Approaching a manifestly diffeomorphism-invariant Description of Particle and Black Hole Dynamics

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with Markus Markl and Michael Müller

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Miniworkshop on Quantum Gravity
Online - International

NAWI Graz
Natural Sciences

What is this talk about?

QG: 1908.02140

- Why an invariant formulation?
  - Path integral formulation and symmetries
  - Canonical quantum gravity

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  - Emergence of flat-space QFT

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  - Emergence of flat-space QFT
- Black holes
  - Black-hole-particle interaction

Path integral and global symmetries

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

Path integral and global symmetries

Field – transforms linearly under a group $\phi^a \rightarrow G^{ab}\ \phi^b$

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

Path integral and global symmetries

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

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

Integration range
- contains all orbits $G\,\phi$

Path integral and global symmetries

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

Path integral and global symmetries

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

- 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

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

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Path integral and global symmetries

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

- Relative charge measurement averaged over all possible starting points

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

Path integral and global symmetries

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

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

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Field – transforms locally under a group $\phi^a(x) \rightarrow G^{ab}(x)\phi^b(x)$

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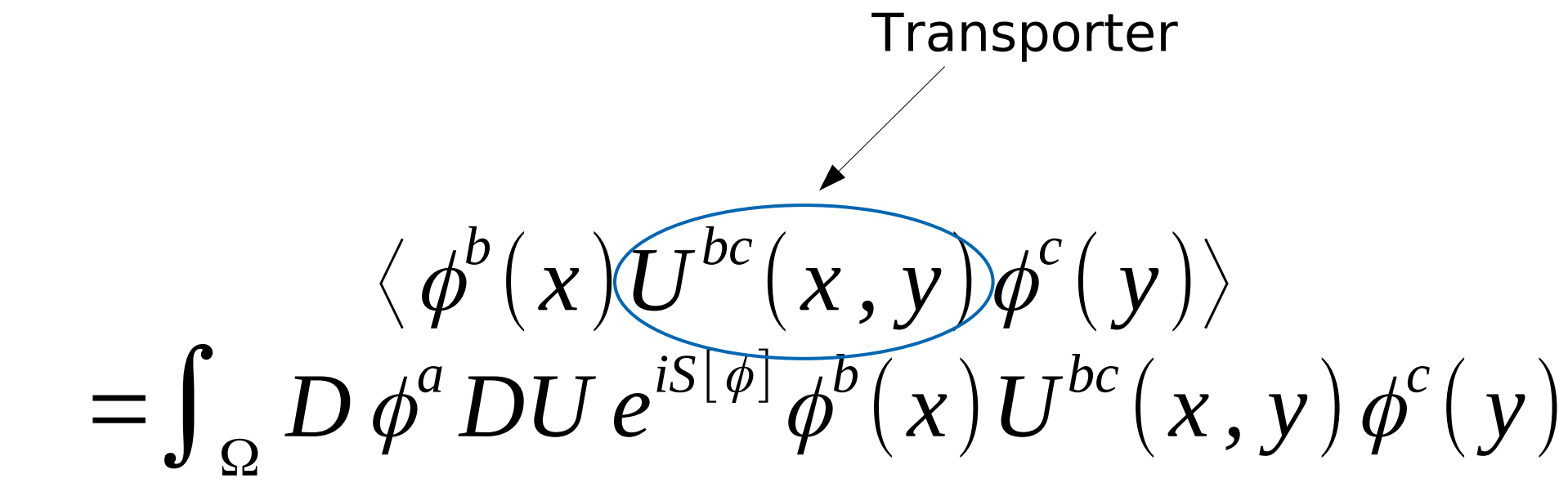
- No longer invariant under gauge transformations
  - Vanishes just as any other non-invariant quantity

Path integral and global symmetries



- Transporter compensates gauge transformations
  - Implemented by gauge fields

Path integral and global symmetries

$$\langle \phi^b(x) U^{bc}(x,y) \phi^c(y) \rangle$$
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Path integral and global symmetries

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

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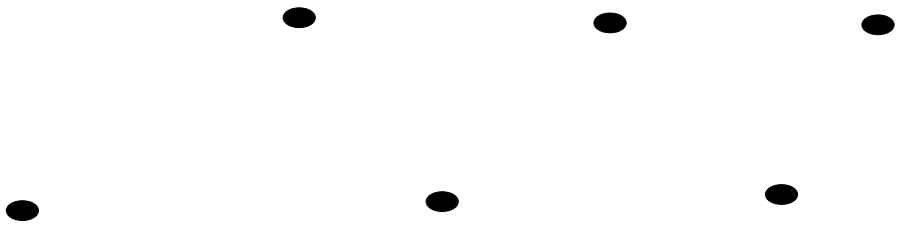
  - Spin degeneracies and selection rules due to spin conservation
  - Global or effective structure
- Particle physics gauge symmetries and global symmetries should remain the same

Gravity as a gauge theory

[Hehl et al.’76]

Set of events with
neighbor relations



Gravity as a gauge theory

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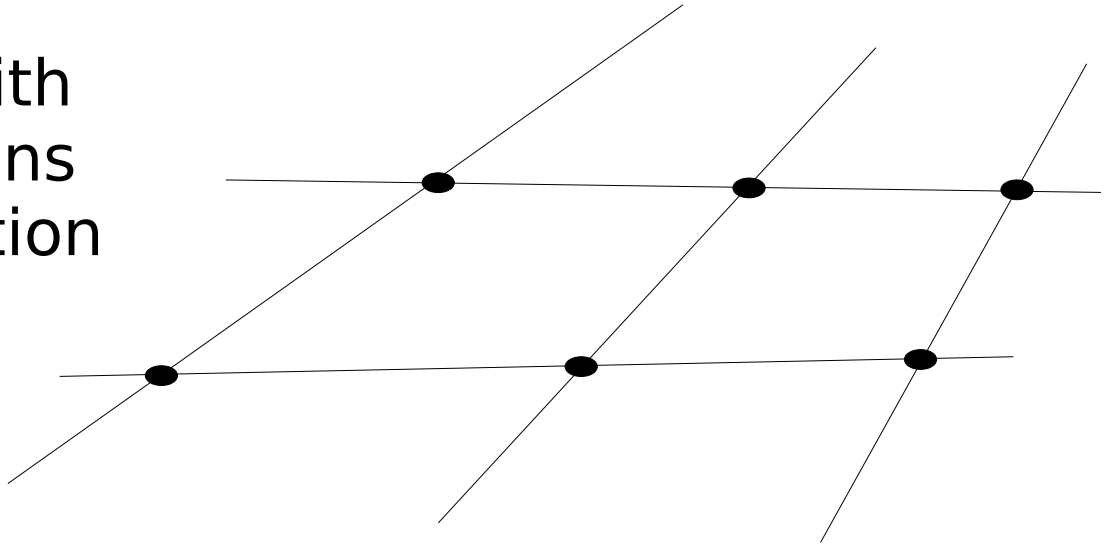
Set of events with neighbor relations
E.g. R^4 in definition of manifold



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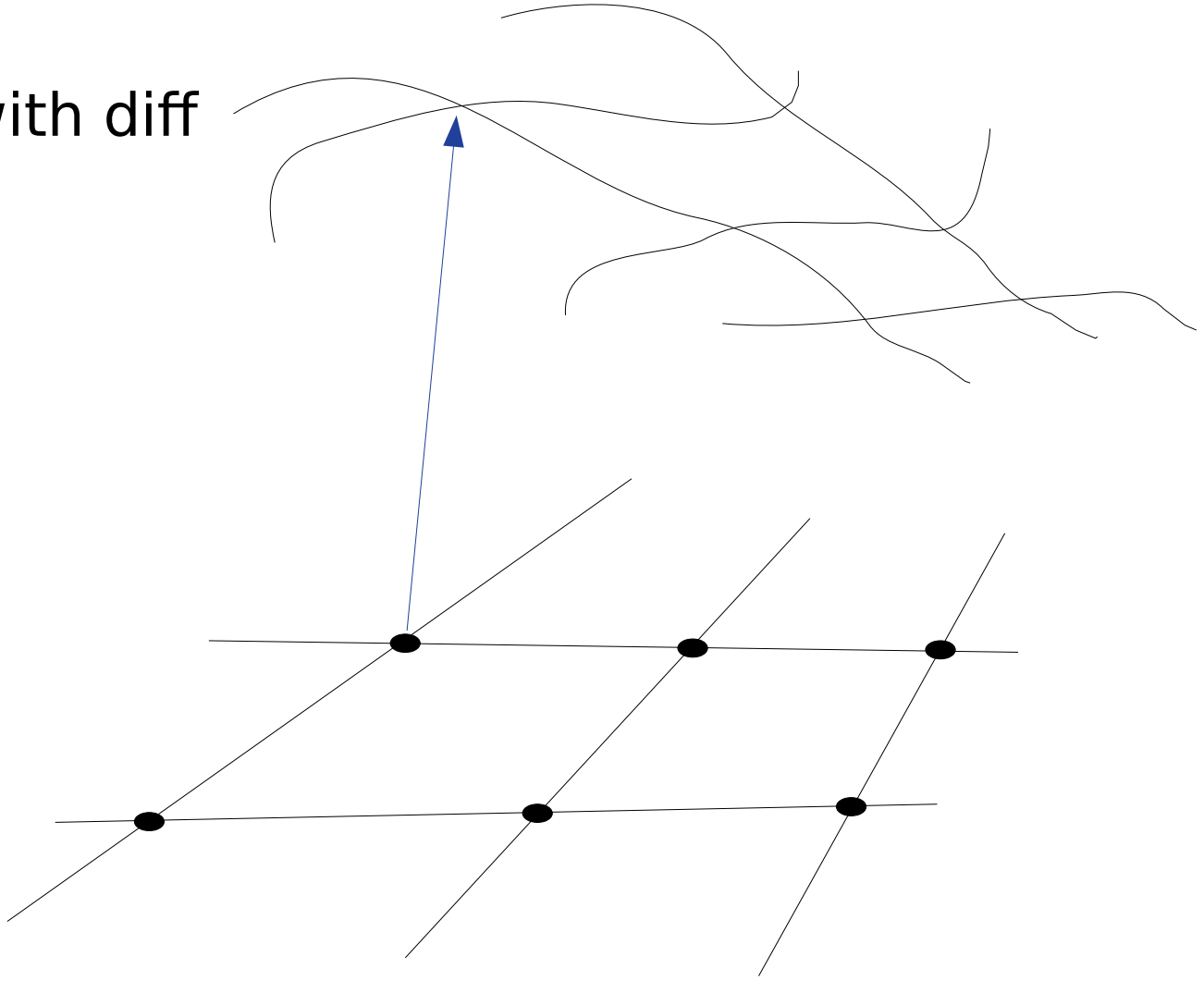
Manifold with diff symmetry



Gravity as a gauge theory

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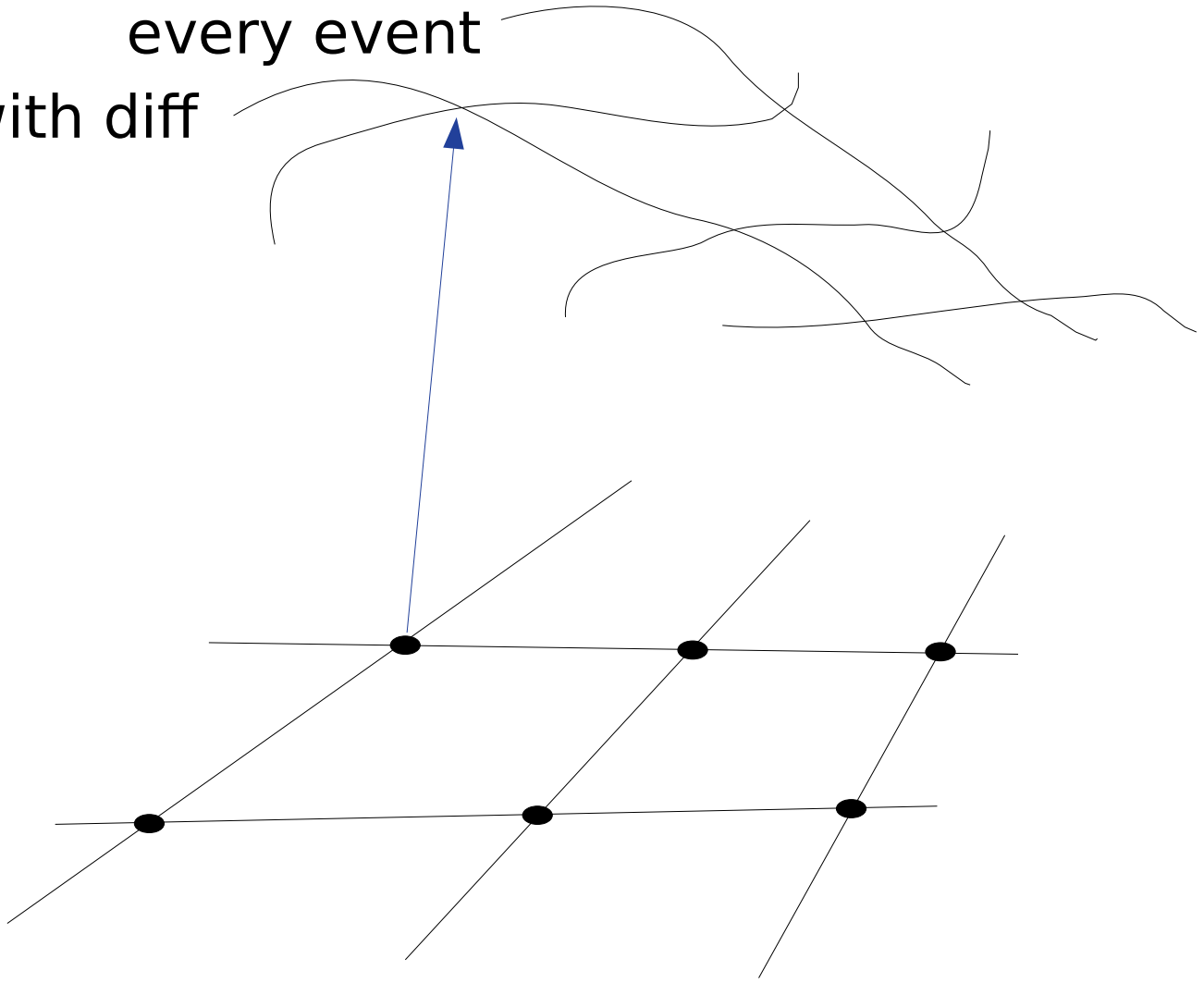
Metric g at every event

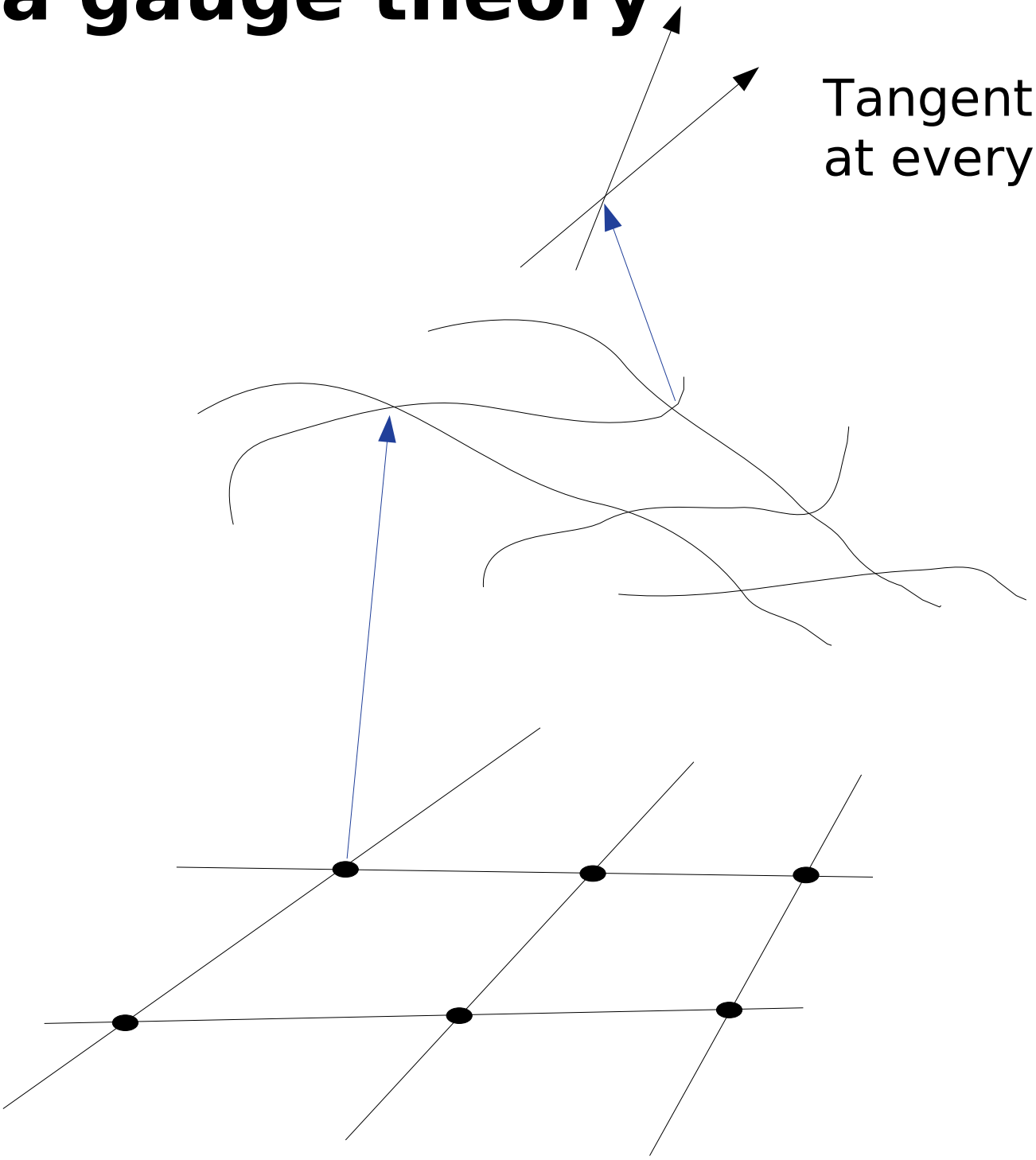
Manifold with diff symmetry



Gravity as a gauge theory

[Hehl et al.'76]

Tangent space
at every event



Gravity as a gauge theory

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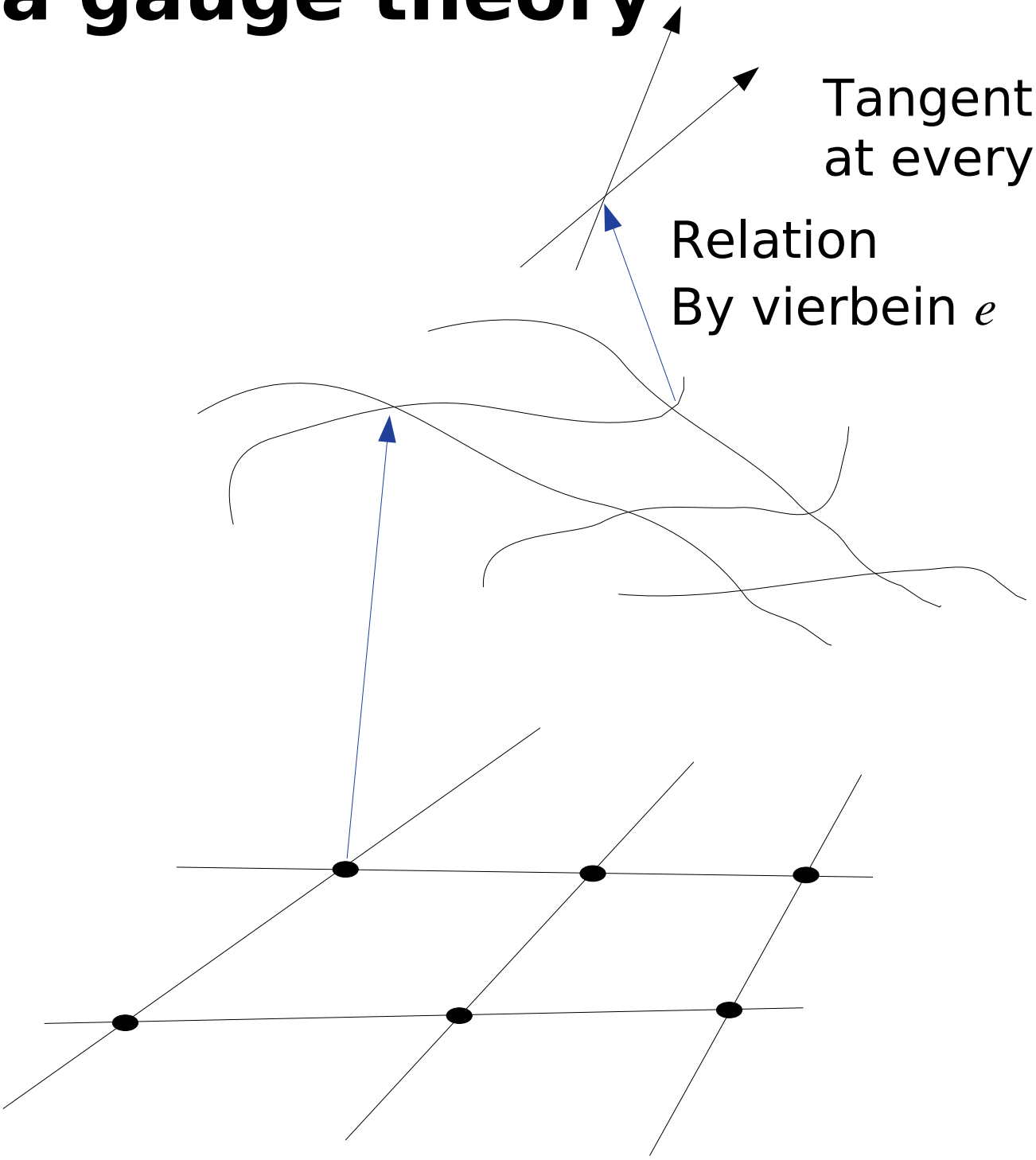

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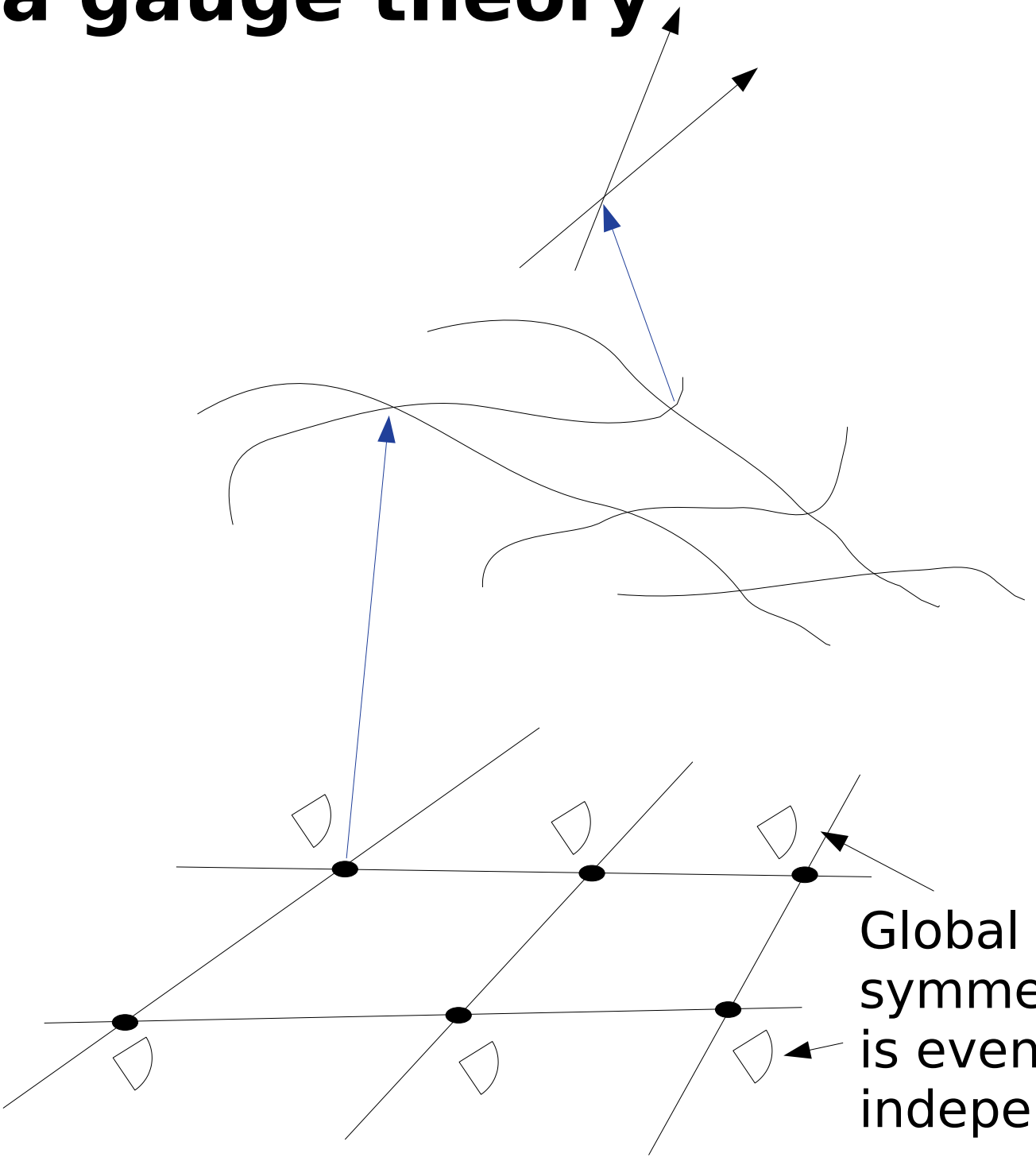

Gravity as a gauge theory

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Gauge symmetry
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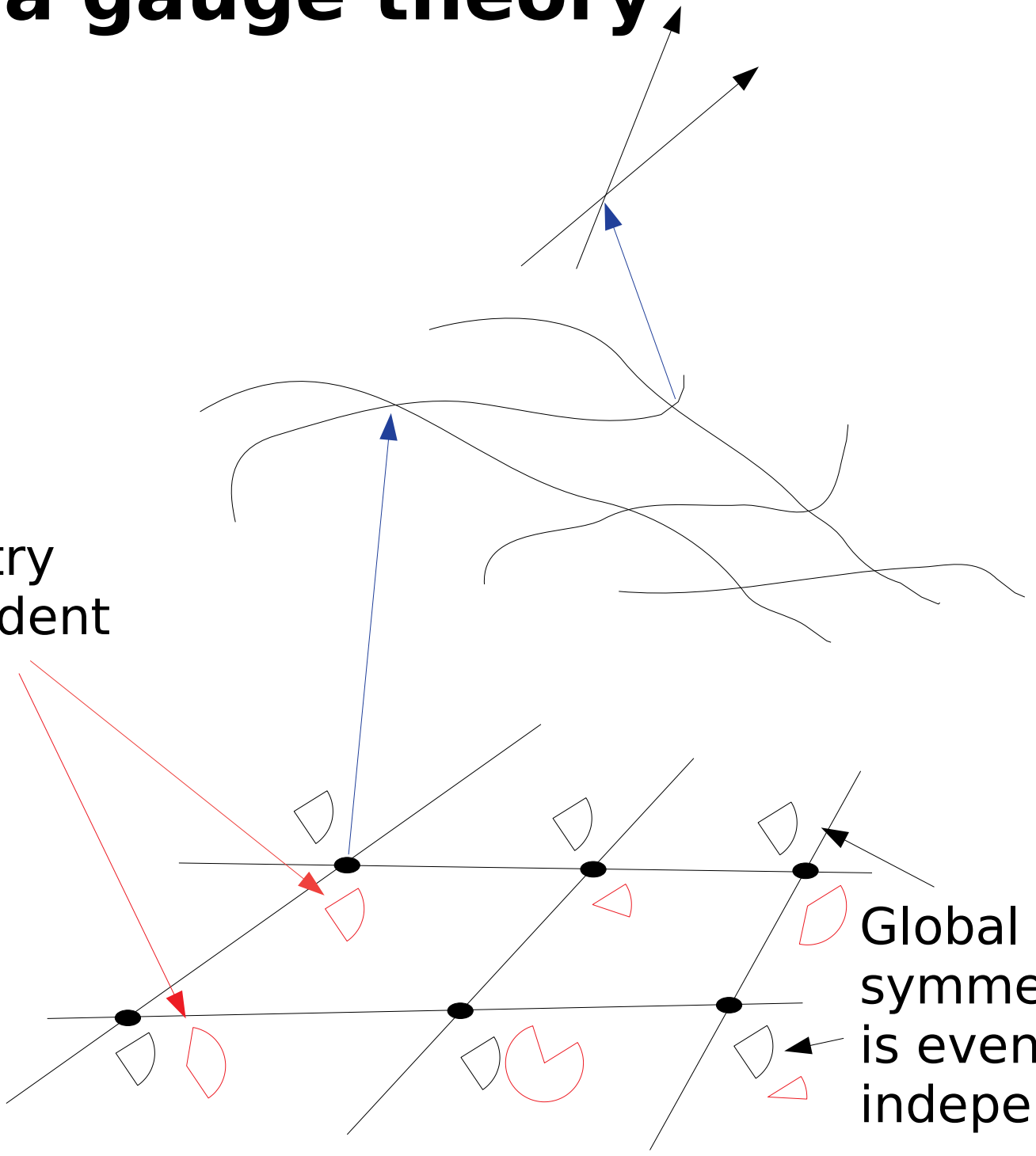

Global
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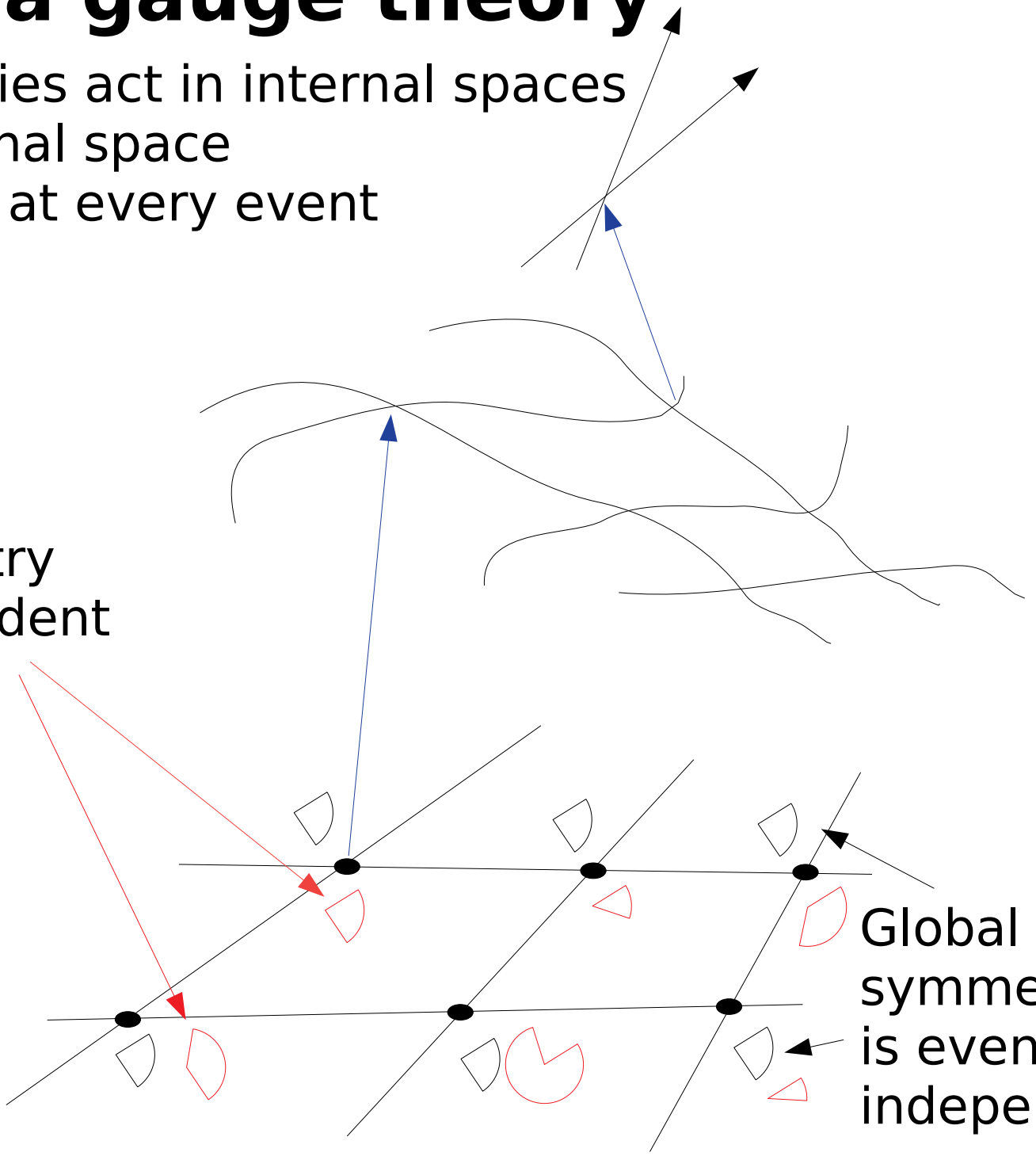
Gravity as a gauge theory

[Hehl et al.'76]

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



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Dynamical formulation

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

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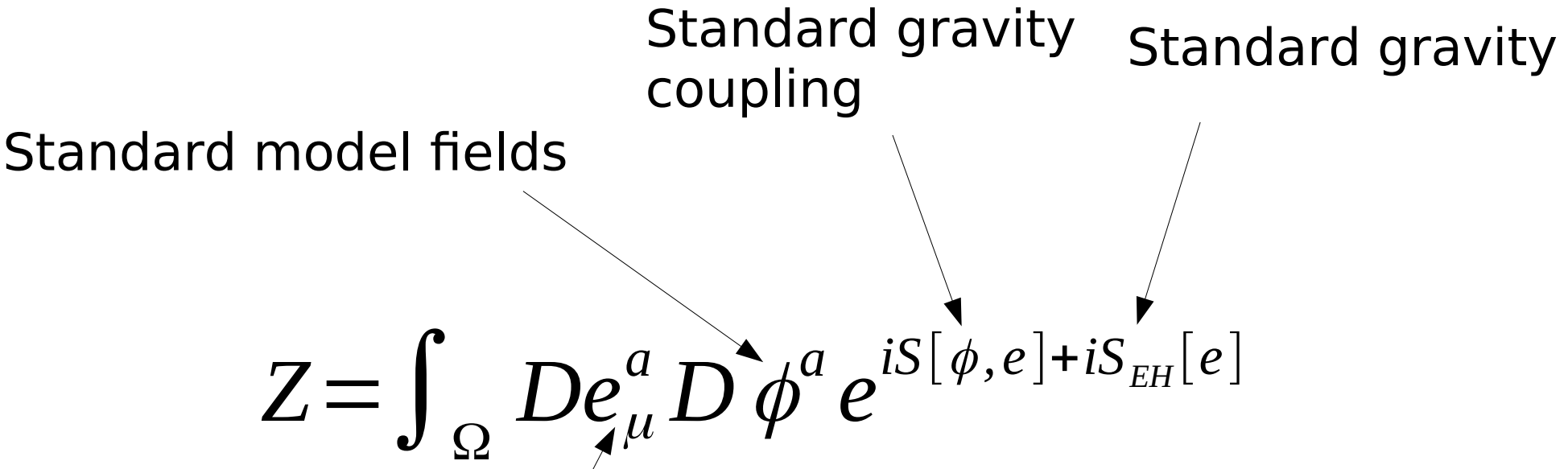
  - Other choices possibles

Dynamical formulation



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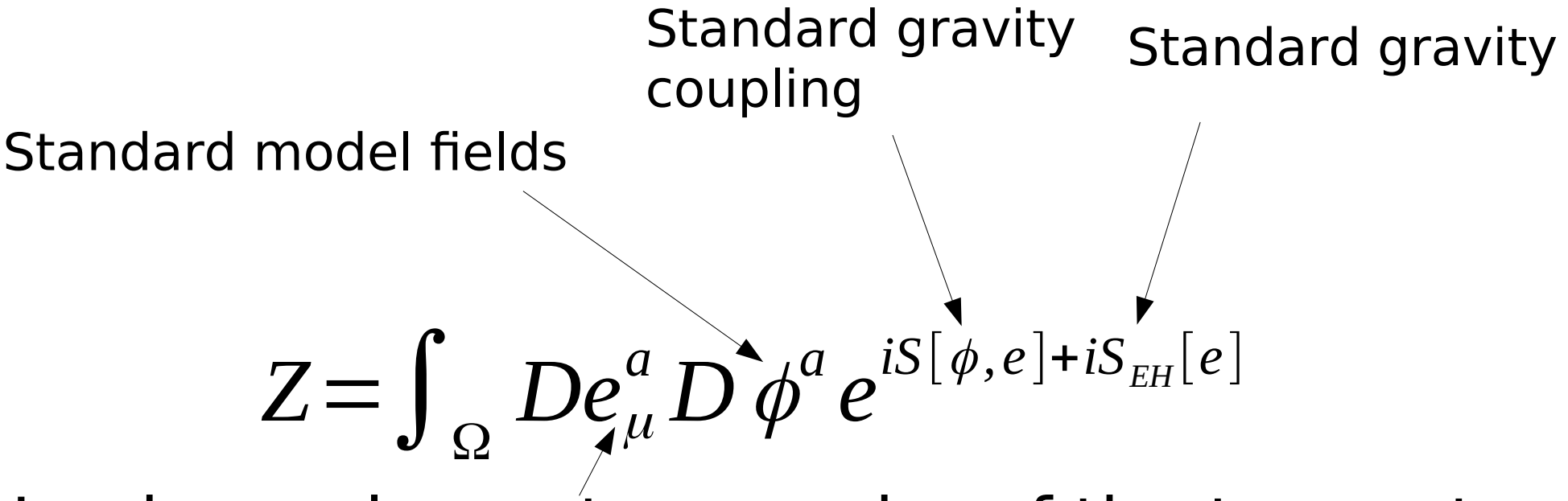

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- Otherwise standard
  - E.g. Asymptotic safety for ultraviolet stability

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Needs to be invariant

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

Dynamical formulation

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

Needs to be invariant

- Locally under Diffeomorphism
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  - Invariants identify the particular type

Simpelst object: Scalar

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

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Completely scalar: Invariant under all symmetries

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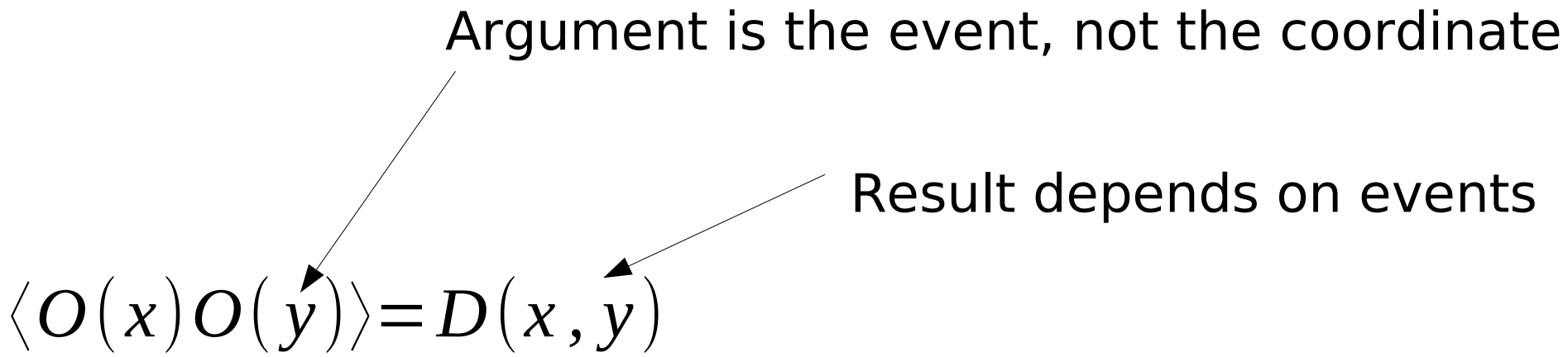

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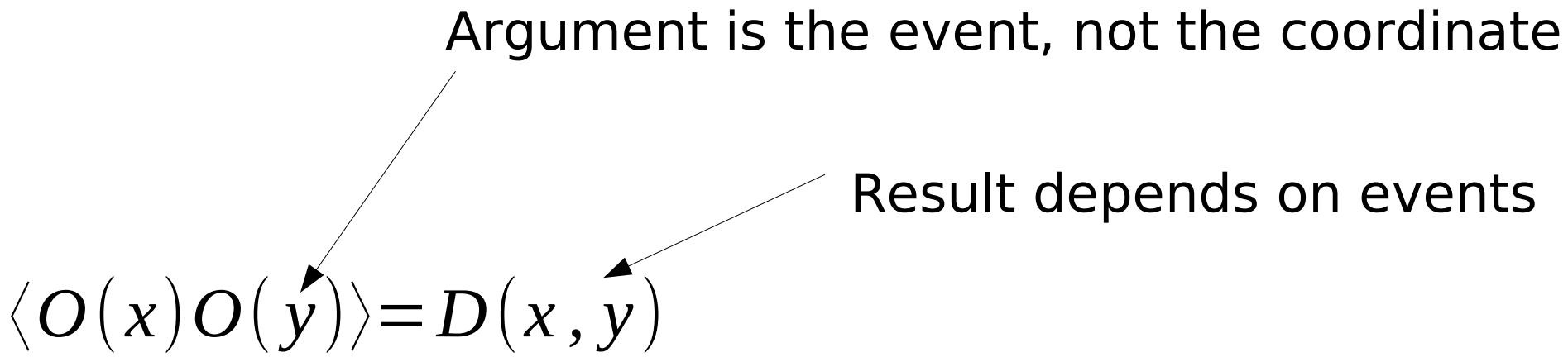

- Consider a scalar particle
  - E.g. described by a scalar field $O(x)$
  - Completely invariant
  - Events not a useful argument

Simpelst object: Scalar

[Schaden'15]

Some distance function

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

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- Distance is a quantum object: Expectation value
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[Schaden'15,Maas'19]

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[Schaden'15,Maas'19]

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Separate calculation

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Simpelst object: Scalar

[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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- Generalization of flat-space arguments

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- Works very well in particle physics

Applying FMS

- Our universe is well-approximated by a classical metric
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- Our universe is well-approximated by a classical metric
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- 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

Distance

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

- Application to distance between two events

Distance

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Classical geodesic distance

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

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

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

Classical geodesic distance

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

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

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

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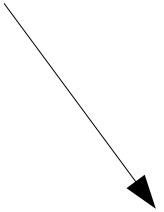
Leading term is flat space propagator

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

- Double expansion

Propagators

Corrections from quantum distance effects



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

- Double expansion
  - Quantum fluctuations in the argument

Propagators

Corrections from metric fluctuations

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

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- Double expansion
  - Quantum fluctuations in the argument
  - Quantum fluctuations in the action

Propagators

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- Reduces to QFT at vanishing gravity

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- Double expansion
  - Quantum fluctuations in the argument
  - Quantum fluctuations in the action
- Reduces to QFT at vanishing gravity
  - Higgs and W/Z mass in quantum gravity calculated

Speculative phenomenology

- Macroscopic gravitational objects need to be build in the same way

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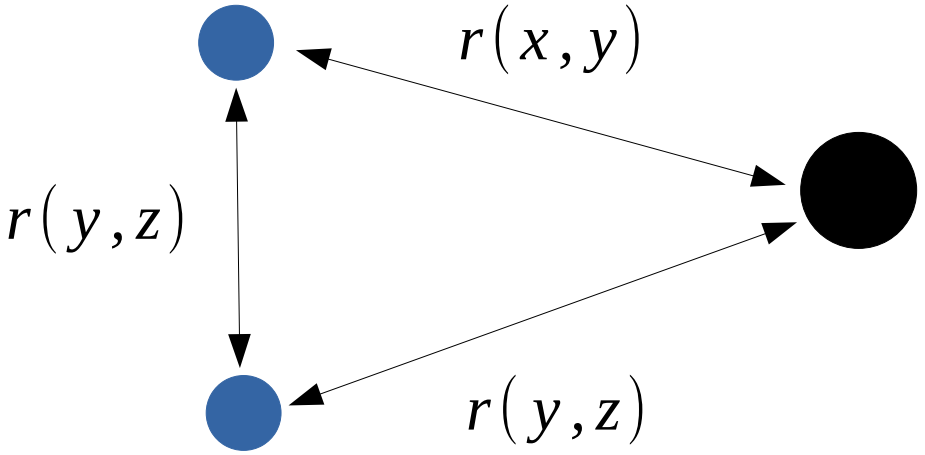
    - Will have overlap with $R(x)$

Speculative phenomenology

- 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
    - Will have overlap with $R(x)$
  - Product of separate diff-invariant operators
    - Geon star: Similar to neutron star
    - Hawking radiation as tunneling

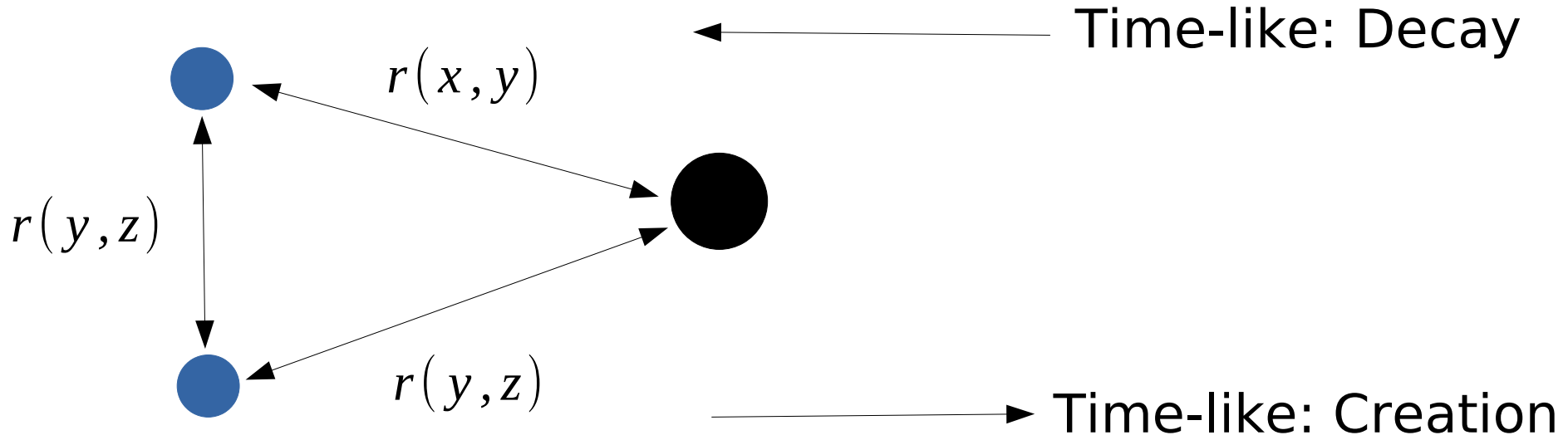
Black-hole particle interaction

Black-hole particle interaction



Black-hole particle interaction

- Black-hole creation and decay



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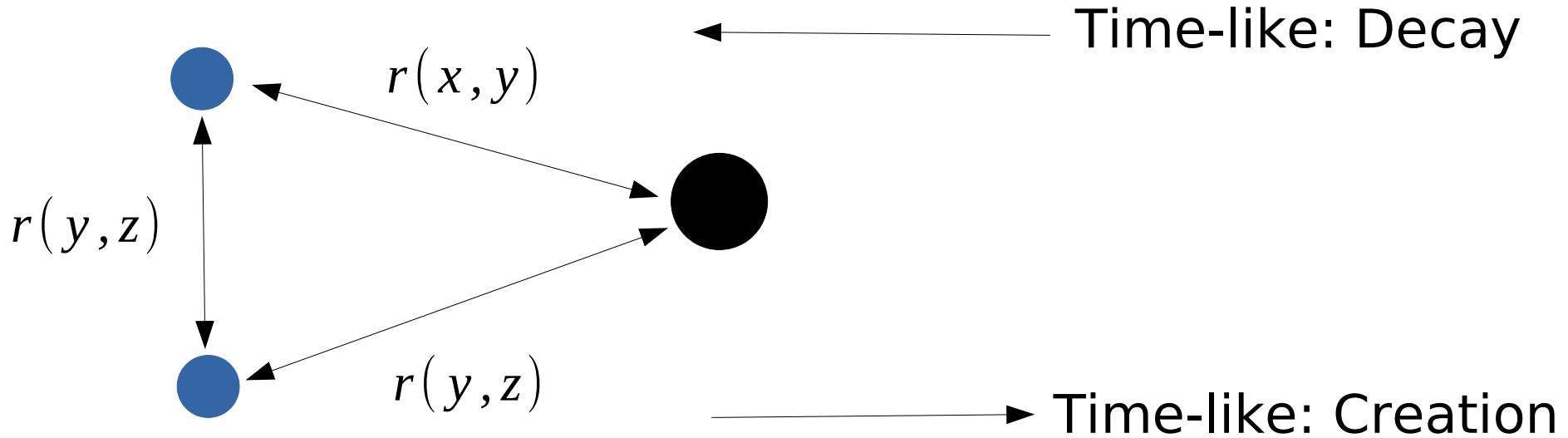
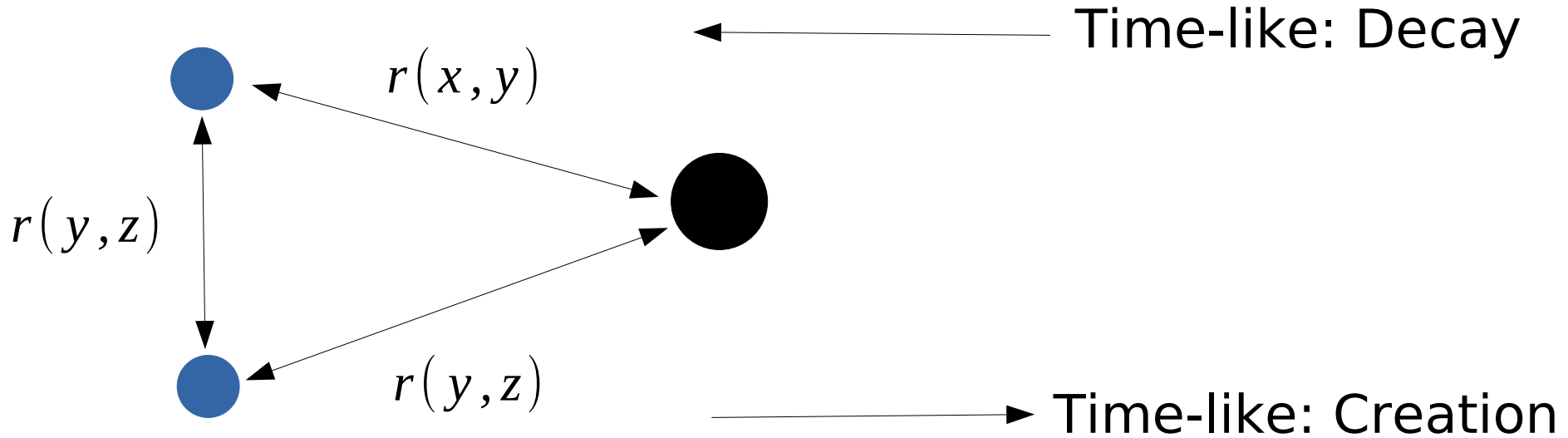


$$\langle B\phi\phi\rangle(r(x,y),r(y,z),r(x,z))=\int_{\Omega} De\,D\phi B(x)\phi(y)\phi(z)e^{iS}$$

Black-hole particle interaction

- Black-hole creation and decay



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$$\approx B^{c}_{Schwarzschild}(x(y,z),w_{Singularity})<\phi\phi>(r(y,z))$$

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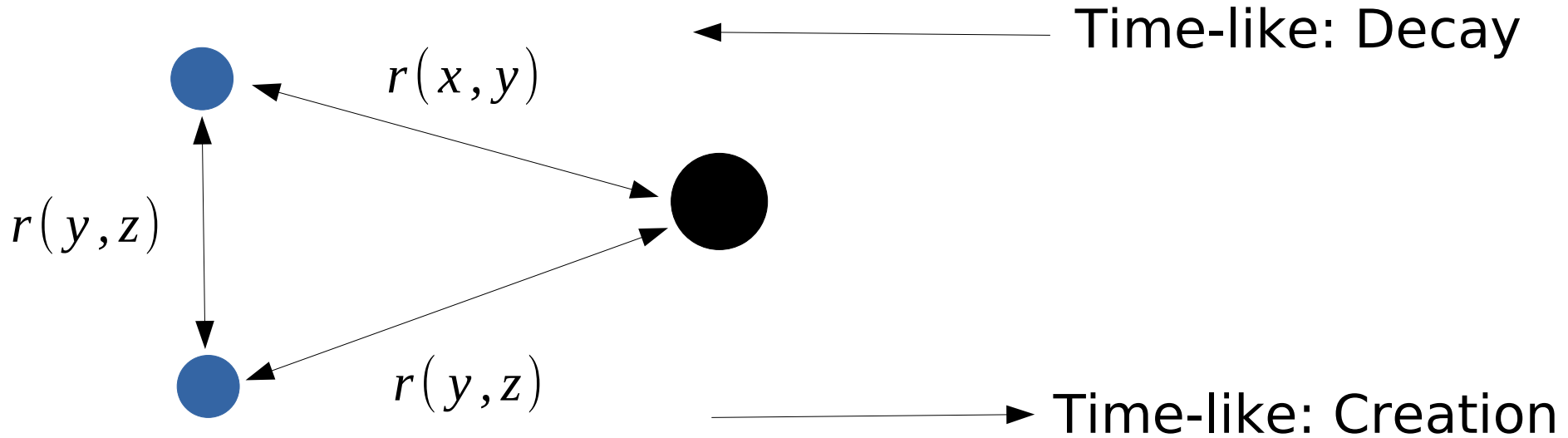

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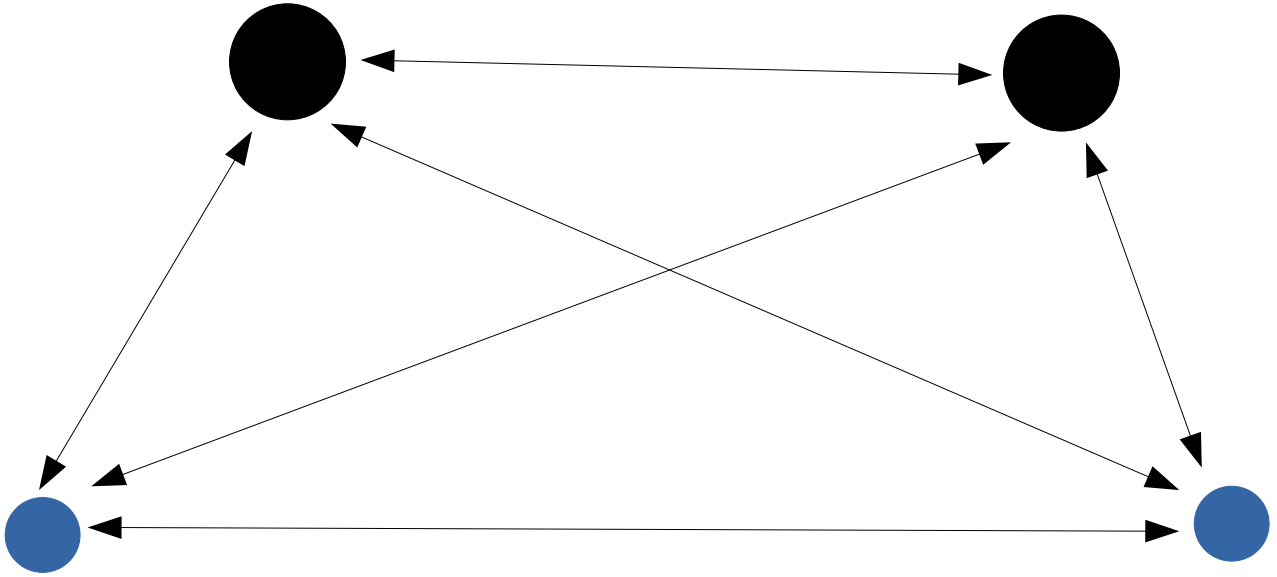
- Strong modification of effective mass
  - Details under way

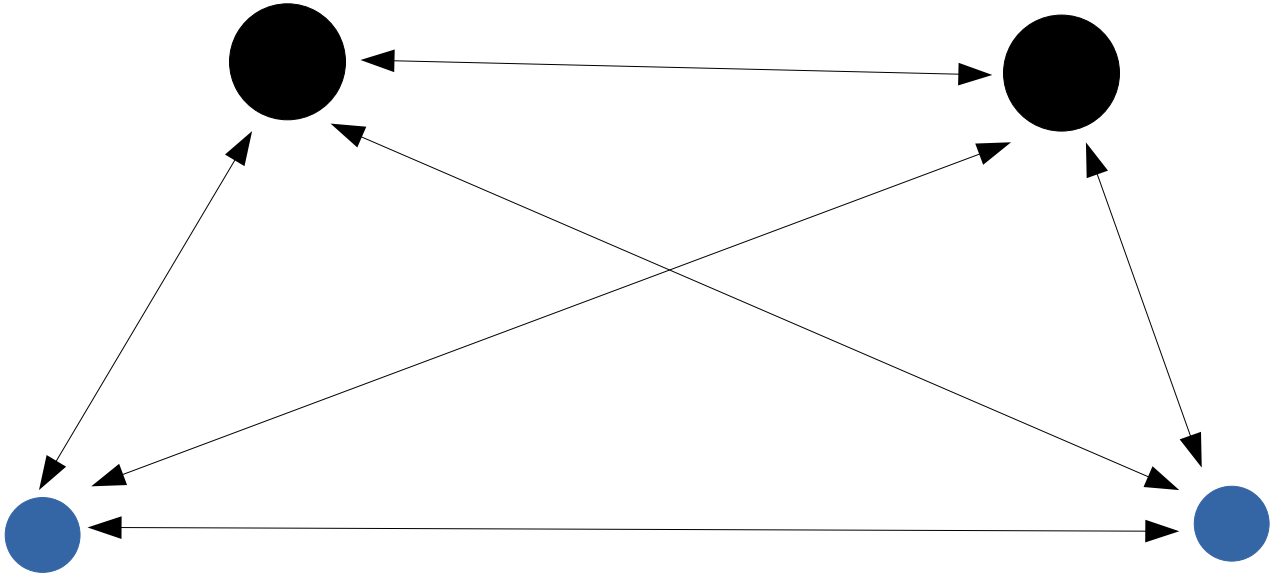
Black-hole particle interaction

- Black-hole-particle scattering



Black-hole particle interaction

- Black-hole-particle scattering



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Black-hole particle interaction

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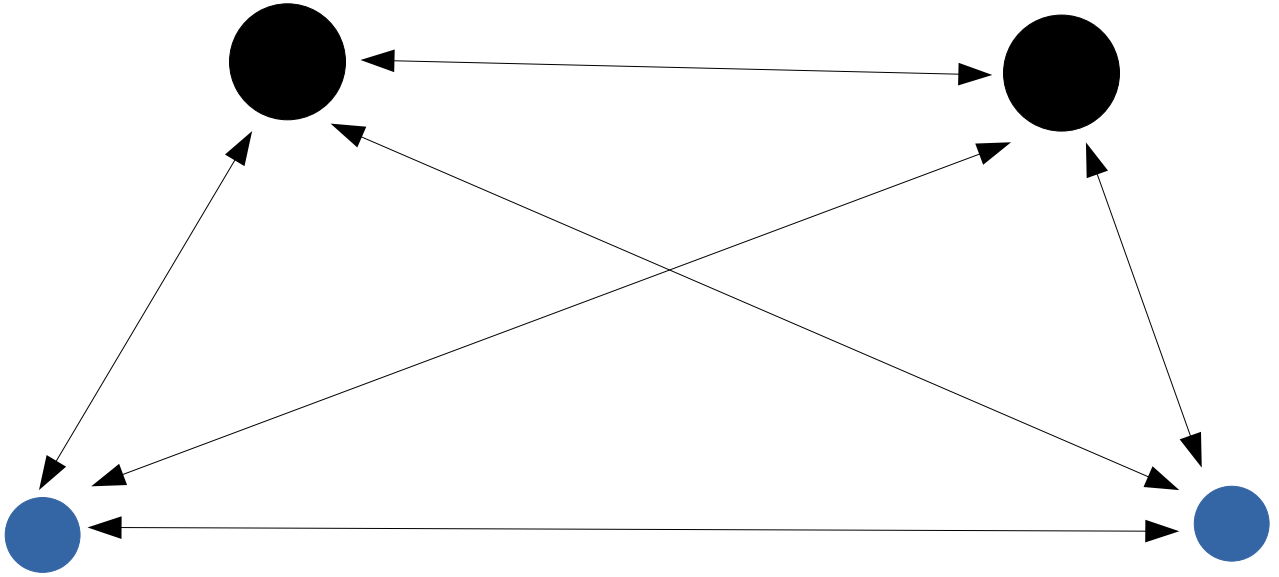
-



$$\langle BB\,\phi\,\phi\rangle = \int_{\Omega} De\,D\,\phi B(x)B(w)\,\phi(y)\,\phi(z)\,e^{iS}$$
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Black-hole particle interaction

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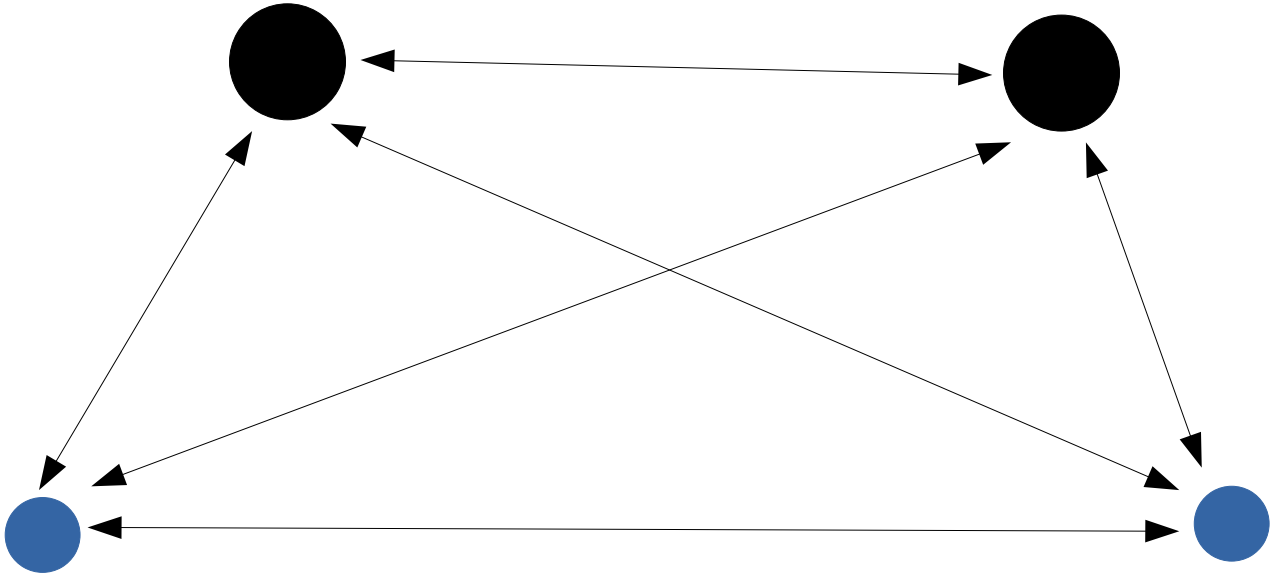

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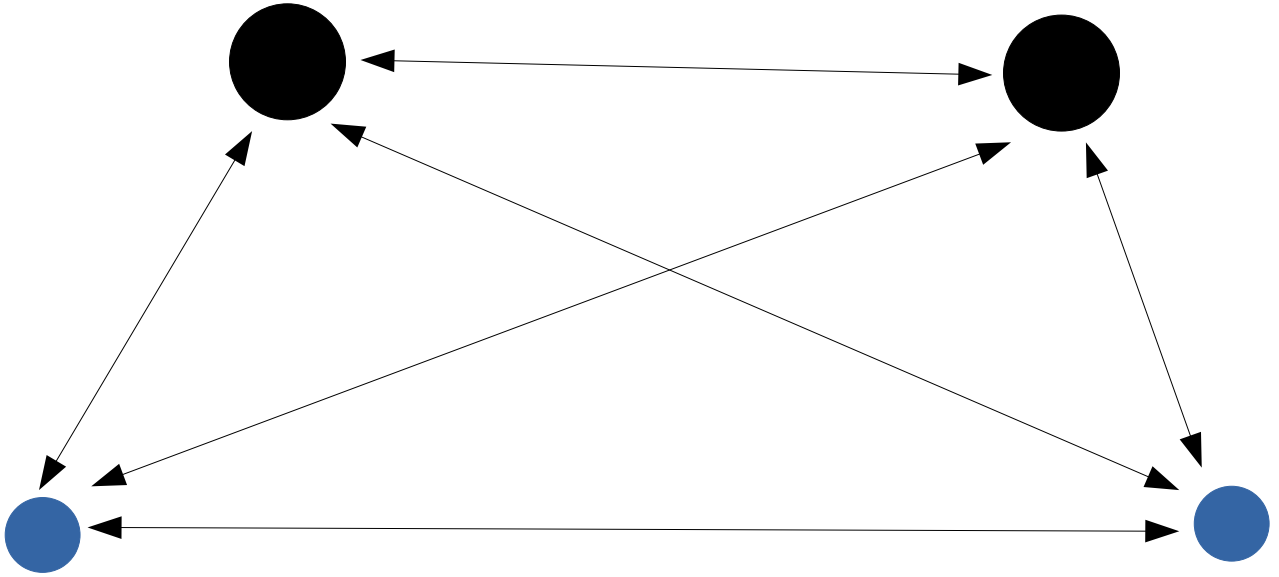
Black-hole particle interaction

- Black-hole-particle scattering



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- Absorption: Two black holes, one particle
  - Vanishes at this level: Quantum effects dominate

Summary

- Full invariance necessary for physical observables in path integrals

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

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- Gives a new perspective on strong and quantum gravity