from gravitational effect of the DM "fluid" have:

$m \lesssim 10^{+57}\,\text{eV}$ MACHO searches

$\left(m_{\text{sun}} \sim 10^{66}\,\text{eV} \right.$

$m_{\text{earth}} \sim 10^{60}\,\text{eV}$

$\left. m_{\text{moon}} \sim 10^{58}\,\text{eV} \right)$

$m_{\text{boson}} \gtrsim 10^{-22}\,\text{eV}$ dwarf galaxy

$m_{\text{fermion}} \gtrsim 10^{3}\,\text{eV}$ " "

background density: $\sim \frac{\text{GeV}}{m^3}$ (cosmology)

in halos: $\rho_{\text{halo}} \sim 1/r^2$

$\rho_{\text{at earth}} \sim 3 \cdot 10^{5}\,\frac{\text{GeV}}{m^3}$

$\rho_{\text{water}} \sim 10^{30}\,\frac{\text{GeV}}{m^3}$

$\rho_{\text{solar system}} \sim \frac{M_{\text{sun}}}{R^3_{\text{solar system}}} \sim \frac{10^{57}\,\text{GeV}}{(10^3\,\text{AU})^3} \sim \frac{10^{15}\,\text{GeV}}{m^3}$

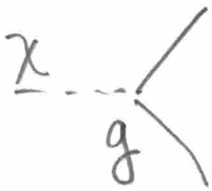
($\text{AU} \approx 10^{11}\,m$)

$\Rightarrow \rho_{DM}$ not observable in solar system gravity

V_{DM} in halo (galaxy) $\sim 10^{-3} c$

Assume it is a "particle" $\Rightarrow M \lesssim M_{pe} \sim 10^{19}$ GeV

stability? massive particle χ



negligible masses

$$\Gamma \sim \frac{g^2}{8\pi} m_\chi$$

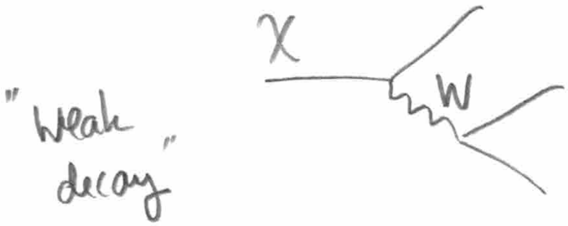
$$\tau = \frac{1}{\Gamma} \gg \text{age of universe } 10^{10} \text{ yrs}$$

$$\Rightarrow \Gamma < \frac{1}{10^{10} \text{ yrs}} \frac{1}{\pi \, 10^7 \text{ s/yr}} \, 7 \, 10^{-16} \text{ eV s} \approx 2 \cdot 10^{-33} \text{ eV}$$

$$\Rightarrow g^2 < 10^{-9} \left[\frac{10^{-22} \text{ eV}}{m_\chi}\right]$$

very small couplings, even for smallest mass.

higher dimensional operator ?



$$\Gamma \sim \frac{m_X^5}{m_W^4}$$

$$\Rightarrow m_X \lesssim (\Gamma m_W^4)^{1/5} \sim (10^{-33} eV\, (10^{11} eV)^4)^{1/5} \sim 100 \text{ eV}$$

dim 5 operator $\Gamma \sim \frac{m_X^3}{M^2}$

e.g. axion $M \sim 10^{10}$ GeV $m_X \sim 10^{-10}$ GeV

$$\Rightarrow \Gamma \sim 10^{-50} \text{ GeV}$$

Conclusion: $g_{eff}(m_X) \ll 1$ <u>or</u>

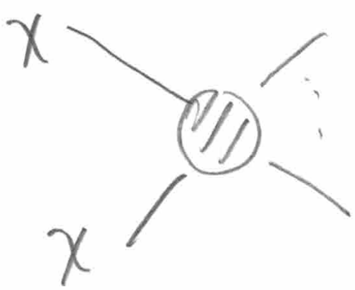
stable due to quantum # (e.g. e^- electric charge, p^+ baryon #)

<u>Simplest possibility</u>: $\mathbb{Z}_2$ charge $\leftrightarrow$ "DM parity"

$$\chi \to -\chi$$
$$SM \to +SM$$

χ lightest parity odd particle (e.g. SUSY R-parity)

consequence: vertex has even # of χ



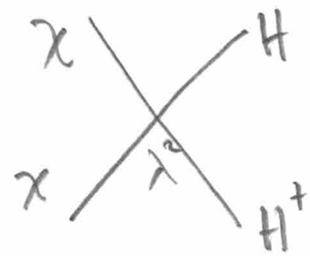
but not

simplest: χ scalar $\mathcal{L} \sim \lambda^2 \chi^2 H^\dagger H$ Higgs portal DM

assuming λ^2 not too small ...

at high temperatures, densities (early universe)

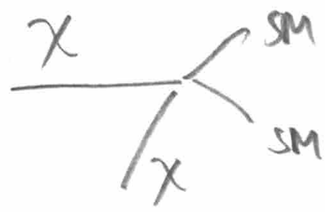
$$T \gg m_\chi, m_H$$



$$\sigma \sim \frac{\alpha^2}{E_{CM}^2} \sim \frac{\alpha^2}{T^2} \qquad \alpha = \frac{\lambda^2}{4\pi}$$

compare with expansion rate of universe $H \equiv \frac{\dot{R}}{R} \sim \frac{T^2}{M_{pl}}$

need rate of scattering



σ from definition of flux $\sigma \sim \frac{1}{|v_1 - v_2|} \cdots$

$$\Gamma \sim n_\chi \langle \sigma v \rangle \sim T^3 \frac{\alpha^2}{T^2} \sim \alpha^2 T$$

($\langle \sigma v \rangle$: averaged over thermal distribution; $\frac{\alpha^2}{T^2}$: relativistic)

$\Rightarrow$ scattering frequent when $\frac{\Gamma}{H} \sim \alpha^2 \frac{M_{pl}}{T} \gg 1$

eg. $\lambda \sim 1 \Rightarrow$ always frequent

non-relativistic $n \sim (MT)^{3/2} e^{-M/T}$

$$\Rightarrow \Gamma/H \sim e^{-M/T}$$

interactions become infrequent, "freeze-out"

annihilations stop ⇒ relic abundance of DM [Melissa's talk]

"WIMP miracle" $\Gamma = n_\chi \langle \sigma v \rangle \approx H$

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

get $\Omega_\chi = 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m}{100\,\text{GeV}}\right)^2$

↑

want $\Omega_\chi \sim 0.25$

$$\left[\begin{array}{l} \alpha_W \sim 0.03 \\ \alpha_{em} \sim 0.01 \end{array}\right]$$

Indirect detection of DM

residual annihilation today:

rate for 1 to scatter $\Gamma \sim n \langle \sigma v \rangle$

rate for particle scatters per volume: $\frac{N}{V} \Gamma = n \cdot \Gamma = n^2 \langle \sigma v \rangle$

but $n = \frac{\rho}{m_\chi}$