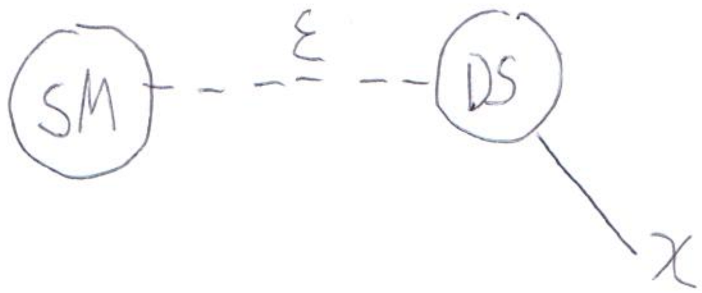
III Dark Pheno

PLAN

I) decoupled
- A) min mass
- B) self-interactions

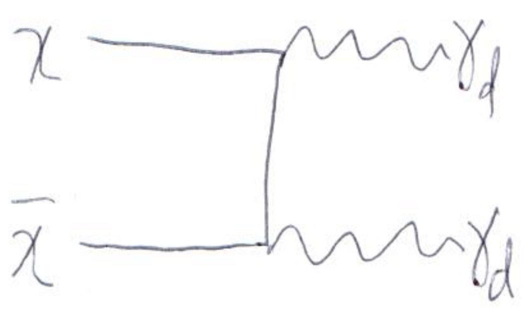
II) coupled
- A) indirect
- B) direct

- pheno depends on how DM couples to SM



- DM may be unobservable (beyond gravity)

ex)



$m_\chi \sim 10$ TeV

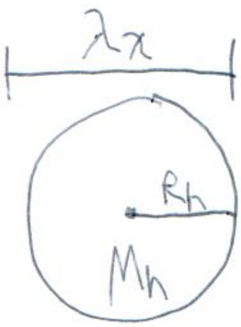
$\alpha_d \sim 0.1$

$\varepsilon = 0$

A) Min. DM mass

Scalar DM

- de Broglie λ_x must fit in dwarfs



$$M_h \sim 10^6 M_\odot \qquad M_\odot = 2 \times 10^{30}\,\mathrm{kg}$$

$$R_h \sim 0.1\,\mathrm{kpc}$$

- Virial thm: $\langle V \rangle \simeq \sqrt{\frac{G M_h}{R_h}}$

$$R_h > \lambda_x = \frac{h}{p} \sim \frac{1}{m_x V} \simeq \frac{M_{pl}}{m_x}\sqrt{\frac{R_h}{M_h}}$$

$$m_x \gtrsim \frac{M_{pl}}{\sqrt{M_h R_h}} \sim 10^{-21}\,\mathrm{eV}$$

Fermionic DM

- Tremaine-Gunn bound:

fermion degeneracy pressure sets a min. halo mass

$$M_h = m_X \cdot V_h \int d^3p\, f(\vec{p}) \lesssim m_X \cdot V_h \int d^3p\, f(\vec{p}) \sim m_X V_h (m_X v)^3$$

$$V_h \sim R_h^3 \qquad v \simeq \frac{1}{M_{pl}} \sqrt{\frac{M_h}{R_h}}$$

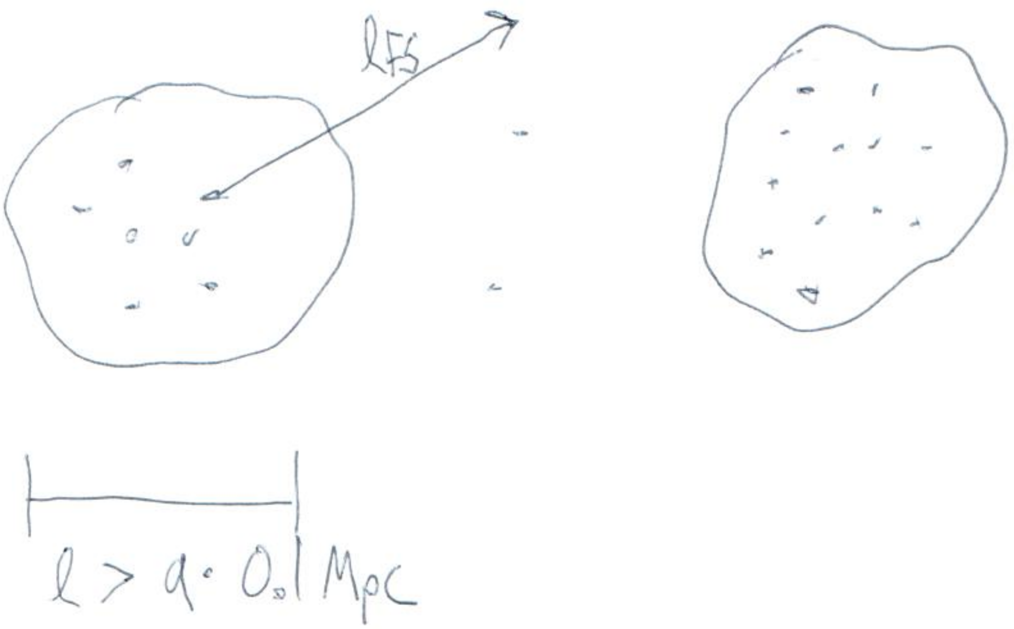
$$m_X \gtrsim M_{pl}^{3/4}\, R_h^{-3/8}\, M_h^{-1/8} \simeq 0.4\ \mathrm{keV}$$

$R_h \sim 0.1\ \mathrm{kpc}$
$M_h \sim 10^6 M_\odot$

- DM is not active neutrinos

Warm DM

- structures form from initial DM overdensities



- comoving free streaming length: $\lambda_{FS} = a\, l_{FS}$
- Structure suppressed on scales $l < \lambda_{FS}$
- bound: $\boxed{\lambda_{FS} < 0.1\,\mathrm{Mpc}}$

$$\lambda_{FS} = \int_0^{t_0} dt\, \frac{v(t)}{a(t)}$$

- suppose DM is kinetically decoupled before it turns non-relativistic at time t_{NR}

$$\lambda_{FS} = \int dt\, \frac{v(t)}{a(t)} \sim \int_{t_{NR}}^{t_{eq}} dt\, \frac{v(t)}{a(t)}$$

$$a(t) = a_{eq}\left(\frac{T_{eq}}{T}\right) \propto \sqrt{t} \qquad T_{eq} \simeq 0.8\,\mathrm{eV}$$

$$v(t) = c\,\frac{a_{NR}}{a(t)}$$

$$\lambda_{FS} \sim \frac{2c\,t_{NR}}{a_{NR}} \log\left(\frac{a_{eq}}{a_{NR}}\right)$$

$$t_{NR} \sim t_{eq}\left(\frac{T_{eq}}{T_{NR}}\right)^2$$

$$\lambda_{FS} \sim \left(\frac{2c\,t_{eq}\,T_{eq}}{a_{eq}}\right)\frac{1}{T_{NR}} \log\left(\frac{T_{NR}}{T_{eq}}\right)$$

$$a_{eq} \simeq z_{eq}^{-1} \simeq (3400)^{-1}$$
$$t_{eq} \simeq 6\times10^4\,\mathrm{y}$$

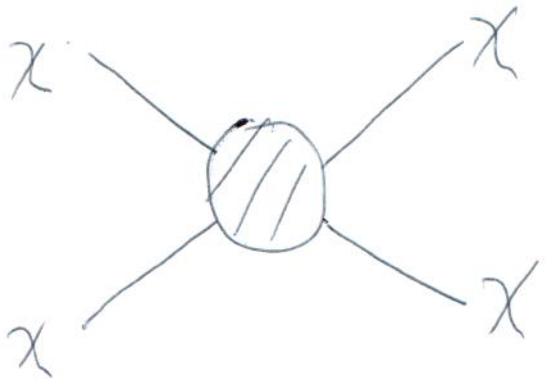
$\to 0.1\,\mathrm{Mpc}\cdot\mathrm{keV}$

$$\lambda_{FS} \sim 0.1\,\mathrm{Mpc}\left(\frac{1\,\mathrm{keV}}{T_{NR}}\right)\log\left(\frac{T_{NR}}{T_{eq}}\right)$$

$$m \sim T_{NR} \gtrsim 1\,\mathrm{keV}$$

- applies to thermal relics, freeze-in, superWIMP
- does not apply to non-thermal DM w/ $v \ll c$
  ex) axion

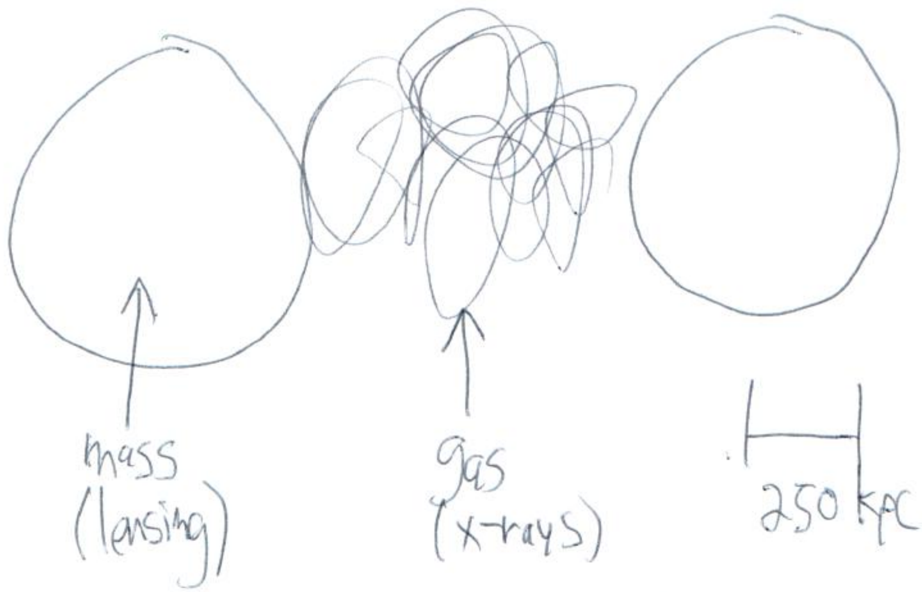
B) Self-Interactions

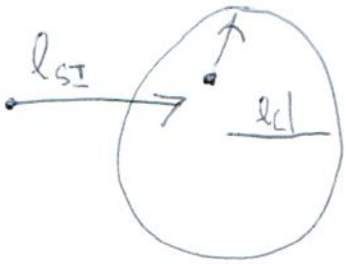


σ_{SI}

- cluster mergers do not show DM self-interactions

ex) bullet cluster





- DM mean free path is larger than the cluster halo

$$l_{SI} > l_{cl} \sim 250 \text{ kpc} \sim 10^{24} \text{ cm}$$

$$l_{SI} = \left(n_{cl}\, \sigma_{SI}\right)^{-1} \qquad n = \frac{\rho \leftarrow \text{known}}{m \leftarrow \text{unknown}}$$

$$= \left(\rho_{cl} \frac{\sigma_{SI}}{m}\right)^{-1} \qquad \rho_{cl} \sim 6 \times 10^{4} \rho_c h^{-2} \sim 10^{-24}\, \text{g}/\text{cm}^3$$

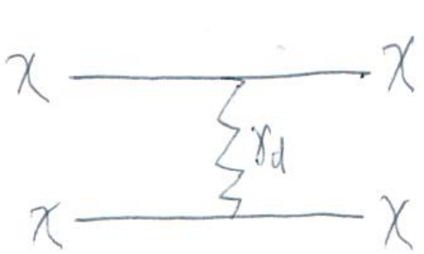
$$\frac{\sigma_{SI}}{m} > \frac{\rho_{cl}}{\ell_{cl}} \sim 1\ \mathrm{cm^2/g} \sim \frac{1}{(60\ \mathrm{MeV})^3}$$

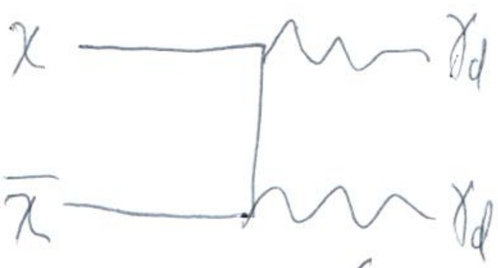
· <u>WIMP</u>

$$\sigma_{SI} \sim \langle \sigma_{ann} v \rangle \sim \frac{1}{T_{eq} \cdot M_{pl}} \sim \frac{1}{(20\ \mathrm{TeV})^2}$$

$$\frac{\sigma_{SI}}{m} \sim 10^{-15} \left(\frac{1\ \mathrm{TeV}}{m}\right) \mathrm{cm^2/g} \qquad \text{small}$$

• <u>Forbidden</u>

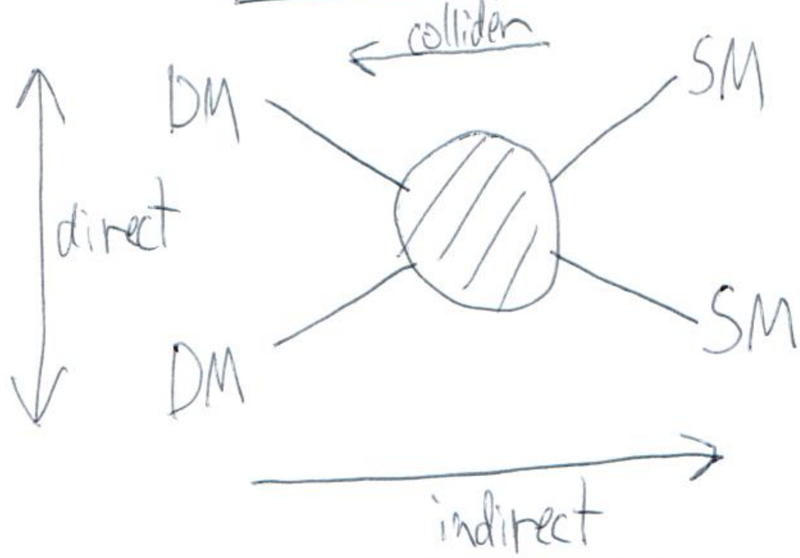




$$\sigma_{SI} \sim \frac{\alpha_d^2}{m_\chi^2} \qquad \langle \sigma_{ann} v \rangle \sim e^{-2\delta m/T} \frac{\alpha_d^2}{m_\chi^2}$$

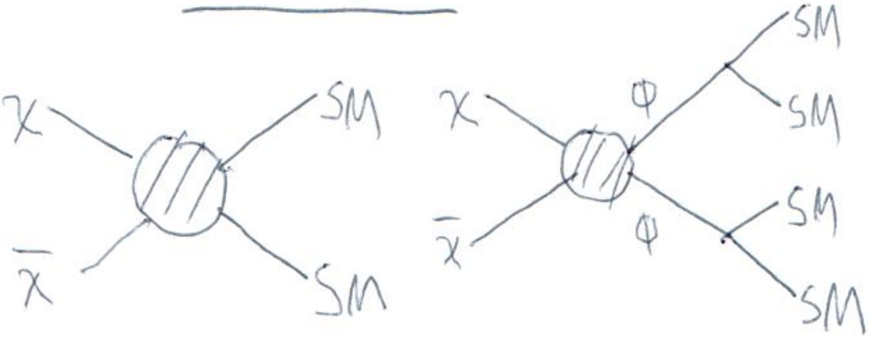
$$\frac{\sigma_{SI}}{m} \sim 1\ \mathrm{cm^2/g} \left(\frac{10\ \mathrm{MeV}}{m_\chi}\right)^3 \times \left(\frac{\alpha_d}{0.03}\right)^2 \qquad \text{large!}$$

II Coupled

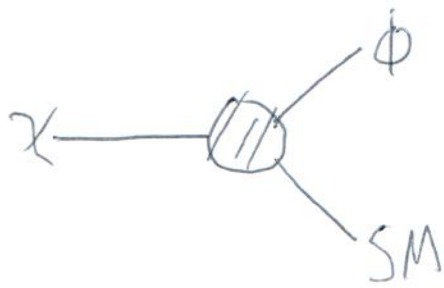


A) indirect detection

annihilations



decay



- CMB probes energy injection during recombination
  $T_{rec} \sim 0.3$ eV $\quad z_{rec} \sim 1100$
- energy from annihilations:

$$\frac{dE}{dt\,dV} = n_\chi^2 \langle \sigma v \rangle f(z)\, m_\chi = \rho_\chi^2 f(z) \frac{\langle \sigma v \rangle}{m_\chi}$$

- efficiency factor: $f(z)$
  $f_{eff} = f(z=600) \sim \mathcal{O}(1)$ for SM particles (not ν)
  1506.03811

- Planck: $\frac{f_{eff} \langle \sigma v \rangle}{m_\chi} < 3.2 \times 10^{-28} \frac{cm^3}{s \cdot GeV}$

1807.06209

$$m_\chi > 19 \, GeV \times \left(\frac{f_{eff}}{0.2} \right) \times \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26} cm^3/s} \right)$$

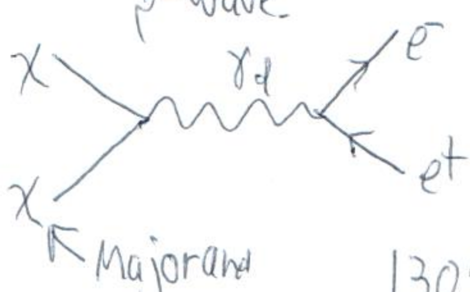
- light WIMPs excluded by CMB
- loophole: $\langle \sigma v \rangle_{rec} \ll \langle \sigma v \rangle_{FO}$

$$\langle \sigma v \rangle = \langle a + b v^2 + O(v^4) \rangle$$

s-wave: $a \neq 0$ p-wave: $a = 0$, $b \neq 0$

ex) s-wave:

p-wave:



1305.1611

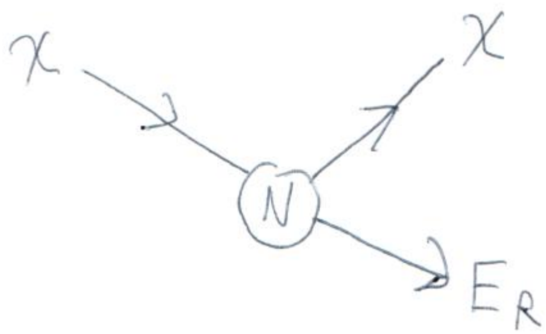
- p-wave is CMB safe:

$$v_{DM} = \sqrt{\frac{3 T_{DM}}{m_{DM}}} < \sqrt{\frac{3 T_{rec}}{m_{DM}}} \sim 5 \times 10^{-5} \sqrt{\frac{1 \, GeV}{m_{DM}}}$$

- forbidden is CMB safe:

$$\langle \sigma v \rangle_{rec} \sim \underbrace{e^{-\delta m / T_{rec}}}_{\ll 1} \frac{\alpha_d^2}{m_\chi^2}$$

B) direct detection



- momentum transfer: $q \sim m_\chi v$

$$v \sim \sqrt{\frac{G M_h}{R_h}}$$

- Milky Way $M_h \sim 10^{12} M_\odot$, $R_h \sim 100\ \text{kpc}$

$$v \sim 7 \times 10^{-4} c \sim 200\ \text{km/s}$$

$$E_R = \frac{q^2}{2 m_N} \sim 20\ \text{keV} \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2 \times \left(\frac{100\ \text{GeV}}{m_N}\right)$$

$$\rho_0 \simeq 0.3 \frac{\text{GeV}}{\text{cm}^3} \qquad \text{rate} \propto n_\chi = \frac{\rho_0}{m_\chi}$$

- Scattering rate per detector mass:

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \int dv\, v f(v) \frac{d\sigma}{dE_R}$$

N_T: # nuclei / mass

$f(v)$: assume: Maxwell-Boltzmann

- Spin-independent:

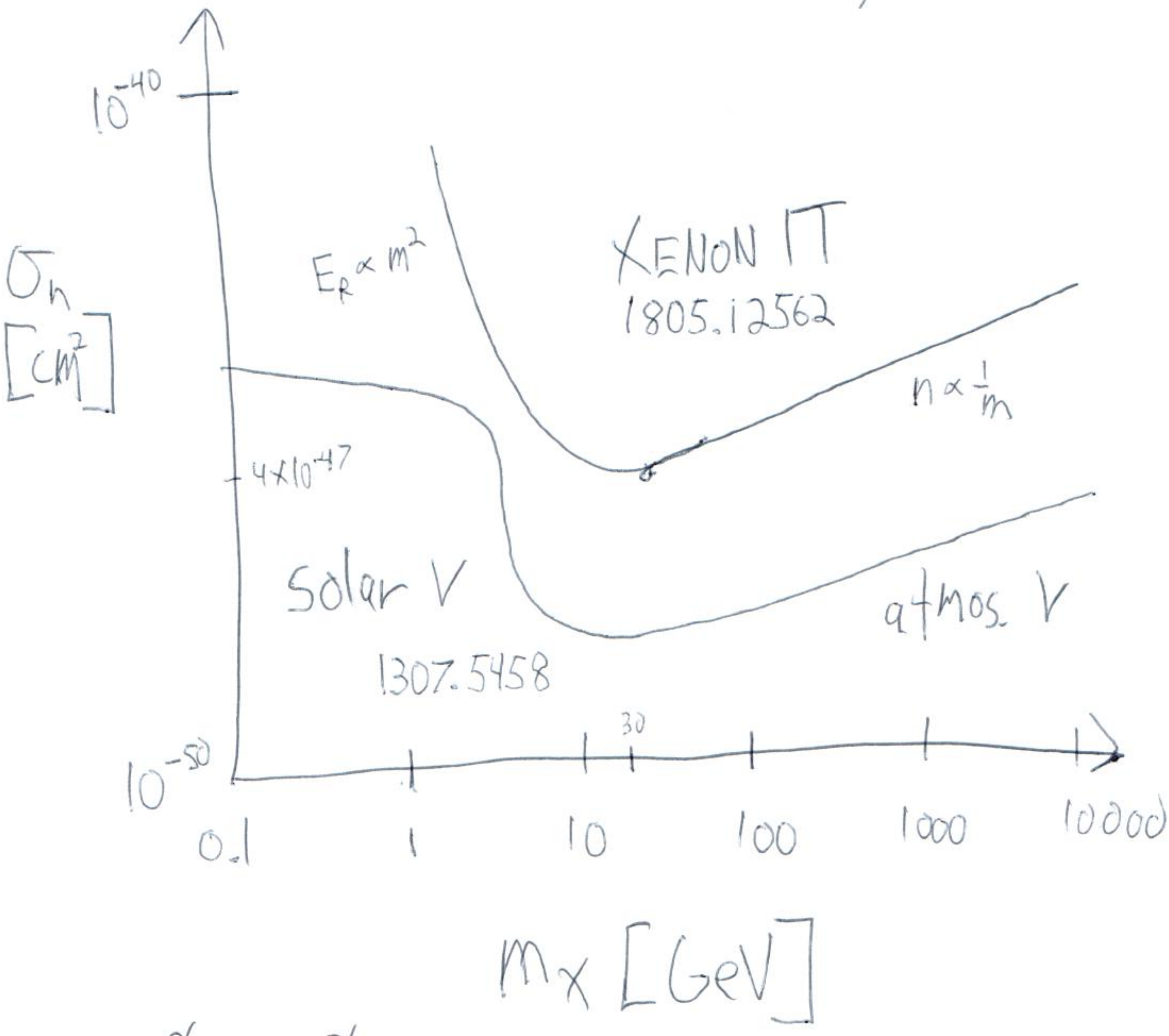
$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2}\,\frac{\sigma_n}{\mu_n^2}\,\frac{\left(f_p Z + f_n (A-Z)\right)^2}{f_n^2}\,F^2(E_R)$$

DM-neutron cross

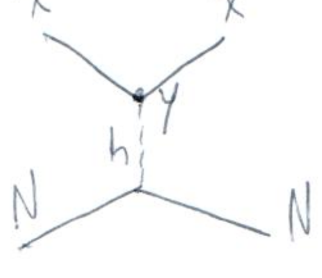
DM-nucleon reduced mass

$\propto A^2$ (nuclear coherence)

form factor



ex)



$$\sigma \simeq 8\times10^{-47}\,cm^2 \left(\frac{y}{0.01}\right)^2$$