• dominant production?

$\chi\chi \to YY$ vertex $=$ eff. dim $4+n$ coupling $\Rightarrow \langle\sigma v\rangle \cdot n^2 \xrightarrow[T\gg m]{} \Lambda^{-2n} T^{2n-2}\, T^6$

[$n>0$ e.g. motivated by necessary smallness of $\langle\sigma v\rangle$]

$nH \longrightarrow T^3 \cdot T^2$

$\Rightarrow$ dominant production @ $\begin{cases} T \sim m_\chi & \text{for } n \le 0 \quad \text{"IR freeze-in"} \\ T \sim T_{RH} & \text{for } n > 0 \quad \text{"UV freeze-in"} \end{cases}$

• Required coupling for $\langle\sigma v\rangle \sim \frac{\alpha^2}{m_\chi^2}$: (IR freeze-in)

$$\partial_t (a^3 n) = a^3 n_{MB}^2 \langle\sigma v\rangle$$

$$\Rightarrow a^3 n \sim a^3 n_{MB}^2 \langle\sigma v\rangle t \Big|_{t = t_{fi} \sim H^{-1} \sim \frac{M_{Pl}}{T_{fi}^2}} \quad ; T_{fi} \sim m_\chi$$

$$\Rightarrow n_{fi} \sim m_\chi^6 \frac{\alpha^2}{m_\chi^2} \frac{M_{Pl}}{m_\chi^2}$$

$$\overset{!}{\sim} \frac{s_\chi^{eq}}{m_\chi} \left(\frac{T_{fi}}{T_{eq}}\right)^3 \sim T_{eq}\, m_\chi^2$$

$$\Rightarrow \boxed{\alpha \sim \left(\frac{T_{eq}}{M_{Pl}}\right)^{1/2} \sim 10^{-10}}$$

NB: no $m_\chi$-dependence! $\leftrightarrow$ WIMPs

• Detection prospects for FIMPs?

feeble... [for direct/indirect/collider searches]

exceptions: i) very low re-heating temperature [in UV case]

("just before BBN")

e.g. freeze-in of scalar singlet: potential impact on invisible Higgs decay width

ii) light DM

$\rightsquigarrow$ free-streaming effects / structure formation

(dominant production @ higher T than freeze-out, but also "more time to redshift" $\rightsquigarrow$ overall similar)

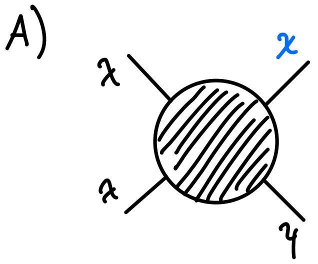
e.g. $m_{WDM} > 3.5$ keV $\hat{=}$ $m_{FIMP} > 9.2$ keV [2012.01446]

[most conservative maybe only 1.9 keV]

# I.3 Alternatives

roughly 2 options:

A)

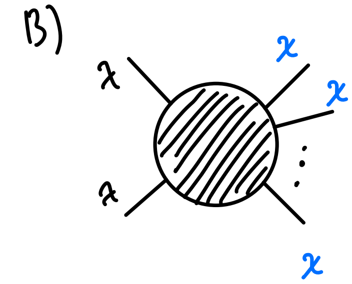



$\longleftrightarrow$ "DM from semi-annihilations"

$\longleftarrow$ "pandemic DM"

⌜$\chi\chi\chi\psi$ vertex : "coscattering"⌟

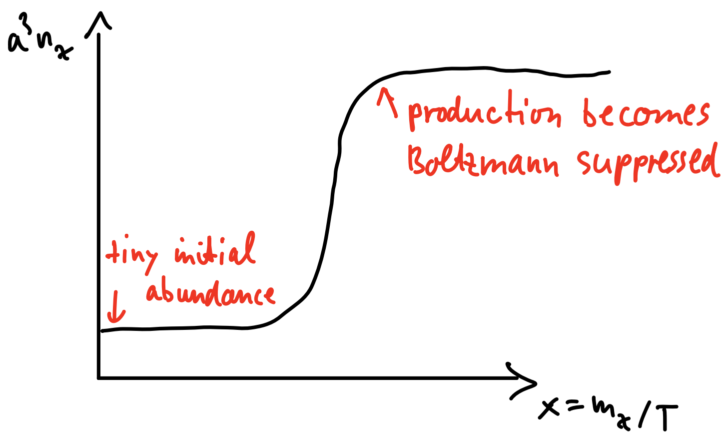
B)




"SIMP DM"

A) consider only production ( $f_\chi \ll 1$ ) :

$$\boxed{\dot n_\chi + 3 H n_\chi = \langle \sigma v \rangle n_\chi n_\psi} \Rightarrow \text{exponential growth}$$




fun fact : <u>same</u> equation describes spread of diseases!

$$\dot I = \beta S I - \gamma I$$

$I$ = # infected individuals

$S$ = # susceptible individuals

$R$ = # recovered individuals

= tot − S − I

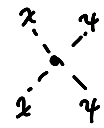
⇝ "pandemic" DM...

$\beta$ = infection rate "=" $\langle \sigma v \rangle$

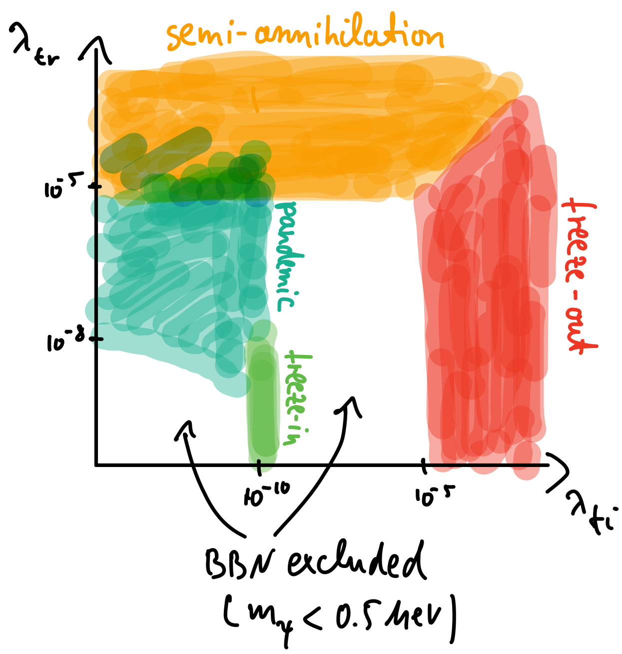
$\gamma$ = recovery rate "=" $3H$

[for comoving $a^3 n_\chi$, there is no recovery! Hence finite RD... ]

- How does this compare to other mechanisms?

⇝ toy model:  $= i\lambda_{tr}$  $= i\lambda_{ti}$

+ fix $\Omega_{DM} h^2 = 0.12$ ; $m_\psi / m_\chi \overset{\text{e.g.}}{=} 1.2$ ⇒ couplings only free parameters



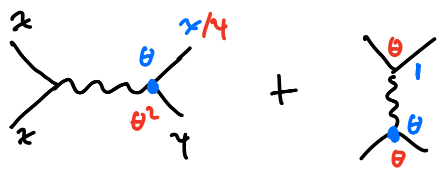

"phase diagram for DM production from thermal bath"

model building:

generic realization of $\langle \sigma v \rangle_{tr} \gg \langle \sigma v \rangle_{ti}$ ?

⇝ mediator + mass mixing!

e.g. $\mathcal{L} \supset \bar{\chi} A \chi + \delta m\, \bar{\chi} \psi$ ⇝ $\theta \sim \frac{\delta m}{m_\chi}$



$\Rightarrow$ $\mathcal{M}_{tr} \propto \theta$

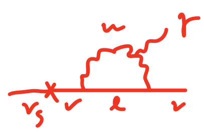
$\mathcal{M}_{fi} \propto \theta^2$

application : "minimal sterile neutrino DM" [2206.10630]

- SM $\nu_s$ production : ~ freeze-in via oscillations
  + EW scattering processes

  "Dodelson - Widrow"

  $\rightarrow$ excluded by X-ray constraints ($\nu_s \rightarrow \nu \gamma$)



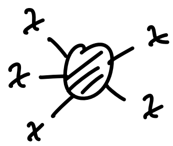
- adding one scalar d.o.f. ($\rightsquigarrow$ "minimal")

  - allows "pandemic" production
    (through mediator, as above)

    $\rightsquigarrow$ new viable parameter space

  - observational opportunities :
    - $\nu_s \rightarrow \nu \gamma$ (not modified)
    - $\lambda_{FS}$, $r_s$ (modified bounds)
    - $\nu_s$ DM self-interactions (new bound)

## B) SIMP DM




⇝ DM can self-equilibrize !

⌜chemically ⟷ only kinetically for $\chi\chi \leftrightarrow \chi\chi$⌟

- rates in EQ: $\leftarrow \; = n_{eq}^2 \langle \sigma v \rangle$

$\rightarrow \; = n_{eq}^3 \, "\langle \sigma v^2 \rangle"$ "just a name", defined by $C[f]$

detailed balance ($\leftarrow = \rightarrow$)

$\Rightarrow [\sigma v^2] = [n^{-1}\sigma] = \text{mass}^{-5}$

$$\Rightarrow \langle \sigma v^2 \rangle \equiv \frac{\alpha_{eff}^3}{m_\chi^5}$$

- outside EQ: $n^2 \langle \sigma v \rangle = n^2 n_{eq} \langle \sigma v^2 \rangle$ ⌜keep scaling with $n^2$ + recover EQ case for $n \to n_{eq}$⌟

$$\Rightarrow \boxed{\dot{n} + 3Hn = -\langle \sigma v^2 \rangle_{3\to 2} \left(n^3 - n^2 n_{eq}\right)}$$

⇝ freeze-out at $Hn \sim \langle \sigma v^2 \rangle n^3 \sim \frac{\alpha_{eff}^3}{m_\chi^5} n^3$ | $H \sim \frac{T_f^2}{M_{pl}}$ ; $n \sim \frac{\rho_\chi(T_{eq})}{m_\chi} \frac{T_f^3}{T_{eq}^3} \sim \underbrace{\frac{T_f}{m_\chi}}_{\sim 1/15} T_{eq} T_f^2$

⌜$M_{pl}^{-1} \sim \alpha_{eff}^3 m_\chi^{-3} T_{eq}^2 (T_f/m_\chi)^4$⌟

$$\Rightarrow \boxed{m_\chi \sim \alpha_{eff} \left(T_{eq}^2 M_{pl}\right)^{1/3}}$$ ⟷ WIMP: $m_\chi \sim \alpha_{eff} (T_{eq} M_{pl})^{1/2}$

e.g. for $\alpha_{eff} \sim 1$, $m_\chi \sim 100$ MeV : strong scale

⇝ a "SIMP miracle" ⌜~ same argument: in principle unrelated scales.

BUT: nothing like hierarchy problem that would independently suggest new physics at this scale!

generalization: not $3 \Leftrightarrow 2$ but $n \Leftrightarrow 2$

or this

$$\Rightarrow m_\chi \sim \alpha_{eff} \left(T_{eq}^{n-1} M_{pl}\right)^{1/n}$$

NB: $3 \to 2$ heats up DM particles!

$\rightsquigarrow$ option a) additional $\chi\chi \leftrightarrow \psi\psi$ $\quad \sigma = \dfrac{\alpha_\psi^2}{m_\chi^2}$

cools DM to $T_\chi = T$ (as assumed in estimate above)

b) completely secluded dark sector:

DM "cannibalizes itself to keep warm"

$\rightsquigarrow \lambda_{FS}$ much larger than for WDM!

$\rightsquigarrow$ conserved entropy in dark sector:

$$s_\chi = \frac{g_\chi \boxed{+ p_\chi}}{T_\chi} \sim \frac{m_\chi}{T_\chi} (m_\chi T_\chi)^{3/2} e^{-m_\chi / T_\chi}$$

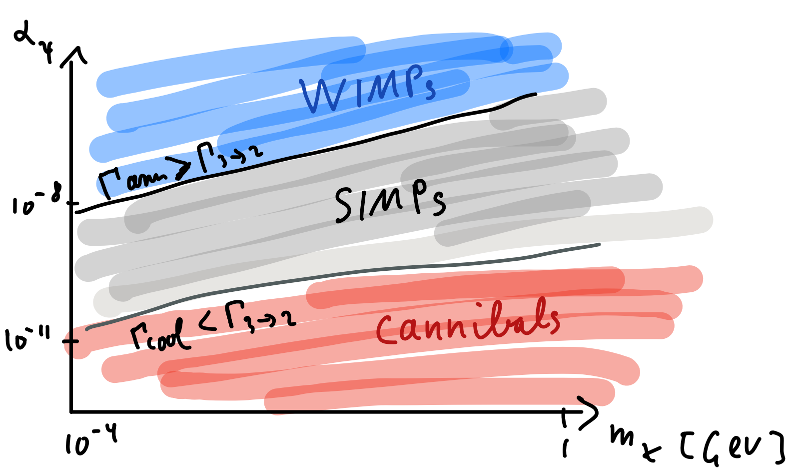
$$a^3 s_\chi = \text{const.} \underset{a \propto \frac{1}{T}}{\Rightarrow} T_\chi \sim \frac{1}{\log(1/T)}$$

$\rightarrow$ fast growth of $\frac{T_\chi}{T}$ during cannibal phase!

$\Rightarrow$ e.g. for $m_\chi \sim 10$ MeV (!)

must start w/ $s_\chi \lesssim 3 \cdot 10^{-5} s_{SM}$ [1602.4219]

$\Leftrightarrow (T_\chi / T)_{T \to \infty} \sim \mathcal{O}(10^{-2} - 10^{-1})$




$\alpha_\psi \ll 0.01$ because $m_\chi \ll 100$ GeV