Dark Matter

- What we know about DM:

  * Zwicky (1933) → mass of Coma cluster.

    I) count galaxies ~ 800

    add up total luminosity

    convert to mass $\sim 10^{8} M_{\odot}$
    (calibration from local systems)

    $M_{tot} \sim 2 \times 10^{45}$ g

    II) Observe velocity for galaxies $\sigma \sim (1000 \pm 300)$ km/s

    Virial theorem ⟶ grav. potential: $K = -\frac{1}{2} V \quad \left(V = -\frac{3}{5} G \frac{M^2}{R}\right)$

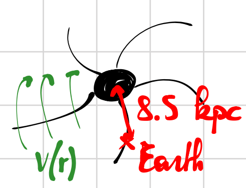
    ↳ $R \sim 10^{6}$ lyr

    $\Rightarrow M \sim \frac{\langle v^2 \rangle R}{G} \sim 3 \times 10^{47}$ g $\quad$ [1 lyr $\sim 3 \times 10^{8}$ m/s $\cdot\ \pi \times 10^{7}$ s $=$ $\sim 10^{16}$ m]

⇒ II is greater by a factor ~100 [~400 actually]

↳ luminous matter → 1% of total ⟶ 99% of mass not showing up! → DM

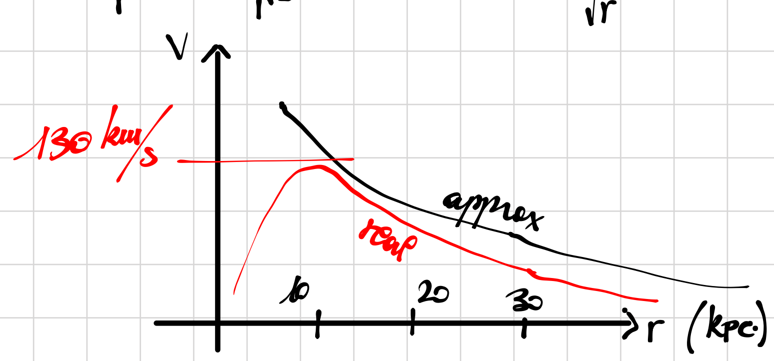
* 1970's: rotation curves

  → in spiral galaxies: 

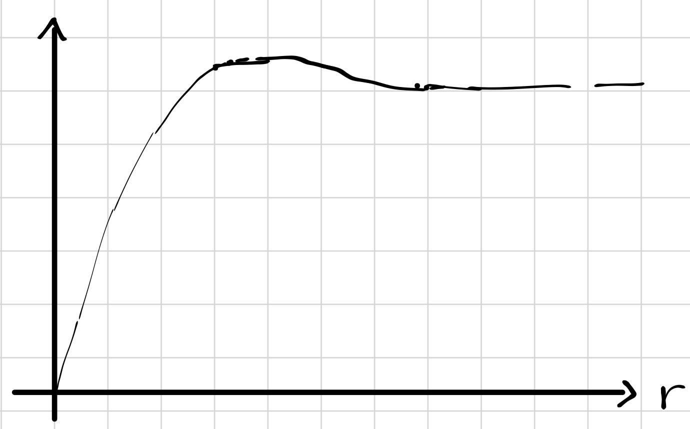
→ study of velocity $v = v(r)$

  ↳ If mass is concentrated in central region: Newtonian gravity

$$m \frac{v^2}{r} = \frac{GMm}{r^2} \longrightarrow v \propto \frac{1}{\sqrt{r}}$$



While data looked like:



* $v = \text{const} \longrightarrow M = M(r) \propto r \longrightarrow \rho \propto \frac{1}{r^2}$ s.t. $\int_0^R dr\, r^2 \rho \propto R$

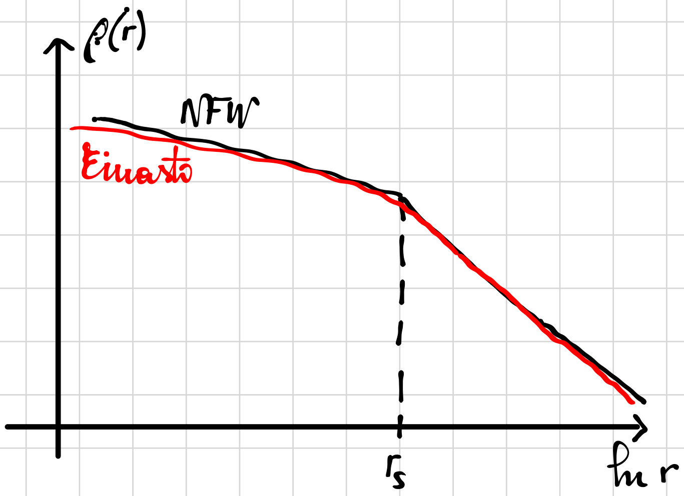
$\Rightarrow$ extended "halo" of non-luminous matter $\longrightarrow$ DM

or Newtonian gravity is wrong (at this scale) $\longrightarrow$ MOND (MOdified Newtonian Dynamics)

* Modern version: Simulate galaxy formations with DM (NR and grav. int. only)

$\Rightarrow$ NFW profile:

$$\rho(r) = \rho_0 \frac{\left(r/r_s\right)^{-1}}{\left(1 + r/r_s\right)^2}$$



$\Rightarrow$ Einasto profile:

$$\rho(r) = \rho_{-2} \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_2}\right)^{\alpha} - 1\right)\right]$$

from simul: $\alpha = 0.17$ for MW-sized halos

- r_2 s.t. $\frac{d \ln\rho}{d \ln r} = -2$

$\longrightarrow$ Very diff. to include everything inside the simulations!

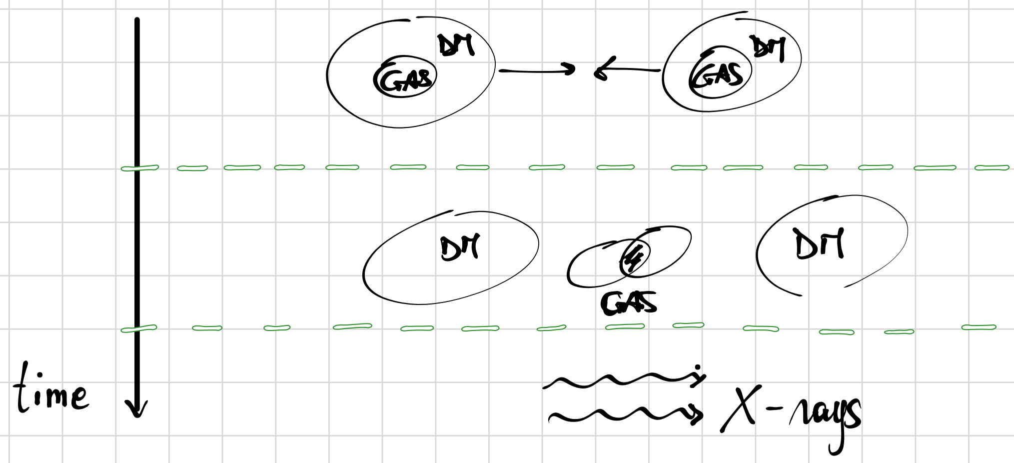
$\rightsquigarrow$ SMALL SCALE PROBLEMS of CDM

* discrepancies between sims and obs
* sims tend to overpredict DM density on small scales ($\lesssim 10$ kpc) [1707.04256]
* "too big to fail" / "cusp-core problem" $\longrightarrow$ dwarf galaxies $[10^7 - 10^8 M_\odot]$ seem to be less concentrated than predicted (evidence for $\sim 0.1 \div 1$ kpc "cores" of flat dens.)

* Some claimed evidence of < 10 kpc cores in:
  - galaxy clusters
  - galaxies

* must run sims with ordinary matter + DM to be more precise [1405.7544]

COLLIDING CLUSTERS



- X-rays → where GAS is
- Lensing → where MASS is

⇒ Constrains interaction (σ) for DM-DM scatt ⇒ $\frac{\sigma}{m} \sim O(1)\ \mathrm{cm}^2/\mathrm{g}$ [1605.04307]

→ What kind of self-interacting σ do you need to perturb the syst.?

scatt. rate $\gtrsim 1$ / DM part

$$\hookrightarrow \quad n_\chi \langle \sigma v \rangle \sim \frac{1}{\tau} \longrightarrow \frac{\rho_\chi}{m_\chi} \sigma v \sim \frac{1}{\tau} \longrightarrow \frac{\sigma}{m_\chi} \sim \frac{1}{\tau v \rho_\chi}$$

→ Near Earth: DM density: $\rho_\chi \sim 0.4\ \mathrm{GeV\ cm^{-3}}$

DM vel: $v \sim 10^{-3} c$

dynamical time (MW) / collision time (bullet clust)

DM time of interest: $\tau \sim 10^9$ yr (for MW (Milky Way))

$$\Rightarrow \frac{\sigma}{m_\chi} \sim 0.1 \div 1\ \mathrm{cm}^2/\mathrm{g} \sim \frac{1}{(100\ \mathrm{MeV})^3}$$ → QCD scale!

DM & CMB

LS surf.: $T \sim 0.3\,eV$ (10^3 present day temp.)

$z \sim 1000$

CMB homog up to 10^{-5}

→ plasma of γ, e^-, p + neutrinos + DM (?) [+ perturb to dens. temp.]

perturbations oscillate :

* gravity: density ↑
* rad. press : density ↓

⇒ OSCILLATIONS

→ Anisotropies of CMB probe oscill. pattern ⇒ depends on fraction of matter that feels rad. pressure

⇒ Measure :

i) amount of matter that interacts w/ radiation. ("baryons")

ii) amount of matter that interacts gravitationally only

→ to percent-level precision DM is about 0.265 of critical density

* After LS surface → γ decouple from baryons
→ overdensities grow under gravity collapse eventually into virialized structures
→ CDM : small structures → large struct.

→ if DM is too fast (relativ): HDM → free streaming lenght erases small pert. struct
⇓
LARGE STRUCT FIRST (Galaxy cluster)
→ INCONSISTENT
[should be $O(1\%)$ or less of total DM]

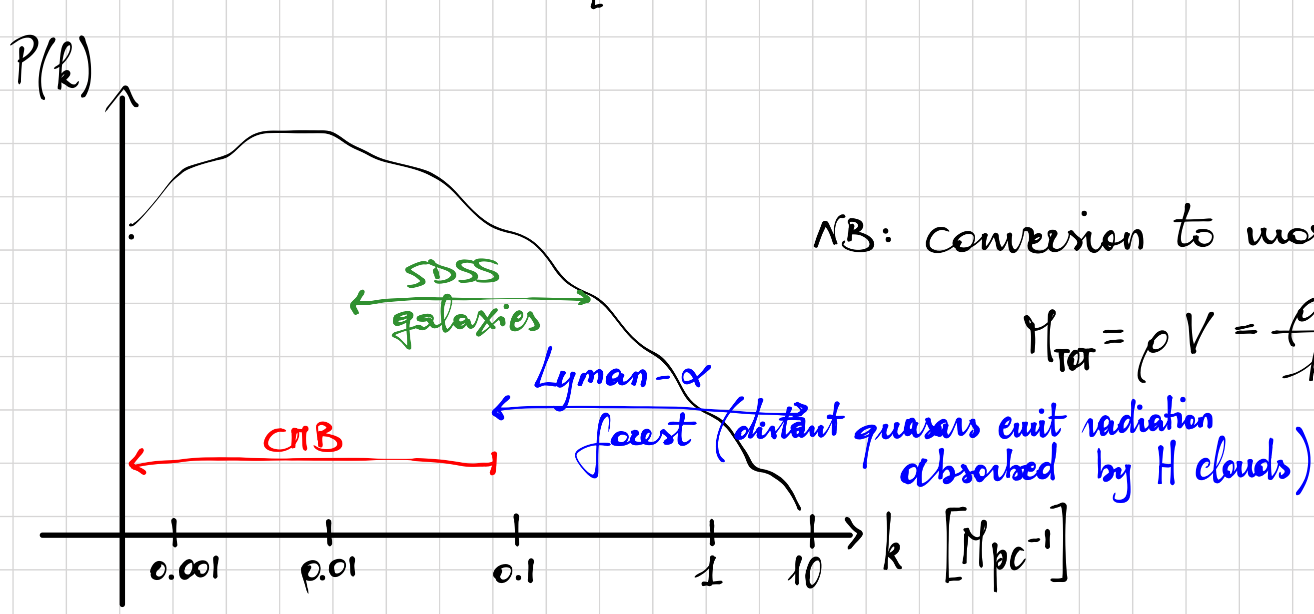
intermediate CDM - HDM
↓
→ WDM: non negligible FS lenght wipes out small struct

Matter Power Spectrum

$$\delta(\vec{r}) = \frac{\rho(\vec{r}) - \bar{\rho}}{\bar{\rho}} \longrightarrow \delta(\vec{k}) = \mathcal{F}[\delta(\vec{r})](\vec{k}) \Rightarrow P(\vec{k}) = \langle |\delta(\vec{k})|^2 \rangle$$

matter density

power spectrum



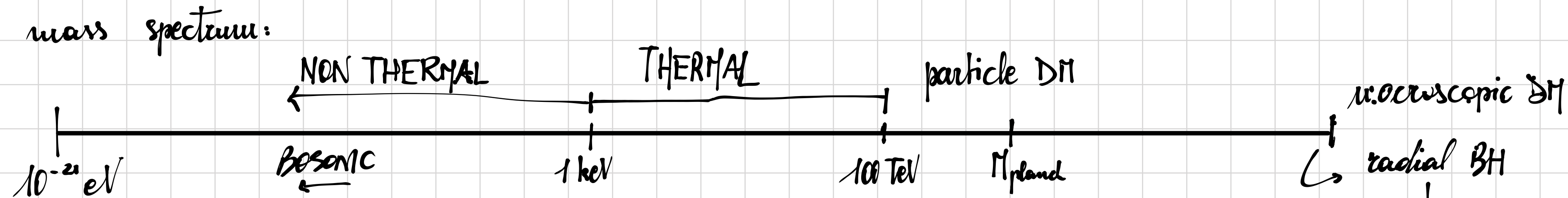
NB: conversion to mass scale

$$M_{TOT} = \rho V = \frac{\rho_{DM}}{k^3}$$

- WDM: $k_{FS} \sim 5 \text{ Mpc}^{-1} \left(\frac{m_X}{1 \text{ keV}}\right)\left(\frac{T_\nu}{T_X}\right)$ [1306.2314, 1702.01764]

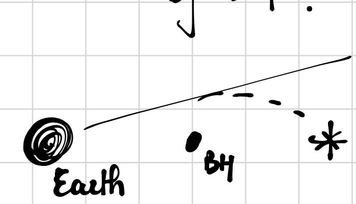
$m_X \gtrsim 5.3$ keV if thermal

DM mass spectrum:



- $m_{DM} \gtrsim \frac{1}{\text{galaxy size}} \gtrsim 10^{-21}$ eV from Ly-α limits

↓
could they be 100% of DM?



[1705.05567]

- thermal DM: $m_{\chi} \gtrsim 1$ keV $m_{\chi} \lesssim 100$ TeV (unitarity limits)

→ Tremaine - Gunn bound: phase - space density $\sim \frac{n_\chi}{p^3} \sim \frac{\rho_\chi}{m_\chi (m_\chi v)^3} \lesssim 2$ (fermions)

$$\Rightarrow m_\chi \gtrsim \left(\frac{\rho_\chi}{v^3}\right)^{1/4} \sim \left(\frac{1\ \mathrm{GeV/cm^3}}{(10^{-5} c)^3}\right)^{1/4} \sim \text{few hundred eV}$$

MW measurements

⇒ 1) light, bosonic, cold DM (non thermal):

* can have mass down to 10^{-21} eV → AXION

2) Thermal → $m_\chi \gtrsim$ keV

* can be bos/ferm
* inter with SM

→ WIMP

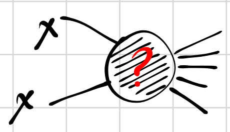
[$m_\chi \lesssim 1$ MeV → acts as radiation during nucleosynthesis]

Thermal freeze out

DM evolution: * no no.-changing interactions : $\frac{d}{dt}(n_\chi a^3) = 0$

$$\frac{dn_\chi}{dt} + 3 H n_\chi = 0$$

Suppose non grav. interact:

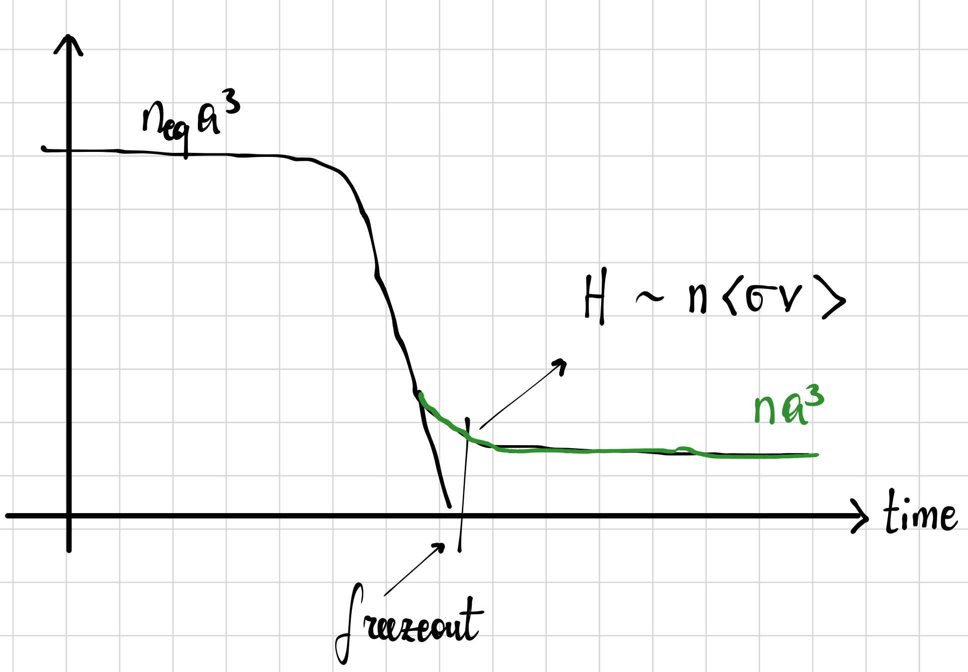


[posit on annihilation process 2DM ↔ SM]

⇒ $T \gg m_\chi$ ⟿ $T \lesssim m_\chi$

DM + DM ⟷ SM   DM + DM ⟶ SM [DM depletion!]

$$\Rightarrow \frac{dn_\chi}{dt} + 3 H n_\chi = -\frac{n_\chi^2}{2} \langle \sigma v \rangle$$



Same can happen for relat $\to$ $n_{\text{late time}} \sim T^3_{\text{late time}}$

$\to$ COLD RELIC: f.o. while non relat. $\to H \sim \langle \sigma v \rangle (m_\chi T)^{3/2} e^{-m_\chi/T}$

$$H^2 \sim \rho \sim T^4 \longrightarrow H \sim \frac{T^2}{m_{pl}}$$

$\to$ $H = H(m_\chi)\, x^{-2}$ $\quad \left(x = \frac{m_\chi}{T}\right)$

$\hookrightarrow$ $$e^{-x_f} = \frac{x_f^{-1/2}}{\left(\frac{m_\chi^3 \langle \sigma v \rangle}{H(m_\chi)}\right)}$$

$\Rightarrow$ $n_f \sim m_\chi^3\, x_f^{-\frac{3}{2}}\, e^{-x_f} \sim H(m_\chi)\, x_f^{-2} / \langle \sigma v \rangle$

$\Rightarrow$ After freezeout DM no. scales as $1/a^3$ $\longrightarrow$ same as photon no. at freezeout

$$n_\gamma \sim T_f^3 \sim m_\chi^3 / x_f^3$$

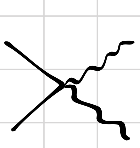
$\Rightarrow$ $$\frac{n_\chi}{n_\gamma} \sim \underbrace{\frac{H(m_\chi)}{m_\chi^2}}_{\sim \frac{1}{m_{pl}}} \cdot \frac{x_f}{m_\chi} \cdot \frac{1}{\langle \sigma v \rangle} \Rightarrow \frac{\rho_\chi}{n_\gamma} \sim \frac{m_\chi n_\chi}{n_\gamma} \sim \frac{1}{m_{pl}} \cdot \frac{x_f}{\langle \sigma v \rangle}$$

i.e.: $\langle \sigma v \rangle$ determines ρ_χ today!

$\Rightarrow$ DM mass density ~ 5 GeV per baryon no. dens:

$$\frac{\rho_\chi}{n_\gamma} \sim 2.5 \times 10^{-9}\ \text{GeV} \sim \frac{1}{m_{pl}} \frac{x_f}{\langle \sigma v \rangle}$$

- Guess $x_f \simeq 1 \Rightarrow \langle \sigma v \rangle \sim \frac{1}{100\ \text{TeV}^2}$

 $\sim \frac{\alpha_\chi^2}{m_\chi^2}$ $\Rightarrow$ if $\alpha_\chi \lesssim 1 \to m_\chi \lesssim 100$ TeV

Matter - radiation equality

$$\rho_m = \rho_{rad} \Rightarrow \overset{n_\chi m_\chi \sim T_{eq}^4}{\rho_\chi \sim \rho_{rad}} \Rightarrow n_\chi \sim n_f \left(\frac{T_{eq}}{T_f}\right)^3 \text{ if } T_{eq} < T_f$$

→ assume $T_f \sim m_\chi$: $n_f \sim T_{eq} m_\chi^2 \Rightarrow H_f \sim \frac{T_f^2}{m_{pl}}$ during RD

⇝ $\langle \sigma v \rangle \sim \frac{1}{m_{pl} T_{eq}}$.

→ classic WIMP [int. mediated by W, Z, H]

↳ e.g.: lightest NEUTRALINO in SUSY (fermionic superp. of W, Z, H)

AXION DM

→ motivated by strong CP problem [hep-ph/0011376]

$$\Rightarrow \mathcal{L}_\theta = \frac{\theta}{16\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$ → gluon field strength

↳ expected from CP violation in quark sector

→ induce neutron EDM: $d_n \simeq 5.2 \times 10^{-16}\, \theta$ e cm

but experim $\theta \lesssim 10^{-10}$

→ Axion solution:

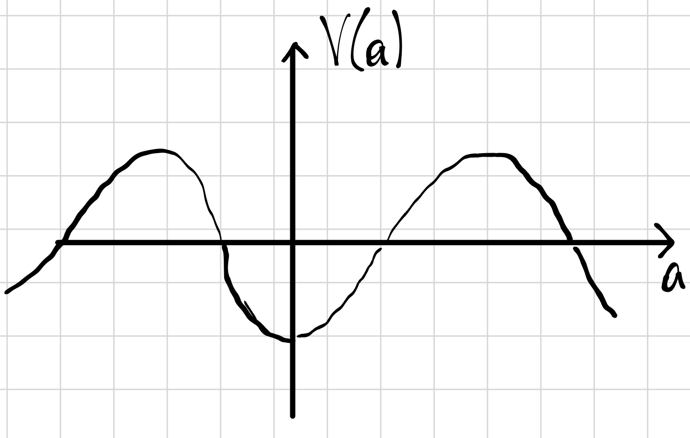
replace θ by $\frac{a}{f_a}$ → Need to explain why $\langle a \rangle$ evolves to small value

a → axion field

f_a → effective coupling

→ Effective potential for a :

$$V(a) = - m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} \cos\left(\frac{a}{f_a}\right)$$



→ minima at $a = 2n\pi$

Examine around $a=0$: $V(a) \sim - m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} + \frac{1}{2} a^2 \left(\frac{f_\pi}{f_a}\right)^2 m_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d}$

$$\Rightarrow m_a = \frac{f_\pi m_\pi}{f_a} \left(\frac{m_u m_d}{(m_u + m_d)^2}\right)^{1/4} \simeq 0.6 \text{ meV} \left(\frac{10^{10}\text{ GeV}}{f_a}\right)$$

→ small m_a ⇒ small $\frac{1}{f_a}$

→ Were axions ever in thermal equil. with SM?

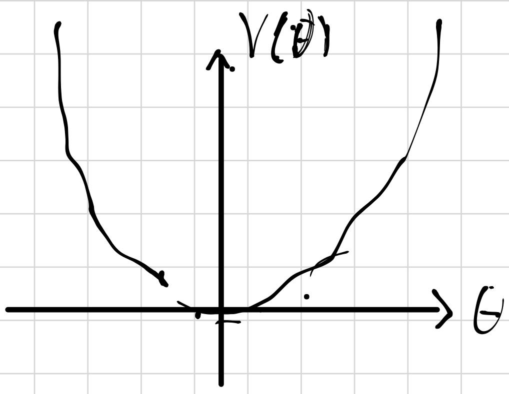
→ Are they stable?

* Time scale for decay to photons → $\tau \sim 10^{24}\,s \left(\frac{m_a}{1\,eV}\right)^{-5} \Rightarrow m_a \lesssim 20\,eV.$

* if $10^{-3}\,eV \lesssim m_a \lesssim 1\,eV$ ⟶ axions can be (subdominant) HDM

$$\frac{\Omega_{axions}}{\Omega_{DM}} \sim \mathcal{O}\left(\frac{m_a}{100\,eV}\right)$$

Consider $\theta = \langle a \rangle$:



$\rightarrow V(\theta)\Big|_{minimum} = \frac{1}{2} m_a^2 \theta^2$ ⟶ classical scalar field

e.o.m.: $$\frac{d^2\theta}{dt^2} + 3H\frac{d\theta}{dt} + m_a^2\,\theta = 0$$

1) $m_a \ll H \rightarrow \theta = const$ is a sol.

2) $m_a \gtrsim H$ → oscillations! $\quad$ [if no H term: $\theta \propto \theta_0 \cos(m_a t)$]

→ More carefully:

$$\theta(t) = \theta_0\, f(t) \cos(m_a t) \qquad [\,f(t) \propto a^{-3/2}\,]$$

$f(t)$: slowly varying w/ time

Moreover: ENERGY DENS: $\rho \propto a^{-3}$

Then

* early times $\longrightarrow \rho = \frac{1}{2} m_a^2 \theta_0^2$.

* $H \sim m_a \longrightarrow \rho \sim a^{-3}$

$\Rightarrow$ minima at $\frac{\theta}{f_a} = \theta = 2n\pi \longrightarrow -\pi \leq \theta < \pi \longrightarrow$ MISALIGNEMENT ANGLE

$\longrightarrow$ if axions are 100 % of DM $\longrightarrow f_a \gtrsim 5 \times 10^{11}$ GeV $\longrightarrow m_a \lesssim 0.1$ meV

1) θ set after inflation ($H_I \gg f_a$) $\longrightarrow$ diff parts of cosmos should have diff $\theta \longrightarrow$ now: ensemble average

2) θ set before $\longrightarrow \theta$ same everywhere (could be very small)

Axion searches: [1602.00039]

1) 

2) "catch" DM axions using B-fields $\rightarrow$ induce EM

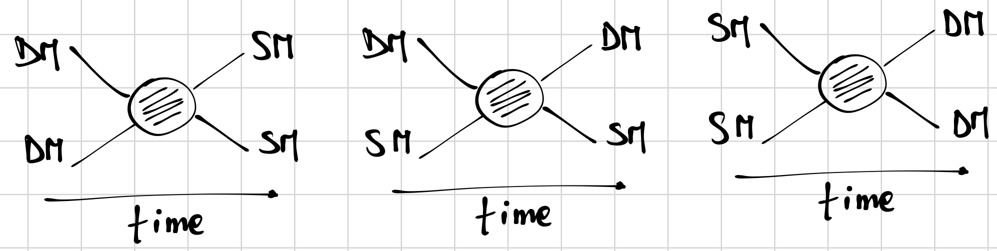
$\rightarrow$ photon-axion conversion:

* astro/cosmo : enhance stellar cooling (0806.2807)
  ↳ see γ from higher redshifts sources

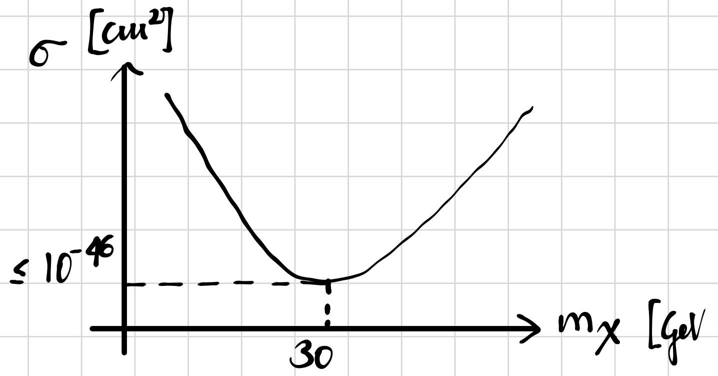
* light-shining through a wall [1009.4875]

* ADMX exp [1310.8642]
* ABRACADABRA [1602.01086]
* ...

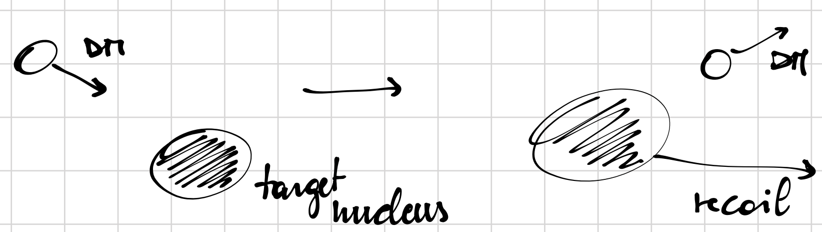
DM searches: → direct searches
→ collider



INDIRECT DIRECT COLLIDER



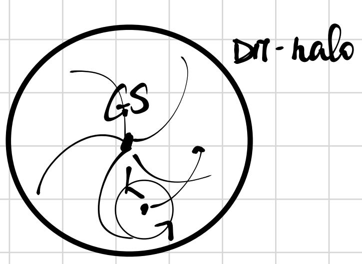
* DIRECT DETECTION



⇒ arXiv: 1705.06655

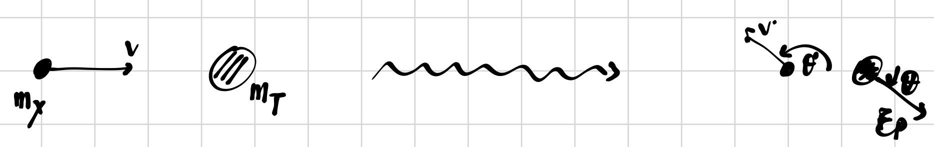
→ underground experim.

→ look for DM-specific features such as periodic modulation "WIMP wind" due to Sun's motion through MW Earth's motion ⇒ signal modulates with period of one year



* Consider DM of mass m_χ → target nucleus of mass m_T (at rest in lab frame)

observable: $\frac{dR}{dE_R} = \frac{\text{scatt. rate}}{\text{recoil energy}}$



$$\Rightarrow \frac{1}{2} m_\chi v^2 = \frac{1}{2} m_\chi v'^2 + E_R \longrightarrow E_R = \frac{2\mu^2 v^2 \cos\theta}{m_T} \quad , \quad \mu = \frac{m_T m_\chi}{m_T + m_\chi}$$

$$\hookrightarrow \quad 0 \leq E_R \leq \frac{2\mu^2 v^2}{m_T}$$

* $m_\chi \ll m_T \Rightarrow \mu \sim m_\chi \Rightarrow E_R \sim 1$ keV → very hard to see!

* $m_\chi \sim 100$ GeV, $v \sim 10^{-3} \Rightarrow (E_R)_{max} \lesssim 200$ keV $\quad (m_T \sim m_\chi)$

→ Spectrum/rate?

⇒ How do ampl. from diff. nucleons in T combine?

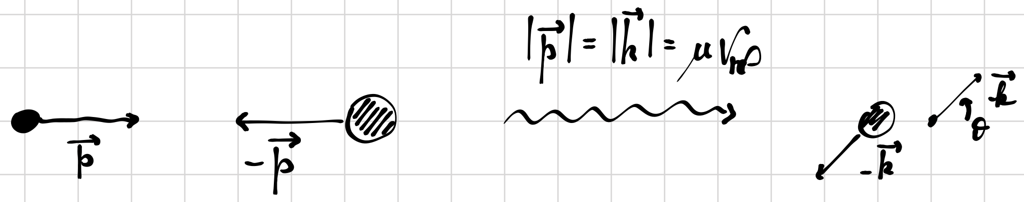
- spin indep → constr. interf. between nucleon ampl. → nuclear form factor
- spin dep → rate scales as total spin of nucleus

• How does DM couple to quarks and gluons?

[does DM couple equally to p and n?]

⇒ Astrophysical inputs ⟶ DM density & velocity

⇒ SPECTRUM:



⇒ 3-momentum transfer: $q^2 = |\vec{p} - \vec{k}|^2 = 2\mu^2 v_{rel}^2 (1 - \cos\theta) = 2 m_T E_R$

$$\Rightarrow \frac{dR}{dE_R} = \frac{m_T}{\mu^2 v_{rel}^2} \frac{dR}{d\cos\theta} \overset{\text{no } \phi \text{ dep.}}{=} \frac{2\pi m_T}{\mu^2 v_{rel}^2} \underbrace{\frac{dR}{d\Omega}}_{\text{differential rate}}$$

$$n_\chi N_T v_{rel} \frac{d\sigma}{d\Omega}$$

$$\Rightarrow \frac{dR}{dE_R} = \frac{2\pi (\rho_\chi / m_\chi) m_T N_T}{\mu^2 v_{rel}^2} \frac{d\sigma}{d\Omega}$$

particle physics: $\left.\frac{d\sigma}{d\Omega}\right|_{com} = \frac{1}{s} \cdot \frac{1}{64\pi^2} |M|^2$

Suppose:

$$M = \underbrace{\mathcal{F}(q)}_{\text{form-factor}} \left[Z f_p + (A - Z) f_n \right] \quad \text{where } q = \sqrt{2 m_T E_R}$$

→ Def. "single nucleon σ": $\sigma_{\chi n} := \sigma_{\chi T}\big|_{q=0} \frac{\mu_{\chi n}^2}{\mu^2} \frac{1}{A^2}$ → $\mathcal{F}(0) = 1$

→ Assume no angular dep in σ, i.e. $\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi}$

$$\sigma_{\chi n} = \frac{1}{16\pi} \frac{\mu_{m}^2}{m_\chi^2 m_T^2} \frac{|Z f_p + (A-Z) f_n|^2}{A^2}$$

$$\Rightarrow \frac{dR}{dE_R} = \underbrace{\frac{\sigma_{\chi n}}{m_\chi \mu_{\chi n}^2}}_{\text{PARTICLE PHYSICS}} \underbrace{A^2 m_T N_T}_{\text{TARGET}} \underbrace{\frac{\rho_\chi}{2 v_{rel}}}_{\text{ASTRO-PH}} \left| \mathcal{F}\left(\sqrt{2 m_T E_R}\right) \right|^2$$

NB: v_{rel} has a distribution

$$\frac{d\rho_\chi}{dv_{rel}} = \rho_\chi f(v_{rel}) \quad \text{s.t.} \quad \int_0^\infty dv\, f(v) = 1$$

Typical approach: → assume $\sigma_{\chi n}$ indep of $E_R (q^2)$ and v_{rel}

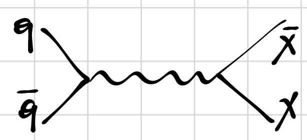
→ assume $f(v_{rel}) = \frac{4}{\sqrt{\pi}} \frac{1}{v_0^3} v^2 e^{-\frac{v^2}{v_0^2}}$

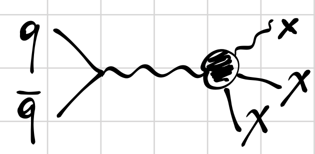
Recall that the spectrum extends from $E_R = 0$ to $E_R = \frac{2\mu^2 v_{lab}^2}{m_T} \Rightarrow v_{min} = \sqrt{\frac{m_T E_R}{2\mu^2}}$

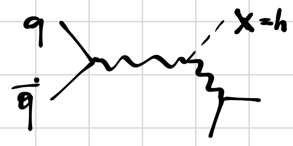
$$\Rightarrow \int_{v_{min}} dv \, \frac{1}{v} f(v) = \frac{2}{\sqrt{\pi}} \frac{1}{v_0} e^{-\frac{E_R m_T}{2\mu^2 v_0^2}} \longrightarrow \text{shape of spectrum: exponentially falling funct. of } E_R \cdot |\mathcal{F}(E_R)|^2$$

Collider searches

- DM is stable → if produced should escape
- should give rise to missing E_T
- search in "mono-X" channels
- look for visible partner recoiling from invisible DM







ATL-PHYS-PROC-2016-048

→ model dep. searches

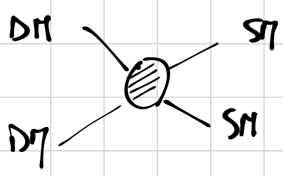
* Wino, higgsino DM - nearly-degenerate chargino, disappearing track searches
* DM bound states could show up in resonance or multilepton searches

→ approaches:

1) build UV-complete model w/ full spec. (eg SUSY)
2) build simplified model w/ minimal ingredients ⟶ generic searches!

→ Indirect detection of DM

• EARLY UNIVERSE:



→ After freezeout of DM relic (thermal) what could annihilation do?

→ AFTER f.o. : $n \sim a^{-3}$ $\Longrightarrow$ $\langle \sigma v \rangle n^2 a^3 H^{-1} \sim a^{-3} H^{-1} \longrightarrow \begin{cases} \sim a^{-1} & (RD) \\ \sim a^{-3/2} & (MD) \end{cases}$

in a Hubble time

At f.o. fract of DM annihilating per H^{-1} is $O(1)$

e.g.: take 100 GeV DM f.o. happen. around 1 TeV

BBN : $T \sim 1$ MeV (~ 1 in 5000 DM part annihilates per H^{-1})

↳ 10^{-3} of total mass energy in baryons is liberated

↳ ~ 1 MeV/baryons [0906. 2087]

CMB: $T \sim 1$ eV → $O\left(\frac{1}{5} \times 10^{-9}\right)$ of DM will annihilate ~~per~~ H^{-1}.

⇒ 10^{-9} of energy per baryon added ⟶ $\frac{1 \text{ eV}}{\text{baryon}}$

→ enough to ionize 10% of hydrogen

Const thermal σ is ruled out by CMB measurements