Title: PSI 2018/2019 - String Theory Review - Lecture 14

Speakers: Davide Gaiotto

Collection: PSI 2018/2019 - String Theory Review (Gaiotto)

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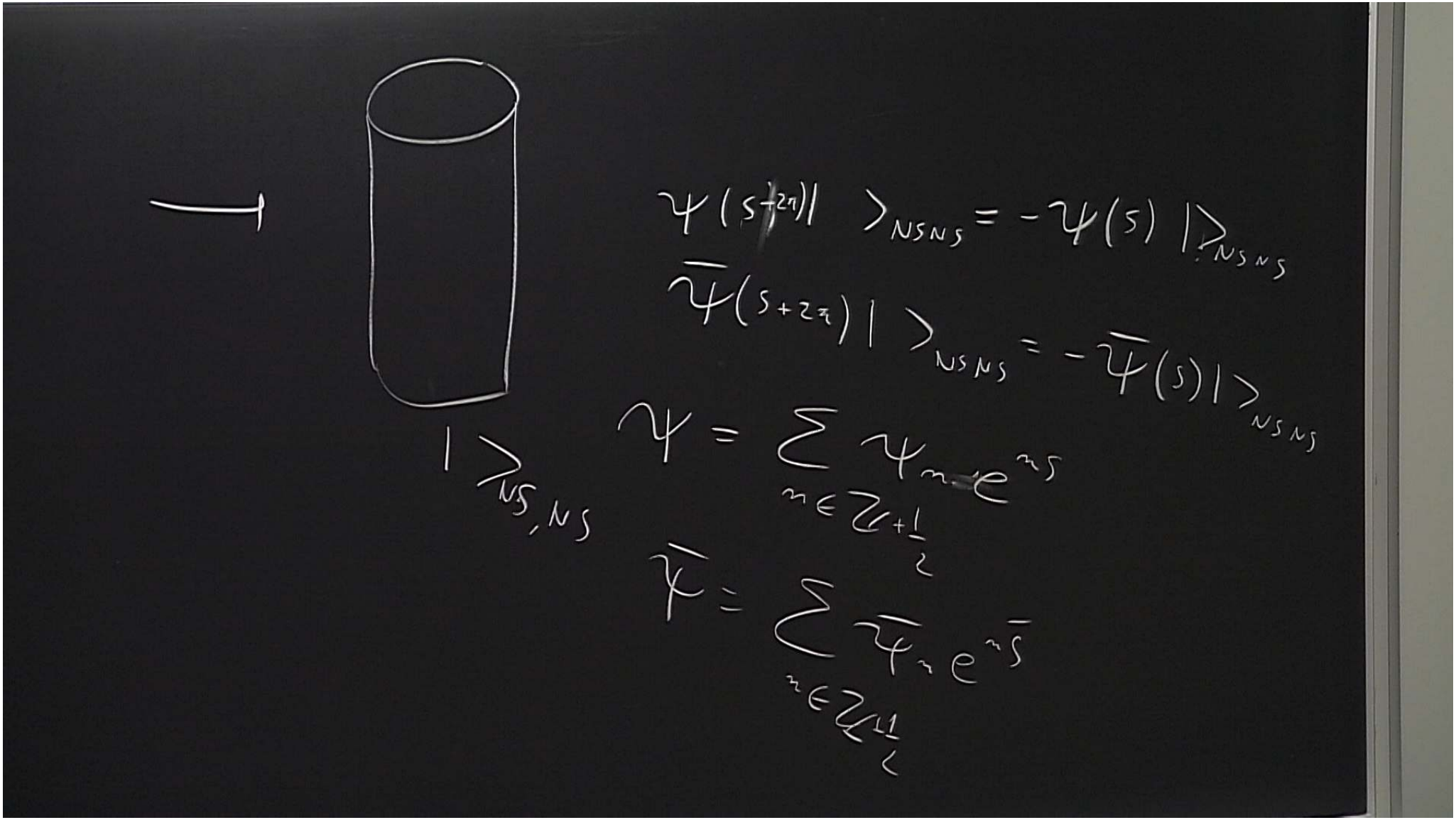
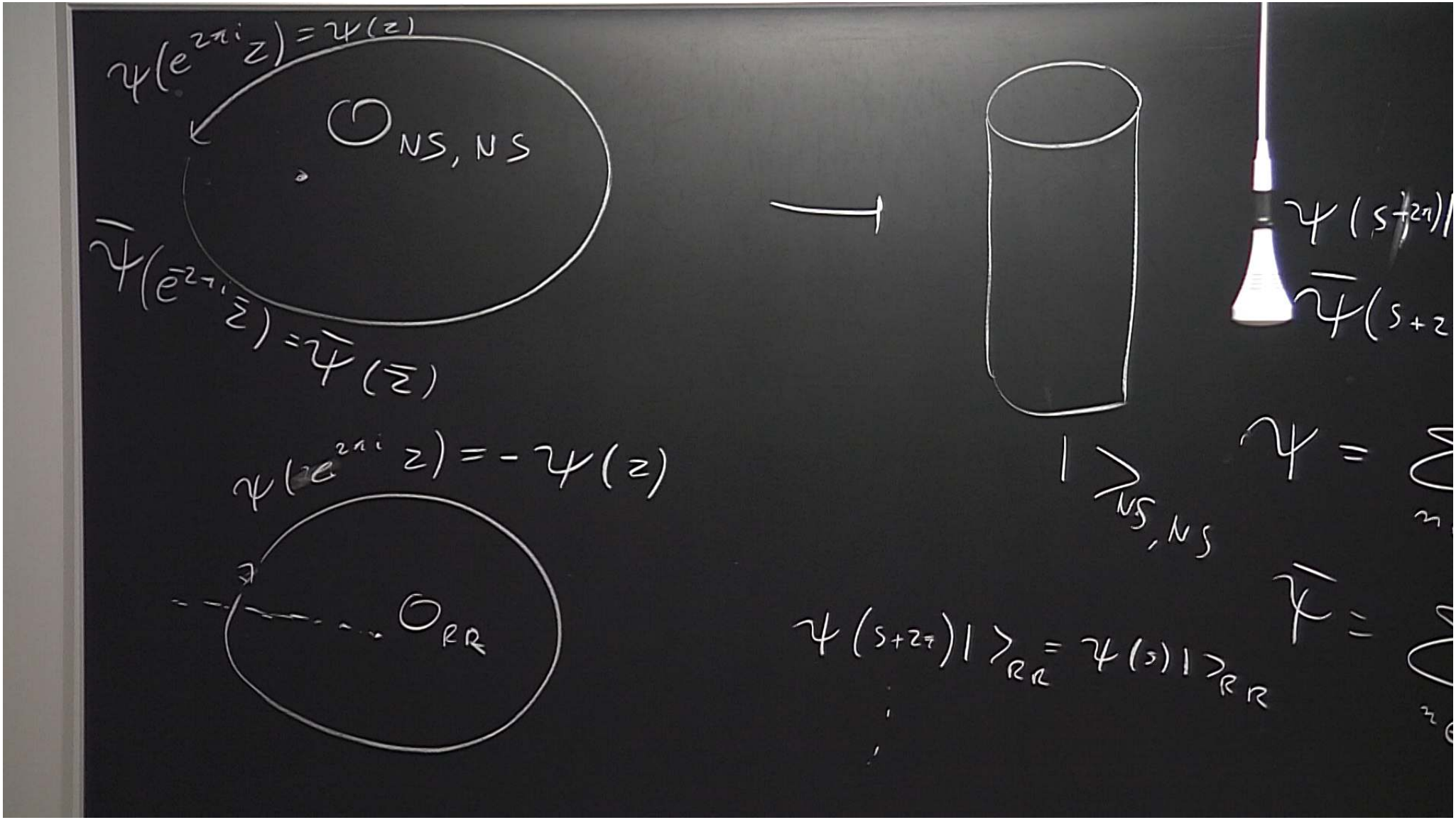
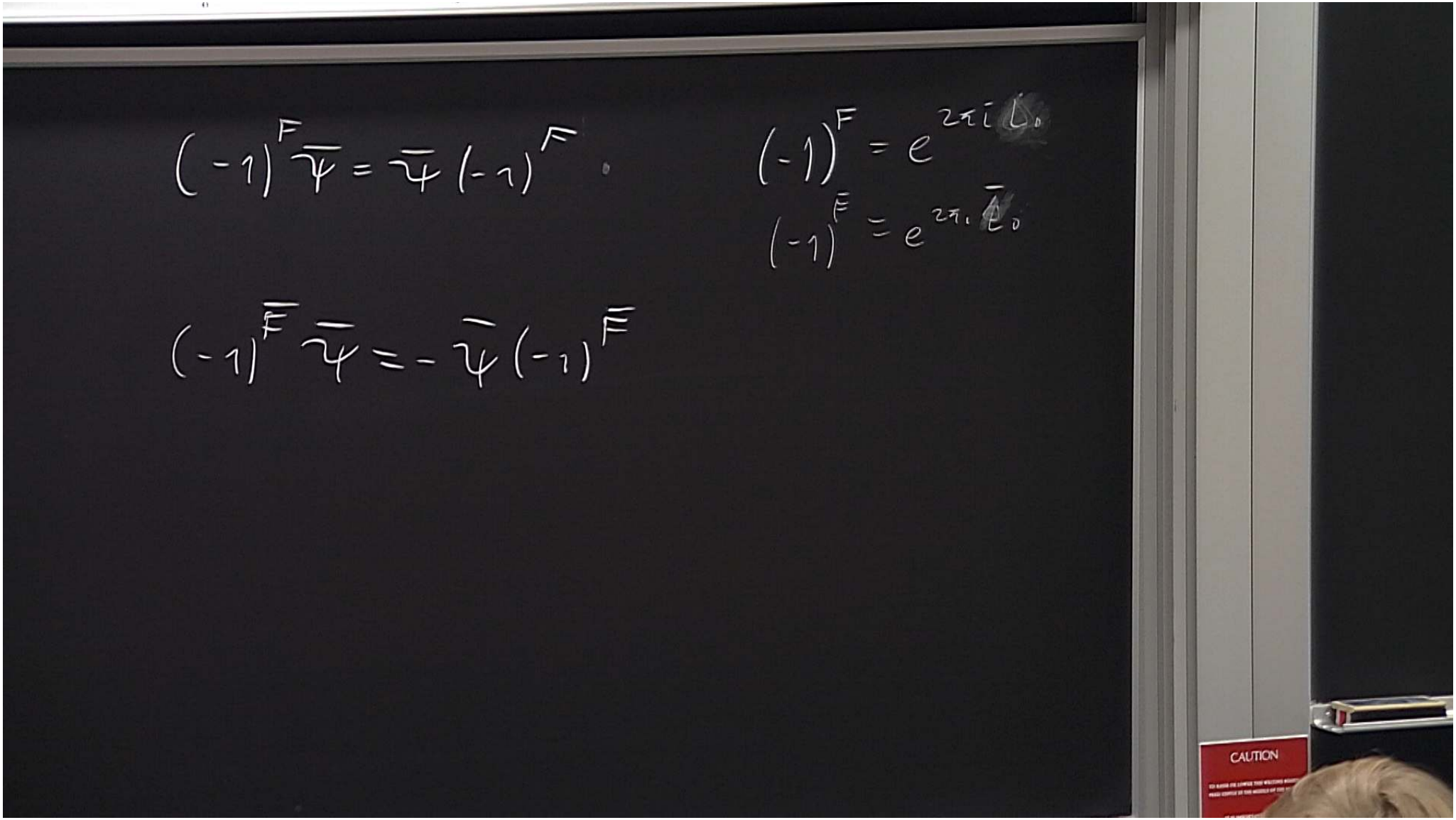

$|>_{NS,NS}$
$\psi(s+2\pi)|>_{NSNS} = -\psi(s)|>_{NSNS}$
$\bar{\psi}(s+2\pi)|>_{NSNS} = -\bar{\psi}(s)|>_{NSNS}$
$\psi = \sum_{m\in\mathbb{Z}+\frac{1}{2}} \psi_m e^{ms}$
$\bar{\psi} = \sum_{m\in\mathbb{Z}+\frac{1}{2}} \bar{\psi}_m e^{m\bar{s}}$


$\psi(e^{2\pi i} z) = \psi(z)$
$O_{NS,NS}$
$\bar{\psi}(e^{2\pi i} \bar{z}) = \bar{\psi}(\bar{z})$
$\psi(e^{2\pi i} z) = -\psi(z)$
O_{RR}
$|\rangle_{NS,NS}$
$\psi(s+2\pi)|$
$\bar{\psi}(s+2$
$\psi =$
$\bar{\psi} =$
$\psi(s+2\pi)|\rangle_{RR} = \psi(s)|\rangle_{RR}$


$(-1)^F \bar{\psi} = \bar{\psi} (-1)^F$
$(-1)^F = e^{2\pi i L_0}$
$(-1)^F = e^{2\pi i \bar{L}_0}$
$(-1)^F \bar{\psi} = -\bar{\psi} (-1)^F$
CAUTION

$$(-1)^F \psi = -\psi (-1)^F \qquad (-1)^F \bar{\psi} = \bar{\psi} (-1)^F$$

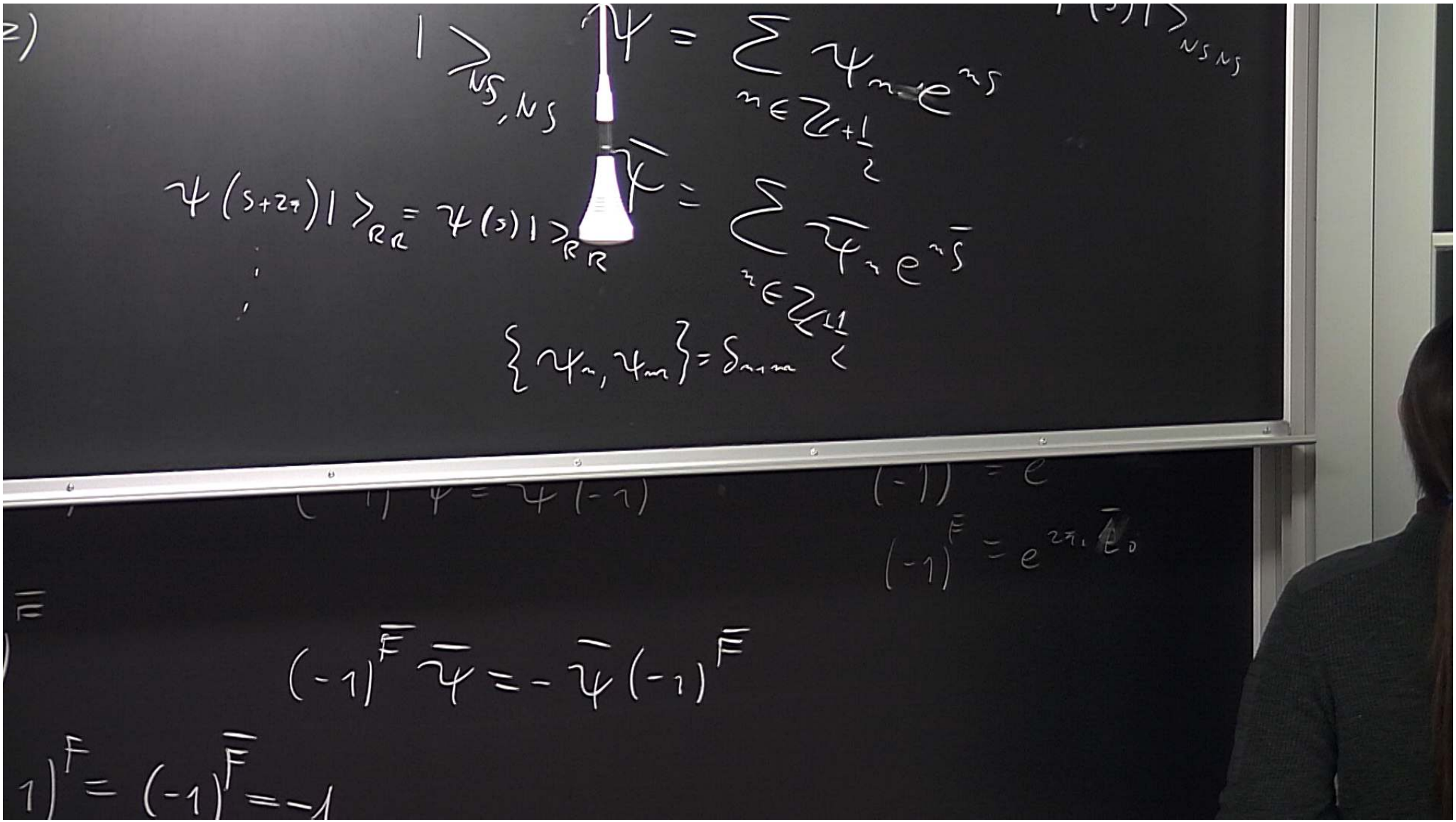
$$(-1)^F \psi = \psi (-1)^{\bar{F}} \qquad (-1)^{\bar{F}} \bar{\psi} = -\bar{\psi} (-1)^{\bar{F}}$$

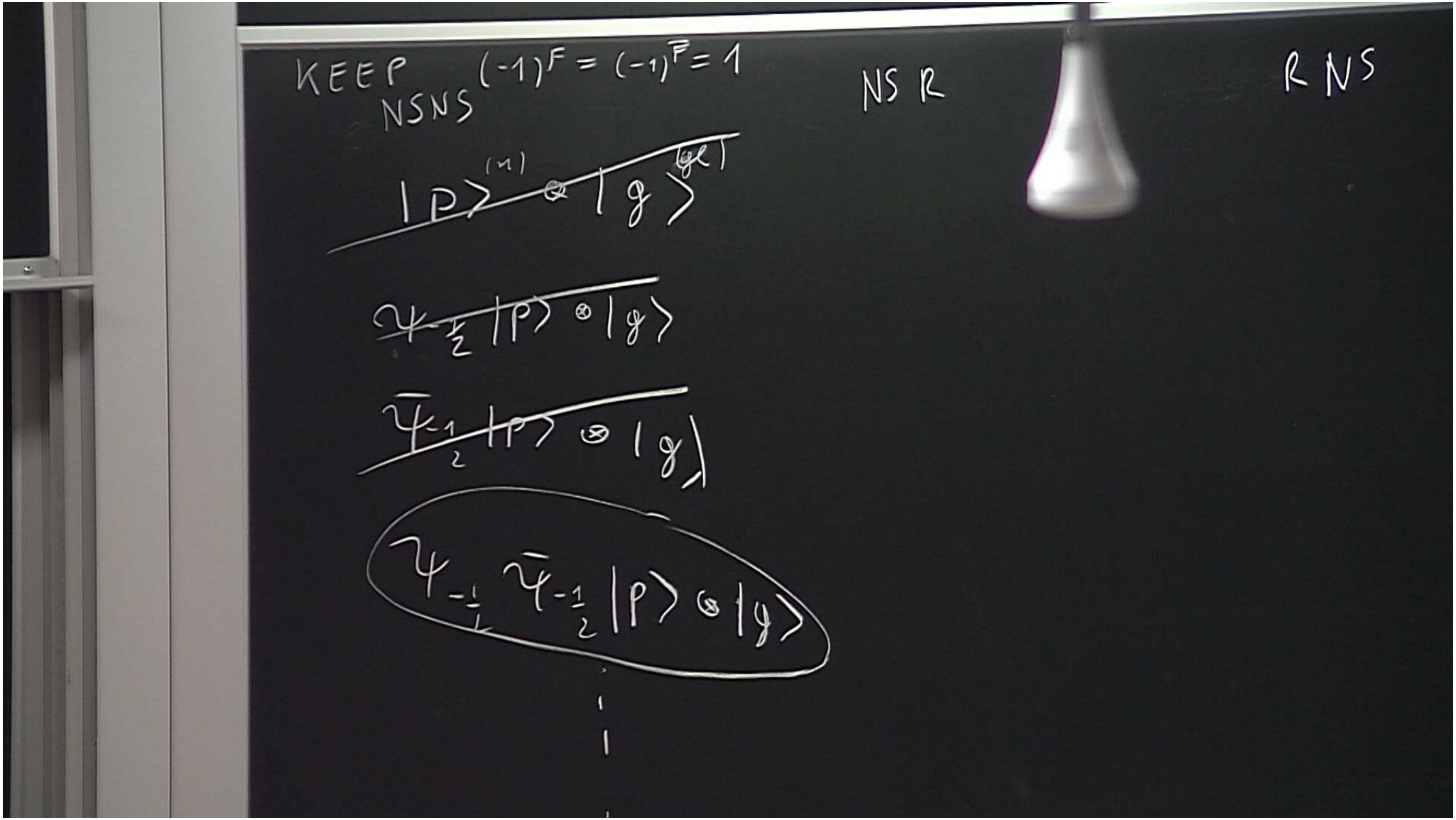
$$|g\rangle^{R}_{NS}$$

$$(-1)^F \psi = -\psi (-1)^F \qquad (-1)^F \bar{\psi} = \bar{\psi} (-1)^F$$

$$(-1)^{\bar{F}} \psi = \psi (-1)^{\bar{F}} \qquad (-1)^{\bar{F}} \bar{\psi} = -\bar{\psi} (-1)^{\bar{F}}$$

$$|g\rangle^{gh}_{NS\,NS} \qquad (-1)^F = (-1)^{\bar{F}} = -1$$


$|\rangle_{NS,NS}$
$\psi = \sum_{n \in \mathbb{Z}+\frac{1}{2}} \psi_n e^{ns}$
$\psi(s+2\pi i)|\rangle_{RR} = \psi(s)|\rangle_{RR}$
$\bar{\psi} = \sum_{n \in \mathbb{Z}+\frac{1}{2}} \bar{\psi}_n e^{n\bar{s}}$
$\{\psi_n, \psi_m\} = \delta_{n+m}$
$(-1)^F \bar{\psi} = -\bar{\psi}(-1)^F$
$(-1)^F = e^{2\pi i \bar{L}_0}$
$(-1)^F = (-1)^{\bar{F}} = -1$

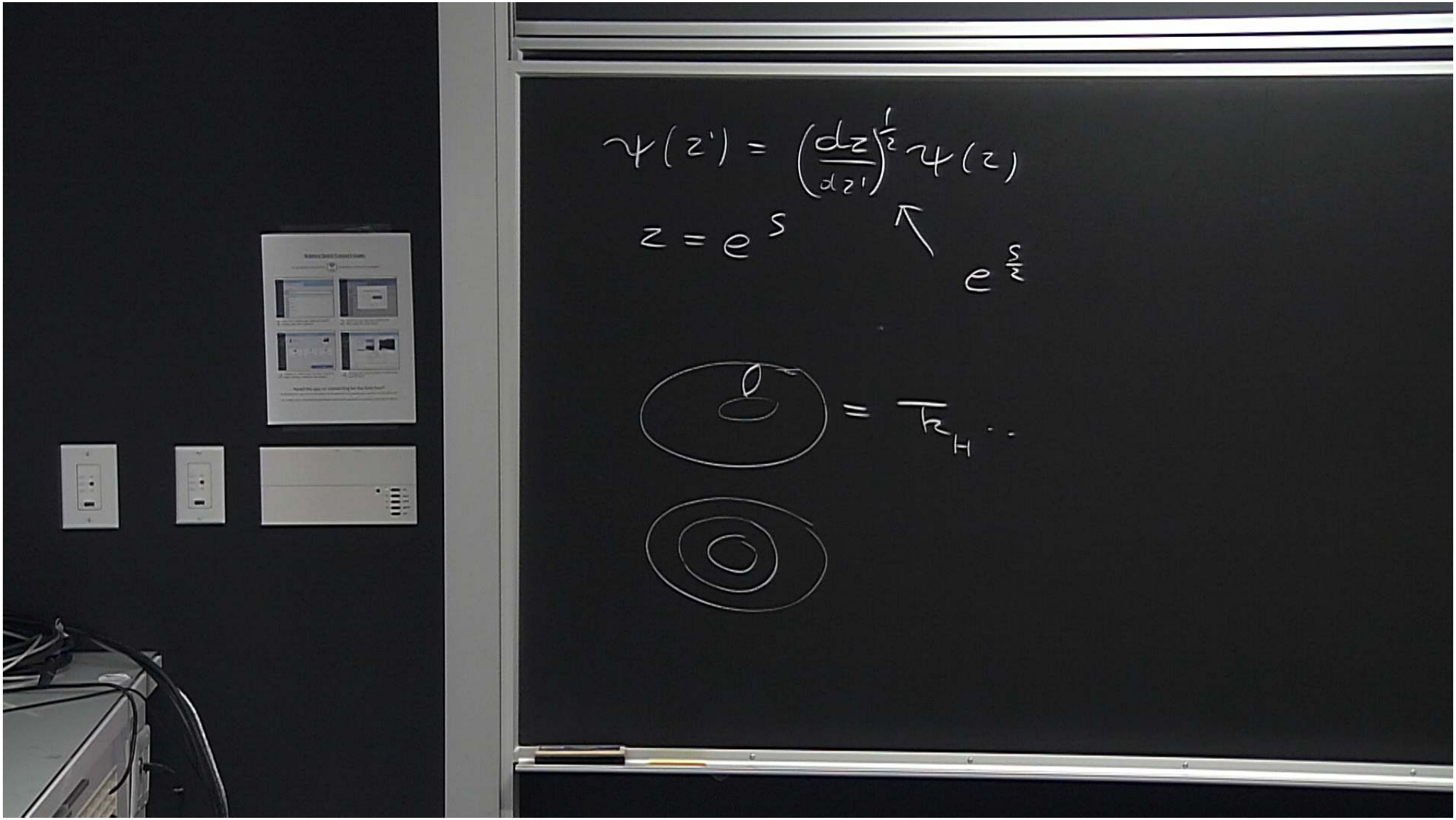

KEEP NSNS
$(-1)^F = (-1)^{\bar{F}} = 1$
NS R
R NS
$|p\rangle^{(-1)} \otimes |g\rangle^{(g_s^{-1})}$
$\psi_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\bar{\psi}_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\psi_{-\frac{1}{2}} \bar{\psi}_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$

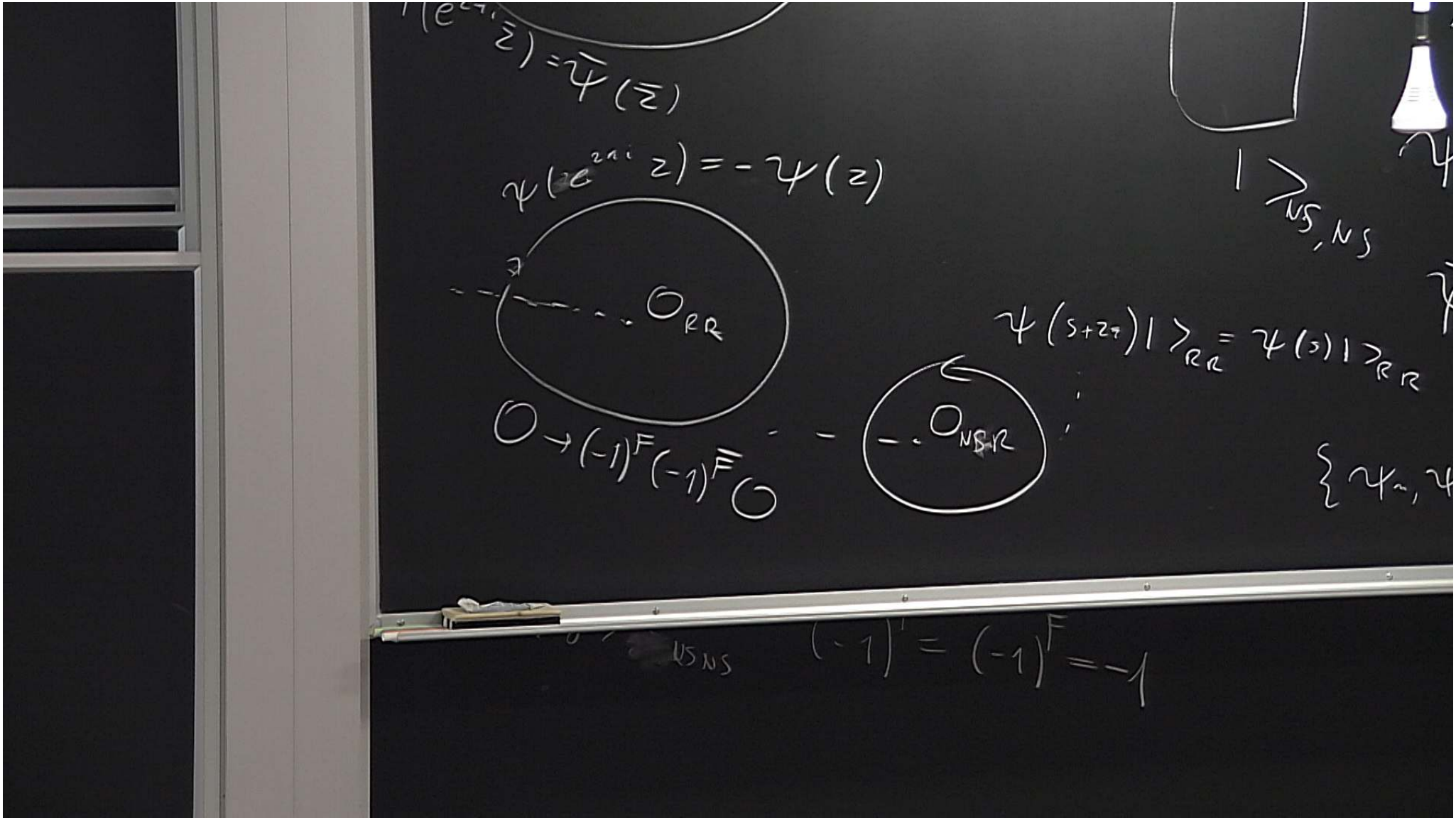
$(-1)^F \psi = -\psi (-1)^F$ $\quad (-1)^F \bar{\psi} = \bar{\psi} (-1)^F$ $\quad (-1)^F = e^{2\pi i L_0}$

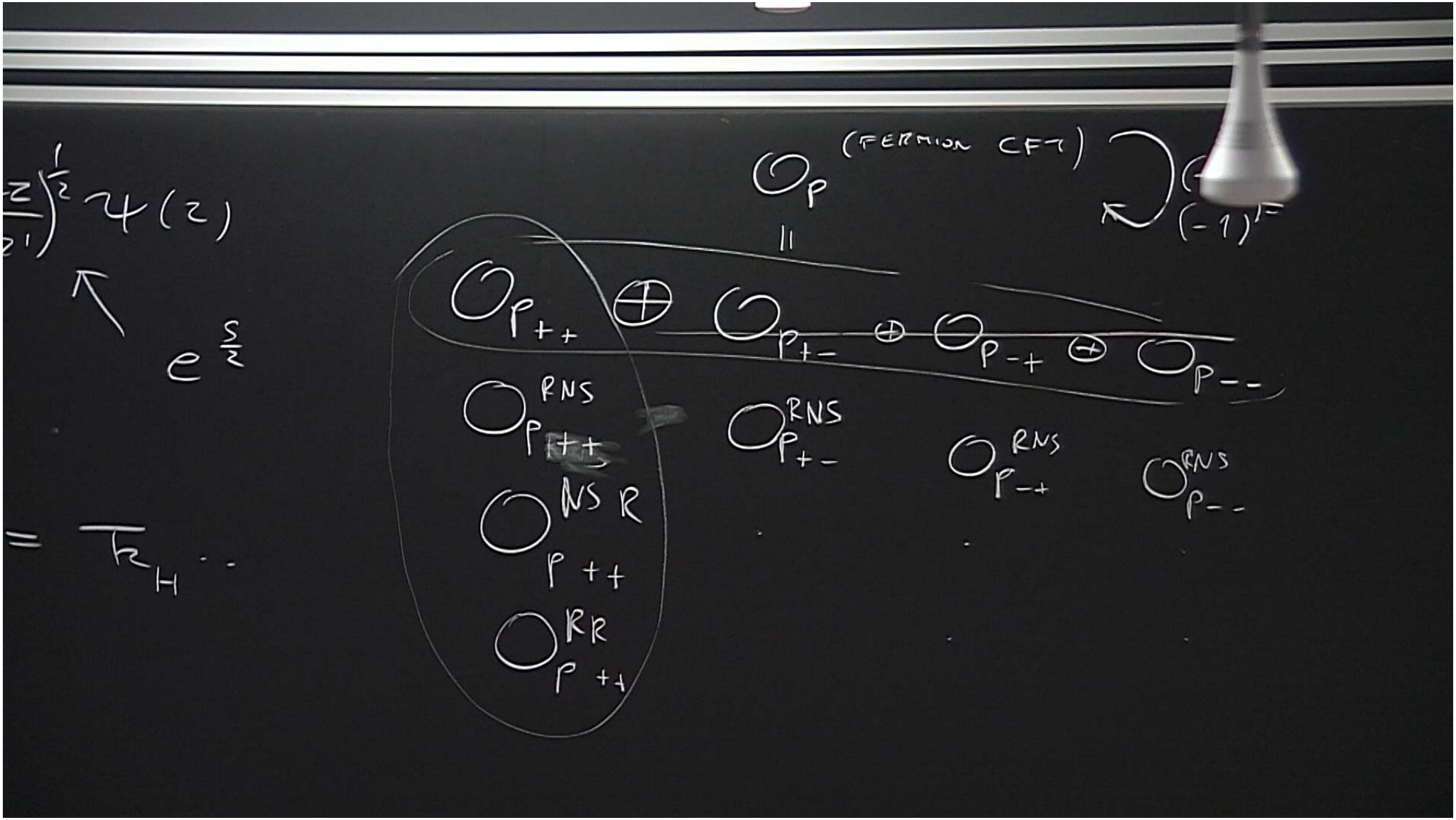
$(-1)^{\bar{F}} = e^{2\pi i \bar{L}_0}$

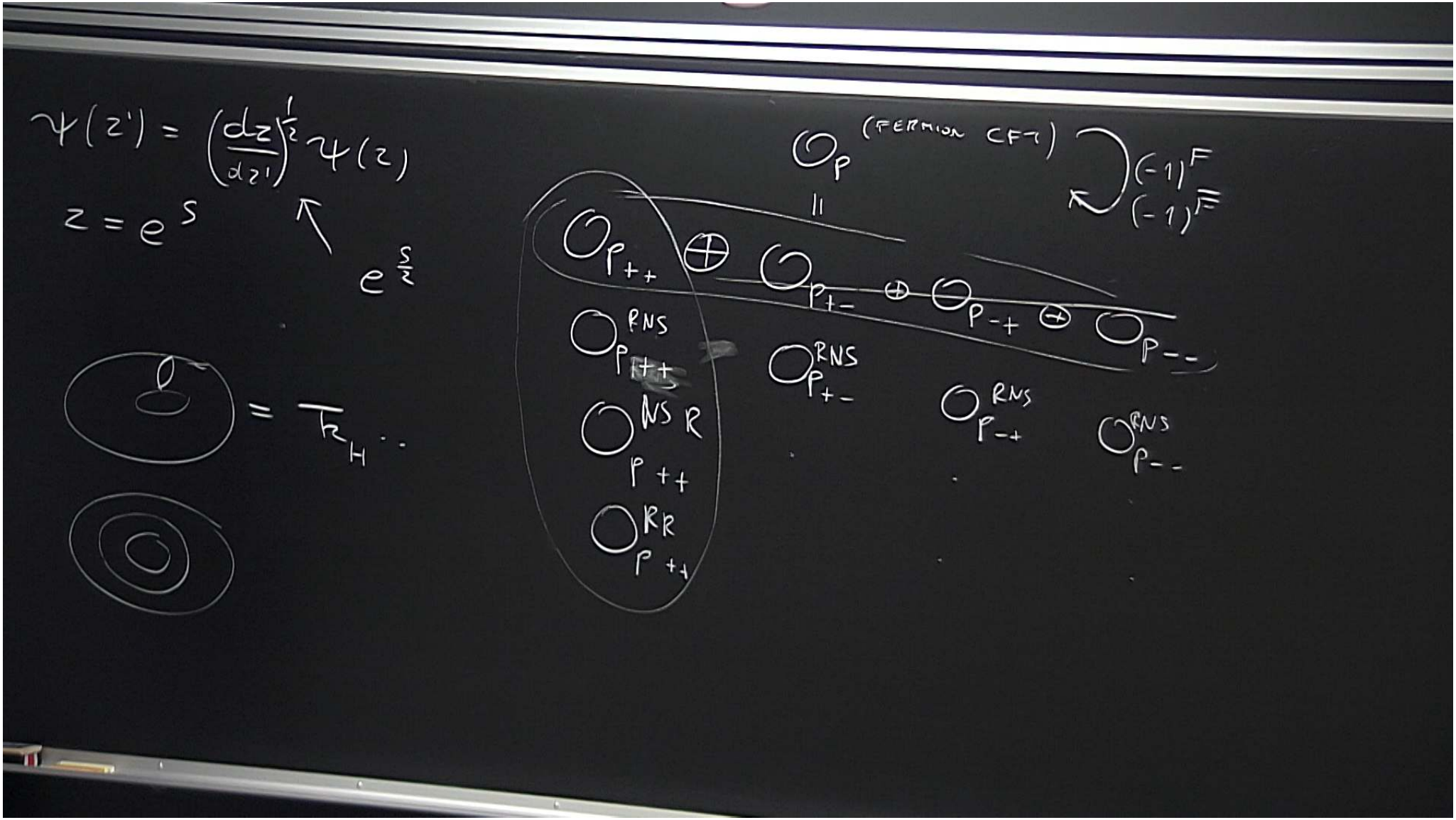
$(-1)^F \psi = \psi (-1)^{\bar{F}}$ $\quad (-1)^F \bar{\psi} = -\bar{\psi} (-1)^{\bar{F}}$

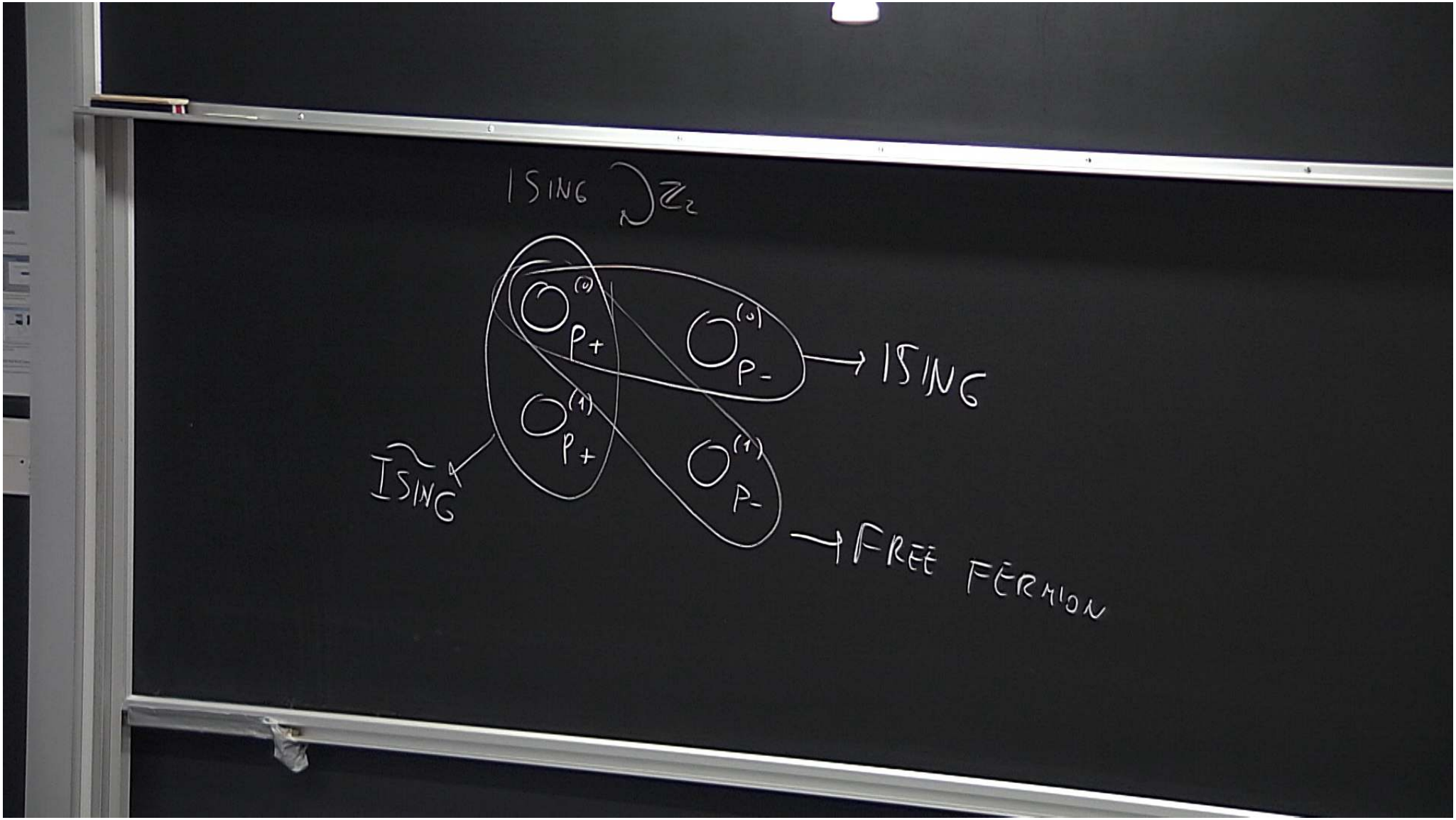
$|g\rangle^{IR}_{NS}$ $\quad (-1)^F = (-1)^{\bar{F}} = -1$

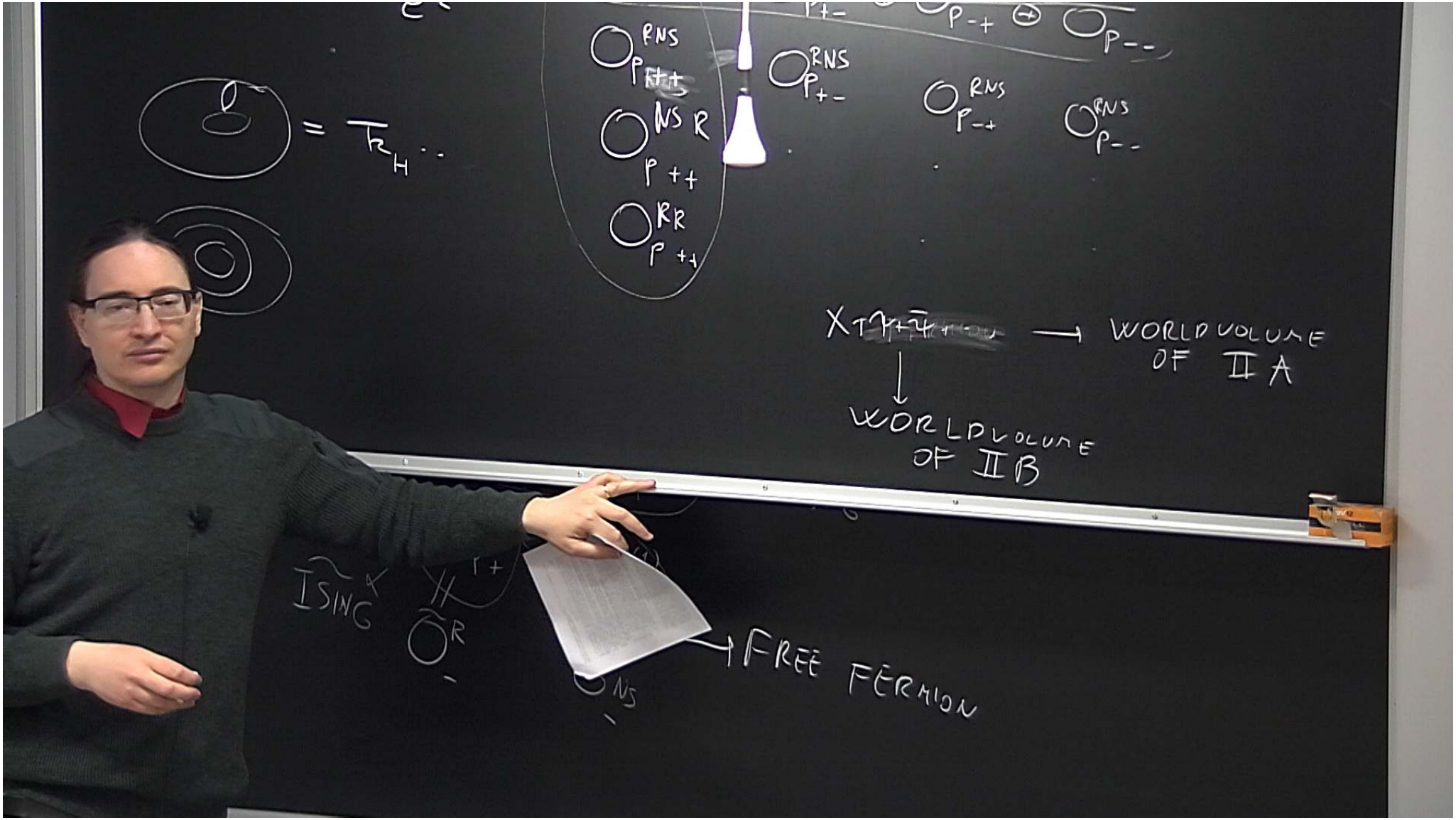

$\psi(z') = \left(\frac{dz}{dz'}\right)^{\frac{1}{2}} \psi(z)$
$z = e^{s}$
$e^{\frac{s}{2}}$
$= \bar{k}_H \ldots$

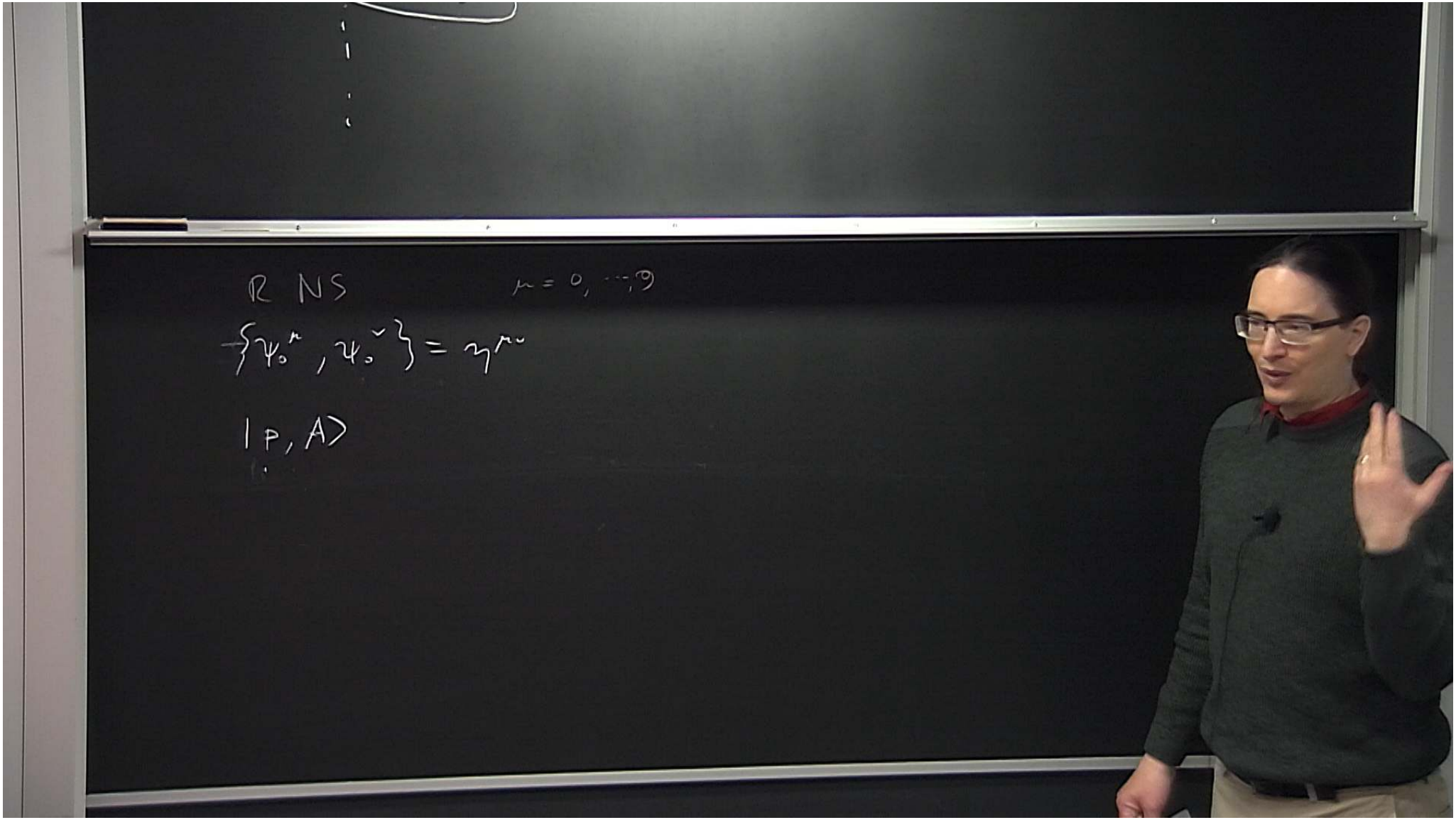

$\psi(e^{2\pi i} z) = -\psi(z)$
$|>_{NS,NS}$
O_{RR}
$\psi(s+2\eta)|>_{RR} = \psi(s)|>_{RR}$
$O \to (-1)^F (-1)^F O$
$O_{NS,R}$
$\{\psi_m, \psi$
$(-1)^F = (-1)^F = -1$

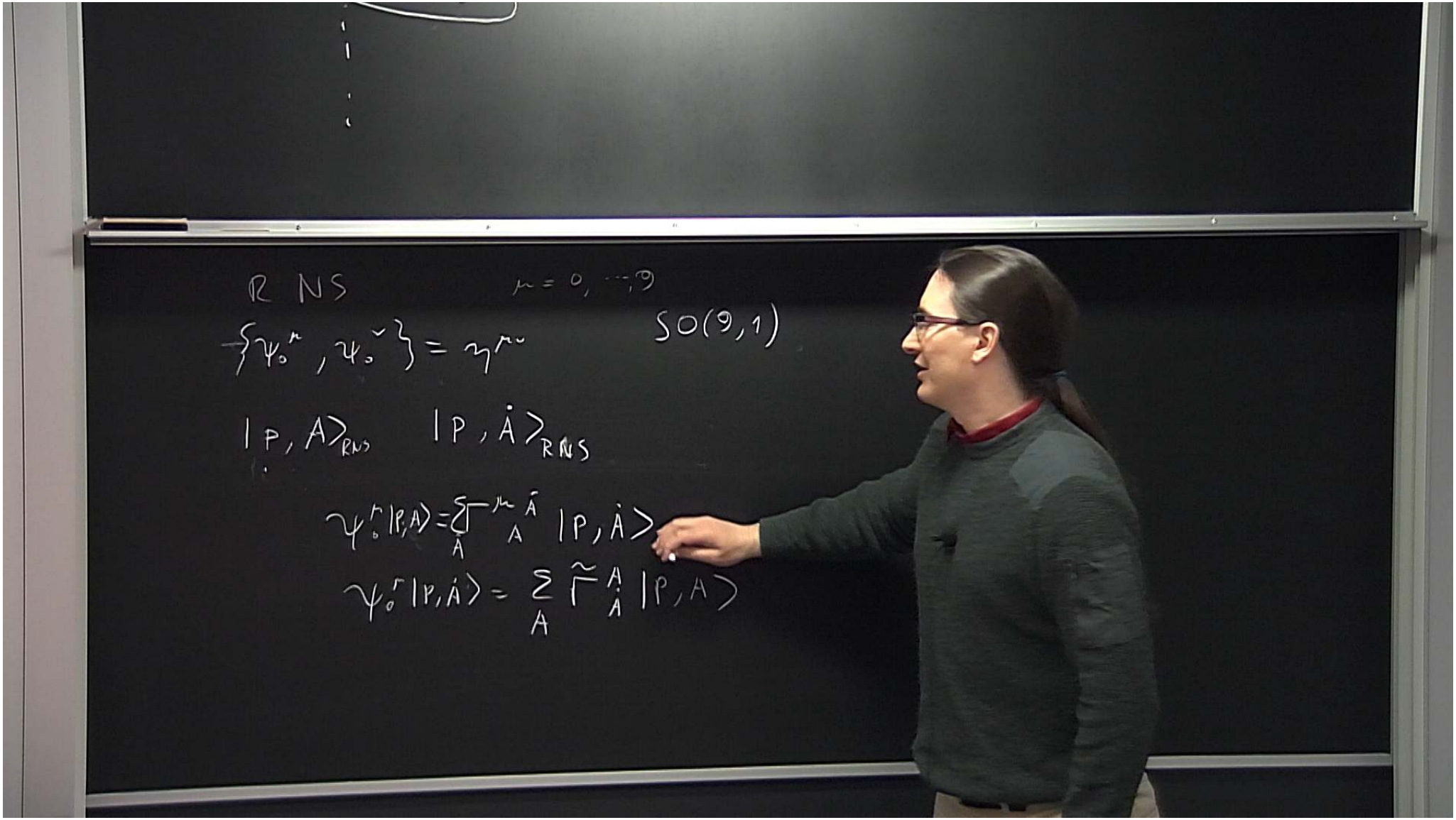

(FERMION CFT)
$\mathcal{O}_P$
$(-1)^F$
$\mathcal{O}_{P_{++}} \oplus \mathcal{O}_{P_{+-}} \oplus \mathcal{O}_{P_{-+}} \oplus \mathcal{O}_{P_{--}}$
$\mathcal{O}^{RNS}_{P_{++}}$
$\mathcal{O}^{RNS}_{P_{+-}}$
$\mathcal{O}^{RNS}_{P_{-+}}$
$\mathcal{O}^{RNS}_{P_{--}}$
$\mathcal{O}^{NS\,R}_{P\,++}$
$\mathcal{O}^{RR}_{P\,+1}$
$e^{\frac{S}{2}}$
Tr_H

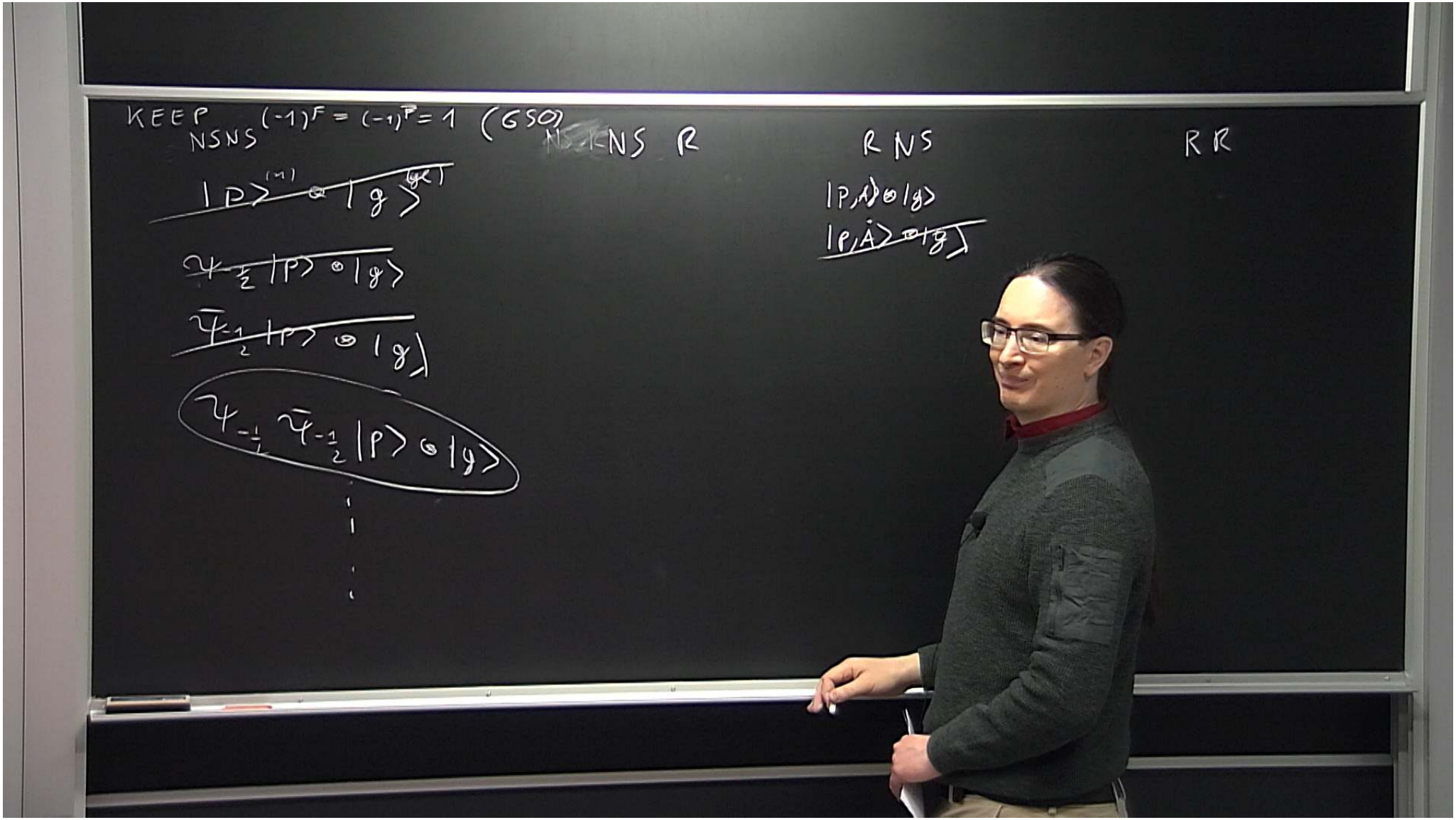

$\psi(z') = \left(\frac{dz}{dz'}\right)^{\frac{1}{2}} \psi(z)$
$z = e^{s}$
$e^{\frac{s}{2}}$
$= \mathrm{Tr}_{H} \cdots$
$\mathcal{O}_P$ (FERMION CFT)
$(-1)^F$
$(-1)^{\bar{F}}$
$\mathcal{O}_{P_{++}} \oplus \mathcal{O}_{P_{+-}} \oplus \mathcal{O}_{P_{-+}} \oplus \mathcal{O}_{P_{--}}$
$\mathcal{O}^{RNS}_{P_{++}}$
$\mathcal{O}^{NS\,R}_{P_{++}}$
$\mathcal{O}^{RR}_{P_{++}}$
$\mathcal{O}^{RNS}_{P_{+-}}$
$\mathcal{O}^{RNS}_{P_{-+}}$
$\mathcal{O}^{RNS}_{P_{--}}$

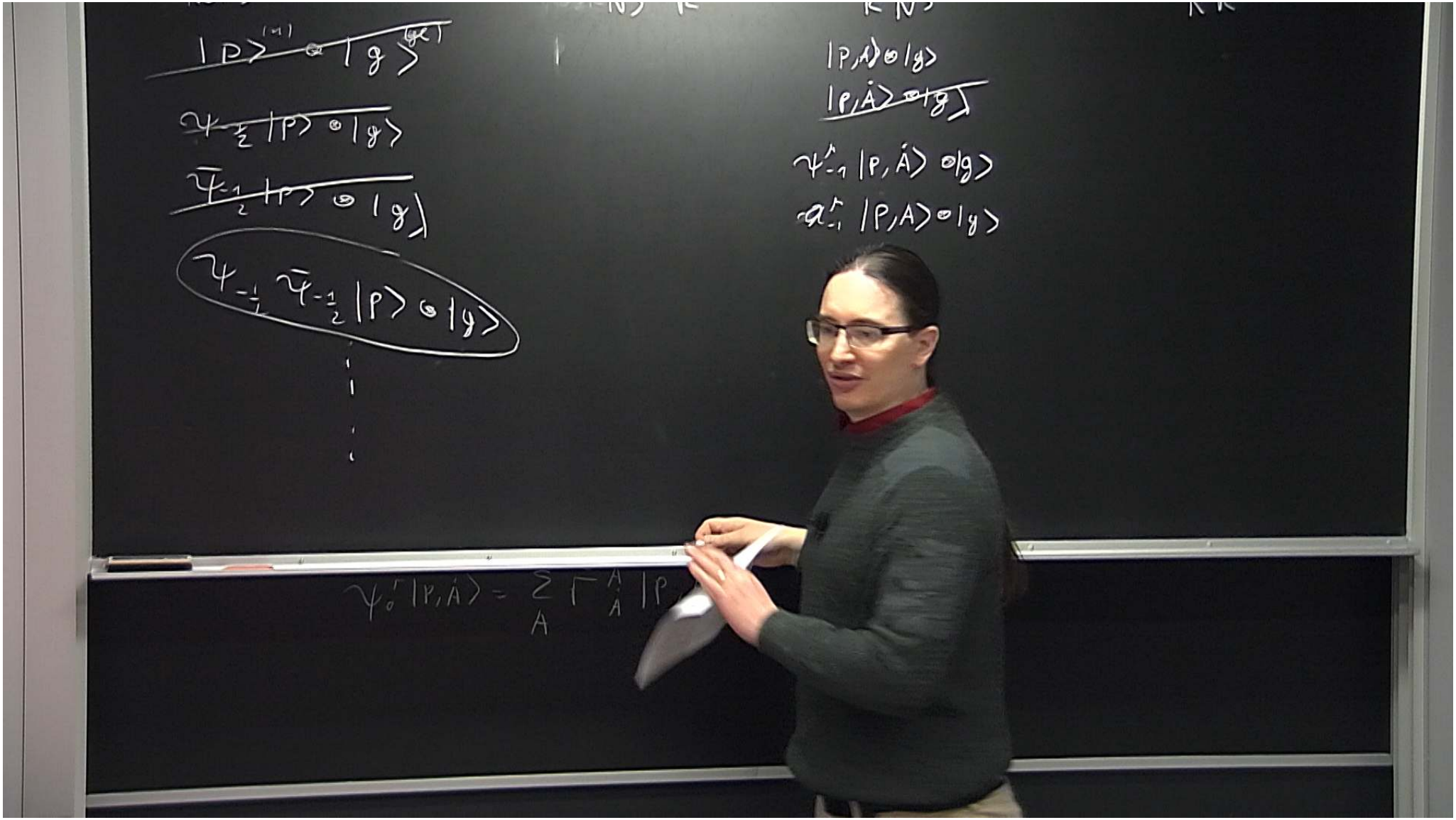

ISING $\supset \mathbb{Z}_2$
$\mathcal{O}^{(0)}_{P+}$
$\mathcal{O}^{(0)}_{P-}$
ISING
$\mathcal{O}^{(1)}_{P+}$
ISING
$\mathcal{O}^{(1)}_{P-}$
FREE FERMION

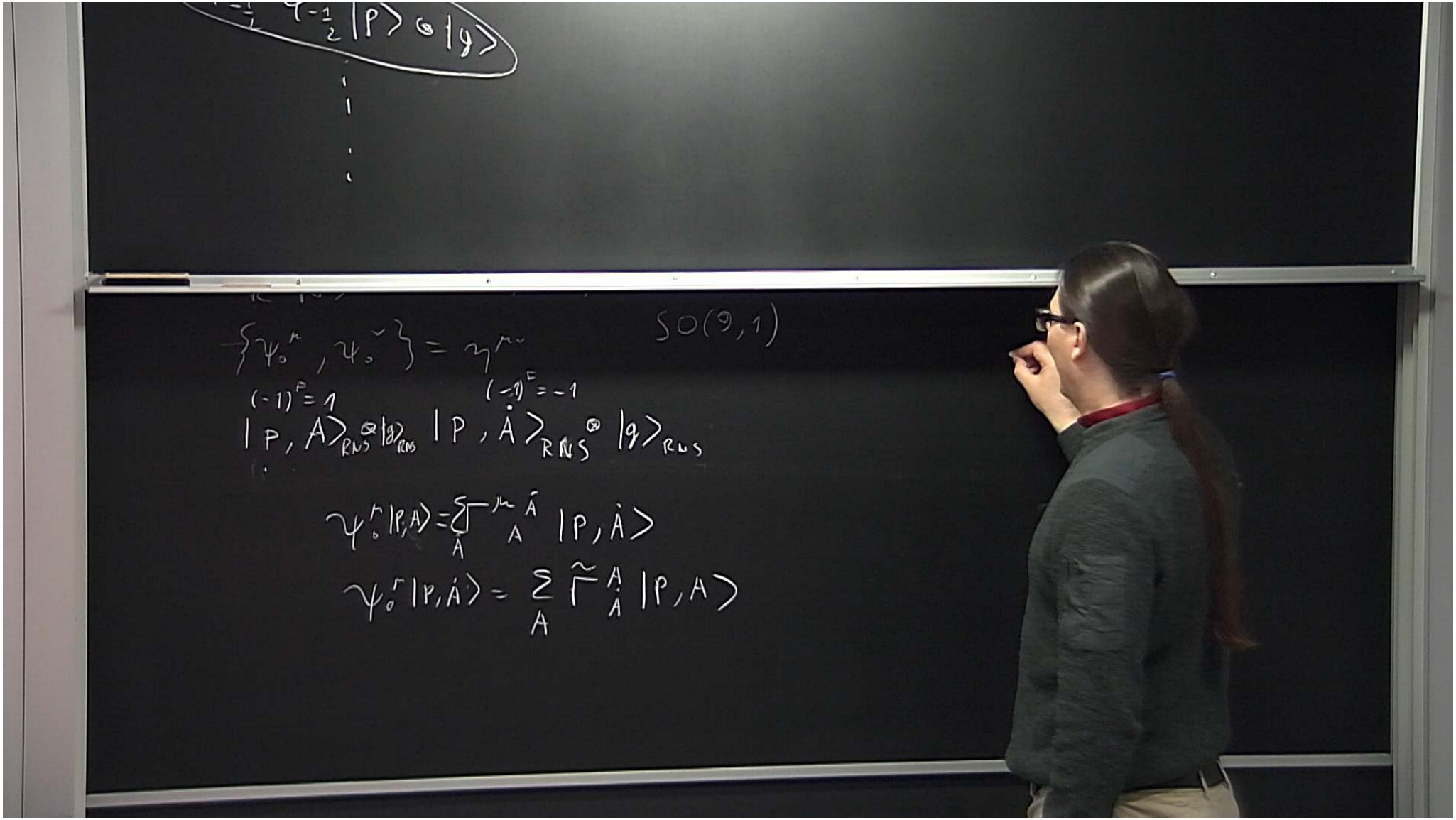

WORLD VOLUME OF IIA
WORLD VOLUME OF IIB
ISING
FREE FERMION

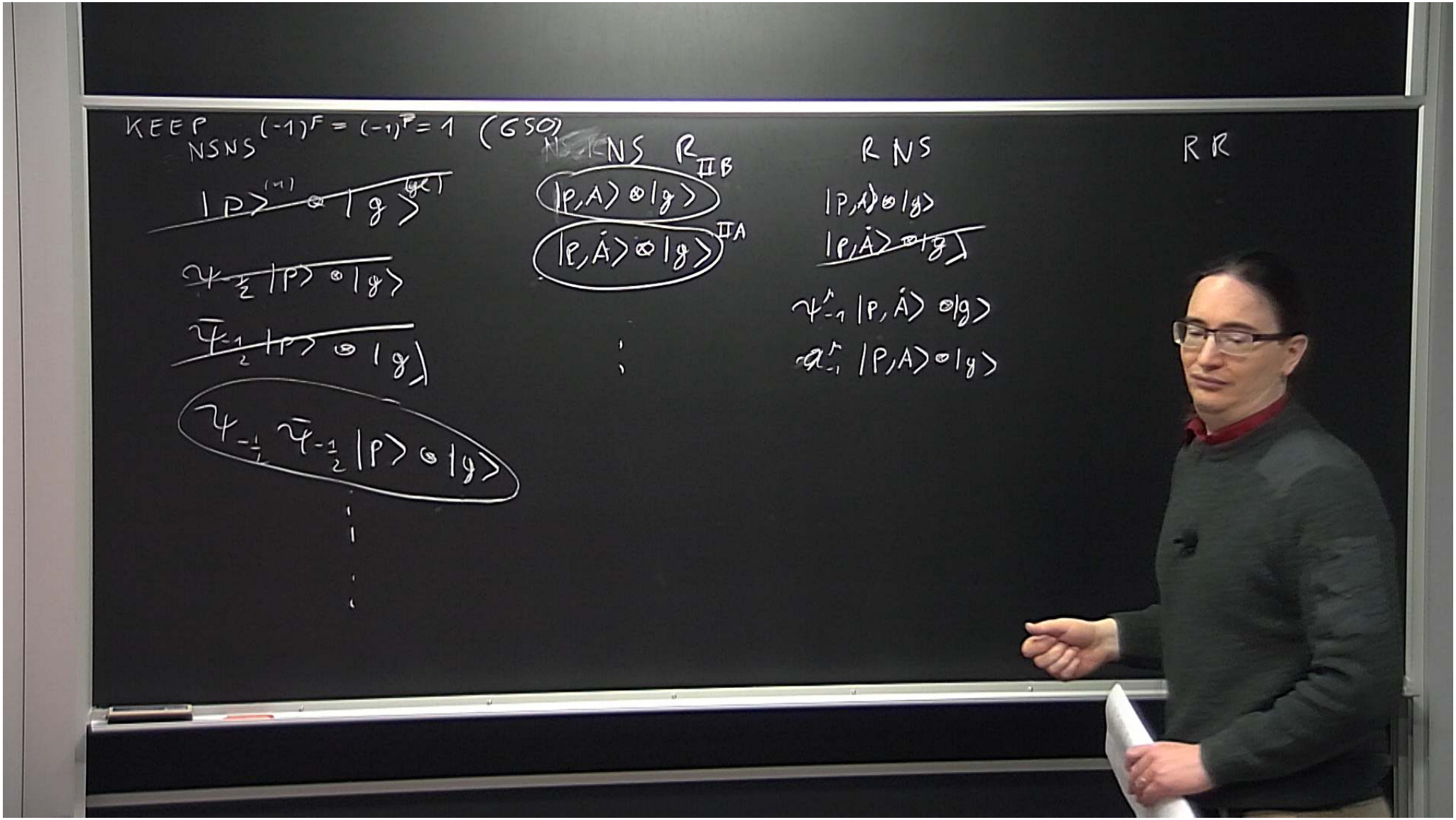

R NS
$\mu = 0, \cdots, 9$
$\{\psi_0^\mu, \psi_0^\nu\} = \eta^{\mu\nu}$
$|p, A\rangle$

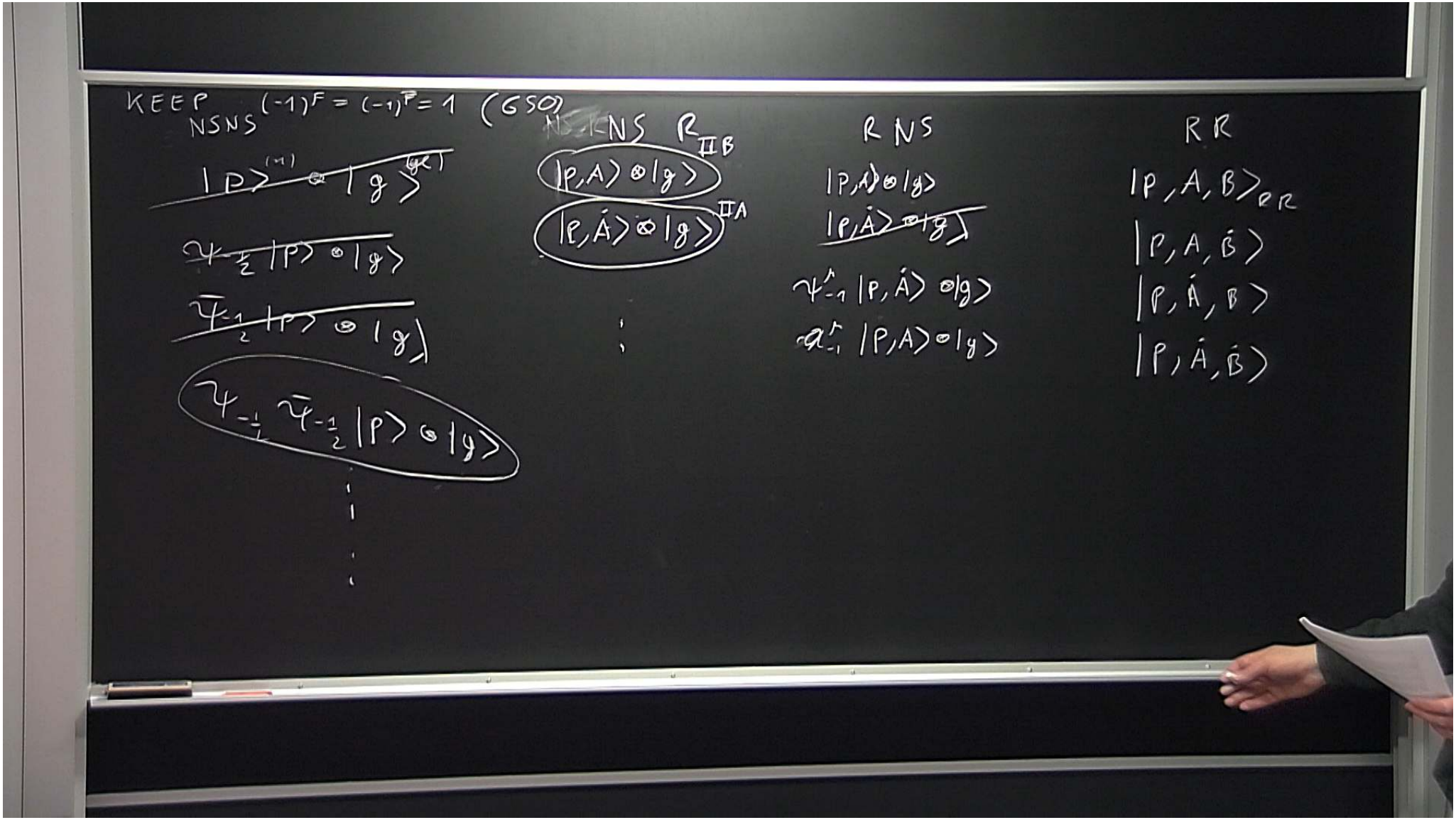

R NS
$\mu = 0, \cdots, 9$
$\{\psi_0^\mu, \psi_0^\nu\} = \eta^{\mu\nu}$
$SO(9,1)$
$|p, A\rangle_{RNS}$
$|p, \dot{A}\rangle_{RNS}$
$\psi_0^\mu |p, A\rangle = \sum_{\dot{A}} \Gamma^\mu_{A\dot{A}} |p, \dot{A}\rangle$
$\psi_0^\mu |p, \dot{A}\rangle = \sum_{A} \tilde{\Gamma}^{\dot{A}}_{A} |p, A\rangle$

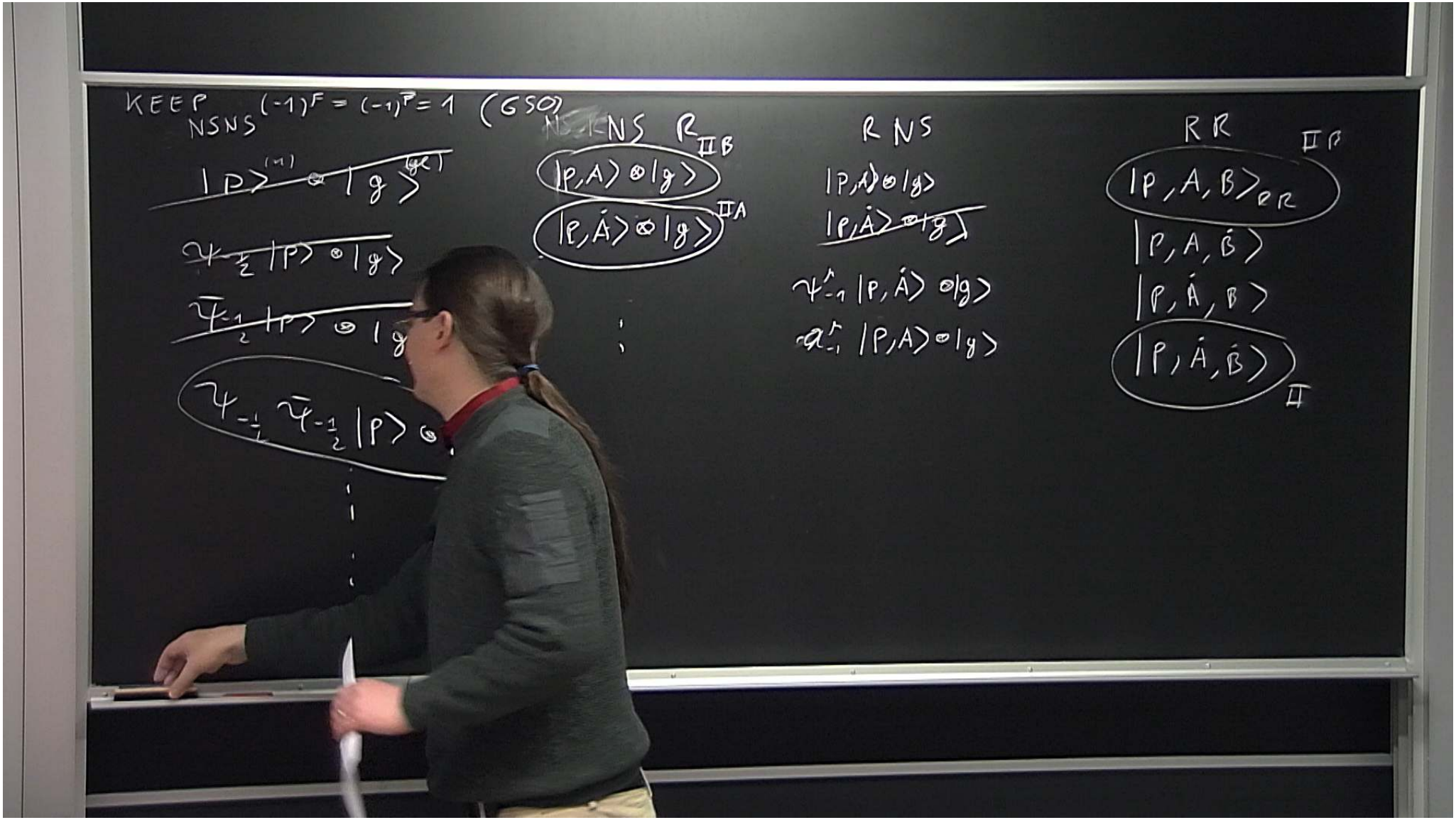

KEEP $(-1)^F = (-1)^{\bar{F}} = 1$ (GSO)
NSNS
NS-NS R
R NS
R R
$|p\rangle^{(-1)} \otimes |g\rangle$
$\psi_{-\frac{1}{2}}|p\rangle \otimes |g\rangle$
$\bar{\psi}_{-\frac{1}{2}}|p\rangle \otimes |g\rangle$
$\psi_{-\frac{1}{2}}\bar{\psi}_{-\frac{1}{2}}|p\rangle \otimes |g\rangle$
$|p,A\rangle \otimes |g\rangle$
$|p,\dot{A}\rangle \otimes |g\rangle$

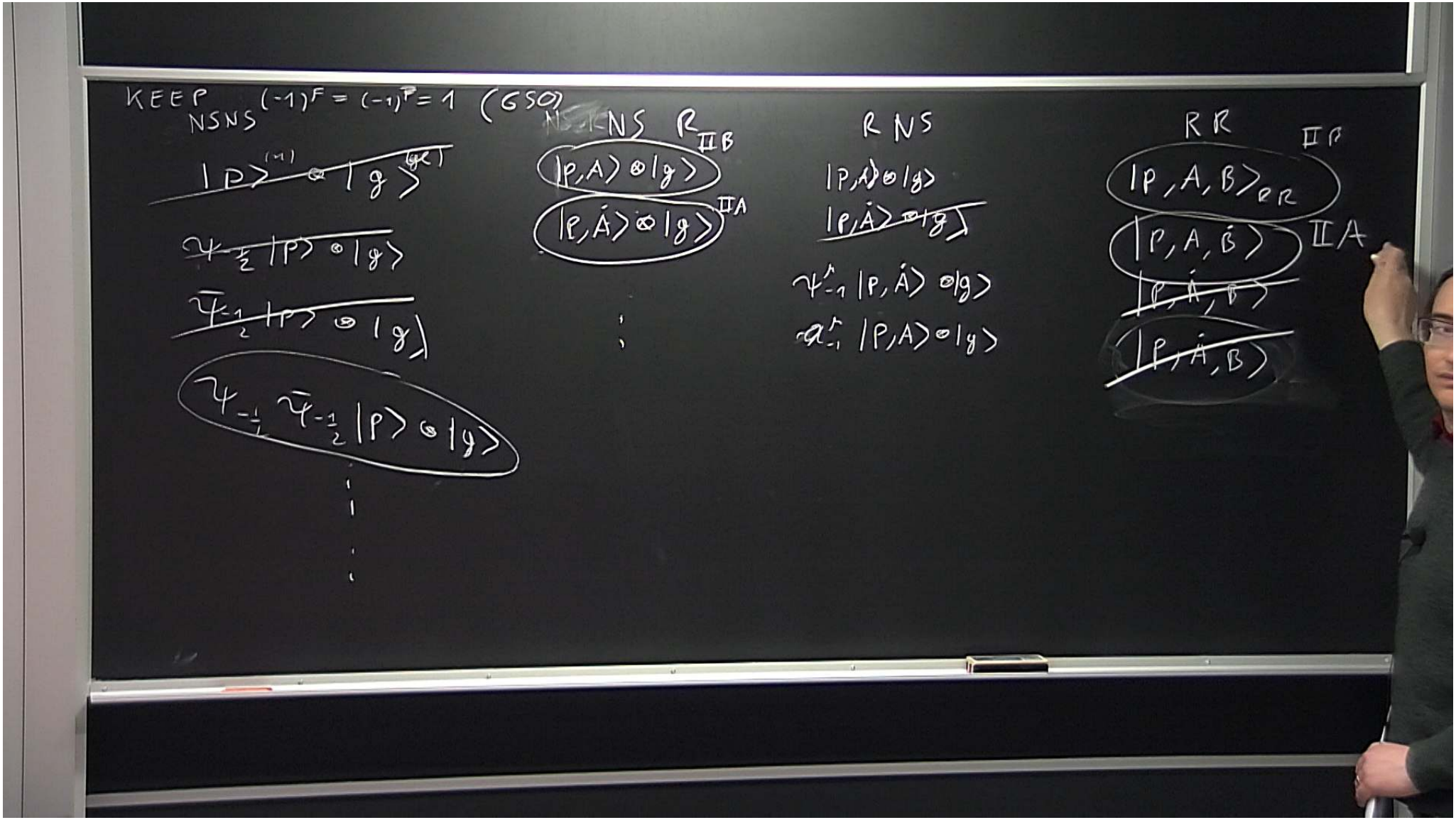

$|p\rangle^{(n)} \otimes |g\rangle^{(n)}$
$\psi_{\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\bar{\psi}_{\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\psi_{-\frac{1}{2}} \bar{\psi}_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
$|p,\hat{A}\rangle \otimes |g\rangle$
$|p,\hat{A}\rangle \otimes |g\rangle$
$\psi^{\dagger}_{-1} |p,\hat{A}\rangle \otimes |g\rangle$
$a^{\dagger}_{-1} |p,A\rangle \otimes |g\rangle$
$\psi_0 |p,\hat{A}\rangle = \sum_A \Gamma^{A}_{\hat{A}} |p$

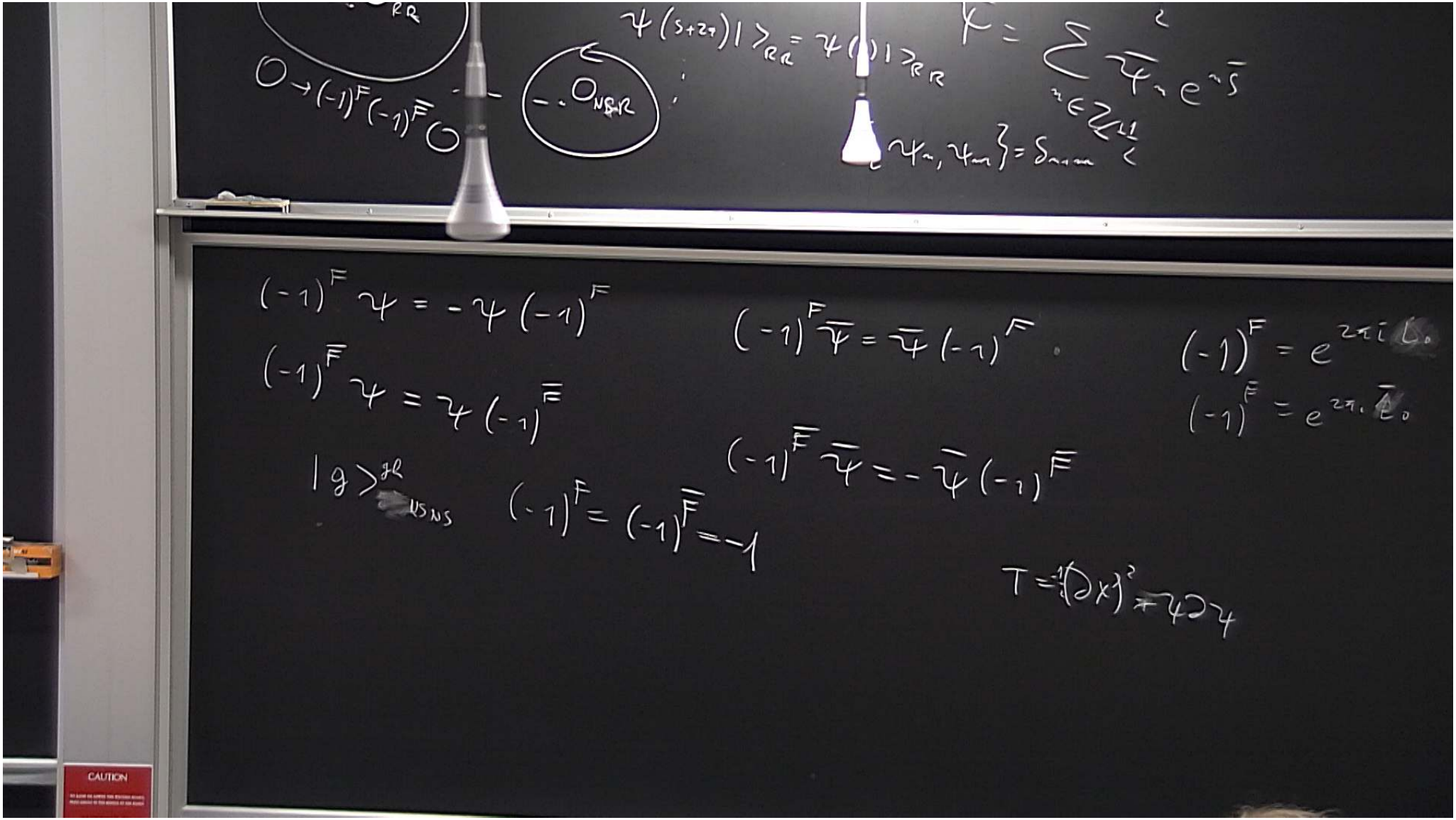

$\psi_{-\frac{1}{2}}|p\rangle \otimes |g\rangle$
$\{\psi_0^\mu, \psi_0^\nu\} = \eta^{\mu\nu}$
$SO(9,1)$
$(-1)^F = 1$
$(-1)^F = -1$
$|p,A\rangle_{RNS} \otimes |g\rangle_{RNS}$
$|p,\dot{A}\rangle_{RNS} \otimes |g\rangle_{RNS}$
$\psi_0^\mu |p,A\rangle = \sum_{\dot{A}} \Gamma^\mu_{A\dot{A}} |p,\dot{A}\rangle$
$\psi_0^\mu |p,\dot{A}\rangle = \sum_{A} \tilde{\Gamma}^\mu_{\dot{A}A} |p,A\rangle$

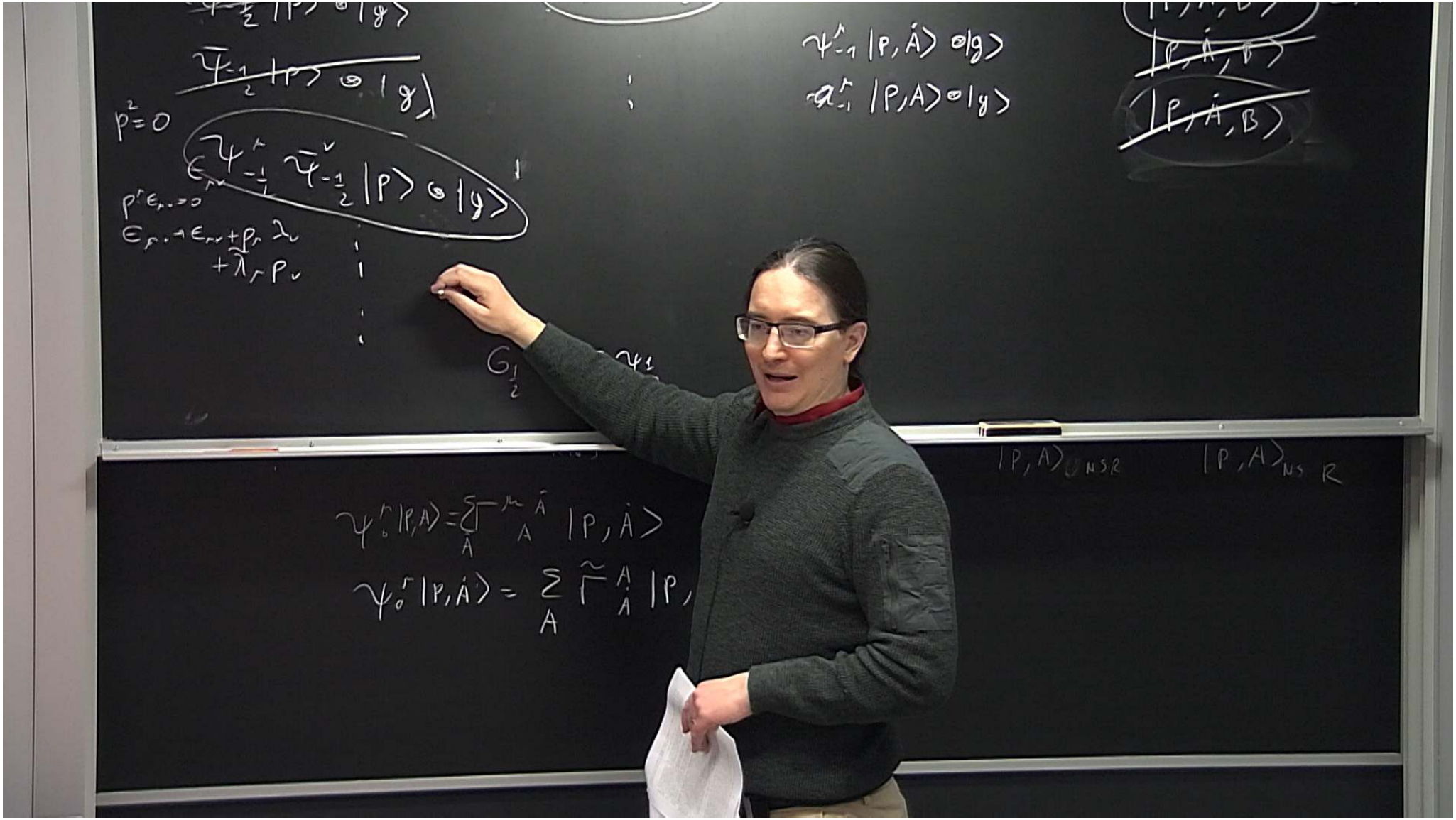

KEEP $(-1)^F = (-1)^{\bar{F}} = 1$ (GSO)
NSNS
$|p\rangle^{(-1)} \otimes |g\rangle^{(g)}$
$\psi_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\bar{\psi}_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\psi_{-\frac{1}{2}} \bar{\psi}_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
NS R
IIB
$|p,A\rangle \otimes |g\rangle$
IIA
$|p,\dot{A}\rangle \otimes |g\rangle$
RNS
$|p,A\rangle \otimes |g\rangle$
$|p,\dot{A}\rangle \otimes |g\rangle$
$\psi^{\mu}_{-1} |p,\dot{A}\rangle \otimes |g\rangle$
$a^{\mu}_{-1} |p,A\rangle \otimes |g\rangle$
RR

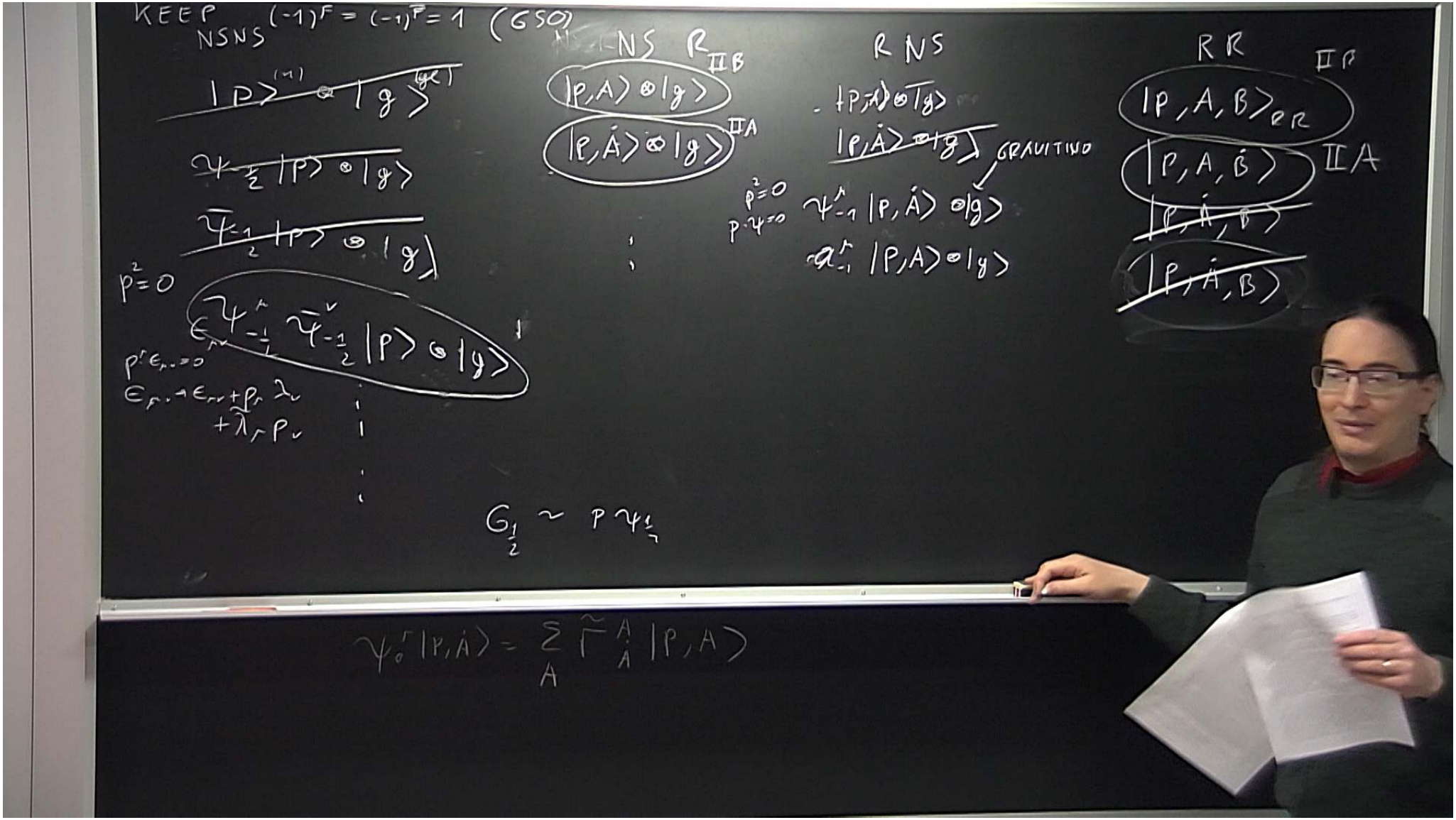

KEEP $(-1)^F = (-1)^{\bar{F}} = 1$ (GSO)
NSNS
$|p\rangle^{(-1)} \otimes |g\rangle^{(gl)}$
$\psi_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\bar{\psi}_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
$\psi_{-\frac{1}{2}} \bar{\psi}_{-\frac{1}{2}} |p\rangle \otimes |g\rangle$
NS R
$|p,A\rangle \otimes |g\rangle$ IIB
$|p,\dot{A}\rangle \otimes |g\rangle$ IIA
RNS
$|p,A\rangle \otimes |g\rangle$
$|p,\dot{A}\rangle \otimes |g\rangle$
$\psi^{\mu}_{-1} |p,\dot{A}\rangle \otimes |g\rangle$
$a^{\mu}_{-1} |p,A\rangle \otimes |g\rangle$
RR
$|p,A,B\rangle_{RR}$
$|p,A,\dot{B}\rangle$
$|p,\dot{A},B\rangle$
$|p,\dot{A},\dot{B}\rangle$

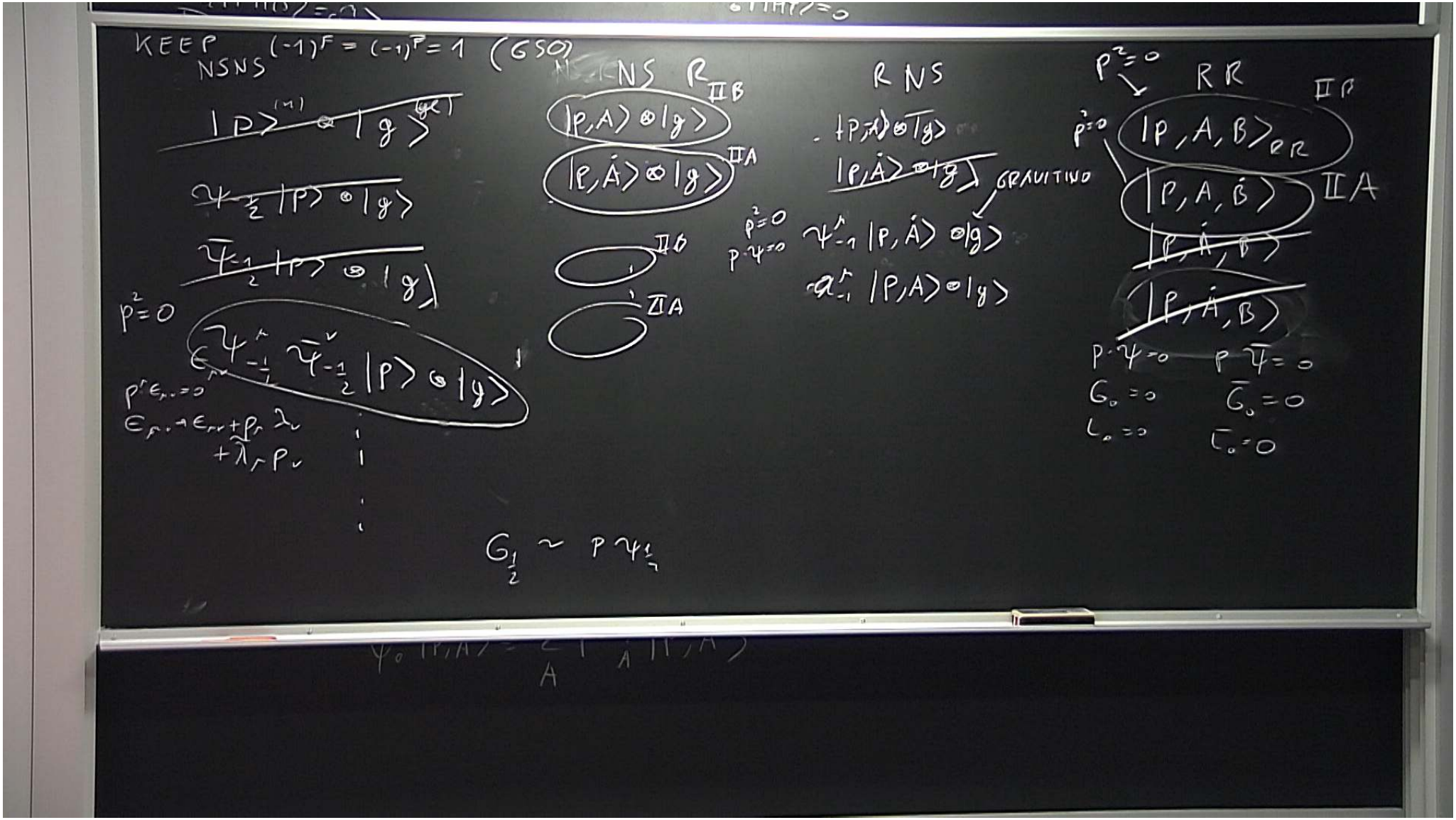

KEEP
NSNS
(-1)^F = (-1)^P = 1 (GSO)
NS R
IIB
|p,A⟩ ⊗ |g⟩
IIA
|p,Ȧ⟩ ⊗ |g⟩
RNS
|p,A⟩ ⊗ |g⟩
|p,Ȧ⟩ ⊗ |g⟩
RR
IIB
|p,A,B⟩ RR
|p,A,Ḃ⟩
|p,Ȧ,B⟩
|p,Ȧ,Ḃ⟩
II

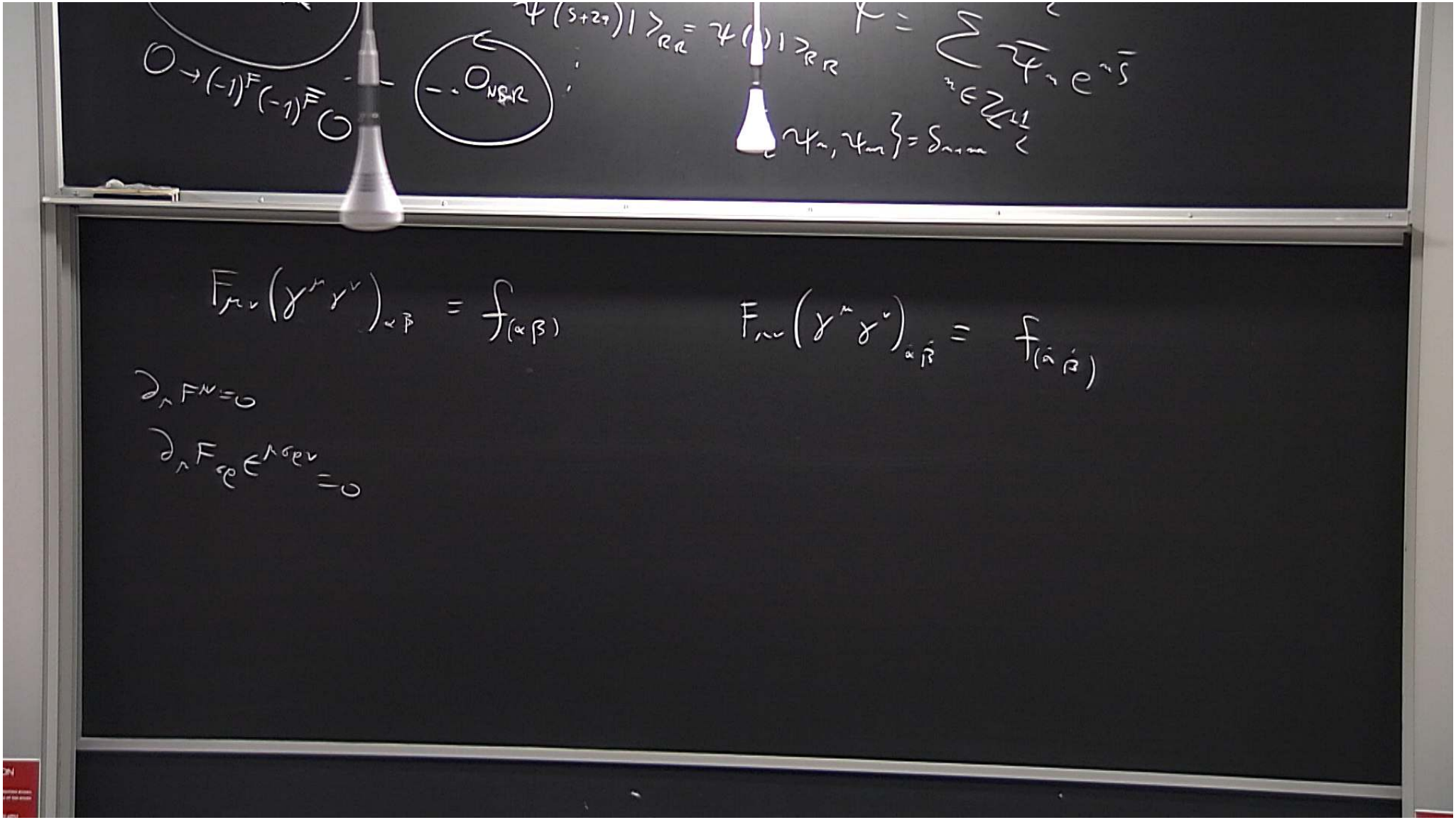

KEEP $(-1)^F = (-1)^{\tilde{F}} = 1$ (GSO)
NSNS
$|p\rangle^{(-1)} \otimes |g\rangle^{(R)}$
$\psi_{-\frac{1}{2}}|p\rangle \otimes |g\rangle$
$\tilde{\psi}_{-\frac{1}{2}}|p\rangle \otimes |g\rangle$
$\psi_{-\frac{1}{2}}\tilde{\psi}_{-\frac{1}{2}}|p\rangle \otimes |g\rangle$
NS-NS
R_{IIB}
$|p,A\rangle \otimes |g\rangle$
$|p,\dot{A}\rangle \otimes |g\rangle$ IIA
R NS
$|p,A\rangle \otimes |g\rangle$
$|p,\dot{A}\rangle \otimes |g\rangle$
$\psi_{-1}|p,\dot{A}\rangle \otimes |g\rangle$
$a_{-1}|p,A\rangle \otimes |g\rangle$
RR
IIB
$|p,A,B\rangle_{QR}$
$|p,A,\dot{B}\rangle$
$|p,\dot{A},B\rangle$
$|p,\dot{A},\dot{B}\rangle$
IIA

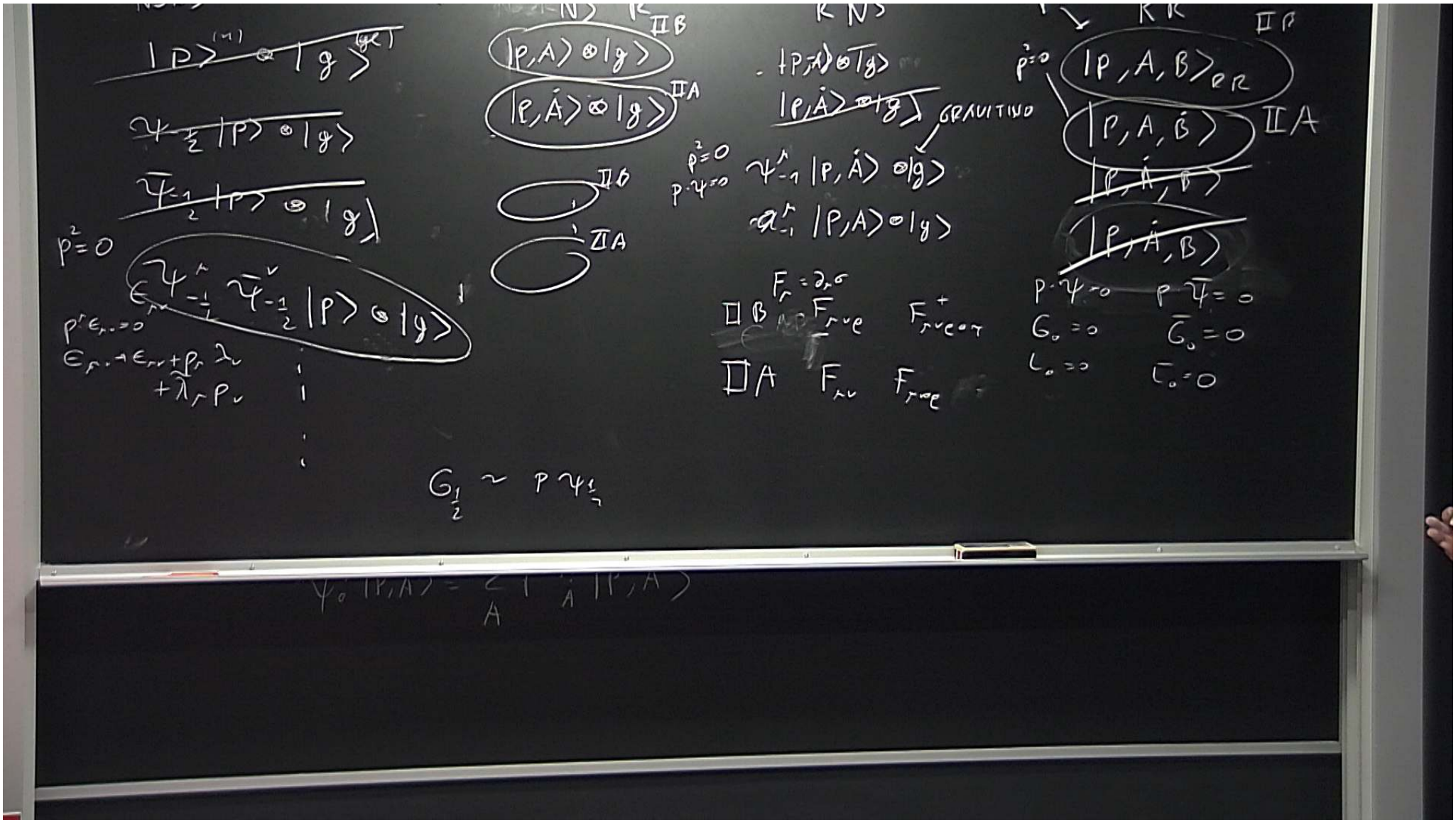

$\psi(s+2\pi)|\rangle_{RR} = \psi(s)|\rangle_{RR}$
$O \to (-1)^F (-1)^{\bar{F}} O$
$O_{NS,R}$
$\{\psi_m, \psi_n\} = \delta_{m+n,0}$
$(-1)^F \psi = -\psi (-1)^F$
$(-1)^{\bar{F}} \psi = \psi (-1)^{\bar{F}}$
$(-1)^F \bar{\psi} = \bar{\psi} (-1)^F$
$(-1)^{\bar{F}} \bar{\psi} = -\bar{\psi} (-1)^{\bar{F}}$
$(-1)^F = e^{2\pi i L_0}$
$(-1)^{\bar{F}} = e^{2\pi i \bar{L}_0}$
$|g\rangle_{NS}^{R}$
$(-1)^F = (-1)^{\bar{F}} = -1$
$T = \frac{1}{2}(\partial X)^2 + \psi \partial \psi$
CAUTION


$p^2=0$
$p^\mu \epsilon_\mu = 0$
$\epsilon_\mu \to \epsilon_\mu + p_\mu \lambda_\nu + \lambda_\mu p_\nu$
$|p,A\rangle_{NSR}$
$|p,A\rangle_{NS\,R}$


KEEP $(-1)^F = (-1)^{\bar{F}} = 1$ (GSO)
NSNS
NS NS
R NS
RR
GRAVITINO
$p^2 = 0$
$p \cdot \psi = 0$
$p^2 = 0$
$p \cdot \epsilon_\mu = 0$
$\epsilon_{\mu\nu} \sim \epsilon_{\mu\nu} + p_\mu \lambda_\nu + \lambda_\mu p_\nu$
$G_{-\frac{1}{2}} \sim p \psi_{-\frac{1}{2}}$
$\psi_0^\mu |p, \dot{A}\rangle = \sum_A \tilde{\Gamma}^\mu_{\dot{A}A} |p, A\rangle$


KEEP $(-1)^F = (-1)^{\tilde{F}} = 1$ (GSO)
NSNS
NS-NS
IIB
IIA
RNS
RR
IIB
IIA
GRAVITINO
$p^2 = 0$
$p \cdot \psi = 0$
$p \cdot \tilde{\psi} = 0$
$G_0 = 0$
$\tilde{G}_0 = 0$
$L_0 = 0$
$\tilde{L}_0 = 0$
$p^2 = 0$
$p \cdot \epsilon_r = 0$
$\epsilon_r \to \epsilon_r + p_r \lambda$
$+ \lambda_r p$
$G_{\frac{1}{2}} \sim p \psi_{\frac{1}{2}}$


$O \to (-1)^F (-1)^F O$
$O_{NS,R}$
$\psi(s+2\pi)|\rangle_{RR} = \psi(s)|\rangle_{RR}$
$\psi = \sum_{n \in \mathbb{Z}+\frac{1}{2}} \psi_n e^{ns}$
$\{\psi_n, \psi_m\} = \delta_{n+m}$
$F_{\mu\nu}(\gamma^\mu\gamma^\nu)_{\alpha\beta} = f_{(\alpha\beta)}$
$F_{\mu\nu}(\gamma^\mu\gamma^\nu)_{\dot\alpha\dot\beta} = f_{(\dot\alpha\dot\beta)}$
$\partial_\mu F^{\mu\nu} = 0$
$\partial_\mu F_{\rho\sigma} \epsilon^{\mu\rho\sigma\nu} = 0$


GRAVITINO
GRAVITON