Title: On a partially Reduced Phase Space Quantisation of General Relativity Conformally Coupled to a Scalar Field

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Abstract: We comment on a certain partially reduced phase space quantisation of general relativity conformally coupled to a scalar field, and its extension to standard model matter fields. The partially reduced phase space is reached by trading the Hamiltonian constraint for the generator of local conformal transformations on all phase space variables, inspired by the ideas of shape dynamics, and constructing conformally invariant connection variables. Furthermore, we review this trading of symmetries from the gauge fixing/unfixing perspective, which is dual to the concept of a linking theory. Finally we point out possible applications and open problems.

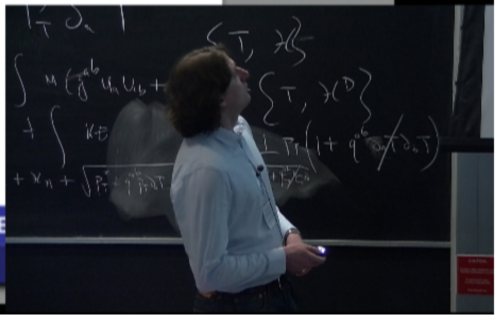
Content of the talk

Central topics

- Gauge fixing/unfixing [Mitra & Rajaraman, 1989, Anishetty & Vytheeswaran, 1993]
  as a dual picture to linking theories [Gomes & Koslowski, 2011]
- Application of the former to general relativity + matter
  using ideas from shape dynamics [Barbour, Gomes, Gryb, Mercati, Koslowski, 2011]
- Variables with simple conformal transformation behaviour
  ↳ Construction of a partially reduced phase space quantisation
  ↳ Extension to standard model matter
- Possible applications of the quantisation & open problems

Outline

1. Gauge fixing/unfixing
   - Gauge unfixing one part of the constraints
   - The role of observables
   - Trading dynamics
2. Gravity conformally coupled to a scalar field
   - Motivation & setup
   - Connection formulation & solution of the conformal constraints
   - Quantisation & observables
3. Extensions to standard model matter fields
   - Conformally invariant matter field actions
   - Scalar field potentials
   - Cosmological constant
4. Possible applications and open problems



Section outline

1. Gauge fixing/unfixing
   - Gauge unfixing one part of the constraints
   - The role of observables
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2. Gravity conformally coupled to a scalar field
3. Extensions to standard model matter fields
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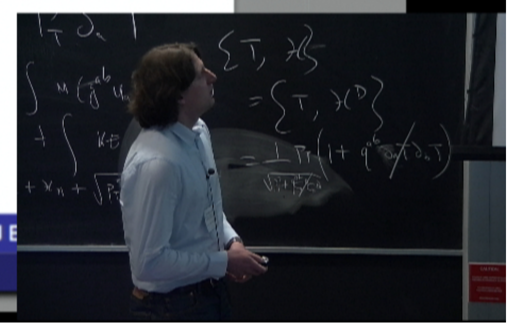


General setup for partial gauge fixing

Totally constrained, first class, irreducible system

- **Constraints** $\{\mathcal{H}[N, \vec{N}]\}$ $\longrightarrow$ **Section 2:** Dirac algebra

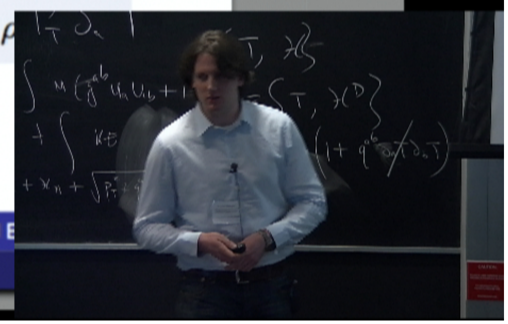
$$\{\mathcal{H}[N, \vec{N}], \mathcal{H}[N', \vec{N}']\} = \mathcal{H}(f^{\mathcal{H}}(p, q; N, N', \vec{N}, \vec{N}')) \quad (1)$$

- **Splitting** of the constraint $\{\mathcal{H}[N, \vec{N}]\} = \{\mathcal{H}[N], \mathcal{H}_a[N^a]\}$
- **Gauge conditions** $\{\mathcal{D}[\rho]\}$ for $\{\mathcal{H}[N]\}$

$$\{\mathcal{H}[N], \mathcal{D}[\rho]\} = (N, \underbrace{M}_{\text{Dirac matrix}} \rho), \; M \text{ invertible on "gauge cut"} \quad (2)$$

- **Invariance** of the gauge conditions under $\{\mathcal{H}_a[N^a]\}$

$$\{\mathcal{H}_a[N^a], \mathcal{H}[N]\} = \mathcal{H}[N^a \triangleright N], \qquad \{\mathcal{H}_a[N^a], \mathcal{D}[\rho]\} = \mathcal{D}[N^a \triangleright \rho$$



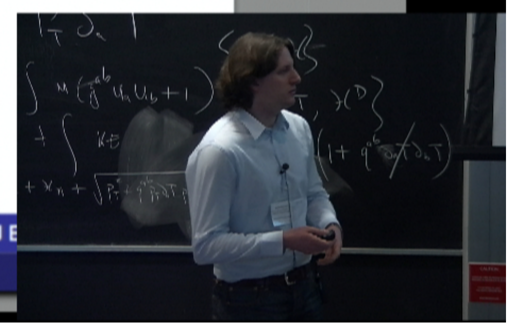
Gauge unfixing one part of the constraints

Additional structure of the gauge conditions

The gauge conditions are themselves first class functions

$$\{\mathcal{D}[\rho], \mathcal{D}[\rho']\} = \mathcal{D}(f^{\mathcal{D}}(p, q; \rho, \rho')). \tag{4}$$

Section 2: $\mathcal{D}$ = generator of local conformal transformations



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Section 2: $\mathcal{D}$ = generator of local conformal transformations

Crucial Observation

The two sets of phase space functions

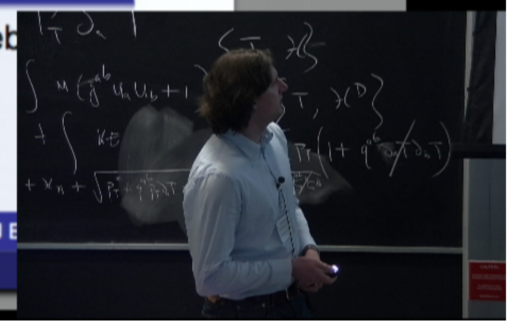
$$\{\mathcal{H}[N, \vec{N}]\} \text{ and } \{\mathcal{D}[\rho], H_a[N^a]\}$$

define the same reduced phase space, at least locally.

Conclusion?

$\mathcal{H}$-invariance can be traded for $\mathcal{D}$-invariance $\longrightarrow$ simplify the gauge algeb

Use $\{\mathcal{D}[\rho], H_a[N^a]\}$ as constraints!



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Dirac observables

Observables are defined as gauge invariant functions on the resp. constraint surfaces

$$\{\mathcal{H}[N], \mathcal{O}\} \approx 0, \; \{\mathcal{H}_a[N^a], \mathcal{O}\} \approx 0 \qquad \mathcal{H}\text{-observables} \qquad (5)$$

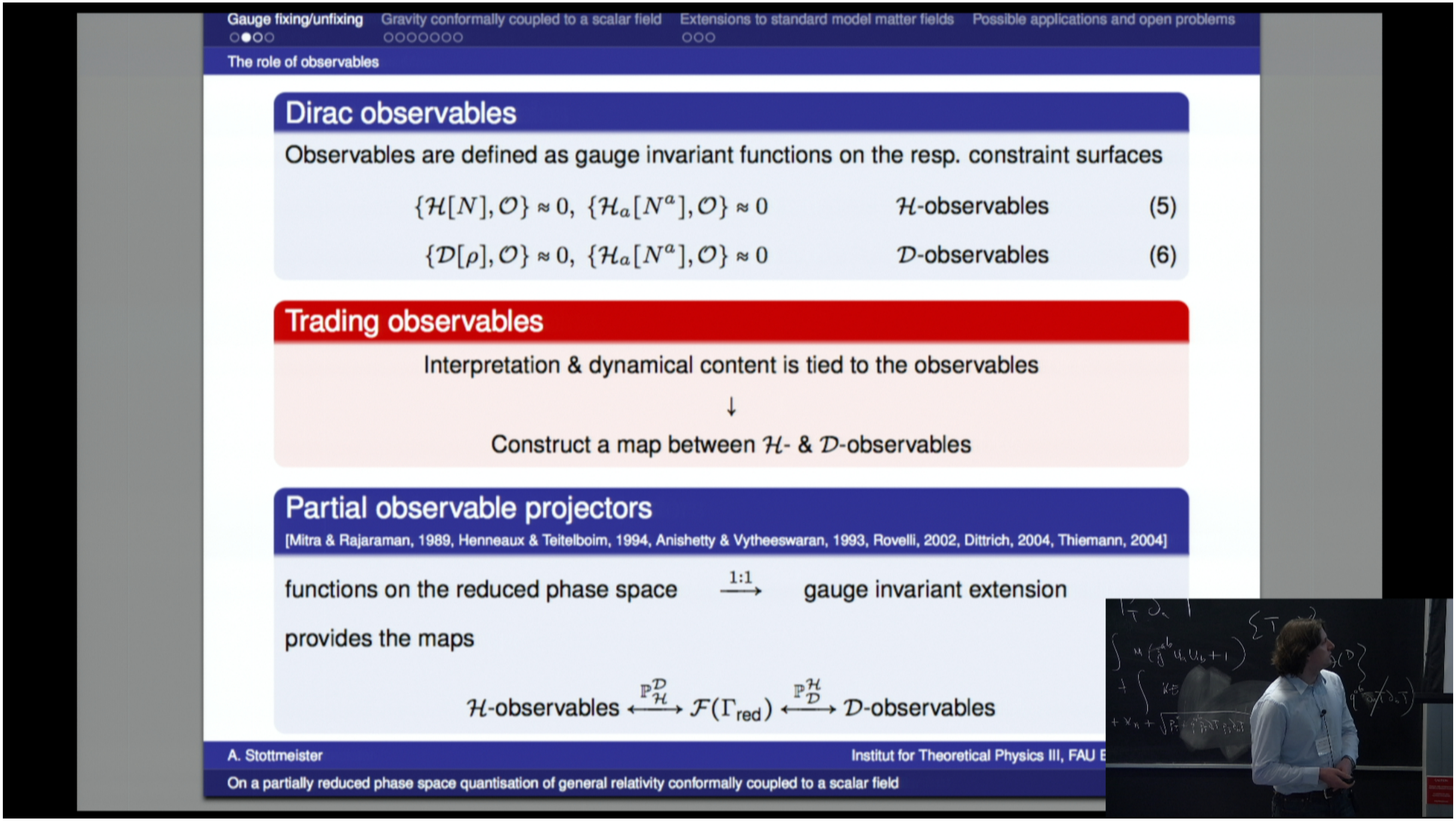
$$\{\mathcal{D}[\rho], \mathcal{O}\} \approx 0, \; \{\mathcal{H}_a[N^a], \mathcal{O}\} \approx 0 \qquad \mathcal{D}\text{-observables} \qquad (6)$$

Trading observables

Interpretation & dynamical content is tied to the observables

↓

Construct a map between $\mathcal{H}$- & $\mathcal{D}$-observables



Gauge fixing/unfixing
Gravity conformally coupled to a scalar field
Extensions to standard model matter fields
Possible applications and open problems
The role of observables
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Partial observable projectors
[Mitra & Rajaraman, 1989, Henneaux & Teitelboim, 1994, Anishetty & Vytheeswaran, 1993, Rovelli, 2002, Dittrich, 2004, Thiemann, 2004]
functions on the reduced phase space $\xrightarrow{1:1}$ gauge invariant extension
provides the maps
$\mathcal{H}$-observables $\xleftrightarrow{\mathbb{P}^{\mathcal{D}}_{\mathcal{H}}} \mathcal{F}(\Gamma_{\text{red}}) \xleftrightarrow{\mathbb{P}^{\mathcal{H}}_{\mathcal{D}}}$ $\mathcal{D}$-observables
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On a partially reduced phase space quantisation of general relativity conformally coupled to a scalar field

Explicit construction of $\mathbb{P}$

[Mitra & Rajaraman, 1989, Henneaux & Teitelboim, 1994, Anishetty & Vytheeswaran, 1993, Rovelli, 2002, Dittrich, 2004, Thiemann, 2004]

The projectors $\mathbb{P}$ can be given in terms of a power series. In short hand notation:

$$\mathbb{P}^{\mathcal{H}}_{\mathcal{D}}(f) = e^{-\{\mathcal{D}[\rho],\,.\,\}}(f)_{|\rho=M^{-1}\mathcal{H}}, \tag{8}$$

$$\mathbb{P}^{\mathcal{D}}_{\mathcal{H}}(f) = e^{\{\mathcal{H}[N],\,.\,\}}(f)_{|N=M^{-1}\mathcal{D}}. \tag{9}$$

- Allows for the construction of $\mathcal{D}$-observables from $\mathcal{H}$-observables!
- $\mathbb{P}$ is a (weak) Poisson isomorphism: $\{\mathbb{P}(\,.\,),\mathbb{P}(\,.\,)\} \approx \mathbb{P}(\{\,.\,,\,.\,\}^*)$!

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Possible caveat

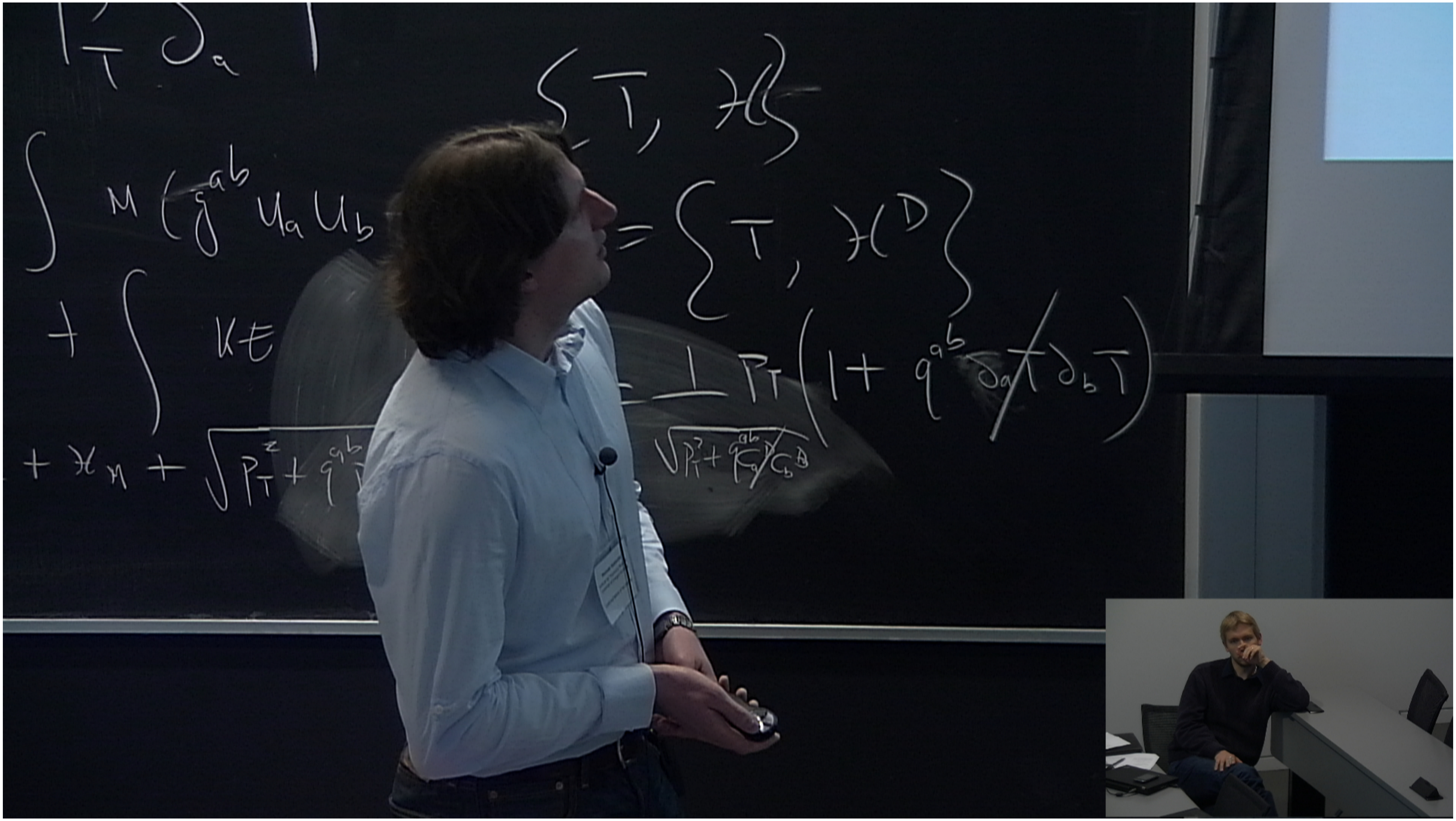
Only applicable if the constraints used for extension are first class!

$\downarrow$

Hamiltonian constraints in general relativity do not have this property.
$\hookrightarrow$ Only in combination with diffeomorphism constraints

$\Downarrow$

Inversion of the trading seems difficult $\longleftarrow$ no partial reduction through $\mathbb{P}^{\mathcal{D}}_{\mathcal{H}}$



Motivation & Setup $\mathcal{H}[N], \mathcal{H}_a[N^a]$ - Dirac algebra, $\mathcal{D}[\rho]$ - local conformal generator

Quantisation of shape dynamics

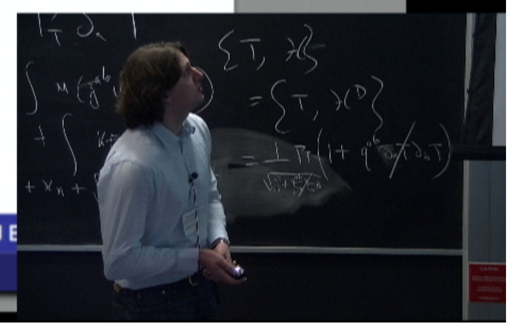
Problem: No connection formulation with simple conformal transformation behaviour

[pointed out to us by Sean Gryb at QGC 6]

↳ This is due to the affine part of the connection

↓

Find conformally invariant variables



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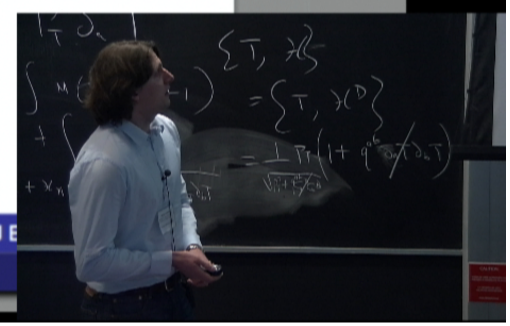
Elimination of the Hamiltonian constraint

Problem: Effective treatment of the Hamiltonian constraint in loop quantum gravity

↳ Use the ideas from shape dynamics to eliminate it completely.



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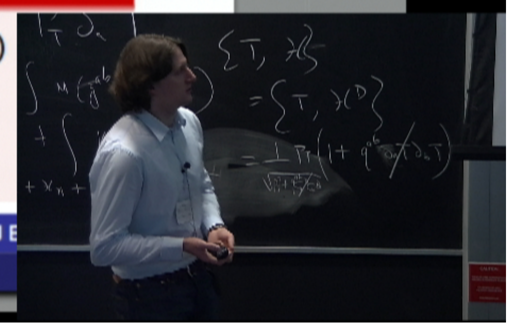
Important Observation

The metric variables (P^{ab}, q_{ab}) posses non-trivial conformal weights (Δ^P, Δ^q)

Idea: Couple a matter field Φ that also has non-trivial weight Δ^Φ.

↳ Check, if the conformal generator still acts as gauge fixing.



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$D+1$-split of the action

One gets

$$S = \int_{\mathbb{R}} dt \int_{\sigma} d^D x \left[P^{ab}\dot{q}_{ab} + \pi_\Phi \dot{\Phi} - N^a \mathcal{H}_a - N\mathcal{H} \right], \tag{15}$$

where $\mathcal{H}$, $\mathcal{H}_a$ generate the usual hypersurface deformation algebra.

Gauge fixing [Dirac, 1959], [Lichnerowicz 1944, Choquet-Bruhat 1962, Brill, York 1971, York & O'Murchadha, 1973, York & O'Murchadha & Isenberg 1976]

As in shape dynamics, we introduce the **gauge conditions**

$$\mathcal{D} := \Delta^q q_{ab} P^{ab} + \Delta^\Phi \Phi \pi_\Phi = \Delta^q \frac{1-D}{\kappa} \sqrt{q} q^{ab} K_{ab}, \tag{16}$$

which is the generator of local conformal transformations on the canonical variables.

This amounts to the choice of a maximal hypersurface

$$\mathrm{tr}_q K = 0, \tag{17}$$

only using $\mathrm{tr}_q K$ as a time function requires a CMC foliability.

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Dirac matrix

Leads to the **Dirac matrix**

$$\{\kappa\mathcal{H}[N], \mathcal{D}[\rho]\} = \kappa\mathcal{H}[...] + \mathcal{D}[...] \tag{18}$$

$$+ \int_\sigma d^D x \, (D-1)\sqrt{q}\Delta^q \rho[D_a D^a - \mathcal{P}(x)]N. \tag{19}$$

On the gauge cut: Quadratic form of an elliptic PDO.

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Invertibility of the Dirac matrix

(Local) admissibility of the gauge is determined by the elliptic PDE

$$[D_aD^a - \mathcal{P}(x)]N(x) = 0. \tag{20}$$

It is invertible if we assume the dominant energy condition for Φ.

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$\mathcal{P} > 0$ (strict positivity)

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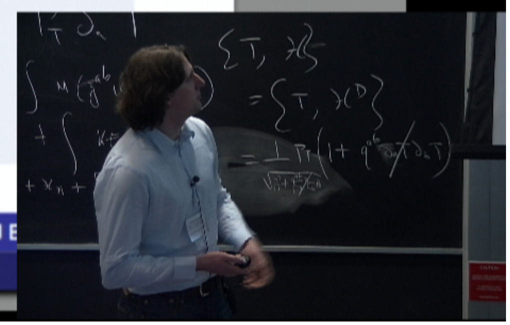


Connection formulation & solution of the conformal constraints

Invariant metric variables

Restricting to a $\Phi = e^{\phi}$ Dilaton-type field & rescaling the metric variables by the field

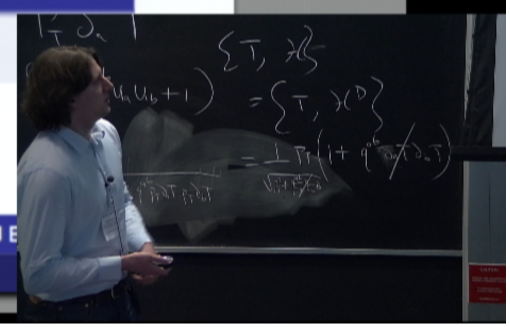
$$\{q_{ab}, P^{cd}, \Phi, \pi_{\Phi}\} \longrightarrow \{q_{ab},\ P^{cd}, \phi := \ln\Phi,\ \pi_{\phi} := \Phi\pi_{\Phi}\} \quad (21)$$

$$\{q_{ab}, P^{ab}, \phi, \pi_{\phi}\} \longrightarrow \{\tilde{q}_{ab} := e^{\frac{4}{D-1}\phi} q_{ab},\ \tilde{P}^{ab} := e^{-\frac{4}{D-1}\phi} P^{ab},\ \tilde{\phi} := \phi,\ \tilde{\pi}_{\tilde{\phi}} := \frac{1}{\Delta^{\Phi}}\mathcal{D}\} \quad (22)$$

we end up with invariant metric variables & $\mathcal{D}$ as the momentum of the scalar field $\tilde{\phi}$.

Remark

Opposite conformal weights of (q_{ab}, P^{ab}) require a Dilaton-type field



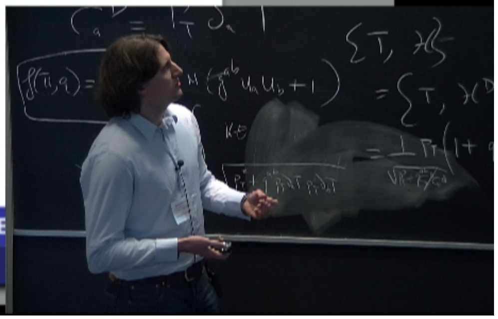
Quantisation & observables

Loop quantisation

Employ loop quantum gravity methods ⟶ physical Hilbert space

$$\mathfrak{H}_{\text{phys}} := \{\text{gauge \& diffeomorphism invariant spin networks}\} \tag{24}$$

↳ Obtain physical spectra of observables, solve non-dynamical problems



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Interpretation

Interpretation of a quantum $\mathcal{D}$-observable $\hat{\mathcal{O}}$

↓

Spectrum gives the measurement values for $\mathcal{O}$ at "time" $\mathcal{D} = 0$

Dynamics

Implementation of dynamics on the $\mathcal{D}$-observables so far only through $\mathbb{P}^{\mathcal{D}}_{\mathcal{H}}$

↳ But there is a clear geometric picture of the time $\mathcal{D}$.

Conformally invariant matter field actions

General structure

Given a conformally invariant matter field action

$$S = \int_{\mathbb{R}} dt \int_{\sigma} d^D x \, \left(P^{ab} \dot{q}_{ab} + \pi^I_{\varphi} \dot{\varphi}_I - N \mathcal{H}_{\varphi} - N^a \mathcal{H}_a - \lambda_i \mathcal{C}^i \right), \tag{25}$$

where the C^i denote gauge constraints of the field φ_I. We observe, that

- the conformal generator acquires new contributions

$$\mathcal{D} \longrightarrow \mathcal{D} + \Delta^{\varphi} \pi^I_{\varphi} \varphi_I \tag{26}$$

- the form of the Dirac matrix remains unchanged,
- the invertibility of the Dirac matrix follows along the same lines.

↳ Inclusion of Yang-Mills fields, $\underbrace{\text{fermions}}_{\text{spatial half densities}}$ $(\Delta = 0)$ & conf. coupled scalar multiplets

Observation

The model is flexible enough to include various matter fields.

Extension of the gauge fixing

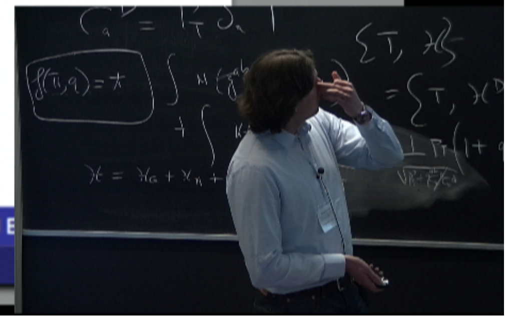
Replacing

$$\mathcal{D} \longrightarrow \mathcal{D} - \sqrt{q}\delta \tag{31}$$

allows to include arbitrary cosmological constant $\longrightarrow$ CMC-gauge ($q^{ab}K_{ab} = const.$).

Application to non-dynamical problems

- Spectra of observables $\longrightarrow$ Geometric operators acquire different interpretation
  ↳ **Symbolically:** $\hat{A}^{\text{inv}} = \Phi^2 \hat{A}^{\text{LQG}}, \quad \hat{V}^{\text{inv}} = \Phi^{2D/(D-1)} \hat{V}^{\text{LQG}}$
  ↳ Non-vanishing vacuum expectation $\langle \Phi \rangle$ might increase fundamental scale
- Black hole state counting $\longrightarrow$ isolated horizons framework extended to conformally coupled scalar field
  [Ashtekar et al., 2003, Ashtekar & Corichi, 2003]
  ↳ Interesting black hole solutions with non-trivial horizon topologies in locally asymptotically adS space-times [Nadalini et al., 2008]



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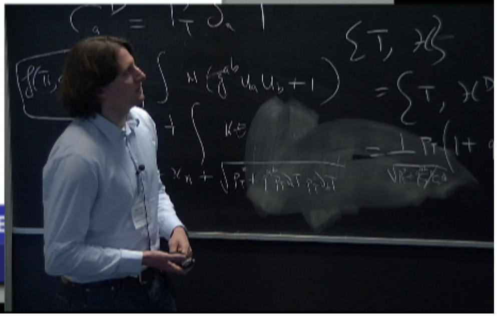

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Open problems

- Implementation of dynamics ⟶ deparametrisation not suitable
  - ↳ **Problem:** Clock variable $\mathcal{D}$ is not a space-time scalar [Kuchař, 1992]
- Construction of spatially diffeomorphism invariant observables
- Extension to asymptotically flat situations ⟶ canonical maximal time function
  - ↳ **Problem:** Gauge fixing of Supertranslations
  - ↳ ADM-Energy as natural generator of time-evolution
- Extension to supergravity?