Title: PSI 2018/2019 - Quantum Field Theory I - Lecture 16

Date: Dec 07, 2018 10:00 AM

URL: http://pirsa.org/18120003

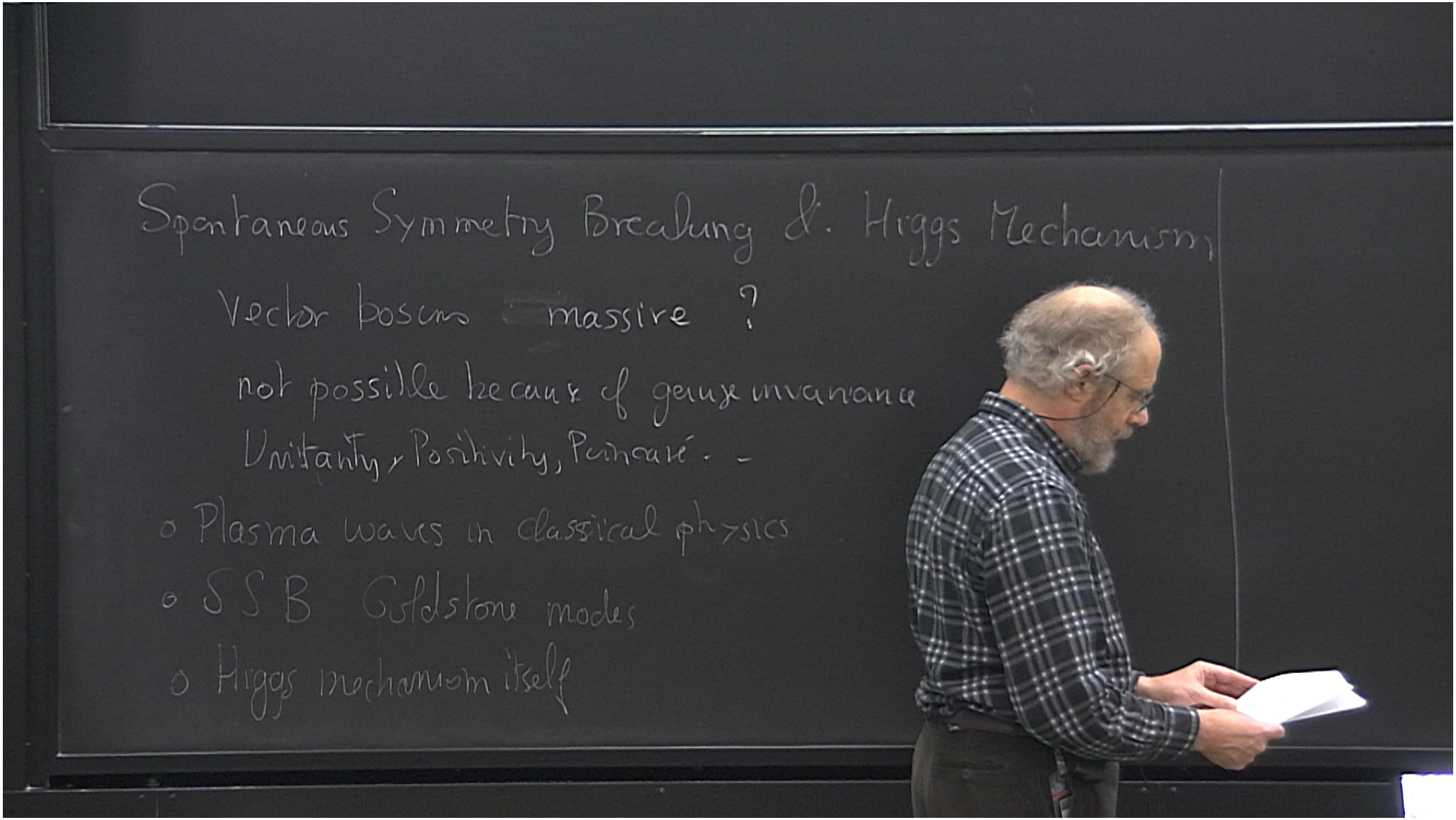
Abstract:

Spontaneous Symmetry Breaking & Higgs Mechanism

Vector bosons massive ?

not possible because of gauge invariance

Unitarity, Positivity, Poincaré. -


Spontaneous Symmetry Breaking & Higgs Mechanism
Vector bosons : massive ?
not possible because of gauge invariance
Unitarity, Positivity, Poincaré. -
o Plasma waves in classical physics
o SSB Goldstone modes
o Higgs mechanism itself

anism

Langmuir & Tonk 1929

Plasma oscillations

"Cold" Plasma  Ion background fixed density $n_i$  $m_{ion} = \infty$

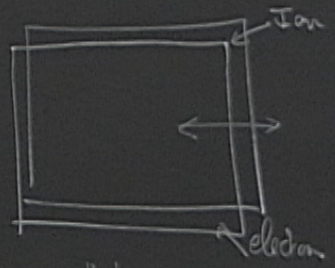
Free electrons $\langle n_e \rangle = n_i$  $m_e$ finite

Maxwell Equation

CGS units with c = 1

$$\vec{\nabla}\cdot\vec{E} = 4\pi\rho \qquad \vec{\nabla}\times\vec{B} = 4\pi\vec{j} + \frac{\partial\vec{E}}{\partial t}$$

$$\vec{\nabla}\cdot\vec{B} = 0 \qquad \vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$




oscillations of the electrons

position individual e⁻

$$x(t) = x_0 + \delta \sin(\omega t)$$

amplitude, frequency

$\rho = 0$ density charg

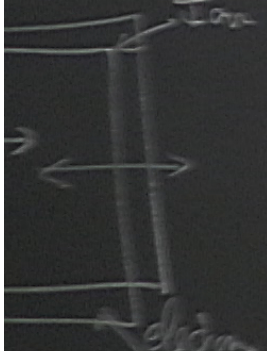
current

$$j(t) = -e\, n_e\, V_0 \cos(\omega t)$$

$$V_0 = \delta \cdot \omega$$

$n_i$ $m_{ions} = \infty$

$m_e$ finite



ork 1929

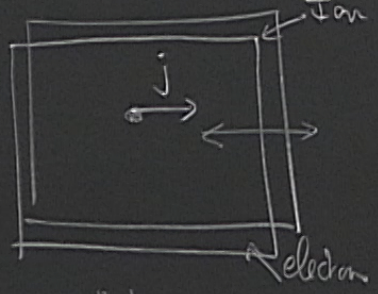
Ion background fixed density $n_i$ $m_{ions} = \infty$

Free electrons $\langle n_e \rangle = n_i$ $m_e$ finite

$c = 1$

$$\vec{\nabla} \times \vec{B} = 4\pi \vec{j} + \frac{\partial \vec{E}}{\partial t}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \| \quad 0$$




oscillations of the electrons in phase

position individual e⁻

$$x(t) = x_0 + \delta \sin(\omega t)$$

$\delta$: amplitude, $\omega$: frequency

$\rho = 0$ density charge

current (oscillating)

$$j(t) = -e\, n_e\, V_0 \cos(\omega t)$$

$V_0 = \delta \cdot \omega$

oscillating $\vec{E}$ field

$$\vec{E}(t) = E_0 \sin(\omega t)$$

$$E_0 \cdot \omega = 4\pi e^2 n_e / \omega$$

- SSB Goldstone modes
- Higgs mechanism itself

e.o.m for the electron

$$\boxed{m \frac{dv}{dt} = -e E}$$

$$j = -e\, v$$

$$\Rightarrow \quad m \omega v_0 = 4\pi e^2 n_e / \omega \, v_0$$

- ~~SSB~~ Goldstone modes
- Higgs mechanism itself

e.o.m for the electron

$$m \frac{dv}{dt} = -e E$$

$$j = -e\, v$$

$\Rightarrow$ $m \omega V_0 = 4\pi e^2 n_e / \omega \, V_0$

$V_0$ arbitrary

$$\omega_{pl}^2 = \frac{4\pi}{m} n_e e^2$$

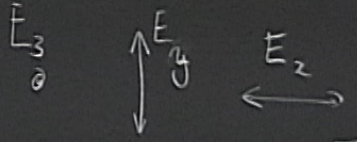
Plasma frequency

$E \rightarrow$ current $\leftrightarrow V$ Maxwell

$V \leftrightarrow E$ Newton

Space homogeneous oscillation of e

Space const oscillating E field




EM. waves with $\vec{k} = 0$, $\omega = \omega_{pl}$

3 possible polarizations

- SSB Goldstone modes
- Higgs mechanism itself

$\nabla \cdot \vec{B} = 0$ $\quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

e.o.m for the electron

$$m \frac{dv}{dt} = -eE$$

$j = -ev$

$E \rightarrow$ current $\leftrightarrow V$ Maxwell

$V \Leftarrow E$ Newton

$\vec{E}$ and electrons oscillates in phase

Space homogeneous oscillation of e

Space const oscillating E field

$\Rightarrow \quad m\omega V_0 = 4\pi e^2 n_e / \omega \, V_0$

$E_3$ (0) $\quad E_y \uparrow\downarrow \quad E_x \leftrightarrow$

$V_0$ arbitrary

$$\omega_{pl}^2 = \frac{4\pi}{m} n_e e^2$$

Plasma frequency

Resonance phenomenon

EM-waves with $\vec{k} = 0$, $\omega = \omega_{pl}$

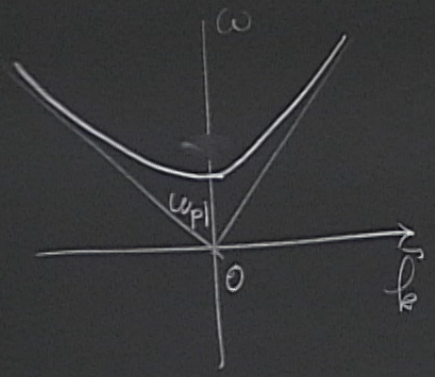
3 possible polarizations

Oscillations of the electrons in phase

$\vec{E}$ and electrons oscillates in phase

Plasma or Langmuir waves

if $\omega \neq \omega_{pl}$, $\vec{k} = 0$




propagating plasma wave only if $\omega > \omega_{pl}$

$k, \omega$ very large

$\omega = |\vec{k}|$ free e.m waves

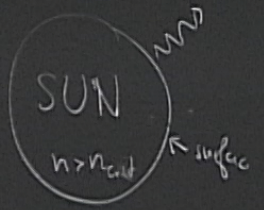
in phase

no propagation if $\omega < \omega_{pl}$

given $\omega$; there is a critical density $n_{crit}$

$n > n_{crit}$ no propagation

$n < n_{crit}$ propagation




$n < n_{crit}$

for $\omega \approx$ thermal radiation

propagating

plasma wave

if $\omega > \omega_{pl}$

$\omega$ very large

$\vec{E}$ free e.m waves

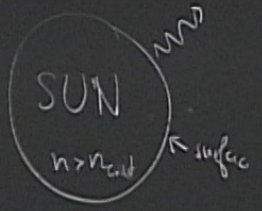
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$n < n_{crit}$

for $\omega \triangleq$ thermal radiation

non-relativistic description

?

relativistic plasma

propagating

plasma wave

if $\omega > \omega_{pl}$

$\omega$ very large

$\vec{E}$ free e.m waves

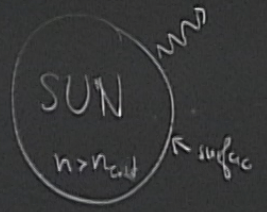
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non-relativistic description

?

relativistic plasma

gaz of $e_+$, $e_-$

$n_e \rightarrow 2n_e$

opagating

lasma wave

ds if $\omega > \omega_{pl}$

$\omega$ ; very large

$\vec{E}$ | free e.m waves

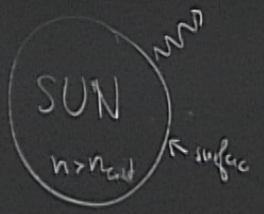
in phase

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for $\omega$ : thermal radiation

non-relativistic description

?

relativistic plasma

gaz of $e_+$, $e_-$

$n_e \rightarrow 2n_e$

plasma: bosons, charged

Charged K.G. particle $\Rightarrow$ Complex Field  U(1) symm $\Rightarrow$ charge  $\phi = \phi_1 + i\phi_2$, $\bar{\phi} = \phi_1 - i\phi_2$

$\phi(x) = \phi_1(x) + i\phi_2(x)$  $(\phi_1, \phi_2) \in$ Fund representation of $U(1)$

$$\mathcal{A}[\phi] = \int d^4x \; \frac{1}{2}\left(\partial_\mu \bar{\phi}\, \partial_\mu \phi\right) + \frac{t}{2}\left(\bar{\phi}\phi\right) + \frac{g}{8}\left(\bar{\phi}\phi\right)^2$$

if $g = 0$  $t = m^2 > 0$  $m$ = mass of the free particle

Charged K.G. particle $\Rightarrow$ Complex Field  U(1) symm $\Rightarrow$ charge  $\phi = \phi_1 + i\phi_2$, $\bar{\phi} = \phi_1 - i\phi_2$

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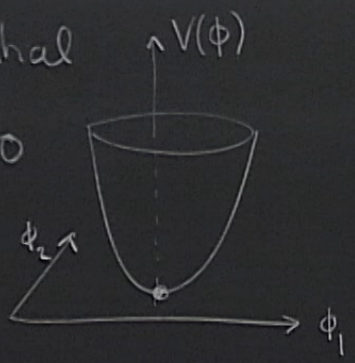
Euclidean or Minkowski

if $g = 0$  $t = m^2 > 0$  $m$ = mass of the free particle  $\rightsquigarrow$ shape of $V(\phi)$ potential

$\langle n(x) \rangle = \langle \bar{\phi}\phi(x) \rangle$  $\phi \sim a^\dagger, a$  density $n \sim a^\dagger a$

density

$g>0$ stable potential




$t>0$ $\langle\phi\rangle=0$

$U(1)$ symmetry

symmetric phase

spectrum: 2 particles of mass $m=\sqrt{t}$

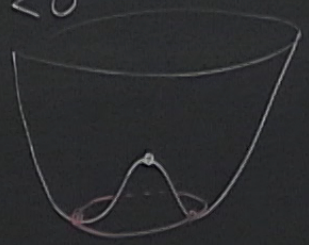
boson & its anti-particle

charge +, charge −

currents, coupling to Maxwell.

Scalar QED

$t<0$

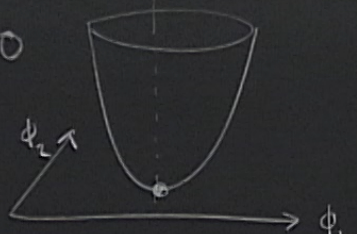


$g>0$ stable potential $V(\phi)$

$t>0$ $\langle\phi\rangle=0$

U(1) symmetry

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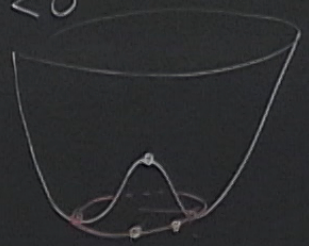
boson & its anti particle

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Scalar QED

$t<0$



"Spontaneously broken symmetry" phase

ensemble of possible "ground state" $|\alpha\rangle$

$\langle\phi\rangle = \phi_0 e^{i\alpha}$ $\alpha$ arbitrary phase

$\phi_0 = \sqrt{\frac{(-2t)}{g}}$

$E(t) = E_0 \sin(\omega t)$

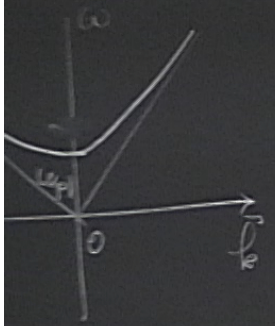
oscillations of the electrons ?

in phase

electrons oscillates in phase

or Langmuir waves

$\neq \omega_{pl}$, $\vec{k} = 0$ propagating plasma wave only if $\omega > \omega_{pl}$




$k, \omega$ very large

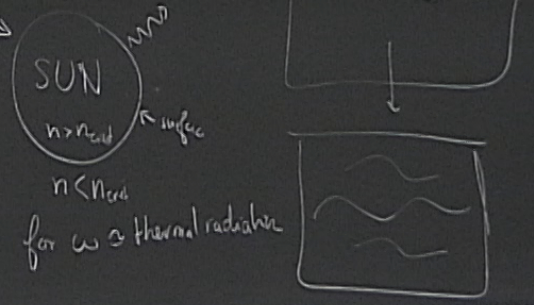
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non-relativistic description

?

relativistic plasma

gaz of $e_+, e_-$

$n_e \rightarrow 2n_e$

plasma: bosons, charged

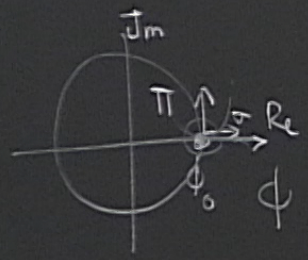
$$V(\phi) = \frac{g}{8}\left(\bar{\phi}\phi - \phi_0^2\right)^2$$

quantum fluctuations around $|\alpha = 0\rangle$

$\Pi$ is massless

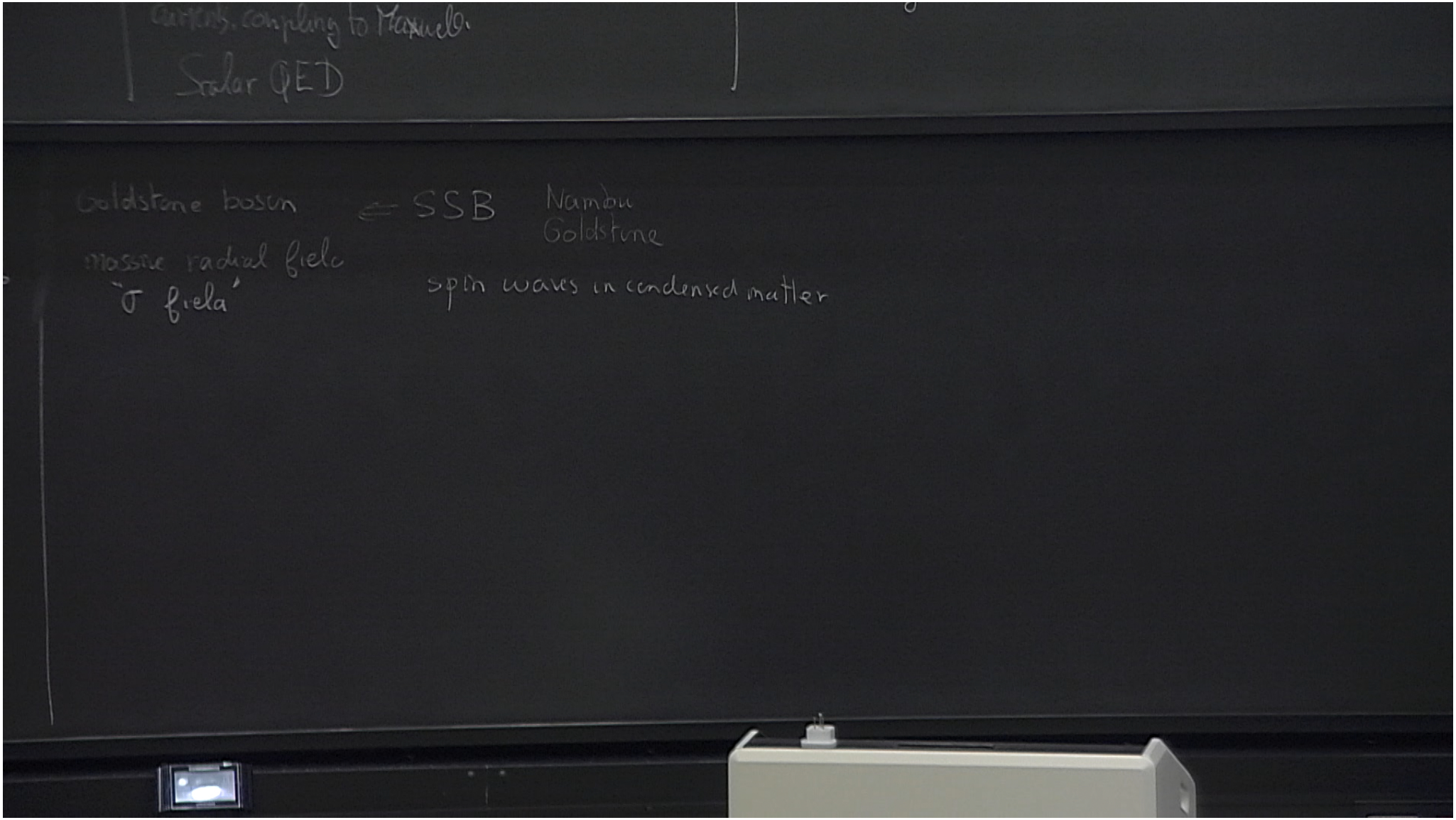
$\sigma$ is massive $M_\sigma = \sqrt{g}\cdot\phi_0$

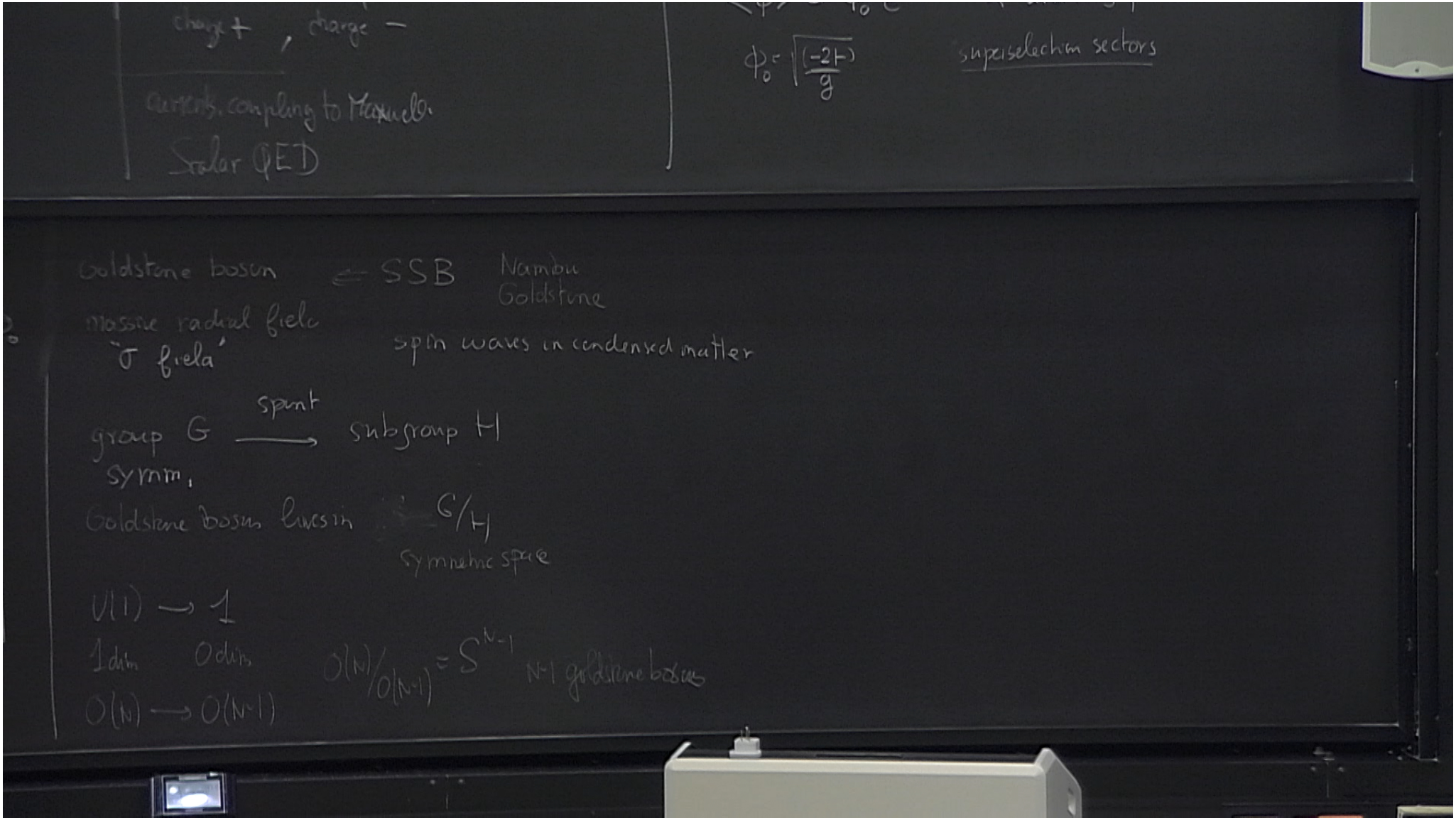
$$\langle\phi\rangle_0 = (\phi_0, 0) \quad , \quad \phi(x) = (\phi_0 + \sigma(x), \Pi(x))$$

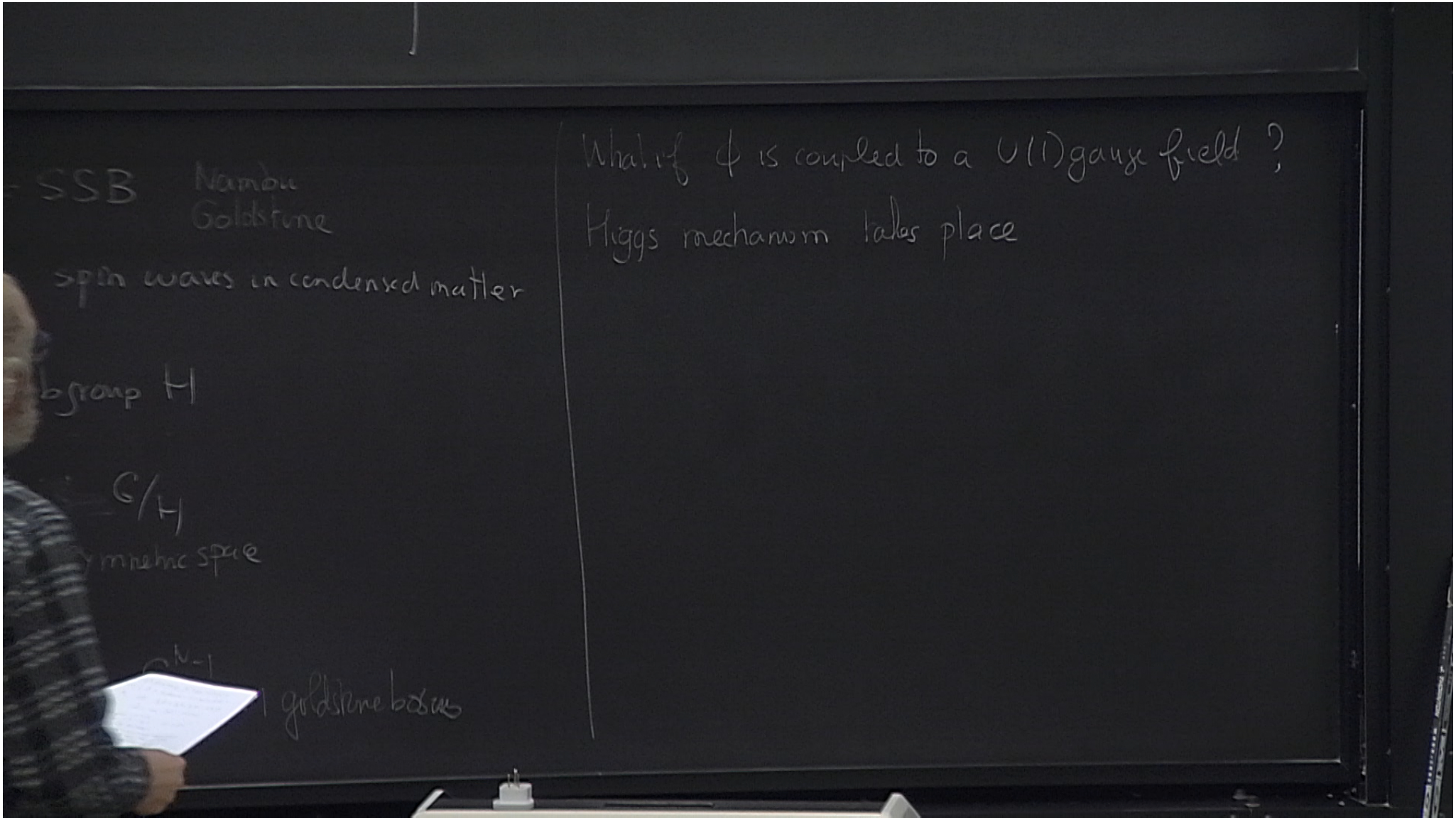


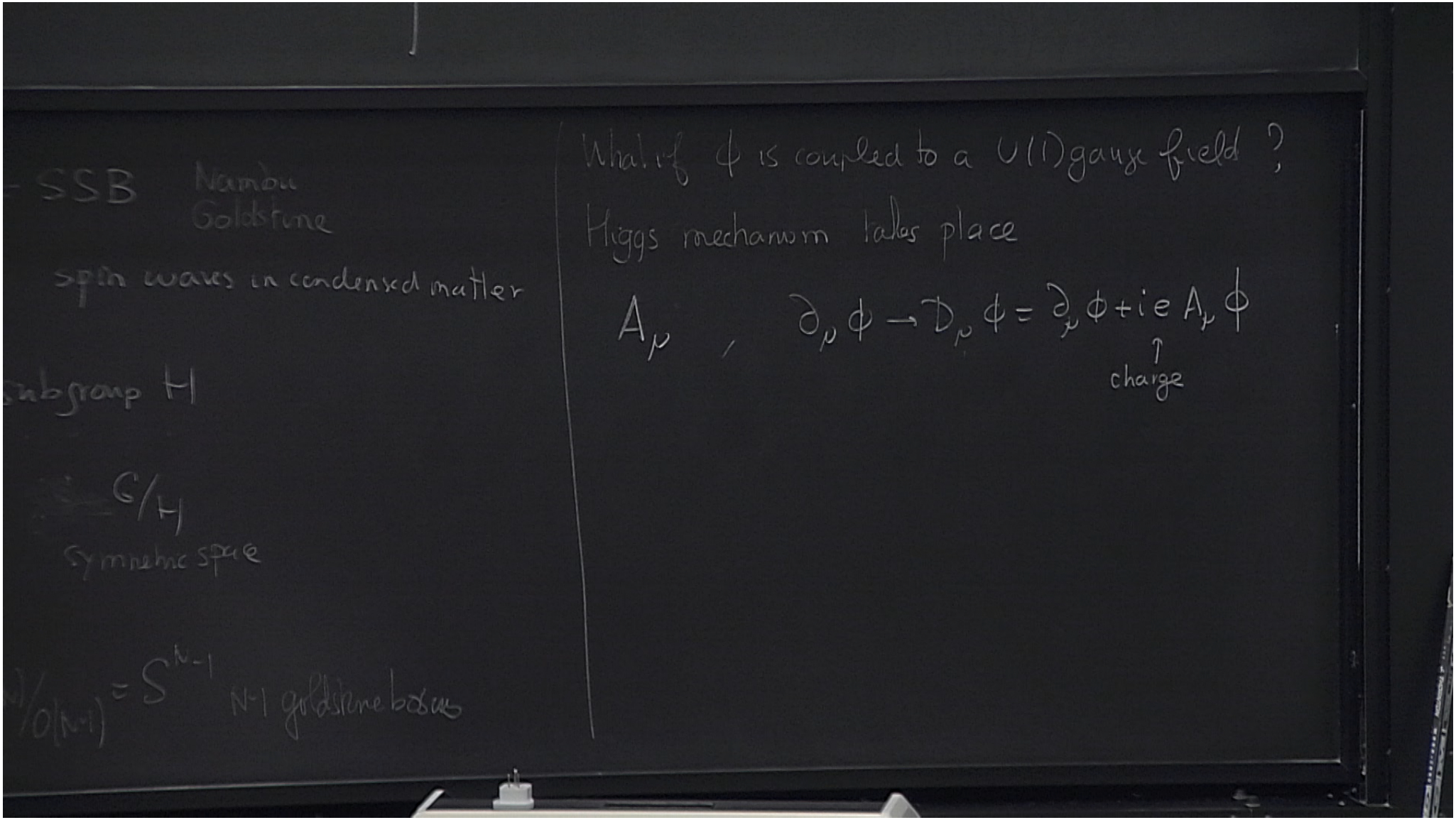

$$A[\phi] = \int d^4x \left[ \frac{1}{2}(\partial_\mu \Pi)^2 + \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{g}{2}\phi_0^2\sigma^2 + \frac{g}{8}\Pi^4 + \frac{g}{8}\sigma^4 + \frac{g}{2}\phi_0\sigma^3 + \frac{g}{2}\phi_0\sigma\Pi^2 + \frac{g}{4}\Pi^2\sigma^2 \right]$$

interactions between $\Pi$ and $\sigma$


Scalar QED
Goldstone boson ⇐ SSB Nambu Goldstone
massive radial field
"σ field"
spin waves in condensed matter


charge +
charge −
currents coupling to Maxwell
Scalar QED
$\phi_0 = \sqrt{\frac{(-2\Gamma)}{g}}$
superselection sectors
Goldstone boson ⇐ SSB Nambu Goldstone
massive radial field
"σ field"
spin waves in condensed matter
group G —spont→ subgroup H
symm.
Goldstone bosons live in G/H
symmetric space
U(1) → 1
1 dim 0 dim
O(N) → O(N-1)
O(N)/O(N-1) = S^{N-1}
N-1 goldstone bosons


SSB
Nambu
Goldstone
spin waves in condensed matter
group H
G/H
symmetric space
goldstone bosons
What if φ is coupled to a U(1) gauge field ?
Higgs mechanism takes place


SSB
Nambu
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spin waves in condensed matter
subgroup H
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N-1 goldstone bosons
What if φ is coupled to a U(1) gauge field ?
Higgs mechanism takes place
$A_\mu$ , $\partial_\mu \phi \to D_\mu \phi = \partial_\mu \phi + ie A_\mu \phi$
charge

SSB Nambu Goldstone

spin waves in condensed matter

subgroup H

$G/H$

symmetric space

$S^{N-1} = O(N)/O(N-1)$ N-1 goldstone bosons

What if $\phi$ is coupled to a $U(1)$ gauge field ?

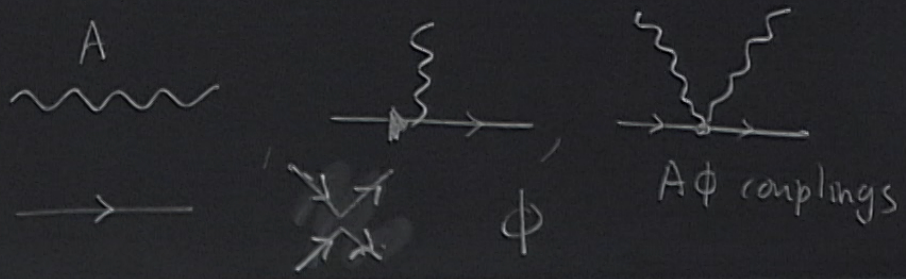
Higgs mechanism takes place

$A_\mu$ , $\partial_\mu \phi \to D_\mu \phi = \partial_\mu \phi + ie A_\mu \phi$

charge

ordinary Maxwell Action for A

$$\int (\partial_\mu A_\nu - \partial_\nu A_\mu)^2$$



Gauge invariance

$A_\mu \to A_\mu + \partial_\mu \alpha$

$\alpha$ is a gauge parameter

$\alpha = \alpha(x)$ arbitrary

$\phi \to \phi e^{i\alpha}$

$\bar{\phi} \to \bar{\phi} e^{-i\alpha}$

same physical theory

as long as $t > 0$ not a problem $|0\rangle$

if SSB $t < 0$ $|\alpha\rangle$

Gauge invariance

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only one vacuum! SSB?

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only one vacuum! SSB? $\Rightarrow$ Goldstone modes!

Gauge invariance

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same physical theory

$A_\mu \to \vec{E}, \vec{B} \Leftarrow \vec{E} = \vec{B} = 0$

$A_\mu$ ↓ gauge

$A_\mu = 0$

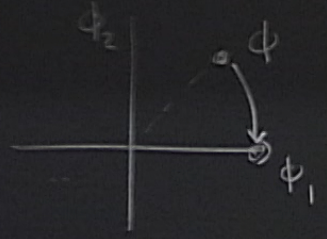
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only one vacuum! SSB? ⇒ Goldstone modes!

U(1) case




$\vec{E} = \vec{B} = 0$

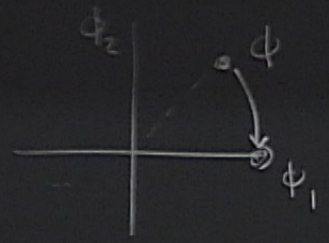
$(\phi_1(x), \phi_2(x)) = \phi(x)$

for x fixed, gauge transformation by angle $= -\operatorname{Arg} \phi(x)$

gauge fixing condition depends on $\phi$

$\vec{E} = \vec{B} = 0$

U(1) case




$(\phi_1(x), \phi_2(x)) = \phi(x)$

for x fixed, gauge transformation by angle $= -\mathrm{Arg}\,\phi(x)$

gauge fixing condition depends on $\phi$

$\phi(x) = (\phi_0 + H(x), 0)$

gauge fixing $\Rightarrow \Pi(x) = 0$

still $A_\mu(x)$

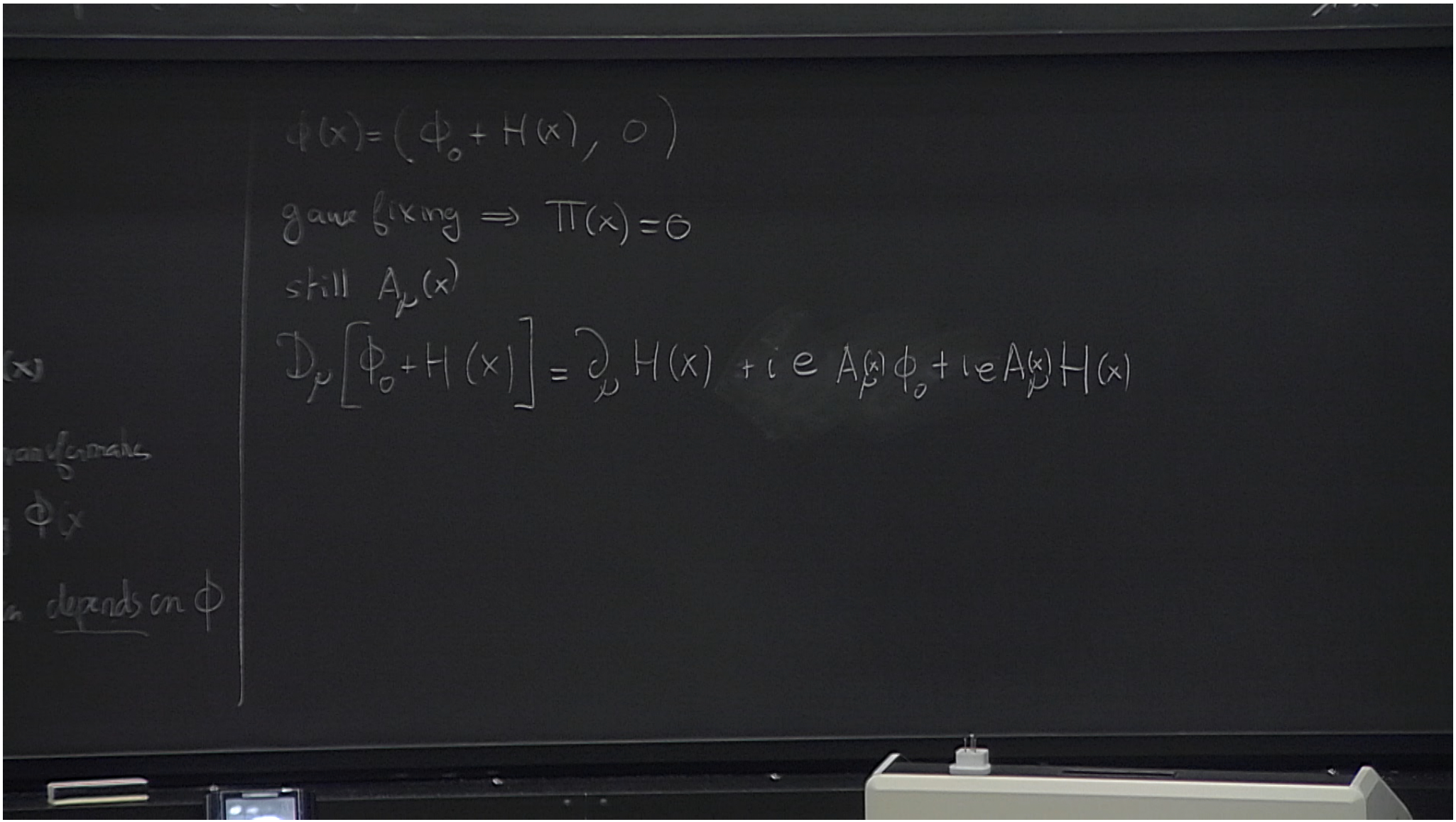
$D_\mu [\phi_0 + H(x)] = \partial_\mu H(x)$

$\phi(x) = (\phi_0 + H(x), 0)$

gauge fixing $\Rightarrow \Pi(x) = 0$

still $A_\mu(x)$

$D_\mu [\phi_0 + H(x)] = \partial_\mu H(x) + ie A_\mu(x) \phi_0 + ie A_\mu(x) H(x)$



$\phi(x) = (\phi_0 + H(x), 0)$

gauge fixing $\Rightarrow \Pi(x) = 0$

still $A_\mu(x)$

$$D_\mu [\phi_0 + H(x)] = \partial_\mu H(x) + ie A_\mu(x) \phi_0 + ie A_\mu(x) H(x)$$

Kinetic term for $\phi$

$$D_\mu \phi \, \partial^\mu \bar{\phi} = D_\mu [\phi_0 + H] [\overline{D^\mu (\phi_0 + H)}] = (\partial_\mu H)^2 + e^2 \phi_0^2 A_\mu^2 + e^2 A_\mu^2 H^2 + 2e^2 \phi_0 A_\mu^2 H$$

Potential term for $\phi$

$$V(H) = \frac{g}{8} (\phi_0^2 - H^2)^2$$

$$\phi(x) = (\phi_0 + H(x),\ 0)$$

gauge fixing $\Rightarrow \Pi(x) = 0$

still $A_\mu(x)$

$$D_\mu[\phi_0 + H(x)] = \partial_\mu H(x) + ie A_\mu(x)\phi_0 + ieA_\mu(x)H(x)$$

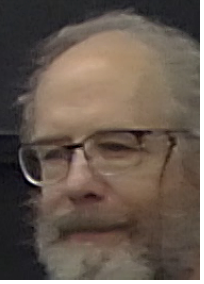
Kinetic term for $\phi$

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Potential term for $\phi$

$$V(H) = \tfrac{9}{8}(\phi_0^2 - H^2)^2$$

Maxwell term $(\partial_\nu A_\nu - \partial_\nu A_\mu)^2$



the vacuum. SSB ⇒ Goldstone modes!

Vector field $A_\mu(x)$ spin 1

Transverse field $H(x)$ real spin 0 (no charge)

the vacuum. SSB ⇒ Goldstone modes

Vector field $A_\mu(x)$ spin 1

Transverse field $H(x)$ real spin 0 (no charge)

Quadratic terms in the action

$H \qquad \frac{1}{2}(\partial_\mu H)^2$

# Scalar QED

$$\phi(x) = (\phi_0 + H(x),\ 0)$$

gauge fixing $\Rightarrow \Pi(x) = 0$

still $A_\mu(x)$

$$D_\mu[\phi_0 + H(x)] = \partial_\mu H(x) + ie A_\mu(x)\phi_0 + ieA_\mu(x)H(x)$$

Kinetic term for $\phi$

$$D_\mu\phi\, \partial^\mu\bar{\phi} = D_\mu[\phi_0+H][\overline{D_\mu(\phi_0+H)}] = (\partial_\mu H)^2 + e^2\phi_0^2 A_\mu^2 + e^2 A_\mu^2 H^2 + 2e^2\phi_0 A_\mu^2 H$$

Potential term for $\phi$

$$V(H) = \frac{g}{8}\left[\phi_0^2 - (\phi_0+H)^2\right]^2$$

Maxwell term $(\partial_\mu A_\nu - \partial_\nu A_\mu)^2$

$\phi(x) = (\phi_0 + H(x), 0)$

gauge fixing $\Rightarrow \Pi(x) = 0$

still $A_\mu(x)$

$$D_\mu[\phi_0 + H(x)] = \partial_\mu H(x) + ie A_\mu(x)\phi_0 + ieA_\mu(x)H(x)$$

Kinetic term for $\phi$

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Potential term for $\phi$

$$V(H) = \frac{g}{8}\left[\phi_0^2 - (\phi_0 + H)^2\right]^2$$

Maxwell term $(\partial_\mu A_\nu - \partial_\nu A_\mu)^2$

$$\frac{g}{8}(2H\phi_0 + H^2)^2$$

only one vacuum; SSB ⇒ Goldstone modes

Vector field $A_\mu(x)$ spin 1

Transverse field $H(x)$ real spin 0 (no charge)

Quadratic terms in the action

$H$ $\quad \frac{1}{2}(\partial_\nu H)^2 + \frac{g}{2}\phi_0^2 H^2 + \dots$

$A_\mu$ $\quad (\partial_\mu A_\nu - \partial_\nu A_\mu)^2$

only one vacuum; SSB ? ⇒ Goldstone modes ?

Vector field $A_\mu(x)$ spin 1

Transverse field $H(x)$ real spin 0 (no charge)

Quadratic terms in the action

$$H \quad \frac{1}{2}(\partial_\mu H)^2 + \frac{g}{2}\phi_0^2 H^2 + \dots$$

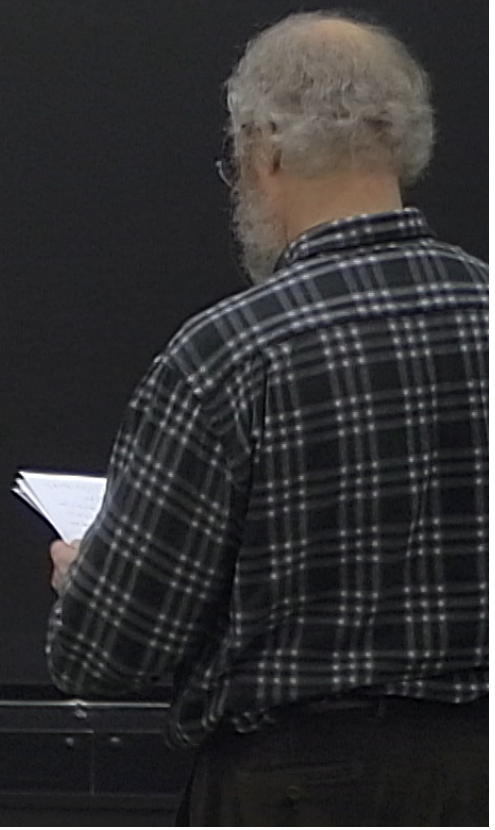
$H$ is massive

$M_H = e\phi_0$

$$A_\mu \quad (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 + e^2\phi_0^2 A_\mu^2$$

Vector Field — mass term

Vector field massive $\boxed{M_A = e\phi_0}$



only one vacuum? SSB? ⇒ Goldstone modes?

Vector field $A_\mu(x)$ spin 1

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Quadratic terms in the action

$$H \quad \frac{1}{2}(\partial_\nu H)^2 + \frac{g}{2}\phi_0^2 H^2 + \dots$$

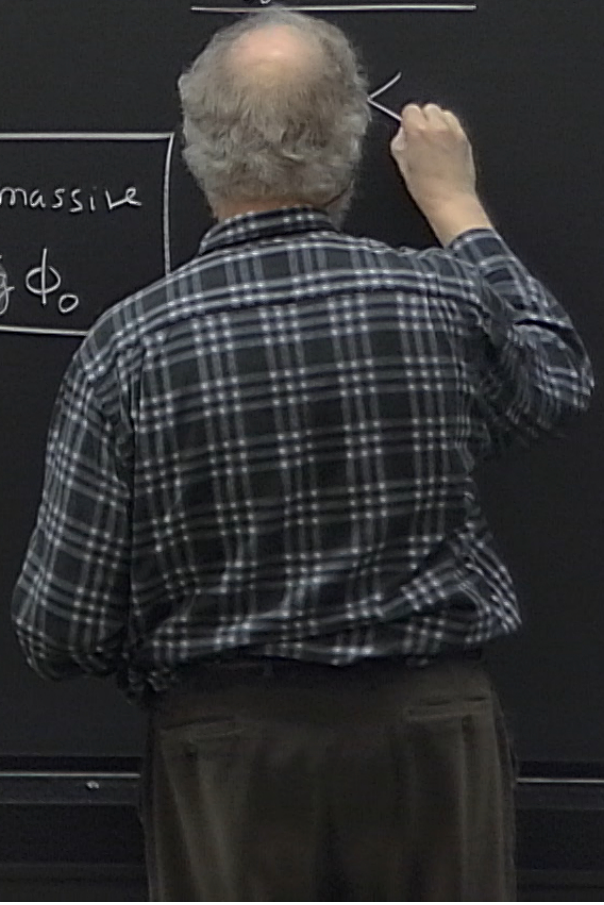
$$A_\mu \quad (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 + e^2\phi_0^2 A_\mu^2$$

Vector Field — mass term

Vector field massive $\boxed{M_A = e\phi_0}$ ⇐

H is massive $\boxed{M_H = \sqrt{g}\,\phi_0}$

Higgs Mechanism



$V(H) = \frac{g}{8}\left[\phi_0^2 - (\phi_0 + H)^2\right]$

$\frac{g}{8}\left(2H\phi_0 + H^2\right)^2$

## Higgs Mechanism

o charge)

$\langle \phi^2 \rangle = \phi_0^2 > 0$

non zero density of particles

"condensate"

$\Downarrow$

coupling to U(1) field
makes it massive

$\Rightarrow$ 3 polarizations

H is massive

$M_H = \sqrt{g}\,\phi_0$

$V(H) = \frac{g}{8}\left[\phi_0^2 - (\phi_0 + H)^2\right]$

$\frac{g}{8}\left(2H\phi_0 + H^2\right)^2$

## Higgs Mechanism

$\langle \phi^2 \rangle = \phi_0^2 > 0$

non zero density of particles

"condensate"

$\Downarrow$

coupling to U(1) field makes it massive

$\Rightarrow$ 3 polarizations at rest

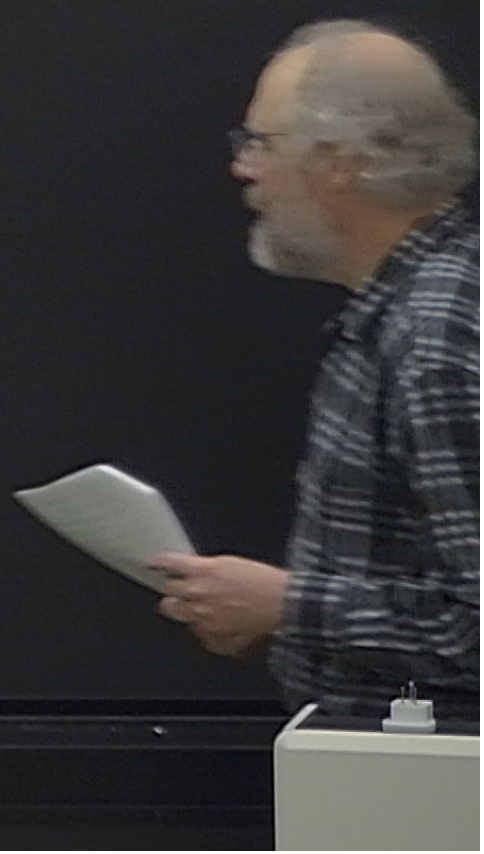


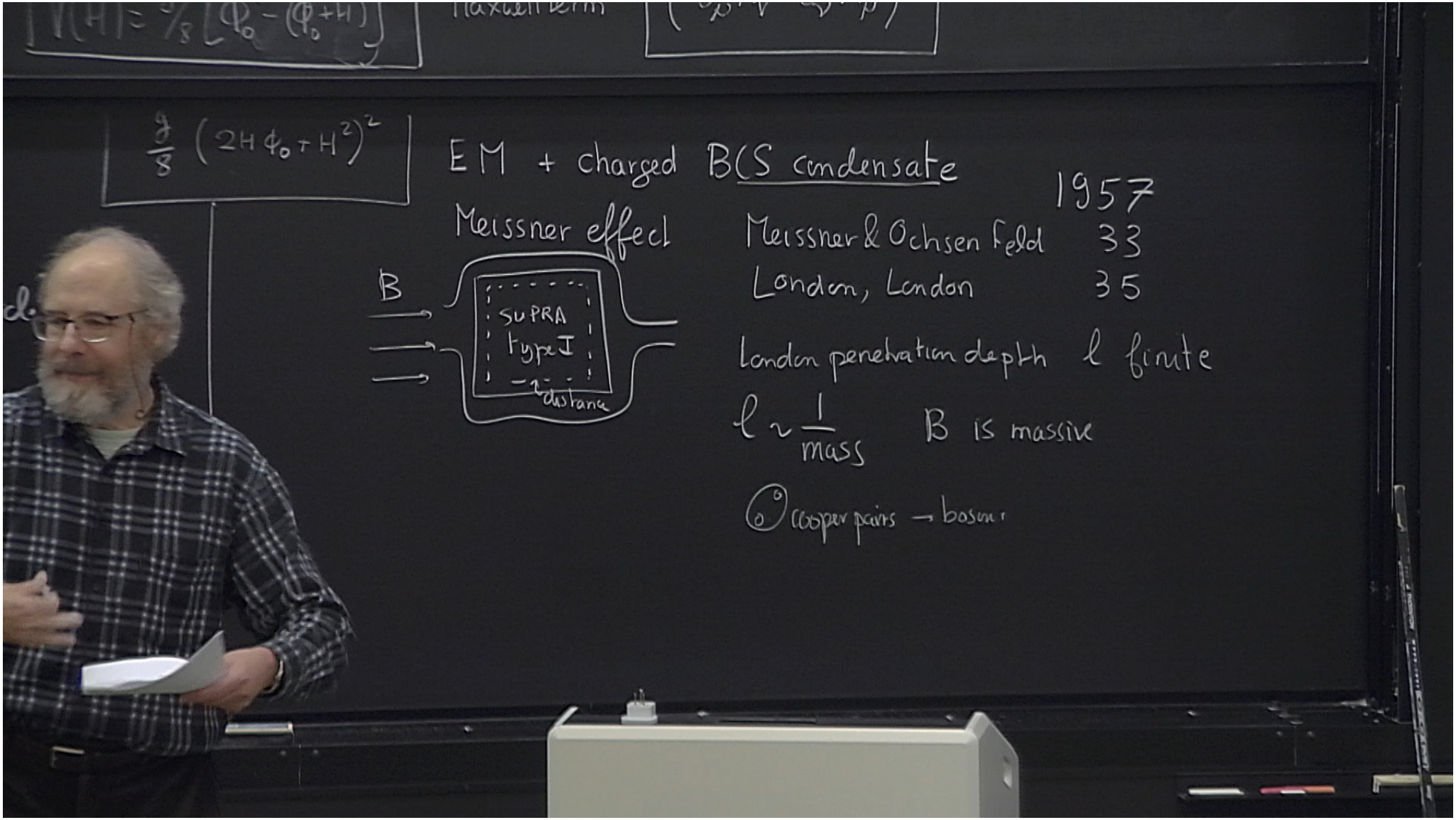
H is massive

$M_H = \sqrt{g}\,\phi_0$

if only V=C

2 polarizations

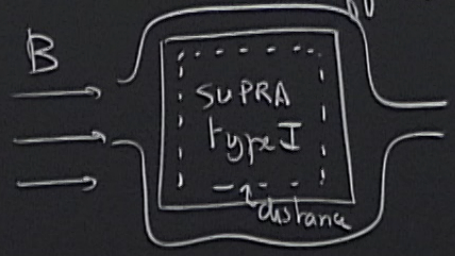



$\frac{g}{8}(2H\phi_0 + H^2)^2$
EM + charged BCS condensate
1957
Meissner effect
Meissner & Ochsen Feld 33
London, London 35
B
SUPRA
type I
distance
London penetration depth $\ell$ finite
$\ell \sim \frac{1}{\text{mass}}$ B is massive
Cooper pairs → boson

$\frac{g}{8}(2H\phi_0 + H^2)^2$

EM + charged BCS condensate

Meissner effect




PW Anderson 62

↳ QFT (non-relativistic)

64 Brout Englert | Higgs | Guralnik, Hagen-Kibble

1957

Meissner & Ochsen Feld 33

London, London 35

London penetration depth $\ell$ finite

$\ell \sim \frac{1}{\text{mass}}$ B is massive

Cooper pairs → boson → condensate

$V(H) = \frac{g}{8}\left[\phi_0^2 - (\phi_0 + H)^2\right]$

Higgs Mechanism

H = Higgs Field

$\frac{g}{8}(2H\phi_0 + H^2)^2$

EM + charge

Meissner effect

(no charge)

H is massive

$M_H = \sqrt{g}\,\phi_0$

$\langle \phi^2 \rangle = \phi_0^2 > 0$

non zero density of particles

"condensate"

⇓

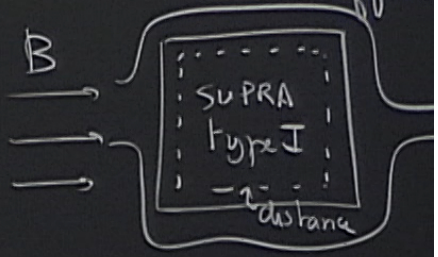
coupling to U(1) field

makes it massive

⇒ 3 polarizations at rest



B




only V=C

polarizations

PW Anderson 62

↳ QFT (non-relativistic)

64 Brout Englert | Higgs | Guralnik

SSB ⇒ Goldstone modes

$V(H) = \frac{g}{8}(\phi_0 - (\phi_0 +$

(x) spin 1

H(x) real spin 0 (no charge)

in the action

$(\partial_\nu H)^2 + \frac{g}{2}\phi_0^2 H^2 + \ldots$

H is massive

$M_H = \sqrt{g}\,\phi_0$

$(\partial_\nu A_\mu - \partial_\nu A_\mu)^2 + e^2\phi_0^2 A_\mu^2$

Vector Field — mass term

massive

$M_A = e\phi_0$ ⇐

if only V = C

2 polarizations

A massive vector bosons

Higgs Mechanism

H = Higgs Field

$\langle\phi^2\rangle = \phi_0^2 > 0$

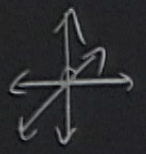
non zero density of particles

"condensate"

⇓

coupling to U(1) field makes it massive

⇒ 3 polarizations at rest



$\frac{g}{8}(2H\phi_0 + H$

PW An

↳ φ

64 Bro

- SSB Goldstone modes
- Higgs mechanism itself

## SSB and Gauge Fields

$A_\mu$ — 2 polarizations
$\pi$ — Goldstone — 1 stale
$\nabla$ — massive — 1 stale

gauge "eats" the goldstone boson and became massive ⇒ $A_\mu$ 3 polarizacija

$H$ — no polarizacija

$\partial f$ 0

electron

oscillations of the electrons?

in phase

$E(t) = E_0 \sin(\omega t)$

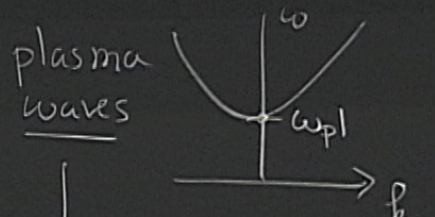
C Matter

Gauge Field

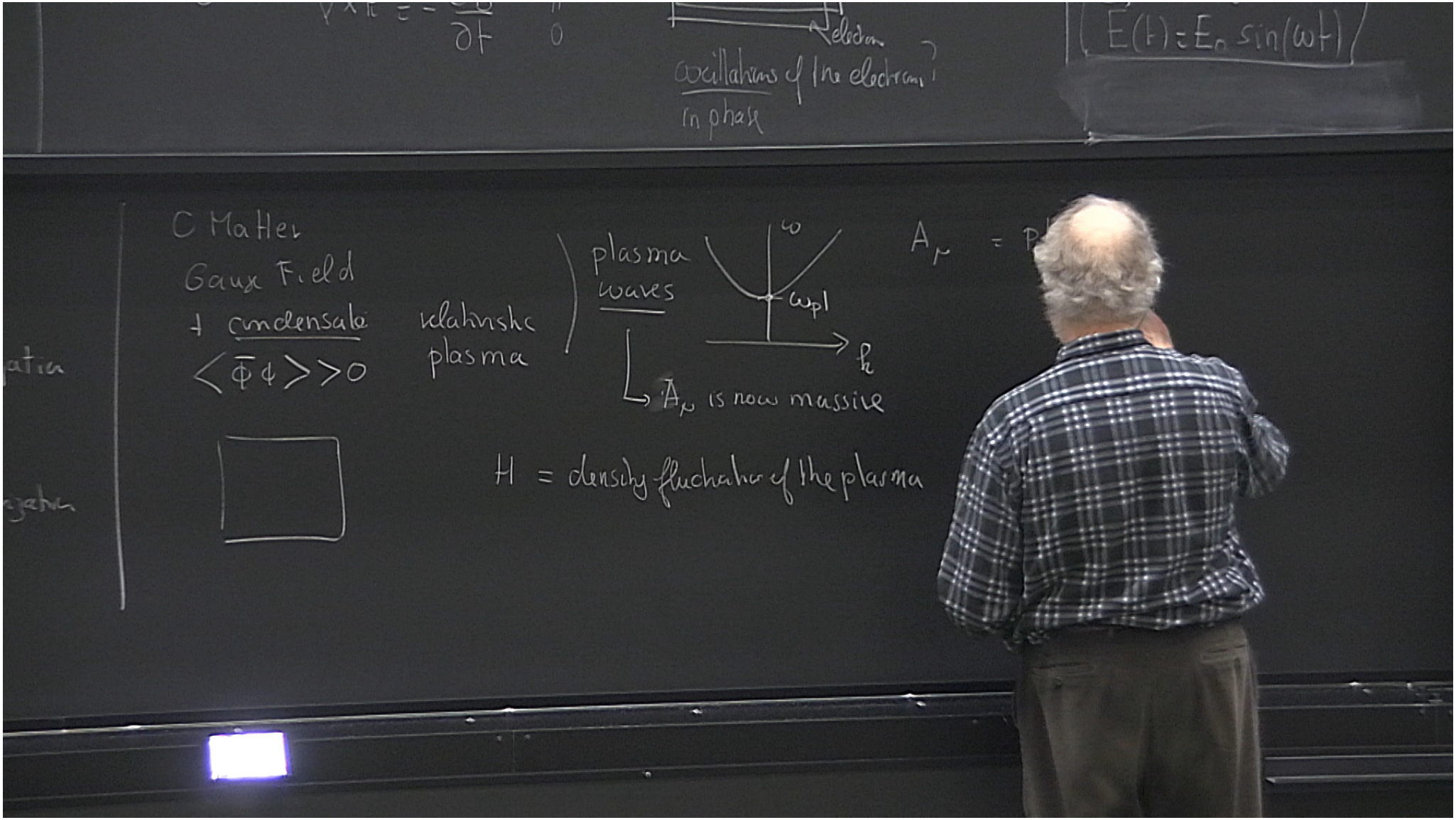
+ condensate $\langle \bar{\Phi} \Phi \rangle >> 0$

relativistic plasma

plasma waves




↳ $\vec{A}_\mu$ is now massive


$E(t) = E_0 \sin(\omega t)$
electron
oscillations of the electrons?
in phase
C Matter
Gauge Field
+ condensate
$\langle \bar{\Phi} \Phi \rangle >> 0$
relativistic plasma
plasma waves
$\omega$
$\omega_{pl}$
$k$
$A_\mu$ is now massive
$A_\mu$ =
H = density fluctuation of the plasma

$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ $\quad \vec{J} = 0$

electron

oscillations of the electrons in phase

$E(t) = E_0 \sin(\omega t)$

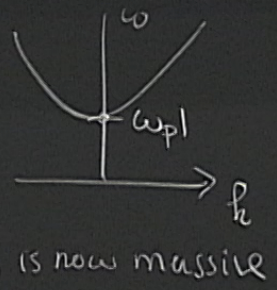
C Matter

Gaux Field

+ condensate $\langle \bar{\Phi} \phi \rangle >> 0$

relativistic plasma

plasma waves




$\bar{A}_\mu$ is now massive

$A_\mu$ = plasmon

density $n_e = \langle \phi^2 \rangle = \phi_0^2$

$\delta\rho$ = density fluctuation of the plasma

$\partial f \quad 0$

electron

oscillations of the electrons in phase

$E(t) = E_0 \sin(\omega t)$

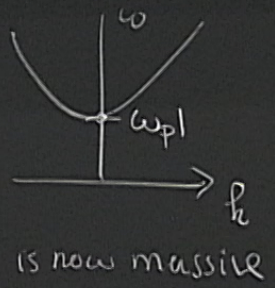
C Matter

Gaux Field

+ condensate $\langle \bar{\Phi} \phi \rangle >> 0$

relativistic plasma

plasma waves




$\bar{A}_\mu$ is now massive

$A_\mu$ = plasmon

density $n_e = \langle \phi^2 \rangle = \phi_0^2$

$M_A = \omega_{pl} = e\phi_0$

$M_A^2 = \omega_{pl}^2 = e^2 \phi_0^2 = e^2 n$

$H$ = density fluctuation of the plasma