Title: Einstein's Equivalence principle for superpositions of gravitational fields

Speakers: Flaminia Giacomini

Series: Quantum Gravity

Date: February 04, 2021 - 2:30 PM

URL: http://pirsa.org/21020014

Abstract: The Principle of Equivalence, stating that all laws of physics take their special-relativistic form in any local inertial frame, lies at the core of General Relativity. Because of its fundamental status, this principle could be a very powerful guide in formulating physical laws at regimes where both gravitational and quantum effects are relevant. However, its formulation implicitly presupposes that reference frames are abstracted from classical systems (rods and clocks) and that the spacetime background is well defined. Here, we we generalise the Einstein Equivalence Principle to quantum reference frames (QRFs) and to superpositions of spacetimes. We build a unitary transformation to the QRF of a quantum system in curved spacetime, and in a superposition thereof. In both cases, a QRF can be found such that the metric looks locally flat. Hence, one cannot distinguish, with a local measurement, if the spacetime is flat or curved, or in a superposition of such spacetimes. This transformation identifies a Quantum Local Inertial Frame. These results extend the Principle of Equivalence to QRFs in a superposition of gravitational fields. Verifying this principle may pave a fruitful path to establishing solid conceptual grounds for a future theory of quantum gravity.

PERIMETER INSTITUTE

Einstein’s Equivalence Principle for superpositions of gravitational fields

Flaminia Giacomini

Perimeter Institute for Theoretical Physics

F. Giacomini, Č. Brukner, arXiv:2012.13754 (2020)

Quantum Gravity Seminar PI, 4 February 2021

Einstein Equivalence Principle

Fundamental principle of the theory

Experimental tool

Metric structure of GR → ? → *Alternative theories*

*Gravitating quantum systems?**

Lack of classical spacetime

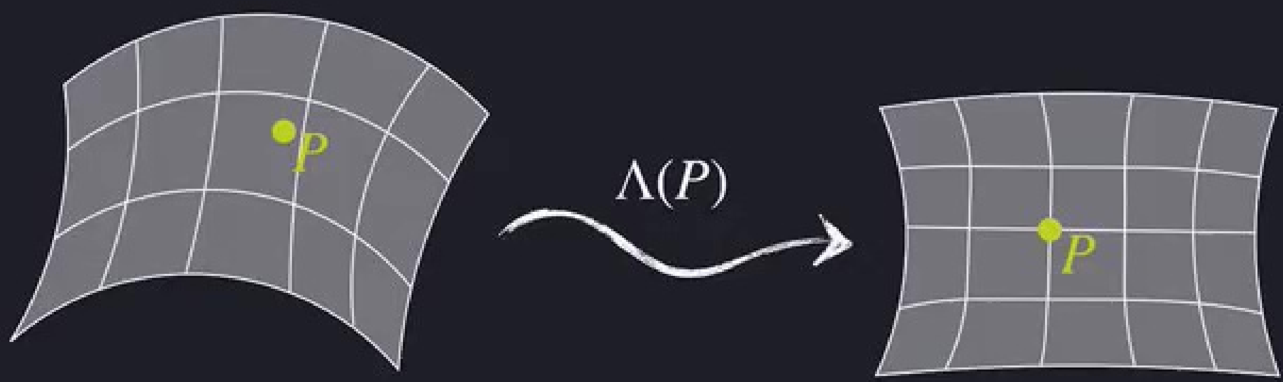
Validity
Elements to retain

Does the EEP hold?

Violations
Elements to modify

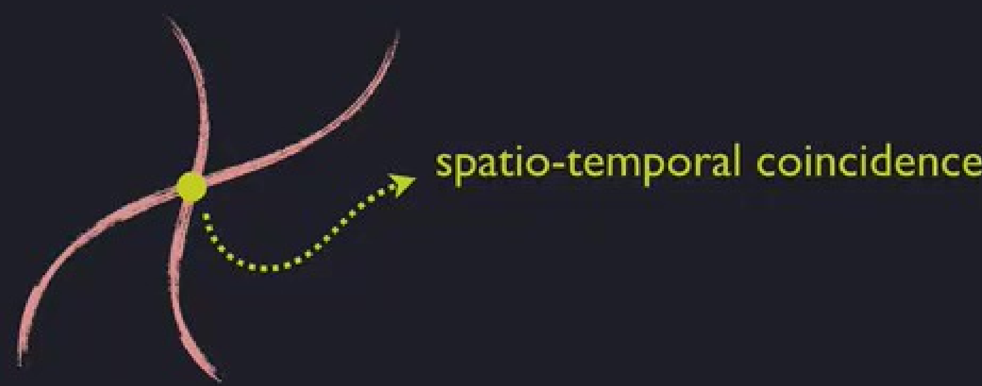
*Ongoing discussion: Bose et al. PRL (2017), Marletto,Vedral, PRL (2017), many others!

Einstein Equivalence Principle



Principle of Relativity

(implies General Covariance)

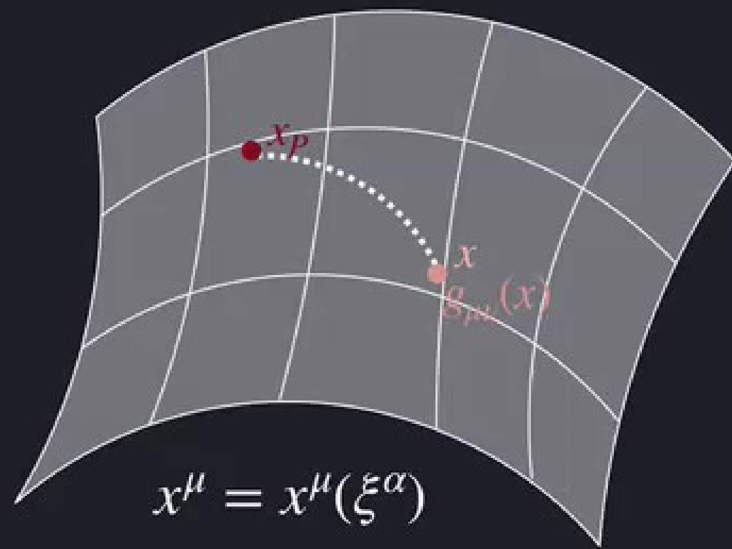


Locally Inertial Frames

$$x^\mu = x^\mu_P + \left.\frac{\partial x^\mu}{\partial \xi^\alpha}\right|_{x_P} \xi^\alpha + \cdots$$ **Linear term**

$$f^\mu_\alpha = \left.\frac{\partial x^\mu}{\partial \xi^\alpha}\right|_{x_P}$$ **16 free parameters**

$$\tilde{g}_{\alpha\beta}(\xi) = \frac{\partial x^\mu}{\partial \xi^\alpha}\frac{\partial x^\nu}{\partial \xi^\beta} g_{\mu\nu}(x_P + f\xi)$$



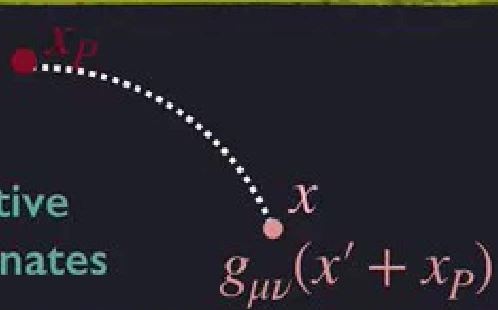
$$\tilde{g}_{\alpha\beta}(0) = f^\mu_\alpha f^\nu_\beta g_{\mu\nu}(x_P)$$ **10 quantities to fix**

$$\tilde{g}_{\alpha\beta}(\xi) = \eta_{\alpha\beta} + O(\xi^2)$$

Locally Minkowski!

Step 1

Relative coordinates



Step 2

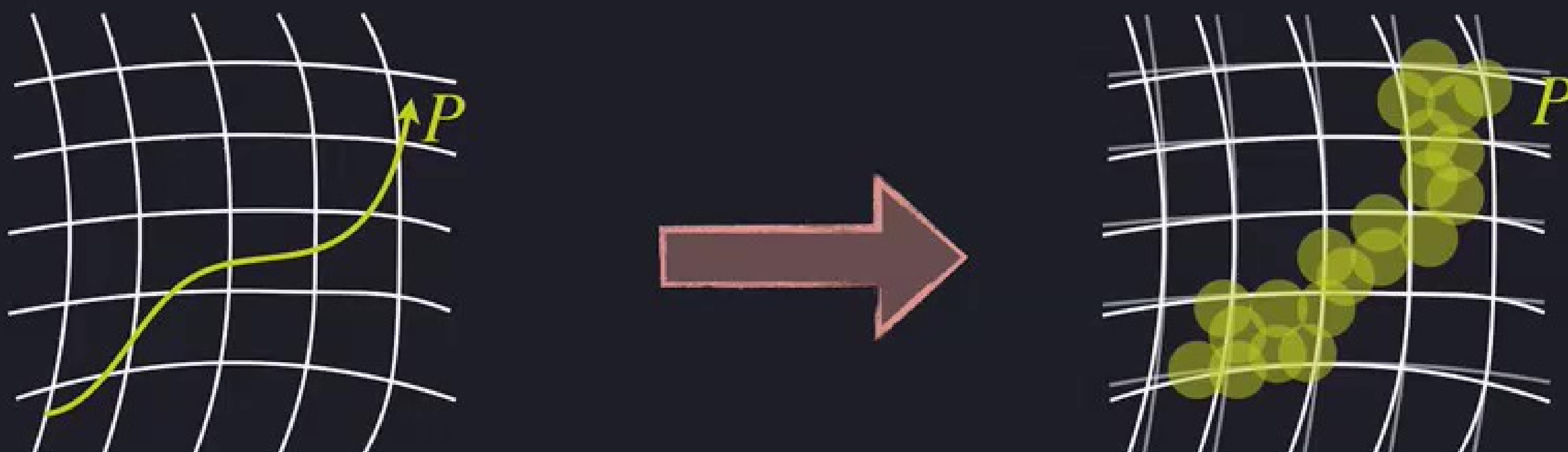
"Straighten" the metric at one point

What are reference frames?

Operational view of reference frames

Rods and clocks

Quantum systems: superposition, entanglement



Classical system on classical spacetime

Quantum system on superposition of spacetimes

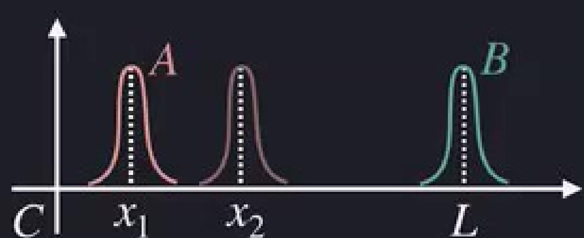
What are reference frames?

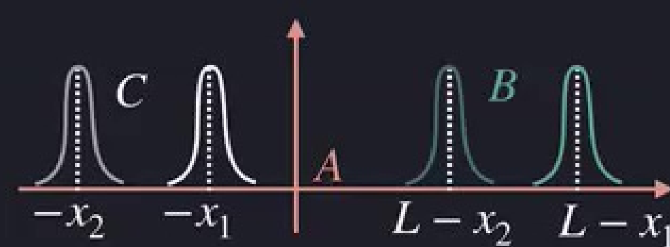
Operational view of reference frames

Rods and clocks

Quantum systems: superposition, entanglement

Quantum Reference Frames





Giacomini, Castro Ruiz, Brukner, Nat. Commun. (2019)

classical spacetime

superposition of spacetimes

Adapted from Misner, Thorne, Wheeler "Gravitation"

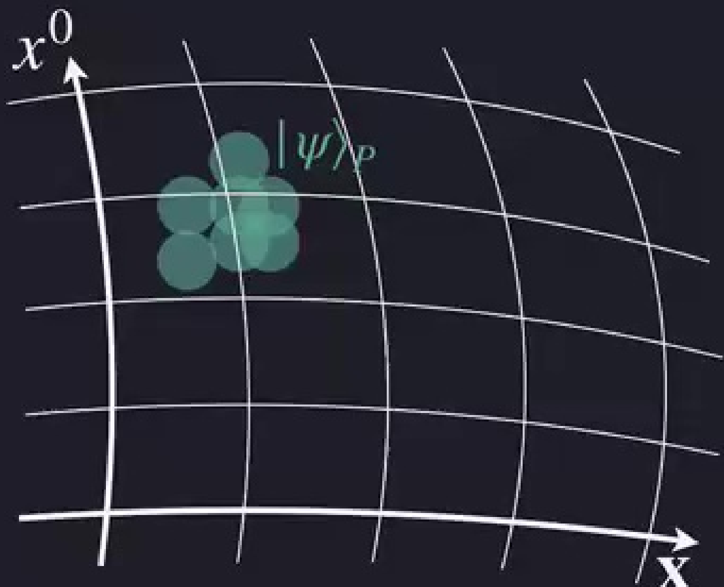
In any and every ***Quantum*** *Locally Inertial Frame (QLIF), anywhere and anytime in the universe, all the (nongravitational) laws of physics must take on their familiar non-relativistic form.*

Gravitational field G

Test particle M "surveying" the gravitational field

Particle P serving as a Quantum Reference Frame

Generalisation of the EEP



Quantum system in a superposition in spacetime

$$|\psi\rangle_P = \int d^4x \sqrt{-g(x)}\, \psi(x)\, |x\rangle_P$$

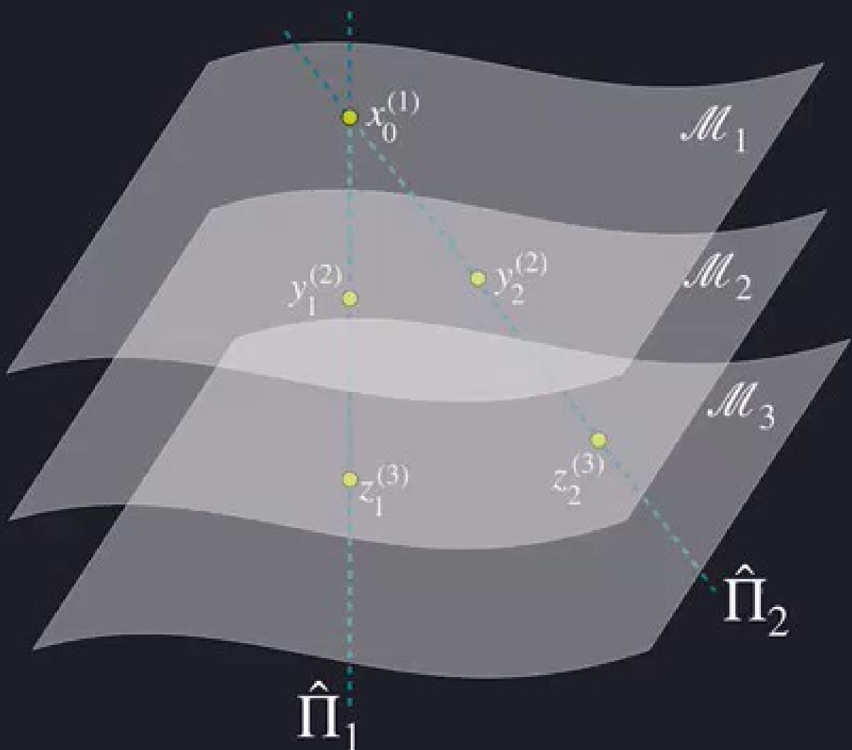
Quantum superposition of classical spacetimes

$|g^1\rangle \quad |g^2\rangle \quad |g^3\rangle$

Macroscopically distinguishable

Superposition principle holds

Identification across spacetimes



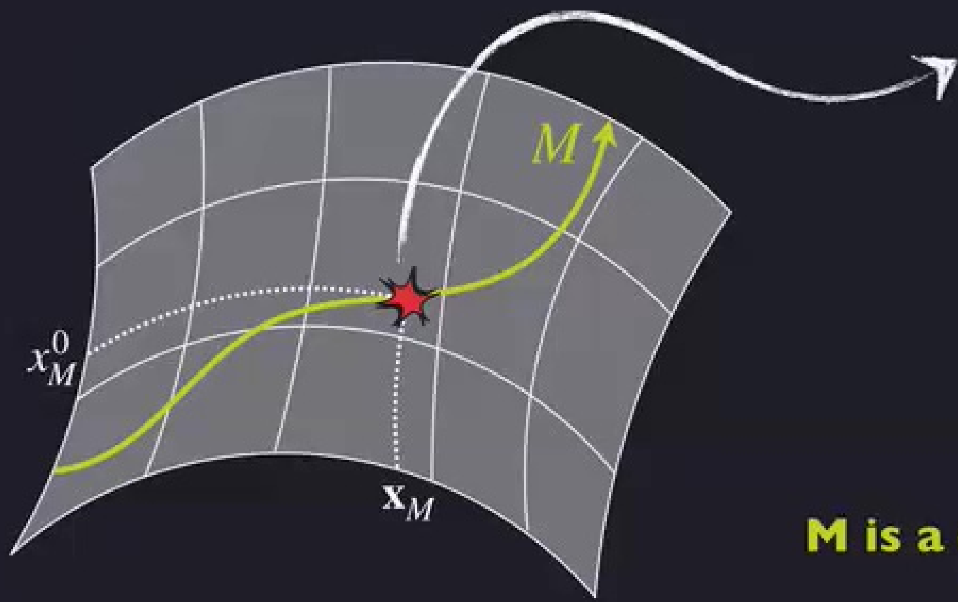
$$|\phi \triangleright g\rangle = \sum_i |\phi_i \triangleright g_i\rangle$$

$$\hat{\Pi}_1 |\phi \triangleright \phi\rangle \longrightarrow \{x_0^{(1)}, y_1^{(2)}, z_1^{(3)}\}$$

$$\hat{\Pi}_2 |\phi \triangleright \phi\rangle \longrightarrow \{x_0^{(1)}, y_2^{(2)}, z_2^{(3)}\}$$

Different identifications correspond to different measurement choices.

Physical coincidences



$g_{\mu\nu}(x_M)$

Coordinates of M

$x_M = (x_M^0, \mathbf{x}_M)$

We need a physical system to have information about the metric

M is a quantum system in spacetime: $|\phi\rangle_M$

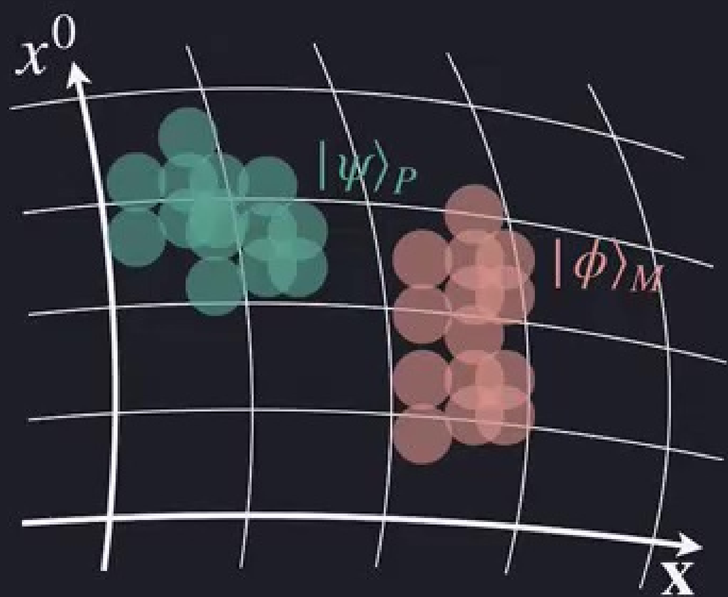
$$|\phi \triangleright g\rangle = \int d^4x_M \sqrt{-g(x_M)}\, \phi(x_M)\, |g(x_M)\rangle\, |x_M\rangle$$

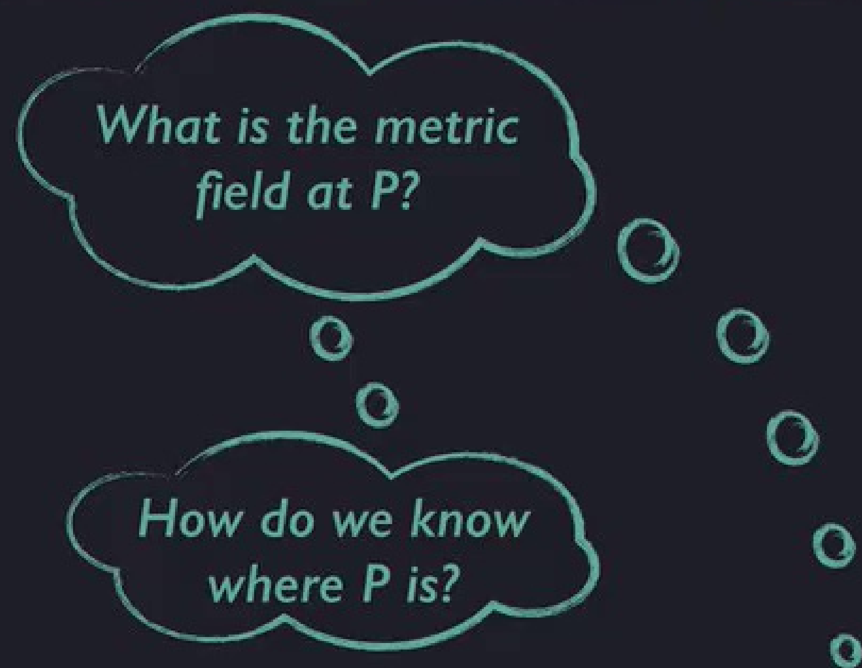
The metric field "correlates" with the coordinates of M

Fine

Von Neumann-like measurement

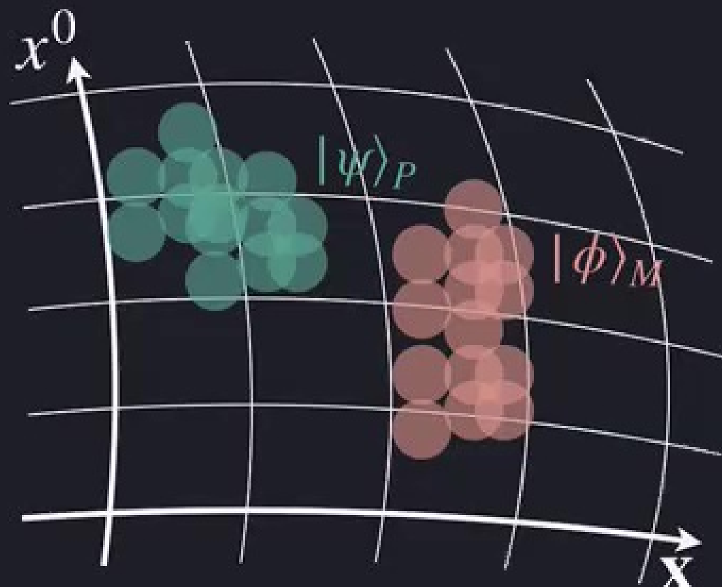
M probes the metric field anywhere it has support





Quantum Reference Frames

Von Neumann-like measurement



What is the metric field at P?

$$|\psi\,;\,\phi \triangleright g\rangle = \sum_i |\psi_i\rangle_P\,|\phi_i \triangleright g_i\rangle$$

$$e^{\frac{i}{\hbar}\hat{x}_P\hat{p}_M}|x'\rangle_P\,|x\rangle_M = |x'\rangle_P\,|x - x'\rangle_M$$

$${}_M\langle 0|\,e^{\frac{i}{\hbar}\hat{x}_P\hat{p}_M}\,|\psi\,;\,\phi \triangleright g\rangle$$

$$\sum_i \int d^4x_i\sqrt{-g^i(x_i)}\;\psi_i(x_i)\;\phi_i(x_i)\,|\,g_i(x_i)\rangle\,|x_i\rangle_P$$

EEP for Quantum Reference Frames

QRF as particle P

What is a quantum state in spacetime?

Covariant representation

How to identify points across different spacetimes?

Projection operation and notion of "physical point"

Test particle M correlated with G

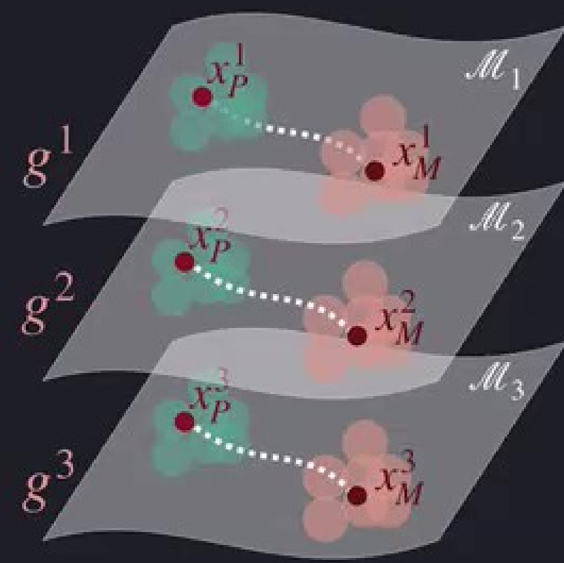
How to write the state of a non-classical gravitational field?

Superpositions of classical spacetimes

What is the metric at P?

EEP for Quantum Reference Frames

Generalise Locally Inertial Frames transformations



Principle of linear superposition applied twice

1. *Within the same spacetime (positions)*
2. *Across different spacetimes (metrics)*

$$\left(f^{(i)}\right)^{\mu}_{\ \alpha} = \frac{\partial x^{\mu}}{\partial \xi^{\alpha}}\bigg|^{(i)}_{x_P}$$

16 free parameters

$$\tilde{g}^{i}_{\alpha\beta}(\xi) = \left(\frac{\partial x^{\mu}}{\partial \xi^{\alpha}}\right)^{(i)} \left(\frac{\partial x^{\nu}}{\partial \xi^{\beta}}\right)^{(i)} g^{i}_{\mu\nu}(x^{i}_{P} + f^{i}\xi^{i})$$

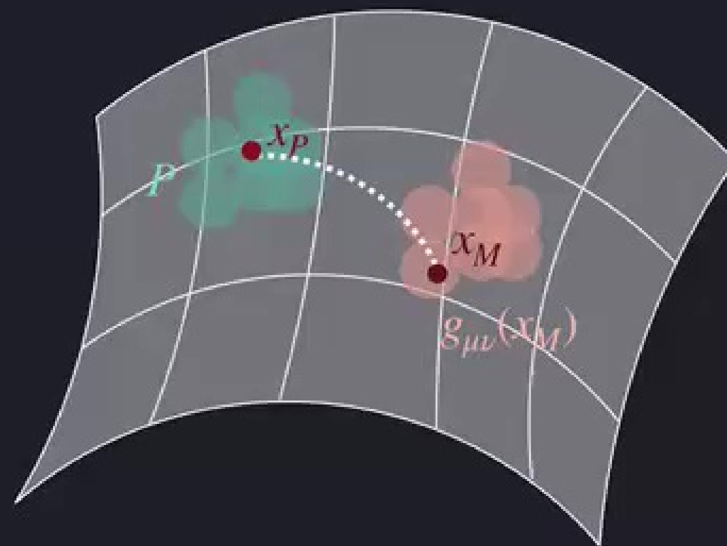
$$\tilde{g}^{i}_{\alpha\beta}(0) = \left(f^{(i)}\right)^{\mu}_{\ \alpha} \left(f^{(i)}\right)^{\nu}_{\ \beta} g^{i}_{\mu\nu}(x^{i}_{P})$$

10 quantities

At each point x_P
In each spacetime g^i

Transformation to a QLIF

Classical and curved spacetime



Different transformation at each point x_P

1. Centre origin in x_P
2. Straighten coordinates around x_P

$$|\psi;\phi \triangleright g\rangle = \int d^4x_P\sqrt{-g(x_M)}\psi(x_P)\,|\,x_P\rangle_P \int d^4x_M\sqrt{-g(x_M)}\,\phi(x_M)\,|\,g(x_M)\rangle\,|\,x_M\rangle$$

Unitary! $\hat{S}^i$

$$\xi = f(x_P)(x_M - x_P) + \cdots$$

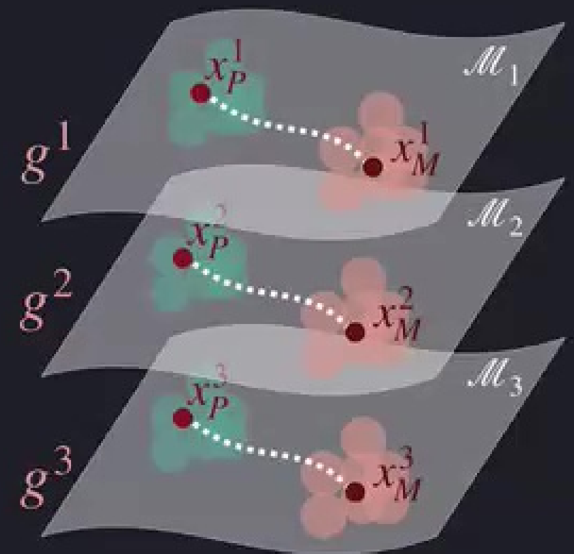
Quantum-controlled (P) transformation on M.

Transformation to a QLIF

Superposition of classical spacetimes

Different transformation at each point x_P and for each g^i

1. Centre origin in x^i_P for each g^i
2. Straighten coordinates around x^i_P for each g^i



$$|\psi;\phi \triangleright g\rangle = \sum_{i=1}^{N} \int d^4x_P^i \sqrt{-g^i(x_M^i)}\,\psi_i(x_P^i)\,|x_P^i\rangle_P \int d^4x_M^i \sqrt{-g^i(x_M^i)}\,\phi_i(x_M^i)\,|g^i(x_M^i)\rangle\,|x_M^i\rangle$$

Unitary! $\hat{S}$

$$\xi^i = f^i(x_P^i, i)(x_M^i - x_P^i) + \cdots$$

Quantum-controlled (P, G) transformation on M.

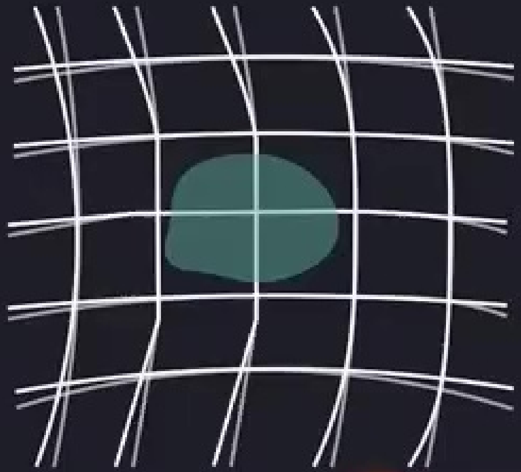
Metric in the QLIF

State in the Quantum Locally Inertial Frame (QLIF)

$$\hat{S}\,|\,\psi;\phi \triangleright g\rangle$$

Probe the metric at origin of QLIF

$${}_M\langle 0\,|\,e^{\frac{i}{\hbar}\hat{x}_P\hat{p}_M}\hat{S}\,|\,\psi;\phi \triangleright g\rangle$$



$$\tilde{g}^{i}_{\alpha\beta}(\xi) = \eta_{\alpha\beta} + O(\xi^2)$$

Locally Minkowski for all i's!

Fine

Conclusions

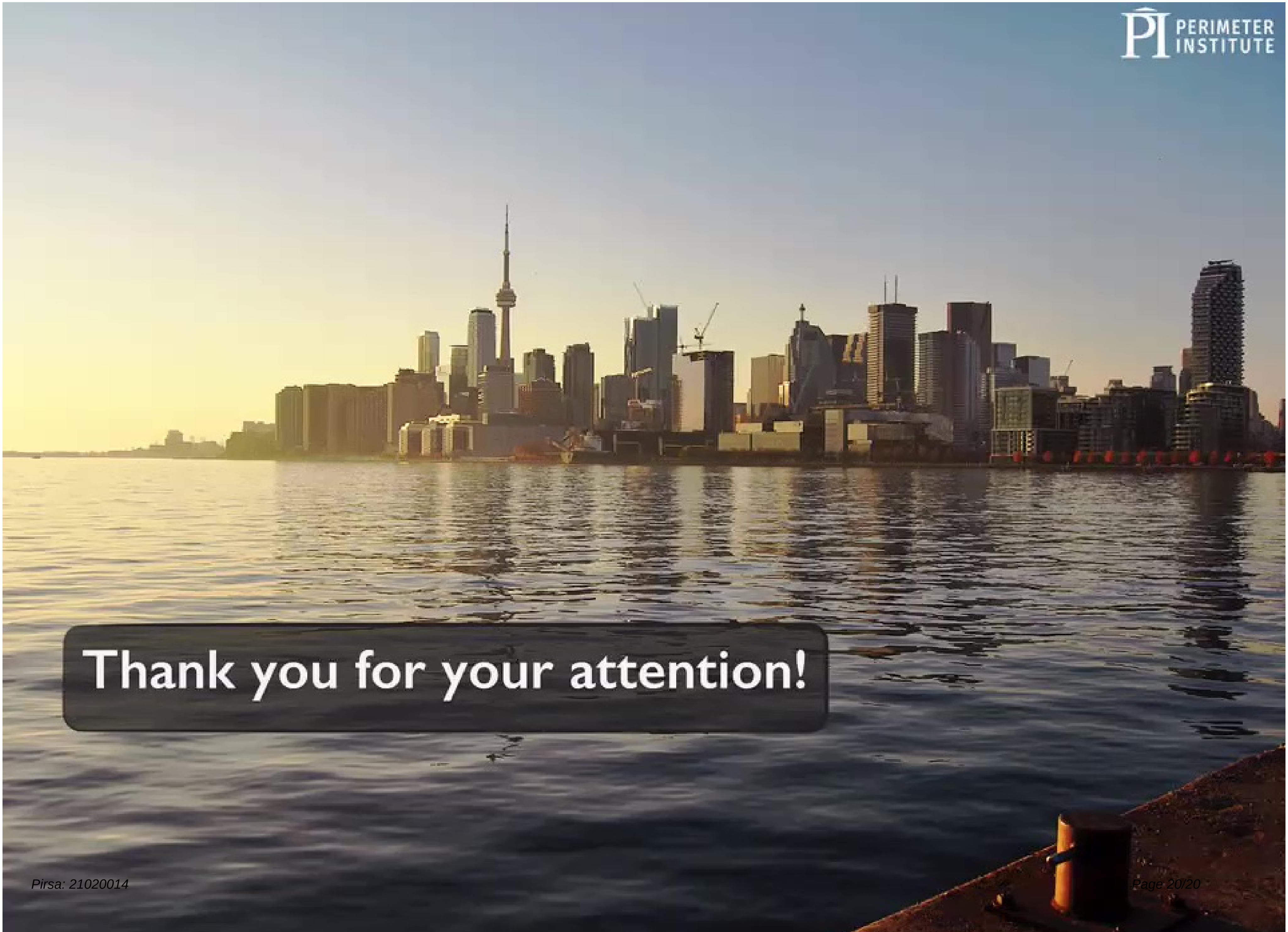
Generalisation of Quantum Reference Frames to curved spacetimes and superposition of spacetimes.

Introduction of "Quantum Locally Inertial Frames"

For every quantum state of a system P living in a superposition of classical spacetimes, one can find a Quantum Locally Inertial Frame transformation to the Quantum Reference Frame of P such that the metric is locally Minkowski at the origin of the Quantum Reference Frame.

Not covered: Freely-falling quantum systems

Fine


PERIMETER INSTITUTE
Thank you for your attention!