NON WIMP DARK MATTER - ICTP School '21

[Yonit Hochberg, HUJI]

Hi!! :) Rough plan - 2 × 1.5 hours

Give taste of exciting stuff - methods & tricks

Ballpark - set the stage + mechanisms + models

[complementary to Boehm & Lin]

Outline:

- Set the stage (intro + early universe)
- 2 → 2 : zoo (WIMP + beyond)
- 3 → 2 : SIMPs (& more)
- Dark sectors

Setting the stage:

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

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

$\rho_{DM} = 0.3 \frac{GeV}{cm^3}$

- massive $(m = ???)$

10^{-30} — 80 orders of mag.! — 10^{50} [GeV]

too fluffy — multiverse

- shouldn't interact too strongly w/ known forces
  QED, QCD.
- " " " " " w/ itself.
- wouldn't be here w/o it!

want to know: what is it?
mechanisms in early universe to get its abundance
model building (& how to detect & constraints)

Early universe cheat-sheet:

universe is expanding $\ell \Rightarrow \tilde{\ell} = a\ell$

a: scale factor. volume expands like a^3

$ds^2 = dt^2 - a(t)^2 dx^2$, $H = \frac{\dot{a}}{a} = \frac{1}{a}\frac{\partial a}{\partial t}$ Hubble

$$H^2 = \frac{\rho}{3M_{pl}^2}, \quad \rho \propto T^4 \quad \text{black body}$$

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

Early universe = thermal environment. phase space distributions for species in th. eq. $\Rightarrow$ number density & energy density:

Ballpark:

$$\underline{\underline{\begin{cases} n \sim T^3 & R \\ \rho \sim T^4 & R \end{cases}}}$$

$$\underline{\underline{\begin{cases} n \sim (mT)^{3/2} e^{-(m-\mu)/T} & NR \\ \rho \sim m \cdot n & NR \end{cases}}}$$

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

$\Rightarrow$ $\underline{\underline{n \propto e^{-m/T}}}$ exp'l suppressed.

Entropy density, $\underline{\underline{s \sim T^3}}$ (Rel')

Boltzmann Equations:

Consider a system w/ no collisions - free particles:

$$\frac{\partial N}{\partial t} = 0$$

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

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

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

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

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

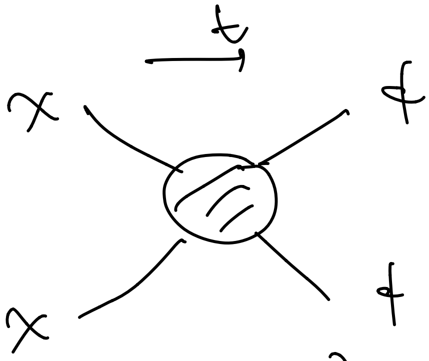
$$\frac{\partial n}{\partial t} + 3nH = -C[n]$$

MECHANISMS:

types of processes in early universe that set the relic abundance of DM.

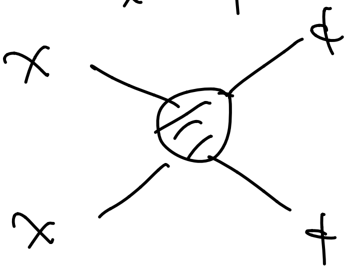
The 2→2 zoo:

DM = χ $\xrightarrow{\text{time}}$



WIMP (ann.)

$m_\chi < m_\phi$



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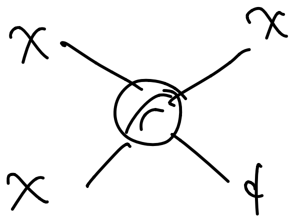
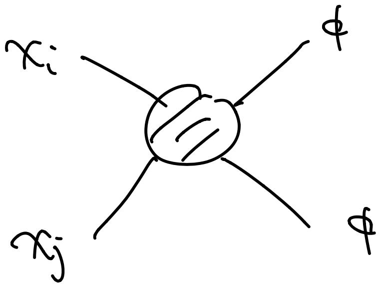
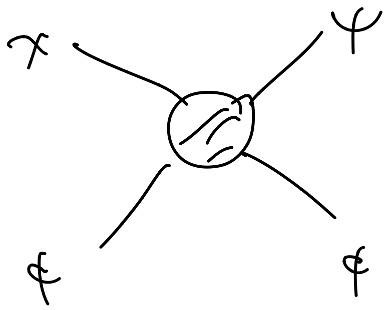


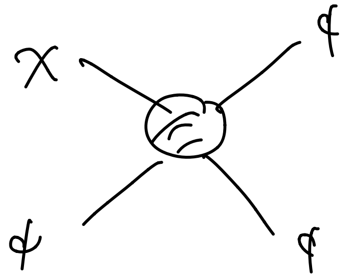
semi-ann.



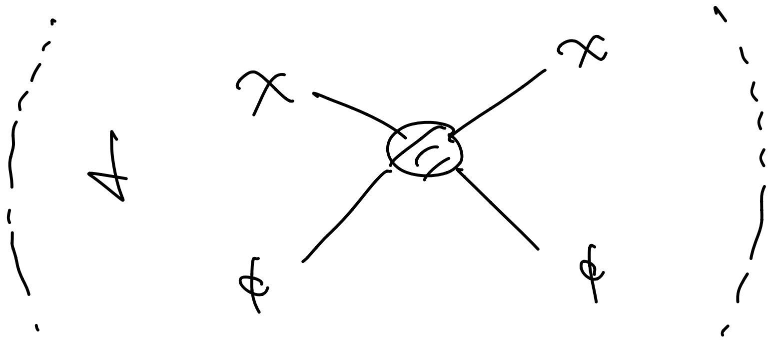
coannihilation



coscattering



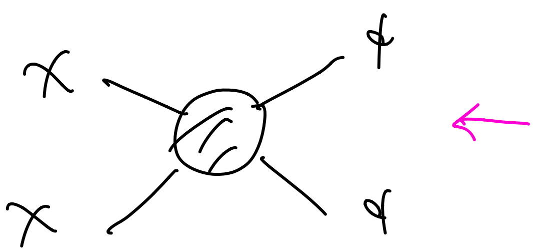
zombie



ELDER

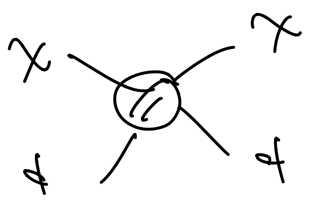
WIMP: Star of the show for 40+ years.

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



$$\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -C[n_\chi]$$ if fast, $\mu_\chi = \mu_\phi$

(<u>Sidenote:</u> always elastically scattering $\chi\phi \to \chi\phi$



both particle, $\mu_\phi = 0$

fixes T.

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

Let's write the collision term:

Roughly, rates = th. averaged xsec × number density

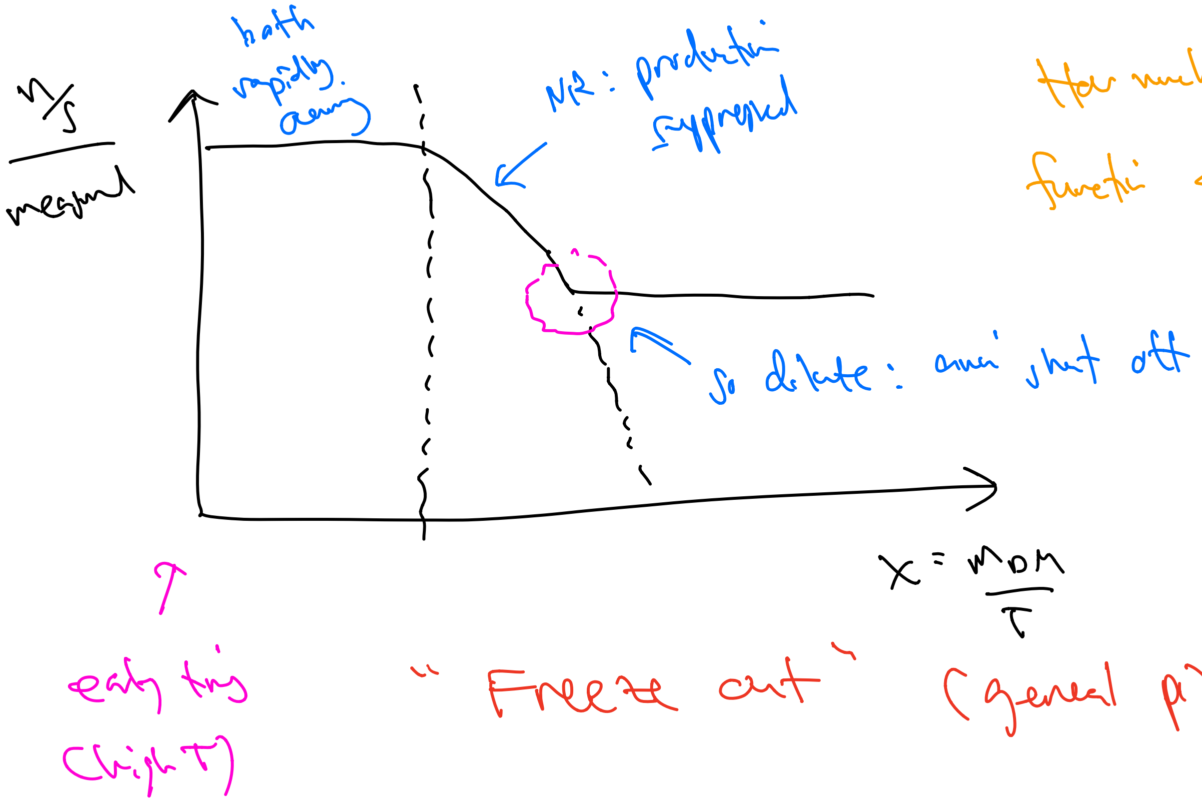
$$\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\underset{(\chi\chi\to\phi\phi)}{\langle\sigma v\rangle}\left(n_\chi^2 - n_{eq,\chi}^2\right)$$

why?

use trick: detailed balance!

In eq., forward & backward both rapid & should cancel out! ⇒ write in this way.

What happens? Instead of particle density in a box, think of particle density in a box that's expanding w/ universe - (yield $Y = \frac{n}{s} \sim n a^3$)



How much left = function $\langle \sigma v \rangle$

"Freeze out" (general picture)

Back of envelope:

F.O. @ $\Gamma_{2\to 2} \sim H$ (think of it as if you're the DM)

(*) $\Gamma_{2\to 2} \sim n_x \langle \sigma v \rangle \overset{!}{\sim} H \sim \frac{T^2}{M_{pl}}$ (How to meet 1 DM particle)

relate to measured quantities

play w/ redshifts:

entropy conserved: $\overset{\text{const}}{\overset{\shortparallel}{S}} = s a^3$ — use to redshift:

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

After F.O., comoving number density of DM is constant – redshift back.

Here – redshift to T_{eq} = matter-radiation equality:

$(T_{eq} \sim 0.8\ \text{eV})$

parameterize: $\langle \sigma v \rangle \equiv \dfrac{\alpha_{eff}^2}{m_\chi^2}$

@ matter-rad. equality: $\rho_{matter}^{eq} = \rho_\chi^{eq} + \rho_{baryons}^{eq} = \rho_\gamma^{eq}$

$$\rho_\chi \simeq 5 \rho_{baryons} \Rightarrow \underline{\underline{\rho_\chi^{eq} \simeq \rho_\gamma^{eq}}}$$

(neglect detail)

$$\Rightarrow \underline{\underline{n_\chi^{FO}}} \sim n_\chi(T_{eq}) \left(\frac{T_F}{T_{eq}}\right)^3 \sim \frac{\rho_\chi(T_{eq})}{m_\chi} \frac{T_F^3}{T_{eq}^3} \sim$$

$$\sim \frac{\rho_\gamma(T_{eq})}{m_\chi} \frac{T_F^3}{T_{eq}^3} \underset{\underset{\rho_\gamma \sim T^4}{\uparrow}}{\sim} \frac{T_{eq} T_F^3}{m_\chi} \underset{\underset{x_F = \frac{m_\chi}{T_F}}{\uparrow}}{\sim} \underline{\underline{\frac{T_{eq} m_\chi^2}{x_F^3}}}$$

compare to f.o. condition (*) :

$$\Gamma_{2\to 2} = n_{FO} \cdot \frac{\alpha_{eff}^2}{m_\chi^2} \sim \frac{\alpha_{eff}^2 T_{eq}}{x_f^3} \overset{!}{\sim} H_F \sim \frac{T_F^2}{M_{pl}} \sim \frac{m_\chi^2}{x_f^2 M_{pl}}$$

$$\Rightarrow \underline{\underline{m_\chi \simeq \alpha_{eff}\sqrt{T_{eq} M_{pl}}}} \sim \underline{\underline{\alpha_{eff} \cdot (30\ \text{TeV})}}$$

If $\alpha_{eff} \sim 10^{-2}$, weak scale emerges! - WIMP miracle,

coincidence of scales (M_{pl}, T_{eq})

If $\alpha_{eff} \ll 10^{-2}$, $m_\chi \ll$ weak scale. Also Light Dark Matter.

What value is x_f?

Assume instantaneous f.o. - plug eq. densities for χ's @ f.o. :

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

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

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

$$x_F = \frac{m_\chi}{T_F} \sim 20-30 \text{ for } m_\chi \sim \text{MeV}-\text{TeV}$$

Another way: $\langle \sigma v \rangle = \frac{\alpha_{eff}^2}{m_\chi^2} \sim \frac{1}{T_{eq} M_{pl}}$

unitarity bound: $\alpha_{eff} \lesssim 4\pi \Rightarrow m_\chi \lesssim 300$ TeV

[Griest, Kamionkowski 1989]

∃ ways to evade — thermal relics w/ mass that exceeds this by $\lesssim 12$ orders of magnitude!

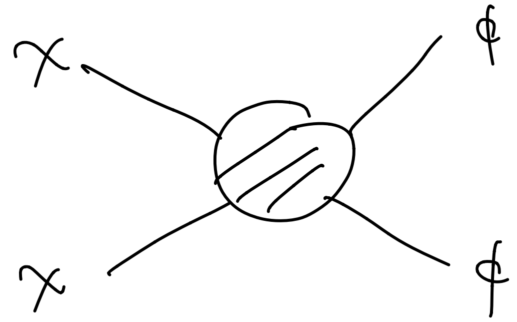
NN-chain ← [Super Heavy Thermal DM, Kafilt? Kim PRL 1906.00981]

Zombie ← [Zombies, Kramer, ... PRL 2003.04900]

$m_{DM} \gtrsim$ keV & above ($\lesssim 300$ TeV + caveats)

FORBIDDEN :

[Griest & Seckel 1991
Ruderman & D'Agnolo JCAP 0707
PRL]



$m_\chi < m_\phi$

@ $T=0$: process forbidden.
But the early universe is a thermal environment – can happen by living off of the Boltzmann tail of the distribution.

See: Boltzmann eq. :

$$\frac{\partial n}{\partial t} + 3nH = -n_\chi^2 \langle \sigma v \rangle_{\chi\chi \to \phi\phi} + n_\phi^{eq\,2} \langle \sigma v \rangle_{\phi\phi \to \chi\chi}$$

Trick – detailed balance: In eq., RHS = 0

$$\Rightarrow \underset{\text{(forbidden)}}{\langle \sigma v \rangle_{\chi\chi \to \phi\phi}} = \frac{(n_\phi^{eq})^2}{(n_\chi^{eq})^2} \underbrace{\langle \sigma v \rangle_{\phi\phi \to \chi\chi}}_{\text{ordinary} \,\sim\, \frac{\lambda_{eff}^2}{m_\chi^2}} \sim$$

$$\sim e^{-2\left(\frac{m_\phi - m_\chi}{T}\right)} \langle \sigma v \rangle_{\phi\phi \to \chi\chi}$$

$$\Rightarrow \frac{\partial n}{\partial t} + 3nH = -\langle \sigma v \rangle_{\phi\phi\to\chi\chi} \left(n_\chi^2 e^{-\frac{2\Delta m}{T}} - n_\phi^{eq\,2} \right)$$

F.O. : $\Gamma_{\chi\chi\to\phi\phi} \sim H$

$$n_\chi \, e^{-2\Delta x} \frac{\alpha_{eff}^2}{m_\chi^2} \overset{!}{\sim} H \sim \frac{T^2}{M_{pl}} \sim \frac{x_f^2}{m_\chi^2 M_{pl}}$$

$$\left(\Delta x = \frac{m_\phi - m_\chi}{m_\chi} \right)$$

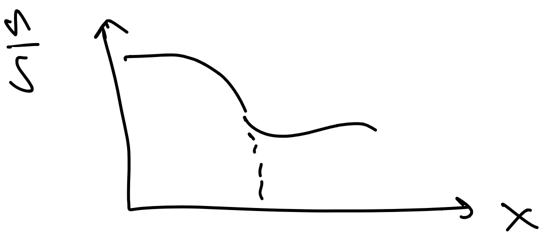
$$\Rightarrow m_\chi \sim \alpha_{eff} \sqrt{T_{eq} M_{pl}} \, e^{-\Delta x}$$

$\ll$ "WIMP"

- exponentially smaller masses than the WIMP

$m_{DM} \gtrsim$ keV & above

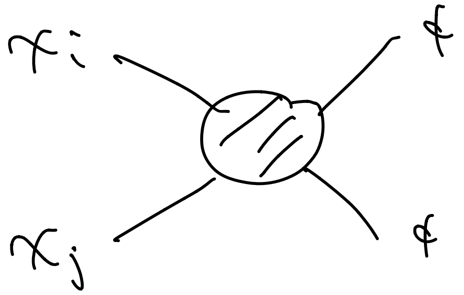
Note: - F.O. picture looks exactly like the WIMP:



– likewise $x_F \sim 20$ still.

Co-ANNIHILATIONS: [Griest & Seckel, 1991]

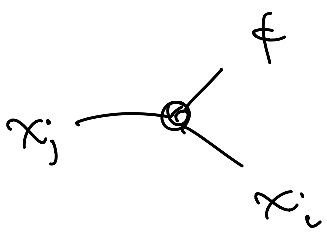
Spectrum of N dark states, lightest is DM.

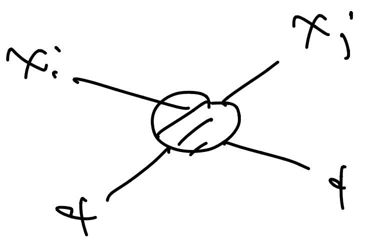


In general, described by N coupled Boltzmann Eqs.

whole tower can participate @ F.O.

assume rapid exchange $\chi_i \leftrightarrow \chi_j \Rightarrow \mu_i = \mu_j$





tower is in chemical eq. w/ itself.

$$\Rightarrow \quad \frac{n_i}{n_j} \simeq \frac{n_i^{eq}}{n_j^{eq}}$$ removes $N-1$ eqs.

consider $n = \sum_i n_i$ total number density

(eventually, everything sits in DM)

$$\Rightarrow \quad \frac{\partial n}{\partial t} + 3nH = -\langle \sigma v \rangle_{eff} \left(n^2 - n_{eq}^2 \right)$$

$$\langle \sigma v \rangle_{eff} = \sum_{i,j} \frac{(n_i^{eq})(n_j^{eq})}{(n^{eq})^2} \langle \sigma_{ij} v \rangle$$

Identical to WIMP otherwise - so use

$$\langle \sigma v \rangle_{eff} \sim \frac{1}{T_{eq} M_{pl}}$$

{@ F.O., the whole tower is populated, @ late times they decay down}.

The sum needn't be dominated by the lightest particle!

In particular, abundance could be set by interactions entirely of other particles w/o even involving the lightest one.

Abundance can be independent of int. of DM!

(Happens in SUSY~)

Implications for phenomenology!