IV Dark matter ~~1603.03797~~, 1705.01987

IV.1. Evidence for dark matter ← 85% of the universe matter density (Planck data)

- Galaxy rotation curve (see chap I)
  ↳ also at the level of galaxy cluster dynamics
- CMB (see chap I + below)
- Gravitational lensing (see chap I)
- Dwarf galaxies: contain 100-1000 times less stars than normal galaxies ($10^8 - 10^9$ stars; Milky Way: $\sim 10^{11}$ stars)
  ↳ could be made of 90% of DM, or even more
- Bullet cluster: formed by the collision of 2 cluster of galaxies. Grav. lensing shows that normal and dark matter are concentrated in ≠ location
- structure formation: see chap. I.

⇒ identify the nature of DM is one of the primary question in (astro) particle physics

→ this lecture: DM from a particle physicist's standpoint
↳ the most attractive scenario involves thermal relics

IV.2. From photon and neutrino relics to light CDM

IV.2.1 Basic cosmological parameters

* The Hubble constant H_0 ⇝ describes the expansion of the universe
  ⇝ two objects in the universe move away from each other with a velocity proportional to their distance:

$$H_0 = \frac{\dot{r}}{r} \simeq 70\ \mathrm{km/s/Mpc} \quad \left(\Leftrightarrow h = \frac{H_0}{100\frac{\mathrm{km}}{\mathrm{s\,Mpc}}} \simeq 0.7\right)$$

* The cosmological constant Λ ⇝ dark energy ⇝ accelerating expansion of the universe
  ⇝ defined through the Einstein-Hilbert action $S_{EH} = \frac{M_{Pl}^2}{2}\int d^4x\sqrt{-g}\,(R-2\Lambda)$

⇒ we usually use $\Omega_\Lambda = \frac{\Lambda}{3H_0^2}$ ≡ cosmological constant part of the energy budget of the universe

* The matter content of the universe : $\Omega_m = \frac{\rho_m}{\rho_c}$ ← matter density; ρ_c ← critical density

$= 3\bar{M}_{Pl}^2 H_0^2 \simeq (2.5 \cdot 10^{-3}\, eV)^4$ ← = density allowing to switch from an expanding to collapsing universe (H_0 impact = G impact)

Similarly: $\Omega_r = \frac{\rho_r}{\rho_c}$ = radiation density

Ω_m can be split into Ω_b (baryons) and Ω_χ (dark matter)

IV.2.2 Expanding universe

The expansion of the universe depends on time : $H(t)$ (The Hubble constant is not constant).

A line element in space-time is in general written as

$$ds^2 = dt^2 - \underset{\substack{\uparrow \\ \text{scale factor}}}{a^2(t)} \left(\frac{dr^2}{1-\underset{\substack{\uparrow \\ k = \pm 1, 0 \,\equiv\, \text{curvature}}}{k} r^2} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\varphi^2 \right)$$

= motion of objects in the universe due to its expansion ($r(t) = a(t)\, r(t)$) $\Rightarrow$ $\boxed{H(t) = \frac{\dot{a}(t)}{a(t)}}$ (from $H(t) = \frac{\dot{r}(t)}{r(t)}$)

Assuming the general metric above, we can solve Einstein equations

→ Friedmann equation : $\frac{\dot{a}^2(t)}{a^2(t)} + \frac{k}{a^2(t)} = \underbrace{\frac{\rho_m(t) + \rho_r(t) + \rho_\Lambda(t)}{3\bar{M}_{Pl}^2}}_{\text{full energy density of the universe}}$

$\equiv \rho_t(t)$ ($\rho_\Lambda(t) = \Omega_\Lambda(t) \bar{M}_{Pl}^2$)

→ symmetry of the energy-momentum tensor: $\frac{2\ddot{a}(t)}{a(t)} + \frac{\dot{a}^2(t)}{a^2(t)} + \frac{k}{a^2(t)} = -\frac{P(t)}{\bar{M}_{Pl}^2}$

($P(t)$ = pressure corresponding to T_{00})

$$\Rightarrow \frac{\ddot{a}(t)}{a(t)} = -\frac{\rho_t(t) + 3P(t)}{6\bar{M}_{Pl}^2}$$ = Friedmann-Lemaître-Robertson-Walker model

- Pressure and density are however related (eq. of state in thermodynamics)

$$p(t) = \begin{cases} 0 & \text{non-relativistic matter} & m \\ \rho(t)/3 & \text{relativistic radiation} & r \\ -\rho(t) & \text{vacuum energy} & \Lambda \end{cases}$$

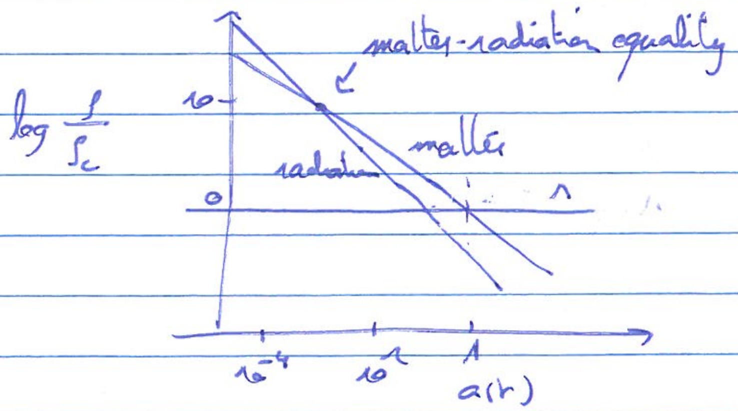
$\Rightarrow$ We need the evolution of ρ with time. From general relativity (vanishing covariant derivative of the momentum tensor):

$$\rho(a) \propto \begin{cases} a^{-3} & \text{non-rel. matter} \\ a^{-4} & \text{rel. radiation} \\ \text{const} & \text{vacuum energy} \end{cases} \quad \text{with } a(t) \sim \begin{cases} t^{2/3} \\ t^{1/2} \\ e^{\sqrt{\Lambda(t)/3}\, t} \end{cases}$$

↳ is not a power law
$\Rightarrow$ inflationary expansion

IV. 2.3. Universe composition

Since at constant entropy, $a(T) \sim 1/T$:
- at large T, the universe is dominated by radiation
- with $T \downarrow\downarrow$, the relative fraction of matter $\uparrow\uparrow$
- Λ is constant $\rightarrow$ will eventually dominate ($\sim$ today)



Friedmann eq.

In the early universe, k and ρ_Λ play no role $\Rightarrow$
$$\begin{cases} H^2(t) = \dfrac{\rho_m(t) + \rho_r(t)}{3 \bar{M}_{pl}^2} \\ 1 = \Omega_m(t) + \Omega_r(t) \end{cases}$$

contains both baryons and DM.

We now link the time t with the temperature T. What matters is the theory number of degrees of freedom g (= 2 for massless boson, 2 for fermions, etc...)

$$\rightarrow \rho_r(T) = \frac{\pi^2}{30} g_{eff}(T)\, T^4$$

$$\hookrightarrow \sum_{boson} g_b \frac{T_b^4}{T^4} + \sum_{ferm.} \frac{7}{8} g_f \frac{T_f^4}{T^4}$$

$T_b \neq T$, $T_f \neq T$ if not in thermal equilibrium

$\rho = g\int \frac{d^3p}{(2\pi)^3} \frac{E}{e^{E/T} \mp 1}$

$n = g\int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{E/T} \mp 1}$

ex: $g_{eff}(T > m_t) = 106.75$ [SM]

$g_{eff}(T_0) = 3.6$ [SM]

$$\rightarrow \text{In the early universe: } H^2(t) = \left(\frac{\pi\sqrt{g_{eff}}}{\sqrt{90}} \frac{T^2}{M_{Pl}}\right)^2 \quad (\rho_m \sim 0)$$

t, T and H are connected ≡ 3 possible evolution scales

If matter plays a role: $\rho_m = m g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$ (quantum mechanics effects irrelevant: $g_{eff} \rightarrow g$)

(Similarly: $n_m = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$)

$n_b = \frac{\zeta_3}{\pi^2} g T^3$ and $n_f = \frac{\zeta_3}{\pi^2} \frac{3}{4} g T^3$)

IV.2.4 Relic photons

- In the early universe, all particles were pair-produced in a thermal bath. Their density dropped with $\frac{1}{T}$.
  - → important to know which particles are in equilibrium.
    - ↳ photon example
- Photons maintain equilibrium through $e^-\gamma \rightarrow e^-\gamma$: $\sigma_{e\gamma} = \frac{\pi\alpha^2}{m_e^2}$ ($E, T \ll m_W$).
- $\Gamma = \sigma v n$ ≡ interaction rate of the above process. ⇒ drops with the expansion of the universe ($n \searrow\searrow$)
  - velocity, number density
  - ⇒ at some point, photons will decouple.

$$\Downarrow$$

$$\frac{\Gamma(T_{dec})}{H(T_{dec})} = 1$$

However, at the time of photon decoupling, nucleosynthesis happened → very few electrons.

$$\Rightarrow n_e(T_{dec}) = \underbrace{\frac{n_e(T_{dec})}{n_B(T_{dec})}}_{\substack{\sim 10^{-2} \\ \text{hypothesis}}} \underbrace{\frac{n_B(T_{dec})}{n_\gamma(T_{dec})}}_{\substack{\sim 10^{-10} \\ \text{data}}} \underbrace{n_\gamma(T_{dec})}_{\substack{\frac{\zeta^3}{\pi^2} 2T^3 \\ \text{section 2.3}}}$$

$$\Rightarrow \frac{\Gamma(T_{dec})}{H(T_{dec})} = 1 \Leftrightarrow \frac{\pi\alpha^2}{m_e^2} 10^{-12} \frac{\zeta^3}{\pi^2} 2T_{dec}^3 \frac{\sqrt{90}}{\pi\sqrt{g_{eff}}} \frac{M_{Pl}}{T_{dec}^2} = 1$$

$$\Leftrightarrow T_{dec} = 10^{12} \frac{\pi^2}{6\sqrt{10}\,\zeta_3} \frac{m_e^2}{M_{Pl}} \frac{\sqrt{g_{eff}}}{\alpha^2} \quad \sim 5.5 \ (e^\pm \text{ and } \gamma)$$

$$\simeq 0.26 \text{ eV} \equiv \text{CMB photons}$$

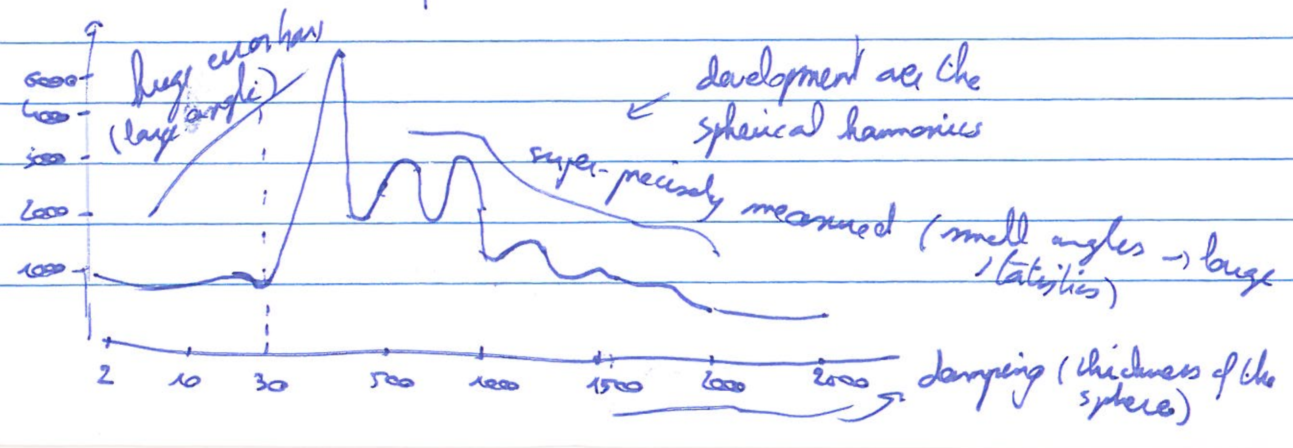
<u>Rq</u>: $T_{dec} \ll 13.6$ eV to avoid the photon tail (energetic and could ionize H)

After accounting for the expansion of the universe: $T_{0,\gamma} \approx \frac{T_{dec}}{1000} \approx 2.73$ K.

↳ $n_\gamma(T_0) \approx 410$ photons / cm^3.

- <u>CMB</u>: fluctuations driven by the fact that Earth moves in the CMB. Main effect = dipole + $\delta T/T$ fluctuation of $\sim 10^{-5}$.
  ⇒ favors rapid inflation ($T \sim$ constant)

  Modifications of this at temperature ⇔ new picture instead of $e^\pm$, γ, neutrinos and DM particles in the thermal bath at T_{dec} (neglected so far).



The structure exhibits several physics effects:

(1) acoustic osillations: in the early universe, photons are strongly coupled with baryons and electrons ≡ fluid. DM generates gravitational wells → matter accumulation → photon pressure against the wells ≈ oscillations ≈ sound waves

(2) Sachs-Wolfe effects: impact of gravity on CMB photons (the grav. potential changes during the decoupling)

(3) Peak 1: sound wave with a wave length = twice the size of the horizon at decoupling → shows that the universe is flat.

(4) Other peaks: sound waves undergoing one compression + rarefaction for peak 2. And so on...

relative amplitude gives Ω_b { - Even-numbered peaks: compression by the gravitational potential (DM ...) - Odd-numbered peaks: rarefaction → counter-effect of the radiative pressure

DM only contributes to compression (it does not respond to radiation pressure)
↳ third peak ≡ Ω_χ. ⇒ we have a lot of DM in the universe.

$\boxed{\text{→ we can extract } \Omega_m h^2, \Omega_b h^2, \Omega_\Lambda \text{ and } \Omega_t \text{ from the CMB } (T_0 \text{ gives } \Omega_r \text{ and thus } \Omega_t) \text{ and deduce the universe energy budget (at } t_0)}$

Planck results: $\left\{\begin{array}{l} \Omega_\chi h^2 = 0.1198 \pm 0.0015 \\ \Omega_b h^2 = 0.02225 \pm 0.00016 \\ \Omega_\Lambda = 0.6844 \pm 0.0091 \\ H_0 = 67.27 \pm 0.66 \ \frac{km}{Mpc\, s} \end{array}\right.$ Precision cosmology

↳ derived: $h^2 = \frac{\Omega_m h^2}{\Omega_t - \Omega_\Lambda}$ at t_0 $\left(h^2 = \frac{H_0}{100 \frac{km}{Mpc\, s}} \right)$

From structure formation simulations, DM has to be <u>cold</u>
(i.e. when radiation can be neglected)
↳ other options give issues with small structure formation

IV.2.5 Relic neutrinos

Similarly as for the CMB, we can compute the CνB. There exists a temperature at which neutrinos decoupled from the photons and electrons. This is driven by

$$\underbrace{\nu_e \bar{\nu}_e \to e^+ e^-}_{\text{larger}} \quad \text{and} \quad \underbrace{\bar{\nu}_e e^- \to \bar{\nu}_e e^-}_{\text{small}} \quad (\text{weak processes})$$

$$\sigma \sim \sigma_{\nu e} = \frac{\pi \alpha^2 T^2}{s_W^4 M_W^4} \quad \text{for } T \ll M_W \quad (\text{and } m_\nu \simeq 0)$$

$$\Rightarrow \frac{\Gamma(T_{dec})}{H(T_{dec})} = \frac{\pi \alpha^2}{s_W^4 M_W^4} T_{dec}^2 \; \frac{\zeta_3}{\pi^2} \underbrace{g}_{=1:\ 1 \text{ family of LH neutrinos involved in the } \nu e \to \nu e \text{ process.}} T_{dec}^3 \; \frac{\sqrt{90}}{\pi \sqrt{\underbrace{g_{eff}}_{=10.75\ (e^\pm,\ 3 \text{ gen. of } \nu,\ \text{photons})}}} \frac{M_{Pl}}{T_{dec}} = 1$$

$$\Rightarrow T_{dec} \sim 1 \text{ MeV} \equiv \text{before nucleosynthesis}$$

Soon after, the $e^\pm$ decouple $\Rightarrow$ to be accounted for when computing $T_{\nu,0}$.
The entropy of the $e^\pm$ is transfered to the photons (only particles in equilibrium)
$\hookrightarrow T_\gamma = \left(\frac{11}{4}\right)^{1/3} T_\nu$. (cf. thermodynamics)

$$\rho_r(T) \frac{\pi^2}{30} g_{eff} T^4 \Leftrightarrow \rho_r(T_\gamma) = \frac{\pi^2}{30} \times 3.4 \times T_\gamma^4$$

$\hookrightarrow$ 500 photons at $2.4\ 10^{-4}$ eV and 406 ν at $1.7\ 10^{-4}$ eV.

Also we could include a 4th neutrino species in the calculation. $m_\nu \sim 10$ eV gives the right relic density $\to$ issues with structure formation:

- $n_\nu(T_\gamma) = \frac{\zeta_3}{\pi^2} \frac{3}{4} 2 T_\nu^3 = \frac{6 \zeta_3}{11 \pi^2} T_\gamma^3$ (relativistic)

- at t_0 $\to$ non relativistic: $\rho_\nu(T_{0\gamma}) = m_\nu n_\nu = \frac{6 m_\nu \zeta_3}{11 \pi^2} T_{0\gamma}^3$

$$\Rightarrow \Omega_\nu h^2 = m_\nu \frac{6 \zeta_3}{11 \pi^2} T_{0\gamma}^3 \frac{h^2}{3 M_{Pl}^2 H_0^2} = \frac{m_\nu}{85 \text{ eV}}$$

IV.2.6. Cold dark matter (light)

The problem with neutrino DM is that they are relativistic at the wrong moment of the history of the universe → structure formation issues.
↳ non-thermal relics

One of the best example consists in axions a:

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a + c_\gamma \frac{a}{f_a}\frac{\alpha}{8\pi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ \frac{\partial_\mu a}{2 f_a} \sum_\psi c_\psi \bar{\psi}\gamma^\mu\gamma_5 \psi$$

Cf. completeness: axions arise from the breaking of a global symmetry:

$$\phi \to \phi\, e^{ia/f_a}$$
$$\psi_{L,R} \to e^{\pm ia/2f_a}\, \psi_{L,R}$$

} The Yukawa $\phi \bar{\psi}_R \psi_L$ generates a ψ mass
The kin. term generate the last term above

QCD: $\frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta_{QCD}\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$ → the axion explains the small neutron dipole moment.

QCD will generate an axion potential with a min. at $\frac{\langle a \rangle}{f_a} = \theta_{QCD}$ (after hadron formation):

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu a)\partial^\mu a - \frac{1}{2}K^2\left(\theta_{QCD} - \frac{a}{f_a}\right)^2 - \lambda_a\left(\theta_{QCD} - \frac{a}{f_a}\right)^4 + \dots$$

QCD also makes the axion massive: $m_a^2 = \frac{K^2}{f_a^2} \approx \frac{m_\pi^2 f_\pi^2}{2 f_a^2}$

⇒ super-light DM ($m_a \sim \underset{\text{correct relic}}{10^{-6} - 10^{-4}}$ eV) ⇒ hard to detect
(large m_a ⟺ smaller f_a)

→ we look through them via their photon couplings: $K^+ \to \pi^+ a, \dots$
$a \to \gamma\gamma, \dots$

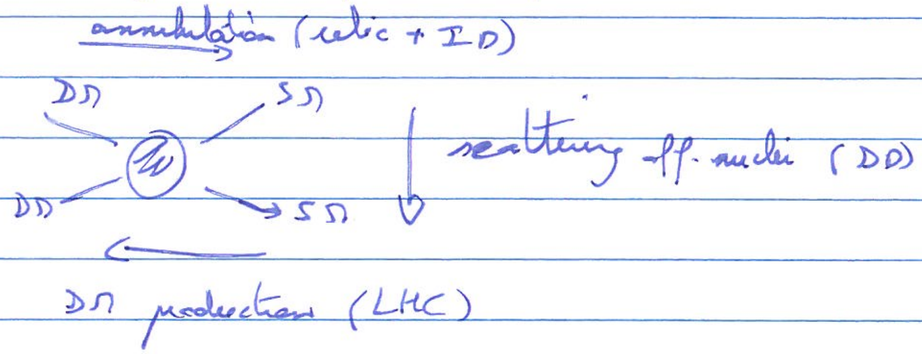
⇒ Axion-like particles: we remove the QCD connection → axions can be much lighter than the $[10^{-6}, 10^{-4}]$ eV range

IV. 3. The WIMP miracle

- WIMPs are amongst the most popular candidates for DM.
  → masses of at least a few GeV ⇒ cold DM ⟺ DM is non-relativistic when it decouples

<u>Assumption:</u> · DM is created thermally
- Its relic density arises from the freeze-out mechanism

- The key diagram — the reason why particle physicists love DM.



IV. 3.1 The WIMP relic density = the WIMP miracle

- At decoupling, $\Gamma(T_{dec}) = H(T_{dec})$.

$$\Rightarrow \sigma_{\chi\chi}\, v\, n_\chi = \sigma_{\chi\chi} \underbrace{\sqrt{\frac{2T_{dec}}{m_\chi}}}_{\substack{\text{typical velocity}\\ \simeq \text{assumption}}} g \left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T_{dec}} = \frac{\pi\sqrt{g_{eff}}}{\sqrt{90}} \frac{T_{dec}^2}{M_{Pl}}$$

⇒ the dependence on T_{dec} simplifies: $e^{-m_\chi/T_{dec}} = \frac{\pi^{5/2}}{3\sqrt{10}} \frac{\sqrt{g_{eff}}}{m_\chi M_{Pl}\sigma_{\chi\chi}}$

▷ But in the NR limit and for $T_{dec} << m_\chi$, $\sigma_{\chi\chi}$ does not depend on T.

▷ Assuming the top + the weak bosons have decoupled, $g_{eff} \simeq 86.25$

$\Rightarrow e^{-m_\chi/T_{dec}} = f(m_\chi)$ ⇒ we link T_{dec} and m_χ

$$\Rightarrow n_\chi(T_{dec}) = \frac{\pi}{3\sqrt{10}\,\Omega_{pl}} \sqrt{\frac{m_\chi}{T_{dec}}} \sqrt{g_{eff}}\, T_{dec}^2\, \sigma_{\chi\chi}$$

The energy density at present time can then be deduced:

$$\Omega_\chi h^2 = \frac{h^2}{3\Omega_{pl}^2 H_0^2} m_\chi n_\chi(T_0) = m_\chi n_\chi(T_{dec}) \underbrace{\left[\frac{a(T_{dec})}{a(T_0)}\right]^3}_{} \cdot \frac{h^2}{3\Omega_{pl}^2 H_0^2}$$

since $a(T)\cdot T \simeq cst \simeq 1/28$
↳ can be deduced

$$\Rightarrow \boxed{\Omega_\chi h^2 = m_\chi \frac{T_0^3}{T_{dec}^3} \frac{1}{28} \frac{h^2}{3\Omega_{pl}^2 H_0^2} \frac{\pi}{3\sqrt{10}\,\Omega_{pl}} \sqrt{\frac{m_\chi}{T_{dec}}} \sqrt{g_{eff}}\, T_{dec}^2\, \sigma_{\chi\chi}}$$

The WIMP miracle: $\left.\begin{array}{l}\sigma_{\chi\chi} \sim \text{EW cross section} \\ m_\chi \sim \text{EW mass}\end{array}\right\} \rightarrow \Omega_\chi h^2 \simeq 0.12$

⚠ · $m_\chi \ll m_W$ not fullfilled perfectly
· Some of the assumptions stem from the neutrino calculation (concerning the m_χ dependence) —
⇒ more robust approach through the Boltzmann eq.

IV 3.2 The WIMP density from the Boltzmann equation

· The variation of $n(t)$ with time:

$$0 = \frac{d}{dt}\left[n(t)\, a^3(t)\right] \Leftrightarrow \dot{n}(t) + 3H(t)\, n(t) = 0$$

· The process involved is $\chi\chi \leftrightarrow f\bar{f}$
· We need to thermally average (n is global: $\int d(\text{velocity})$).
↳ $\dot{n}(t) + 3H(t)\,n(t) = -\langle\sigma_{\chi\chi} v\rangle \left(n^2(t) - n_{eq}^2(t)\right)$

for $n = n_{eq}$, only the expansion of the universe matter

$$\hookrightarrow \frac{\int d^3p_{\chi_1}\, d^3p_{\chi_2}\, e^{-(E_{\chi_1}+E_{\chi_2})/T}\, \sigma_{\chi\chi} v}{\int d^3p_{\chi_1}\, d^3p_{\chi_2}\, e^{-(E_{\chi_1}+E_{\chi_2})/T}}$$

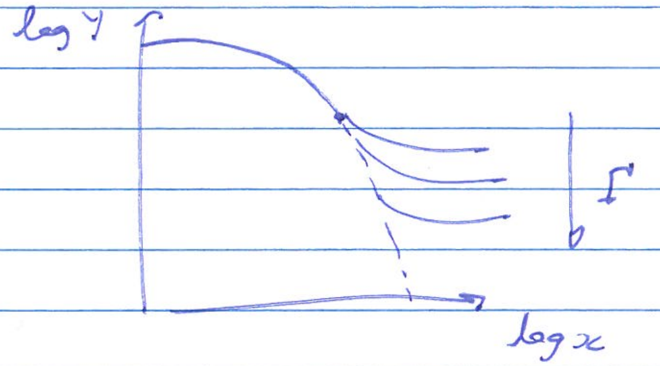
$\rightarrow$ we get $$\frac{dY(x)}{dx} = -\frac{\lambda(x)}{x^2}\left(Y^2(x) - \underbrace{Y_{eq}^2(x)}_{\text{small}}\right)$$

with $Y(x) = \frac{n(x)}{T^3}$ $\quad x = m_\chi / T$

$$\lambda(x) = \frac{m_\chi^3 \langle \sigma_{\chi\chi} v\rangle(1)}{H(x=1)} = \frac{\sqrt{g_*}\, M_{Pl}\, m_\chi}{\pi \sqrt{g_{eff}}} \langle \sigma_{\chi\chi} v\rangle(x)$$

$v \to 0$ expansion

$$\rightarrow \Omega_\chi h^2 = \frac{h^2 \pi}{28\sqrt{5}} \frac{\sqrt{g_{eff}}}{M_{Pl}} \frac{x_{dec}}{\langle \sigma_{\chi\chi} v\rangle} \frac{T_0^3}{3 M_{Pl}^2 H_0^2} \rightarrow \underline{\text{works}}$$



$\equiv$ Freeze-out.

Rk: (a) Need to be generalized if more than 1 particle $\Rightarrow$ coannihilations
$\rightarrow$ $\exp[-\Delta m / T]$ suppression $\rightarrow$ 10% mass difference at most

(b) Radiative corrections can be important $\neq$ Sommerfeld enhancement
$\hookrightarrow$ large threshold corrections

IV. 4. Freeze-in production : FIMPs

In the above discussion, the coupling between DM and the SM is large (otherwise, we cannot get thermal equilibrium). If not $\rightarrow$ new type of DM.

The DM density here arises from decays / annihilations of SM particles (until the SM densities become Boltzmann-suppressed)

Ex: $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} - y\, m_B\, \bar{\chi} \underset{\text{SM part.}}{B} \chi$ with $m_B > 2m_\chi$

can be much lighter than WIMPs (keV)

$$\Rightarrow \dot{n}_\chi(t) + 3H(t)\, n_\chi(t) = \underbrace{S(B\to\chi\chi)}_{\text{source term}}$$

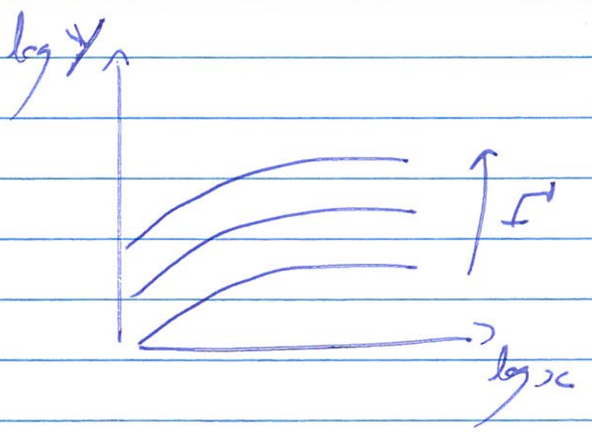
$$\text{with } S(B\to\chi\chi) = g_B \int \frac{d^3p_B}{(2\pi)^3}\, e^{-E_B/T}\, \frac{m_B}{E_B}\, \Gamma(B\to\chi\chi)$$

$$= \frac{g_B m_B^2}{2\pi^2}\, \Gamma(B\to\chi\chi)\, T\, \underbrace{K_1(m_B/T)}$$

$\propto T/m_B$ for $m_B \ll T$

$\propto \frac{T e^{-m_B/T}}{m_B}$ for $T \ll m_B$

the density increases with $T \downarrow$ (and then expon. suppression)



We can also calculate: $n_{eq} = g_B \int \frac{d^3p_B}{(2\pi)^3}\, e^{-E_B/T} \Rightarrow S(B\to\chi\chi) = \Gamma(B\to\chi\chi)\, n_B^{eq} \times \frac{K_1(m_B/T)}{K_2(m_B/T)}$

$$\Rightarrow \boxed{\Omega_\chi h^2 = \frac{\sqrt{90}\, h^2}{12\pi^2}\, \frac{g_B}{\sqrt{g_{eff}}}\, \frac{m_\chi}{m_B^2}\, \frac{T_0^3}{H^2 M_{Pl}}\, \Gamma(B\to\chi\chi)}$$

IV.5 Searches for DM

IV.5.1 Indirect searches

Rely on non-grav. interaction of DM with matter: $\chi\chi \to SM\ SM$

motivated in many cases

- Ex: $\chi\chi \to q\bar{q}$ ≡ proton/antiproton fluxes on Earth (cosmic rays)
  $\gamma\gamma$ ≡ gamma rays (could also be radiated)
  - Particles come from many potential sources; not true for antiparticles
  - Check for particle/antiparticle ratios ⇒ shoulders or cutoff in the energy spectrum of $\bar{p}/p$ ratio for instance
- Measurements by satellites

IV.5.2. Direct searches

- Recoil of a nucleus when hit by a DM particle on Earth.
- Best nuclei for WIMPs: Xenon (~ 10 keV recoils).
- Depends on Earth motion ⇒ annual modulation

$$\sigma^{SI}(\chi A \to \chi A) = \frac{1}{16\pi s} \sum_N |Z M_p + (A-Z) M_n|^2$$

(coherent scattering as realized for wimp-recoils)

↳ connection to quarks and gluons:

- $$\langle N | \sum_q \chi\chi q q | N \rangle = \sum_q \chi\chi \langle N | q\bar{q} | N \rangle$$

cf. the nucleon mass operator: $\langle N | m_N | N \rangle = \sum_q \langle N | m_q q\bar{q} | N \rangle$

$$m_N \underbrace{\langle N | N \rangle}_{f_N} = \sum_q m_q \langle N | q\bar{q} | N \rangle$$

$$\Rightarrow \langle N | \sum_q \chi\chi q\bar{q} | N \rangle = \sum_q \chi\chi \frac{m_N}{m_q} f_q$$

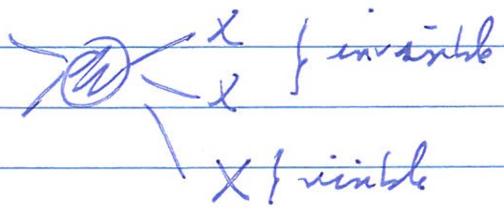
(Lattice)

↳ form factor ≡ finding a quark q at $p^2 < m_N^2$.

IV.5.3 Collider searches

- DM couples to the SM via a mediator
- Large luminosities → can find rare phenomena
- DM is invisible

We need a mono-X signature:



we reconstruct the invisible from the visible.