Title: A non-minimal perspective on the misalignment mechanism

Speakers: Gonzalo Alonso-Ã•lvarez

Series: Particle Physics

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Abstract: Non minimal couplings of scalar fields to gravity are a generic feature of Lagrangian formulations of gravity. Although challenging to probe at low energies and small curvature, such couplings can play a crucial role in cosmological setups. We focus on their impact in the production of scalar dark matter and its interplay with inflationary physics. We show how the standard non-thermal production mechanism of scalar dark matter, the misalignment mechanism, is modified, and explore how alternative scenarios like production from inflationary fluctuations become viable. We study potentially observable features of these scenarios, such as the enhancement of dark matter substructure at small scales and the generation of an isocurvature component in the fluctuations of the CMB.

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↳ Non-thermal production of DM

→ Axions / ALPs – misalignment

↳ Gravitational interactions

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} M_p^2 R + \mathcal{L}_\phi \right) \rightarrow G_{\mu\nu} = \frac{1}{M_p^2} T_{\mu\nu}$$

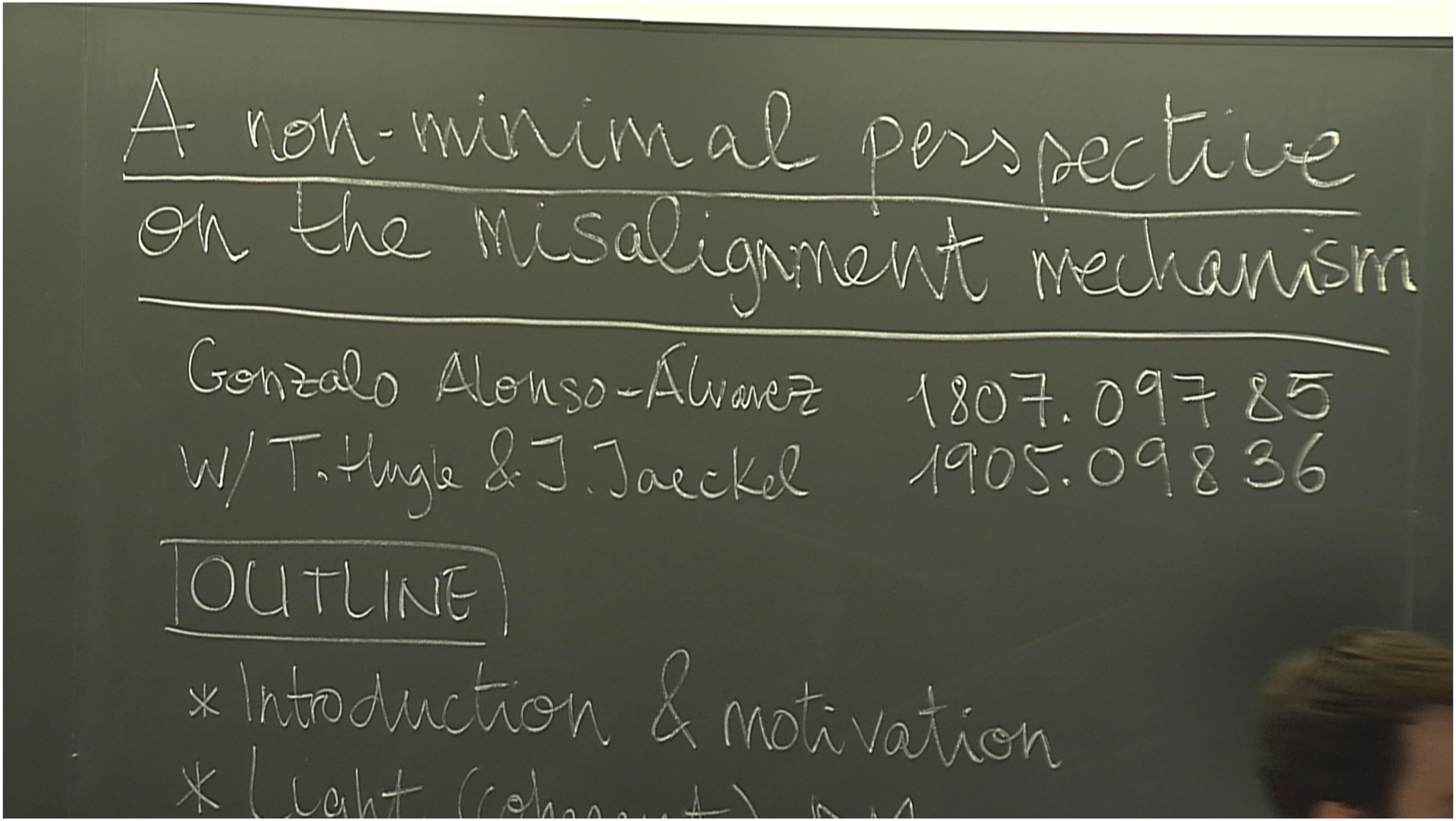
→ Axions/ALPs – misalignment

↳ Gravitational interactions

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{2}M_p^2 R + \mathcal{L}_\phi\right) \rightarrow G_{\mu\nu} = \frac{1}{M_p^2} T_{\mu\nu}$$

<u>BUT</u>:

– EFT of gravity: R^2, $R_{\mu\nu}R^{\mu\nu}$, $\phi^2 R$, $R^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$, ...

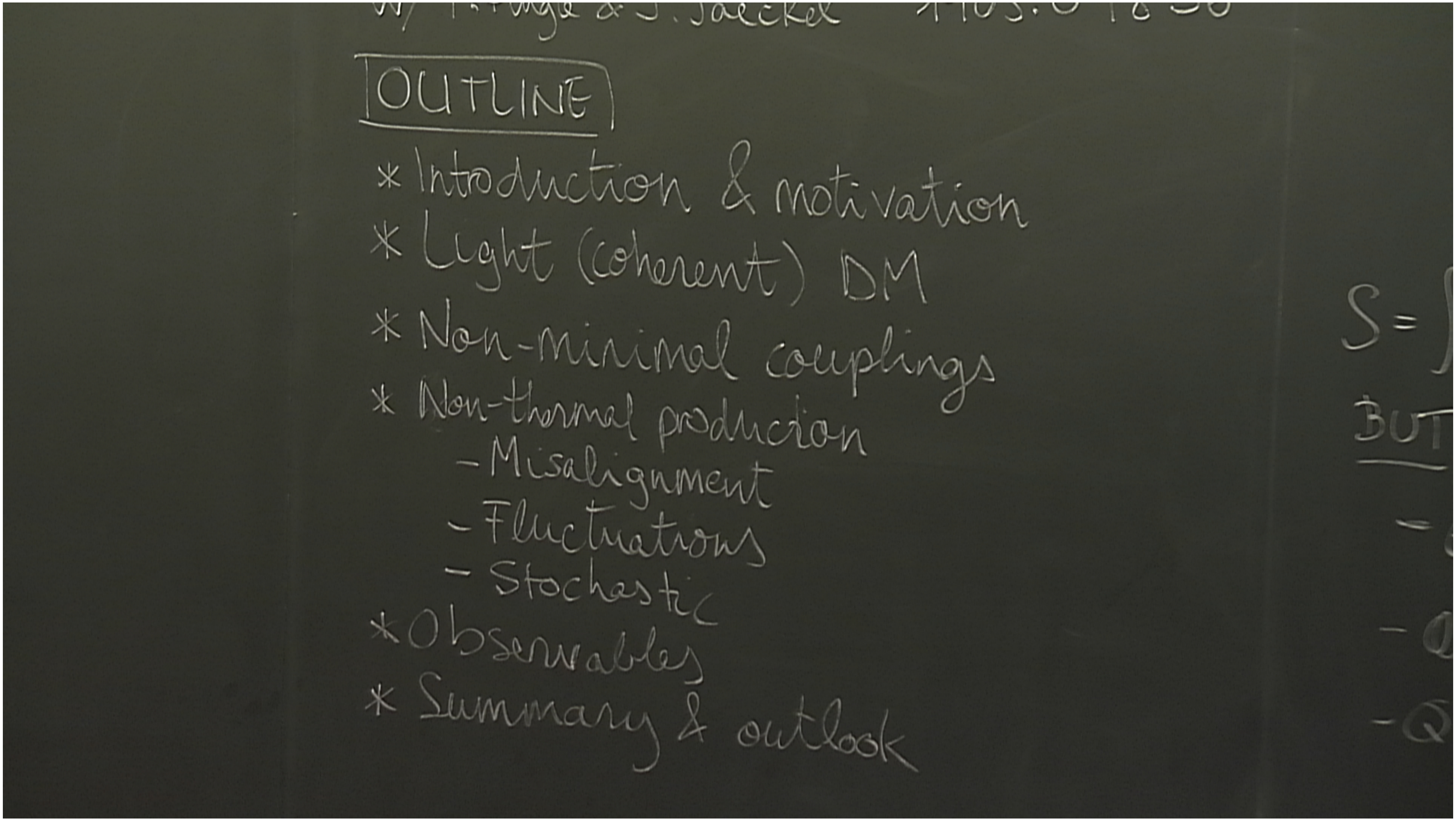

A non-minimal perspective
on the misalignment mechanism
Gonzalo Alonso-Álvarez 1807.09785
w/ T. Hugle & J. Jaeckel 1905.09836
OUTLINE
* Introduction & motivation

↪ Gravitational interactions

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} M_p^2 R + \mathcal{L}_\phi \right) \rightarrow G_{\mu\nu} = \frac{1}{M_p^2} T_{\mu\nu}$$

BUT:

- EFT of gravity: $R^2, R_{\mu\nu}R^{\mu\nu}, \phi^2 R, R^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi, \ldots$
- Quantisation in classical curved background
- QG: Asymptotic safety, ...


OUTLINE
* Introduction & motivation
* Light (coherent) DM
* Non-minimal couplings
* Non-thermal production
- Misalignment
- Fluctuations
- Stochastic
* Observables
* Summary & outlook
S =
BUT

A non-minimal perspective on the misalignment mechanism

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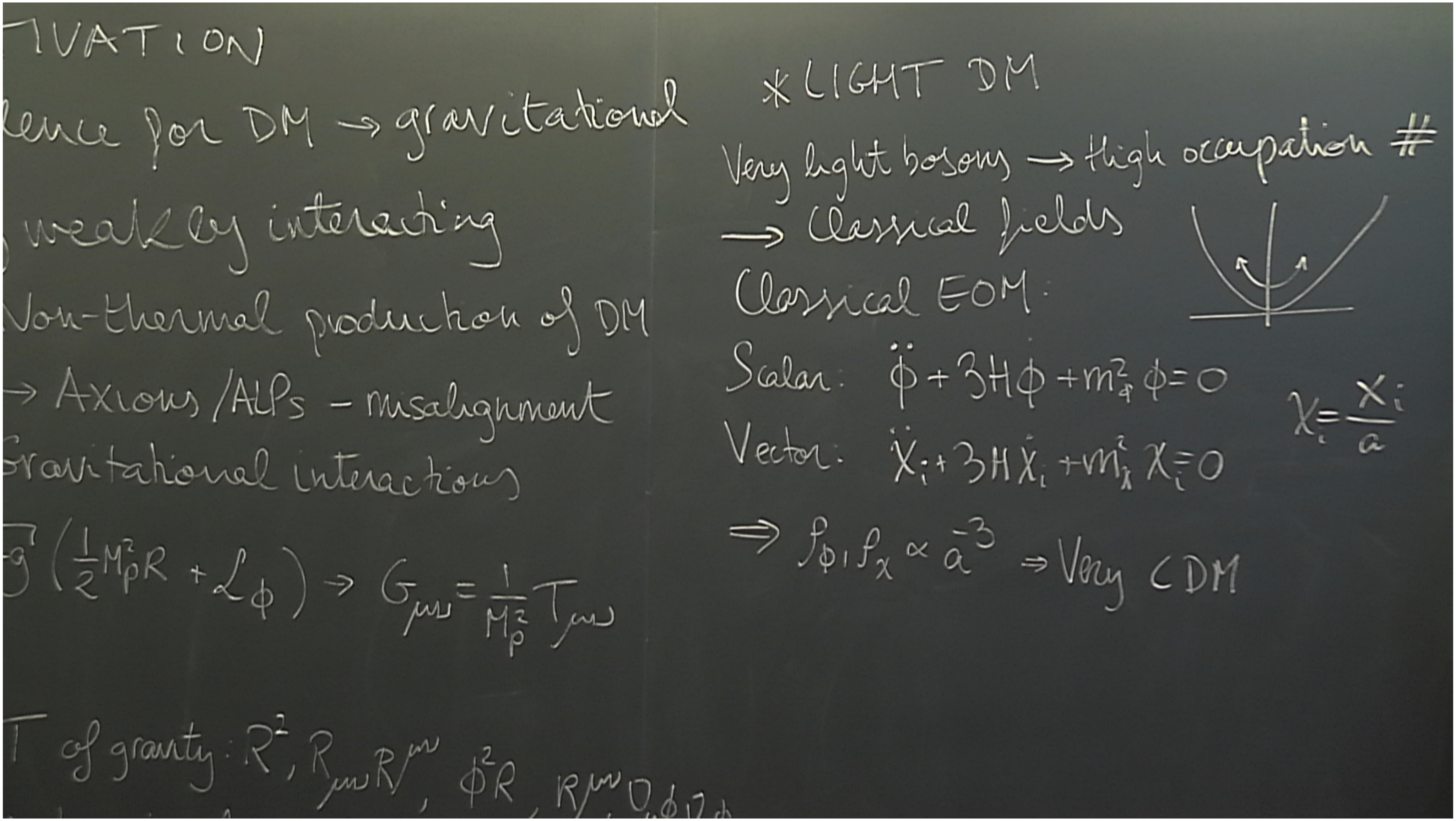
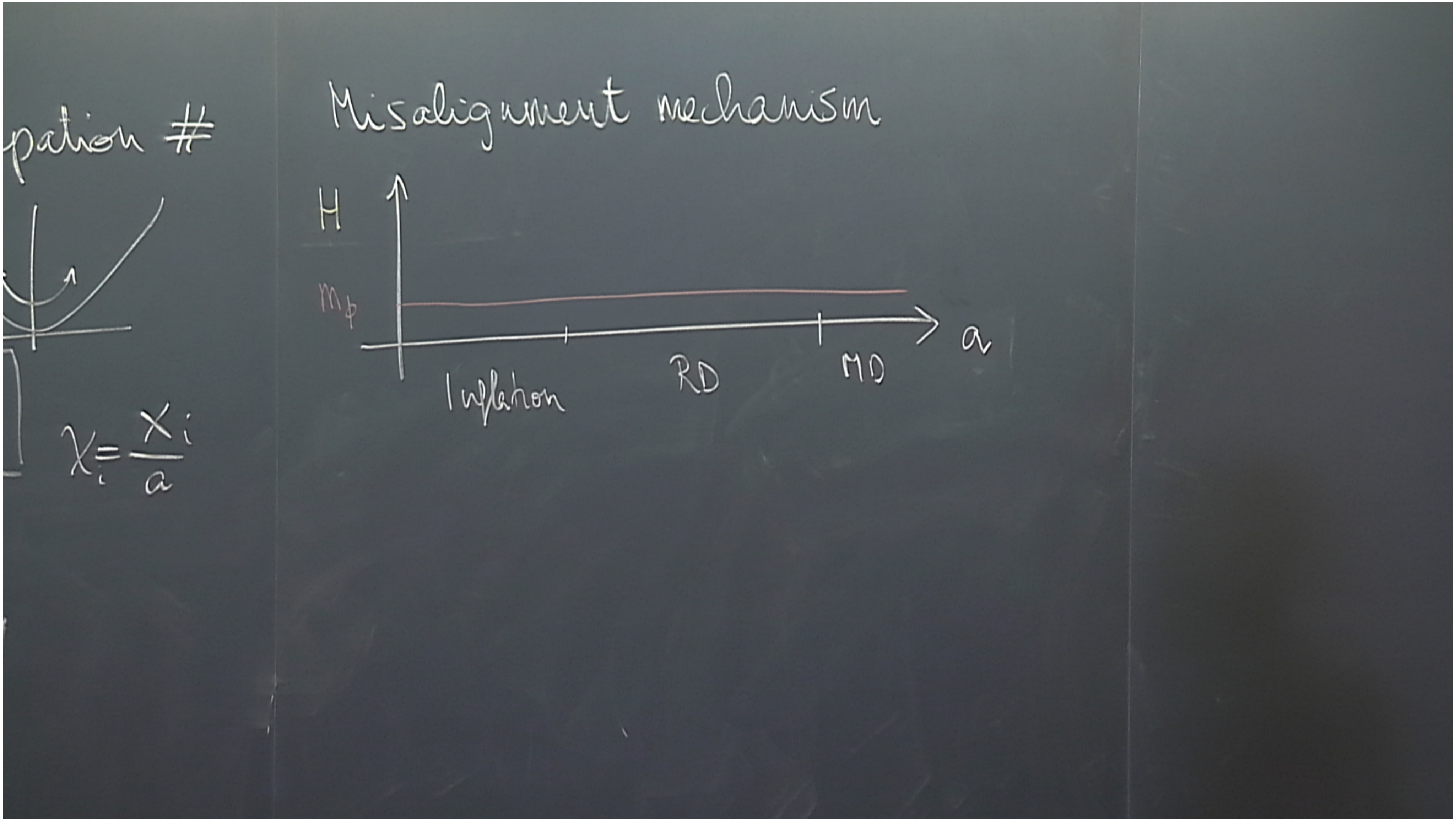
OUTLINE

* Introduction & motivation
* Light (coherent) DM
* Non-minimal couplings

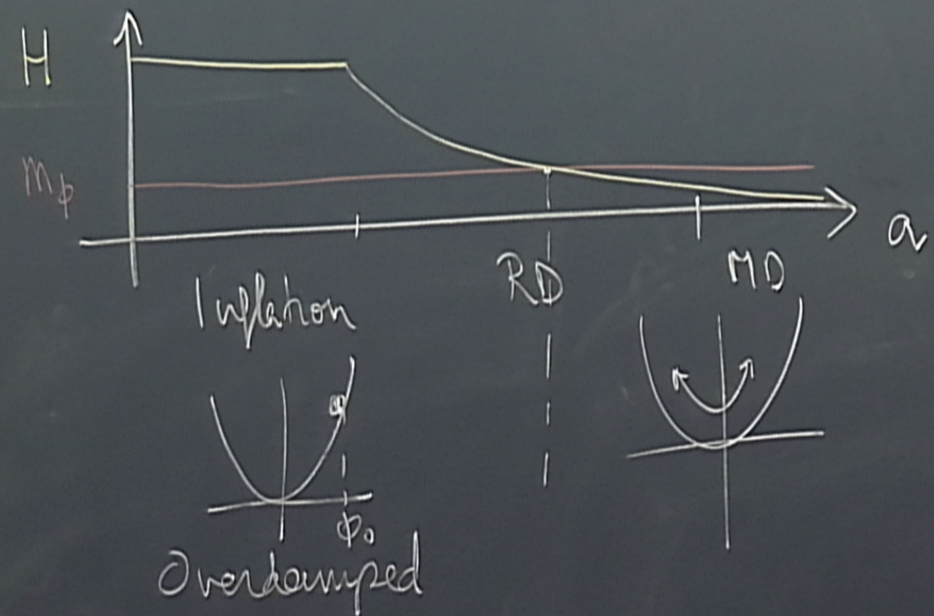

IVATION
ence for DM → gravitational
weakly interacting
Non-thermal production of DM
→ Axions/ALPs – misalignment
Gravitational interactions
$g \left(\frac{1}{2}M_p^2 R + \mathcal{L}_\phi\right) \to G_{\mu\nu} = \frac{1}{M_p^2} T_{\mu\nu}$
T of gravity: R^2, $R_{\mu\nu}R^{\mu\nu}$, $\phi^2 R$, $R^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$
* LIGHT DM
Very light bosons → High occupation #
→ Classical fields
Classical EOM:
Scalar: $\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$
Vector: $\ddot{\chi}_i + 3H\dot{\chi}_i + m_\chi^2 \chi_i = 0$
$\chi_i = \frac{X_i}{a}$
$\Rightarrow \rho_\phi, \rho_\chi \propto a^{-3} \Rightarrow$ Very CDM


pation #
Misalignment mechanism
H
m_φ
a
Inflation
RD
MD
χ_i = X_i / a

on #

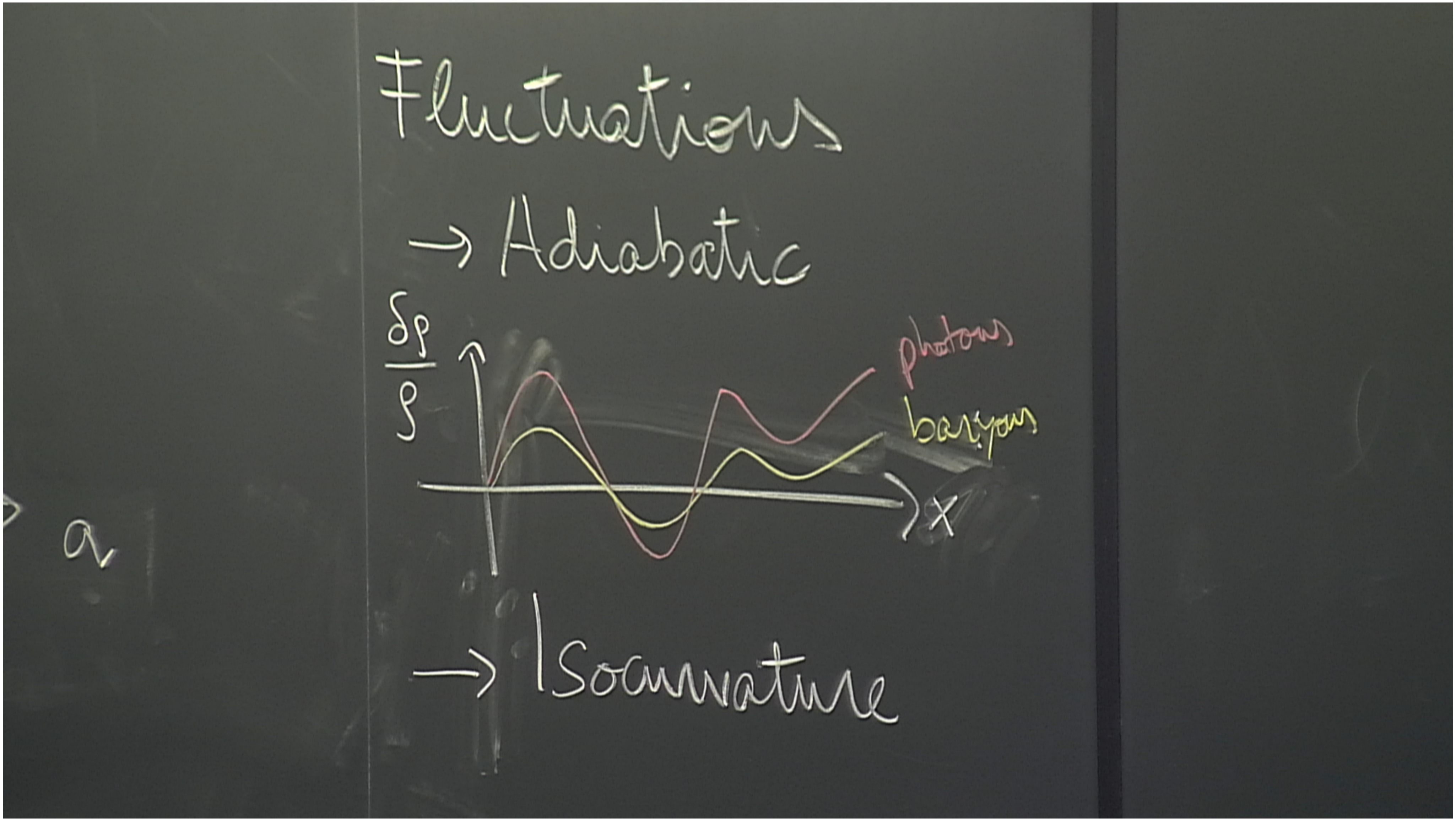
$$= \frac{x_i}{a}$$

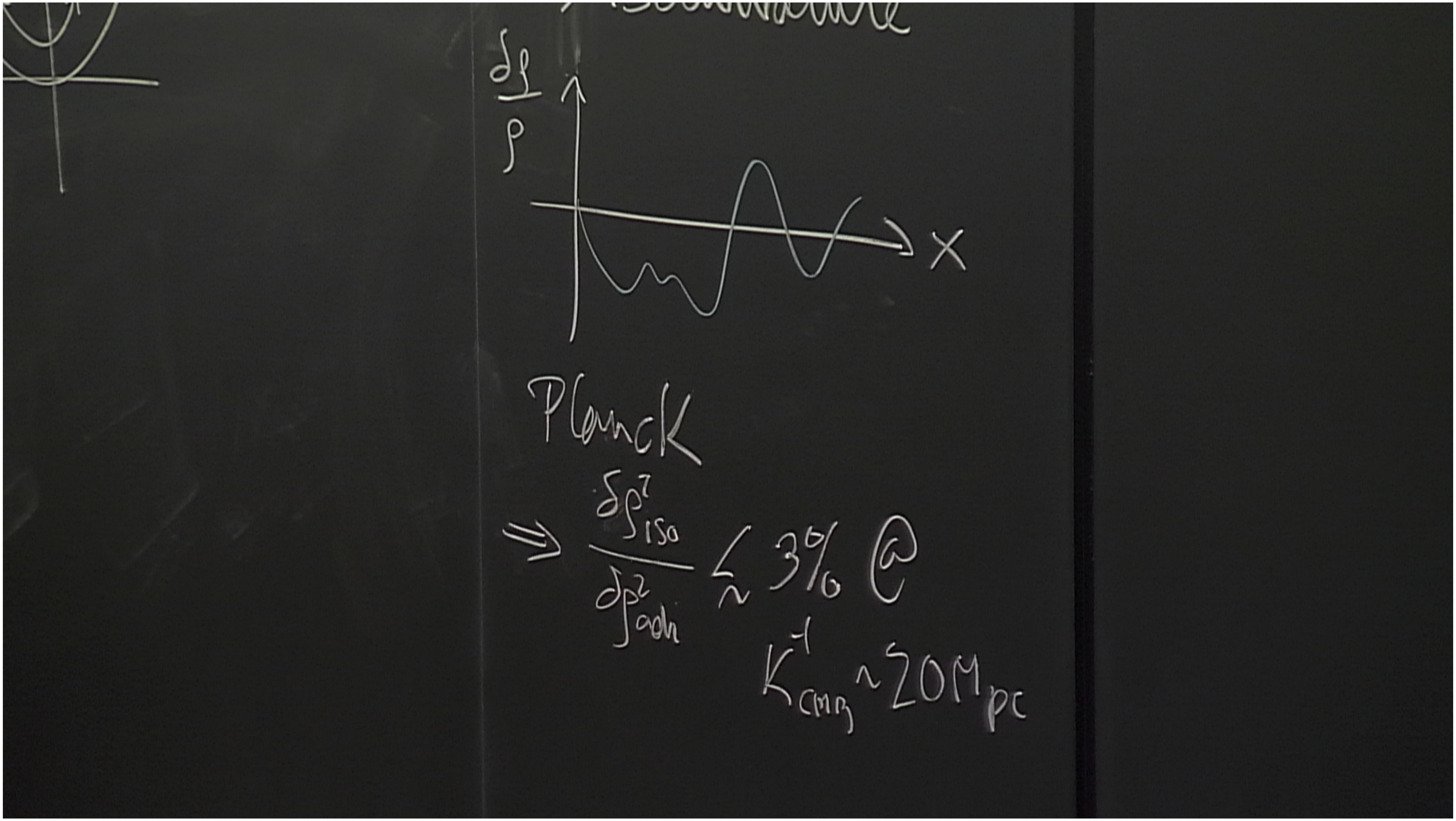
Misalignment mechanism

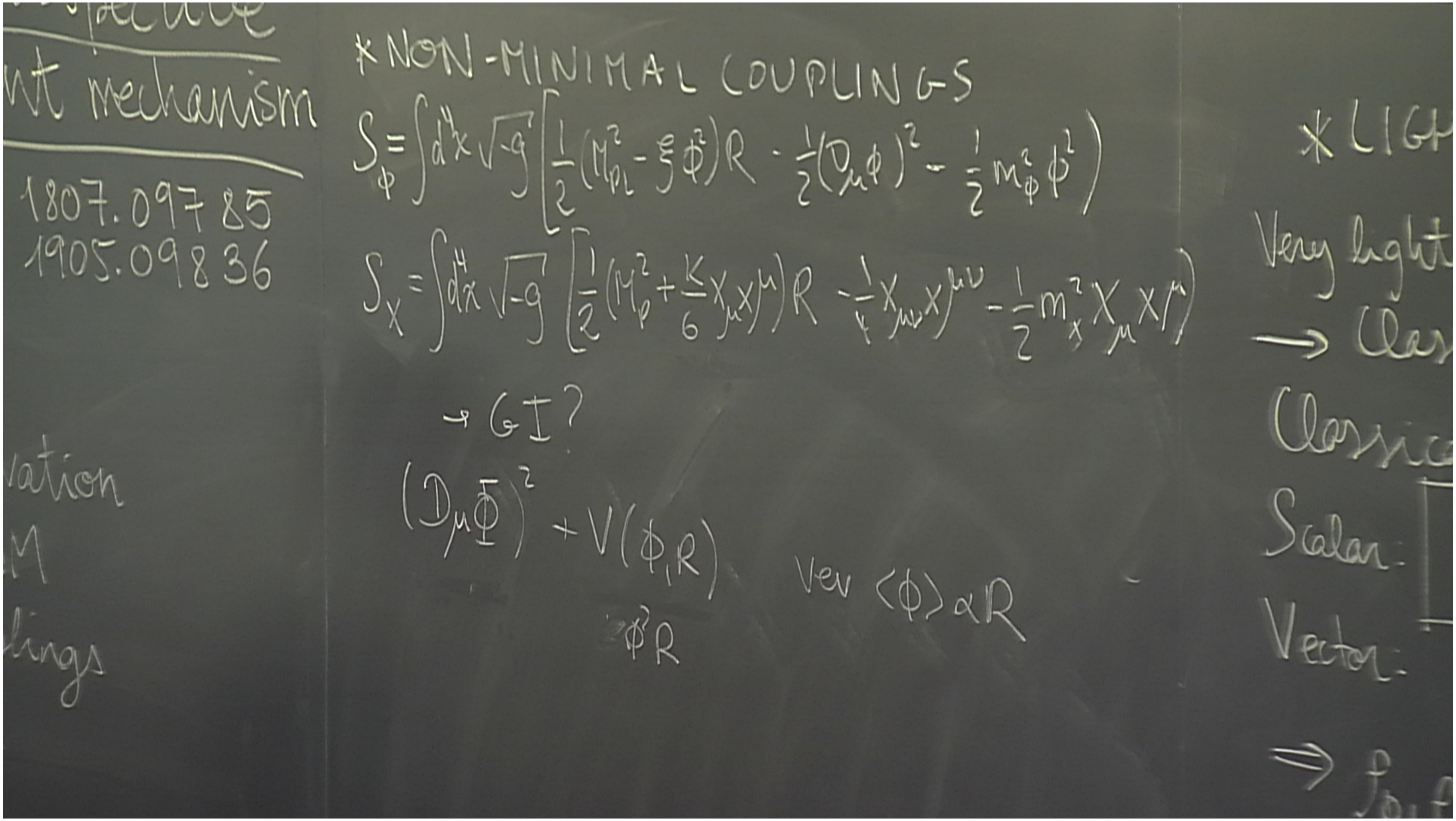


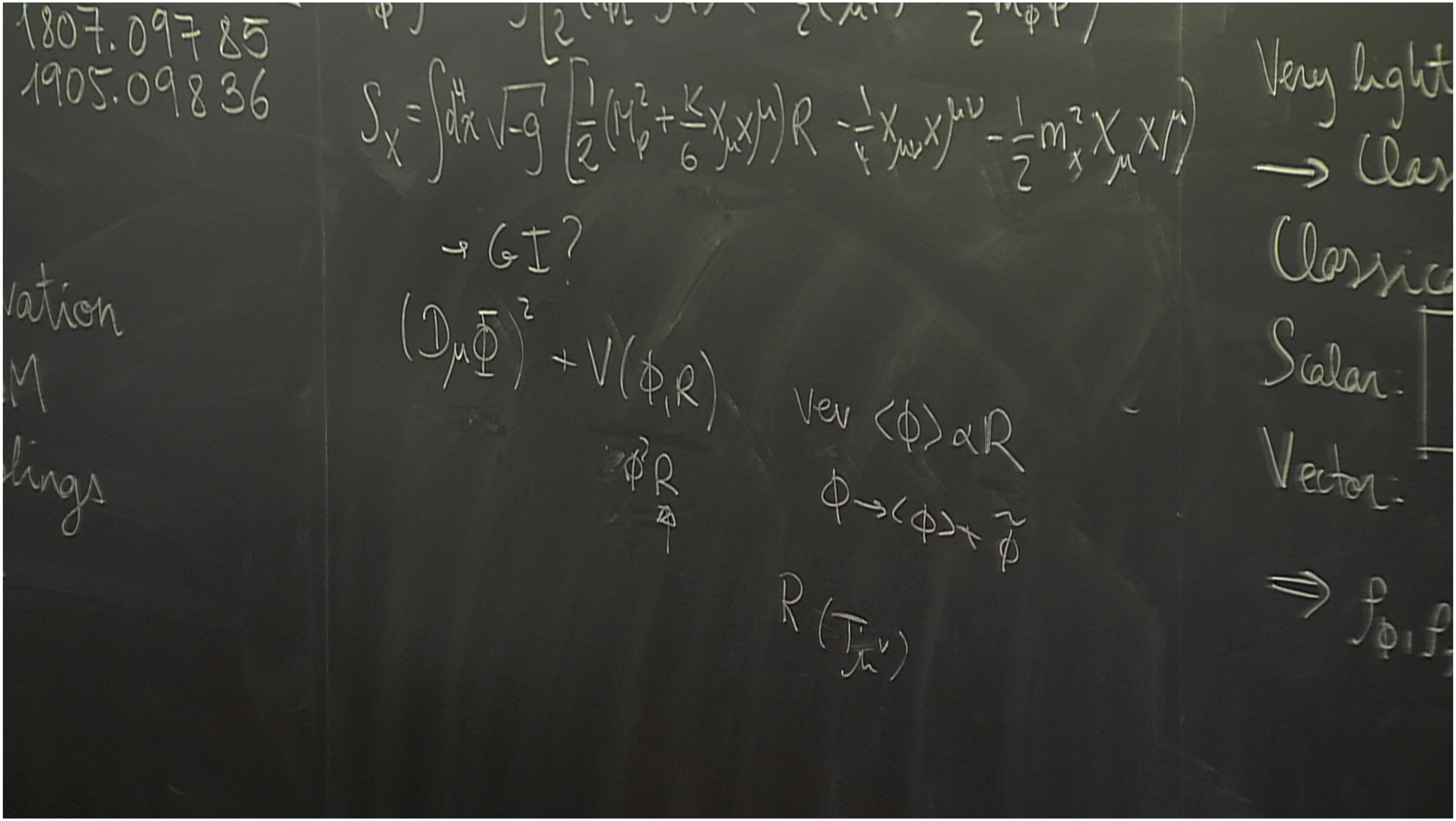
$$\frac{\Omega_\phi}{\Omega_{CDM}} \sim \left(\frac{\phi_0}{10^{11}\,\text{GeV}}\right)^2 \sqrt{\frac{m}{1\,\text{eV}}}$$

Fluctuations


Fluctuations
→ Adiabatic
δρ/ρ
photons
baryons
x
→ Isocurvature
a


$\frac{\delta\rho}{\rho}$
x
Planck
$\Rightarrow \frac{\delta\rho^2_{iso}}{\delta\rho^2_{adi}} \lesssim 3\%$ @
$k^{-1}_{CMB} \sim 20 Mpc$


nt mechanism
1807.09785
1905.09836
ation
lings
* NON-MINIMAL COUPLINGS
$S_\phi = \int d^4x \sqrt{-g} \left[\frac{1}{2}(M_{Pl}^2 - \xi \phi^2) R - \frac{1}{2}(D_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 \right)$
$S_X = \int d^4x \sqrt{-g} \left[\frac{1}{2}(M_P^2 + \frac{\kappa}{6} X_\mu X^\mu) R - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2} m_X^2 X_\mu X^\mu \right)$
→ GI?
$(D_\mu \Phi)^2 + V(\phi, R)$
$\phi^2 R$
Vev $\langle \phi \rangle \propto R$
* LIGH
Very light
⟹ Clas
Classic
Scalar:
Vector:
⟹


1807.09785
1905.09836
$S_\chi = \int d^4x \sqrt{-g} \left[\frac{1}{2}\left(M_p^2 + \frac{\kappa}{6}\chi_\mu \chi^\mu\right) R - \frac{1}{4}\chi_{\mu\nu}\chi^{\mu\nu} - \frac{1}{2} m_\chi^2 \chi_\mu \chi^\mu \right]$
→ GI?
$(D_\mu \Phi)^2 + V(\phi, R)$
$\phi^3 R$
Vev $\langle\phi\rangle \propto R$
$\phi \to \langle\phi\rangle + \tilde{\phi}$
$R(T_\mu{}^\nu)$
vation
lings
Very light
Classic
Scalar:
Vector:

ion

gs

$\rightarrow$ GI? $\rightarrow$ Ghost instability?

$$(D_\mu \Phi)^2 + V(\phi, R)$$

vev $\langle \phi \rangle \propto R$

$\phi^2 R$

$\phi \rightarrow \langle \phi \rangle + \tilde{\phi}$

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

$R\,(T_\mu^{\ \nu})$

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

$$\frac{\xi \phi}{M_p} << 1$$

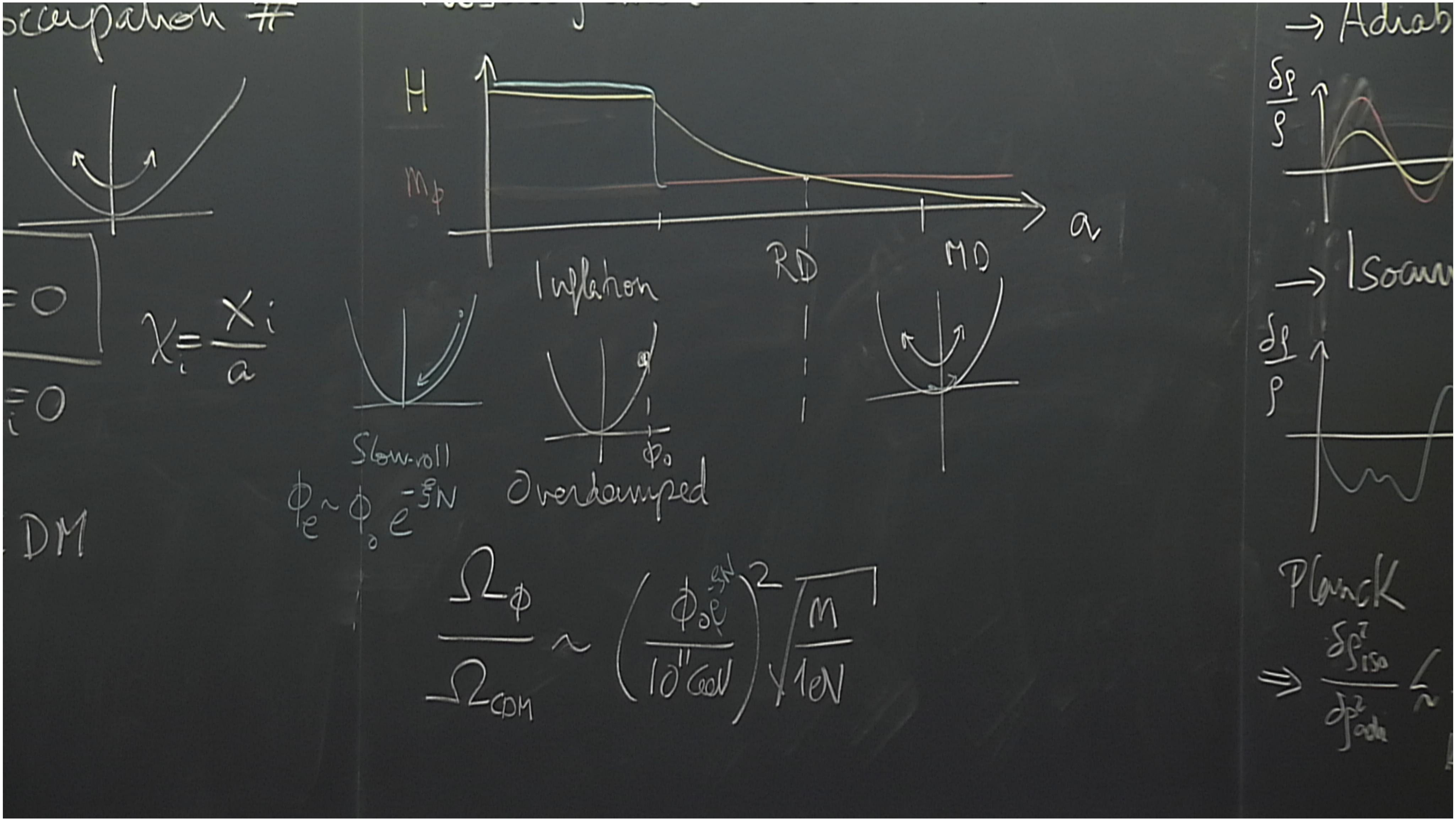
$$\Rightarrow m_{eff}^2 = m_\phi^2 + \xi R$$

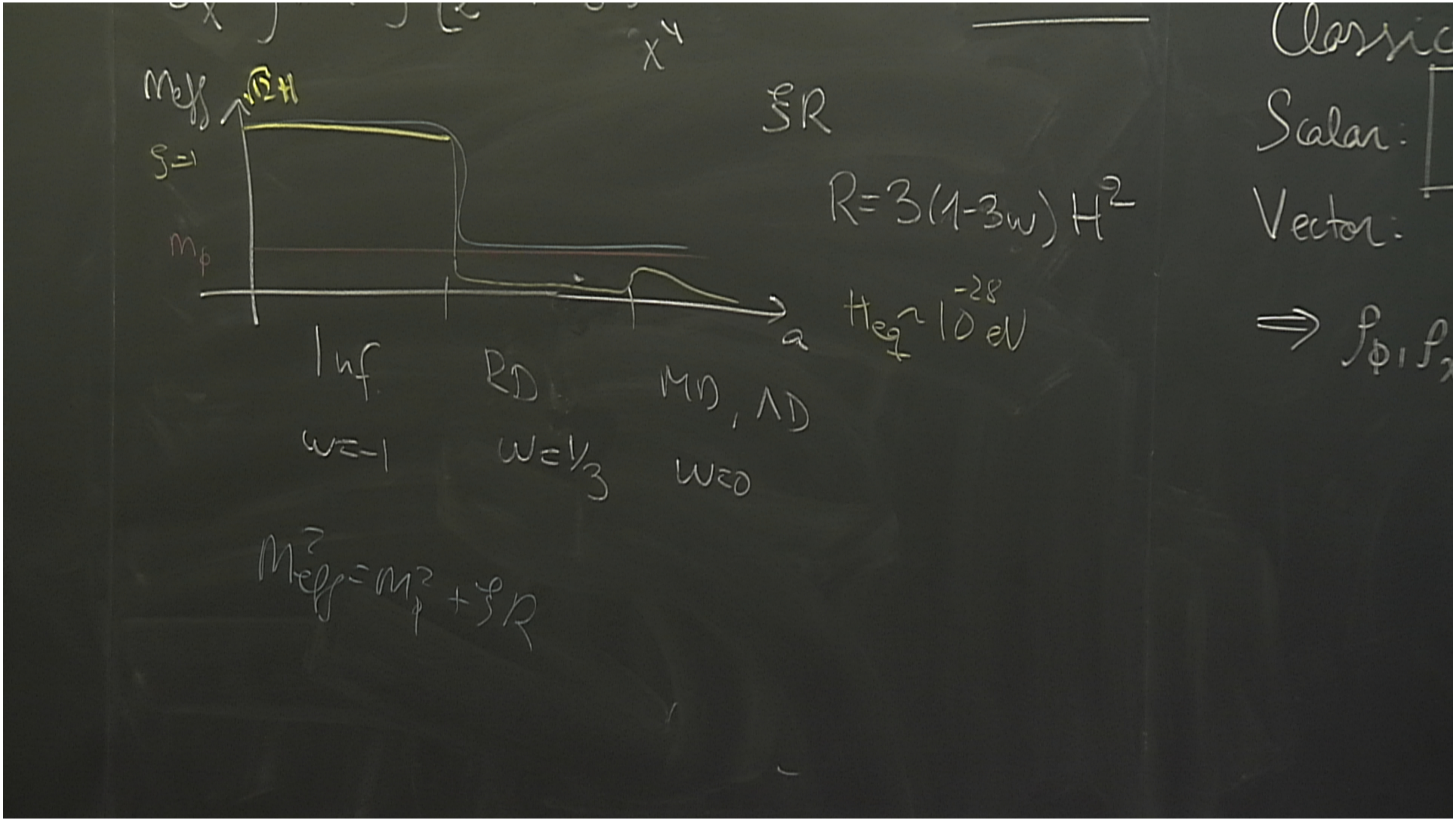
Classi

Scalar:

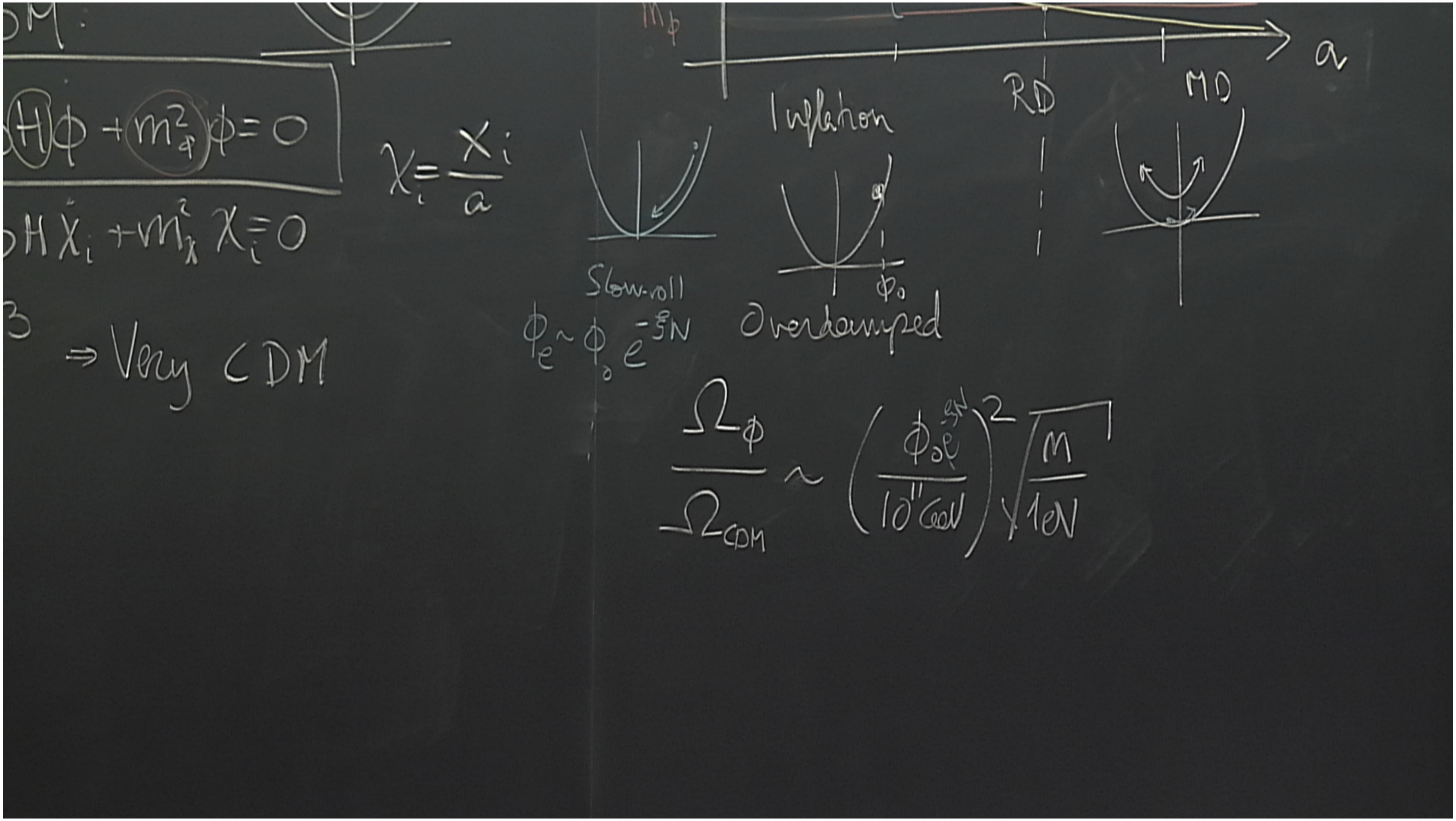
Vector:

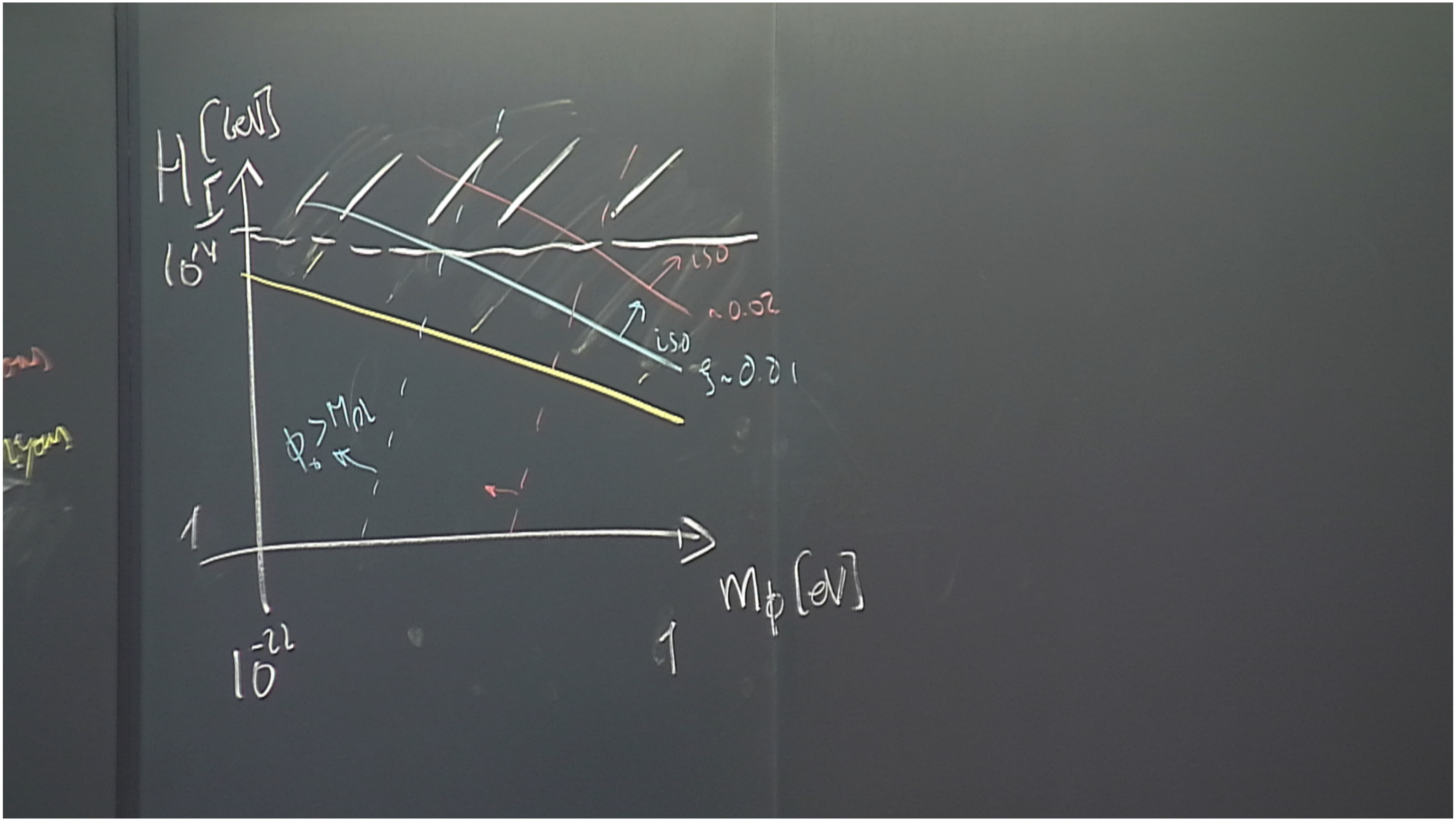
$\Rightarrow f_\phi, f$


H
m_ϕ
a
RD
MD
Inflation
Slow-roll
Overdamped
$\chi_i = \frac{X_i}{a}$
DM
Planck

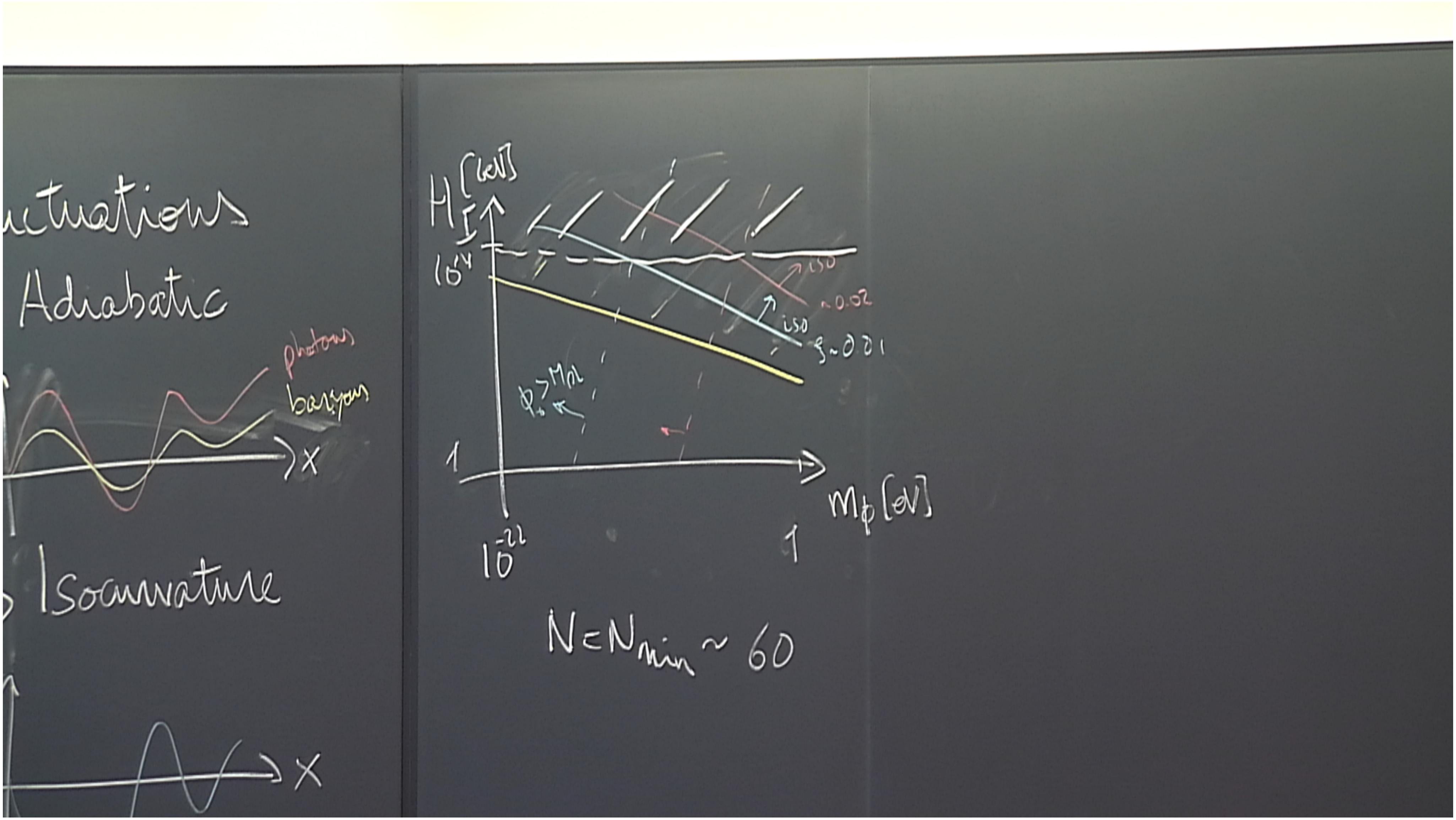


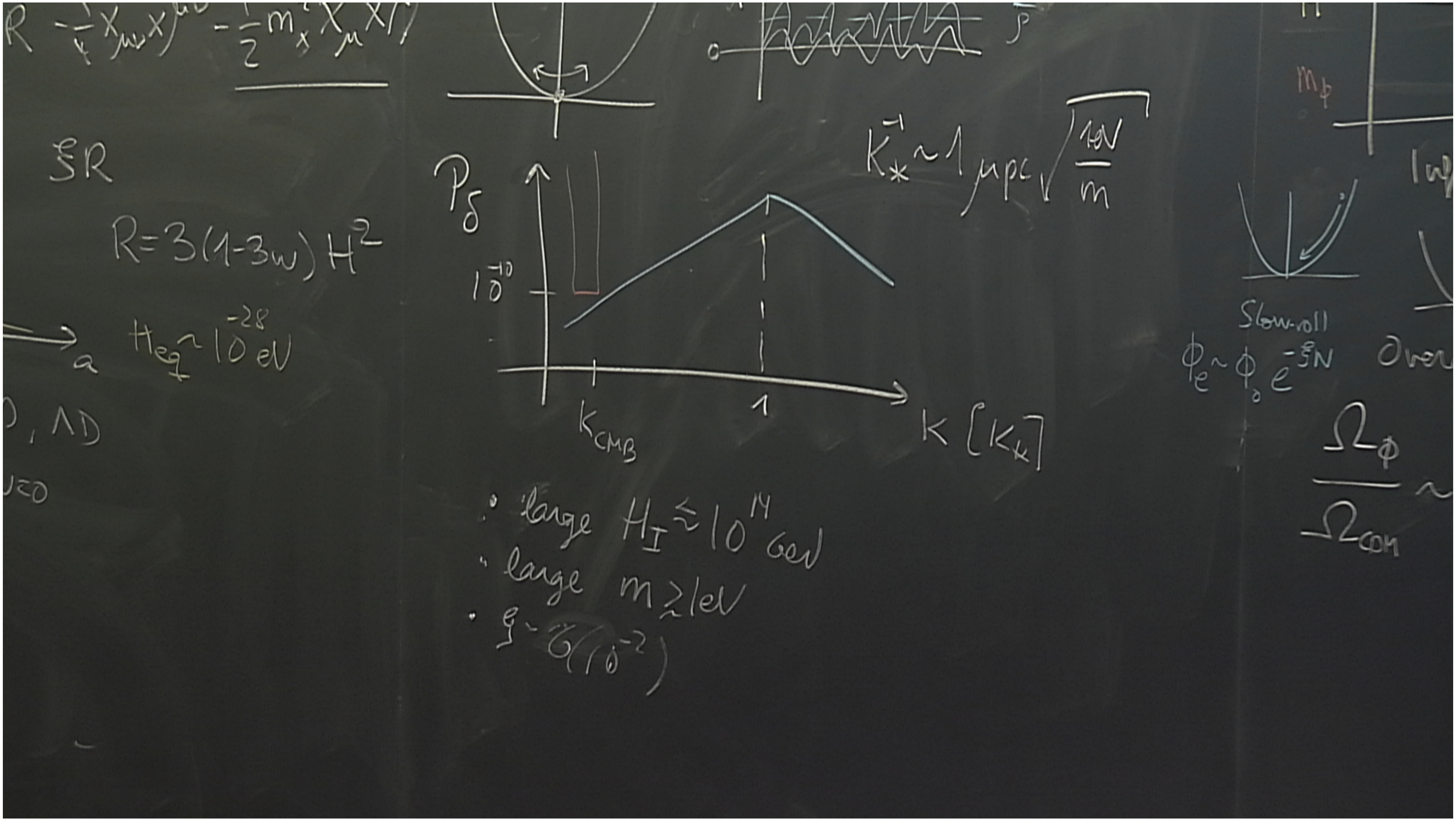
x^4
m_{eff}
$\xi=1$
m_ϕ
a
ξR
$R = 3(1-3w)H^2$
$H_{eq} \sim 10^{-28}$ eV
Inf
RD
MD, ΛD
w=-1
w=1/3
w=0
$m_{eff}^2 = m_\phi^2 + \xi R$
Classic
Scalar:
Vector:

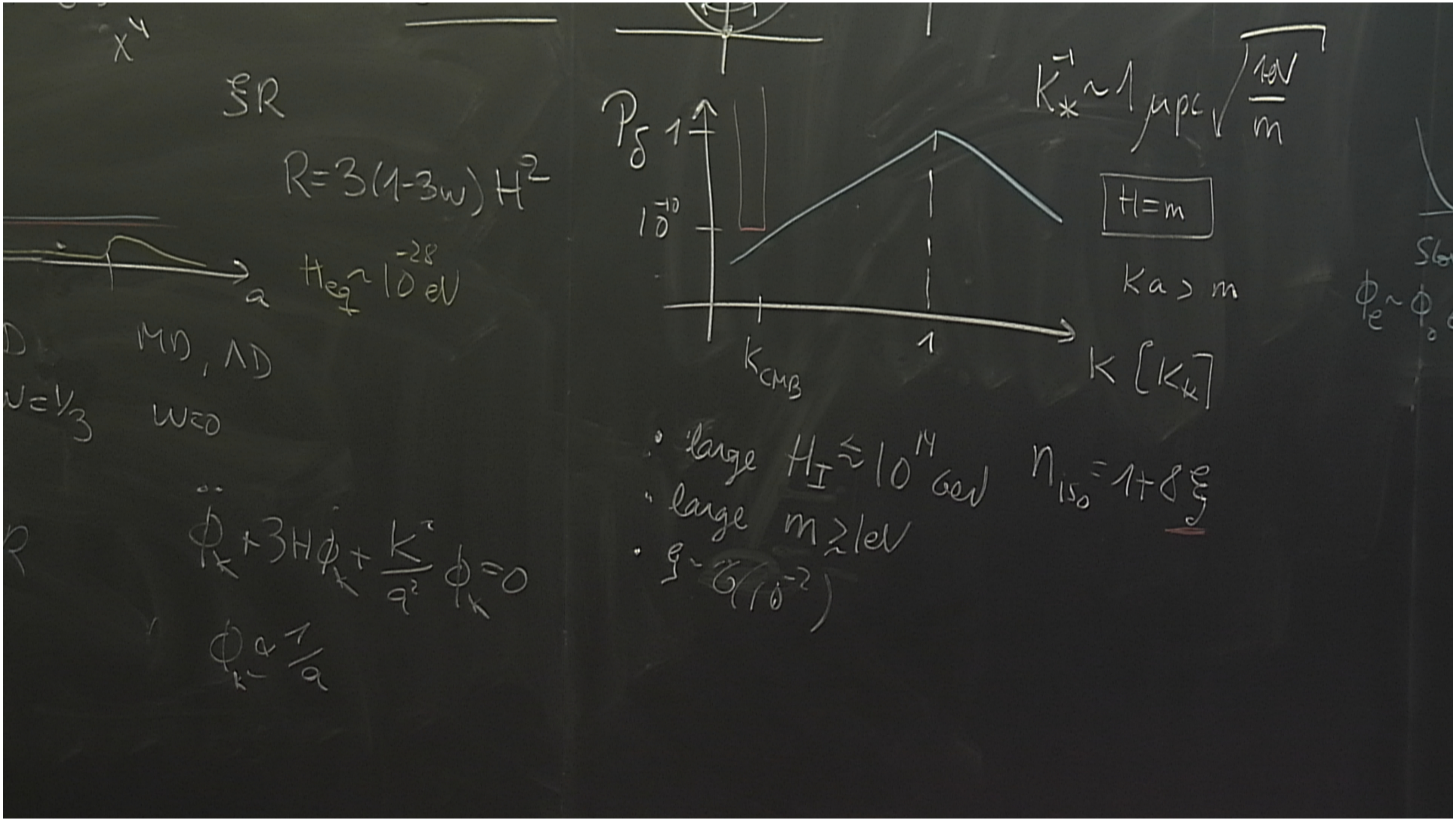

a
RD
MD
Inflation
Slow-roll
Overdamped
⇒ Very CDM



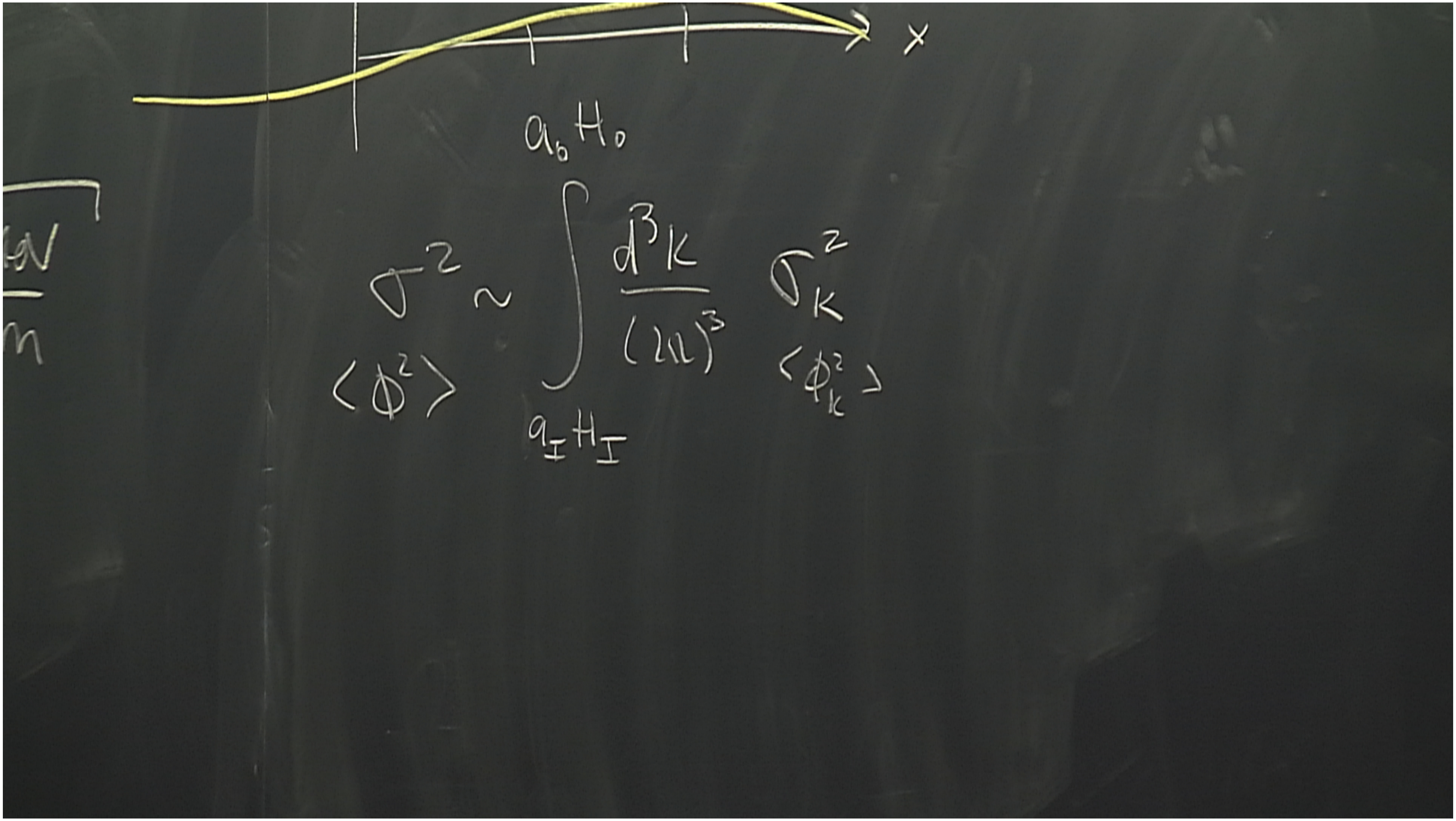
H_I [GeV]
10^{14}
iso
~0.02
iso
ξ ~ 0.01
$\phi_0 > M_{pl}$
1
m_ϕ [eV]
10^{-22}
1

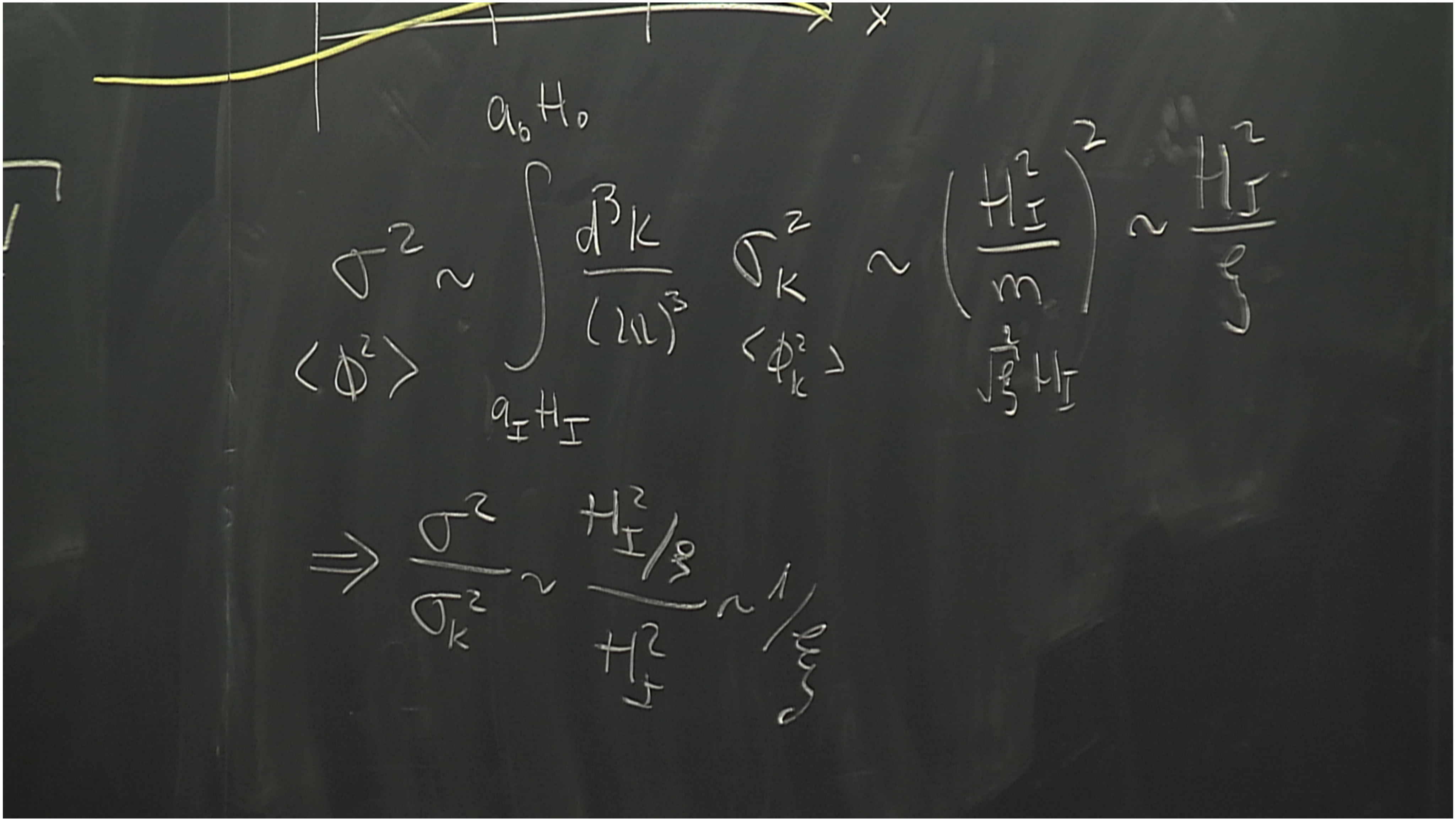

uctuations
Adiabatic
photons
baryons
x
Isocurvature
x
H_I [eV]
10^4
iso
~0.02
iso
ξ~0.01
1
10^-22
1
m_φ [eV]
N<N_min ~ 60

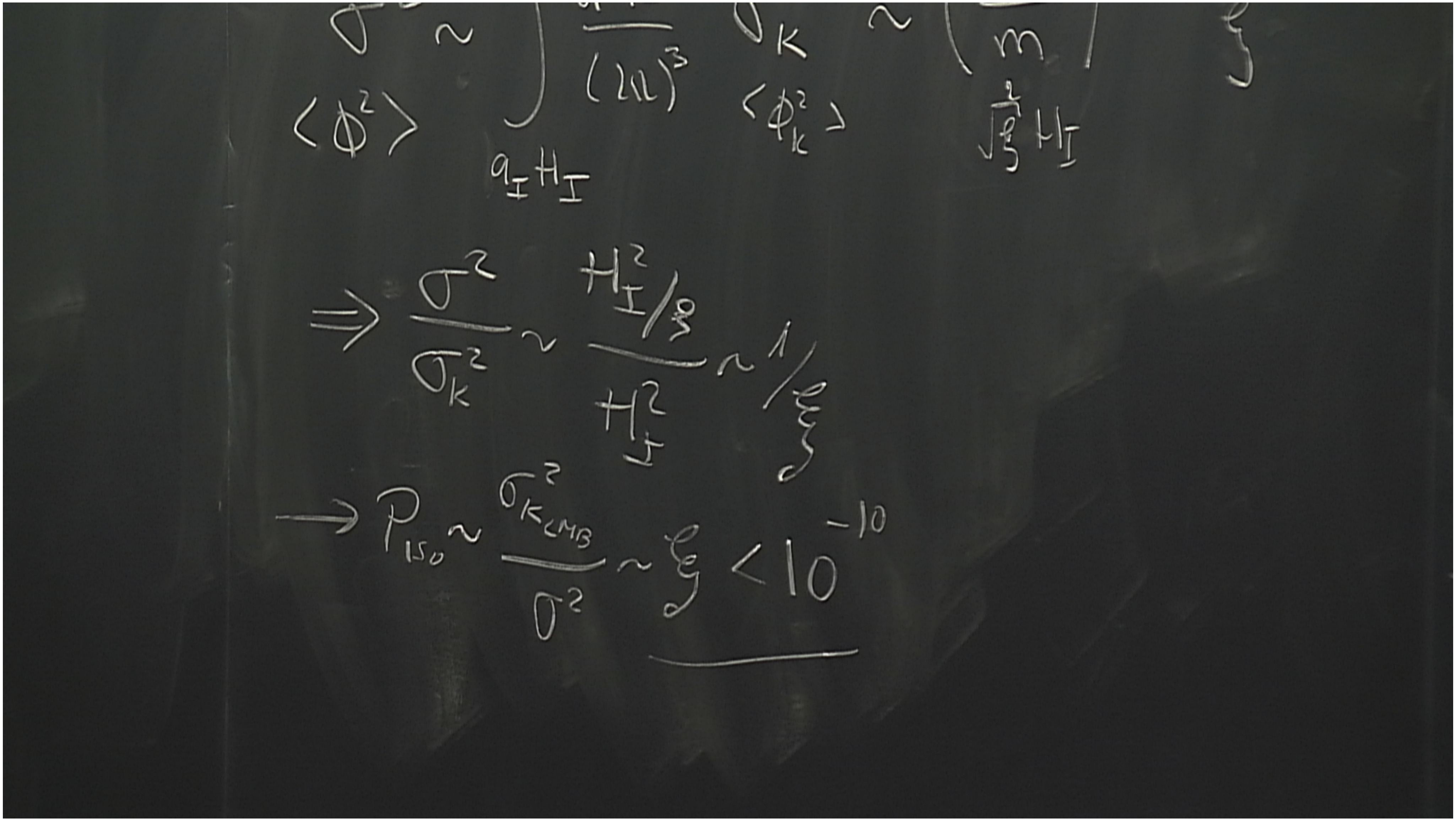

ξR
R=3(1-3w)H^2
H_eq ~ 10^-28 eV
P_δ
10^-10
k_CMB
k [k_*]
k_*^-1 ~ 1 μpc √(1eV/m)
• large H_I ≲ 10^14 GeV
• large m ≳ 1eV
• ξ ~ O(10^-2)
Slow-roll
φ_e ~ φ_0 e^-ξN
Ω_φ / Ω_CDM

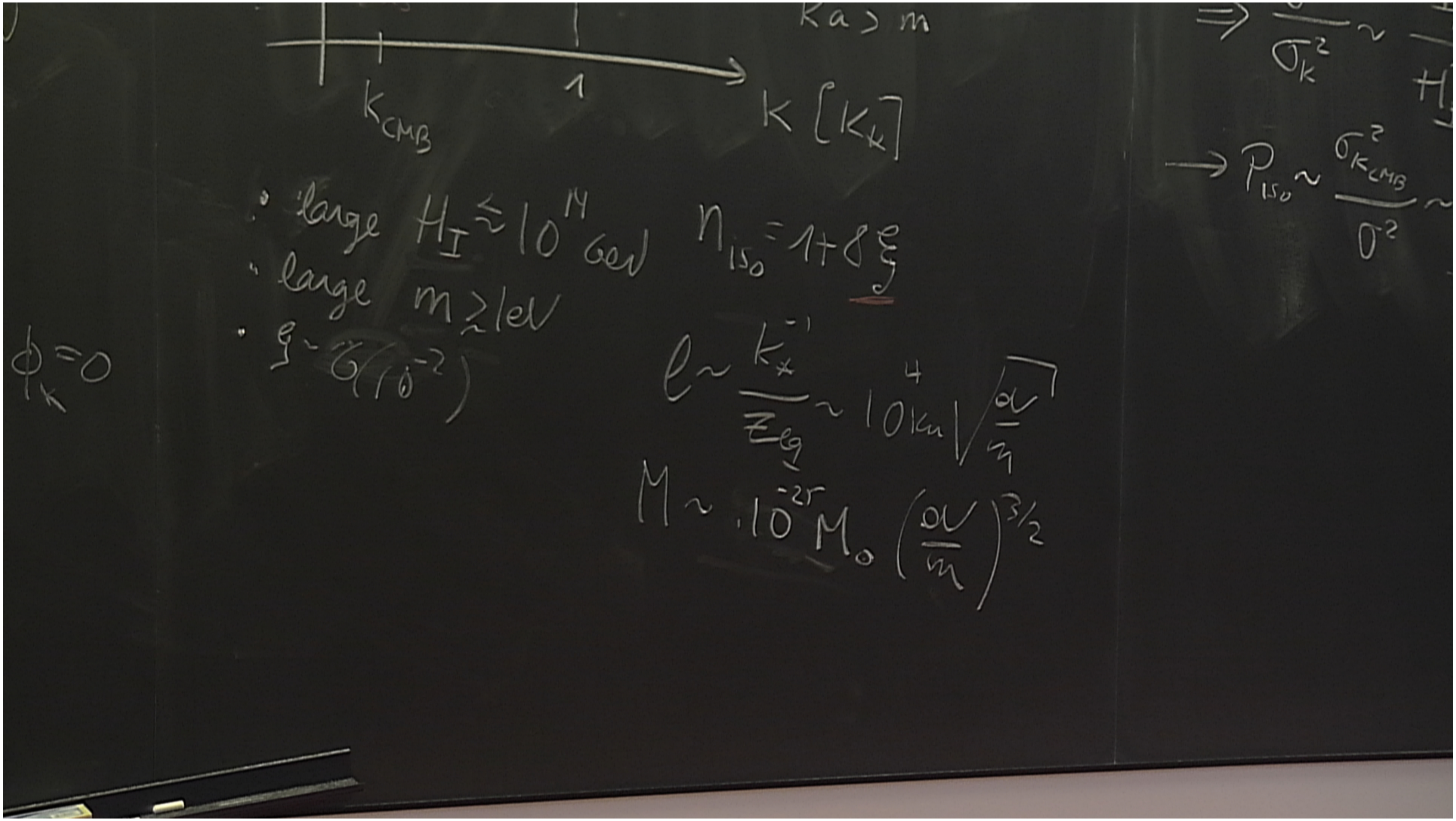


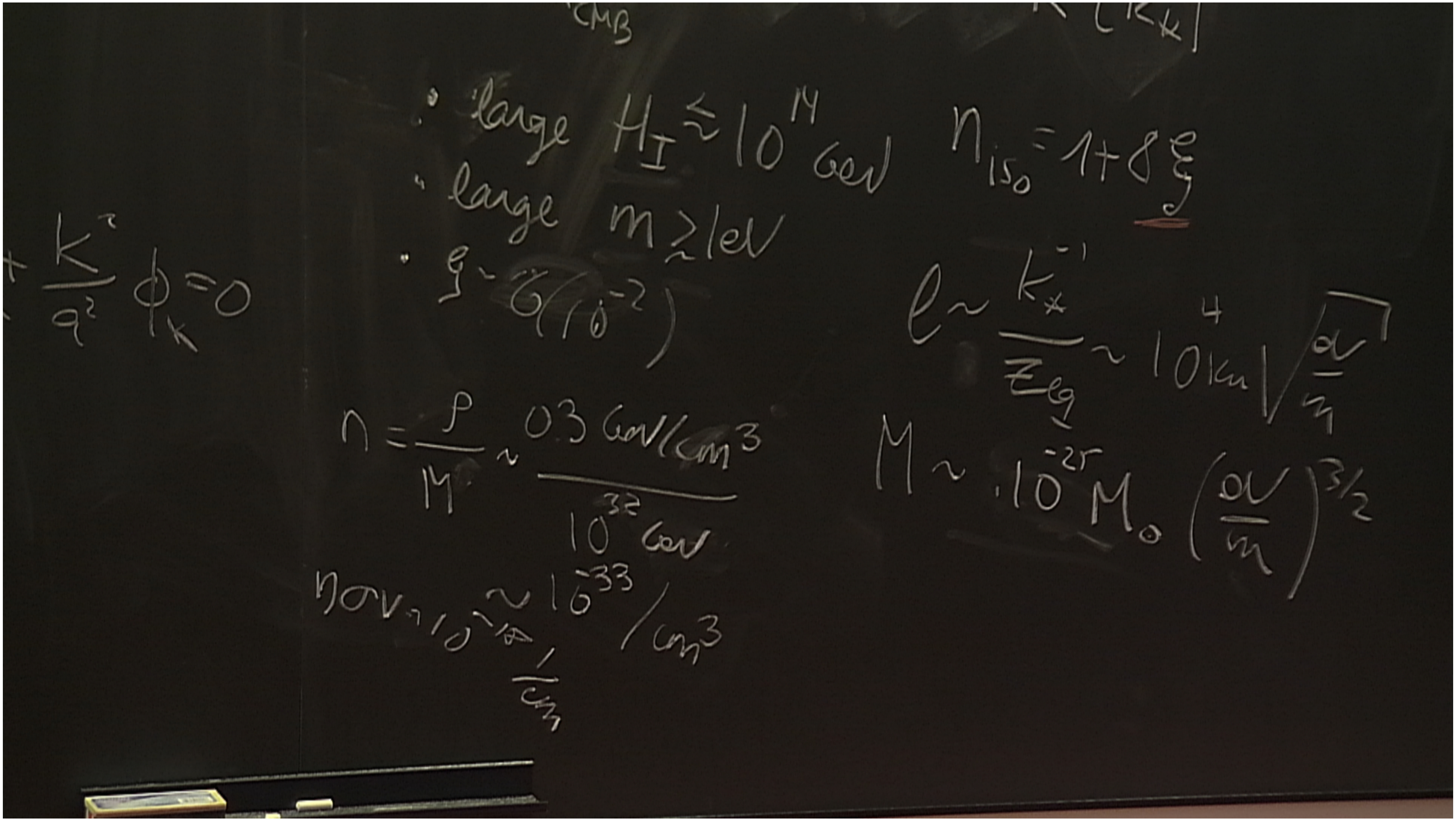
ξR
R=3(1-3w)H²
H_eq ~ 10^-28 eV
MD, ΛD
w=0
K*^-1 ~ 1 μpc √(1eV/m)
H=m
ka > m
k [k*]
k_CMB
large H_I ≲ 10^14 GeV
large m ≳ 1eV
n_iso = 1+8ξ

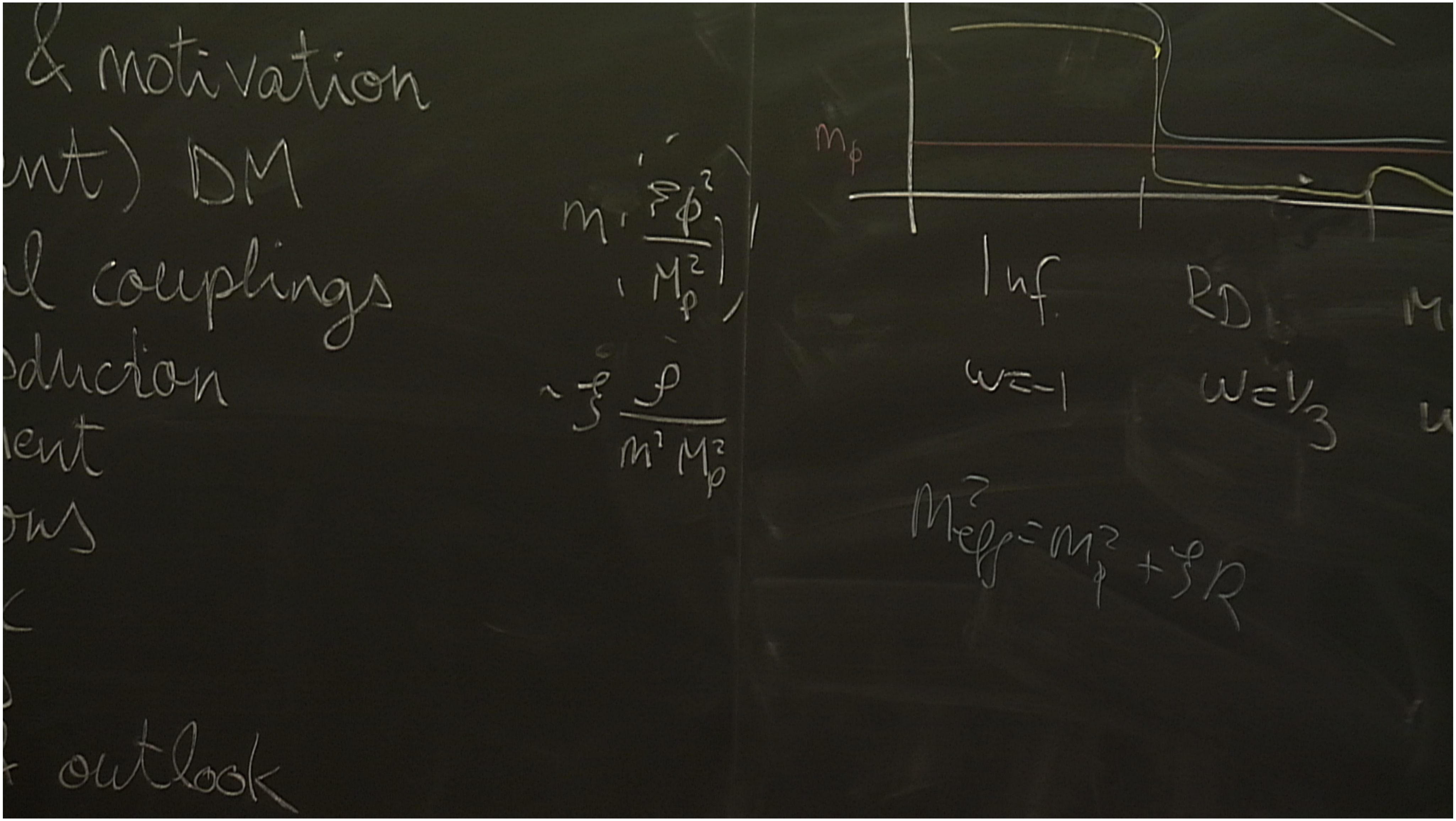

x
$a_0 H_0$
$\sigma^2 \sim \int \frac{d^3k}{(2\pi)^3} \sigma_k^2$
$\langle \phi^2 \rangle$
$\langle \phi_k^2 \rangle$
$a_I H_I$


x
$a_0 H_0$
$\sigma^2 \sim \int \frac{d^3k}{(2\pi)^3} \sigma_k^2 \sim \left(\frac{H_I^2}{m}\right)^2 \sim \frac{H_I^2}{\xi}$
$\langle \phi^2 \rangle$
$\langle \phi_k^2 \rangle$
$\sqrt{\xi} H_I$
$a_I H_I$
$\Rightarrow \frac{\sigma^2}{\sigma_k^2} \sim \frac{H_I^2/\xi}{H_I^2} \sim 1/\xi$


$\langle \phi^2 \rangle$
$(2\pi)^3$
$\langle \phi_k^2 \rangle$
$\sqrt{\xi} H_I$
$a_I H_I$
$\Rightarrow \frac{\sigma^2}{\sigma_k^2} \sim \frac{H_I^2/\xi}{H_I^2} \sim 1/\xi$
$\rightarrow P_{iso} \sim \frac{\sigma_{k_{CMB}}^2}{\sigma^2} \sim \xi < 10^{-10}$


k a > m
k_CMB
1
k [k_*]
• large H_I ≲ 10^14 GeV
• large m ≳ 1eV
n_iso = 1 + 8 ξ
φ_k = 0
P_iso ~


CMB
large $H_I \lesssim 10^{14}$ GeV
$n_{iso} = 1 + 8\xi$
large $m \gtrsim 1$ eV
$\xi \sim O(10^{-2})$
$\frac{k^2}{a^2}\phi_k = 0$
$\ell \sim \frac{k_*^{-1}}{z_{eq}} \sim 10^4 \mathrm{km} \sqrt{\frac{eV}{m}}$
$n = \frac{\rho}{M} \sim \frac{0.3\,GeV/cm^3}{10^{32}\,GeV}$
$M \sim 10^{-25} M_\odot \left(\frac{eV}{m}\right)^{3/2}$
$n\sigma v \sim 10^{-33}/cm^3$


& motivation
DM
couplings
outlook
m_ϕ
Inf.
RD
w=-1
w=1/3