Physical Observables In Canonical Quantum Gravity

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Perimeter, Canada
Online

What is this talk about?

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

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- Fröhlich-Morchio-Strocchi mechanism
  - Emergence of flat-space QFT

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- Fröhlich-Morchio-Strocchi mechanism
  - Emergence of flat-space QFT
- Connecting to other approaches

Path integral and global symmetries

[Review: Maas'17]

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

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

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Measure is invariant
- no anomalies

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Action is invariant

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

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Integration range
- contains all orbits $G\phi$

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

- 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

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

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

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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

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

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

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- 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

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Path integral and local symmetries

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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 structure

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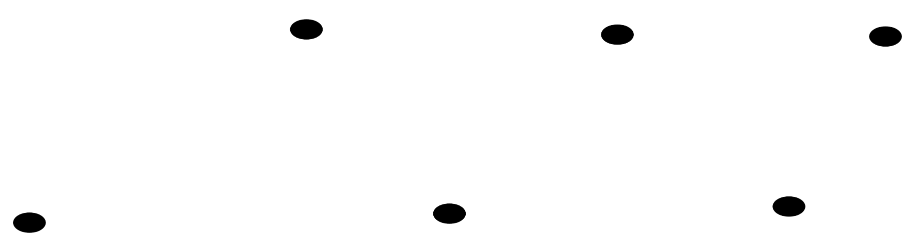
- Spin seems to be an observable?
  - Spin degeneracies and selection rules due to spin conservation
  - Global or effective structure
- Particle physics gauge symmetries and global symmetries should remain the same

Gravity as a gauge theory

[Hehl et al.'76]

Set of events with
neighbor relations



Gravity as a gauge theory

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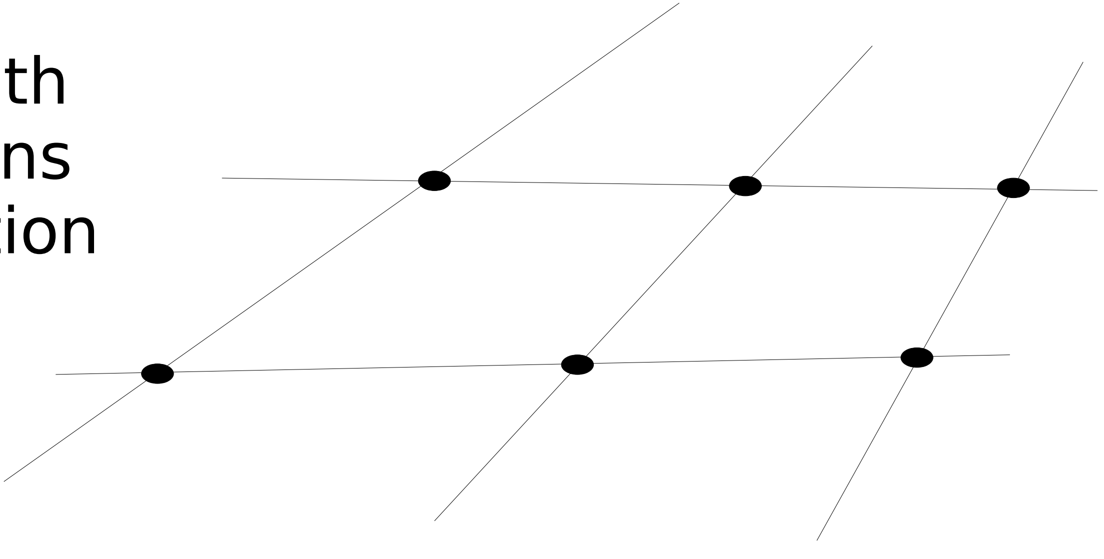
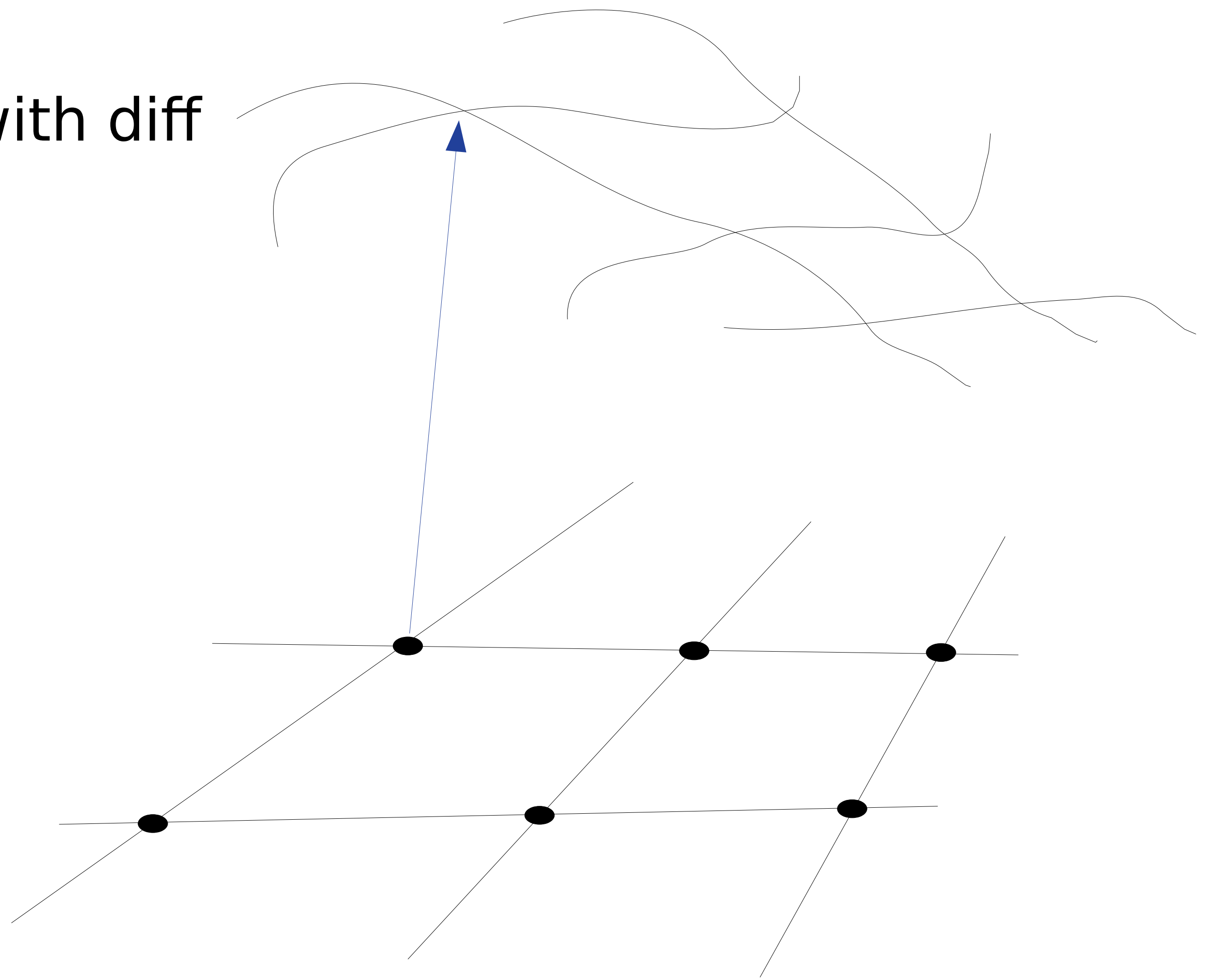
Set of events with
neighbor relations
E.g. R^4 in definition
of manifold



Gravity as a gauge theory

[Hehl et al.’76]

Manifold with diff symmetry



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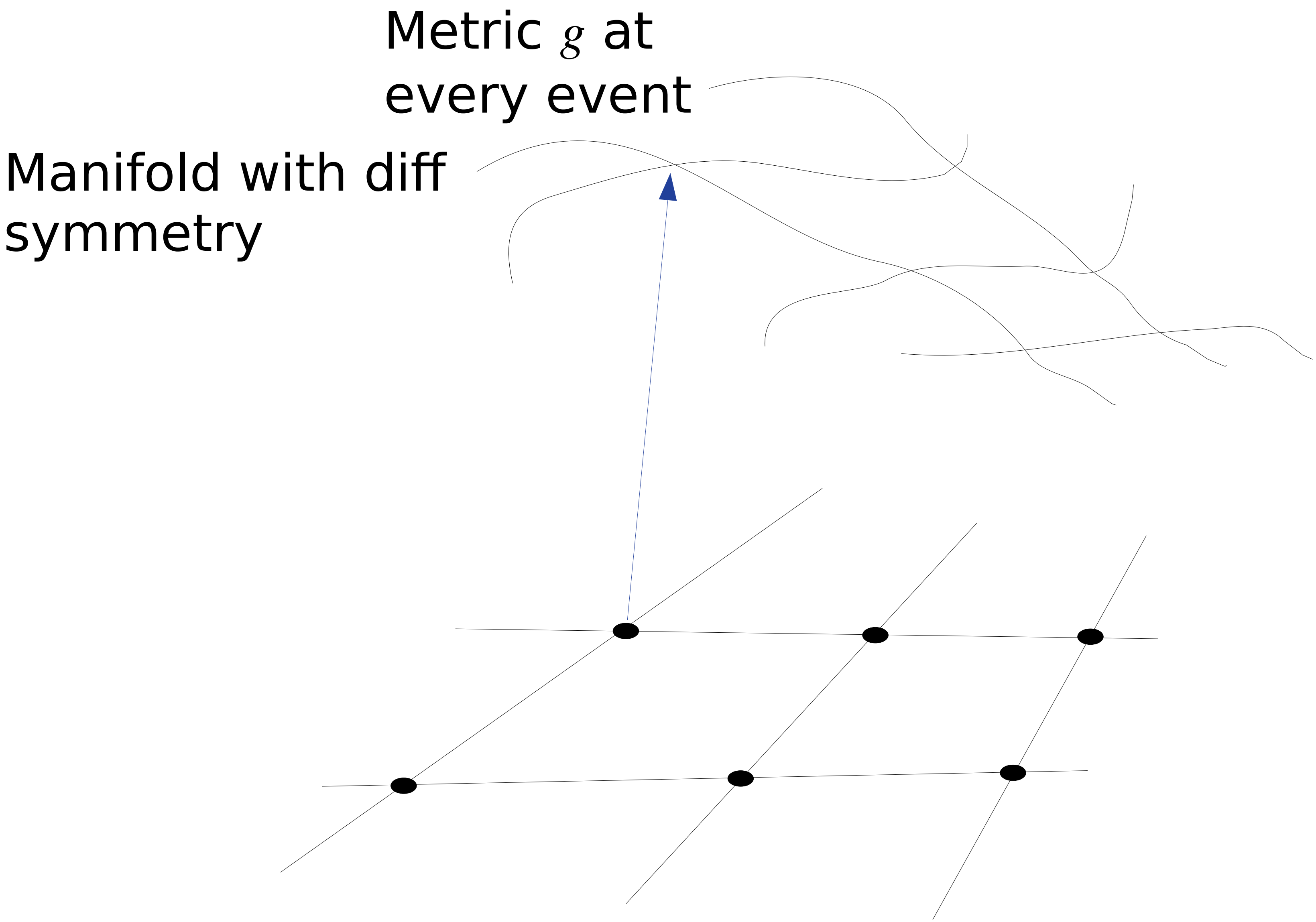
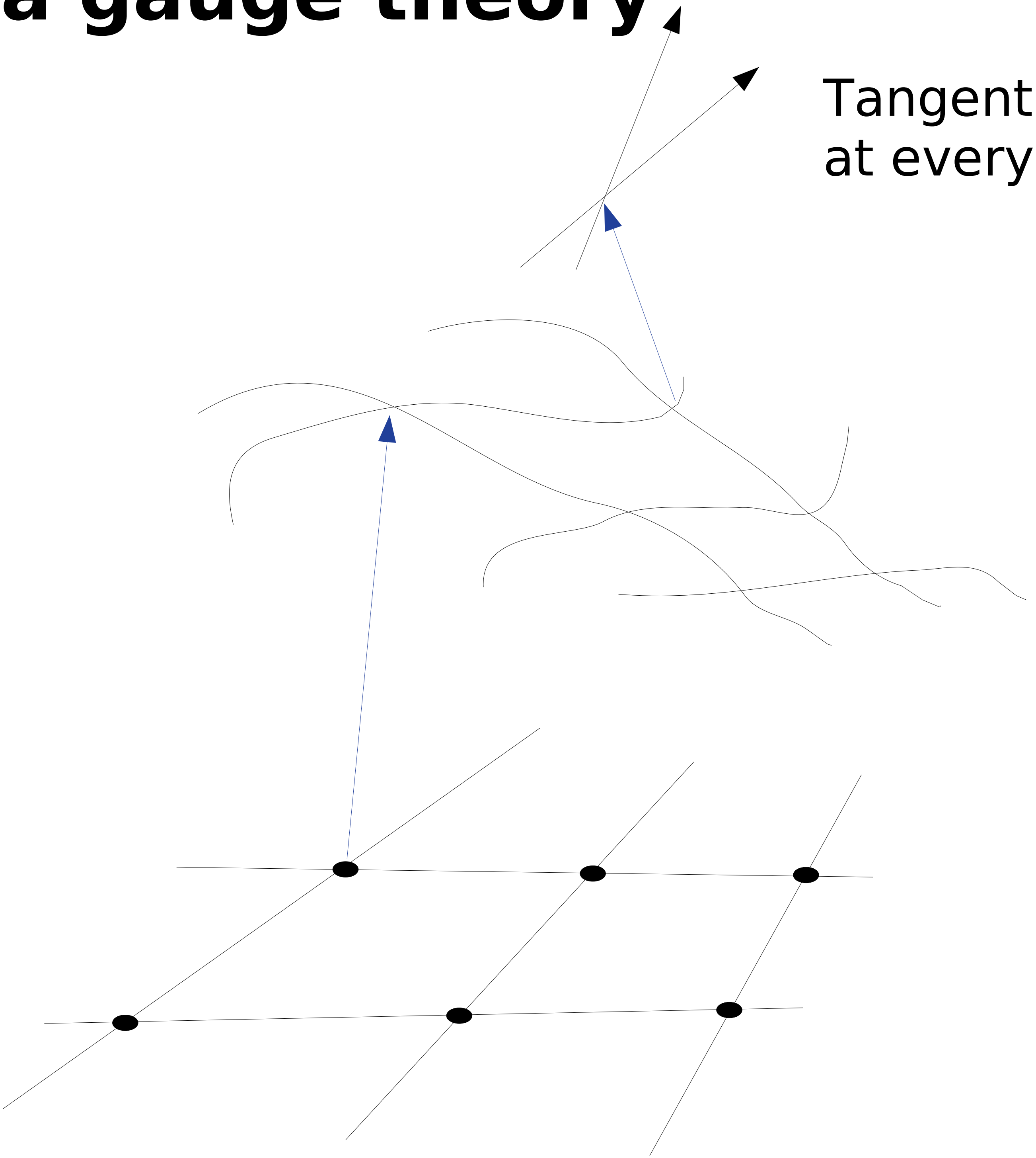


Gravity as a gauge theory

[Hehl et al.'76]

Tangent space
at every event



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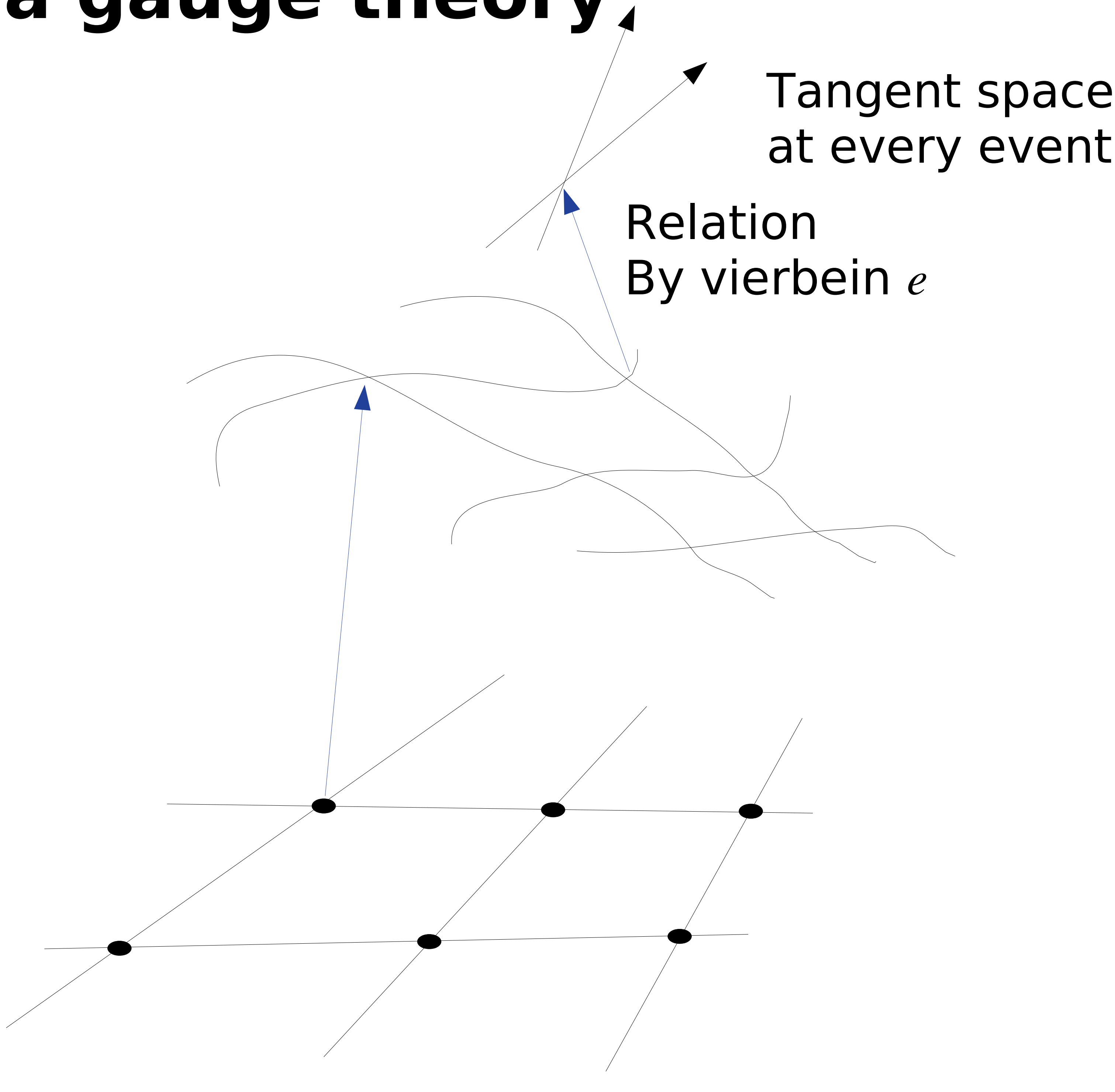

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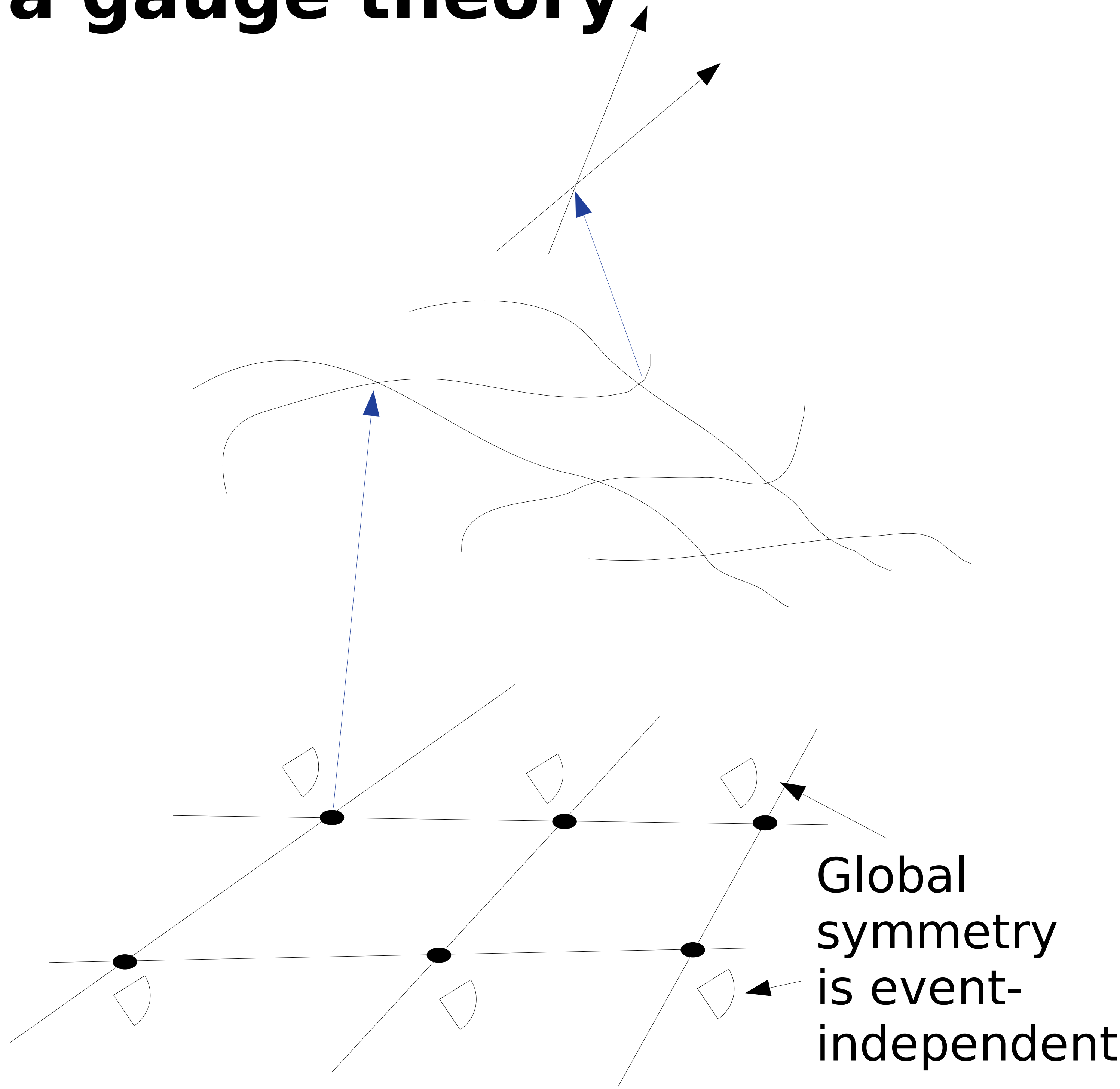

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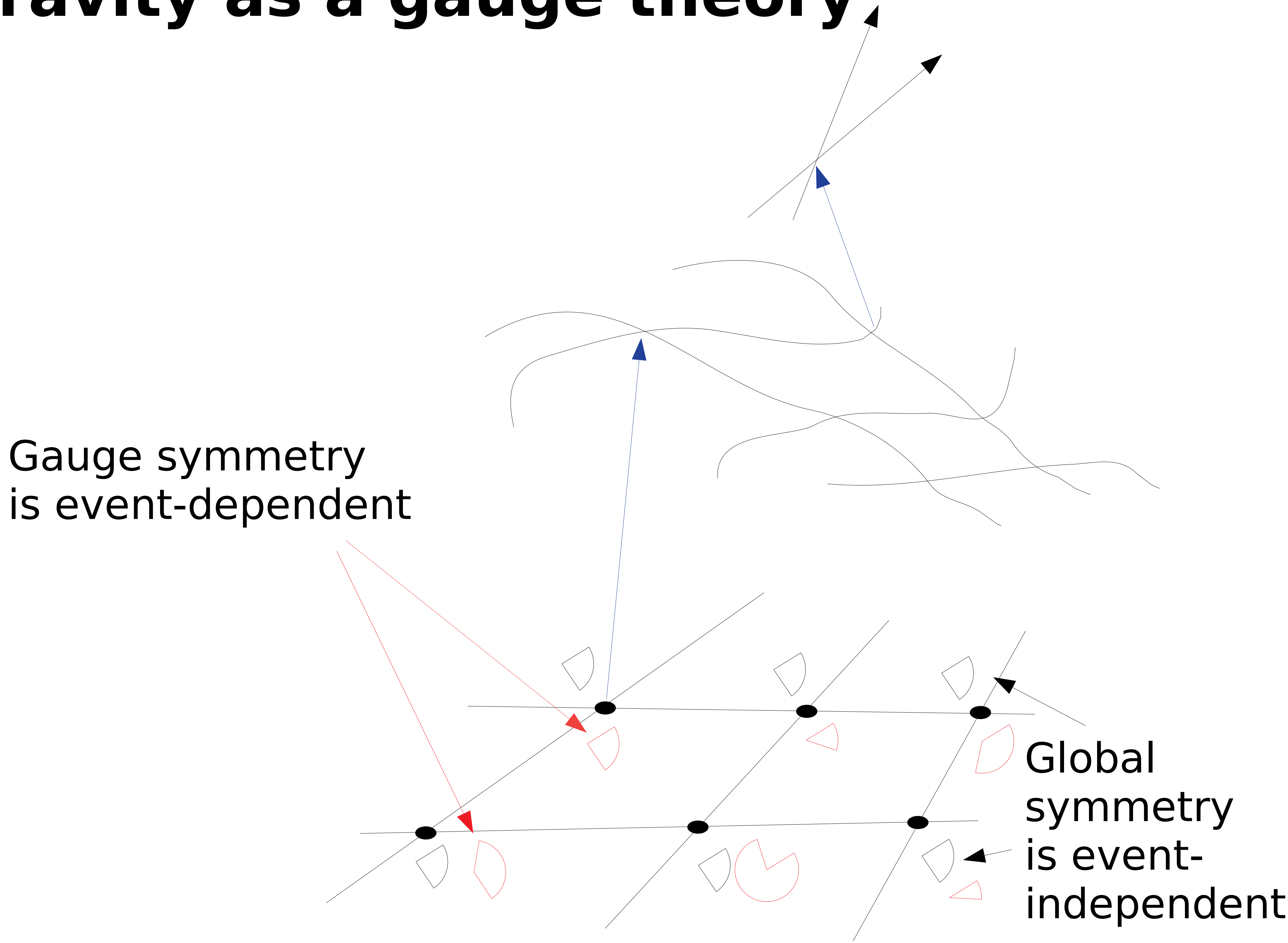
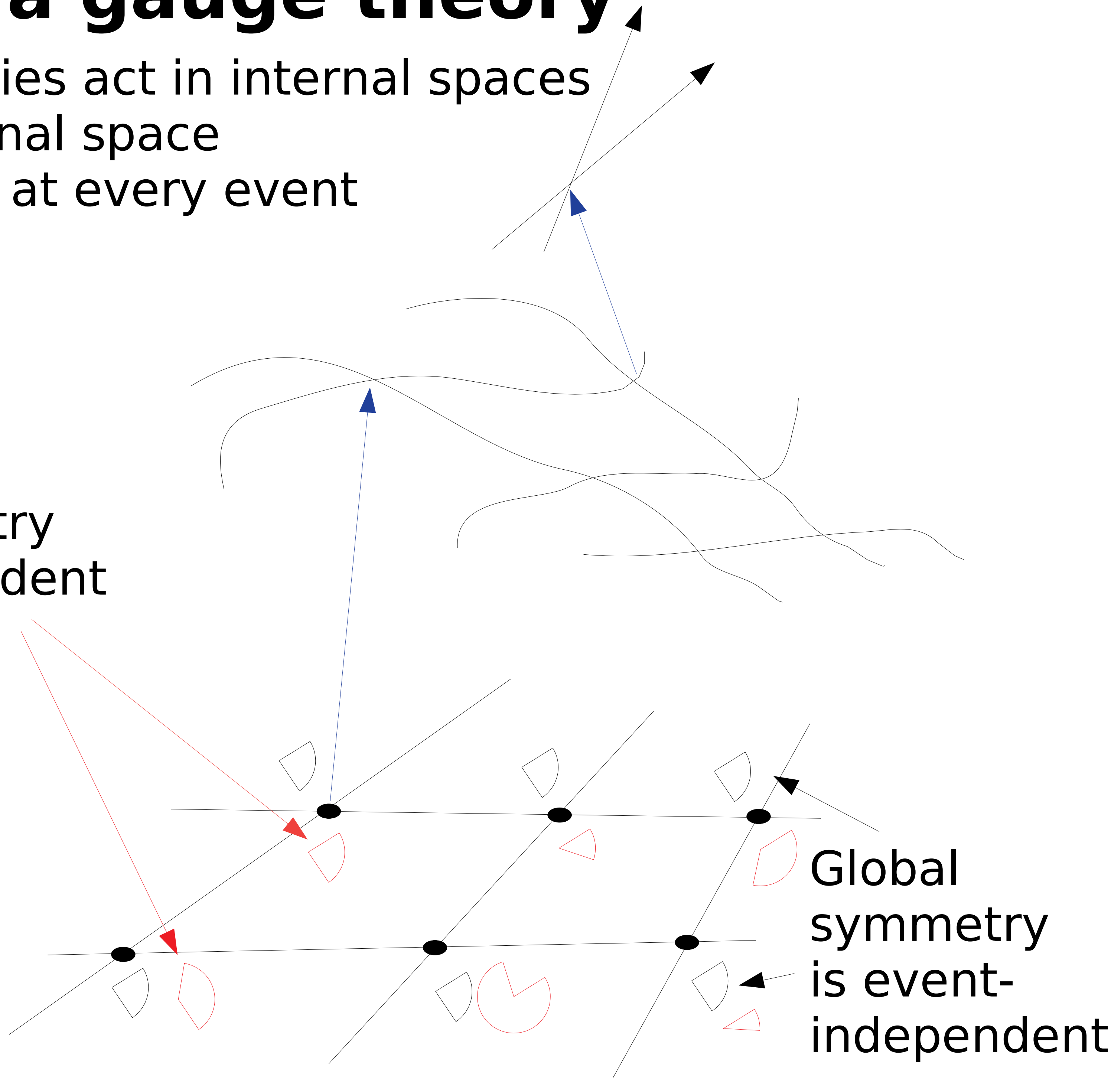


Gravity as a gauge theory

[Hehl et al.'76]

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

Gauge symmetry
is event-dependent



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

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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

[Maas'19]

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

Dynamical formulation

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

Dynamical formulation

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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]

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Space-time structure

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- 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

- 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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Simpelst object: Scalar

Argument is the event, not the coordinate

Result depends on events

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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

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

Some distance function

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

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

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

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  - Diff-invariant distance: Geodesic distance

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Separate calculation

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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

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

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- Generalization of flat-space arguments

What about cosmology?

[Maas et al.’22]

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

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  - Evolution of a matter/curvature concentration

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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

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  - Calculate order-by-order in quantum corrections

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- Works very well in particle physics

FMS in a nutshell

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

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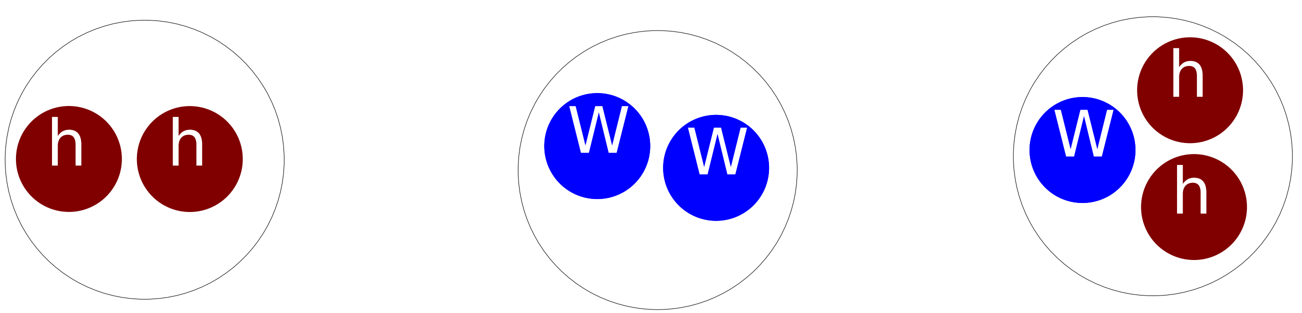
- Physical spectrum: Observable particles
  - Peaks in (experimental) cross-sections
- Higgs, W, Z,... fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



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

Higgs field

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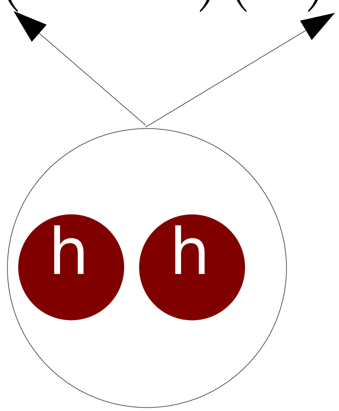

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$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = v^2 \langle \eta^+(x)\eta(y)\rangle$$
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$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = v^2 \langle \eta^+ (x)\eta(y)\rangle + v\langle \eta^+ \eta^2 + \eta^{+2} \eta\rangle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

3) Standard perturbation theory

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

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$$+ \langle \eta^+(x)\eta(y)\rangle \langle \eta^+(x)\eta(y)\rangle + O(g, \lambda)$$

4) Compare poles on both sides

Fröhlich-Morchio-Strocchi Mechanism

[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 $h=v+\eta$

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Flavor

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  - Global SU(3) generation
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- Can this be true? Lattice test

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[Afferrante,Maas,Sondenheimer,Törek'20]

- Only mock-up standard model
  - Compressed mass scales
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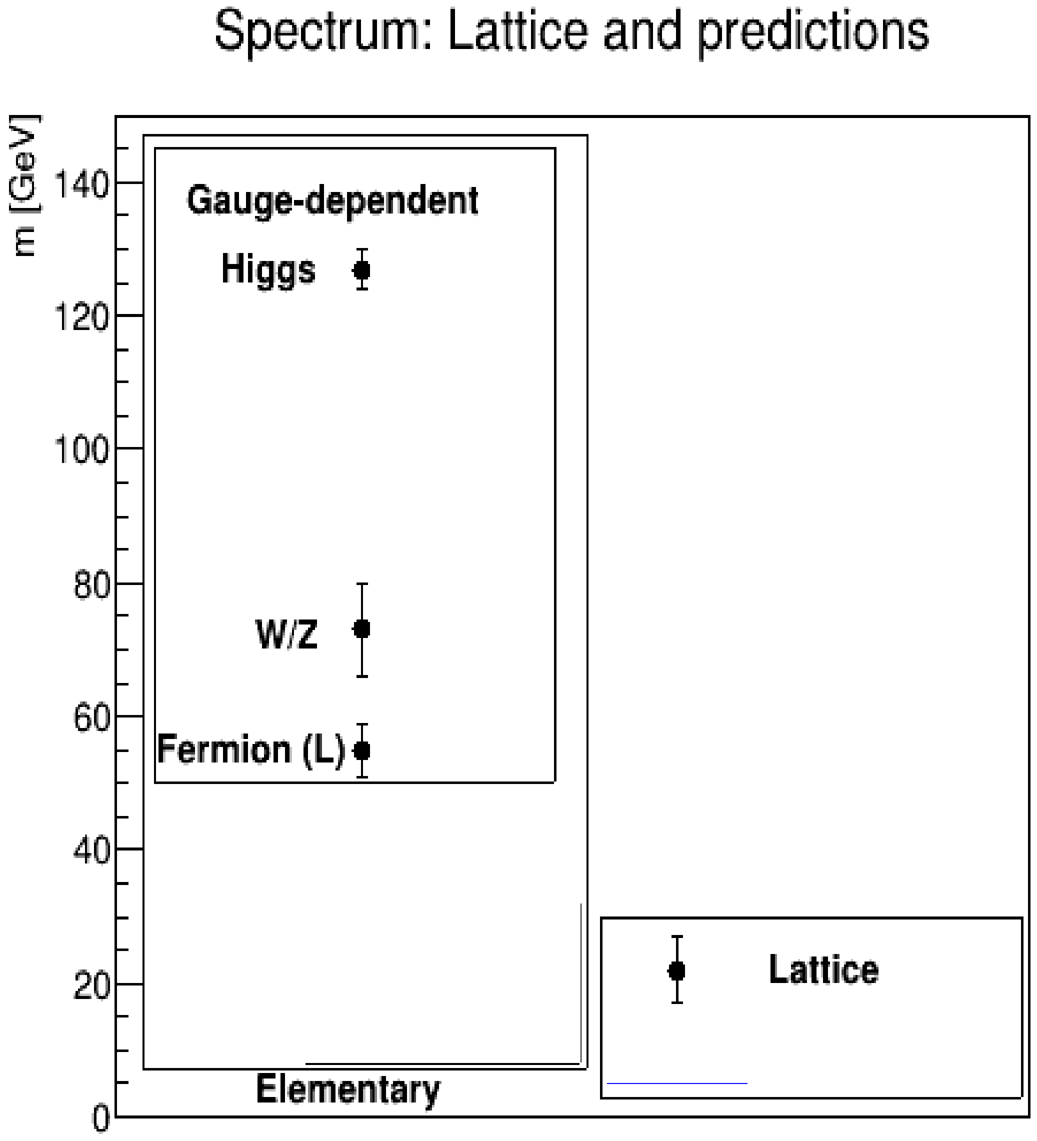

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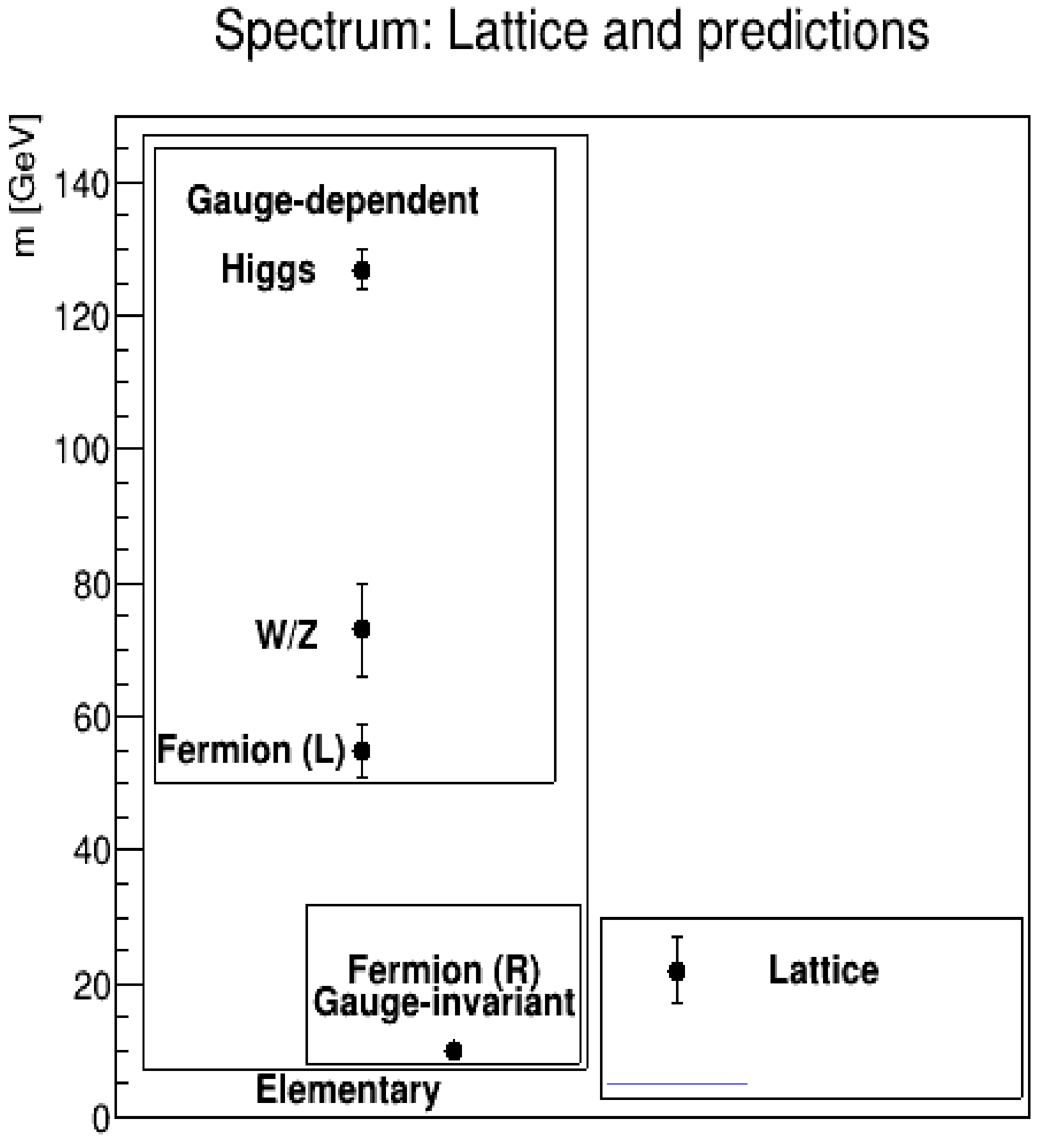

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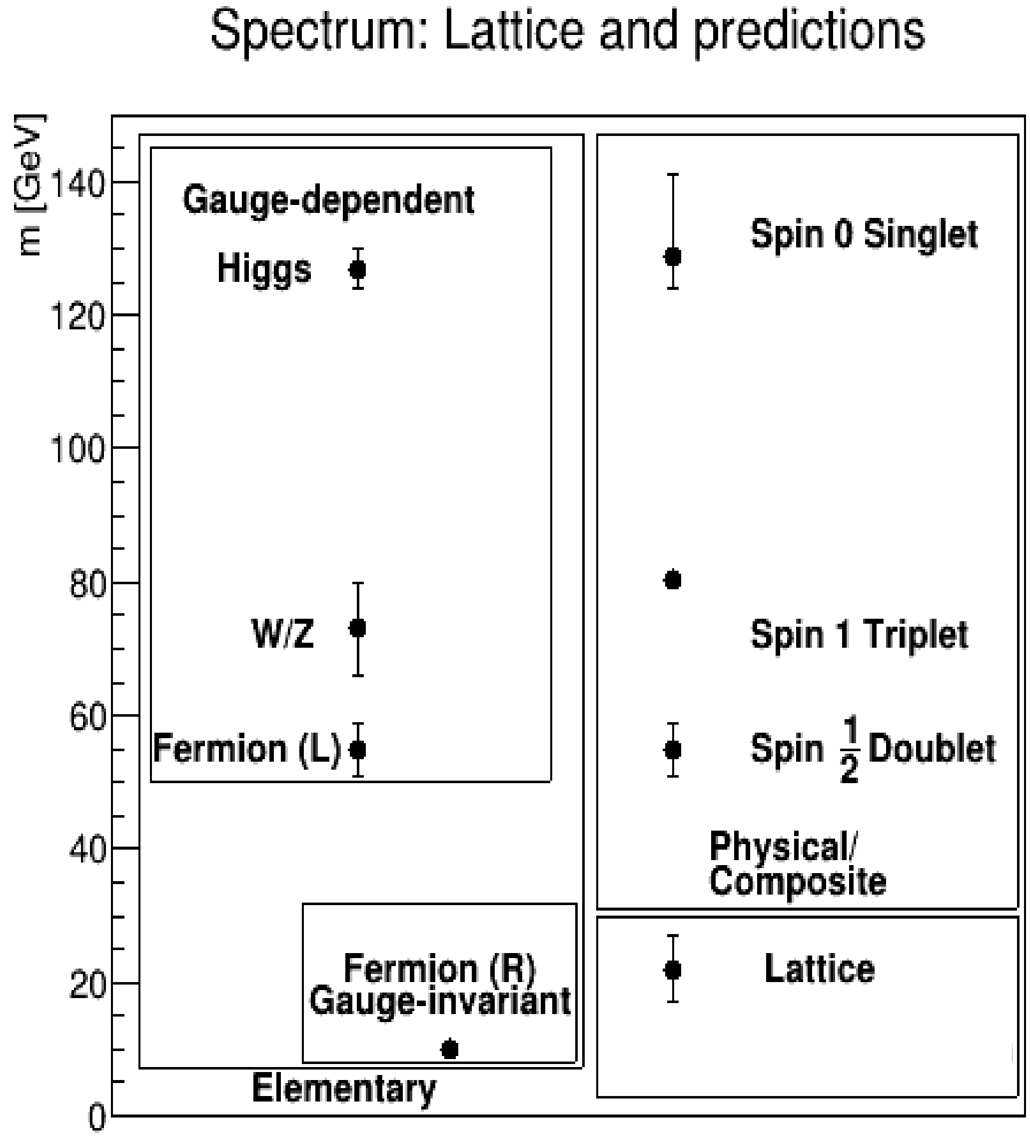

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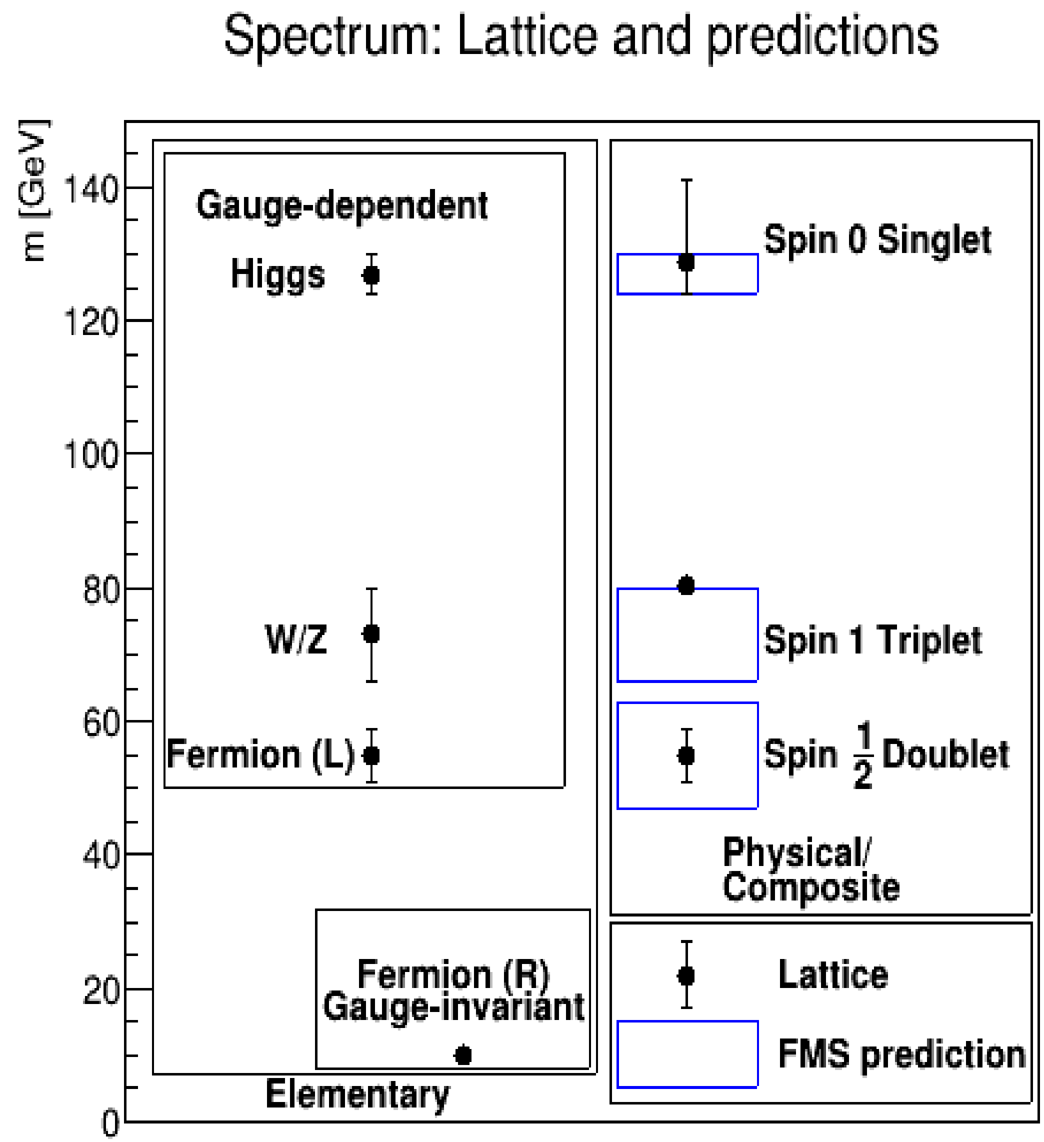

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    - Will avoid Bloch-Nordsieck violations
- Valence Higgs detectable at LHC?
  - Strong couplings to Higgs: tops, weak gauge bosons

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

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- 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!
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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 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

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  - Simple choice: Haywood gauge $g^{\mu\nu}\partial_\nu g_{\mu\rho}=0$
  - Inverse fluctuation satisfies Dyson equation

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

  - Infinite series at tree-level

Distance

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

- Application to distance between two events

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Classical geodesic distance

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

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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

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Leading term is
flat space propagator

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

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Propagators

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Corrections from quantum distance effects

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  - 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

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Graviton propagator

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- Flat space: Better divergence properties

[Maas & Sondenheimer'20]

Predictions for CDT

[Maas ’22,Ambjorn et al.’12]

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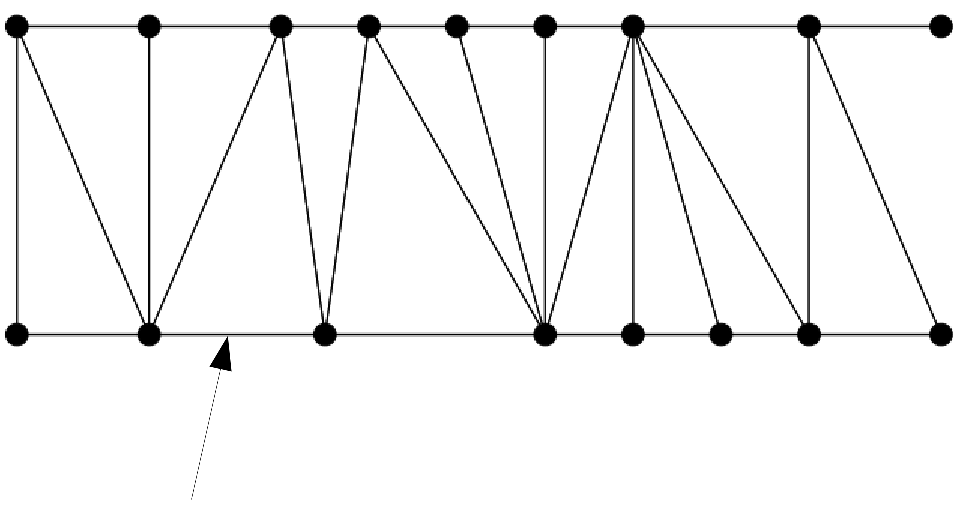

Space-like hypersurface (“now”)

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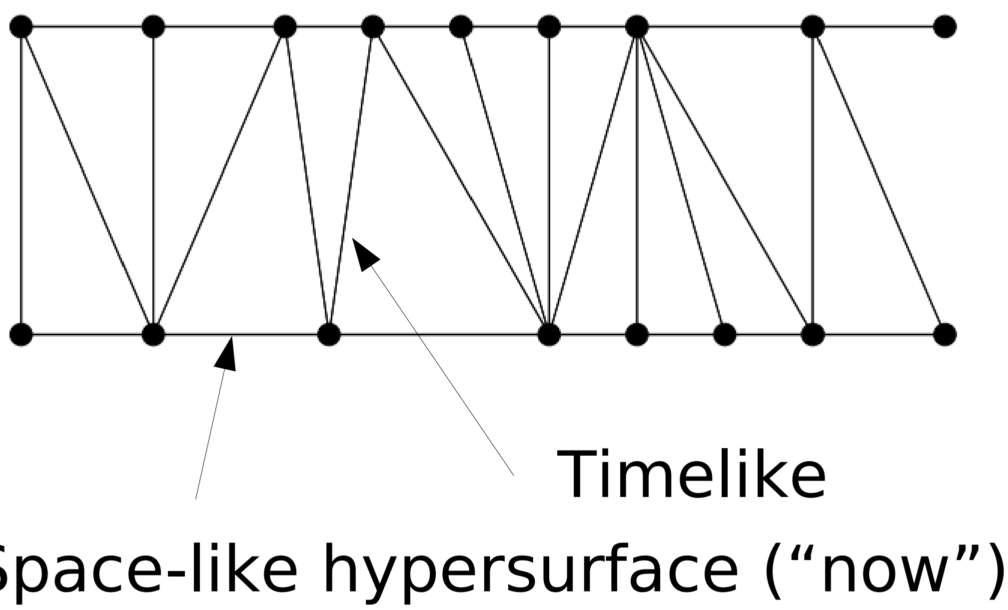

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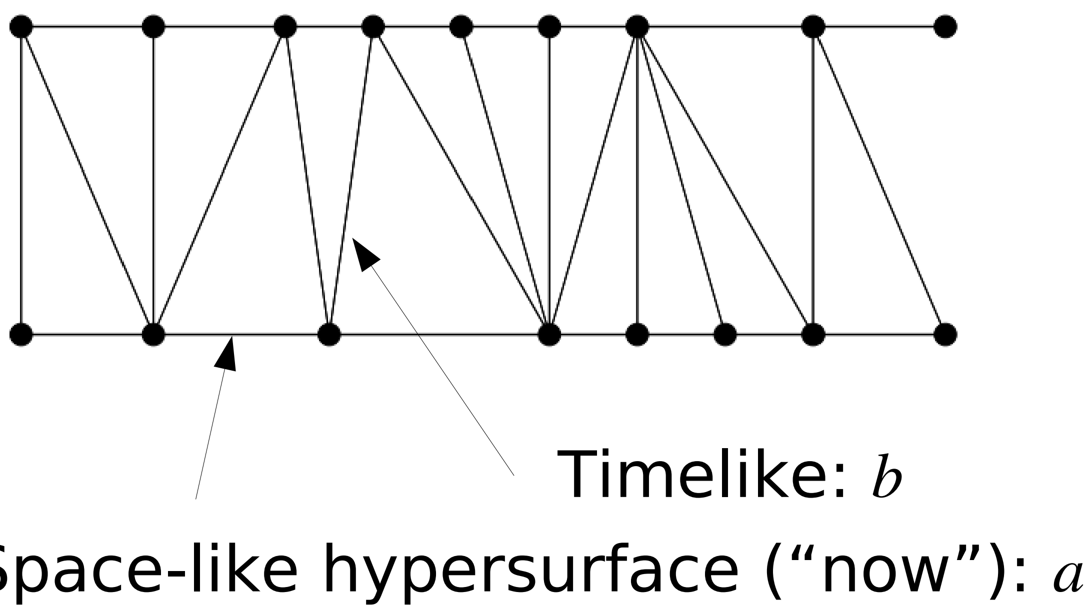

Predictions for CDT

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

- CDT vertex structure can be mapped to events
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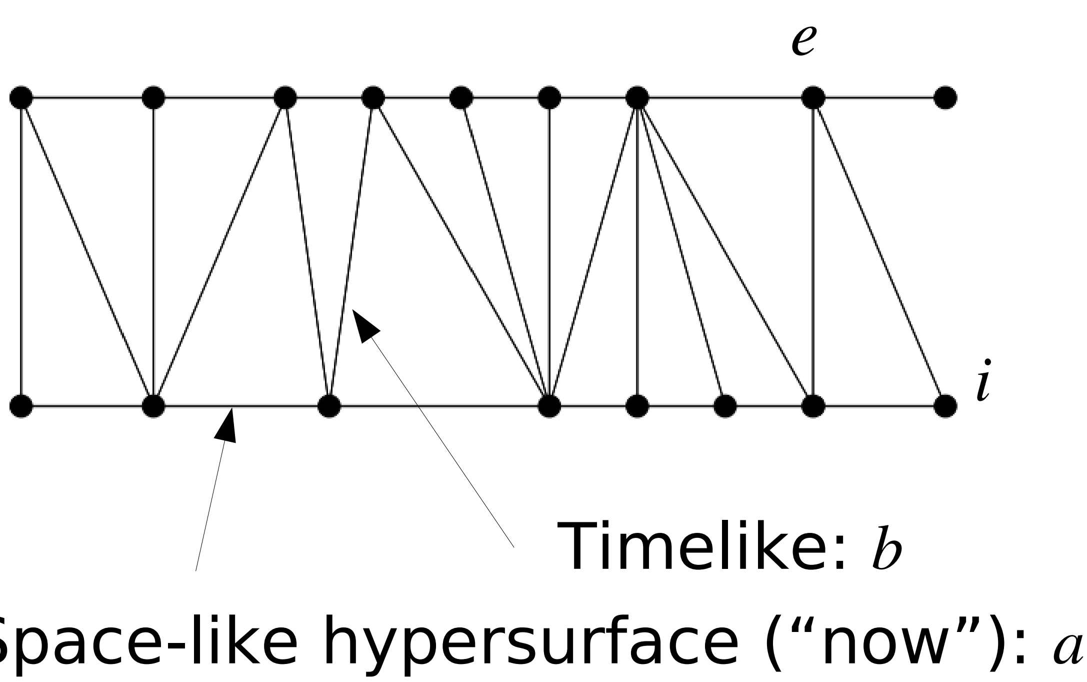

$$d(e,i)=b=\frac{g_{\mu\rho}(e)}{b}\frac{dz_\mu}{d\tau}\frac{dz_\rho}{d\tau}$$

Predictions for CDT

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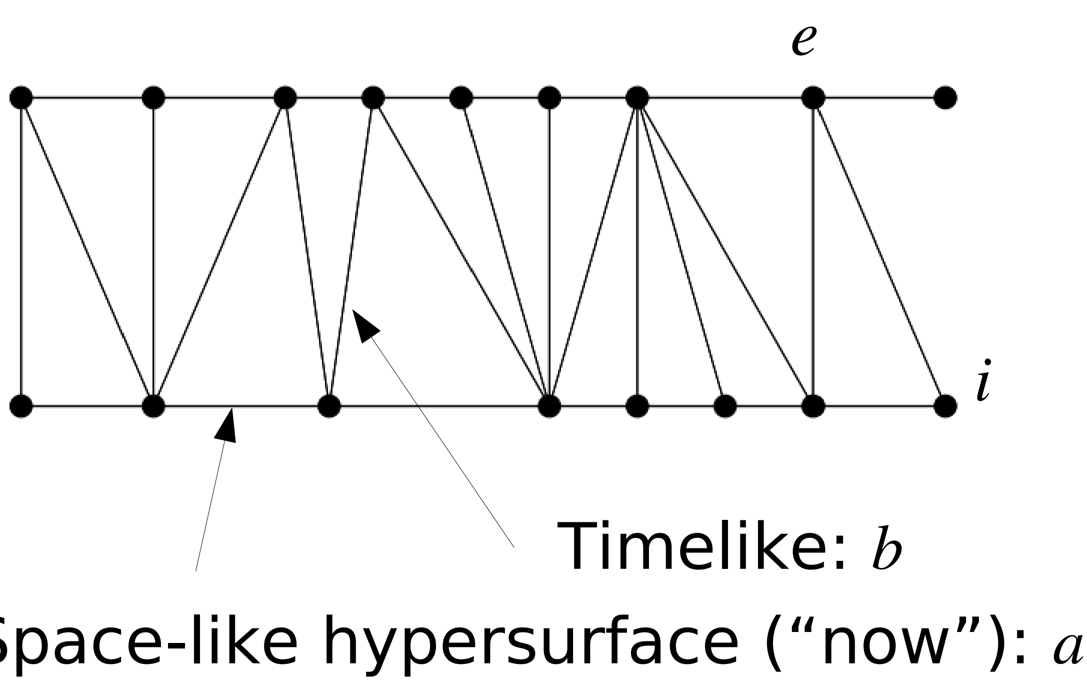

$$d(e,i)=b=\frac{g_{\mu\rho}(e)}{b}\frac{dz_\mu}{d\tau}\frac{dz_\rho}{d\tau}$$

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

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

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  - 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

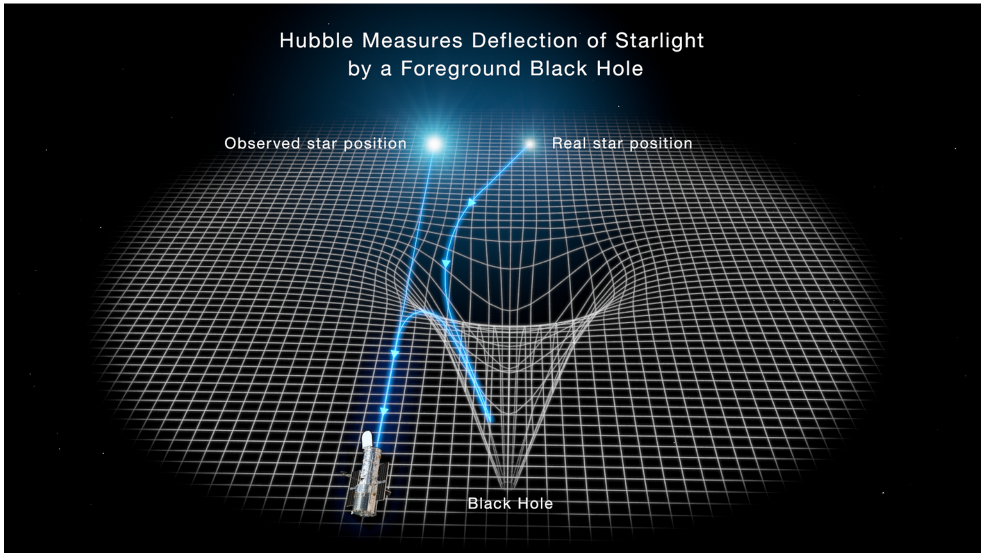
[Maas ’19]

- 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



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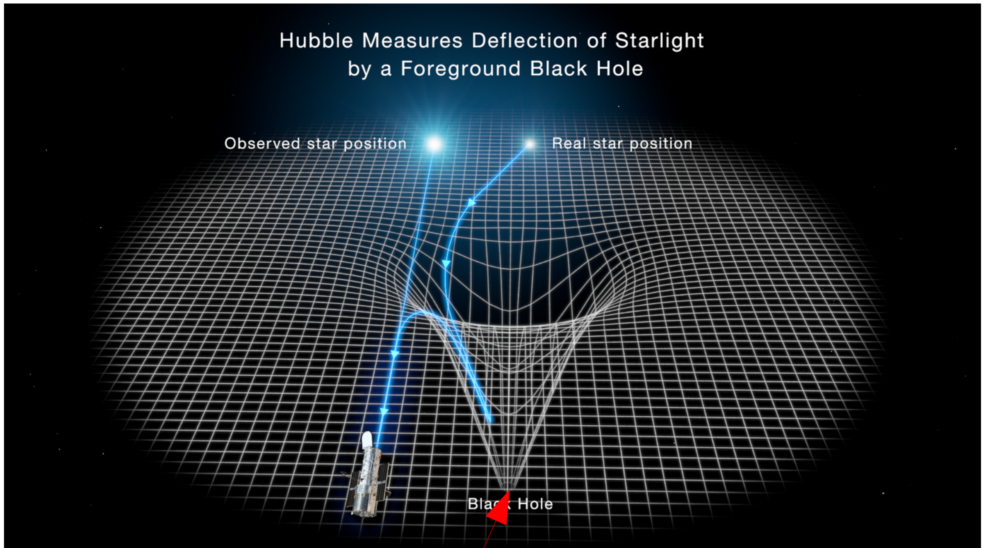
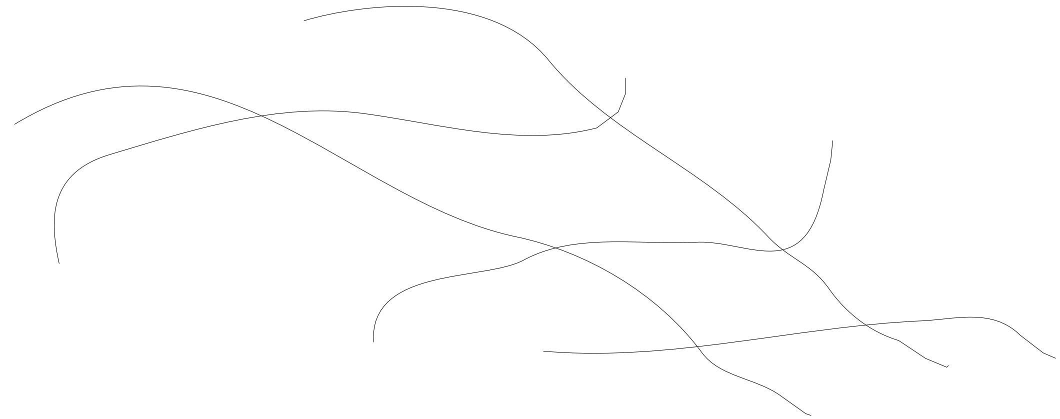


But this is a special worldline, determining the full metric!

Not possible in a quantum expectation value.

Views of black holes

Averaging over this!



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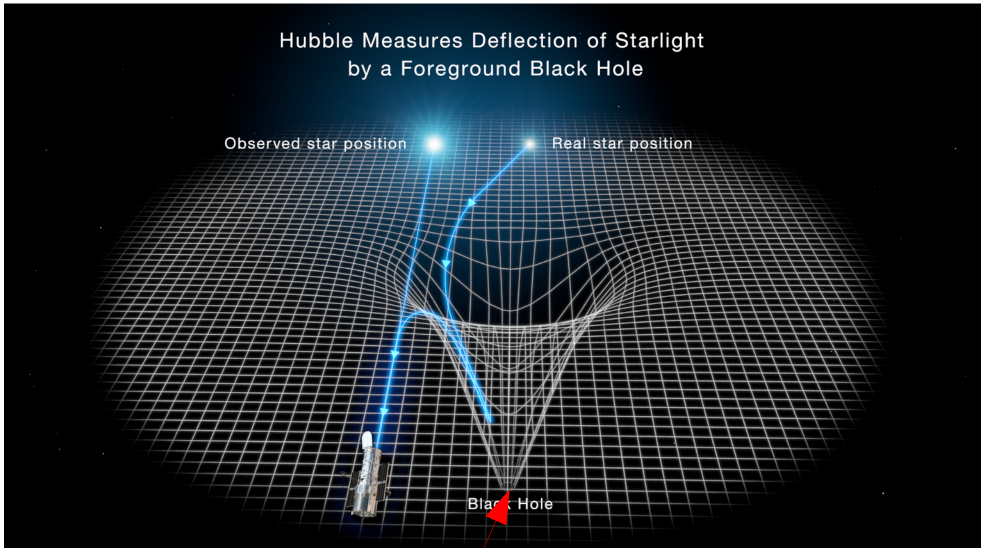

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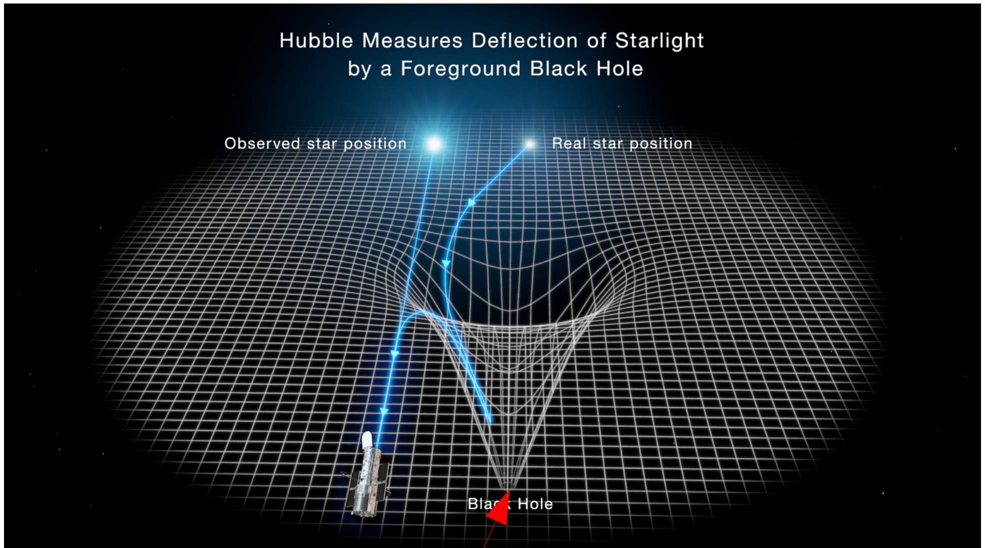

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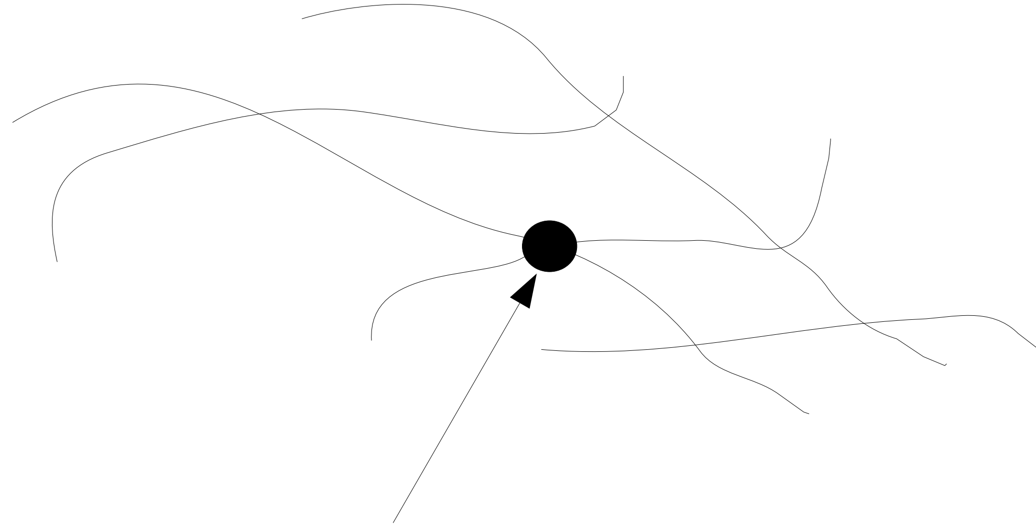

Need to put a black hole creation operator at an event

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

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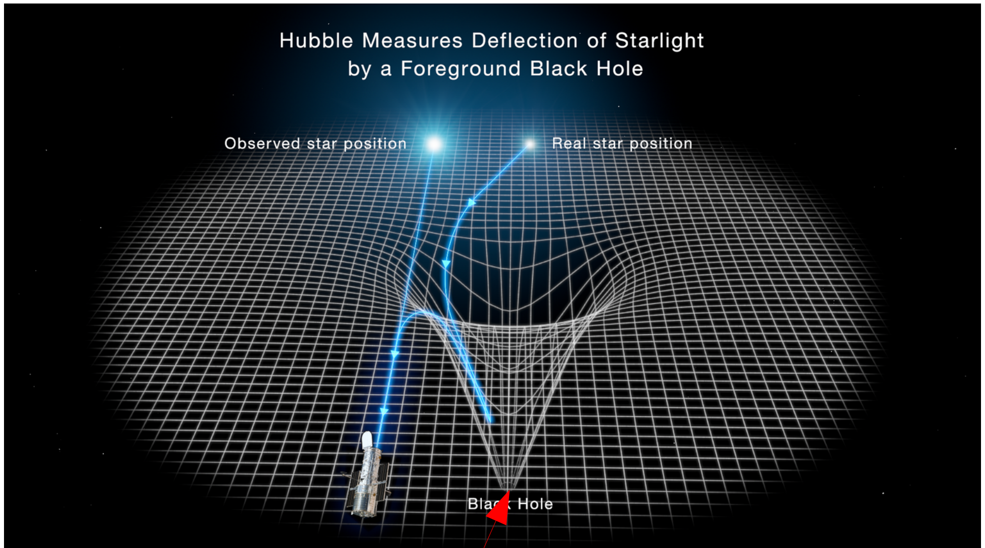

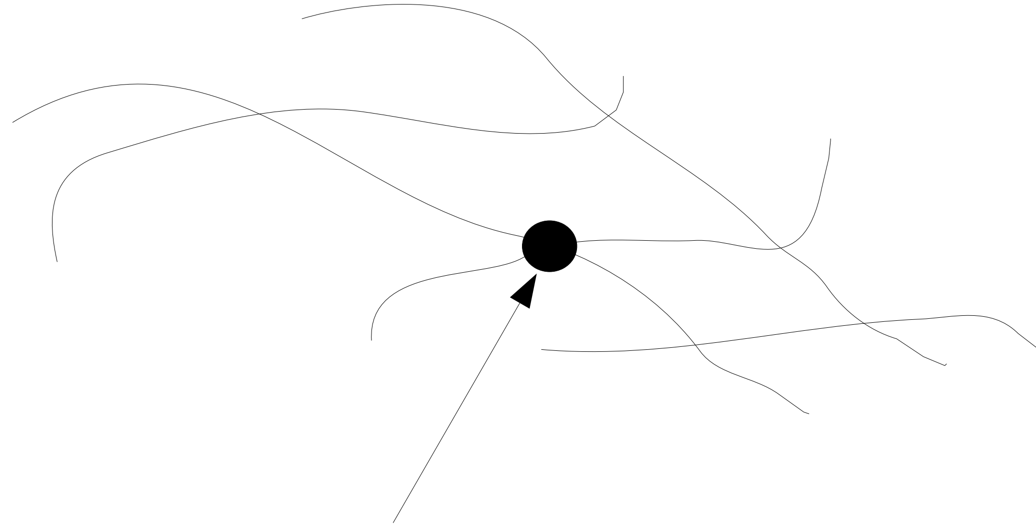

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$$\langle B(x)\rangle = d$$

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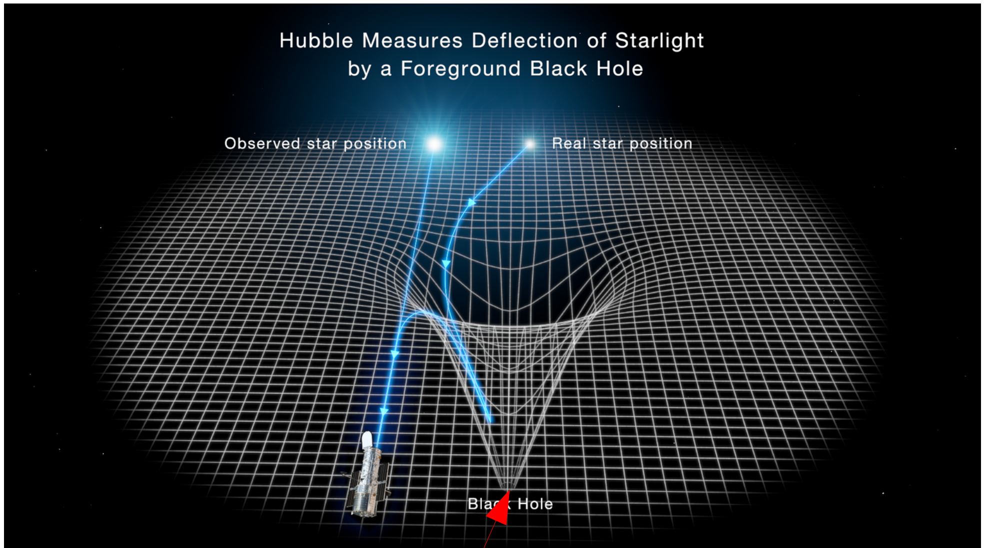

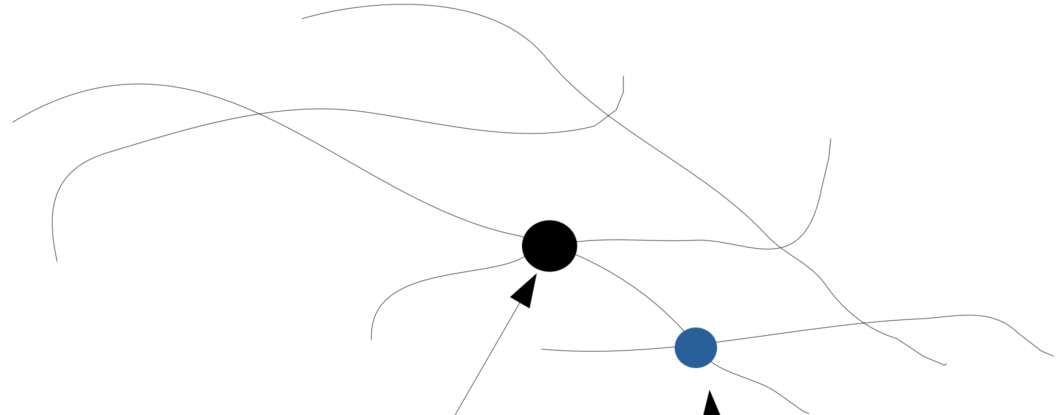

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Need to put a black hole creation operator at an event - but it would still be a constant

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]

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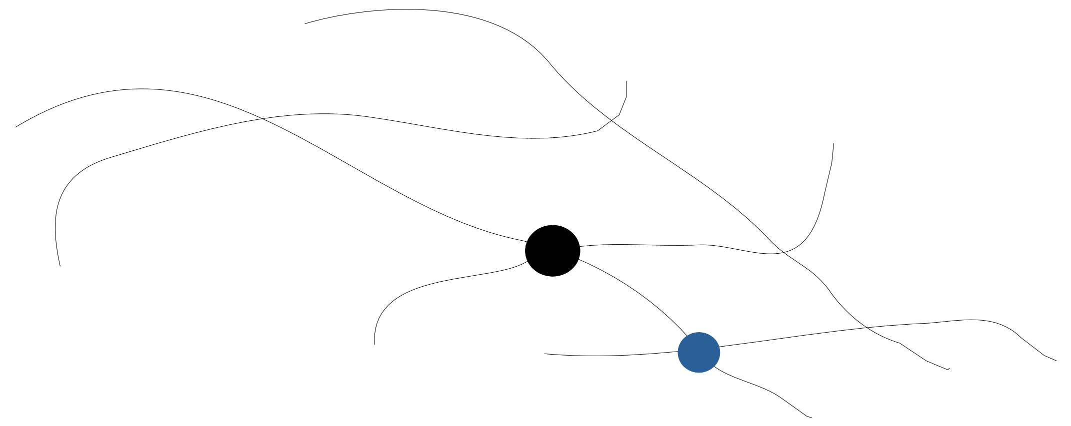

In FMS: Splitted further

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Views of black holes

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In FMS: Splitted further

(Small) fluctuations
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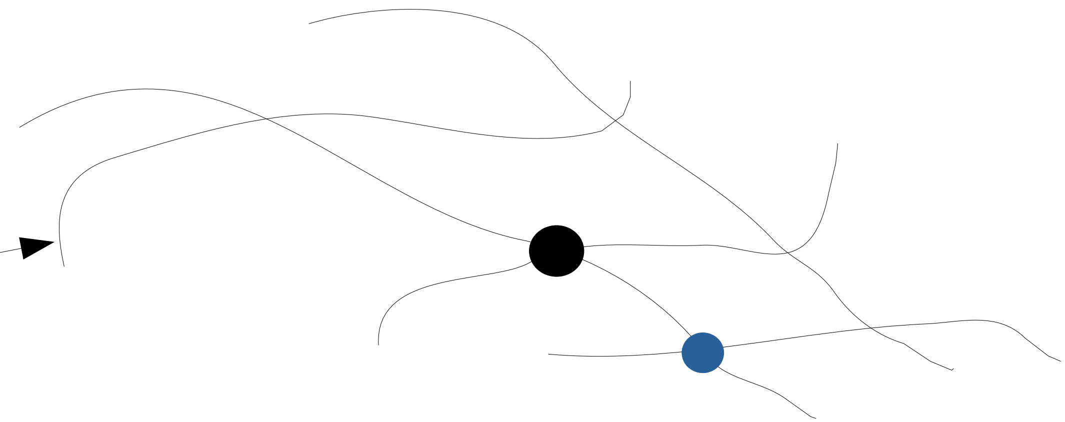
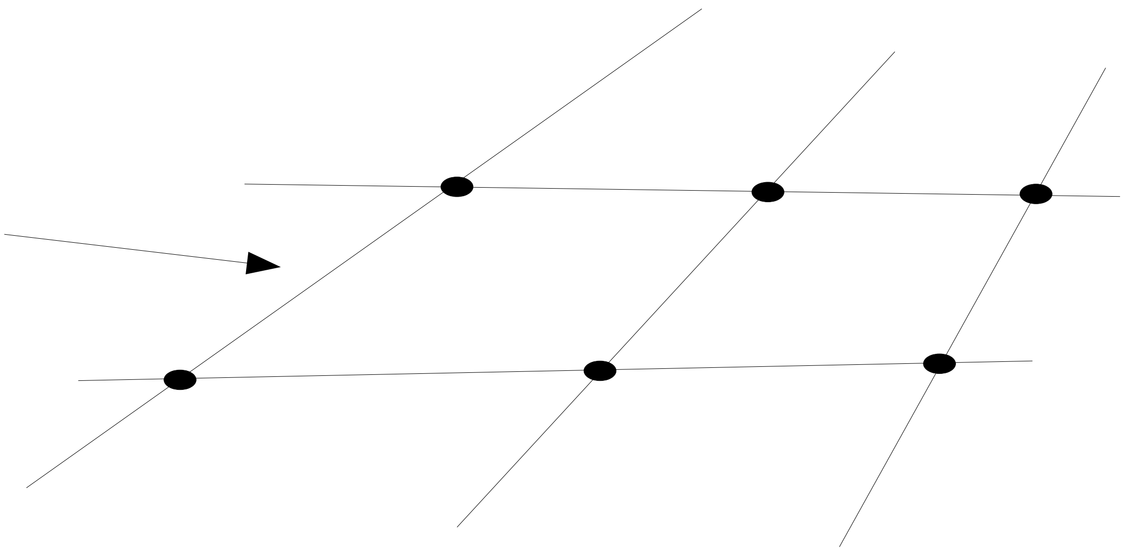


Expansion metric,
without preferred events



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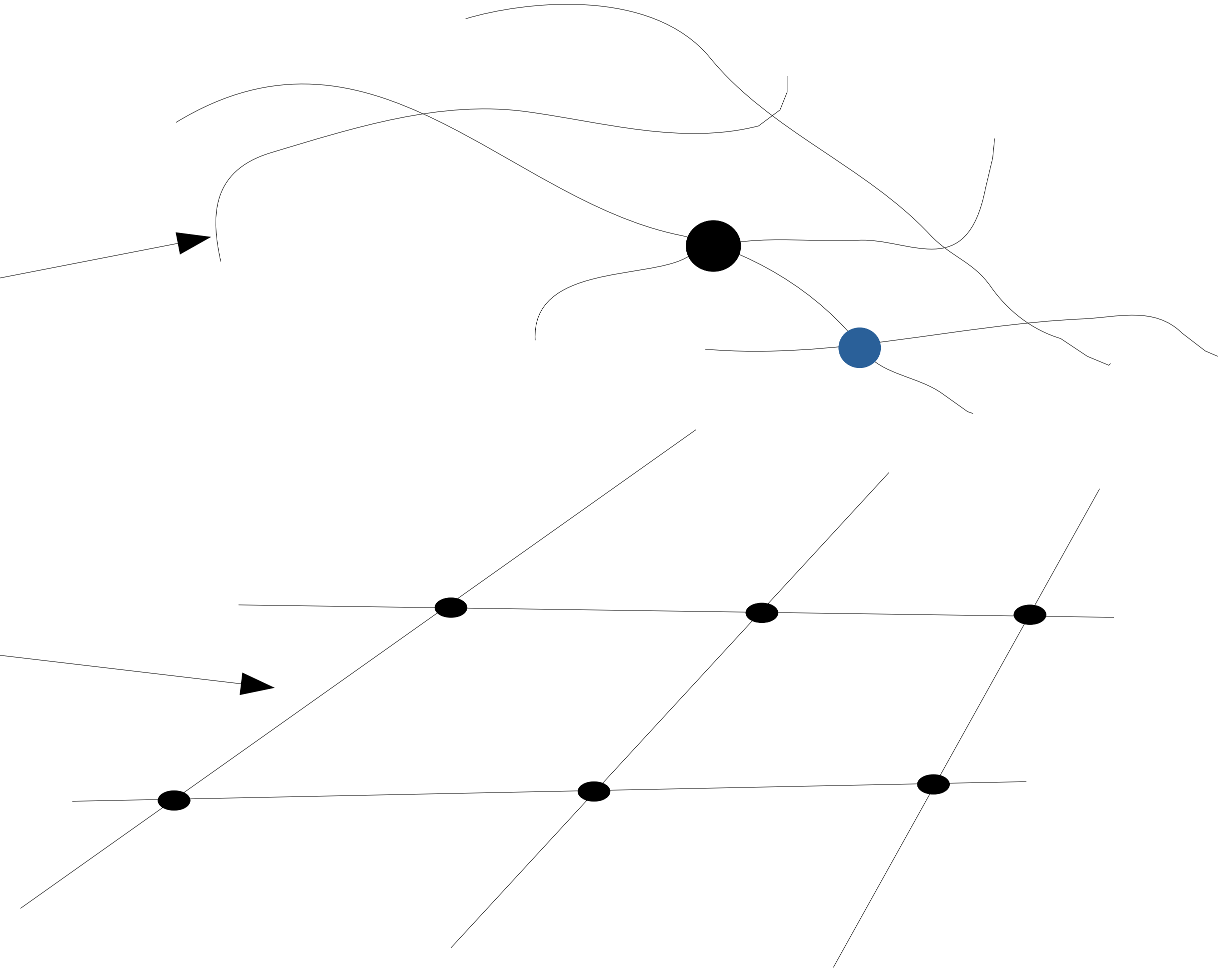

Expansion metric,
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Calculate expansion:

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

Classical field result

Speculative phenomenology

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  - Pure: Geon star, similar to neutron star

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

- Gives a new perspective on strong and quantum gravity

People involved

Christina Perner
(Bachelor)

Markus Markl
(Master)

Michael Müller
(Master)

Bernd Riederer
(PhD)

Simon Plätzer
(Staff)