Chern-Simons portal Dark Matter

III Saha Theory Workshop: Aspects of Early Universe Cosmology

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Outline

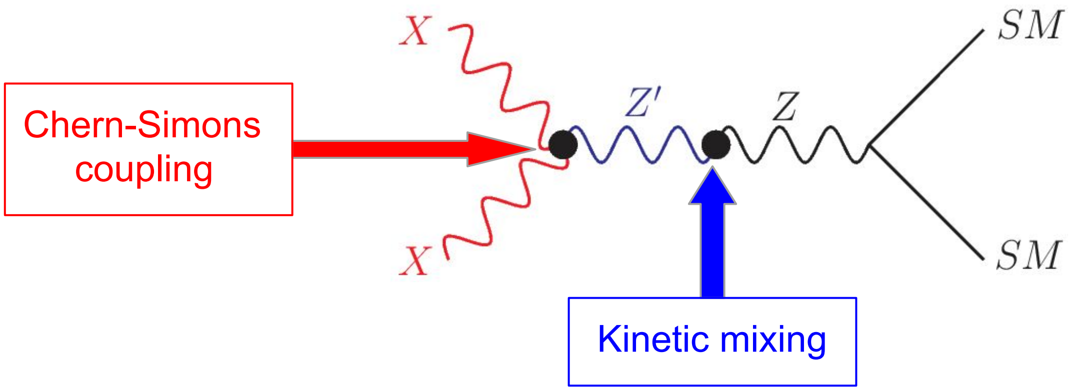
I. The Chern-Simons couplings
  A. Vector dark matter
  B. Green-Schwartz & Chern-Simons terms
II. WIMP with Chern-Simons portal
  A. Relic density
  B. Constraints
III. SIMP with Chern-Simons portal
  A. The SIMP miracle
  B. Why SIMP ?
  C. SIMP with Chern-Simons portal

Vector dark matter

- Symmetry, invariance and conservation principles have being widely and successfully used in physics

- Gauge symmetry and the Standard Model provide an excellent description of the physics up to TeV scale

➡ Consider a dark matter candidate X as a gauge field

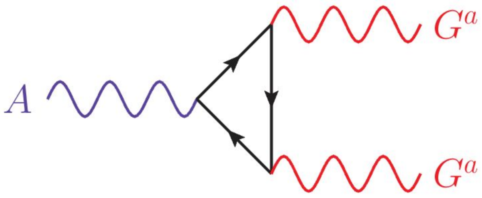


Chern-Simons coupling

Kinetic mixing

Anomalies

- Anomalies are violation of a symmetry at the loop level



Under a gauge transformation

$$A^\mu \to A^\mu + \partial^\mu \alpha \quad \Longrightarrow \quad \delta\mathcal{L}_{\text{1-loop}} = \alpha\Delta\,\mathrm{Tr}[G \wedge G]$$

- If $\Delta = \mathrm{Tr}[QT^aT^a] \neq 0$ theory anomalous !

- In the Standard Model (SM) : “accidental” anomaly cancellation

  example : U(1) - SU(2) - SU(2) : (-½) + 3 (⅙) = 0

- Chiral anomalies for gauge symmetries exact at 1-loop!

Green-Schwartz mechanism and Chern-Simons terms

- If U(1)’ anomalous → Introduce axion ! $\mathcal{L}_{\text{axion}} = \frac{1}{2}(\partial_\mu a + M A_\mu)^2 + \Delta \frac{a}{M}\mathrm{Tr}[G \wedge G]$

Under a gauge transformation :

$$a \to a - M\alpha \Longrightarrow \delta\mathcal{L}_{\text{axion}} = -\alpha\Delta\mathrm{Tr}[G \wedge G]$$

- We cancelled the anomaly and given a mass to A → Green-Schwartz mechanism

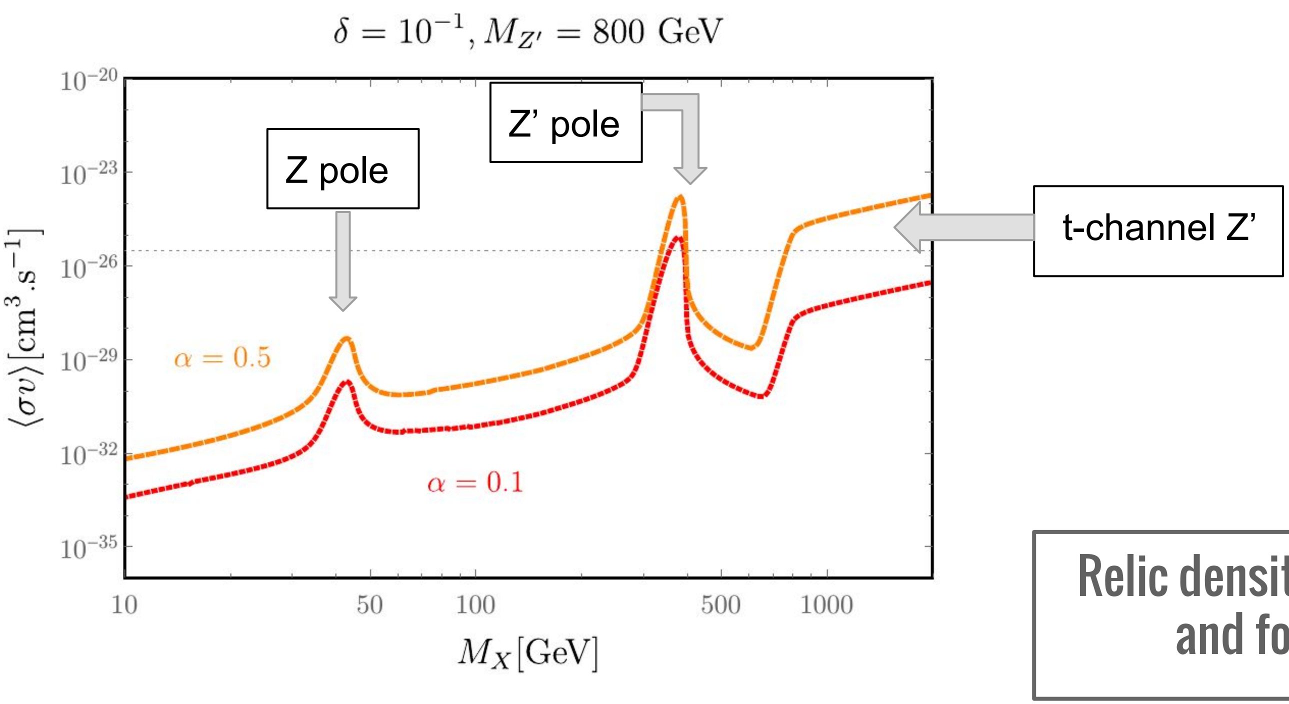
- If U(1)’ anomalous : we cannot cancel the U(1)’ - U(1)$_Y$ mixed anomalies with the axion

→ we introduce Generalized Chern-Simons gauge variant terms :

$$\epsilon^{\mu\nu\rho\sigma} Z'_\mu Y_\nu \partial_\rho Y_\sigma$$

WIMP Dark Matter with Chern-Simons portal

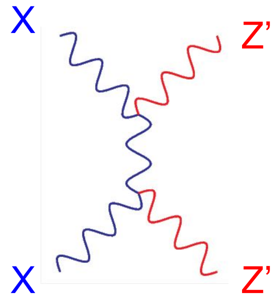
$$\mathcal{L} = \mathcal{L}_{\rm SM} \underbrace{\boxed{-\frac{1}{4}X^{\mu\nu}X_{\mu\nu}}}_{\text{U(1)}_X} \underbrace{\boxed{-\frac{1}{4}Z'^{\mu\nu}Z'_{\mu\nu}}}_{\text{U(1)}_{Z'}} - \frac{\sin\delta}{2}Z'^{\mu\nu}B_{\mu\nu} + \alpha\epsilon^{\mu\nu\rho\sigma}X_\mu Z'_\nu X_{\rho\sigma} + \frac{m_{Z'}^2}{2}Z'^\mu Z'_\mu + \frac{m_X^2}{2}X^\mu X_\mu$$



Z pole

Z’ pole

t-channel Z’



$$\langle\sigma v\rangle_{Z'Z'} \simeq \frac{8\alpha^4 M_X^2}{9\pi M_{Z'}^4}$$

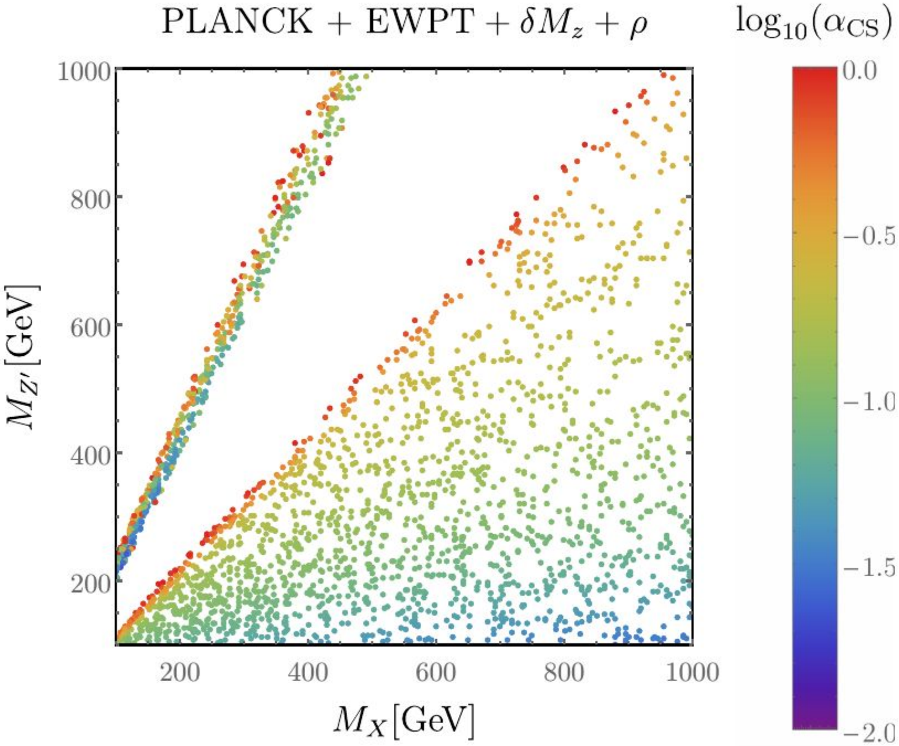
Relic density achievable at the Z’ pole and for t-channel if $M_X > M_{Z'}$

Constraints on this model ?

Because of the Z'- Z/gamma mixing :

- ElectroWeak Precision Test (EWPT) : $\delta \lesssim \arctan\left[0.4\left(\frac{M_{Z'}}{\text{TeV}}\right)\right]$
- Rho parameter and corrections to M_Z
- Direct detection : suppressed $\sigma \propto \alpha^2\delta^2$
- Indirect detection : Not velocity suppressed

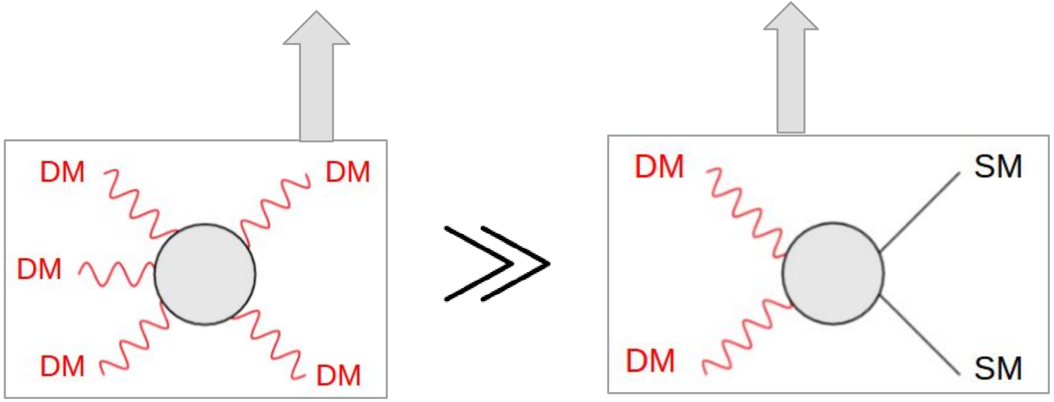
  so OK if correct relic density required
- Collider constraints : upcomming!



The Strongly Interactive Massive Particles miracle

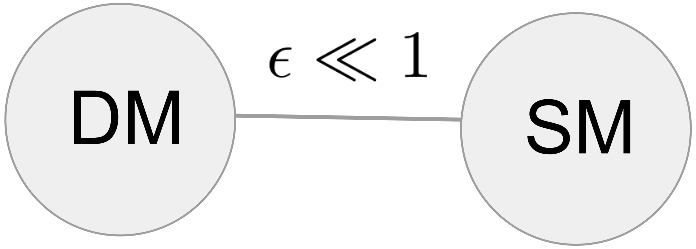
(Y.Hochberg, E.Kuflik ,T.Volansky and J.G.Wacker : arXiv:1402.5143)

$$\frac{\partial n}{\partial t} + 3Hn = -(n^3 - n^2 n_{\rm eq})\langle\sigma v\rangle_{3\to 2} - (n^2 - n_{\rm eq}^2)\langle\sigma v\rangle_{\rm ann}$$



DM in thermal equilibrium with the SM and freeze-out is controlled by the $3 \to 2$ process

- Interactions between the DM particles can be sizable.
- Thereeze-out can occur at $\frac{m_{\rm DM}}{T_F} \sim 20$ for $m_{\rm DM} \sim 50$ MeV



Why SIMP ?

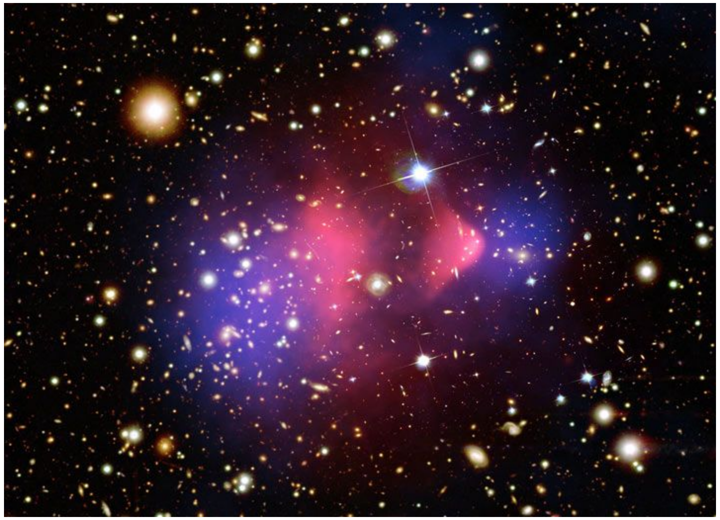
- Self interacting dark matter : From N-body simulations, solution to the "core VS cusp" and "too big to fail" problem

$$\left(\frac{\sigma_{\text{scatter}}}{m_{\text{DM}}}\right)_{\text{obs}} = (0.1 - 10)\ \text{cm}^2/\text{g}$$

- Bullet cluster and halo shapes : $\frac{\sigma_{\text{scatter}}}{m_{\text{DM}}} \lesssim 1\ \text{cm}^2/\text{g}$

- DM in equilibrium with SM → LHC signatures

- m_{DM} ~ MeV → scattering on electron



SIMP Dark Matter with Chern-Simons portal

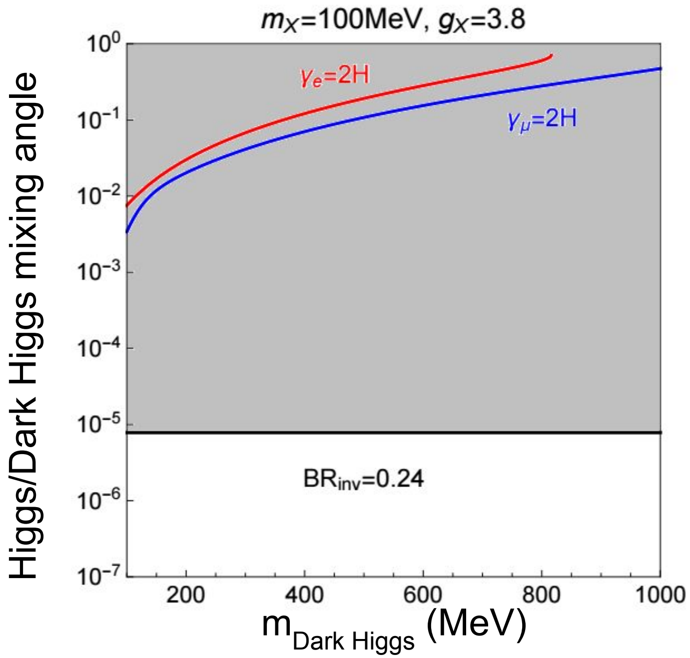
$$\mathcal{L} \supset \underbrace{\boxed{-\frac{1}{4}\vec{X}^{\mu\nu}\cdot\vec{X}_{\mu\nu}}}_{SU(2)_X}\underbrace{\boxed{-\frac{1}{4}Z'^{\mu\nu}Z'_{\mu\nu}}}_{U(1)_{Z'}} - \frac{\sin\delta}{2}Z'^{\mu\nu}B_{\mu\nu} + \alpha\epsilon^{\mu\nu\rho\sigma}Z'_{\mu}\vec{X}_{\nu}\cdot(\partial_{\rho}\vec{X}_{\sigma} - \partial_{\sigma}\vec{X}_{\rho}) + \mathcal{L}^{\text{scalar}}$$

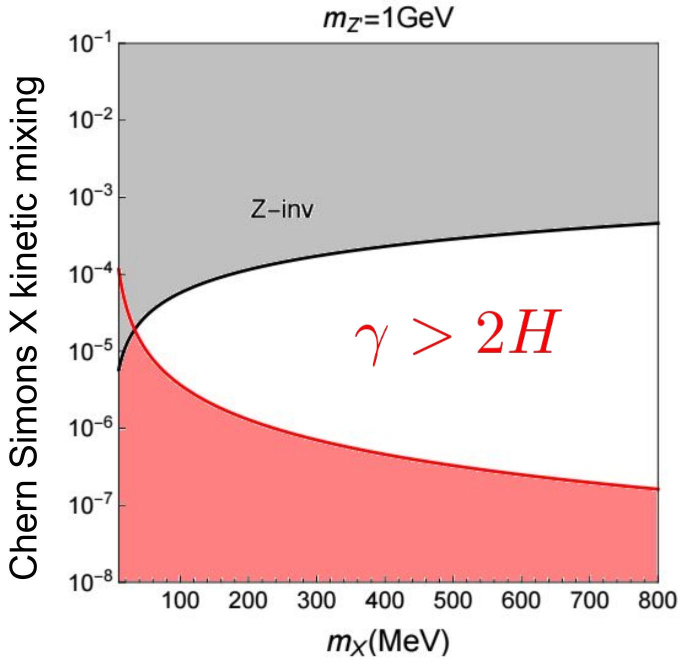
$$\mathcal{L}_{\text{scalar}} = \overbrace{|D_{\mu}H|^2}^{\text{SM Higgs}} + \underbrace{\boxed{|D_{\mu}\Phi|^2}}_{\text{“Dark Higgs” : breaking } SU(2)_X} + \overbrace{\boxed{|D_{\mu}S|^2}}^{\text{Scalar : breaking } U(1)_{Z'}} - \underbrace{V(H,\Phi,S)}_{\text{Generating mixing}}$$

We get 3 Dark Matter degenerate candidates and 1 Dark Higgs in the hidden sector in addition to the Z’ mediator and the SM content

SIMP conditions

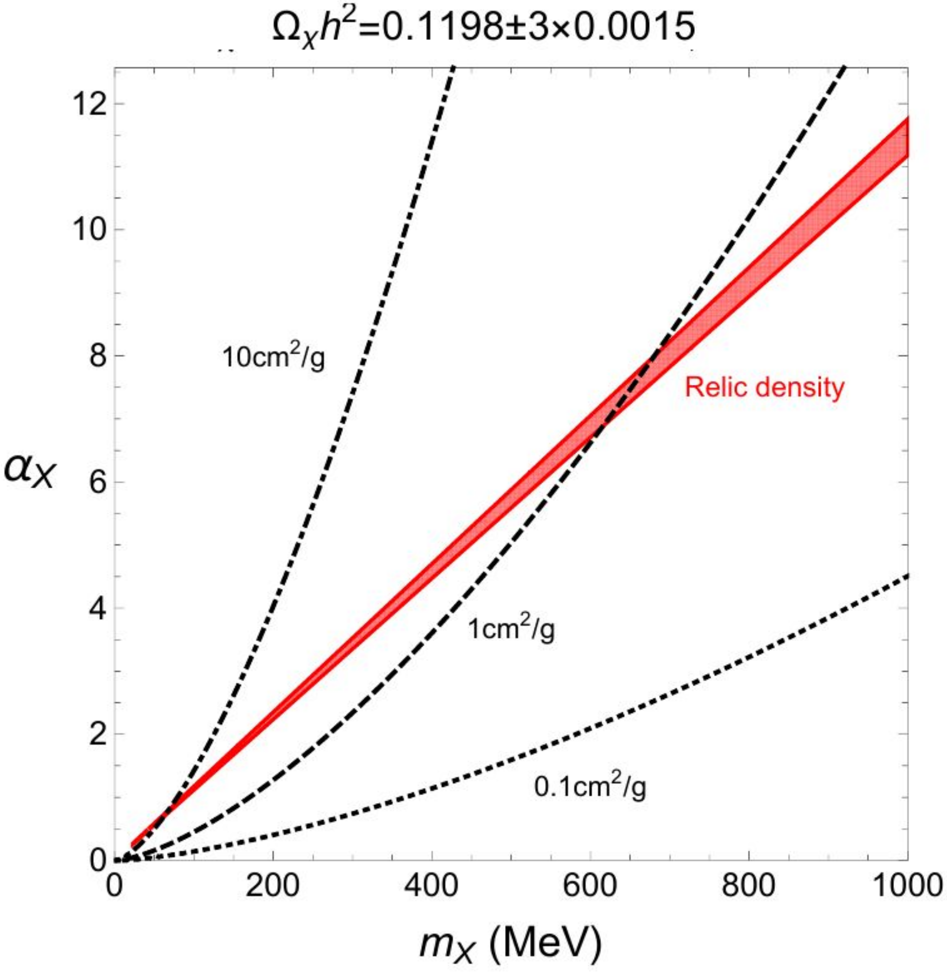
Kinetic equilibrium ? Compute the momentum relaxation rate $\Gamma_{\text{kin}} \equiv \gamma(T)$





Kinetic equilibrium not possible with Higgs portal coupling only but possible with the Chern-Simons

Relic density and self interacting dark matter



Relic density can be achieved for a sizable self-interaction cross section

Conclusion and perspectives

- Chern-Simons terms arise from anomaly cancellation, they could allow the Dark Sector to couple to the SM

- WIMP vector dark matter is a viable scenario but need large DM mass

- SIMP dark matter appealing! and allowing for a self interacting dark matter compatible with the relic density constraints

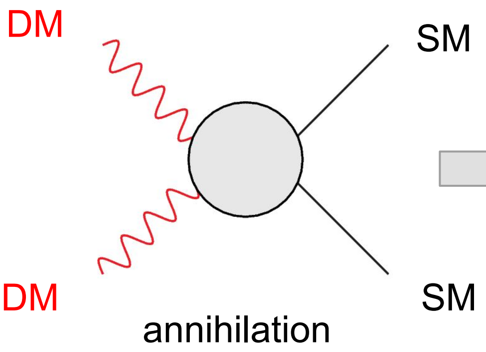
- We are working on UV completion of the models!   Feel free to discuss with us!

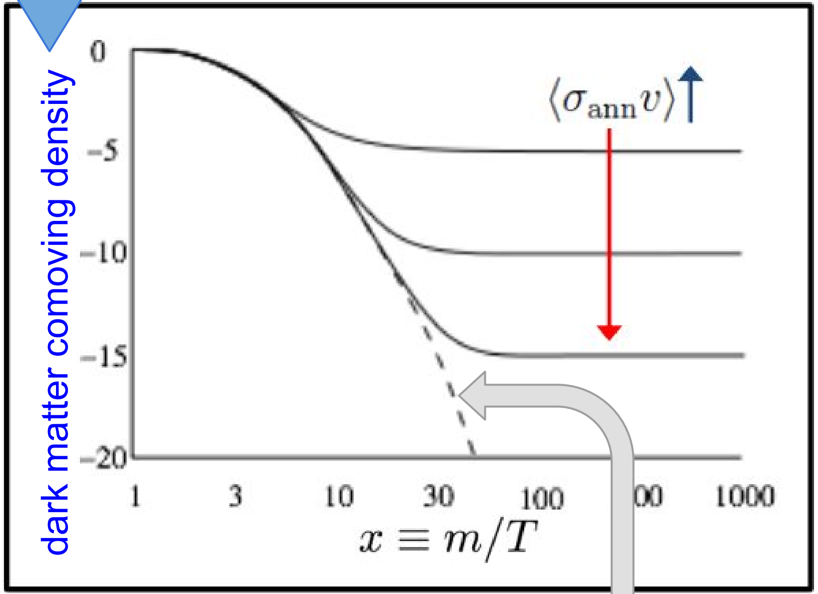
Thank you for your attention!

Back-up slides

The WIMP paradigm in a nutshell

$$\boxed{\frac{\partial n}{\partial t} + 3Hn} = -(n^2 - n_{\mathrm{eq}}^2)\langle\sigma_{\mathrm{ann}} v\rangle$$





thermal equilibrium

For DM mass ~ GeV-TeV typical electro-weak cross sections and couplings emerge → the WIMP paradigm !

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