DARK MATTER ③ - GGI '22 :

[Yonit Hochberg;
HUJI]

Additional refs. for $2 \to 2$:

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

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

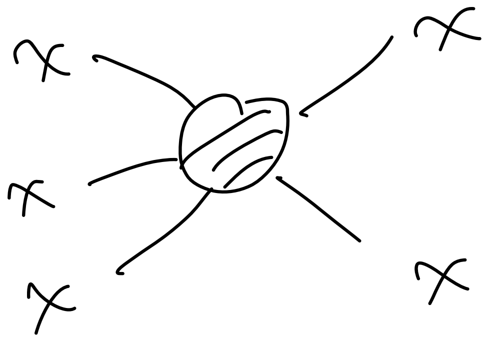
[Asymmetric Dark Matter : Kaplan, Luty, Zurek 0901.4117
Review - Zurek 1308.0338]

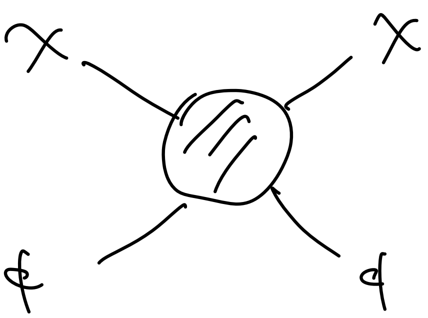
$$d(sa^3) = -\sum_i \frac{\mu_i}{T_i} d(na^3).$$

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)





SIMP: 1st decouples   decouples 2nd.

what if order was reversed?

⇒ CANNIBALS FIRST:

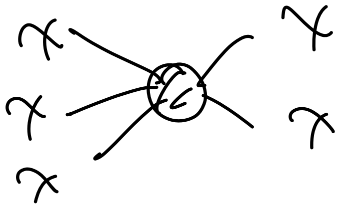
Outline:
- Cannibals
- ELDERs
- INDYs
- Dark sectors

} mechanisms.

CANNIBALISM: [Carlson, Machacek, Hall 1992]

look @ 3→2: what if don't have light abundant species to dump entropy into?

No reason for having the same T as SM.



"cannibalism" - the χ's eat themselves to stay warm.

How much do they heat up?

χ's don't talk to anyone else - comoving entropy is conserved.

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

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

⇒ conservation of entropy thus implies:

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

⇒ The χ temp' is going exp' compared to the SM bath!

also estimate the abundance:

$$\frac{m_\chi n_\chi^0}{s^0} = \frac{m_\chi n_\chi^{fo}}{s^{fo}} = \frac{T_{\chi f} s_\chi^{fo}}{s^{fo}} \quad \leftarrow (*)$$

$$\underline{\underline{\Omega_\chi}} = \frac{m_\chi n_\chi^0}{\rho_c} \underset{\overset{\uparrow}{(*)}}{=} \frac{T_{\chi f} s_\chi^{f}}{s^{fo}} \frac{s^0}{\rho_c} = 0.6\, \frac{m_\chi/\mathrm{eV}}{x_{\chi f}} \frac{s_{\chi f}}{s_f} \quad \leftarrow$$

Superlight DM unless huge temp difference / # of dof difference.

FROM CANNIBALS T' ELDERS:

we just saw that a bath of particles χ undergoing

$\chi\chi\chi \to \chi\chi$ undergoes cannibalization.

Suppose @ some time before 3→2 freezeout, bath was in

th' eq. w/ SM & decoupled @ $T_{\chi,d} = T_d$

$$① \Rightarrow \frac{s_{\chi_F}}{s_F} = \frac{s_{\chi d}}{s_d}$$

$$\Rightarrow \Omega_\chi = \frac{0.6\,\frac{m_\chi}{eV}}{x_{\chi F}} \cdot \underbrace{\frac{s_{\chi d}}{s_d}}$$

$$\underbrace{\frac{s_{\chi d}}{s_d}} \sim \begin{cases} O(1) \ \left(\begin{array}{c}\text{or ratio}\\ \text{of dof}\end{array}\right) & T_d \gg m_\chi \text{ (R)} \\ \# \left(\frac{m_\chi}{T_d}\right)^{5/2} \underline{\boxed{e^{-m_\chi/T_d}}} & T_d \ll m_\chi \text{ (NR)} \end{cases}$$

when do the sectors decouple?

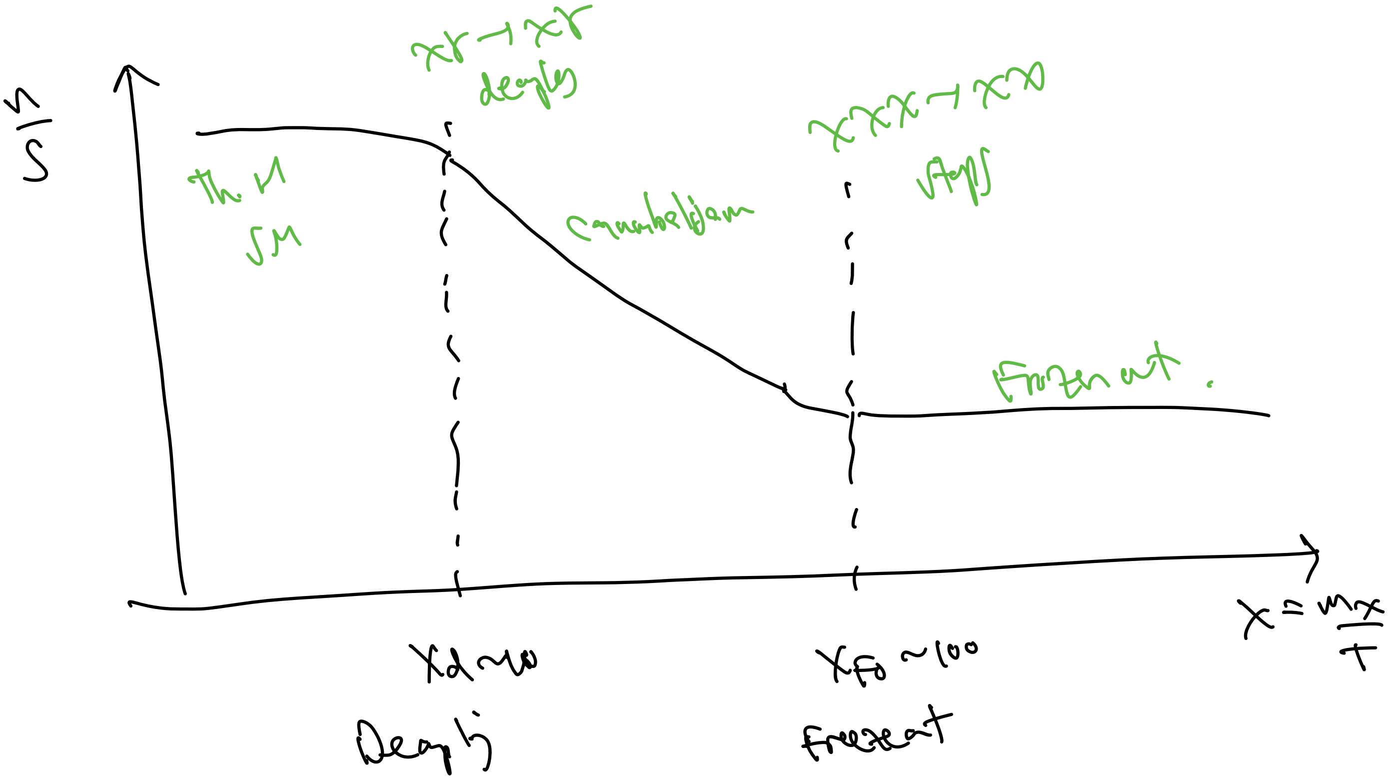
elastic scattering $\chi\gamma \to \chi\gamma$ stops:

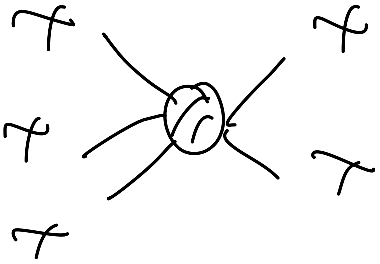
$$\underbrace{n_\gamma}_{\text{have to meet a SM particle}} \cdot \langle\sigma v\rangle_{el} \sim H \sim \frac{T_d^2}{M_{pl}} \Rightarrow T_\gamma^3 \langle\sigma v\rangle_{el} \sim \frac{T_d^2}{M_{pl}}$$

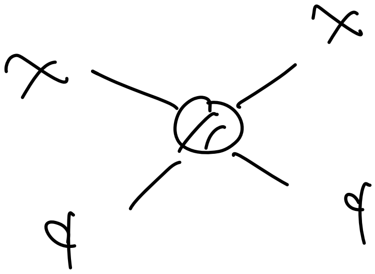
$$\Rightarrow \langle\sigma v\rangle_{el} \sim \frac{1}{T_d M_{pl}} \sim \underbrace{\frac{m_\chi}{T_d}} \left(\frac{1}{m_\chi M_{pl}}\right)$$

$$\Rightarrow \Omega_\chi \propto e^{-\langle\sigma v\rangle_{el}\cdot(\text{stuff})}$$

DM relic abundance is determined by elastic scattering process! Elastically Decoupling Relic (ELDER).





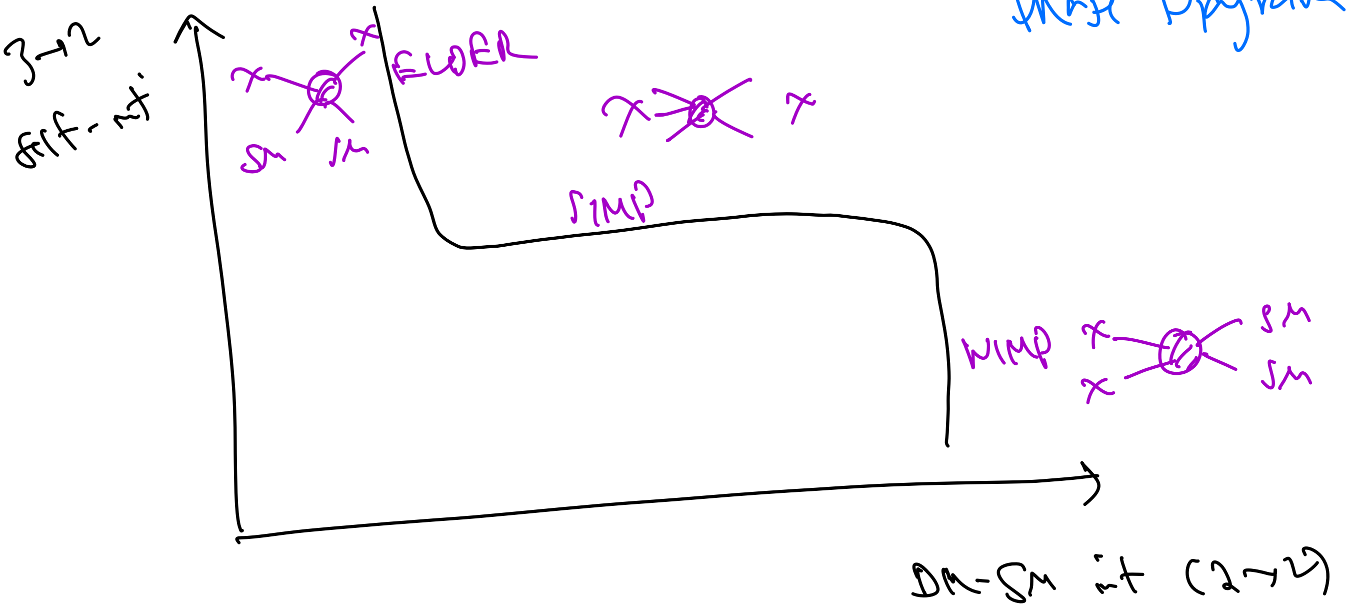


SIMPs : dec. 1st dec. 2nd

ELDER : dec. 2nd dec. 1st

[Kuflik, Perelstein et al PRL 1512.04545
+ 1706.05381]

Phase Diagram



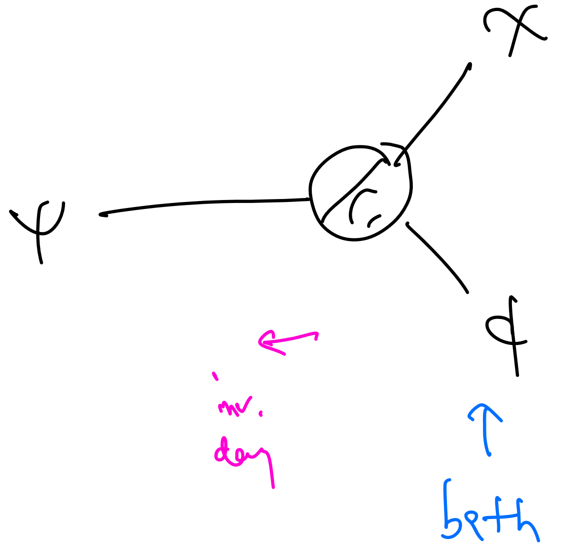
INDY DM:

another example of phases in coupling space.

[Frumkin, UH, Kuflik, Murayama 2211.14857]

F.O. of inverse decays?

χ, ψ dark



$(+ \psi\psi \to \phi\phi$ rapid $)$

$$\psi \leftrightarrow \chi\phi$$

$m_\psi > m_\chi$. χ = DM , ψ = unstable dark particle that has some number of χ's in decay products.

B.F.:

$$\dot{n}_\chi + 3 n_\chi H = \Gamma \left(n_\psi - \underbrace{n_\chi \frac{n_\psi^{eq}}{n_\chi^{eq}}}_{\text{detailed balance}} \right)$$

↑ decay rate for $\psi \to \chi\phi$

F.O. $\Gamma_{\text{inv decay}} \sim H$:

$$\Gamma_{\text{inv decay}} = \Gamma_{\chi\phi\to\psi} = \Gamma \frac{n_\psi^{eq}}{n_\chi^{eq}} \overset{!}{\sim} H \sim \frac{T^2}{M_{pl}} \overset{x = \frac{m}{T}}{\sim} \frac{m_\chi^2}{x_f^2 M_{pl}}$$

$\underline{\Gamma} \sim m_\chi \cdot \alpha_{decay}$

$$\underline{\underline{\frac{n_\varphi^{eq}}{n_\chi^{eq}}}} \underset{\uparrow \atop NR}{\sim} \left(\frac{m_\varphi}{m_\chi}\right)^{3/2} e^{-\frac{m_\varphi - m_\chi}{T}} \underset{\uparrow}{\sim} (1+\Delta)^{3/2} e^{-\Delta x}$$

$$\Delta \equiv \frac{m_\varphi - m_\chi}{m_\chi}$$

$$\Rightarrow m_\chi \cdot \alpha_{decay} \cdot (1+\Delta)^{3/2} e^{-\Delta x_f} \sim \frac{m_\chi^2}{x_f^2 M_{pl}}$$

[solve for e^{-x}]

$$\Rightarrow \underline{e^{-x_f}} \sim \left(\frac{m_\chi}{M_{pl}\, \alpha_{decay}}\right)^{\frac{1}{\Delta}}$$

Now use eq. distribution for n_χ @ F.O. $\overset{!}{\sim}$ our back-of-envelope

$n_\chi \sim \underline{\underline{m^2 T_{eq}}}$

$$\Rightarrow n_\chi \sim (m_\chi^2)^{3/2} \underline{\underline{e^{-x}}} \overset{!}{\sim} m^2 T_{eq}$$

$$\Rightarrow \underline{\underline{m_\chi \sim \alpha_{decay}^{\frac{1}{1+\Delta}} \left(T_{eq}^{\Delta} M_{pl}\right)^{\frac{1}{1+\Delta}}}}$$

INDY DM.

$\Delta = 1$ WIMP
$\Delta = 2$ SIMP } scaling

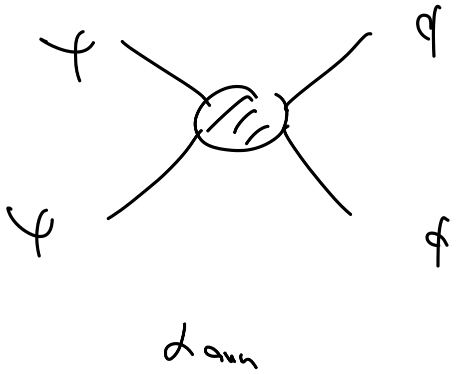
For small mass splitting $\Delta < 1 \rightarrow$ small coupling for same

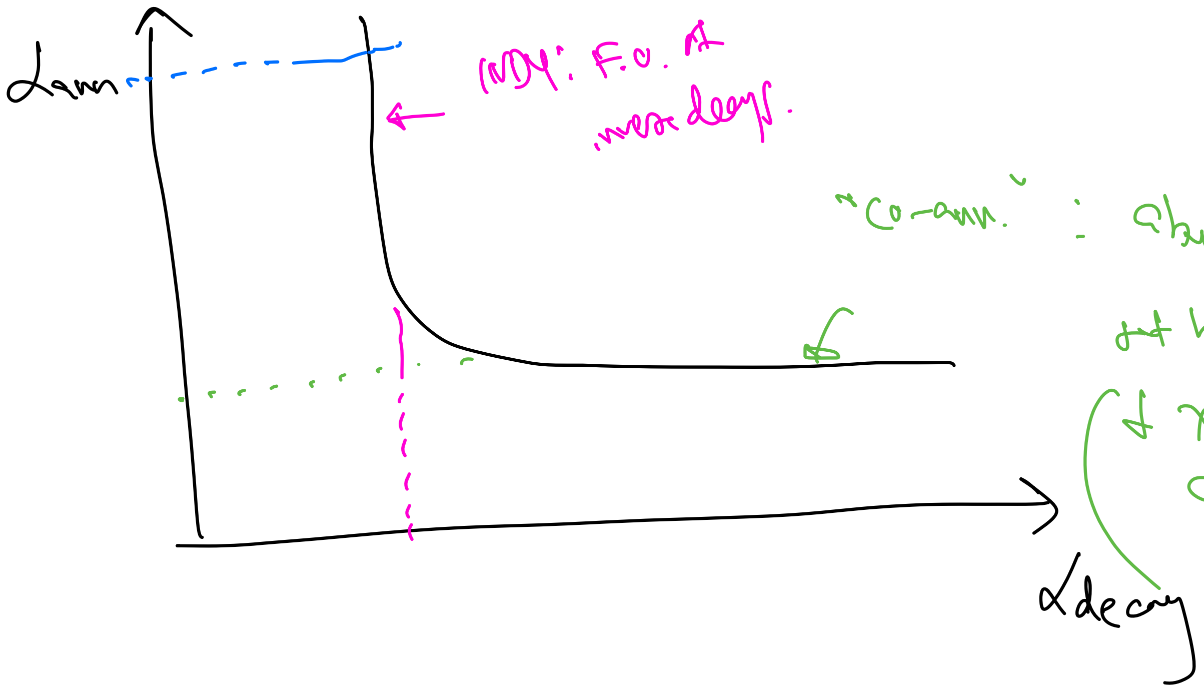
mass / large mass
for same coupling

⇒ heavy DM (beyond unitarity)

Actually phase diagram:

,





(NDY: F.O. of inverse decays.

"co-ann.": abundance of χ set by ann. of φ
(χ ↔ φ in ch. eq. via decay + inv. decay)

DARK SECTORS?

Developed mechanisms & understand the behavior (m, α ....)

⇒ Models = theories that realize these mechanisms.

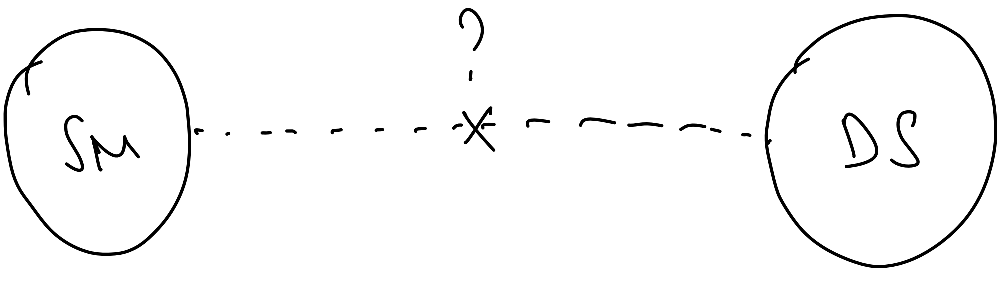
(SUSY = partner field for WIMP / co-ann

Sp gauge theory for 3→2 SIMP)

These mechanisms generic in theory land.

DARK SECTOR ZOO:

why not in the dark sector too?



zoo of particles

symm. structure

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

New gauge sym?

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

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

kinetically mixed dark photon V

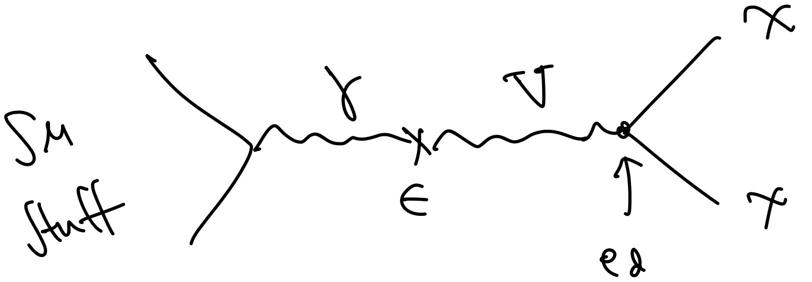
Strongly coupled gauge theory (something γ_d)

QCD-like, "dark QCD"

could be just a dark U(1) - dark QED w/ dark particles charged under it.

$$\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

dark e_d (dark α_d)



Kinetic mixing gives DM-SM way to communicate couple to SM. SIMPLE DS.

Can be more complicated - QCD-like dark sector.

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

QCD-like theory - host of mesons $(\underbrace{\pi, K, \rho, \ldots}_{\text{dark mesons}})$

Pions = PNGBs of the theory : can play the role of the H!