# DARK MATTER - GGI '22 SCHOOL [Jan 2022 Zoom]

Hi!! Rough plan - 1.5h x 5 + 2 discussion (Tue + Thurs)

Give taste of exciting developments in the field, tricks, methods -

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

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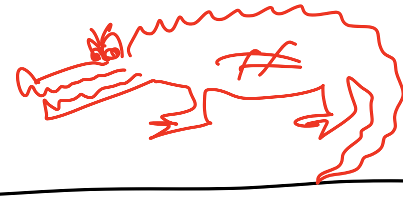
## Crocodile challenge



## I outline:

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

} $2 \to 2$ too.

## What we do & don't know:

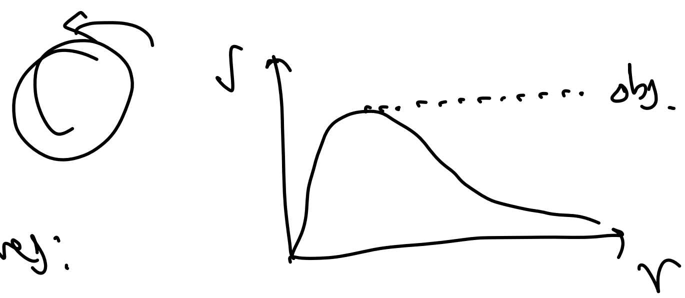
DM = 27% of energy content of the universe

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

How do we know? e.g.:

### * Motion of stars:

looking vs. motion




$\Rightarrow$ Galaxy rotation curves:

something is out there.

permeating the galaxy, extends to its halo.

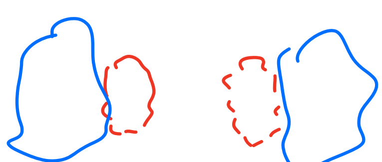
### * Gravitational lensing:

Bending & twisting of light.

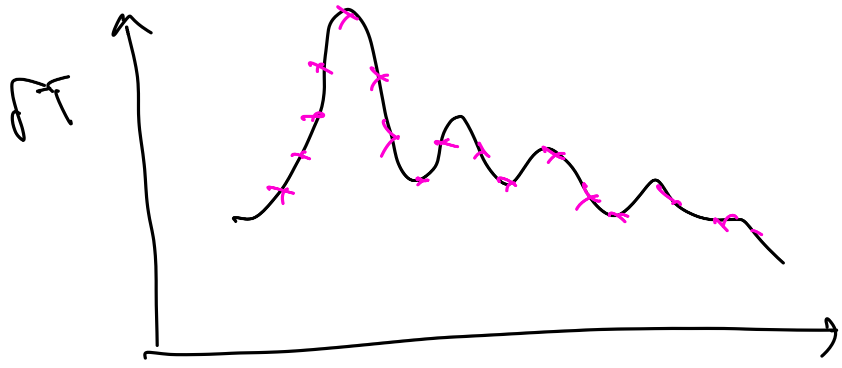
"cheshire cat grin"

### * Colliding clusters such as bullet cluster:

visible center vs. gravitational center



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




[ Rouven Essig, MITP School on DM, lecture #1 - for very detailed evidence ]

$\Rightarrow$ Properties :

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

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

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

- 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.

[⟷ signal? see later]

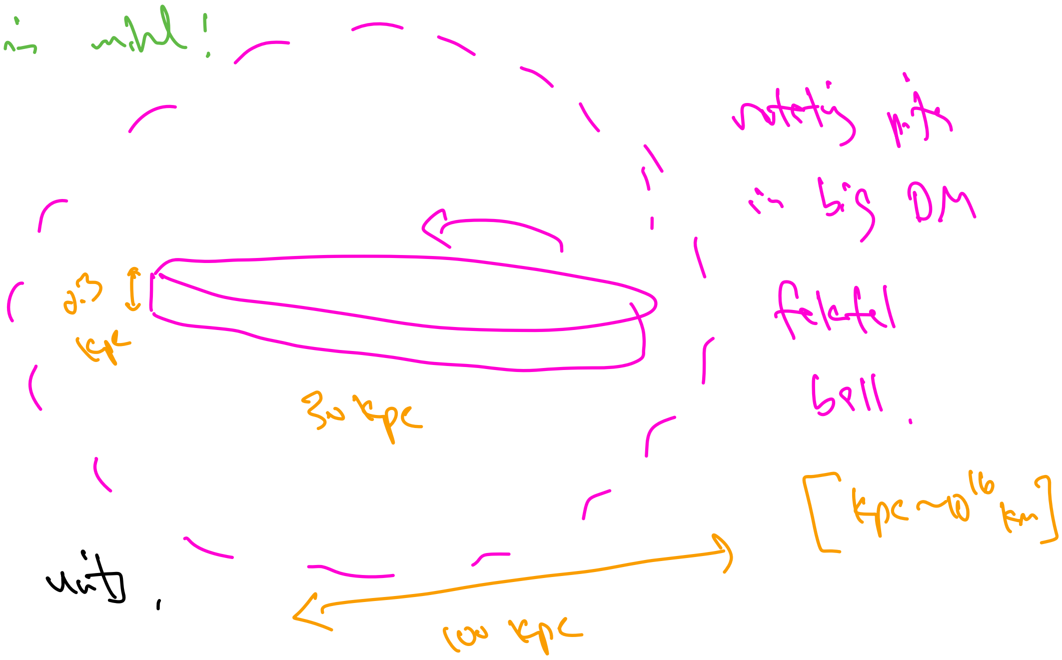
- wouldn't be here w/o it!

Picture to keep in mind!

DM mod.

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

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




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

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

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

Early universe = thermal environment. For species in th. eq. phase space distribution.

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

( + : fermion
− : boson )

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

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

$g$ = # 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')

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

In particular, when $\mu = 0$ (# changing process are fast)

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

exp' suppression of $n$!

entropy density: $\underline{s} = \frac{2\pi^2}{45} g_{*s} T^3 \sim \underline{T^3}$ (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:

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

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

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

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

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

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

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

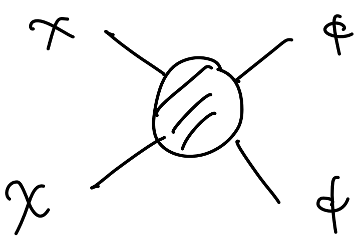
# MECHANISM :

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

## The 2→2 zoo :

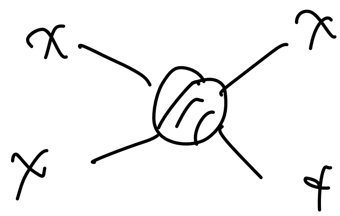
$\mathrm{DM} \equiv \chi$ $\qquad \xrightarrow[\text{time}]{}$

(as starting point, or later go beyond)

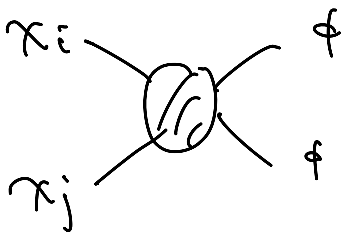



WIMP (ann.)

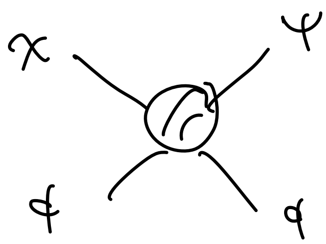

forbidden



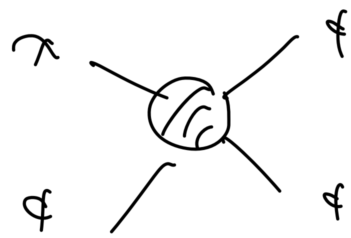

semi-annihilating



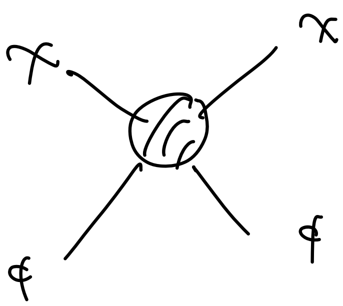

co-annihilation




co-scattering



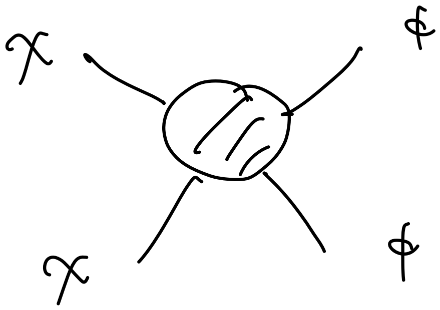

zombie




ELDER

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

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

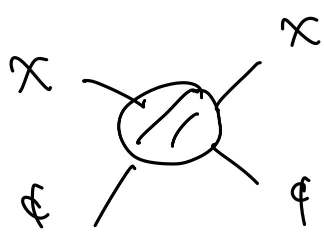



$$\frac{\partial n_\chi}{\partial t} + 3 n_\chi H = -C[n_\chi]$$

let's write out the collision term!

if fast rxns

$\mu_\chi = \mu_\phi$




Sidenote: also elastic scattering $\chi\phi \to \chi\phi$ & assume $\phi$ = bath particle (SM or thermalized w/ SM), $\mu_\phi = 0$ at this temp.

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

(almost always, $\chi\chi \to \phi\phi$ shuts off before $\chi\phi \to \chi\phi$ because $n_\chi$ NR, $\phi$ is R.)

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

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

av. over all initial & final dof.

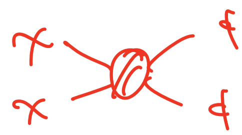
where $d\Pi_a = g_a \dfrac{d^3 p_a}{(2\pi)^3\, 2E_a}$ = Lorentz inv phase space.

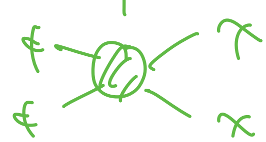
(making sense)

Roughly - thermally av' crosssection (= x-sec) · number densities.

write in following way:

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




why??

use trick: detailed balance!

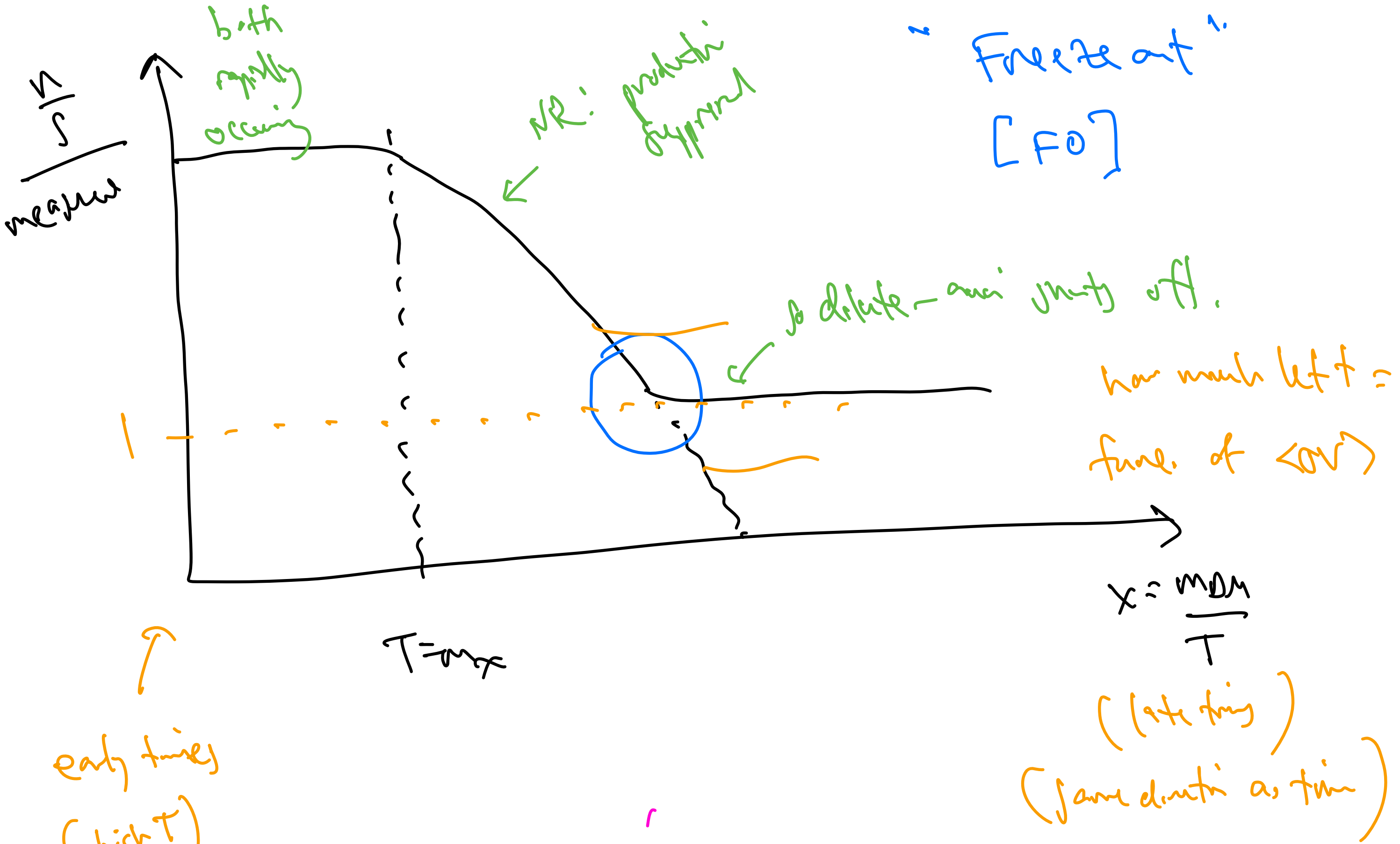
In equilibrium, forward & backward process are rapid & should cancel out. ⇒ allowed to write the backreaction in this way.

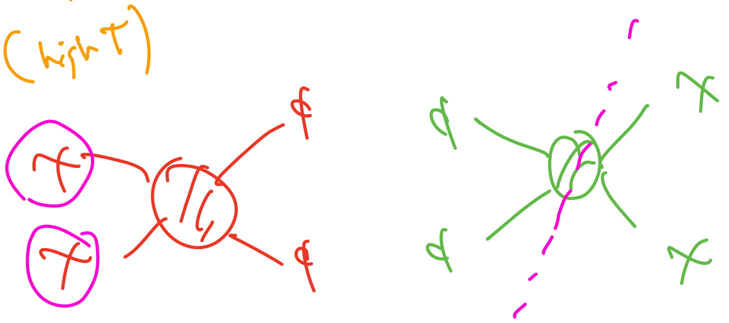
what happens? Instead of particle density in a box ⇒ in a box that expands w/ the universe:

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

"Freeze out"

[FO]




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

(*) $\Gamma_{2\to 2} = \underline{n_\chi} \, \underline{\langle \sigma v \rangle} \sim H \sim \frac{T^2}{M_{pl}}$

(have to meet 1 particle)

strength of int

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.:

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

$(t_0 \to x_0)$

NR today so energy density:

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

<u>plug in values:</u>

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

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

what value is $x_F$?

Assume instantaneous f.o. - plug in eq. density of $\chi$'s @ FO:

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

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

$\Rightarrow$ $x_F \sim \ln(\text{parameters})$ - roughly same over broad range.

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

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

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

Roughly what get for weak force interaction!

Weakly interacting Massive Particle (WIMP).

"WIMP Miracle".