Title: Particle Physics Lecture - 230322

Speakers: Junwu Huang

Collection: Particle Physics (2022/2023)

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Classical Logic

NOT

in	out
0	1
1	0

OR

in		out	
a	b	a	a OR b
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	1

NAND

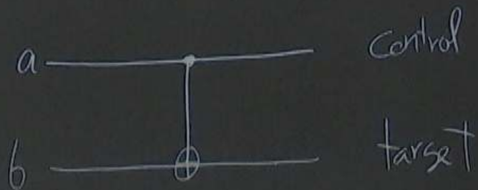
in		out	
a	b	a	a NAND b
0	0	0	1
0	1	0	1
1	0	1	1
1	1	1	0

AND

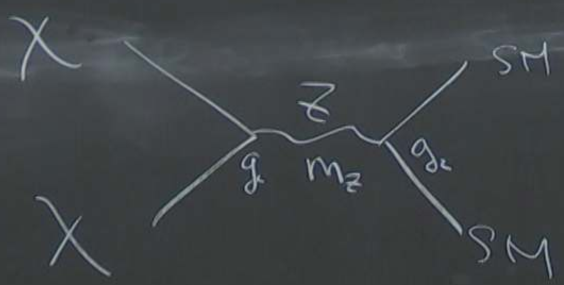
in		out	
a	b	a	$a \cdot b$
0	0	0	0
0	1	0	0
1	0	1	0
1	1	1	1

XOR (CNOT)

in		out	
a	b	a	$a \oplus b$
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0



Lecture 9: Weakly Interacting Massive Particles (WIMPs) & Thermal Freezeout

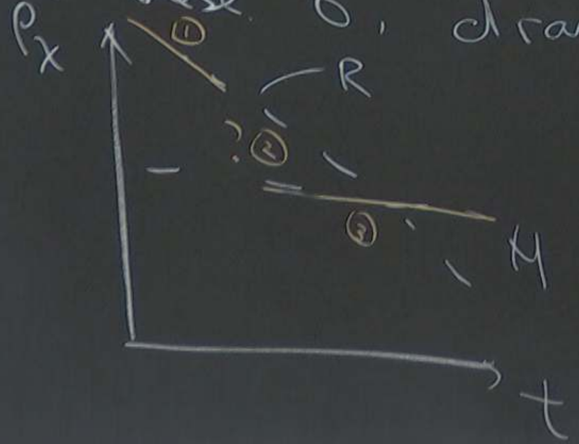


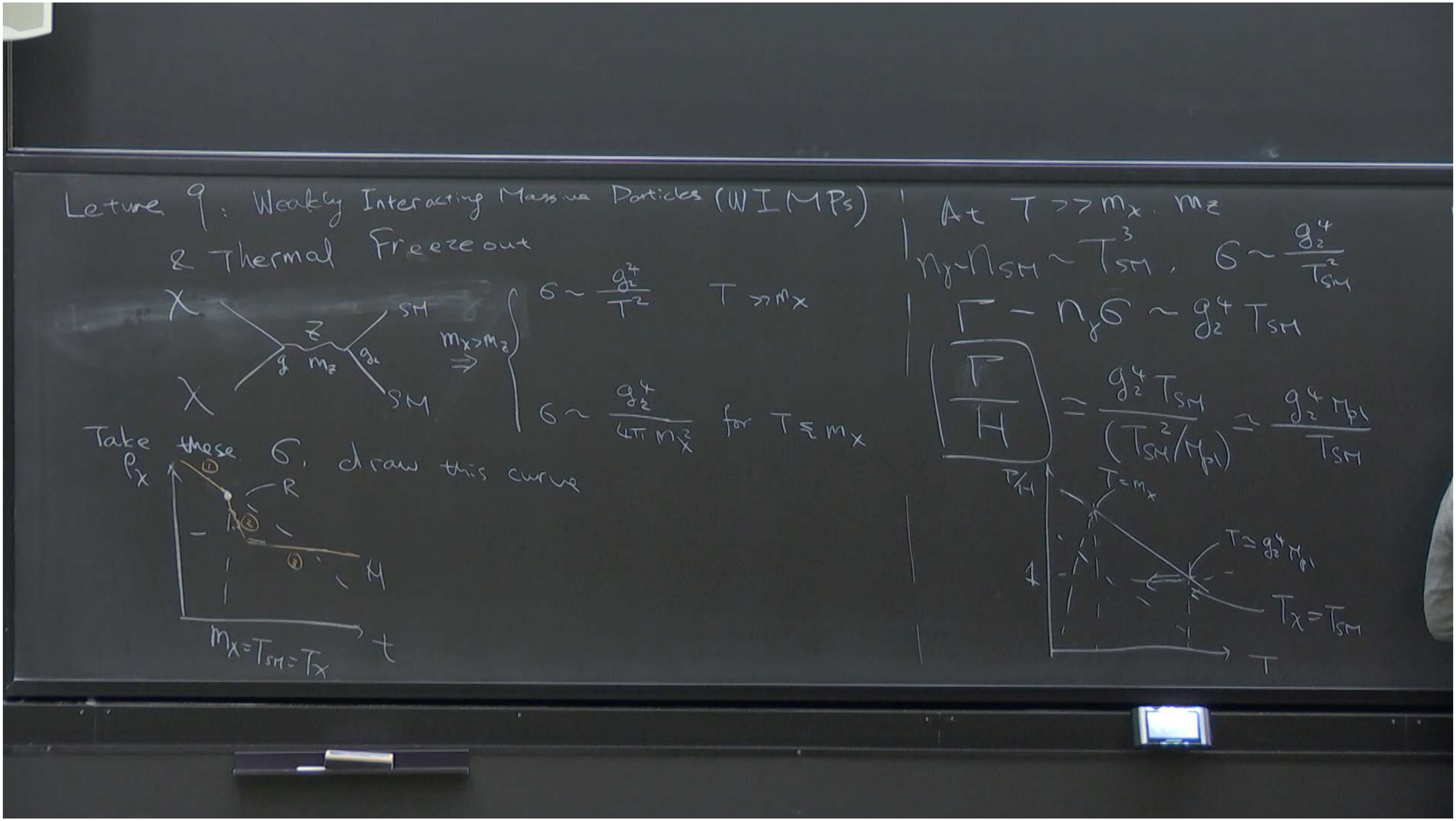
$m_\chi > m_Z \Rightarrow$

$$\sigma \sim \frac{g_Z^4}{T^2} \qquad T \gg m_\chi$$

$$\sigma \sim \frac{g_Z^4}{4\pi m_\chi^2} \quad \text{for } T \lesssim m_\chi$$

Take these σ, draw this curve



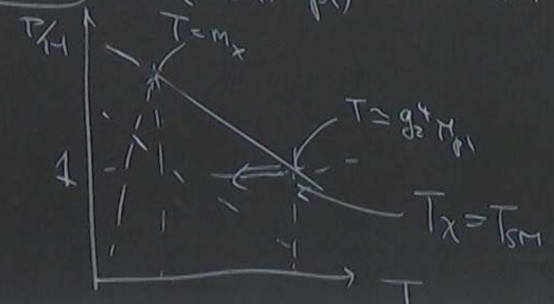

Leture 9: Weakly Interacting Massive Particles (WIMPs)
& Thermal Freezeout
X
X
SM
SM
Z
m_Z
g
g_Z
$m_X > m_Z$ ⇒
$\sigma \sim \frac{g_Z^4}{T^2}$ $T \gg m_X$
$\sigma \sim \frac{g_Z^4}{4\pi m_X^2}$ for $T \lesssim m_X$
Take these σ, draw this curve
ρ_X
R
M
$m_X = T_{SM} = T_X$
t
At $T \gg m_X, m_Z$
$n_X \sim n_{SM} \sim T_{SM}^3$, $\sigma \sim \frac{g_Z^4}{T_{SM}^2}$
$\Gamma \sim n_X \sigma \sim g_Z^4 T_{SM}$
$\boxed{\frac{\Gamma}{H}} = \frac{g_Z^4 T_{SM}}{(T_{SM}^2/M_{pl})} \simeq \frac{g_Z^4 M_{pl}}{T_{SM}}$
Γ/H
$T = m_X$
$T \simeq g_Z^4 M_{pl}$
1
$T_X = T_{SM}$
T

At $T \gg m_\chi, m_Z$

$n_\gamma \sim n_{SM} \sim T_{SM}^3, \quad \sigma \sim \frac{g_Z^4}{T_{SM}^2}$

$\Gamma \sim n_\gamma \sigma \sim g_Z^4 T_{SM}$

$$\boxed{\frac{\Gamma}{H}} \simeq \frac{g_Z^4 T_{SM}}{(T_{SM}^2/M_{pl})} \simeq \frac{g_Z^4 M_{pl}}{T_{SM}}$$



What is $g_{I.C}$ below which there is no thermalization?

$$T_{th} \sim g_{I.C}^4 M_{pl} > m_\chi \Rightarrow g_{I.C} \gtrsim \left(\frac{m_\chi}{M_{pl}}\right)^{1/4} \sim 10^{-5}\left(\frac{m_\chi}{\text{GeV}}\right)^{1/4}$$

Thermal – Freeze-in

Time is not infinite.

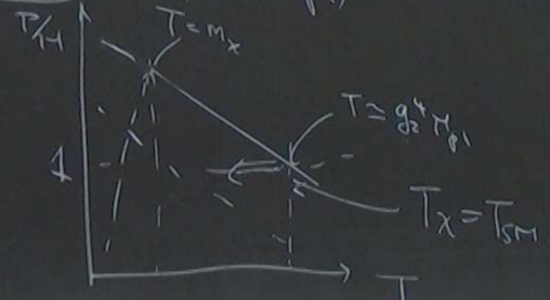
$$\frac{\Gamma}{H} = \frac{n_{\chi,f}\cdot\sigma}{\ }$$

At $T \gg m_\chi, m_Z$

$n_\gamma \sim n_{SM} \sim T_{SM}^3$, $\sigma \sim \frac{g_2^4}{T_{SM}^2}$

$\Gamma \sim n_\gamma \sigma \sim g_2^4 T_{SM}$

$$\boxed{\frac{\Gamma}{H}} \simeq \frac{g_2^4 T_{SM}}{(T_{SM}^2/M_{pl})} \simeq \frac{g_2^4 M_{pl}}{T_{SM}}$$



What is $g_{I.C}$ below which there is no thermalization?

$$T_{th} \sim g_{I.C}^4 M_{pl} > m_\chi \Rightarrow g_{I.C} \gtrsim \left(\frac{m_\chi}{M_{pl}}\right)^{1/4} \sim 10^{-5} \left(\frac{m_\chi}{GeV}\right)^{1/4}$$

Thermal - Freeze-in

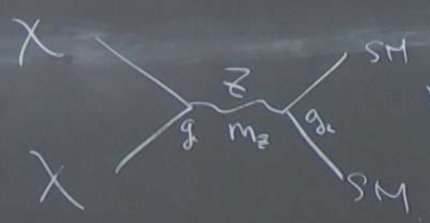
Time is not infinite.

$$\frac{\Gamma}{H} = \frac{n_{\chi f} \cdot \sigma}{(T_{\chi f}^2/M_{pl})} = 1$$

$$\Rightarrow n_{\chi f} \simeq \frac{H}{\sigma} \simeq \frac{m_\chi^2 T_{\chi f}^2}{\alpha_2^2 M_{pl}}$$

$$\frac{n_{\chi f}}{n_\gamma} \sim \frac{m_\chi^2}{T_{\chi f} M_{pl}}$$

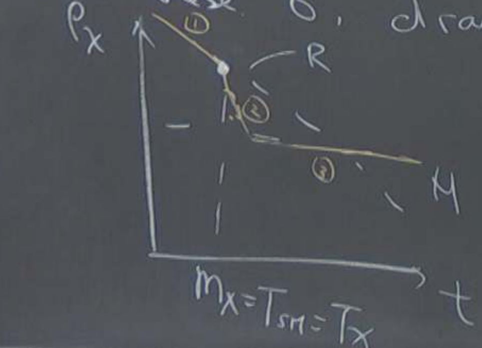
Lecture 9: Weakly Interacting Massive Particles (WIMPs) & Thermal Freezeout



$m_X > m_Z \Rightarrow$

$$\begin{cases} \sigma \sim \dfrac{g_Z^4}{T^2} & T \gg m_X \\ \sigma \sim \dfrac{g_Z^4}{4\pi m_X^2} & \text{for } T \lesssim m_X \end{cases}$$

Take these σ, draw this curve

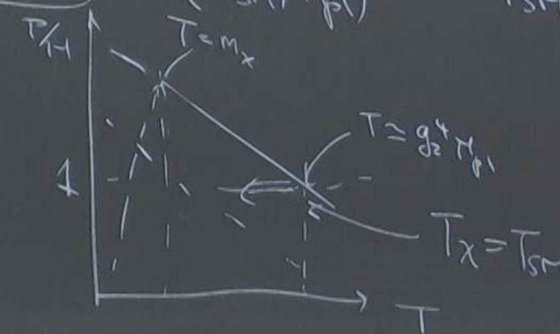


At $T \gg m_X, m_Z$

$n_\gamma \sim n_{SM} \sim T_{SM}^3$, $\sigma \sim \dfrac{g_Z^4}{T_{SM}^2}$

$\Gamma \sim n_\gamma \sigma \sim g_Z^4 T_{SM}$

$$\boxed{\frac{\Gamma}{H}} \simeq \frac{g_Z^4 T_{SM}}{(T_{SM}^2/M_{pl})} \simeq \frac{g_Z^4 M_{pl}}{T_{SM}}$$



What is $T_{X,f}$?

What is $g_{I.C}$ below which there is no thermalization?

$$T_{th} \sim g_{I.C}^4 M_{pl} > m_X \Rightarrow g_{I.C} \gtrsim \left(\frac{m_X}{M_{pl}}\right)^{1/4} \sim 10^{-5} \left(\frac{m_X}{GeV}\right)^{1/4}$$

Thermal - Freeze-in

Time is not infinite:

$$\frac{\Gamma}{H} = \frac{n_{x.f} \cdot \sigma}{(T_{x.f}^2 / M_{pl})} = 1$$

$$\Rightarrow n_{x.f} \simeq \frac{H}{\sigma} \simeq \frac{m_X^2 T_{x.f}^3}{\alpha_2^2 M_{pl}}$$

$$\frac{n_{x.f}}{n_\gamma} \sim \frac{m_X^2}{T_{x.f} M_{pl}}$$

③ Redshifting:

We know @ $T = T_{eq}$ $\rho_{\chi, eq} = \rho_{\gamma, eq} = T_{eq}^4$

$$T_{eq}^4 = \rho_{\chi, eq} = m_\chi \cdot n_{\chi, eq}$$

$$= m_\chi \left(\frac{T_{eq}}{T_{\chi f}}\right)^3 \cdot n_{\chi f}$$

$$= m_\chi \cdot \left(\frac{T_{eq}}{T_{\chi f}}\right)^3 \cdot T_{\chi f}^2 \cdot m_\chi^2 / \alpha_2^2 M_{pl}$$

$$\Rightarrow m_\chi = \left(\frac{1}{20} \underset{\substack{\downarrow \\ 0.1 \cdot eV}}{T_{eq}} \underset{\substack{\downarrow \\ 10^{19} GeV}}{M_{pl}} \cdot \underset{10^{-3}}{\alpha_2^2}\right)^{1/2}$$

$$\simeq (\mathrm{TeV})$$

WIMP Miracle!

② What is $T_{x.f}$?

$$n_x = (m_x \cdot T_{x.f})^{3/2} \cdot \exp\left(-\frac{m_x}{T_{x.f}}\right) = n_{x.f} = \frac{m_x^2 T_{x.f}^2}{\alpha_2^2 M_{pl}}$$

$$\underline{n_{x.f} \simeq \left(\frac{1}{20}\right)^2 \cdot \frac{1}{\alpha_2^2} \cdot \frac{m_x^4}{M_{pl}}}$$

$$\frac{m_x}{T_{x.f}} = \underbrace{\log\left(\frac{M_{pl}}{m_x}\right)}_{\sim 20}$$

$$\boxed{T_{x.f} \simeq \frac{m_x}{20}}$$

$T_\chi = T_{SM}$

T

$n_\gamma \sim \frac{m_\chi}{T_{\chi.f} M_{pl}}$

③ Redshifting.

We know @ $T = T_{eq}$ $\rho_{\chi.eq} = \rho_{\gamma.eq} = T_{eq}^4$

$M_{\tilde{N}_1} \sim 1.1 \text{ TeV}$

$$T_{eq}^4 = \rho_{\chi.eq} = m_\chi \cdot n_{\chi.eq}$$

$$= m_\chi \left(\frac{T_{eq}}{T_{\chi f}}\right)^3 \cdot n_{\chi.f}$$

$$= m_\chi \cdot \left(\frac{T_{eq}}{T_{\chi.f}}\right)^3 \cdot T_{\chi f}^2 \cdot m_\chi^2 / \alpha_2^2 M_{pl}$$

$$\Rightarrow m_\chi = \left(\frac{1}{20} T_{eq} M_{pl} \cdot \alpha_2^2\right)^{1/2}$$

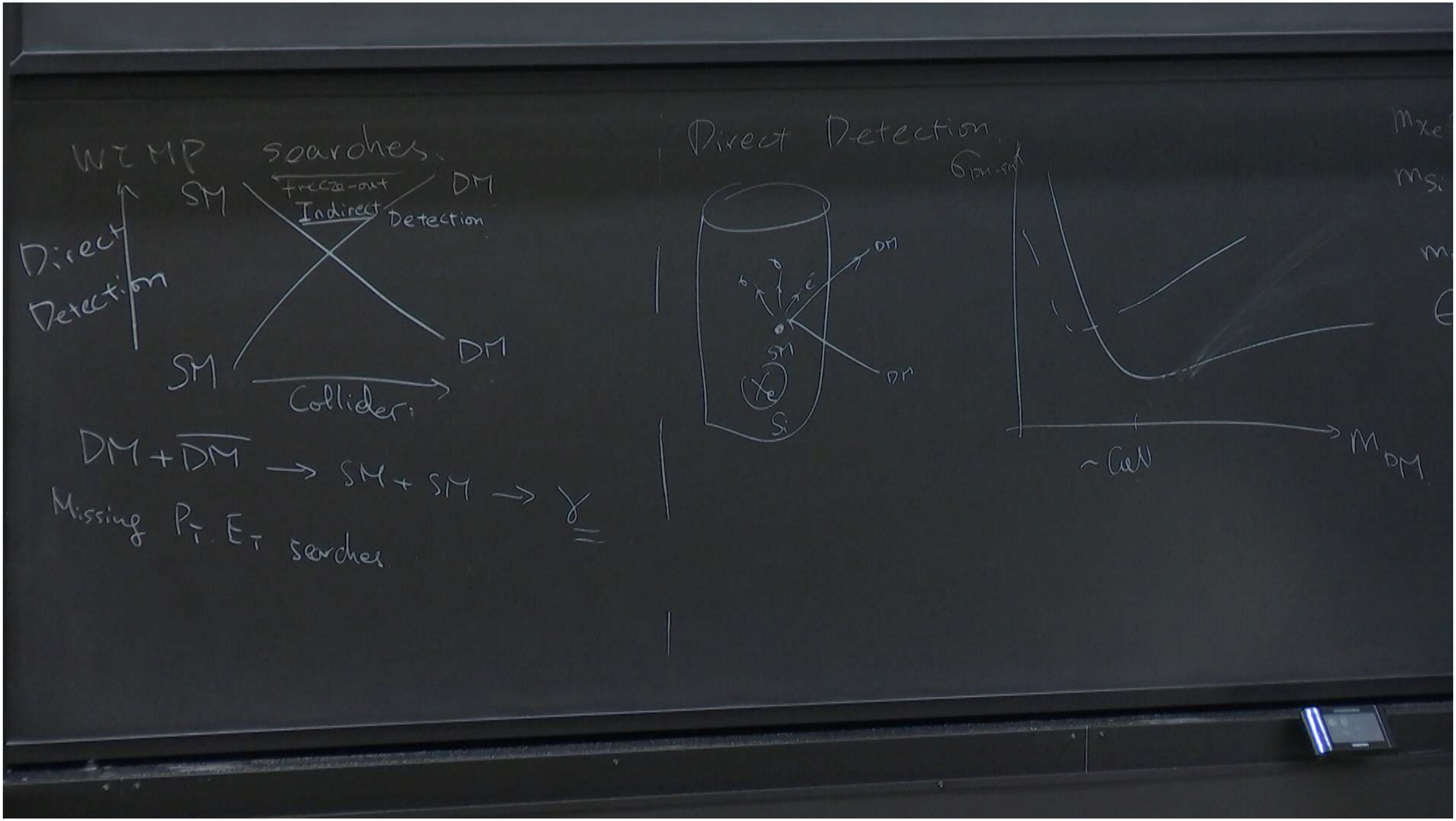
$T_{eq} \to 0.1 \text{ eV}$, $M_{pl} \to 10^{19} \text{ GeV}$, $\alpha_2^2 \to 10^{-3}$

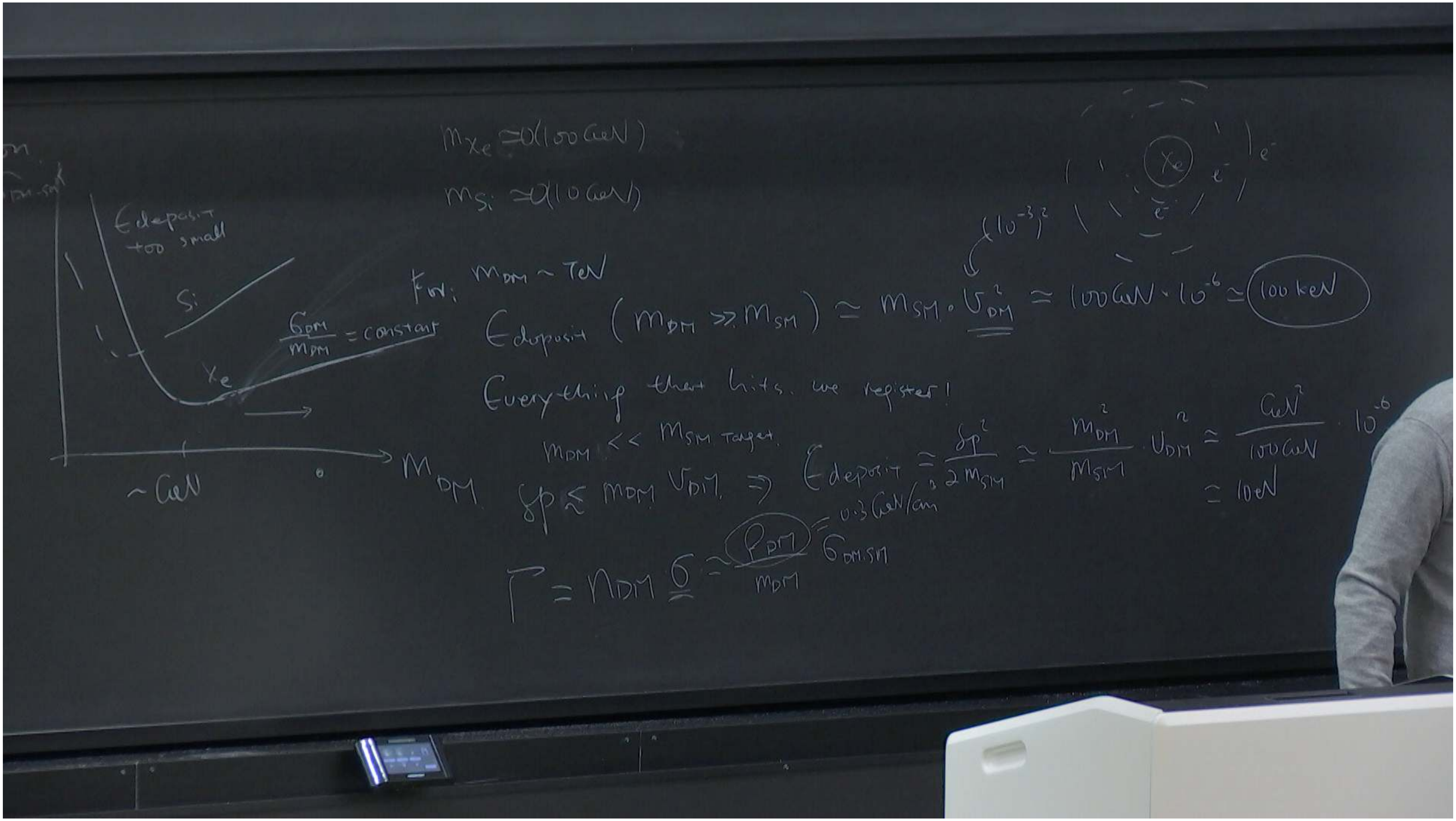
$\simeq (\text{TeV})$

WIMP Miracle!

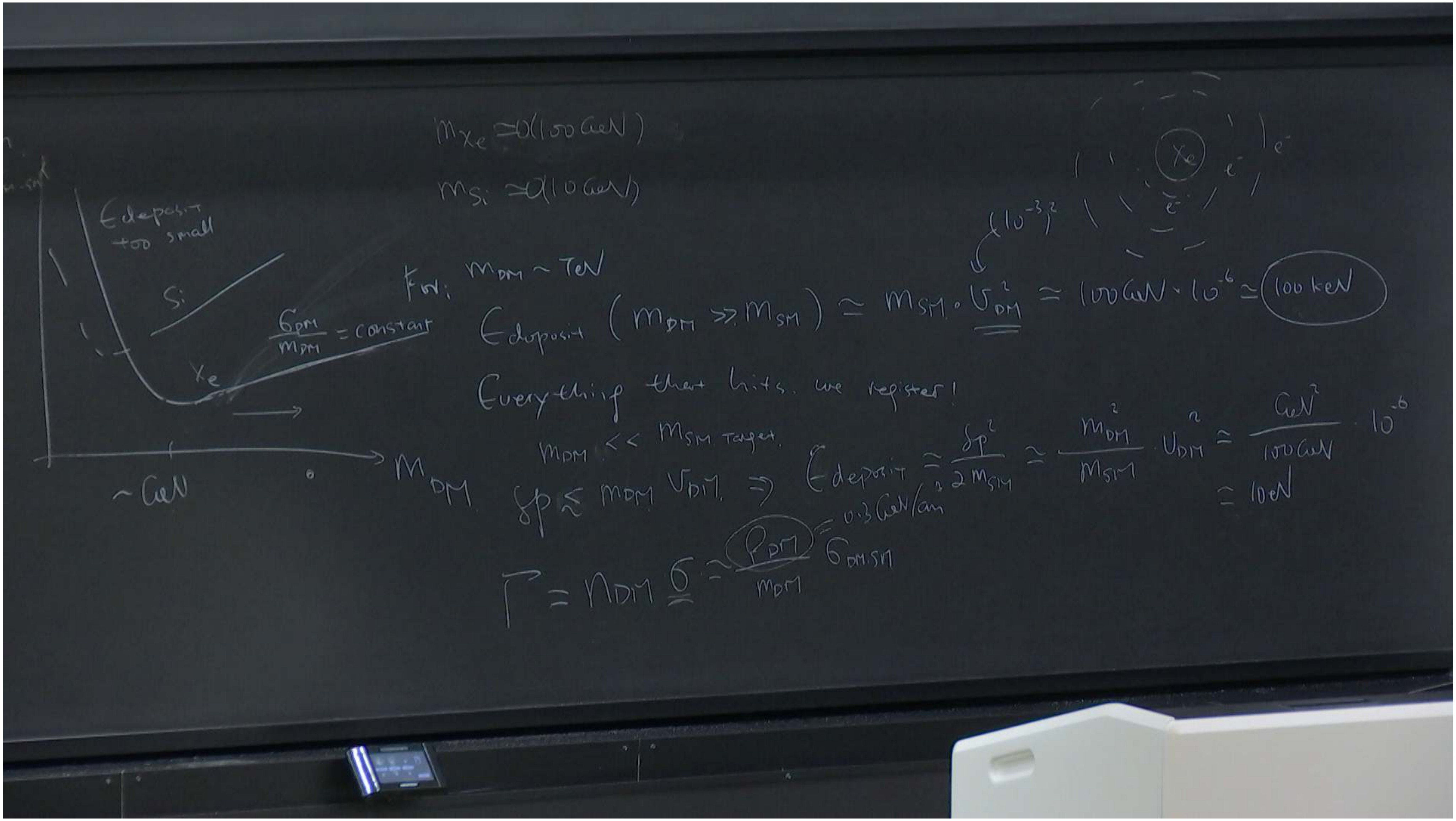
Dark Matter Candidate

1. Lagrangian, motivated by theoretical puzzles
2. Cosmology (Production)
3. How do we look for it?


WIMP searches
SM
DM
freeze-out
Indirect Detection
Direct Detection
SM
DM
Collider
DM + $\overline{DM}$ → SM + SM → γ
Missing P_T E_T searches
Direct Detection
DM
SM
DM
Xe
Si
σ_{DM-SM}
~ GeV
M_{DM}



$m_{Xe} \simeq \mathcal{O}(100\,\mathrm{GeV})$
$m_{Si} \simeq \mathcal{O}(10\,\mathrm{GeV})$
$E_{deposit}$ too small
Si
$\frac{\sigma_{DM}}{m_{DM}}$ = constant
Xe
~ GeV
M_{DM}
e^-
For: $m_{DM} \sim$ TeV
$E_{deposit}\,(m_{DM} \gg m_{SM}) \simeq m_{SM} \cdot v_{DM}^2 \simeq 100\,\mathrm{GeV} \cdot 10^{-6} \simeq 100\,\mathrm{keV}$
$(10^{-3})^2$
Everything that hits, we register!
$m_{DM} << m_{SM}$ Target
$\delta p \lesssim m_{DM} v_{DM} \Rightarrow E_{deposit} \simeq \frac{\delta p^2}{2 m_{SM}} \simeq \frac{m_{DM}^2}{m_{SM}} \cdot v_{DM}^2 \simeq \frac{\mathrm{GeV}^2}{100\,\mathrm{GeV}} \cdot 10^{-6}$
$\simeq 10\,\mathrm{eV}$
$\Gamma = n_{DM}\,\sigma \simeq \frac{\rho_{DM}}{m_{DM}}\,\sigma_{DM\text{-}SM}$
$\rho_{DM} = 0.3\,\mathrm{GeV/cm^3}$


m_Xe ≃ O(100 GeV)
m_Si ≃ O(10 GeV)
E deposit too small
Si
Xe
σDM / mDM = constant
~ GeV
M DM
For: mDM ~ TeV
E deposit (mDM >> mSM) ≃ mSM · vDM^2 ≃ 100 GeV · 10^-6 ≃ 100 keV
(10^-3)^2
Xe
e-
Everything that hits we register!
mDM << mSM Target
δp ≲ mDM vDM ⇒ E deposit ≃ δp^2 / 2 mSM ≃ mDM^2 / mSM · vDM^2 ≃ GeV^2 / 100 GeV · 10^-6
≃ 10 eV
Γ = nDM σ ≃ ρDM / mDM σDM.SM
= 0.3 GeV/cm^3