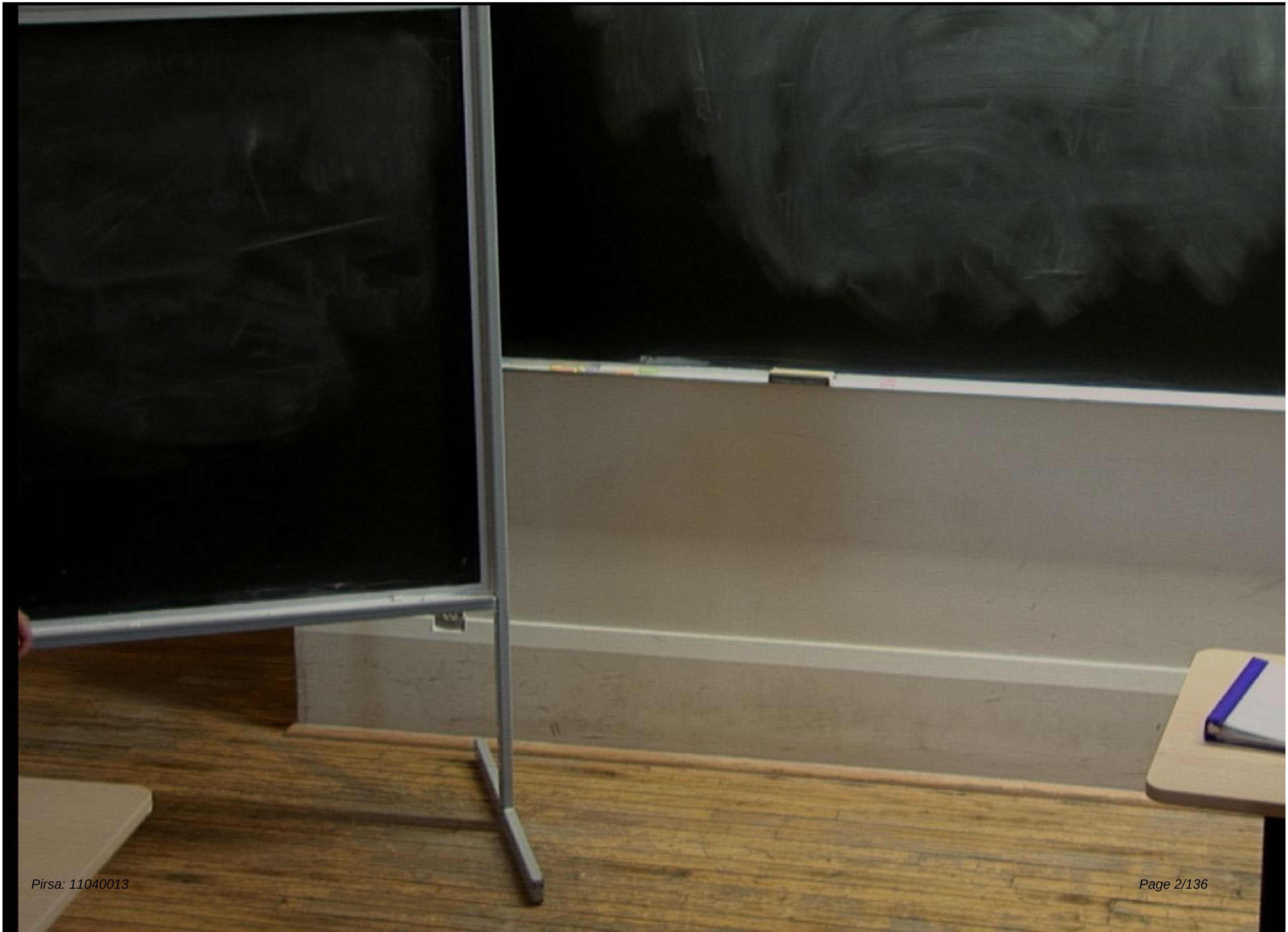
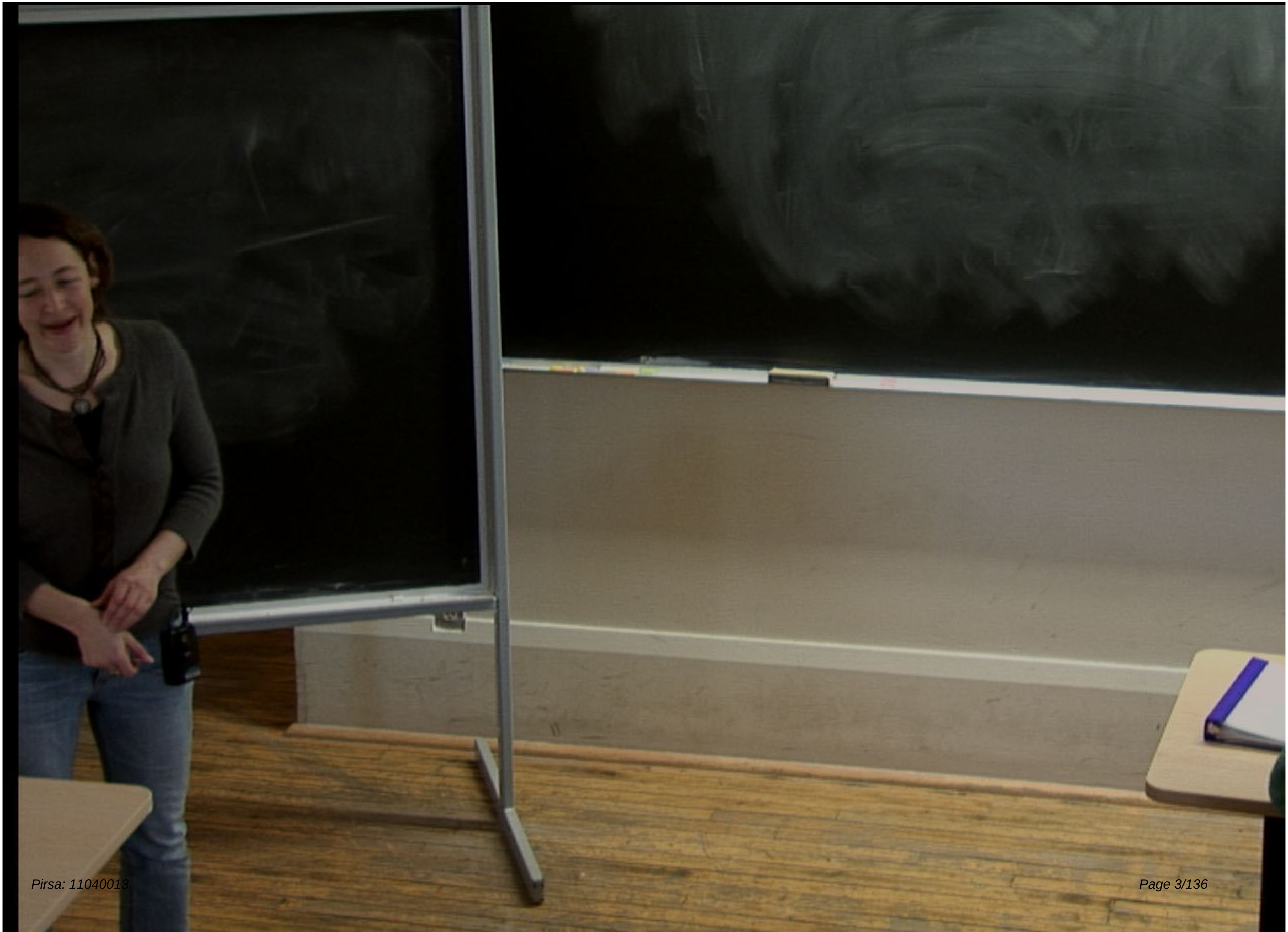
Title: Explorations in Cosmology - Lecture 9

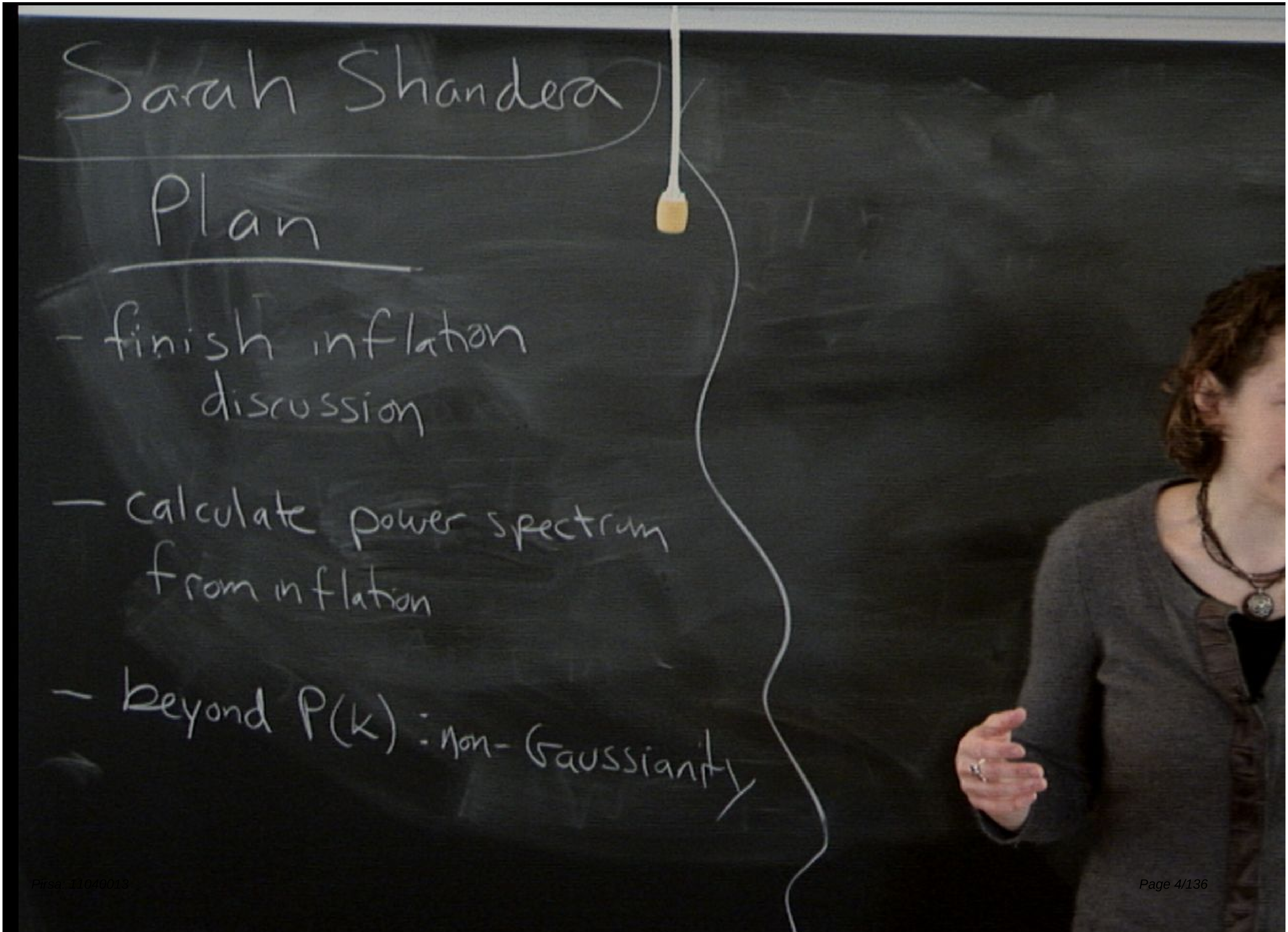
Date: Apr 14, 2011 10:15 AM

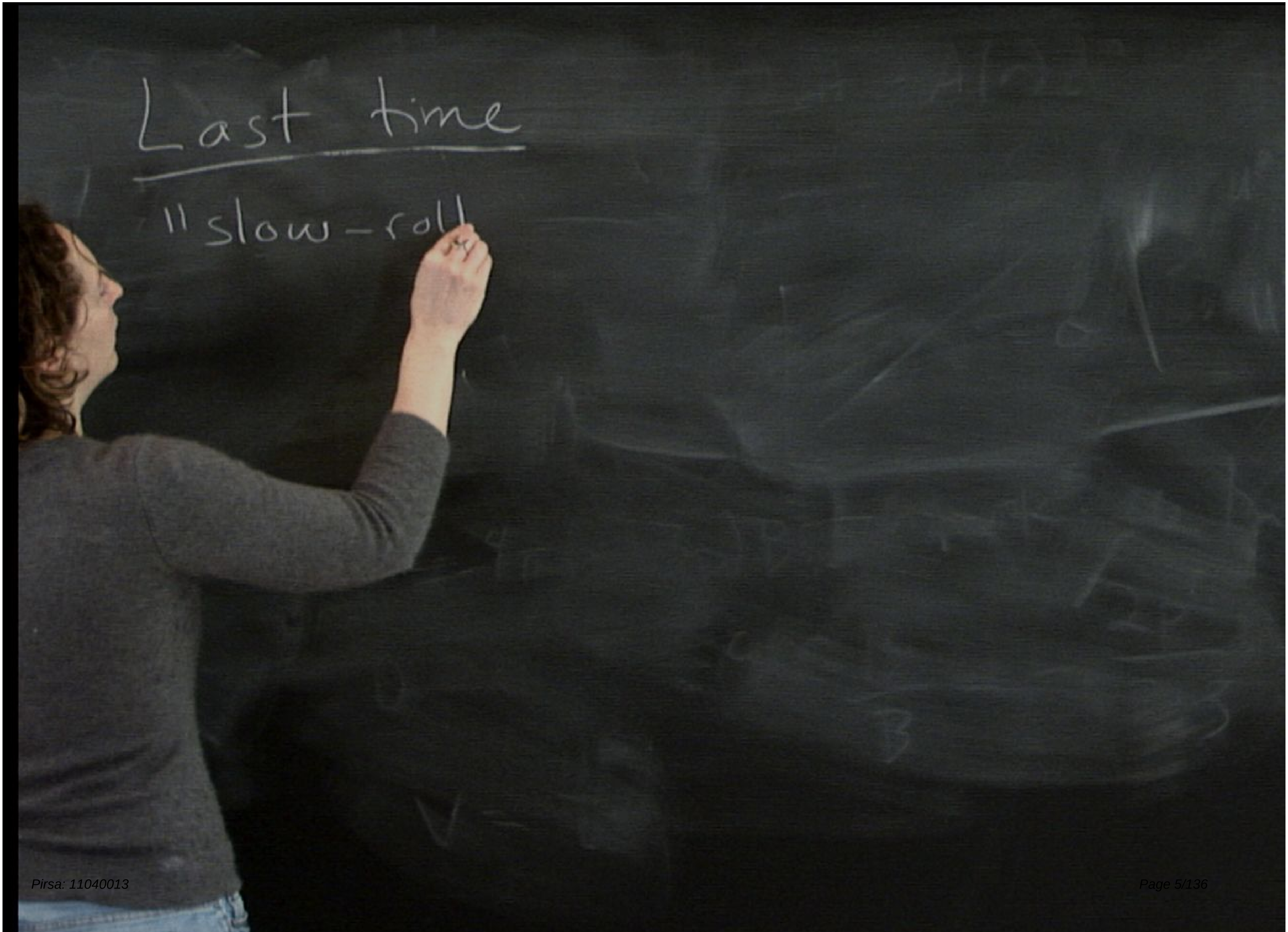
URL: http://pirsa.org/11040013

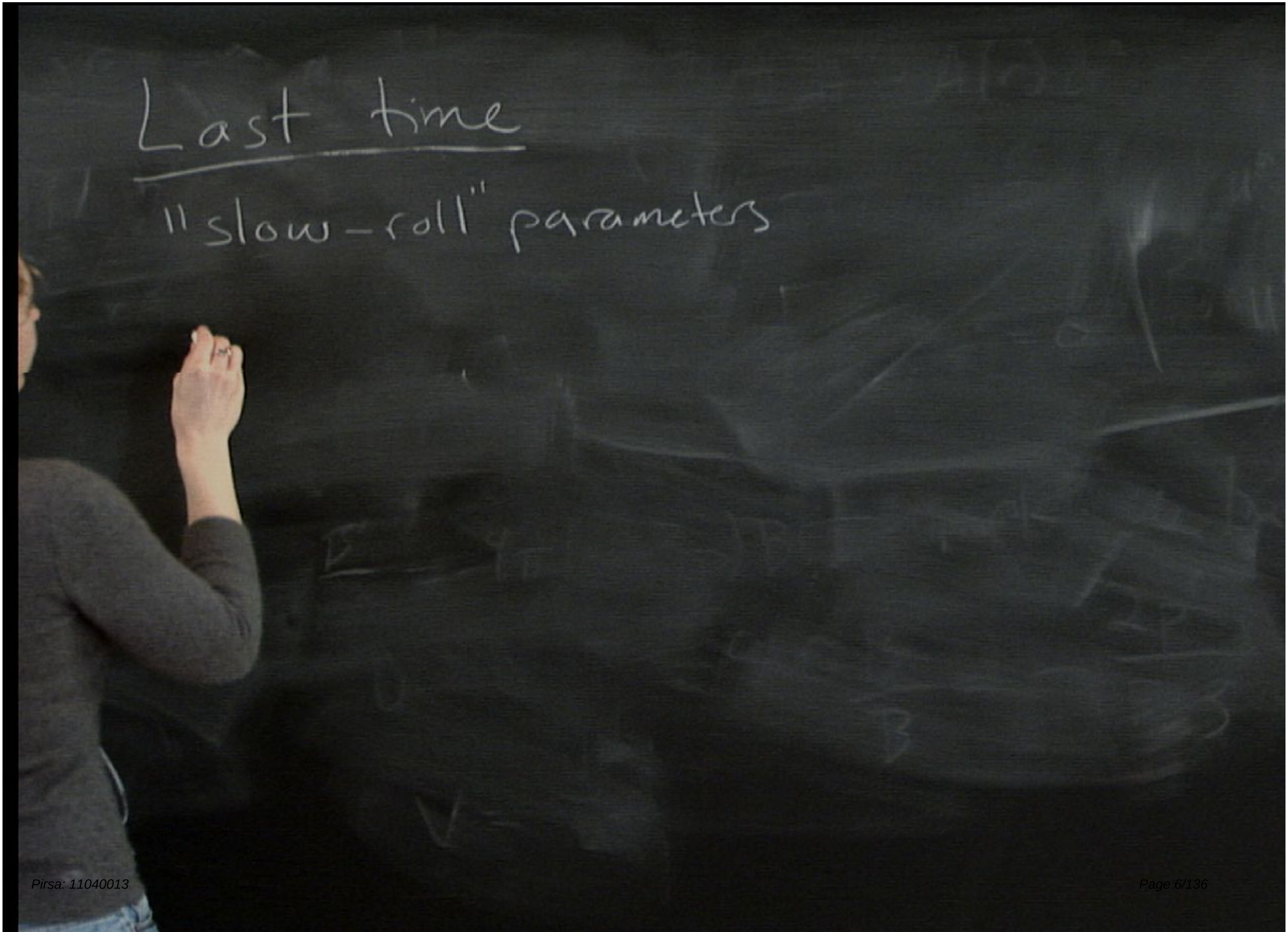
Abstract:






Sarah Shandera
Plan
- finish inflation discussion
- calculate power spectrum from inflation
- beyond P(k): non-Gaussianity


Last time
"slow-roll


Last time
"slow-roll" parameters

Last time

$$V' = \frac{\partial V}{\partial \phi}$$

"slow-roll" parameters

① $\epsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)$

$$V' = \frac{\partial V}{\partial \phi}$$

Last time

"slow-roll" parameters

(1) $\epsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 < 1$ condition for infl

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Last time

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② $\eta \equiv M_p^2 \frac{V''}{V}$

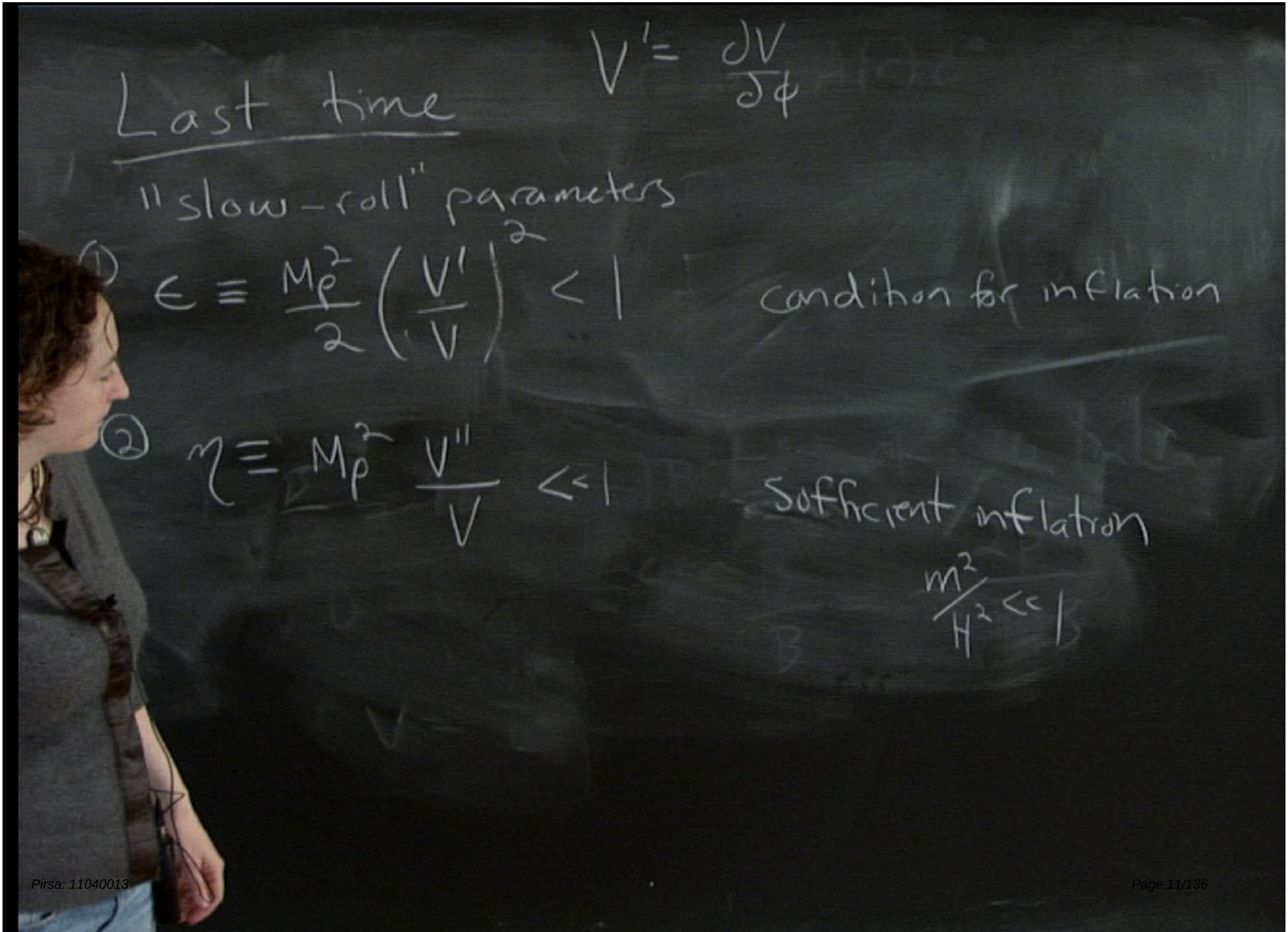
Last time

$$V' = \frac{\partial V}{\partial \phi}$$

"slow-roll" parameters

① $$\epsilon \equiv \frac{M_p^2}{2} \left(\frac{V'}{V} \right)^2 < 1$$ condition for inflation

② $$\eta \equiv M_p^2 \frac{V''}{V} << 1$$ sufficient inflation


Last time
$V' = \frac{\partial V}{\partial \phi}$
"slow-roll" parameters
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sufficient inflation
$\frac{m^2}{H^2} << 1$

$$V' = \frac{\partial V}{\partial \phi}$$

Last time

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① $\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 < 1$ condition for inflation

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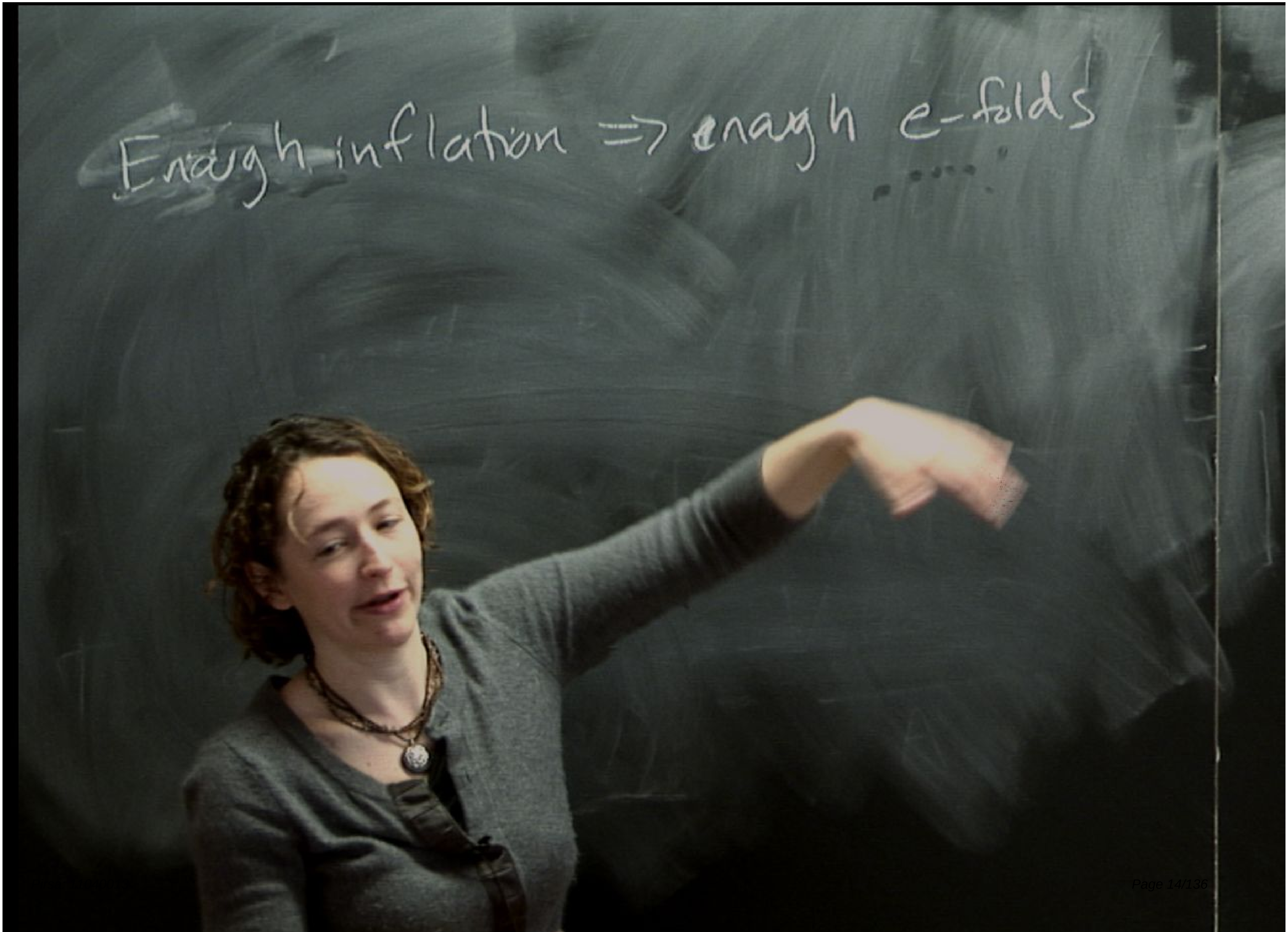
$\frac{m^2}{H^2} \ll 1$

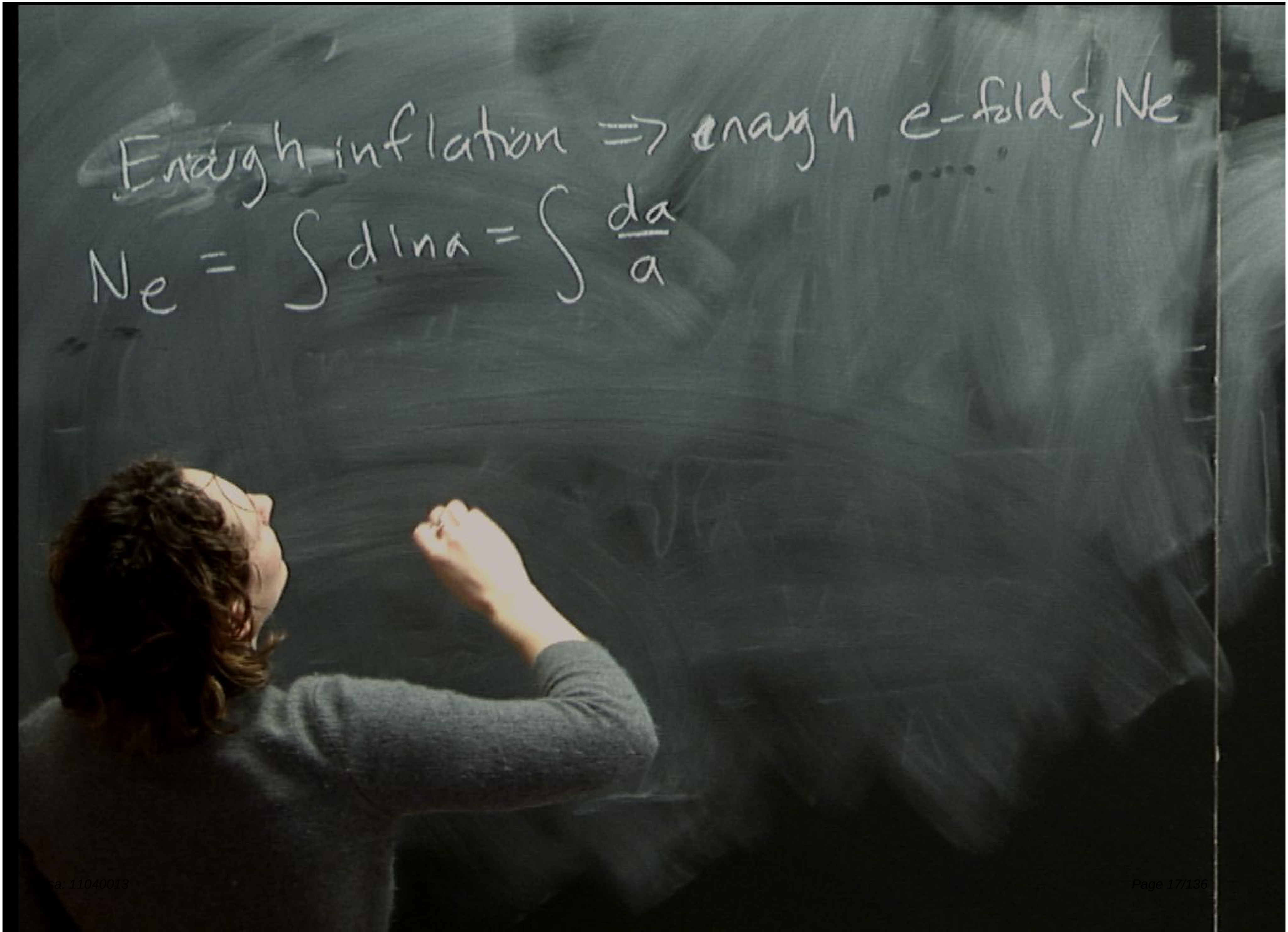
Enough inflation $\Rightarrow$ enough e-folds

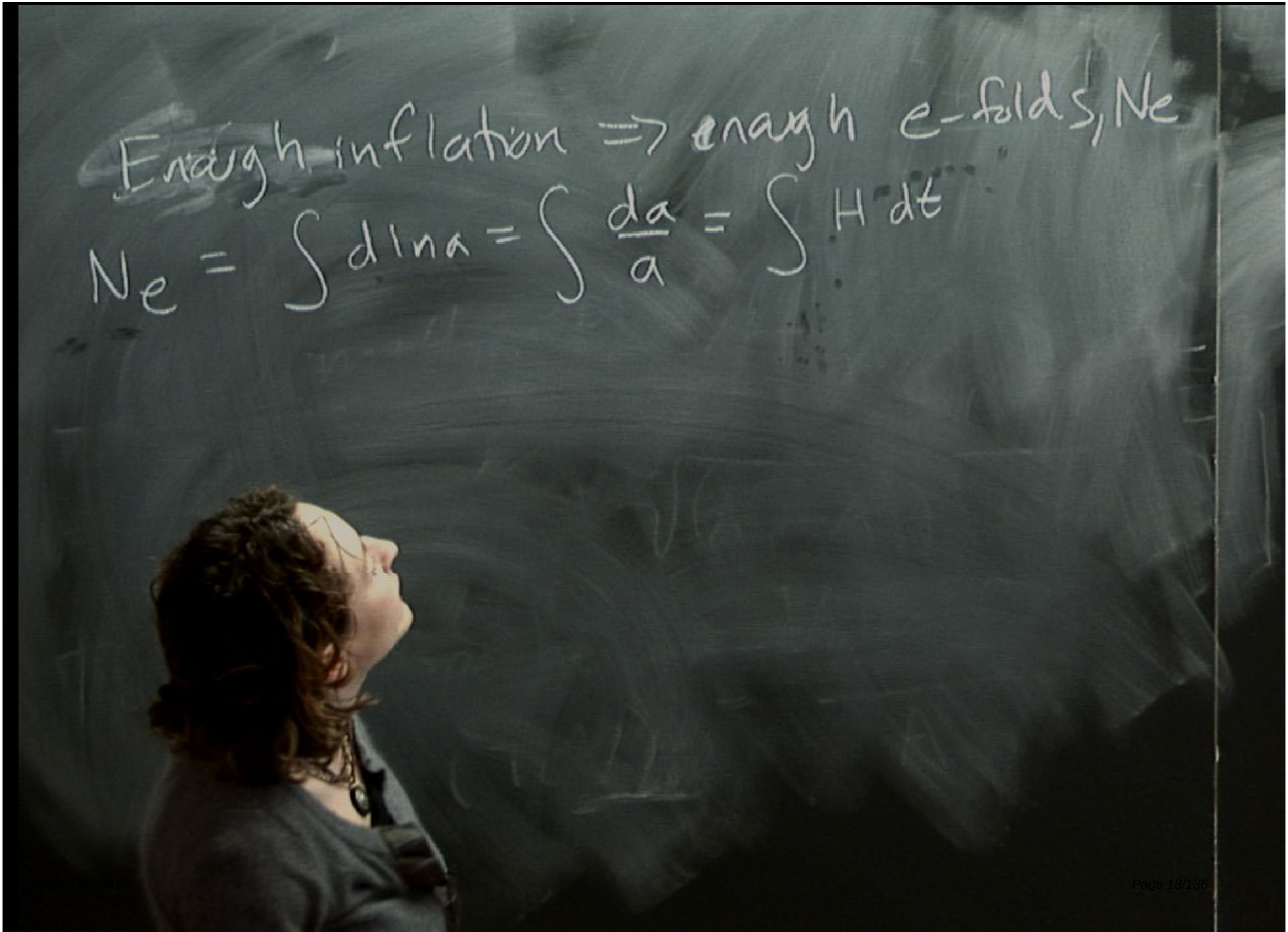

Enough inflation ⇒ enough e-folds

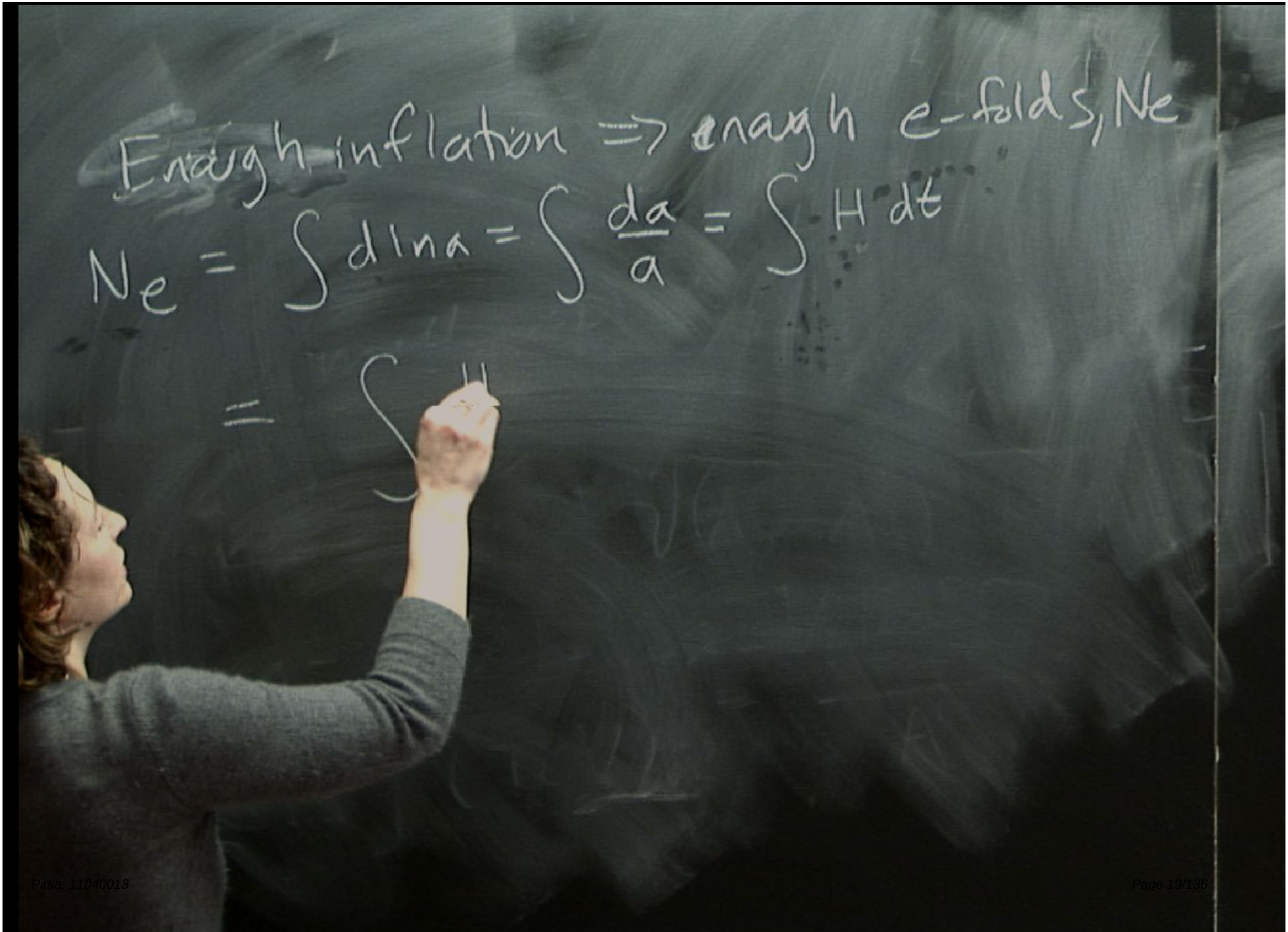
Enough inflation $\Rightarrow$ enough e-folds, N_e

Enough inflation $\Rightarrow$ enough e-folds, N_e

$N_e =$


Enough inflation ⇒ enough e-folds, N_e
$N_e = \int d\ln a = \int \frac{da}{a}$

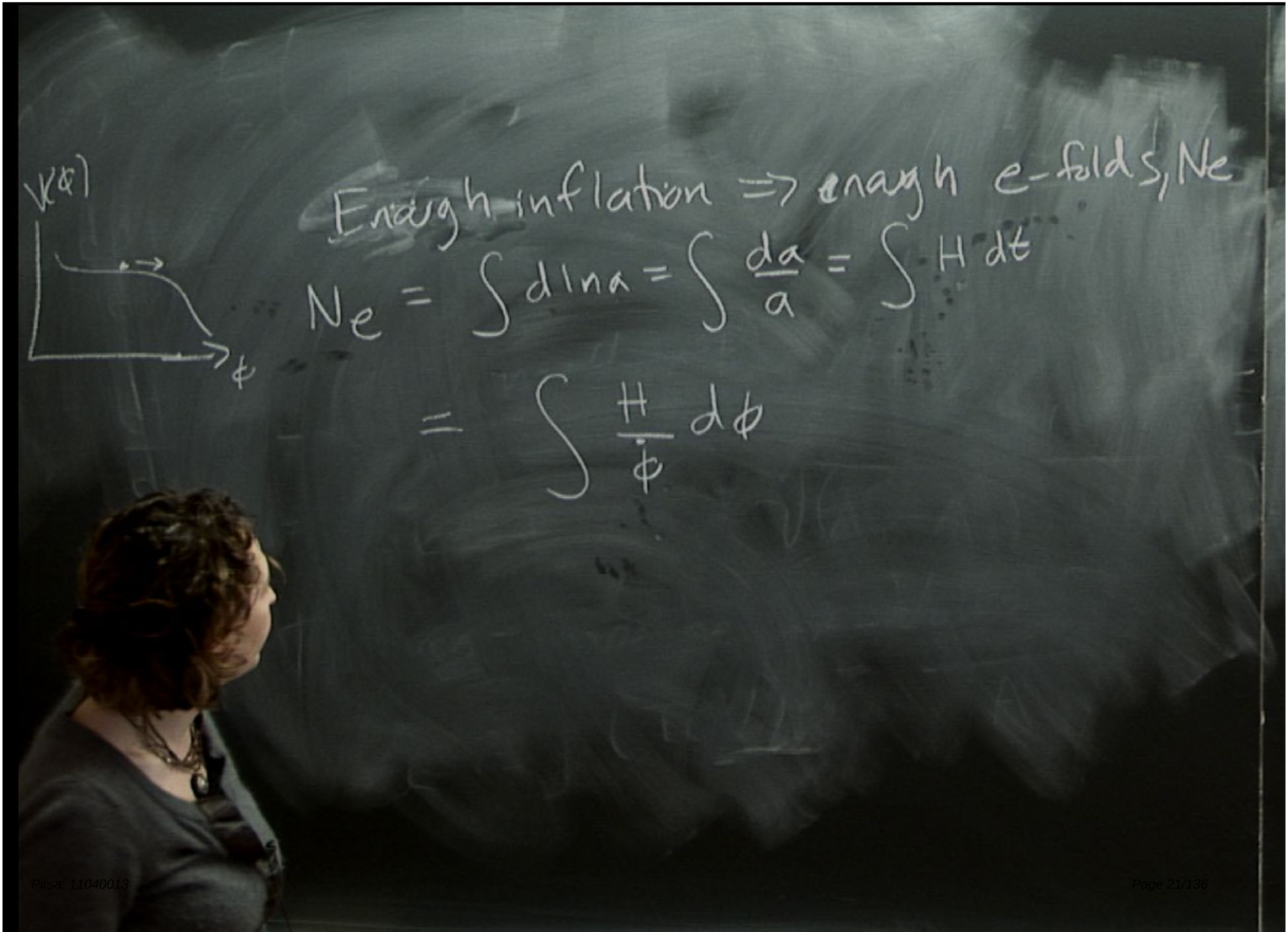

Enough inflation ⇒ enough e-folds, Ne
$N_e = \int d\ln a = \int \frac{da}{a} = \int H\,dt$


Enough inflation ⟹ enough e-folds, Ne
$N_e = \int d\ln a = \int \frac{da}{a} = \int H\,dt$
$= \int$

Enough inflation $\Longrightarrow$ enough e-folds, N_e

$$N_e = \int d\ln a = \int \frac{da}{a} = \int H\,dt$$

$$= \int \frac{H}{\dot{\phi}}\,d\phi$$


V(φ)
φ
Enough inflation ⇒ enough e-folds, N_e
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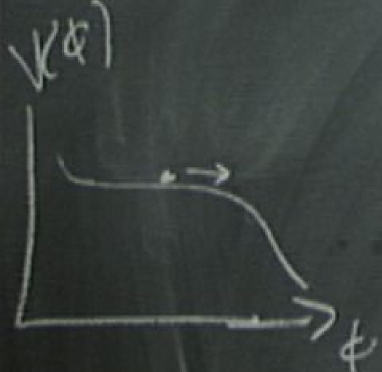
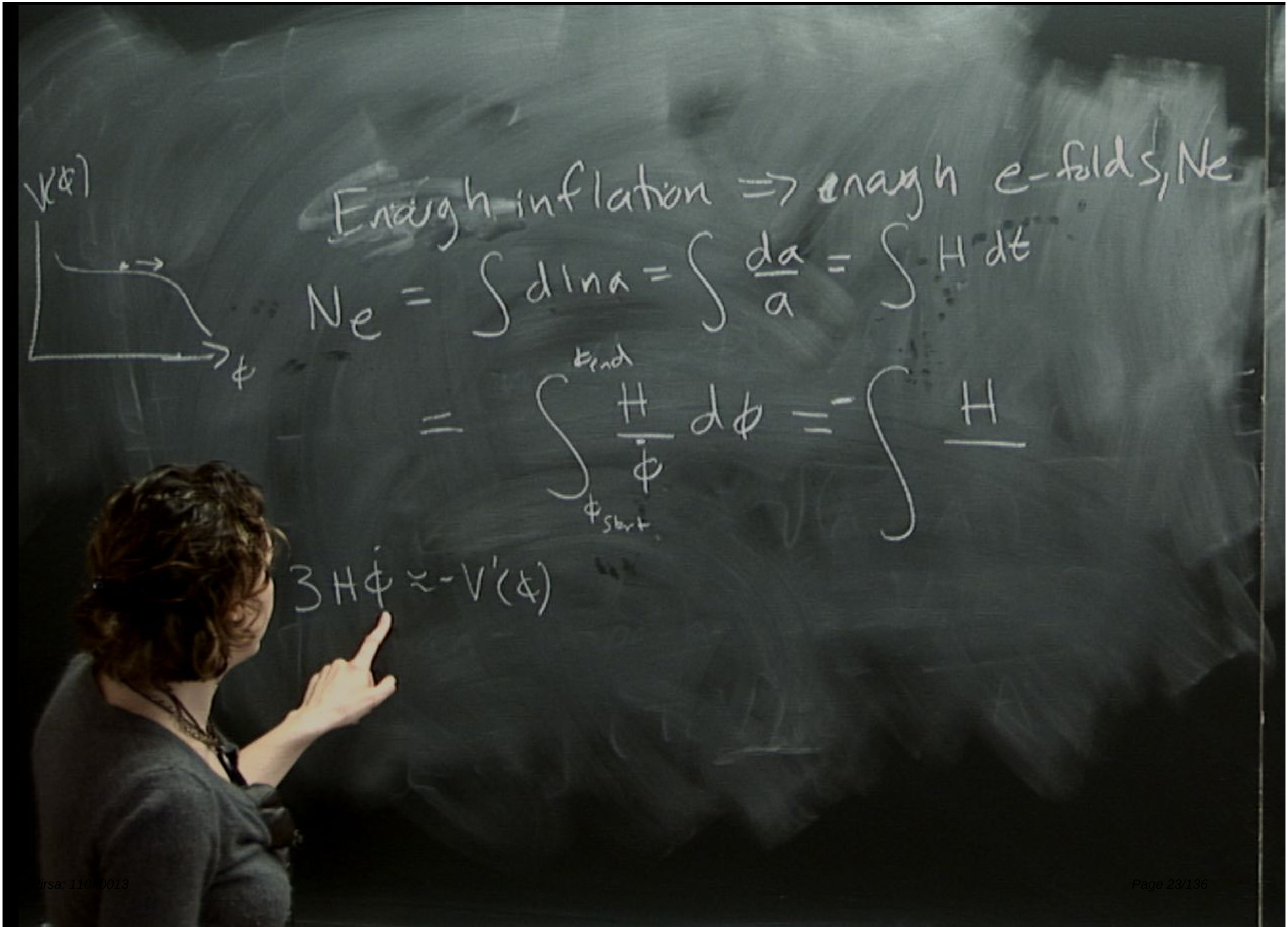


Enough inflation $\Rightarrow$ enough e-folds, N_e

$$N_e = \int d\ln a = \int \frac{da}{a} = \int H\,dt$$

$$= \int_{\phi_{start}}^{\phi_{end}} \frac{H}{\dot{\phi}}\,d\phi = \int H$$


V(φ)
φ
Enough inflation ⇒ enough e-folds, N_e
$N_e = \int d\ln a = \int \frac{da}{a} = \int H\,dt$
$= \int_{\phi_{start}}^{\phi_{end}} \frac{H}{\dot\phi}\,d\phi = -\int \frac{H}{\quad}$
$3H\dot\phi \simeq -V'(\phi)$

Enough inflation ⇒ enough e-folds, N_e

$$N_e = \int d\ln a = \int \frac{da}{a} = \int H\,dt$$

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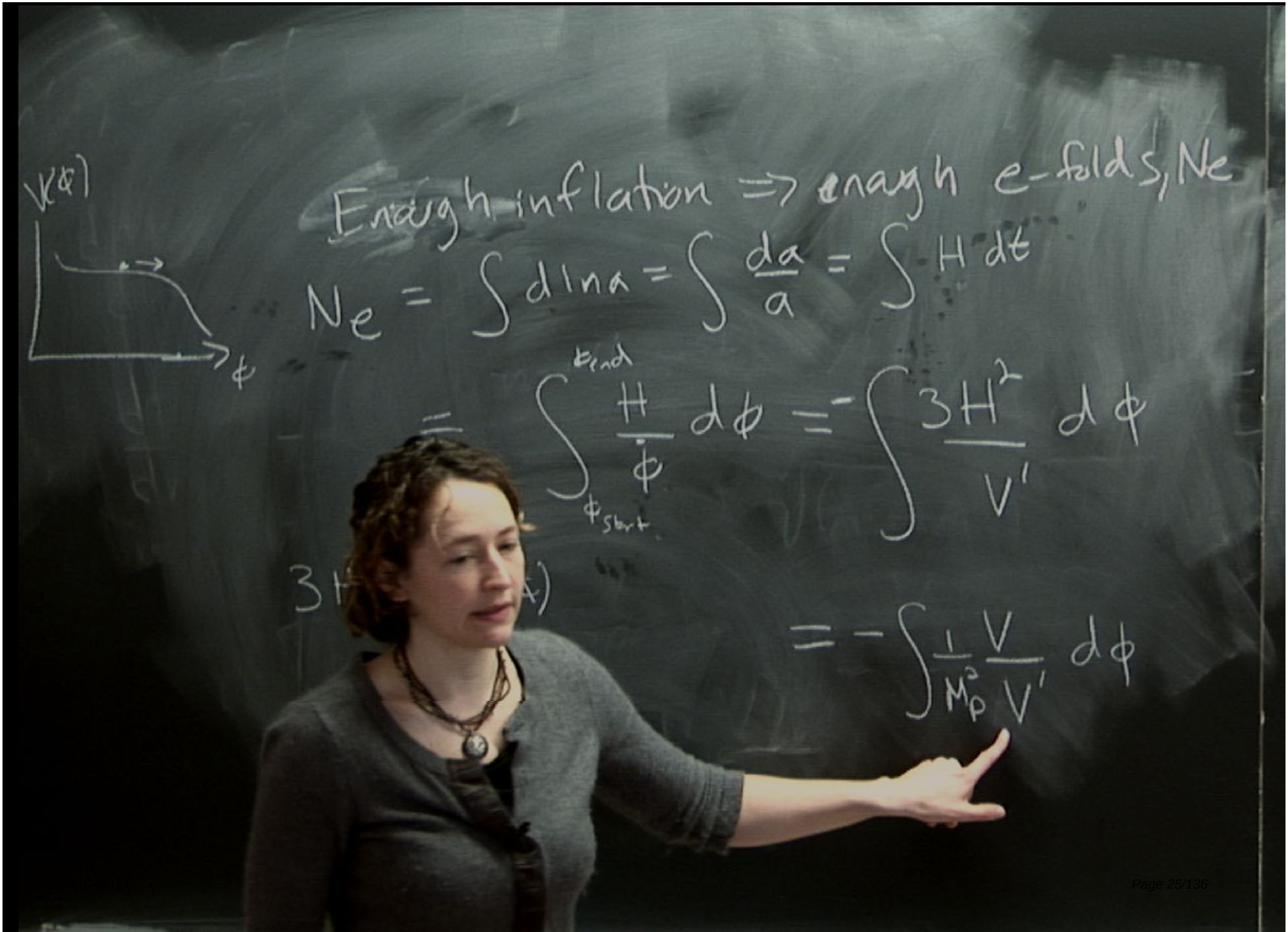

$V(\phi)$
ϕ
Enough inflation ⇒ enough e-folds, N_e
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$= -\int \frac{1}{M_p^2}\frac{V}{V'}\,d\phi$

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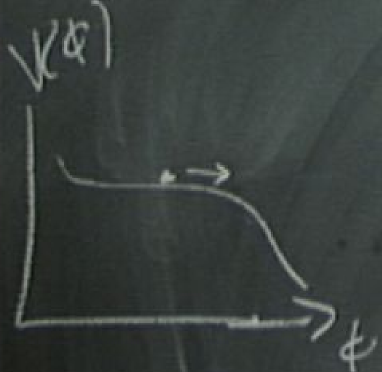
$$= -\int \frac{1}{M_p^2} \frac{V}{V'}\, d\phi$$

$$= -\frac{1}{M_p} \int \frac{1}{\sqrt{2\epsilon}}$$



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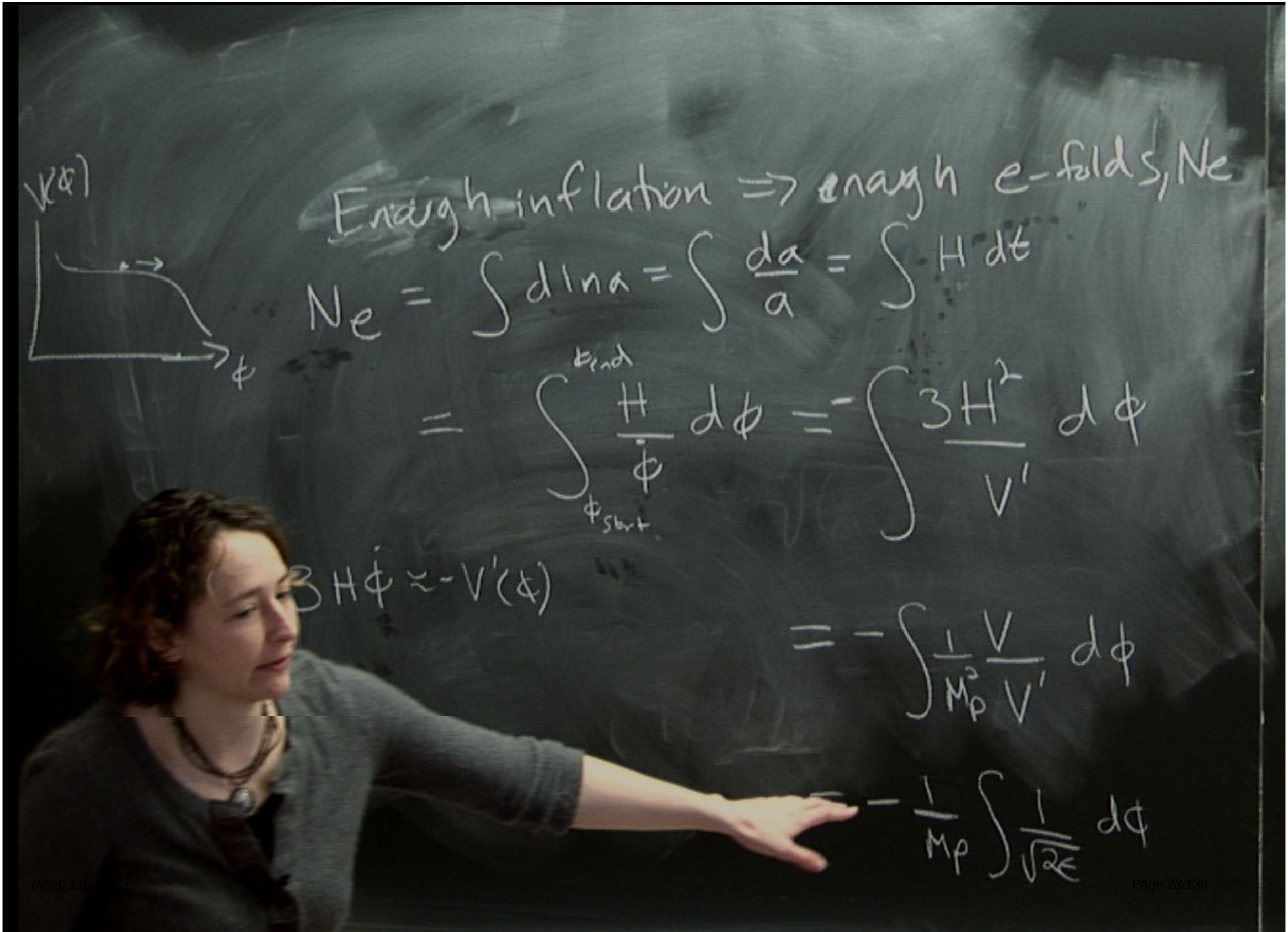
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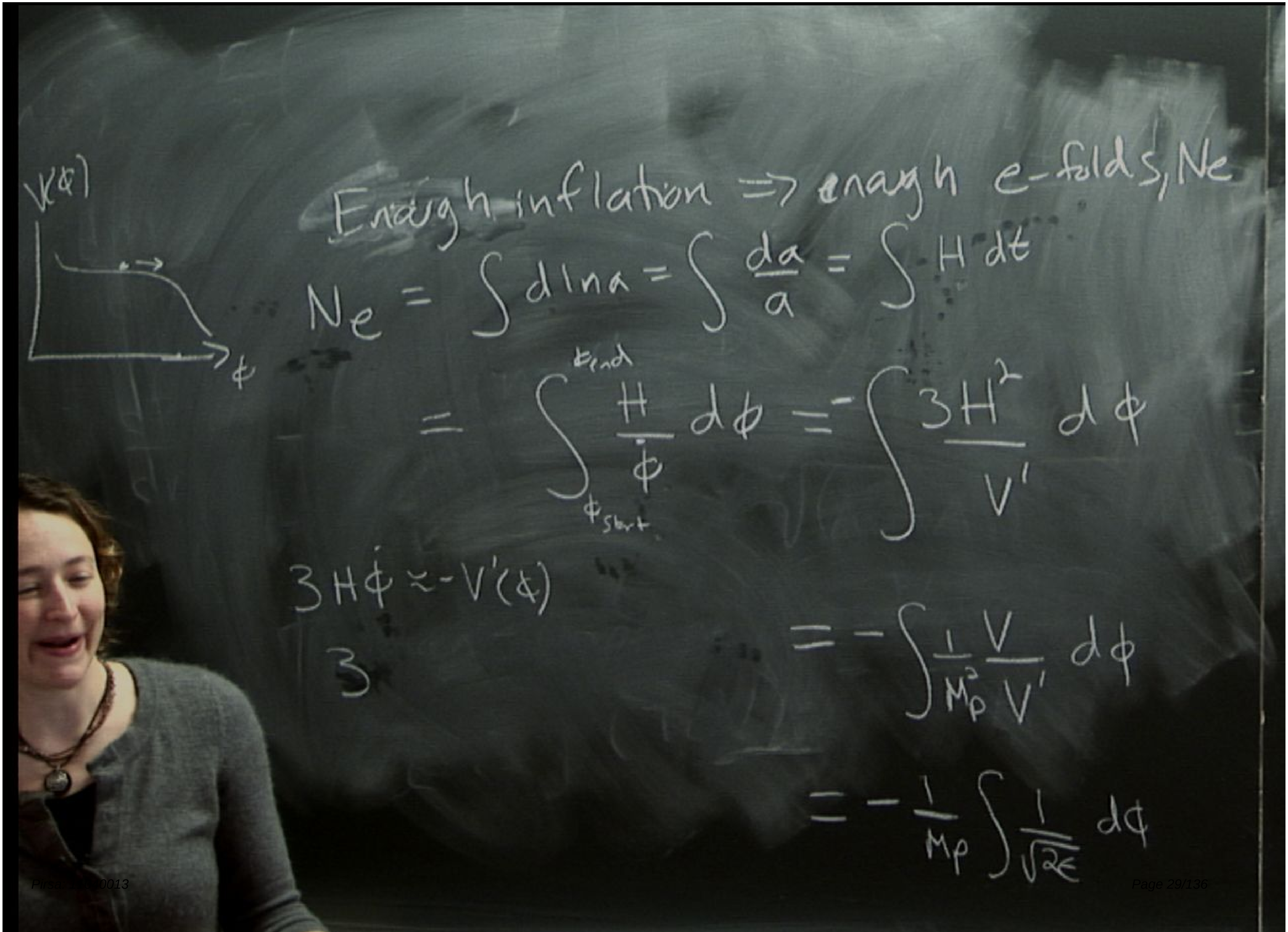
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$$3M_p^2 H^2 = V(\phi)$$

$$= -\int \frac{1}{M_p^2}\frac{V}{V'}\,d\phi$$

$$= -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\,d\phi$$

Example

$$V(\phi) = \frac{\lambda}{n!}\phi^n$$

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$$V'(\phi) = \frac{n \lambda \phi^{n-1}}{n!} \quad , \quad V''(\phi) = \frac{n(n-1) \lambda \phi^{n-2}}{n!}$$

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$$\epsilon = \frac{M_p^2}{2}$$

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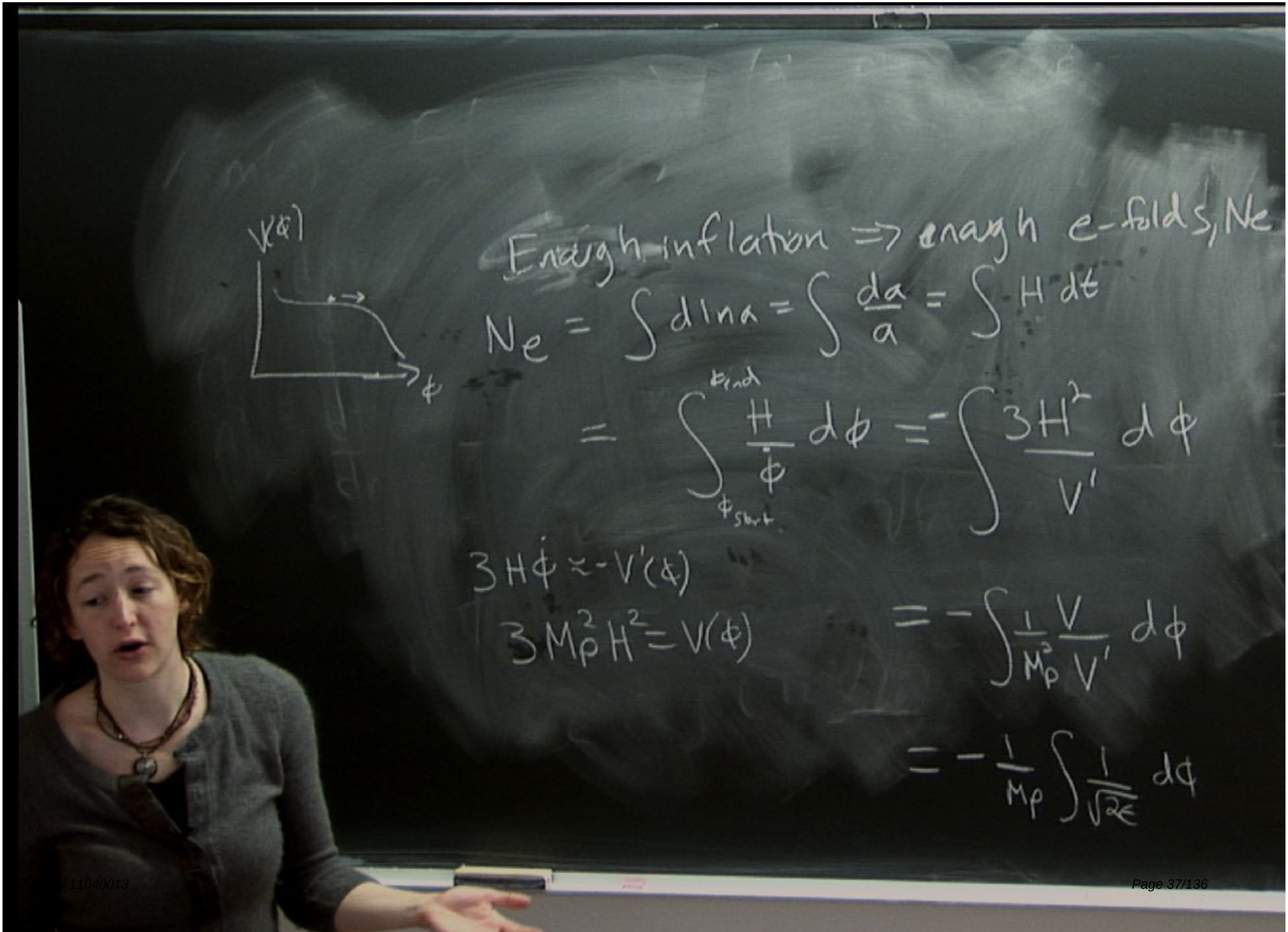
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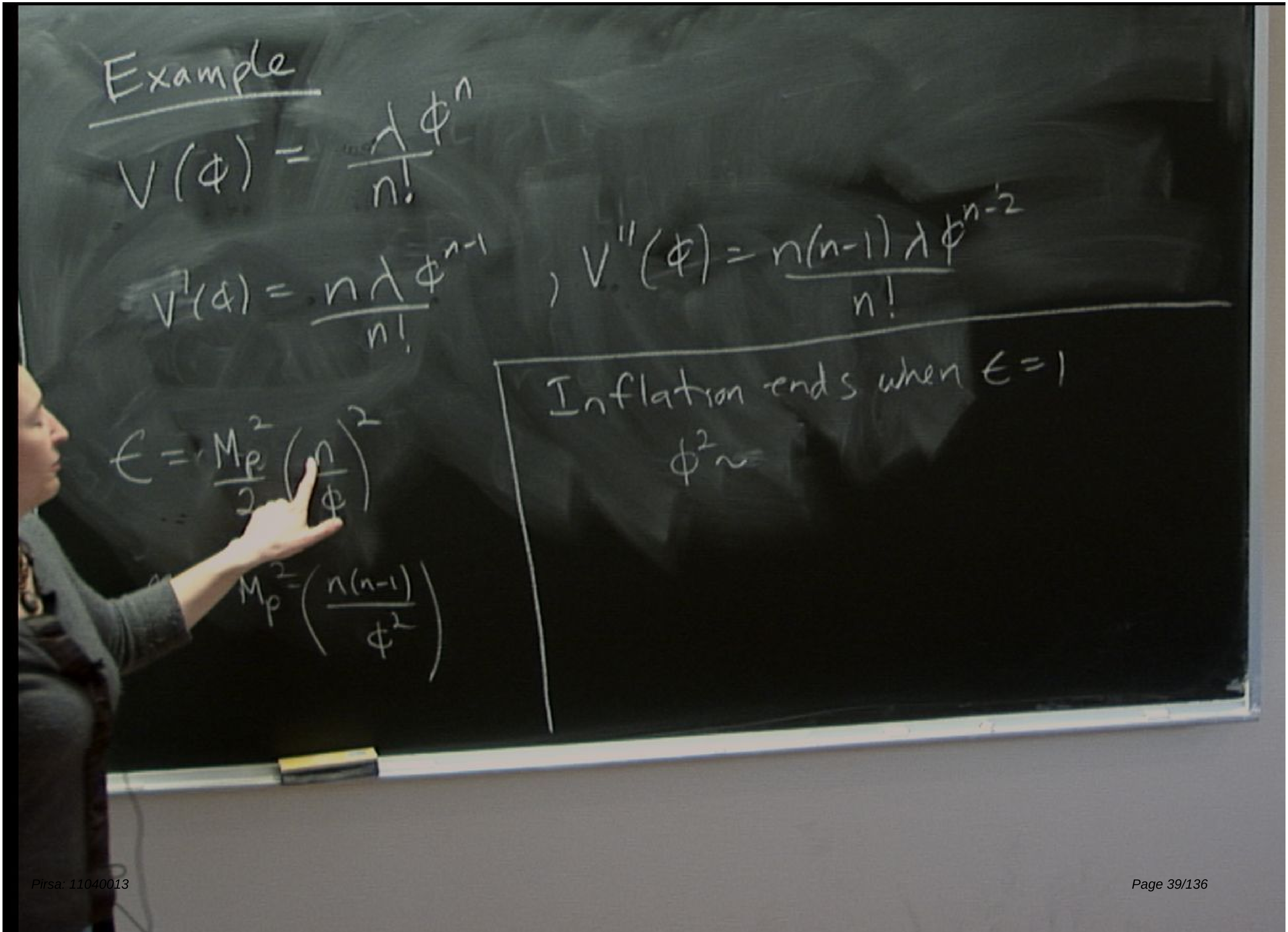
Inflation ends when $\epsilon = 1$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$M_p^2 \left(\frac{n(n-1)}{\phi^2}\right)$
Inflation ends when $\epsilon = 1$
$\phi^2 \sim$

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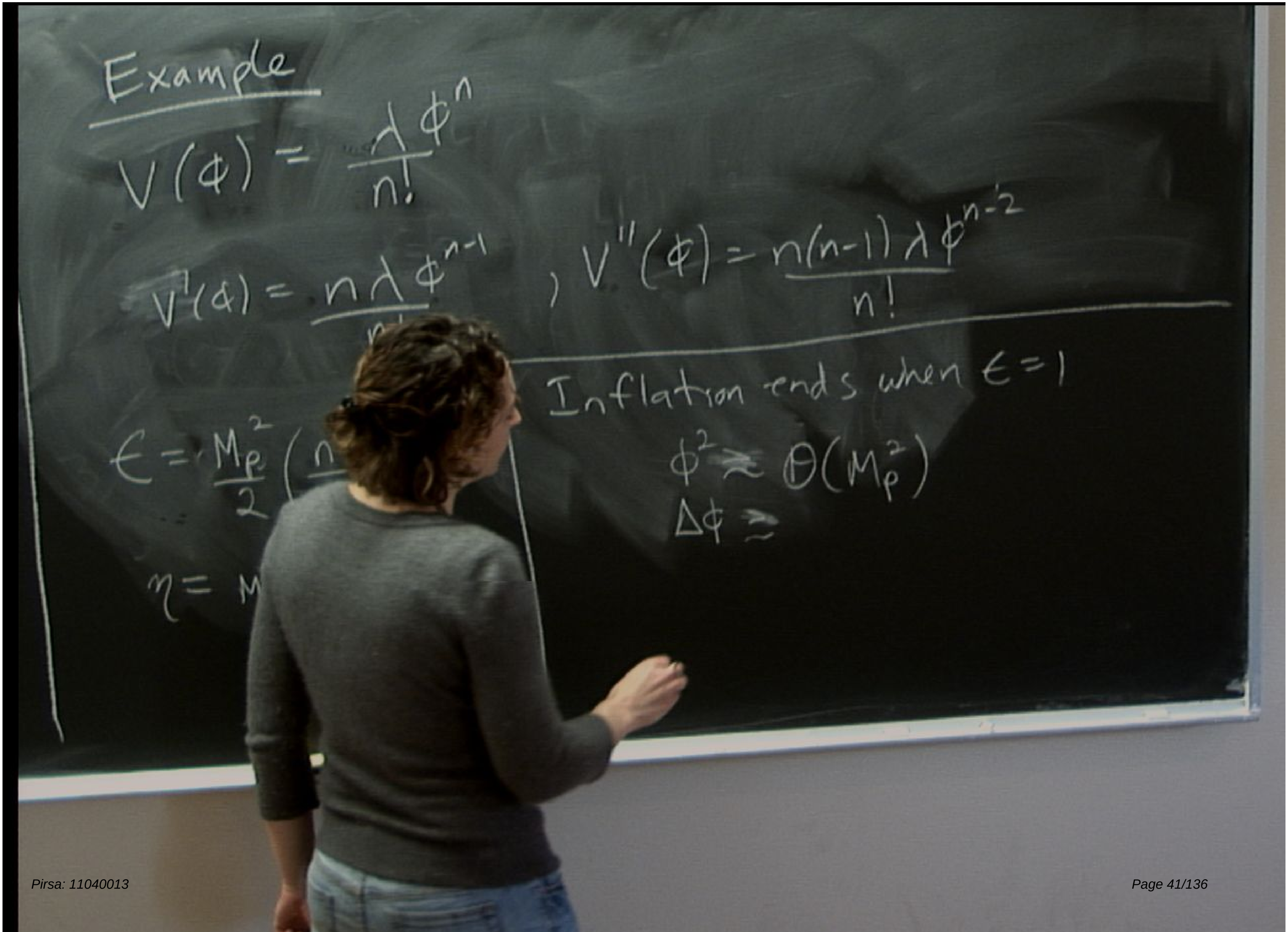
Inflation ends when $\epsilon = 1$

$$\phi^2 \simeq \mathcal{O}(M_p^2)$$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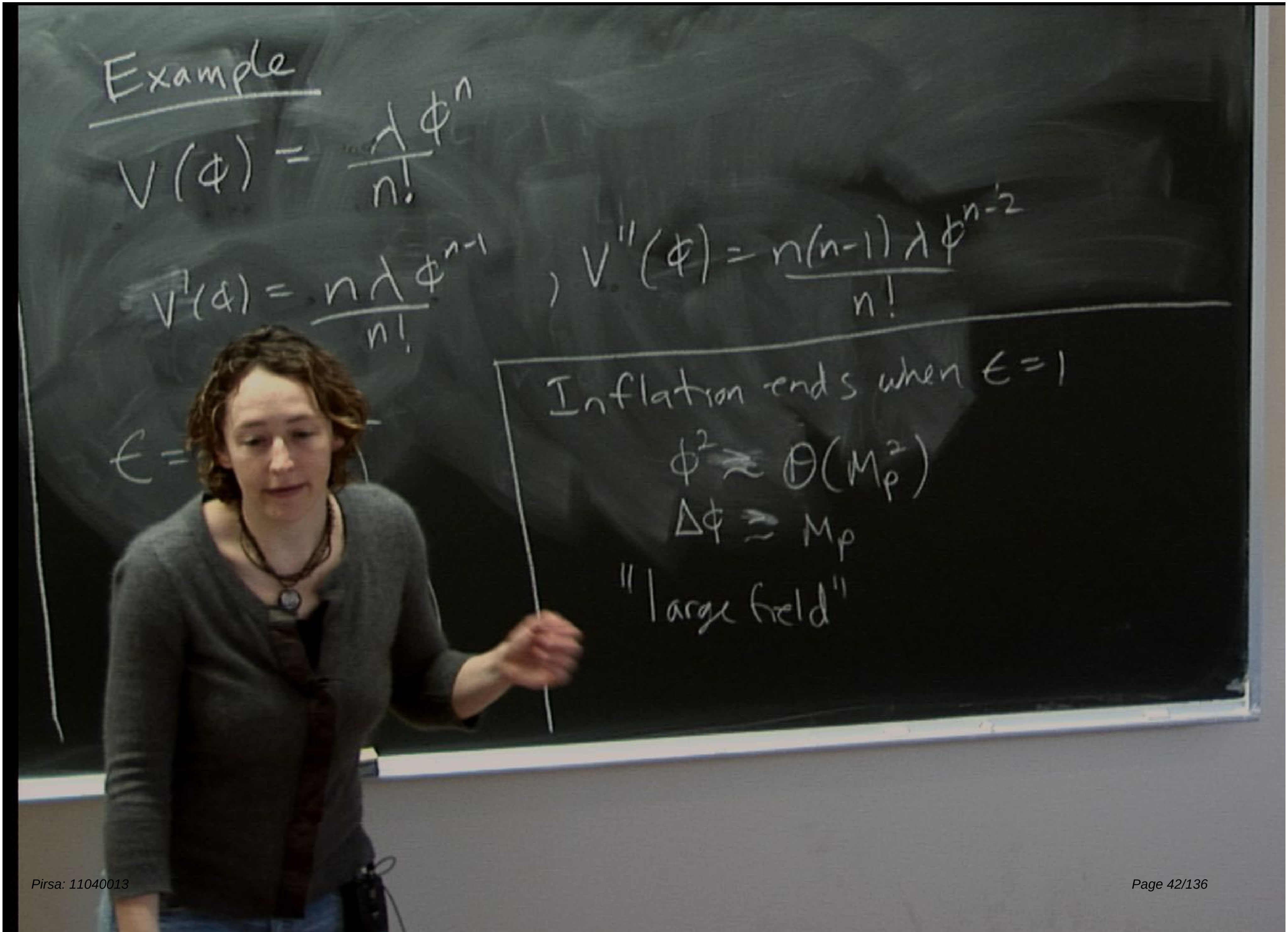
Inflation ends when $\epsilon = 1$
$\phi^2 \simeq O(M_p^2)$
$\Delta\phi \simeq$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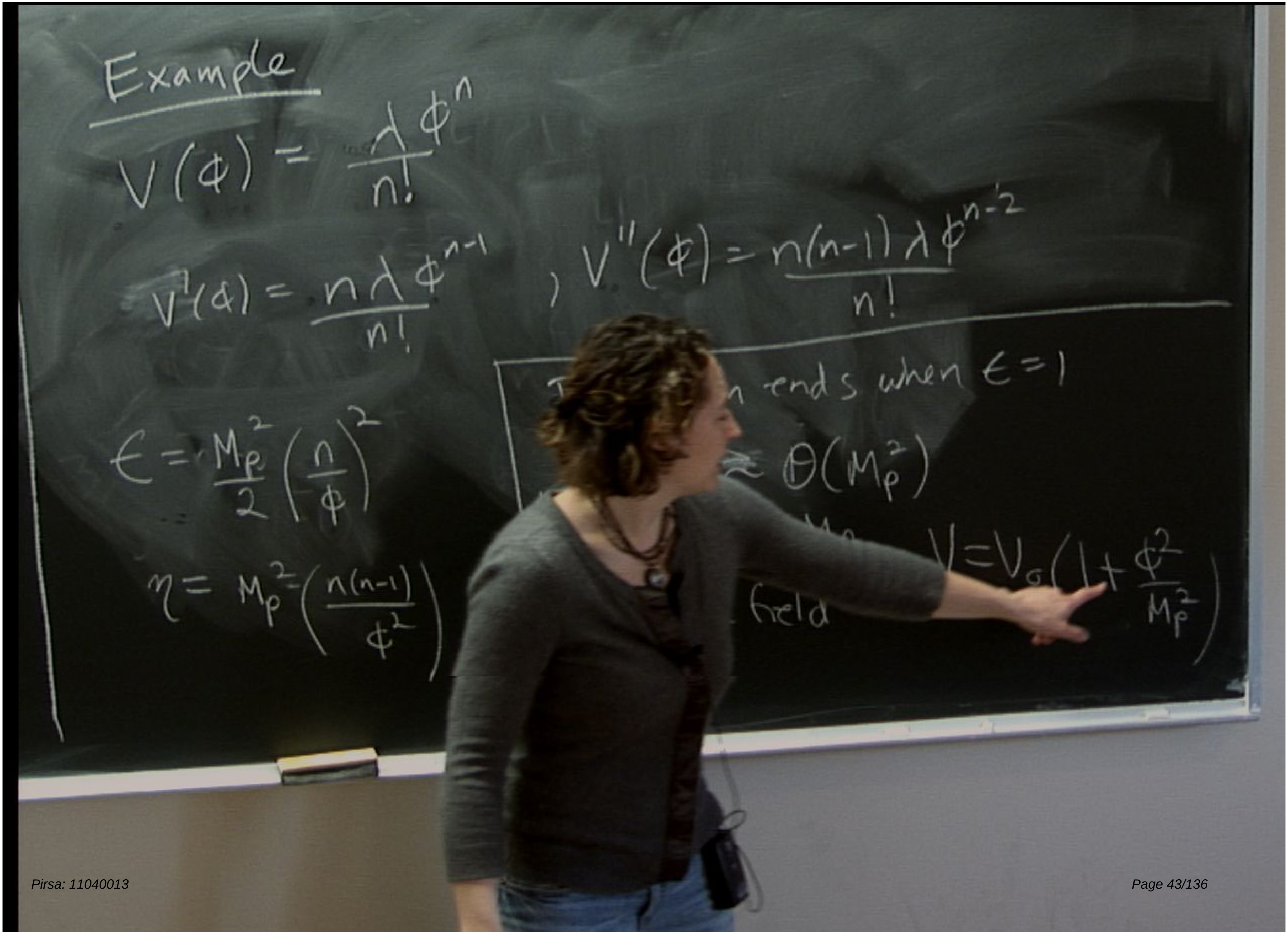
$\epsilon =$
Inflation ends when $\epsilon = 1$
$\phi^2 \simeq \mathcal{O}(M_p^2)$
$\Delta\phi \simeq M_p$
"large field"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$V'(\phi) = \frac{n \lambda \phi^{n-1}}{n!}$, $V''(\phi) = \frac{n(n-1) \lambda \phi^{n-2}}{n!}$
$\epsilon = \frac{M_p^2}{2} \left(\frac{n}{\phi}\right)^2$
$\eta = M_p^2 \left(\frac{n(n-1)}{\phi^2}\right)$
ends when $\epsilon = 1$
$\mathcal{O}(M_p^2)$
field
$V = V_0\left(1 + \frac{\phi^2}{M_p^2}\right)$

Example

$$V(\phi) = \frac{\lambda \phi^n}{n!}$$

$$V'(\phi) = \frac{n \lambda \phi^{n-1}}{n!} \quad , \quad V''(\phi) = \frac{n(n-1) \lambda \phi^{n-2}}{n!}$$

$$\epsilon = \frac{M_p^2}{2} \left(\frac{n}{\phi} \right)^2$$

$$\eta = M_p^2 \left(\frac{n(n-1)}{\phi^2} \right)$$

Inflation ends when $\epsilon = 1$

$$\phi^2 \simeq \mathcal{O}(M_p^2)$$

$$\phi_s - \phi_e = \Delta\phi \simeq M_p$$

"large field"

$$V = V_0 \left(1 + \frac{\phi^2}{M_p^2} \right)$$

Example

$$V(\phi) = \frac{\lambda \phi^n}{n!}$$

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$$\epsilon = \frac{M_p^2}{2}\left(\frac{n}{\phi}\right)^2$$

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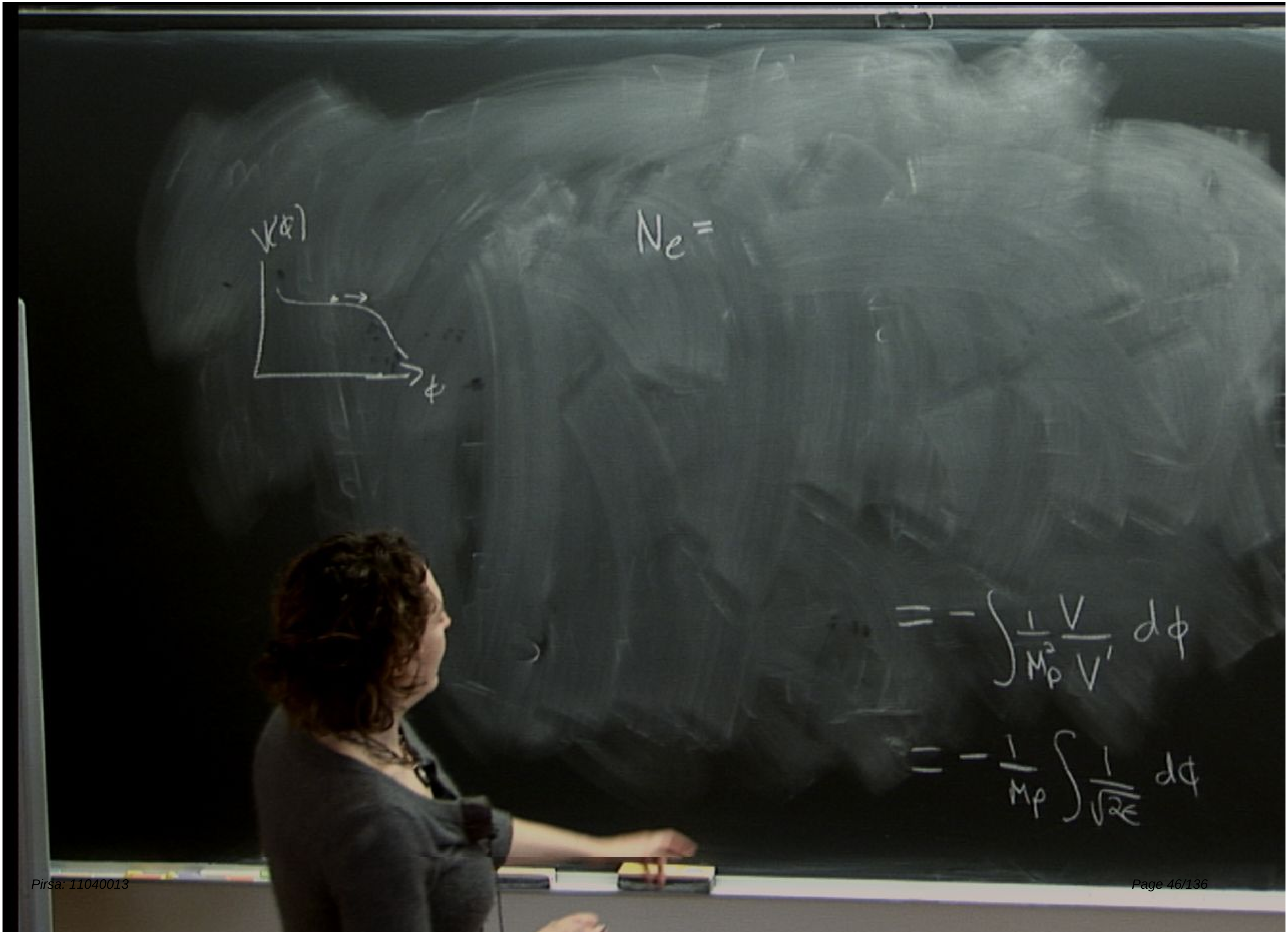
Inflation ends when $\epsilon = 1$

$$\phi^2 \simeq \Theta(M_p^2)$$

$$\phi_s - \phi_e = \Delta\phi \simeq M_p$$

"large field"

$$V = V_0\left(1 + \frac{\phi^2}{M_p^2}\right)$$


$V(\phi)$
ϕ
$N_e =$
$= -\int \frac{1}{M_p^2} \frac{V}{V'} \, d\phi$
$= -\frac{1}{M_p} \int \frac{1}{\sqrt{2\epsilon}} \, d\phi$

$$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi =$$

$$= -\int \frac{1}{M_p^2}\frac{V}{V'}\, d\phi$$

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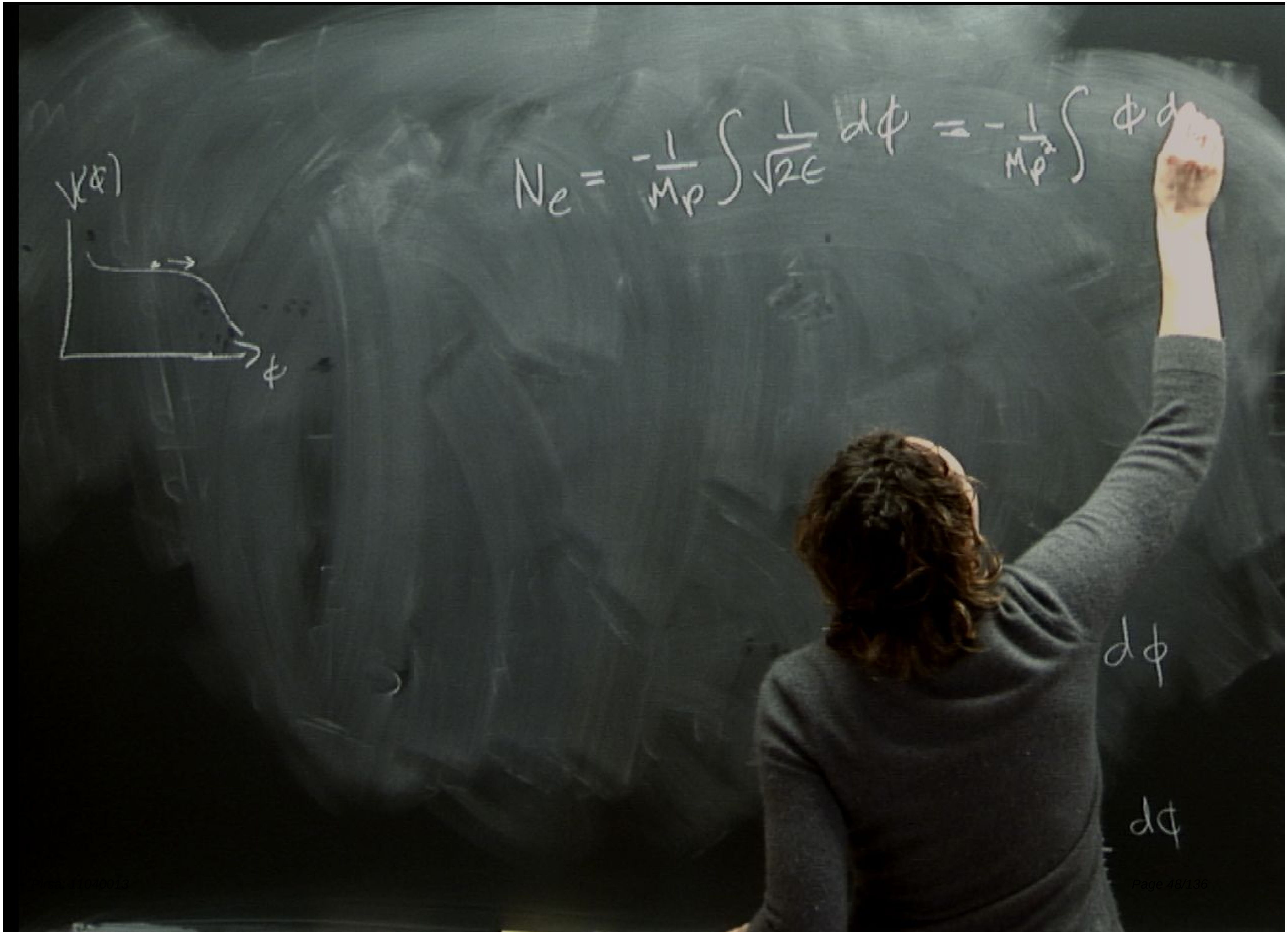
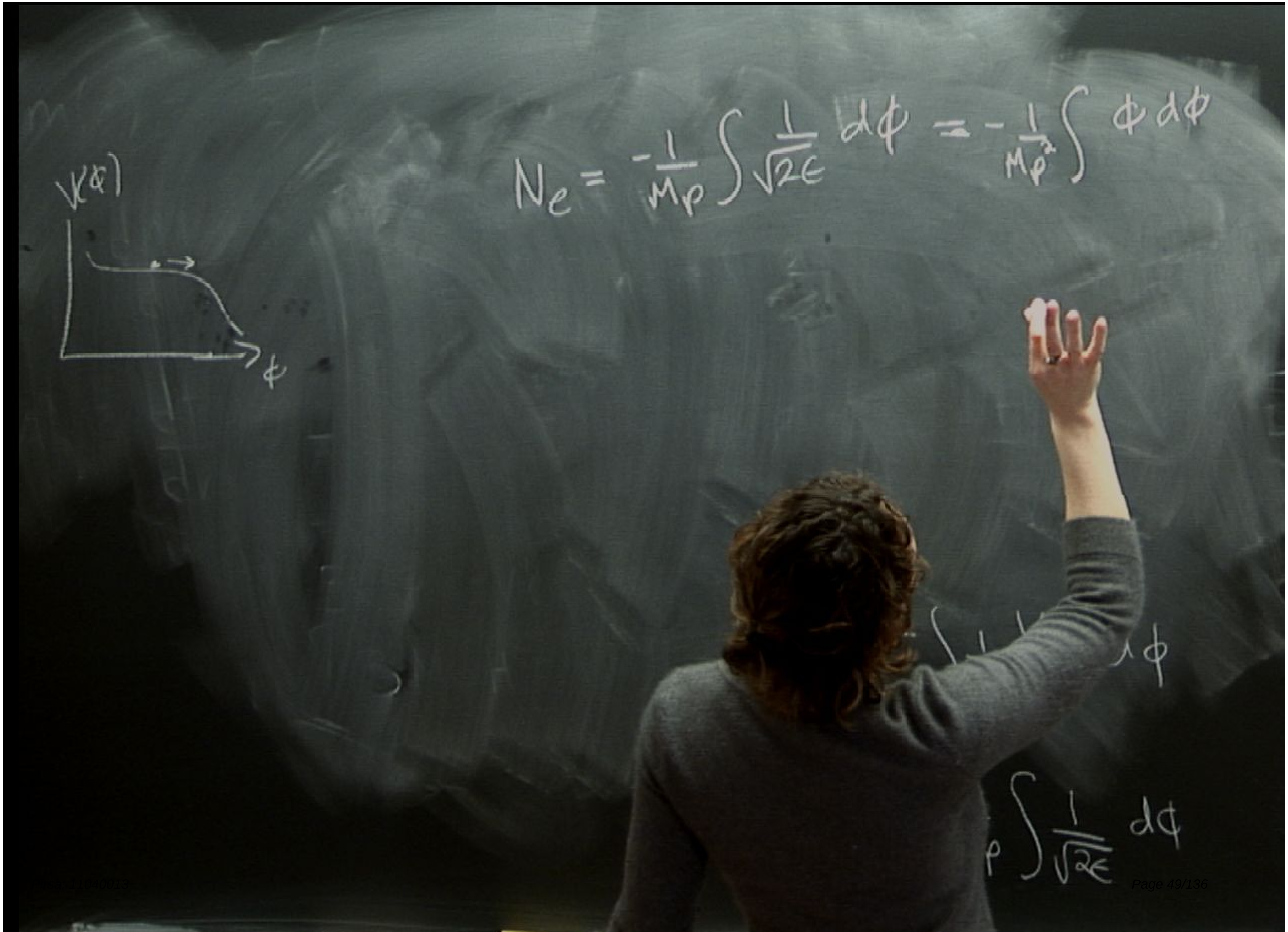
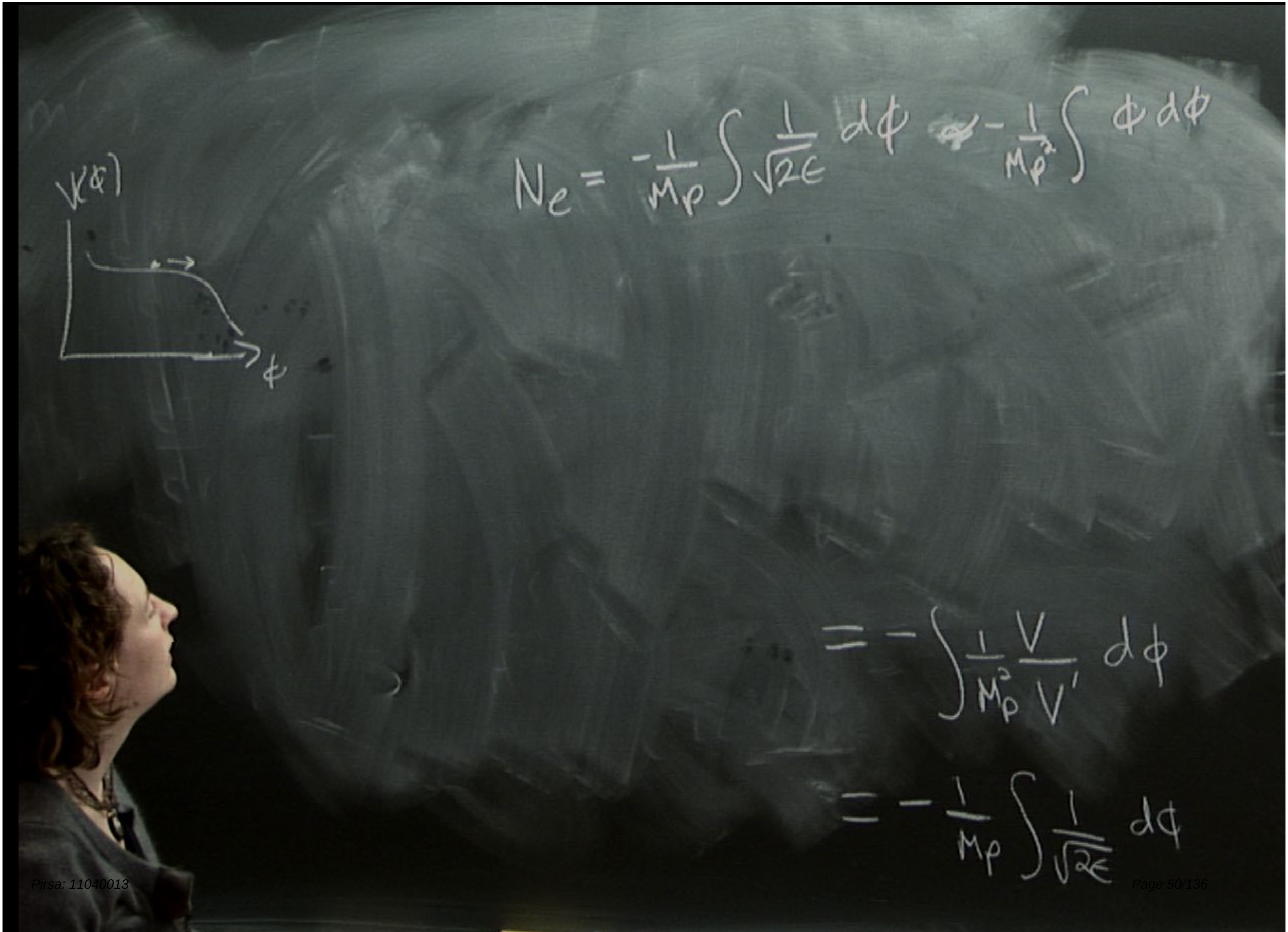

$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d$
$V(\phi)$
ϕ
$d\phi$
$d\phi$


$V(\phi)$
ϕ
$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi$


$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi \quad \cancel{\phi} - \frac{1}{M_p^2}\int \phi\, d\phi$
$V(\phi)$
ϕ
$= -\int \frac{1}{M_p^2}\frac{V}{V'}\, d\phi$
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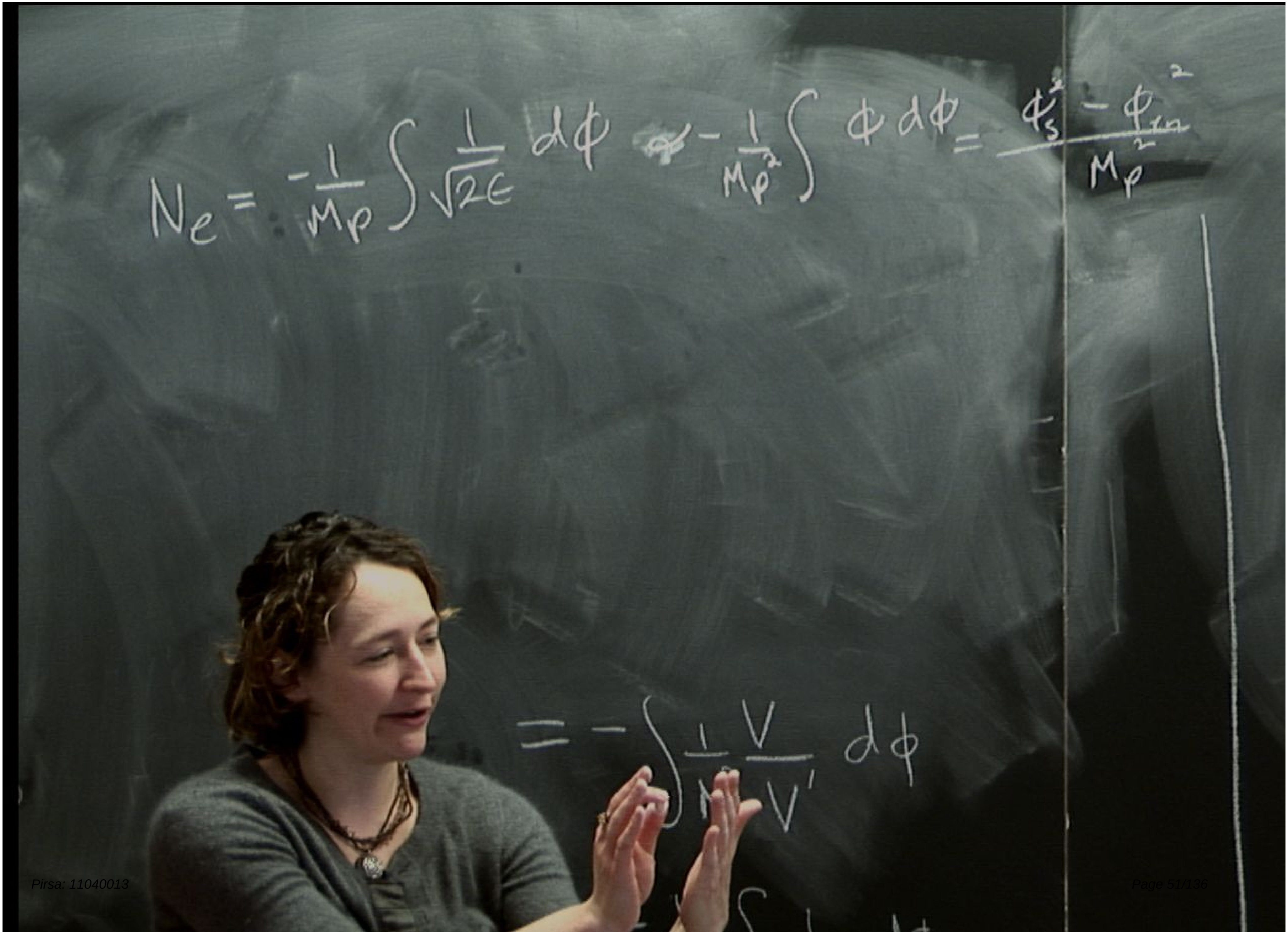
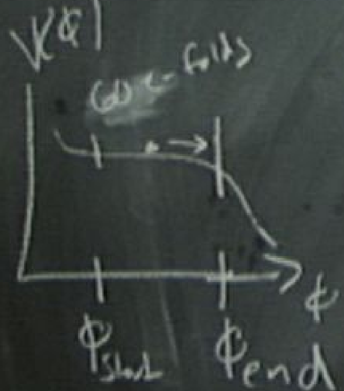


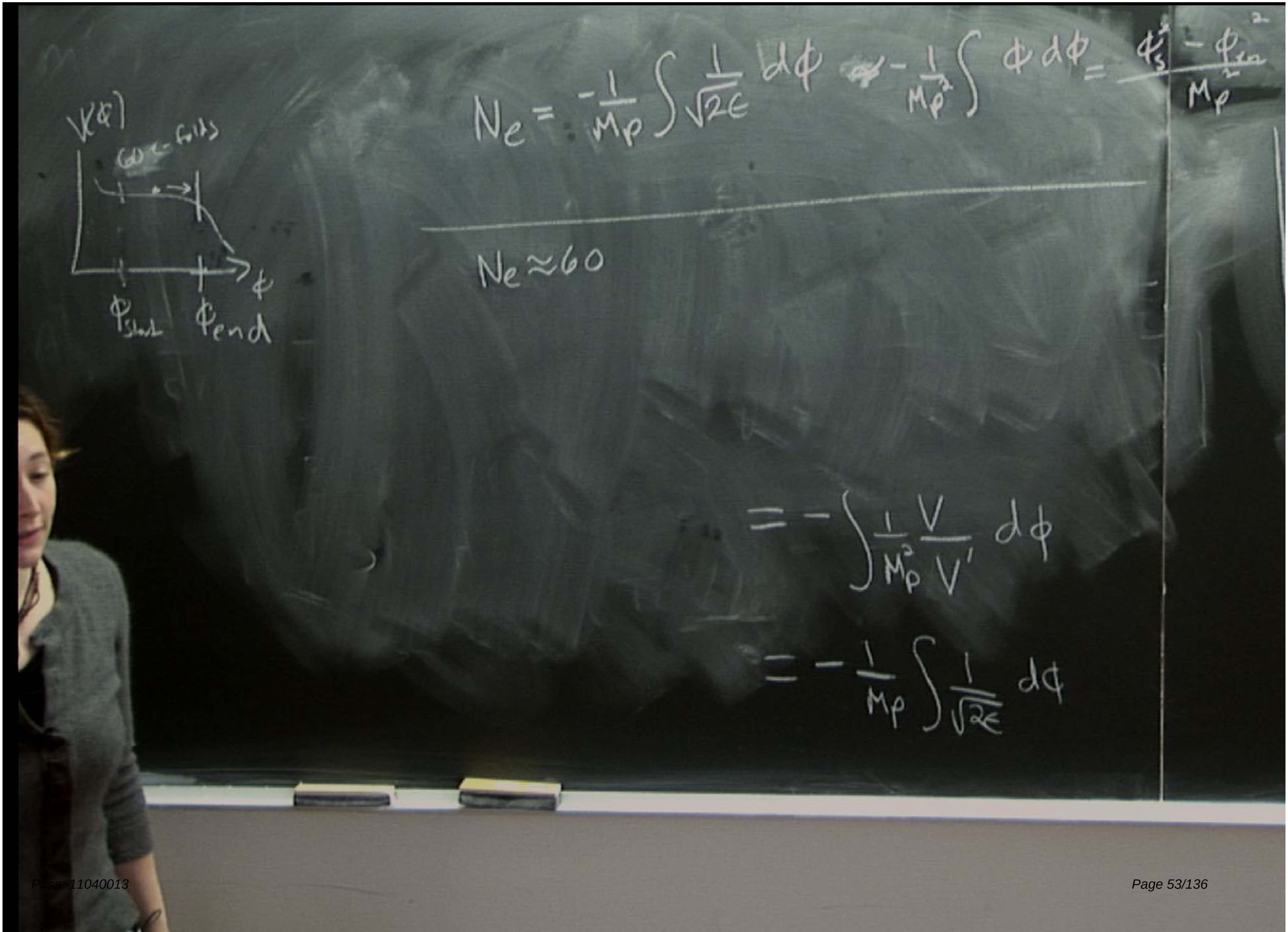
$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi \approx -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{in}^2}{M_p^2}$
$= -\int \frac{1}{M} \frac{V}{V'}\, d\phi$



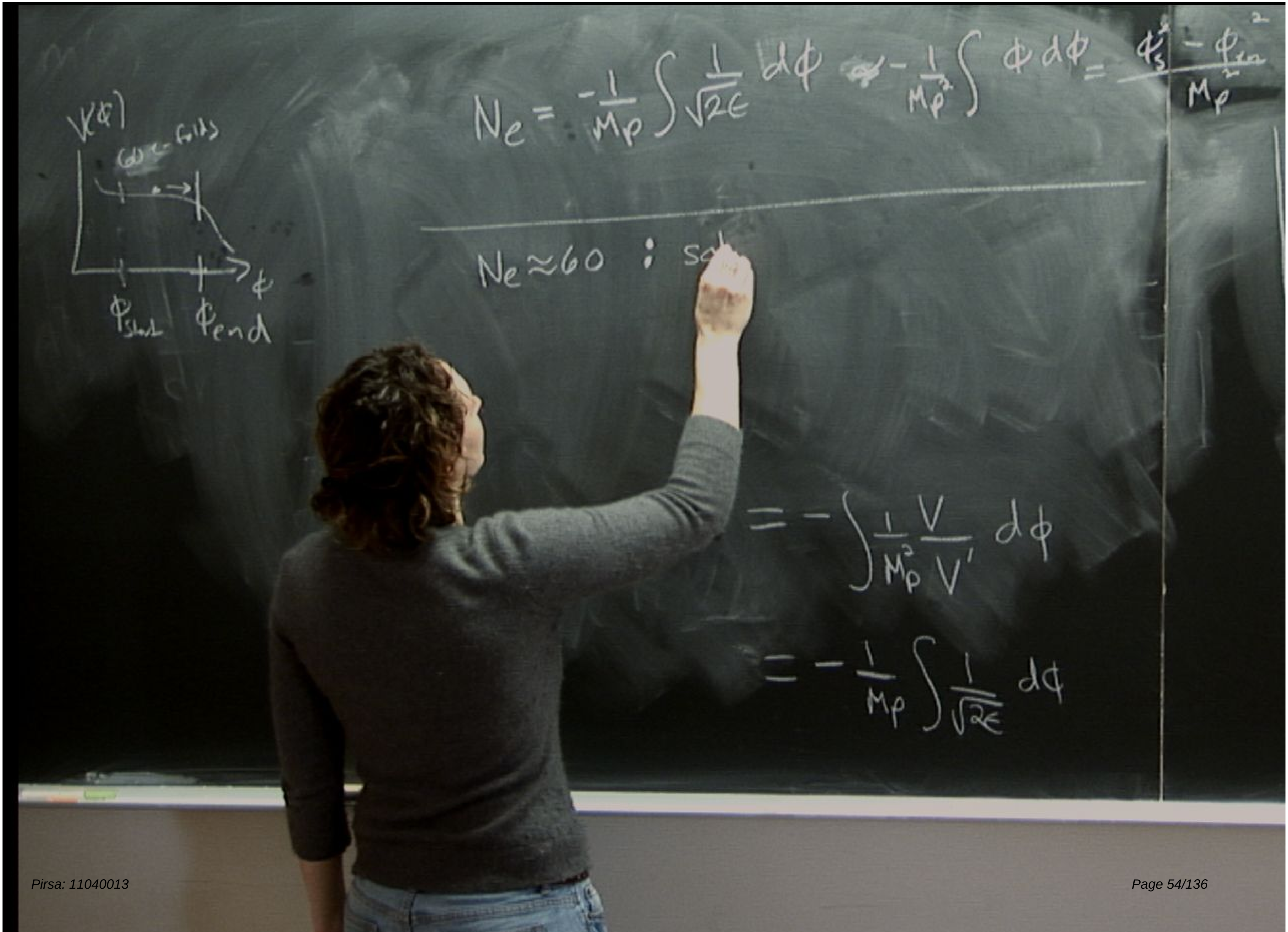
$$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{en}^2}{M_p^2}$$

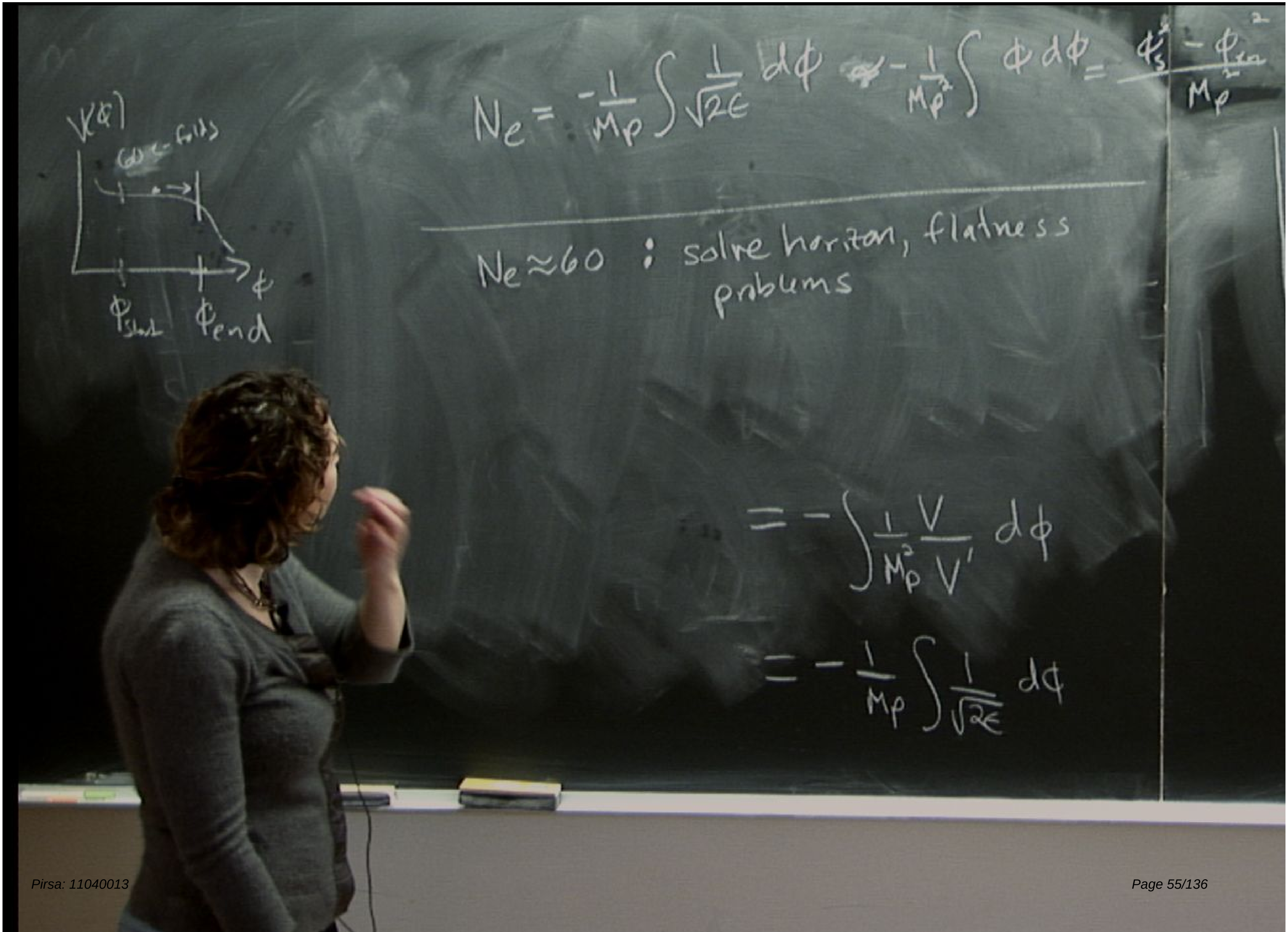
$$= -\int \frac{1}{M_p^2}\frac{V}{V'}\, d\phi$$

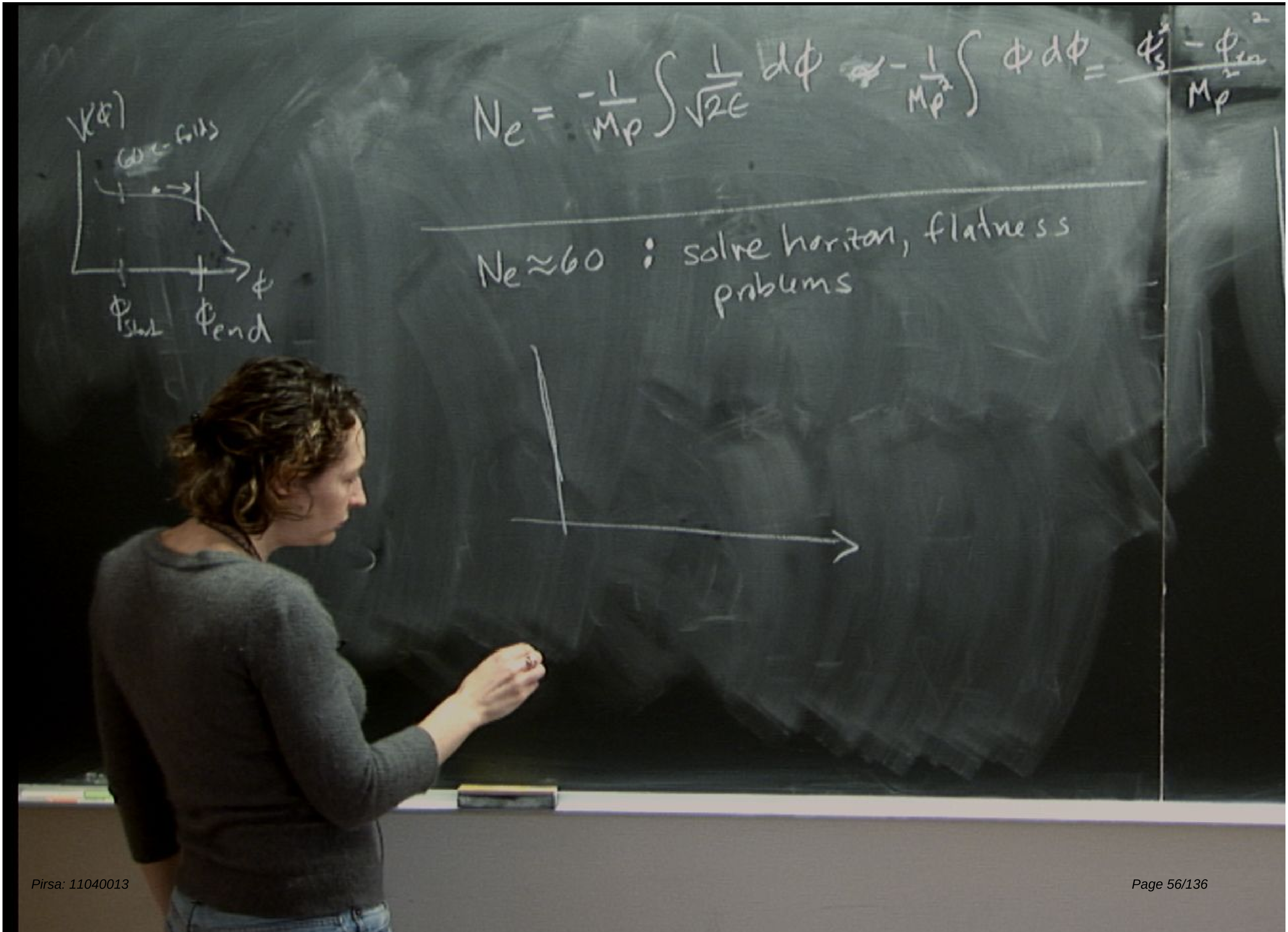
$$= -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi$$



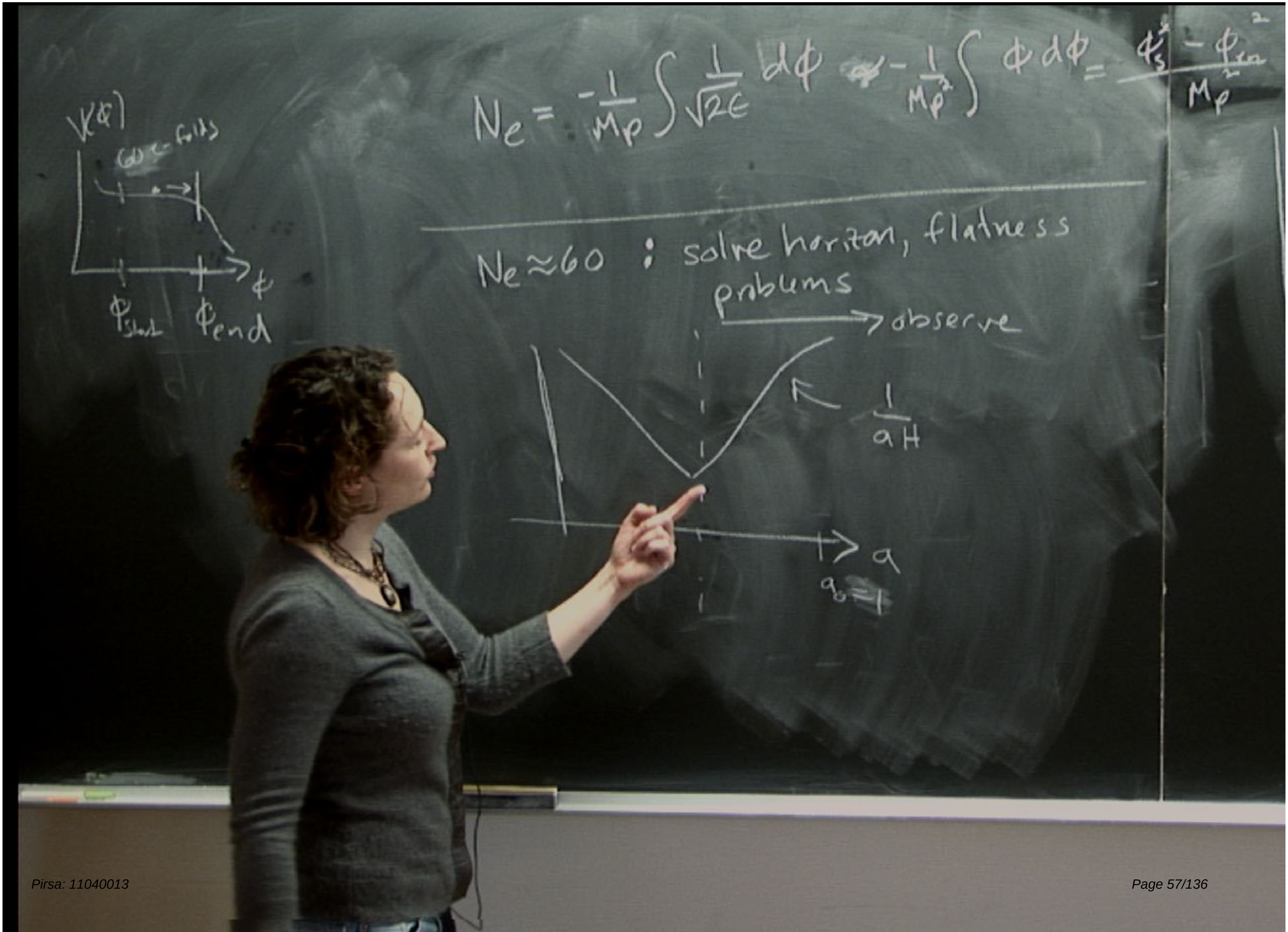
$V(\phi)$
60 e-folds
ϕ_{start}
ϕ_{end}
ϕ
$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{end}^2}{M_p^2}$
$N_e \approx 60$
$= -\int \frac{1}{M_p^2}\frac{V}{V'}\, d\phi$
$= -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi$


$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi$
$-\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{end}^2}{M_p^2}$
$V(\phi)$
ϕ_{start}
ϕ_{end}
$N_e \approx 60$: so
$= -\int \frac{1}{M_p^2}\frac{V}{V'}\, d\phi$
$= -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi$

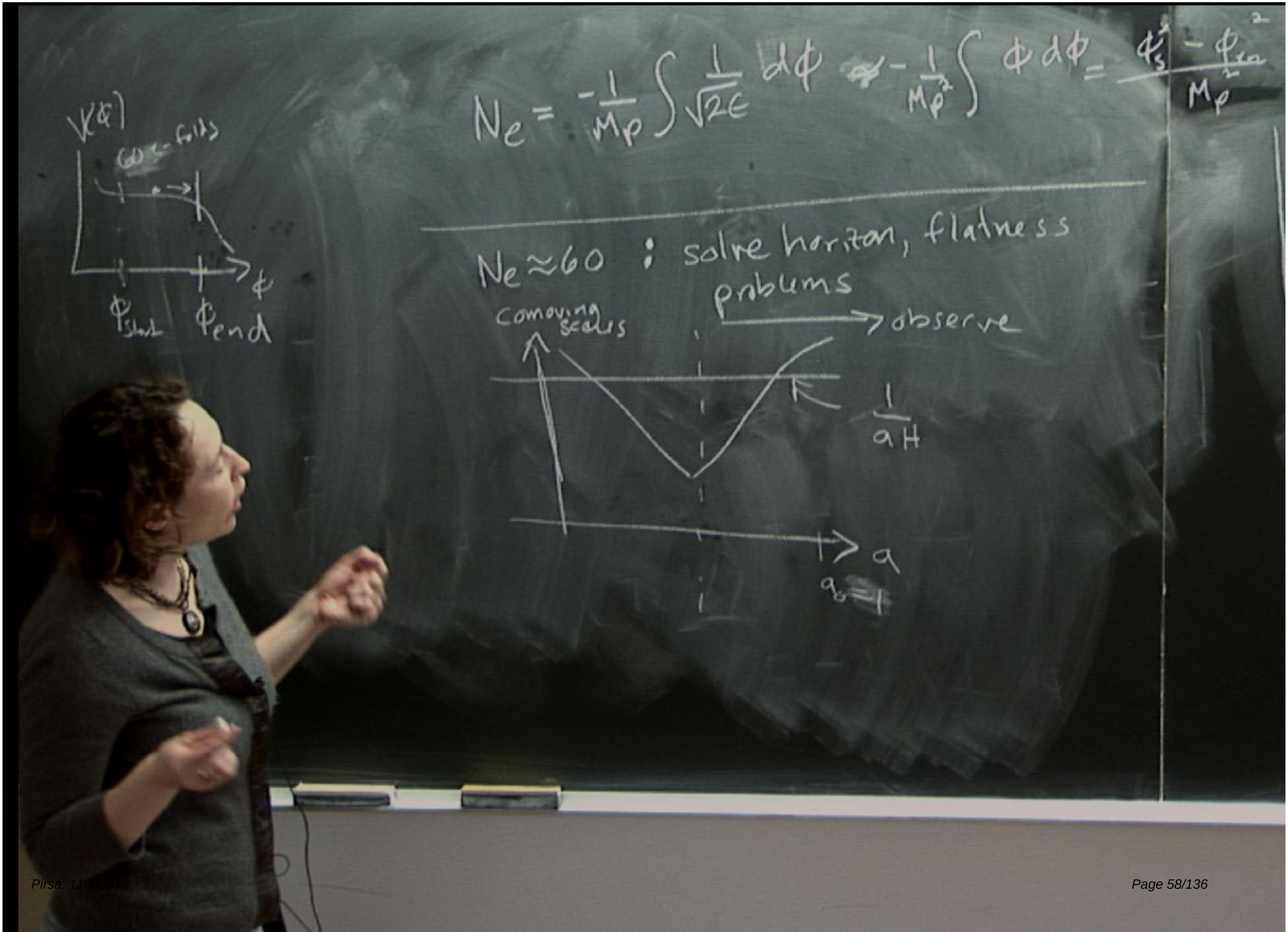

$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{end}^2}{M_p^2}$
$V(\phi)$
ϕ_{start} ϕ_{end} ϕ
$N_e \approx 60$: solve horizon, flatness problems
$= -\int \frac{1}{M_p^2}\frac{V}{V'}\, d\phi$
$= -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi$



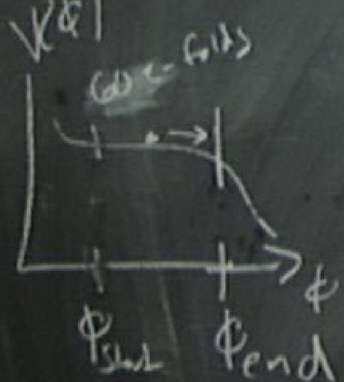
Ne = -1/Mp ∫ 1/√2ε dφ = -1/Mp² ∫ φ dφ = (φs² - φend²)/Mp²
V(φ)
e-folds
φ
φstart
φend
Ne ≈ 60 : solve horizon, flatness problems



V(φ)
e-folds
φ
φstart φend
Ne = -1/Mp ∫ 1/√2ε dφ = -1/Mp² ∫ φ dφ = (φs² - φen²)/Mp²
Ne ≈ 60 ; solve horizon, flatness problems
observe
1/aH
a
a0 = 1

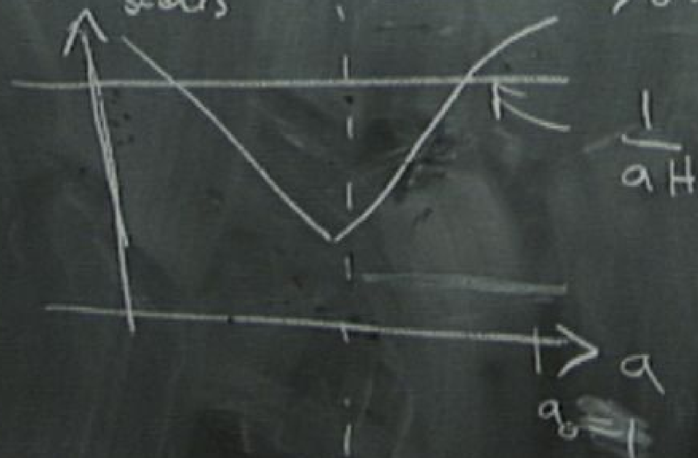

$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{end}^2}{M_p^2}$
$V(\phi)$
e-folds
ϕ
ϕ_{start}
ϕ_{end}
$N_e \approx 60$: solve horizon, flatness problems
comoving scales
observe
$\frac{1}{aH}$
a
$a_0 = 1$

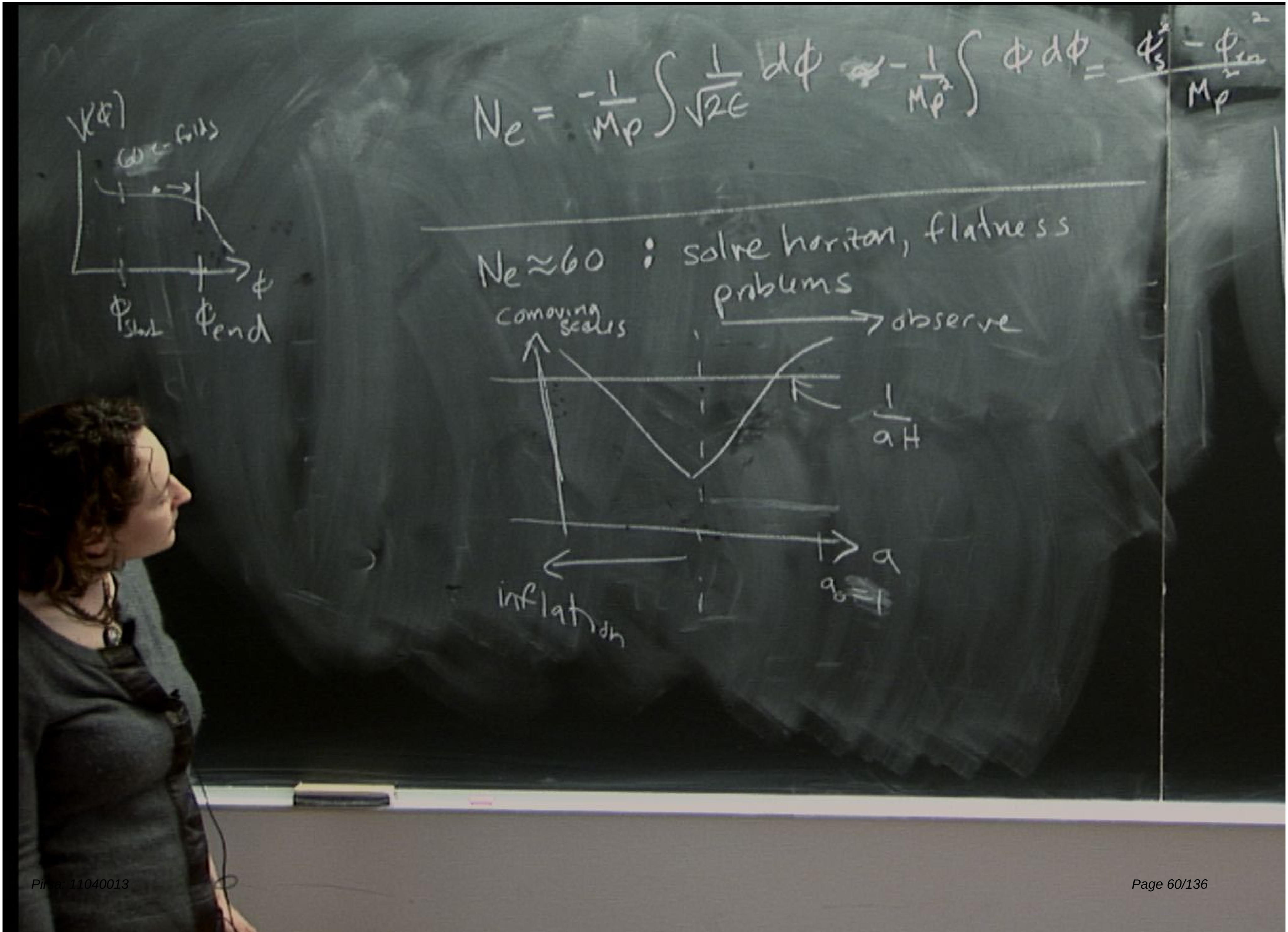
$$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{end}^2}{M_p^2}$$



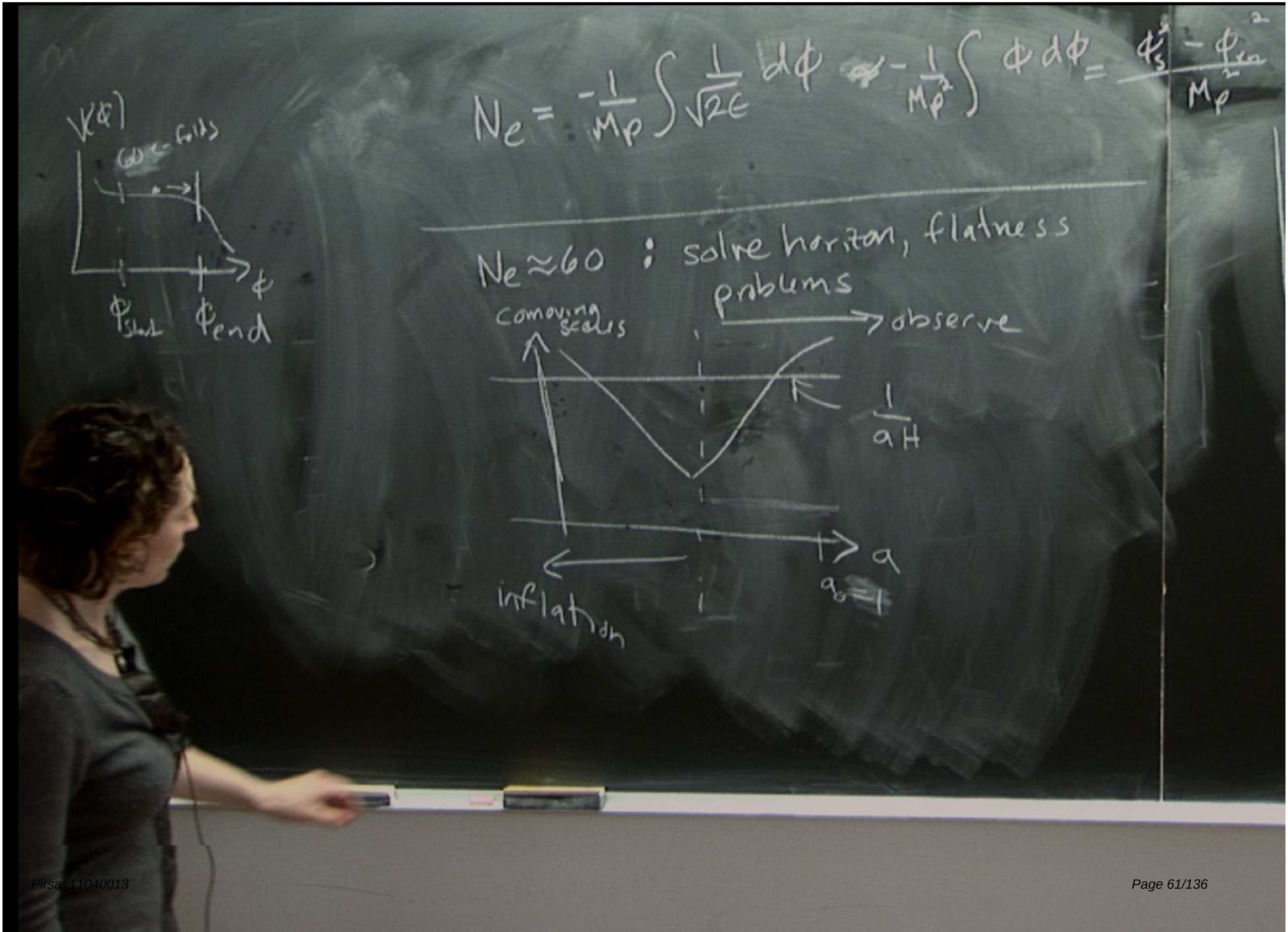
$N_e \simeq 60$: solve horizon, flatness problems

$\longrightarrow$ observe





$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{end}^2}{M_p^2}$
$V(\phi)$
e-folds
ϕ
ϕ_{start}
ϕ_{end}
$N_e \approx 60$: solve horizon, flatness problems
comoving scales
observe
$\frac{1}{aH}$
a
$a_0 = 1$
inflation


$N_e = -\frac{1}{M_p}\int \frac{1}{\sqrt{2\epsilon}}\, d\phi = -\frac{1}{M_p^2}\int \phi\, d\phi = \frac{\phi_s^2 - \phi_{end}^2}{M_p^2}$
$V(\phi)$
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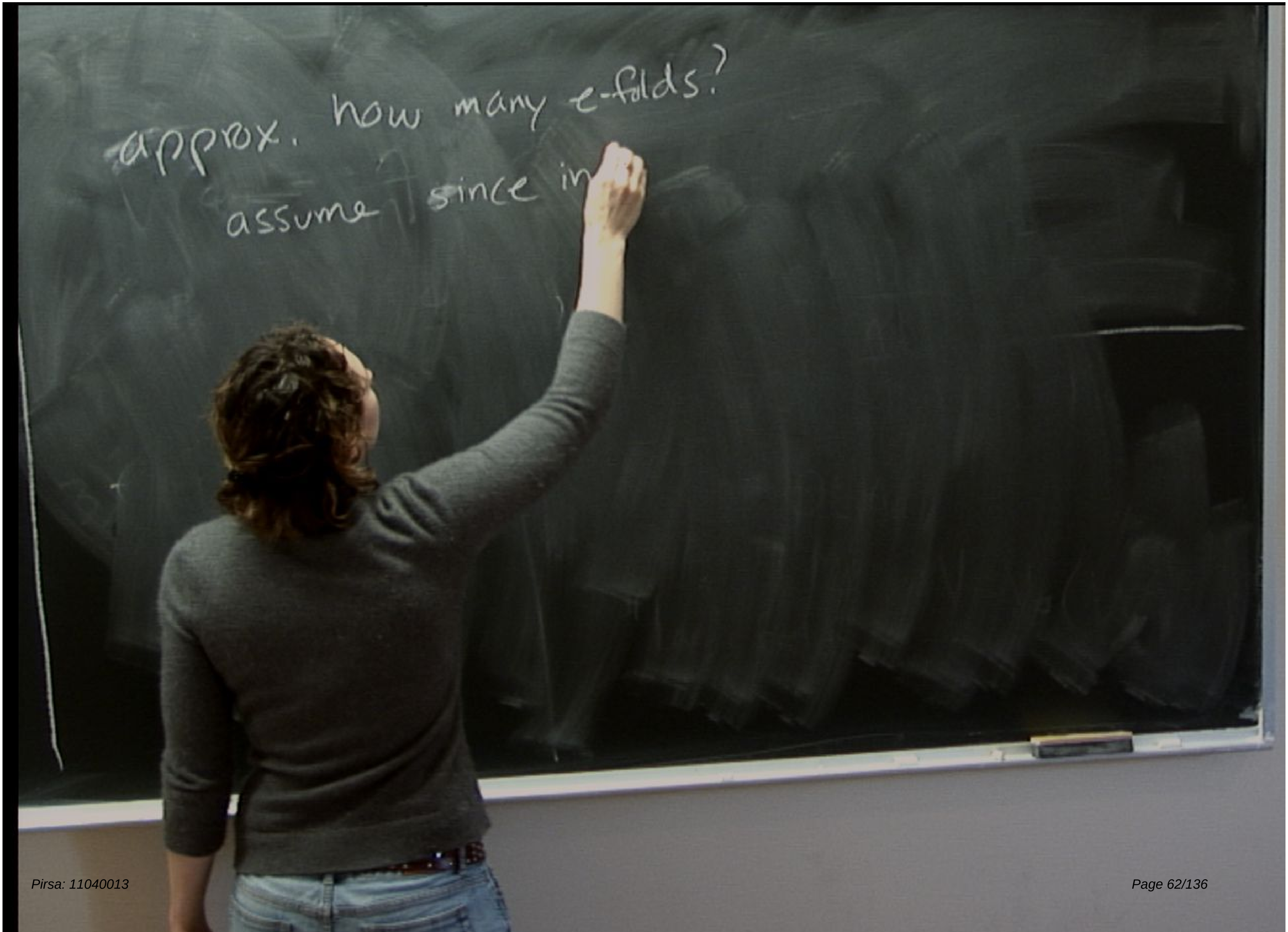
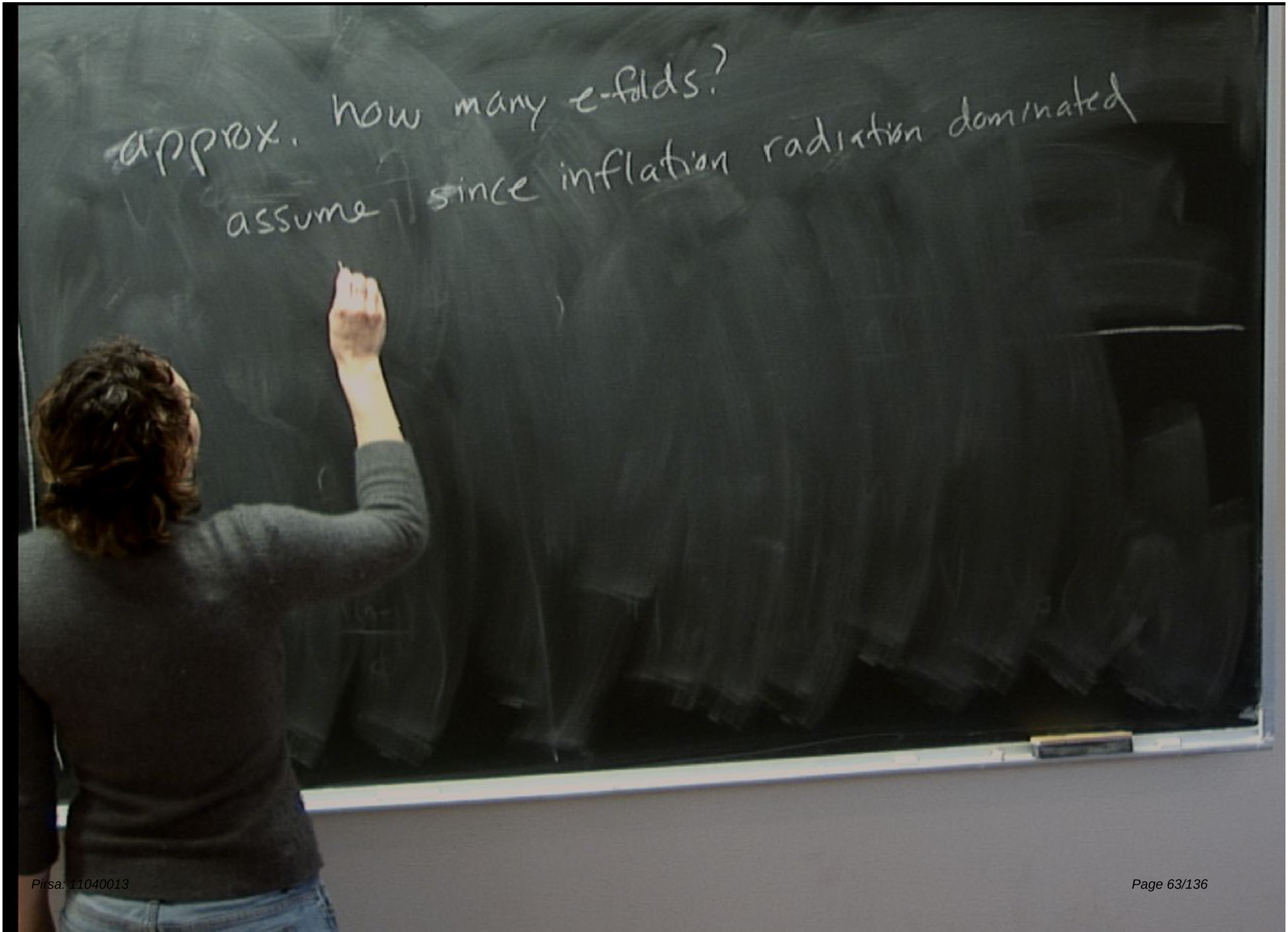
ϕ_{start} ϕ_{end}
$N_e \approx 60$: solve horizon, flatness problems
comoving scales
observe
$\frac{1}{aH}$
a
$a_0 = 1$
inflation

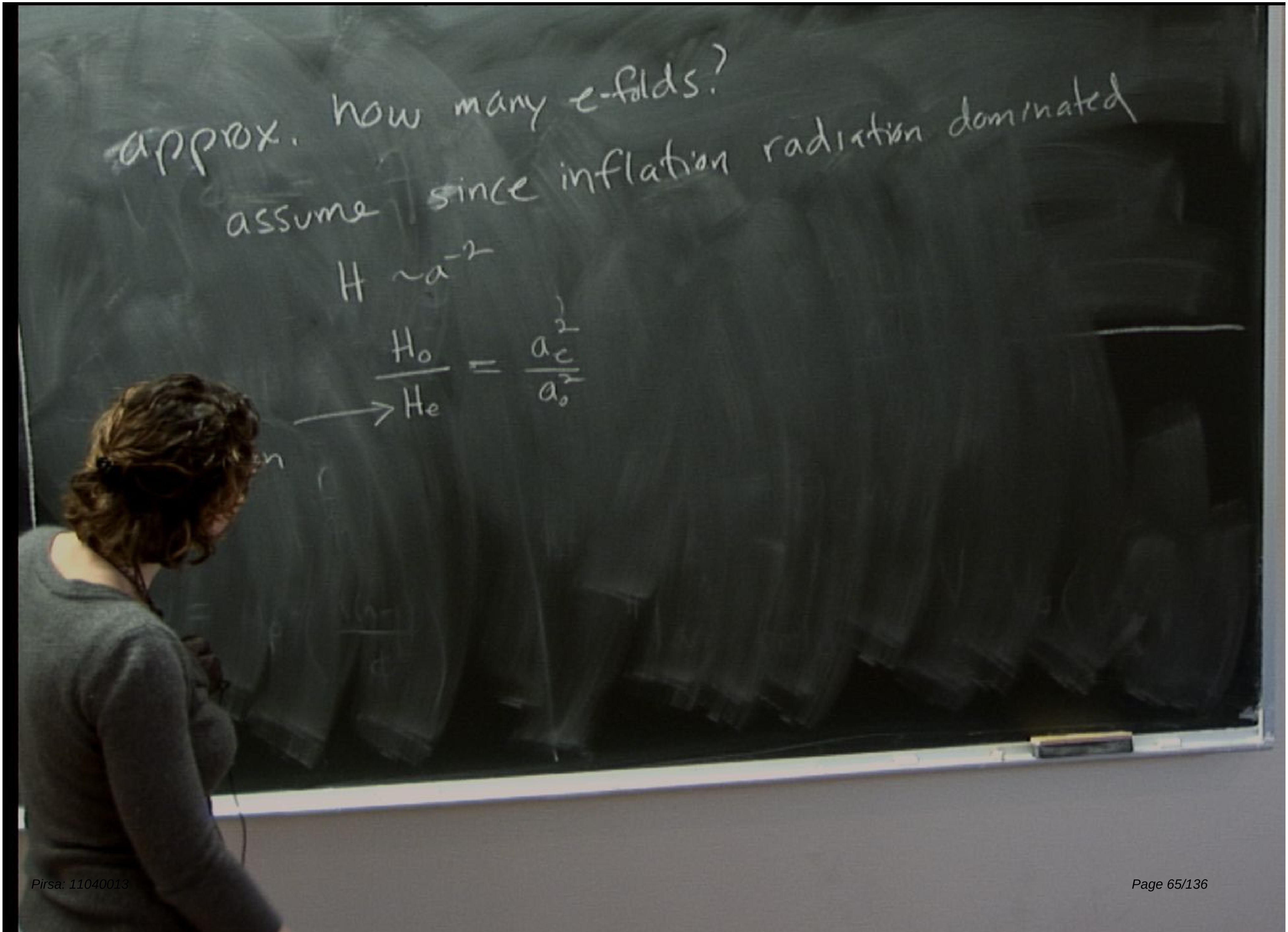

approx. how many e-folds?
assume since in


approx. how many e-folds?
assume since inflation radiation dominated

approx. how many e-folds?

assume since inflation radiation dominated

$H \sim a^{-2}$


approx. how many e-folds?
assume since inflation radiation dominated
$H \sim a^{-2}$
$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$

approx. how many e-folds?

assume since inflation radiation dominated

$$H \sim a^{-2}$$

$$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$$

end of inflation $\rightarrow H_e$

$$\frac{a_0 H_0}{\quad}$$

approx. how many e-folds?

assume since inflation radiation dominated

$$H \sim a^{-2}$$

$$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$$

end of inflation $\longrightarrow H_e$

$$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0}$$

approx. how many e-folds?

assume since inflation radiation dominated

$$T \sim \frac{1}{a}$$

$$H \sim a^{-2}$$

$$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$$

end of inflation → H_e

$$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0} = \frac{T_0}{T_e} = 10^{-4}\,\mathrm{eV}$$

approx. how many e-folds?

assume since inflation radiation dominated

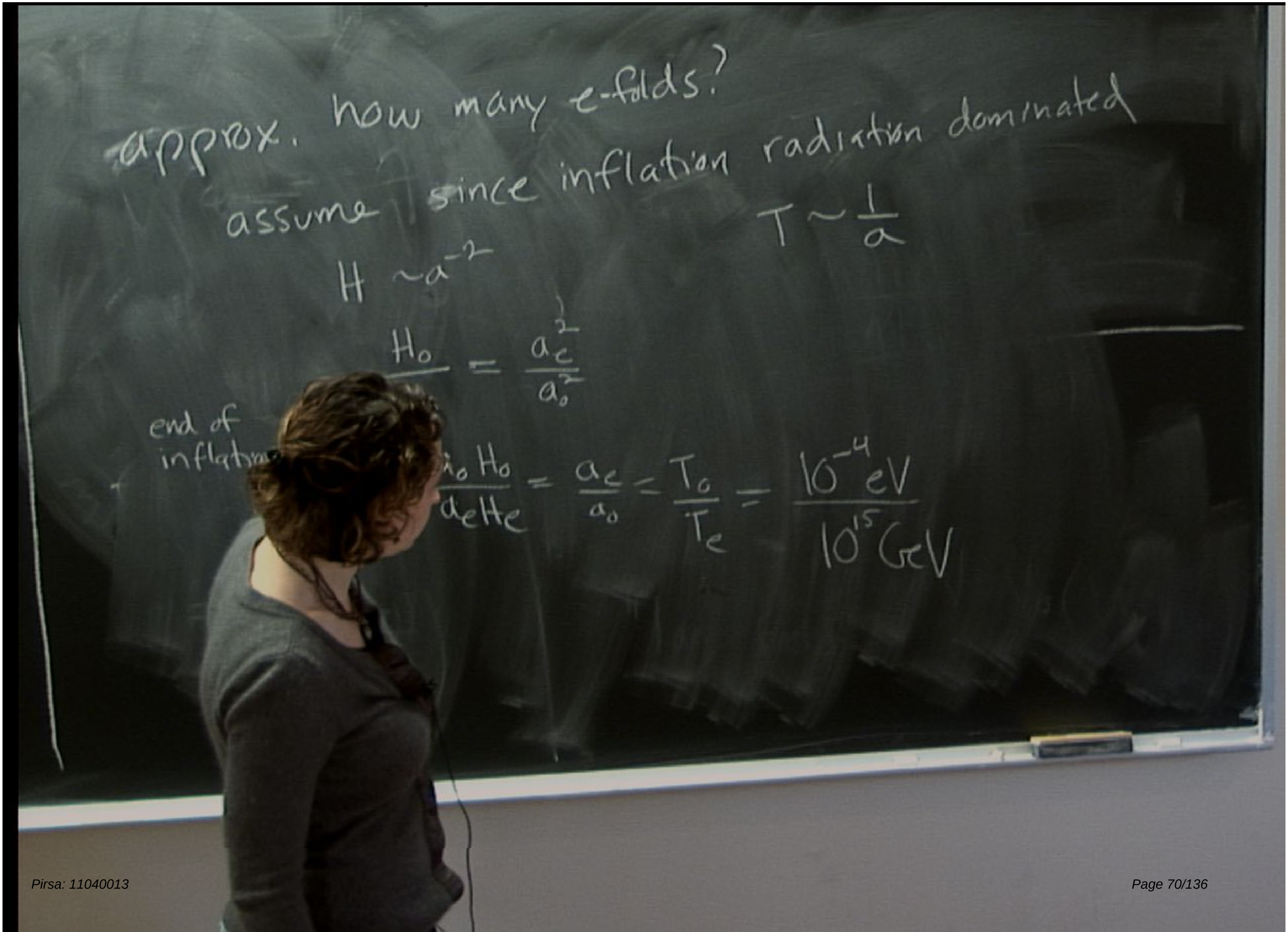
$$T \sim \frac{1}{a}$$

$$H \sim a^{-2}$$

$$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$$

end of inflation $\longrightarrow H_e$

$$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0} = \frac{T_0}{T_e} = \frac{10^{-4}\,\mathrm{eV}}{}$$


approx. how many e-folds?
assume radiation dominated since inflation
T ~ 1/a
H ~ a^-2
H0/He = ae^2/a0^2
end of inflation
a0H0/aeHe = ae/a0 = T0/Te = 10^-4 eV / 10^15 GeV

approx. how many e-folds?

assume radiation dominated since inflation

$$T \sim \frac{1}{a}$$

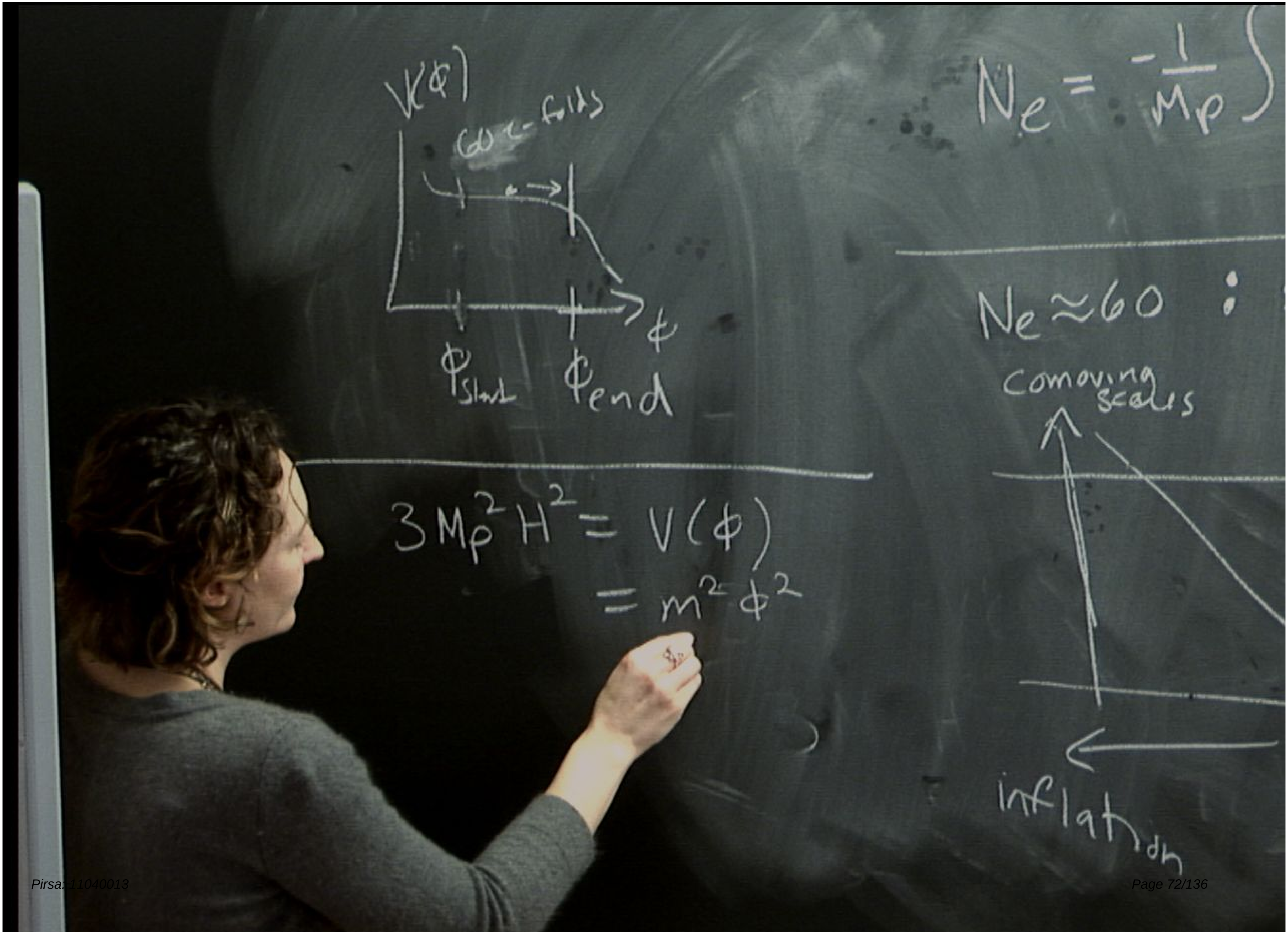
$$H \sim a^{-2}$$

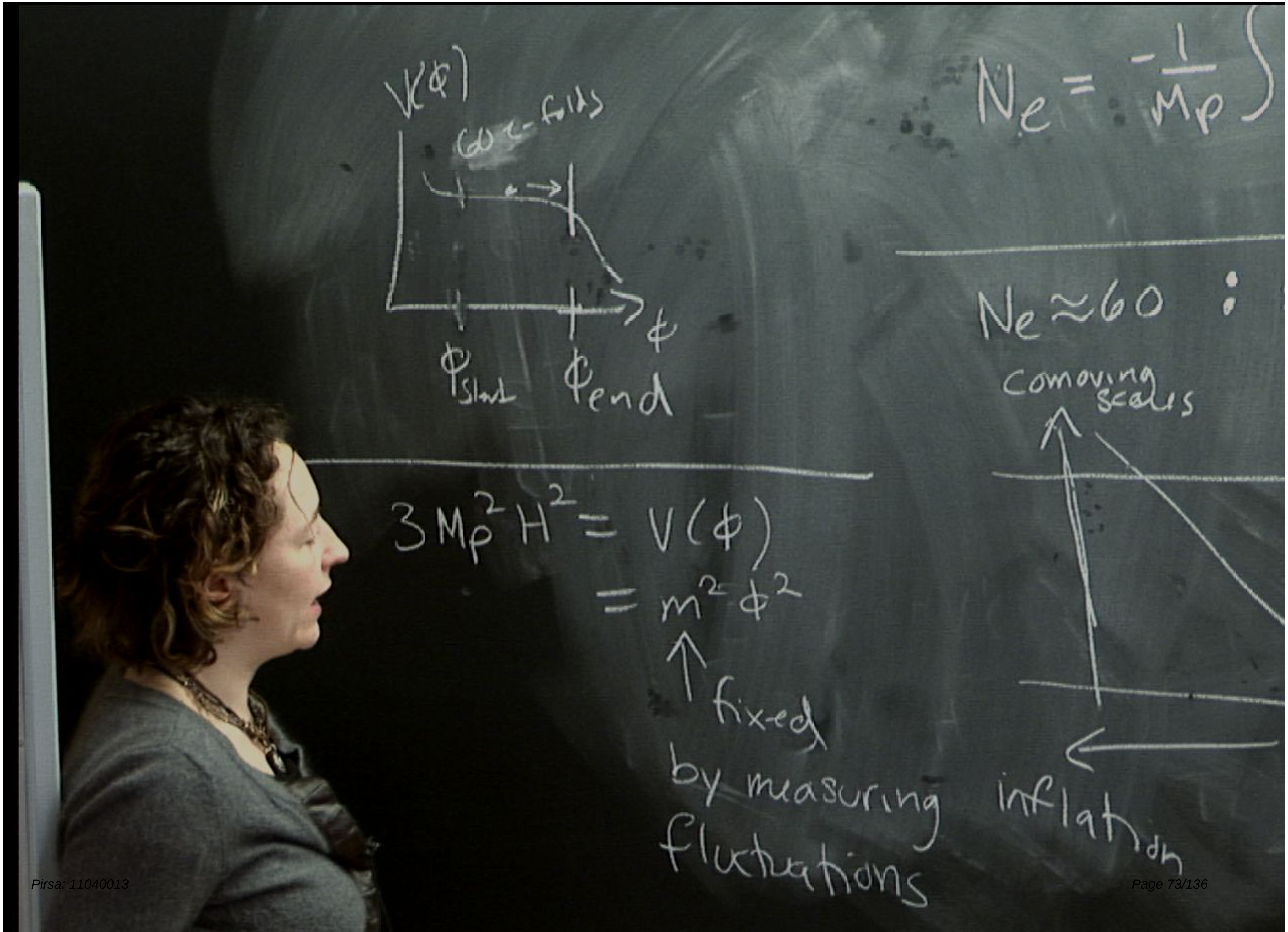
$$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$$

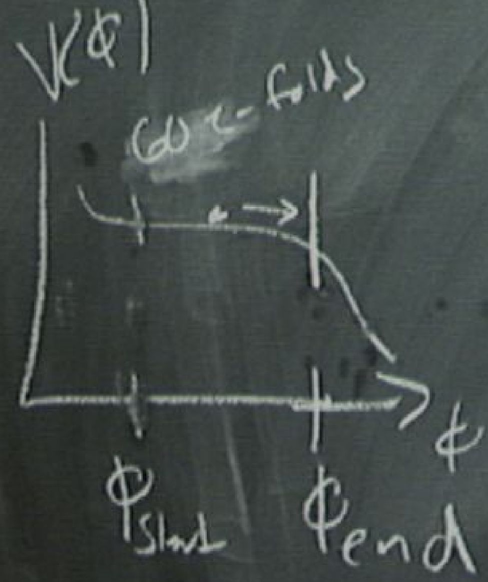
end of inflation → H_e

$$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0} = \frac{T_0}{T_e} = \frac{10^{-4}\,\text{eV}}{10^{15}\,\text{GeV}} = 10^{-28}$$

$(10^{15} \cdot 10^{9}\,\text{eV})$


V(φ)
60 e-folds
φ
φstart
φend
Ne = -1/Mp ∫
Ne ≈ 60 :
comoving scales
3 Mp² H² = V(φ)
= m² φ²
inflation


V(φ)
60 e-folds
φstart φend
φ
Ne = -1/Mp ∫
Ne ≈ 60 :
comoving scales
3 Mp² H² = V(φ)
= m² φ²
fixed by measuring fluctuations
inflation



$$N_e = -\frac{1}{M_p}\int$$

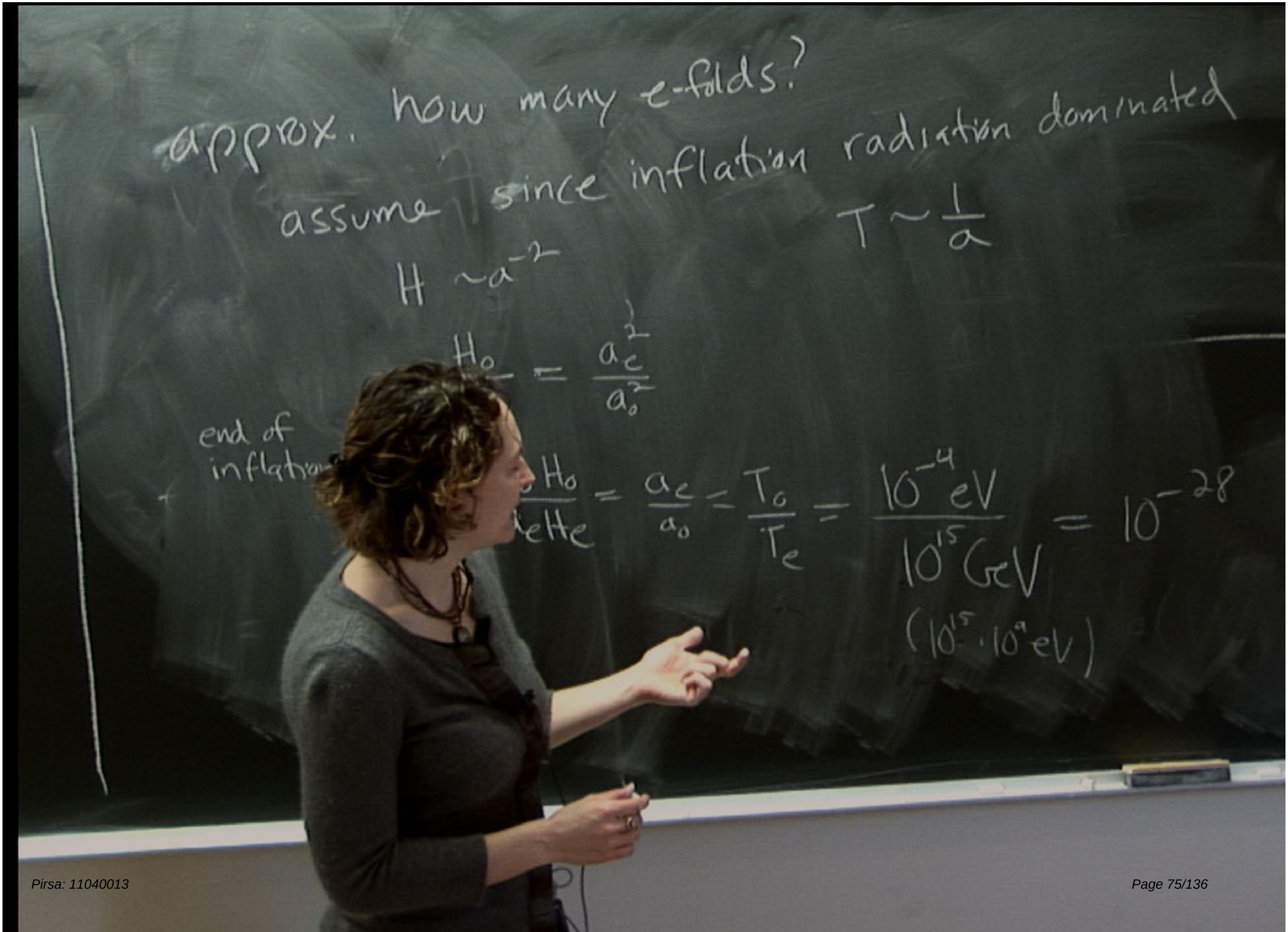
$$3M_p^2H^2 = V(\phi)$$
$$= m^2\phi^2$$

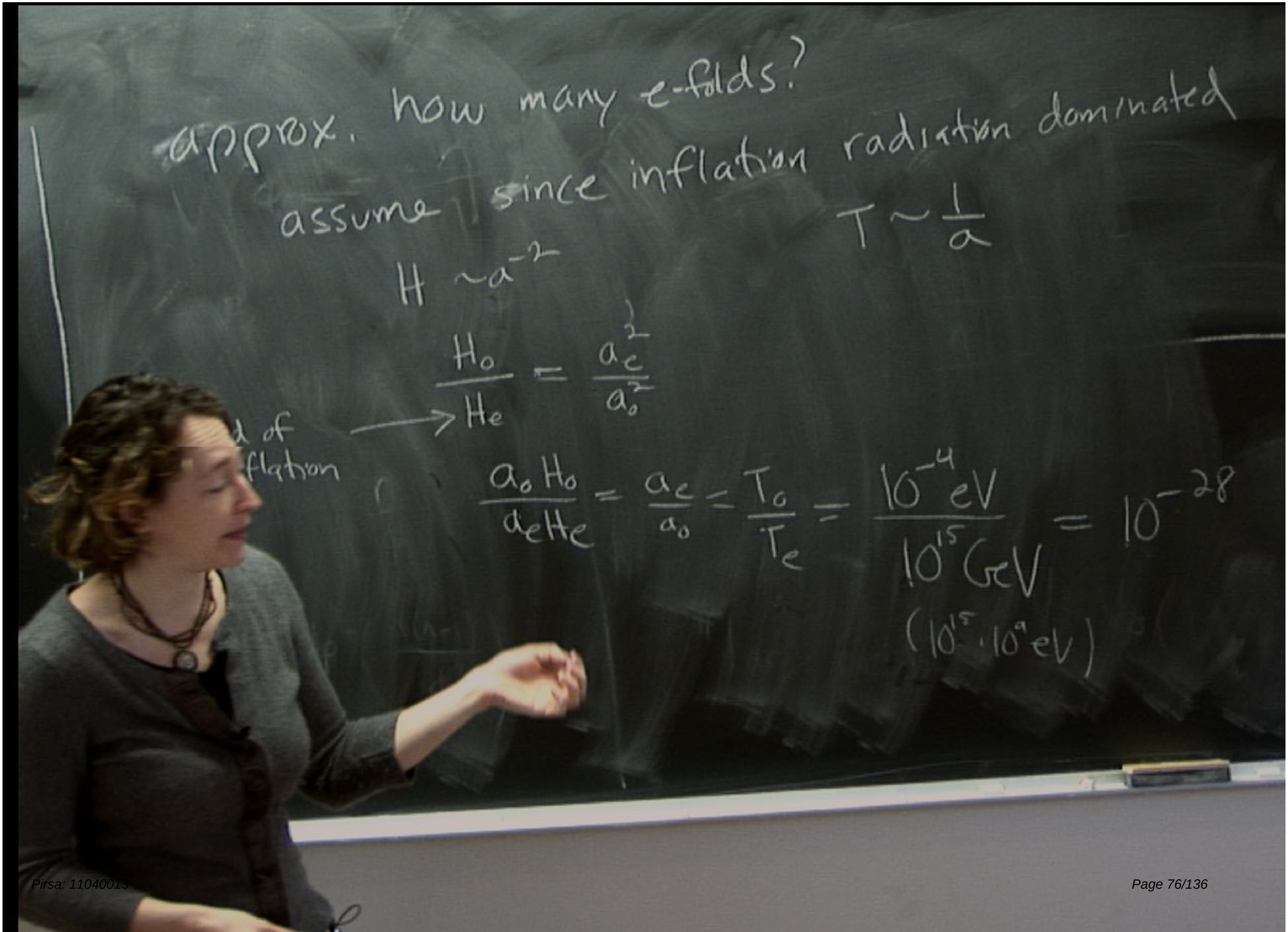
fixed by measuring fluctuations

$N_e \approx 60$:

comoving scales

inflation


approx. how many e-folds?
assume since inflation radiation dominated
T ~ 1/a
H ~ a^-2
H0 = ae^2 / a0^2
end of inflation
Ho / HeHe = ae / a0 = T0 / Te = 10^-4 eV / 10^15 GeV = 10^-28
(10^15 · 10^9 eV)


approx. how many e-folds?
assume since inflation radiation dominated
$T \sim \frac{1}{a}$
$H \sim a^{-2}$
$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$
end of inflation
$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0} = \frac{T_0}{T_e} = \frac{10^{-4}\,eV}{10^{15}\,GeV} = 10^{-28}$
$(10^{15} \cdot 10^{9}\,eV)$

approx. how many e-folds?

assume since inflation radiation dominated

$$T \sim \frac{1}{a}$$

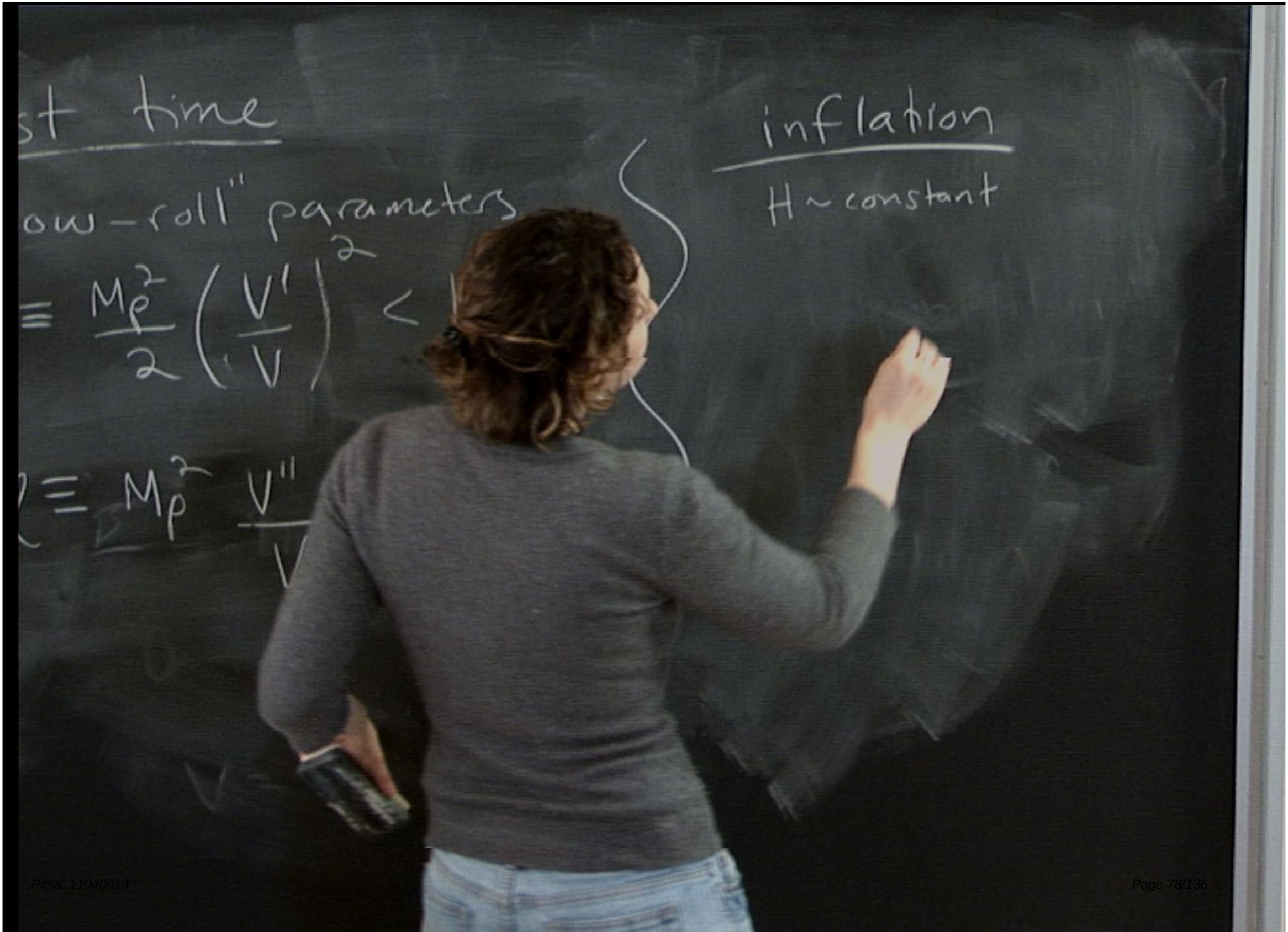
$$H \sim a^{-2}$$

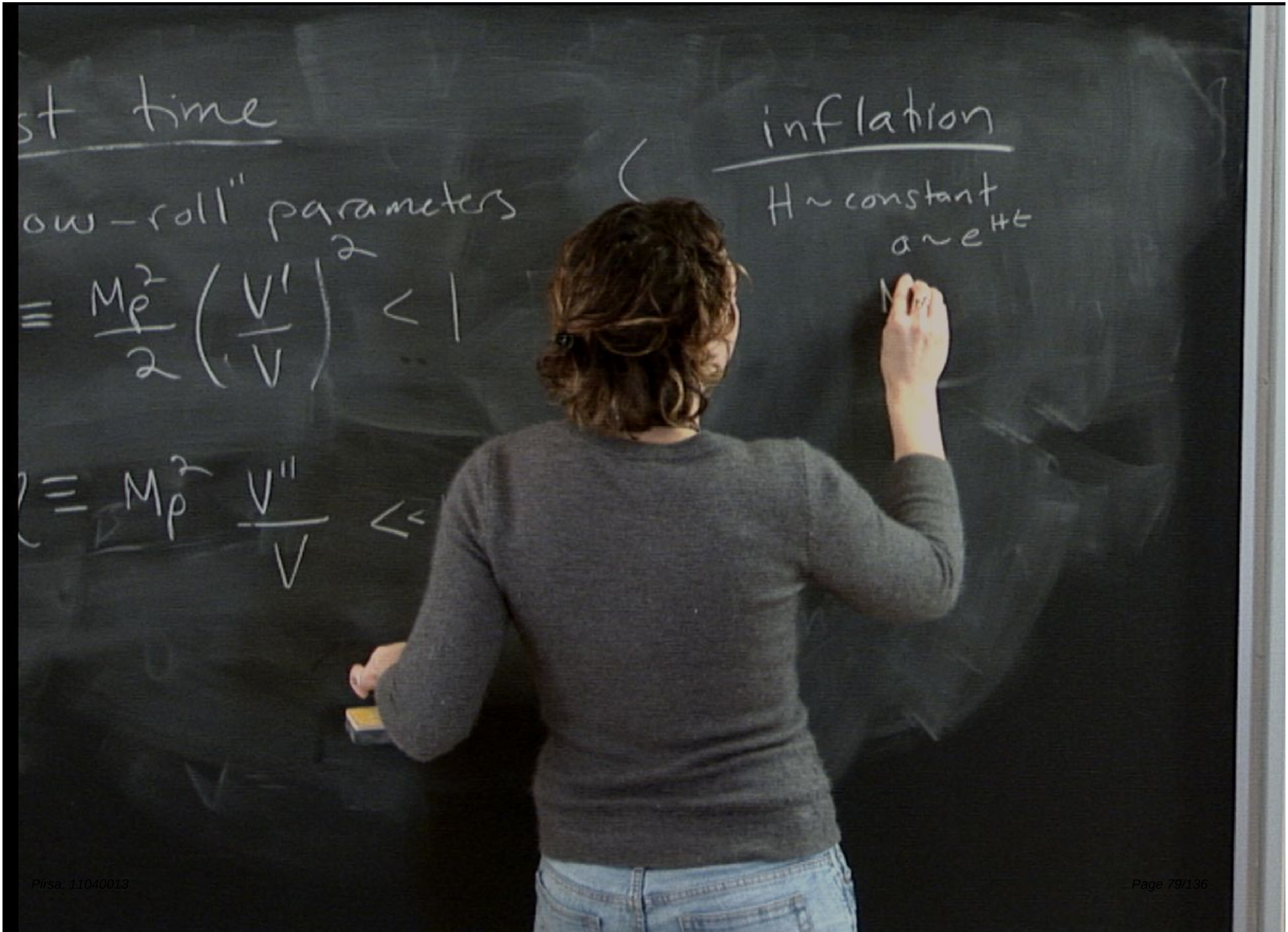
$$\frac{H_0}{H_e} = \frac{a_e^2}{a_0^2}$$

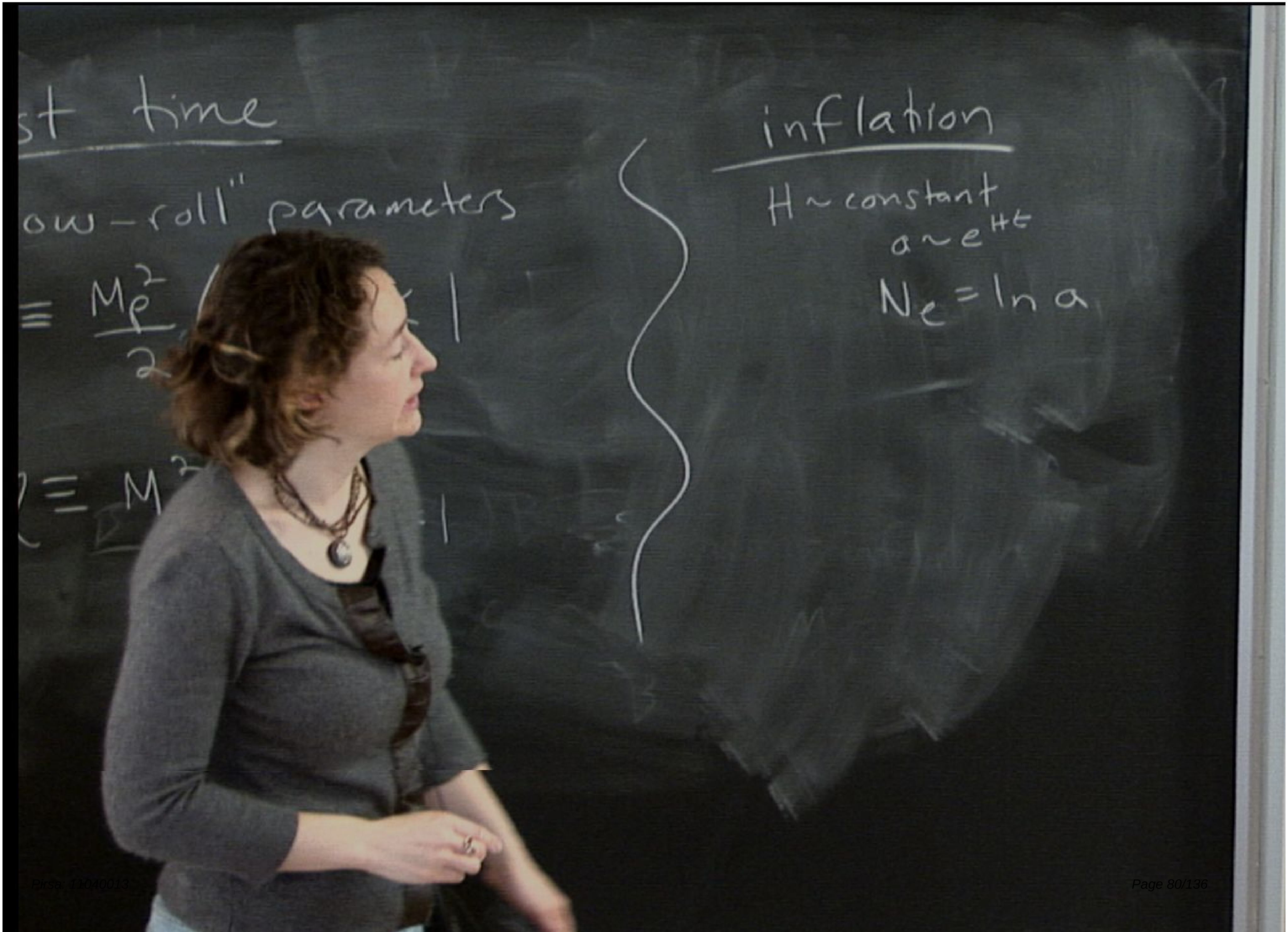
end of inflation → H_e

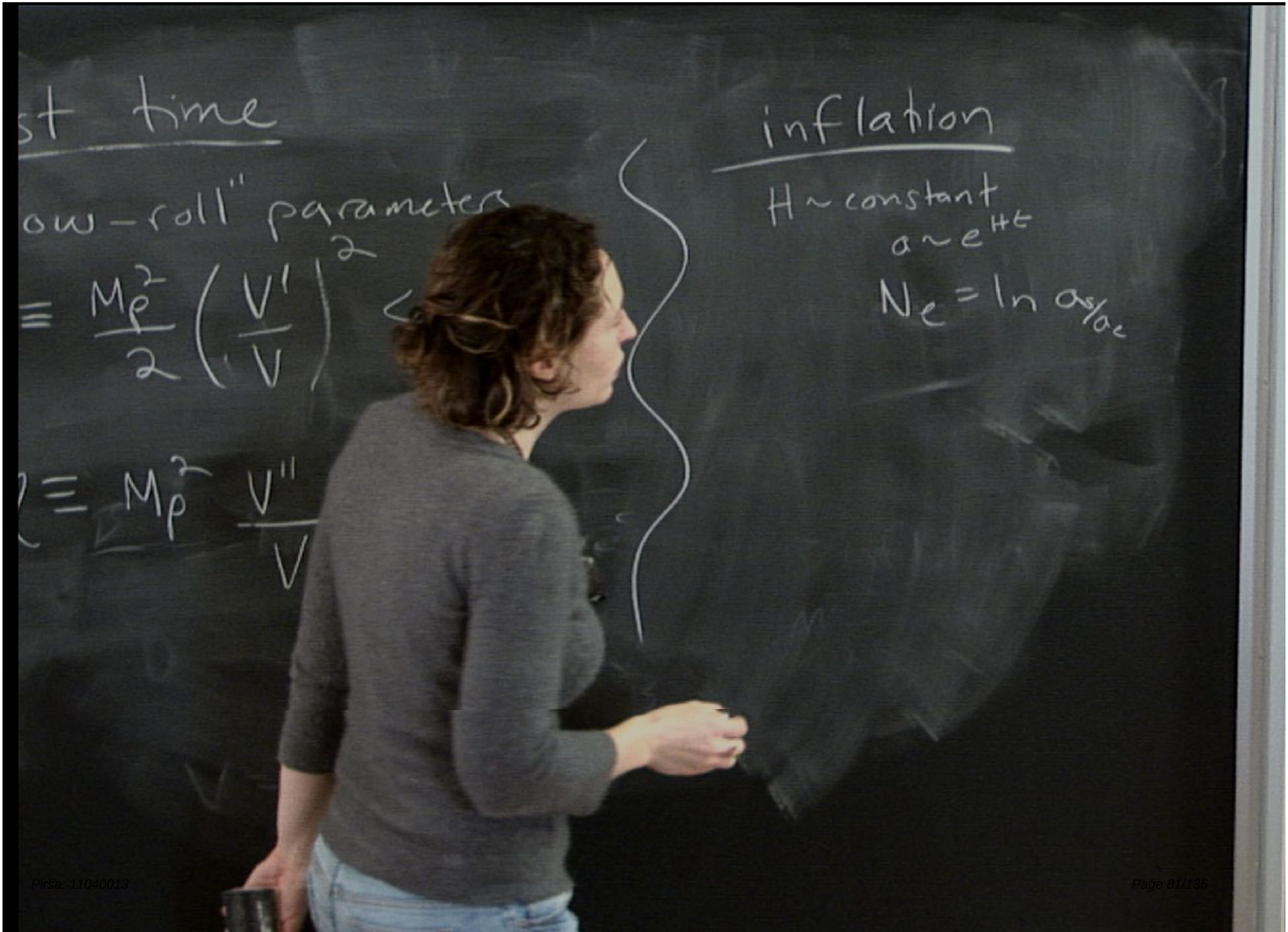
$$\frac{a_0 H_0}{a_e H_e} = \frac{a_e}{a_0} = \frac{T_0}{T_e} = \frac{10^{-4}\,eV}{10^{15}\,GeV} = 10^{-28}$$

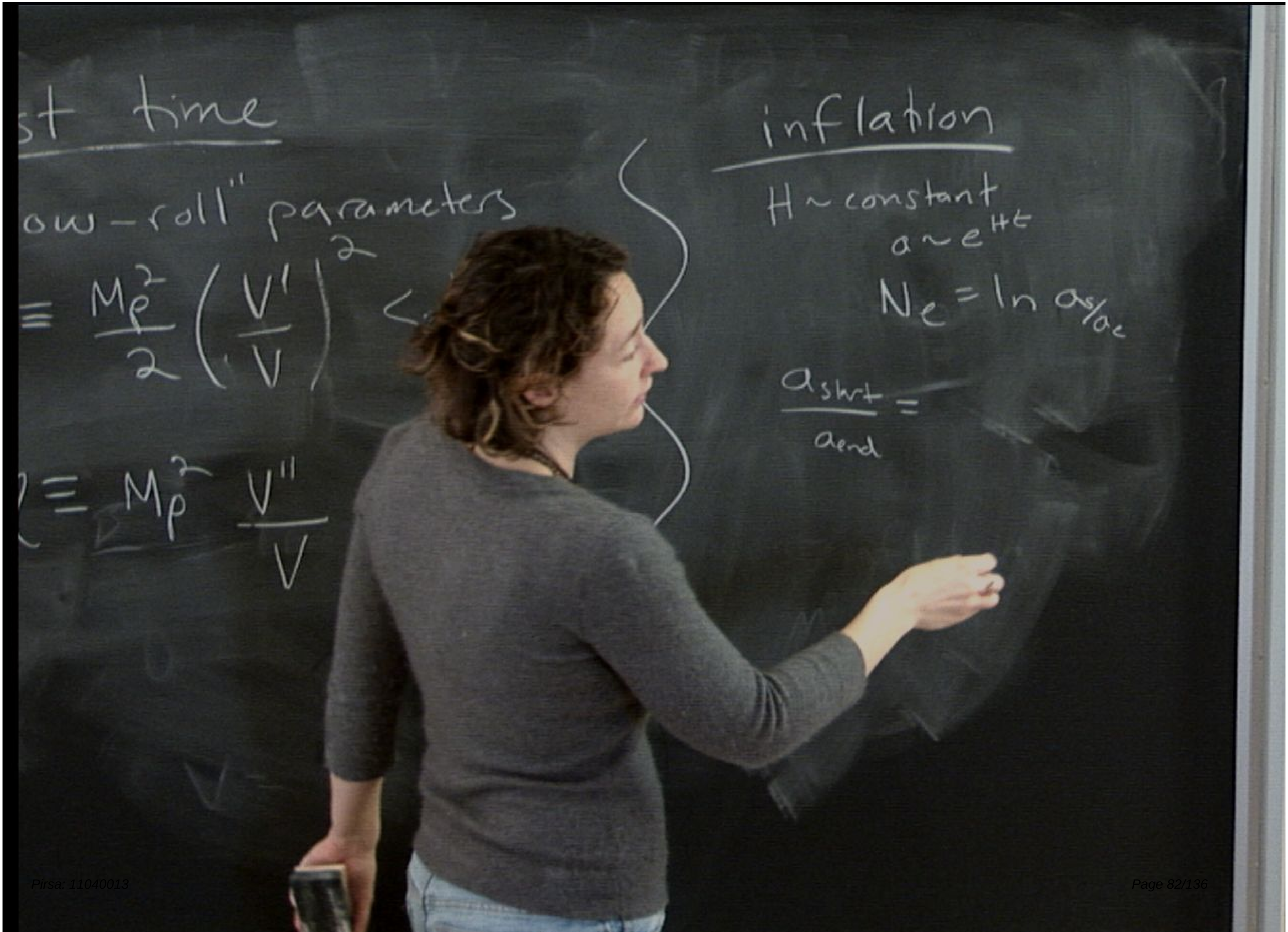
$$(10^{15} \cdot 10^{9}\,eV)$$


st time
ow-roll" parameters
inflation
H ~ constant


st time
inflation
ow-roll" parameters
H ~ constant
a ~ e^{Ht}
≡ Mp^2/2 (V'/V)^2 < 1
≡ Mp^2 V''/V <<


st time
ow-roll" parameters
inflation
H ~ constant
a ~ e^Ht
N_e = ln a


st time
"ow-roll" parameters
≡ Mp² / 2 (V' / V)² <
≡ Mp² V'' / V
inflation
H ~ constant
a ~ e^Ht
Ne = ln as/ae


st time
"ow-roll" parameters
inflation
H ~ constant
$a \sim e^{Ht}$
$N_e = \ln a_s/a_e$
$\frac{a_{start}}{a_{end}} =$
$\equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2$
$\equiv M_p^2 \frac{V''}{V}$

st time

ow-roll" parameters

$$\equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 < 1$$

$$\eta \equiv M_p^2 \frac{V''}{V} << 1$$

inflation

H ~ constant

$a \sim e^{Ht}$

$N_e = \ln a_s/a_e$

$$\frac{a_{start}}{a_{end}} = 10^{28} = \left(\frac{a_e H_e}{a_0 H_0}\right)$$

st time

ow-roll" parameters

$$\equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 < 1$$

$$\eta \equiv M_p^2 \frac{V''}{V} << 1$$

inflation

H ~ constant

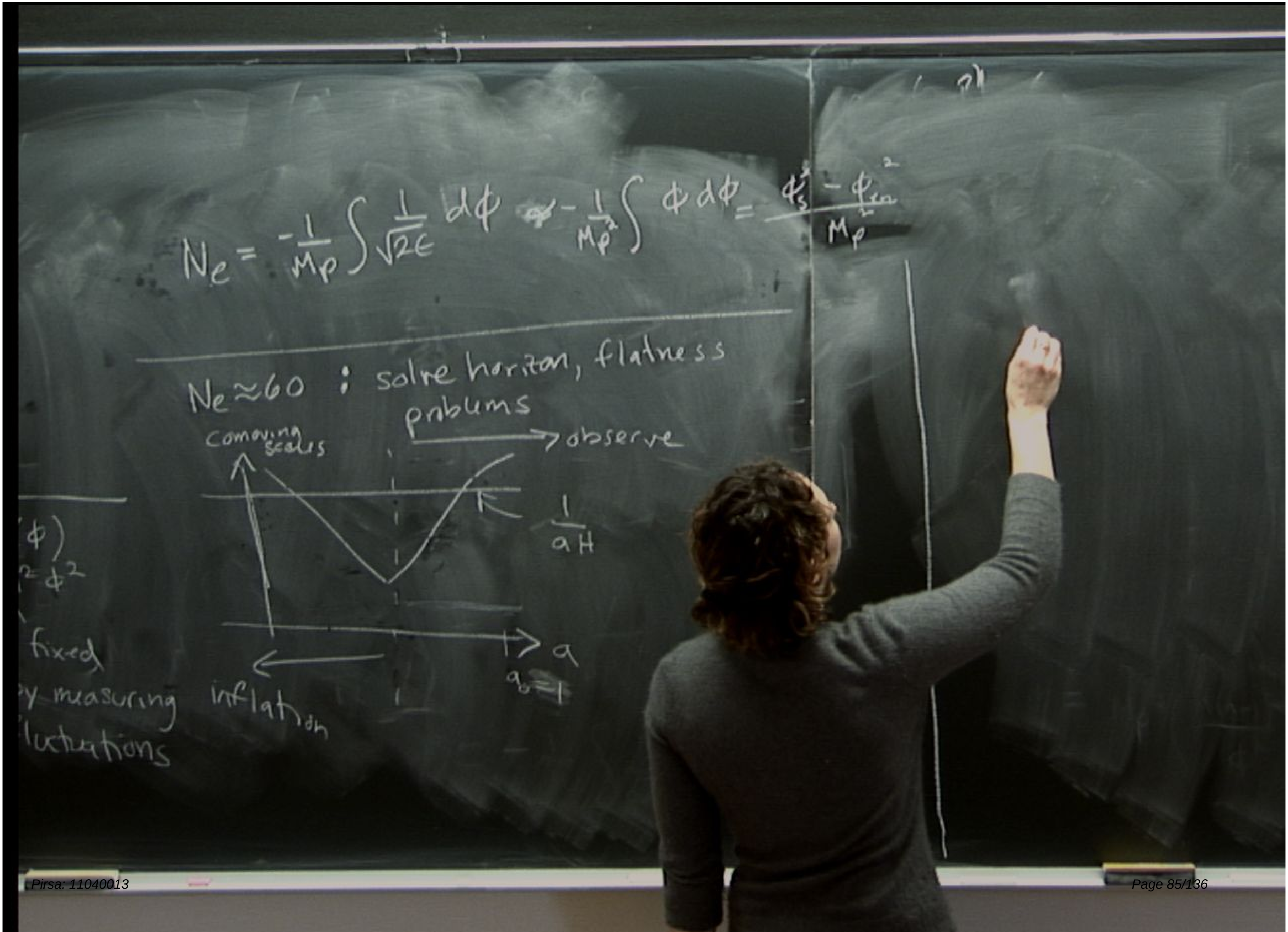
$a \sim e^{Ht}$

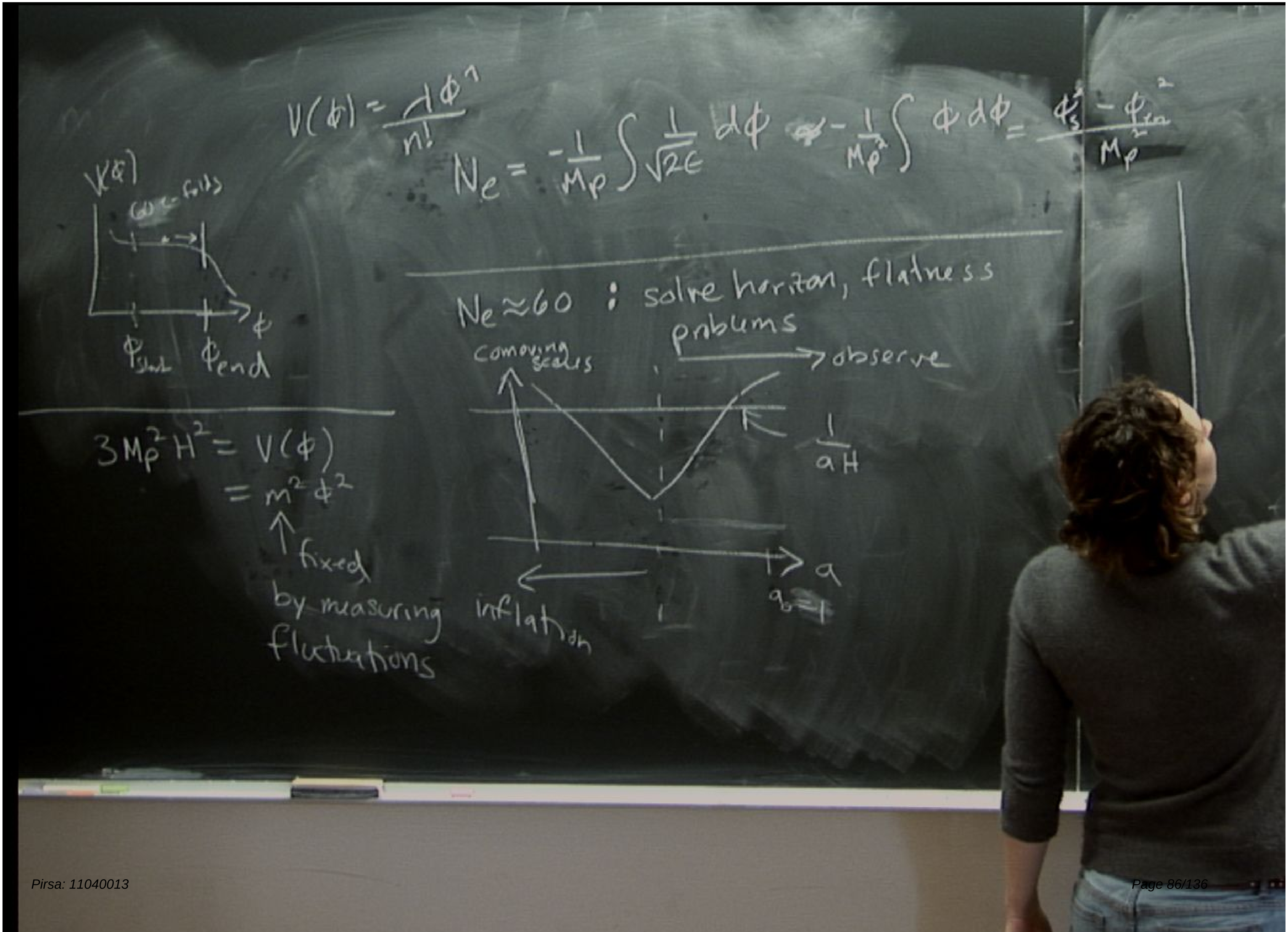
$N_e = \ln a_s/a_e$

$$\frac{a_{start}}{a_{end}} = 10^{28} = \left(\frac{a_e H_e}{a_0 H_0}\right)$$

$$N_e = \ln(10^{28})$$

$$\simeq 64$$


Ne = -1/Mp ∫ 1/√2ε dφ = -1/Mp² ∫ φ dφ = (φs² - φen²)/Mp²
Ne ≈ 60 : solve horizon, flatness problems
comoving scales
observe
1/aH
a
a0 = 1
inflation
fixed
measuring
fluctuations


V(φ) = λφ^n / n!
N_e = -1/M_p ∫ 1/√(2ε) dφ = -1/M_p^2 ∫ φ dφ = (φ_s^2 - φ_end^2)/M_p^2
V(φ)
φ_start φ_end
N_e ≈ 60 : solve horizon, flatness problems
comoving scales
observe
1/aH
a
a_0 = 1
inflation
3M_p^2 H^2 = V(φ)
= m^2 φ^2
fixed by measuring fluctuations

$\phi_{end} \approx n M_p$

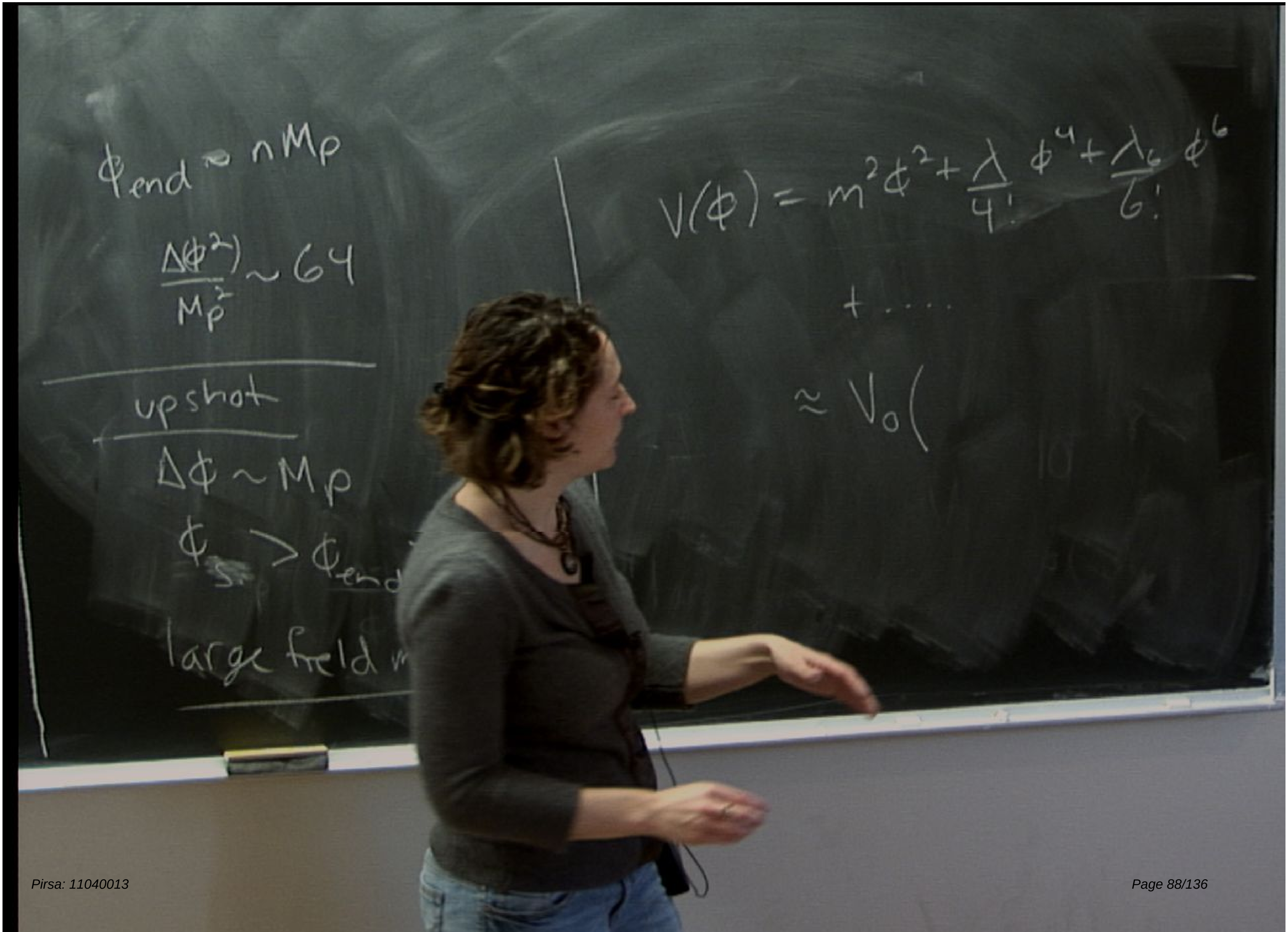
$\frac{\Delta(\phi^2)}{M_p^2} \sim 64$

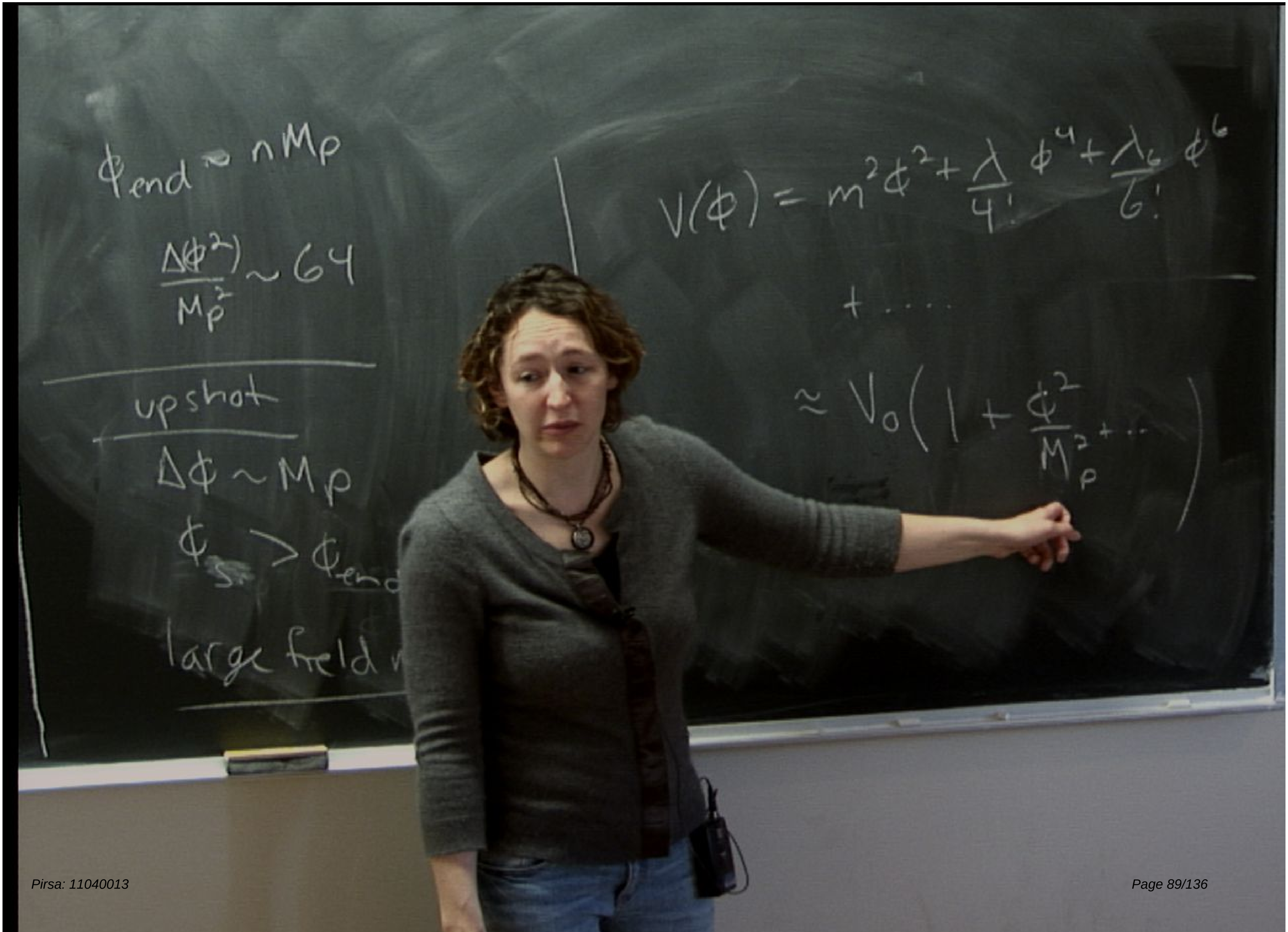
upshot

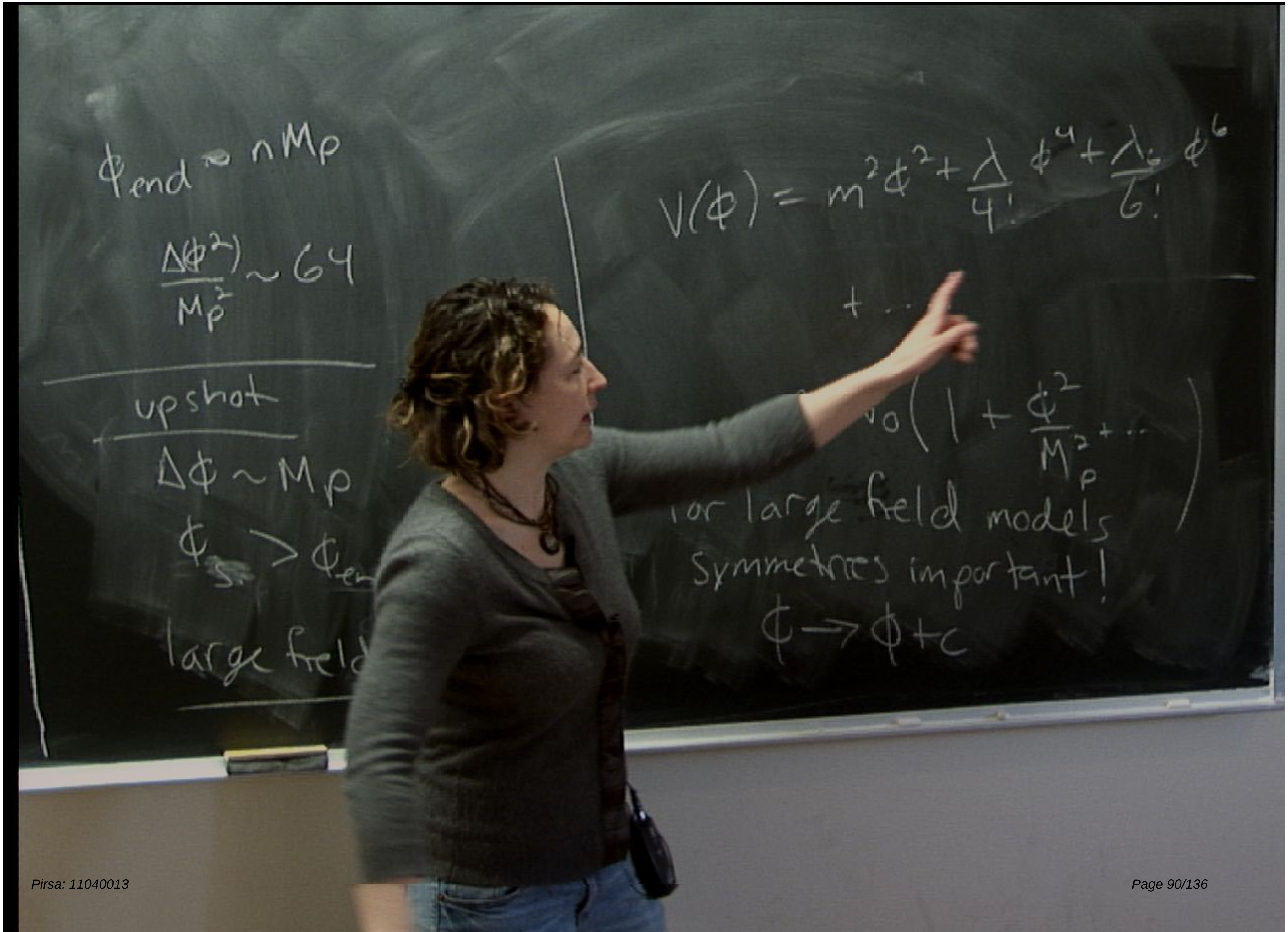
$\Delta\phi \sim M_p$

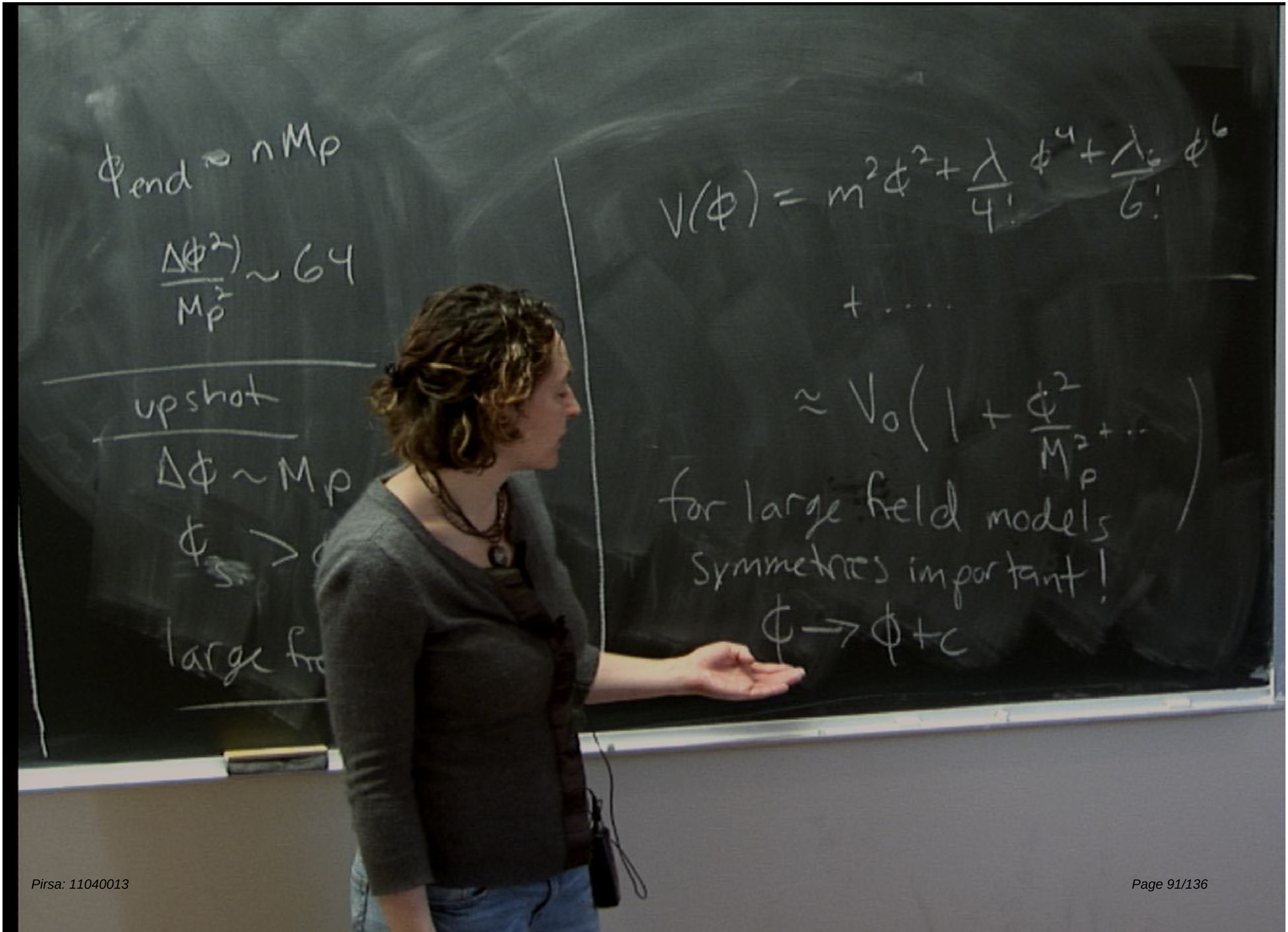
$\phi_s > \phi_{end} > M_p$

large field models


φ_end ≈ n M_p
Δ(φ²)/M_p² ~ 64
upshot
Δφ ~ M_p
φ_s > φ_end
large field
V(φ) = m²φ² + λ/4! φ⁴ + λ_6/6! φ⁶
+ .....
≈ V_0(


$\phi_{end} \approx n M_p$
$\frac{\Delta(\phi^2)}{M_p^2} \sim 64$
upshot
$\Delta\phi \sim M_p$
$\phi_s > \phi_{end}$
large field
$V(\phi) = m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{\lambda_6}{6!}\phi^6$
$+ \ldots$
$\approx V_0\left(1 + \frac{\phi^2}{M_p^2} + \ldots\right)$


$\phi_{end} \approx n M_p$
$\frac{\Delta(\phi^2)}{M_p^2} \sim 64$
upshot
$\Delta\phi \sim M_p$
$\phi_s > \phi_{en}$
large field
$V(\phi) = m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{\lambda_6}{6!}\phi^6$
$+ \ldots$
$V_0\left(1 + \frac{\phi^2}{M_p^2} + \ldots\right)$
for large field models
Symmetries important!
$\phi \to \phi + c$


$\phi_{end} \approx n M_p$
$\frac{\Delta(\phi^2)}{M_p^2} \sim 64$
upshot
$\Delta\phi \sim M_p$
$V(\phi) = m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{\lambda_6}{6!}\phi^6$
$+ \ldots$
$\approx V_0\left(1 + \frac{\phi^2}{M_p^2} + \ldots\right)$
for large field models
Symmetries important!
$\phi \to \phi + c$

$\phi_{end} \approx n M_p$

$$\frac{\Delta(\phi^2)}{M_p^2} \sim 64$$

upshot

$\Delta\phi \sim M_p$

$\phi_s > \phi_{end} > M_p$

large field models

$$V(\phi) = m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{\lambda_6}{6!}\phi^6$$

$$+ \dots$$

$$\approx V_0\left(1 + \frac{\phi^2}{M_p^2} + \dots\right)$$

for large field models

Symmetries important!

$\phi \to \phi + c$

$\phi_{end} \approx n M_p$

$$\frac{\Delta(\phi^2)}{M_p^2} \sim 64$$

upshot

$\Delta\phi \sim M_p$

$\phi_s > \phi_{end} > M_p$

large field models

$$V(\phi) = m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{\lambda_6}{6!}\phi^6 + \dots$$

$$\approx V_0\left(1 + \frac{\phi^2}{M_p^2} + \dots\right)$$

for large field models

Symmetries important!

$\phi \to \phi + c$

$\phi_{end} \approx n M_p$

$\frac{\Delta(\phi^2)}{M_p^2} \sim 64$

upshot

$\Delta\phi \sim M_p$

$\phi_s > \phi_{end} > M_p$

large field models

$V(\phi) = m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{\lambda_6}{6!}\phi^6$

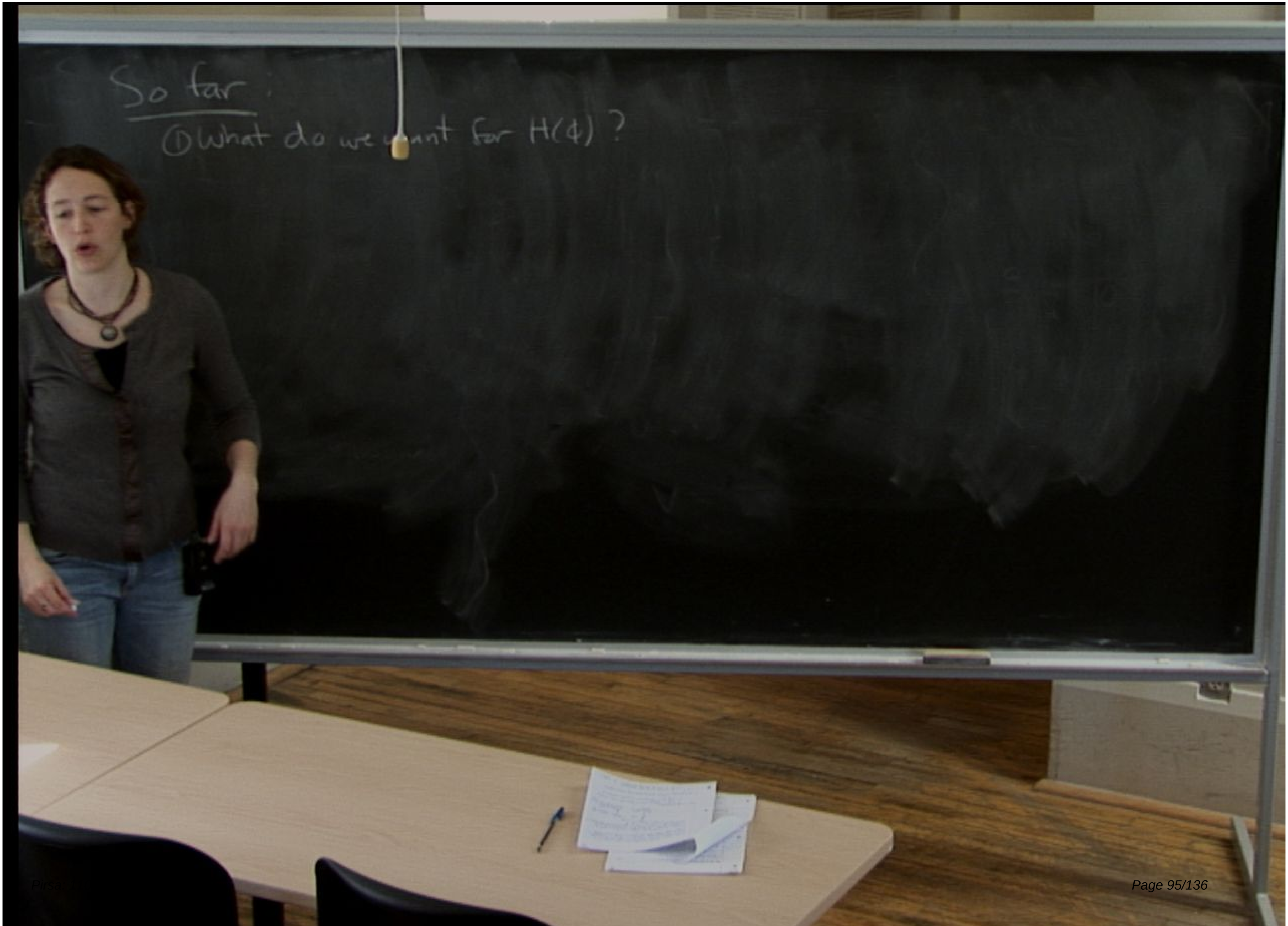
$+ \ldots$

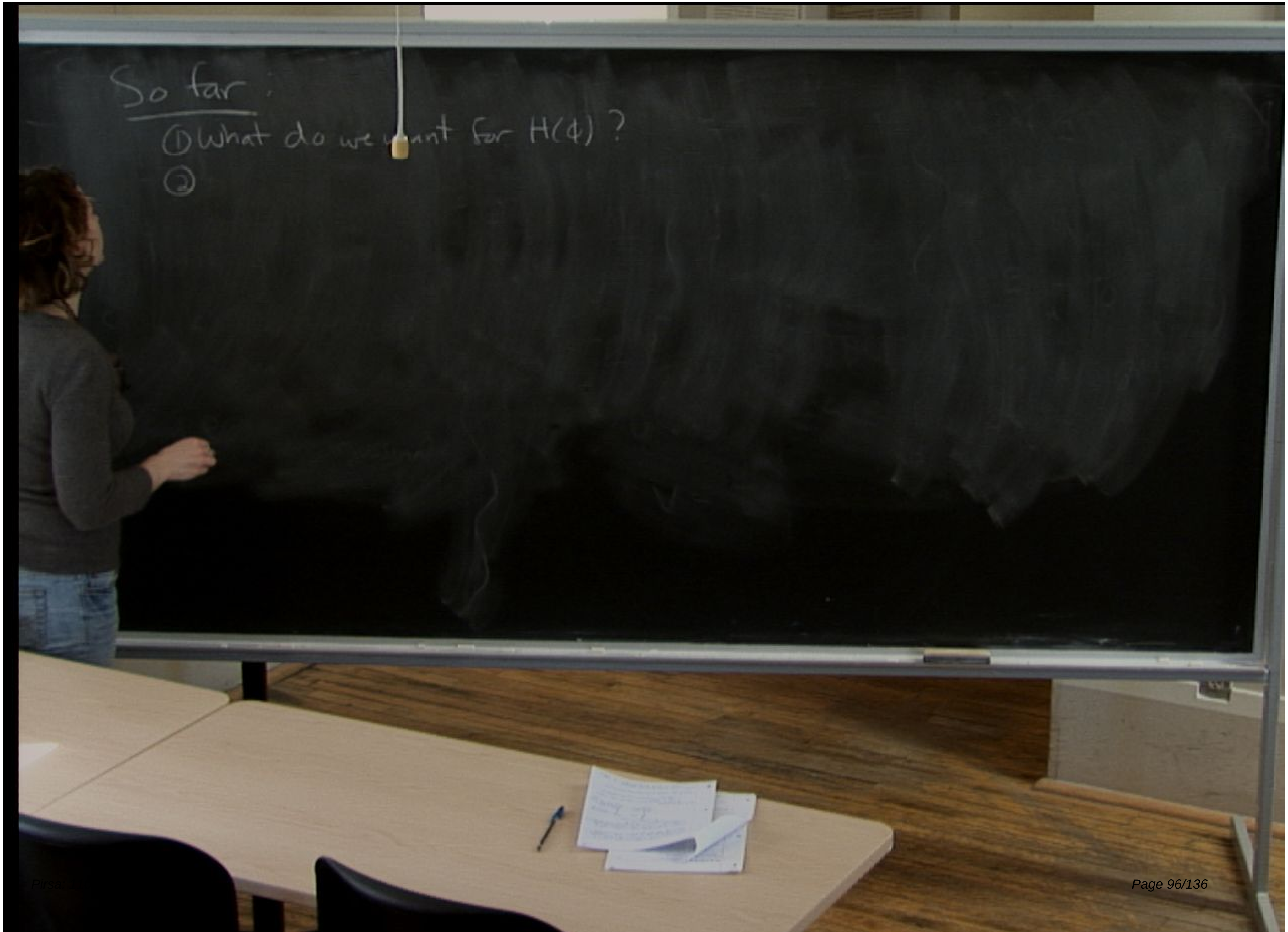
$\approx V_0\left(1 + \frac{\phi^2}{M_p^2} + \ldots\right)$

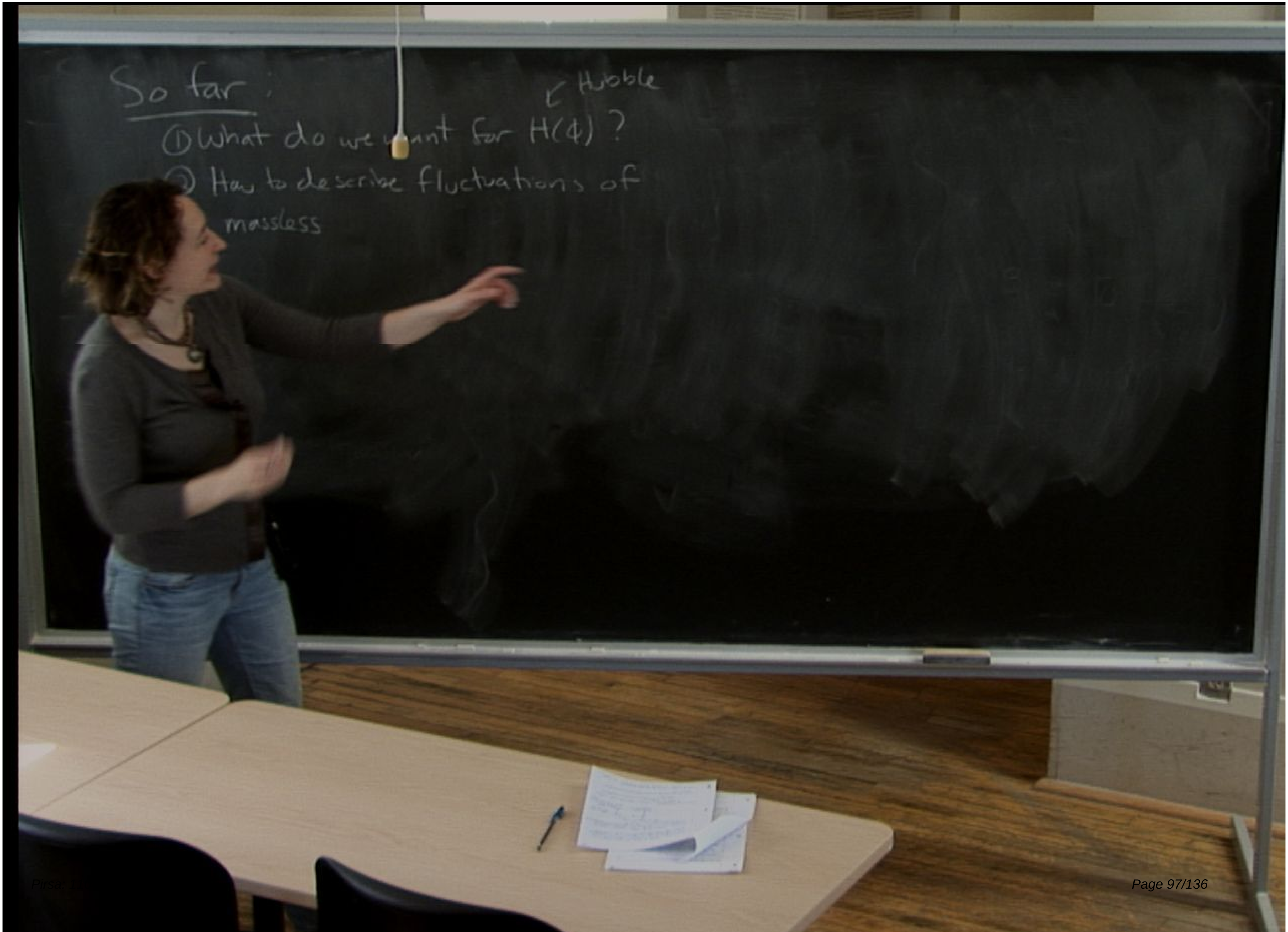
for large field models

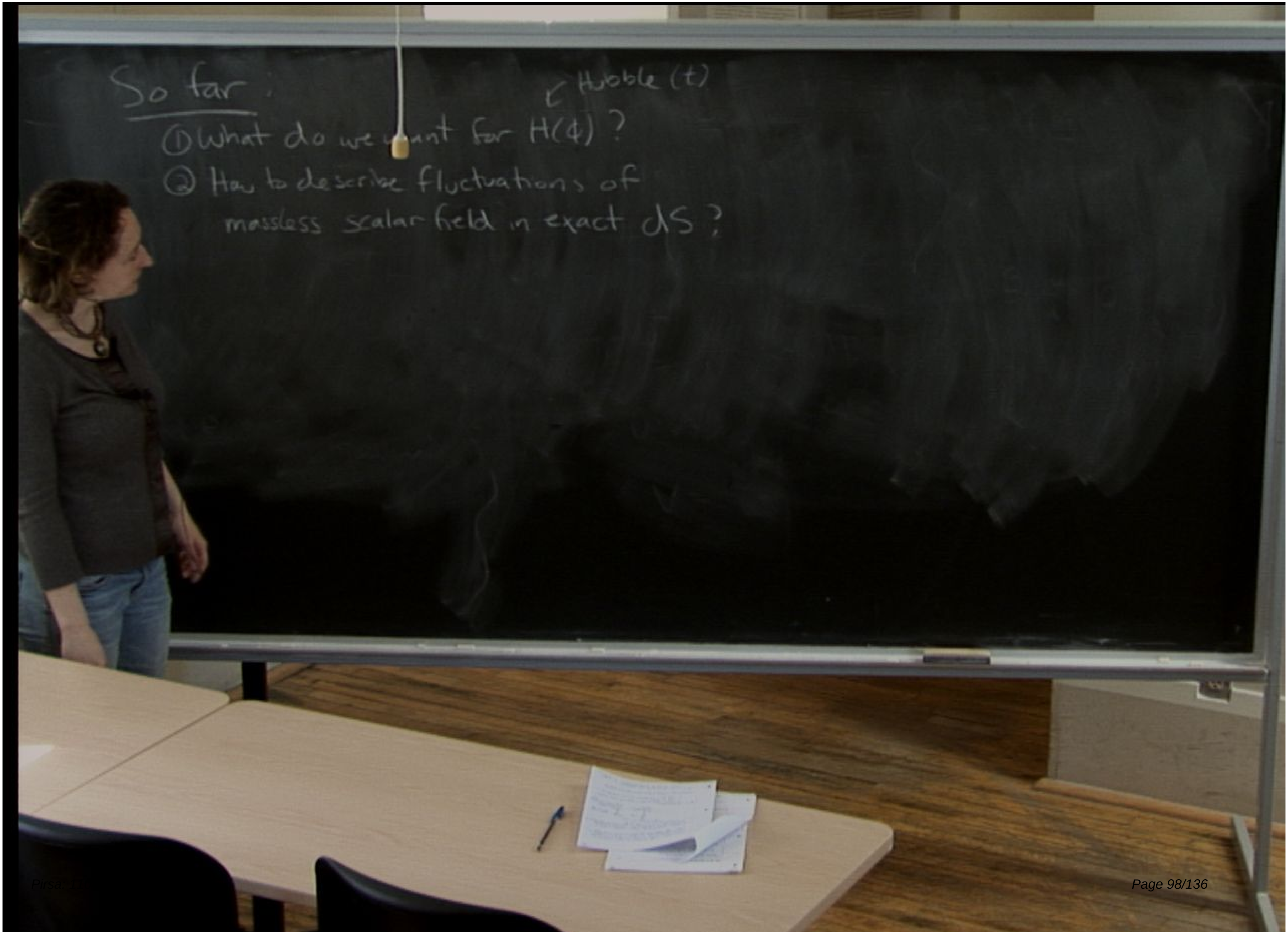
Symmetries important!

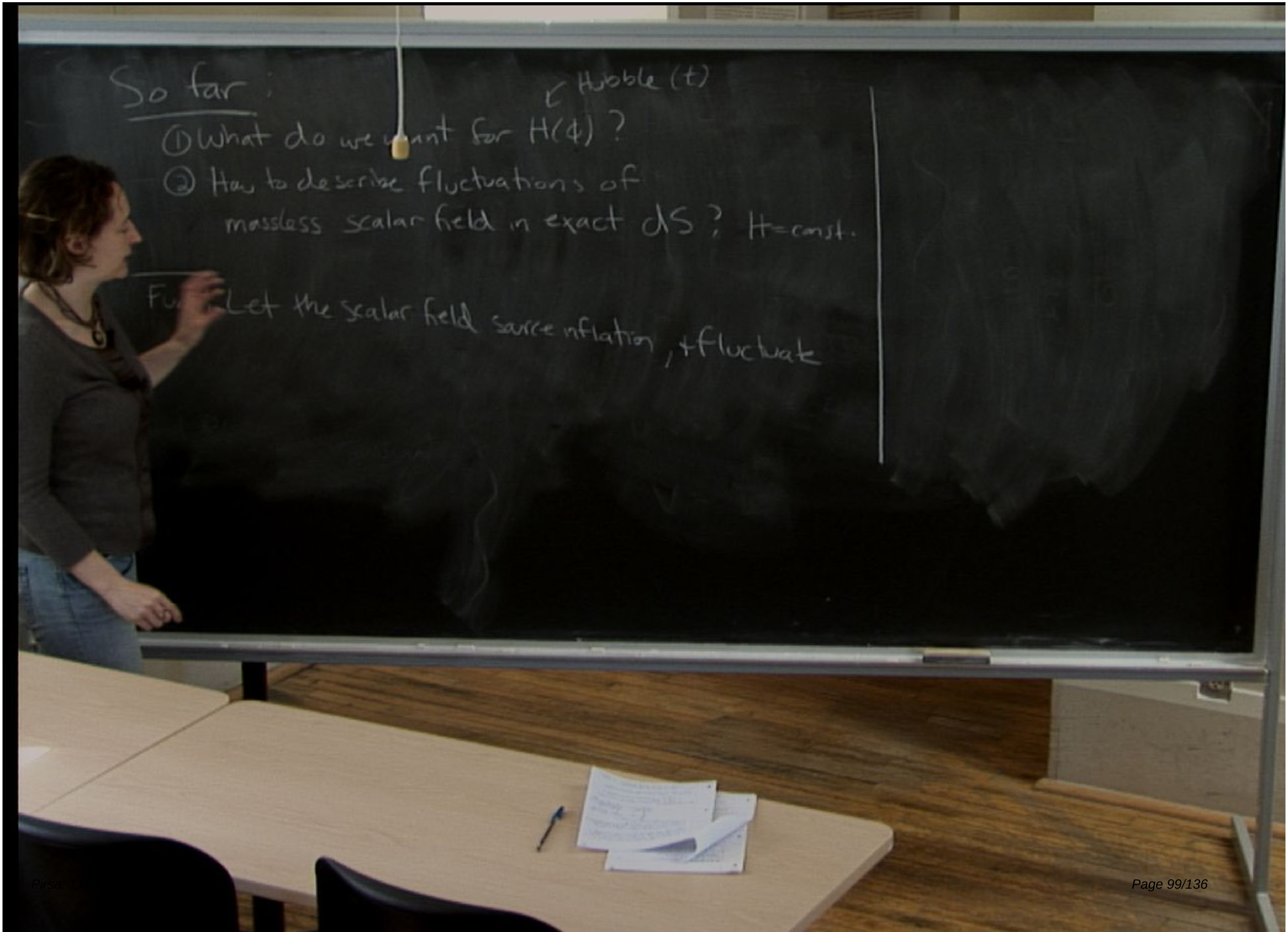
$\phi \to \phi + c$

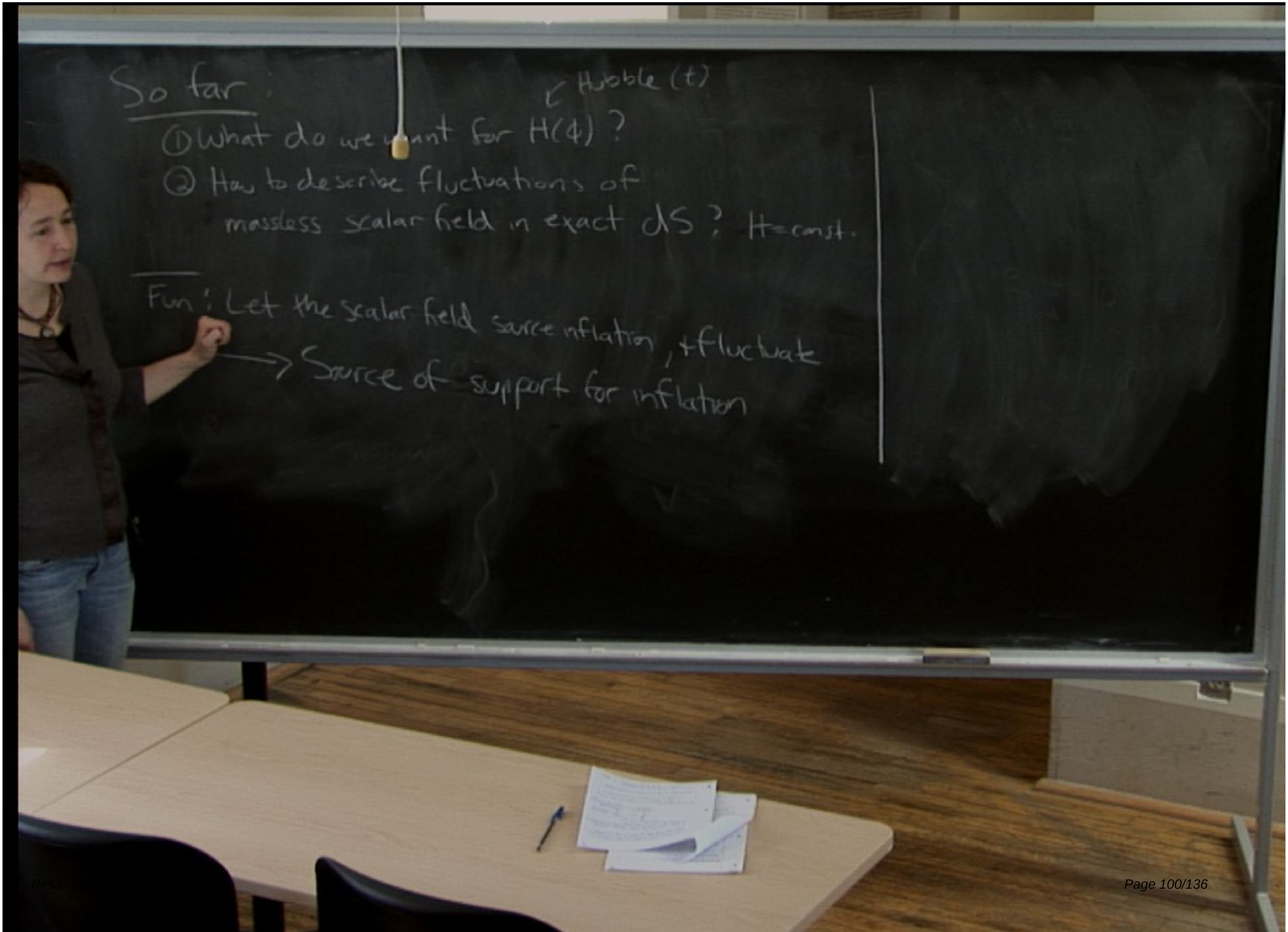

So far:
① What do we want for H(φ)?


So far:
① What do we want for H(ϕ)?
②


So far:
Hubble
① What do we want for H(ϕ)?
② How to describe fluctuations of
massless


So far:
Hubble (t)
① What do we want for H(φ)?
② How to describe fluctuations of
massless scalar field in exact dS?


So far:
Hubble (t)
① What do we want for H(φ)?
② How to describe fluctuations of
massless scalar field in exact dS? H=const.
Let the scalar field source inflation, + fluctuate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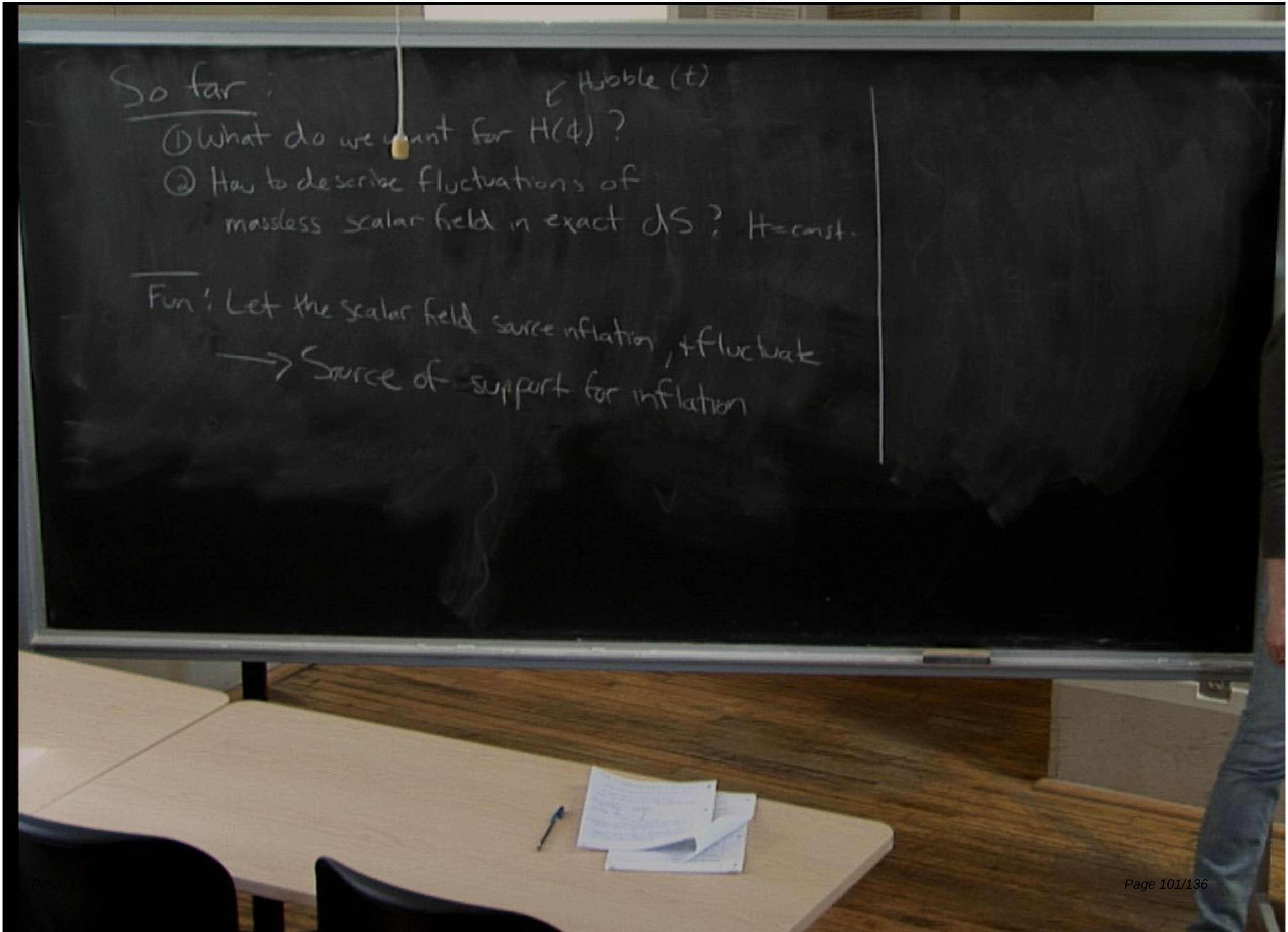
Fun: Let the scalar field source inflation, + fluctuate
→ Source of support for inflation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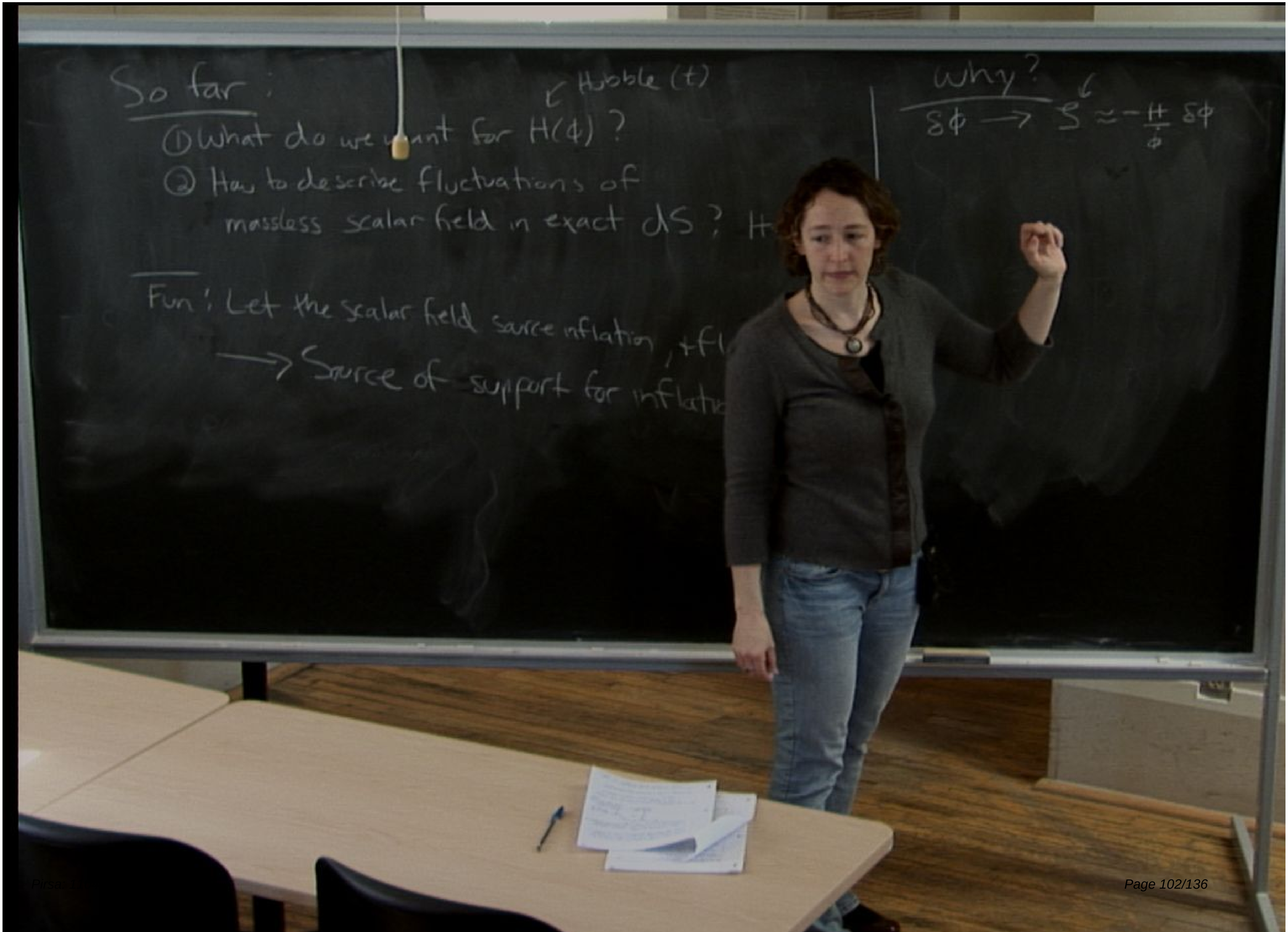

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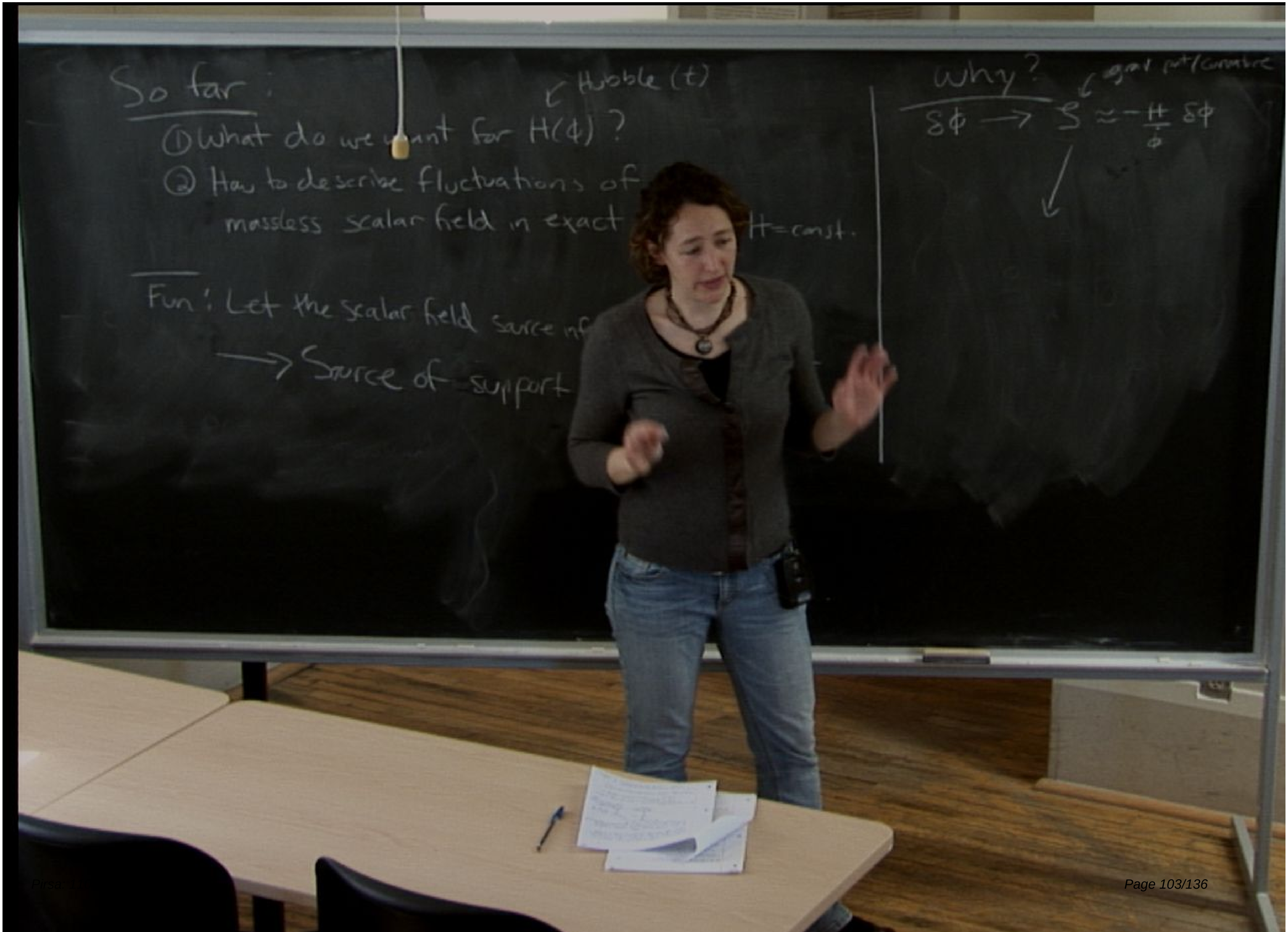
→ Source of support for
why?
δϕ → ζ ≈ −H/ϕ̇ δϕ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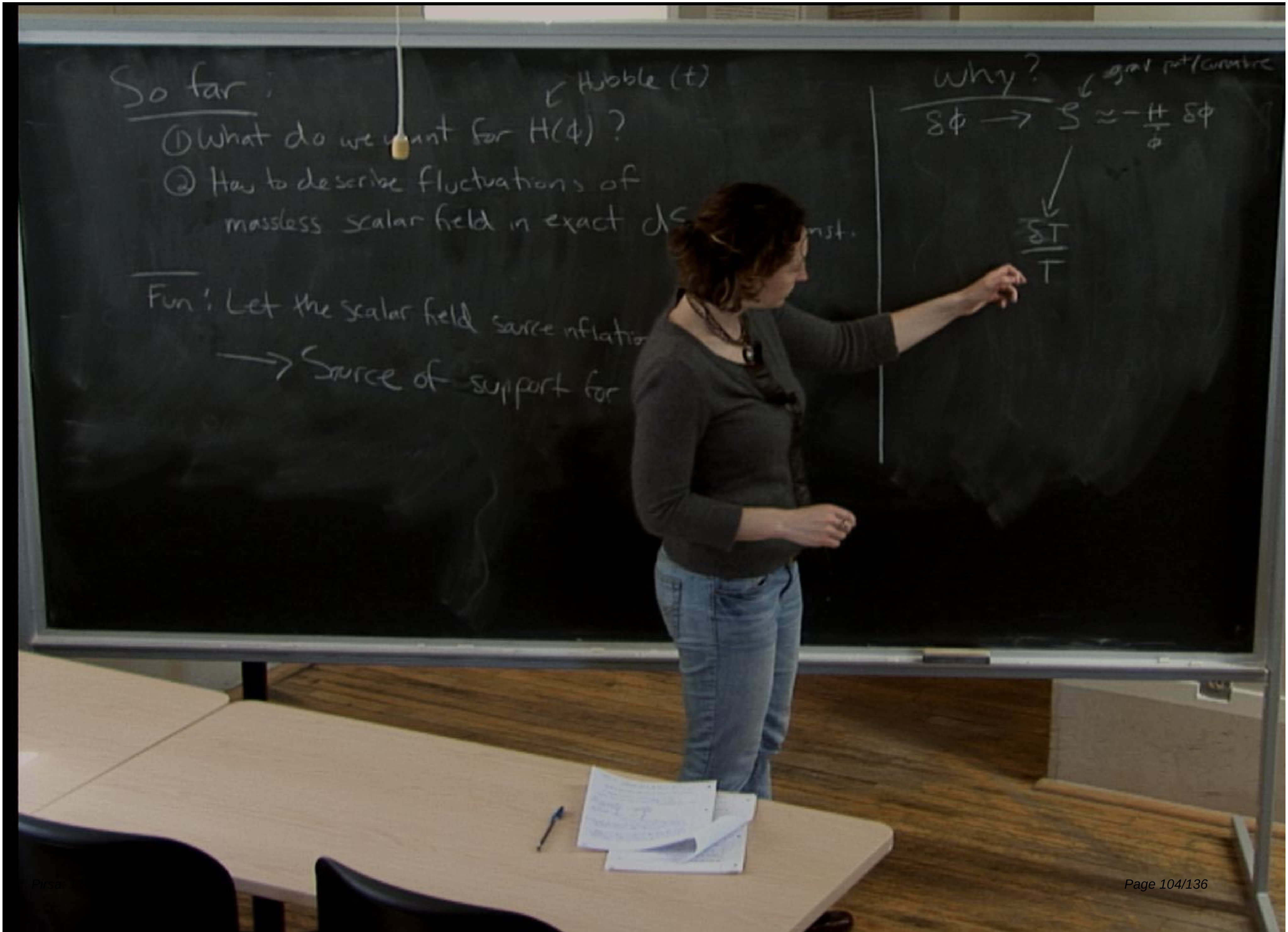
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Hubble (t)
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Fun: Let the scalar field source inflation
→ Source of support for
Why?
grav pot/curvature
δφ → ζ ≈ −H/φ̇ δφ
δT/T

Why?

grav pot / curvature

$$\delta\phi \longrightarrow \zeta \approx -\frac{H}{\dot{\phi}}\,\delta\phi$$

$$\frac{\delta T}{T}$$

CMB

WMAP satellite

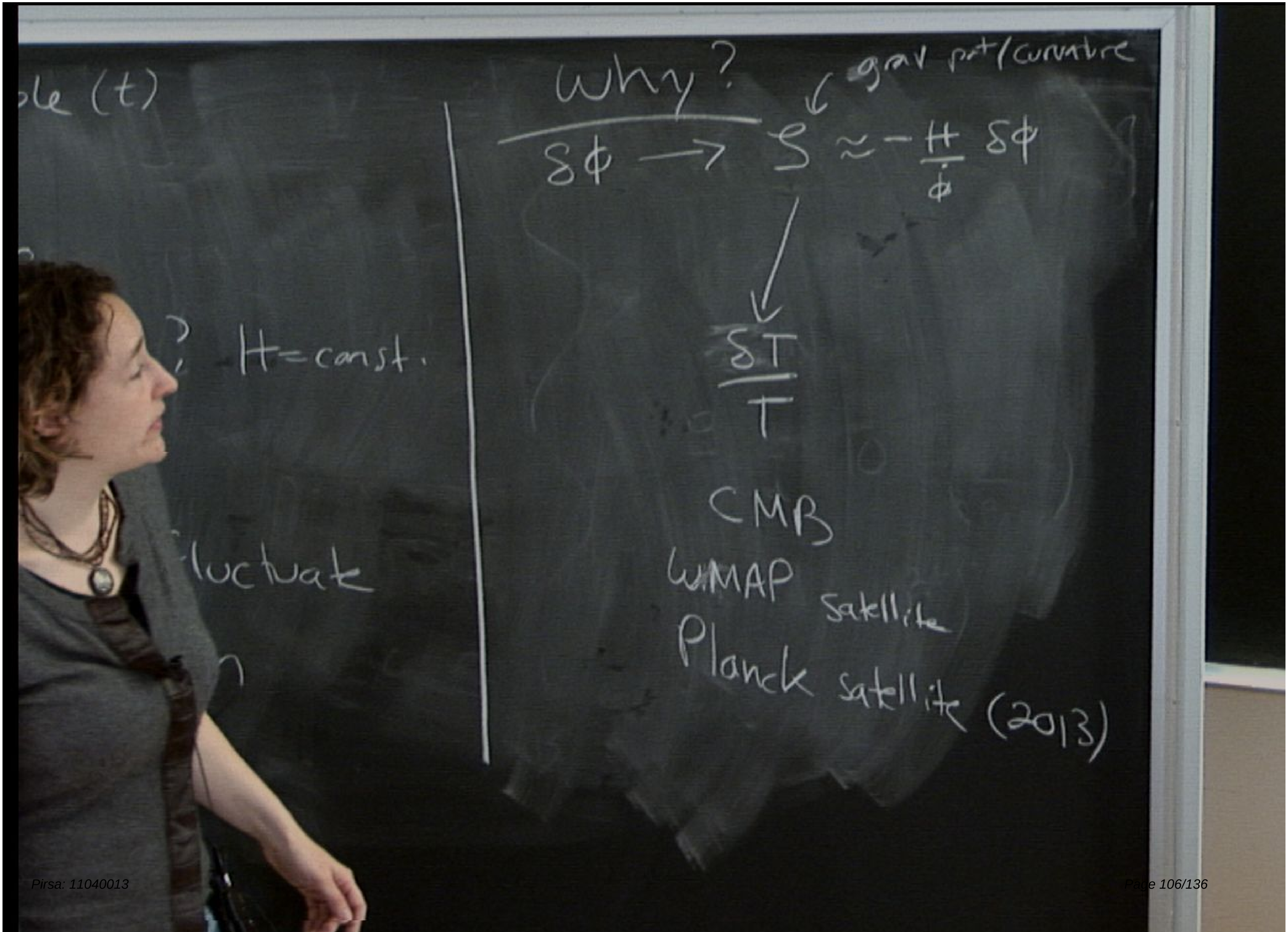
Planck satellite

$= \text{const.}$

uat

ϕ_s

$3 M_P$



le (t)
why?
grav pot/curvature
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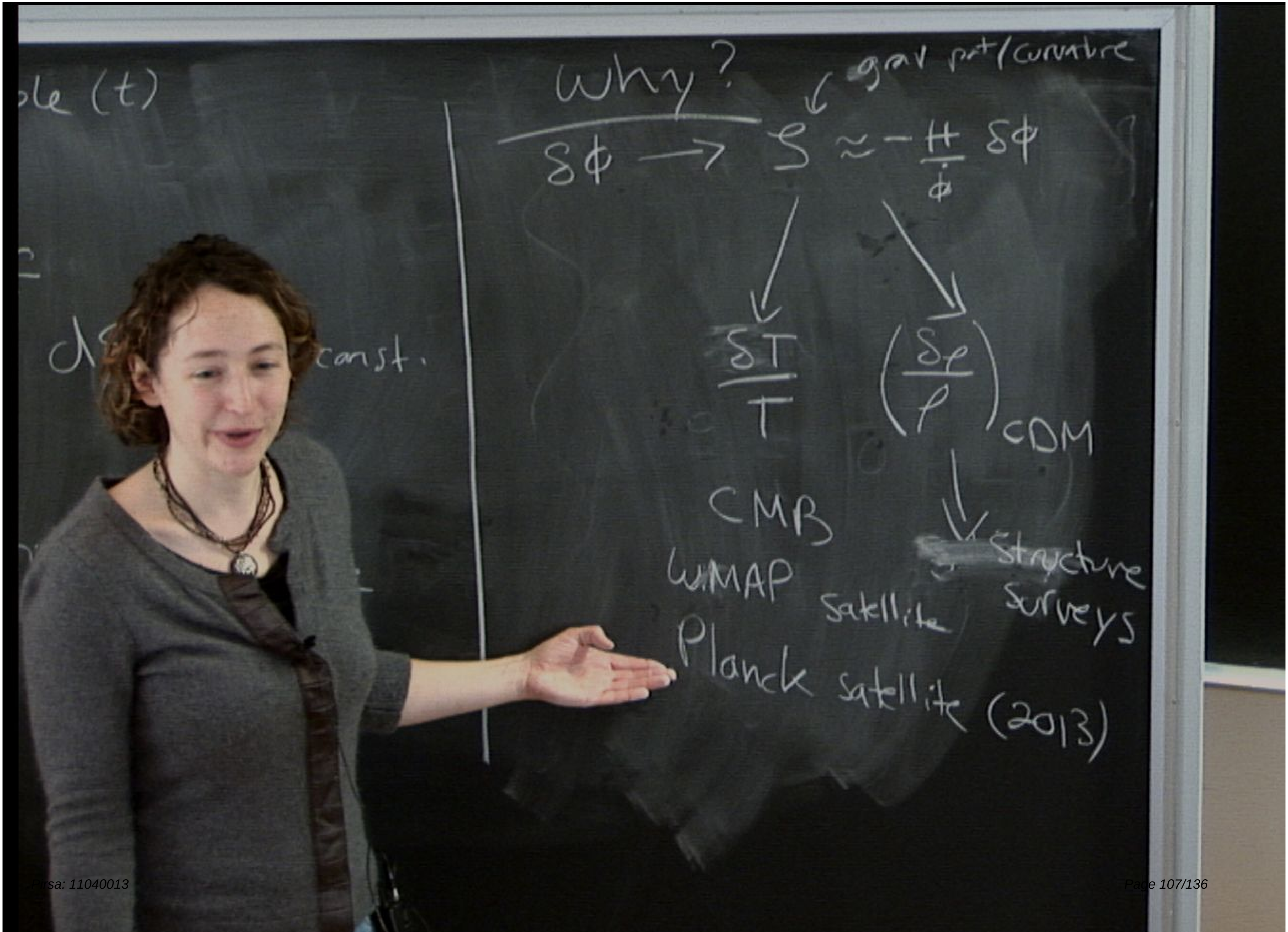
H=const.
$\frac{\delta T}{T}$
CMB
fluctuat
WMAP satellite
Planck satellite (2013)


why?
grav pot/curvature
δφ → ζ ≈ − H/φ̇ δφ
δT/T
(δρ/ρ)
CDM
CMB
WMAP satellite
Planck satellite (2013)
structure surveys
const.

ble (t)

dS ? H = const.

ion, + fluctuat

inflation

why? gravitational potential / curvature

$$\delta\phi \longrightarrow \zeta \approx -\frac{H}{\dot\phi}\,\delta\phi$$

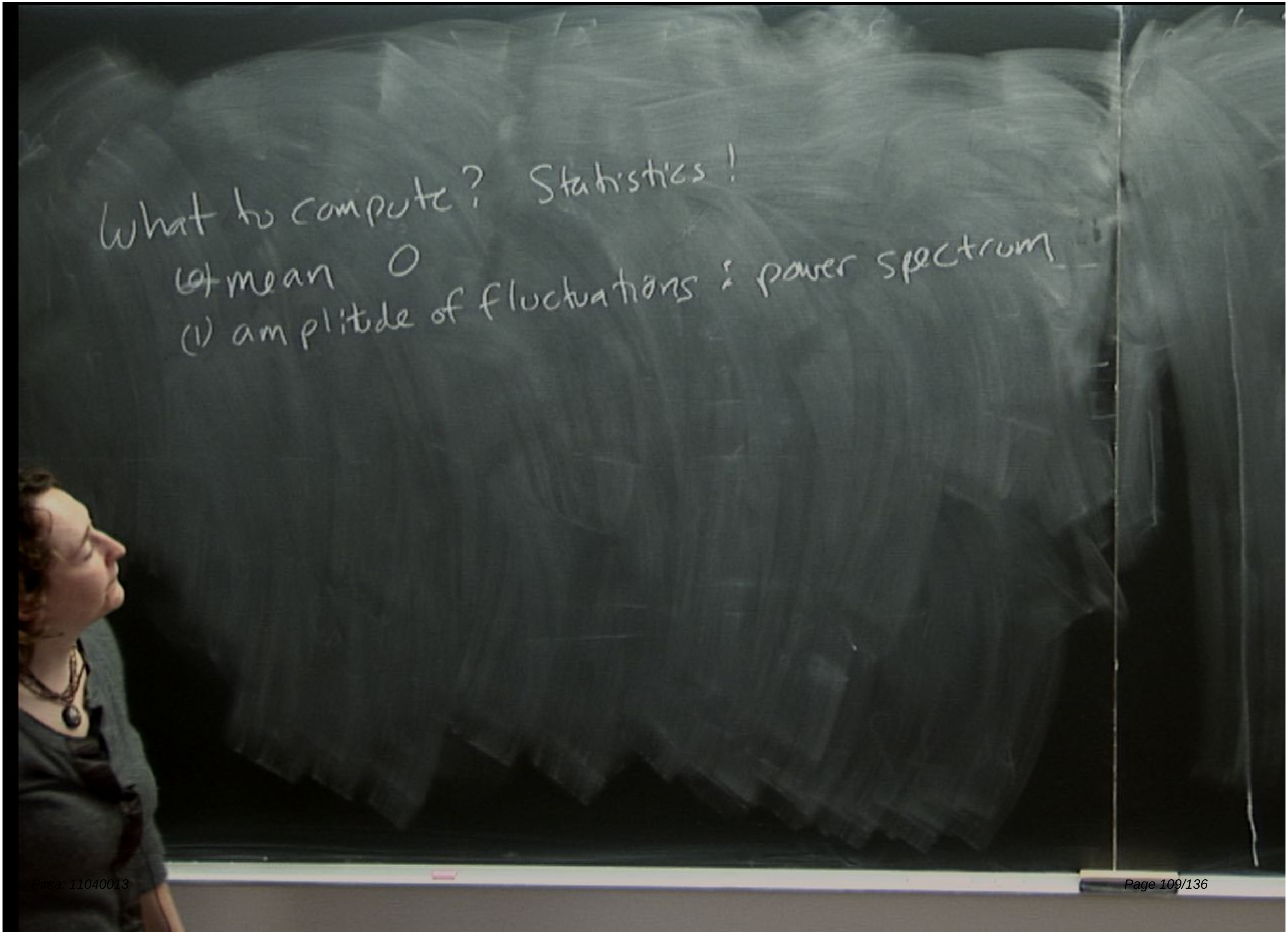
$$\frac{\delta T}{T} \qquad \left(\frac{\delta\rho}{\rho}\right)_{CDM}$$

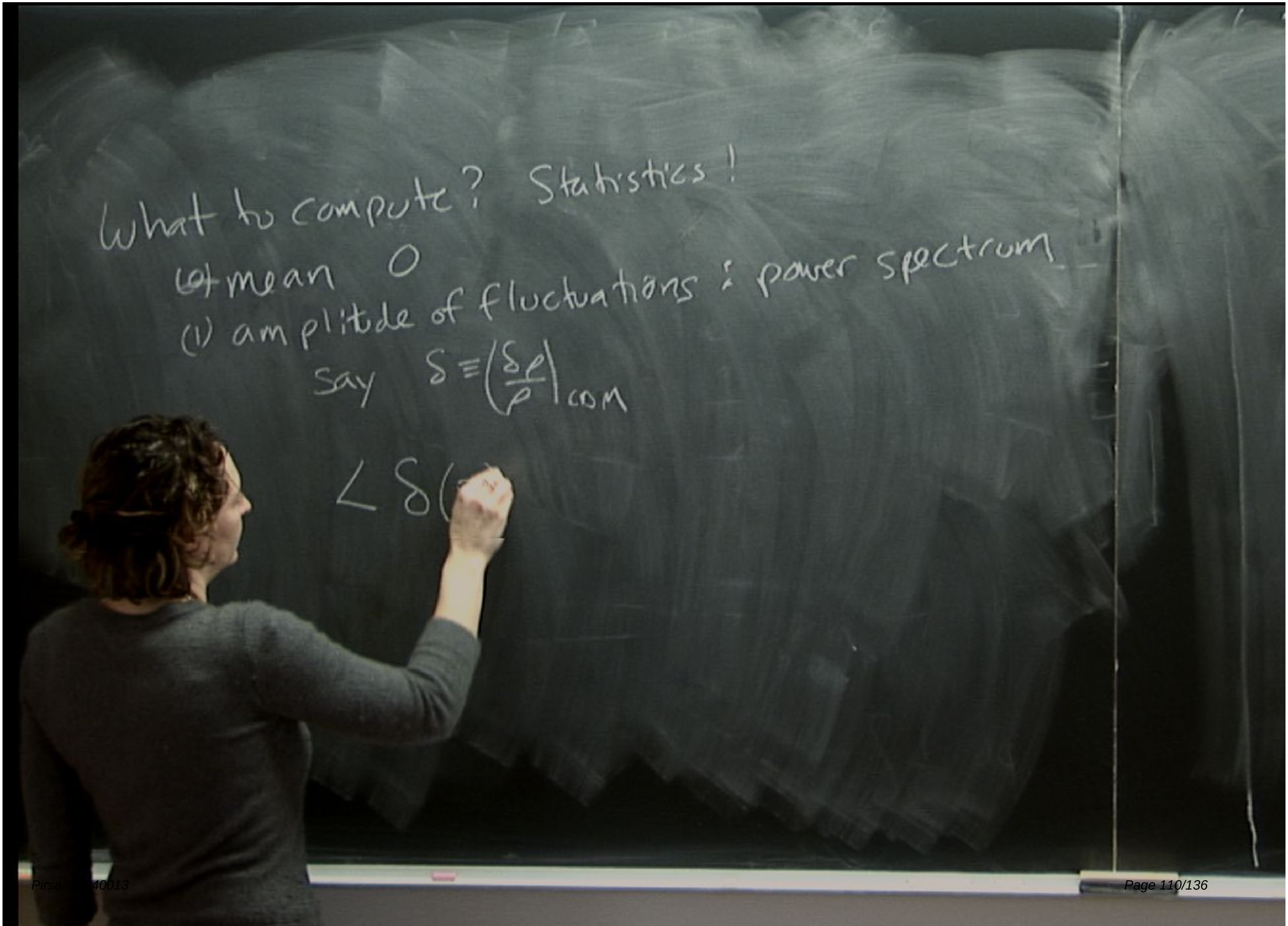
CMB

WMAP satellite

Planck satellite (2013)

structure surveys


What to compute? Statistics!
(0) mean 0
(1) amplitude of fluctuations : power spectrum



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say $\delta \equiv \left(\frac{\delta\rho}{\rho}\right)_{com}$
$\langle \delta($

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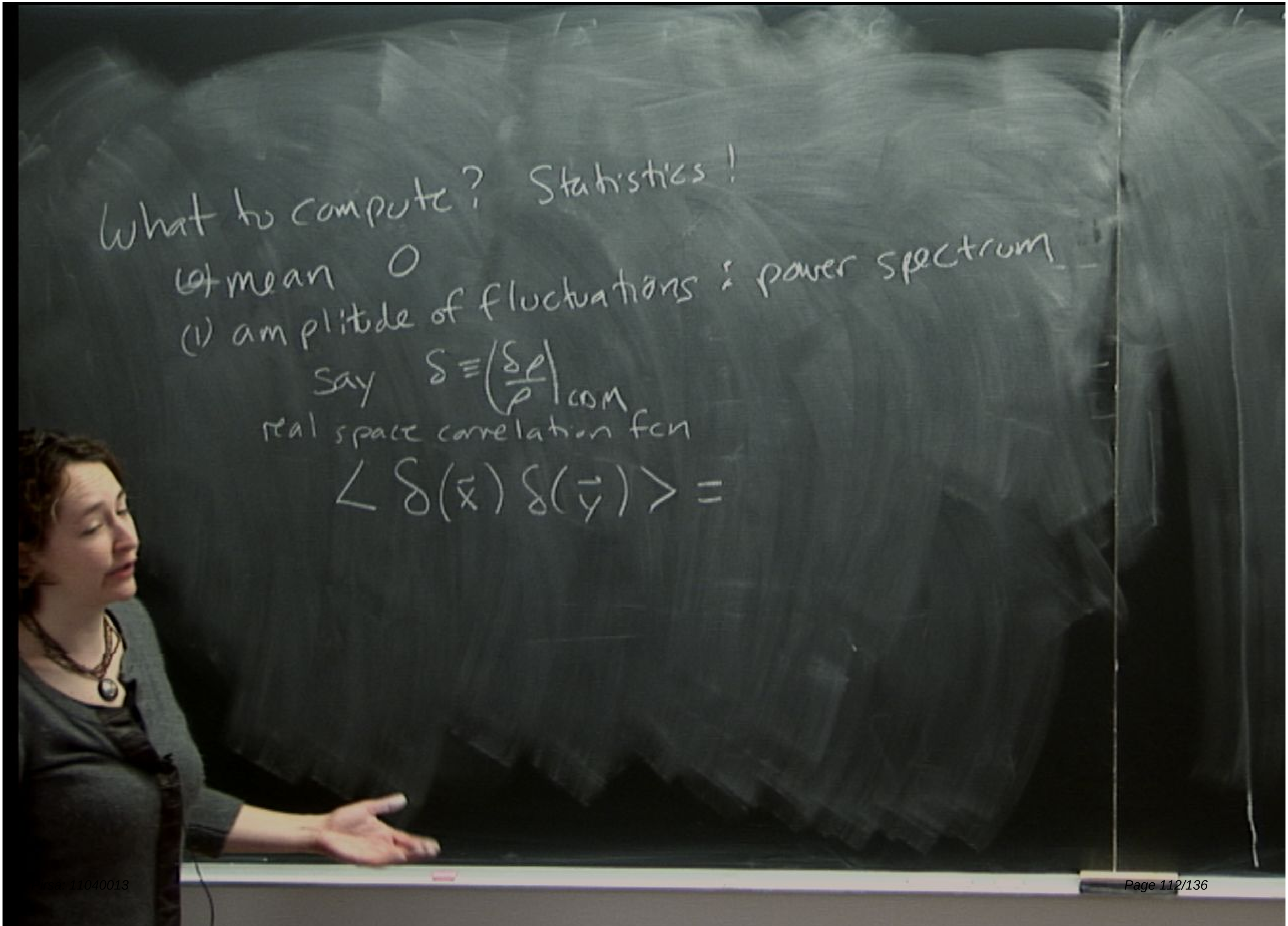
$$\langle \delta(\vec{x})\, \delta(\vec{y}) \rangle$$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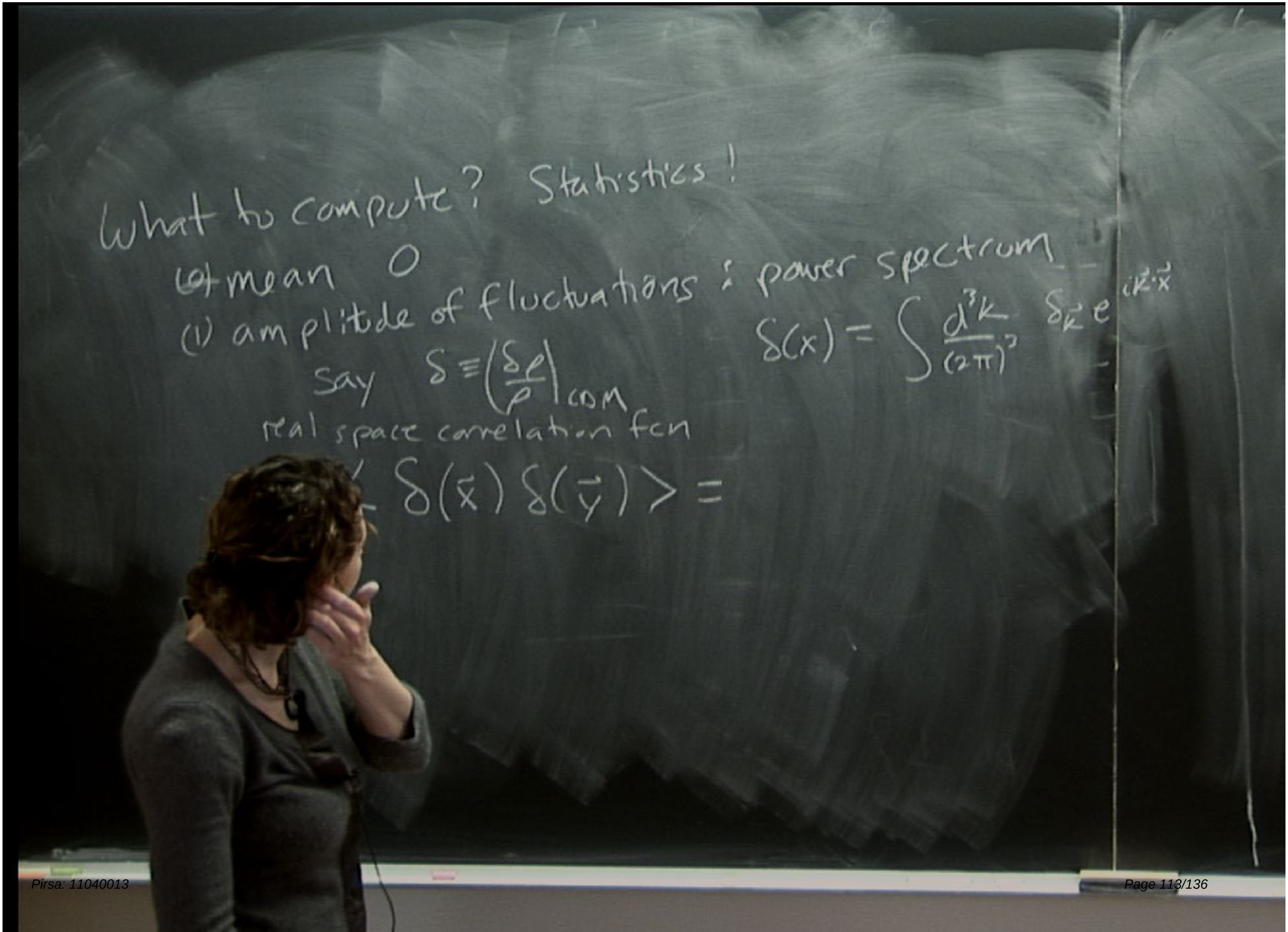
say δ ≡ (δρ/ρ)com
real space correlation fcn
< δ(x⃗) δ(y⃗) > =


What to compute? Statistics!
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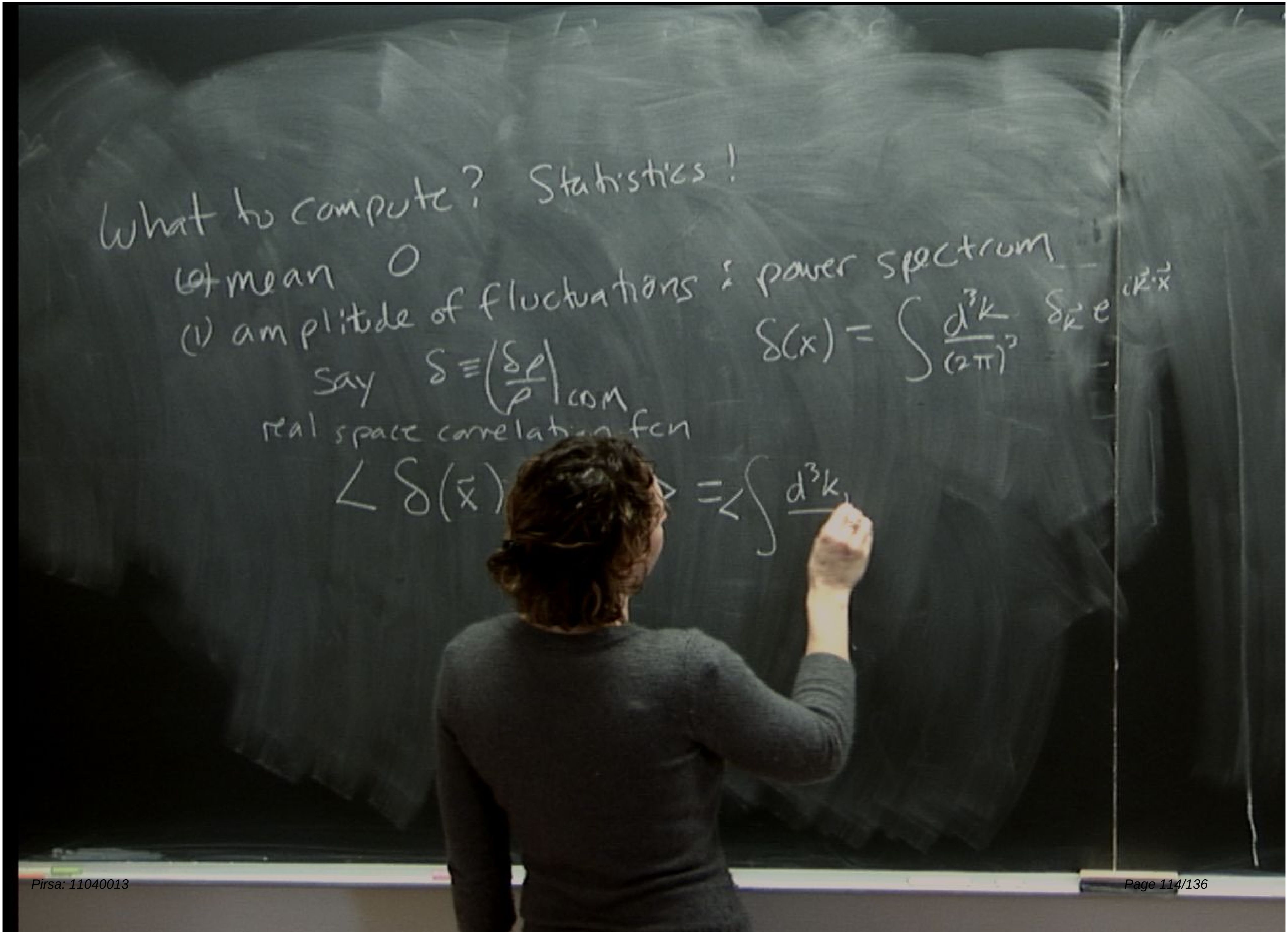
say $\delta \equiv \left(\frac{\delta\rho}{\rho}\right)_{CDM}$
$\delta(x) = \int \frac{d^3k}{(2\pi)^3} \delta_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}$
real space correlation fcn
$\langle \delta(\vec{x}) \delta(\vec{y}) \rangle =$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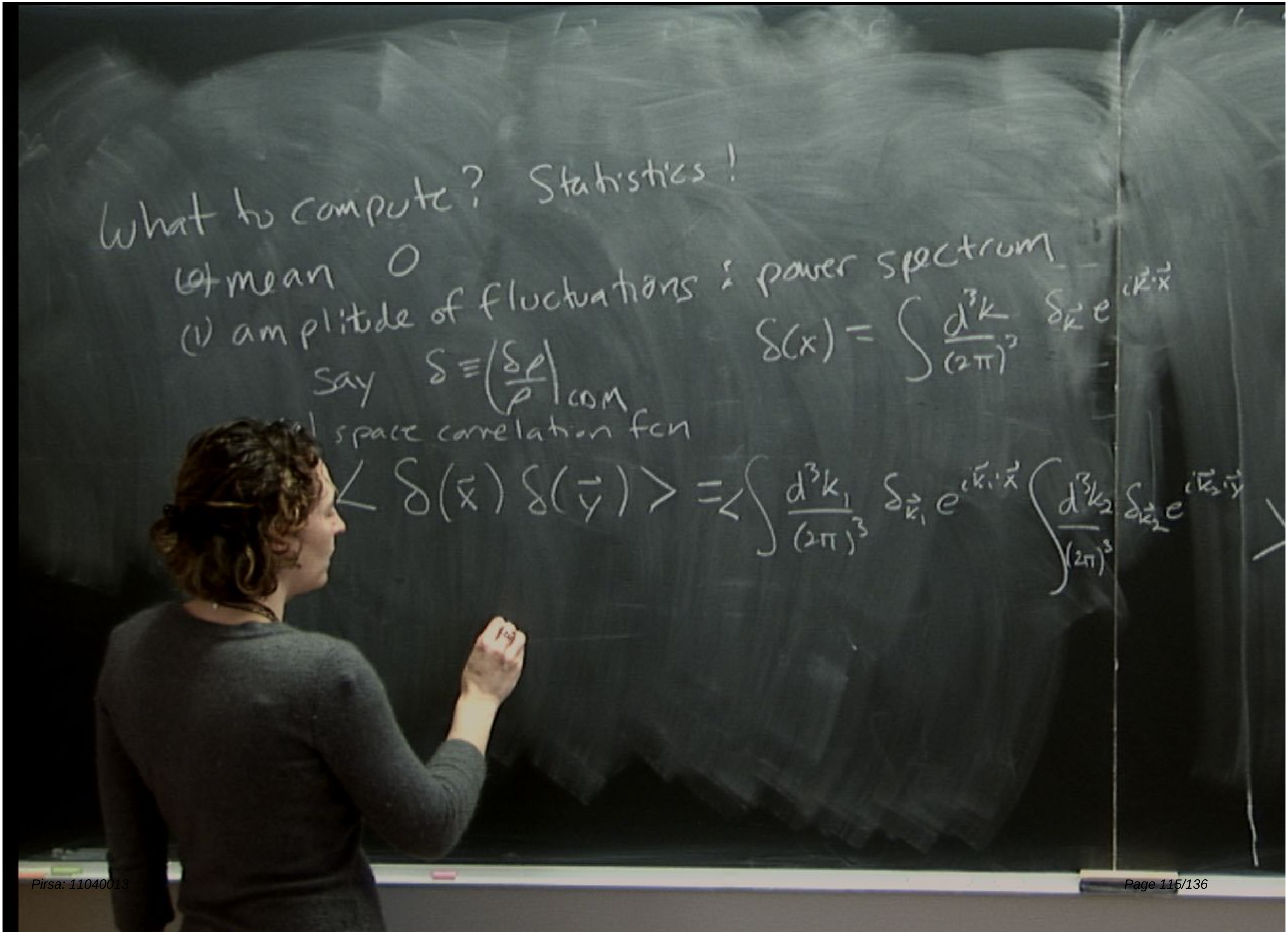
real space correlation fcn
$\langle \delta(\vec{x})$
$\rangle = \langle \int \frac{d^3k}{}$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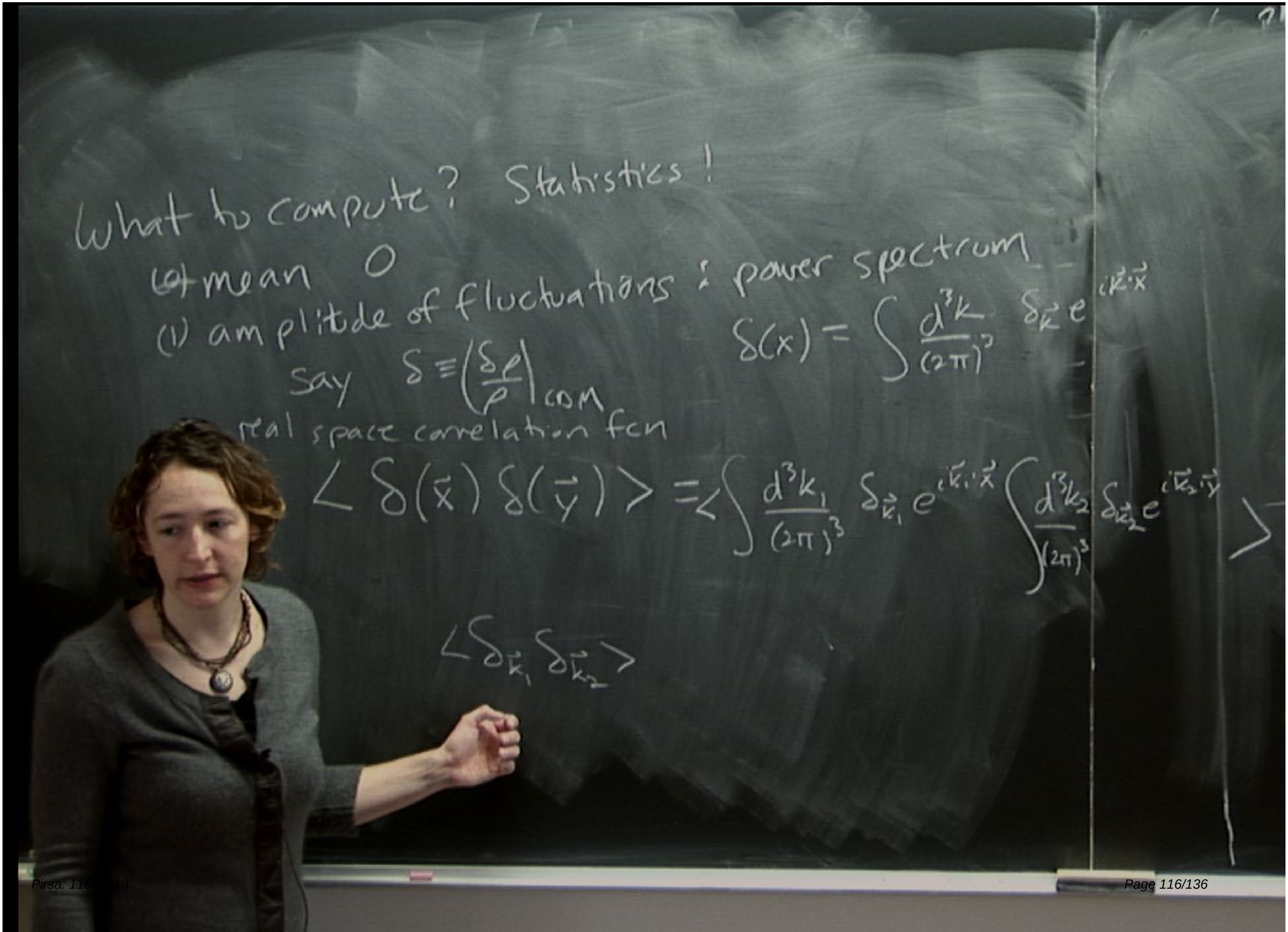
space correlation fcn
$\langle \delta(\vec{x})\,\delta(\vec{y}) \rangle = \langle \int \frac{d^3k_1}{(2\pi)^3} \delta_{\vec{k}_1} e^{i\vec{k}_1\cdot\vec{x}} \int \frac{d^3k_2}{(2\pi)^3} \delta_{\vec{k}_2} e^{i\vec{k}_2\cdot\vec{y}} \rangle$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$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle$

What to compute? Statistics!

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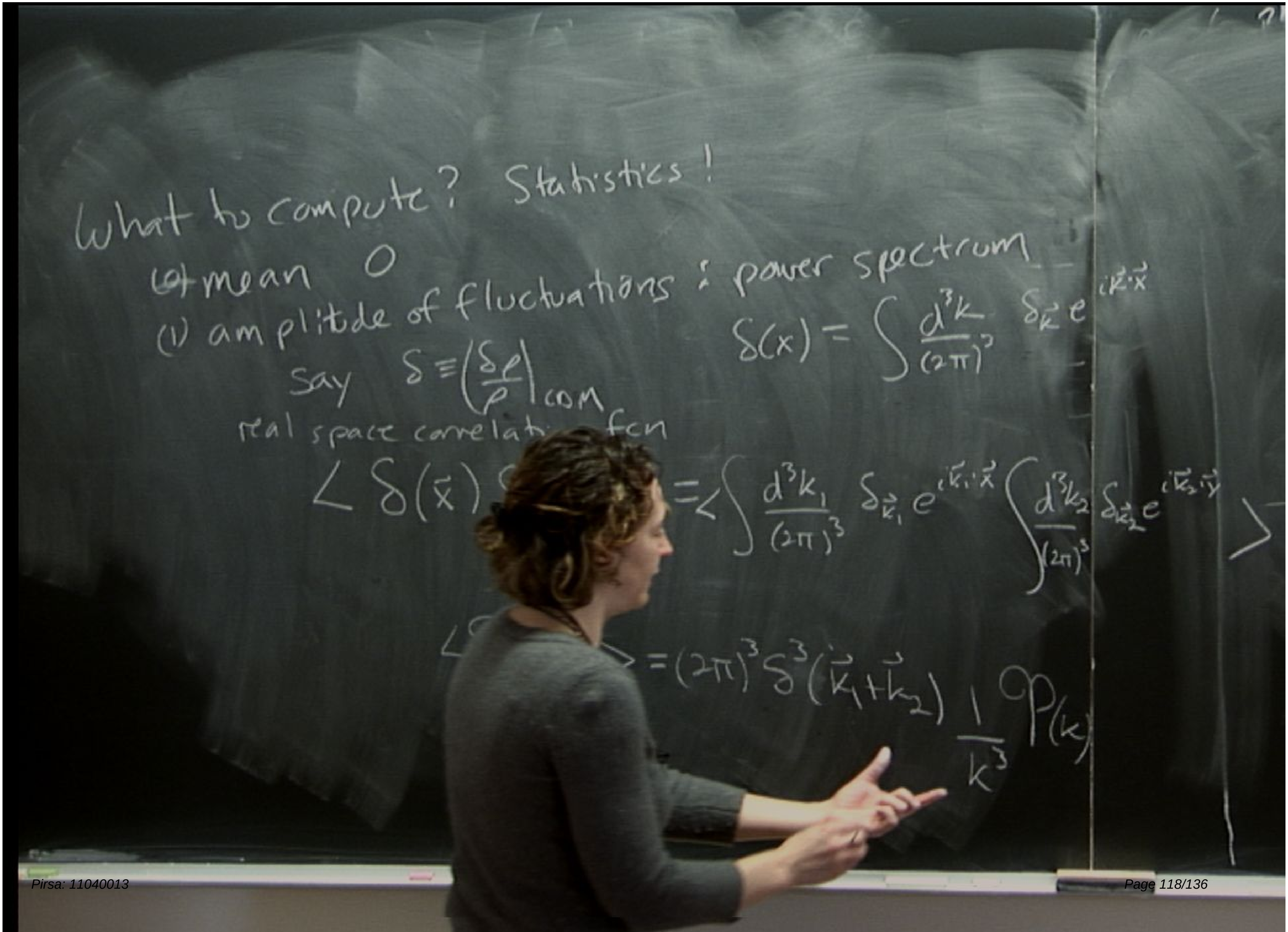
say $\delta \equiv \left(\frac{\delta\rho}{\rho}\right)_{COM}$

$$\delta(x) = \int \frac{d^3k}{(2\pi)^3}\, \delta_{\vec{k}}\, e^{i\vec{k}\cdot\vec{x}}$$

real space correlation fcn

$$\langle \delta(\vec{x})\, \delta(\vec{y}) \rangle = \left\langle \int \frac{d^3k_1}{(2\pi)^3}\, \delta_{\vec{k}_1}\, e^{i\vec{k}_1\cdot\vec{x}} \int \frac{d^3k_2}{(2\pi)^3}\, \delta_{\vec{k}_2}\, e^{i\vec{k}_2\cdot\vec{y}} \right\rangle$$

$$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = (2\pi)^3 \delta^3$$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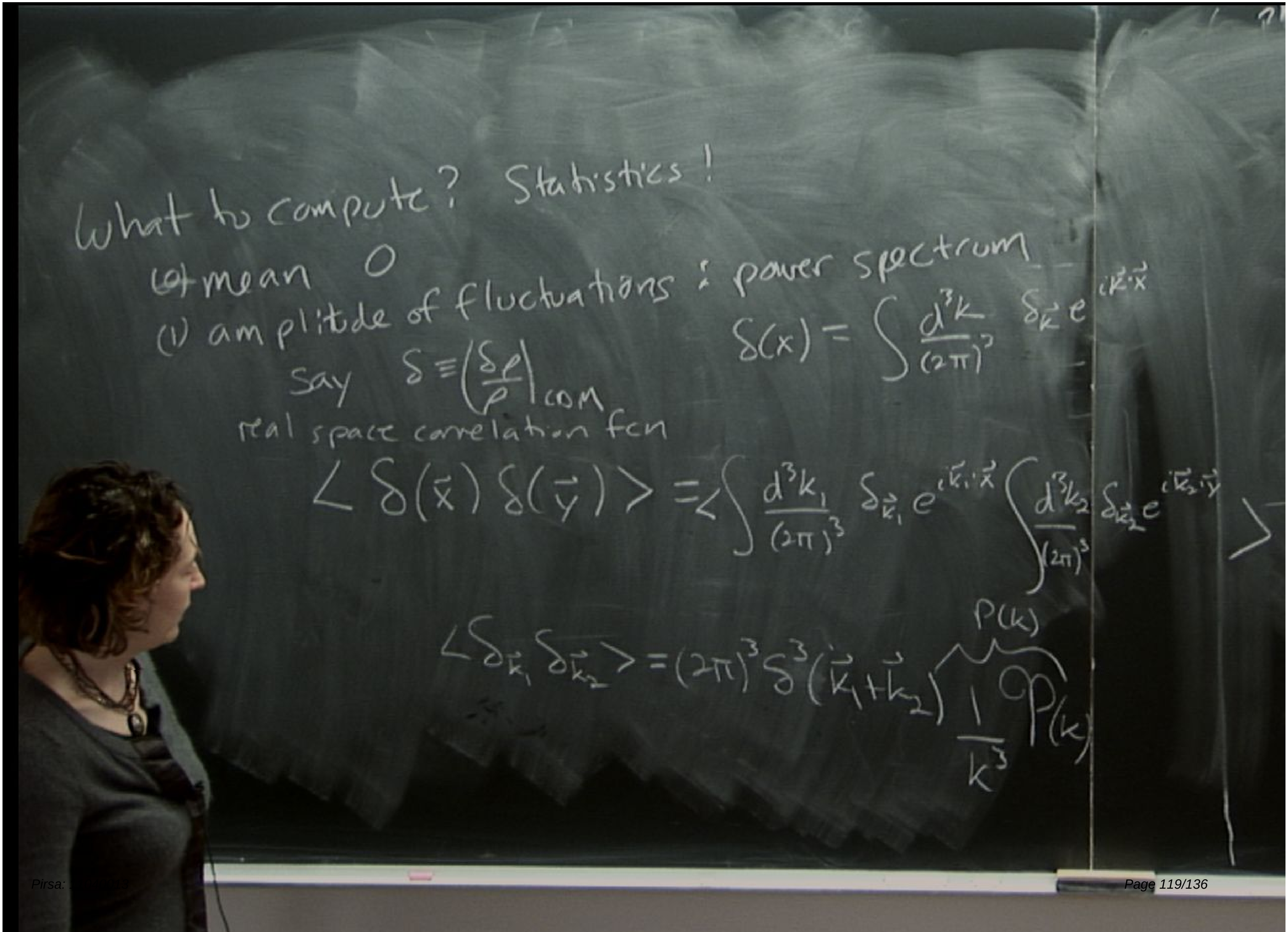
real space correlat fcn
$\langle \delta(\vec{x})$
$= \langle \int \frac{d^3k_1}{(2\pi)^3}\, \delta_{\vec{k}_1}\, e^{i\vec{k}_1\cdot\vec{x}} \int \frac{d^3k_2}{(2\pi)^3}\, \delta_{\vec{k}_2}\, e^{i\vec{k}_2\cdot\vec{y}} \rangle$
$= (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2)\, \frac{1}{k^3}\, \mathcal{P}(k)$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$\langle \delta(\vec{x})\,\delta(\vec{y}) \rangle = \langle \int \frac{d^3k_1}{(2\pi)^3} \delta_{\vec{k}_1} e^{i\vec{k}_1\cdot\vec{x}} \int \frac{d^3k_2}{(2\pi)^3} \delta_{\vec{k}_2} e^{i\vec{k}_2\cdot\vec{y}} \rangle$
$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2) \overbrace{\frac{1}{k^3}\mathcal{P}(k)}^{P(k)}$

What to compute? Statistics!

(0) mean 0

(1) amplitude of fluctuations : power spectrum

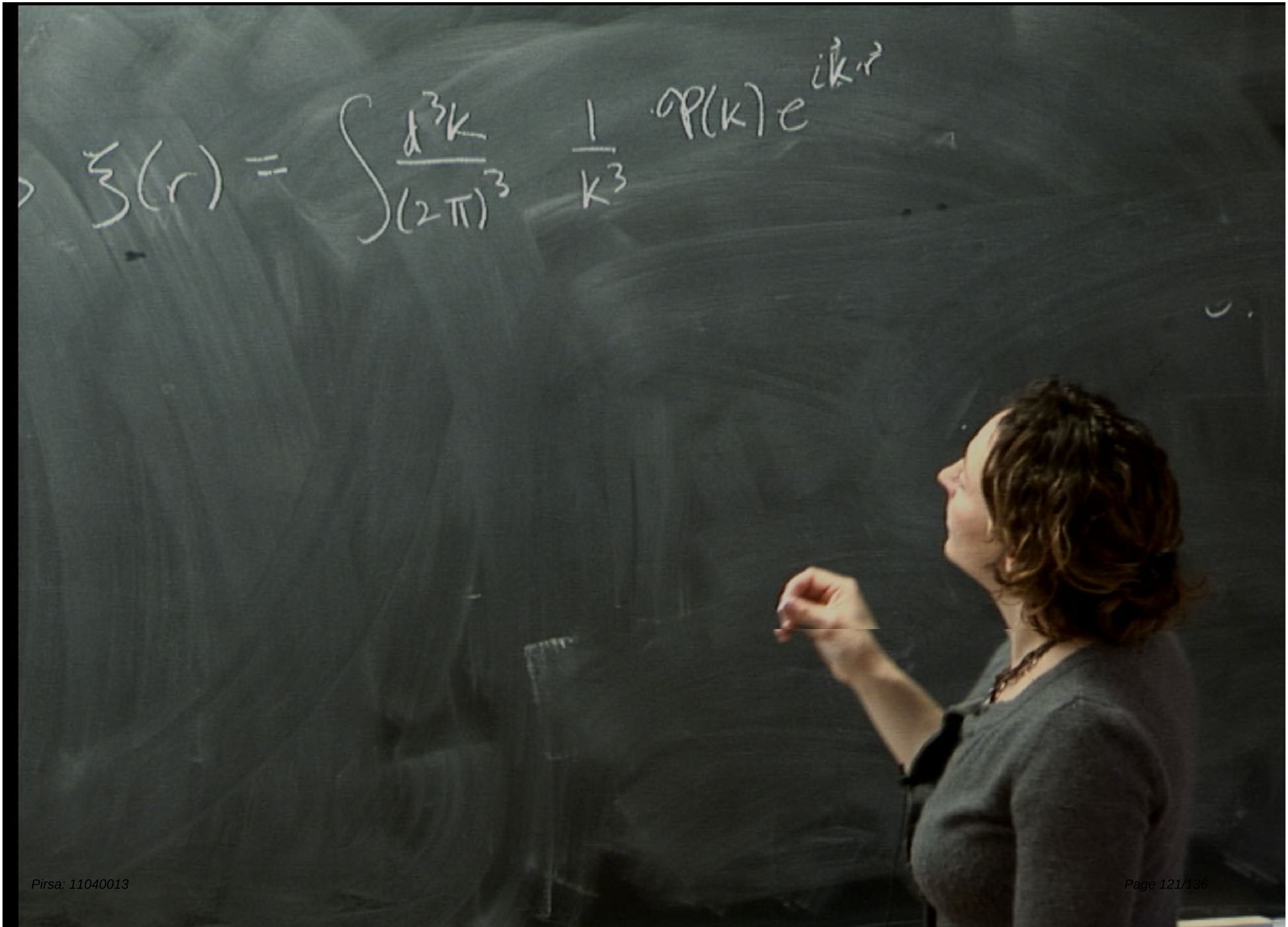
$$\delta(x) = \int \frac{d^3k}{(2\pi)^3} \delta_{\vec{k}}$$

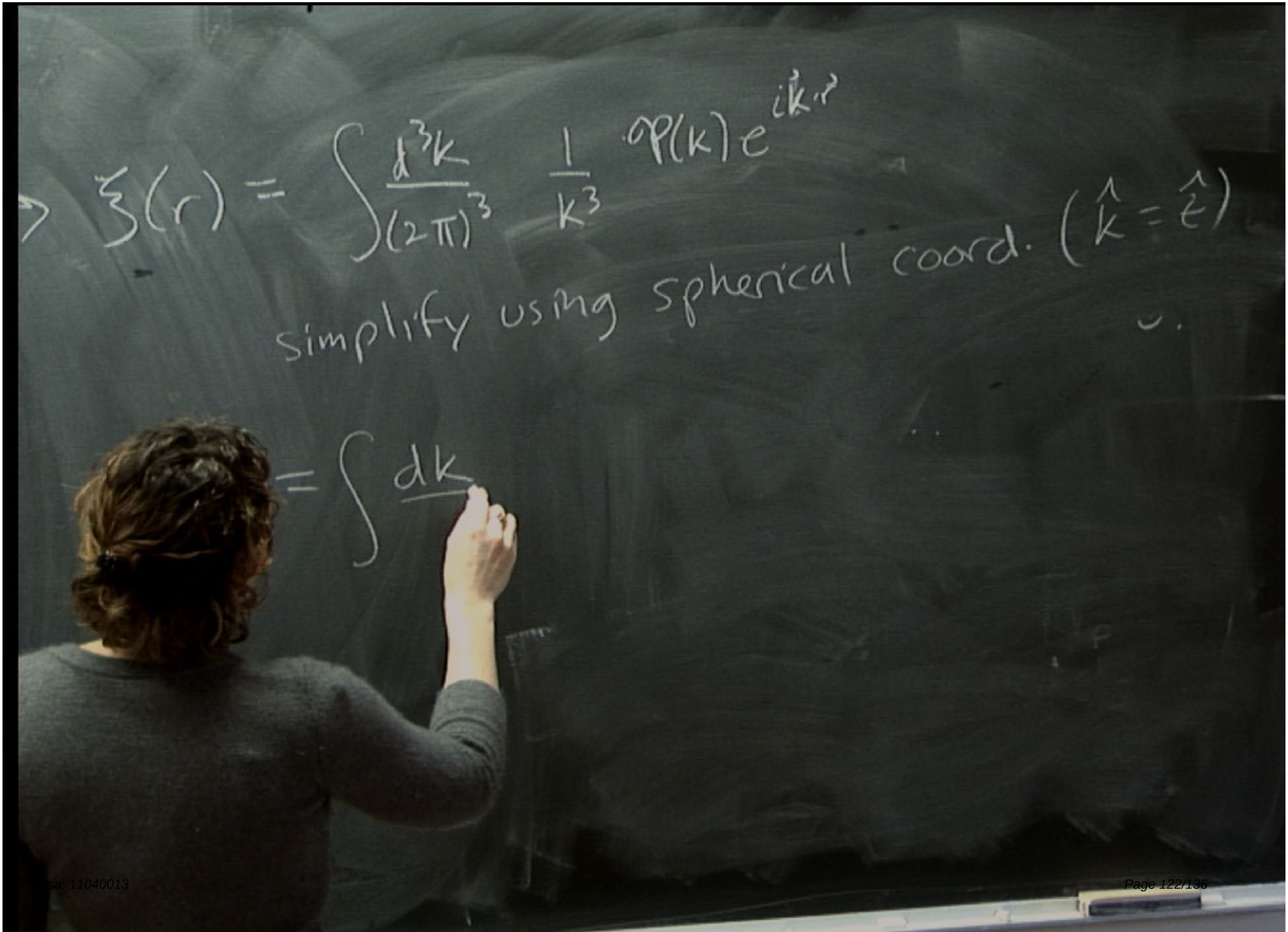
say $\delta \equiv \left(\frac{\delta\rho}{\rho}\right)_{COM}$

real space correlation fcn

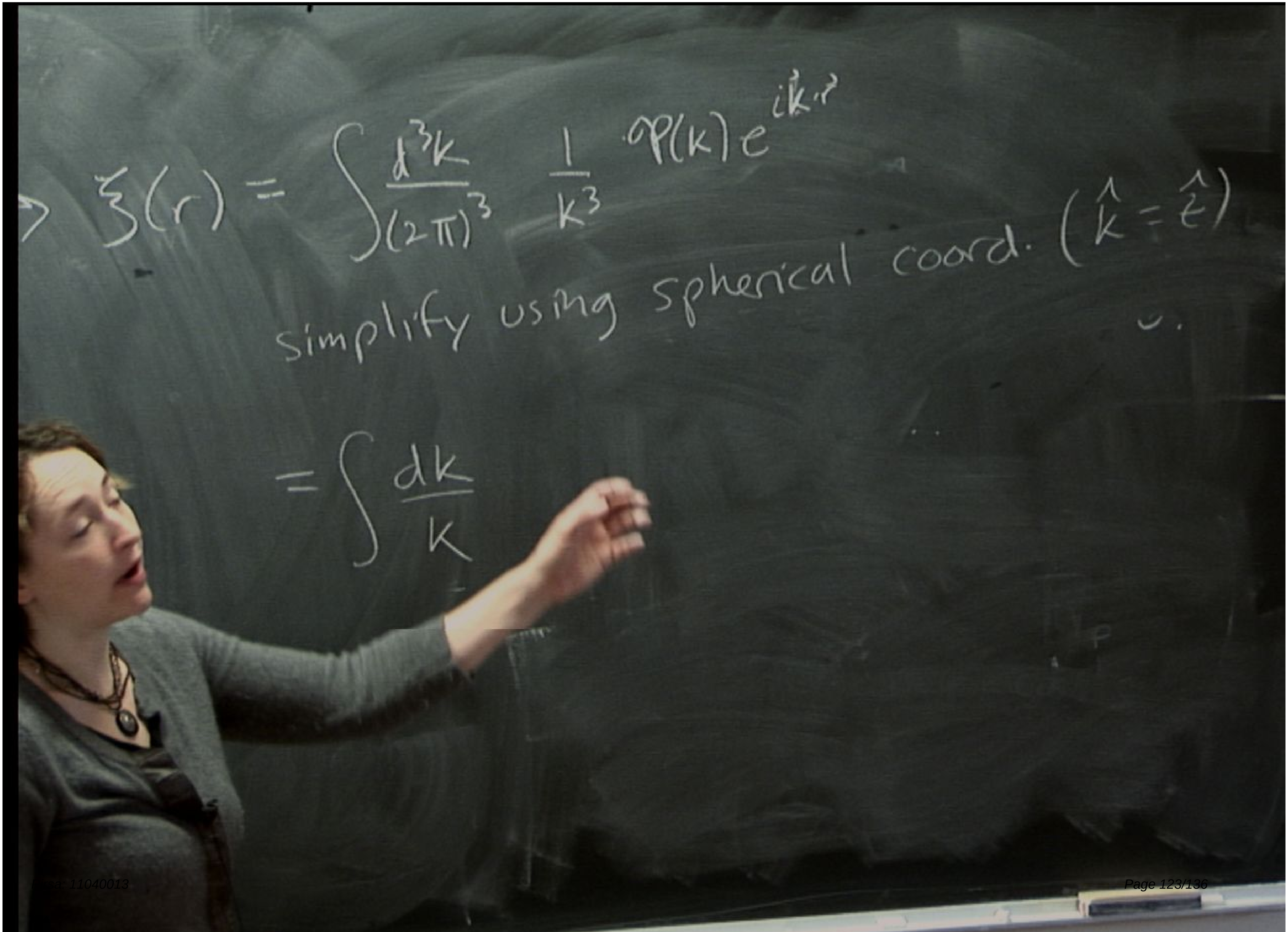
$$\xi(\underbrace{|\vec{x}-\vec{y}|}_{r}) = \langle \delta(\vec{x})\, \delta(\vec{y}) \rangle = \langle \int \frac{d^3k_1}{(2\pi)^3} \delta_{\vec{k}_1} e^{i\vec{k}_1\cdot\vec{x}} \int \frac{d^3k}{(2\pi)}$$

$$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2) \overbrace{\frac{1}{k^3}\mathcal{P}(k}^{P(k)}$$


$\xi(r) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{k^3} \mathcal{P}(k) e^{i\vec{k}\cdot\vec{r}}$



$\Rightarrow \xi(r) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{k^3} \mathcal{P}(k) e^{i\vec{k}\cdot\vec{r}}$
simplify using spherical coord. $(\hat{k} = \hat{z})$
$= \int \frac{dk}{\ }$



$\Rightarrow \xi(r) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{k^3} \cdot P(k) e^{i\vec{k}\cdot\vec{r}}$
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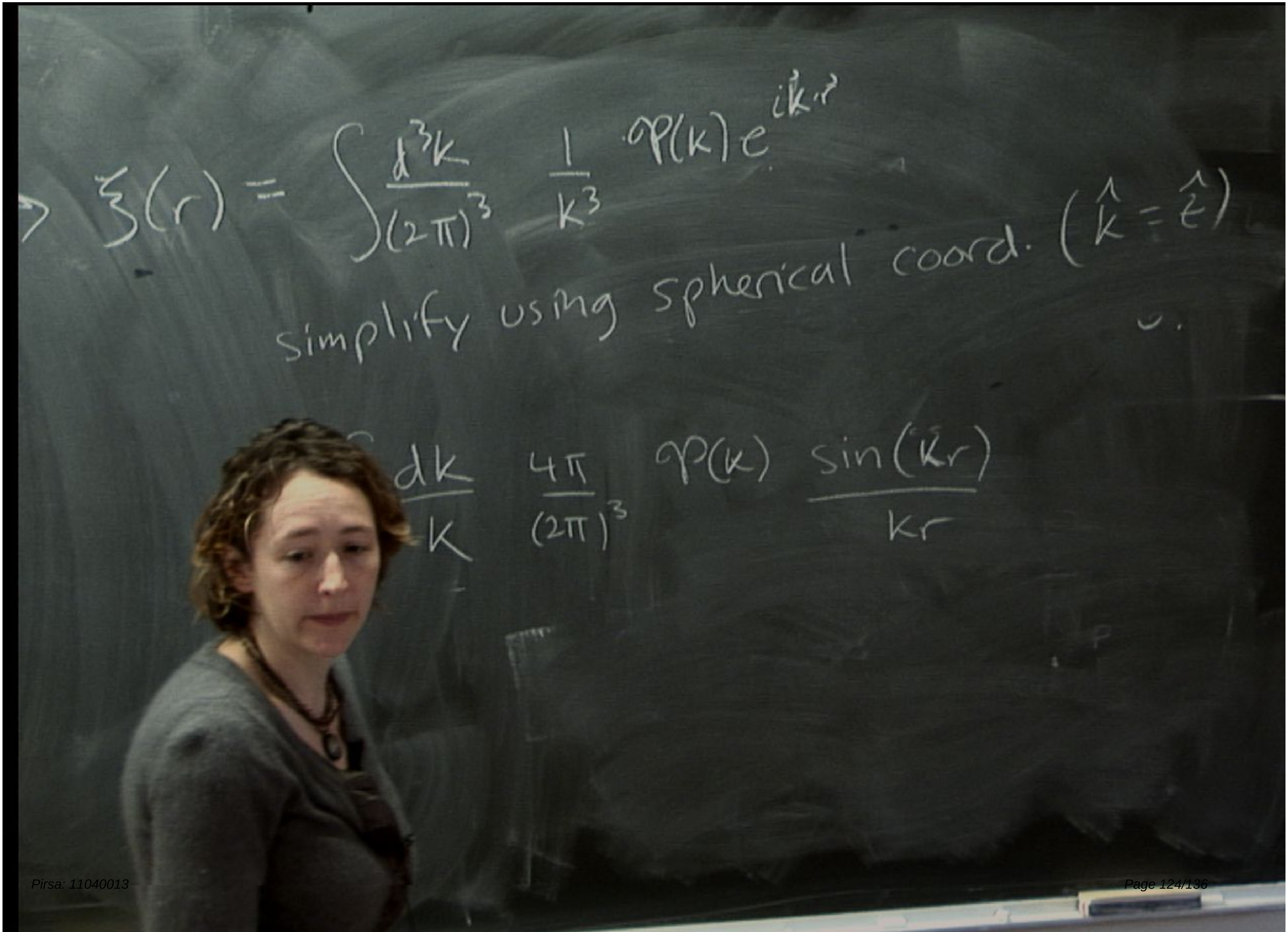
$= \int \frac{dk}{k}$



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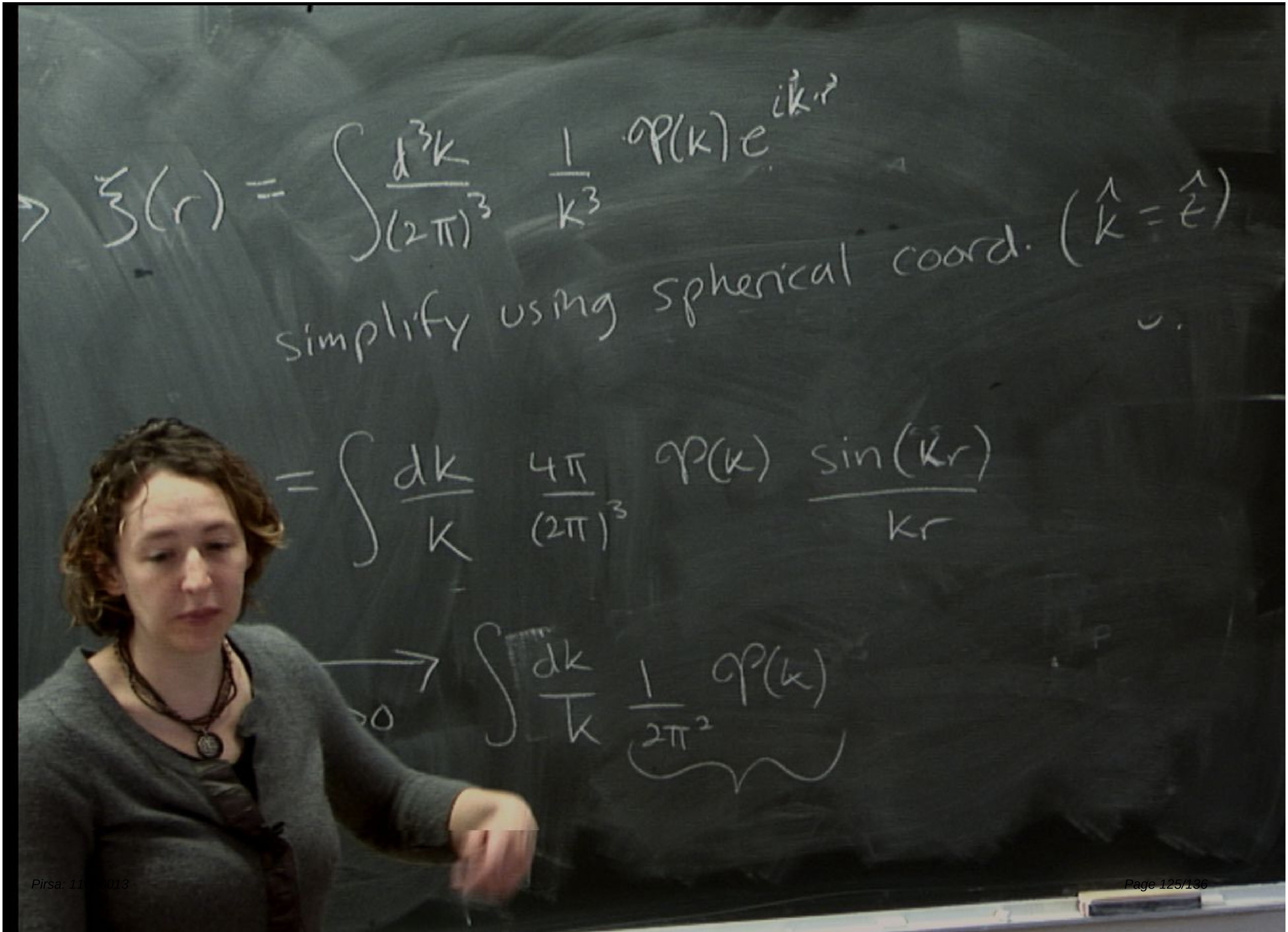
$\int \frac{dk}{k} \frac{4\pi}{(2\pi)^3} \mathcal{P}(k) \frac{\sin(kr)}{kr}$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simplify using spherical coord. $(\hat{k} = \hat{z})$
$= \int \frac{dk}{k} \frac{4\pi}{(2\pi)^3} \mathcal{P}(k) \frac{\sin(kr)}{kr}$
$\longrightarrow \int \frac{dk}{k} \underbrace{\frac{1}{2\pi^2} \mathcal{P}(k)}$

$$\Rightarrow \xi(r) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{k^3} \mathcal{P}(k) e^{i\vec{k}\cdot\vec{r}}$$

simplify using spherical coord. $(\hat{k} = \hat{z})$

$$= \int \frac{dk}{k} \frac{4\pi}{(2\pi)^3} \mathcal{P}(k) \frac{\sin(kr)}{kr}$$

$$\xrightarrow[r\to 0]{} \int \frac{dk}{k} \underbrace{\frac{1}{2\pi^2} \mathcal{P}(k)}_{\Delta^2(k)}$$

$$\Rightarrow \xi(r) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{k^3} \mathcal{P}(k) e^{i\vec{k}\cdot\vec{r}}$$

simplify using spherical coord. $(\hat{k} = \hat{z})$

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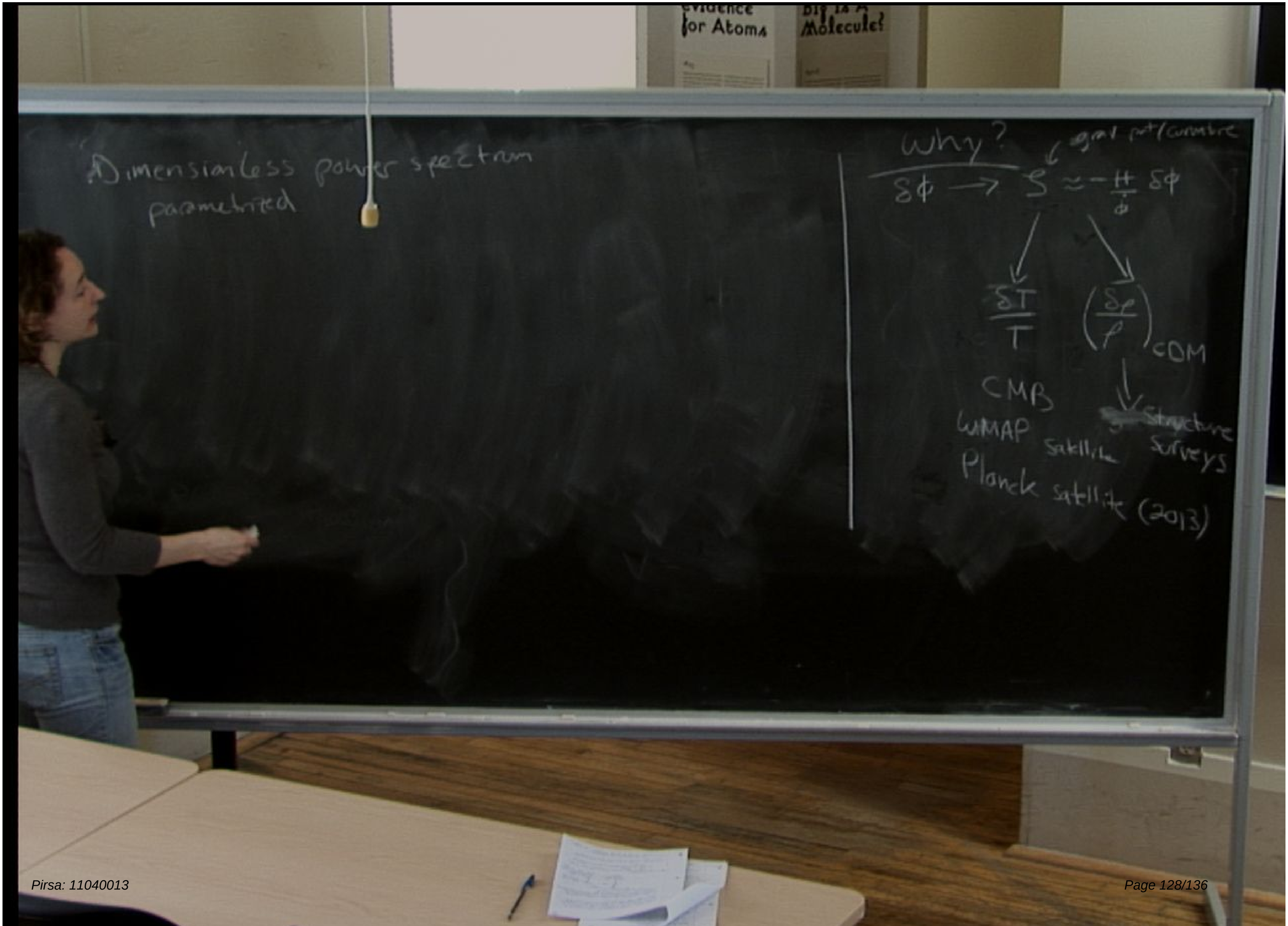
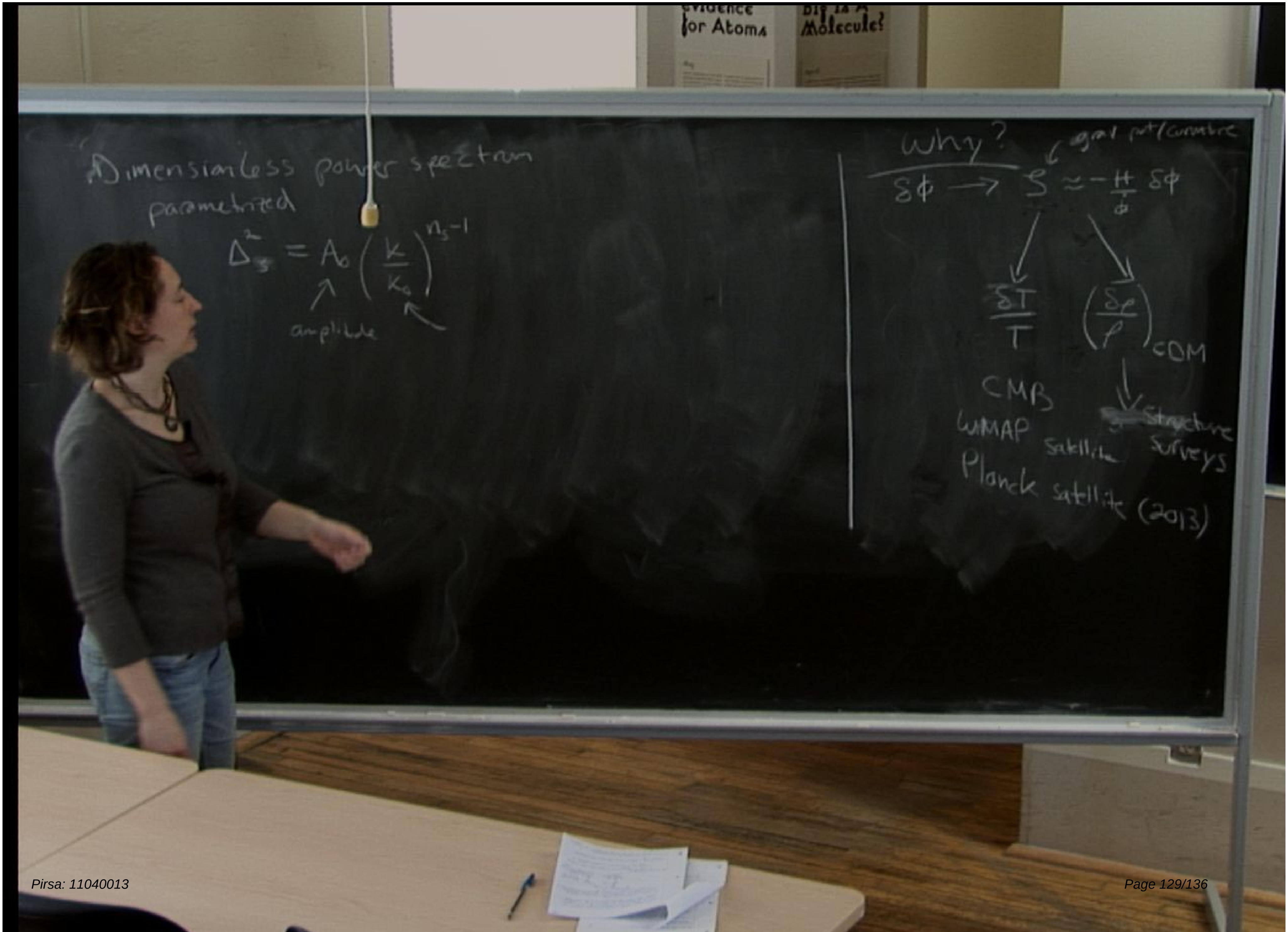
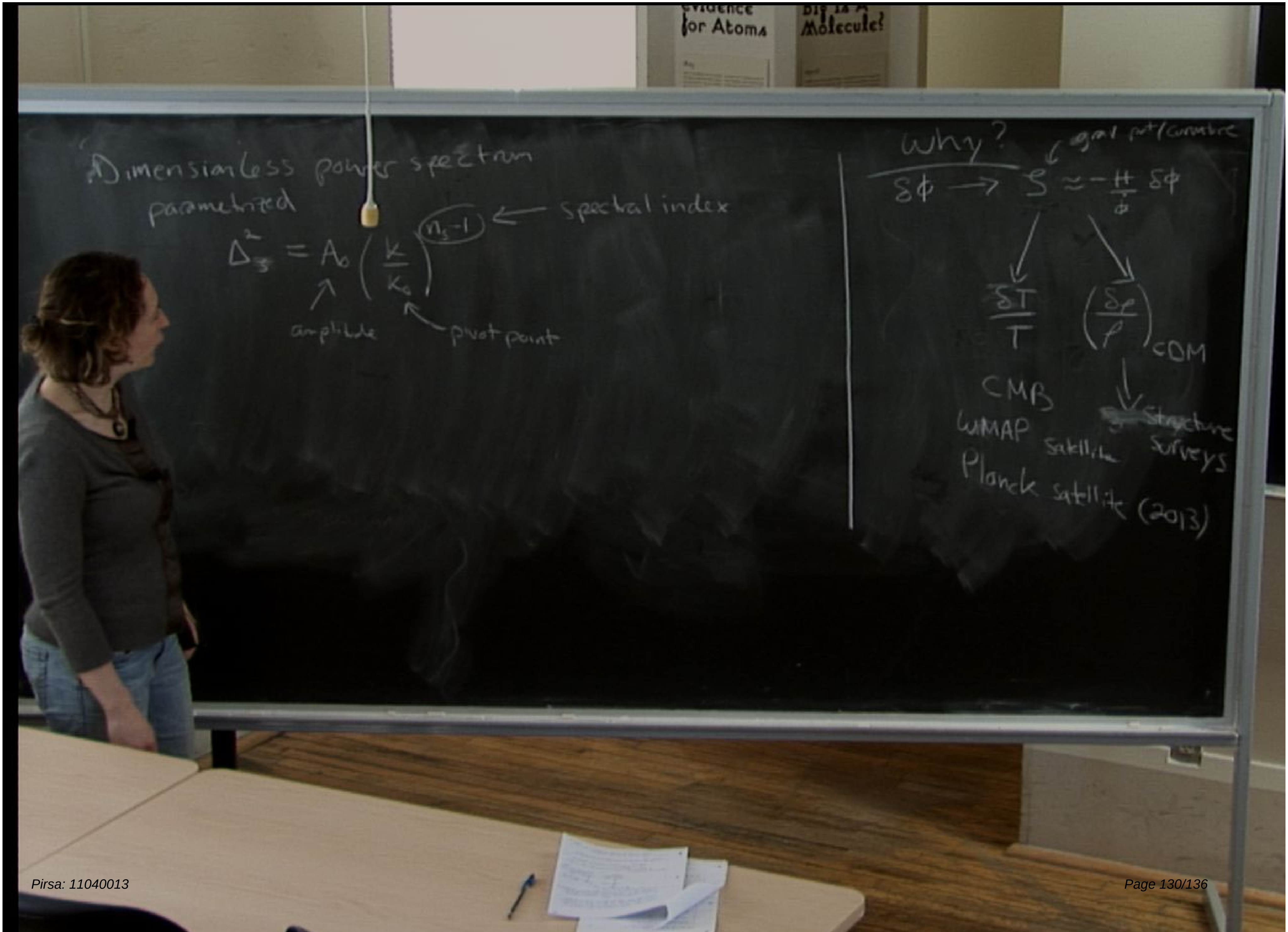

for Atoms
Molecule?
Dimensionless power spectrum
parametrized
Why?
grav pot/curvature
δφ → ζ ≈ − H/φ̇ δφ
δT/T
(δρ/ρ) CDM
CMB
Structure surveys
WMAP satellite
Planck satellite (2013)



for Atoms
Molecule?
Dimensionless power spectrum
parametrized
$\Delta^2_\zeta = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$
amplitude
Why?
grav pot/curvature
$\delta\phi \longrightarrow \zeta \simeq -\frac{H}{\dot\phi}\,\delta\phi$
$\frac{\delta T}{T}$
$\left(\frac{\delta\rho}{\rho}\right)_{CDM}$
CMB
WMAP satellite
Planck satellite (2013)
Structure surveys


for Atoms
Molecule?
Dimensionless power spectrum
parametrized
$\Delta_S^2 = A_0 \left(\frac{k}{k_0}\right)^{n_s-1}$
spectral index
amplitude
pivot point
Why?
grav pot/curvature
$\delta\phi \rightarrow \zeta \simeq -\frac{H}{\dot\phi}\delta\phi$
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CMB
WMAP satellite
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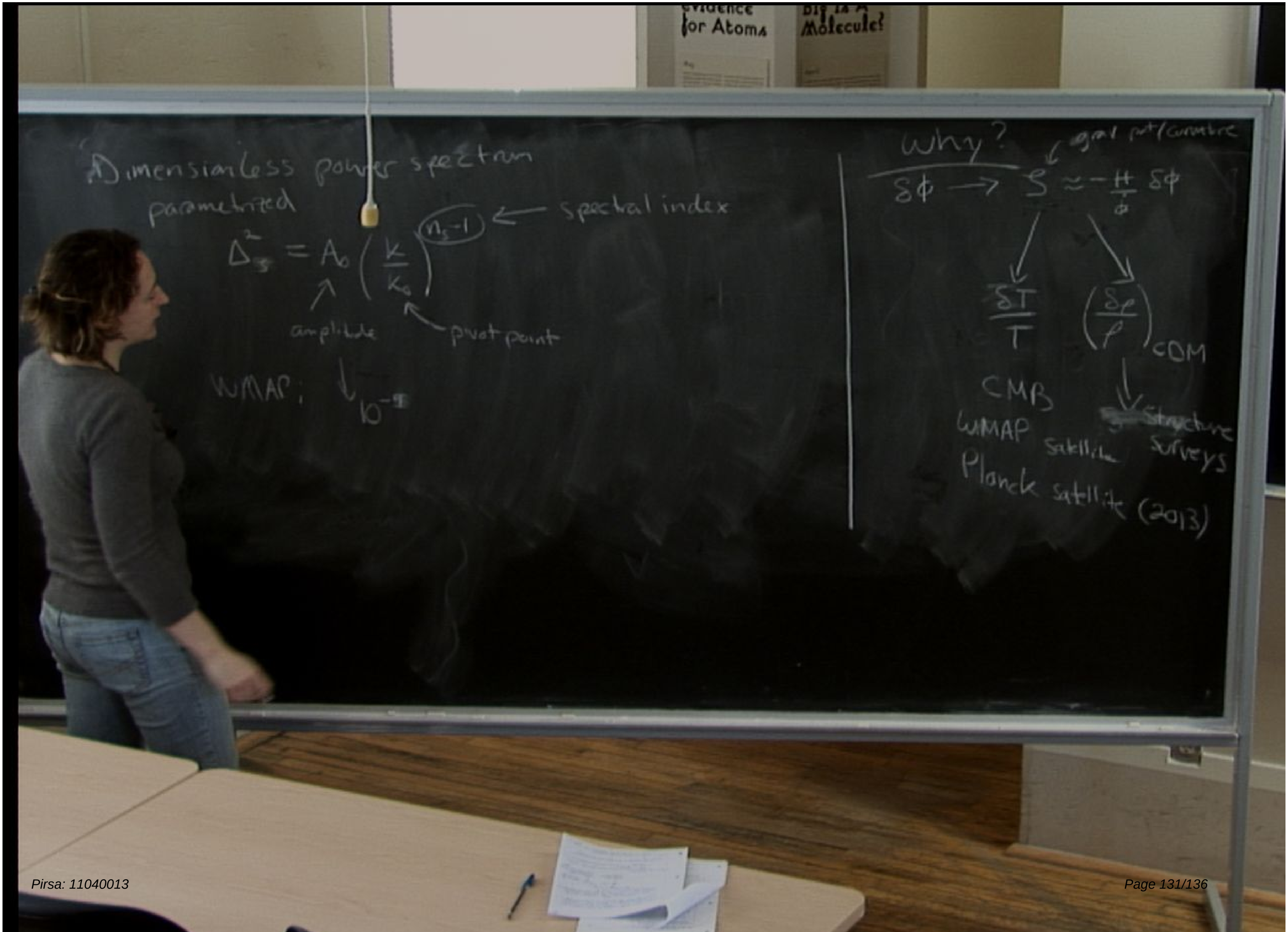
Structure surveys


Dimensionless power spectrum
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WMAP
why?
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CMB
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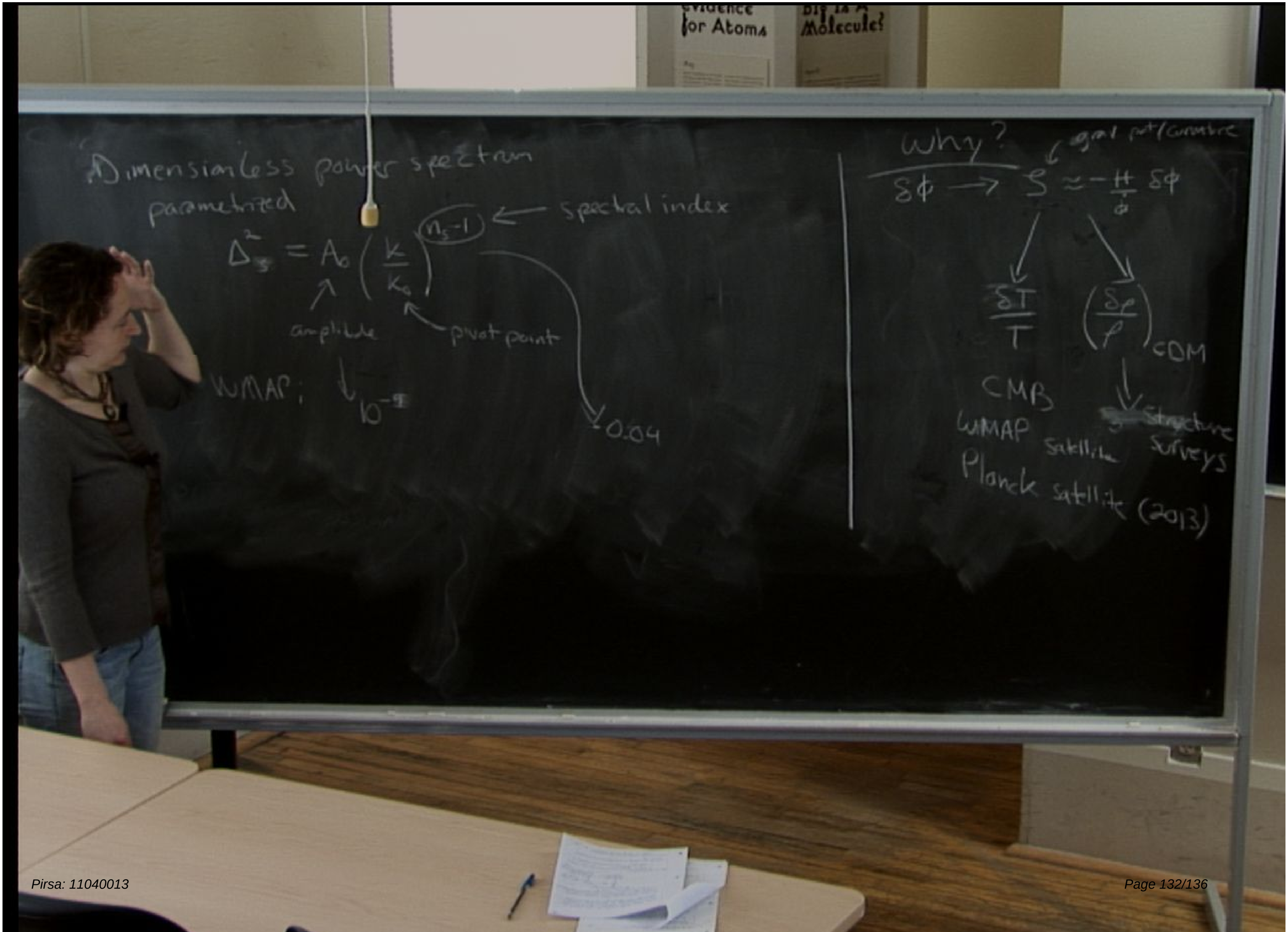
CDM
Structure surveys
evidence for Atoms
Molecule?


for Atoms
Molecule?
Dimensionless power spectrum
parametrized
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spectral index
amplitude
pivot point
WMAP:
10^{-9}
0.04
Why?
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CMB
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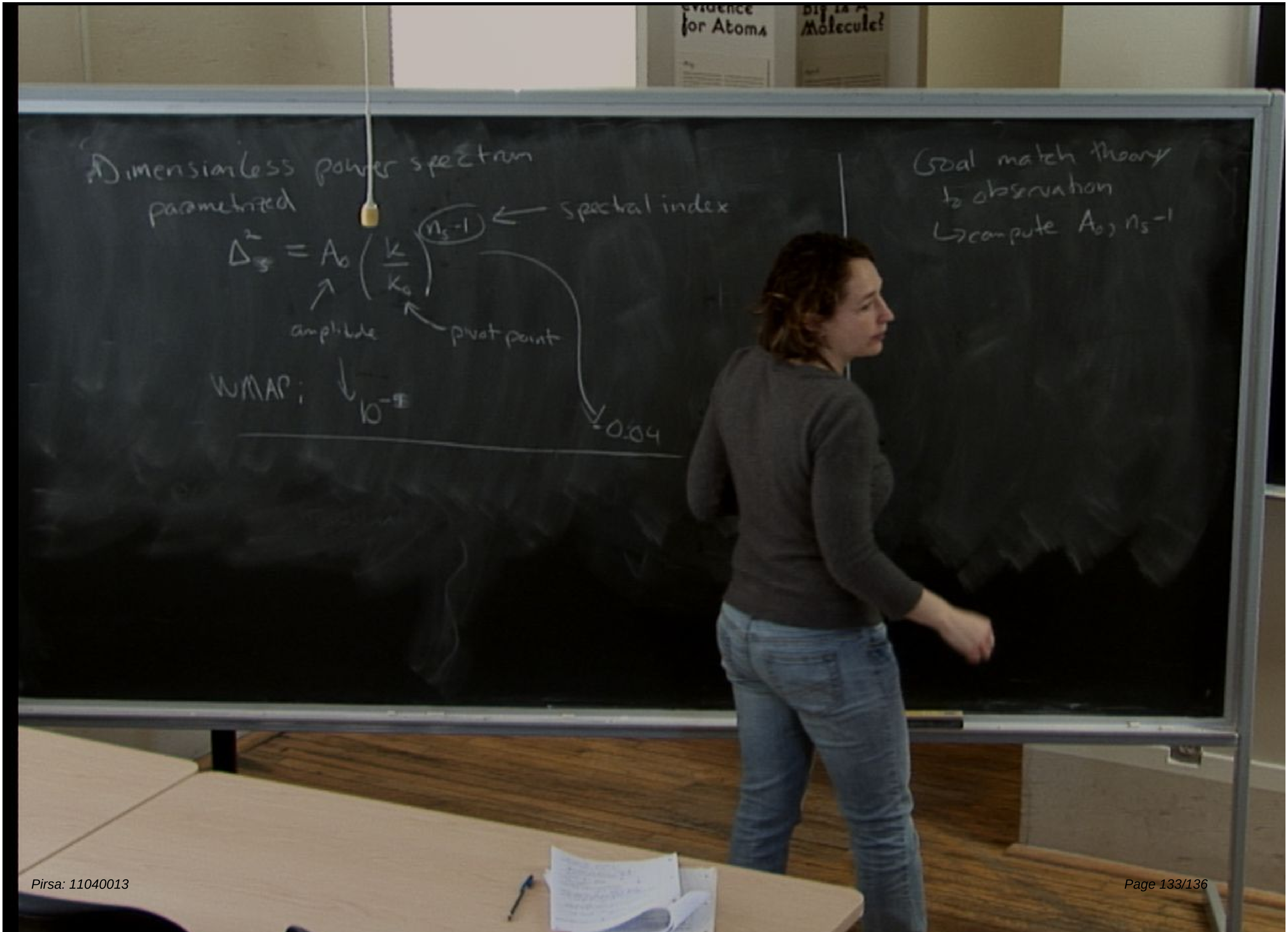
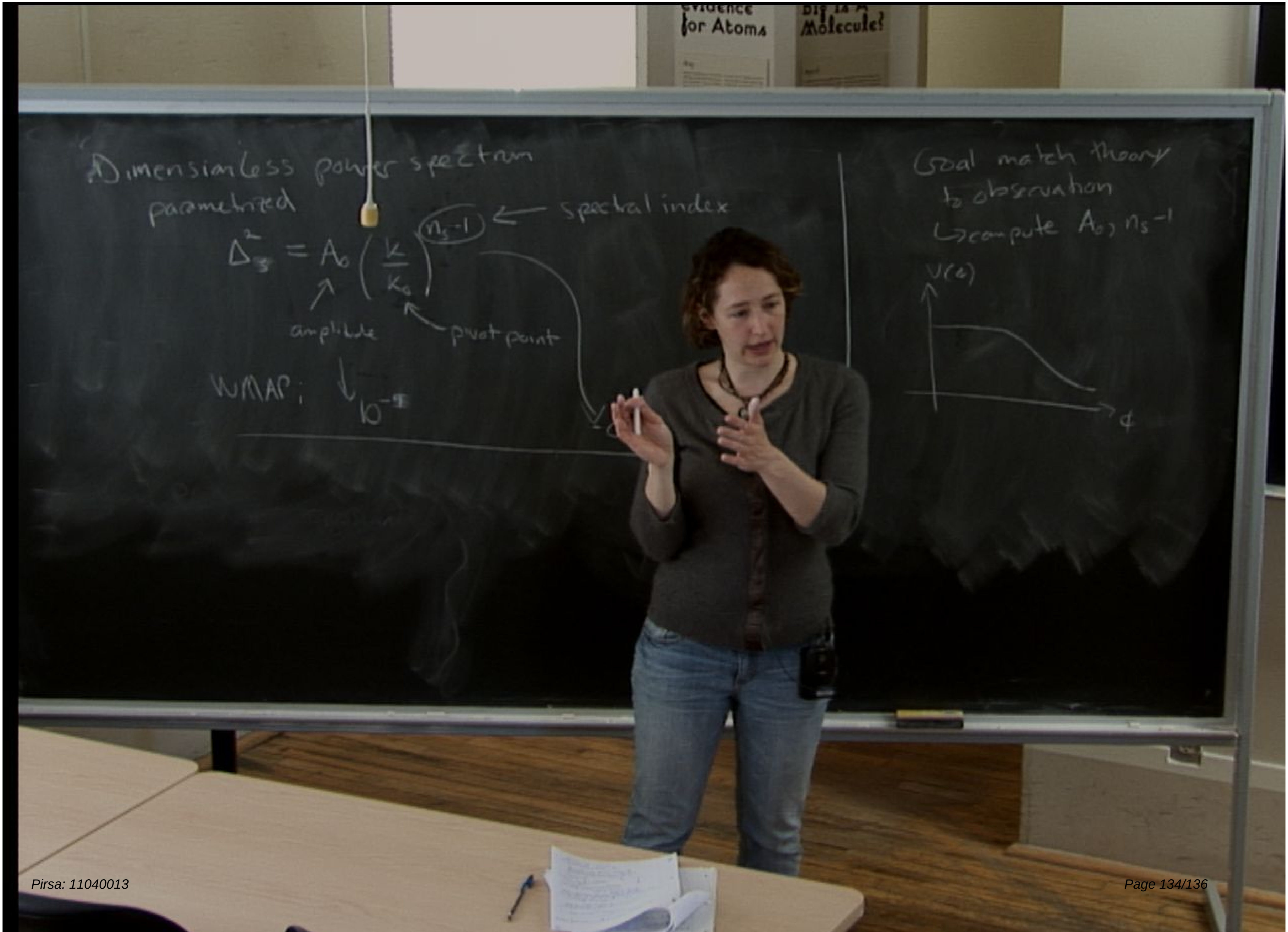
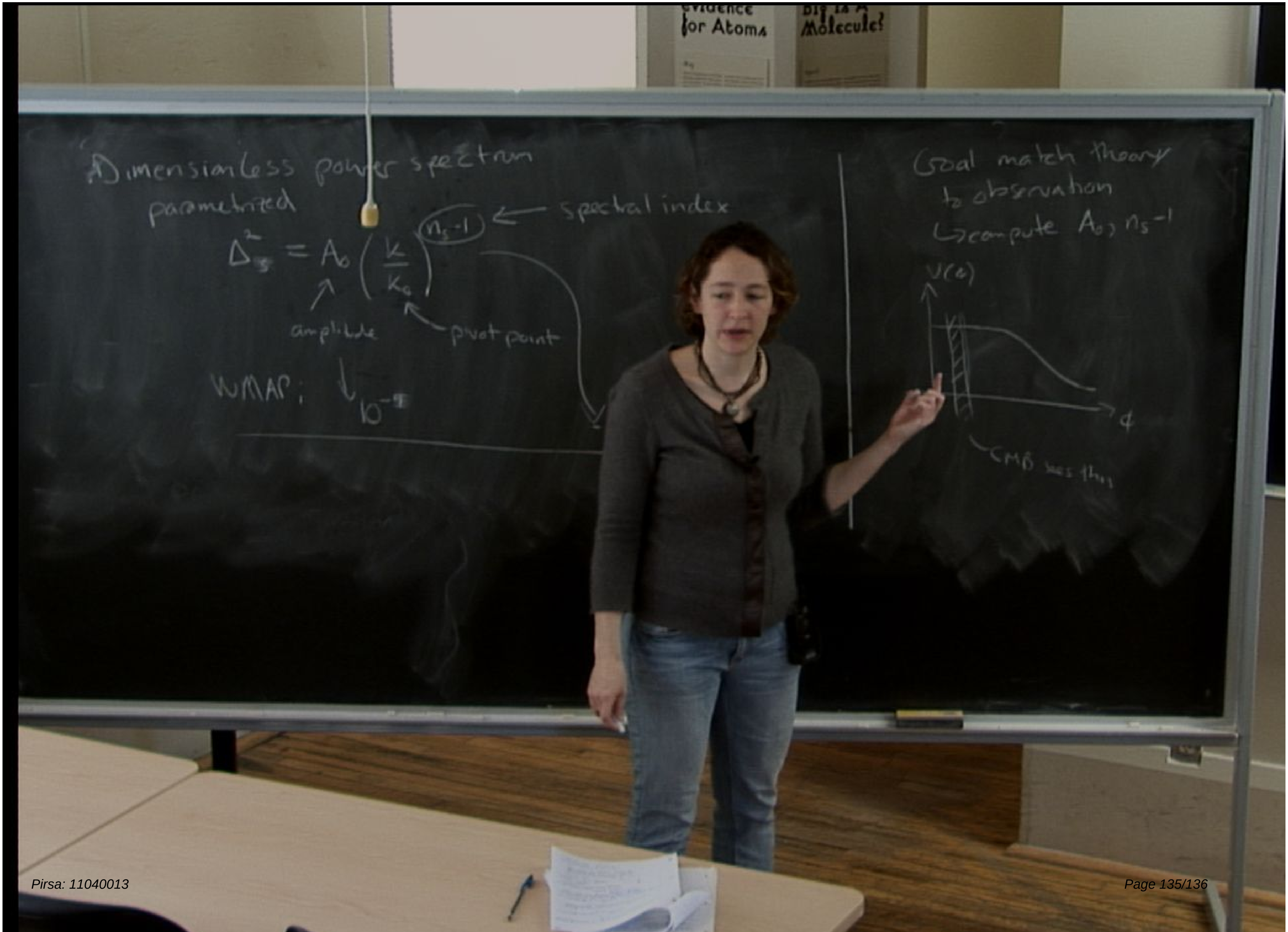
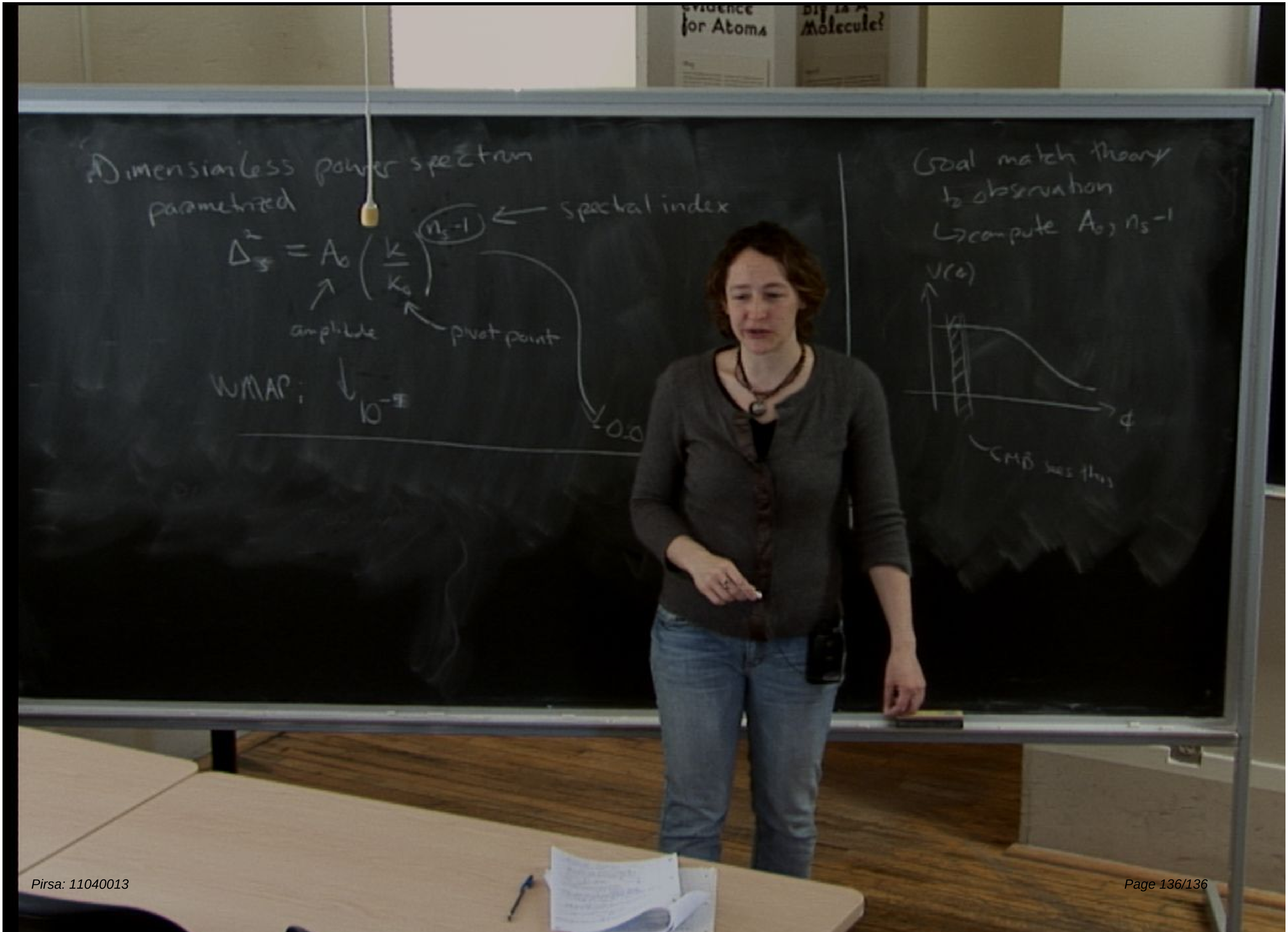
Structure surveys


for Atoms
Molecule?
Dimensionless power spectrum
parametrized
spectral index
amplitude
pivot point
WMAP:
-0.04
Goal match theory
to observation
compute A0, ns-1


for Atoms
Molecule?
Dimensionless power spectrum
parametrized
spectral index
Δ² = A₀ (k/k₀)^(n_s−1)
amplitude
pivot point
WMAP:
Goal match theory
to observation
compute A₀, n_s−1
V(φ)
φ


for Atoms
Molecule?
Dimensionless power spectrum
parametrized
spectral index
amplitude
pivot point
WMAP:
Goal match theory
to observation
compute A_0, $n_s - 1$
CMB sees this


Evidence for Atoms
Is a Molecule?
Dimensionless power spectrum
parametrized
spectral index
amplitude
pivot point
WMAP:
Goal match theory
to observation
compute A₀, nₛ-1
V(ϕ)
ϕ
CMB sees this