Title: Thermal DM

Speakers: Rouven Essig

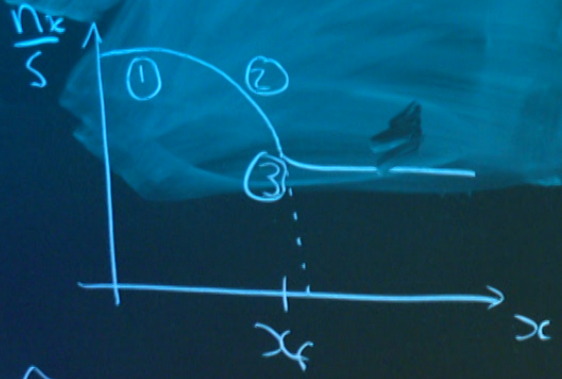
Collection: School on Table-Top Experiments for Fundamental Physics

Date: September 23, 2022 - 3:15 PM

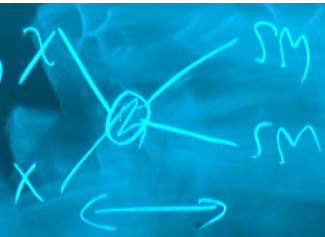
URL: https://pirsa.org/22090029

# Last lecture

Freeze out of a heavy DM particle




1. $n_\chi \sim T^3$, $T \gg m_\chi$
2. $n_\chi \sim (m_\chi T)^{3/2} e^{-m/T}$, $T < m_\chi$
3. Freeze out





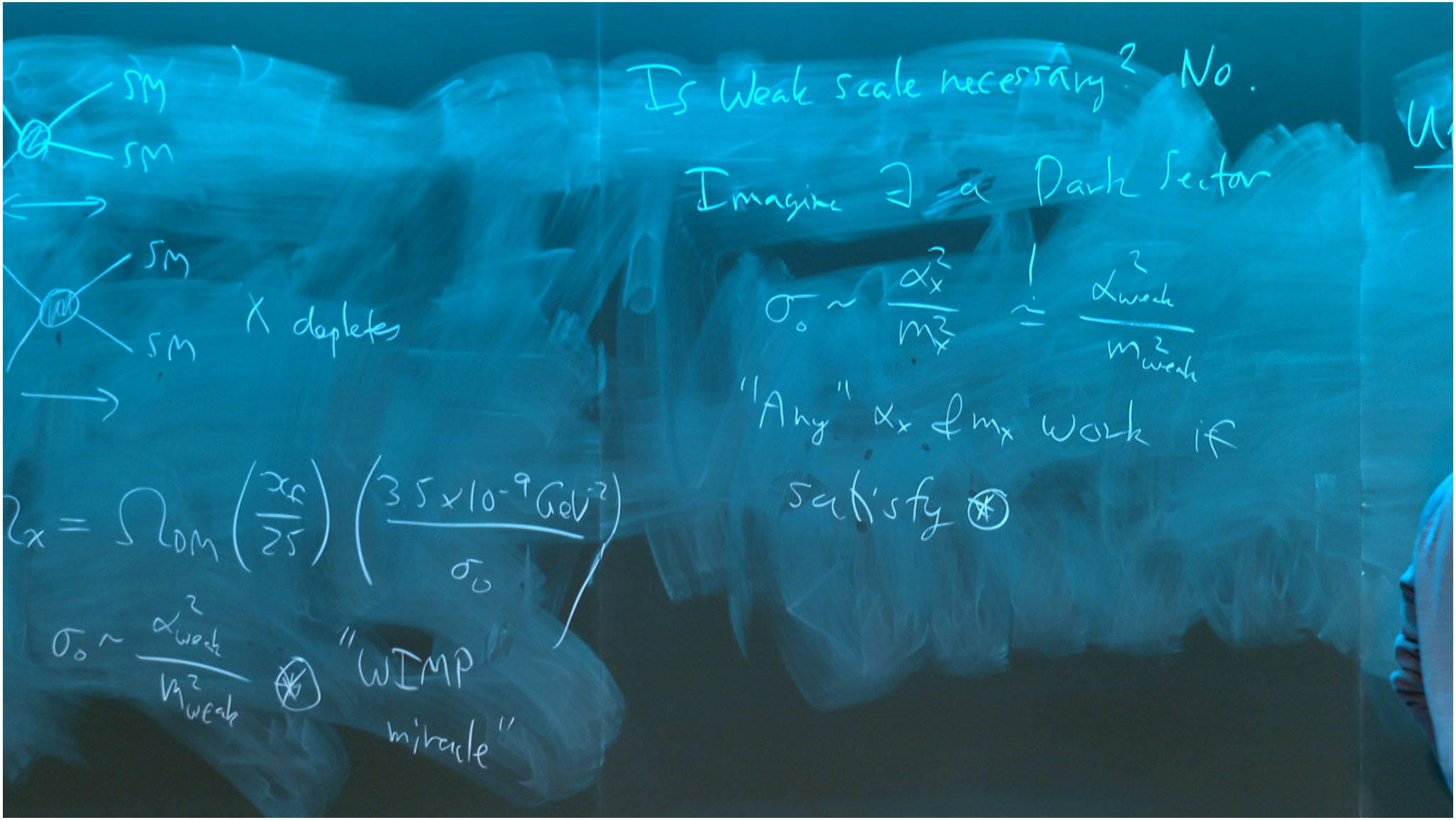


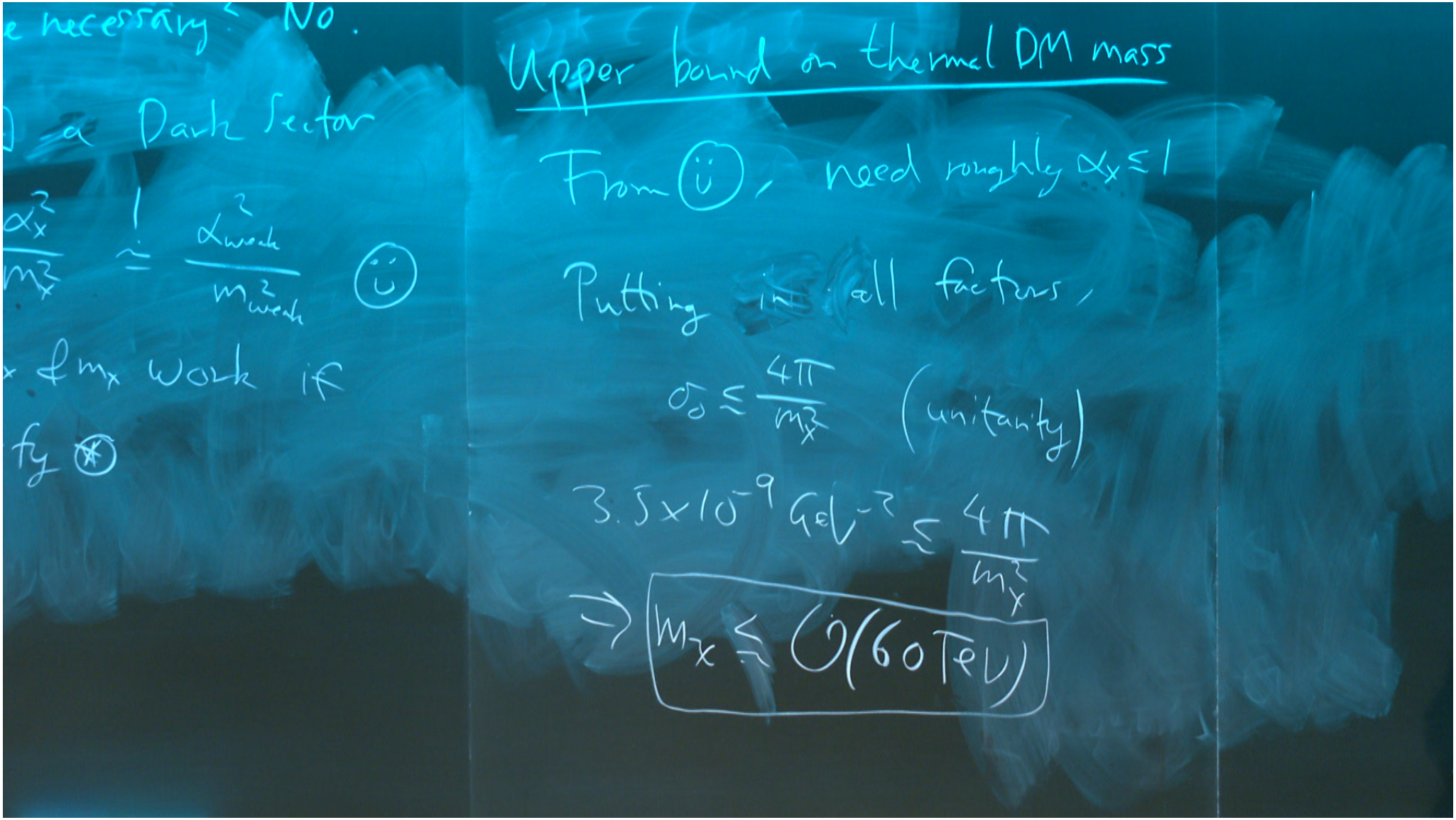
$\chi$ depletes

$$\Omega_\chi = \Omega_{DM}\left(\frac{x_f}{25}\right)\left(\frac{3.5\times10^{-9}\,GeV^{-2}}{\sigma_0}\right)$$

$$\sigma_0 \sim \frac{\alpha_{weak}^2}{m_{weak}^2}$$

"WIMP miracle"


SM
SM
SM
SM
X depletes
Is Weak scale necessary? No.
Imagine ∃ a Dark Sector
$\sigma_0 \sim \frac{\alpha_x^2}{m_x^2} \doteq \frac{\alpha_{weak}^2}{m_{weak}^2}$
"Any" $\alpha_x$ & $m_x$ work if
satisfy ⊛
$\Omega_x = \Omega_{DM}\left(\frac{x_0}{25}\right)\left(\frac{3.5\times10^{-9}\,GeV^{-2}}{\sigma_0}\right)$
$\sigma_0 \sim \frac{\alpha_{weak}^2}{m_{weak}^2}$ ⊛ "WIMP miracle"


e necessary? No.
a Dark Sector
$\frac{\alpha_x^2}{m_x^2} \simeq \frac{\alpha_{weak}^2}{m_{weak}^2}$
& $m_x$ work if
fy ⊛
Upper bound on thermal DM mass
From ⓤ, need roughly $\alpha_x \leq 1$
Putting in all factors,
$\sigma_0 \leq \frac{4\pi}{m_x^2}$ (unitarity)
$3.5 \times 10^{-9}\,\text{GeV}^{-2} \leq \frac{4\pi}{m_x^2}$
$\Rightarrow \boxed{m_x \leq \mathcal{O}(60\,\text{TeV})}$

r bound on thermal DM mass

om (i), need roughly $\alpha_X \leq 1$

tting in all factors,

$\sigma_0 \leq \frac{4\pi}{m_X^2}$ (unitarity)

$.5 \times 10^{-9}\ \text{GeV}^{-2} \leq \frac{4\pi}{m_X^2}$

$\Rightarrow$ $m_X \lesssim \mathcal{O}(60\ \text{TeV})$

Lower bound on DM [illegible] of w/ weak-scale gauge bosons.

Consider $m_X \ll m_{W,t}$




$\sigma \sim \frac{m_X^2}{m_Z^4}$

$\sigma \sim \frac{1}{\pi} G_F^2 m_X^2 \sim \frac{35 \times 10^{-9}}{\text{GeV}^2} \left(\frac{m_X}{5\ \text{GeV}}\right)^2$

$m_X \gtrsim 5\ \text{GeV}$, otherwise

too much

r bound on thermal DM mass

om (ü), need roughly $\alpha_X \leq 1$

tting in all factors,

$\sigma_0 \leq \frac{4\pi}{m_X^2}$ (unitarity)

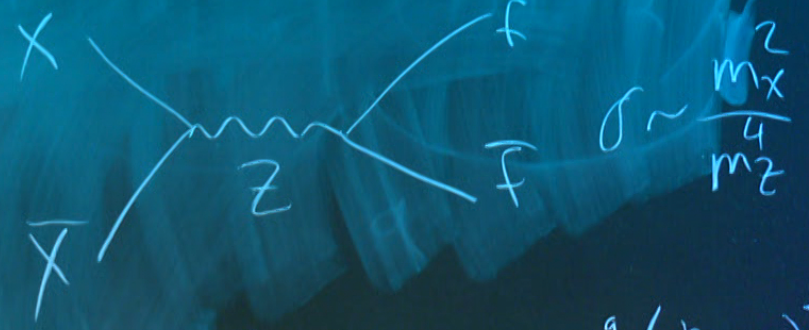
$.5 \times 10^{-9}\ \text{GeV}^{-2} \leq \frac{4\pi}{m_X^2}$

$\Rightarrow \boxed{m_X \lesssim \mathcal{O}(60\ \text{TeV})}$

→Lee-Weinberg bound.

Lower bound on DM interacting w/ weak-scale gauge bosons.

Consider $m_X \ll m_{W,t}$




$\sigma \sim \frac{m_X^2}{m_Z^4}$

$\sigma \sim \frac{1}{\pi} G_F^2 m_X^2 \sim \frac{35 \times 10^{-9}}{\text{GeV}^2} \left(\frac{m_X}{5\ \text{GeV}}\right)^2$

$m_X \gtrsim 5\ \text{GeV}$ otherwise

But w/ light mediators allow for $m_\chi \lesssim 5$ GeV.

→ can have sub-GeV thermal DM, but need light mediators.

→ this simple scenario + variations are viable sub-GeV thermal candidates.

Is Weak

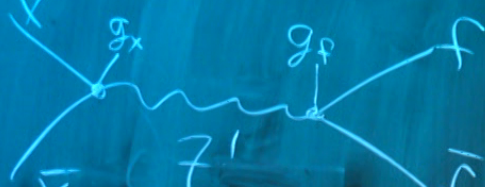
Imagin

$\sigma_0$

"Ang

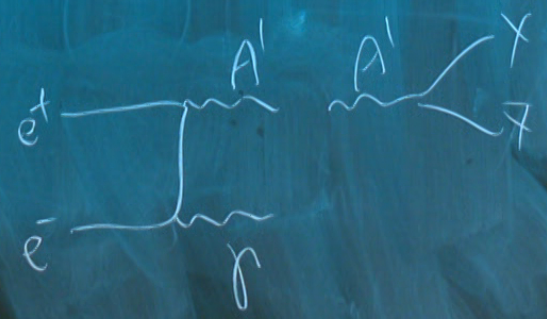
Sc

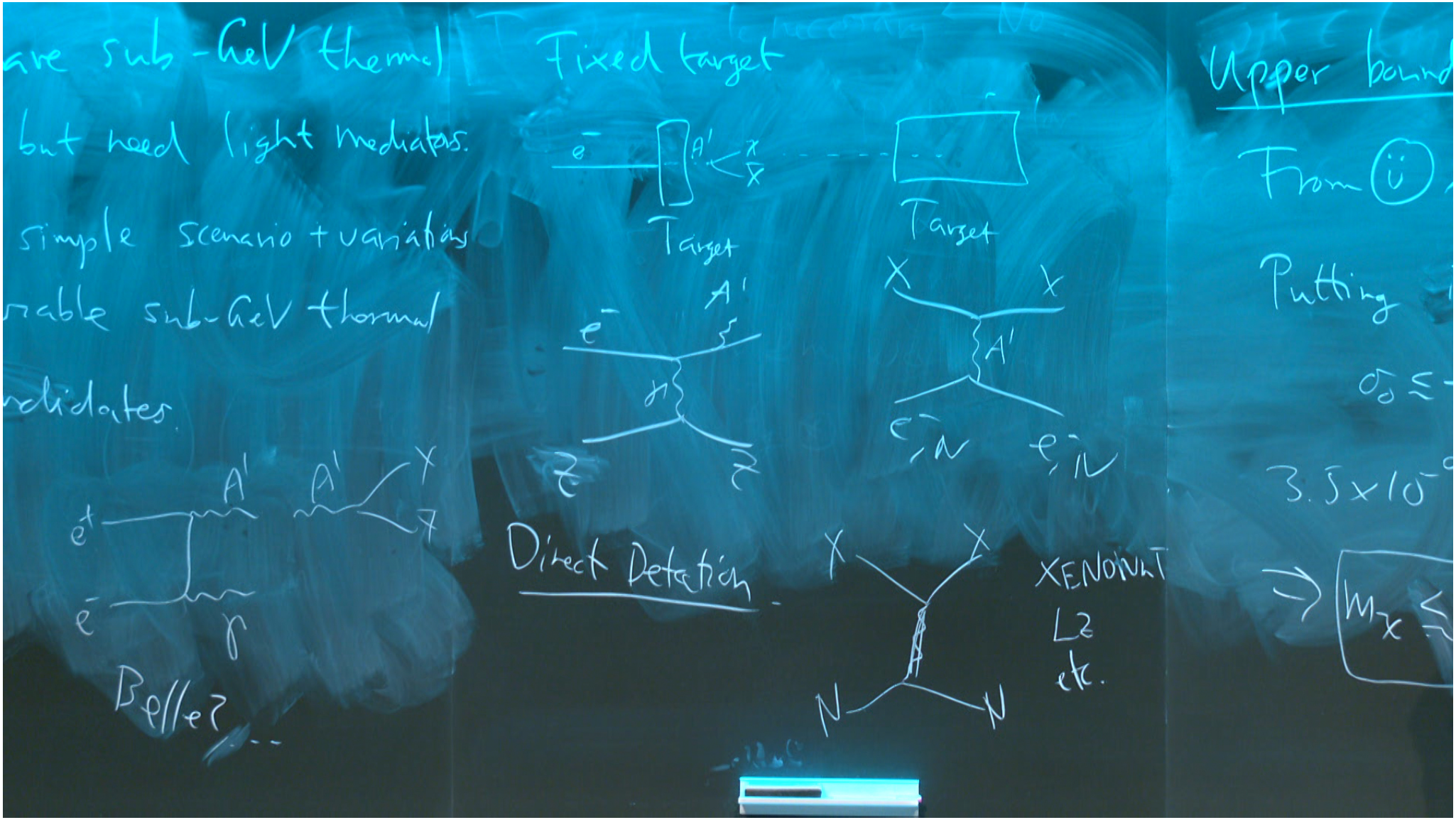
e.g.




e.g. dark photon

$$\sigma \sim (3.5\times10^{-9}\,\text{GeV}^{-2}) \times \left(\frac{g_\chi}{0.5}\right)^2 \left(\frac{g_f}{10^{-3}}\right)^2 \left(\frac{m_\chi}{100\,\text{MeV}}\right)^2 \left(\frac{1\,\text{GeV}}{m_{Z'}}\right)^4$$

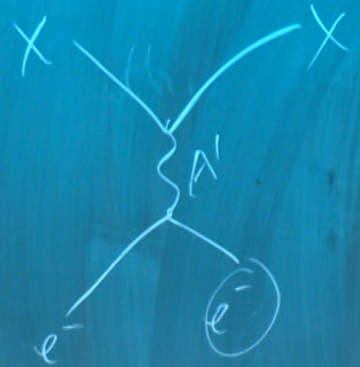



are sub-GeV thermal
but need light mediators.
simple scenario + variations
rable sub-GeV thermal
ediates.
Fixed target
Target
Target
Direct Detection
XENON1T
LZ
etc.
Upper bound
From
Putting
3.5x10
$m_\chi$

Sub-GeV DM

lots of new expts.

can look for $e^-$ recoils




SUPERCDMS

SENSEI

etc.

XENONNT

LZ

etc.

WIMP

Lower bound on DM inter

w/ weak-scale gauge b

Consider $m_X \ll m_{W,Z}$




$\sigma \sim \frac{m_X^2}{m_Z^4}$

$\sigma \sim \frac{1}{\pi} G_F^2 m_X^2 \sim \frac{3.5 \times 10^{-9}}{\text{GeV}^2} \left(\frac{m_X}{5\,\text{GeV}}\right)^2$

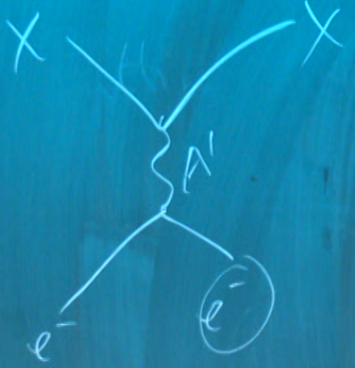
$m_X \gtrsim 5$ GeV, otherwise

too much

Sub-GeV DM

lots of new expts.

can look for $e^-$ recoils




SUPERCDMS

SENSEI

etc.

Lower bound on thermal DM?

Yes. $m_X \gtrsim 1$ MeV

CMB, BBN.

$T \sim 1$ MeV, $t \sim 1$ s

- e becomes non-rel.
- Weak interactions decouple
  - $\nu$'s decouple
  - BBN starts
  - neutrons decouple

$e^+e^-$ annihilate to $\gamma\gamma$, heats up photon bath,

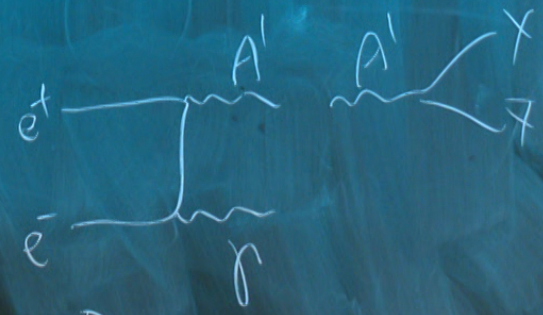
$$T_{\gamma,0} = \left(\frac{11}{3}\right)^{1/3} T_{\nu,0}$$

$\uparrow$

$\sim 1.4$

→ can have sub-GeV thermal DM, but need light mediator.

→ this simple scenario + variations are viable sub-GeV thermal candidates.




Belle?

annihilate to $\gamma\gamma$,

is up photon bath,

$T_{\gamma,0} = \left(\frac{11}{3}\right)^{1/3} T_{\nu,0}$

$\uparrow$

$\approx 1.4$

expansion rate tightly constrained

if DM is in thermal equ$^{m}$ at $T \sim 1$ MeV & couples to $e^-/e^+/\gamma$ or $\nu$s then it

change $\frac{T_\nu}{T_\gamma}$

$\longrightarrow$ roughly $\boxed{m_\chi \gtrsim 1\text{–}10\ \text{MeV}}$

Fixed target




$T_{target}$

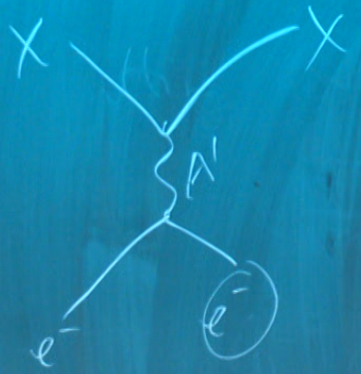



Direct Detection

Sub-GeV DM

lots of new expts.

can look for $e^-$ recoils

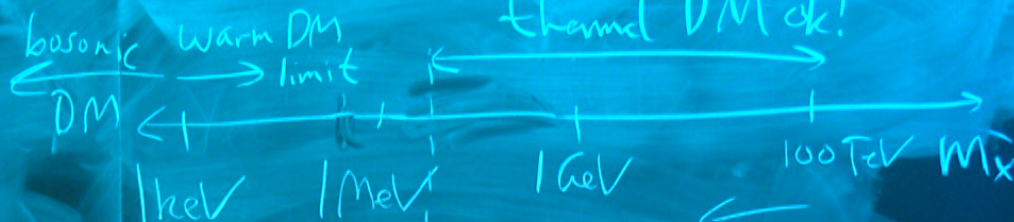



SUPERCDMS

SENSEI

etc.

Thermal DM summary




unitarity limit

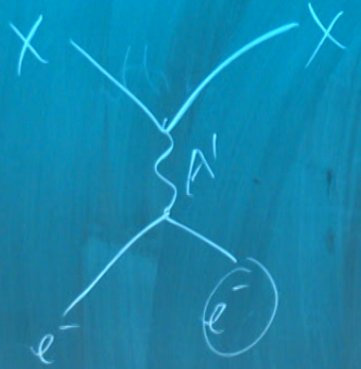
BBN, CMB

need light mediators.

Sub-GeV DM

lots of new expts.

can look for $e^-$ recoils

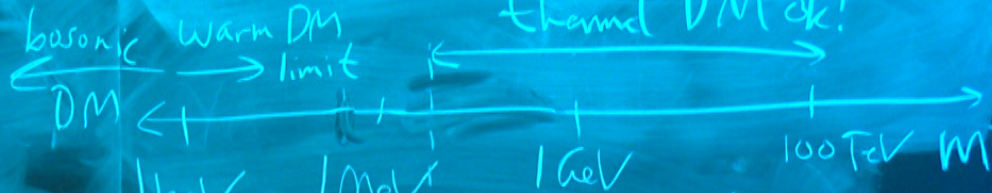



SUPERCDMS

SENSEI

etc.

Thermal DM summary




unitarity limit

BBN, CMB

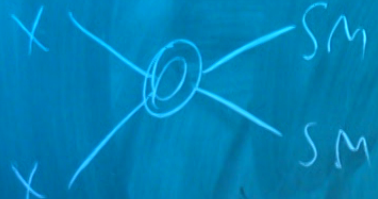
need light mediators.

new expts.

LHC, XENON nT, LZ

## Other bound on DM

### CMB.

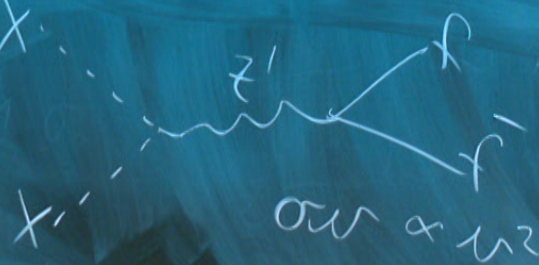



DM annihilation to SM during CMB injects charged particles → affects CMB power spectrum

$\Rightarrow \sigma_0 = \sigma v \leq 3\times10^{-26}\,\frac{cm^3}{s}\left(\frac{m_\chi}{10\,GeV}\right)$

So can we have thermal DM below 10 GeV?

Yes, but cannot have "s-wave" annihilation, i.e. $\sigma v \propto v^0$

e.g. $\chi$: 

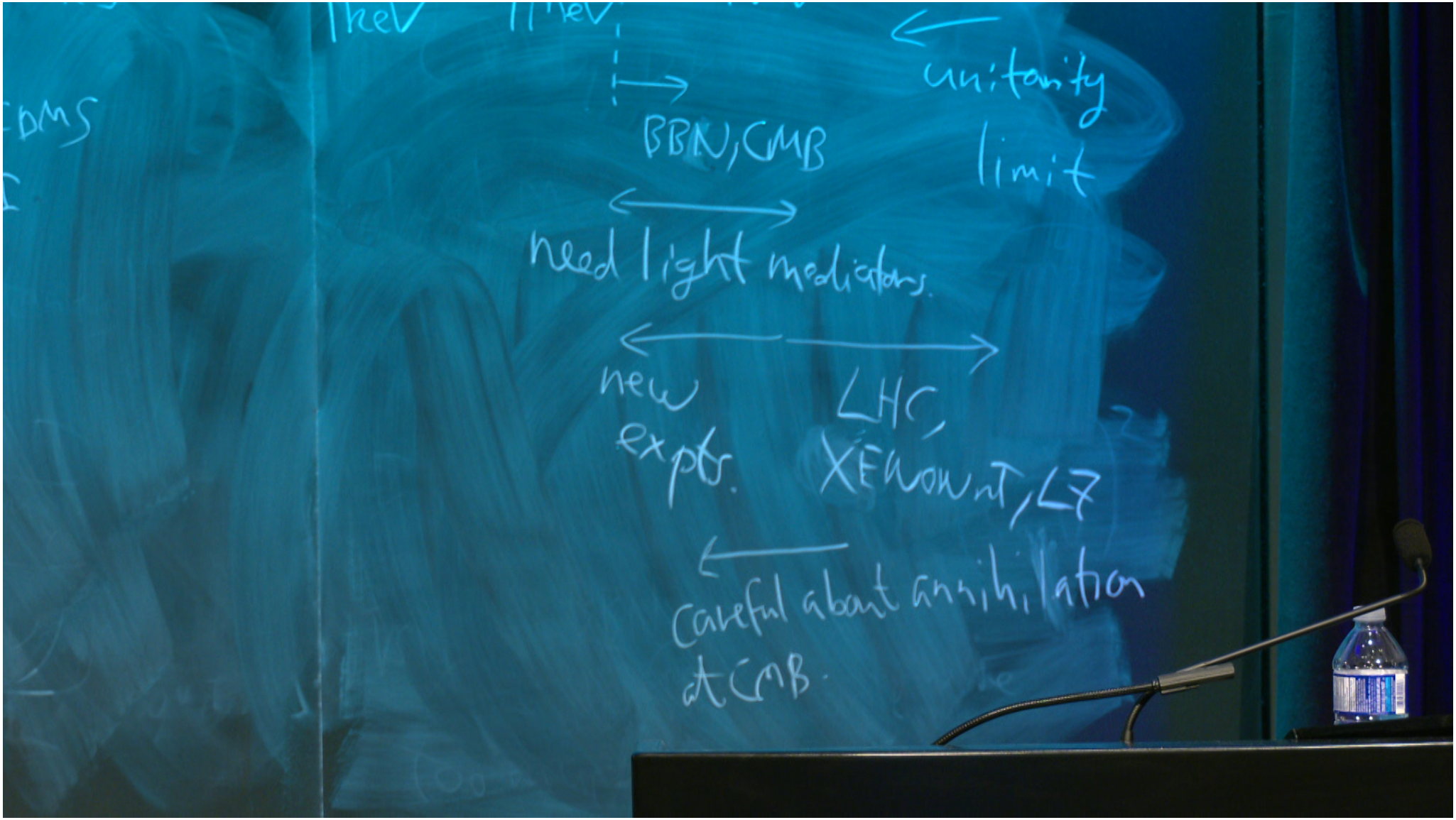

$\sigma v \propto v^2$

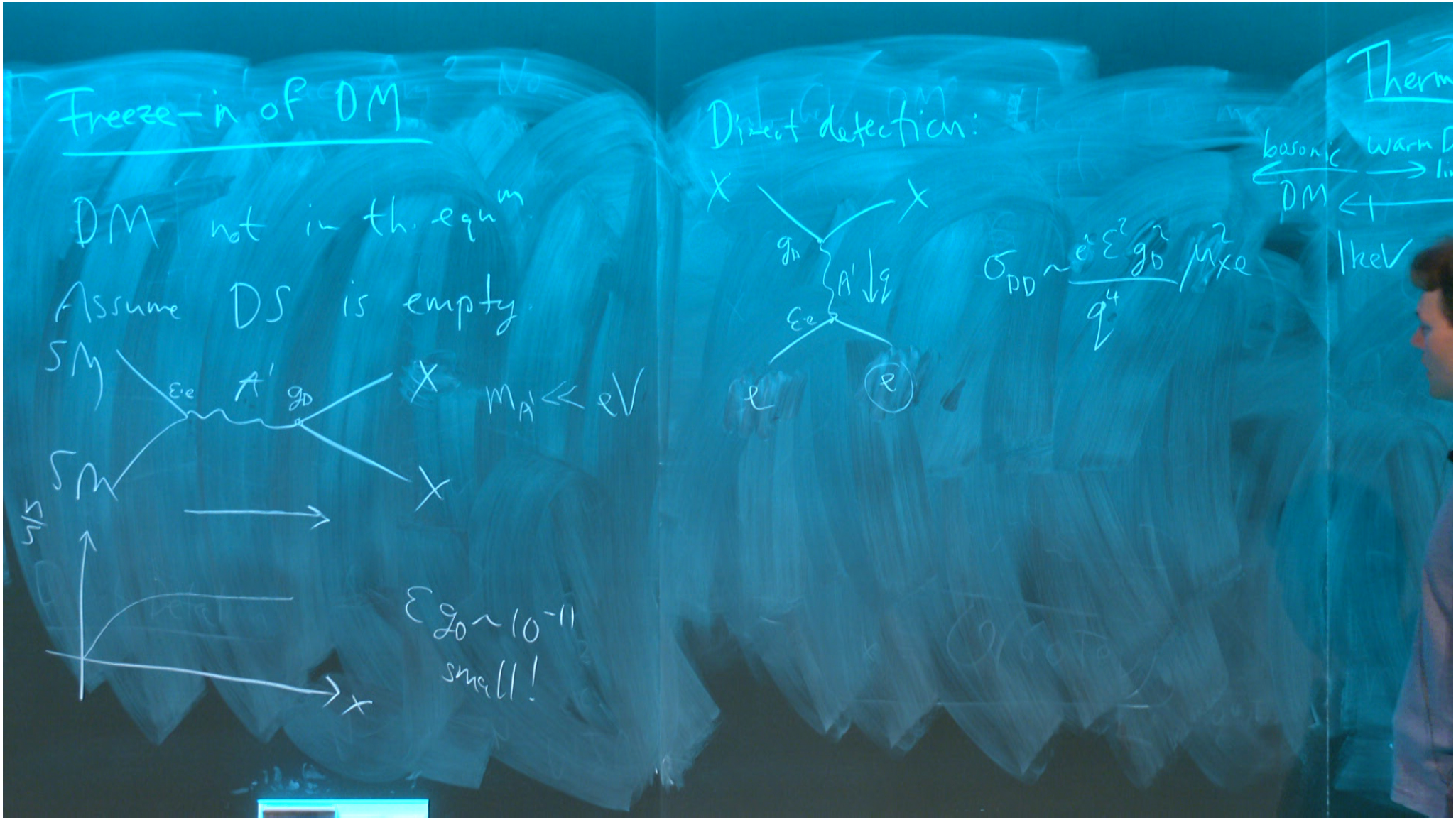
Fixed

e⁻

e⁻

Direct D


1keV
11keV
unitarity
limit
BBN, CMB
need light mediators.
new
expts.
LHC,
XENON nT, LZ
Careful about annihilation
at CMB.


Freeze-in of DM
DM not in th. equ^m
Assume DS is empty
SM
ε e
A'
g_D
χ
m_A' << eV
SM
χ
ε g_D ~ 10^-11
small!
Direct detection:
χ
χ
g_m
A'
q
ε e
e
e
σ_DD ~ e^2 ε^2 g_D^2 / M_χe / q^4
Therm
bosonic
Warm
DM
1keV

## Freeze-in of DM

DM not in th. equ$^{m}$.

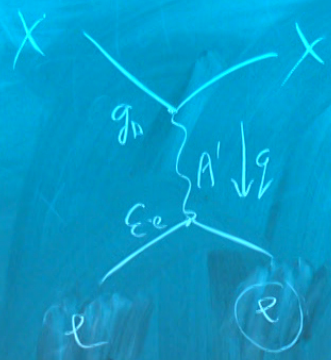
Assume DS is empty.




$m_{A'} \ll eV$

$\varepsilon g_D \sim 10^{-11}$ small!

## Direct detection:




$\sigma_{DD} \sim \frac{e^2 \varepsilon^2 g_D^2}{q^4} \mu_{Xe}^2$

can be probed by next-gen. of expts.

## Therm

bosonic DM

warm D

1 keV