Title: Universality classes of inflation as phases of condensed matter: slow-roll, solids, gaugids etc.

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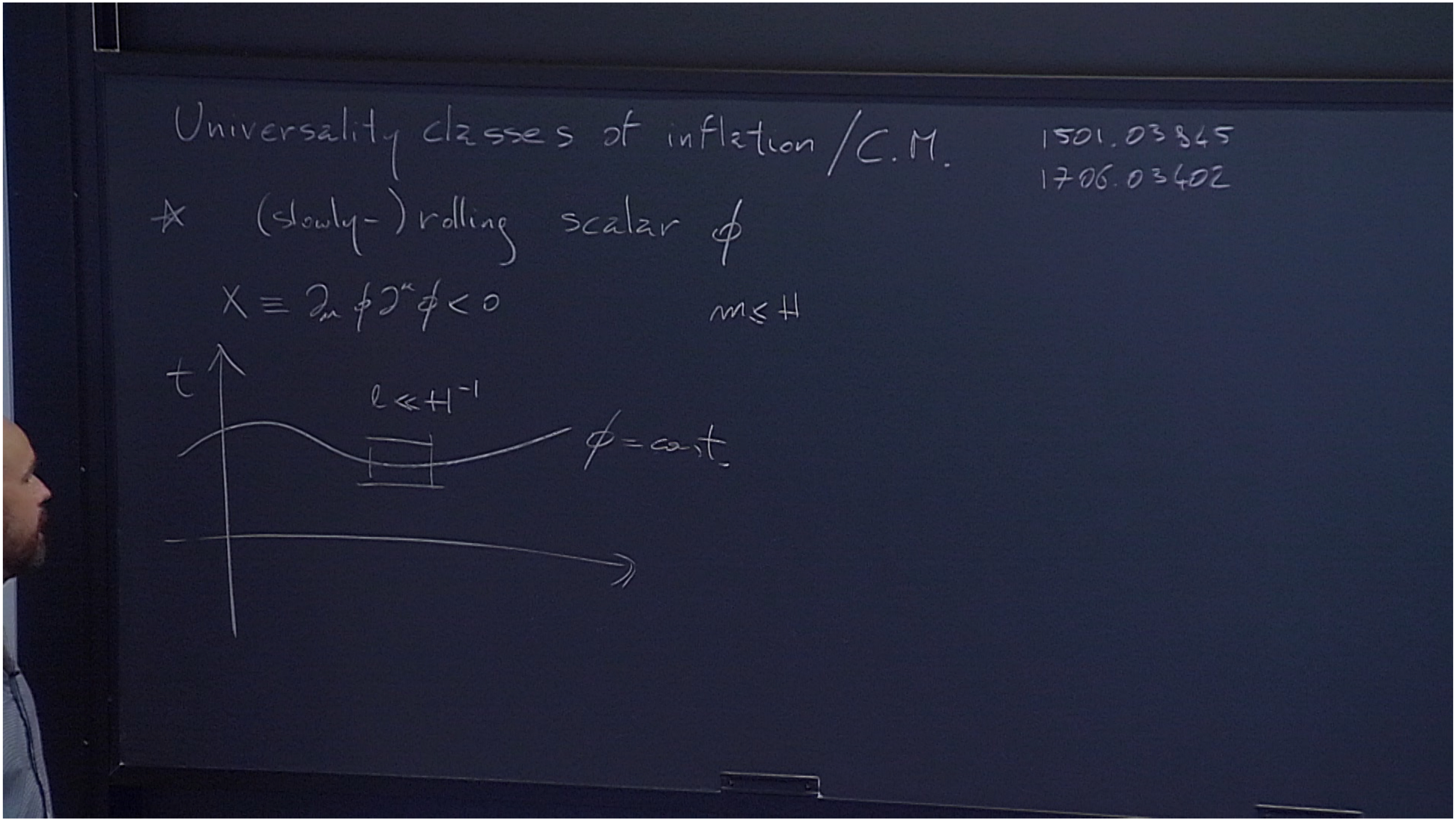
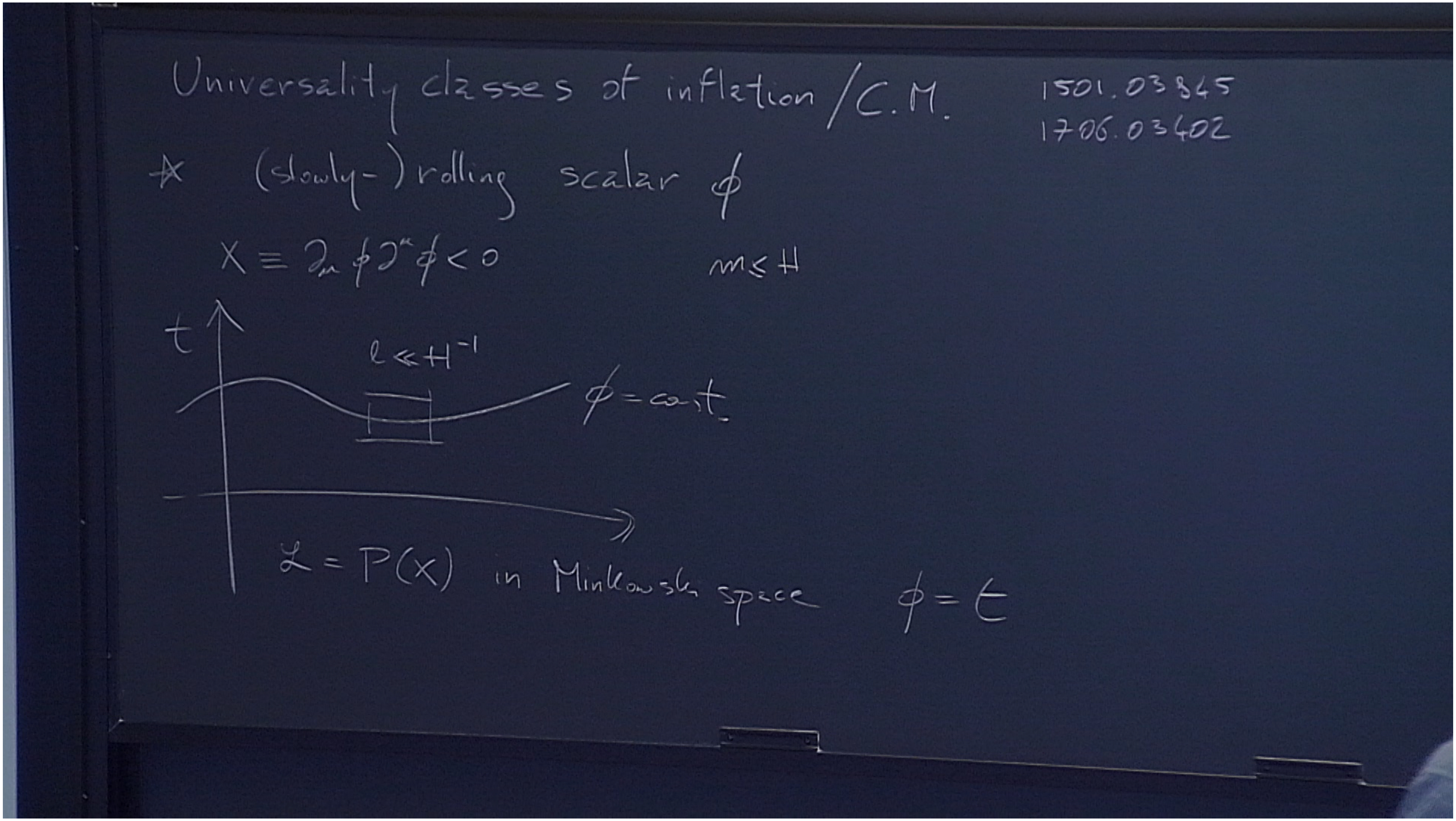
Abstract: <p>Universality classes of inflation as phases of condensed matter: slow-roll, solids, gaugids etc.
Abstract: Cosmology and condensed matter systems share the same basic symmetries: both are characterised by a (spontaneous) breaking of Lorentz boosts and by approximate translation and rotation invariances. It is therefore not completely surprising that the basic mechanisms for cosmic acceleration be in one to one correspondence with different condensed matter realisations. This point of view has recently unveiled inflationary models well beyond single-field inflation. The different inequivalent ways in which translation and rotation invariance can be recovered at low energy lead to different "universality classesâ€• for cosmic acceleration. Among those, solid inflation and the recently proposed gaugid inflation have substantially different properties than those of single-field slow-roll scenarios.</p>


Universality classes of inflation / C.M.
1501.03845
1706.03402
★ (slowly-) rolling scalar ϕ
$X \equiv \partial_\mu \phi \partial^\mu \phi < 0$
$m \lesssim H$
t
$\ell \ll H^{-1}$
$\phi = \text{const.}$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$\phi = \text{const.}$
$\mathcal{L} = P(X)$ in Minkowski space
$\phi = t$

Poincaré generators $\cancel{K_i}$

$\cancel{H}$ P_i J_i

internal sym.

$\cancel{Q}$ $[U(1)]$

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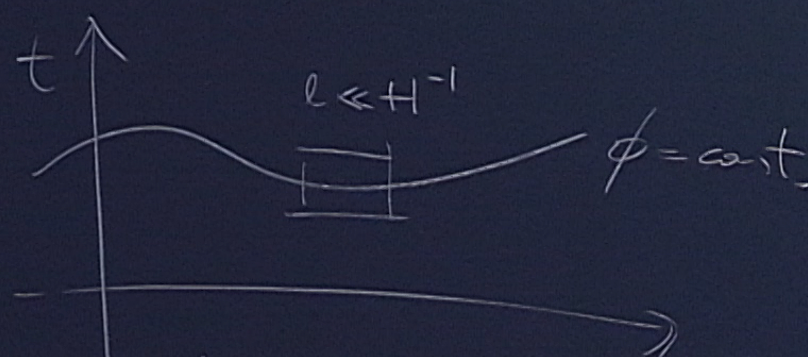
★ (slowly-) rolling scalar ϕ

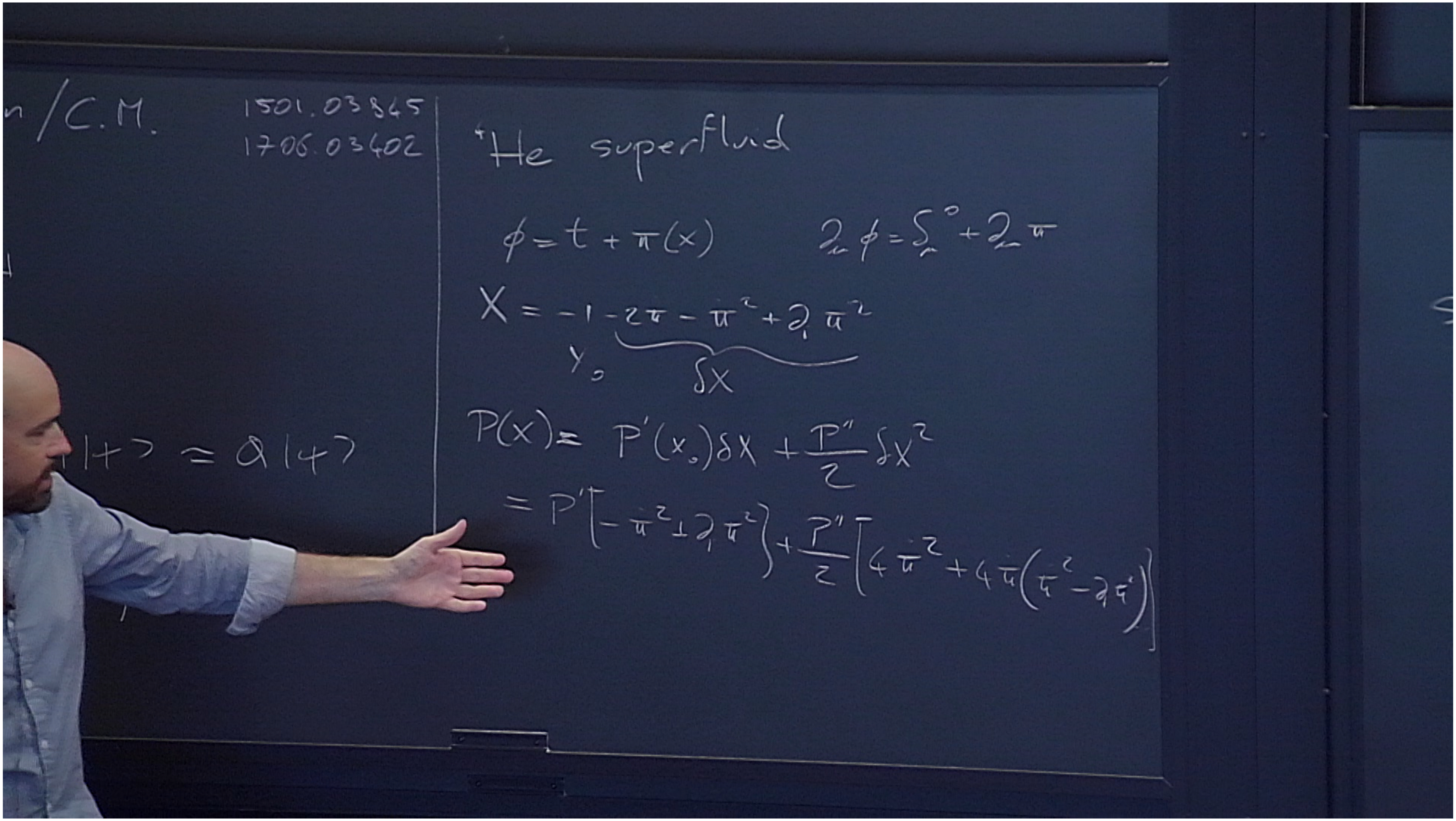
$X \equiv \partial_\mu \phi \partial^\mu \phi < 0$ $m \lesssim H$

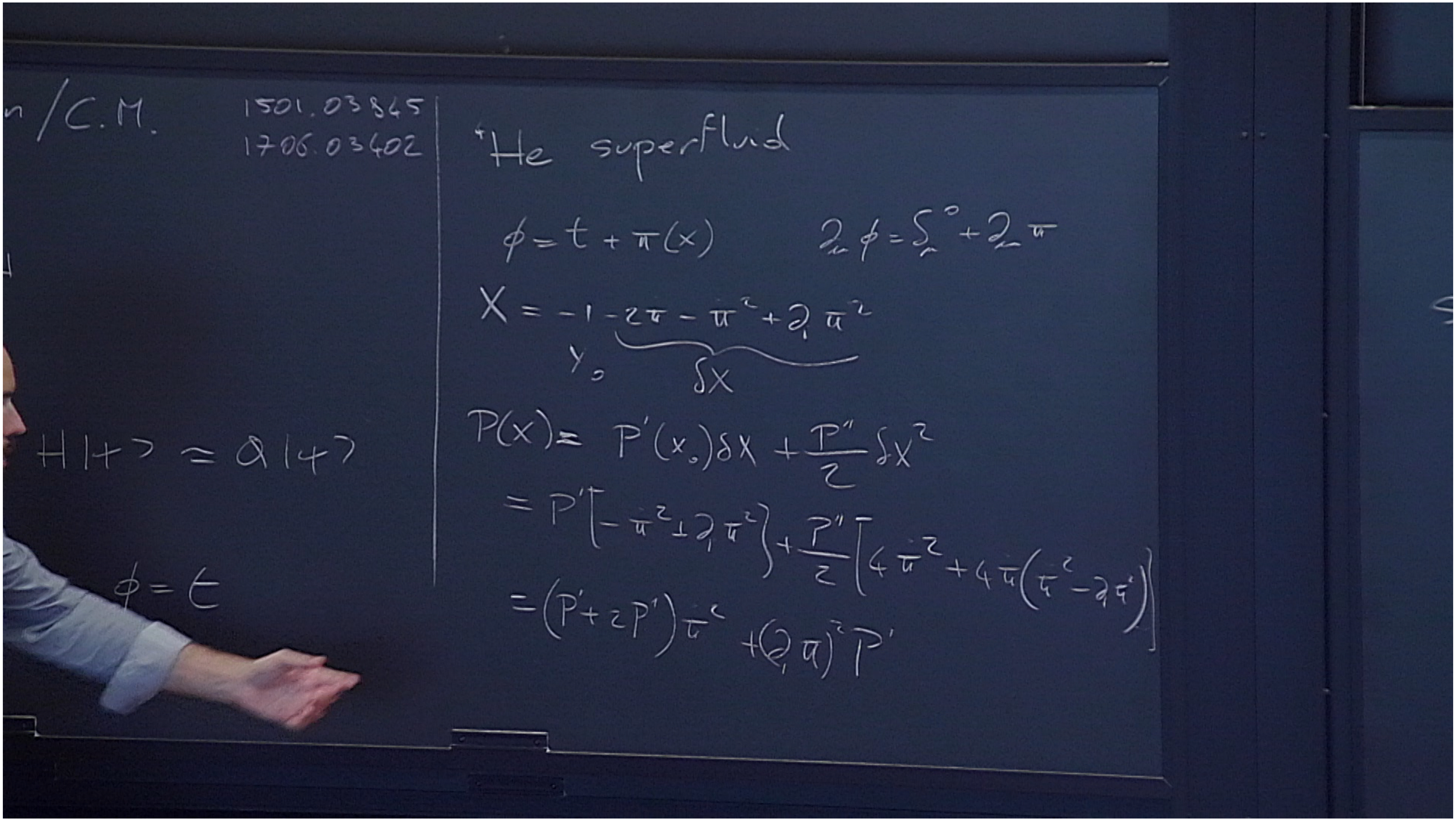


$H|\psi\rangle \simeq Q|\psi\rangle$

$\mathcal{L} = P(X)$ in Minkowski space $\phi = t$

shift : $\phi \to \phi + c$


n /C.M.
1501.03845
1706.03402
|ψ⟩ = a|ψ⟩
⁴He superfluid
φ = t + π(x)
∂_μ φ = δ_μ^0 + ∂_μ π
X = −1 − 2π̇ − π̇² + ∂_i π²
X_0
δX
P(X) = P′(X_0) δX + P″/2 δX²
= P′[−π̇² + ∂_i π²] + P″/2 [4π̇² + 4π̇(π̇² − ∂π²)]


n / C.M.
1501.03845
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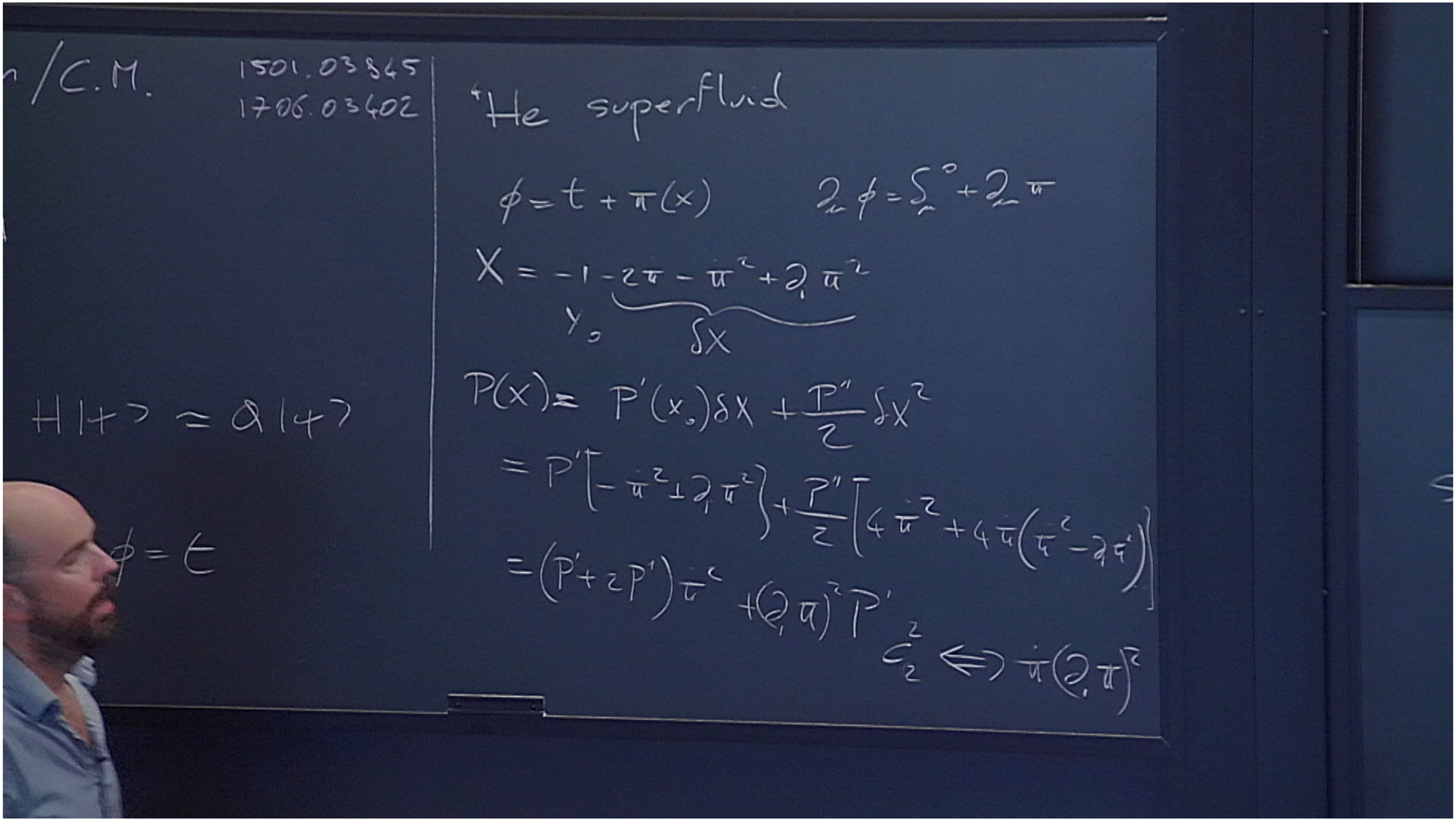
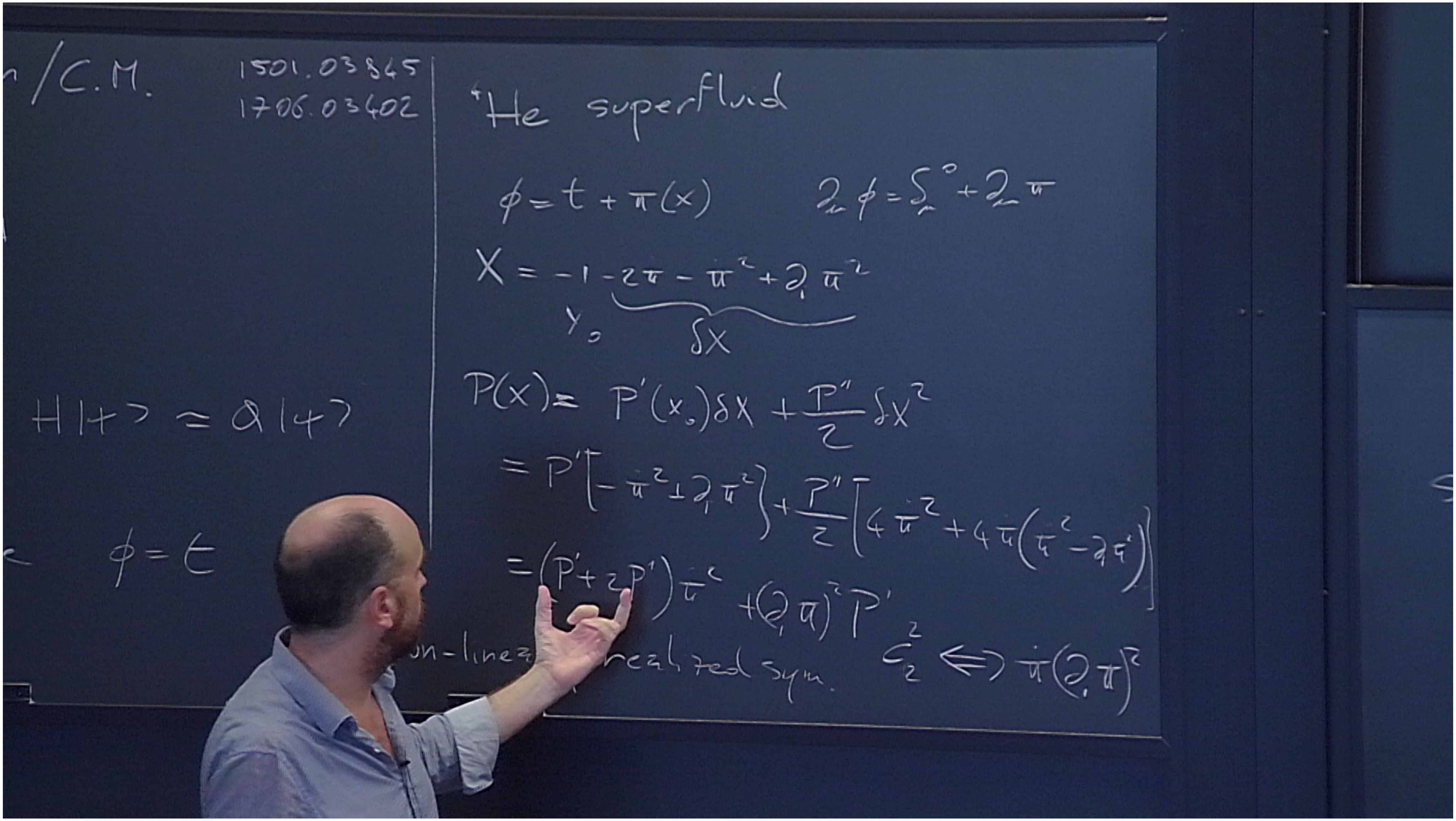


/C.M.
1501.03845
1706.03402
^{4}He superfluid
$\phi = t + \pi(x)$
$\partial_\mu \phi = \delta_\mu^0 + \partial_\mu \pi$
$X = \underbrace{-1}_{X_0} \underbrace{-2\dot{\pi} - \dot{\pi}^2 + \partial_i \pi^2}_{\delta X}$
$P(X) = P'(X_0)\delta X + \frac{P''}{2}\delta X^2$
$= P'[-\dot{\pi}^2 + \partial_i \pi^2] + \frac{P''}{2}[4\dot{\pi}^2 + 4\dot{\pi}(\dot{\pi}^2 - \partial_i \pi^2)]$
$= (P' + 2P'')\dot{\pi}^2 + (\partial_i \pi)^2 P'$
$c_s^2 \Leftrightarrow \dot{\pi}(\partial_i \pi)^2$
$H|\psi\rangle = a|\psi\rangle$
$\phi = t$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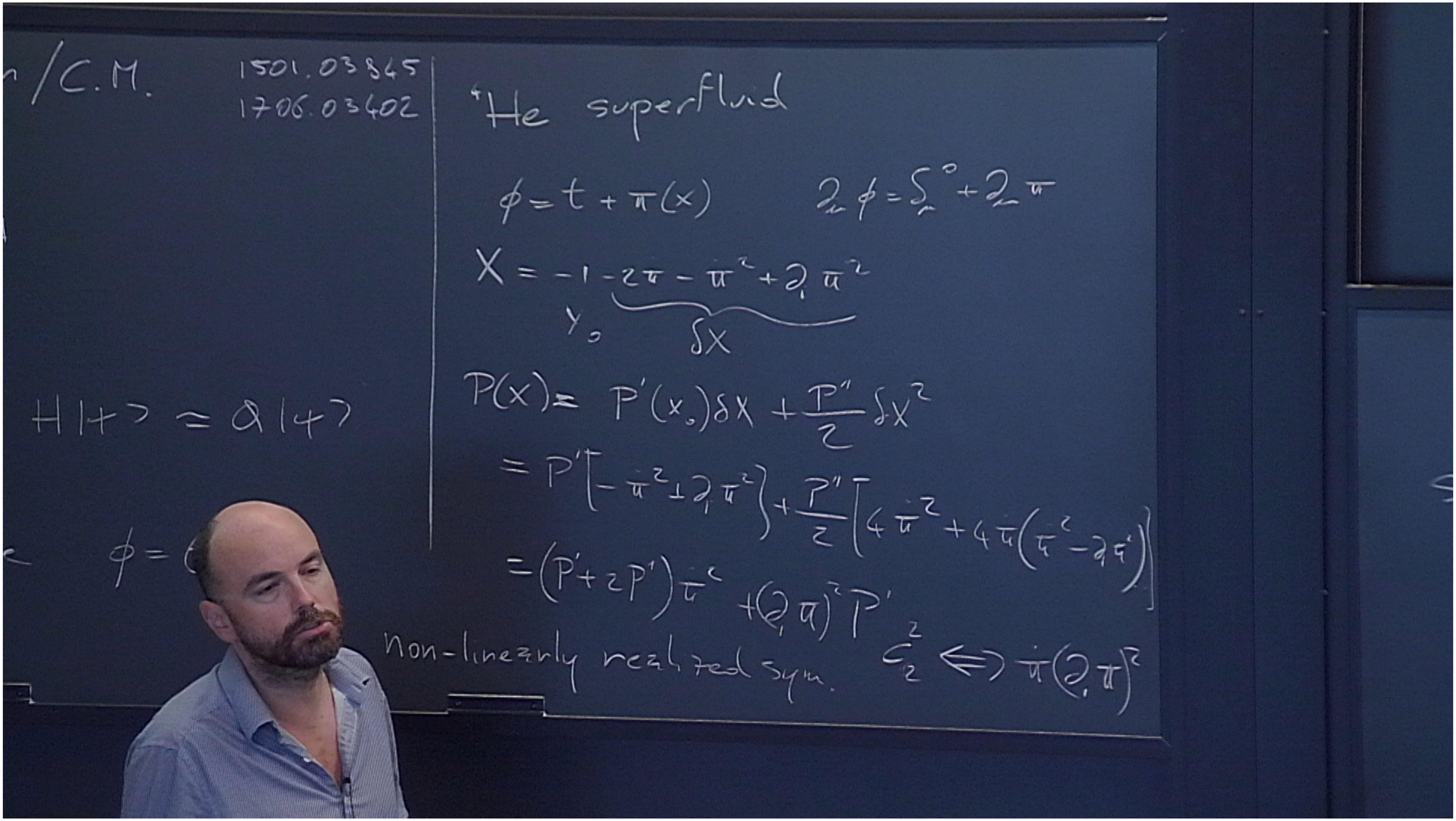
$H|\psi\rangle \simeq a|\psi\rangle$
$P(X) = P'(X_0)\delta X + \frac{P''}{2}\delta X^2$
$\phi = t$
non-linearly realized sym.
$c_s^2 \Leftrightarrow \dot\pi(\partial_i \pi)^2$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1501.03845
1706.03402

...g scalar ϕ

$m \lesssim H$

$\phi = \text{const.}$

$H|\psi\rangle \simeq a|\psi\rangle$

in Minkowski space $\quad \phi = t$

$\phi \to \phi + c$

$\omega^2 = c_s^2 k^2 + \lambda k^4$ non-linearly realized sym.

^{4}He superfluid

$$\phi = t + \pi(x) \qquad \partial_\mu \phi = \delta_\mu^0 + \partial_\mu \pi$$

$$X = \underbrace{-1}_{X_0} \underbrace{- 2\dot\pi - \dot\pi^2 + (\partial_i \pi)^2}_{\delta X}$$

$$P(X) = P'(X_0)\,\delta X + \frac{P''}{2}\delta X^2$$

$$= P'\left[-\dot\pi^2 + (\partial_i\pi)^2\right] + \frac{P''}{2}\left[4\dot\pi^2 + 4\dot\pi\left(\dot\pi^2 - (\partial_i\pi)^2\right)\right]$$

$$= (P' + 2P'')\dot\pi^2 + (\partial_i\pi)^2 P'$$

$$c_s^2 \Longleftrightarrow \dot\pi(\partial_i\pi)^2$$

shift : $\phi \to \phi + c$

$\omega^2 = c_s^2 k^2 + \lambda k^4$ non-linearly realized sym.

Cosmology $\equiv$ CM at play with gravity

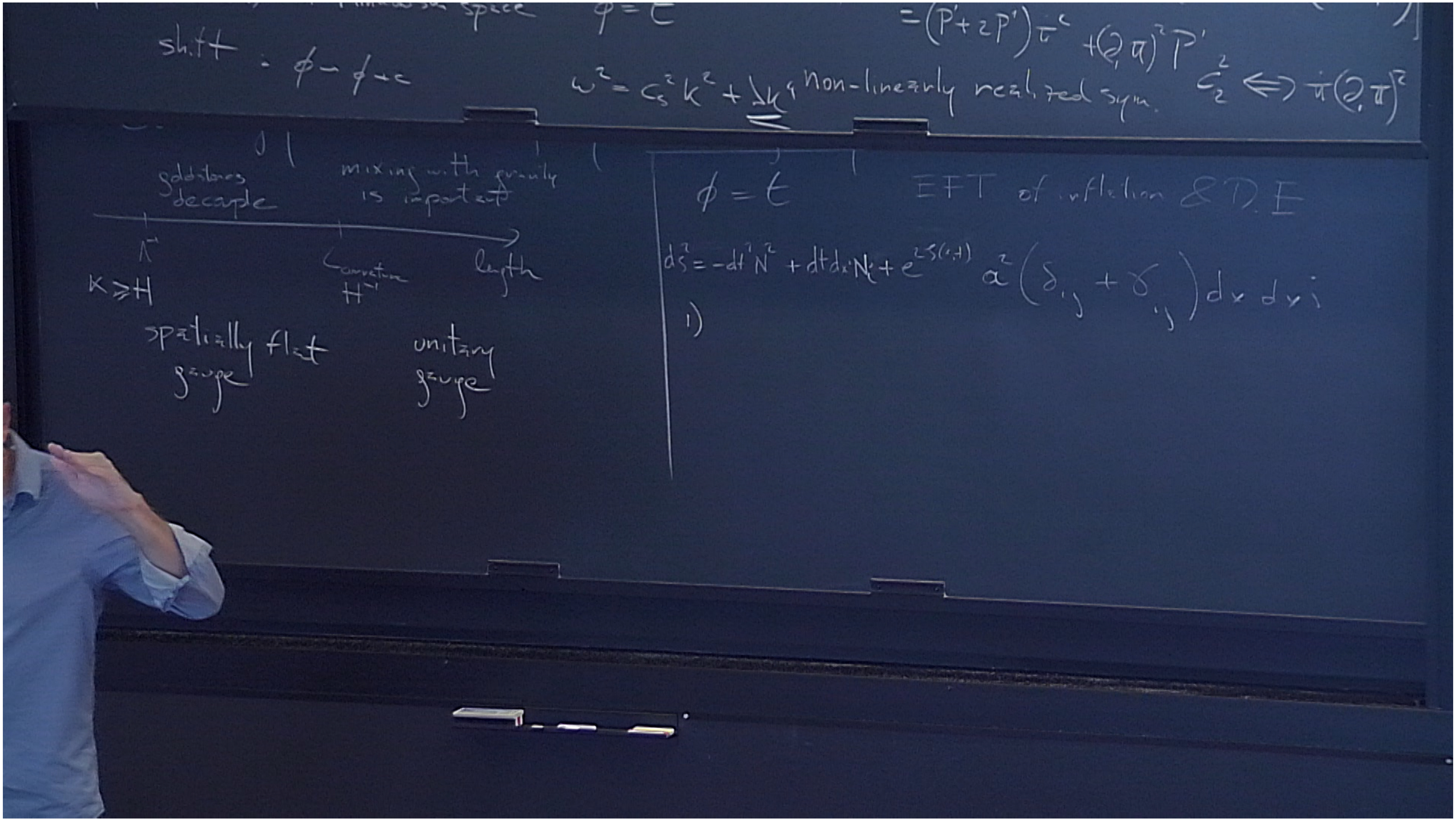
goldstones decouple

mixing with gravity is important

Λ^{-1}

$L_{\text{curvature}}$ H^{-1}

length


shift : $\phi \to \phi + c$
$= (P' + 2P'')\dot{\pi}^2 + (\partial_i \pi)^2 P'$
$\omega^2 = c_s^2 k^2 + \Delta k^4$ non-linearly realized sym. $c_s^2 \Leftrightarrow \dot{\pi}(\partial_i \pi)^2$
goldstones decouple
mixing with gravity is important
Λ^{-1}
curvature H^{-1}
length
$k \gg H$
spatially flat gauge
unitary gauge
$\phi = t$
EFT of inflation & D.E
$ds^2 = -dt^2 N^2 + dt\, dx^i N_i + e^{2\zeta(x,t)} a^2 (\delta_{ij} + \gamma_{ij}) dx^i dx^j$
1)

$\omega^2 = c_s^2 k^2 + \underline{\lambda k^4}$ non-linearly realized sym. $c_s \Leftrightarrow \dot{\pi}(\partial_i \pi)^2$

$\phi = t$ EFT of inflation & D.E

$$ds^2 = -dt^2 N^2 + dt\, dx^i N_i + e^{2\zeta(x,t)} a^2 (\delta_{ij} + \gamma_{ij}) dx^i dx^j$$

$\boxed{\zeta = 0 \quad \gamma_{ii} = 0}$

1) ζ & γ_{ij} are conserved on $k \ll H$

2) $\Delta_\gamma^2 \sim \frac{H^2}{M_p^2}$

3) $\Delta_s^2 \sim \frac{H^2 M_p^2}{M_p^2 \epsilon c_s}$

$f_{NL} \sim c_s^{-2}$

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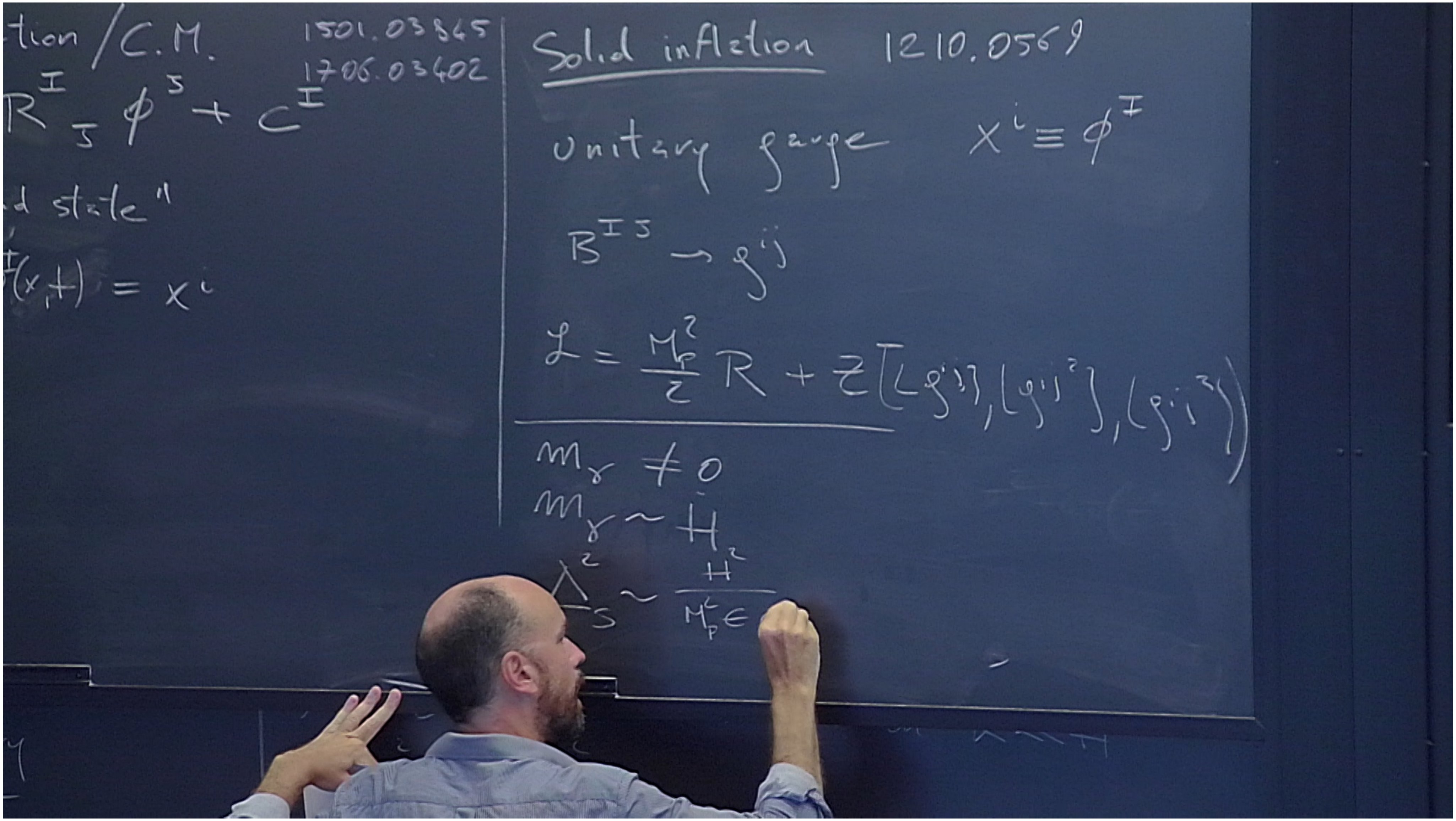
3-scalar fields $\quad \phi^I \to R^I{}_J\, \phi^J + c^I$

$B^{IJ} = \partial_\mu \phi^I \partial^\mu \phi^J$ "ground state"

$[B], [B^2], [B^3]$ $\quad \phi^I(x,t) = x^i$

$\mathcal{L} = \mathcal{L}([B],[B^2],[B^3])$


tion / C.M.
1501.03845
1706.03402
R^I_J φ^J + C^I
d state"
(x,t) = x^i
Solid inflation 1210.0569
unitary gauge x^i ≡ φ^I
B^IJ → g^ij
L = M_p^2/2 R + Z[[g^ij], [g^ij 2], [g^ij 3]]
m_γ ≠ 0
m_γ ~ H
Δ_S^2 ~ H^2 / M_p^2 ε

tion / C.M. 1501.03845
1706.03402

$R^I{}_J \phi^J + C^I$

d state"

$\phi^I(x,t) = x^i$

Solid inflation 1210.0569

unitary gauge $x^i \equiv \phi^I$

$B^{IJ} \to g^{ij}$

$$\mathcal{L} = \frac{M_p^2}{2} R + F\left([g^{ij}], [g^{ij\,2}], [g^{ij\,3}]\right)$$

$m_\gamma \neq 0$

$m_\gamma \sim \dot{H}$

$$\Delta_S^2 \sim \frac{H^2}{M_p^2 \epsilon c_s^5}$$

2) $\Delta_\gamma^2 \sim \frac{H^2}{M^2}$

interal sym.

$\cancel{Q}$ $[U(1)]$

$\bar{H} = H - \mu Q$

ISO(3)

\# goldstones $\leq$ broken generators

1

3

	Poincaré generators			$\cancel{K_i}$	internal sym.
superfluid	$\cancel{H}$	P_i	J_i		Q $[U(1)]$ $\quad \bar{H} = H - \mu Q$
solid	H	$\cancel{P_i}$	$\cancel{J_i}$		$ISO(3)$
supersolids	$\cancel{H}$	$\cancel{P_i}$	$\cancel{J_i}$		$U(1) \times ISO(3)$
Framids (type I & II)	H	P_i	J_i		
	H	P_i	$\cancel{J_i}$		
superfluid (type II)	$\cancel{H}$	P_i	$\cancel{J_i}$		
"galileids"	H	$\cancel{P_i}$	J_i		galileid symmetry
	$\cancel{H}$	$\cancel{P_i}$	J_i		

$m_\gamma \sim H$

$\Delta_S^2 \sim \frac{H^2}{M_p^2 \epsilon c_S^5}$

Gaugids $\quad ISO(3) : \quad U(1)^3_{\text{gauge}} \times SO(3)$

$A^I_\mu \to A^I_\mu + \partial_\mu \alpha^I \; ; \; F^I_{\mu\nu} \equiv \partial_\mu A^I_\nu - \partial_\nu A^I_\mu \; , \; \tilde F^I_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu}{}^{\rho\sigma} F_{\rho\sigma}$

$Y^{IJ} = F^I_{\mu\nu} F^{J\mu\nu} \; , \; \tilde Y^{IJ} = F^I_{\mu\nu} \tilde F^{J\mu\nu}$

$X = [Y] \; , \; I_A \quad A = 1 \ldots 10$

$I_1 = \frac{[Y^2]}{[Y]^2}$

$\mathcal{L} = \frac{M_p^2}{2} R + Z(X, I_A)$

$\epsilon \sim \frac{\partial \ln Z}{\partial \ln X}$

"galileids"

$A \quad P_i \quad \cancel{K_i}$

$H \quad \cancel{P_i} \quad J_i$

$\cancel{H} \quad \cancel{P_i} \quad J_i$

galileid symmetry

Bianchi identities $\partial_{[\mu} F_{\nu\rho]} = 0$

$$\dot{\vec{B}}^I + \vec{\mathrm{rot}}\, \vec{E}^I = 0$$

$$B^I{}_j = f_1(t)\, \delta^1{}_j \qquad f_1 = \text{const}$$

$$E^I{}_j = f_2(t)\, \delta^1{}_j$$

Magnetic gaugid $\quad E^I = 0$

"galileids"

$\cancel{A} \quad \cancel{P_i} \quad \cancel{\xi_i}$

$H \quad \cancel{P_i} \quad \xi_i$

$\cancel{A} \quad \cancel{P_i} \quad \xi_i$

galileid symmetry

Bianchi identities $\partial_{[\mu} F_{\nu\rho]} = 0$

$$\dot{\vec{B}}^I + \vec{\mathrm{rot}}\,\vec{E}^I = 0$$

$$B^I{}_j = f_1(t)\,\delta^1{}_j \qquad f_1 = \mathrm{const}$$

$$E^I{}_j = f_2(t)\,\delta^1{}_j$$

Magnetic galileid $\quad E^I = 0$

$$B^I{}_j = \delta^I{}_j \qquad \boxed{A^I_\mu = \epsilon_{I\mu k}\, x^k}$$

ρ_i galileid symmetry

ζ_i

ζ_i

Perturbations A^I_0 non dynamical

$$A^I_j = \epsilon_{ijk} x^k + a_{ij}$$

helicity decomposition

$$a_{ij} = \alpha \delta_{ij} + \partial_i \partial_j S + \partial_i S^T_j + \partial_j S^T_i + E_{ij} + \epsilon_{ijk}\left(V^T_k + \frac{\partial_k T}{\sqrt{-\partial^2}}\right)$$

ρ_i galileid symmetry

ζ_i

ζ_i

cans!

Perturbations A^I_0 : non dynamical

$$A^I_j = \epsilon_{ijk}\, x^k + a_{ij} \qquad \boxed{U(1)^3 \text{ gauge trans}}$$

helicity decomposition

$$a_{ij} = \alpha\,\delta_{ij} + \cancel{\partial_i \partial_j S} + \cancel{\partial_i S^T_j} + \cancel{\partial_j S^T_i} + E_{ij} + \epsilon_{ijk}\left(V^T_k + \frac{\partial_k T}{\sqrt{-\partial^2}}\right)$$

$+\epsilon_{ijk}\left(v_k + \frac{\partial_k}{\sqrt{-\partial^2}}\right)$

" ± 2 E_{ij} γ_{ij}

① Scalars $\equiv$ scalars in solids $\Rightarrow \Delta_s^2 = 1/c_s^5$

② tensors $\neq$ solids' tensors $\quad \mathcal{L}_{int} \sim \epsilon_{ijk}\,\partial_j E_{il}\,\gamma_{kl}$

$$\Delta_t^2 \sim \frac{H^2}{M_p^2}\cdot\frac{1}{c_E^3\,\epsilon}$$

$$r \sim \frac{c_s^5}{c_E^3}$$