Title: Physical Observables in Canonical Quantum Gravity

Speakers: Axel Maas

Series: Quantum Gravity

Date: February 09, 2023 - 2:30 PM

URL: https://pirsa.org/23020038

Abstract:

Canonical Quantum Gravity can be considered as a gauge theory of translations. Just like in other gauge theories this implies that physical observables need to be gauge-invariant. Hence, quantities like the metric cannot be observables. This poses new challenges, as this requires to rephrase in the quantum theory how to characterize physics. Moreover, such observables are usually composite. To determine them, the Fröhlich-Morchio-Strocchi mechanism from QFT can be borrowed, to have an augmented perturbative approach.

Zoom Link: https://pitp.zoom.us/j/97927004145?pwd=ekFJaUJSc21UUGdkcDZDWCtpSmdIUT09

Physical Observables In Canonical Quantum Gravity

Axel Maas

9^{th} of February 2023
Perimeter, Canada
Online

UNI GRAZ

NAWI Graz
Natural Sciences

What is this talk about?

- Why an invariant formulation?
  - Path integral formulation and symmetries
  - Canonical quantum gravity
- Space-time structure
  - What's a universe in quantum gravity?
- Particles & black holes
- Fröhlich-Morchio-Strocchi mechanism
  - Emergence of flat-space QFT
- Connecting to other approaches

Path integral and global symmetries

[Review: Maas'17]

Measure is invariant
- no anomalies

$$Z = \int_{\Omega} D\phi^a e^{iS[\phi]}$$

Action is invariant

$$S[\phi] = S[G\phi]$$

Path integral and global symmetries

[Review: Maas'17]

$$Z = \int_{\Omega} D\phi^a e^{iS[\phi]}$$

Integration range
- contains all orbits $G\phi$

Path integral and global symmetries

[Review: Maas'17]

$$\langle \phi^b(x) \rangle = \int_\Omega D\phi^a \, e^{iS[\phi]} \, \phi^b(x)$$

Path integral and global symmetries

[Review: Maas'17]

$$\langle \phi^b(x) \rangle = \int_\Omega D\phi^a e^{iS[\phi]} \phi^b(x)$$

- There is no preferred point on the group orbit
  - There is no absolute orientation/frame in the internal space
  - Does not change when averaging over position
  - There is no absolute charge

Path integral and global symmetries

[Review: Maas'17]

$$\langle \phi^b(x) \rangle = \int_\Omega D\phi^a e^{iS[\phi]} \phi^b(x) = 0$$

- There is no preferred point on the group orbit
  - There is no absolute orientation/frame in the internal space
  - Does not change when averaging over position
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Path integral and global symmetries

[Review: Maas'17]

$$\langle \phi^b(x)\phi^c(y)\rangle = \int_\Omega D\phi^a e^{iS[\phi]}\phi^b(x)\phi^c(y) = 0$$

- Relative charge measurement averaged over all possible starting point
  - Vanishes because no preferred absolute starting point

Path integral and global symmetries

[Review: Maas'17]

$$\langle \delta_{bc} \phi^b(x) \phi^c(y) \rangle$$
$$= \int_\Omega D\phi^a e^{iS[\phi]} \delta_{bc} \phi^b(x) \phi^c(y)$$

- Group-invariant quantity
  - Measures relative orientation
  - Created from an invariant tensor δ_{ab}

Path integral and global symmetries

[Review: Maas'17]

$$\langle \delta_{bc} \phi^b(x) \phi^c(y) \rangle$$
$$= \int_\Omega D\phi^a e^{iS[\phi]} \delta_{bc} \phi^b(x) \phi^c(y) \neq 0$$

- Group-invariant quantity
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Path integral and local symmetries

[Review: Maas'17]

Measure is invariant
- no anomalies

$$Z=\int_{\Omega} D\phi^{a}\, e^{iS[\phi]}$$

Action is invariant
$S[\phi]=S[G\phi]$

Path integral and local symmetries

[Review: Maas'17]

$$\langle \delta_{bc} \phi^b(x) \phi^c(y) \rangle$$
$$= \int_\Omega D\phi^a e^{iS[\phi]} \delta_{bc} \phi^b(x) \phi^c(y) = 0$$

- No longer invariant under gauge transformations
  - Vanishes just as any other non-invariant quantity

Path integral and local symmetries

[Review: Maas'17]

Transporter

$$\langle \phi^b(x) U^{bc}(x,y) \phi^c(y) \rangle$$

$$= \int_\Omega D\phi^a DU\, e^{iS[\phi]} \phi^b(x) U^{bc}(x,y) \phi^c(y)$$

- Transporter compensates gauge transformations
  - Implemented by gauge fields

Path integral and local symmetries

[Review: Maas'17]

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- Transporter compensates gauge transformations
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Path integral and local symmetries

[Review: Maas'17]

Reduced integration range

$$\langle \phi^b(x)\, \phi^c(y) \rangle$$

$$= \int_{\Omega_c} D\phi^a\, DU\, W(U, \phi)\, e^{iS[\phi]}\, \phi^b(x)\, \phi^c(y) \neq 0$$

- Reduction of integration region by gauge fixing
  - Arbitrary choice of coordinates
  - Weight factor to keep gauge-invariant quantities the same

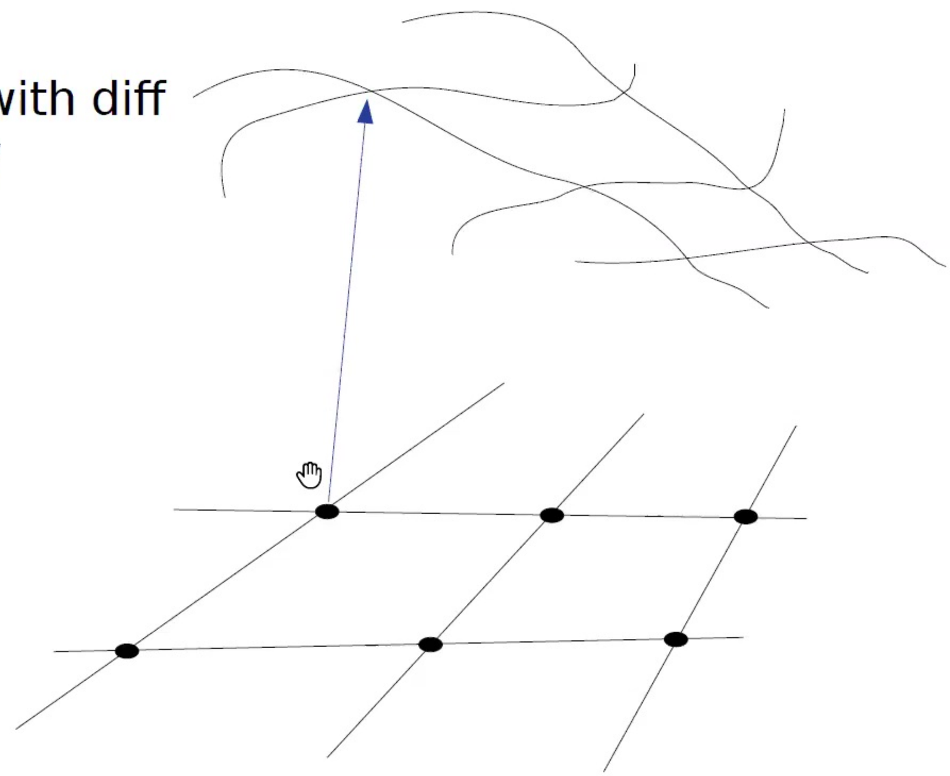
Quantum gravity: Setting the scene

- QFT setting – no strings or other non-QFT settings
- Diffeomorphism is like a non-standard gauge symmetry
  - Arbitrary local choices of coordinates do not affect observables – pure passive formulation
  - Physical observables must be manifestly invariant
- Spin seems to be an observable?
  - Spin degeneracies and selection rules due to spin conservation
  - Global or effective structure
- Particle physics gauge symmetries and global symmetries should remain the same

Gravity as a gauge theory

[Hehl et al.'76]

Manifold with diff symmetry



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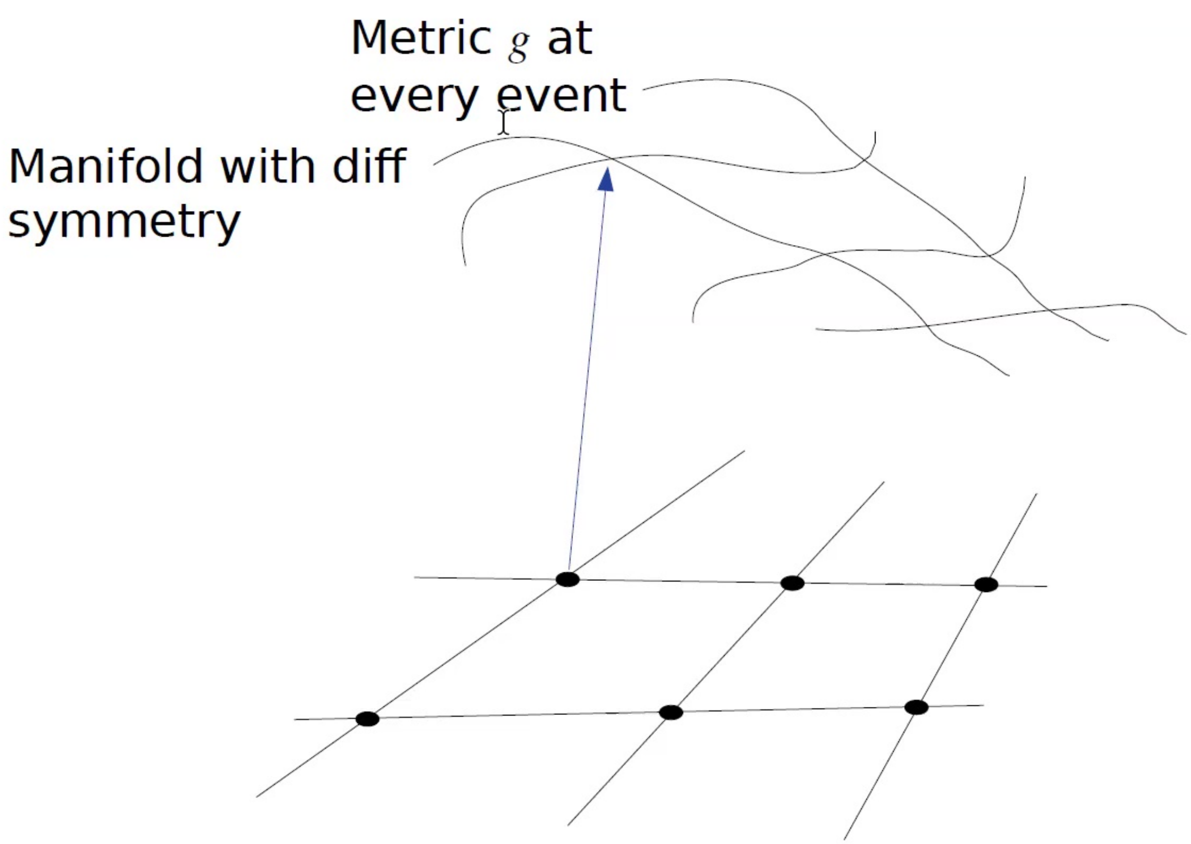

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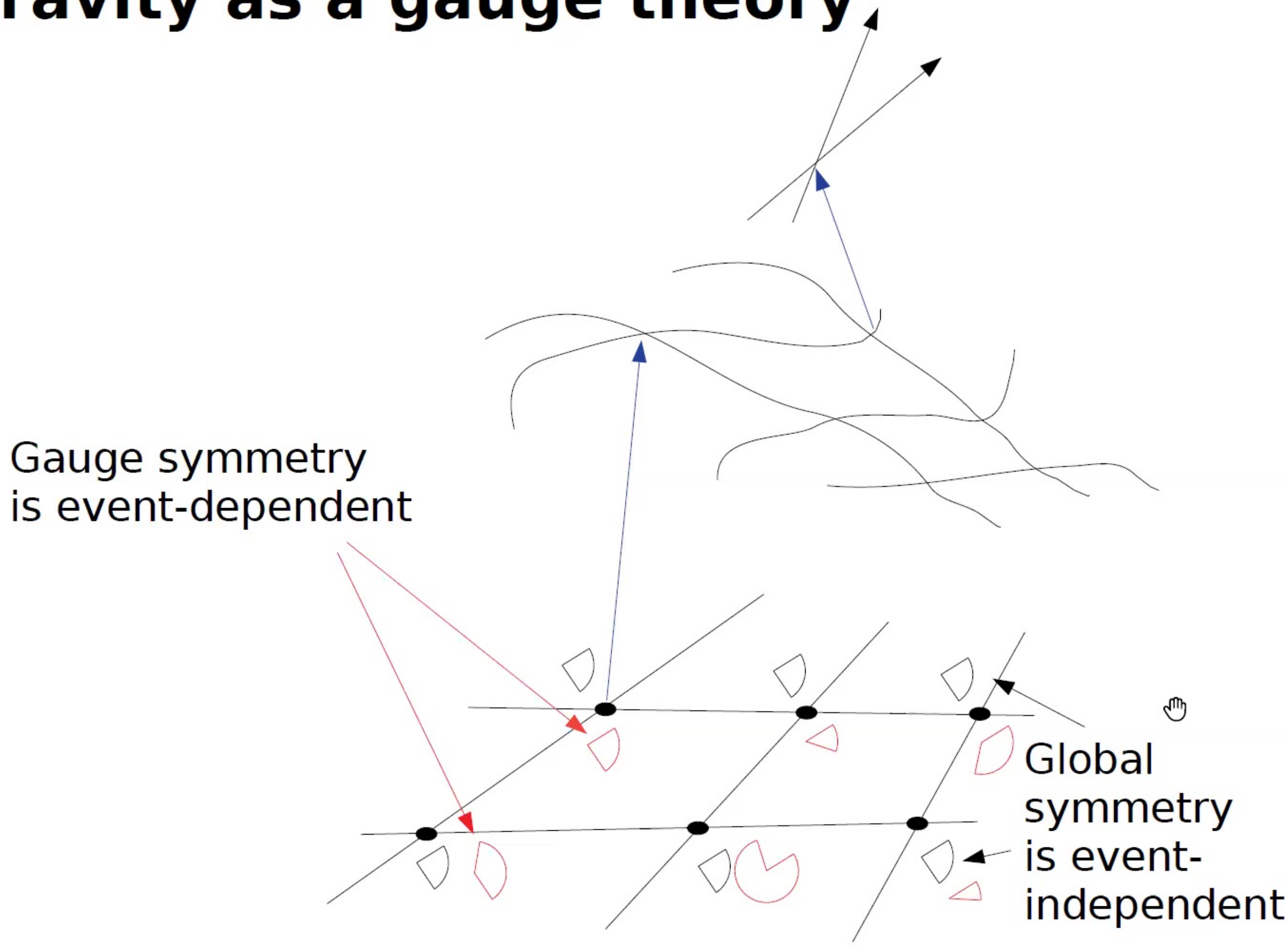
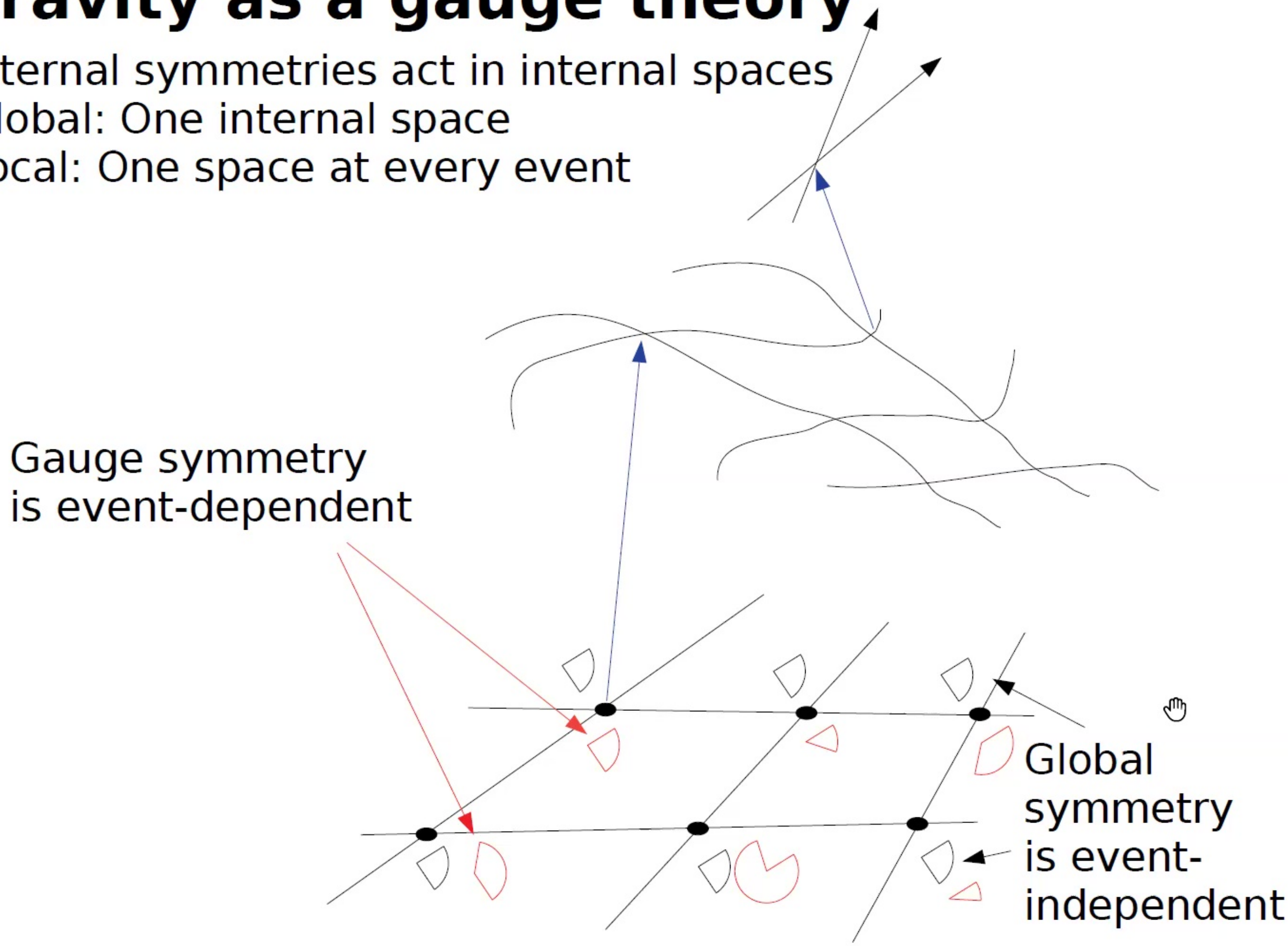


Gravity as a gauge theory

[Hehl et al.'76]

Internal symmetries act in internal spaces
Global: One internal space
Local: One space at every event



Dynamical formulation

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

Dynamical formulation

Standard gravity

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

- 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

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

- 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

[Maas'19]

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

Dynamical formulation

[Maas'19]

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

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: $\langle g_{\mu\nu}(x)\rangle = 0$
- Characterization by invariants e.g.

$$\frac{\langle \int d^d x \sqrt{\det g}\, R(x)\rangle}{\langle \int d^d x \sqrt{\det g}\rangle} = const$$

- No preferred events
  - Space-time on average homogenous and isotropic
  - Average space-time is flat or (anti-)de Sitter for canonical gravity
  - Invariants identify the particular type

Simpelst object: Scalar

Argument is the event, not the coordinate

Result depends on events

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

- Consider a scalar particle
  - E.g. described by a scalar field $O(x)$
  - Completely invariant

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Result depends on events

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

- Consider a scalar particle
  - E.g. described by a scalar field $O(x)$
  - Completely invariant
  - Events not a useful argument

Simpelst object: Scalar

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

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

- Distance is a quantum object: Expectation value
  - Needs a diff-invariant formulation

Simpelst object: Scalar

[Ambjorn et al.'12, Schaden'15, Maas'19]

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

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

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  - Diff-invariant distance: Geodesic distance

Simpelst object: Scalar

[Ambjorn et al.'12, Schaden'15, Maas'19]

Reduces the full dependence: Definition
Dependence on events will only vanish if all events on the average are equal – probably true

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[Ambjorn et al.'12, Schaden'15, Maas'19]

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

Separate calculation

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

- Distance is a quantum object: Expectation value
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What about cosmology?

[Maas et al.'22]

- Big bang a preferred event - not possible!
- Description of a universe?

$$\langle O(x)P(x)\ldots Q(y_1)\ldots R(y_n)\rangle$$

  - Originate at same event: Big bang
  - Distances between x and y_i future time-like
  - Distances between y_i space-like
  - Evolution of a matter/curvature concentration
  - Properties measureable
    - E.g. size as maximum space-like distance of y_i
    - Preceived life-time in an eigenframe at one y_i

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    - Preceived life-time in an eigenframe at one y_i
  - A universe is a scattering process

Fröhlich-Morchio-Strocchi mechanism

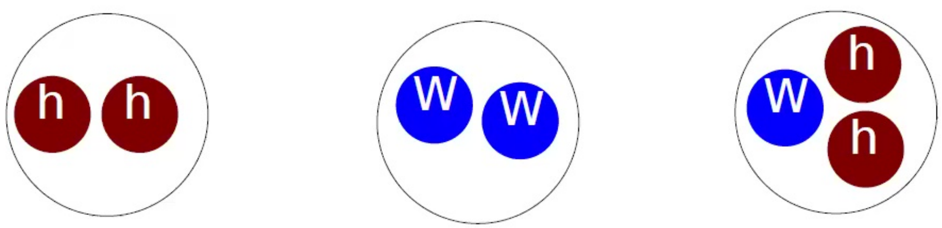
[Fröhlich et al.'80,'81
Review: Maas'17]

- Horrible complicated calculation
- FMS mechanism allows simplification
  - Requires: Dominance of a configuration
    - Usually: Classical solutions
    - Depends on parameters
- FMS prescription:
  - 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
- Works very well in particle physics

FMS in a nutshell

[Fröhlich et al.'80,'81
Review: Maas'17]

- Consider the standard model
- Physical spectrum: Observable particles
  - Peaks in (experimental) cross-sections
- Higgs, W, Z,... fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



Fröhlich-Morchio-Strocchi Mechanism

[Fröhlich et al.'80,'81
Maas'12,'17]

1) Formulate gauge-invariant operator

0^+ singlet: $\langle (h^+ h)(x)(h^+ h)(y) \rangle$

2) Expand Higgs field around fluctuations $h = v + \eta$

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle = v^2 \langle \eta^+(x)\eta(y) \rangle + v \langle \eta^+ \eta^2 + \eta^{+2} \eta \rangle + \langle \eta^{+2} \eta^2 \rangle$$

3) Standard perturbation theory

Bound state mass →
Higgs mass →

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle = v^2 \langle \eta^+(x)\eta(y) \rangle + \langle \eta^+(x)\eta(y) \rangle \langle \eta^+(x)\eta(y) \rangle + O(g,\lambda)$$

4) Compare poles on both sides

Fröhlich-Morchio-Strocchi Mechanism

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Standard Perturbation Theory

3) Standard perturbation theory

Bound state mass

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = v^2\langle \eta^+(x)\eta(y)\rangle + \langle \eta^+(x)\eta(y)\rangle\langle \eta^+(x)\eta(y)\rangle + O(g,\lambda)$$

4) Compare poles on both sides

Flavor

[Fröhlich et al.'80,
Egger, Maas, Sondenheimer'17]

- Flavor has two components
  - Global SU(3) generation
  - Local SU(2) weak gauge (up/down distinction)
- Same argument: Weak gauge not observable
- Replaced by bound state – FMS applicable

$$\left\langle \left(\begin{pmatrix} h_2 & -h_1 \\ h_1^* & h_2^* \end{pmatrix} \begin{pmatrix} \nu_L \\ l_L \end{pmatrix} \right)_i (x)^+ \left(\begin{pmatrix} h_2 & -h_1 \\ h_1^* & h_2^* \end{pmatrix} \begin{pmatrix} \nu_L \\ l_L \end{pmatrix} \right)_j (y) \right\rangle \overset{h=v+\eta}{\approx} v^2 \left\langle \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}_i (x)^+ \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}_j (y) \right\rangle + O(\eta)$$

- Gauge-invariant state, but custodial doublet
- Yukawa terms break custodial symmetry
  - Different masses for doublet members

Flavor on the lattice

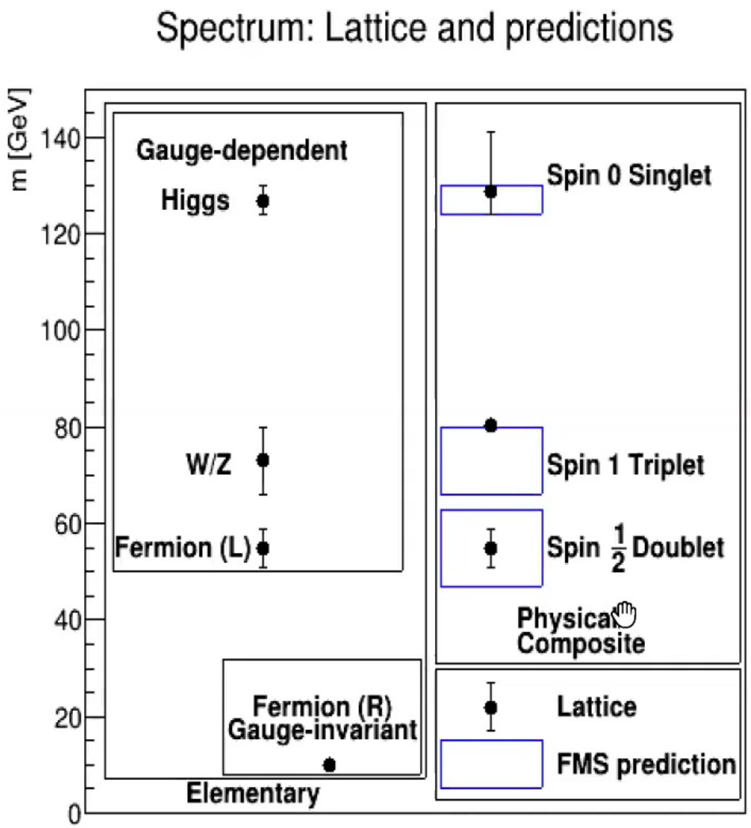
[Afferrante,Maas,Sondenheimer,Török'20]

- Only mock-up standard model
  - Compressed mass scales
  - One generation
  - Degenerate leptons and neutrinos
  - Dirac fermions: left/right-handed non-degenerate
  - Quenched

Flavor on the lattice

[Afferrante,Maas,Sondenheimer,Törek'20]

- Only mock-up standard model
  - Compressed mass scales
  - One generation
  - Degenerate leptons and neutrinos
  - Dirac fermions: left/right-handed non-degenerate
  - Quenched
- Same qualitative outcome
  - FMS construction
  - Mass defect
  - Flavor and custodial symmetry patterns
- Supports FMS prediction



Protons

[Egger, Maas, Sondenheimer'17]

- True for all weakly charged particles
  - This includes left-handed quarks!
- Proton is a mix of left-handed and right-handed quarks
  - qqq cannot be weakly gauge invariant
  - Replacement: qqq**h**
    - FMS: At low energies just the proton

Further consequences

- In SM physics: Quantitative changes
  - Anomalous couplings/form factors
  - (Small) differences in various kinematic regimes
  - More: See 1701.00182, 1811.03395, 2002.01688, 2008.07813, 2009.06671, 2204.02756, 2212.08470

Further consequences

- In SM physics: Quantitative changes
  - Anomalous couplings/form factors
  - (Small) differences in various kinematic regimes
  - More: See 1701.00182, 1811.03395, 2002.01688, 2008.07813, 2009.06671, 2204.02756, 2212.08470

- In BSM physics: Sometimes qualitative changes
  - Even different spectrum
  - Affects viability of BSM Scenarios
  - More: See 1709.07477, 1804.04453, 1912.086680, 2002.08221, 2211.05812, 2211.16937

Applying FMS to gravity

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

Applying FMS to gravity

- Our universe is well-approximated by a classical metric
  - Due to the parameter values – special!
  - 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 needed (assumed) small

Details (and challenges)

[Maas et al.'22]

- Classical metric needs to be useful
  - Should not have special events
    - Only flat and (anti-)de Sitter possible
  - Should satisfy gauge choice
- Split after gauge-fixing!
  - No linear condition possible
  - Simple choice: Haywood gauge $g^{\mu\nu}\partial_\nu g_{\mu\rho}=0$

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- Split after gauge-fixing!
  - No linear condition possible
  - Simple choice: Haywood gauge $g^{\mu\nu}\partial_\nu g_{\mu\rho}=0$
  - Inverse fluctuation satisfies Dyson equation

$$\gamma^{\mu\nu}=-(g^c)^{\mu\sigma}\gamma_{\sigma\rho}\left((g^c)^{\rho\nu}+\gamma^{\rho\nu}\right)$$

  - Infinite series at tree-level

Distance

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

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

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

Classical geodesic distance

- Application to distance between two events
  - Yields to leading order classical distance
    - Yields at leading-order classical space-time

Propagators

[Maas'19]

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

Leading term is
flat space propagator

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

- Double expansion

Propagators

[Maas'19]

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- Double expansion
  - Quantum fluctuations in the argument and action
  - Consistent with EDT results [Dai'22]

Propagators

[Maas'19]

$$\langle O(x) O(y) \rangle = D_c(r^c)$$

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

- 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

Differential operator

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

Graviton propagator

Non-trivial geon

[Maas et al.'22]

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Differential operator

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

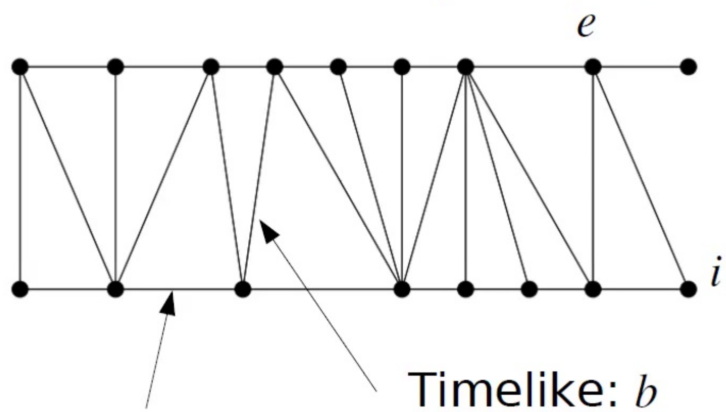
Graviton propagator

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

Predictions for CDT

[Maas '22,Ambjorn et al.'12]

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



$$d(e,i)=b=\frac{g_{\mu\rho}(e)}{b}\frac{dz_\mu}{d\tau}\frac{dz_\rho}{d\tau}$$

$$0=\frac{g^{\mu\nu}(e)}{b}\left(g_{\nu\rho}(e)-g_{\nu\rho}(i)\right)$$

Haywood condition

Predictions for CDT

[Maas '22,Ambjorn et al.'12]

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- deSitter structure observed in CDT
  - Metric fluctuations per configuration should be small compared to de Sitter metric

Predictions for CDT

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- CDT vertex structure can be mapped to events
  - 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

Speculative phenomenology

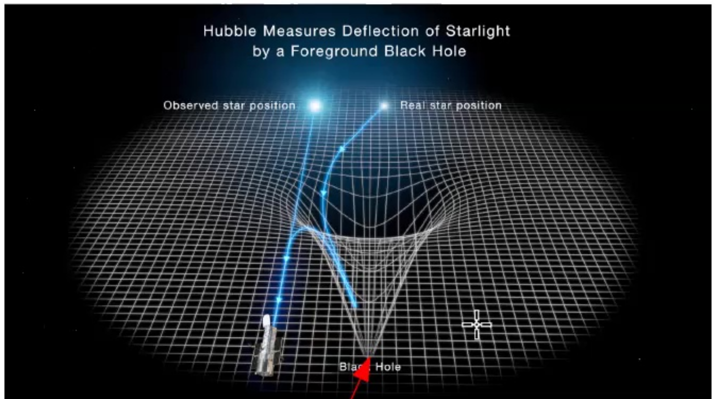
[Maas '19]

- Macroscopic gravitational objects need to be build in the same way
  - Just like neutron stars from QCD

Views of black holes

[Picture: NASA, Maas et al'22]

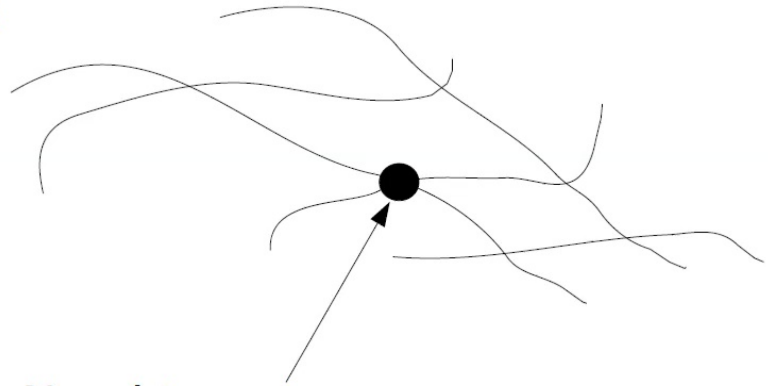
Classical picture of a black hole



But this is a special worldline, determining the full metric!

Not possible in a quantum expectation value.

Averaging over this!



Need to put a black hole creation operator at an event - but it would still be a constant

$$\langle B(x) \rangle = d$$

Views of black holes

[Picture: NASA, Maas et al'22]

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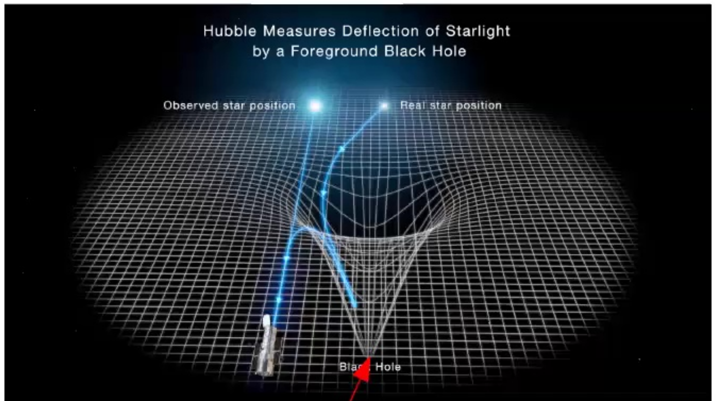

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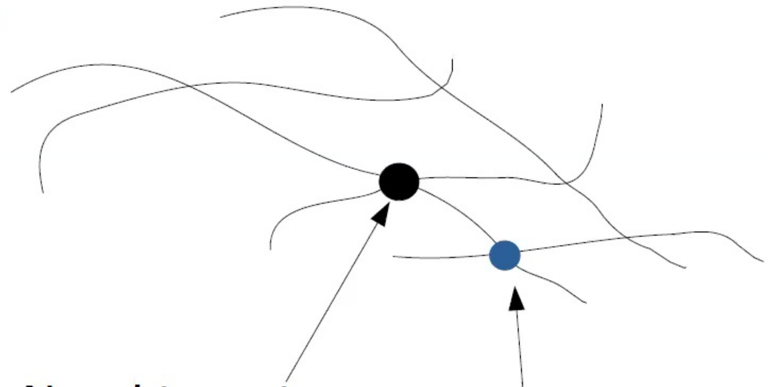


Need to put a black hole creation operator at an event - but it would still be a constant

Need to correlate with e.g. curvature

$$\langle B(x)R(y)\rangle = d(r(x,y))$$

Views of black holes

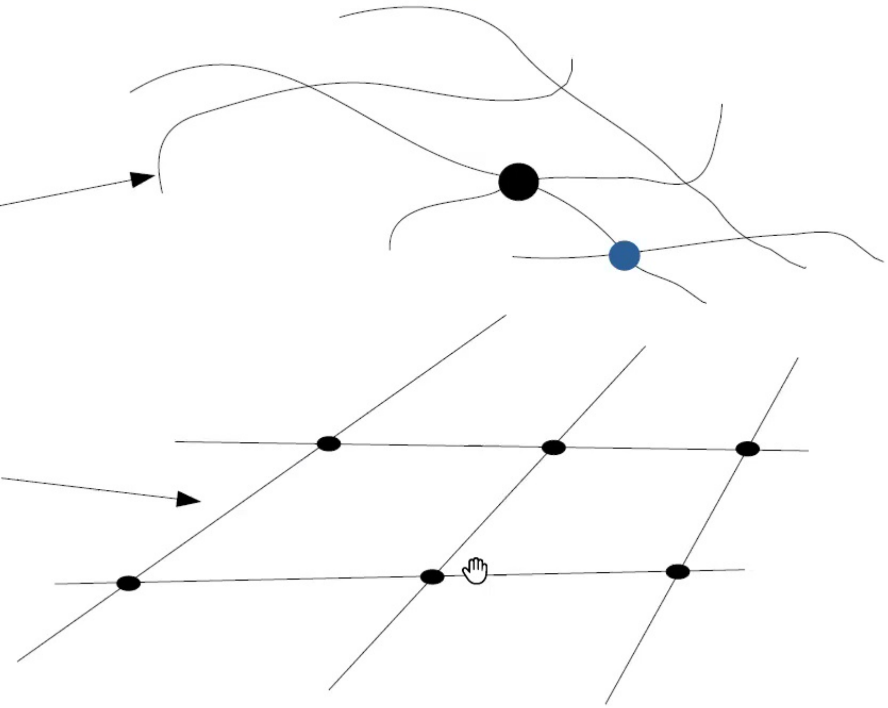
[Maas et al'22]

Averaging over this!

In FMS: Splitted further

(Small) fluctuations
of the metric

Expansion metric,
without preferred events



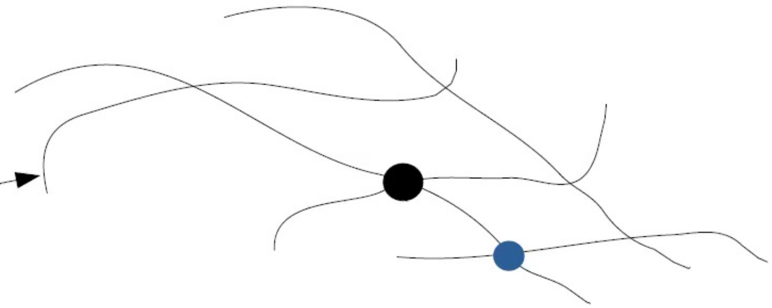
$$\langle B(x) R(y) \rangle$$

Views of black holes

[Maas et al'22]

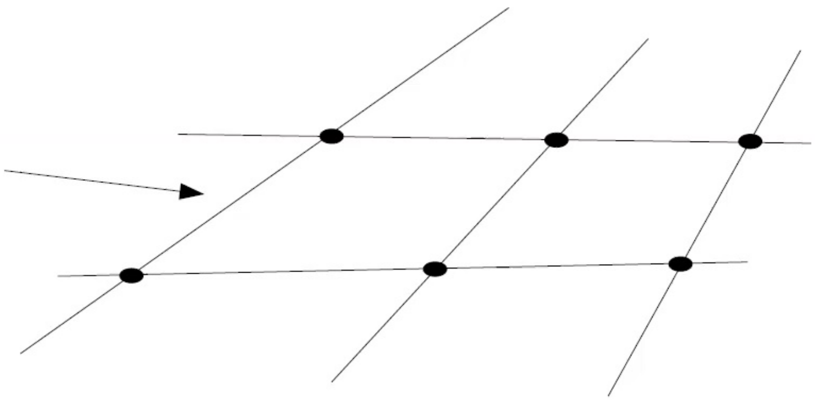
Averaging over this!

In FMS: Splitted further



(Small) fluctuations of the metric

Expansion metric, without preferred events



Calculate expansion:

$$\langle B(x)R(y)\rangle = d^c(r^c(x,y)) + quantum$$

Classical field result

Speculative phenomenology

[Maas '19]

- Macroscopic gravitational objects need to be build in the same way
  - Just like neutron stars from QCD
- Black hole: Two options
  - Single operator $B(x)$ without decomposition
    - Monolithic, essentially elementary particle
    - May have overlap with $R(x)$
  - Product of separate diff-invariant operators
    - Hawking radiation as tunneling
- Differing operators for pure (e.g. Schwarzschild) or stellar collapse black hole
  - Pure: Geon star, similar to neutron star

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 strong and quantum gravity

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