17. Quantum Gravity and Spacetime

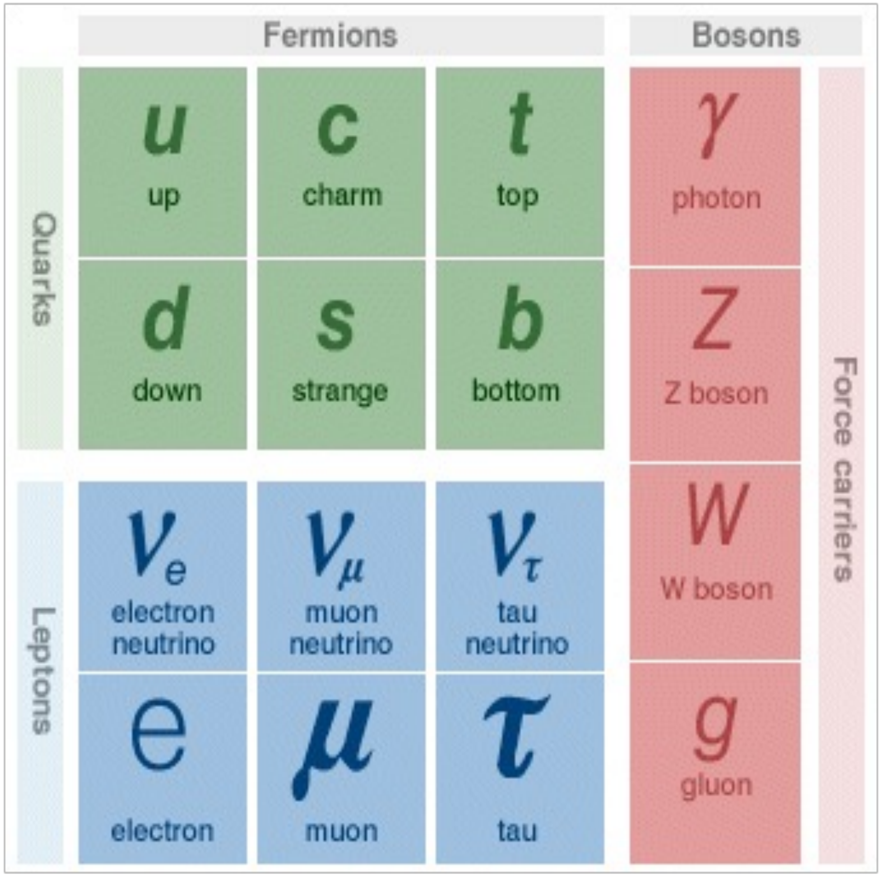
Theory of Matter

Relativistic Quantum Field Theories (RQFTs)

Quantum Electrodynamics (1940's)
- RQFT of *electromagnetic* force.
- Matter fields: leptons, quarks.
- Force field: γ (photon).
- $U(1)$ symmetry.

Electroweak theory (1960's)
- RQFT of *EM* and *weak* forces.
- Matter fields: leptons, quarks.
- Force fields: γ, W^+, W^-, Z.
- $U(1) \times SU(2)$ symmetry.

Quantum Chromodynamics (1970's)
- RQFT of *strong* force.
- Matter fields: quarks.
- Force fields: gluons (8 types).
- $SU(3)$ symmetry.



Standard Model (1970's-80's)
- RQFT of *EM*, *strong*, and *weak* forces.
- Matter fields: leptons, quarks.
- Force fields: γ, W^+, W^-, Z, gluons.
- $U(1) \times SU(2) \times SU(3)$ symmetry.

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Theory of Spacetime

General Relativity (GR) (1916)

- Classical (non-quantum) theory of *gravitational* force.
- $Diff(M)$ symmetry.

Inconsistent!

Standard Model (1970's-80's)

- RQFT of *EM*, *strong*, and *weak* forces.
- Matter fields: leptons, quarks.
- Force fields: γ, W^+, W^-, Z, gluons.
- $U(1) \times SU(2) \times SU(3)$ symmetry.

Theory of Matter

Relativistic Quantum Field Theories

- Flat Minkowski spacetime, unaffected by matter.
- Matter/energy and forces are quantized.
- "Compact" symmetries.

Theory of Spacetime

General Relativity

- Curved Lorentzian spacetimes, dynamically affected by matter.
- Matter/energy and forces are classical.
- "Non-compact" symmetries.

Two General Approaches to Reconciliation

(A) Background-Dependent Approach.

- Start with a spacetime with a fixed metric (*e.g.*, Minkowski spacetime).
- Try to construct a quantized gravitational field on it.

Problem: Standard method of quantizing classical fields, when applied to the gravitational field, produces a "non-renormalizable" RQFT.

(B) Background-Independent Approach.

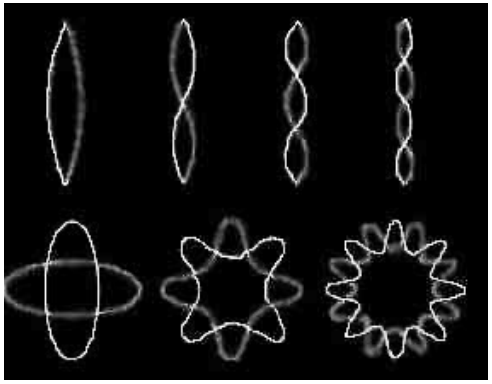
- Start with a spacetime with *no* fixed metric (as in GR).
- Try to construct a quantized gravitational field on it.

Problem: Standard method of quantizing classical fields requires a background metrical structure.

Background-Dependent. Ex 1: String Theory

- *General Idea*: Take QFT as a given and try to force GR into its mold.

Procedure:



- Replace 0-dim point particles with 1-dim strings.
  - *Consequence: Many "non-renormalizable" divergences are tamed in the standard approach to quantization.*

Problems:

1. Requires extra spatial dimensions.
   - *Require that these extra dimensions are "compactified": severely "rolled-up" so that we can't normally experience them.*
2. No testable predictions after ~30 years of work.
3. Takes no lesson from Einstein's insightful geometrization of gravity.
   - *Gravitational force is treated on par with the other forces.*
   - *Spacetime is represented by flat Minkowski spacetime (background-dependence).*

Background-Independent. Ex 1: Loop Quantum Gravity

- *General Idea*: Take GR as a given and try to force QFT into its mold.

Procedure:

- Try to identify the "observables" of GR: very hard to do!
  - *Because of the strange Diff(M) symmetry of GR, its observables are strange; in particular, there are no local observables!*
  - *Identify non-local "loop" observables (quantities that depend on particular closed paths in spacetime).*

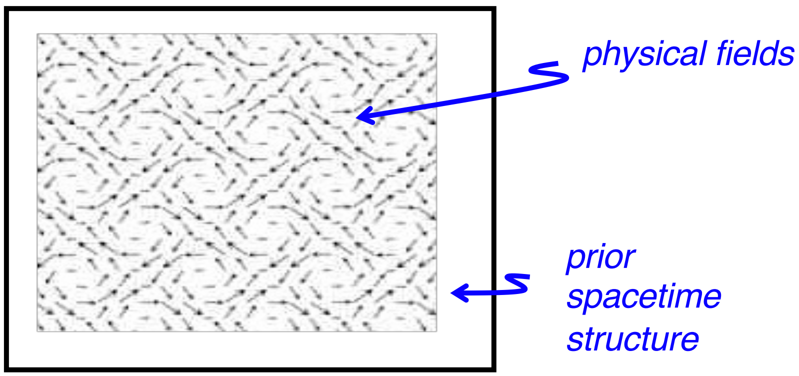
Standard method of quantizing a classical field theory requires identifying the theory's "observables" (quantities that are invariant under the theory's symmetries).

- Spacetime structure is not fixed, but is determined by the quantum (loop) version of the Einstein equations.

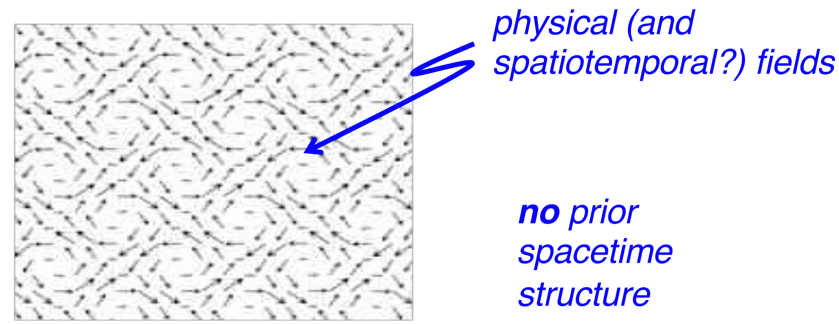
Problems:

1. Constraint equations that result from quantization have yet to be solved.
2. No testable predictions after ~30 years of work.
3. Takes no lesson from the QFT approach's insightful suggestion that QFTs are low-energy approximations to a more fundamental theory.

Question: What do background-dependent and background-independent approaches to quantum gravity suggest about the nature of spacetime?



Background-dependent approach



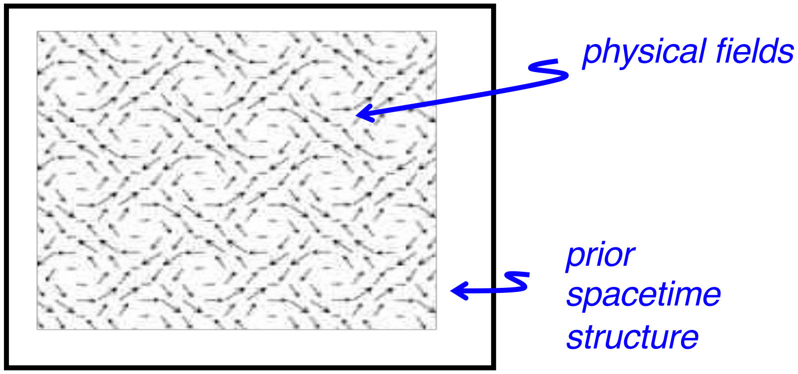
Background-independent approach

- *Claim*: Both approaches may be interpreted in either *substantivalist* or *relationist* terms.

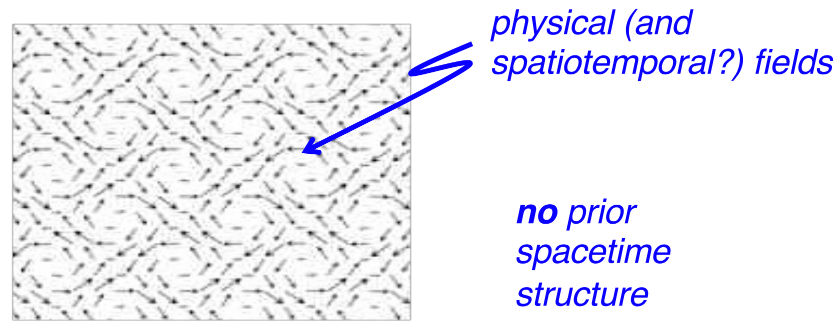
Background-Dependence

- A *substantivalist* may claim that the prior spatiotemporal structure is exhibited by real, substantival spacetime.
- A *relationist* may claim that the prior spatiotemporal structure is exhibited by a real physical field (the metric field, say).

Question: What do background-dependent and background-independent approaches to quantum gravity suggest about the nature of spacetime?



Background-dependent approach



Background-independent approach

- *Claim*: Both approaches may be interpreted in either *substantivalist* or *relationist* terms.

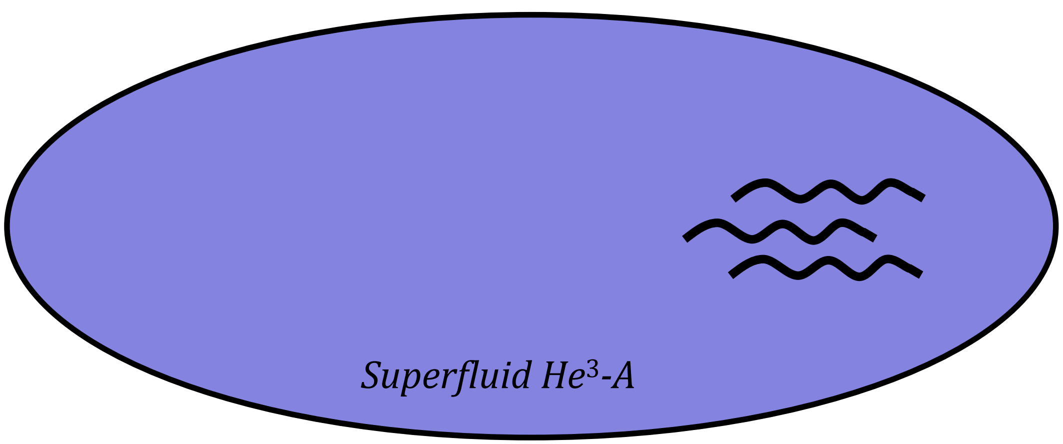
Background-Independence

- A *substantivalist* may claim that spatiotemporal structure depends (as in GR) on physical fields, but once it is so-determined, it exists in its own right.
- A *relationist* may claim that spatiotemporal structure is exhibited by the relations between physical objects, so only such objects exist.

Background-Dependent. Ex 2: Condensed Matter Approaches

- *General Idea*: Suppose GR and the Standard Model describe the low-energy fluctuations of a condensed matter system (like a superfluid, or a superconductor).
- *Then*: The condensate would explain the origin of *both* spacetime and gravity (as described by GR), *and* matter fields and the other forces (as described by the Standard Model).
- *In Fact*: Some non-relativistic condensed matter systems exhibit low-energy fluctuations that resemble aspects of GR and the Standard Model.

Example: Superfluid Helium 3-A. Low-energy fluctuations behave like relativistic massless fields coupled to an electromagnetic field.



- *Tickle (non-relativistic) superfluid He^3-A with small amount of energy.*
- *Low-energy ripples behave like relativistic fermions coupled to EM field.*

How can spacetime be thought of in the Condensed Matter approach?

- A *background-dependent* approach:
  - *The fundamental condensate has prior non-relativistic (Galilean) spatiotemporal structure.*
- A *substantivalist* may say:
  - *"The prior Galilean spatiotemporal structure is given by properties of real spacetime points in a Galilean spacetime. Take the fundamental condensate out of the universe and real Galilean spacetime would be left."*
- A *relationist* may say:
  - *"The prior Galilean spatiotemporal structure is given by properties of the fundamental condensate. Take it out of the world and nothing would be left."*

Problems:

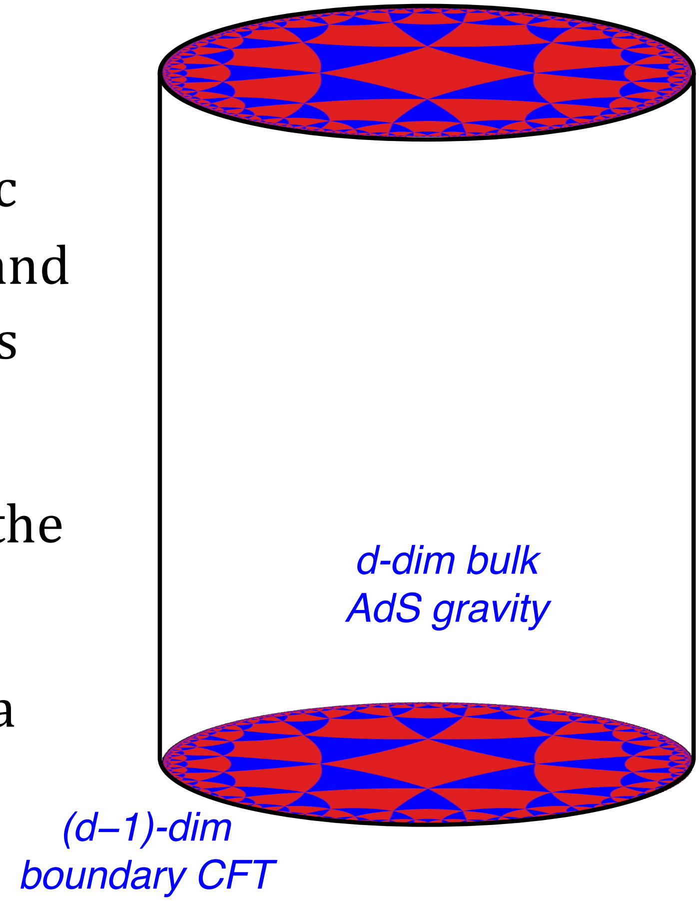
1. No condensed matter system has yet been identified that reproduces GR and the Standard Model exactly in the low-energy regime.
2. Many disanalogies between real condensed matter systems and their idealized low-energy regimes.

Ex 3: AdS/CFT Correspondence

- *General Idea*: One can construct correspondences between certain types of simple general relativistic spacetimes ("anti-de Sitter", or AdS, spacetimes), and certain types of very simple quantum field theories in one less dimension (conformal QFTs, or CFTs).

- *Image*: The AdS spacetime lives in the "bulk", and the CFT lives on the "boundary".

- *Holographic Principle*: The essential properties of a physical system in a d-dim bounded space can be encoded in aspects of its $(d-1)$-dim boundary.



Open questions:

1. Which is fundamental: the flat boundary spacetime, or the curved bulk spacetime?
2. Is this a background dependent approach (CFT), or a background independent (AdS) approach?