Title: PSI 2015/2016 More/Beyond Standard Model - Lecture 14

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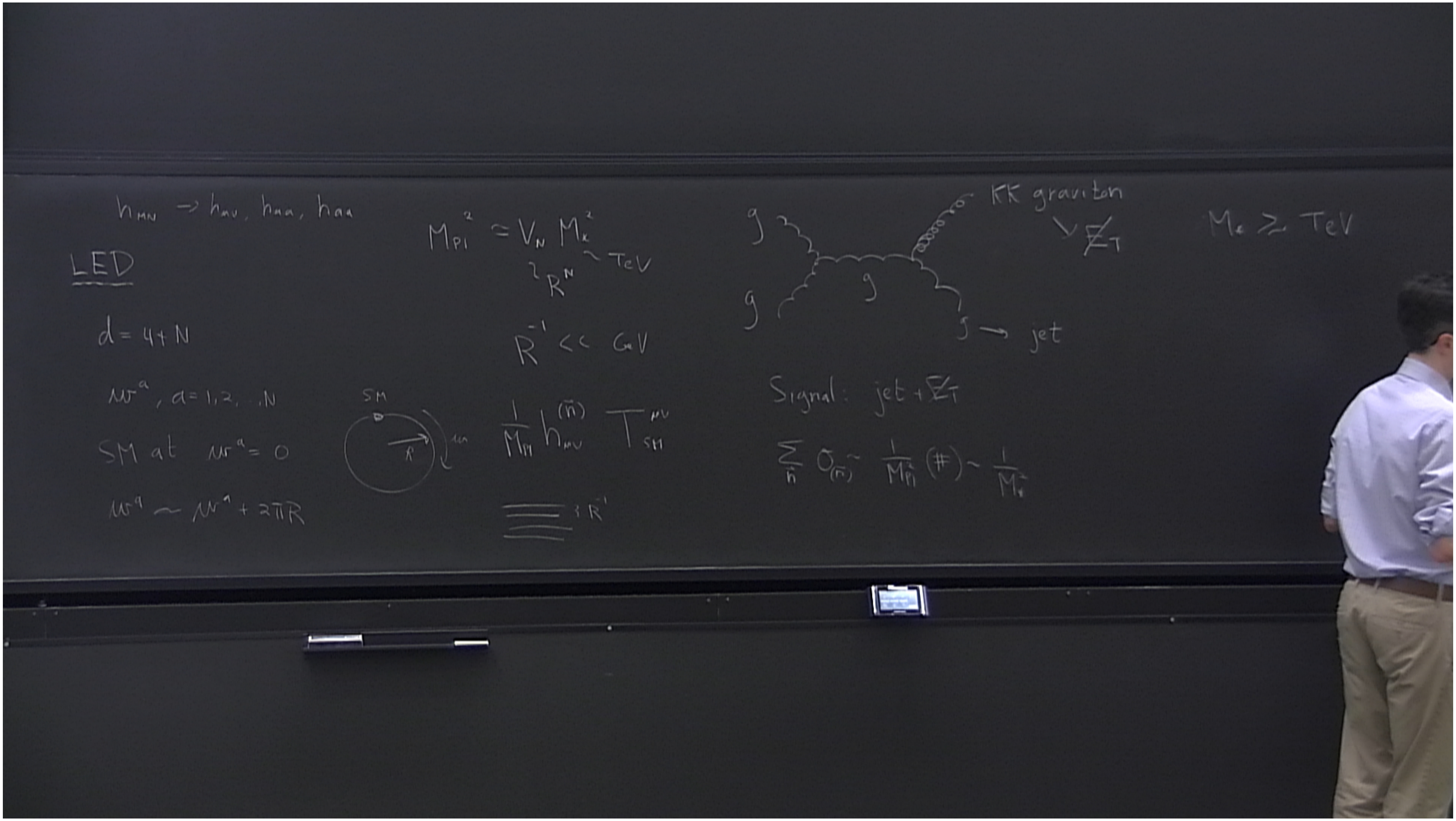
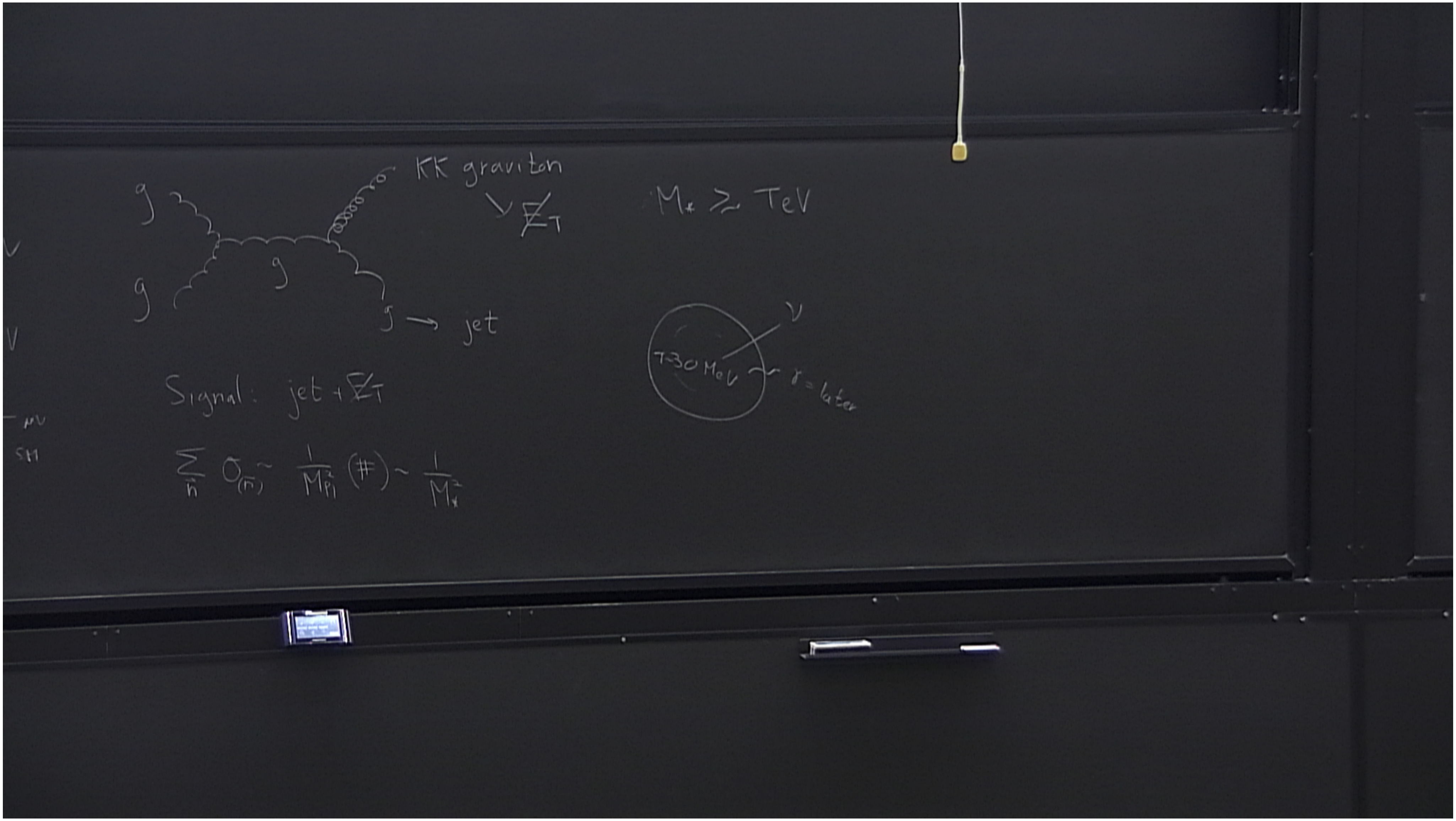
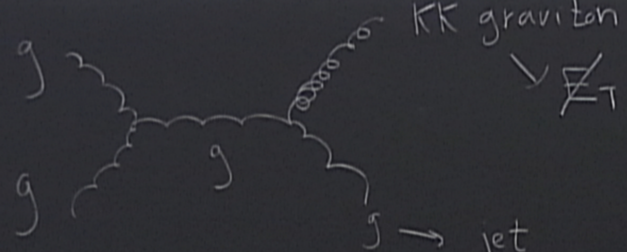
Abstract:



h_MN → h_μν, h_μa, h_aa
LED
d = 4 + N
w^a, a = 1, 2, .. N
SM at w^a = 0
w^a ~ w^a + 2πR
SM
R
M_Pl^2 ≃ V_N M_*^2
~ R^N
~ TeV
R^-1 << GeV
1/M_Pl h_μν^(n) T_SM^μν
R^-1
g
g
g
g → jet
KK graviton
E̸_T
M_* ≳ TeV
Signal: jet + E̸_T
Σ_n σ_(n) ~ 1/M_Pl^2 (#) ~ 1/M_*^2

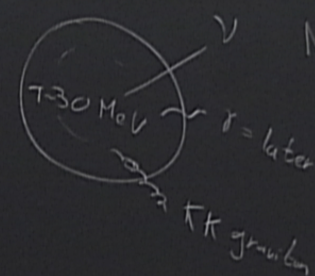

KK graviton
$\to \not{E}_T$
g
g
g
$g \to$ jet
Signal: jet + $\not{E}_T$
$\sum_n \sigma_{(n)} \sim \frac{1}{M_{Pl}^2}(\#) \sim \frac{1}{M_*^2}$
$M_* \gtrsim$ TeV
T~30 MeV
ν
γ = later



$M_* \gtrsim$ TeV

$N=2$; $M_* \gtrsim 10$ TeV

$N=3$, $M_* \gtrsim 2$ TeV



Signal: jet + $\not{E}_T$

$$\sum_{\vec{n}} \mathcal{O}_{(\vec{n})} \sim \frac{1}{M_{Pl}^2}(\#) \sim \frac{1}{M_*^2}$$

Randall-Sundrum (RS)

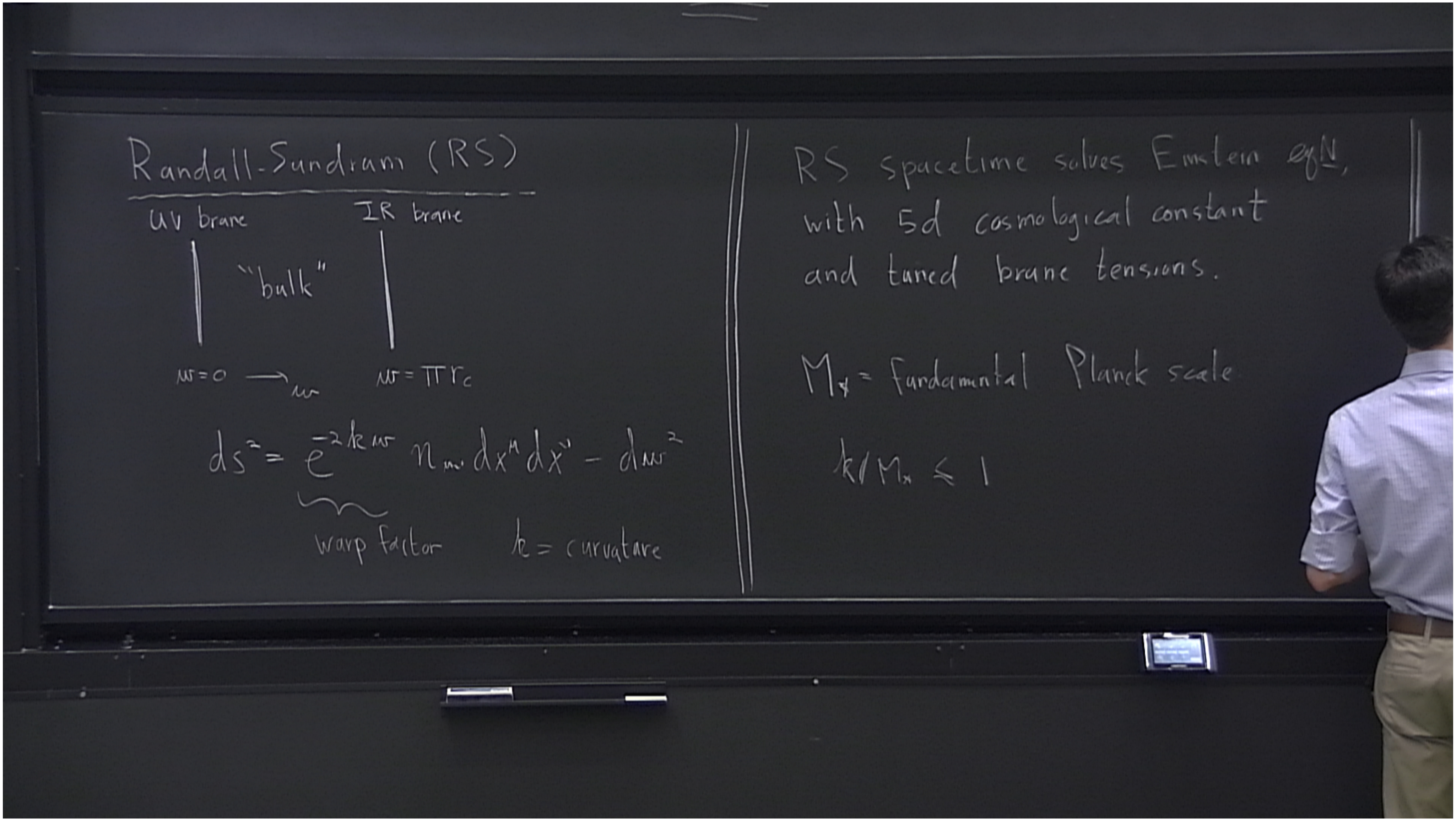
UV brane — $w = 0 \longrightarrow w$

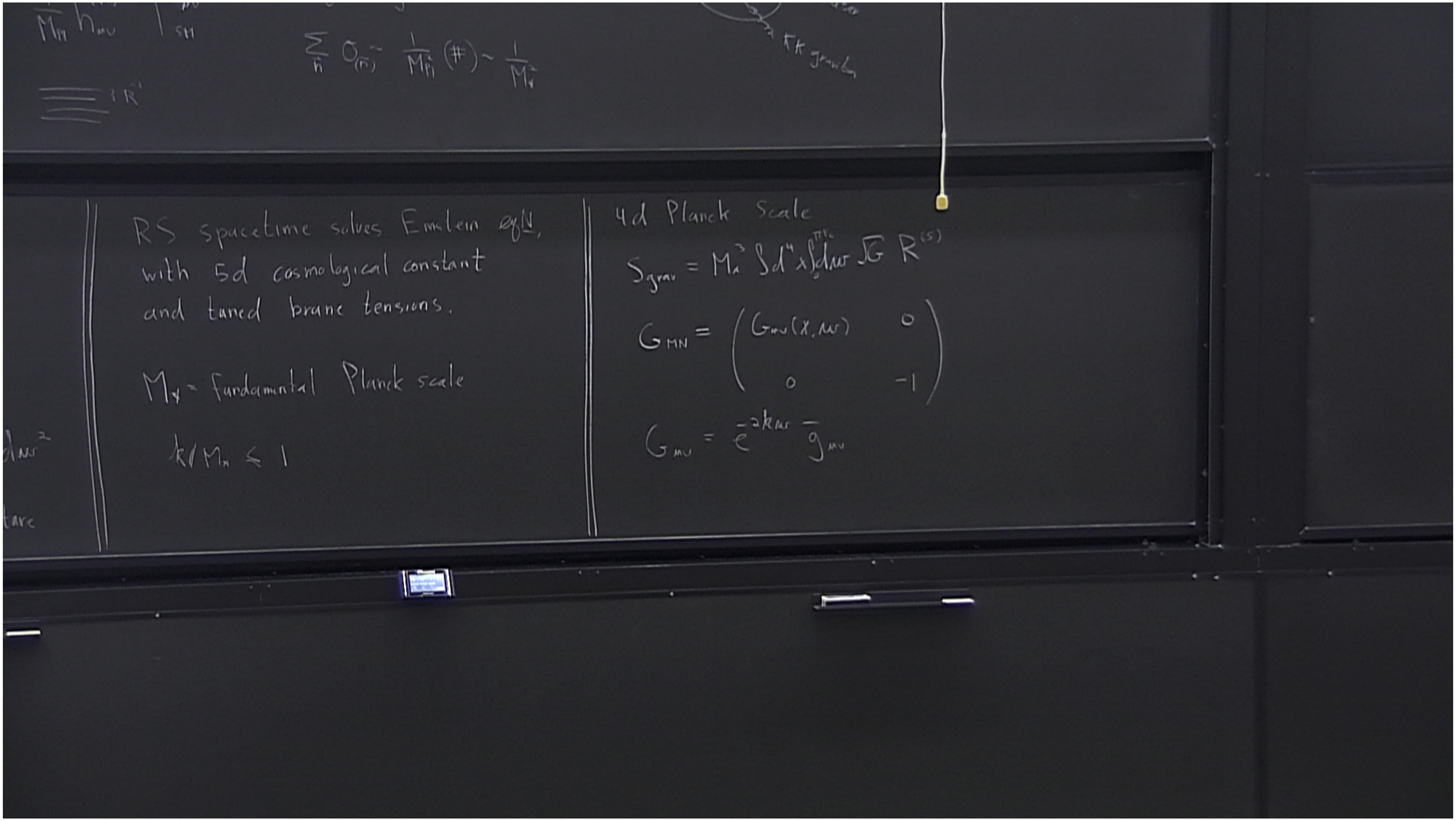
IR brane — $w = \pi r_c$

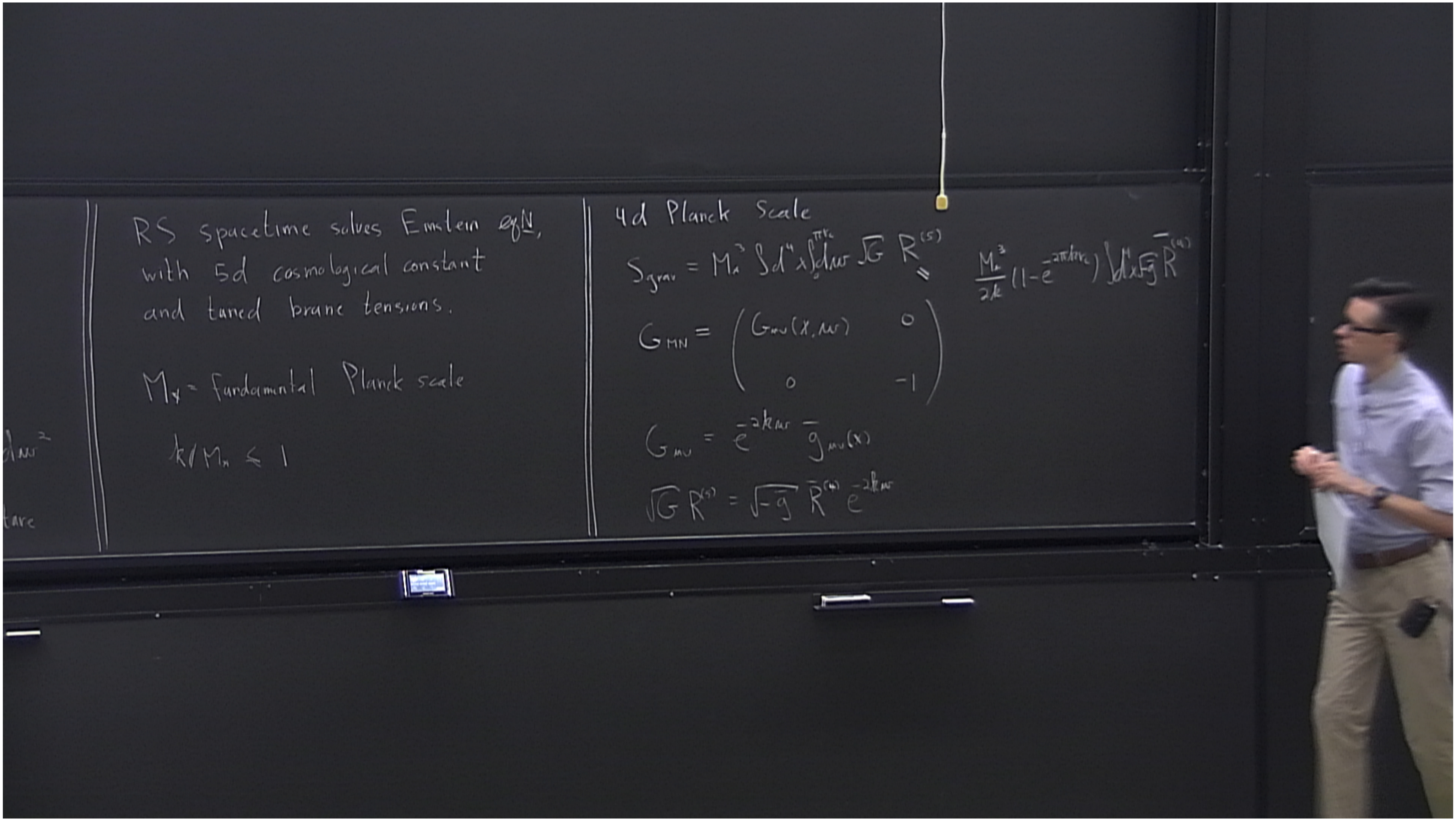
$$ds^2 = \underbrace{e^{-2kw}}_{\text{warp factor}} \eta_{\mu\nu} dx^\mu dx^\nu - dw^2$$

k = curvature

RS sp


Randall-Sundrum (RS)
UV brane
IR brane
"bulk"
$w = 0 \longrightarrow w$
$w = \pi r_c$
$ds^2 = e^{-2kw} \eta_{\mu\nu} dx^\mu dx^\nu - dw^2$
warp factor
k = curvature
RS spacetime solves Einstein eqN, with 5d cosmological constant and tuned brane tensions.
M_* = fundamental Planck scale
$k/M_* \lesssim 1$


$\sum_n O_{(n)} \sim \frac{1}{M_{Pl}^2}(\#) \sim \frac{1}{M_*^2}$
KK graviton
RS spacetime solves Einstein eqN, with 5d cosmological constant and tuned brane tensions.
M_* = fundamental Planck scale
$k/M_* \lesssim 1$
4d Planck Scale
$S_{grav} = M_*^3 \int d^4x \int_0^{\pi r_c} dw \sqrt{G}\, R^{(5)}$
$G_{MN} = \begin{pmatrix} G_{\mu\nu}(x,w) & 0 \\ 0 & -1 \end{pmatrix}$
$G_{\mu\nu} = e^{-2kw}\, \bar{g}_{\mu\nu}$


RS spacetime solves Einstein eqN, with 5d cosmological constant and tuned brane tensions.
$M_* =$ fundamental Planck scale
$k/M_* \leq 1$
4d Planck Scale
$S_{grav} = M_*^3 \int d^4x \int_0^{\pi r_c} dw \sqrt{G}\, R^{(5)} = \frac{M_*^3}{2k}(1-e^{-2\pi k r_c}) \int d^4x \sqrt{-\bar{g}}\, \bar{R}^{(4)}$
$G_{MN} = \begin{pmatrix} G_{\mu\nu}(x,w) & 0 \\ 0 & -1 \end{pmatrix}$
$G_{\mu\nu} = e^{-2kw}\, \bar{g}_{\mu\nu}(x)$
$\sqrt{G}\, R^{(5)} = \sqrt{-\bar{g}}\, \bar{R}^{(4)} e^{-2kw}$

RS spacetime solves Einstein eq$^{\underline{N}}$, with 5d cosmological constant and tuned brane tensions.

M_* = fundamental Planck scale

$k/M_* \lesssim 1$

4d Planck Scale

$$S_{grav} = M_*^3 \int d^4x \int_0^{\pi r_c} d\omega \sqrt{G}\, R^{(5)} \Rightarrow \underbrace{\frac{M_*^3}{2k}\left(1-e^{-2\pi k r_c}\right)}_{\frac{M_{Pl}^2}{2}} \underbrace{\int d^4x \sqrt{\bar{g}}\, \bar{R}^{(4)}}_{4d\text{-}EH}$$

$$G_{MN} = \begin{pmatrix} G_{\mu\nu}(x,\omega) & 0 \\ 0 & -1 \end{pmatrix}$$

$$G_{\mu\nu} = e^{-2k\omega}\, \bar{g}_{\mu\nu}(x)$$

$$\sqrt{G}\, R^{(5)} = \sqrt{-\bar{g}}\, \bar{R}^{(4)} e^{-2k\omega}$$

$$\underset{2.4\times10^{18}\,GeV}{\overset{}{M_{Pl}^2}} = \frac{M_*^3}{k}\left(1-e^{-2\pi r_c k}\right)$$

negligible

$d\omega^2$

$w=0 \longrightarrow w \qquad w=\pi r_c$

$$ds^2 = e^{-2kw}\,\eta_{\mu\nu}\,dx^\mu dx^\nu - dw^2$$

warp factor $\qquad k$ = curvature

M_* = fundamental Planck scale

$k/M_* \lesssim 1$

$G_{MN} = \begin{pmatrix} \cdots & \\ 0 & -1 \end{pmatrix}$

$$G_{\mu\nu} = e^{-2kw}\,\bar{g}_{\mu\nu}(x)$$

$$\sqrt{G}\,R^{(5)} = \sqrt{-\bar{g}}\,\bar{R}^{(4)}\,e^{-2kw}$$

$M_{Pl}^2 = \ldots$

Warping and the Higgs

$$G = \det(G_{MN}) = \left(e^{-2kw}\right)^4 \cdot 1 \quad , \quad G^{\mu\nu} = e^{+2kw}\eta^{\mu\nu}dx_\mu dx_\nu - dw^2$$

H = Higgs field, on IR brane

$$V(|H|) = -\mu^2|H|^2 + \frac{\lambda}{2}|H|^4$$

$$S_H = \int d^4x \int_0^{\pi r_c} dw\,\sqrt{G}\left[G^{\mu\nu}\partial_\mu H^\dagger \partial_\nu H - V(|H|)\right]\delta(w-\pi r_c)$$

$$= \int d^4x\, e^{-4k\pi r_c}\left[e^{2k\pi r_c}|\partial H|^2 - V(|H|)\right] \qquad \boxed{H = e^{\pi k r_c}\tilde{H}}$$

$$= \int d^4x\left[|\partial\tilde{H}|^2 - e^{-4\pi k r_c}\,V\!\left(e^{\pi k r_c}|\tilde{H}|\right)\right]$$

"bulk"

$w = 0 \longrightarrow w \qquad w = \pi r_c$

$$ds^2 = \underbrace{e^{-2kw}}_{\text{warp factor}} \eta_{\mu\nu} dx^\mu dx^\nu - dw^2$$

k = curvature

and tuned brane tensions.

M_* = fundamental Planck scale

$k/M_* \lesssim 1$

$$G_{MN} = \begin{pmatrix} G_{\mu\nu}(x, w) & 0 \\ 0 & -1 \end{pmatrix}$$

$$G_{\mu\nu} = e^{-2kw} \bar{g}_{\mu\nu}(x)$$

$$\sqrt{G} R^{(5)} = \sqrt{-\bar{g}} \bar{R}^{(4)} e^{-2kw}$$

$2k$ 4d-EH

$$\frac{M_{Pl}^2}{2}$$

$$\underbrace{M_{Pl}^2}_{\simeq 4\times 10^{18}\ \text{GeV}} = \frac{M_*^3}{k}\left(1 - e^{-2\pi r_c k}\right)$$

negligible

Warping and the Higgs

$$G = \det(G_{MN}) = \left(e^{-2kw}\right)^4 \cdot 1, \quad G^{\mu\nu} = e^{+2kw} \eta^{\mu\nu} dx_\mu dx_\nu - dw^2$$

H = Higgs field, on IR brane

$$S_H = \int d^4x \int_0^{\pi r_c} dw \sqrt{G} \left[G^{\mu\nu} \partial_\mu H^\dagger \partial_\nu H - V(|H|) \right] \delta(w - \pi r_c)$$

$$= \int d^4x\, e^{-4k\pi r_c} \left[e^{2k\pi r_c} |\partial H|^2 - V(|H|) \right]$$

$$= \int d^4x \left[|\partial \tilde{H}|^2 - e^{-4\pi k r_c} V(e^{\pi k r_c} |\tilde{H}|) \right]$$

$$\boxed{H = e^{\pi k r_c} \tilde{H}}$$

$$V(|H|) = -\mu^2 |H|^2 + \frac{\lambda}{2} |H|^4$$

$$e^{-4\pi k r_c} V(e^{\pi k r_c} |\tilde{H}|) = -(\mu^2 e^{-2\pi k r_c}) |\tilde{H}|^2 + \frac{\lambda}{2} |\tilde{H}|^4$$

$$\equiv V_{phys}(|\tilde{H}|)$$

$$\mu \sim M_*$$

$$M_{eff} \sim M_* \underbrace{e^{-\pi k r_c}}_{11\text{-}12} \sim \text{TeV}$$

KK excitations

$$z = \frac{1}{k} e^{kw}, \quad z \in [\underset{k^{-1}}{L_0}, \underset{k^{-1}e^{\pi k r_c}}{L_1}]$$

x^{3} #

$$\frac{L_1}{L_0} = e^{\overbrace{\pi k r_c}^{11}}$$

$$ds^2 = \left(\frac{L_0}{z}\right)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right) = \left(\frac{L_0}{z}\right)^2 \eta_{MN} dx^M dx^N$$

$e^{-\pi k r_c}\langle \hat{H} \rangle)]$

$\mu \sim M_*$

$M_{eff} \sim M_* e^{-\pi k r_c} \sim \text{TeV}$

$G^{MA} G^{NB} F_{MN} F_{AB}$

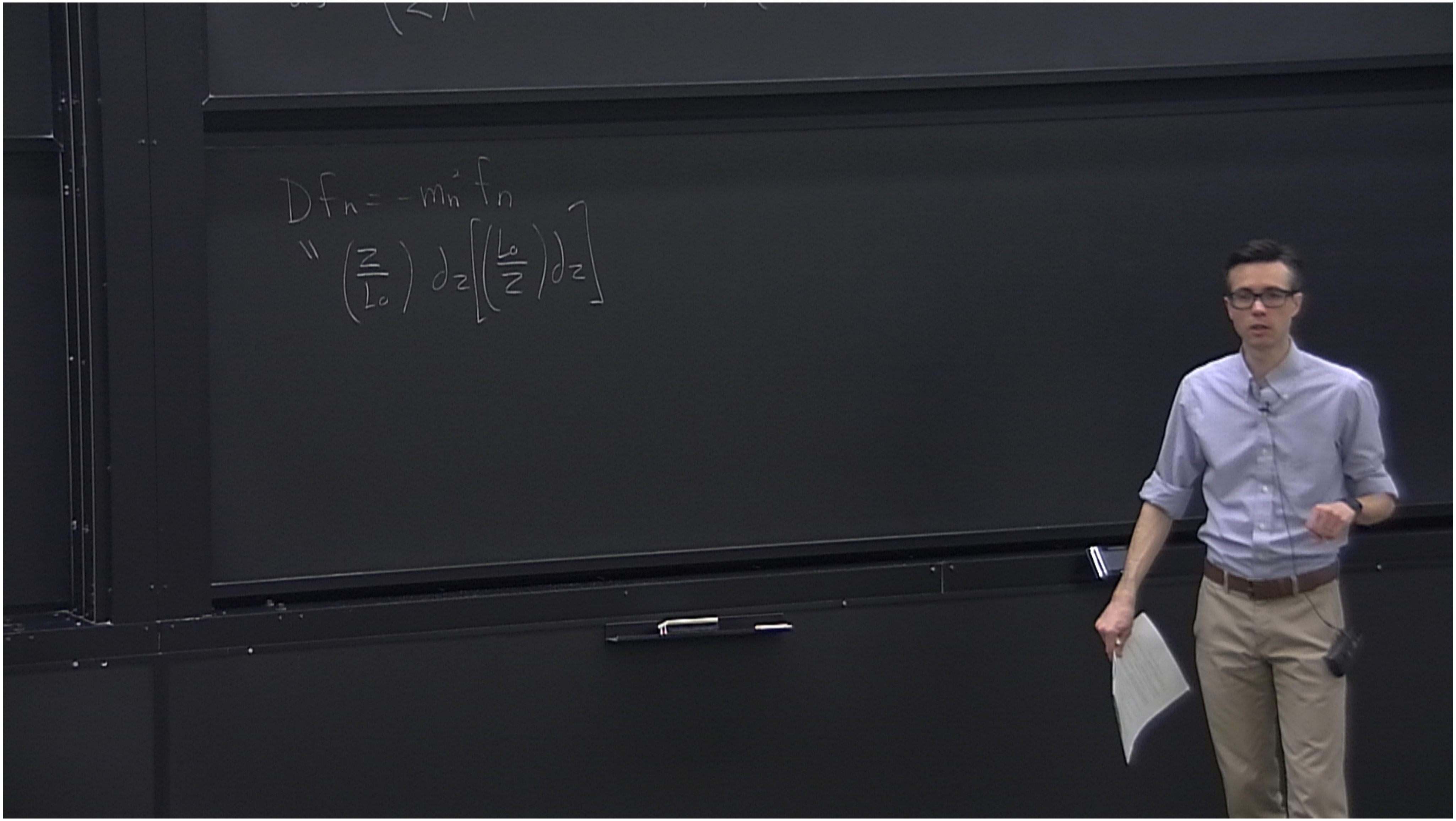
$\text{"} \partial_M A_N - \partial_N A_M$

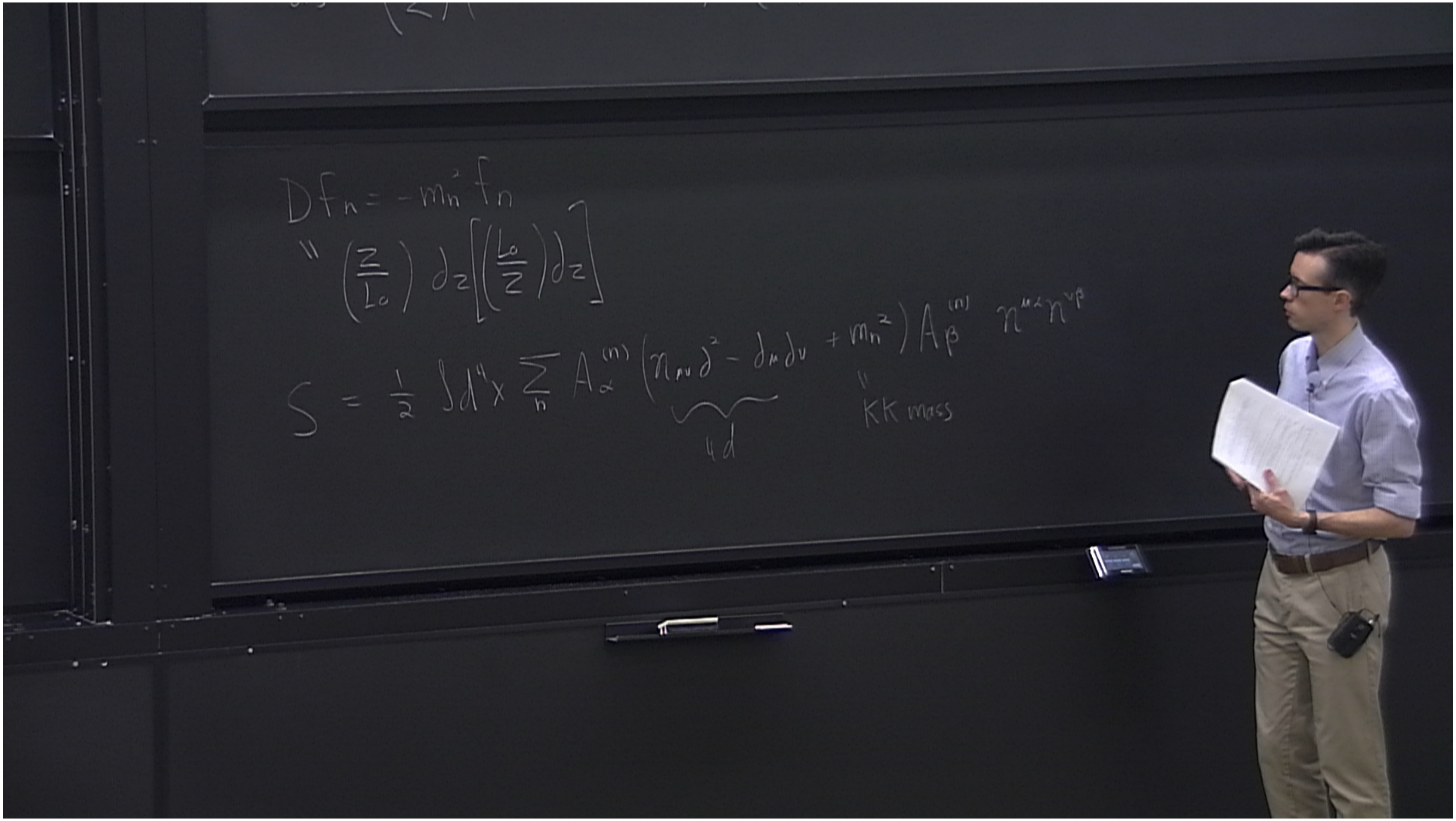
$$\rightarrow S = \frac{1}{2} \int d^4x \int_{L_0}^{L_1} dz \left(\frac{L_0}{z}\right) \Big(A_\alpha \left(\eta_{\mu\nu} \partial^2 - \partial_\mu \partial_\nu\right) A_\beta \eta^{\alpha\mu} \eta^{\beta\nu} - \left(\frac{z}{L_0}\right) A_\mu \, \partial_z \left[\left(\frac{L_0}{z}\right) \partial_z \right] A_\nu \eta^{\mu\nu} \Big)$$

$$A_\mu(x,z) = \sum_n A_\mu^{(n)}(x) \cdot f_n(z)$$

$$\int_{L_0}^{L_1} \underbrace{dz \left(\frac{L_0}{z}\right)}_{\text{measure}} \cdot f_n(z) f_m(z) = \delta_{mn}$$

A_M


$D f_n = - m_n^2 f_n$
$= \left(\frac{z}{L_0}\right) \partial_z \left[\left(\frac{L_0}{z}\right) \partial_z \right]$



$Df_n = -m_n^2 f_n$
$\parallel \left(\frac{z}{L_0}\right) \partial_z\left[\left(\frac{L_0}{z}\right)\partial_z\right]$
$S = \frac{1}{2}\int d^4x \sum_n A_\alpha^{(n)} (\underbrace{\eta_{\mu\nu}\partial^2 - \partial_\mu\partial_\nu}_{4d} + m_n^2) A_\beta^{(n)} \eta^{\mu\alpha}\eta^{\nu\beta}$
m_n^2 = KK mass