# NON WIMP DARK MATTER (II):

[Yonit Hochberg, HUJI]

Additional refs. for 2→2 :

[coscattering : D'Agnolo, Pappadopulo, Ruderman PRL
1906.09263]

[semi-annihilating : D'Eramo, Thaler 1003.5912]

[Asymmetric Dark Matter : Kaplan, Luty, Zurek 0901.4117
Review - Zurek 1308.0338]

$$d(sa^3) = -\sum_i \frac{\mu_i}{T_i} d(na^3).$$

So entropy is conserved in equilibrium, provided that chemical potentials are small or that the number or fields with large chemical potentials have slow varying number densities. This is a very good approximation in the early universe.

Additional resources :

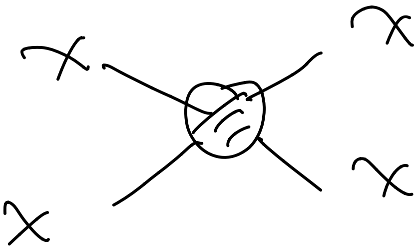
- Roni Harnik, MITP school, DM, for very detailed DM evidence (lecture 1)
- Josh Ruderman, IIAS Winter school 2013, lecture 4
- Daniel Baumann - Cosmology Notes (Amsterdam)

# 3→2 - SIMP :

[YH, Kuflik, Volansky, Wacker PRL
1402.5143]

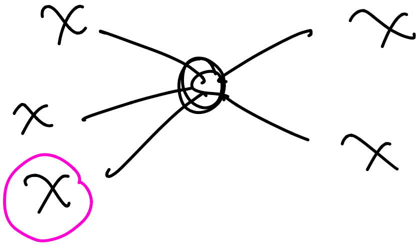
DM = lightest state in nearly-secluded sector (on beach!!)

self-interactions - set relic abundance



doesn't change
# density

⇒ first that does:



3→2

(note: DM scalar for 3→2)

Let's use our estimating tools:

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

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

$$\Gamma_{3\to2}\sim \underbrace{n_\chi^2}\ \underbrace{\langle\sigma \boxed{v^2}\rangle_{3\to2}} \overset{!}{\sim} H$$

if $\chi$ a DM, need to meet another 2.

$v^2$ - flux $(nv)^2$.

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

[ Dimensions of $\langle \sigma v^2 \rangle_{3\to 2}$: from rate or detailed balance ]

Take $n_\chi^{FO}$ from our "redshift to $T_{eq}$" trick:

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

$$\left( x_f = \frac{m_\chi}{T_f} \right)$$

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

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

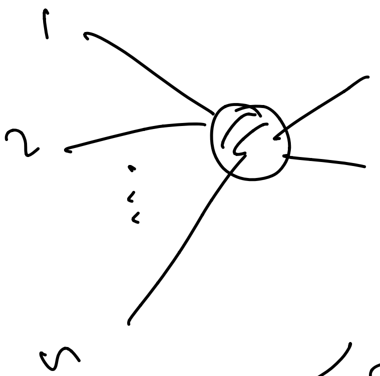
"Strongly interacting massive particle"

(SIMP).

"generalized geometric mean"

much lighter masses than WIMP, very different interactions!

More generally, n→2 : ( $\not{\mathbb{Z}}_2$ symmetry, DM fer'n.. )



n→2

first interacting .

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

detailed balance : forward = backward in eq:

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

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

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

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

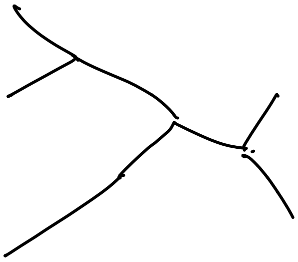
e.g. $n=4 \longrightarrow m_\chi \sim \alpha \cdot (100 \text{ keV})$

$n \to 2$ process less familiar than $2 \to 2$ ...

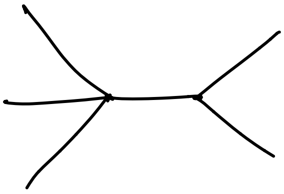
## Toy model (later Dark Sector):

$3 \to 2$ toy model $\mathbb{Z}_3$: Single scalar

$$\chi^3, \quad |\chi|^4$$



or



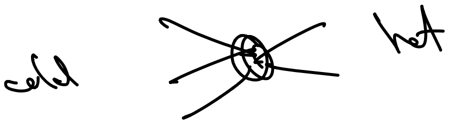
3 vertices

(compensate for "$\lambda_{eff}^3$")

$3 \times 3$pt.

3pt + 4pt.

"Been cheating": Implicitly assumed 1 temp' for entire system. But $3 \to 2$ pumps heat into system:

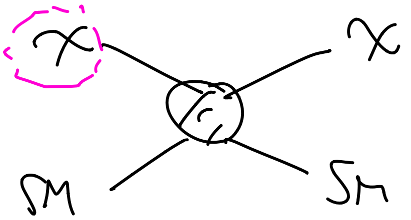


Need to be able to cool, to dump entropy!

Can be to light state or SM.

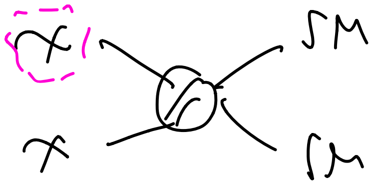
Exchange heat w/ SM:

cool:



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

ann?



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

what's important is who you need to meet!

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

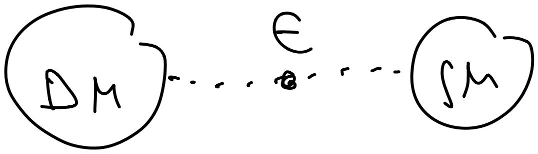
↑

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

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

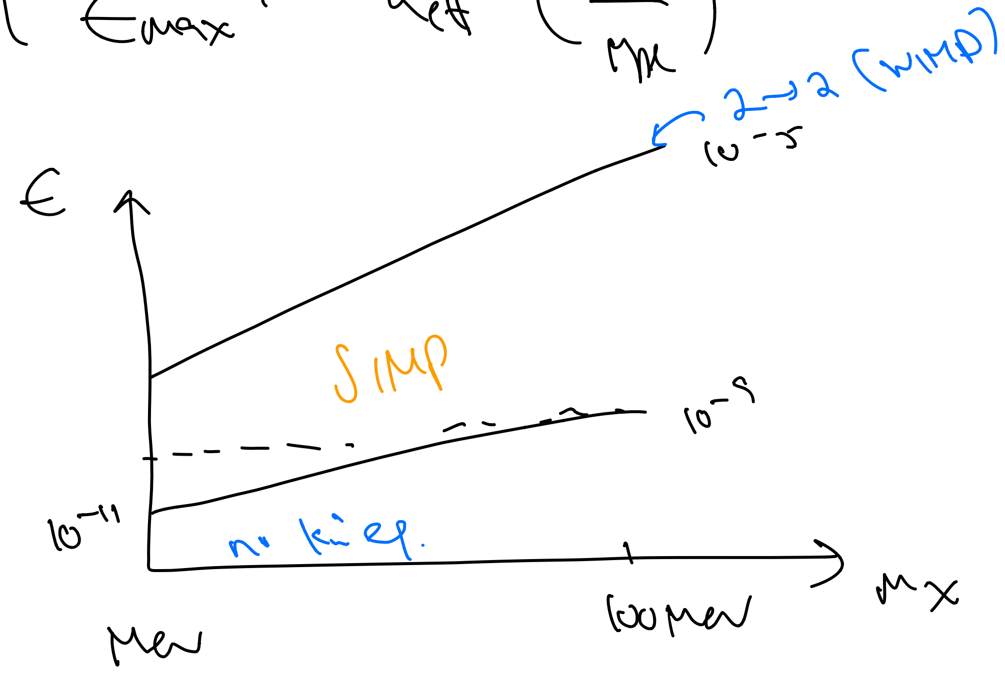
⇒ parametrize SIMP-SM interaction:

$$\langle\sigma v\rangle_{kin} \sim \langle\sigma v\rangle_{ann} \overset{?}{=} \frac{\epsilon^2}{m_\chi^2}$$



⇒ Range of ε where works:

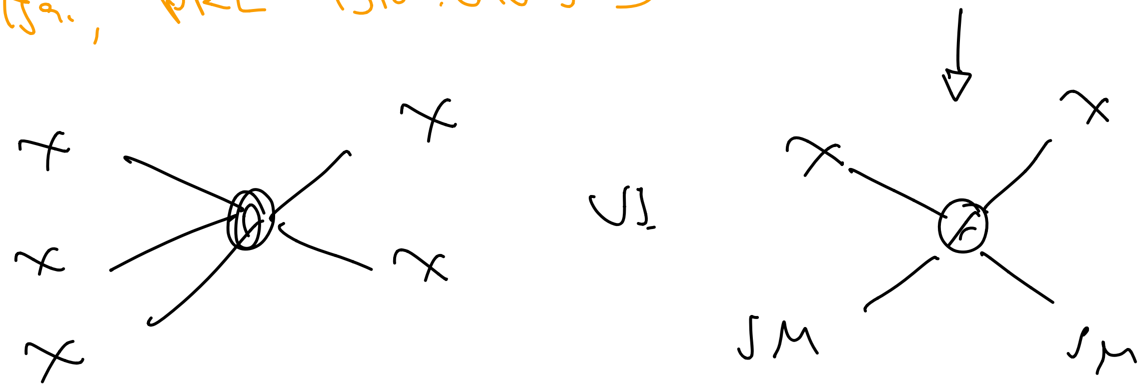
$$\begin{cases} \epsilon_{min} \sim \alpha_{eff}^{1/2} \left(\frac{T_{eq}}{M_{pl}}\right)^{1/3} \\ \epsilon_{max} \sim \alpha_{eff} \left(\frac{T_{eq}}{M_{pl}}\right)^{1/6} \end{cases}$$



( as long as $\epsilon_{min} \leq \epsilon \leq \epsilon_{max}$, precise value doesn't matter. )

# Relate to ELDER ?

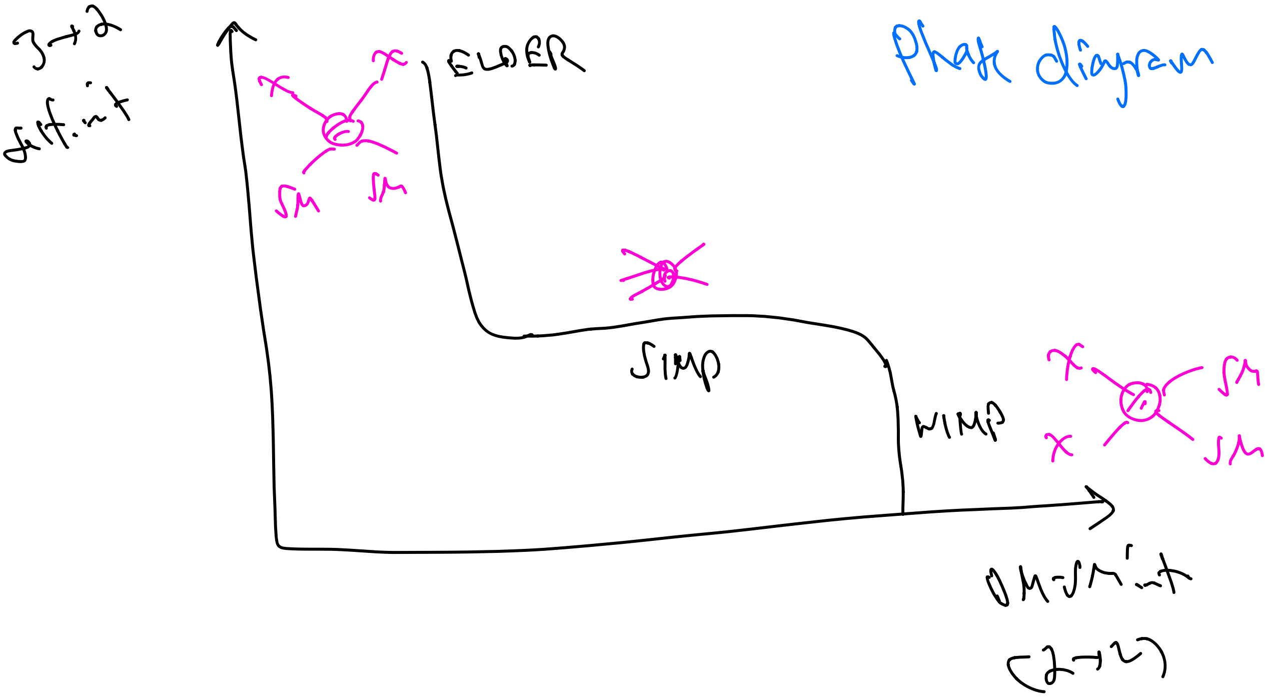
[Kuflik, Perelstein, Rey-Le Lorier, Tsai, PRL 1512.04545]



| | | |
|---|---|---|
| SIMP : | dec. 1st | dec. 2nd (active during F.O.) |
| ELDER : | dec. 2nd | dec. 1st |

$\Rightarrow \Omega_{DM} \propto e^{-\langle \sigma v \rangle_{elastic}}$ [details in Q&A (cannibalization)]

(Because: $\Omega_{DM}$ depends on entropy ratio @ time that decoupled. DM entropy is getting exp suppressed, $e^{-x}$ & $x$ (at T) is power law w/ elastic scattg xsec.)



Phase diagram

# DARK SECTORS:

Developed several mechanisms & understood behavior

$(m, \alpha, \ldots)$

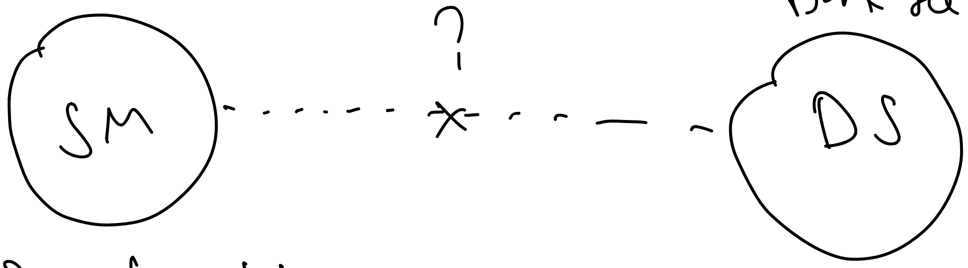
⇒ Models = theories that realize these mechanisms.

( SUSY = poster child for WIMP/coann.
Saw toy [illegible] model for 3→2 SIMPs )

These mechanisms are <u>generic in Theoryland.</u>

# Dark sector zoo :

Why not in the Dark sector too?



Zoo of particles
Sym' structure

$SU(3)_c \times SU(2)_w \times U(1)_Y$

New gauge sym?

Inspired by SM : $SU(3)_{dark} \times U(1)_{dark}$

$$\downarrow$$

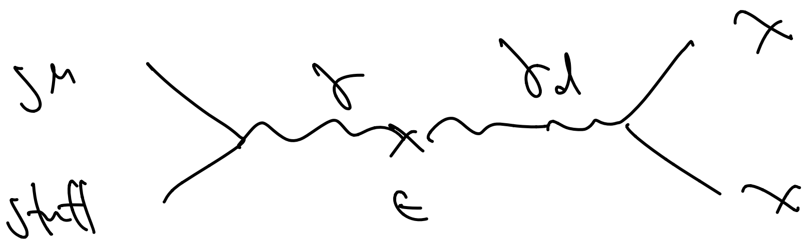
$$\underbrace{SU(N_c), SO(N_c), Sp(N_c)}$$

strongly coupled gauge theory,
QCD-like theory
"dark QCD"

Kinetically mixed dark photon $\gamma'$ ($\gamma_d$)

Could be just dark U(1) - dark QED w/ dark particles charged under it : $\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$

dark $\alpha_d$ ($e_d$)



Kinetic mixing gives DM-SM way to communicate

Simple DS.

Could be more complicated - QCD-like dark sectors.

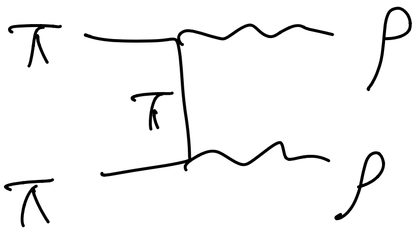
Rich theory - rich playground for many DM mechanisms & process to occur.

QCD-like theories - have lot of mesons (π, ρ, K..)

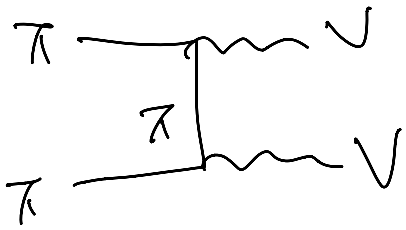
dark mesons

Pions = PNGB of the theory = can play the role of DM.

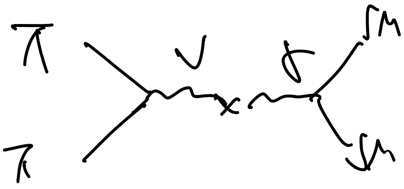
## E.g. 2→2:



$m_\rho \gtrsim m_\pi$

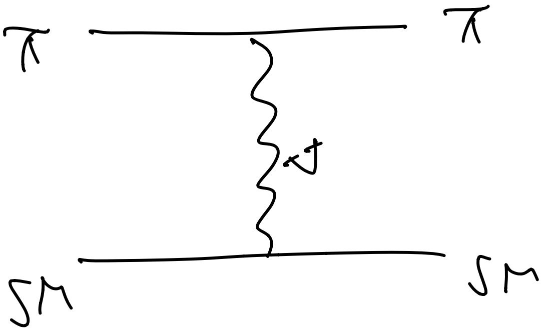


2→2 ann. (WIMP)



2→2 ann. (WIMP)

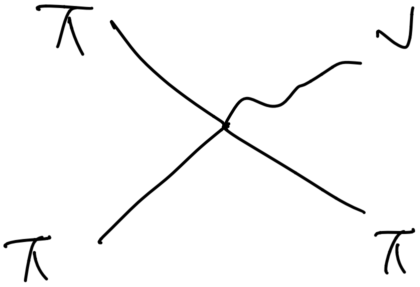
forbidden



elastic scattering

Kinetic eq.

(or ELDER)



semi-ann.

(gauged WZW)

In each case, compute from your $\mathcal{L}$ $(\alpha_d, m_\pi, f_\pi, m_V \ldots)$

the cross section you need for DM abundance -

$$\langle \sigma v \rangle = f(\text{parameters})$$

⇒ translate the xsec we developed previously into this model! to under what parameters are needed here.

E.g. 3→2 SIMP :

For a very 3→2 more "exotic" - less familiar.

But actually here in SM!

Reminder - QCD:

An $SU(3)$ gauge theory, w 3 light flavors - u, d, s

$SU(3)_L \times SU(3)_R$ global sym.

The theory confines - $\chi SB$ occurs:

$$SU(3)_L \times SU(3)_R \longrightarrow SU(3)_{diag}.$$

Have 8 PNGB - kaons, pions, etc

Has 5-pt. interactions! $K^+ K^- \rightarrow \pi^+ \pi^- \pi^0$

Through a topological term in $\mathcal{L}$ called WZW term

[Wess, Zumino 1971
Witten 1983 × 2]

If calculate the rate, just right to be a SIMP

if $m_{\pi} \sim 100$ MeV!

⇒ Inspired by this - QCD-like theories!

SU(N) gauge theory w/ $N_f$ flavors degenerate mass.

$SU(N)_L \times SU(N)_R$ global sym.

$\chi SB \longrightarrow SU(N)_{\text{diagonal}}$ = exact!

$N_\pi$ of PNGB = the pions = DM.

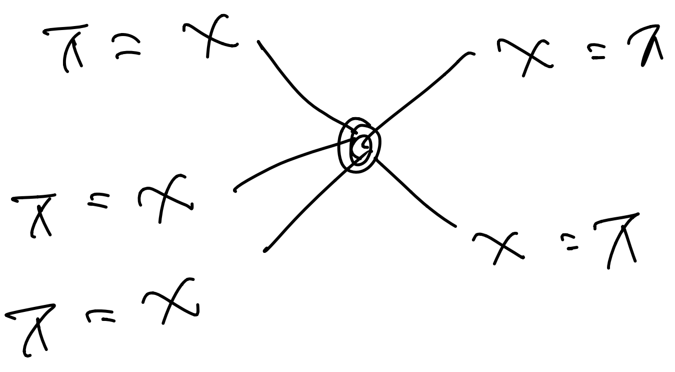
5-pt. interactions - WZW:

$$\mathcal{L}_{WZW} = \frac{2N}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\,\mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right]$$

5 pions contracted in particular way!

pion decay constant

Can do this for any SU(N), SO(N), Sp(N)
($N_f \geq 3$, $N_f \geq 3$, $N_f \geq 2$)

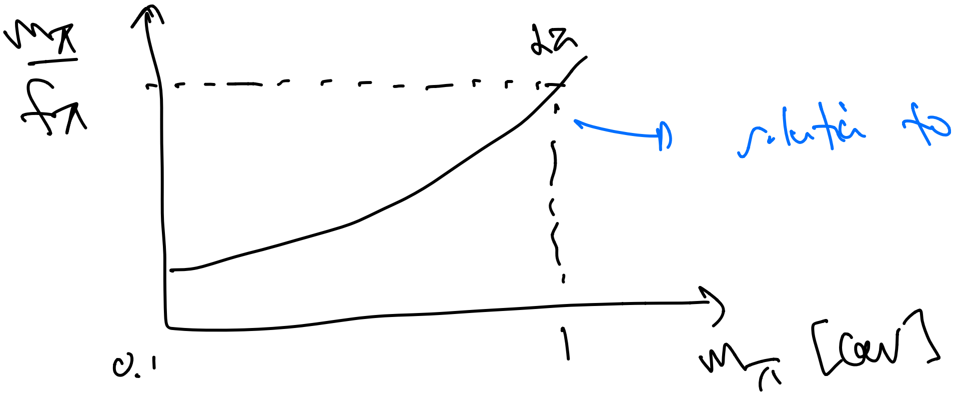


generic in QCD-like dark sectors

$$\langle \sigma v^2 \rangle_{3\to 2} = \underbrace{\frac{5\sqrt{5}}{2\pi^5} \frac{N^2}{\boxed{x_f^2}}}\ \underbrace{\frac{m_\pi^5}{f_\pi^{10}}}\ \underbrace{\left( \frac{t^2}{N_\pi^3} \right)}$$

combinatorial factor.
depend on Sp & $N_f$

$\Rightarrow$ translate : $\alpha_{\rm eff} \sim \# \left( \frac{m_\pi}{f_\pi} \right)^{10/3}$



solution to Boltzmann eq.

$m_\pi \sim \mathcal{O}(100\ \text{MeV})$ strongly coupled

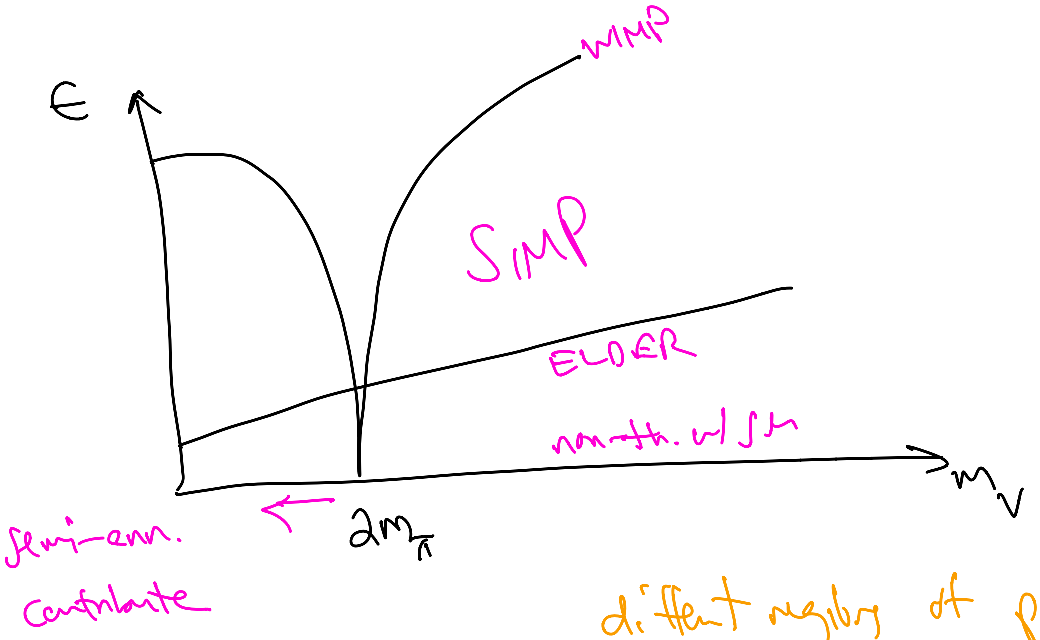
YH, Kuflik, Murayama, Volansky, Wacker PRL 1411.3727

YH, Kuflik, Murayama 1512.07917

3→2 Snowballs : Carlson, Hall, Machacek 1992
Soni, Zhang 2016
Forestell et al 2017

# Also predictions!

QCD-like × dark U(1) : $\gamma \sim\sim\sim \overset{\epsilon}{\times} \sim\sim\sim V$
photon dark photon.



@ fixed gauge cpl, $m_\pi$

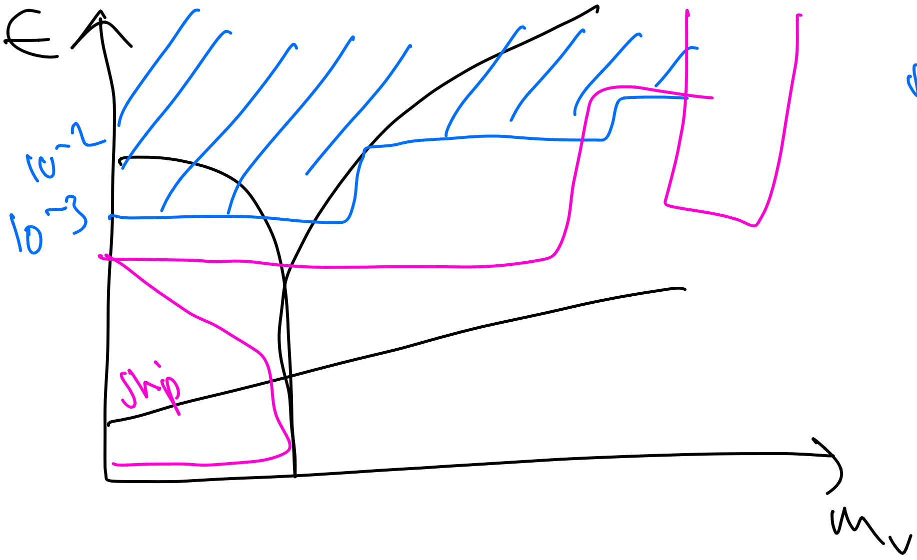
different regions of parameter space give different mechanisms for DM!

Constraints on this parameter space - high energy & low energy colliders.

& future probes - high & low energy machines (LHC, Belle-II, ILC).

beam dumps & fixed target (APEX, SHiP)

Direct detection - (electron recoils - SuperCDMS, SENSEI... )



roughly $\epsilon \lesssim 10^{-2} - 10^{-3}$
already $m_\nu$ maps

many future probes.

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Summarize:

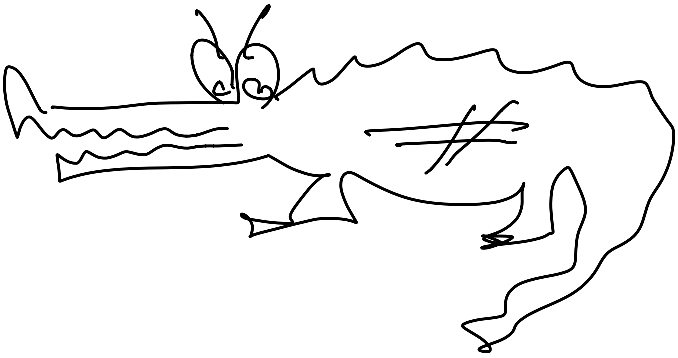
DM - is exciting!

mechanisms & models

Think outside of standard box !!

✓

Thanks ☺



# CANNIBALISM! [Hall, Carlson, Machacek 1992]

$3\to 2$ : what if can't shed heat?

don't have light abundant particles to dump entropy into?

$3 \to 2$ Cannibals - the $\chi$'s eat themselves to stay warm.

How much do they heat up?

$$s_\chi a^3 = \text{const}$$

$$s_\chi \sim \frac{\rho_\chi}{T_\chi} = \frac{m_\chi n_\chi}{T_\chi} \underset{\substack{\uparrow \\ NR}}{\simeq} \frac{m_\chi}{T_\chi}\left(\frac{m_\chi T_\chi}{2\pi}\right)^{3/2} e^{-m_\chi/T_\chi}$$

$\Rightarrow$ conservation of entropy:

$$T_\chi \sim \frac{1}{\log a} \sim \frac{1}{\log(1/T_\gamma)}$$

The $\chi$ temperature is going exp compared to SM bath!

$$\frac{m_\chi n_\chi^0}{s^0} = \frac{m_\chi n_\chi^{fo}}{s^{fo}} = \frac{T_{\chi_f} s_\chi^{fo}}{s^{fo}}$$

$$\underline{\underline{\Omega_\chi}} = \frac{m_\chi n_{\chi_0}}{\rho_c} = \frac{m_\chi n_\chi^{fo}}{\rho_c} \frac{s^0}{s^{fo}} = \frac{0.6\, m_\chi/eV}{x_{\chi_f}} \frac{s_{\chi f}}{s_f}$$

$$\Longrightarrow \frac{s_{\chi d}}{s_d}$$

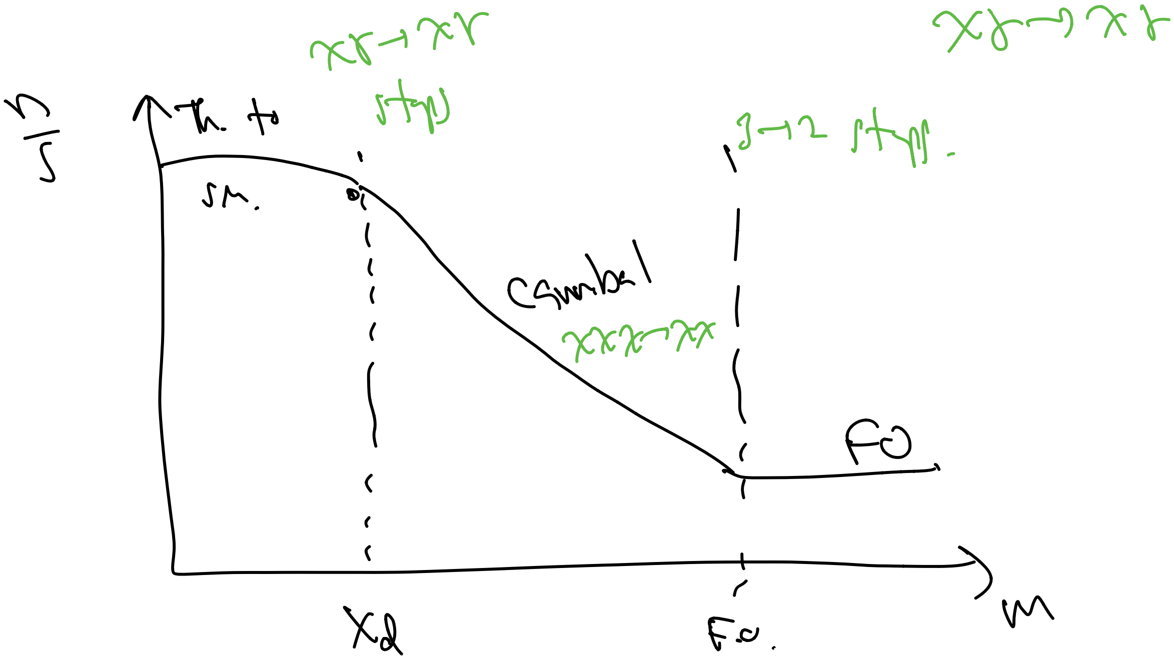
$$\frac{s_{\chi d}}{s_d} \underset{\underset{NR}{\uparrow}}{\sim} \underline{\underline{e^{-m_\chi/T_d}}} \qquad T_d \ll m_\chi$$

When do we decouple? elastic scatting $\chi\gamma \to \chi\gamma$ stops:

$$\underset{\underset{T_d^3}{\uparrow}}{n_\gamma} \langle\sigma v\rangle_{el} \sim \frac{T_d^2}{M_{pl}} \Rightarrow \underline{\underline{\langle\sigma v\rangle_{el} \sim \frac{m_\chi}{T_d}}}$$

$$\Rightarrow \Omega_\chi \propto e^{-\langle\sigma v\rangle_{el}}$$

<u>ELDER</u>.


xγ→xγ
stops
xγ→xγ
η/s
Th. to
sm.
3→2 stops.
Cumbel
xxx→xx
FO
Xd
Fo.
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