# Non-string quantum gravity

Fotini Markopoulou
Perimeter Institute

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Dynamical Triangulations

Canonical Quantum Gravity

Spin Foams

Loop Quantum Gravity

Causal Dynamical Triangulations

Semi-classical GR (Black holes etc)

Causal Sets

Asymptotic freedom

Quantum gravity phenomenology

Quantum Causal Histories

The Computational Universe

Internal Relativity

Doubly Special Relativity

Background-independent cond matt models

Physics of the Fermi point

# Unifying theme

Order the different approaches using the notion of background independence

# Outline

- What is background independence?
- How it has been implemented traditionally: examples
- A (personal) assessment and a central question
- New approaches: background independence in a new light

# GR and background independence

$$S_{\mathrm{HE}} = \int d^4x \, \sqrt{g} R$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T_{\mu\nu}$$

manifold $\mathcal{M}$
metric $g_{\mu\nu}$
curvature $R_{\mu\nu}$
matter $T_{\mu\nu}$

Solutions to the Einstein Equations are $\mathrm{Diff}\mathcal{M}$ -invariant.

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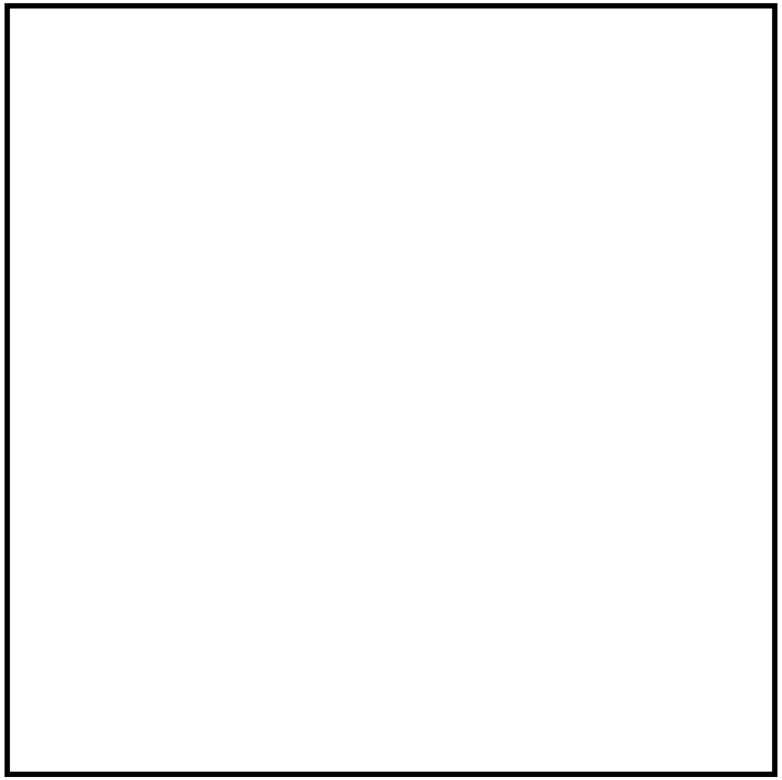

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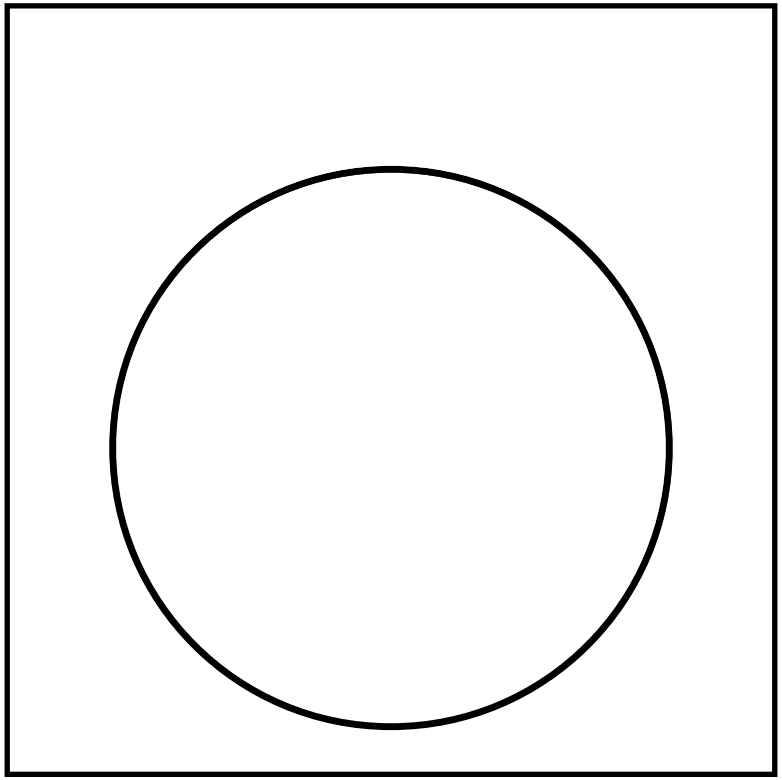

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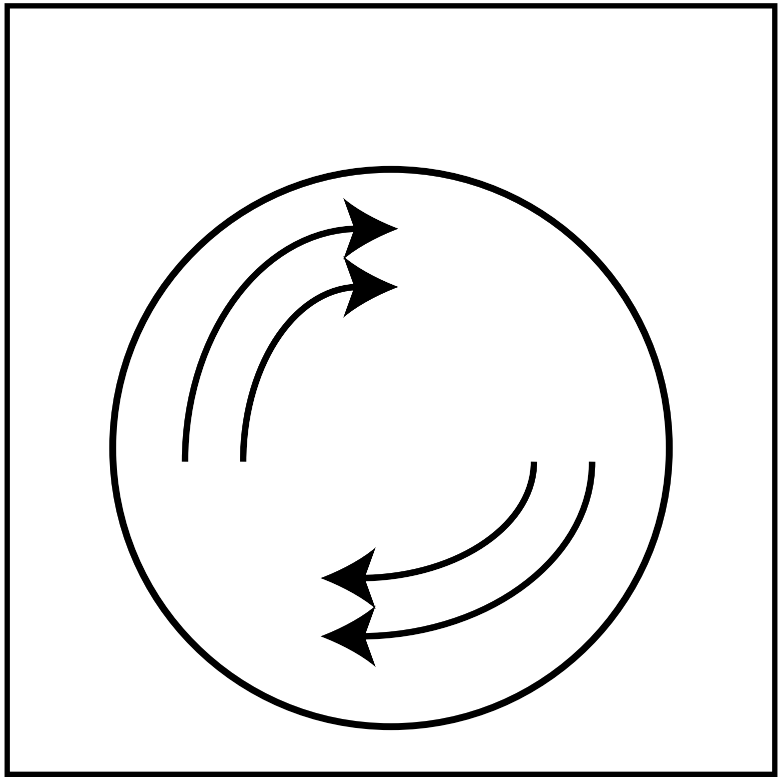

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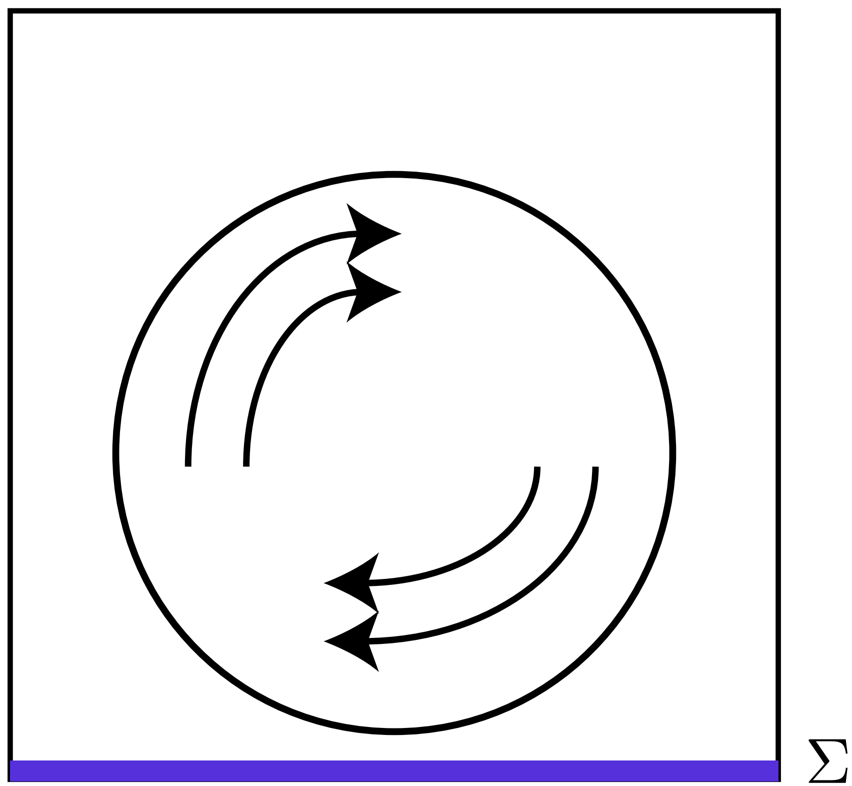


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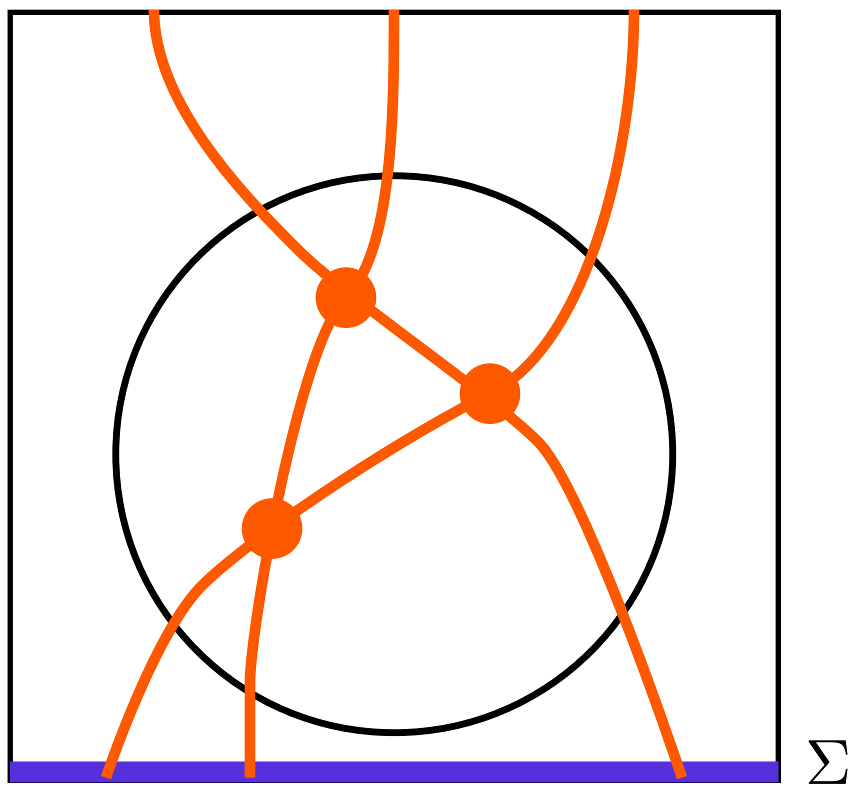

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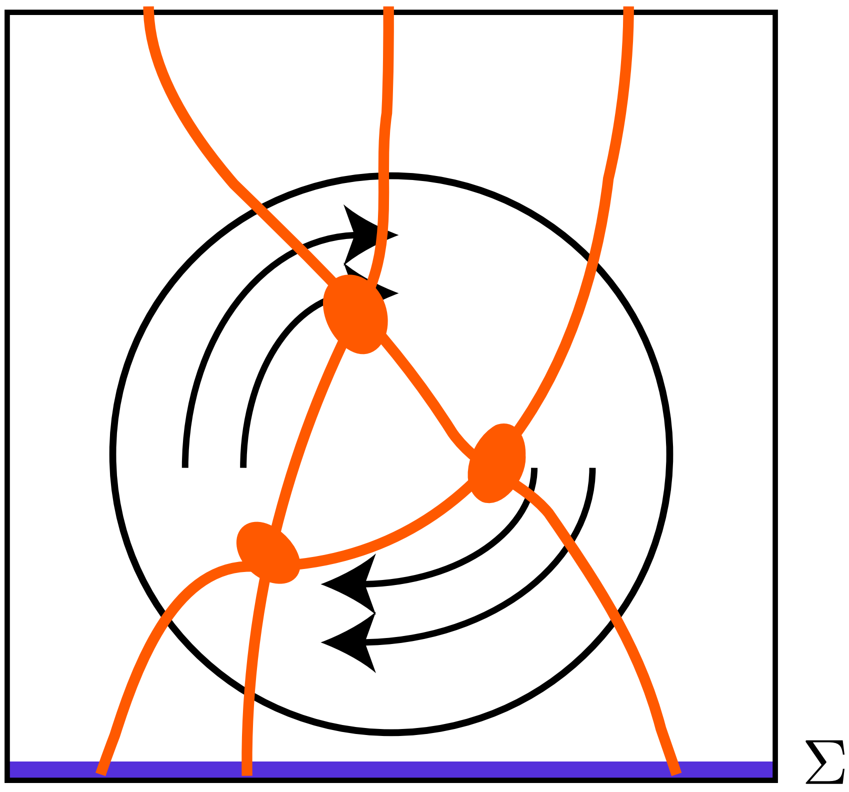


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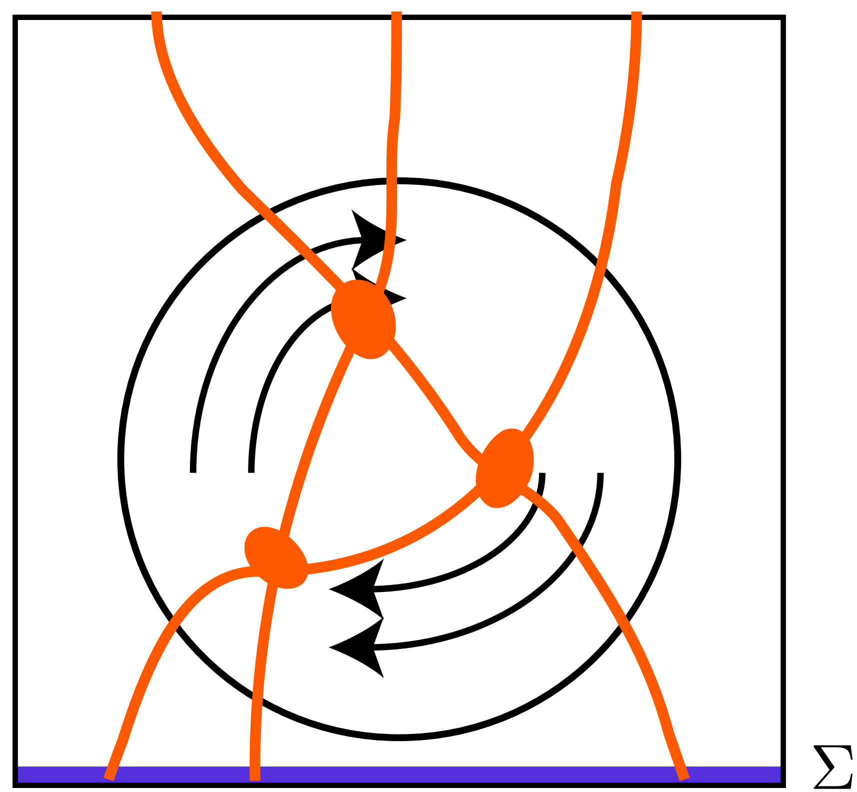



$$\phi \in \text{Diff}\Sigma$$

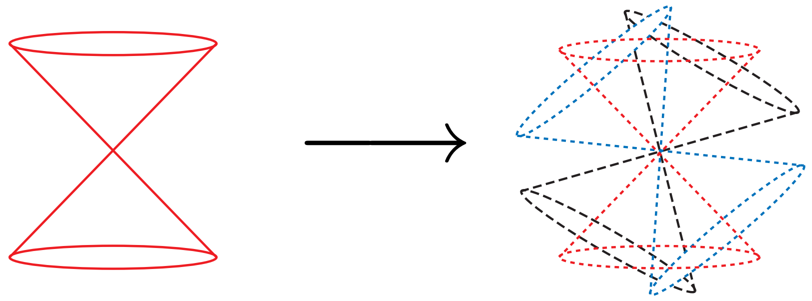
- Only events and causal relations are physical: Background Independence
- The metric is dynamical

# Background independence as a principle in quantum gravity

Background Independence I:

There should be no preferred geometry in the formulation of the quantum theory of gravity.

Quantum gravity is given by a quantum superposition of quantum geometries.



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Causal Dynamical Triangulations

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Canonical Quantum Gravity

Loop Quantum Gravity

Background independence I
implemented via
superposition of quantum geometries

Semi-classical GR (Black holes etc)

Asymptotic freedom

Background independence II
without geometry

Quantum Causal Histories

The Computational Universe

Internal Relativity

Background-independent cond matt models

Quantum gravity phenomenology } Influential

Doubly Special Relativity

Physics of the Fermi point

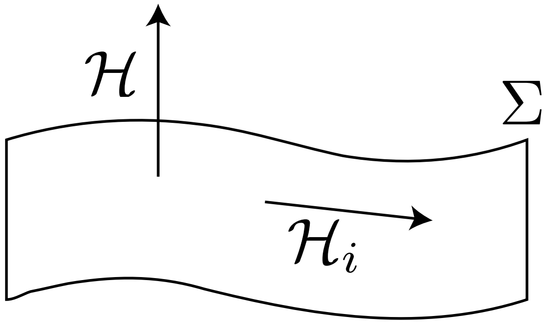
# Loop Quantum Gravity:

gr-qc/0210094

Canonical quantization of General Relativity.

$$S_{\mathrm{HE}} = \int d^4x \, \sqrt{g} R \quad \longrightarrow \quad S_{3+1} = \int d^3x \, dt \, \left( \mathcal{H} N + \mathcal{H}_i N^i \right)$$

$$\mathcal{H} = 0 = \mathcal{H}_i$$



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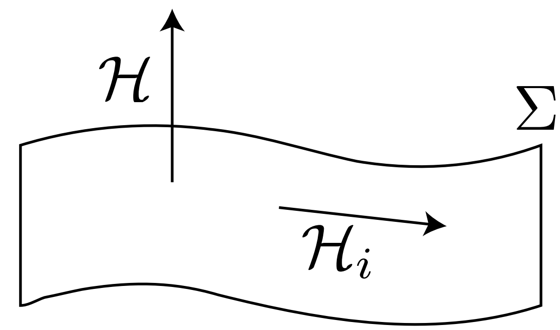

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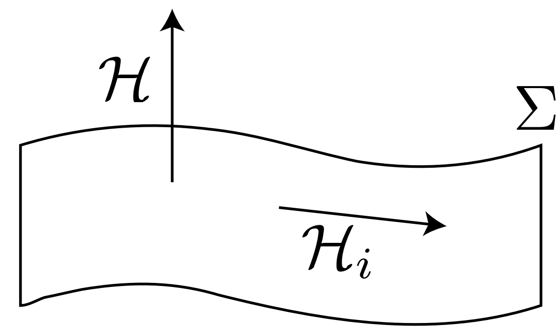


But: $\mathrm{Diff}\,\mathcal{M} \neq \mathrm{Diff}\,\Sigma \times R$

$$\{\mathcal{H}(x), \mathcal{H}(x')\} = g^{ij} \, \mathcal{H}_i \delta_{,j}(x, x') - (x \leftrightarrow x')$$

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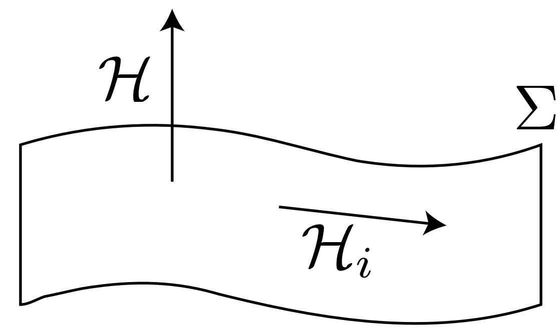


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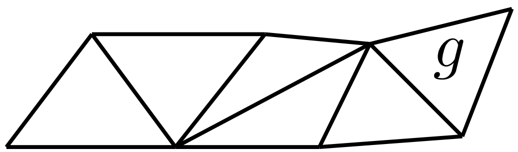
- The physical sector ( $\mathrm{Diff}\,\mathcal{M}$-invariant states) is not known.
- General relativity $\underset{?}{\overset{\text{quantize}}{\rightleftarrows}}$ loop quantum gravity
- Low energy limit and contact with observations runs into problem of time

# Causal Dynamical Triangulations:

hep-th/0604212

A statistical model of quantum geometries, weighed by the Einstein action.




$$A\left(L(in), L(out), 1\right) = \frac{g^2 L_1 L_2}{(1 - L_1)(1 - gL_1 - gL_2)}$$

$$A_{L(in)\to L(out)} = \sum_{t=0}^{\infty} A\left(L(in), L(out), t\right)$$

Causality condition: advance everyone at every step.

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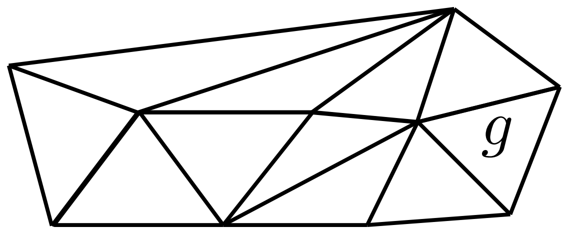


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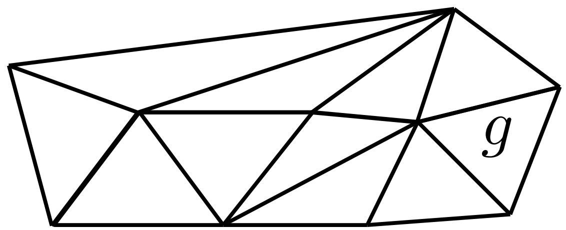


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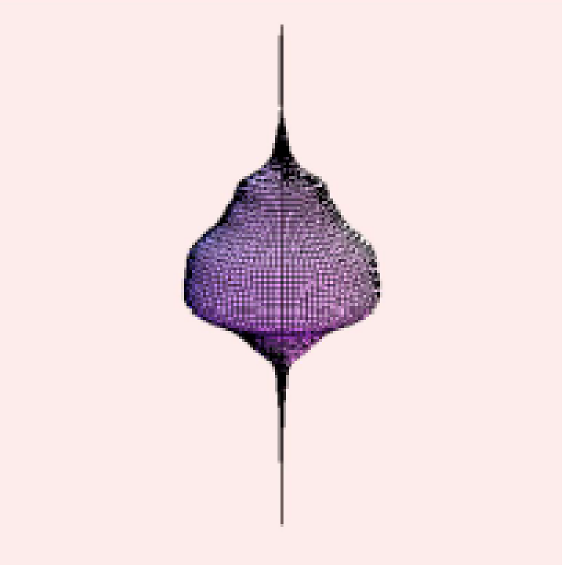
- ✓ Well-behaved typical histories
- ✓ Also when matter is added
- ✓ Correct dimension
- ✓ High-energy prediction: evidence for 2d.
- ✓ New universality class discovered.



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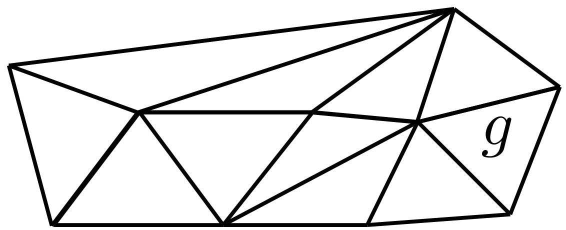


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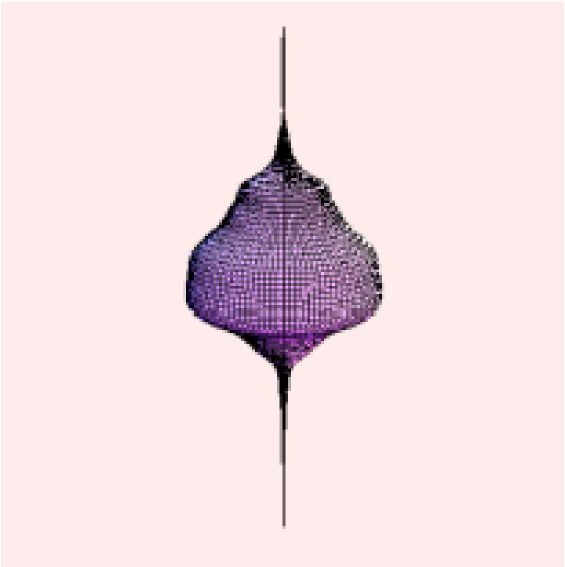

- Gravity in progress.
- What is the meaning of the causality condition?

# My view

Quantum gravity phenomenology: $l_{\rm Pl}$ within reach means pressure for predictions.
$\Longrightarrow$ Emphasis on the classical, low energy limit.

Crucial feature: time. Have time, can predict. Is it ok to have time?

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# Main open issue

| Is gravity/geometry fundamental or emergent? |
|---|

Arguments for emergent geometry/time:

- Black hole thermodynamics
- Einstein Equation of state gr-qc/9504004
- Holographic arguments
- Cond matt approaches
- Problem of time

# Revisit Background Independence

Background Independence I:

There should be no preferred geometry in the formulation of the quantum theory of gravity.

Quantum gravity is given by a quantum superposition of quantum geometries.

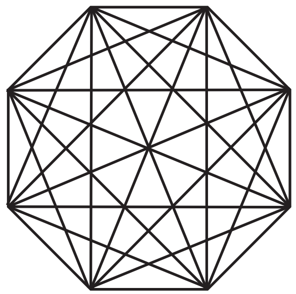
Background Independence II:

There are no geometric or gravitational degrees of freedom in the fundamental theory.

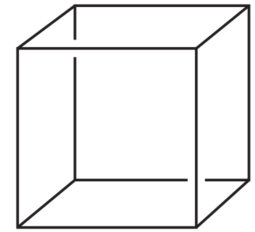
Geometry is only a classical, emergent concept.

# Quantum graphity: an example of a BI II model.

hep-th/0611197



geometrogenesis
phase transition



High- $T$

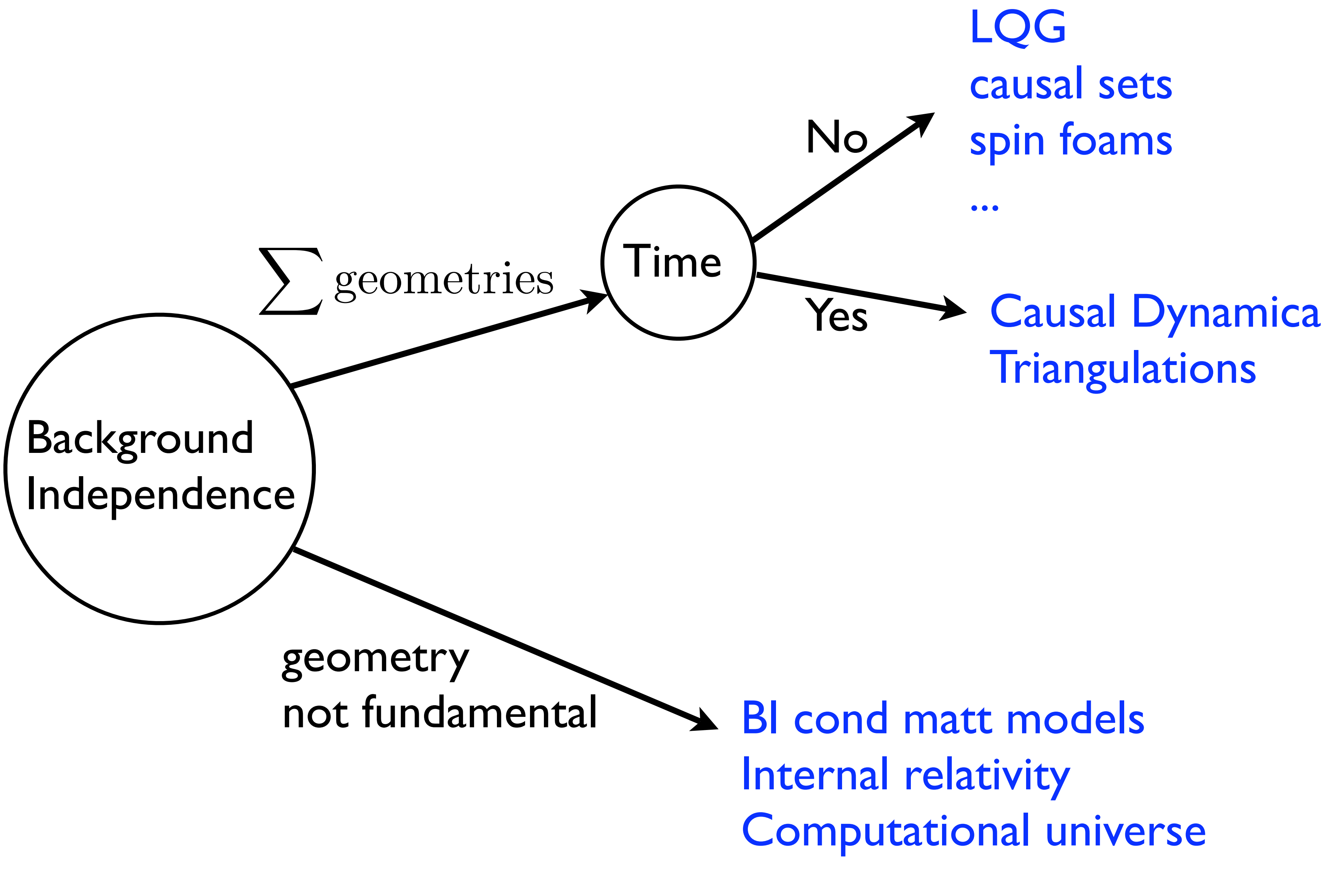
- Permutation symmetry
- No locality
- Relational
- $\langle d_{ij} \rangle = 1$
- $\sim \infty$-dimensional
- external time
- micro-matter

Low- $T$

- Translations
- Local
- Relational
- $\langle d_{ij} \rangle$ large
- low-dimensional
- external and internal time
- macro-matter and dynamical geometry

Einstein equations are to be derived, not quantized (ask O.Dreyer how).

# Summary



LQG
causal sets
spin foams
...
No
$\sum$ geometries
Time
Yes
Causal Dynamical
Triangulations
Background
Independence
geometry
not fundamental
BI cond matt models
Internal relativity
Computational universe
...

# More open questions

- Relevance of $l_{\mathrm{Pl}}$
- Time seems to imply a bath
- The quantum/classical transition
- Pre-geometry signature in early universe cosmology