Title: Quantum reference systems: Where foundations meets gravity

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Abstract: Quantum foundations and (quantum) gravity are usually considered independently. However, I will demonstrate by means of quantum reference systems how tools and perspectives from quantum gravity can help to solve problems in quantum foundations and, conversely, how quantum foundation perspectives can be useful to constrain spacetime structures.
First, I will show how one can derive transformations between quantum reference frames from a gravity inspired symmetry (essentially Machâ€™s) principle. This principle enforces a perspective neutral theory in which choosing the perspective of a specific frame becomes a choice of gauge and all physical information is relational. This setting enables one to derive and generalize, from first principles, frame transformations that have been proposed earlier in the foundations literature. Moreover, the framework extends to the relational paradigm of dynamics, familiar from quantum gravity, and thereby provides a unifying method for changes of perspective in the quantum theory, incl. changes of both spatial and temporal quantum reference systems.
Subsequently, I will take a quantum information inspired perspective on frame synchronization and transformations. Without presupposing specific spacetime structure, I will exhibit how the Lorentz group follows from operational conditions on quantum communication, exemplifying how quantum information protocols can constrain the spacetime structures in which they are feasible.

Quantum reference systems: Where foundations meets gravity

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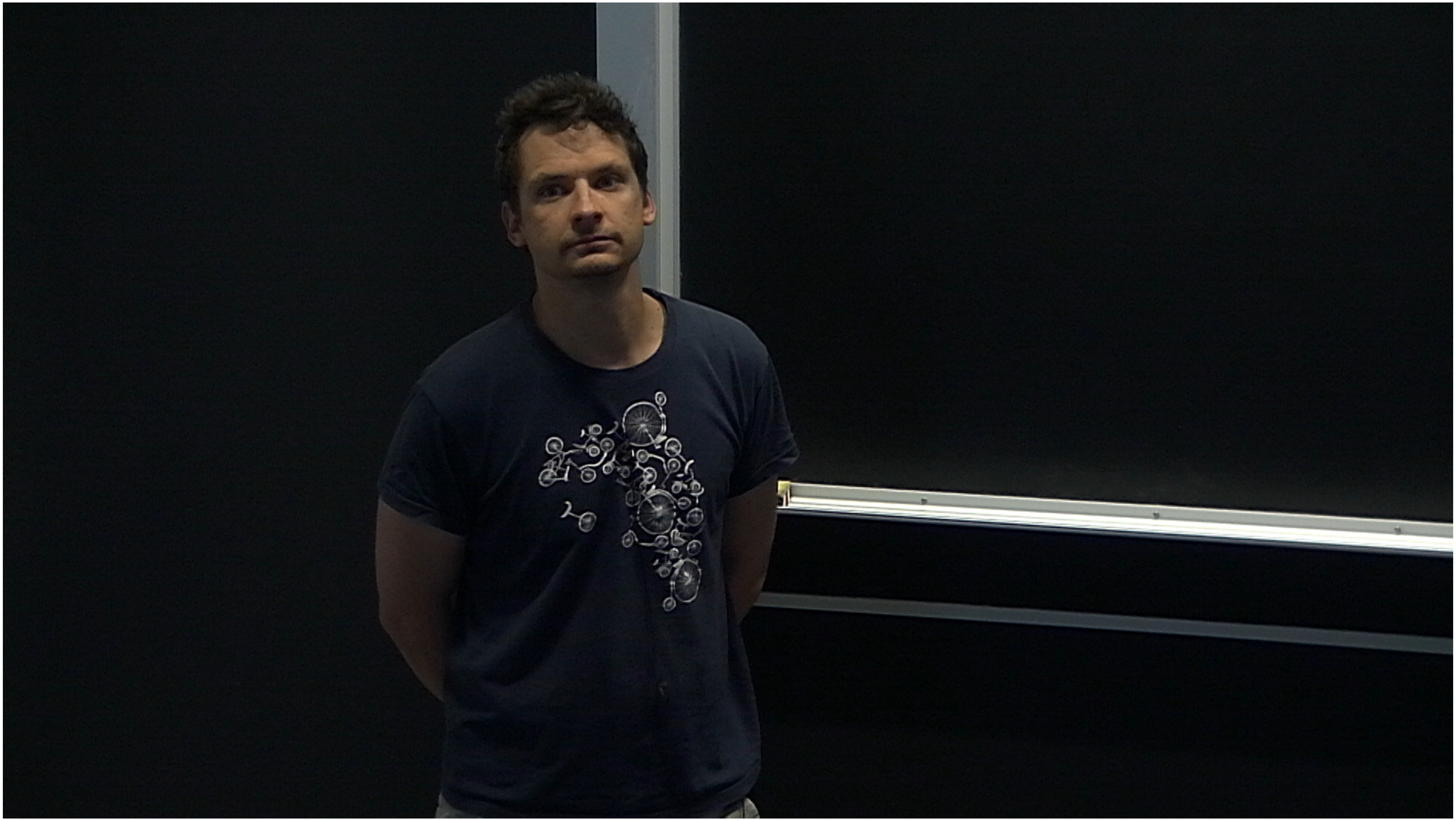
Foundations of Quantum Mechanics
Perimeter, 2018

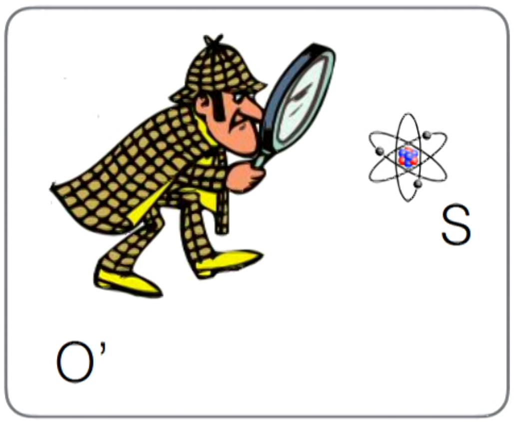


The observer observed

Universality of QT

O

Wigner friend scenario



how do you change perspective?

- external reference?
- perspective neutral super structure?

Perspective on perspectives

Perspective: Physics $\longrightarrow$ description

Perspective on perspectives

perspective neutral

$$\varphi : \ \mathcal{S}_{\text{phys}} \longrightarrow \mathcal{S}_{\text{des}}$$

Examples:

spatial velocities	$\longrightarrow$	$\mathbb{R}^3$
GR/spacetime	$\longrightarrow$	$\mathbb{R}^4$ (locally)
quantum states	$\longrightarrow$	density matrices
$\mathcal{H}_{\text{phys}}$	$\longrightarrow$	$\mathcal{H}_{\text{red}}$

$$\vdots$$

φ usually associated with reference frame

perspective change: $T_{A\to B} = \varphi_B \circ \varphi_A^{-1}$

Perspective on perspectives

perspective neutral

$$\varphi : \mathcal{S}_{\text{phys}} \longrightarrow \mathcal{S}_{\text{des}}$$

Examples: spatial velocities $\longrightarrow$ $\mathbb{R}^3$

GR/spacetime $\longrightarrow$ $\mathbb{R}^4$ (locally)

quantum states $\longrightarrow$ density matrices

$\mathcal{H}_{\text{phys}} \longrightarrow \mathcal{H}_{\text{red}}$

$\vdots$

φ usually associated with reference frame

via persp. neutral structure

perspective change: $T_{A\to B} = \varphi_B \circ \varphi_A^{-1}$

learn a lot about Physics through relations of perspectives —> symmetries

QF meets (Q)G

now focus on quantum reference systems
and perspective changes in the QT

new perspectives for both QF & (Q)G

Part I

perspective neutral ➡ internal perspectives

symmetry principle ⟶ frame transf. ⟶ operational consequences

makes physics relational

AIM:
unifying framework for switches of temporal and spatial quantum reference systems

Part II

perspective neutral? ⟵ internal perspectives

symmetry principle? ⟵ frame transf. ⟵ operational conditions

AIM:
operationally constrain
spacetime structure
—> rebuild perspective neutral description

Part I

perspective neutral → internal perspectives

relational clock changes via perspective neutral QT

Bojowald, PH, Tsobanjan, CQG 28,035006, (2011)
Bojowald, PH, Tsobanjan, PRD 83,125023 (2011)
PH, Kubalova, Tsobanjan, PRD 86, 065014 (2012)

QRF transformations

Giacomini, Castro-Ruiz, Brukner arXiv:1712.07207

AIM:
unifying framework for switches of temporal and spatial quantum reference systems

with A. Vanrietvelde, F. Giacomini, E. Castro-Ruiz, C. Brukner forthcoming

Toy model: Mach's principle in 1D

$$L = \frac{1}{2}\left(\dot{q}_A^2 + \dot{q}_E^2 + \dot{q}_F^2\right) - \overbrace{\frac{1}{6}\left(\dot{q}_A + \dot{q}_E + \dot{q}_F\right)}^{E_{\rm kin}^{\rm cm}} - V(\{q_a - q_b\})$$

L invar. under translations $\quad q_a, \dot{q}_a \mapsto q_a + f(t), \dot{q}_a + f'(t)$

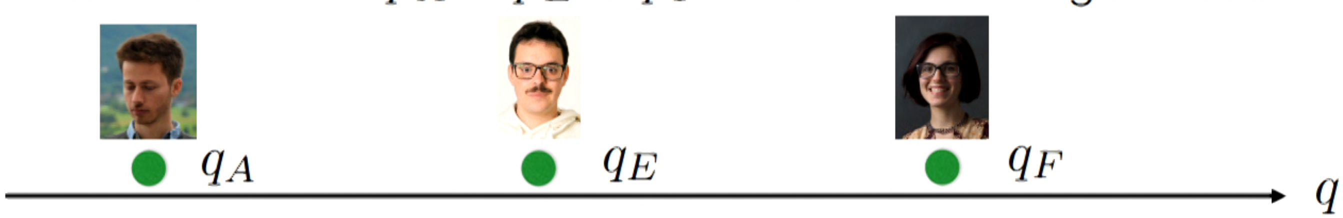
Legendre tr. $\downarrow$

arbitrary

$$H = \frac{1}{2}\left(p_A^2 + p_E^2 + p_F^2\right) + V(\{q_a - q_b\}) + \lambda P$$

Localization in Newtonian space unphysical, only relational motion

Constraint $\quad P = p_A + p_E + p_F \approx 0 \quad$ translation generator



Choosing perspective = choosing gauge

gauge symmetry: $q_a(t)$ not physical

gauge inv. observables: $(q_E - q_A), (q_F - q_A), (q_E - q_F), p_A, p_E, p_F$

$\Rightarrow$ commute with $P = p_A + p_E + p_F$

perspective neutral description

$\Rightarrow$ but redundant (only 4 indep. gauge inv. obs)

- fix symmetry, **take A perspective** $q_A = 0$ (fixes $\lambda = -p_A$ so that $\dot{q}_A = 0$)

  $(q_{E,F} - q_A) \mapsto q_{E,F}$ become rel. distance to A

- Hamiltonian reduces to

$$H_{EF|A} = p_E^2 + p_F^2 + p_E p_F + V(q_E, q_F)$$

$\Rightarrow$ **switching to F-perspective is gauge transformation**

Reduced quantization: QT in A-perspective

- quantize reduced class. model in A-perspective

$$[\hat{q}_{E,F}, \hat{p}_{E,F}] = i \qquad \text{on} \qquad \mathcal{H}_{EF|A} = L^2(\mathbb{R}^2)$$

with Hamiltonian

$$\hat{H}_{EF|A} = \hat{p}_E^2 + \hat{p}_F^2 + \hat{p}_E\hat{p}_F + V(\hat{q}_E, \hat{q}_F)$$

Dirac quantization - perspective neutral

- quantize 1st on $\mathcal{H}_{\text{kin}} = L^2(\mathbb{R}^3)$ solve constraint in QT

$$\hat{P}|\psi\rangle_{\text{phys}} = (\hat{p}_A + \hat{p}_E + \hat{p}_F)|\psi\rangle_{\text{phys}} = 0$$

Projection $\Pi : \mathcal{H}_{\text{kin}} \to \mathcal{H}_{\text{phys}}$

$$|\psi\rangle_{\text{kim}} \mapsto \delta(\hat{P})|\psi\rangle_{\text{kin}} = \frac{1}{2\pi}\int ds\, e^{is\hat{P}}\, |\psi\rangle_{\text{kin}}$$

concretely $|\psi\rangle_{\text{kim}} = \int dp_A dp_E dp_F\, \psi_{\text{kin}}(p_A, p_E, p_F)|p_A, p_E, p_F\rangle$

$$\mapsto |\psi\rangle_{\text{phys}} = \int dp_E dp_F\, \psi_{\text{kin}}(-p_E - p_F, p_E, p_F)\,| - p_E - p_F, p_E, p_F\rangle$$

- need new inner prod.

$$(\phi, \psi)_{\text{phys}} := \langle\phi|\delta(\hat{P})|\psi\rangle_{\text{kin}}$$

- observables on $\mathcal{H}_{\text{phys}}$ $[\hat{O}, \hat{P}] = 0$ e.g. $\hat{q}_a - \hat{q}_b, \hat{p}_a$

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- need new inner prod.

$$(\phi, \psi)_{\text{phys}} := \langle\phi|\delta(\hat{P})|\psi\rangle_{\text{kin}}$$

- observables on $\mathcal{H}_{\text{phys}}$ $\quad [\hat{O}, \hat{P}] = 0 \quad$ e.g. $\quad \hat{q}_a - \hat{q}_b, \hat{p}_a$

Go to A-perspective in QT

- remove redundant A-variables with isometry to red. QT

$$\mathcal{T}_A := e^{i\hat{q}_A(\hat{p}_E+\hat{p}_F)}$$

$$\Rightarrow \quad |\psi\rangle_{A,EF} := \mathcal{T}_A|\psi\rangle_{\text{phys}} = |p=0\rangle_A \otimes \underline{\int dp_E dp_F\, \psi_{\text{kin}}(-p_E - p_F, p_E, p_F)|p_E, p_F\rangle}$$

$$:= |\psi\rangle_{EF|A}$$

- observables transform correctly

$$\mathcal{T}_A\,(\hat{q}_{E,F} - \hat{q}_A)\,\mathcal{T}_A^\dagger = \hat{q}_{E,F} \qquad\qquad \mathcal{T}_A\,\hat{p}_{E,F}\,\mathcal{T}_A^\dagger = \hat{p}_{E,F}$$

$$\mathcal{T}_A\,\hat{H}\,\mathcal{T}_A^\dagger = \hat{H}_{EF|A} = \hat{p}_E^2 + \hat{p}_F^2 + \hat{p}_E\hat{p}_F + V(\hat{q}_E, \hat{q}_F)$$

$\Rightarrow$ defines isometry to A-perspective

$$\mathcal{H}_{\text{phys}} \to \mathcal{H}_{EF|A}$$

Switch from A- to F-perspective in QT

Wigner friend like scenario

perspective neutral

$$\begin{tikzcd}
 & \mathcal{H}_{\mathrm{phys}} \arrow[dr, "\mathcal{T}_F"] & \\
\mathcal{H}_{A,EF} \arrow[ur, "\mathcal{T}_A^\dagger"] & & \mathcal{H}_{F,AE} \arrow[d, "{}_F\langle p=0|/\delta(0)"] \\
\mathcal{H}_{EF|A} \arrow[u, "|p=0\rangle_A \otimes"] & & \mathcal{H}_{AE|F}
\end{tikzcd}$$

reduced QT in A-perspective

reduced QT in F-perspective

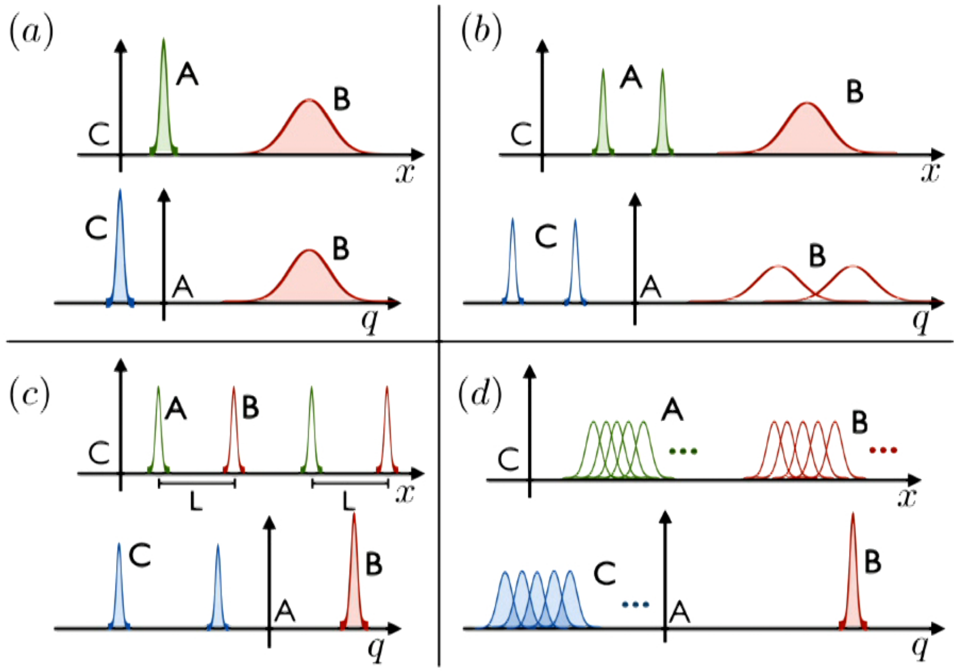
concretely

$$S_{A\to F} = {}_F\langle p=0|/\delta(0)\, \mathcal{T}_F\, \mathcal{T}_A^\dagger\, |p=0\rangle_A \otimes$$
$$= \mathcal{P}_{FA}\, e^{i\hat{q}_F \hat{p}_E}$$

parity swap

$\Rightarrow$ exactly QRF transf. proposed by Giacomini, Castro-Ruiz, Brukner (arXiv:1712.07207)

Operational consequences (stolen from GC-RB paper)



$\Rightarrow$ see Giacomini, Castro-Ruiz, Brukner arXiv:1712.07207 or Flaminia's talk on PIRSA

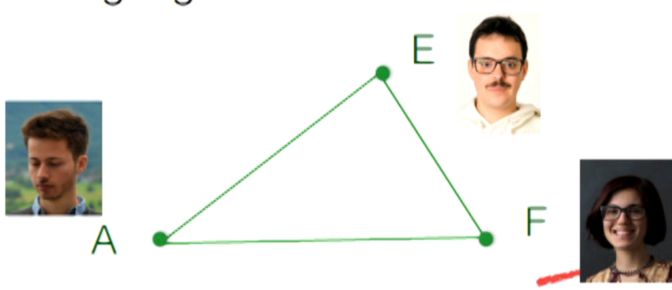
Generalize to 3D with "Mach principle"

- incl. also rotational invar.

$$H = \sum_{a=A,E,F} \vec{p}_a{}^2 + V\left(\{|\vec{q}_a - \vec{q}_b|\}\right) + \vec{\lambda}\vec{P} + \vec{\mu}\vec{J}$$

where $$J_i = \sum_a \epsilon_{ijk}\, q_a^j\, p_a^k$$

- gauge inv. motion and observables $|\vec{q}_a - \vec{q}_b|, \vec{p}_a{}^2$



perspective neutral

$\Rightarrow$ gauge fix to A-perspective

A: origin
E: in z-direction
F: in x-z-plane

$\Rightarrow$ quantize reduced theory on

$$\mathcal{Q} = \mathbb{R}^2_+ \times \mathbb{R}$$

Perspective switch

perspective neutral

$$\begin{tikzcd}
 & \mathcal{H}_{\text{phys}} \arrow[dr, "\mathcal{T}_F"] & \\
\mathcal{H}^{\text{rot}}_{A,EF} \arrow[ur, "\mathcal{T}_A^\dagger"] & & \mathcal{H}^{\text{rot}}_{F,AE} \arrow[d, "\mathcal{R}_{E,A}"] \\
\mathcal{H}^{\text{rot}}_{E,F|A} \arrow[u, "\mathcal{R}^{-1}_{E,F}"] & & \mathcal{H}^{\text{rot}}_{E,A|F} \arrow[d, "\pi_F^{\text{red}}"] \\
\mathcal{H}^{\text{red}}_{E,F|A} \arrow[u, "(\pi_A^{\text{red}})^{-1}"] \arrow[rr, "S_{A\to F} = \varphi_F \circ \varphi_A^{-1}"] & & \mathcal{H}^{\text{red}}_{E,A|F}
\end{tikzcd}$$

preliminary results on perspective dep. entanglement

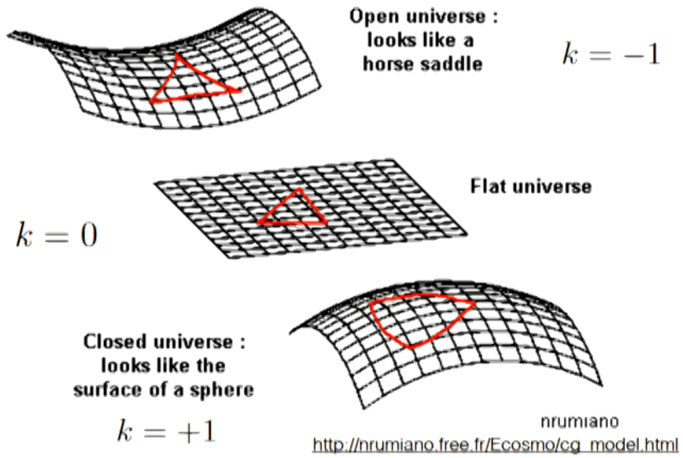
reduced QT in A-perspective

reduced QT in F-perspective

Relational dynamics in FRW

- homogeneous & isotropic universe

$$ds^2 = -dt^2 + a(t)\left(\frac{dr^2}{1-kr^2} + r^2\, d\Omega^2\right)$$



- Hamiltonian constraint incl. homog. field

$$C_H = p_\phi^2 - p_\alpha^2 - 4k\, e^{4\alpha} + 4m^2\phi^2\, e^{6\alpha} \approx 0$$

$$\alpha = \ln a$$

$\Rightarrow$ time evol. generated is gauge transf.

$$\dot\phi = \{\phi, C_H\} = 2p_\phi$$
$$\dot\alpha = \{\alpha, C_H\} = -2p_\alpha$$

can go through 0, thus not necessarily monotonic

$\Rightarrow$ want to use α or ϕ as relational "clock"

k=0 FRW with massless scalar

- Hamiltonian constraint of Klein-Gordon form

$$C_H = p_\phi^2 - p_\alpha^2 \approx 0$$

$$\Rightarrow \quad \phi(t) = 2p_\phi\, t + \phi_0$$
$$\alpha(t) = -\,2p_\alpha\, t + \alpha_0$$

- choose α as "clock"

$$\Rightarrow \quad \phi(\tau) = -\frac{p_\phi}{p_\alpha}(\tau - \alpha_0) + \phi_0$$

rel. observable $\{\phi(\tau), C_H\} = 0$

- get rid of redundant α, p_α

$$p_\alpha = \pm|p_\phi| = \pm H$$

generates fwd/bwd evol.

$$\phi^{\pm}(\tau) = \pm\mathrm{sgn}(\mathrm{p}_\phi)\tau + \phi$$

$\Rightarrow$ red. QT $\quad i\partial_\tau|\psi\rangle = \pm|\hat{p}_\phi|\,|\psi\rangle$

Dirac quantization and clock change

perspective neutral

$$\mathcal{H}_{\text{phys}}$$

$$\mathcal{T}_\alpha^{-1} \qquad\qquad \mathcal{T}_\phi$$

$$\mathcal{H}_\alpha^{\text{red}} = \mathcal{H}_\alpha^+ \oplus \mathcal{H}_\alpha^- \qquad\qquad \mathcal{H}_\phi^{\text{red}} = \mathcal{H}_\phi^+ \oplus \mathcal{H}_\phi^-$$

red. in α time　　　　red. in ϕ time

where

$$\mathcal{T}_\alpha = \mathcal{T}_{\alpha+} + \mathcal{T}_{\alpha-} \qquad\qquad \mathcal{T}_{\alpha\pm} = \sqrt{2|\hat{p}_\phi|}\, e^{\pm i\hat{\alpha}(|\hat{p}_\phi|-\epsilon)}\, \theta(\mp\hat{p}_\alpha)$$

$\Rightarrow$ observables transform correctly, e.g.

$$\mathcal{T}_\alpha : \hat{\phi}(\tau) \mapsto \hat{\phi}^+(\tau)\,\theta(-\hat{p}_\alpha) + \hat{\phi}^-(\tau)\,\theta(\hat{p}_\alpha)$$

can change rel. clock in the QT

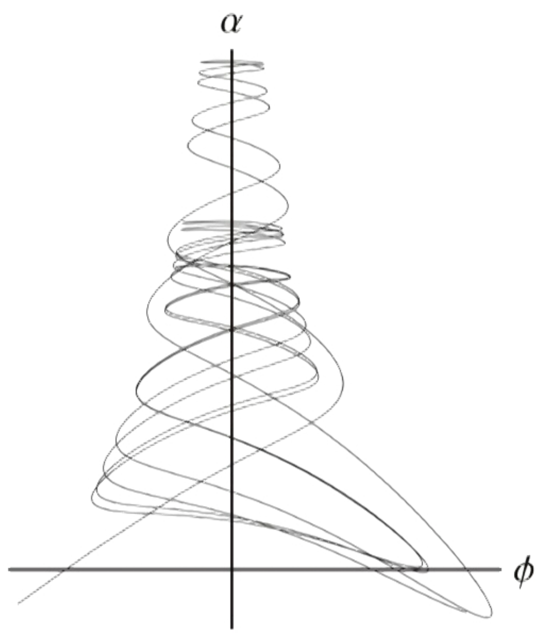
Relational dynamics more generally

- can get arbitrarily complicated

$$C_H = p_\phi^2 - p_\alpha^2 - 4k\, e^{4\alpha} + 4m^2\phi^2\, e^{6\alpha} \approx 0$$

chaos for massive field

interacting clocks,
global problem of time,
non-unitarity, transient clocks



see
Bojowald, PH, Tsobanjan, CQG 28,035006, (2011)
Bojowald, PH, Tsobanjan, PRD 83,125023 (2011)
PH, Kubalova, Tsobanjan, PRD 86, 065014 (2012)
Dittrich, PH, Koslowski, Nelson, PLB 769, 554 (2017)

New approach to interpreting quantum cosmology?

- no global operational state —> global state perspective neutral
- only relative operational states

"Wave function of the universe" as a perspective neutral state?

Operational interpretation from transformation to specific reduced theory?

PH, Quantum 1, 38 (2017)
PH, JPCS 880, 012014 (2017)

Part II

perspective neutral? ← internal perspectives

symmetry principle? ← frame transf. ← operational conditions

AIM:
constrain spacetime structure
through quantum information protocols

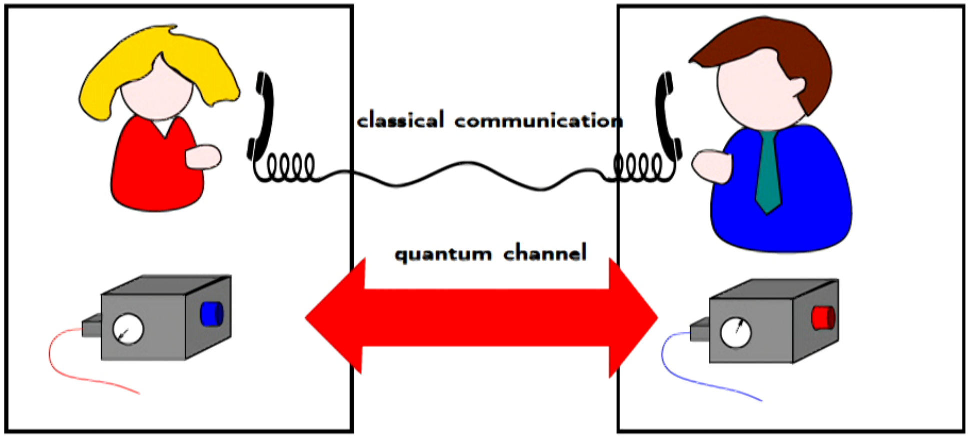
PH, M. Müller, NJP 18, 063026 (2016)
and wip with
D. Rätzel, M. Müller and C. Pfeifer

Lorentz transformations from quantum communication

idea: quantum reference frame synchronization game

Alice and Bob live in some logically conceivable world

- not given: particular spacetime structure or local symmetry group
- given:
  1. local frame for Alice and Bob
  2. abstract quantum theory holds locally
  3. communication channel

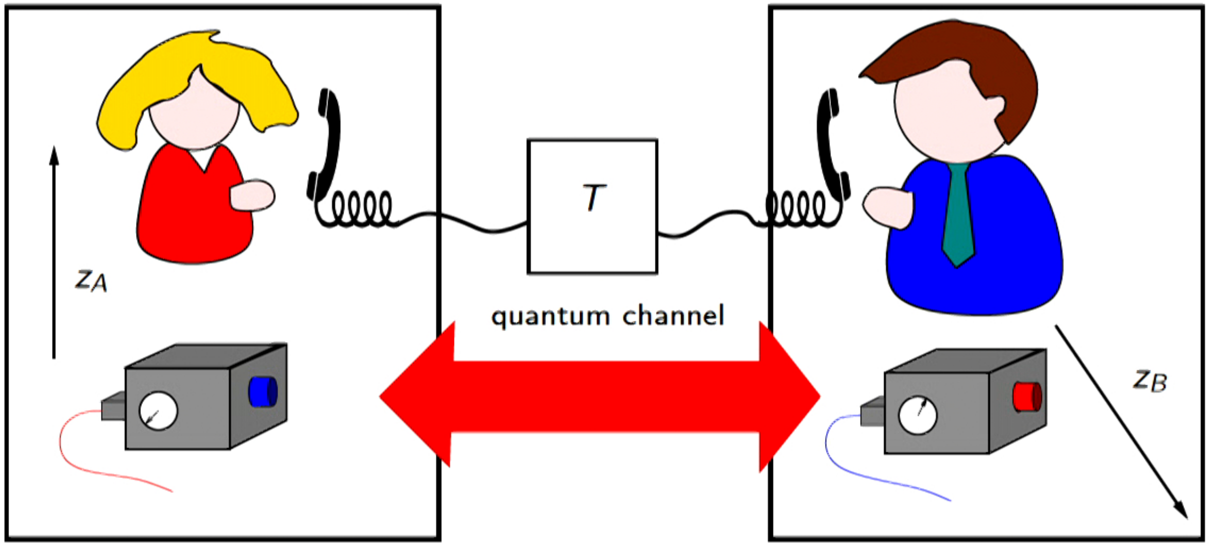


question:

smallest set of transfs. between A's & B's description of quantum systems?

$\Rightarrow$ reconstruct $\mathrm{SO}(3,1)$ from operational conds. on quantum communication!

Quantum reference frame synchronization game [PH, Müller NJP '16]

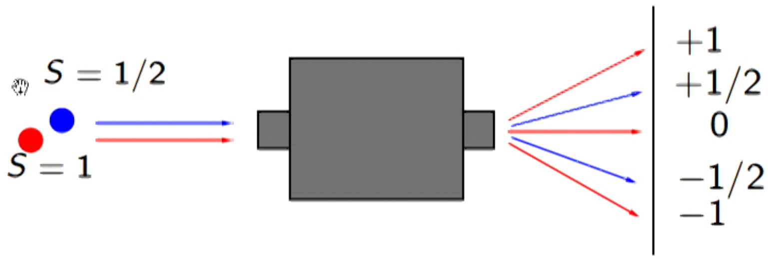


- A and B never met, play game: "synchronizing quantum descriptions"
- A and B do tomography $\Rightarrow$ determine correcting transformation T between their descriptions

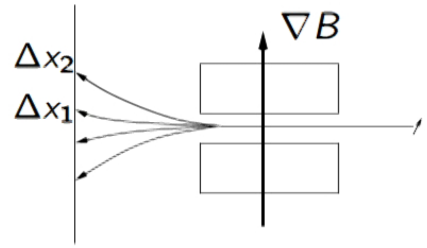
$\Rightarrow$ win (a not very exciting!) game

universal measurement devices [PH, Müller NJP '16]

different types of systems react differently to same measurement device



e.g. different particle species



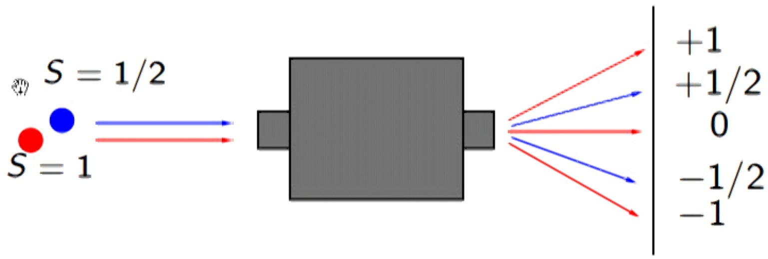
e.g. different state of motion

- repeat game for all types? $\Rightarrow$ arbitrarily complex task!
- transfer synchronization from one type to another?

$\Rightarrow$ need: same observable on different types $\Rightarrow$ universal measurement devices

universal measurement devices [PH, Müller NJP '16]

different types of systems react differently to same measurement device



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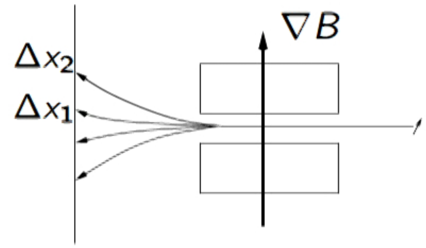

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5 / 9

universal measurement devices [PH, Müller NJP '16]

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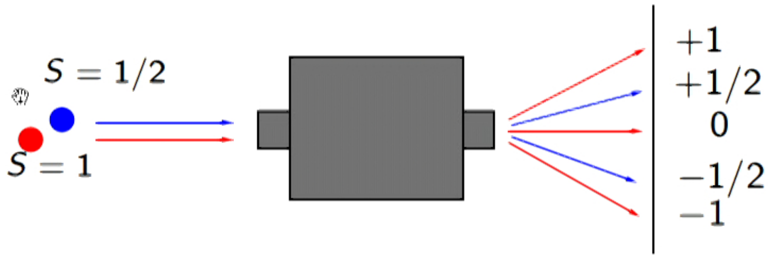

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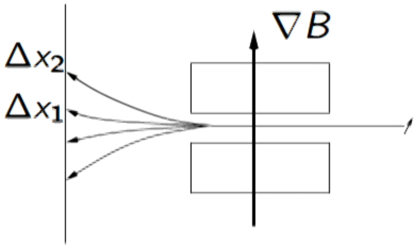

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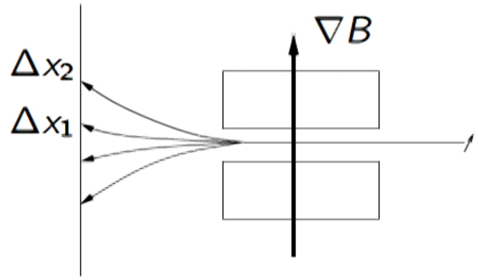
logic

usually: symmetry group $\Rightarrow$ conserved quant. $\Rightarrow$ UMD

here: UMD $\Rightarrow$ carrier indep. quant. $\Rightarrow$ symmetry group

What does it mean to be universally measurable? [PH, Müller NJP '16]



- UMD defines observables $O(S), O(S'), \ldots$ for different systems $S, S', \ldots$

$\Rightarrow$ for relations assume:

1. $O(S)$ outcomes have 'size'
2. $O_1(S) \leq O_2(S) \Rightarrow O_1(S') \leq O_2(S')$ (order preservation)
3. $O(S) = 0 \Rightarrow O(S') = 0$ ('no measurement' preservation)

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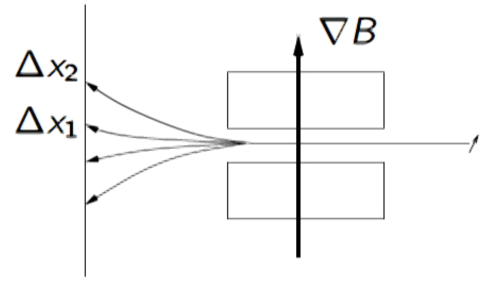

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3. $O(S) = 0 \Rightarrow O(S') = 0$ ('no measurement' preservation)

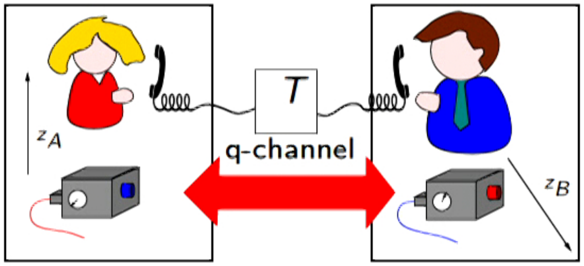
Lemma

If S, S' of same dim. then $O(S) = X\, O(S')\, X^\dagger, \qquad X \in \mathrm{GL}(\mathrm{N}, \mathbb{C})$

Theorem

If $\dim S \neq \dim S''$ and $\{O_i\}$ universal and tomographically complete on S'' then A and B can lift synchronization from S to S'' using class. commun.

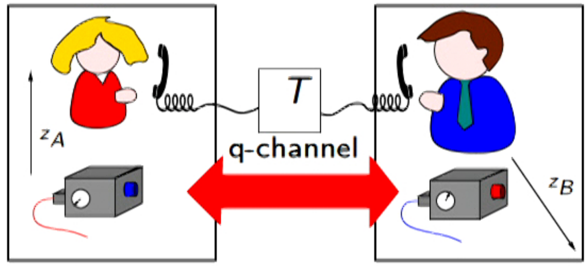
Lorentz group from quantum communication [PH, Müller NJP '16]



Theorem

If $\exists$ enough tomographically complete, universal qubit observables, then it takes A and B a fixed element $T \in \mathbb{R}_+ \times \mathrm{SO}^+(3,1)$ to win game for arbitrary types of (finite dim.) quantum systems.

Lorentz group from quantum communication [PH, Müller NJP '16]



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intuition:

1. B sends A many qubits of fixed type, A does state tomography
2. A will find $O(S_A) = X\, O(S_B)\, X^\dagger$, $X \in \mathrm{GL}(2,\mathbb{C})$

$\Rightarrow$ $T \in \mathbb{R}_+ \times \mathrm{PSL}(2,\mathbb{C}) \simeq \mathbb{R}_+ \times \mathrm{SO}^+(3,1)$, ($\mathbb{R}_+$: 'unit conversion factor')

3. A & B lift qubit synchronization via UMDs to arbitrary quantum systems

Outlook

- relation to Poincare transf. and Wigner reps?
- why metric geometries?
  —> reconstruct using QI perspective?