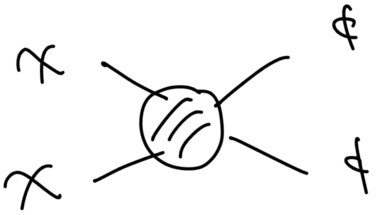
(II) Beyond WIMP ;

[Yonit Hochberg, HUJI]

Outline ; - forbidden channels
- co-annihilating
- $3\to 2$, $n \to 2$: SIMP
- Cannibals

Forbidden channels ;

DM = χ [Griest & Seckel 1991; Ruderman, D'Agnolo 1505.07107]



@ $T=0$: this process is forbidden.

But early universe is a thermal environment $\to$ can happen by living off of the Boltzmann tail of the distribution.

$m_\chi < m_\phi$

annih $\longrightarrow$

$\longleftarrow$ production

See: Boltzmann eq :

$$\frac{dn_\chi}{dt} + 3n_\chi H = -n_\chi^2 \langle\sigma v\rangle_{\chi\chi\to\phi\phi} + n_\phi^2 \langle\sigma v\rangle_{\phi\phi\to\chi\chi}$$

trick : use detailed balance :

In eq. : RHS $= 0$

$$\Rightarrow -n_\chi^{2\,eq} \langle\sigma v\rangle_{\chi\chi\to\phi\phi} + n_\phi^{2\,eq}\langle\sigma v\rangle_{\phi\phi\to\chi\chi} = 0$$

$$\Rightarrow \underbrace{\langle\sigma v\rangle_{\chi\chi\to\phi\phi}}_{\text{(forbidden)}} = \left(\frac{n_\phi^{eq}}{n_\chi^{eq}}\right)^2 \underbrace{\langle\sigma v\rangle_{\phi\phi\to\chi\chi}}_{\text{ordinary}}, \quad (\sim)$$

$$\sim \frac{\alpha_{eff}^2}{m_\chi^2}$$

$$\underbrace{\quad}_{\sim\, e^{-2\frac{(m_\phi - m_\chi)}{T}}}$$

$$\sim \; e^{-2\frac{\Delta m}{T}} \langle \sigma v \rangle_{\phi\phi \to \chi\chi}$$

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

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

$$n_\chi \underbrace{e^{-\frac{2\Delta m}{T}}}_{} \frac{\alpha_{eff}^2}{m_\chi^2} \sim \frac{T^2}{M_{pl}} \sim \frac{x_f^2}{m_\chi^2 M_{pl}}$$

only difference from the WIMP eq.

$x = \frac{m_\chi}{T}$

$$\Rightarrow \boxed{m_\chi \sim \alpha_{eff} \sqrt{T_{eq} M_{pl}} \cdot e^{-\Delta x}} \ll \text{"WIMP"}$$

$$\left(\Delta x = \frac{\Delta m}{T} \right)$$

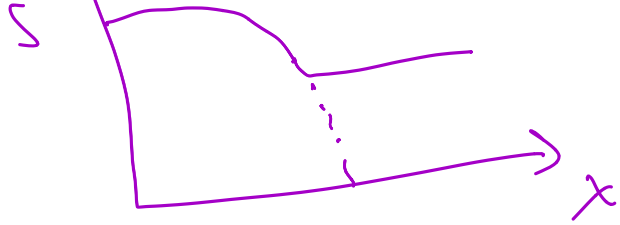
Exponentially smaller masses than "WIMP-like" case.

Light DM ($<$ weak scale, $<$ GeV)

$m_\chi \gtrsim$ keV & above.

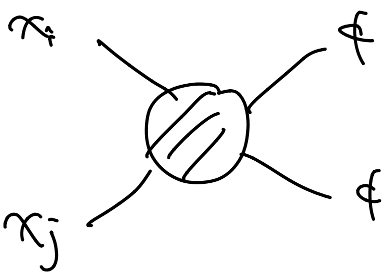
Note: - F.O. picture exactly the same:

$\Omega \uparrow$



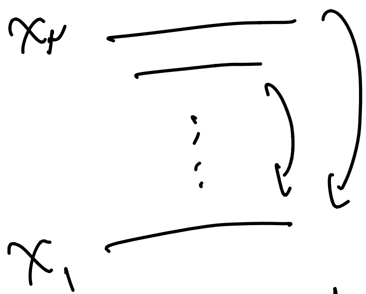
- Freeze: $x_F \sim 20$ still.

Co-ANNIHILATIONS: [Griest-Seckel 1991]



whole tower can participate @ f.o.

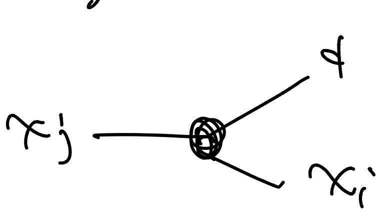
Spectrum of N dark states, lightest one is DM.

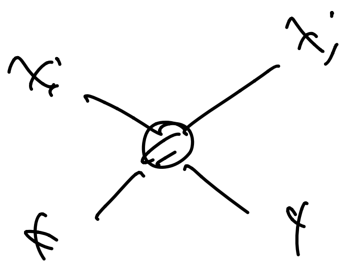


In general described by N coupled Boltzmann eqs.

<u>Trick</u>: assume rapid exchange. $\chi_i \leftrightarrow \chi_j$

$$\Rightarrow \mu_i = \mu_j$$





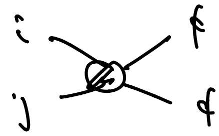
tower is in chemical eq. w/ itself.

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

⇒ Consider $n = \sum_i n_i$ total number density.

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

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



Identical to WIMP otherwise – so use:

$$\langle \sigma v\rangle_{eff} \overset{!}{\simeq} \frac{1}{T_{eq} M_{pl}} \;!$$

thermal (→ effective xsec) need not be controlled/dominated by the lightest particle!

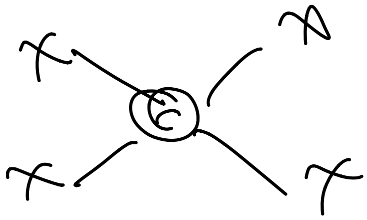
In particular, abundance could be set by interacting entirely of completely other particles.

Abundance can independent of int. of DM!

$\underbrace{3 \to 2 \;:\; \text{SIMPs}}$ [Hochberg, Kuflik, Volansky, Wacker PRL 1402.5143] (on the beach!! ☺)

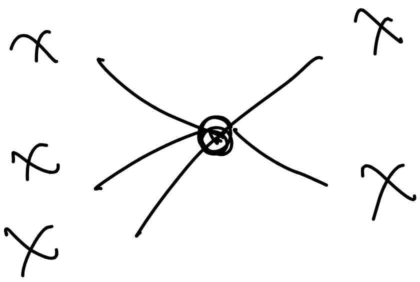
DM = lightest state in secluded dark sector.

What if what's important isn't how DM interacts w/ other things, rather itself?



self-scattering – don't change the number density.

⇒ first process that does: $3 \to 2$



let's use the estimating tools:

$$\left[\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\langle \sigma v^2 \rangle_{3\to2} \left(n_\chi^3 - n_\chi^2 n_\chi^{eq} \right) \right]$$

F.O. : $\Gamma_{3\to2} \sim H$

(*) $\Gamma_{3\to2} \sim \underbrace{n_\chi^2}\ \underbrace{\langle \sigma v^2 \rangle_{3\to2}} \sim H$ @ FO

if I am a DM particle, have to meet 2 more

v^2 – flux $(nv)^2$, stand in notation for collision term.

$\underbrace{\qquad} = \langle \sigma v^2 \rangle_{3\to2} \equiv \dfrac{\alpha_{eff}^3}{m_\chi^5}$

$[\Gamma] = 1$, $[n] = 3$, $[n^2] \sim 6 \longrightarrow \left[\langle \sigma v^2 \rangle_{3\to2} \right] \sim -5$

take n_χ^{FO} – from our "redshift to T_{eq}" trick:

$$n_\chi^{fo} \sim \frac{T_{eq}\, m_\chi^2}{x_f^3} \Rightarrow \text{plug into } (*):$$

$$\Rightarrow \frac{T_{eq}^2\, m_\chi^4}{x_f^6} \cdot \frac{\alpha_{eff}^3}{m_\chi^5} \sim \frac{T^2}{M_{pl}} \sim \frac{m_\chi^2}{x_f^2 M_{pl}}$$

$$\Rightarrow \boxed{m_\chi \sim \alpha_{eff} \left(T_{eq}^2 M_{pl} \right)^{1/3} \sim \alpha_{eff} \cdot (100\,\text{MeV})}$$

"generalized geometric mean".

If $\alpha_{eff} \sim 1$, strong scale emerges!

"The SIMP miracle"

Strongly (self) interacting massive particle.

much lighter DM mass, very different interactions!

(Note: $x_f \sim 20$ still, f.o. when NR:

$$n_\chi \sim (mT)^{3/2} e^{-m/T}$$

$$n_\chi^2 \sim (mT)^3 e^{-2m/T}$$

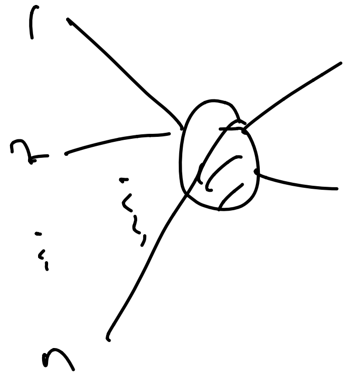
f.o.: $$n_\chi^2 \langle \sigma v^2 \rangle_{3\to 2} \sim (mT)^3 \underbrace{e^{-2m/T}}_{e^{-2x_f}} \frac{\alpha_{eff}^3}{m_\chi^5} \sim \frac{m_\chi^2}{x_f^2 M_{pl}}$$

$$\Rightarrow x_f \sim -\frac{1}{2} \ln\left(\frac{x_f m}{M_{pl}} \right)$$

SIMPs freezing out when NR, $T \sim m/20$.)

More generally, $n \to 2$; (DM is fermion - $\cancel{3\to 2}$, $\mathbb{Z}_2$)

$n \to 2$



Self-interacting

$$\langle \sigma v^{n-1} \rangle_{n\to 2} \simeq \frac{\alpha^n}{m_\chi^{2+3(n-2)}}$$

Detailed balance: forward = backward in eq:

$$(n^{eq})^n \langle \sigma v^{n-1} \rangle_{n\to 2} - (n^{eq})^2 \langle \sigma v \rangle_{2\to n} = 0$$

$$\Rightarrow \langle \sigma v^{n-1} \rangle_{n\to 2} = \underbrace{(n^{eq})^{2-n}}_{[m^{3(2-n)}]} \underbrace{\langle \sigma v \rangle_{2\to n}}_{[m^{-2}]} = [m^{-(2+3(n-2))}]$$

F.O. : $\Gamma_{n\to 2} \sim H$

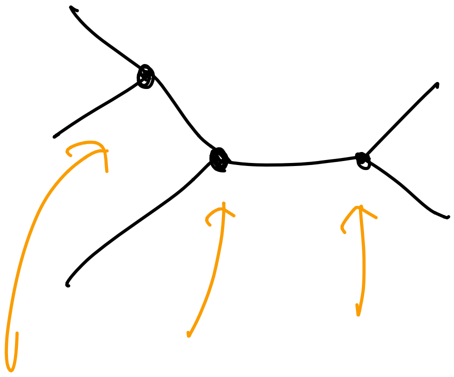
$$\Gamma_{n\to 2} \sim n_\chi^{n-1} \langle \sigma v^{n-1} \rangle_{n\to 2} \sim H$$

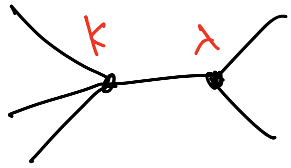
$$\Rightarrow \boxed{m_\chi \sim \alpha \left(T_{eq}^{n-1} M_{pl} \right)^{\frac{1}{n}}}$$

e.g. $n=4$; $4\to 2$: $m_\chi \sim \alpha \cdot 100$ keV

$3\to 2$ toy $\mathbb{Z}_3$ model: Single scalar w/ $\mathbb{Z}_3$ sym':

$\mathcal{L} \supset \chi^3, \ |\chi|^4$





4pt + 3pt.

3 3pt. interactions

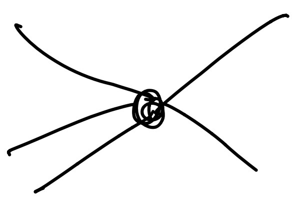
Required $\langle\sigma v^2\rangle_{3\to2} \sim \frac{\alpha^{3}}{m^5}$

$\# \frac{(\kappa\lambda)^2}{f(m_\chi)} = \frac{\alpha_{eff}^3}{m_\chi^5}$

"Been cheating?!"

Implicitly assumed that 1 Temperature for the entire system. But $3\to2$ pumps heat:

Cold



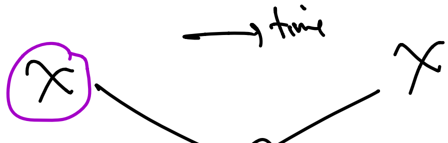
hot

need to shed heat - be able to cool, to dump entropy!

Can be to other light state or to SM.

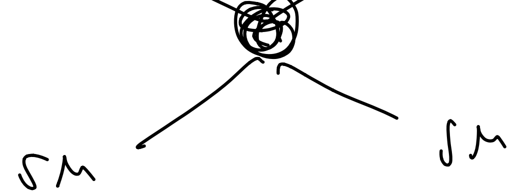
Exchange heat w/ SM:

Cool: χ $\longrightarrow$ time



χ

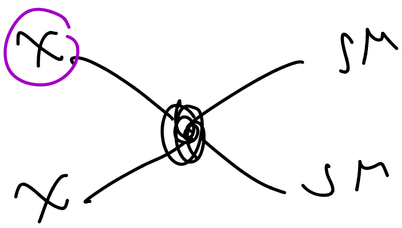
$\Gamma_{kin} \sim n_{SM}\langle\sigma v\rangle_{2\to2}$



want to be active while $3\to2$ is f.o.

[what matters is who you need to meet!]

ann.?



$$\Gamma_{ann} \sim \underline{\underline{n_\chi}} \langle \sigma v \rangle_{2\to2}$$

want to cool but not annihilate!

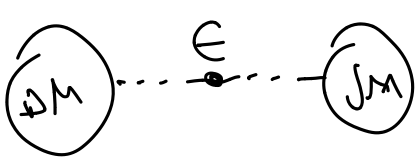
Can it be done? yes!

$$\frac{\Gamma_{ann}}{\Gamma_{kin}} \sim \frac{n_\chi}{n_{SM}} \sim e^{-m_\chi/T} \sim 10^{-8} \ll 1$$

scatter off of light SM species, $e, \nu, \gamma \ldots$

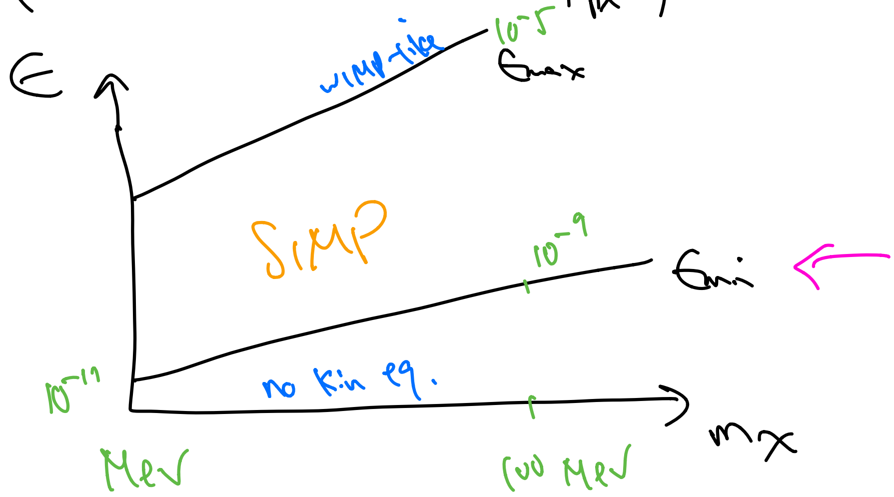
Conditions: $\left.\frac{\Gamma_{kin}}{\Gamma_{3\to2}}\right|_{T=T_F} \gtrsim 1$, $\left.\frac{\Gamma_{ann}}{\Gamma_{3\to2}}\right|_{T_F} \lesssim 1$

parametrize SIMP-SM interactions $\langle \sigma v\rangle_{kin} \sim \langle \sigma v \rangle_{ann} \equiv \frac{\epsilon^2}{m_\chi^2}$



⇒ Range of ϵ where works:

$$\begin{cases} \epsilon_{min} \sim \alpha_{eff}^{1/2} \left(\frac{T_{eq}}{M_{pl}}\right)^{1/3} \\ \epsilon_{max} \sim \alpha_{eff} \left(\frac{T_{eq}}{M_{pl}}\right)^{1/6} \end{cases}$$



CANNIBALISM : [Carlson, Machacek, Hall, 1992]

look back @ 3→2, what if didn't dump entropy into light species? (3→2 w/o additional abundant particles, dark sector w/ mass gap).

No reason to have same T as SM.

When DM becomes NR ($T_\chi < m_\chi$), 3→2 converting mass χ into kinetic energy of the others.

The resulting χ's are Rel', quickly scatter off of χ particles ($\chi\chi \to \chi\chi$) = distribute the kinetic energy back into χ bath. Heating up the bath raises T_χ.

"Cannibalization" — the χ's eat themselves to stay warm.

How much do they heat up?

comoving entropy conserved. $S_\chi a^3 = \text{const}$.

$$S_\chi = \frac{\rho_\chi + P_\chi}{T_\chi} \underset{\text{NR}}{=} \frac{\rho_\chi}{T_\chi} = \frac{m_\chi n_\chi}{T_\chi} \underset{n_\chi \sim \text{NR}}{\sim} \frac{m_\chi}{T_\chi}\left(\frac{m_\chi T_\chi}{2\pi}\right)^{3/2} e^{-m_\chi/T_\chi}$$

$\Rightarrow$ conservation of entropy implies:

$$\Rightarrow \quad T_\chi \propto \frac{1}{\log a} \sim \frac{1}{\log(1/T_\gamma)} \qquad \left(a \sim \frac{1}{T}\right)$$

The temperature of χ is growing exponentially compared to the SM bath!

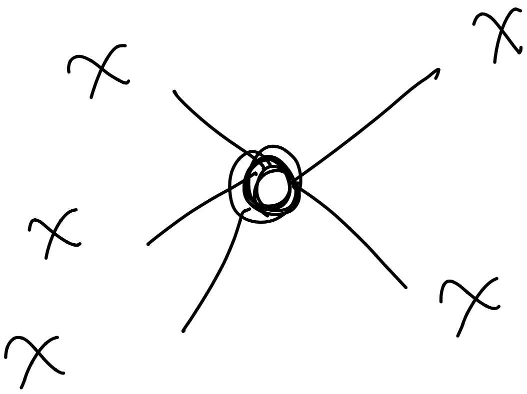
Also estimate abundance:

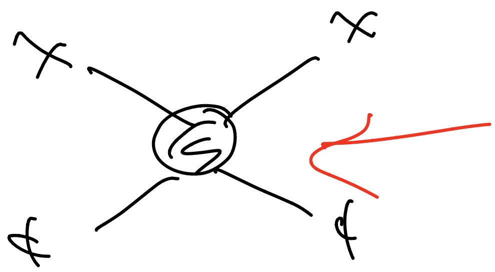
$$\frac{m_\chi n_\chi^0}{s^0} = \frac{m_\chi n_\chi^{FO}}{s^{FO}} = \frac{T_{\chi_F}\, S_\chi^{FO}}{s^{FO}}$$

$$\Rightarrow \Omega_\chi = \frac{m_\chi n_\chi^0}{\rho_c} = \frac{m_\chi n_\chi^{FO}}{\rho_c}\frac{s^0}{s_{FO}} = \frac{Y_{\chi F} s_\chi^{FO} s^0}{\rho_c s^{FO}} =$$

$$= 0.6 \frac{m_\chi / eV}{x_{\chi F}} \frac{S_{\chi F}}{S_F}$$

Relates to ELDER [Kuflik, Perelstein, Rey-Le Lorier, Tsai PRL 1512.04545]





SIMP: dec. 1st | dec. 2nd (active during f.o.)

ELDER: dec. 2nd. | dec. 1st

$$\Rightarrow \Omega_\chi \sim e^{-\langle\sigma v\rangle_{elastic}}$$

[TA Jeff Dror]

"phase diagram"