Title: Thermal DM

Speakers: Rouven Essig

Collection: School on Table-Top Experiments for Fundamental Physics

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URL: https://pirsa.org/22090023

Thermal DM

- Why care?
- WIMP miracle
  ↪ ??
- thermal DM

  ~ MeV - 100 TeV

$\hbar = c = k_B = 1$

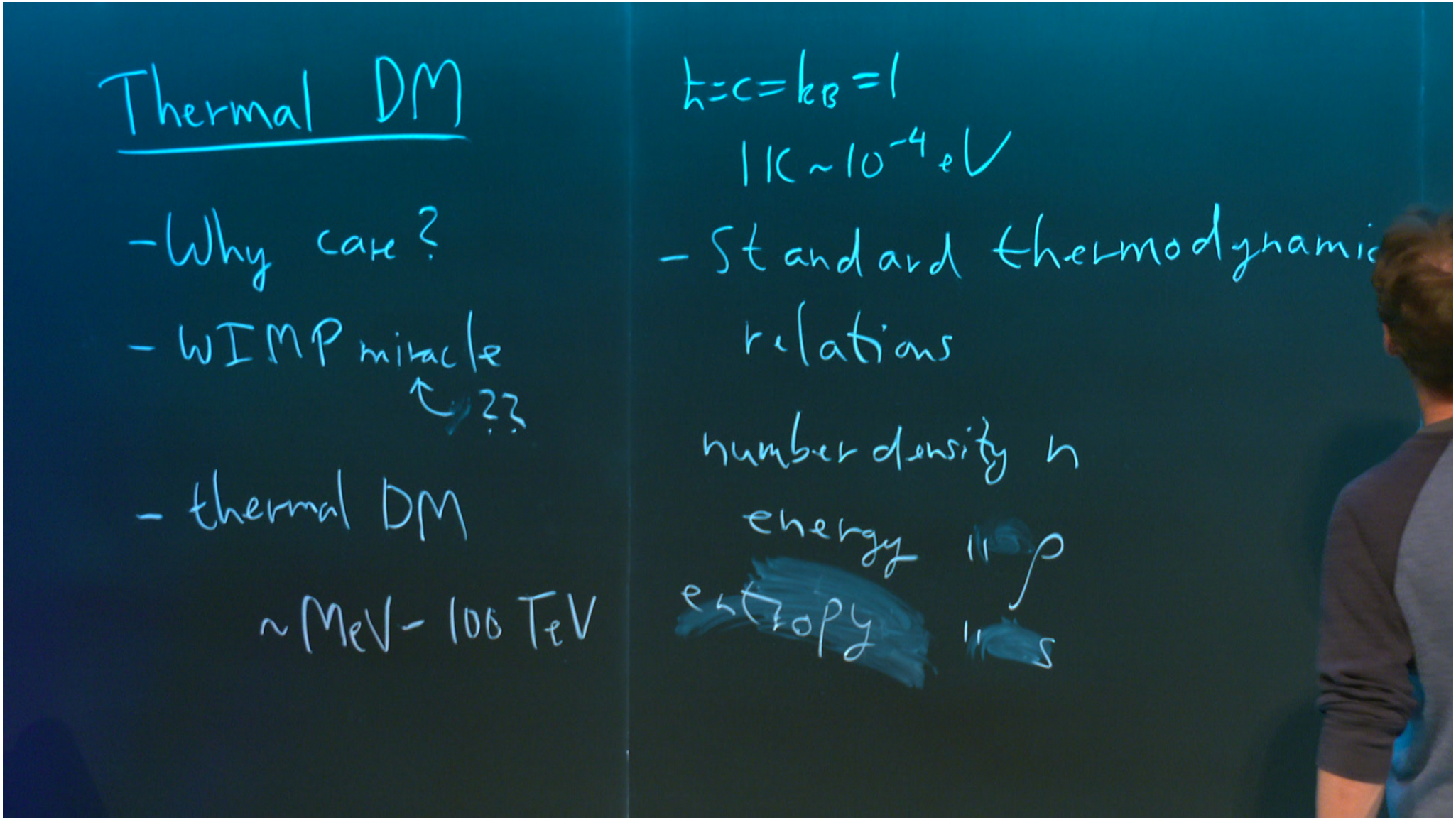
$1\,K \sim 10^{-4}\,eV$

- Standard thermodynamic relations

number density n

energy ρ

entropy s


Thermal DM
- Why care?
- WIMP miracle
↳ ??
- thermal DM
~ MeV - 100 TeV
ħ = c = k_B = 1
1/K ~ 10^-4 eV
- Standard thermodynamic
relations
number density n
energy ρ
entropy s

$n \sim T^3$ (rel.)

$n \sim (mT)^{3/2} e^{-m/T}$ (non-rel.)

amic

critical energy density

$$\rho_{crit} = \frac{3}{8\pi G} H_0^2$$

$$\sim 5 \times 10^{-6} \frac{GeV}{cm^3}$$

$$\sim 5 \frac{m_{proton}}{m^3}$$

non-rel.)

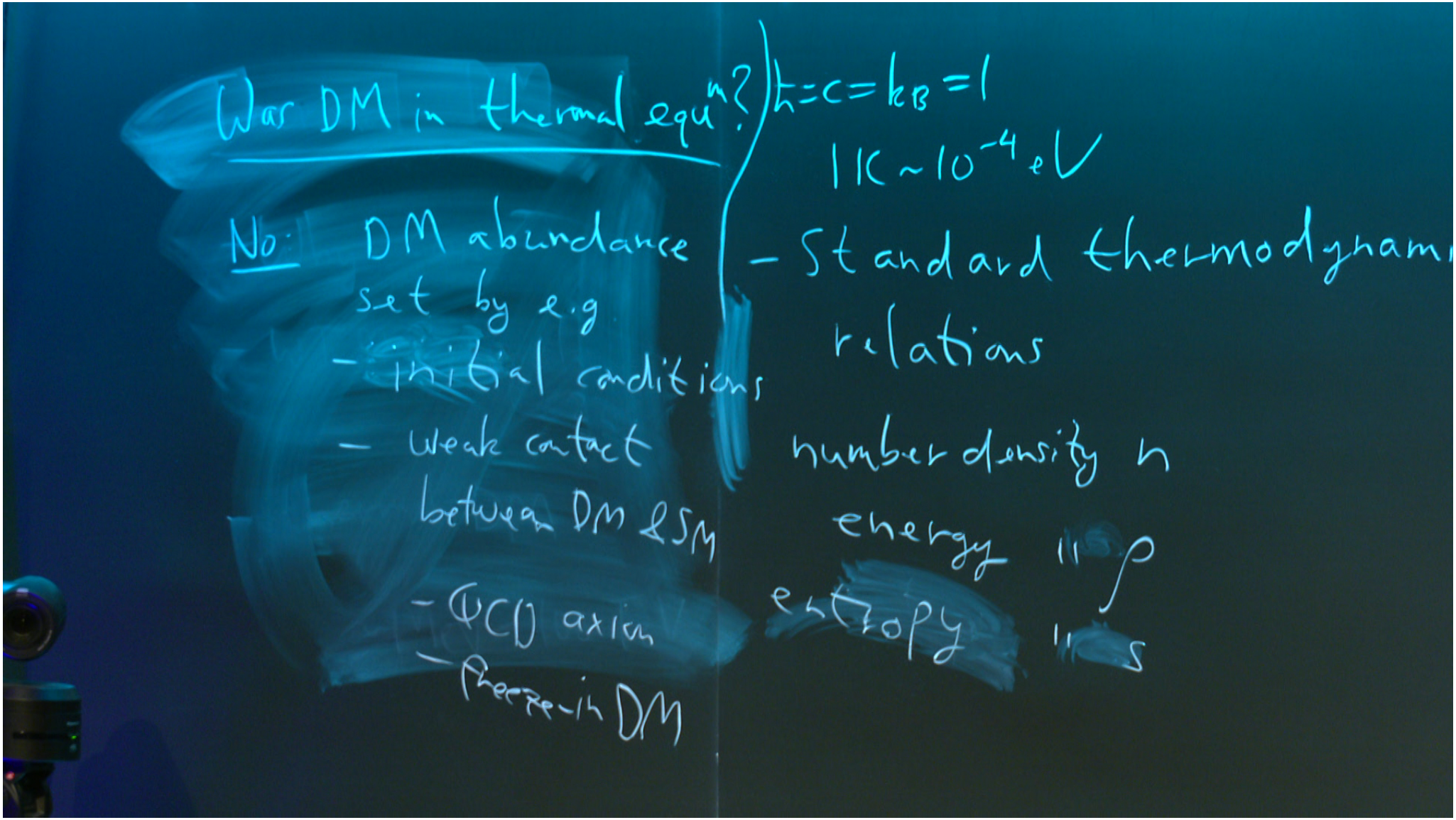
ensity

$\frac{\text{GeV}}{\text{cm}^3}$

$$\Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}} \sim 0.26$$

$$\Rightarrow n_{DM,0} = \frac{\rho_{DM,0}}{m_{DM}} \simeq 1.3 \times 10^{-3}\,\text{cm}^{-3} \times \left(\frac{1\,\text{MeV}}{m_{DM}}\right)$$

$$n_{DM,\text{local}} \simeq 400\,\text{cm}^{-3} \left(\frac{1\,\text{MeV}}{m_{DM}}\right)$$


Was DM in thermal equ^n?
No: DM abundance set by e.g.
- initial conditions
- weak contact between DM & SM
- PQ axion
- Phase-in DM
ħ = c = k_B = 1
1 K ~ 10^-4 eV
- Standard thermodynam. relations
number density n
energy ~ ρ
entropy ~ s

hermal equ^{n}?

undance

e.g

al conditions

contact

an DM & SM

) axion

Re-th DM

· Yes: initially $n_\chi \sim T_\gamma^3 \sim s$

$\Rightarrow n_{\chi,0} = 400\ \mathrm{cm}^{-3}$

$\gg n_{DM,0}$ unless

$m_\chi \leq 10\ \mathrm{eV}$

Goal: get rid of (most of) the DM.

$n \sim T^3$ (rel.)

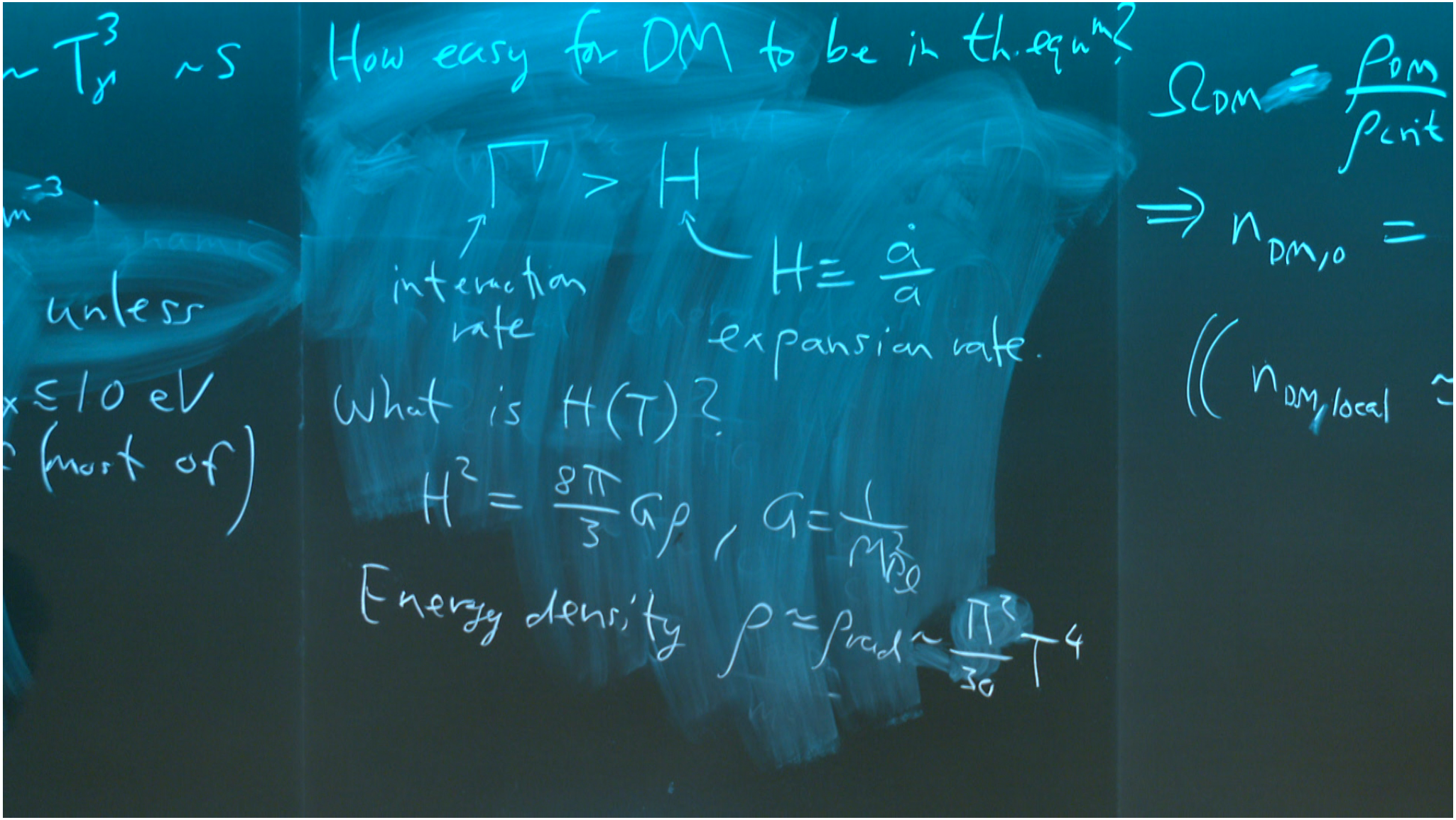
$n \sim (mT)^{3/2} e^{-m}$

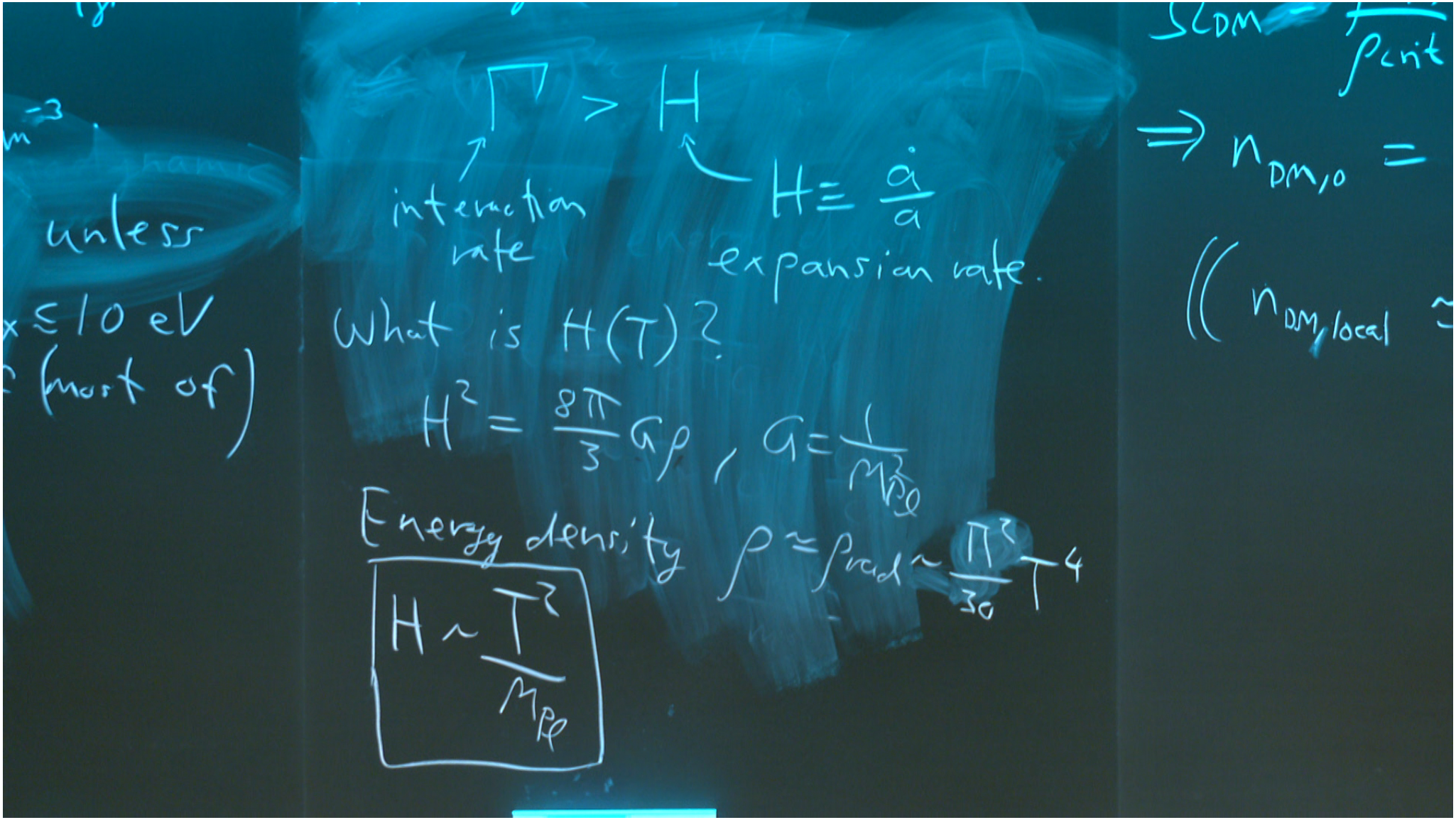
critical energ

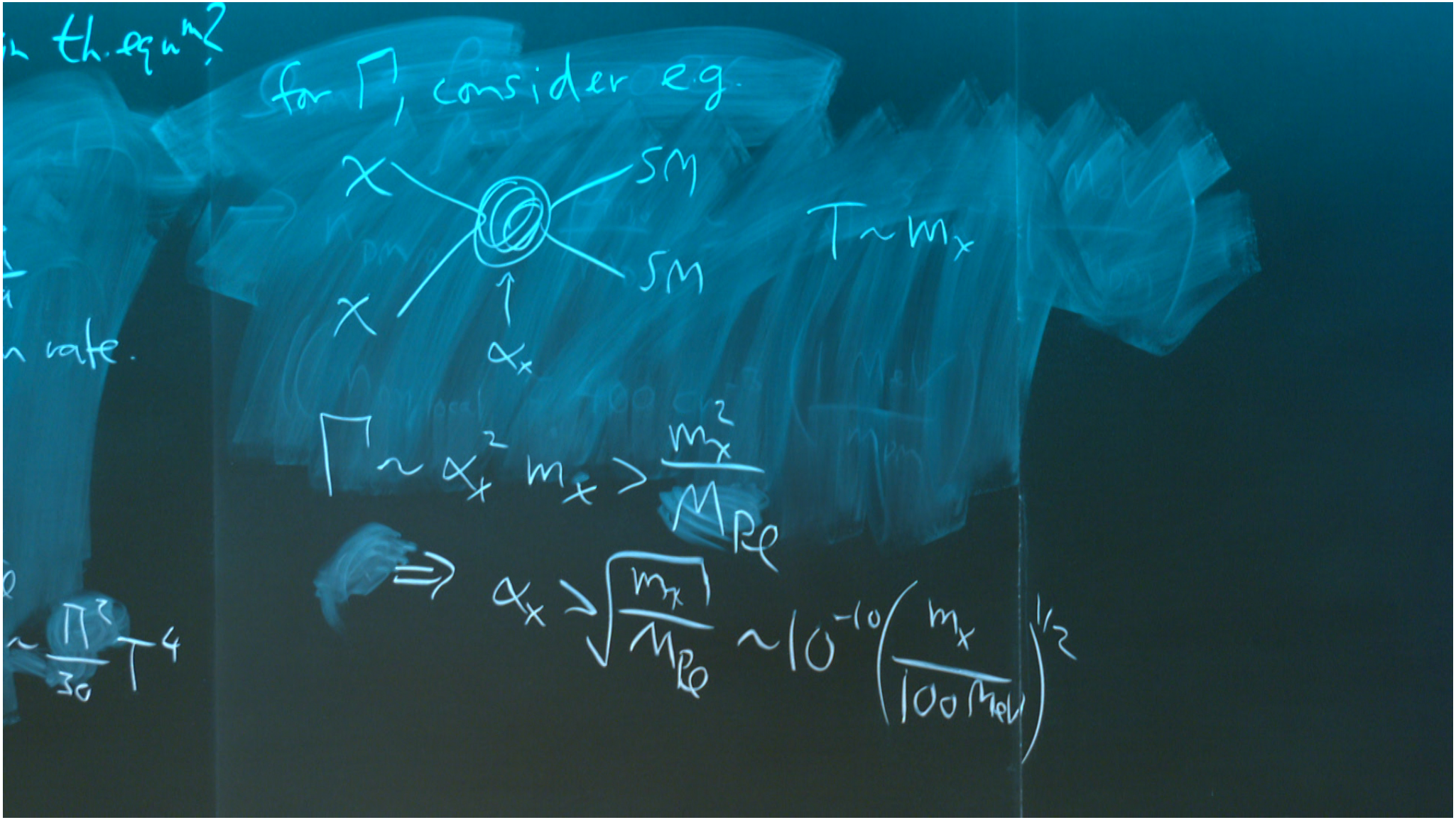
$\rho_{crit} = \frac{3}{8\pi}$

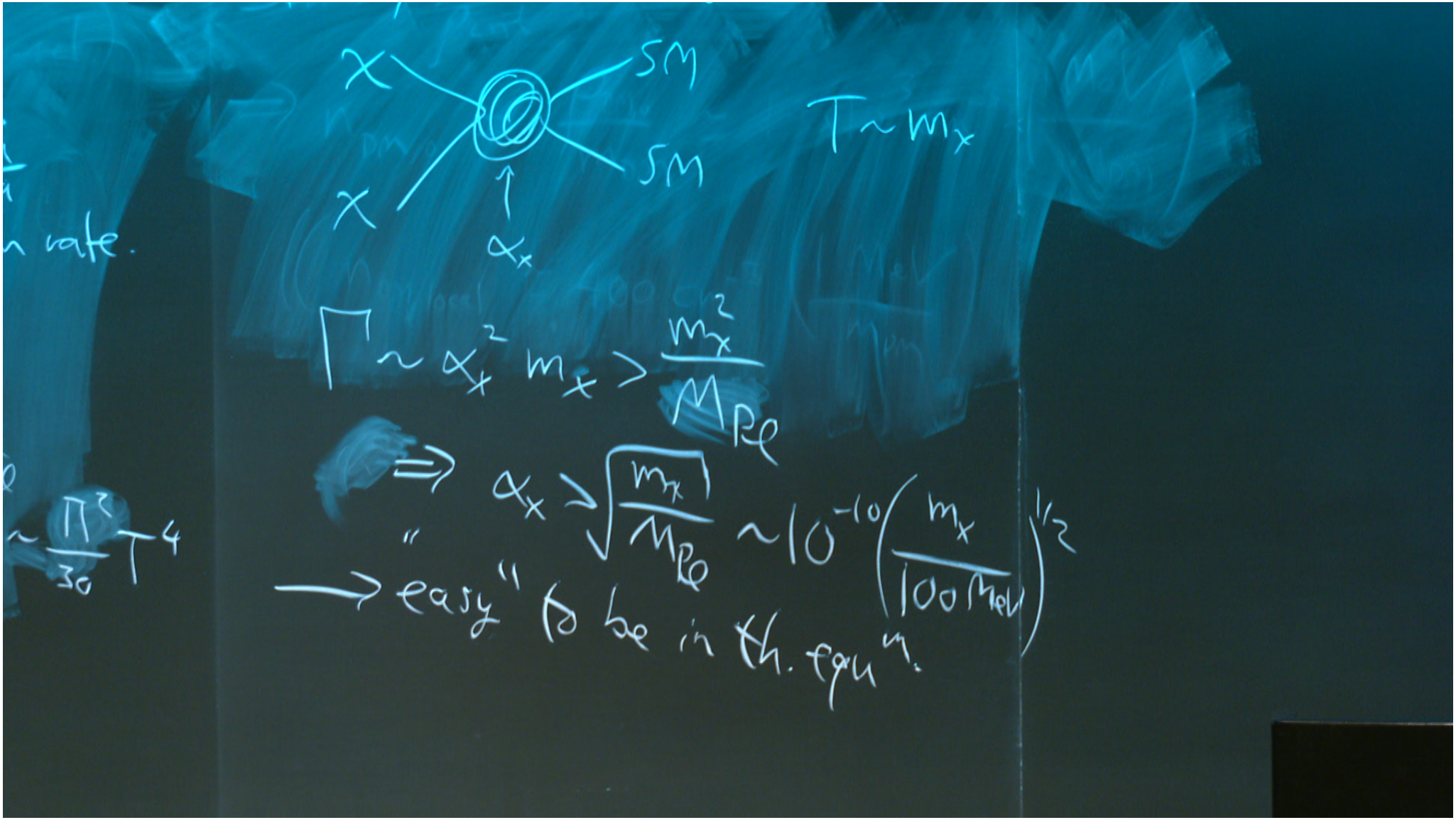
$\sim 5 \times 1$

~ 5 M


How easy for DM to be in th. equ^m?
Γ > H
interaction rate
H ≡ ȧ/a
expansion rate.
What is H(T)?
H² = 8π/3 Gρ , G = 1/m_Pl²
Energy density ρ ≈ ρ_rad ≈ π²/30 T⁴
Ω_DM = ρ_DM / ρ_crit
⇒ n_DM,0 =
((n_DM,local ≈
~ T_γ³ ~ s
unless
≲ 10 eV
(most of)


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th. equm?
for Γ, consider e.g.
χ
SM
SM
χ
α_x
$T \sim m_x$
n rate.
$\Gamma \sim \alpha_x^2 m_x > \frac{m_x^2}{M_{Pl}}$
$\Rightarrow \alpha_x > \sqrt{\frac{m_x}{M_{Pl}}} \sim 10^{-10} \left(\frac{m_x}{100\,\mathrm{MeV}}\right)^{1/2}$
$\sim \frac{\pi^2}{30} T^4$


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$\sim \frac{\pi^2}{30} T^4$
"easy" to be in Th. eqm.

Distinguish between cold vs warm vs hot DM.

"hot relic": decouples when relativistic

→ hot DM $m_X \lesssim 1\,eV$

→ warm DM $m_X \gtrsim 1\,eV$

Current limit: $m_X \gtrsim 1\,keV$

"cold relic" – cold DM

– decouples when non-rel.

Decoupling when non. rel.

$X\bar{X} \longleftrightarrow f\bar{f}$

↳ SM particles

at high T, $n_X \sim T^3$ – but for $T < m_X$,

X non. rel.

$\Rightarrow n_X \sim (m_X T)^{3/2} e^{-m_X/T}$

If X remains in th. equ^m for long $\Rightarrow$ negligible abundance

BUT: process "decouples" or "freezes out" $\longrightarrow$ fixes n_X.

occurs when $\Gamma < H$.

Freeze-out when $\Gamma = H$.

for Γ, consider e.g.



$$\Gamma \sim \alpha_X^2 m_X > \frac{m_X^2}{M_{Pl}}$$

$$\Rightarrow \alpha_X > \sqrt{\frac{m_X}{M_{Pl}}} \sim 1$$

$\longrightarrow$ "easy" to be in th.

$\Gamma \sim n \langle \sigma v \rangle \equiv n \sigma_0 \quad , v \sim 0.3c$

$\sigma v \sim v^0$ "s-wave" ← do this

$\sigma v \sim v^2$ "p-wave"

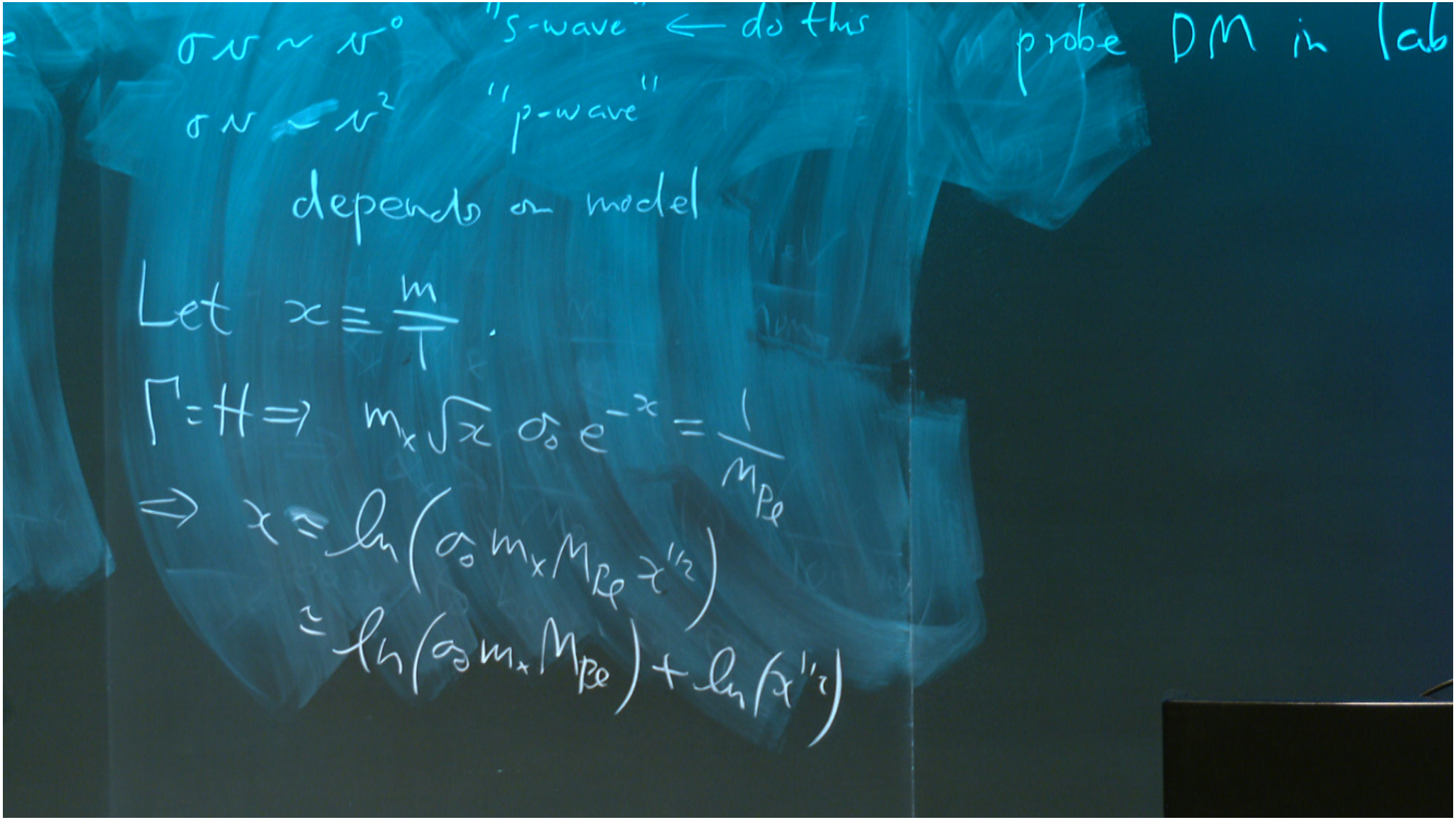
depends on model

→ Couplings not small - probe DM in lab

Let $x \equiv \frac{m}{T}$.

$\Gamma = H \Rightarrow m_x \sqrt{x}\, \sigma_0\, e^{-x} = \frac{1}{M_{Pl}}$

$\Rightarrow x = \ln\left(\sigma_0 m_x M_{Pl} x^{1/2}\right)$


$\sigma v \sim v^0$ "s-wave" ← do this
$\sigma v \sim v^2$ "p-wave"
depends on model
probe DM in lab
Let $x \equiv \frac{m}{T}$.
$\Gamma = H \Rightarrow m_\chi \sqrt{x}\, \sigma_0\, e^{-x} = \frac{1}{M_{Pl}}$
$\Rightarrow x = \ln\left(\sigma_0 m_\chi M_{Pl} x^{1/2}\right)$
$\simeq \ln\left(\sigma_0 m_\chi M_{Pl}\right) + \ln\left(x^{1/2}\right)$

$\sigma v \equiv n \sigma_0$, $v \sim 0.3c$

$\sim v^0$ "s-wave" ← do this

$\sim v^2$ "p-wave"

depends on model

$x \equiv \frac{m}{T}$.

$\Rightarrow m_x \sqrt{x}\, \sigma_0 e^{-x} = \frac{1}{M_{Pl}}$

$\approx \ln\left(\sigma_0 m_x M_{Pl} x^{1/2}\right)$

$\approx \ln(\sigma_0 m_x M_{Pl}) + \ln x^{1/2}$

If $\sigma_0 \sim \frac{1}{m_x^2}$ (dim. anal.), then

$x \approx \ln\left(\frac{M_{Pl}}{m_x}\right) + \ln x^{1/2}$

negligible

$m_x \sim 100$ GeV

$x \approx \mathcal{O}(10) \Rightarrow T_f \sim \frac{m_x}{\mathcal{O}(10)}$

Now use $\Gamma \sim H$

i.e. $n_{X,f}\,\sigma_0 = \frac{T_f^2}{M_{Pl}}$

$\Rightarrow n_{X,f} \simeq \frac{T_f^2}{\sigma_0 M_{Pl}}$

"cold relic" – cold DM

– decouples when non-rel.

Decoupling when non. rel.

$X\bar{X} \leftrightarrow f\bar{f}$

↳ SM particle

at high T, $n_X \sim T^3$ – but for T

X non. rel.

$\Rightarrow n_X \sim (m_X T)^{3/2} e^{-m_X/T}$

only changes due to expansion.

Now use $\Gamma \sim H$

i.e. $n_{x,f}\,\sigma_0 = \dfrac{T_f^2}{M_{Pl}}$

$\Rightarrow n_{x,f} \simeq \dfrac{T_f^2}{\sigma_0 M_{Pl}}$

$\Rightarrow n_{x,0} = \left(\dfrac{a_f}{a_0}\right)^3 n_{x,f}$

For iso-entropic Universe,

$S a^3 = \text{constant}$

$\Rightarrow n_{x,0} = \left(\dfrac{S_0}{S_f}\right) n_{x,f}$

After f.o. n_x in a comoving vol. is fixed, i.e. n_x

$S_0 \simeq T_0^3 \sim 10^3\,\text{cm}^{-3}$, $S_f \sim T_f^3$

If

Now use

i.e. $n_{X,f}\,\sigma_0 = \dfrac{T_f^2}{M_{Pl}}$

$\Rightarrow n_{X,f} \simeq \dfrac{T_f^2}{\sigma_0 M_{Pl}}$

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$S_0 \sim T_0^3 \sim 10^3\,\text{cm}^{-3}$, $S_f \sim T_f^3$

$\Rightarrow n_{X,0} \sim \dfrac{S_0}{T_f\,\sigma_0 M_{Pl}}$

long

BUT

f

occu

Fre

and $\Omega_x \sim \frac{m_x n_{x,0}}{\rho_c} \sim \frac{s_0 Y_f}{\rho_c \sigma_0 M_{Pl}}$

$\Omega_x \propto \frac{1}{\sigma_0}$

$\left(Y \equiv \frac{n_x}{s}\right)$



↓ Increasing σ_0.

$\Gamma \sim n \sigma v \equiv n \sigma_0$,

$\sigma v \sim v^0$ "s-wa

$\sigma v \sim v^2$ "p-wa

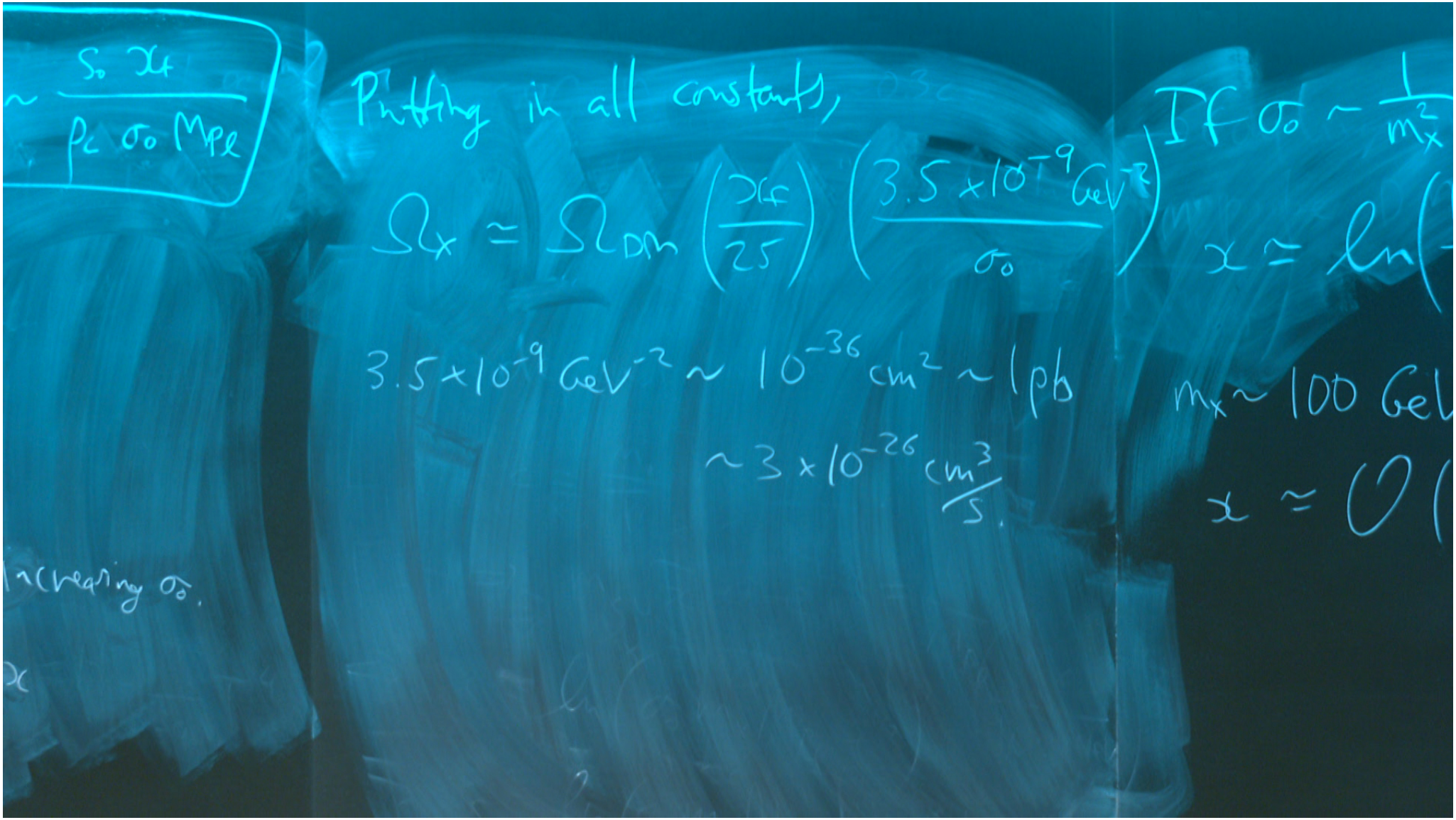
depends on

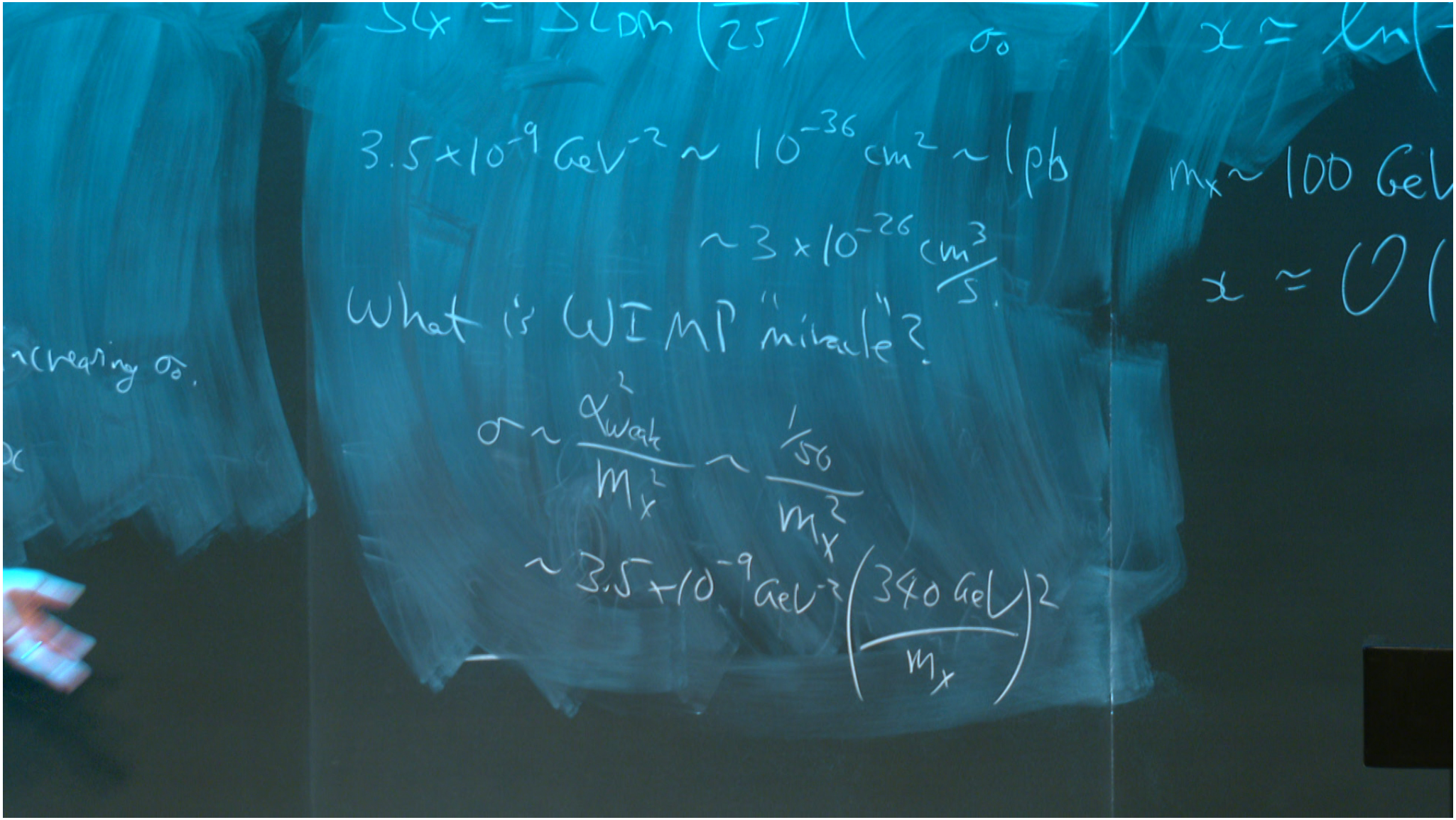
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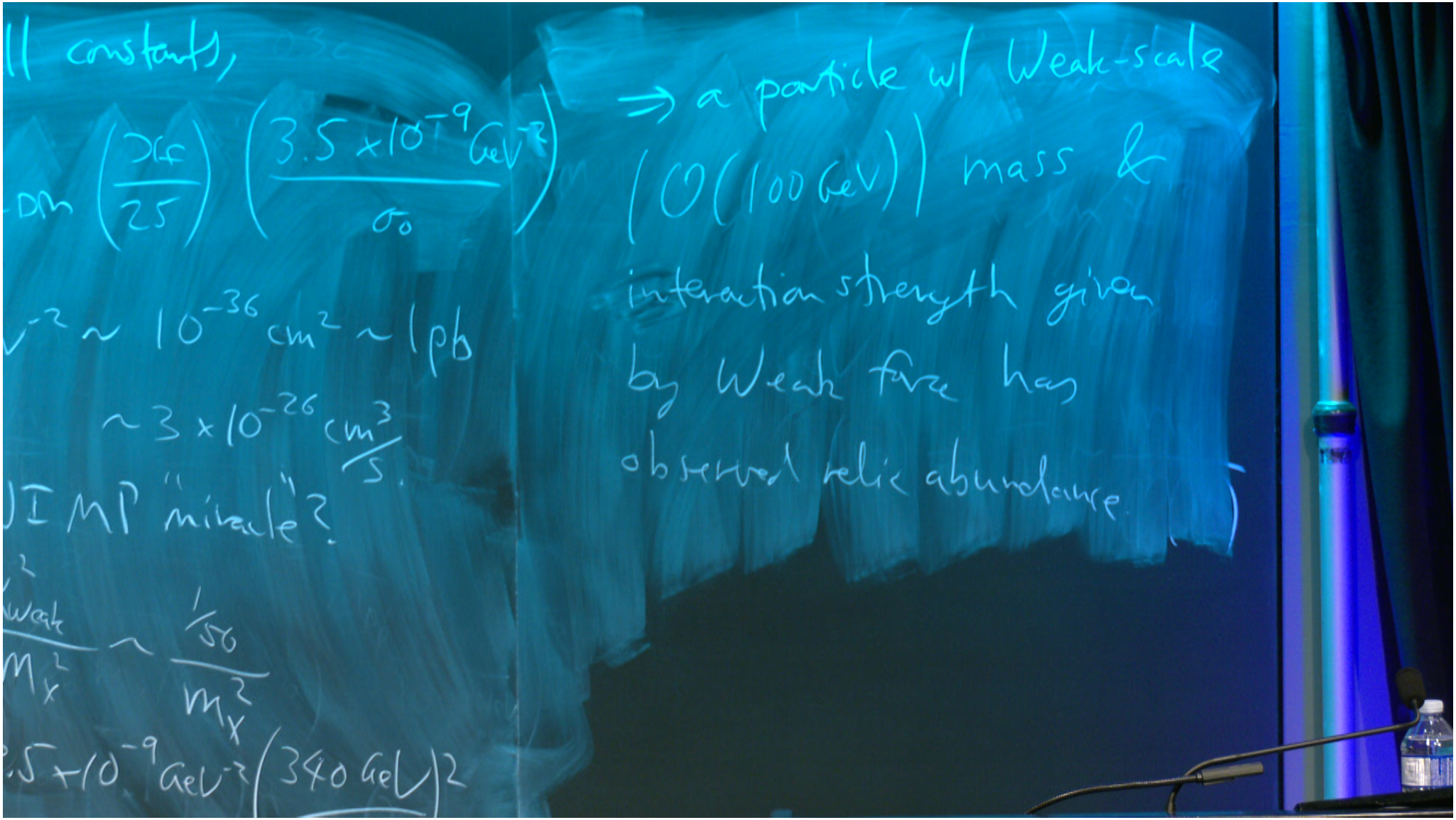
$\Gamma = H \Rightarrow m_x \sqrt{x}\, \sigma_0 e$

$\Rightarrow x \simeq \ln(\sigma_0 m_x M_$

$\Rightarrow x_f \simeq$


$\sim \frac{s_0 \chi_f}{p_c \sigma_0 M_{Pl}}$
Putting in all constants,
$\Omega_\chi \simeq \Omega_{DM} \left(\frac{\chi_f}{25}\right) \left(\frac{3.5 \times 10^{-9} GeV^{-2}}{\sigma_0}\right)$
If $\sigma_0 \sim \frac{1}{m_\chi^2}$
$3.5 \times 10^{-9} GeV^{-2} \sim 10^{-36} cm^2 \sim 1 pb$
$\sim 3 \times 10^{-26} \frac{cm^3}{s}$.
$x \simeq \ln($
$m_\chi \sim 100$ Ge
$x \simeq 0($
increasing σ_0.


$3.5 \times 10^{-9}\ \mathrm{GeV}^{-2} \sim 10^{-36}\ \mathrm{cm}^2 \sim 1\ \mathrm{pb}$
$\sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$
$m_\chi \sim 100\ \mathrm{GeV}$
What is WIMP "miracle"?
$\sigma \sim \frac{\alpha_{weak}^2}{m_\chi^2} \sim \frac{1/30}{m_\chi^2}$
$\sim 3.5 \times 10^{-9}\ \mathrm{GeV}^{-2} \left(\frac{340\ \mathrm{GeV}}{m_\chi}\right)^2$


ll constants,
$\left(\frac{2\text{TeV}}{25}\right)\left(\frac{3.5\times10^{-9}\,\text{GeV}^{-2}}{\sigma_0}\right)$
$\Rightarrow$ a particle w/ Weak-scale
(O(100 GeV)) mass &
interaction strength given
by Weak fire has
observed relic abundance
$\sim 10^{-36}\,\text{cm}^2 \sim 1\,\text{pb}$
$\sim 3\times10^{-26}\,\text{cm}^3/\text{s}$
"WIMP miracle"?
$\frac{1/50}{m_X^2}$
$(340\,\text{GeV})^2$