A new approach to Observables in Quantum Gravity

Axel Maas

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ICHEP
Bologna, Italy

NAWI Graz
Natural Sciences

@axelmaas

Setup

- QFT setting – no strings or other non-QFT structures

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- Diffeomorphism is like a gauge symmetry [Hehl et al.'76]
  - Arbitrary local choices of coordinates do not affect observables – pure passive formulation
  - Physical observables must be manifestly invariant [Fröhlich et al.'80]

Dynamical formulation

$$Z = \int_{\Omega} Dg_{\mu\nu} D\phi^{a} e^{iS[\phi, e] + iS_{EH}[e]}$$

Dynamical formulation

Standard gravity

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- Integration variable currently arbitrary choice
  - Here: Metric – not relevant at leading order
  - Other choices (e.g. vierbein) possible

Dynamical formulation

Standard gravity coupling

Standard gravity

Other fields

$$Z=\int_{\Omega} Dg_{\mu\nu} D\phi^a e^{iS[\phi,e]+iS_{EH}[e]}$$

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- Integration variable currently arbitrary choice
  - Here: Metric – not relevant at leading order
  - Other choices (e.g. vierbein) possible
- Otherwise standard
  - E.g. Asymptotic safety for ultraviolet stability

Dynamical formulation

$$\langle O \rangle = \int_{\Omega} Dg_{\mu\nu} D\phi^a O e^{iS[\phi,e]+iS_{EH}[e]}$$

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$$0 \neq \langle O \rangle = \int_{\Omega} Dg_{\mu\nu} D\phi^{a} O\, e^{iS[\phi,e] + iS_{EH}[e]}$$

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Needs to be invariant

- Locally under Diffeomorphism
- Locally under Lorentz transformation
- Locally under gauge transformation
- Globally under custodial,... transformation

to be non-zero

Space-time structure

[Maas'19]

- Average metric vanishes: $\langle g_{\mu\nu}(x)\rangle = 0$

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  - Invariants identify the particular type

Simpelst object: Scalar

[Maas'19]

- Consider a scalar particle
  - E.g. described by a scalar field
  - Completely invariant

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$$\langle O(x) O(y) \rangle = D(x, y)$$

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Completely scalar: Invariant under all symmetries

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Argument is the event, not the coordinate

Result depends on events

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  - Completely invariant
  - Events not a useful argument

Simpelst object: Scalar

[Schaden'15, Ambjorn et al.'12]

Some distance function

$$\langle O(x)O(y)\rangle = D(r(x,y))$$

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[Schaden'15,
Ambjorn et al.'12]

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- Distance is a quantum object: Expectation value
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$$r(x,y) = \langle min_z \int_x^y d\lambda\, g_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \rangle$$

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Separate calculation

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- Generalization of flat-space arguments

Fröhlich-Morchio-Strocchi mechanism

[Fröhlich et al.'80'81]

- Horrible complicated calculation

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  - Chose a gauge compatible with the desired classical behavior
  - Split **after** gauge-fixing fields such that they become classical fields plus quantum corrections
  - Calculate order-by-order in quantum corrections

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- FMS prescription:
  - Chose a gauge compatible with the desired classical behavior
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  - Calculate order-by-order in quantum corrections
- Works very well in particle physics [Review: Maas’19a]

Applying FMS

[Maas'19
Maas et al.'22]

- Our universe is well-approximated by a classical metric
  - Due to the parameter values – special!
  - Small quantum fluctuations at large scales
    - Empirical result

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  - Small quantum fluctuations at large scales
    - Empirical result
- FMS split after (convenient) gauge fixing
  - $g_{\mu\nu} = g^{c}_{\mu\nu} + \gamma_{\mu\nu}$
  - Classical part g^c is a metric, chosen to give exact (observed) curvature
  - Quantum part is assumed small
  - Haywood gauge convenient

Distance

[Maas'19]

$$r(x,y)=\langle min_z \int_x^y d\lambda\, g_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \rangle$$

- Application to distance between two events

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$$=\left\langle min_z \int_x^y d\lambda\, g^c_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \right\rangle + \left\langle min_z \int_x^y d\lambda\, \gamma_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \right\rangle$$

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$$= r^c(x,y) + \langle min_z \int_x^y d\lambda\, \gamma_{\mu\nu} \frac{dz^\mu}{d\lambda} \frac{dz^\nu}{d\lambda} \rangle = r^c + \delta r$$

Classical geodesic distance

- Application to distance between two events
  - Yields to leading order classical distance

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  - Yields to leading order classical distance
    - Yields at leading-order classical space-time

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Classical geodesic distance

Quantum corrections

- Application to distance between two events
  - Yields to leading order classical distance
    - Yields at leading-order classical space-time
  - Quantum corrections depends on events

Propagators

[Maas'19]

$$\langle O(x)O(y)\rangle$$

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$$\langle O(x)O(y)\rangle = D_c(r^c) + \sum (\delta r)^n \partial_r^n D_c(r) + \langle O(x)O(y)\rangle_\gamma$$

- Double expansion

Propagators

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Leading term is
flat space propagator

$$D_c = \langle O(x)O(y)\rangle_{g^c}$$

- Double expansion

Propagators

[Maas'19]

Corrections from quantum distance effects

$$\langle O(x)O(y)\rangle = D_c(r^c) + \sum(\delta r)^n \partial_r^n D_c(r) + \langle O(x)O(y)\rangle_\gamma$$

$$D_c = \langle O(x)O(y)\rangle_{g^c}$$

- Double expansion
  - Quantum fluctuations in the argument

Propagators

[Maas'19]

Corrections from
metric fluctuations

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  - Quantum fluctuations in the argument and action

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$$D_c = \langle O(x)O(y)\rangle_{g^c}$$

- Double expansion
  - Quantum fluctuations in the argument and action
  - Consistent with EDT results [Dai'22]
- Reduces to QFT at vanishing gravity
  - Higgs and W/Z mass in quantum gravity calculated

Non-trivial geon

[Maas et al.'22]

- Pure gravity excitation: Curvature-curvature correlator

Non-trivial geon

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- Pure gravity excitation: Curvature-curvature correlator

$$\langle R(x)R(y)\rangle$$

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- Pure gravity excitation: Curvature-curvature correlator

$$\langle R(x)R(y)\rangle = D^{\mu\nu\rho\sigma}\langle \gamma_{\mu\nu}(x)\gamma_{\rho\sigma}(y)\rangle(d(x,y)) + O(\gamma^3)$$

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[Maas et al.'22]

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Differential operator

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Graviton propagator

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Graviton propagator

- In Minkowski space-time: No propagating mode at lowest order

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Graviton propagator

- In Minkowski space-time: No propagating mode at lowest order
- Flat space: Better divergence properties

[Maas & Sondenheimer'20]

Predictions for CDT

- CDT vertex structure can be mapped to events
  - Allows reconstruction of metric in a fixed gauge on every configuration

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  - Allows reconstruction of metric in a fixed gauge on every configuration
- deSitter structure observed in CDT
  - Metric fluctuations per configuration should be small compared to de Sitter metric
- Geon propagator should behave as contracted metric propagator
  - As a function of the geodesic distance

Summary

- Full invariance necessary for physical observables in path integrals

- FMS mechanism allows estimates of quantum effects in a systematic expansion

- Gives a new perspective on quantum gravity testable by simulations

More: 2202.05117, 1908.02140