Title: The fate of the big bang

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Abstract:

# The fate of the Big Bang

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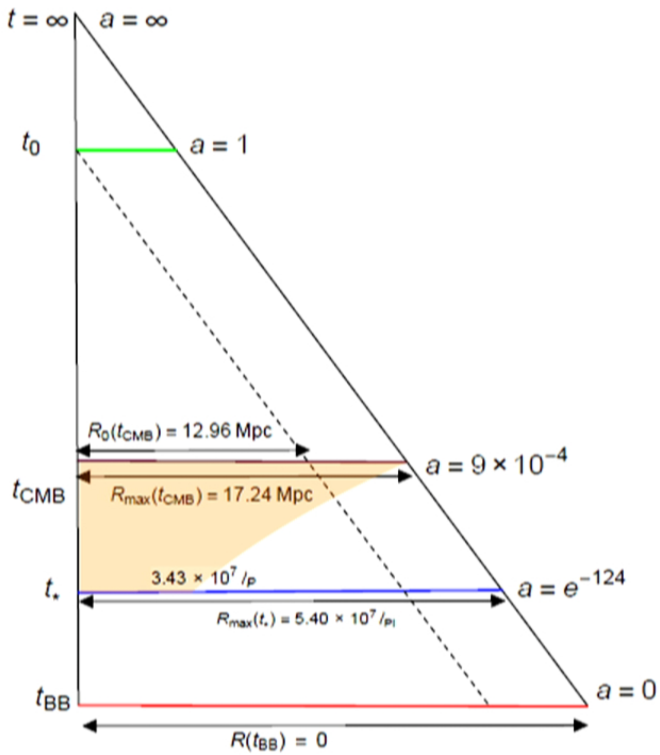
The concrete results used for illustrating the underlying ideas
and status come from many researchers, especially
Agullo, Barrau, Bojowald, Bonga, Corichi, Gupt, Kaminski,
Lewandowski, Mena, Nelson, Olmedo, Pawlowski, Singh, Sloan, ...

**Time in Cosmology; PI, June 27-30, 2016**

# Universe according to Planck




- Using PLANCK data, one can determine space-time to the future of the CMB epoch. Major change: Because of 'dark energy', there are cosmological horizons.

- Striking feature: the early universe is extraordinarily simple. Distinction between what theory allows and what is realized in nature is central for our discussion. For concreteness, consider Starobinsky inflation: Even when the curvature is some $10^{65}$ times that at the horizon of a solar mass black hole, (quantum) cosmological perturbations on FLRW space-time suffice!

- But we cannot use GR to go further back once we reach the Planck regime. So what happens to the big-bang –a prediction of GR, but beyond its domain of applicability– in a quantum gravity theory?

# Some key questions to QG Theories

- Is an extra input –such as a new boundary condition or introduction of matter fields violating energy conditions– necessary to resolve the big bang singularity? If not, what is the QG input that causes the qualitative change?

- What do you mean by singularity resolution? $\Psi(a, \phi)|_{a=0} = 0$ is unlikely to be sufficient. WKB type approximations likely to be inadequate in the Planck regime.

- What is the nature of the Planck regime? What does 'time evolution' mean? Do we only have quantum states $\Psi$ and operators or is there also an effective space-time metric dressed by quantum corrections?

- Do quantum corrections that tame the singularity accumulate over cosmological time scales causing undesirable departures from GR predictions?

- Is there an extension of the QFT in curved space-times to handle quantum cosmological perturbations in the Planck regime?

- Are there observable implications of the new Planck scale dynamics?

- What happens to the arrow of time? Are there physically motivated initial conditions at the bounce (e.g., a quantum extension of Penrose's Weyl curvature hypothesis)? Could the universe continue to be extraordinarily simple also in the Planck regime? If so, all the general situations allowed in quantum gravity may be irrelevant to cosmology

# Illustration: Answers from LQC

**Several of these considerations extend to other bouncing scenarios.**

- Is an extra input –such as a new boundary condition or introduction of matter fields violating energy conditions– necessary to resolve the big bang singularity? If not, what is the QG input that causes the qualitative change?

No new boundary conditions. Standard matter satisfying energy conditions. Rather, quantum geometry creates a brand new repulsive force in the Planck regime, overwhelming classical attraction. The Big Bang is replaced by a Big Bounce.

The new feature is quantum Riemannian geometry of LQG. Fundamental microscopic parameter: the minimum non-zero eigenvalue of $\hat{A}$, the Area gap $\Delta_{\rm A}$. Analogy with the energy gap $\Delta_{\rm E}$ in superconductivity that determines macroscopic parameters such as the critical temperature $T_{\rm crit} = {\rm const}\Delta_{\rm E}$. In LQC, the macroscopic parameter $\rho_{\rm sup} = {\rm const}/\Delta^3$.

- What do you mean by singularity resolution? $\Psi(a,\phi)|_{a=0} = 0$ is unlikely to be sufficient. WKB type approximations likely to be inadequate in the Planck regime.

There is a natural, well-defined scalar product on physical states –the solutions to the quantum Hamiltonian constraint. A complete set of Dirac observables that diverges at the singularity in the classical theory has well-defined upper bounds on the entire physical Hilbert space. Singularity resolution analyzed in detail using the Hamiltonian, Path integral and consistent histories frameworks.

• What is the nature of the Planck regime? What does 'time evolution' mean? Do we only have quantum states $\Psi$ and operators or is there also an effective space-time metric dressed by quantum corrections?

States $\Psi(a, \phi)$ which are sharply peaked at late times, remain so also in the Planck regime. Time-evolution is with respect to a relational time variable, typically taken to be the scalar field. The peak obeys effective equations which incorporate quantum geometry corrections to GR. The effective trajectory (and the wave function) bounces when $\rho = (18\pi)/(G^2\hbar\Delta_{\rm A}^3) \approx 0.42\rho_{\rm Pl} \equiv \rho_{\rm sup}$. Mater density and curvature have an absolute upper bound on the full physical Hilbert space.

• Do quantum corrections that tame the singularity accumulate over cosmological time scales causing undesirable departures from GR predictions?

Quantum corrections become negligible once curvature falls below, say, $10^{-4}{\rm cuvv}_{\rm Pl}$. The repulsive force of quantum geometry origin is strong enough to overwhelm the classical attraction in the Planck regime but dies very quickly. Passes some interestingly stringent tests.

(The effective Friedmann equation is $H^2 = (8\pi G/3)\,(\rho - \rho/\rho_{\rm sup})$ and the effective Raychaudhuri equation is $\dot{H} = -4\pi G(\rho + p)(1 - 2\rho/\rho_{\rm sup})$.)

# Some key questions to QG Theories

- Is an extra input –such as a new boundary condition or introduction of matter fields violating energy conditions– necessary to resolve the big bang singularity? If not, what is the QG input that causes the qualitative change?

- What do you mean by singularity resolution? $\Psi(a, \phi)|_{a=0} = 0$ is unlikely to be sufficient. WKB type approximations likely to be inadequate in the Planck regime.

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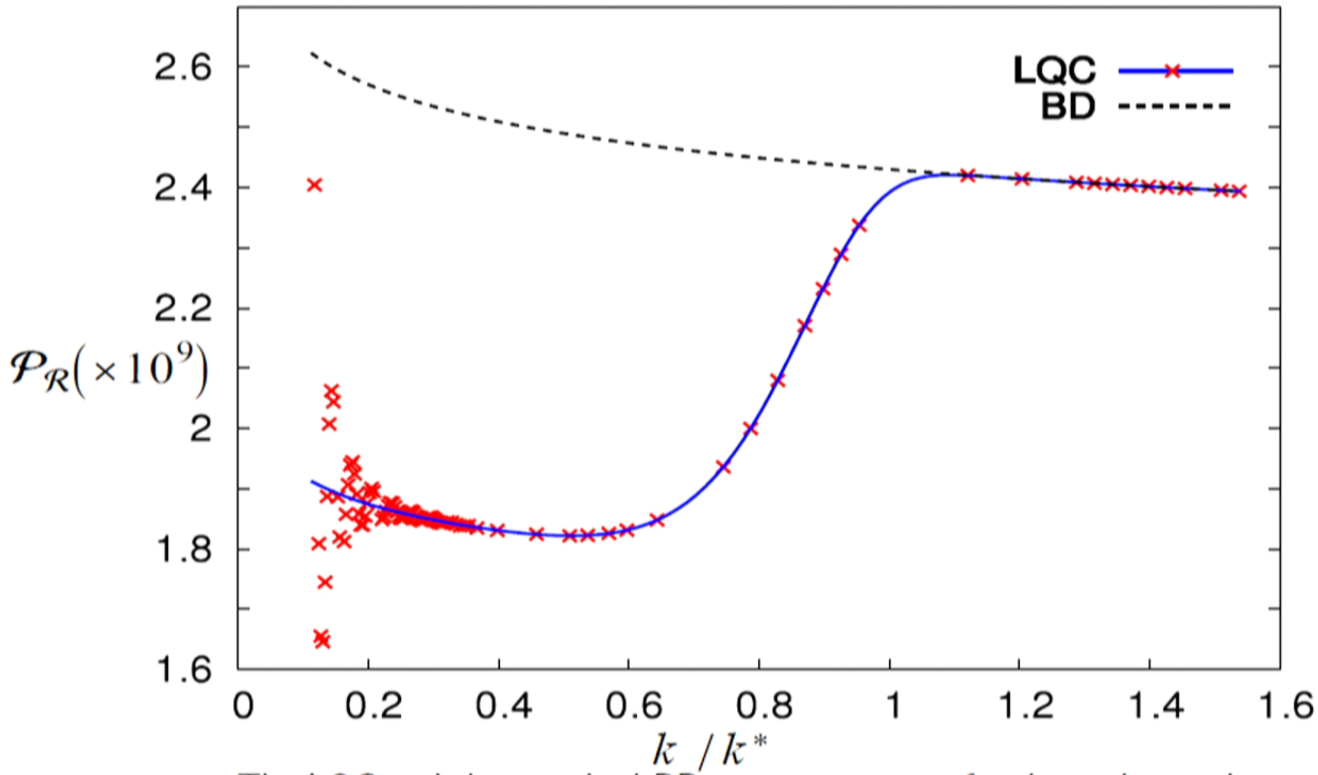
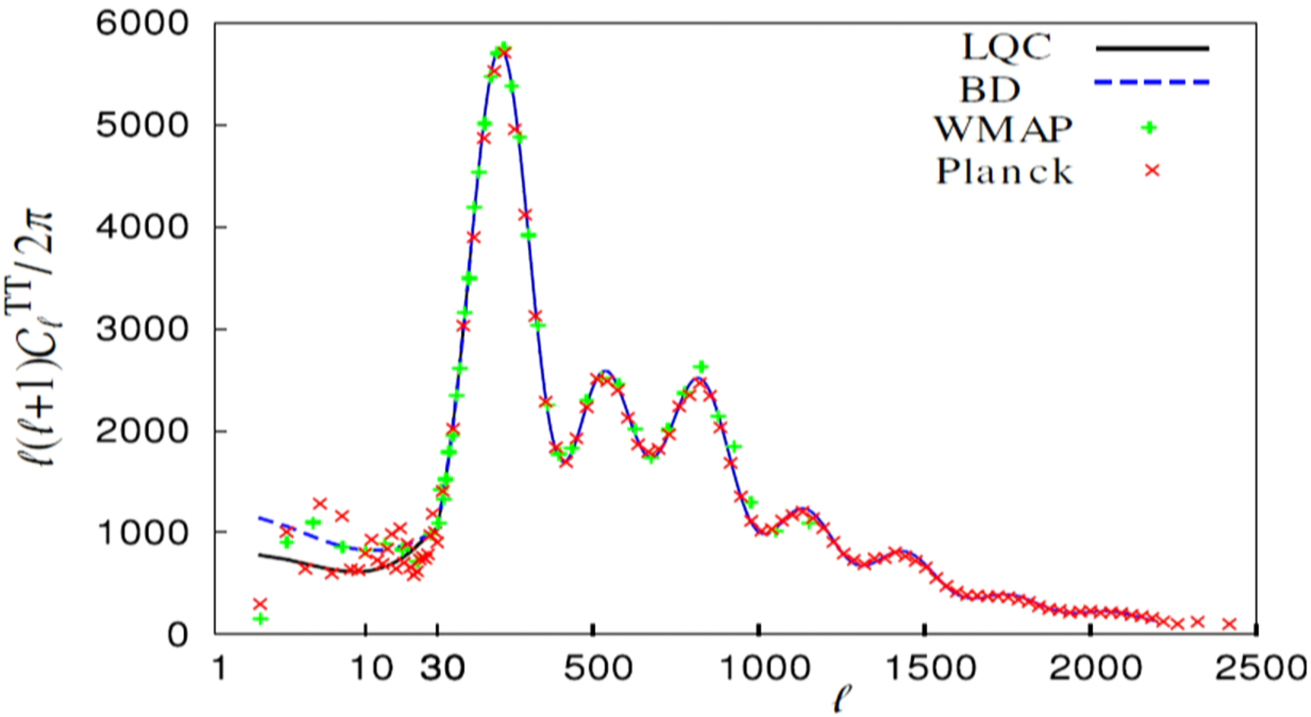
# The Scalar Power spectrum

"A Top-down approach"



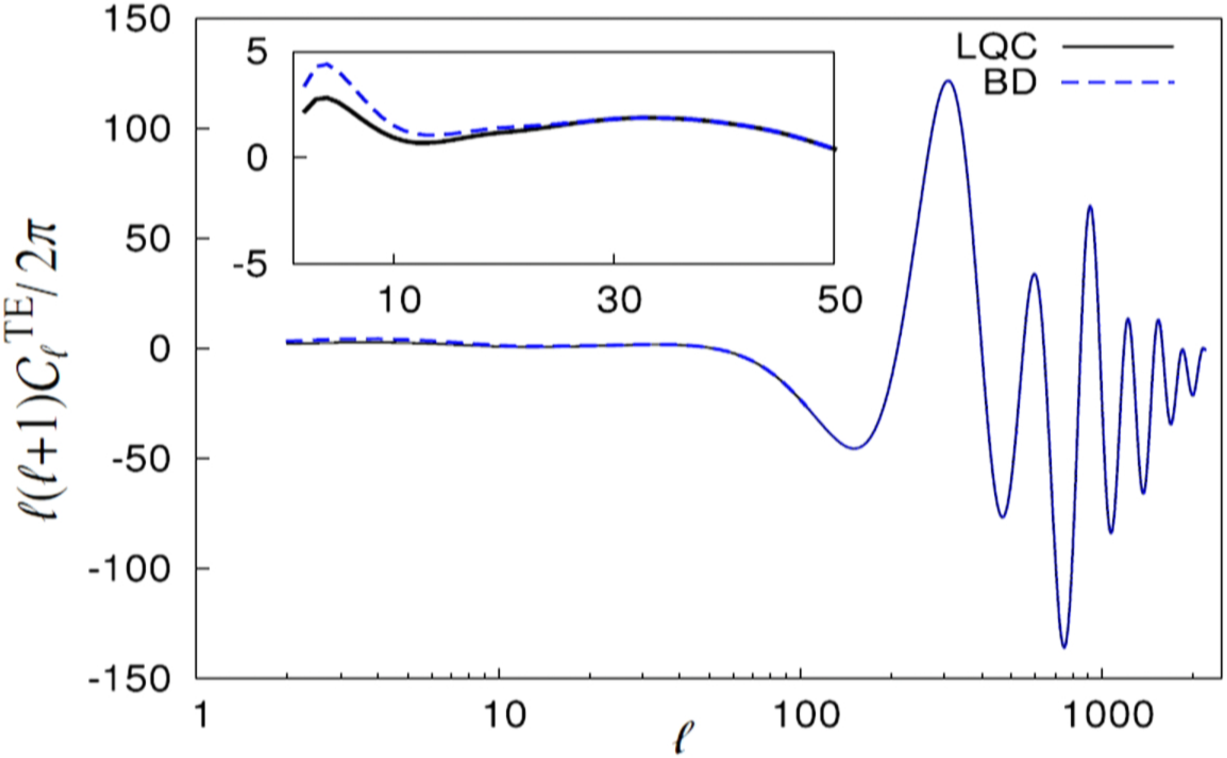

The LQC and the standard BD power spectrum for the scalar mode.
Red: Raw 'data' from LQC. blue: best fit curve. (AA, Gupt)

# LQC: Predicted TT-Power spectrum



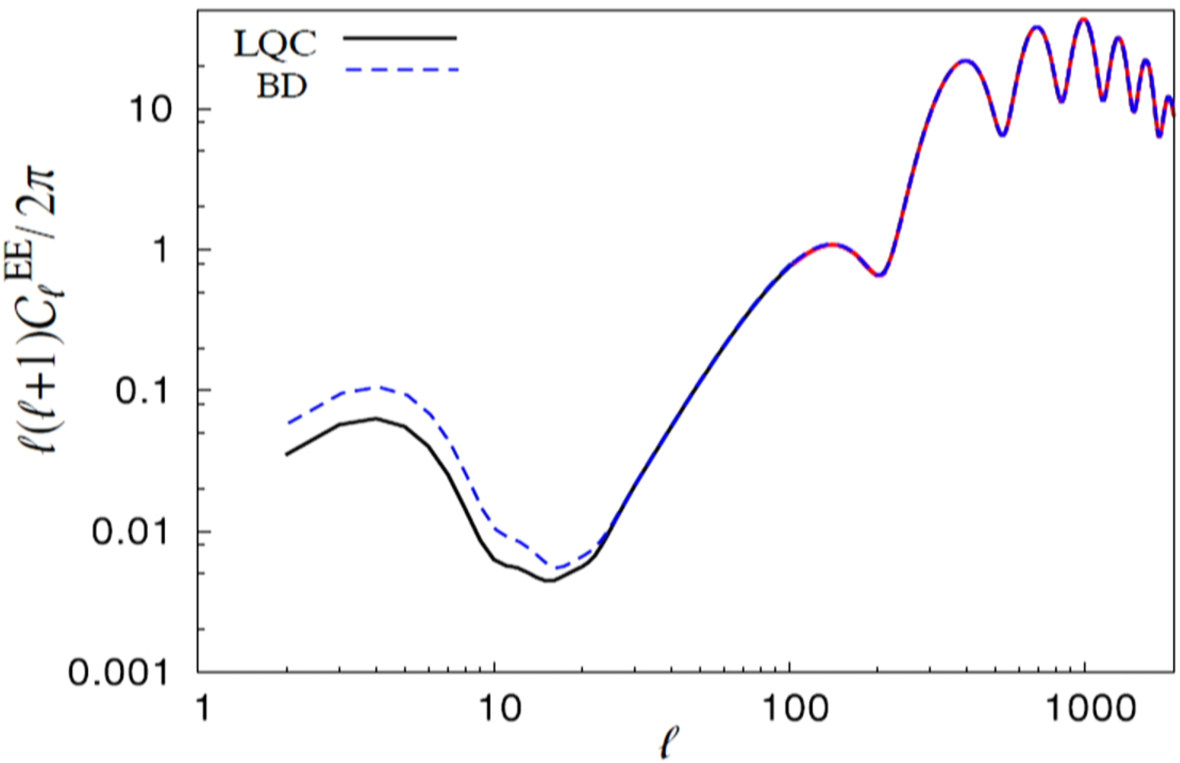

With our initial conditions for $\Psi_o \otimes \psi$, the LQC power spectrum agrees with the standard BD power spectrum for $\ell \gtrsim 30$, but in LQC power is suppressed for $\ell \lesssim 30$. Thus, the LQC curve provides a better $\chi^2$-fit to the data for $\ell \lesssim 30$. (AA, Gupt)

# LQC: Predicted TE Correlations

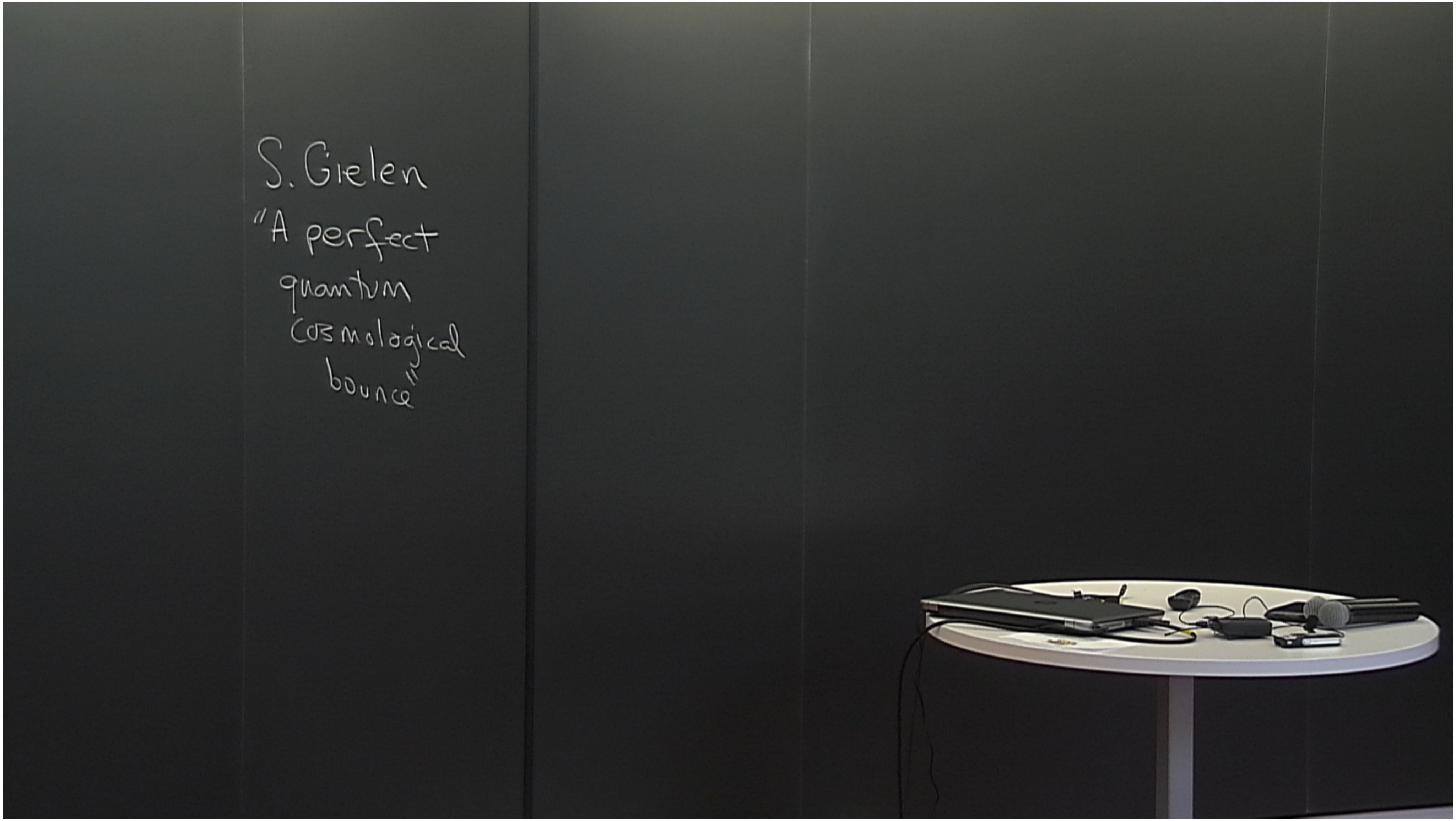



The LQC prediction for the TE spectrum, for the initial state that gave the TT-spectrum in the last slide. (AA, Gupt)

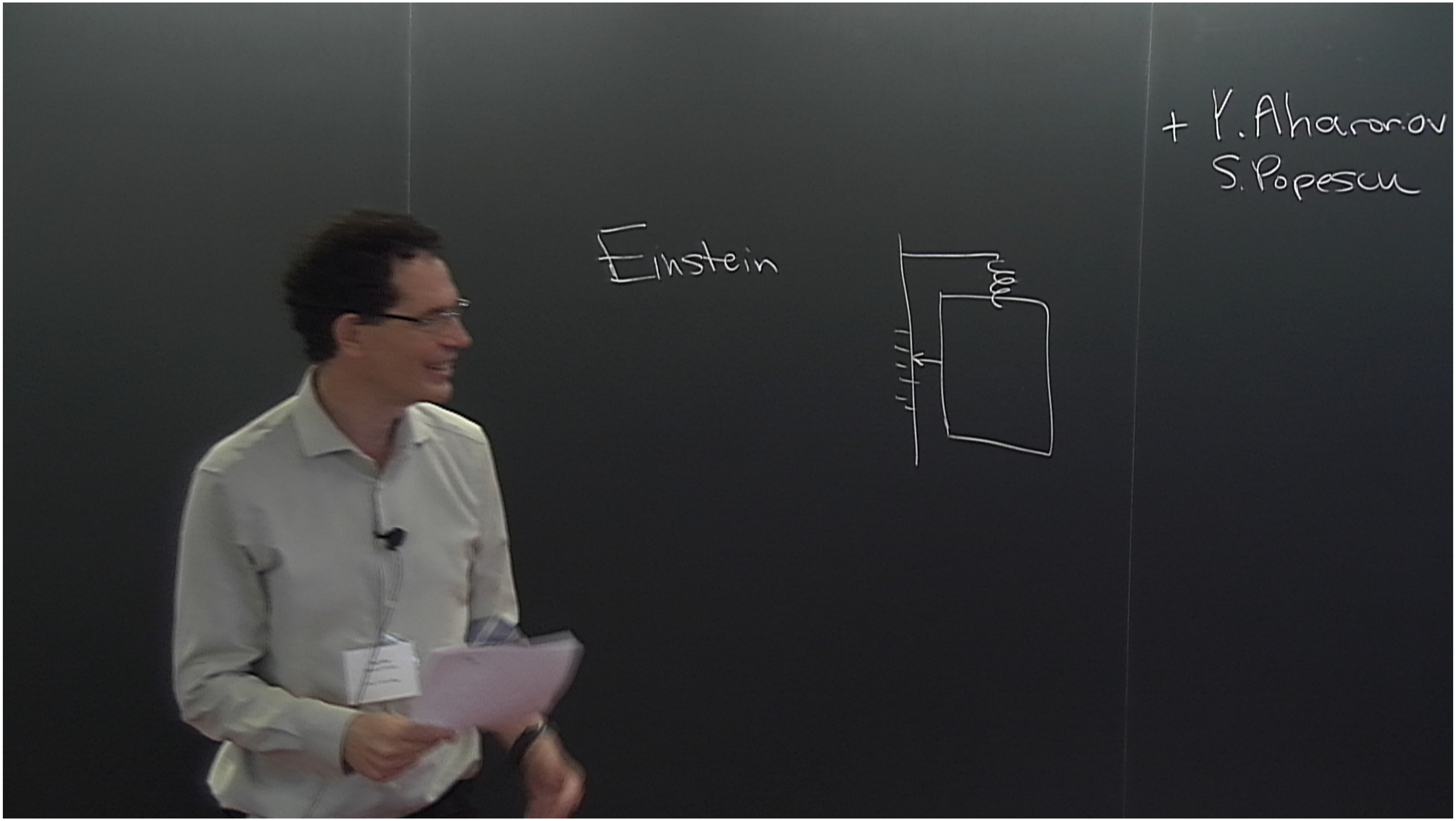
# LQC: Predicted EE Correlations

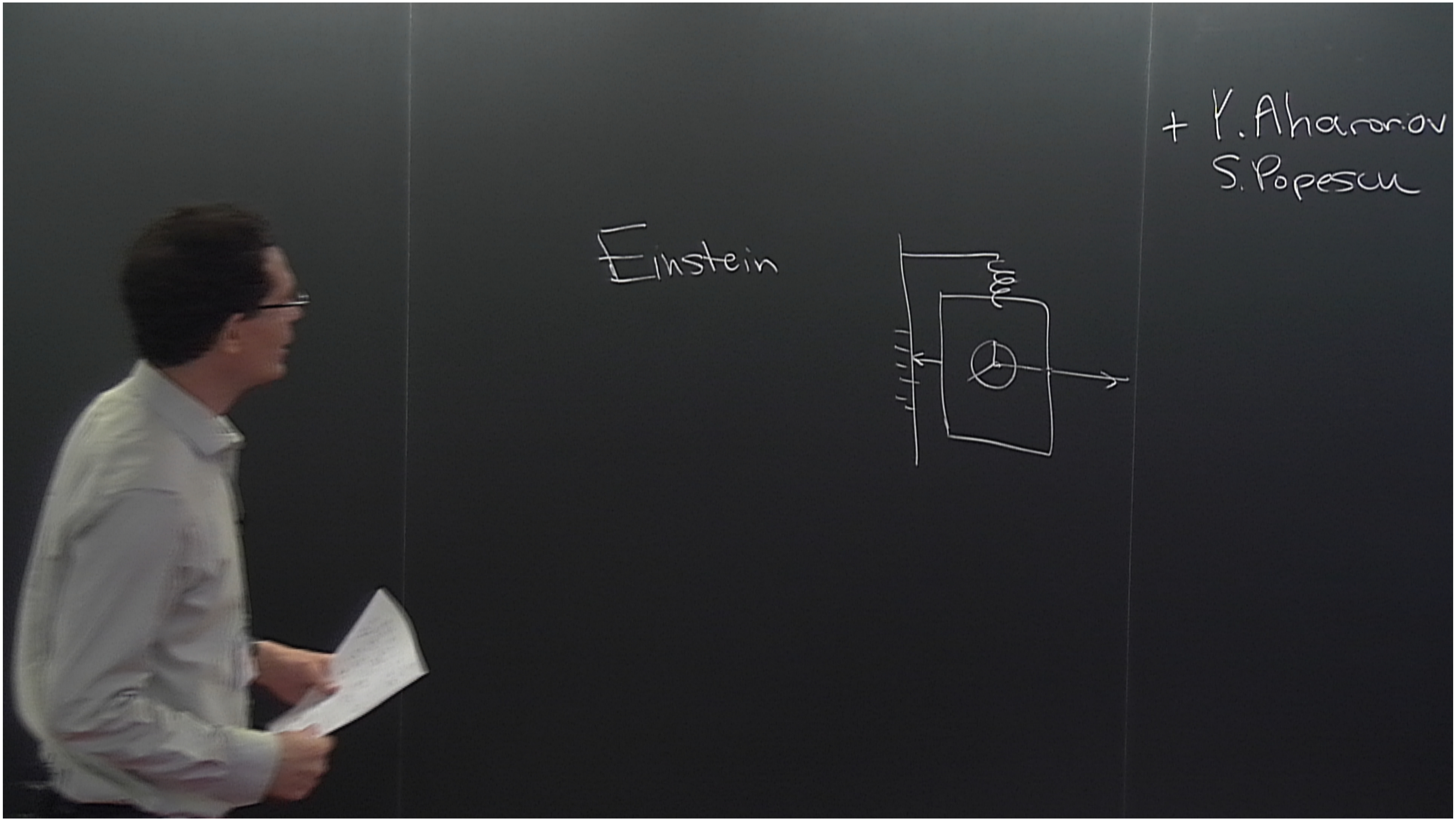



The LQC prediction for the TE spectrum, for the initial state that gave the TT-spectrum in the last but one slide. The small suppression of power at small $\ell$ is a signature that the TT power suppression is of primoridial origin. (AA, Gupt)


S. Gielen
"A perfect
quantum
cosmological
bounce"

Y. Aharonov
S. Popescu


+ Y. Aharonov
S. Popescu
Einstein


+ Y. Aharonov
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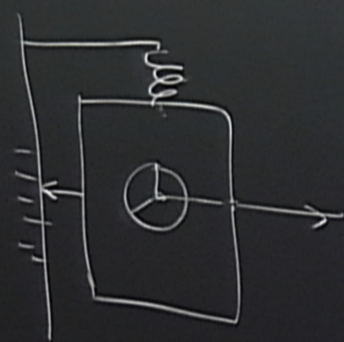
Einstein



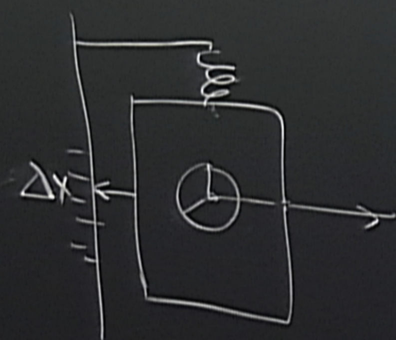
+ Y. Aharonov
S. Popescu

Einstein : can make

$\Delta E \Delta t$ as small as you like!

+ Y. Aharonov
S. Popescu

Einstein

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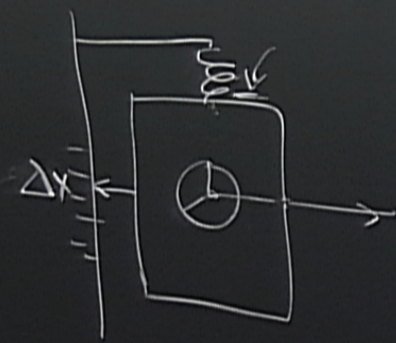
$\Delta E \Delta t$ as small as you like!

Einstein




+ Y. Aharonov
S. Popescu

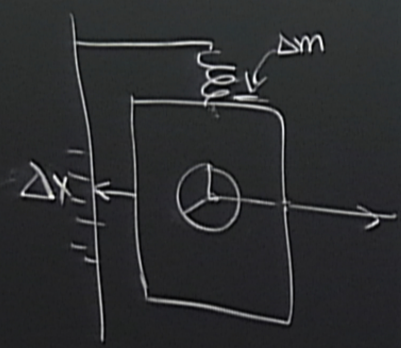
Einstein : can make

$\Delta E \Delta t$ as small as you like!

$\Delta p > \frac{h}{\Delta x}$

weighing

Einstein




+ Y. Aharonov
S. Popescu

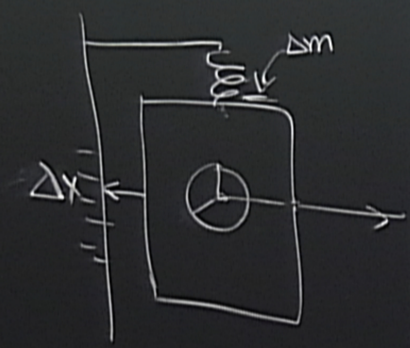
Einstein: can make

$\Delta E \Delta t$ as small as you like!

$$\Delta p > \frac{h}{\Delta x}$$

weighing $g \Delta m t > \Delta p$

Einstein




+ Y. Aharonov
S. Popescu

Einstein : can make

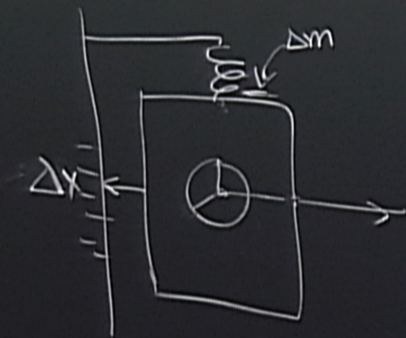
$\Delta E \Delta t$ as small as you like!

$$\Delta p > \frac{h}{\Delta x}$$

weighing $g \Delta m t > \Delta p$ ($\Delta m \to \Delta E / c^2$)

$$\Rightarrow h < g \frac{\Delta E}{c^2} t \Delta x$$

Einstein




+ Y. Aharonov
S. Popescu

Einstein : can make

$\Delta E \Delta t$ as small as you like!

$\Delta p > \frac{h}{\Delta x}$

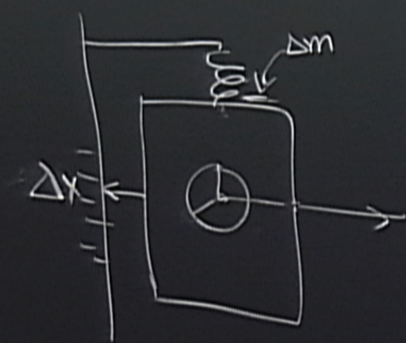
weighing $g \overset{\Delta E/c^2}{\Delta m}\, t > \Delta p$

$\Rightarrow h < g \frac{\Delta E}{c^2} t \Delta x$

Bohr : $\frac{\Delta t}{t} = g \frac{\Delta x}{c^2}$

+ Y. Aharonov
S. Popescu

Einstein




Einstein : can make

$\Delta E \Delta t$ as small as you like!

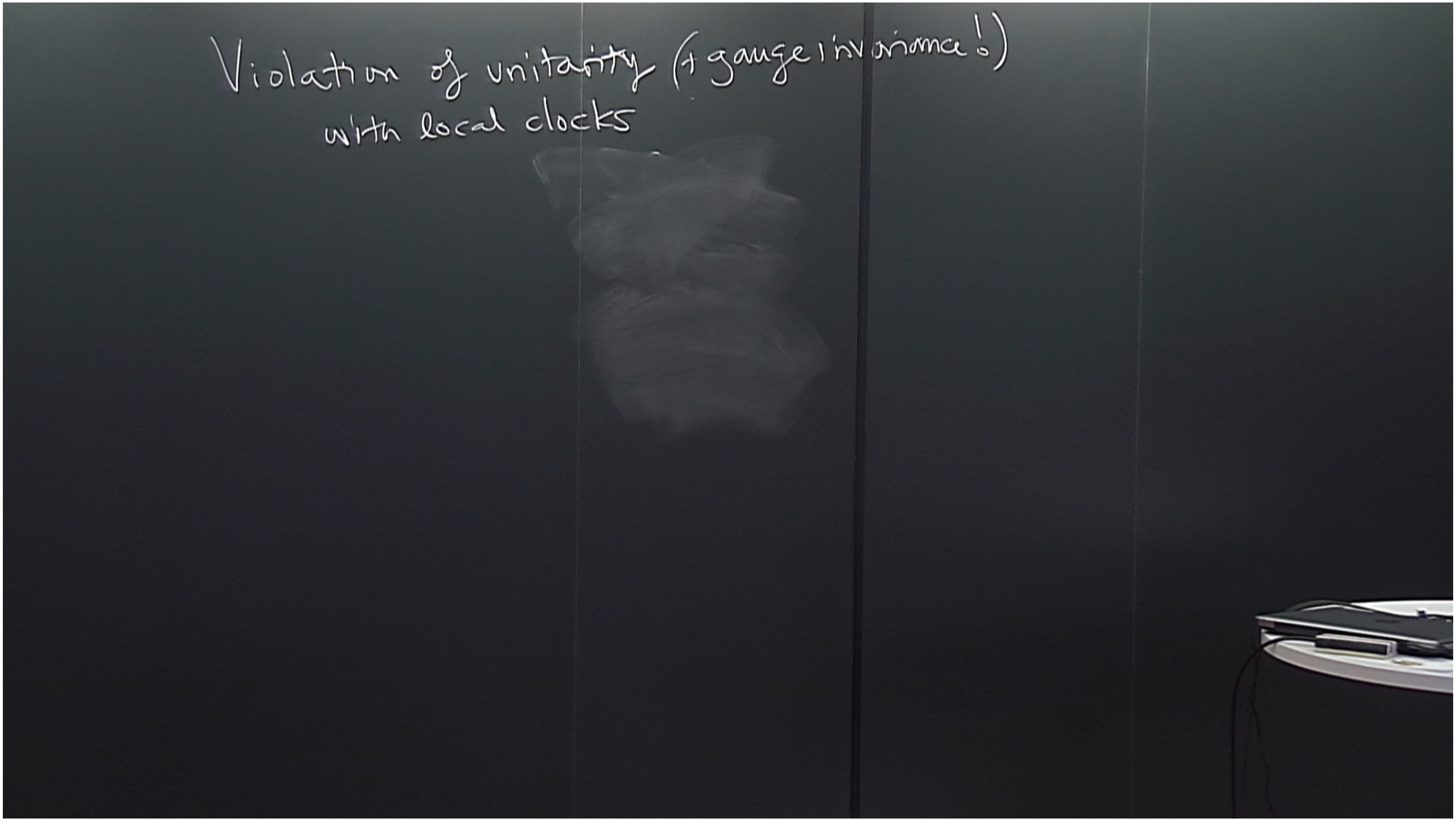
$\Delta p > \frac{h}{\Delta x}$

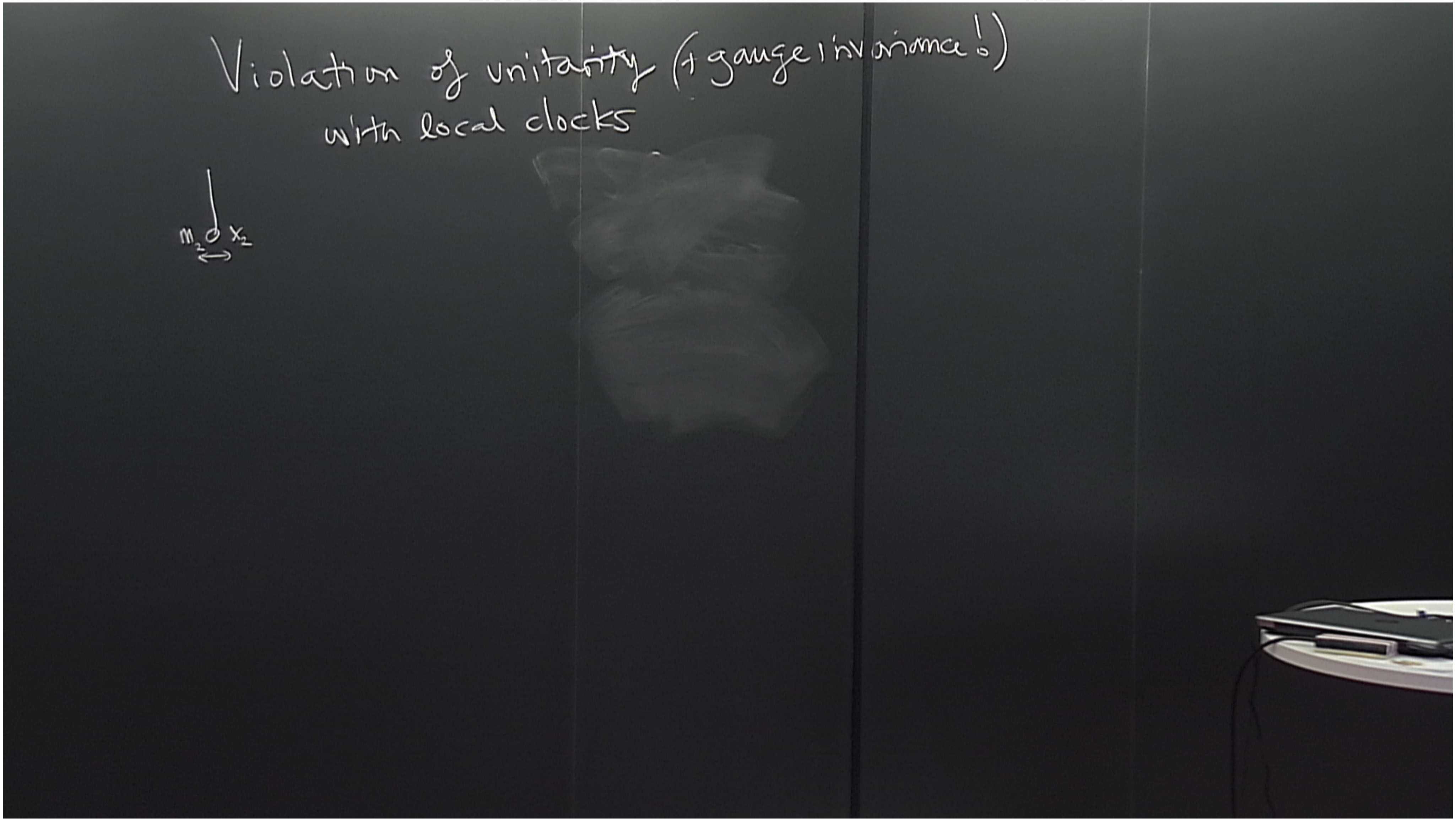
weighing $g \overset{\Delta E / c^2}{\Delta m}\, t > \Delta p$

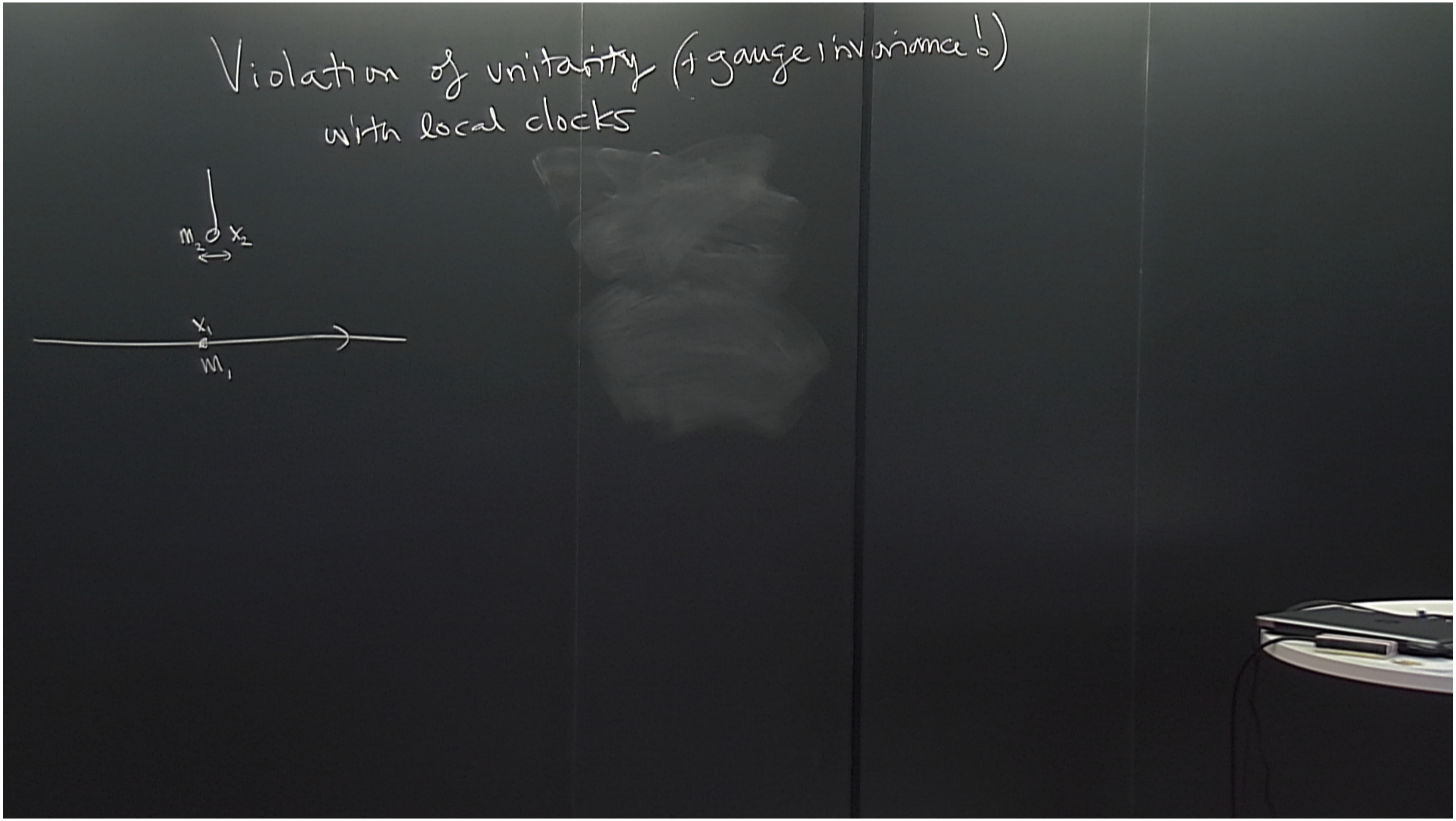
$\Rightarrow h < g \frac{\Delta E}{c^2} t \Delta x$

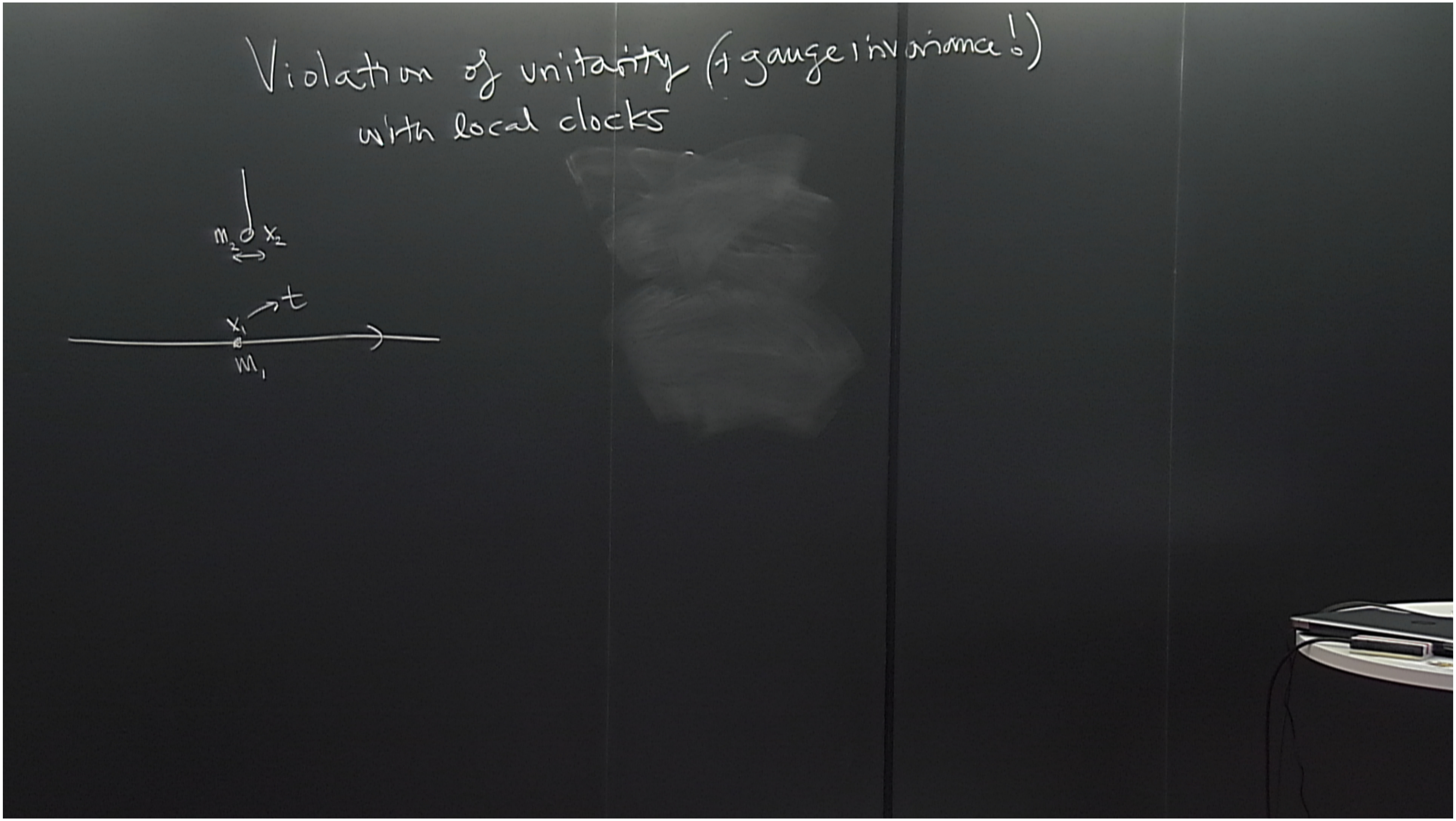
Bohr: $\frac{\Delta t}{t} = g \frac{\Delta x}{c^2}$

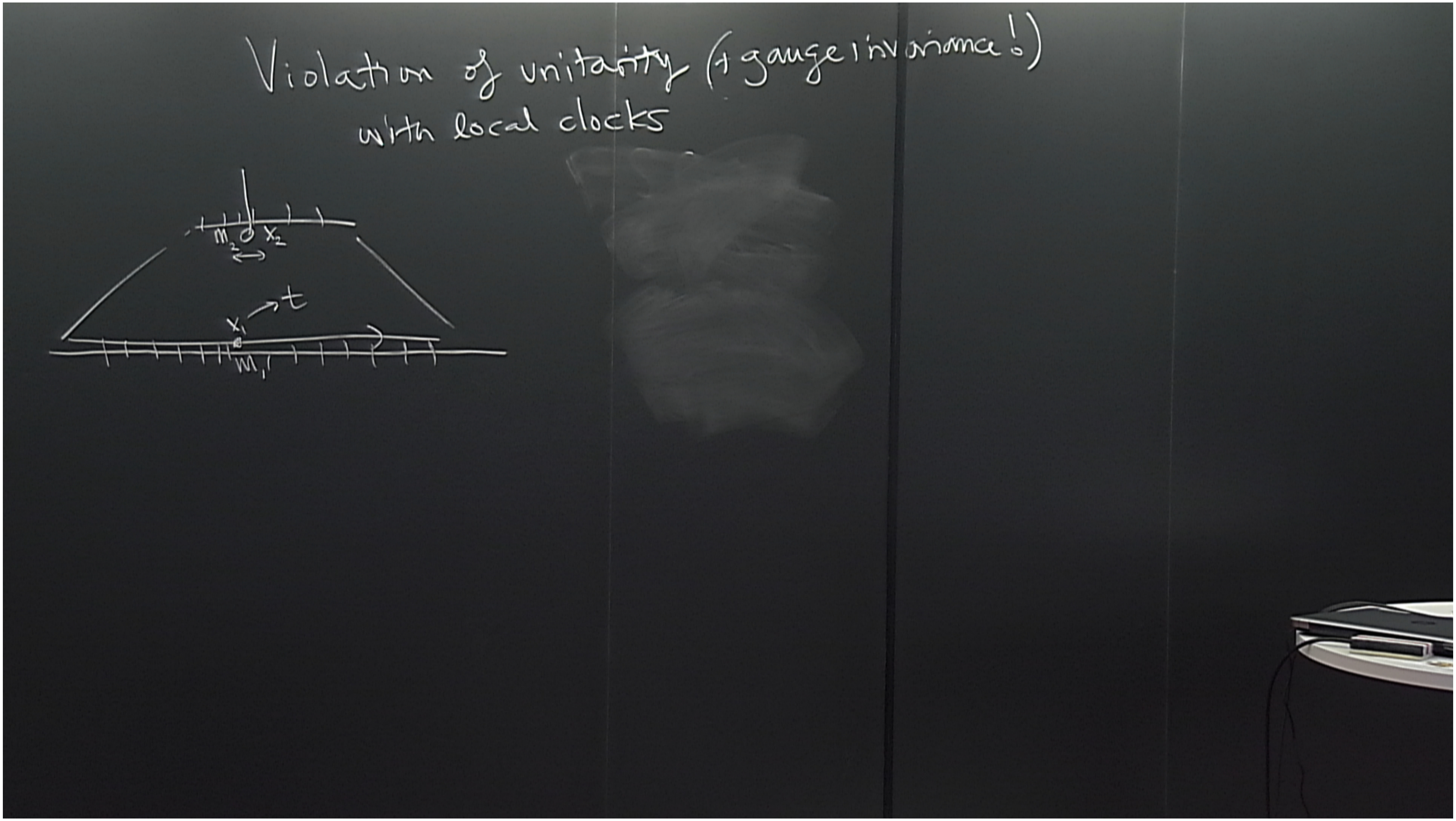
$\underline{h < \Delta E \Delta t}$

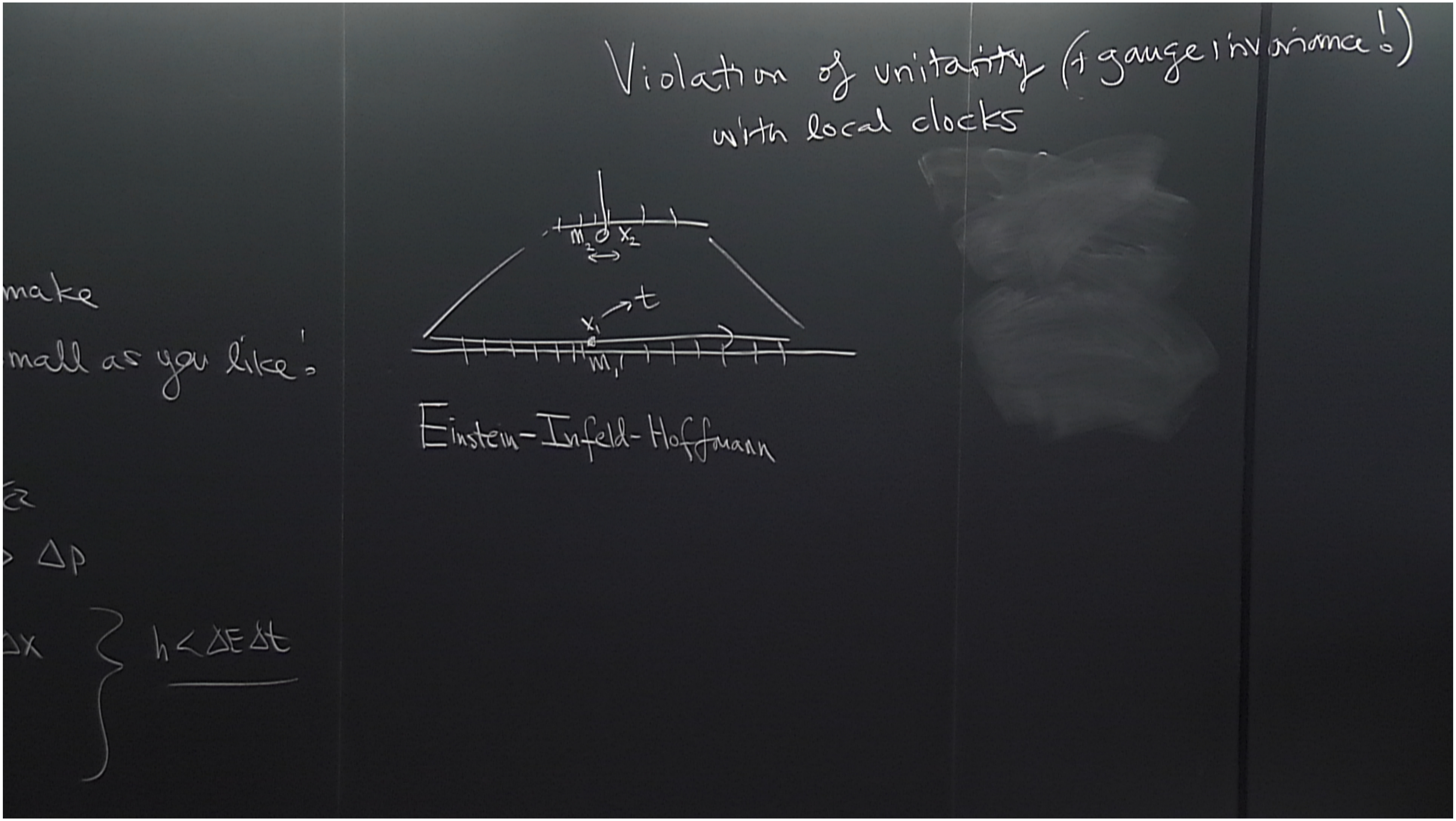

Violation of unitarity (+ gauge invariance!)
with local clocks

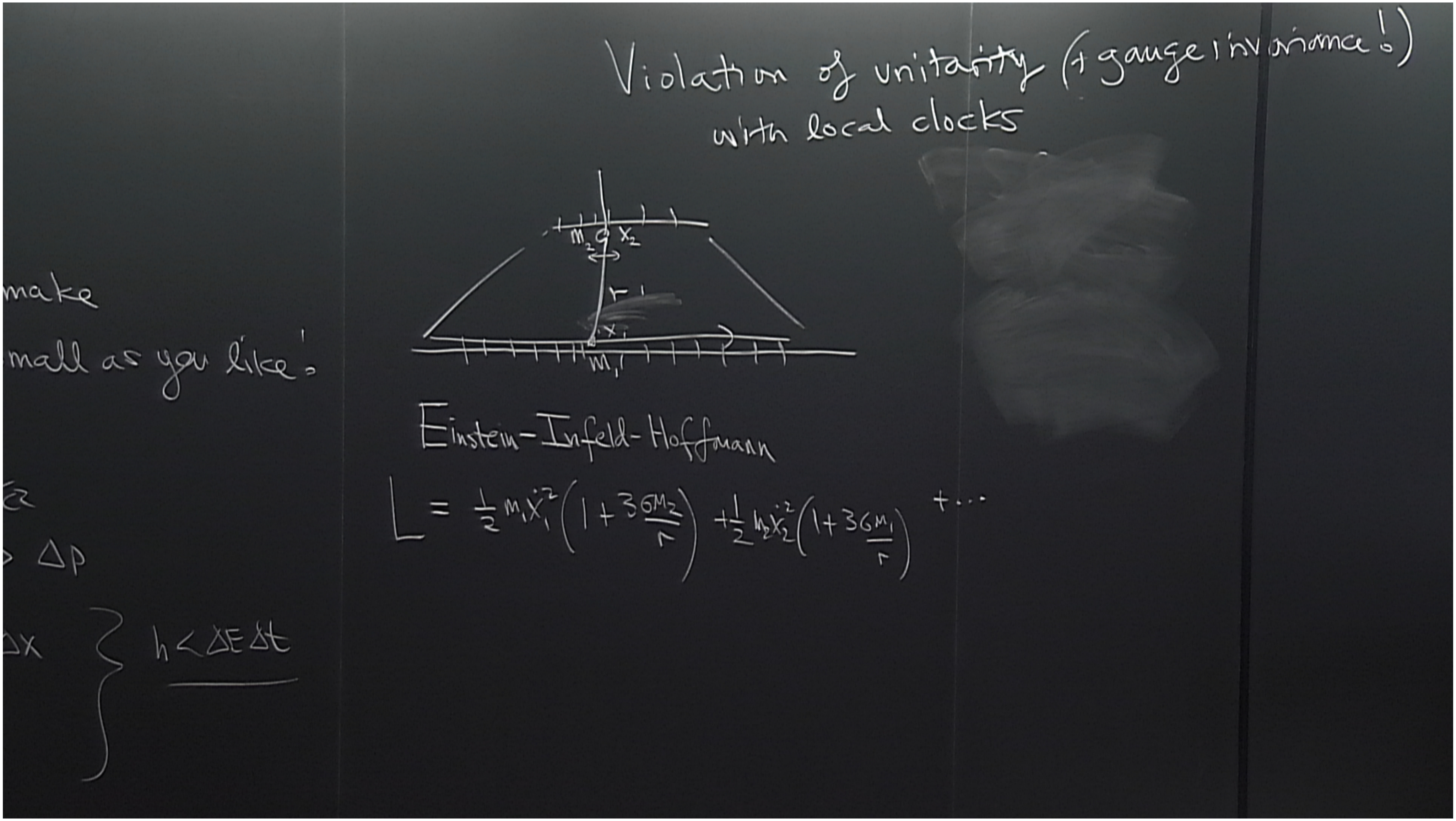

Violation of unitarity (+ gauge invariance!)
with local clocks
m2
x2


Violation of unitarity (+ gauge invariance!)
with local clocks
m2
x2
x1
m1


Violation of unitarity (+ gauge invariance!)
with local clocks
m2
x2
x1
t
m1


Violation of unitarity (+ gauge invariance!)
with local clocks
m2
x2
x1
t
m1


Violation of unitarity (+ gauge invariance!)
with local clocks
$m_2$
$x_2$
$x_1$
$t$
$m_1$
Einstein-Infeld-Hoffmann
make
mall as you like!
$\Delta p$
$\Delta x$
$h < \Delta E \Delta t$



Violation of unitarity (+ gauge invariance!)
with local clocks
$m_2$ $x_2$
$r$
$x_1$
$m_1$
Einstein-Infeld-Hoffmann
$L = \frac{1}{2} m_1 \dot{x}_1^2 \left(1 + \frac{3GM_2}{r}\right) + \frac{1}{2} m_2 \dot{x}_2^2 \left(1 + \frac{3GM_1}{r}\right) + \ldots$
make
mall as you like!
$\Delta p$
$h < \Delta E \Delta t$

Violation of unitarity (+ gauge invariance!)
with local clocks

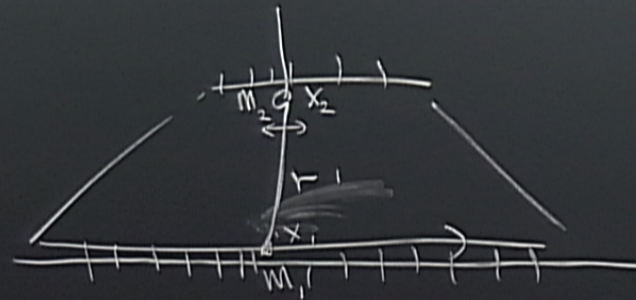
make

mall as you like!

$\Delta p$

$\Delta x$

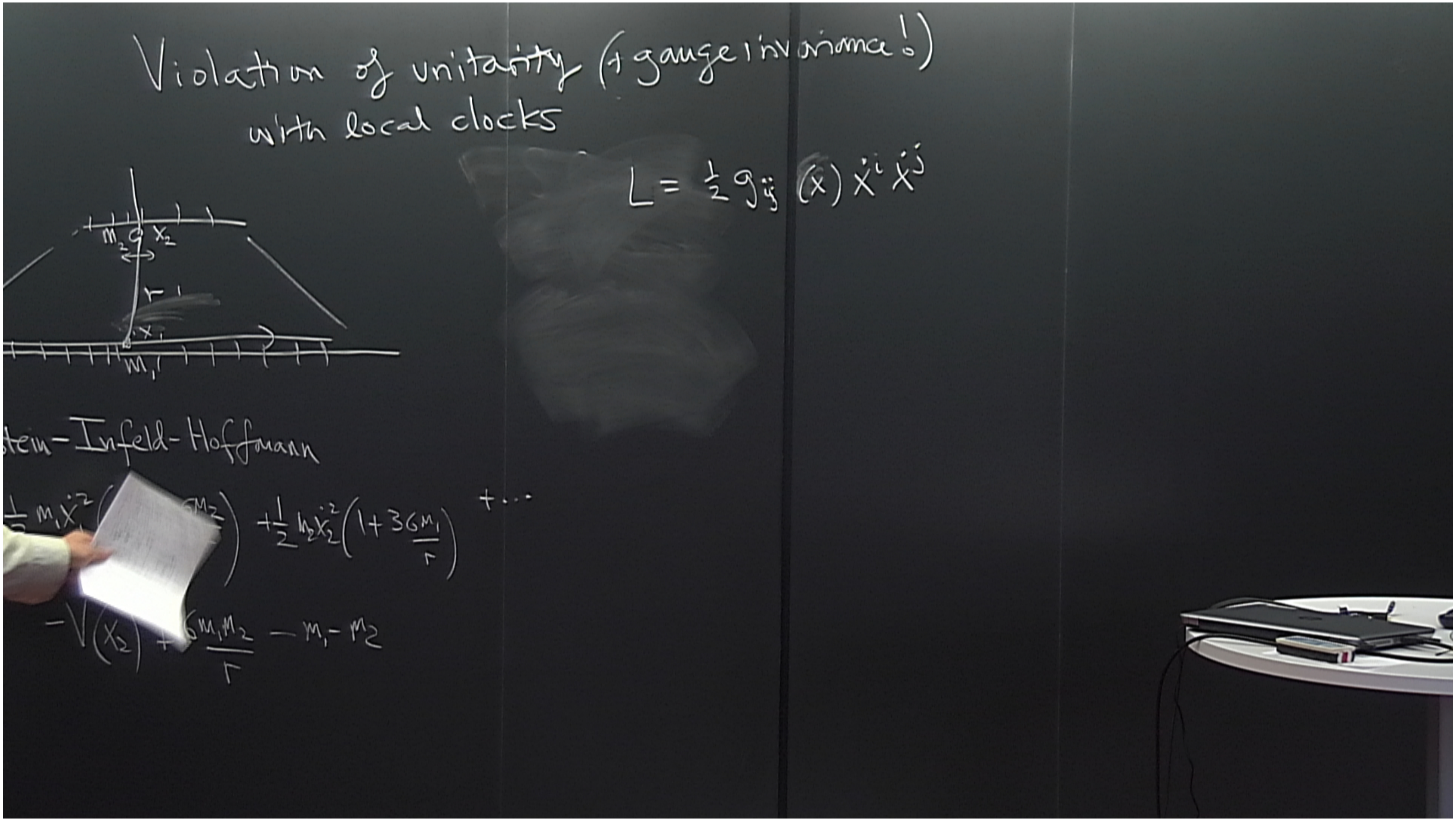
$h < \Delta E \Delta t$

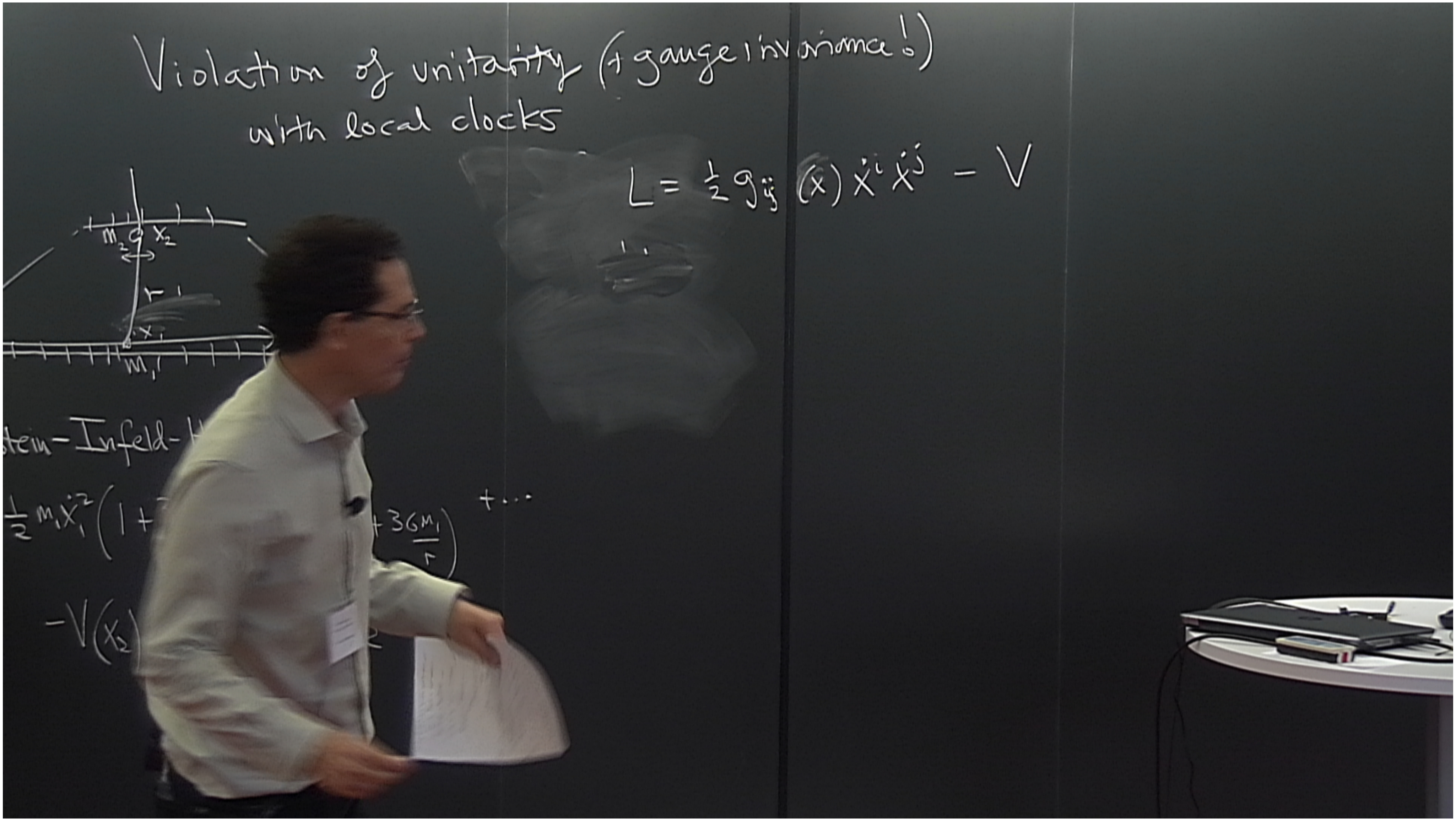


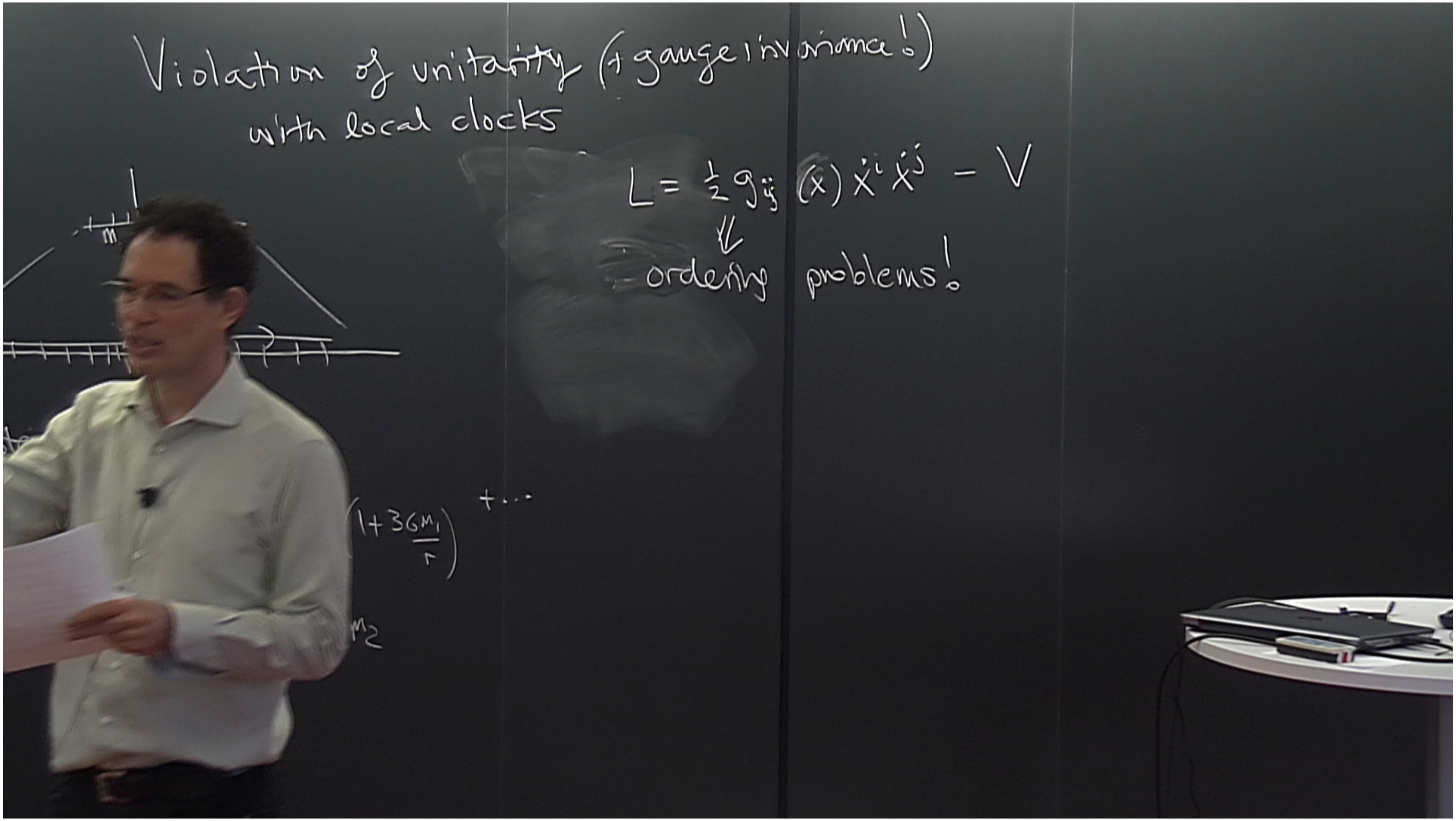

Einstein-Infeld-Hoffmann

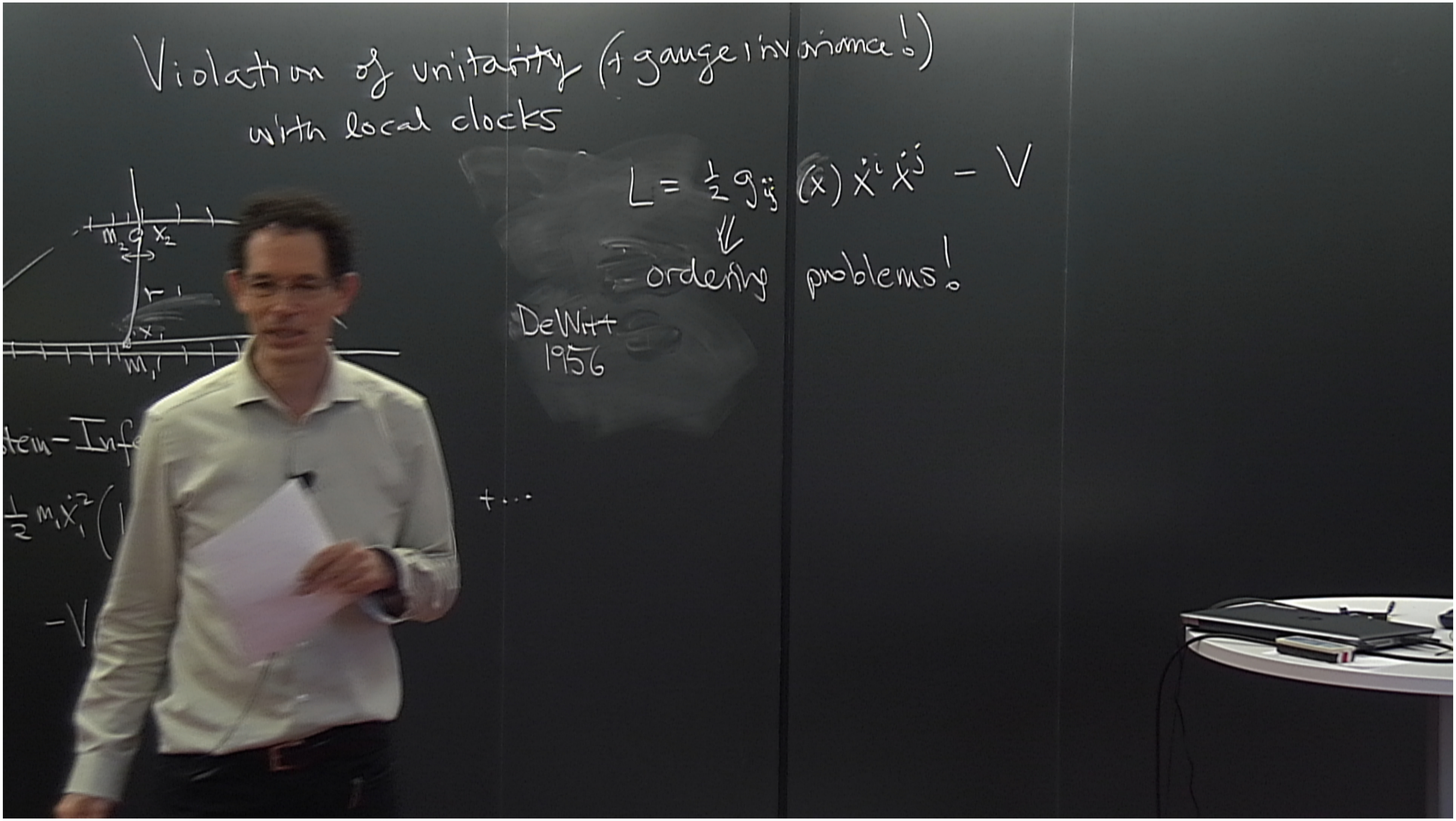
$$L = \frac{1}{2} m_1 \dot{x}_1^2 \left(1 + \frac{3GM_2}{r}\right) + \frac{1}{2} m_2 \dot{x}_2^2 \left(1 + \frac{3Gm_1}{r}\right) + \dots$$

$$- V(x_2) + \frac{Gm_1 m_2}{r} - m_1 - m_2$$


Violation of unitarity (+ gauge invariance!)
with local clocks
L = 1/2 g_ij (x) x^i x^j
stein-Infeld-Hoffmann
+ 1/2 m_2 x_2^2 (1 + 3Gm_1/r)
+ ...
- V(x_2) + Gm_1m_2/r - m_1 - m_2

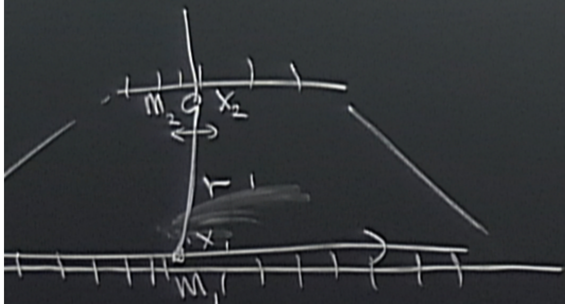

Violation of unitarity (+ gauge invariance!)
with local clocks
L = ½ g_ij (x) ẋ^i ẋ^j − V
stein−Infeld−
+ 3 G m₁ / r
+ . . .
−V(x₂)


Violation of unitarity (+ gauge invariance!)
with local clocks
L = ½ g_ij (x) ẋ^i ẋ^j − V
ordering problems!



Violation of unitarity (+ gauge invariance!)
with local clocks
$L = \frac{1}{2} g_{ij}(x)\dot{x}^i \dot{x}^j - V$
$\Downarrow$
ordering problems!
DeWitt
1956
$+ \dots$

Violation of unitarity (+ gauge invariance!)
with local clocks



$$L = \frac{1}{2} g_{ij}(x)\,\dot{x}^i\dot{x}^j - V$$

$\Downarrow$

ordering problems!

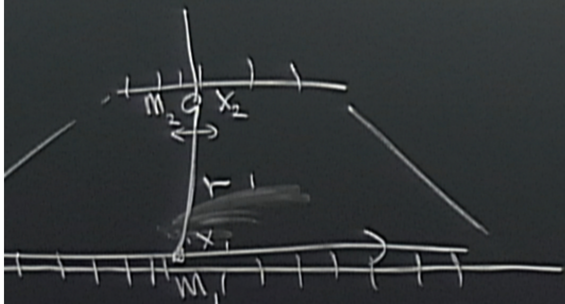
DeWitt 1956 $\int dx\sqrt{g}$

stein–Infeld–Hoffmann

$$\frac{1}{2}m_1\dot{x}_1^2\left(1+3\frac{Gm_2}{r}\right) + \frac{1}{2}m_2\dot{x}_2^2\left(1+3\frac{Gm_1}{r}\right) + \dots$$

$$-V(x_2) + \frac{Gm_1m_2}{r} - m_1 - m_2$$

Violation of unitarity (+ gauge invariance!)
with local clocks




stein-Infeld-Hoffmann

$$\frac{1}{2} m_1 \dot{x}_1^2 \left(1 + 3\frac{Gm_2}{r}\right) + \frac{1}{2} m_2 \dot{x}_2^2 \left(1 + 3\frac{Gm_1}{r}\right) + \dots$$

$$-V(x_2) + \frac{Gm_1 m_2}{r} - m_1 - m_2$$

DeWitt 1956

$$L = \frac{1}{2} g_{ij}(x)\, \dot{x}^i \dot{x}^j - V$$

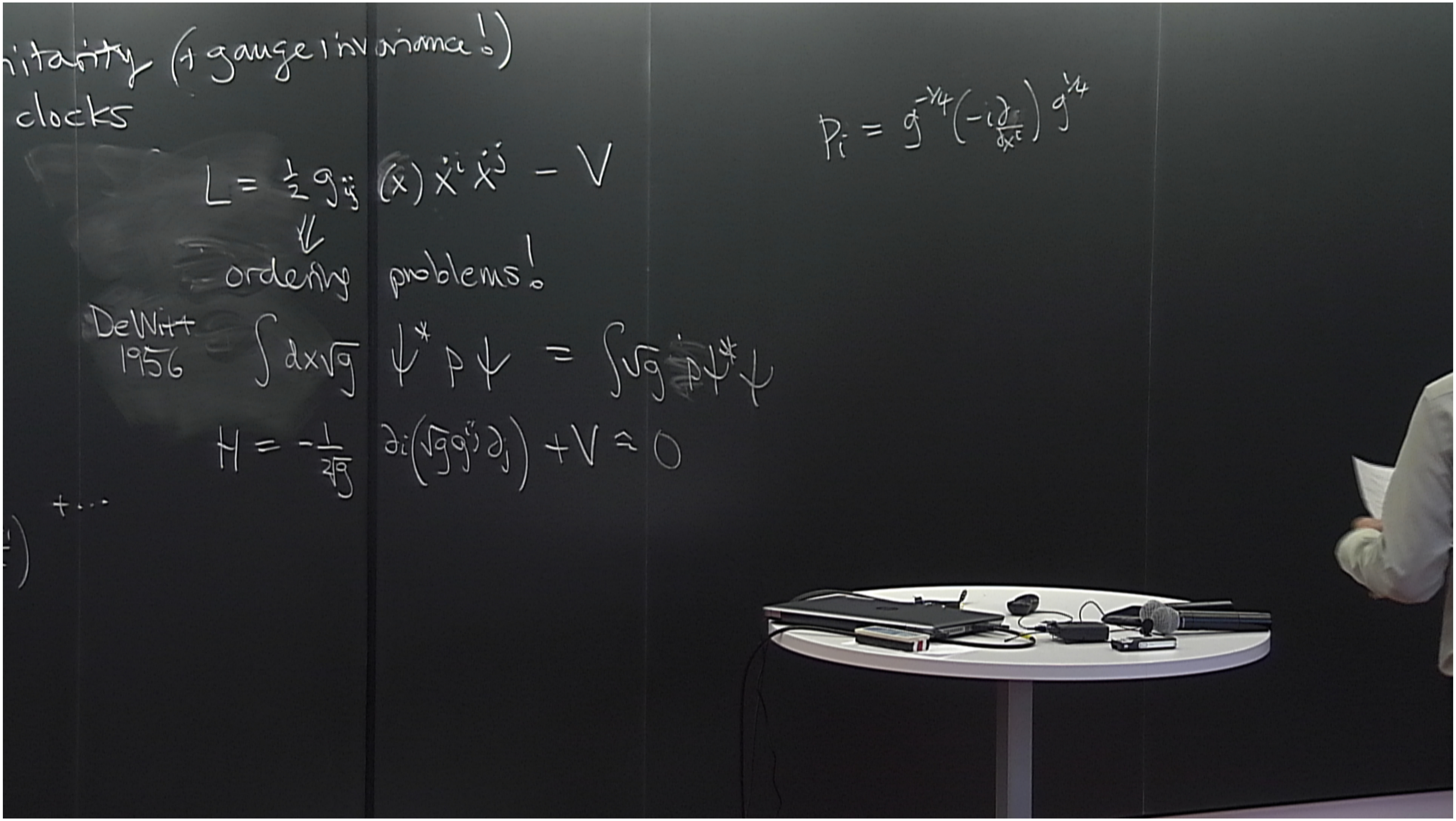
$\Downarrow$

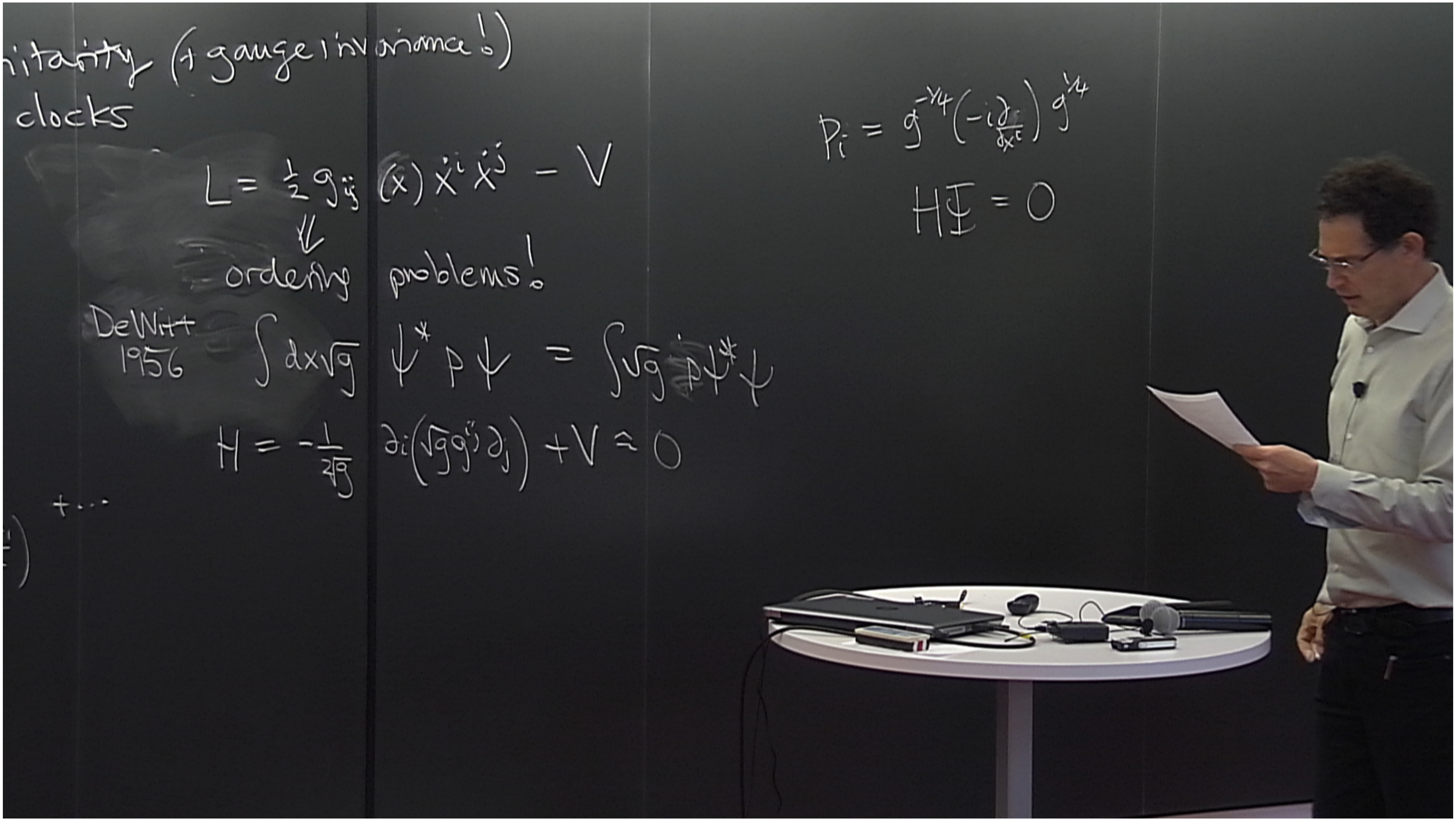
ordering problems!

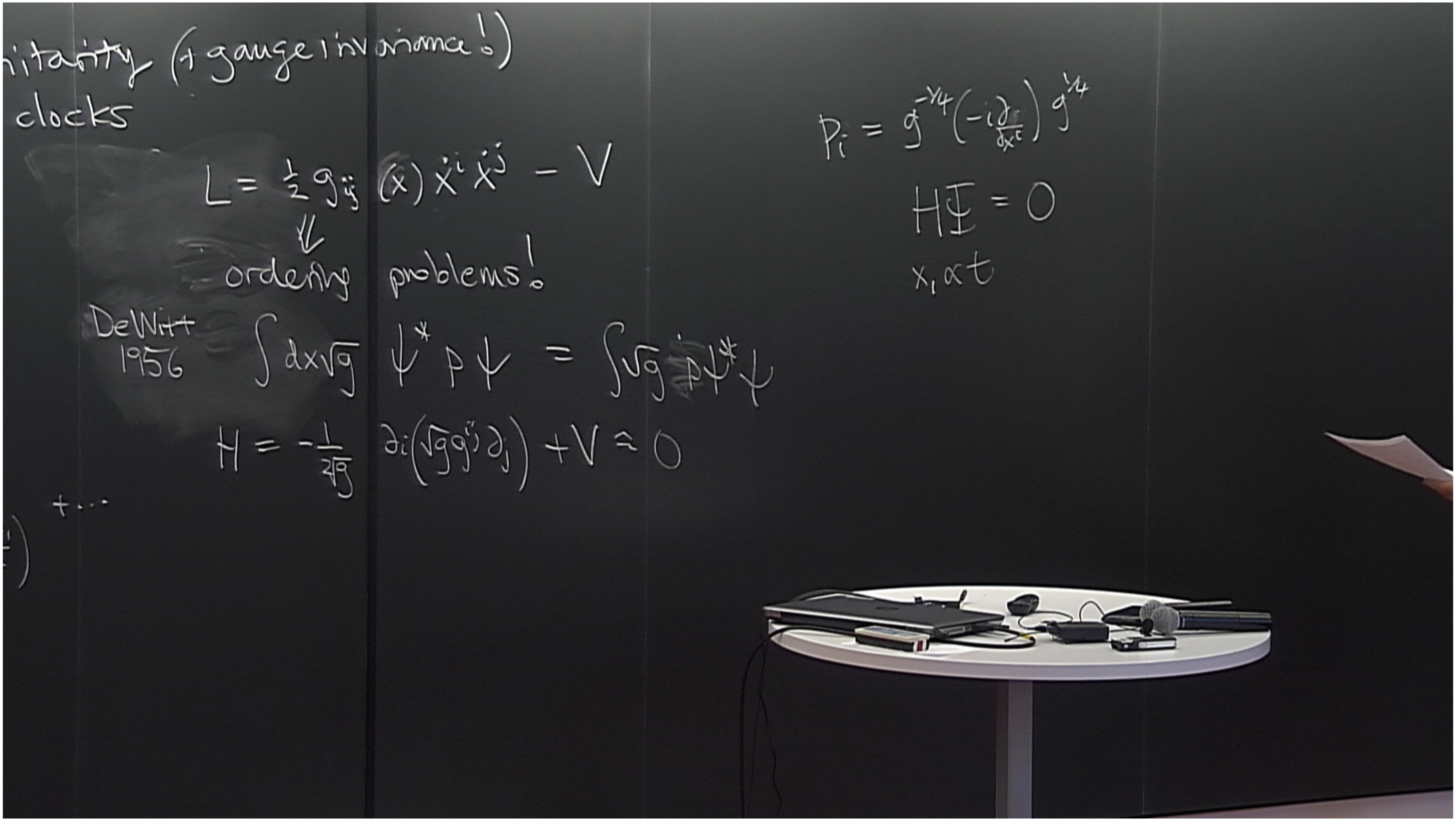
$$\int dx \sqrt{g}$$

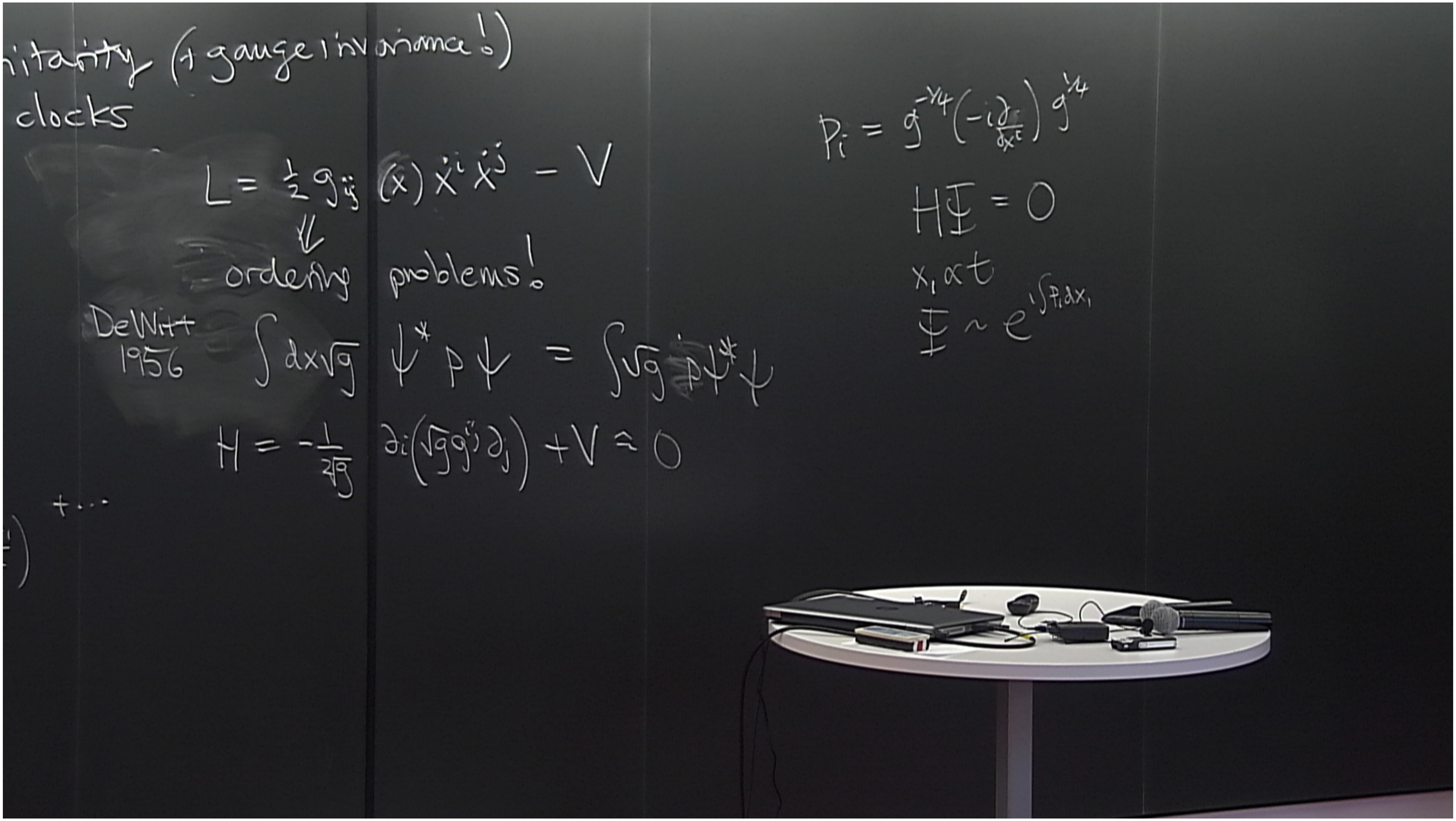
$$H = -\frac{1}{2\sqrt{g}}\, \partial_i\left(\sqrt{g}\, g^{ij} \partial_j\right) + V \approx 0$$

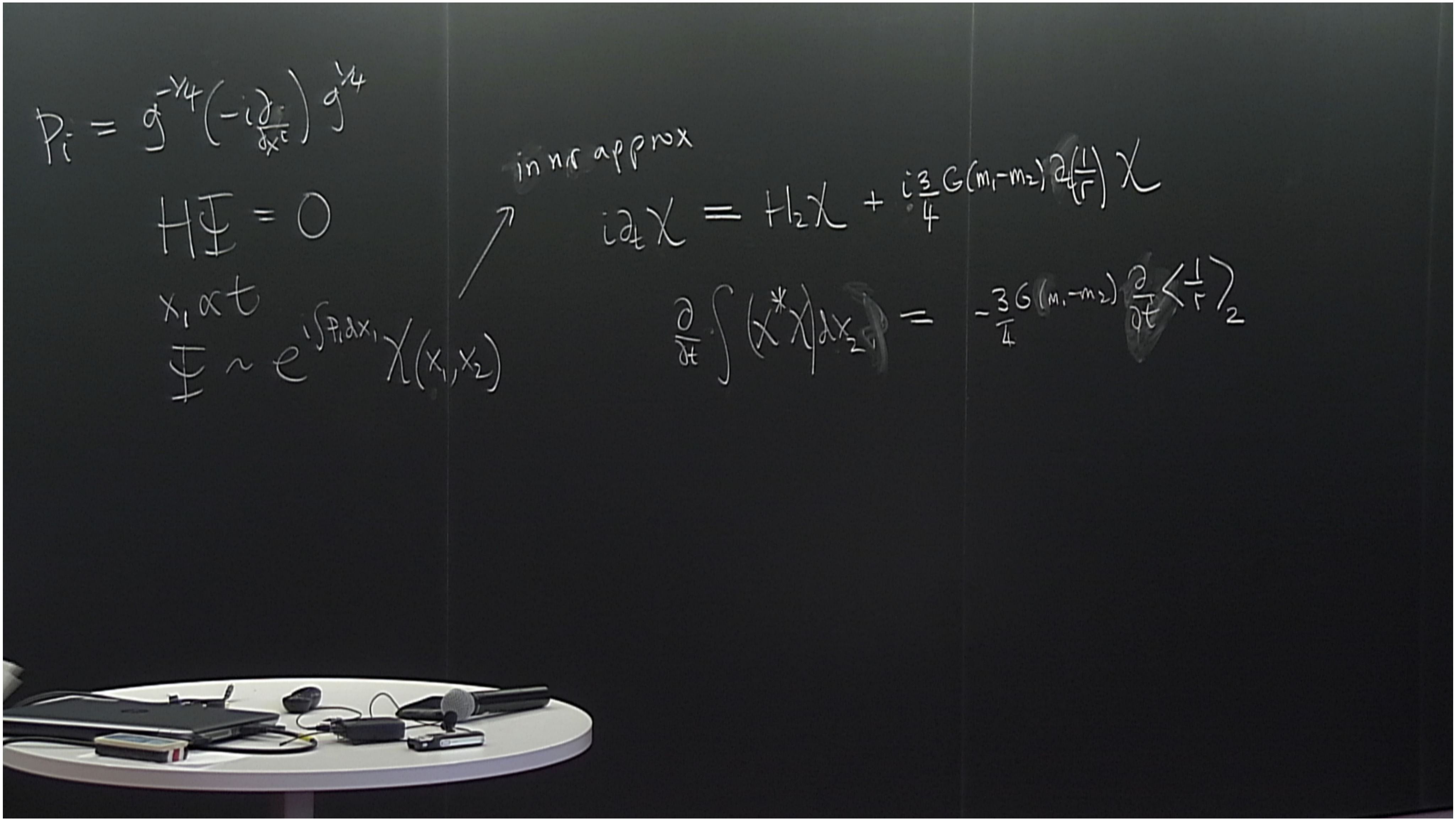

$p_i = g^{-1/4}\left(-i\frac{\partial}{\partial x^i}\right) g^{1/4}$


itarity (+ gauge invariance!)
clocks
L = ½ g_ij (x) ẋ^i ẋ^j − V
ordering problems!
DeWitt 1956
∫ dx √g ψ* p ψ = ∫ √g p ψ* ψ
H = −1/(2√g) ∂_i(√g g^ij ∂_j) + V ≈ 0
+ . . .
p_i = g^(−1/4) (−i ∂/∂x^i) g^(1/4)

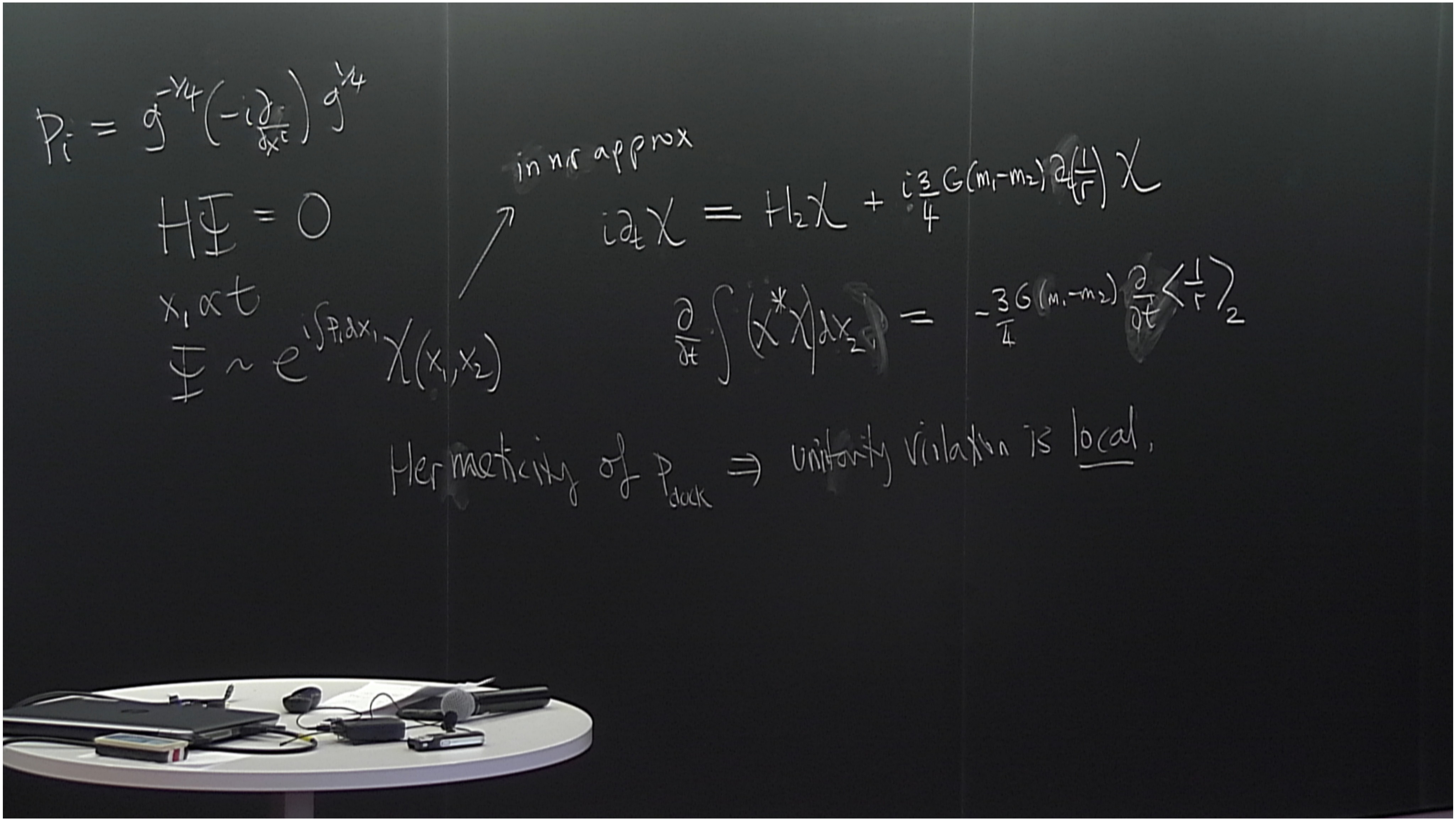

itarity (+ gauge invariance!)
clocks
$L = \frac{1}{2} g_{ij}(x)\dot{x}^i \dot{x}^j - V$
ordering problems!
DeWitt
1956
$\int dx \sqrt{g}\, \psi^* p \psi = \int \sqrt{g}\, p \psi^* \psi$
$H = -\frac{1}{2\sqrt{g}} \partial_i (\sqrt{g} g^{ij} \partial_j) + V \approx 0$
$p_i = g^{-1/4}\left(-i \frac{\partial}{\partial x^i}\right) g^{1/4}$
$H\Psi = 0$

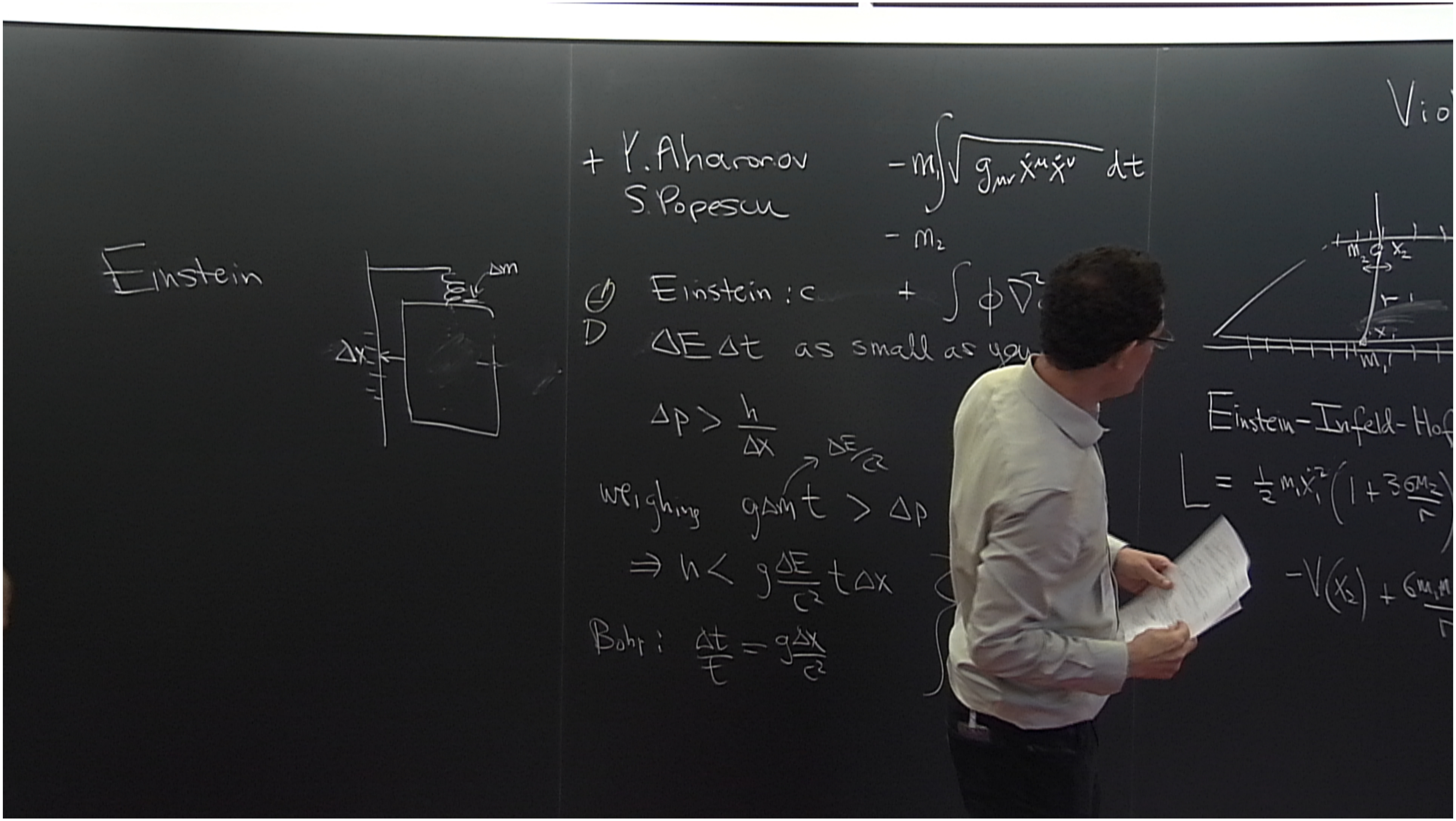

itarity (+ gauge invariance!)
clocks
$L = \frac{1}{2} g_{ij}(x)\dot{x}^i\dot{x}^j - V$
ordering problems!
DeWitt
1956
$\int dx\sqrt{g}\,\psi^* p\psi = \int\sqrt{g}\,p\psi^*\psi$
$H = -\frac{1}{2\sqrt{g}}\partial_i(\sqrt{g}g^{ij}\partial_j) + V \approx 0$
+ ...
$p_i = g^{-1/4}(-i\partial_{x^i})\,g^{1/4}$
$H\Psi = 0$
$x_1 \propto t$


itarity (+ gauge invariance!)
clocks
$L = \frac{1}{2} g_{ij}(x)\dot{x}^i \dot{x}^j - V$
ordering problems!
DeWitt 1956
$\int dx\sqrt{g}\,\psi^* p \psi = \int \sqrt{g}\, p\psi^* \psi$
$H = -\frac{1}{2\sqrt{g}} \partial_i(\sqrt{g} g^{ij} \partial_j) + V \approx 0$
$p_i = g^{-1/4}(-i\frac{\partial}{\partial x^i}) g^{1/4}$
$H\Psi = 0$
$x_1 \propto t$
$\Psi \sim e^{i\int p_1 dx_1}$



$p_i = g^{-1/4}\left(-i\frac{\partial}{\partial x^i}\right) g^{1/4}$
$H\Psi = 0$
$x_1 \propto t$
$\Psi \sim e^{i\int p_1 dx_1} \chi(x_1, x_2)$
in n.r. approx
$i\partial_t \chi = H_2 \chi + i\frac{3}{4} G(m_1 - m_2)\,\partial_t\left(\frac{1}{r}\right)\chi$
$\frac{\partial}{\partial t}\int (\chi^* \chi)\, dx_2 = -\frac{3}{4} G(m_1 - m_2)\frac{\partial}{\partial t}\left\langle \frac{1}{r}\right\rangle_2$


$P_i = g^{-1/4}(-i\partial_{x^i})\, g^{1/4}$
$H\Psi = 0$
$x_1 \propto t$
$\Psi \sim e^{i\int P_1 dx_1}\chi(x_1, x_2)$
in nr approx
$i\partial_t \chi = H_2\chi + i\frac{3}{4}G(m_1-m_2)\partial_t\left(\frac{1}{r}\right)\chi$
$\frac{\partial}{\partial t}\int (\chi^*\chi)\, dx_2 = -\frac{3}{4}G(m_1-m_2)\frac{\partial}{\partial t}\left\langle\frac{1}{r}\right\rangle_2$
Hermeticity of $P_{clock}$ $\Rightarrow$ unitarity violation is local.


Einstein
Δm
Δx
+ Y. Aharonov
S. Popescu
− m₁ ∫ √(g_μν ẋ^μ ẋ^ν) dt
− m₂
Einstein : c
+ ∫ φ ∇²
ΔE Δt as small as you
Δp > h/Δx
ΔE/c²
weighing gΔm t > Δp
⇒ h < g ΔE/c² t Δx
Bohr : Δt/t = gΔx/c²
m₂ x₂
r
x₁
m₁
Einstein-Infeld-Ho
L = ½ m₁ ẋ₁² (1 + 3 GM₂/r)
−V(x₂) + Gm₁m