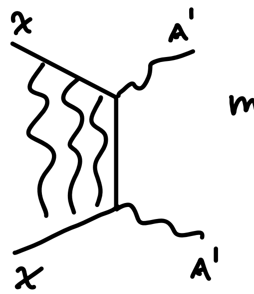
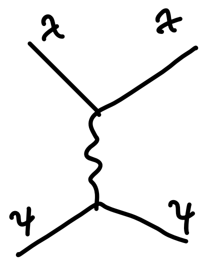
e.g.: • Sommerfeld enhancement (near parametric resonances)



$m_{A'} \lesssim m_\chi$

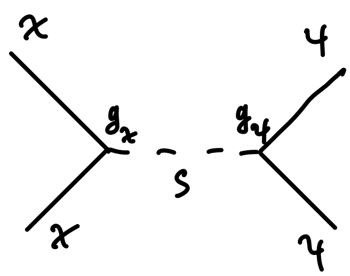


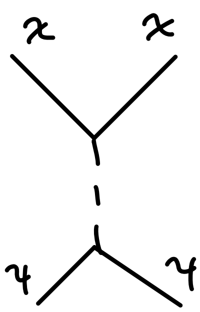
$\sigma v \propto a + \frac{b}{v^2}$

⇝ second era of annihilations

⇝ late KD

• narrow resonances





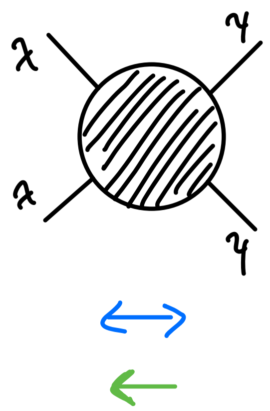
⇒ need very small $g_\chi g_\psi$ for $m_\chi \sim m_S/2$!

(for correct $\Omega_\chi h^2$)

⇒ early KD: $x_{kd} \sim x_{cd}$

⇝ fully implemented in DarkSUSY...

I.2 Freeze-in mechanism



- freeze-out: initial eq. w/ heat bath

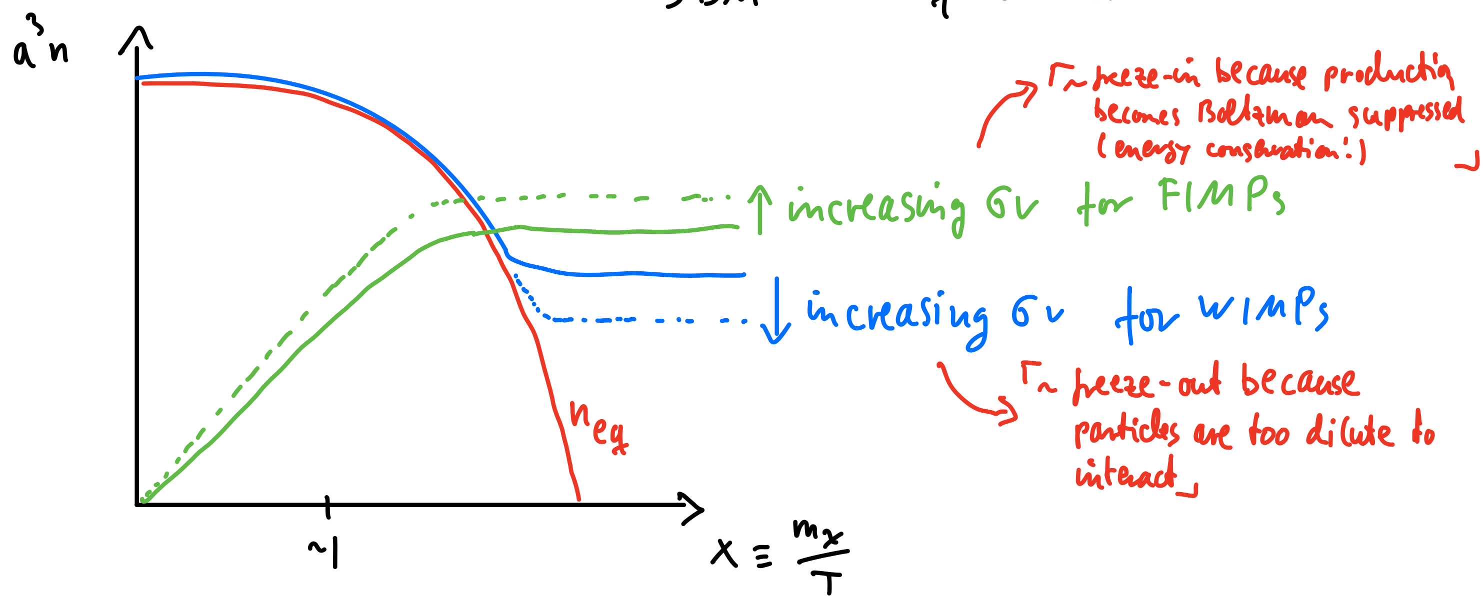
  $\Leftrightarrow \langle \sigma v \rangle n_{eq} > H$ "WIMPs"

  $\Rightarrow g > g_{min}$

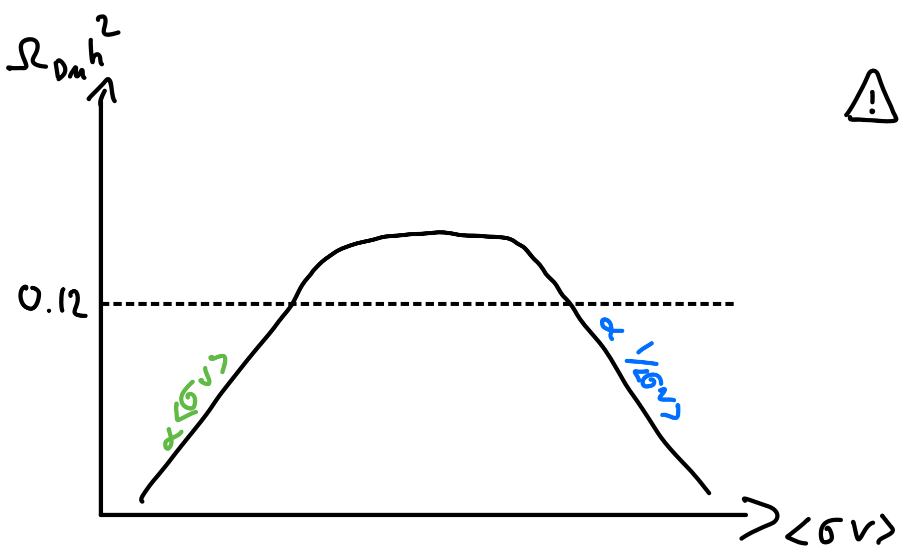
- freeze-in: $g \ll g_{min}$ "FIMPs"

  (partially motivated by absence of DM signals)

  $\Rightarrow$ DM never equilibrizes

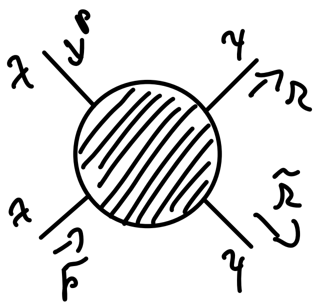


$\Rightarrow$ always <u>two</u> possibilities to obtain correct relic density!



⚠ FIMPs are sensitive to initial conditions, WIMPs are not

Collision operator



$$C_n = \int\frac{d^3p}{(2\pi)^3 2E}\int\frac{d^3\tilde p}{(2\pi)^3 2\tilde E}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde k}{(2\pi)^3 2\tilde\omega}\,(2\pi)^4\delta^{(4)}(p+\tilde p-k-\tilde k)$$

$$\times |M|^2\left\{f_\psi(\omega)f_\psi(\tilde\omega) - f_\chi(E)f_\chi(\tilde E)\underbrace{[1\pm f_\psi(\omega)]}_{\equiv \bar f_\psi(\omega)}[1\mp f_\psi(\tilde\omega)]\right\}$$

↗ CP invariance

$f_\chi \ll 1 \Rightarrow$ • $\bar f_\chi \simeq 1$ [BUT $\bar f_\psi \neq 1$!]

⌜relativistic production
⟺ WIMPs : cons. of $E\sim m \gg T \Rightarrow f_\psi \ll 1$⌟

• [still:] only production ("⟶" = 0)
("def. of freeze-in")
[⇝ "non-thermal production"]

NB: $f_\psi(\omega) = \frac{1}{e^{\omega/T}\pm 1}$ only in cosmic (plasma) frame!
⌜⟺ WIMPs : all (NR) frames equivalent⌟

math identity: $f_\psi(\omega)f_\psi(\tilde\omega) = f_\psi(\omega)f_\psi(\tilde\omega)\,e^{(\omega+\tilde\omega)/T}\,\underbrace{e^{-E/T}}_{\equiv f_\chi^{MB}(E)}\,e^{-\tilde E/T}$

↑ $\omega+\tilde\omega = E+\tilde E$

$$= f_\chi^{MB}(E)\,f_\chi^{MB}(\tilde E)\,\bar f_\psi(\omega)\,\bar f_\psi(\tilde\omega)$$

⇒ production can be described by the annihilation of a would-be population of χ with MB distribution!

⌜⟺ WIMPs actually follow MB in eq. !⌟

$$\Rightarrow \boxed{\dot{n}_\chi + 3Hn = \langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}\,(n_\chi^{MB})^2}$$ 2111.14871

- formal analogy to WIMP case (w/ annihilation cross section)
  ⇝ highly useful for
  - numerical implementation
  - resonances w/ off-shell bath particles

- allows direct integration over t (or T)
  ⌈r.h.s. no longer depends on n⌋

- quantum statistics / finite-T effects : → are taken into account, despite appearance

$$\sigma v_{Møl} = \underbrace{\frac{1}{N_\gamma}\frac{1}{4E\tilde{E}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}(2\pi)^4\delta^{(4)}(p+\tilde{p}-k-\tilde{k})|M|^2}_{\text{standard def., in vacuum}}\,\underline{f_\gamma(\omega)\,f_\gamma(\tilde{\omega})}$$

($\frac{1}{2}$ for self-conjugate)

$$= f(s,\gamma)$$

↖ Lorentz factor between CMS and plasma frame

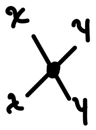
⌈must be possible to write in this form: f_γ singles out frame, but still O(3) symmetric!⌋

⋮

$$\boxed{\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = \frac{8x^2}{K_2^2(x)}\int_1^\infty d\tilde{s}\,\tilde{s}(\tilde{s}-1)\int_1^\infty d\gamma\,\sqrt{\gamma^2-1}\,e^{-2\sqrt{\tilde{s}}\,x\gamma}\,\sigma(s,\gamma)}$$

$$\xrightarrow[\sigma(s,\gamma)\to\sigma(s)]{} \int_1^\infty d\tilde{s}\,\frac{4x\sqrt{\tilde{s}}(\tilde{s}-1)K_1(2\sqrt{\tilde{s}}\,x)}{K_2^2(x)}\,\sigma(s) \quad ✓ \quad = \text{Gondolo-Gelmini}$$

• dominant production?



= eff. dim $4+n$ operator $\Rightarrow \langle\sigma v\rangle \cdot n_\chi^2 \xrightarrow{T \gg m} \Lambda^{-2n}\, T^{2n-2}\, T^6$ (scale of eff. operator: Λ)

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

$n_\chi H \longrightarrow T^3 \cdot T^2$

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

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

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

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

$$\Rightarrow n_{fi} \sim m_\chi^6 \frac{\alpha^2}{m_\chi^2} \frac{M_{pl}}{m_\chi^2} \overset{!}{\simeq} \frac{s_\chi^{eq}}{m_\chi} \left(\frac{T_{fi}}{T_{eq}}\right)^3 \sim T_{eq} m_\chi^2$$

$$\Rightarrow \boxed{\alpha \sim \left(\frac{T_{eq}}{M_{pl}}\right)^{1/2} \sim 10^{-14}}$$

NB: no m_χ-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

⇝ free-streaming effects / structure formation

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

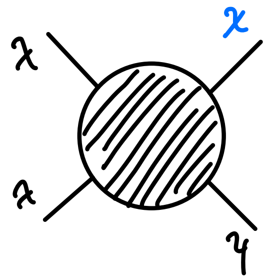
e.g. $m_{WDM} > 3.5$ keV $\hat{=}$ $m_{FIMP} > 9.2$ keV [2012.01446]

↑ [most conservative maybe only 1.9 keV]

II.3 Alternatives

roughly 2 options:

A)

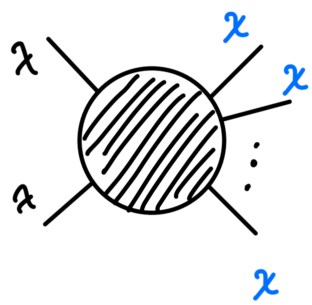


$\longleftrightarrow$ "DM from semi-annihilations"

$\longleftarrow$ "pandemic DM"

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

B)

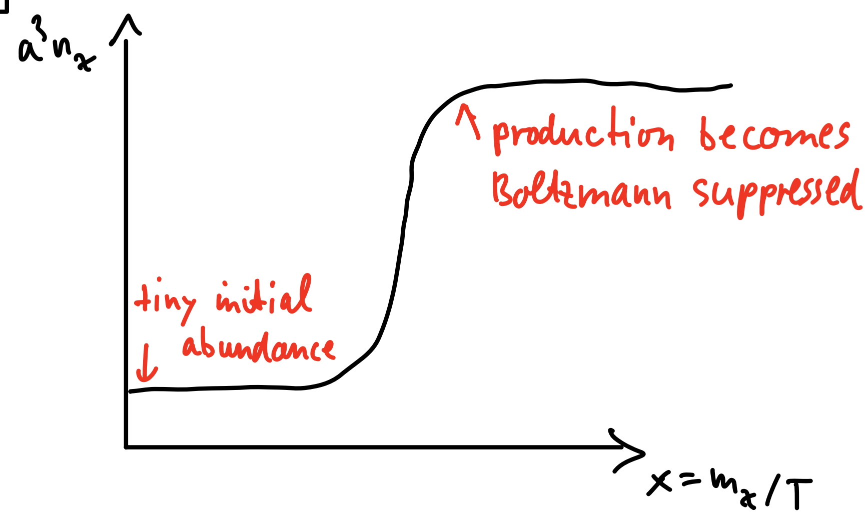


"SIMP DM"

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

$$\boxed{\dot{n}_\chi + 3 H n_\chi = \langle \sigma v \rangle n_\chi n_\gamma}$$

$\Rightarrow$ exponential growth



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

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

I = # infected individuals

S = # susceptible "

R = # recovered "

$= \text{tot} - S - I$

⇝ "pandemic" DM...

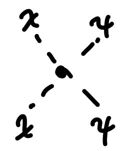
β = infection rate "=" $\langle \sigma v \rangle$

γ = recovery rate "=" $3H$

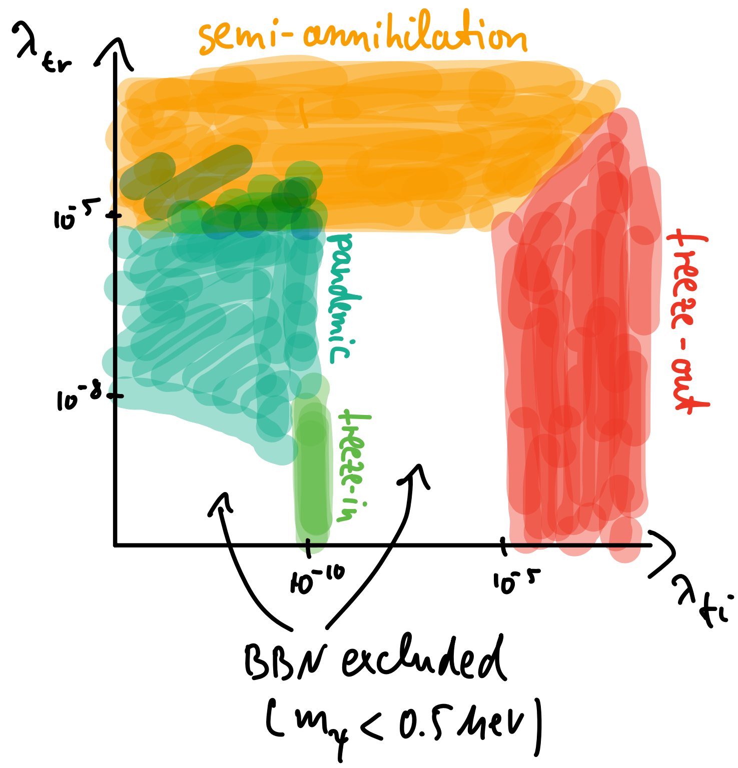
[for comoving $a^3 n_\chi$, there is no recovery! Hence finite RD...]

- 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



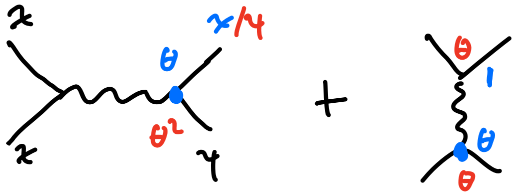
"phase diagram for DM production from thermal bath"

model building:

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

⇝ mediator + mass mixing!

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



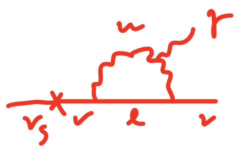
$\Rightarrow$ $\mathcal{M}_{tr} \propto \theta$

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

application: "minimal sterile neutrino DM" [2206.10630]

- SM ν_s production: ~ freeze-in via oscillations + EW scattering processes
  "Dodelson-Widrow"

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



- adding one scalar d.o.f. (~ "minimal")
  - allows "pandemic" production (through mediator, as above)

    ⇝ new viable parameter space
  - observational opportunities:
    - $\nu_s \to \nu\gamma$ (not modified)
    - λ_{FS}, r_s (modified bounds)
    - ν_s DM self-interactions (new bound)