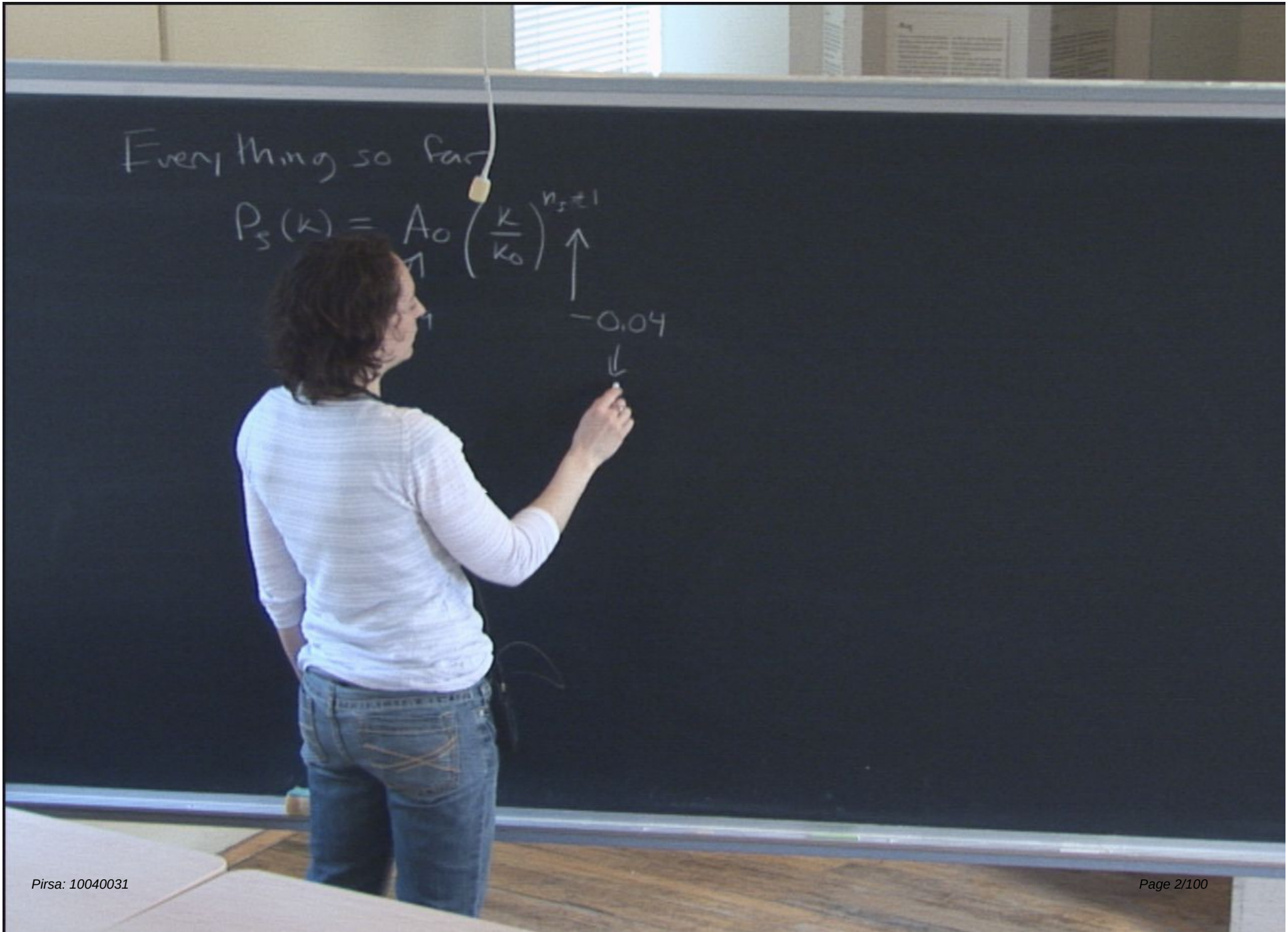
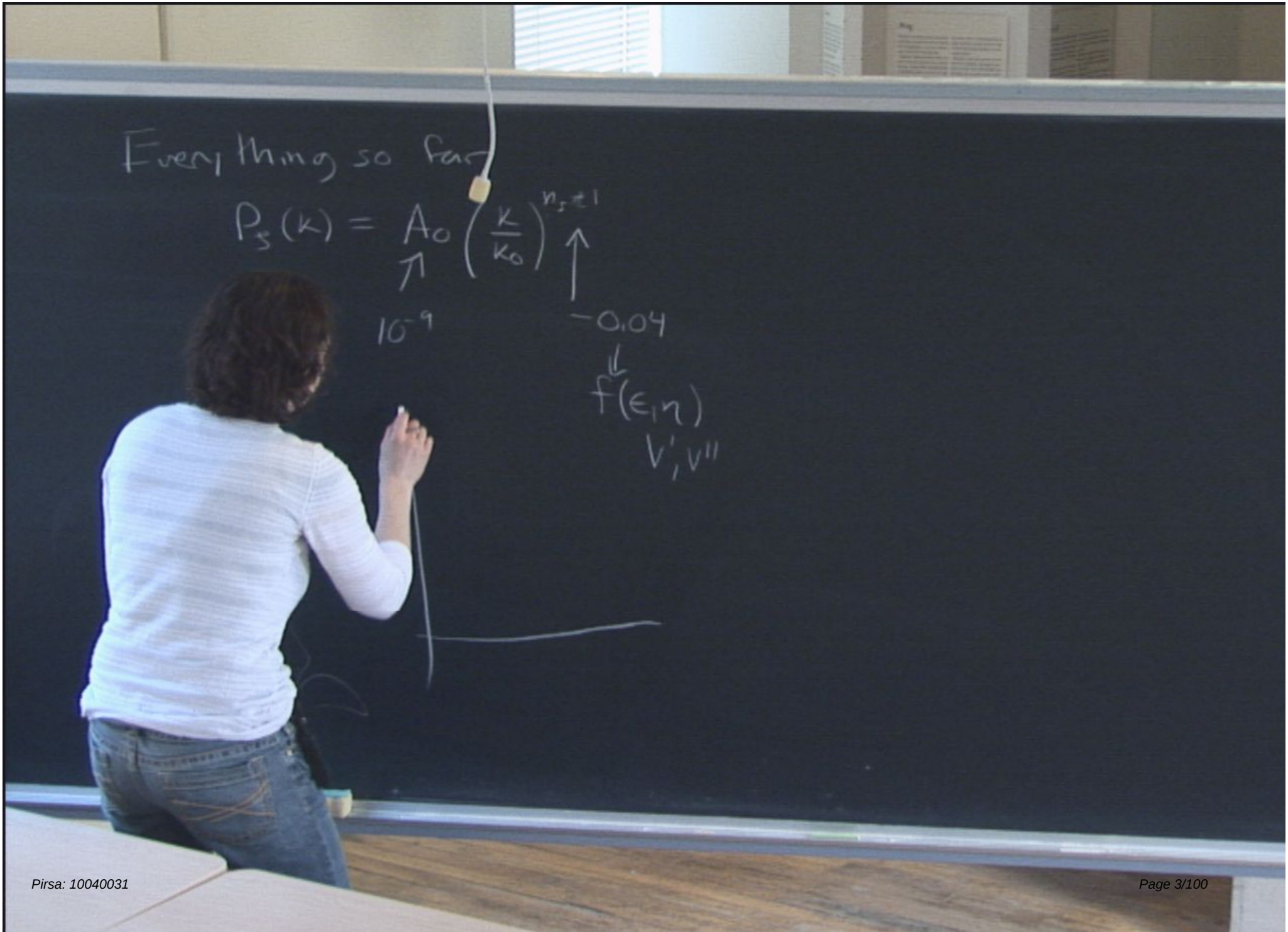
Title: Explorations in Cosmology (PHYS 649) - Lecture 15

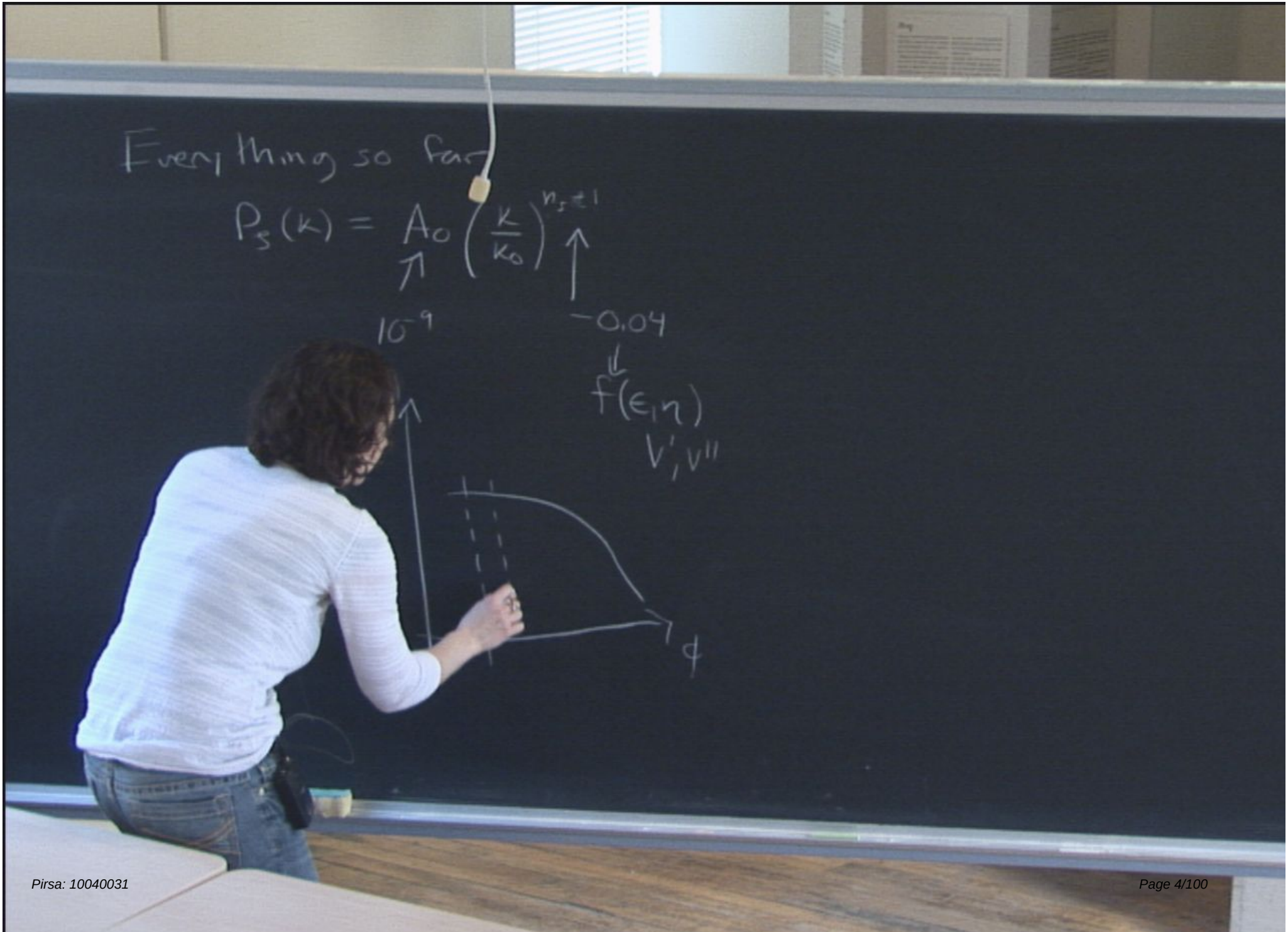
Date: Apr 01, 2010 09:00 AM

URL: http://pirsa.org/10040031

Abstract:


Everything so far
$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$
-0.04


Everything so far
$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$
10^{-9}
-0.04
$f(\epsilon, \eta)$
V', V''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-0.04
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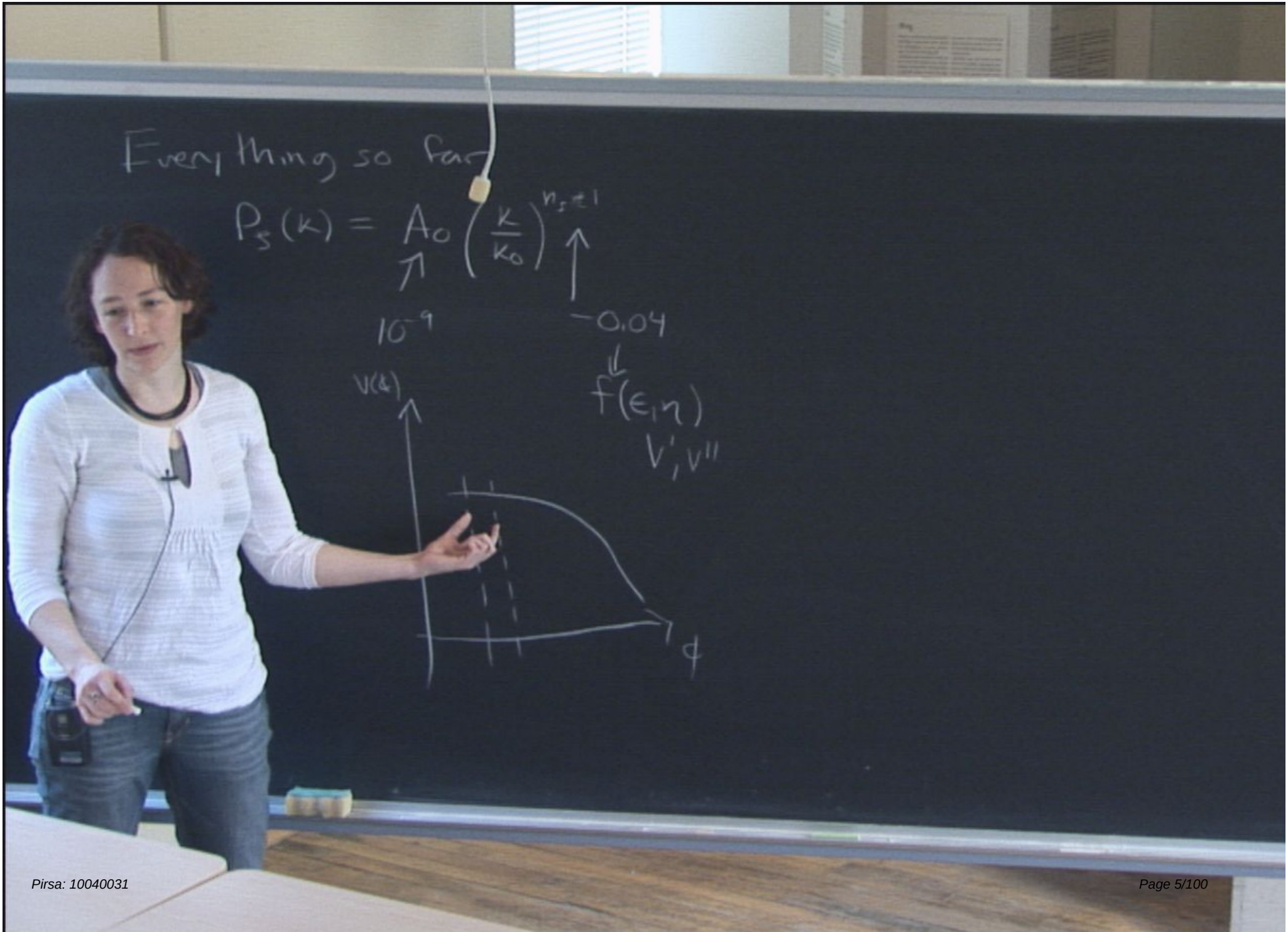
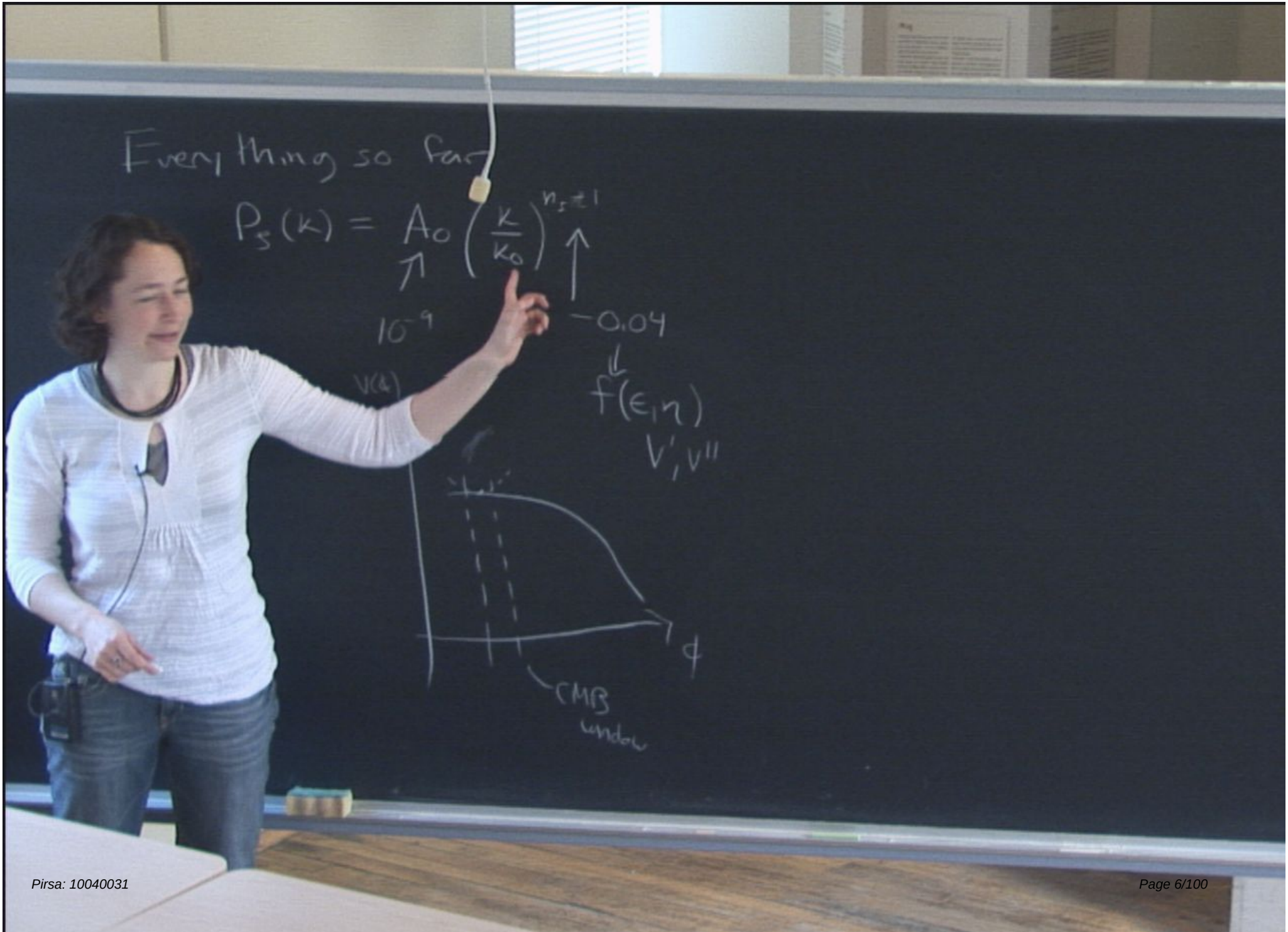
V', V''
q


Everything so far
$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$
10^{-9}
-0.04
$V(\phi)$
$f(\epsilon, \eta)$
V', V''
ϕ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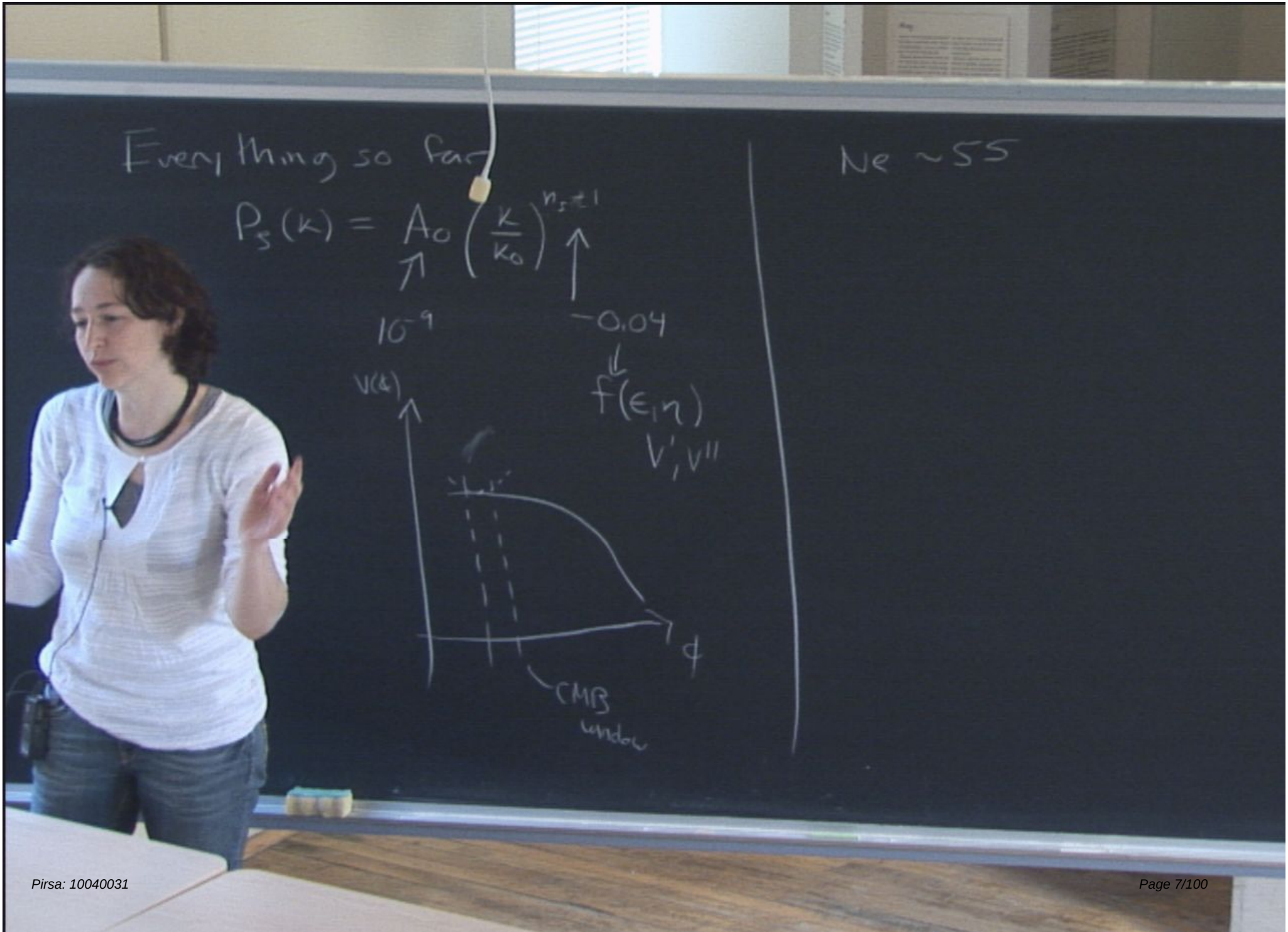
10^{-9}
-0.04
$f(\epsilon, \eta)$
V', V''
$V(\phi)$
ϕ
CMB
window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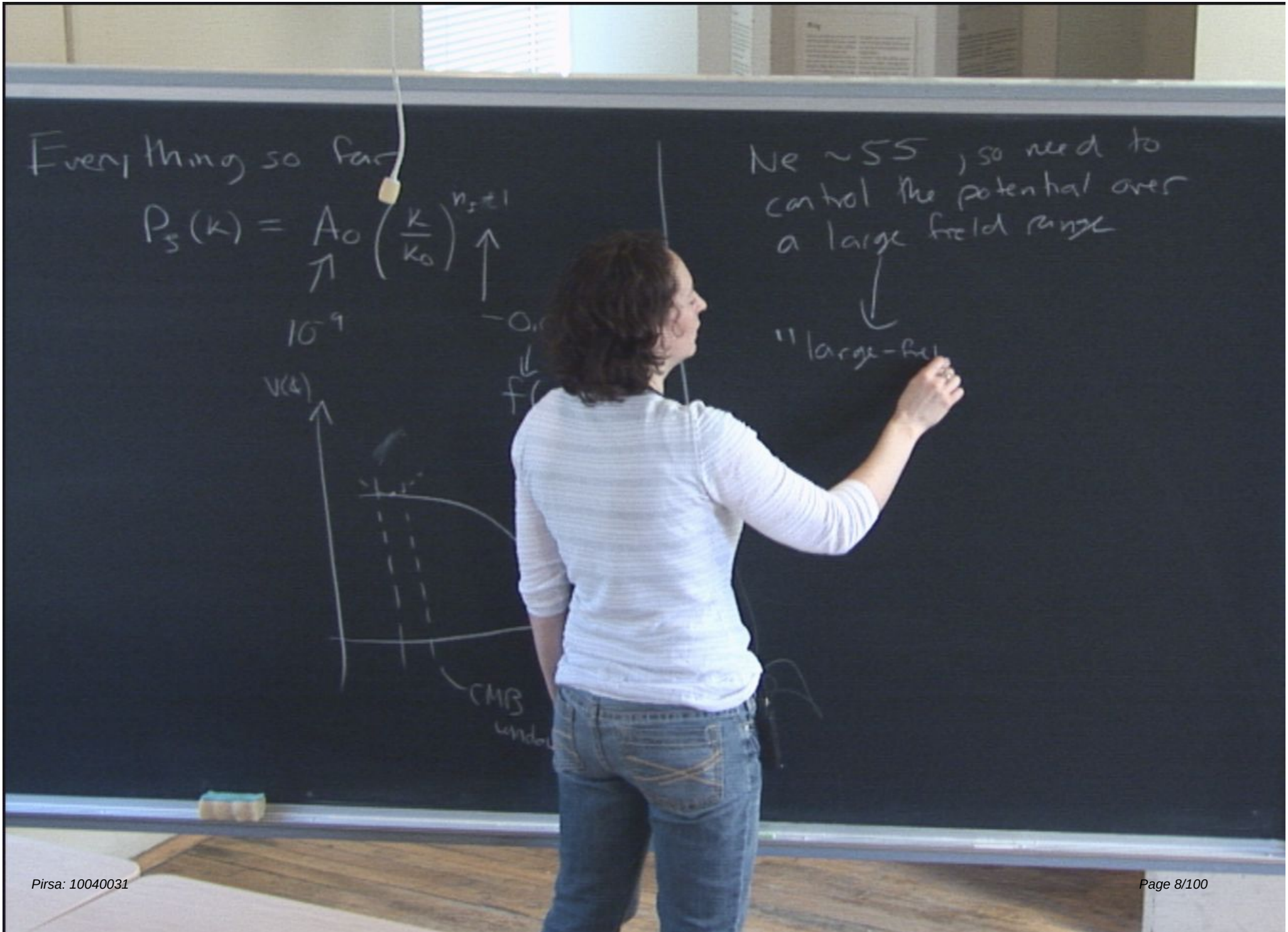
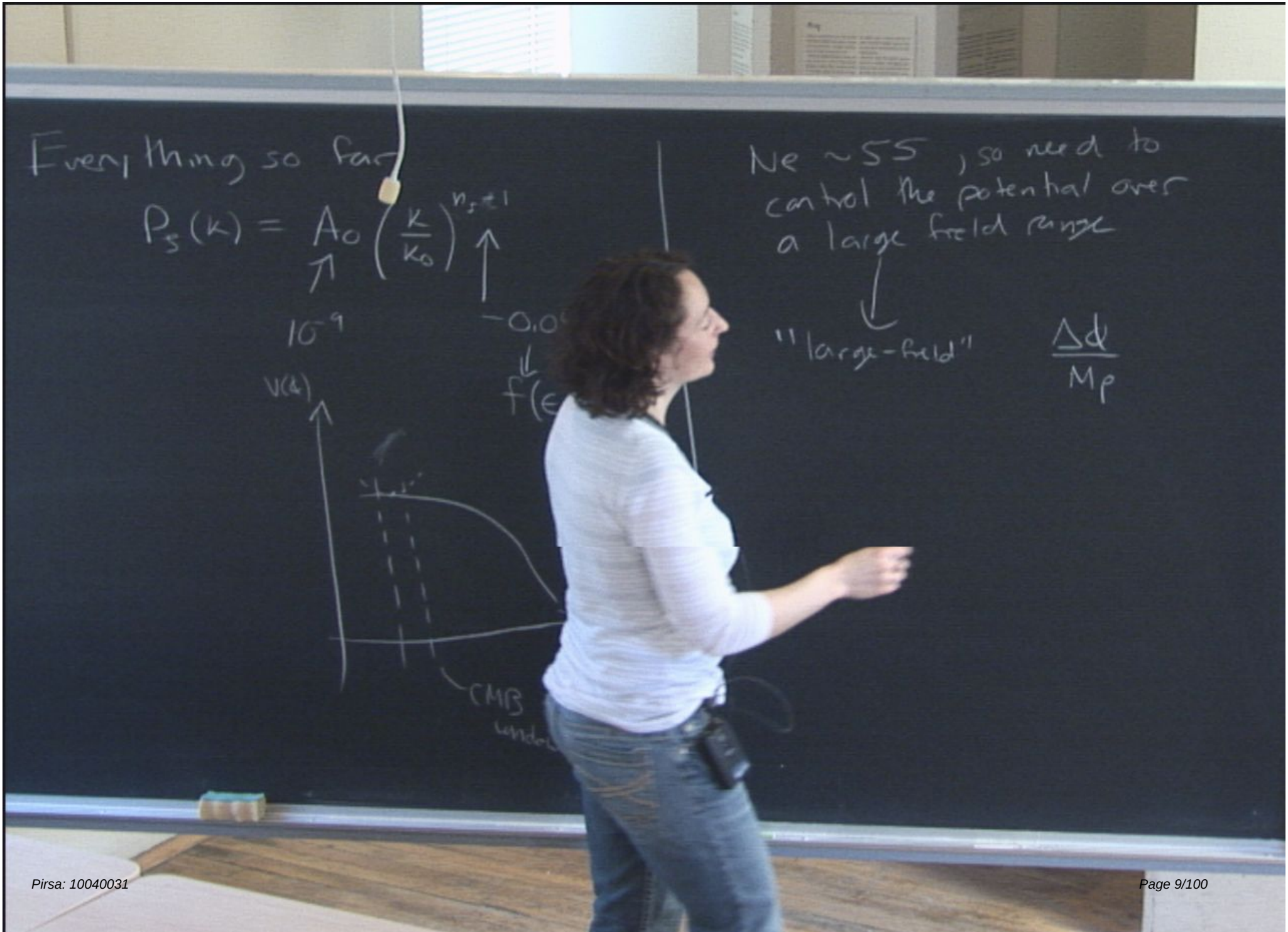
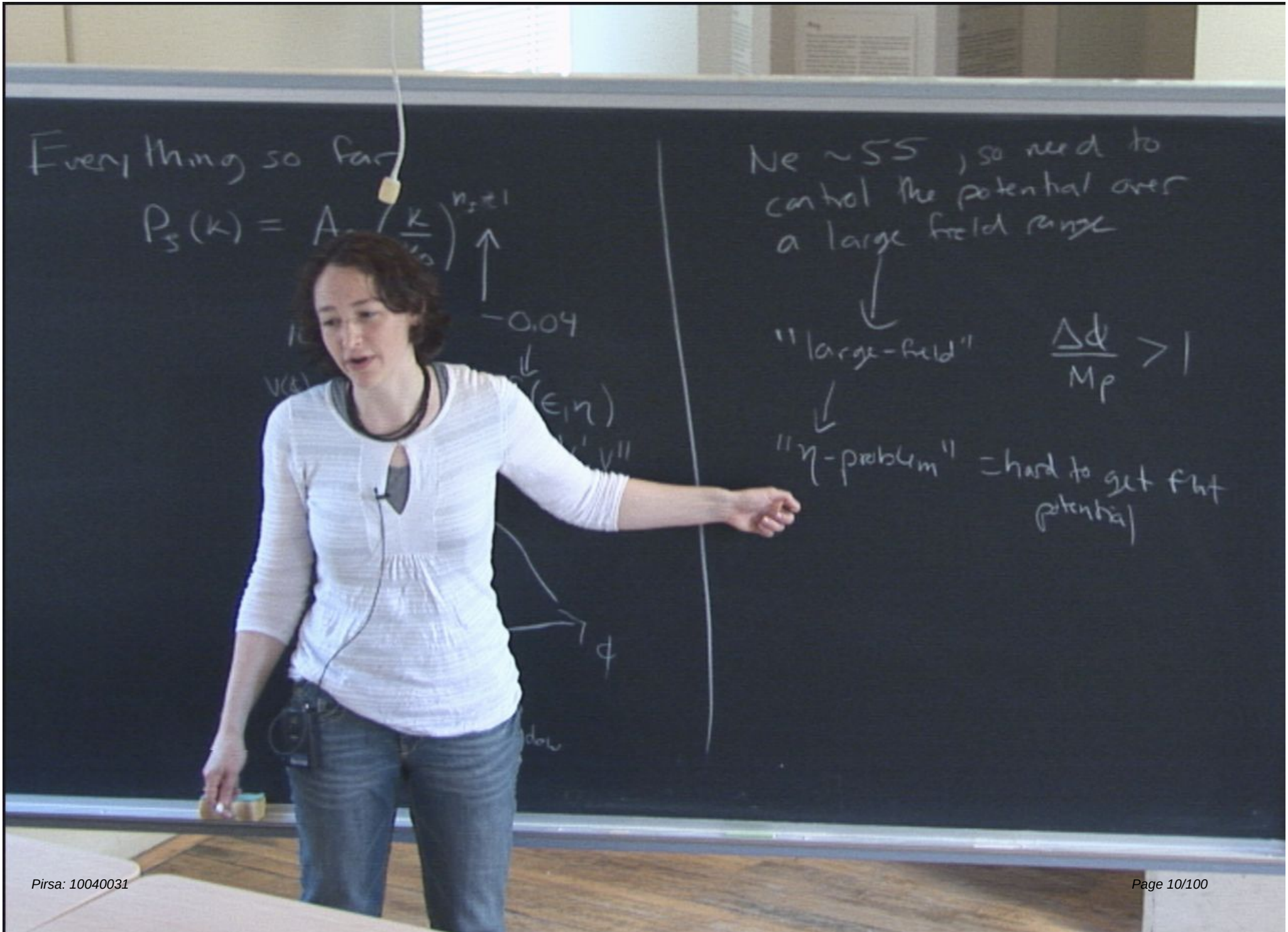
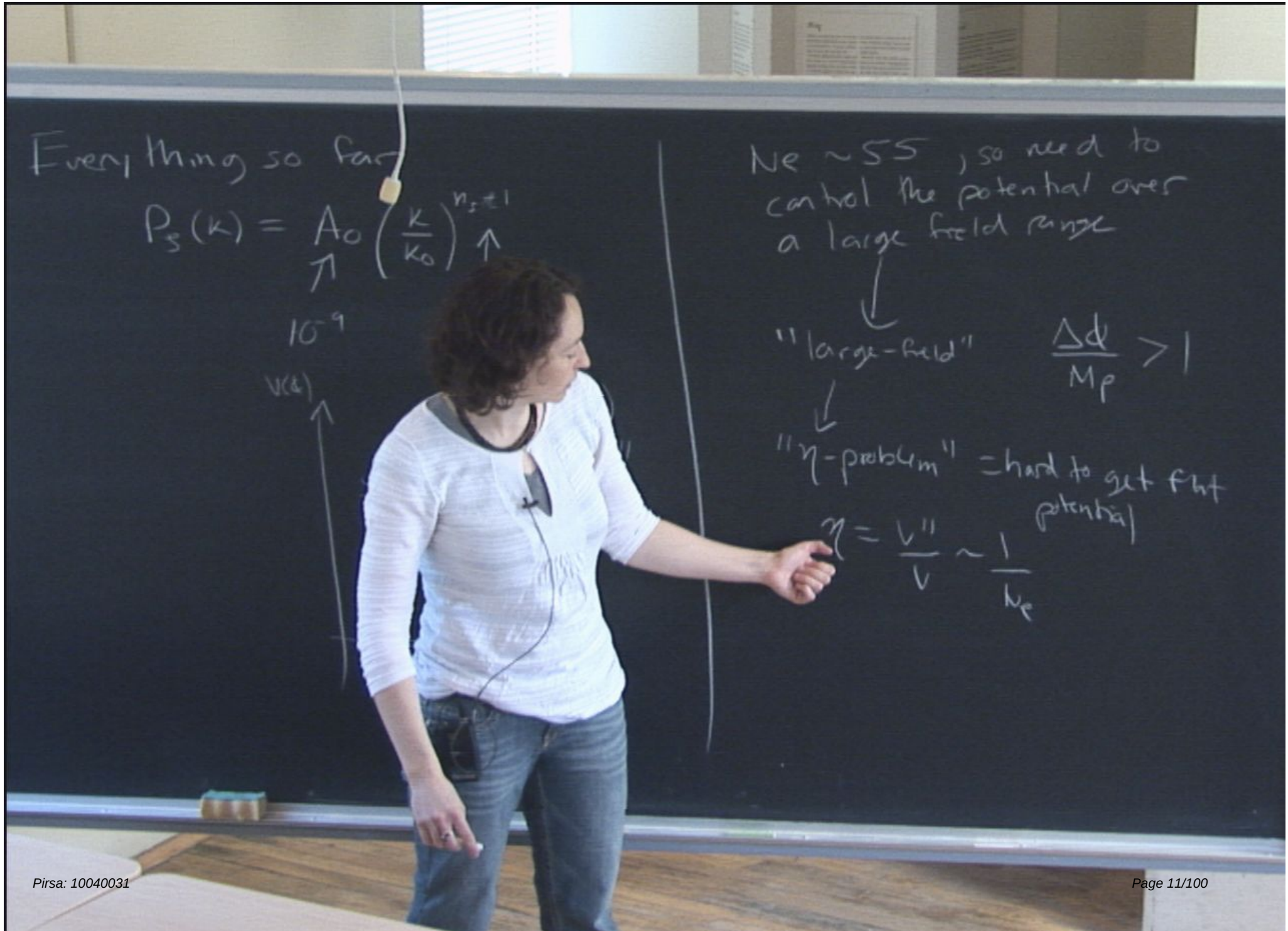
10^{-9}
-0.04
$f(\epsilon, \eta)$
V', V''
$V(\phi)$
ϕ
CMB window
Ne ~55


Everything so far
$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$
10^{-9}
V(φ)
CMB
Ne ~ 55, so need to control the potential over a large field range
"large-fie


Everything so far
$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$
10^{-9}
-0.0
$f(\epsilon$
V(ϕ)
CMB
Ne ~ 55, so need to control the potential over a large field range
"large-field"
$\frac{\Delta\phi}{M_p}$


Everything so far
$P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s+1}$
−0.04
(ϵ, η)
ϕ
Ne ~55, so need to control the potential over a large field range
"large-field"
$\frac{\Delta\phi}{M_p} > 1$
"η-problem" = hard to get flat potential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10^{-9}
V(ϕ)
Ne ~ 55, so need to control the potential over a large field range
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"η-problem" = hard to get flat potential
$\eta = \frac{V''}{V} \sim \frac{1}{M_p}$

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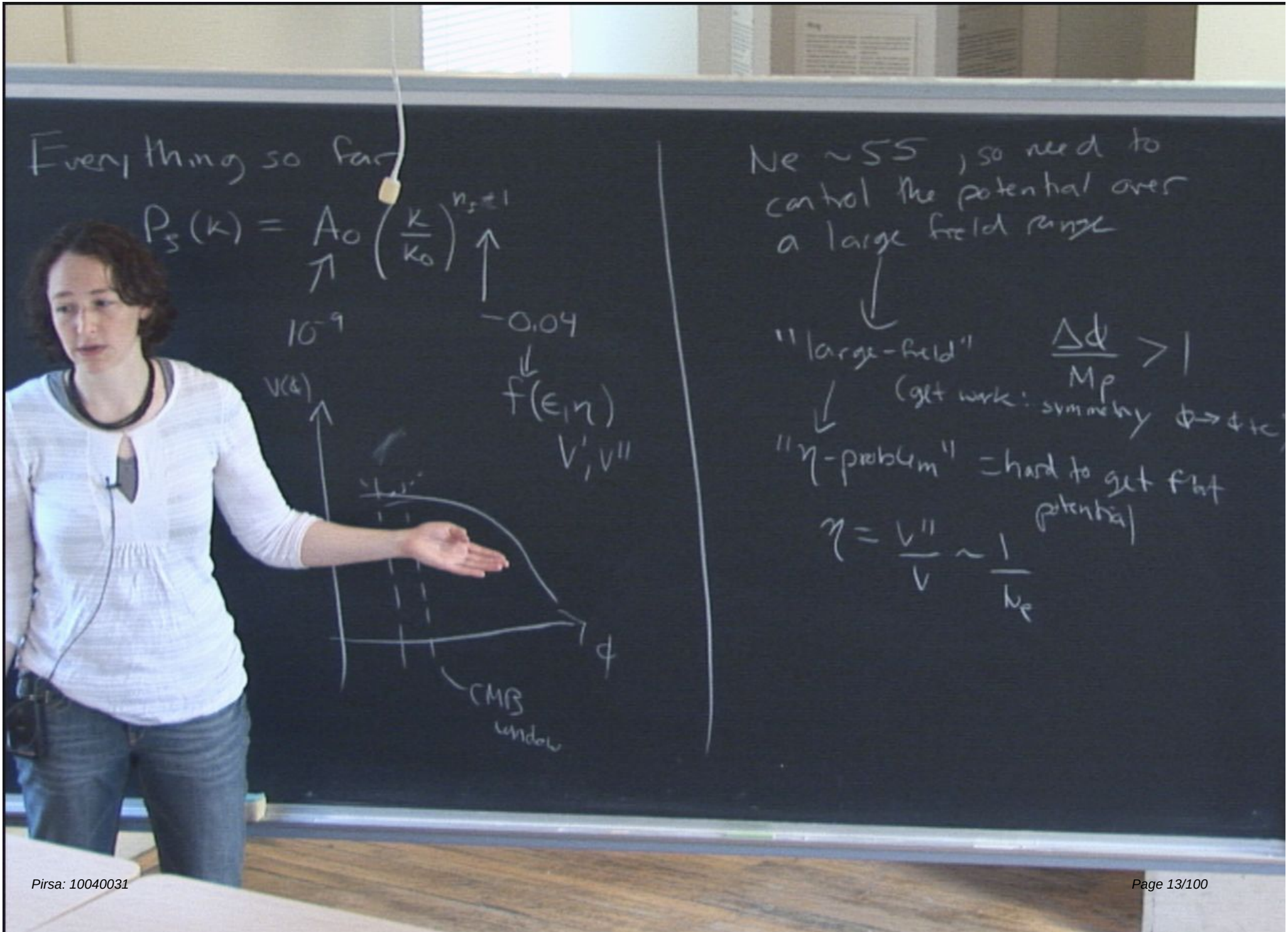
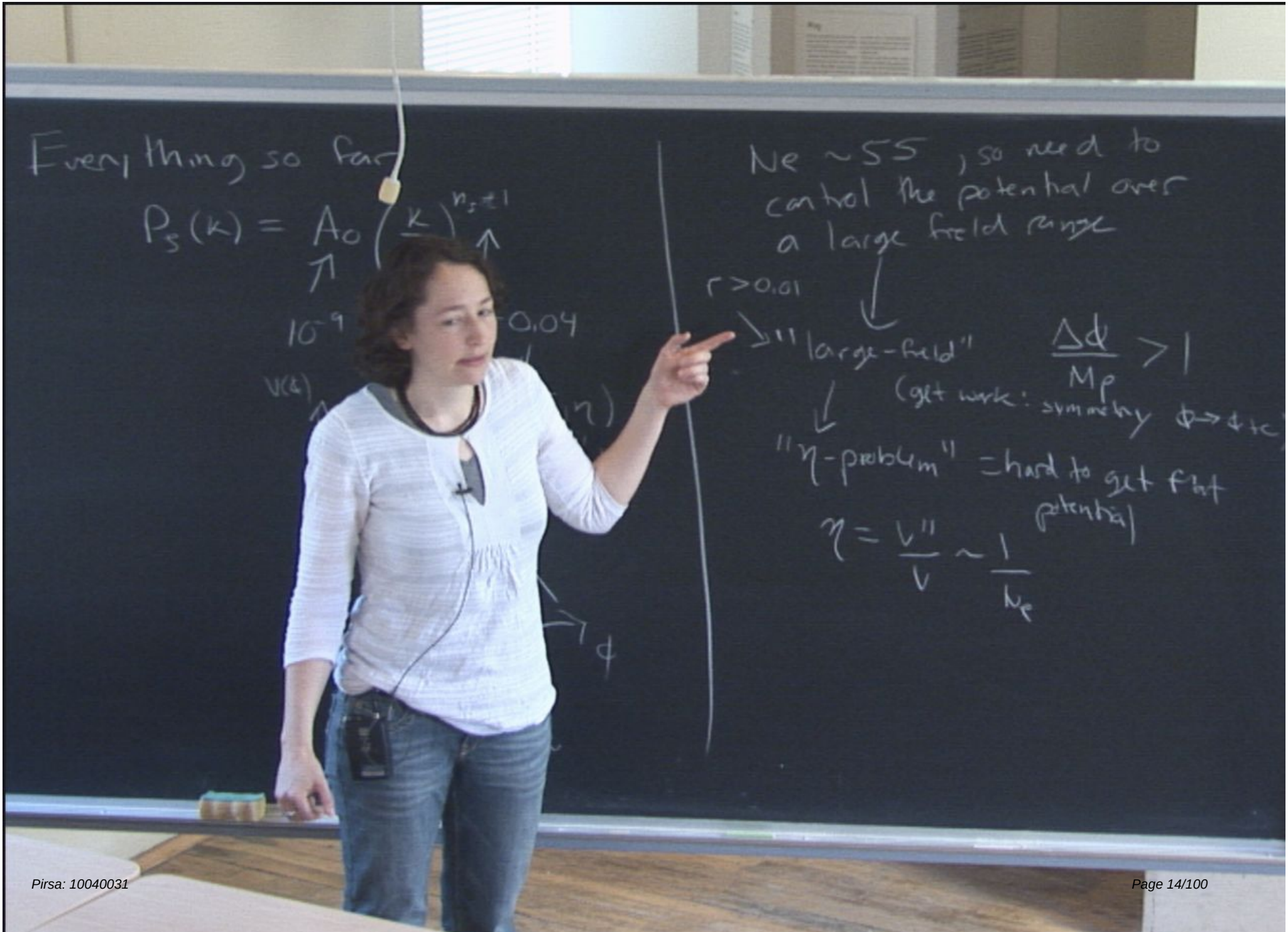

Everything so far
$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$
10^{-9}
-0.04
$f(\epsilon, \eta)$
V', V''
$V(\phi)$
ϕ
CMB window
Ne ~ 55, so need to control the potential over a large field range
"large-field"
$\frac{\Delta\phi}{M_p} > 1$
(get work: symmetry $\phi \to \phi + c$)
"η-problem" = hard to get flat potential
$\eta = \frac{V''}{V} \sim \frac{1}{N_e}$


Everything so far
$P_s(k) = A_0 \left(\frac{k}{\quad}\right)^{n_s - 1}$
10^{-9}
0.04
V(φ)
φ
Ne ~ 55, so need to control the potential over a large field range
r > 0.01
"large-field"
$\frac{\Delta\phi}{M_p} > 1$
(get work: symmetry φ → φ + c)
"η-problem" = hard to get flat potential
$\eta = \frac{V''}{V} \sim \frac{1}{M_p}$

Everything so far

$$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$$

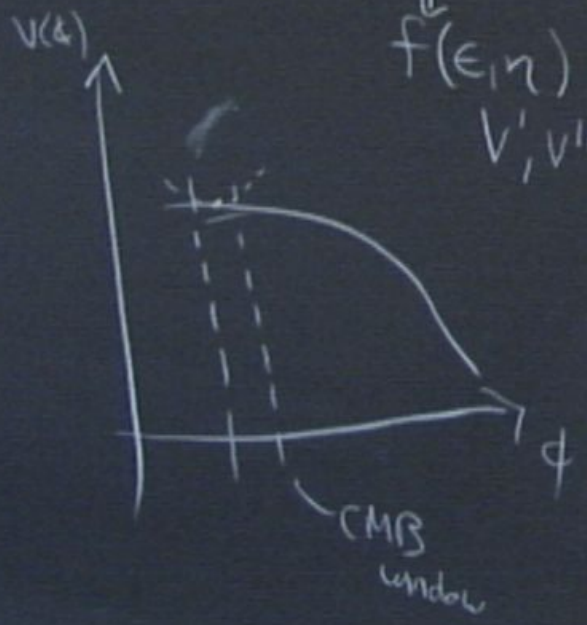
$A_0 \sim 10^{-9}$

$n_s - 1 \sim -0.04$

$\Downarrow$

$f(\epsilon, \eta)$

V', V''



$N_e \sim 55$, so need to control the potential over a large field range

$r > 0.01$

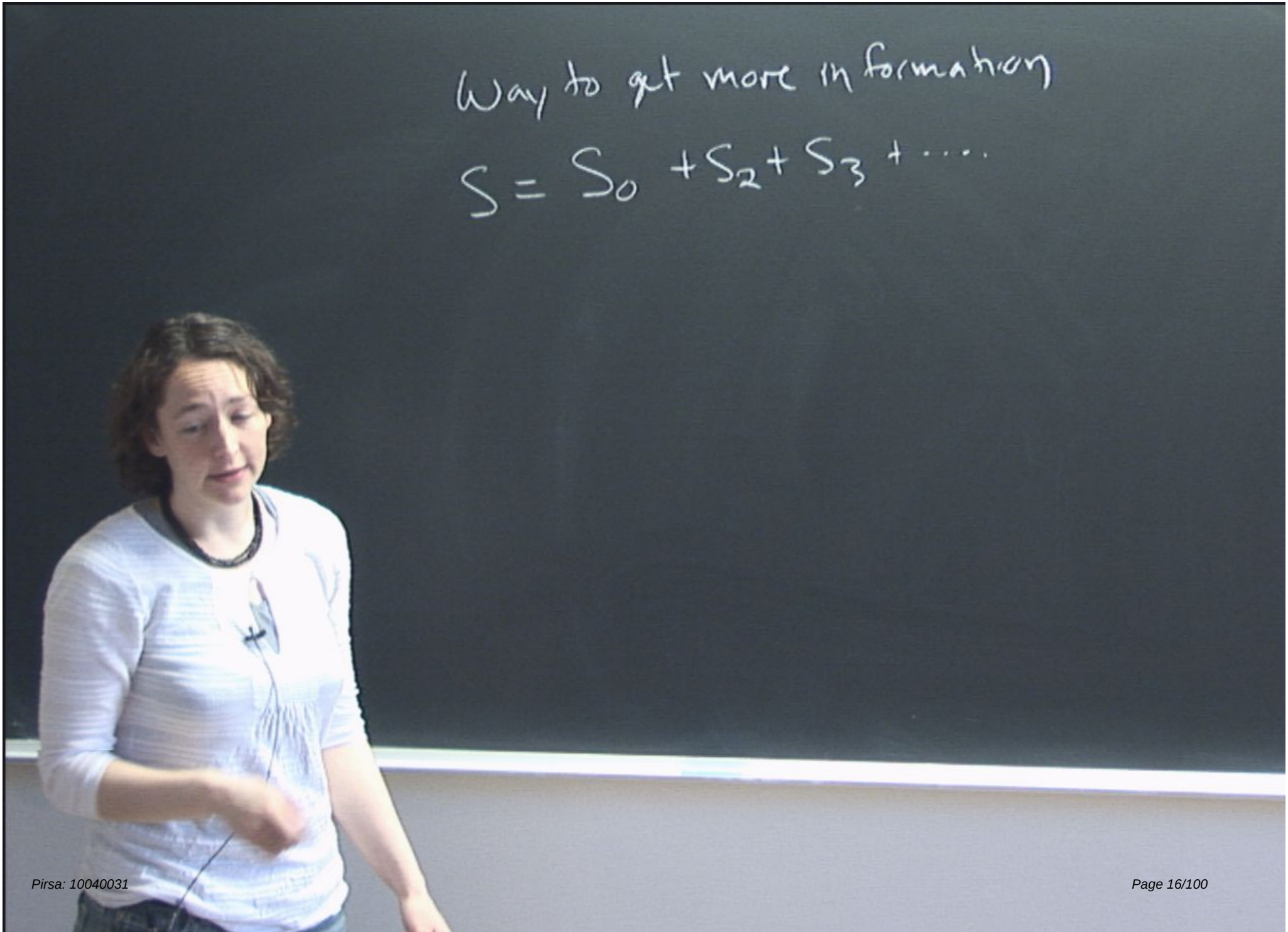
$\Rightarrow$ "large-field" $\frac{\Delta\phi}{M_p} > 1$

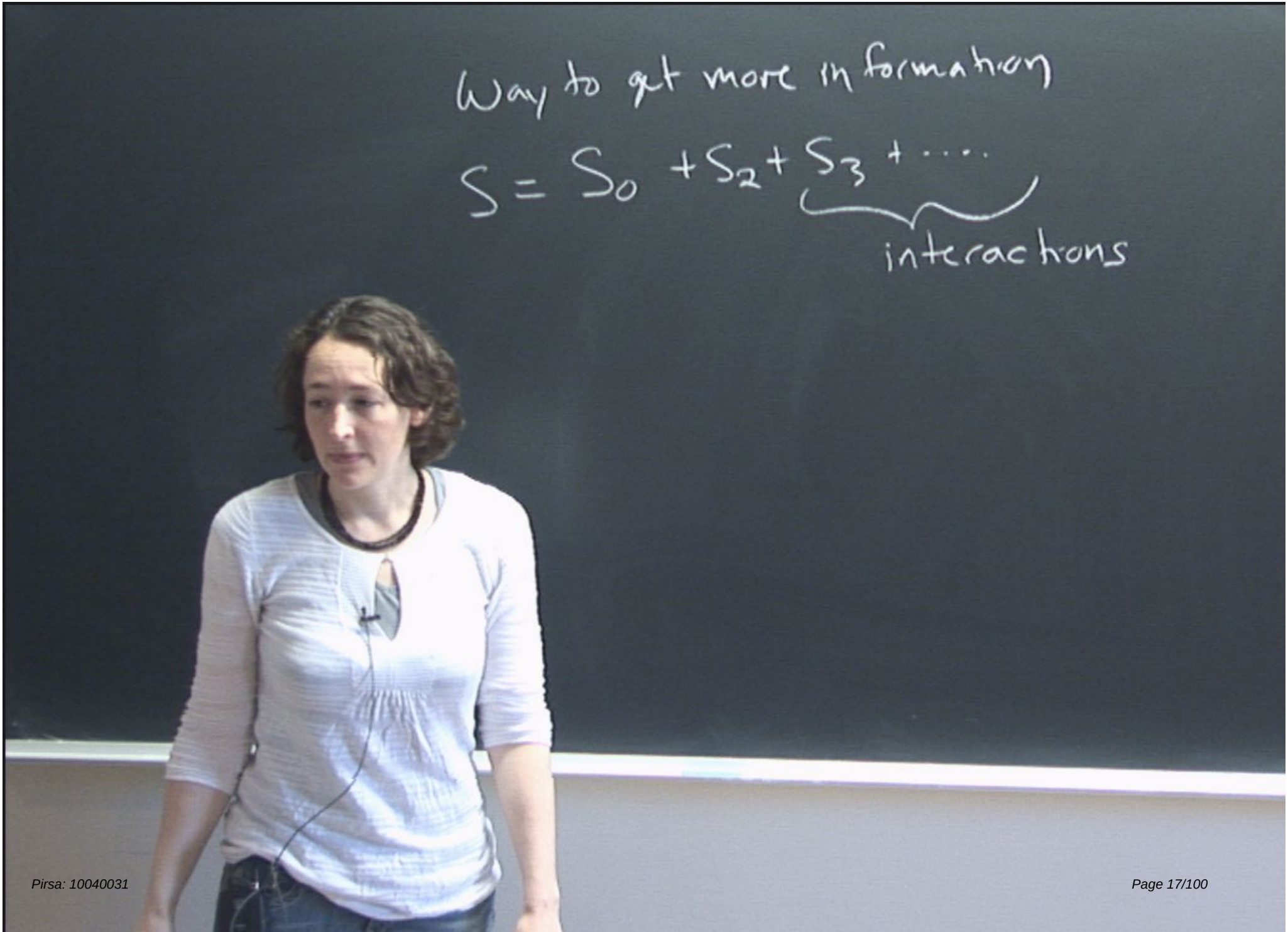
(get work: symmetry $\phi \to \phi + c$)

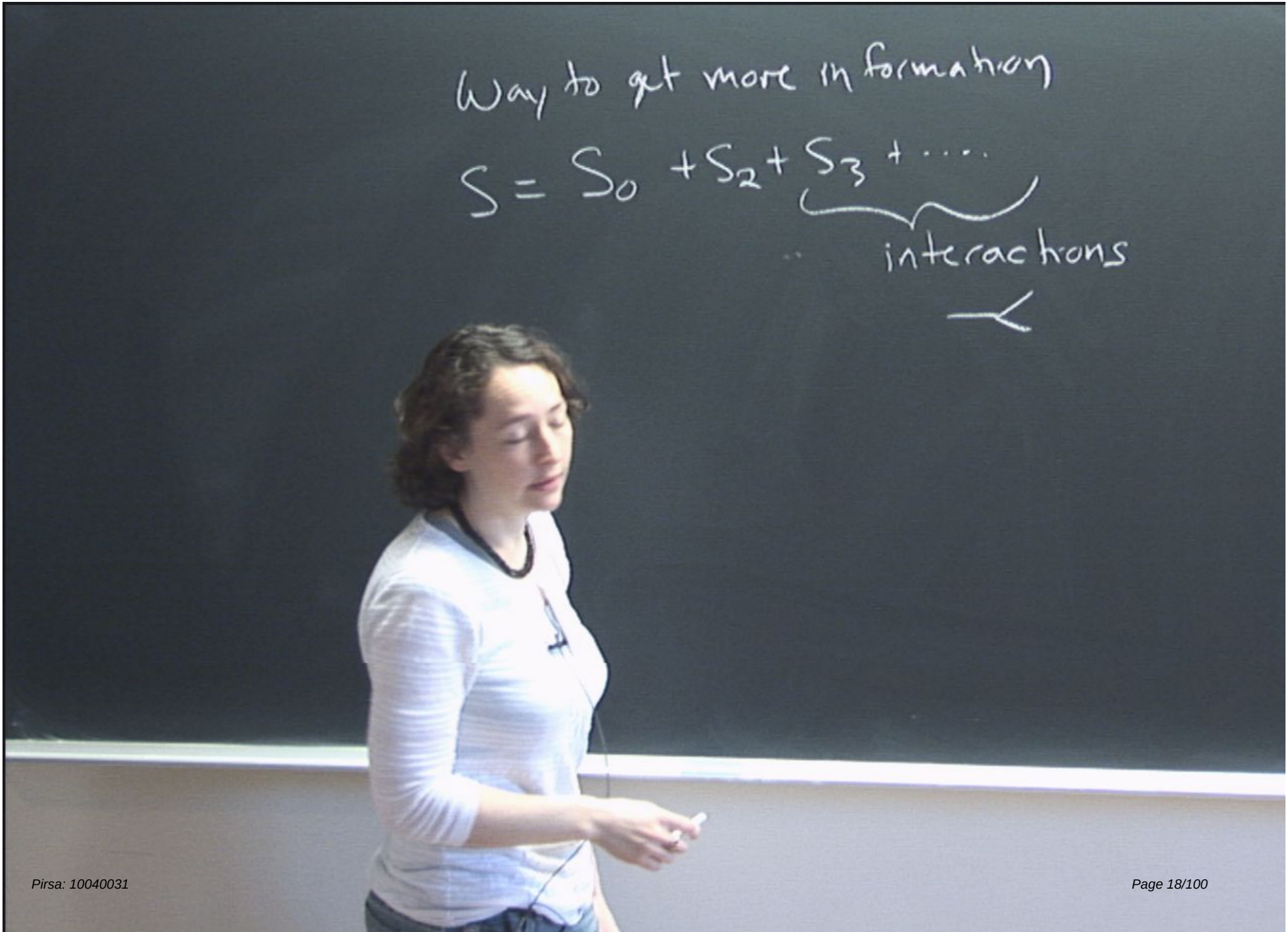
$\Downarrow$

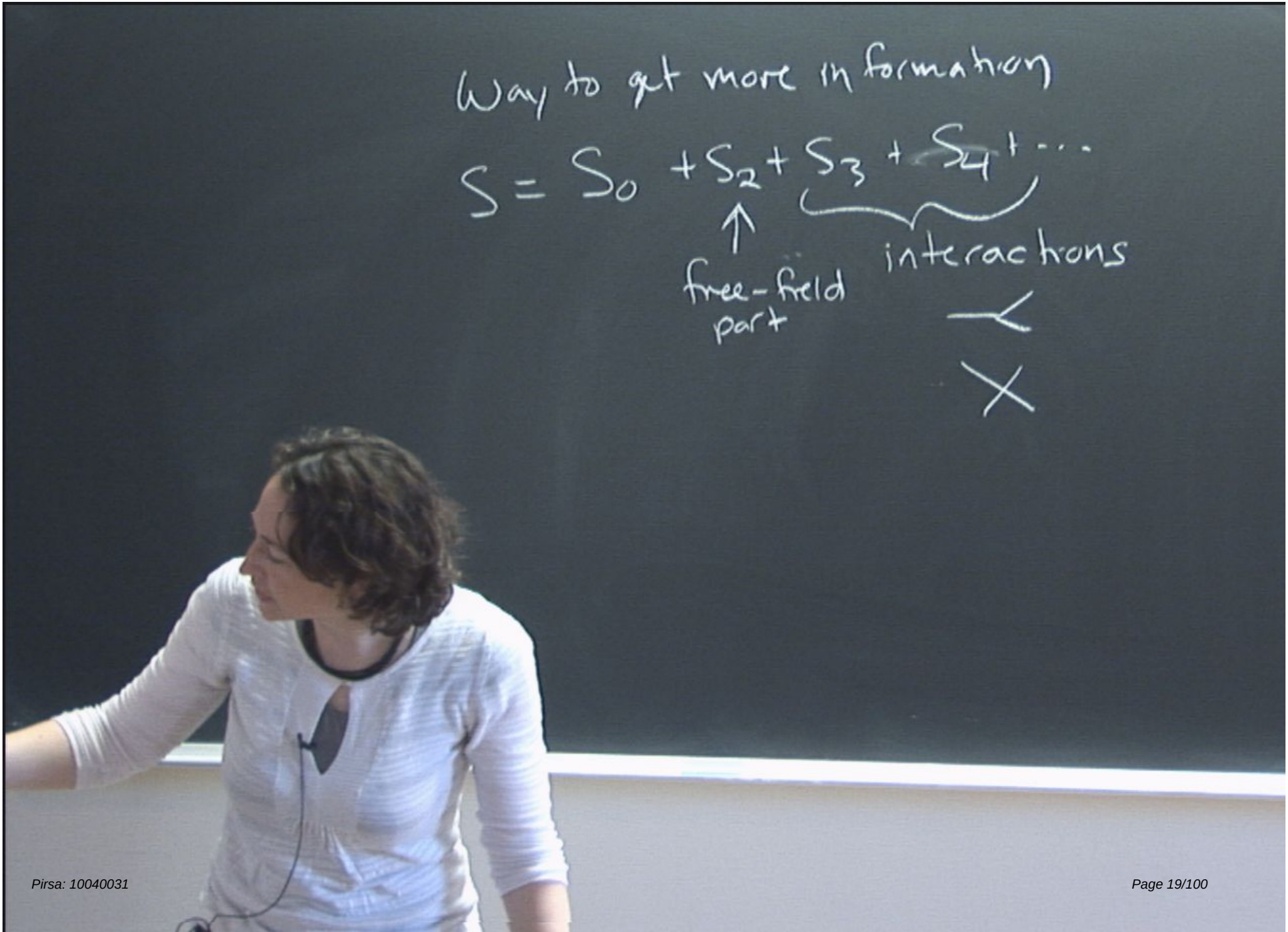
"η-problem" = hard to get flat potential

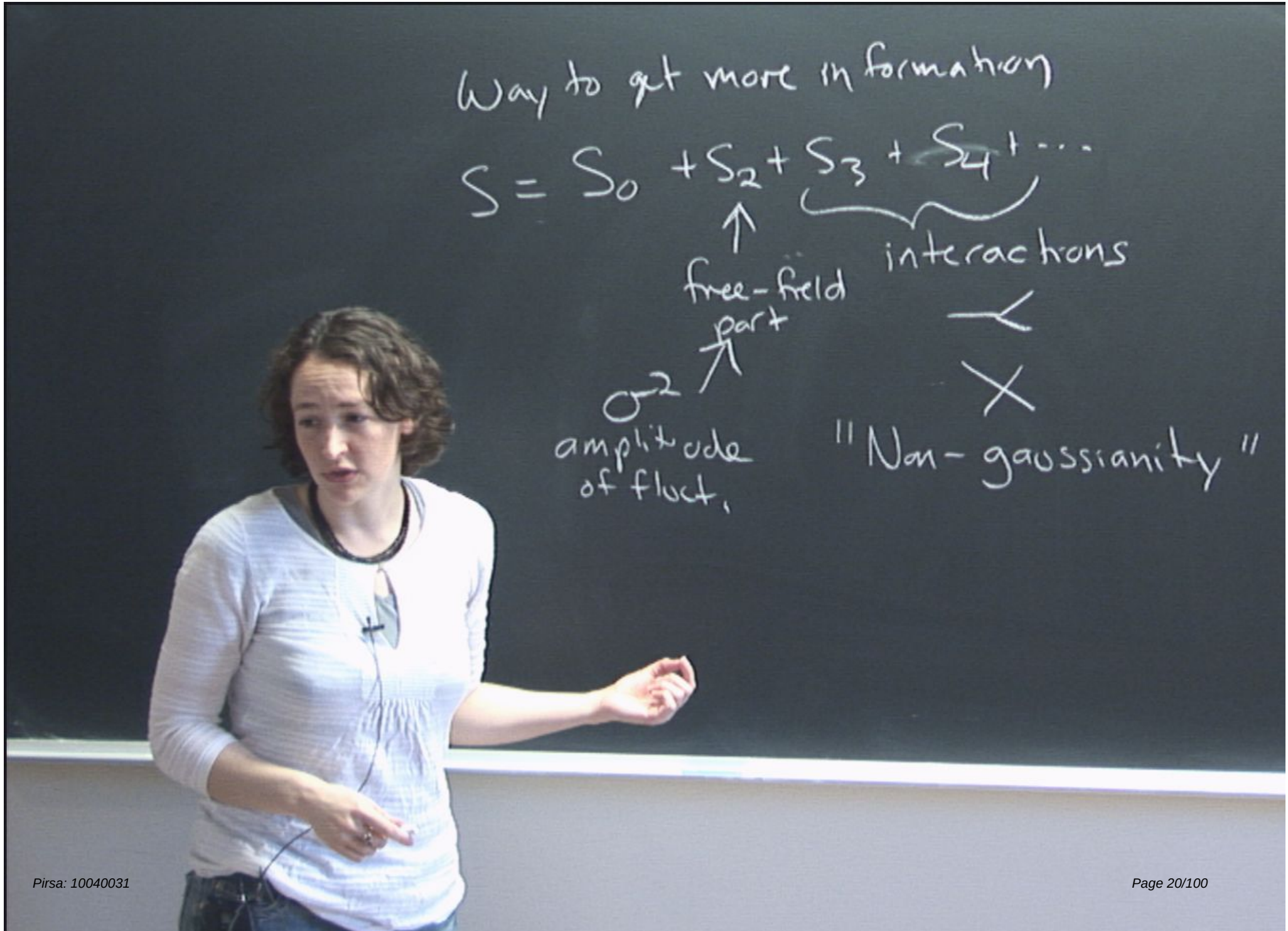
$$\eta = \frac{V''}{V} \sim \frac{1}{N_e}$$

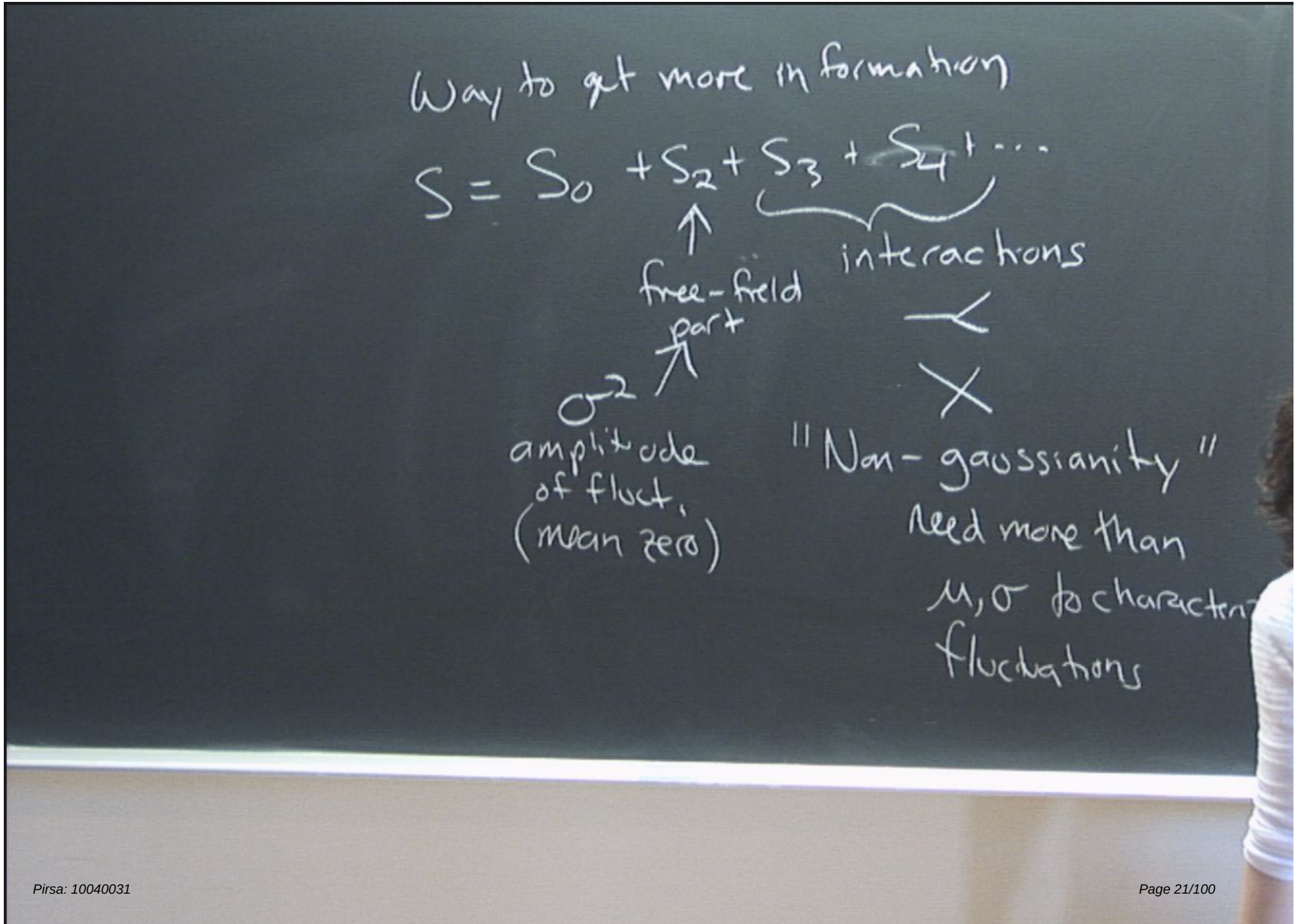

Way to get more information
$S = S_0 + S_2 + S_3 + \cdots$


Way to get more information
$S = S_0 + S_2 + S_3 + \cdots$
interactions


Way to get more information
$S = S_0 + S_2 + S_3 + \cdots$
interactions


Way to get more information
$S = S_0 + S_2 + S_3 + S_4 + \cdots$
free-field part
interactions


Way to get more information
$S = S_0 + S_2 + S_3 + S_4 + \cdots$
free-field part
interactions
σ^{-2}
amplitude of fluct.
"Non-gaussianity"


Way to get more information
$S = S_0 + S_2 + S_3 + S_4 + \cdots$
free-field part
interactions
σ^2
amplitude of fluct, (mean zero)
"Non-gaussianity"
need more than μ, σ to characterize fluctuations

Everything so far

$$P_s(k) = A_0 \left(\frac{k}{k_0}\right)^{n_s - 1}$$

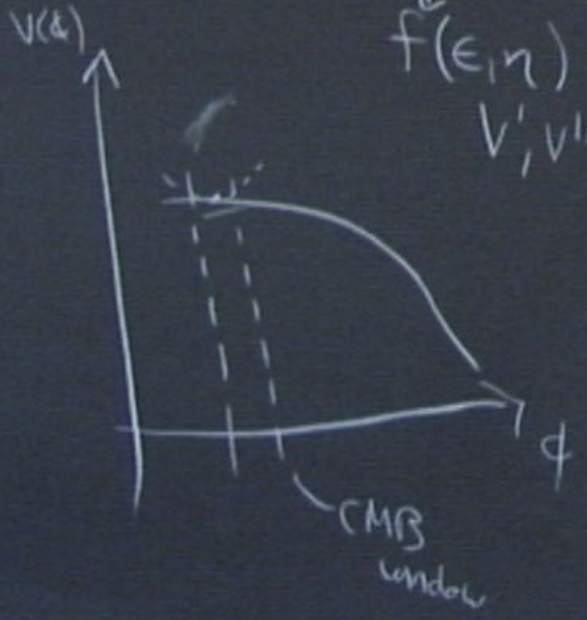
$A_0 \sim 10^{-9}$

$n_s - 1 \sim -0.04$

$\Downarrow$

$f(\epsilon, \eta)$

V', V''



Ne ~ 55, so need to control the potential over a large field range

$r > 0.01$

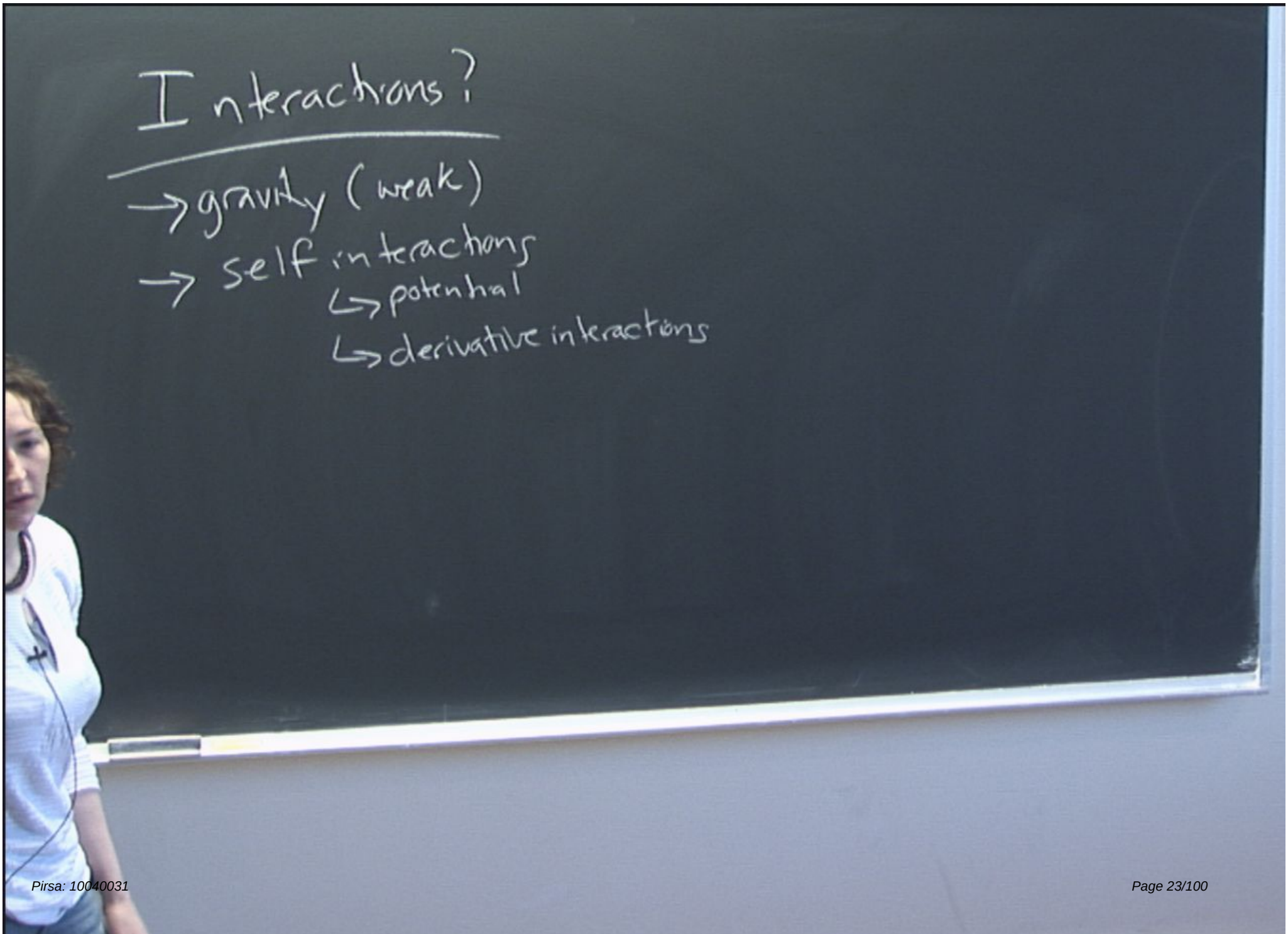
$\Rightarrow$ "large-field" $\frac{\Delta\phi}{M_p} > 1$

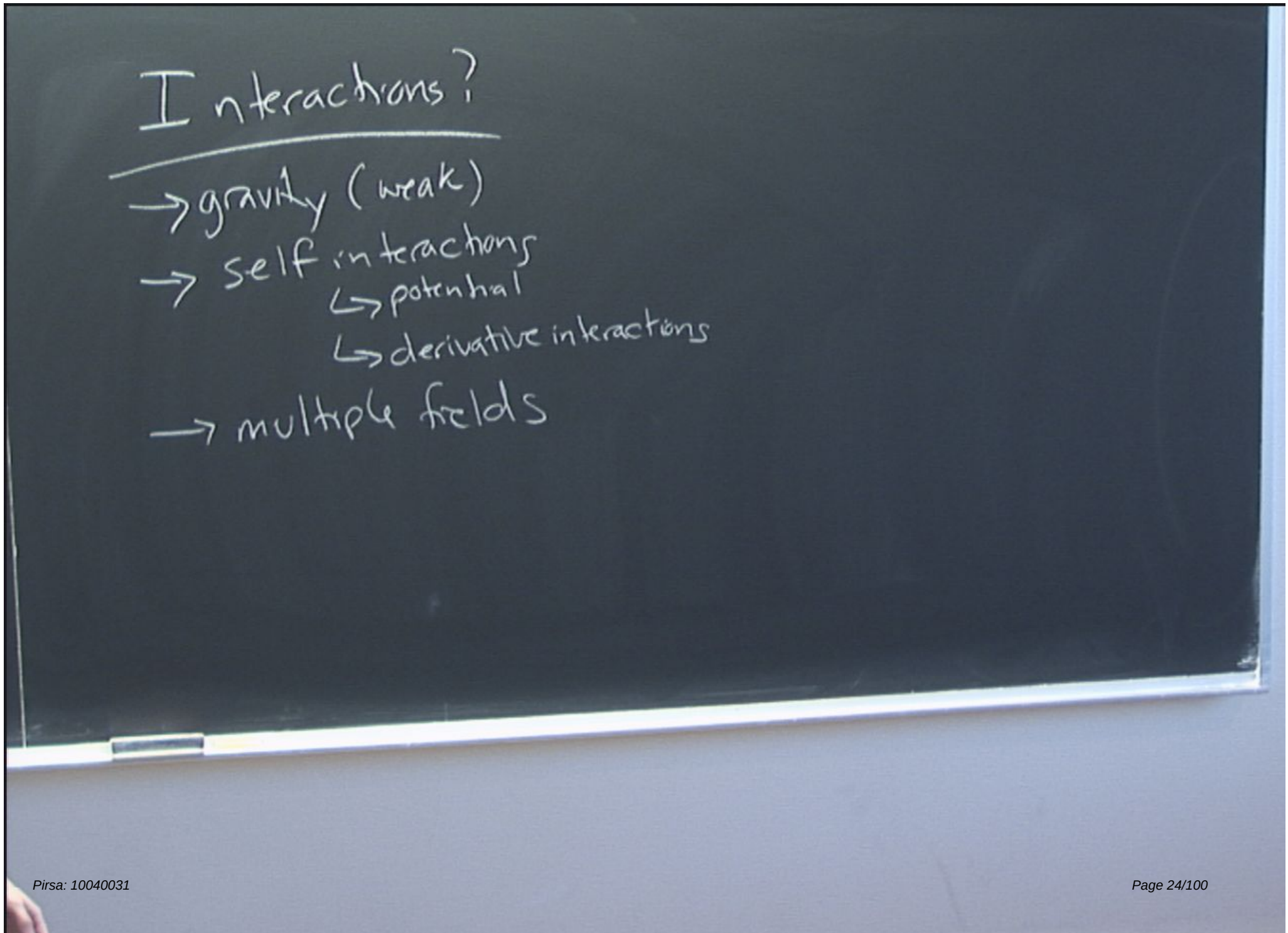
(get work: symmetry $\phi \to \phi + c$)

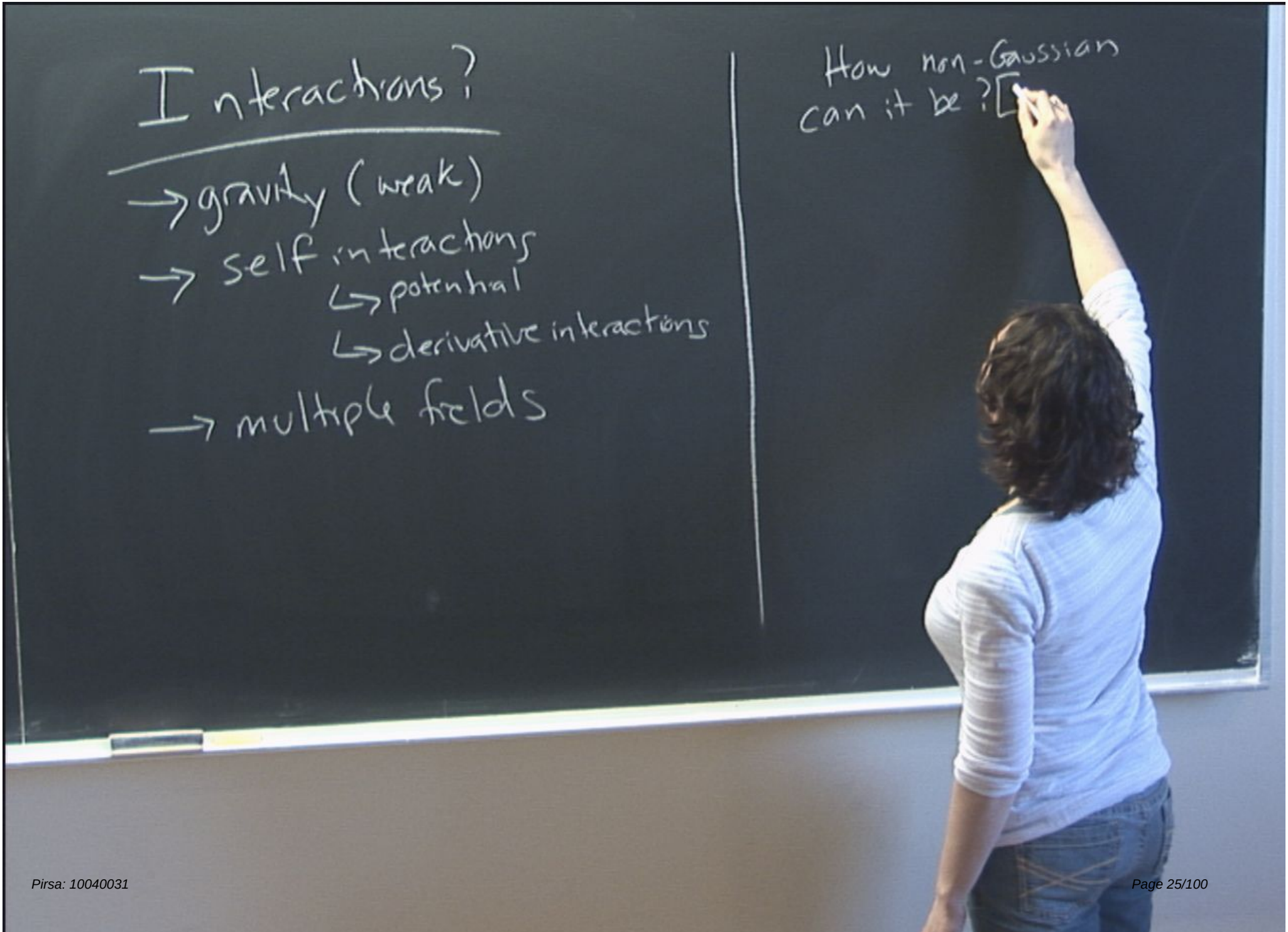
$\downarrow$

"η-problem" = hard to get flat potential

$$\eta = \frac{V''}{V} \sim \frac{1}{M_p}$$


Interactions?
→ gravity (weak)
→ self interactions
↳ potential
↳ derivative interactions


Interactions?
→ gravity (weak)
→ self interactions
↳ potential
↳ derivative interactions
→ multiple fields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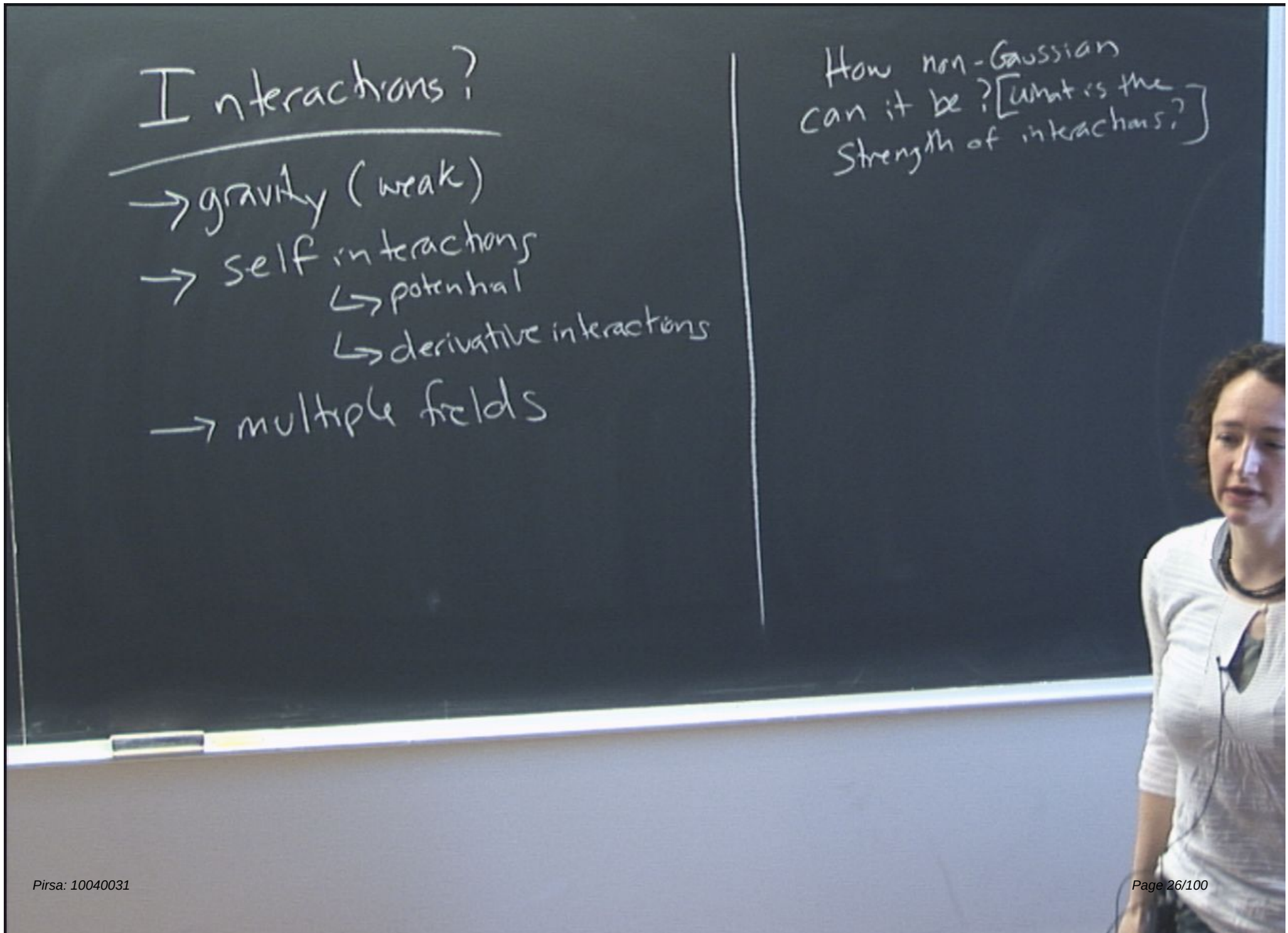
How non-Gaussian can it be? [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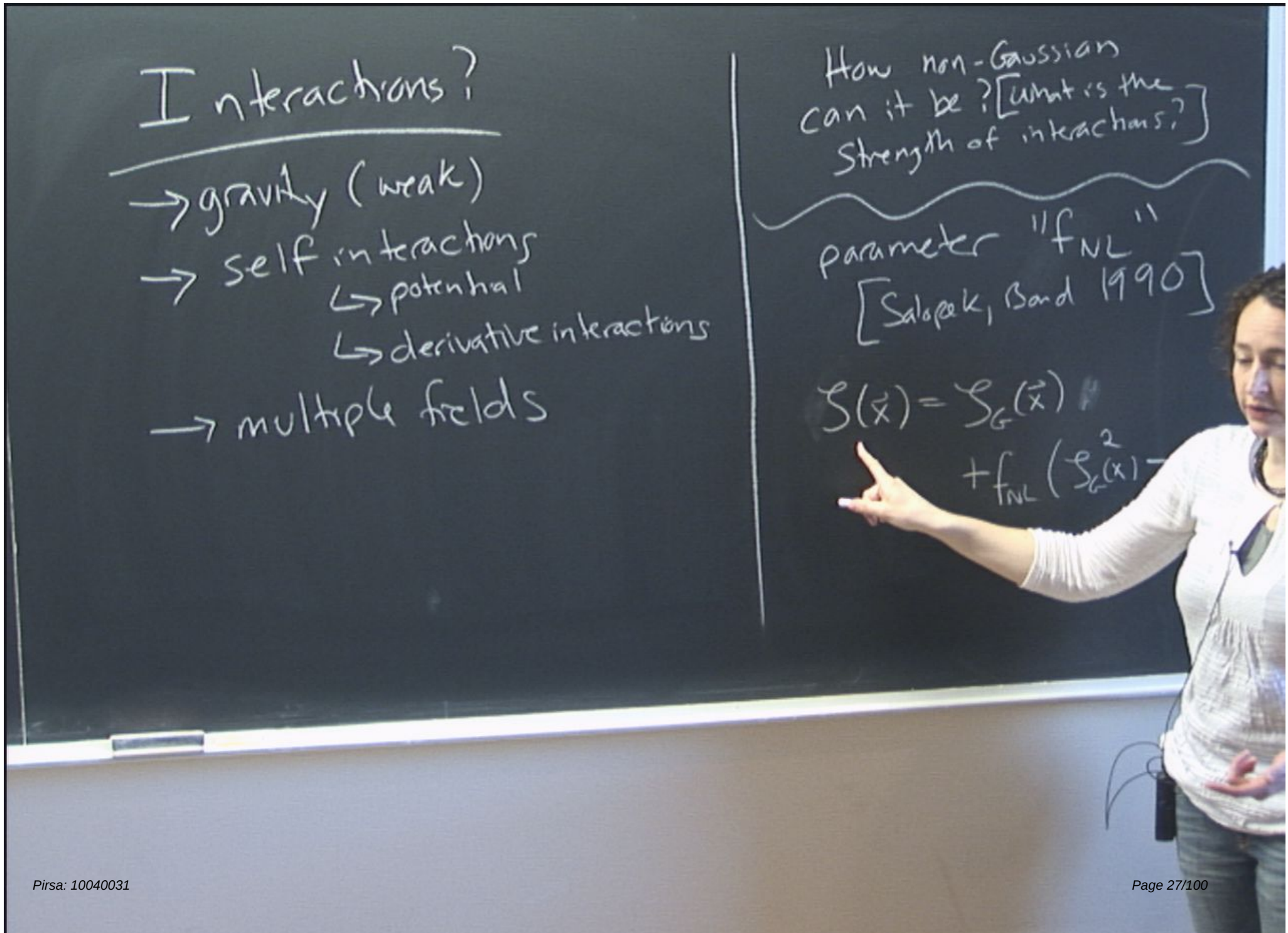
How non-Gaussian can it be? [What is the strength of interactions?]


Interactions?
→ gravity (weak)
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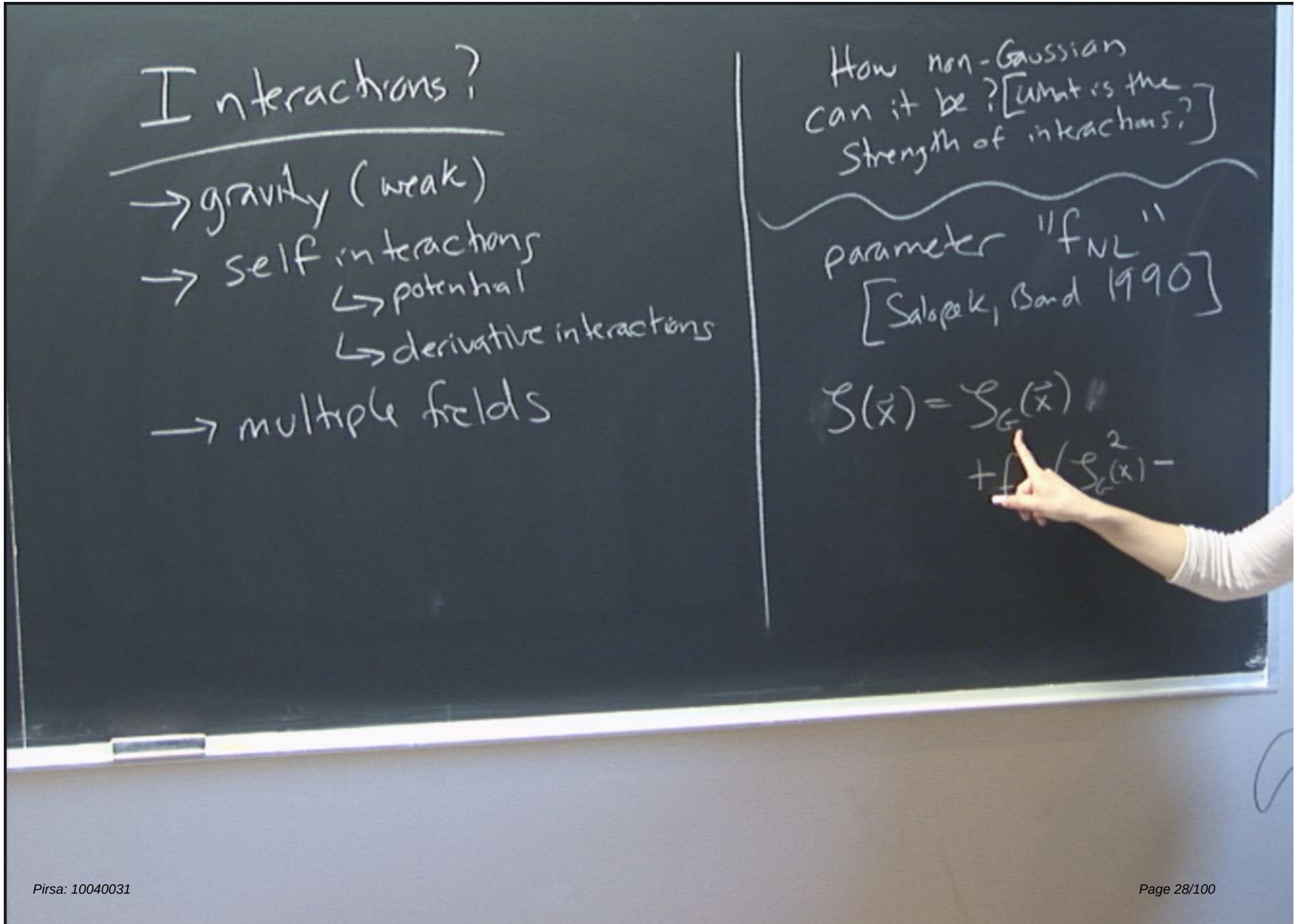
How non-Gaussian can it be? [What is the strength of interactions?]
parameter "f_{NL}"
[Salopek, Bond 1990]
$\zeta(\vec{x}) = \zeta_G(\vec{x})$
$+ f_{NL}(\zeta_G^2(x)$


Interactions?
→ gravity (weak)
→ self interactions
↳ potential
↳ derivative interactions
→ multiple fields
How non-Gaussian can it be? [What is the strength of interactions?]
parameter "f_{NL}"
[Salopek, Bond 1990]
$\zeta(\vec{x}) = \zeta_G(\vec{x})$
$+ f(\zeta_G^2(x) -$

Interactions?

→ gravity (weak)

→ self interactions
- ↳ potential
- ↳ derivative interactions

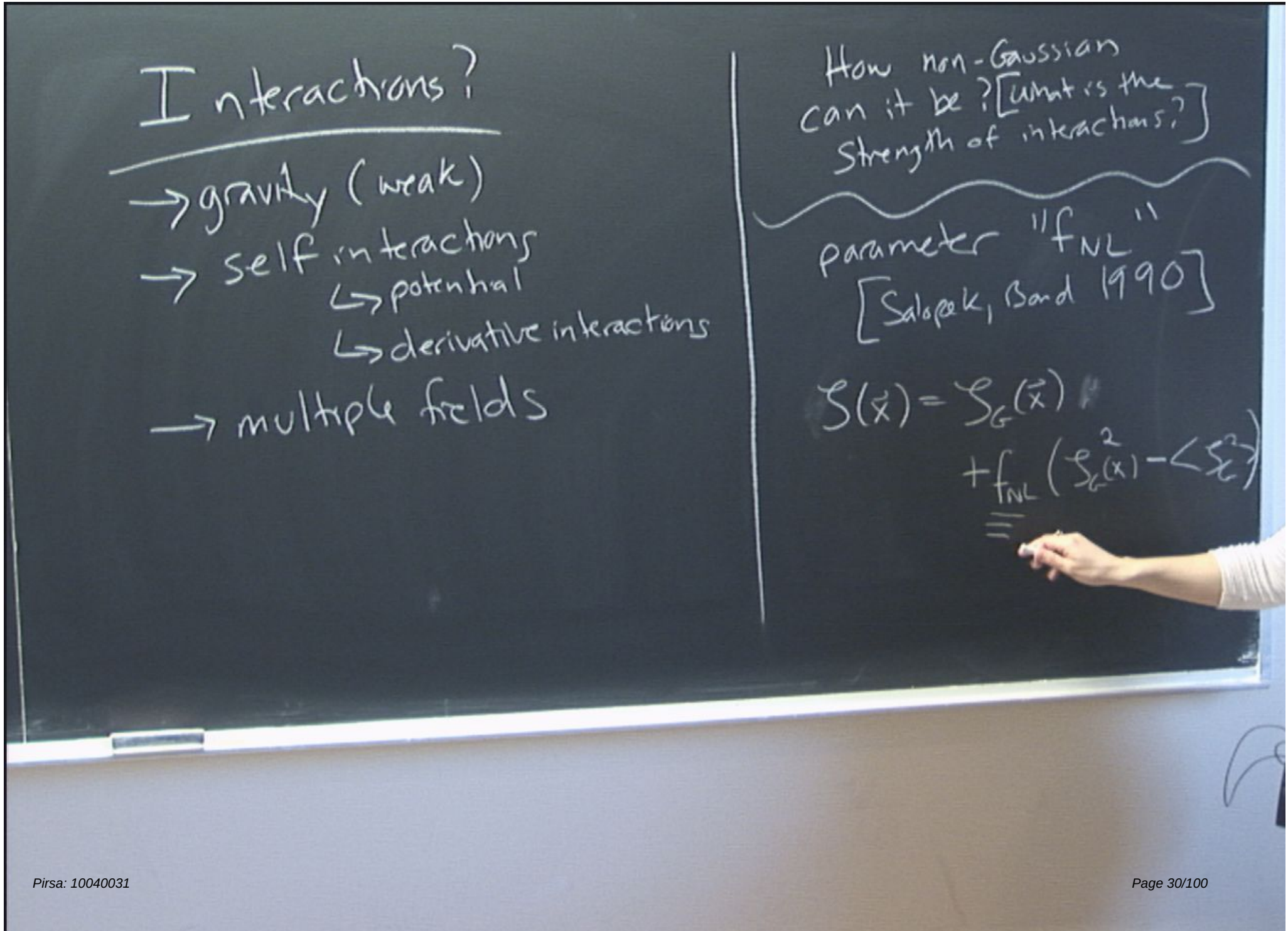
→ multiple fields

How non-Gaussian can it be? [What is the strength of interactions?]

parameter "f_{NL}"

[Salopek, Bond 1990]

$$\zeta(\vec{x}) = \zeta_G(\vec{x}) + f_{NL}\left(\zeta_G^2(x) - \langle \zeta_G^2 \rangle\right)$$


Interactions?
→ gravity (weak)
→ self interactions
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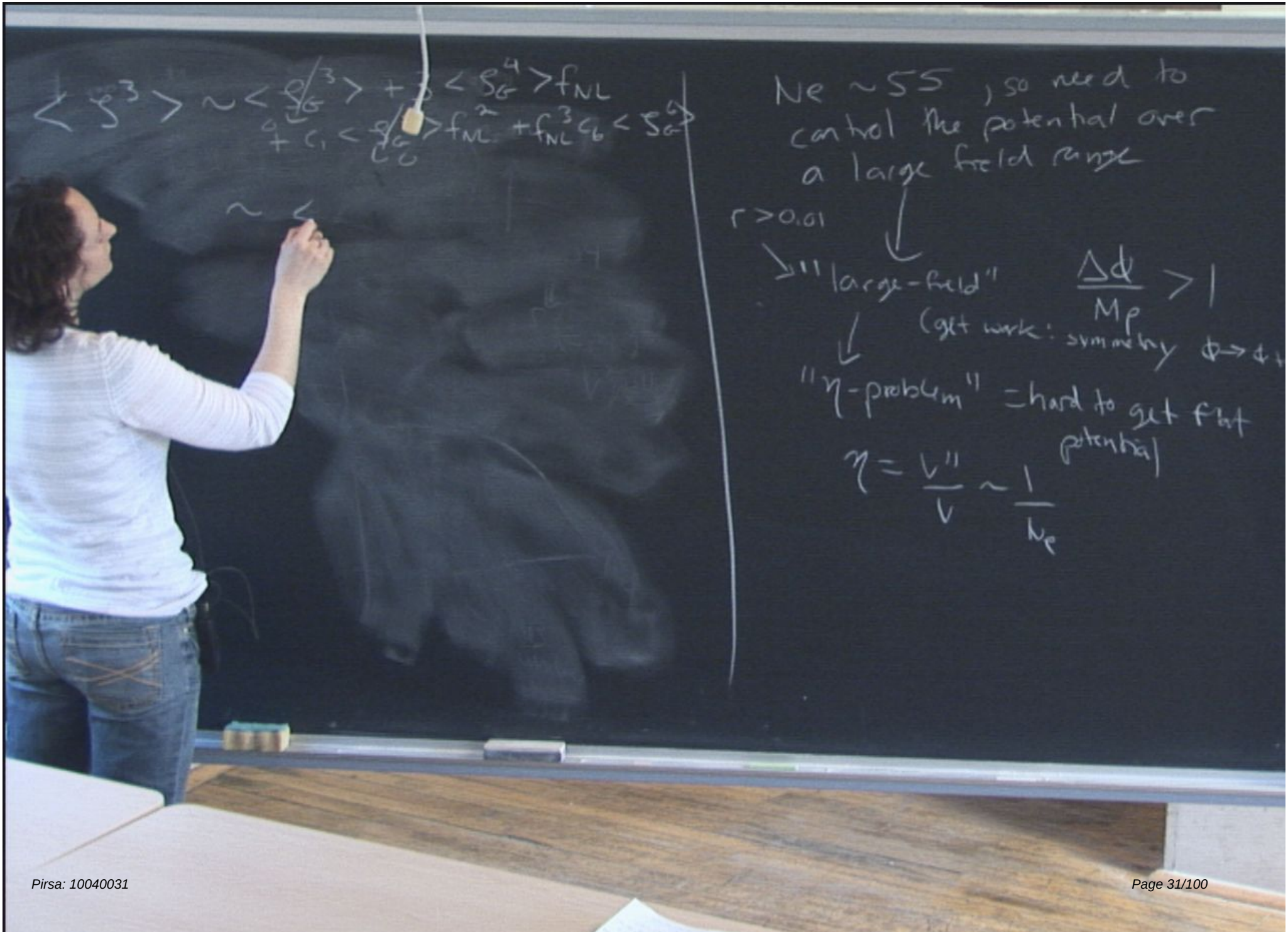
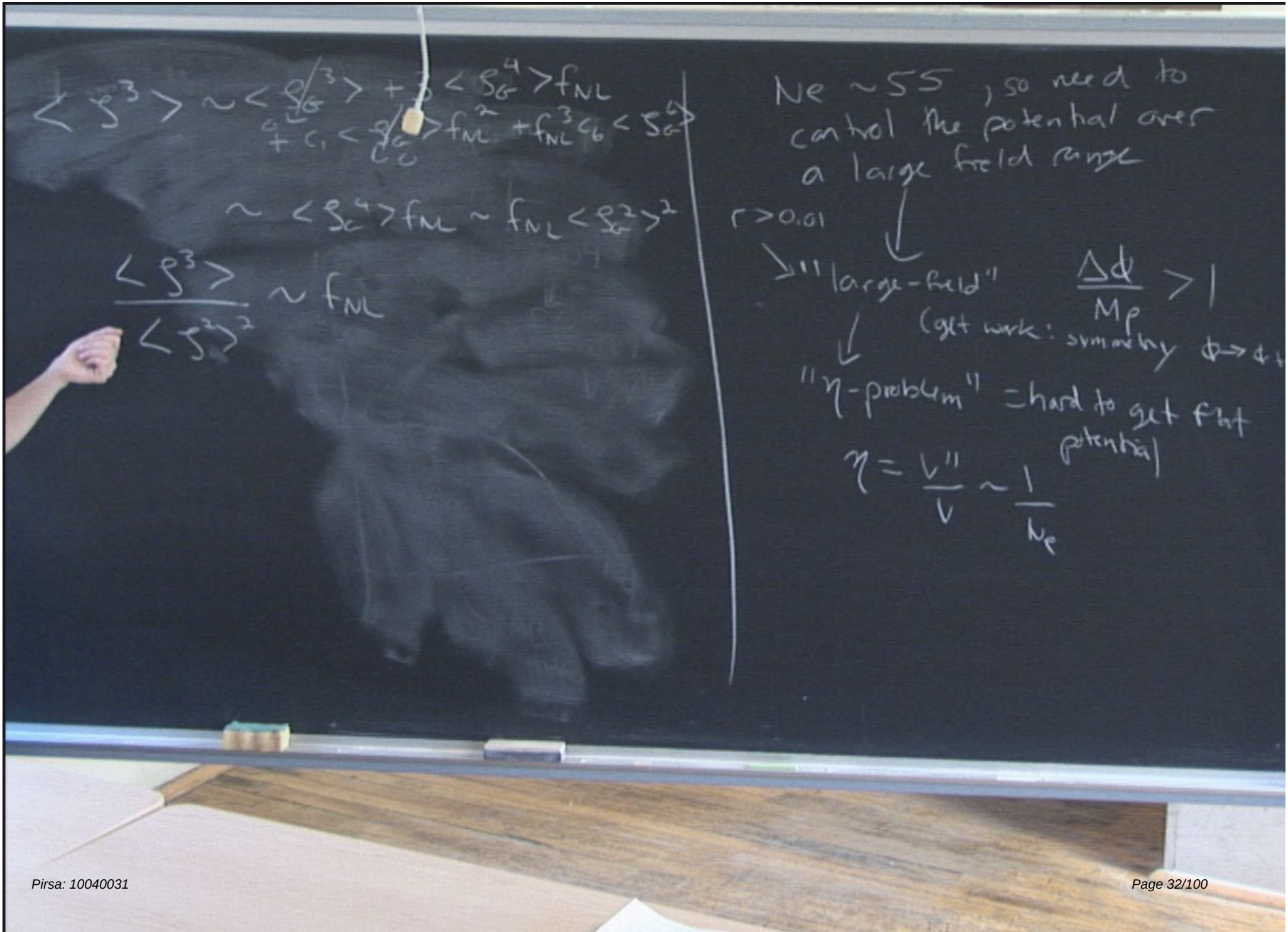
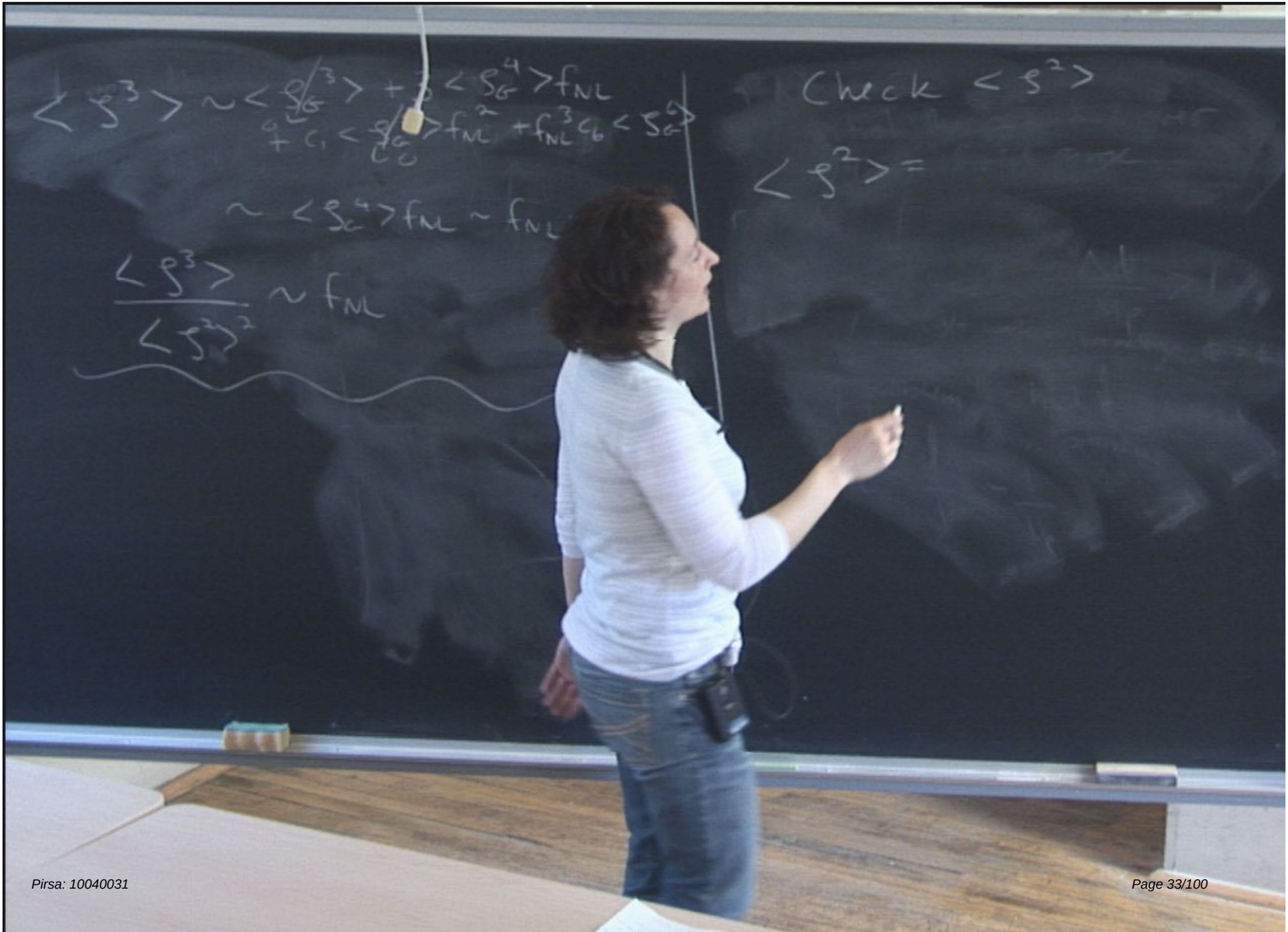
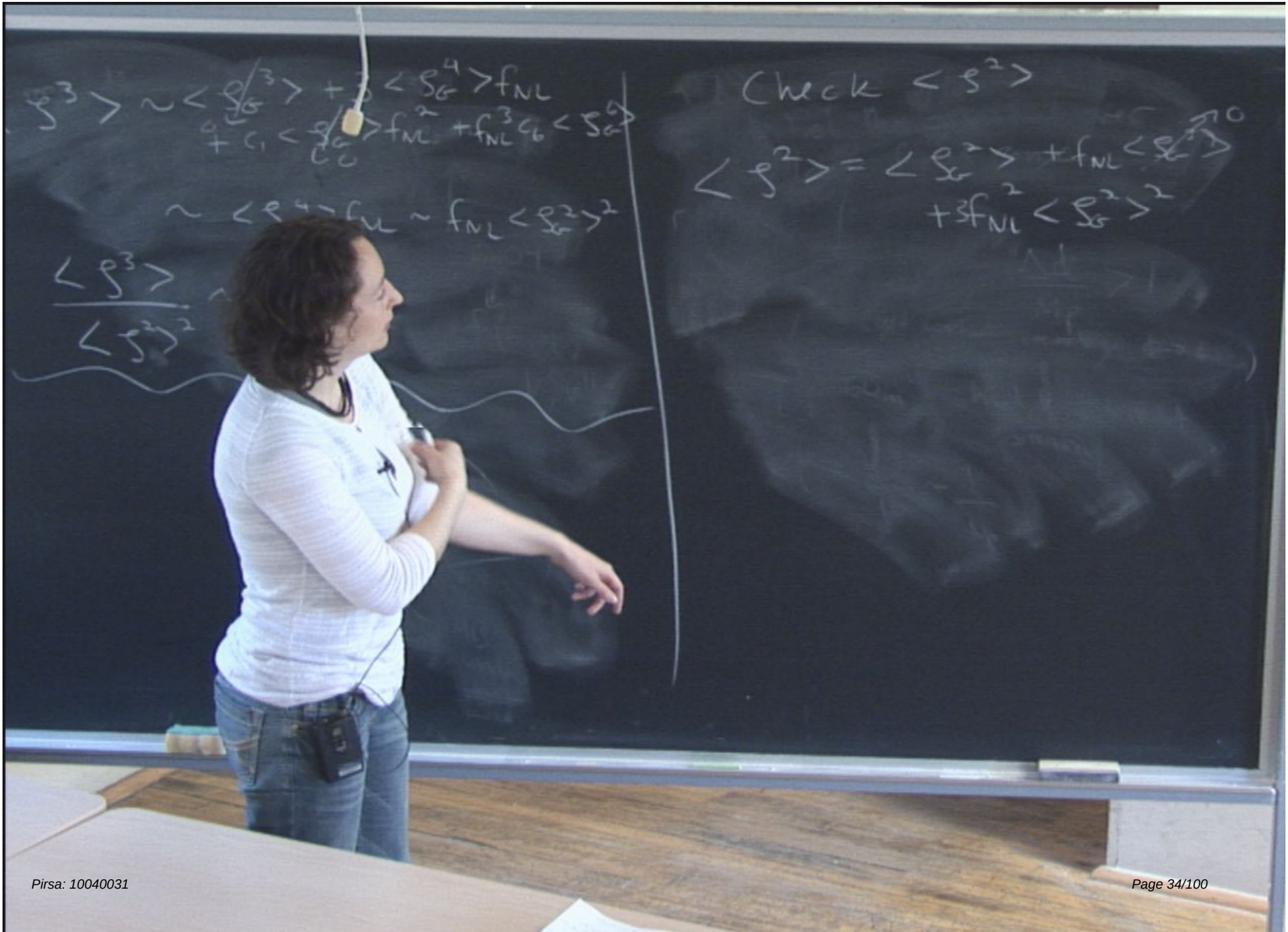
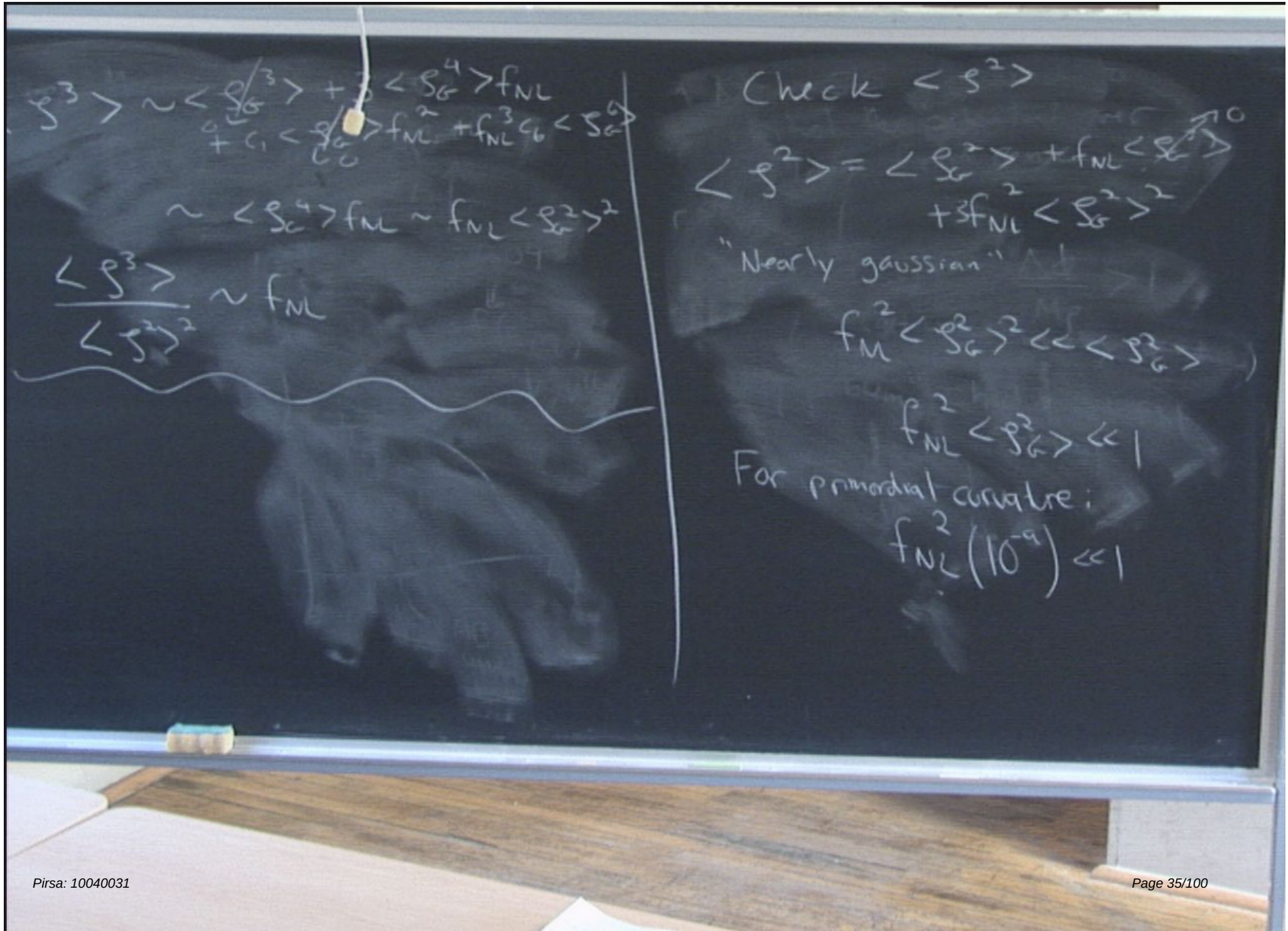
↳ derivative interactions
→ multiple fields
How non-Gaussian can it be? [What is the strength of interactions?]
parameter "f_{NL}"
[Salopek, Bond 1990]
$\zeta(\vec{x}) = \zeta_G(\vec{x}) + f_{NL}(\zeta_G^2(x) - \langle \zeta_G^2 \rangle)$

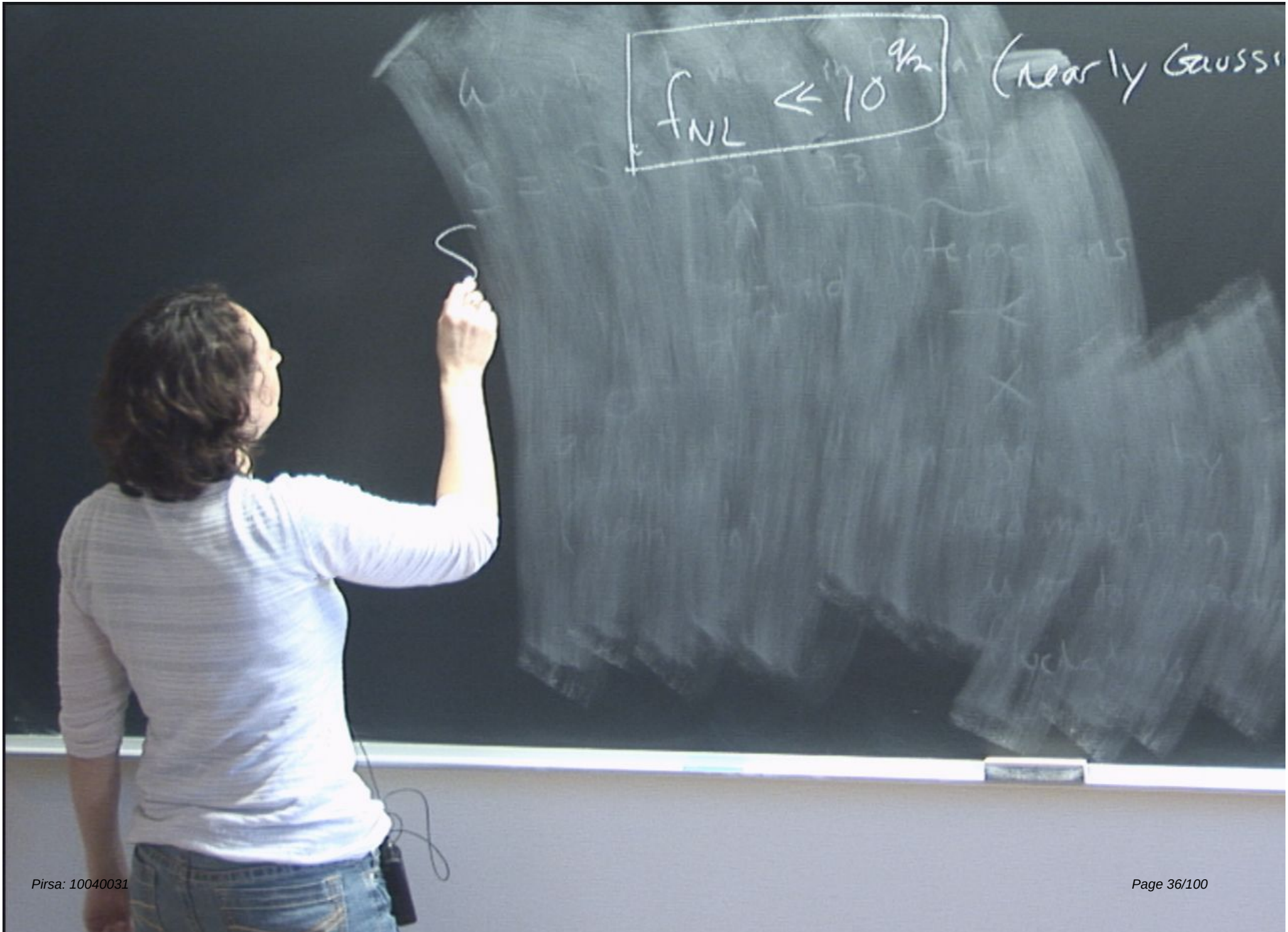

Ne ~ 55, so need to control the potential over a large field range
r > 0.01
"large-field"
Δφ / Mp > 1
(get work: symmetry φ → φ +
"η-problem" = hard to get flat potential
η = V'' / V ~ 1 / Ne

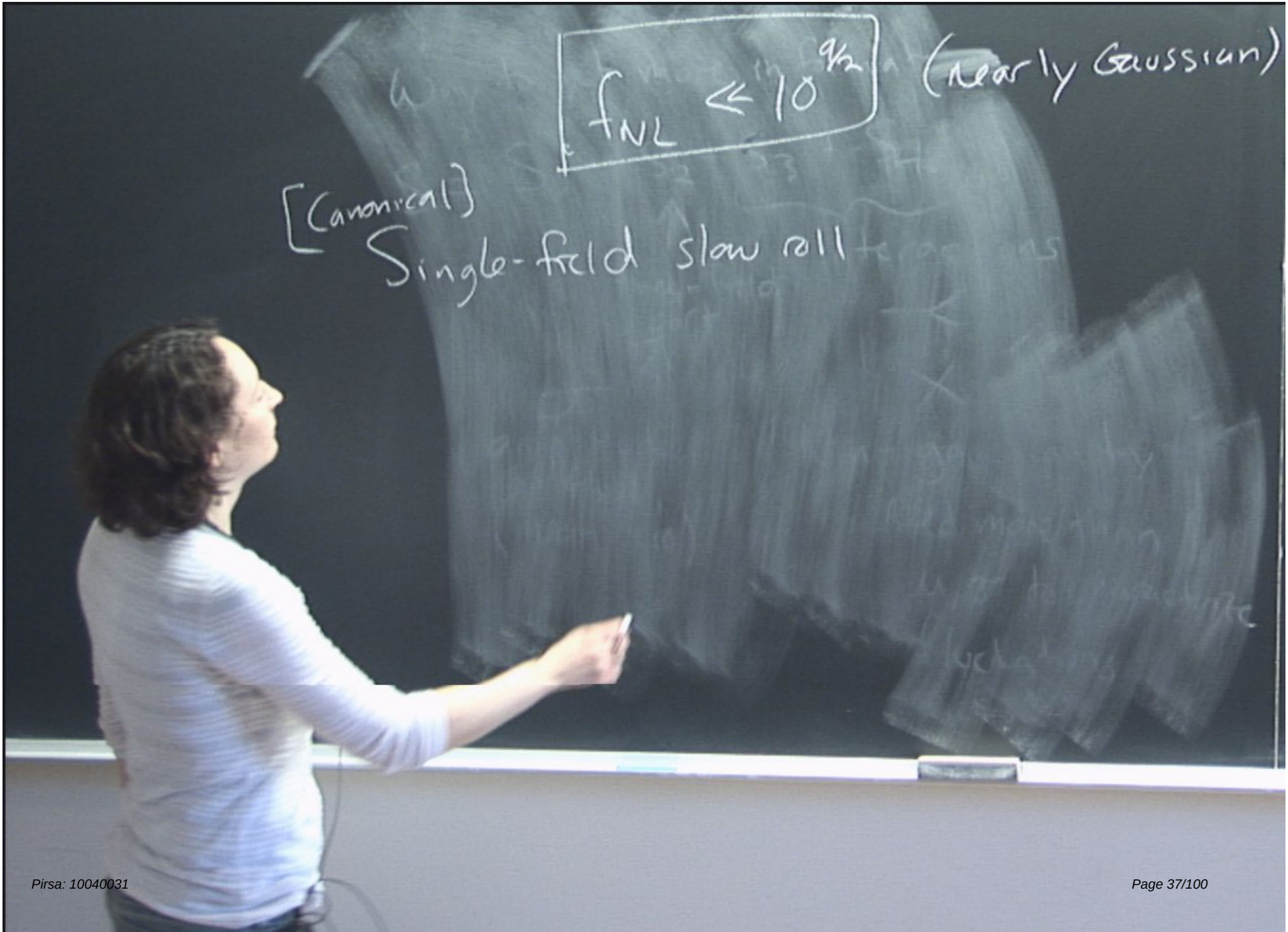

$\langle \zeta^3 \rangle \sim \langle \zeta_G^3 \rangle + \langle \zeta_G^4 \rangle f_{NL}$
$+ c_1 \langle \zeta_G^2 \rangle f_{NL}^2 + f_{NL}^3 c_6 \langle \zeta_G^6 \rangle$
$\sim \langle \zeta_G^4 \rangle f_{NL} \sim f_{NL} \langle \zeta_G^2 \rangle^2$
$\frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^2} \sim f_{NL}$
Ne ~ 55, so need to control the potential over a large field range
$r > 0.01$
"large-field" $\frac{\Delta\phi}{M_p} > 1$
(get work: symmetry $\phi \to \phi +$
"η-problem" = hard to get flat potential
$\eta = \frac{V''}{V} \sim \frac{1}{M_p}$

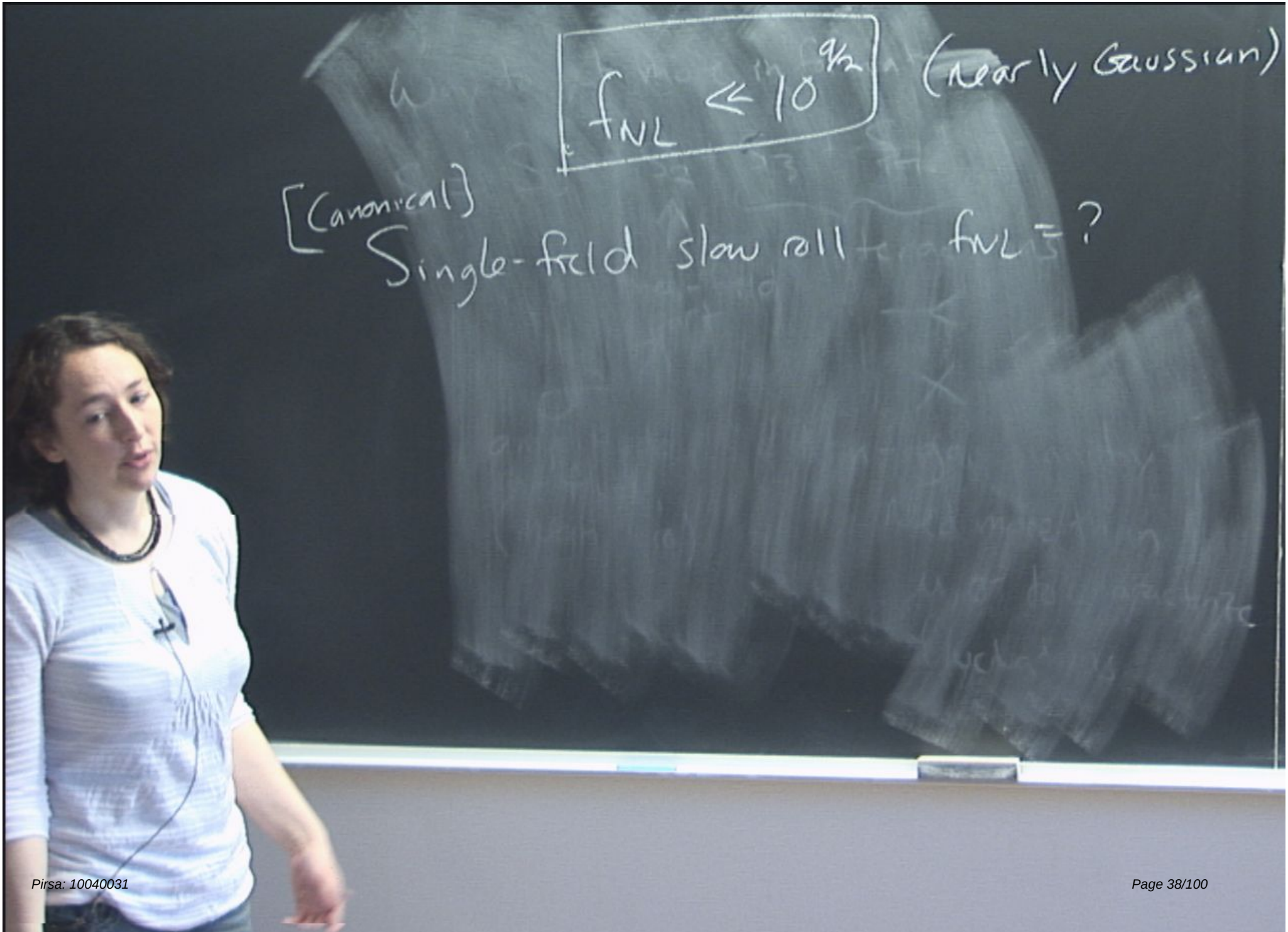

Check

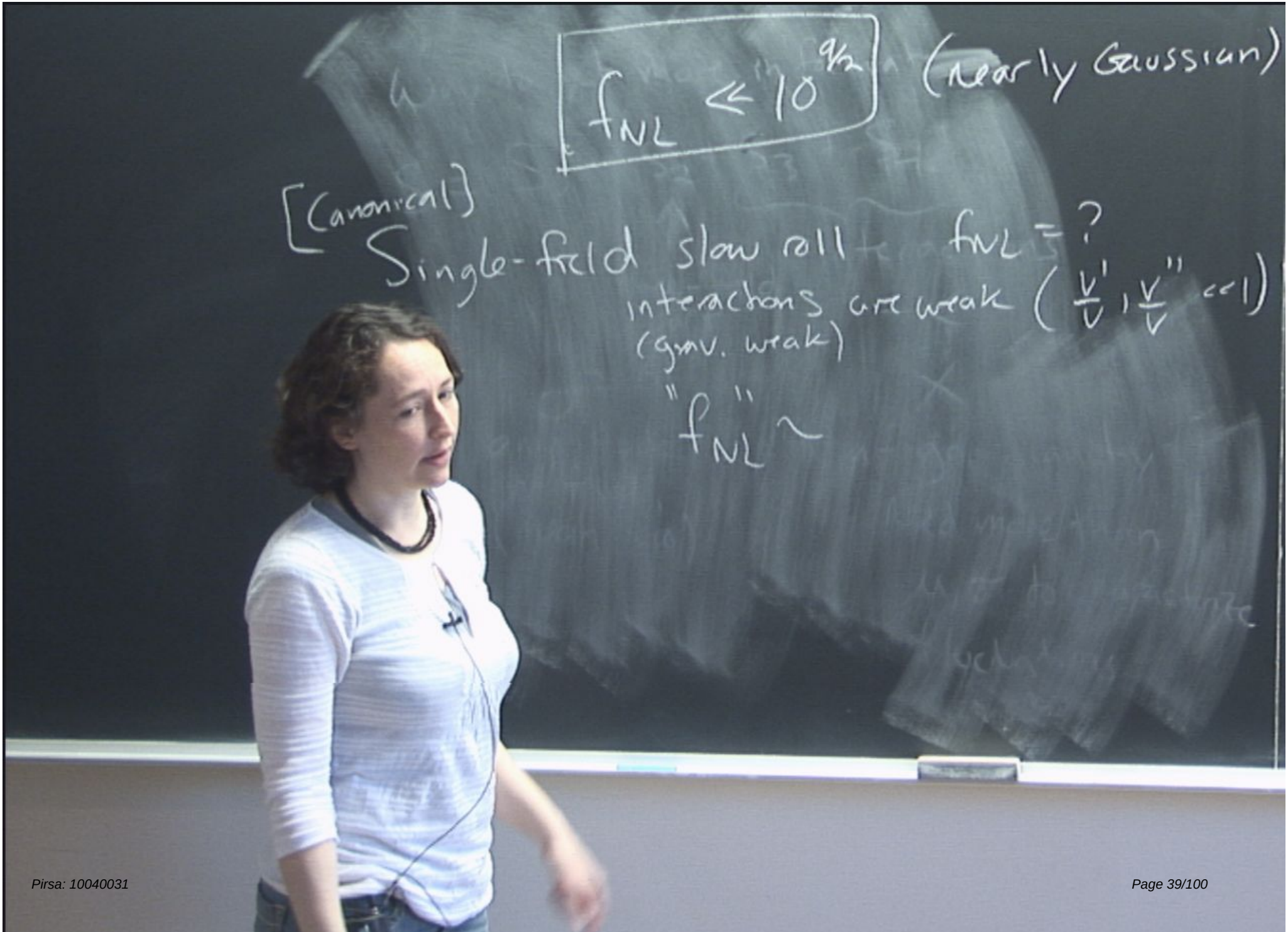

Check


$\langle \zeta^3 \rangle \sim \langle \zeta_G^3 \rangle + \langle \zeta_G^4 \rangle f_{NL}$
$+ c_1 \langle \zeta_G \rangle f_{NL}^2 + f_{NL}^3 c_0$
$\sim \langle \zeta_G^4 \rangle f_{NL} \sim f_{NL} \langle \zeta_G^2 \rangle^2$
$\frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^2} \sim f_{NL}$
Check $\langle \zeta^2 \rangle$
$\langle \zeta^2 \rangle = \langle \zeta_G^2 \rangle + f_{NL} \langle \zeta_G \rangle^0$
$+ 3 f_{NL}^2 \langle \zeta_G^2 \rangle^2$
"Nearly gaussian"
$f_{NL}^2 \langle \zeta_G^2 \rangle^2 \ll \langle \zeta_G^3 \rangle$
$f_{NL}^2 \langle \zeta_G^2 \rangle \ll 1$
For primordial curvature:
$f_{NL}^2 (10^{-9}) \ll 1$


$f_{NL} \ll 10^{9/2}$
(nearly Gaussi


$f_{NL} \ll 10^{-1/2}$
(nearly Gaussian)
[Canonical]
Single-field slow roll


$f_{NL} \ll 10^{-1/2}$
(nearly Gaussian)
[Canonical]
Single-field slow roll
$f_{NL} = ?$


$f_{NL} \ll 10^{-1/2}$ (nearly Gaussian)
[Canonical]
Single-field slow roll
$f_{NL} = ?$
interactions are weak ($\frac{V'}{V}, \frac{V''}{V} \ll 1$)
(grav. weak)
"f_{NL}" ~

$f_{NL} \ll 10^{-2}$ (nearly Gaussian)

[Canonical]

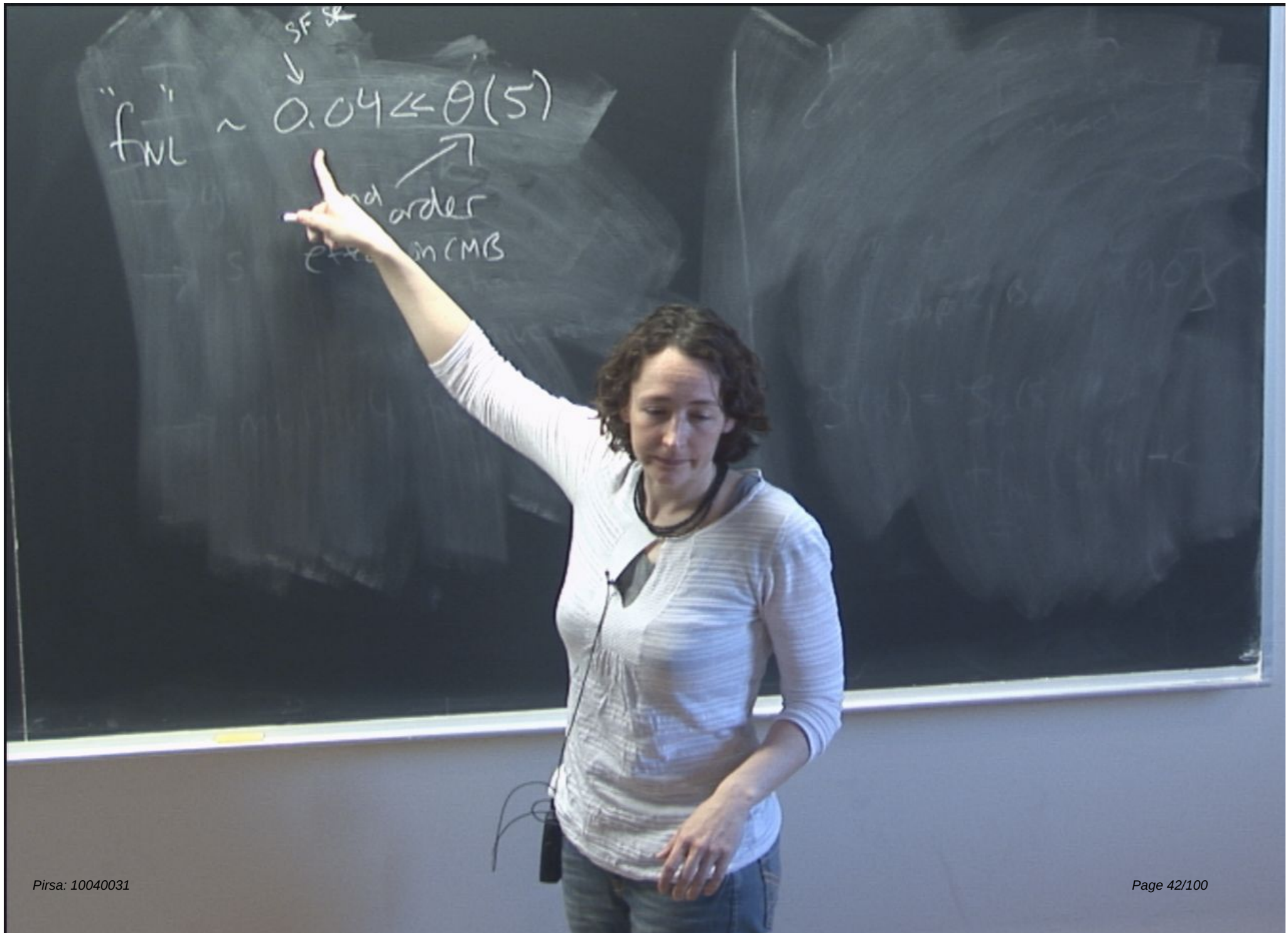
Single-field slow roll $f_{NL} = ?$

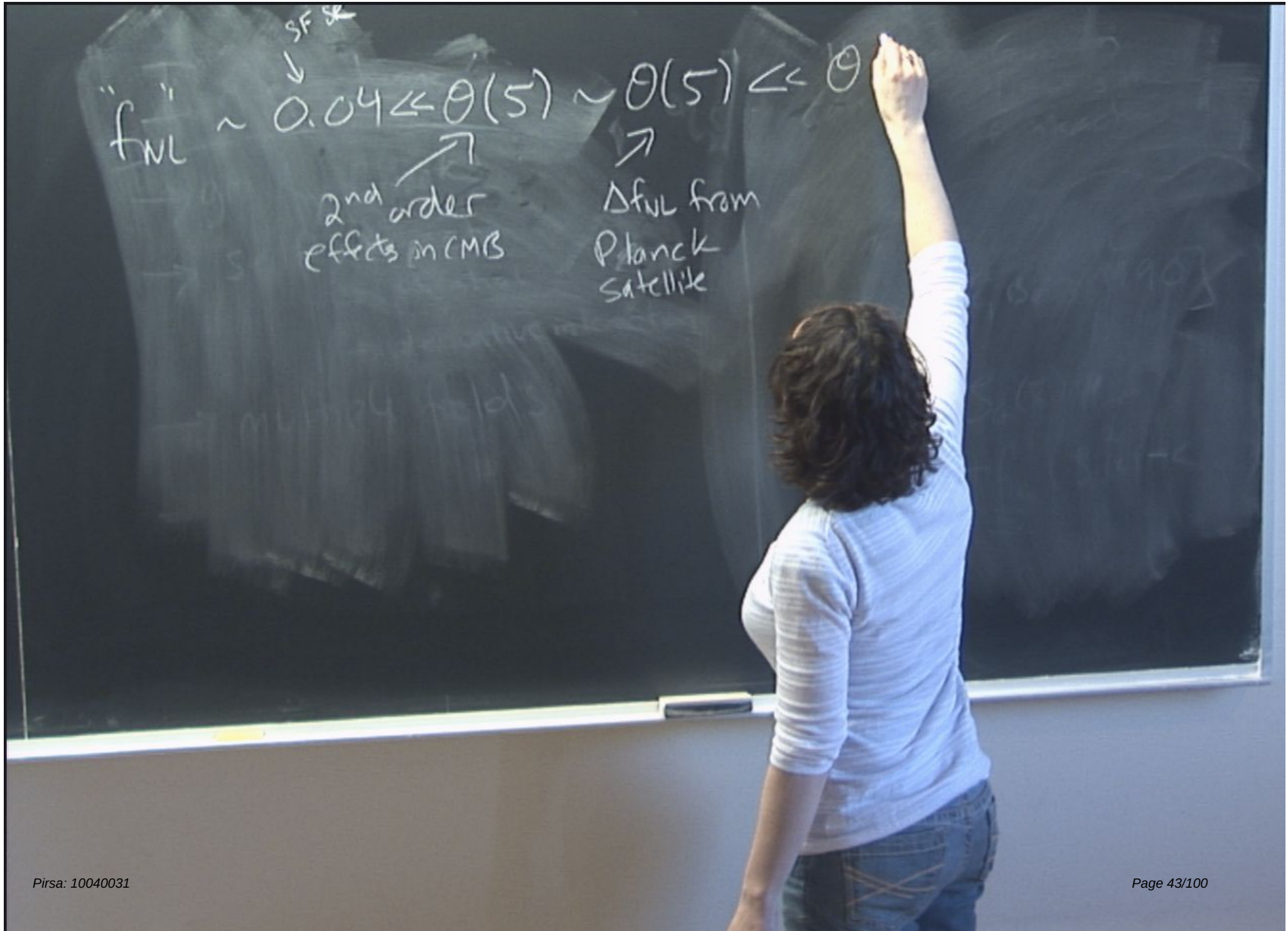
interactions are weak $\left(\frac{V'}{V}, \frac{V''}{V} \ll 1\right)$

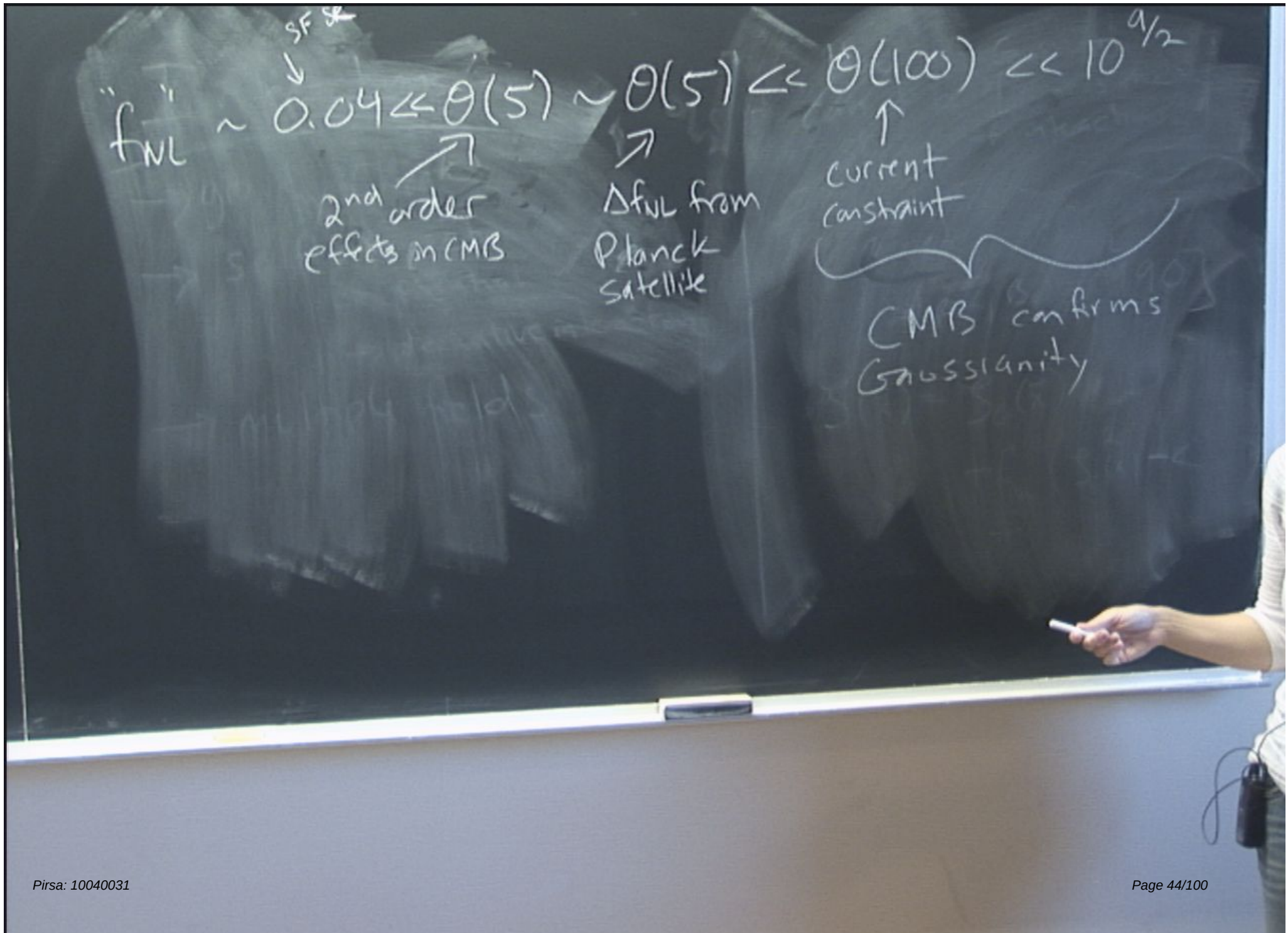
(grav. weak)

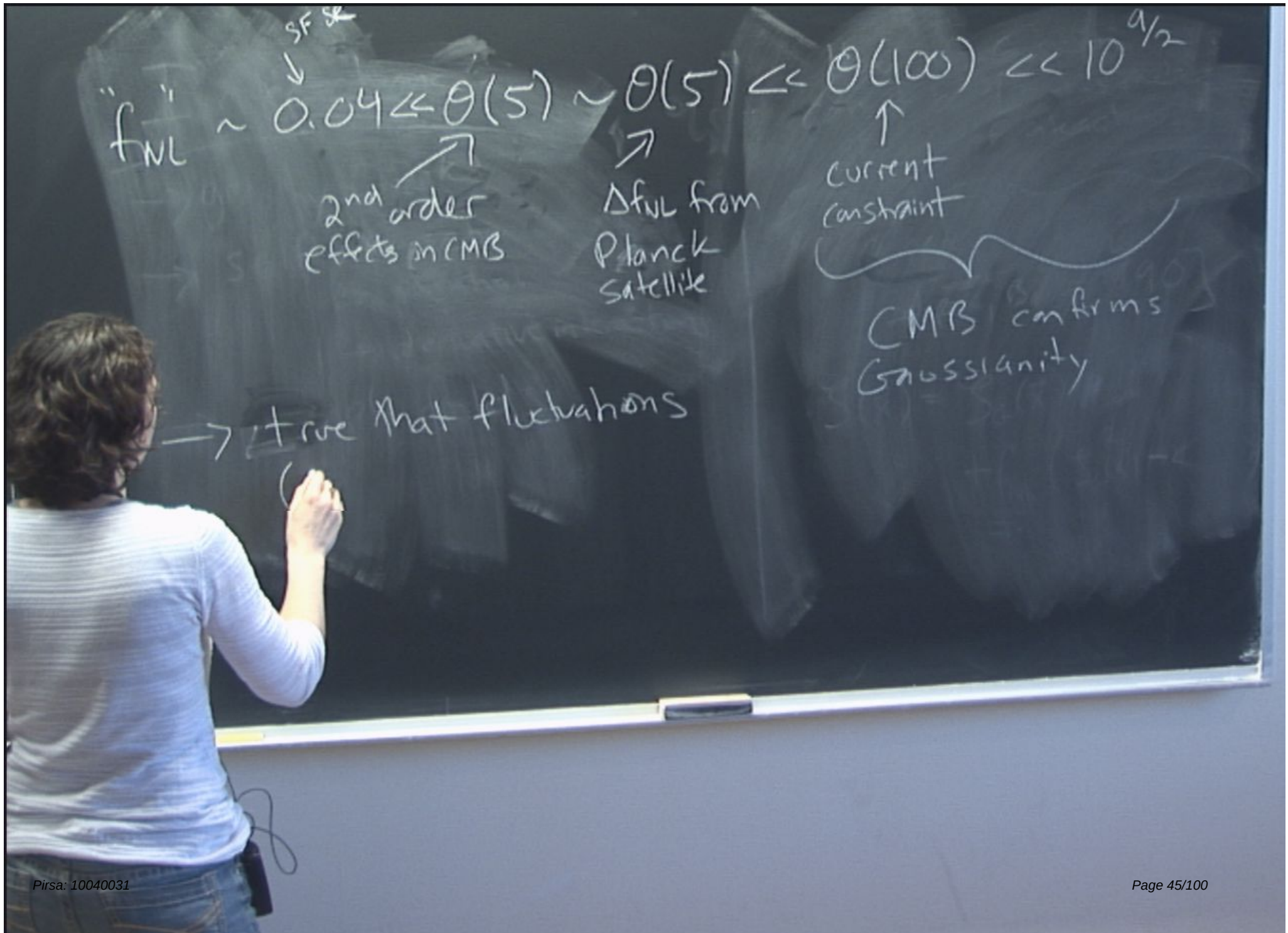
"f_{NL}" $\sim n_s - 1 \sim 0.04$

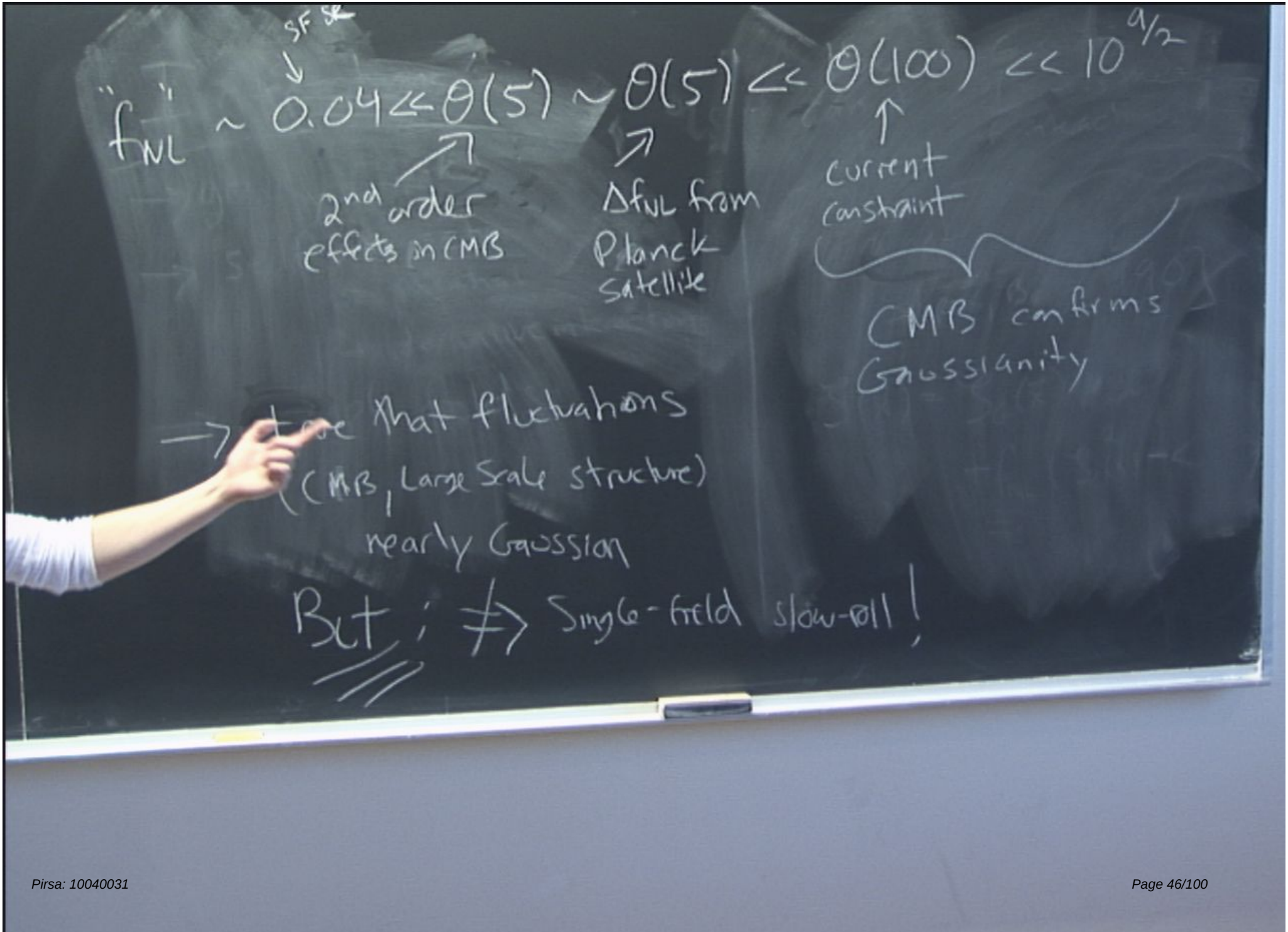
"f_NL" ~ 0.04

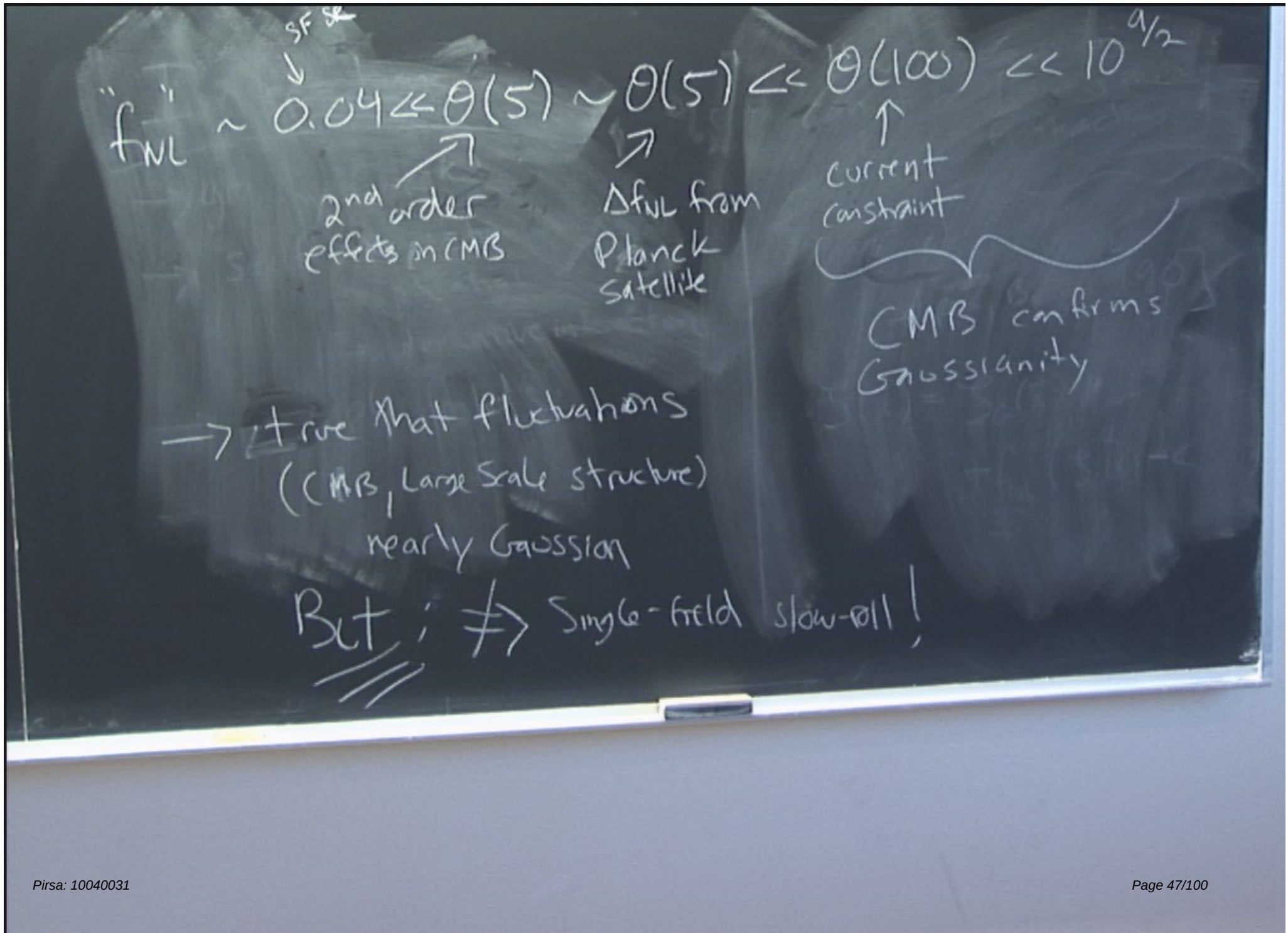

SF
"f_NL" ~ 0.04 < θ(5)
order
CMB

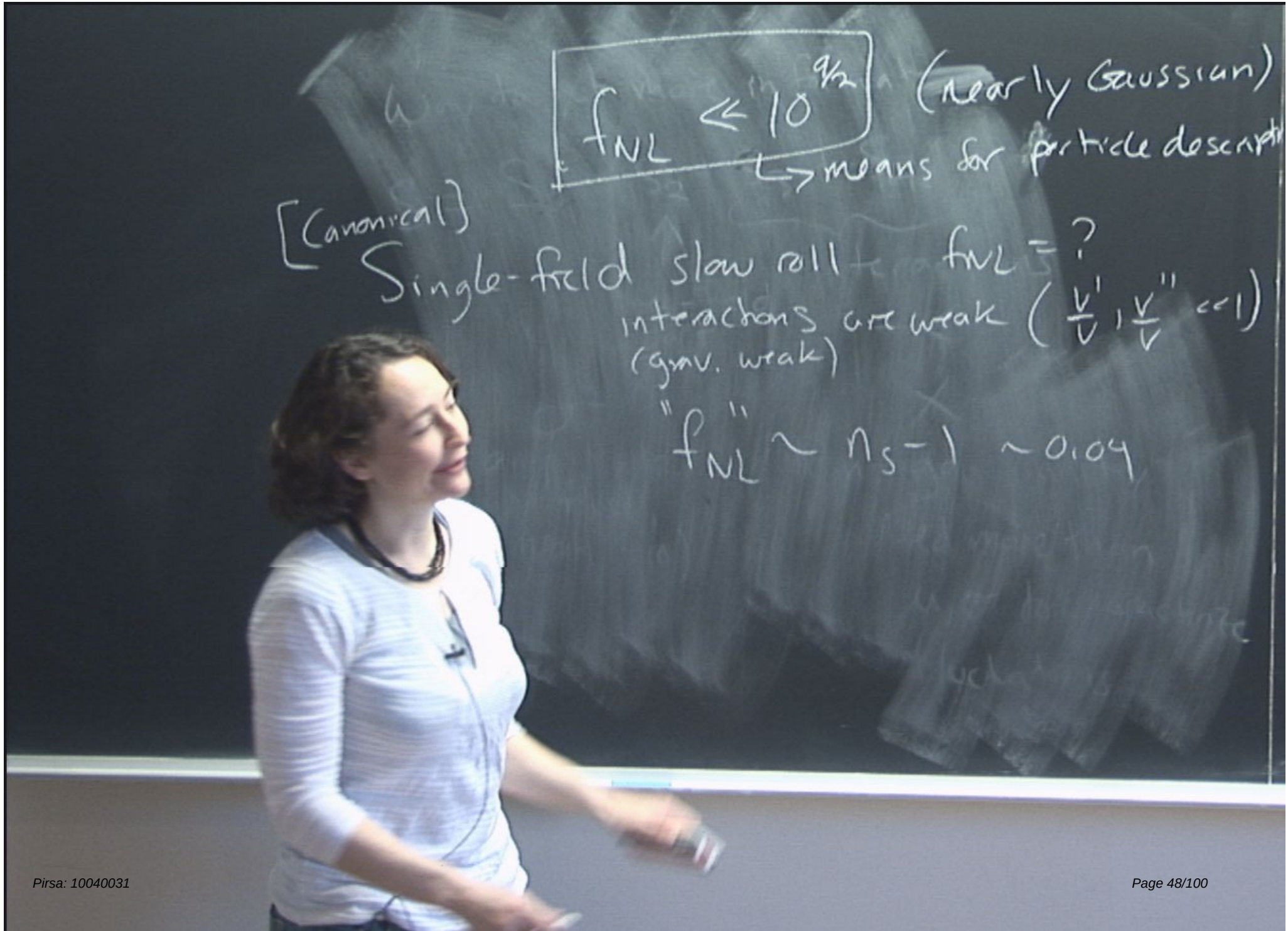

SF SK
"f_NL" ~ 0.04 << θ(5) ~ θ(5) << θ
2nd order effects in CMB
Δf_NL from Planck satellite


SF
"f_{NL}" ~ 0.04 << $\Theta(5)$ ~ $\Theta(5)$ << $\Theta(100)$ << $10^{9/2}$
2nd order effects in CMB
Δf_{NL} from Planck satellite
current constraint
CMB confirms Gaussianity


SF SR
"f_{NL}" ~ 0.04 << $\mathcal{O}(5)$ ~ $\mathcal{O}(5)$ << $\mathcal{O}(100)$ << $10^{9/2}$
2nd order effects in CMB
Δf_{NL} from Planck satellite
current constraint
CMB confirms Gaussianity
→ true that fluctuations


SF SL
"f_{NL}" ~ 0.04 << O(5) ~ O(5) << O(100) << $10^{9/2}$
2nd order effects in CMB
Δfnl from Planck satellite
current constraint
CMB confirms Gaussianity
→ these that fluctuations
(CMB, Large Scale structure)
nearly Gaussian
But ; ≠> Single-field slow-roll !


SF SR
"f_{NL}" ~ 0.04 << $\mathcal{O}(5)$ ~ $\mathcal{O}(5)$ << $\mathcal{O}(100)$ << $10^{9/2}$
2nd order effects in CMB
Δf_{NL} from Planck satellite
current constraint
CMB confirms Gaussianity
→ true that fluctuations ((CMB, Large Scale structure) nearly Gaussian
But ; ⇏ Single-field slow-roll !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↳ means for particle descripti
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Single-field slow roll
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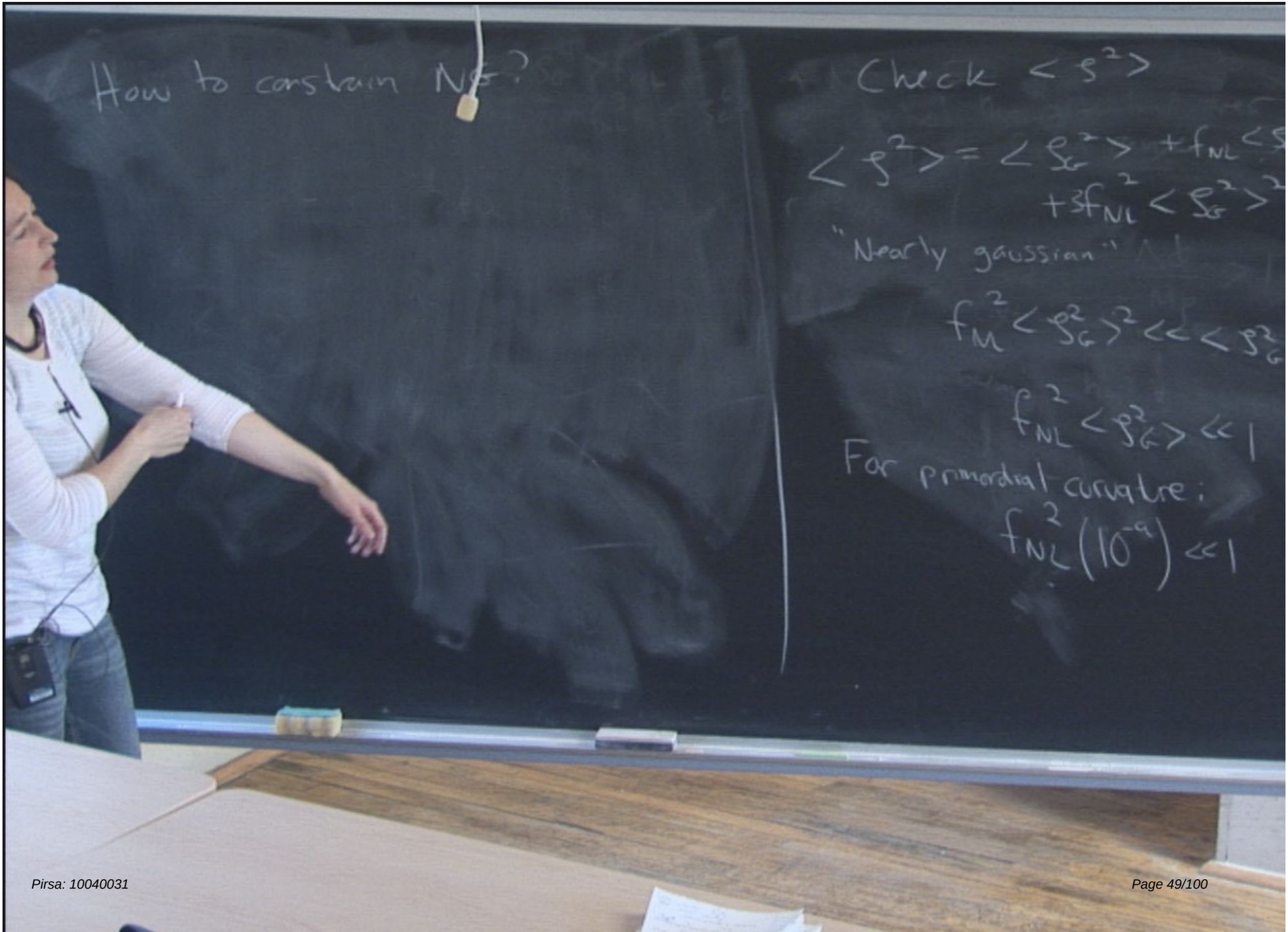
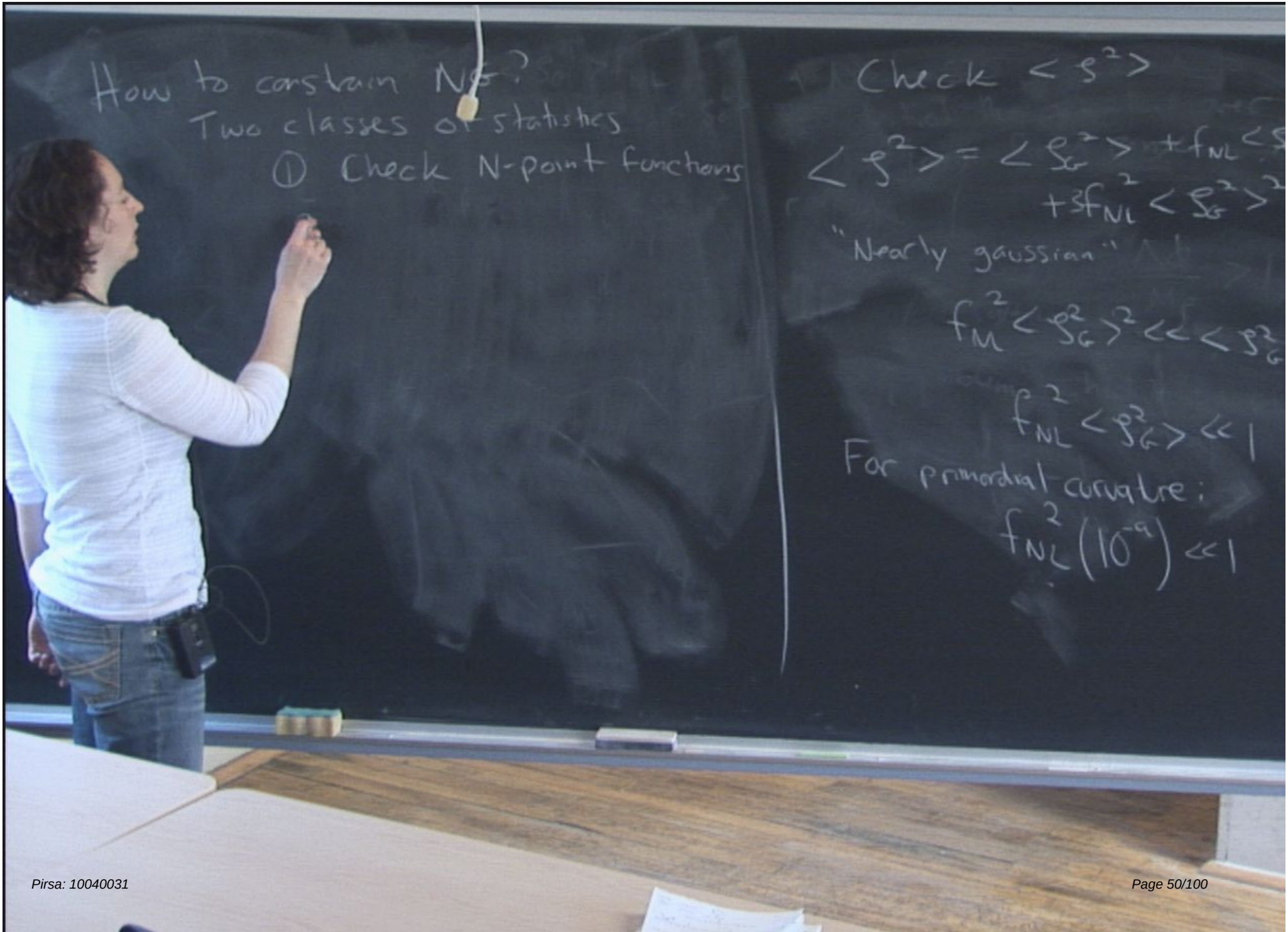

How to constrain NG?
Check $\langle \zeta^2 \rangle$
$\langle \zeta^2 \rangle = \langle \zeta_G^2 \rangle + f_{NL} \langle$
$+ 3 f_{NL}^2 \langle \zeta_G^2 \rangle^2$
"Nearly gaussian"
$f_{NL}^2 \langle \zeta_G^2 \rangle^2 \ll \langle \zeta_G^2$
$f_{NL}^2 \langle \zeta_G^2 \rangle \ll 1$
For primordial curvature:
$f_{NL}^2 (10^{-9}) \ll 1$


How to constrain NG?
Two classes of statistics
① Check N-point functions
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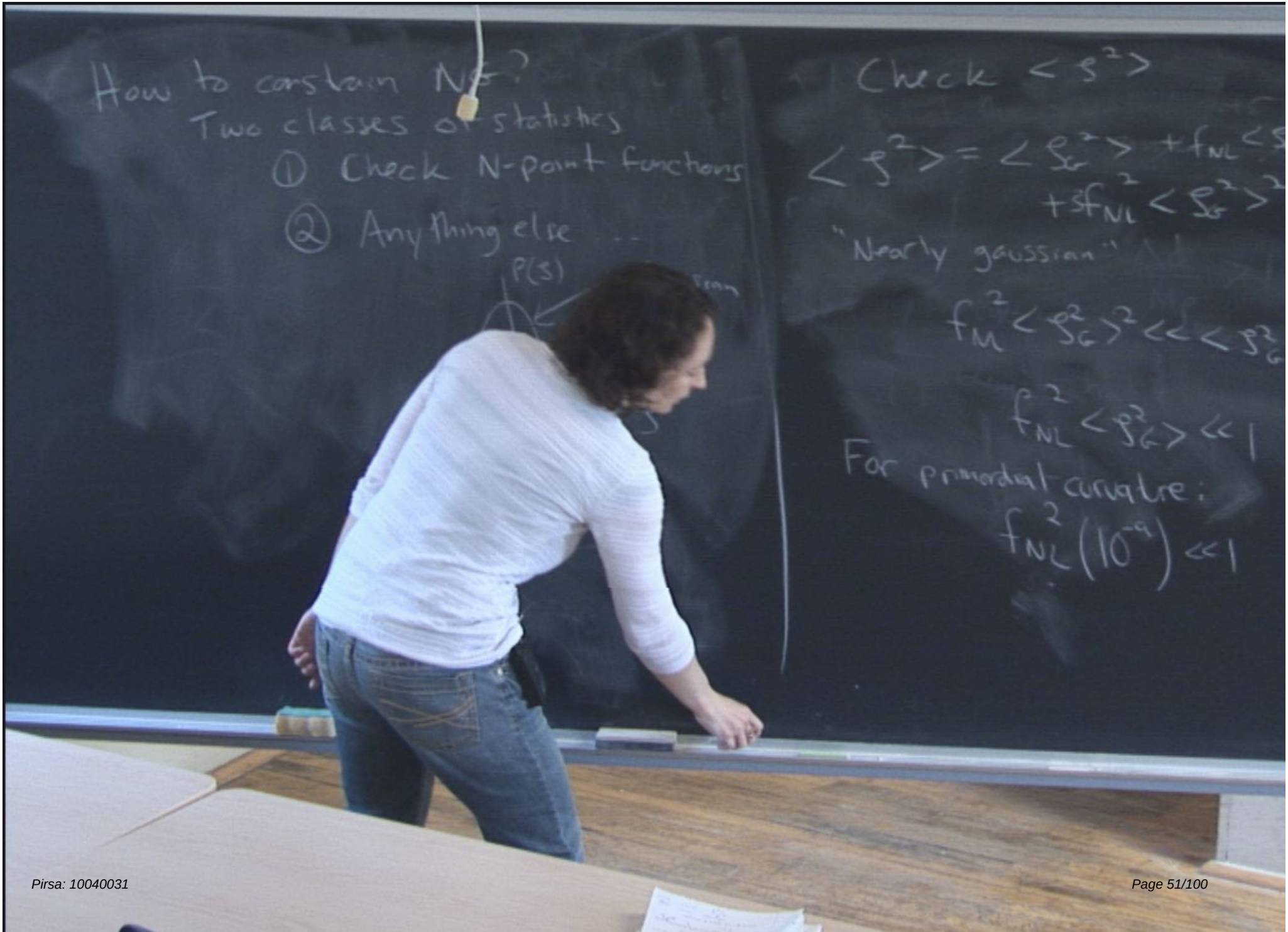
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① Check N-point functions
② Anything else ...
P(S)
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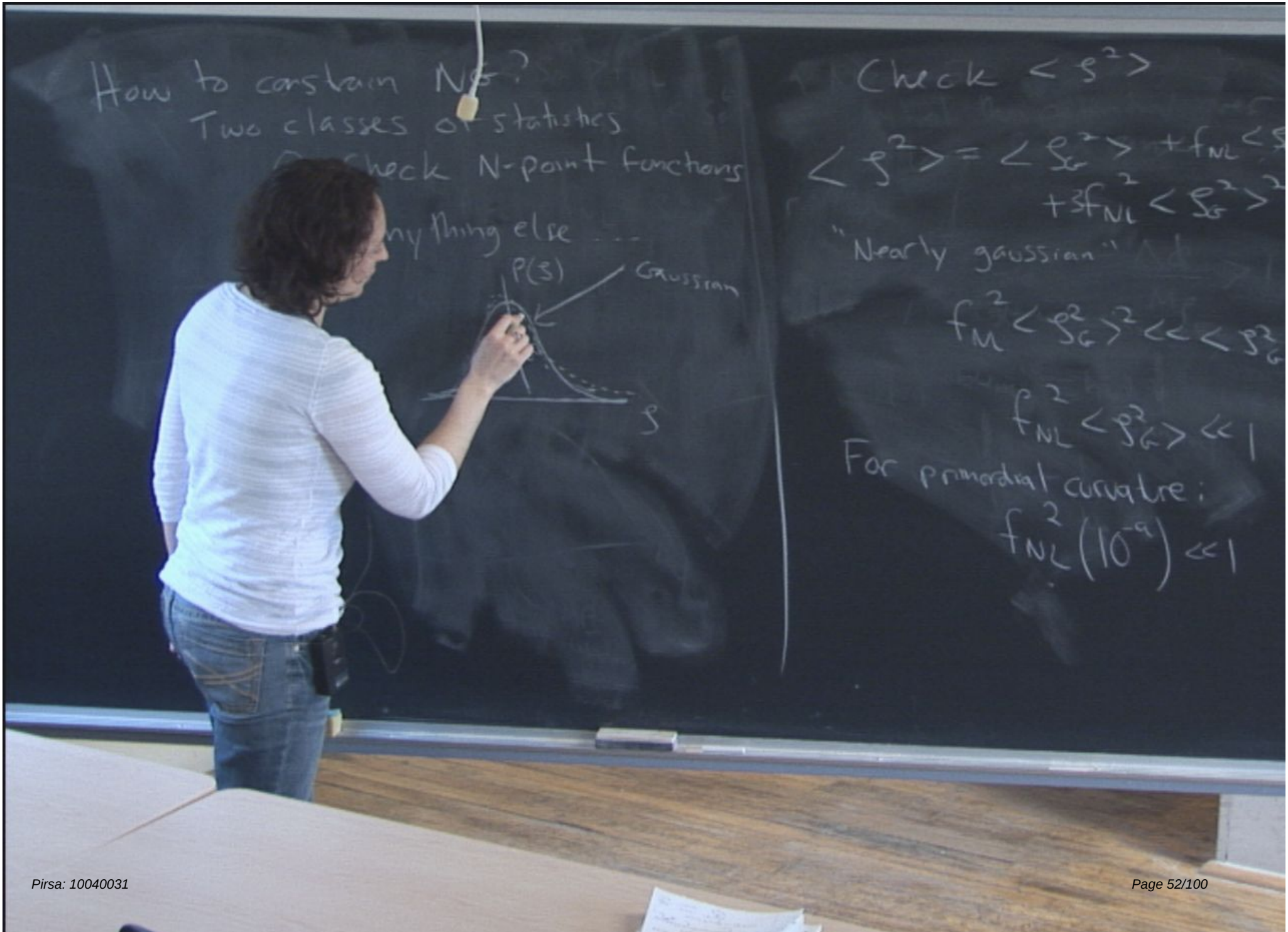
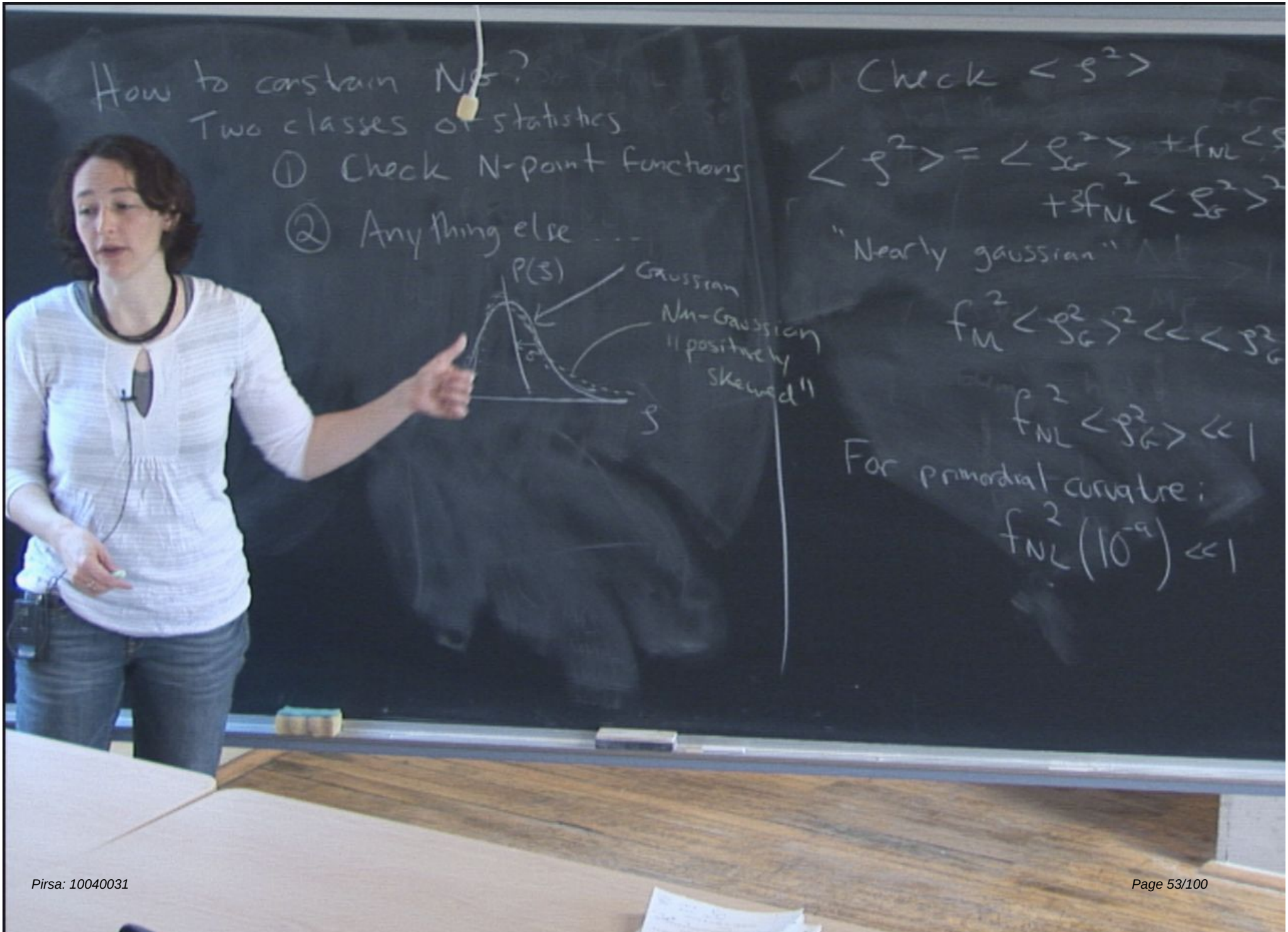

How to constrain NG?
Two classes of statistics
Check N-point functions
anything else ...
P(ζ)
Gaussian
ζ
Check <ζ²>
<ζ²> = <ζG²> + fNL <
+3fNL² <ζG²>²
"Nearly gaussian"
fNL² <ζG²>² << <ζG²
fNL² <ζG²> << 1
For primordial curvature:
fNL² (10⁻⁹) << 1


How to constrain NG?
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P(ζ)
Gaussian
Non-Gaussian
"positively skewed"
ζ
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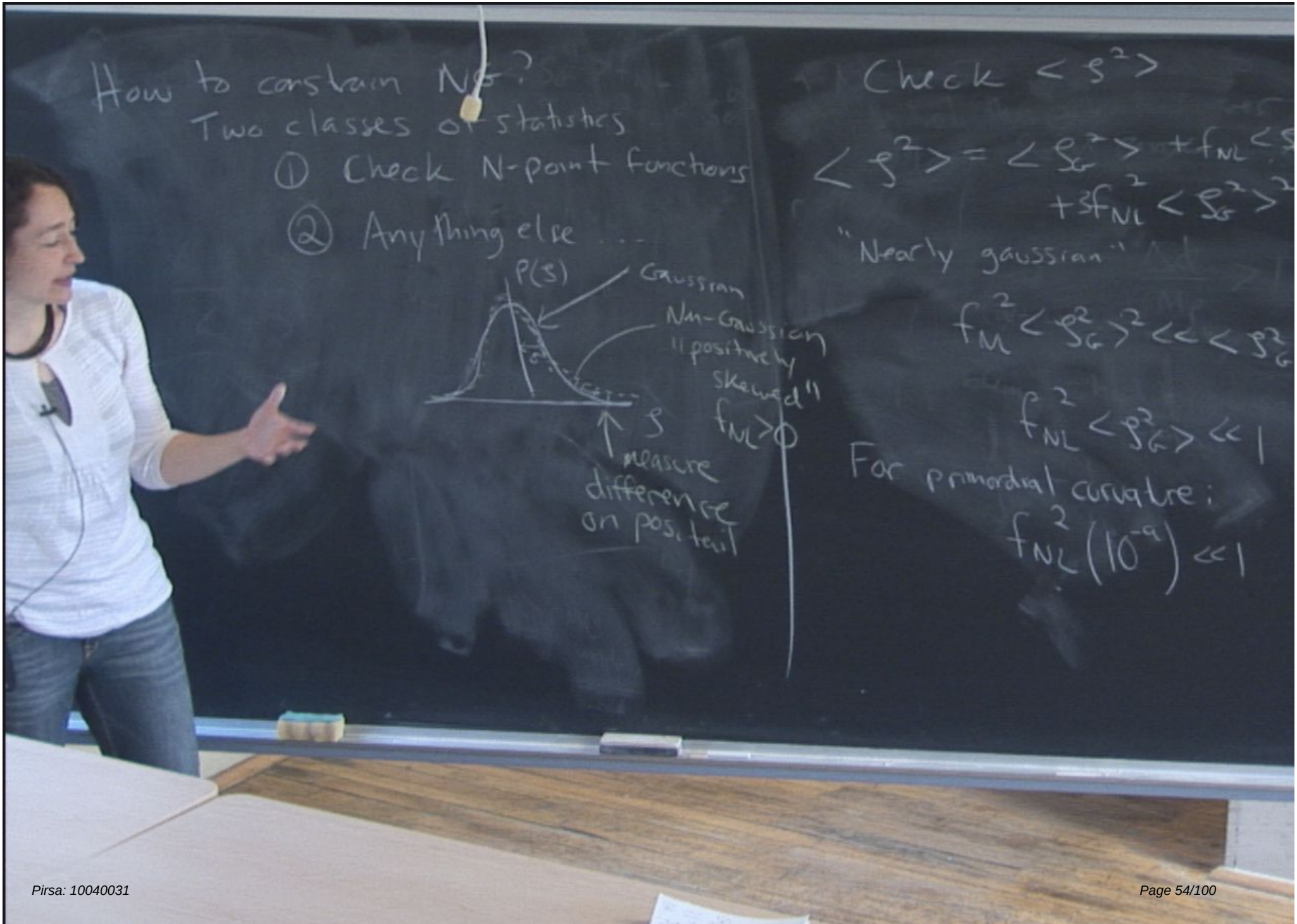
How to constrain NG?
Two classes of statistics
① Check N-point functions
② Anything else ...
P(S)
Gaussian
Non-Gaussian "positively skewed"
S
measure difference on positive
Check $\langle \zeta^2 \rangle$
$\langle \zeta^2 \rangle = \langle \zeta_G^2 \rangle + f_{NL} \langle$
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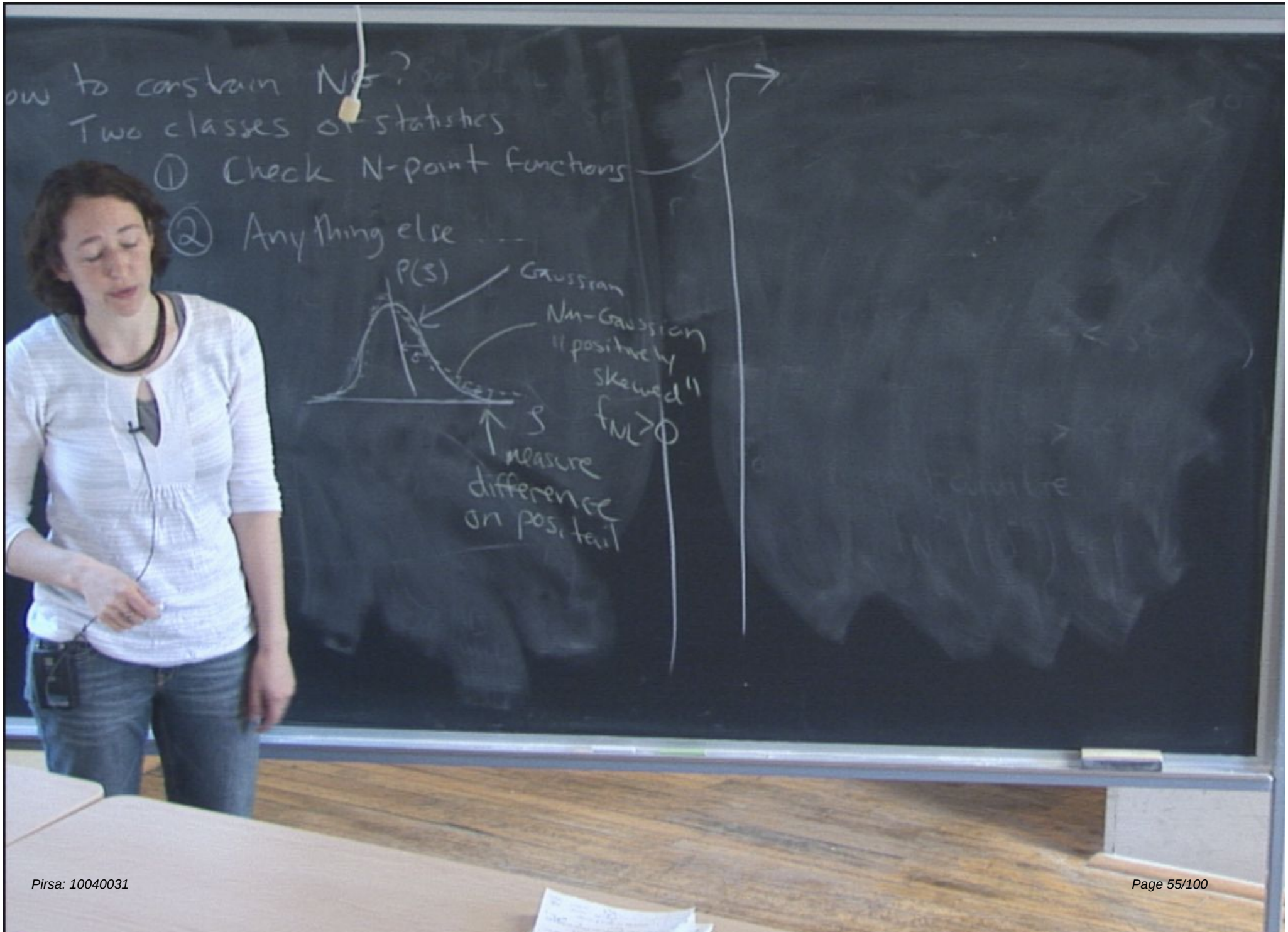
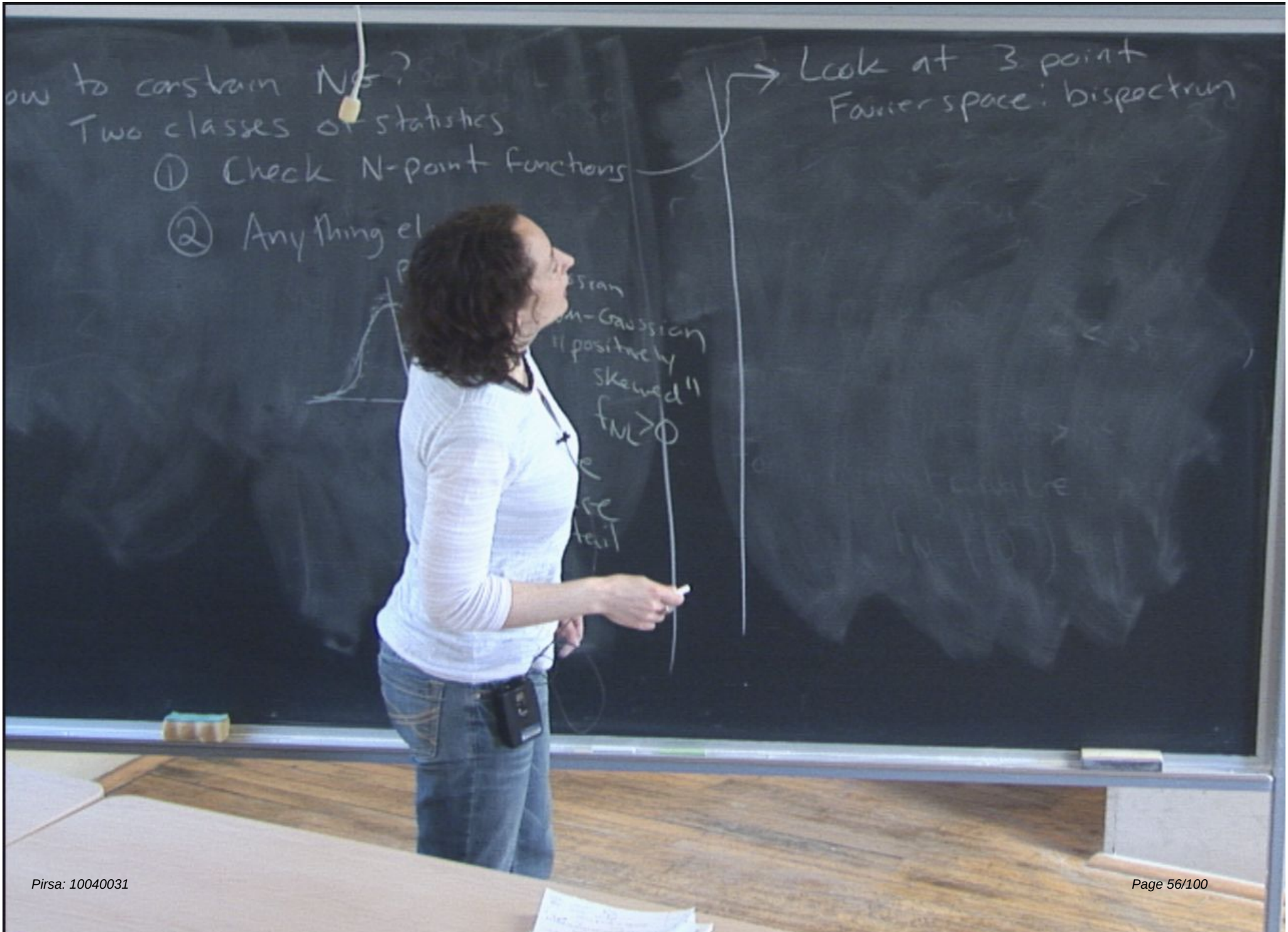
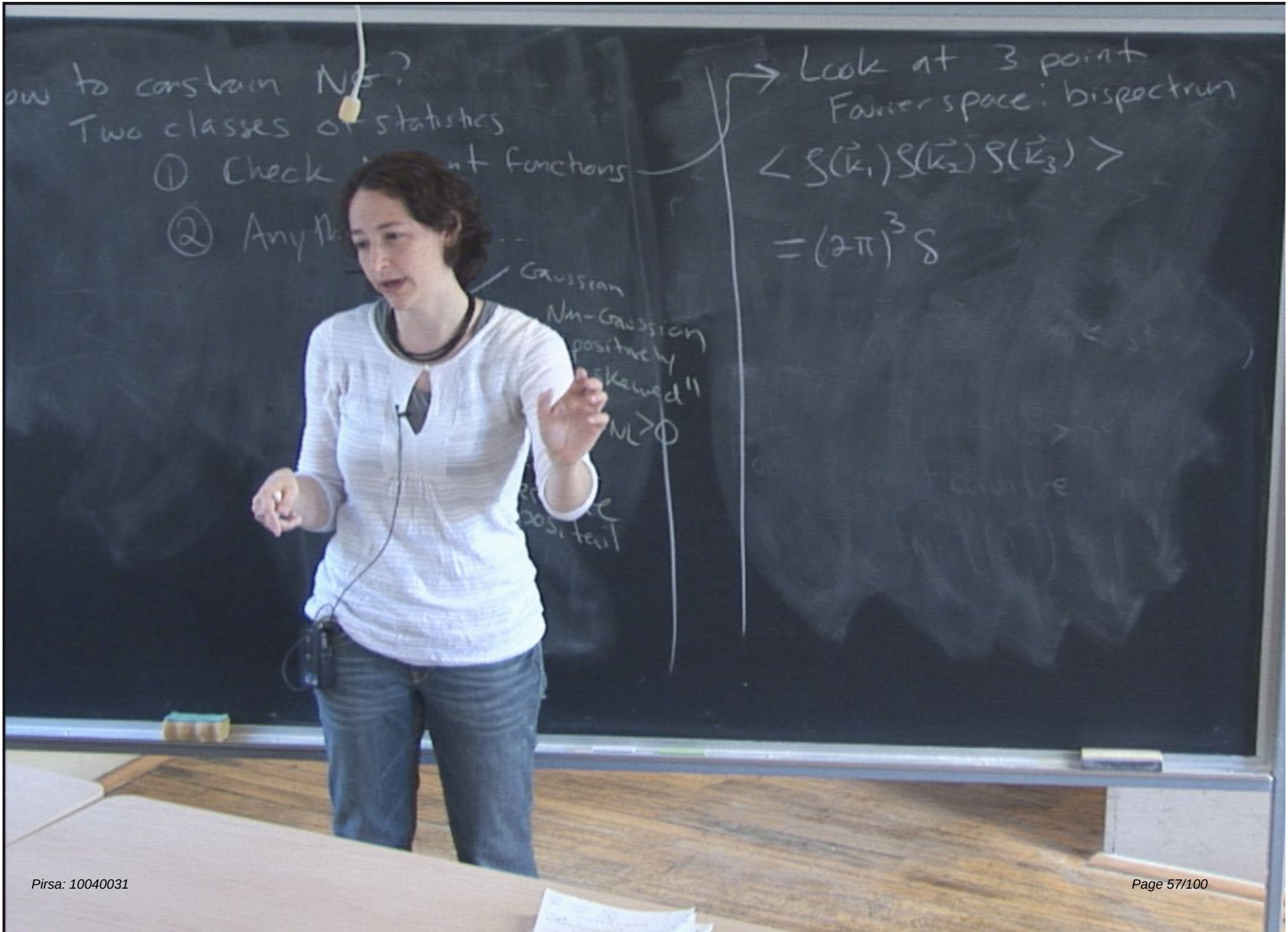
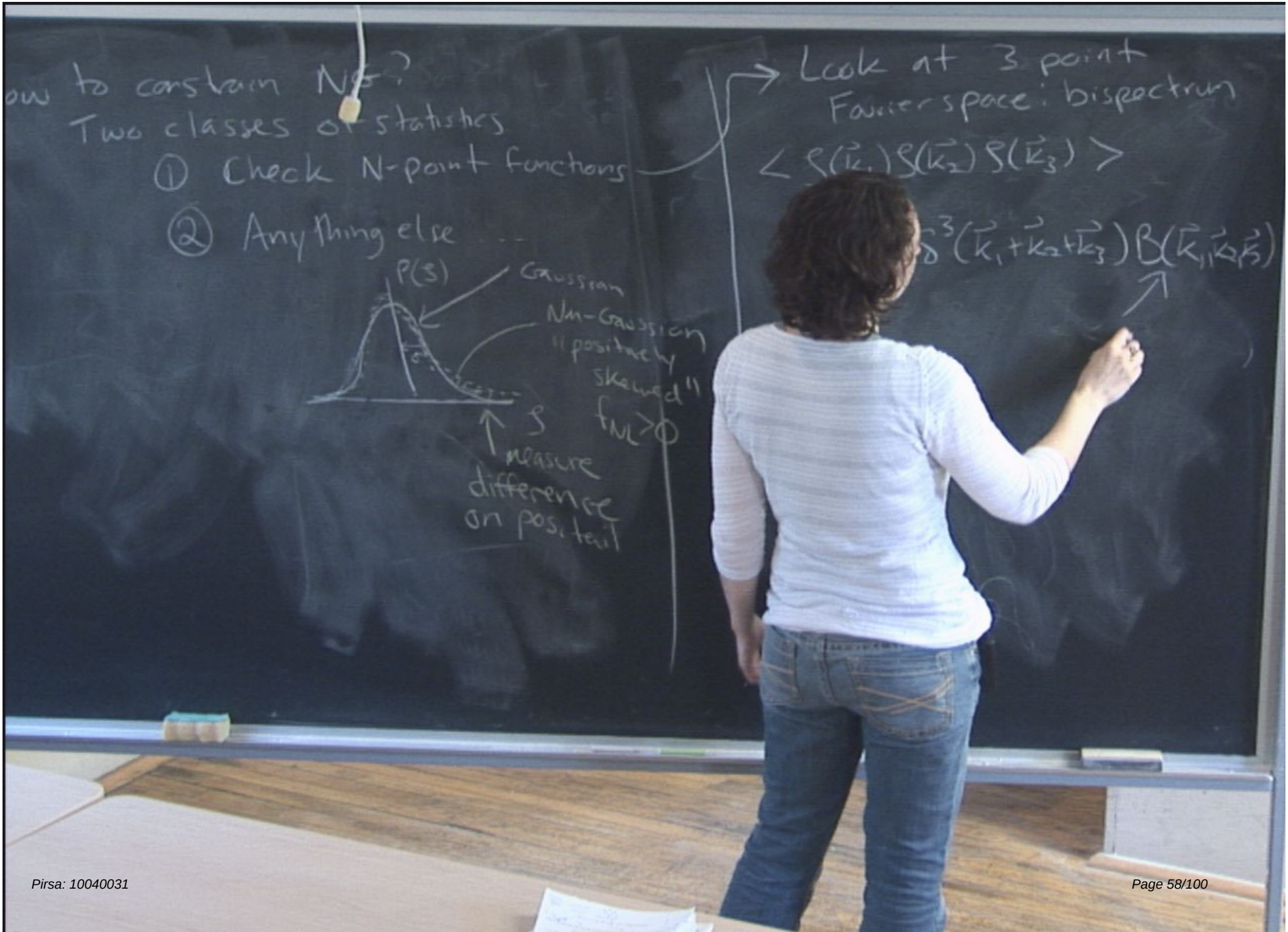

ow to constrain NG?
Two classes of statistics
① Check N-point functions
② Anything else ...
P(S)
Gaussian
Non-Gaussian
"positively
skewed"
$f_{NL} > 0$
S
measure
difference
on positive


ow to constrain NG?
Two classes of statistics
① Check N-point functions
② Anything el
Look at 3 point
Fourier space: bispectrum
fNL>0


ow to constrain NG?
Two classes of statistics
① Check
② Any
nt functions
Look at 3 point
Fourier space: bispectrum
$\langle \delta(\vec{k}_1)\delta(\vec{k}_2)\delta(\vec{k}_3)\rangle$
$=(2\pi)^3\delta$
Gaussian
Non-Gaussian
positively
skewed"
NL>0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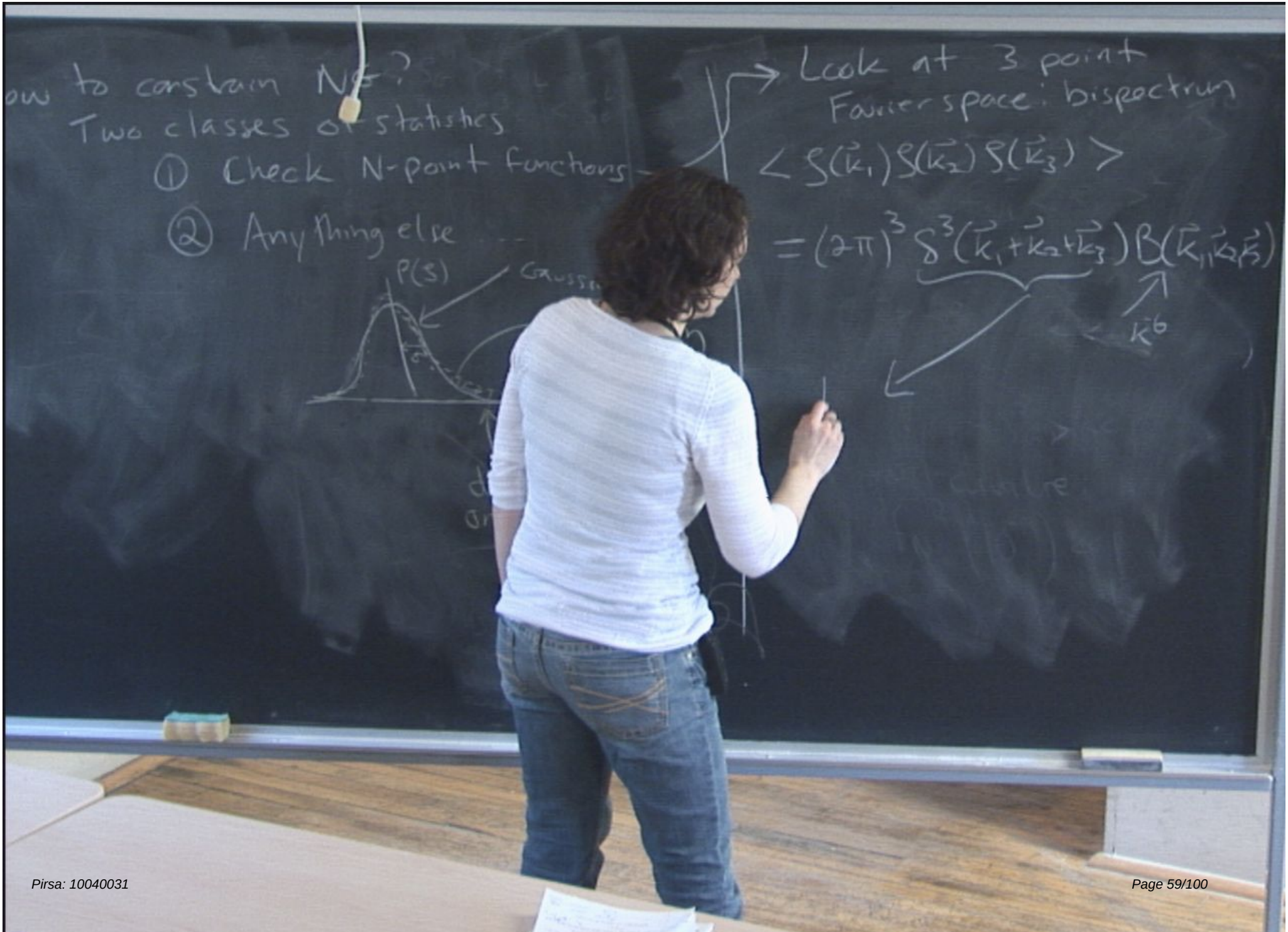
P(s)
Gaussian
Non-Gaussian "positively skewed"
$f_{NL}>0$
s
measure difference on positive
Look at 3 point Fourier space: bispectrum
$\langle \delta(\vec{k}_1)\delta(\vec{k}_2)\delta(\vec{k}_3)\rangle$
$\delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)B(\vec{k}_1,\vec{k}_2,\vec{k}_3)$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Two classes of statistics
① Check N-point functions
② Anything else ...
P(s)
Look at 3 point
Fourier space: bispectrum
$\langle \delta(\vec{k}_1)\delta(\vec{k}_2)\delta(\vec{k}_3)\rangle$
$= (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3) B(\vec{k}_1,\vec{k}_2,\vec{k}_3)$
k^6

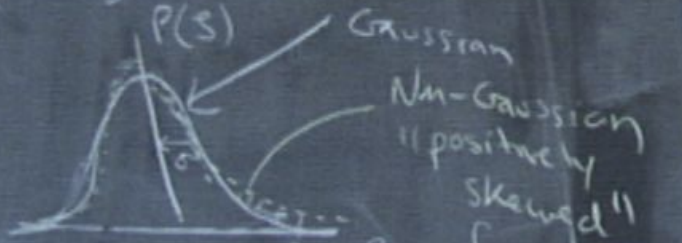
ow to constrain N_L?

Two classes of statistics

① Check N-point functions → Look at 3 point Fourier space: bispectrum

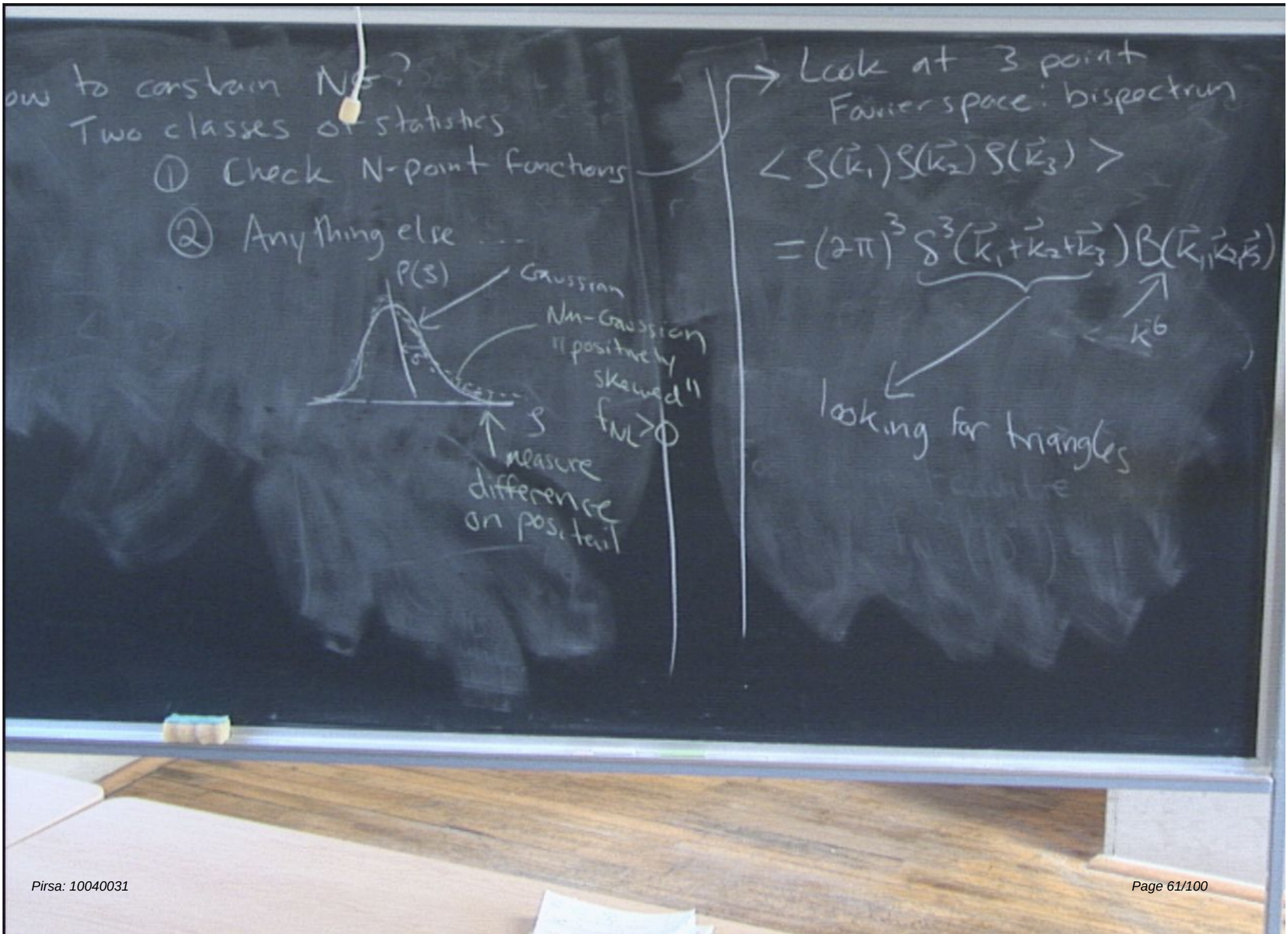
② Anything else...

$$\langle \delta(\vec{k}_1)\delta(\vec{k}_2)\delta(\vec{k}_3)\rangle = (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3) B(\vec{k}_1,\vec{k}_2,\vec{k}_3)$$



k^6

looking for triangles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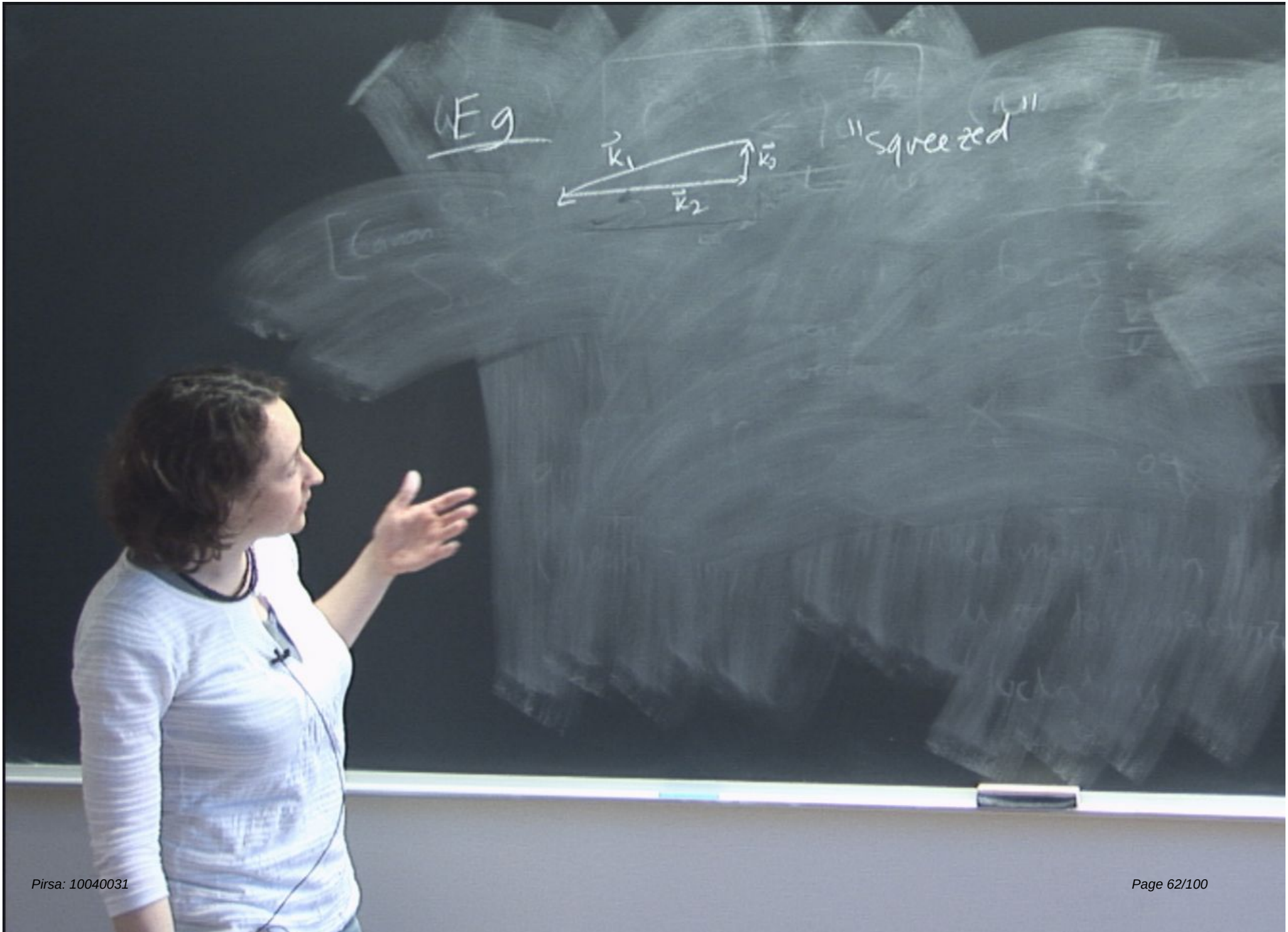
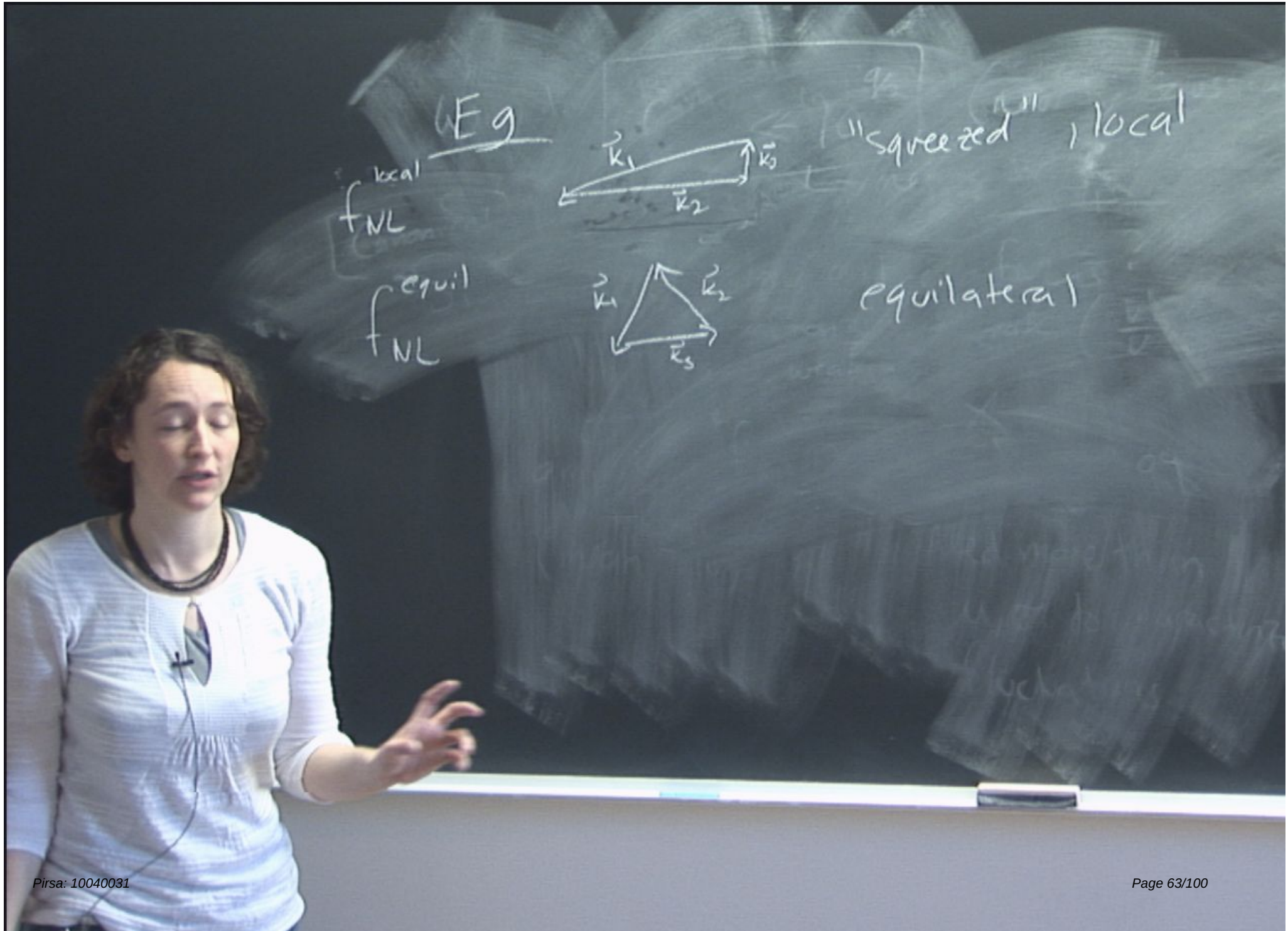
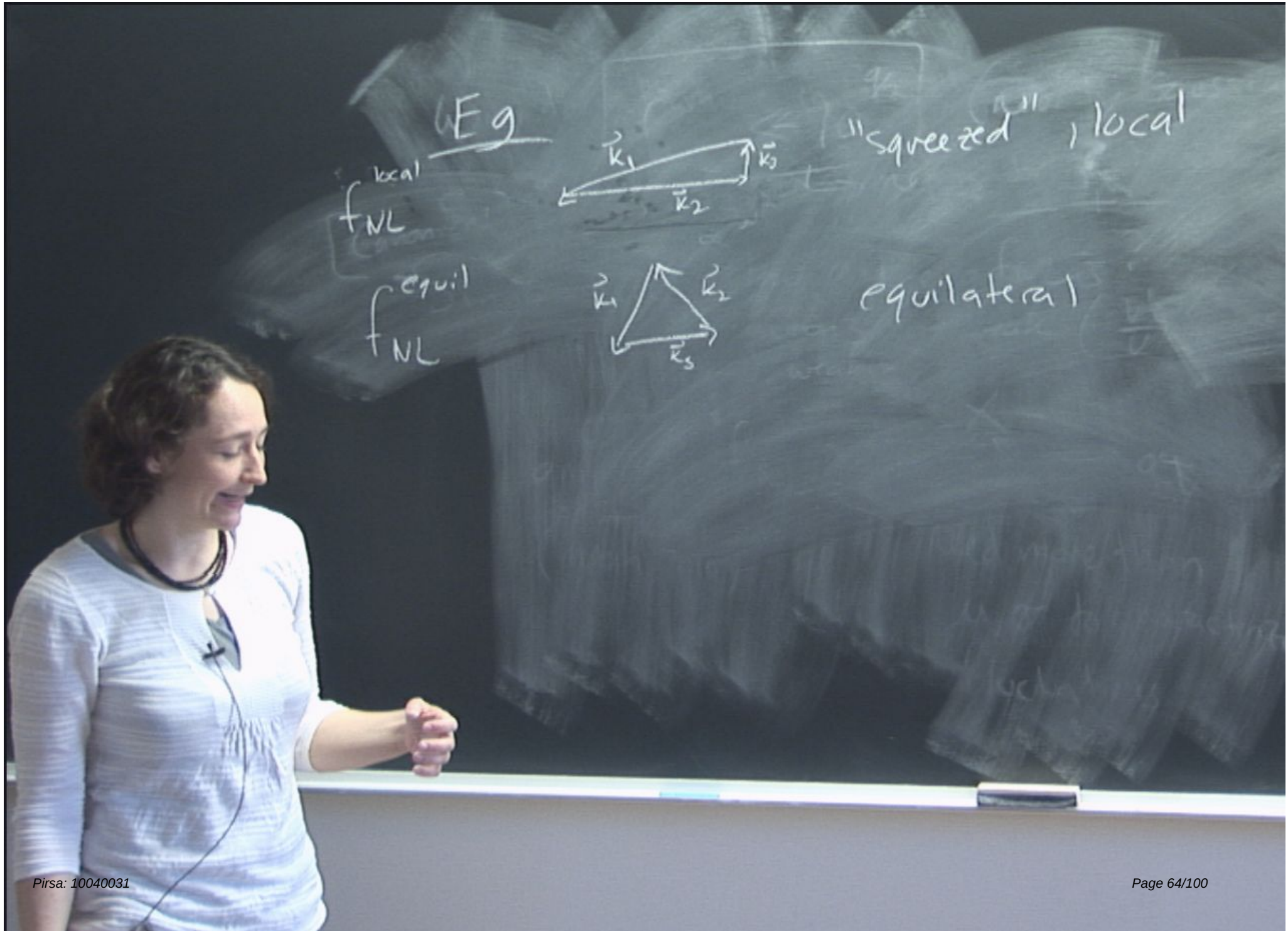
Two classes of statistics
① Check N-point functions
② Anything else ...
P(ζ)
Gaussian
Non-Gaussian
"positively skewed"
$f_{NL} > 0$
ζ
measure difference on positail
Look at 3 point
Fourier space: bispectrum
$\langle \zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3) \rangle$
$= (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3) B(\vec{k}_1,\vec{k}_2,\vec{k}_3)$
k^{-6}
looking for triangles


Eg
$\vec{k}_1$
$\vec{k}_3$
$\vec{k}_2$
"squeezed"


Eg
f_{NL}^{local}
$\vec{k}_1$
$\vec{k}_3$
$\vec{k}_2$
"squeezed", local
f_{NL}^{equil}
$\vec{k}_1$
$\vec{k}_2$
$\vec{k}_3$
equilateral


Eg
f_{NL}^{local}
$\vec{k}_1$
$\vec{k}_3$
$\vec{k}_2$
"squeezed", local
f_{NL}^{equil}
$\vec{k}_1$
$\vec{k}_2$
$\vec{k}_3$
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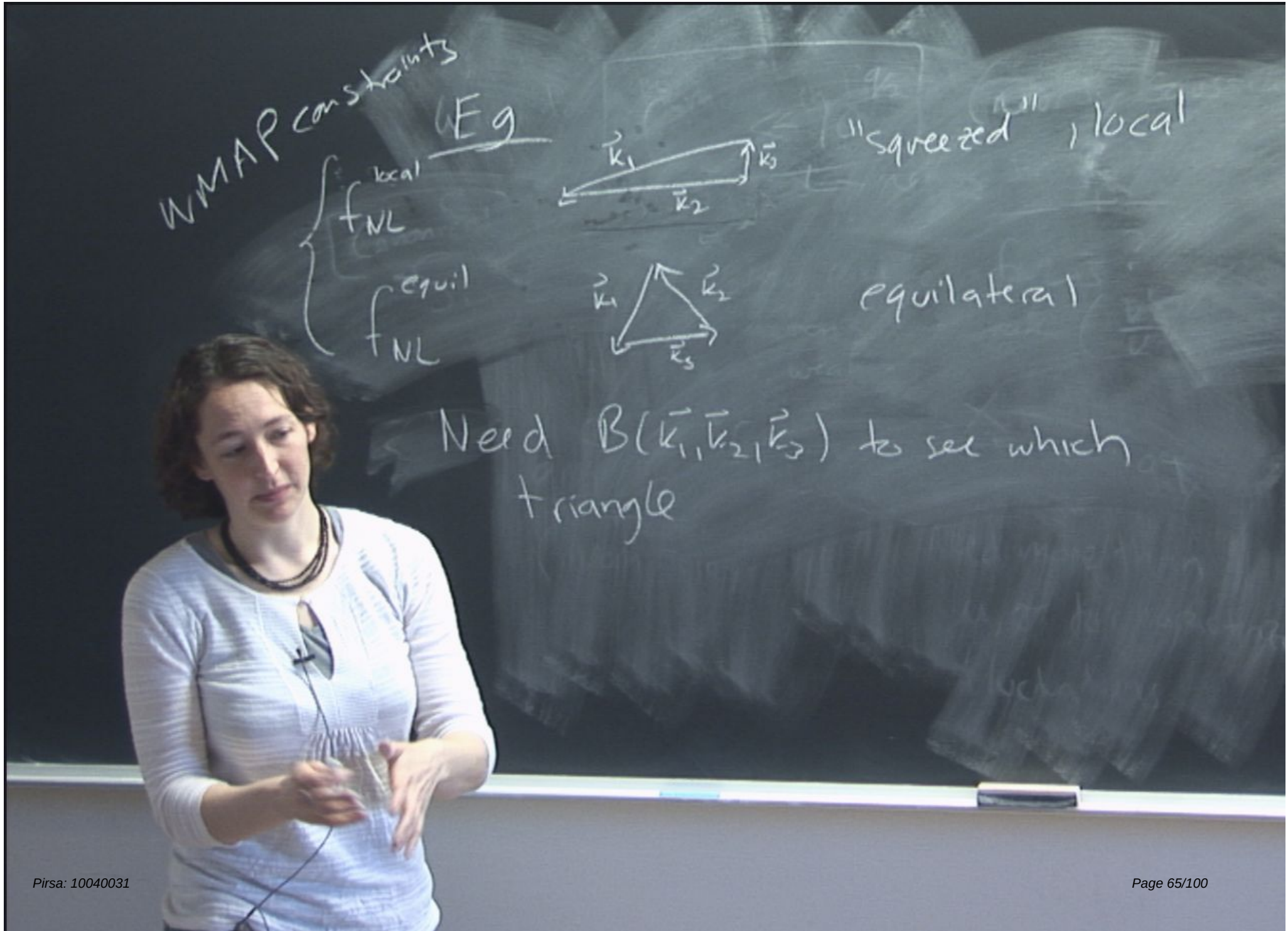
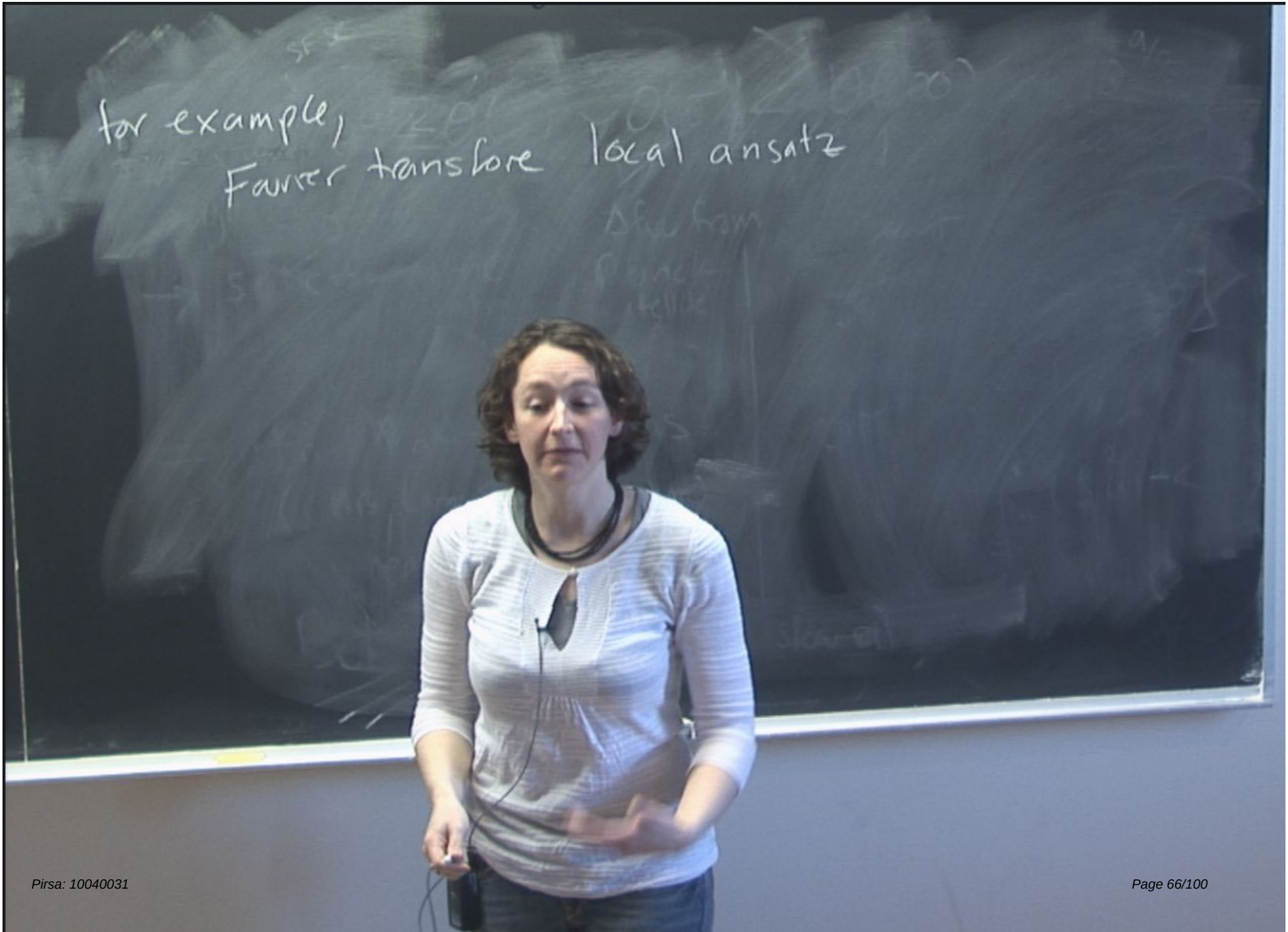
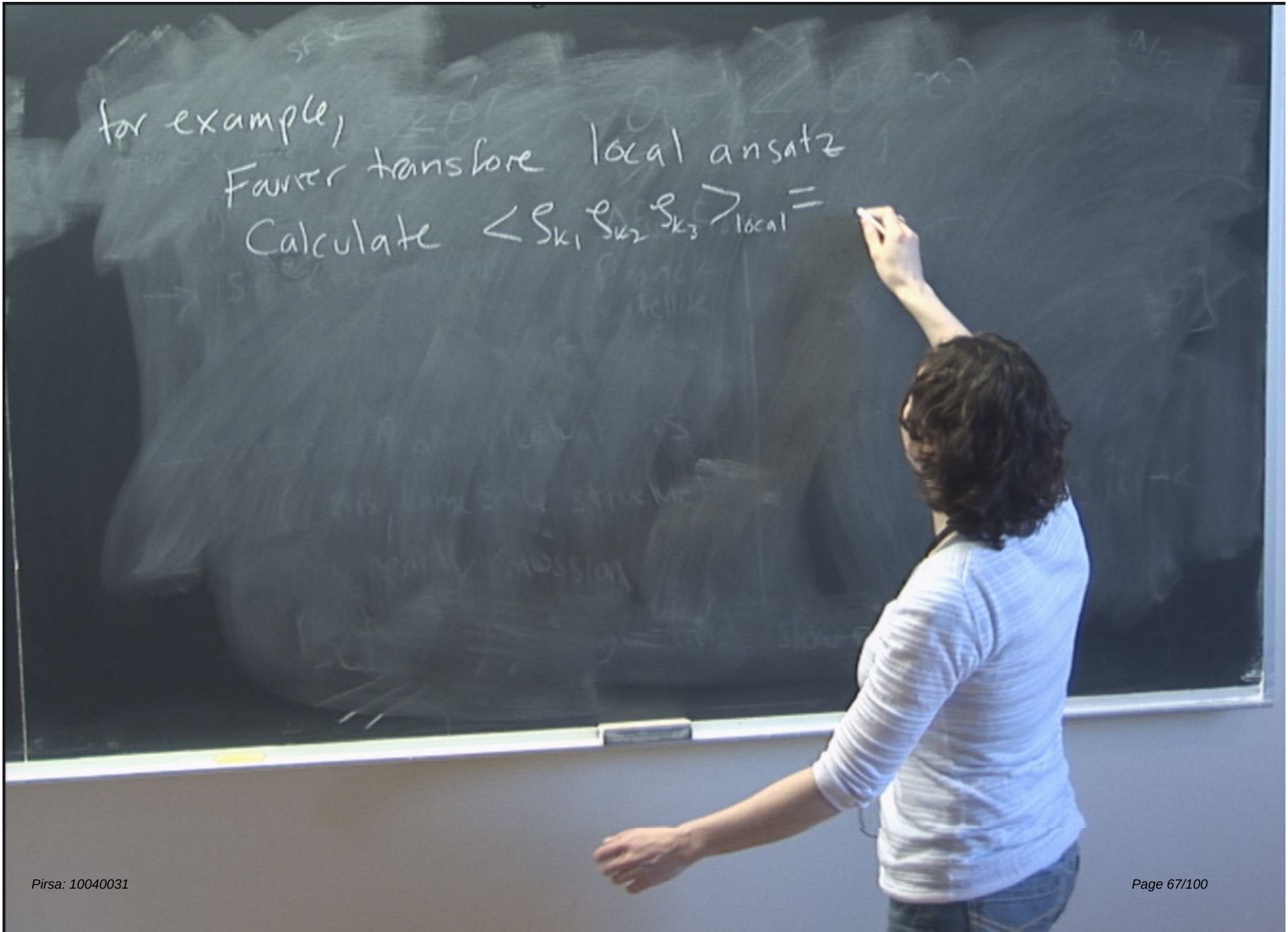
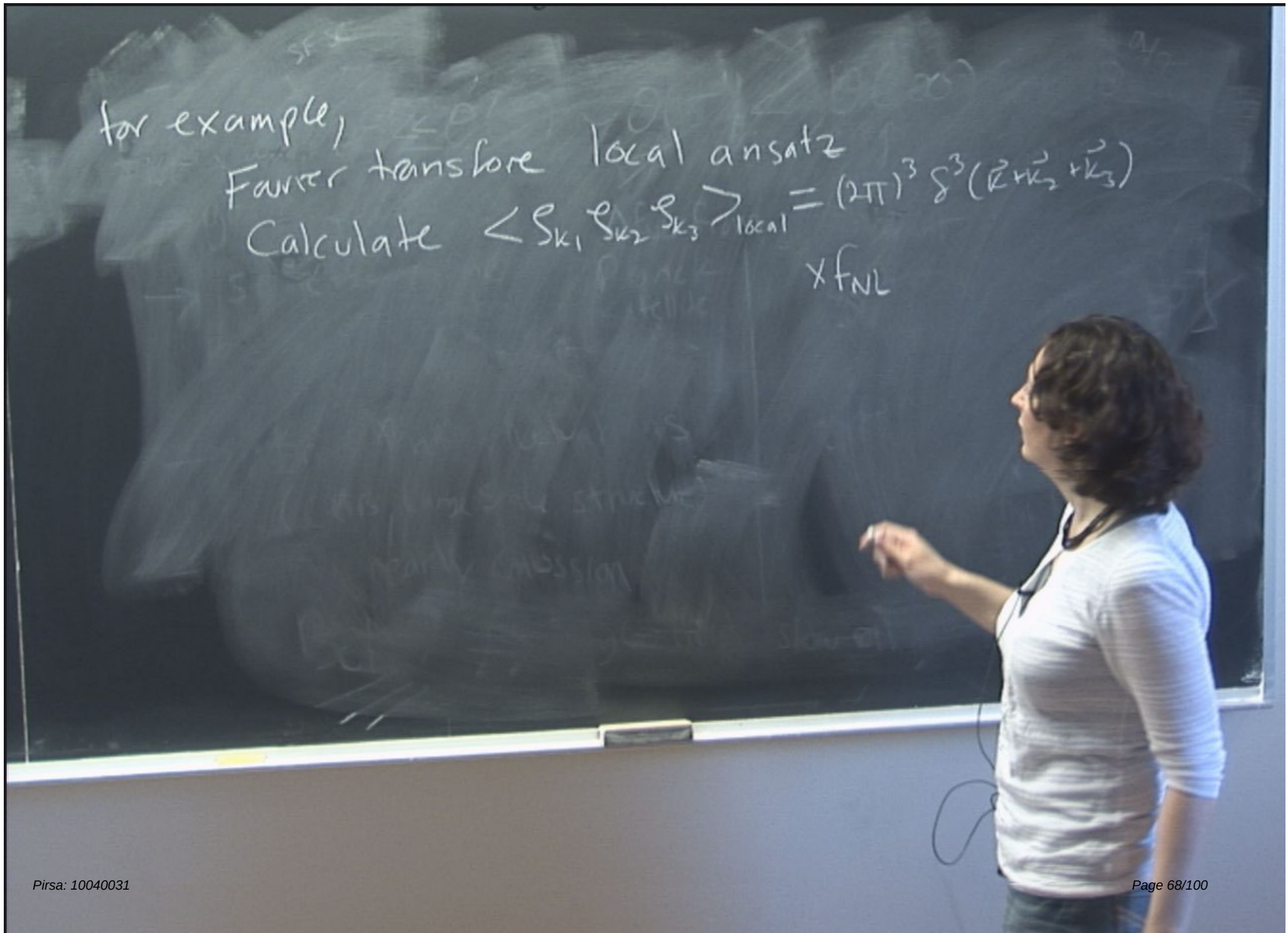
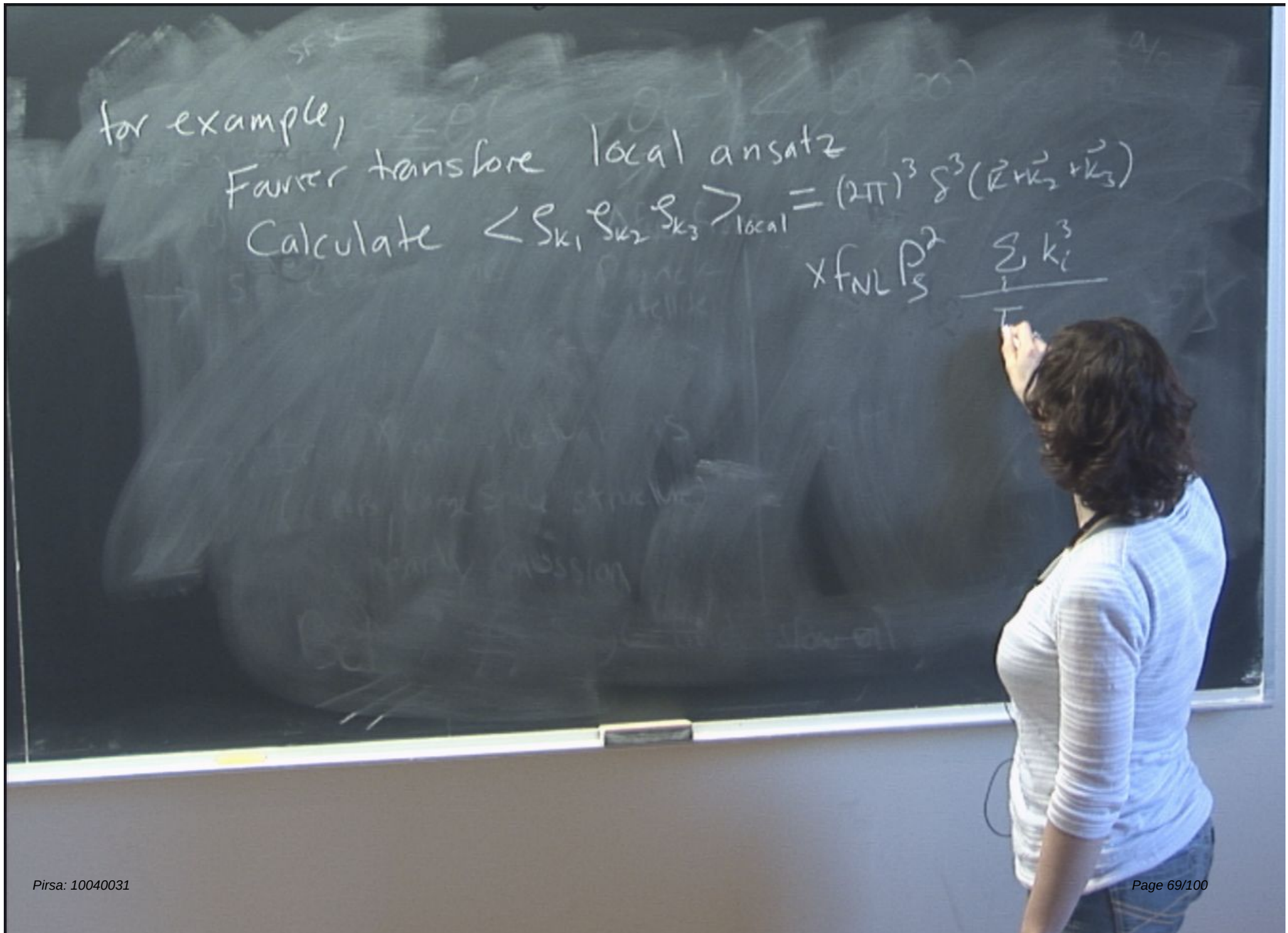

WMAP constraints
Eg
f_{NL}^{local}
f_{NL}^{equil}
$\vec{k}_1$
$\vec{k}_2$
$\vec{k}_3$
"squeezed", local
equilateral
Need $B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$ to see which triangle


for example,
Fourier transform local ansatz


for example,
Fourier transform local ansatz
Calculate $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle_{local} =$


for example,
Fourier transform local ansatz
Calculate $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle_{local} = (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)$
$\times f_{NL}$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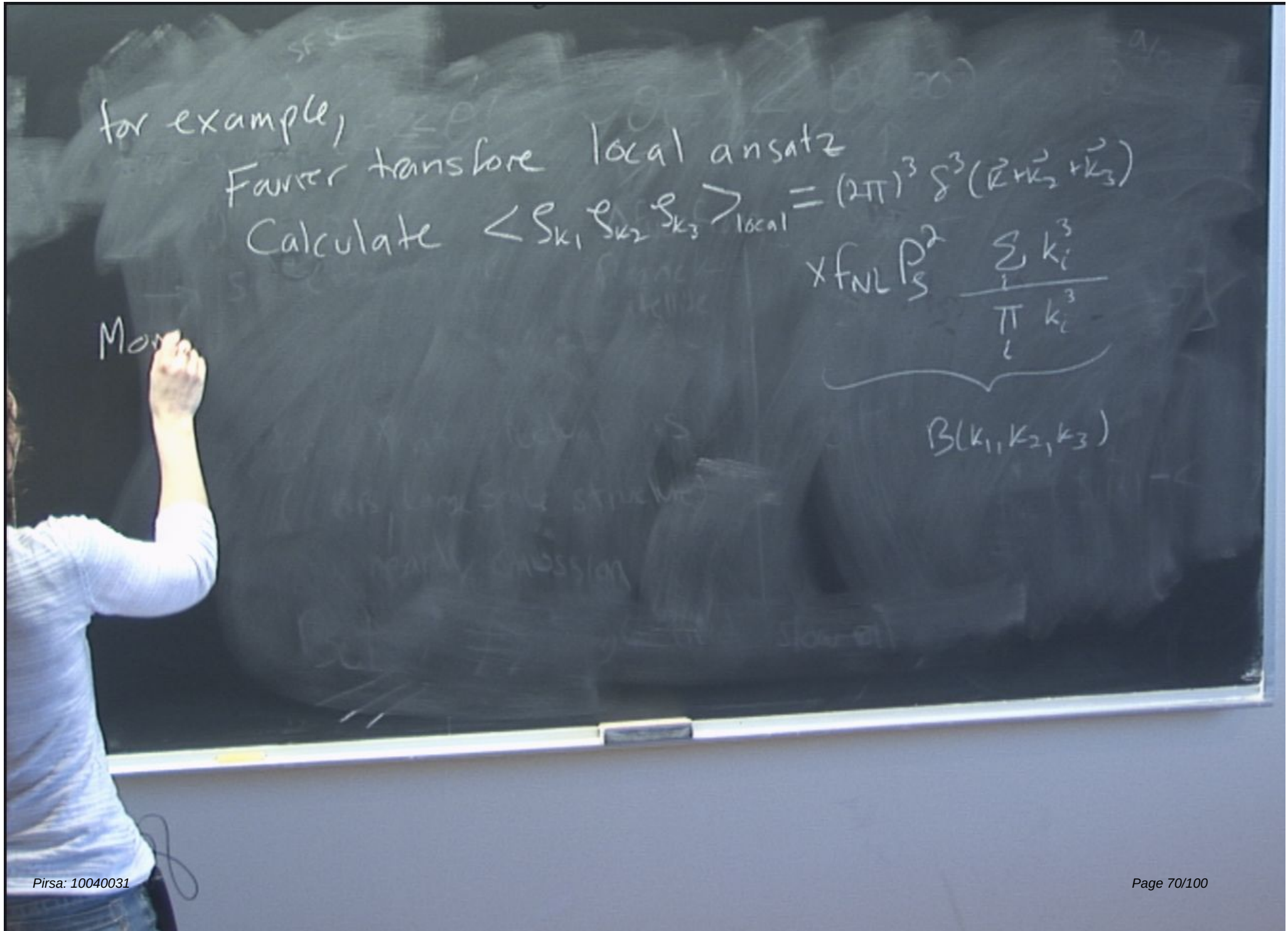
$\times f_{NL} P_\zeta^2 \frac{\sum_i k_i^3}{\prod_i k_i^3}$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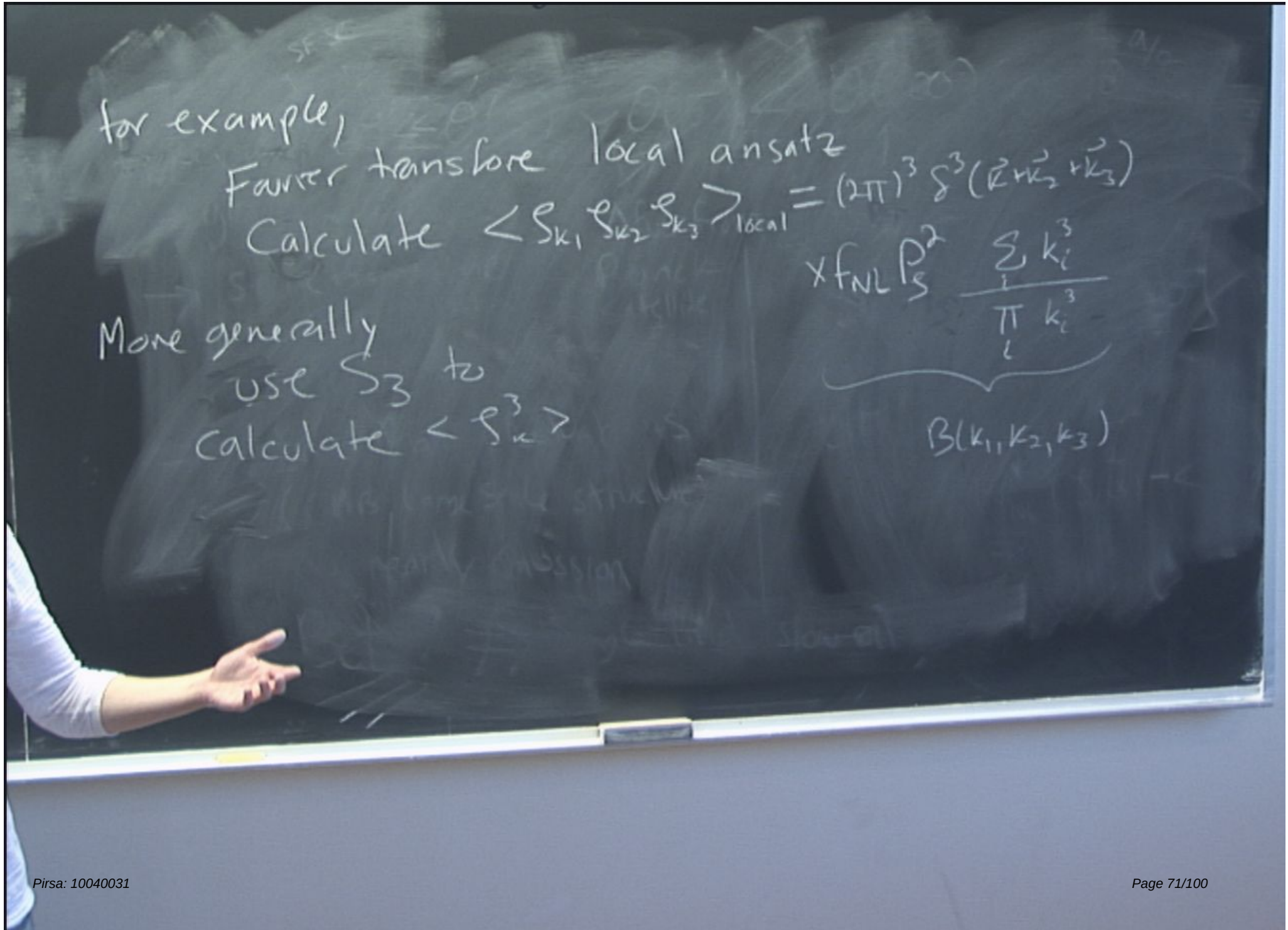
$B(k_1, k_2, k_3)$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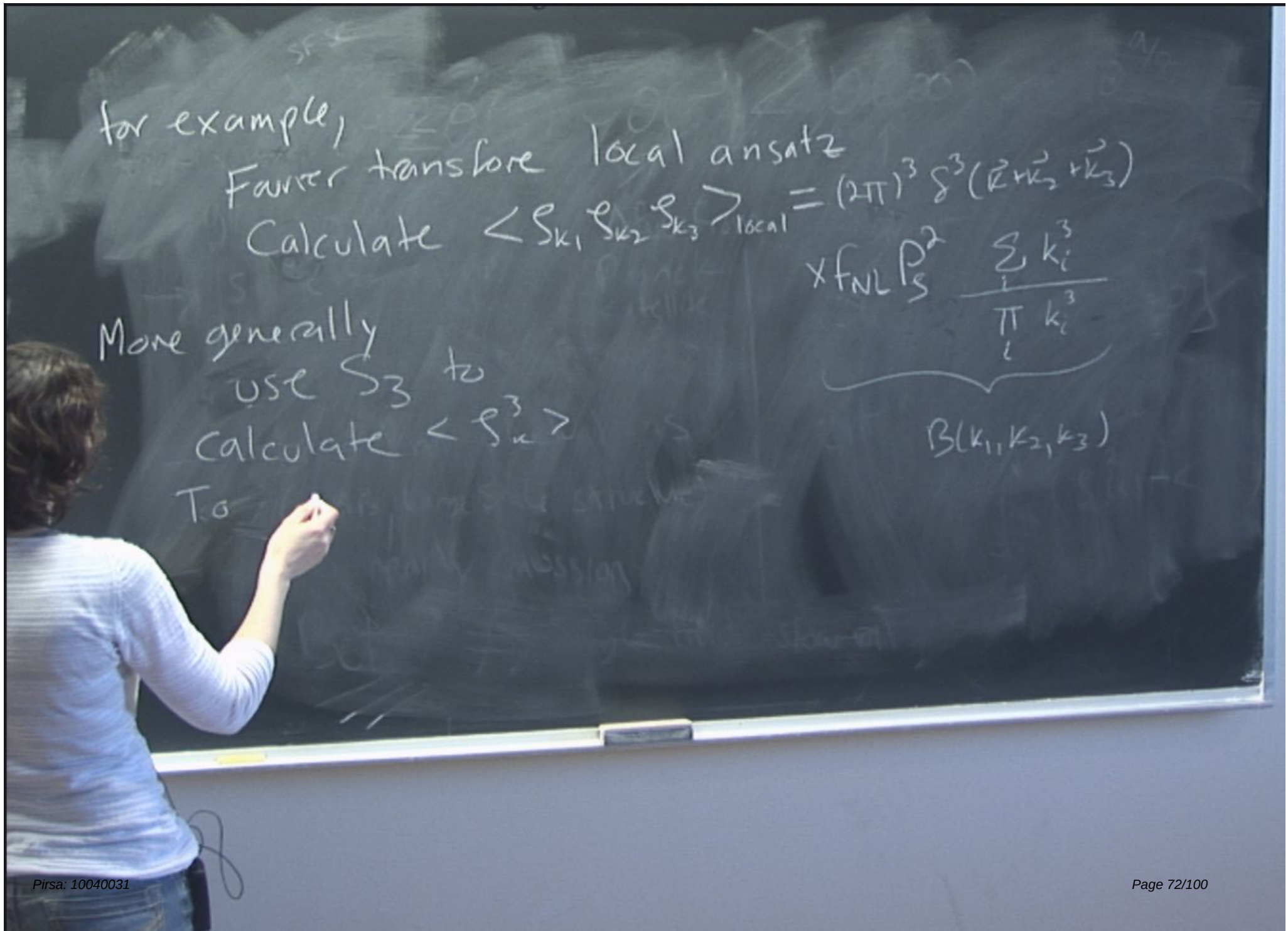
$B(k_1, k_2, k_3)$
More generally
use S_3 to
Calculate $\langle \zeta_k^3 \rangle$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More generally
use ζ_3 to
Calculate $\langle \zeta_k^3 \rangle$
To

for example,

Fourier transform local ansatz

Calculate $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle_{local} = (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)$

$\times f_{NL} P_\zeta^2 \underbrace{\frac{\sum_i k_i^3}{\prod_i k_i^3}}_{B(k_1, k_2, k_3)}$

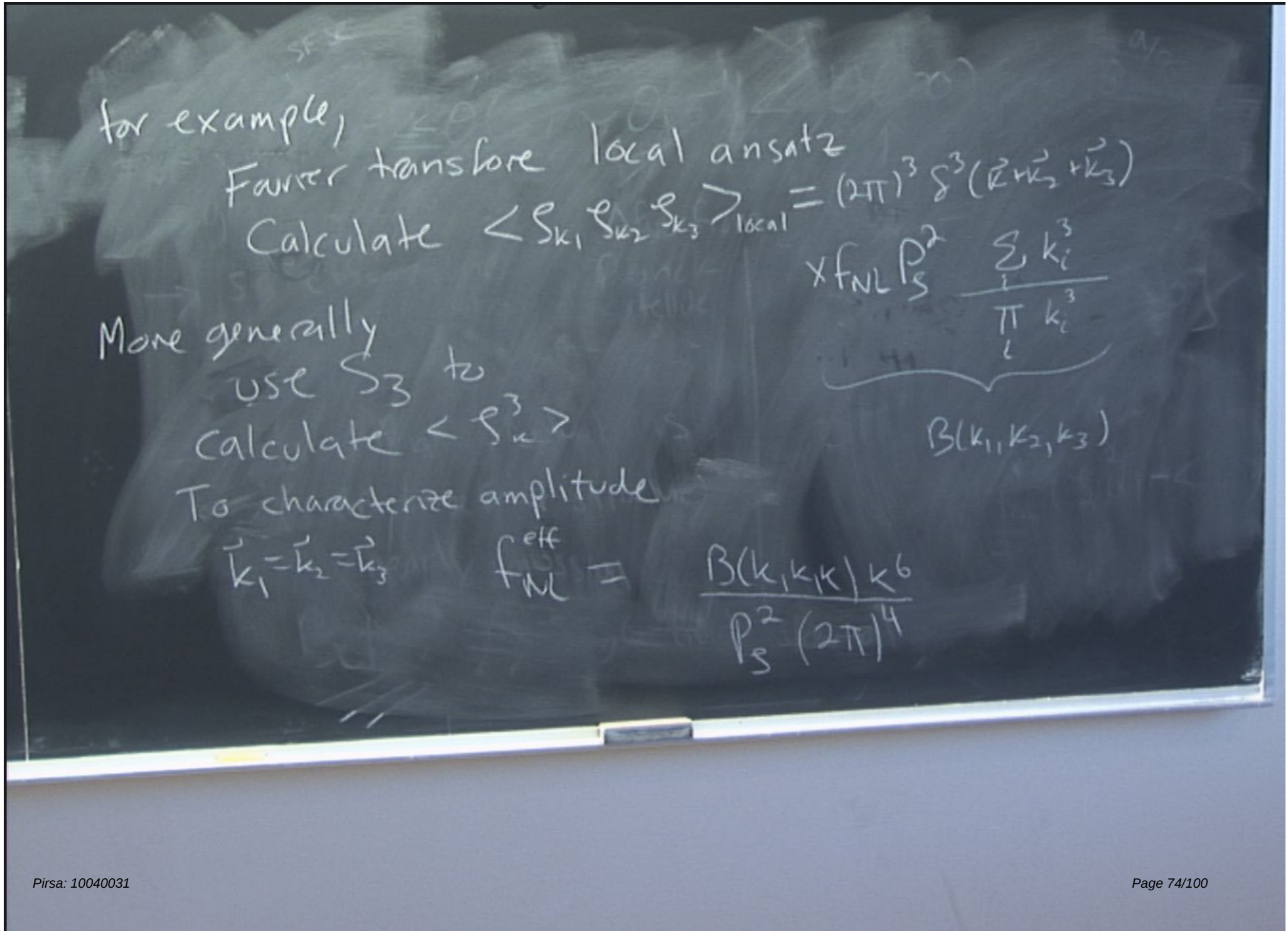
More generally

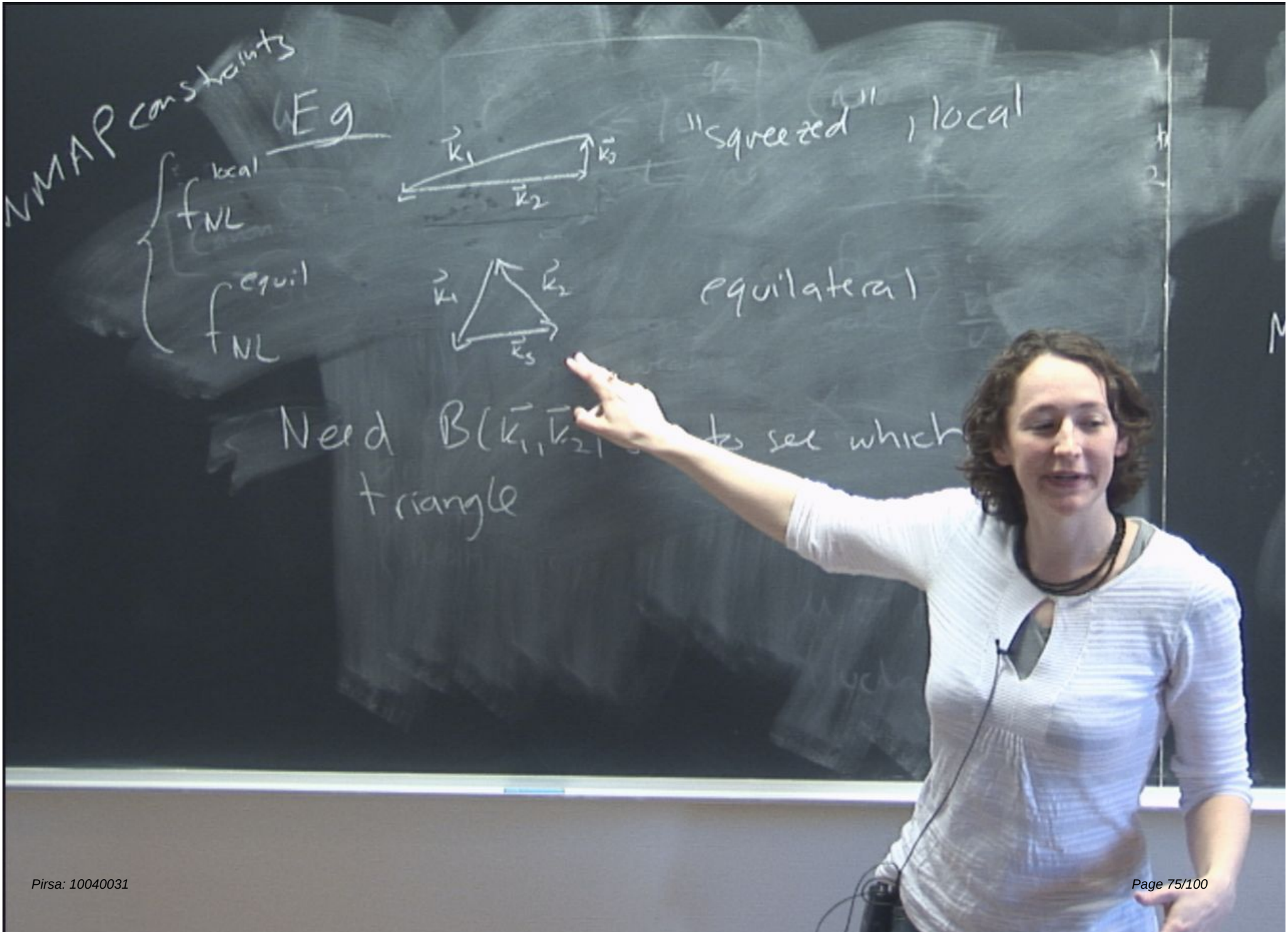
use S_3 to

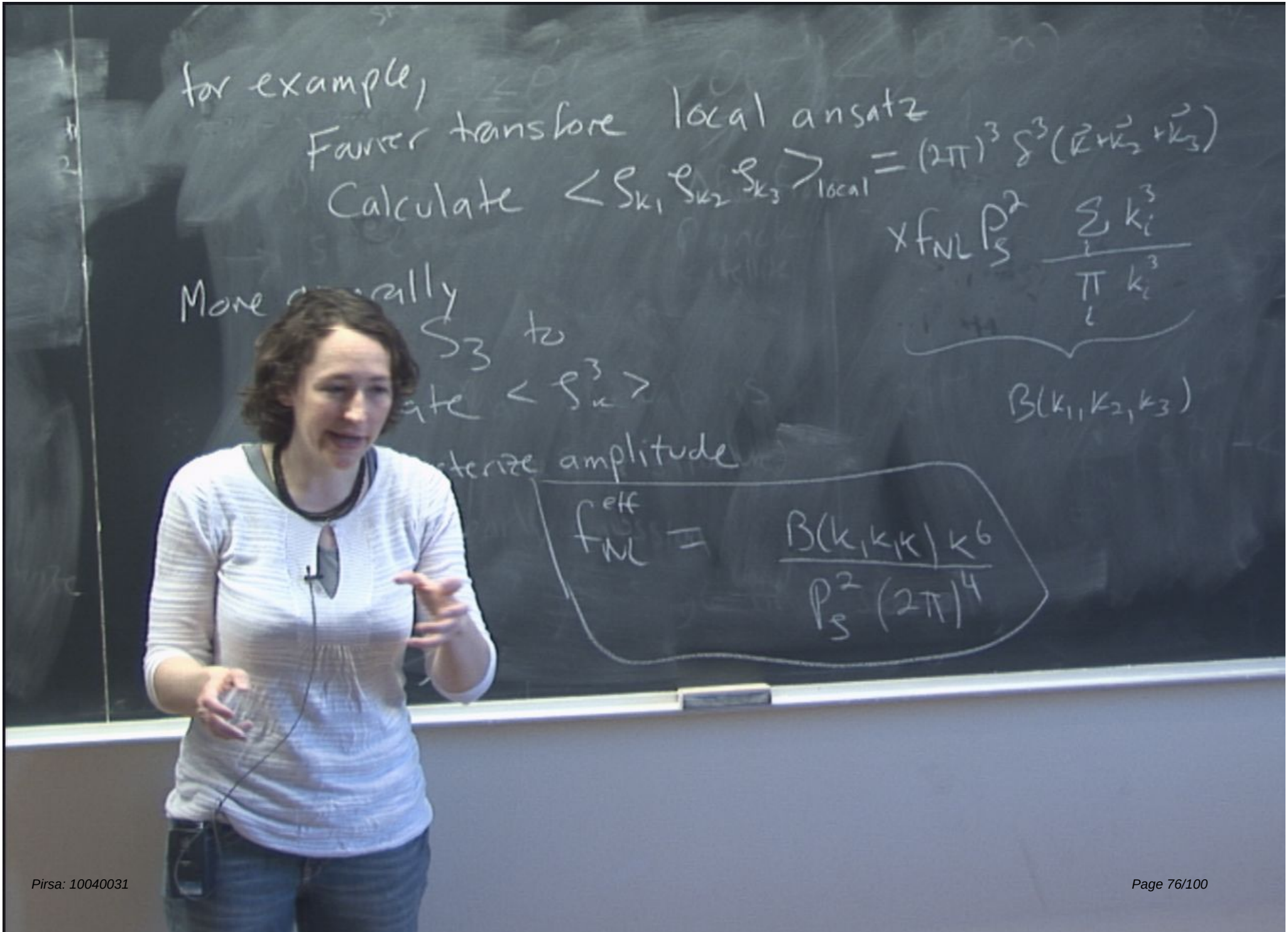
Calculate $\langle \zeta_k^3 \rangle$

To characterize amplitude

$\vec{k}_1 = \vec{k}_2 = \vec{k}_3$ $\quad f_{NL}^{eff}$


for example,
Fourier transform local ansatz
Calculate $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle_{local} = (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)$
$\times f_{NL} P_\zeta^2 \frac{\sum_i k_i^3}{\prod_i k_i^3}$
$B(k_1, k_2, k_3)$
More generally
use S_3 to
Calculate $\langle \zeta_k^3 \rangle$
To characterize amplitude
$\vec{k}_1 = \vec{k}_2 = \vec{k}_3$
$f_{NL}^{eff} = \frac{B(k,k,k)\, k^6}{P_\zeta^2 (2\pi)^4}$


WMAP constraints
Eg
f_{NL}^{local}
f_{NL}^{equil}
"squeezed", local
equilateral
Need B(
to see which
triangle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$B(k_1, k_2, k_3)$
More generally
ζ_3 to
$\langle \zeta_k^3 \rangle$
terize amplitude
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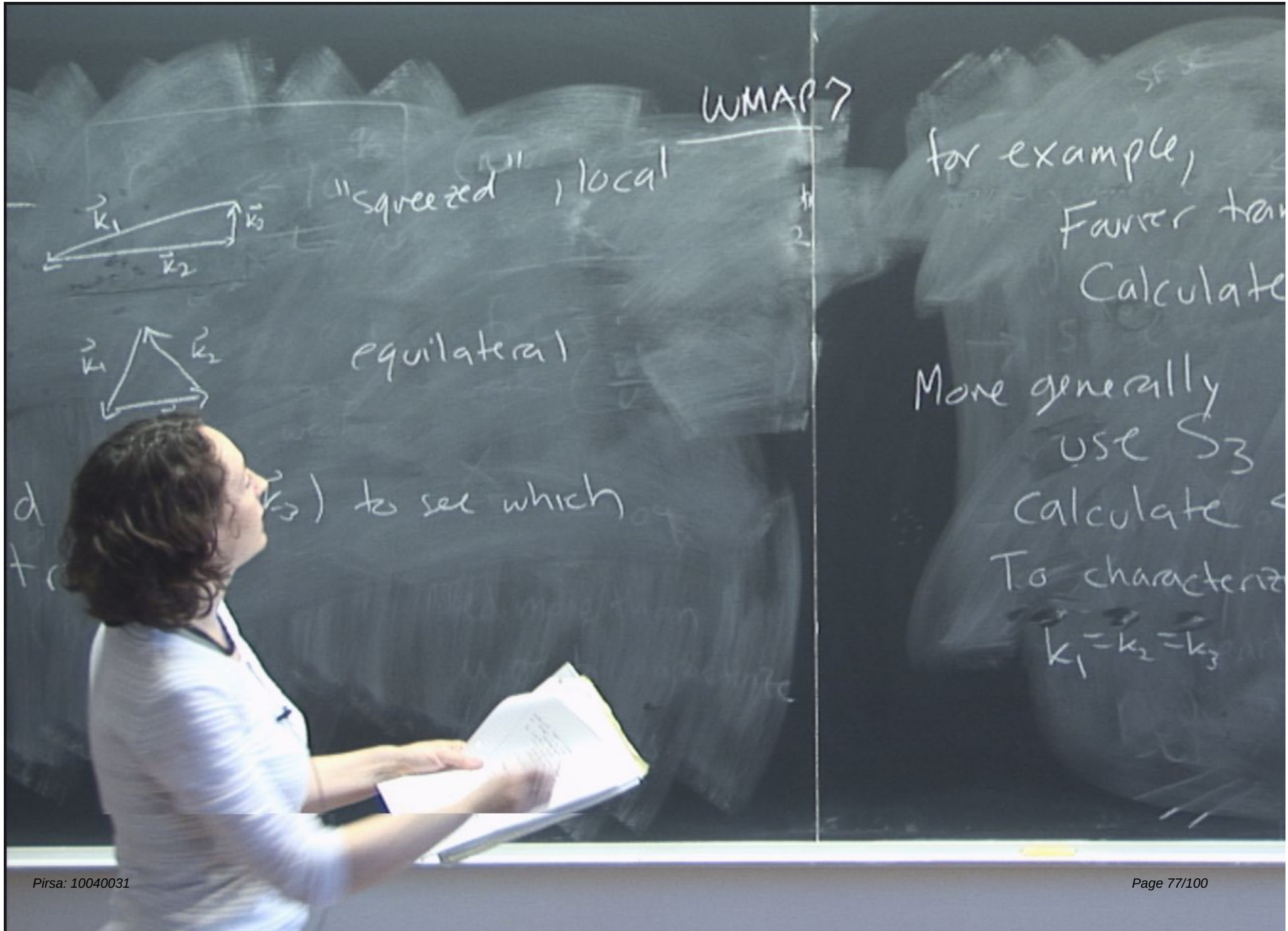
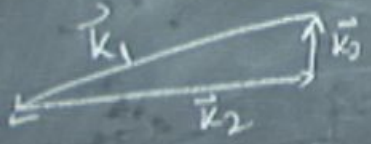
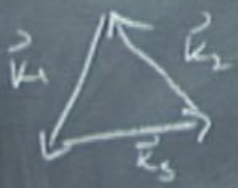

WMAP 7
"squeezed", local
$\vec{k}_1$
$\vec{k}_2$
$\vec{k}_3$
equilateral
$\vec{k}_1$
$\vec{k}_2$
$\vec{k}_3$) to see which
for example,
Fourier tra
Calculate
More generally
use S_3
Calculate
To characteriz
$k_1 = k_2 = k_3$

WMAP 7 (2σ)



"squeezed", local

$-10 < f_{NL}^{local} < 74$



equilateral

$-214 < f_{NL}^{equil} < 266$

d $B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$ to see which triangle

for example, Fourier tran

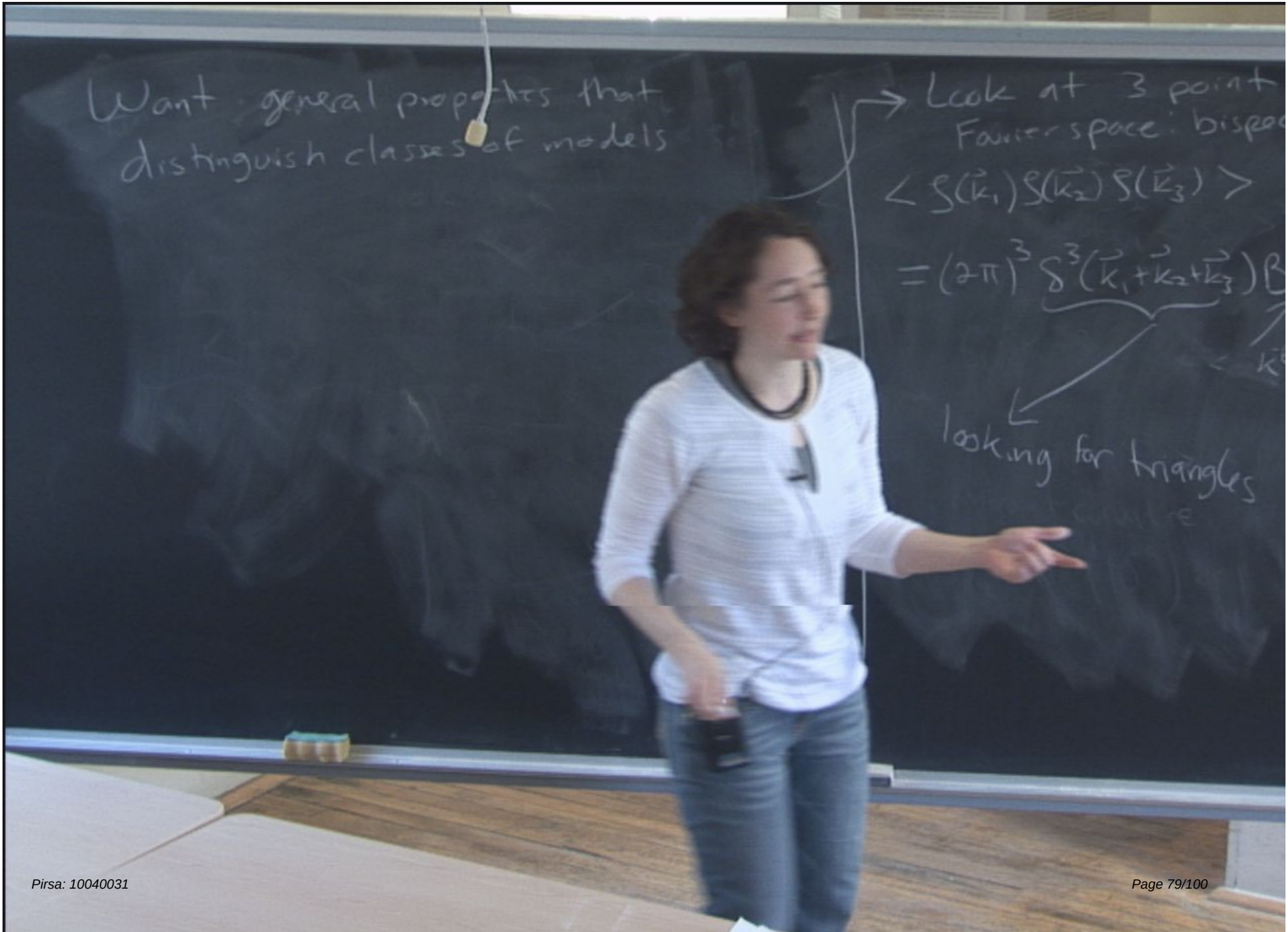
Calculate

More generally use S_3

Calculate

To characteriz

$k_1 = k_2 = k_3$


Want general properties that
distinguish classes of models
Look at 3 point
Fourier space: bispec
looking for triangles

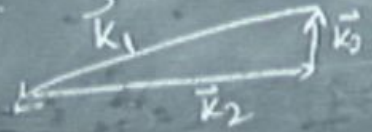
WMAP constraints
Eg
local
f_{NL}
equil
$\vec{k}_1$
$\vec{k}_2$
$\vec{k}_3$
"squeezed", local
$-10 < f_{NL}^{local} < 74$
→ multiple field
equilateral
$-214 < f_{NL}^{equil} < 266$
→ derivative interactions
WMAP
$B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$ to see which
triangle

WMAP constraints

Eg

f_{NL}^{local}

f_{NL}^{equil}



"squeezed", local

WMAP

$-10 < f_{NL}^{local} < 74$ (2)

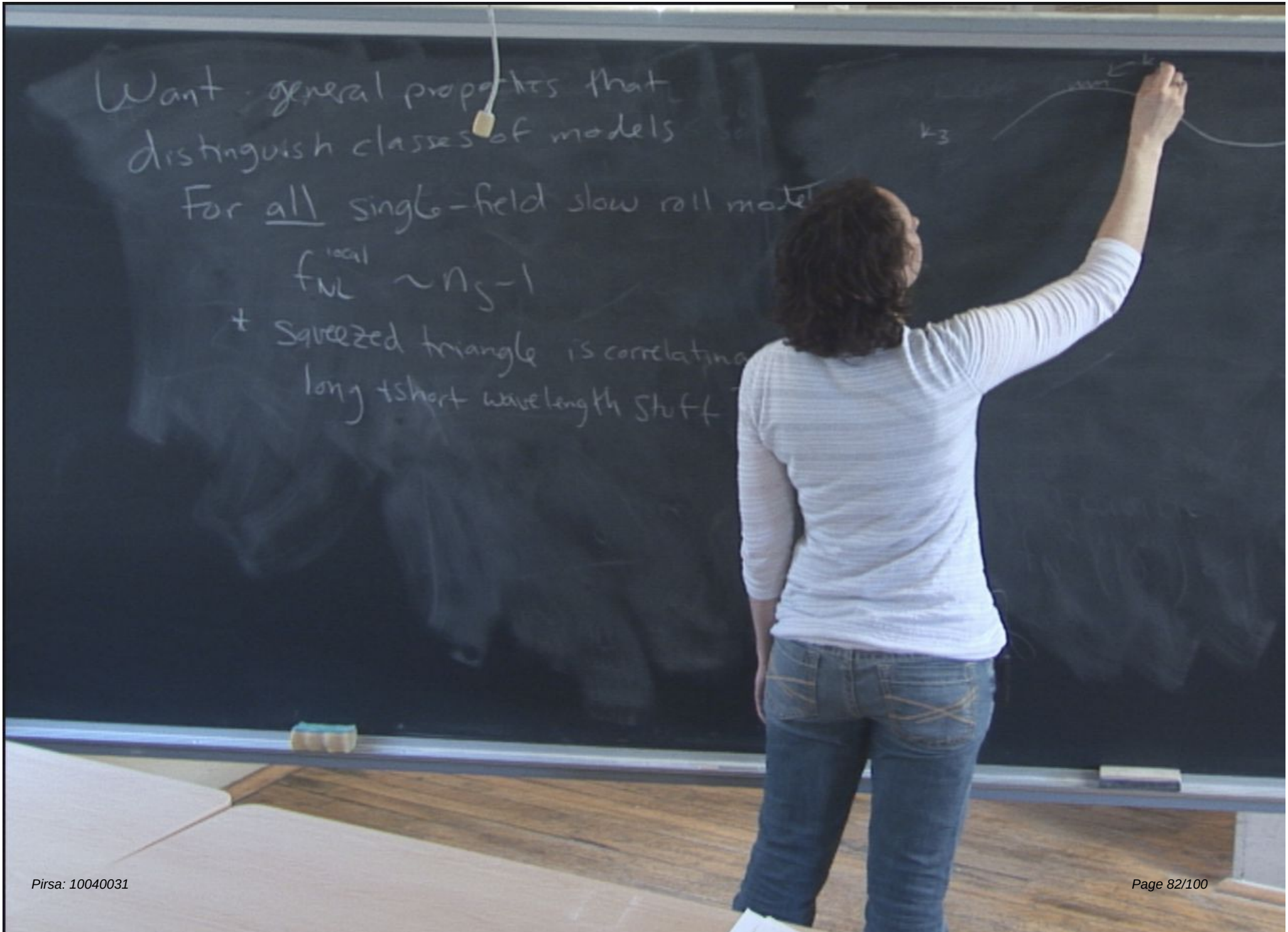
→ multiple field

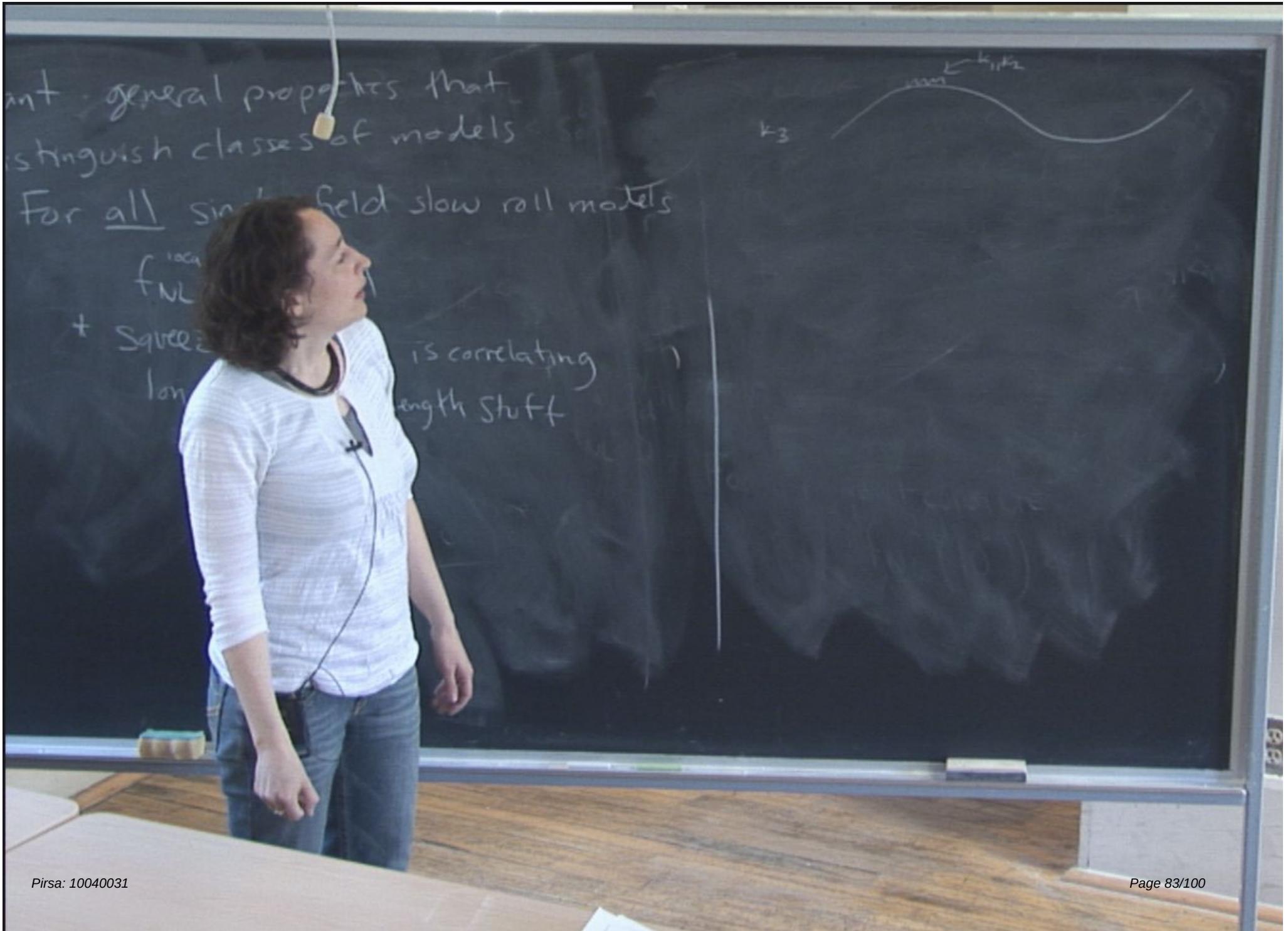
equilateral

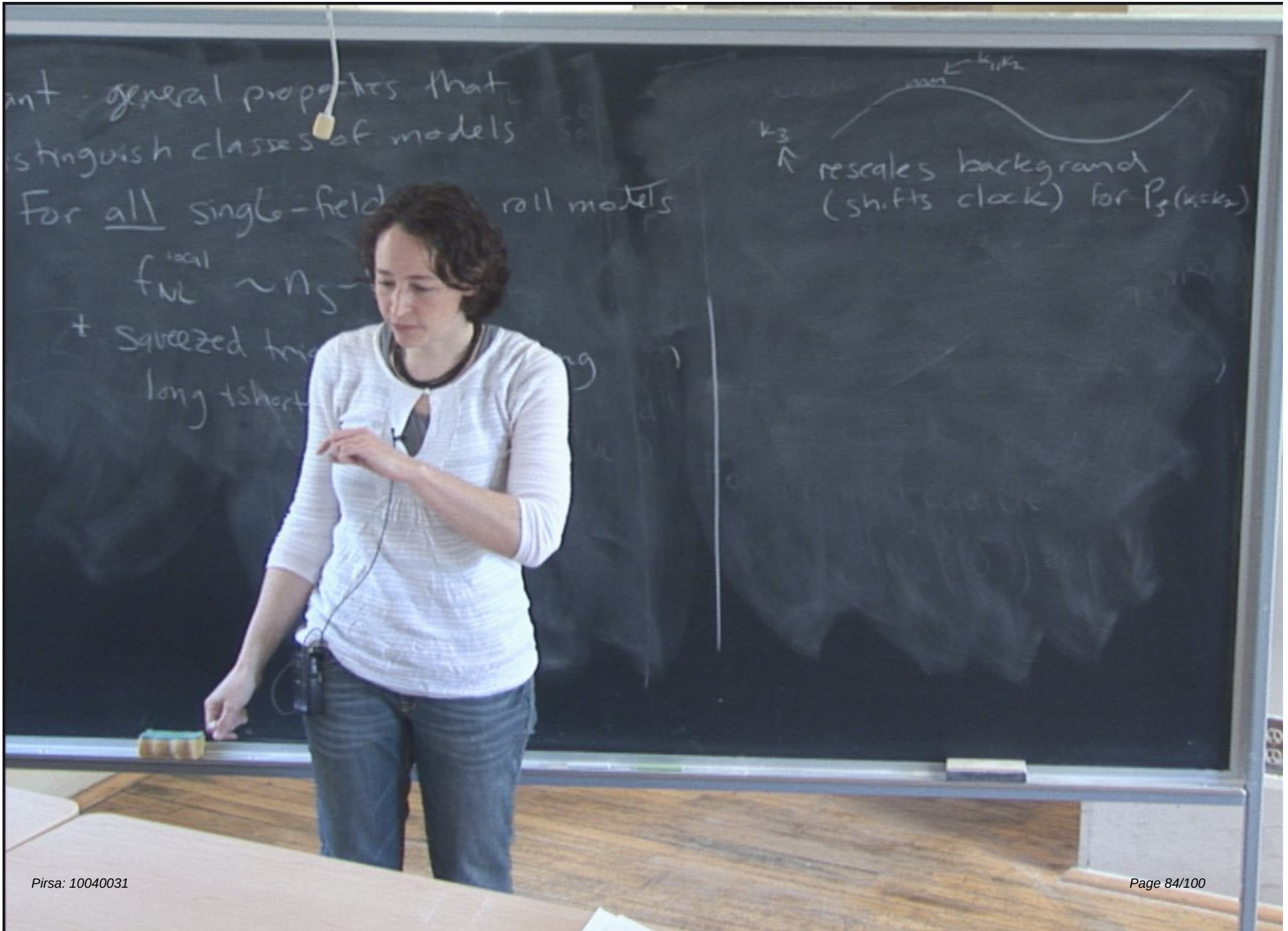
$-214 < f_{NL}^{equil} < 266$

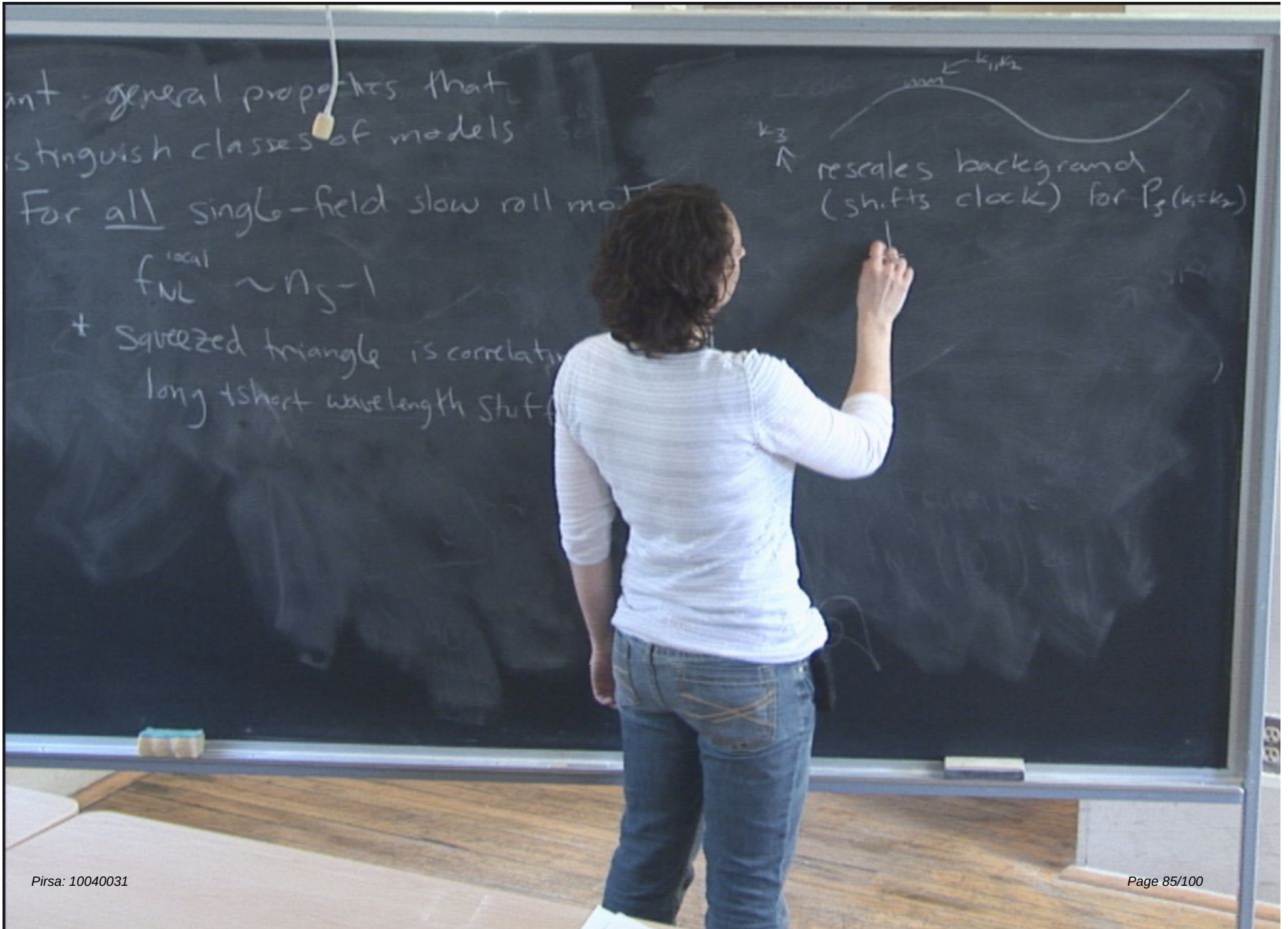
→ derivative interactions

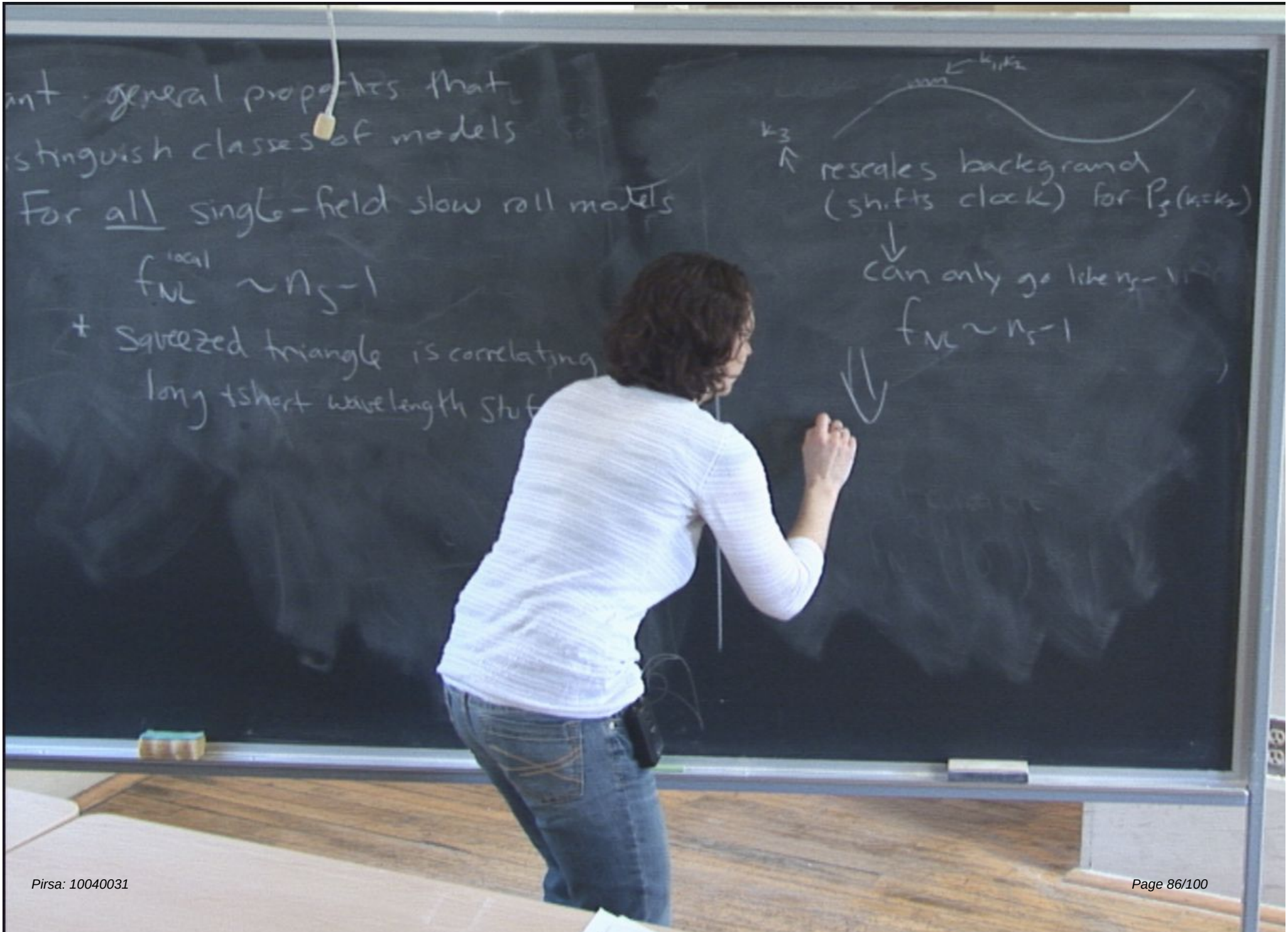
Need $B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$ to see which triangle


Want general properties that
distinguish classes of models
For all single-field slow roll mode
$f_{NL}^{local} \sim n_s - 1$
+ squeezed triangle is correlating
long + short wavelength stuff
k_3


general properties that
classes of models
For all
field slow roll models
is correlating
length stuff
k3


general properties that
distinguish classes of models
For all single-field
rall models
rescales background
(shifts clock) for


ant general properties that
istinguish classes of models
For all single-field slow roll mo
$f_{NL}^{local} \sim n_s - 1$
+ squeezed triangle is correlati
long & short wavelength stuf
$k_1 \approx k_2$
k_3
rescales background
(shifts clock) for $P_s(k_1 = k_2)$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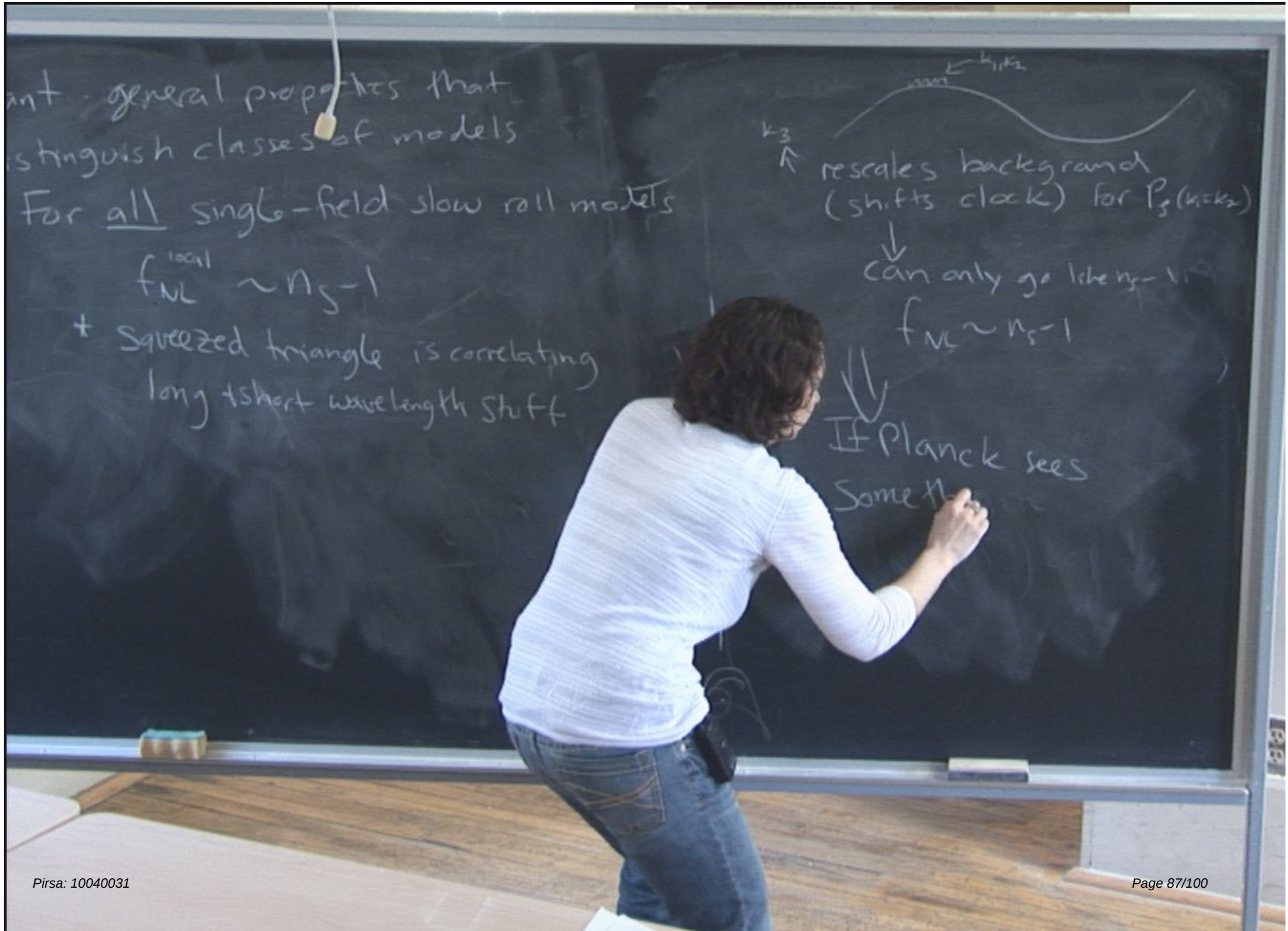
$f_{NL}^{local} \sim n_s - 1$
+ squeezed triangle is correlating
long & short wavelength
k_3
rescales background
(shifts clock) for $P_s(k_1 = k_2)$
can only go like $n_s - 1$
$f_{NL} \sim n_s - 1$


general properties that
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+ squeezed triangle is correlating
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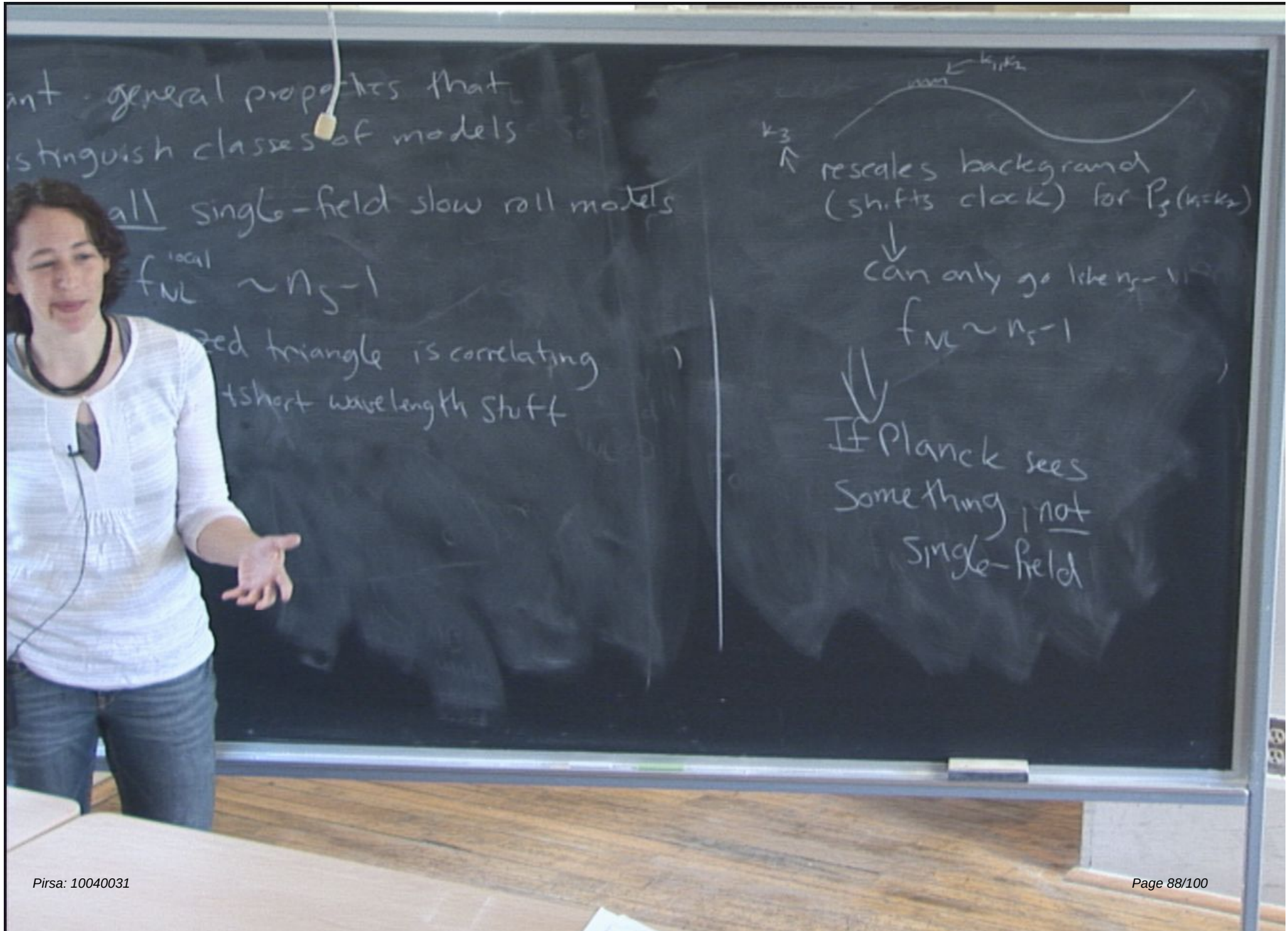
$k_1 = k_2$
k_3
rescales background
(shifts clock) for $P_s(k_1 = k_2)$
can only go like $n_s - 1$
$f_{NL} \sim n_s - 1$
If Planck sees


ant general properties that
istinguish classes of models
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$f_{NL}^{local} \sim n_s - 1$
ed triangle is correlating
t short wavelength stuff
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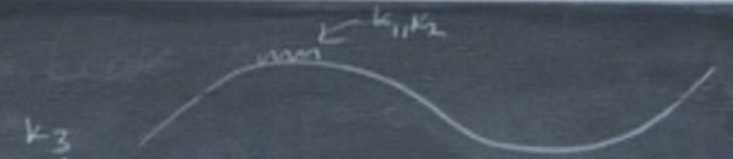
rescales background
(shifts clock) for $P_s(k_1 = k_2)$
can only go like $n_s - 1$
$f_{NL} \sim n_s - 1$
If Planck sees
something, not
single-field

ant general properties that
istinguish classes of models

For all single-field slow roll models

$f_{NL}^{local} \sim n_s - 1$

+ squeezed triangle is correlating long + short wavelength stuff



rescales background (shifts clock) for $P_s(k_1 = k_2)$

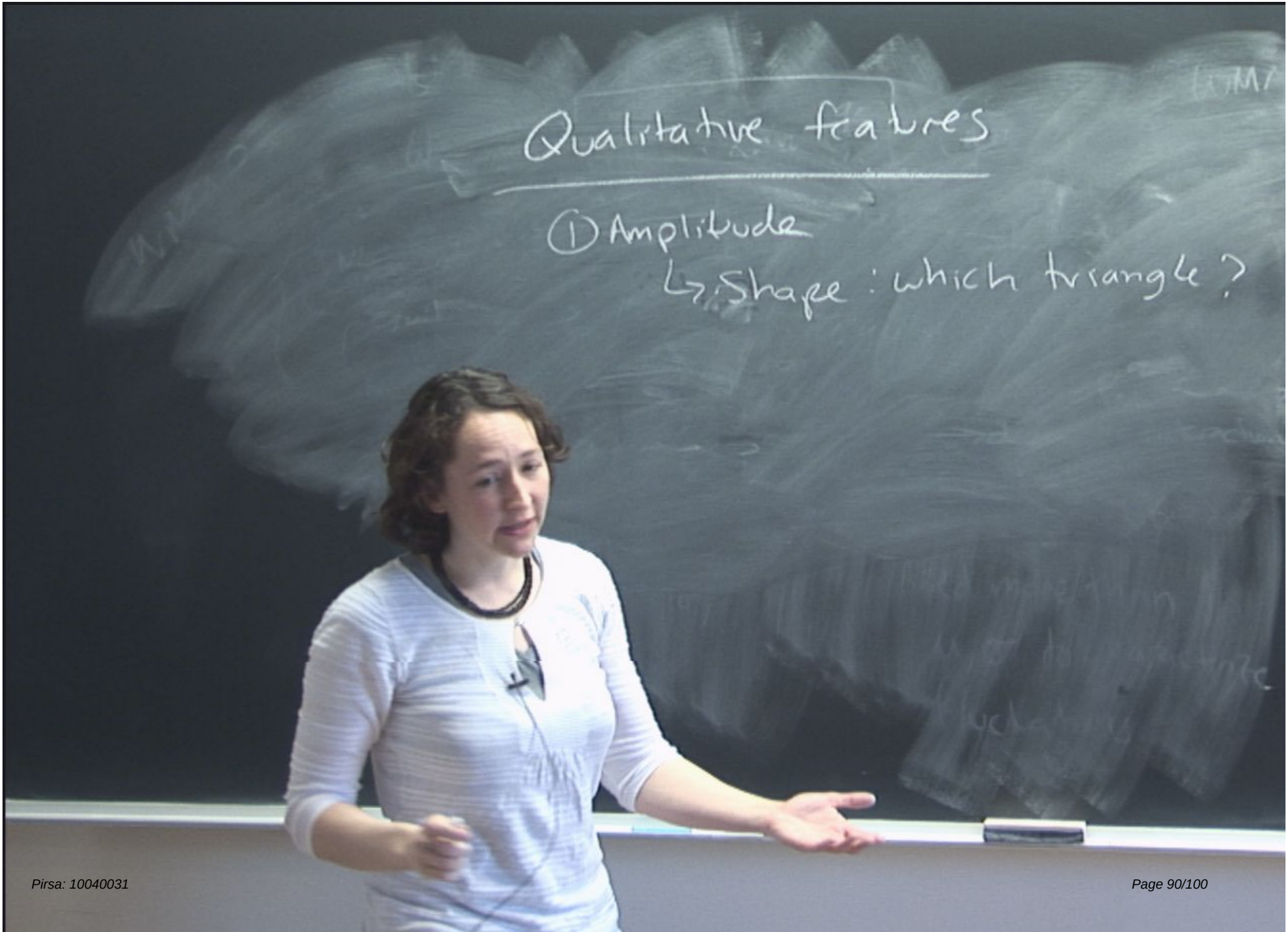
↓

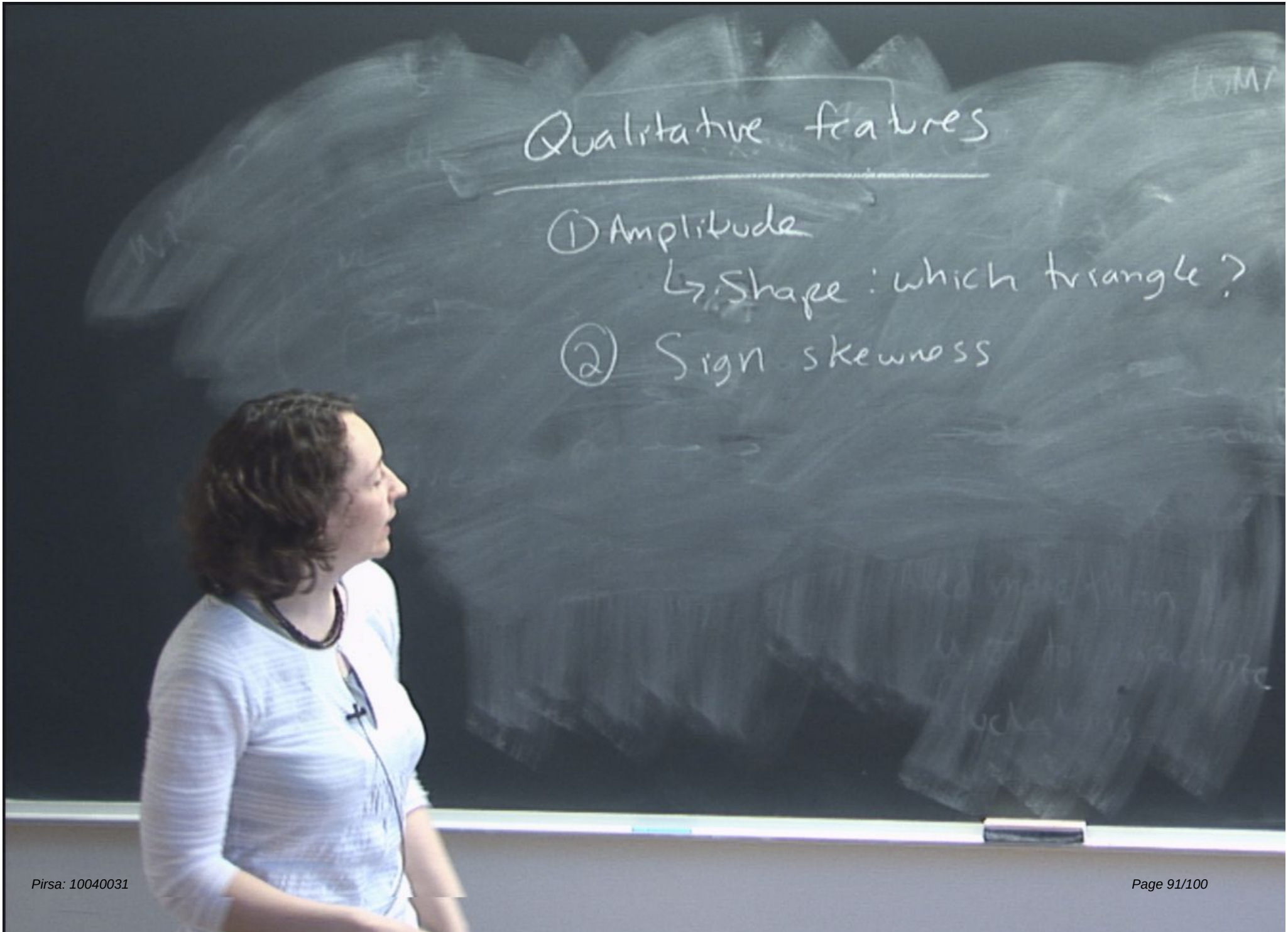
can only go like $n_s - 1$

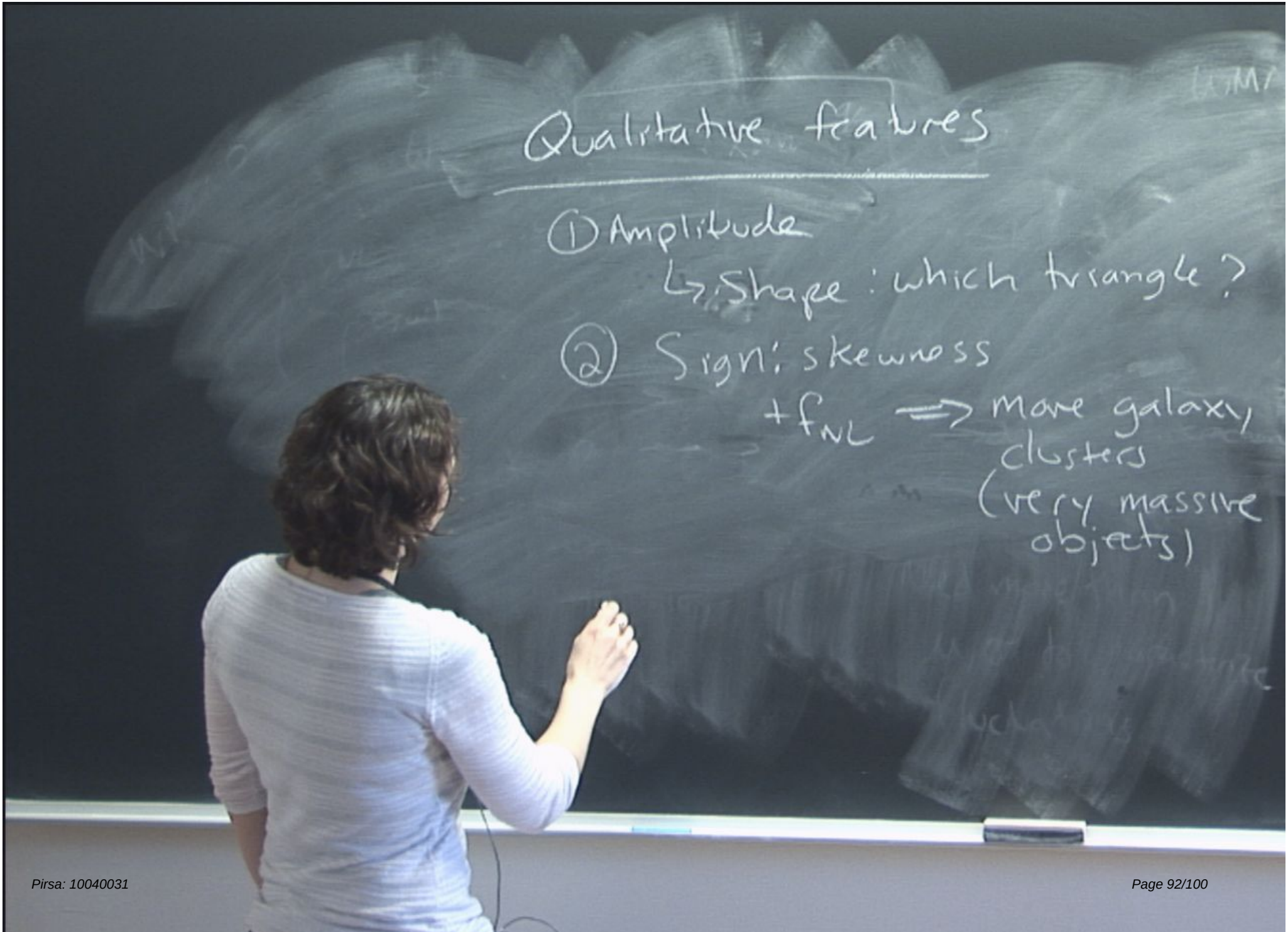
$f_{NL} \sim n_s - 1$

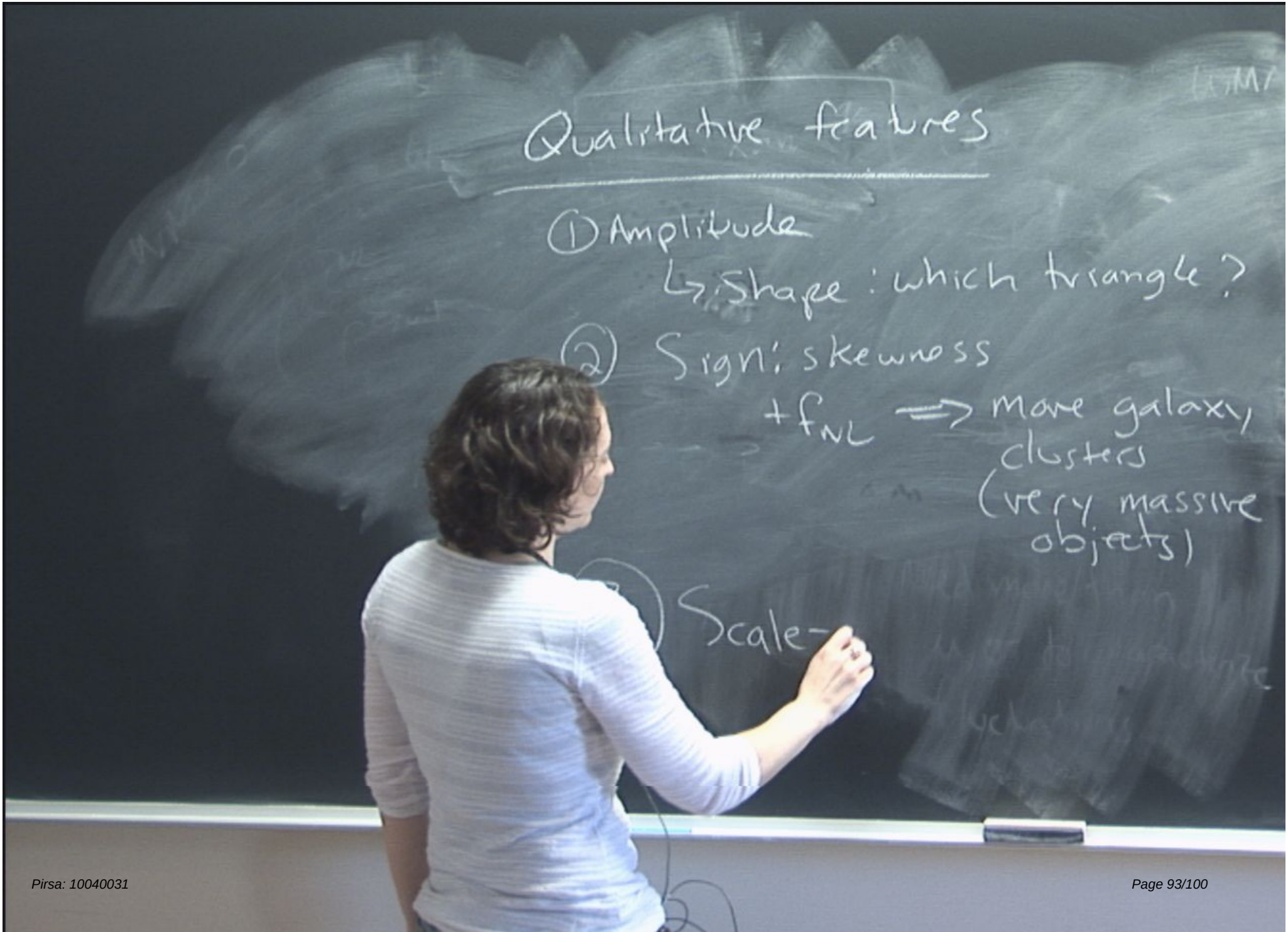
⇓

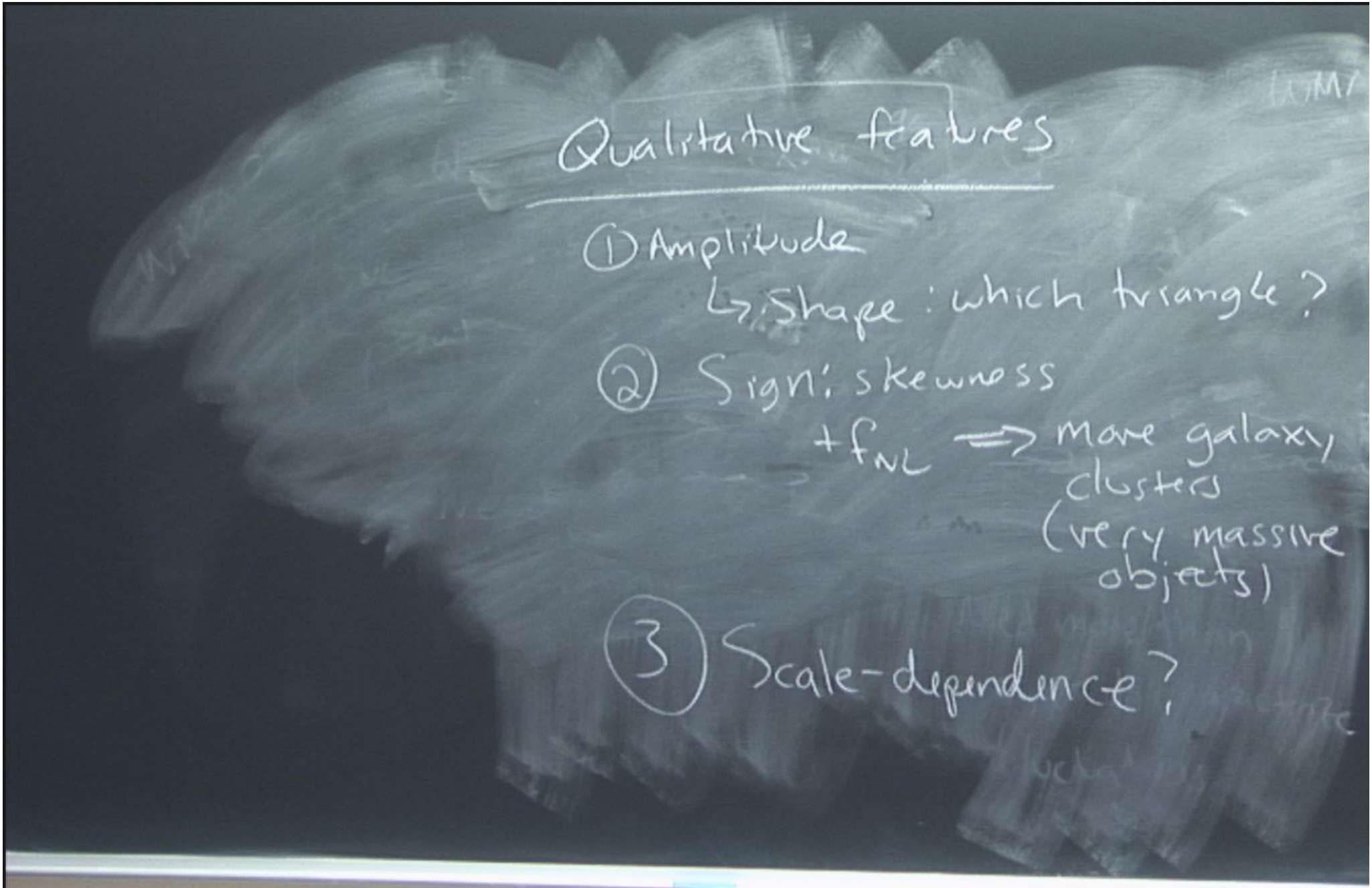
If Planck sees something, not single-field

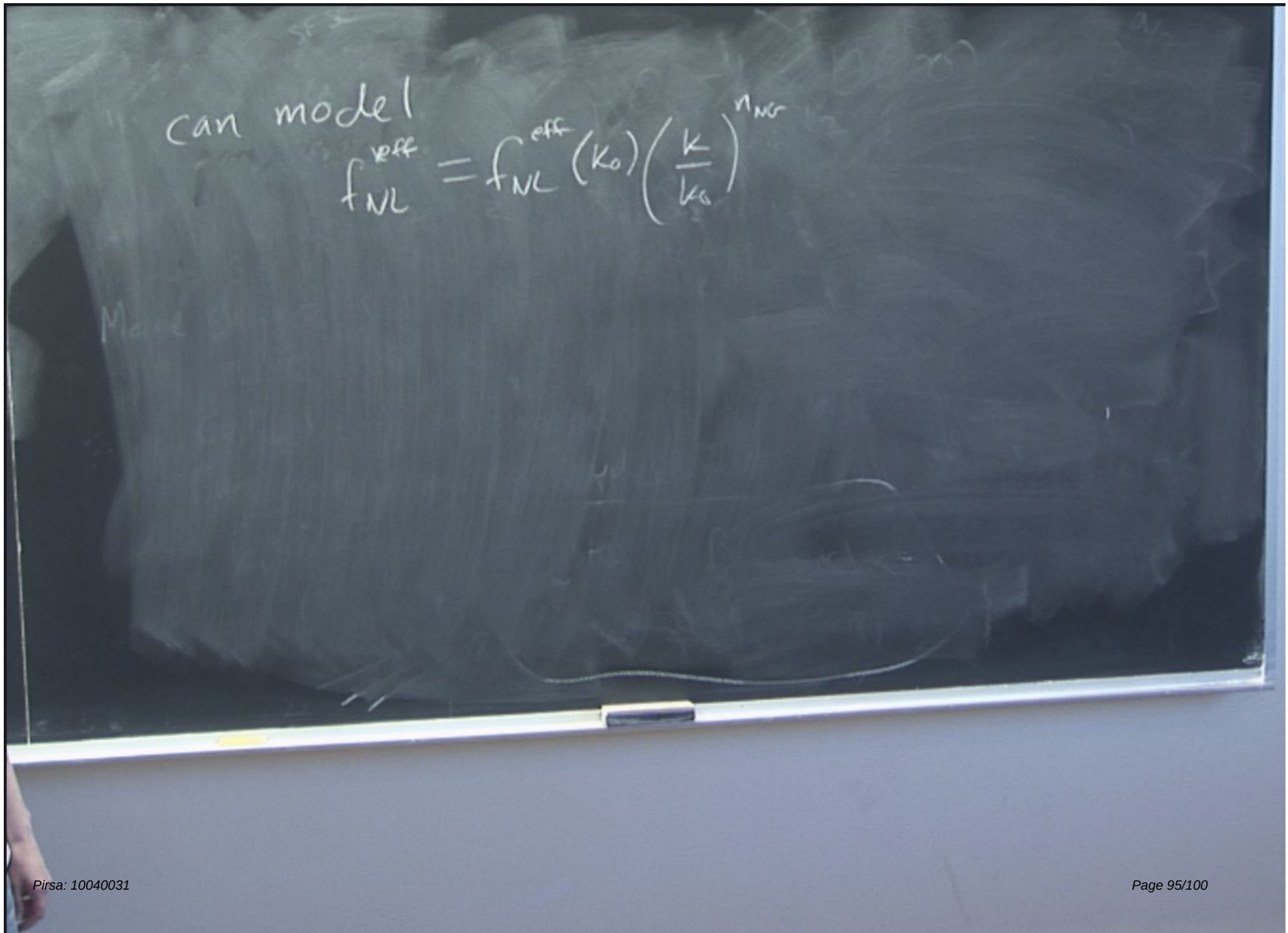

Qualitative features
① Amplitude
↳ Shape : which triangle ?

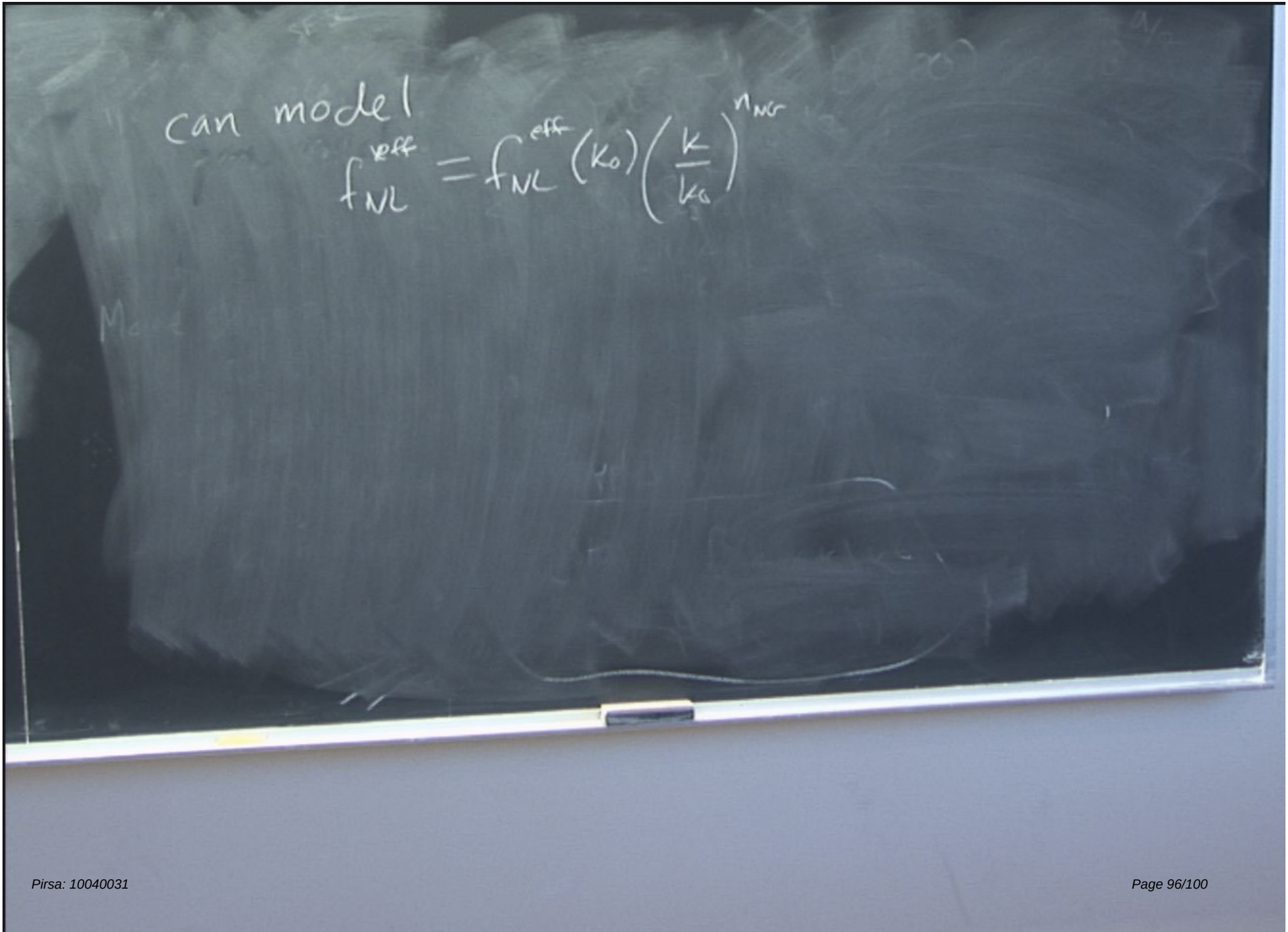

Qualitative features
① Amplitude
↳ Shape : which triangle ?
② Sign skewness


Qualitative features
① Amplitude
↳ Shape : which triangle ?
② Sign : skewness
+ f_{NL} ⟹ more galaxy clusters (very massive objects)


Qualitative features
① Amplitude
↳ Shape : which triangle ?
② Sign: skewness
+ f_{NL} ⟹ more galaxy clusters (very massive objects)
Scale-


Qualitative features
① Amplitude
↳ Shape : which triangle ?
② Sign : skewness
+ f_{NL} ⟹ more galaxy clusters (very massive objects)
③ Scale-dependence ?

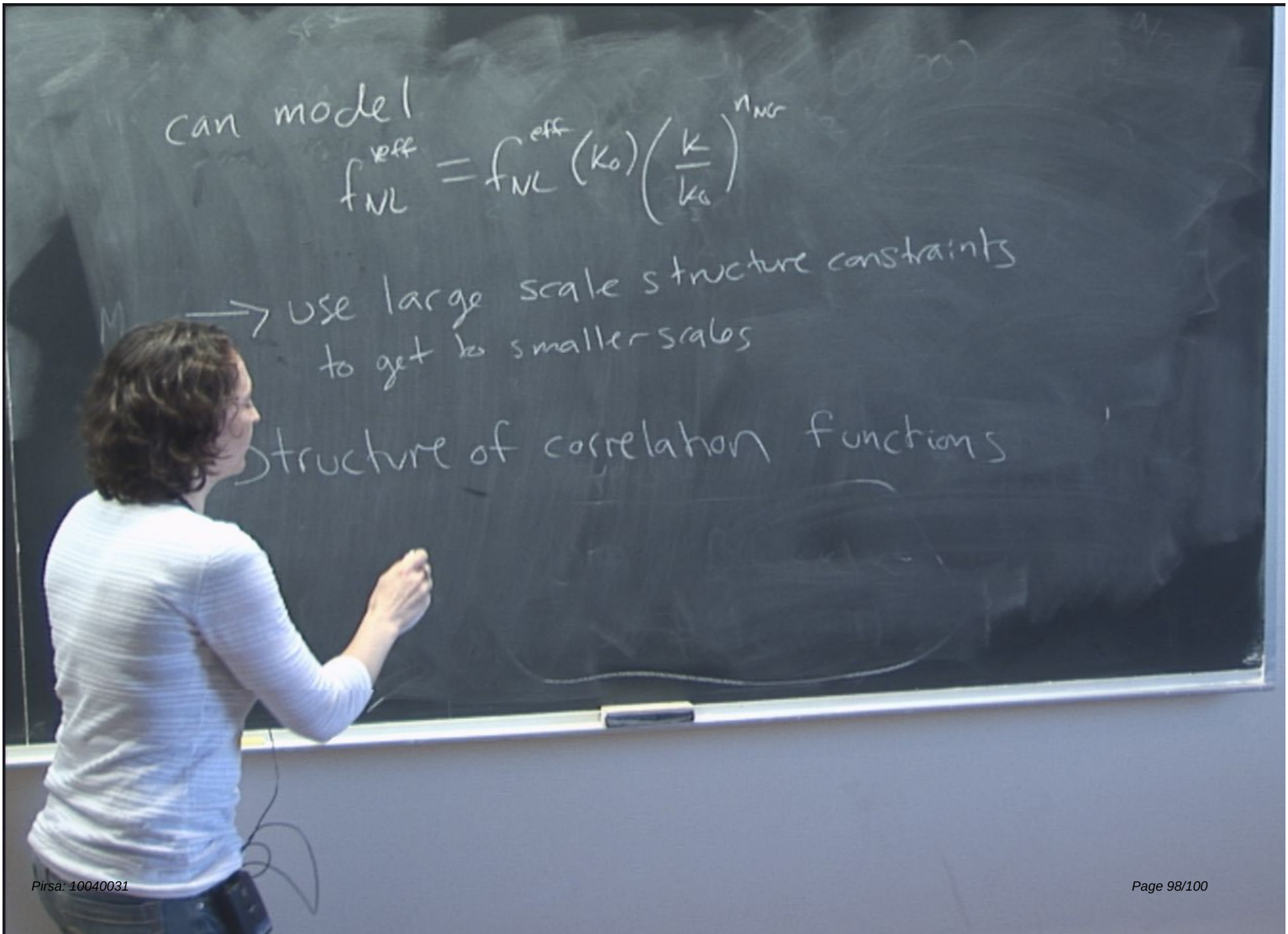

can model
$f_{NL}^{eff} = f_{NL}^{eff}(k_0)\left(\frac{k}{k_0}\right)^{n_{NG}}$

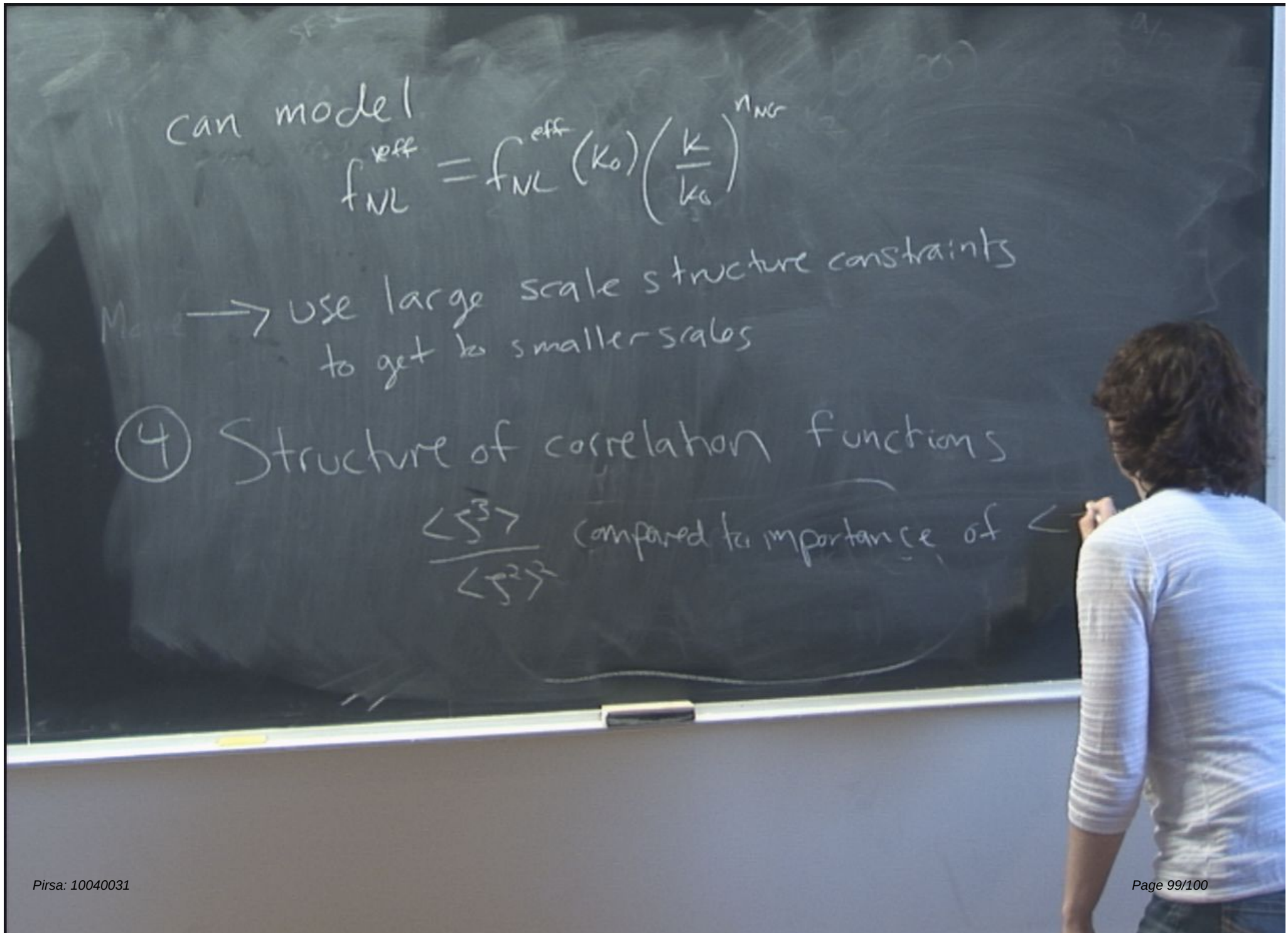

can model
$f_{NL}^{eff} = f_{NL}^{eff}(k_0)\left(\frac{k}{k_0}\right)^{n_{NG}}$

can model

$$f_{NL}^{\text{eff}} = f_{NL}^{\text{eff}}(k_0)\left(\frac{k}{k_0}\right)^{n_{NG}}$$

→ use large scale structure constraints to get to smaller scales


can model
$f_{NL}^{k\,\mathrm{eff}} = f_{NL}^{\mathrm{eff}}(k_0)\left(\frac{k}{k_0}\right)^{n_{NG}}$
use large scale structure constraints
to get to smaller scales
structure of correlation functions


can model
$f_{NL}^{\text{eff}} = f_{NL}^{\text{eff}}(k_0)\left(\frac{k}{k_0}\right)^{n_{NG}}$
→ use large scale structure constraints
to get to smaller scales
④ Structure of correlation functions
$\frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^2}$ compared to importance of

can model

$$f_{NL}^{\text{eff}} = f_{NL}^{\text{eff}}(k_0)\left(\frac{k}{k_0}\right)^{n_{NG}}$$

→ use large scale structure constraints to get to smaller scales

④ Structure of correlation functions

$\frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^2}$ compared to importance of $\langle \zeta^4 \rangle$.