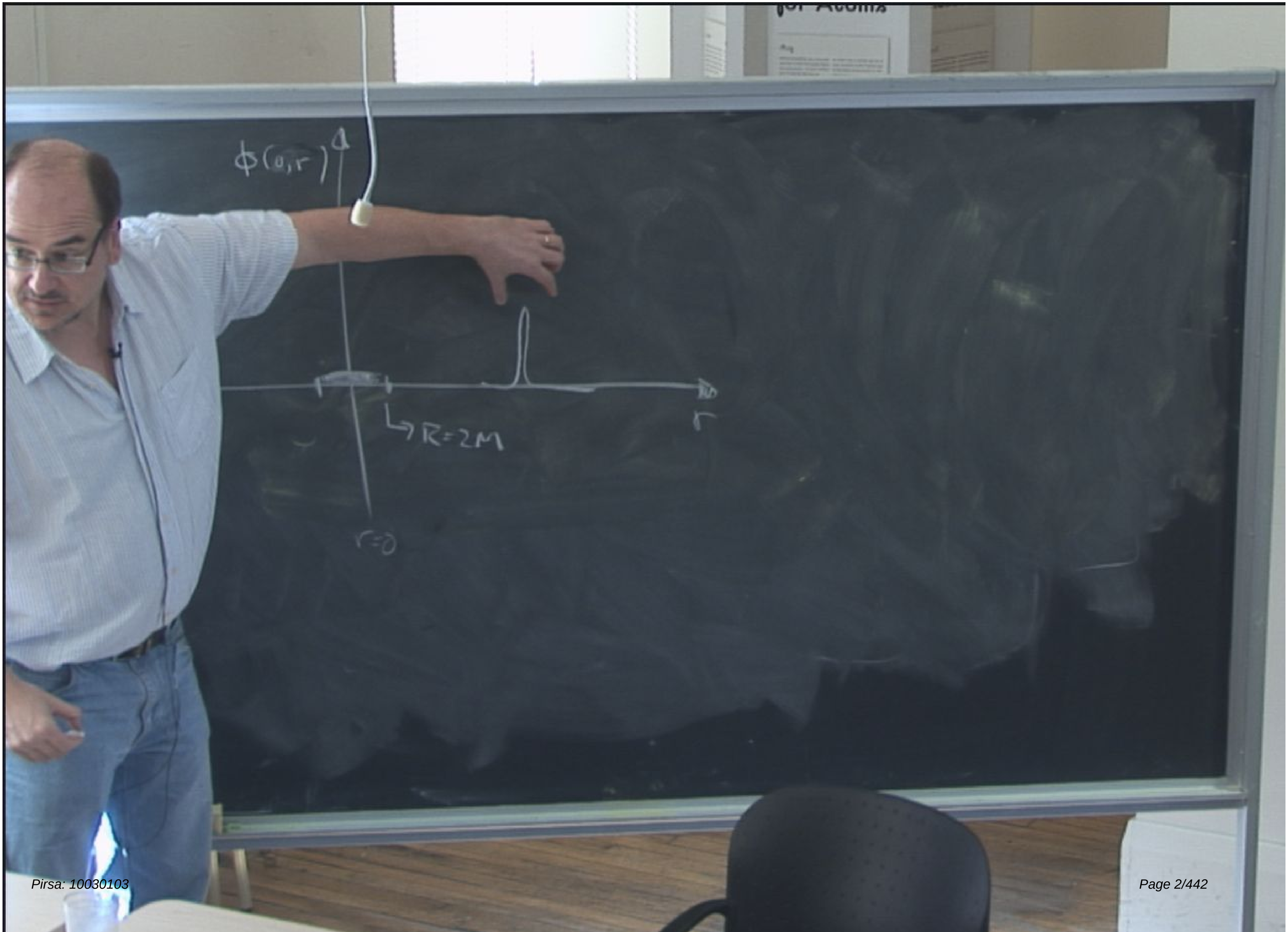
Title: Explorations in Numerical Relativity (PHYS 642) - Lecture 4

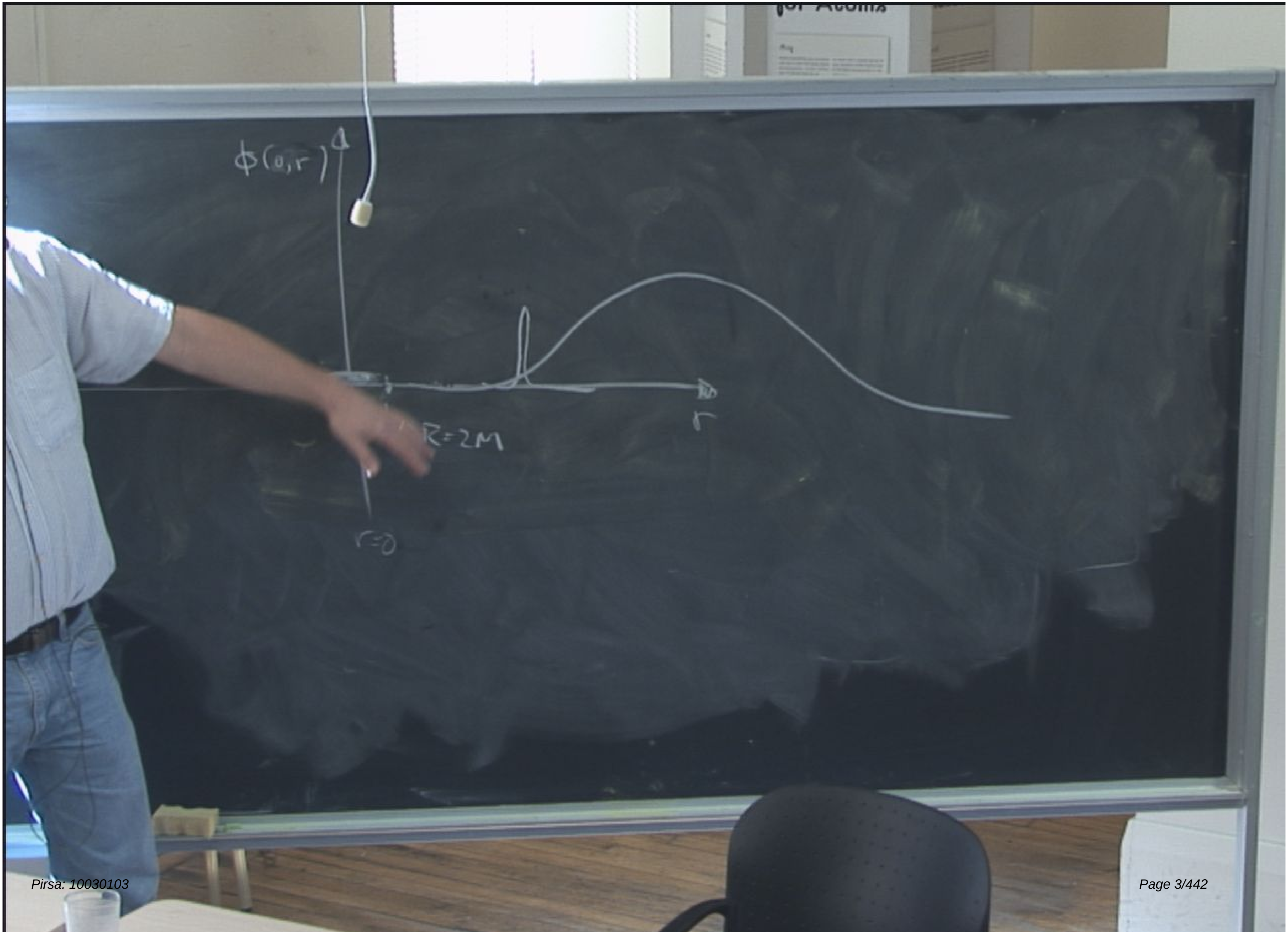
Date: Mar 18, 2010 11:20 AM

URL: http://pirsa.org/10030103

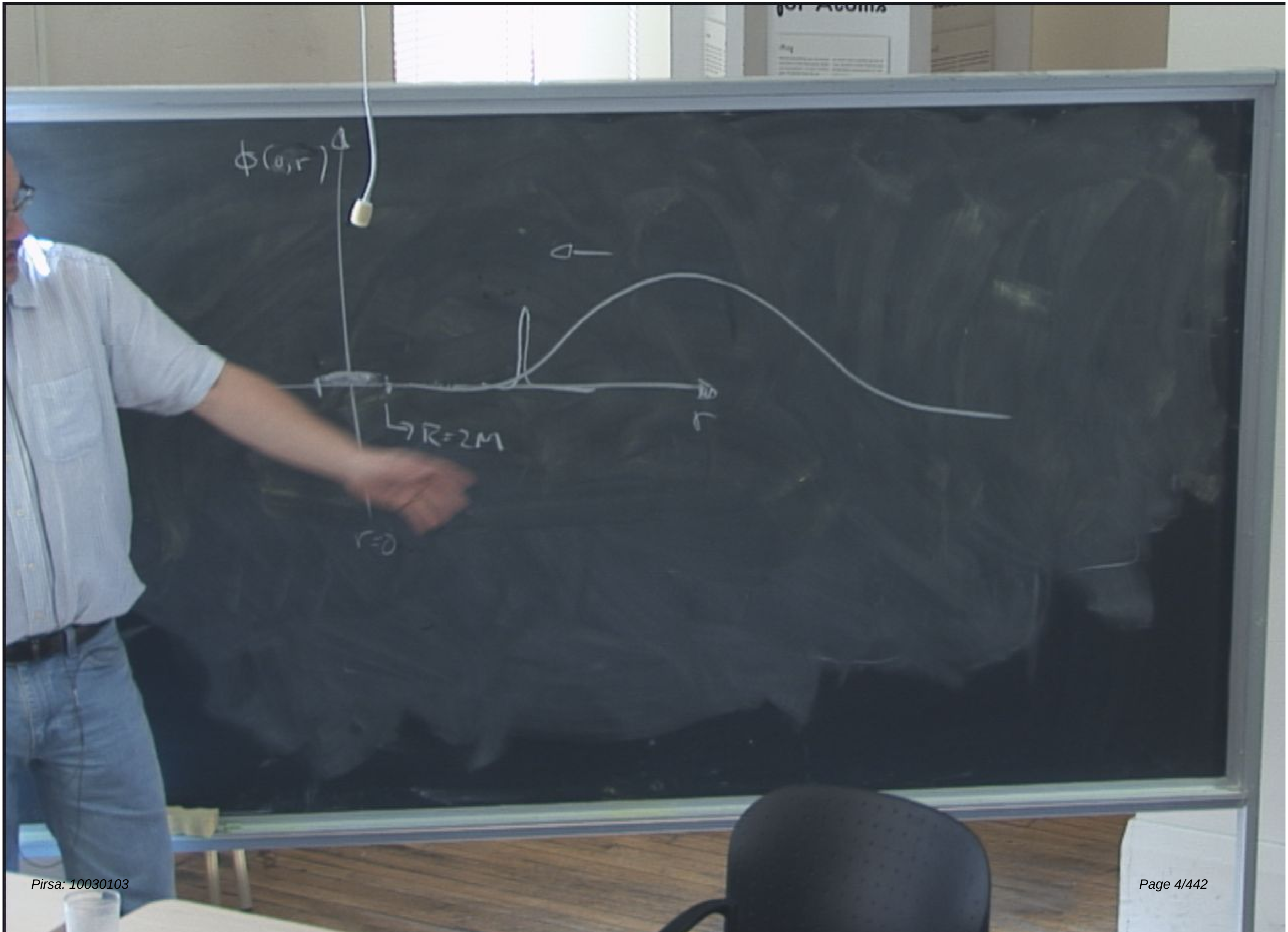
Abstract:



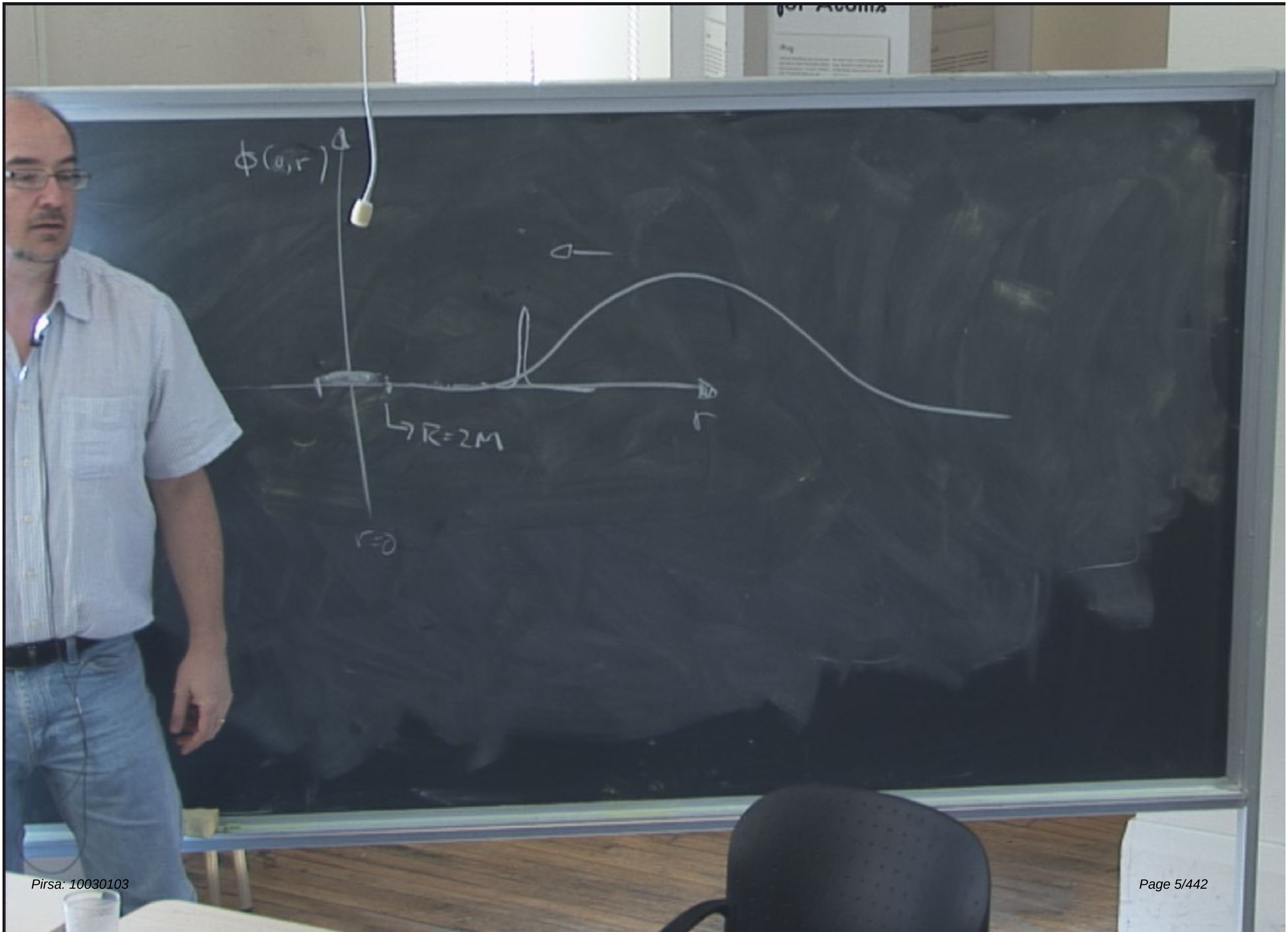
$\phi(0,r)$
$R=2M$
r
$r=0$

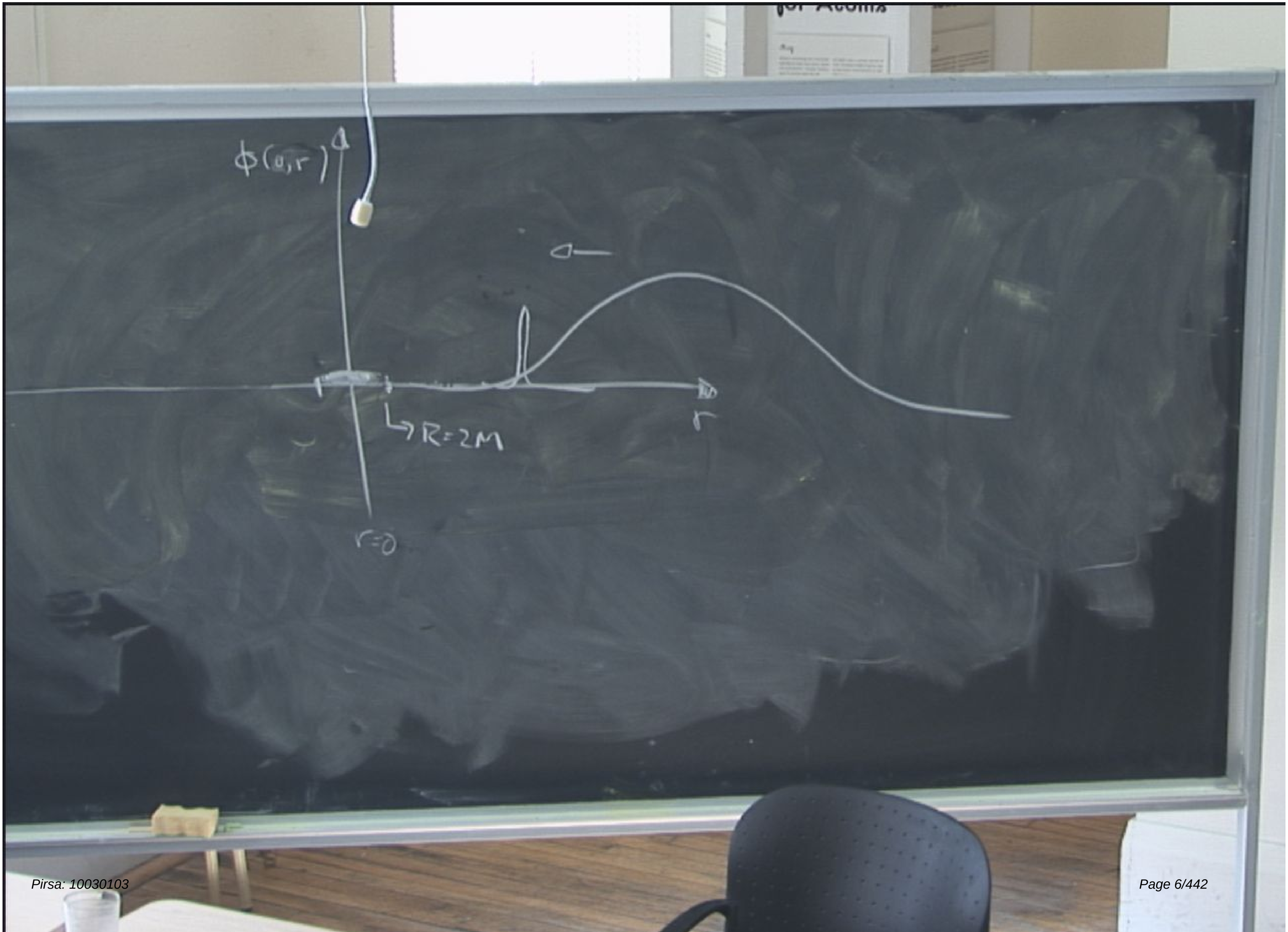


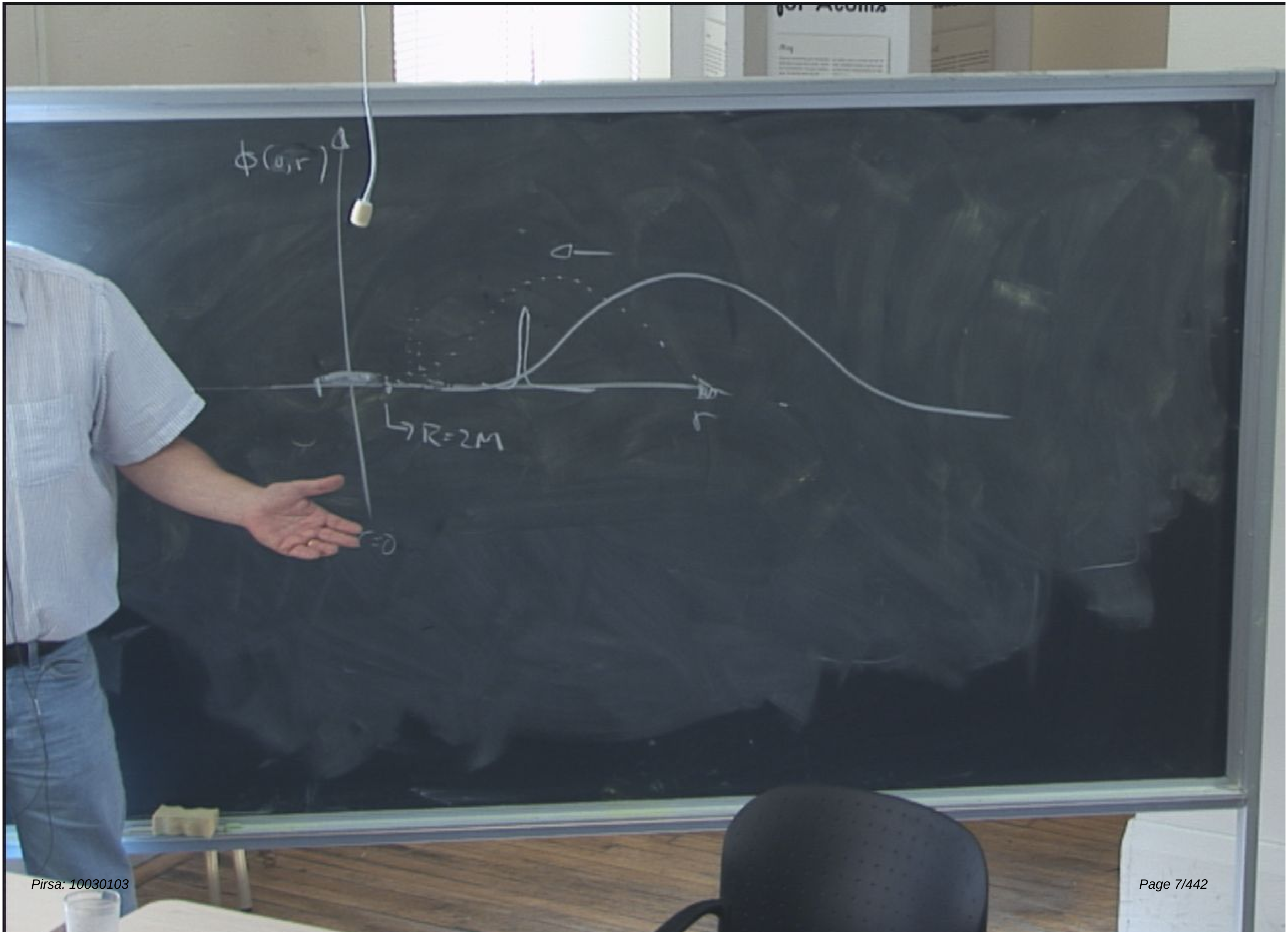
ϕ(0,r)
r
R=2M
r=0

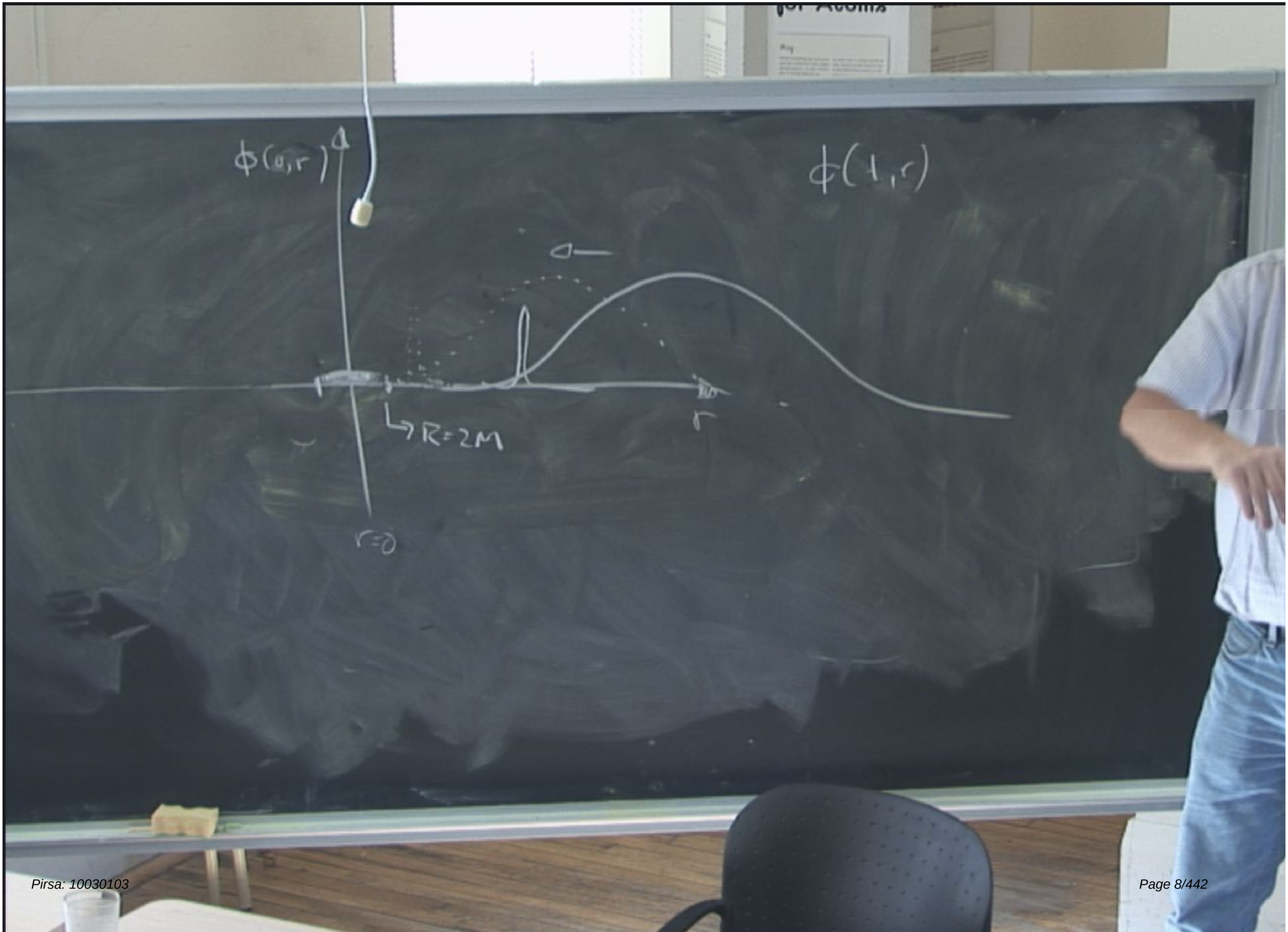


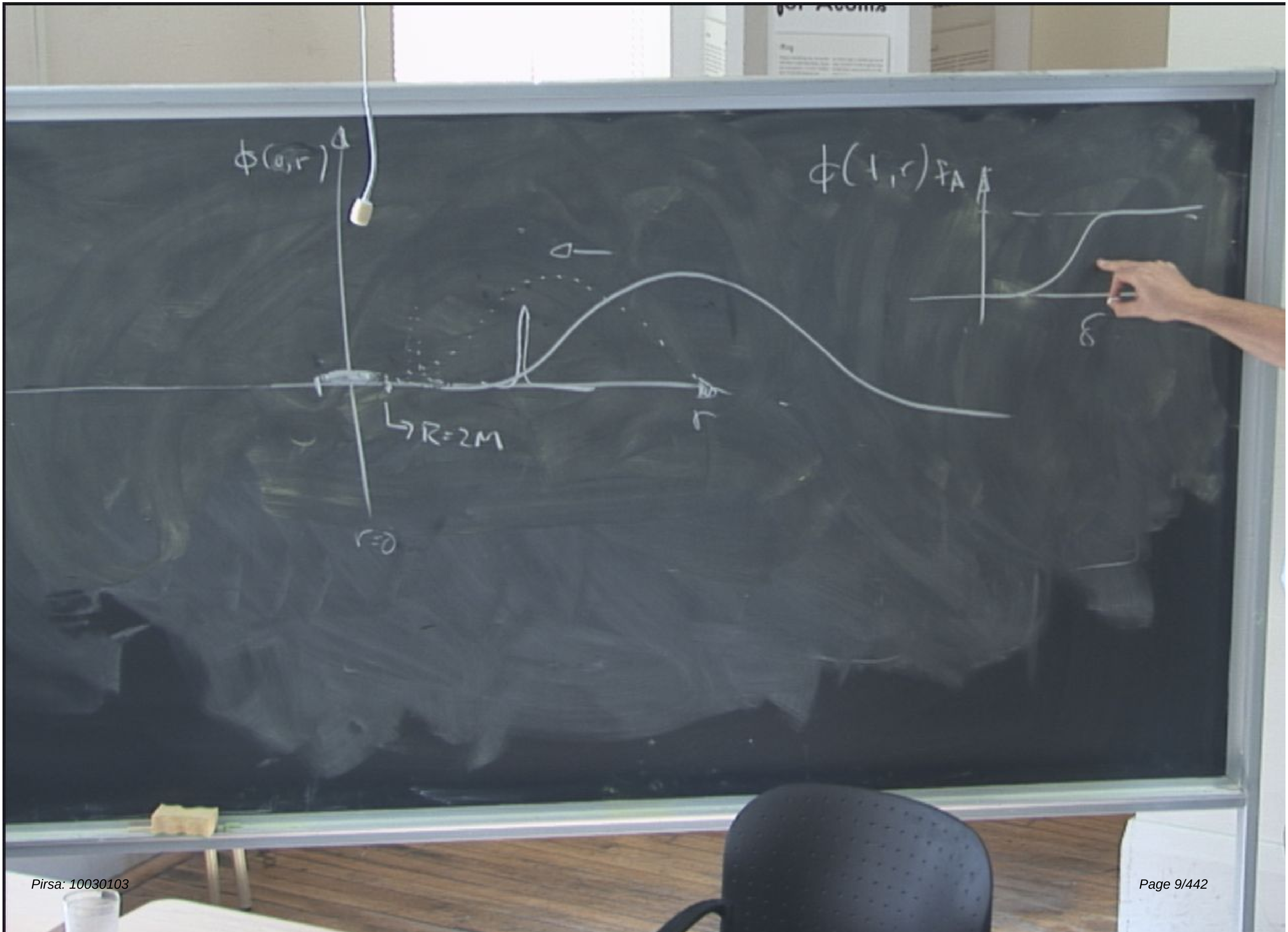
$\phi(0,r)$
$R=2M$
r
$r=0$

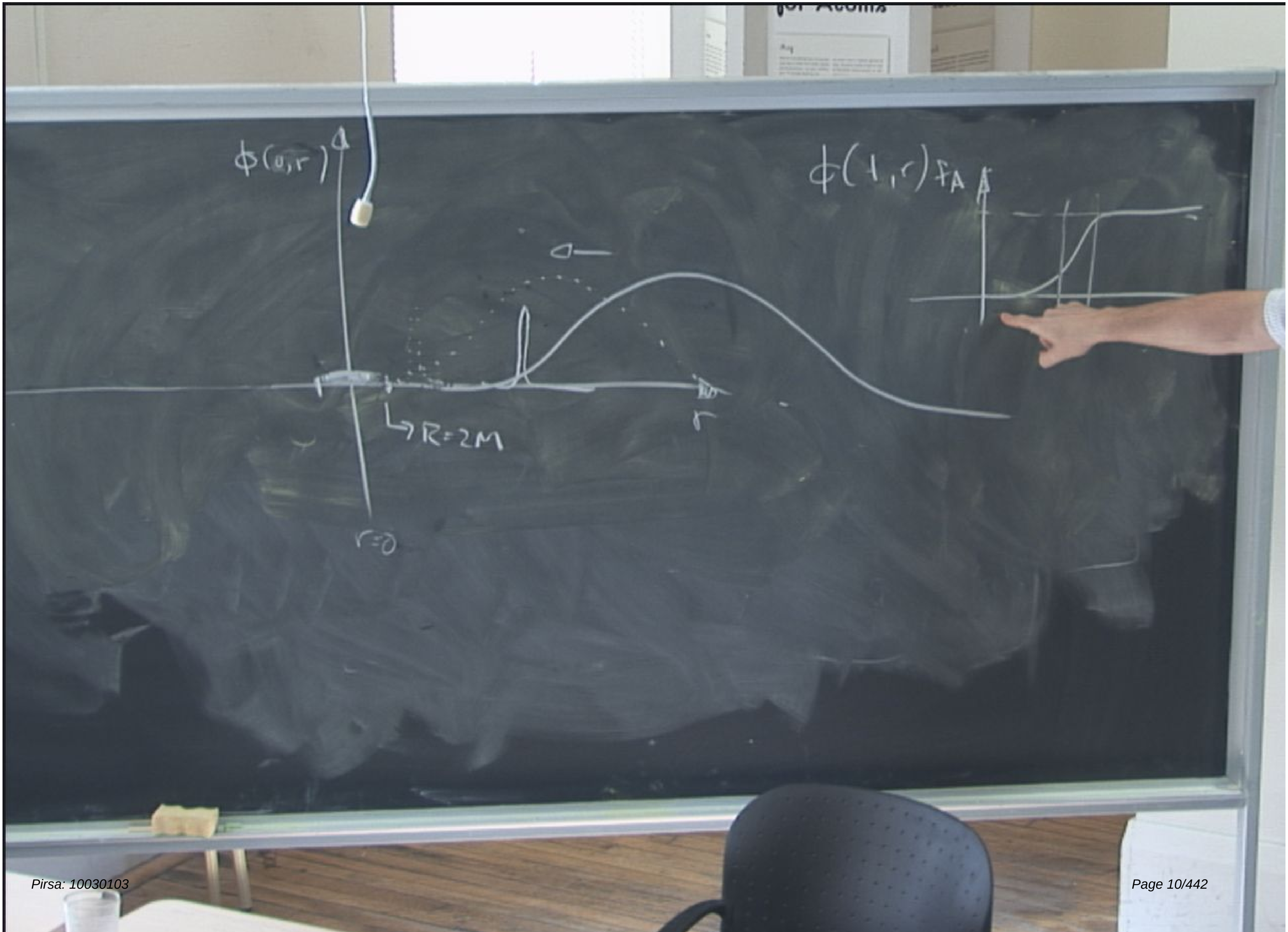

$\phi(0,r)$
$R=2M$
r
$r=0$

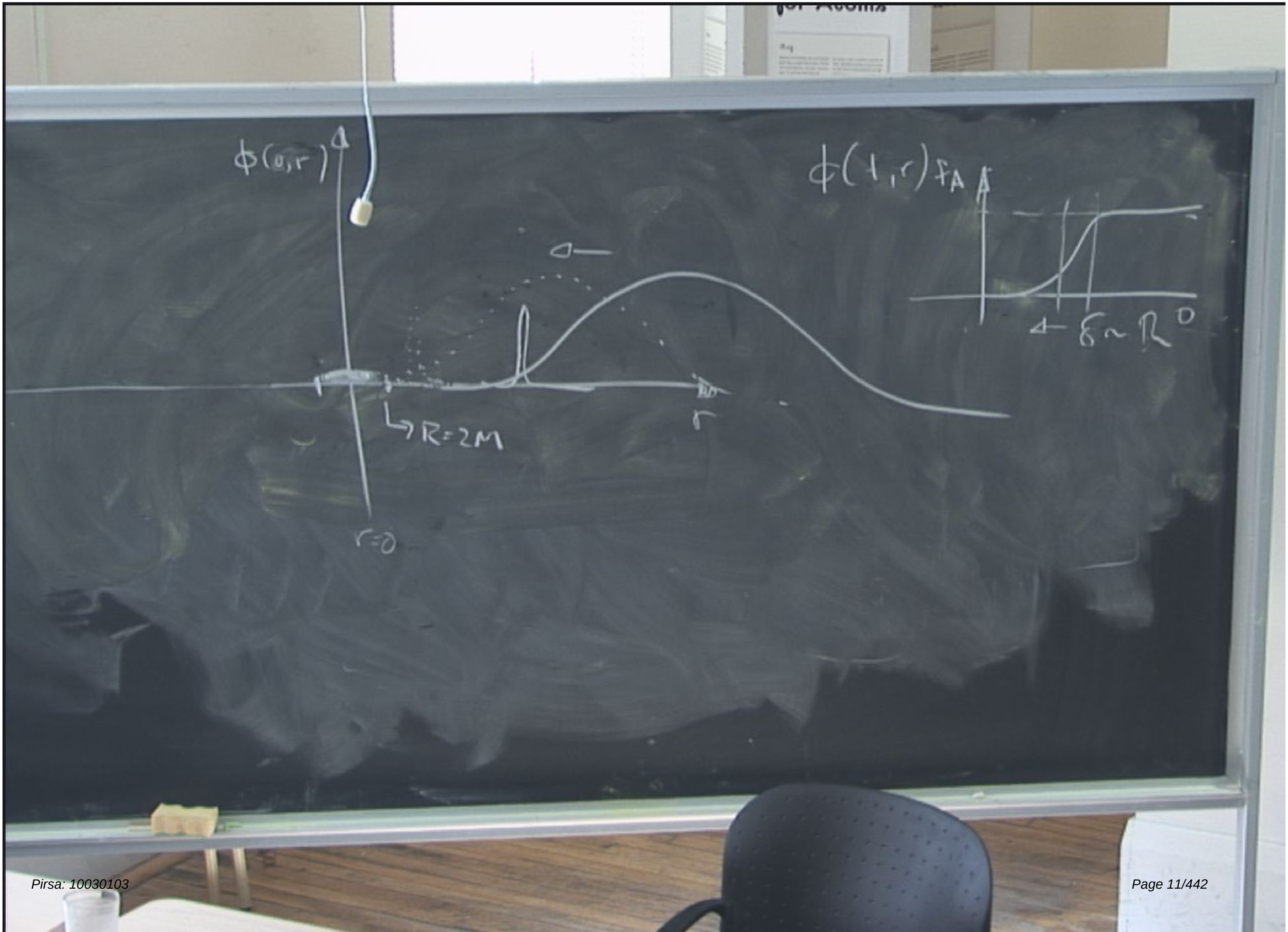

$\phi(0,r)$
$R=2M$
r
$r=0$

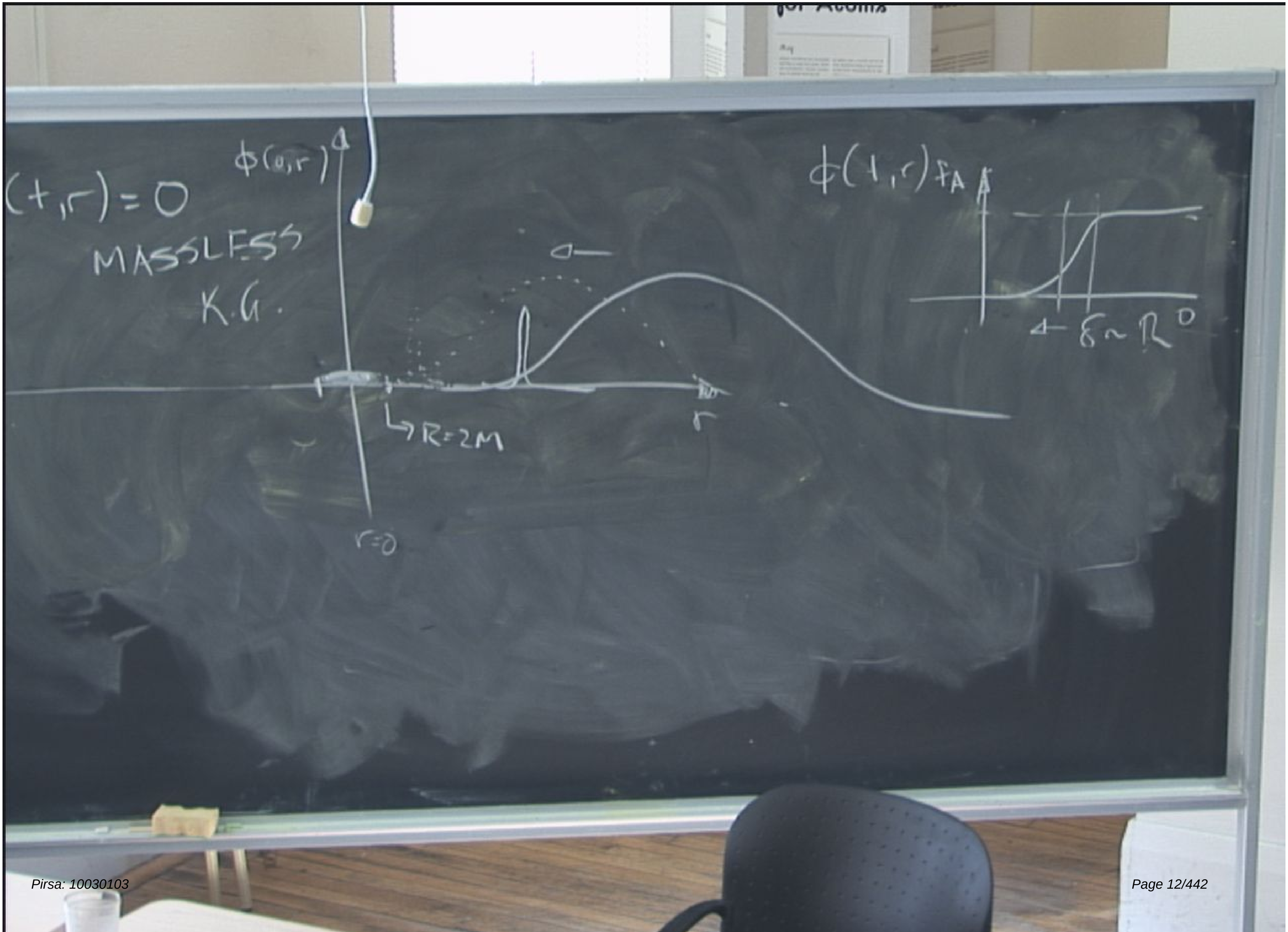

φ(0,r)
R=2M
r
r=0


ϕ(0,r)
ϕ(t,r)
R=2M
r
r=0

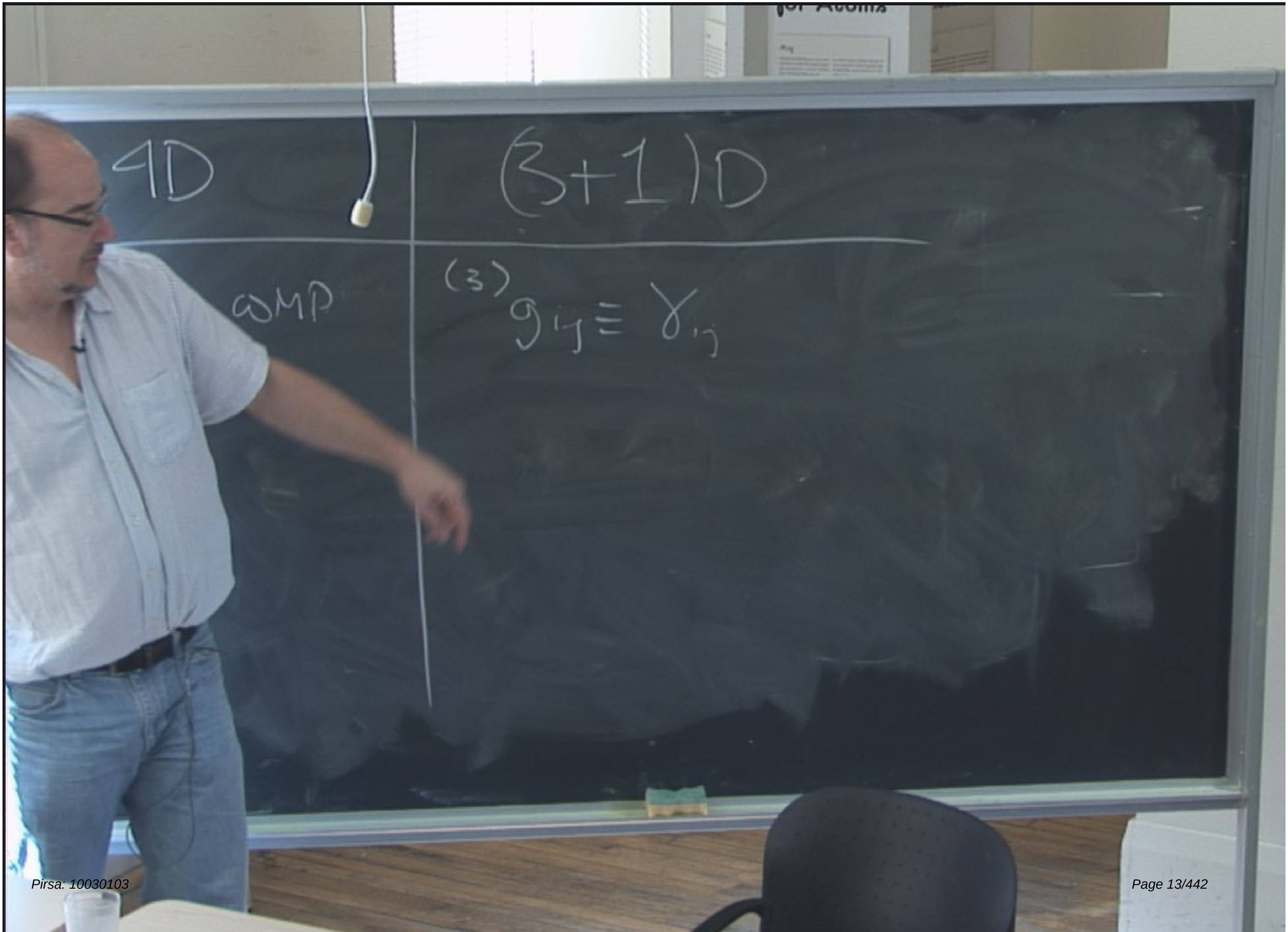

φ(0,r)
φ(t,r) f_A
R=2M
r
r=0
ε

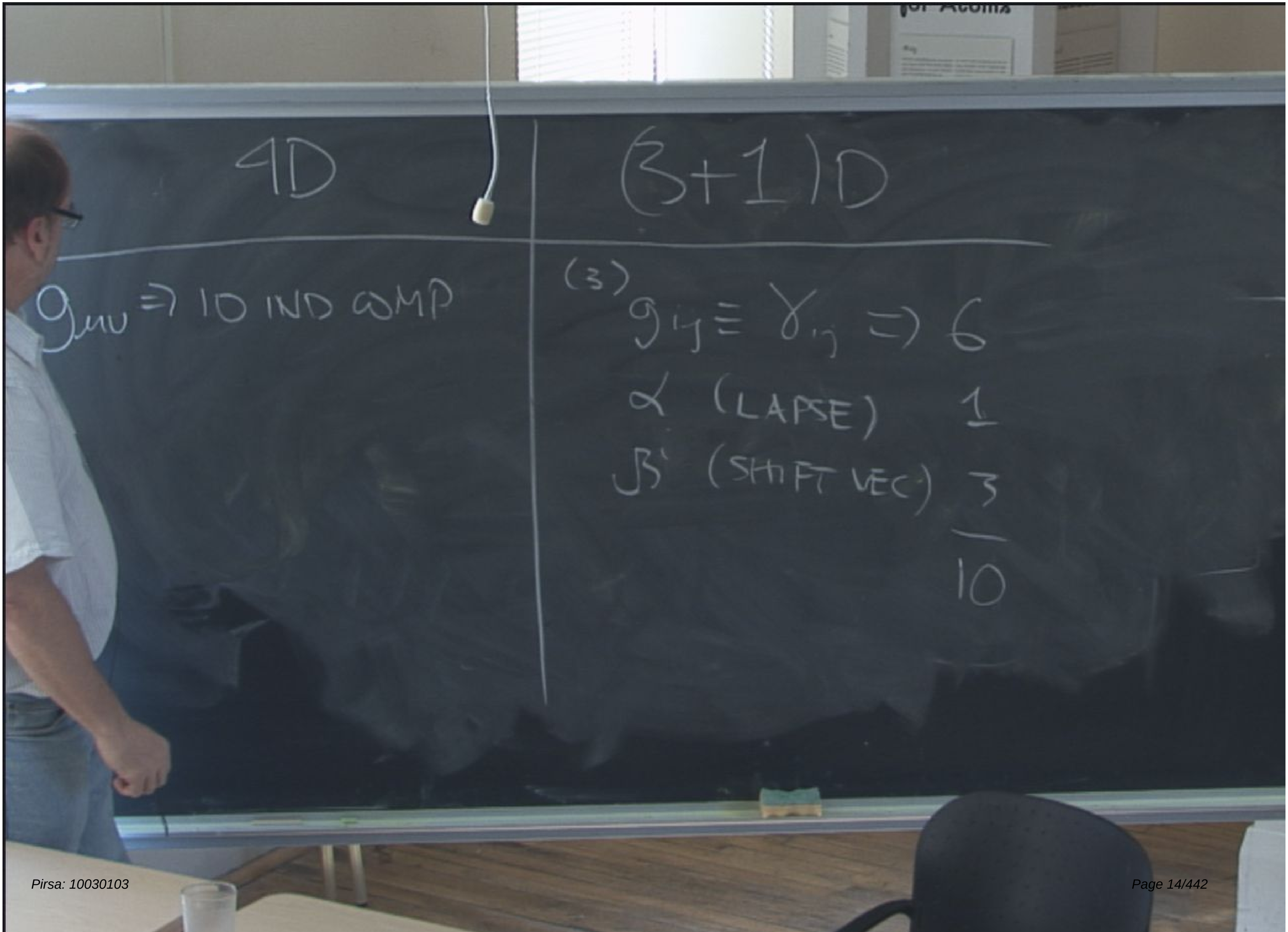

ϕ(0,r)
r
R=2M
r=0
ϕ(t,r) f_A

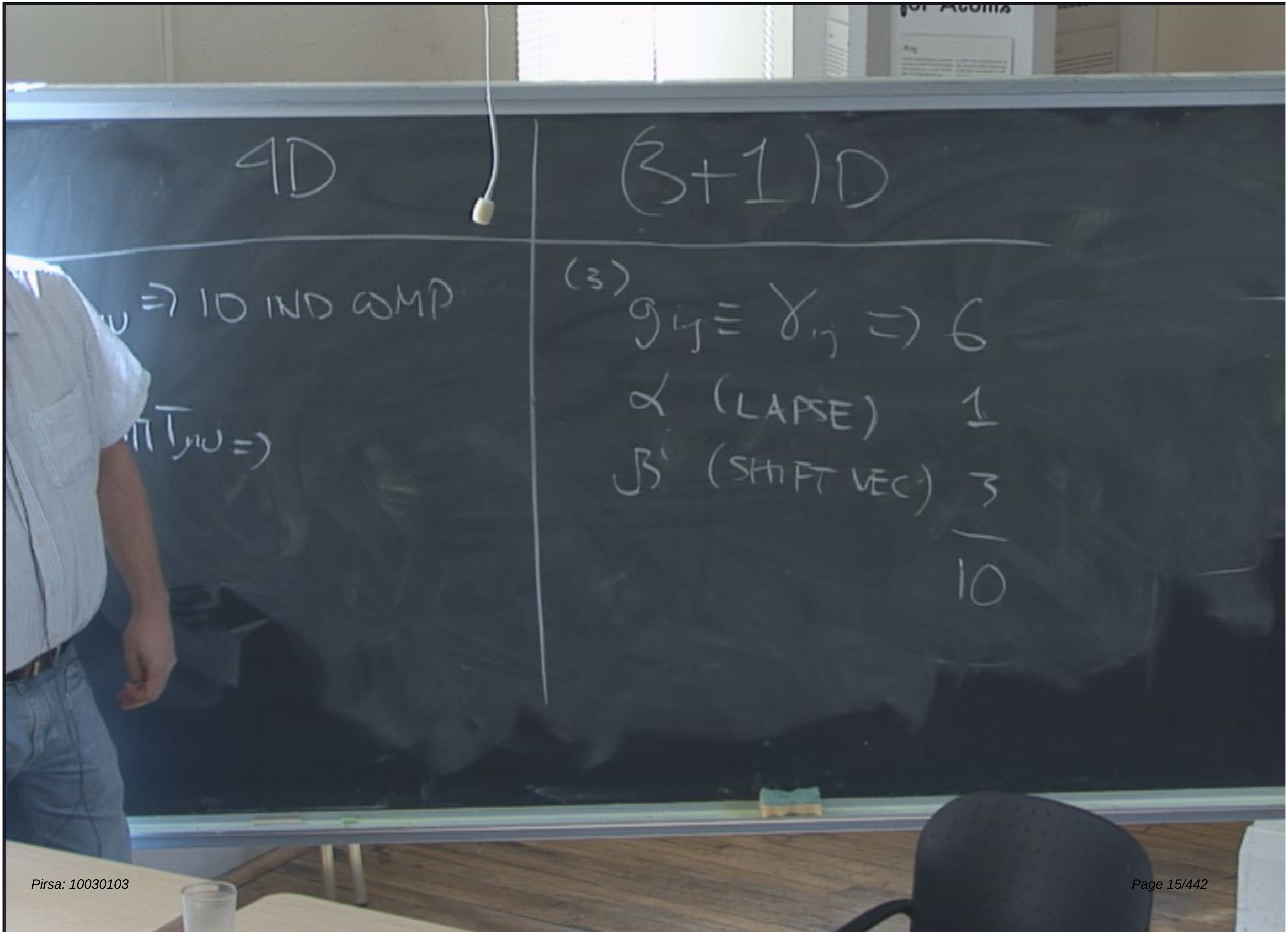

φ(0,r)
φ(t,r) f_A
R=2M
r
r=0
δ ~ R^0

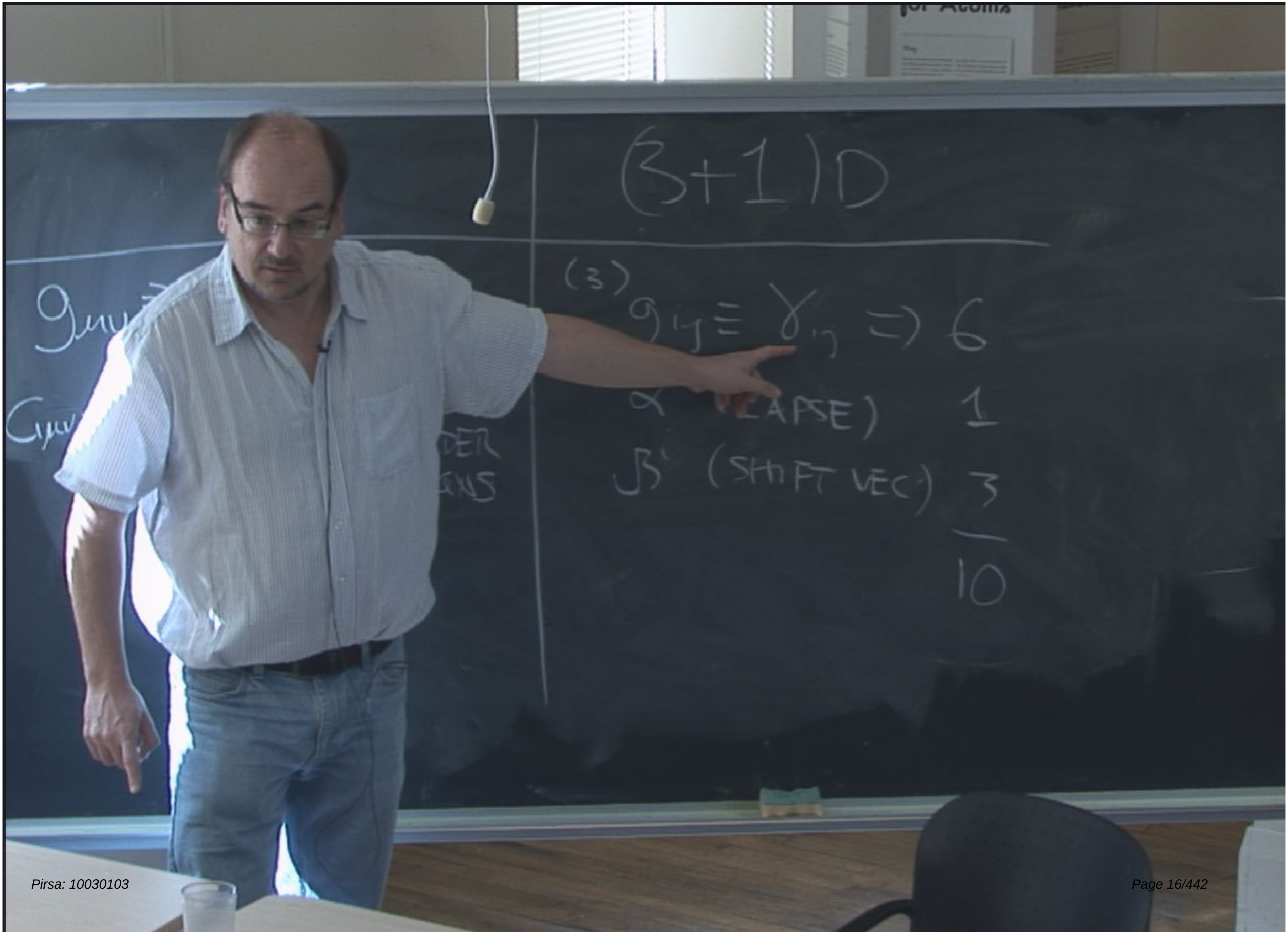


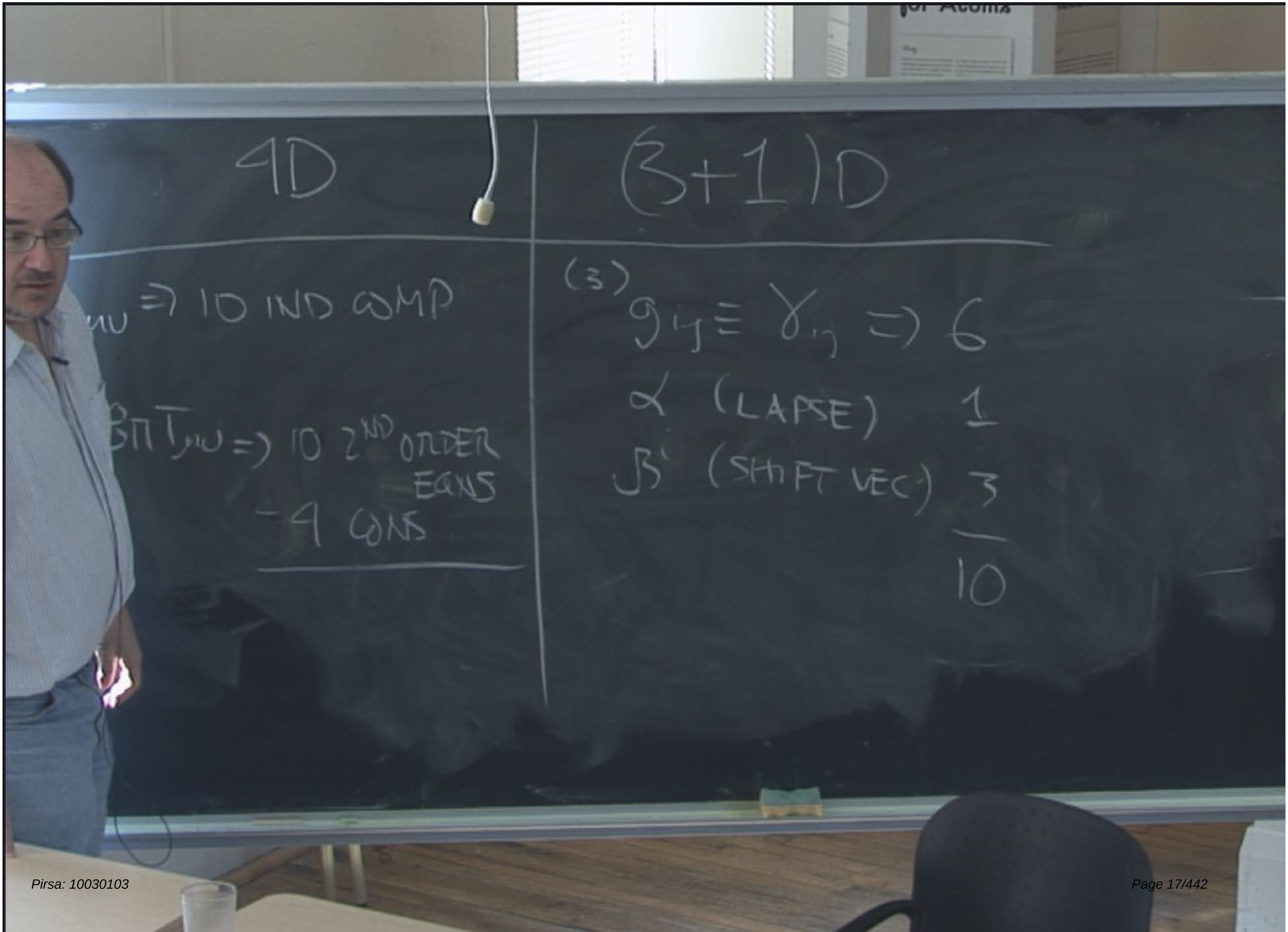
(t,r) = 0
MASSLESS
K.G.
φ(0,r)
R=2M
r
r=0
φ(t,r) f_A
δ ~ R^0

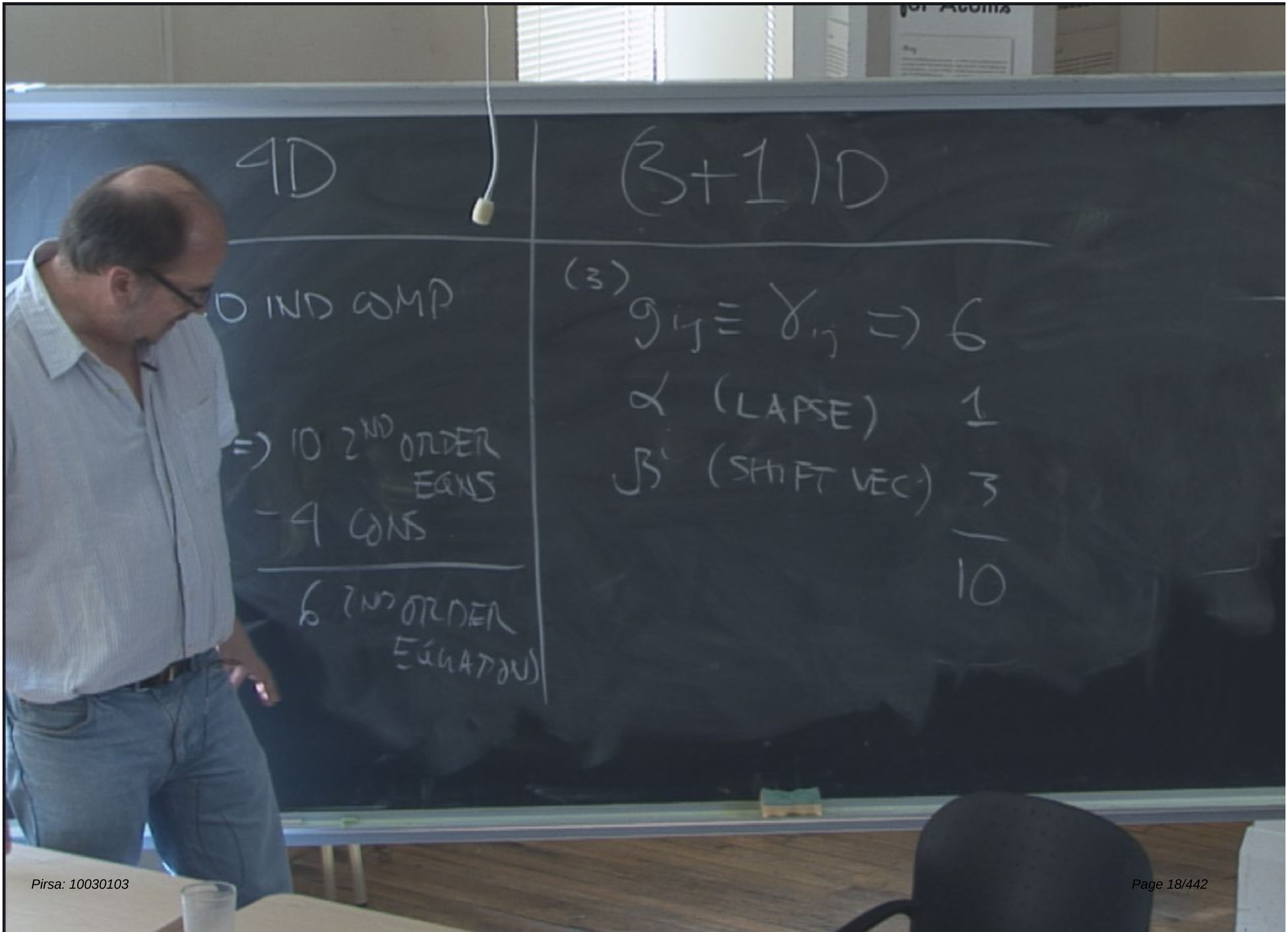

4D
(3+1)D
ωMP
(3) gij ≡ γij

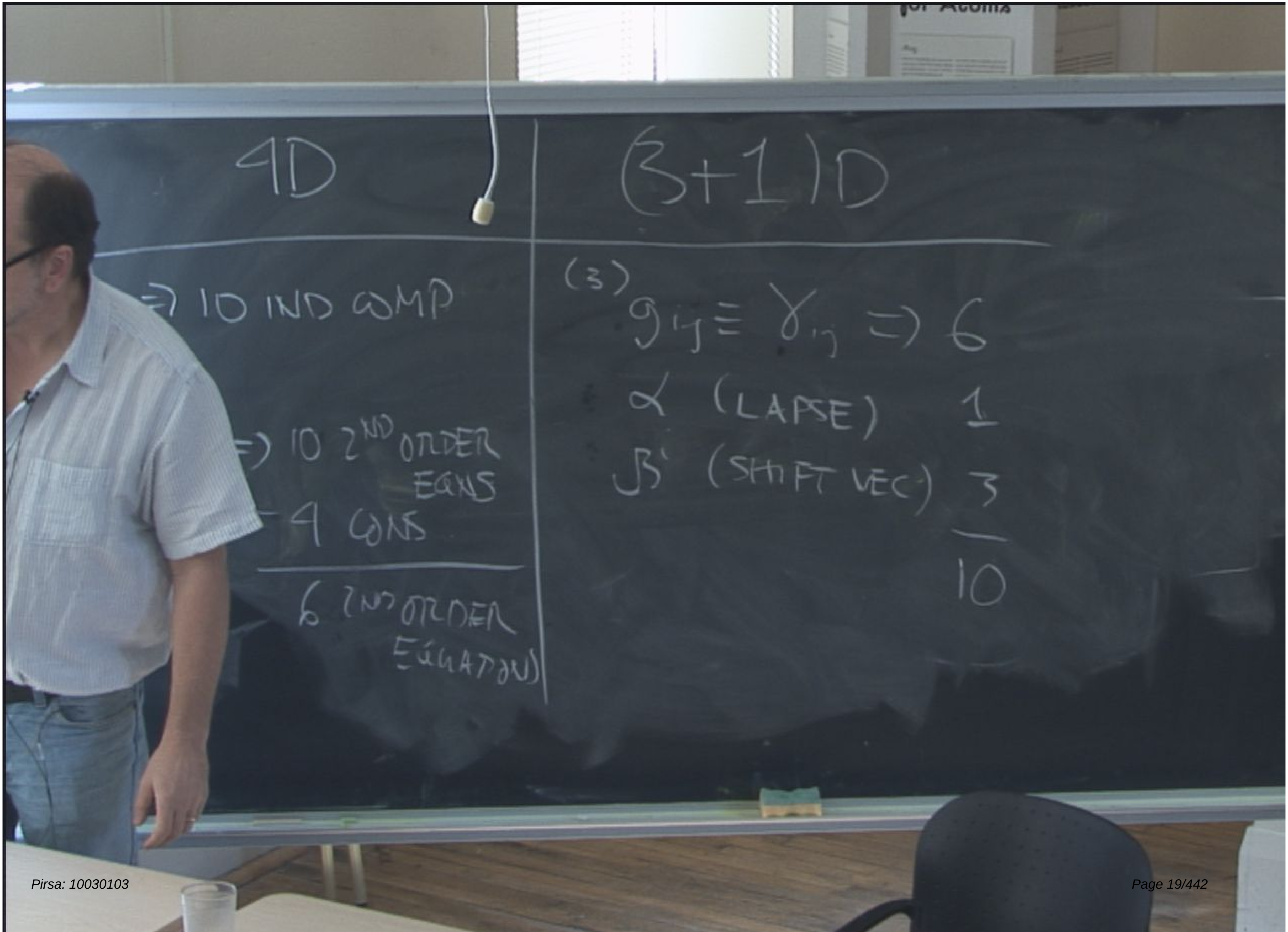

4D
(3+1)D
$g_{\mu\nu} \Rightarrow$ 10 IND COMP
${}^{(3)}g_{ij} \equiv \gamma_{ij} \Rightarrow 6$
α (LAPSE) 1
β^i (SHIFT VEC) 3
10


4D
(3+1)D
⇒ 10 IND COMP
(3)
$g_{ij} \equiv \gamma_{ij} \Rightarrow 6$
α (LAPSE) 1
β^i (SHIFT VEC) 3
10
$T_{\mu\nu} \Rightarrow$


(3+1)D
(3)
gij ≡ γij ⇒ 6
α (LAPSE) 1
β^i (SHIFT VEC) 3
10


4D
(3+1)D
$\mu\nu \Rightarrow$ 10 IND COMP
$^{(3)}g_{ij} \equiv \gamma_{ij} \Rightarrow 6$
α (LAPSE) 1
$8\pi T_{\mu\nu} \Rightarrow$ 10 2ND ORDER EQNS
β^i (SHIFT VEC) 3
-4 CONS
10


4D
(3+1)D
0 IND COMP
=> 10 2ND ORDER EQNS
-4 CONS
6 2ND ORDER EQUATIONS
(3) $g_{ij} \equiv \gamma_{ij} \Rightarrow 6$
α (LAPSE) 1
β^i (SHIFT VEC) 3
10


4D
(3+1)D
⇒ 10 IND COMP
⇒ 10 2ND ORDER EQNS
4 CONS
6 2ND ORDER EQUATIONS
(3) g_ij ≡ γ_ij ⇒ 6
α (LAPSE) 1
β^i (SHIFT VEC) 3
10

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THE 3+1 EINSTEIN EQUATIONS

These notes rework the calculation of the 3+1 equations as presented in *Kinematics and Dynamics of General Relativity*, by J. W. York, Jr., which itself is contained in the volume *Sources of Gravitational Radiation*, edited by L. Smarr. Many calculational details omitted from that source are included here.

(**Note:** A colleague of mine, who will remain anonymous this week, has used these notes to demonstrate the power of his symbolic manipulation software and has found at least one error amongst the many "intermediate" results that are derived below. There is a $234 Argentinian peso reward for the PSI student who first identifies such an error and who submits a hand-written explanation of the gaffe, along with the corrected expression, to the tutor.)

1) Foliations and Normals

As before, we consider a spacetime M with metric g_{ab} which is sliced into a foliation $\{\Sigma\}$ defined by the isosurfaces of a scalar field τ (the time parameter). Then the spacelike hypersurfaces are, at least locally, described by a *closed* one-form (dual vector field), Ω_a:

$$\Omega_a = \nabla_a \tau \, . \tag{1}$$

Note that since Ω_a is the gradient of a scalar function, and ∇_a is torsion-free, we have obe Acrobat Standard - [387n-04-york-3+1-derivation.pdf]

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PHY 387N SPHERICAL SYMMETRY (SS)

- IN SS SPACETIME NEED MATTER FOR DYNAMICS (BIRKHOFF'S THM, UNIQUENESS of SCHWARZSCHILD SOL^N AS SOL^N of $G_{ab} = 0$)

- WILL RESTRICT MATTER CONTENT TO SINGLE, MASSLESS, MINIMALLY-COUPLED SCALAR FIELD, ϕ
  - GOOD MODEL PROBLEM FOR STUDYING STRONG-FIELD, RADIATIVE S.T.'S - INCLUDING BLACK HOLE FORMATION
  - EXHIBITS INTERESTING PHYSICAL BEHAVIOUR → CRITICAL PHENOMENA aka BLACK HOLE THRESHOLD PHENOMENA

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LAGRANGIAN DENSITY FOR EMKG SYSTEM

$$\mathcal{L} = \mathcal{L}_{GRAV} + \mathcal{L}_{\phi}$$

$$= \sqrt{-g}\left(R - \tfrac{1}{2} \nabla_a \phi \nabla^a \phi \right)$$

"COVARIANT" E.O.M

$$G_{ab} = 8\pi T_{ab} = 8\pi \left(\nabla_a \phi \nabla_b \phi - \tfrac{1}{2} g_{ab} \nabla_c \phi \nabla^c \phi \right)$$

$$\Box \phi = \nabla^a \nabla_a \phi = 0$$

3.1 FORM of SPACETIME METRIC IN SS

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$$G_{ab} = 8\pi T_{ab} = 8\pi \left(\nabla_a \phi \nabla_b \phi - \tfrac{1}{2} g_{ab} \nabla_c \phi \nabla^c \phi \right)$$

$$\Box \phi = \nabla^a \nabla_a \phi = 0$$

3.1 FORM OF SPACETIME METRIC IN SS

- COORDINATES (t, r, θ, φ) ADAPTED TO S.S.

METRIC ON UNIT 2-SPHERE $d\Omega^2 = d\theta^2 + \sin^2\theta \, d\phi^2$

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3.1 FORM OF SPACETIME METRIC IN SS

- COORDINATES (t, r, θ, ϕ) ADAPTED TO S.S.

METRIC ON UNIT 2-SPHERE $d\Omega^2 = d\theta^2 + \sin^2\theta \, d\phi^2$

- THEN MOST GENERAL 3-METRIC IS

$$\gamma_{ij} = \mathrm{diag}\left(a^2(r,t),\ r^2 b^2(r,t),\ r^2 b^2 \sin^2\theta\right) \qquad (1)$$

THE LAPSE FUNCTION IS $\alpha(r,t)$, AND THE SHIFT VECTOR $\beta^i(r,t)$ HAS ONLY A RADIAL COMPONENT, $\beta(r,t)$

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- THEN MOST GENERAL 3-METRIC IS

$$\gamma_{ij} = \mathrm{diag}\left(a^2(r,t),\ r^2 b^2(r,t),\ r^2 b^2 \sin^2\theta\right) \qquad (1)$$

THE LAPSE FUNCTION IS $\alpha(r,t)$, AND THE SHIFT VECTOR $\beta^i(r,t)$ HAS ONLY A RADIAL COMPONENT, $\beta(r,t)$

$$\beta^i = (\beta, 0, 0) \qquad (2)$$

$$\beta_i = \gamma_{ij}\beta^j = (a^2\beta, 0, 0) \qquad (3)$$

- THE MOST GENERAL 4-METRIC IS THEN

$$ds^2 = (-\alpha^2 + \beta^i\beta_i)\,dt^2 + 2\beta_i\,dt\,dx^i + \gamma_{ij}\,dx^i dx^j$$

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- THEN MOST GENERAL 3-METRIC IS

$$\gamma_{ij} = \mathrm{diag}\left(a^2(r,t),\ r^2 b^2(r,t),\ r^2 b^2 \sin^2\theta\right) \qquad (1)$$

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$$ds^2 = (-\alpha^2 + \beta^i\beta_i)\,dt^2 + 2\beta_i\,dt\,dx^i + \gamma_{ij}\,dx^i dx^j$$

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- THEN MOST GENERAL 3-METRIC IS

$$\gamma_{ij} = \mathrm{diag}\left(a^2(r,t),\ r^2 b^2(r,t),\ r^2 b^2 \sin^2\theta\right) \qquad (1)$$

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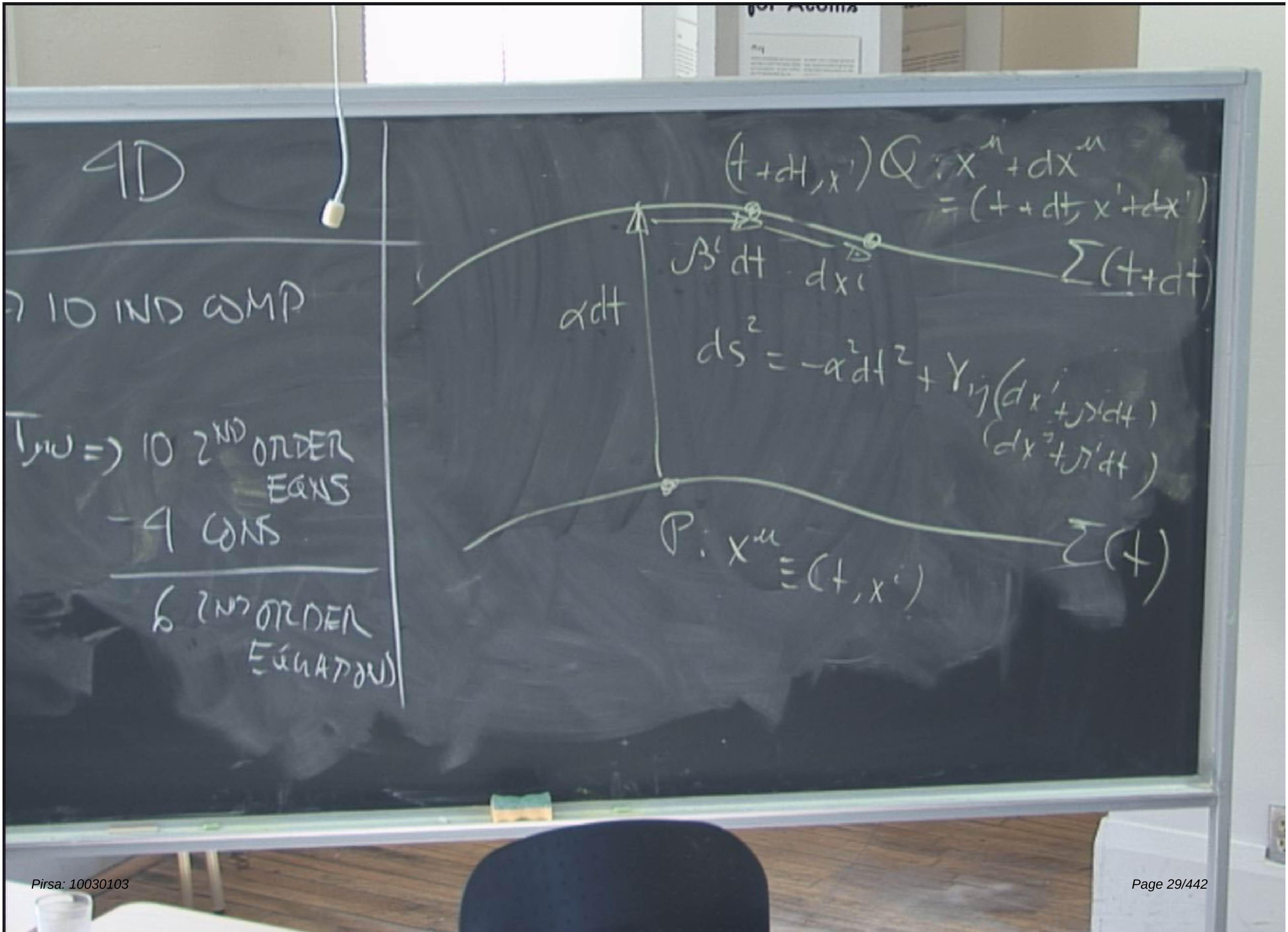
- THE MOST GENERAL 4-METRIC IS THEN

$$ds^2 = (-\alpha^2 + \beta^i\beta_i)\,dt^2 + 2\beta_i\,dt\,dx^i + \gamma_{ij}\,dx^i dx^j$$


4D
→ 10 IND COMP
$T_{\mu\nu}$ ⇒ 10 2ND ORDER EQNS
−4 CONS
6 2ND ORDER EQUATIONS
$(t+dt, x^i)$ $Q: x^\mu + dx^\mu = (t+dt, x^i+dx^i)$
$\beta^i dt$
dx^i
$\Sigma(t+dt)$
αdt
$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$
$P: x^\mu = (t, x^i)$
$\Sigma(t)$

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• THE MOST GENERAL 4-METRIC IS THEN

$$ds^2 = (-\alpha^2 + \beta^i\beta_i)\,dt^2 + 2\beta_i\,dt\,dx^i + \gamma_{ij}\,dx^i dx^j$$

$$= (-\alpha^2 + a^2\beta^2)\,dt^2 + 2a^2\beta\,dt\,dr + a^2 dr^2 + r^2 b^2 d\Omega^2 \quad (4)$$

• CORRESPONDING EXTRINSIC CURVATURE TENSOR, $K^i{}_j$, LIKE γ_{ij}, HAS ONLY TWO INDEPENDENT COMPONENTS

$$K^i{}_j = \mathrm{diag}\big(K^r{}_r(r,t),\ \underbrace{K^\theta{}_\theta(r,t),\ K^\theta{}_\theta}_{}\big) \quad (5)$$

EASY TO SHOW EQUALITY FROM

$$K_{ij} = (2\alpha)^{-1}\left(-\partial_t\gamma_{ij} + D_i\beta_j + D_j\beta_i\right)$$

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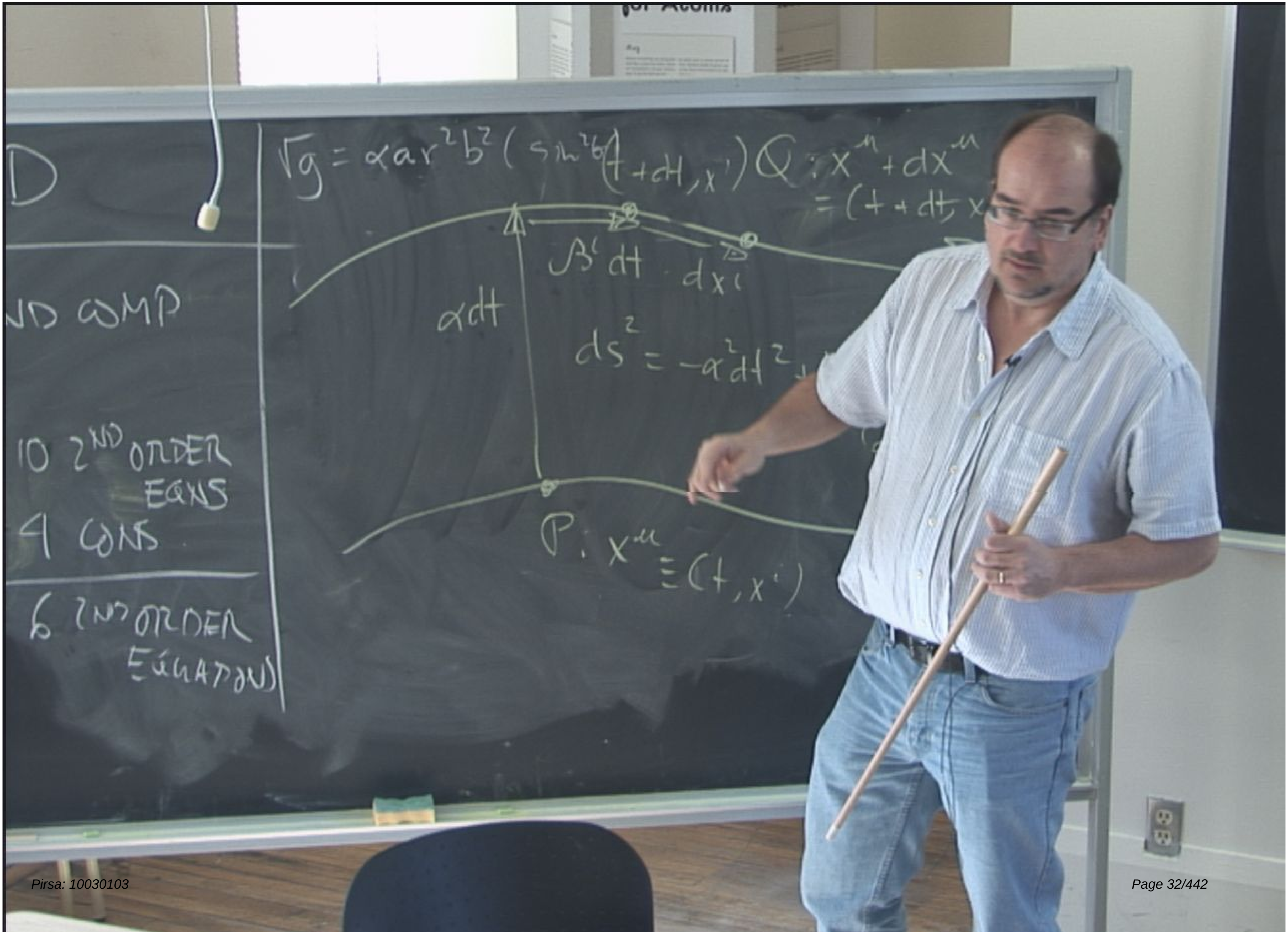
PHYS 3EA4 SPHERICAL SYMMETRY ②

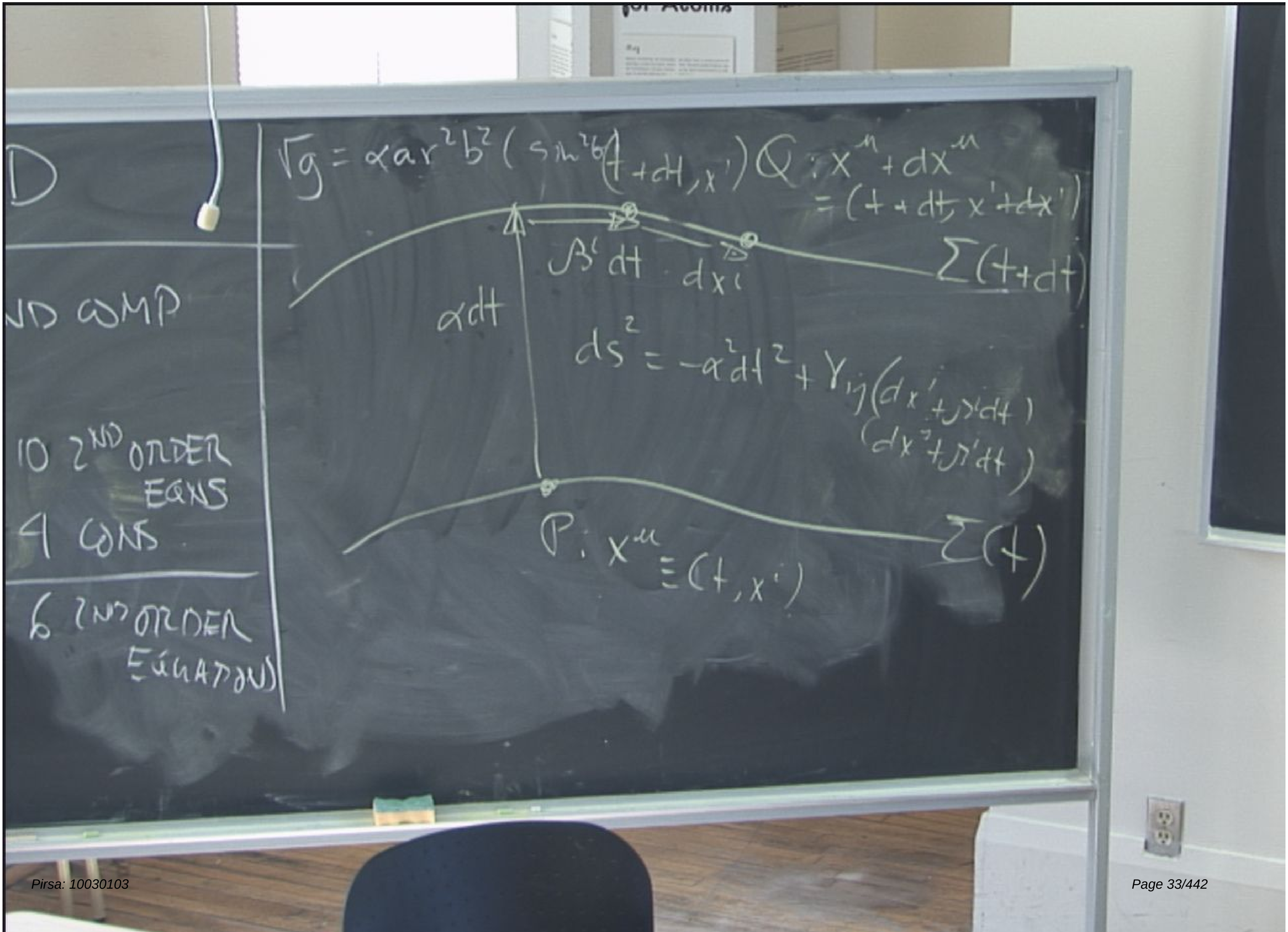
- SO, HAVE REDUCED TOTAL # OF GRAVITATIONAL KIN. DYN VBLS FROM 16 TO 6, AND, OF COURSE, THESE VBLS ARE FUNCTIONS only of (r,t) RATHER THAN (x,y,z,t)

EINSTEIN EQUATIONS

(1) CONSTRAINTS

$$\boxed{R - K^{i}{}_{j} K^{j}{}_{i} + K^{2} = 16\pi\rho \qquad (6)}$$


√g = αar²b²(sin²θ
(t+dt, xⁱ) Q: x^μ + dx^μ
= (t + dt, x
βⁱdt
dxⁱ
αdt
ds² = −α²dt² +
ND COMP
10 2ND ORDER EQNS
4 CONS
6 2ND ORDER EQUATIONS
P: x^μ = (t, xⁱ)



ND COMP
10 2ND ORDER EQNS
4 CONS
6 2ND ORDER EQUATIONS
$\sqrt{g} = \alpha a r^2 b^2 (\sin^2\theta)$
$(t+dt, x^i)$
$Q: x^\mu + dx^\mu = (t+dt, x^i+dx^i)$
$\beta^i dt$
dx^i
$\Sigma(t+dt)$
αdt
$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$
$P: x^\mu = (t, x^i)$
$\Sigma(t)$

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EINSTEIN EQUATIONS

(1) CONSTRAINTS

$$\boxed{\begin{aligned} &R - K^{i}{}_{j} K^{j}{}_{i} + K^{2} = 16\pi\rho \quad (6) \\ &D_j K_i{}^{j} - D_i K = 8\pi j_i \quad (7) \end{aligned}}$$

↳ NOTE INDEX SHIFT RELATIVE TO PREVIOUS TEXT

WHERE $\rho = n_\mu n_\nu T^{\mu\nu}$ (8)

$$j_i = \gamma_{ik} j^k = -n_\mu T^{\mu}{}_{i} \quad (9)$$

RECALL: $n_\mu = (-\alpha, 0, 0, 0)$ (10)

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$$\boxed{D_j K_i{}^j - D_i K = 8\pi j_i} \qquad (7)$$

NOTE INDEX SHIFT RELATIVE TO PREVIOUS TEXT!

WHERE $\quad \rho = n_\mu n_\nu T^{\mu\nu} \qquad (8)$

$$j_i = \gamma_{ik} j^k = - n_\mu T^\mu{}_i \qquad (9)$$

RECALL: $\quad n_\mu = (-\alpha, 0, 0, 0) \qquad (10)$

(2) EVOLUTION EQUATIONS $\quad \left(\dot{} \equiv \frac{\partial}{\partial t} \equiv \partial_t \right)$

$$\dot{\gamma}_{ij} = -2\alpha \gamma_{ik} K^k{}_j + \beta^k \partial_k \gamma_{ij} + \gamma_{ik} \partial_j \beta^k + \gamma_{kj} \partial_i \beta^k \qquad (11)$$

$$\dot{K}^i{}_j = \beta^k \partial_k K^i{}_j - \partial_k \beta^i K^k{}_j + \partial_j \beta^k K^i{}_k - D^i D_j \alpha$$

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…) EVOLUTION EQUATIONS $\left(\dot{} \equiv \frac{\partial}{\partial t} \equiv \partial_t \right)$

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$$\dot{K}^i{}_j = \beta^k \partial_k K^i{}_j - \partial_k \beta^i K^k{}_j + \partial_j \beta^k K^i{}_k - D^i D_j \alpha$$

$$+ \alpha \left(R^i{}_j + K K^i{}_j + 4\pi (S - \rho) \delta^i{}_j - 8\pi S^i{}_j \right) \quad (12)$$

WHERE $S_{ij} = T_{ij}$ (13), $S^i{}_j = \gamma^{ik} S_{kj}$ (14), $S = S^i{}_i$ (15)

… NEED CHRISTOFFEL SYMBOLS $\Gamma^i{}_{jk}$, RICCI COMPONENTS $R^i{}_j$ AND RICCI SCALAR R ASSOCIATED WITH γ_{ij} (1). USING STANDARD FORMULAE FIND FOLLOWING NON-VANISHING $\Gamma^i{}_{jk}$

$\left(' = \frac{\partial}{\partial r} = \partial_r \right)$

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NEED CHRISTOFFEL SYMBOLS $\Gamma^i{}_{jk}$, RICCI COMPONENTS $R^i{}_j$ AND RICCI SCALAR R ASSOCIATED WITH γ_{ij} (1). USING STANDARD FORMULAE FIND FOLLOWING NON-VANISHING $\Gamma^i{}_{jk}$ ($' \equiv \frac{\partial}{\partial r} \equiv \partial_r$)

$$\Gamma^r{}_{rr} = \frac{a'}{a} \qquad \Gamma^r{}_{\theta\theta} = -\frac{(r^2b^2)'}{2a^2} \qquad \Gamma^r{}_{\phi\phi} = \sin^2\theta\, \Gamma^r{}_{\theta\theta}$$

$$\Gamma^\theta{}_{r\theta} = \Gamma^\theta{}_{\theta r} = \frac{(r^2b^2)'}{2(r^2b^2)} \qquad \Gamma^\theta{}_{\phi\phi} = -\sin\theta\cos\theta \qquad (16a\text{-}g)$$

$$\Gamma^\phi{}_{r\phi} = \Gamma^\phi{}_{\phi r} = \Gamma^\theta{}_{\theta r} \qquad \Gamma^\phi{}_{\theta\phi} = \Gamma^\phi{}_{\phi\theta} = \cot\theta$$

FROM THESE WE COMPUTE NON-VANISHING $R^i{}_j$

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$$\Gamma^r{}_{rr} = \frac{a'}{a} \qquad \Gamma^r{}_{\theta\theta} = -\frac{(r^2b^2)'}{2a^2} \qquad \Gamma^r{}_{\phi\phi} = \sin^2\theta\, \Gamma^r{}_{\theta\theta}$$

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$$\Gamma^\phi{}_{r\phi} = \Gamma^\phi{}_{\phi r} = \Gamma^\theta{}_{\theta r} \qquad \Gamma^\phi{}_{\theta\phi} = \Gamma^\phi{}_{\phi\theta} = \cot\theta$$

FROM THESE WE COMPUTE NON-VANISHING $R^i{}_j$

$$R^r{}_r = \frac{-2}{arb}\left(\frac{(rb)'}{a}\right)' \qquad (17a)$$

$$R^\theta{}_\theta = R^\phi{}_\phi = \frac{1}{a(rb)^2}\left(a - \left(\frac{rb}{a}(rb)'\right)'\right) \qquad (17b)$$

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$$\frac{\quad}{a(rb)^2}\left(\alpha - \left(\frac{\quad}{a} \right) \right)$$

AND FINALLY, THE SCALAR CURVATURE, $\mathcal{R}$, IS

$$\mathcal{R} = R^r{}_r + R^\theta{}_\theta + R^\phi{}_\phi = R^r{}_r + 2R^\theta{}_\theta$$

$$= -\frac{2}{arb}\left(\left(\frac{(rb)'}{a}\right)' + \frac{1}{rb}\left(\left(\frac{rb}{a}(rb)'\right)' - a\right)\right) \qquad (16)$$

FOR THE EVOLUTION EQUATION FOR $K^i{}_j$ WE NEED TO EVALUATE $D^i D_j \alpha$:

DAY 3 ? SPHERICAL SYMMETRY

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EVALUATE $D^i D_j \alpha$:

DAM 3E7M SPHERICAL SYMMETRY (5)

$$D^i D_j \alpha = \gamma^{ik} D_k D_j \alpha = \gamma^{ik} D_k \partial_j \alpha$$

$$= \gamma^{ik} \left(\partial_k \partial_j \alpha - \Gamma^m{}_{jk} \partial_m \alpha \right)$$

USING RESULTS FROM ABOVE, WE FIND

$$D^r D_r \alpha = \frac{1}{a} \left(\frac{\alpha'}{a} \right)' \qquad (19a)$$

$$D^\theta D_\theta \alpha = D^\phi D_\phi \alpha = \frac{\alpha' (rb)'}{} \qquad (19b)$$

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EVALUATE $D^i D_j \alpha$:

DAY 3E7M   SPHERICAL SYMMETRY   ⑤

$$D^i D_j \alpha = \gamma^{ik} D_k D_j \alpha = \gamma^{ik} D_k \partial_j \alpha$$

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EVALUATE $D^i D_j \alpha$:

DAM BEAM SPHERICAL SYMMETRY (5)

$$D^i D_j \alpha = \gamma^{ik} D_k D_j \alpha = \gamma^{ik} D_k \partial_j \alpha$$

$$= \gamma^{ik} \left(\partial_k \partial_j \alpha - \Gamma^m{}_{jk} \partial_m \alpha \right)$$

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EVALUATE $D^i D_j \alpha$:

PHY 387M SPHERICAL SYMMETRY (5)

$$D^i D_j \alpha = \gamma^{ik} D_k D_j \alpha = \gamma^{ik} D_k \partial_j \alpha$$

$$= \gamma^{ik} \left(\partial_k \partial_j \alpha - \Gamma^m{}_{jk} \partial_m \alpha \right)$$

USING RESULTS FROM ABOVE, WE FIND

$$D^r D_r \alpha = \frac{1}{a} \left(\frac{\alpha'}{a} \right)' \qquad (19a)$$

$$D^b D_b \alpha = D^d D_d \alpha = \frac{\alpha' (rb)'}{} \qquad (19b)$$

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EVALUATE $D^i D_j \alpha$:

DAN BERN SPHERICAL SYMMETRY ③

$$D^i D_j \alpha = \gamma^{ik} D_k D_j \alpha = \gamma^{ik} D_k \partial_j \alpha$$

$$= \gamma^{ik} \left(\partial_k \partial_j \alpha - \Gamma^m{}_{jk} \partial_m \alpha \right)$$

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EVALUATE $D^i D_j \alpha$:

DAM BEAM SPHERICAL SYMMETRY (5)

$$D^i D_j \alpha = \gamma^{ik} D_k D_j \alpha = \gamma^{ik} D_k \partial_j \alpha$$

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EVALUATE $D^i D_j \alpha$:

DAY SEVEN SPHERICAL SYMMETRY ①

$$D^i D_j \alpha = \gamma^{ik} D_k D_j \alpha = \gamma^{ik} D_k \partial_j \alpha$$

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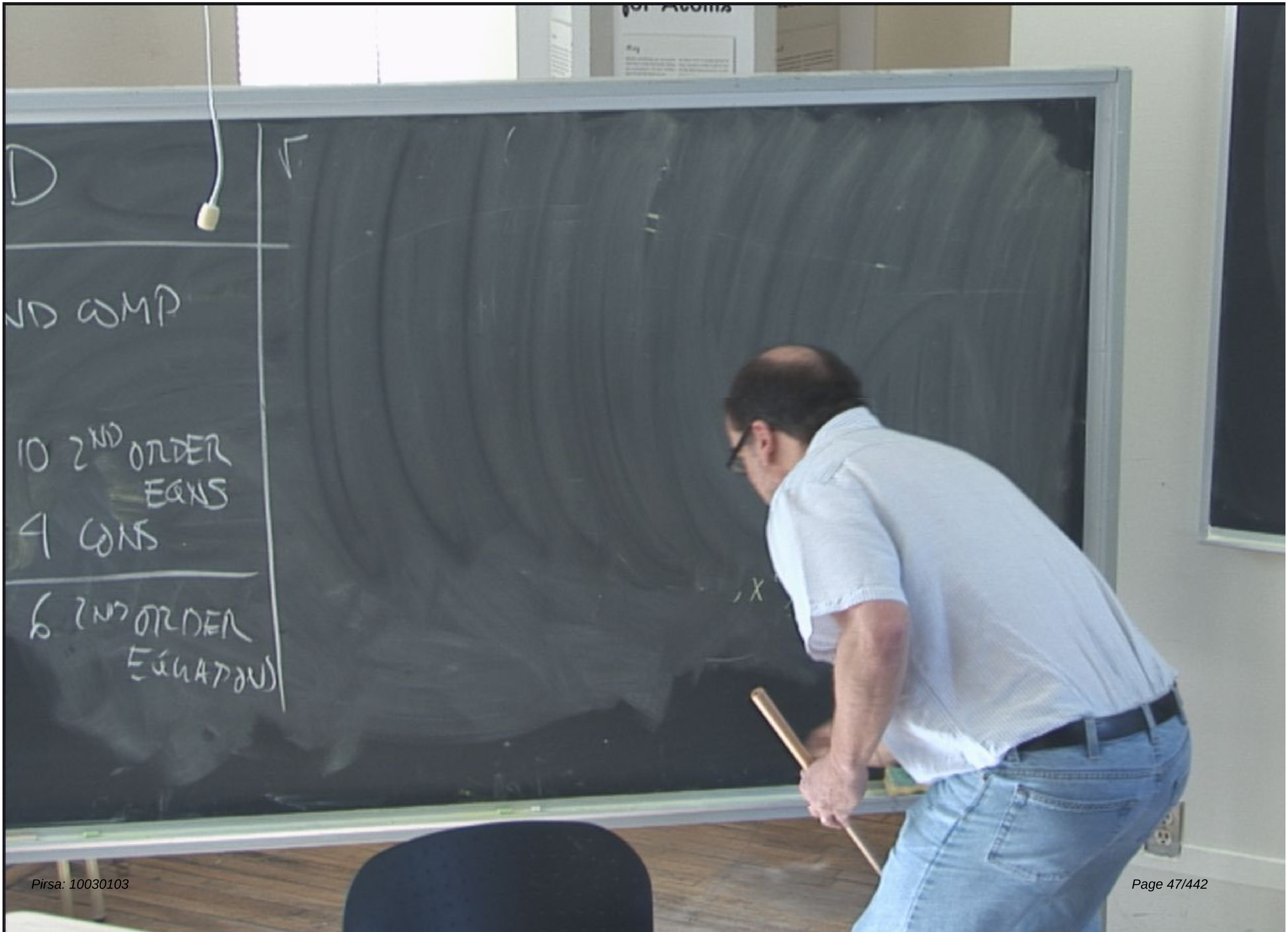
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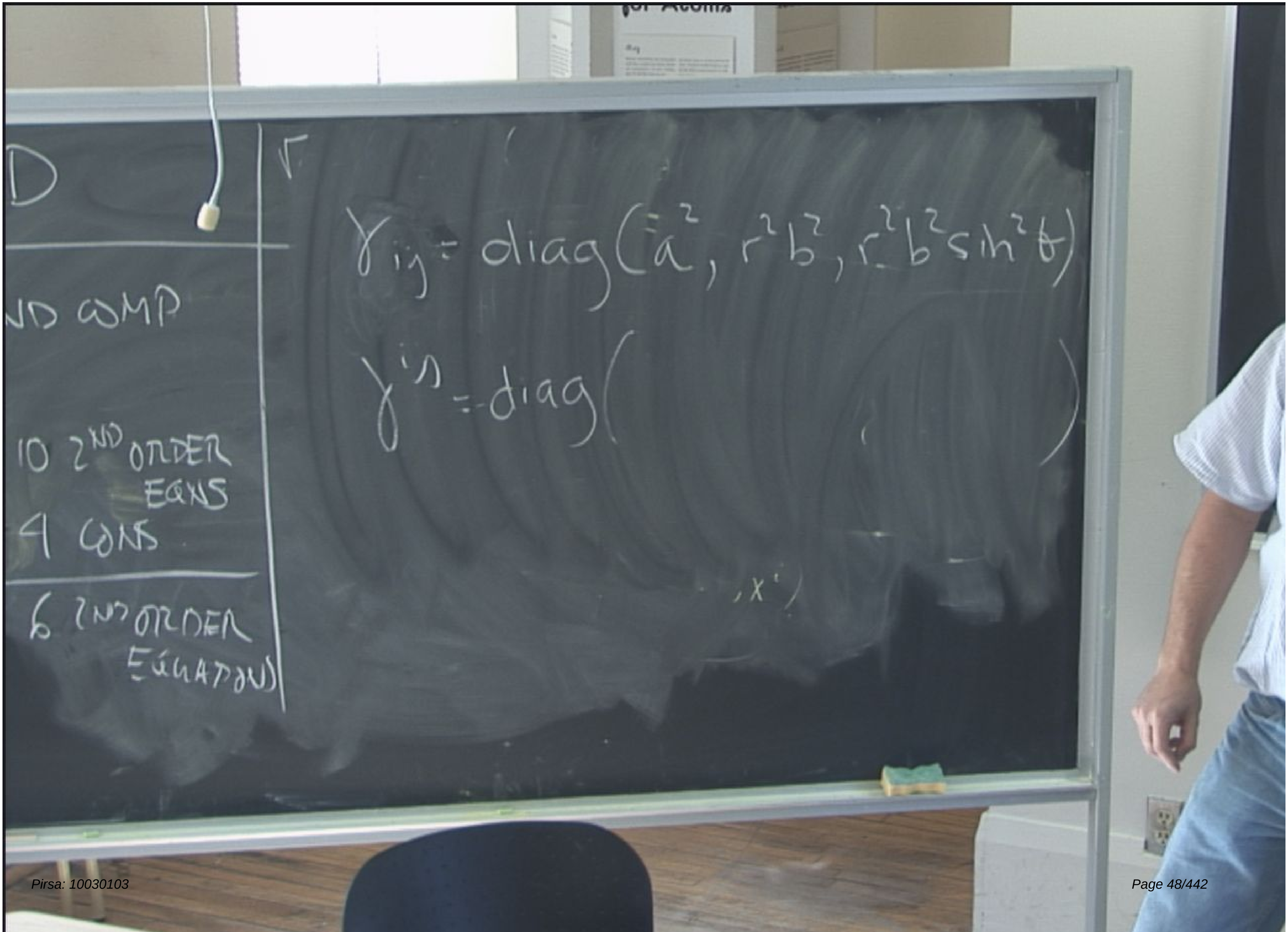
EQNS
4 CONS
6 2ND ORDER
EQUATIONS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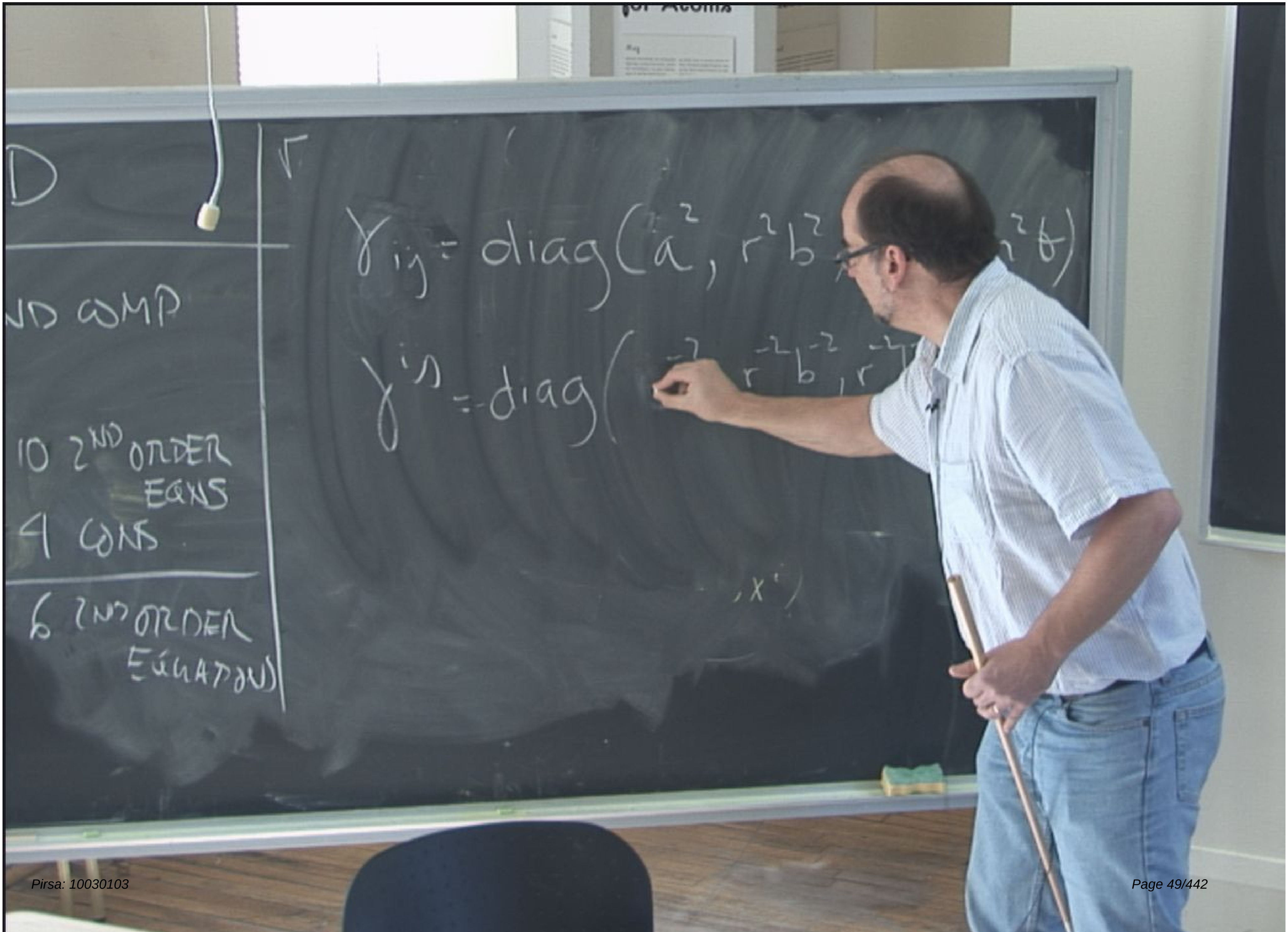
4 CONS
6 2ND ORDER EQUATIONS
$\gamma_{ij} = \mathrm{diag}(a^2, r^2 b^2, r^2 b^2 \sin^2\theta)$
$\gamma^{ij} = \mathrm{diag}($ $)$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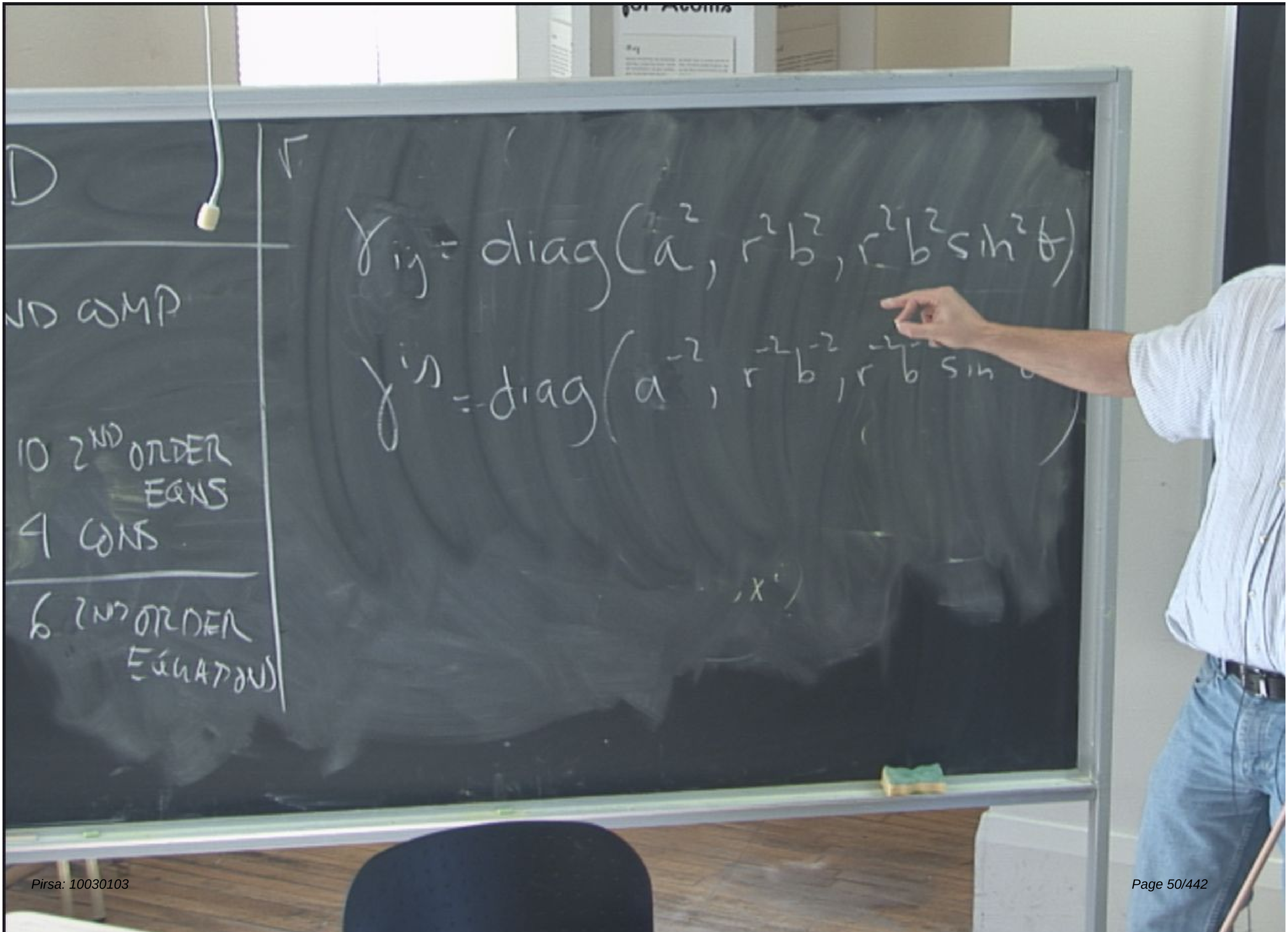
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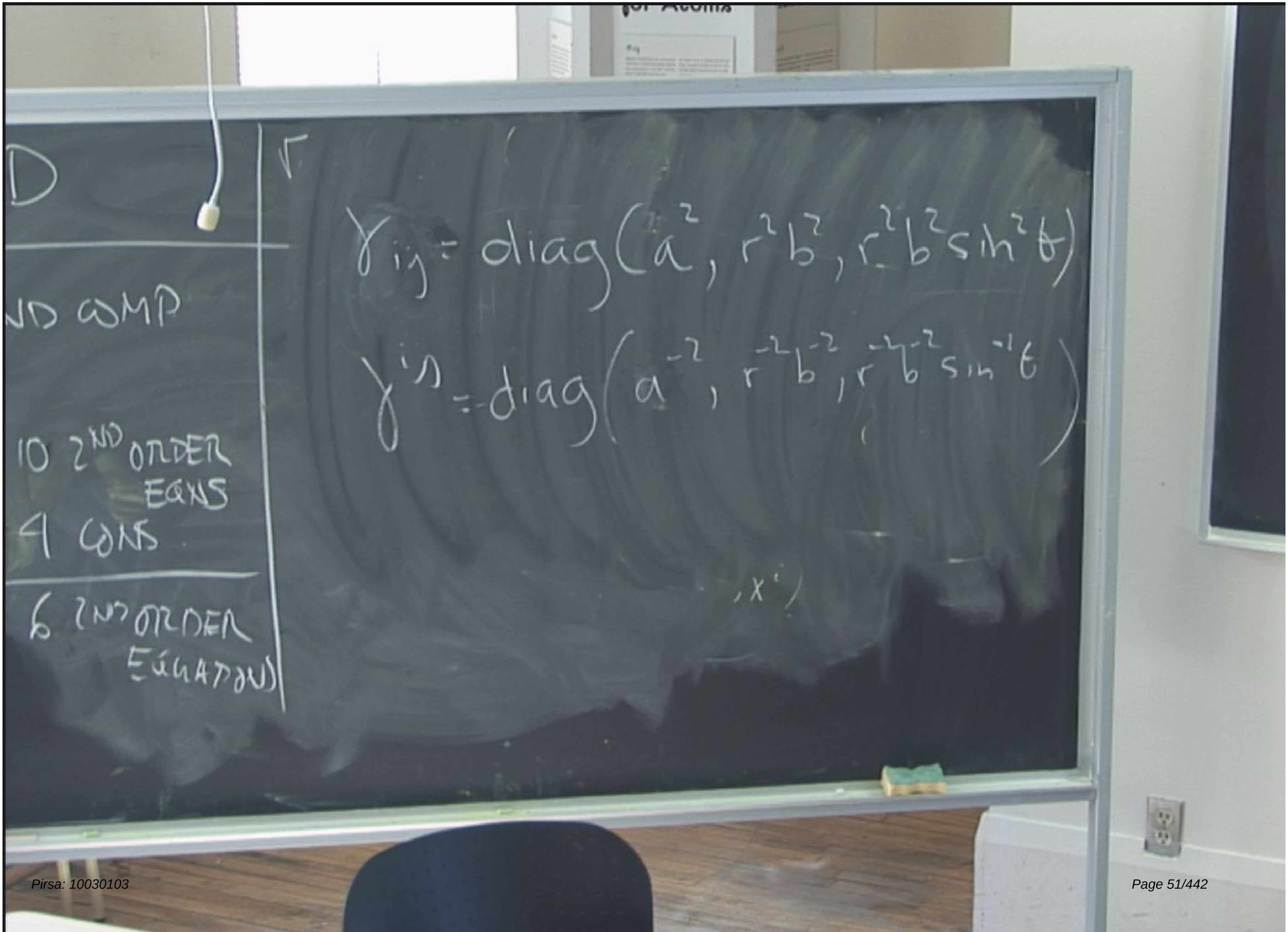
γij = diag(a2, r2b2, r2b2sin2θ)
γij = diag(a-2, r-2b-2, r-2b-2 sin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- ALSO NEED STRESS-TENSOR "COMPONENTS" ρ, j_i, $S^i{}_j$

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- ALSO NEED STRESS-TENSOR "COMPONENTS" β, j^i, $S^i{}_j$

- IN SPIRIT OF HAMILTONIAN APPROACH, IT IS CONVENIENT TO INTRODUCE AUXILIARY FUNCTIONS

$$\Phi(r,t) \equiv \phi'(r,t) = \partial_r \phi(r,t) \qquad (20)$$

$$\Pi(r,t) \equiv \frac{a}{\alpha}\left(\dot{\phi} - \beta \phi'\right) \qquad (21)$$

VIEW Φ, Π AS "REAL" DYNAMICAL VARS FOR SCALAR FIELD; NOTE: FOR MASSLESS FIELD, VALUE OF ϕ IS MEANINGLESS ($\phi \to \phi + \text{const}$ STILL SATISFIES $\Box \phi = 0$) ALL "ACTION" IS IN GRADIENTS

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(22a-e)

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$$(\nabla^\mu \phi)(\nabla_\mu \phi) = \phi^{,\mu}\phi_{,\mu} = \frac{\Phi^2 - \Pi^2}{a^2} \qquad (2b)$$

AND, AGAIN RECALLING THAT $n_\mu = (-\alpha, 0, 0, 0)$, WE FIND

$$\rho = n_\mu n_\nu T^{\mu\nu} = \alpha^2 T^{tt} = \alpha^2\left(\phi^{,t}\phi^{,t} - \tfrac{1}{2} g^{tt}\phi^{,\mu}\phi_{,\mu}\right)$$

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AND, ACTUALLY RECALLING ~~THAT~~ $n_\mu = (-\alpha, 0, 0, 0)$, WE FIND

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PHY 387M SPHERICAL SYMMETRY (4)

FINALLY, WE HAVE THE SPATIAL STRESS COMPONENTS

$$S^i{}_j = \gamma^{ik} S_{kj} = \gamma^{ik} T_{kj}$$

FROM WHICH WE FIND

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$$= \frac{\ldots}{2a^2} \quad (26)$$

$$j_i = (j_r, 0, 0)$$

$$j_r = -n_\mu T^\mu{}_i = \alpha T^0{}_i = \alpha \, \phi'^{+} \phi_{,r} = -\frac{\epsilon \pi}{a} \quad (27)$$

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PHY 387M SPHERICAL SYMMETRY ④

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PHY 387M SPHERICAL SYMMETRY 4

FINALLY, WE HAVE THE SPATIAL STRESS COMPONENTS

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FROM WHICH WE FIND

$$S^r{}_r = p = \frac{\Phi^2 + \Pi^2}{2a^2} \qquad (28)$$

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$$S - \rho = 2 S^\theta{}_\theta = \frac{\Pi^2 - \Phi^2}{a^2} \qquad (30)$$

* WE CAN NOW ASSEMBLE THE ABOVE RESULTS TO PRODUCE

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• WE CAN NOW ASSEMBLE THE ABOVE RESULTS TO PROJECT

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$$2a^2$$

$$S^{\theta}{}_{\theta} = S^{\phi}{}_{\phi} = \frac{\pi^2 - \Phi^2}{2a^2} \qquad (29)$$

$$S - \rho = 2S^{\theta}{}_{\theta} = \frac{\pi^2 - \Phi^2}{a^2} \qquad (30)$$

- WE CAN NOW ASSEMBLE THE ABOVE RESULTS TO DEDUCE THE SPHERICALLY-SYMMETRIC SPECIALIZATION OF THE GENERAL 3+1 EQUATIONS (6), (7), (11) ; (12)

A) HAMILTONIAN CONSTRAINT

$$R - K^i{}_j K^j{}_i + K^2 = 16\pi \rho$$

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THE SPHERICALLY-SYMMETRIC SPECIALIZATION of THE GENERAL 3+1 EQUATIONS (6), (7), (11) ; (12)

A) HAMILTONIAN CONSTRAINT

$$R - K^i{}_j K^j{}_i + K^2 = 16\pi\rho$$

$$-K^i{}_j K^j{}_i + K^2 = -(K^r{}_r{}^2 + 2K^\theta{}_\theta{}^2) + (K^r{}_r + 2K^\theta{}_\theta)^2$$

$$= 4K^r{}_r K^\theta{}_\theta + 2K^\theta{}_\theta{}^2$$

$$\boxed{R + 4K^r{}_r K^\theta{}_\theta + 2K^\theta{}_\theta{}^2 = 8\pi \frac{\Phi^2 + \Pi^2}{a^2} \quad (31)}$$

SEE (18)

B) MOMENTUM CONSTRAINT (ONLY r-COMPONENT IS NONTRIVIAL)

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A) HAMILTONIAN CONSTRAINT

$$R - K^i{}_j K^j{}_i + K^2 = 16\pi\rho$$

$$-K^i{}_j K^j{}_i + K^2 = -\left({K^r{}_r}^2 + 2{K^\theta{}_\theta}^2\right) + \left(K^r{}_r + 2K^\theta{}_\theta\right)^2$$

$$= 4K^r{}_r K^\theta{}_\theta + 2{K^\theta{}_\theta}^2$$

$$\boxed{R + 4K^r{}_r K^\theta{}_\theta + 2{K^\theta{}_\theta}^2 = 8\pi \frac{\bar{\Phi}^2 + \Pi^2}{a^2} \quad (31)}$$

SEE (18)

B) MOMENTUM CONSTRAINT (ONLY r-COMPONENT IS NONTRIVIAL)

• FIRST NOTE THAT

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$$R - K^i{}_j K^j{}_i + K^2 = 16\pi\rho$$

$$-K^i{}_j K^j{}_i + K^2 = -\left({K^r{}_r}^2 + 2{K^\theta{}_\theta}^2\right) + \left(K^r{}_r + 2K^\theta{}_\theta\right)^2$$

$$= 4K^r{}_r K^\theta{}_\theta + 2{K^\theta{}_\theta}^2$$

$$\boxed{R + 4K^r{}_r K^\theta{}_\theta + 2{K^\theta{}_\theta}^2 = 8\pi\,\frac{\Phi^2 + \Pi^2}{a^2} \quad (31)}$$

SEE (18)

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B) MOMENTUM CONSTRAINT (ONLY r-COMPONENT IS NONTRIVIAL)

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$$D_i K^i{}_r = \partial_i K^i{}_r + \Gamma^i{}_{mi} K^m{}_r - \Gamma^m{}_{ri} K^i{}_m$$

$$= K^r{}_r{}' + 2\Gamma^\theta{}_{r\theta}\left(K^r{}_r - K^\theta{}_\theta\right)$$

$$D_r K = \left(K^r{}_r + 2K^\theta{}_\theta\right)'$$

THEN WE HAVE FROM (7) AND (27)

$$K^\theta{}_\theta{}' + \frac{(rb)'}{rb}\left(K^\theta{}_\theta - K^r{}_r\right) = 4\pi \frac{\Phi\Pi}{a} \quad (32)$$

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THEN WE HAVE FROM (2) AND (27)

$$\boxed{K^\theta{}_\theta{}' + \frac{(rb)'}{rb}\left(K^\theta{}_\theta - K^r{}_r\right) = 4\pi \frac{\Phi \Pi}{a}} \qquad (32)$$

c) EVOLUTION EQUATIONS FOR γ_{ij} (a, b)

• FOLLOW DIRECTLY FROM (11), RECALL, CAN BE VIEWED AS DEF^{N} OF $K^i{}_j$

$$\dot a = -\alpha a K^r{}_r + (a\beta)' \qquad (33)$$

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$$\boxed{K^{\theta}{}_{\theta}{}' + \frac{(rb)'}{rb}\left(K^{\theta}{}_{\theta} - K^{r}{}_{r}\right) = 4\pi\frac{\Phi\Pi}{a}} \qquad (32)$$

c) EVOLUTION EQUATIONS FOR γ_{ij} (a, b)

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PHY 387N SPHERICAL SYMMETRY ⑤

$$\dot{K}^\theta{}_\theta = \beta K^\theta{}_\theta{}' + \frac{\alpha}{\ldots} - \frac{1}{\ldots}\left(\alpha r b \, (rb)'\right)' + \alpha K K^\theta{}_\theta$$

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PHY 387N SPHERICAL SYMMETRY (5)

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PHY 387N SPHERICAL SYMMETRY ⑤

$$\boxed{\dot{K}^\theta{}_\theta = \beta K^\theta{}_\theta{}' + \frac{\alpha}{(rb)^2} - \frac{1}{a(rb)^2}\left(\frac{\alpha rb}{a}(rb)'\right)' + \alpha KK^\theta{}_\theta \qquad (36)}$$

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PHY 387N SPHERICAL SYMMETRY 5

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PHY 387N SPHERICAL SYMMETRY

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MASSLESS KLEIN GORDON EQUATION

• NEED E.O.M. FOR Φ AND Π

• RECALL DEF^{N} OF Π, (27)

$$\Pi = \frac{a}{\alpha}\left(\dot{\phi} - \beta\phi'\right)$$

$$\rightarrow \quad \dot{\phi} = \frac{\alpha}{a}\Pi + \beta\phi' = \frac{\alpha}{a}\Pi + \beta\,\Phi$$

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MASSLESS KLEIN GORDON EQUATION

- NEED E.O.M. FOR Φ AND Π

- RECALL DEF^{N} OF Π, (29)

$$\Pi = \frac{a}{\alpha}\left(\dot{\phi} - \beta \phi'\right)$$

$$\rightarrow \quad \dot{\phi} = \frac{\alpha}{a}\Pi + \beta \phi' = \frac{\alpha}{a}\Pi + \beta \Phi$$

- BUT $\dot{\phi}' = \dot{\Phi}$, SO

$$\boxed{\dot{\Phi} = \left(\beta \Phi + \frac{\alpha}{a}\Pi\right)' \qquad (32)}$$

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$$\Box \phi = 0 \rightarrow \partial_\mu \left(\sqrt{-g}\, g^{\mu\nu} \partial_\nu \phi \right) = 0$$

$$\rightarrow \partial_t \left(\sqrt{-g}\, g^{\nu t} \partial_\nu \phi \right) + \partial_r \left(\sqrt{-g}\, g^{\nu r} \partial_\nu \phi \right)$$

$$= \partial_t \left(\alpha a r^2 b^2 \left(-\alpha^{-2} \dot{\phi} + \lambda \alpha^{-2} \phi' \right) \right)$$

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$$\dot{\Phi} = \left(\beta \Phi + \frac{\alpha}{a} \Pi \right)' \qquad (32)$$

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$$\Box\phi = 0 \rightarrow \partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\partial_\nu\phi\right) = 0$$

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$$= \partial_t\left(\alpha a r^2 b_0^2\left(-\alpha^{-2}\dot{\phi} + \beta\alpha^{-2}\phi'\right)\right)$$

$$+ \partial_r\left(\alpha a r^2 b^2\left(\left(a^{-2} - \beta^2\alpha^{-2}\right)\phi' + \beta\alpha^{-2}\dot{\phi}\right)\right)$$

$$= 0$$

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$$\rightarrow \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

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$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\quad \right)$$

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WRITE AS $(r^2b^2)\dot{\Pi} + \dot{(r^2b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\dot{\Pi} = \ldots$$

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$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

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$$\to \left(r^2 b^2 \Pi\right)^{\cdot} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\cdot}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\dot{\Pi} = \frac{1}{\ }\left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

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$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\partial_\nu\phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\partial_\nu\phi\right)$$

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$$= 0$$

$$\to \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

WRITE AS $(r^2b^2)\dot{\Pi} + \dot{(r^2b^2)}\,\Pi$ AND USE

EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\dot{\Pi} = \frac{1}{\ }\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{\ }\Phi\right)\right)'$$

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$$\to \partial_t \left(\sqrt{-g}\, g^{t\nu} \partial_\nu \phi \right) + \partial_r \left(\sqrt{-g}\, g^{r\nu} \partial_\nu \phi \right)$$

$$= \partial_t \left(\alpha a r^2 b^2 \left(-\alpha^{-2} \dot{\phi} + \beta \alpha^{-2} \phi' \right) \right)$$

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$$\to \dot{\left(r^2 b^2 \Pi \right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)'$$

↳ WRITE AS $(r^2 b^2) \dot{\Pi} + \dot{(r^2 b^2)}\, \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{\;} \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)'}$$

$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2\left(-\alpha^{-2}\dot{\phi} + \beta\alpha^{-2}\phi'\right)\right)$$

$$+ \partial_r\left(\alpha a r^2 b^2\left(\left(a^{-2} - \beta^2\alpha^{-2}\right)\phi' + \beta\alpha^{-2}\dot{\phi}\right)\right)$$

$$= 0$$

$$\to \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

WRITE AS $(r^2b^2)\dot{\Pi} + \dot{(r^2b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{\quad}\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'}$$

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$$\rightarrow \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2\left(-\alpha^{-2}\dot{\phi} + \beta\alpha^{-2}\phi'\right)\right)$$

$$+ \partial_r\left(\alpha a r^2 b^2\left(\left(a^{-2} - \beta^2\alpha^{-2}\right)\phi' + \beta\alpha^{-2}\dot{\phi}\right)\right)$$

$$= 0$$

$$\rightarrow \left(r^2 b^2 \Pi\right)^{\cdot} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

↳ WRITE AS $(r^2b^2)\dot{\Pi} + (r^2b^2)^{\cdot}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\dot{\Pi} = \frac{1}{\ldots}\left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

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$$\rightarrow \partial_t\left(\sqrt{-g}\, g^{t\nu}\partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\partial_\nu\phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2\left(-\alpha^{-2}\dot\phi + \beta\alpha^{-2}\phi'\right)\right)$$

$$+ \partial_r\left(\alpha a r^2 b^2\left(\left(a^{-2} - \beta^2\alpha^{-2}\right)\phi' + \beta\alpha^{-2}\dot\phi\right)\right)$$

$$= 0$$

$$\rightarrow \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

WRITE AS $\dot{(r^2b^2)}\,\Pi + (r^2b^2)\,\dot\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot b$

$$\boxed{\dot\Pi = \frac{1}{\ldots}\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'}$$

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$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2\left(-\alpha^{-2}\dot{\phi} + \beta\alpha^{-2}\phi'\right)\right)$$

$$+ \partial_r\left(\alpha a r^2 b^2\left(\left(a^{-2} - \beta^2\alpha^{-2}\right)\phi' + \beta\alpha^{-2}\dot{\phi}\right)\right)$$

$$= 0$$

$$\to \left(r^2 b^2 \Pi\right)^{\cdot} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

$\hookrightarrow$ WRITE AS $(r^2b^2)\dot{\Pi} + \dot{(r^2b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{\quad}\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'}$$

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$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2 \left(-\alpha^{-2}\dot\phi + \beta\alpha^{-2}\phi'\right)\right)$$

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↳ WRITE AS $(r^2b^2)\dot\Pi + (r^2b^2)^{\cdot}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot b$

$$\dot\Pi = \frac{1}{\cdots}\left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

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$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\partial_\nu\phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\partial_\nu\phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2\left(-\alpha^{-2}\dot\phi + \beta\alpha^{-2}\phi'\right)\right)$$

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$$= 0$$

$$\to \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

WRITE AS $\left(r^2b^2\right)\dot\Pi + \dot{\left(r^2b^2\right)}\Pi$ AND USE

EVOLUTION EQUATION (39) FOR $\dot b$

$$\dot\Pi = \frac{1}{\ldots}\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

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$$= \partial_t \left(\alpha a r^2 b^2 \left(-\alpha^{-2} \dot\phi + \beta \alpha^{-2} \phi' \right) \right)$$

$$+ \partial_r \left(\alpha a r^2 b^2 \left(\left(a^{-2} - \beta^2 \alpha^{-2} \right) \phi' + \beta \alpha^{-2} \dot\phi \right) \right)$$

$$= 0$$

$$\to \dot{\left(r^2 b^2 \Pi \right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)'$$

WRITE AS $(r^2 b^2) \dot\Pi + \dot{(r^2 b^2)} \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot b$

$$\dot\Pi = \frac{1}{\ } \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)'$$

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$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\partial_\nu\phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\partial_\nu\phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2\left(-\alpha^{-2}\dot\phi + \beta\alpha^{-2}\phi'\right)\right)$$

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$$\to \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

WRITE AS $(r^2b^2)\dot\Pi + \dot{(r^2b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot b$

$$\dot\Pi = \frac{1}{\ } \left(r^2b^2\left(\beta\Pi + \frac{\alpha}{\ }\Phi\right)\right)'$$

$$\rightarrow \partial_t\left(\sqrt{-g}\, g^{t\nu}\partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\partial_\nu \phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2\left(-\alpha^{-2}\dot\phi + \beta\alpha^{-2}\phi'\right)\right)$$

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$$\rightarrow \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

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$$= \partial_t(\alpha a r^2 b^2(-\alpha^{-2}\dot\phi + \beta\alpha^{-2}\phi'))$$

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$$= 0$$

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↳ WRITE AS $(r^2b^2)\dot{\Pi} + \dot{(r^2b^2)}\,\Pi$ AND USE

EVOLUTION EQUATION (39) FOR $\dot{b}$

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$$\rightarrow \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

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WRITE AS $\dot{(r^2b^2)}\,\Pi + (r^2b^2)\,\dot\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot b$

$$\Pi = \frac{1}{\ \ }\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{\ }\Phi\right)\right)'$$

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WRITE AS $(r^2b^2)\dot{\Pi} + \dot{(r^2b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

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$$\to \partial_t\left(\sqrt{-g}\, g^{t\nu}\, \partial_\nu \phi\right) + \partial_r\left(\sqrt{-g}\, g^{r\nu}\, \partial_\nu \phi\right)$$

$$= \partial_t\left(\alpha a r^2 b^2 \left(-\alpha^{-2}\dot{\phi} + \beta\alpha^{-2}\phi'\right)\right)$$

$$+ \partial_r\left(\alpha a r^2 b^2 \left(\left(a^{-2} - \beta^2\alpha^{-2}\right)\phi' + \beta\alpha^{-2}\dot{\phi}\right)\right)$$

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$$\to \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

WRITE AS $\left(r^2b^2\right)\dot{\Pi} + \dot{\left(r^2b^2\right)}\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\dot{\Pi} = \frac{1}{\ }\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

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$$\rightarrow \partial_t \left(\sqrt{-g}\, g^{t\nu} \partial_\nu \phi \right) + \partial_r \left(\sqrt{-g}\, g^{r\nu} \partial_\nu \phi \right)$$

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$$+ \partial_r \left(\alpha a r^2 b^2 \left(\left(a^{-2} - \beta^2 \alpha^{-2} \right) \phi' + \beta \alpha^{-2} \dot{\phi} \right) \right)$$

$$= 0$$

$$\rightarrow \left(r^2 b^2 \Pi \right)^{\cdot} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)'$$

$\hookrightarrow$ WRITE AS $(r^2b^2)\dot{\Pi} + (r^2b^2)^{\cdot}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\Pi = \frac{1}{\ldots} \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{\ldots} \Phi \right) \right)'$$

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$= 0$

$$\rightarrow (r^2 b^2 \Pi)^{\cdot} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\cdot}\, \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (32)$$

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$$\rightarrow (r^2 b^2 \dot{\pi}) = (r^2 b^2 (\beta \pi + \frac{\alpha}{a} \Phi))'$$

WRITE AS $(r^2 b^2)\dot{\pi} + (r^2 b^2)^{\circ} \pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \pi + \frac{\alpha}{a} \Phi \right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb} \right) \pi} \quad (32)$$

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$$\rightarrow (r^2 b^2 \Pi)^{\cdot} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

↳ WRITE AS $(r^2b^2)\dot{\Pi} + (r^2b^2)^{\circ}\,\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\mathring{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (3e)$$

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$$\rightarrow \left(r^2 b^2 \dot{\Pi}\right) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + (\dot{r^2 b^2})\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2\left(\beta \Pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (3E)$$

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WRITE AS $(r^2 b^2)\dot{\Pi} + (\dot{r^2 b^2})\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (3E)$$

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WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\, \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (52)$$

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$$\rightarrow \left(r^2 b^2 \Pi\right)^{\bullet} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\, \Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (3E)$$

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$$\rightarrow \left(r^2 b^2 \Pi\right)^{\bullet} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\, \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (32)$$

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$$\rightarrow (r^2 b^2 \dot{\Pi}) = (r^2 b^2 (\beta \Pi + \frac{\alpha}{a} \Phi))'$$

$\hookrightarrow$ WRITE AS $(r^2 b^2)\dot{\Pi} + (\dot{r^2 b^2})\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (3E)$$

$$\rightarrow \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2\left(\beta \Pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (3e)$$

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$$\rightarrow \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (38)$$

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WRITE AS $\left(r^2 b^2\right) \dot{\Pi} + \left(r^2 b^2\right)^{\circ} \Pi$ AND USE

EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi \qquad (3e)}$$

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$$\to \dot{(r^2 b^2 \Pi)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi \qquad (3e)}$$

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$$\rightarrow \left(r^2 b^2 \pi\right)^{\boldsymbol{\cdot}} = \left(r^2 b^2 \left(\beta \pi + \frac{\alpha}{a} \Phi\right)\right)'$$

$\hookrightarrow$ WRITE AS $(r^2 b^2)\dot{\pi} + (\dot{r^2 b^2})\pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta \frac{(rb)'}{rb}\right)\pi} \qquad (3e)$$

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$$\rightarrow \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\phi}{}_{\phi} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (52)$$

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$$\rightarrow \quad \left(r^2 b^2 \Pi\right)^{\cdot} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\cdot}\, \Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta \frac{(rb)'}{rb}\right)\Pi \qquad (3b)}$$

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$$\rightarrow (r^2 b^2 \dot{\Pi}) = (r^2 b^2 (\beta \Pi + \frac{\alpha}{a} \Phi))'$$

$\hookrightarrow$ WRITE AS $(r^2 b^2) \dot{\Pi} + (r^2 \dot{b^2}) \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2} \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)' + 2 \left(\alpha K^\theta{}_\theta - \beta \frac{(rb)'}{rb} \right) \Pi} \quad (3E)$$

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$$\to \left(r^2 b^2 \Pi\right)^{\cdot} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\cdot}\,\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (3E)$$

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$$\rightarrow \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (3e)$$

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$$\rightarrow (r^2 b^2 \dot{\Pi}) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 \dot{b}^2)\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

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$$\rightarrow (r^2 b^2 \Pi)^{\bullet} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)'$$

$\hookrightarrow$ WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\, \Pi$ AND USE

EVOLUTION EQUATION (34) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2} \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb} \right) \Pi} \quad (32)$$

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$$\rightarrow \left(\dot{r^2 b^2 \Pi}\right) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

$\hookrightarrow$ WRITE AS $(r^2b^2)\dot{\Pi} + (\dot{r^2b^2})\Pi$ AND USE

EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2b^2}\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta\frac{(rb)'}{rb}\right)\Pi} \qquad (3E)$$

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$$\rightarrow (r^2 b^2 \dot{\Pi}) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

$\hookrightarrow$ WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\,\Pi$ AND USE EVOLUTION EQUATION (34) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi \qquad (35)}$$

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$$\rightarrow \left(r^2 b^2 \dot{\Pi}\right) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (3E)$$

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$$\rightarrow \left(r^2 b^2 \dot{\Pi}\right) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (\dot{r^2 b^2})\Pi$ AND USE

EVOLUTION EQUATION (3A) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (3E)$$

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$$\rightarrow (r^2 b^2 \Pi)^{\bullet} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ} \Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \quad (3E)$$

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$$\rightarrow \left(r^2 b^2 \Pi\right)^{\bullet} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\, \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

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$$\rightarrow \left(\dot{r^2 b^2 \Pi}\right) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + (\dot{r^2 b^2})\Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (3E)$$

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$$\rightarrow \dot{(r^2 b^2 \Pi)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

↳ WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta\frac{(rb)'}{rb}\right)\Pi} \quad (3e)$$

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$$\rightarrow \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a}\Phi\right)\right)'$$

↳ WRITE AS $(r^2b^2)\dot{\Pi} + \overset{\circ}{(r^2b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (34) FOR $\dot{b}$

$$\boxed{\overset{\circ}{\Pi} = \frac{1}{r^2b^2}\left(r^2b^2\left(\beta\Pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^\theta{}_\theta - \beta\frac{(rb)'}{rb}\right)\Pi \qquad (35)}$$

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$$\to \dot{\left(r^2 b^2 \Pi\right)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + \dot{(r^2 b^2)}\,\Pi$ AND USE EVOLUTION EQUATION (34) FOR $\dot{b}$

$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi} \qquad (35)$$

$$\rightarrow \dot{\left(r^2 b^2 \pi\right)} = \left(r^2 b^2 \left(\beta \pi + \frac{\alpha}{a} \Phi\right)\right)'$$

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$$\boxed{\mathring{\pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \pi + \frac{\alpha}{a}\Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\pi \qquad (3e)}$$

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$$\rightarrow (r^2 b^2 \Pi)^{\cdot} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2) \dot{\Pi} + (r^2 b^2)^{\cdot} \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

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$$\rightarrow \dot{(r^2 b^2 \Pi)} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2) \dot{\Pi} + (r^2 \dot{b}^2) \Pi$ AND USE

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$$\rightarrow (r^2 b^2 \dot{\Pi}) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2) \dot{\Pi} + (r^2 b^2)^{\circ}\, \Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

$$\boxed{\overset{\circ}{\Pi} = \frac{1}{r^2 b^2} \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)' + 2 \left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb} \right) \Pi} \qquad (3E)$$

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$$\rightarrow \left(r^2 b^2 \dot{\Pi}\right) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 \dot{b}^2)\Pi$ AND USE

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$$\rightarrow \left(r^2 b^2 \Pi\right)^{\bullet} = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2 b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\, \Pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

$$\boxed{\mathring{\Pi} = \frac{1}{r^2 b^2}\left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)' + 2\left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb}\right)\Pi \qquad (52)}$$

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$$\rightarrow \left(r^2 b^2 \pi\right)^{\circ} = \left(r^2 b^2 \left(\beta \pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $\left(r^2 b^2\right)\dot{\pi} + \left(r^2 b^2\right)^{\circ} \pi$ AND USE EVOLUTION EQUATION (39) FOR $\dot{b}$

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$$\rightarrow (r^2 b^2 \dot{\Pi}) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)'$$

WRITE AS $(r^2 b^2) \dot{\Pi} + (\dot{r^2 b^2}) \Pi$ AND USE

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$$\boxed{\dot{\Pi} = \frac{1}{r^2 b^2} \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi \right) \right)' + 2 \left(\alpha K^{\theta}{}_{\theta} - \beta \frac{(rb)'}{rb} \right) \Pi} \quad (32)$$

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$$\longrightarrow \left(r^2 b^2 \dot{\Pi}\right) = \left(r^2 b^2 \left(\beta \Pi + \frac{\alpha}{a} \Phi\right)\right)'$$

WRITE AS $(r^2b^2)\dot{\Pi} + (r^2 b^2)^{\circ}\,\Pi$ AND USE EVOLUTION EQUATION (3a) FOR $\dot{b}$

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