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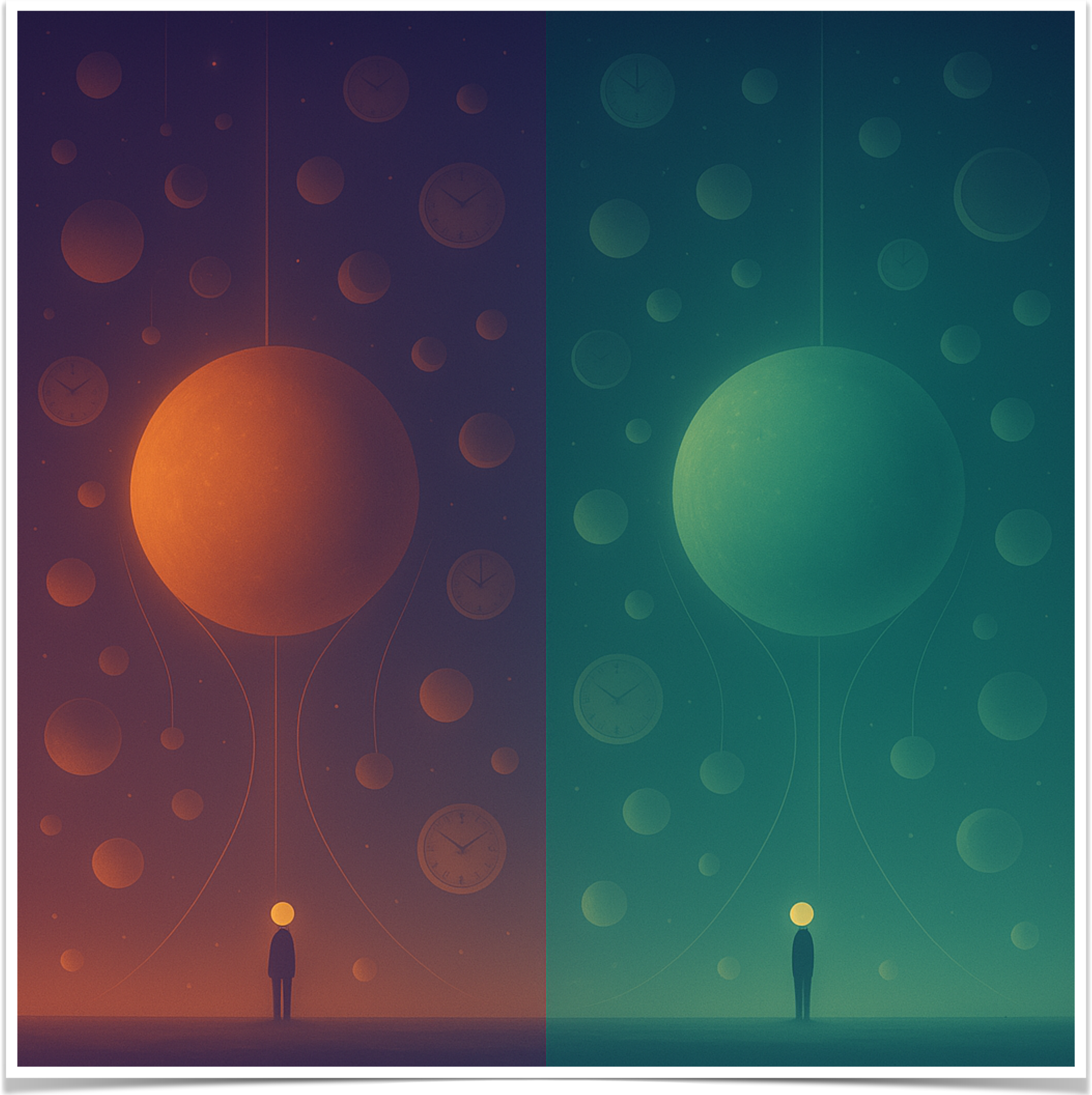
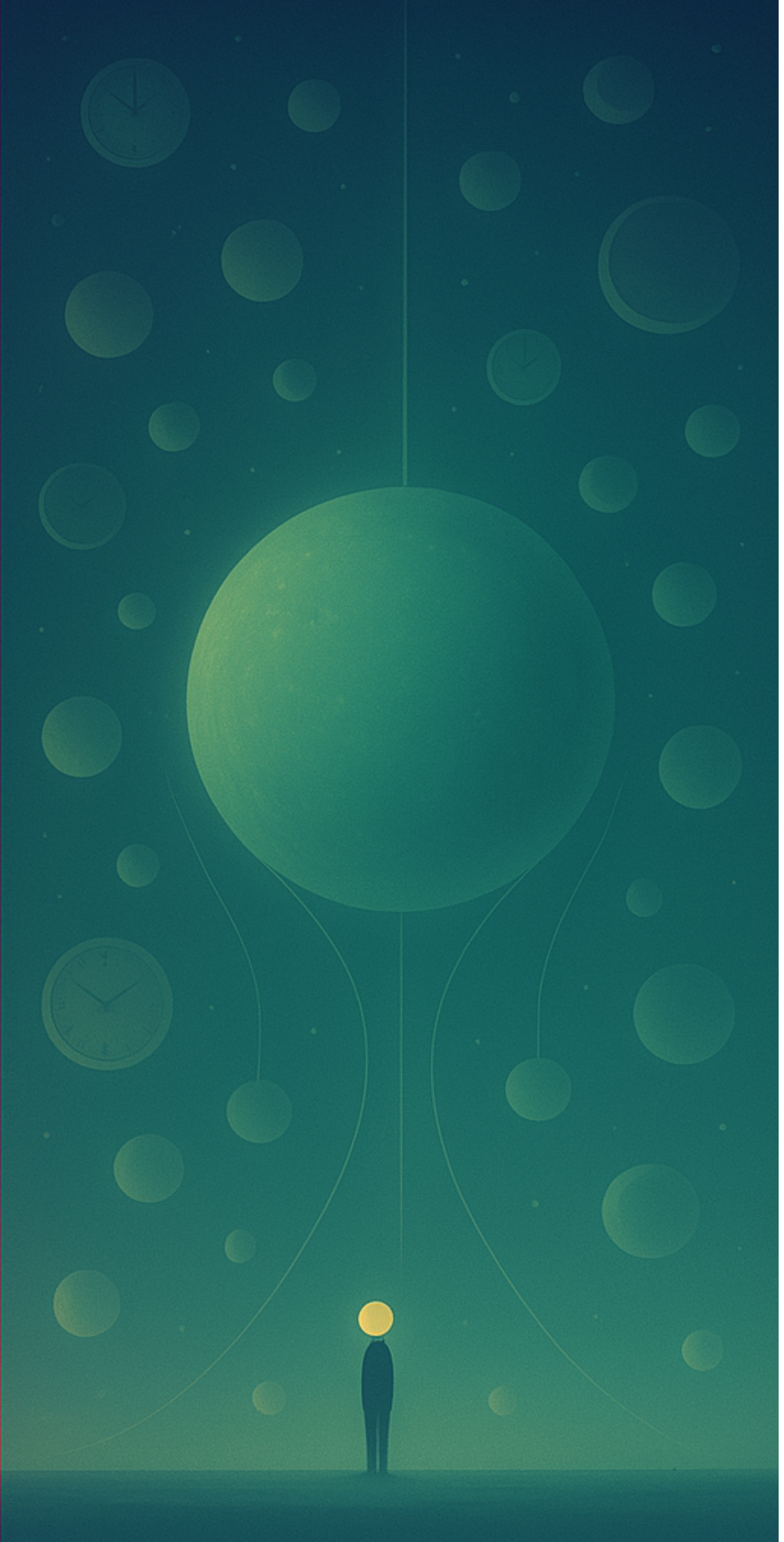
QISS | THE QUANTUM INFORMATION STRUCTURE OF SPACETIME

Quantum Reference Frames:
From Quantum Information to Spacetime



Anne-Catherine de la Hamette

Solstice of Foundations, June 2025



Outline

<u>Part I:</u> Quantum reference frames as a tool for predictions

- Gravity sourced by a mass in superposition
- Extended symmetry principles

<u>Part II:</u> Quantum reference frames for superpositions of spacetimes

- Superpositions of semi-classical spacetimes
- Symmetries and counterparts
- Quantum coordinates

<u>Part III:</u> Conceptual implicationsIdentification and localisation of events

- Localisation of events
- Indefinite causal order

Part I: Quantum reference frames as a tool for predictions

First-principles approach to quantum gravity

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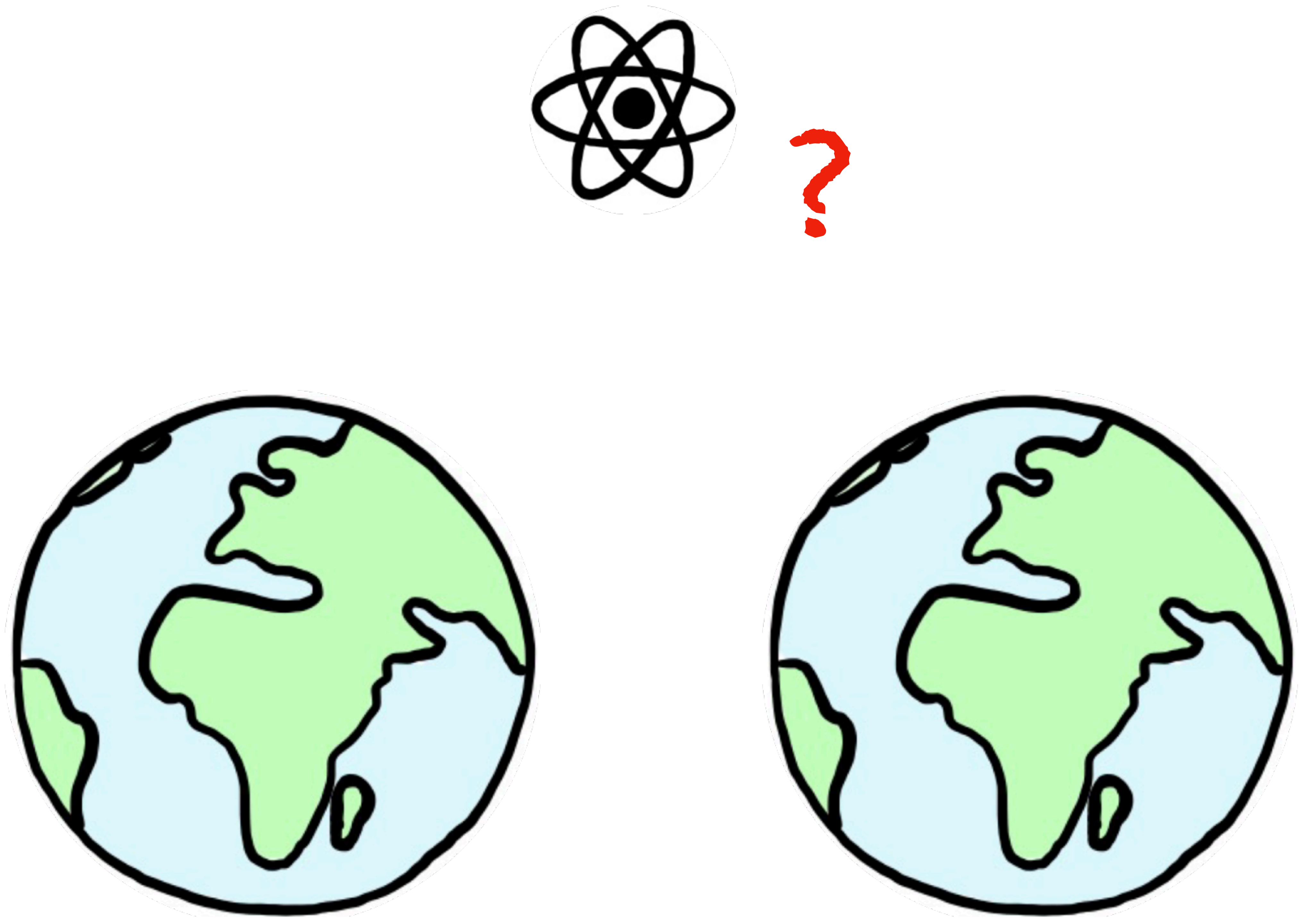
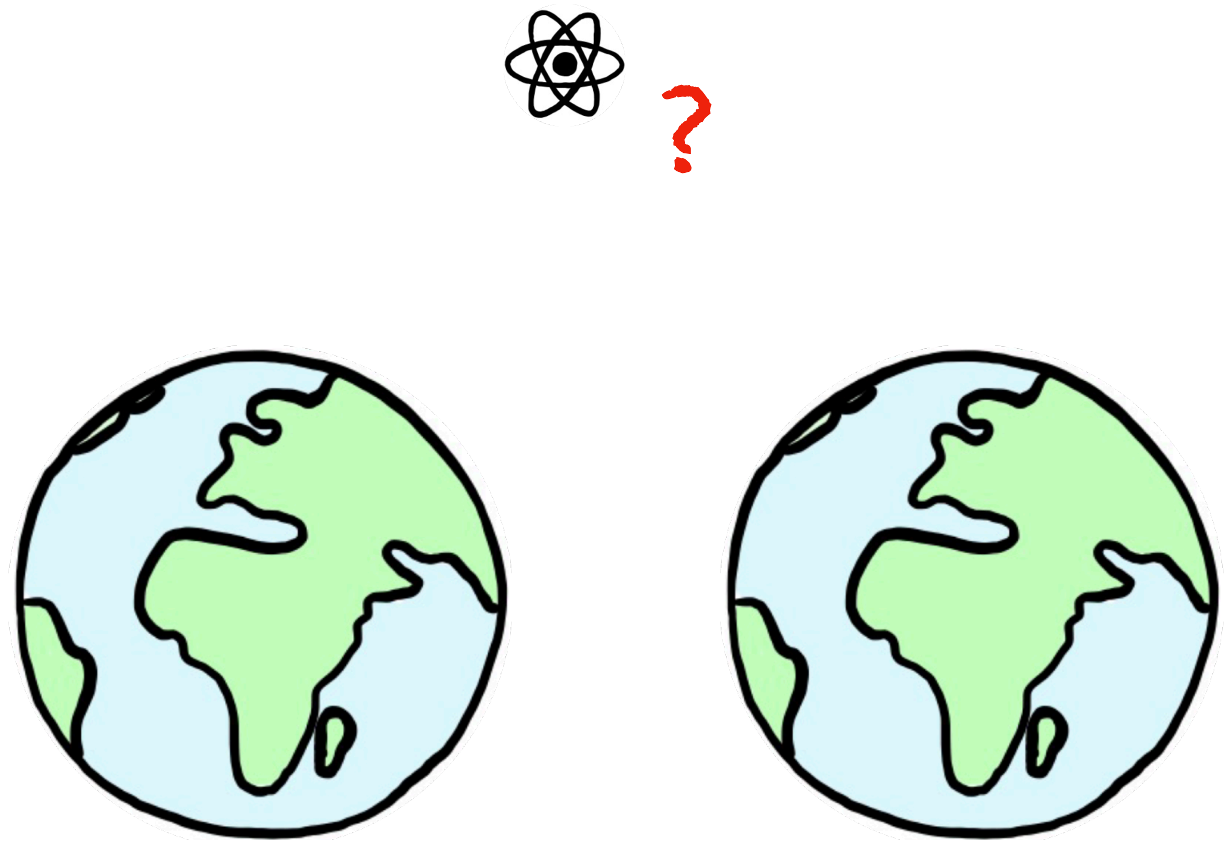
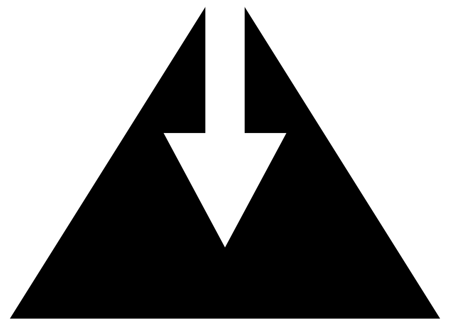


First-principles approach to quantum gravity

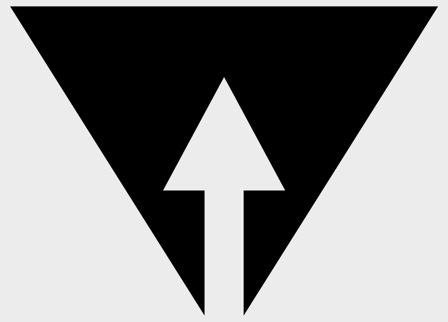


Top-down approaches in which quantum theory and general relativity are derived from a larger theory of quantum gravity.

- String Theory
- Loop Quantum Gravity, Spin Foam Models, …



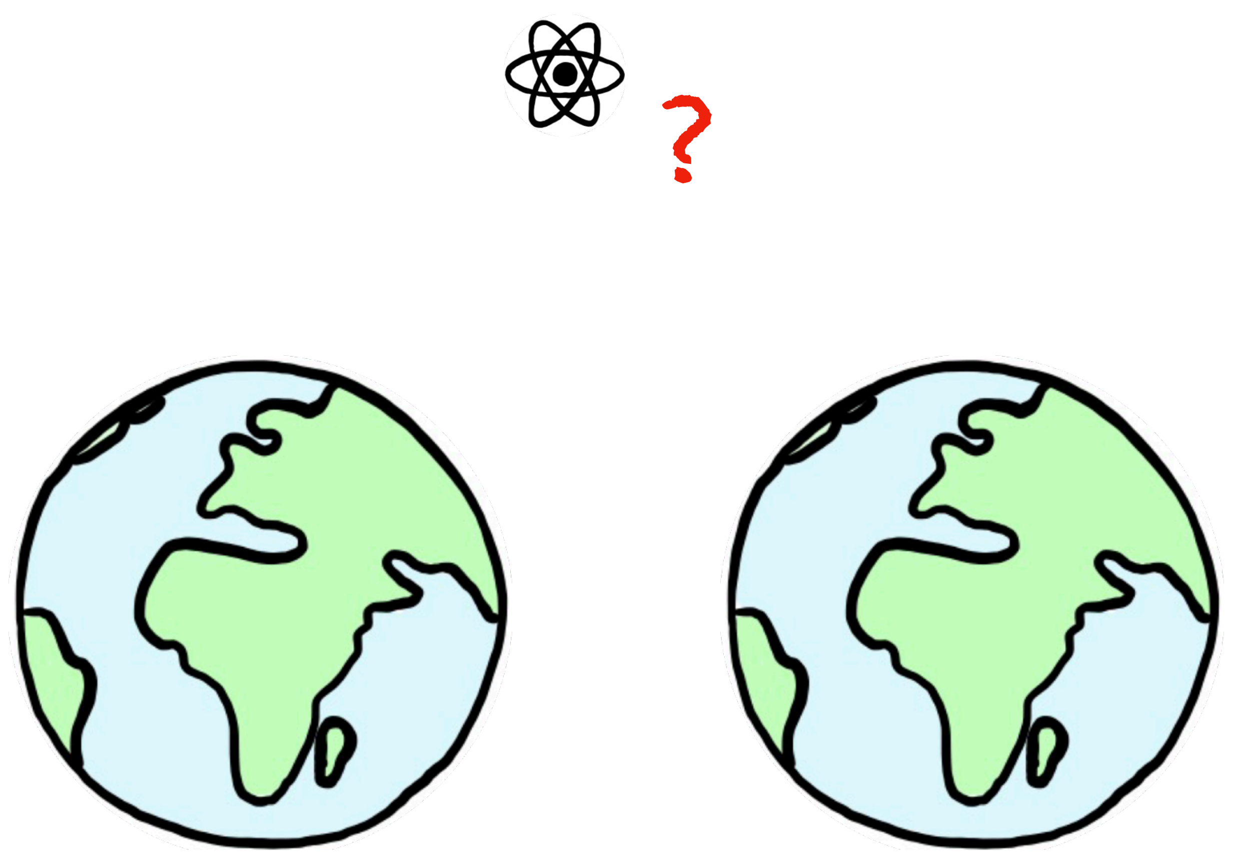
Top-Down Approach



Bottom-Up Approach

Idea: Take principles of quantum theory and *known* theories with *classical* spacetime (general relativity / quantum field theory on curved spacetime) and try to push them as far as possible.

First-principles approach to quantum gravity



Symmetries of *known* physical theories with classical spacetime (GR; QFTCS)

$+$

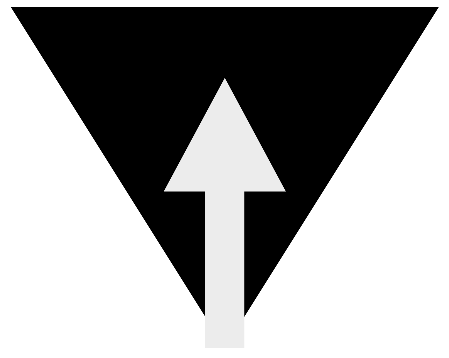
Linearity of Quantum Theory

$\downarrow$

Extended Symmetry Principles

→ Concrete predictions for applicable regimes without the need to rely on perturbative methods

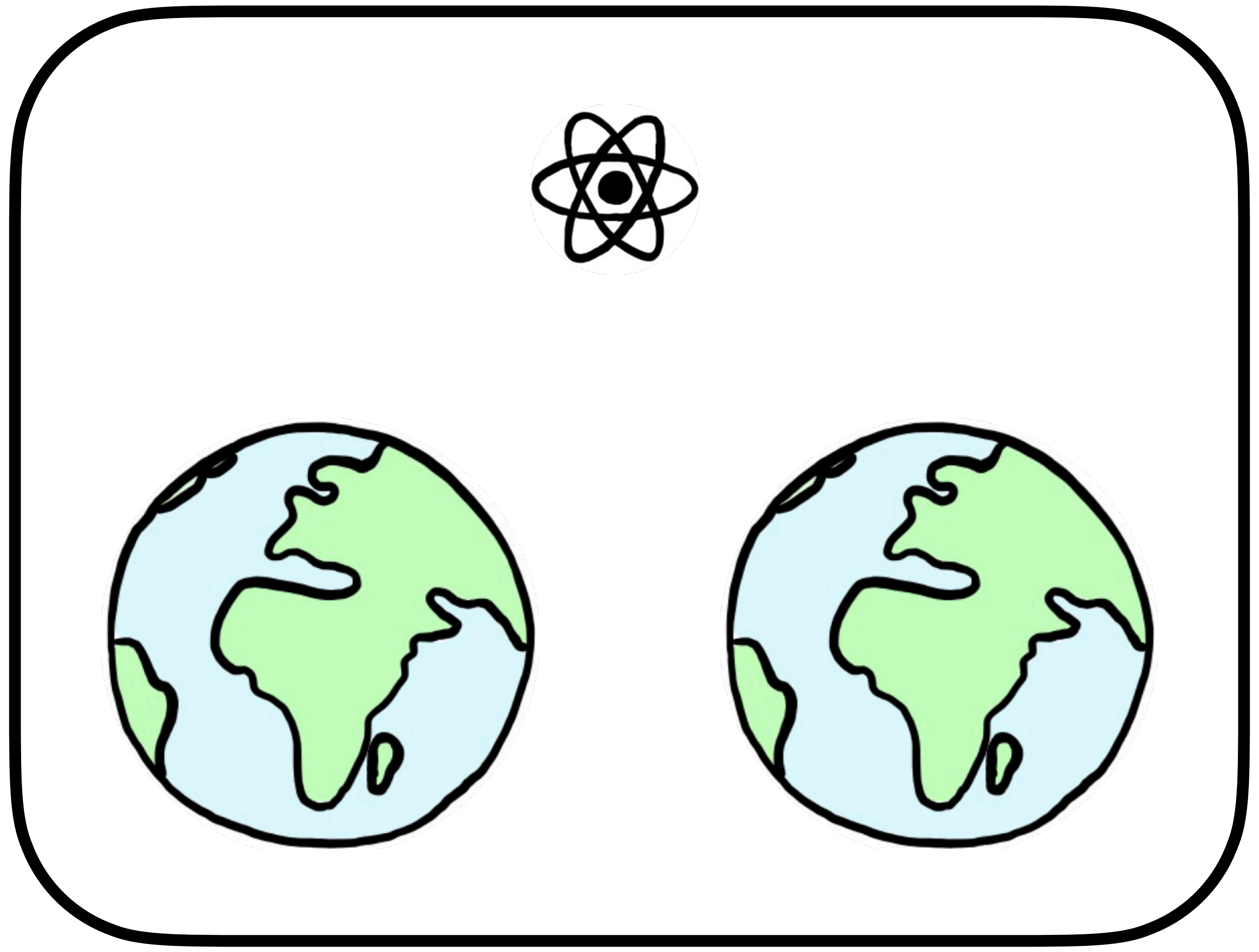
Quantum Reference Frames



Bottom-Up Approach

Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition



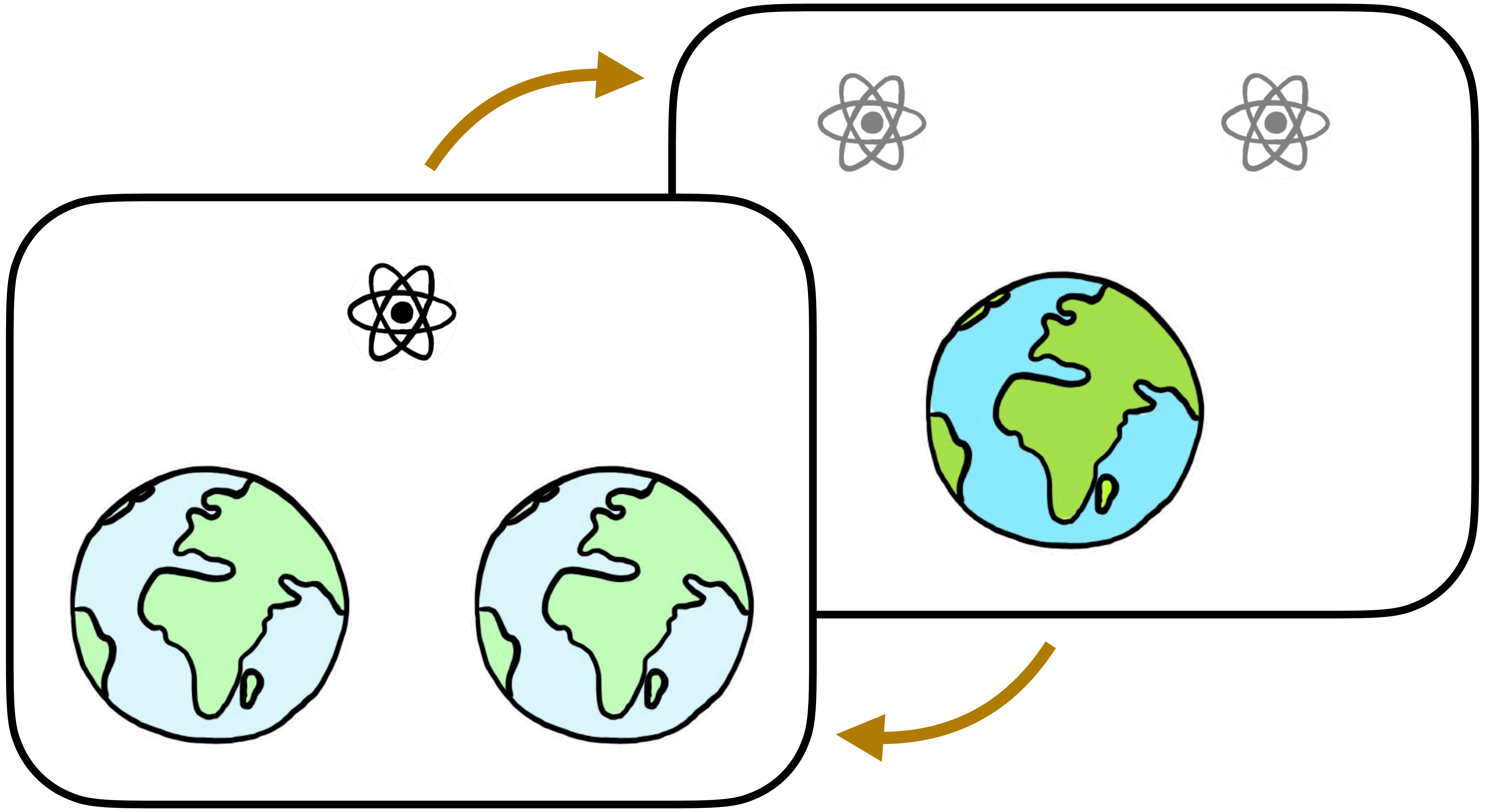
Goal: Describe motion of test particle in presence of a gravitational source in superposition.

...while remaining "agnostic" about the nature of the gravitational field!

ACdlH, V. Kabel, E. Castro-Ruiz, Č. Brukner, Commun Phys 6, 231 (2023).

Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition



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Quantum reference frames as a tool for predictions

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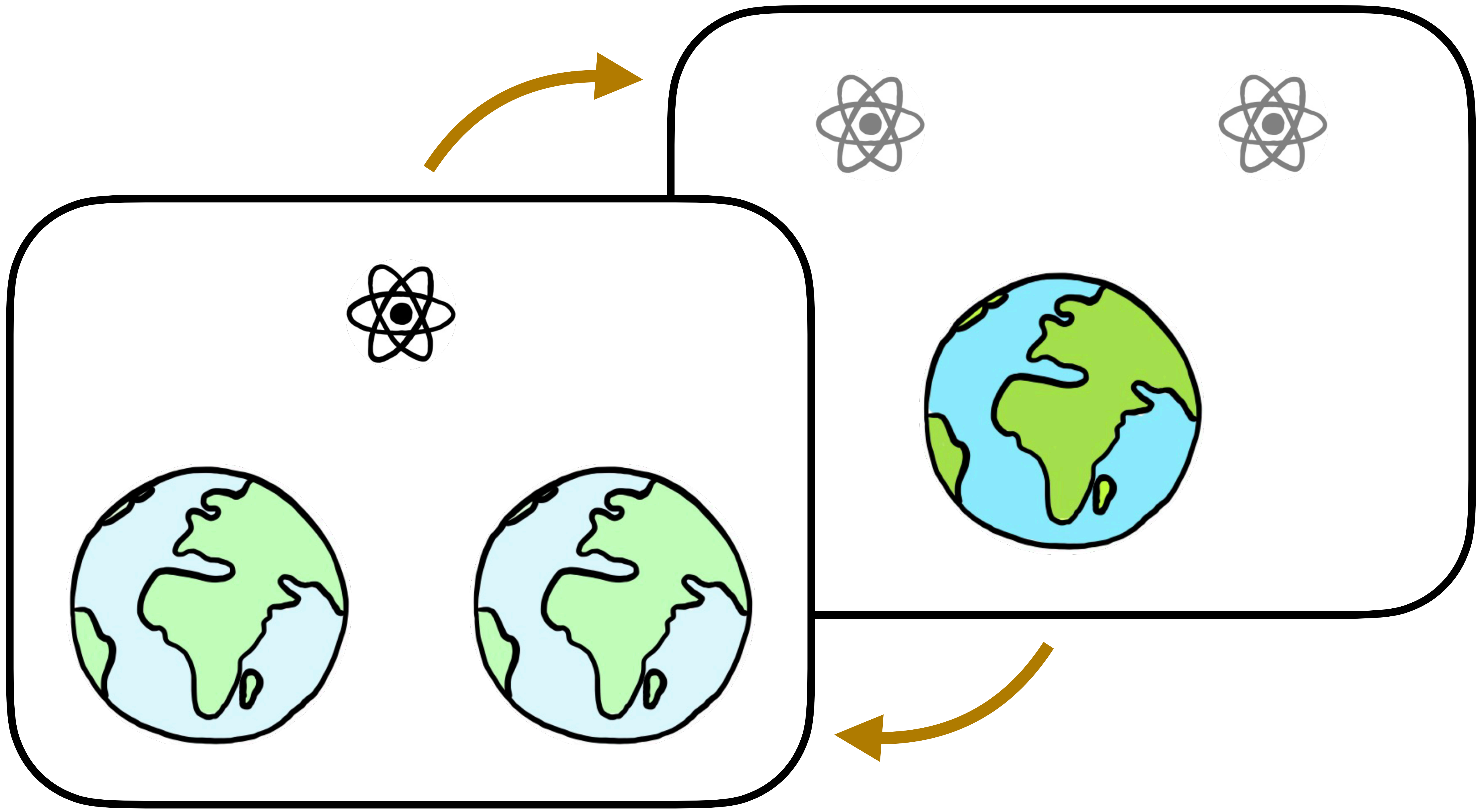

Covariance of dynamical laws under coordinate transformations:
Physical laws retain their form under coordinate transformations.

ACdlH, V. Kabel, E. Castro-Ruiz, Č. Brukner, Commun Phys 6, 231 (2023).

Quantum reference frames as a tool for predictions

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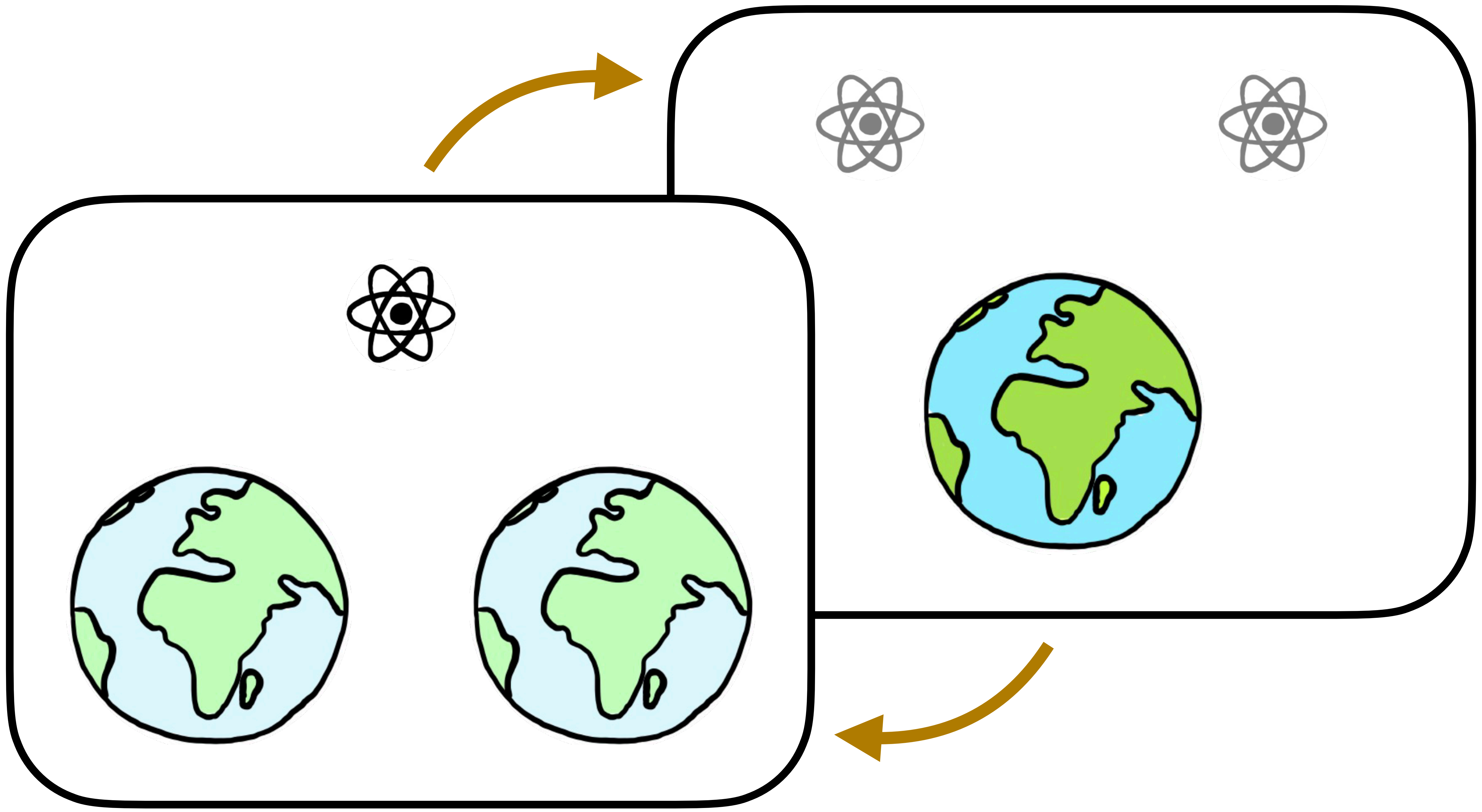


"extended symmetry principle"

Covariance of dynamical laws under **quantum** coordinate transformations:
Physical laws retain their form under ***quantum*** coordinate transformations.

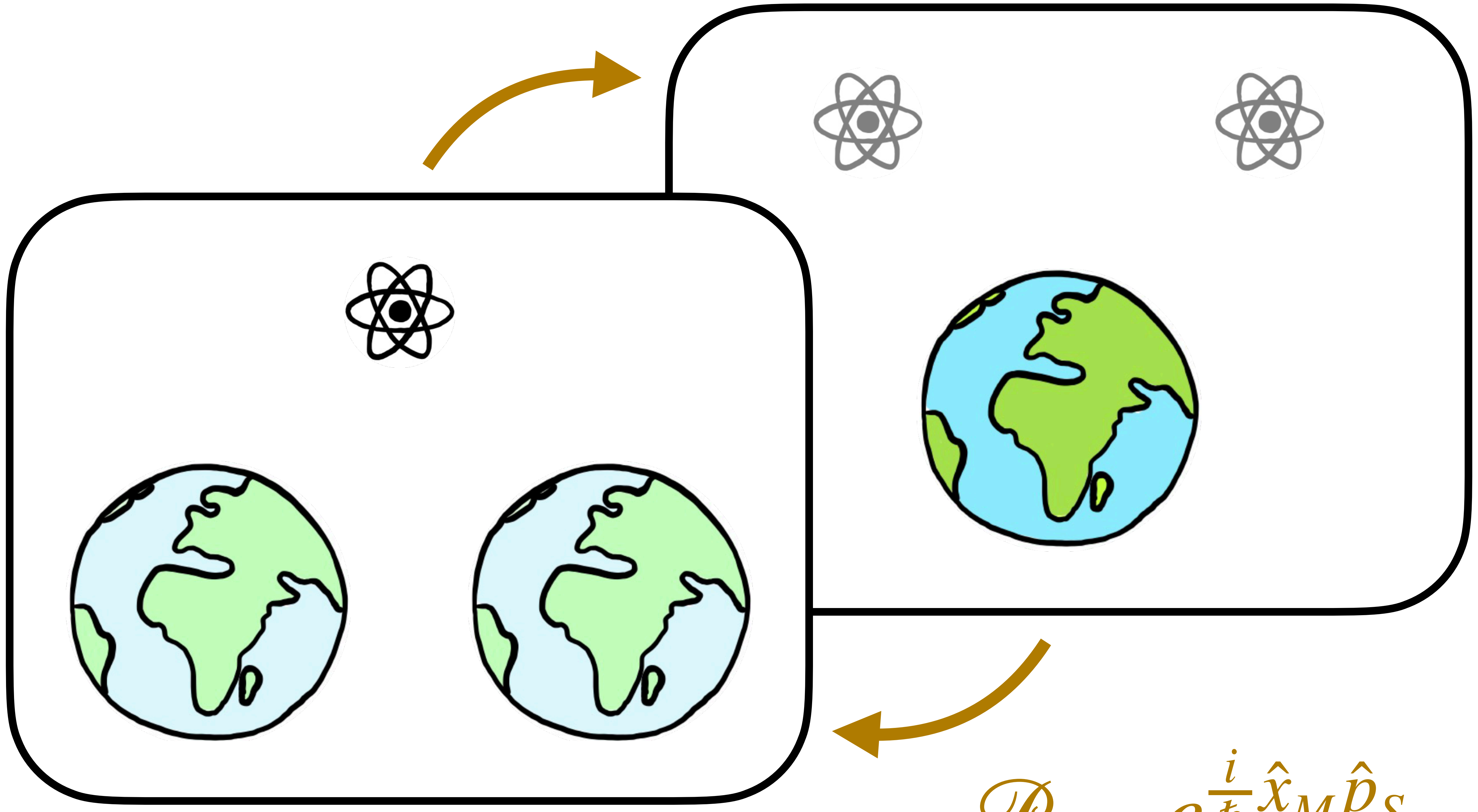
ACdlH, V. Kabel, E. Castro-Ruiz, Č. Brukner, Commun Phys 6, 231 (2023).

Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition

Strategy

- Change into QRF in which the gravitational source is definite.



$$\mathcal{P}_{RM} e^{\frac{i}{\hbar}\hat{x}_M \hat{p}_S}$$

Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition

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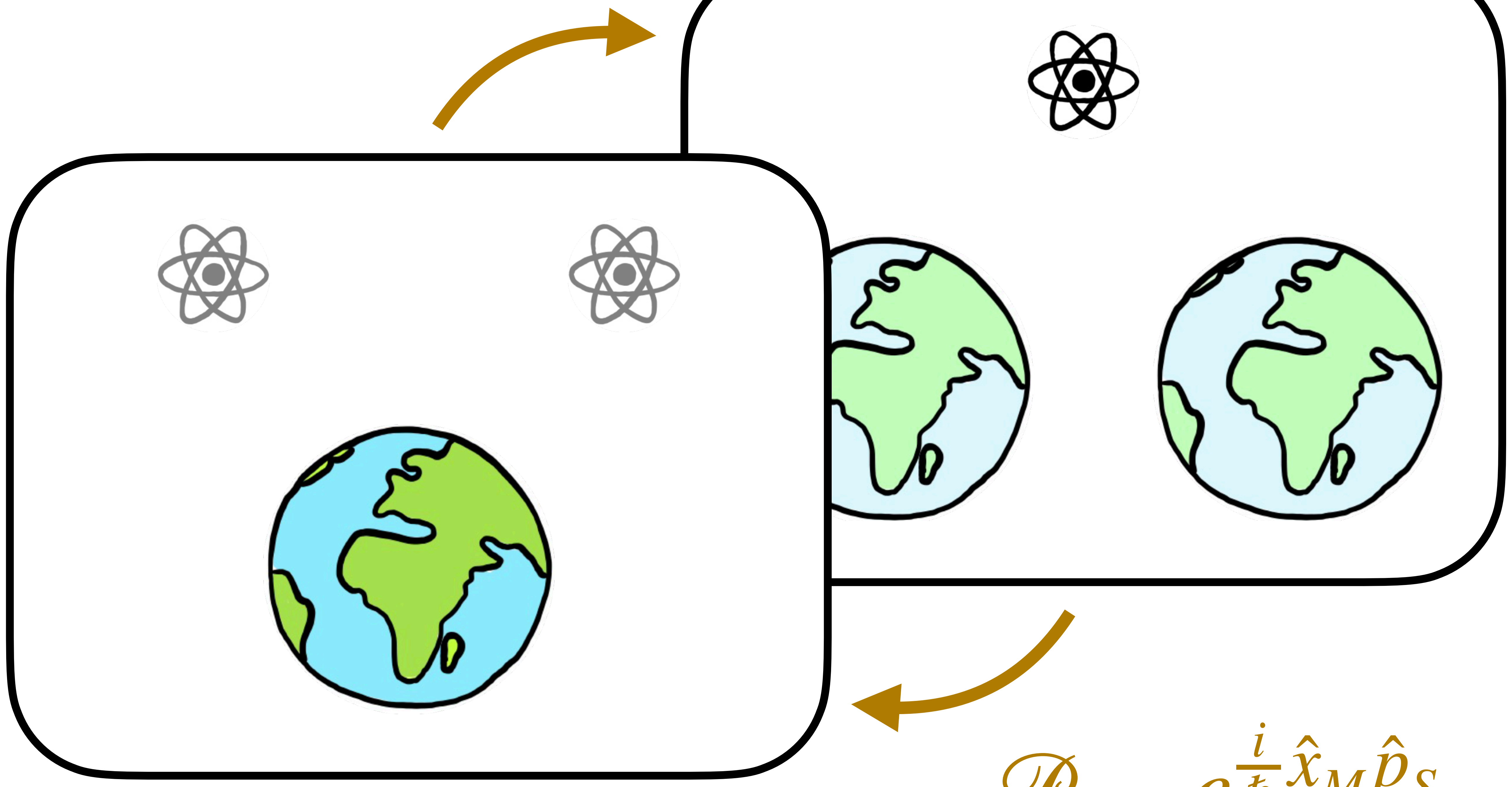

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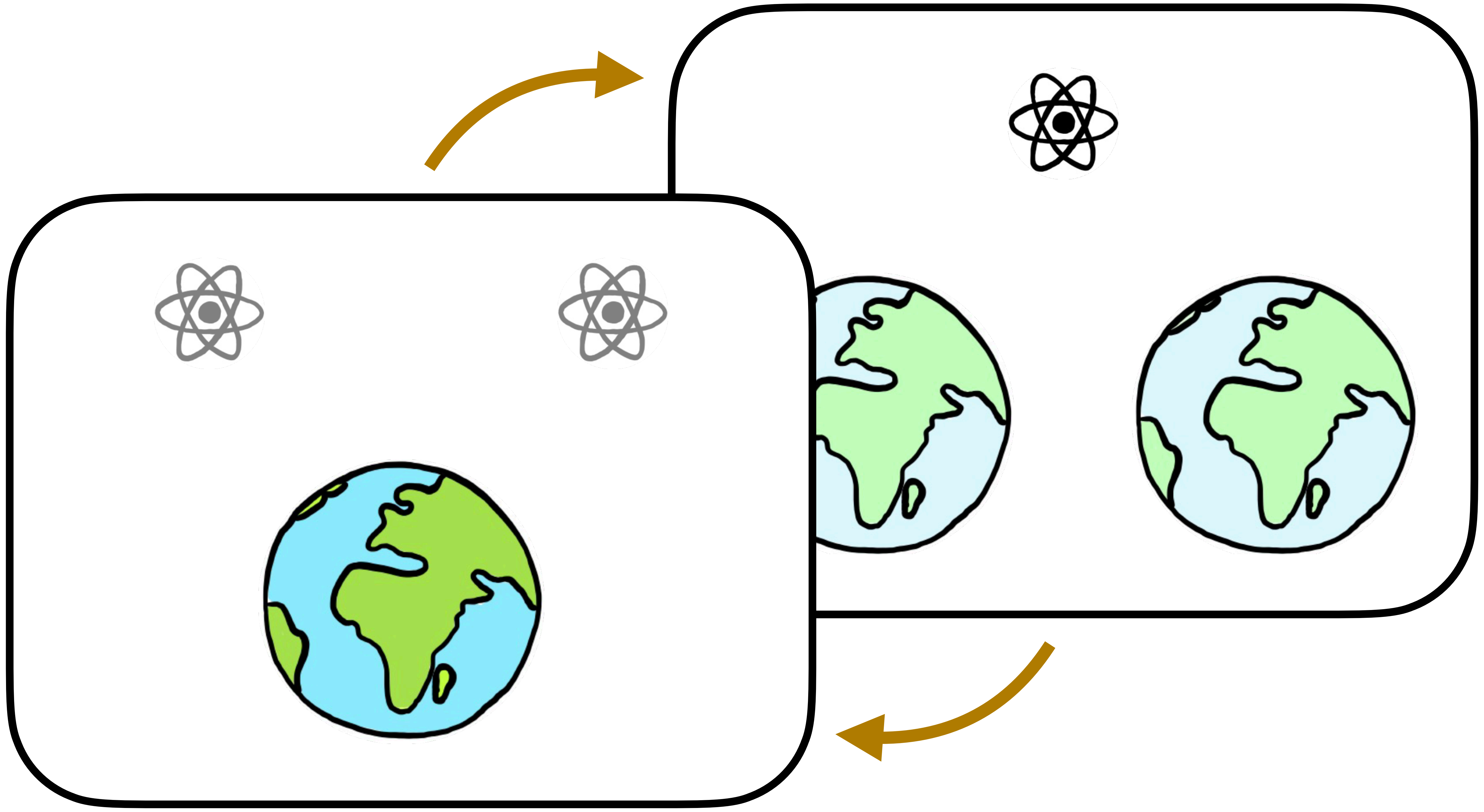
Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition

Strategy

- Change into QRF in which the gravitational source is definite.
- Solve problem in the new reference frame.



geodesic motion

$$\frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\nu\rho}\frac{dx^\nu}{d\tau}\frac{dx^\rho}{d\tau} = 0$$

quantum phase

$$\Phi^{(i)} = \int_{A^{(i)}}^{B^{(i)}} m_S \sqrt{-g_{\mu\nu}dx^\mu dx^\nu}$$

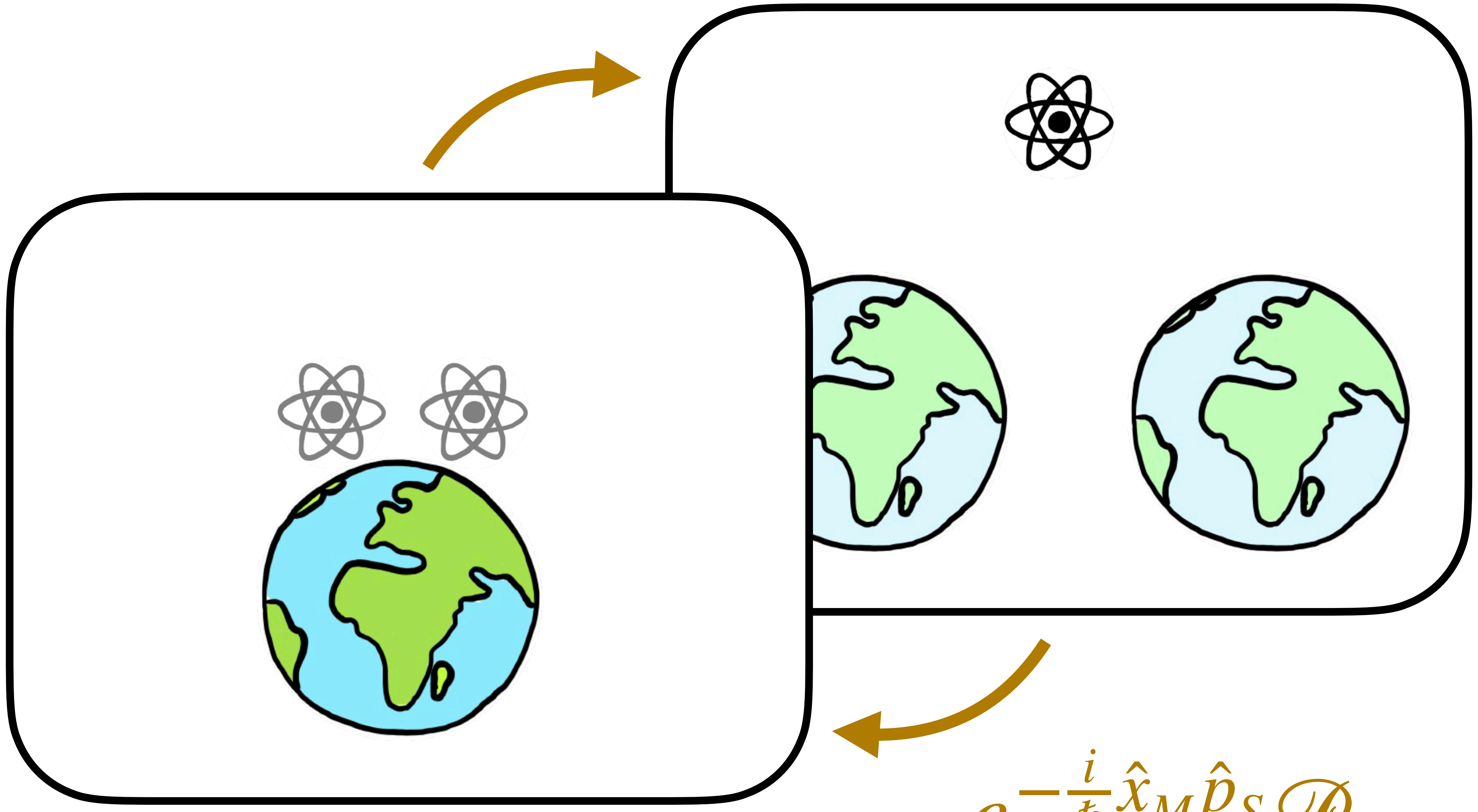
L. Stodolsky, Matter and Light Wave Interferometry in Gravitational Fields, Gen. Rel. Grav. 11, 391-405 (1979).

Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition

Strategy

- Change into QRF in which the gravitational source is definite.
- Solve problem in the new reference frame.
- Transform back to infer the dynamics *assuming that the change of QRF is a symmetry of the equations of motion*.



$$e^{-\frac{i}{\hbar}\hat{x}_M \hat{p}_S \mathscr{P}_{MR}}$$

Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition

Strategy

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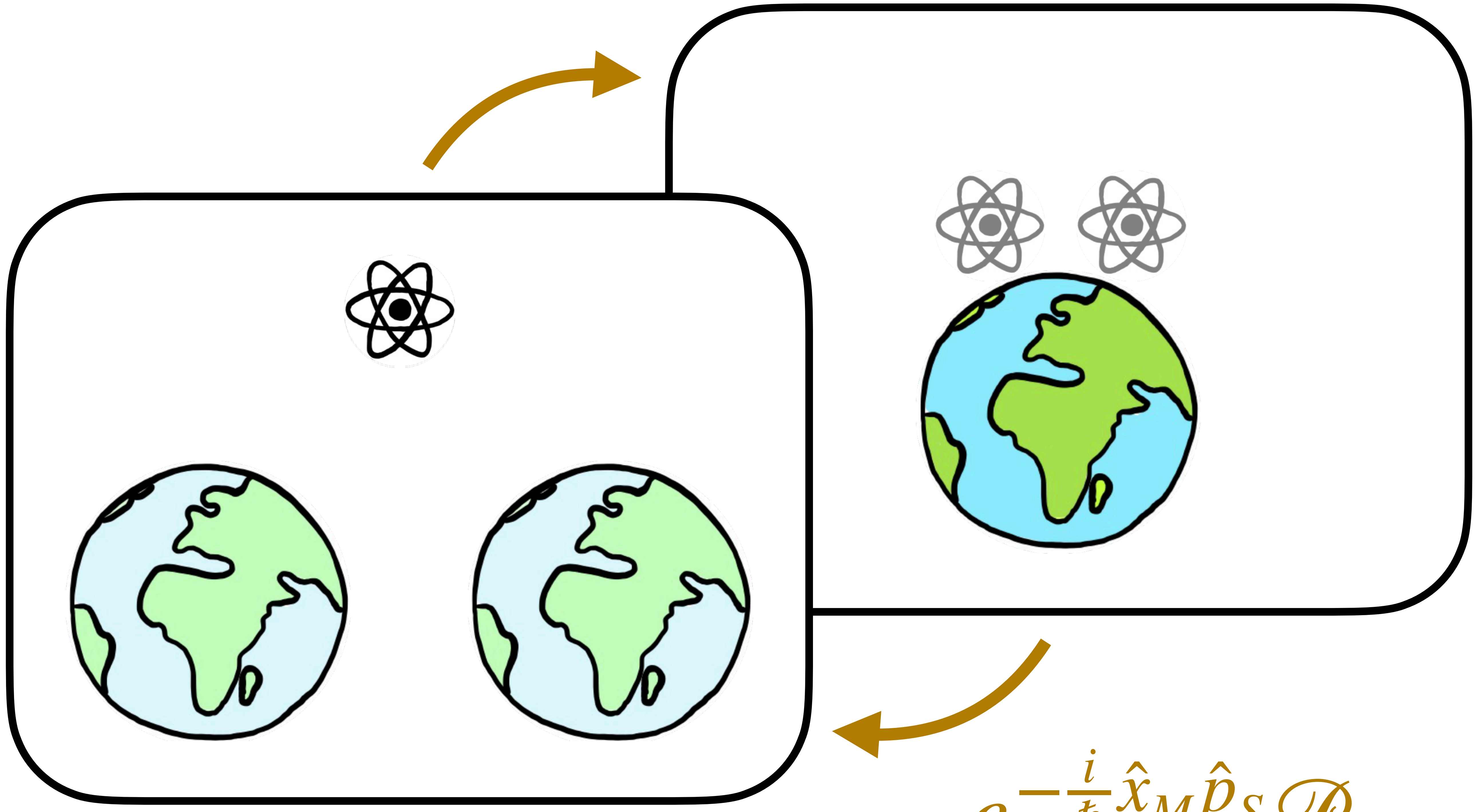
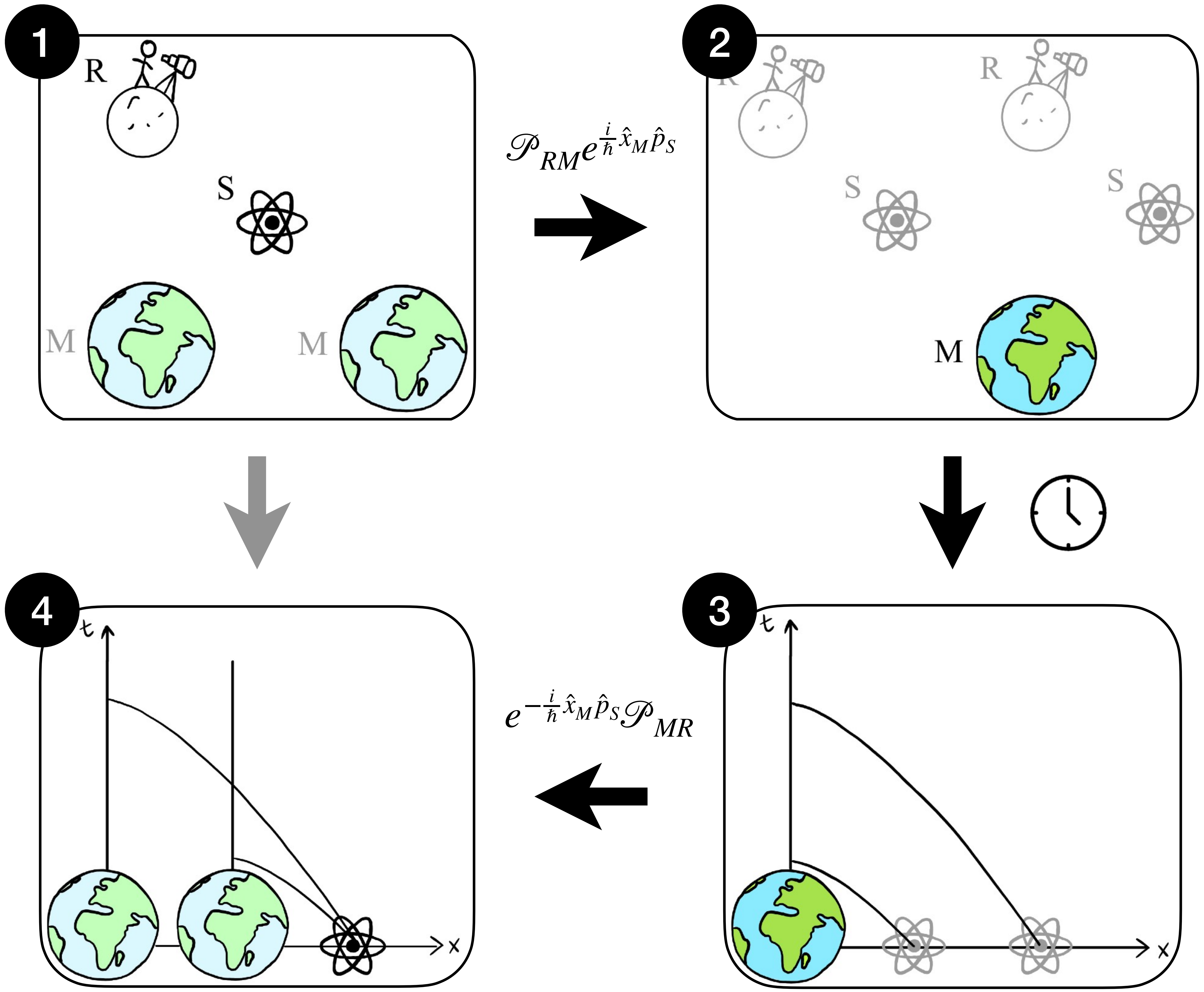
"extended symmetry principle"



$$e^{-\frac{i}{\hbar}\hat{x}_M\hat{p}_S}\mathscr{P}_{MR}$$

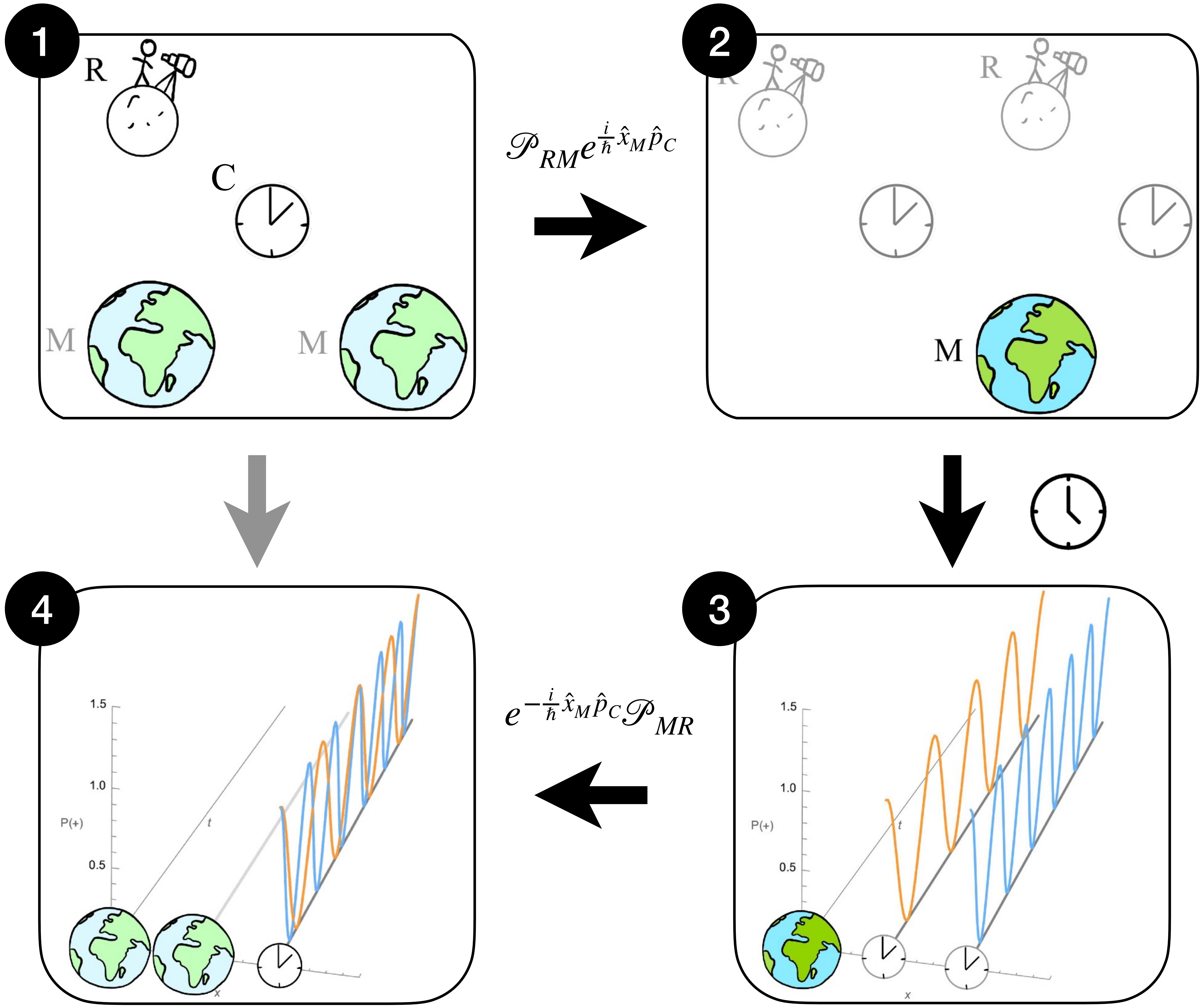
Quantum reference frames as a tool for predictions

Motion of a test particle



Quantum reference frames as a tool for predictions

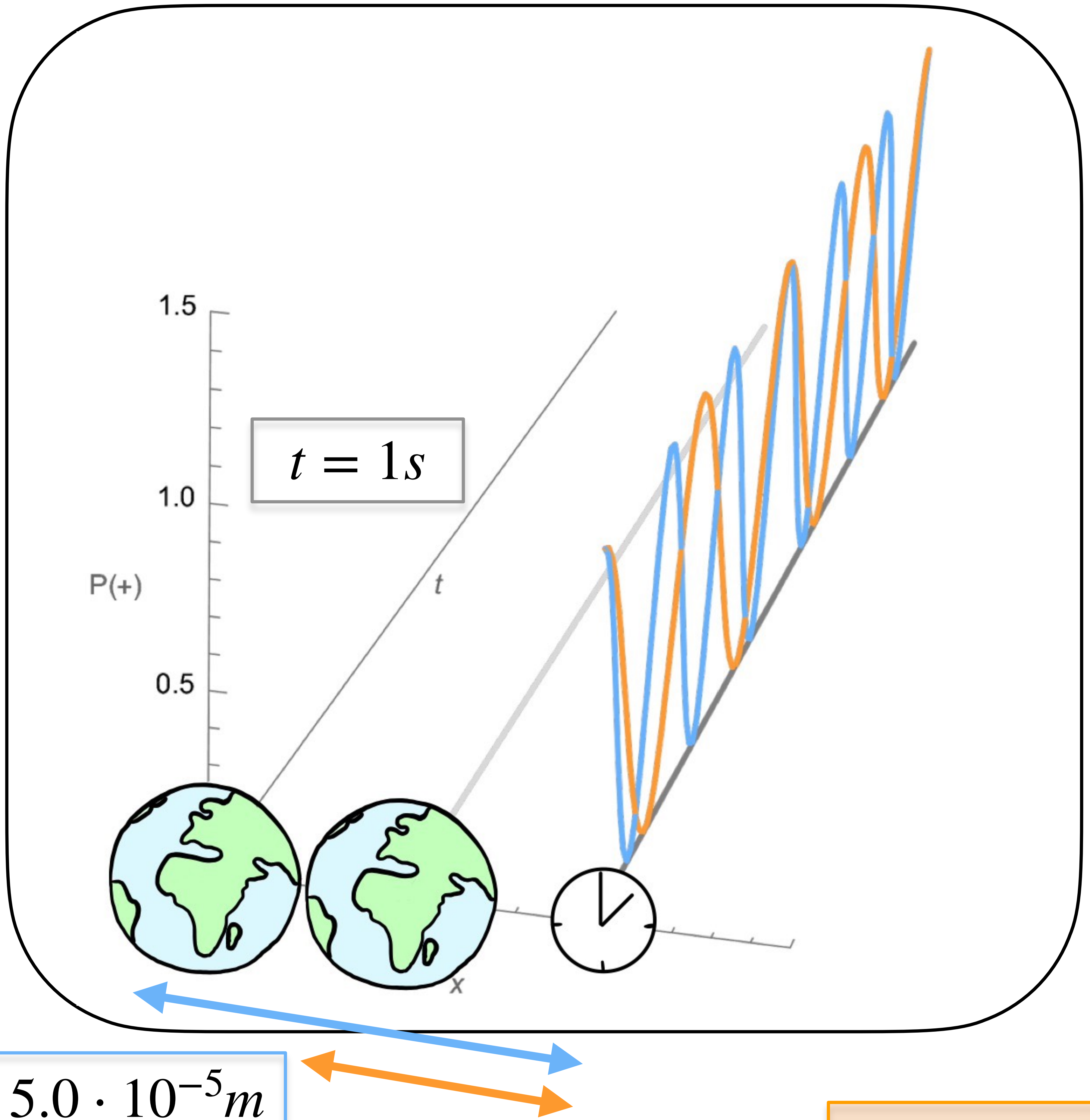
Application: Time dilation



Quantum reference frames as a tool for predictions

Application: Time dilation

$M = 10^{-8} kg$



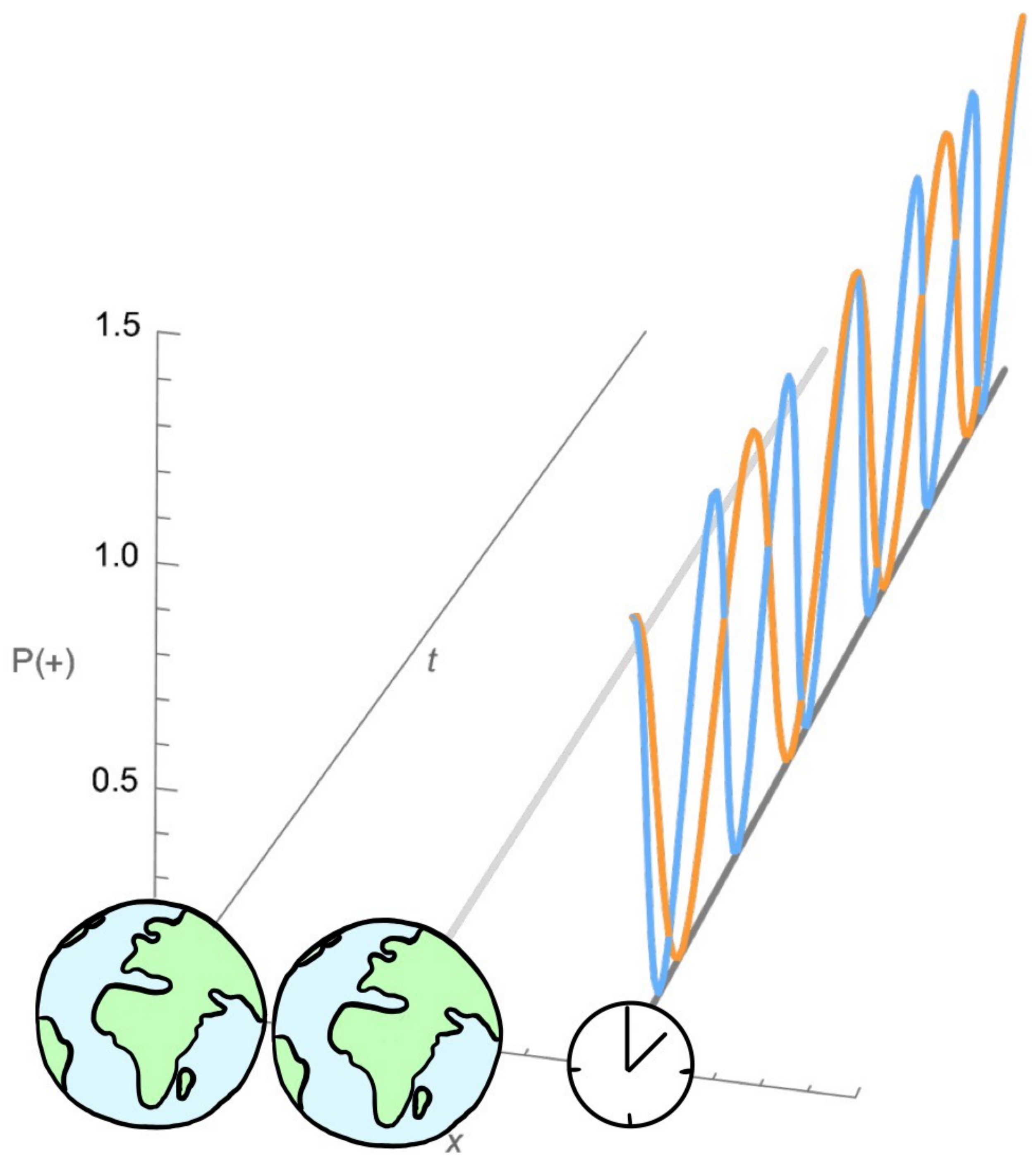
$l^{(1)} = 5.0 \cdot 10^{-5} m$

$l^{(2)} = 5.5 \cdot 10^{-5} m$

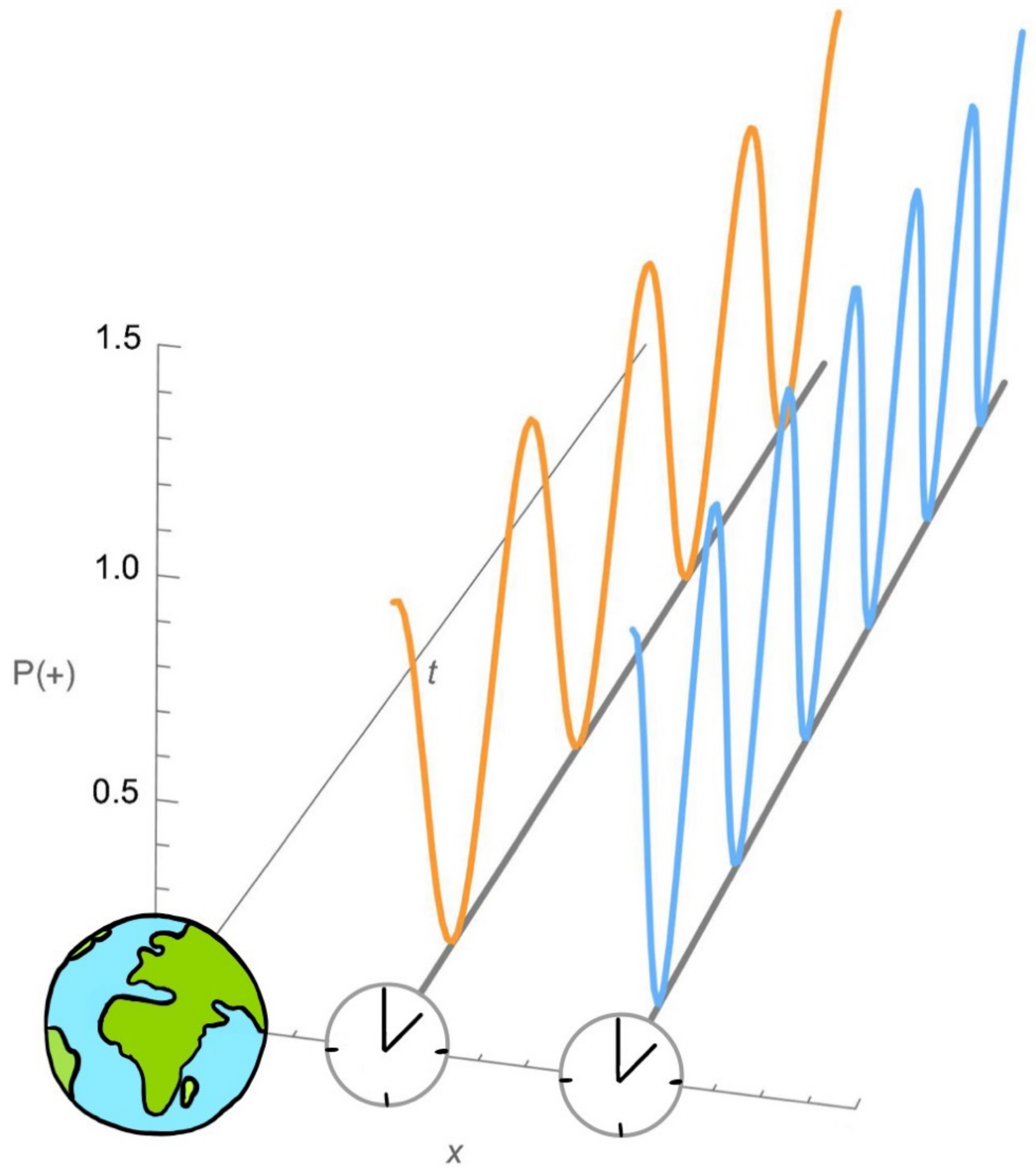
$$\Delta\tau = \tau^{(2)} - \tau^{(1)} \approx 10^{-32} s$$

Quantum reference frames as a tool for predictions

Application: Time dilation



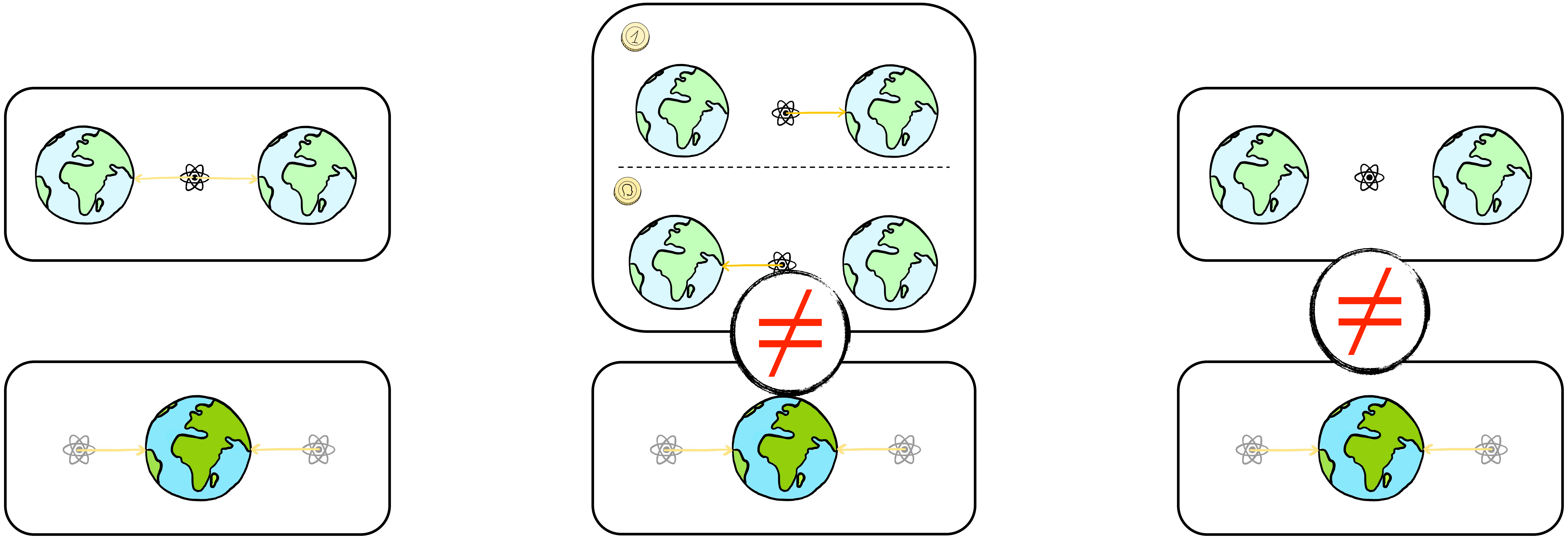
Consistent with gravitational field in superposition.



ACdlH, V. Kabel, E. Castro-Ruiz, Č. Brukner, Commun Phys 6, 231 (2023).

Quantum reference frames as a tool for predictions

Comparison with other approaches



Quantum General Covariance

Collapse Models

Semi-Classical Gravity

Consistent with gravitational field in superposition.

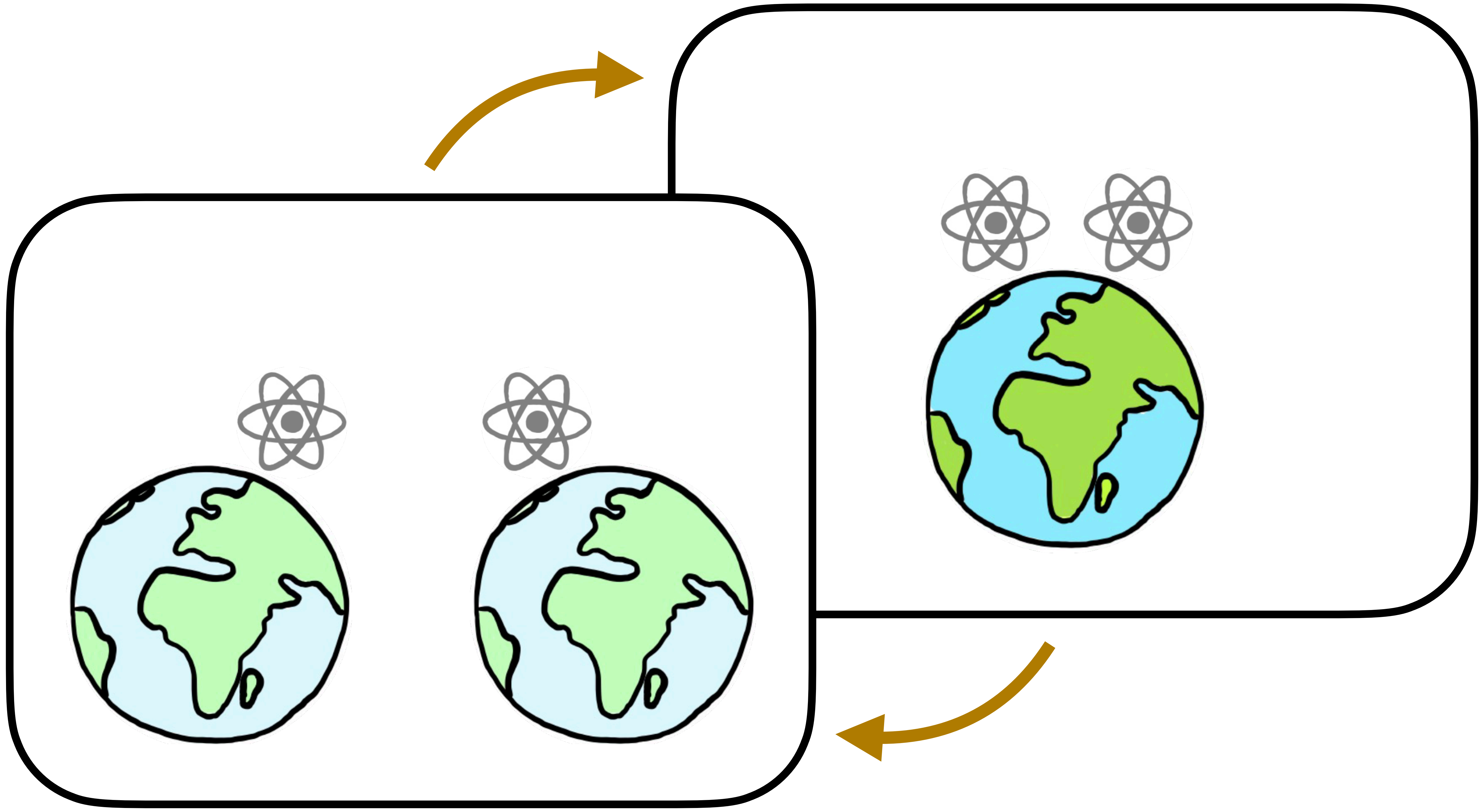
ACdlH, V. Kabel, E. Castro-Ruiz, Č. Brukner, Commun Phys 6, 231 (2023).

Quantum reference frames as a tool for predictions

Gravity sourced by a mass in superposition

Implications

- Concrete predictions while staying agnostic about the quantum nature of the gravitational field.
- Coherence check for the quantum nature of the gravitational field sourced by a massive object in superposition.



Caveats

- Restricted to superposition of *semiclassical* position states of the gravitational source.

Extended symmetry principles

Quantum reference frames as a tool

Bottom-Up Approach

Symmetries of *known* physical theories + **Linearity of quantum theory** → **Extended symmetry principles**

Invariance under quantum-controlled symmetry transformations

Examples

- Translations, Galilei group [1712.07207]
- Spin rotations [1811.08228, 2103.05022]
- Euclidean group [2112.11473]
- Conformal Transformations [2207.00021]
- Lorentz boosts [2212.14081]
- Quantum Diffeomorphisms [2211.15685] [2402.10267]

Part II: Quantum reference frames for superpositions of spacetimes

A comment on superpositions of spacetimes

Why Study Superpositions of Semi-Classical Spacetimes?

- Particular regime of interest at the intersection of gravity and quantum theory, **complementary** to approaches to a full theory.
- Expected to arise e.g. when a massive object is placed in a spatial SP of two semi-classical configurations

(i) Minimal, well-founded assumptions

(a) *Semi-classical states* of the spacetime metric, peaked around classical solutions to Einstein's equations

(b) *Linearity of quantum theory*

cf. ACdlH, Quantum Reference Frames: From Quantum Information to Spacetime, Doctoral thesis (2025).

A comment on superpositions of spacetimes

Why Study Superpositions of Semi-Classical Spacetimes?

- Particular regime of interest at the intersection of gravity and quantum theory, **complementary** to approaches to a full theory.

- Expected to arise e.g. when a massive object is placed in a spatial SP of two semi-classical configurations

(i) Minimal, well-founded assumptions

(ii) Agreement with predictions from linearised quantum gravity

(iii) Testability in near-future experiments

(iv) Extended symmetry principles from combining classical symmetries with linearity

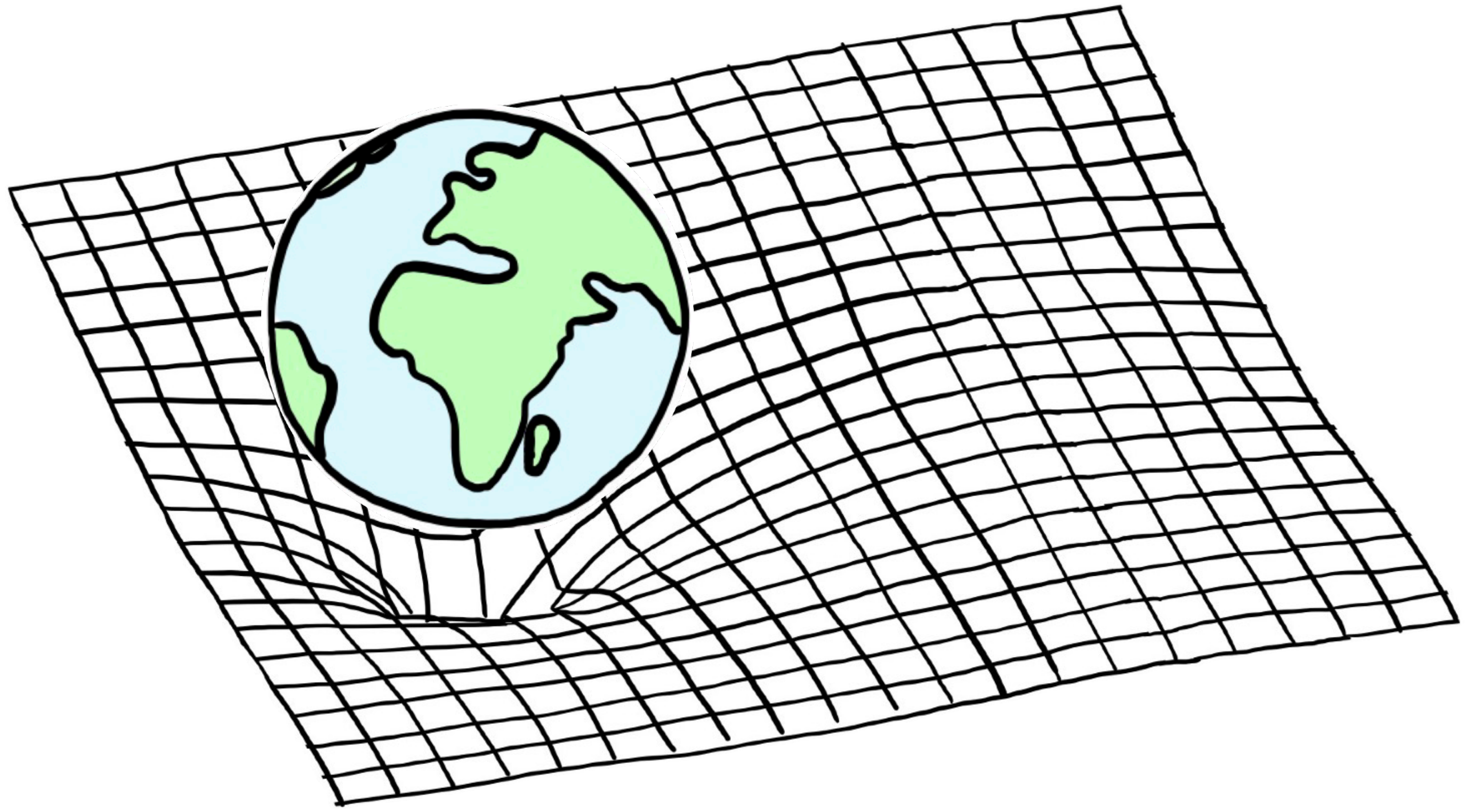
Leads to quantum-controlled symmetry transformations

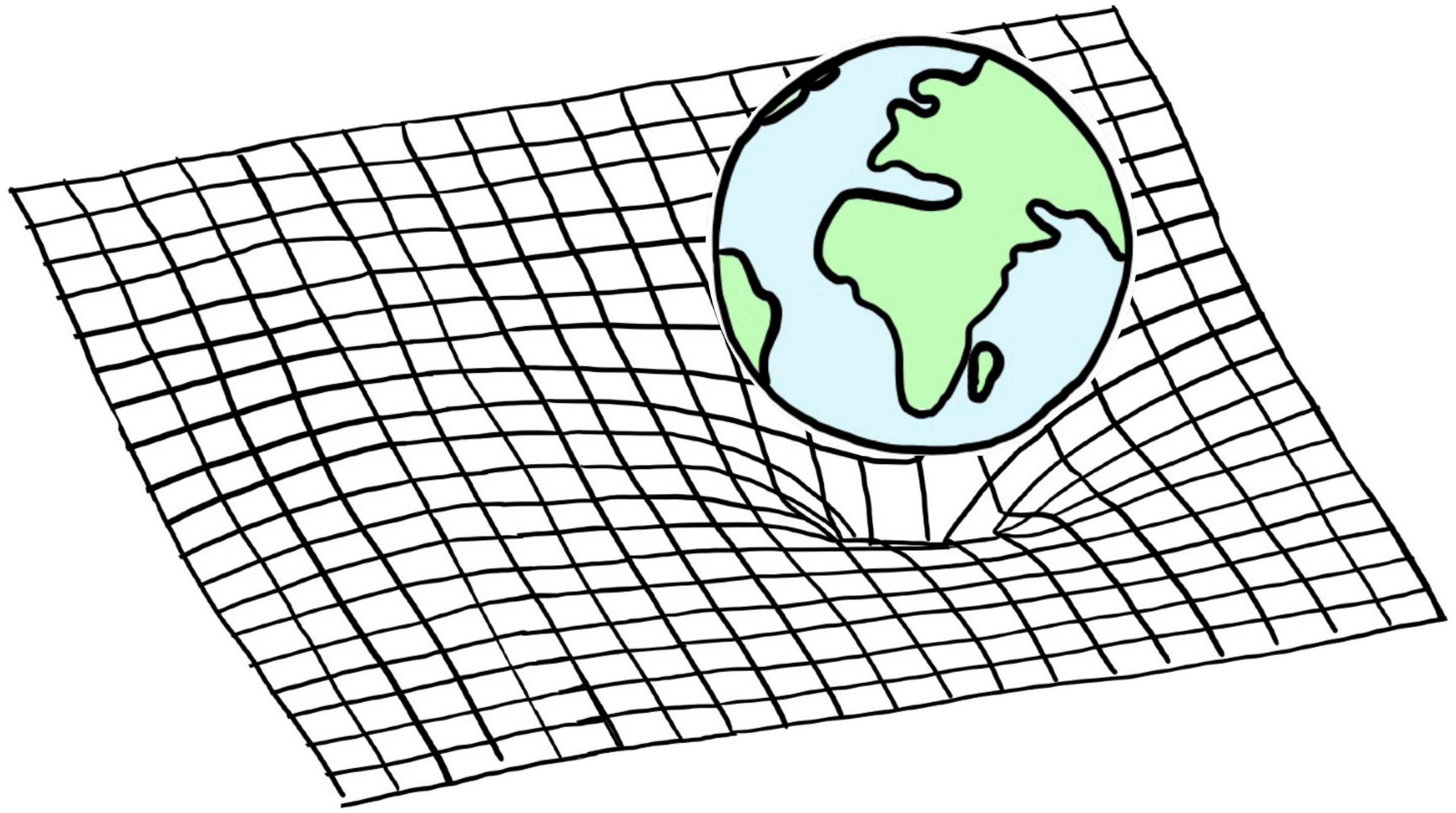
→ Identified with QRF transformations under the classical symmetry group

→ Enables search for QRF invariants and insight into observables in quantum gravity

cf. ACdlH, Quantum Reference Frames: From Quantum Information to Spacetime, Doctoral thesis (2025).

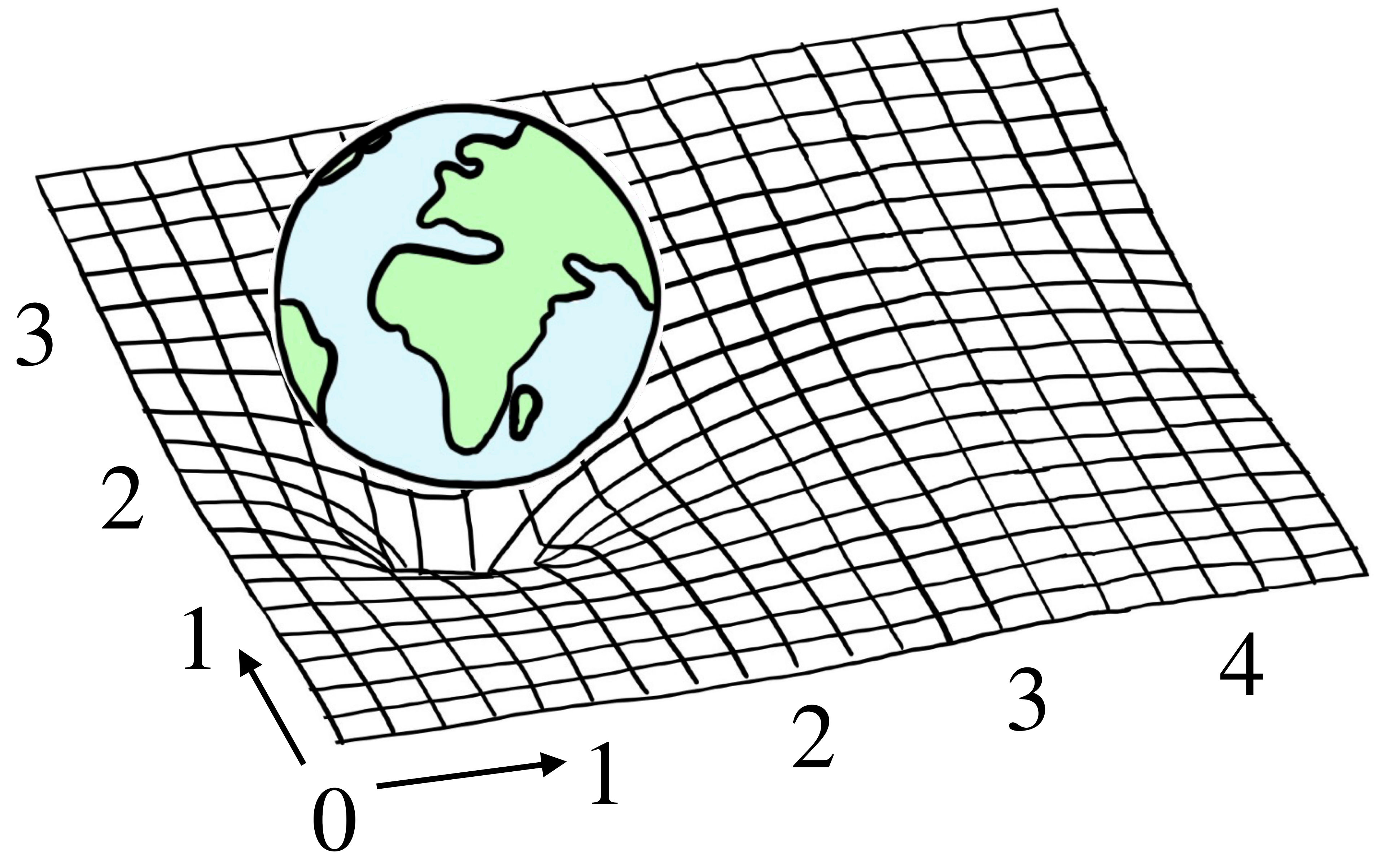
Quantum Reference Frames for Spacetimes

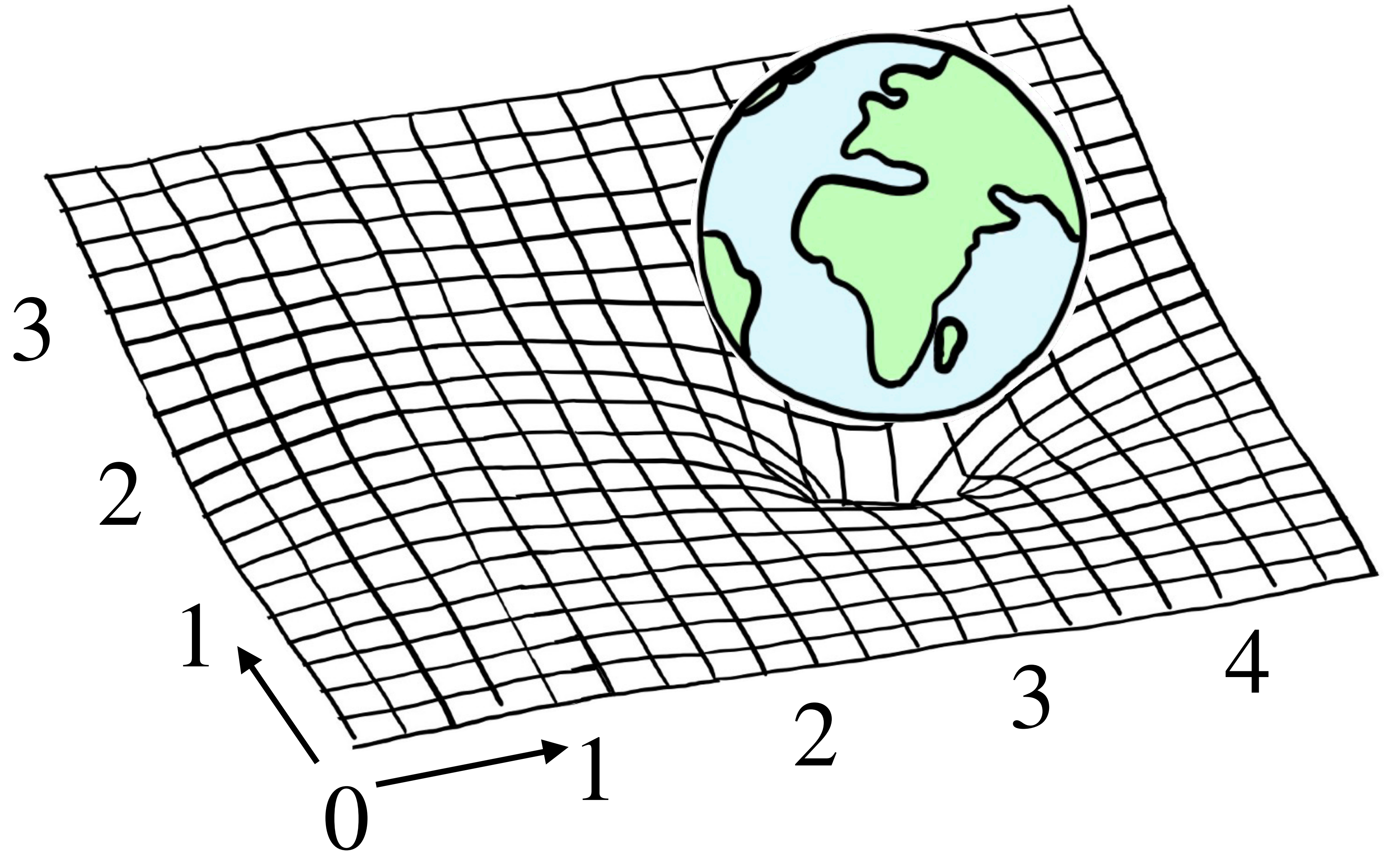




What does it even mean that the mass is
in a superposition of locations?

Quantum Reference Frames for Spacetimes

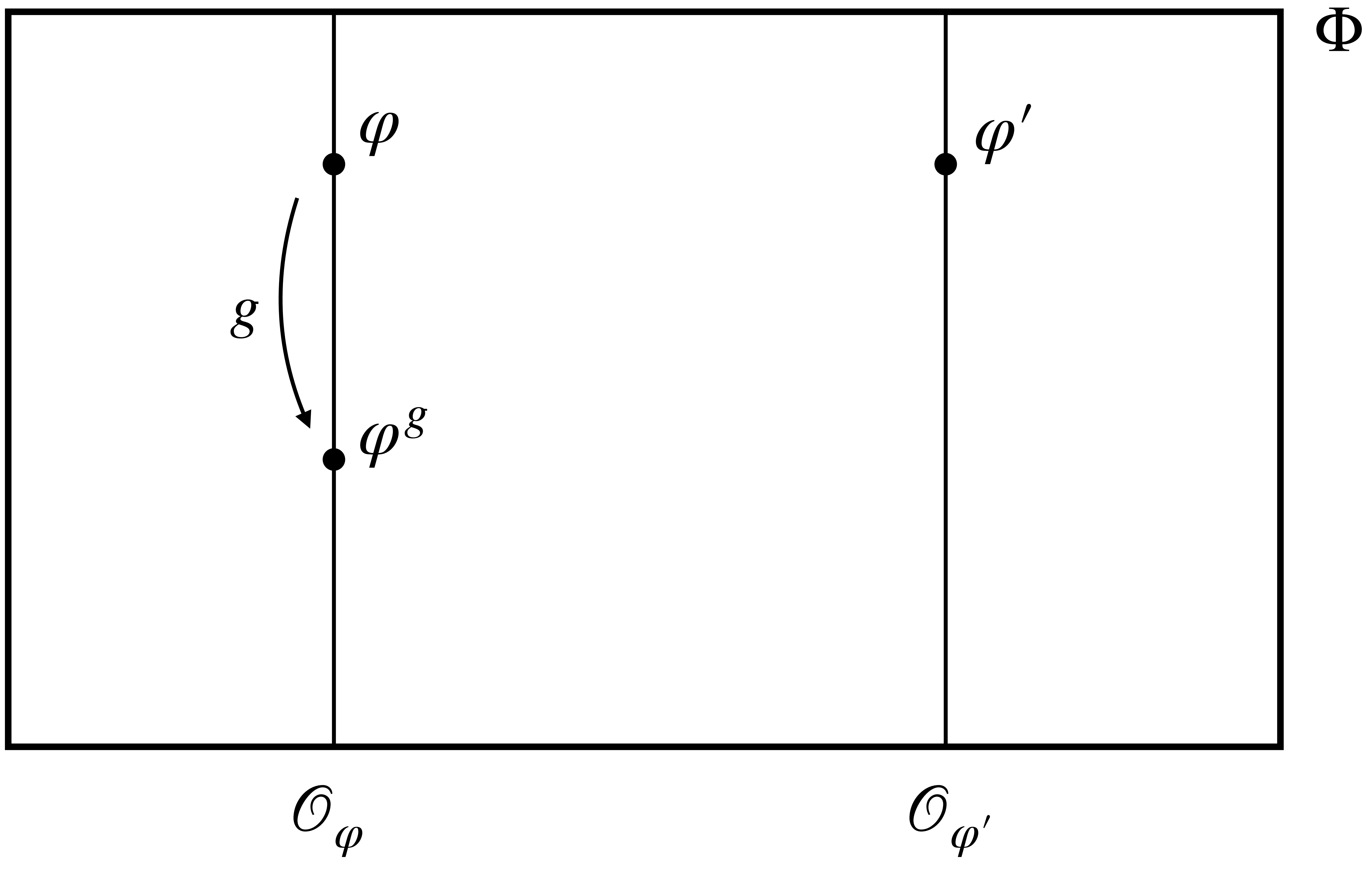




What does it even mean that the mass is in a superposition of locations?

Symmetries & Counterparts

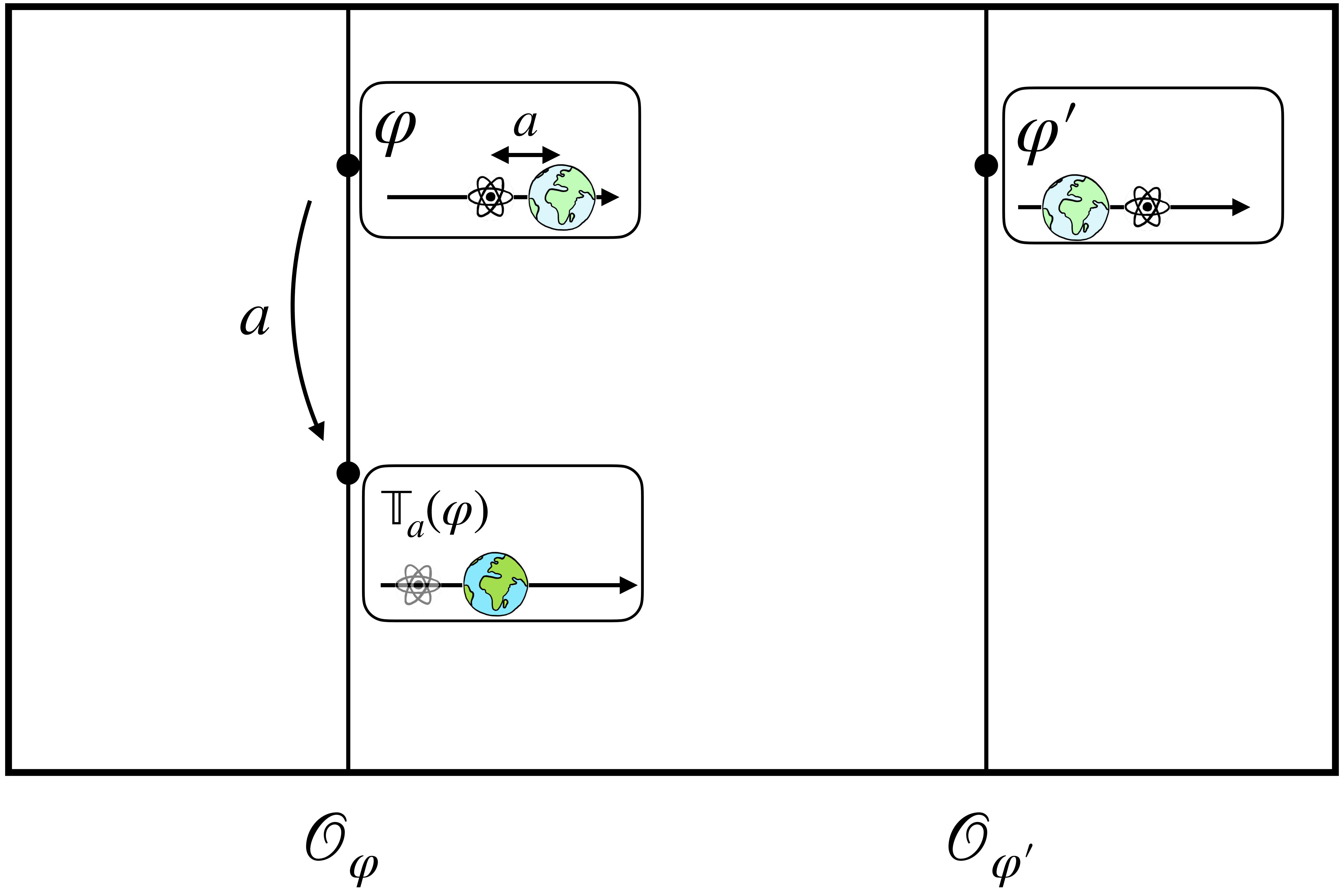
- Consider a theory with symmetry group G.
- The space of all possible configurations (models) can be partitioned into orbits of G.
- Models on a given orbit are taken to represent the ***same*** physical state of the world.



Symmetries & Counterparts

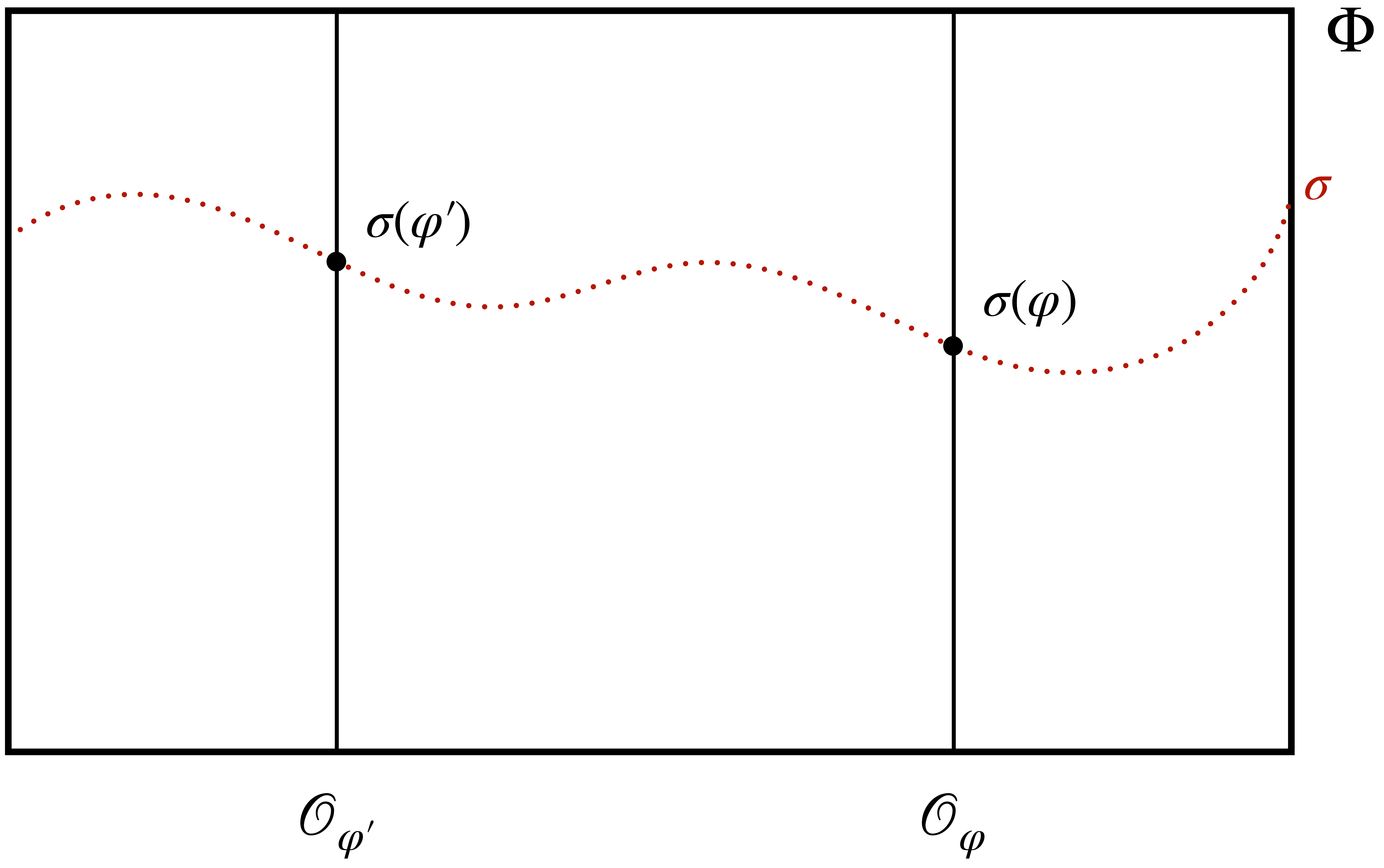
Example: Translation Group

- Newton's theory of a gravitating particle is invariant under the translation group.
- Two models related by a **rigid translation** live on the same orbit.
- Such situations are taken to be **physically equivalent**.



Symmetries & Counterparts

- A **section** picks one representative $\sigma(\varphi)$ on each orbit $\mathcal{O}_\varphi$.
- The choice of section is a matter of ***convention*** and can be seen as a choice of **reference frame**.



Gomes (2021), Gomes & Butterfield (2023)

Symmetries & Counterparts

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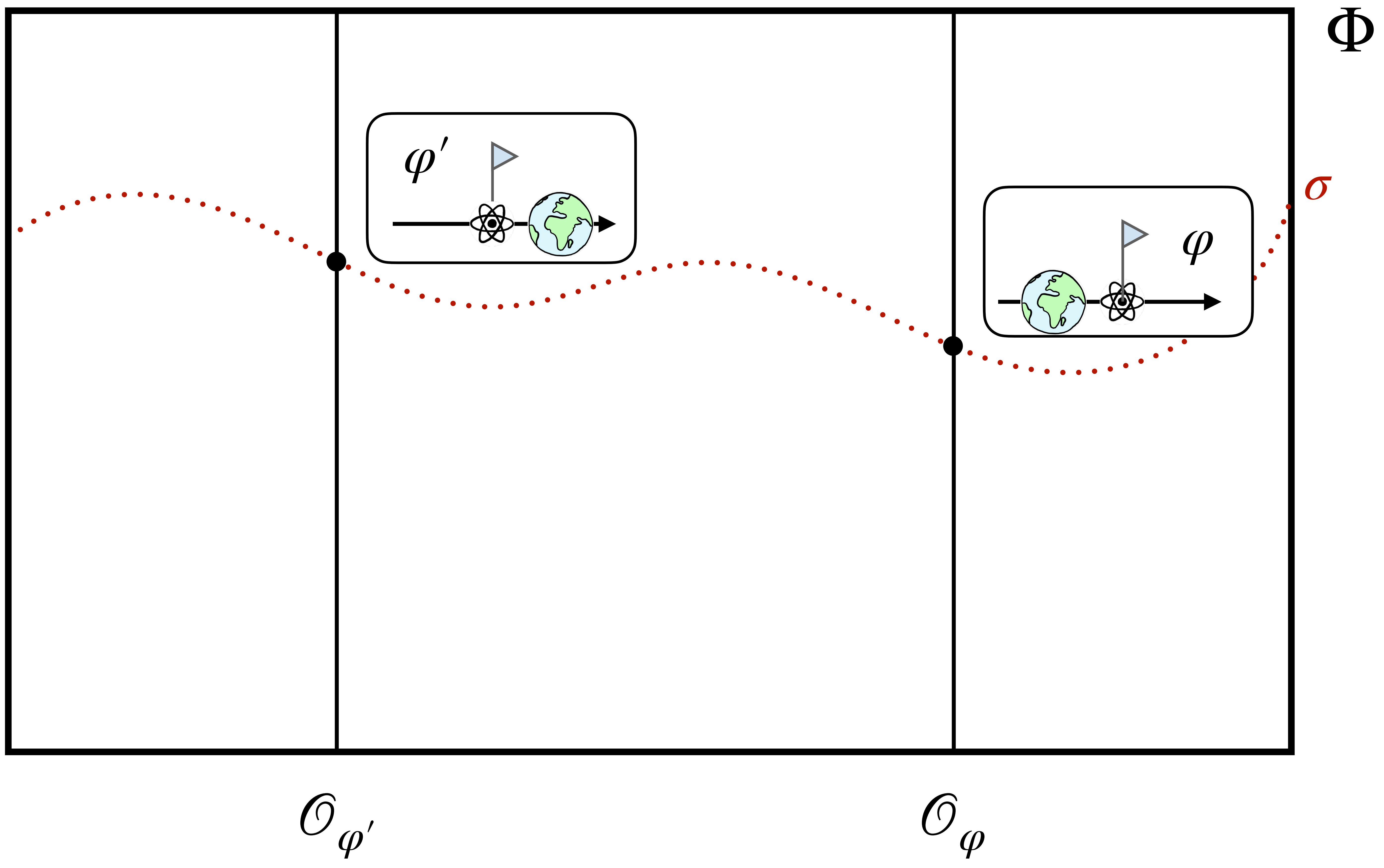
- The choice of section is a matter of ***convention*** and can be seen as a choice of **reference frame**.
- **Example:** choice of origin in translationally invariant theory.



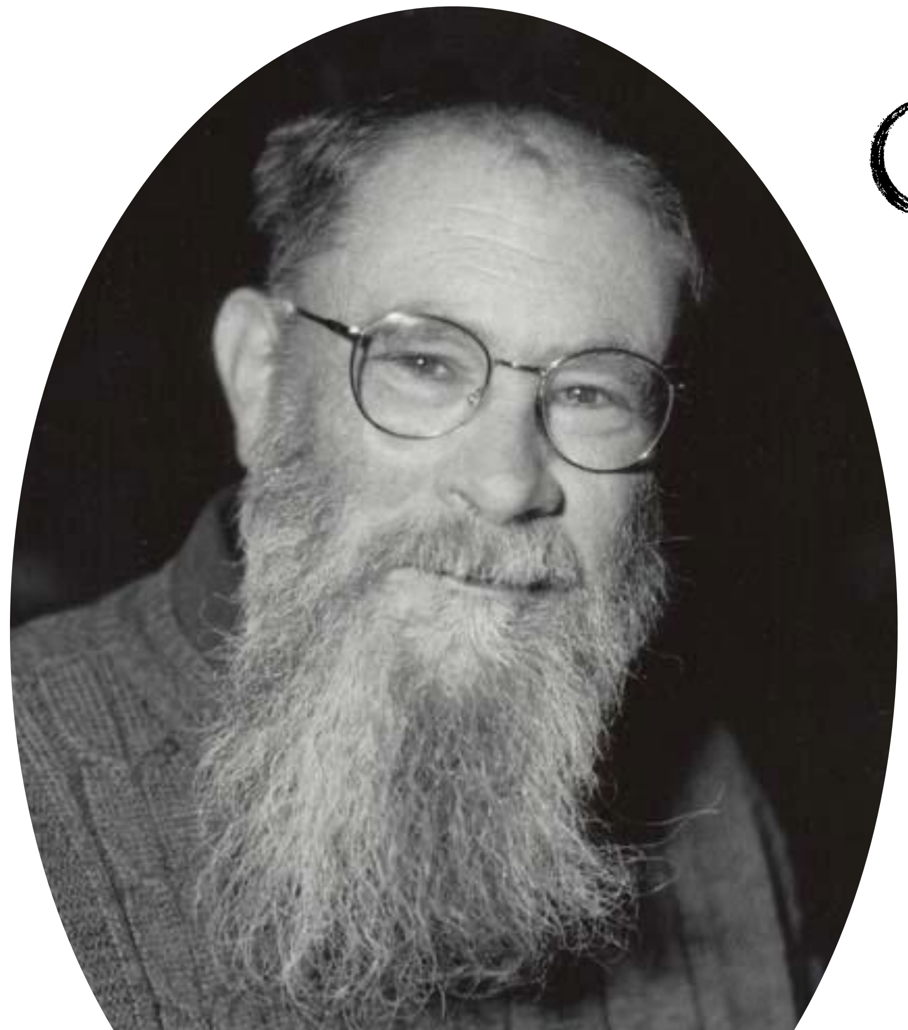
Symmetries & Counterparts

Counterpart Relation

Objects in different possible worlds
are **never identical**.

They are **counterparts** of each other.

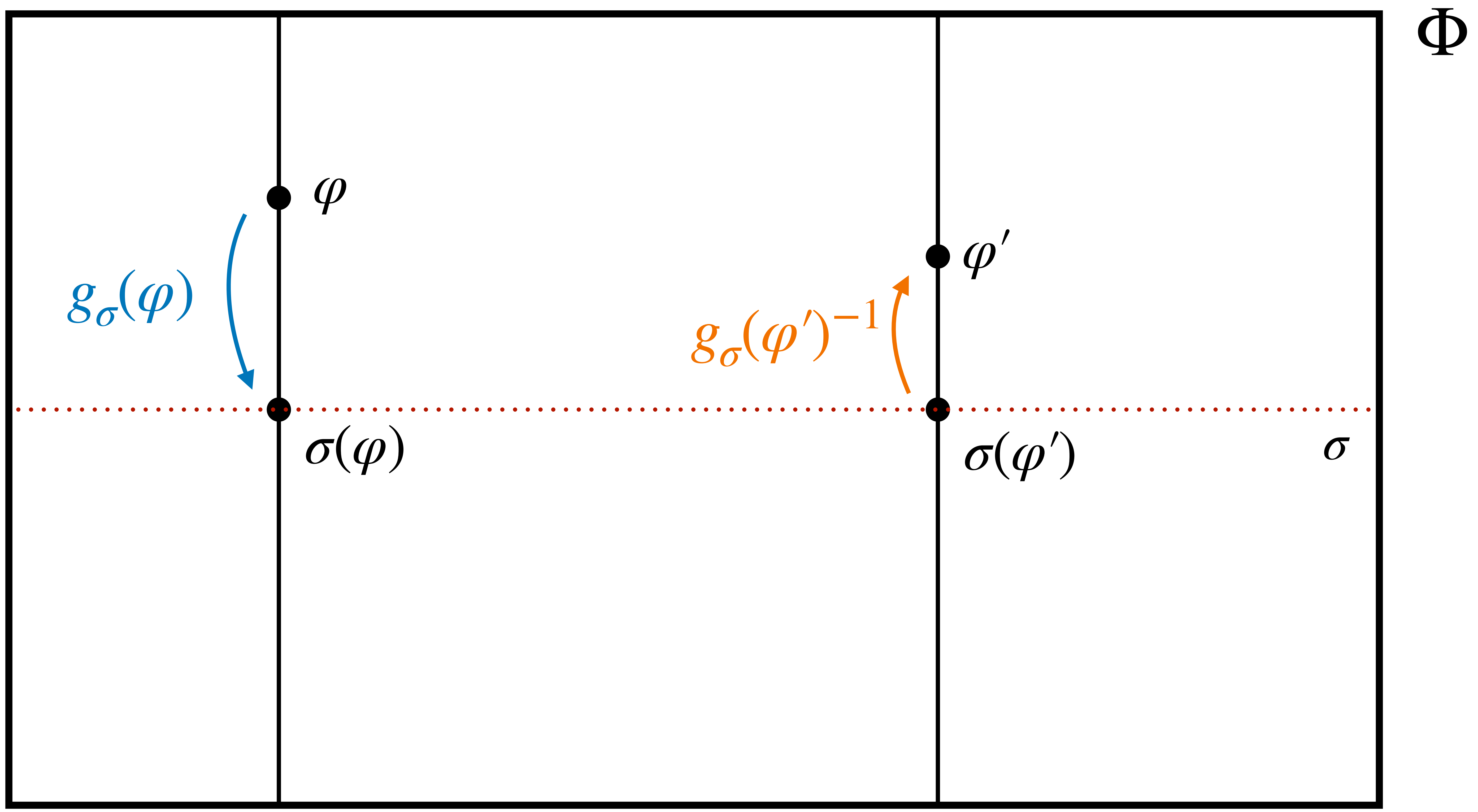
Objects are counterparts if they
are **similar** in relevant aspects -
which aspects is **“up to us”**.



Lewis (e.g. 1973)

Symmetries, counterparts, identification

- The choice of section determines how to **compare** different possible configurations.
- The **counterpart relation** allows us to state whether two configurations are **“the same”** or **“different”**.



$$\mathrm{Counter}_\sigma(\varphi, \varphi') = \boxed{g_\sigma(\varphi')^{-1}}\boxed{g_\sigma(\varphi)}$$

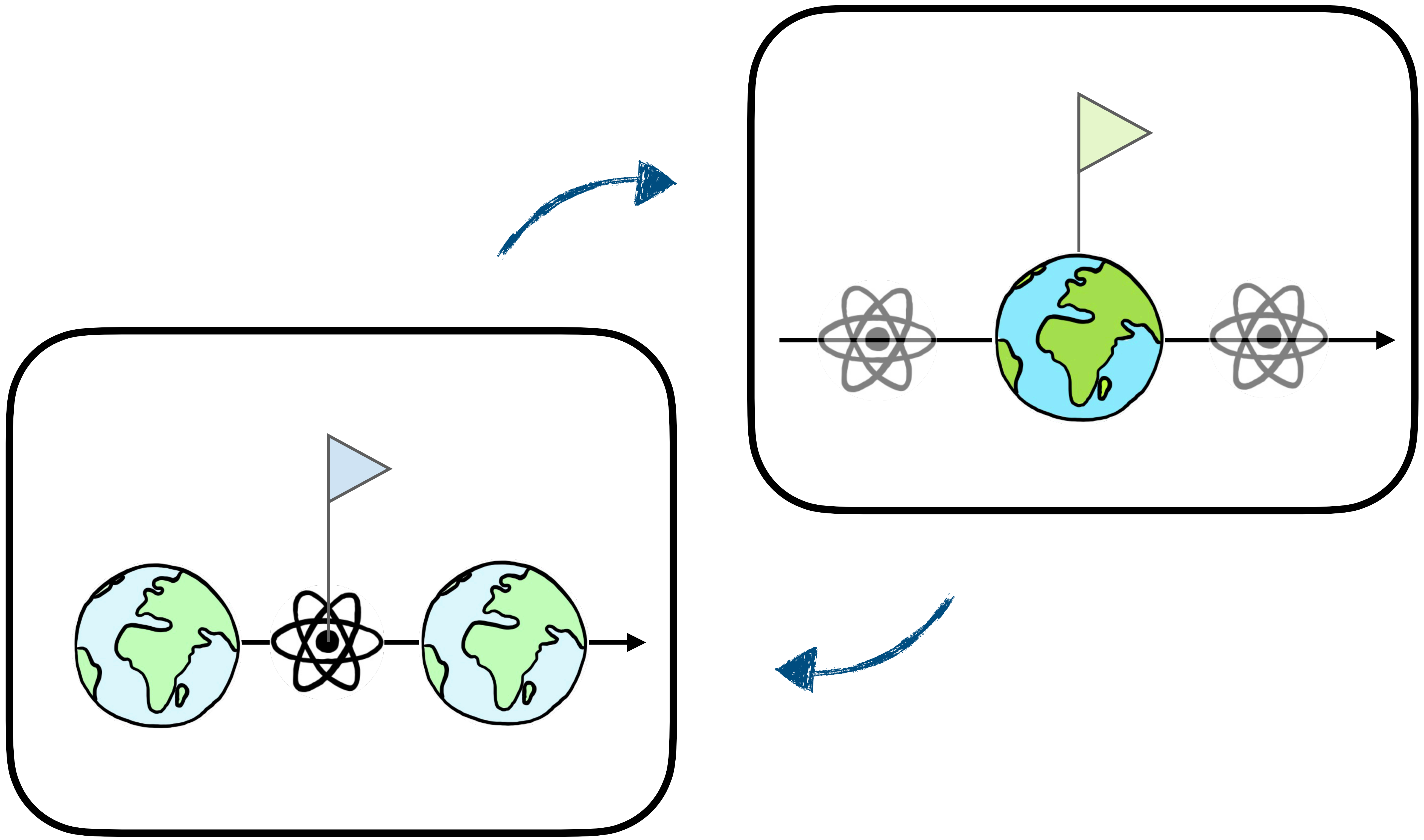
Gomes & Butterfield (2023), Gomes (2024)

Quantum Reference Frames

Example: Translation Group

- **Idea:** a **choice of QRF** corresponds to a **choice of section**
- A QRF tells us what the **same** or **different** elements are **relative** to it.
- In the frame of P, the position of P is **identified** across both branches

$$|\psi\rangle^{(M)}_{MP} = |0\rangle_M \otimes (\alpha|a\rangle_P + \beta|-a\rangle_P)$$



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Quantum Reference Frames

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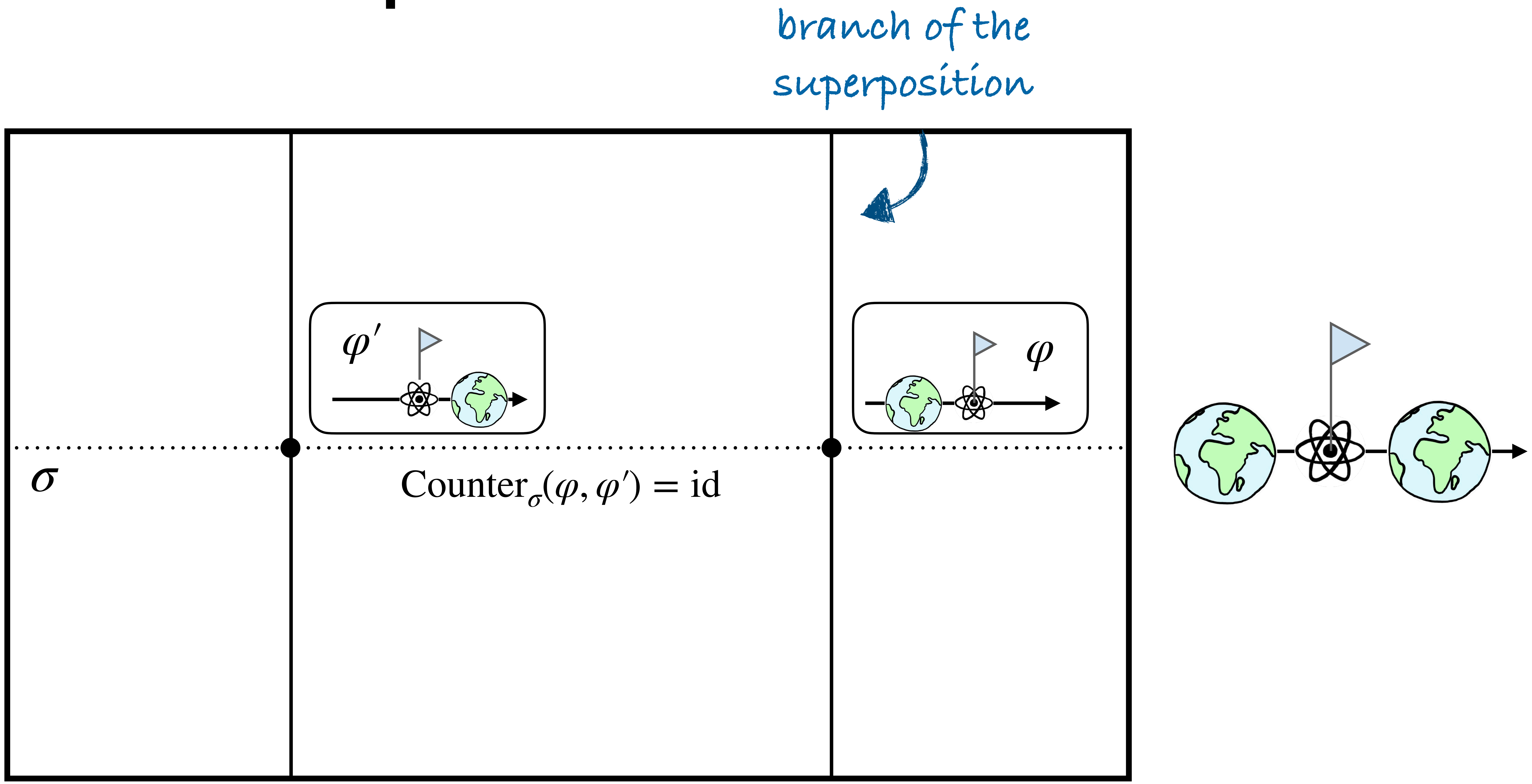

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Quantum Reference Frames

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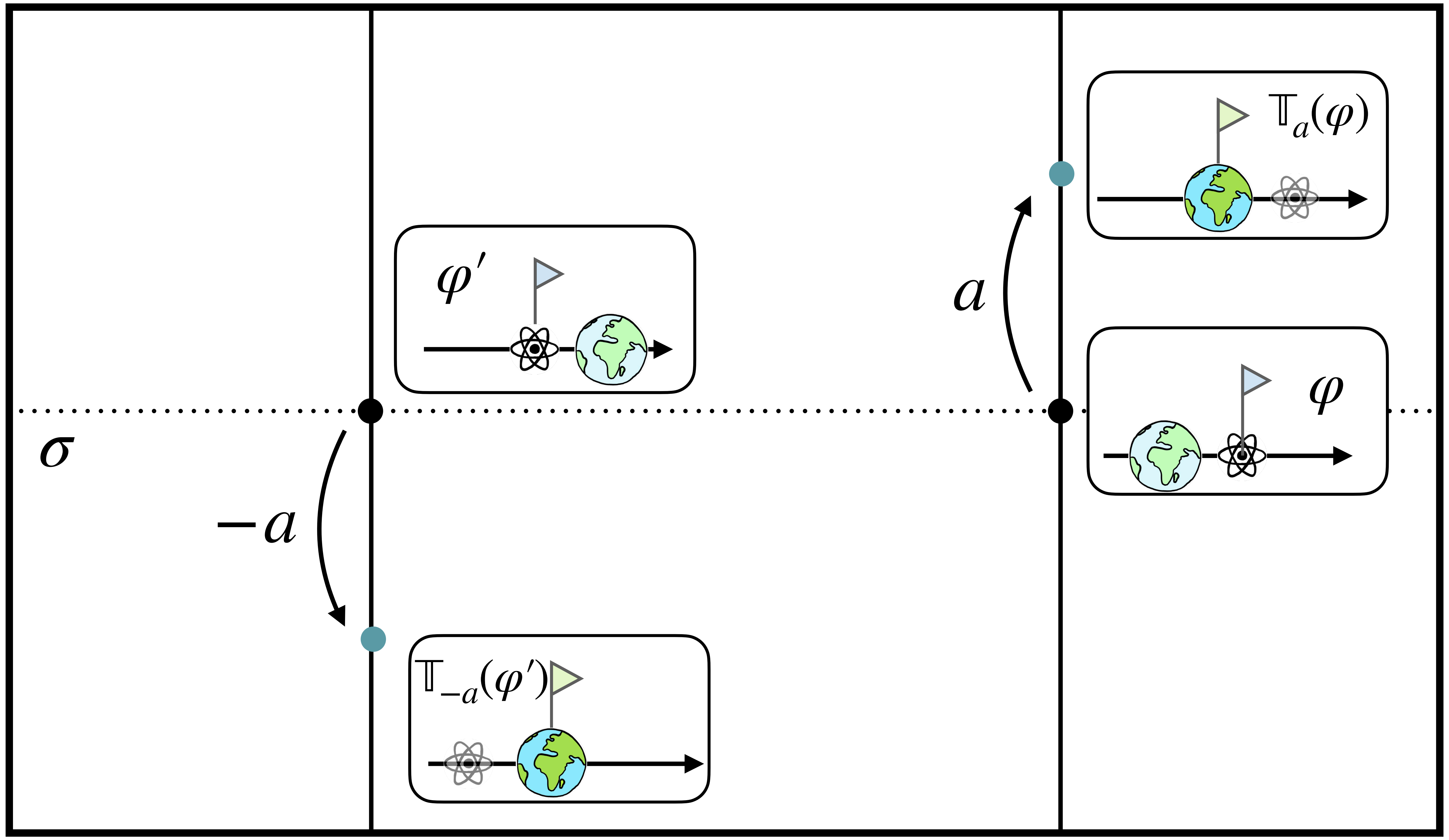

Quantum Reference Frames

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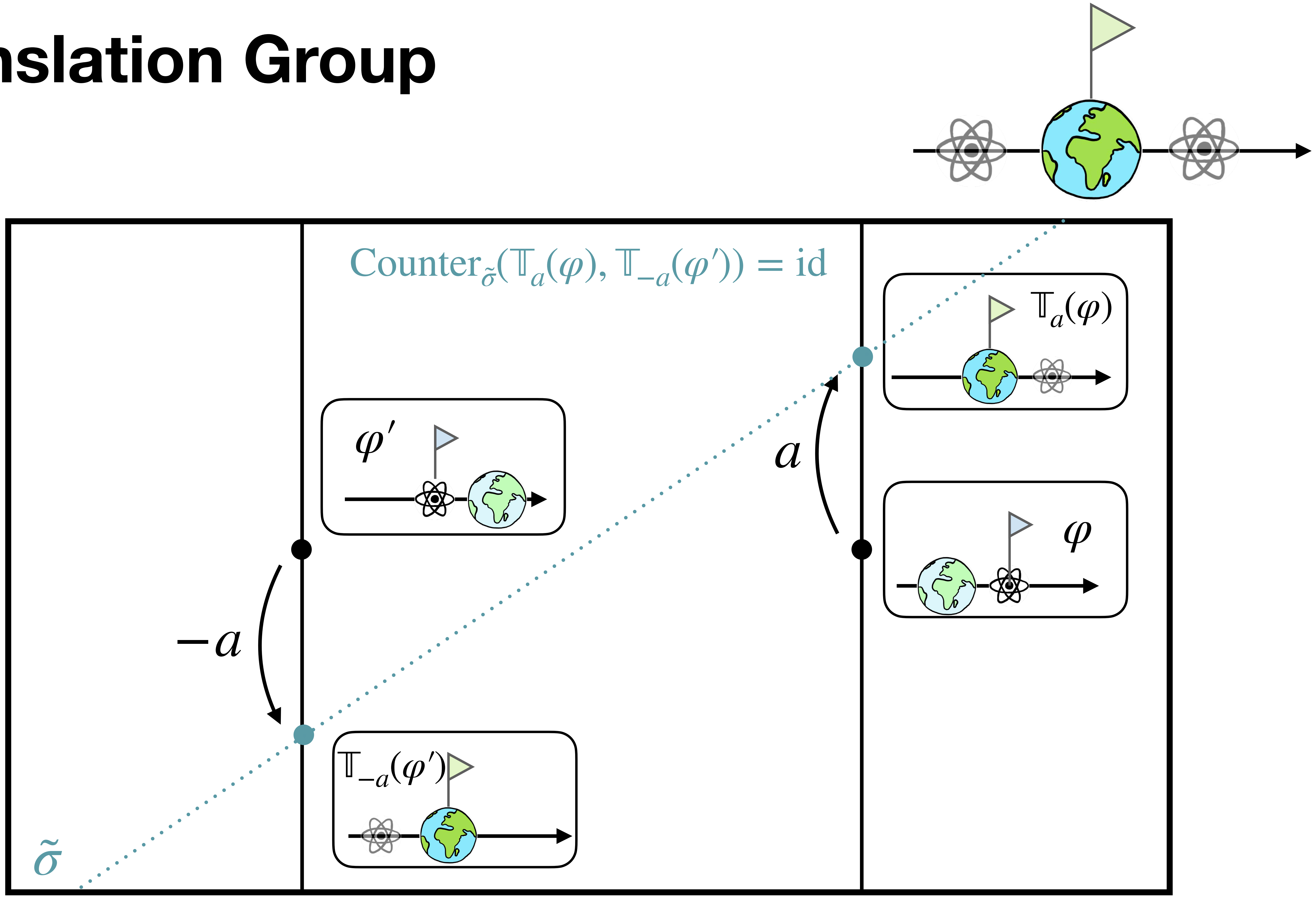

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Quantum Reference Frames

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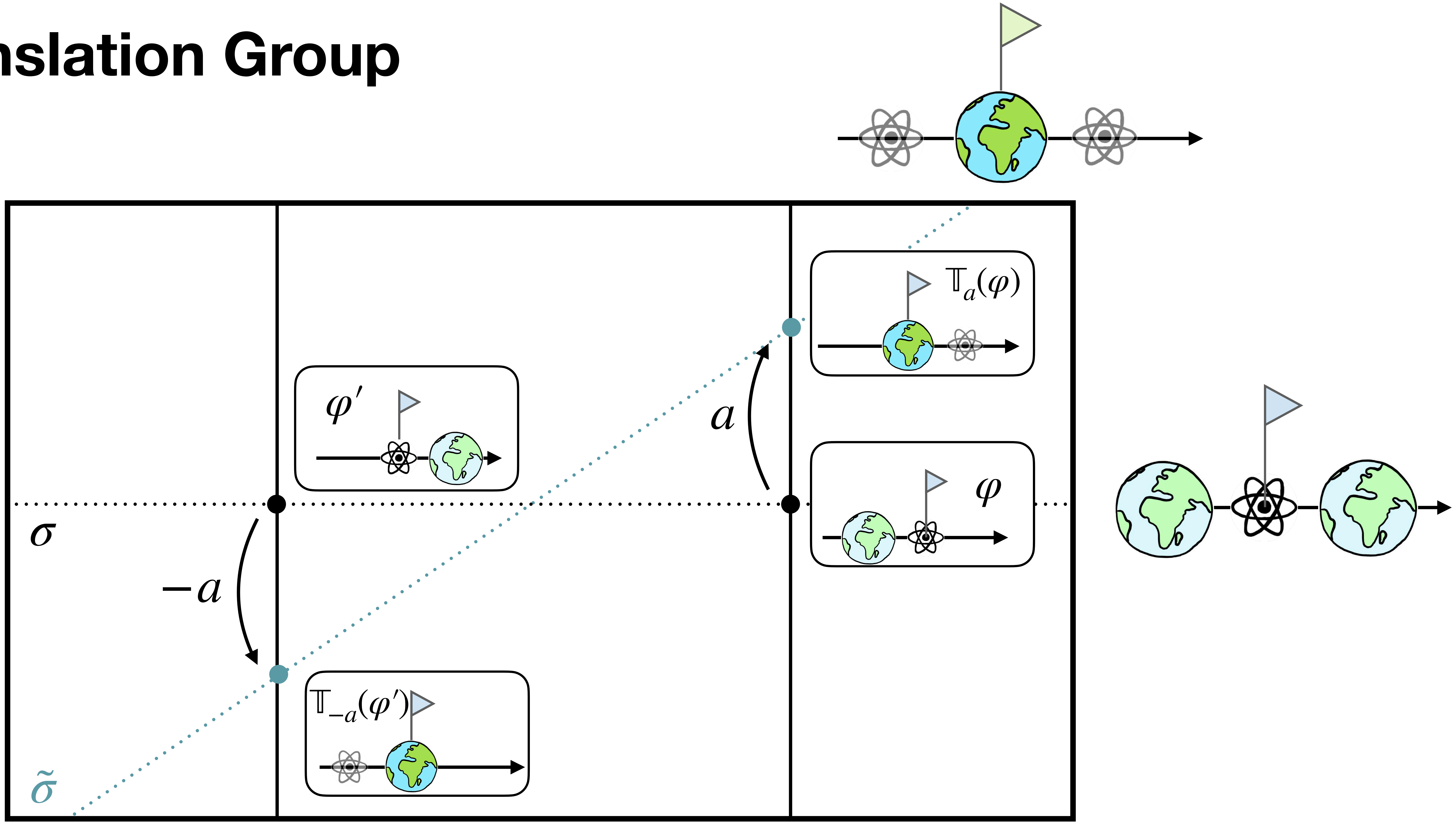
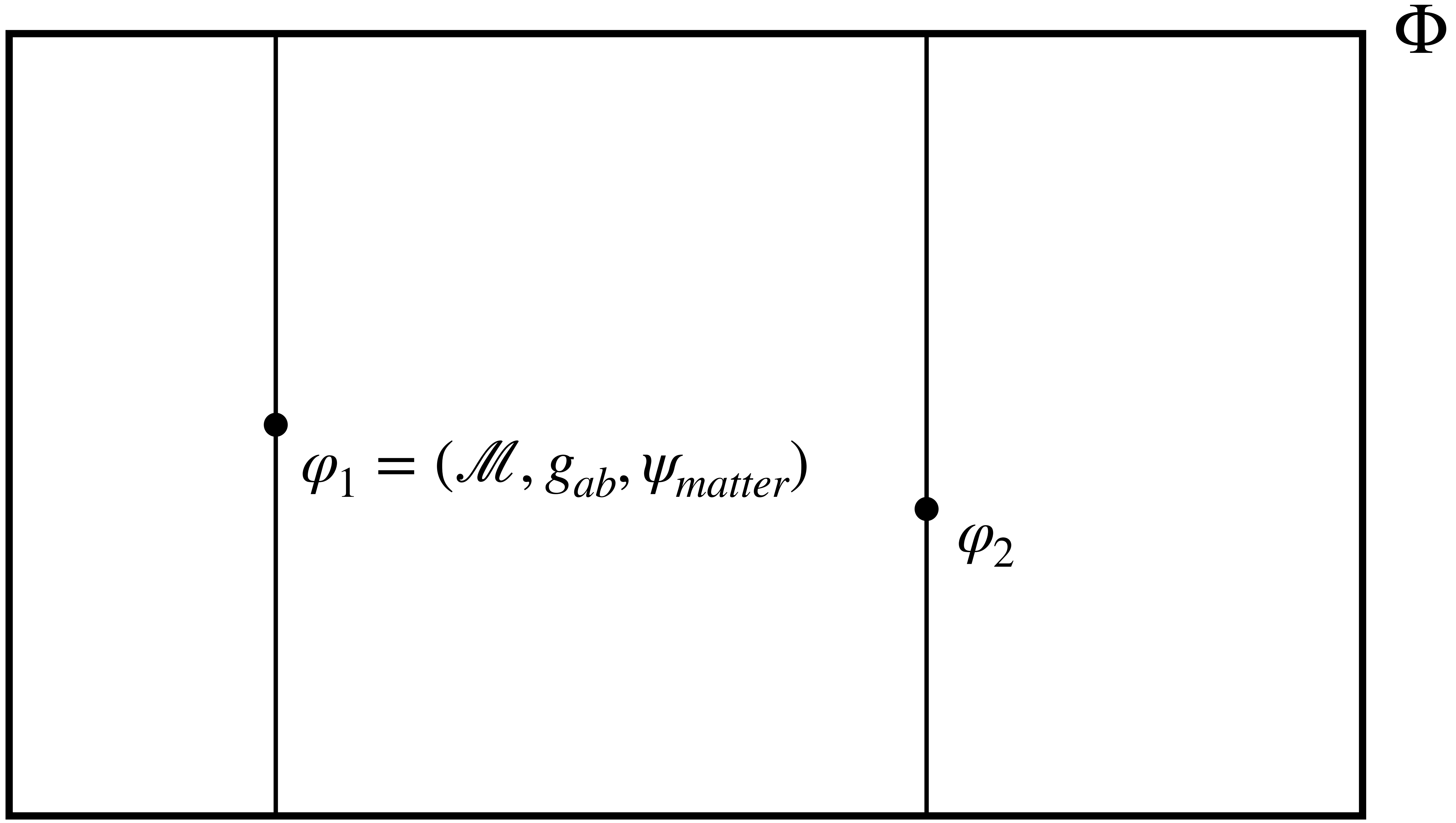


How we identify position across the branches changes with the QRF.

→ Superposition becomes a reference frame dependent feature.

QRFs for superpositions of spacetimes

- A **model** is a tuple $(\mathscr{M}, g_{ab}, \psi_{matter})$.
- Space of models Φ is the set of **kinematically possible** models.



QRFs for superpositions of spacetimes

- A **model** is a tuple $(\mathscr{M}, g_{ab}, \psi_{matter})$.
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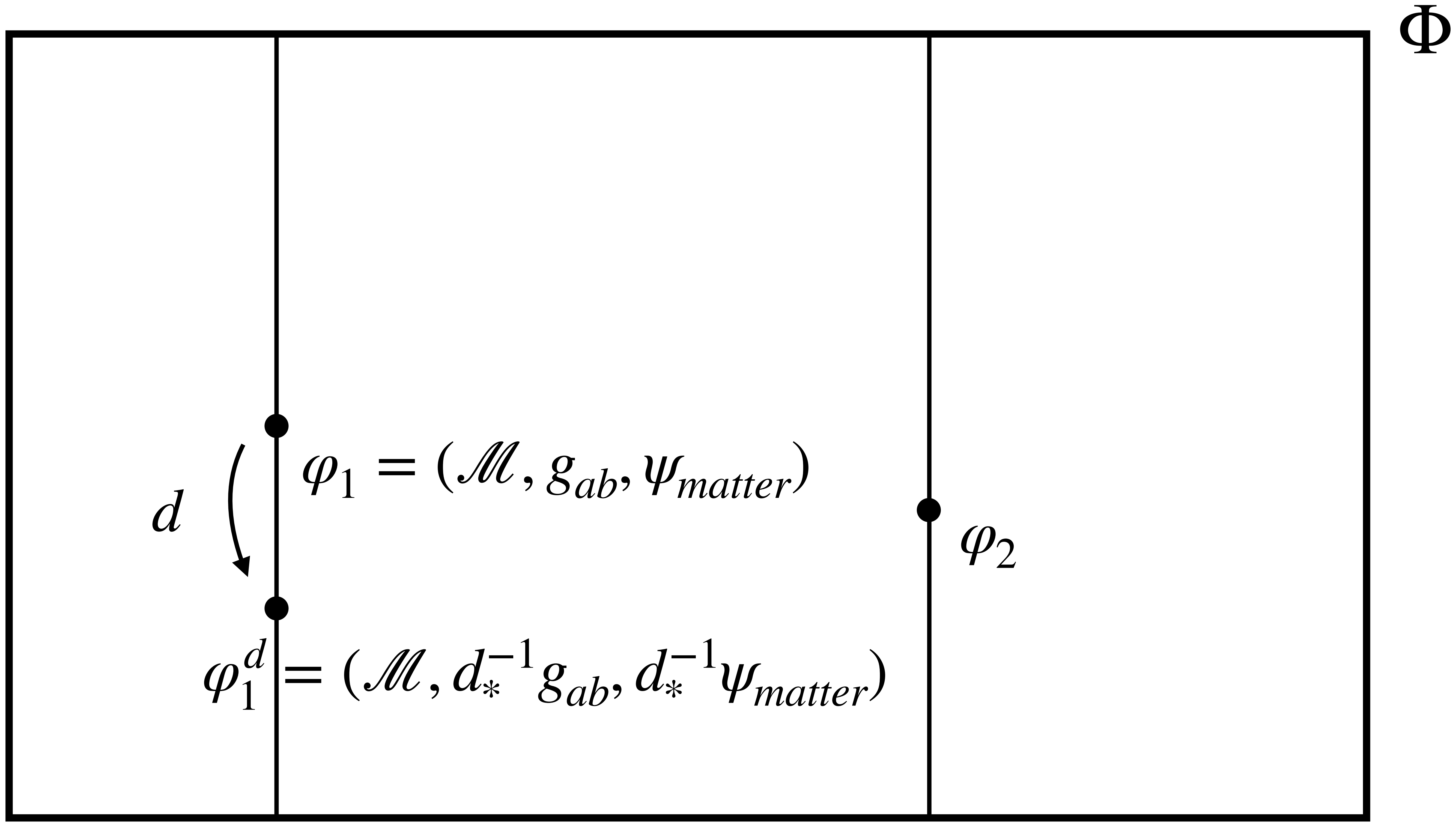
- Symmetry group is $G = \mathrm{Diff}(\mathscr{M})$.



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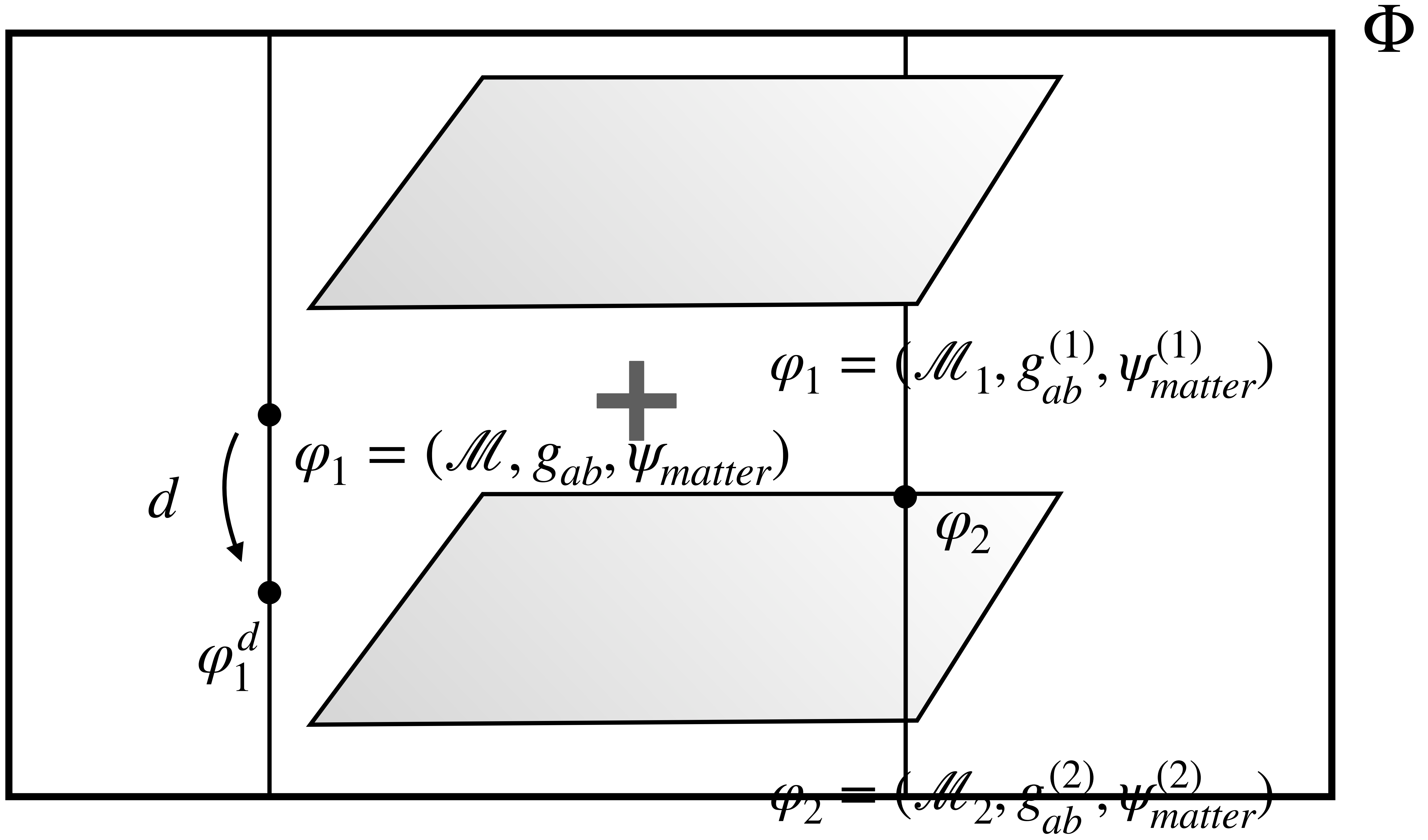

QRFs for superpositions of spacetimes

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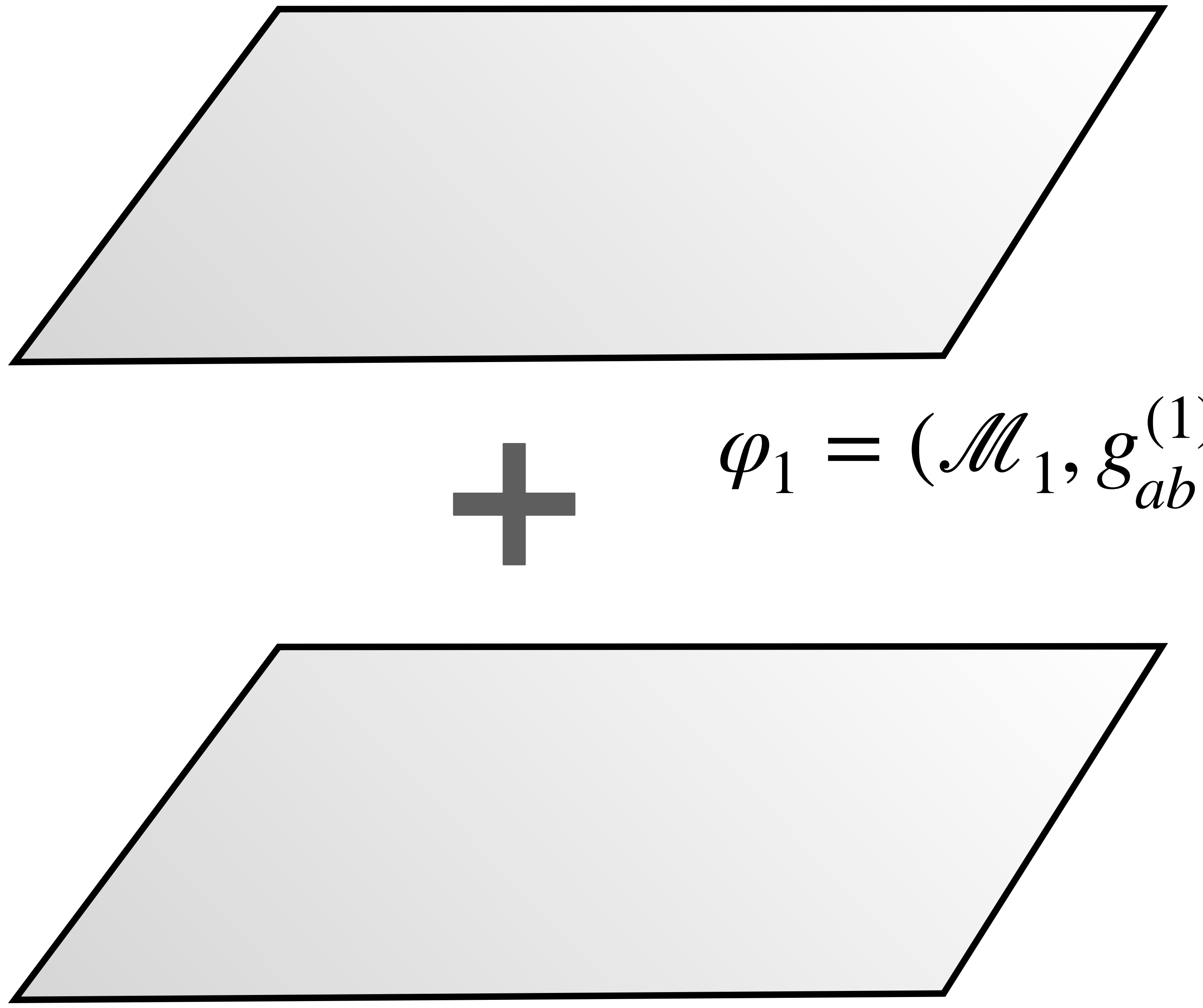
- Space of models Φ is the set of **kinematically possible** models.
- Symmetry group is $G = \mathrm{Diff}(\mathscr{M})$.
- Find ~~Add~~ a set of four scalar fields $\{\chi_{(A)}\}_{A=0,1,2,3}$.

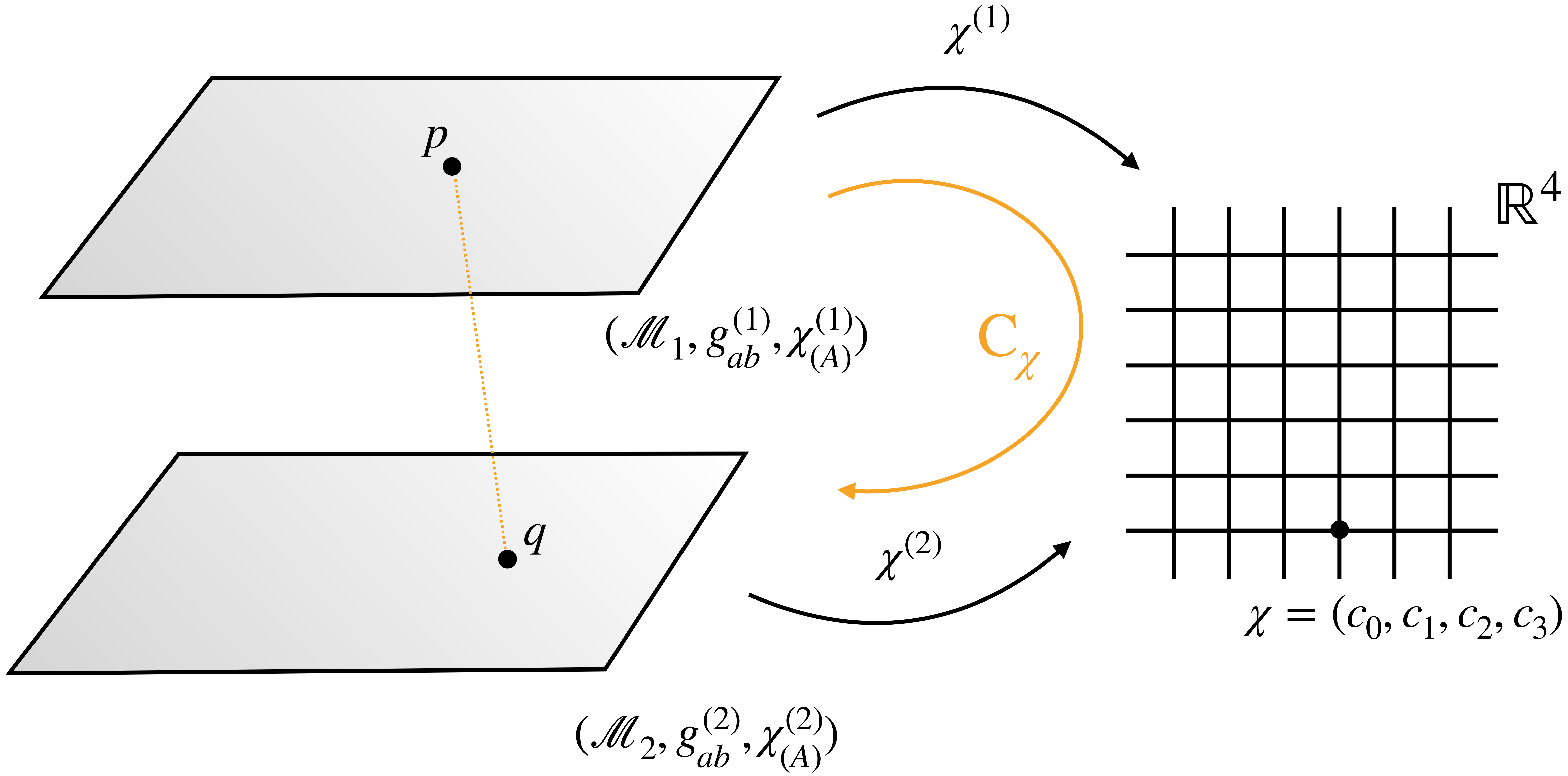


$\varphi_1 = (\mathscr{M}_1, g_{ab}^{(1)}, \chi_{(A)}^{(1)}, \tilde{\psi}_{matter}^{(1)})$

$\varphi_2 = (\mathscr{M}_2, g_{ab}^{(2)}, \chi_{(A)}^{(2)}, \tilde{\psi}_{matter}^{(2)})$

Identification across a Superposition of Spacetimes

The Comparison Map



Use coincidences of fields to identify points across the spacetimes in superposition.

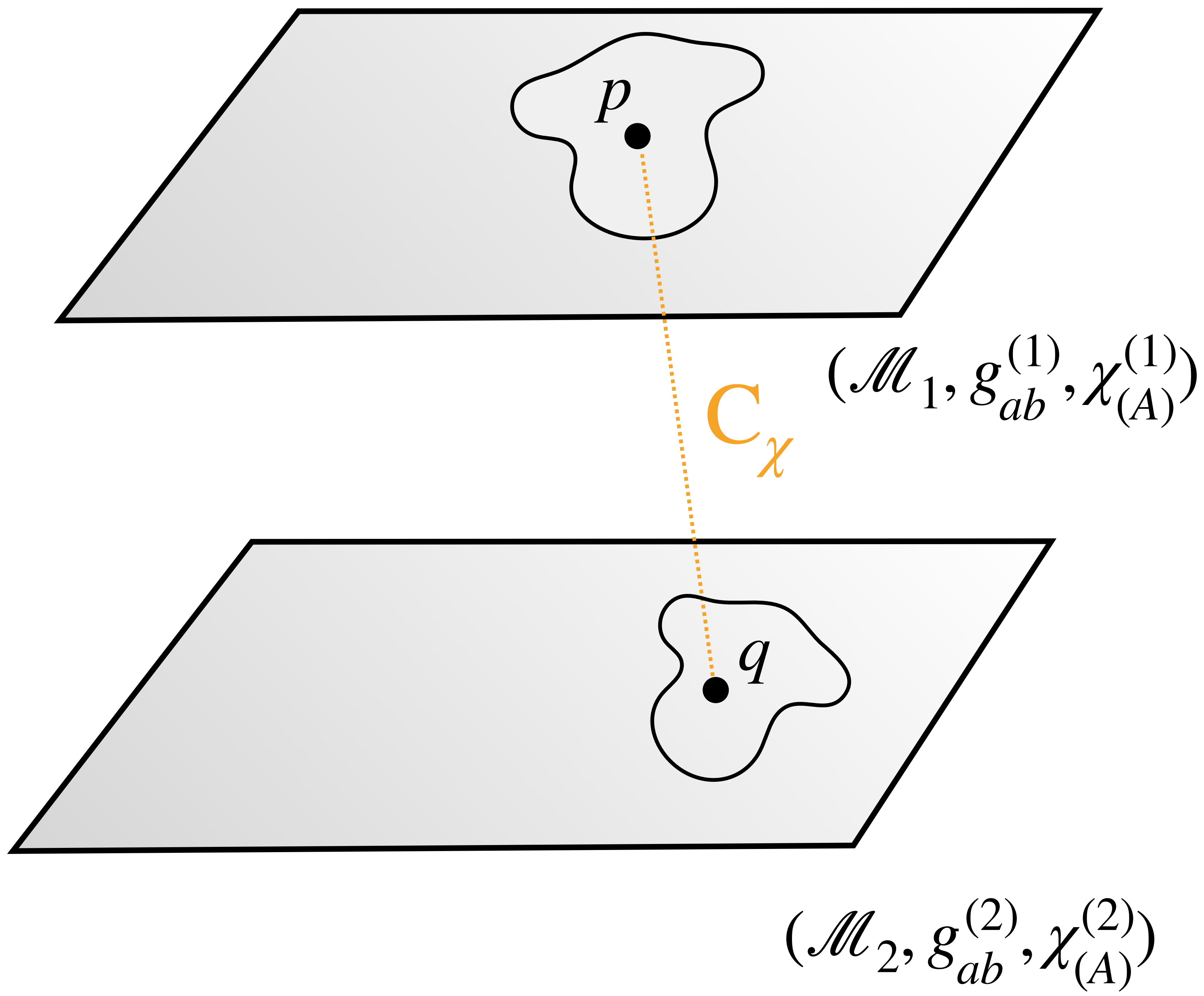
Kabel, ACdlH, Apadula et al. (2024)
cf. Westman and Sonego (2009); Hardy (2020)

Identification across a Superposition of Spacetimes

The Comparison Map

$$\boxed{\mathrm{C}_\chi \equiv (\chi^{(2)})^{-1} \circ \chi^{(1)} : \mathscr{M}_1 \to \mathscr{M}_2}$$

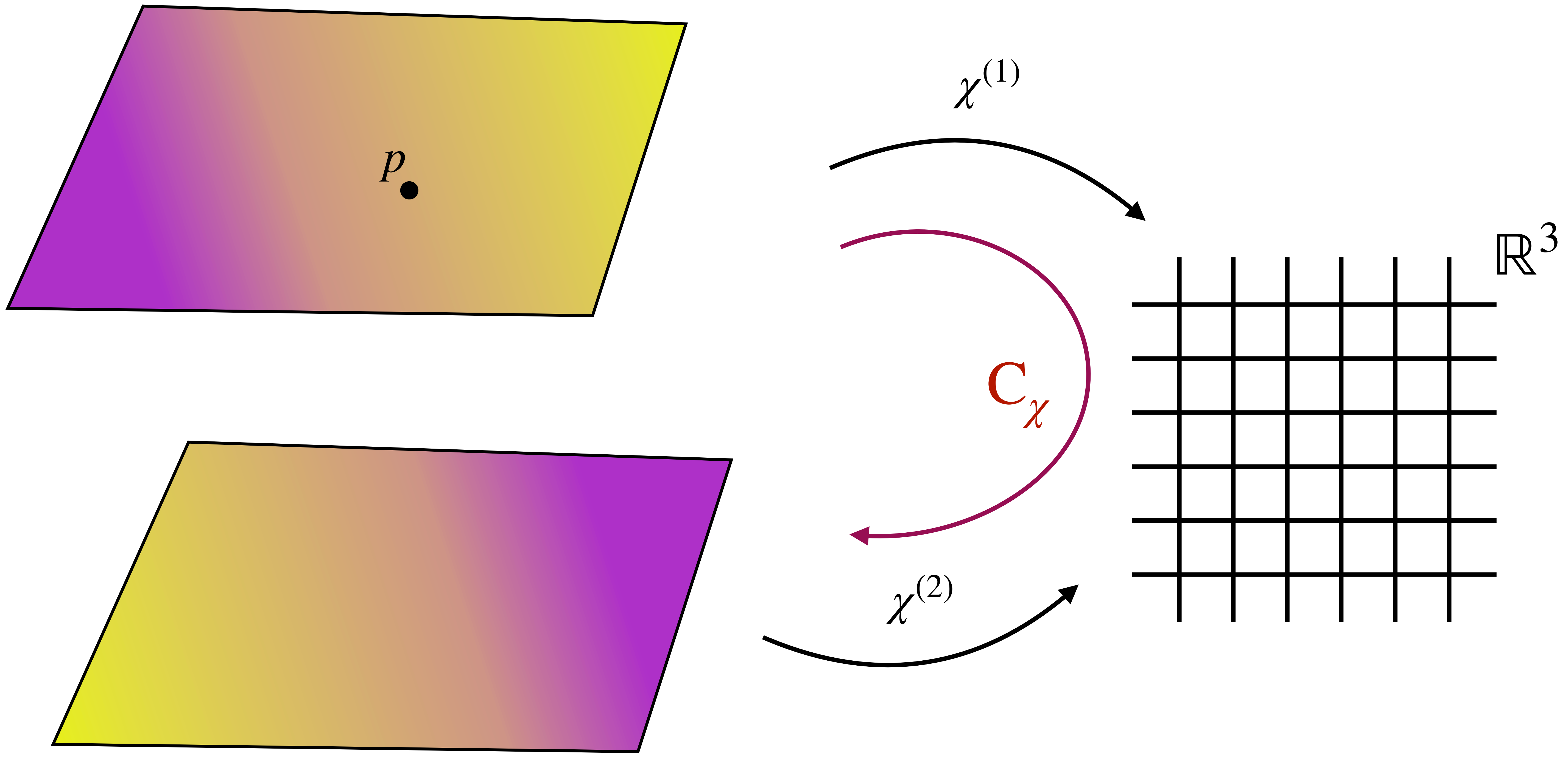
- If the four scalar fields define a **bijective** map from $\mathscr{M}$ to $\mathbb{R}^4$, then fixing field values **removes redundancy** induced by diff-invariance.
- Bijectiveness requires
  1. fields **inhomogeneous** enough, or
  2. restriction to sufficiently small open **subregion** of $\mathscr{M}$



Identification across a Superposition of Spacetimes

A concrete toy example

- Take **two models** of a 3D space of models in superposition.

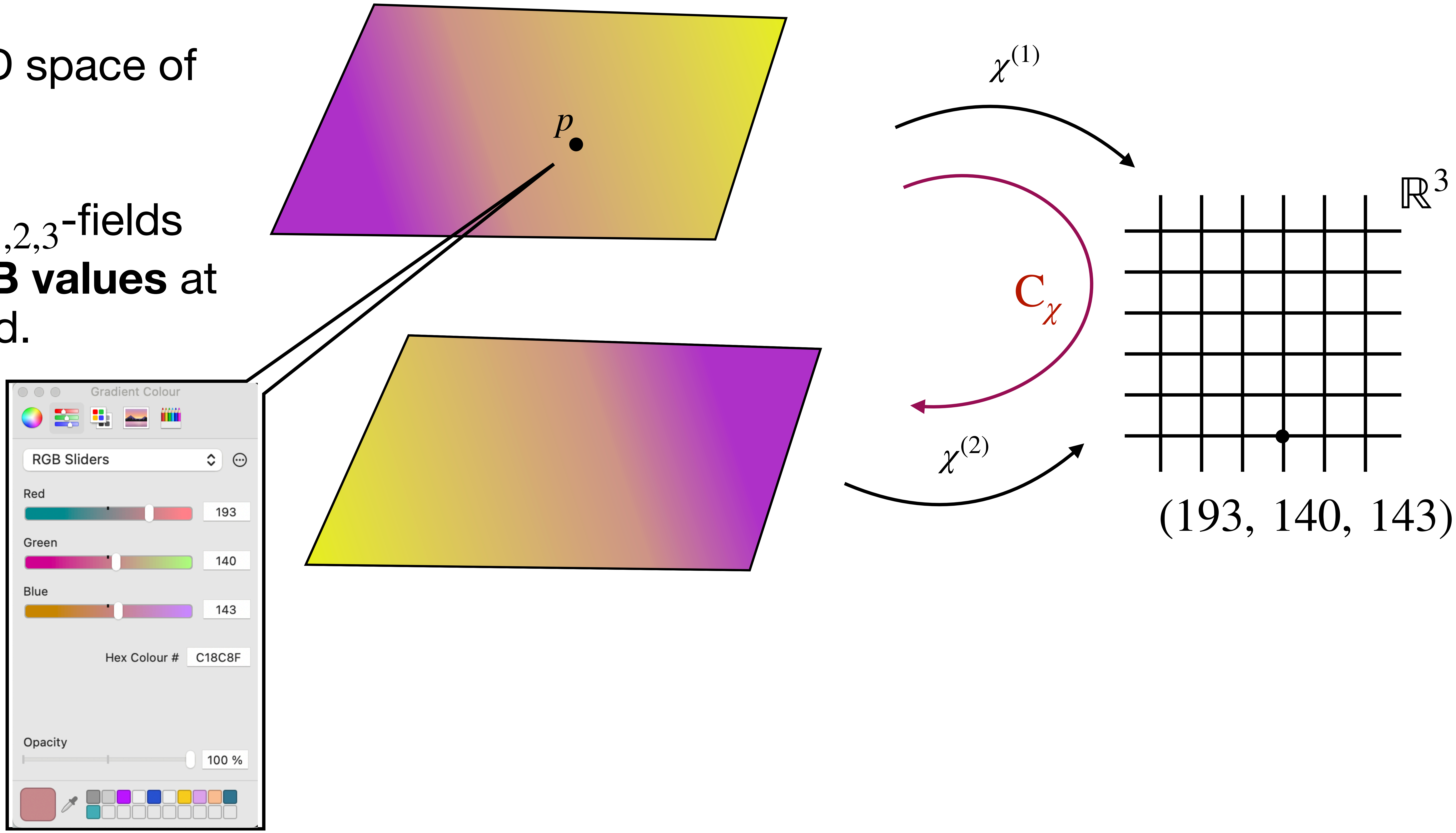


Identification across a Superposition of Spacetimes

A concrete toy example

- Take **two models** of a 3D space of models in superposition.

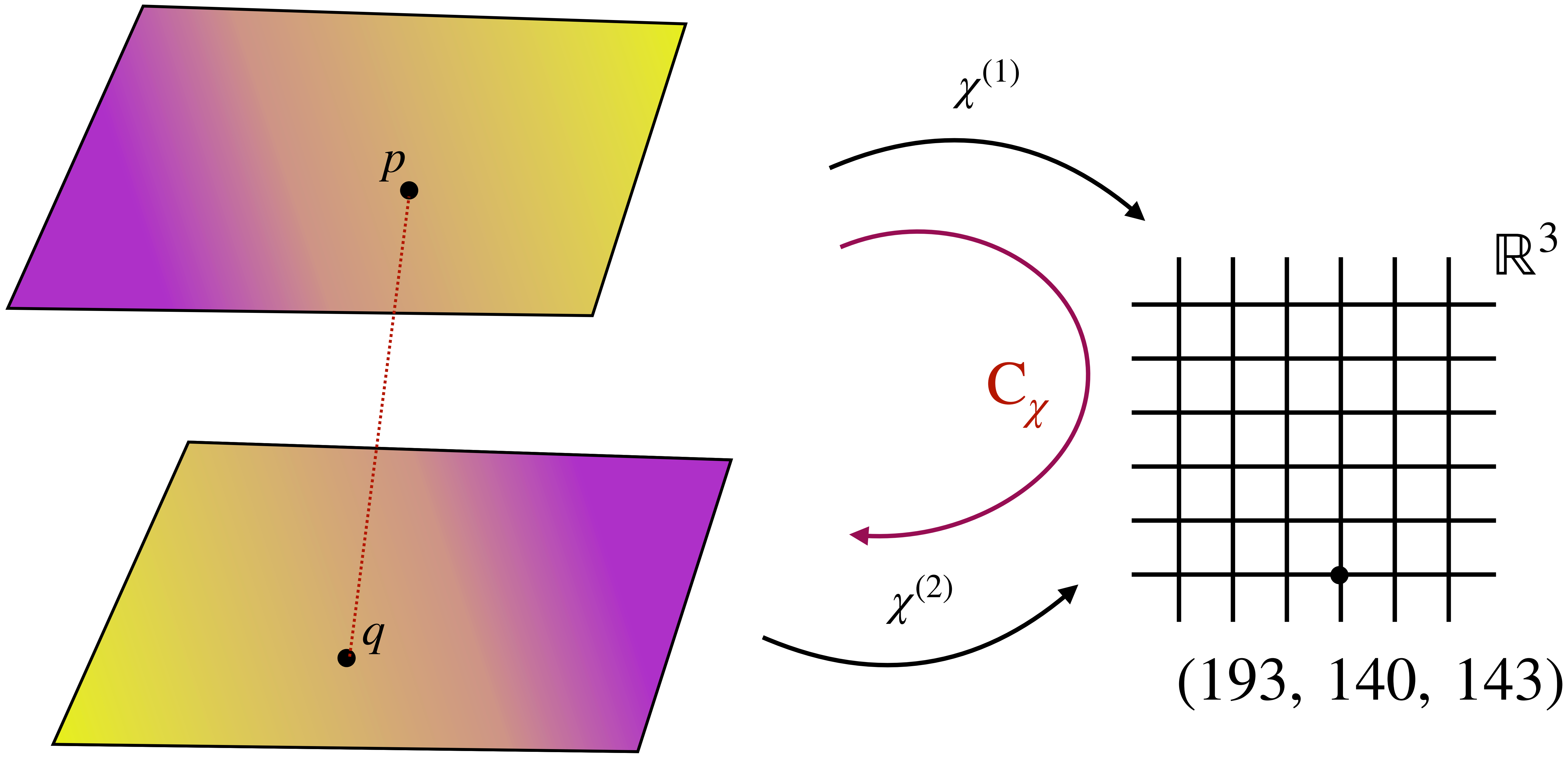
- Consider three $\{\chi_{(A)}\}_{A=1,2,3}$-fields that return the **three RGB values** at any **point** on the manifold.



Identification across a Superposition of Spacetimes

A concrete toy example

- Take **two models** of a 3D space of models in superposition.
- Consider three $\{\chi_{(A)}\}_{A=1,2,3}$-fields that return the **three RGB values** at any **point** on the manifold.
- If $\chi^{(1)}(p) = (193,\ 140,\ 143) = \chi^{(2)}(q)$, then p and q are **identified** relative to these χ-fields.



Identification across a Superposition of Spacetimes

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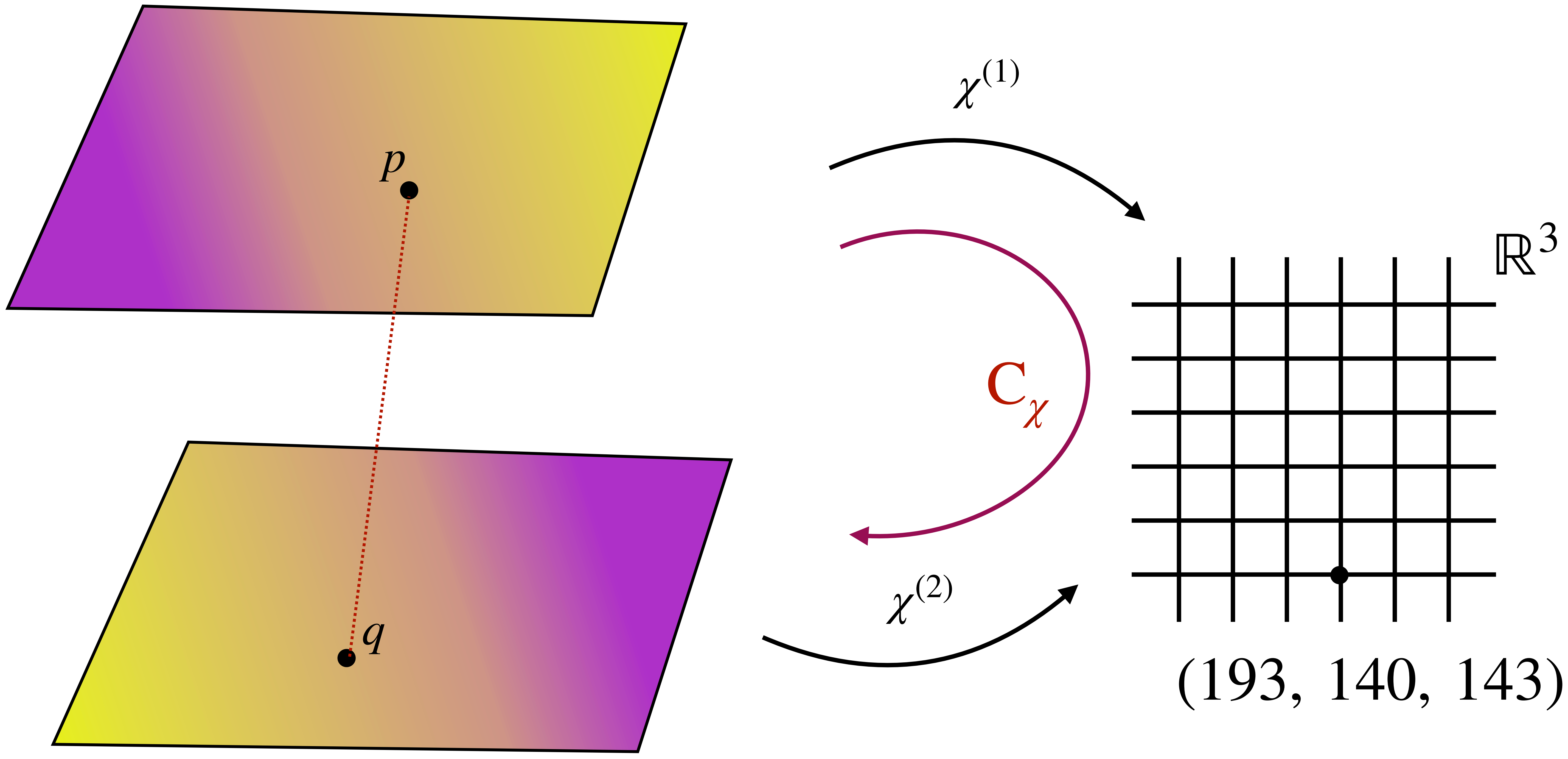


- Taking $\chi^{(1)}$ and $\chi^{(2)}$ to be different configurations of the **same physical fields**, we find a **natural** strategy to identify points across manifolds.

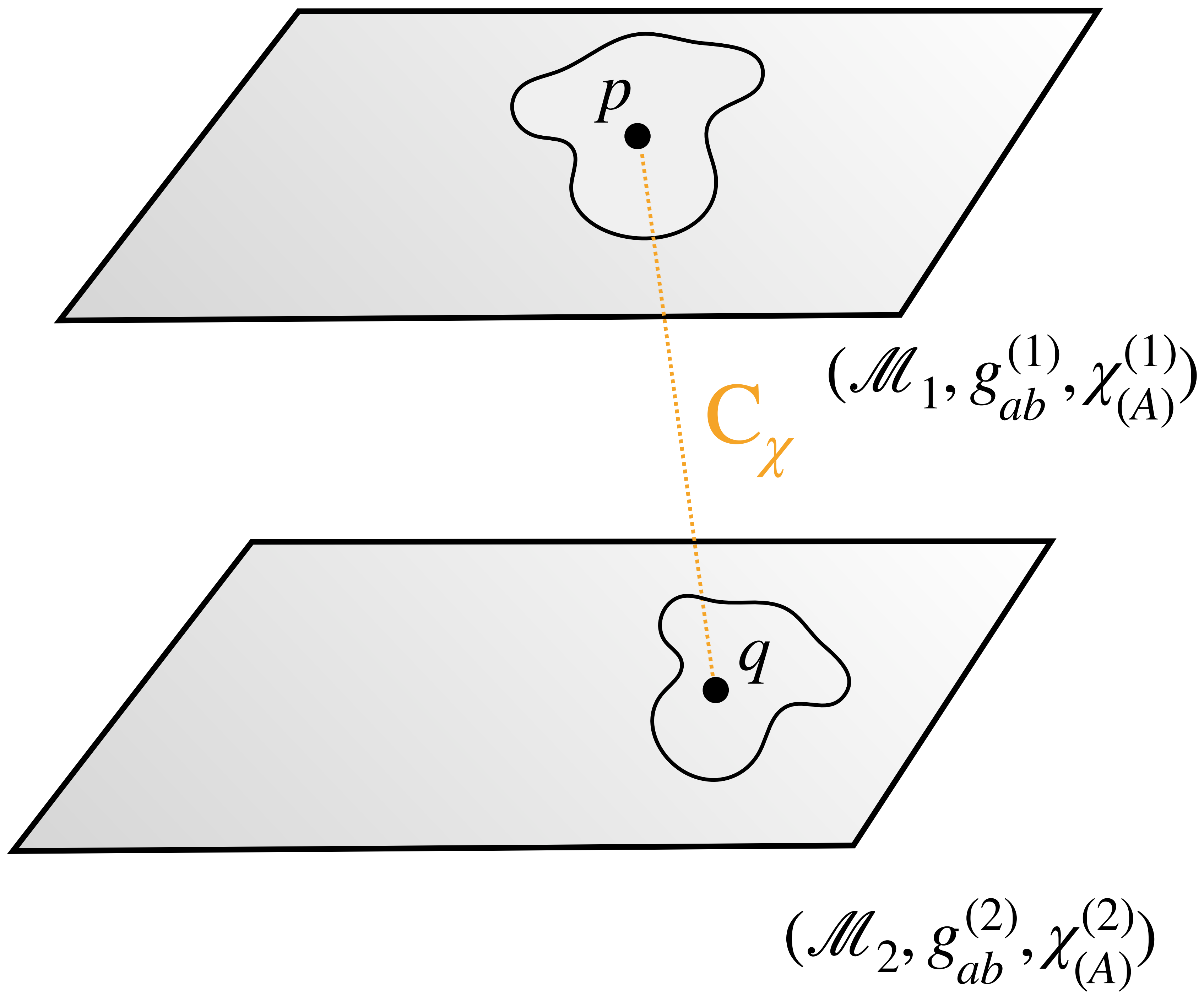
Identification across a Superposition of Spacetimes

Quantum coordinate fields

Three options for modelling scalar **reference fields**:

1. idealised or coordinate fields
2. dynamical fields without back-reaction
3. dynamical fields with back-reaction

Free to pick either one.



Rovelli (1991); Bamonti (2023)

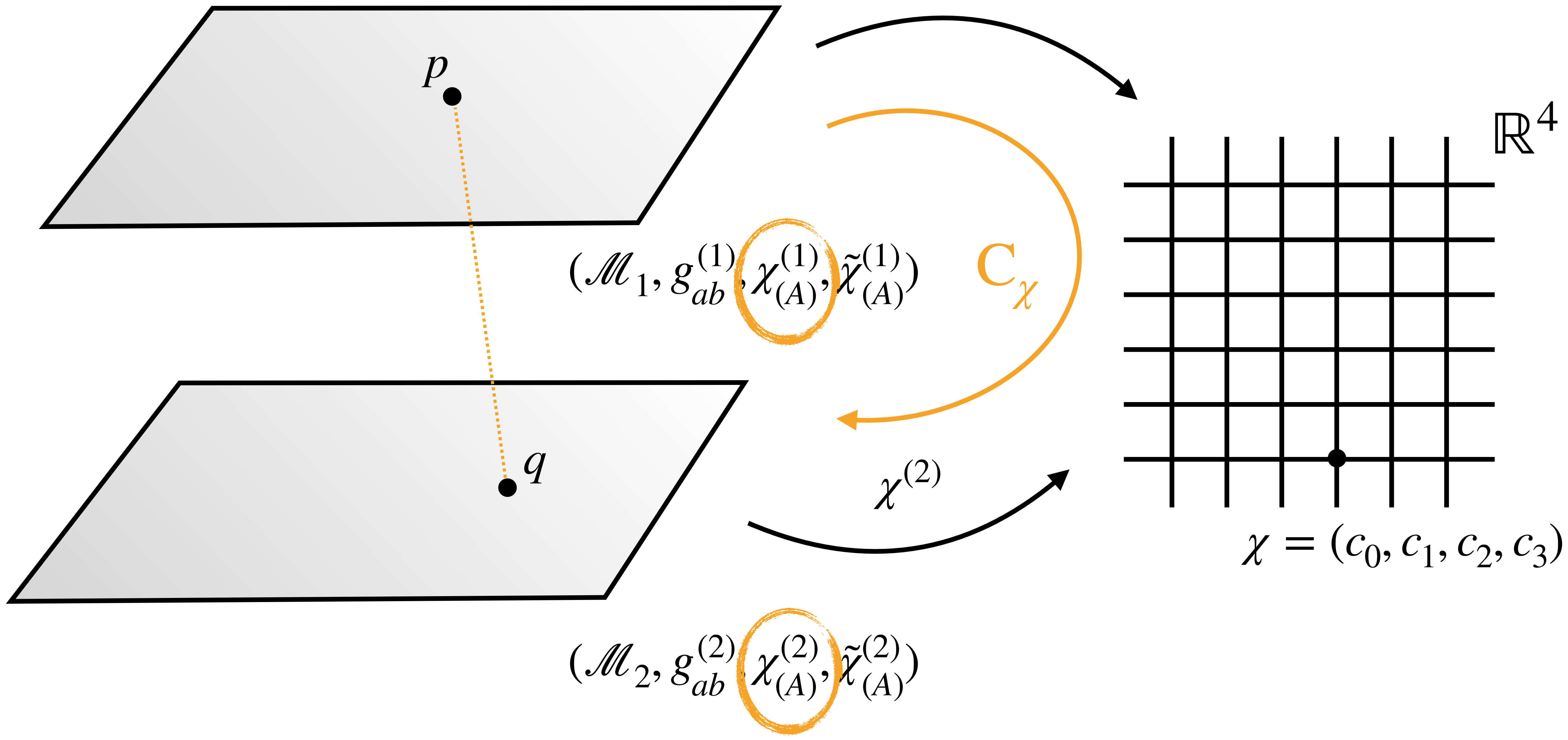
Identification across a Superposition of Spacetimes

Changes of QRF

- **Choice of QRF** ~ choice of scalar fields and corresponding identification
- **Change of QRF** $\chi \to \tilde{\chi}$

  (i) apply **quantum-controlled diffeomorphism** to make the reference fields definite

  (ii) change the comparison map from C_χ to $C_{\tilde{\chi}}$



Identification across a Superposition of Spacetimes

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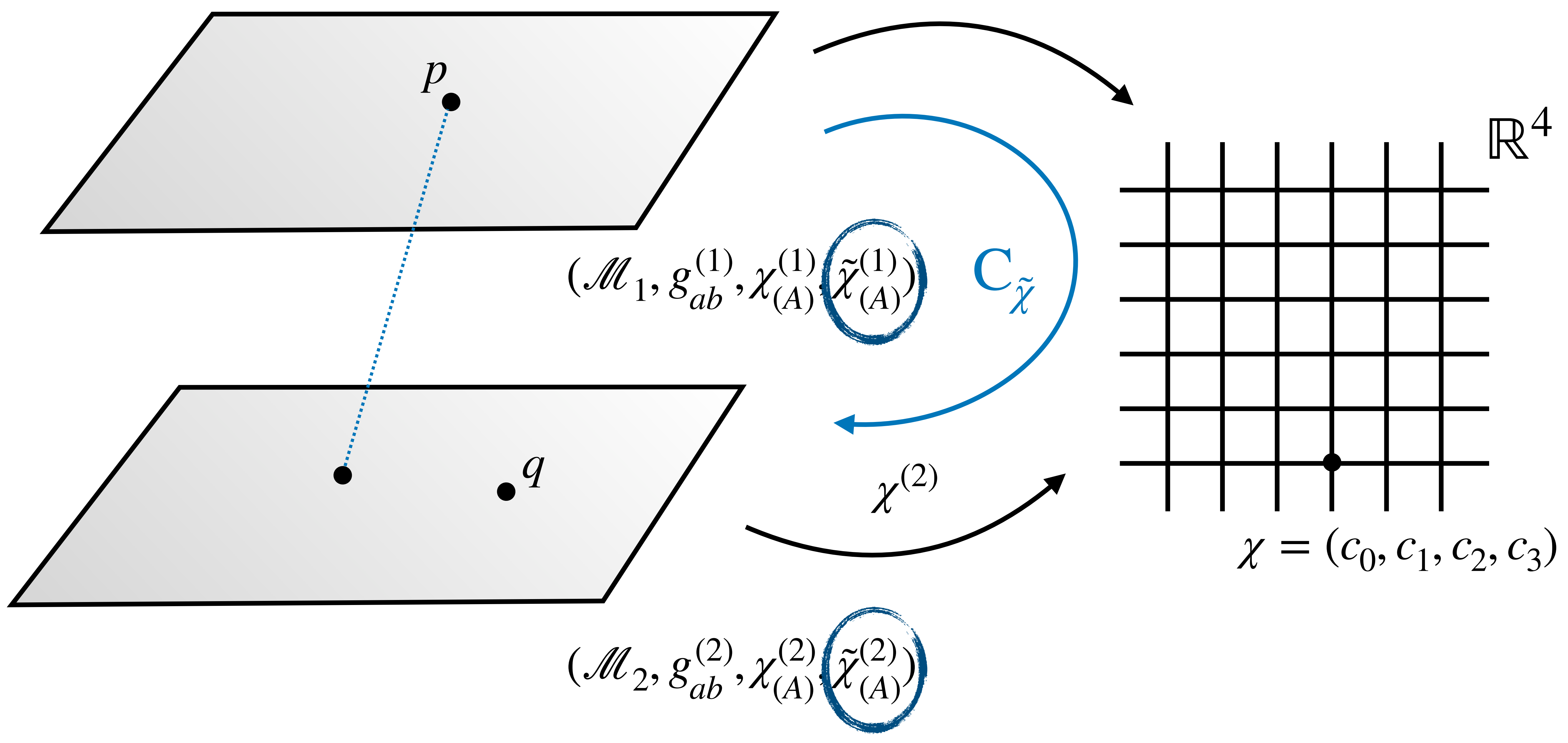
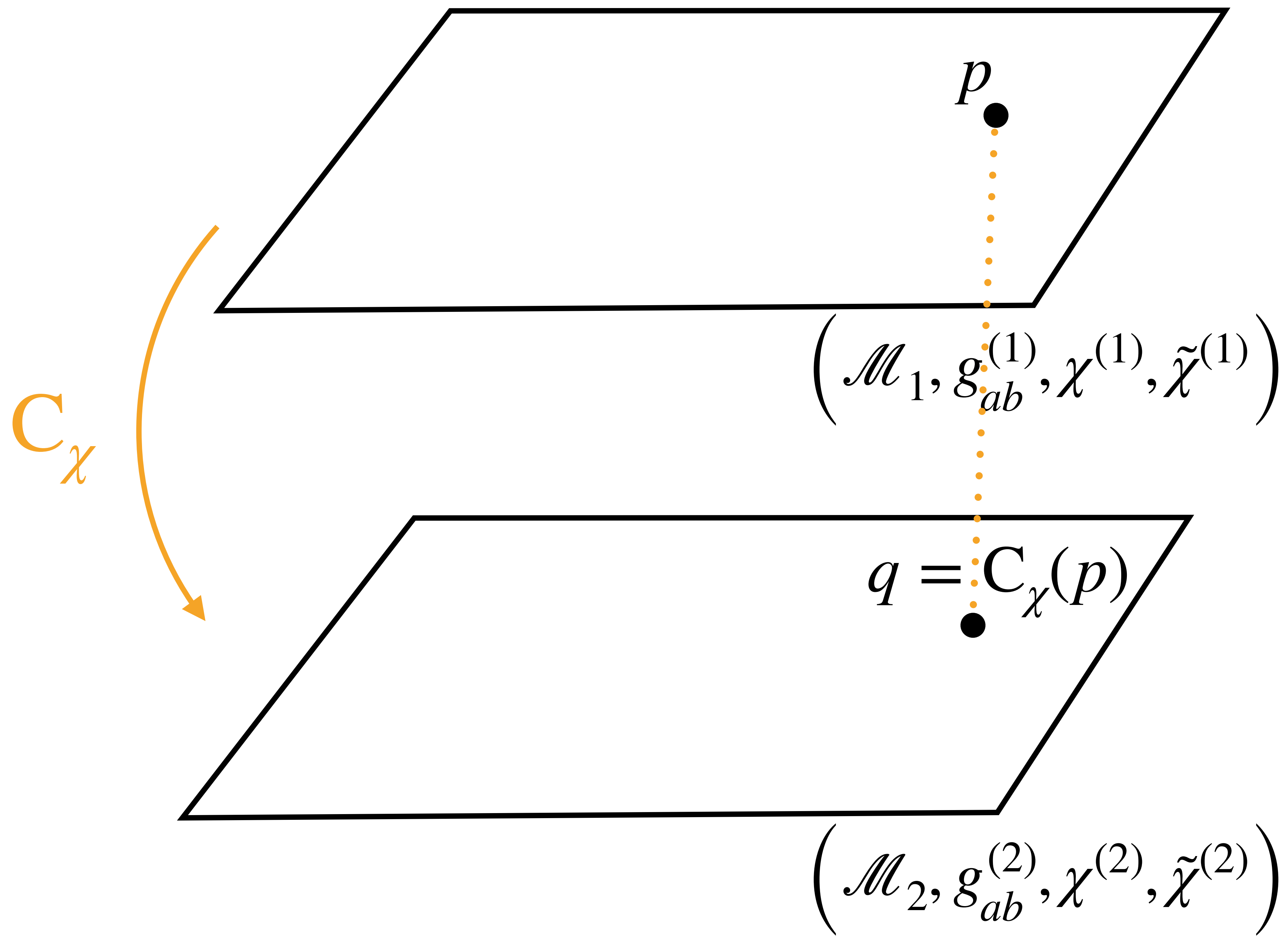


Part III: Conceptual implications

Localisation of events

Quantum diffeomorphisms and quantum coordinates

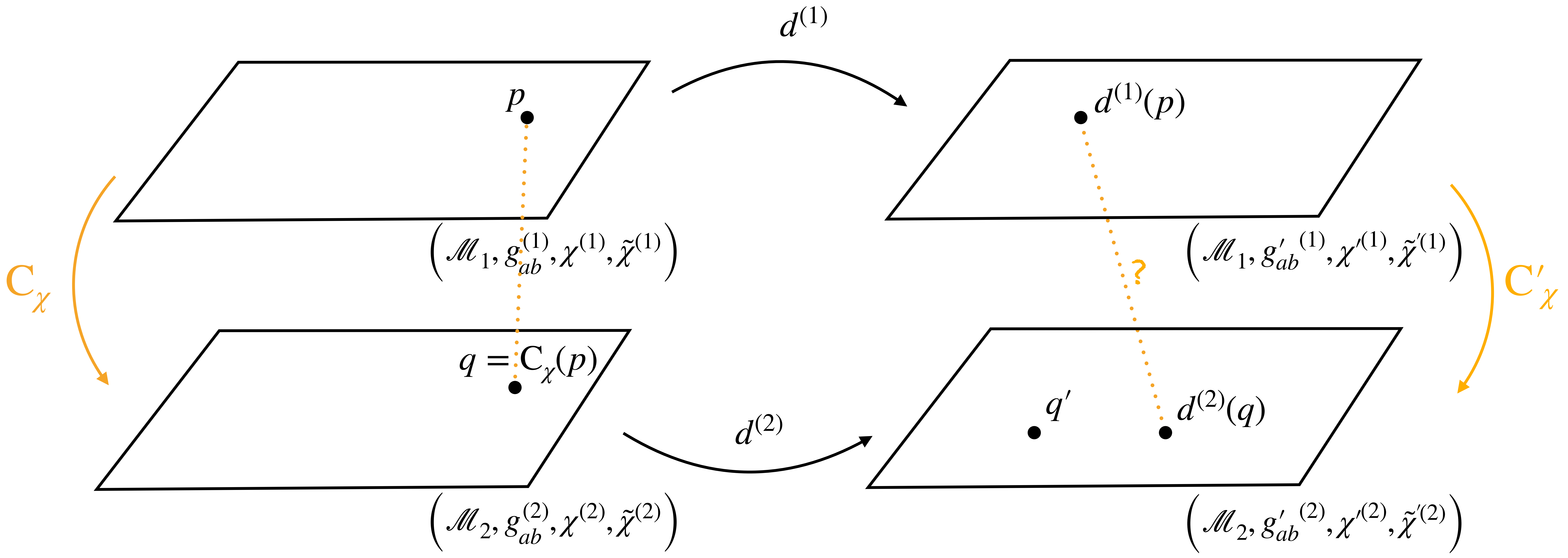
Localisation of events



The pair (p, q) where $p \in \mathscr{M}_1$ and $q \in \mathscr{M}_2$
is localised iff $\boxed{q = \mathrm{C}_\chi(p).}$

Quantum diffeomorphisms and quantum coordinates

Localisation of events



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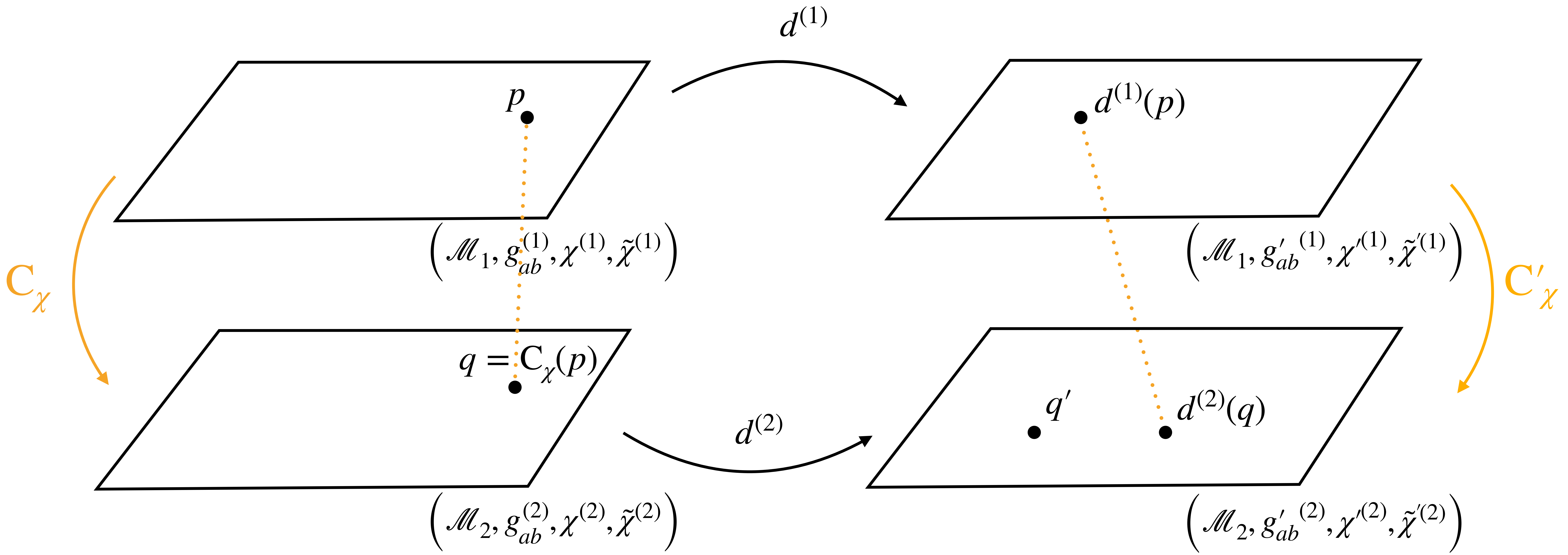
Quantum diffeomorphisms and quantum coordinates

Localisation of events



$$\boxed{q = C_\chi(p)}$$

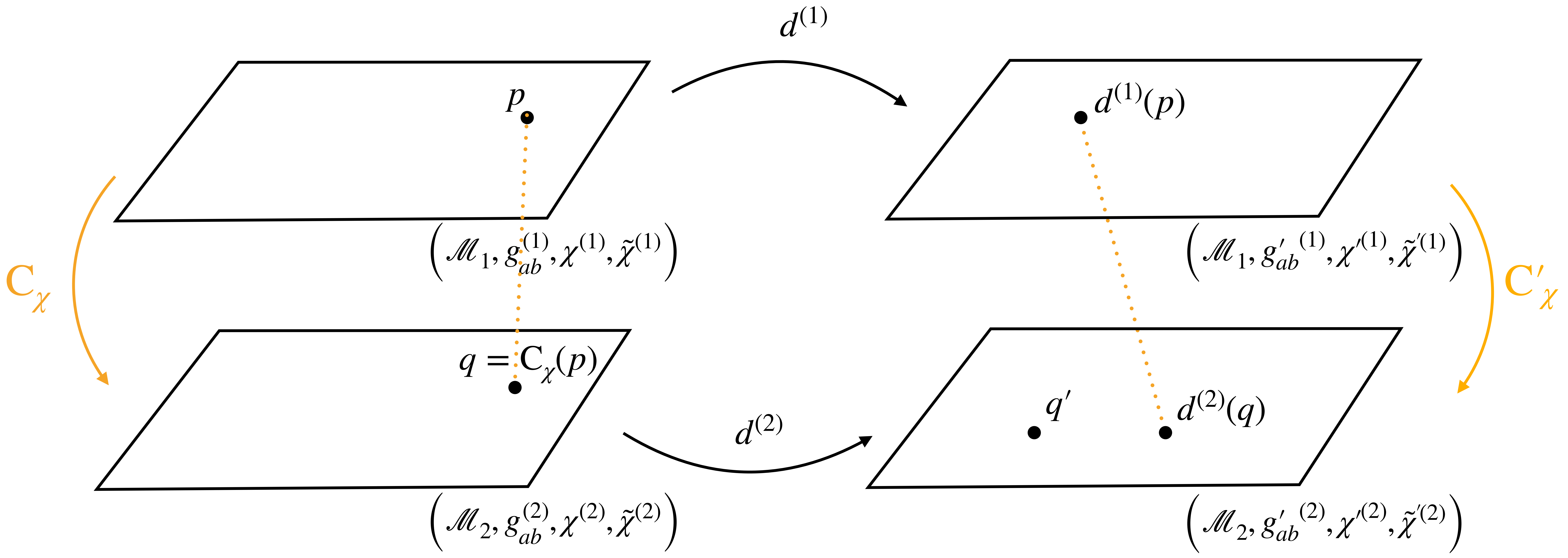
$$C_\chi = (\chi^{(2)})^{-1} \circ \chi^{(1)}$$

$$\mathrm{C}'_\chi = (d_*^{(2)}(\chi^{(2)}))^{-1} \circ (d_*^{(1)}(\chi^{(1)})) = d^{(2)} \circ \mathrm{C}_\chi \circ (d^{(1)})^{-1}$$

$$\boxed{d^{(2)}(q)} = d^{(2)} \circ C_\chi(p) = d^{(2)} \circ C_\chi \circ \underbrace{(d^{(1)})^{-1} \circ d^{(1)}}(p) = \boxed{C'_\chi(d^{(1)}(p))}$$

Quantum diffeomorphisms and quantum coordinates

Localisation of events



The pair (p, q) where $p \in \mathscr{M}_1$ and $q \in \mathscr{M}_2$ is localised iff $q = \mathrm{C}_\chi(p)$.

The pair $(d^{(1)}(p), d^{(2)}(q))$ remains localised: $d^{(2)}(q) = \mathrm{C}'_\chi(d^{(1)}(p))$.

Quantum diffeomorphisms and qua

Localisation of events is reference frame dependent.

Localisation of events

The pair (p, q) where $p \in \mathscr{M}_1$ and $q \in \mathscr{M}_2$ is localised iff $q = C_\chi(p)$.

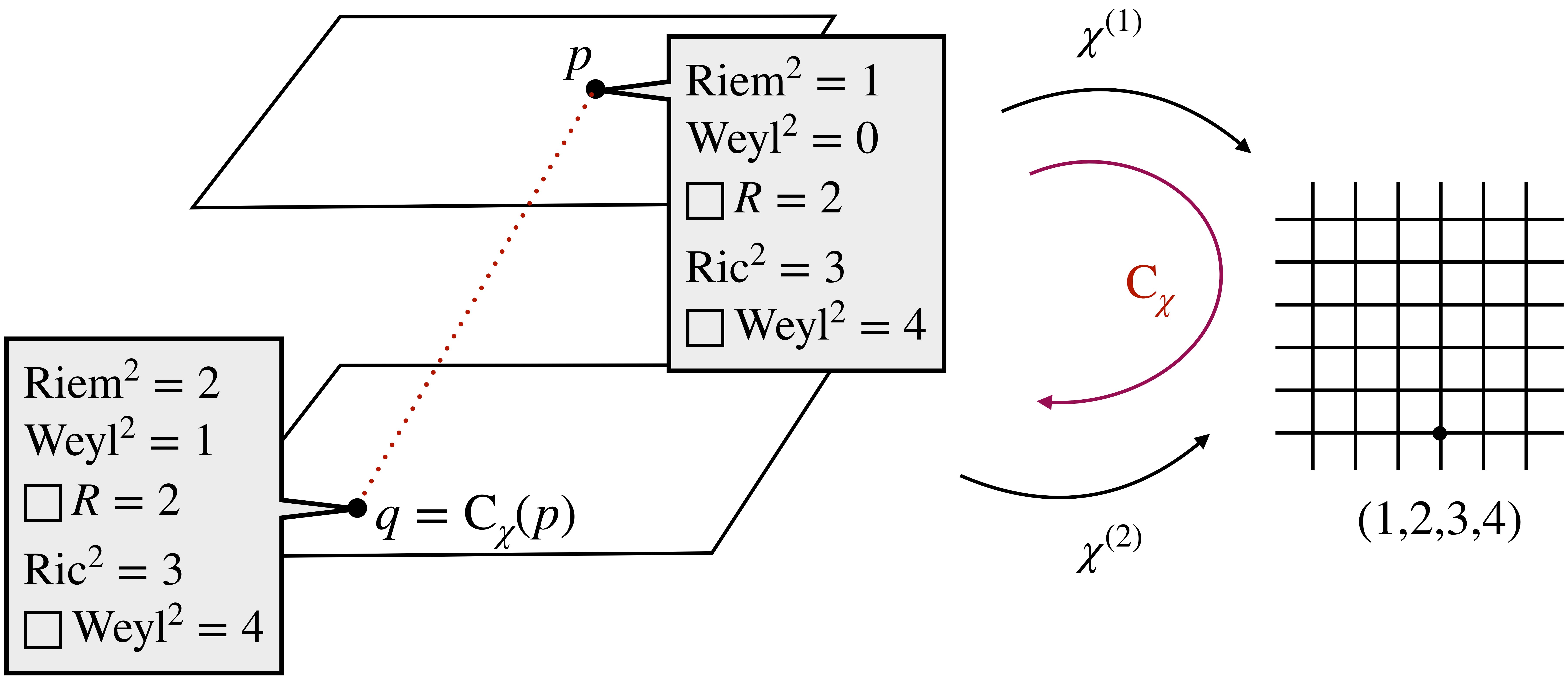
The pair $(d^{(1)}(p), d^{(2)}(q))$ will in general not be localised: $d^{(2)}(q) \neq C'_{\tilde{\chi}}(d^{(1)}(p))$.

Quantum diffeomorphisms and quantum coordinates

A concrete toy example

χ-fields: $(\mathrm{Riem}^2 - \mathrm{Weyl}^2, \Box R, \mathrm{Ric}^2, \Box\,\mathrm{Weyl}^2)$

$\tilde{\chi}$-fields: $(\mathrm{Riem}^2, \Box R, \mathrm{Ric}^2, \Box\,\mathrm{Weyl}^2)$



Quantum diffeomorphisms and quantum coordinates

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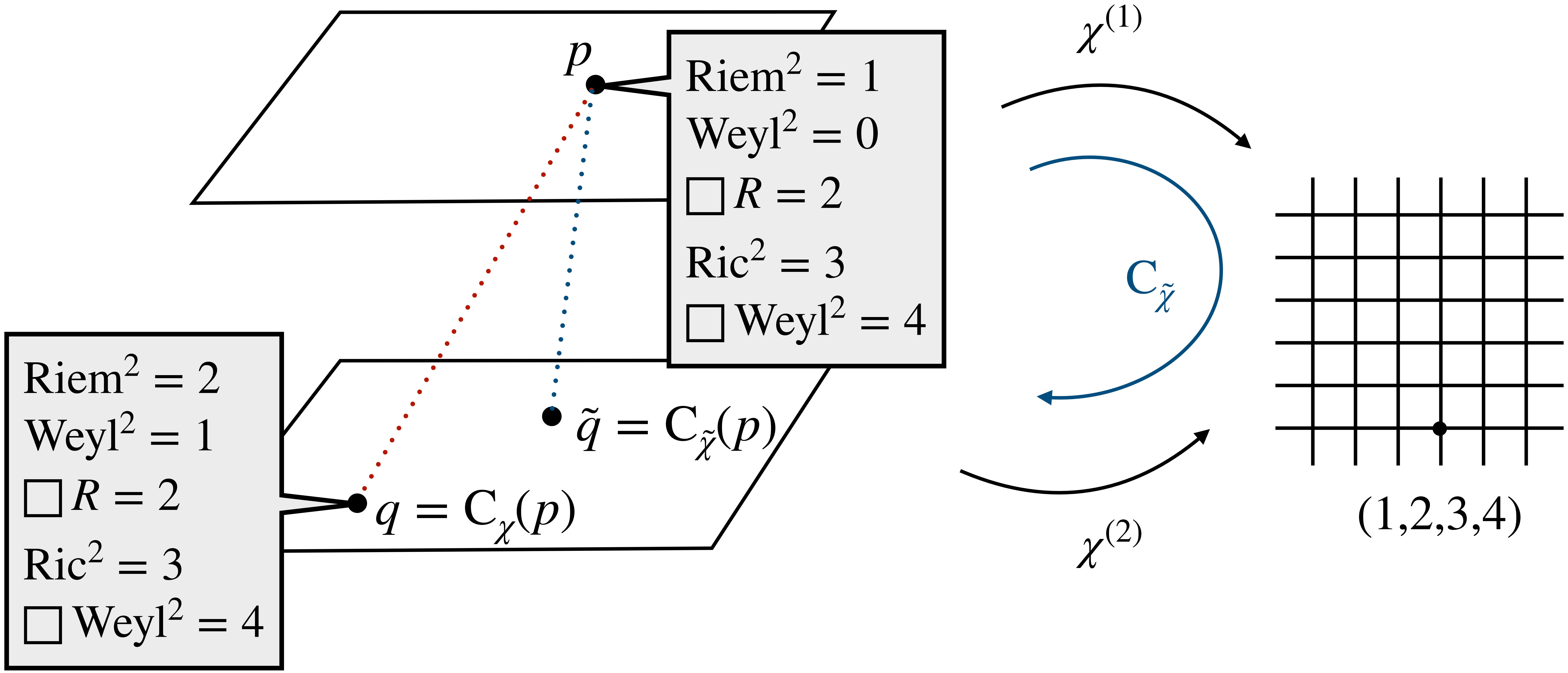
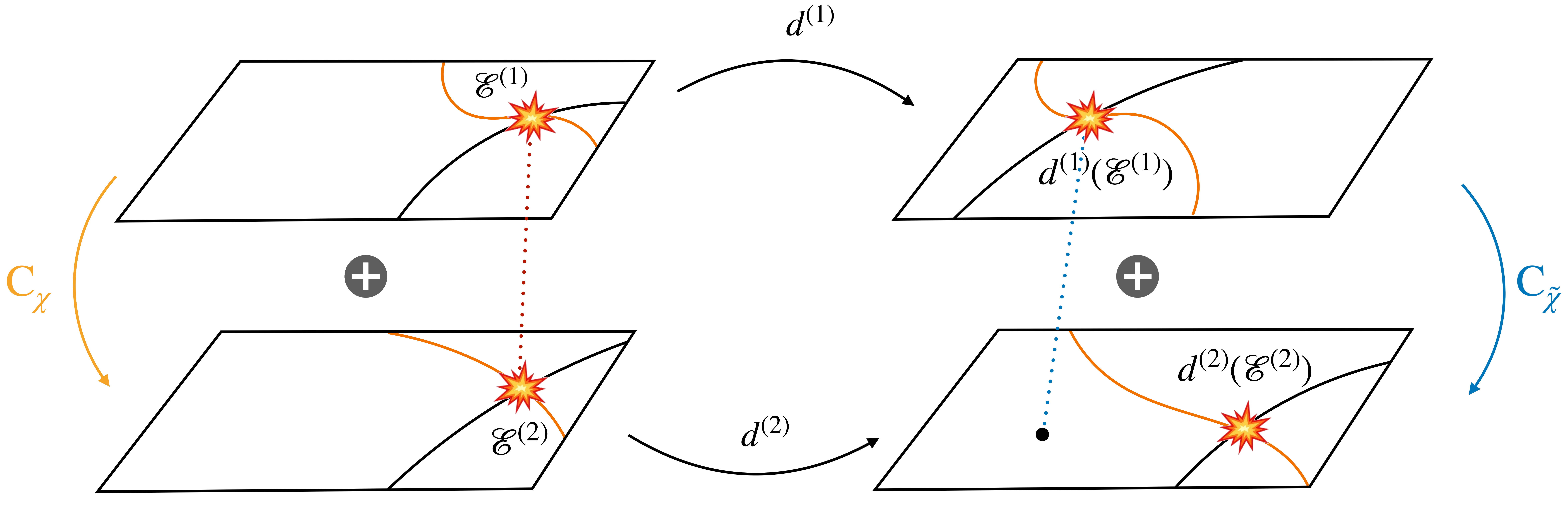


Quantum diffeomorphisms and quantum coordinates

Localisation of events



Identification of spacetime points and **localisation of events** are **frame-dependent** and have no absolute physical meaning.

Indefinite causal order

Indefinite Causal Structures

General Relativity	Quantum Theory
dynamical causal structure	fixed causal structure
deterministic	probabilistic

Hardy, A Framework for Probabilistic Theories with Non-Fixed Causal Structure (2006)


We want to describe the probabilities for outcomes a,b:

$$\boxed{P(a, b)}$$

$\mathscr{H}^{B_{out}}$

$\mathscr{H}^{B_{in}}$

$\mathcal{N}^B_b$ → outcome b with probability P(b)

$\mathscr{H}^{A_{out}}$

$\mathscr{H}^{A_{in}}$

$\mathscr{M}^A_a$ → outcome a with probability P(a)

We want to describe the probabilities for outcomes a,b:

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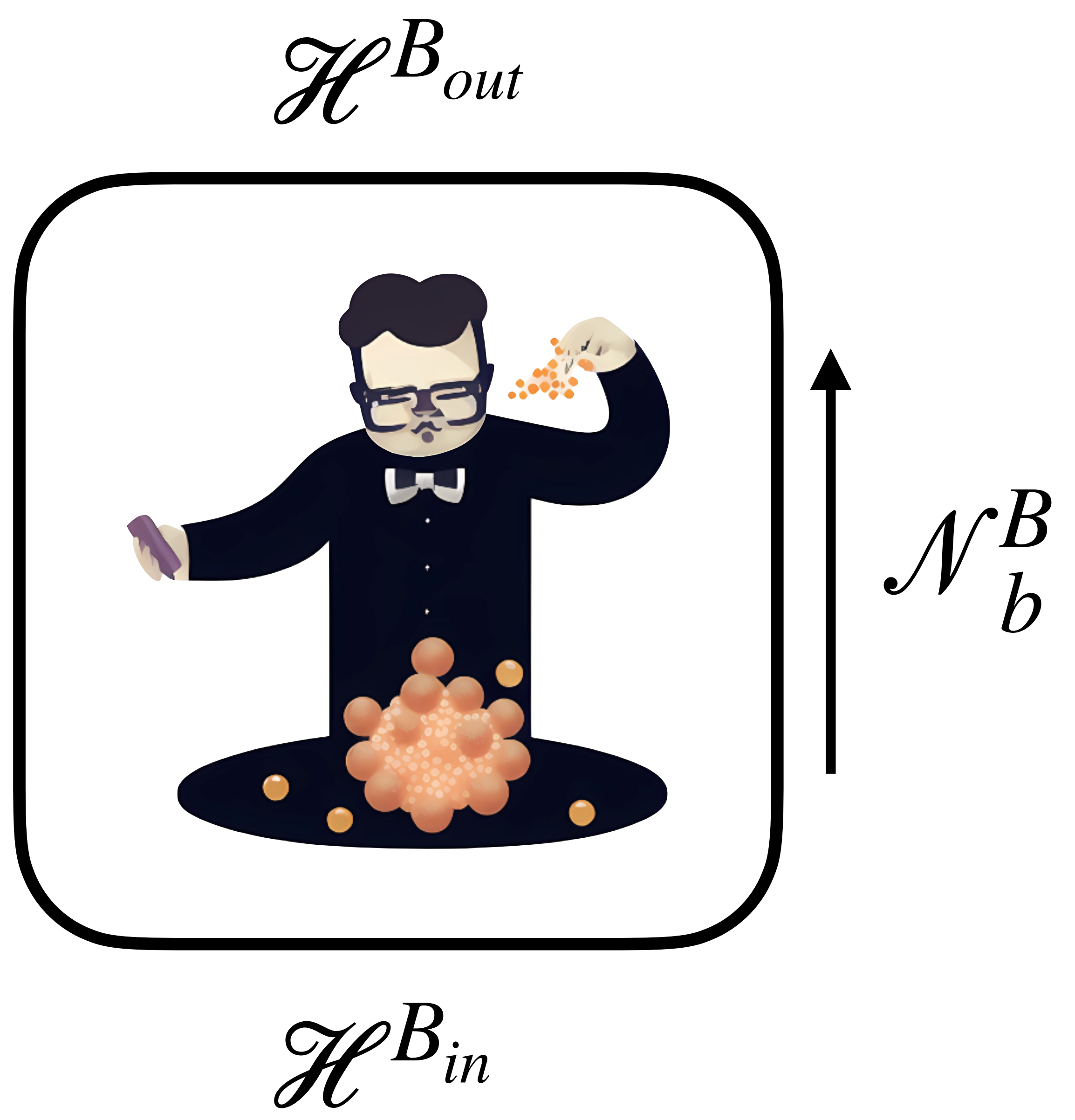
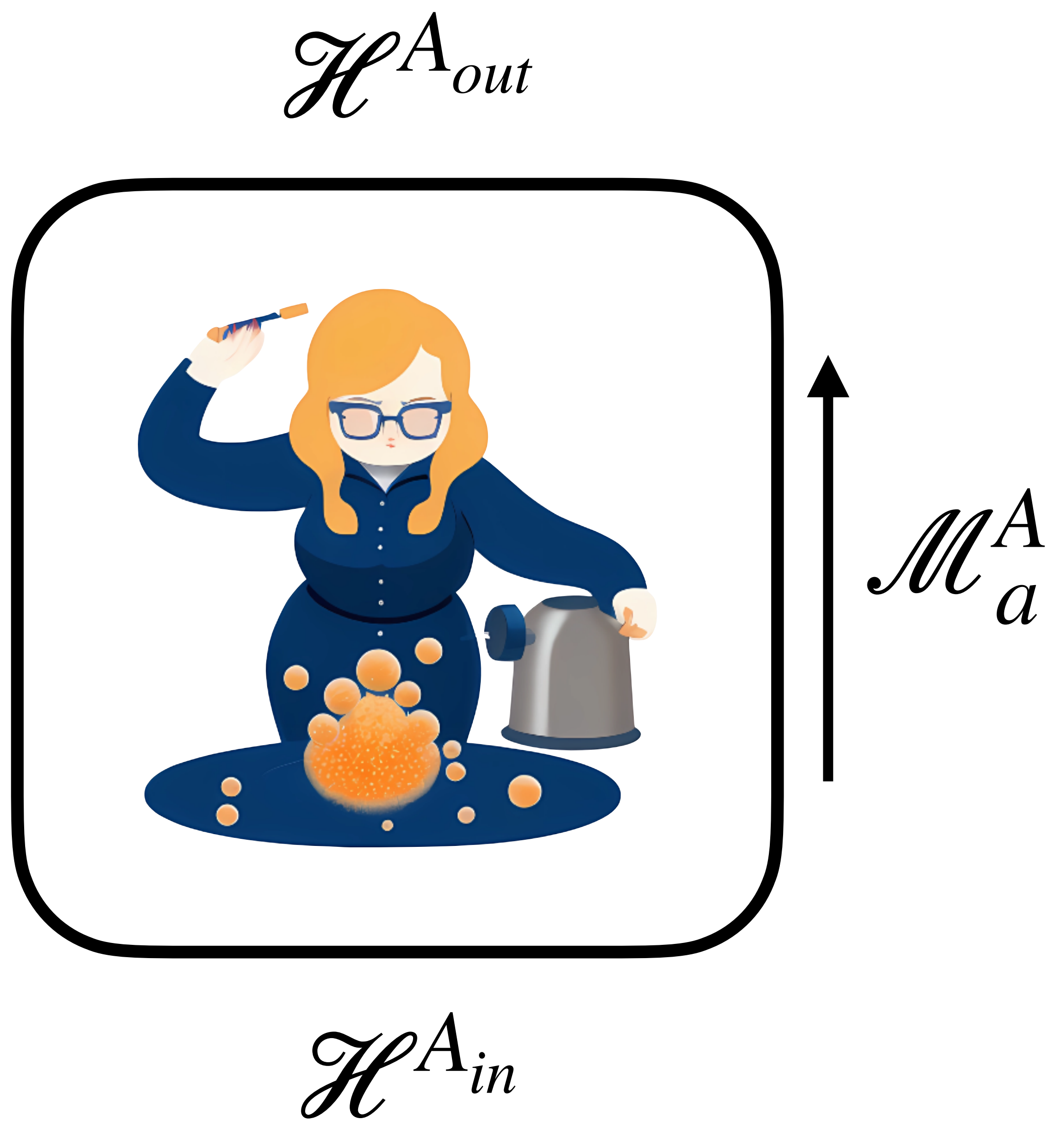
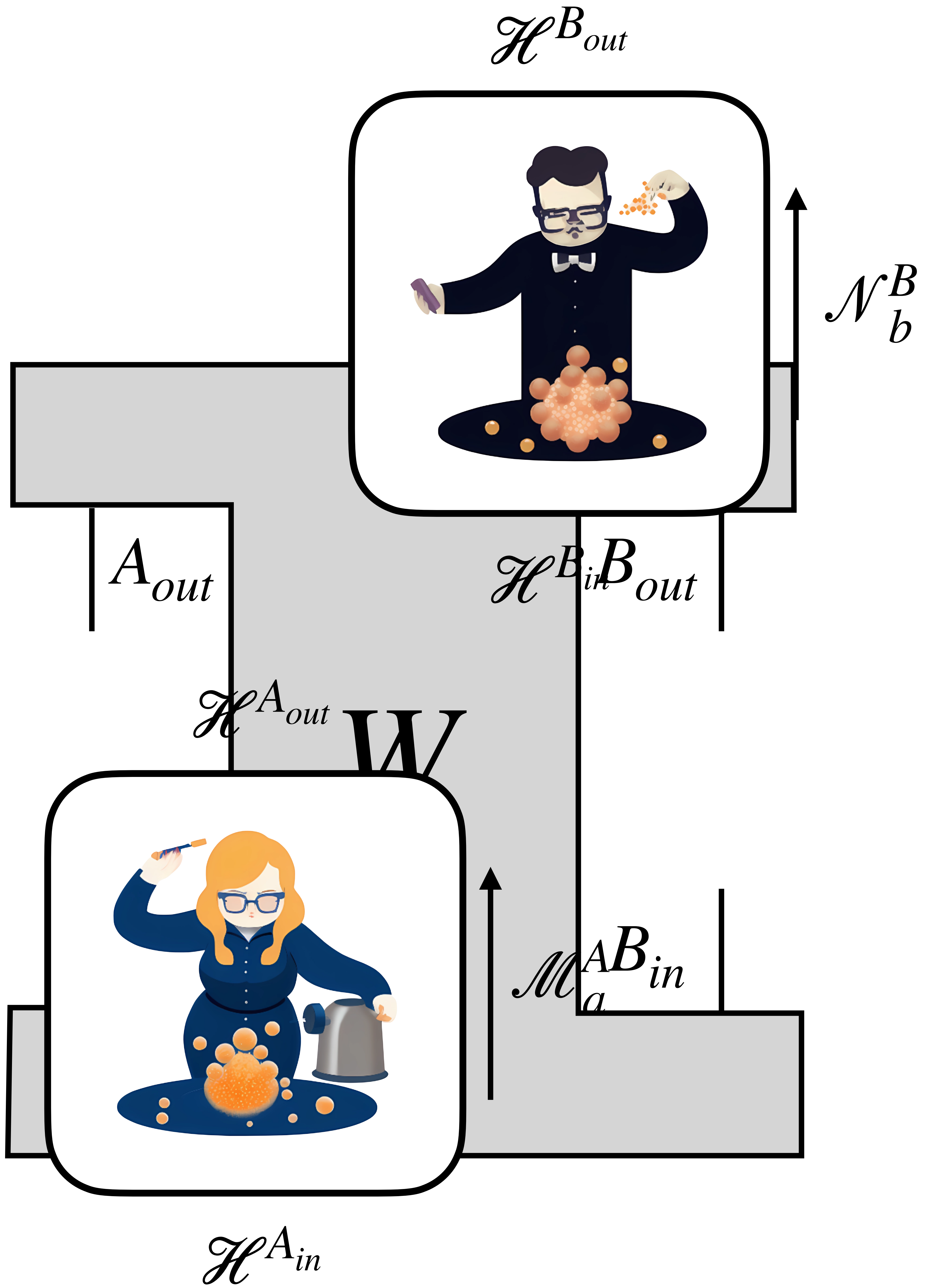


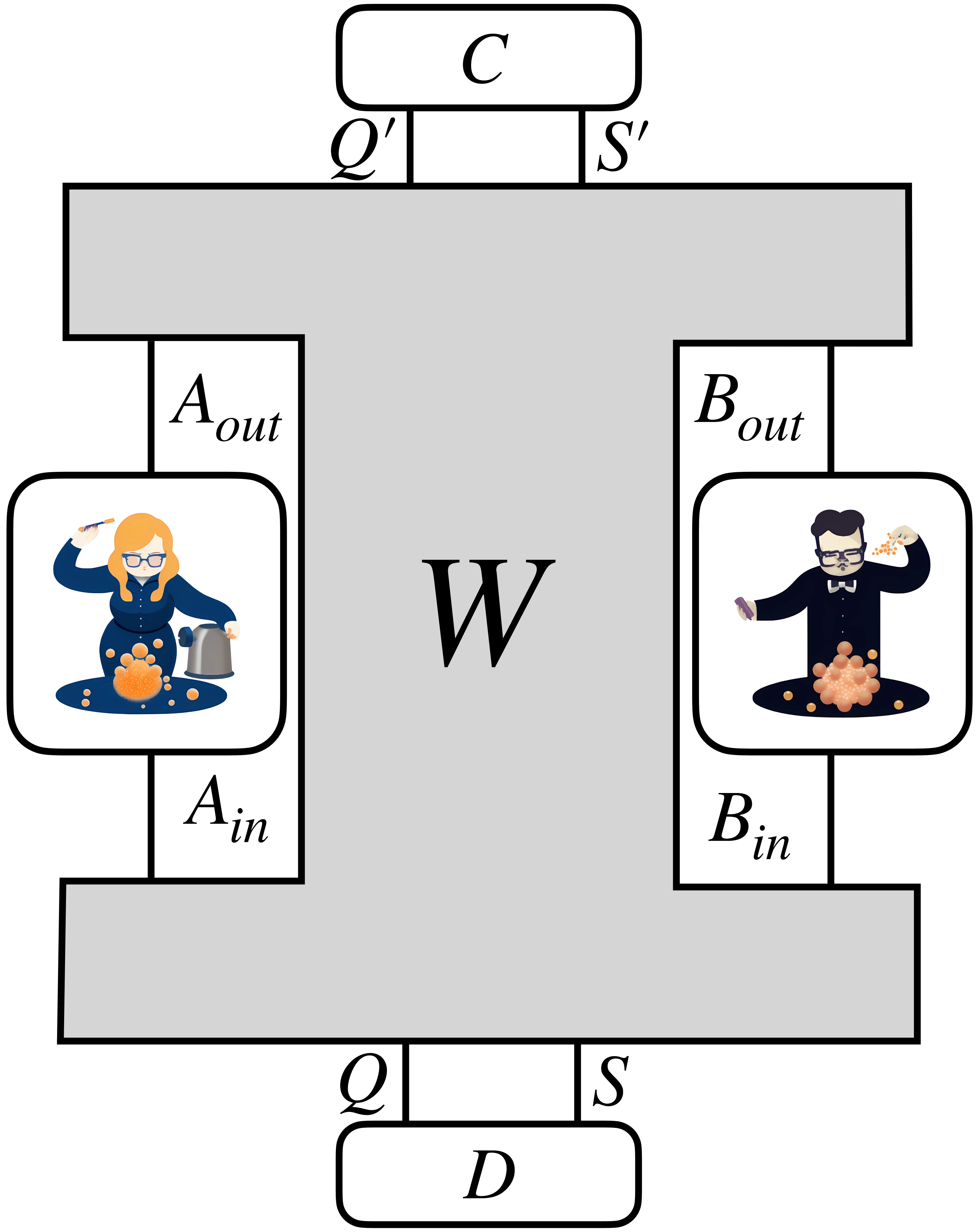




Oreshkov, Costa, Brukner (2013).

Processes with indefinite causal order

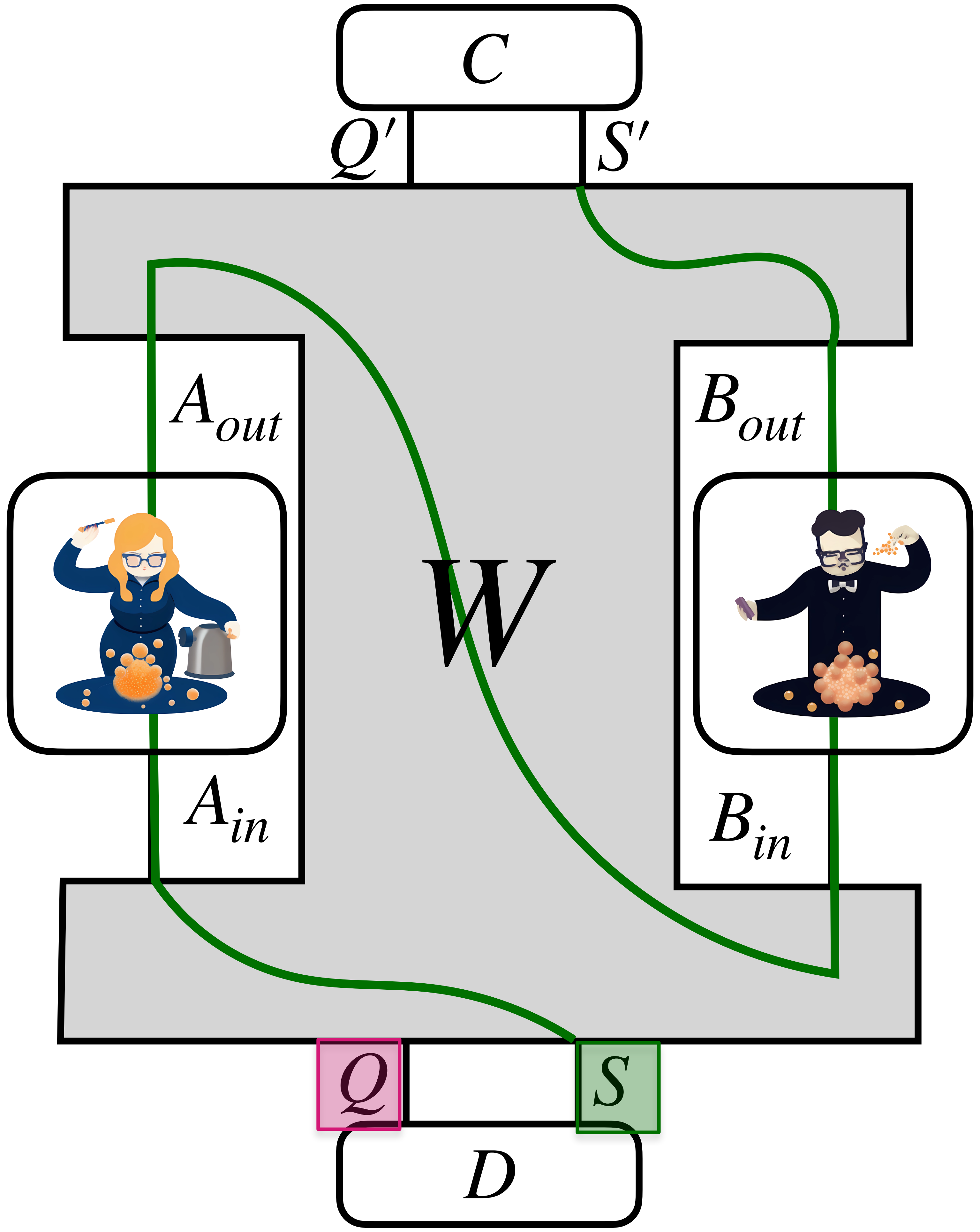
The Quantum SWITCH



Chiribella, D'Ariano, Perinotti, Valiron (2013); Oreshkov (2019)

Processes with indefinite causal order

The Quantum SWITCH



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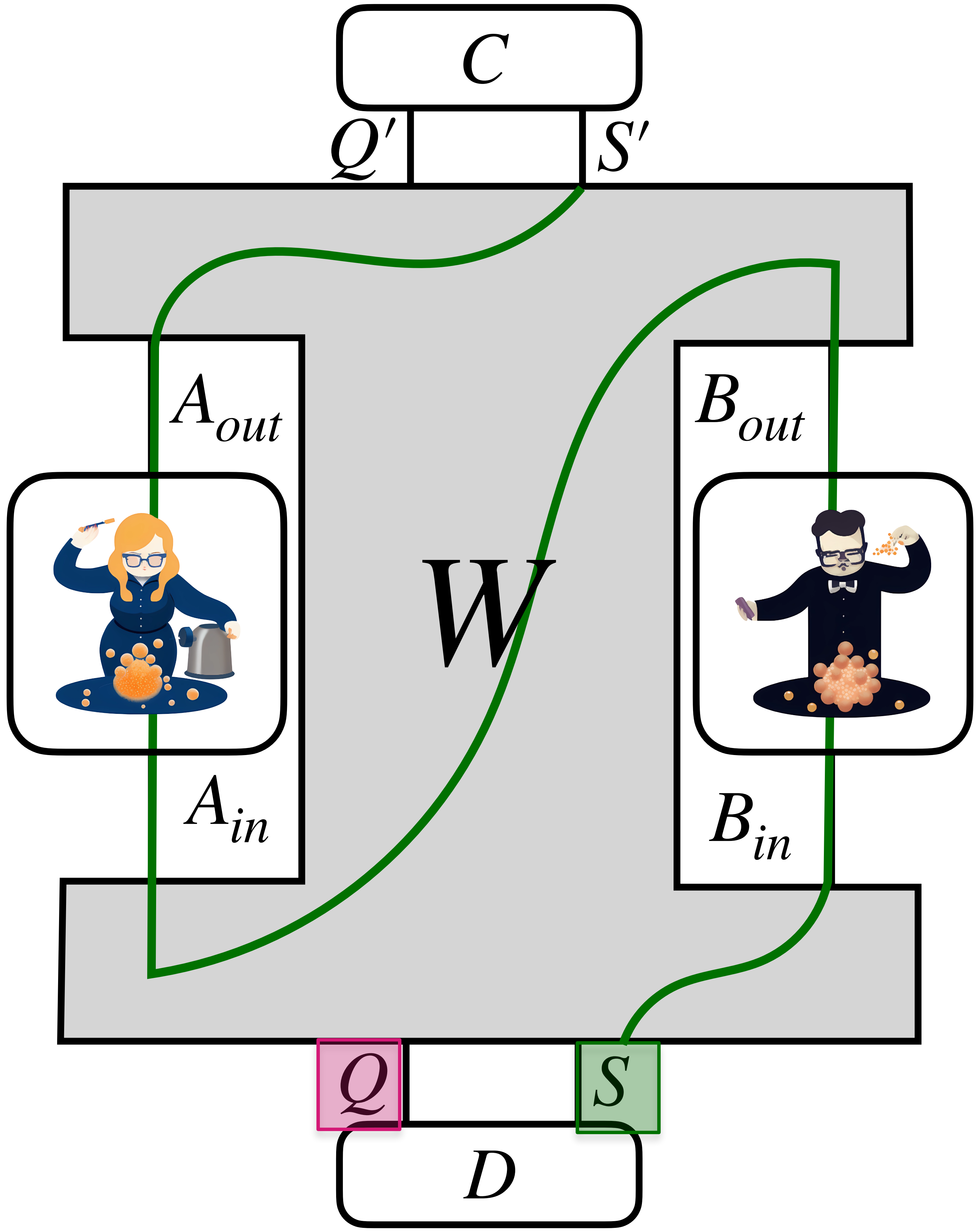

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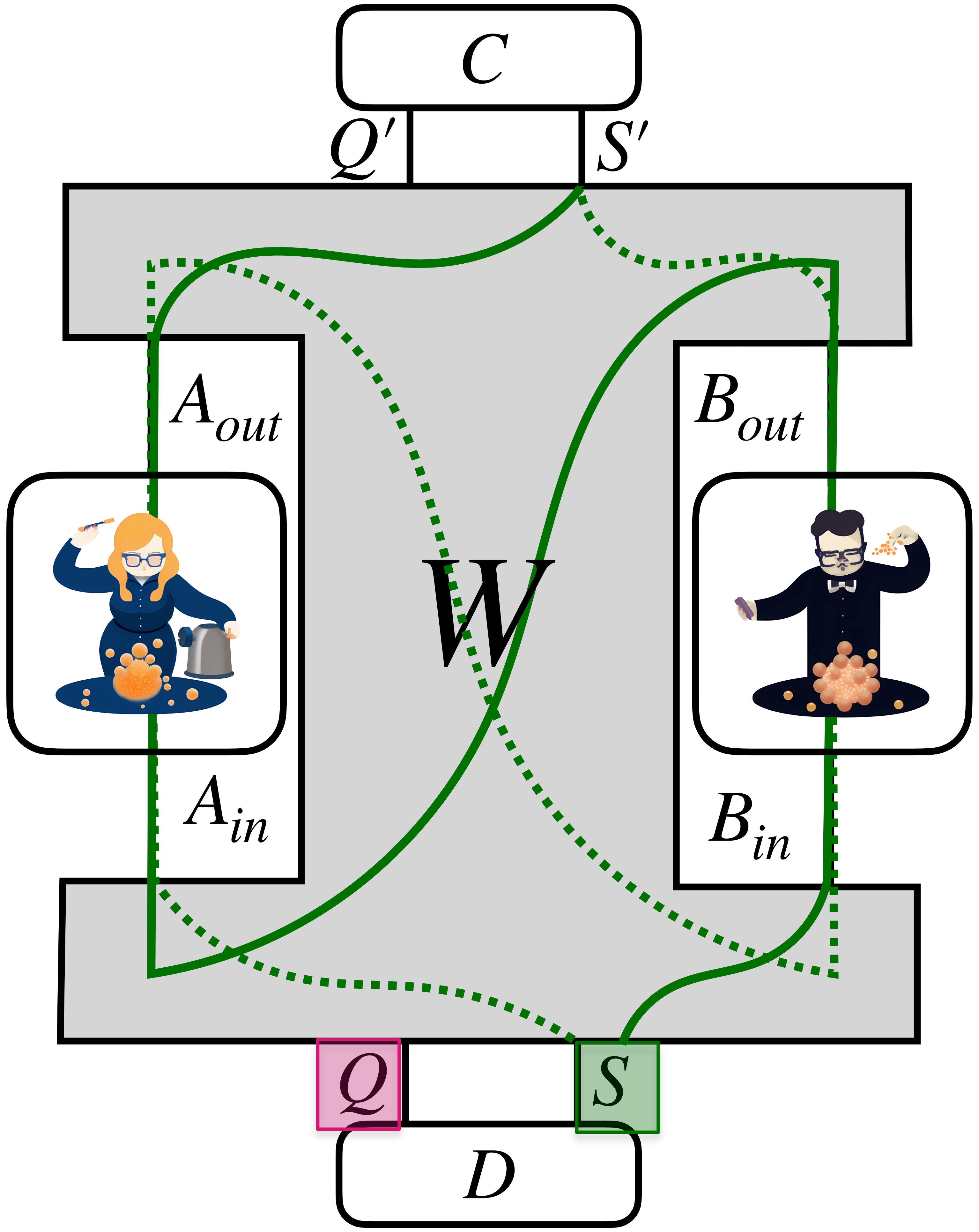

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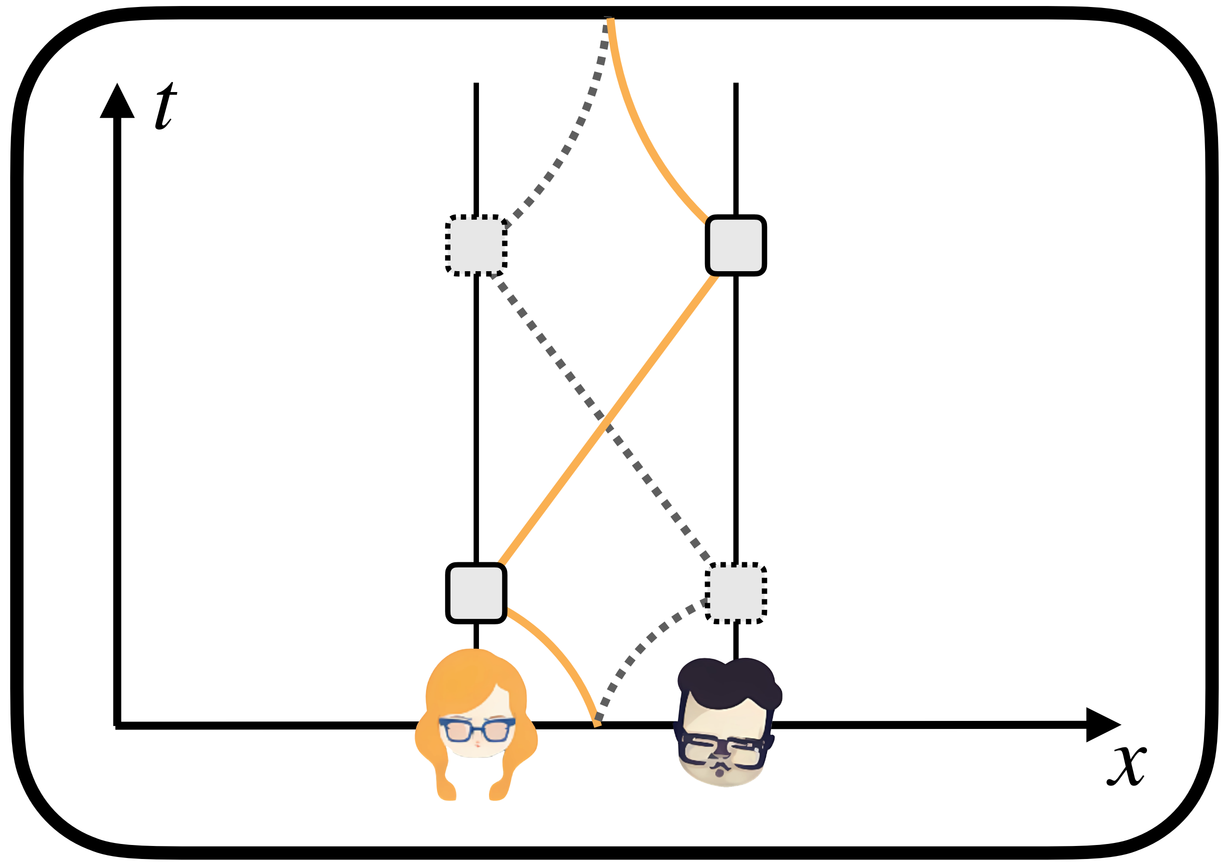
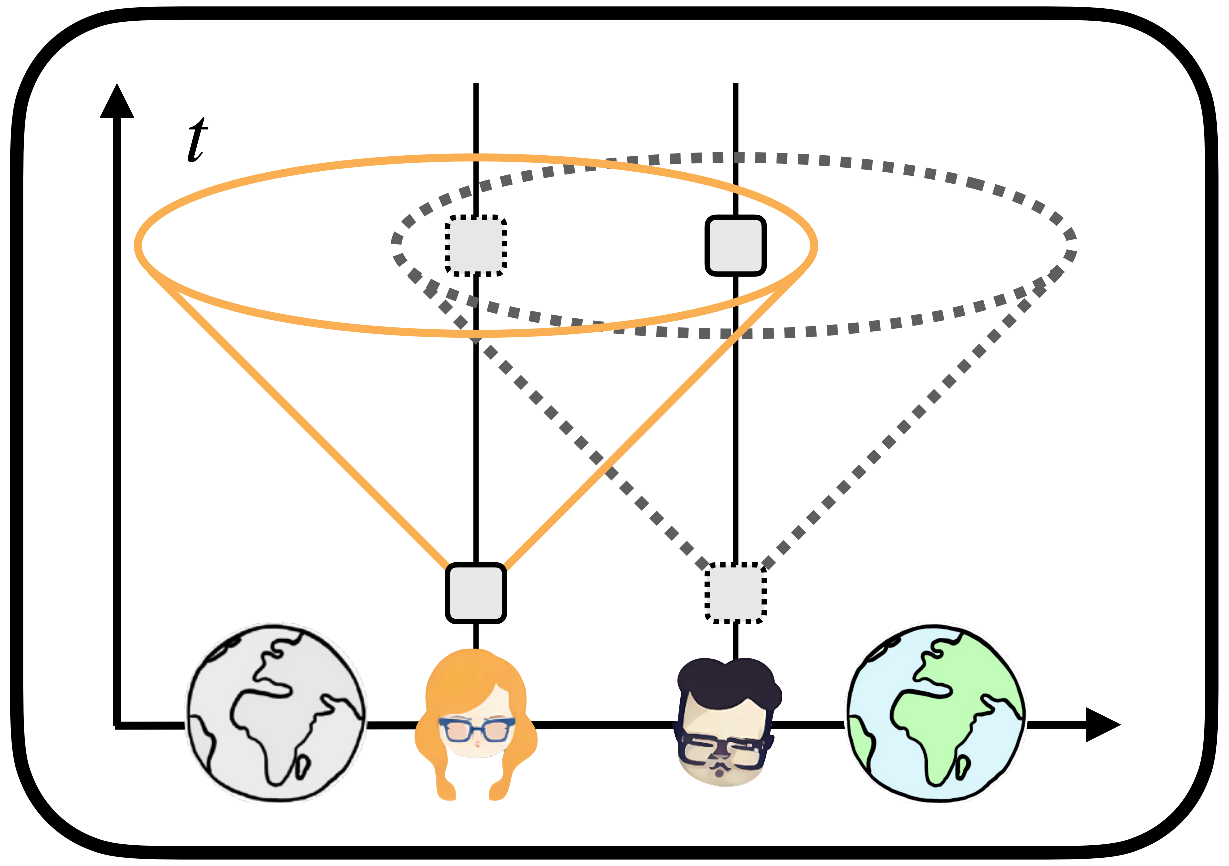


Optical Quantum Switch



Gravitational Quantum Switch

- **Indefinite Causal Order (ICO):** no classical mixture of $A \prec B$ and $B \prec A$
- Process with ICO : the **quantum SWITCH**

$$|\Psi\rangle_{CT} = \frac{1}{\sqrt{2}}\left(|0\rangle_C U_B U_A + |1\rangle_C U_A U_B\right)|\Psi^{in}\rangle_T$$

- Different implementations of this abstract process.

Hardy, J. Phys. A 40, 3081(2007).
Oreshkov, Costa, Brukner, Nat Commun 3, 1092 (2012).
Chiribella, D'Ariano, Perinotti, Valiron, Phys. Rev. A 88, 022318 (2013).
Zych, Costa, Brukner, Nat Commun 10, 3772 (2019).

Processes with Indefinite Causal Order

The optical quantum switch

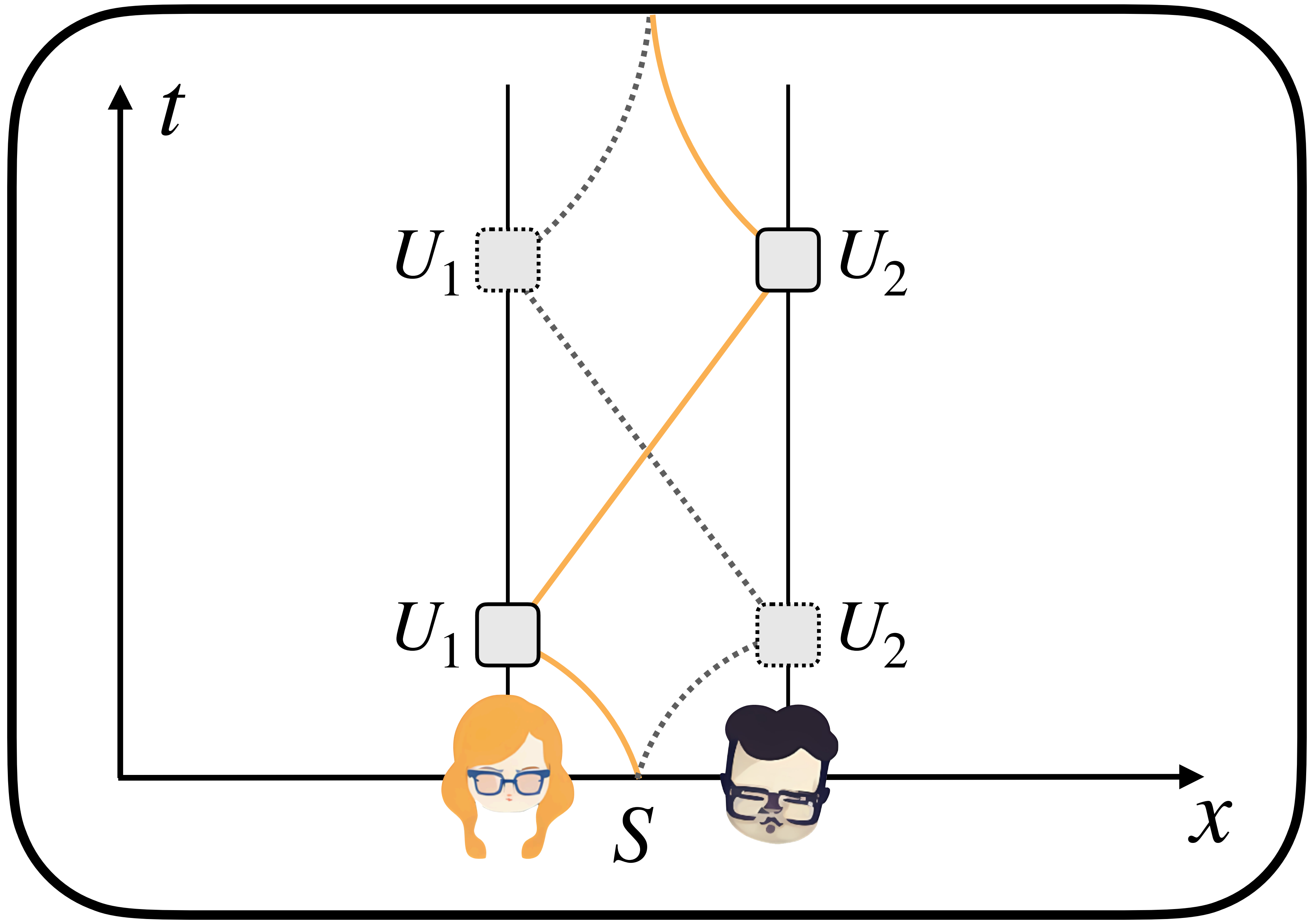
✦ Two experimenters - Alice and Bob.

✦ Each of them

- receives a physical system
- performs an operation U_i on it, and
- sends it out of their laboratory.

✦ If the system moves in a superposition of paths, the operations are performed in a superposition of orders.

Indefinite causal order through superposition of paths.

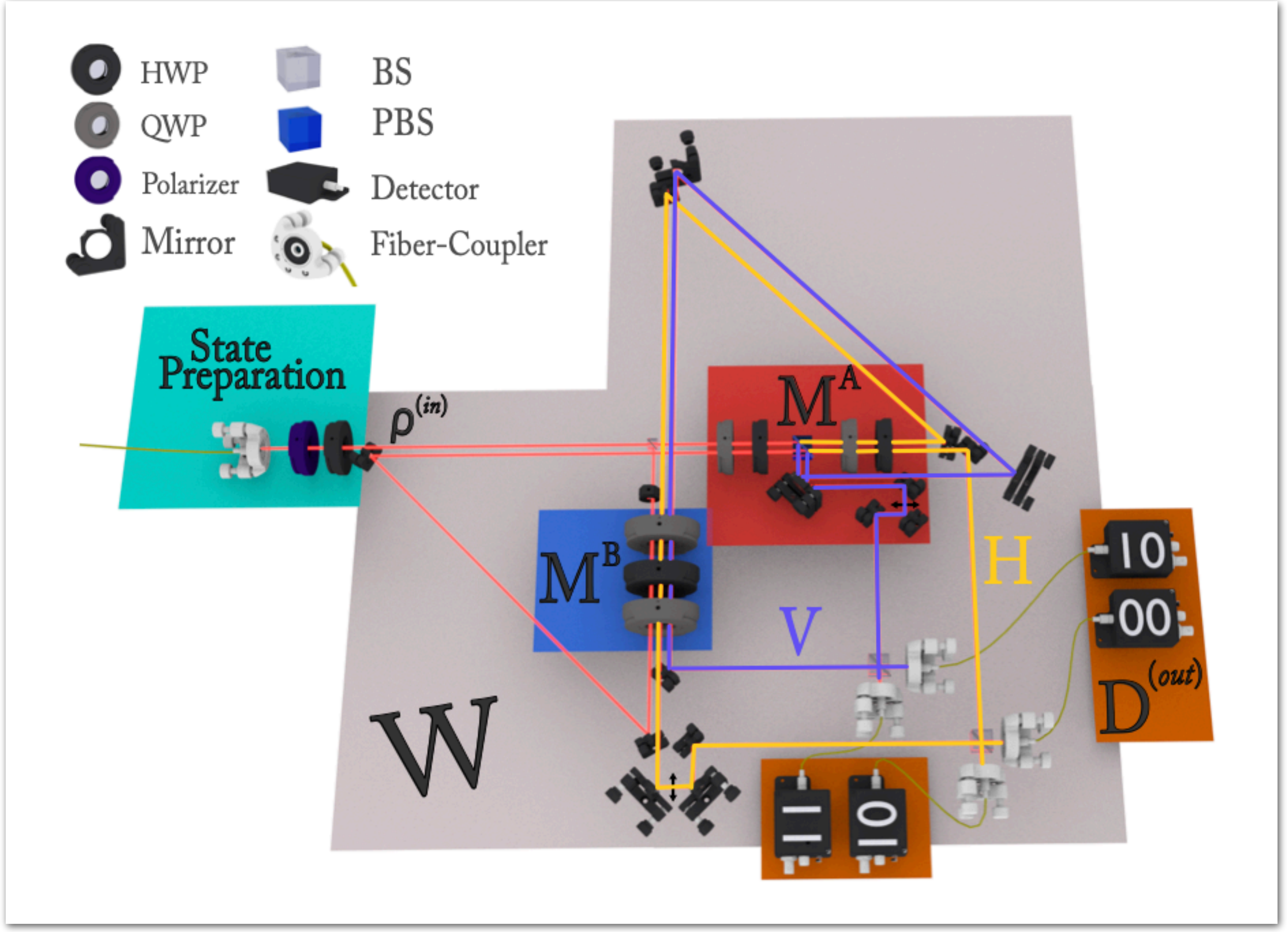


Chiribella, D'Ariano, Perinotti, Valiron (2013); Oreshkov (2019)

Processes with Indefinite Causal Order

The optical quantum switch

- Has been realised in **optical experiments**:
  - Path as control
  - Polarisation as control
- Debated whether this counts as genuine **realisation** of ICO.



Rubino et al. (2016)

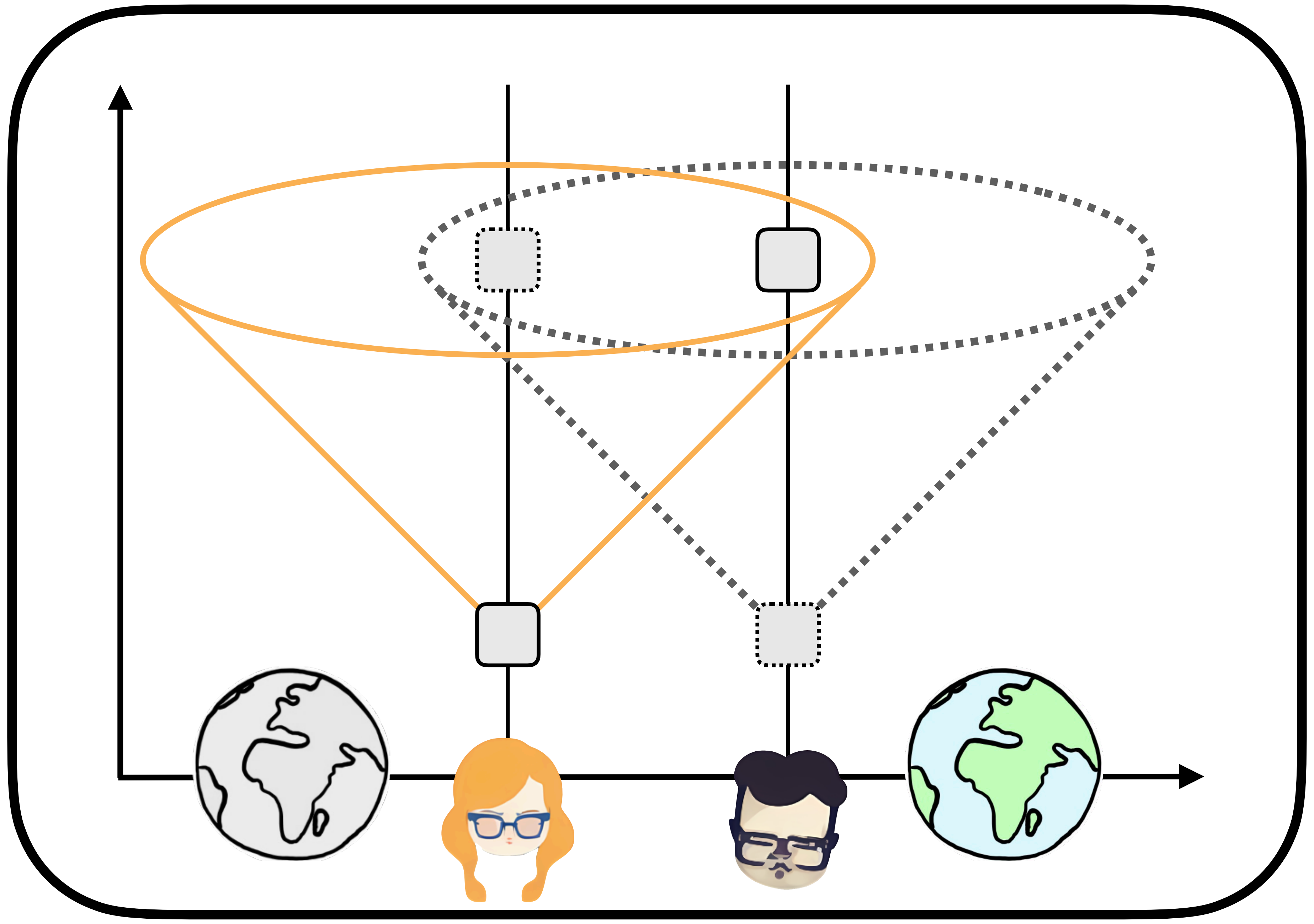
Can we get ICO through superposition of gravitational fields?

Procopio et al. (2014), Rubino et al. (2016), Goswami et al. (2018)

Processes with Indefinite Causal Order

The gravitational quantum switch

- ✦ Two experimenters - Alice and Bob.
- ✦ Each of them performs an operation U_i at fixed proper time τ_*.
- ✦ Gravitational field sourced by a massive object in superposition of locations.



Zych, Costa, Pikovski, Brukner (2019).

Processes with Indefinite Causal Order

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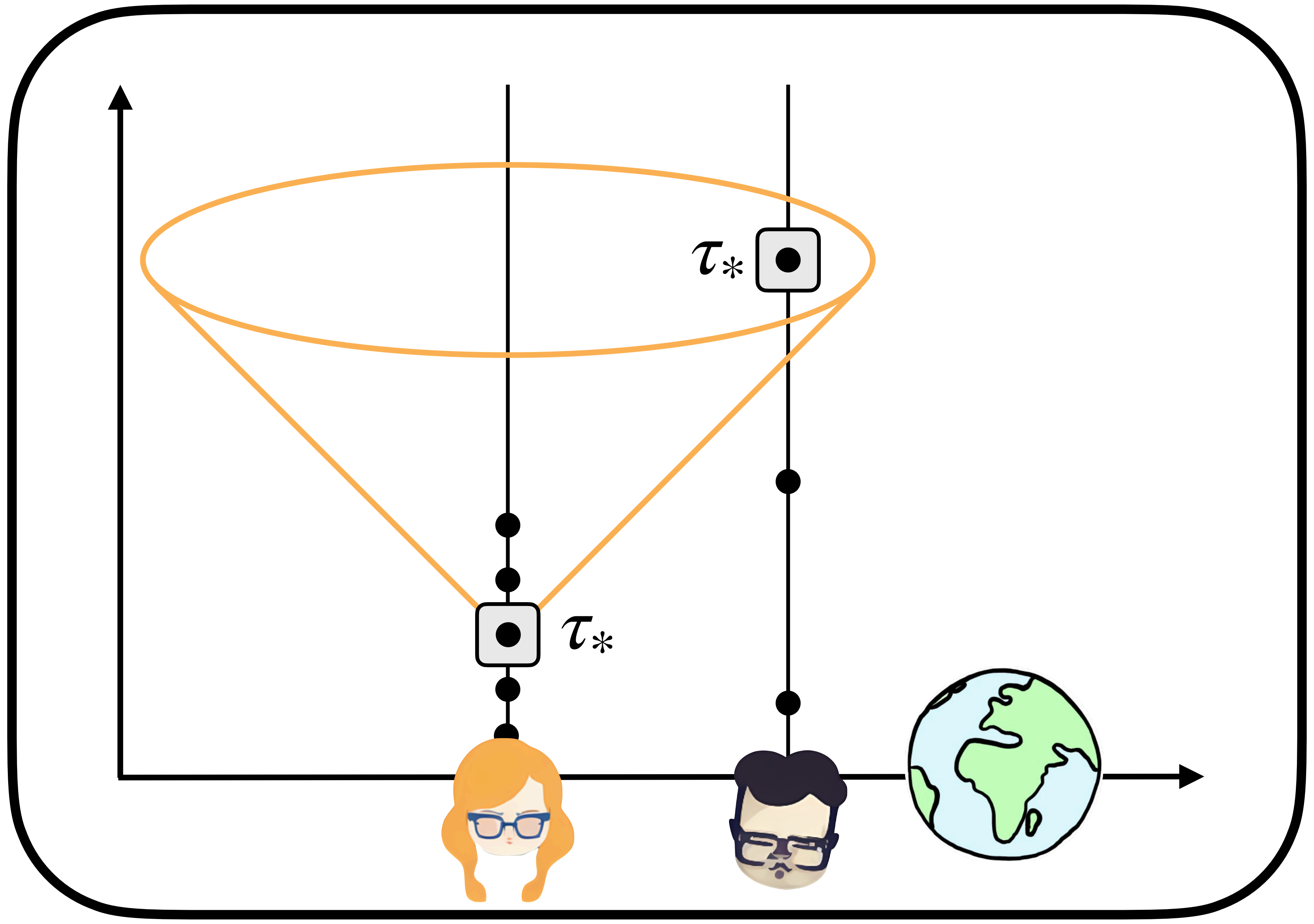
  1. Bob experiences stronger time dilation: $A \prec B$



Zych, Costa, Pikovski, Brukner (2019).

Processes with Indefinite Causal Order

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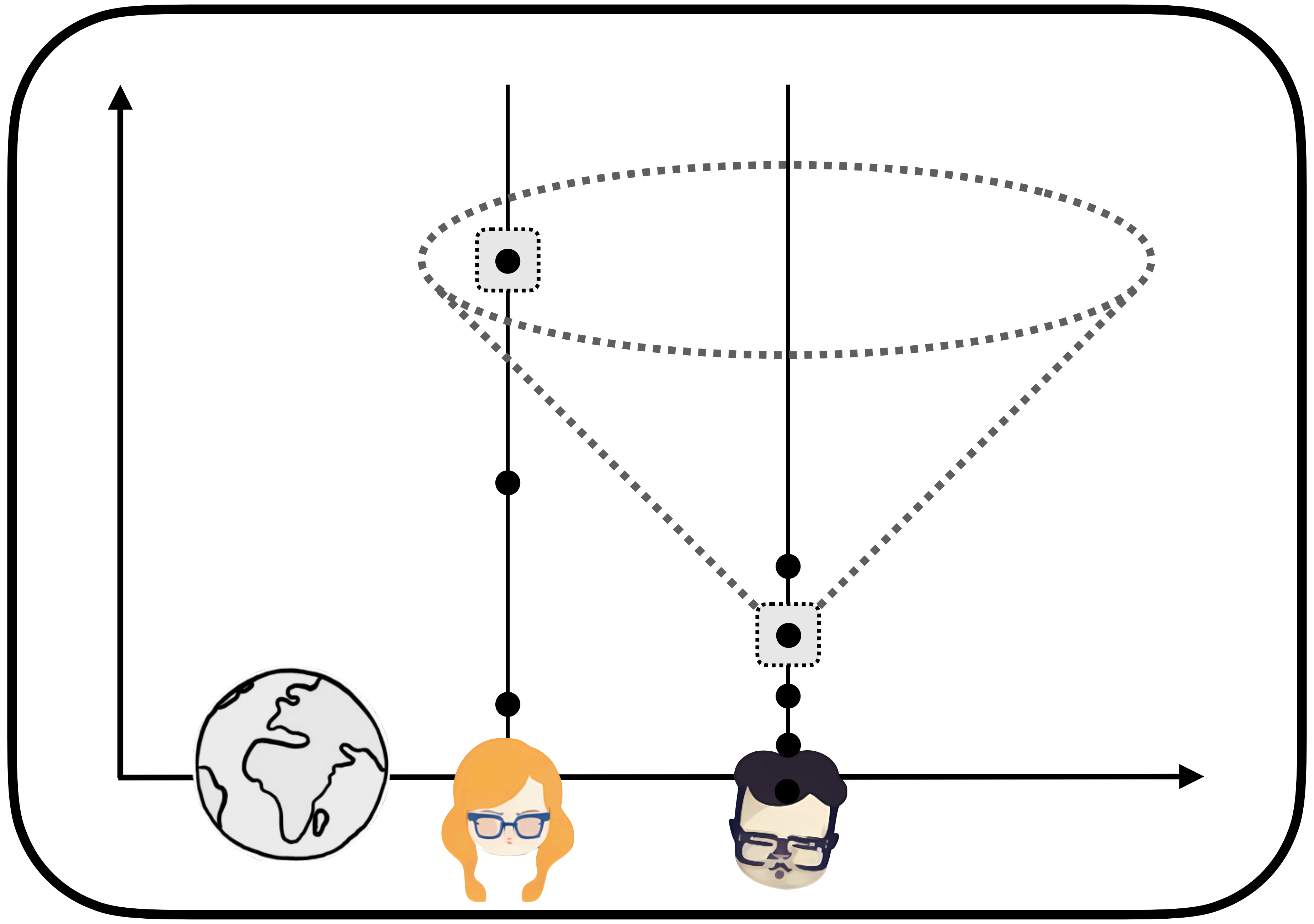

Zych, Costa, Pikovski, Brukner (2019).

Processes with Indefinite Causal Order

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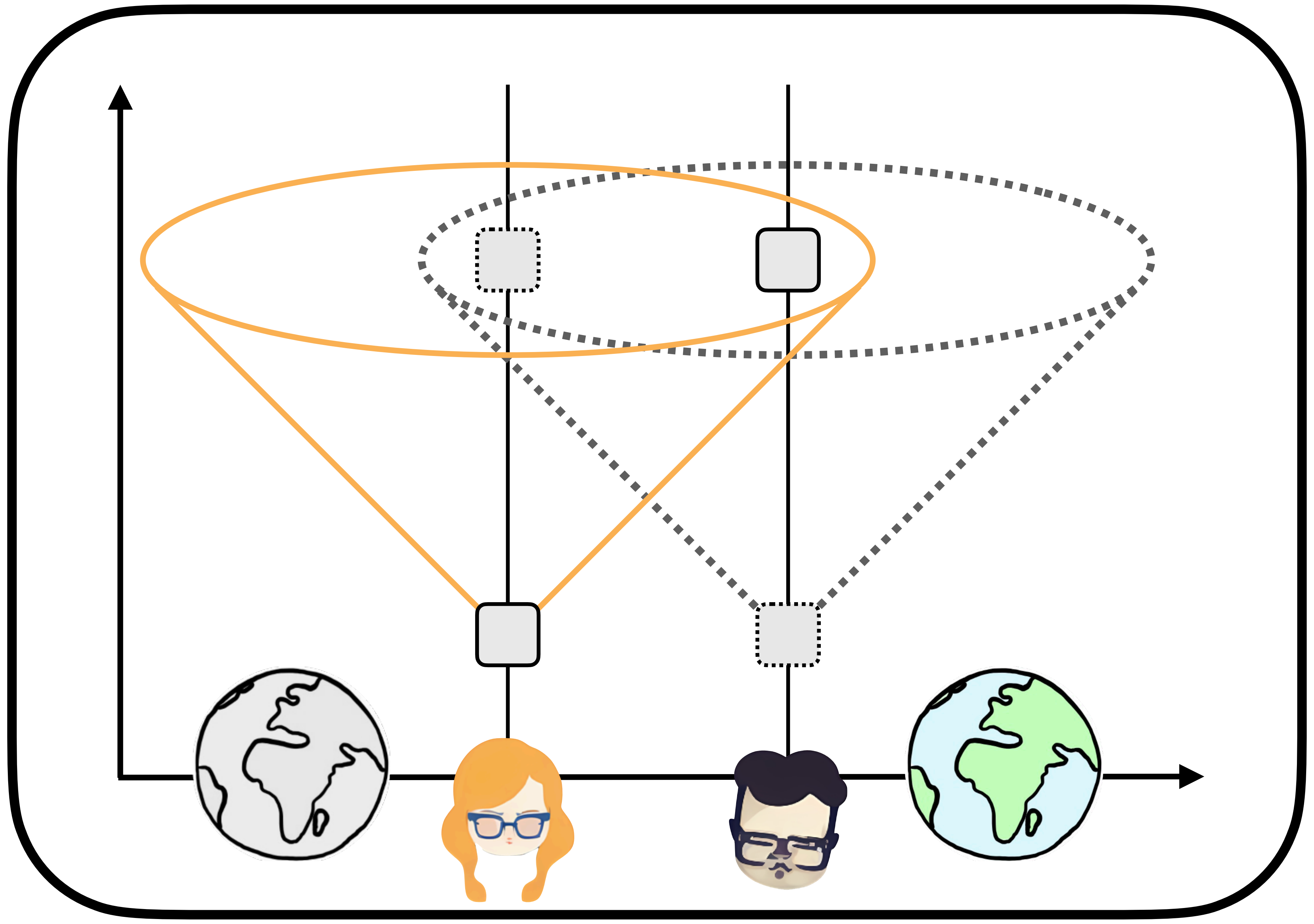
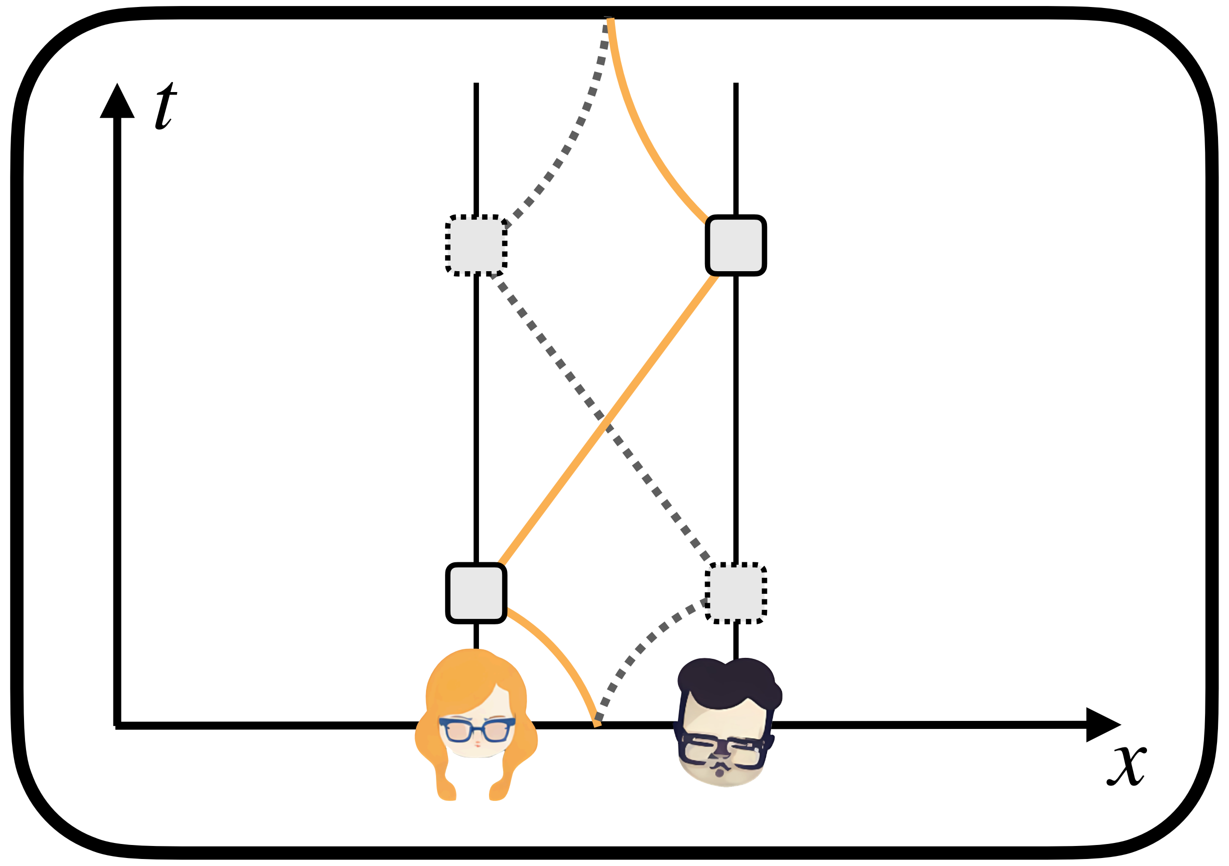


Indefinite causal order through superposition of gravitational fields.

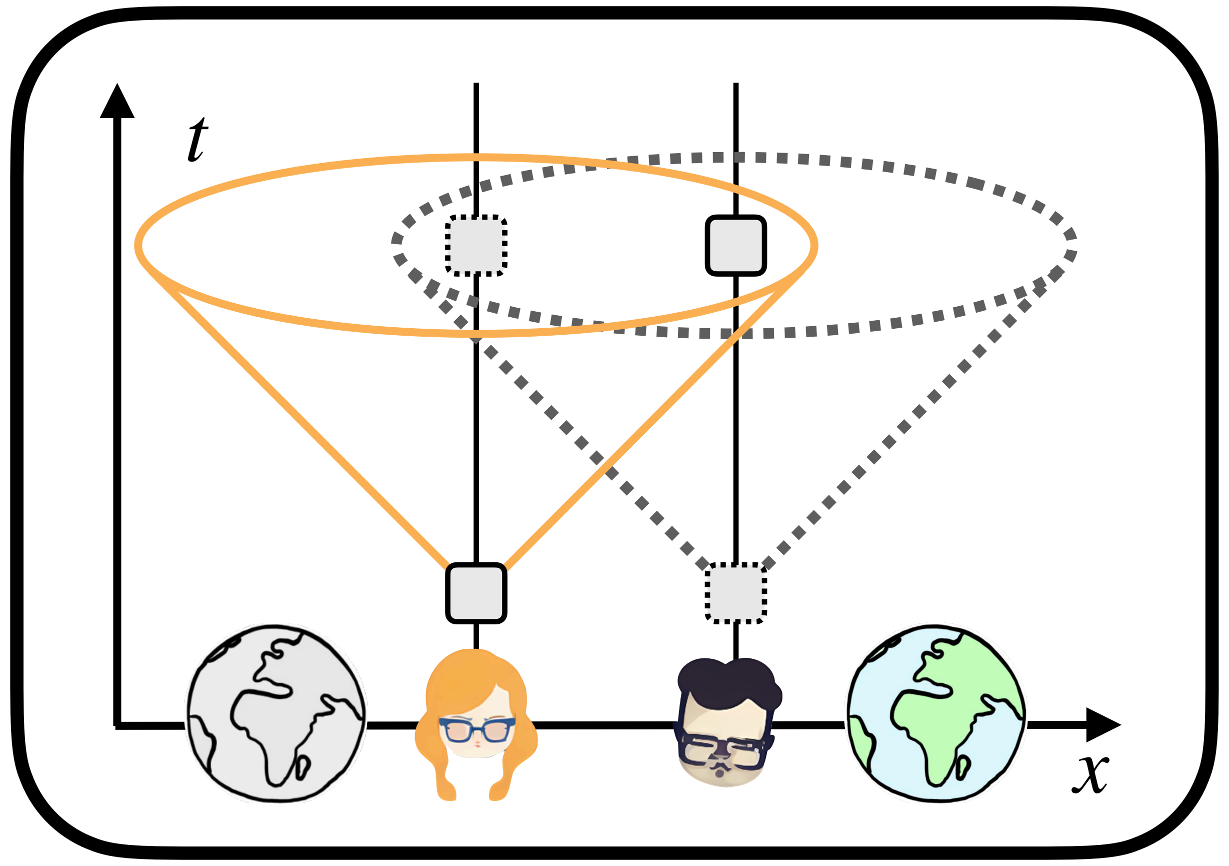
Zych, Costa, Pikovski, Brukner (2019).

QRFs for indefinite causal order

The quantum switch controversy



Optical Quantum Switch



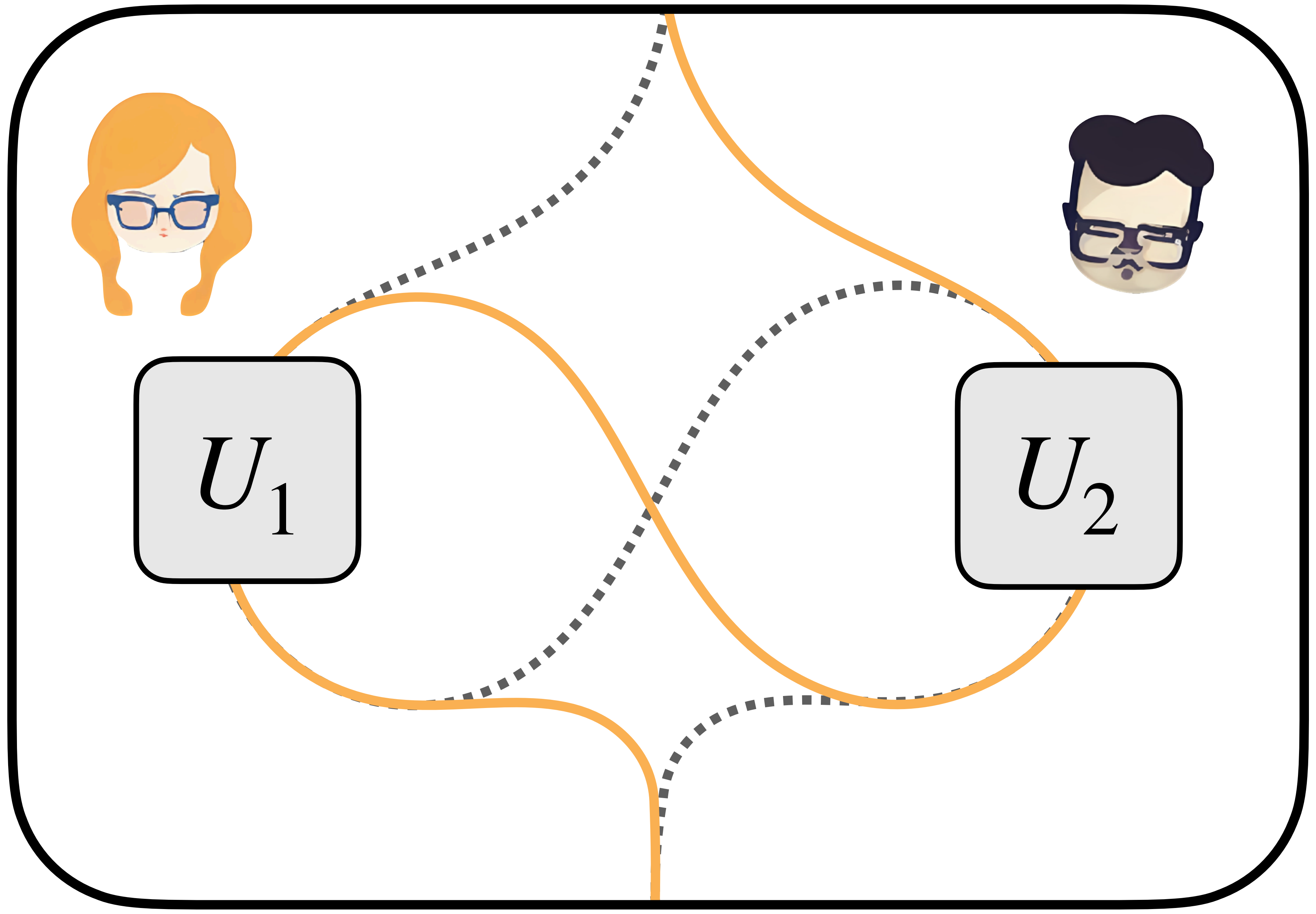
Gravitational Quantum Switch

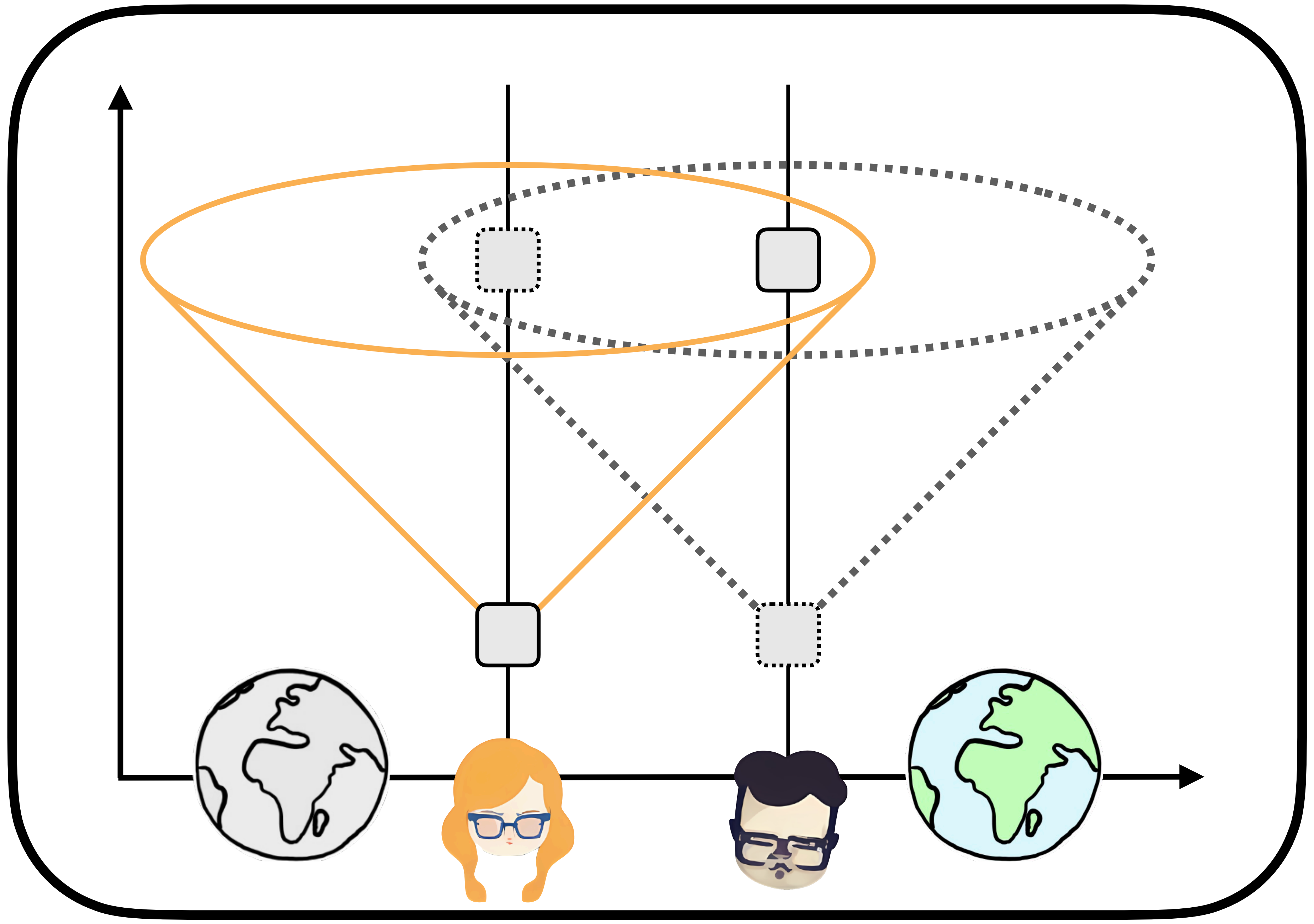
- Ongoing debate regarding the implementation of the "quantum switch" exhibiting **indefinite causal order**.

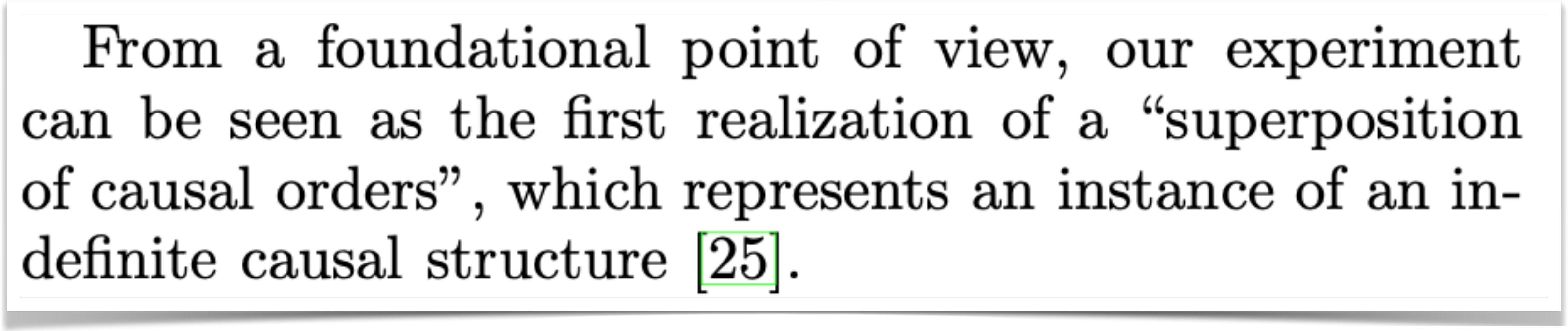
Oreshkov (2019), Quantum 3, 206 (2019).
Paunkovic & Vojinovic, Quantum 4, 275 (2020).
Ormrod, Vanrietvelde, Barrett, Quantum 7, 1028 (2023).

Indefinite causal order

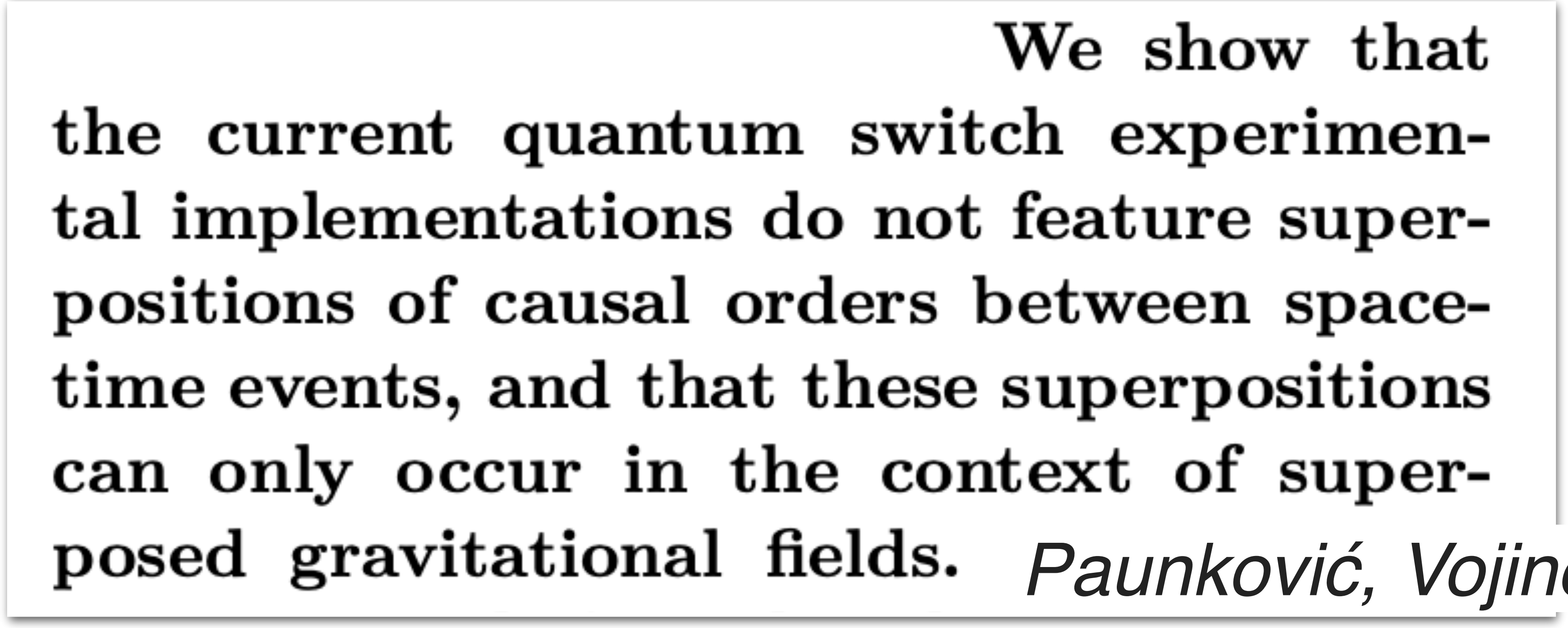
Simulation vs Realisation






From a foundational point of view, our experiment can be seen as the first realization of a "superposition of causal orders", which represents an instance of an indefinite causal structure [25].

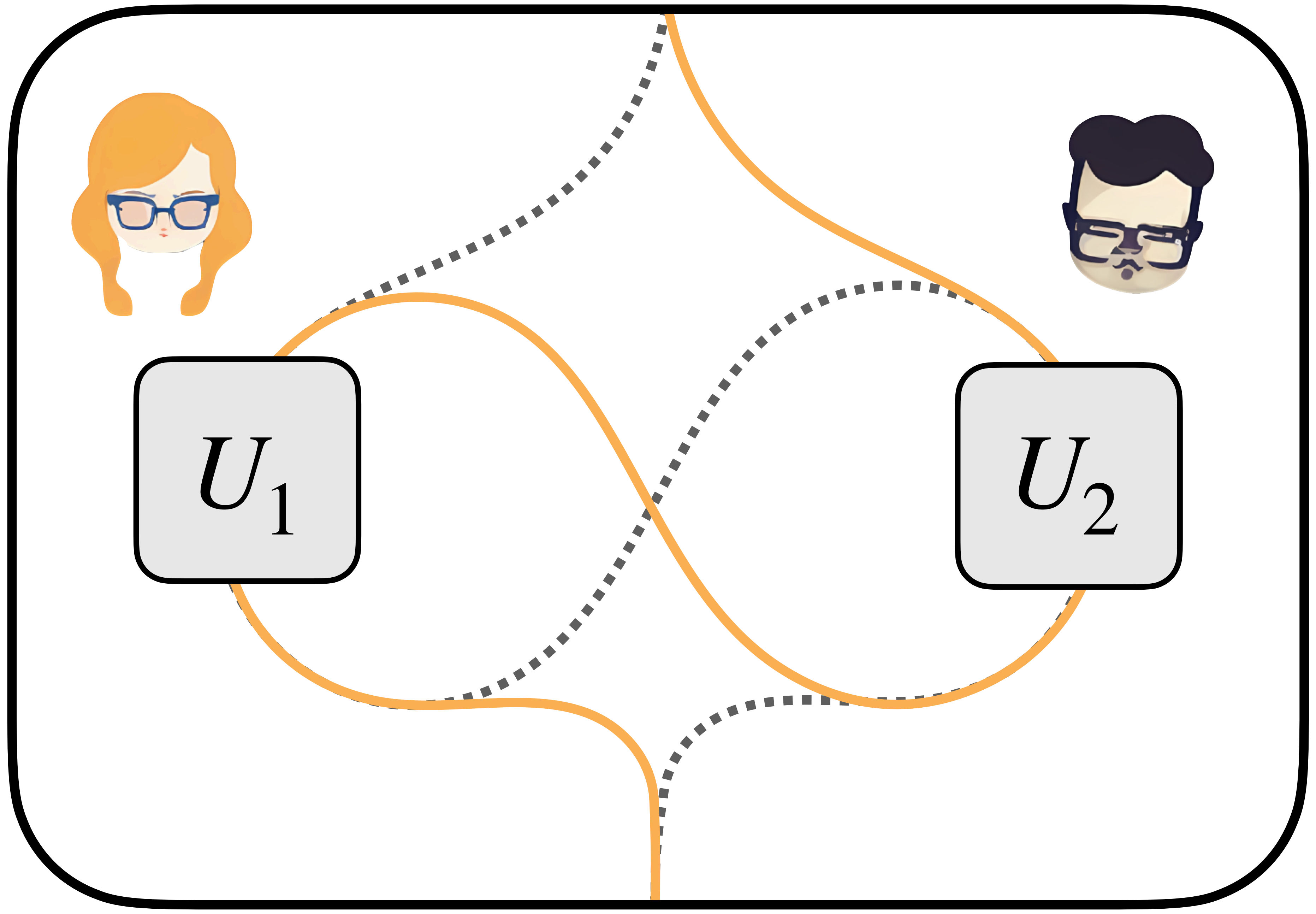
Procopio, Moquanaki, Araujo, et. al. (2014)

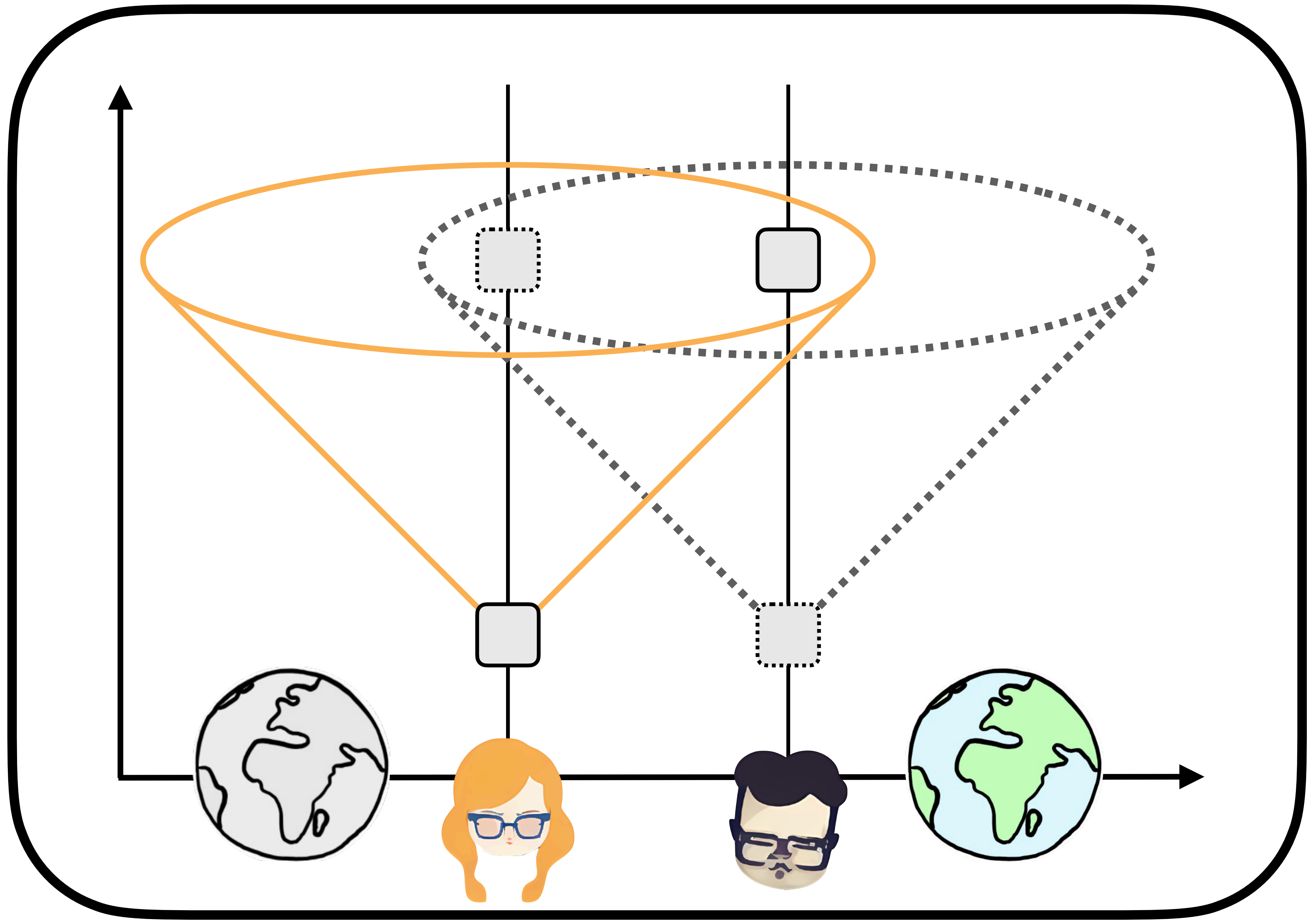

We show that the current quantum switch experimental implementations do not feature superpositions of causal orders between spacetime events, and that these superpositions can only occur in the context of superposed gravitational fields.

Paunković, Vojinović (2020)

Indefinite causal order

Simulation vs Realisation



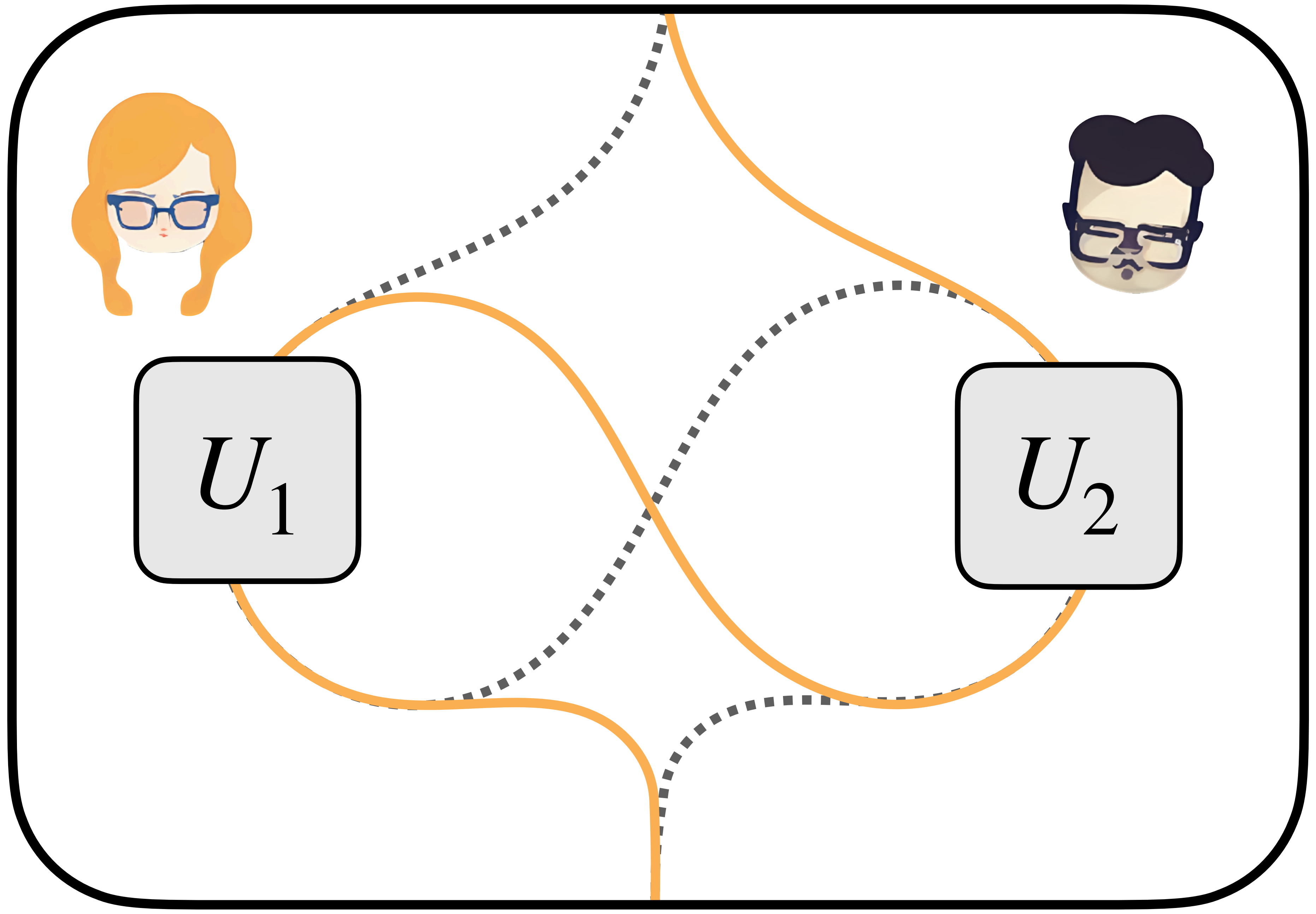


However, the interpretation of such experiments as realizations of a process with indefinite causal structure as opposed to some form of simulation of such a process has remained controversial.

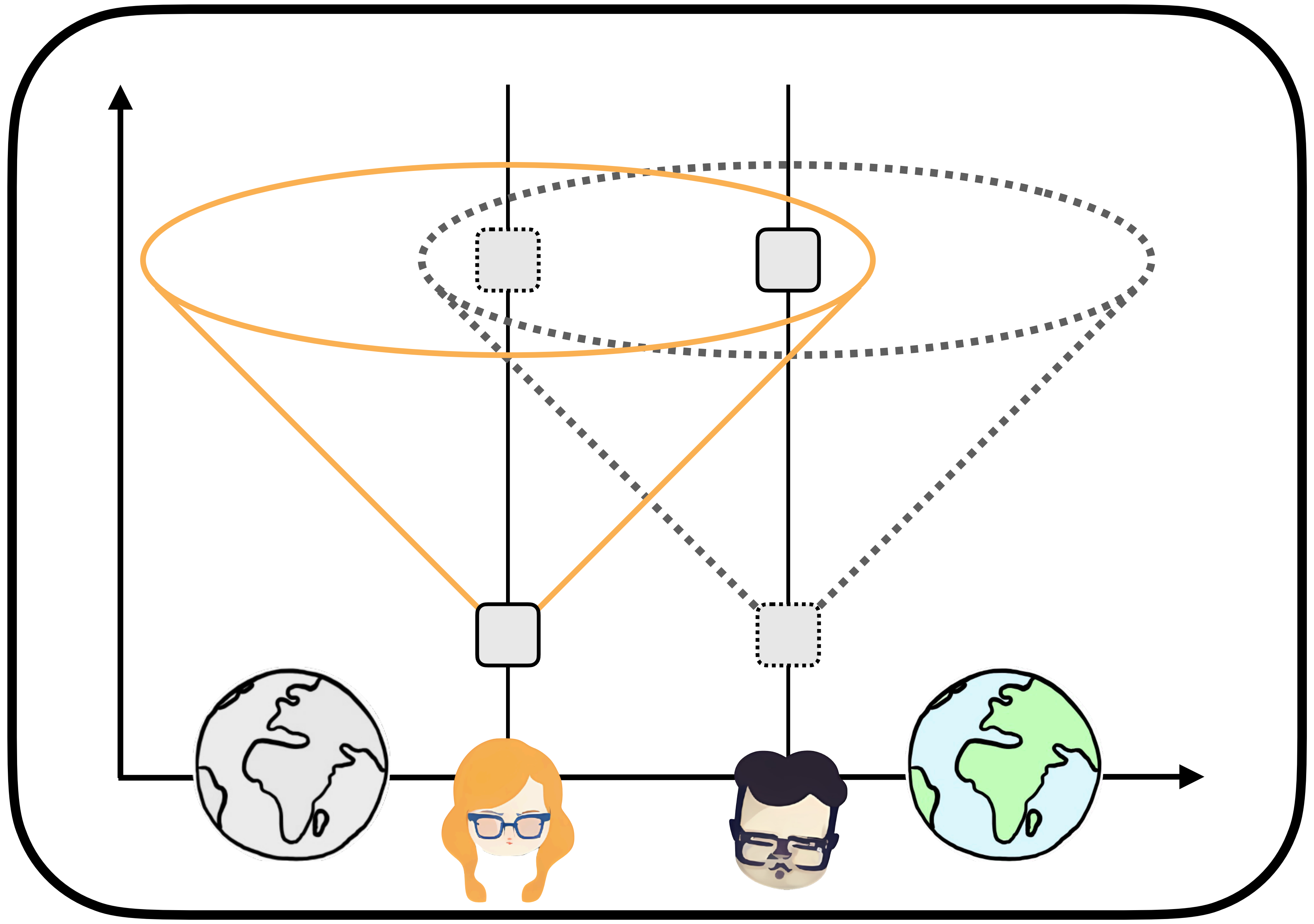
Oreshkov (2019)

Indefinite causal order

Optical vs gravitational implementations



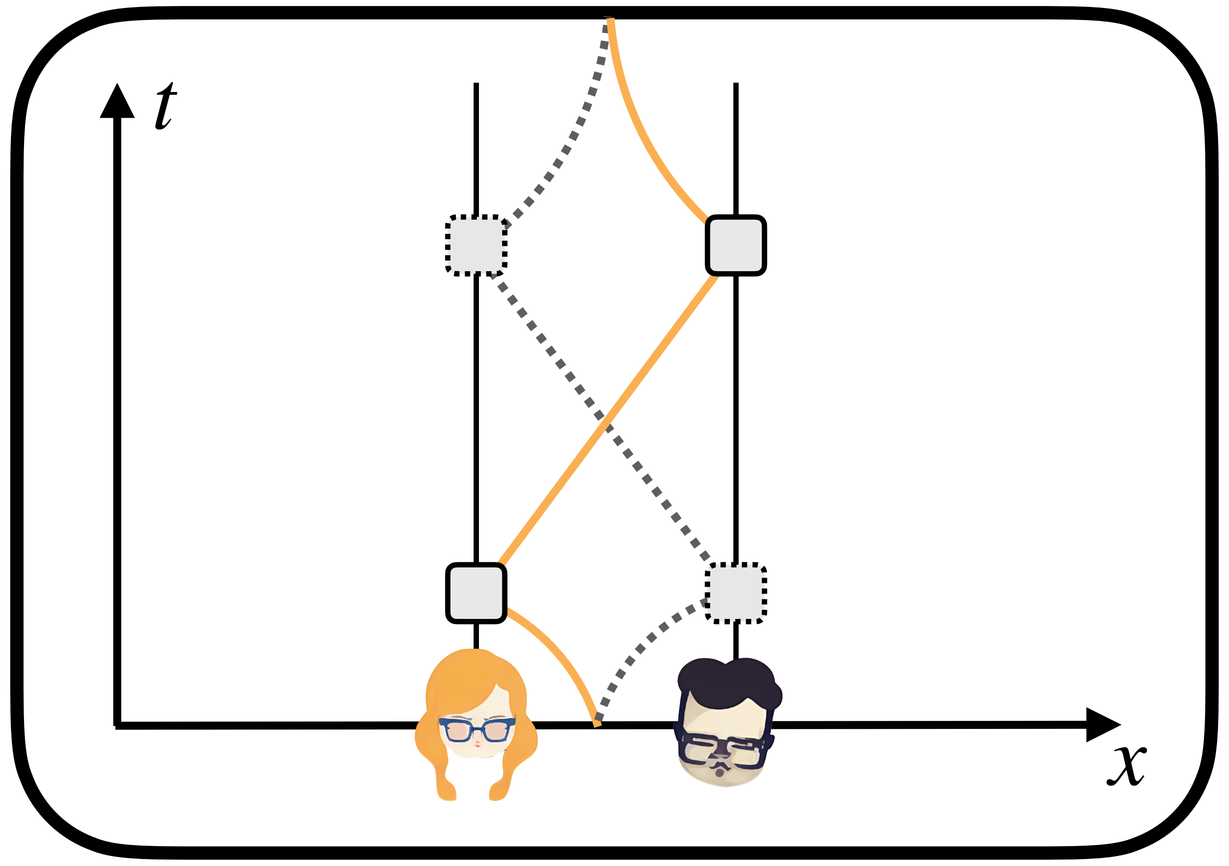
Indefinite causal order through superposition of paths.



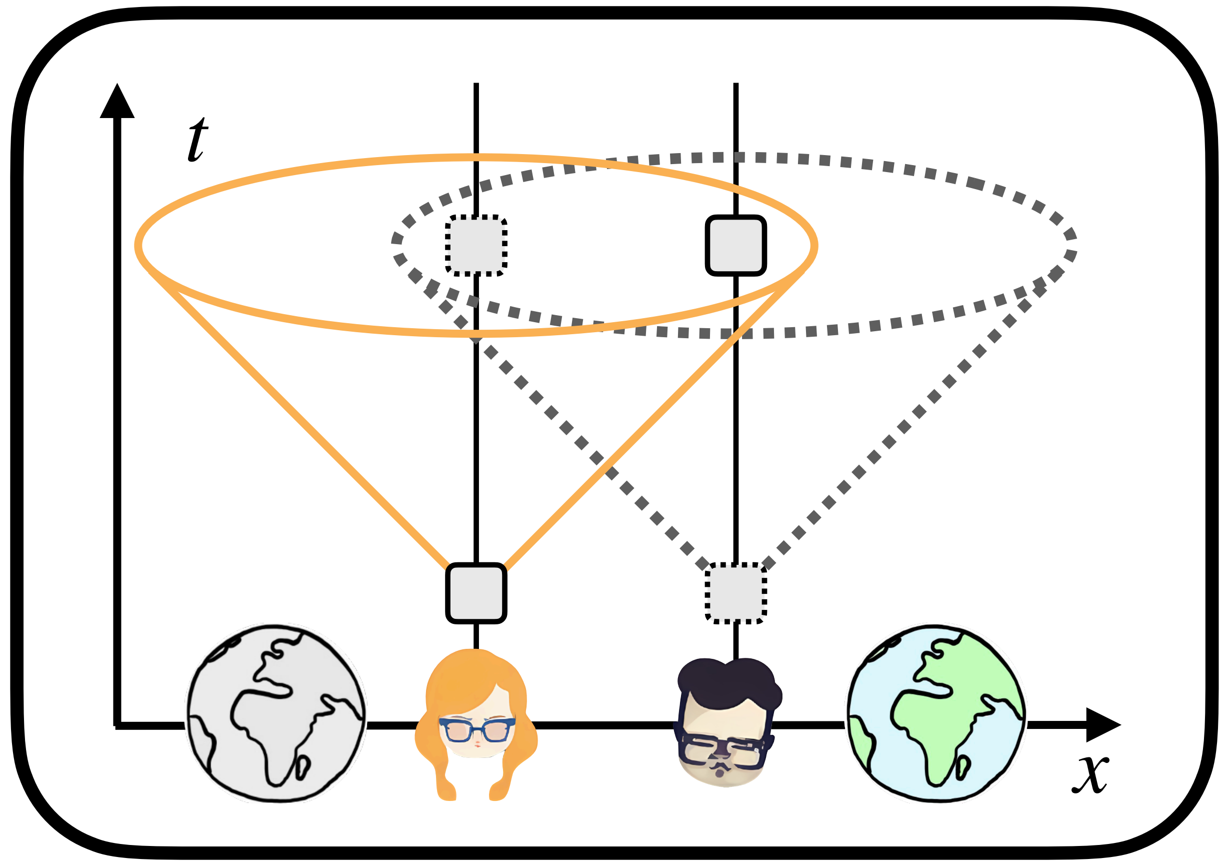
Indefinite causal order through superposition of gravitational fields.

QRFs for indefinite causal order

The quantum switch controversy



Optical Quantum Switch



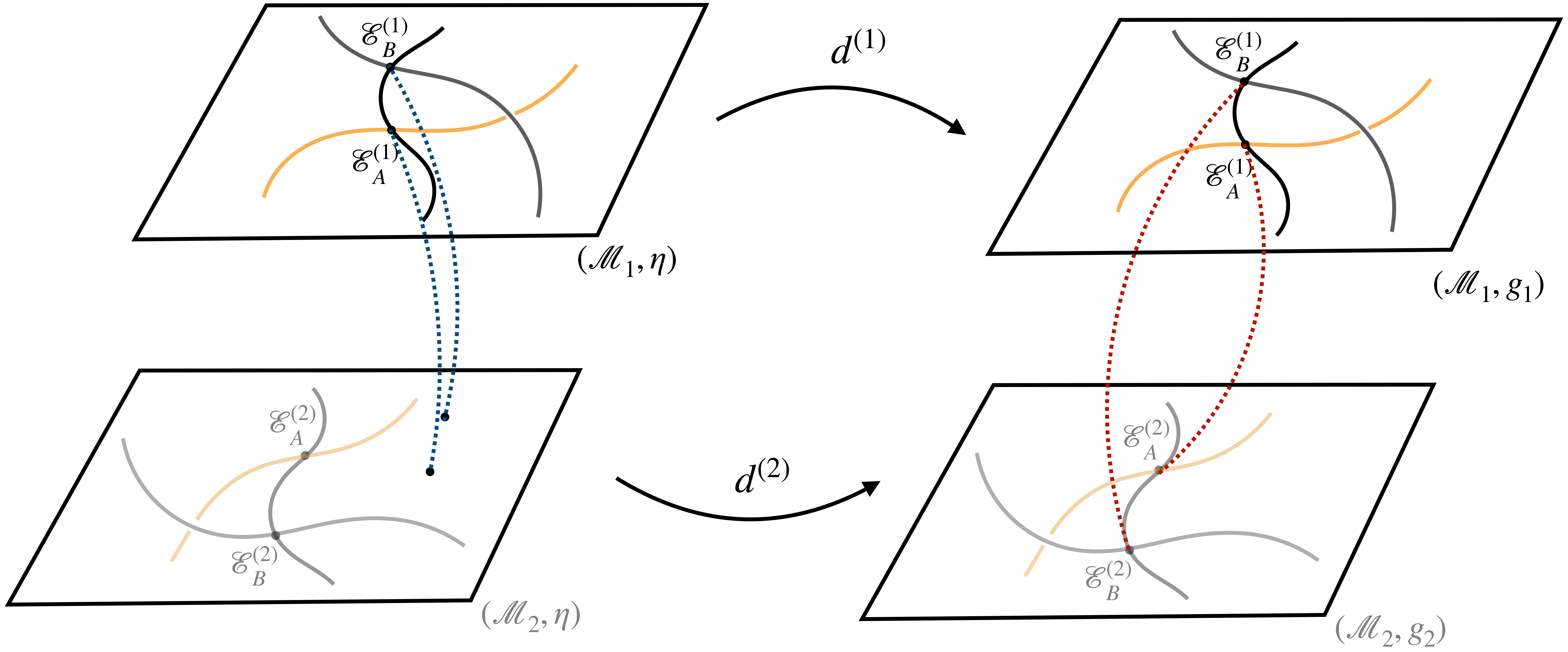
Gravitational Quantum Switch

- Ongoing debate regarding the implementation of the "quantum switch" exhibiting **indefinite causal order**.
- Core of the debate: **how many events** are there?
  - **"Spatiotemporalists":** 4 events (spacetime points)
  - **"Operationalists":** 2 events (application of operation)
- **Insight:** change of QRF can change the number of spacetime points.

Ormrod, Vanrietvelde, Barrett, Quantum 7, 1028 (2023).

QRFs for indefinite causal order

The quantum switch controversy



Four different spacetime points.
Fixed spacetime.

Two different spacetime points.
Superposition of spacetimes.

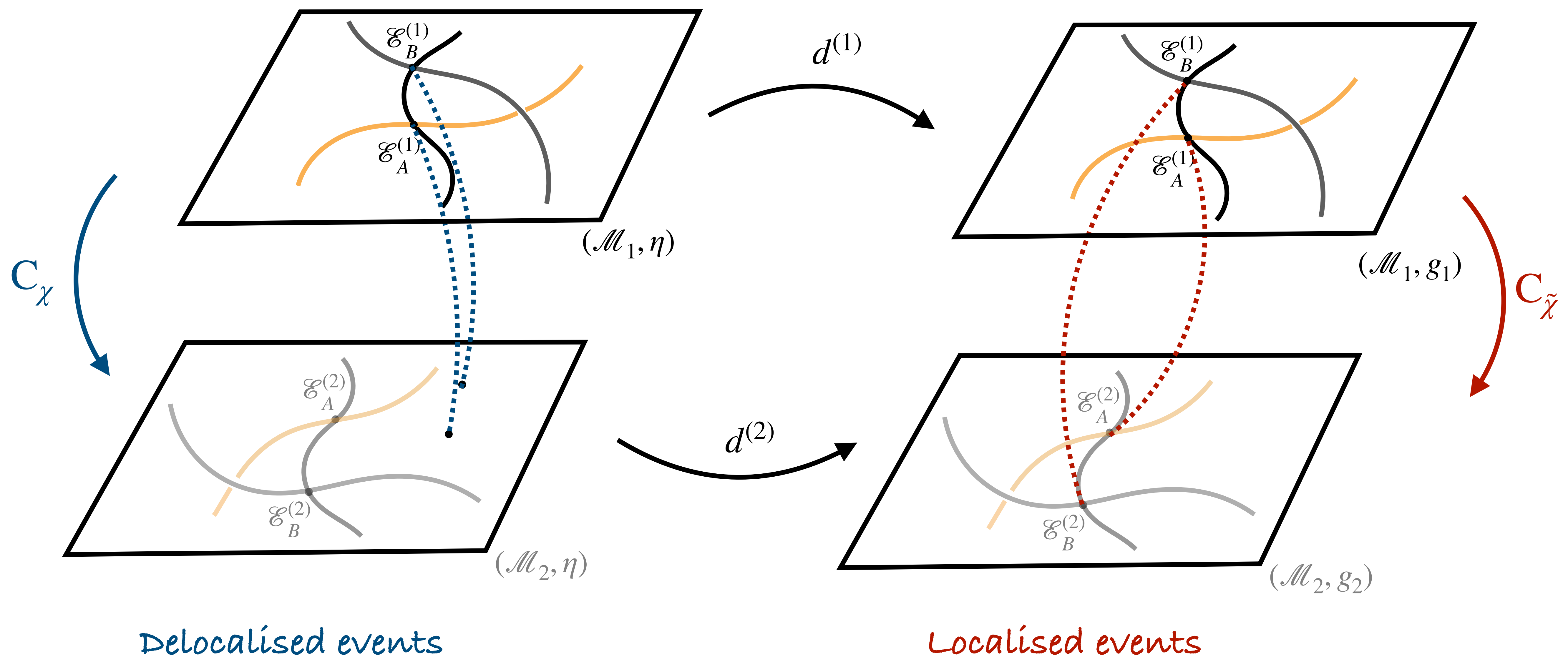
ACdlH, Kabel, Christodoulou, Brukner (2022); Kabel, ACdlH, Apadula et al. (2024).

QRFs for indefinite causal order

The quantum switch controversy

Whether a process displays ICO ‘due’ to delocalised events or a superposition of spacetime metrics can change under quantum diffeomorphisms.

1. ICO ‘due’ to delocalised events in fixed spacetime.



ICO due to delocalised events in fixed spacetime

↓

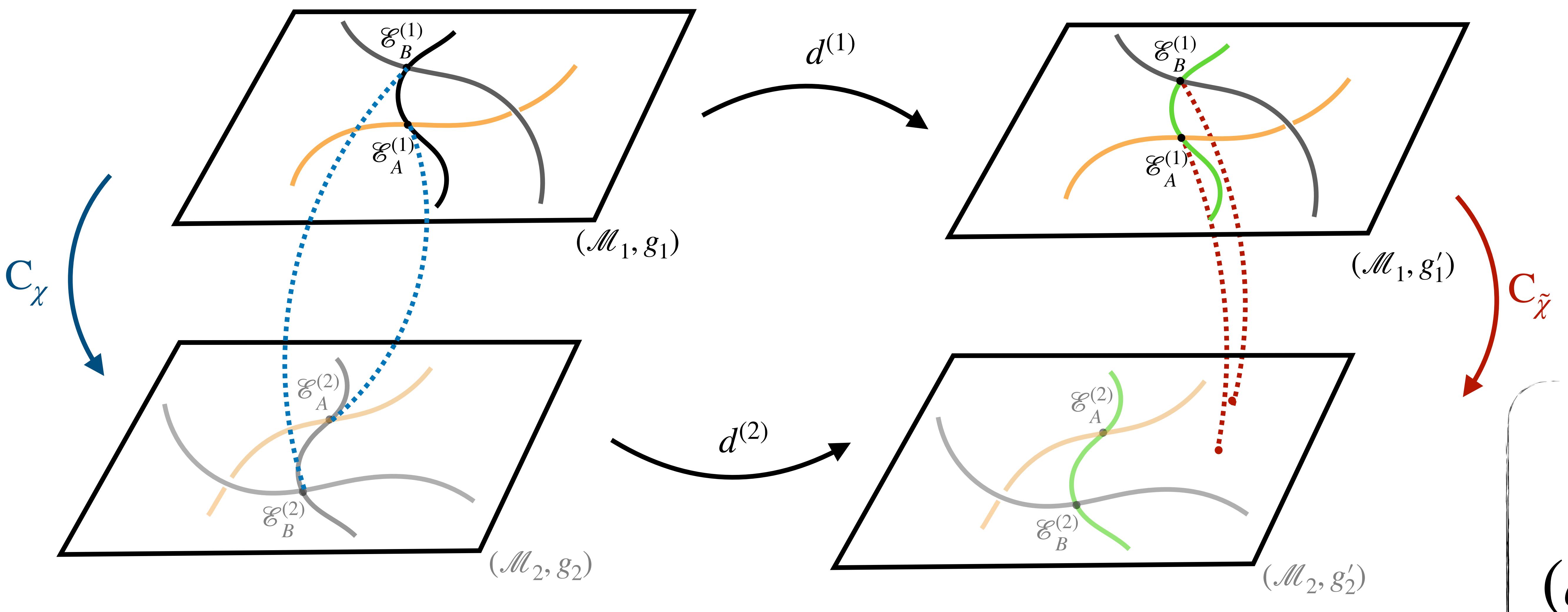
ICO due to superposition of spacetime metrics at localised events

QRFs for indefinite causal order

The quantum switch controversy

Whether a process displays ICO ‘due’ to delocalised events or a superposition of spacetime metrics can change under quantum diffeomorphisms.

2. ICO ‘due’ to a superposition of spacetime metrics.



Superposition of spacetime metrics

Delocalised events, flat metric along γ_0 between $\mathscr{E}_A^{(i)}$ and $\mathscr{E}_B^{(i)}$

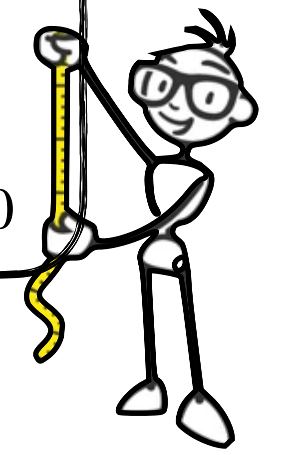
ICO due to superposition of spacetime metrics

↓

ICO due to delocalised events

Fermi normal coordinates along γ_0 :

$$(d^{(1)})_*^{-1}(g^{(1)})\,|_{\gamma_0} = (d^{(2)})_*^{-1}(g^{(2)})\,|_{\gamma_0} = \eta\,|_{\gamma_0}$$



QRFs for indefinite causal order

Whether ICO is due to delocalised events or a superposition of metrics depends on the choice of quantum coordinates.

A no-go theorem

There is no quantum coordinate system in which the following three statements hold:

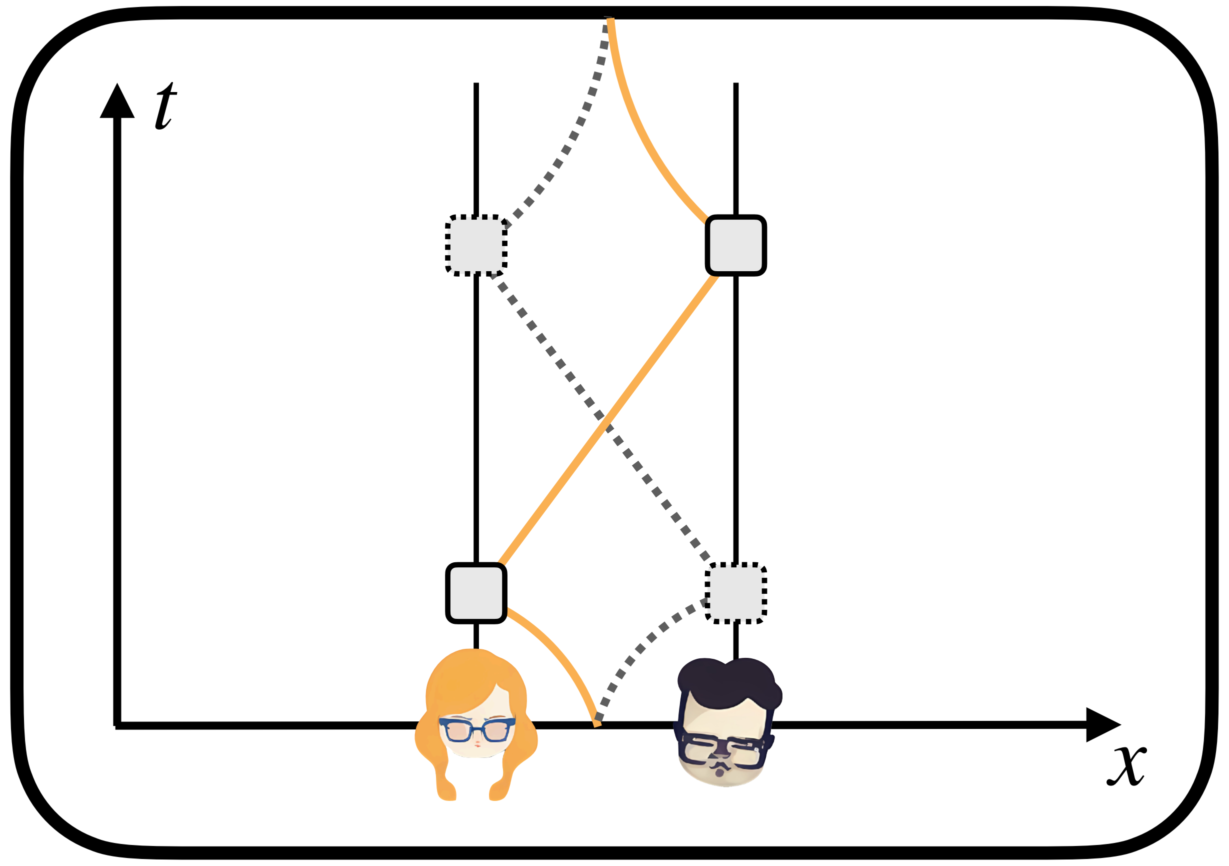
1. Both **events** $\mathscr{E}_A$ and $\mathscr{E}_B$ are **localised**.
2. The spacetime **metric** is **definite**.
3. The **causal order** between $\mathscr{E}_A$ and $\mathscr{E}_B$ is **indefinite**.

*consistent with Cor. 8.2 in Vilasini & Renner PRA 110, 022227 (2024).

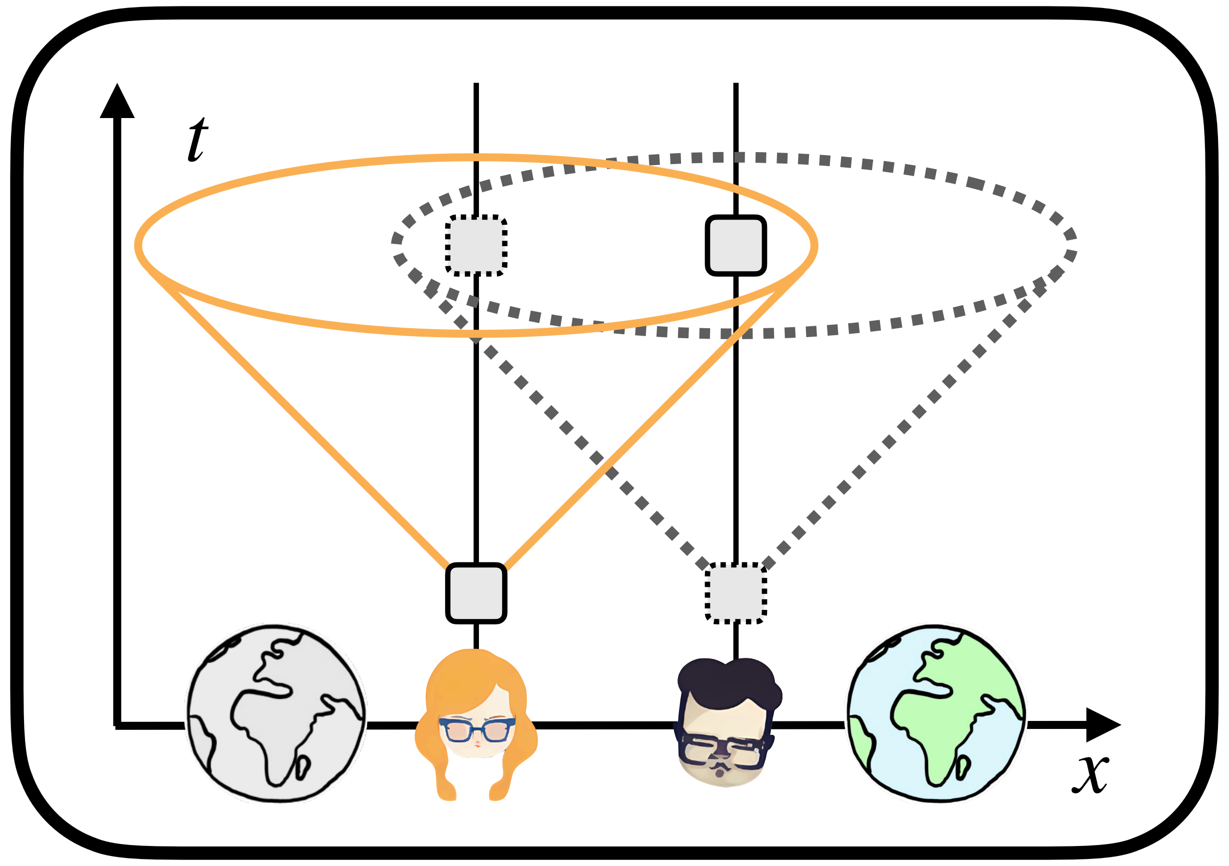
ACdlH, Kabel, Christodoulou, Brukner (2022); Kabel, ACdlH, Apadula et al. (2024).

QRFs for indefinite causal order

The quantum switch controversy



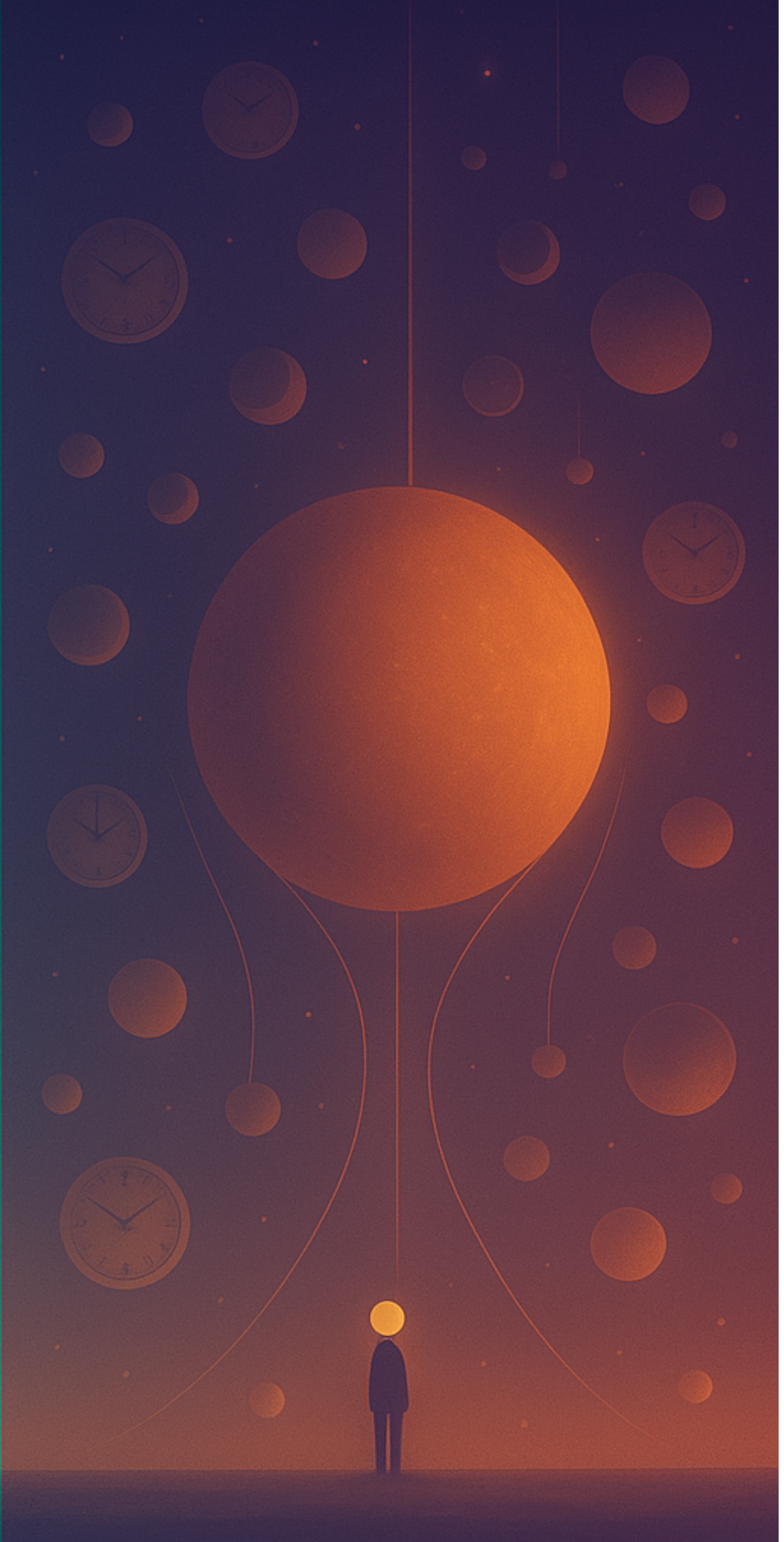
Optical Quantum Switch



Gravitational Quantum Switch

- Ongoing debate regarding the implementation of the "quantum switch" exhibiting **indefinite causal order**.
- Core of the debate: **how many events** are there?
  - **"Spatiotemporalists":** 4 events (spacetime points)
  - **"Operationalists":** 2 events (application of operation)
- **Insight:** change of QRF can change the number of spacetime points.

  Should not take spacetime location of event as relevant property.
- When formulated in an **invariant** manner, optical and gravitational QS exhibit same type of ICO.



Summary

<u>Part I:</u> Quantum reference frames as a tool for predictions

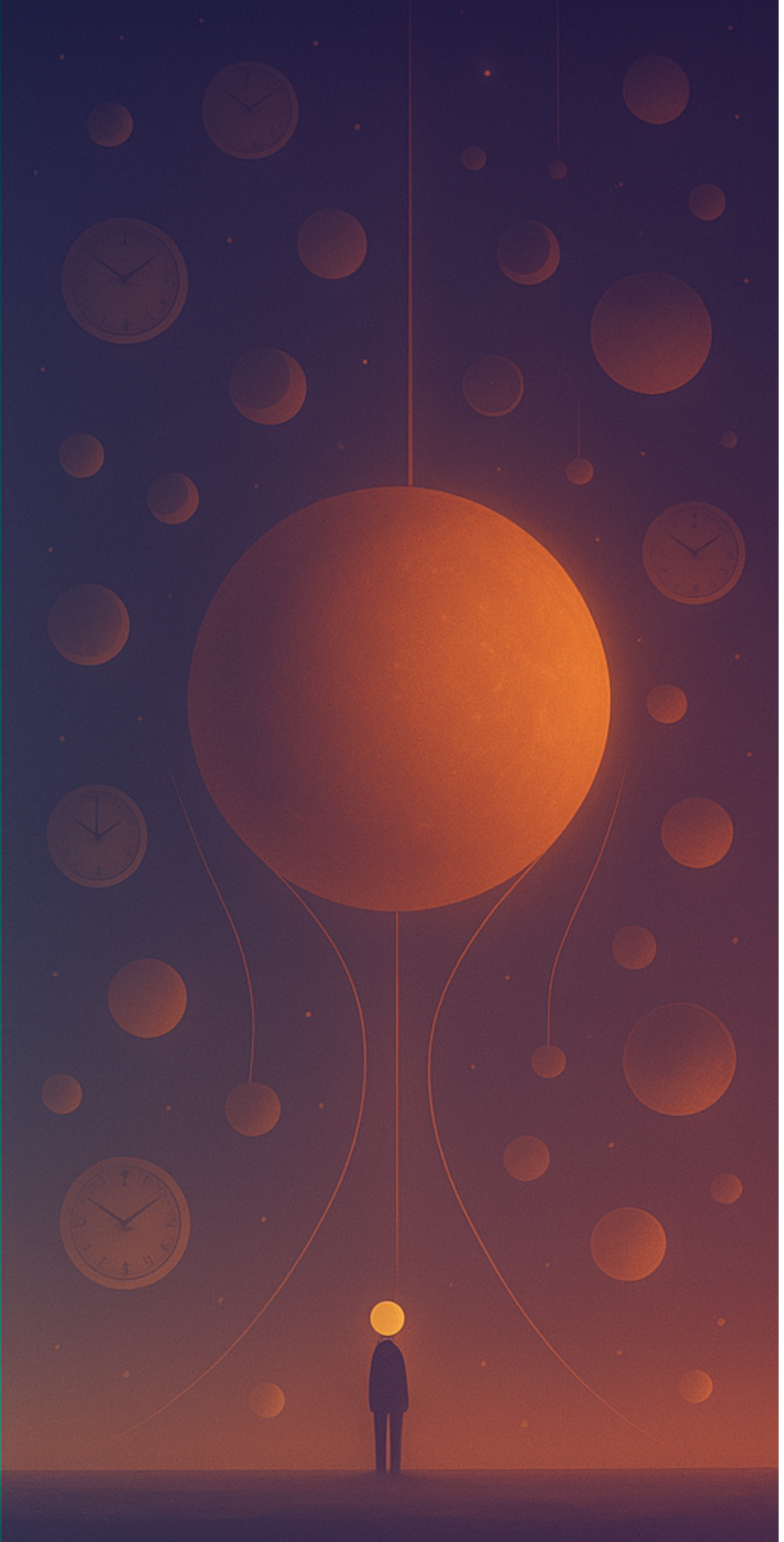
- Gravity sourced by a mass in superposition
- Extended symmetry principles

<u>Part II:</u> Quantum reference frames for superpositions of spacetimes

- Superpositions of semi-classical spacetimes
- Symmetries and counterparts
- Quantum coordinates

<u>Part III:</u> Conceptual implicationsIdentification and localisation of events

- Localisation of events
- Indefinite causal order



Outlook (non-exhaustive)

Thank you for your attention!

- Go beyond
  - semi-classical spacetimes in superposition (model genuine spacetime **fluctuations**)
  - semi-classical reference field configurations in superposition
- **Quantum equivalence principle** for general non-classical spacetime
- Model **non-ideal** frames for non-classical spacetimes
  - no perfect spacetime **localisation**
- Model **measurement** in QRFs (see work by Fewster & Verch for construction in AQFT)
- Clarify how **different QRF approaches** relate to each other (perspectival, perspective-neutral, operational, quantum information and its extensions) and which situations each is most suited for