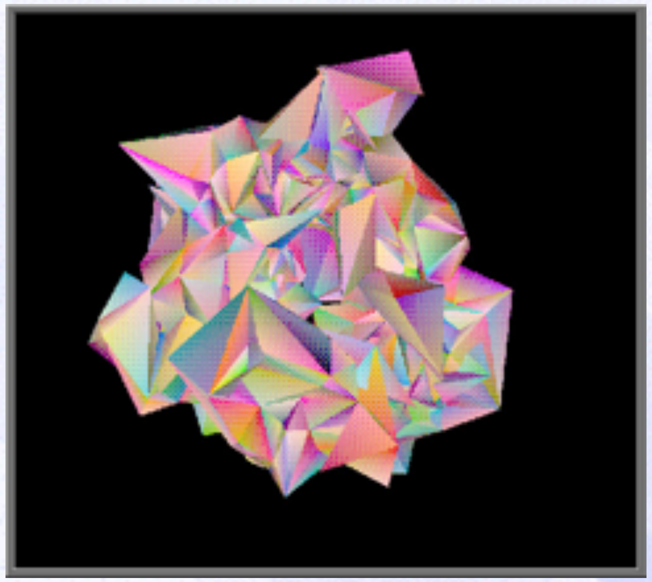


triangulated model of quantum space



- modern implementation: **Causal Dynamical Triangulations (CDT)**, a nonperturbative, background-independent, manifestly coordinate-invariant path integral, regularized on *dynamical* lattices
- N.B.: nontrivial scaling limit needed, no "fundamental discreteness"

CDT Quantum Gravity

is a promising nonperturb. candidate theory of quantum gravity that
(a) uses a minimalist set of ingredients and prior assumptions,
(b) uses only standard tools from QFT, stat mech, critical systems,
(c) comes with a quantitative reality check: computational tools,
(d) gets a few things right previous approaches did not.

CDT is 'as simple as possible, but not simpler', with nontrivial results.

In absence of experiments and observations to guide us, Monte Carlo simulations help to 'keep us honest' and produce quantitative results.

As one would expect in standard QFT, the theory has divergences in the limit as the UV regulator is removed, which must be renormalized.

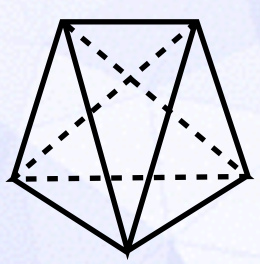
REVIEWS: J. Ambjørn, A. Görlich, J. Jurkiewicz & RL, Phys. Rep. 519 (2012) 127 [arXiv: 1203.3591]); **NEW**: RL, arXiv:1905.08669

N.B.: interesting Pisa contributions from M. D'Elia and collaborators

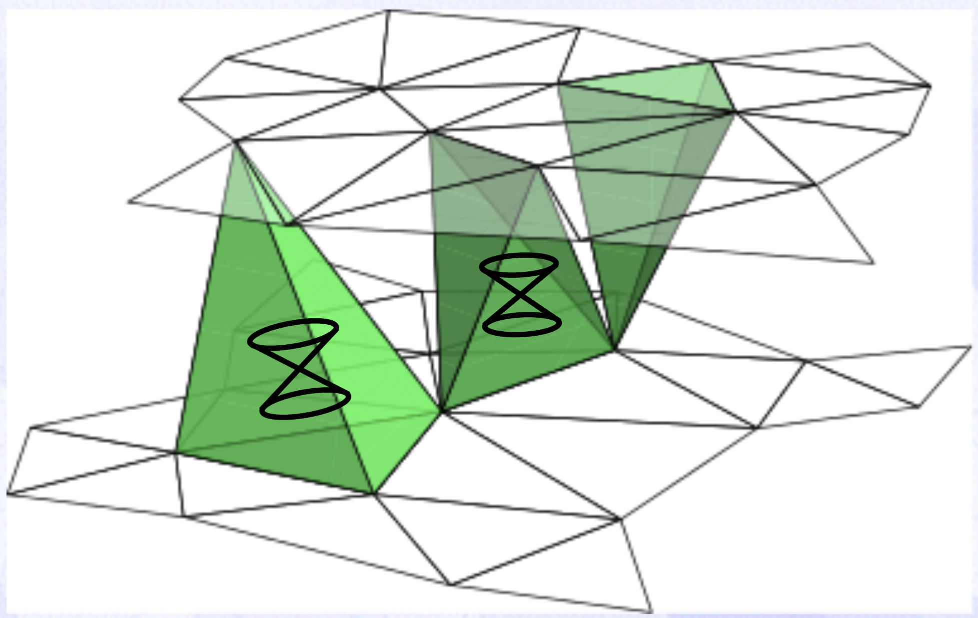
Can we really describe Planckian physics?

In the absence of experimental verification, isn't nonperturbative quantum gravity one giant free lunch at the Planck scale?

- No, because the classical limit (GR) must come out right!
- In other approaches, classical limit is not known/computable.
- not so in **Causal Dynamical Triangulations**!
- It uses tiny, 4D triangular building blocks to approximate and compute a quantum superposition of curved spacetimes.



- To obtain results compatible with the classical theory, the gluing rules must implement a well-defined causal (light cone) structure. **Causal structure and 'time' do not emerge.**



part of a causal triangulation in *d=3*

My magic wand: Feynman path integral, "Sum over Histories"

Newton's constant — cosmological constant — Einstein-Hilbert action

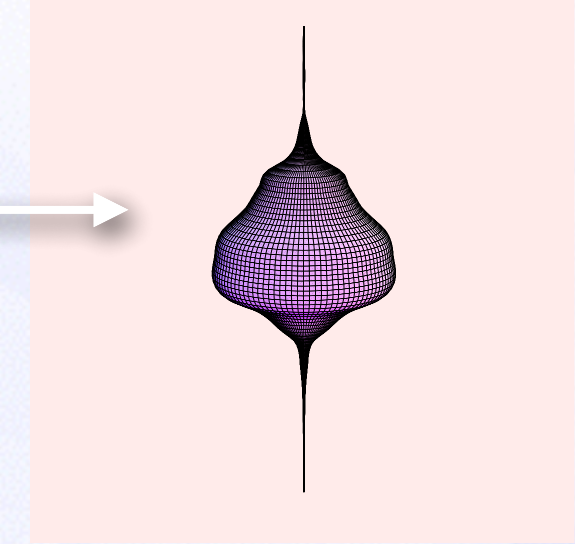
$$Z(G_N, \Lambda) = \int_{\substack{\text{spacetimes} \\ g \in \mathcal{G}}} \mathcal{D}g \; \mathrm{e}^{iS^{\mathrm{EH}}[g]}$$

- quantum superposition applied to spacetime itself
- each "path" is a four-dimensional, curved spacetime geometry *g*, which can be thought of as a three-dimensional, spatial geometry developing in time
- the challenge is to make the path integral $Z(G_N,\Lambda)$ into a well-defined, computable quantity; this is exactly what CDT does

The Emergence of Classicality from Causal Dynamical Triangulations (CDT)

From pure quantum excitations, CDT generates a spacetime with semiclassical properties *dyna-mically*, without using a background metric.

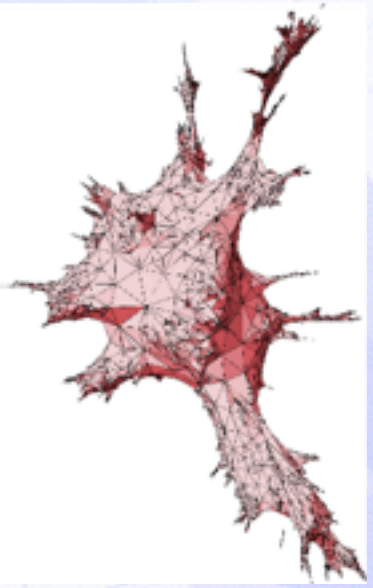
how to obtain a macroscopic universe with a ***de Sitter shape***:



Other key results/properties:

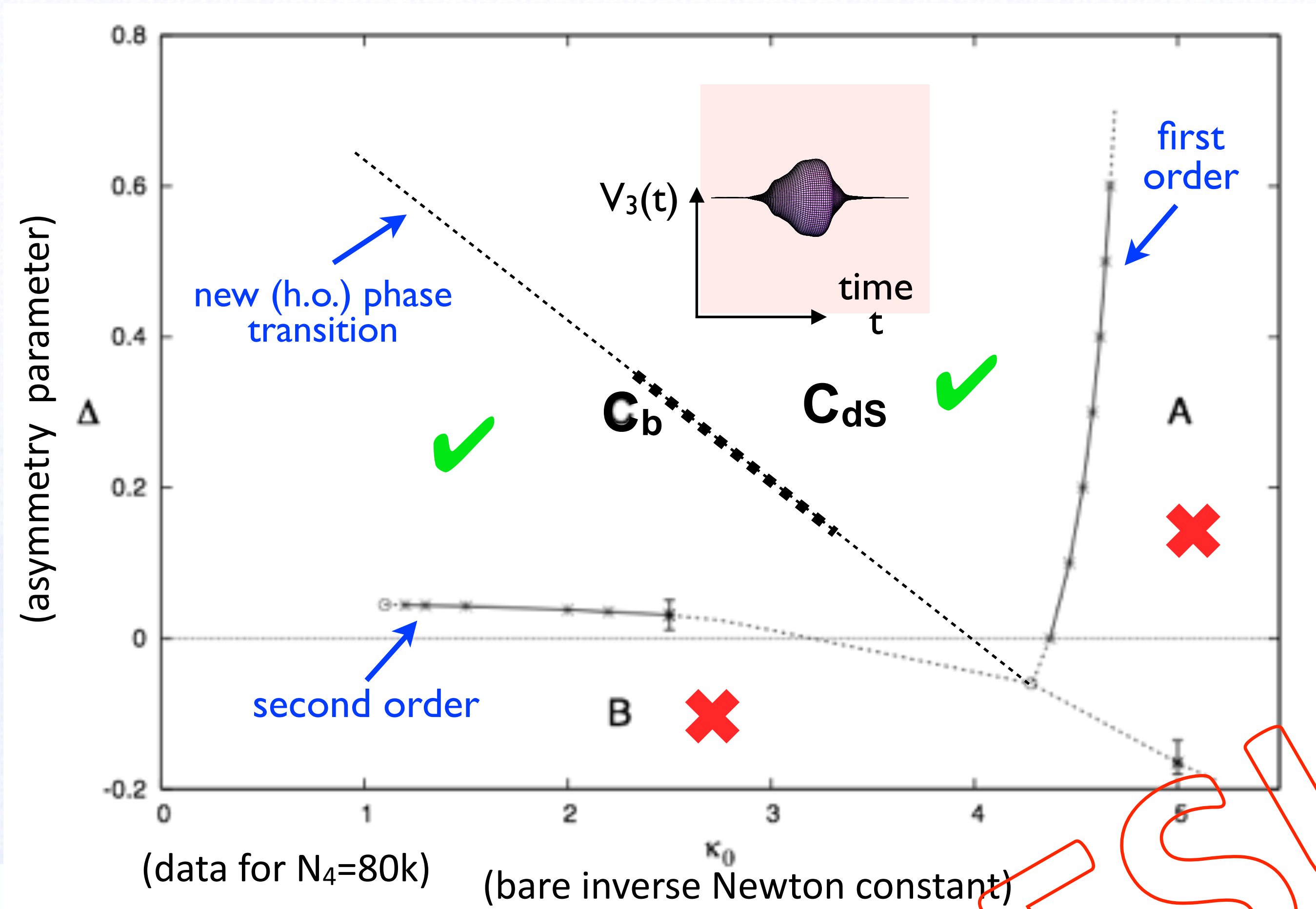
- crucial role of causal structure
- nontrivial phase structure, with "classical" phases
- second-order phase transitions (unique)
- scale-dependent spacetime dimension (2 → 4)
- applicability of renormalization group methods

from a superposition of "wild" path integral histories:

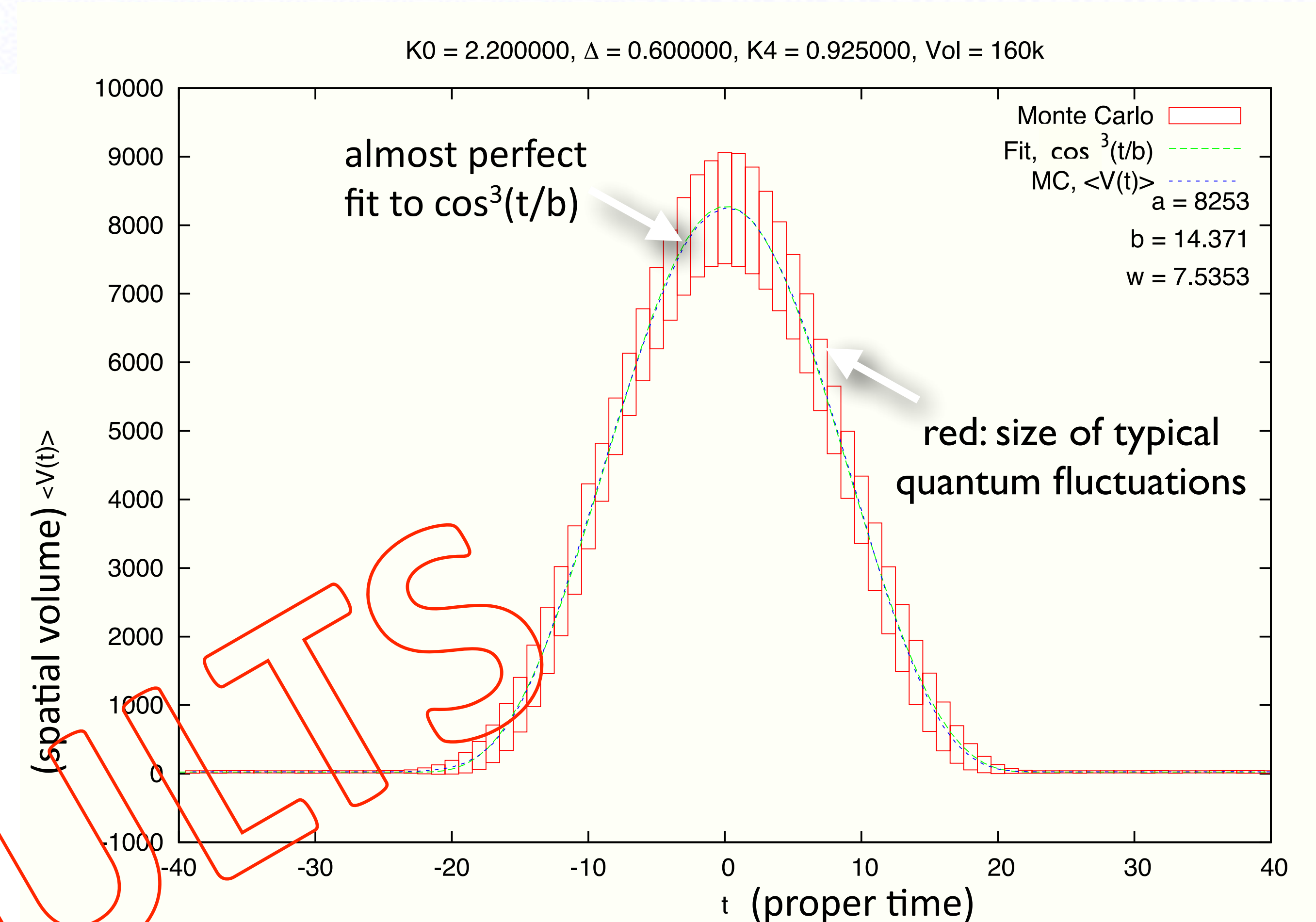


Everything we have learned about "quantum spacetime" in CDT QG comes from measuring a few <u>quantum observables</u>.

Phase diagram of CDT QG

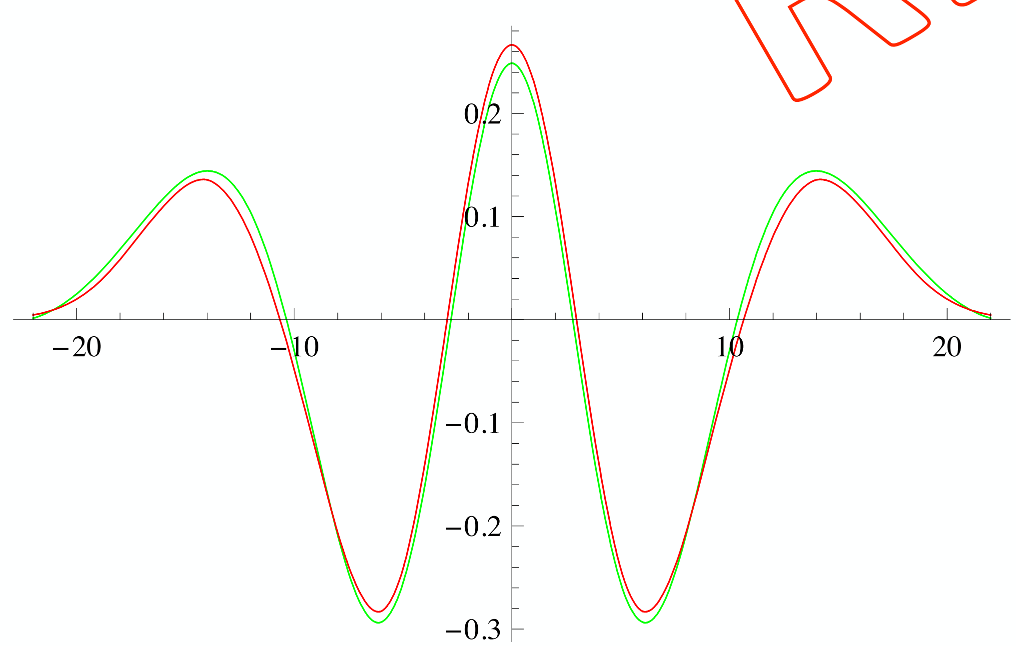


The universe is de Sitter-shaped



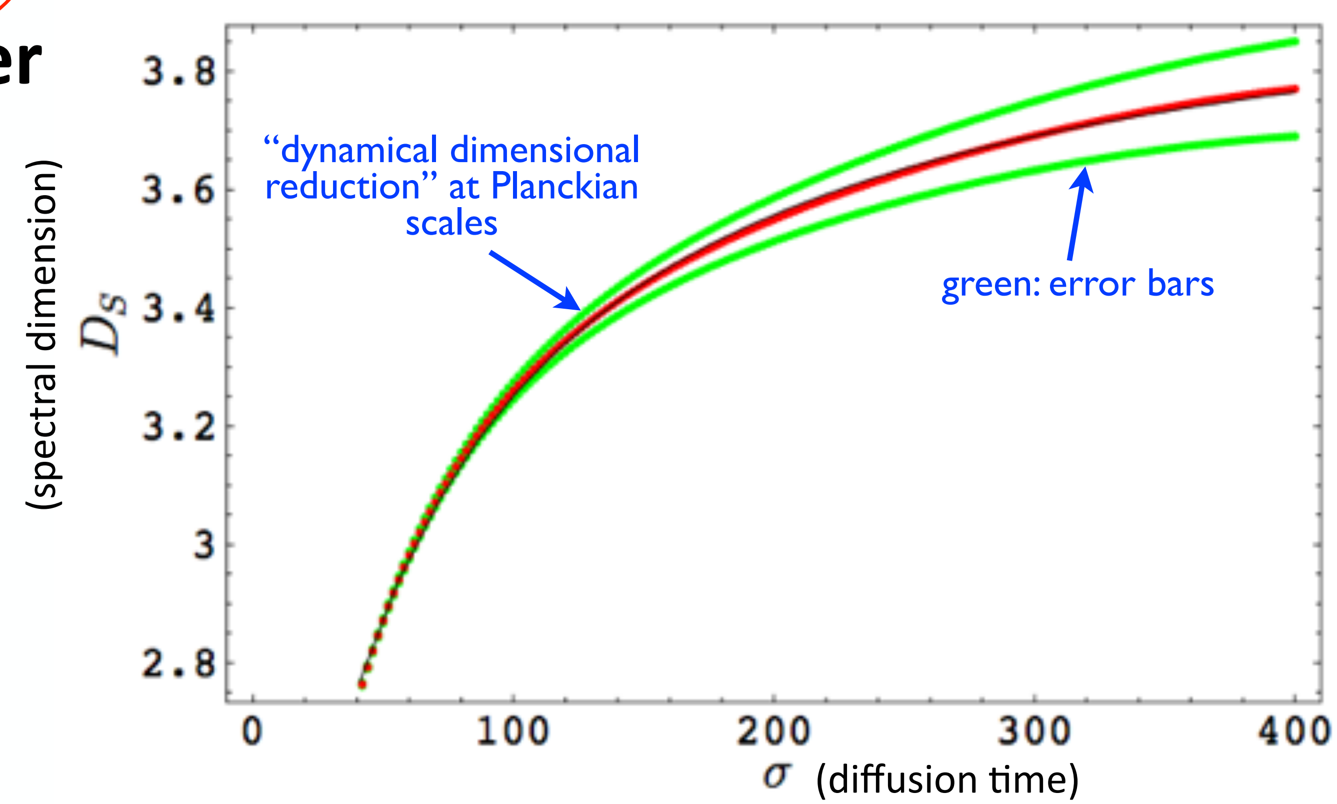
RESULTS

Volume fluctuations around de Sitter



(low-lying eigenmode matches with semiclassical expectation)

Spectral dimension of the universe



Nonperturbative "geometry" behaves strangely

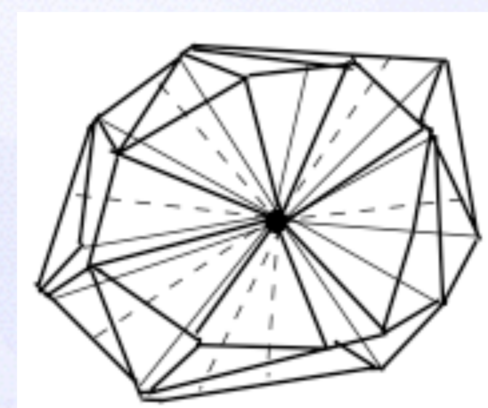
Isn't it obvious that by gluing together four-dimensional building blocks, one will obtain a (quantum) spacetime of dimension 4?

No. Generically it does not happen when quantum fluctuations are large.

This was only gradually understood, using computer "experiments". In DT models prior to CDT, one of two things happened to "quantum geometry":

it polymerized (small G_N^{bare}), $d_H = 2$

Hausdorff dimension



it crumpled (large G_N^{bare}), $d_H = \infty$

This degenerate behaviour is generic for (Euclidean) DT in dimension d > 2. Branched polymers are a generic finding of stat mech models of QG.

***Causal* DT was invented to cure this problem and appears to do so!**

Dimension is not what it used to be …

Totally unexpected: spacetime **dimension**, a "pregeometric" property, **becomes dynamical** in the presence of large curvature fluctuations.

The absence of any regime where the dimension at large scales is equal to 4 is enough to rule out a candidate theory of quantum gravity!

"Dimension" in nonperturbative quantum gravity is no longer fixed a priori, but reflects a particular quantum dynamics. It is *not* pre-determined by the dimensionality of the building blocks used.

Besides the *Hausdorff dimension*, one can also measure the quantum geometry's *spectral dimension* (by setting up a diffusion process).

In **CDT quantum gravity**, one first observed the phenomenon of "dynamical dimensional reduction", where within measuring accuracy the spectral dimension changes from **d = 4** on large to **d = 2** on short scales!

Summary & Outlook

We live in the "Century of Gravity", with *Quantum* Gravity as an outstanding challenge.

Nonperturbative quantum gravity can be studied in a **lattice** setting, in close analogy with lattice QCD, but taking into account the dynamical nature of geometry, as exemplified by CDT.

Causal Dynamical Triangulations is a conceptually simple and computionally accessible candidate theory of quantum gravity, which has been making significant strides towards a full-fledged quantum theory.

It provides a highly nontrivial example of the emergence of classical geometric properties, and also exhibits true quantum signatures.

We are working hard on making this candidate theory more complete, and to eventually predict observable effects.

Quantum Gravity made simple, but not too simple

Pisa, 24 Oct 2019

Thank you!

Concrete, interesting open questions

Crucial (for any approach to quantum gravity): find and measure further gauge-invariant quantum observables, including the new quantum Ricci curvature.

Implementing these **in CDT quantum gravity**,

➡ understand the physical properties of the dynamically generated vacuum state, and quantify how far its *local* geometric properties are from those of a (semiclassical) de Sitter space,

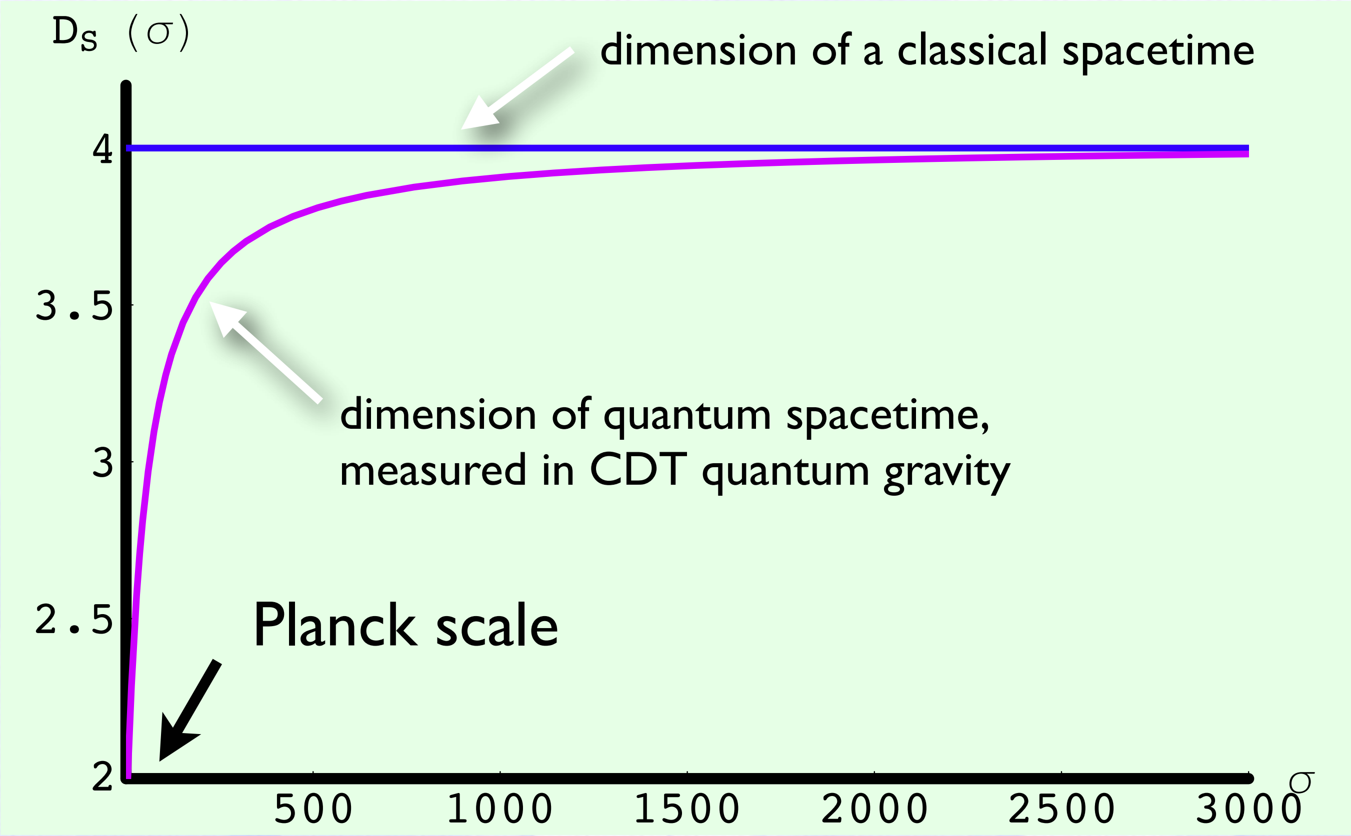
➡ analyze the renormalization group flows ('lines of constant physics') near 2nd-order phase transitions, looking for ultraviolet fixed points,

➡ quantum gravity's holy grail: derive a true quantum effect that has observable (e.g. astrophysical) consequences.

Dimension of quantum spacetime: a surprise

We can measure the dimension of an unknown space or medium by letting a drop of ink fall into it.

From the speed with which the "ink drop" spreads, one can determine the dimension D_s of the space.



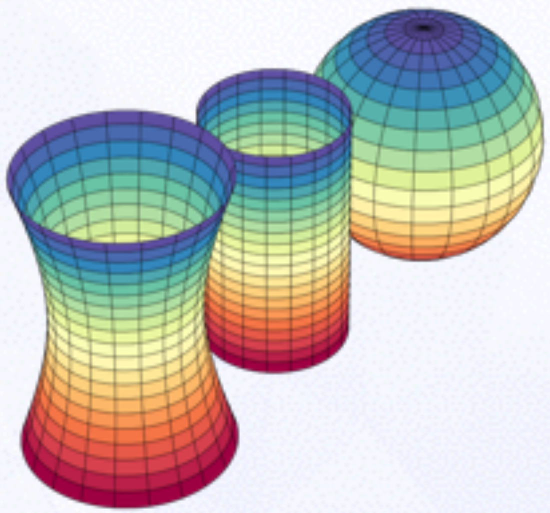
dimension D_s of quantum spacetime as function of the distance scale σ (schematic)

$D_s = 4$ on large scales (as expected), but $D_s \approx 2$ near ℓ_{Pl} due to quantum fluctuations.

At intermediate scales, the dimension is not an integer!

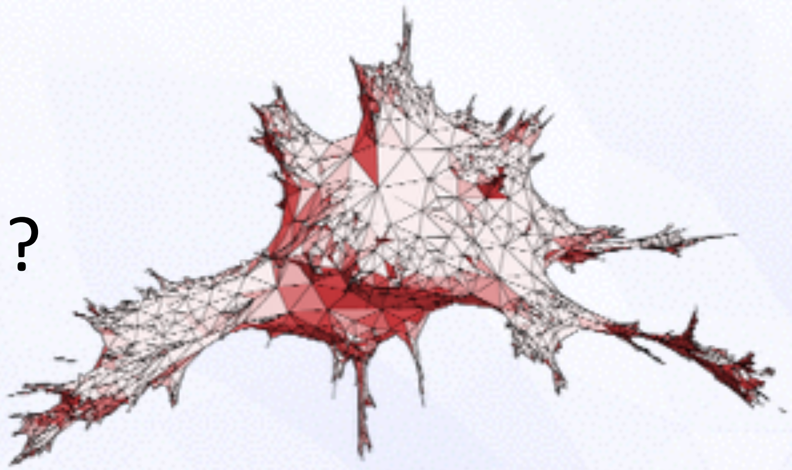
This is definitely **not** a classical spacetime.

The challenge of "quantum curvature"



from classical

to quantum?



Individual spacetime geometries (= path integral histories) in CDT are continuous, but *not* smooth, and far from (semi-)classical.

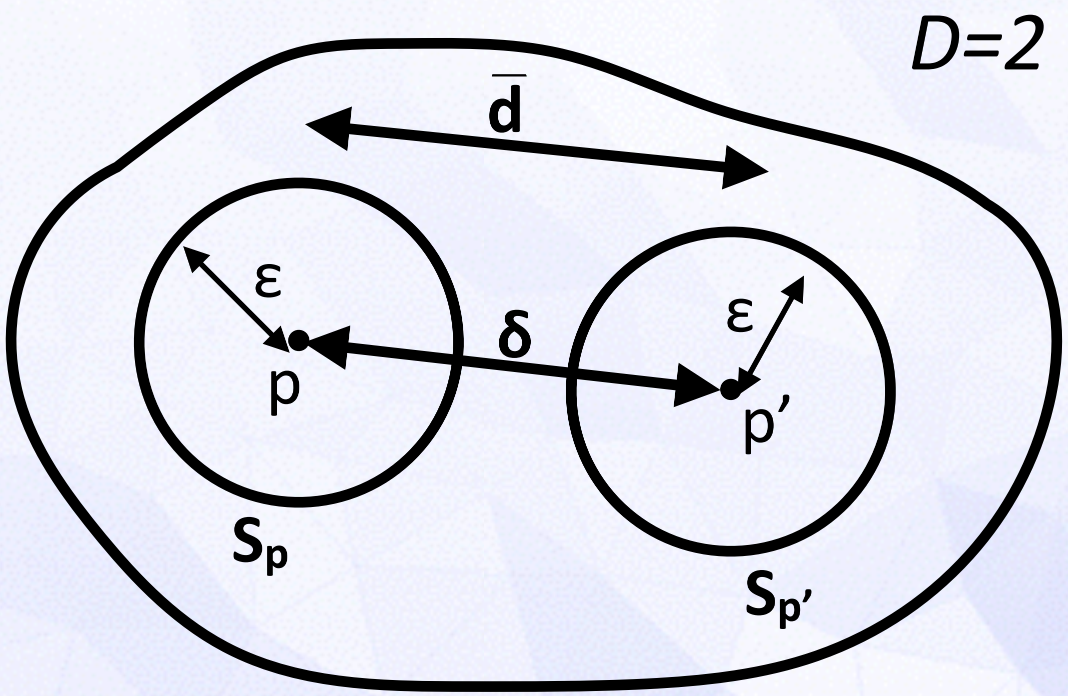
- Which properties continue to hold on such spaces?
- How can we make sense of curvature and curvature tensors?
- How can we average/coarse-grain them?

We have successfully defined and tested ***quantum Ricci curvature.***
(N. Klitgaard & RL, PRD 97 (2018) no.4, 0460008 and no.10, 106017, work in progress with J. Brunekreef and N. Klitgaard)

Introducing quantum Ricci curvature

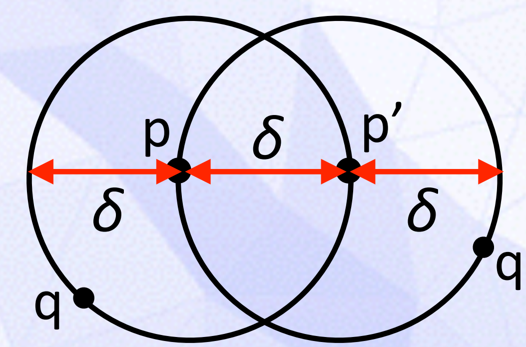
In *D* dimensions, the key idea is to compare the distance $\bar{d}$ between two *(D-1)*-spheres with the distance δ between their centres.

The sphere-distance criterion:
"On a metric space with positive (negative) Ricci curvature, the distance $\bar{d}$ of two nearby spheres S_p and $S_{p'}$ is smaller (bigger) than the distance δ of their centres."



(c.f. Y. Ollivier, J. Funct. Anal. 256 (2009) 810)

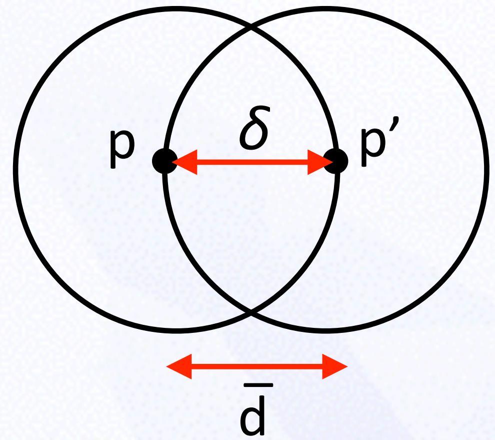
Our variant uses the ***average sphere distance*** $\bar{d}$ of two spheres of radius δ whose centres are a distance δ apart,



- involves only distance and volume measurements
- the directional/tensorial character is captured by the "double sphere"
- coarse-graining is captured by the variable scale δ

Implementing quantum Ricci curvature

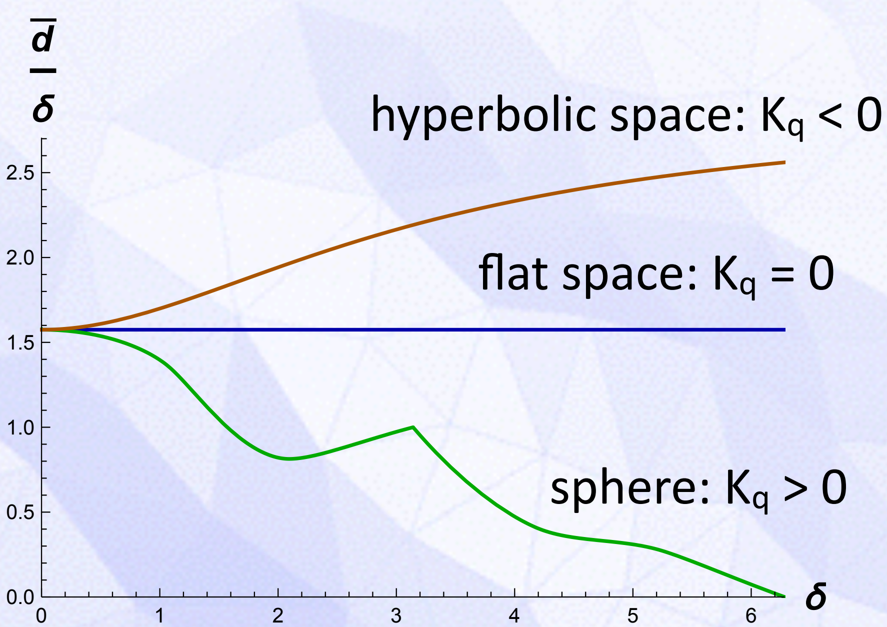
We measure the **"quantum Ricci curvature K_q at scale δ"**,



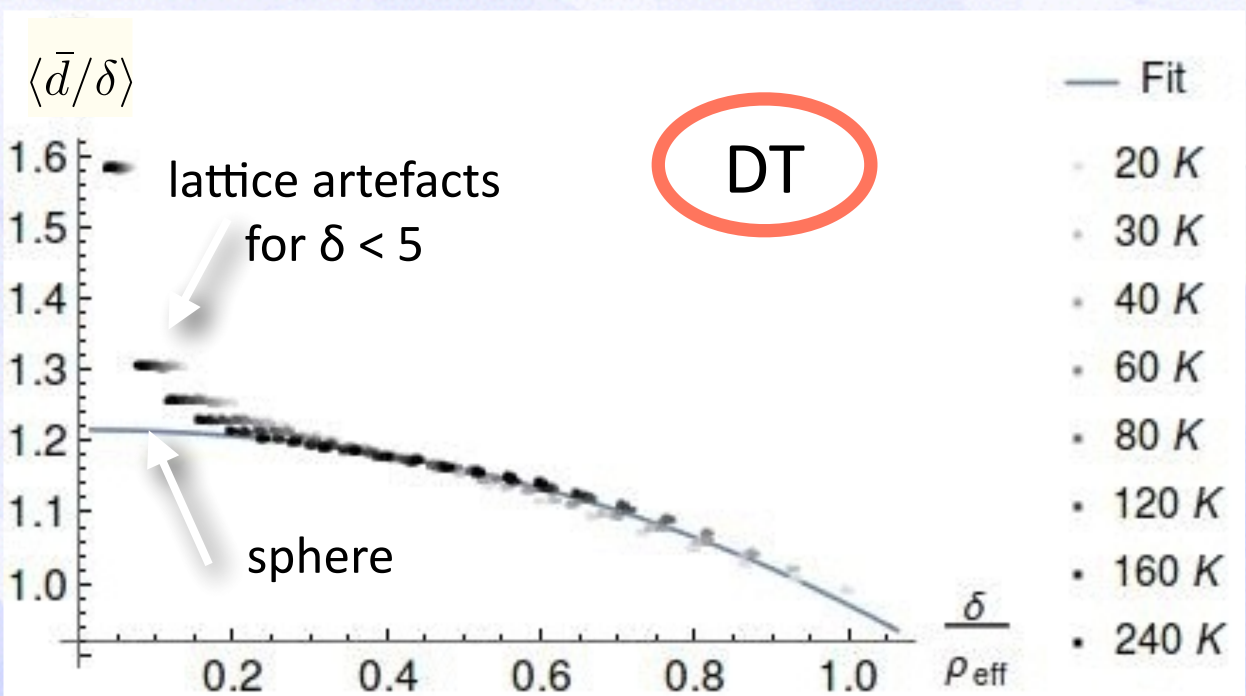
non-univ. constant

$$\frac{\bar{d}(S_p^\delta, S_{p'}^\delta)}{\delta} = c_q(1 - K_q(p,p')), \quad \delta = d(p,p'), \quad 0 < c_q < 3,$$

on the quantum ensemble and compare it with the behaviour on simple continuum "reference spaces" (constantly curved; ellipsoids; cones). Remarkably, for the highly fractal quantum geometry of 2D quantum gravity, quantum Ricci curvature displays a robust, sphere-like scaling behaviour:



K_q on classical, constantly curved spaces in D=2 (curvature radius 1)



triangles N∈[20k, 240k]; error bars too small to be shown