Title: TBA

Speakers: Robert Brandenberger

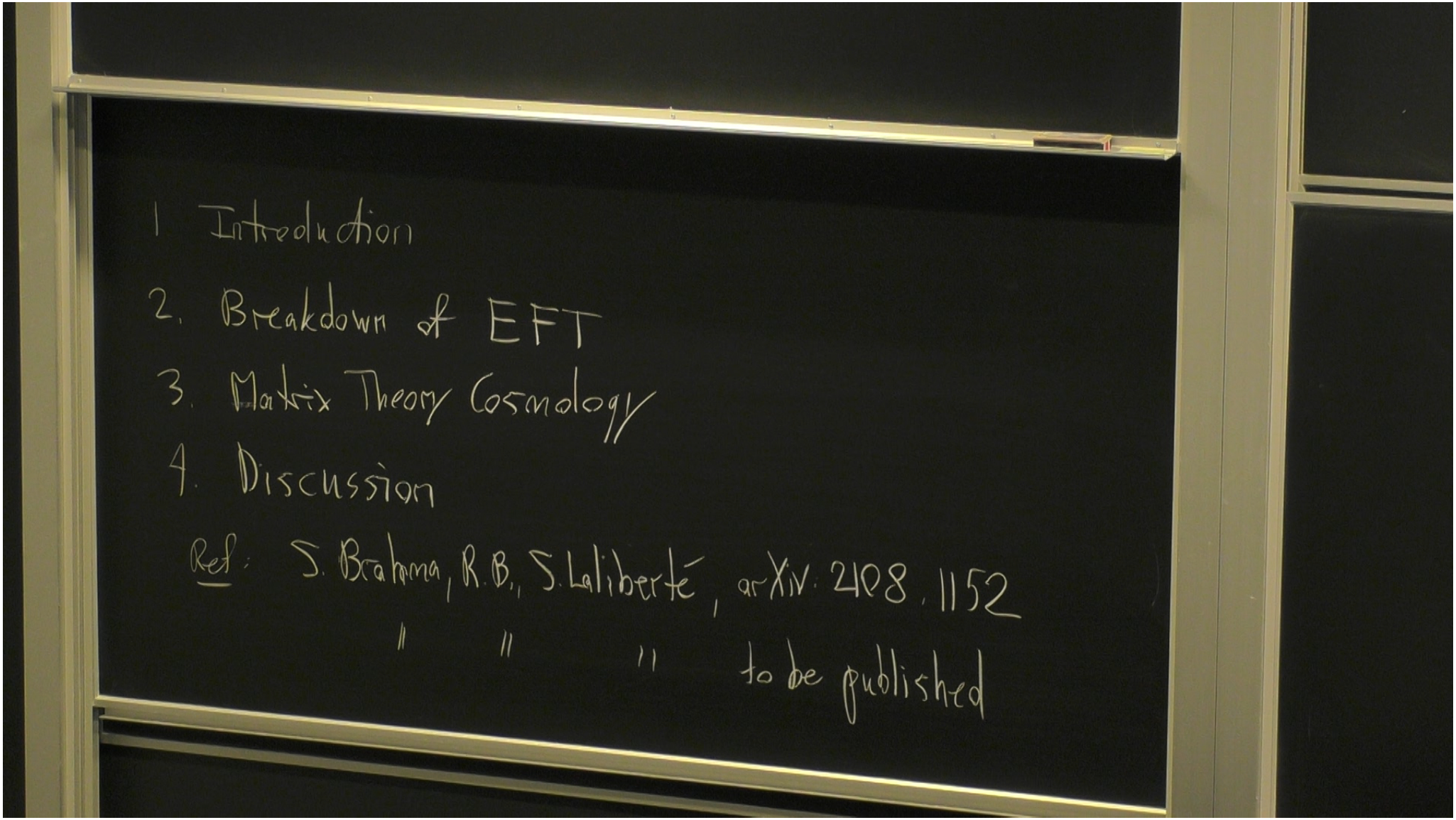
Series: Quantum Gravity

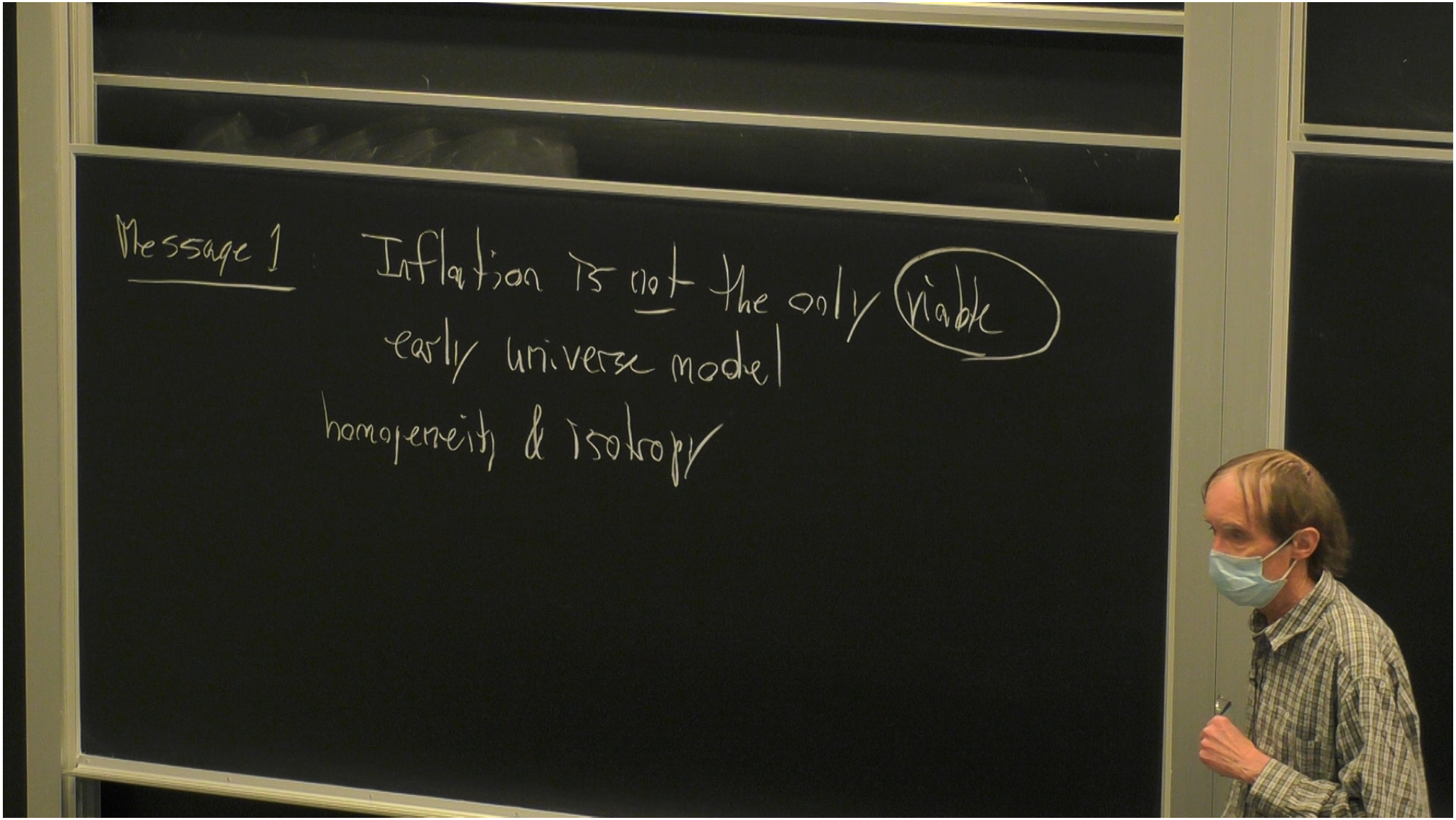
Date: May 11, 2022 - 2:30 PM

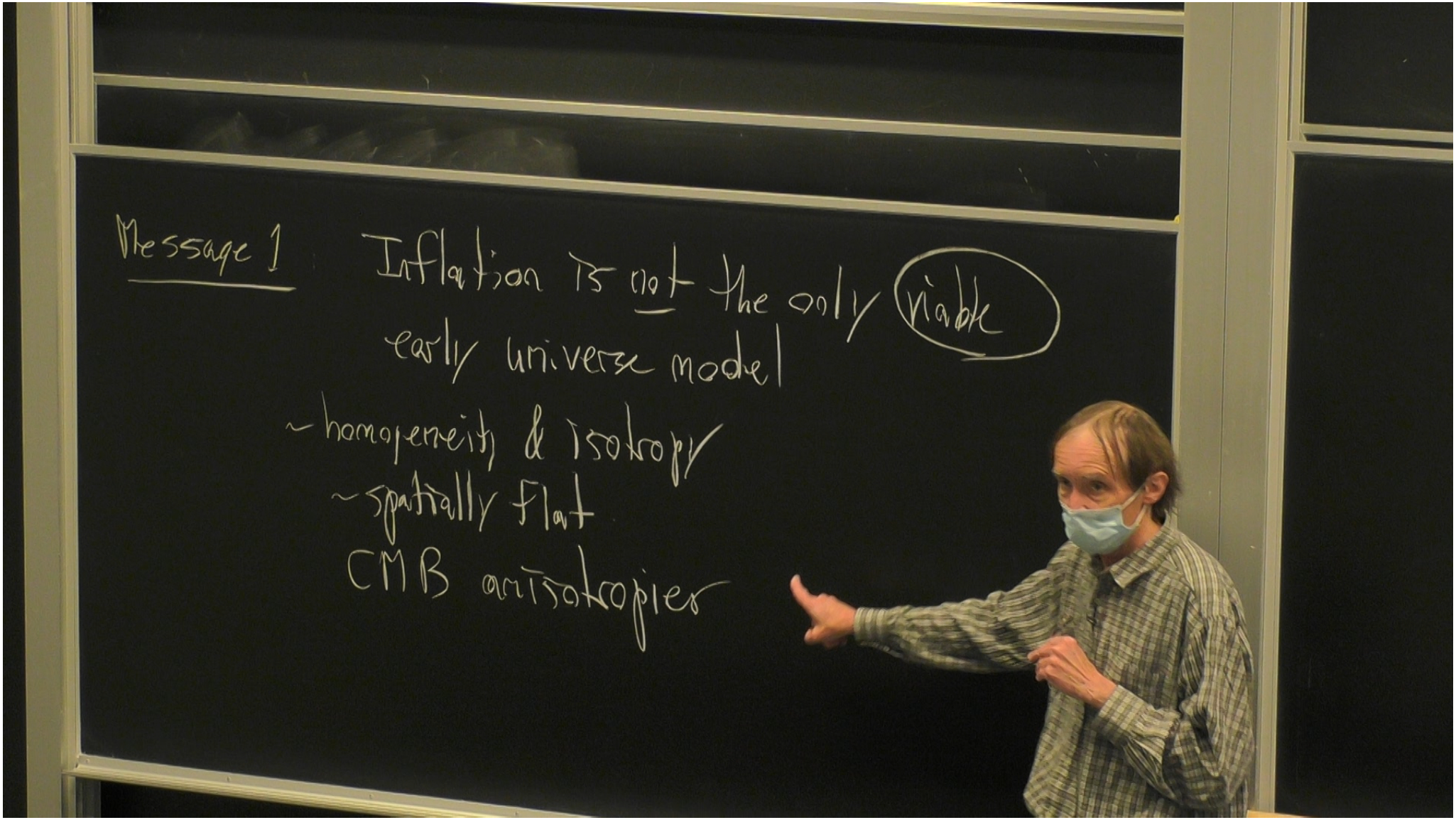
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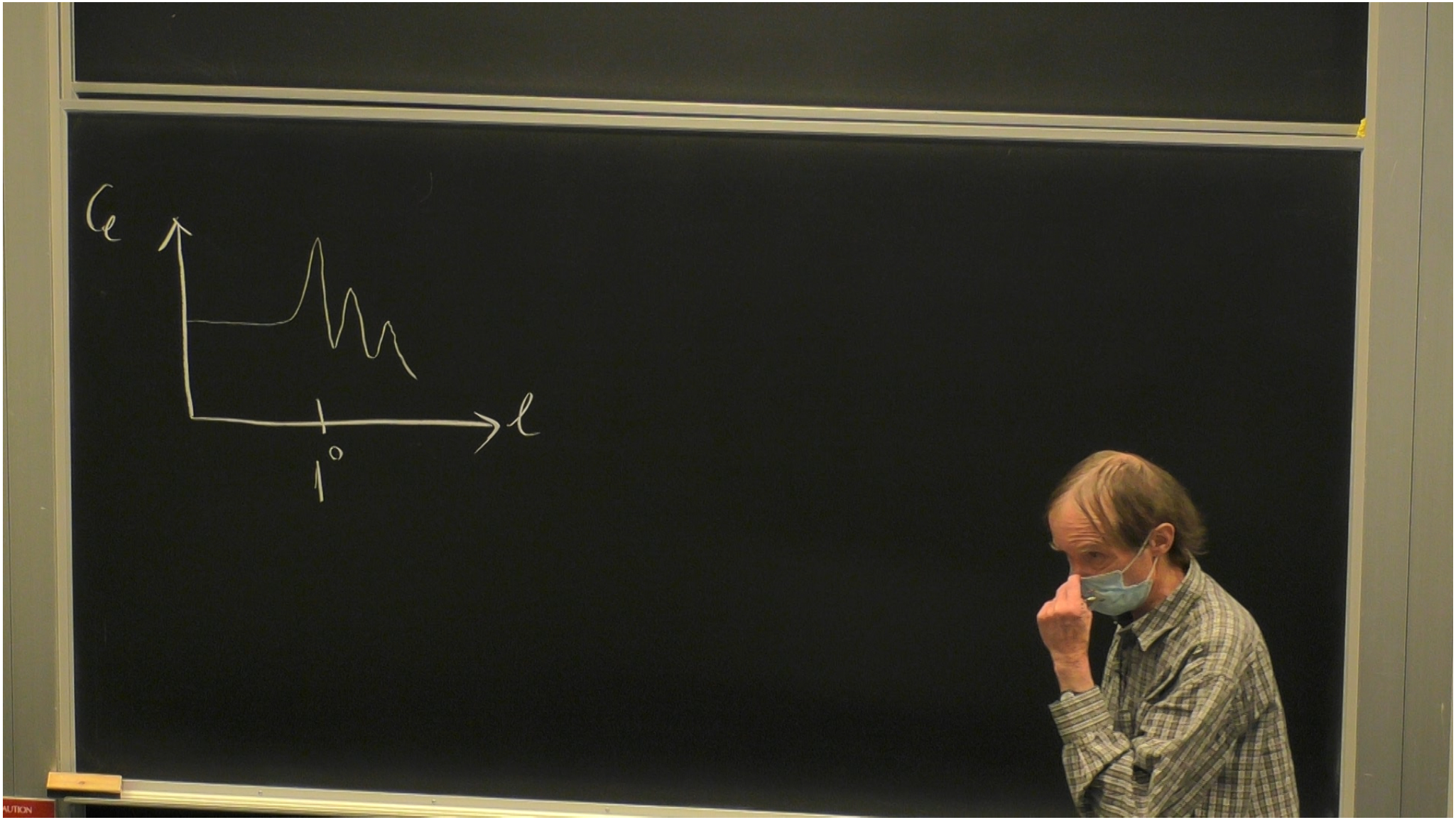
Abstract: Abstract: TBD

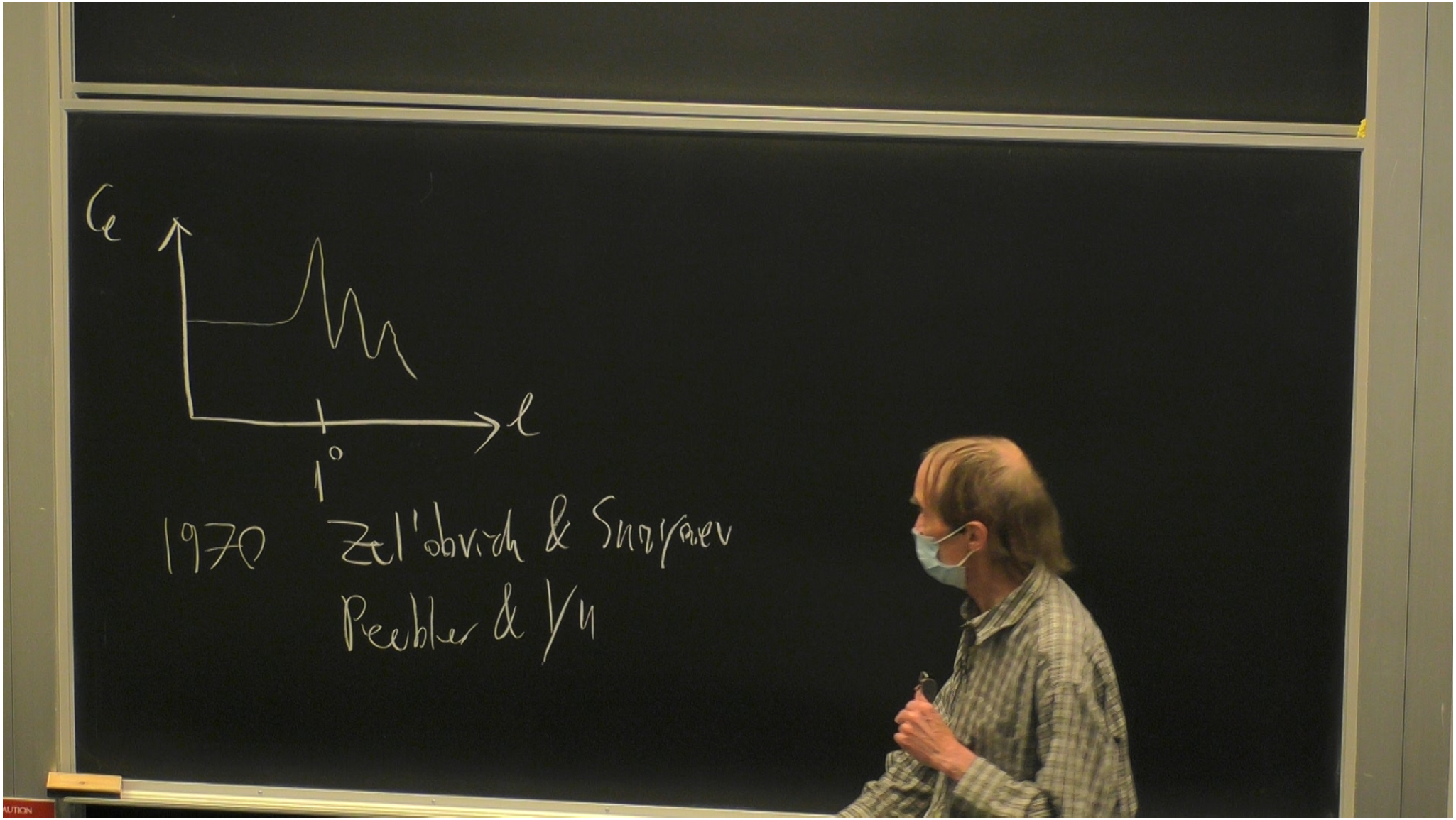
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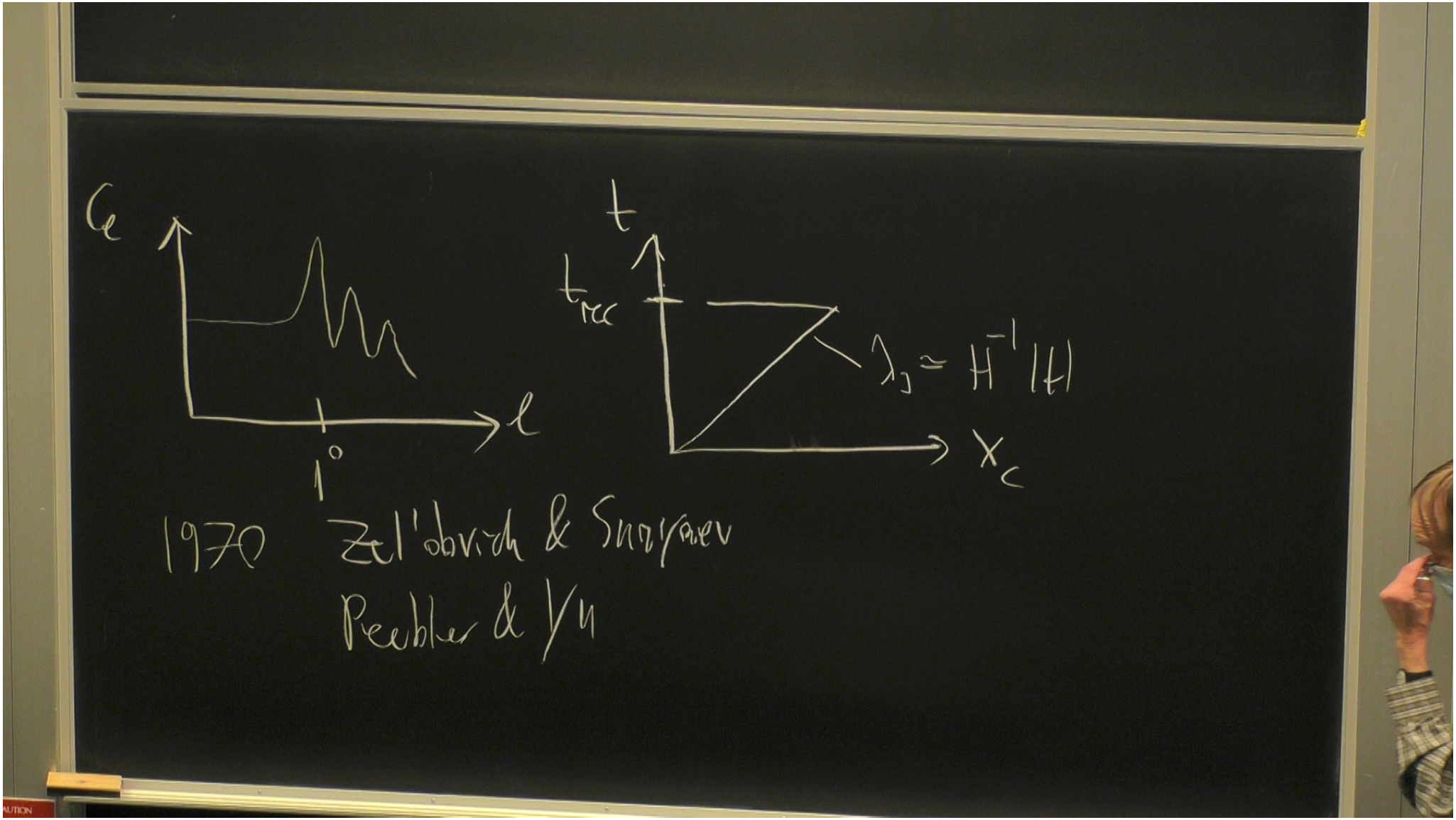

1 Introduction
2. Breakdown of EFT
3. Matrix Theory Cosmology
4. Discussion
Ref: S. Brahma, R.B., S. Laliberté, arXiv: 2108.1152
" " " to be published

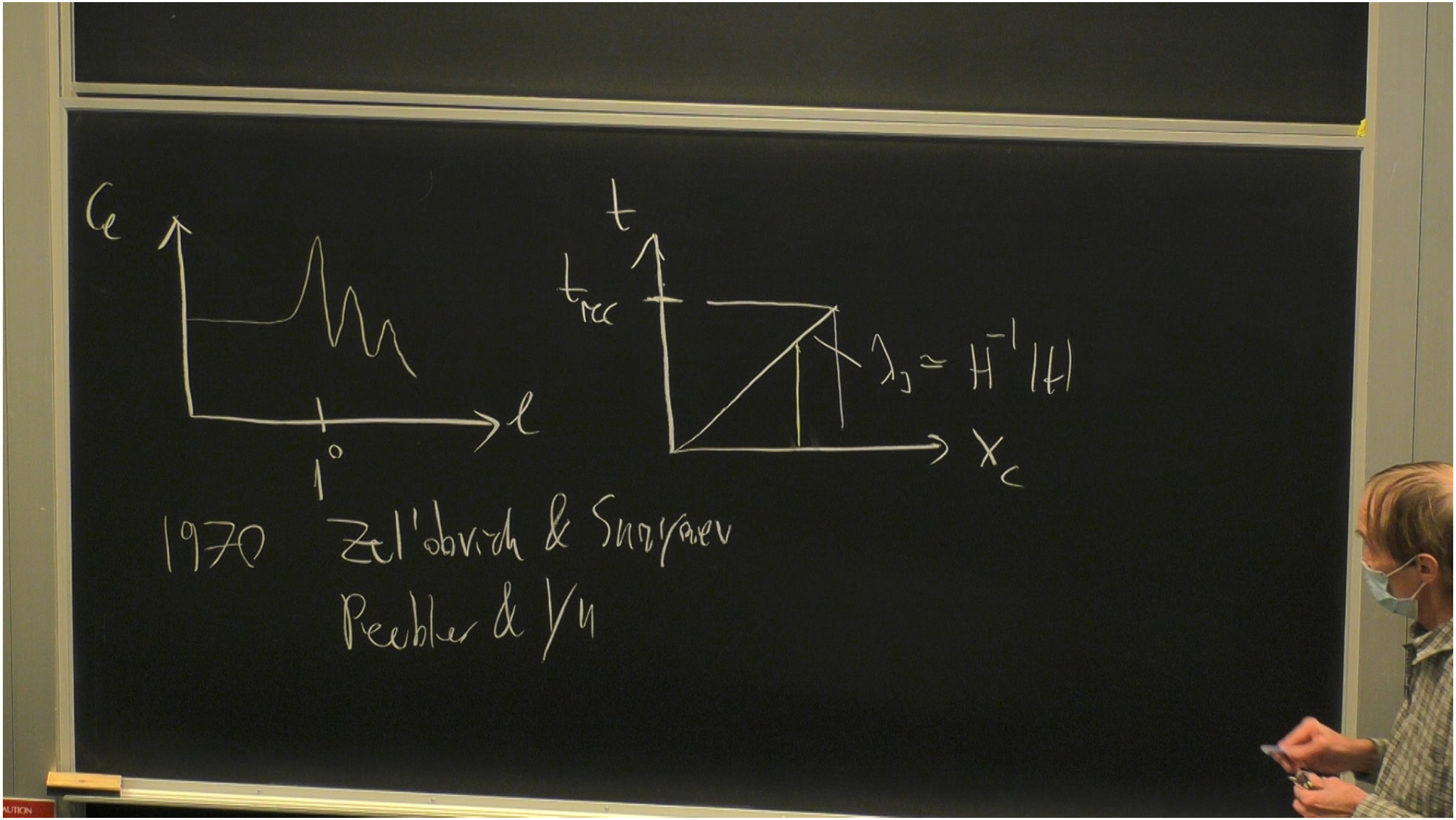

Message 1
Inflation is not the only viable
early universe model
homogeneity & isotropy

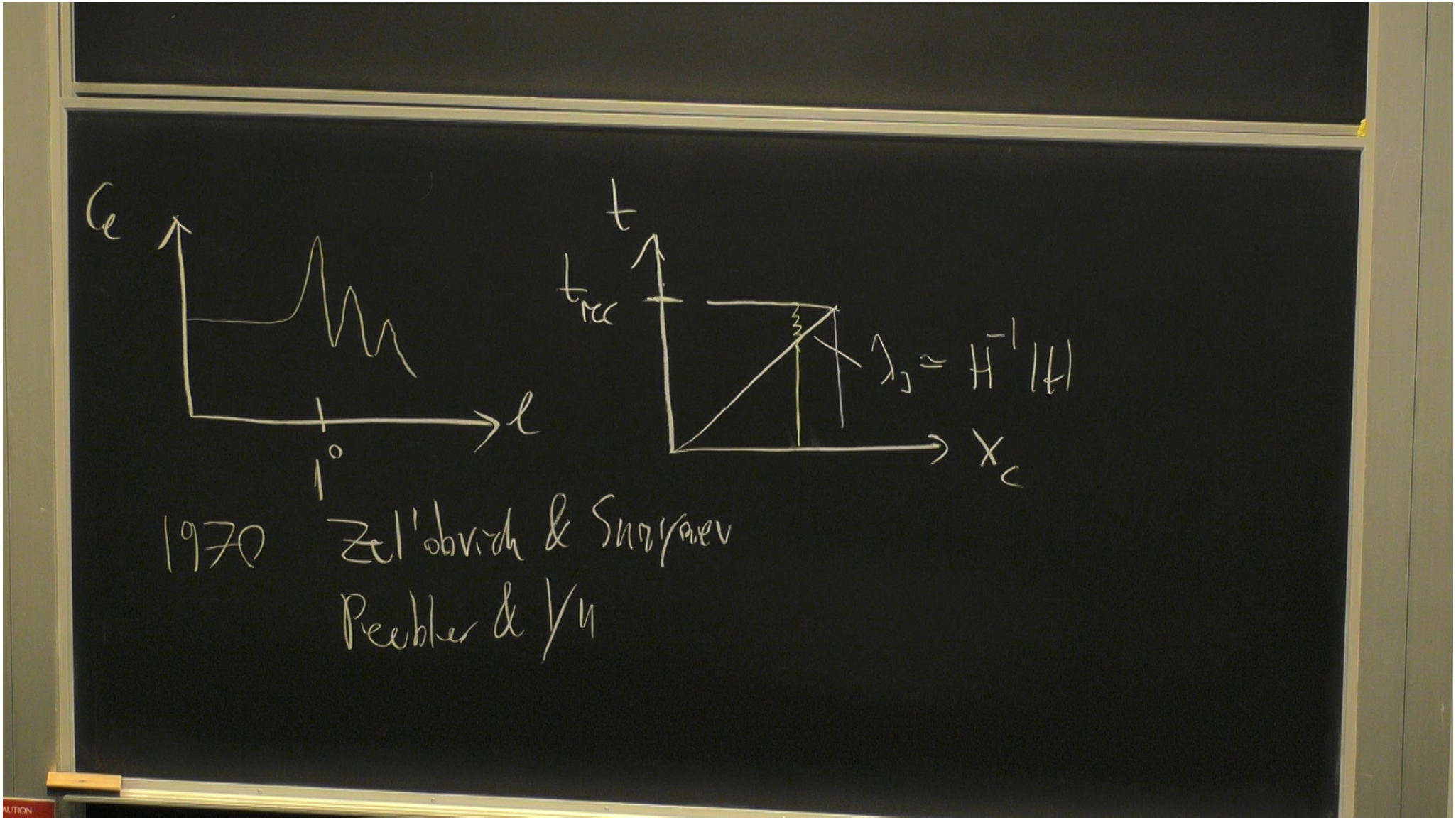

Message 1
Inflation is not the only viable
early universe model
~ homogeneity & isotropy
~ spatially flat
CMB anisotropies

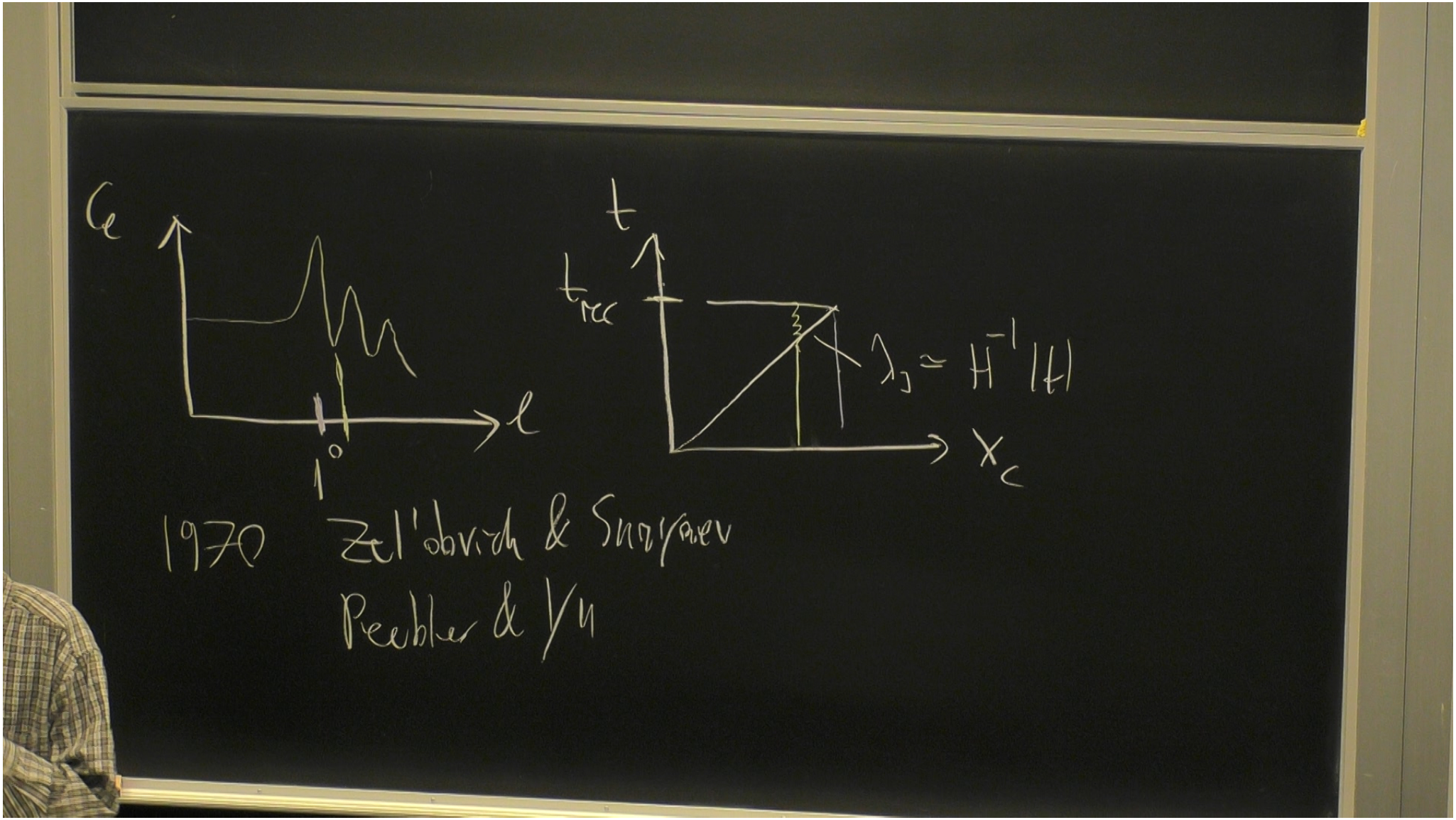

C_ℓ
ℓ
1°

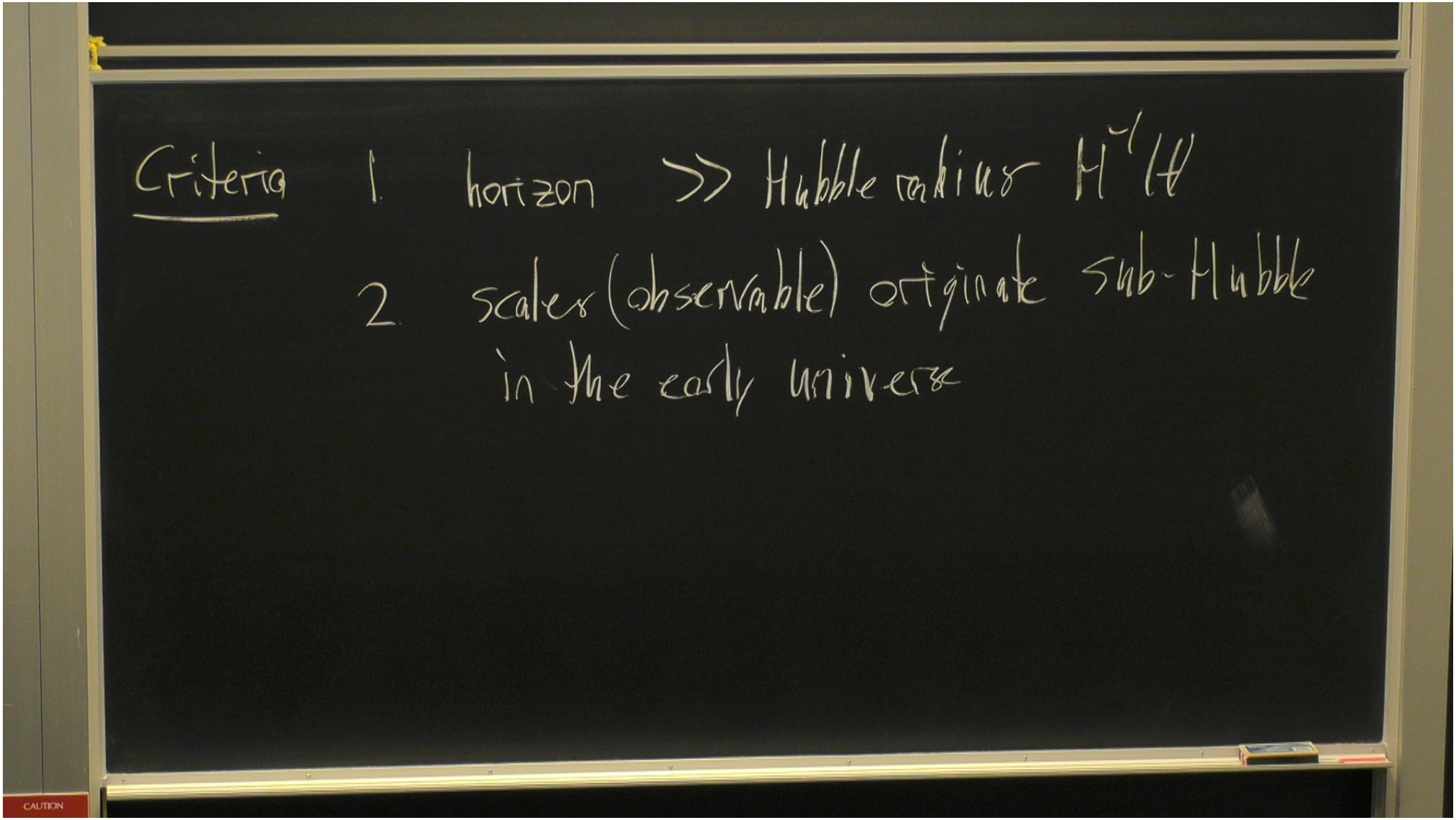

C_ℓ
ℓ
1°
1970 Zel'dovich & Sunyaev
Peebles & Yu

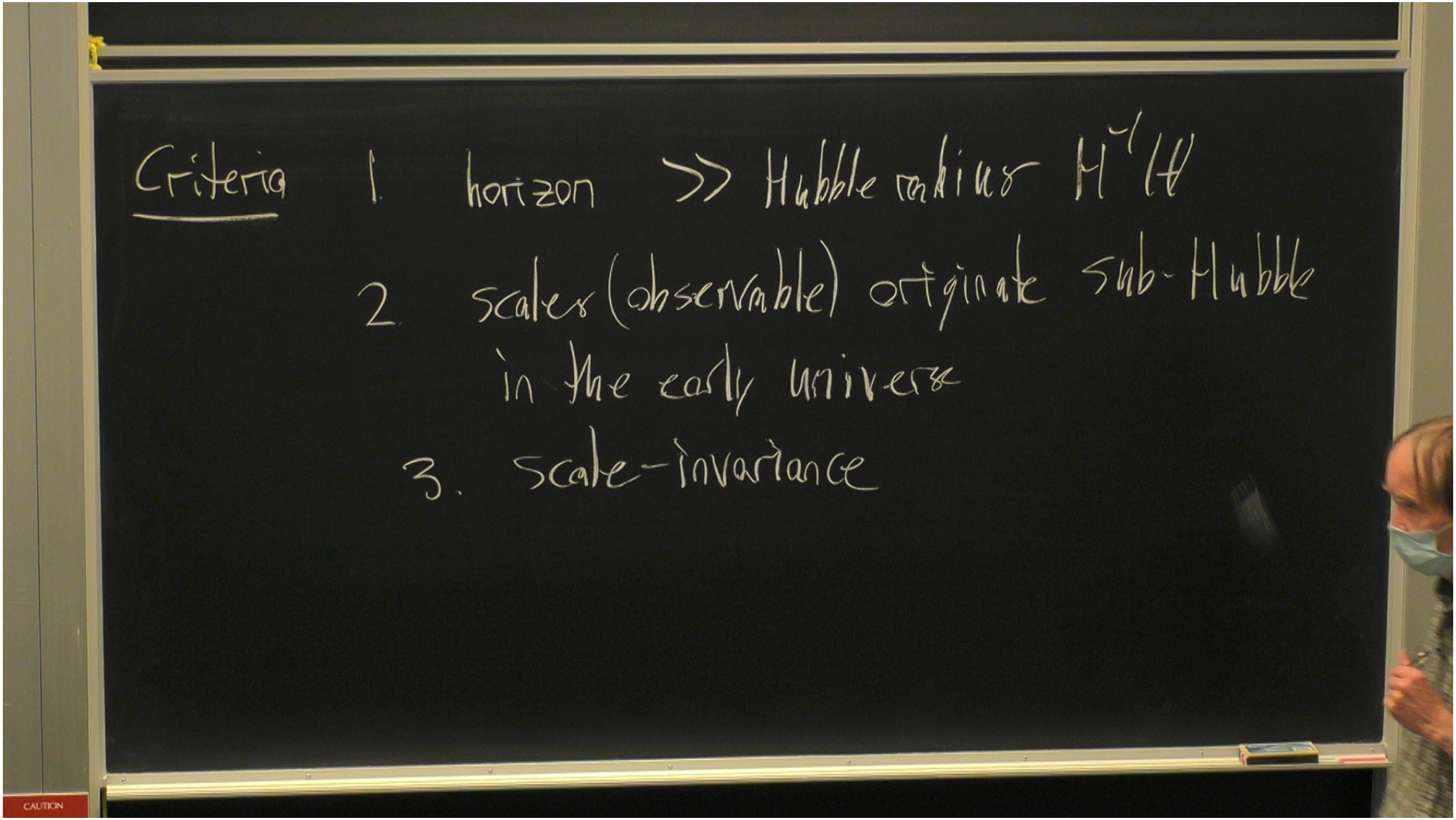

C_ℓ
ℓ
1°
t
t_{rec}
$\lambda_J \simeq H^{-1}(t)$
x_c
1970 Zel'dovich & Sunyaev
Peebles & Yu

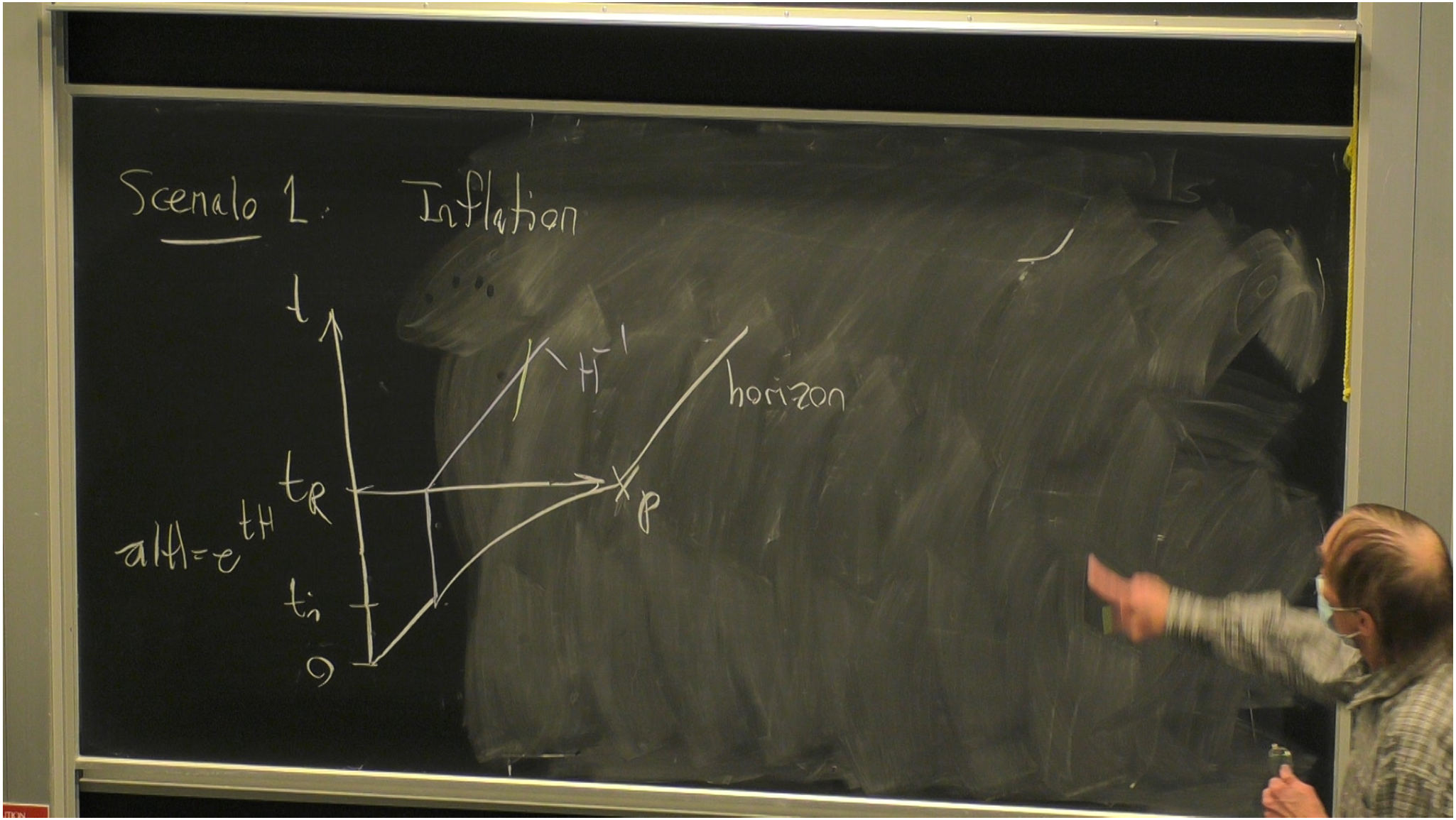

δ_ℓ
ℓ
1°
t
t_{rec}
$\lambda_J \simeq H^{-1}(t)$
x_c
1970 Zel'dovich & Sunyaev
Peebles & Yu

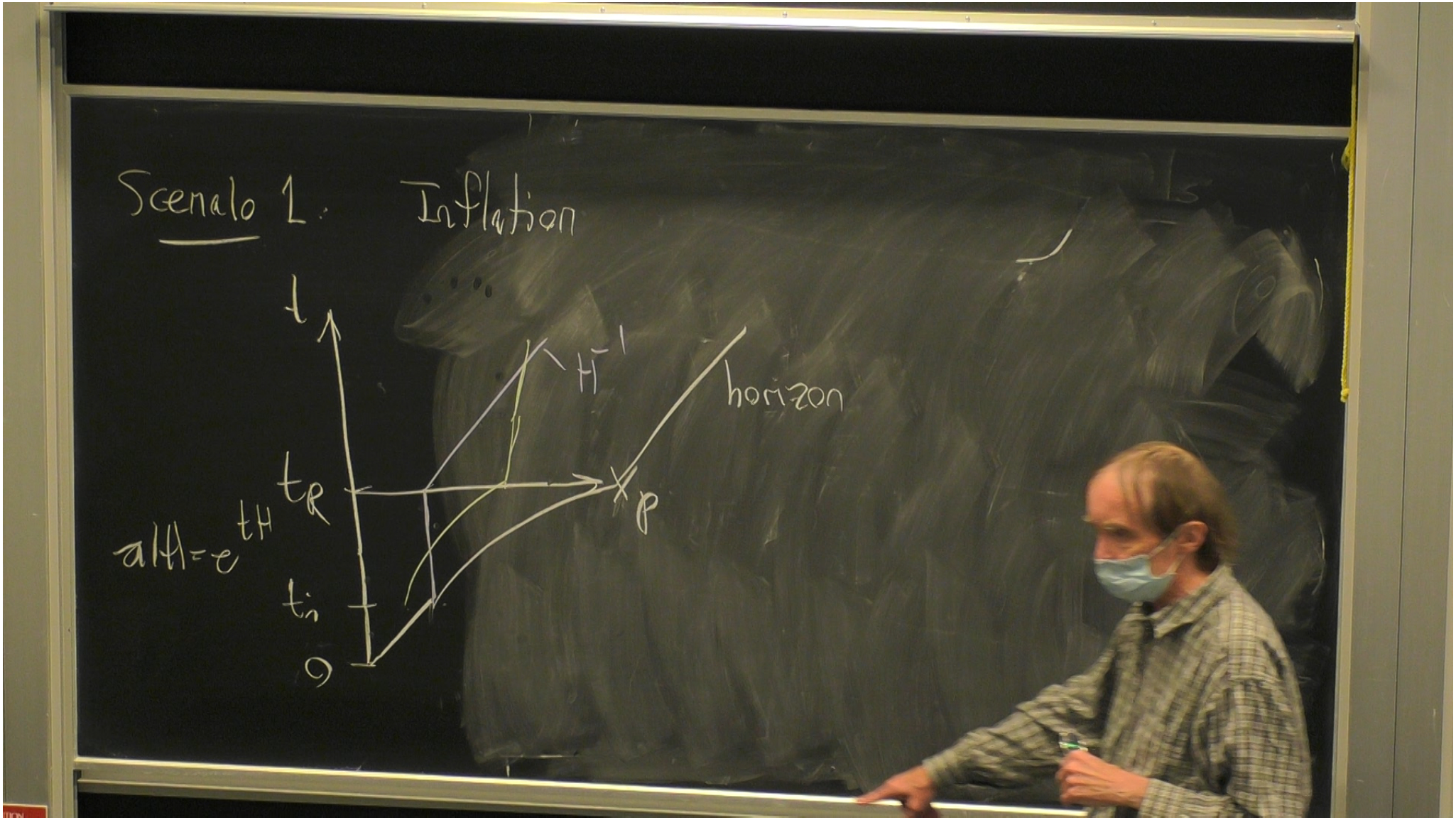

δ_ℓ
ℓ
1°
t
t_{rec}
$\lambda_J \simeq H^{-1}(t)$
x_c
1970 Zel'dovich & Sunyaev
Peebles & Yu

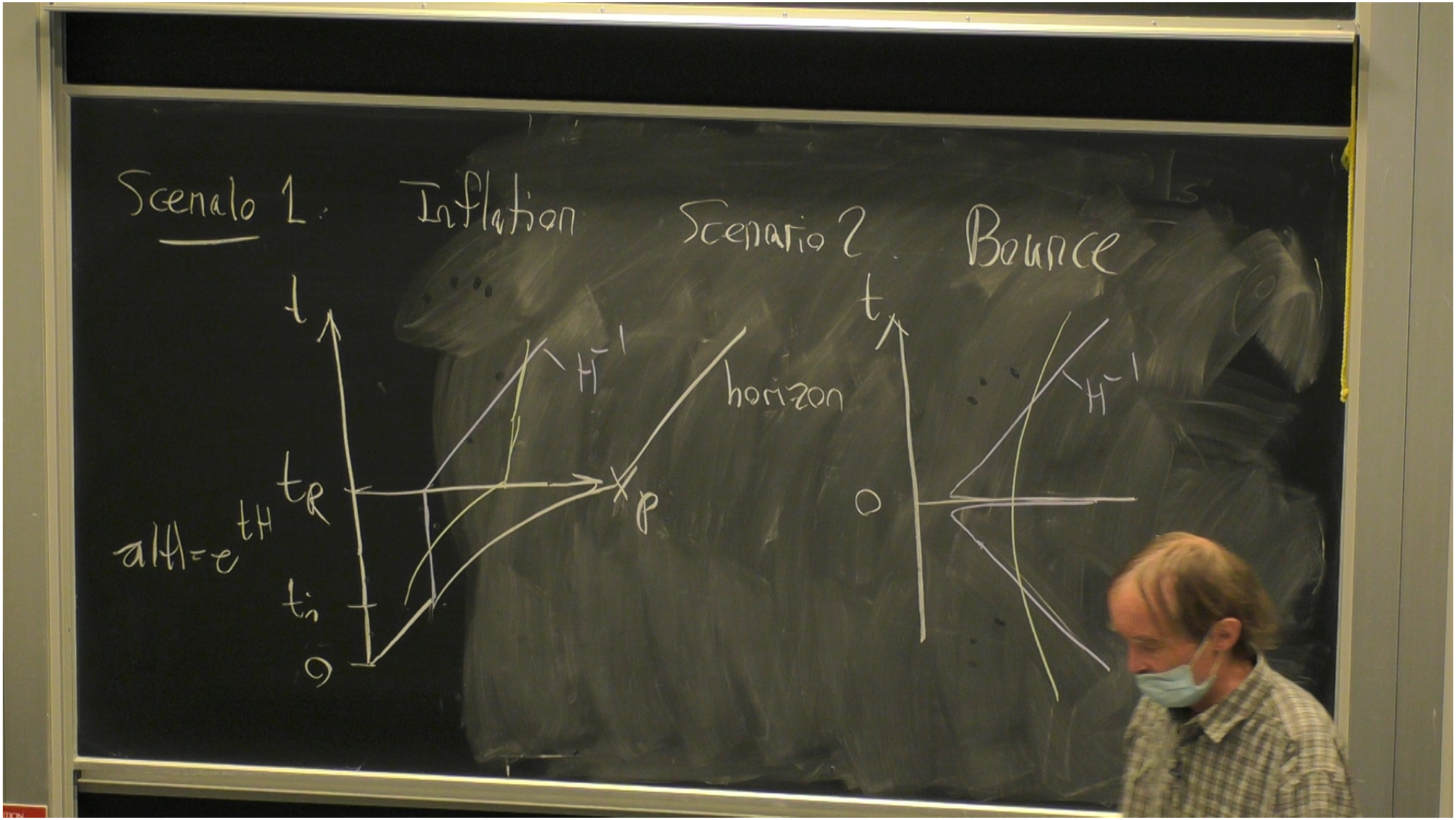

δ
l
1°
t
t_{rec}
$\lambda_J \simeq H^{-1}(t)$
X_c
1970 Zel'dovich & Sunyaev
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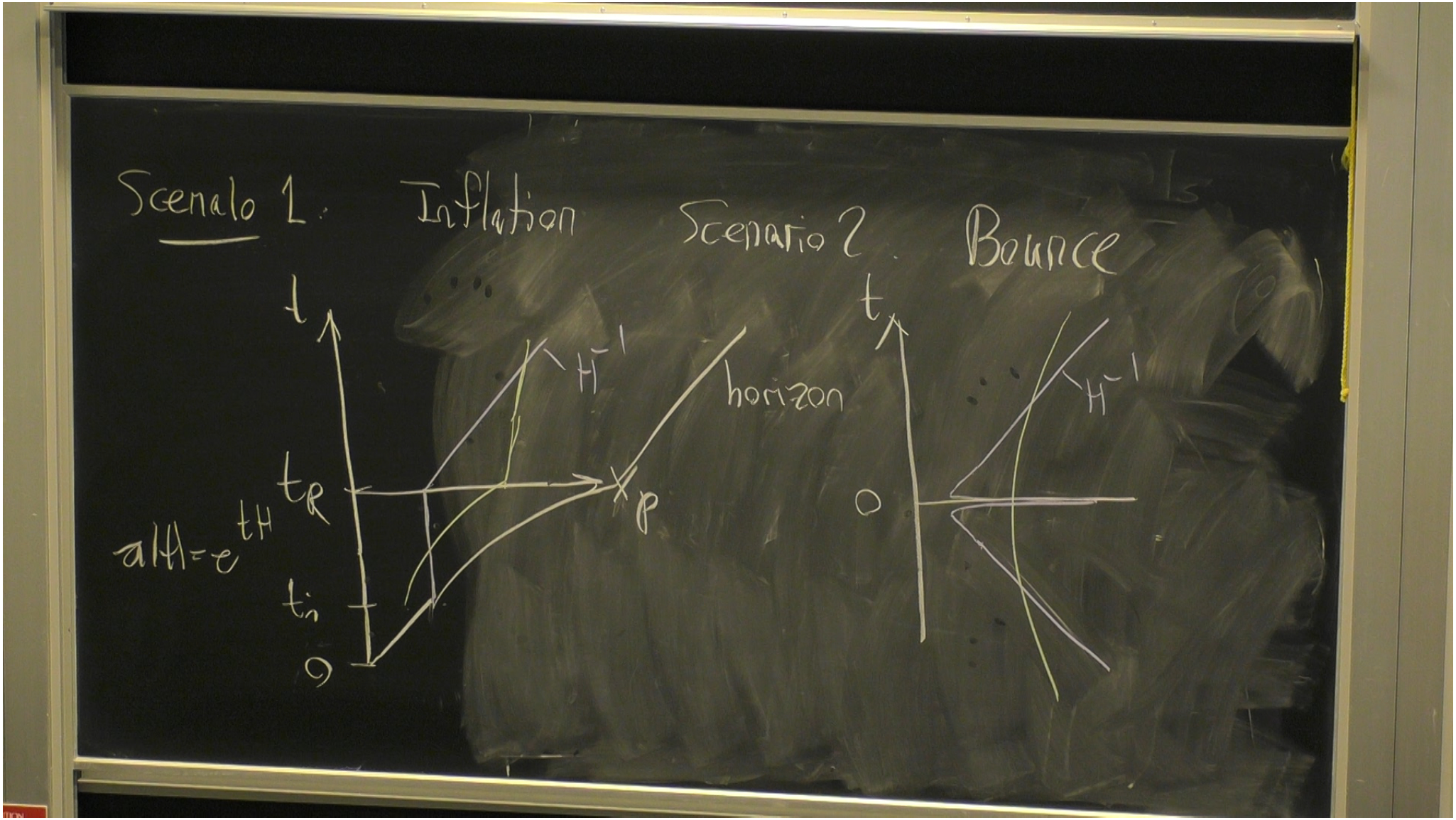

Criteria
1. horizon >> Hubble radius $H^{-1}(t)$
2. scales (observable) originate sub-Hubble
in the early universe
CAUTION

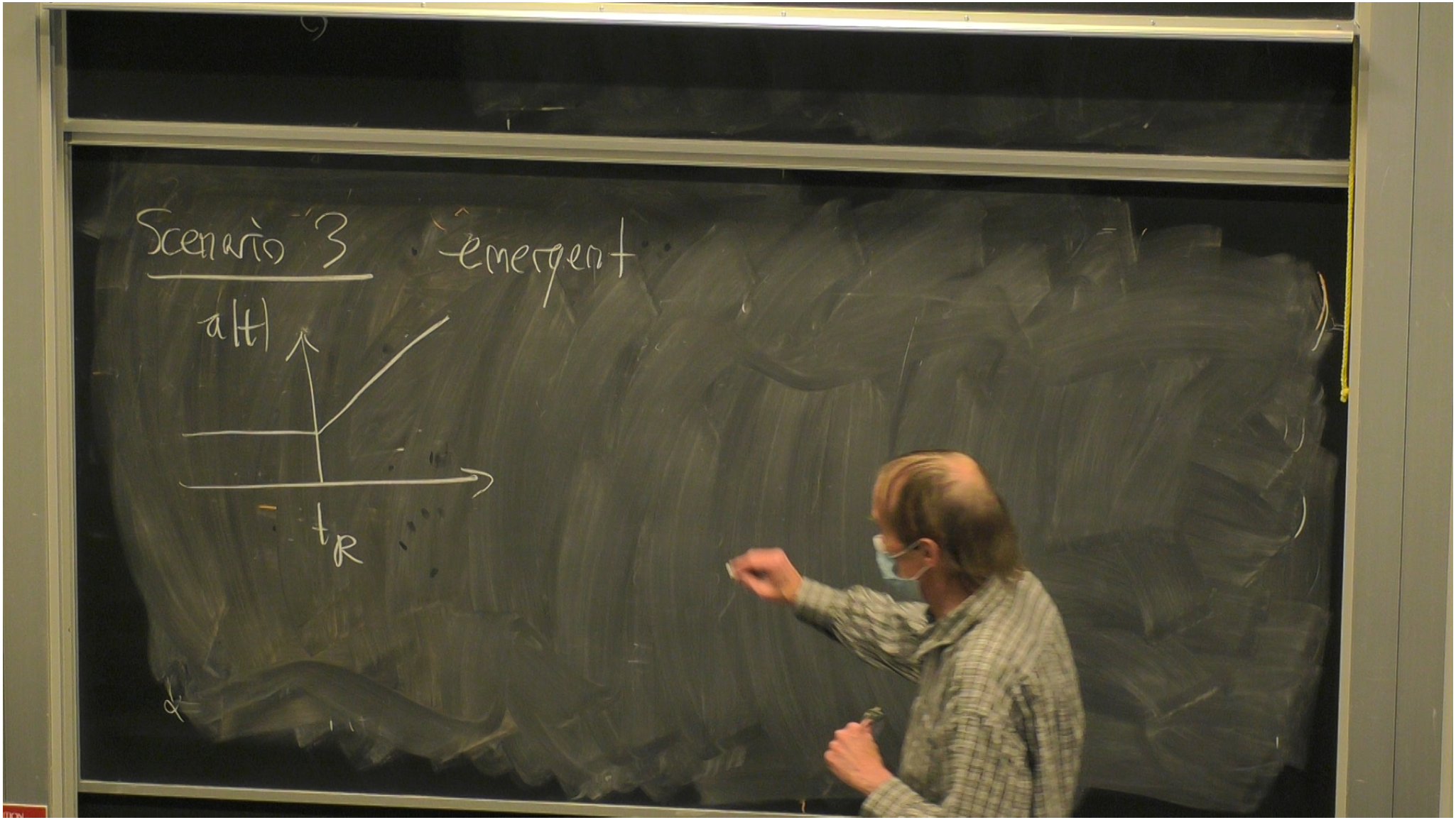

Criteria
1. horizon >> Hubble radius H^{-1}/h
2. scales (observable) originate sub-Hubble in the early universe
3. scale-invariance
CAUTION

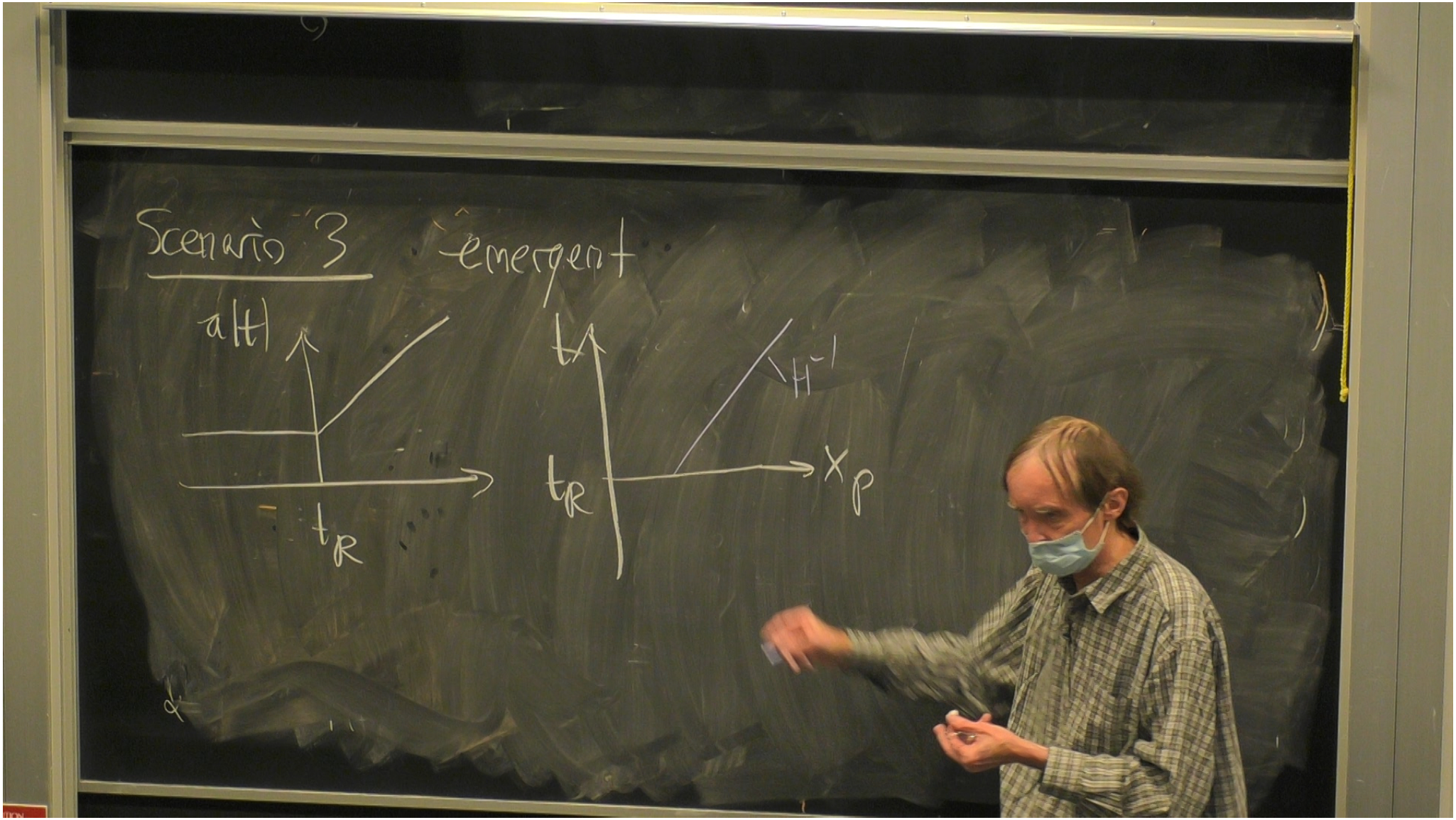

Scenario 1: Inflation
t
H^{-1}
horizon
t_R
p
$a(t) = e^{tH}$
t_i
0

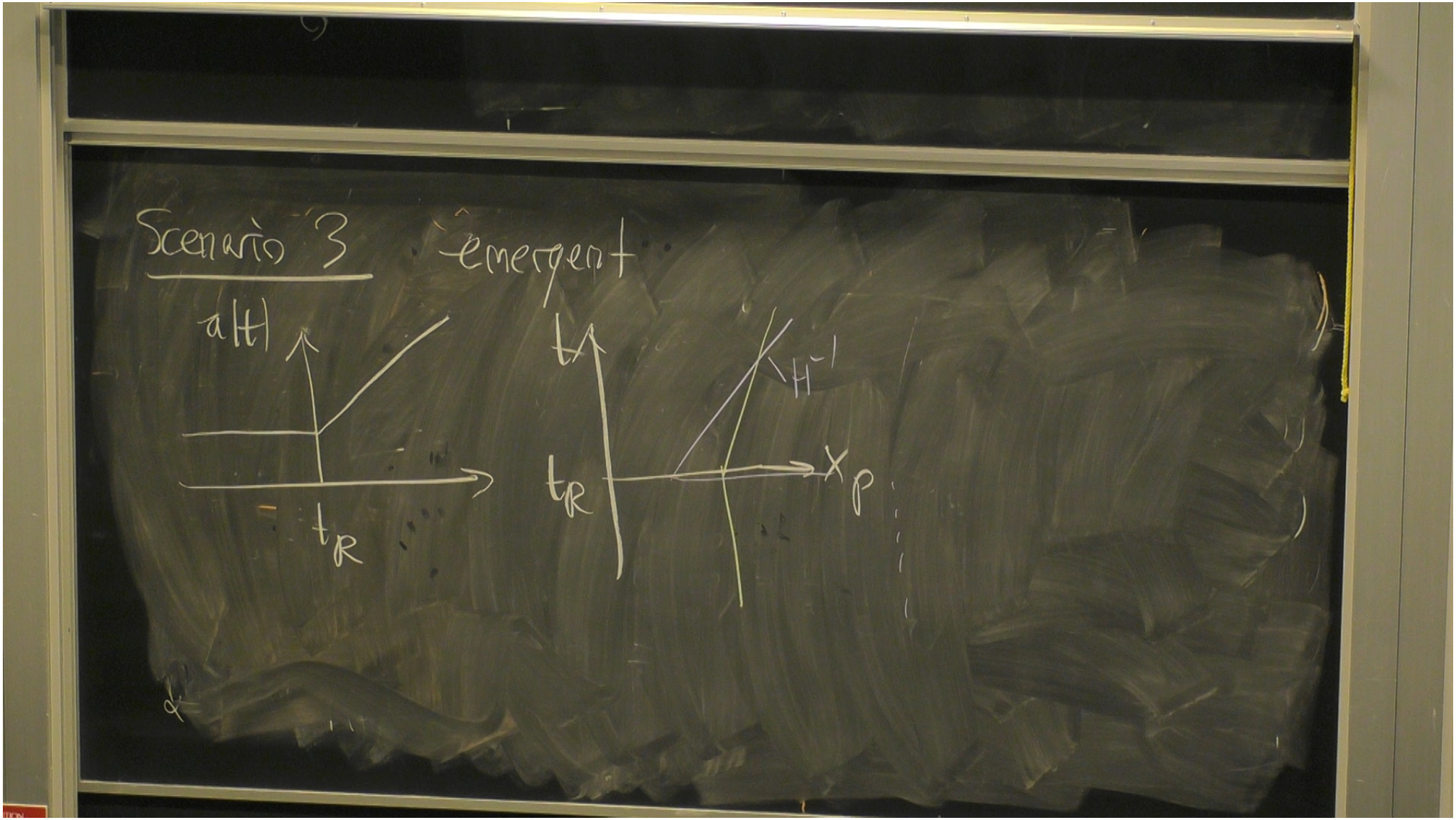

Scenalo 1: Inflation
t
H⁻¹
horizon
t_R
p
$a(t) = e^{tH}$
t_i
0

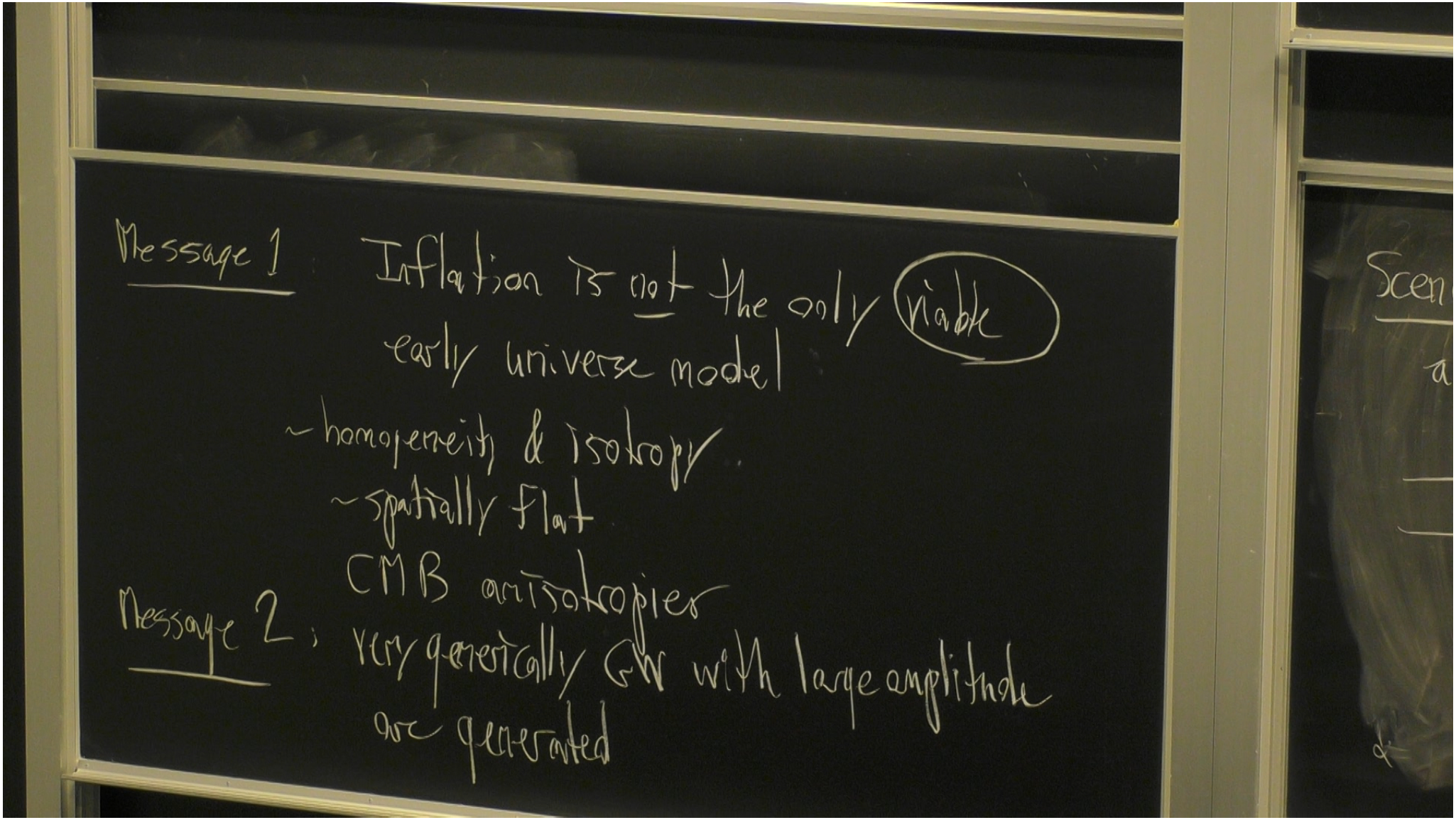

Scenario 1: Inflation
Scenario 2: Bounce
t
H⁻¹
horizon
t_R
p
a(t) = e^{tH}
t_i
0
t
H⁻¹
0

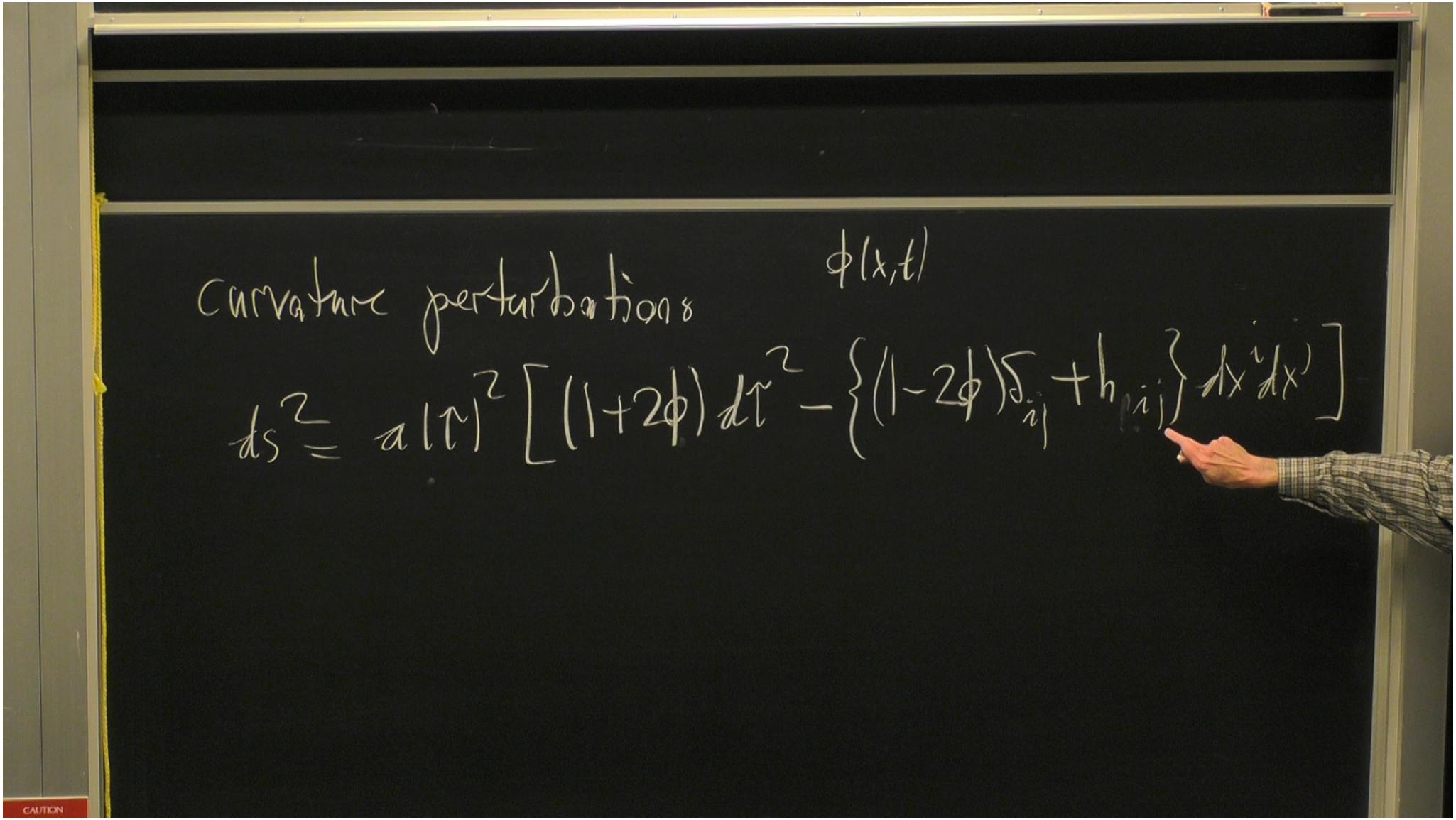

Scenario 1: Inflation
Scenario 2: Bounce
t
H^{-1}
horizon
t_R
P
$a(t) = e^{tH}$
t_i
0
t
H^{-1}
0

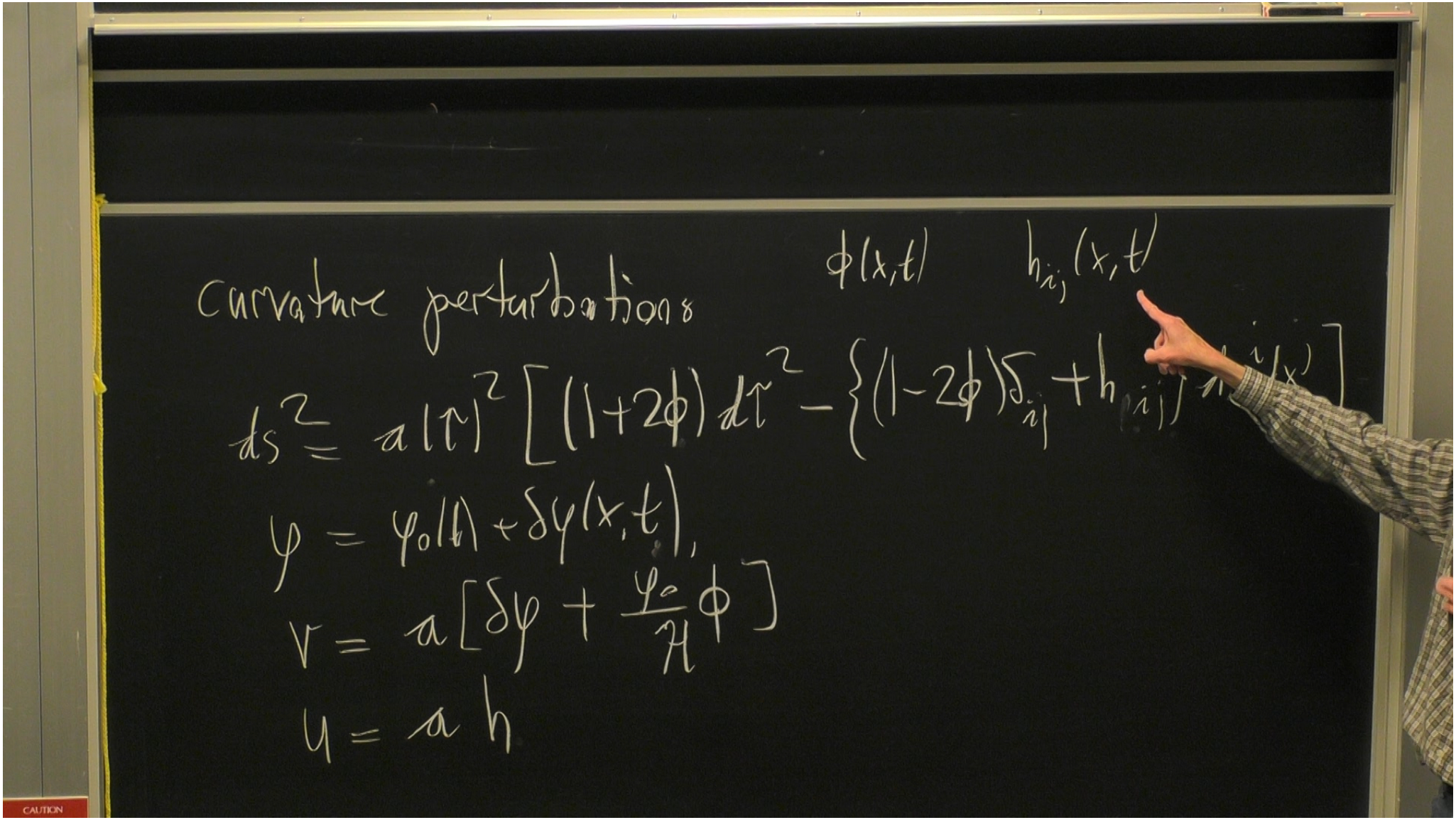

Scenario 3
emergent
a(t)
t_R


Scenario 3
emergent
a(t)
t_R
t
H^{-1}
t_R
x_p


Scenario 3
emergent
a(t)
t_R
t
H^{-1}
t_R
x
p


Message 1
Inflation is not the only viable early universe model
~ homogeneity & isotropy
~ spatially flat
CMB anisotropies
Message 2: very generically GW with large amplitude are generated


Curvature perturbations
$\phi(x,t)$
$ds^2 = a(\tau)^2\left[(1+2\phi)\,d\tau^2 - \left\{(1-2\phi)\delta_{ij} + h_{ij}\right\} dx^i dx^j\right]$
CAUTION


Curvature perturbations
$\phi(x,t)$
$h_{ij}(x,t)$
$ds^2 = a(\tau)^2\left[(1+2\phi)\,d\tau^2 - \{(1-2\phi)\delta_{ij} + h_{ij}\}\right]$
$\varphi = \varphi_0(t) + \delta\varphi(x,t)$,
$v = a\left[\delta\varphi + \frac{\varphi_0}{\mathcal{H}}\phi\right]$
$u = a\,h$
CAUTION

Curvature perturbations $\phi(x,t)$ $h_{ij}(x,t)$

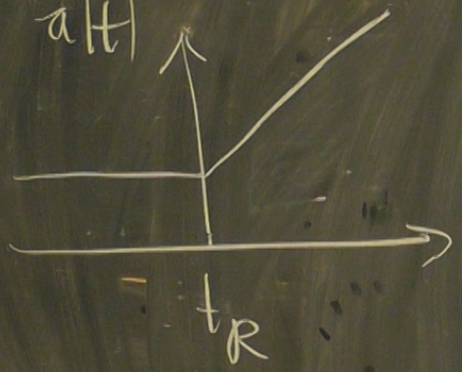
$$ds^2 = a(\tau)^2\left[(1+2\phi)\,d\tau^2 - \left\{(1-2\phi)\delta_{ij} + h_{ij}\right\}dx^i dx^j\right]$$

$$\varphi = \varphi_0(t) + \delta\varphi(x,t),$$

$$v = a\left[\delta\varphi + \frac{\varphi_0}{\mathcal{H}}\phi\right]$$

$$u = a\,h \quad \text{gravit. waves}$$

Scenario 3 emergent



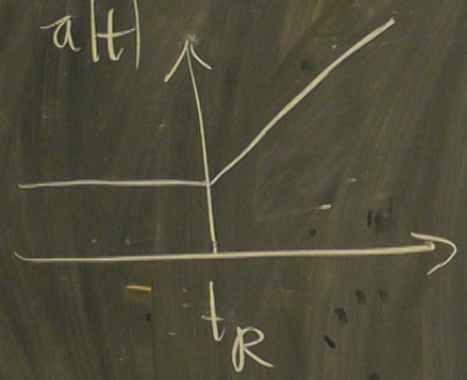
$$v_k'' + \left(k^2 - \frac{z''}{z}\right) v_k = 0$$

$$u_k'' + \left(k^2 - \frac{a''}{a}\right) u_k = 0$$

adiab. pert. time indep. EoS

$z \sim a$

Scenario 3 emergent



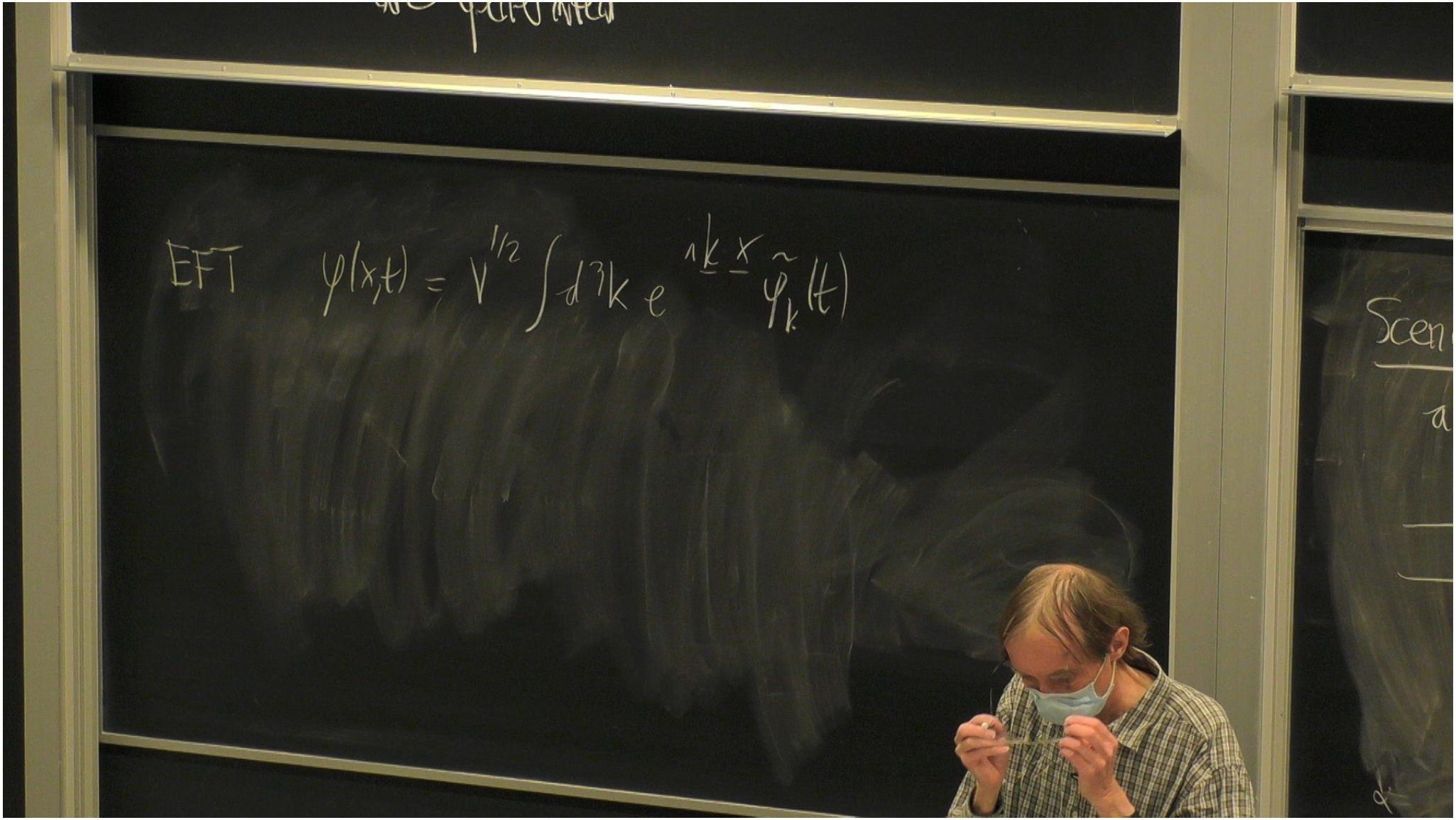
$$v_k'' + \left(k^2 - \frac{z''}{z}\right) v_k = 0$$

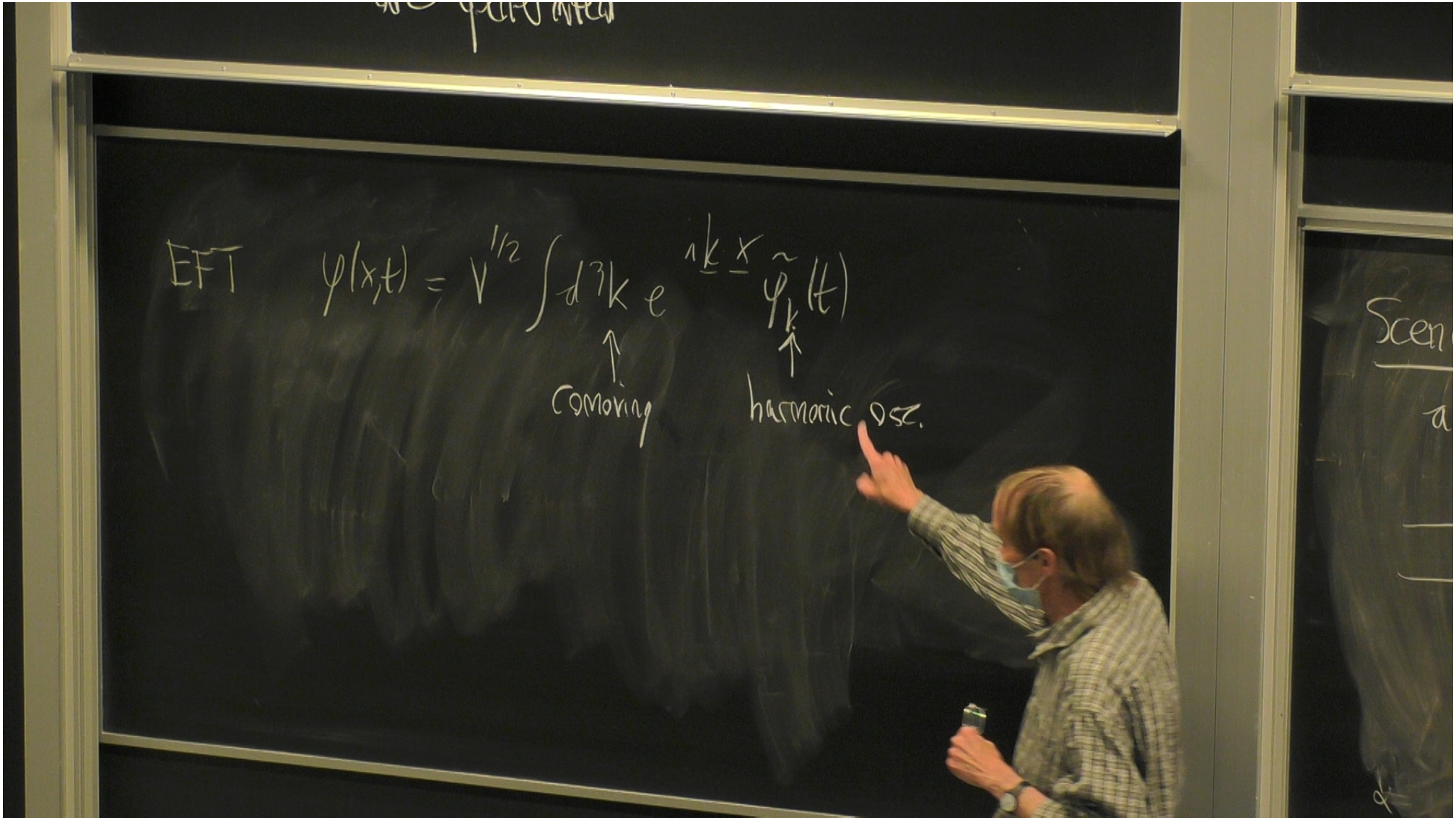
$$u_k'' + \left(k^2 - \frac{a''}{a}\right) u_k = 0$$

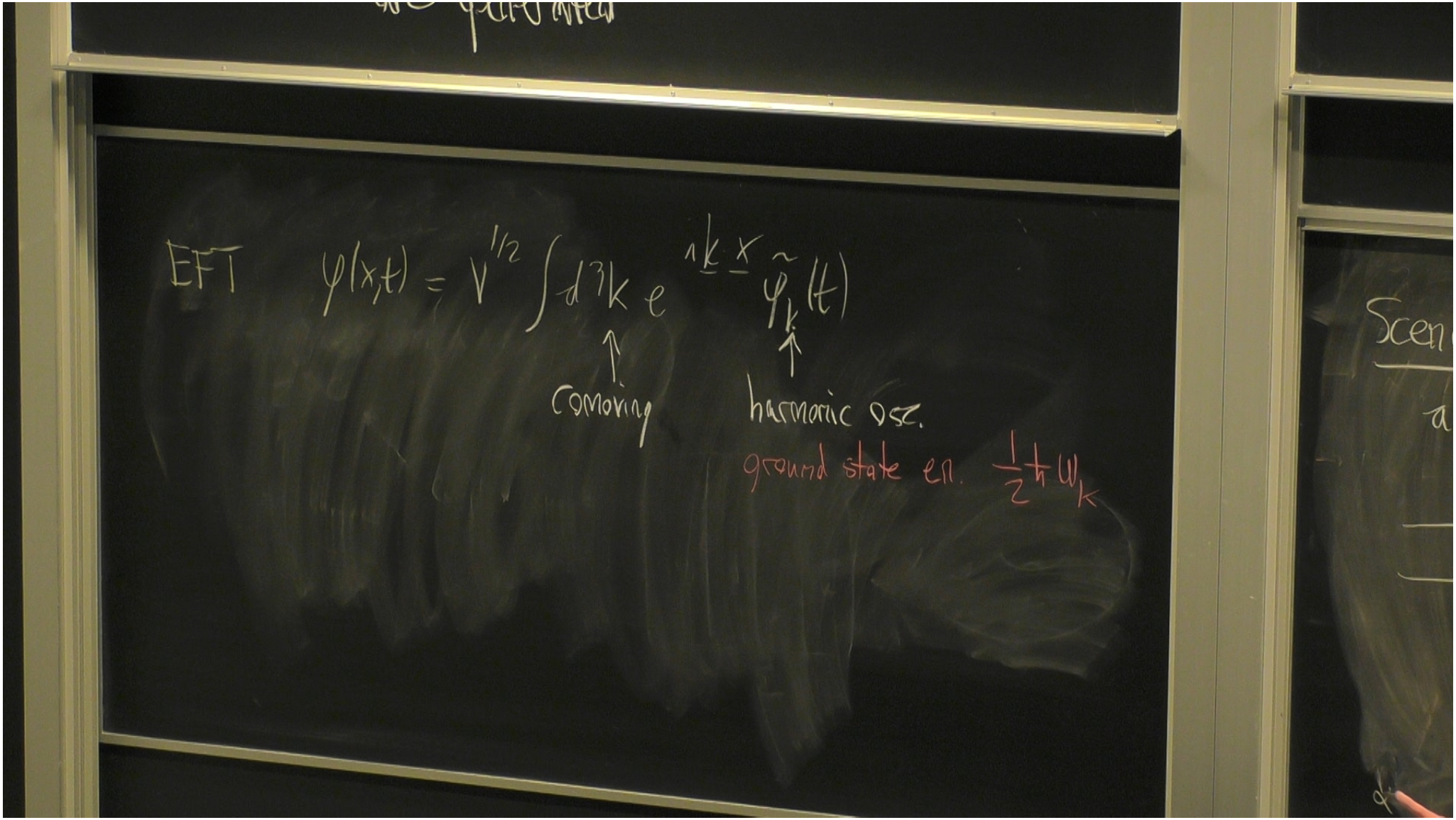
adiab. pert. time indep. EoS

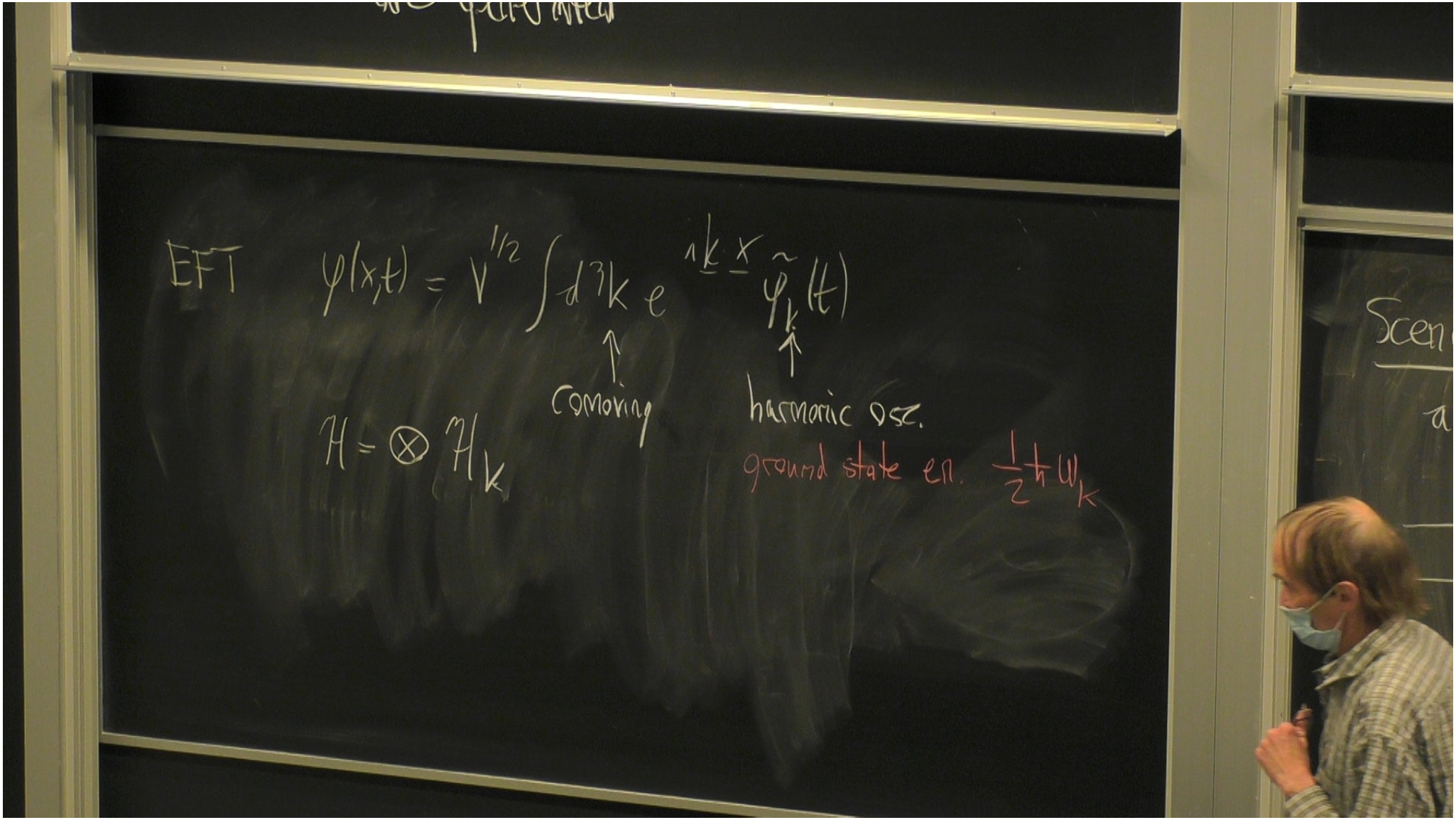
$$z \sim a$$

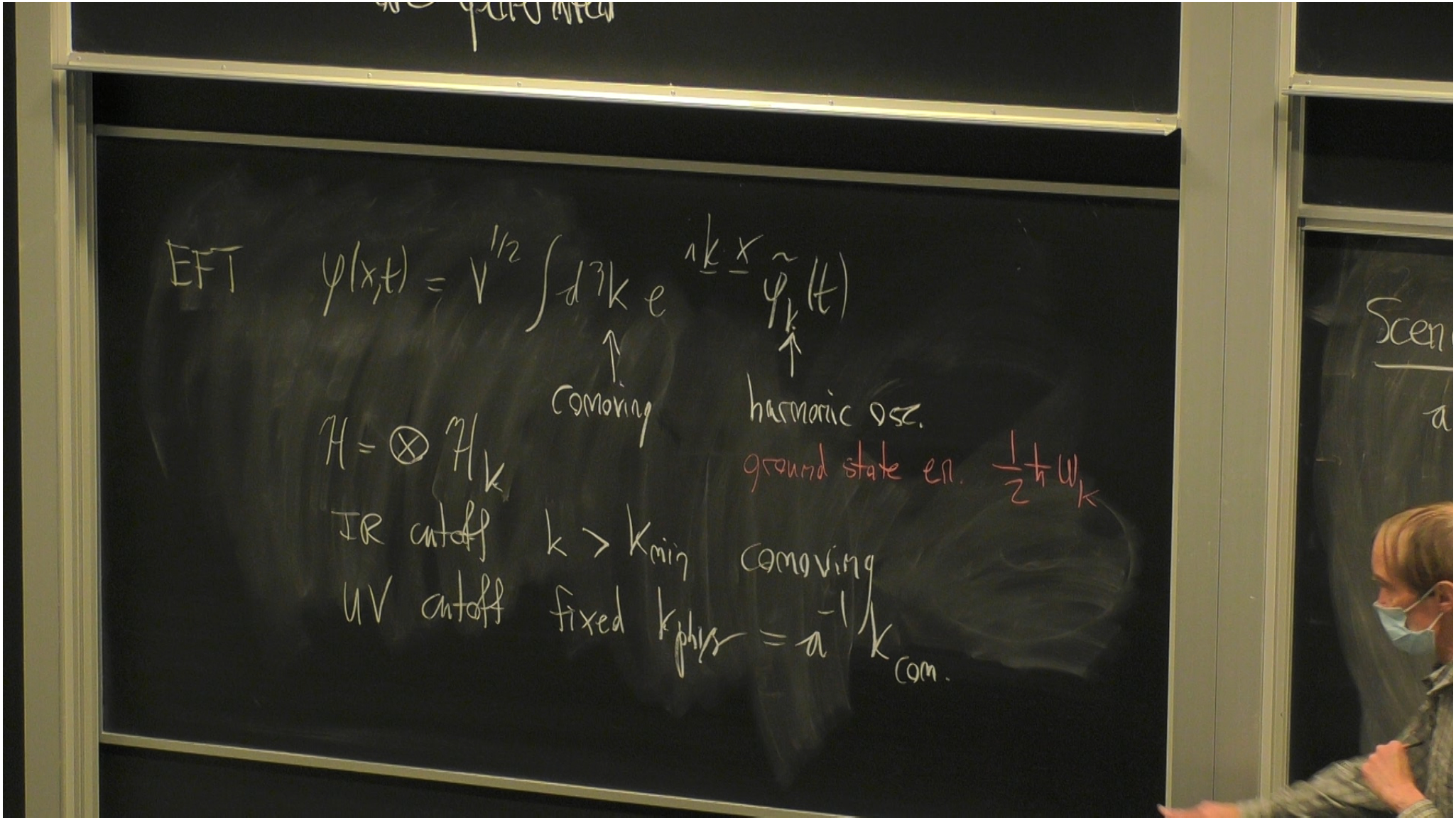
$$z = a \frac{\dot{\varphi}_0}{H}$$

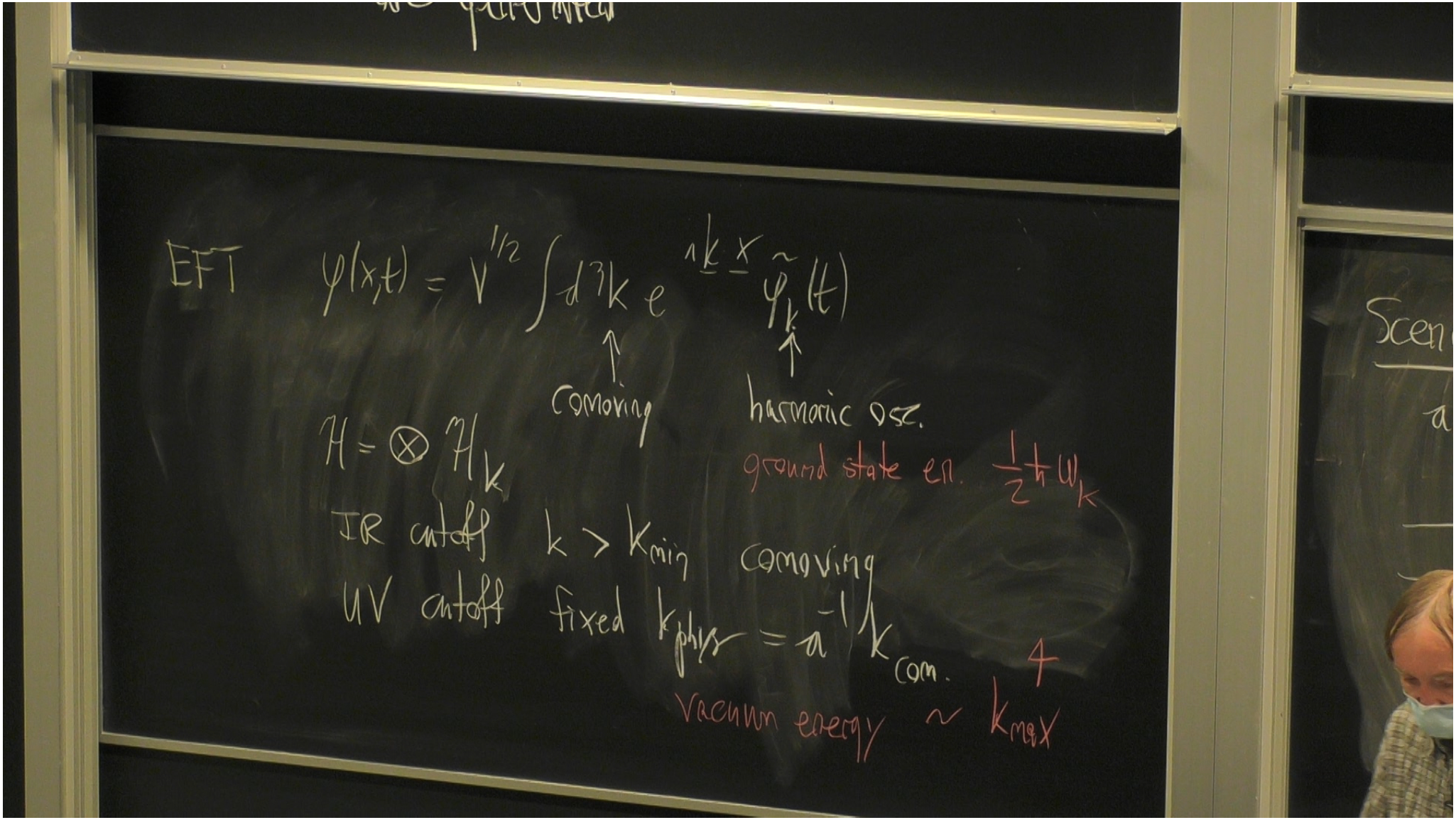

EFT
$\varphi(x,t) = V^{1/2} \int d^3k \, e^{i\underline{k}\cdot\underline{x}} \tilde{\varphi}_{\underline{k}}(t)$

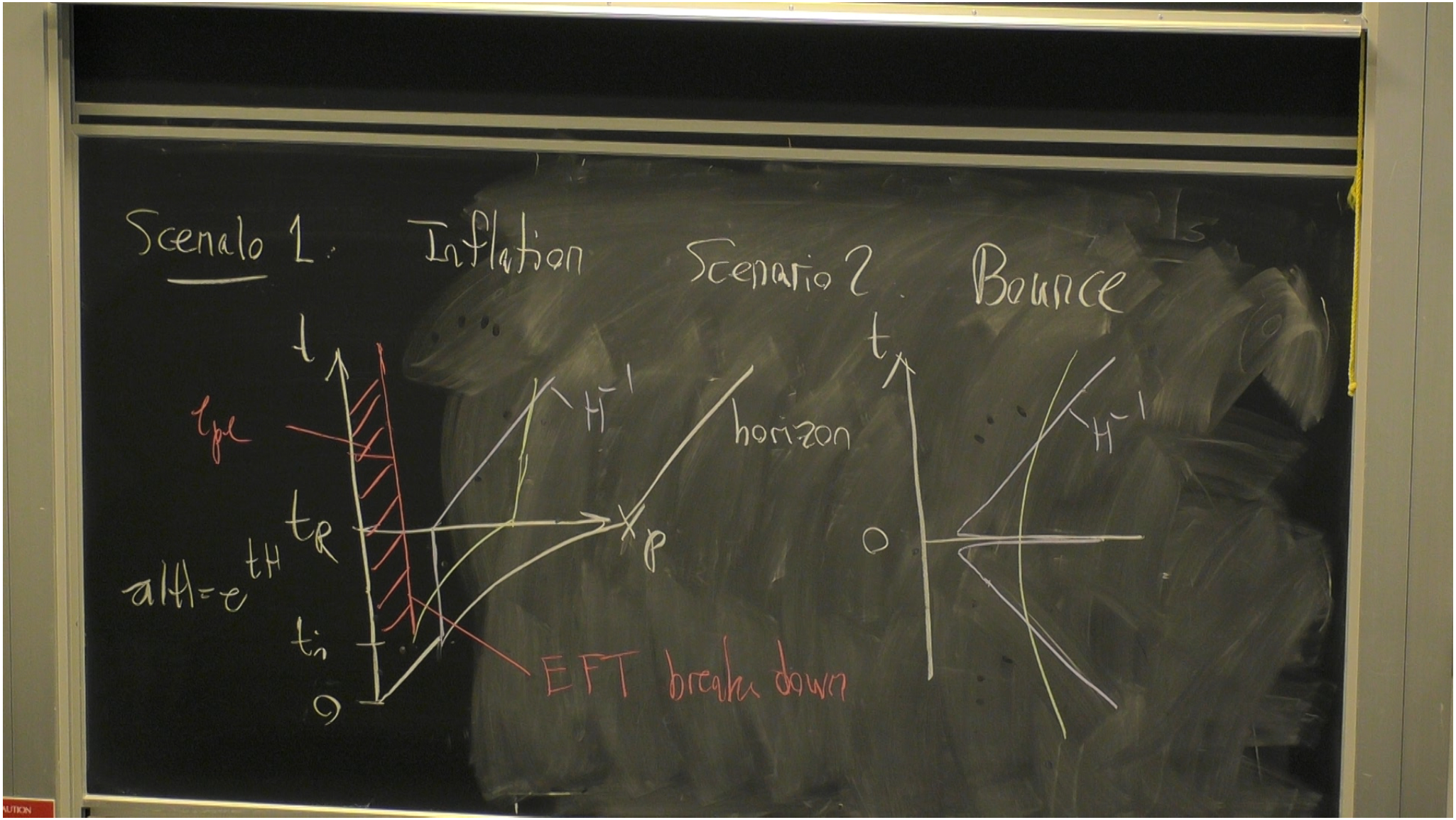

EFT
$\varphi(x,t) = V^{1/2} \int d^3k\, e^{i\vec{k}\cdot\vec{x}}\, \tilde{\varphi}_k(t)$
comoving
harmonic osc.

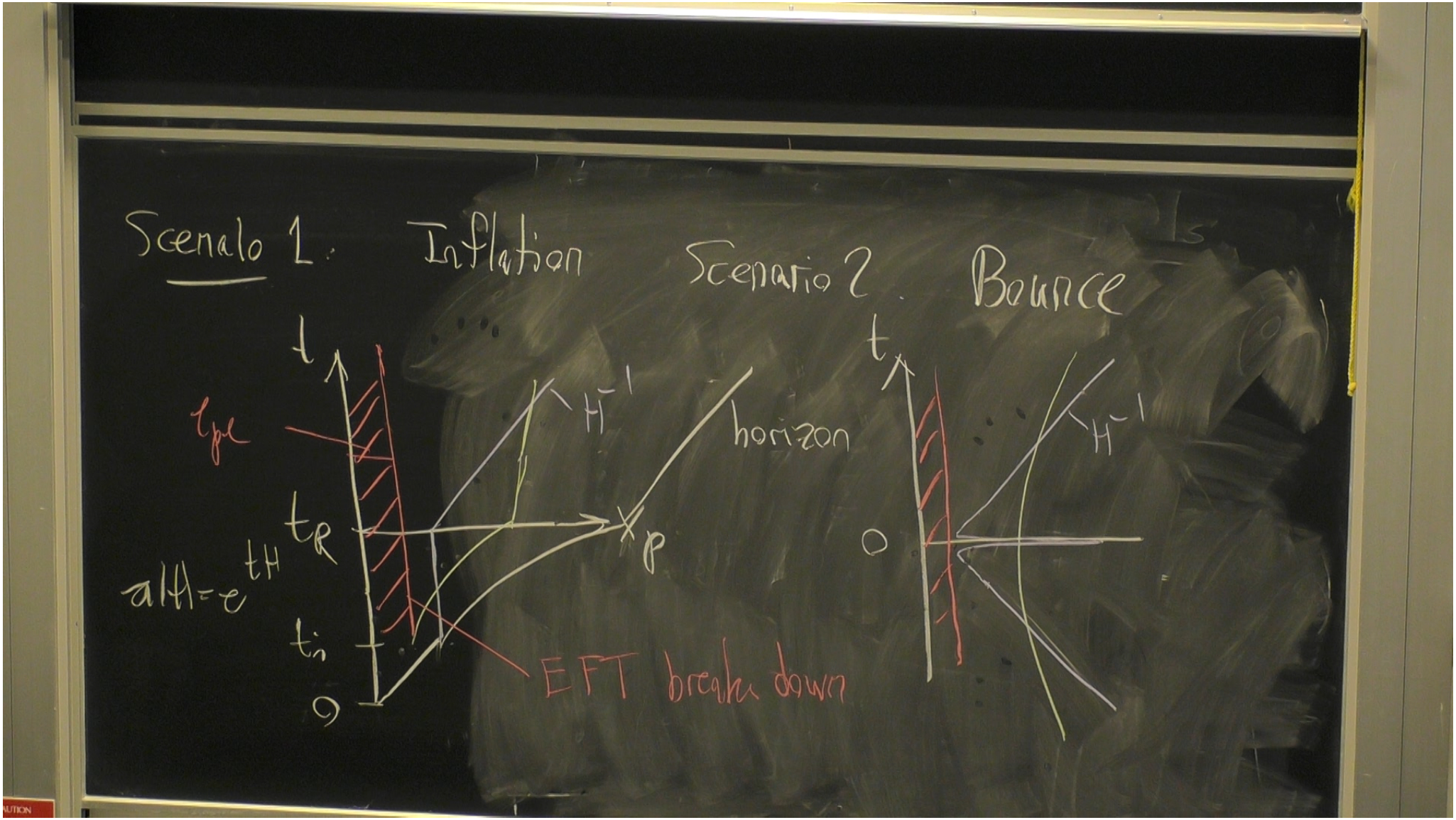

EFT
$\varphi(x,t) = V^{-1/2} \int d^3k \, e^{i\vec{k}\cdot\vec{x}} \tilde{\varphi}_k(t)$
comoving
harmonic osc.
ground state en. $\frac{1}{2}\hbar\omega_k$


EFT
$\varphi(x,t) = V^{1/2} \int d^3k\, e^{i\vec{k}\cdot\vec{x}}\, \tilde{\varphi}_k(t)$
comoving
harmonic osc.
$\mathcal{H} = \bigotimes \mathcal{H}_k$
ground state en. $\frac{1}{2}\hbar\omega_k$


EFT
$\varphi(x,t) = V^{1/2} \int d^3k\, e^{i\vec{k}\cdot\vec{x}}\, \tilde{\varphi}_k(t)$
comoving
harmonic osc.
ground state en. $\frac{1}{2}\hbar\omega_k$
$\mathcal{H} = \bigotimes \mathcal{H}_k$
IR cutoff $k > k_{min}$ comoving
UV cutoff fixed $k_{phys} = a^{-1} k_{com.}$

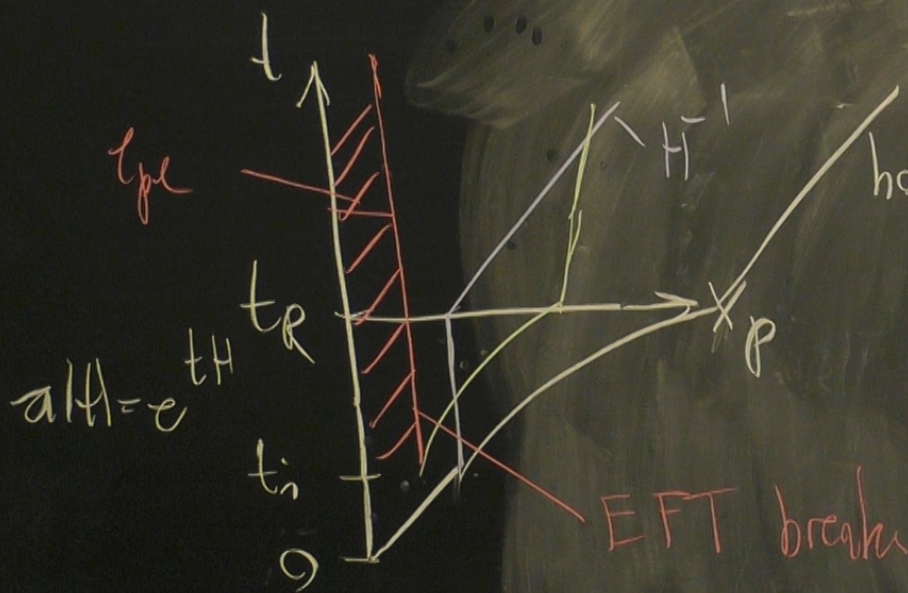

EFT
$\varphi(x,t) = V^{1/2} \int d^3k \, e^{i\vec{k}\cdot\vec{x}} \tilde{\varphi}_k(t)$
comoving
harmonic osc.
ground state en. $\frac{1}{2}\hbar\omega_k$
$\mathcal{H} = \bigotimes \mathcal{H}_k$
IR cutoff $k > k_{min}$ comoving
UV cutoff fixed $k_{phys} = a^{-1} k_{com.}$
vacuum energy $\sim k_{max}^4$


Scenario 1: Inflation
Scenario 2: Bounce
t
t_{pl}
t_R
$a(t) = e^{tH}$
t_i
0
H^{-1}
horizon
p
EFT breaks down
t
H^{-1}
0


Scenario 1. Inflation
Scenario 2. Bounce
t
t_{pl}
t_R
t_i
0
$a(t) = e^{tH}$
H^{-1}
horizon
P
EFT breaks down
t
0
H^{-1}

Scenario 1: Inflation

Bedroya & Vafa 2019

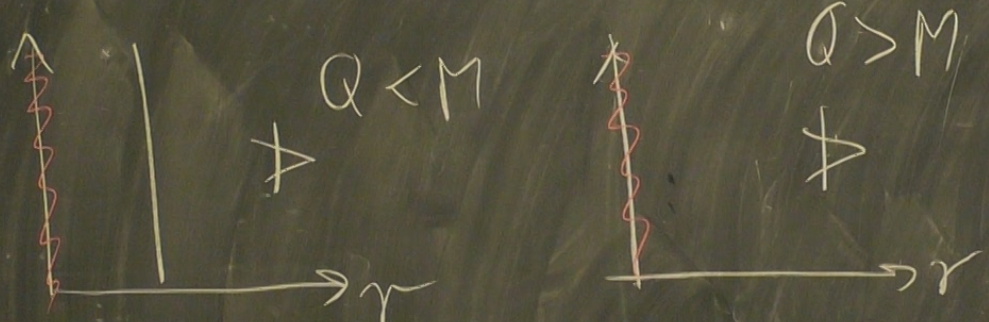


TCC

horizon $\left[\frac{a(t_R)}{a(t_i)} t_{pe} < H^{-1}(t_R)\right]$

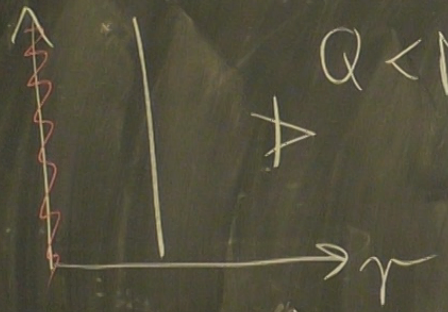

Justif. #1 Penrose
Q<M
r

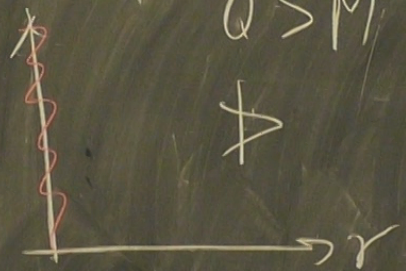
Justif. #1 Penrose



distant observer shielded from sing. b/ horizon

Justif. #1 Penrose



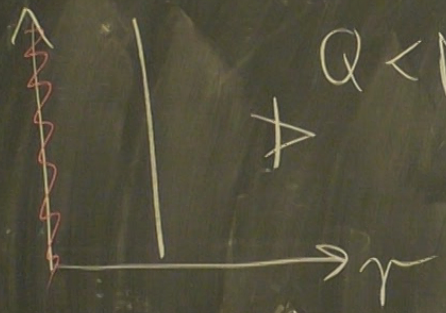


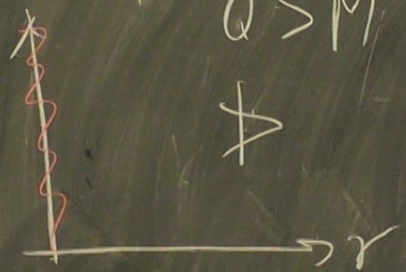
position space
↓
momentum space

horizon → Hubble horizon

distant observer shielded from sing. b/ horizon

Justif. #1 Penrose



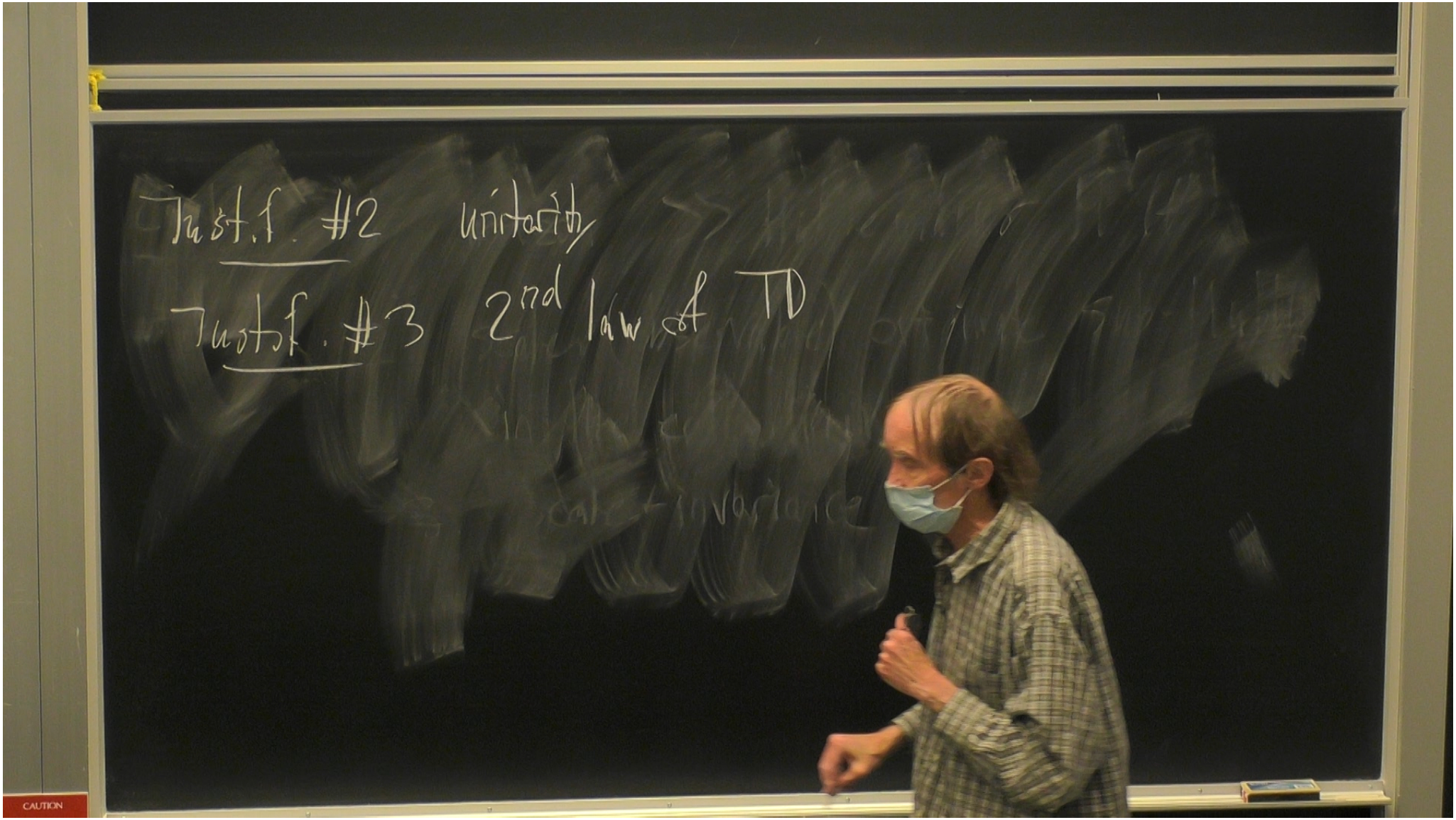


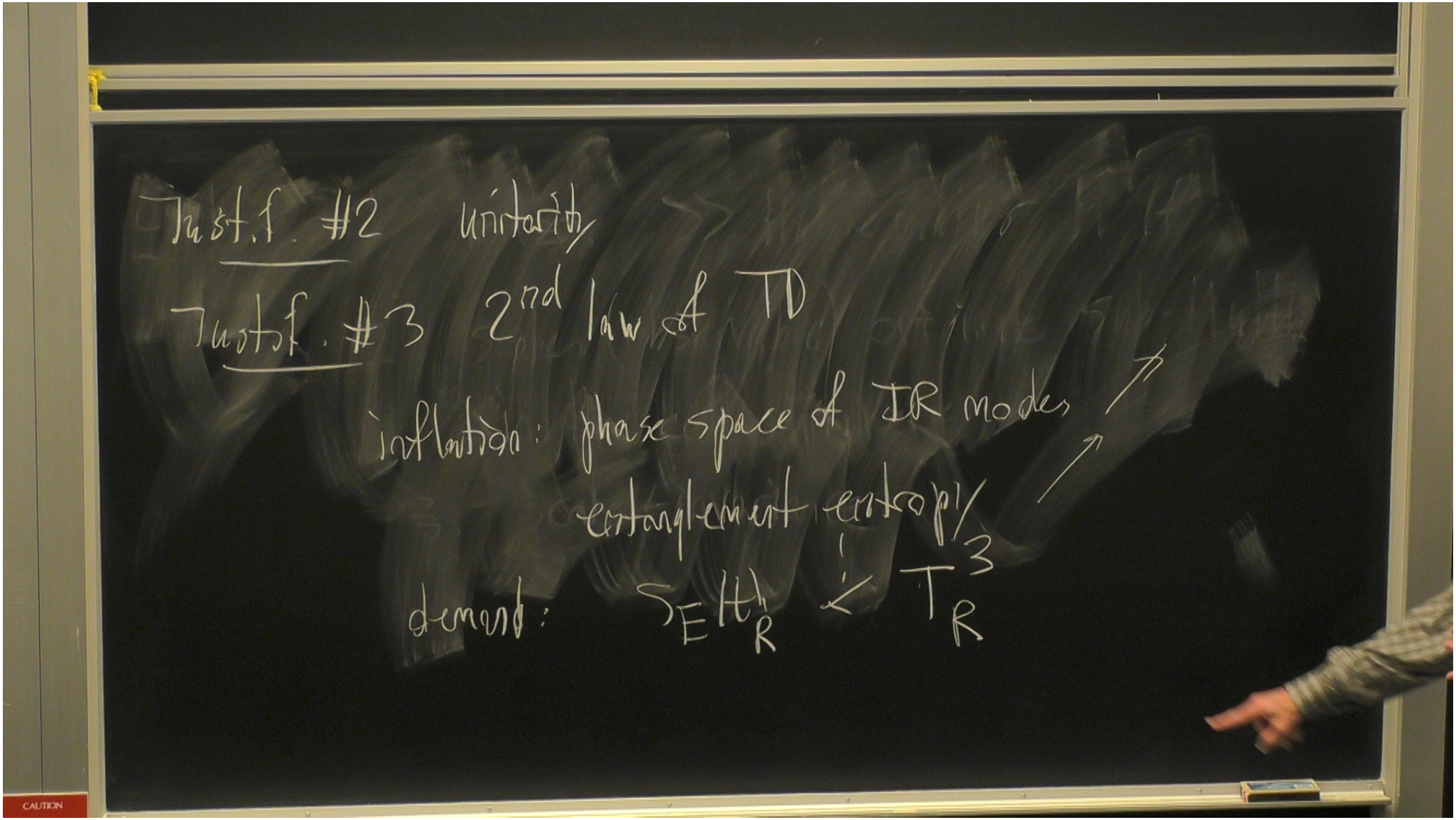
position space
↓
momentum space

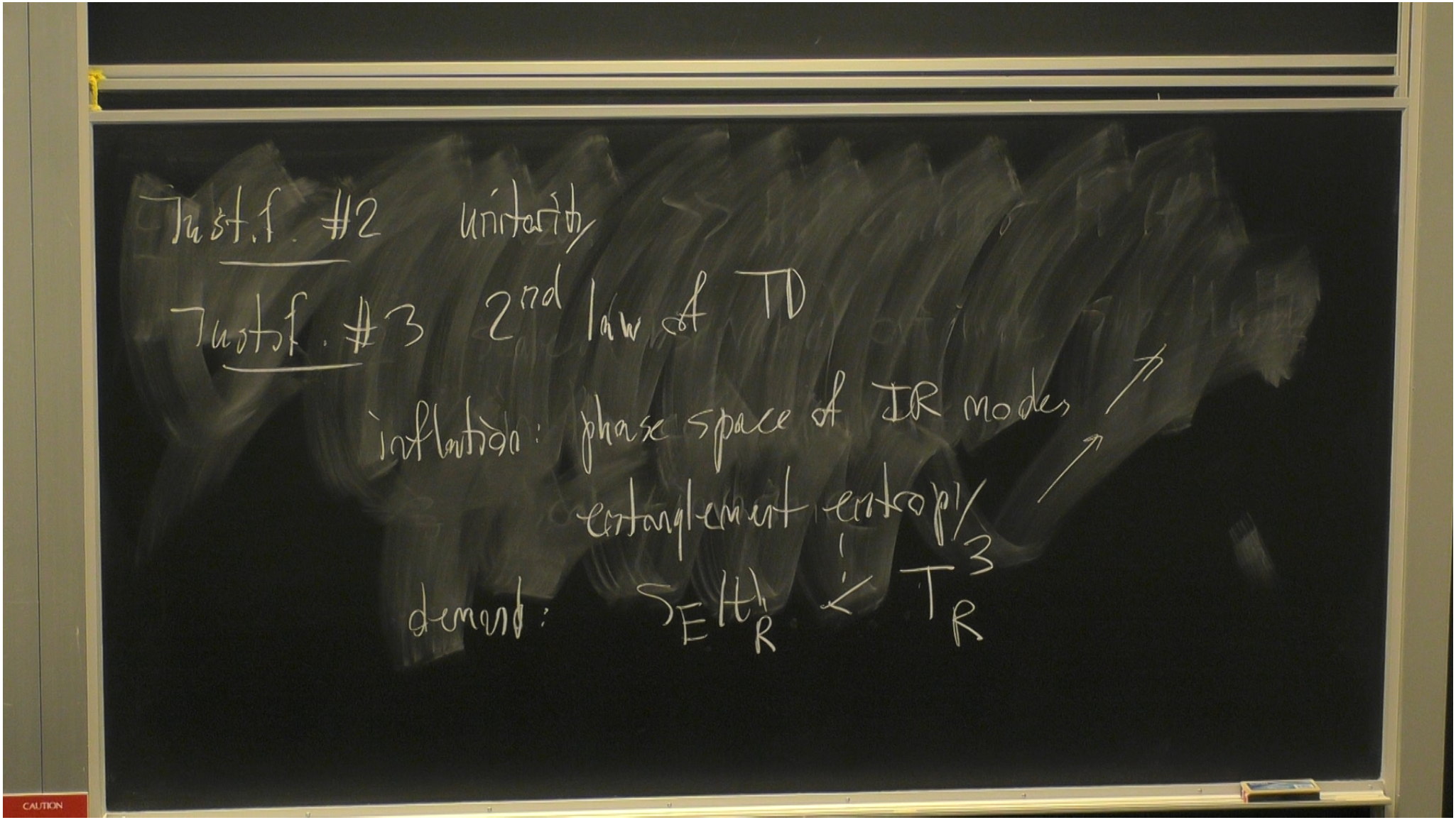
horizon → Hubble horizon

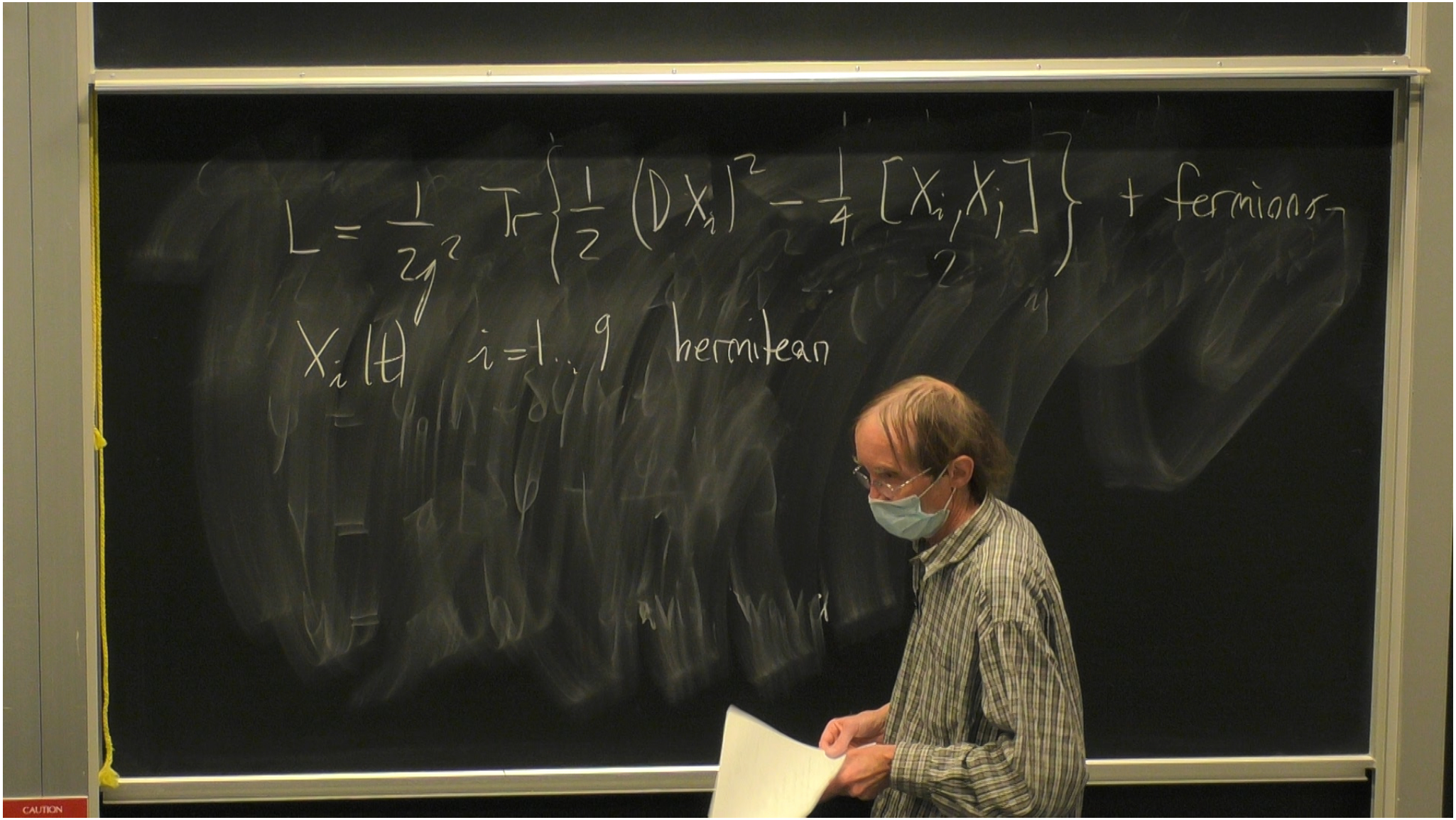
distant observer shielded from sing. by horizon

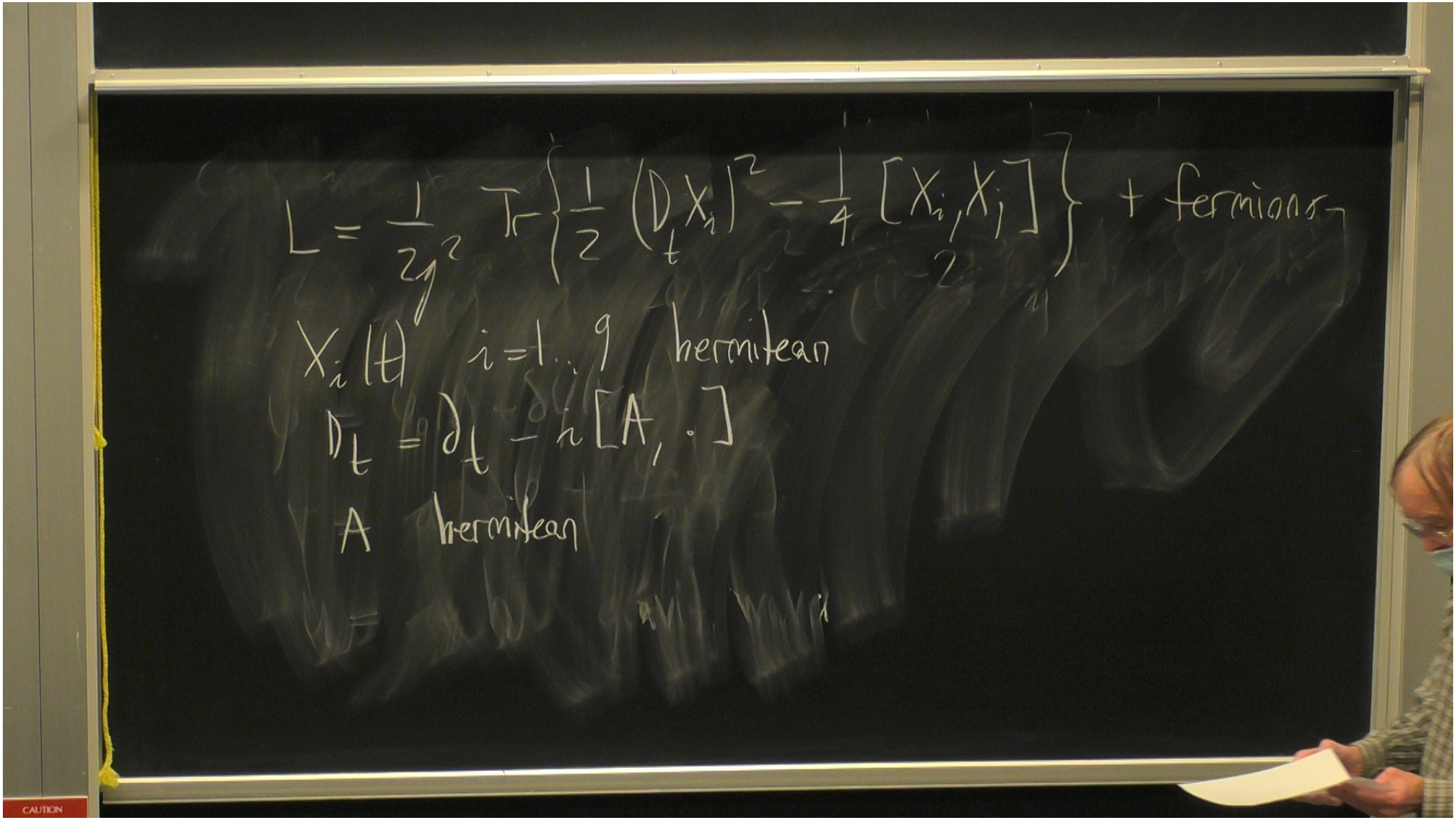
obs. measuring ″ ″ trans-Planckian by Hubble
super-Hubble stuff modes radius

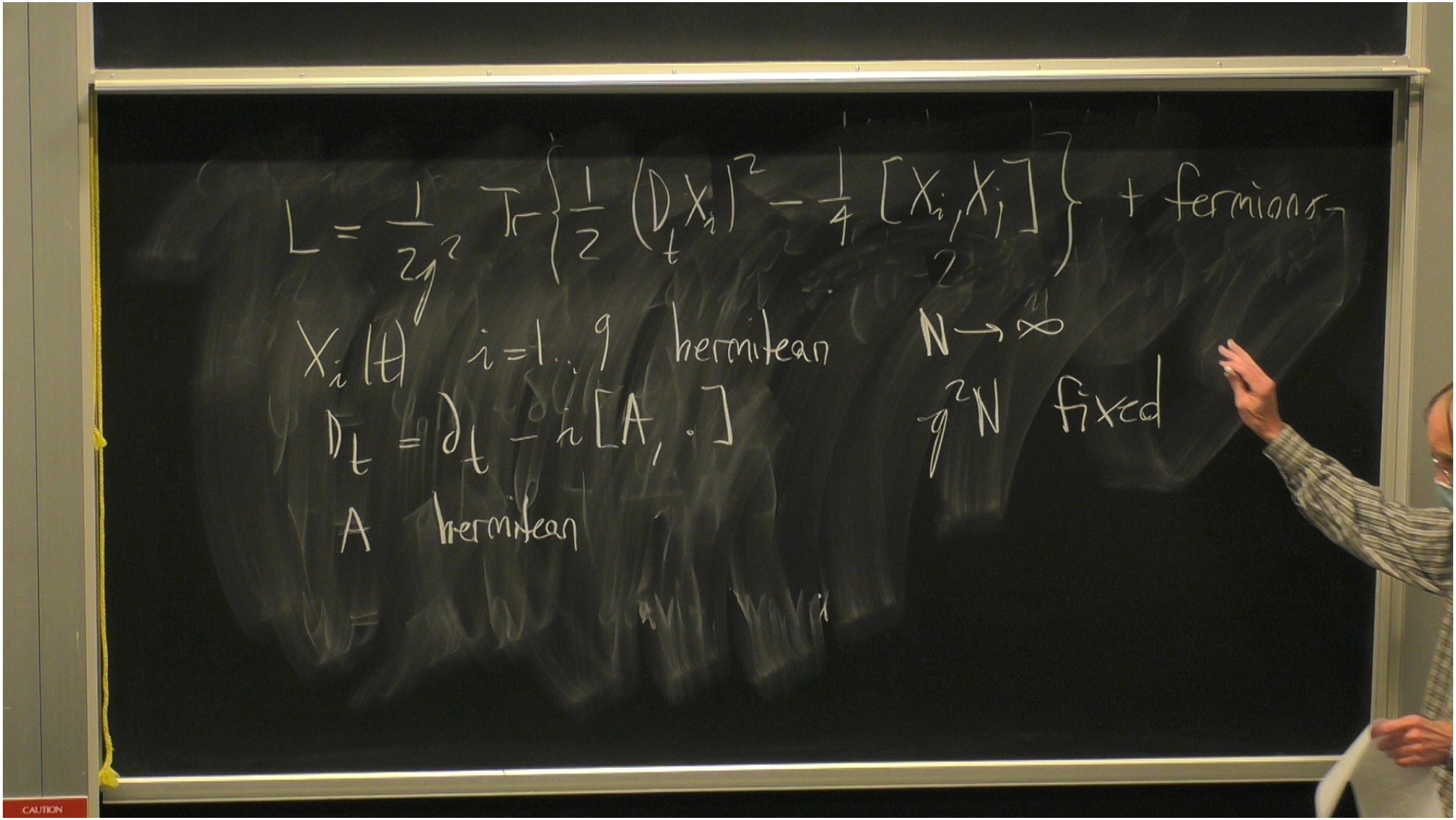

Thm t.f. #2 unitarity
Thm t.f. #3 2nd law of TD

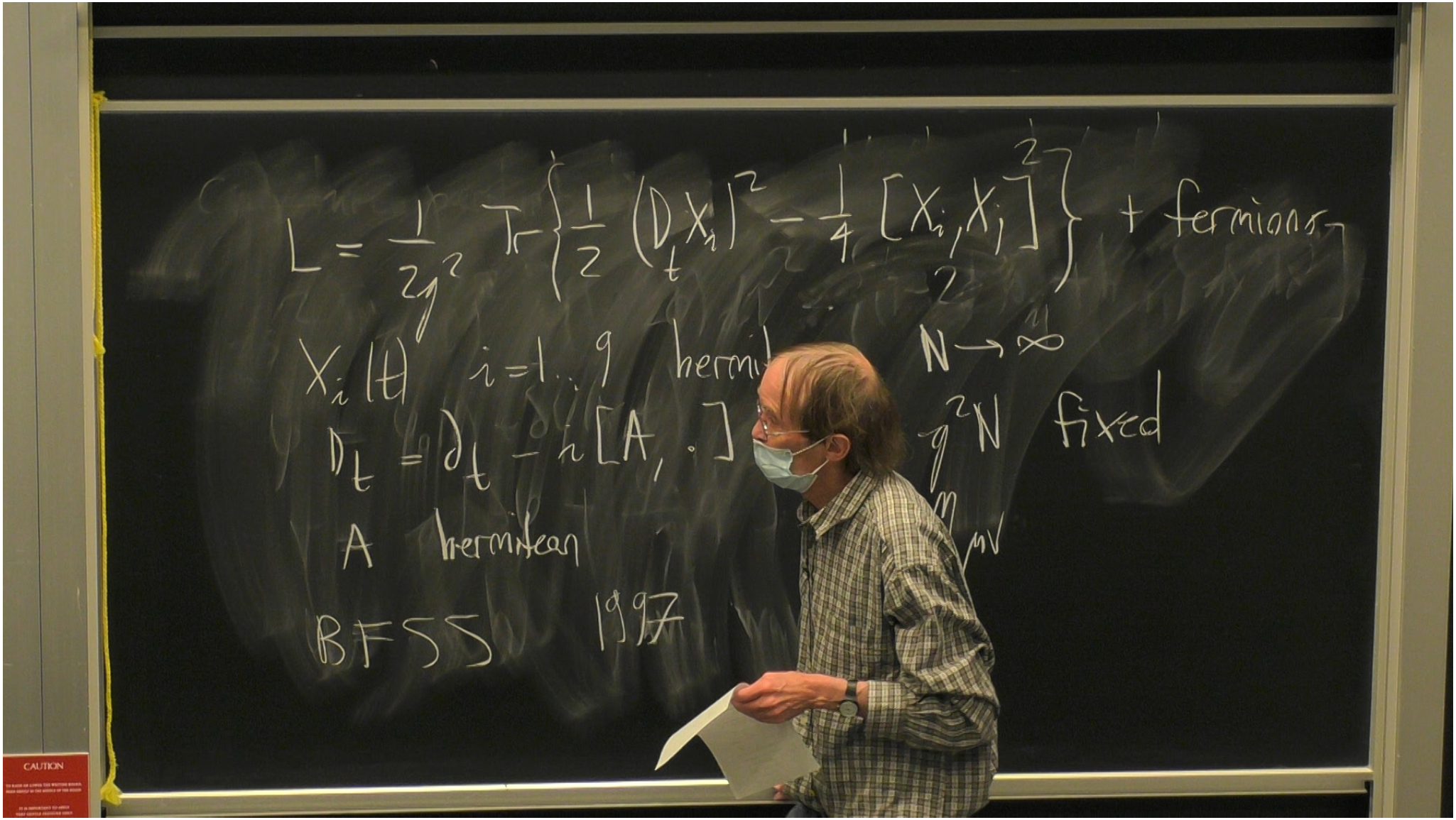

Instf. #2 unitarity
Instf. #3 2nd law of TD
inflation: phase space of IR modes
entanglement entropy
demand: $S_E(t)_R \leq T_R^3$

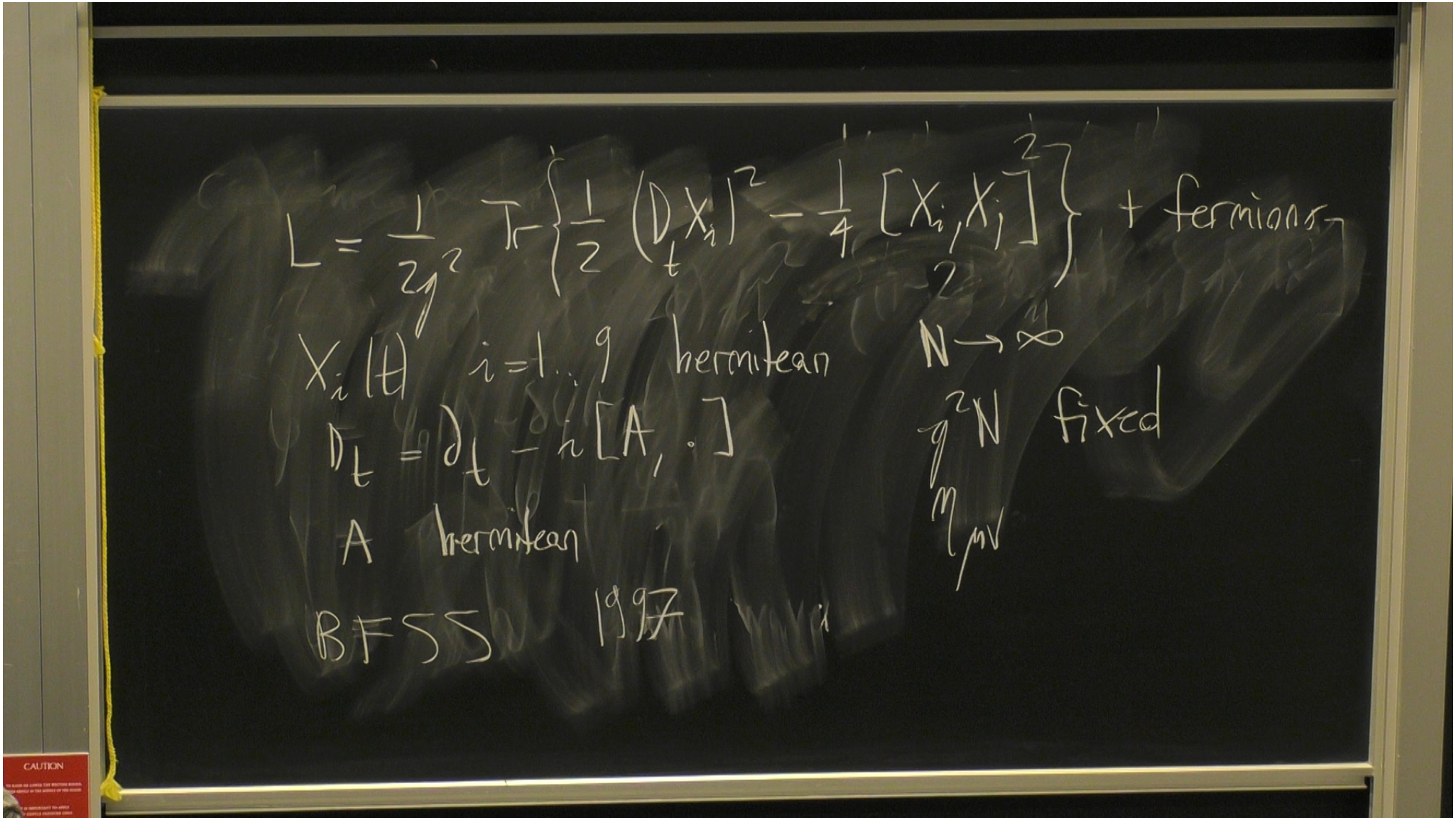

Test f. #2 unitarity
Test f. #3 2nd law of TD
inflation: phase space of IR modes
entanglement entropy
demand: $S_E(t)_R \leq T_R^3$

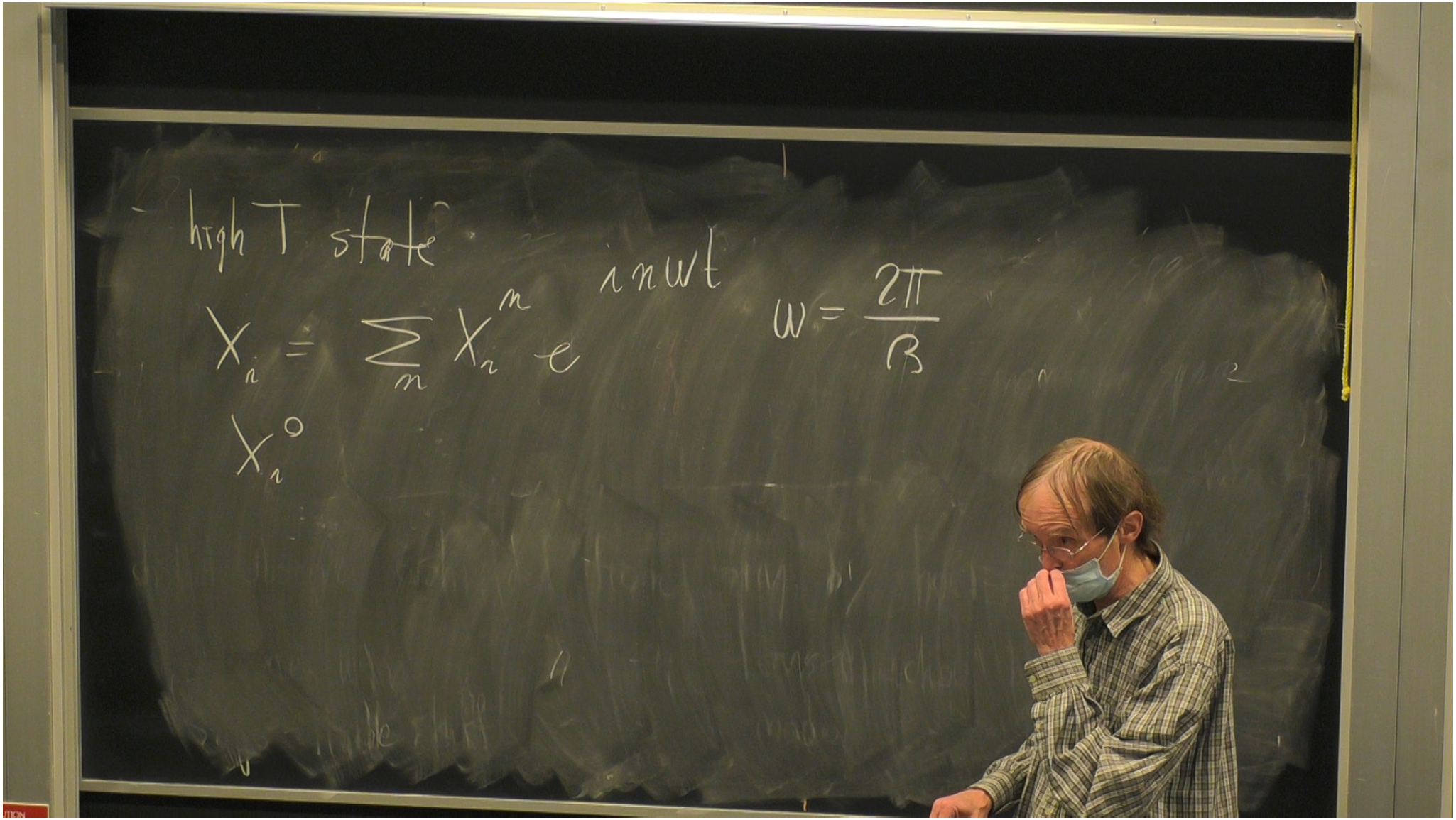

$L = \frac{1}{2g^2} \mathrm{Tr}\left\{ \frac{1}{2} (D X_i)^2 - \frac{1}{4} [X_i, X_j]^2 \right\}$ + fermions
$X_i(t)$ $i = 1 \ldots 9$ hermitean

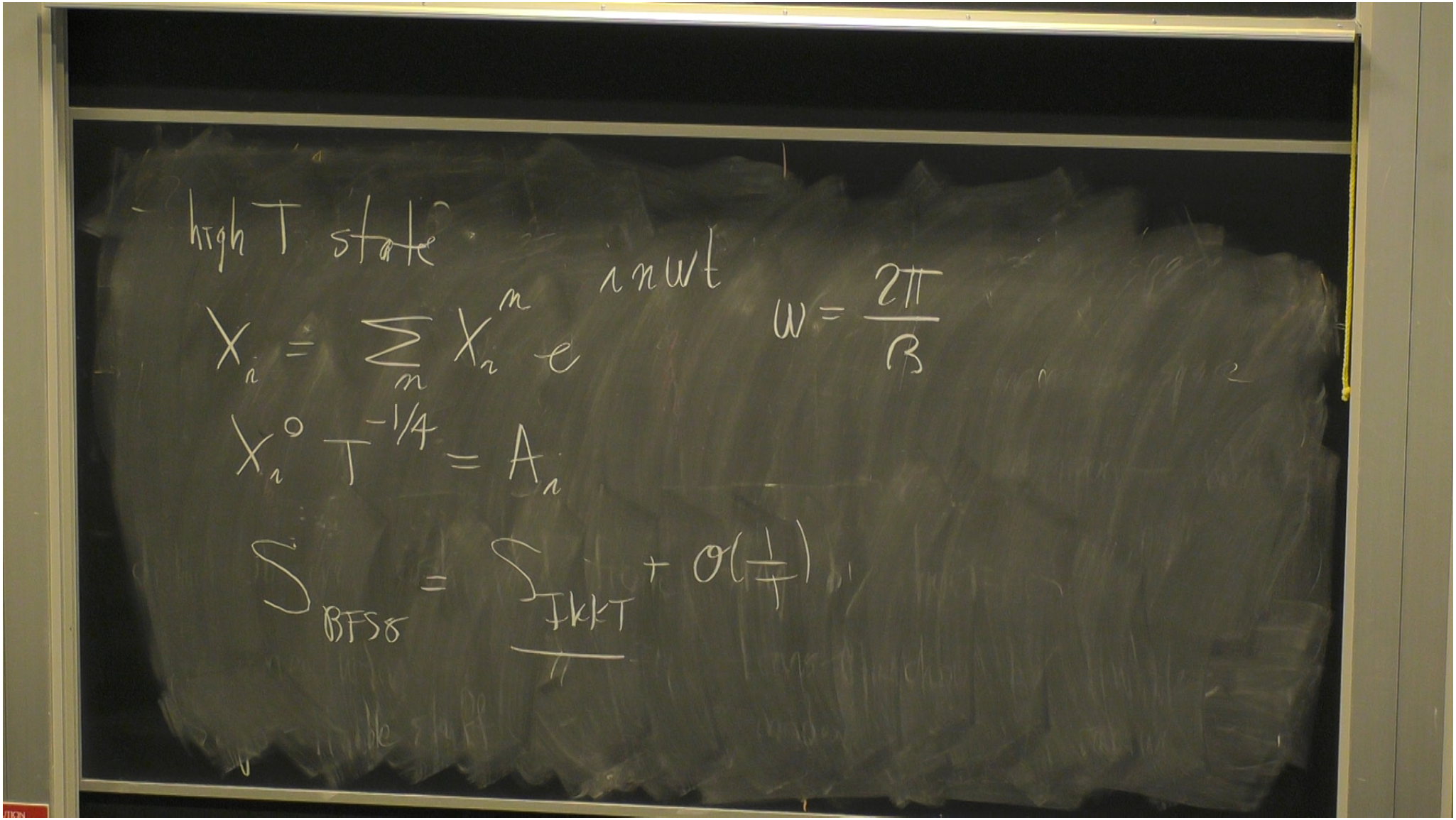

$L = \frac{1}{2g^2} \mathrm{Tr}\left\{ \frac{1}{2} (D_t X_i)^2 - \frac{1}{4} [X_i, X_j]^2 \right\}$ + fermions
$X_i(t)$ $i = 1 \ldots 9$ hermitean
$D_t = \partial_t - i[A, \cdot]$
A hermitean

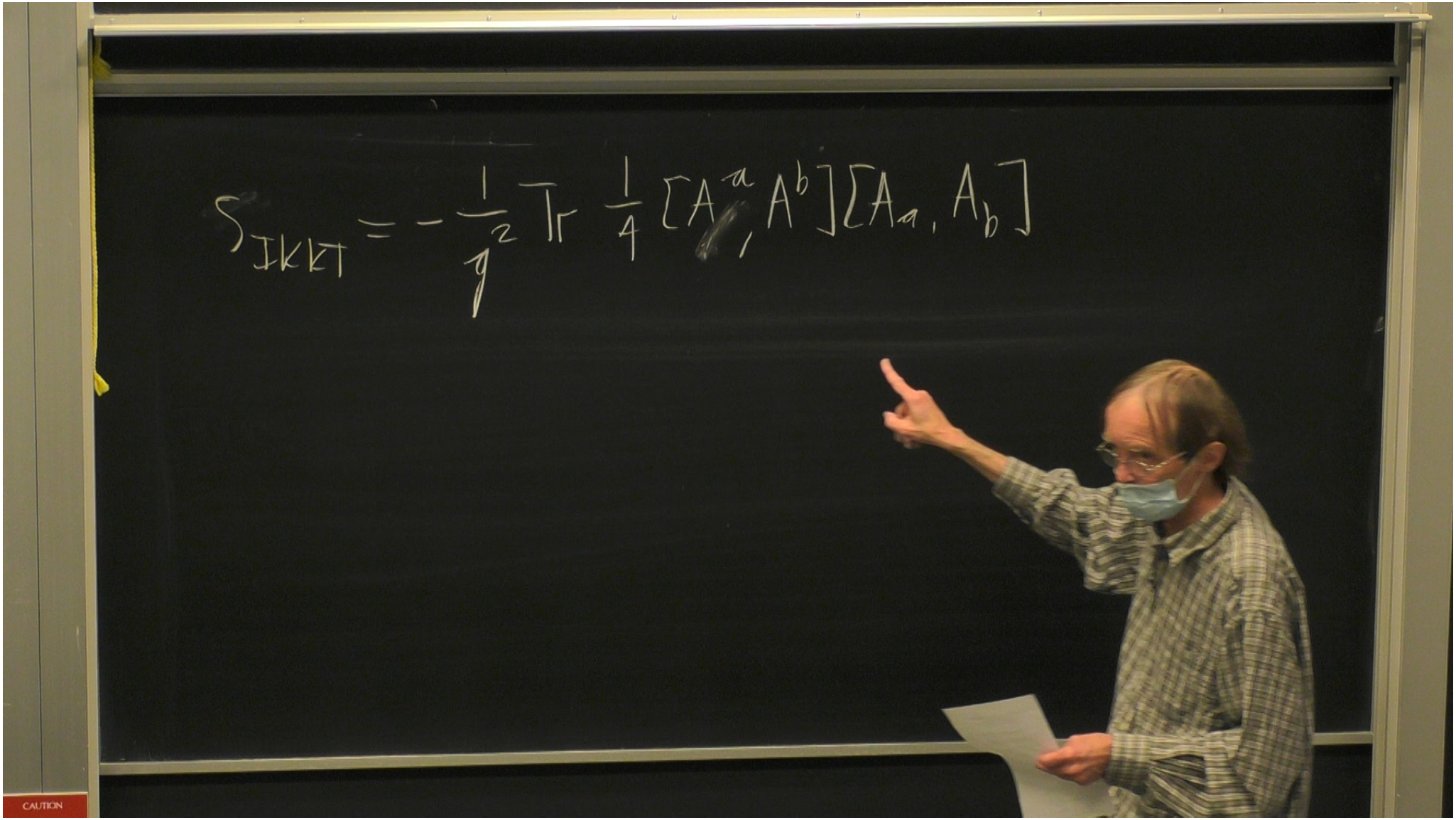

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$X_i(t)$ $i = 1 \ldots 9$ hermitean
$N \to \infty$
$D_t = \partial_t - i[A, \cdot]$
$g^2 N$ fixed
A hermitean


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BFSS 1997
CAUTION


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$N \to \infty$
$g^2 N$ fixed
$m_{\mu\nu}$
BFSS 1997


high T state
$X_i = \sum_n X_i^n e^{in\omega t}$
$\omega = \frac{2\pi}{\beta}$
X_i^0


high T state
$X_n = \sum_m X_n^m e^{inwt}$
$w = \frac{2\pi}{\beta}$
$X_n^0 T^{-1/4} = A_n$
$S_{BFSS} = S_{IKKT} + O(\frac{1}{T})$


$S_{IKKT} = -\frac{1}{g^2} \mathrm{Tr} \frac{1}{4} [A^a, A^b][A_a, A_b]$
CAUTION

$$S_{IKKT} = -\frac{1}{g^2} \mathrm{Tr}\left(\frac{1}{4}[A^a, A^b][A_a, A_b]\right) + \text{fermionic}$$

basis in which A_0 diagonal $\quad \alpha_n$ emergent time

$$A_0 - \mathrm{diag}(\alpha_{-\frac{N}{2}}, \ldots \alpha_{\frac{N}{2}})$$

$$S_{IKKT} = -\frac{1}{g^2} \mathrm{Tr}\left(\frac{1}{4}[A^a, A^b][A_a, A_b]\right) + \text{fermionic}$$

basis in which A_0 diagonal $\quad \alpha_n$ emergent time

$$A_0 \sim \mathrm{diag}(\alpha_{-\frac{N}{2}}, \ldots \alpha_{\frac{N}{2}})$$

$$\frac{1}{N} < \mathrm{tr}\, A_0^2 > \sim K N$$

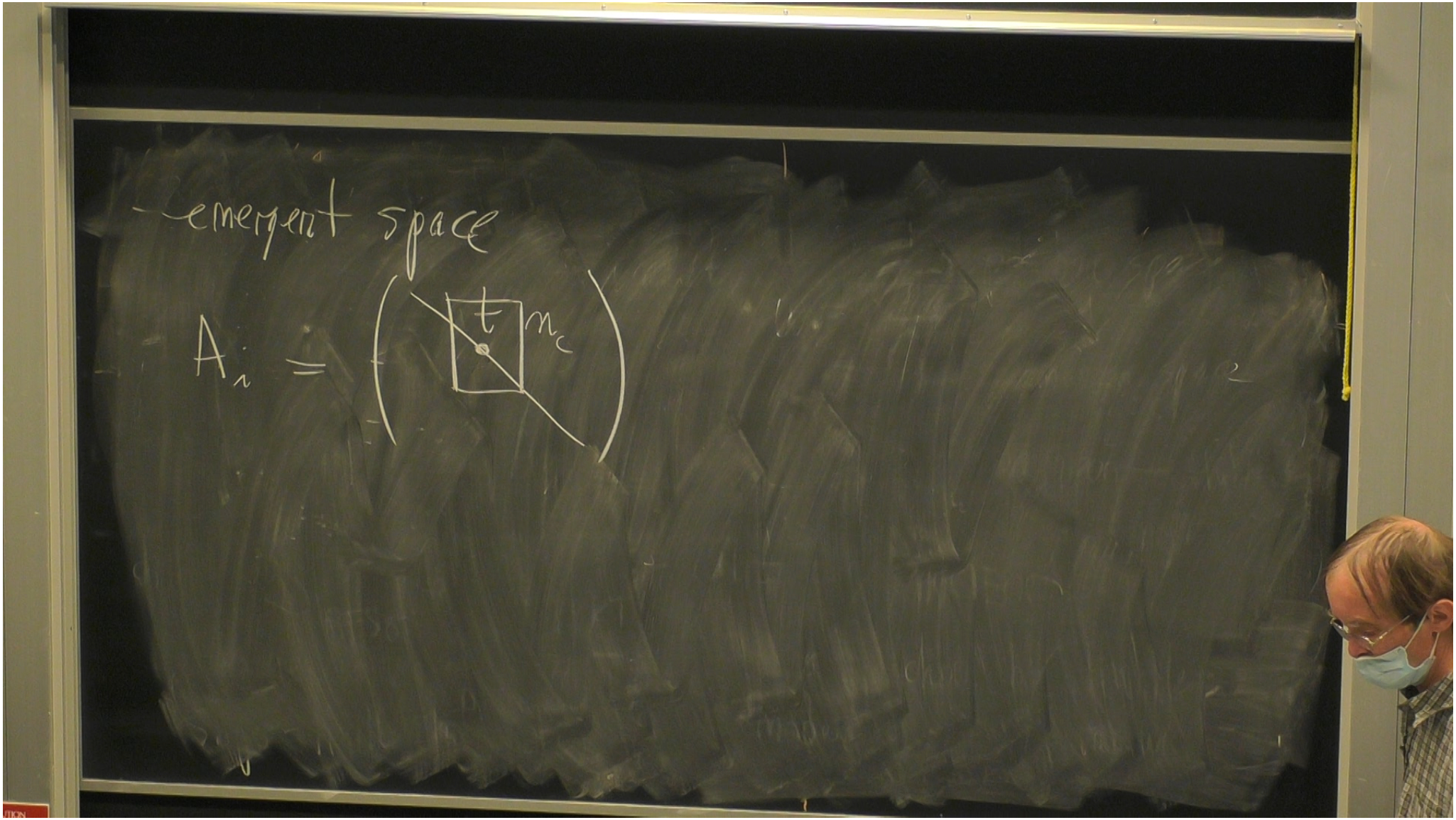
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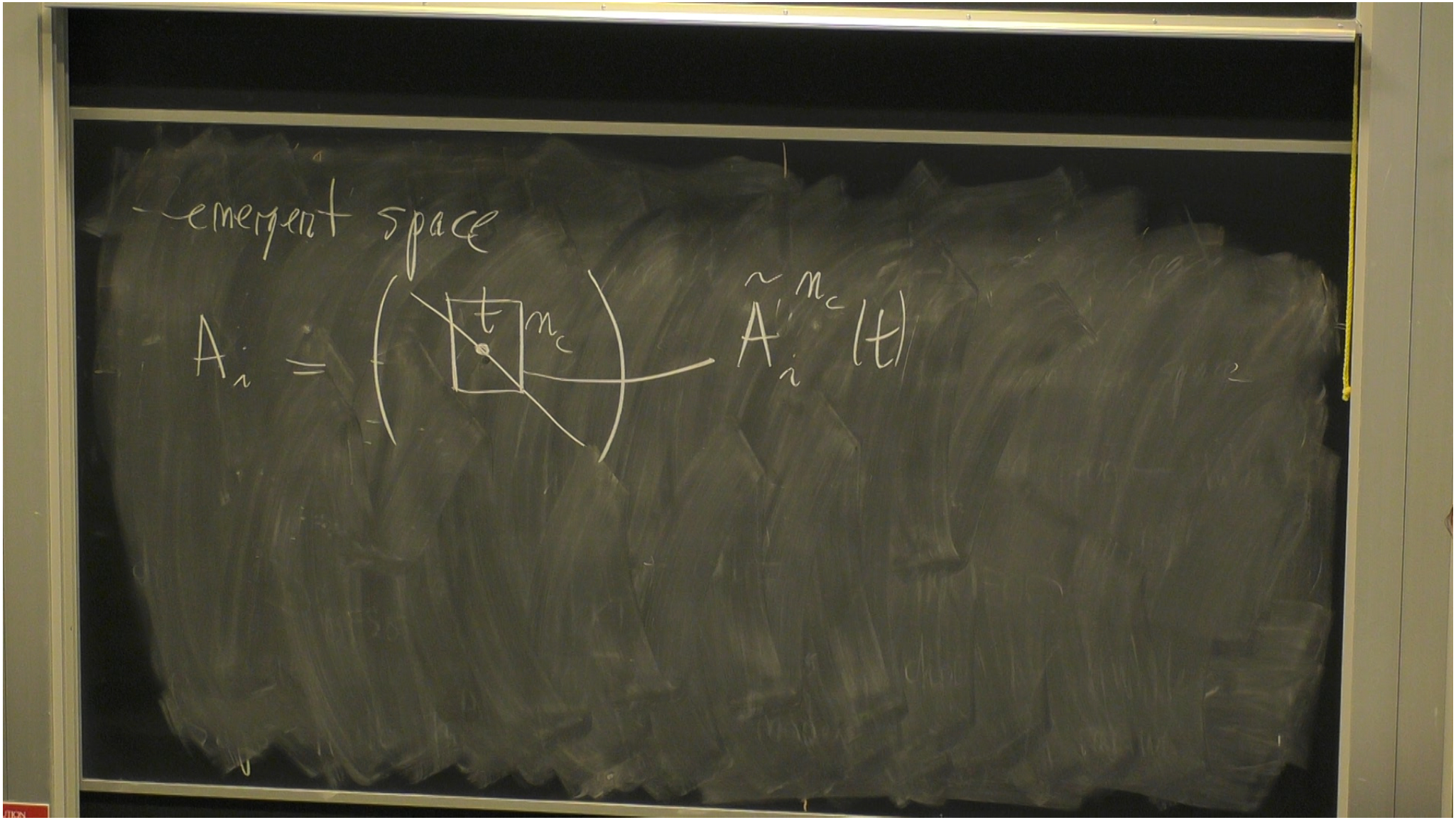
basis in which A_0 diagonal $\quad \alpha_n$ emergent time

$$A_0 - \mathrm{diag}\left(\alpha_{-\frac{N}{2}}, \ldots \alpha_{\frac{N}{2}}\right) \quad \Rightarrow T_{total} \sim \sqrt{N}$$

$$\Delta t \sim \frac{1}{\sqrt{N}}$$

$$\frac{1}{N} < \mathrm{tr}\, A_0^2 > \sim K N$$


emergent space
$A_i =$
t
m_c

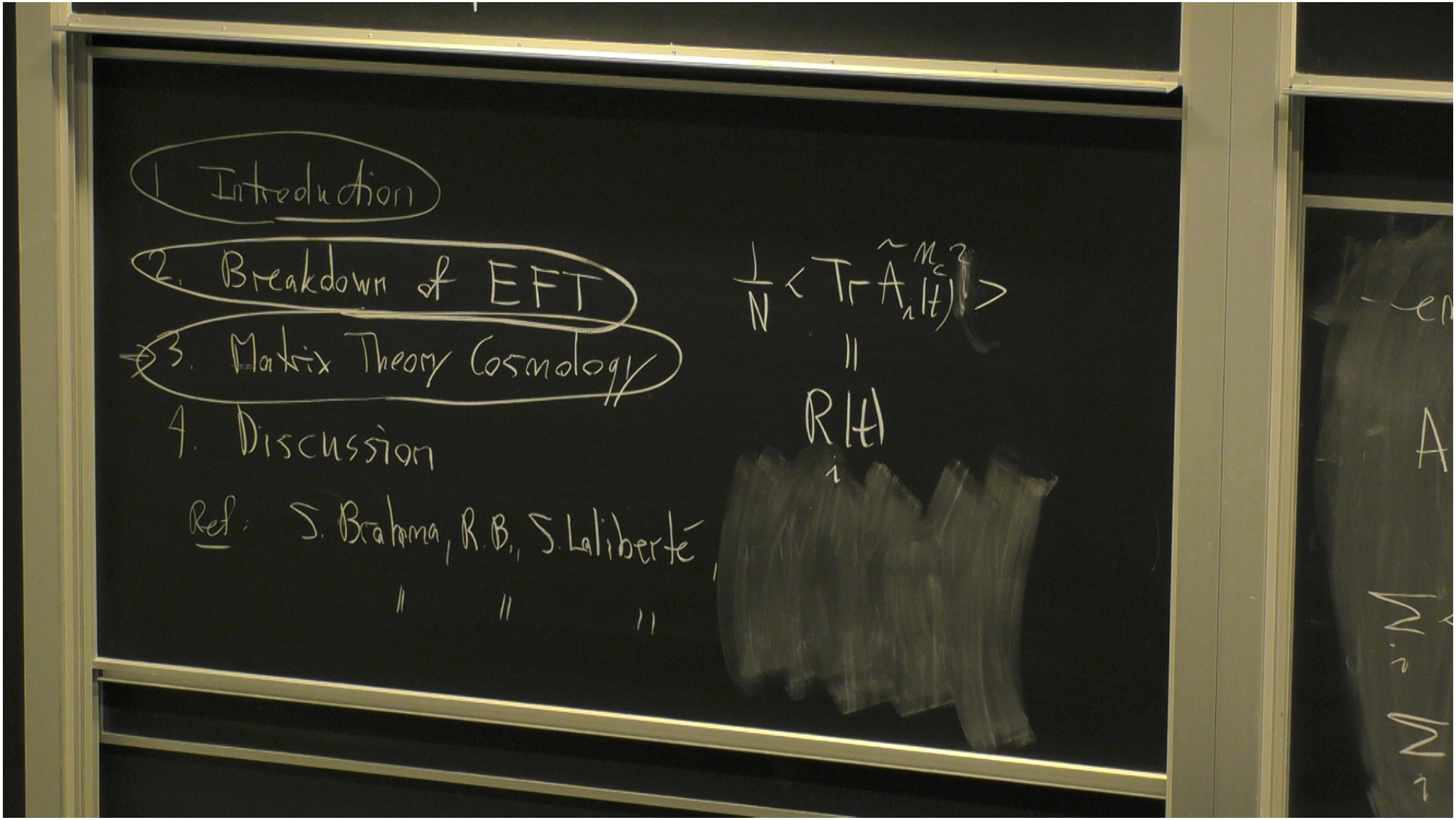

emergent space
$A_i =$
t
n_c
$\tilde{A}_i^{n_c}(t)$

emergent space

$$A_i = \left(\; t \;\; n_c \right) \tilde{A}_i^{n_c}(t)$$

$$\sum_i \langle |\tilde{A}_i|^2_{ab} \rangle \searrow \text{as } |a-b| \nearrow$$

$$\sum_i \langle |\tilde{A}_i|_{ab} \rangle \sim \text{const } |a-b| = n < n_c$$


1. Introduction
2. Breakdown of EFT
3. Matrix Theory Cosmology
4. Discussion
Ref: S. Brahma, R. B., S. Laliberté,
" " "
$\frac{1}{N}\langle \mathrm{Tr}\,\tilde{A}_i^{n_c}(t)\rangle$
=
$R(t)$
i

1. Introduction

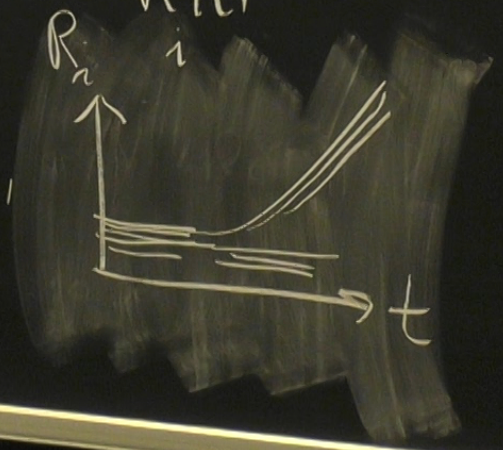
2. Breakdown of EFT

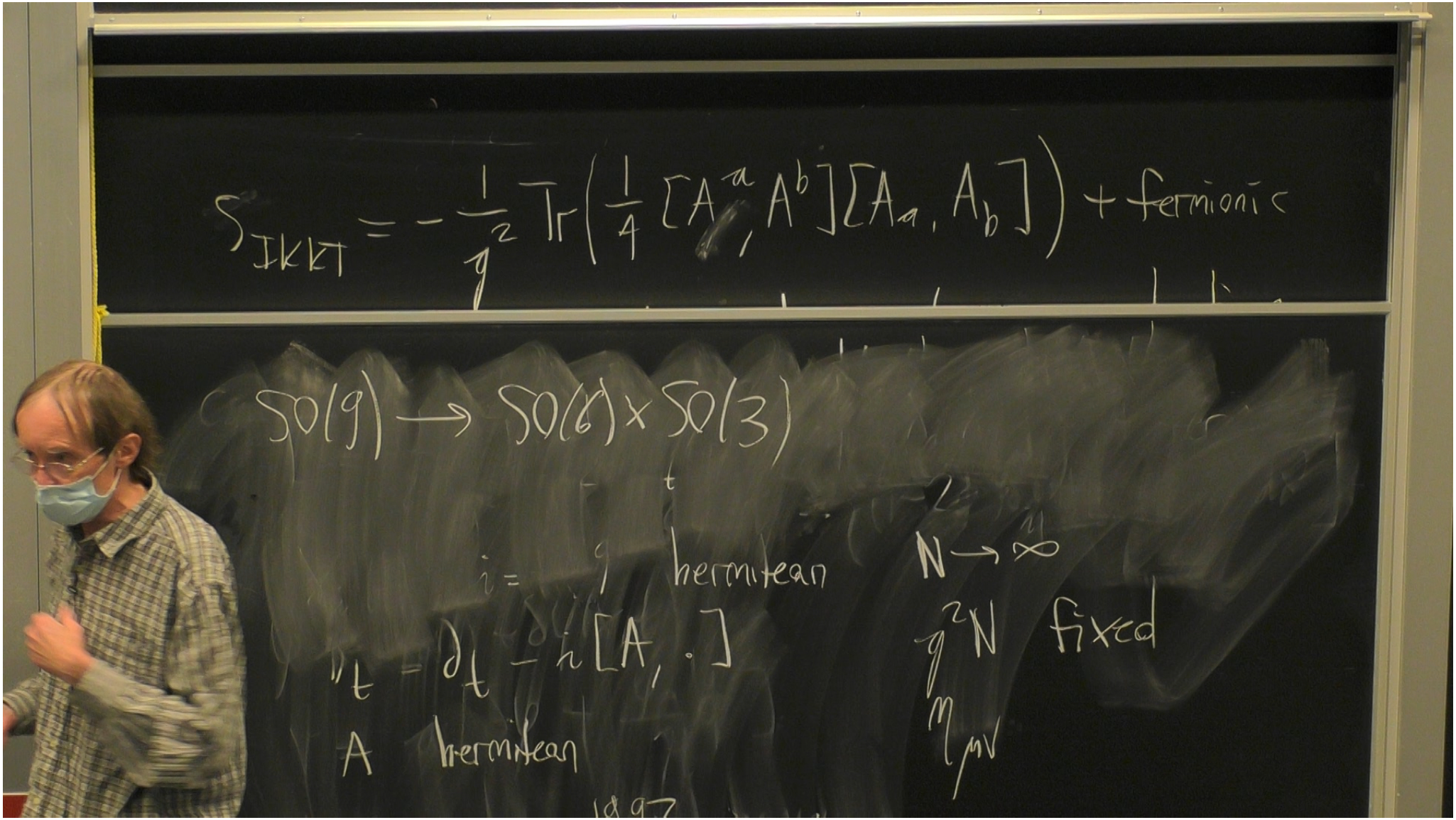
3. Matrix Theory Cosmology

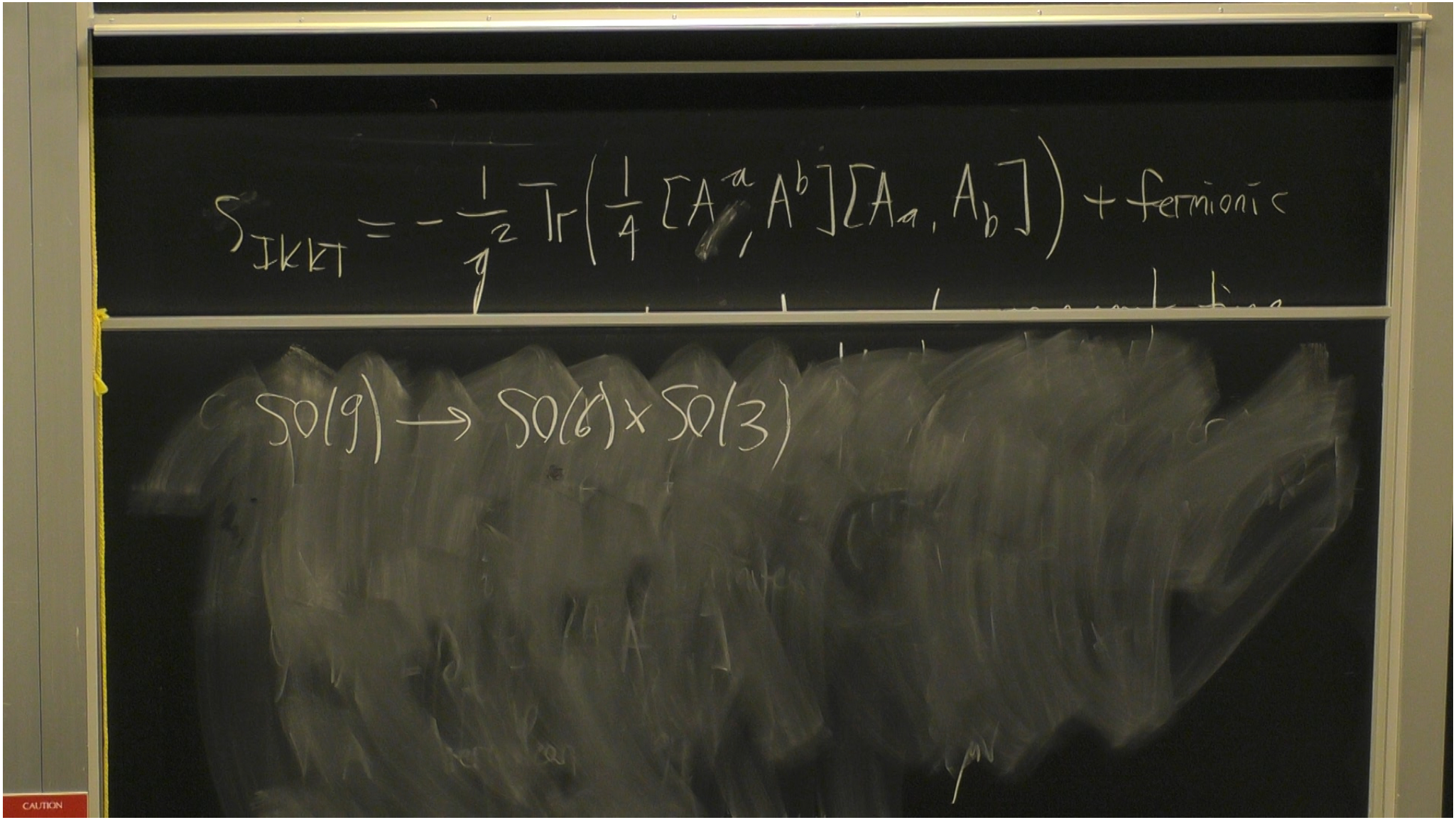
4. Discussion

Ref: S. Brahma, R.B., S. Laliberté,
" " "

$$\frac{1}{N}\langle \mathrm{Tr}\,\tilde{A}_i^{n_c}(t)\rangle = R_i(t)$$




$S_{IKKT} = -\frac{1}{g^2} \mathrm{Tr}\left(\frac{1}{4}[A^a, A^b][A_a, A_b]\right) + \text{fermionic}$
$SO(9) \longrightarrow SO(6) \times SO(3)$
$i = \quad$ hermitean
$\nabla_t = \partial_t - i[A, \cdot]$
A hermitean
$N \to \infty$
$g^2 N$ fixed
$\eta_{\mu\nu}$
1897


$S_{IKKT} = -\frac{1}{g^2} \mathrm{Tr}\left(\frac{1}{4}[A^a, A^b][A_a, A_b]\right) + \text{fermionic}$
$SO(9) \longrightarrow SO(6) \times SO(3)$
CAUTION

$$S_{IKKT} = -\frac{1}{g^2} \mathrm{Tr}\left(\frac{1}{4}[A^a, A^b][A_a, A_b]\right) + \text{fermionic}$$

$SO(9) \longrightarrow SO(6) \times SO(3)$ $\quad n_c \sim \sqrt{N}$

Proposal: $n < n_c$ comoving coord.

$$\ell_n = \langle A_n^{2-n}(t) \rangle \quad \text{phys. dist.}$$

CAUTION

$S_{IKKT} = -\frac{1}{g^2} \mathrm{Tr}\left(\frac{1}{4}[A^a, A^b][A_a, A_b]\right) + \text{fermionic}$

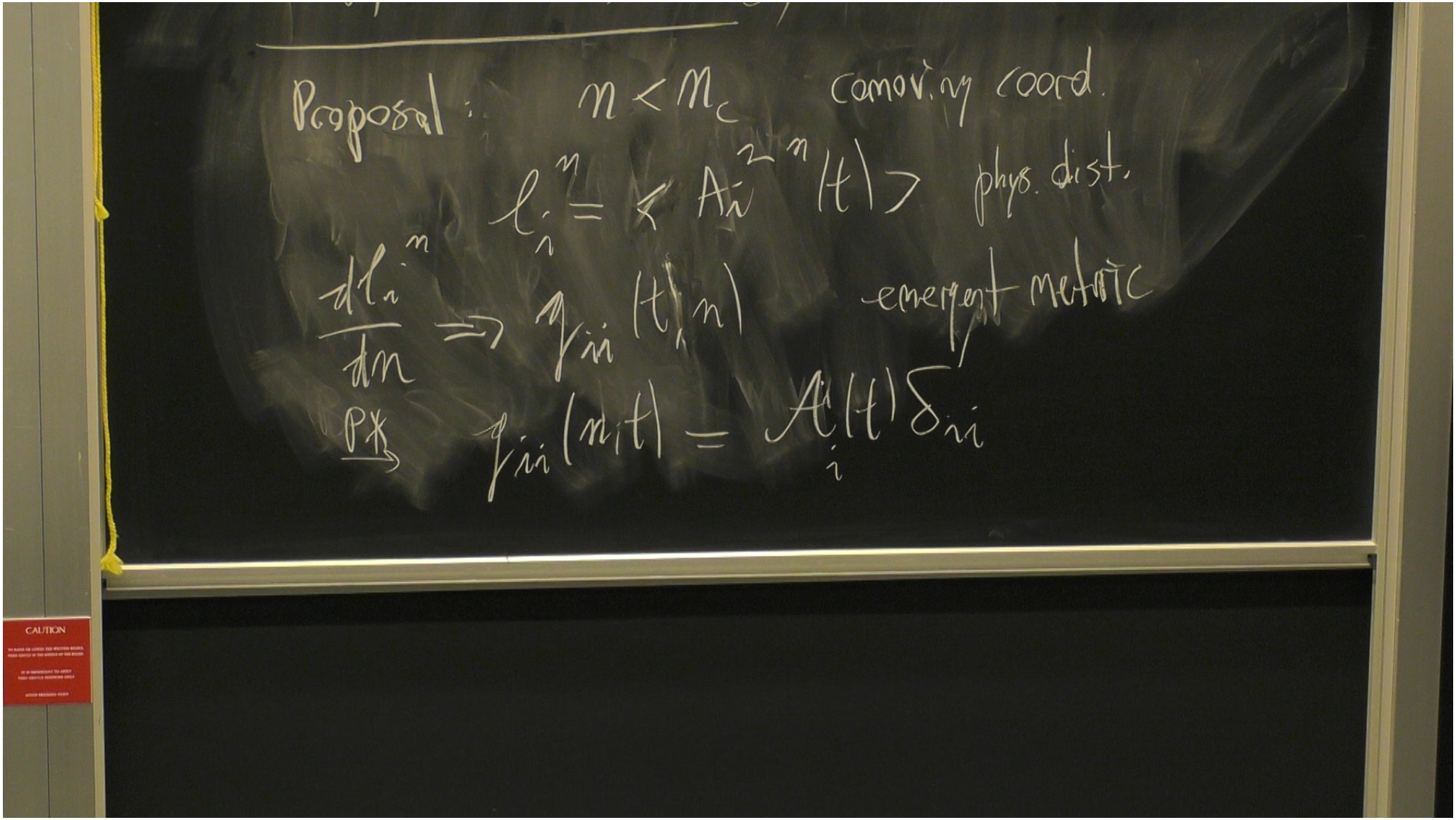
$SO(9) \longrightarrow SO(6) \times SO(3)$ $\quad n_c \sim \sqrt{N}$

Proposal: $n < n_c$ comov. ng coord.

$l_i^n = \langle A_i^2{}^n(t) \rangle$ phys. dist.

$\frac{dl_i^n}{dn} \Rightarrow g_{ii}(t)$ emergent metric

CAUTION


Proposal: $n < n_c$ comoving coord.
$l_i^n = \langle A_i^{2-n}(t) \rangle$ phys. dist.
$\frac{dl_i^n}{dn} \Rightarrow \gamma_{ii}(t;n)$ emergent metric
PX $\Rightarrow \gamma_{ii}(n;t) = A_i^{2-n}(t)\,\delta_{ii}$

$SO(9) \longrightarrow SO(6) \times SO(3)$ $\quad n_c \sim \sqrt{N}$

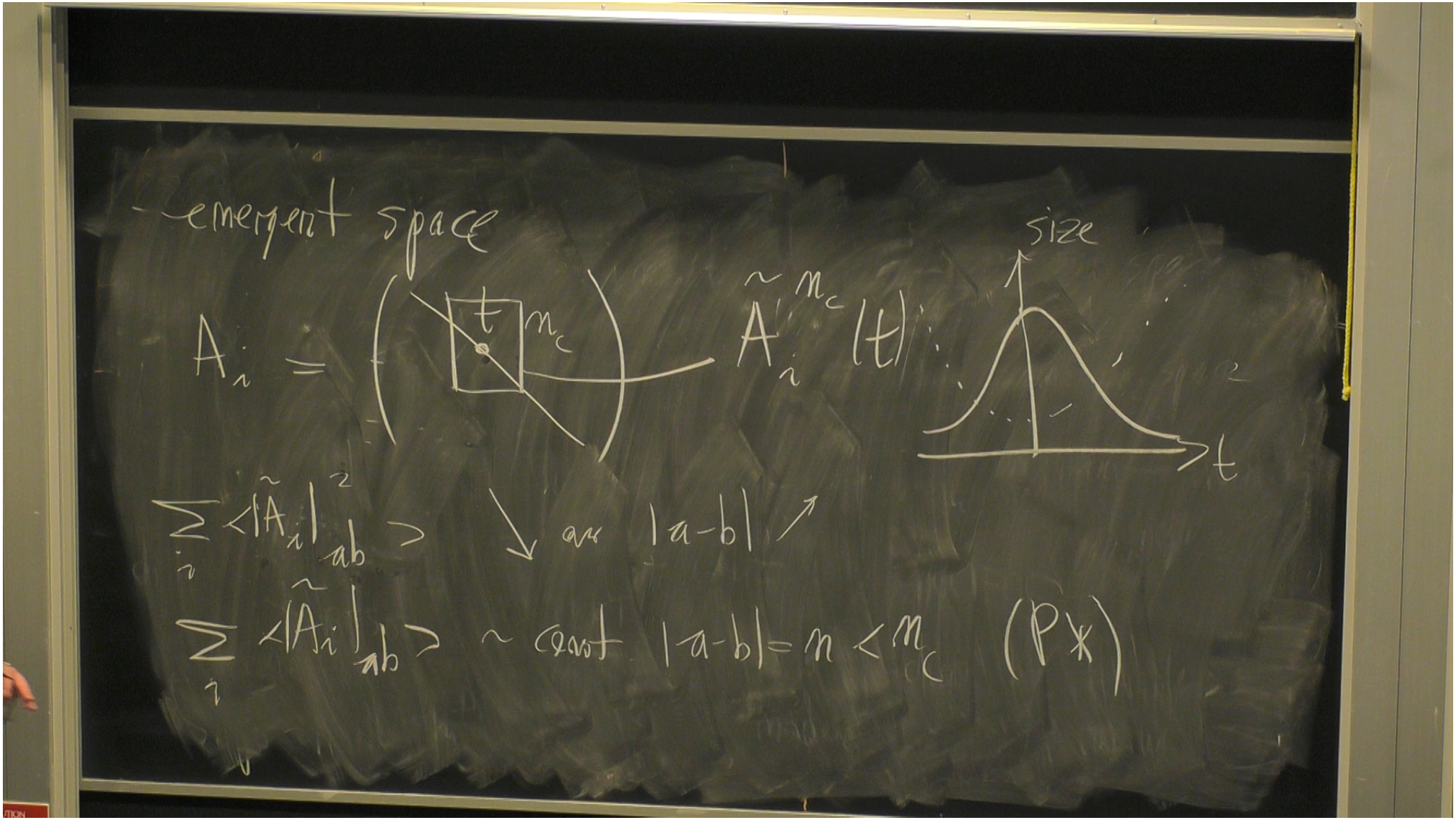
Proposal: $n < n_c$ comoving coord.

$\ell_i^n = \langle A_i^{2n}(t) \rangle$ phys. dist.

$\frac{d\ell_i^n}{dn} \Rightarrow g_{ii}(t,n)$ emergent metric

PS $\Rightarrow g_{ii}(n,t) = A_i(t)\,\delta_{ii}$

CAUTION


emergent space
$A_i = \left(\right) \tilde{A}_i^{n_c}(t)$
t
n_c
size
t
$\sum_i \langle |\tilde{A}_i|^2_{ab} \rangle$ ↘ as $|a-b|$ ↗
$\sum_i \langle |\tilde{A}_i|_{ab} \rangle \sim \text{const}\ |a-b| = n < n_c$ (P*)