SIMPs, Cannibals & ELDERs - Les Houches 2021

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Hi!! :)   Rough plan - 2×1.5 hours

<u>Outline</u>: Setting the stage

$2 \to 2$: WIMP

$3 \to 2$: SIMPs, Cannibals, ELDERs

Dark sectors

(Crocodile challenge! tomorrow)

<u>Setting the stage:</u>

- universe is dark - $\rho_{DM} \simeq 5\, \rho_{baryons}$

- massive : $m = ???$

10^{-30} ⟷ 10^{50} [GeV]

~80 orders of mag!

↑ too fluffy

↑ misleading

- shouldn't interact too strongly w/ QED, QCD
- not too strongly w/ itself ↔ (signal ?)
- wouldn't be here w/o it !

What is DM? mechanism in early universe to get its relic abundance / model building (how to detect it & constraints)

Early universe cheat sheet:

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

a: scale factor

volume expands like a^3

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

Hubble

$$H^2 = \frac{\rho}{3M_{pl}^2}, \quad \rho \propto T^4 \Rightarrow \underline{\underline{H \sim \frac{T^2}{M_{pl}}}}$$

Early universe = th. environment → phase space distributions $f_{eq}(p)$ ⇒ number density & energy density:

<u>Ballpark</u>: $\underline{\underline{\begin{cases} n \sim T^3 & R \\ \rho \sim T^4 & R \end{cases}}}$

$$\underline{\underline{\begin{cases} n \propto (mT)^{3/2} e^{-(m-\mu)/T} & NR \\ & T \ll m \\ \rho = \left(m + \frac{3}{2}T\right) n \sim mn & NR \end{cases}}}$$

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

$n \propto e^{-m/T}$ exp' suppression.

& entropy density: $\underline{\underline{s \sim T^3}}$

Boltzmann equation:

Consider a system w/ no collisions - free particles:

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

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

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

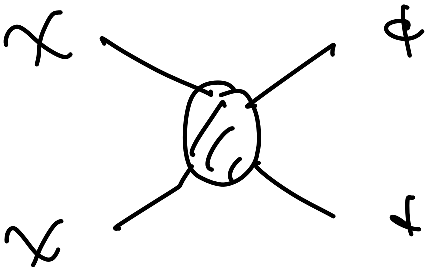
$$\Rightarrow \frac{\partial n}{\partial t} + 3n \underbrace{\left(\frac{\dot{a}}{a} \right)}_{H} = 0$$

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

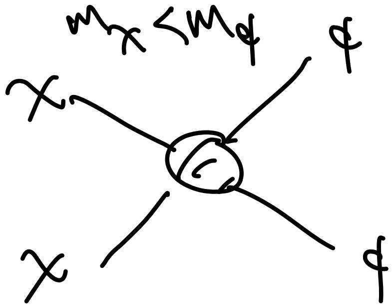
$$\frac{\partial n}{\partial t} + 3nH = -C[n]$$

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

$2 \to 2$ too: $\chi = DM$. $\longrightarrow$ time



WIMP (ann.)



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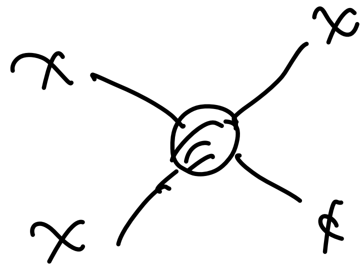
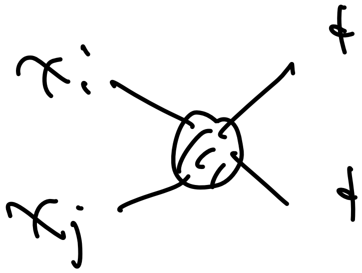
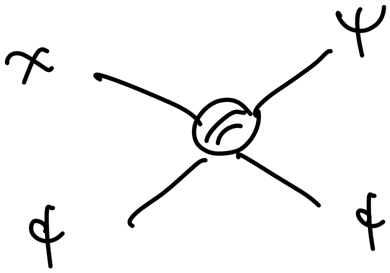


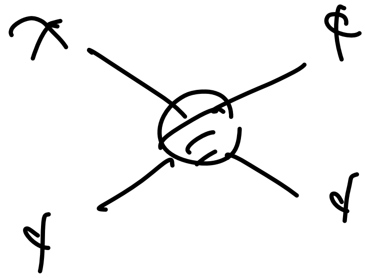
semi-annihilation



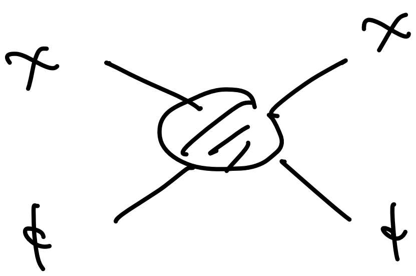
coannihilating



coscattering



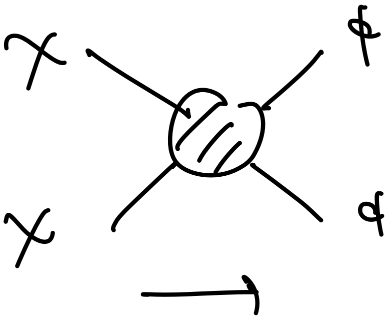
zombie



ELDER

WIMP: star of the show for 40^+ years.

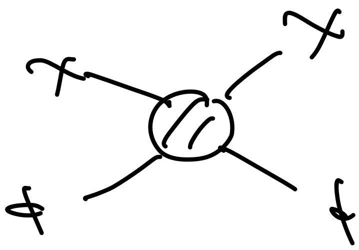
$$\chi\chi \to \phi\phi$$



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

(if fast, sets $\mu_\chi = \mu_\phi$)

sidenote: always also have elastic scattering



& assume φ bath particle

$\mu_\phi = 0$ & high $T \to$

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

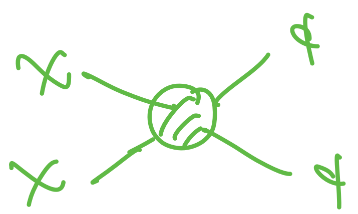
[almost always $\chi\chi \to \phi\phi$ shuts off before $\chi\phi \to \chi\phi$]

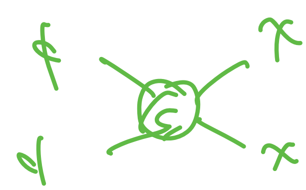
Collision term:

Roughly, rate = thermal averaged cross section × number density

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

why?





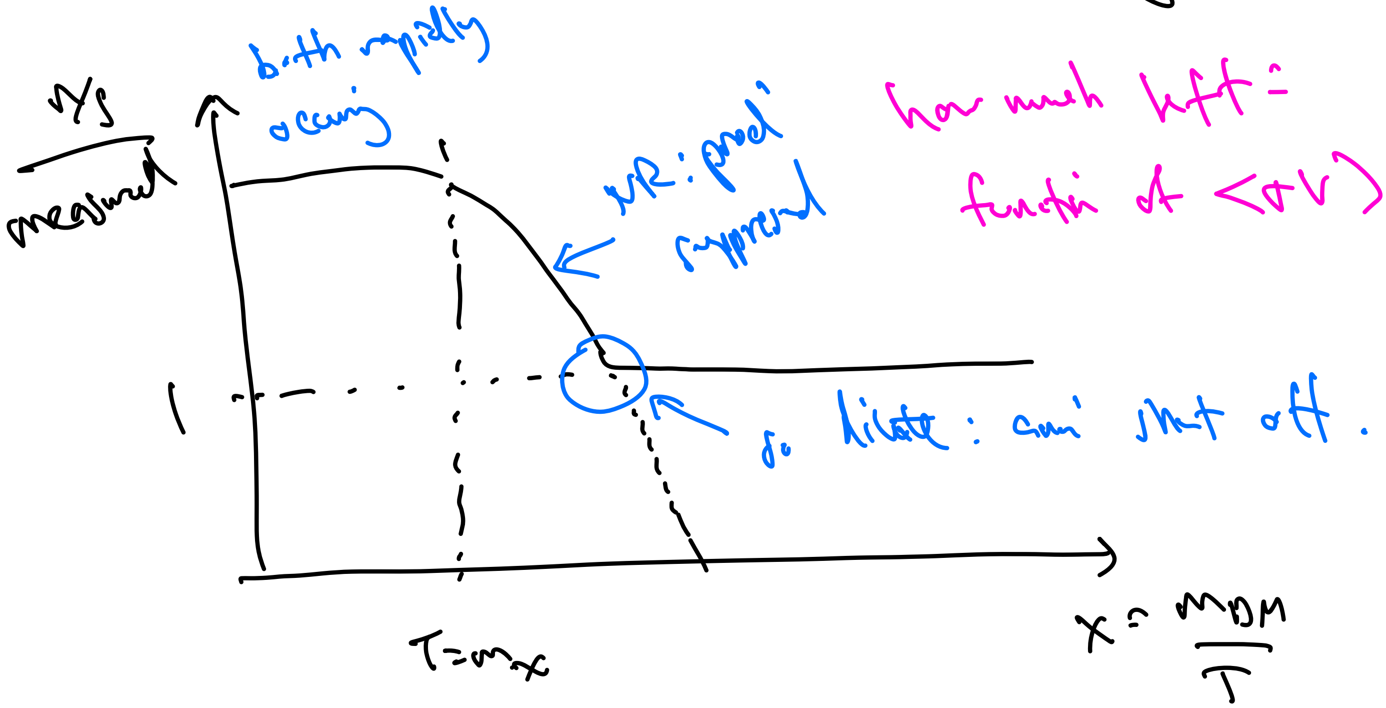
use trick: detailed balance!

In eq., forward & backward processes both rapid

& should cancel out!

$\Rightarrow$ can avoid the backreaction in this way.

What happens? Particle density in a box that expanding w/ universe — (yield $Y = \frac{n}{s} \sim na^3$)



"Freeze out standard picture"

Back of envelope: E.g. $\Gamma_{2\to2} \sim H$

(*) $\Gamma_{2\to2} = n_\chi \cdot \langle \sigma v \rangle \sim H \sim \frac{T^2}{M_{pl}}$

have to meet 1 DM particle.

relate to measured quantities.

Play w/ redshifts:

entropy S conserved: $\tilde{S} = s a^3$ — use this to redshift.

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

Redshift to T_{eq} — matter-radiation equality ($T_{eq} \sim 0.8$ eV)

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

@ matter-radiation eq.:

$$\rho_{matter}^{eq} = \rho_\chi^{eq} + \rho_b^{eq} = \rho_r^{eq}$$

$$\rho_\chi \simeq 5\rho_b \Rightarrow \rho_\chi^{eq} \simeq \rho_r^{eq}$$

(neglect $\mathcal{O}(1)$, see how to keep them.)

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

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

(*) compare to F.O. condition:

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

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

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

Coincidence of scales (M_{Pl}, T_{eq})

another way! $\underline{\underline{\langle \sigma v \rangle}} = \frac{\alpha_{eff}^2}{m_\chi^2} \sim \underline{\underline{\frac{1}{T_{eq} M_{Pl}}}}$

$\longleftrightarrow$ Rudeman

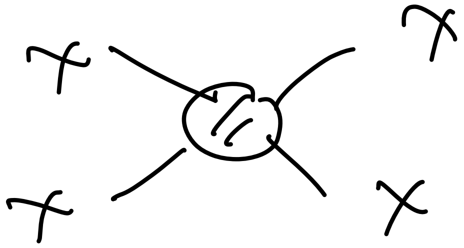
3→2 - SIMPs: [4th Kuflik, Volansky, Wacker PRL 1402.5143]

What is most important (on the beach!!)

i) how DM talks to itself?

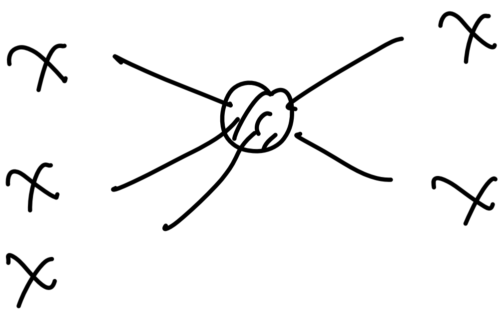
DM = lightest state in nearly secluded sector

Self interacting set the relic abundance:



doesn't change the # densities

$\Rightarrow$ first process that does:



$3 \to 2$ (note: DM scalar, $3\to2$)

Let's use our estimating tools:

$$\partial_t n + 3Hn = -\langle \sigma v^2 \rangle_{3\to2}\left(n_\chi^3 - n_\chi^2 n_\chi^{eq}\right)$$

F.O. when $\Gamma_{3\to2} \sim H$ (**)

$$\Gamma_{3\to2} \sim n_\chi^2 \langle \sigma v^2 \rangle_{3\to2}$$

- if I am a DM, need to meet another 2

v^2 - flux $(nv)^2$, standard notation for collision term.

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

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

$$n_\chi^{FO} \sim \frac{T_{eq}\, m_\chi^2}{x_F^3}$$

$$(**) \quad \frac{T_{eq}^2\, m_\chi^4}{x_F^6} \cdot \frac{\alpha_{eff}^3}{m_\chi^5} \sim \frac{T^2}{M_{pl}} \sim \frac{m_\chi^2}{x_F^2 M_{pl}}$$

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

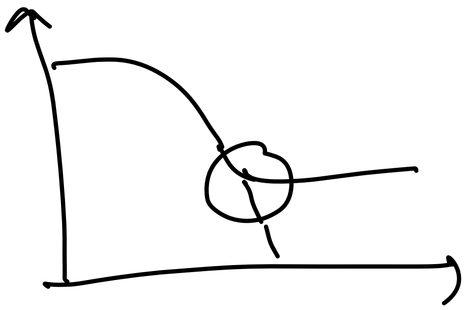
"generalized geometric mean T_{eq}, M_{pl}".

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

"The SIMP Miracle".

much lighter DM than typical for WIMP,

very diff' interactions ! (MeV – GeV scale)

[ F.O. picture - same]

what temp' does freeze out, $x_F = ?$

NR

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

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

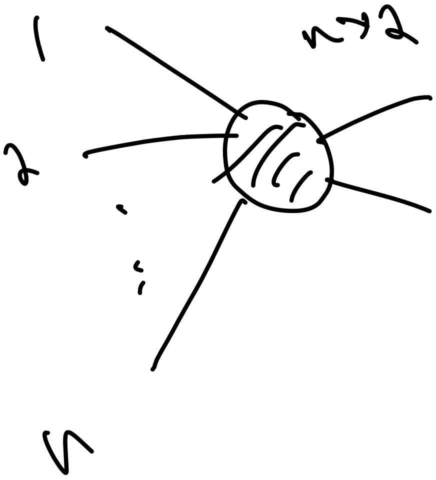
(**) $$n_\chi^2 \langle \sigma v^2 \rangle_{3\to2} \sim (mT)^3 \underbrace{e^{-2m/T}}_{-2x_F} \frac{\alpha_{eff}^3}{m_\chi^5}$$

$$\overset{!}{\sim} \frac{T^2}{M_{pl}} \sim \frac{m_\chi^2}{x_F^2 M_{pl}}$$

$x = \frac{m}{T}$

$\Rightarrow$ $\underline{\underline{x_F}} \sim -\frac{1}{2} \ln(\text{parameters}) \underline{\underline{\sim 20}}$

$\underbrace{\text{More generally, } n \to 2 \text{ ;}}$ (Ada sym', or fermion) $\cancel{3\to2}$



Self interactions

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

detailed balance: forward = backward in eq:

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

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

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

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

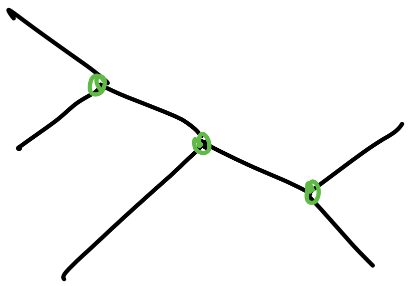
(each n_χ has T_{eq})

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

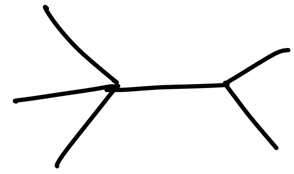
$n \to 2$ we're familiar the $2 \to 2$ ... Toy Model:

(later - tomorrow - Dark sectors)

$3 \to 2$ Toy Model: Single scalar χ^3, $|\chi|^4$



or



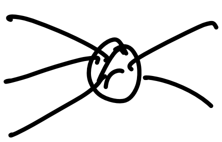
(3 vertices - inspired parametrization of α^3 in xsec $3 \to 2$)

3×3pt. or 1 3pt $+$ 1 4pt.

"Been cheating you!"

Implicitly assumed 1 temp' for entire system.

cold



hot

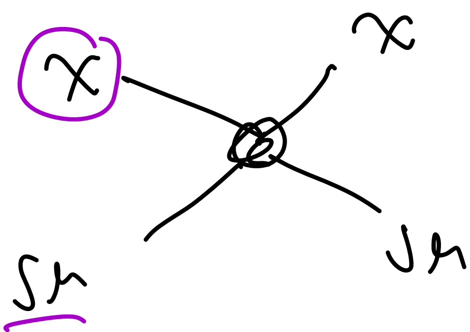
but $3 \to 2$ pumps heat!

(problematic for structure formation).

Need to be able to cool, to dump entropy!

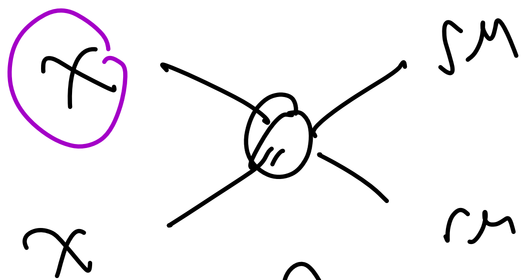
Can be into other light state or SM

Exchange heat w/ SM!



$\Gamma_{kin} \sim n_{SM} \langle \sigma v \rangle$

cool



$\Gamma_{ann} \sim n_{\chi} \langle \sigma v \rangle$

ann?

can it be done - cool but not ann?

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

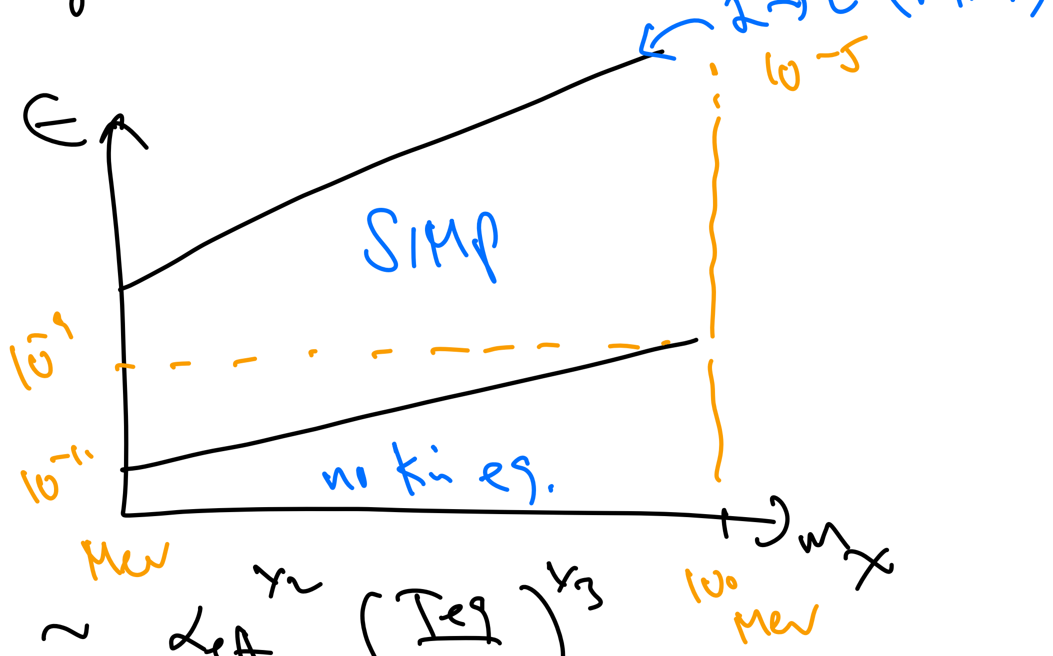
scatter off
abundant particles
e, γ, ν

scatter off light SM species!

Conditions: $\left.\frac{\Gamma_{kin}}{\Gamma_{2\to2}}\right|_{T_F} \gtrsim 1 \,, \quad \left.\frac{\Gamma_{ann}}{\Gamma_{2\to2}}\right|_{T_F} \ll 1$

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

$\Rightarrow$ Range for ϵ where works?



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

as long as $\epsilon_{min} \leq \epsilon \leq \epsilon_{max}$, precise

value don't matter — SMP.