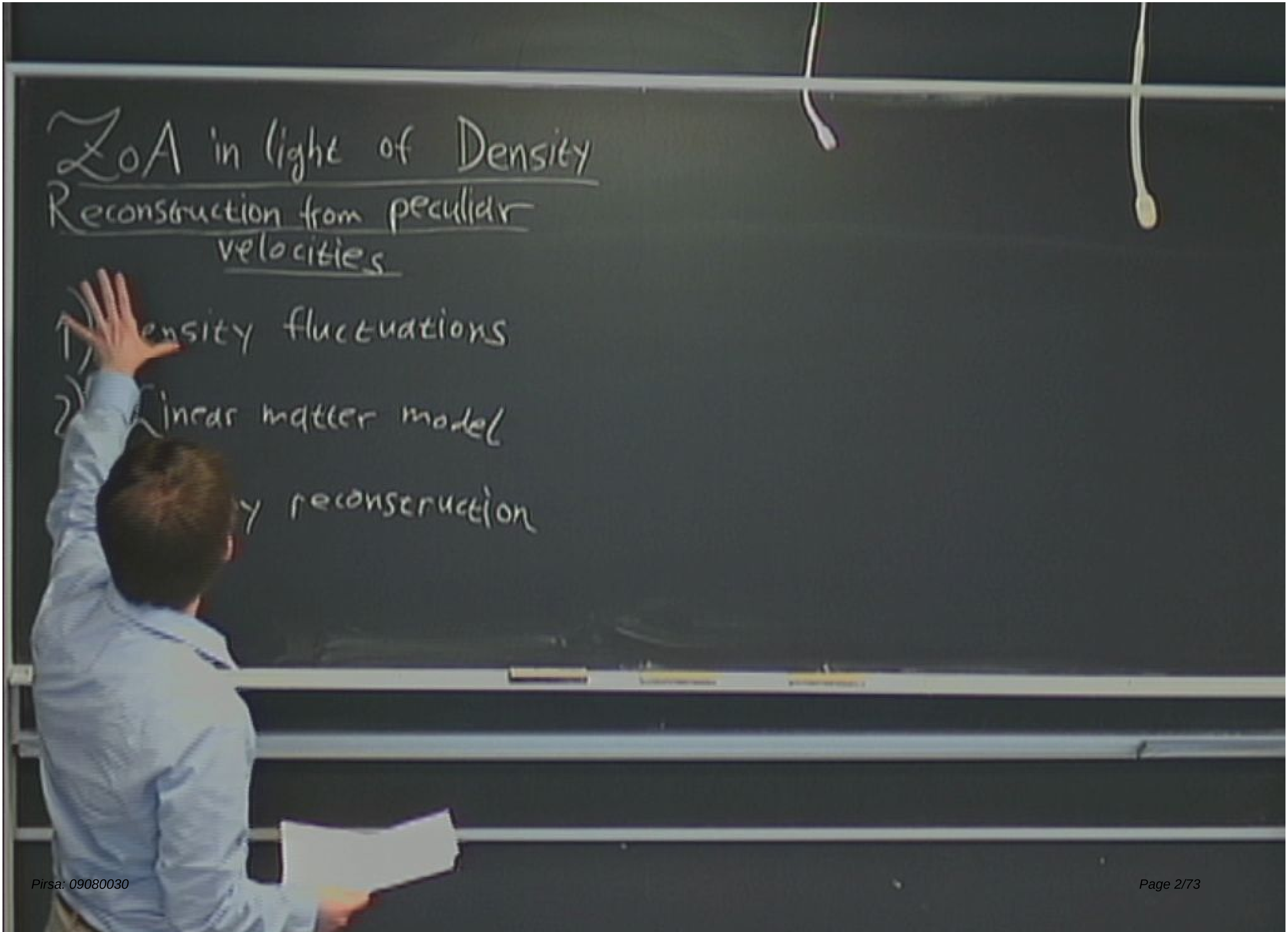
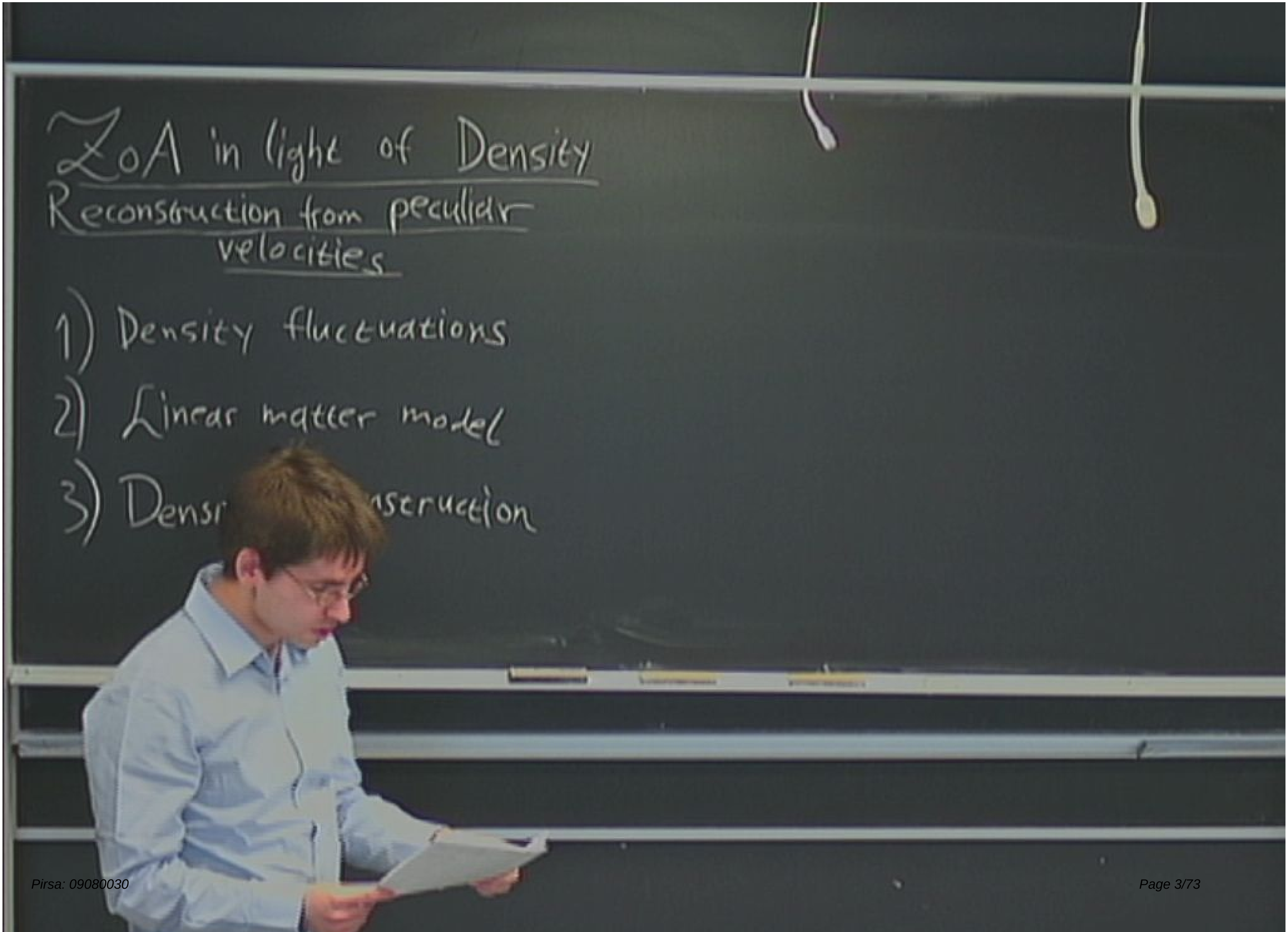
Title: Summer Undergraduate Student Talk

Date: Aug 14, 2009 02:00 PM

URL: http://pirsa.org/09080030

Abstract:


ZoA in light of Density
Reconstruction from peculiar velocities
1) ensity fluctuations
2) Linear matter model
y reconstruction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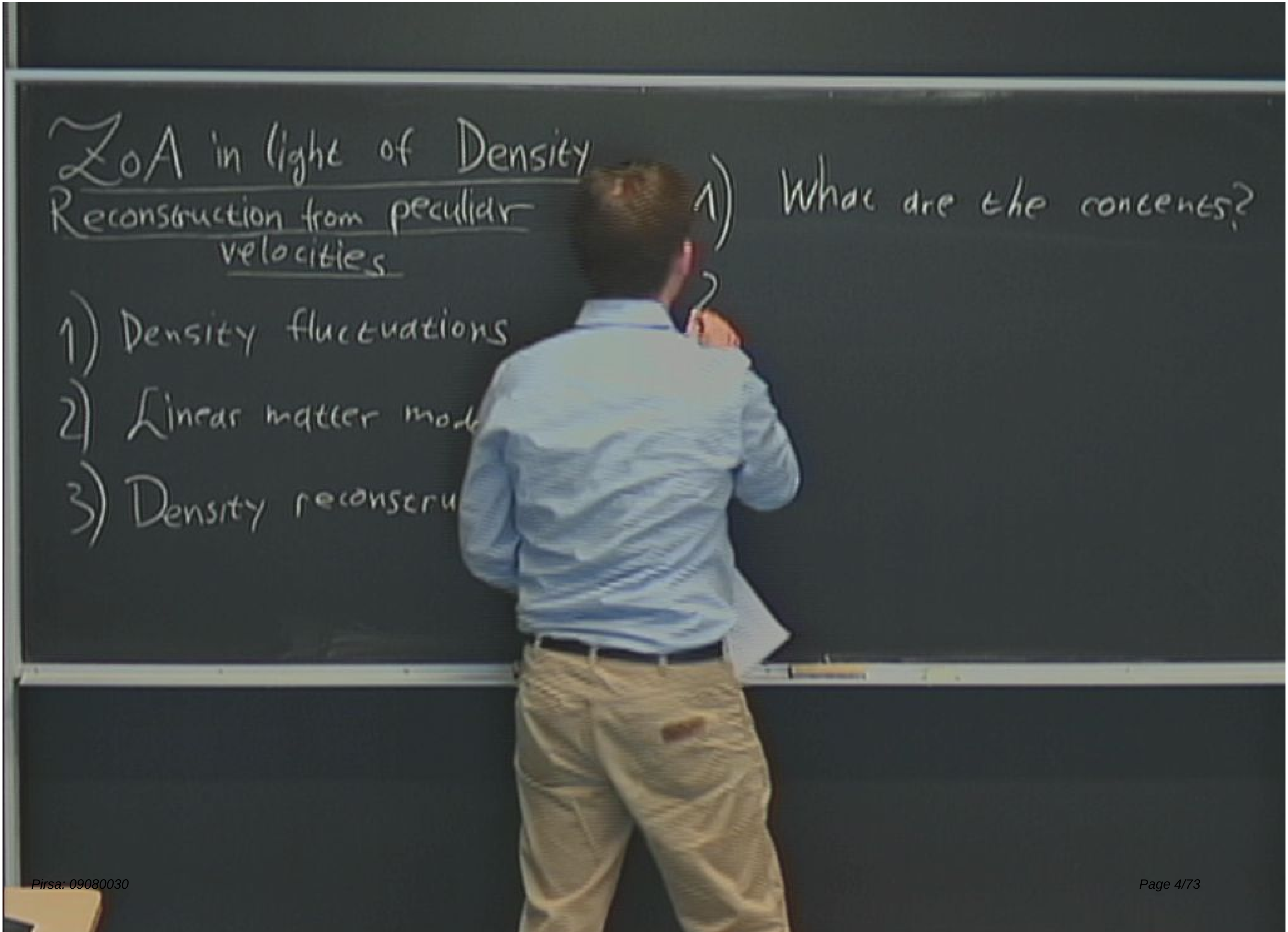
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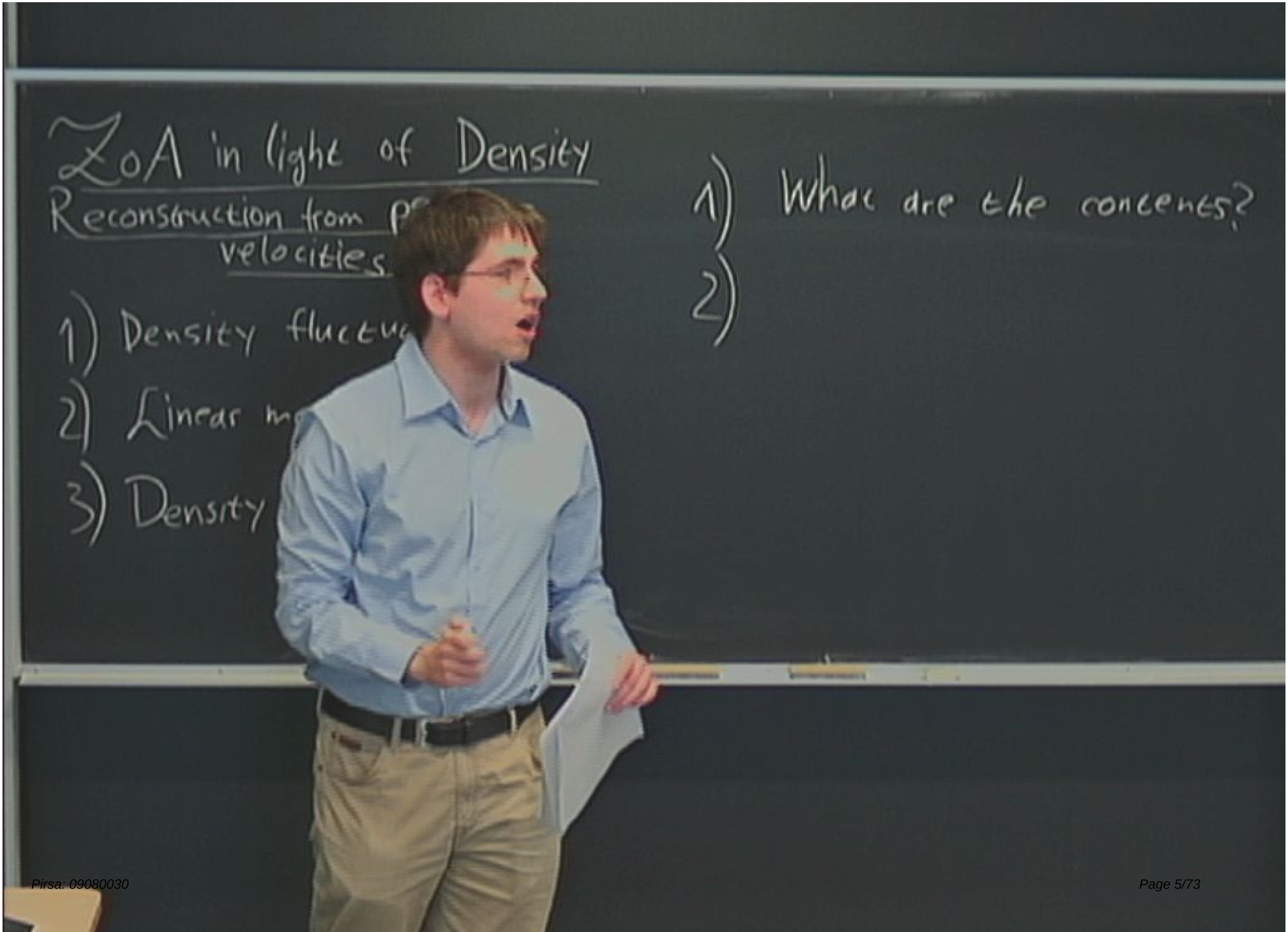
2)


ZoA in light of Density
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2) Linear
3) Density
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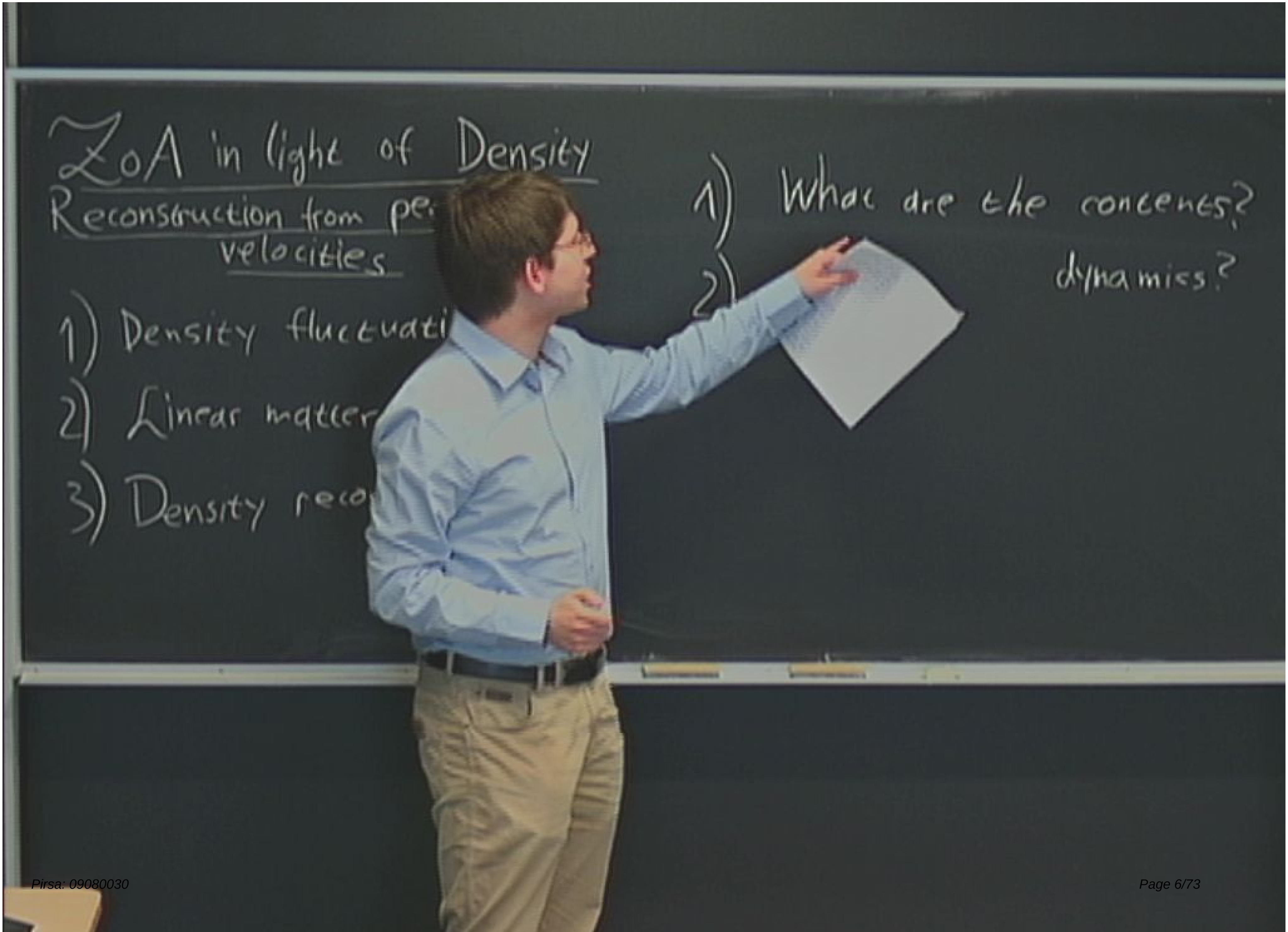

ZoA in light of Density
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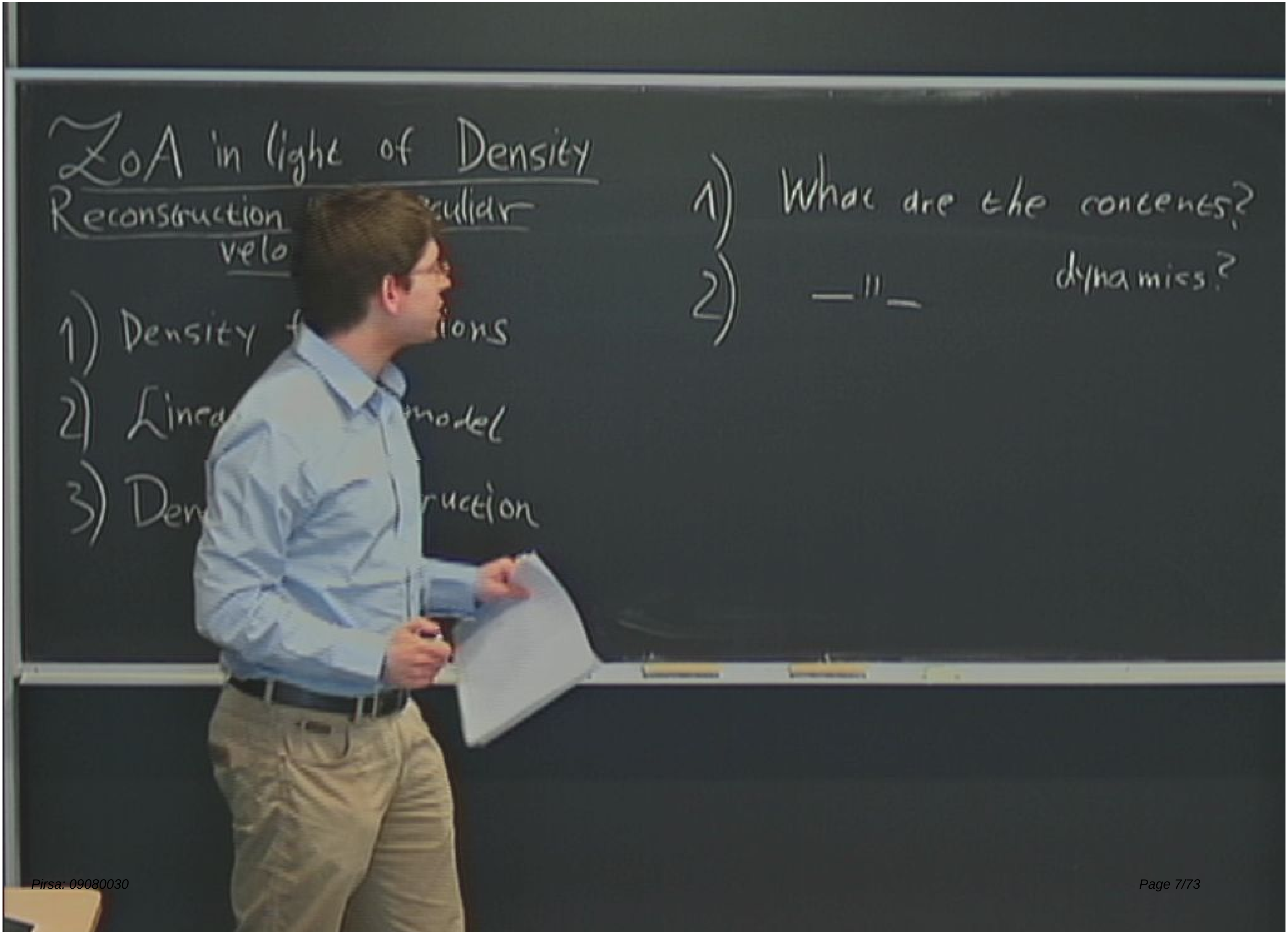
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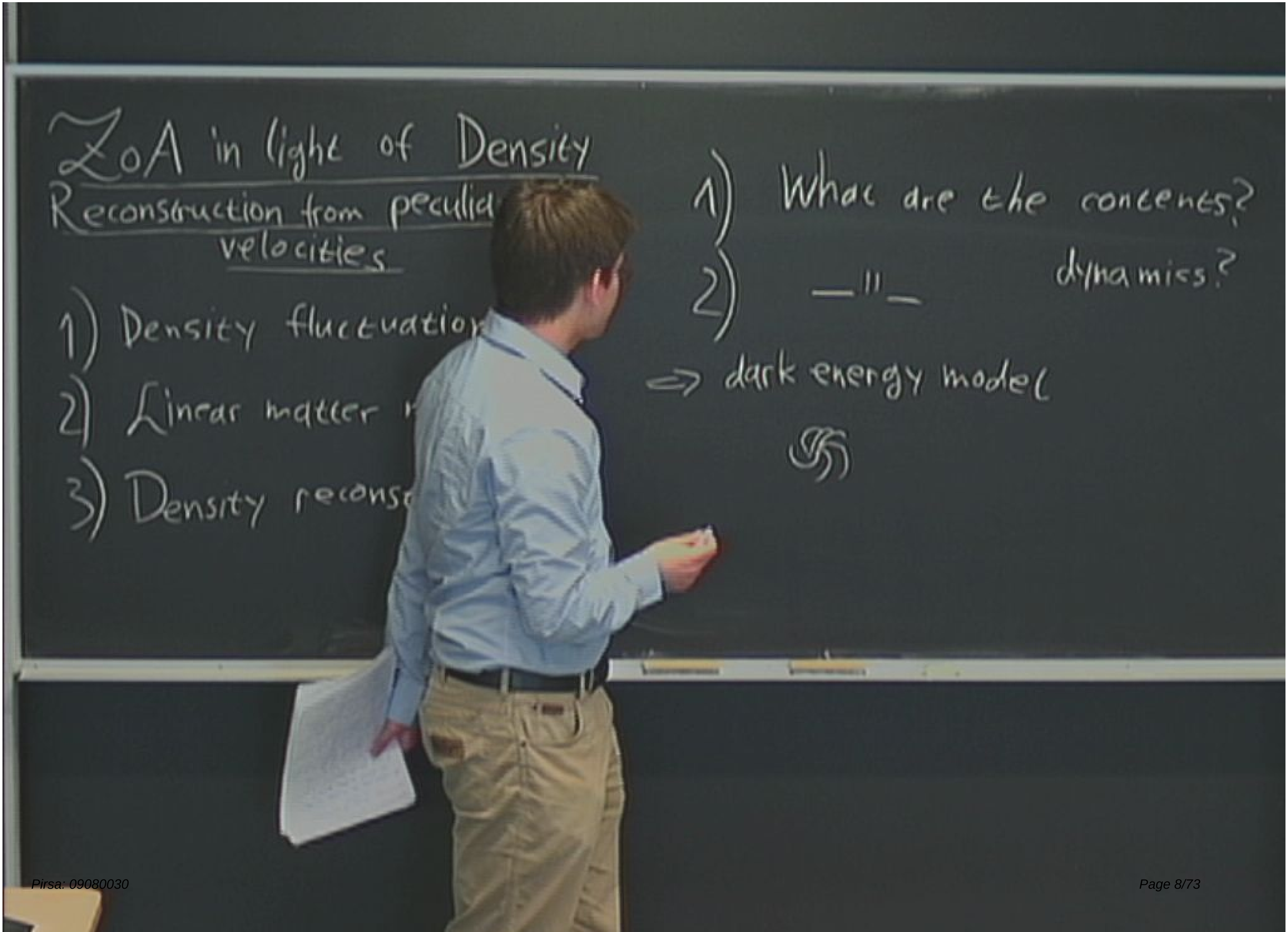
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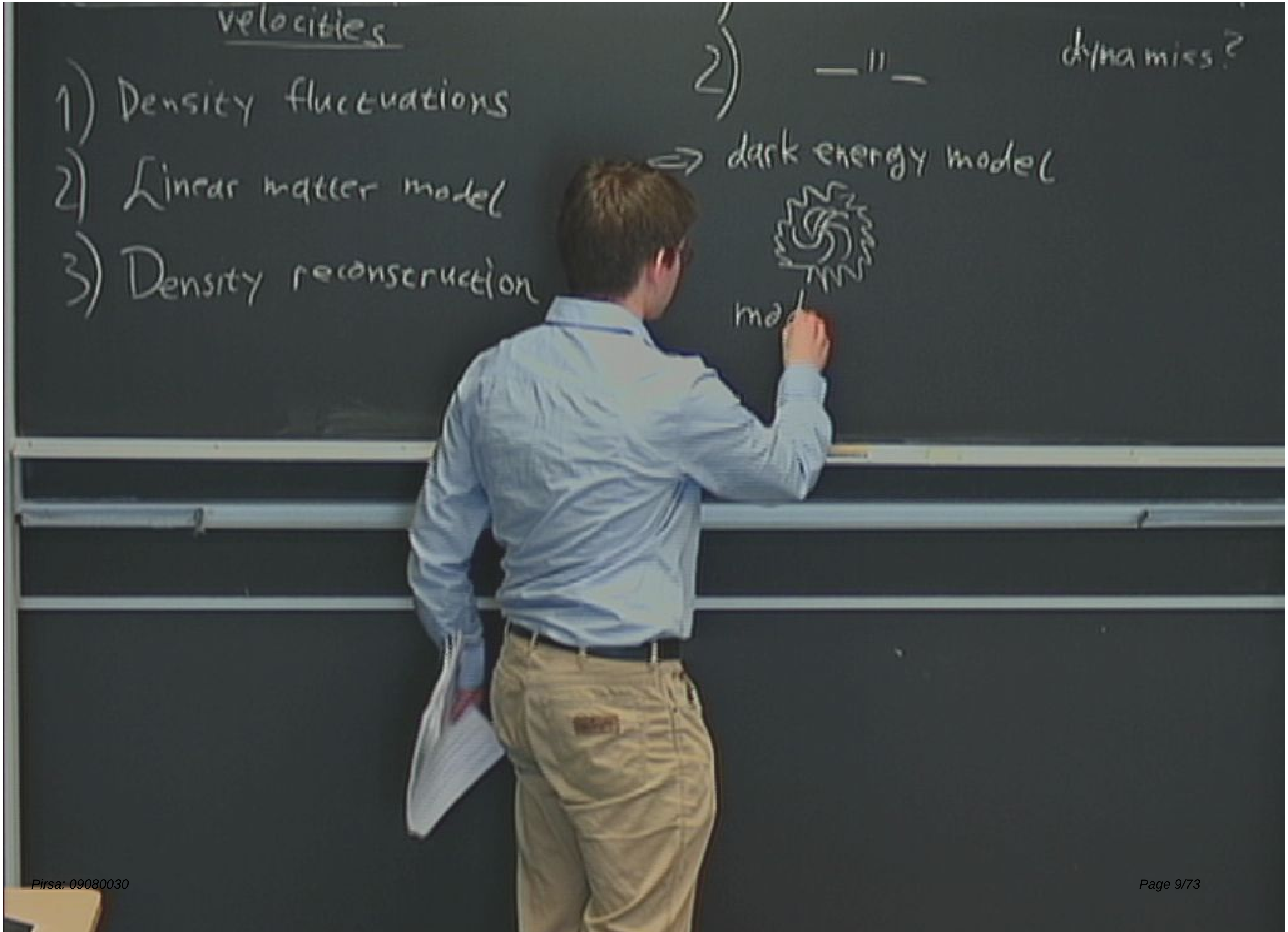
⇒ dark energy model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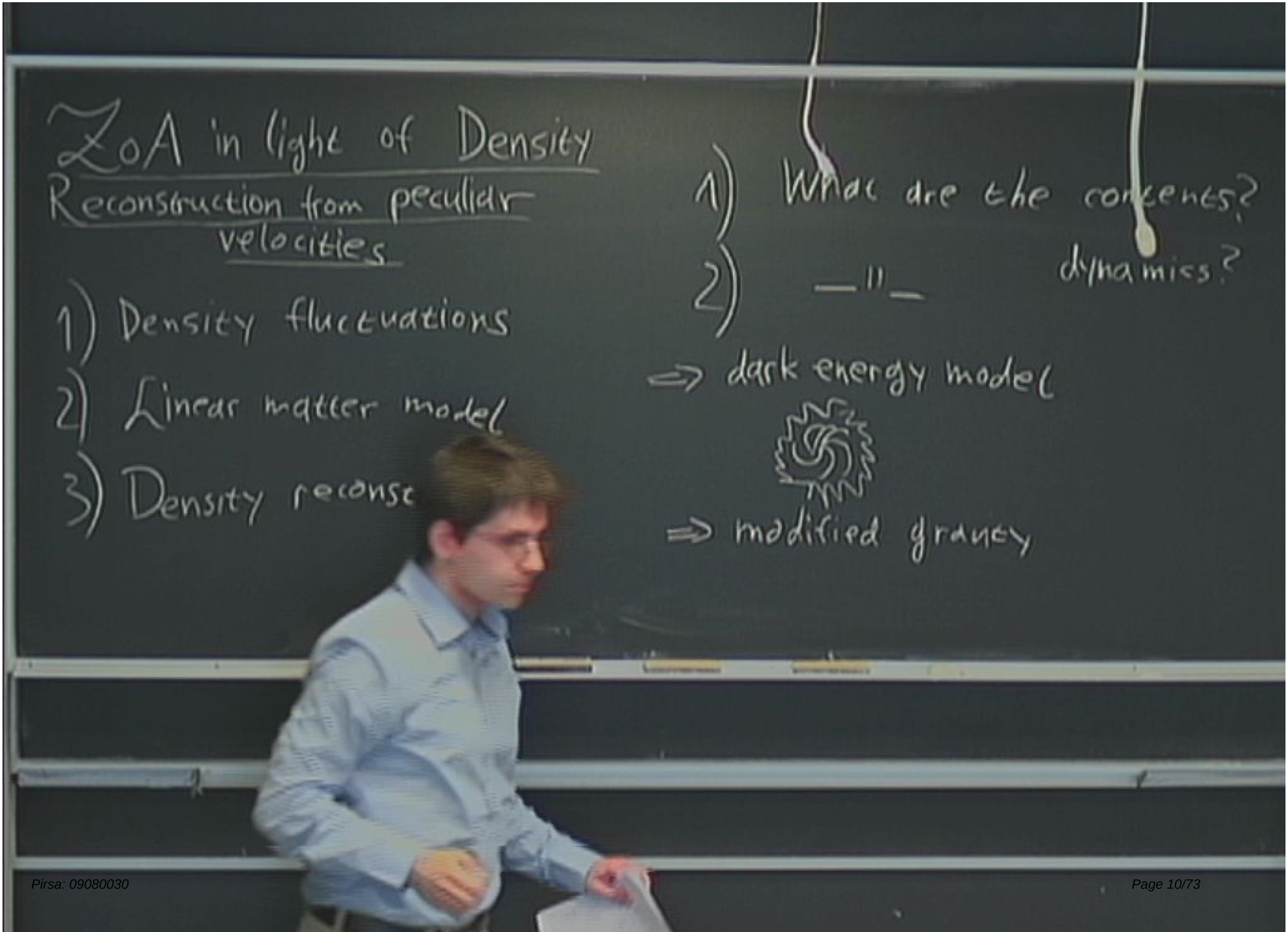
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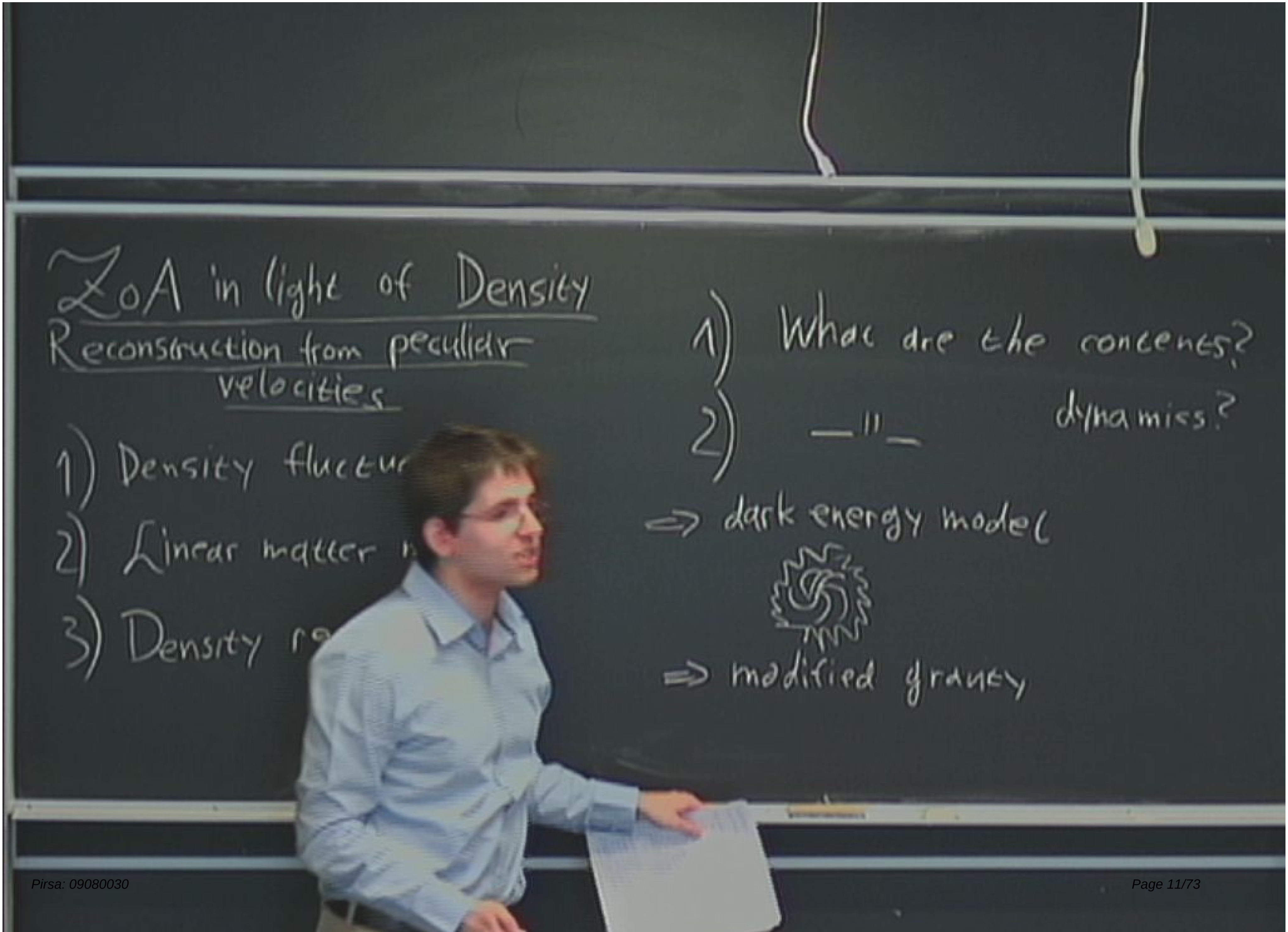
⇒ dark energy model
⇒ modified gravity



ZoA in light of Density
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2) —"— dynamics?
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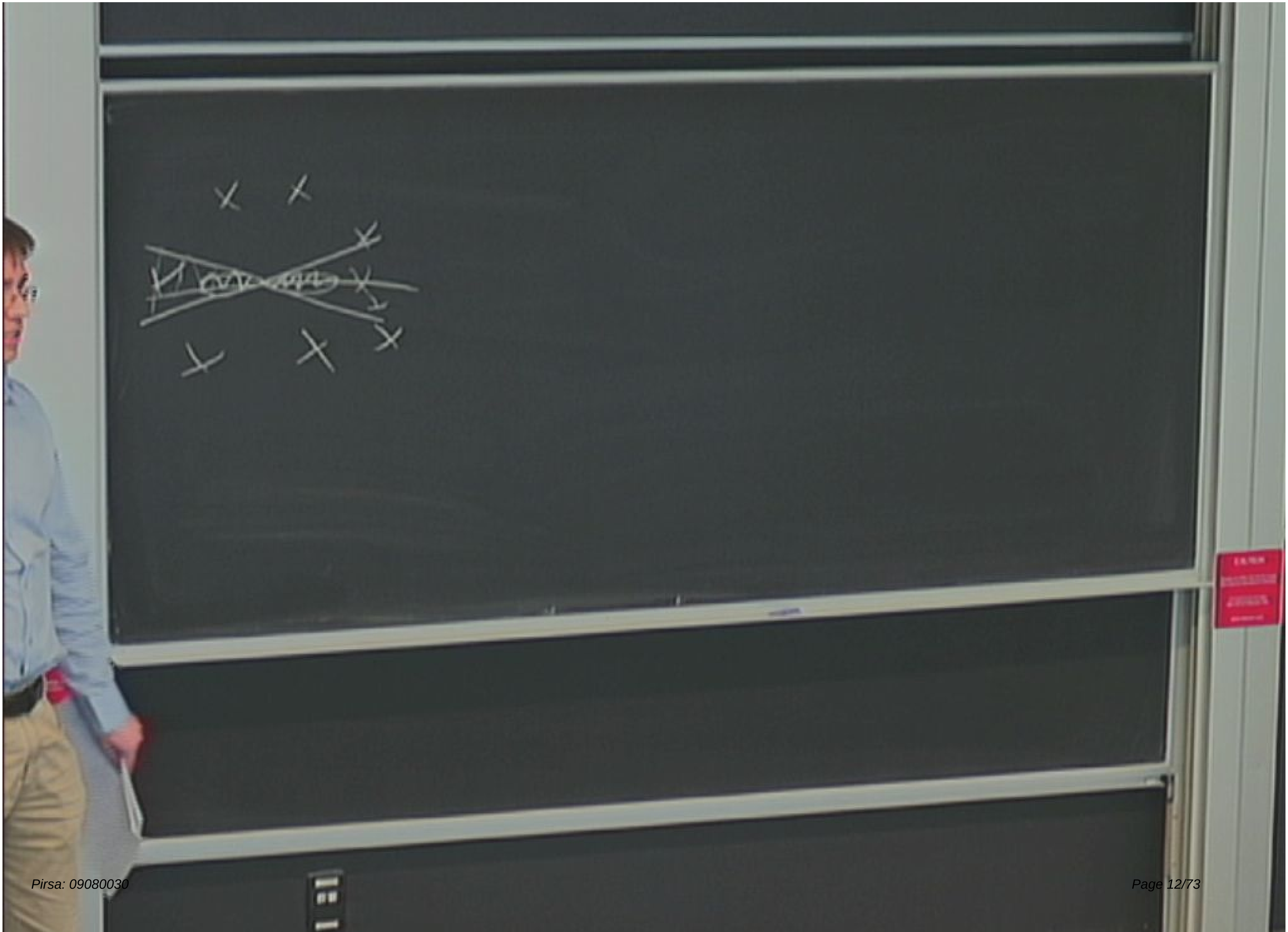
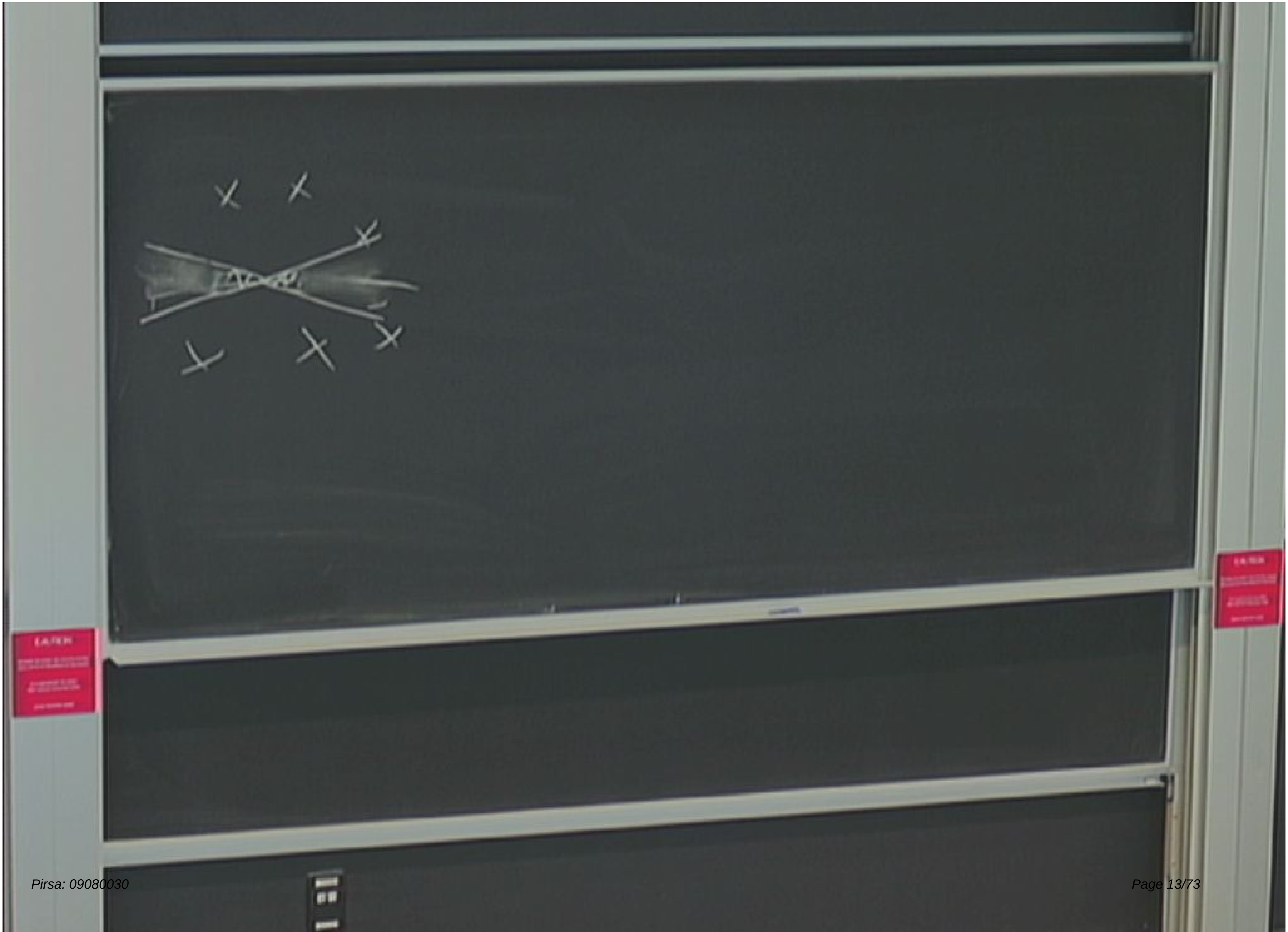
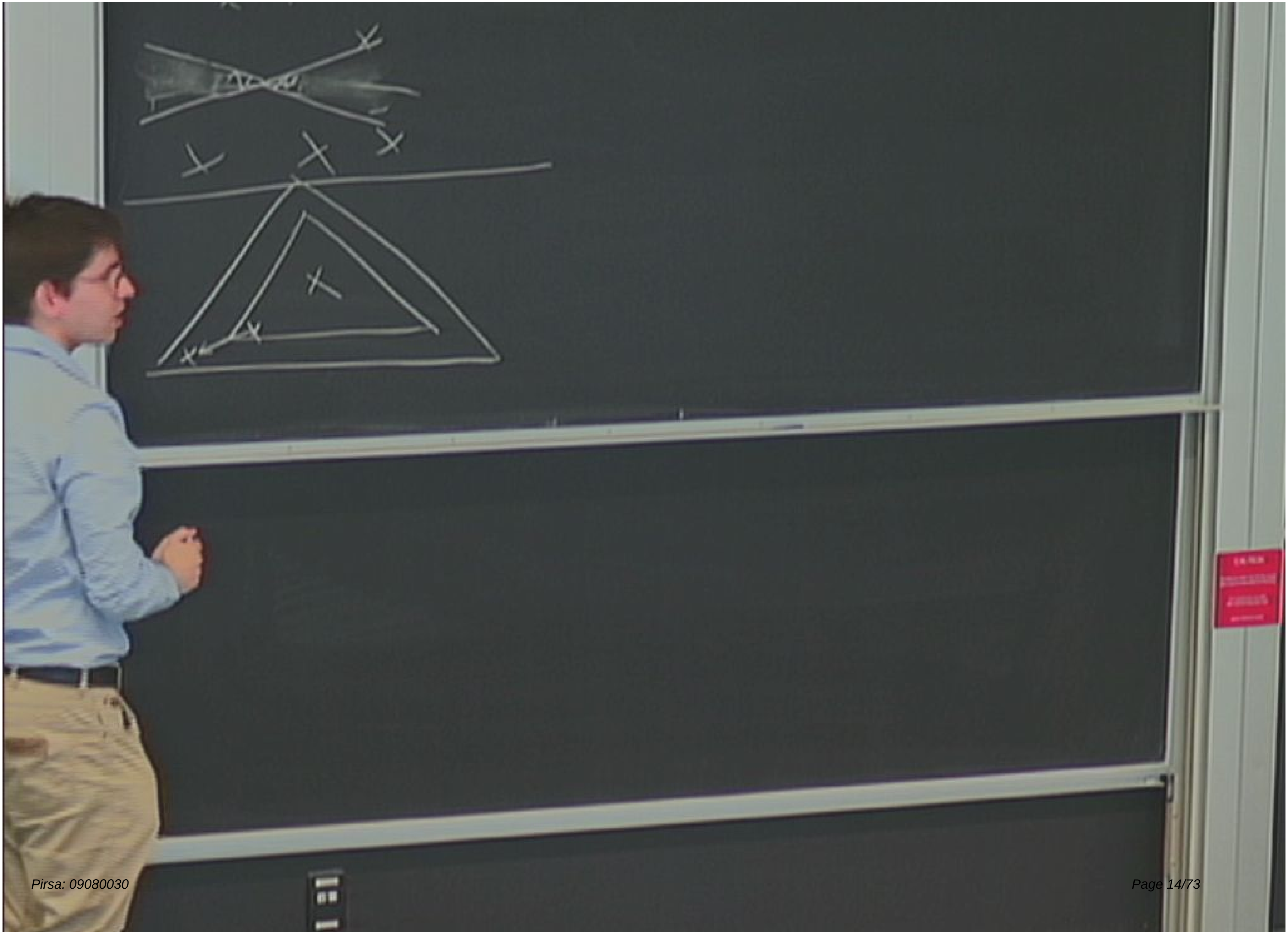
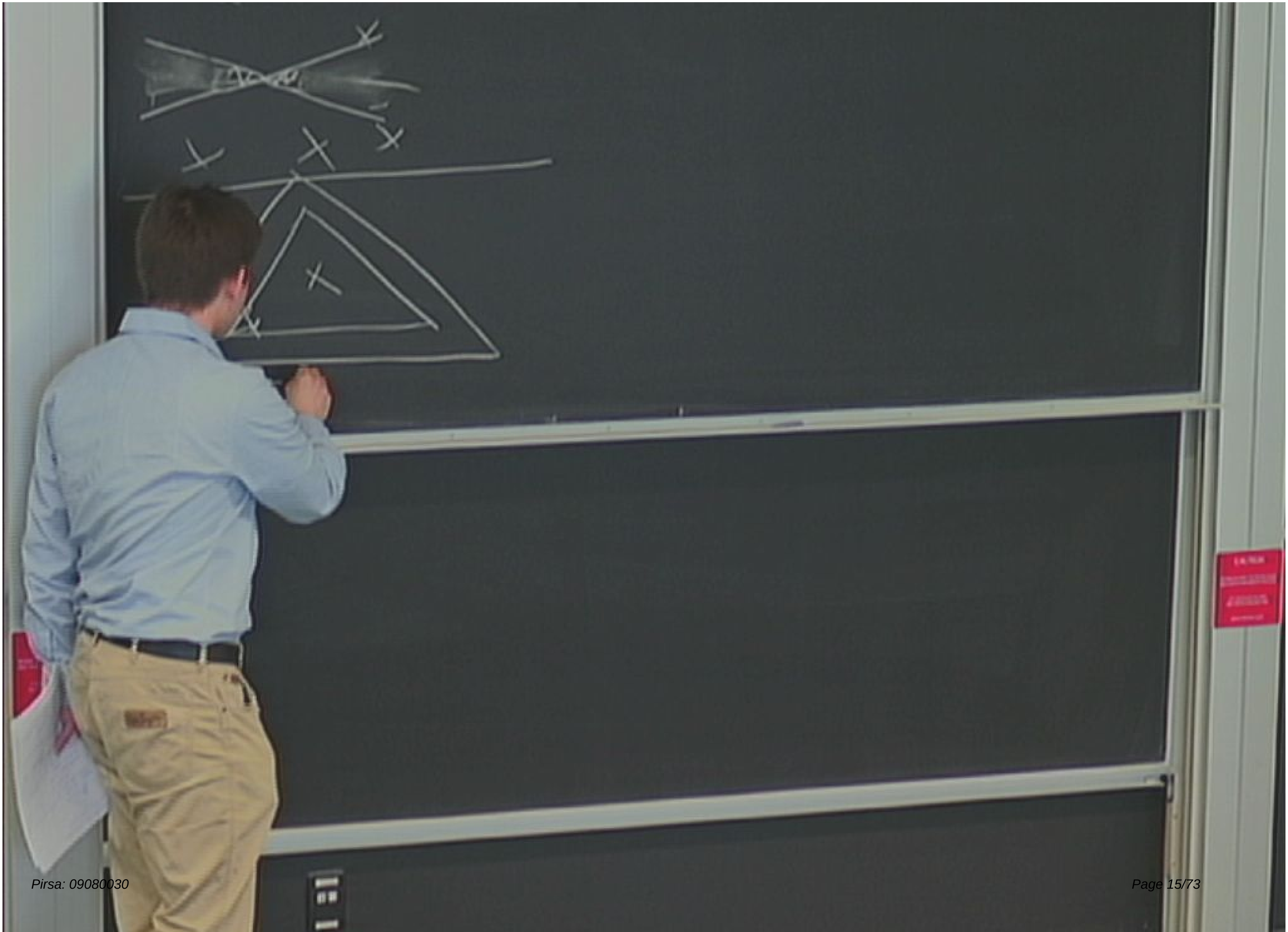
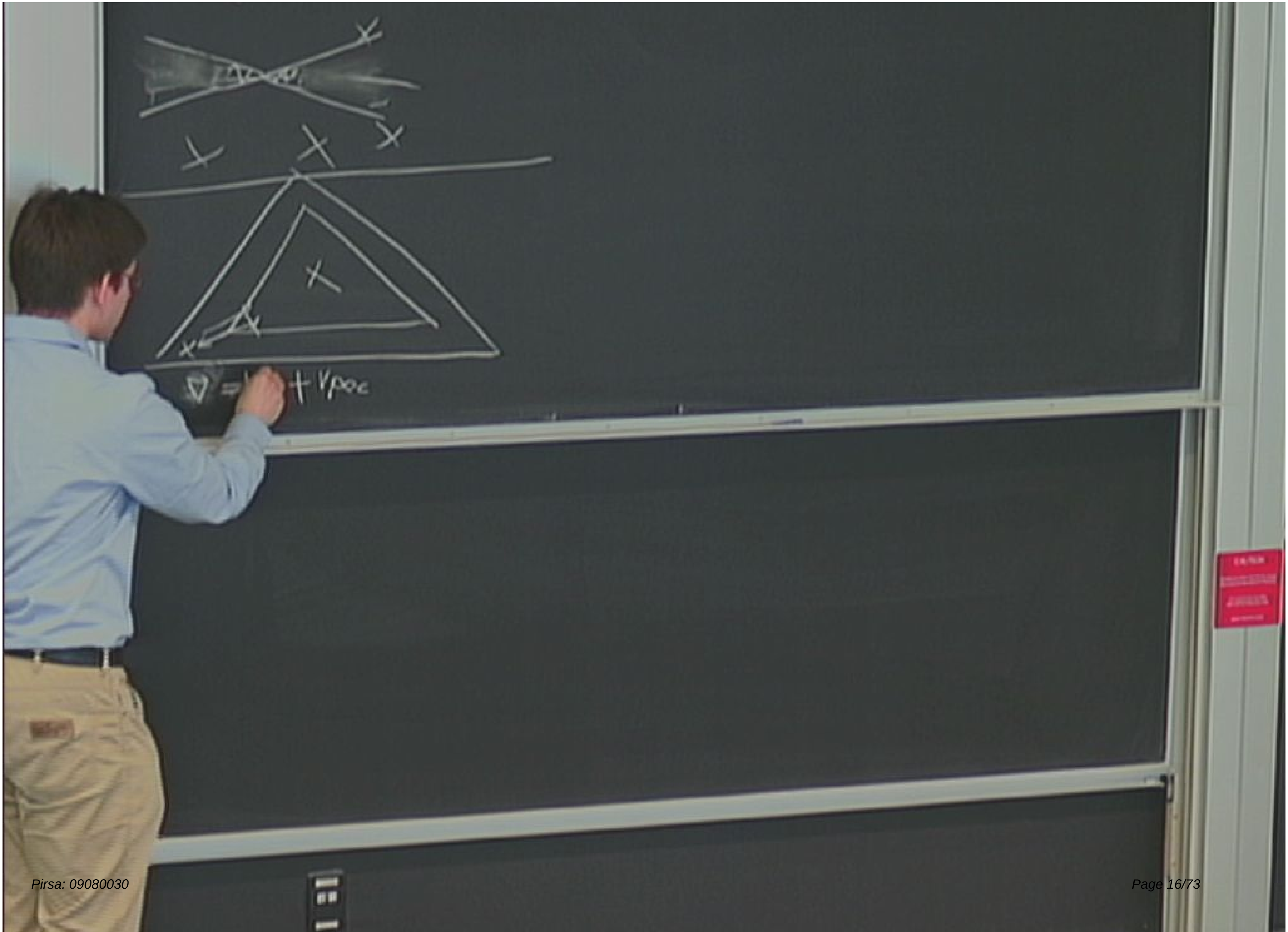
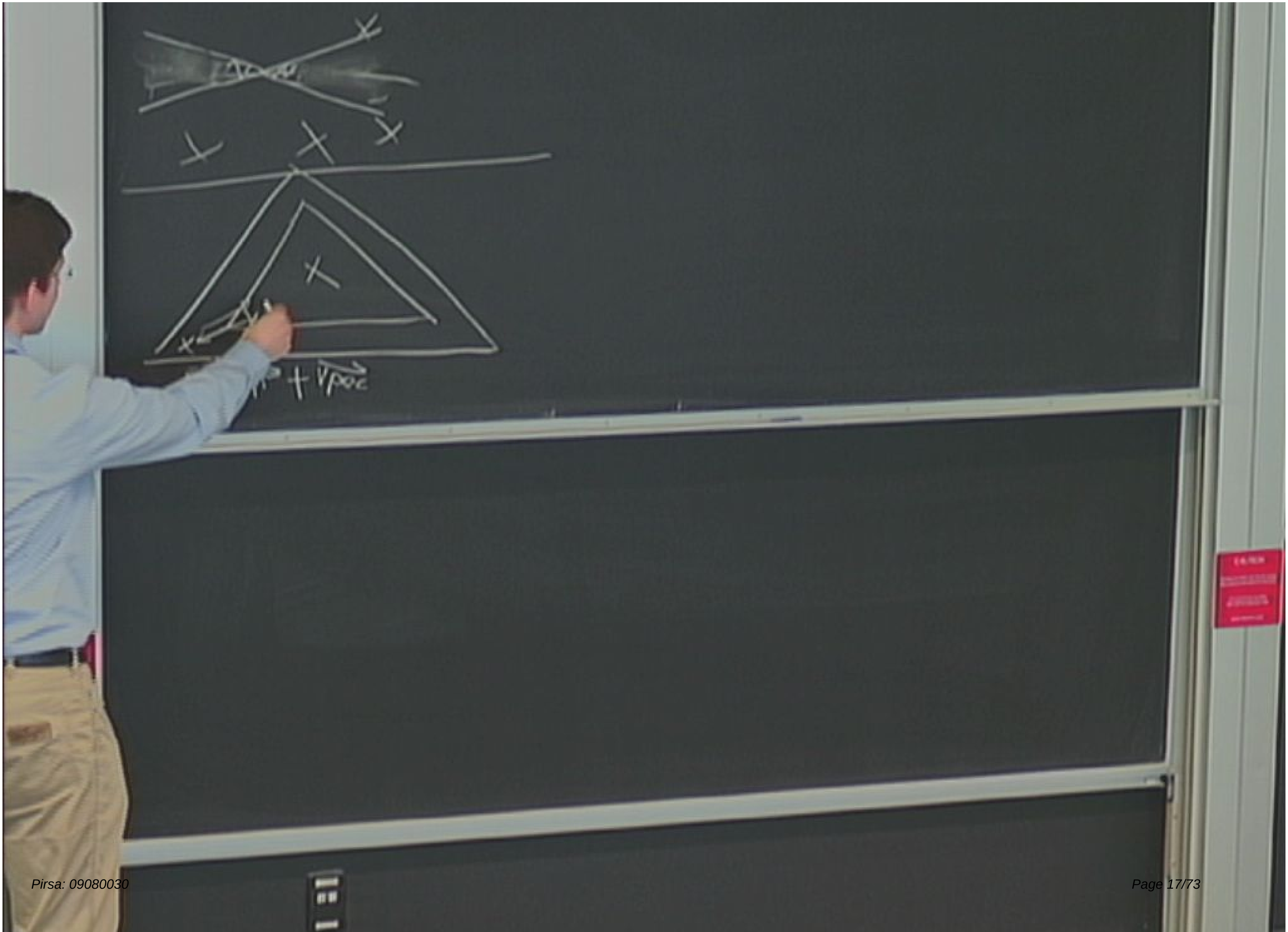


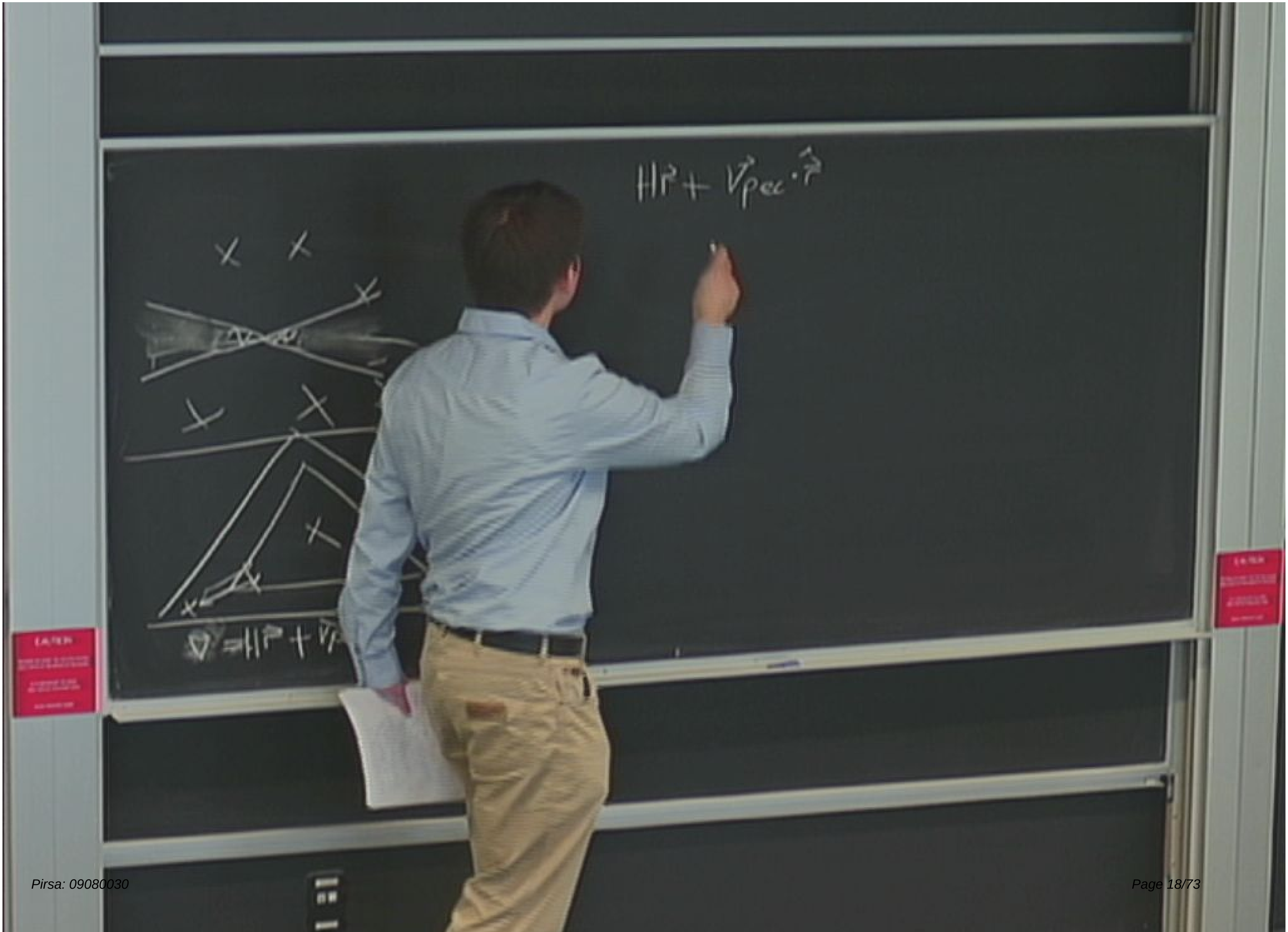


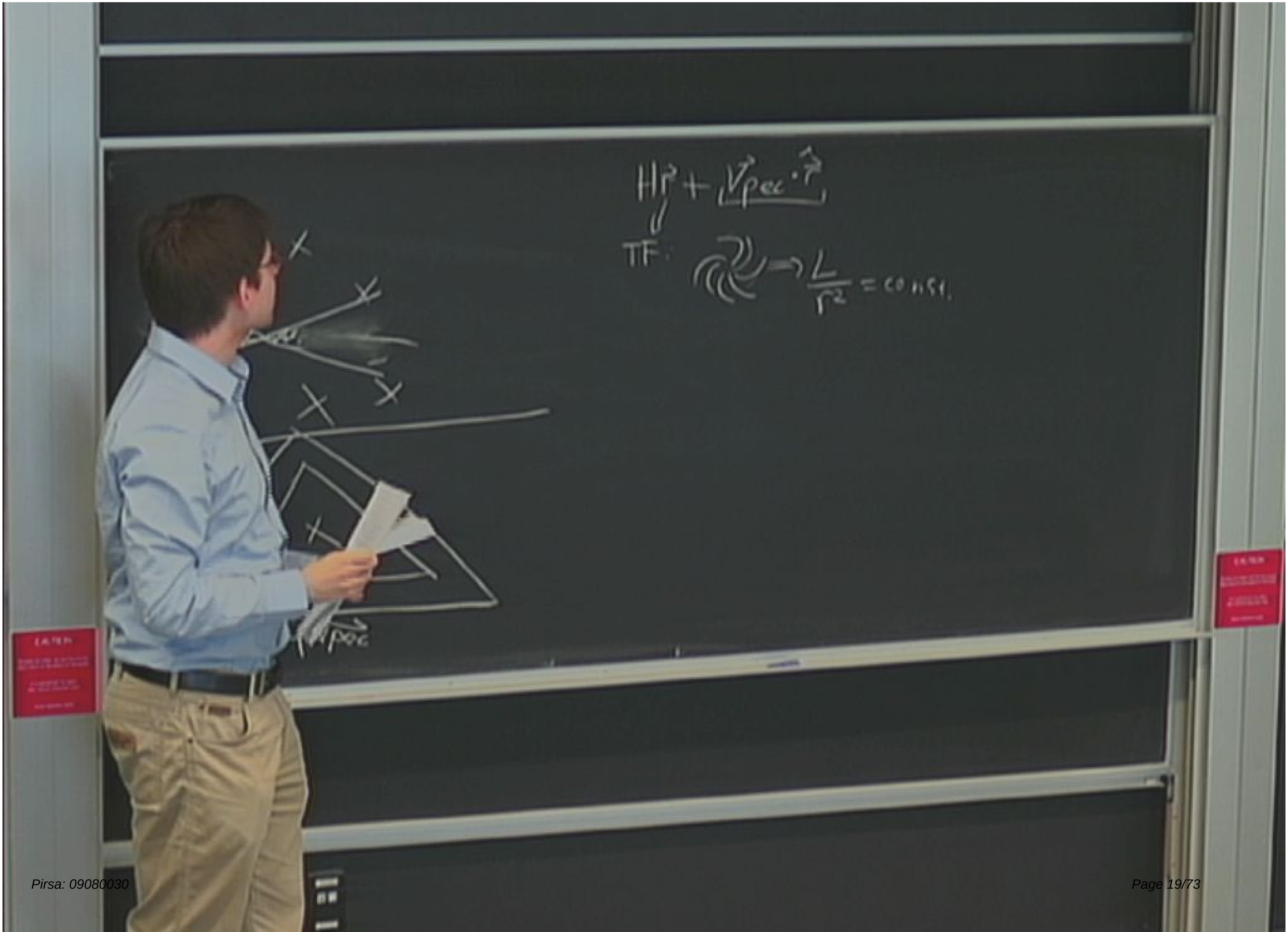




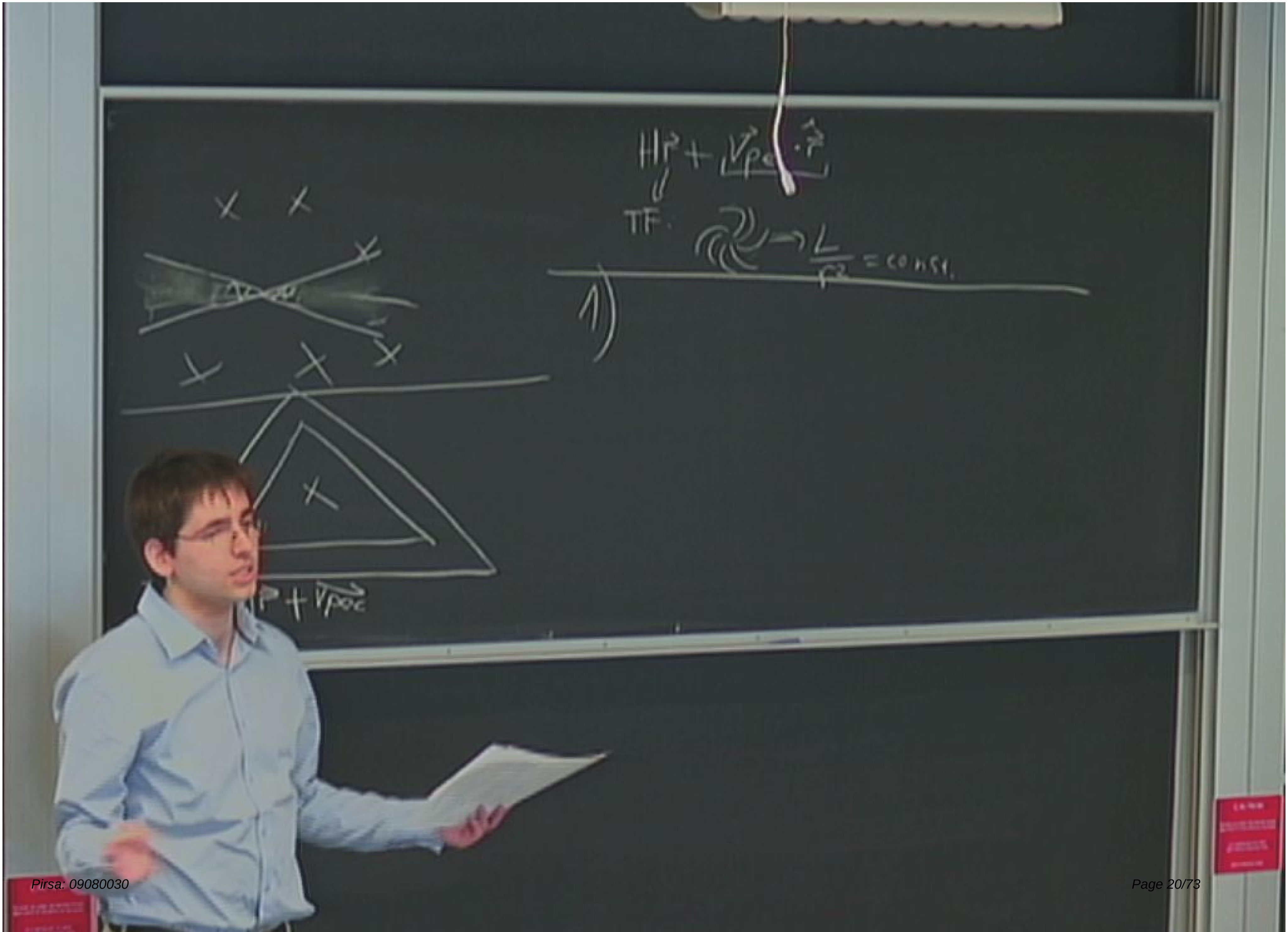




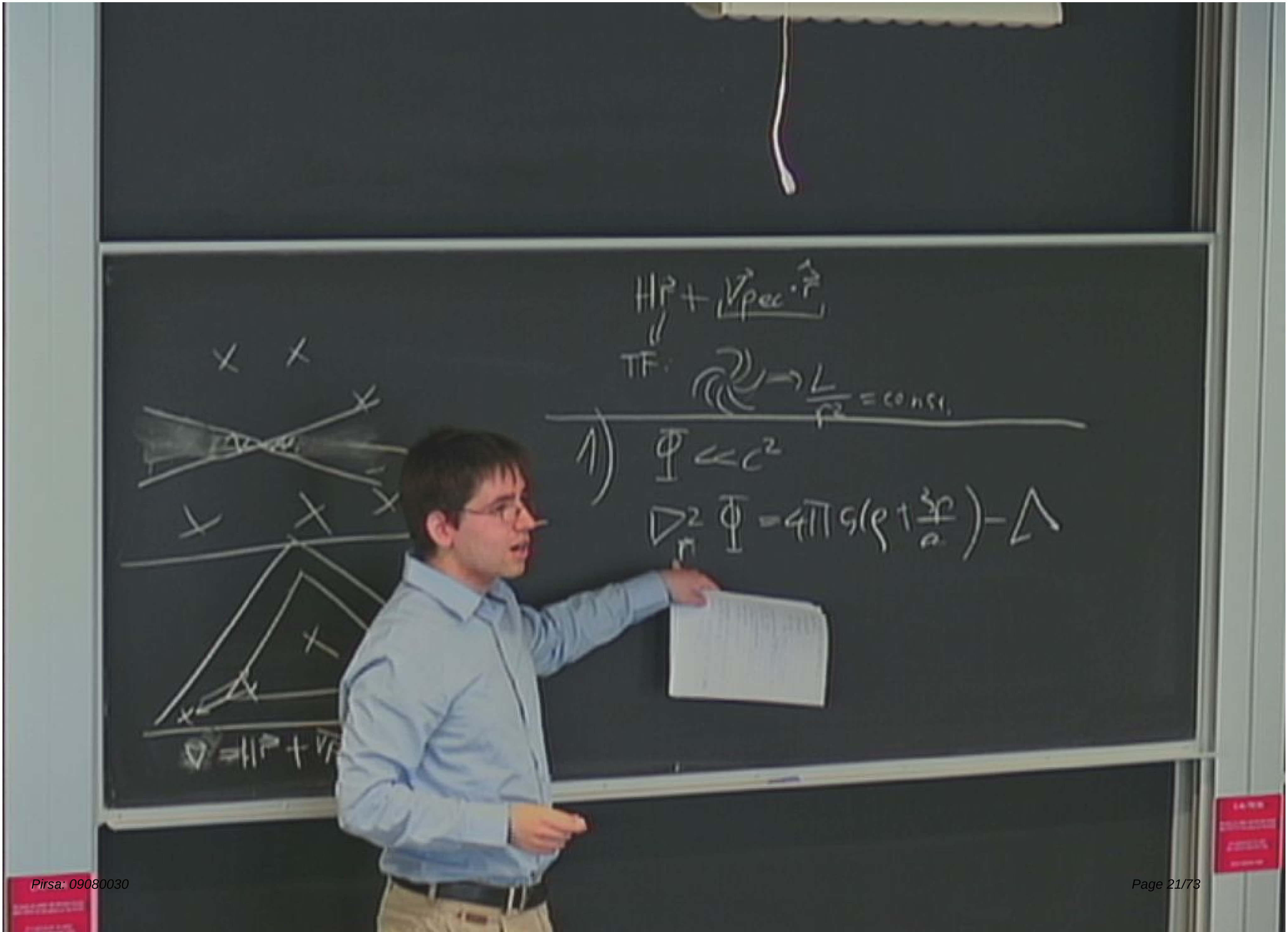

$\mathbb{H}^P + \vec{V}_{pec}\cdot\vec{r}$

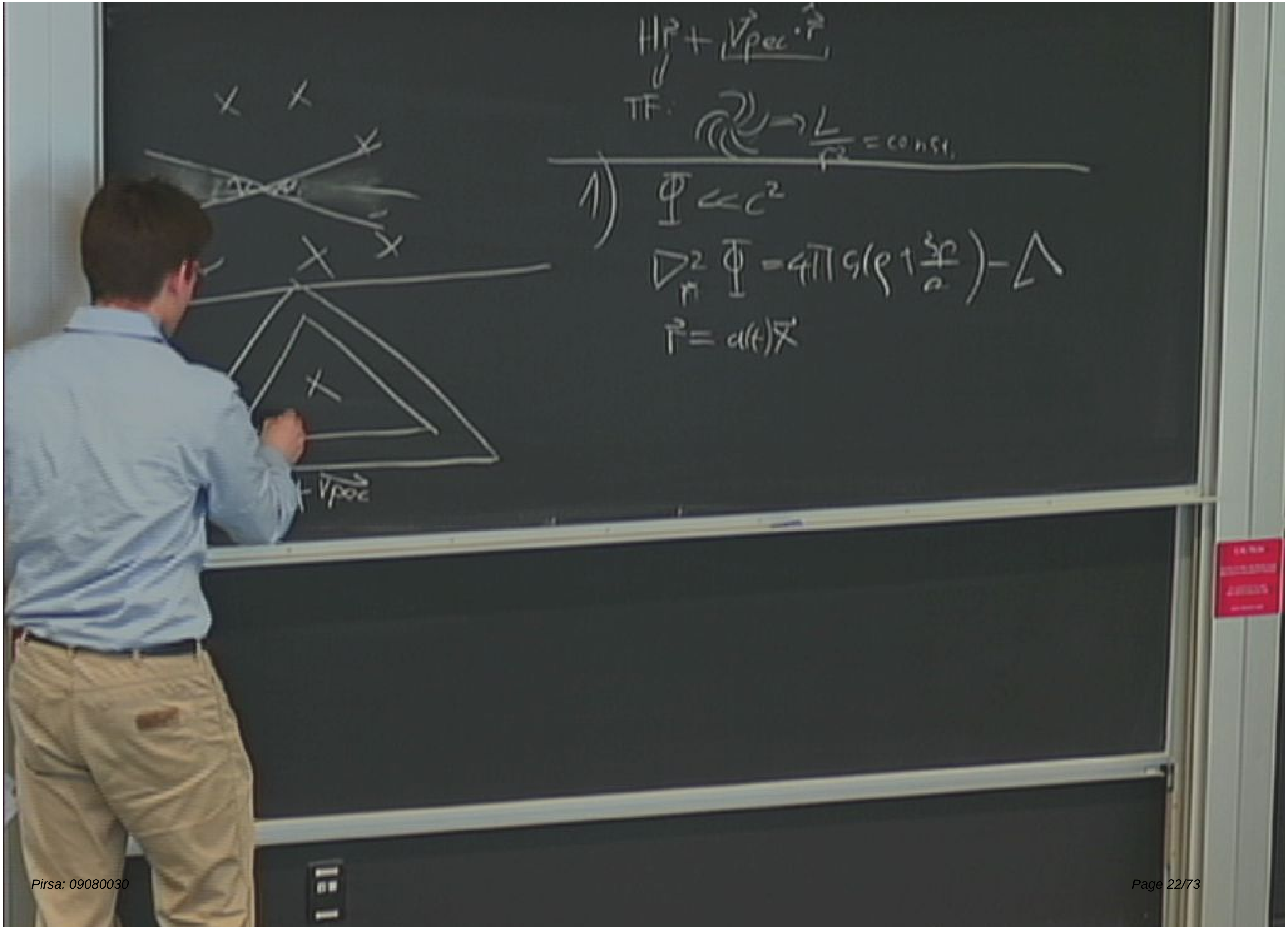


Hr + Vpec · r
TF:
L / r2 = const.
Vpec

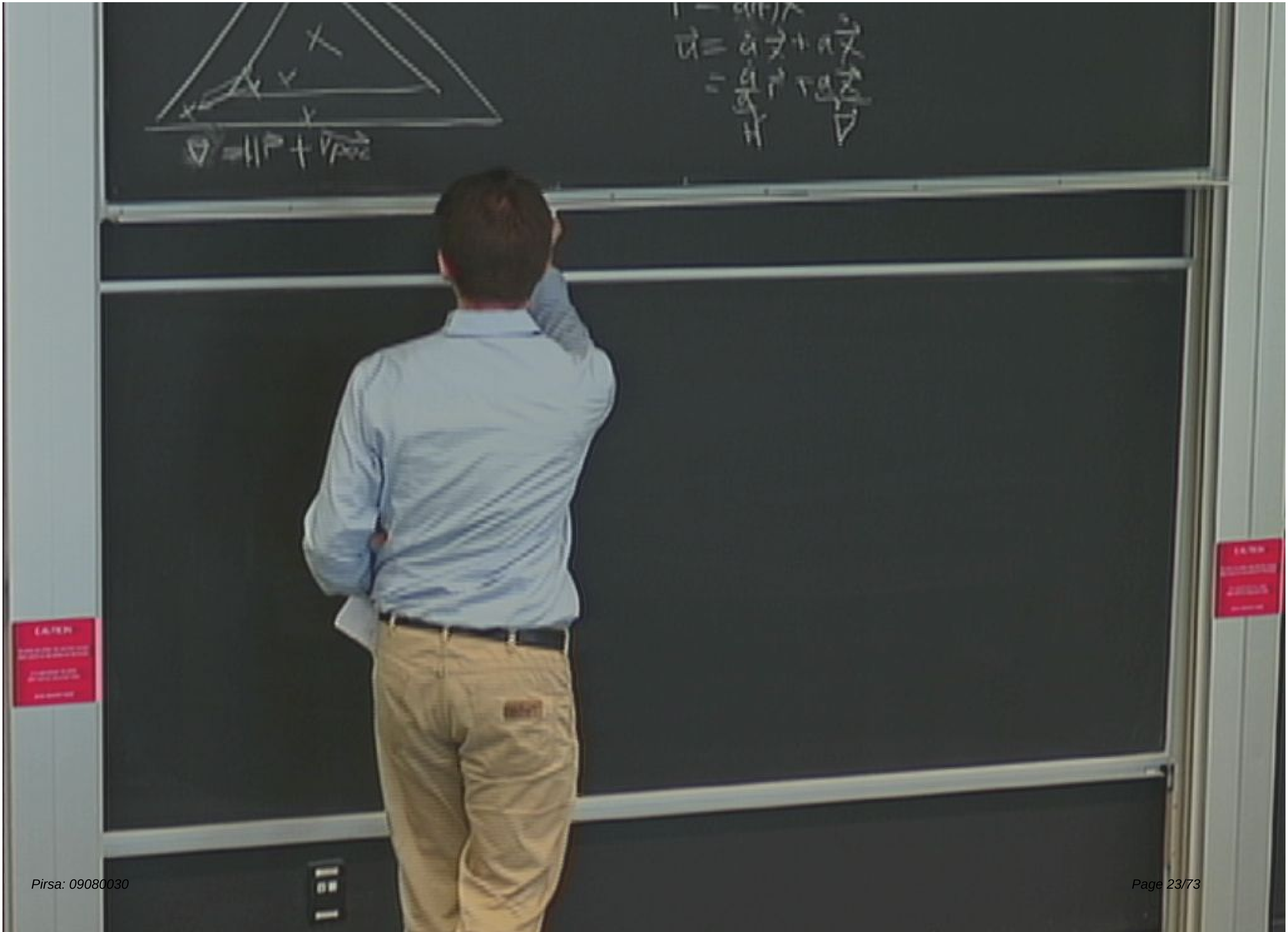


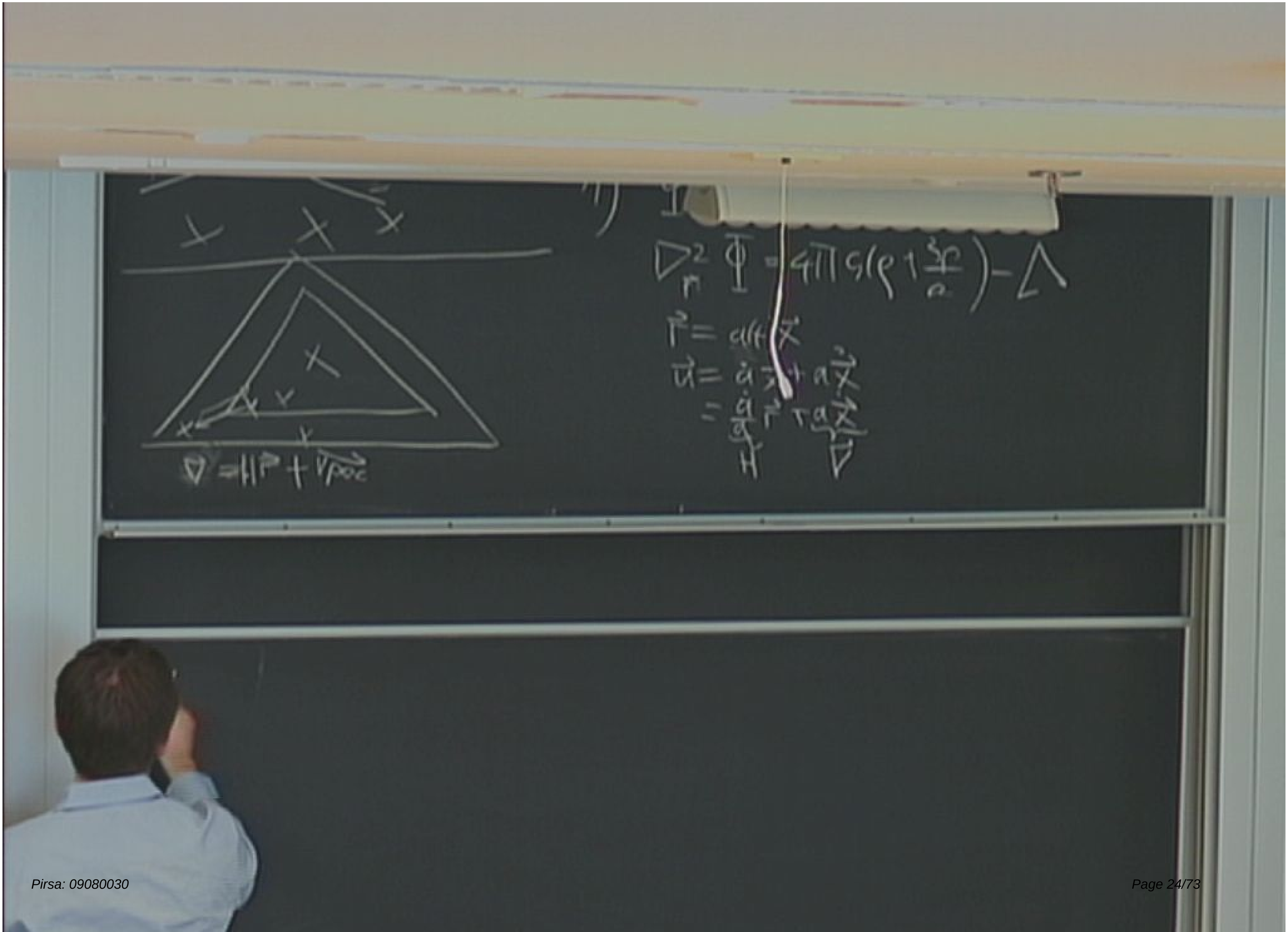
$HP + \vec{V}_{pec} \cdot \vec{r}$
TF.
$\frac{L}{r^2} = const.$
1)
$HP + \vec{V}_{pec}$

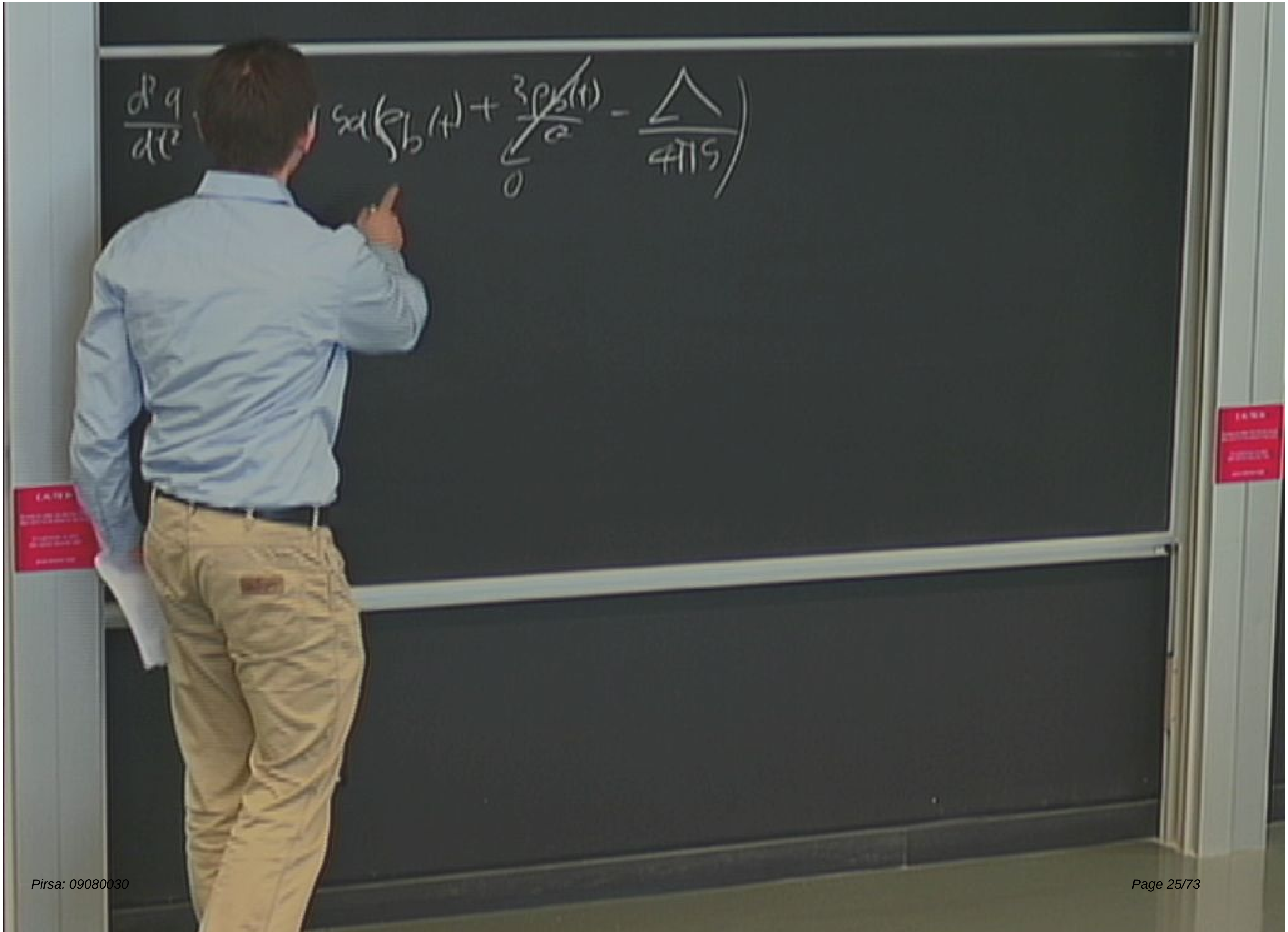

Hr + v_pec · r
TF:
= const.
1) Φ << c²
∇² Φ = 4πG(ρ + 3p/c²) − Λ

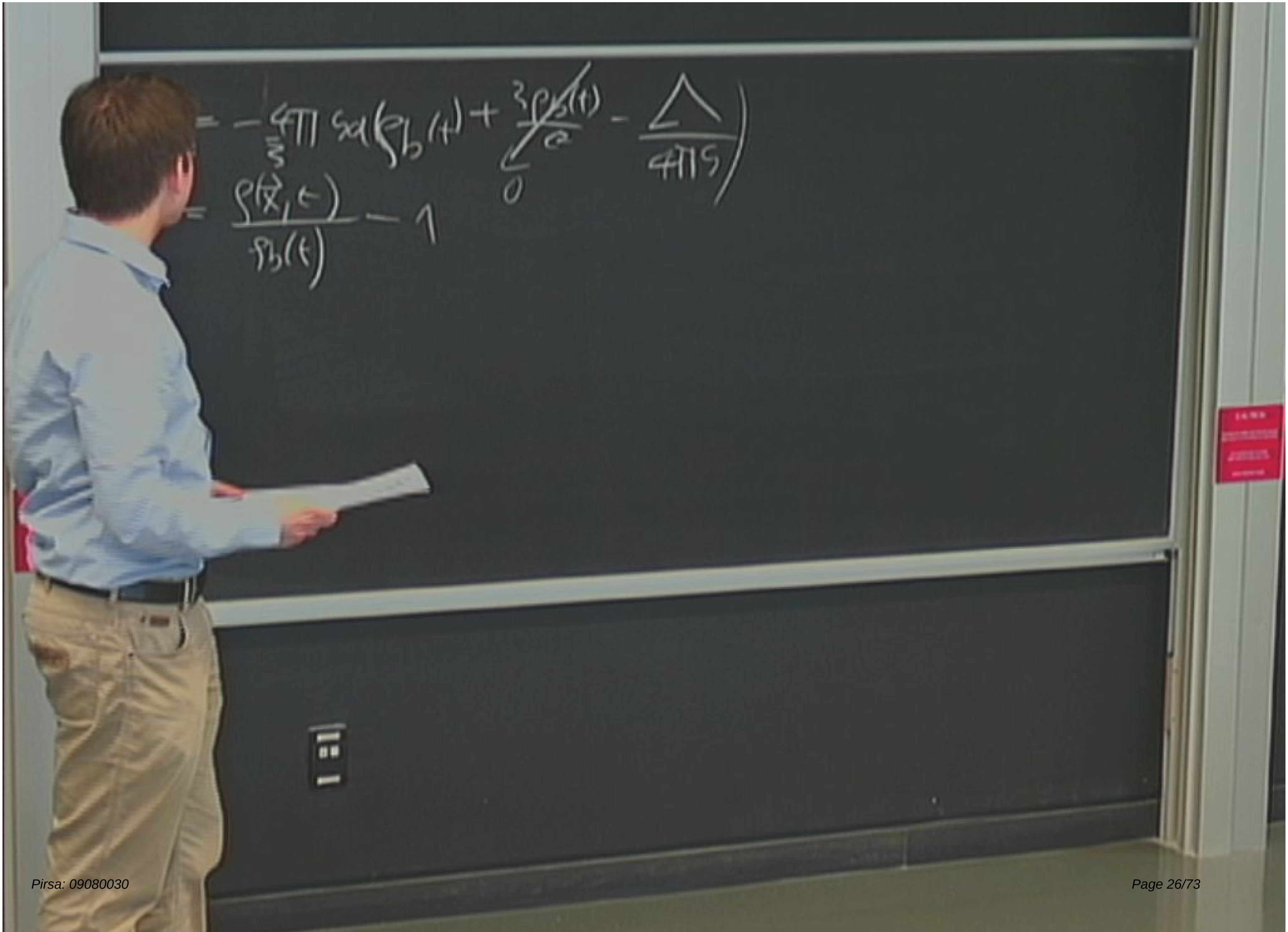


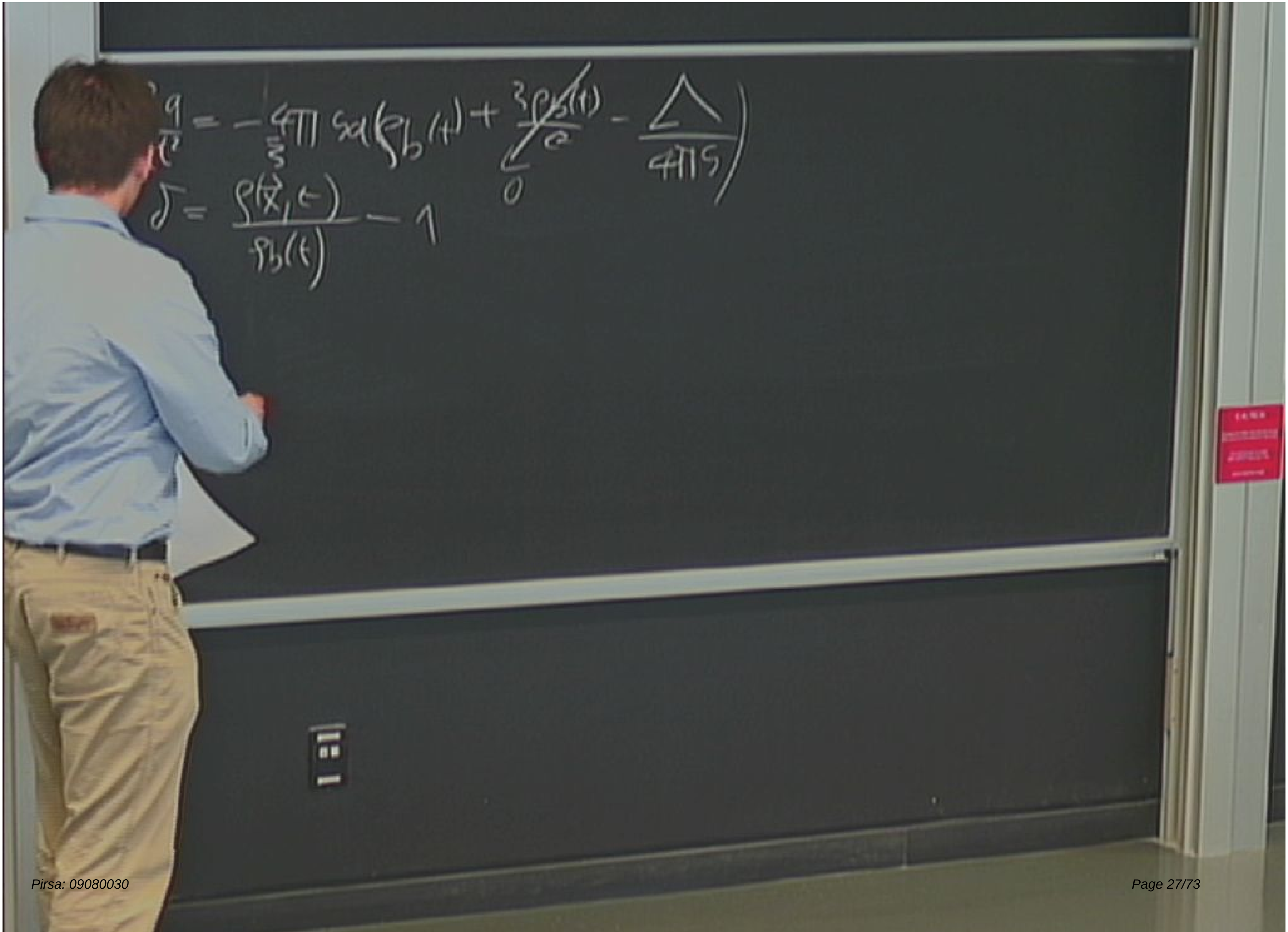
$H\vec{r} + \vec{V}_{pec}\cdot\vec{r}$
TF:
$= const.$
1) $\Phi \ll c^2$
$\nabla_r^2 \Phi = 4\pi G(\rho + \frac{3p}{c^2}) - \Lambda$
$\vec{r} = a(t)\vec{x}$
$+ \vec{V}_{pec}$




$\vec r = a(t)\vec x$
$\vec u = \dot a \vec x + a\dot{\vec x}$
$= \frac{\dot a}{a}\vec r + a\dot{\vec x}$




= -4πG a (ρ_b(t) + 3p_b(t)/c² - Λ/4πG)
= ρ(x,t)/ρ_b(t) - 1


$= -\frac{4\pi}{3} G a \left(\rho_b(t) + \frac{3p_b(t)}{c^2} - \frac{\Lambda}{4\pi G}\right)$
$\delta = \frac{\rho(\vec{x},t)}{\rho_b(t)} - 1$

$$\frac{d^2 a}{dt^2} = -\frac{4\pi}{3} G a \left(\rho_b(t) + \underbrace{\cancel{\frac{3 p_b(t)}{c^2}}}_{0} - \frac{\Lambda}{4\pi G} \right)$$

$$\delta = \frac{\rho(\vec{x}, t)}{\rho_b(t)} - 1$$

$$\nabla_{\vec{x}}^2 \phi = 4\pi G a^2 \left(\rho(\vec{x}, t) - \rho_b(t) \right), \quad \phi = \Phi + \frac{1}{2} a \ddot{a} x^2$$

$$\frac{d^2 a}{dt^2} = -\frac{4\pi}{3} G a \left(\rho_b(t) + \underbrace{\cancel{\frac{3 p_b(t)}{c^2}}}_{0} - \frac{\Lambda}{4\pi G} \right)$$

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$$\nabla_{\vec{x}}^2 \Phi = 4\pi G a^2 \rho_b \delta$$

$$\frac{d^2 a}{dt^2} = -\frac{4\pi}{3} G a \left(\rho_b(t) + \underbrace{\cancel{\frac{3 p_b(t)}{c^2}}}_{0} - \frac{\Lambda}{4\pi G} \right)$$

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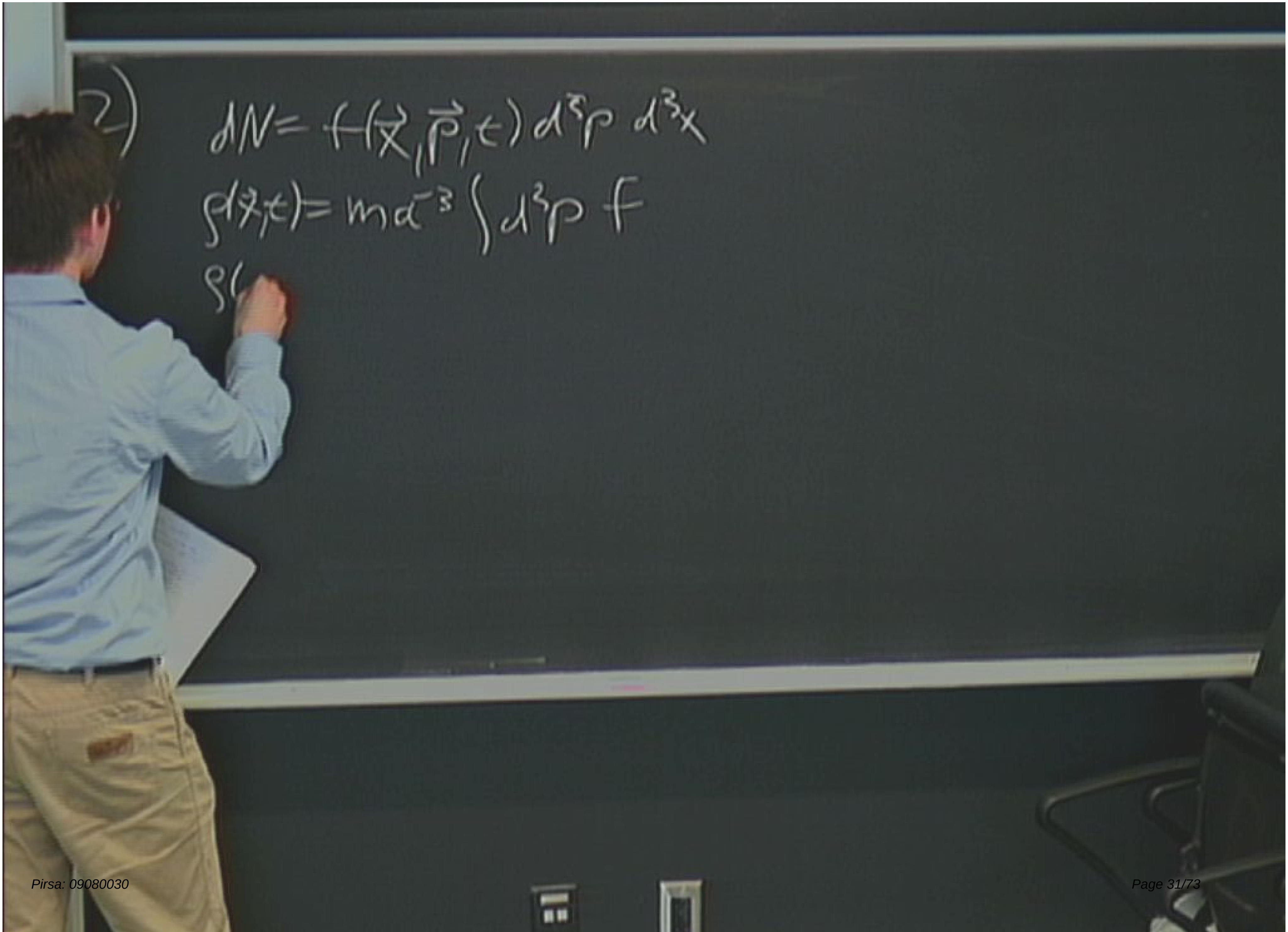
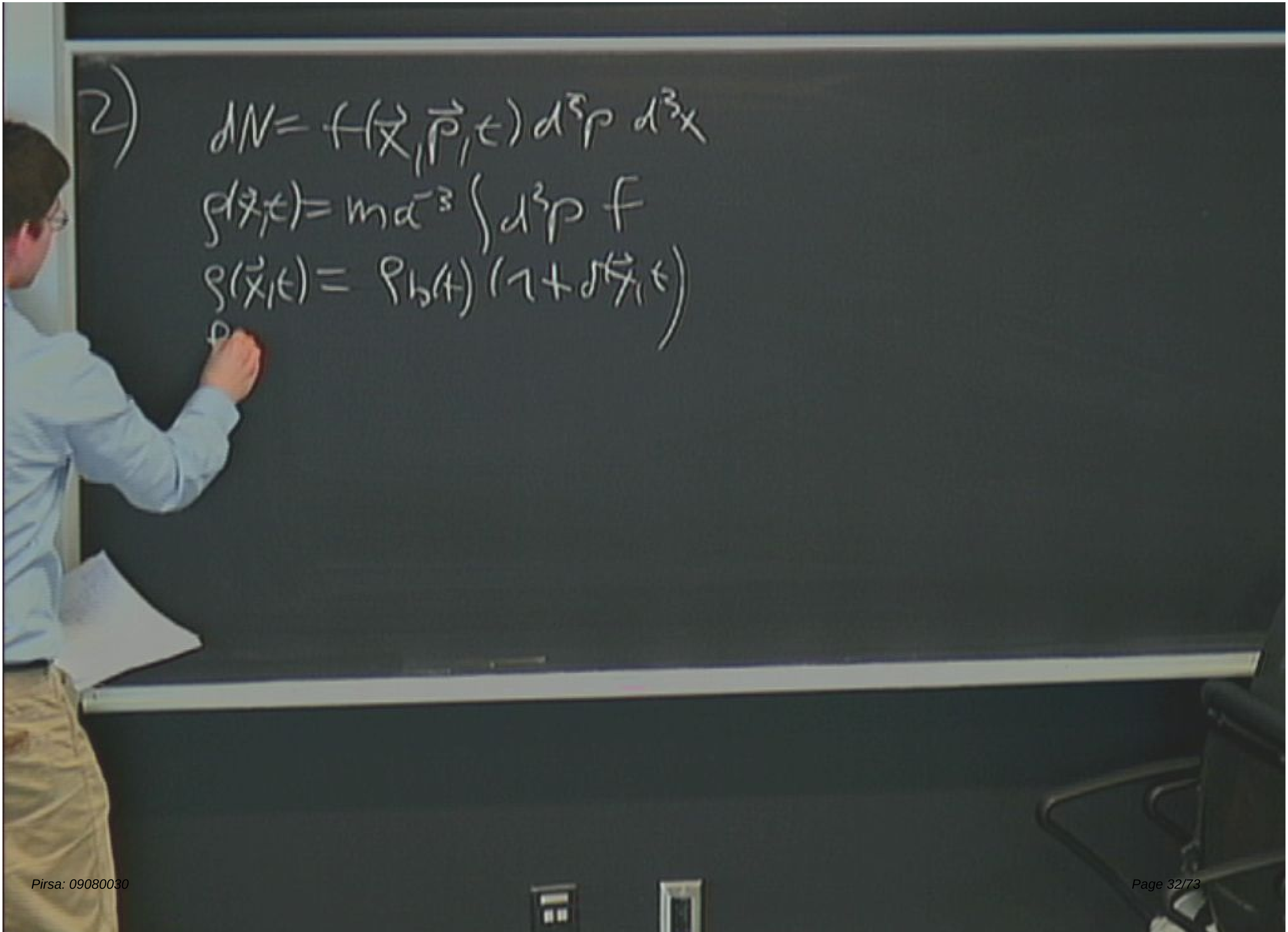

2)
$dN = f(\vec{x}, \vec{p}, t)\, d^3p\, d^3x$
$\rho(\vec{x}, t) = m a^{-3} \int d^3p\, f$
$\rho($


2) $dN = f(\vec{x}, \vec{p}, t)\, d^3p\, d^3x$
$\rho(\vec{x}, t) = m a^{-3} \int d^3p\, f$
$\rho(\vec{x}, t) = \rho_b(t)\,(1 + \delta(\vec{x}, t))$

2)

$$dN = f(\vec{x}, \vec{p}, t)\, d^3p\, d^3x$$

$$\rho(\vec{x}, t) = m a^{-3} \int d^3p\, f$$

$$\rho(\vec{x}, t) = \rho_b(t)\left(1 + \delta(\vec{x}, t)\right)$$

$$\boxed{\rho_b(t) \propto a^{-3}}$$

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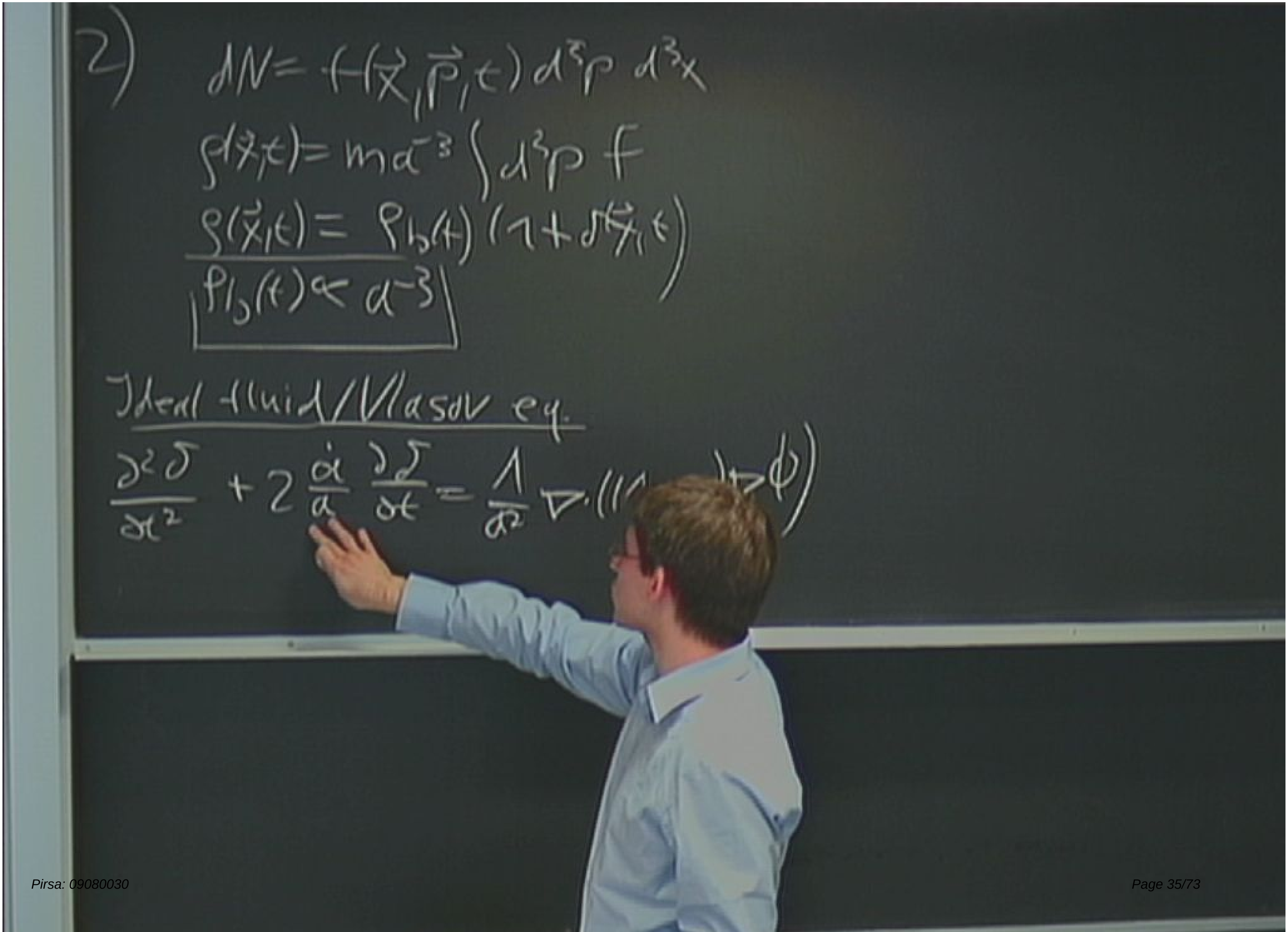
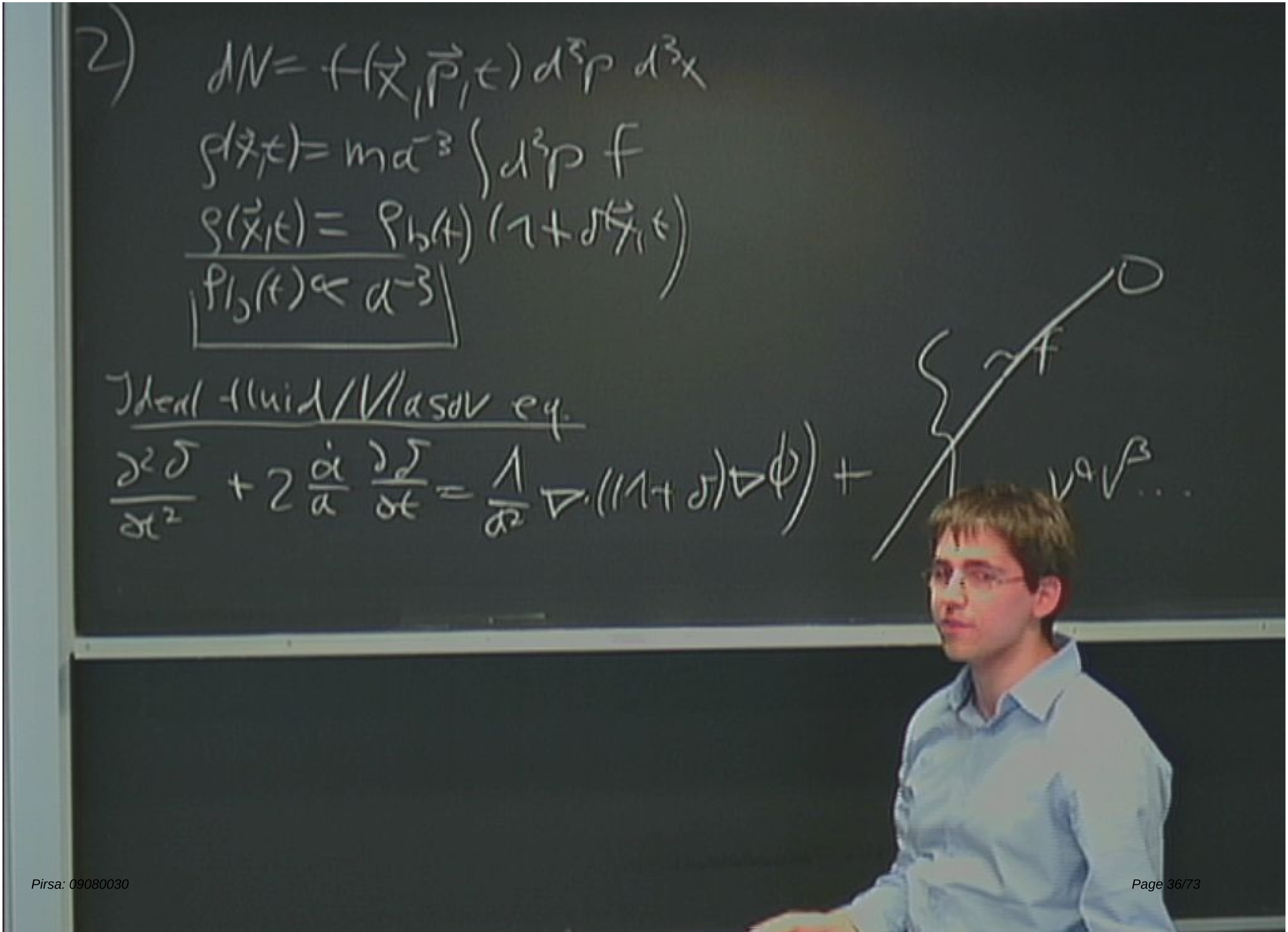
Ideal fluid



2) $dN = f(\vec{x}, \vec{p}, t)\, d^3p\, d^3x$
$\rho(\vec{x}, t) = m a^{-3} \int d^3p\, f$
$\rho(\vec{x}, t) = \rho_b(t)(1 + \delta(\vec{x}, t))$
$\boxed{\rho_b(t) \propto a^{-3}}$
Ideal fluid/Vlasov eq.
$\frac{\partial^2 \delta}{\partial t^2} + 2 \frac{\dot{a}}{a} \frac{\partial \delta}{\partial t} = \frac{1}{a^2} \nabla \cdot ((1 \ldots) \nabla \phi)$


2)
$dN = f(\vec{x},\vec{p},t)\, d^3p\, d^3x$
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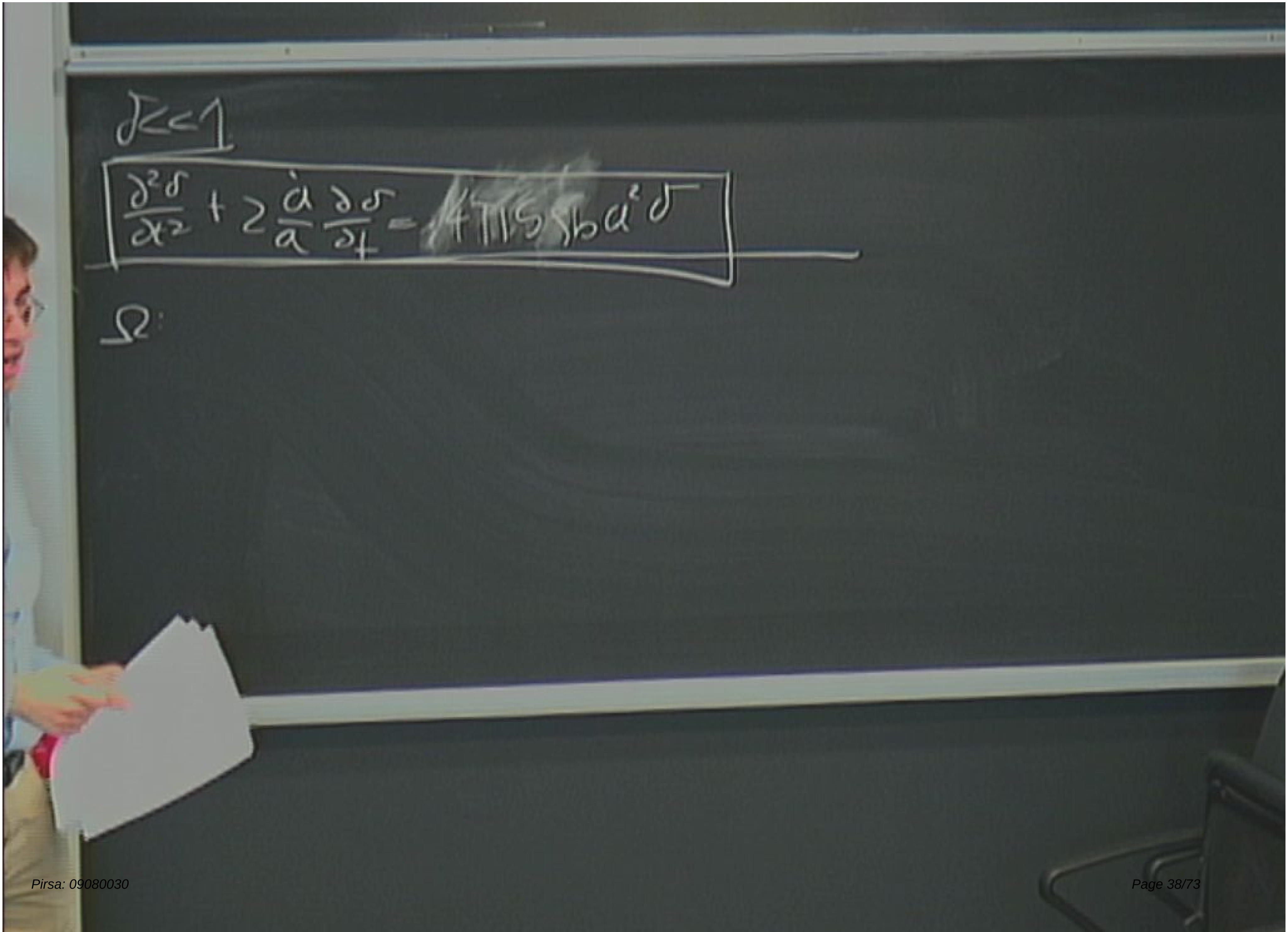
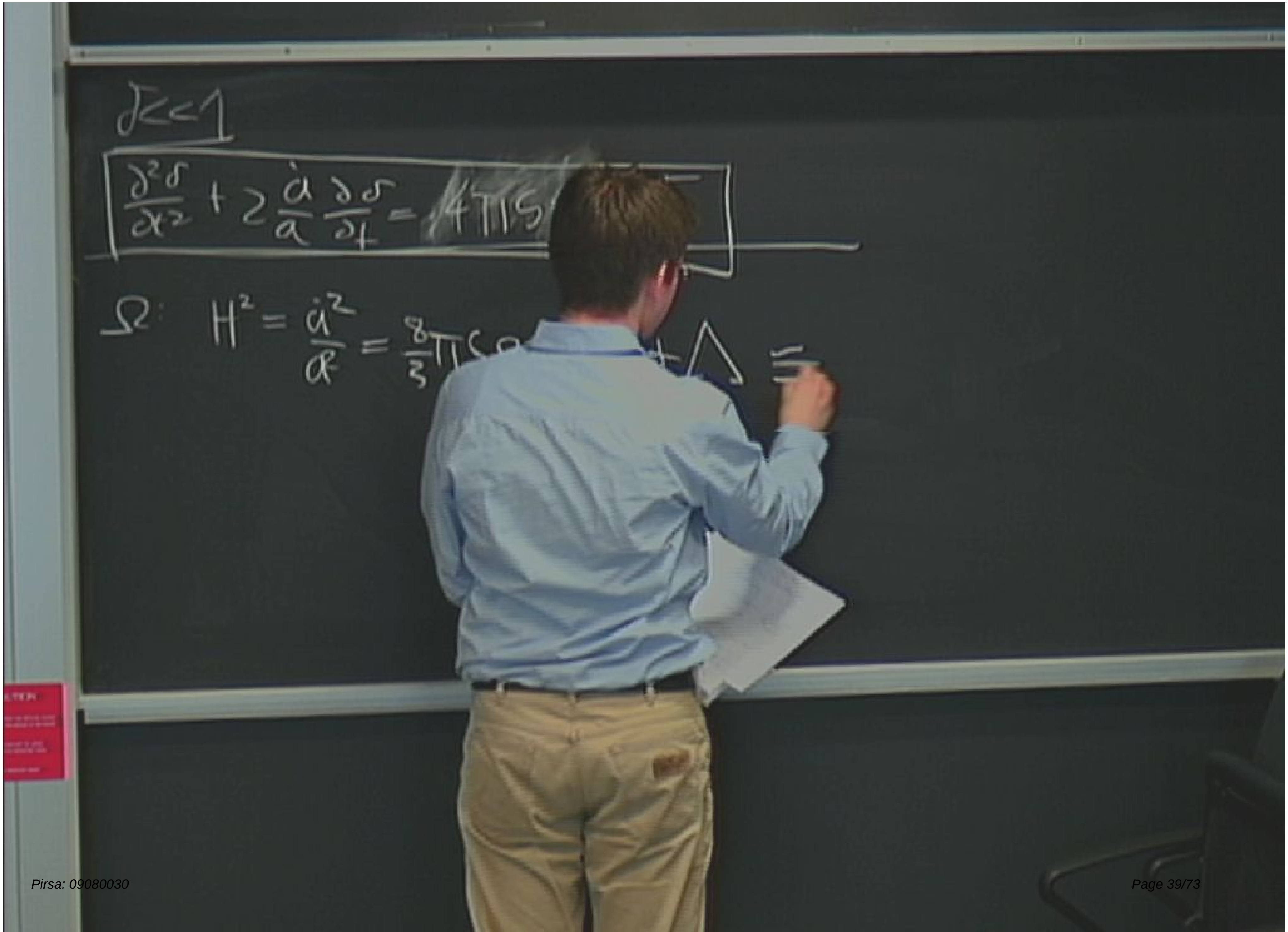
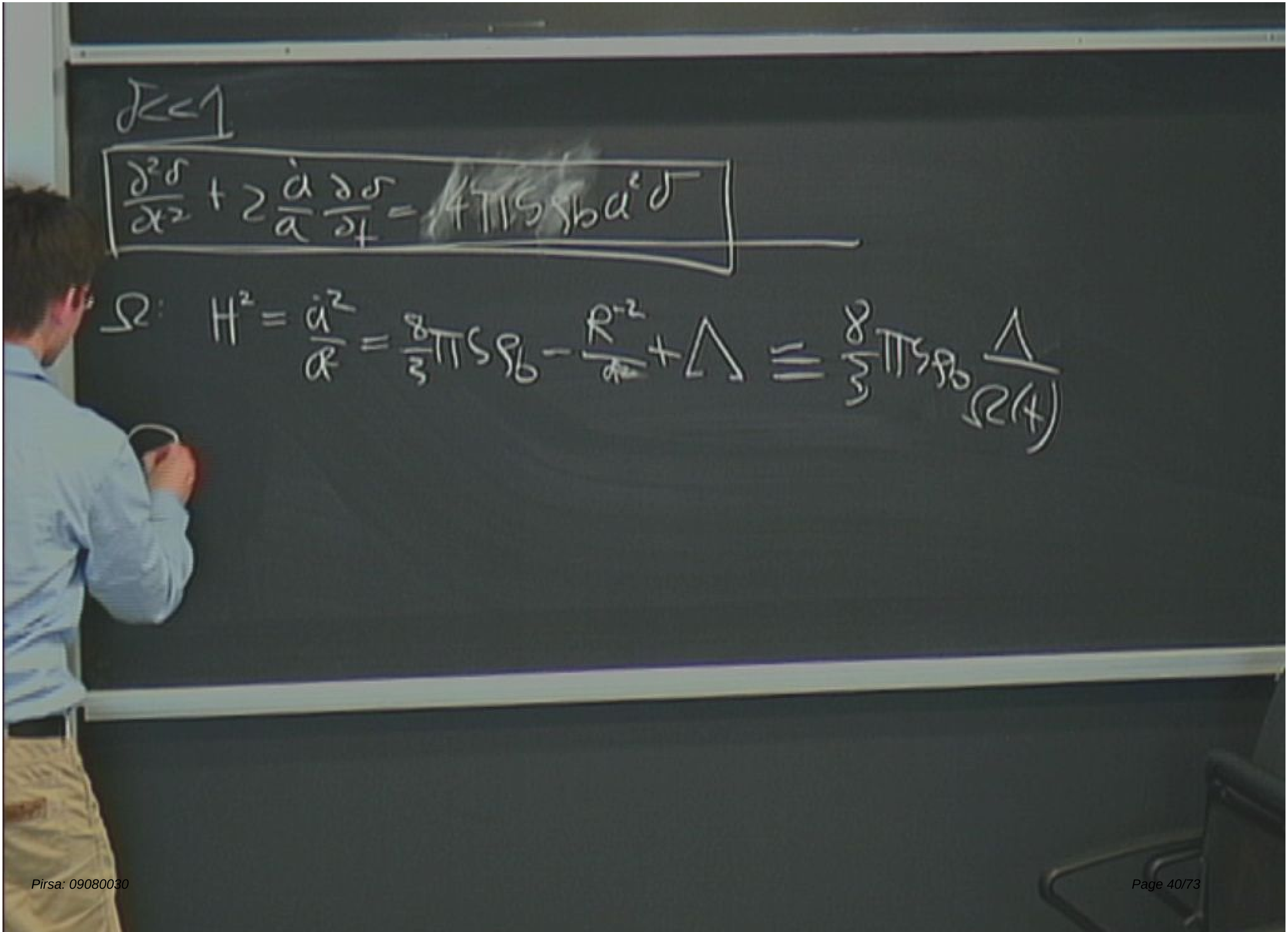
Ideal fluid/Vlasov eq.
$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = \frac{1}{a^2}\nabla\cdot((1+\delta)\nabla\phi) + \ldots v^\alpha v^\beta \ldots$
$\sim f$

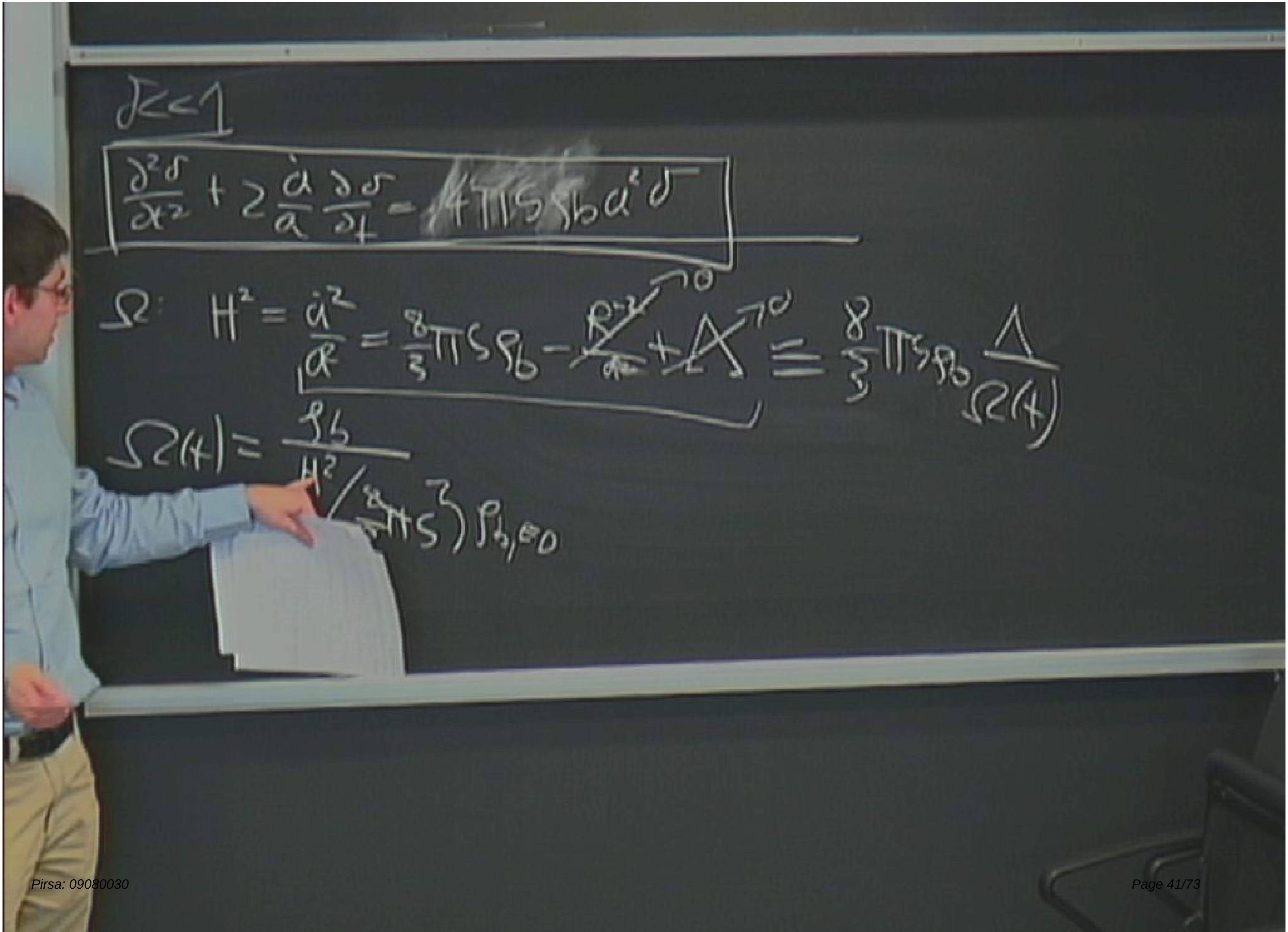
$\underline{\delta \ll 1}$

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = \frac{1}{a^2}\nabla^2 \phi$$


$\delta << 1$
$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G \rho_b a^2 \delta$
Ω:


δ << 1
∂²δ/∂t² + 2 (ȧ/a) (∂δ/∂t) = 4πG
Ω: H² = ȧ²/a² = (8/3)πGρ
Λ ≡


$\delta \ll 1$
$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G \rho_b a^2 \delta$
Ω: $H^2 = \frac{\dot{a}^2}{a^2} = \frac{8}{3}\pi G \rho_b - \frac{R^{-2}}{a^2} + \Lambda \equiv \frac{8}{3}\pi G \rho_b \frac{\Lambda}{\Omega(t)}$



$\delta \ll 1$
$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot a}{a}\frac{\partial \delta}{\partial t} = 4\pi G \rho_b a^2 \delta$
Ω: $H^2 = \frac{\dot a^2}{a^2} = \frac{8}{3}\pi G \rho_b - \frac{k}{a^2} + \Lambda \equiv \frac{8}{3}\pi G \rho_b \frac{1}{\Omega(t)}$
$\Omega(t) = \frac{\rho_b}{H^2 / (\frac{8}{3}\pi G)}$ $\rho_{b,0}$

$\delta \ll 1$

$$\boxed{\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot a}{a}\frac{\partial \delta}{\partial t} = 4\pi G \rho_b a^2 \delta}$$

Ω: $H^2 = \underbrace{\frac{\dot a^2}{a^2} = \frac{8}{3}\pi G \rho_b - \cancel{\frac{R^{-2}}{a^2}}^{\to 0} + \cancel{\Lambda}^{\to 0}} \equiv \frac{8}{3}\pi G \rho_b \frac{\Delta}{\Omega(t)}$

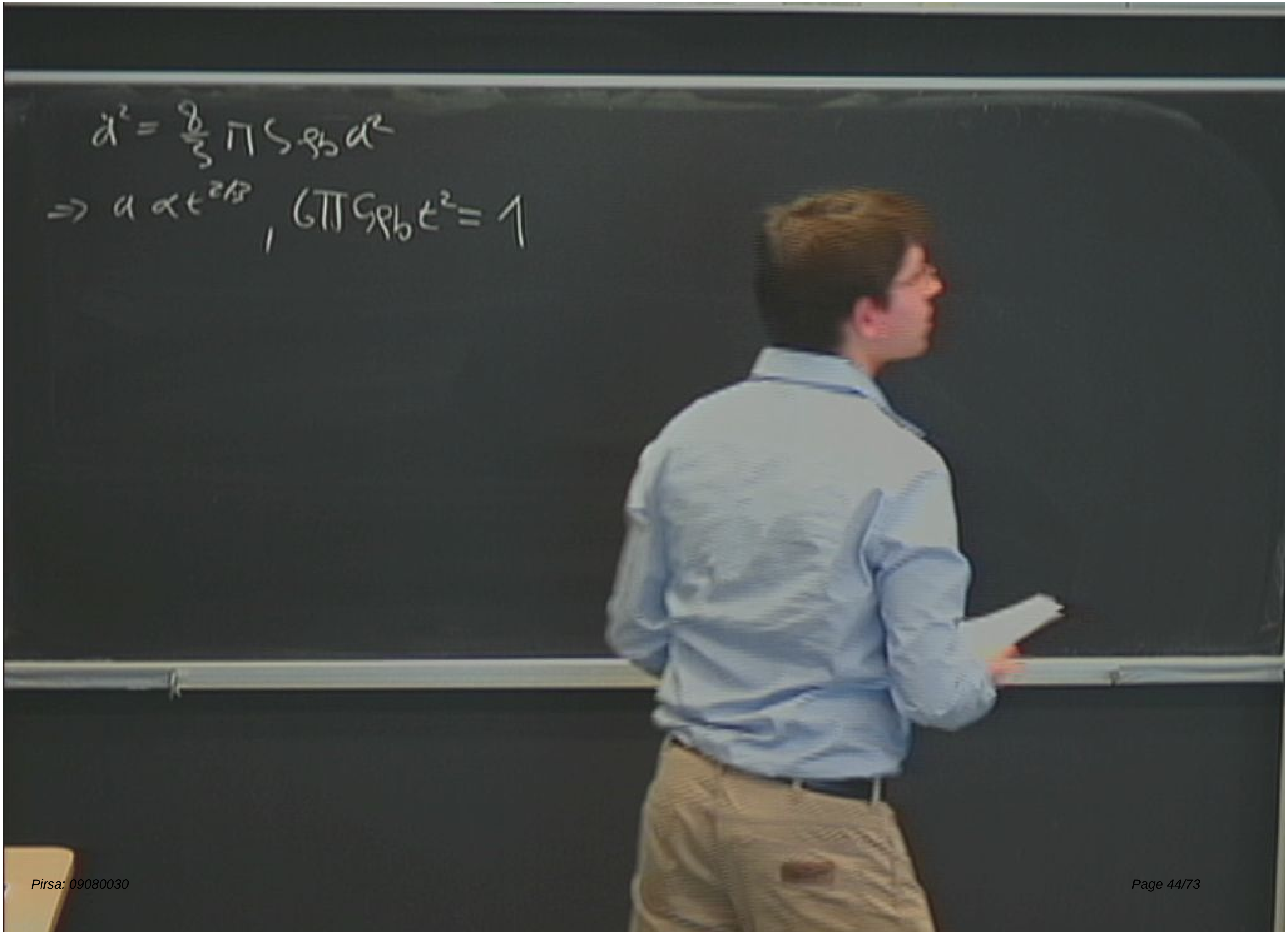
$$\Omega(t) = \frac{\rho_b}{H^2 / \left(\frac{8}{3}\pi G\right)} \rho_{b,ED}$$

$\delta \ll 1$

$$\boxed{\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot a}{a}\frac{\partial \delta}{\partial t} = 4\pi G \rho_b a^2 \delta}$$

$$\Omega: \quad H^2 = \frac{\dot a^2}{a^2} = \frac{8}{3}\pi G \rho_b - \cancel{\frac{k c^2}{a^2}}^{\to 0} + \cancel{\Lambda}^{\to 0} \equiv \frac{8}{3}\pi G \rho_b \frac{\Lambda}{\Omega(t)}$$

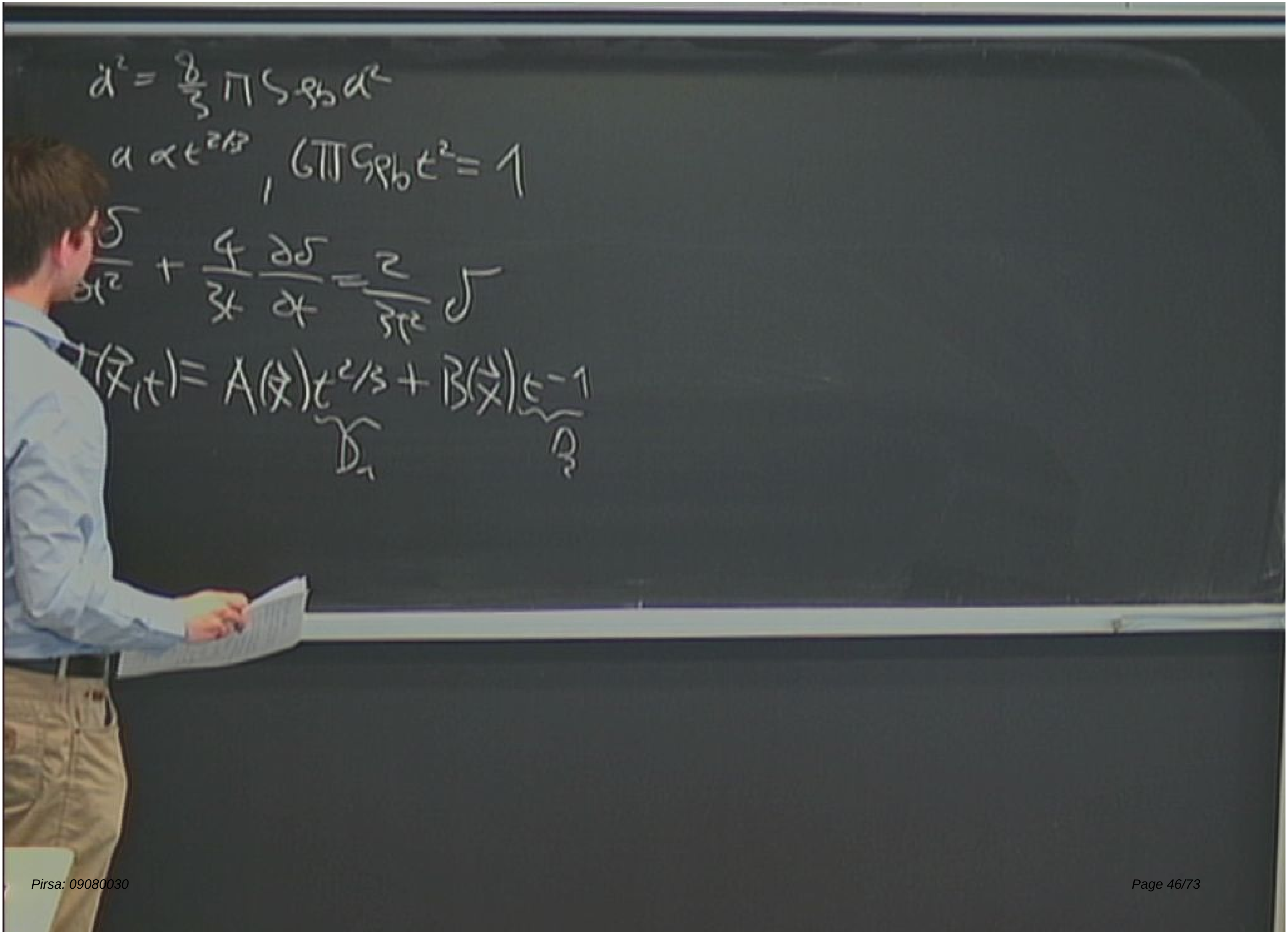
$$\Omega(t) = \frac{\rho_b}{H^2 / \left(\frac{8}{3}\pi G\right)} \rho_{b,ED}$$


$\dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$
$\Rightarrow a \propto t^{2/3}, \; 6\pi G \rho_b t^2 = 1$

$$\dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$$

$$\Rightarrow a \propto t^{2/3}, \quad 6\pi G \rho_b t^2 = 1$$

$$\frac{\partial^2 \delta}{\partial t^2} + \frac{4}{3t}\frac{\partial \delta}{\partial t} = \frac{2}{3t^2}\delta$$

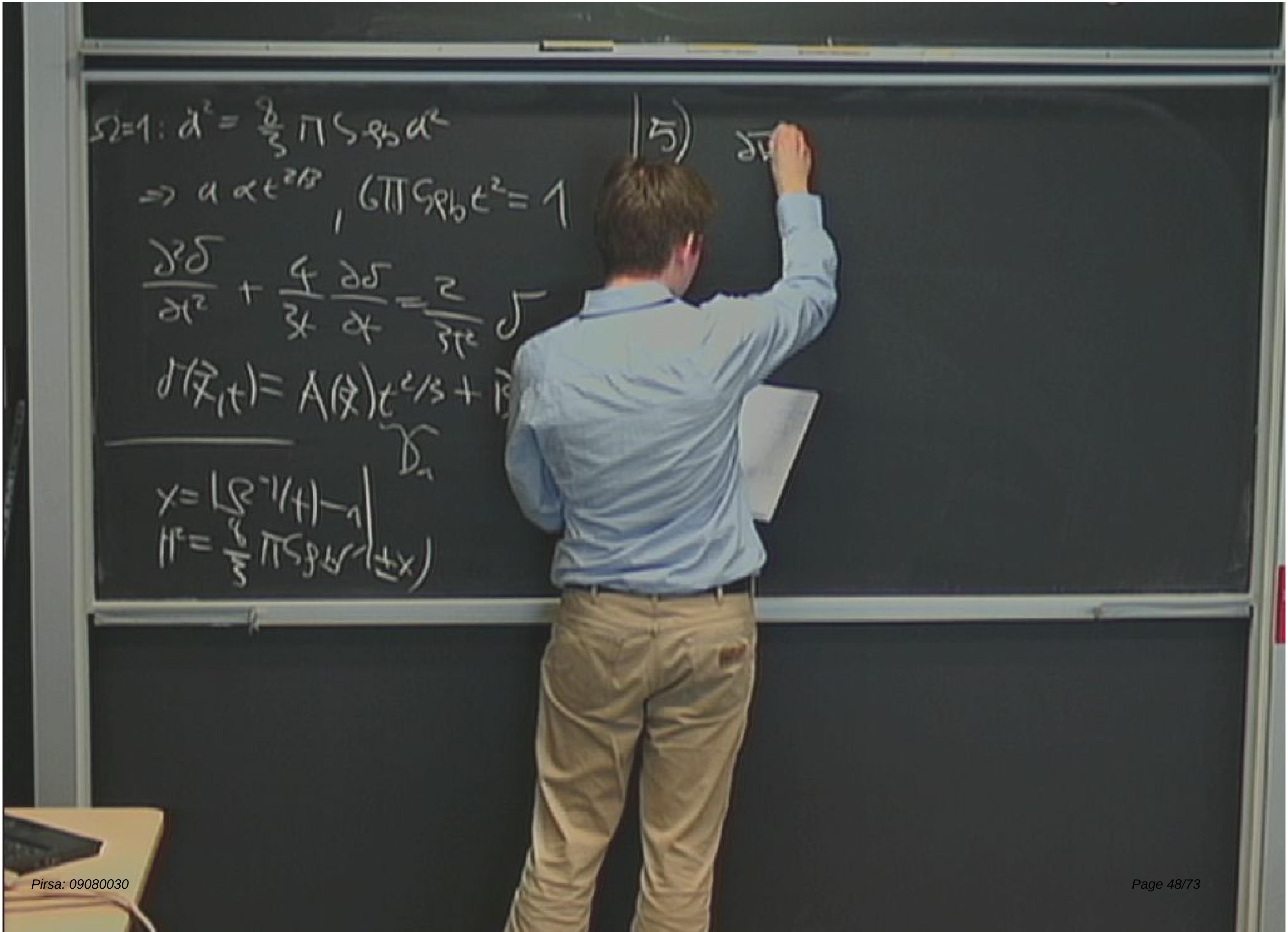

$\dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$
$a \propto t^{2/3}$, $6\pi G \rho_b t^2 = 1$
$\frac{\partial^2 \delta}{\partial t^2} + \frac{4}{3t}\frac{\partial \delta}{\partial t} = \frac{2}{3t^2}\delta$
$\delta(\vec{x}, t) = A(\vec{x})\underbrace{t^{2/3}}_{D_1} + B(\vec{x})\underbrace{t^{-1}}_{D}$

$$\Omega=1: \dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$$

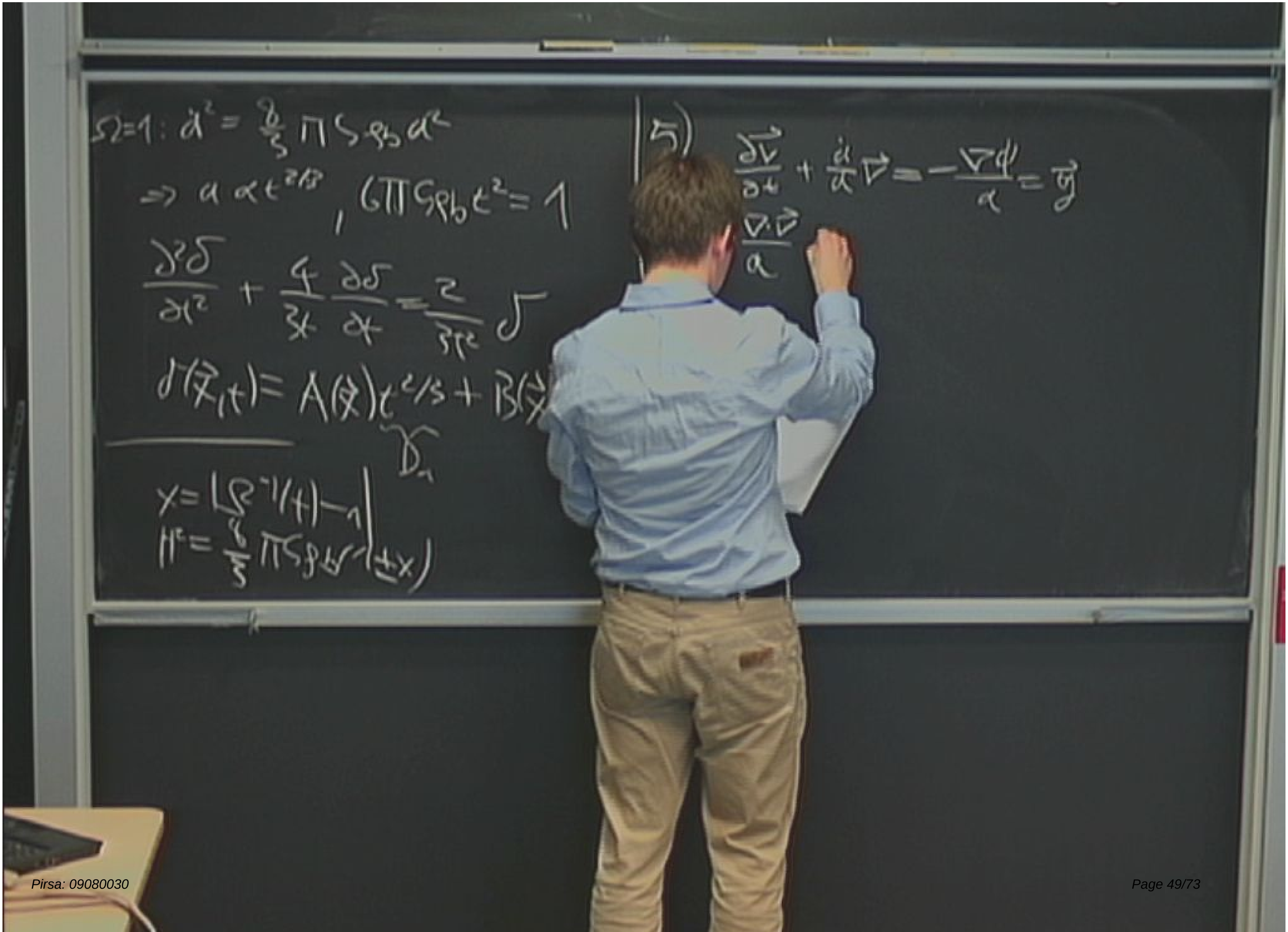
$$\Rightarrow a \propto t^{2/3}, \quad 6\pi G \rho_b t^2 = 1$$

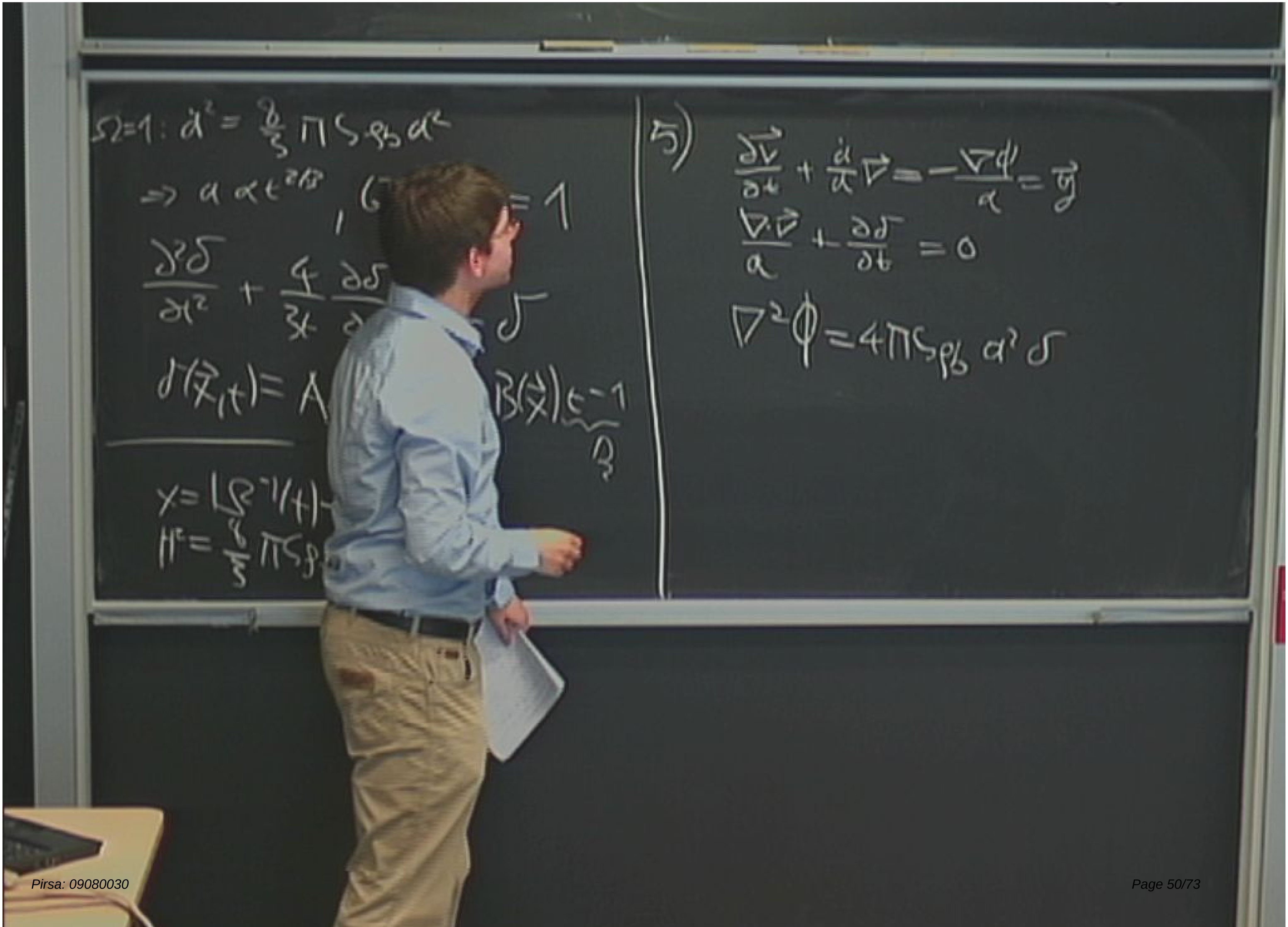
$$\frac{\partial^2 \delta}{\partial t^2} + \frac{4}{3t}\frac{\partial \delta}{\partial t} = \frac{2}{3t^2}\delta$$

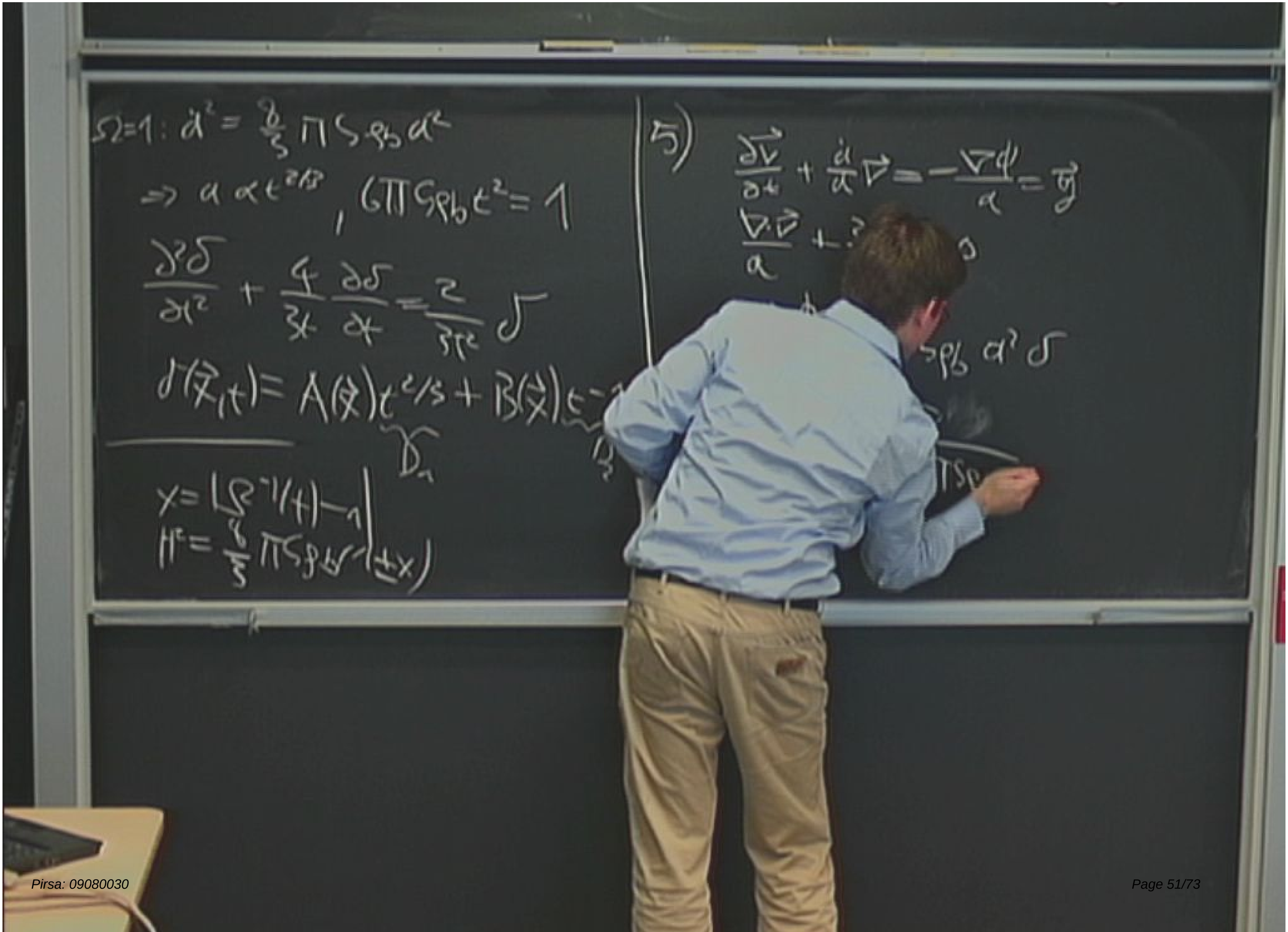
$$\delta(\vec{x},t) = A(\vec{x})\underbrace{t^{2/3}}_{D_1} + B(\vec{x})\underbrace{t^{-1}}_{D_2}$$

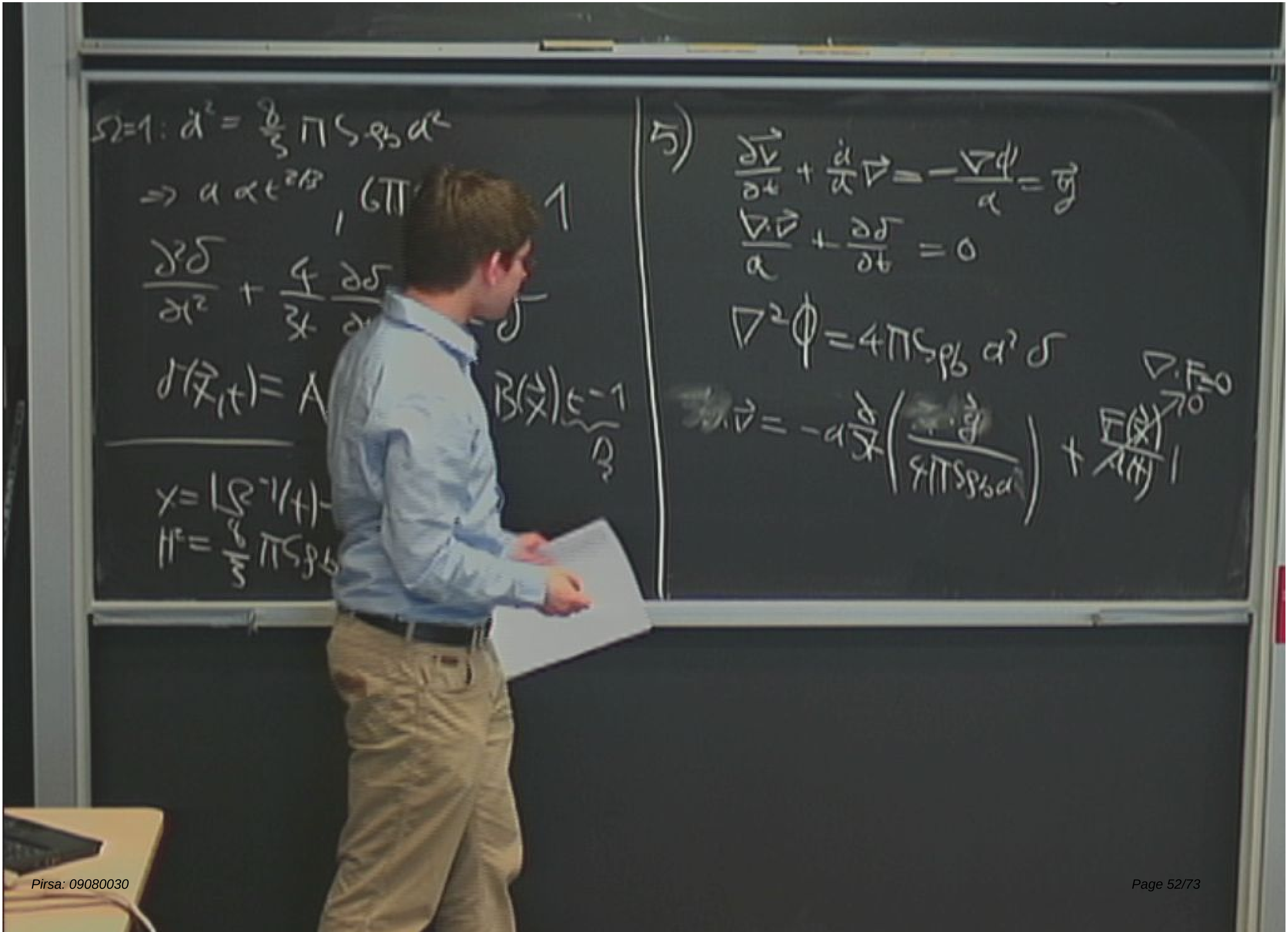


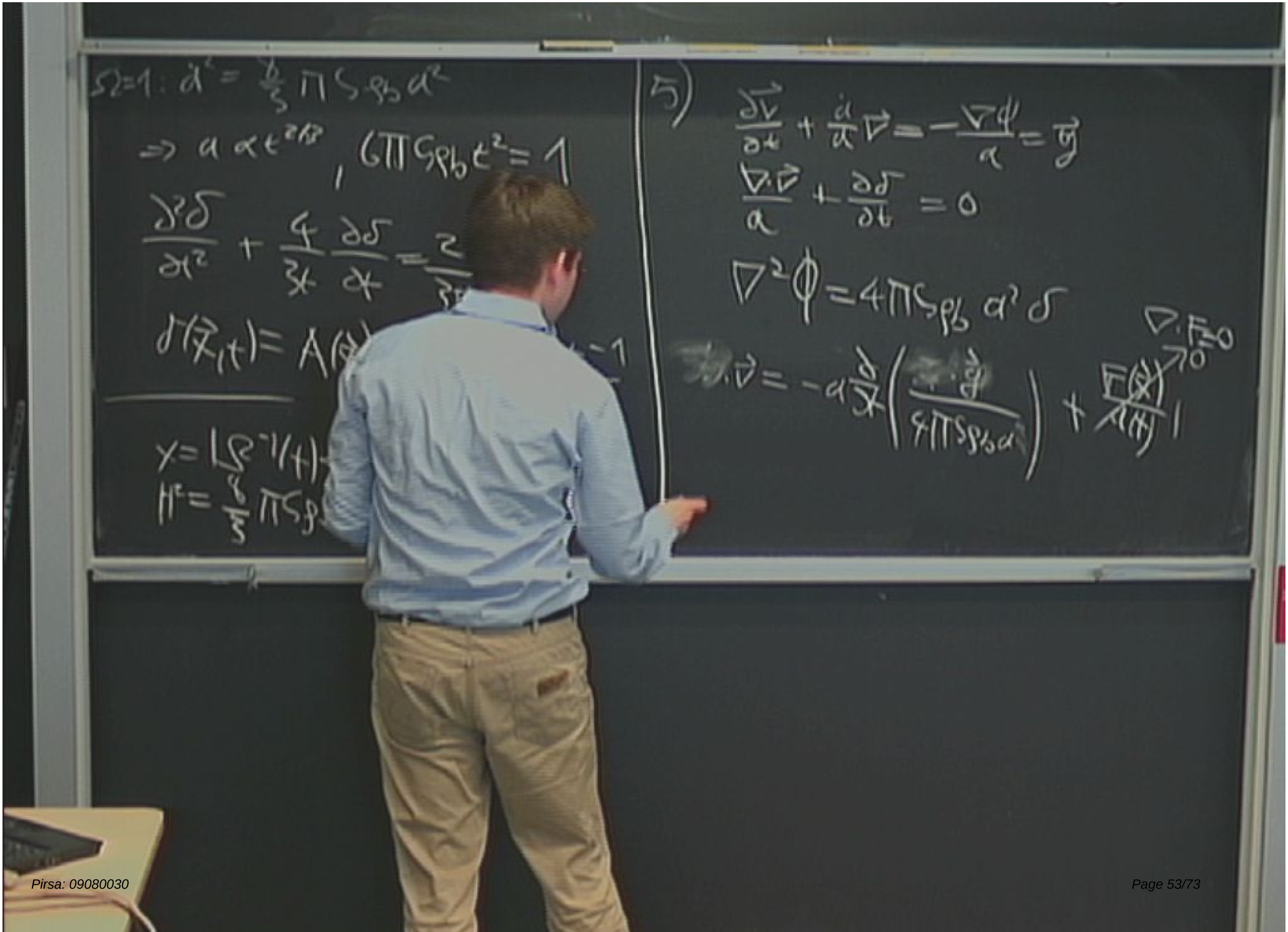
Ω=1 : ȧ² = 8/3 π G ρb a²
⇒ a ∝ t^{2/3} , 6π G ρb t² = 1
∂²δ/∂t² + 4/3t ∂δ/∂t = 2/3t² δ
δ(x, t) = A(x) t^{2/3} + B
5)


Ω=1: ȧ² = 8/3 π G ρb a²
⇒ a ∝ t^(2/3), 6π G ρb t² = 1
∂²δ/∂t² + 4/3t ∂δ/∂t = 2/3t² δ
δ(x,t) = A(x) t^(2/3) + B(x)
D1
x = [Ω⁻¹(t) − 1]
H² = 8/3 π G ρb (1+x)
5)
∂v/∂t + ȧ/a v = −∇φ/a = g
∇·v/a


$\Omega=1: \dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$
$\Rightarrow a \propto t^{2/3}$
$\delta(\vec{x},t) = A$
$B(\vec{x})\, t^{-1}$
5)
$\frac{\partial \vec{v}}{\partial t} + \frac{\dot{a}}{a}\vec{v} = -\frac{\nabla\phi}{a} = \vec{g}$
$\frac{\nabla\cdot\vec{v}}{a} + \frac{\partial\delta}{\partial t} = 0$
$\nabla^2\phi = 4\pi G \rho_b a^2 \delta$


Ω=1: ȧ² = 8/3 πGρb a²
⇒ a ∝ t^2/3 , 6πGρb t² = 1
∂²δ/∂t² + 4/3t ∂δ/∂t = 2/3t² δ
δ(x,t) = A(x) t^2/3 + B(x) t^-1
D+
x = |ρ^-1(t) − 1|
H² = 8/3 πGρb(1±x)
5)
∂v/∂t + ȧ/a v = −∇φ/a = g
∇·v/a
ρb a² δ


$\Omega=1: \dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$
$\Rightarrow a \propto t^{2/3}$
5)
$\frac{\partial \vec{v}}{\partial t} + \frac{\dot{a}}{a}\vec{v} = -\frac{\nabla\phi}{a} = \vec{g}$
$\frac{\nabla\cdot\vec{v}}{a} + \frac{\partial\delta}{\partial t} = 0$
$\nabla^2\phi = 4\pi G\rho_b a^2 \delta$
$\nabla\cdot\vec{F}=0$


$\Omega=1: \dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$
$\Rightarrow a \propto t^{2/3},\ 6\pi G \rho_b t^2 = 1$
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$\Omega=1: \dot{a}^2 = \frac{8}{3}\pi G \rho_b a^2$

$\Rightarrow a \propto t^{2/3}, \quad 6\pi G \rho_b t^2 = 1$

$$\frac{\partial^2 \delta}{\partial t^2} + \frac{4}{3t}\frac{\partial \delta}{\partial t} = \frac{2}{3t^2}\delta$$

$$\delta(\vec{x},t) = A(\vec{x})\underbrace{t^{2/3}}_{D_+} + B(\vec{x})\underbrace{t^{-1}}_{D_-}$$

$x = [\Omega^{-1}(t) - 1]$

$H^2 = \frac{8}{3}\pi G \rho_b a^{-2}(1 \pm x)$

5)

$$\frac{\partial \vec{v}}{\partial t} + \frac{\dot{a}}{a}\vec{v} = -\frac{\nabla\phi}{a} = \vec{g}$$

$$\frac{\nabla\cdot\vec{v}}{a} + \frac{\partial\delta}{\partial t} = 0$$

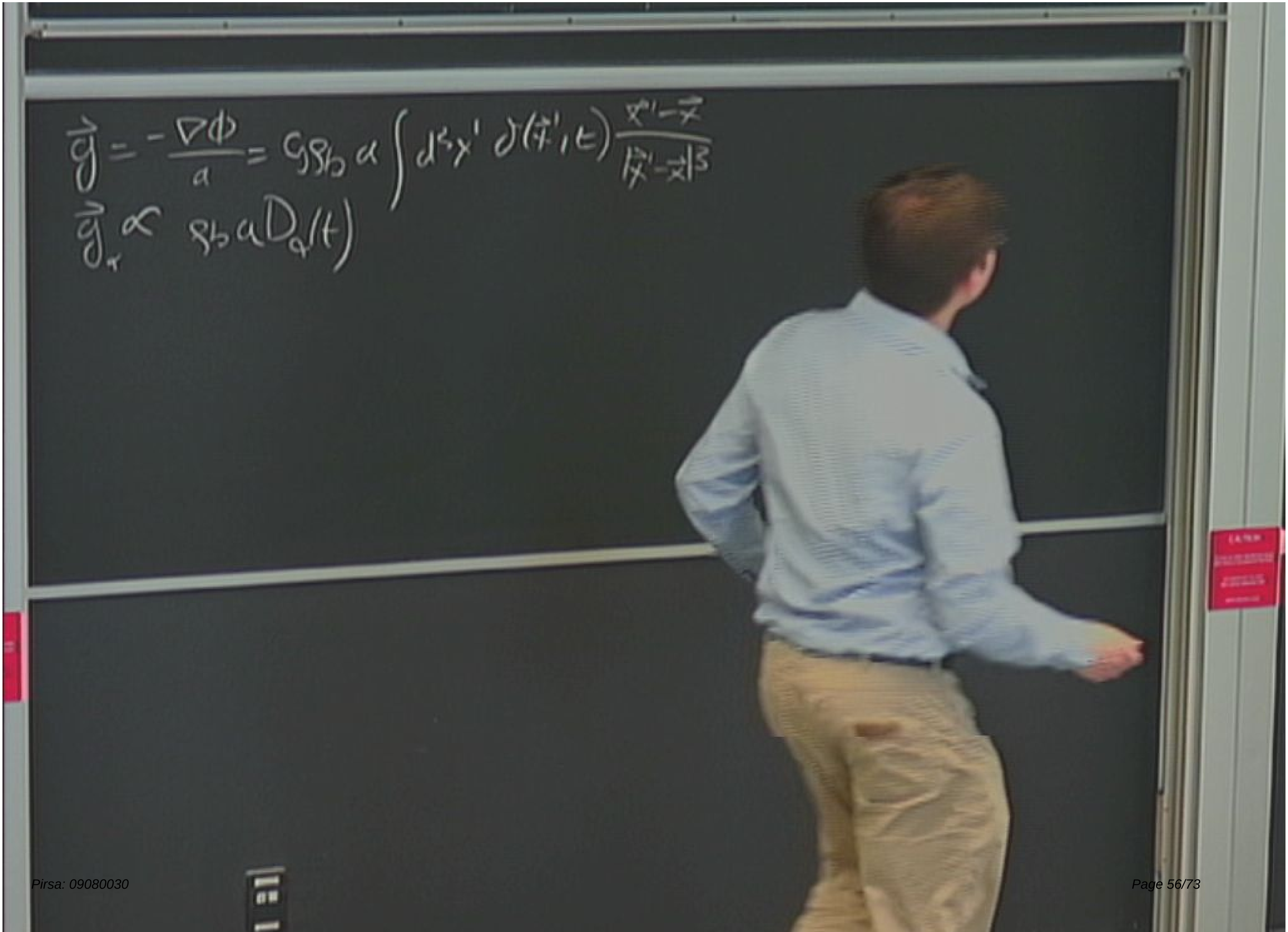
$$\nabla^2\phi = 4\pi G \rho_b a^2 \delta$$

$\nabla\cdot\vec{F}=0$

$$\nabla\cdot\vec{v} = -a\frac{\partial}{\partial t}\left(\frac{\nabla\cdot\vec{g}}{4\pi G\rho_b a}\right) + \cancel{\frac{F(\vec{x})}{a(t)}} \to 0$$

$$\frac{\partial}{\partial t}\, a^2 \frac{\partial}{\partial t}\frac{\vec{g}}{\rho_b a} = 4\pi \vec{g} a$$

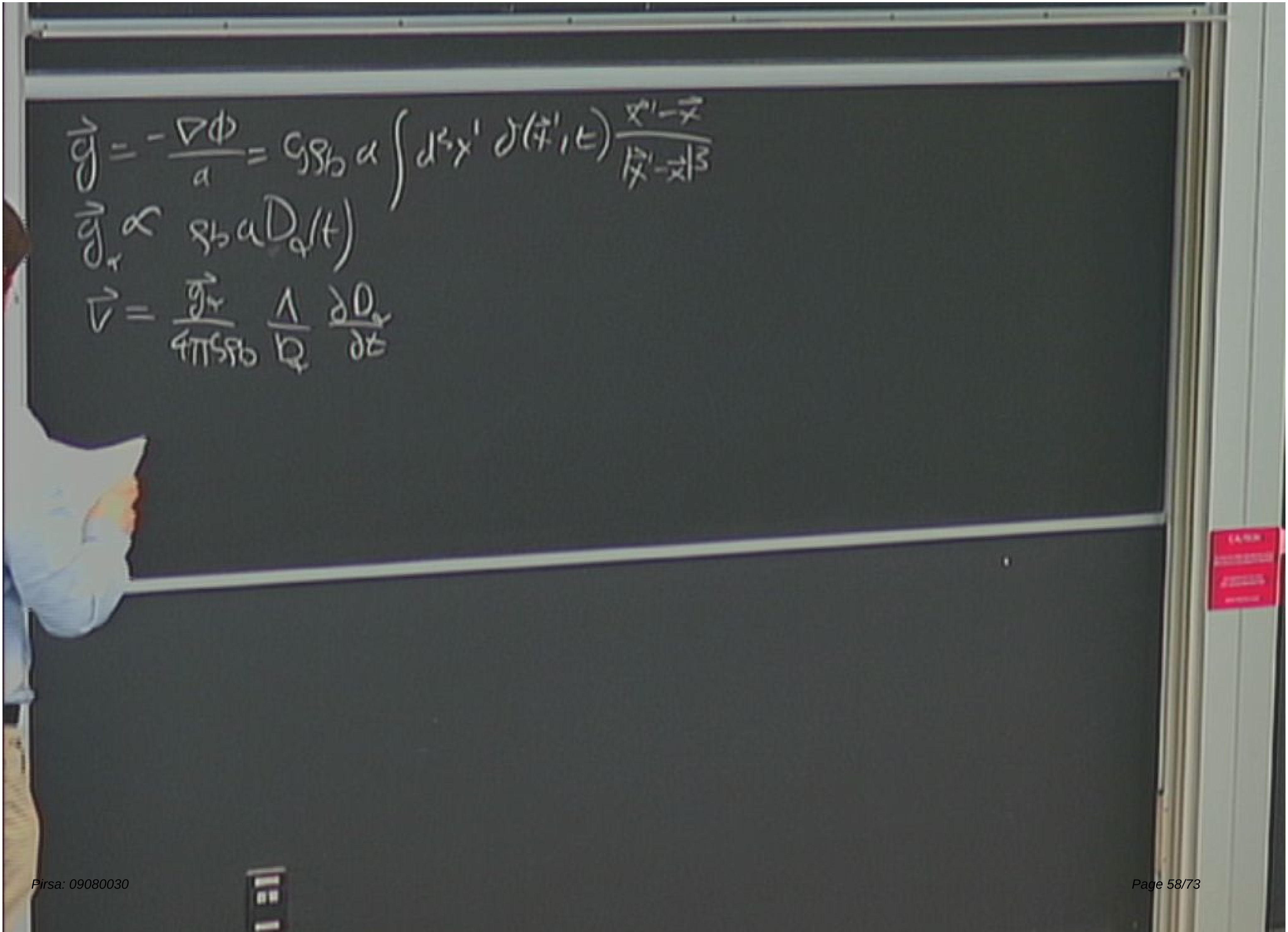
$$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec{x}', t) \frac{\vec{x}' - \vec{x}}{|\vec{x}' - \vec{x}|^3}$$


$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec{x}', t) \frac{\vec{x}' - \vec{x}}{|\vec{x}' - \vec{x}|^3}$
$\vec{g}_x \propto \rho_b a D_\delta(t)$

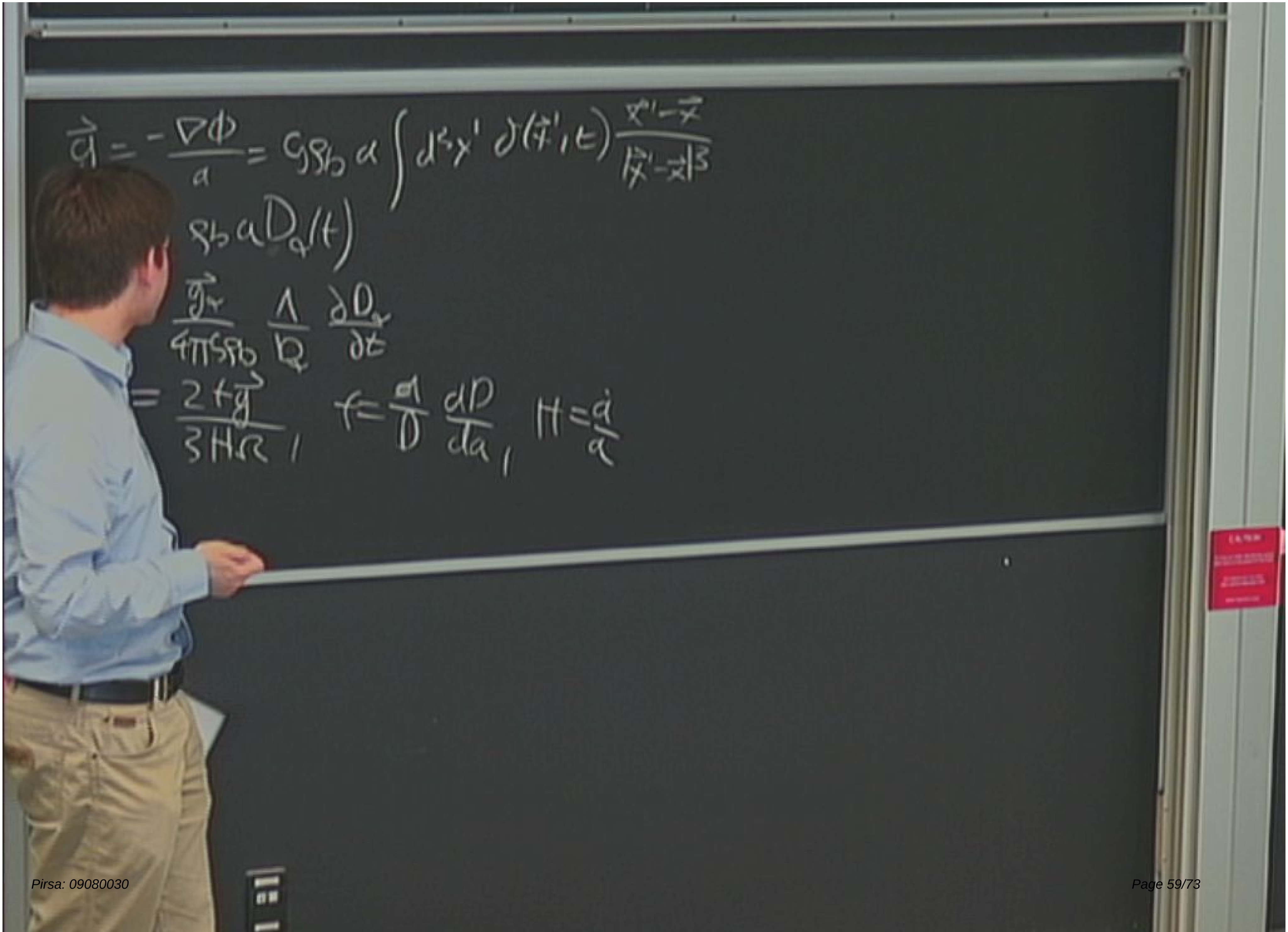
$$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec{x}', t) \frac{\vec{x}' - \vec{x}}{|\vec{x}' - \vec{x}|^3}$$

$$\vec{g}_x \propto \rho_b a D_\delta(t)$$

$$\vec{v} =$$



$\vec g = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec x', t) \frac{\vec x' - \vec x}{|\vec x' - \vec x|^3}$
$\vec g_v \propto \rho_b a D_v(t)$
$\vec V = \frac{\vec g_v}{4\pi G\rho_b} \frac{\Lambda}{D_v} \frac{\partial D_v}{\partial t}$


$\vec{g} = -\frac{\nabla\Phi}{a} = G\bar\rho_b a \int d^3x'\, \delta(\vec{x}', t) \frac{\vec{x}' - \vec{x}}{|\vec{x}' - \vec{x}|^3}$
$\bar\rho_b a D_\delta(t)$
$\frac{\vec{g}_r}{4\pi G\bar\rho_b} \frac{\Lambda}{D} \frac{\partial D_\delta}{\partial t}$
$= \frac{2f\vec{g}}{3H\Omega}, \quad f = \frac{a}{D}\frac{dD}{da}, \quad H = \frac{\dot a}{a}$

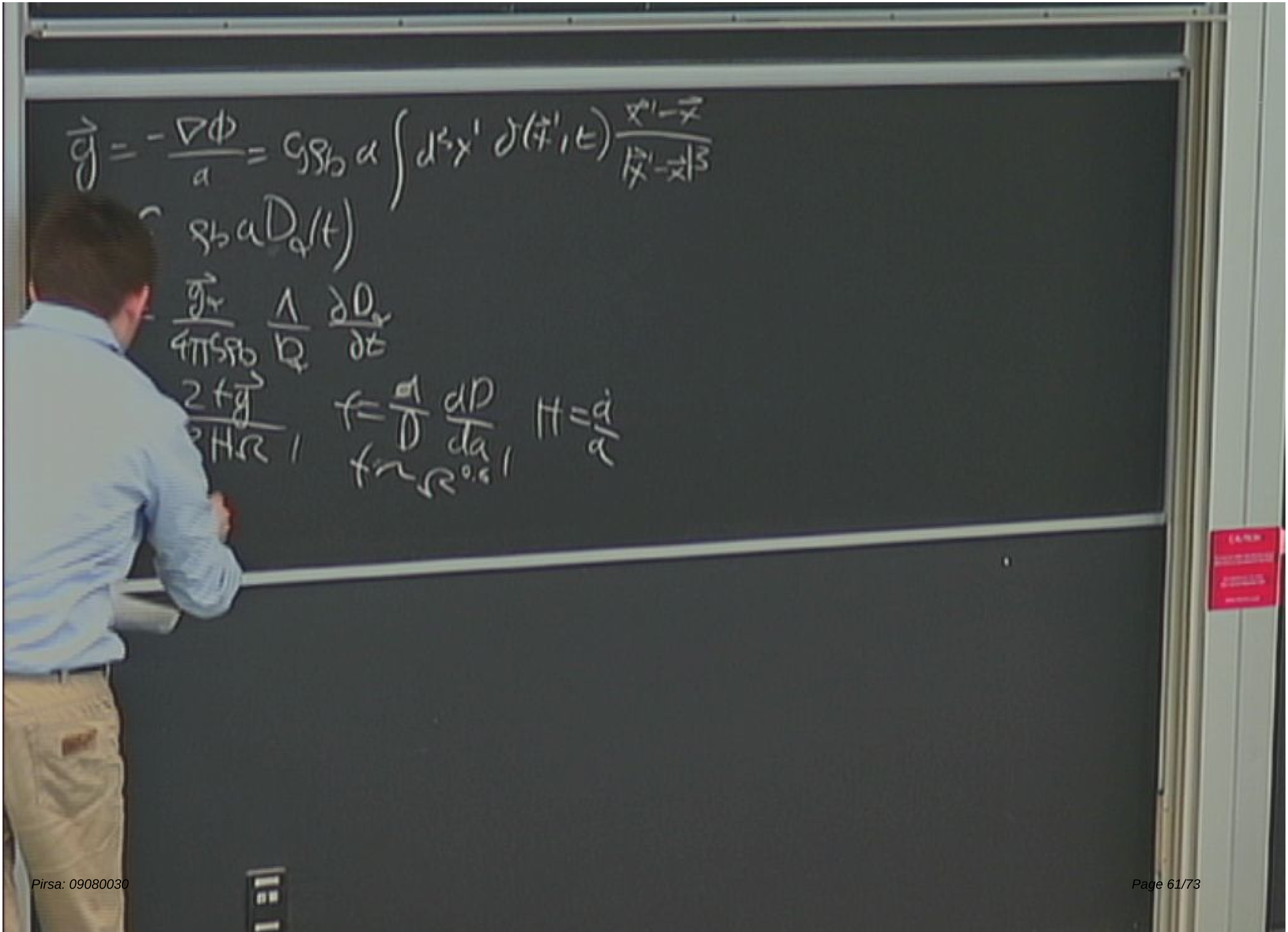
$$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b\, a \int d^3x'\, \delta(\vec{x}',t)\,\frac{\vec{x}'-\vec{x}}{|\vec{x}'-\vec{x}|^3}$$

$$\vec{g}_+ \propto \rho_b\, a\, D_+(t)$$

$$\vec{v} = \frac{\vec{g}_+}{4\pi G\rho_b}\,\frac{1}{D_+}\,\frac{\partial D_+}{\partial t}$$

$$= \frac{2f\vec{g}}{3H\Omega}, \quad f = \frac{a}{D}\frac{dD}{da}, \quad H = \frac{\dot{a}}{a}$$

$$f \sim \Omega^{0.6},$$



$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec{x}', t) \frac{\vec{x}' - \vec{x}}{|\vec{x}' - \vec{x}|^3}$
$\rho_b a D_+(t))$
$\frac{\vec{g}_+}{4\pi G\rho_b} \frac{\Lambda}{D_+} \frac{\partial D_+}{\partial t}$
$\frac{2f\vec{g}}{3H\Omega}, \quad f = \frac{a}{D}\frac{dD}{da}, \quad H = \frac{\dot{a}}{a}$
$f \sim \Omega^{0.6},$

$$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec{x}', t) \frac{\vec{x}' - \vec{x}}{|\vec{x}' - \vec{x}|^3}$$

$$\vec{g}_+ \propto \rho_b a D_+(t)$$

$$\vec{v} = \frac{\vec{g}_+}{4\pi G\rho_b} \frac{\Lambda}{D_+} \frac{\partial D_+}{\partial t}$$

$$= \frac{2 f \vec{g}}{3 H \Omega}, \quad f = \frac{a}{D} \frac{dD}{da}, \quad H = \frac{\dot{a}}{a}$$

$$\vec{v} = \frac{H f a}{4\pi} \int d^3x' \, \frac{\delta(\vec{x}') \, (\vec{x}' - \vec{x})}{|\vec{x}' - \vec{x}|^3}, \quad f \simeq \Omega^{0.6}$$

$$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec{x}', t) \frac{\vec{x}' - \vec{x}}{|\vec{x}' - \vec{x}|^3}$$

$$\vec{g}_{+} \propto \rho_b a D_{+}(t)$$

$$\vec{v} = \frac{\vec{g}_{+}}{4\pi G\rho_b} \frac{1}{D_{+}} \frac{\partial D_{+}}{\partial t}$$

$$= \frac{2f\vec{g}}{3H\Omega}, \quad f = \frac{a}{D}\frac{dD}{da}, \quad H = \frac{\dot{a}}{a}$$

$$f \simeq \Omega^{0.6}$$

$$\vec{v} = \frac{Hfa}{4\pi} \int d^3x' \, \frac{\delta(\vec{x}')(\vec{x}' - \vec{x})}{|\vec{x}' - \vec{x}|^3}$$

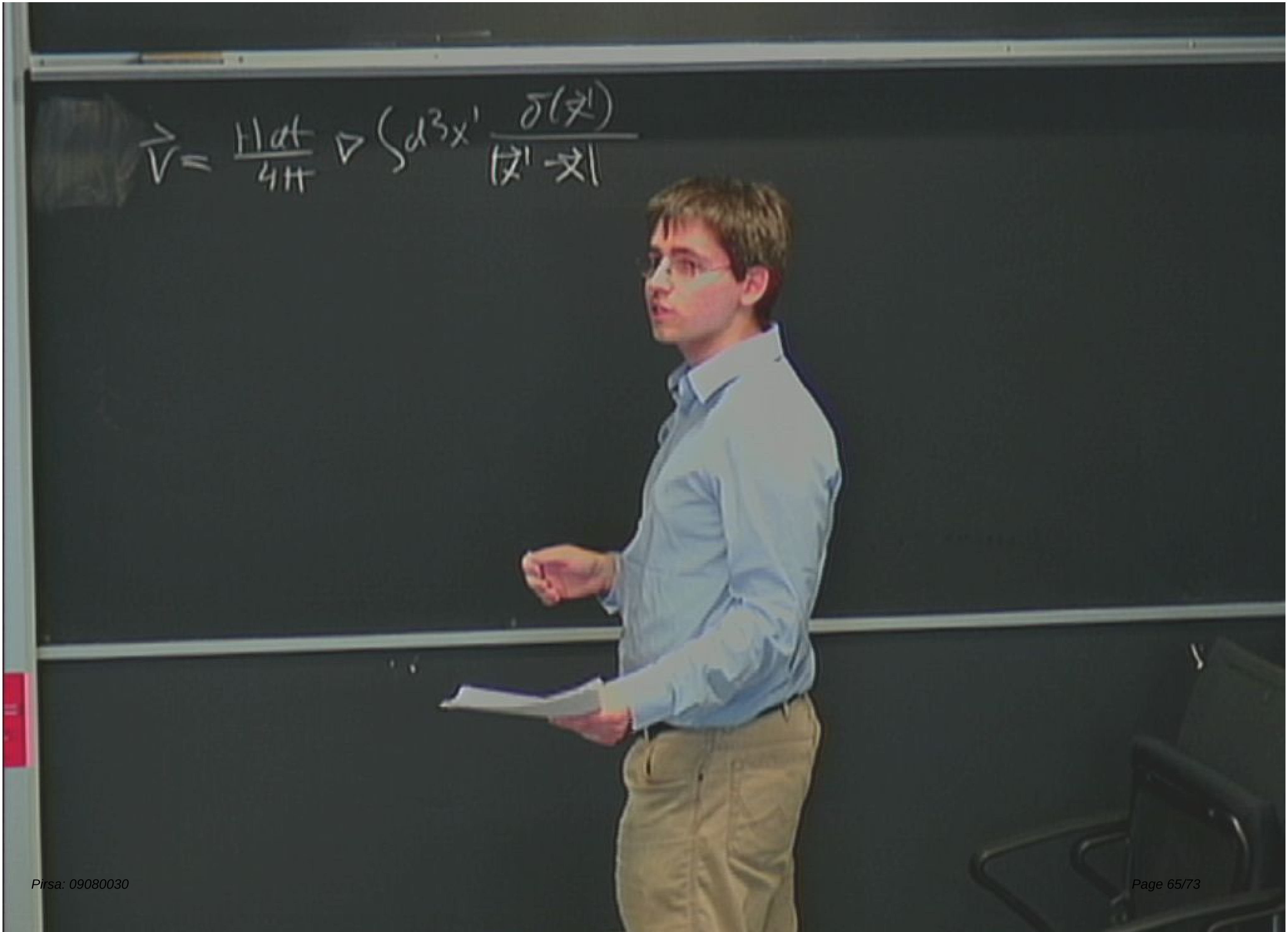
$$\vec{g} = -\frac{\nabla\Phi}{a} = G\rho_b a \int d^3x' \, \delta(\vec{x}',t) \frac{\vec{x}'-\vec{x}}{|\vec{x}'-\vec{x}|^3}$$

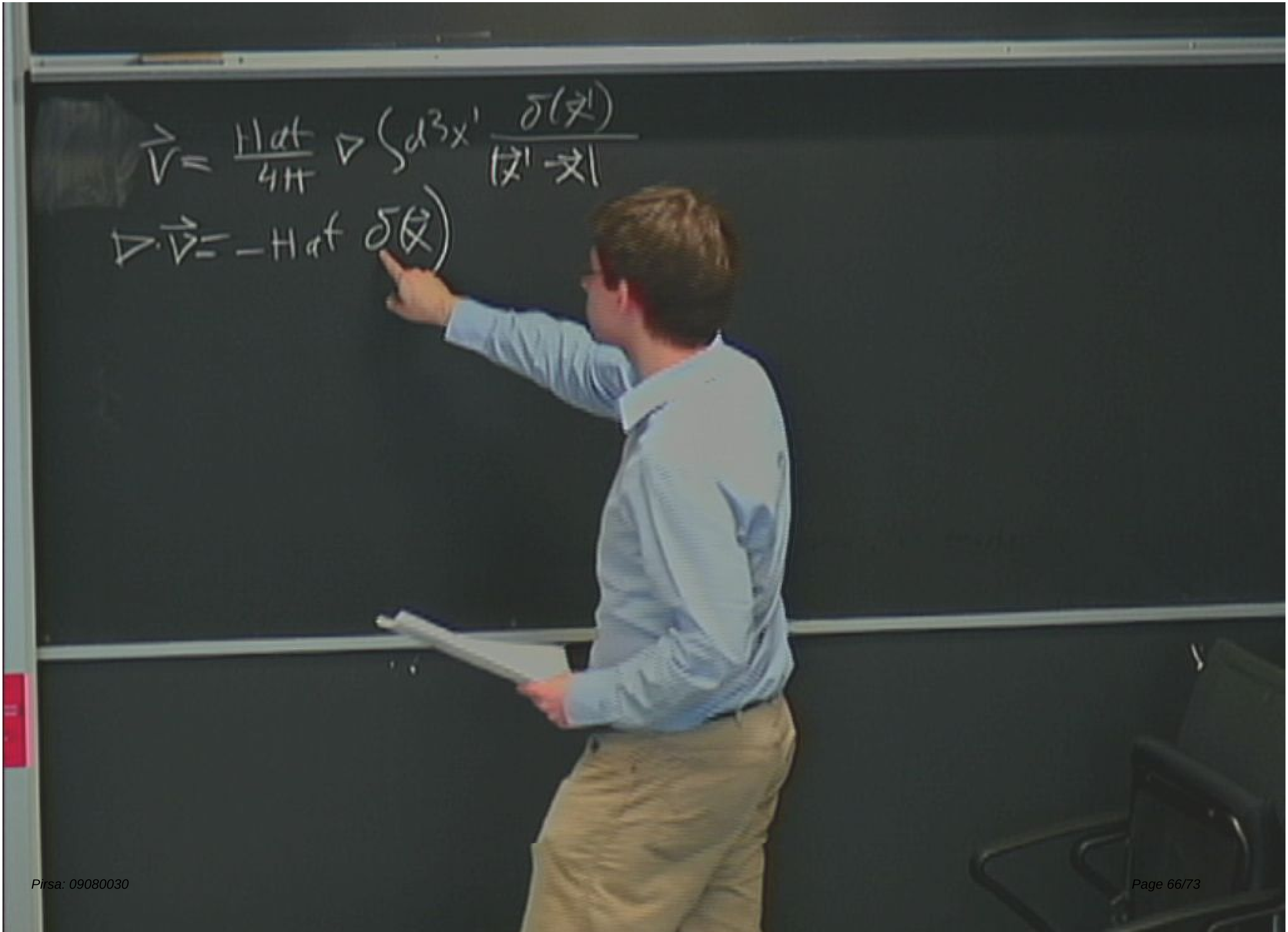
$$\vec{g}_x \propto \rho_b a D_+(t)$$

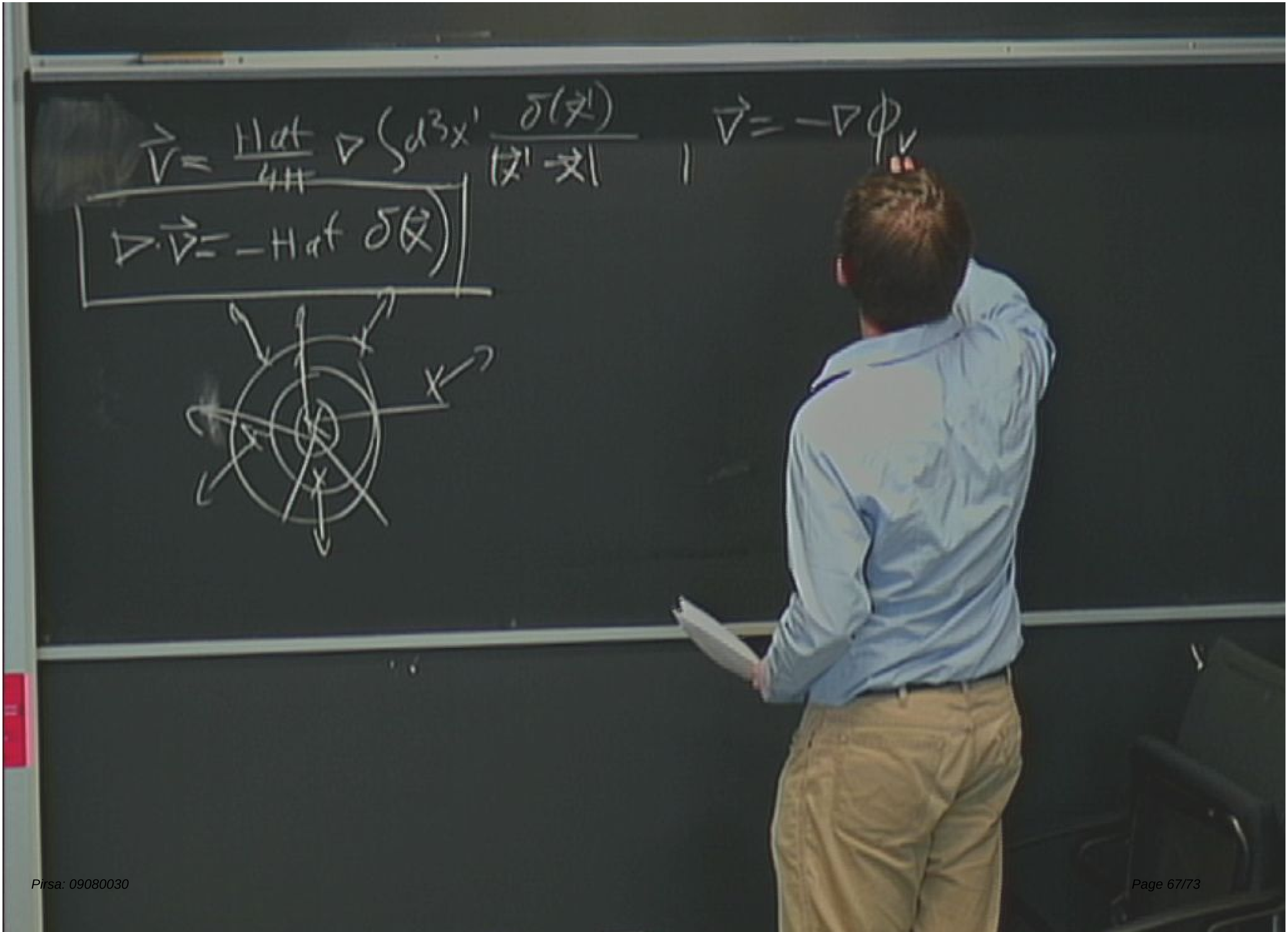
$$\vec{v} = \frac{\vec{g}_x}{4\pi G\rho_b} \frac{\Lambda}{D_+} \frac{\partial D_+}{\partial t}$$

$$= \frac{2f\vec{g}}{3H\Omega}, \quad f = \frac{a}{D}\frac{dD}{da}, \quad H = \frac{\dot{a}}{a}$$

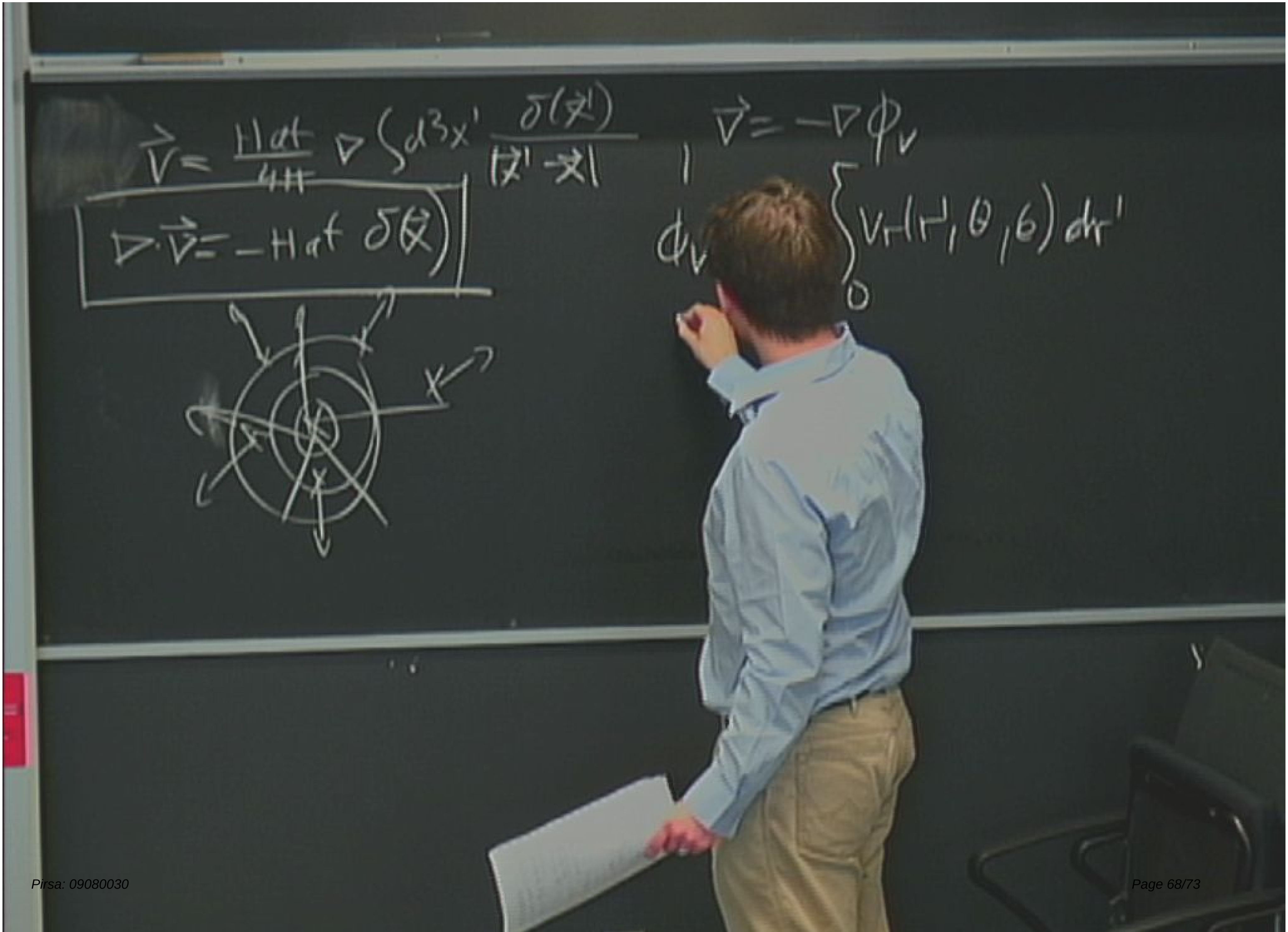
$$\vec{v} = \frac{Hfa}{4\pi} \int d^3x' \, \frac{\delta(\vec{x}')(\vec{x}'-\vec{x})}{|\vec{x}'-\vec{x}|^3}$$


$\vec{v} = \frac{Haf}{4\pi} \nabla \int d^3x' \frac{\delta(\vec{x}')}{|\vec{x}' - \vec{x}|}$

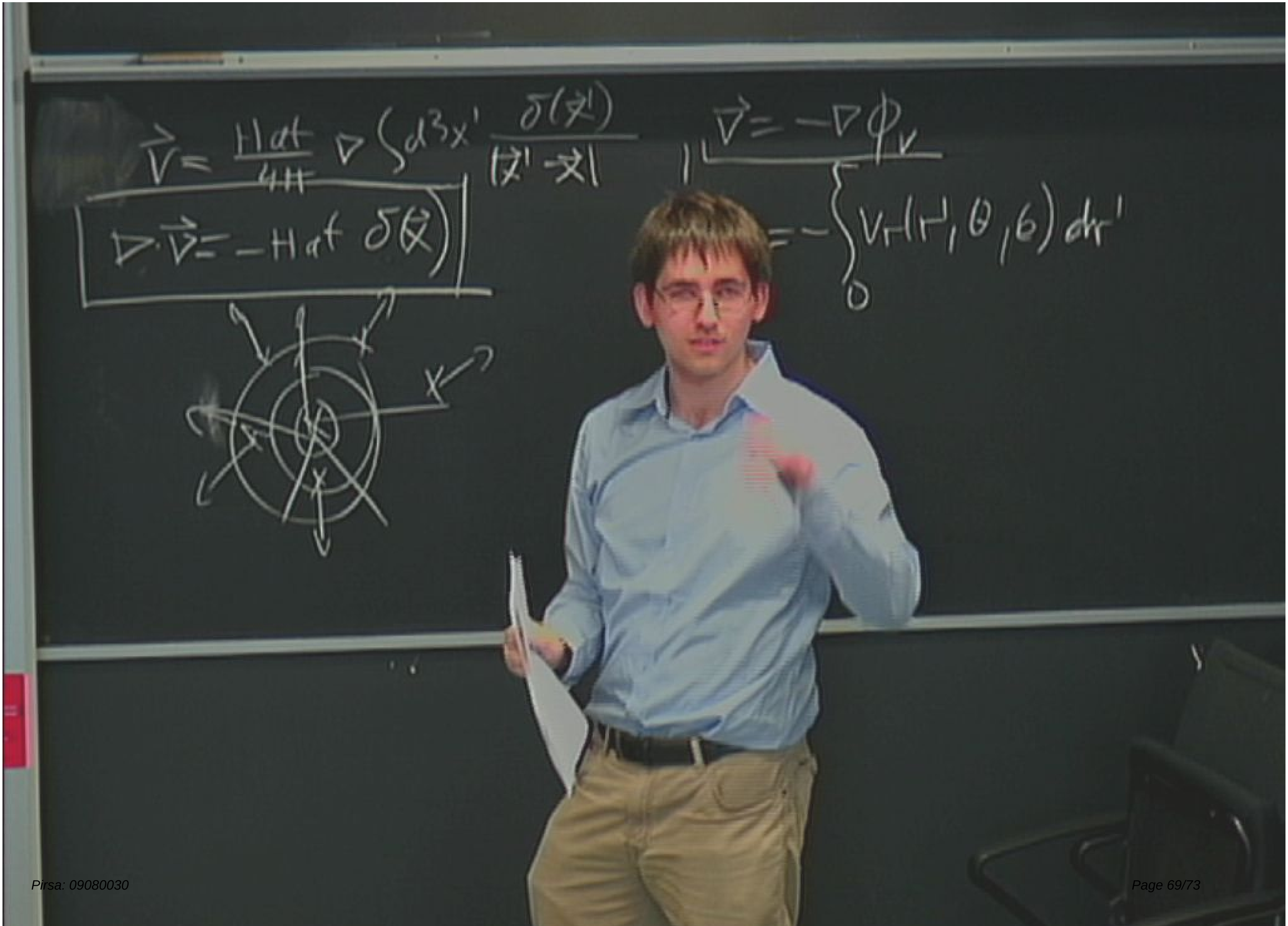

$\vec{V} = \frac{H a t}{4\pi} \nabla \int d^3x' \frac{\delta(\vec{x}')}{|\vec{x}' - \vec{x}|}$
$\nabla \cdot \vec{V} = -H a t \, \delta(\vec{x})$

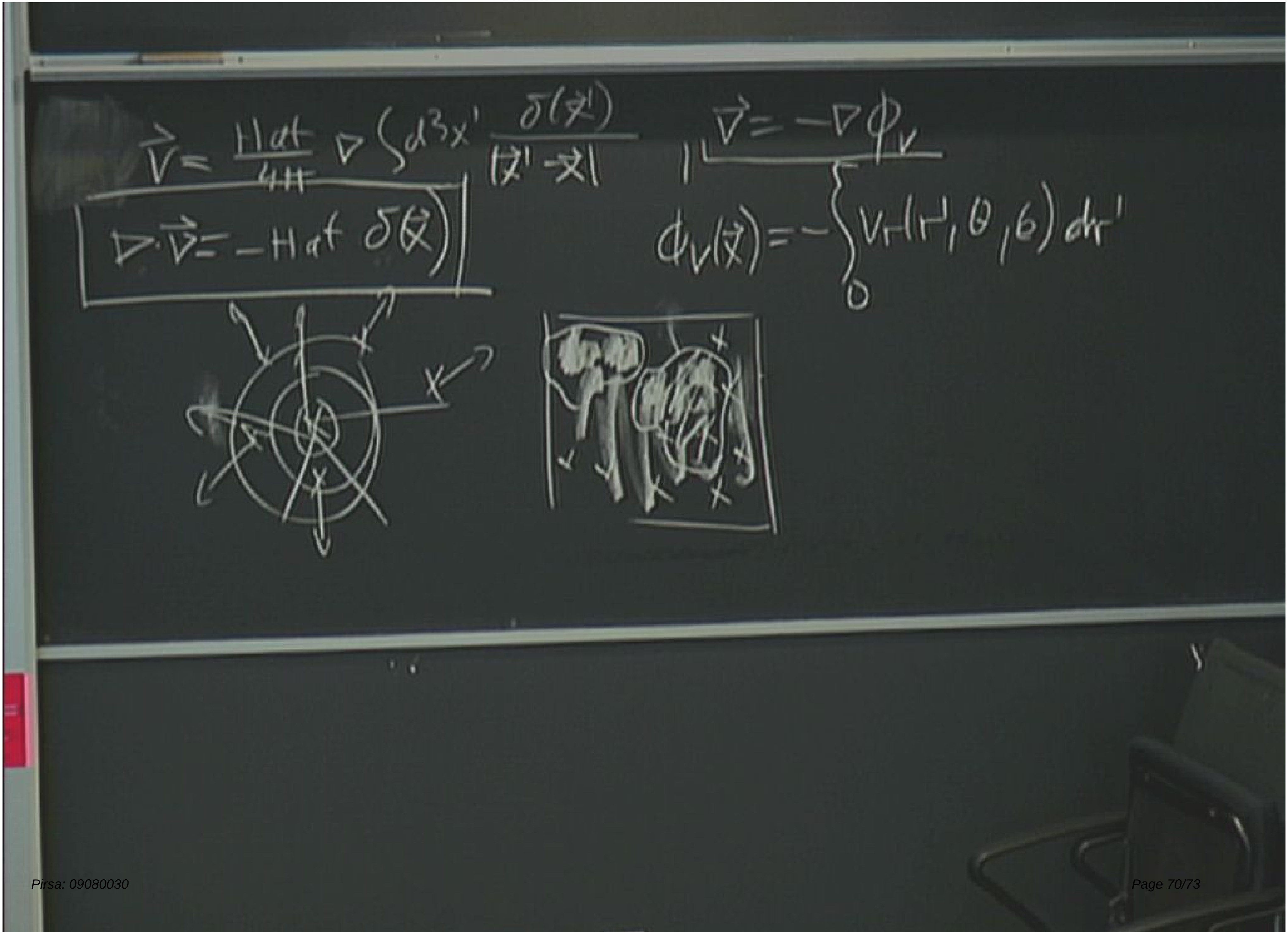


$\vec{v} = \frac{H a t}{4\pi} \nabla \int d^3x' \frac{\delta(\vec{x}')}{|\vec{x}' - \vec{x}|}$
$\vec{v} = -\nabla \phi_v$
$\nabla \cdot \vec{v} = -H a t \, \delta(\vec{x})$



$\vec{v} = \frac{Hat}{4\pi} \nabla \int d^3x' \frac{\delta(\vec{x}')}{|\vec{x}' - \vec{x}|}$
$\nabla \cdot \vec{v} = -Hat\, \delta(\vec{x})$
$\vec{v} = -\nabla \phi_v$
ϕ_v
$\int_0 v_r(r', \theta, \phi)\, dr'$


$\vec{V} = \frac{Hat}{4\pi} \nabla \int d^3x' \frac{\delta(\vec{x}')}{|\vec{x}' - \vec{x}|}$
$\nabla \cdot \vec{V} = -Hat\, \delta(\vec{x})$
$\vec{V} = -\nabla \phi_V$
$= -\int_0 V_r(r', \theta, \phi)\, dr'$


$\vec{V} = \frac{H\,at}{4\pi} \nabla \int d^3x' \frac{\delta(\vec{x}')}{|\vec{x}' - \vec{x}|}$
$\nabla \cdot \vec{V} = -H\,at\,\delta(\vec{x})$
$\vec{V} = -\nabla \phi_V$
$\phi_V(\vec{x}) = -\int_0^r V_r(r', \theta, \phi)\, dr'$

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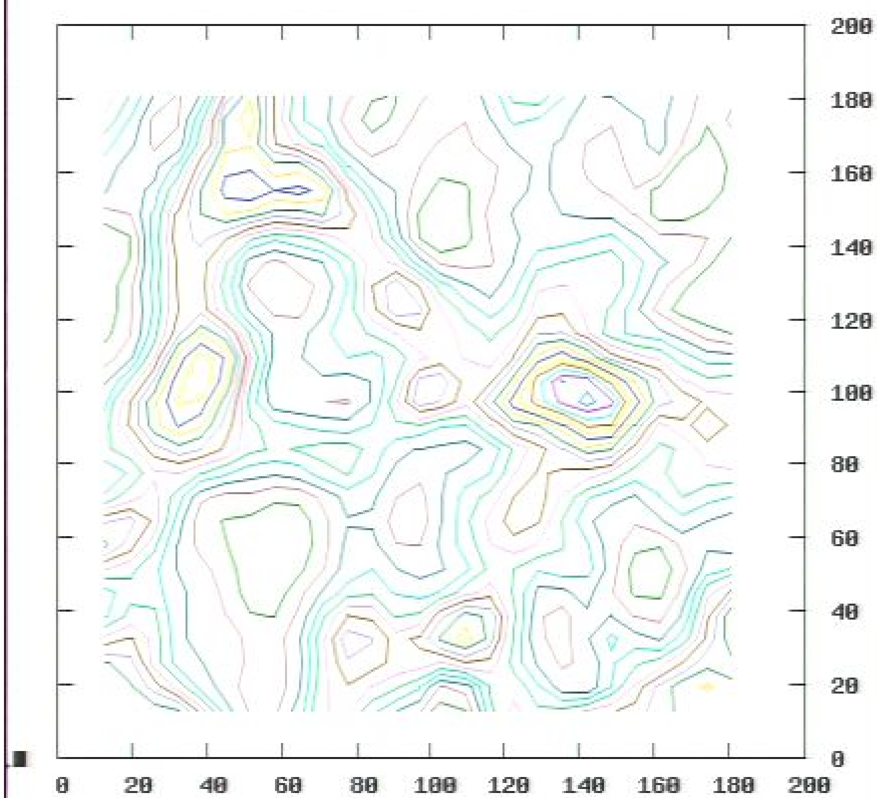

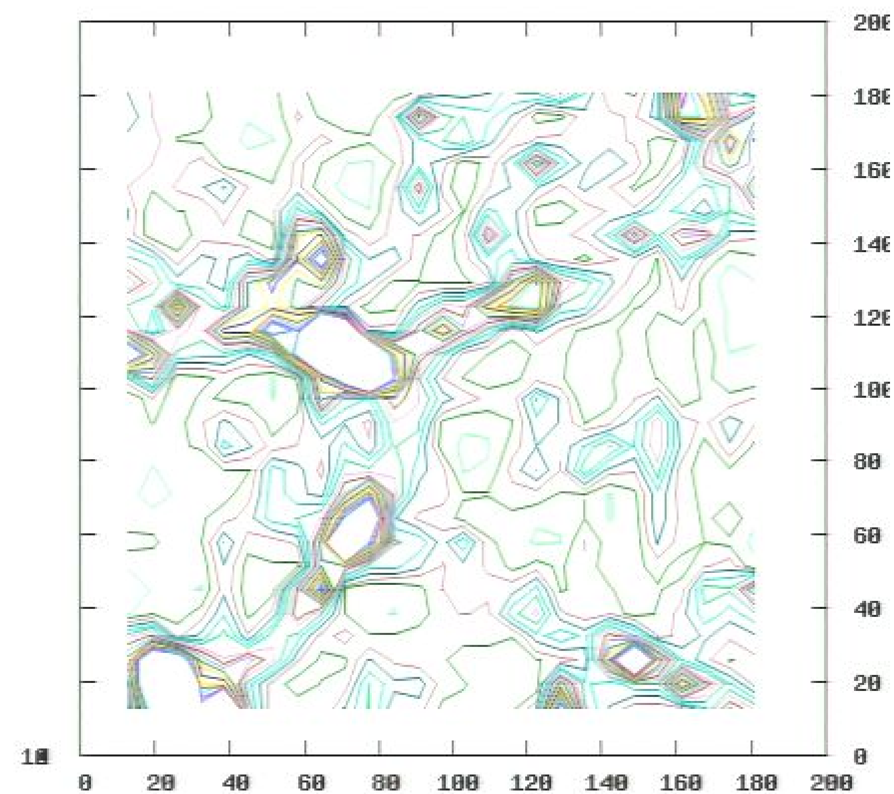

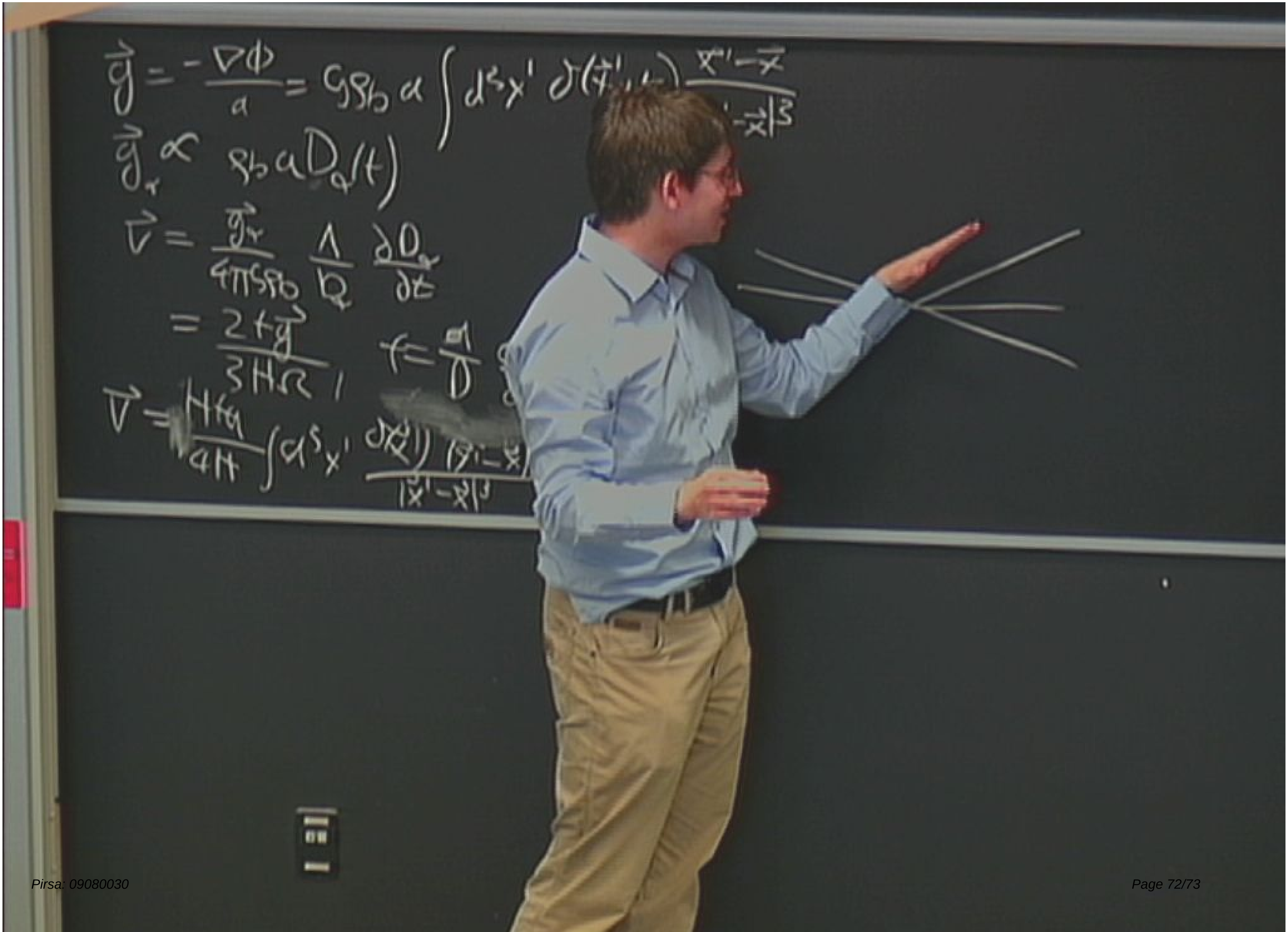

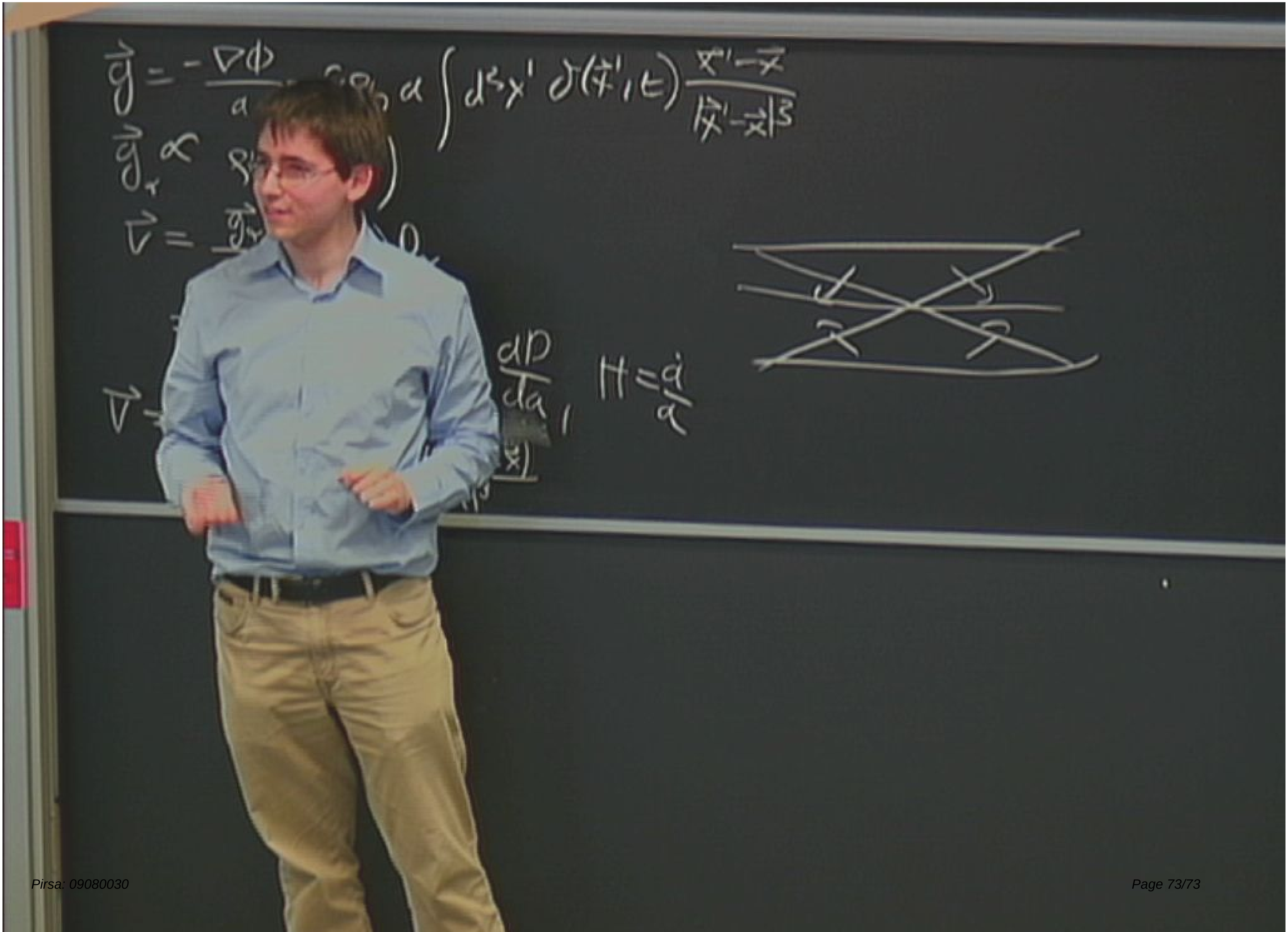
H = ȧ/a