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IQOQI Vienna

Identification is pointless: quantum reference frames, localization of events and quantum hole argument.

Witnessing quantum aspects of gravity in a lab, ICTP-SAIFR/Principia Institute, São Paulo, Brazil

arXiv:2402.10267

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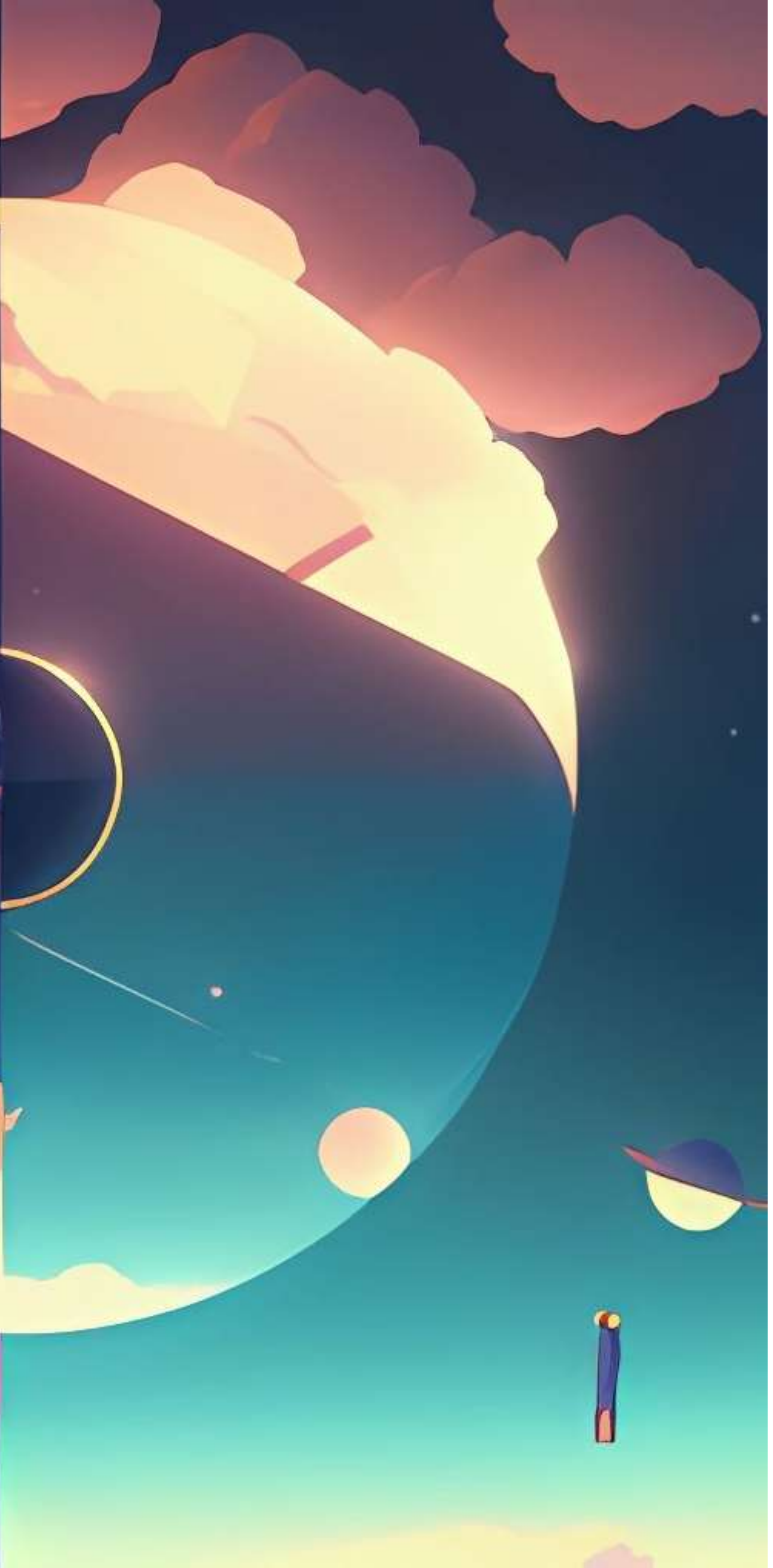
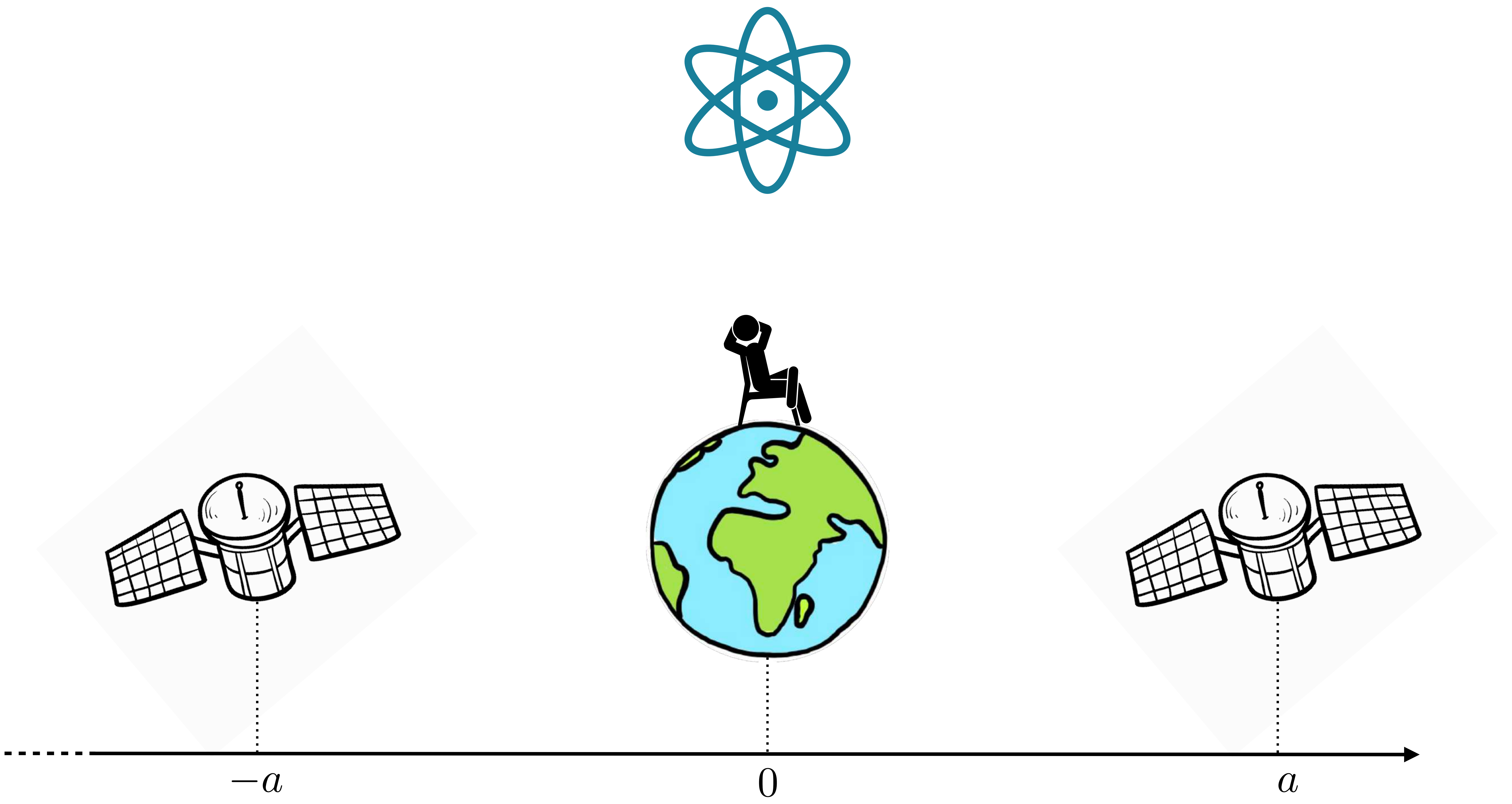
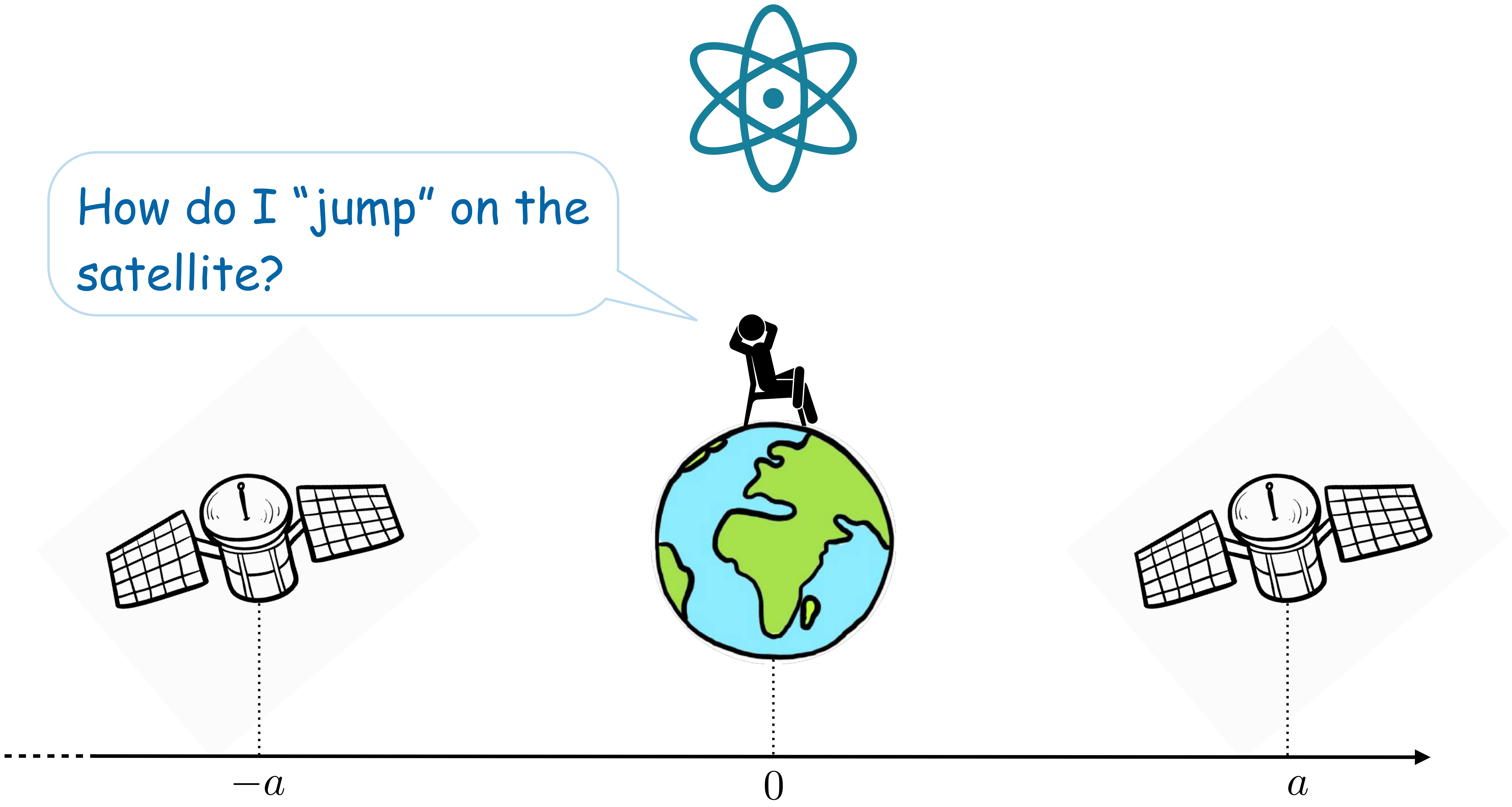


Outline

- QRFs and Superpositions of spacetimes
- Symmetries and counterparts
- QRFs in general relativity
- Physical implications
  - Localisation of events
  - Quantum hole argument
  - Relational observables
- Conclusion



$$|0\rangle \otimes (|-a\rangle + |a\rangle) \otimes |0\rangle$$



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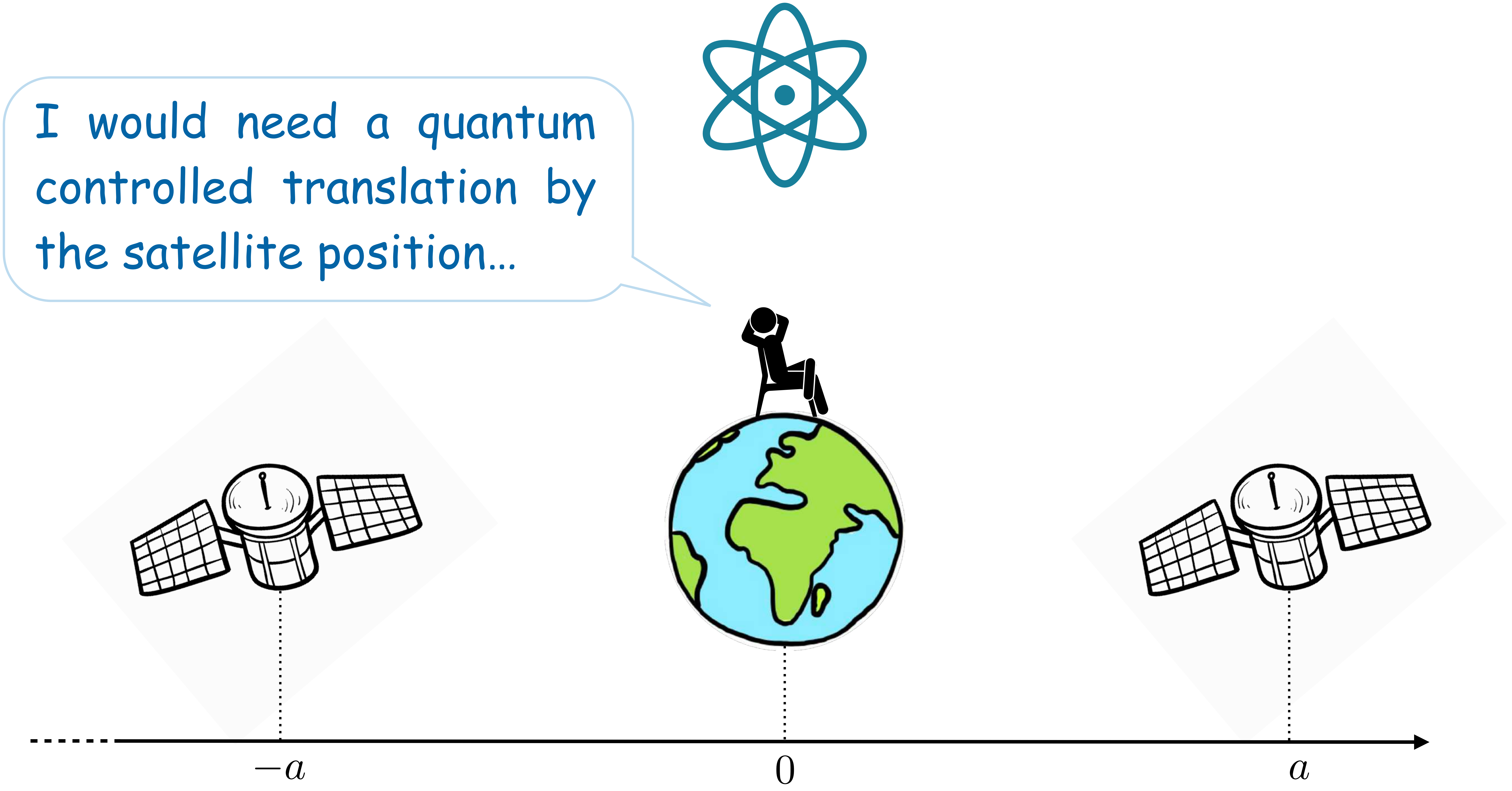
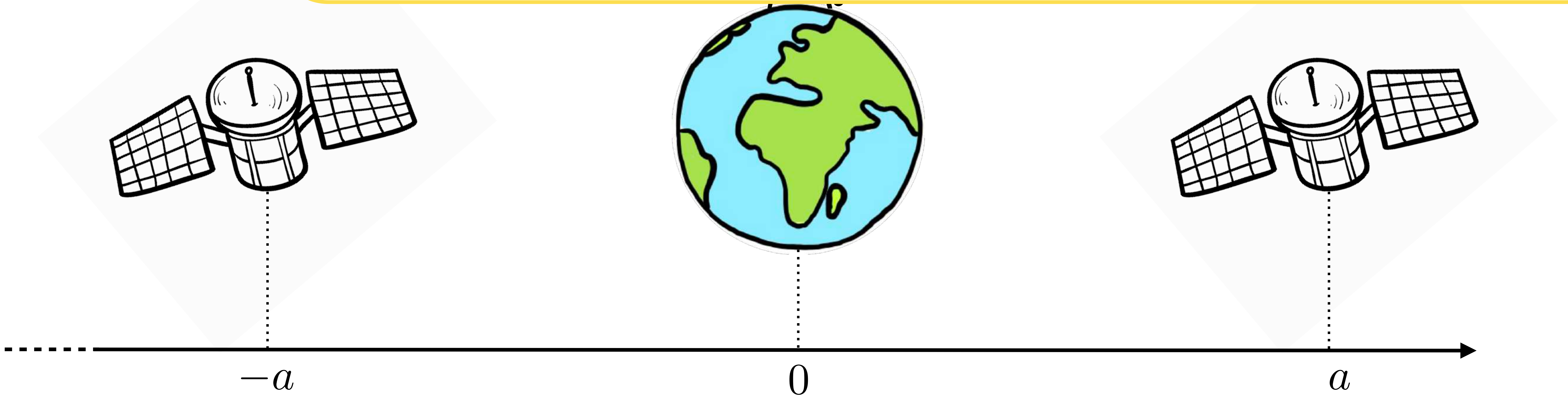


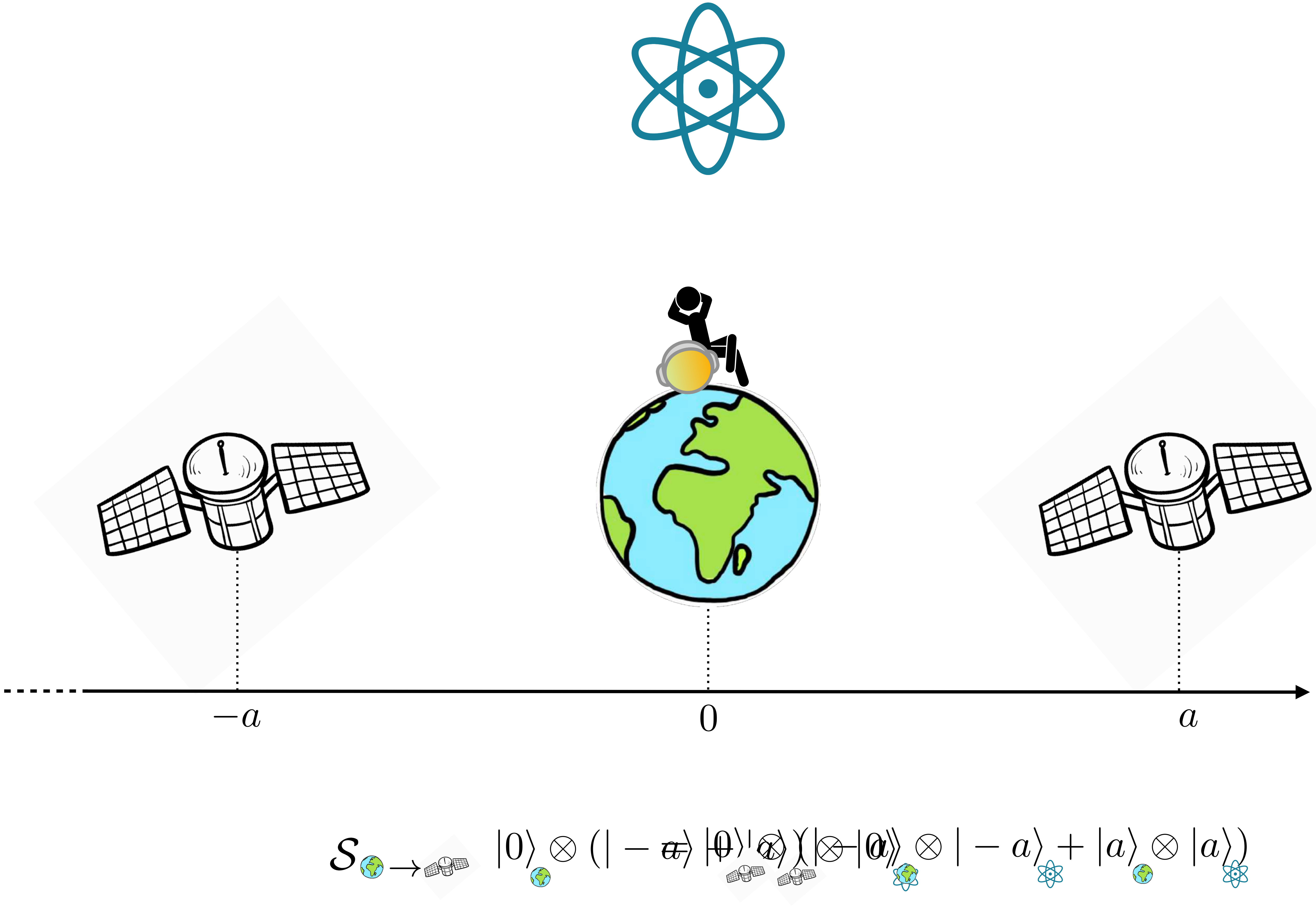
$$|0\rangle \otimes (|-a\rangle + |a\rangle) \otimes |0\rangle$$

Try this one:

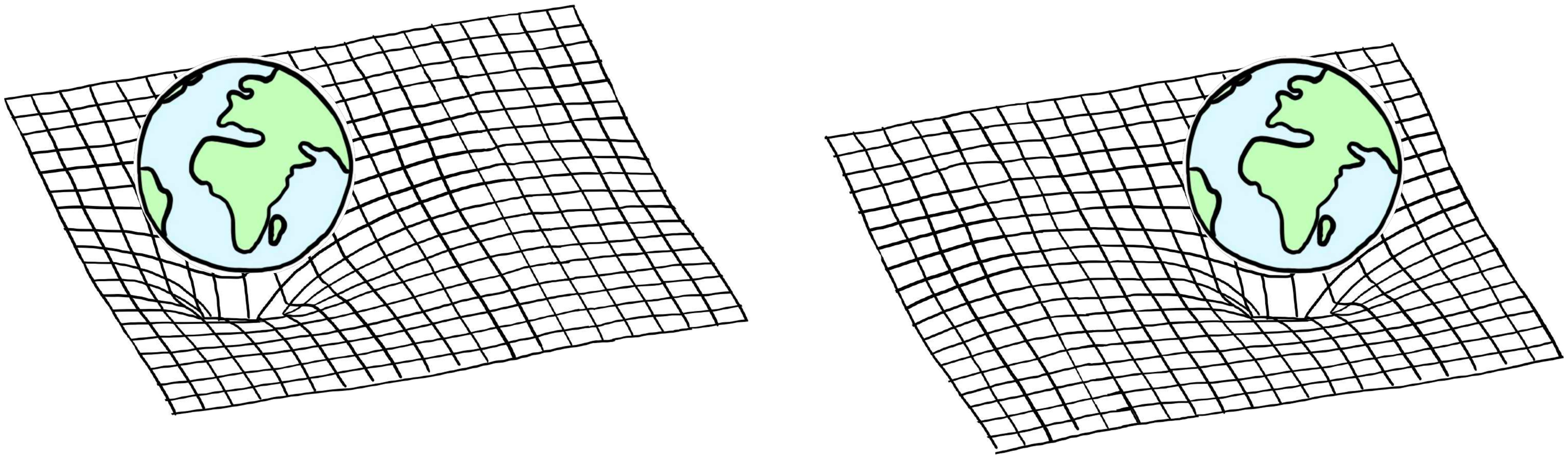
$$\mathcal{S}_{\text{🌍}\to\text{🛰}} = \int dx\,dx' \quad |x-x'\rangle\langle x|_{\text{🌍}} \otimes |x'\rangle\langle x'-x|_{\text{🛰}} \otimes \mathsf{T}^{\dagger}_{\text{⚛}}\,(x'-x)$$



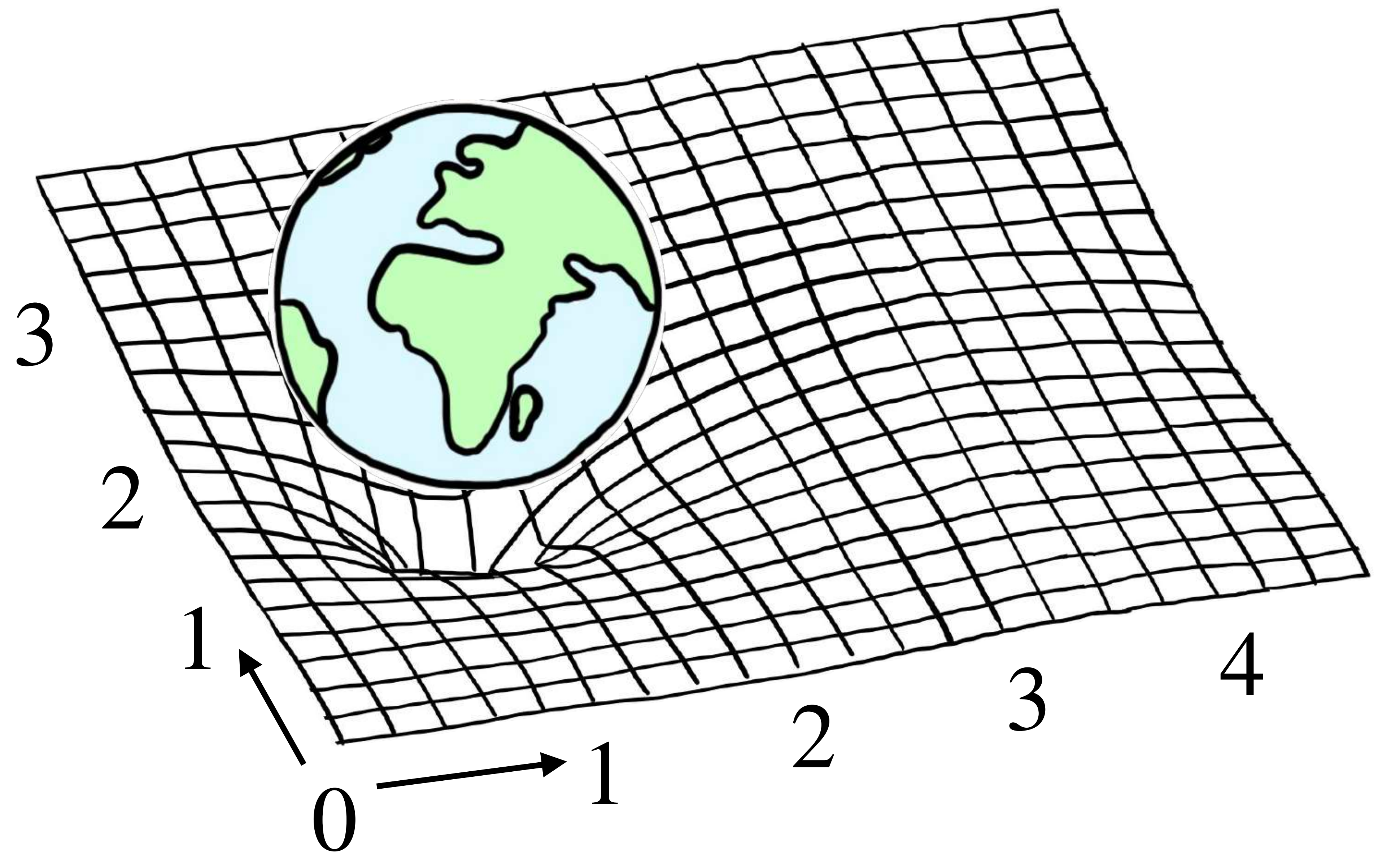
$$|0\rangle_{\text{🌍}} \otimes (|-a\rangle + |a\rangle)_{\text{🛰}} \otimes |0\rangle_{\text{⚛}}$$

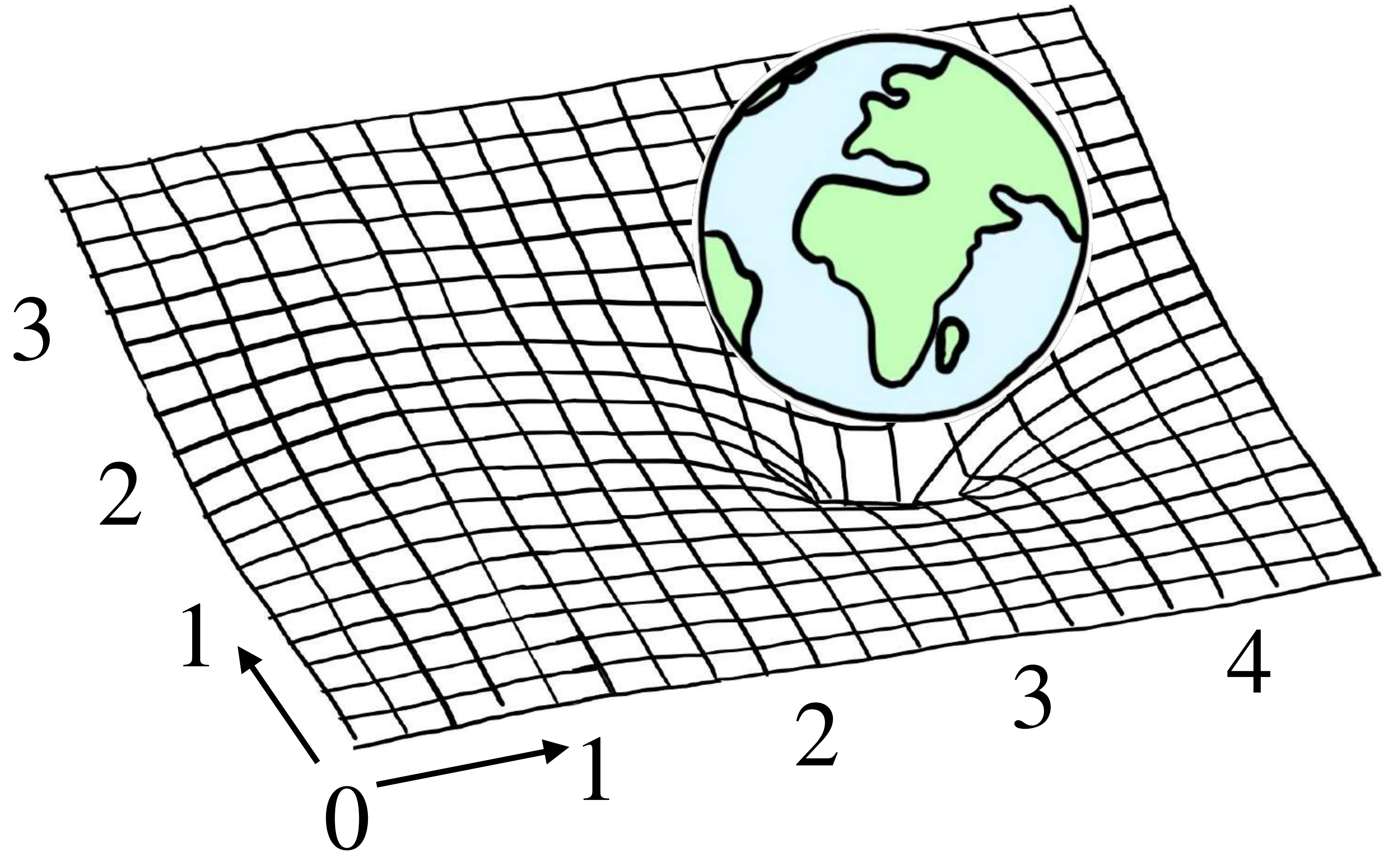


$-a$
0
a



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

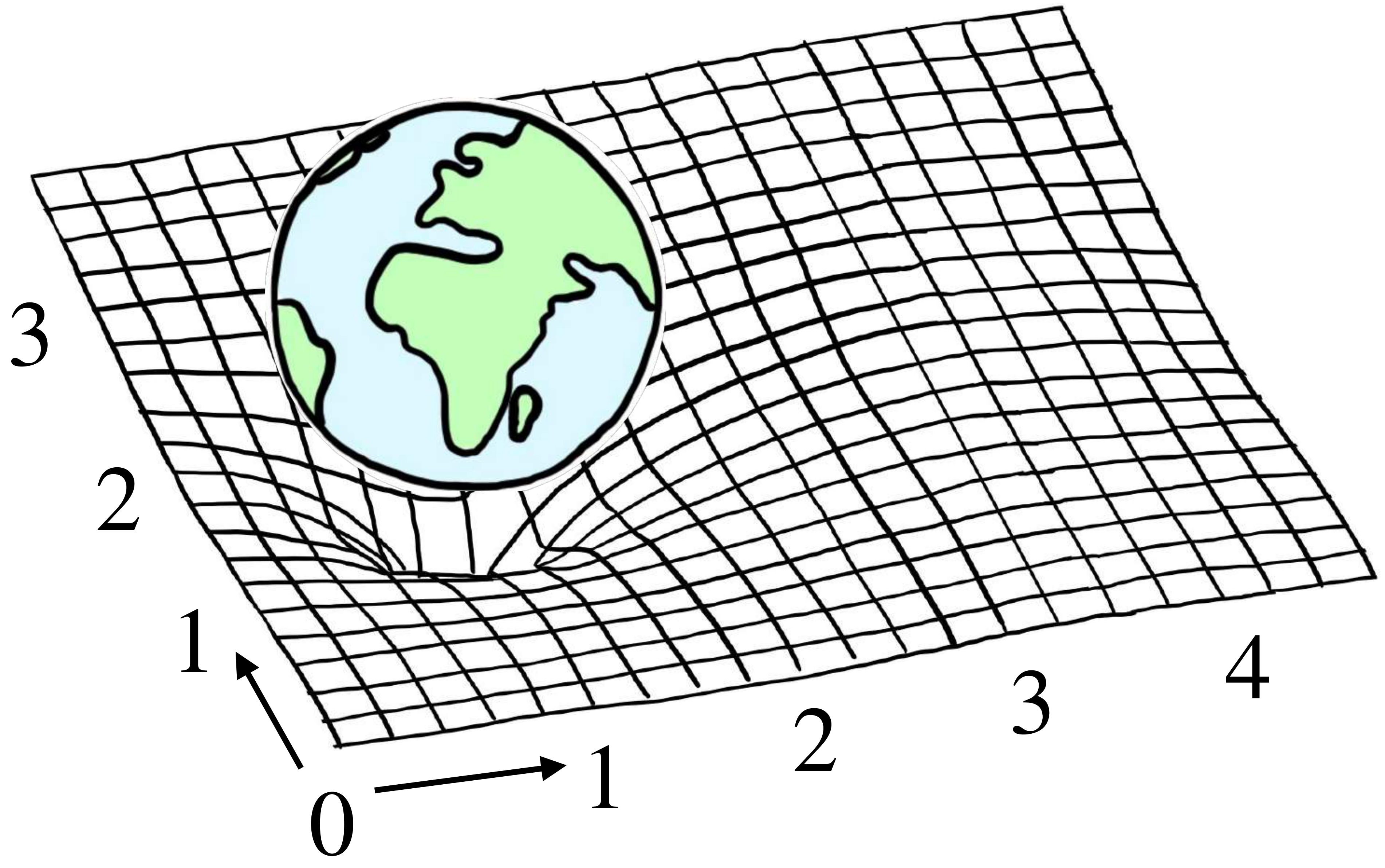


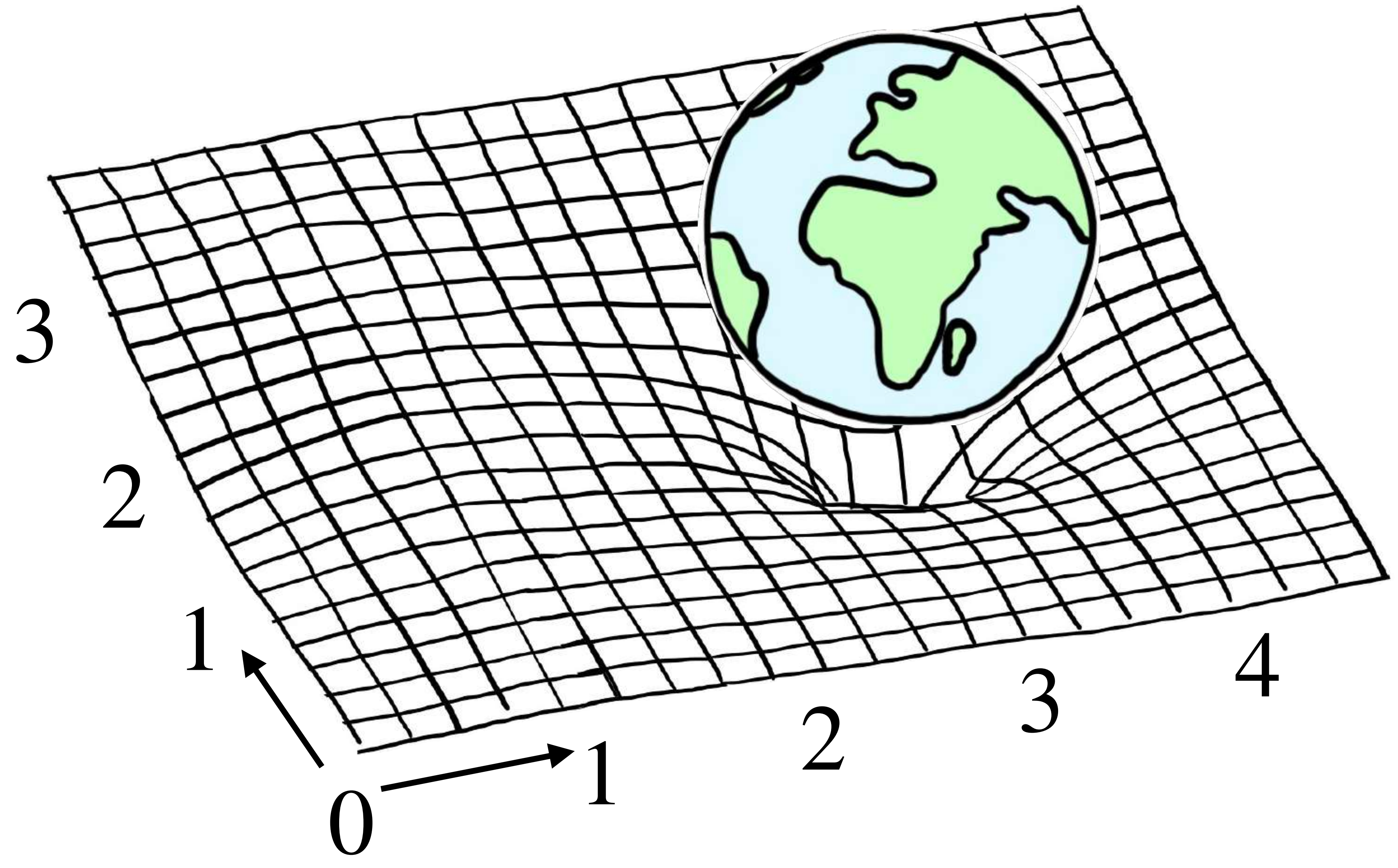


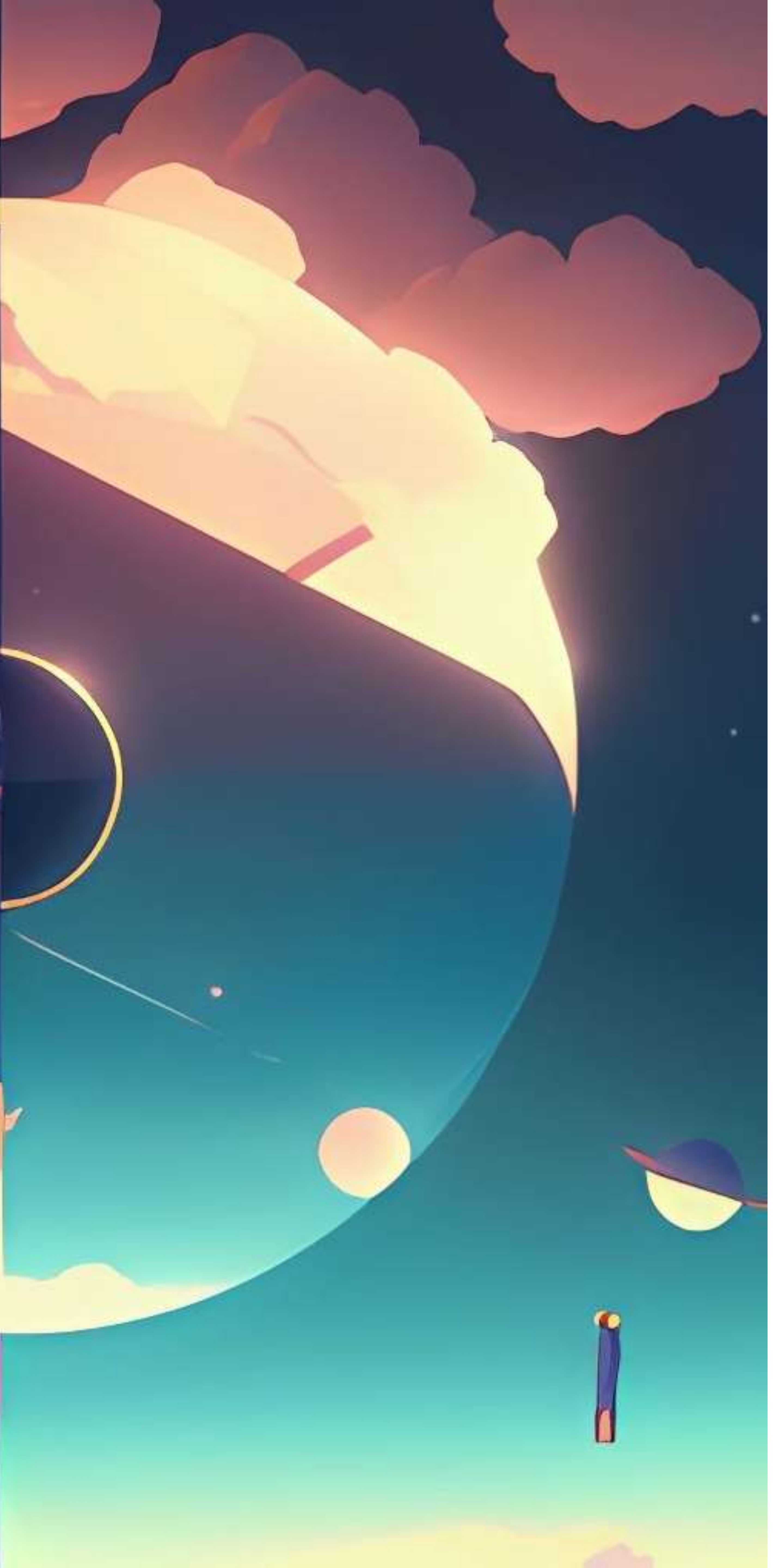
What does it even mean that the mass is in a superposition of locations?

Superposition of Spacetimes

- Superposition of states peaked around semi-classical metric.
- Particular regime of potential theory of quantum gravity, complementary to approaches to a full theory.
- Playground to investigate conceptual questions.







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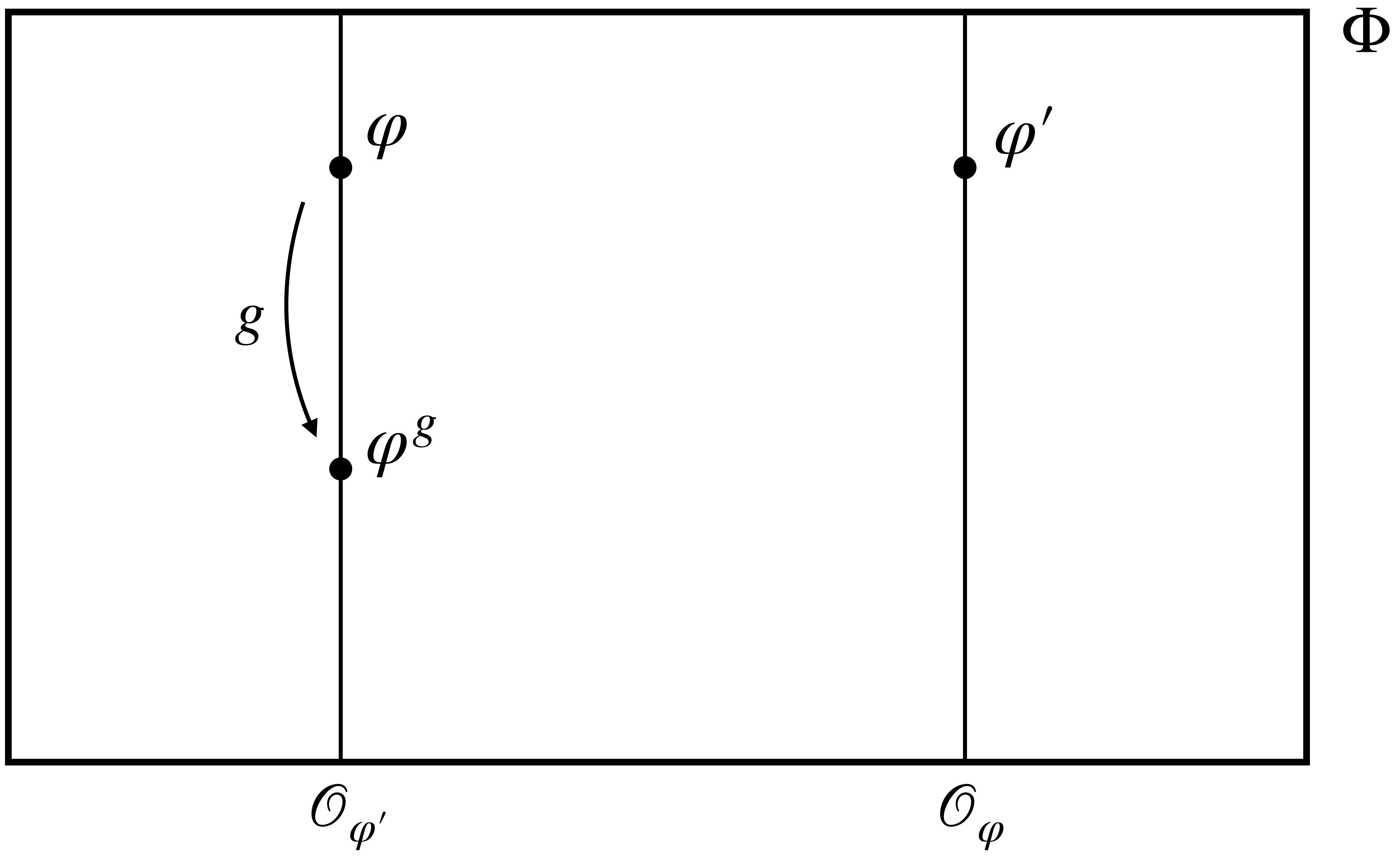
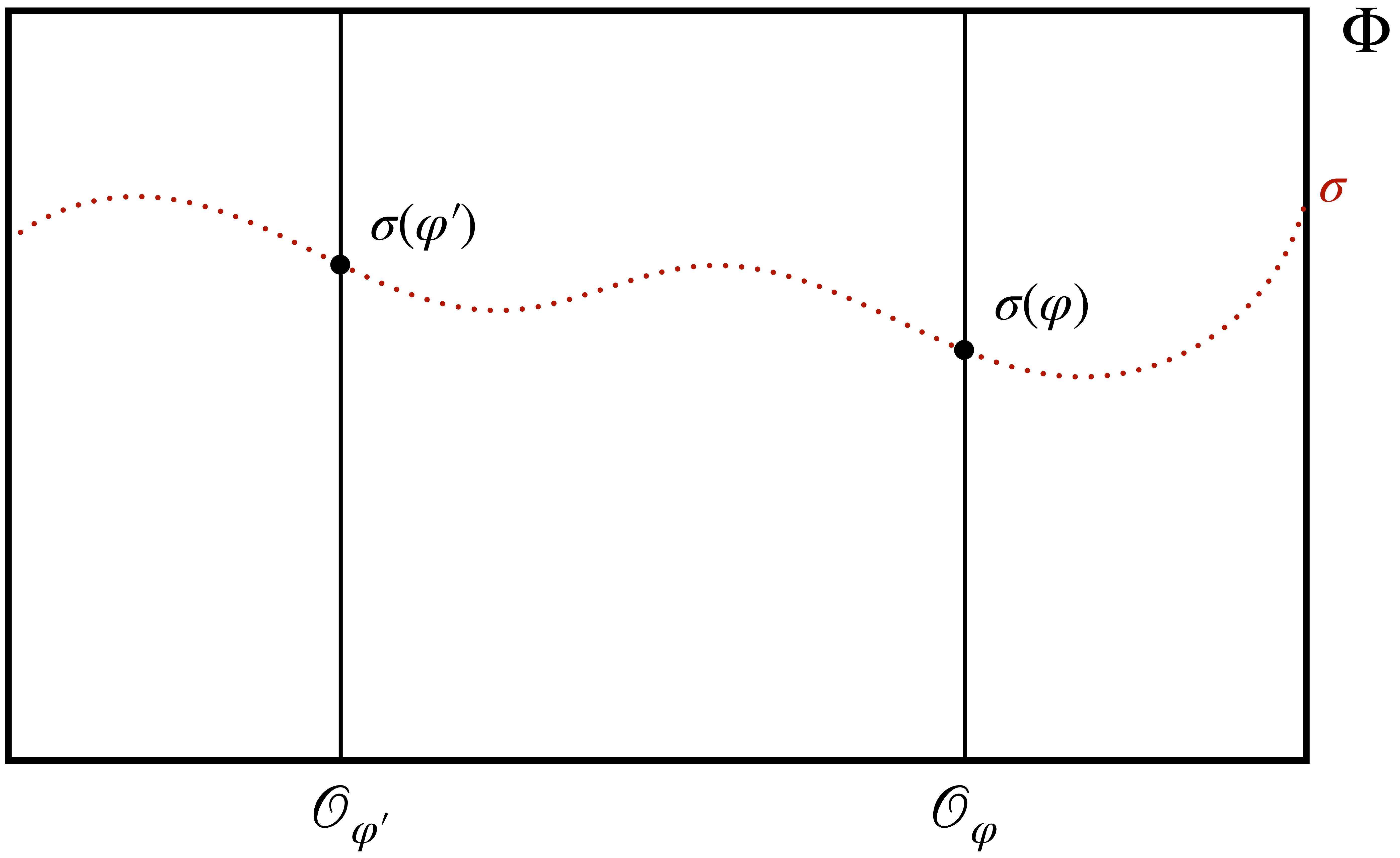
Symmetries & Counterparts

- Consider a theory Φ with symmetry group G.
- The space of all possible configurations (models) can be partitioned into orbits of G.
- Models on a given orbit are physically indistinguishable.



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.



Symmetries & Counterparts

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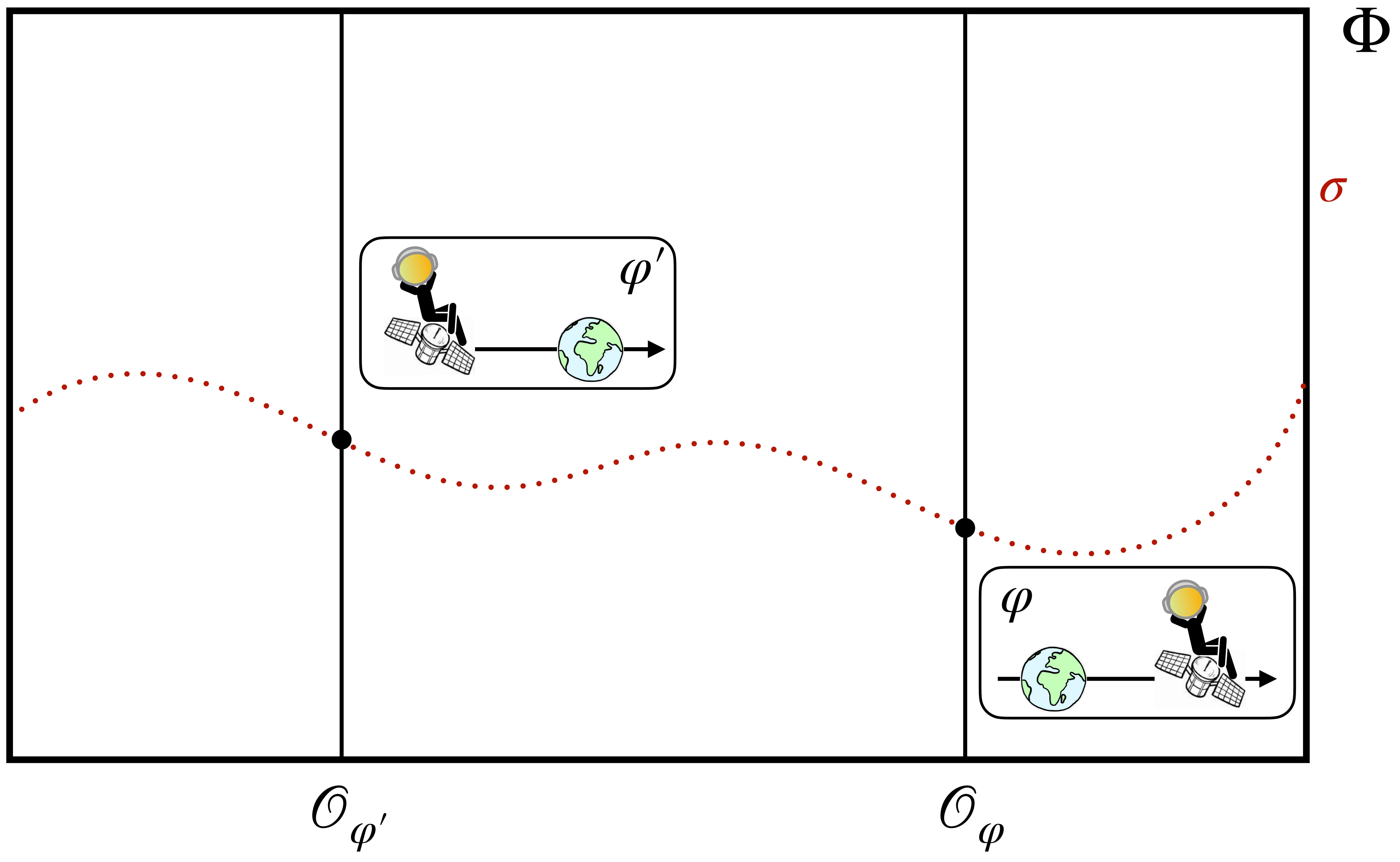
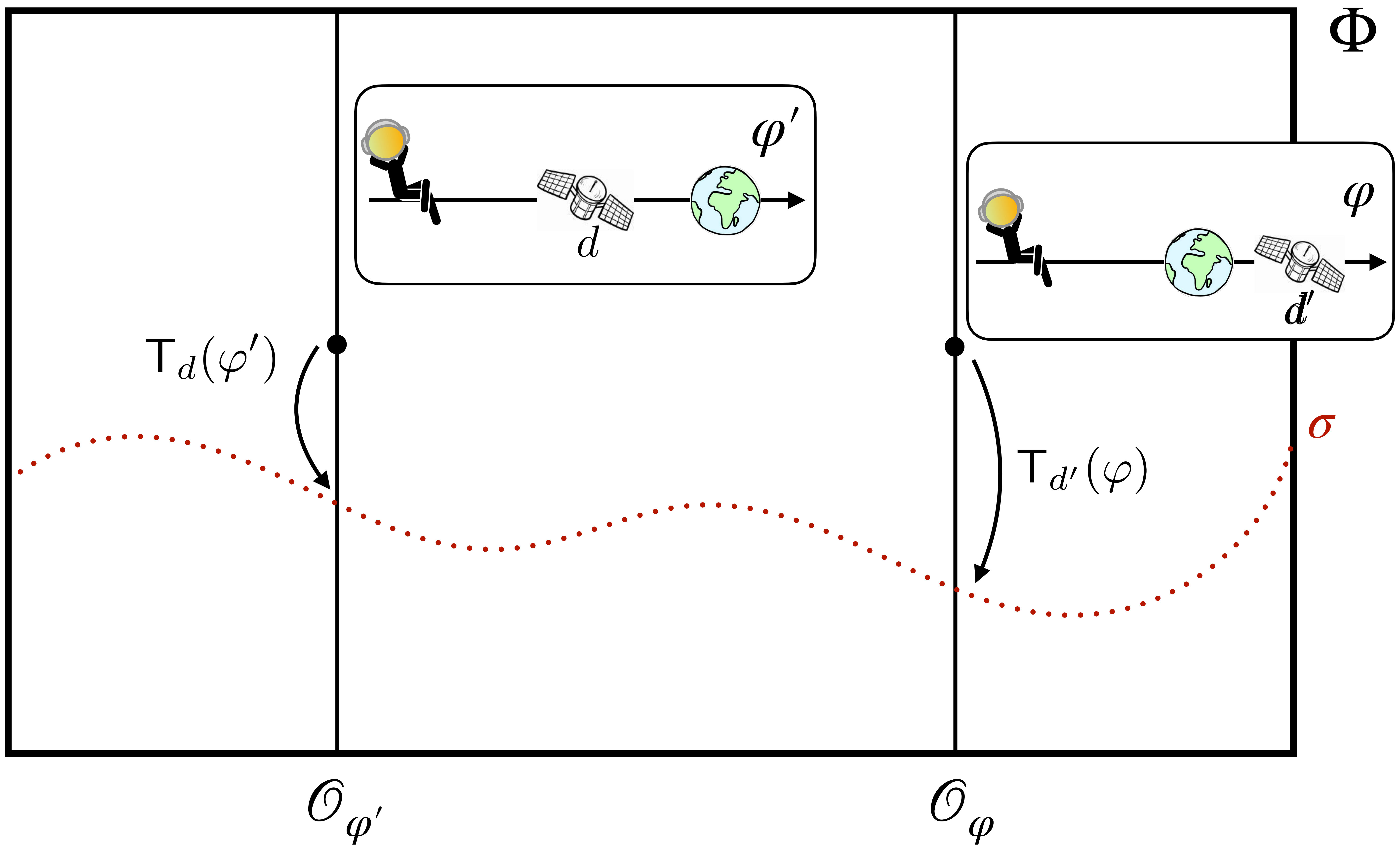
- Example: choice of origin in translationally invariant theory.

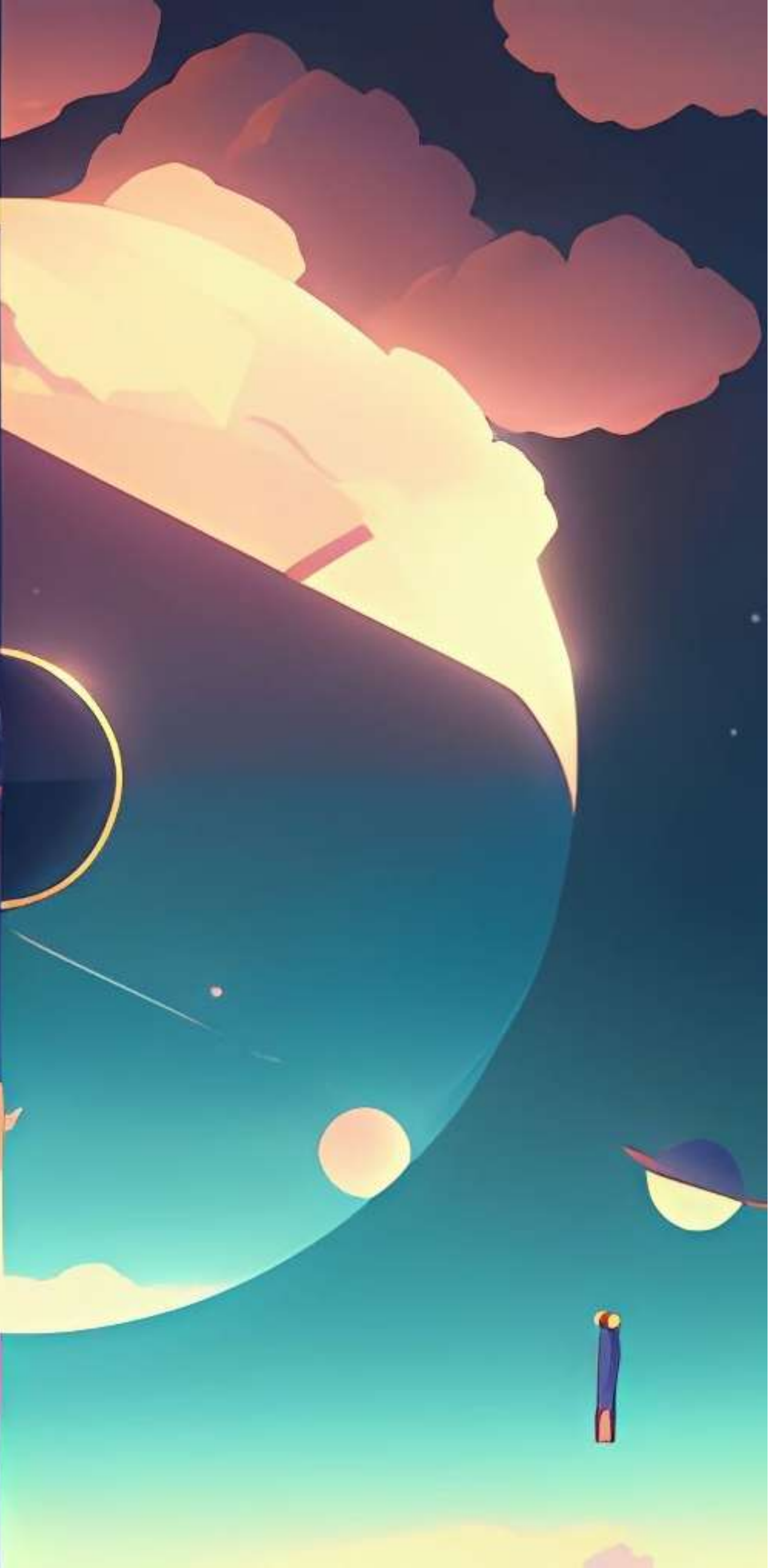


Symmetries & Counterparts

- A section σ 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.
- The counterpart relation allows to compare two configurations by aligning them with respect to the chosen section.



$$\mathrm{Counter}_\sigma(\varphi', \varphi) = \mathsf{T}_d^{-1}(\varphi') \circ \mathsf{T}_{d'}(\varphi)$$



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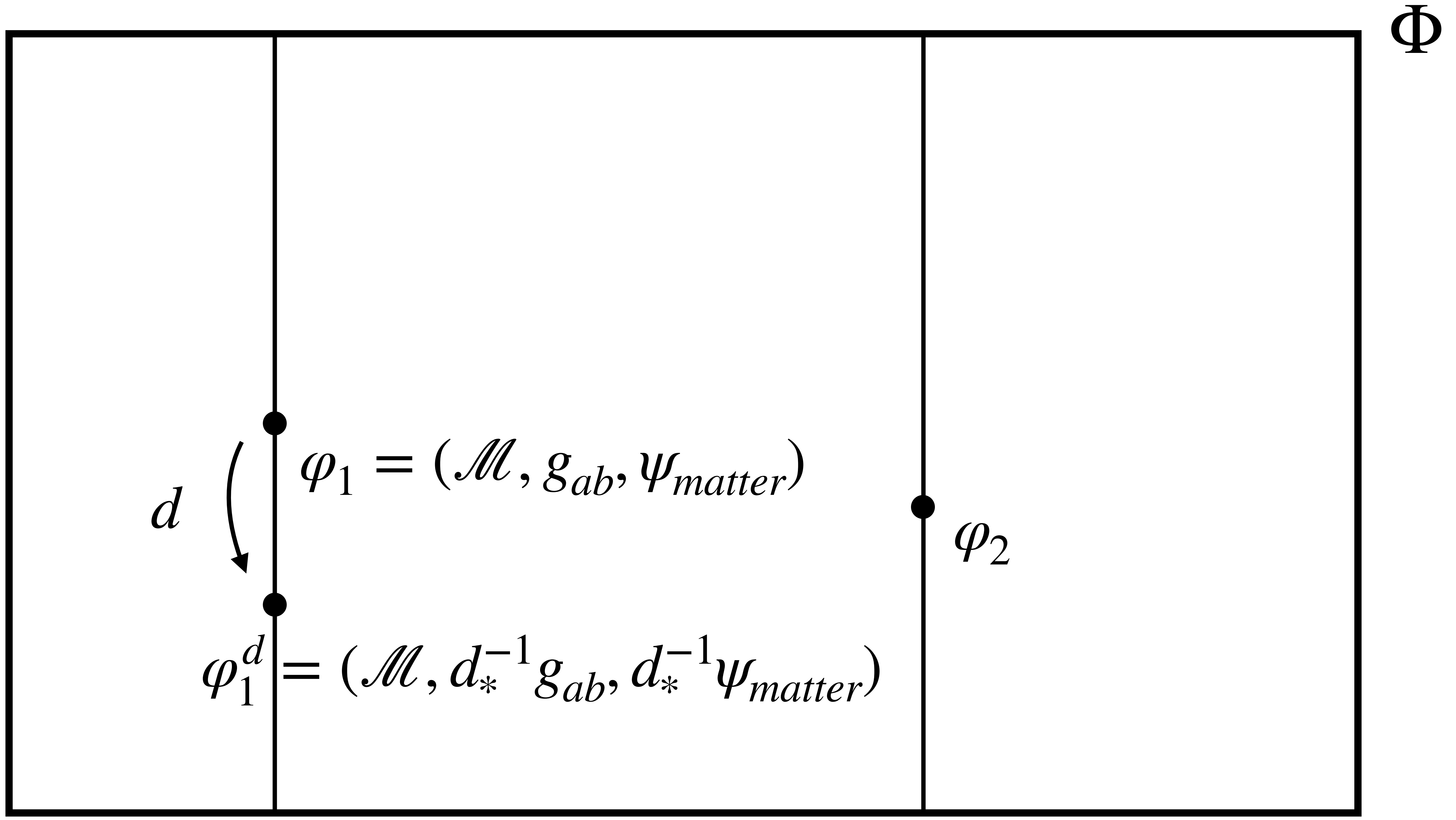
Coordinate fields & comparison of models

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



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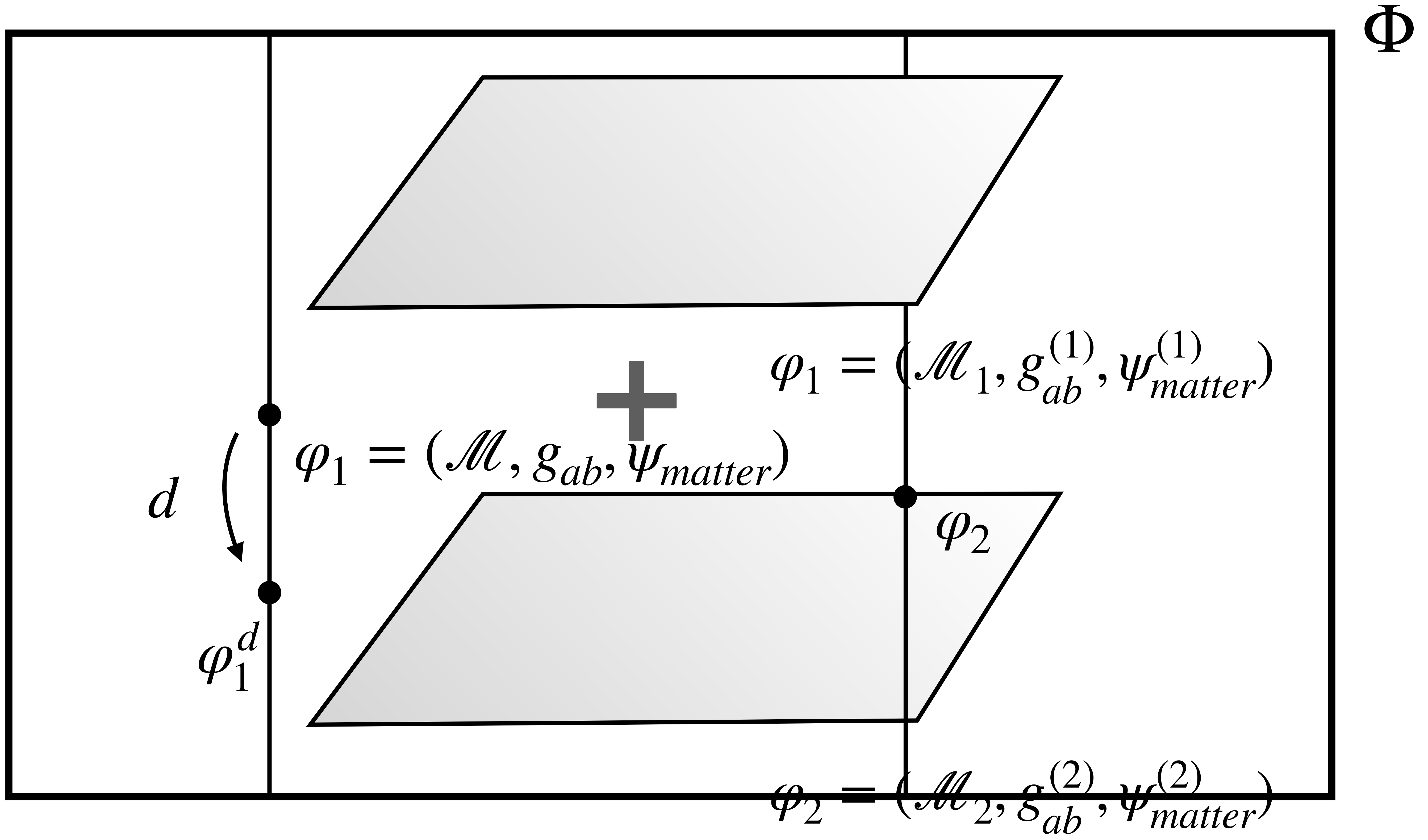
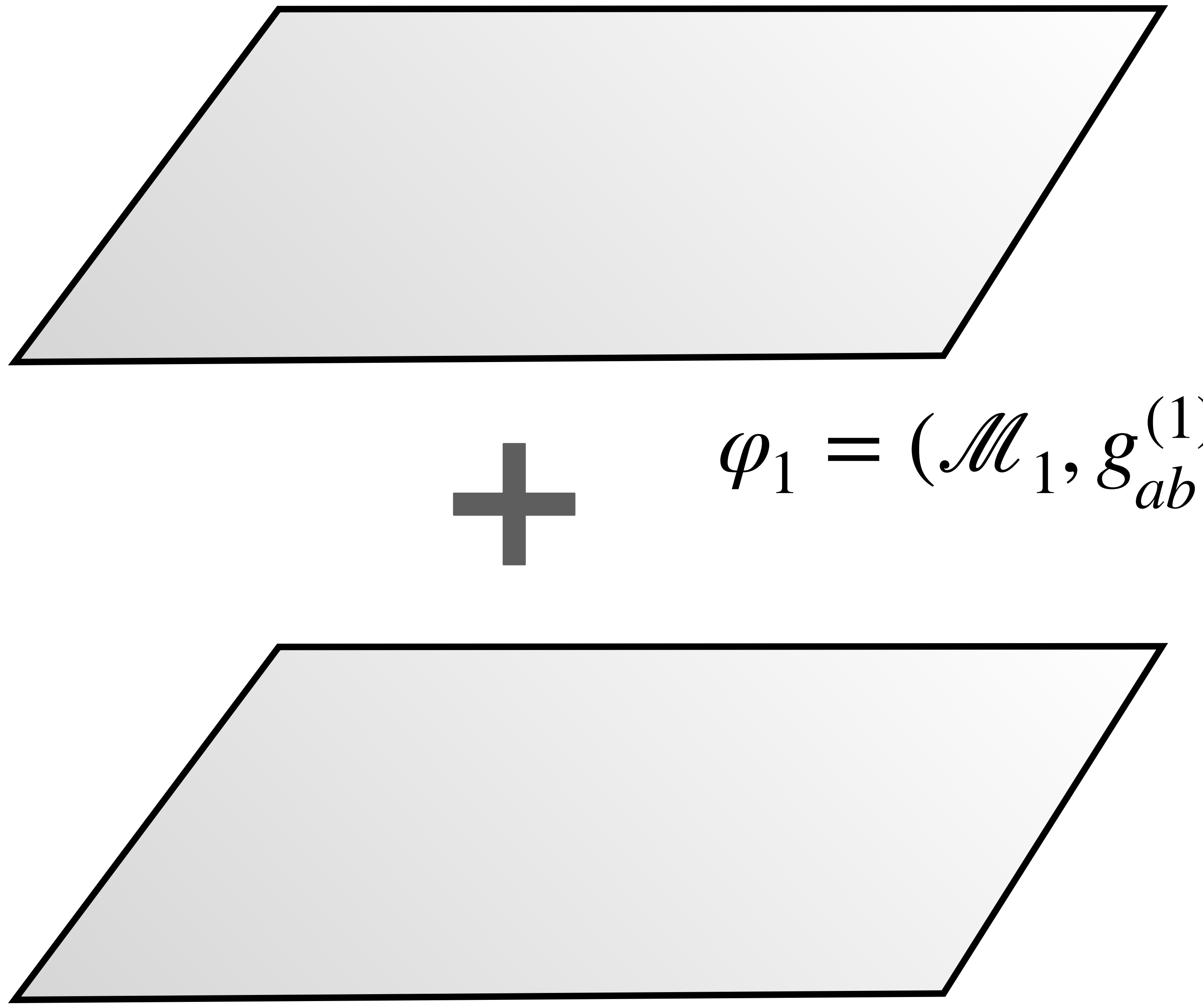


Coordinate fields & comparison of models

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



Coordinate fields & comparison of models

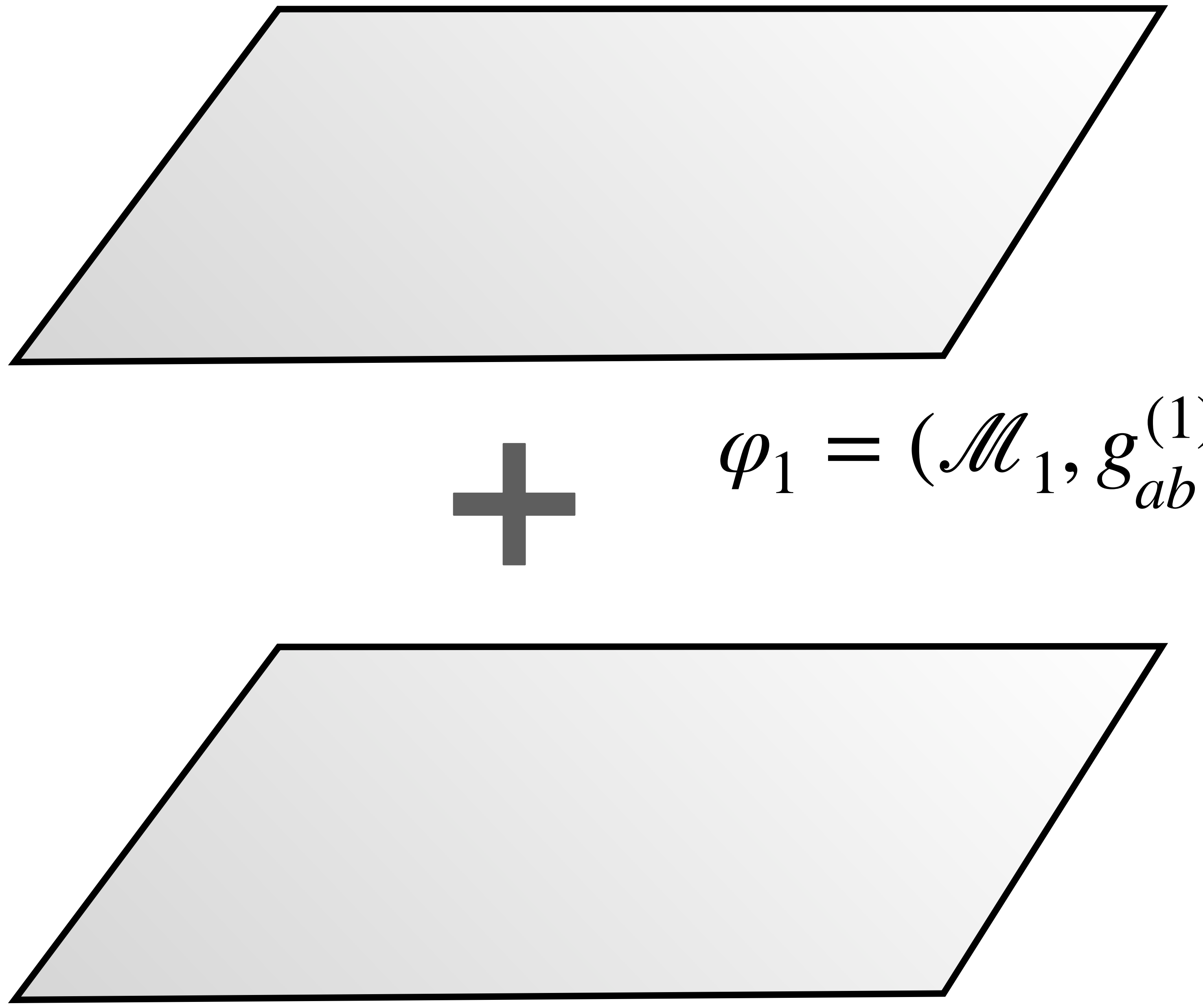
Three options for modelling scalar **reference fields**:

I. idealised or coordinate fields

II. dynamical fields without back reaction

III. dynamical fields with back reaction

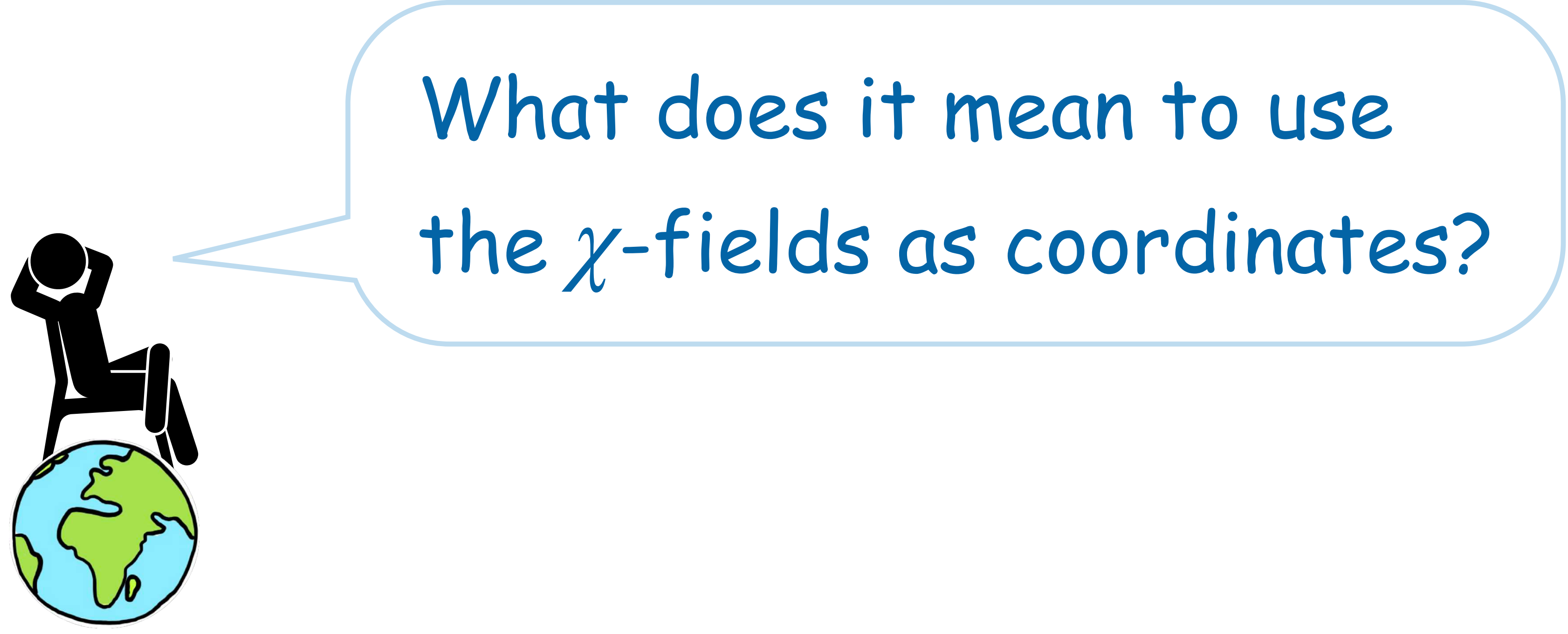
- ⊕ most realistic
- ⊖ restrict freedom in choice of RF drastically



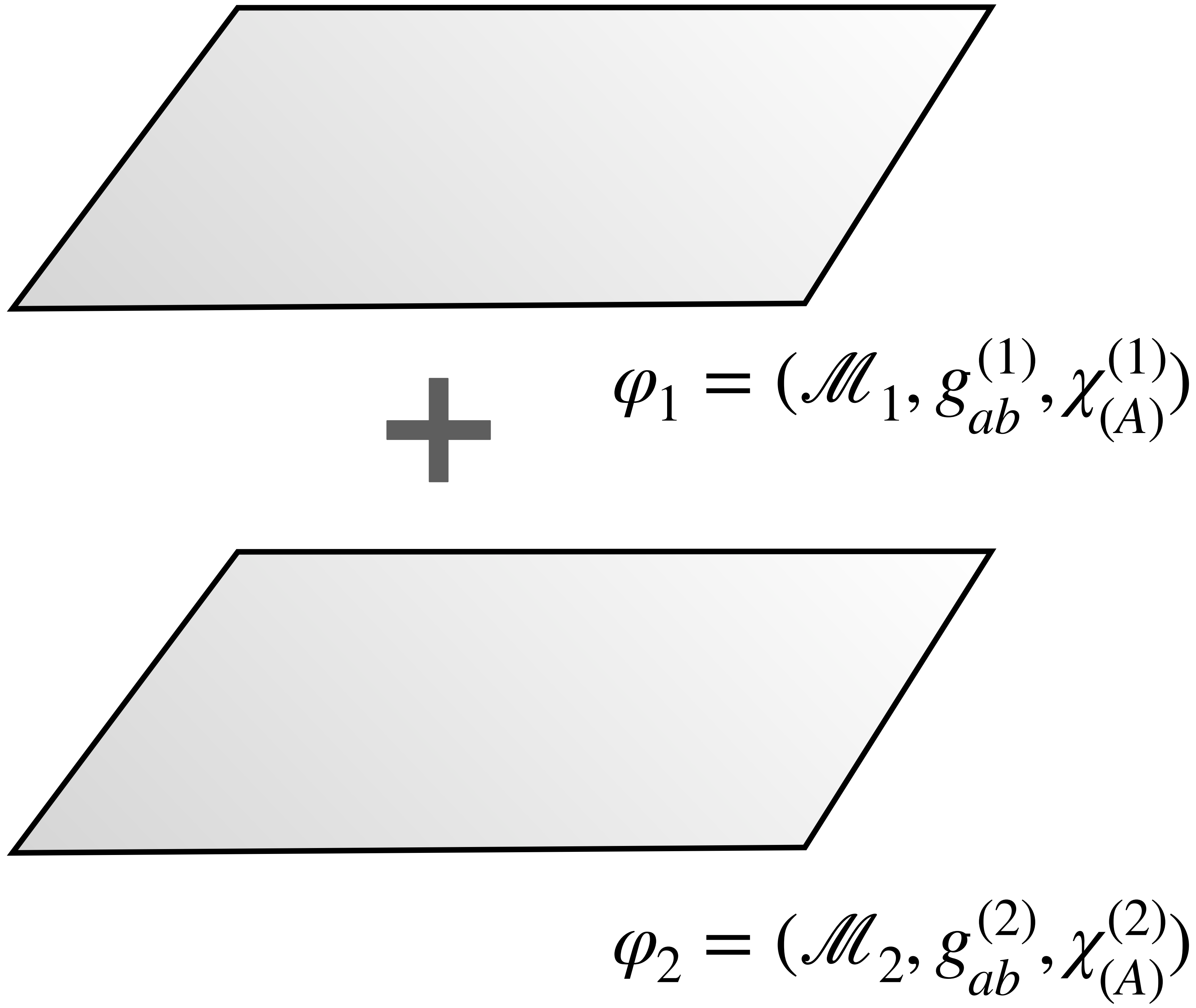
$$\varphi_1 = (\mathcal{M}_1, g_{ab}^{(1)}, \chi_{(A)}^{(1)}, \tilde{\psi}_{matter}^{(1)})$$

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

Coordinate fields & comparison of models



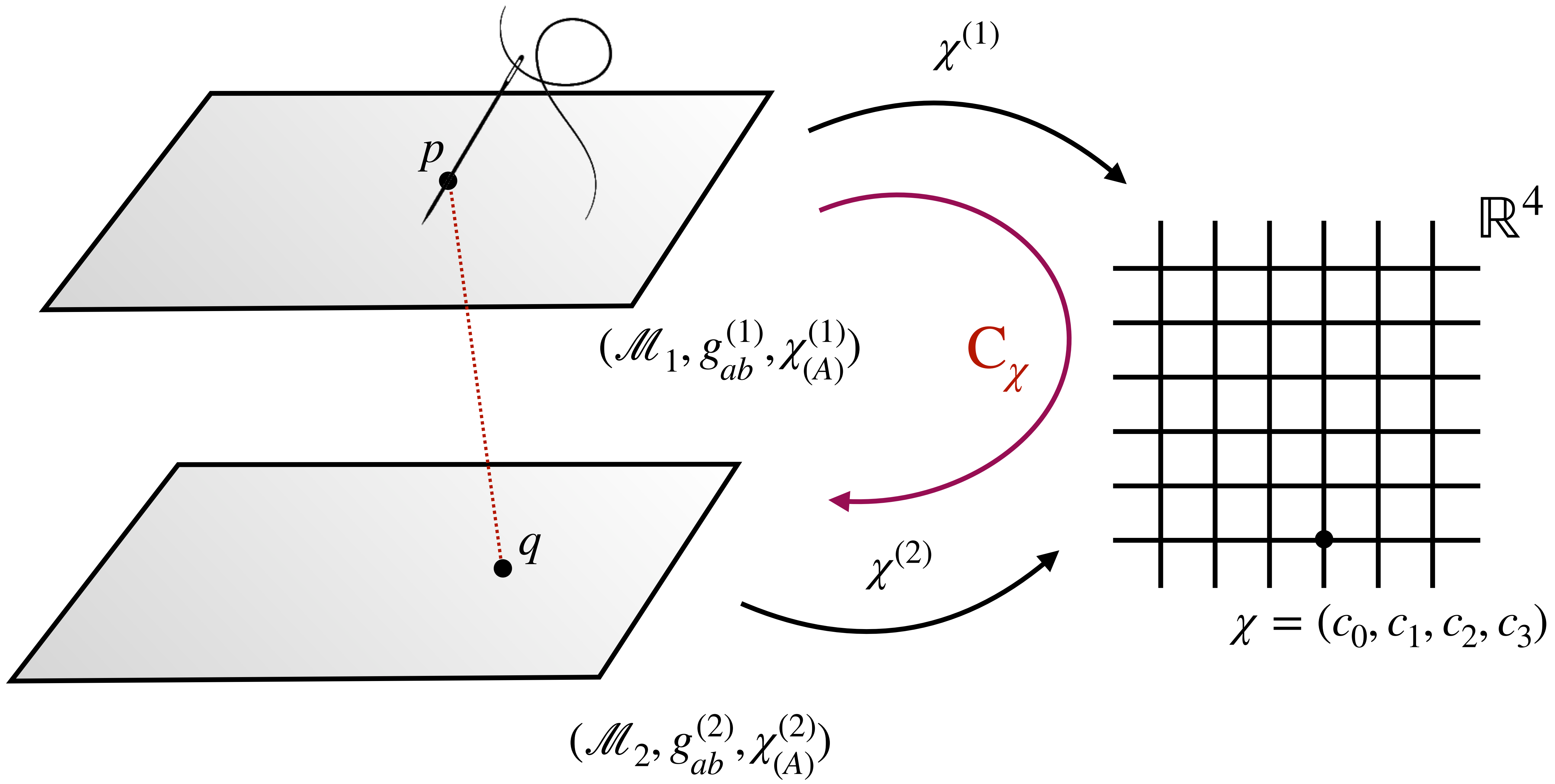
- Use the values of the four scalar fields $\{\chi_{(A)}\}_{A=0,1,2,3}$ to label the points and identify them across the branches in superposition.



Coordinate fields & comparison of models

What does it mean to use the χ-fields as coordinates?

- Use the values of the four scalar fields $\{\chi_{(A)}\}_{A=0,1,2,3}$ to label the points and identify them across the branches in superposition.

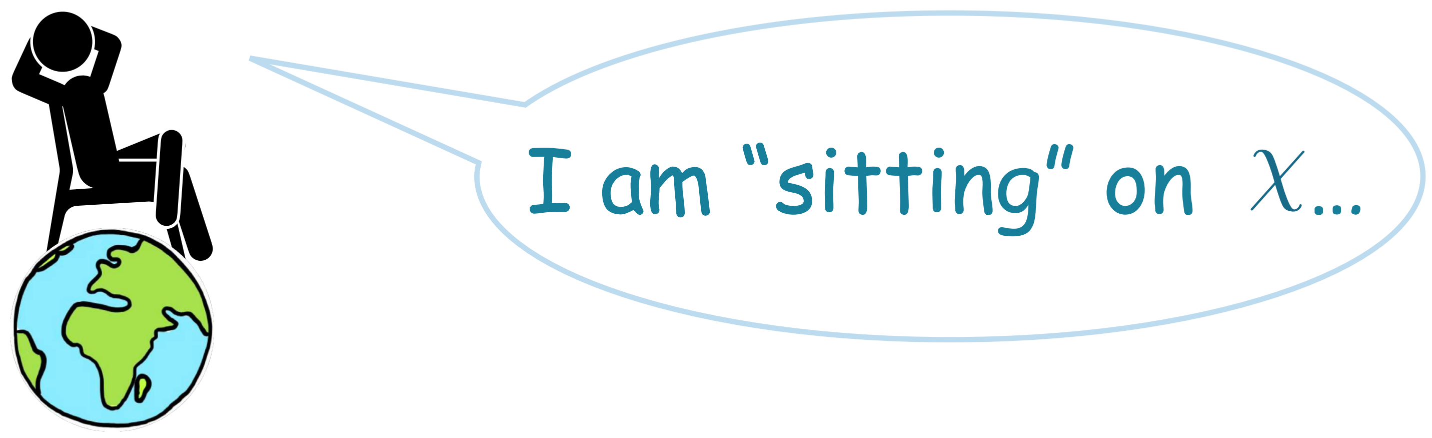


- Identify a point $p \in \mathscr{M}_1$ with a point $q \in \mathscr{M}_2$ iff $\chi^{(1)}(p) = \chi^{(2)}(q)$

- Comparison map relative to χ-fields:

$$C_\chi \equiv (\chi^{(2)})^{-1} \circ \chi^{(1)} : \mathcal{M}_1 \to \mathcal{M}_2$$

Quantum reference frames for GR

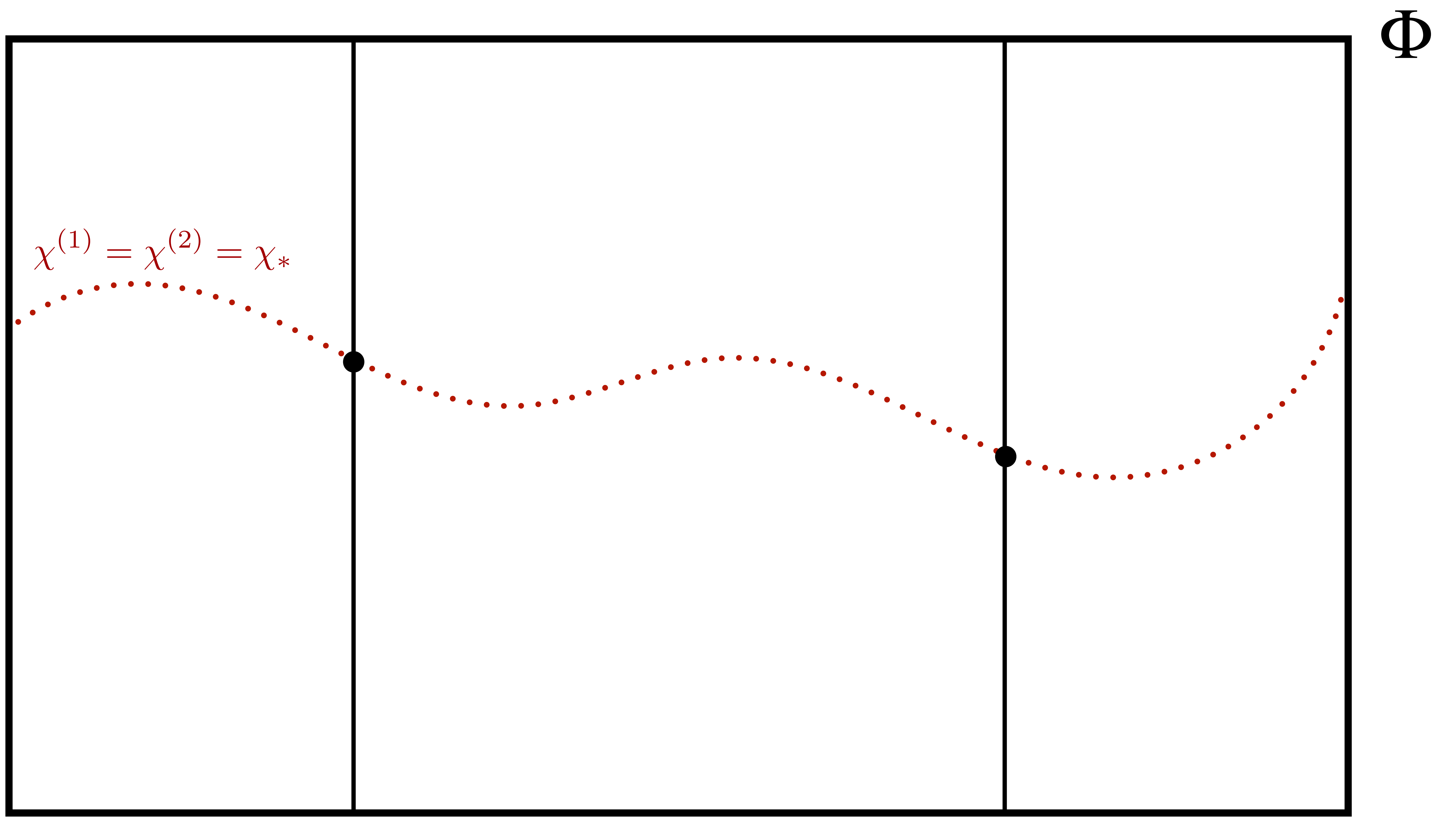


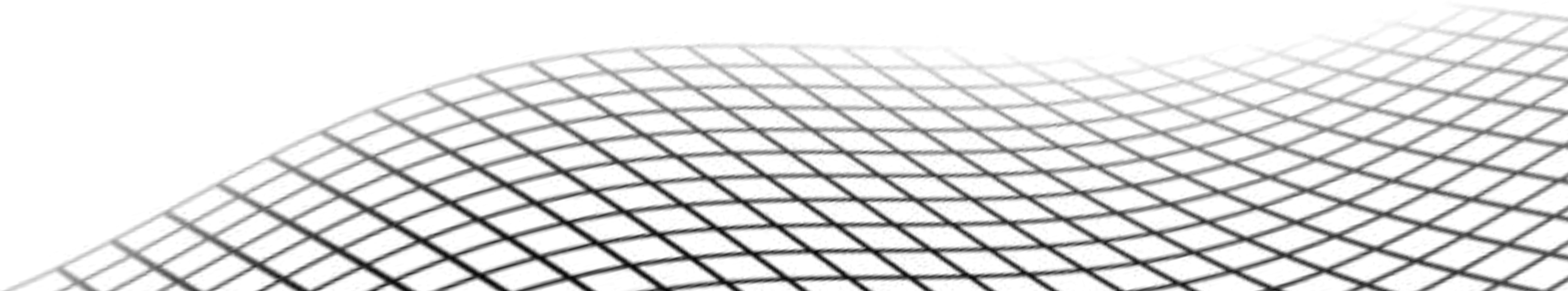
- Models aligned to the section σ identified by the gauge configuration $\chi^{(1)} = \chi^{(2)} = \chi_*$

$$|\psi\rangle^{(\chi)} = |\chi_*\rangle \otimes \left(\alpha|g^{(1)}\rangle|\tilde{\chi}^{(1)}\rangle + \beta|g^{(1)}\rangle|\tilde{\chi}^{(2)}\rangle\right)$$

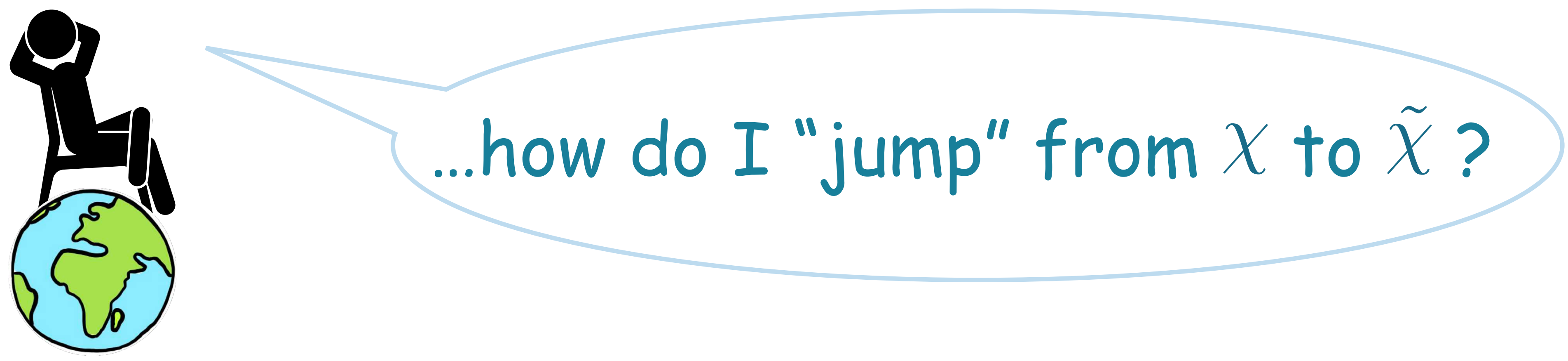
- Comparison map via χ fields:

$$\mathrm{C}_\chi = {\chi^{(2)}}^{-1} \circ \chi^{(1)} = \mathrm{Id}$$





Quantum reference frames for GR



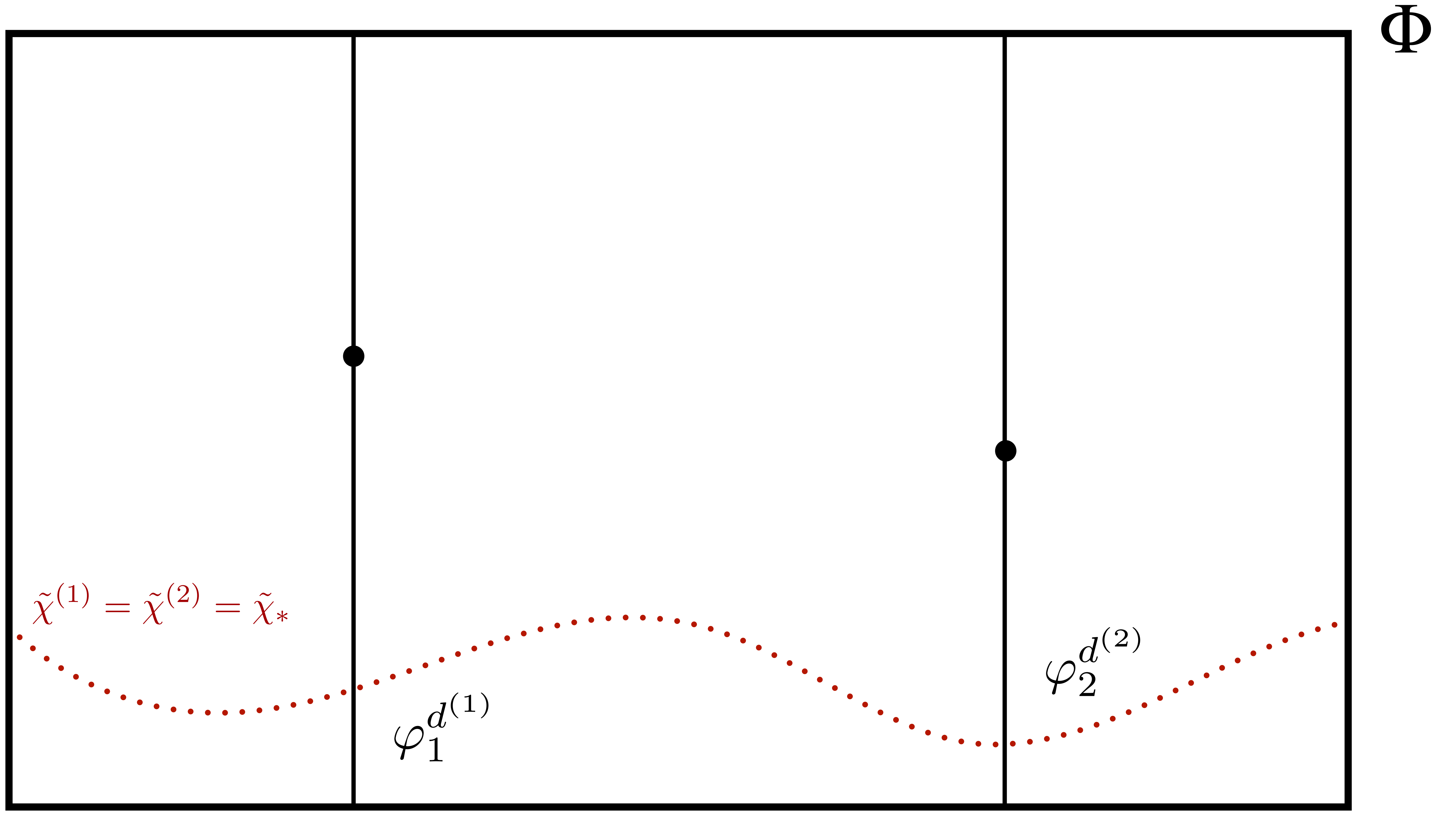
- Chose another section $\tilde{\sigma}$ corresponding to $\tilde{\chi}^{(1)} = \tilde{\chi}^{(2)} = \tilde{\chi}_*$

- Align the model to $\tilde{\sigma}$ via a quantum controlled diffeomorphism:

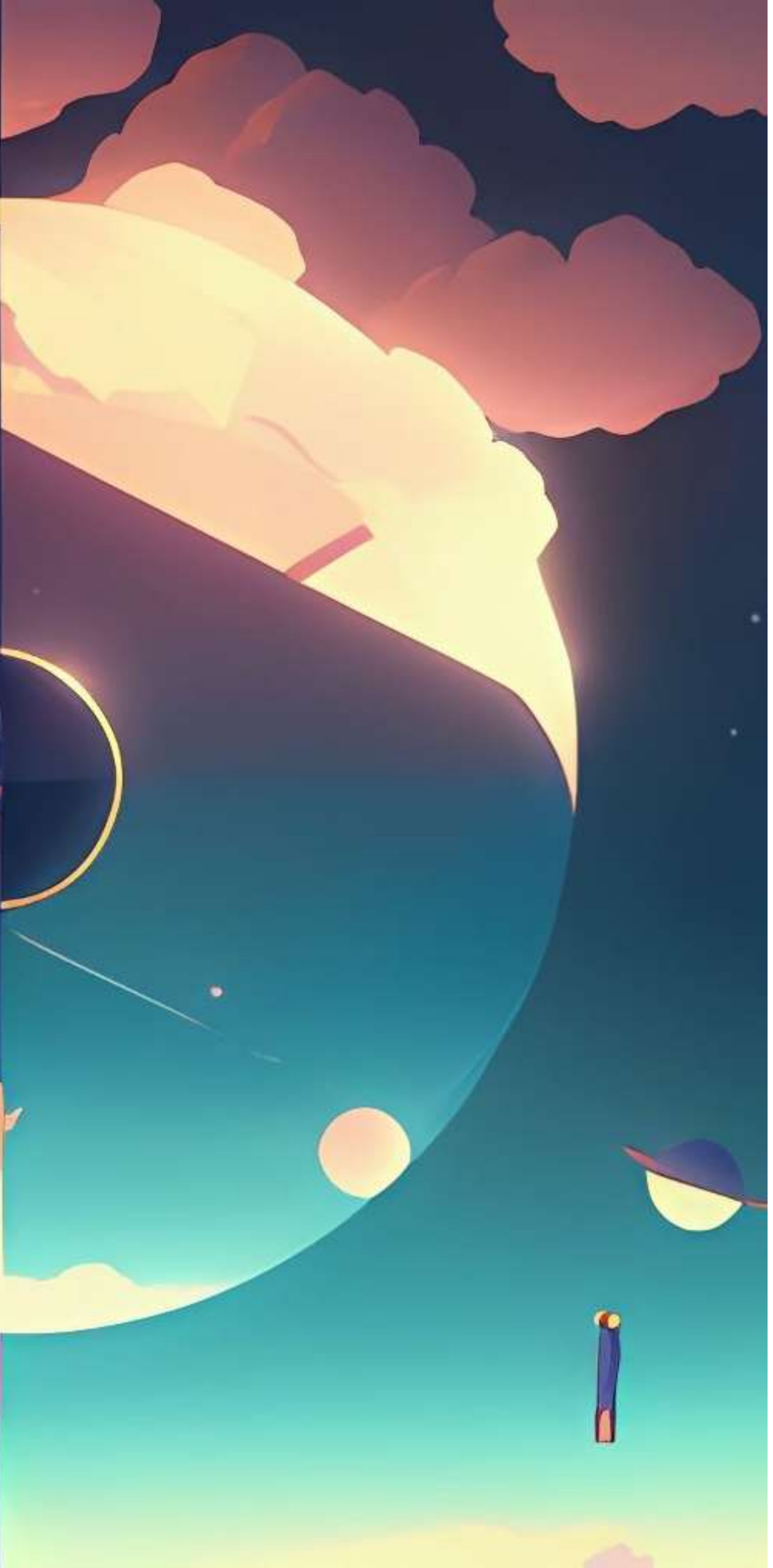
- Comparison map via $\tilde{\chi}$ fields:

$$\mathrm{C}_{\tilde{\chi}} = \tilde{\chi}_*^{-1} \circ \tilde{\chi}_* = \mathrm{Id}$$

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



$$|\psi\rangle^{(\chi)} = |\tilde{\chi}_*\rangle \otimes \left(\alpha |g'^{(1)}\rangle |\chi'^{(1)}\rangle + \beta |g'^{(2)}\rangle |\chi'^{(2)}\rangle\right)$$



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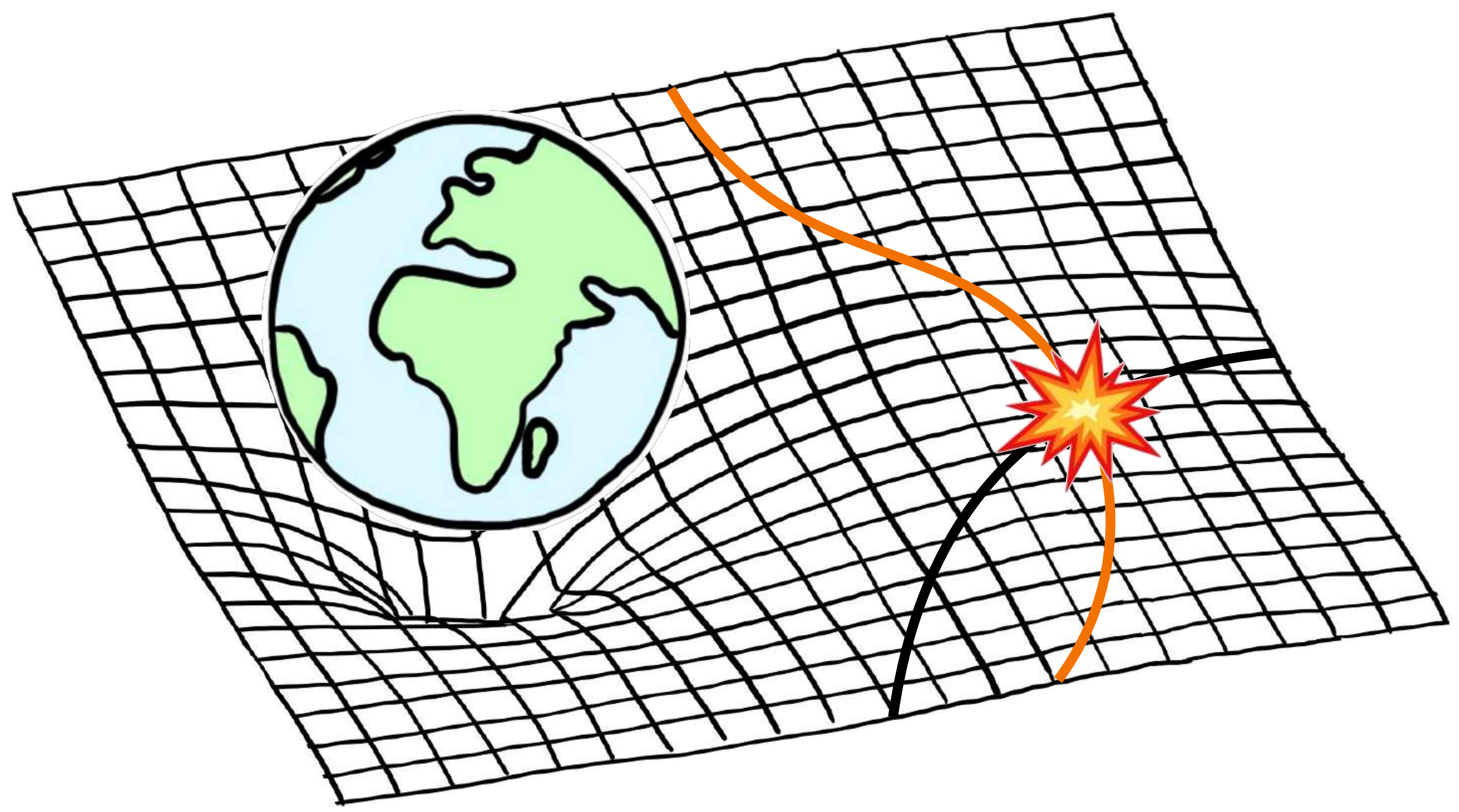
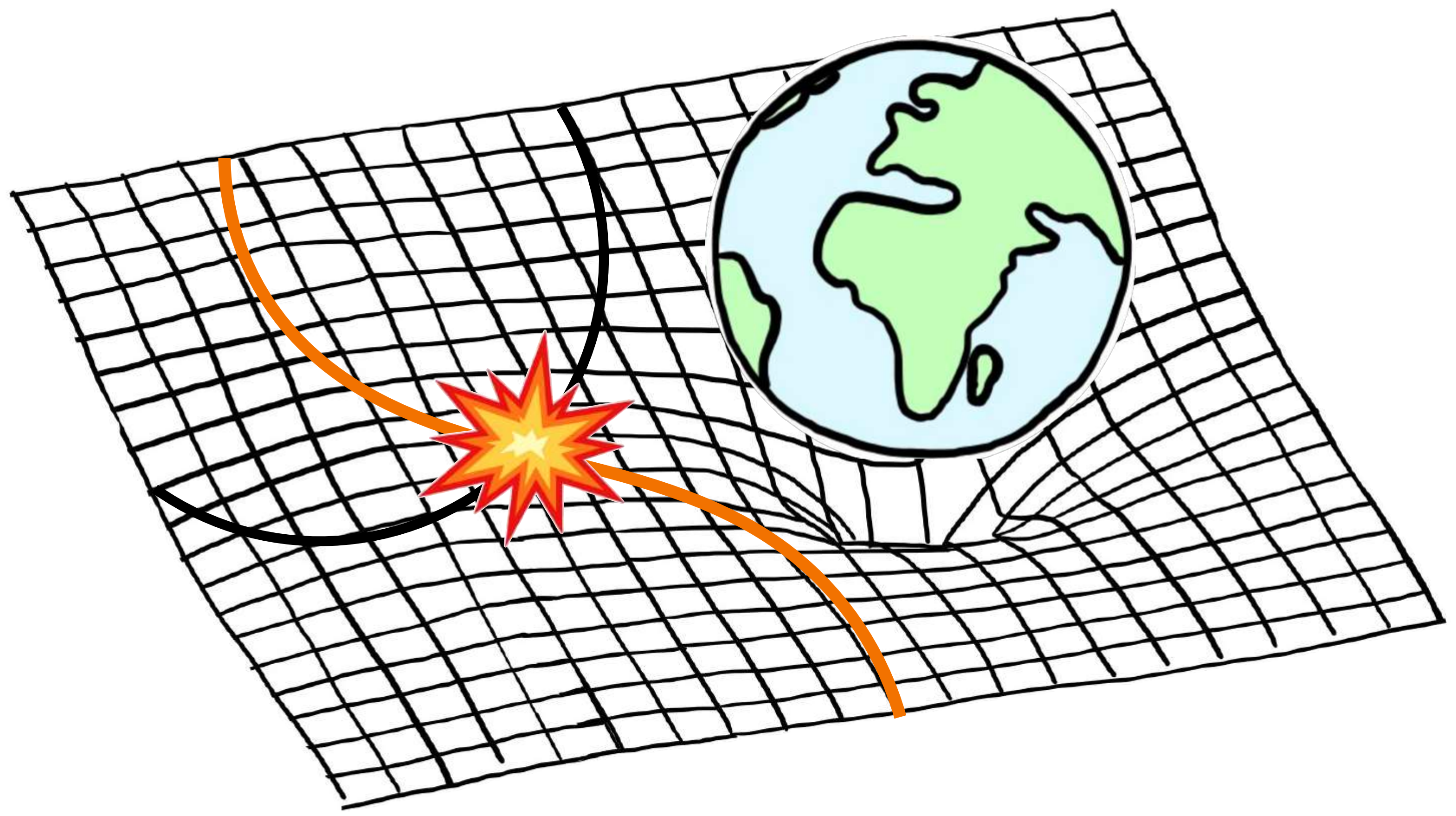
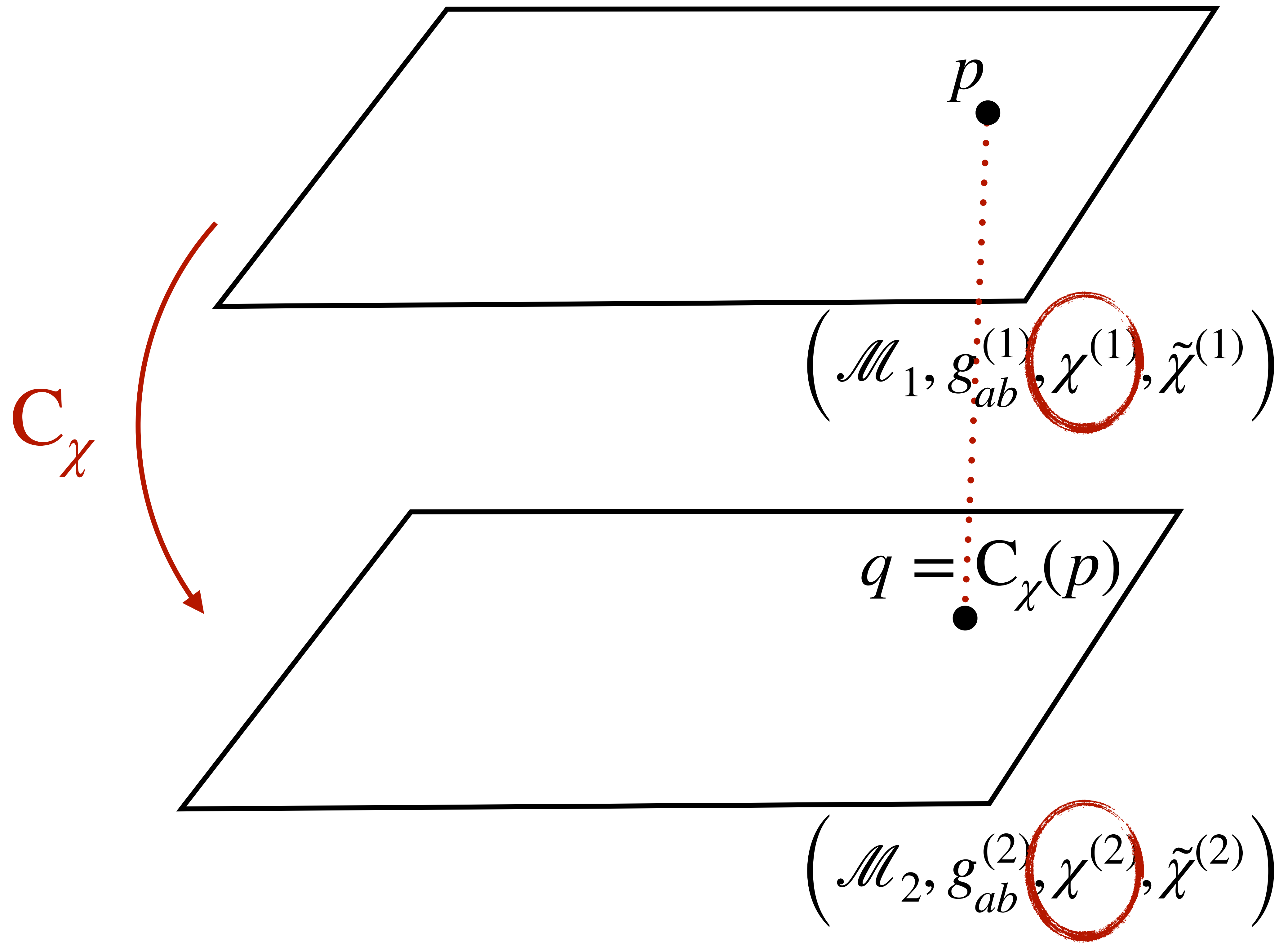
Spacetime Localisation of Events

- What does it mean for an event to be spacetime-localised?
- How does the localisation of an event in spacetime depend on the quantum coordinate system?



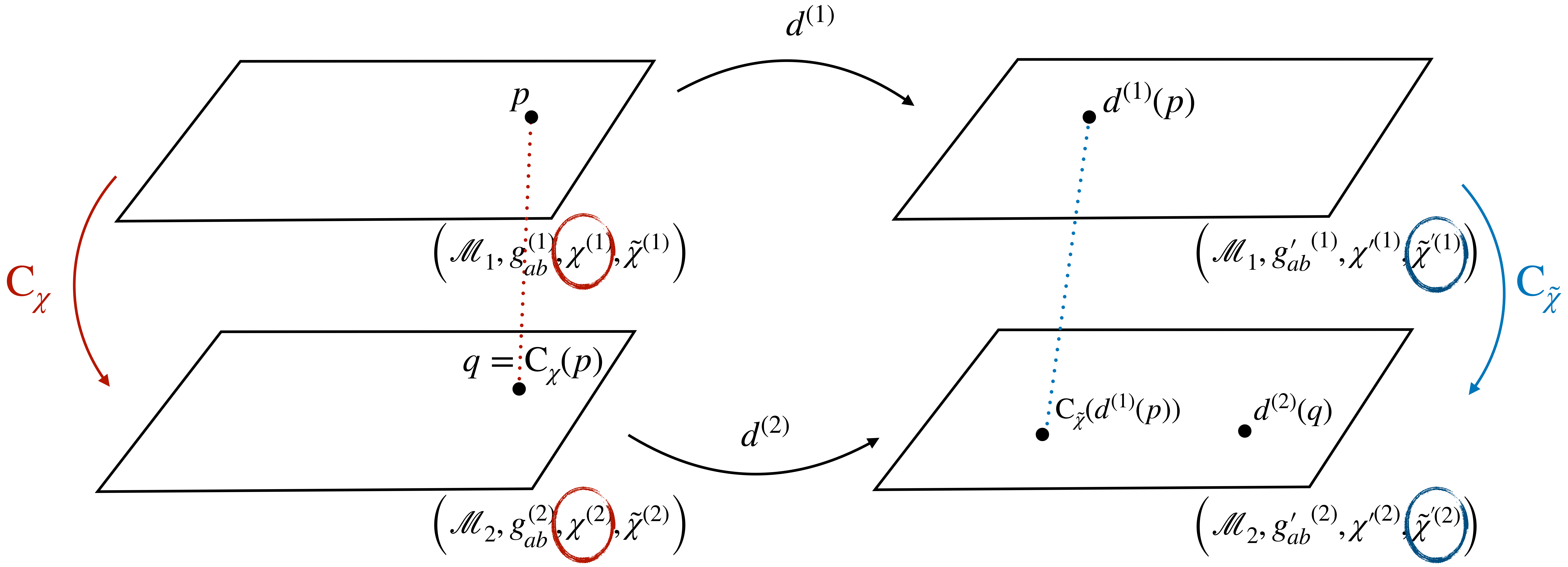


Identification of points



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

Identification of points



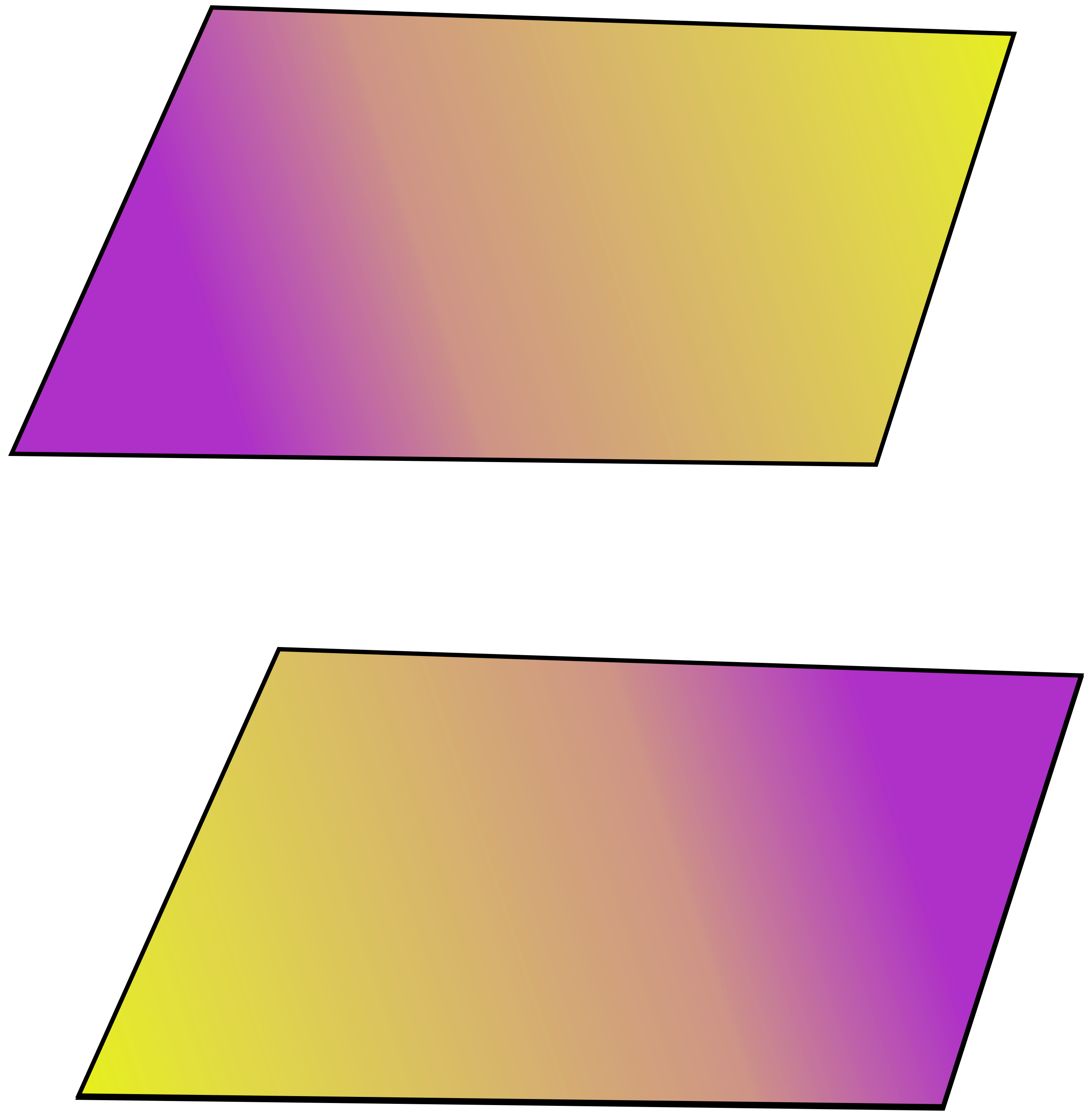
The pair (p, q) where $p \in \mathscr{M}_1$ and $q \in \mathscr{M}_2$ is localised iff $q = \mathrm{C}_\chi(p)$.

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

Identification of points

A concrete toy example

χ-fields: Red - Green - Blue (RGB)



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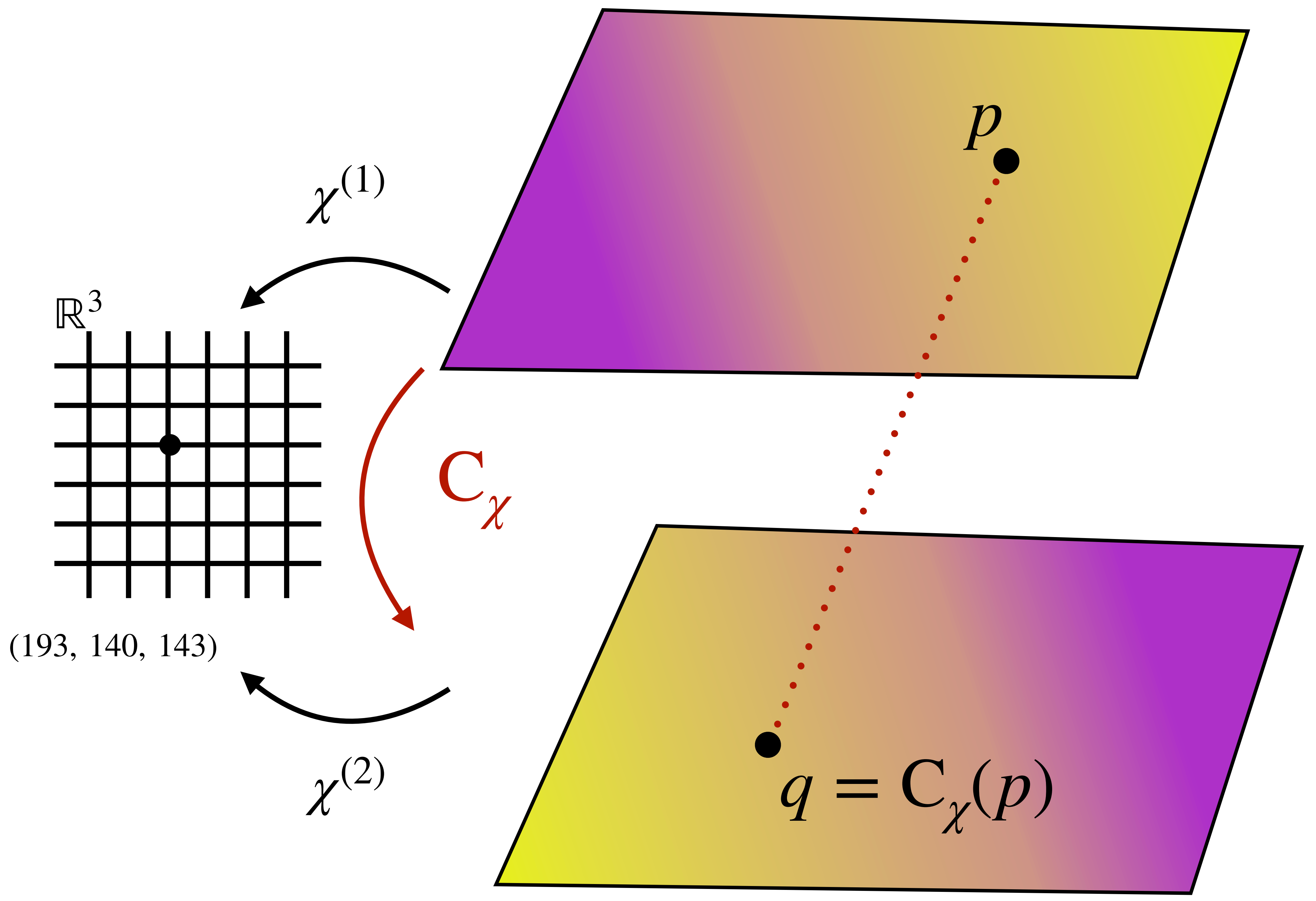

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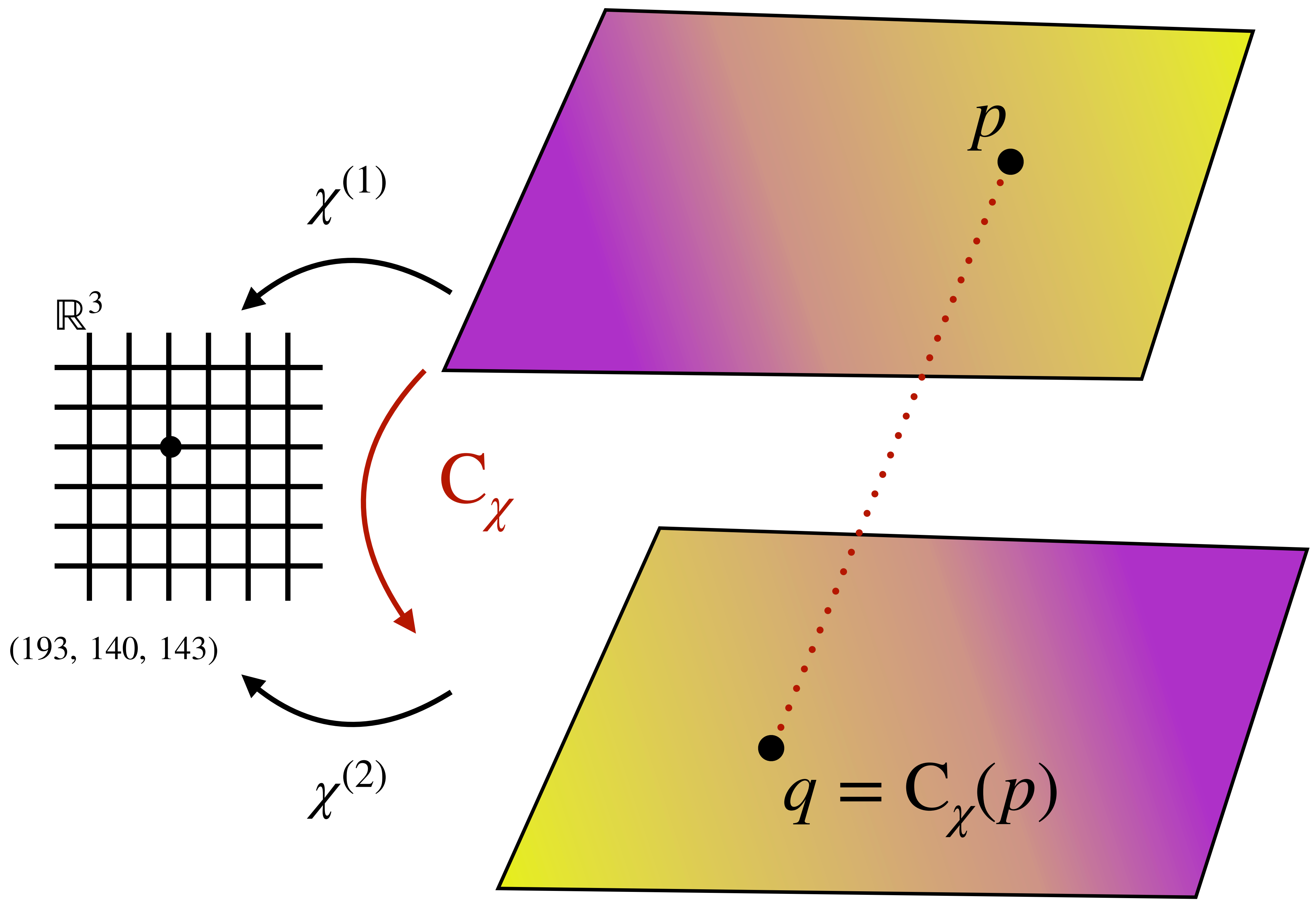
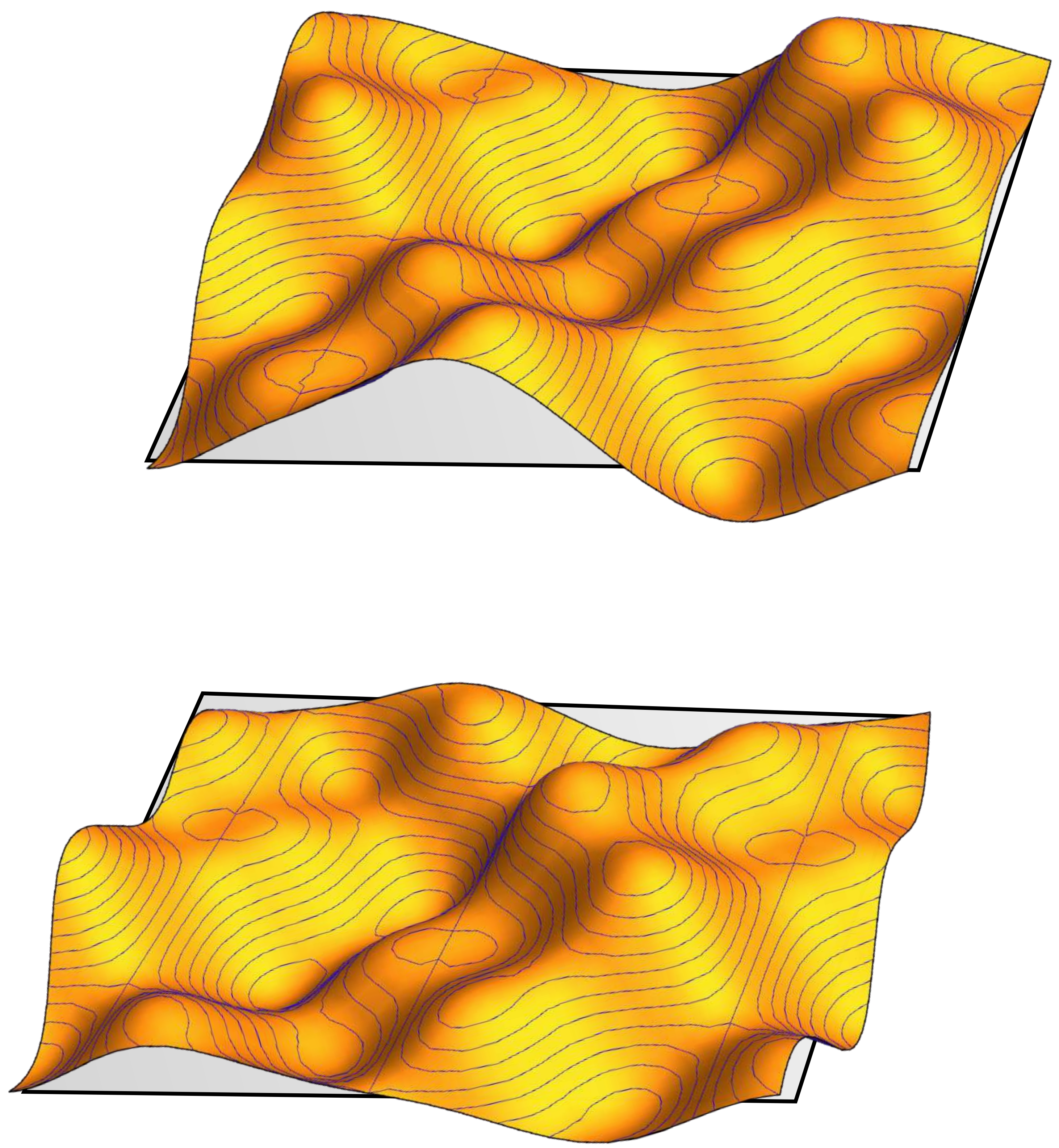


$\tilde{\chi}$-fields: Temperature - Pressure - Luminosity



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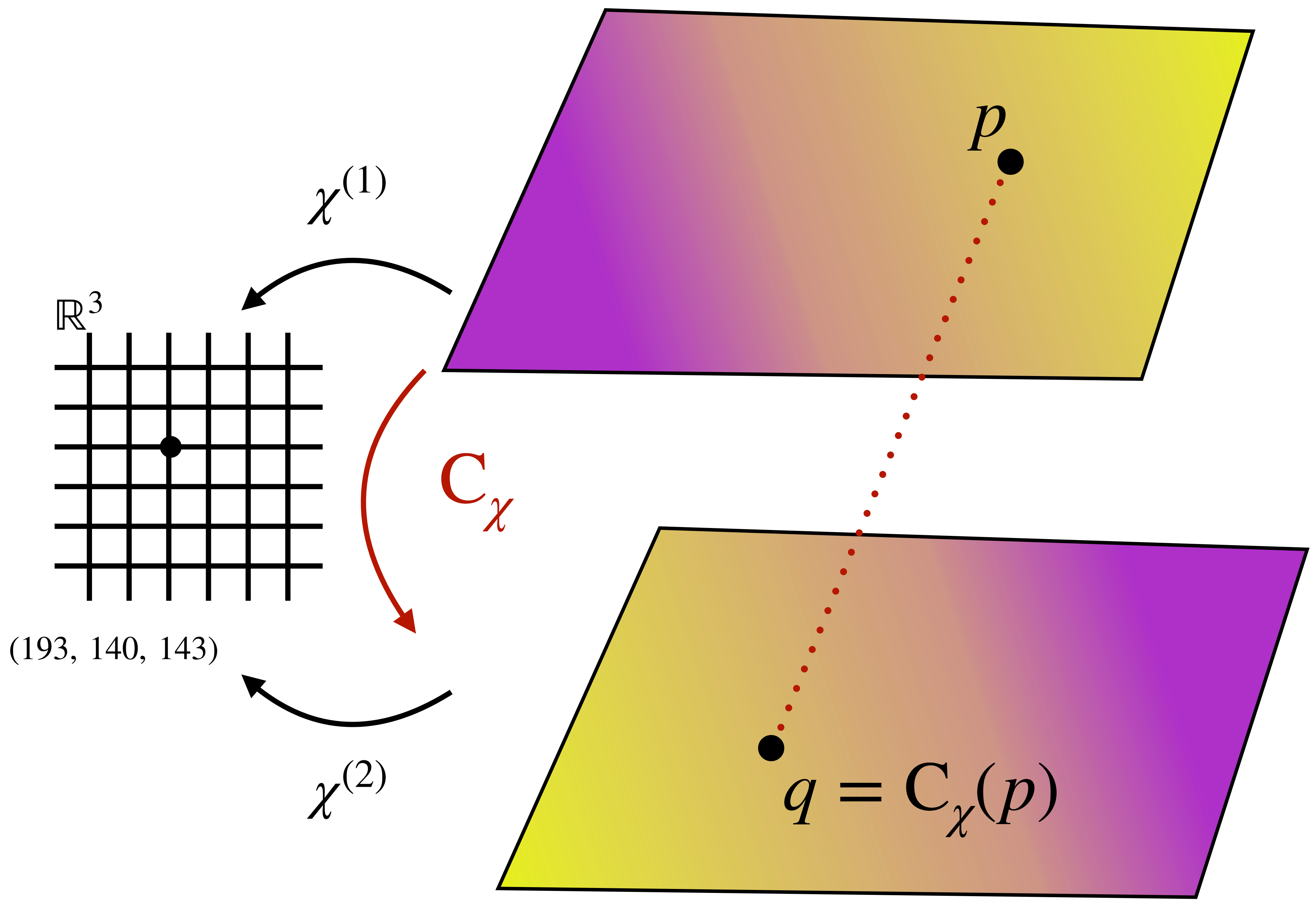

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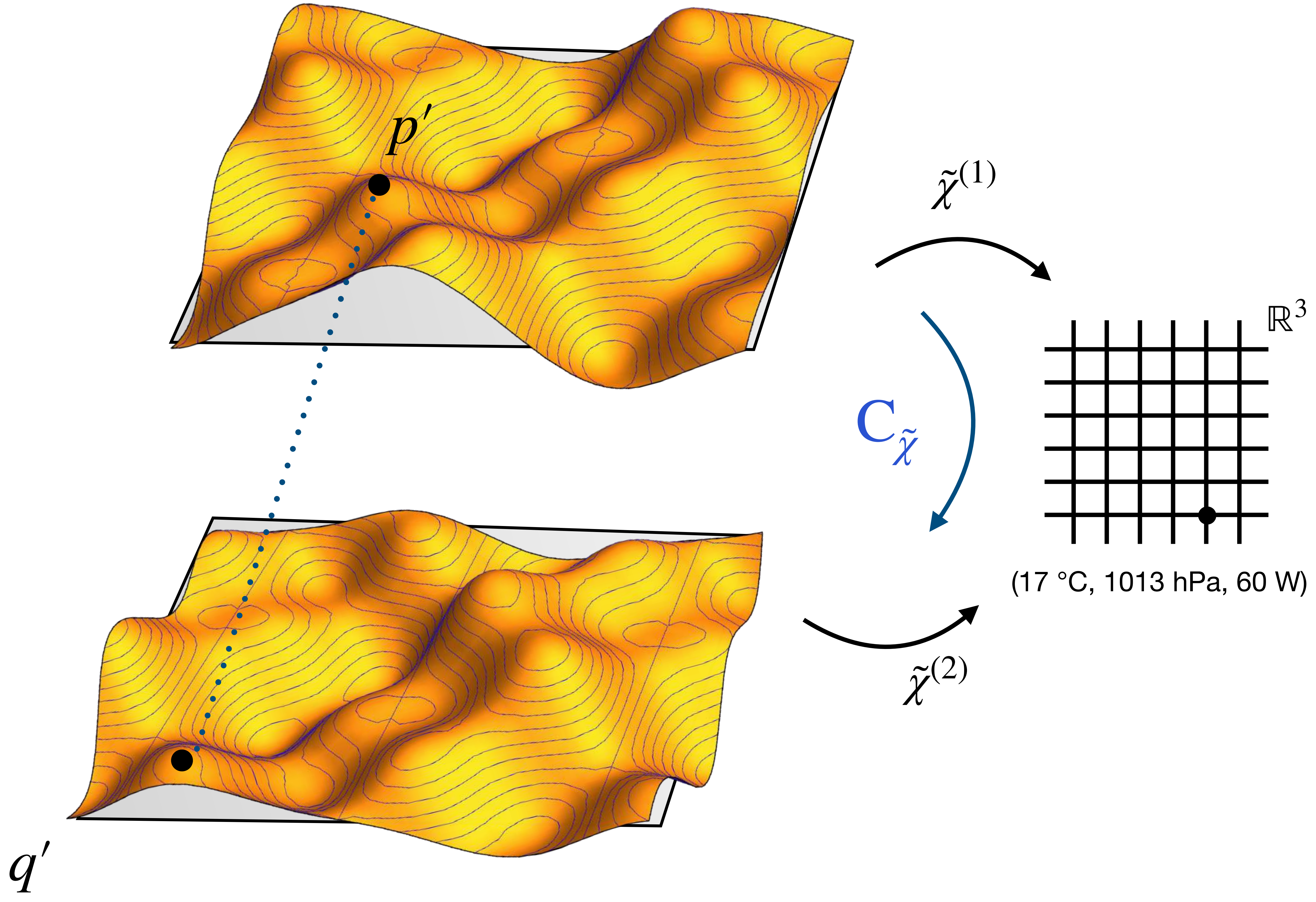

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χ-fields: $(\text{Riem}^2 - \text{Weyl}^2, \Box R, \text{Ric}^2, \Box \text{Weyl}^2)$

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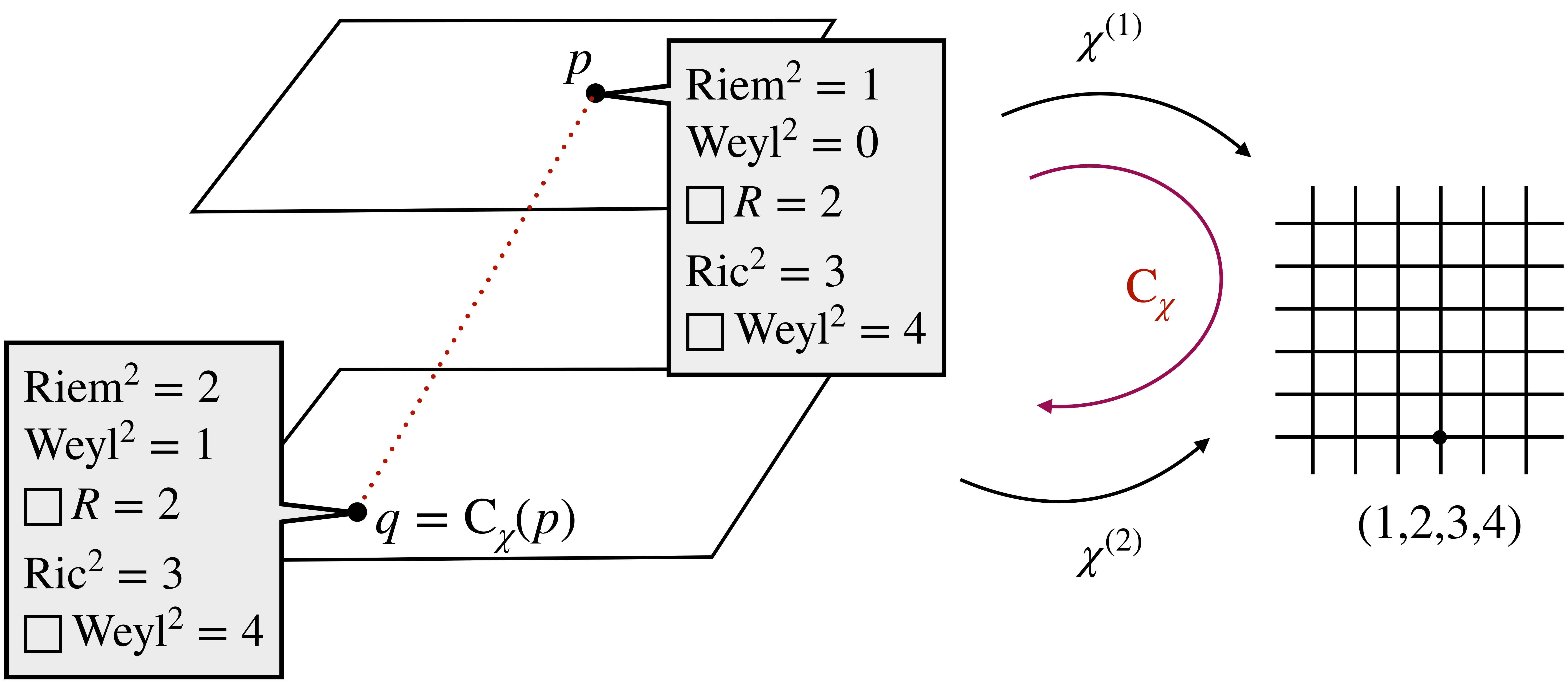

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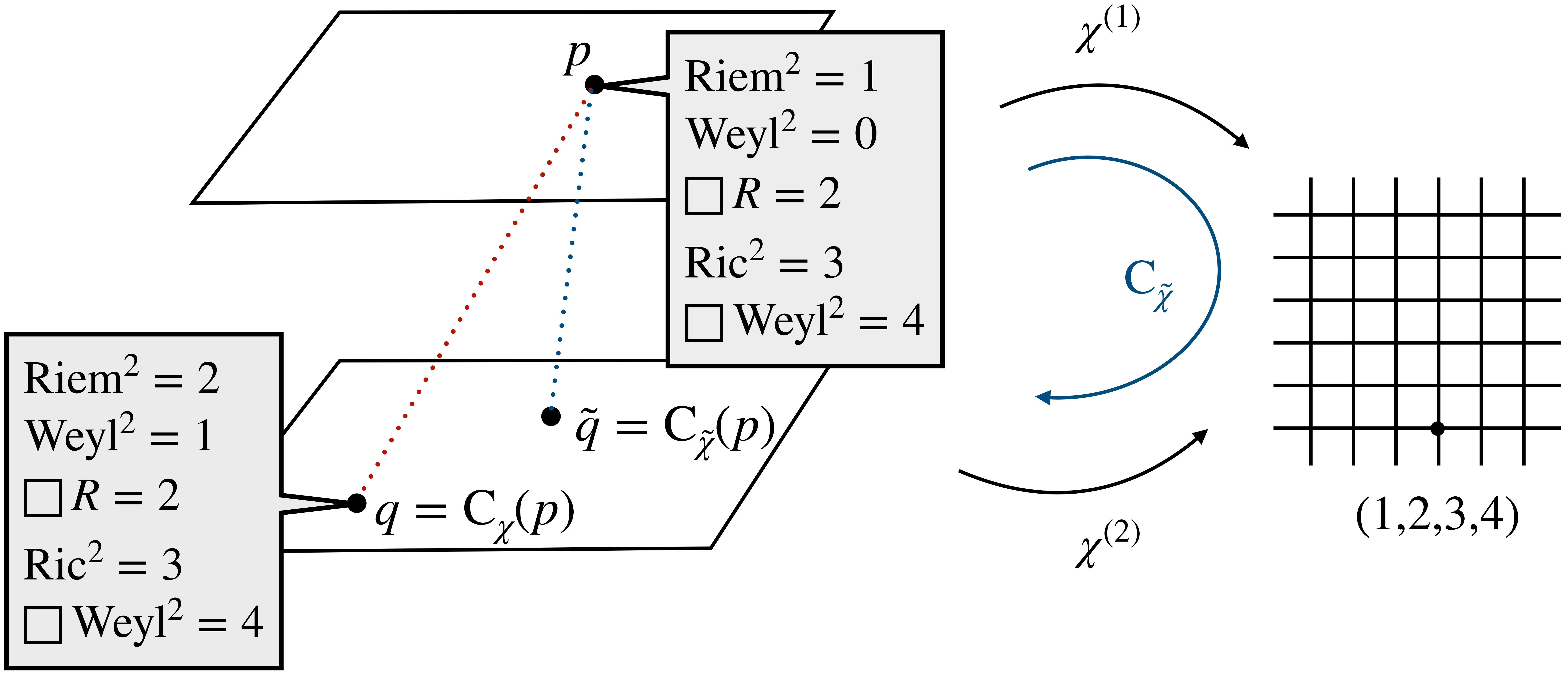

Identification of points

A concrete toy example

Localisation of pairs of points is reference frame dependent…

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

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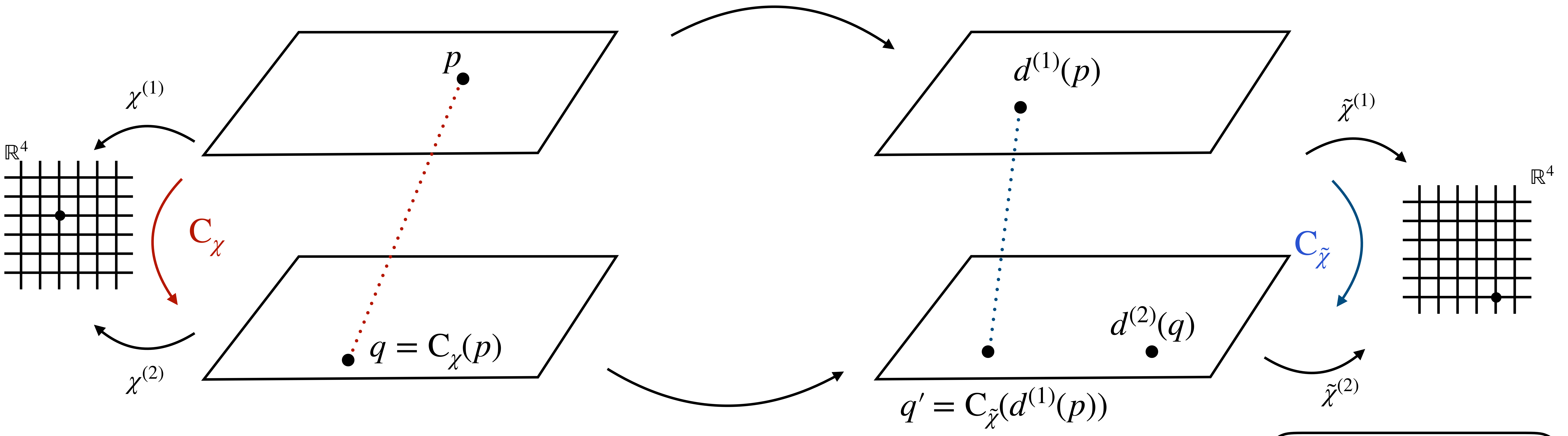
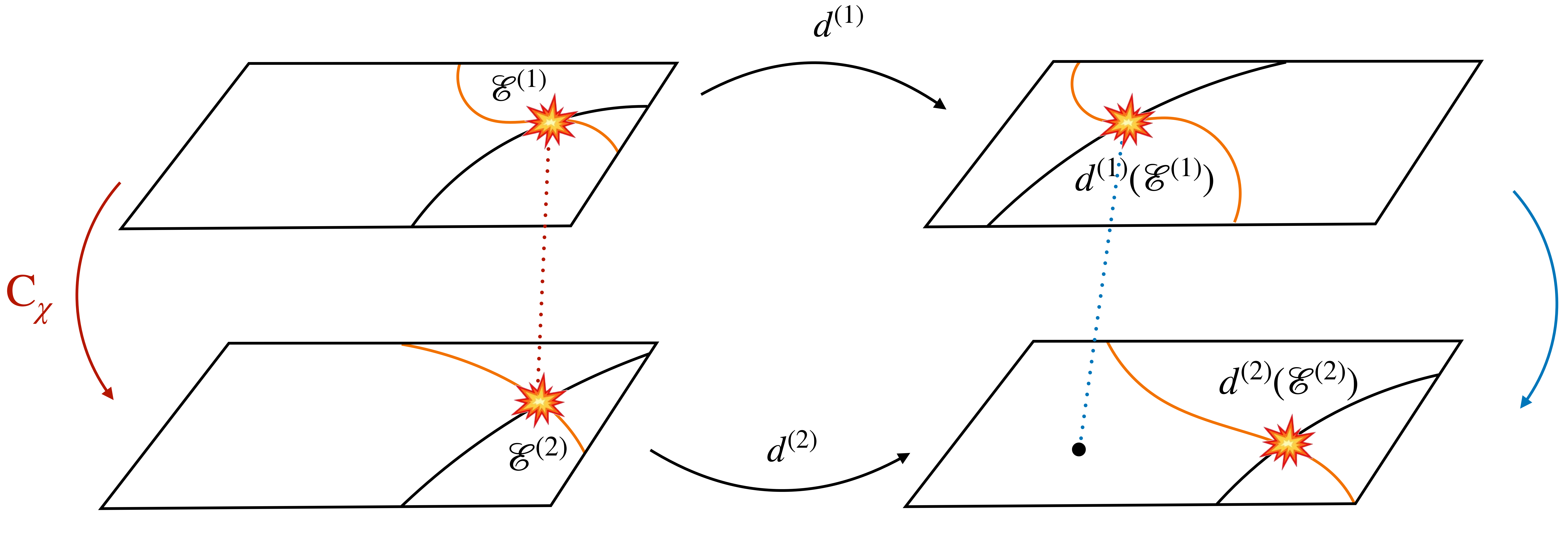


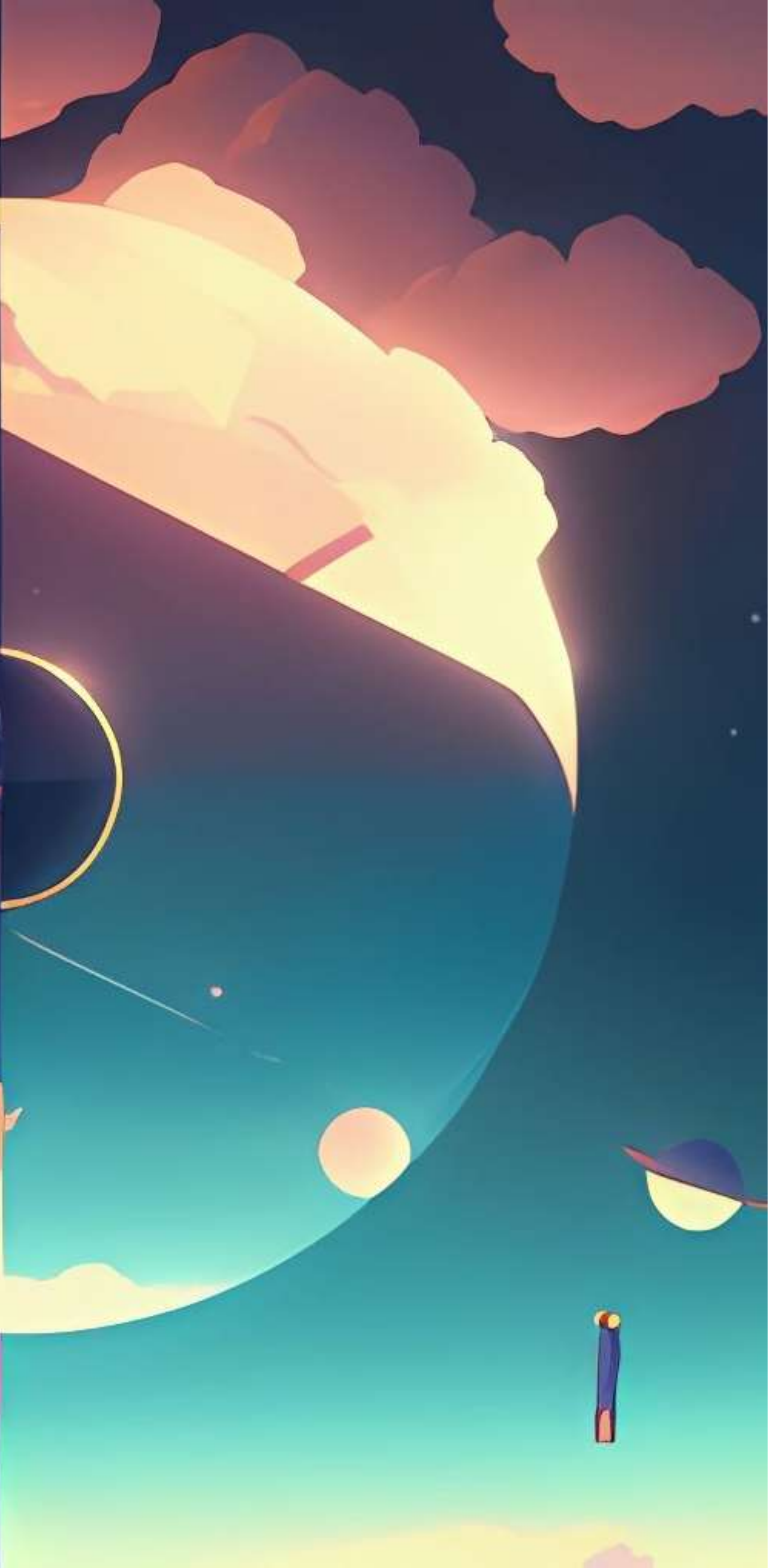
$$d^{(2)}(q) \neq \mathrm{C}_{\tilde{\chi}}(d^{(1)}(p))$$

Spacetime Localisation of Events



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

Quantum Hole Argument



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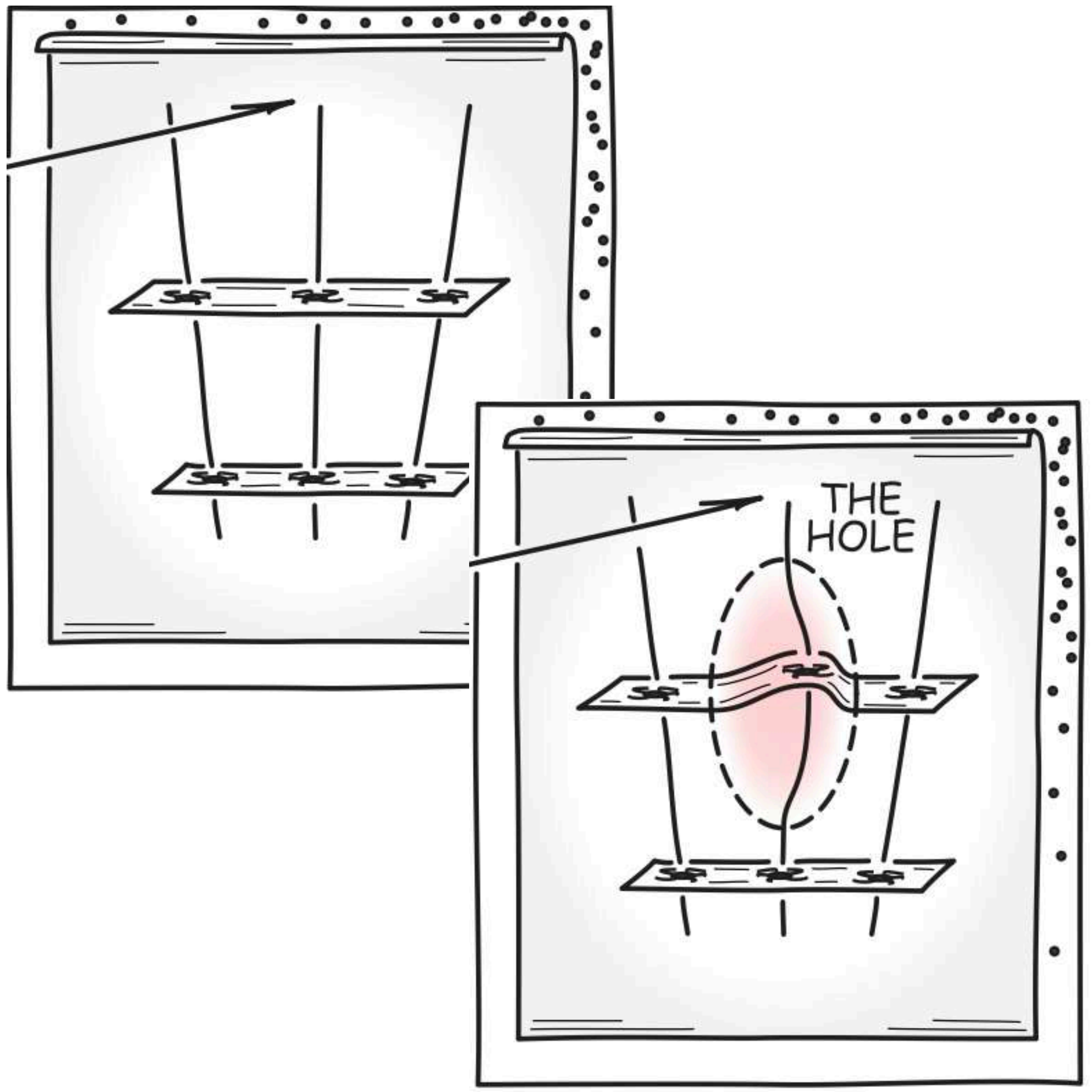
The classical and quantum hole argument

- **Classical hole argument** (against *spacetime substantivalism*)

→ Spacetime points have no physical meaning.



Norton, SEP (2022)

The classical and quantum hole argument

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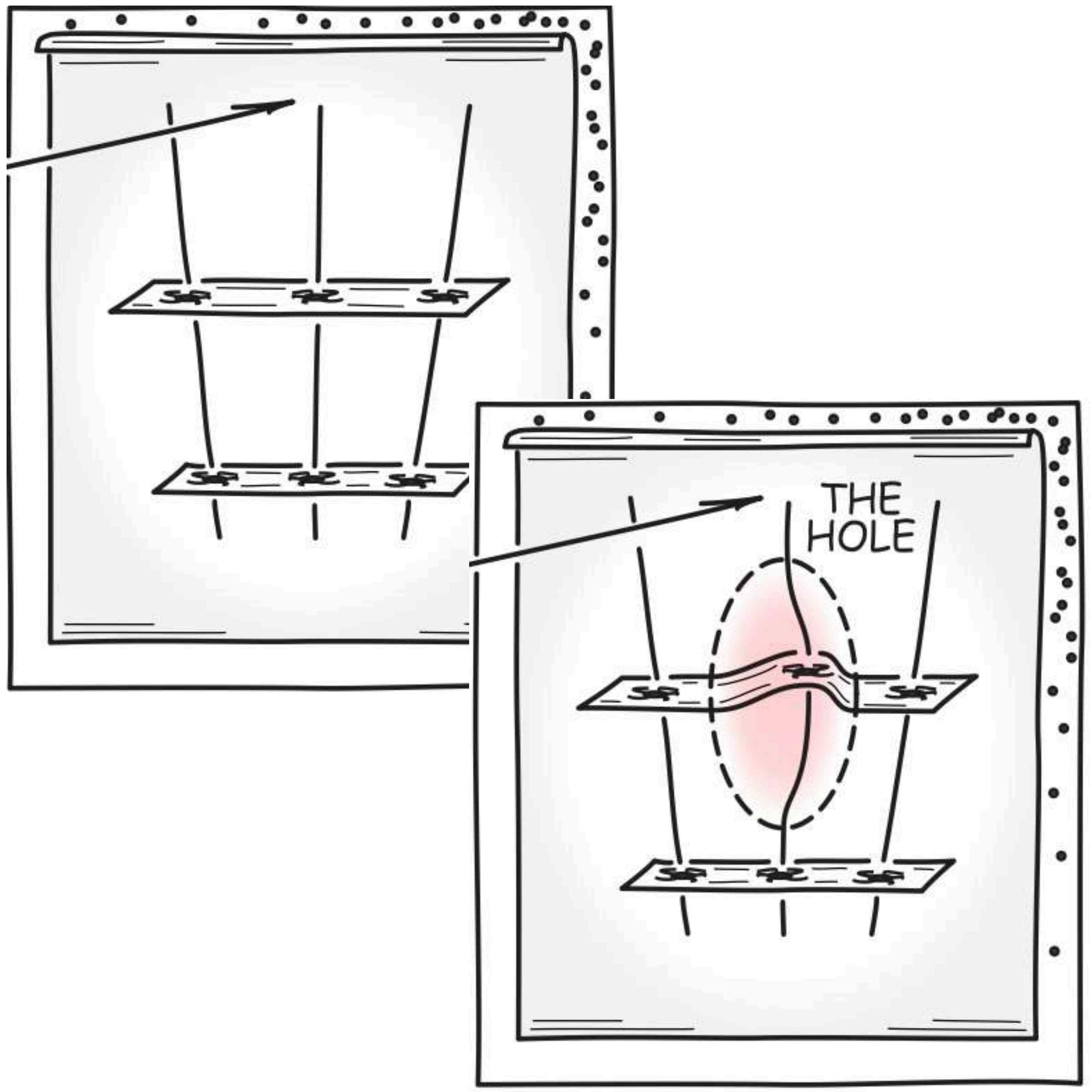
- Remove descriptive redundancy induced by the diffeomorphism invariance by using **point coincidences** of **physical fields.**



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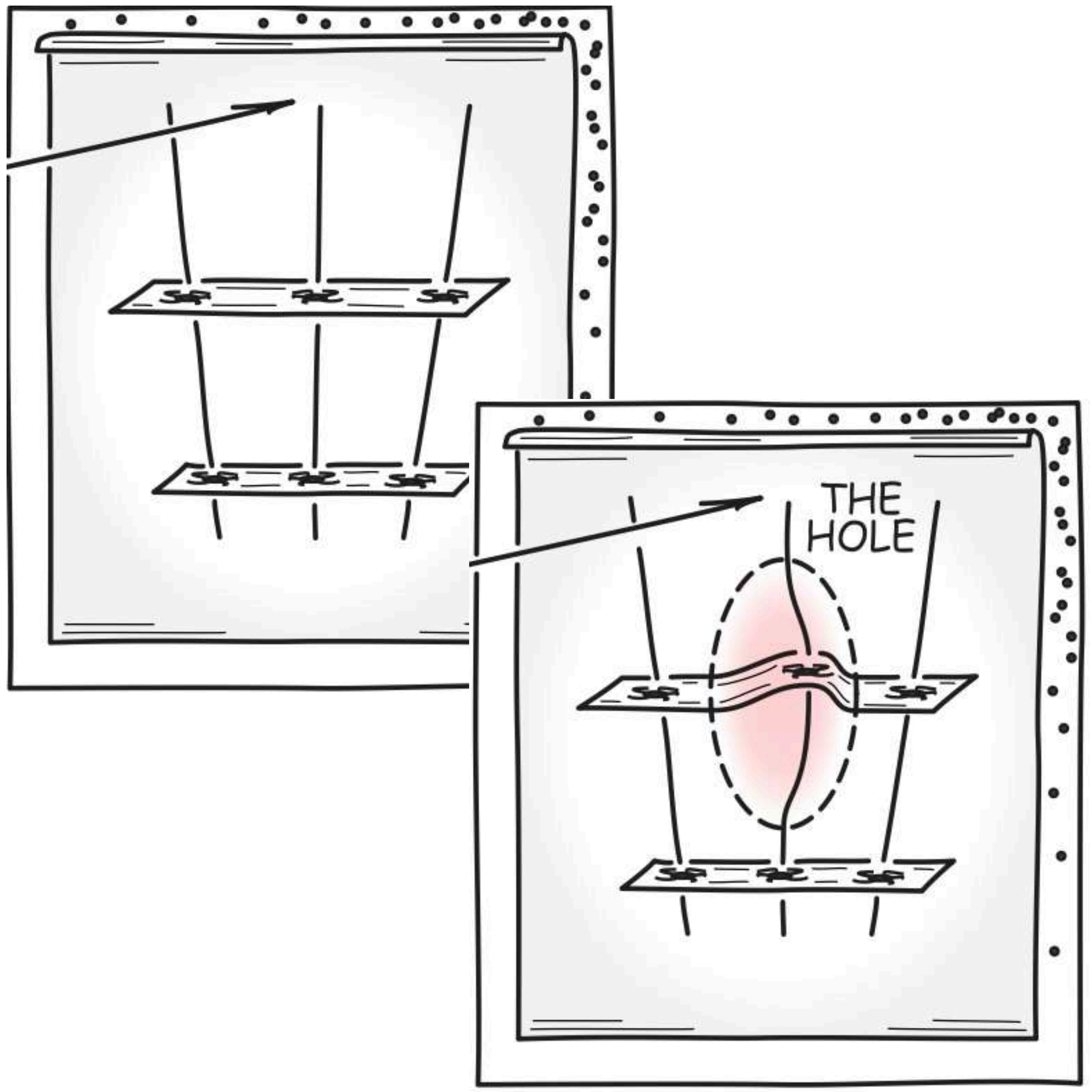
- Identified points across manifolds in superposition by **coincidences of scalar fields** across the **superposition.**



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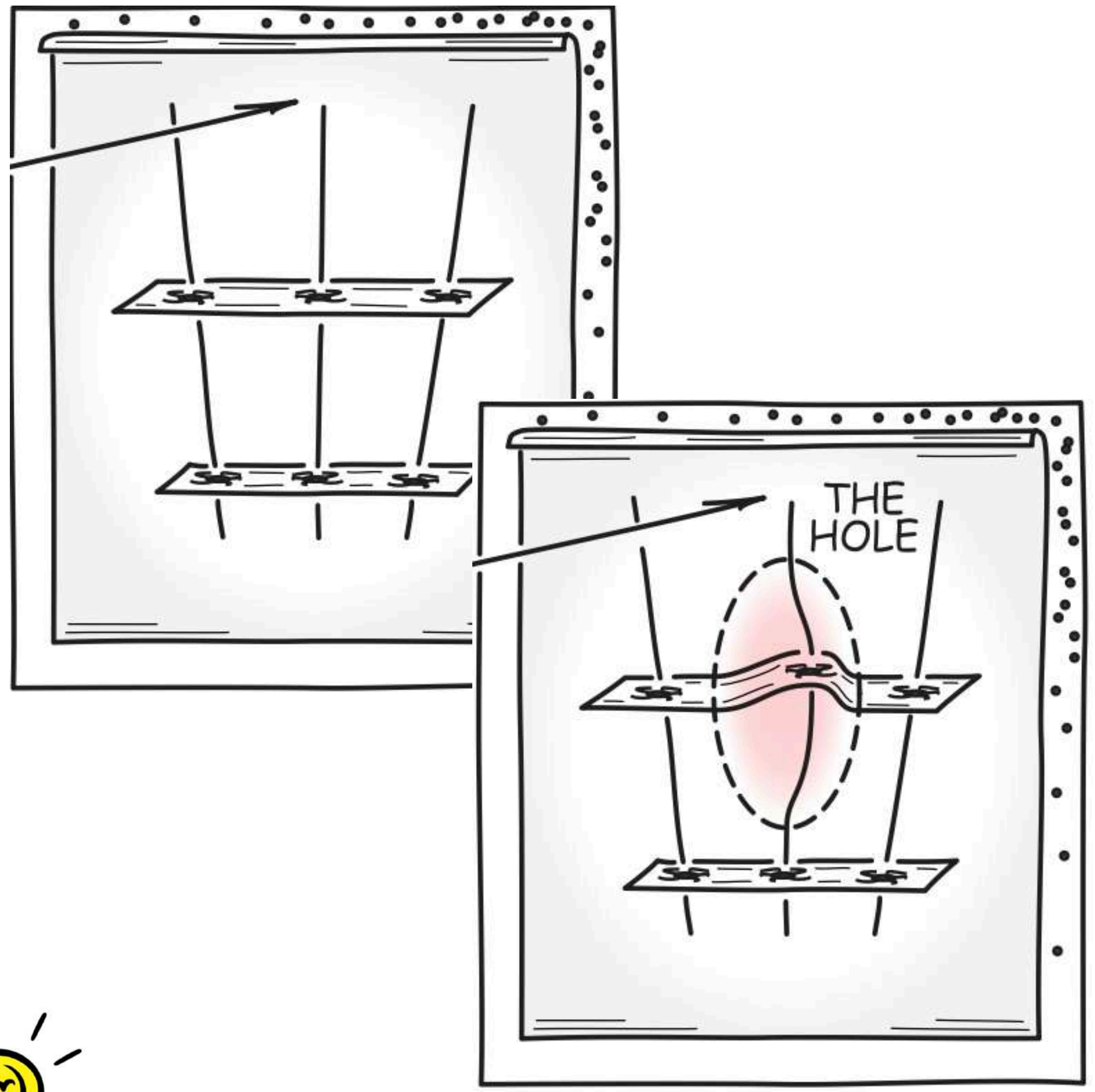
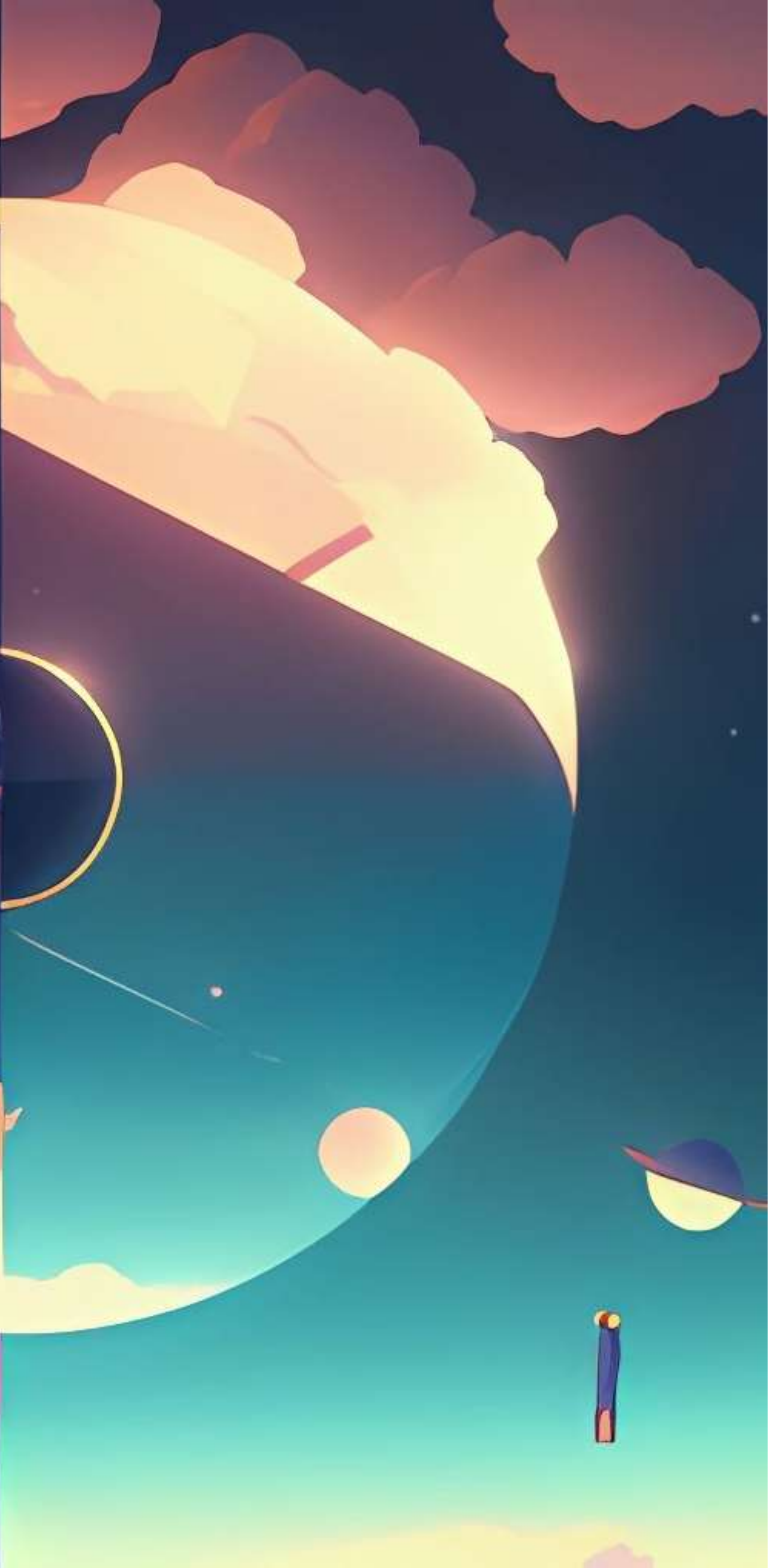
… and yet again an ambiguity!

Namely in the question of *which* reference fields to use to define coincidences!



Quantum Hole Argument!

Norton, SEP (2022)



Outline

- QRFs and Superpositions of spacetimes
- Symmetries and counterparts
- QRFs in general relativity
- Physical implications
  - Localisation of events
  - Quantum hole argument
  - Relational observables
- Conclusion

Relational observables

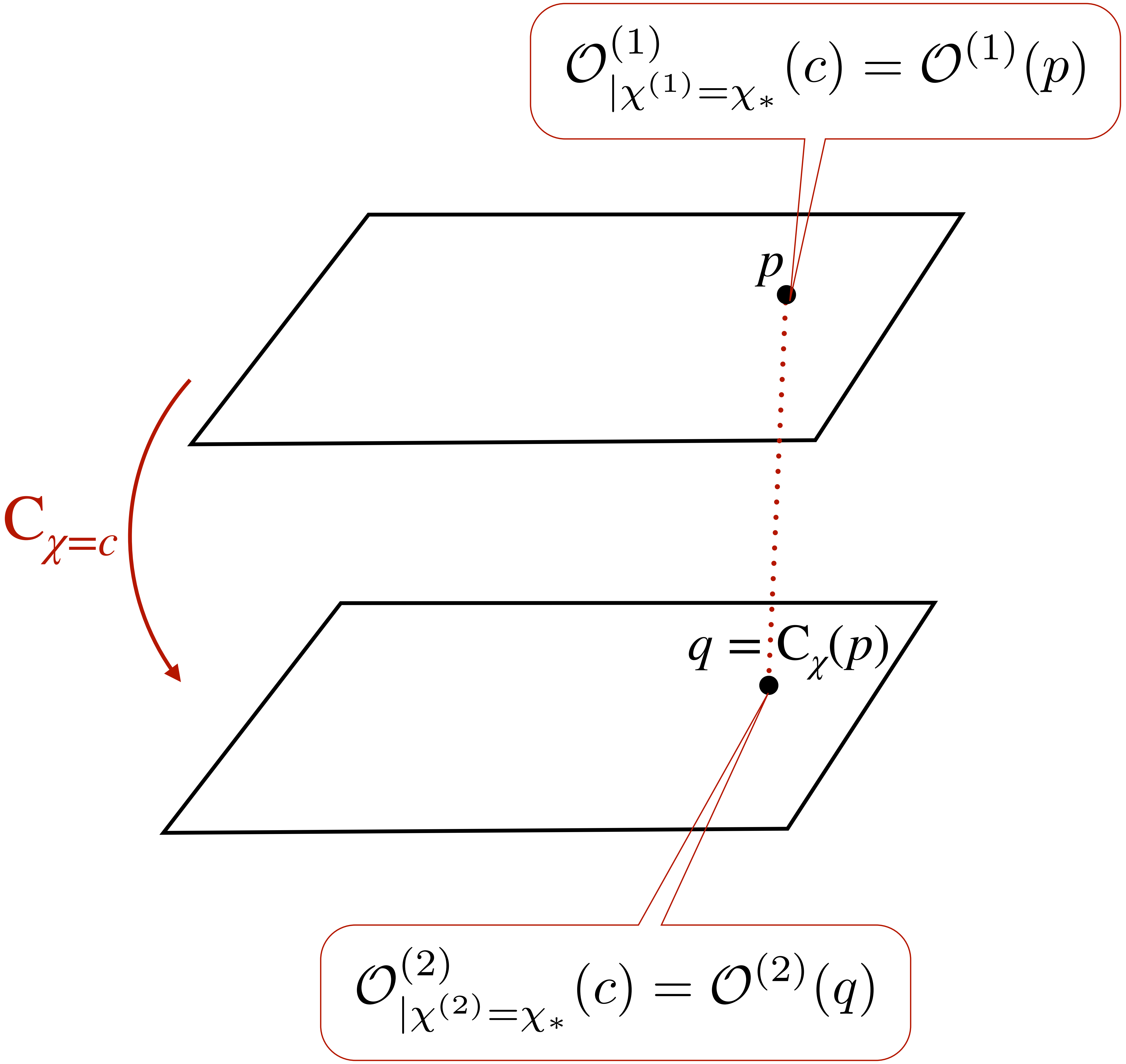
- Partial observables

$$\mathcal{O}^{(i)} := \mathcal{O}[{g_{ab}}^{(i)}, {\Psi_{\text{matter}}}^{(i)}] : \mathcal{M} \to \mathcal{S}$$

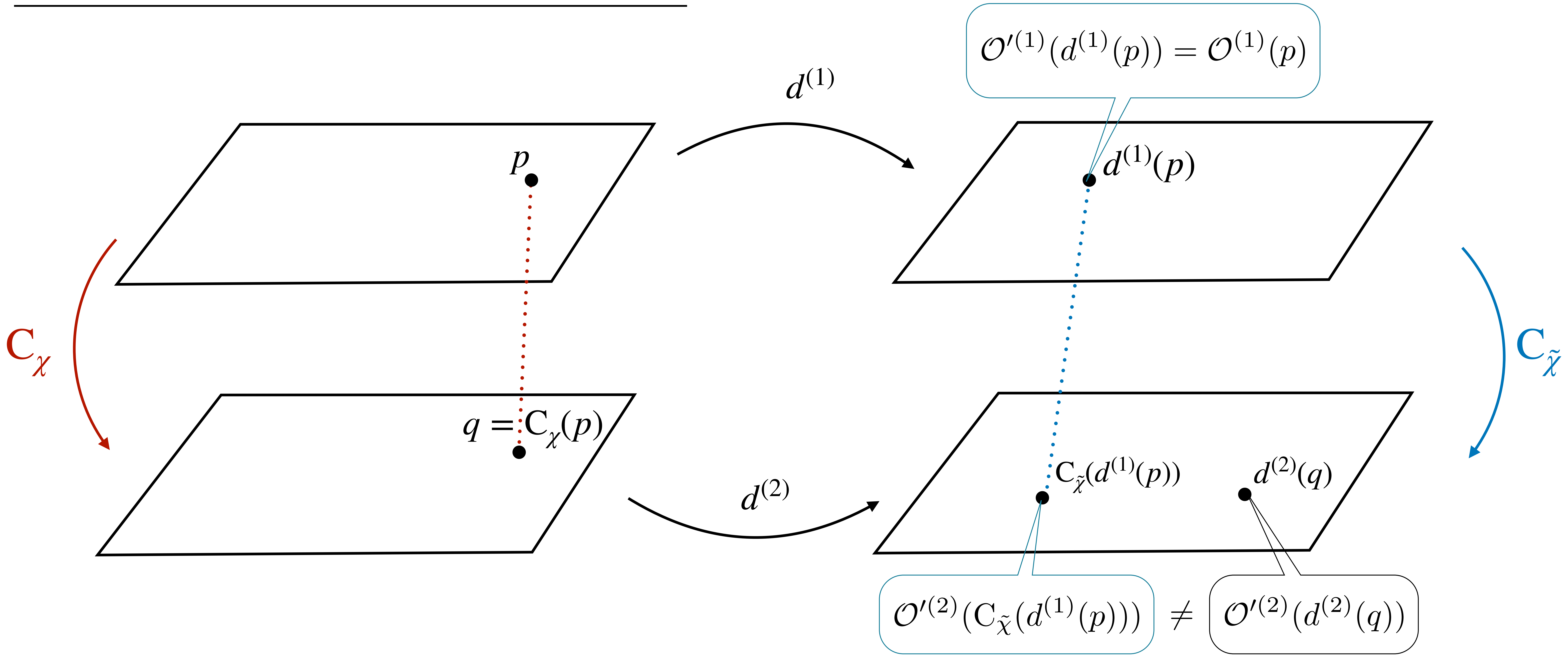
- Dressed observables by making partial observables relative to χ:

$$\mathcal{O}^{(i)}_{|\chi^{(i)}=\chi_*} := \mathcal{O}^{(i)} \circ (\chi^{(i)})^{-1}_{|\chi^{(i)}=\chi_*} : \mathcal{S} \to \mathcal{S}$$

- The observable is definite (not in a superposition) iff $\mathcal{O}^{(1)}(p) = \mathcal{O}^{(2)}(q)$.



Relational observables

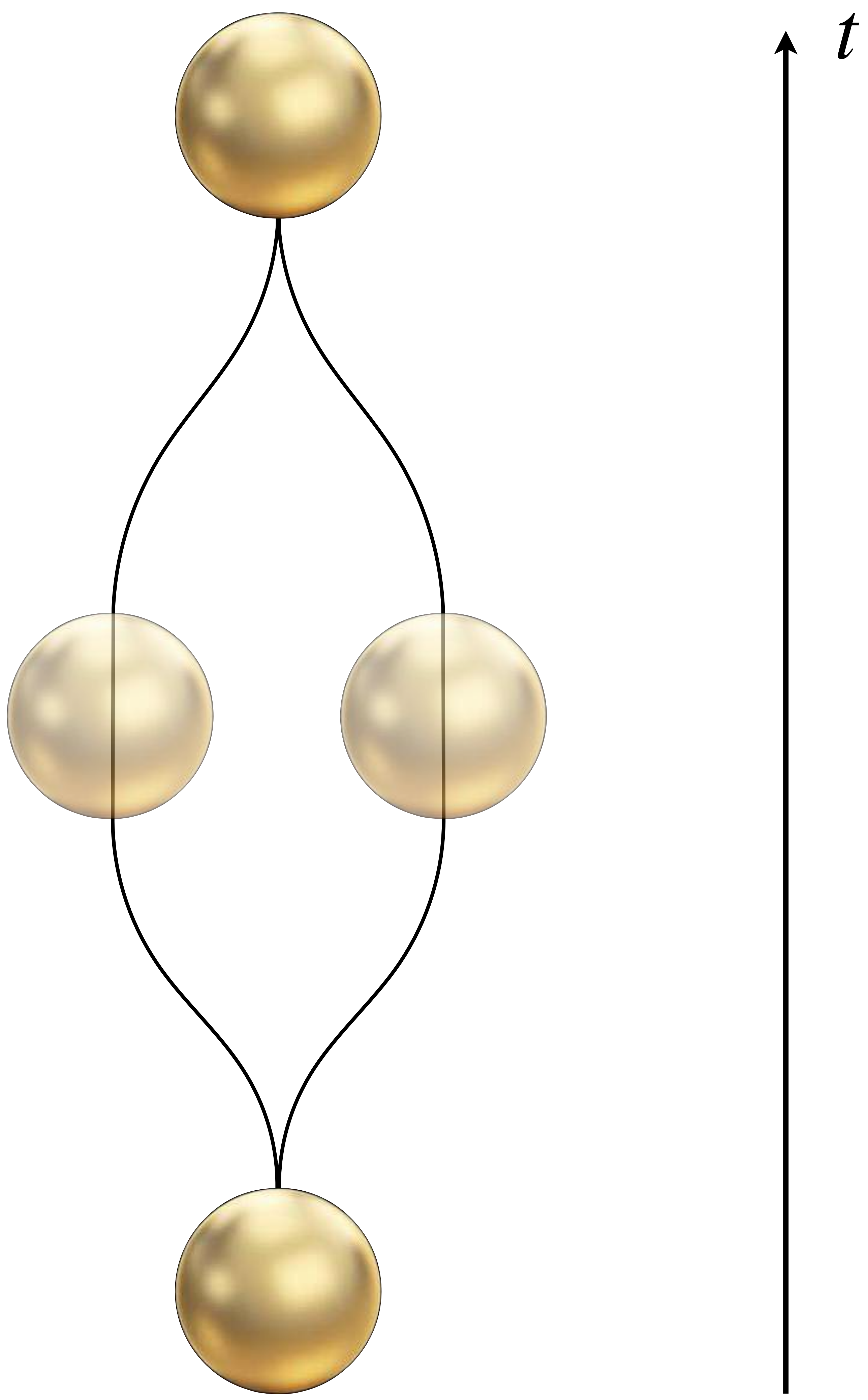


Whether an observable is definite (localized) or in a superposition (delocalized) depends on the choice of the reference frame

Implications for Interference and Recombination?

Consider for illustration the BMV experiment in which two masses in superposition states are taken to get entangled with each other through gravitational interaction (and gravitational interaction alone): the relevant literature tacitly assumes that the location of the masses are all relative to one joint lab frame—no matter whether the experiment is modelled through a Newtonian potential, or (low-energy) metric fields, as done by Christodoulou and Rovelli (2019). But if we perform a quantum diffeomorphism which shifts the point at which the recombination occurs within one of the branches, then the phase change will be different and the interference effects will change.

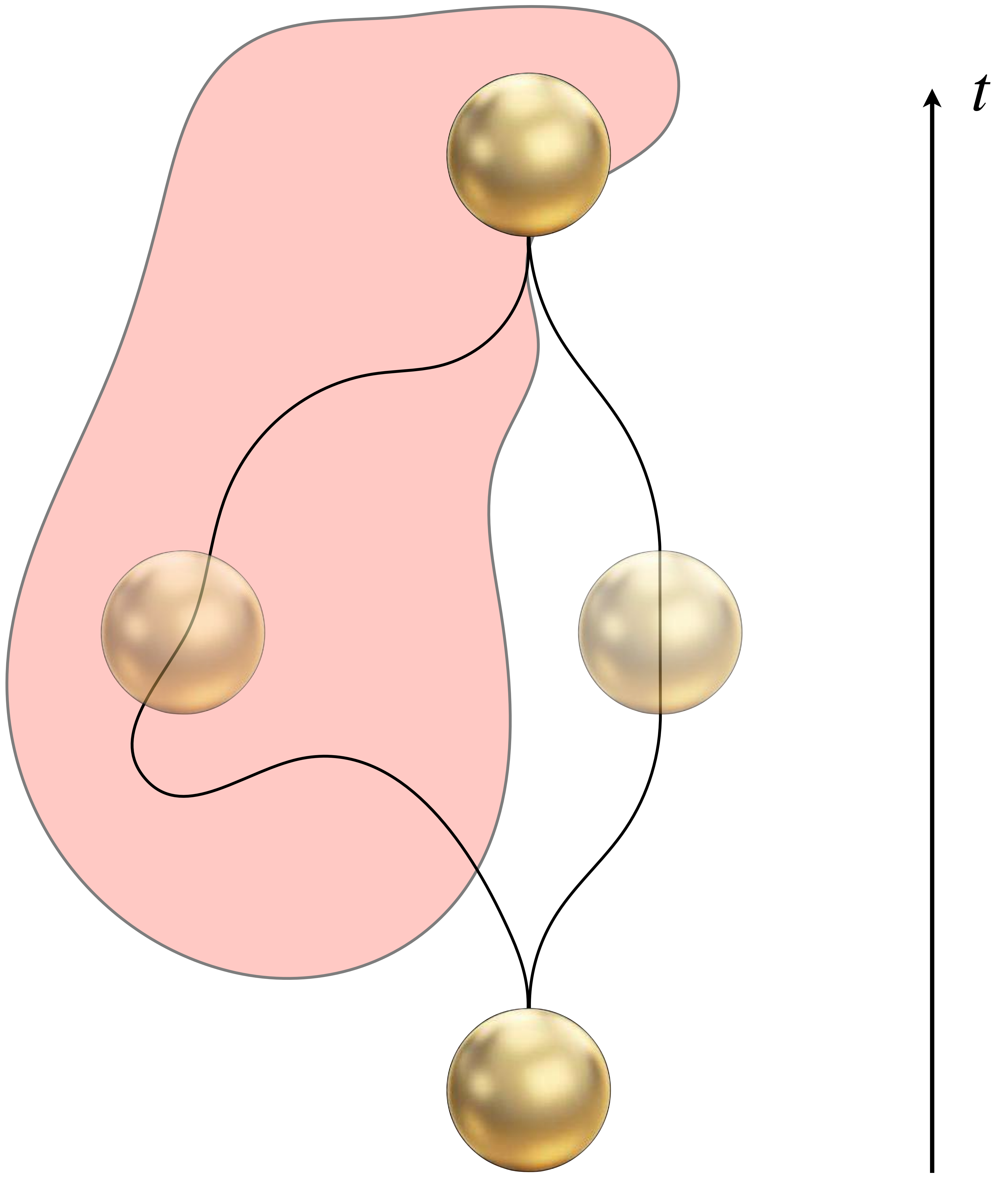
Can a QRF transformation change the relative phase and thus the outcome of an interference experiment?



Adlam, Linnemann, Read (2022)

Implications for Interference and Recombination?

- Consider quantum diffeomorphism that shifts the point at which recombination occurs in one branch.



Implications for Interference and Recombination?

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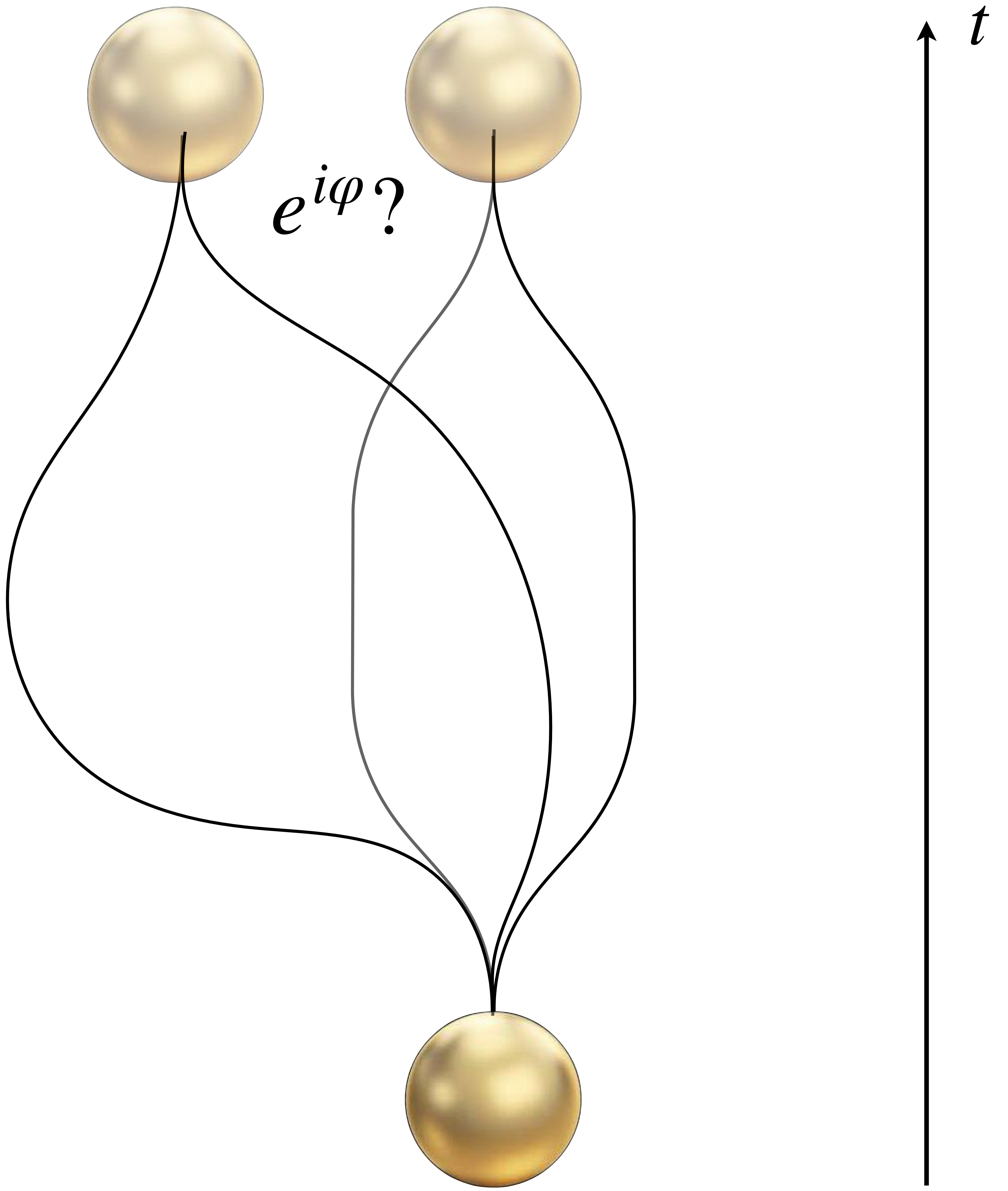
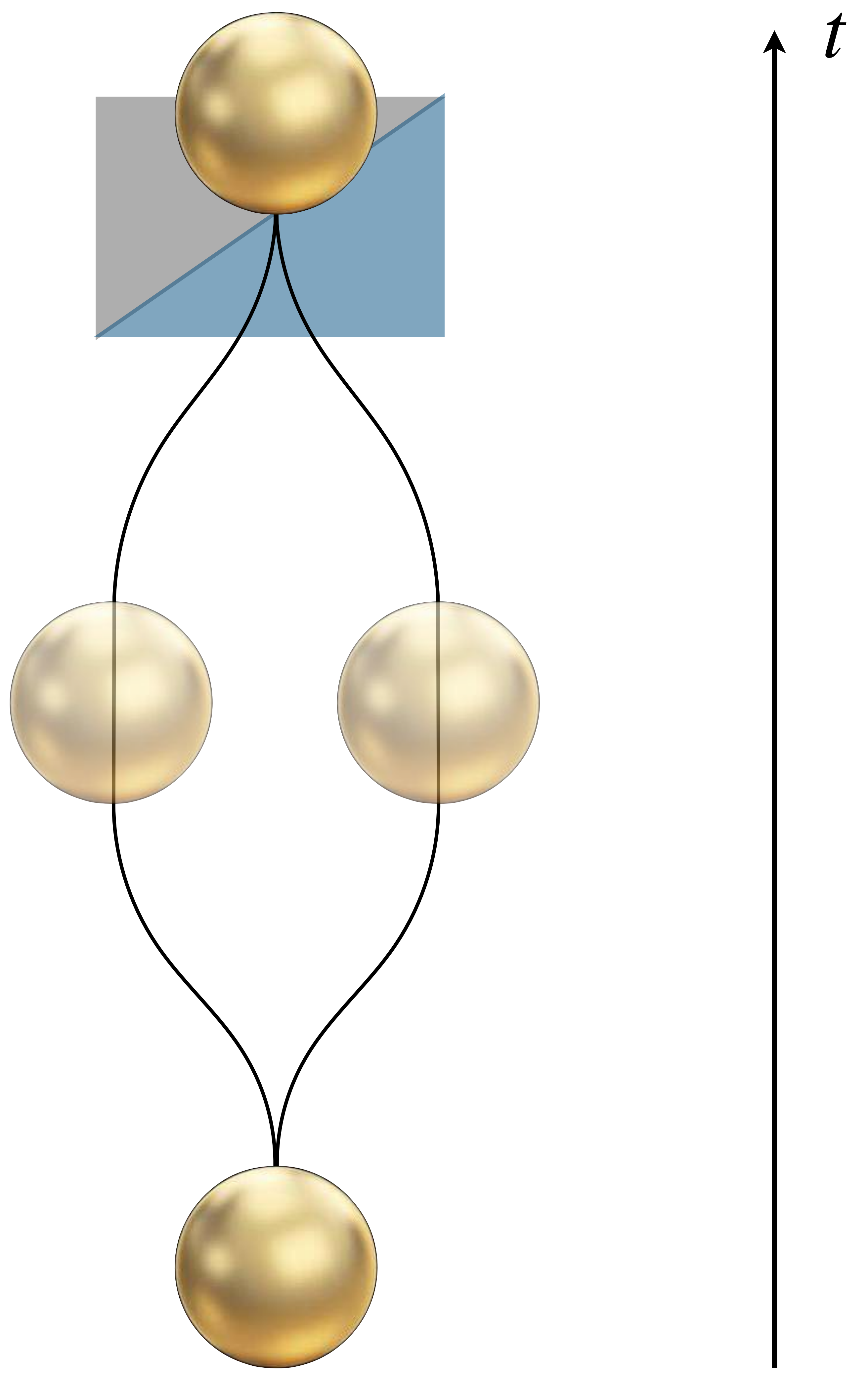


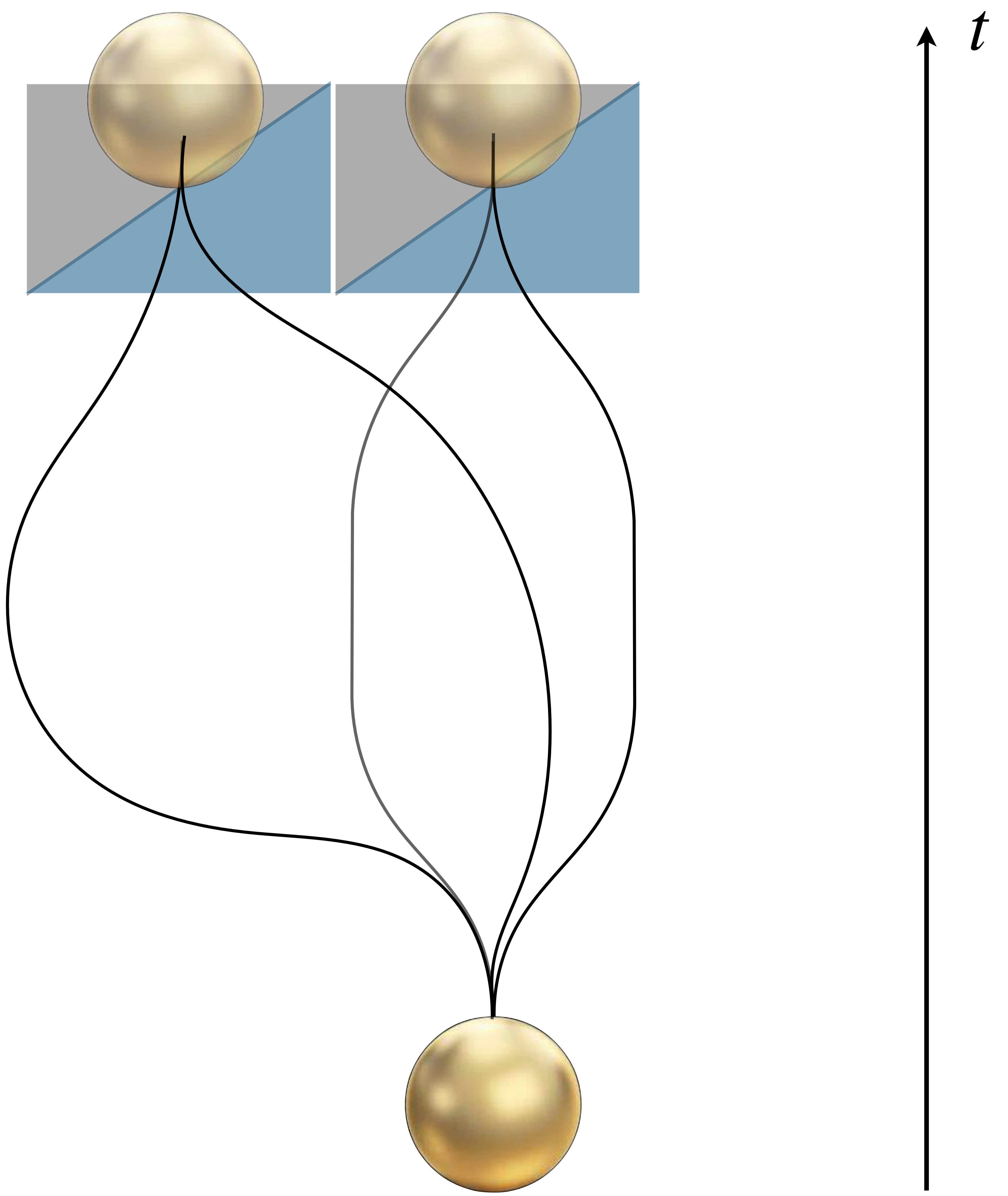
Implications for Interference and Recombination?

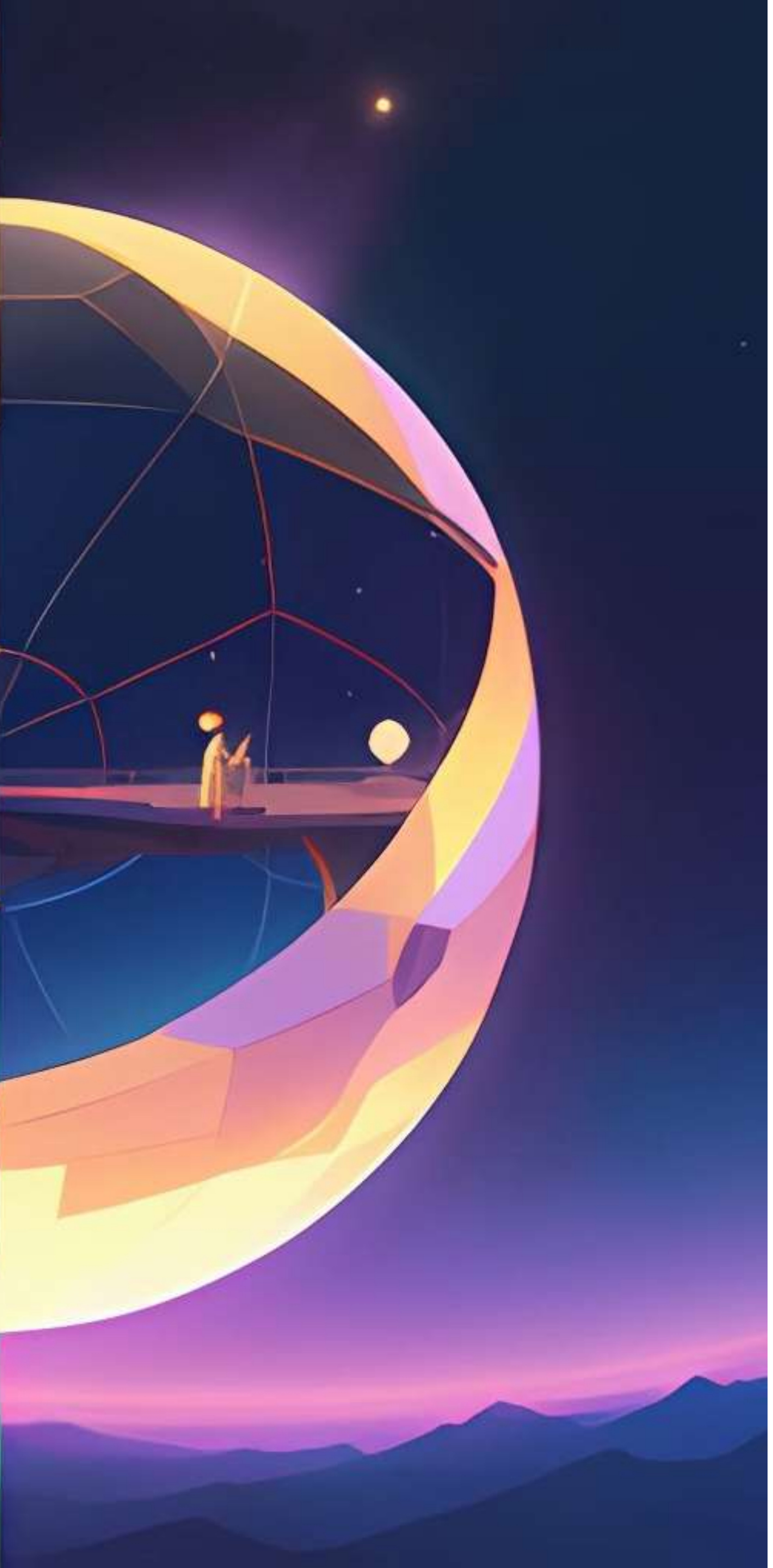
- Consider quantum diffeomorphism that shifts the point at which recombination occurs in one branch.
- What matters is the **relative distance** to the beamsplitter/laboratory.



Implications for Interference and Recombination?

- Consider quantum diffeomorphism that shifts the point at which recombination occurs in one branch.
- What matters is the **relative distance** to the beamsplitter/laboratory.
- While the recombination now occurs in a **superposition of locations**, the **phase** depends only on $x_M - x_{BS}$ and remain **unchanged**.

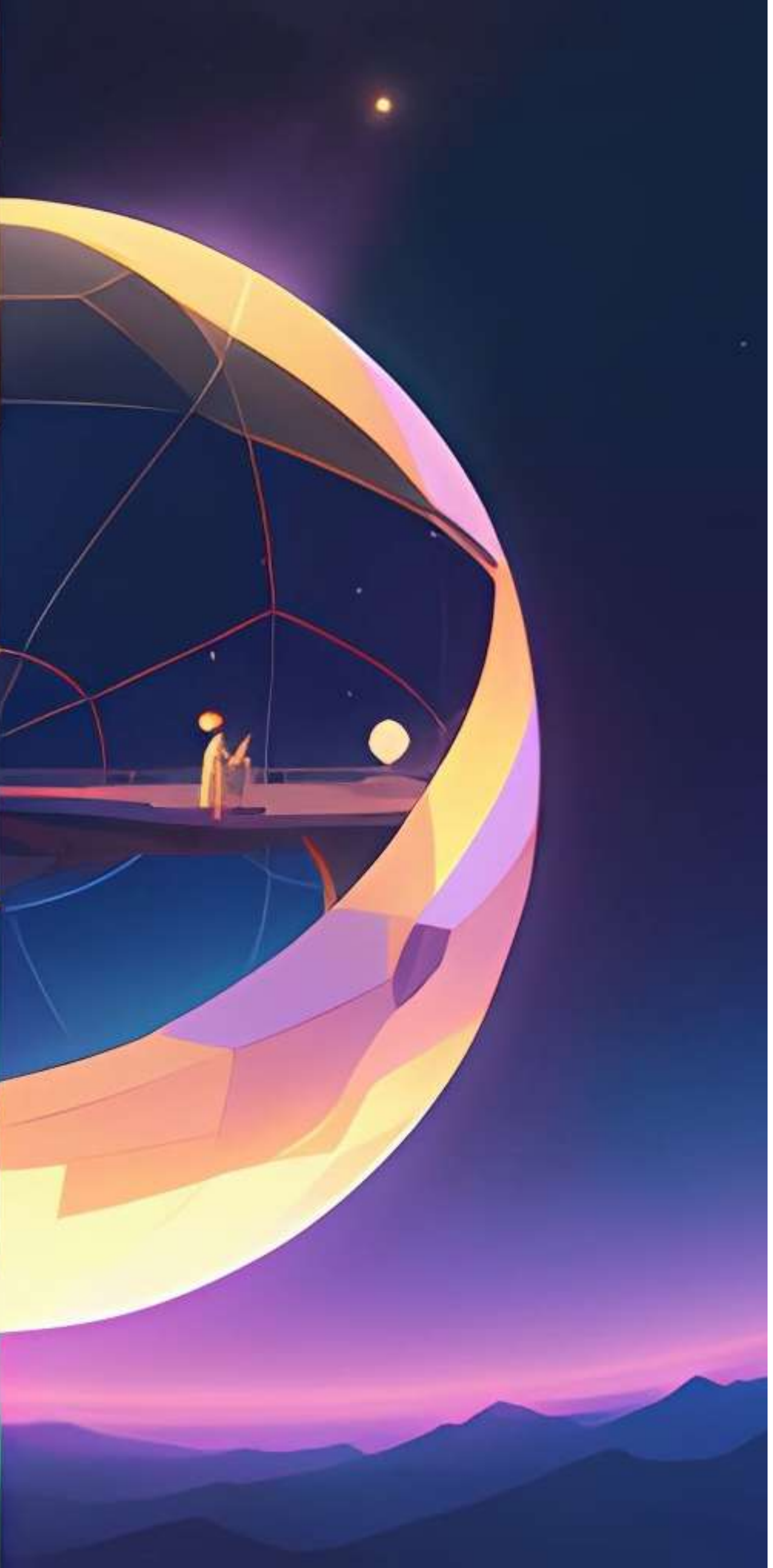




Summary

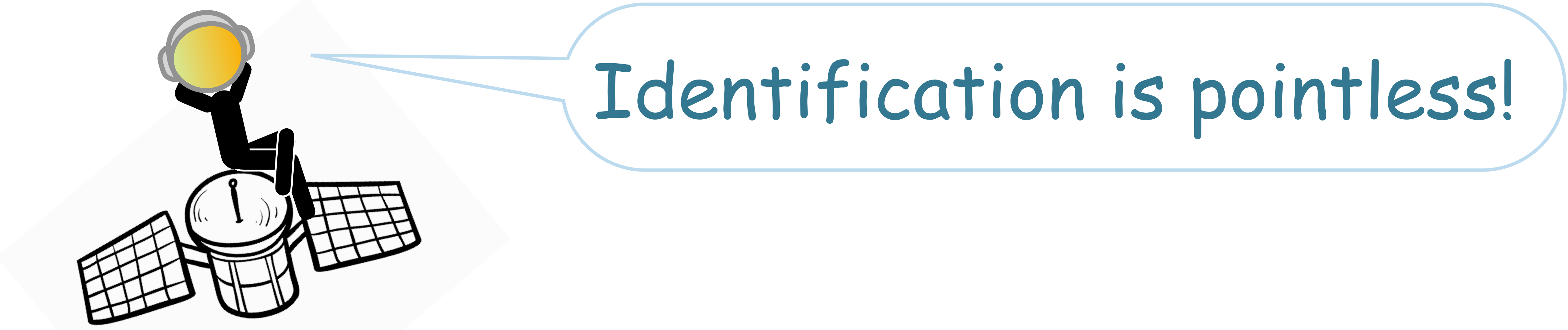
Symmetries, counterparts, and identification

- Framework of QRFs as **choices of sections** in space of models
- Application to **superpositions of semiclassical spacetimes**
- Construction of **quantum coordinate fields** and **comparison map** that identifies points across manifolds via **coincidences of physical field values**

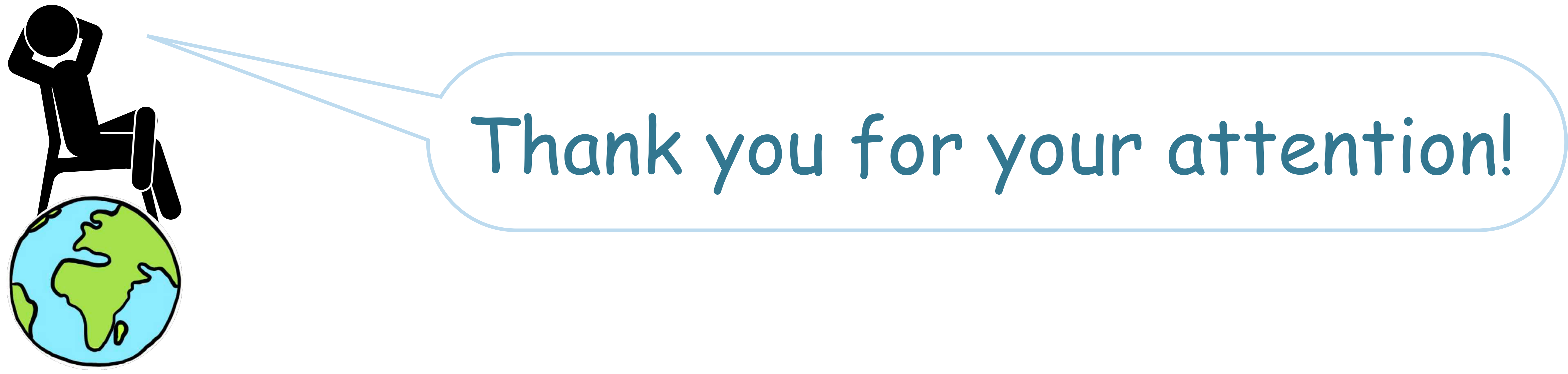


Take home messages

- The **localisation** of **events** is **frame-dependent** and has no absolute physical meaning.



- Observable are either **definite** or in a **superposition** depending on the choice of the reference frame



For more details, see arXiv:2402.10267.