

Title: Spontaneous symmetry breaking, gravity, and spinning objects

Date: May 29, 2014 02:30 PM

URL: <http://pirsa.org/14050111>

Abstract: Space-time symmetries are a crucial ingredient of any theoretical model in physics. Unlike internal symmetries, which may or may not be gauged and/or spontaneously broken, space-time symmetries do not admit any ambiguity: they are gauged by gravity, and any conceivable physical system (other than the vacuum) is bound to break at least some of them. Motivated by this observation, I will sketch how to couple gravity with the Goldstone fields that non-linearly realize spontaneously broken space-time symmetries by weakly gauging the Poincare symmetry group in the context of the coset construction. To illustrate the power of this perspective I will build a low energy effective action that describes spinning objects coupled to gravity and describe its interpretation.

w/ Luca Delacrétaz, Alexander Monin,
Riccardo Penco & Francesco Riva

- Outline:
- ① Review coset w/ spacetime SSB
 - ② GR from coset
 - ③ Point particle w/ gravity
 - ④ Spinning objects

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Gravity & the Coset: Spinning Objects

w/ Luca Delacrétaz, Alexander Monin,
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a, b, c, \rightarrow C.L.
 $\omega, \dot{\omega} \rightarrow$ s.L.L
 μ, ν, \rightarrow s.t.

$$\textcircled{1} \quad G \rightarrow H \rightarrow \frac{H_0}{P}$$
$$X_a = BG$$
$$\bar{P}_a = UB \text{ trans.}$$
$$\bar{T}_A = \text{other UB}$$

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a, b, c, \rightarrow C.L.
 $u, v, k \rightarrow$ s.L.L
 m, v, \rightarrow s.t.

① $G \rightarrow H \rightarrow \frac{H_0}{\overline{P}}$ CCWZ, Vol

$X_a = BG$

$\left[\begin{array}{l} \overline{P}_a = UB \text{ trans.} \\ \overline{T}_A = \text{other UB} \end{array} \right]$

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$a, b, c \rightarrow$ C.L.
 $u, v, t \rightarrow$ s.L.L
 $m, v, \dots \rightarrow$ s.t.

① $G \rightarrow H \rightarrow \frac{H_0}{\bar{P}}$

$$\begin{cases} X_a = BG \\ \bar{P}_a = UB \text{ trans.} \\ \bar{I}_A = \text{other UB} \end{cases}$$

CCWZ, Volkov & Ogivevsky
 ~1974

$$G/H_0 \rightarrow \Omega = e^{i \gamma^a(x) P_a}$$

$$\times e^{i \pi^a(x) X_a}$$

- ③ Point particle w/ gravity
- ④ Spinning objects

$a, b, c \rightarrow$ C.L.
 $\omega, \dot{\omega} \rightarrow$ s.L.L
 $\mu, \nu \rightarrow$ st.

① $G \rightarrow H \rightarrow \frac{H_0}{\bar{P}}$
 $\left[\begin{array}{l} X_a = B\bar{G} \\ \bar{P}_a = UB \text{ trans.} \\ T_A = \dots \end{array} \right]$

CCWZ, Volkov Ogievetsky
 ~1974

$G/H_0 \rightarrow \Omega = e^{i\gamma^a(x)\bar{P}_a}$

$\times e^{i\pi^a(x)X_a}$

$g\Omega \rightarrow \Omega' \frac{h}{e^T}$



$\Omega^{-1} \partial_\mu$

CAUTION
 WARNING: This board may be hot.
 Do not touch the board.
 Thank you.

→ L.L.
k → s.L.L.
→ st.

Volkovt Ogiyevsky
~1974
 $\Omega = e^{i \gamma^a(x) P_a}$
 $\times e^{i \pi^a(x) X_a}$
 $\frac{h}{e T}$

$$\Omega^{-1} \partial_\mu \Omega = E_\mu^a \left(\bar{P}_a + \underbrace{\nabla_a \pi^\alpha X_\alpha}_{\text{tetrad}} + A_a^B T_B \right)$$



CAUTION
Do not touch the chalkboard
if necessary use only
the provided tools

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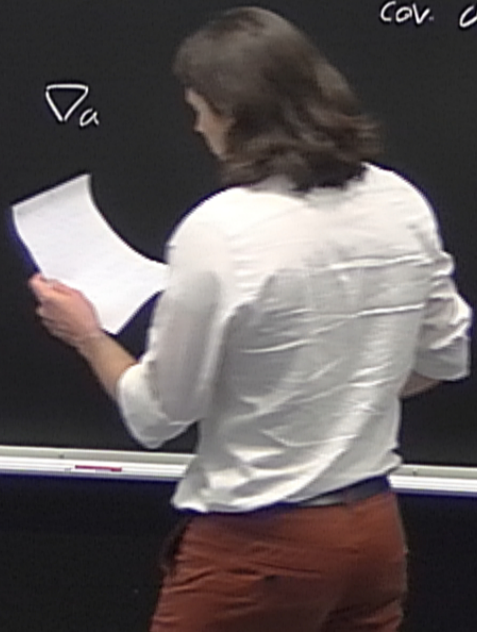
→ C.L.
 k → s.L.L.
 → st.

Volkov & Ogievetsky
 ~1974
 $\Omega = e^{i\gamma^a(x)P_a}$
 $\times e^{i\pi^a(x)X_a}$
 $\frac{h}{eT}$

$$\Omega^{-1} \partial_\mu \Omega = E_\mu^a \left(\bar{P}_a + \underbrace{\nabla_a \pi^\alpha X_\alpha}_{\text{tetrad}} + \underbrace{A_a^B T_B}_{\text{connection}} \right)$$

cov. der = $(\nabla \pi) \rightarrow h \nabla \pi$

∇_a

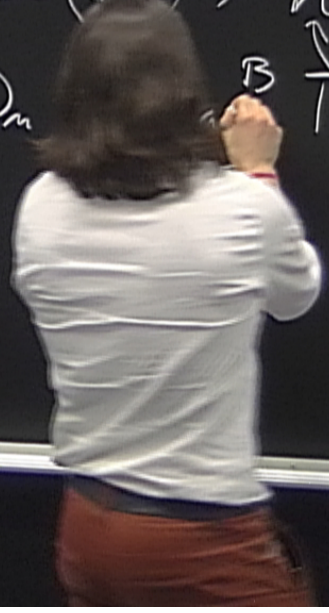


→ C.L.
 k → s.L.L.
 → st.

Volkov & Ogievetsky
 ~1974
 $\Omega = e^{i \gamma^a(x) P_a}$
 $\times e^{i \pi^a(x) X_a}$
 $\frac{h}{e^T}$

$$\Omega^{-1} \partial_\mu \Omega = E_\mu^a \left(\underbrace{\bar{P}_a}_{\text{tetrad}} + \underbrace{\nabla_a \pi^\alpha X_\alpha}_{\text{cov. der} = (\nabla \pi)} + \underbrace{A_a^B T_B}_{\text{connection}} \right)$$

$$\nabla_a^H = \left[(E^{-1})_\mu^a \partial_\mu \quad \begin{matrix} B \\ \uparrow \\ T_B \end{matrix} \right]$$



CAUTION

CAUTION

→ L.L.
 k → s.L.L.
 → st.

Volkov & Ogirovetsky
 ~1974
 $\Omega = e^{i\gamma^a(x)P_a}$
 $\times e^{i\pi^a(x)X_a}$
 $\frac{\hbar}{e^T}$

$$\Omega^{-1} \partial_\mu \Omega = E_\mu^a \left(\bar{P}_a + \underbrace{\nabla_a \pi^\alpha X_\alpha}_{\text{tetrad}} + \underbrace{A_a^B T_B}_{\text{connection}} \right)$$

cov. der = $(\nabla \pi) \rightarrow \hbar \nabla \pi$

$$\nabla_a^H = \left[(E^{-1})_\mu^a \partial_\mu + A_a^B T_B \right]$$

$$S = \int d^d x \det(E)$$



→ C.L.
 k → s.L.L.
 → st.

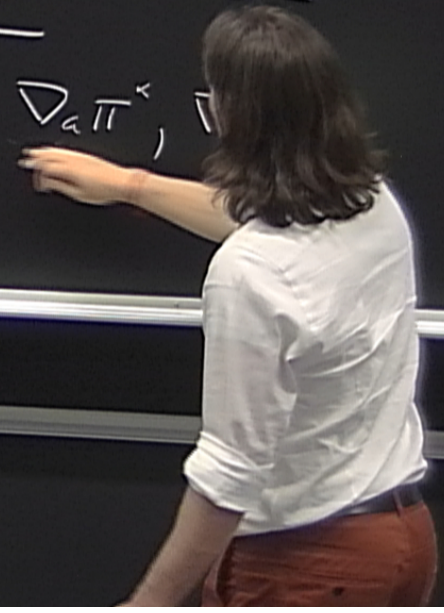
Volkov & Ogievetsky
 ~1974
 $\Omega = e^{i \gamma^a(x) P_a}$
 $\times e^{i \pi^a(x) X_a}$
 $\frac{\hbar}{e^T}$

$$\Omega^{-1} \partial_\mu \Omega = E_\mu^a \left(\bar{P}_a + \underbrace{\nabla_a \pi^\alpha X_\alpha}_{\text{tetrad}} + \underbrace{A_a^B T_B}_{\text{connection}} \right)$$

cov. der = $(\nabla \pi) \rightarrow \hbar \nabla \pi$

$$\nabla_a^H = \left[(E^{-1})_\mu^a \partial_\mu + A_a^B T_B \right]$$

$$S = \int d^d x \det(E) \mathcal{L}(\nabla_a \pi^a, \dots)$$



→ C.L.
 k → s.L.L.
 → st.

Volkov & Ogievetsky
 ~1974
 $\mathcal{L} = e^{i\gamma^a(x)P_a}$
 $\times e^{i\pi^a(x)X_a}$
 $\frac{\hbar}{e^T}$

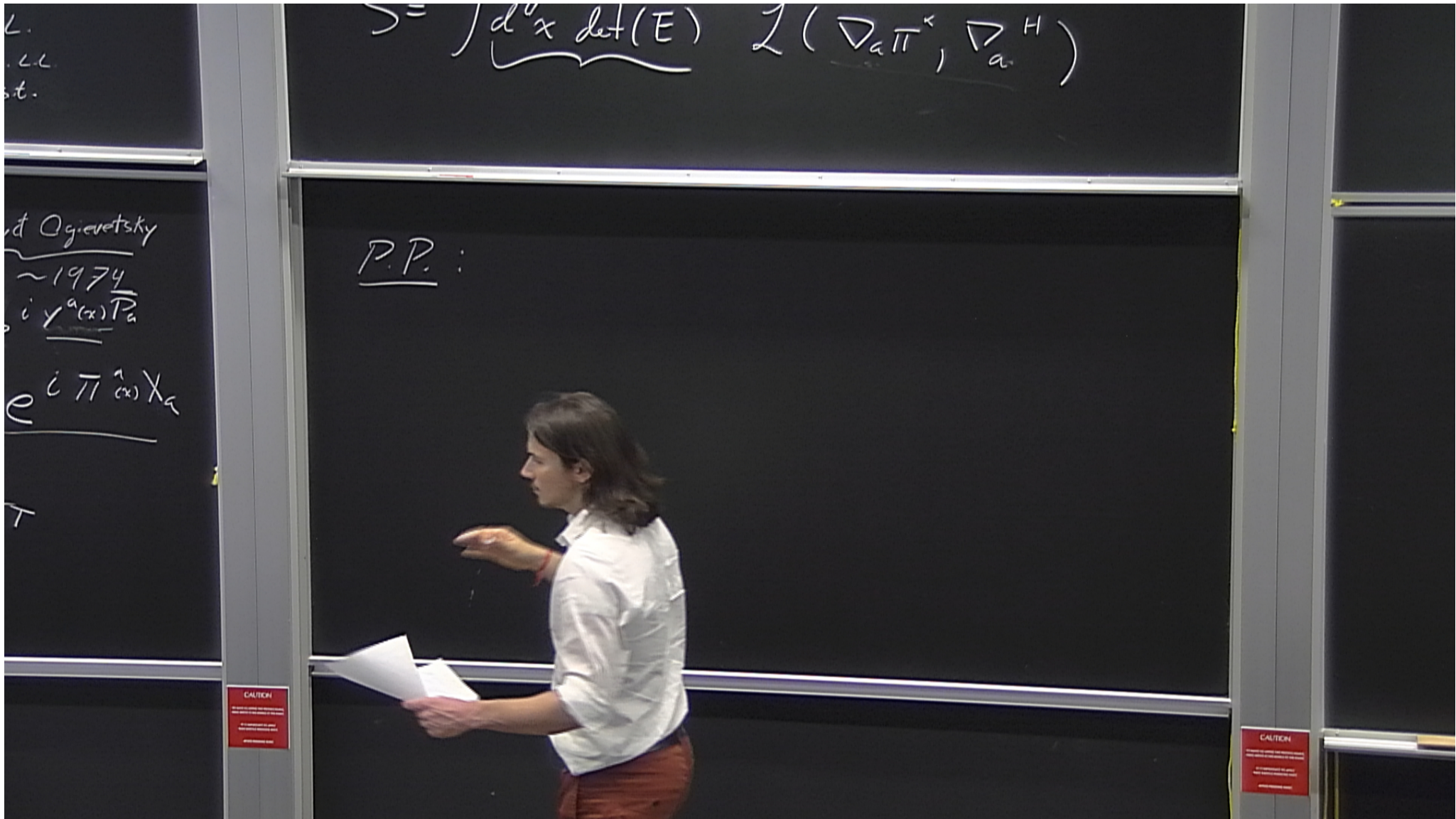
$$\Omega^{-1} \partial_\mu \Omega = E_\mu^a \left(\bar{P}_a + \underbrace{\nabla_a \pi^\alpha X_\alpha}_{\text{tetrad}} + \underbrace{A_a^B T_B}_{\text{connection}} \right)$$

cov. der = $(\nabla \pi) \rightarrow \hbar \nabla \pi$

$$\nabla_a^H = \left[(E^{-1})_a^\mu \partial_\mu + A_a^{(B)} T_B \right]$$

$$S = \int d^d x \det(E) \mathcal{L}(\nabla_a \pi^\alpha, \nabla_a^H)$$



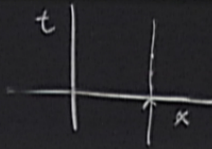


L.
LL
st.

$$\int d^4x \det(E) \mathcal{L}(\nabla_a \pi^a, \nabla_a H)$$

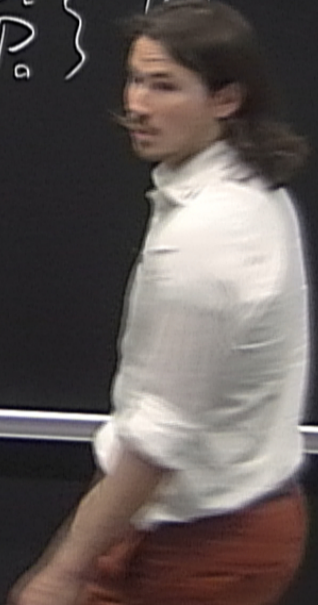
by Ogievetsky
~1974
 $i \gamma^a(x) \bar{P}_a$
 $e^{i \pi^a(x) \chi_a}$
T

P.P. :



S.S.B ST
 \Rightarrow

P_i } BG
 K_i }
 J_i }
 P_a }



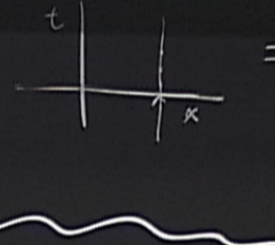
CAUTION

CAUTION

L.
LL
st.

$$\int \det(E) \mathcal{L}(\nabla_a \pi^i, \nabla_a^H)$$

st Ogieretskiy
~1974
 $i y^a(x) \bar{p}_a$
 $e^a(x) X_a$

P.P. :  SSB ST \Rightarrow

P_i	}	BG	6 GB
K_i			
J_i			
P_a			

(?)

CAUTION

CAUTION

L
 LL
 $st.$

 d Ogievetsky
 ~1974
 $i \gamma^{\alpha(x)} \bar{P}_a$

 $e^{i \pi^{\alpha(x)} X_a}$

 T

$$\int d^4x \det(E) \mathcal{L}(\nabla_{a\pi}, \nabla_a^H)$$

P.P.: $\begin{array}{c|c} t & \\ \hline & x \end{array}$ $\xrightarrow{S.S.B \quad ST}$ $\left. \begin{array}{l} P_i \\ K_L \end{array} \right\} \begin{array}{l} B_6 \\ 6 \text{ GB} \\ (Z) \end{array}$

 $\left. \begin{array}{l} J_i \\ P_a \end{array} \right\} UB$

~~~~~  
 Higgs Mechanism:

i)

CAUTION

CAUTION

$L$   
 $LL$   
 $st.$   
  
 d Ogievetsky  
 ~1974  
 $i \gamma^{\mu} \alpha \bar{P}_a$   
  
 $e^{i \pi^{\mu} \alpha} \chi_a$   
  
 $T$

$$\det(L) \sim (\det \pi, \det a)$$

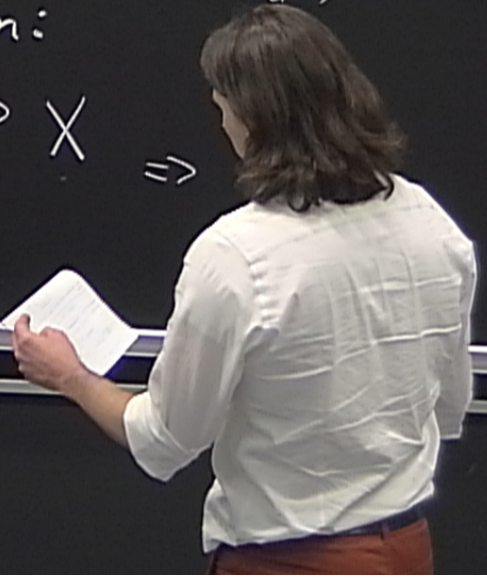
P.P.:  $\begin{matrix} t \\ | \\ | \\ | \\ x \end{matrix}$   $\Rightarrow$  S.S.B ST
   
 $P_i$  } B6 6 GB
   
 $K_i$  } (2)
   


---

 $J_i$  } UB
   
 $P_a$  }

Inverse Higgs Mechanism:

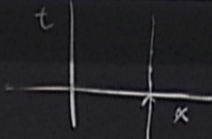
i)  $[\bar{P}, X'] > X \Rightarrow$   
 ii)



L.  
LL  
st.

st Ogievetsky  
~1974  
 $i \gamma^{\mu}(x) \bar{P}_a$   
 $e^{i \pi^{\mu}(x)} \chi_a$   
T

$\underbrace{\dots}_{\dots} \mathcal{L}(\psi_{all}, \psi_a)$

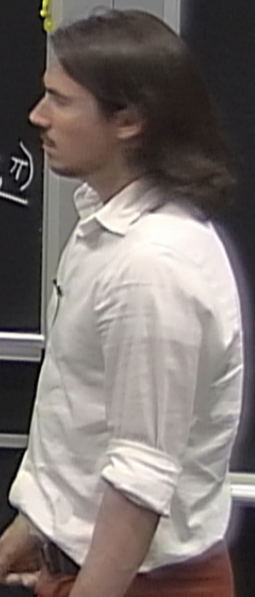
PP:   $\Rightarrow$  5.5B 51

$P_i \} BG \quad 6 GB$   
 $K_i \} \quad \quad (Z)$

---

$J_i \} UB$   
 $P_a \}$

Inverse Higgs Mechanism:  
i)  $[\bar{P}, X'] \supset X \Rightarrow \nabla \pi = 0 \Rightarrow \pi(\partial\pi, \pi)$   
ii)



**CAUTION**

L.  
LL  
st.

st Ogievetsky  
~1974  
 $i \gamma^{\mu} \bar{P}_a$   
 $e^{i \pi^{\mu} X_a}$   
T

$\mathcal{L}(v_{all}, v_a)$

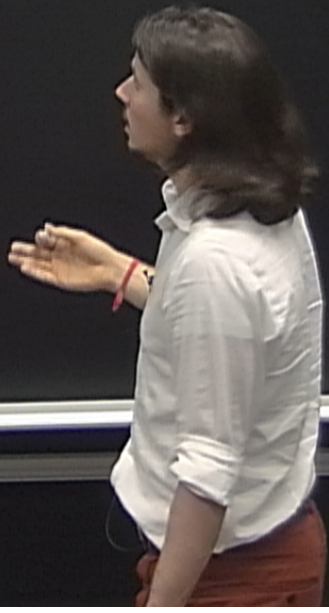
~~~~~  
Inverse Higgs Mechanism: $\left. \begin{matrix} J_i \\ P_a \end{matrix} \right\} \text{UB}$

i) $[\bar{P}, X'] \supset X \Rightarrow \underline{\nabla} \pi = 0 \Rightarrow \underline{\pi}(\partial \pi, \pi)$
ii) $[P_a, k] \sim P_i$



UB
 $\pi = 0 \Rightarrow \pi(\lambda\pi, \pi)$

- ① Consistent
- ② $(\pi X + \pi' X') \langle \Phi \rangle = 0$ } X
- ③ π' are grouped



CAUTION
DO NOT TOUCH THE BOARD
OR THE CHALK

Gravity & the Cosm: Spinning Objects

w/ Luca Delacrétas, Alexander Mann,
Ricardo Porto & Francesco Riva

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$abc \rightarrow c.c.$
 $cd \rightarrow s.c.c.$
 $mn \rightarrow st.$

① $G \rightarrow H = \frac{H_0}{P}$ CCWZ, Valued Symmetry ~1974

$$\begin{cases} X_a = BC \\ \bar{P}_a = UB \text{ (rot)} \\ I_a = \text{other UB} \end{cases}$$

$\mathbb{H}^4 \times \mathbb{S}^1 \xrightarrow{g} \mathbb{Q} \xrightarrow{h} \frac{h}{e} T$

can derive $(\nabla \pi) \rightarrow h \nabla \pi$ connection

$$\nabla_a'' \cdot [(E^a)_{\mu}^{\nu} \rightarrow A_{a(\mu)}^{\nu)} \bar{I}_B]$$

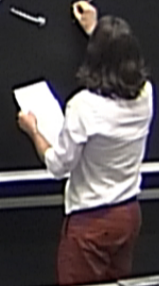
$$S = \int d^4x \text{det}(E) \mathcal{L}(\nabla_a \pi', \nabla_a'')$$

Inverse Higgs Mechanism:

$$\langle \bar{P}, X' \rangle > X \Rightarrow \nabla \pi = 0 \Rightarrow \pi(\sigma, \tau)$$

① $(P, h) \sim P$

- ① Constant
- ② $(\pi X + \pi' X') \langle \bar{I} \rangle = 0 \Rightarrow X$
- ③ π' are gauged



$\left. \begin{array}{l} \dots \\ \dots \end{array} \right\} \text{UB}$
 $\pi = 0 \Rightarrow \pi(\lambda\pi, \pi)$

① Consistent

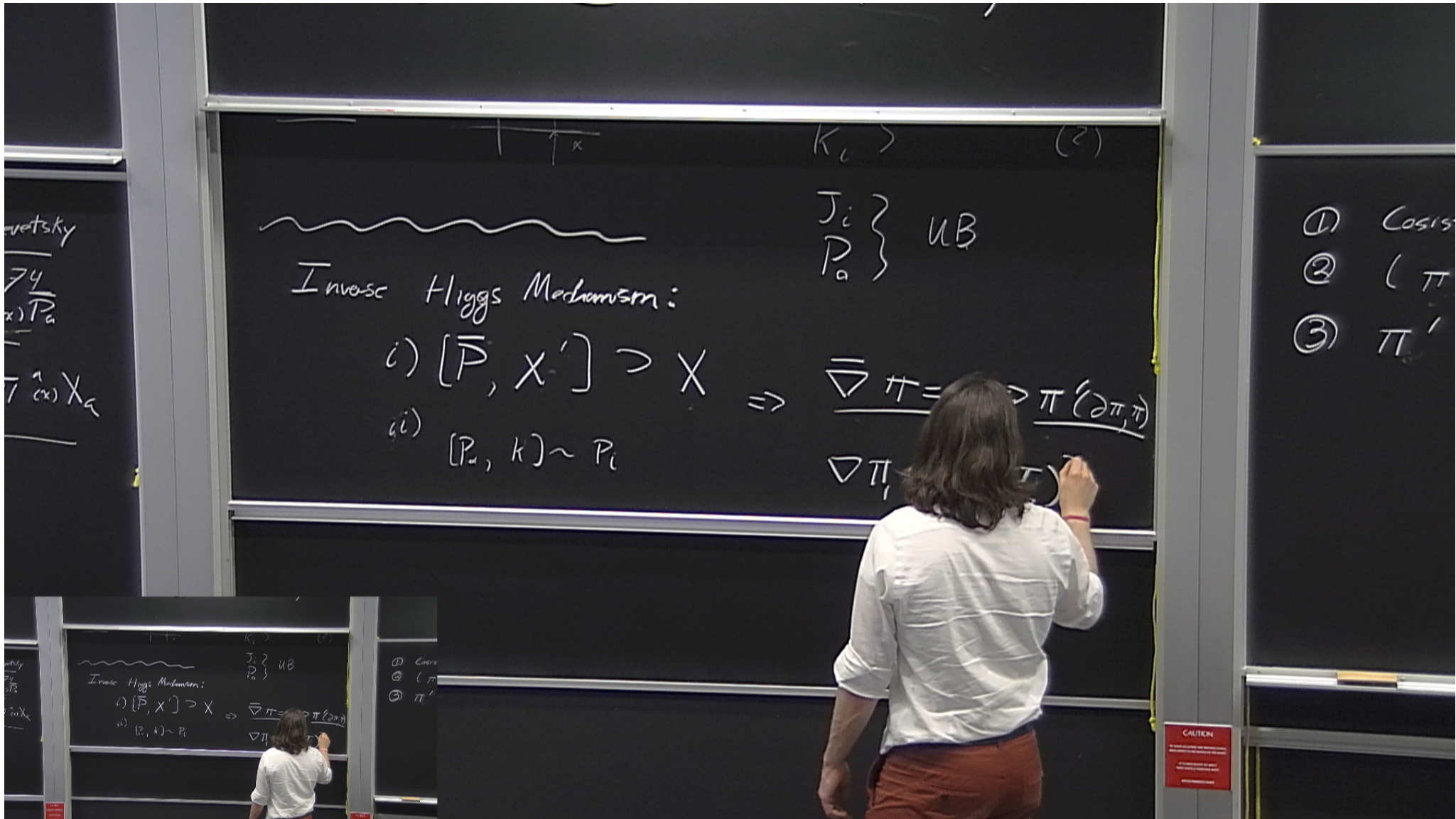
② $(\pi X + \pi' X') \langle \Phi \rangle = 0 \} X$

③ π' are gapped

$$\text{UB} \left\{ \begin{array}{l} \bar{P}_i = P_i + \mu Q \\ \bar{P}_i = P_i \\ \bar{J}_i = J_i - S_i \end{array} \right. \Bigg| \text{BG} \left\{ \begin{array}{l} K_i \\ Q \\ S_i \end{array} \right.$$



CAUTION



$$S = \int d^4x \det(E) \mathcal{L}(\nabla_a \pi^a, \nabla_a H)$$

Inverse Higgs Mechanism:

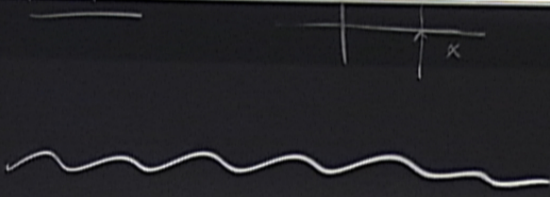
i) $[\bar{P}, X'] \supset X$

ii) $[P_a, k] \sim P_i$

$$\Rightarrow \boxed{\bar{\nabla} \pi = 0} \quad (\partial \pi, \pi)$$

$$\nabla \pi_i + (\dots)$$

- ① Cosis
- ② $(\pi$
- ③ π'



$$K_i \sim (2)$$

$$\left. \begin{matrix} J_i \\ P_a \end{matrix} \right\} \text{UB}$$

Inverse Higgs Mechanism:

$$i) [\bar{P}, X'] \supset X \Rightarrow \boxed{\bar{\nabla} \pi = 0} \Rightarrow \pi(\partial\pi, \pi)$$

$$ii) [P_a, k] \sim P_i \quad \pi' \quad 0 = \nabla \pi_1 + (\nabla \pi_2)^2 \dots$$

- ① Cosis
- ② (π
- ③ π'

CAUTION

CAUTION

B

$$\underline{0} \Rightarrow \underline{\pi} (\partial \pi \pi)$$

$$(\nabla \pi_2)^2 \dots$$

① Consistent

$$\textcircled{2} (\pi X + \pi' X') \langle \Phi \rangle = 0 \quad X$$

③ π' are gapped

$$\begin{array}{l} \text{UB} \left\{ \begin{array}{l} \bar{P}_t = P_t - uR \\ \bar{P}_i = P_i \\ \bar{J}_i = J_i - S_i \end{array} \right. \quad \left. \begin{array}{l} \\ \\ \end{array} \right| \text{BG} \left\{ \begin{array}{l} K_i \\ Q \\ S_i \end{array} \right. \end{array}$$

$$\partial_m \rightarrow \nabla_m = \partial_m + \dots$$

CAUTION

① Consistent

② $(\pi X + \pi' X') \langle \Phi \rangle = 0 \} X$

③ π' are gapped

$\partial_m \rightarrow \nabla_m = \partial_m + i A_m^a V_a$
 $V_a \supset X$

UB $\left\{ \begin{array}{l} \bar{P}_t = P_t - mR \\ \bar{P}_i = P_i \\ \bar{J}_i = J_i - S_i \end{array} \right. \Bigg| \text{BG} \left\{ \begin{array}{l} K_i \\ Q \\ S_i \end{array} \right.$

(2)
B
 $\Rightarrow \pi'(\partial\pi, \pi)$
 $(\nabla\pi_2)^2 \dots$

CAUTION

Gauge Internal Sym $V_a \supset X$

$\left. \begin{matrix} p_i \\ v_i \end{matrix} \right\} \text{BG } 6 \text{ GB } (2)$

$\left. \begin{matrix} p_i \\ p_a \end{matrix} \right\} \text{UB}$

$$\overline{\nabla \pi = 0} \Rightarrow \pi(\partial\pi, \pi)$$

$$\nabla \pi_1 + (\nabla \pi_2)^2 + \dots$$

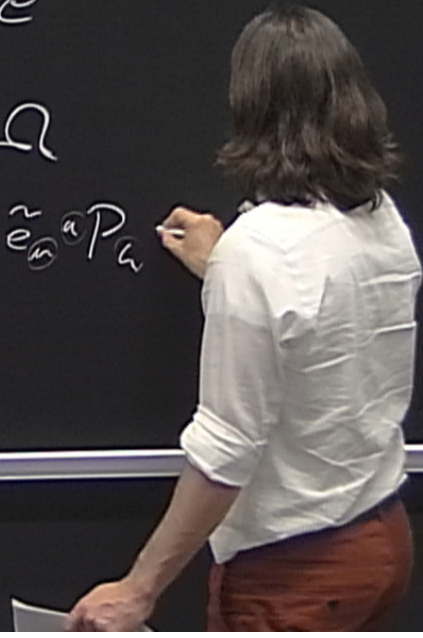
GR: gauge Poincare

$ISO(3,1)/SO(3,1)$

$$\Omega = e^{i\gamma^a(x) P_a}$$

$$\Omega^{-1} \underline{D}_m \Omega$$

$$\partial_m + i \tilde{e}_m^a P_a$$



CAUTION

Gauge Internal Sym $V_a \supset X$

$\left. \begin{matrix} \psi_i \\ \psi_c \end{matrix} \right\} \text{BG } 6 \text{ GB } (2)$

$\left. \begin{matrix} \psi_i \\ \psi_a \end{matrix} \right\} \text{UB}$

$$\overline{\nabla \pi = 0} \Rightarrow \pi(\partial \pi, \pi)$$

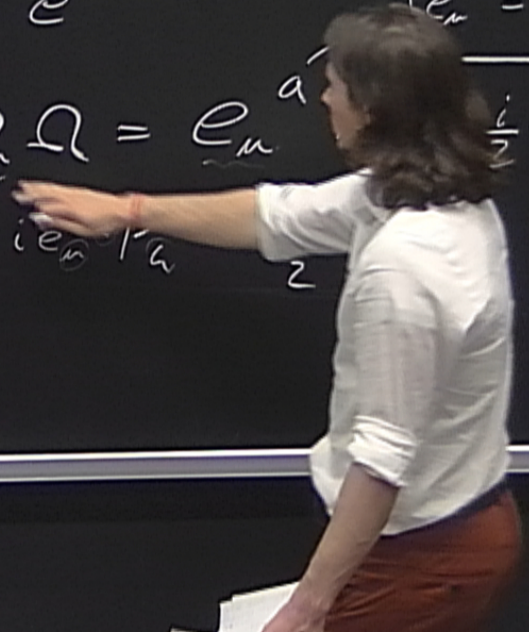
$$\nabla \pi_1 + (\nabla \pi_2)^2 + \dots$$

GR: gauge Poincare $ISO(3,1)/SO(3,1)$

$$\Omega = e^{i\gamma^a(x) P_a}$$

$$e_n^a \equiv \partial_n \gamma^a + \tilde{e}_n^a + \omega_n^{ab} \gamma_b$$

$$\Omega^{-1} \underline{D}_m \Omega = e_n^a (\partial_n + i e_n^b T_b) \frac{i}{2} \omega_n^{ab} J_{ab}$$



CAUTION

Gauge Internal Sym $V_a \supset X$

GR: gauge Poincare $ISO(3,1)/SO(3,1)$

$$\Omega = e^{i\gamma^a(x) P_a}$$

$$e_n^a \equiv \partial_n \gamma^a + \tilde{e}_n^a + \omega_n^{ab} \gamma_b$$

$$\Omega^{-1} \underline{D}_n \Omega = e_n^a P_a + \frac{i}{2} \omega_n^{ab} J_{ab} \quad (\nabla \pi \times)$$

$$(\partial_n + i \tilde{e}_n^a P_a + \frac{i \omega_n^{ab}}{2} J_{ab})$$

$$S = \int d^4x \det(E) \mathcal{L}(\dots)$$

$\left. \begin{matrix} P_i \\ \dots \end{matrix} \right\} \text{BG } 6 \text{ GB } (2)$

$\left. \begin{matrix} P_i \\ P_a \end{matrix} \right\} \text{UB}$

$$\overline{\nabla \pi = 0} \Rightarrow \pi(\partial \pi, \pi)$$

$$\nabla \pi_1 + (\nabla \pi_2)^2 + \dots$$

CAUTION

Charge Internal Sym $V_a \rightarrow X$

$$S = i \int d^4x \det(E) \mathcal{L} \left(\nabla_a^\mu \left(e_a^\mu \partial_m + \frac{1}{2} \omega_m^{ab} J_{ab} \right) \right)$$

$\left. \begin{matrix} \partial_i \\ \partial_a \end{matrix} \right\} \text{BG } 6 \text{ GB } (?)$

$\left. \begin{matrix} \partial_i \\ \partial_a \end{matrix} \right\} \text{UB}$

$$\overline{\nabla \pi = 0} \Rightarrow \pi(\partial \pi, \pi)$$

$$\nabla \pi_1 + (\nabla \pi_2)^2 + \dots$$

$$[\nabla_a^\mu, \nabla_b^\nu] V^c = \underbrace{R^c{}_{dab}}_{\text{curvature}} V^d + \underbrace{T_{ab}{}^d}_{\text{torsion}} \nabla_d^\mu V^c$$



CAUTION

Gauge Invariant
Sym $V_a \rightarrow X$

$$S = i \int d^4x \det(E) \mathcal{L} \left(\nabla_a^\perp \left(e_a^\mu \partial_\mu + \frac{L}{2} \omega_a^{\mu\nu} J_{\mu\nu} \right) \right)$$

$$[\nabla_a^\perp, \nabla_b^\perp] V^c = \underbrace{R^c{}_{dab}}_{\text{curvature}} V^d + \underbrace{T_{ab}{}^d}_{\text{torsion}} \nabla_d^\perp V^c$$

$$S = \int d^4x \det(E) \left(\# \underbrace{R^a{}_b}_{\sim \omega\omega + e\partial\omega} + \sum_1^3 T \cdot T + \dots \right)$$

$\left. \begin{matrix} \pi_i \\ \dots \end{matrix} \right\} \text{BG } 6 \text{ GB } (?)$

$\left. \begin{matrix} \pi_i \\ \dots \end{matrix} \right\} \text{UB}$

$$\overline{\nabla \pi = 0} \Rightarrow \pi(\partial\pi, \pi)$$

$$\nabla \pi_1 + (\nabla \pi_2)^2 + \dots$$

CAUTION

Gauge Internal Sym $V_a \supset X$

$SO(3,1) / SO(3,1)$

$$\Omega = e^{i\gamma^a(x) P_a}$$

$$e_m^a \equiv \partial_m \gamma^a + \tilde{e}_m^a + \omega_m^{ab} \gamma_b$$

$$\Omega^{-1} \underline{D}_m \Omega = e_m^a P_a + \frac{i}{2} \omega_m^{ab} J_{ab} \quad (\nabla \pi \times)$$

$$(\partial_m + i \tilde{e}_m^a P_a + \frac{i \omega_m^{ab}}{2} J_{ab}) \rightarrow (e_m^a \partial_m + \frac{i}{2} \omega_m^{ab} J_{ab})$$

$$S = i \int d^4x \det(e)$$

$$EOM(\omega) \Rightarrow I = 0$$

$\left. \begin{matrix} P_i \\ L_i \end{matrix} \right\} \text{BG } 6 \text{ GB } (2)$

$\left. \begin{matrix} P_a \\ J_a \end{matrix} \right\} \text{UB}$

$$\overline{\nabla \pi = 0} \Rightarrow \pi(\partial \pi, \pi)$$

$$\nabla \pi_1 + (\nabla \pi_2)^2 + \dots$$

CAUTION

Gravity & Higgs: Spinning Objects

w/ Luca Delacrétas, Alexander Mann,
Ricardo Porto & Francesco Riva

- Outline:
- Review const of spinors SSB
 - GR from const
 - Point particle w/ gravity
 - Spinning objects

spinors → C.L.
const → S.C.C.
spinors → S.C.

① $G \rightarrow H = \frac{H_0}{P}$ CCWZ, Valued Symmetry ~1974

$\begin{cases} X_a = BC \\ \vec{P} = UB \text{ term} \\ I_a = \text{other UB} \end{cases}$ $G_H = Q = e^{i \vec{P} \cdot \vec{T}_a}$

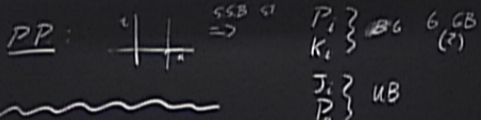
$x e^{i \vec{T} \cdot \vec{a} X_a}$

$g Q \Rightarrow Q' \frac{h}{e T}$

can also $(\nabla \pi) \rightarrow h \nabla \pi$

$$\nabla_a^\mu = [(E^{-1})_a^\mu \partial_a + A_{ab}^\mu \vec{T}_b]$$

$$S = \int d^4x \mathcal{L}(E) \mathcal{L}(\nabla_a \pi, \nabla_a^\mu \pi)$$



Inverse Higgs Mechanism:

- $[P, X] \rightarrow X \Rightarrow \nabla \pi = 0 \Rightarrow$
- $[P, h] \sim P_i \pi' \Rightarrow 0 = \nabla \pi + (S)$

① $(\pi X + \pi' X') \mathcal{L}(E) = 0 \} X$

② π' are gauged $\rightarrow \begin{cases} P_i = P_i \text{ or } Q \\ P_i = P_i \\ J_i = J_i - S_i \end{cases} \left| \begin{matrix} B_L \\ R \\ S_i \end{matrix} \right. \begin{matrix} K_i \\ Q \\ S_i \end{matrix}$

Gauge internal system $V_a \supset X$

$$S = \int d^4x \det(E) \mathcal{L}(\nabla_a^\mu \pi)$$

$[\nabla_a^\mu, \nabla_b^\nu] V^c = R^{ab\ c}{}_{d} V^d + T_{ab}{}^c{}_{d} V^d$

$$S = \int d^4x \det(E) (R^{ab\ c}{}_{d} \dots) \sum T T \dots$$

EOM $(\omega) \Rightarrow T = 0$ ~ with spin



$$\Omega \underbrace{D_m \Omega}_{=} = e_m P_a + \frac{i}{2} \omega_m^{ab} J_{ab} \quad (\nabla \pi \times)$$

$$\left(\partial_m + i \tilde{e}_m^a P_a + \frac{i \omega_m^{ab}}{2} J_{ab} \right)$$

$$S = i \int d^4x \det(E) \mathcal{L} \left(\nabla_a^L \right) \rightarrow \left(e_a^m \partial_m + \frac{i}{2} \omega_m^{ab} J_{ab} \right)$$

$$S = \int d^4x \det(E) \left(\# \underbrace{R^a{}_b}_{ab} \right) \sum_{\substack{1 \\ \downarrow}}^3 T$$

curvature

$$EOM(\omega) \Rightarrow \bar{T} = 0 \sim \omega \omega + e \partial \omega$$

$$\bar{T} = Spin$$

$$\Omega = e^{i\gamma^a(x) P_a}$$

$$e_m^a \equiv \partial_m \gamma^a + \tilde{e}_m^a + \omega_m^{ab} \gamma_b$$

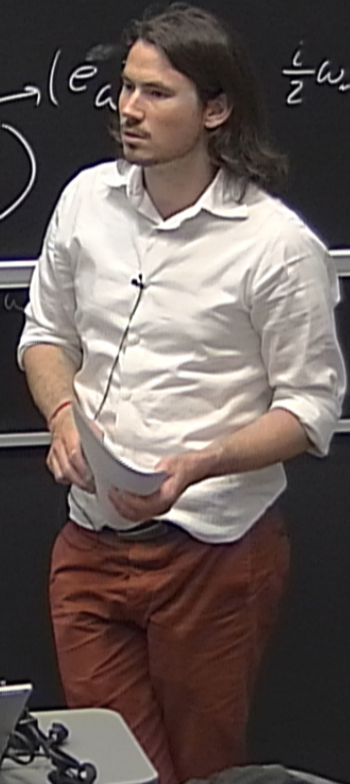
$$\Omega^{-1} \underline{D}_m \Omega = e_m^a P_a + \frac{i}{2} \omega_m^{ab} J_{ab} \quad (\nabla \pi \times)$$

$$(\partial_m + i \tilde{e}_m^a P_a + \frac{i \omega_m^{ab}}{2} J_{ab})$$

$$(e_m^a \quad \frac{i}{2} \omega_m^{ab} J_{ab})$$

$$S = i \int d^4x \det(E) \mathcal{L}(\nabla_a^L)$$

EOM(ω) \Rightarrow $I=0$
 $T = Spin$



- ③ Point particle w/ gravity
- ④ Spinning objects

a, b, c, \rightarrow C.L.
 $u, v, k \rightarrow$ s.L.L
 M, V, \rightarrow st.

① $G \rightarrow H \rightarrow \frac{H_0}{P}$

$$\left[\begin{array}{l} X_a = BG \\ \bar{P}_a = UB \text{ trans.} \\ T_A = \text{other UB} \end{array} \right]$$



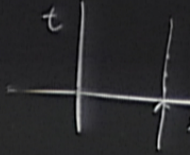
CCWZ, Volkov Ogievetsky

$G/H \rightarrow \Omega = e^{i \gamma^a(x) \bar{P}_a}$ ~1974

$x e^{i \pi^a(x) X_a}$

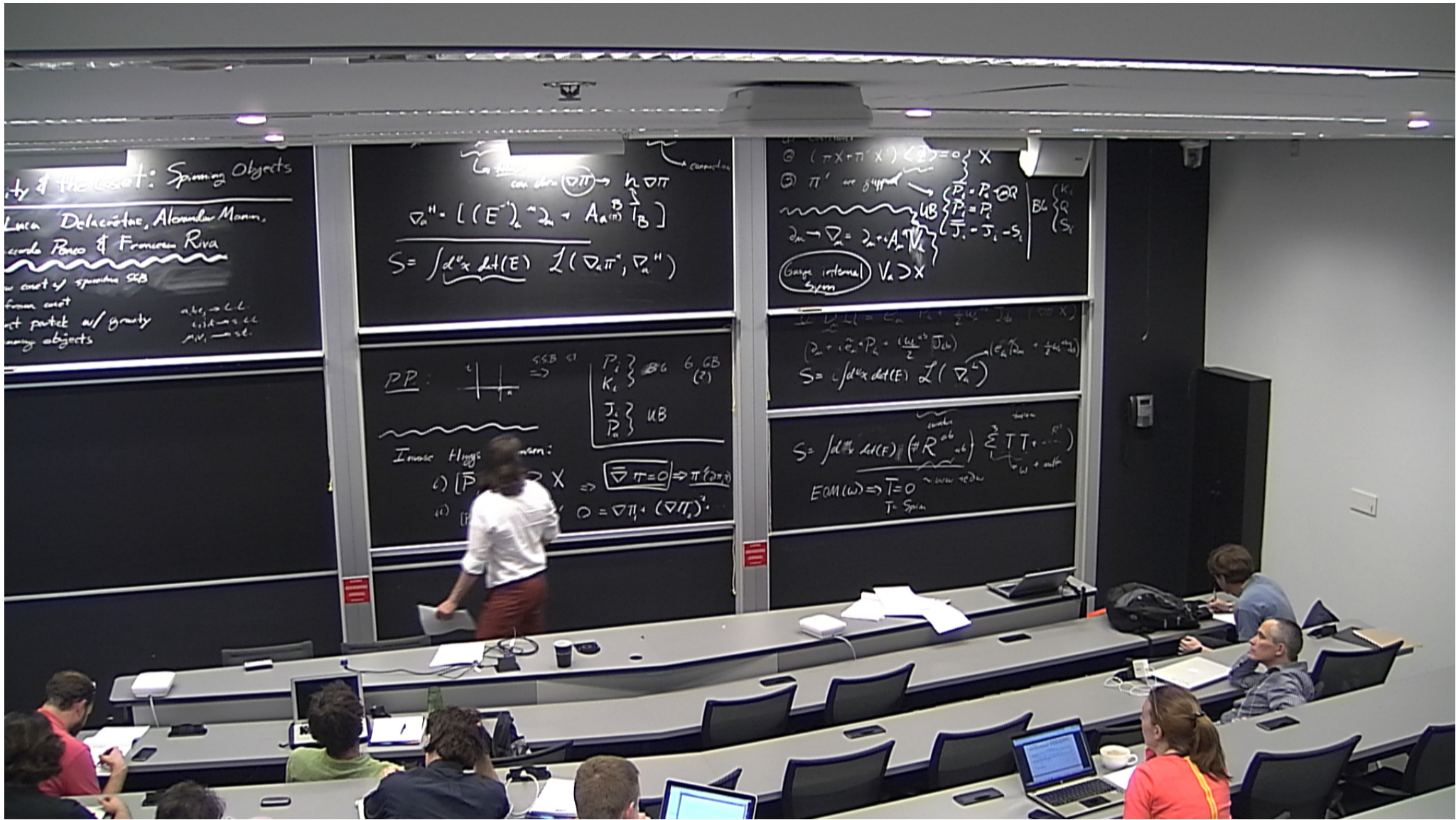
$\Omega' = \frac{h}{T}$

P.P.



Inverse Higgs Mech

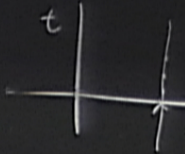
- i) $[\bar{P}, X^a]$
- ii) $[P_a, k] \sim$



- ③ Point particle w/ gravity
- ④ Spinning objects

a, b, c, \rightarrow C.L.
 $\omega, k \rightarrow$ s.L.L.
 μ, ν, \rightarrow st.

P.P.:



Inverse Higgs Mech

i) $[\bar{P}, X]$

ii) $[P_\mu, k] \sim$

CAUTION

$b_i \rightarrow C.L.$
 $c_i, k \rightarrow S.L.L.$
 $v_i \rightarrow st.$

$P_i - \nabla z^i k_i + A^i J_i$
 $= x^v e_v^a \Lambda_a^0(\eta)$
 $\nabla \pi^i = x^v e_v^b \Lambda_b^i(\eta) = 0$
 $\Rightarrow \eta$
 $B^i = \partial_0 x^i$

i) $[P, X'] \supset X \Rightarrow \boxed{\nabla \pi = 0} \Rightarrow \pi(\partial \pi, \pi)$
 ii) $[P_i, k] \sim P_i \quad \pi' \quad 0 = \nabla \pi_1 + (\nabla \pi_2)^2 \dots$

$UB \quad \left\{ \begin{array}{l} \bar{P}_a \\ \bar{J}_i = J_i + S_i \end{array} \right.$ *internal fields*
 $B \quad \left\{ \begin{array}{l} P_i \\ J_i \end{array} \right.$

$b_i \rightarrow C.L.$
 $c_i, k \rightarrow s.L.L.$
 $v_i \rightarrow st.$

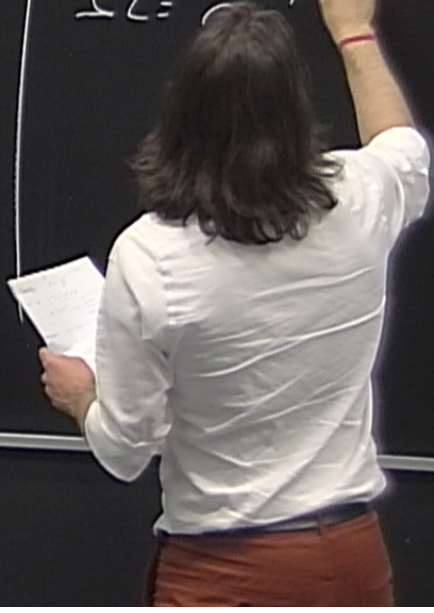
$P_i - \nabla_j k_i + A^c_j$
 $= x^v e_v^a \Lambda_a^0(\eta)$
 $\nabla \pi^i = x^v e_v^b \Lambda_b^i(\eta) = 0$
 $\Rightarrow \eta$
 $\boxed{B^c = \partial_0 X^c}$

i) $[P, X] > X \Rightarrow \boxed{\bar{\nabla} \pi = 0} \Rightarrow \pi(\partial \pi, \pi)$
 ii) $\boxed{[P_i, k] \sim P_i} \pi' \quad 0 = \nabla \pi_1 + (\nabla \pi_2)^2 \dots$

$UB \quad \left\{ \begin{array}{l} \bar{P}_0 \\ \bar{J}_i = J_i - S_i \end{array} \right\} H_0$
inferred relations

$B \quad \left\{ \begin{array}{l} P_i \\ J^{ab} \end{array} \right\}$

$\Omega = \dots^c \gamma$



③ Point particle w/ gravity
 ④ Spinning objects

$a, b, c \rightarrow$ L.L.
 $i, j, k \rightarrow$ s.L.L.
 $m, n \rightarrow$ st.

$$\dot{x}^{\mu} \Omega^{-1} D_{\mu} \Omega = (E) (P_0 + \nabla \pi^i P_i - \nabla \omega^{ab} J_{ab})$$

$$\Omega = e^{i x^a \omega_a P_a} e^{i \eta^i m_i K_i} \rightarrow E = \dot{x}^{\nu} e_{\nu}^{\alpha} \Lambda_{\alpha}^0$$

$$\nabla \pi^i = \dot{x}^{\nu} e_{\nu}^b \Lambda_b^i = 0$$

$$\Rightarrow \eta = \Lambda^{(2)} \Lambda^{(2)}$$

$$\mathcal{B}^i = \partial_0 x^i$$

$$\int d\lambda E(-m)$$

$$-m/d\lambda \int g_{\mu\nu} \dot{x}^{\mu} \dot{x}^{\nu}$$

i) $[P, X]$
 ii) $[P_i, K]$

UB $\left\{ \begin{array}{l} \bar{P}_0 \\ \bar{J}_i \end{array} \right.$
 B $\left\{ \begin{array}{l} P_i \\ J^{ab} \end{array} \right.$