Title: Symmetry Principles in Physics - Lecture 1

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Abstract:

The role of symmetries in physics: variations on a theme

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Emmy Noether 1882-1935

"She was not clay, pressed by the artistic hands of God into a harmonious form, but rather a chunk of human primary rock into which he had blown his creative breath of life."
Hermann Weyl 1935

Topics

- Distinctions and definitions; the 1905 Einstein relativity principle and its historical precedents; Keinstein vs Einstein vs Ignatowski
- Should SR be a template for a fundamental reformulation of QM?
- Noether's first theorem. Some recent applications in QM and EM
- Noether's second theorem; Einstein's 1916 anticipation
- Galilean covariance in QM
- Time reversal invariance, and the birth of statistical mechanics

Galileo's ship

"Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speeds to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and in throwing anything to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though there is no doubt that when the ship is standing still everything must happen this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover that not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still."

Galileo in his 1632 *Dialogue Concerning the Two Chief World Systems*. (Salviati, Second day)

Galileo's relativity principle

- Distinct from the principle of inertia
- How general?
- How does it differ from the Newtonian/Einsteinian principles?
- Absence of any reference to nature of coordinate transformations for "boosts"
- Acts as contraint on laws of fundamental interactions, like the laws of thermodynamics
- Rules out Galileo's own theory of tides

First distinction

"Phenomenological Symmetries"

Relativity principle (boosts)
Isotropy of space (rotations)
Homogeneity of space, time (translations)

like principles of thermodynamics

"Symmetry group principles"

Lorentz covariance (10 parameter inhomogeneous Lorentz group)
Galilean covariance
Gauge invariance
General covariance

specified form of transformations

Choice depends on context: see Einstein's 1905 special relativity

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Second distinction

"Global Symmetries"

Transformations depend on "constant" parameters

Space-time symmetries related to
boosts
rotations
translations

Global phase in QM

Subject of Noether's first theorem

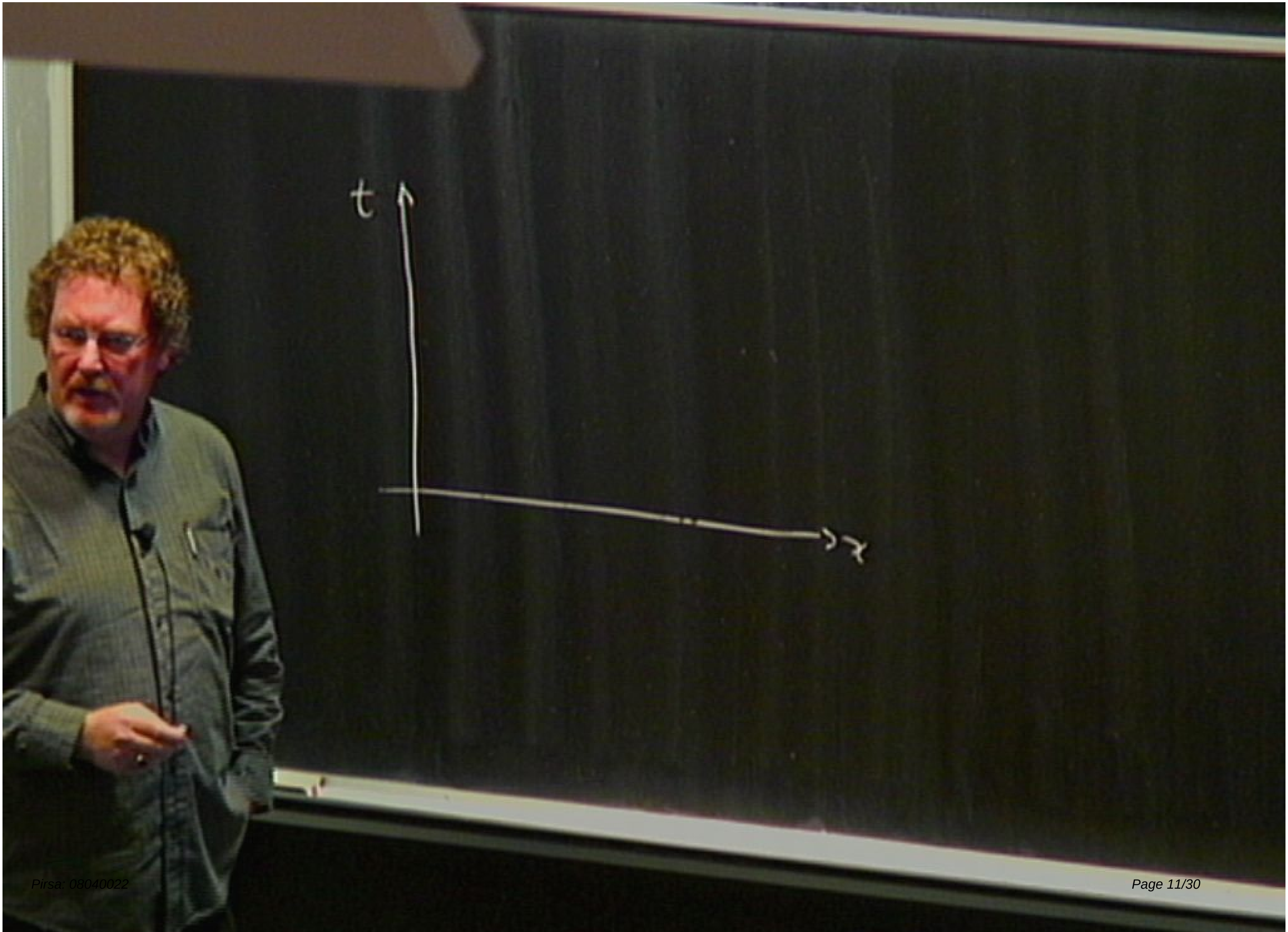
"Local symmetries"

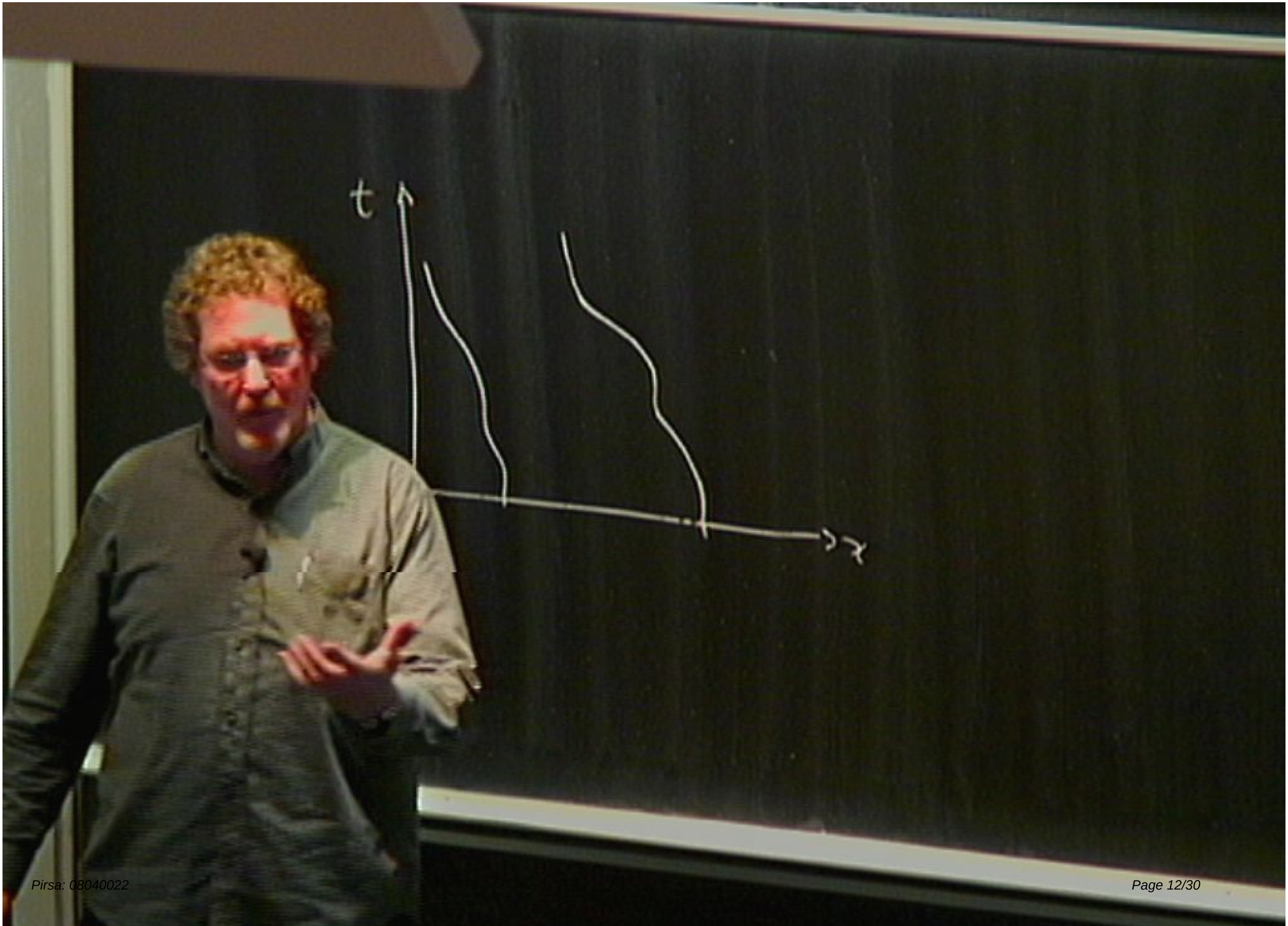
Transformations depend on functions of *x*, *t*

Gauge invariance
General covariance

spectre of underdetermination

Subject of Noether's second theorem


t
x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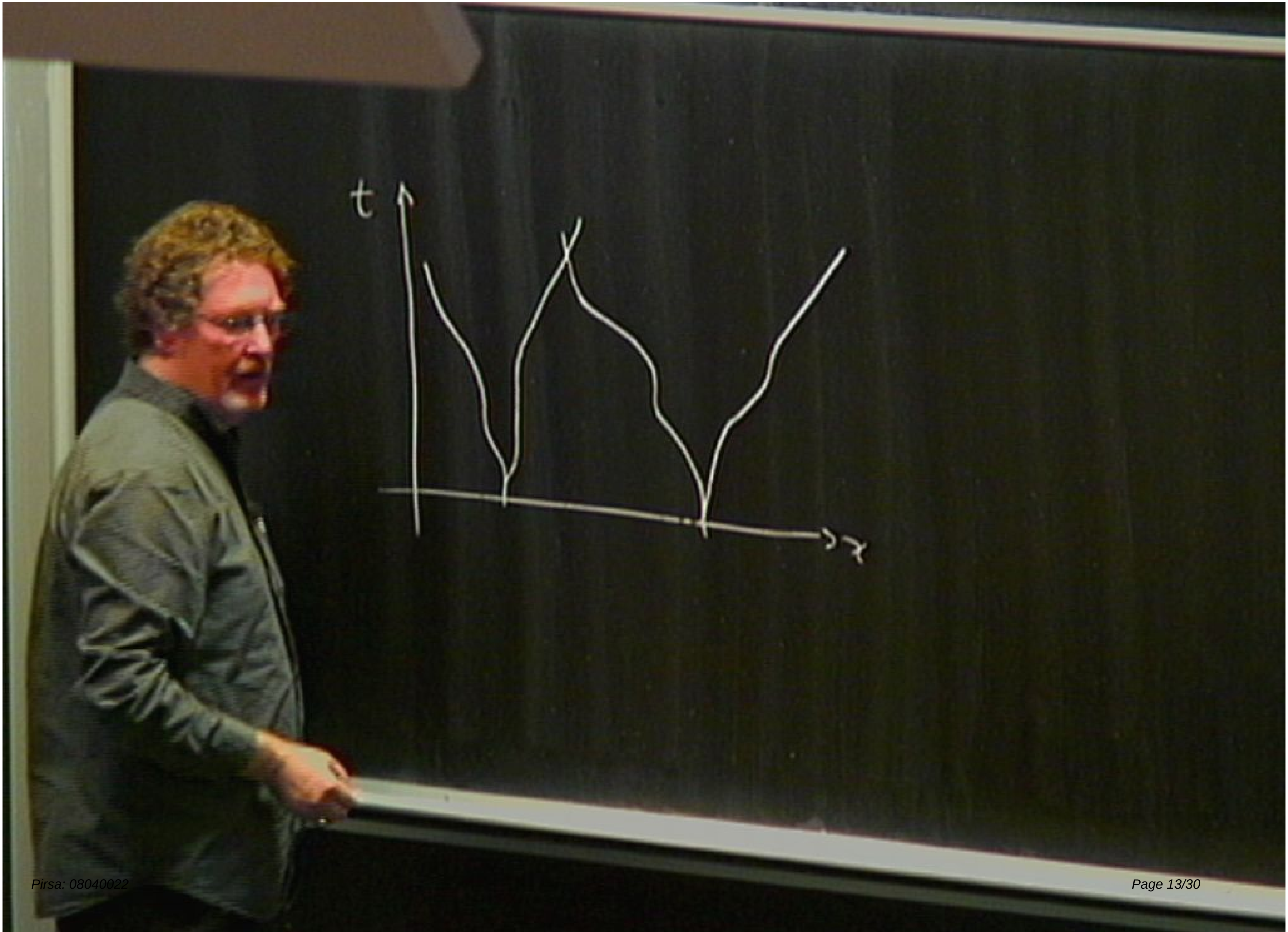
t
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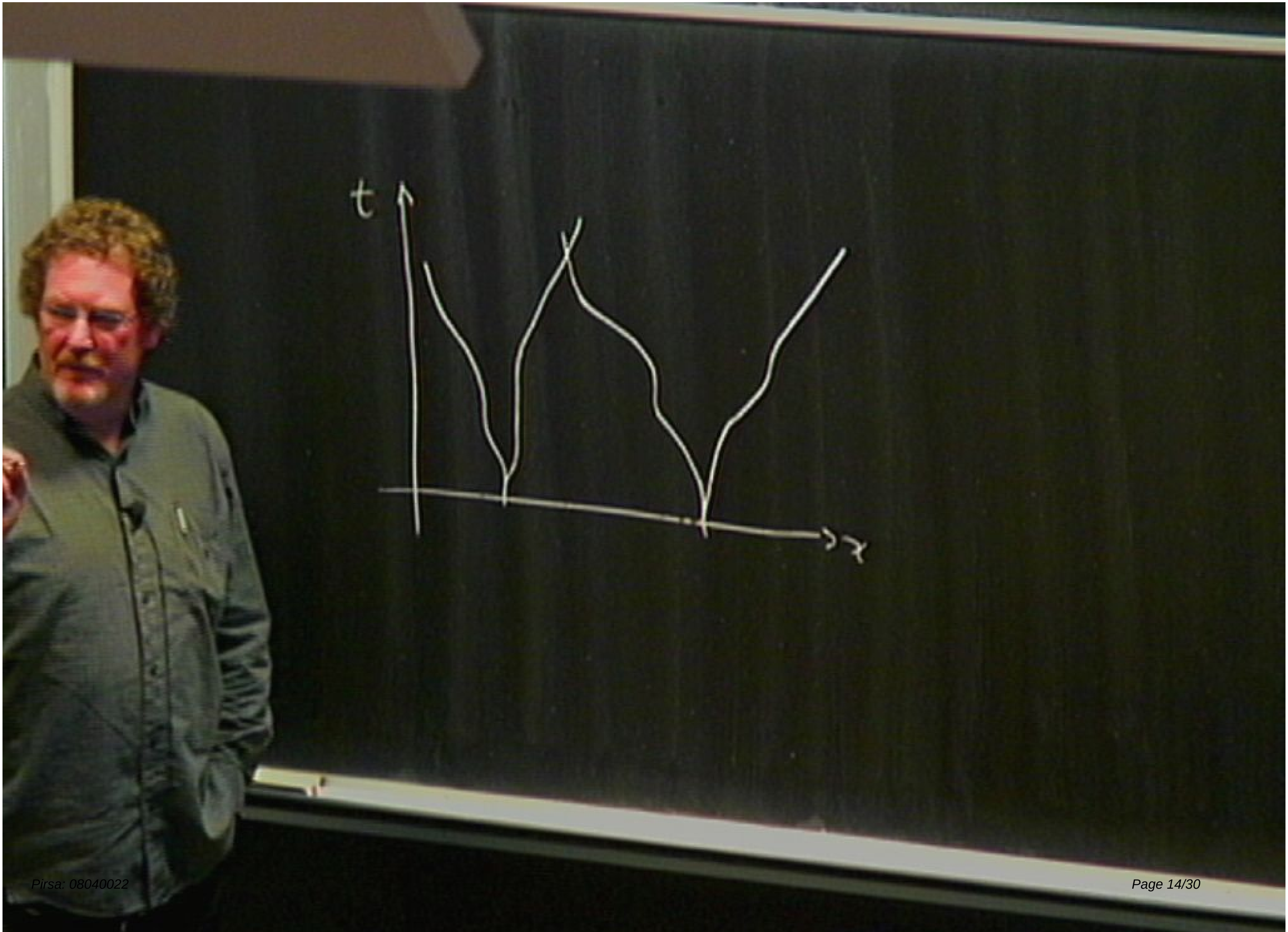
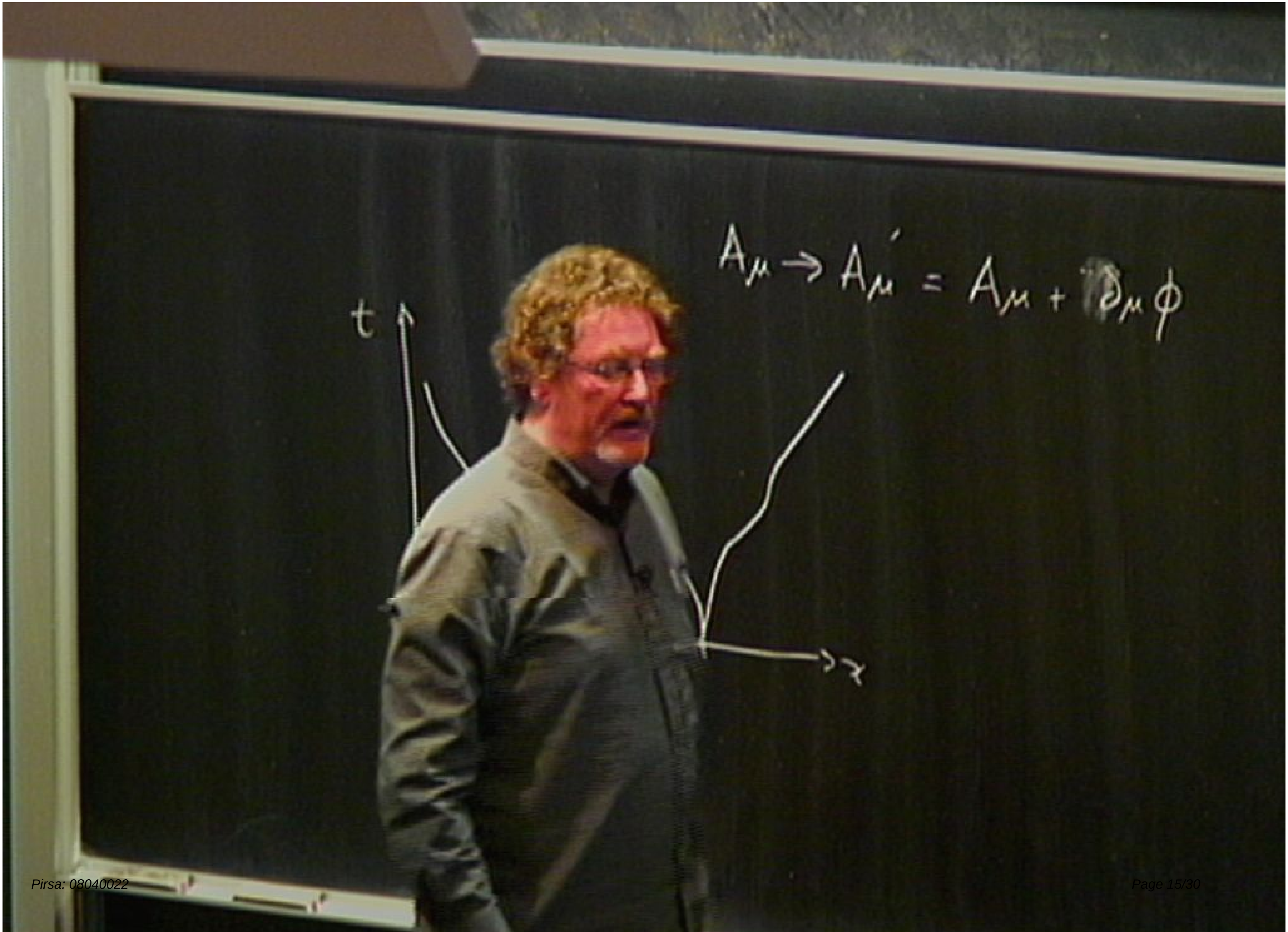
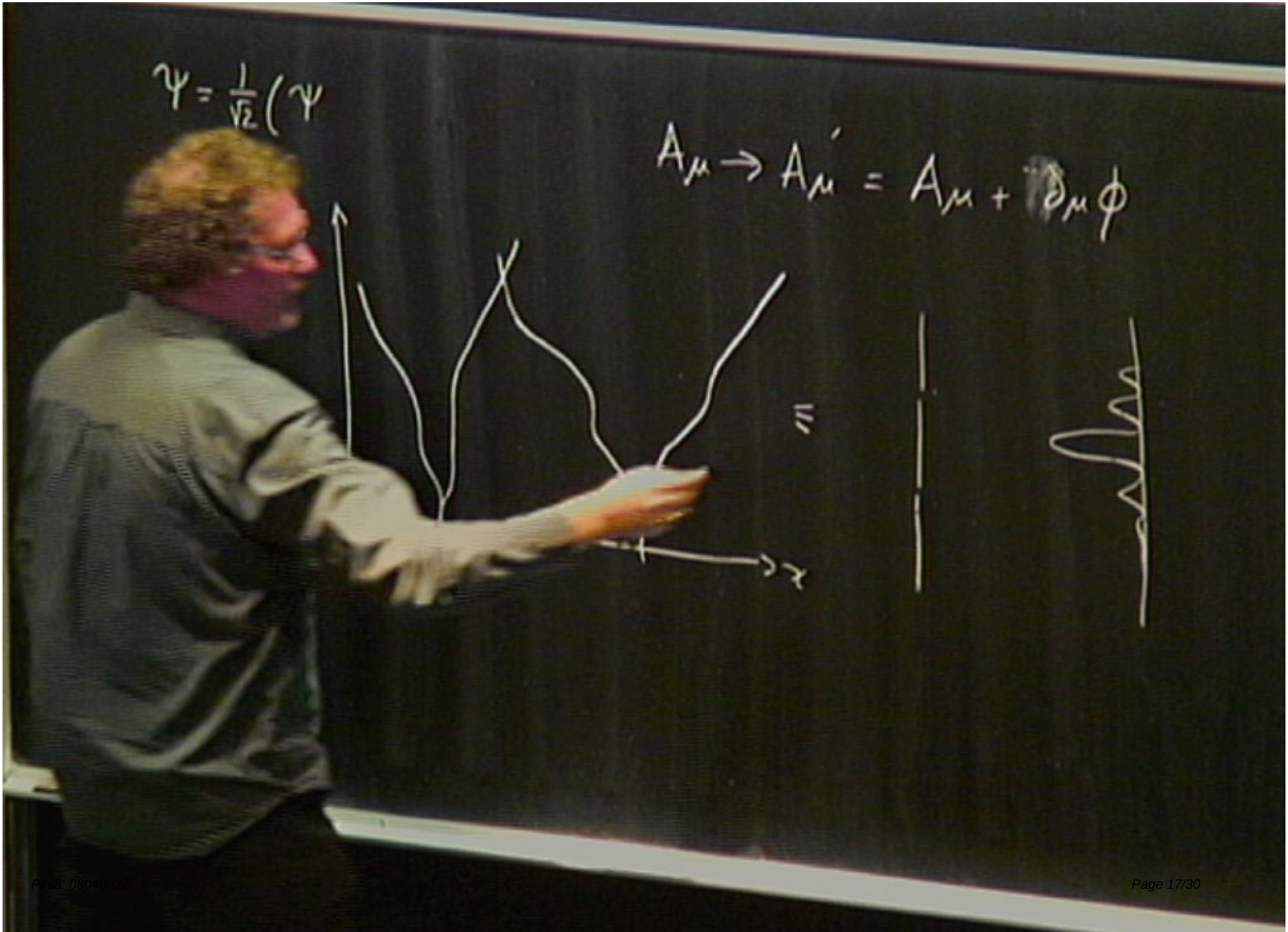

t
z

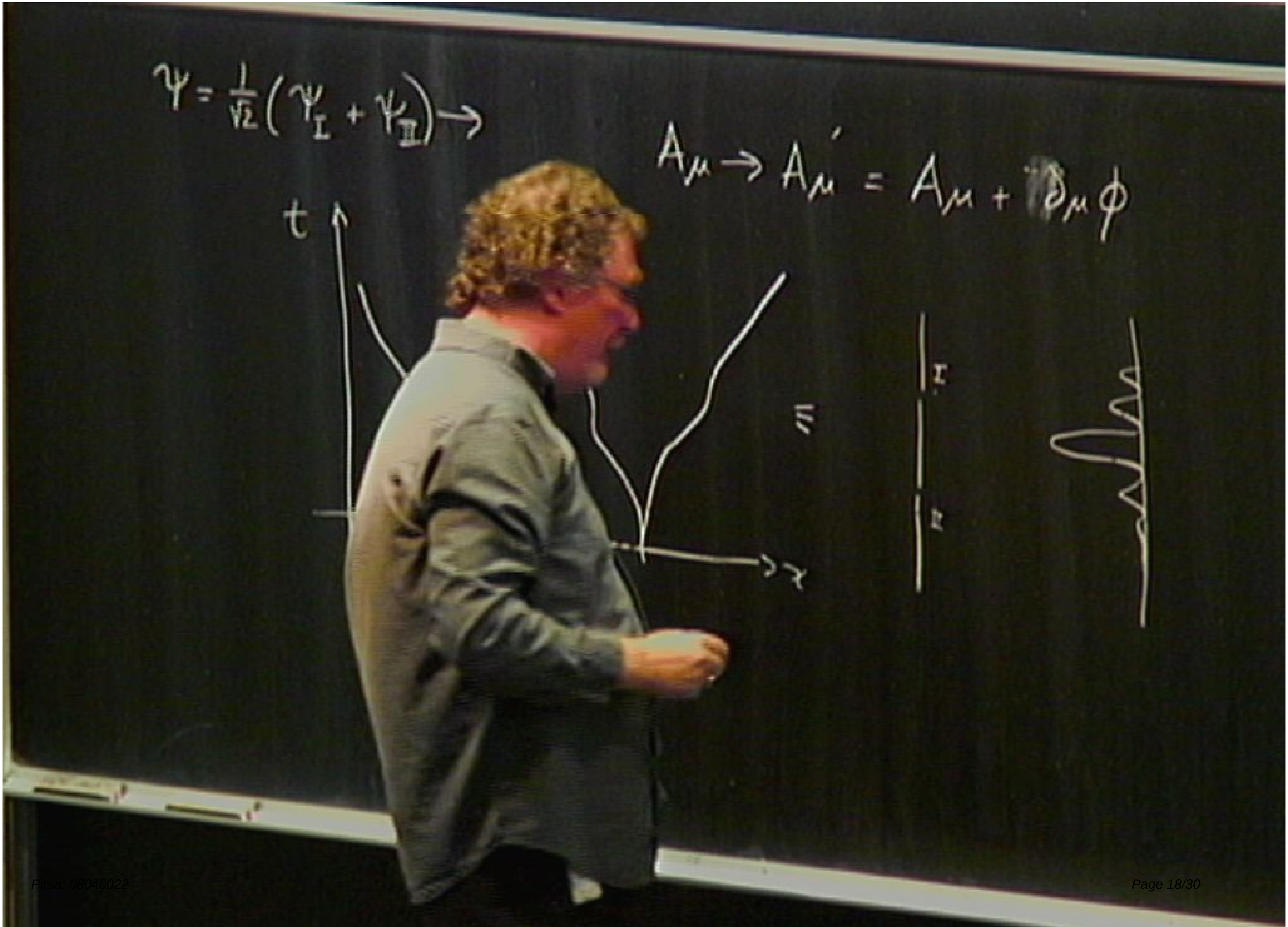

$A_\mu \to A'_\mu = A_\mu + \partial_\mu \phi$
t
z

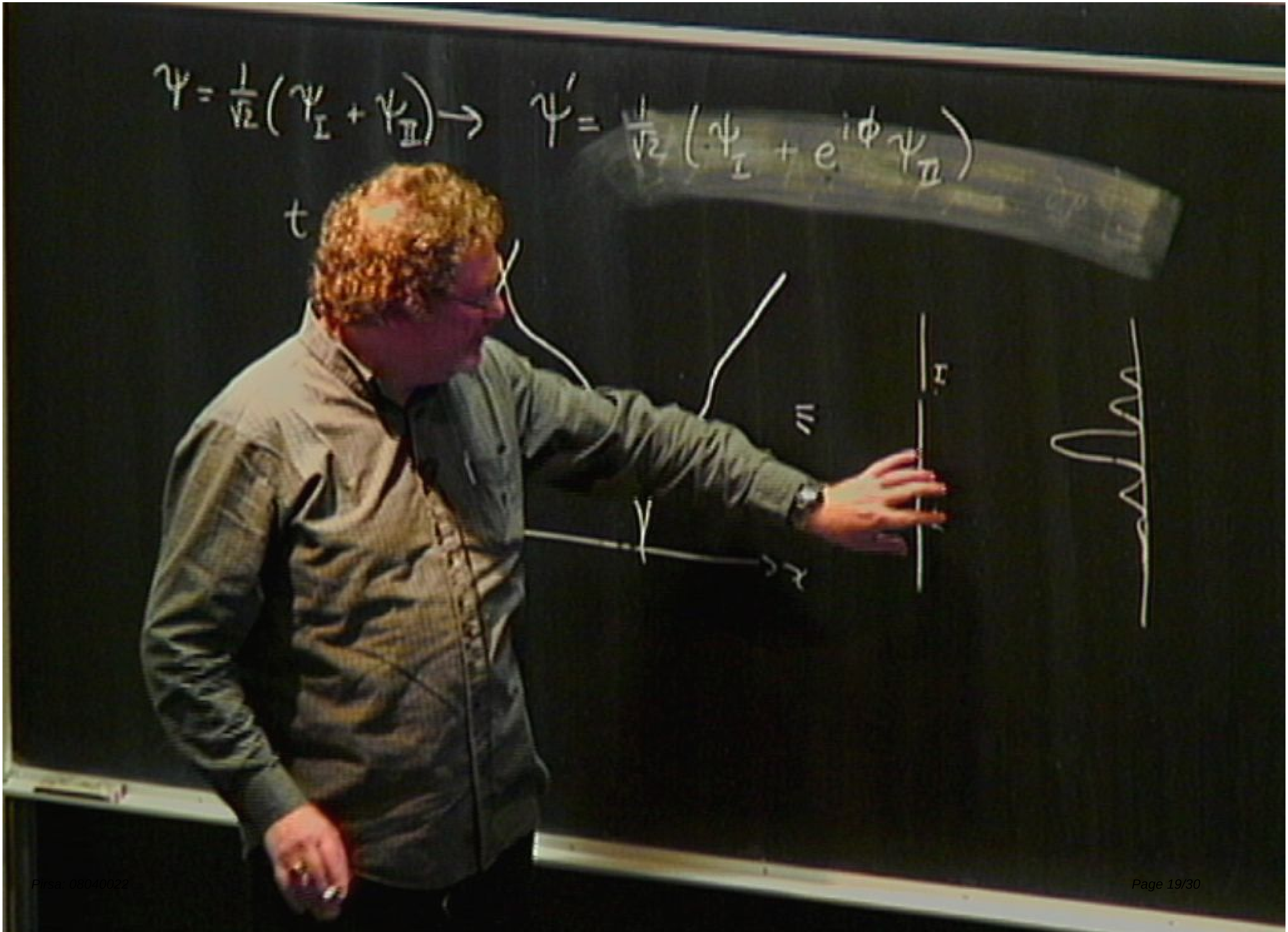
"Observability" of phenomenological symmetries

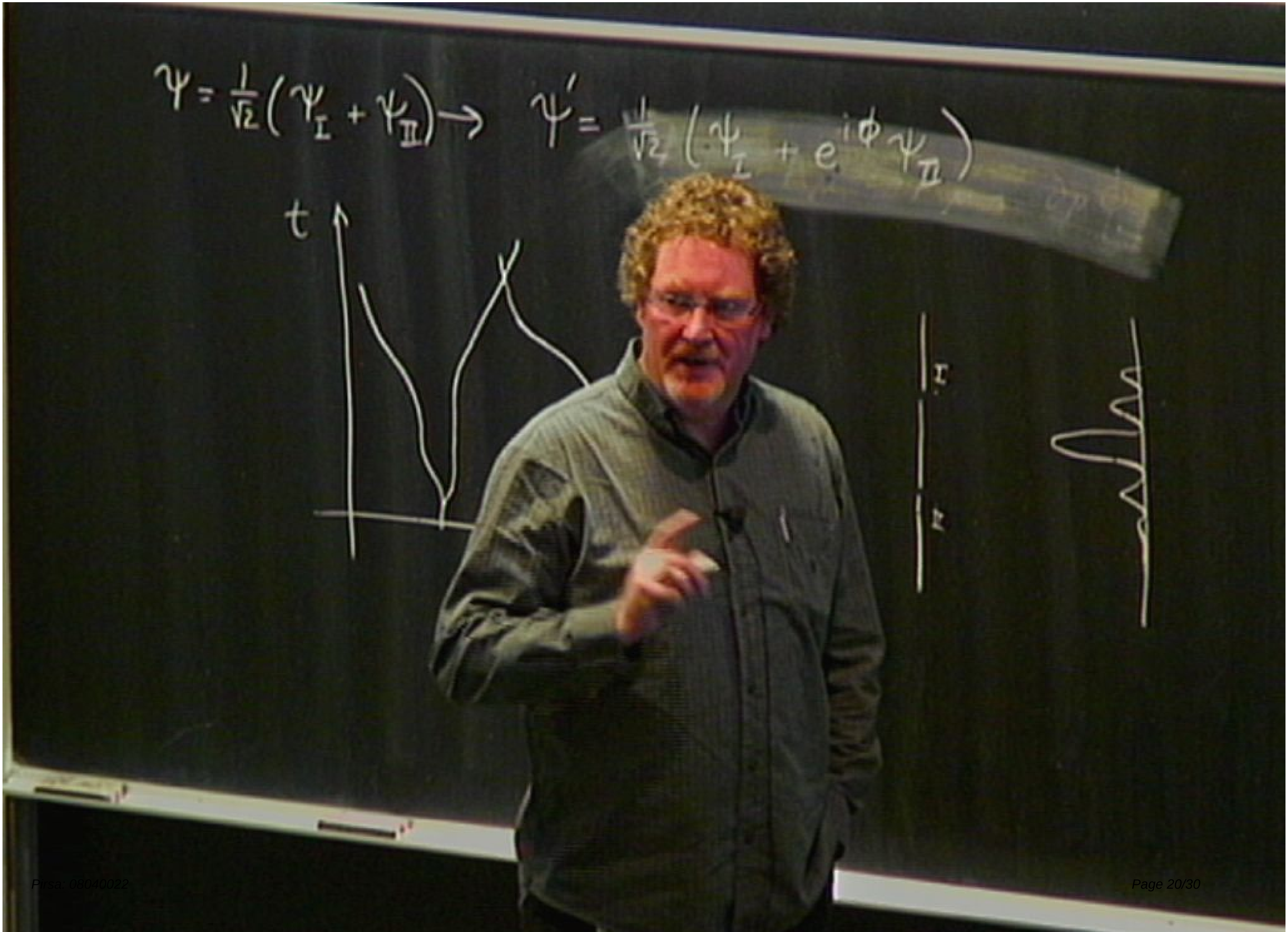
- isolated subsystems of universe (Einstein locality)
- Second distinction: "active" vs. "passive" transformations (Related concepts: symmetries as rules for taking solutions into solutions or covariance principles)
- gauge symmetries: no active interpretation? 't Hooft (1980), Mainzer (1996), Auyang (1995) vs. Brading and Brown (2004)



$\Psi = \frac{1}{\sqrt{2}}(\Psi$
$A_\mu \to A_\mu' = A_\mu + \partial_\mu \phi$
$\equiv$
x


Ψ = 1/√2 (Ψ_I + Ψ_II) →
A_μ → A_μ' = A_μ + ∂_μ φ
t
x
I
II


$\psi = \frac{1}{\sqrt{2}}(\psi_I + \psi_{II}) \rightarrow \psi' = \frac{1}{\sqrt{2}}(\psi_I + e^{i\phi}\psi_{II})$
t
x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t

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Uses of the relativity principle

Keinstein (1705), Einstein (1905), Ignatowski (1910-11)

physics of (inertial) coordinate transformations

$$x' = \frac{1}{\mathcal{C}_{\parallel}}(x - vt)$$

$$y' = \frac{1}{\mathcal{C}_{\perp}}y$$

$$z' = \frac{1}{\mathcal{C}_{\perp}}z$$

$$t' = \frac{1}{(1 - \alpha v)\mathcal{D}}(t - \alpha x).$$

physics of (inertial) coordinate transformations

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$$t' = \frac{1}{(1 - \alpha v)\mathcal{D}}(t - \alpha x).$$

1. The universality of the behaviour of rods and clocks. The length change factors for rods and the dilation factor for clocks do not depend on the constitution of these objects, nor on the means by which the rods and clocks were boosted.

2. The 'boostability' of rulers and clocks. Any object that can act as a rigid ruler in the frame *S* when stationary relative to that frame retains that role in its new rest frame *S'* when boosted. The same assumption holds for ideal clocks. (Einstein 1910)

Albert Keinstein 1705

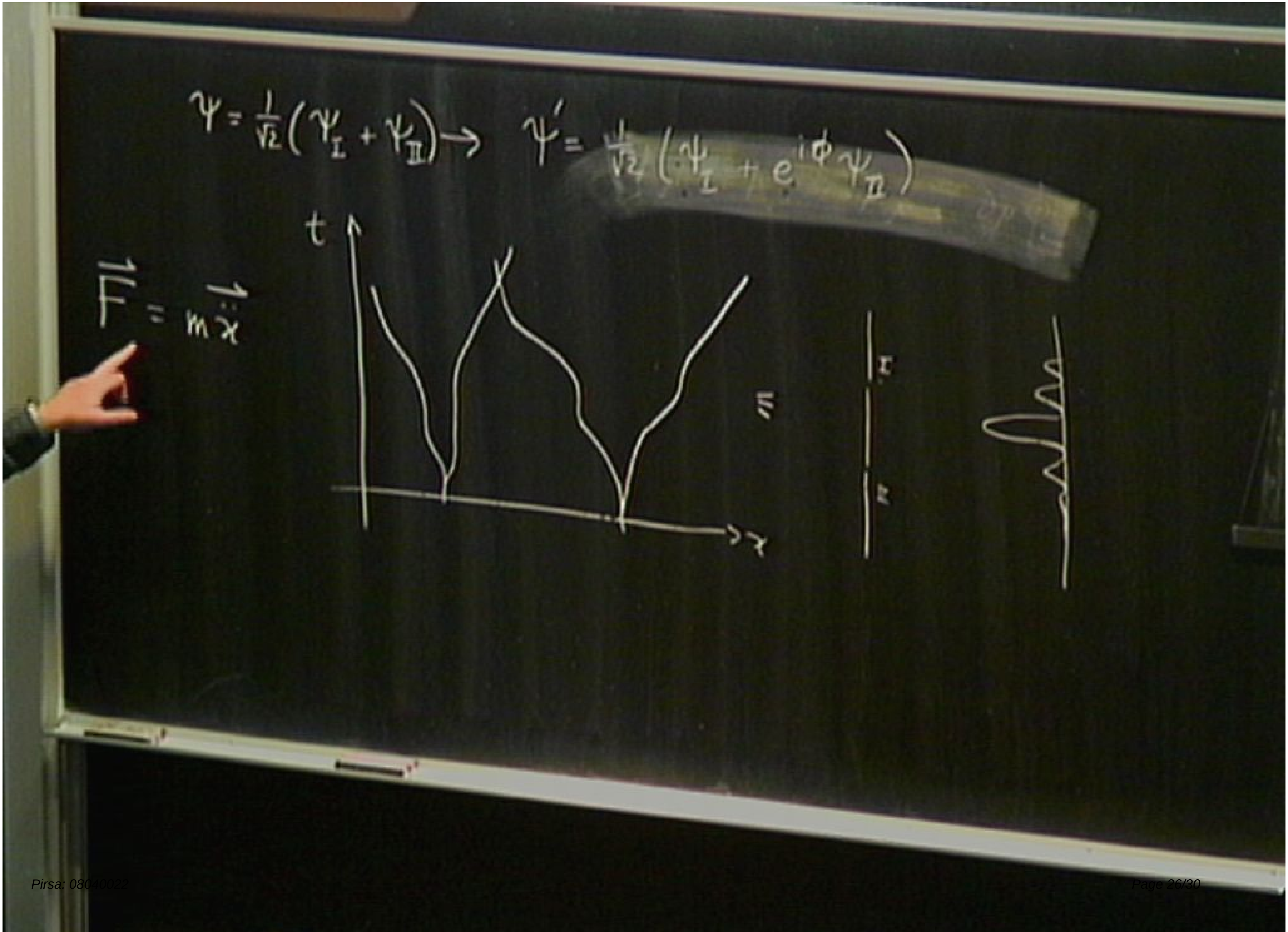
Relativity principle
Newton's second law
Velocity independence of mass, forces

$$\mathcal{D} = \sqrt{\mathcal{C}_{\|}}; \quad \alpha = 0.$$

Reciprocity
spatial isotropy

Galilean transformations

All manner of fable is being attached to my personality, and there is no end to the number of ingeniously devised tales. Albert Einstein


ψ = 1/√2 (ψ_I + ψ_II) → ψ' = 1/√2 (ψ_I + e^{iφ} ψ_II)
F = m ẍ
t
x

Albert Keinstein 1705

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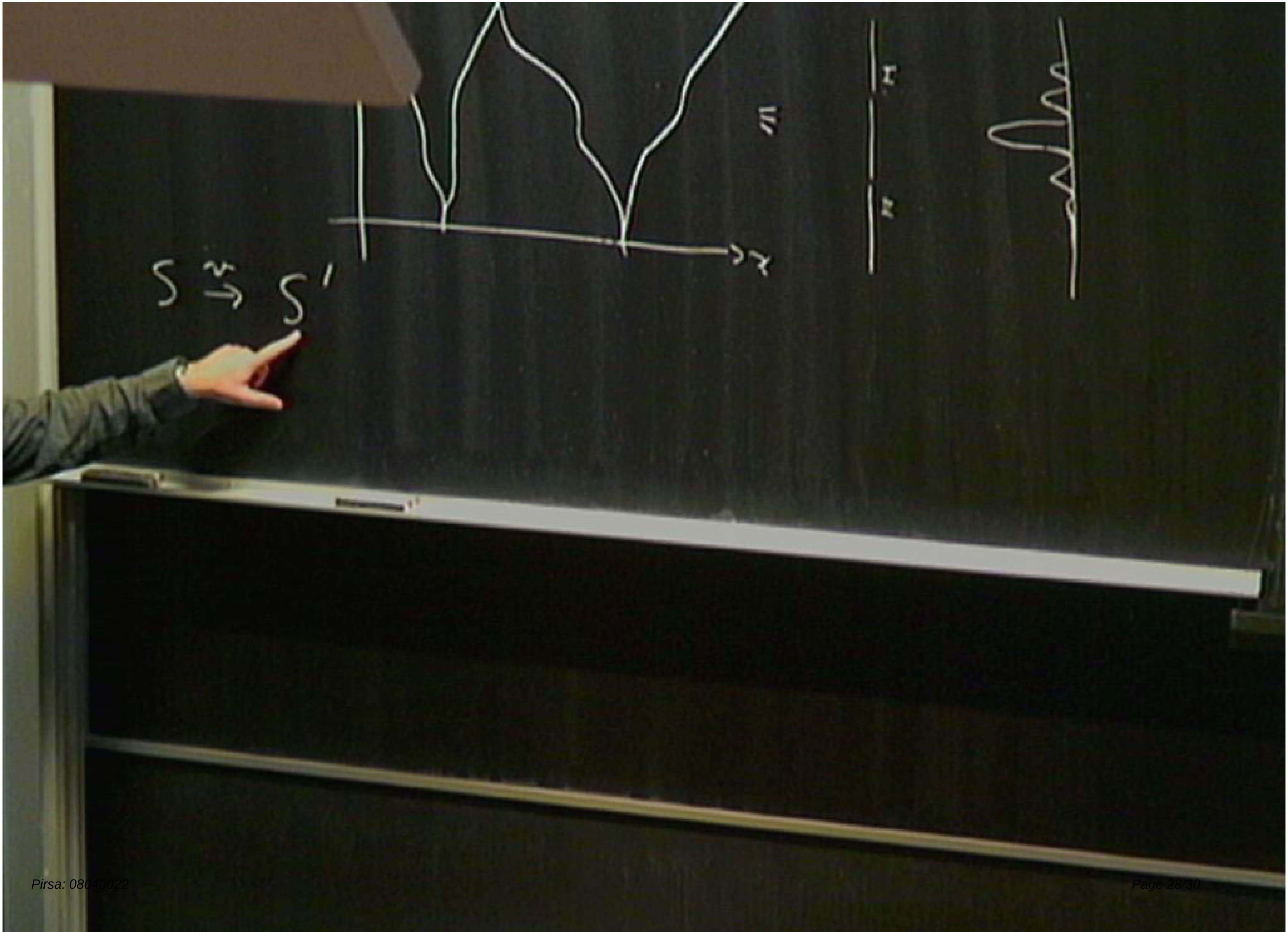

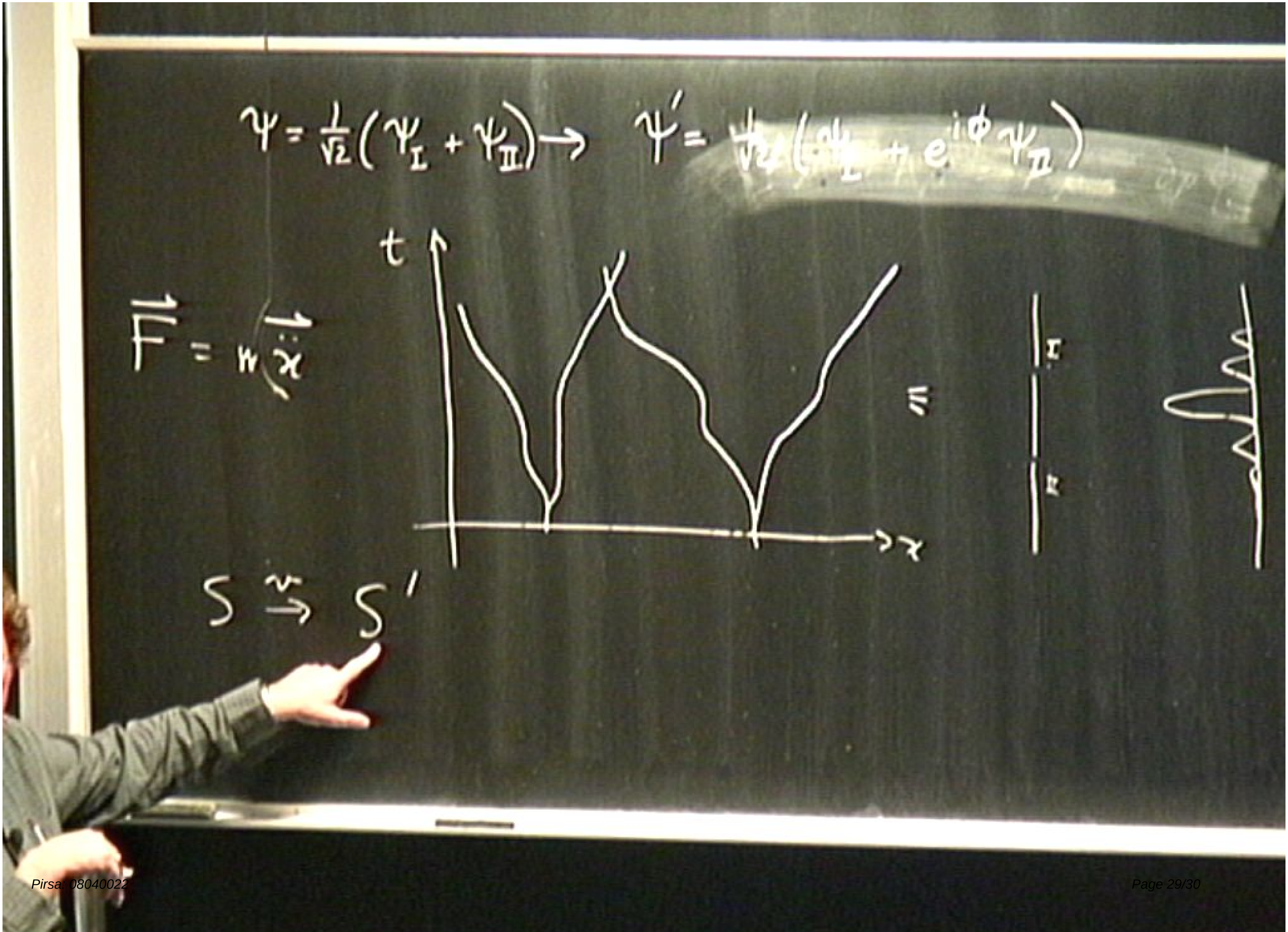

$\psi = \frac{1}{\sqrt{2}}(\psi_I + \psi_{II}) \rightarrow \psi' = \frac{1}{\sqrt{2}}(\psi_I + e^{i\phi}\psi_{II})$
$\vec{F} = m\ddot{\vec{x}}$
t
x
$S \rightarrow S'$

Albert Keinstein 1705

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Velocity independence of mass, forces

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