Observables in effective gravity

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The problem:

How to describe local observation in a quantum-mechanical theory of gravity

Scalar QFT: $\phi(x)$ is a local observable

w/Gravity: diffeomorphism invc.

$$\delta_\xi \phi(x) = \xi^\mu \partial_\mu \phi(x) \neq 0$$

$\therefore$ $\phi(x)$ is not observable

Common attitude:

Just use the S-matrix

But...

Our job as theorists is to explain/predict what our colleagues see at SLAC/Fermilab/CERN, which is not the S-matrix

We are manifestly ~ local observers in our cosmological spacetime

There must be a description of local observation in accord with low-energy symmetries of quantum gravity (diff invc)

Framework: Effective gravity

Small parameter(s): $\sim \frac{p_i \cdot p_j}{M_P^2}$

Quantum EOM/constraints:

$$\mathcal{H}_{WD}|\Psi\rangle = 0, \quad \mathcal{H}_i|\Psi\rangle = 0$$

Gauge invariance:

Yang-Mills: $F_{\mu\nu}(x) \to U^{-1} F_{\mu\nu}(x) U$

$\therefore$ $\mathrm{Tr}\, F^2(x)$ is gauge invt

Gravity: $\mathcal{O} = \int d^4x \sqrt{-g}\, \hat{\mathcal{O}}(x)$

is diff invt ... but not local

The idea:

For certain operators $\hat{\mathcal{O}}(x)$

And in certain states

$$\mathcal{O} = \int d^4x \sqrt{-g}\,\hat{\mathcal{O}}(x)$$

approximately reduces to a local observable

Toy example #1: the Z-model

Begin with a field theory, and supplement it with a set of four free fields Z^i :

$$\Box Z^i = 0,$$

in a state such that

$$\langle \Psi_Z | Z^i | \Psi_Z \rangle = \lambda \delta^i_\mu x^\mu$$

For a given local operator O(x) of the theory, define:

$$\mathcal{O}_\xi = \int d^4x O(x) e^{-\frac{1}{\sigma^2}(Z^i - \xi^i)^2} \left| \frac{\partial Z^i}{\partial x^\mu} \right|$$

...diff invt

Then:

$$\langle \Psi_Z | \mathcal{O}_{\xi_1} \cdots \mathcal{O}_{\xi_N} | \Psi_Z \rangle \approx O(x_1^\mu) \cdots O(x_N^\mu)$$

where $x_A^\mu = \frac{1}{\lambda} \delta_i^\mu \xi_A^i$

So, approximately recover local operators

- for specific operators
- in specific states
- with certain limitations: small backreaction on Z's, etc. Thus finite resolution (more shortly)

Toy example #2: the $\psi^2\phi$ -model

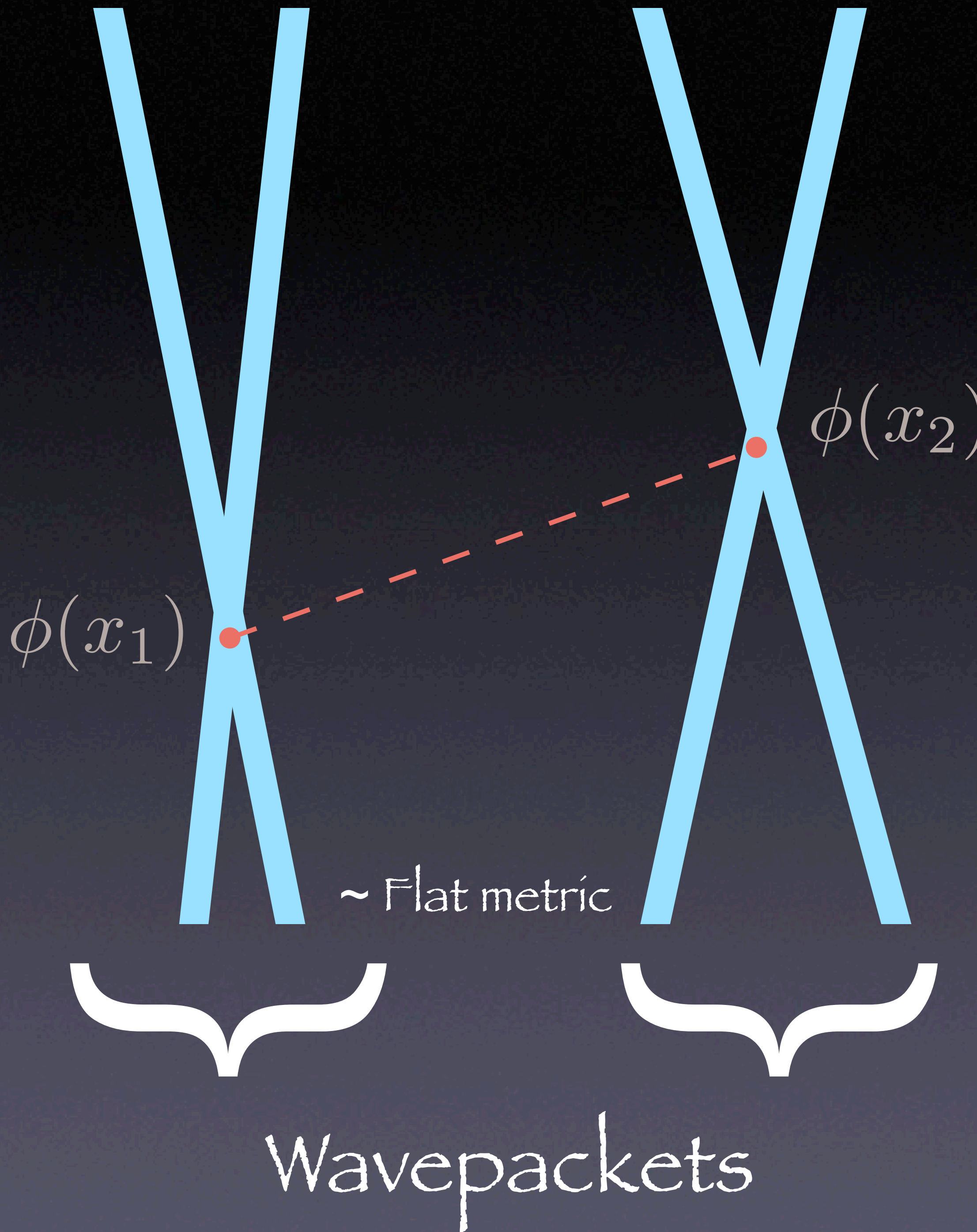
Let ψ and ϕ be massive fields (e.g. free)

Consider the diff-invariant operators

$$\mathcal{O}_{\psi^2\phi} = \int d^4x \sqrt{-g}\,\psi^2(x)\phi(x)$$

In appropriate states, their correlators approximately reduce to correlators of

$\phi(x)$'s:



$\phi(x_2)$
$\phi(x_1)$
~ Flat metric
Wavepackets

More general story:

$$\mathcal{O} = \int d^N x \sqrt{-g}\, O(x)\, m(x)$$

"observed" → $O(x)$

"detector" → $m(x)$

- Terminology: "pseudo-local observables"
- Generalization: multilocal, ~Wilson, etc.
- General feature: relational (~conditional)

Indeed, strings as 2d gravity (toy example #3):

Compute, e.g.: $$\langle \prod_i \mathcal{V}_i \rangle$$

with $$\mathcal{V} = \int d^2\sigma e^{ik\cdot X} P(\nabla^n X)$$

For appropriate states, FT on k gives ~localized expressions on worldsheet (but mass shell subtleties)

Other applications

- Cosmological observables
- Fundamental characterization of quantum states of system

Observables

$\Updownarrow$

Theory of measurement

(Sketch only: see paper!)

Under $\quad \mathcal{L} \to \mathcal{L}' = \mathcal{L} + f\hat{\mathcal{O}}\ ,$

$$\delta\langle\Psi_2|\Psi_1\rangle = f\langle\Psi_2|\mathcal{O}|\Psi_1\rangle$$

For semiclassical backgrounds and measuring devices, this produces appropriate correlations between the "system" and measuring device

Thus, under appropriate conditions, one recovers the Copenhagen theory of measurement

One condition: infinite number of degrees of freedom in measuring device

Otherwise, intrinsic uncertainty $\sim \mathcal{O}(e^{-N})$

Relevant w/ holo bounds ...

(Related discussion: Banks, Fischler, Paban)

Limitations on recovery of local observables (and on physics ...?):

Reduction of pseudo-local observables to local observables clearly constrained:

small backreaction on background state

For example: suppose we wish to instrument a region of space of size R with a state capable of making measurements at resolution r

This requires exciting fields with momenta 1/r in each "cell" of size r. Total energy:

$$E \sim \frac{1}{r}\left(\frac{R}{r}\right)^3$$

Condition for small grav. backreaction:

$$R \gtrsim \frac{1}{M_P^2}\frac{1}{r}\left(\frac{R}{r}\right)^3$$

Possible viewpoint: degrees of freedom that can't in principle be observed don't exist

→ Strong ~holographic constraint:

$$N(R) \sim (M_P R)^{3/2}$$

(c.f. 't Hooft; Cohen, Kaplan, Nelson)

Possibly get $N(R) \sim (M_P R)^2$, accounting for grav DOF (or different eq. of state??)

Arguments such as these and the locality bound (proposed w/Lippert), which are statements regarding inherent limitations on observable degrees of freedom, may be part of a deeper explanation of radical thinning of degrees of freedom in quantum gravity.

(c.f. Heisenberg's microscope)

String theory observables?

(Or other fundamental theory?)

Idea: seek appropriate relational observables.

Indeed, in OSFT (Hashimoto, Itzhaki):

$$\mathcal{O} = \int V\left(\frac{\pi}{2}\right) A$$

Closed string generalizations??

$$\mathcal{O} = \int \Phi \star \Phi \star \Phi \quad ?$$

Conclusions:

- One can formally construct diff-invt observables in quantum gravity
- Certain such observables approximately reduce to local observables in appropriate states. (Relational)
- Limitations on recovery of the local observables of field theory likely represent fundamental limitations of the quantum gravitational theory.
- Locality is relative and approximate