1.

The Problem of Quantum Gravity

Read: QGBH §1

Exp. Fact:

There is a massless spin-2 field (graviton)

This implies diff invariance:

$$\mathcal{L}_{grav} = \mathcal{L}_{grav}\left(g_{\mu\nu}, \nabla_\mu, R_{\mu\nu\alpha\beta}\right)$$

$$R \sim \partial\partial g$$

(Can check this by counting d.o.f.; we'll skip it.)

Gravity as Effective field theory:

We'll just follow the usual rules:

* write down the most general action consistent with d.o.f. and symmetries.
(As derivative expansion)

Each R has 2 derivatives, so it's an expansion in curvature,

$$S_{grav} = \frac{1}{16\pi G_N}\int\sqrt{-g}\left(-2\Lambda + R + c_1 R^2 + c_2 R_{\mu\nu}R^{\mu\nu} + c_3 R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} + \mathcal{O}(R^3)\right)$$

* Coefficients follow dimensional analysis, with

mass scale = "new physics"

$[R] = [\partial\partial g] = 2$, so $\frac{1}{G_N} = (M_{pl})^{D-2}$

So we could set coefficients by M_{pl}.

Caveat: cosmo constant problem!

we'll be more general:

$\sqrt{-g}R$ is non-renorm'able in $D>2 \Rightarrow$

new physics at or below M_{pl}

- at: strongly coupled (e.g. M-th.) cf. QCD
- below: strong or weak (e.g. string th.) (gravity here is weak) cf. Fermi $\mathcal{L}_{weak}$

Define M_s = scale of new physics

$$c_{1,2,3} \sim \frac{1}{M_s^2}, \qquad M_s \leq M_{pl}$$

In perturbative string theory, M_s is the mass of the lightest massive string normal mode. But we are agnostic about this.

In string theory,

$$M_s \sim \frac{1}{\ell_s}, \qquad c_{1,2,3} \sim \ell_s^2 \sim \alpha' \text{ (tension)}$$

* This is a perfectly good QFT below M_S

$S_{grav} + S_{matter}$ is a perfectly good QFT

@ Energy $\ll M_S$

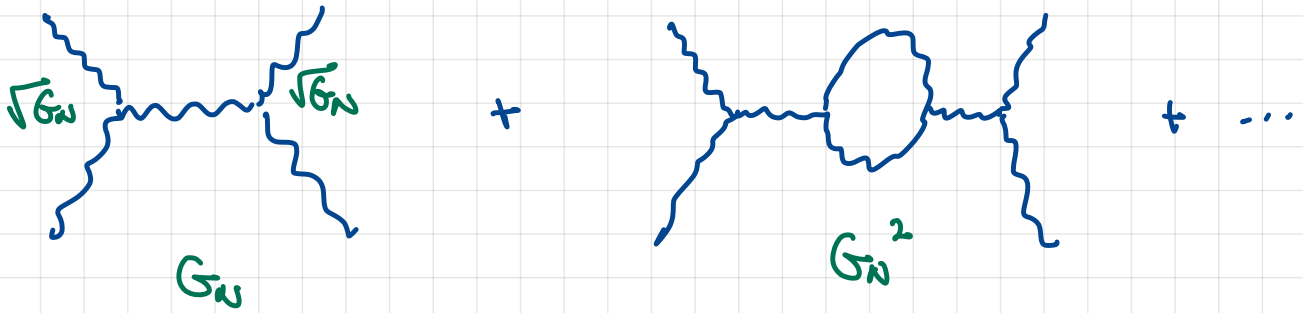
You can use it to calculate loops; RG running of Newton's constant; etc.

You just need to be careful when it's reliable.

Ex: Corrections to Newton+Einstein potential:

$2 \to 2$

(There are more diagrams, but "potential" comes from t-channel exchange - these diagrams).



for $M_S \sim M_{Pl}$,

$E^2/M_{Pl}^2 + E^4/M_{Pl}^2$

Interactions always involve G_N, so theory is weakly coupled for $E \ll M_{Pl}$

(including $E \gtrsim M_S$!)

However, it is acausal for $E \gtrsim M_S$; this requires either

① strong coupling $M_S \sim M_P$

② infinite tower of higher spin particles

$s = 4, 6, 8, \cdots \infty$

@ scale M_S

(string ??)

Comments on acausality:

I won't show this but it comes from a careful analysis of scattering amplitudes with higher curvature terms.

This is a relatively recent result (last 10 years) under active investigation.

E.g. do all UV completions have linear Regge trajectories (like a string)?

So:

- We have an expansion in curvature, with scale M_s (or M_p).
- EFT is perfectly good quantum theory of gravity for $E \ll M_s$
- New physics required @ $E \sim M_s$

The real problem, of course, is the ultraviolet.

QG in the UV

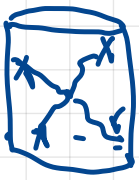
we don't know the answer but much is known:

- "No local observables"

  Bad: $\langle \phi(x_1)\phi(x_2) \cdots \rangle$

  Good: S-matrix (in Minkowski)

  "Bdry correlators" in anti-de Sitter



  ???? in de Sitter or cosmology

  "relative" observables.

This might sound a technical issue, but it's not. It's a radical departure from ordinary QFT's, and must be confronted to address the black hole information paradox.

- Graviton is not composite (Weinberg-Witten)

Maybe graviton is like the pion in QCD? Nope!

ie: $T_{\mu\nu}$ cannot be gauge-invariant in UV.

Uh-oh; we seem stuck. If we have a graviton, it's non-renormalizable and breaks down in the UV.

But Weinberg-Witten says we cannot just eliminate graviton in UV theory. What are our options?

1) New d.o.f. $< M_{pl}$ fix theory

2) Emergent spacetime

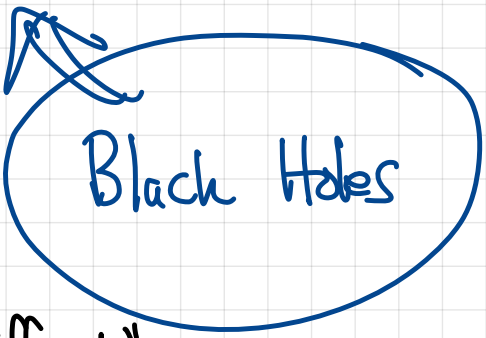
* Spacetime is approximate; only makes sense @ low energies.

* Evades Weinberg-Witten b/c UV is not a QFT in the IR spacetime (though perhaps a QFT nonetheless!)

* Roughly: gravity $\simeq$ hydrodynamics of underlying d.o.f. + much more.

Where do these ideas come from? How do we study them?

Answer: Black Holes



"IR window into the UV"

"UV/IR mixing" "gravity is different"

Course Plan

The goal of this course is to explain the black hole information paradox; the context surrounding it; and recent progress on this ~50-year-old problem.

Along the way I will cover many aspects of Black holes; I will make the case that quantum info is an essential tool in understanding them; and some holographic duality.

1. Some QFT
   (especially finite temperature + CFT)
2. Black Hole thermo

} gonna be quick... but I can slow down, depending on bg and interest!

3. Gravity + Quantum info ; **Hawking's paradox**

Goal! (Review last year)