DARK MATTER – CARGESE 2022 NOTES

[Aug. 2022, Notes]

Hi!! :) Rough plan – 3 lectures (here: more details so 5 sets of notes)

Give taste of exciting developments in the field, tools, methods –

Ballpark – Intro + early universe + mechanisms + models + detection

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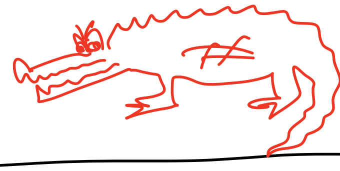
Crocodile challenge



(I) outline:

- Intro
- cheat sheet of early universe
- $2\to 2$: WIMP
- $2\to 2$: Beyond WIMP
- ⋮

$\Big\}$ $2\to 2$ to.

What we do & don't know:

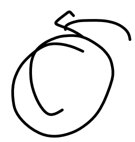
DM = 27% of energy content of the universe

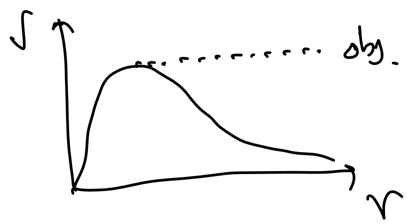
$\Rightarrow \rho_{DM} \simeq 5\, \rho_{baryons}$.

How do we know? e.g.:

* **Motion of stars:**

looking vs. motion





$\Rightarrow$ Galaxy rotation curves:

something is out there,
permeating the galaxy, extending to its halo.

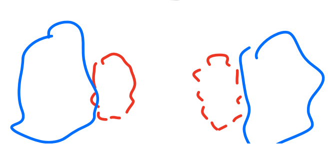
* **Gravitational lensing:**

Bending & twisting of light.

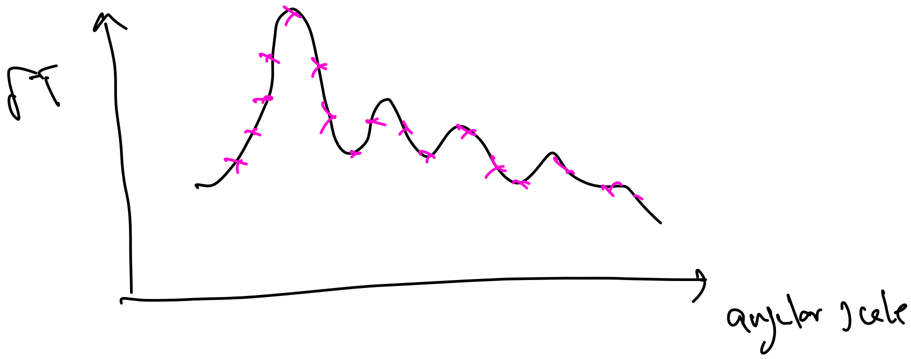
"cheshire cat group"

* **Colliding clusters such as bullet cluster:**

visible center vs. gravitational center



* CMB: Power spectrum - Temp fluctuations vs. angular scales



[Roni Harnik, MITP School on DM, lecture #1 - for very detailed evidence]

$\Rightarrow$ Properties :

- universe is dark. $\Omega_{DM} = \frac{\rho_{DM}}{\rho_{total}} \simeq 0.27$

$$\Leftrightarrow \rho_{DM} \simeq 5 \rho_{baryons}$$

$$\rho_{DM} \simeq 0.3 \text{ GeV/cm}^3$$

- massive $(m = ???)$

10^{-30} ~80 orders of magnitude! 10^{50} [GeV]

too fluffy: wavelength exceeds galaxy size.

- Shouldn't interact too strongly w/ QED, QCD
- not too strongly w/ itself - distinct dynamics in DM halo.

  [$\leftrightarrow$ signal? see later]

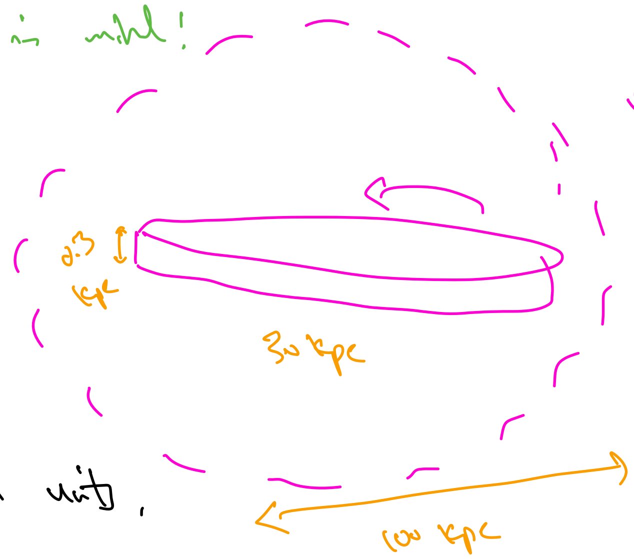
- wouldn't be here w/o it!

Picture to keep in mind!

DM wind.

$v \sim 10^{-3} c$

$= 10^{-3}$ natural units.



rotating disk in big DM felafel ball.

[kpc $\sim 10^{16}$ km]

Want to know what is it? mechanisms in early universe to get its abundance? model building? constraints? how to detect?

Early universe cheat sheet:

Universe is expanding $\quad \ell \nearrow \;\Rightarrow\; \tilde{\ell} = a\,\ell \nearrow \quad$ a: scale factor

volume expanding as a^3

$$ds^2 = dt^2 - a(t)^2\, d\vec{x}^{\,2}\,, \qquad H = \frac{\dot{a}}{a} = \frac{1}{a}\frac{\partial a}{\partial t}$$

Hubble.

convention: $a(t_0) = 1$ today

1^{st} Friedman eq: $\quad H^2 = \dfrac{\rho}{3M_{pl}^2}\,, \quad \rho \propto T^4$ blackbody

$$\Rightarrow\; H \sim \frac{T^2}{M_{pl}}$$

Early universe, $\simeq$ thermal environment. For species in th. eq. phase space distribution.

$$f_{eq}(p) = \frac{1}{e^{(E-\mu)/T} \pm 1}\,, \qquad E = \sqrt{p^2 + m^2}$$

(+ : fermions
− : bosons)

$\Rightarrow$ number density: $n = g \int \frac{d^3p}{(2\pi)^3} f(p)$

energy density: $\rho = g \int \frac{d^3p}{(2\pi)^3} E f(p)$

g = # of internal dof (spin, pol', color, etc)

$\Rightarrow$ Ballpark: $\begin{cases} n \sim T^3 & R \\ \rho \sim T^4 & R \end{cases}$ (R = Rel')

$\begin{cases} n = g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T} & NR \\ \rho = (m + \frac{3}{2}T) n \sim mn & NR \end{cases}$ (NR = non-rel') $T \ll m$

For particular, when $\mu \simeq 0$ (# changing process are fast)

$$n \propto e^{-m/T}$$

exp' suppression of n!

entropy density: $s = \frac{2\pi^2}{45} g_{*s} T^3 \sim T^3$ (Rel')

$$g_{*s} = \sum_{\text{bosons}} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_f g_i \left(\frac{T_i}{T}\right)^3$$

$$\left[\ \rho = g_* \frac{\pi^2}{30} T^4 , \quad g_* = \longrightarrow \left(\frac{T_i}{T}\right)^4 \ \right]$$

Boltzmann Equations:

Consider a system of no collisions - free particles:

$$\frac{\partial N}{\partial t} = 0 \qquad N = n \cdot V$$

$$\frac{\partial (nV)}{\partial t} = V \frac{\partial n}{\partial t} + n \frac{\partial V}{\partial t} = 0$$

$$\Rightarrow \frac{\partial n}{\partial t} + \frac{n}{V} \frac{\partial V}{\partial t} = 0$$

$$\left(V \propto a^3 \ ; \ \frac{1}{V}\frac{\partial V}{\partial t} = \frac{3}{a}\frac{\partial a}{\partial t} \right)$$

$$\Rightarrow \frac{\partial n}{\partial t} + 3n \underbrace{\left(\frac{\dot a}{a}\right)}_{H} = 0$$

If not free - have collisions - RHS is collision term:

$$\boxed{\frac{\partial n}{\partial t} + 3nH = -C[n]}$$

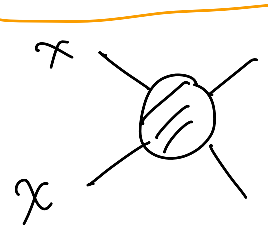
MECHANISMS:

Types of processes in early universe that set the relic abundance of DM. (← Dark Matter = DM).

The 2→2 zoo:

DM ≡ χ ⟶ time

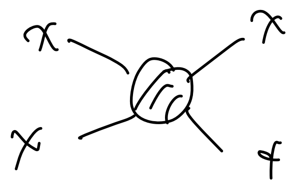
(as starting point, later go beyond)



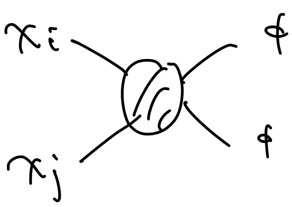
WIMP (ann.)

$m_\chi < m_\phi$

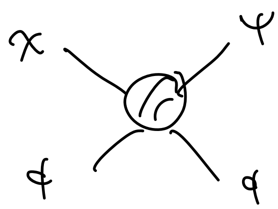
forbidden



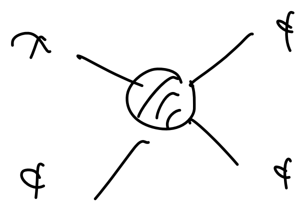
semi-annihilating



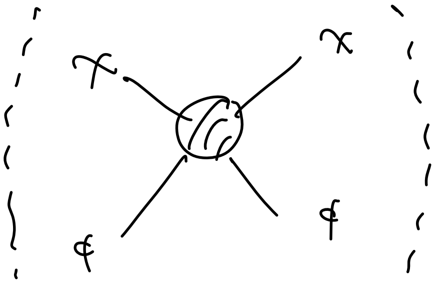
co-annihilation



co-scattering



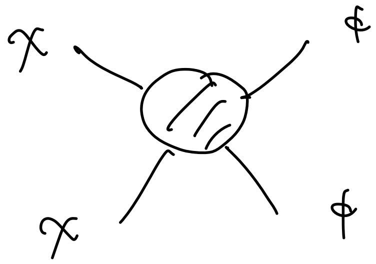
zombie



ELDER

WIMP: star of the show for last 40^+ years.

$\chi\chi \to \phi\phi$



$$\frac{\partial n_\chi}{\partial t} + 3 n_\chi H = - C[n_\chi]$$

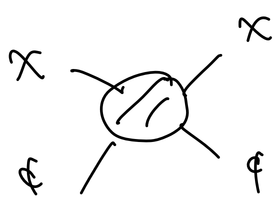
let's write out the collision term!

if fast int's

$\mu_\chi = \mu_\phi$

Sidenote: also elastic scattering $\chi\phi \to \chi\phi$

& assume ϕ = bath particle (SM or thermalized w/ SM), $\mu_\phi = 0$ then at temp!



$\Rightarrow \mu_\chi = \mu_\phi = 0$

(almost always, $\chi\chi \to \phi\phi$ freezes off before $\chi\phi \to \chi\phi$ because n_χ NR, ϕ is R.)

$$C[n] = \int d\Pi_{\chi_1} d\Pi_{\chi_2} d\Pi_{\phi_1} d\Pi_{\phi_2} (2\pi)^4 \delta^{(4)}(p_i - p_f) \cdot$$

$$\cdot |M|^2 \cdot (f_{\chi_1} f_{\chi_2} - f_{\phi_1} f_{\phi_2})$$

av. over all initial & final dof.

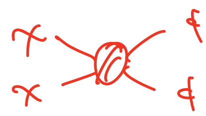
where $d\Pi_a = \frac{g_a \, d^3 p_a}{(2\pi)^3 \, 2E_a}$ = Lorentz inv. phase space.

(makes sense)

Roughly - thermally av' cross section ($\simeq$ x-sec) · number densities.

write in following way:

$$\boxed{\frac{\partial n_\chi}{\partial t} + 3 n_\chi H = - \langle \sigma v \rangle_{\chi\chi \to f f} \left(n_\chi^2 - n_{\chi,eq}^2 \right)}$$



why??

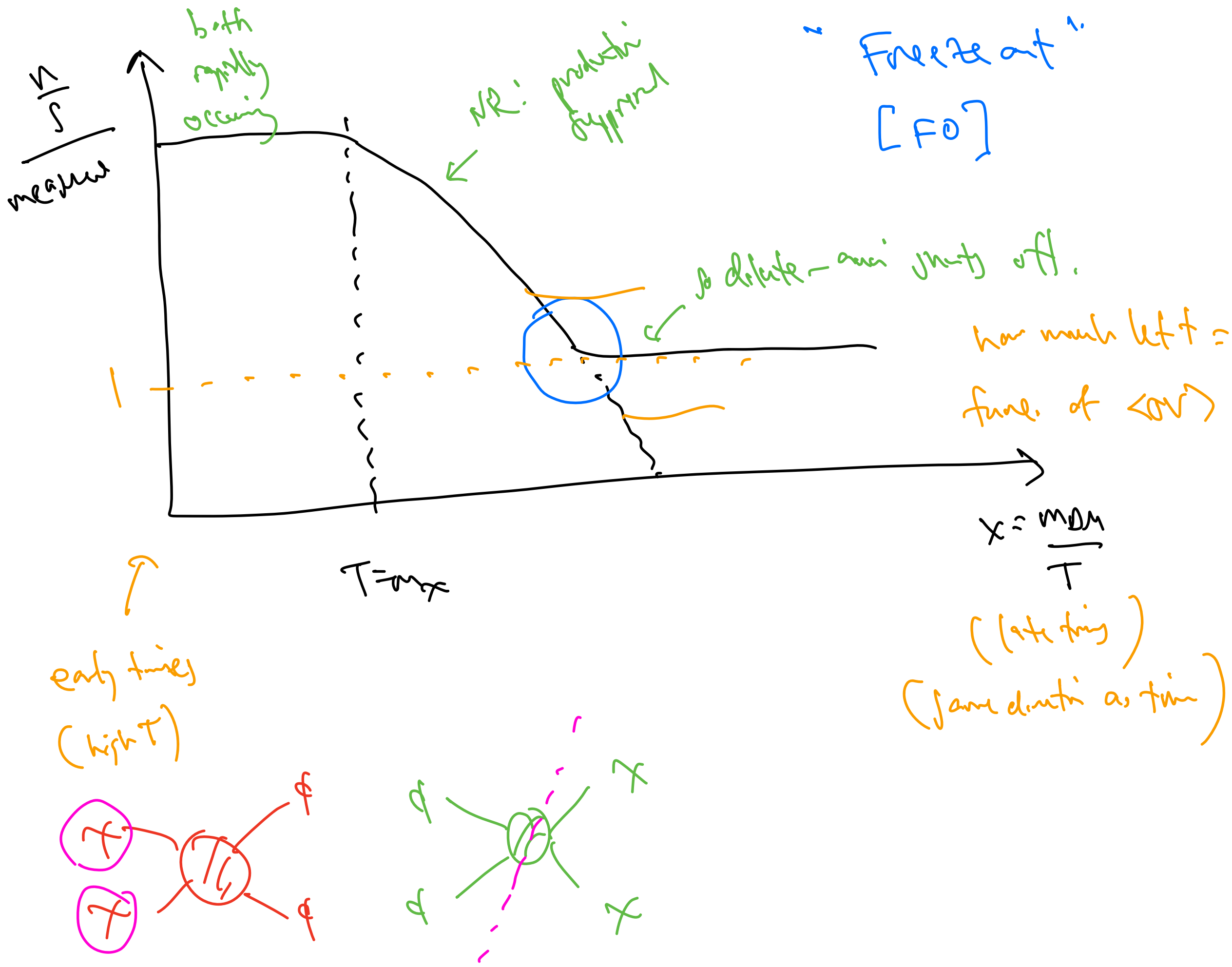
use trick: detailed balance!

In equilibrium, forward & backward process are rapid & should cancel out. ⇒ allowed to write the backreaction in this way.

What happens? Instead of particle density in a box ⇒ in a box that's expanding w/ the universe:

(yield $Y = \frac{n}{s} \sim n a^3$)

"Freeze out" [FO]



Back of envelope: F.O. @ $\Gamma_{2\to 2} \sim H$

(*) $\Gamma_{2\to 2} = \underbrace{n_\chi}_{\text{(have to meet 1 particle)}} \underbrace{\langle \sigma v \rangle}_{\text{strength of int}} \sim H \sim \dfrac{T^2}{M_{pl}}$

redshift: entropy S conserved: $S = s a^3 = \text{const}$

use this to redshift:

$$\Rightarrow s \sim \frac{1}{a^3} \sim T^3 \quad \left(T \sim \frac{1}{a}\right)$$

After F.O. comoving number density of DM is constant ~ redshift from today to F.O.:

$$n_\chi(x_0) = n_\chi(x_F)\,\frac{s(x_0)}{s(x_F)} \underset{(*)}{\overset{\uparrow}{=}} \frac{H(x_F)}{\langle\sigma v\rangle}\,\frac{s(x_0)}{s(x_F)}$$

$(t_0 \to x_0)$

NR today so energy density:

$$\Omega_{DM} = \frac{\rho_{DM}}{\rho_c} = \frac{m_\chi n_\chi}{\rho_c} = \frac{m_\chi}{\rho_c}\,\frac{H(x_F)}{\langle\sigma v\rangle}\,\frac{s(x_0)}{s(x_F)}$$

plug in values:

$$\left(\begin{array}{l} H \sim \dfrac{T^2}{M_{pl}} \underset{x=\frac{m}{T}}{\overset{\uparrow}{\sim}} \dfrac{m_\chi^2}{x_F^2 M_{pl}} \\ s(x_F) \sim T_F^3 \sim \dfrac{m_\chi^3}{x_F^3} \\ s_0 = 2.2 \cdot 10^{-38}\ \text{GeV}^3 \\ \rho_c = 1.053 \cdot 10^5\, h^2\ \dfrac{\text{GeV}}{c^2}\ \text{cm}^{-3} \\ h \sim 0.7 \end{array}\right)$$

$$\Rightarrow \Omega_{DM} = \frac{x_F}{20}\left(\frac{10.75}{g_*}\right)^{\frac{1}{2}} \frac{10^{-9}\ \text{GeV}^{-2}}{\langle\sigma v\rangle}$$

What value is x_F?

Assume instantaneous f.o. - plug in eq. density of χ's @ f.o.:

$(*) \Rightarrow \quad n_\chi^{eq}(x_F)\langle\sigma v\rangle \sim H(x_F)$

$$\Rightarrow \quad \underline{\underline{g_\chi \left(\frac{m_\chi^2}{x_F 2\pi}\right)^{3/2} e^{-x_F}}} \langle\sigma v\rangle \sim \frac{T_F^2}{M_{pl}} \sim \frac{m_\chi^2}{x_F^2 M_{pl}}$$

$\Rightarrow \quad x_F \sim \ln(\text{params})$ – roughly same over broad range.

$\underline{\underline{x_F \sim 20 - 30}}$ for $m_\chi \sim$ MeV - TeV

correct relic abundance: $\Omega_{DM} = 0.27$

$$\Rightarrow \quad \underline{\underline{\langle\sigma v\rangle \sim 10^{-8}\ \text{GeV}^{-2}}}$$

Roughly what get for weak force interaction!

Weakly interacting Massive Particle (WIMP).

"WIMP Miracle".