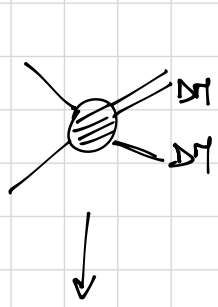
- What is DM?

  * not seen → neutral
  * stable and long-lived
  * structure formation → $M \geq 0$.

} SM fails to find a good candidate

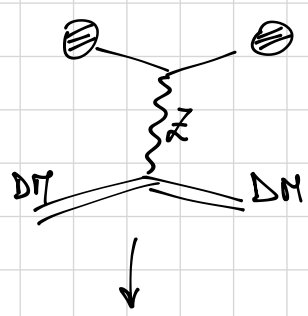
↓

WIMP paradigm (cannot decay)



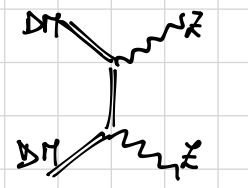
↓

(collider search)



↓

(direct det.)



(COSMOLOGY)

↓

(indirect detection)

- Textbook WIMP is in trouble:

  * Let n = # density of DM → $(\partial_t + 3H)n = -\langle \delta v \rangle (n^2 - n_{eq}^2)$ "Lee-Weinberg"

    H → Hubble rate

    $\langle \delta v \rangle$ → rate coefficient

  * $(\partial_t + 3H)S = 0$ → entropy density:

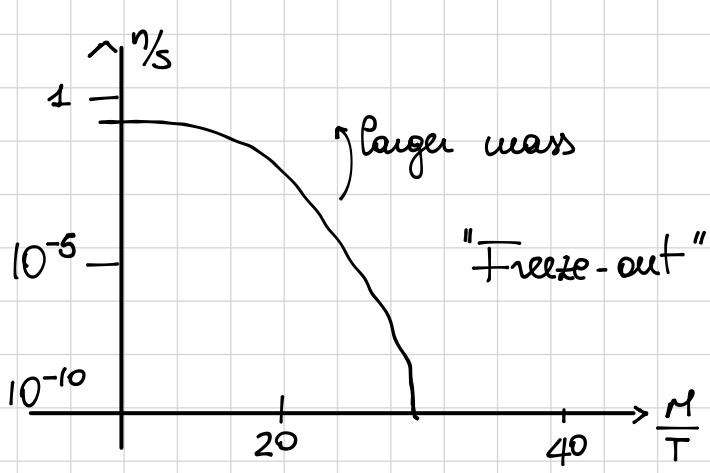
$$\frac{dT}{dt} = -3H\frac{S}{C}$$

C → heat capacity

$$\partial_t\left(\frac{n}{S}\right) = \frac{2C\langle \delta v \rangle}{3H}\frac{n_{eq}}{S}\left(\frac{n}{S} - \frac{n_{eq}}{S}\right)$$

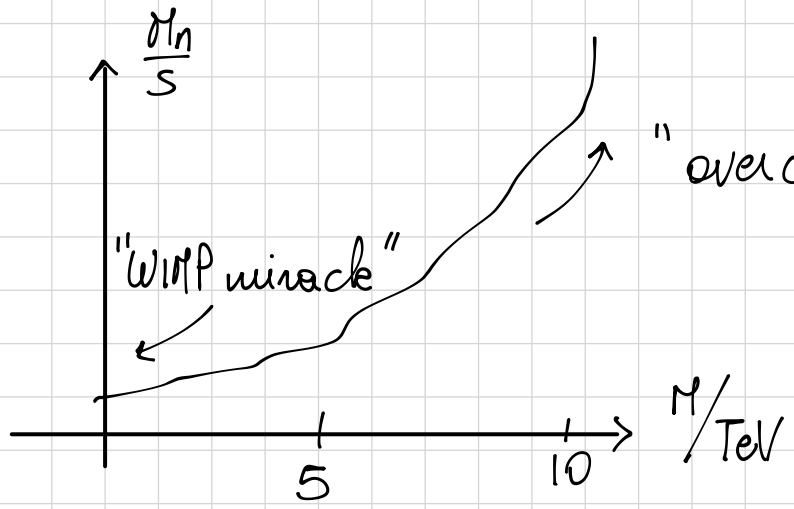
↓

$$\partial_t\left(\frac{n}{S}\right) \sim \frac{m_{pl}\alpha^2}{M^2}\cdot\frac{n_{eq}}{S}\left(\frac{n}{S} - \frac{n_{eq}}{S}\right)$$



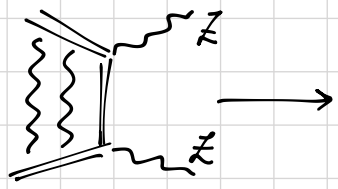
$$n_{eq} \sim \begin{cases} T^3, & T \gg M \\ \left(\frac{MT}{2\pi}\right)^{3/2} e^{-M/T}, & T \ll M \end{cases}$$

$$S \sim T^3$$



"overclosure" → too much DM

- Could efficient annihilation help?

*  → "Sommerfeld effect"

$$\langle \delta v \rangle = \langle \delta_{tree}\, v\, S(v) \rangle$$

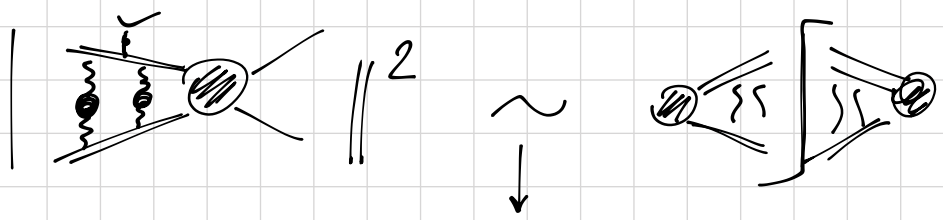
$\sim \frac{1}{v}$ for $v \to 0$

* "bound state effect"

$$M_b = 2M - \Delta E \qquad V(r) = -\frac{\alpha}{r} e^{-m_z r}$$

$$e^{-\frac{M_b}{T}} > e^{-\frac{2M}{T}} \qquad \text{BS exist if } M > \frac{1.6\, m_z}{\alpha} \sim 15\ \text{TeV}$$

- Theoretical framework:



optical theorem

→ Green-function:

$$(H_T - i\Gamma_T - E')\, G(E'; \vec{r}, \vec{r}') = \delta^3(\vec{r} - \vec{r}')$$

$$\lim_{\vec{r}, \vec{r}' \to \vec{0}} \text{Im}\, G = \rho(E')$$

$$\rightarrow H_T = -\frac{1}{M}\nabla^2 + V_T \rightarrow V_T = -\frac{\alpha}{r}\left(m_D + \frac{e^{-m_D r}}{r} \right]$$

$\Gamma_T = \alpha T \phi(m_D r)$ ↝ Landau damping

$$\Rightarrow \langle \delta v \rangle \propto (\dots) \int dE'\, e^{-E'/T} \rho(E')$$

- Heavy-ion collisions ⟹ pp ⇝ Υ_{1S} Υ_{2S} Υ_{3S}
PbPb ⇝ Υ_{1S}

- Contemporary challenge: $\langle \delta v \rangle \uparrow$ can conflict w/ constr. from detection