Title: The Problem of Dynamics in Quantum Gravity

Date: Oct 29, 2004 10:00 AM

URL: http://pirsa.org/04100021

Abstract:

Physical Ramifications of Quantum Geometry

Dual goal:

- Introduction / Context for several presentations in the workshop
- Discuss a few recent developments

Emphasis: Can unravel a lot of interesting physics even though many issues open concerning dynamics of the full theory.

Organization

- Quantum geometry — Fleischhack, LOST
- Quantum cosmology — Bojowald, Singh, Vandersloot, Willis, Noui, Perez, AA, ---
- Quantum black holes — Domagala, Lewandowski, Meissner, Engle, Van Den Broeck, Bojowald, AA, ---

Quantum Geometry

- Spinors ; tetrads

  $S_P(e, \omega) = \frac{1}{4k} \int \epsilon_{IJKL}\, e^I \wedge e^J \wedge \Omega^{KL}$

  $\rightsquigarrow (E^a_i, K_a^i) \in \Gamma_{grav}$: Geometrodynamics

- Other forces of Nature : Connectiondynamics

  $S_H(e, \omega) = S_P - \frac{1}{2k\gamma} \int e^I \wedge e^J \wedge \Omega_{IJ}$

  $\rightsquigarrow (A_a^i, P^a_i) \in \Gamma_{grav}$ (SU(2)-connection) Rep(?)

- Relation: $E^a_i = 8\pi\gamma\, P^a_i$; Riem Geo

  $\gamma K_a^i = A_a^i - \Gamma_a^i$

- Techniques from gauge theories:

  elementary variables
  - Holonomies : $h_e(A)$
  - 'Electric fluxes' : $P_{S,t} = \int_S t_i\, {}^*P^i$

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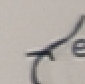
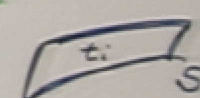
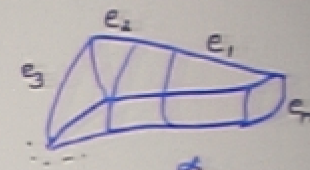




Quantum Kinematics:

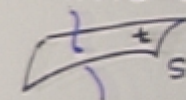


- configuration variables

$F_\alpha(A) = f(h_{e_1}(A), \dots, h_{e_n}(A))$

Holonomy (unital C^*)algebra : $\overline{\text{Cyl}}$.

- Momenta : $P_{S,t}$ define derivations on $\overline{\text{Cyl}}$
(~ Action of VFs)



Fundamental assumption of LQG:
Quantization based on this type of Algebra

Very surprising recent result:

- Quantum algebra $\hat{\mathfrak{a}}$ generated by $\hat{F}_\alpha$, $\hat{P}_{S,t}$ admits a unique diff-invariant state.

(Lewandowski, Okolow, Sahlmann, Thiemann; Fleischhack)

- Chronology

- Contrast with reps of CCR in Minkowskian QFTs. $\underbrace{\text{Diff invariance}}_{\updownarrow}$ qualitatively different

Absence of background geometry

Fleischhack

Piecewise C^ω

Sub-analytic, Finite-Widely triangulated

stratified Analytic

onomies

onentiated electric fluxes

Algebra, C^*;

$e^{i\mu\hat{p}}$ in QM]

↳ (Weak-continuity)

f-inv. state s.t. on

ting rep, Diff acts

LOST

(Lewandowski - Okolow - Sahlmann - Thiemann)

Piecewise C^ω

" same "

" same "

Holonomies

Electric Fluxes

"Mixed" Algebra, $*$-Alg

[Ex: $e^{i\widehat{\lambda x}}$, $\hat{p}$ in QM]

Unique Diff invariant state.

Rep obtained by GNS - construction:

common domain for all Flux operators

Fleischhack

LOS
(Lewandowski- O

holonomies:
Edges

Piecewise C^ω

Piec

Momentum Fluxes:
Surfaces

Sub-analytic, Finite-Widely triangulated

Symmetries:
Diffeos

Stratified Analytic

Algebra

Holonomies
Exponentiated electric fluxes

"Weyl" Algebra, C^*;

[Ex: $e^{i\hat{\lambda x}}$, $e^{i\hat{\mu p}}$ in QM]

↳ (Weak-continuity)

Ele
"Mix
[Ex: $e^{i\hat{\lambda x}}$

Reps:

Unique Diff-inv. state s.t. on the resulting rep, Diff acts 'naturally'.

Unique Di
Rep obtain
construct
Common do
Flux ope

eischhack	LOST (Lewandowski-Okolow-Sahlmann-Thiemann)
Piecewise C^ω	Piecewise C^ω
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2. Application: Quantum Cosmology

(Bojowald)

- symmetry reduction (Ex: Hom Isotropic)

  $A_a^i = c\, \mathring{e}_a^i$ $\qquad P^a_i = p\sqrt{q^o}\; \mathring{e}^a_i$

  scale factor: $a^2 = |p|$; curv $\sim 1/a^n$

- Follow procedure from full theory

  $\hat{h}_\mu = \widehat{\exp i\mu c}$ well-defined but not $\hat{c}$

  $\mathcal{H} = L^2(\bar{R}_{Bohr}, d\mu_o)$

  (AA, Bojowald, Lewandowski)

  New quantum mechanics inequivalent to std QGD Dramatic consequences

- curvature unbounded classically

  QGD: $\hat{a}$ SA ; $\hat{a}^{-1}$ SA unbounded

  Here: $\hat{p} = \circ\ell_p^2 \sum_\mu |\mu\rangle \mu \langle\mu|$; $\langle\mu|\mu'\rangle = \delta_{\mu'\mu}$

  $1/\mu$ not a measurable f^n on $Sp(\hat{p})$

  Naive $\hat{p}^{-1}$ not SA (not even dd)

- $\widehat{p^{-1}}$ defined using strategy from full theory (Thiemann)

  properties:

  - Commutes with $\hat{p}$
  - Eigenvalues $\sim 1/\circ\mu$ when $a \gtrsim 10^2\,\ell_p$
  - Important deviations in the deep Planck regime: operator is bounded above!

    Bound $= \left(\frac{12}{8\pi}\right)\frac{1}{G\hbar}$ $\sim 10^{55} \times$ curv at the horizon of $1 M_\odot$ BH

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- Recall H-atom $E_o = -\frac{me^4}{2\hbar^2}$

Quantum Evolution

- Q. Einstein Eq : Hamiltonian Constraint

$$|\Psi\rangle = \sum \underbrace{\psi_\mu(\phi)}_{\text{Matter}} \underbrace{|\mu\rangle}_{\text{geometry}}$$

$$C_+ \psi_{\mu+4\mu_0}(\phi) + C\psi_\mu(\phi) + C_- \psi_{\mu-4\mu_0}(\phi) = \hat{H}_\phi \psi_\mu(\phi)$$

can be interpreted as an evolution equation in discrete time steps.

$\left.\begin{array}{l} C_-(\mu,\mu_0) \\ C_+(\mu,\mu_0) \end{array}\right\}$ such that evolution does not stop @ $\mu = 0$

singularity resolved, but classical space-time "dissolves" in the deep Planck regime. only quantum state meaningful.

2 • Semi-classical corrections to Friedmann Eq (AA, Bojowald, Willis)

- Non-trivial issue: Semi-classical behavior at arbitrarily large late times
- Conceptually important test of Thiemann-type regularization (in the limited context of quantum cosmology). For example: There is propagation
- Einstein's eqns do get corrections in LQG

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2.3 : New issues raised by Green & Unruh
"Difficulties with closed isotropic LQC"

Issue:

- No 'problem' with the open case.
- Spatial topology S^3 $(k=1)$, Massless scalar field

Sol^{ns} to the Hamiltonian constraint which are also eigenfunctions of scalar field energy (numerically) diverge after a finite no of steps.

Interesting issues raised but no obvious 'difficulty' so far (because of our incompleteness)

→ Physical states in Cyl*. Sol^{ns} may be in Cyl* i.e. genuinely distributional.

→ Not using self-adjoint constraint, cannot ask if there are 'physical' infinities.

→ Semi-classical states SHOULD be constrained but unclear if eigenstates of energy are such states.

BUT burden on us to show there is no problem!
Need to complete the quantization program.

STATUS :

2.4 • Willis (+AA+MB) : Natural SA constraint does exist. Descends from full theory. Again singularity resolved for std matter.

open issues:

compact case, explicit solutions ?

Group averaging a physical Hilbert space?

2.5 • Vandersloot (+ Novi + Perez) : One example.

open model, no Scalar field but Λ.

No true degrees of freedom $\rightsquigarrow$ Phys. H.S. 1 dim?

Yes! Group Averaging ✓

Physical state $\in \mathcal{H}_{kin}$!

Nothing diverges

(Caution:

Factor ordering arrived at using Euclidean Plebanski action. unclear if it can be easily extended to genuine matter (in −+++ domain)

3. Quantum BHs

3.1 : Correction of the ABK counting.

- Horizon quantum geometry ✓
- Idea of CS surface states ⇝ Entropy ✓ $= \ln \mathcal{N}$
- ABK lower bound on $\mathcal{N}$ fine but upper bound incorrect. Thus ABK undercounted $\mathcal{N}$ ⇒ B-I parameter γ changed from 0.1274... to 0.2375...

  (Domagala & Lewandowski; Meissner)

Wheeler's It from Bit
Only partial answer
($j > \frac{1}{2}$ contributions)

BH evaporation
Transitions much richer not just a equidistant line spectrum

Quasi-normal Scenario even less plausible physically.

- [illegible] new possibility (AA-Meissner)

[illegible] ensemble of [illegible]

Meissner's [illegible] equation for γ interpreted as vanishing of the chemical potential

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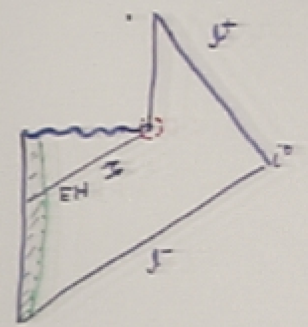
- Attractive new possibility (AA + Meissner)

BH ⟷ Ensemble of punctures

Meissner's algebraic equation ~~for~~ γ interpreted as vanishing of the chemical potential

punctures ⟷ photons, Matter quanta   conversion

Issue of Information



standard scenario

- QFT in CST + Heuristics of back reaction

Limitations:

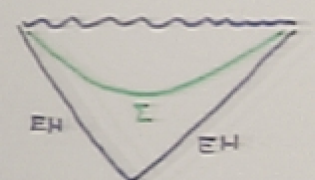
Cannot trust this diagram

i) near the entire singularity

ii) role of event horizon : Global concept

Quantum geometry effects near singularity

Hint : Schwarzschild interior (KS mini superspace)



Σ : $S^2 \times \mathbb{R}$, homogeneous

2 DoF : radius of S^2 : μ
anisotropy : ϕ

Results (AA + Bojowald; Modesto)

- co-triad operator bounded above
- \`Evolution' : $\mu$ as \`time'

$$|\Psi\rangle = \sum_\mu \psi_\mu(\phi)\, |\mu\rangle$$

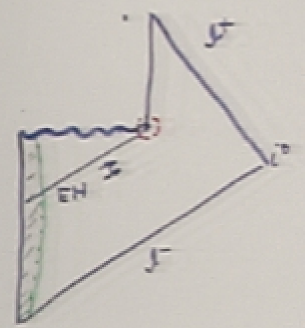
Hamiltonian constraint → Difference eq^n on $\psi_\mu(\phi)$

"Time evolution in discrete steps"

coefficients such that singularity resolved.

But classical space-time "dissolves"

Issue of Information Loss (AA+Bojowald)



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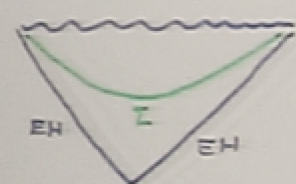

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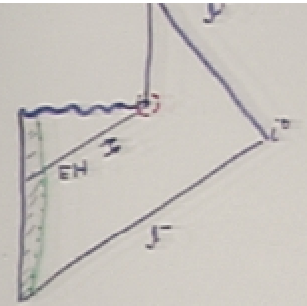

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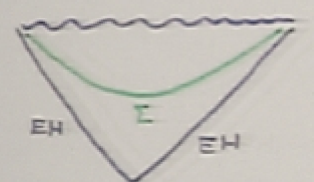

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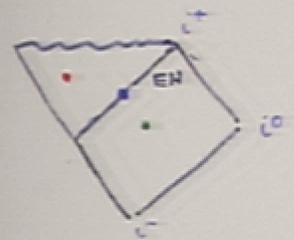
Dynamical horizons

AA + Krishnan

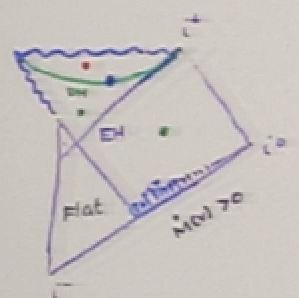


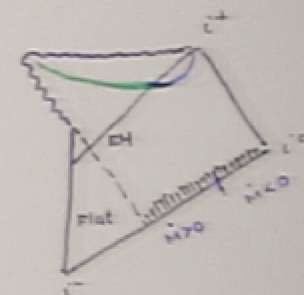
Eternal black hole

- untrapped
- marginally trapped
- Trapped

Dynamical situations : A DH is $S^2 \times \mathbb{R}$, foliated by MTs ($\Theta_{(\ell)} = 0$, $\Theta_{(n)} < 0$) .

Ex : Vaidya solutions (spherical ; null fluid)





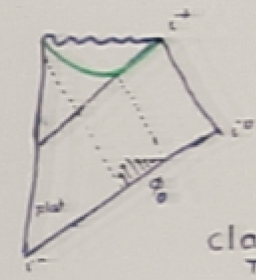
DH:	Space-like	Time-like
Area of MTs	Increases	Decreases
Energy flux	+ve	−ve

Integral generalization of first law holds on general DHs

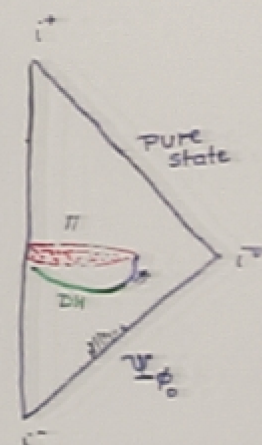
BH evaporation: A possible, consistent paradigm

- Gather these precise results to develop a qualitative heuristic picture within LQG.

- spherical collapse of a scalar field: Large BH



Classical Theory



LQG

Deep Planck regime
No classical space-time

Assumptions:

1) Full quantum state becomes Semi-classical again

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qualitative heuristic picture within LQG.

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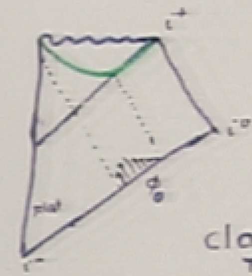

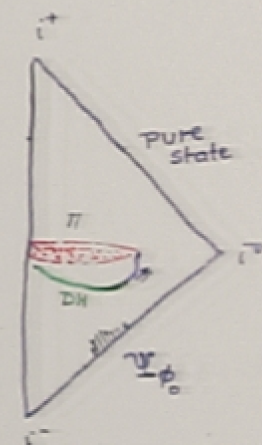

Deep Planck regime
No classical space-time

Assumptions:

i) Full quantum state becomes Semi-classical again

ii) QDH ~ QIH when area $\gg \ell_P^2$
(slow evaporation regime)

• Gather these precise results to develop a qualitative heuristic picture within LQG.

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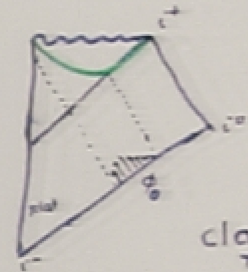
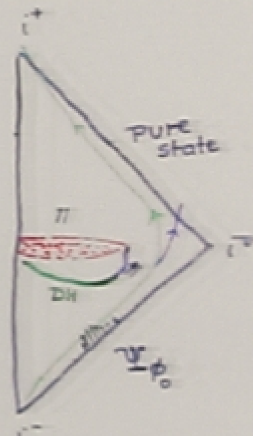


classical Theory

• Space-time does not end in a singularity ⇒ No sink of information.

• pure states on $\mathcal{I}^-$ ⇝ pure states on $\mathcal{I}^+$

• 'Event horizon': No longer a useful notion



LQG

• DHs form in semi-classical region and evaporate.

$$\frac{dR}{dt} = -8\pi G R^2 \cdot T_{ab} \ell^a \hat{r}^b$$

Area Quanta ⇝ ϕ quanta

• Recovery of correlations (patience!)

::: Deep Planck regime
No classical space-time

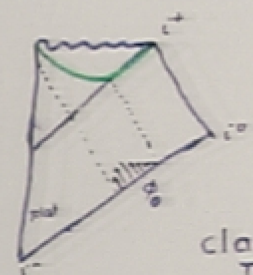
Assumptions:

i) Full quantum state becomes Semi-classical again

ii) QDH ~ QIH when area $\gg \ell_P^2$
(slow evaporation regime)

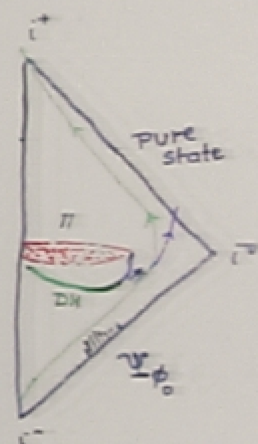
- Gather these precise results to develop a qualitative heuristic picture within LQG.

- spherical collapse of a scalar field: Large BH



classical Theory

- Space-time does not end in a singularity $\Rightarrow$ No sink of information.
- pure states on $\mathscr{I}^-$ $\rightsquigarrow$ pure states on $\mathscr{I}^+$
- 'Event horizon': No longer a useful notion



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Summary:

Even though we do not have a satisfactory treatment of full quantum dynamics, we can address a number of important conceptual issues.

Progress since the last conference in this series 9 months ago is substantial. Solutions to problems which were open & brand new developments

These in turn provide new challenges and great opportunities in the form of concrete new problems as in quantum cosmology as well as brand new directions as in quantum black holes.

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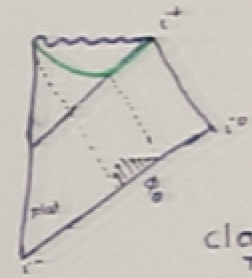

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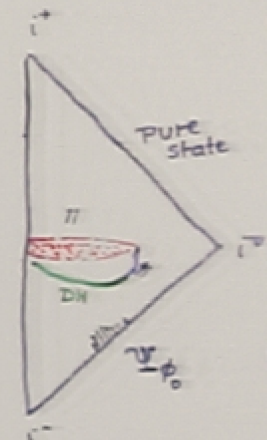

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