4. Modifications of the WIMP idea

4.1 Super WIMPs

Consider a WIMP produced via thermal freeze-out at $T = T_f$.

Assume WIMP is unstable

$$\text{WIMP} \rightarrow \text{SWIMP} + \text{SM}$$

If $\tau_{\text{WIMP}} \gg \frac{1}{H(T_f)}$ the freeze-out calculation is not modified

But if $\tau_{\text{WIMP}} \ll t_{\text{Universe}}$, only SWIMPs will be left today

$$\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}$$

For $m_{\text{SWIMP}} \approx m_{\text{WIMP}}$ the SWIMP inherits the WIMP miracle!

But no need for SWIMP to have weak interactions!

Moreover: WIMP does not need to be good DM candidate (e.g. it can be charged)

Example: Gravitinos

Motivation: The SM has global symmetries (e.g. $U(1)_{B-L}$) and local (gauge) symmetries (e.g. $U(1)_{EM}$)

Similarly SUSY can be global (as in the MSSM) or local (so-called supergravity theories)

In the latter case there is a superpartner for the graviton G: the gravitino $\tilde{G}$ (spin $\frac{3}{2}$)

↳ becomes massive after SUSY breaking

Gravitinos can have $m_{\tilde{G}} \sim$ GeV – TeV
⇒ can be LSP (lightest SUSY particle)

Role of WIMP played by NLSP (next-to-LSP)

↳ often a stau $\tilde{\tau}$ with $m_{\tilde{\tau}} \sim 100$ GeV

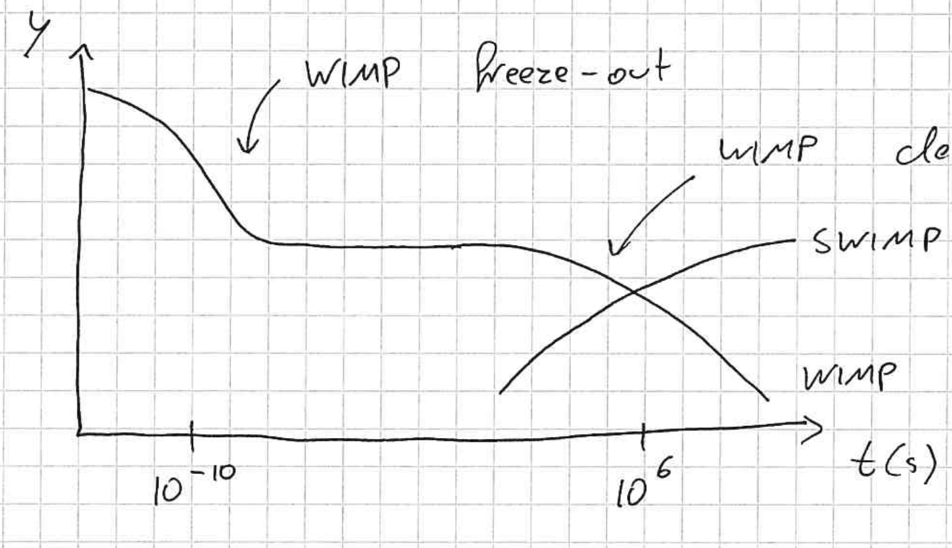
Gravitinos interact only gravitationally

$\Rightarrow$ All cross sections and decay rates are proportional to

$$G_N \sim \frac{1}{M_p^2}$$

Example: $\Gamma(\tilde{\tau} \to \tau \tilde{G}) = \frac{G_N}{6} \frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$

$$\Rightarrow \tau_{\tilde{\tau}} \approx 4 \cdot 10^7 \, s \left[\frac{100 \text{ GeV}}{m_{\tilde{\tau}} - m_{\tilde{G}}}\right]^4 \left[\frac{m_{\tilde{G}}}{100 \text{ GeV}}\right]$$



Important constraint:

BBN very sensitive to decays of heavy particles

↳ spoil element abundances

Require $\tau_{\tilde{\tau}} \lessapprox 10^4$ s

or $m_{\tilde{\tau}} \lessapprox 100$ GeV

Phenomenology:

- Direct detection impossible
- Indirect detection difficult (unless $\tilde{G}$ is also unstable)
- Collider searches!

↳ Central prediction:

New charged particle stable on collider time scales (called HSCP or CHAMP)

⇒ Striking signature

HSCPs can become trapped in the detector and decay after hours (or even months)

↳ energy appearing from "nowhere"

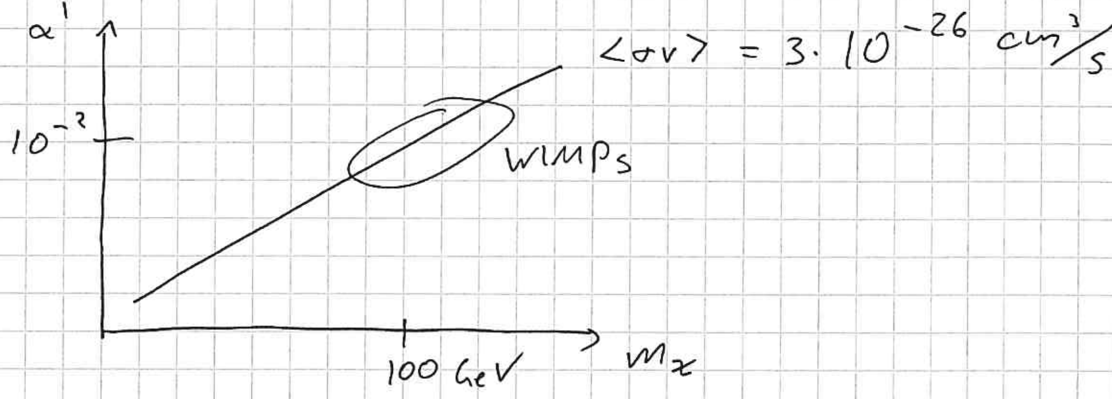
4.2 Light WIMPs

WIMP miracle:

$$\langle \sigma v \rangle \sim \frac{\alpha_w^2}{m_\chi^2} \sim 3 \cdot 10^{-26} \, \frac{cm^3}{s}$$

for $m_\chi \sim v_{EW}$

Works also for different combinations of mass and coupling



Unitarity constraint: $m_\chi < 100$ TeV

What is the lower bound on m_χ?

For s-wave annihilation indirect detection constraints grow stronger with smaller mass:

$$\frac{dR}{dE} \sim \frac{\langle \sigma v \rangle}{2 m_\chi^2}$$

$\Rightarrow$ Typically exclude $m_\chi \lesssim 10$ GeV

For p-wave annihilations m_χ can be much smaller

But: Freeze-out must happen before BBN ($T \sim 100$ keV)

$\Rightarrow$ $m_\chi \gtrsim 2$ MeV

$\Rightarrow$ Lower bound on WIMP mass

How to realize $\alpha' \neq \alpha_w$?

$\rightarrow$ Need new type of interaction!

Popular example: new gauge boson

Idea: extend SM gauge group

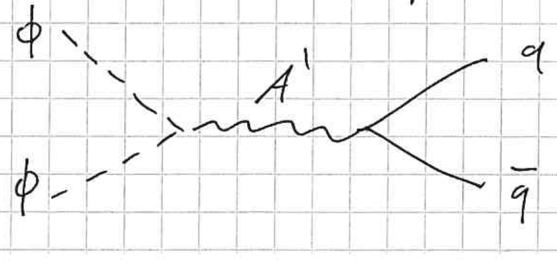
$$\underbrace{SU(3)_c \times SU(2)_w \times U(1)_Y}_{SM} \times U(1)'$$

($U(1)'$ gives rise to dark photon A')

All particles can carry $U(1)'$ charges

Example: $\mathcal{L} \supset g' q_\phi \, \phi^+ D^\mu \phi A'_\mu + g' q_q \bar{q} \gamma^\mu q A'_\mu$

(g': dark gauge coupling; q_ϕ: charge; ϕ: DM particle (spin 0))



Gauge coupling is a free parameter

$\rightarrow$ Can vary $\alpha' = \frac{g'^2}{4\pi}$

$\Rightarrow$ Realisation of MeV DM

Note: DM stability is a consequence of charge conservation

Phenomenology:

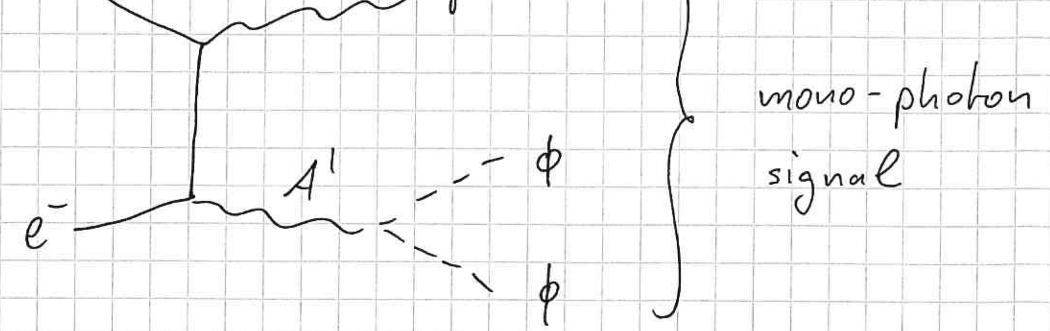
- Indirect detection: p-wave
- Direct detection:

  Energy transfer for nuclear scattering below threshold

  ↳ Need to look for electron scattering

- Collider searches:
  Need low-energy colliders

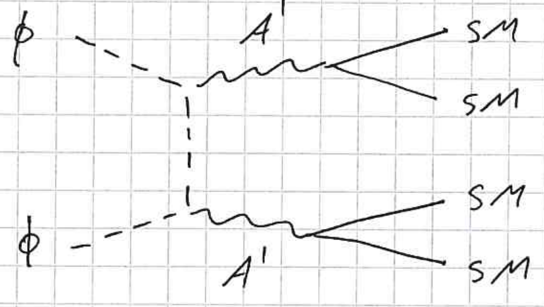
  Example: Belle II



4.3 Secluded DM

What if the dark photon has $m_{A'} < m_\phi$?

$\Rightarrow$ New annihilation channel



$$\sigma(\phi\phi \to 4\,SM) = \sigma(\phi\phi \to A'A') \times BR(A' \to SM\ SM)^2$$

But $BR(A' \to SM\ SM) = 1$ because $A' \to \phi\phi$ is forbidden

$\Rightarrow$ $\langle \sigma v \rangle$ depends only on $g_{DM} = g' q_\phi$

$\Rightarrow$ no dependence on $g_{SM} = g' q_{SM}$

$$\langle \sigma v \rangle = \frac{g_{DM}^4}{4\pi\, m_\phi^2}$$

Direct detection and collider searches have

$$\sigma \sim g_{DM}^2 \, g_{SM}^2$$

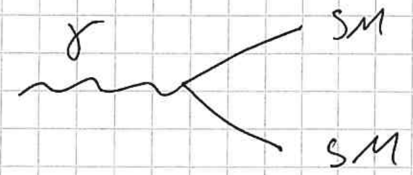
For $g_{SM} \ll g_{DM}$ direct detection and collider constraints are suppressed, but freeze-out (and indirect detection) work normally

↑ cascade annihilation!

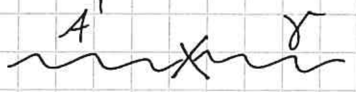
How to achieve $g_{SM} \ll g_{DM}$?

Example: kinetic mixing

Assume SM particles are uncharged under $U(1)'$



But dark photon can mix with visible photon



Such a mixing is always possible for $U(1)$ gauge bosons via the renormalisable interaction

$$\mathcal{L} \supset \varepsilon F^{\mu\nu} F'_{\mu\nu}$$

$$\Rightarrow \quad g_{SM} = \varepsilon \cdot e$$

↖ electric charge

E.g. direct detection

$$\sigma^p \sim \frac{\mu^2 \, g_{DM}^2 \, \varepsilon^2 e^2}{m_{A'}^4}$$

How small can ε be?

→ Need $\varepsilon \gtrsim 10^{-9}$ so that A' decays before BBN

→ Experiments mostly sensitive to $\varepsilon \gtrsim 10^{-4}$ (unless $m_{A'} < 1$ GeV)

⇒ Huge allowed parameter space

↳ Many new experimental ideas

Interesting feature:

For $\varepsilon \lessapprox 10^{-6}$ kinetic equilibrium between visible sector and dark sector cannot be maintained

$$\Rightarrow \quad T_{DM} \neq T_{SM}$$