Time delay observable in classical and quantum geometries

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100 years after Einstein, Prague

Motivation

If I had a theory of Quantum Gravity, what would I do with it?

- Answer should be independent of QG model.
- My answer: Compute qualitative and quantitative QG corrections to experiments and observations.
- Unfortunately, what is easiest to compute in QG is model dependent may not have a direct experimental interpretation.
- Idea: Work backwards! Start with a potential experiment (even if only in principle possible), described operationally. Construct a mathematical model of it and obtain an observable quantity with an unambiguous interpretation.

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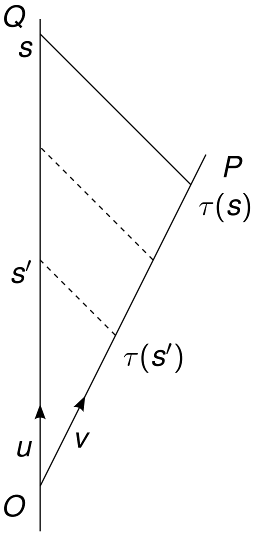
Time Delay Observable

operational definition



- Consider two inertially moving, localized systems: the lab and the probe. Probe is launched from the lab at event O.
- Each carries a proper-time clock. The clocks are synchronized at O.
- The probe broadcasts signals time stamped with the emission time, τ at P.
- The lab records the reception time, s at Q, together with the time stamp $\tau(s)$.
- The time delay

$$\delta\tau(s) = s - \tau(s)$$

  is the observable we seek.
- Diff-invariance by construction.

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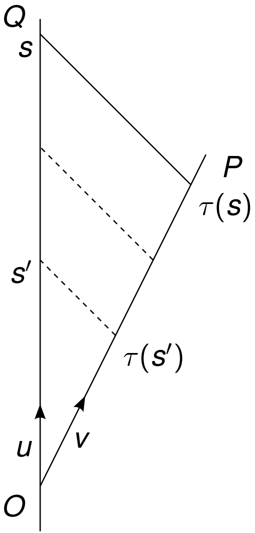

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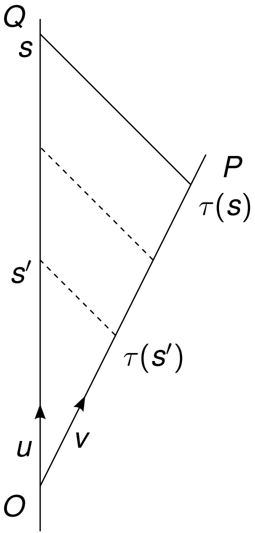

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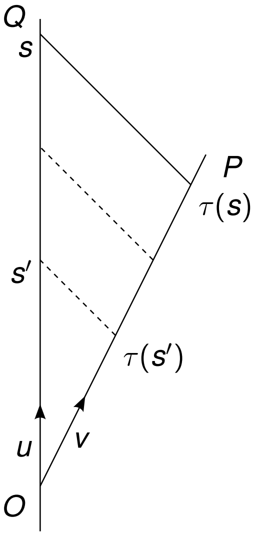

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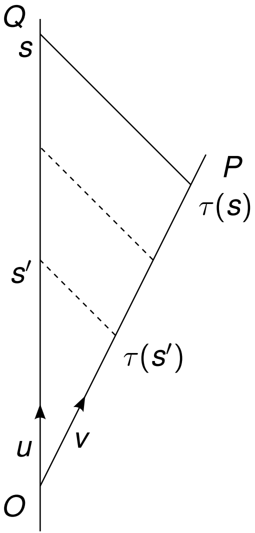

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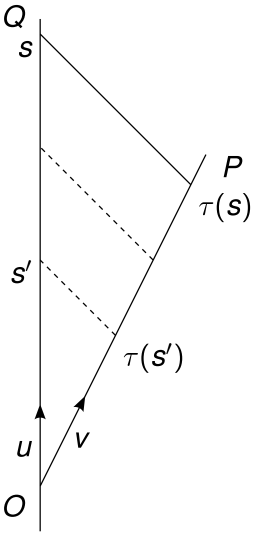

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Time Delay in Quantum Linearized Gravity

- Linearization about Minkowski space: $g_{\mu\nu} \to \eta_{\mu\nu} + h_{\mu\nu}$.
- Quantization as linearized field theory: $h_{\mu\nu} \to \hat{h}_{\mu\nu}$.
- Explicit expression for $\tau(s)$ at order $O(h)$ is available:

$$\begin{aligned} \tau(s) &= \tau[\eta](s) + \tau_1[h](s) + \cdots \\ &= se^{-\theta}(1 + r[h] + \cdots) \\ r[h] &= r^x h_x = H + J \end{aligned}$$

  - θ—rapidity, $v_{\rm rel} = \tanh(\theta)$
  - r^x—integro-differential operator
  - H, J—separately invariant under linearized diffeomorphisms that fix O and e^α
- Note: H, J, … may have been found by brute force, but it would not have been obvious how these invariants would combine into an observable with direct phenomenological interpretation

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Explicit Calculation

basic idea

- Vacuum $|0\rangle$ is Gaussian wrt $\hat{\tau}$, with mean $\tau_{\rm cl}$. Remains to compute variance: $\langle(\Delta\hat{\tau})^2\rangle = \langle\hat{\tau}^2\rangle - \langle\tau\rangle^2 = \tau_{\rm cl}\langle\hat{r}^2\rangle$, with $\hat{r} = r[\hat{h}] = r^x\hat{h}_x$.
- Variance needs the Hadamard 2-point function $G(x,y)$.

$$\langle 0|\hat{r}^2|0\rangle = \frac{1}{2}\langle\{\hat{r},\hat{r}\}\rangle = \frac{1}{2}r^x r^y\langle\{\hat{h}_x,\hat{h}_y\}\rangle = \frac{1}{2}r^x r^y G(x,y)$$

- Integrals in r^x are not sufficient to tame the $x-y\to 0$ divergence of $G(x,y)\sim\ell_p^2/(x-y)^2$. Need to use smeared fields $\tilde{h}$:

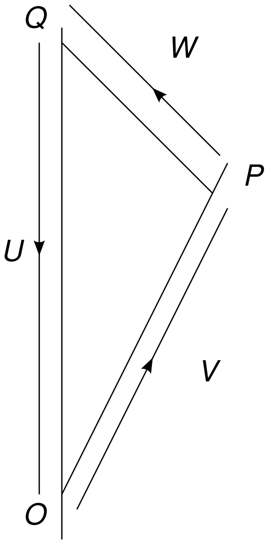
$$\tilde{r} = r^x\tilde{h}_x = r^x\langle\langle\hat{h}_{x-z}\rangle\rangle,$$

$$\langle\langle f(z)\rangle\rangle = \int \mathrm{d}z\, f(z)\tilde{g}(z),$$

where $\tilde{g}(z)$ is a smearing function, localized at $z=0$, of spread $\mu \ll s$: $\langle\langle z^n\rangle\rangle \sim \mu^n$.

Time Delay in Quantum Linearized Gravity

explicit expressions



$$r^x h_x = H + J$$

- Explicit expression:

$$H \sim \sum_{X=V,U,W} (\longrightarrow)_X,$$

$$(\longrightarrow)_X \sim \int_X^{(1)} \nabla h.$$

- H is invariant under linearized diffeomorphisms that fix O and e^α.

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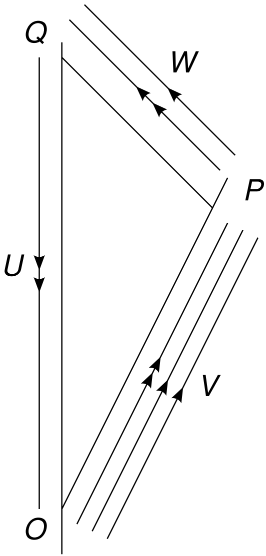

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$$J \sim \sum_{X=V,U,W} \left[(\longrightarrow\!\!\!\!\rightarrow\!\!\!\!\rightarrow)_X + \sum_{Y<X} (\longrightarrow)_Y \right],$$

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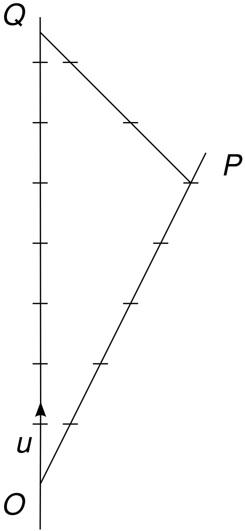
Smearing and Detector Resolution



- In QED, $\langle E(x)^2 \rangle$ diverges, but $\langle \tilde{E}(x)^2 \rangle$ is finite and represents the vacuum noise in a detector of sensitivity profile $\tilde{g}(x)$.
- Physically speaking, μ, the spread of $\tilde{g}(x)$, is the spatial resolution of the detector.
- We can back-of-envelope estimate μ as the wavelength of the light/radio signals exchanged between lab and probe.
- A more detailed detector model should unambiguously fix $\tilde{g}(x)$ for each leg of $\triangle OPQ$.
- Provisionally, set $\tilde{g}(x) \sim \delta(u \cdot x) g(x_\perp^2)$ everywhere.

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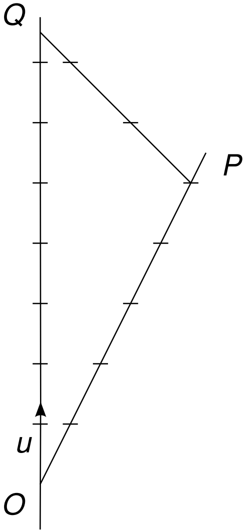

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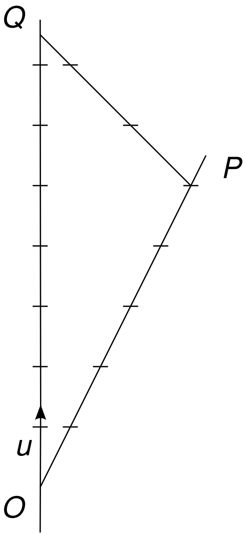

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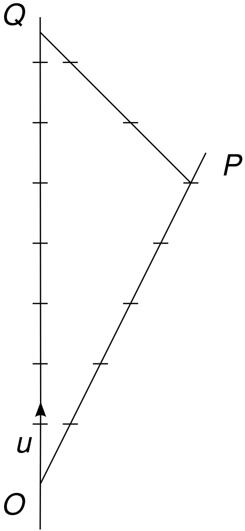

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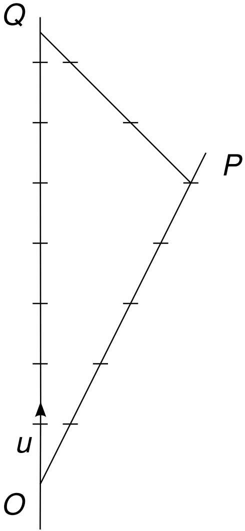

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Explicit Calculation

dimensional analysis

- Dimensional analysis: $[\mu] = [\ell_p] = [z] = 1$, $[\nabla] = -1$, $G \sim \ell_p^2/z^2$.

$$\langle \tilde{r}^2 \rangle \sim s^2 \langle\!\langle \int_X \int_Y \nabla^2 G(z) \rangle\!\rangle \sim s^2 \langle\!\langle \int_X \int_Y \frac{\ell_p^2}{z^4} \rangle\!\rangle$$
$$\sim s^2 \langle\!\langle \frac{\ell_p^2}{s^2 z^2} \rangle\!\rangle \sim \frac{\ell_p^2}{\mu^2}$$

- Detailed calculations reveal terms like $\frac{\ell_p^2}{\mu^2} \ln(s/\mu)$ and even $\frac{s\ell_p^2}{\mu^3}$.
- Expected rms fluctuation in $\hat{\tau}(s) \sim s\sqrt{\langle \tilde{r}^2 \rangle} \sim s\frac{\ell_p}{\mu}$ or $s\frac{s^{1/2}}{\mu^{1/2}}\frac{\ell_p}{\mu}$.

  $\mu \sim 1$nm (X-rays)

laboratory: $s \sim 1\text{m} \sim 10^{-9}\text{s}$, $\frac{\ell_p}{\mu} \sim 10^{-26}$, $\frac{s^{1/2}}{\mu^{1/2}} \sim 10^5$: 10^{-35}s or 10^{-30}s

cosmology: $s \sim 1\text{Mpc} \sim 10^{14}\text{s}$, $\frac{\ell_p}{\mu} \sim 10^{-26}$, $\frac{s^{1/2}}{\mu^{1/2}} \sim 10^{15}$: 10^{-12}s or 10^3s

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Summary & Outlook

- Observables in Quantum Gravity can be constructed by carefully modeling (thought) experiments.
- Unfortunately, perturbative calculations allow only limited conclusions about the quantum causal structure. (see paper)
- Previous work on light cone fluctuations: [Ford *et al* (1995–2006)], issues of gauge invariance and regularization; [Roura & Arteaga (unpublished)].
- This work: explicit gauge invariance, flexible experiment geometry, regularization from detector resolution.
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Thank you for your attention!