Title: Entangling Power of an Expanding Universe

Date: Dec 04, 2007 02:00 PM

URL: http://pirsa.org/07120024

Abstract: Quantum fields in the Minkowski vacuum are entangled with respect to local field modes. This entanglement can be swapped to spatially separated quantum systems using standard local couplings. A single, inertial field detector in the exponentially expanding (de Sitter) vacuum responds as if it were bathed in thermal radiation in a Minkowski universe. Using two inertial detectors, interactions with the field in the thermal case will entangle certain detector pairs that would not become entangled in the corresponding de Sitter case.The two universes can thus be distinguished by their entangling power.

Entangling Power of an Expanding Universe

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G. L. Ver Steeg and N. C. Menicucci, arXiv:0711.3066v3 [quant-ph]

Information in Quantum Field Theory

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- Black holes
  - Hawking radiation

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Operational Approach

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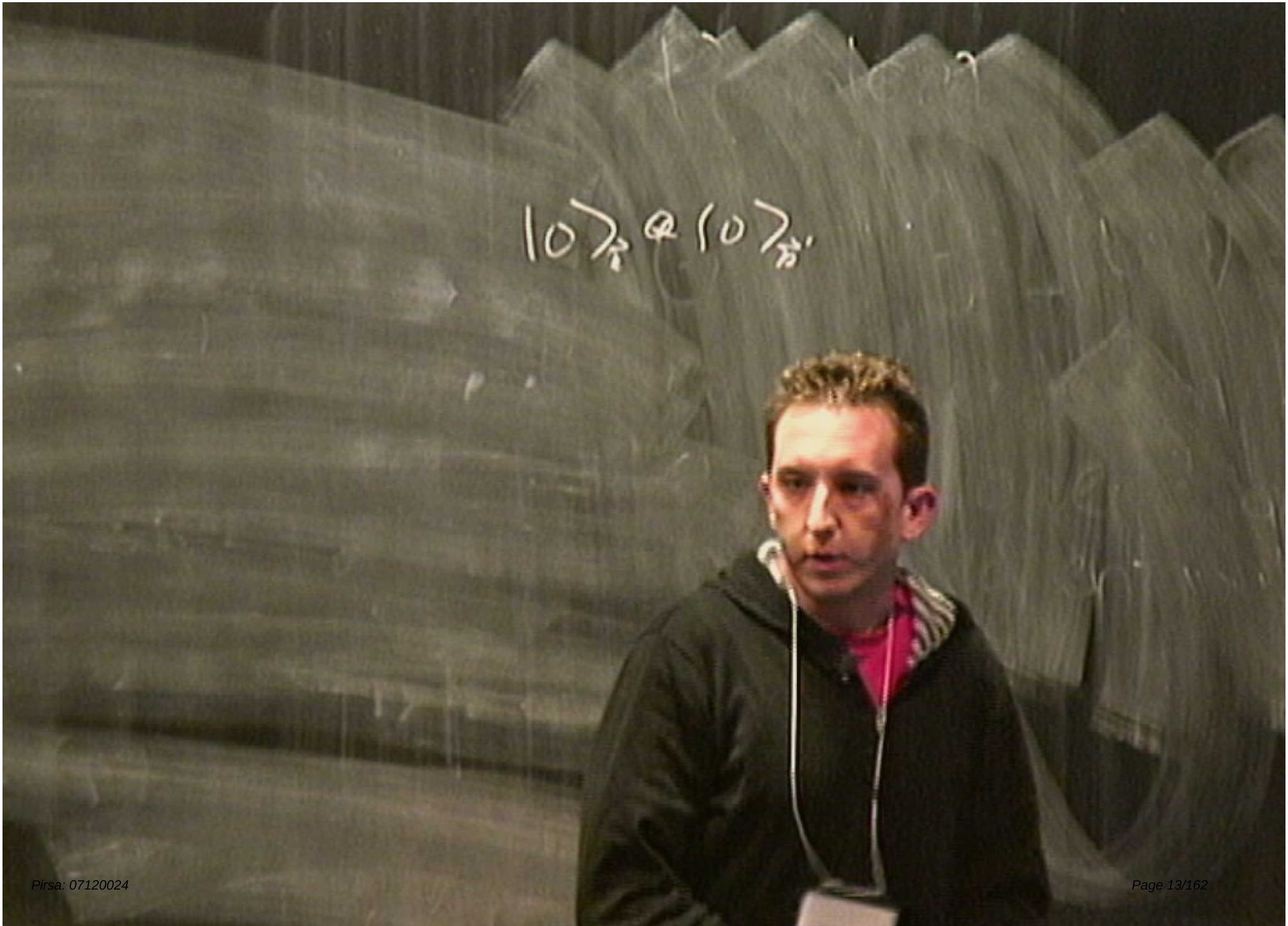

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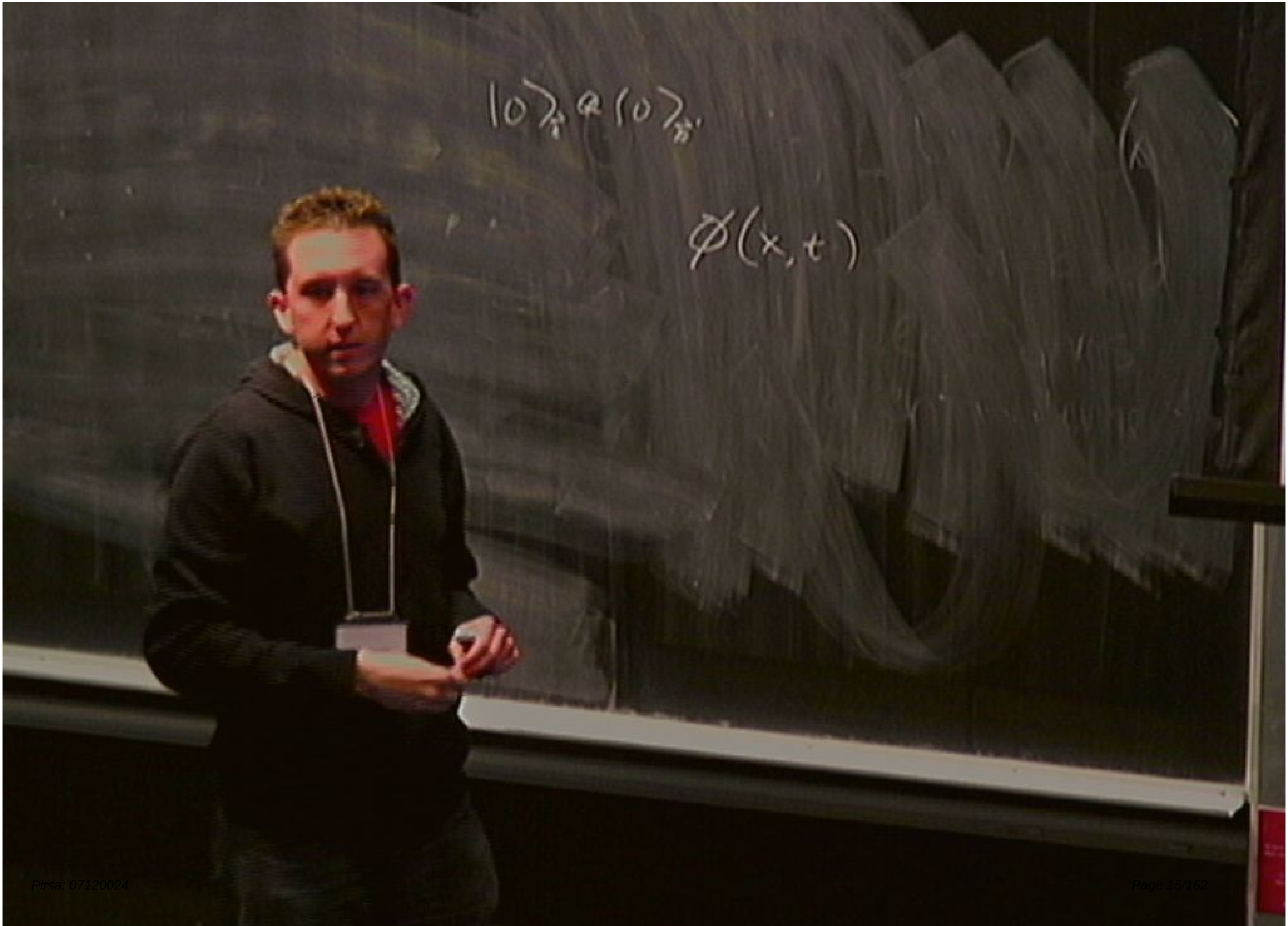
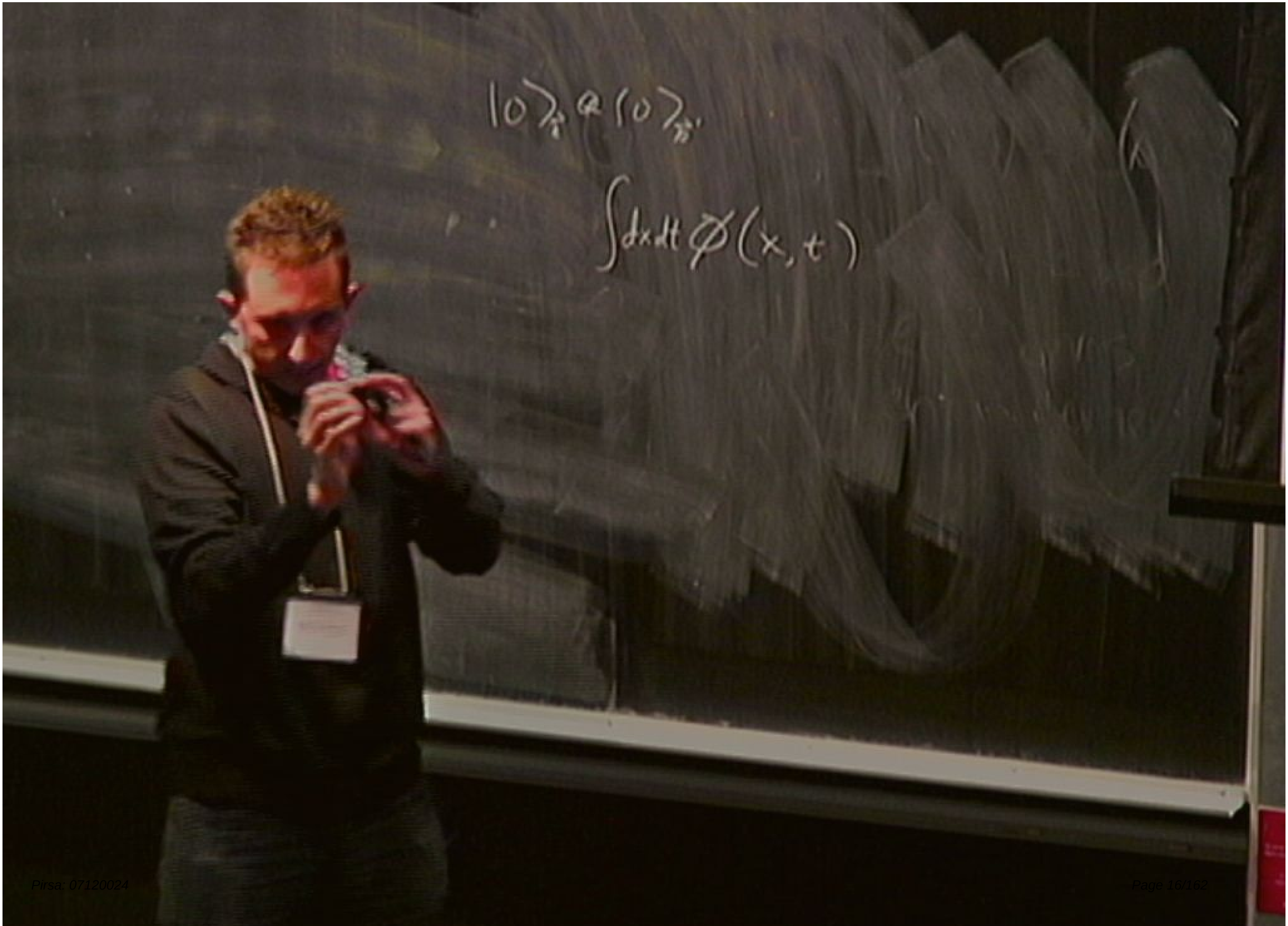

|0⟩_x ⊗ |0⟩_x'
φ(x, t)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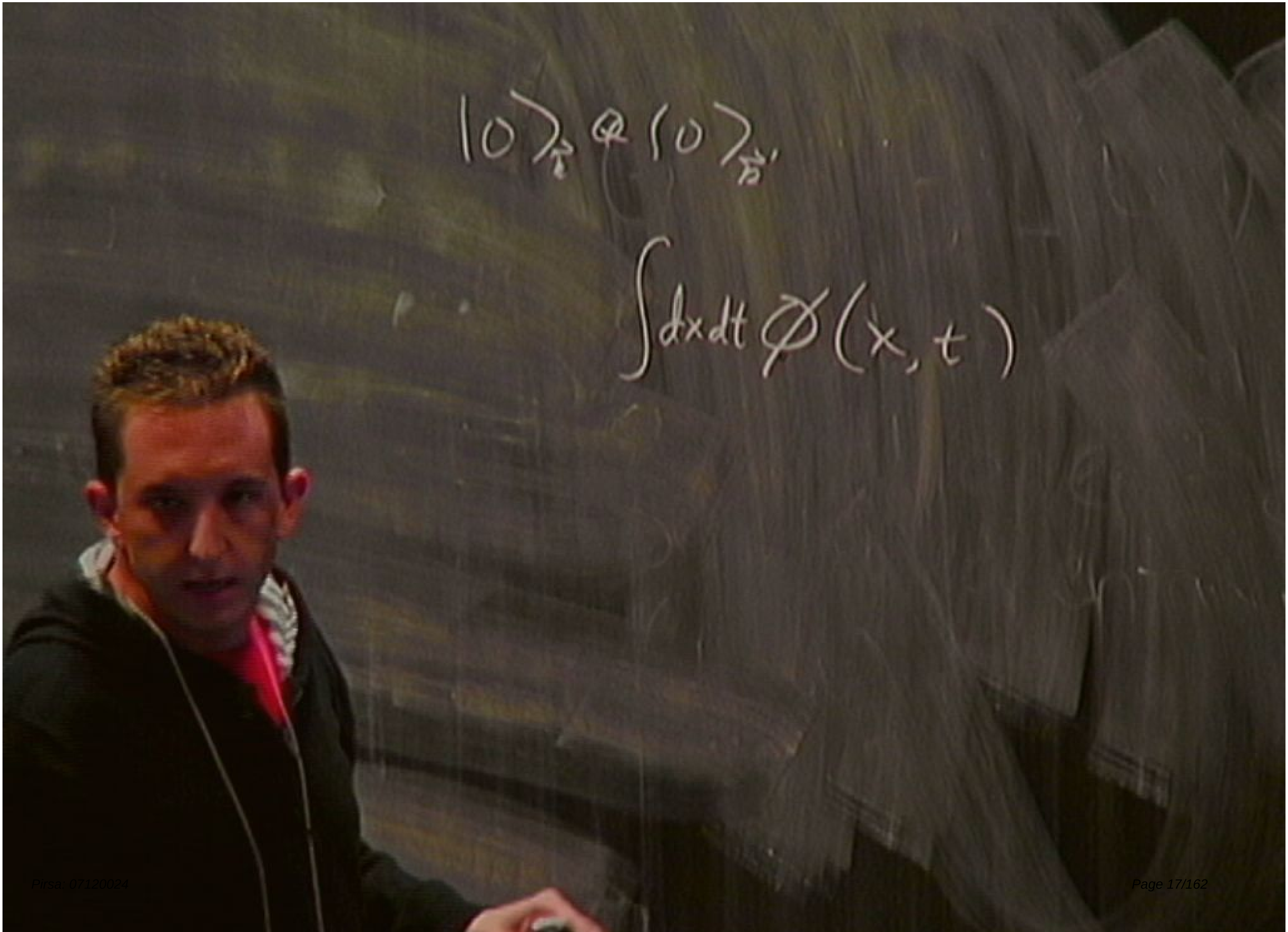
∫dxdt φ(x, t)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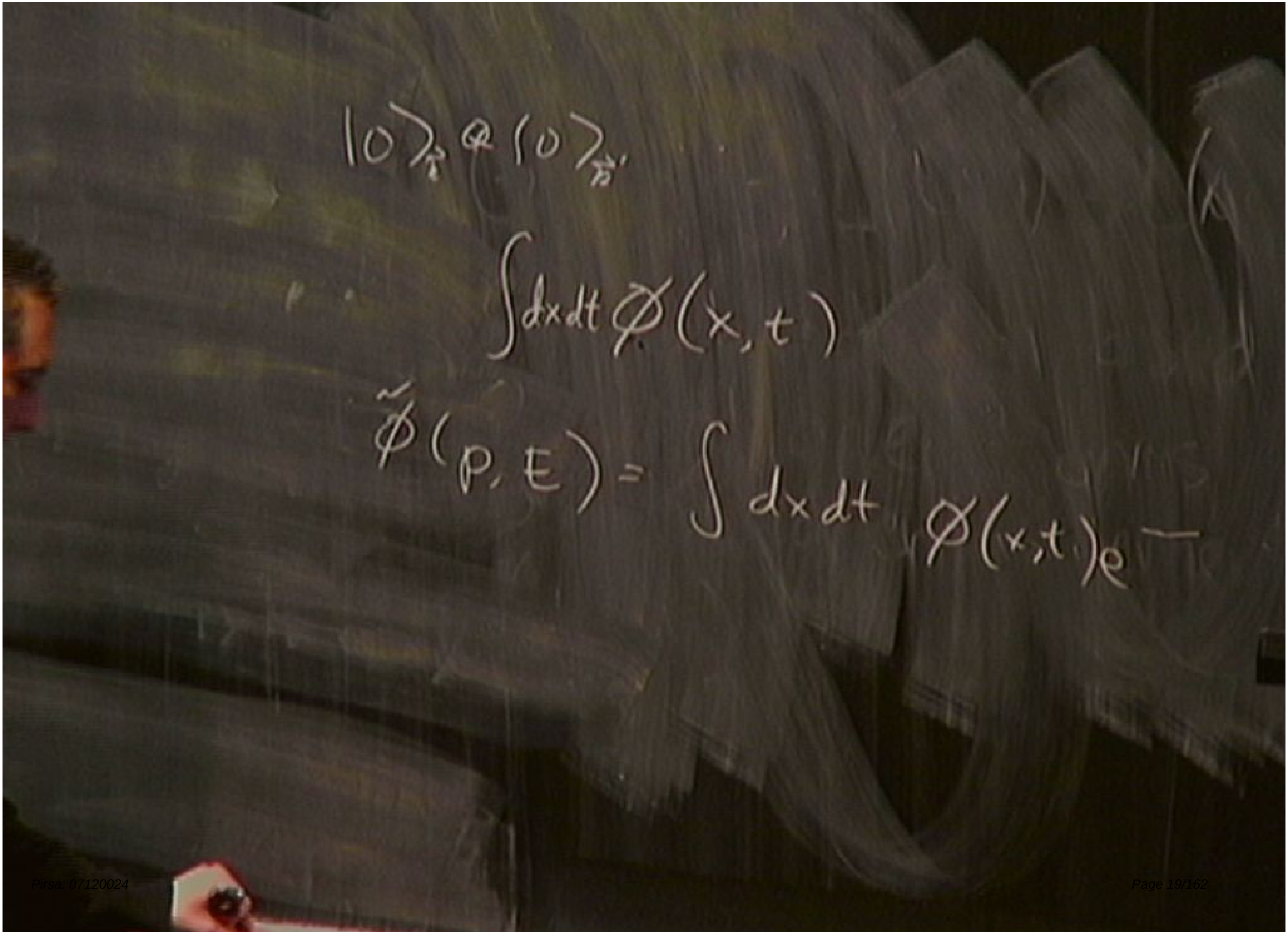

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    - Reznik, *et al.*

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- Entangling power therefore *measures properties of the field and of spacetime*

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  - But maybe…

Question

Can the universes be distinguished by their *entangling power*?

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- Equation of motion (m = 0):

$$[\Box_x + m^2 + \tfrac{1}{6}R(x)]\phi(x) = 0$$

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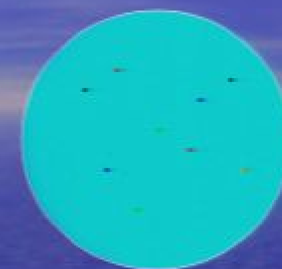

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  - $T_{GH} \sim$ (CMB temp) = 2.7 K $\rightarrow$ $\kappa^{-1} \sim 0.1$ mm

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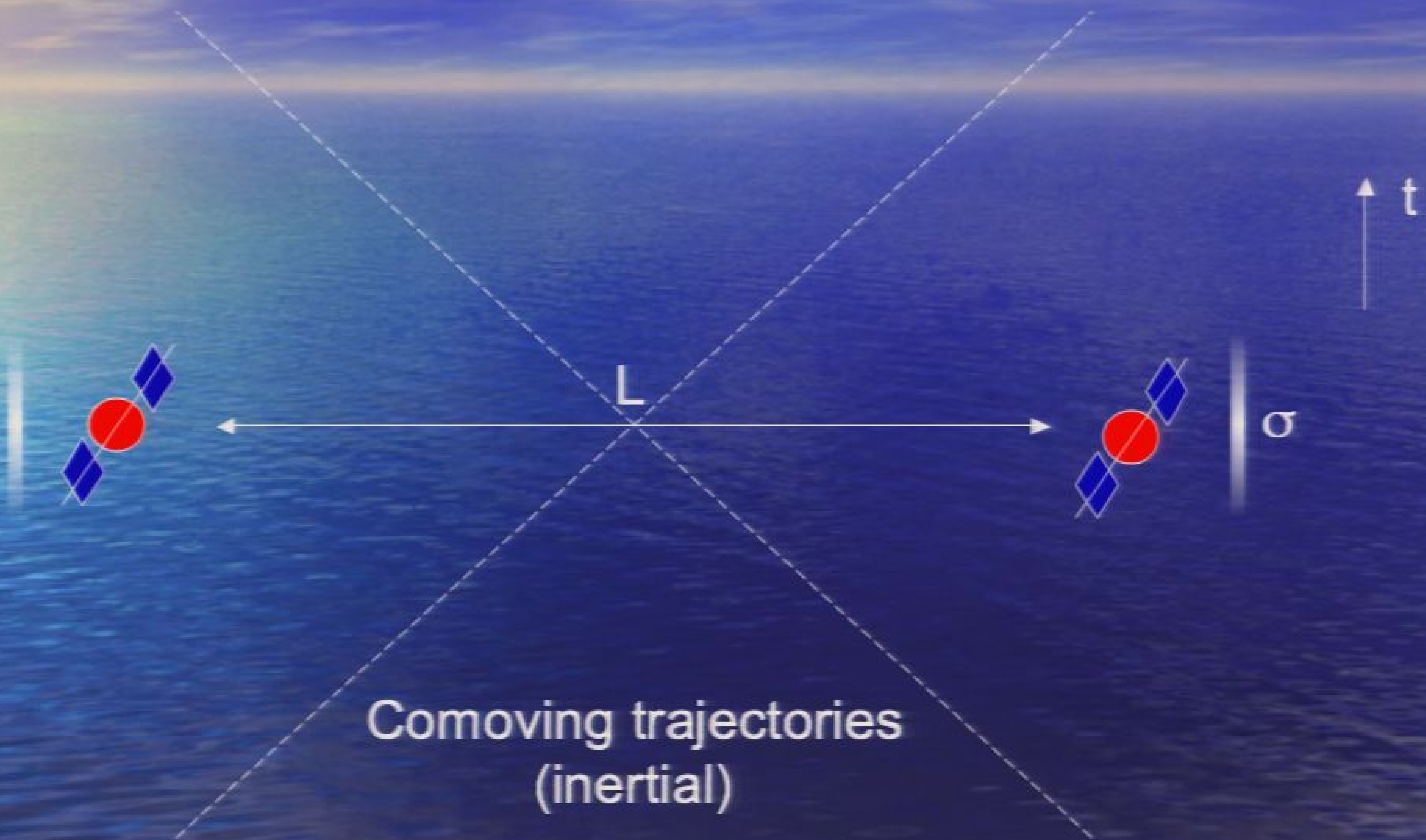

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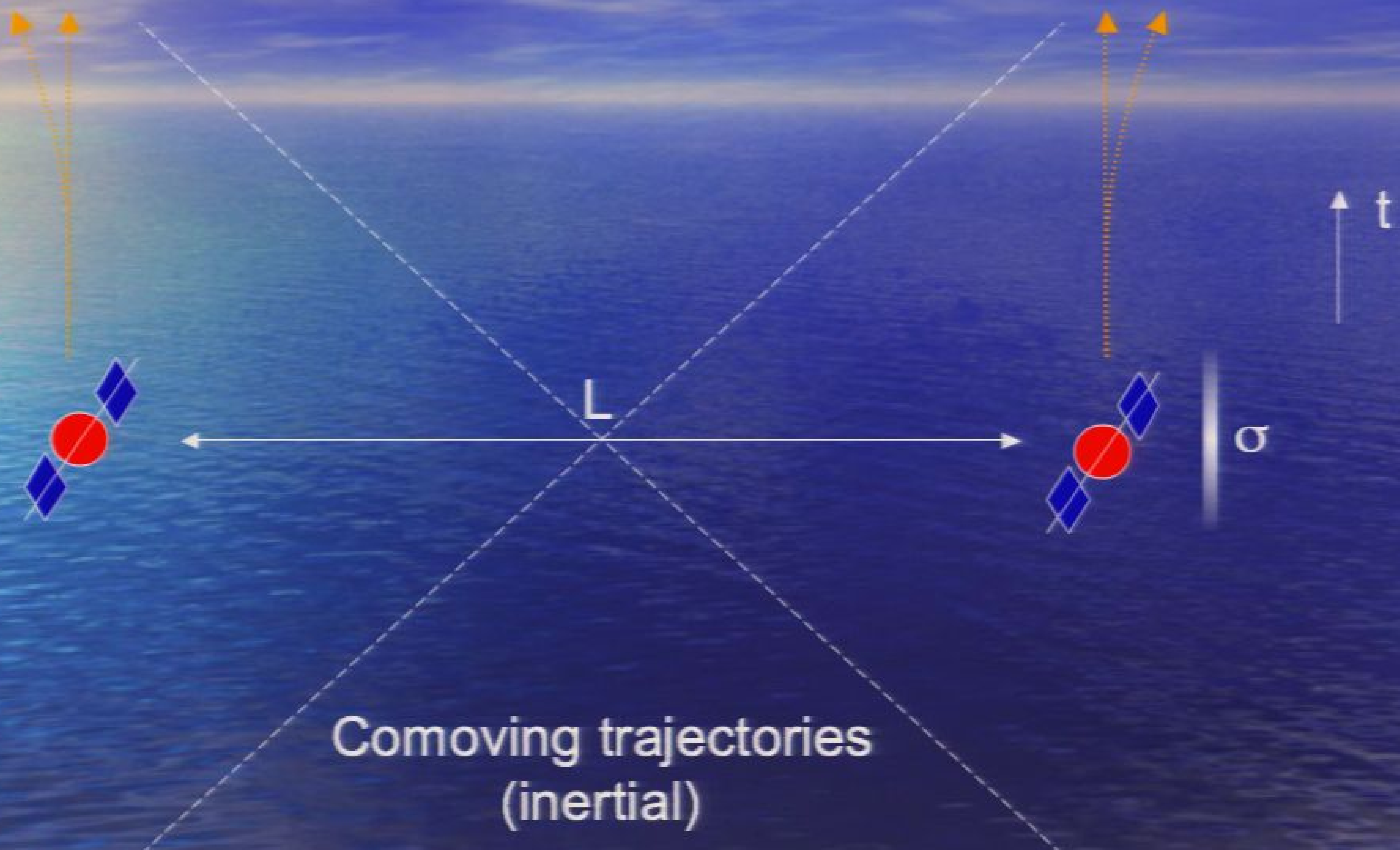
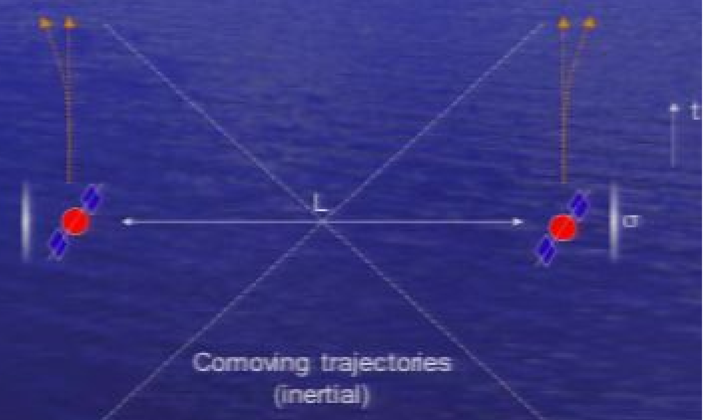


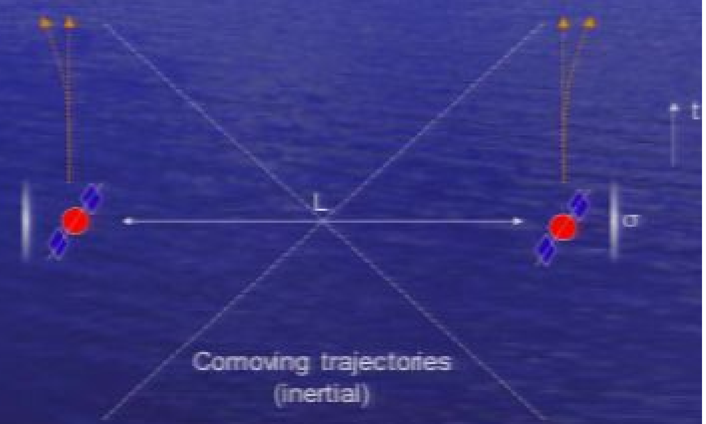
Comoving trajectories
(inertial)

Two detectors



Two detectors

- Qubits with tunable energy gap (Ω)



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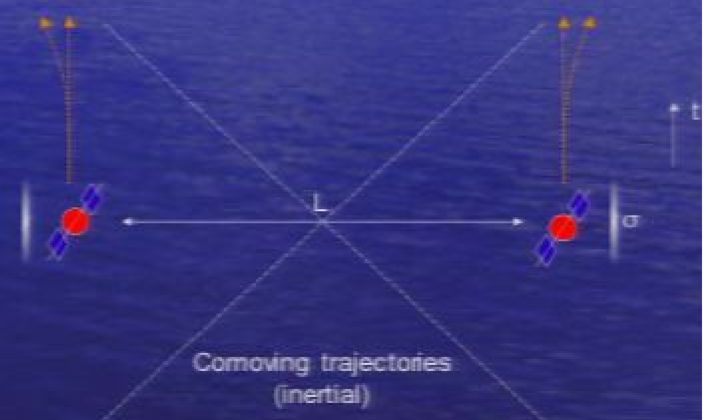

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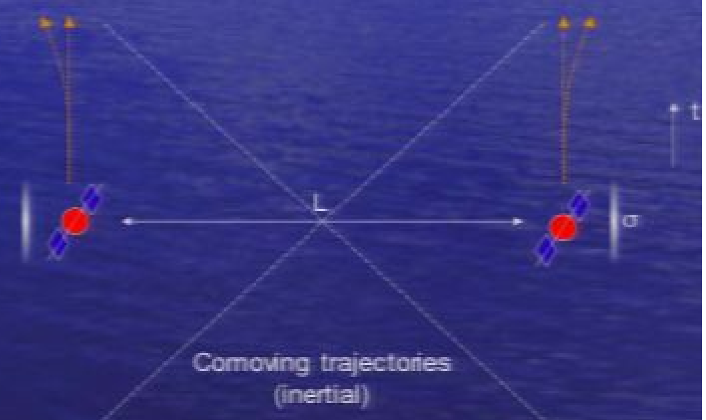

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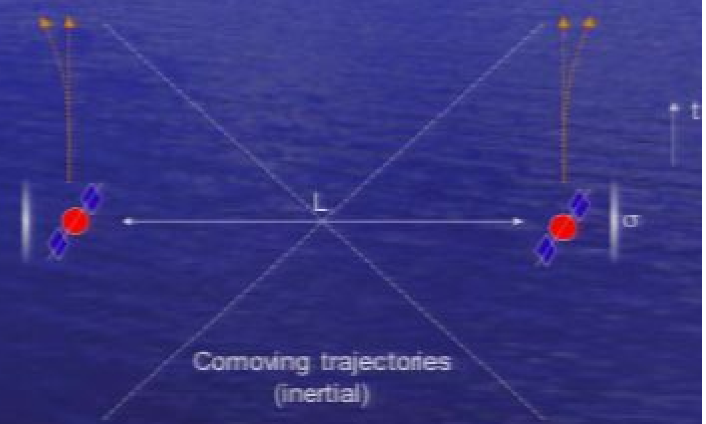

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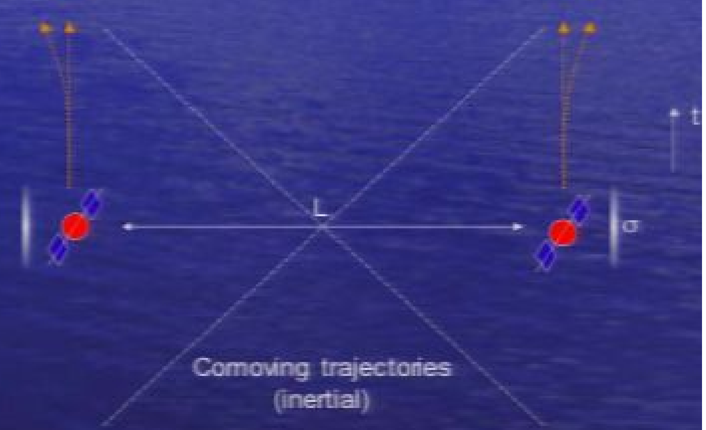

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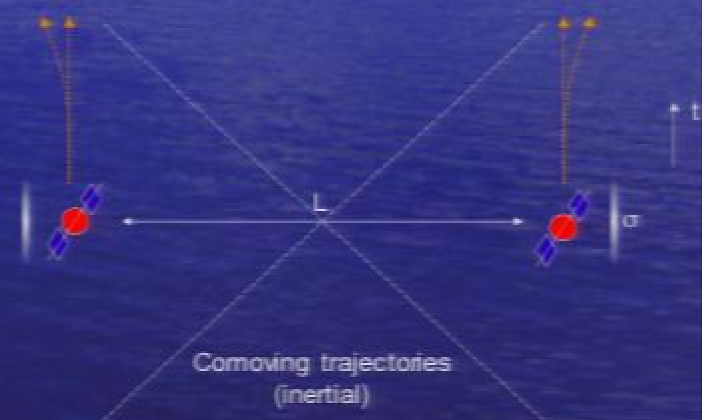
- Interaction Hamiltonian:



$$H_I(\tau) = \eta(\tau)\phi\big(x(\tau)\big)\left(e^{+i\Omega\tau}\sigma^+ + e^{-i\Omega\tau}\sigma^-\right)$$

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  - Use perturbation theory to calculate these

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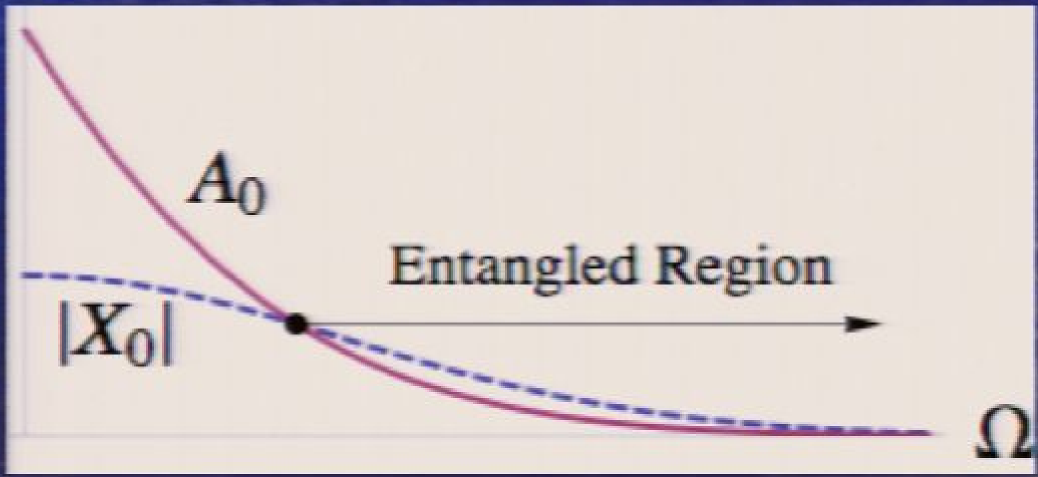

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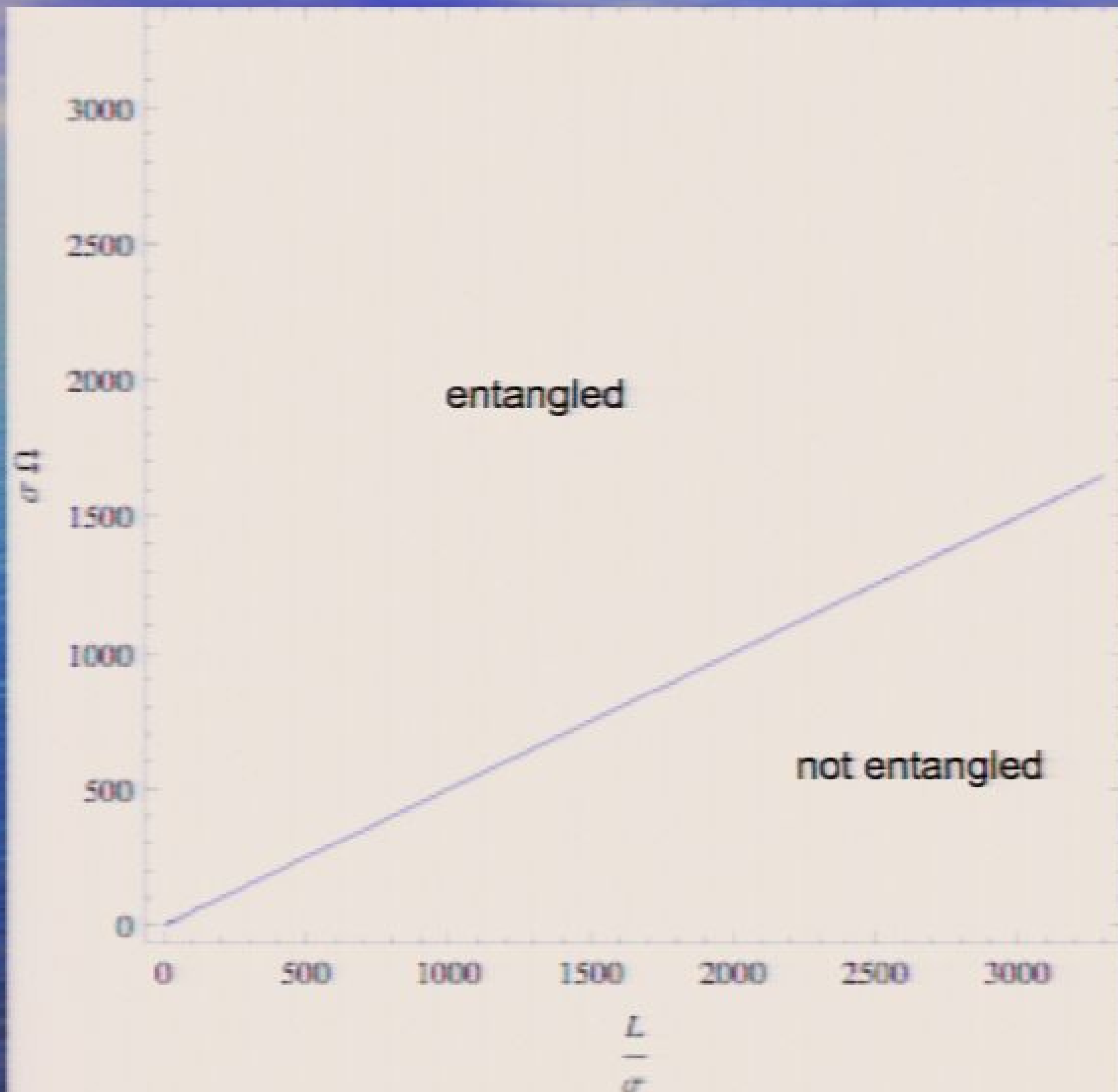

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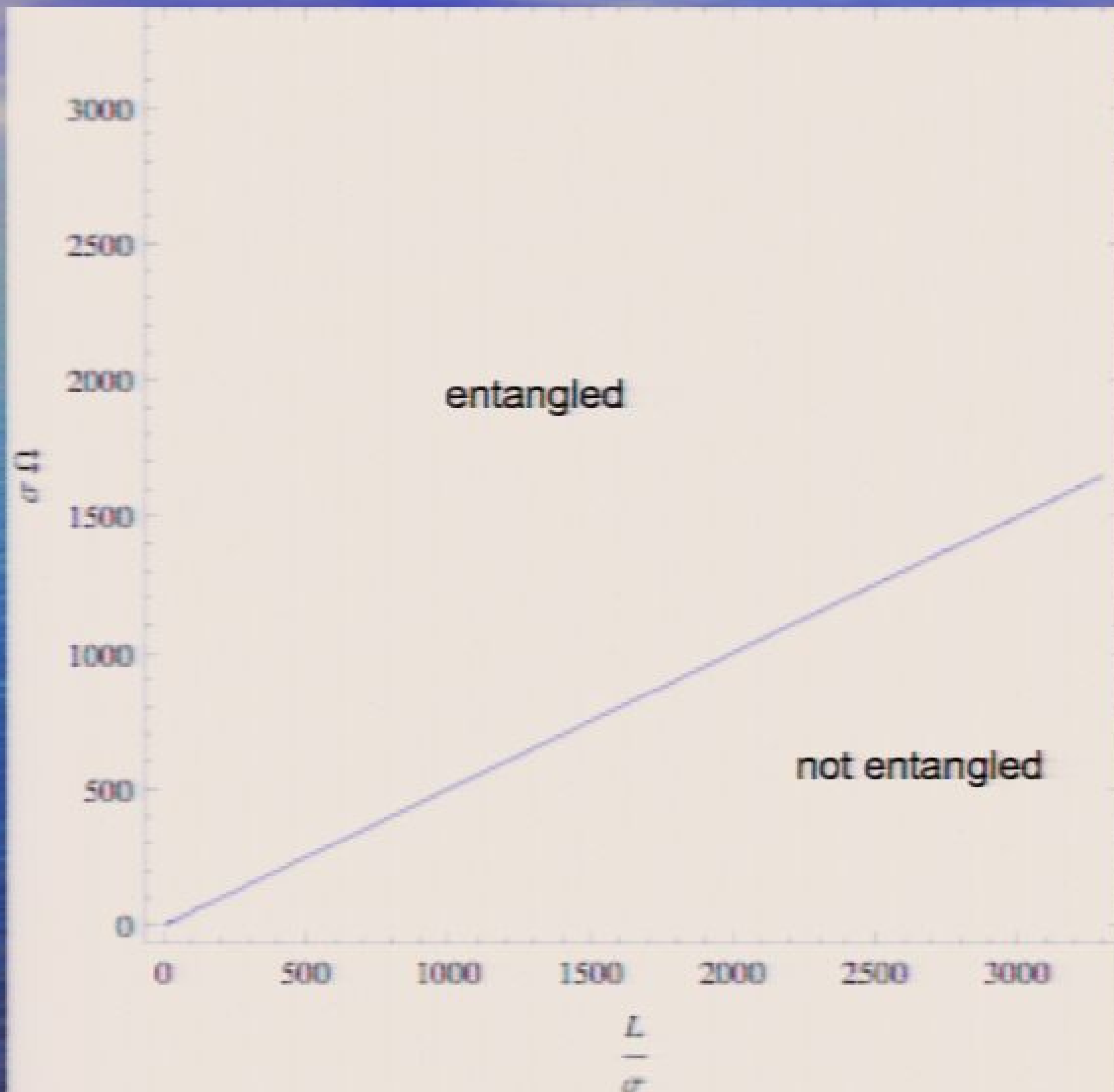
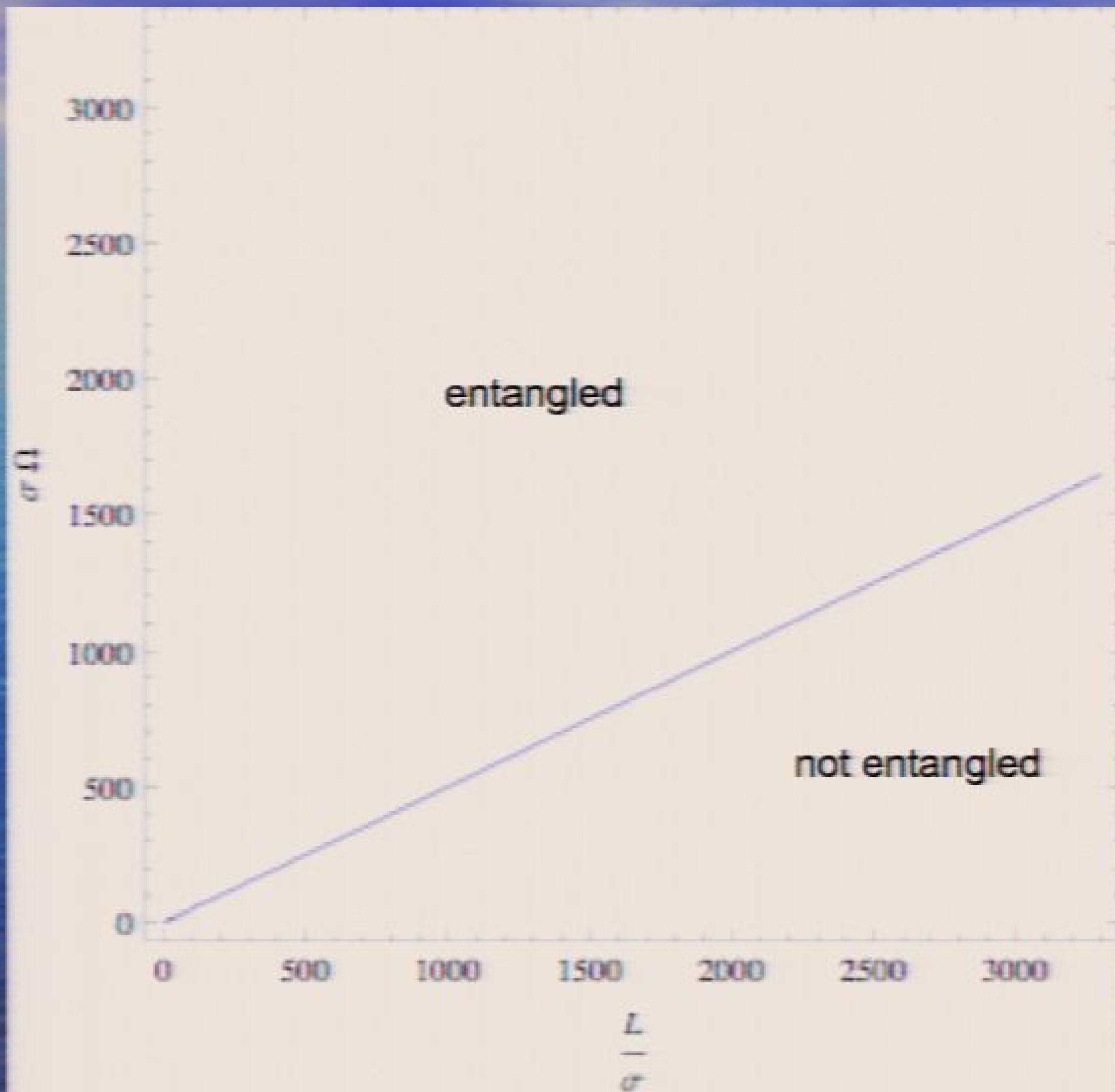


Flat thermal state (Minkowski, T>0)

Flat vacuum result



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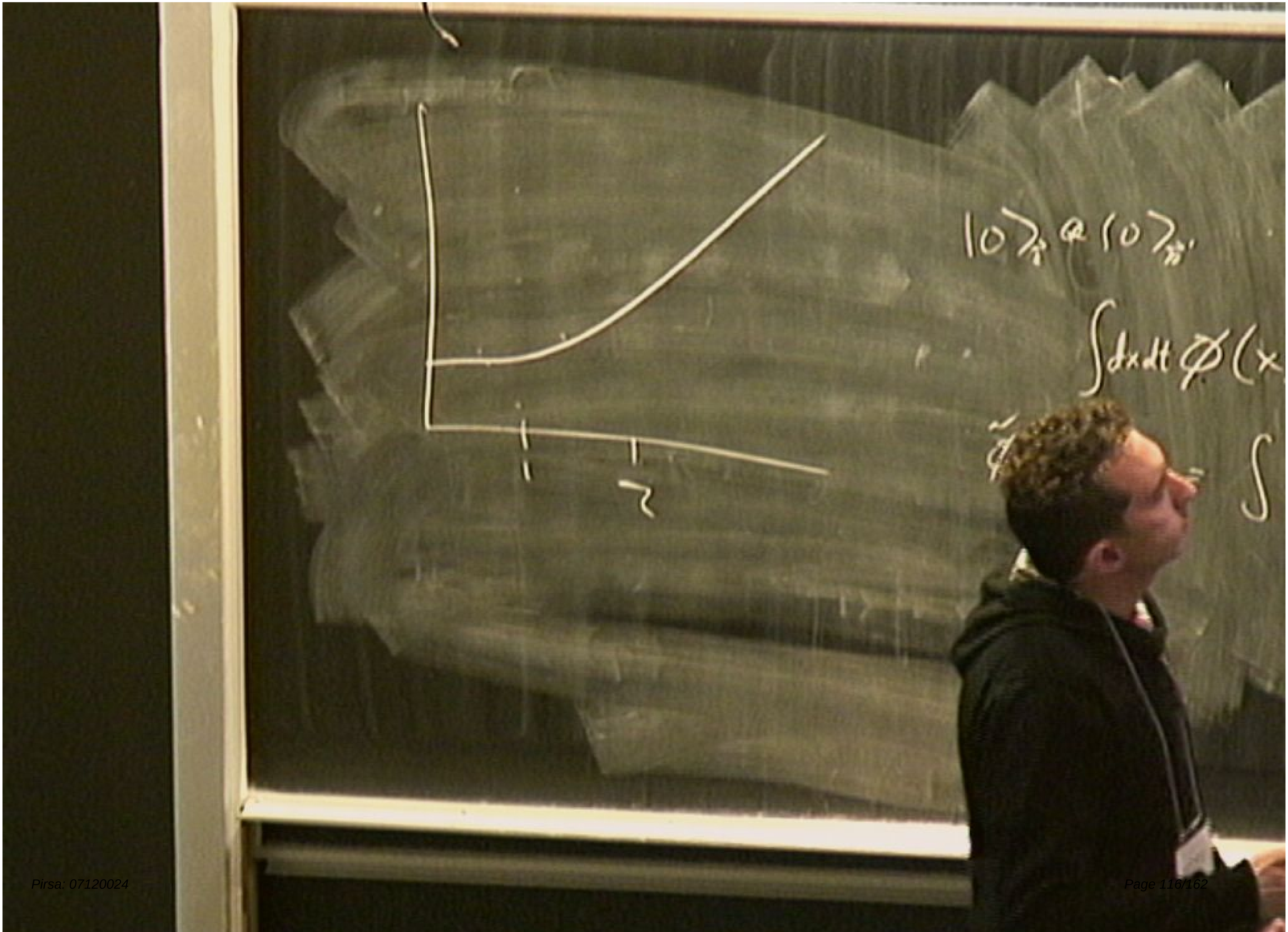
1
2

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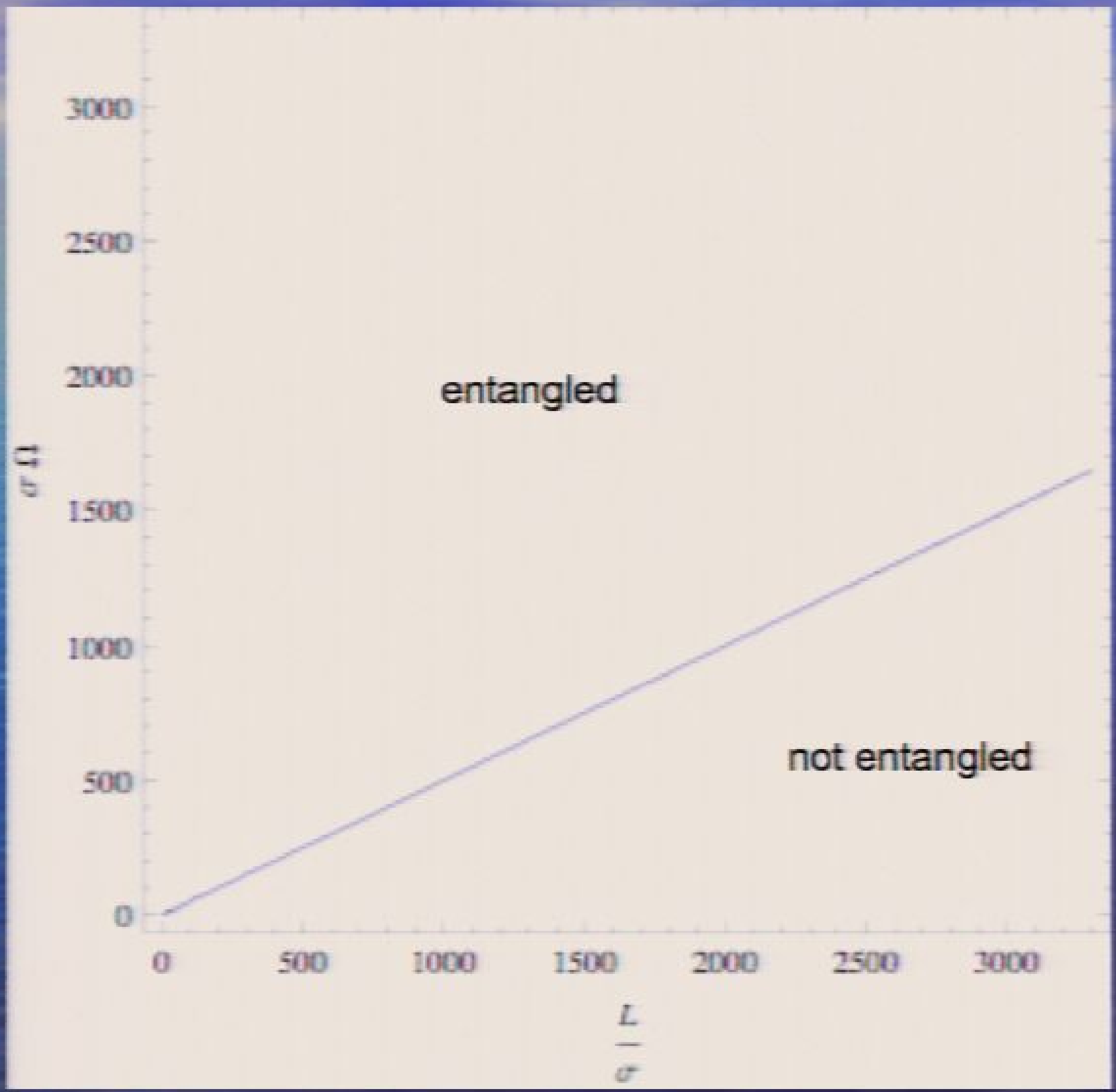

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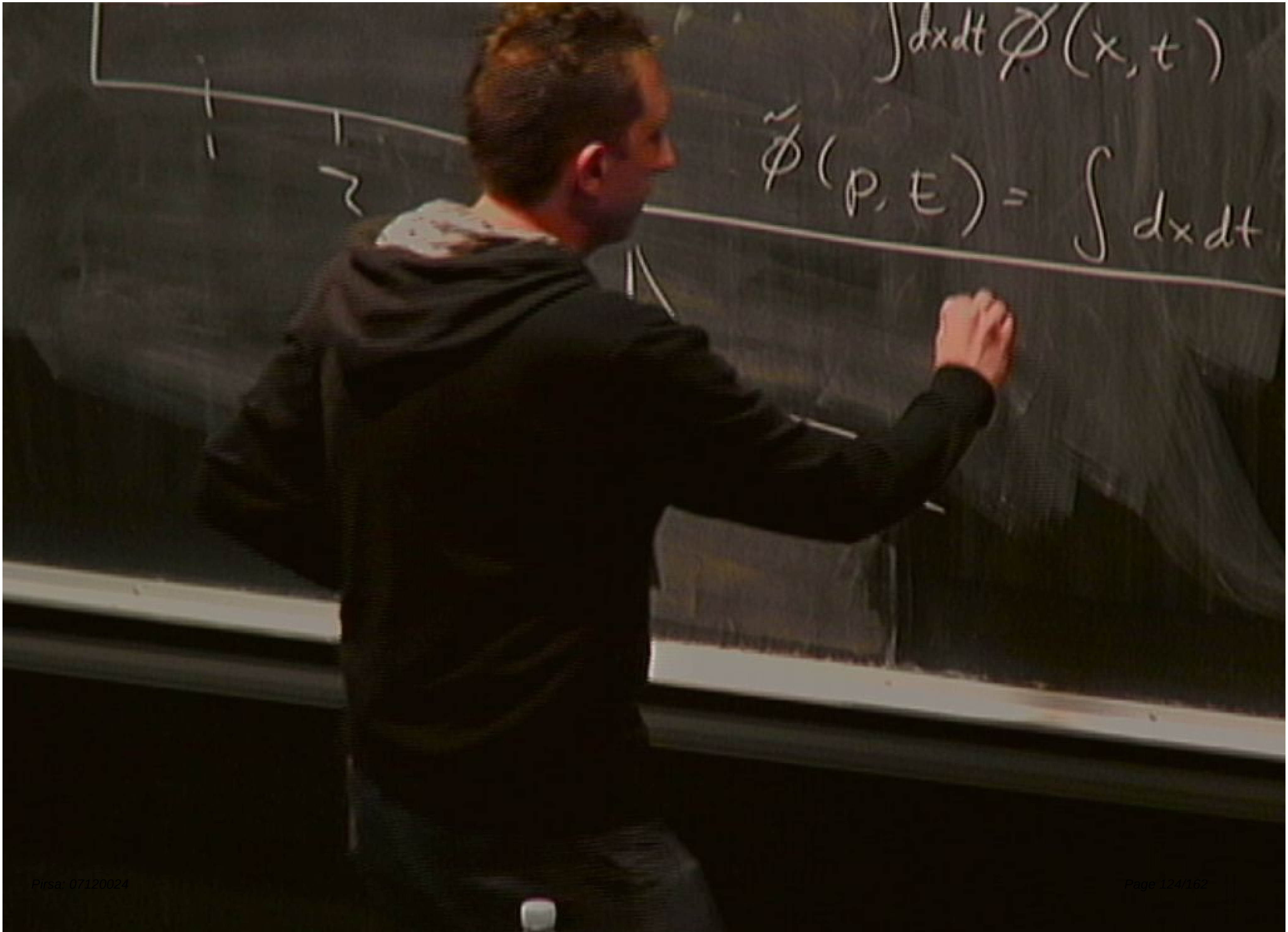
  - Since $g(L)$ decreases monotonically with L, entanglement is restricted to $L < L_{max}$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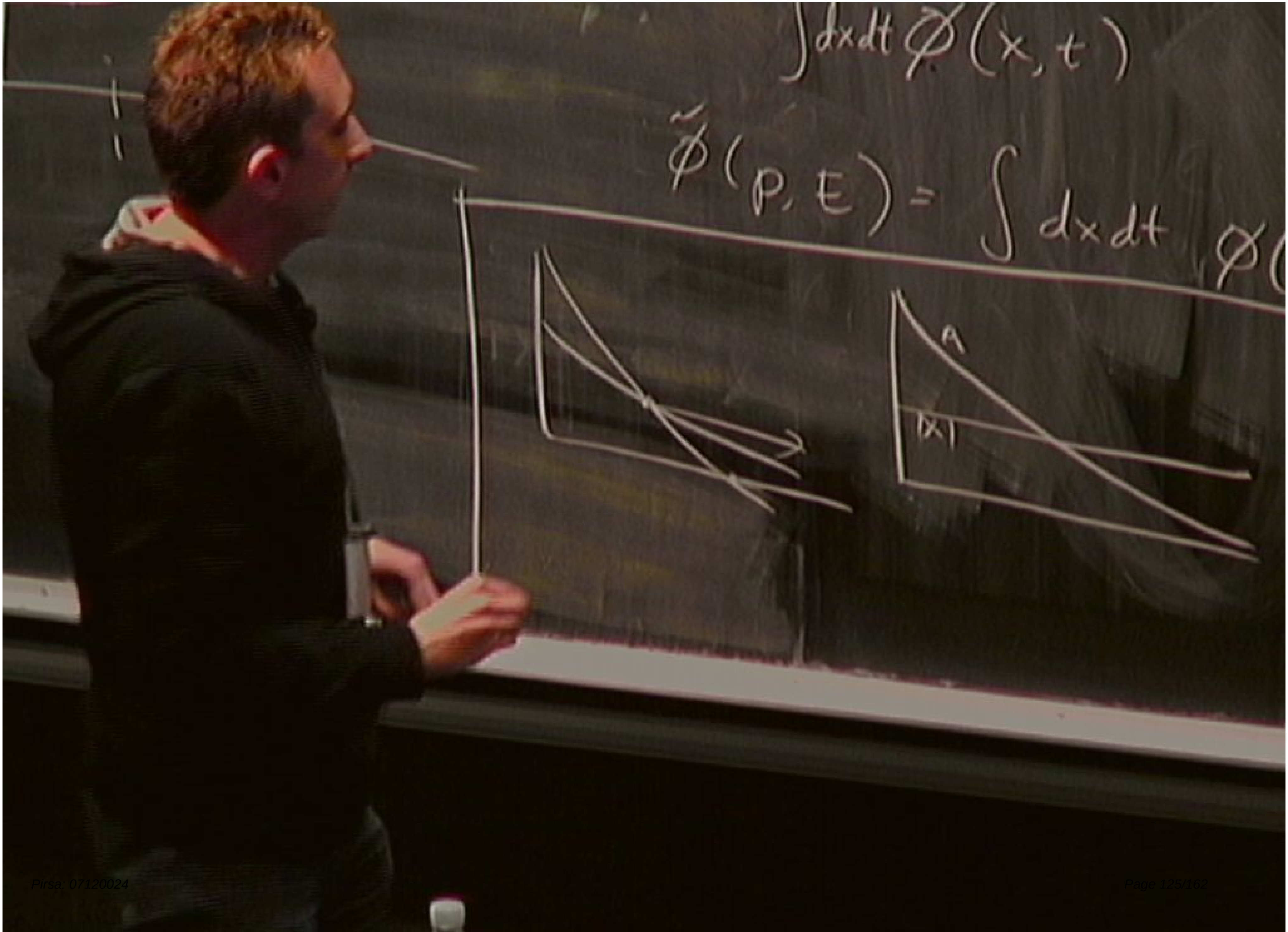
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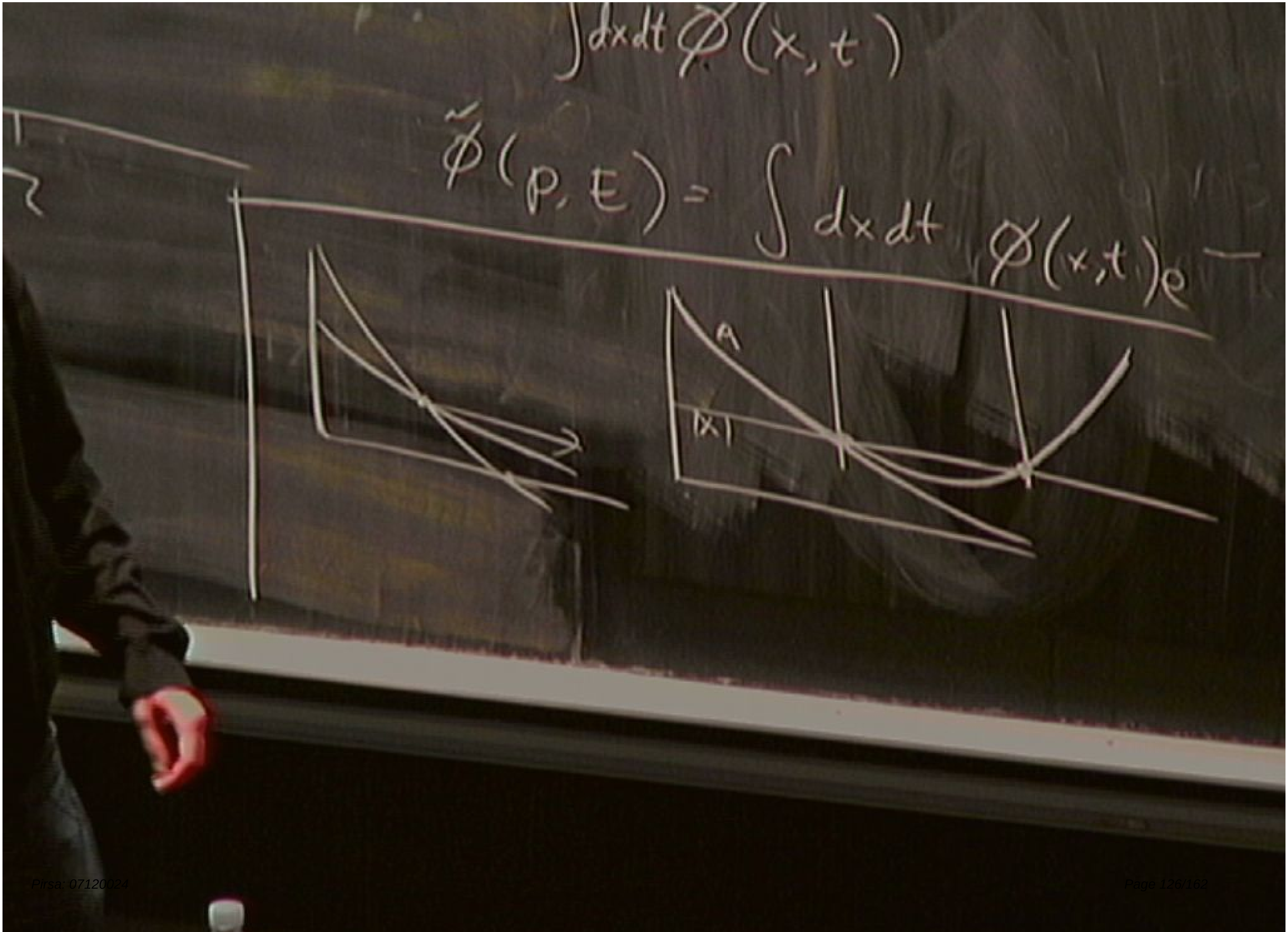
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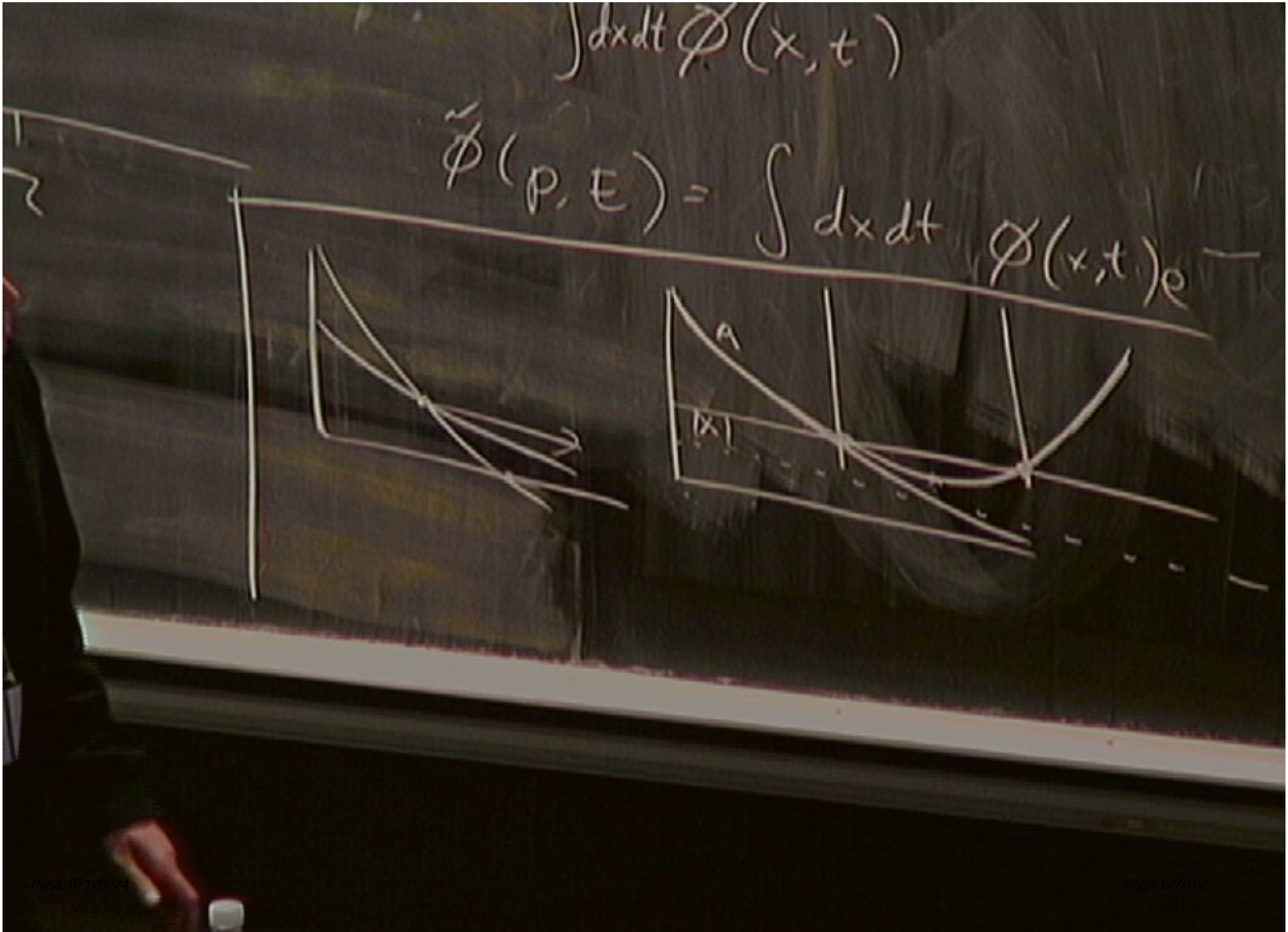
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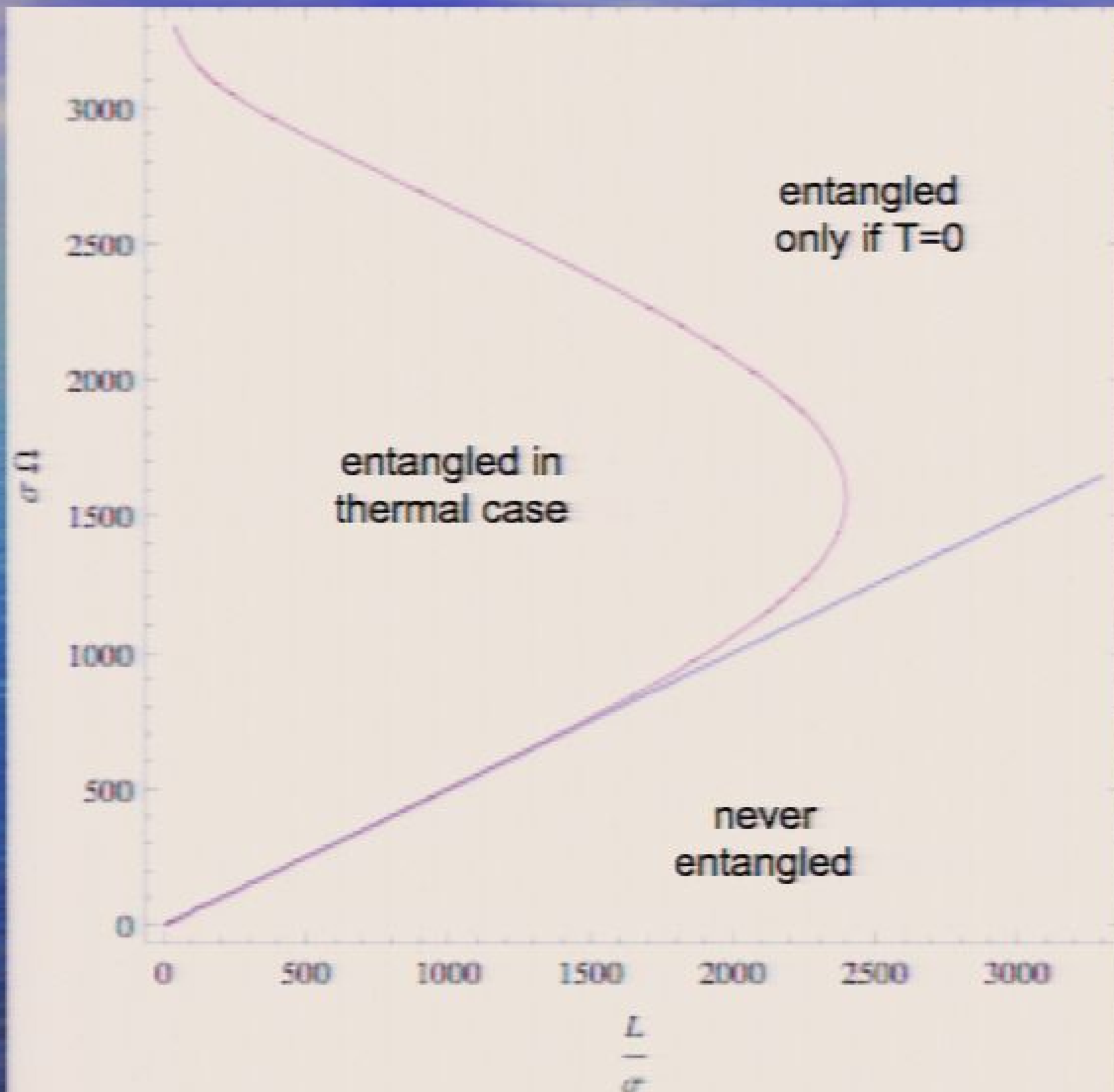
Flat spacetime



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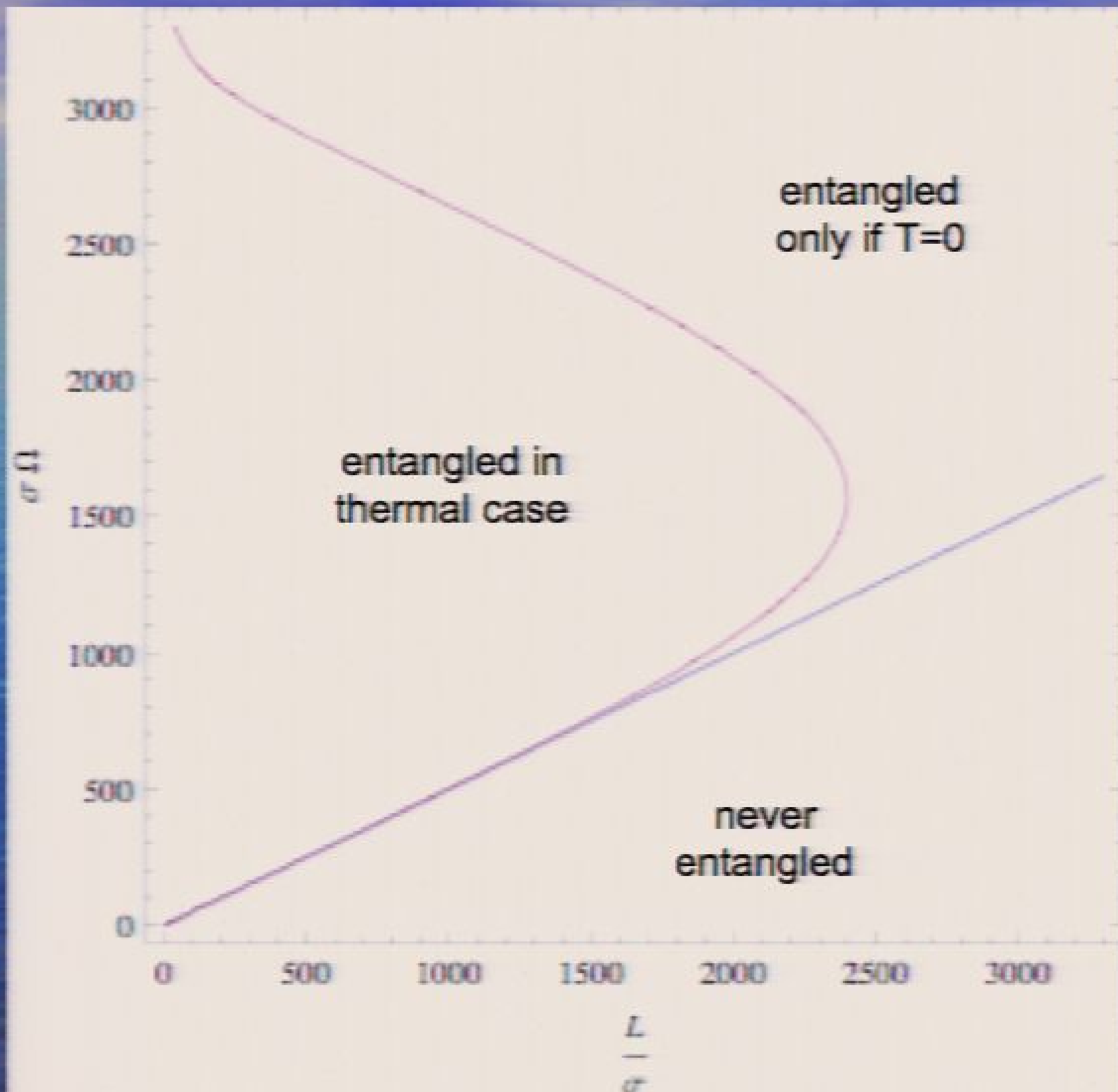

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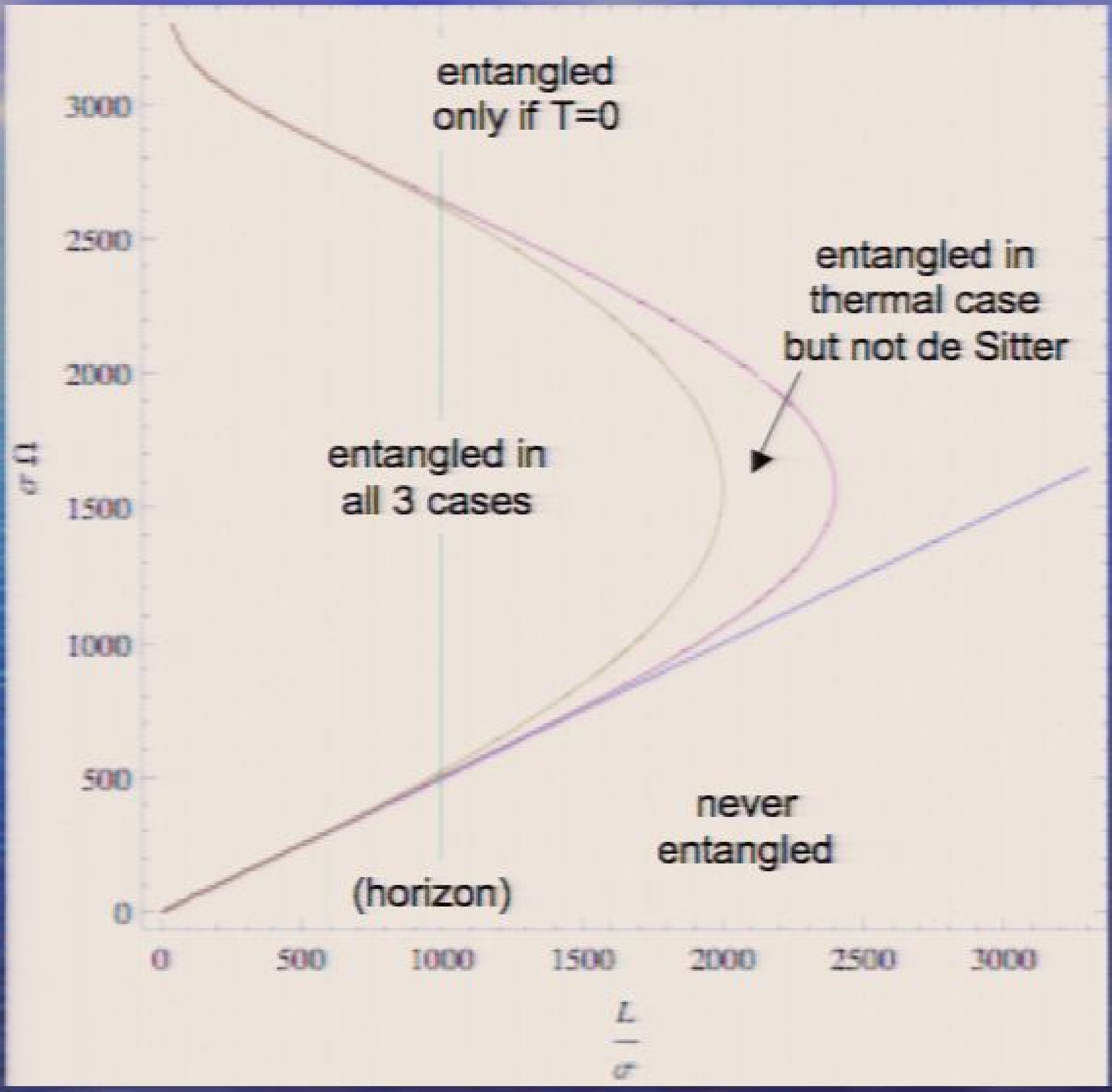

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- de Sitter vacuum and a heated field in flat spacetime have *exactly the same* effect on a single, inertial detector
- Can be distinguished by *entanglement*
- de Sitter vacuum: *less* entangling power than Minkowski thermal state ($T = T_{GH}$)
- Both have less power than the Minkowski vacuum (which has the least local noise)

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  - Other types of curvature

Acknowledgments

- People
  - John Preskill
  - Sean Carroll
  - Gerard Milburn
  - Carl Caves
- Organizations
  - Caltech IQI
  - NSF
  - DoD

Thank you!