Title: The Callan Rubakov Effect

Speakers:

Series: Particle Physics

Date: October 03, 2023 - 1:00 PM

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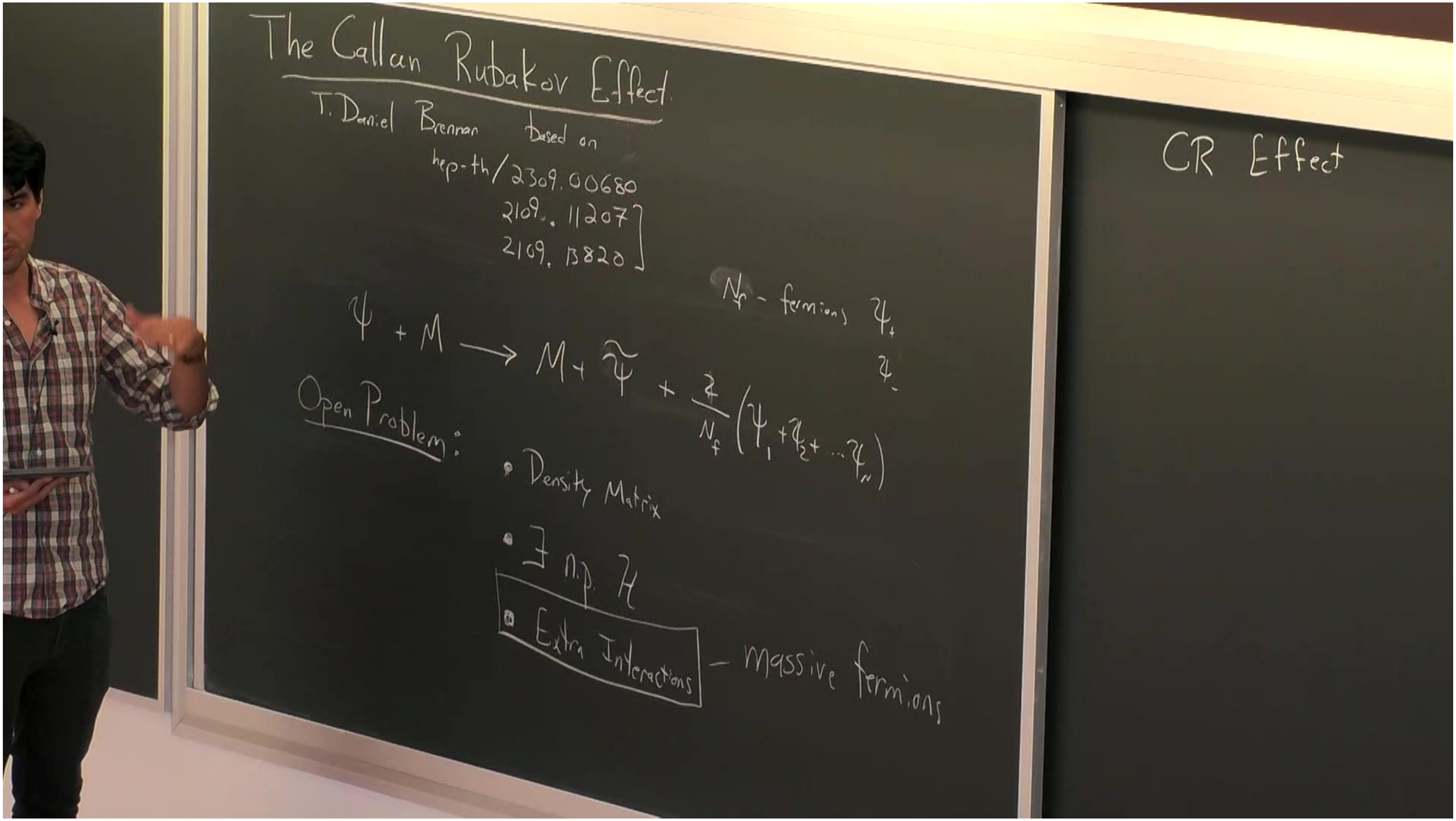
Abstract: The Callan Rubakov Effect describes the interaction between (massless) fermions and a smooth monopole in 4d gauge theory. In this scenario, the fermions can probe the UV physics inside the monopole core which leads to interesting effects such as proton decay in GUT models. However, the monopole-fermion scattering appears to lead to out-states that are not in the perturbative Hilbert space. In this talk, we will review this issue and propose a new physical mechanism that resolves this long-standing confusion.

Zoom link: https://pitp.zoom.us/j/93551249905?pwd=REJvOUtTMlh6RU0vRjZnRVdZckgyZz09


The Callan Rubakov Effect
T. Daniel Brennan based on
hep-th/2309.00680
2109.11207
2109.13820
N_f - fermions ψ_+
ψ_-
$\psi + M \longrightarrow M + \tilde{\psi} + \frac{?}{N_f}(\psi_1 + \psi_2 + \dots \psi_N)$
Open Problem:
• Density Matrix
• ∃ n.p. H
• Extra Interactions
- massive fermions
CR Effect

CR Effect (old)

4d $SU(2)_g$ $+ 2N_f\ \psi$

$+ \Phi$ adj

$\boxed{\text{No Yukawa}}$

$V(\Phi) = (|\Phi|^2 - v^2)^2$

$SU(2)_g$

Smooth monopoles $\longrightarrow$ Dirac

$SU(2)_g \longrightarrow U(1)_g$

$\langle |\vec{\Phi}|^2 \rangle = v^2$ $m_W = v/g$

Sph. Sym (BPS)

$\vec{J} = \vec{L} + \vec{T}$ $\vec{T}$ - $SU(2)_g$

$A_{mono} = T_3 A_{Dirac} \pm \frac{i}{2} T_\pm \underbrace{M(r)} \underbrace{(d\theta \mp i \sin\theta\, d\phi)}_{\omega_\pm}$

$\Phi = v\, T_3\, \underbrace{h(r)}$

$M(r) \longrightarrow 0$

$h(r) \longrightarrow 1 - 1/r \sim e^{-m_W r}$

$A_{mono} \longrightarrow T_3 A_{Dirac}$

$\sin\theta \, d\phi)$

$U_\pm$

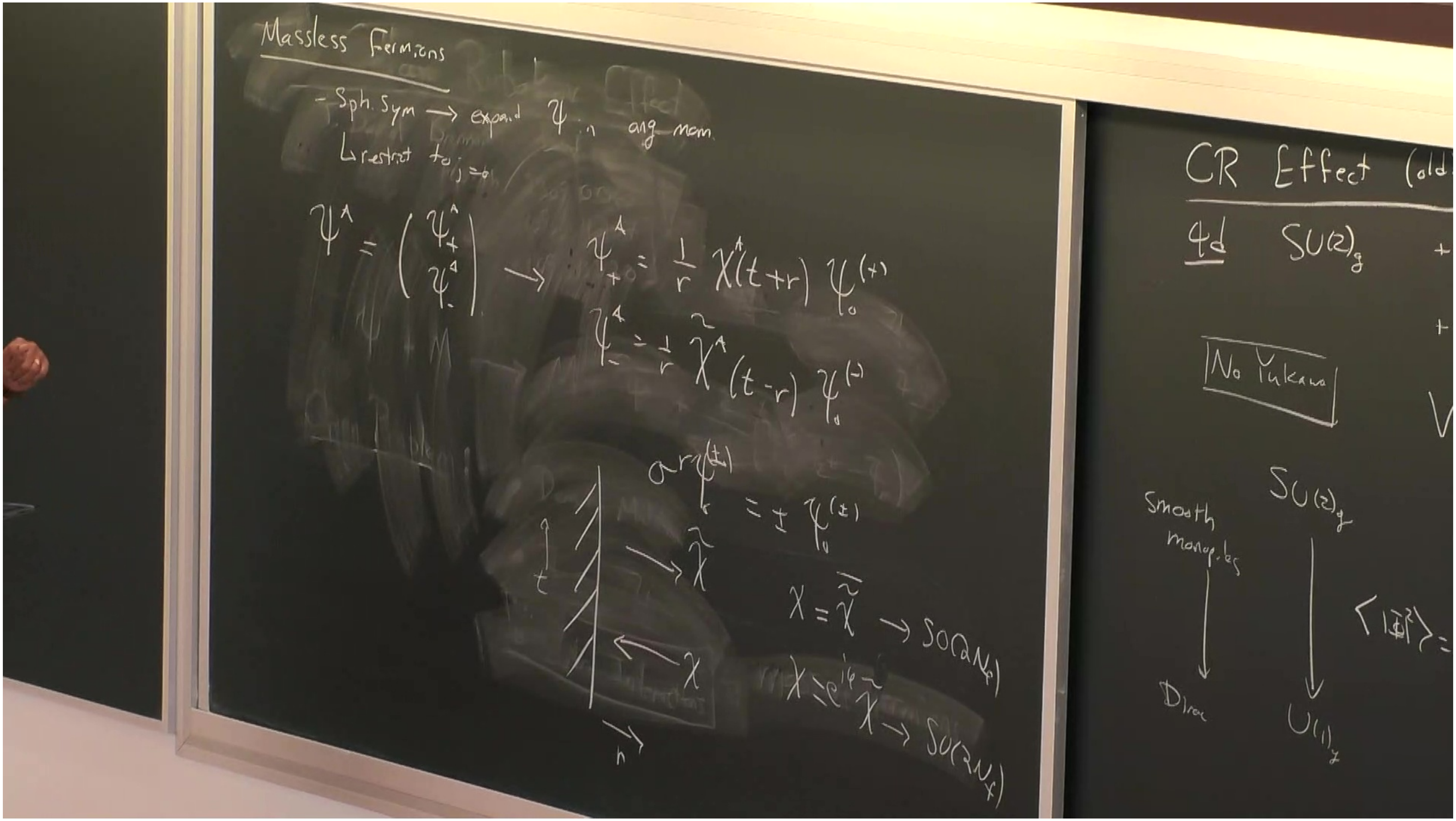
IR modes : photon + $\varphi(t)$

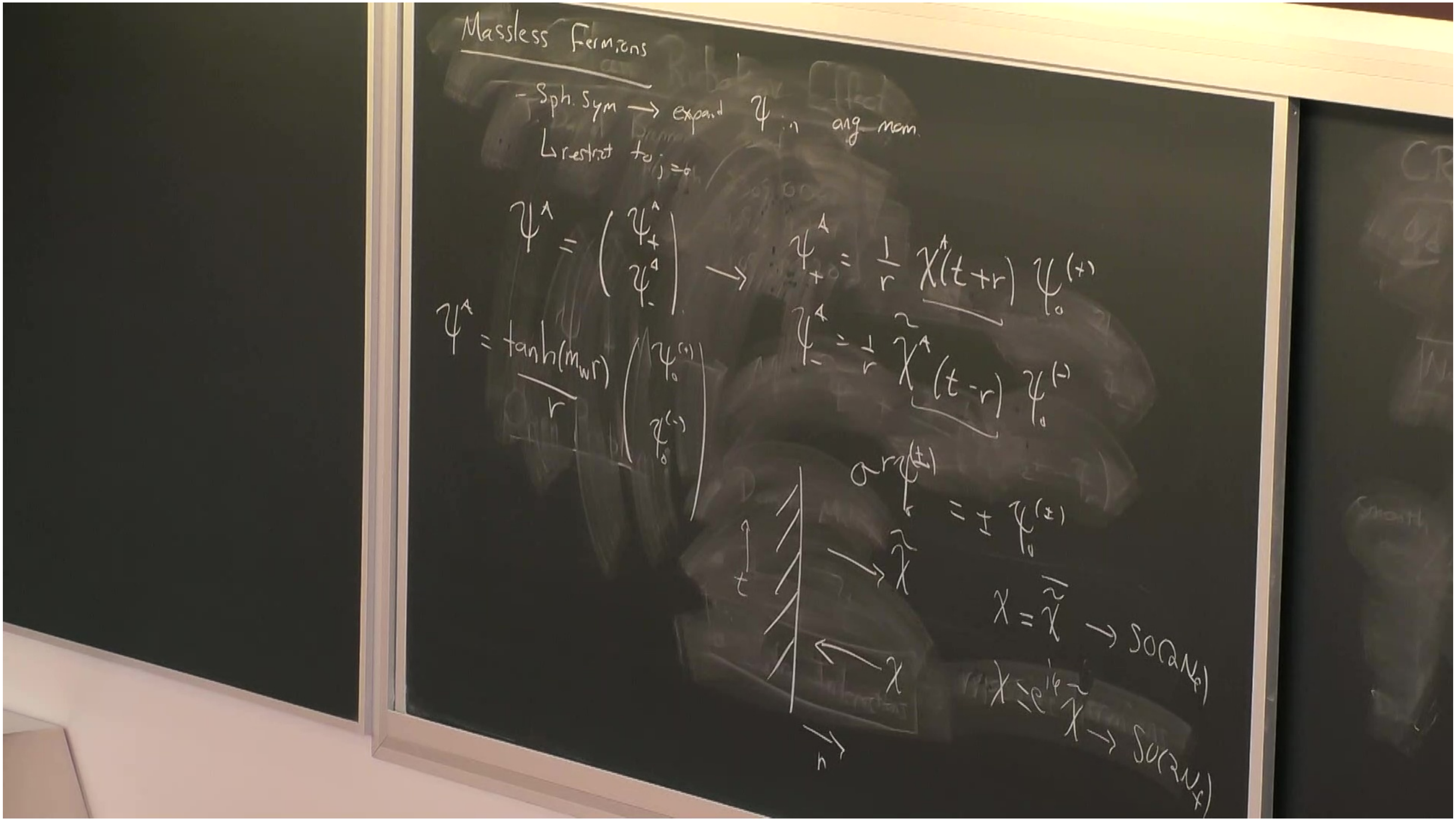
$$S_H = \int \frac{1}{2m_w} \left(\dot{\varphi} - 2A_t \right)^2 dt$$

$$\varphi \sim \varphi + 2\pi$$

$$\hat{H} = \frac{m_w}{2} \hat{p}^2 + 2 A_t \hat{p} \longrightarrow \mathcal{H} = \left\{ |n\rangle \; n \in \mathbb{Z} \;\middle|\; \hat{p}|n\rangle = n|n\rangle \right\}$$

$|n\rangle \longrightarrow 2n$ bulk charge


Massless Fermions
- Sph. Sym → expand ψ in ang mom
↳ restrict to j=0
ψ^A = (ψ^A_+ ψ^A_-) → ψ^A_+ = 1/r χ^A(t+r) ψ_0^(+)
ψ^A_- = 1/r χ̃^A(t-r) ψ_0^(-)
σ^r ψ_0^(±) = ± ψ_0^(±)
t
χ̃
χ
r
χ = χ̃ → SO(2N_f)
χ = e^{iφ} χ̃ → SU(2N_f)
CR Effect (old
4d SU(2)_g
No Yukawa
SU(2)_g
Smooth monopoles
Dirac
U(1)_g
⟨|Φ|²⟩ =


Massless Fermions
- Sph. Sym → expand ψ in ang mom
↳ restrict to j = 0
$\psi^A = \begin{pmatrix} \psi^A_+ \\ \psi^A_- \end{pmatrix} \rightarrow \psi^A_+ = \frac{1}{r} \chi^A(t+r)\, \psi^{(+)}_0$
$\psi^A_- = \frac{1}{r} \tilde{\chi}^A(t-r)\, \psi^{(-)}_0$
$\psi^A = \frac{\tanh(m_W r)}{r} \begin{pmatrix} \psi^{(+)}_0 \\ \psi^{(-)}_0 \end{pmatrix}$
$\sigma_r \psi^{(\pm)}_0 = \pm \psi^{(\pm)}_0$
$\chi = \bar{\tilde{\chi}} \rightarrow SO(2N_f)$
$\chi = e^{i\phi} \tilde{\chi} \rightarrow SU(2N_f)$


Callan Rubakov (New)

Callan Rubakov (New)

$$L = \frac{1}{2m_w}(\dot{\varphi}-2A_0)^2 + \frac{\Theta}{2\pi}(\dot{\varphi}-2a_0).$$

$\Theta \sim \Theta + 2\pi$

$$\hat{p} \to \hat{p} + \frac{\Theta}{2\pi} \Rightarrow \hat{H} = \frac{m_w}{2}\left(\hat{p} - \frac{\Theta}{2\pi}\right)^2 + 2A_0\hat{p}$$

$\Theta \to \Theta + 2\pi$

$|0\rangle \to |1\rangle \Rightarrow$ sources charge 2

Witten Effect: $\Theta_{4d}\int \frac{f \wedge f}{8\pi^2} \Rightarrow$ monopole $\boxed{q_e = \frac{\Theta}{2\pi} q_m}$

$$\Theta_{4d}\int \frac{f\wedge f}{8\pi^2} = \frac{\Theta}{4\pi}\int f_{tr} \to \frac{\Theta}{4\pi}\int(\dot{\varphi}-2A_0)\,dt$$

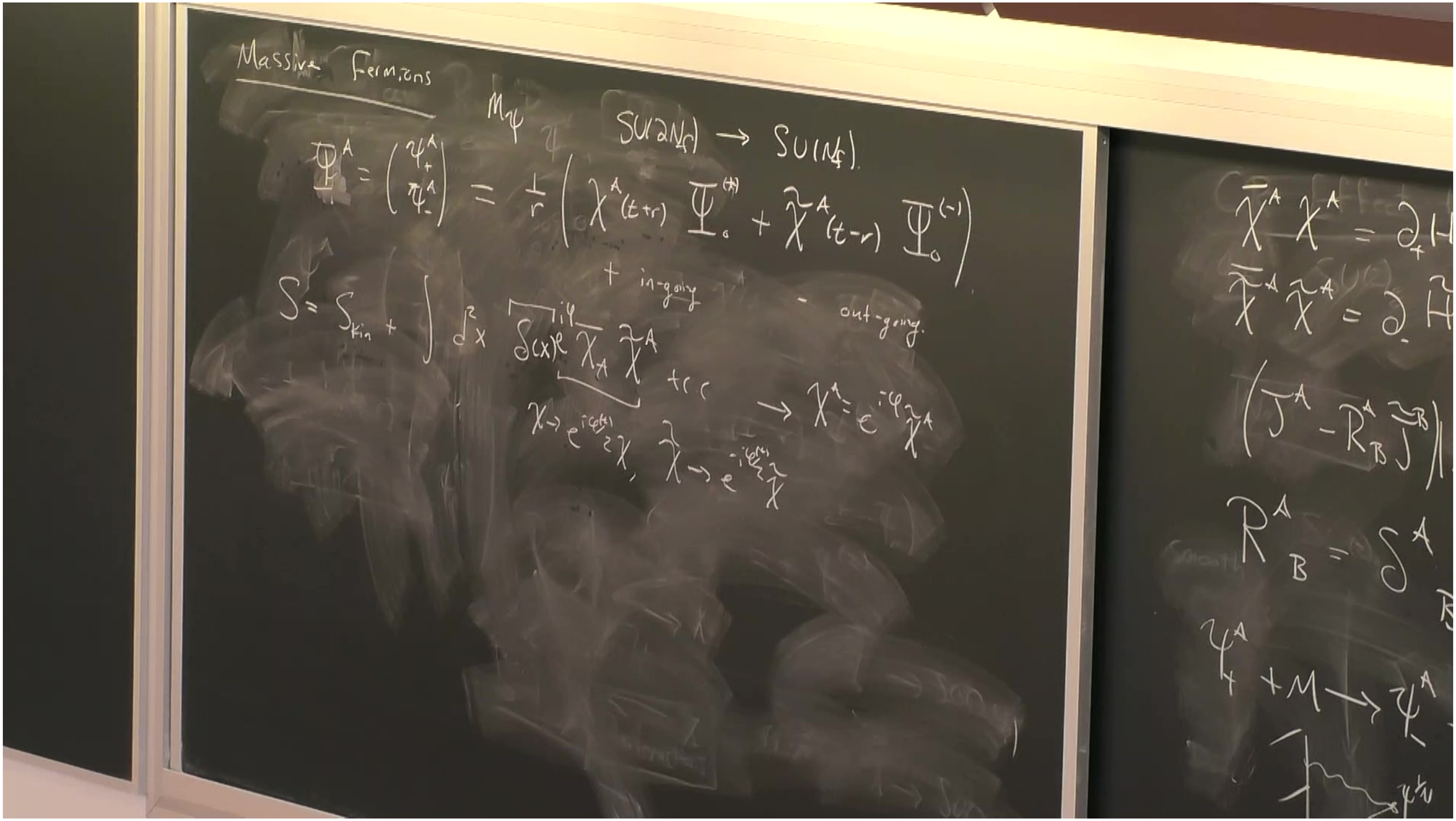
$m_\psi = |m_\psi| e^{i\alpha}$

$\longrightarrow \Theta_{4d} = \alpha$

$\Rightarrow$ Vacuum charge density

$\rho(r) \sim e^{-|m_\psi| r}$

Claim: CR Effect is related!


Massive Fermions
out-going
in-going

$$\bar{\chi}^A \chi^A = \partial_+ H^A = J^A$$
$$\bar{\tilde{\chi}}^A \tilde{\chi}^A = \partial_- \tilde{H}^A = \tilde{J}^A$$
$$h^A = H^A + \tilde{H}^A$$
$$h = \sum h^A$$

$$S_{\text{eff}} = \int d^2x \left(|\partial h|^2 - m_\psi^2 \cos(h^A) - h F_{tr} + \frac{r^2}{2g^2} F_{tr}^2 \right) \qquad \epsilon^{\mu\nu} \partial_\mu h A_\nu^A$$
$$+ \int dt \left(\frac{(\dot{\varphi} - 2A_0)^2}{2m_w} + (\dot{\varphi} - 2A_0)\frac{h}{4\pi} \right)$$
$$\bar{\chi}\left(D_+ - iA_+ - \frac{\dot{\varphi}}{2}\Theta(r)\right)\chi$$

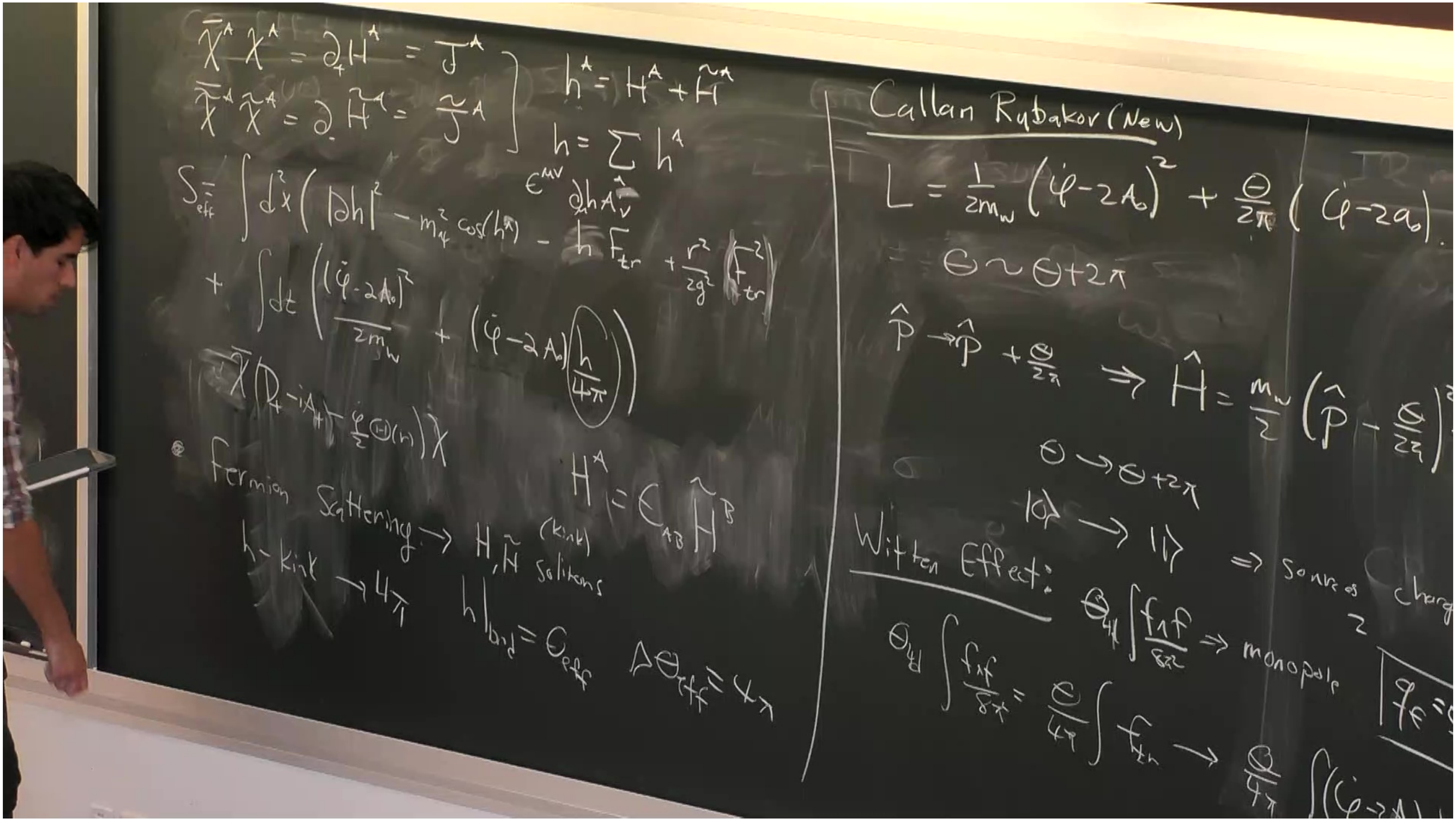
Callan Rubakov (New)

$$L = \frac{1}{2m_w}(\dot{\varphi} - 2A_0)^2 + \frac{\Theta}{2\pi}(\dot{\varphi} - 2a_0).$$
$$\Theta \sim \Theta + 2\pi$$
$$\hat{p} \to \hat{p} + \frac{\Theta}{2\pi} \Rightarrow \hat{H} = \frac{m_w}{2}\left(\hat{p} - \frac{\Theta}{2\pi}\right)^2 + 2A_0\hat{p}$$
$$\Theta \to \Theta + 2\pi$$
$$|0\rangle \to |1\rangle \Rightarrow \text{Sources charge } 2$$

Witten Effect: $\Theta_{4d} \int \frac{f \wedge f}{8\pi^2} \Rightarrow$ monopole

$$\Theta_{4d} \int \frac{f \wedge f}{8\pi^2} = \frac{\Theta}{4\pi} \int f_{tr} \to \frac{\Theta}{4\pi} \int (\dot{\varphi} - 2A_0) \ldots$$

$$\boxed{q_e = \frac{\Theta}{2\pi} q_m}$$



Callan Rubakov (New)
Witten Effect:
Fermion Scattering → H, H̃ solitons
(kink)
h ~ kink → 4π
⇒ monopole

$$\bar{\chi}^A \chi^A = \partial_+ H^A = J^A$$
$$\bar{\tilde{\chi}}^A \tilde{\chi}^A = \partial_- \tilde{H}^A = \tilde{J}^A$$

$$h^A = H^A + \tilde{H}^A$$
$$h = \sum h^A$$

$$S_{eff} = \int d^2x \left(|\partial h|^2 - m_\psi^2 \cos(h^A) - h F_{tr} + \frac{r^2}{2g^2} F_{tr}^2 \right)$$
$$\epsilon^{\mu\nu} \partial_\mu h A_\nu$$
$$+ \int dt \left(\frac{(\dot{\varphi} - 2A_0)^2}{2m_W} + (\dot{\varphi} - 2A_0) \frac{h}{4\pi} \right)$$
$$\bar{\chi} \left(\partial_+ - iA_+ - \frac{\varphi}{2} \Theta(r) \right) \chi$$

- Fermion Scattering $\rightarrow H, \tilde{H}$ solitons (kink)

$$H^A = C_{AB} \tilde{H}^B$$

h-kink $\rightarrow 4\pi$

$|0\rangle \rightarrow |\pi\rangle$

$$h|_{bnd} = \Theta_{eff} \qquad \Delta\Theta_{eff} = 4\pi$$

In 4d

In 4d

$$\psi_+ \to e^{i\alpha}\psi_+ \qquad \overset{\theta}{\alpha} : 0 \to 2\pi$$

$\to$ axionic mode.

$$\psi_+^A + M_{|0\rangle}^{\theta=0} \longrightarrow \psi_-^A + M_{|1\rangle}^{\theta=2\pi} \cong \psi_-^A + D$$

$$R_{charge} \sim 1/m_\psi \to E \sim m_\psi$$

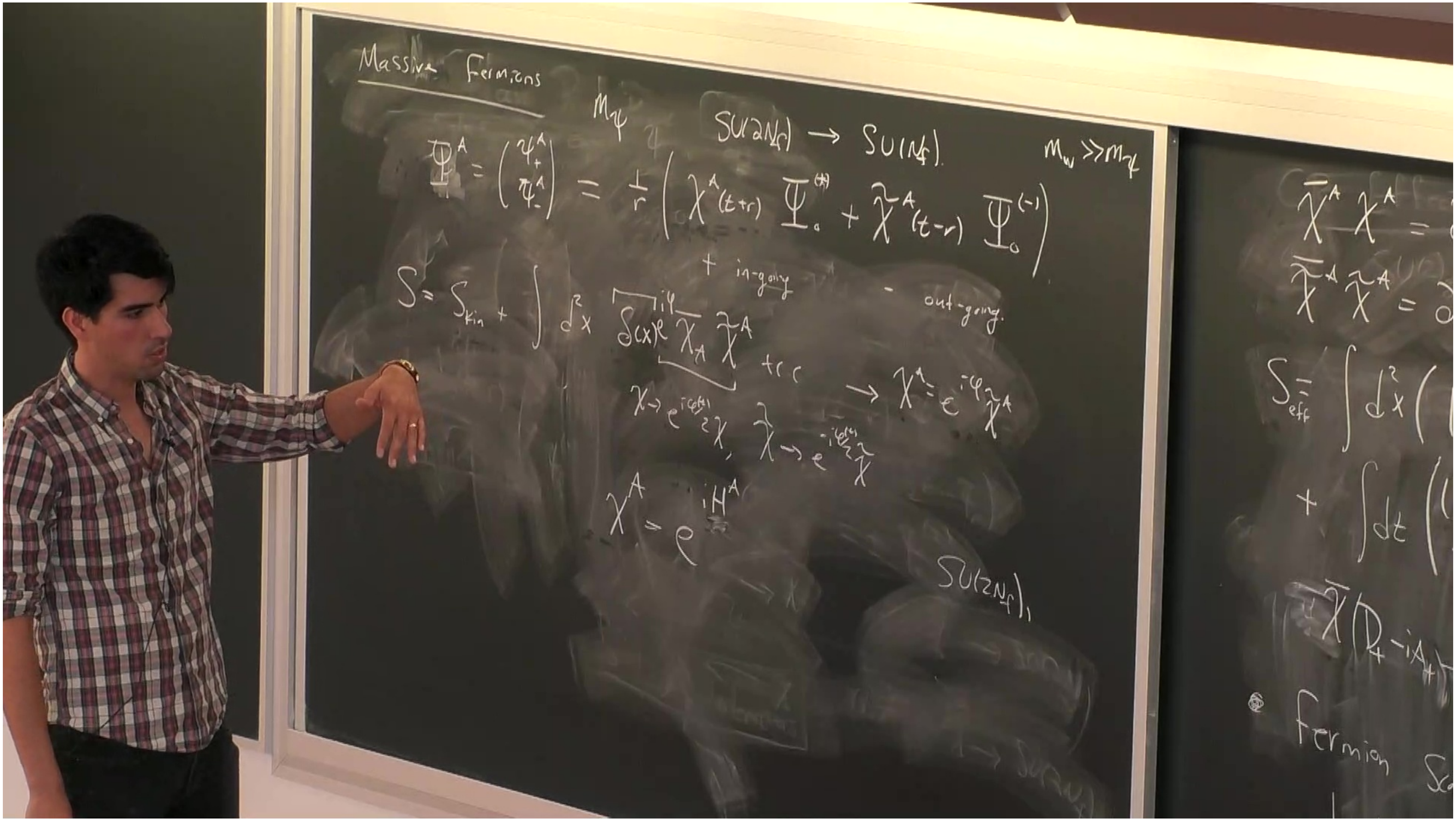
$$m_\psi = |m_\psi| e^{i\alpha}$$

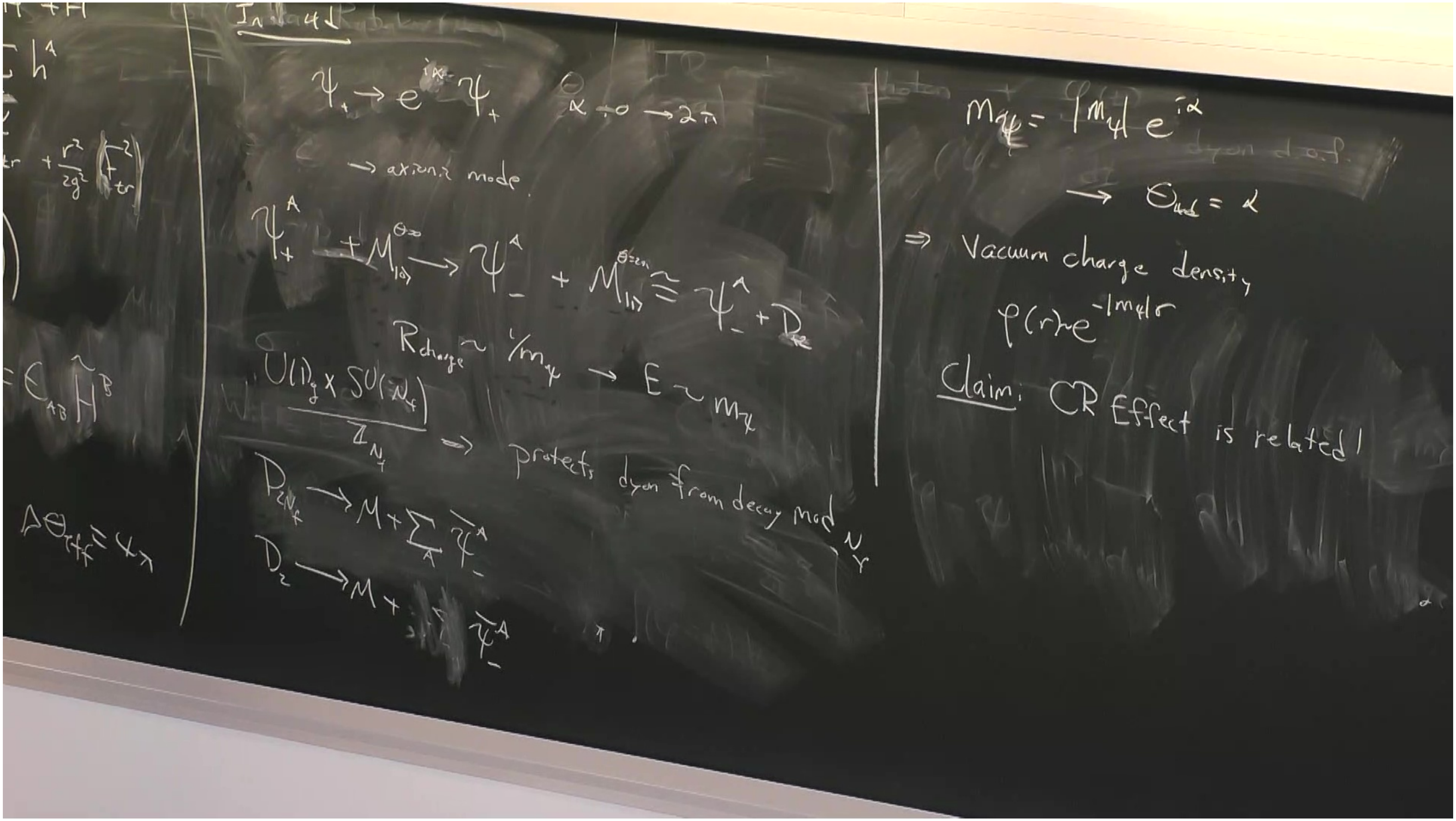
$$\longrightarrow \theta_{ind} = \alpha$$

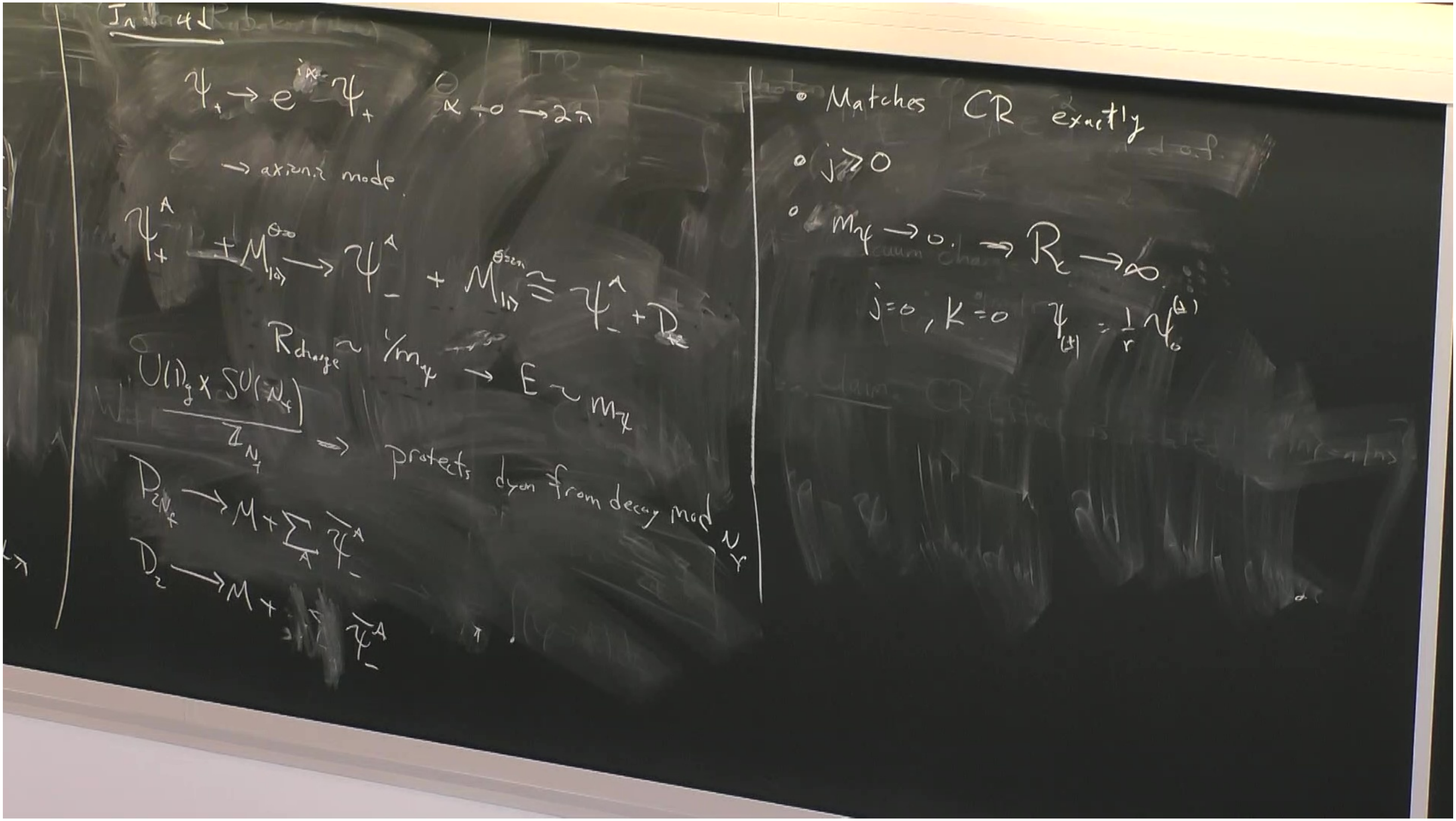
$\Rightarrow$ Vacuum charge density,

$$\rho(r) \sim e^{-|m_\psi| r}$$

Claim: CR Effect is related!


Massive Fermions
SU(2N_f) → SU(N_f)
m_W >> m_ψ
+ in-going
- out-going
SU(2N_f)
Fermion


In 4d
$\psi_+ \to e^{i\alpha}\psi_+$
$\alpha: 0 \to 2\pi$
→ axionic mode
$\psi_+^A + M^{\theta=0}_{|1\rangle} \to \psi_-^A + M^{\theta=2\pi}_{|1\rangle} \cong \psi_-^A + D$
$R_{charge} \sim 1/m_\psi \to E \sim m_\psi$
$\frac{U(1)_g \times SU(N_f)}{\mathbb{Z}_{N_f}}$ ⇒ protects dyon from decay mod N_f
$D_{2N_f} \to M + \sum_A \tilde{\psi}_-^A$
$D_2 \to M + \sum \tilde{\psi}_-^A$
$m_\psi = |m_\psi| e^{i\alpha}$
→ $\theta_{ind} = \alpha$
⇒ Vacuum charge density
$\rho(r) \sim e^{-|m_\psi| r}$
Claim: CR Effect is related!
$\Delta\theta_{eff} = \alpha$


In 4d
$\psi_+ \to e^{i\alpha}\psi_+$ $\alpha : 0 \to 2\pi$
→ axion-like mode
$\psi_+^A + M_{|0\rangle}^{\theta=0} \to \psi_-^A + M_{|1\rangle}^{\theta=2\pi} \cong \psi_-^A + D$
$R_{charge} \sim 1/m_\psi \to E \sim m_\psi$
$\frac{U(1)_g \times SU(N_f)}{\mathbb{Z}_{N_f}}$ ⇒ protects dyon from decay mod N_f
$D_{2N_f} \to M + \sum_A \psi_-^A$
$D_2 \to M + \psi_-^A$
∘ Matches CR exactly
∘ $j \geq 0$
∘ $m_\psi \to 0 \Rightarrow R_c \to \infty$
$j=0,\ K=0$ $\psi_{(+)} = \frac{1}{r}\psi_0^{(+)}$