DILUTED NON-THERMAL DARK MATTER IN AN EARLY MATTER-DOMINATED UNIVERSE

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Outline

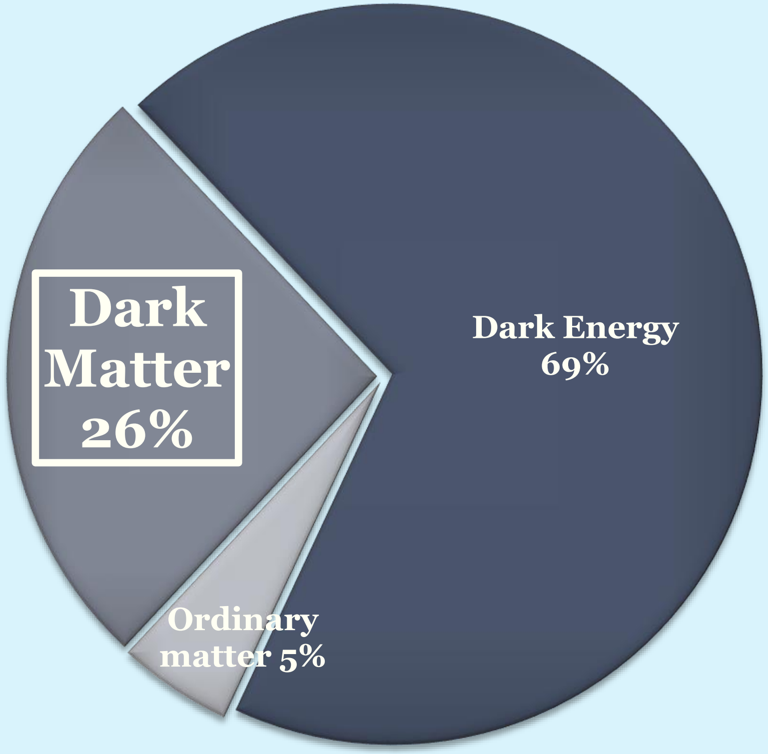
- **Introduction**
- **A Recap of the mechanisms**
  - Freeze-out
  - Dilution
  - Non-thermal production
- **A comprehensive scenario**
- **Conclusion**

Introduction

26% of the energy density of our universe consists of **Cold Dark Matter.**

Particle Physics

- ➢**WIMP** (e.g. neutralino)
- ➢Non-WIMP (e.g. Axions, sterile neutrinos)



If a particle in the WIMP paradigm generates too **much** /too **little** energy density, can it still be a valid DM candidate?

A RECAP OF THE MECHANISMS

Freeze-out

The universe is expanding and cooling down. Interactions become less efficient until the particle species decouples…

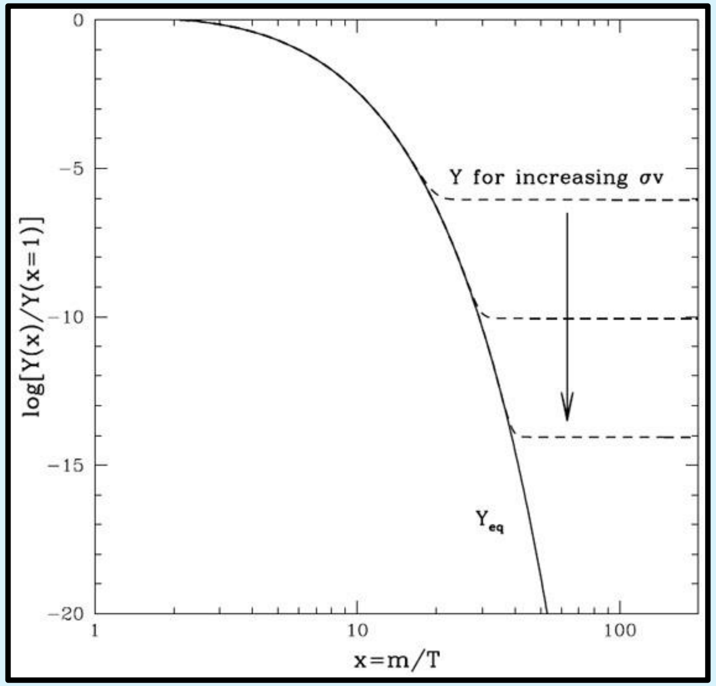
$$n_{DM}(T)\sigma v \leq H(T)$$

Introducing:

- $Y_{DM} = n_{DM}/s$
- $z = m_{DM}/T$

Y(z) behaviour:

- For $z \ll z_{FO}(T \gg T_{FO}) \rightarrow \mathbf{Y(z) \sim Y^{eq}(z)}$
- For $z \gg z_{FO}(T \ll T_{FO}) \rightarrow \mathbf{Y(z) \sim Y^{eq}(z_{FO})}$



Freeze-out

Link between **today's energy density** and **FO abundance**:

$$\Omega_{DM} = \frac{\rho}{\rho_c} = \frac{m_{DM} Y_{DM}^{today} s^{today}}{\rho_c}$$

But $Y_{DM}^{today} = Y_{DM}^{FO}$:

$$\Omega_{DM} h^2 = \frac{m_{DM} Y_{DM}^{FO} s^{today}}{\rho_c} h^2 \approx 0.1 \left(\frac{10^{-9} \mathrm{GeV}^{-2}}{\sigma_0} \right)$$

$$\boxed{\sigma_0 \approx 10^{-9}\, GeV^{-2} \approx 3 \times 10^{-26} cm^3/s}$$

Thermally Decoupled Sector

What happen if a particle provides too **much/little** relic density?

We can still fix it, changing the parameters or
revising the model

Let's add to our model more particles, decoupled from the Standard Model:

- They constitute a thermally decoupled sector (**Dark Sector**) with a different temperature $\mathbf{T_D}$
- We can track this temperature introducing $\boldsymbol{\xi} = \mathbf{T_D/T_{SM}}$
- ξ affects $\mathrm{Y}_{particle}$ (and the *effects that depend on* $Y_{particle}$ *…)*

Dilution

If a particle generates **too much** energy density…
It can be reduced by the effects of **Dilution**

Introducting an **unstable Z_1**, its decay will **increase the entropy** of the universe and Y today is **not equal** to its value at the FO:

$$\Omega_{DM} = \frac{m_{DM} s^{today} Y_{DM}^{today}}{\rho_c} = \frac{1}{D} \frac{m_{DM} s^{today} Y_{DM}^{FO}}{\rho_c}$$

Dilution

Requirements for an **high dilution scenario (D>>1)**:

1. Z_1 **dominates** the energy density of the universe
2. Z_1 is cold at the decay
3. **Hot** Z_1 at the decoupling
4. **Heavy** Z_1
5. **Long-living** Z_1

1 +2 ⟶ The universe is in a phase of **Early-matter domination**…
…but must turn back to a radiation-dominated phase before the BBN!

Non-thermal Production

If a particle generates **too little** energy density … It can be enhanced by the effects of **Non-thermal production (NTP)**

Introducing an **Unstable Z_2**:

$$Z_2 \rightarrow \underbrace{\mathrm{DM} + \mathrm{DM} + \ldots + \mathrm{DM}}_{N}$$

After it decays:

$$Y_{\mathrm{DM}} = Y_{\mathrm{DM}}^{\mathrm{FO}} + Y_{\mathrm{DM}}^{\mathrm{dec}} = Y_{\mathrm{DM}}^{\mathrm{FO}} + N Y_{Z_2}^{\mathrm{FO}}$$

A COMPREHENSIVE SCENARIO

Dark Sector Structure

Three particles:

- X(DM candidate)
- Z_2 (Heavier)
- Z_1 (Lighter)

with the following interactions:

- $Z_1 Z_1 \leftrightarrow Z_2 Z_2$
- $Z_1 Z_1 \leftrightarrow XX$
- $Z_2 \rightarrow X + X + .. + X$
- $Z_1 \rightarrow SM + SM + .. + SM$

Can Z_2 generate both Dilution and NTP?

Yes, but one effect partially compensates the other

- $D \sim m_{Y_2} Y_{Z_2}$
- $Y_{DM}^{dec} \sim N Y_{Z_2}$

$$\longrightarrow \quad \frac{Y_{DM}^{dec}}{D} \sim \frac{N}{m_{Z_2}}$$

Also Z_2 has to be **Hot** at **FO** to provide **D>>1** and so has to be X since it is lighter. This is a Hot Relic DM model…

We need a 100 PeV scale Z_2 to dilute a 1 TeV DM candidate and NTP would just increase this value.

Charatteristic of the particles

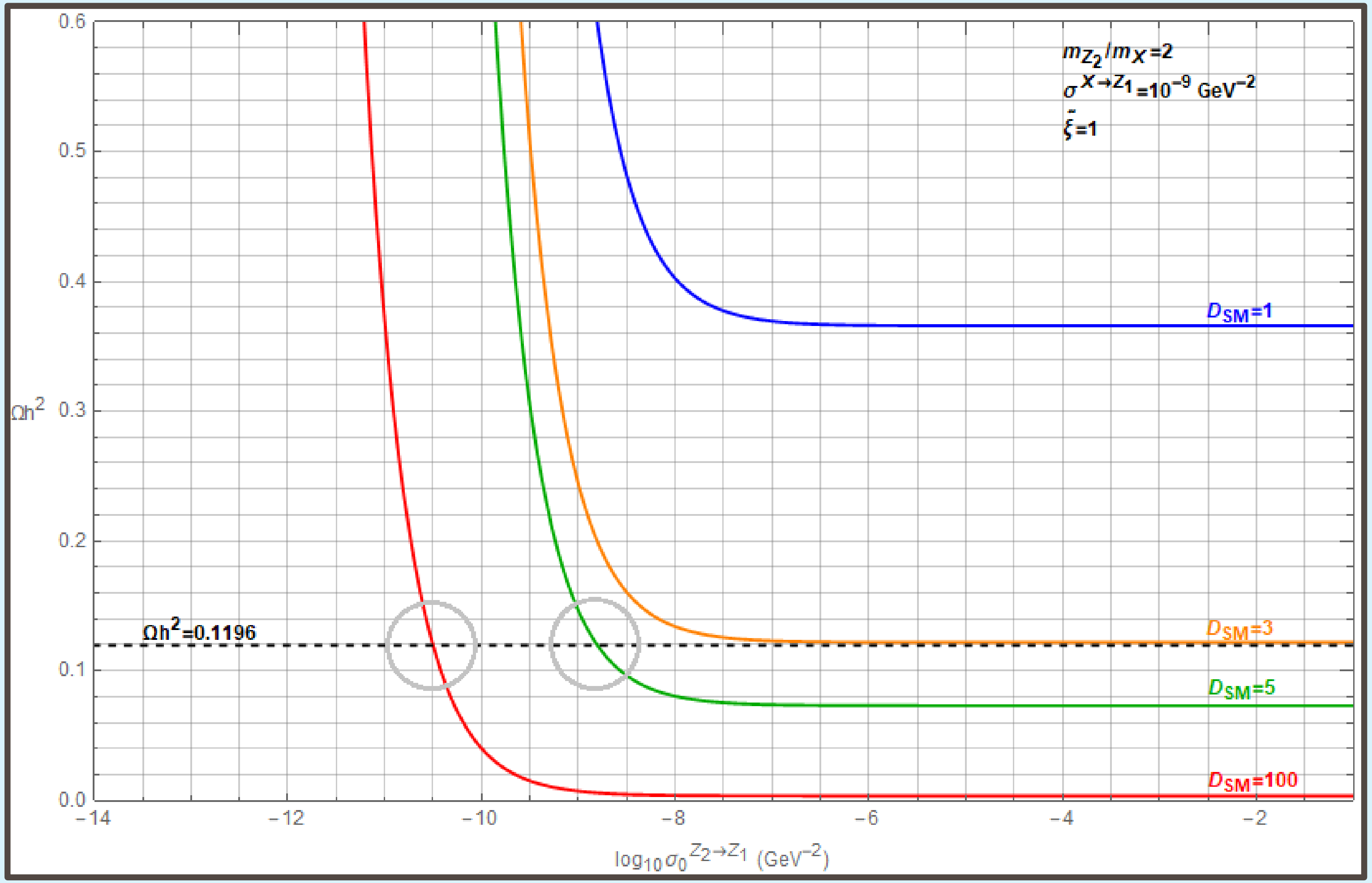
This scenario happens even if we introduce a **3-particles Dark Sector** where both Z_1 and Z_2 decouple while relativistic. To avoid this:

- Z_1 should be ***hot*** at the decoupling
- Z_2 should be ***cold*** at the decoupling
- X should be ***cold*** at the decoupling

These conditions fix the mass hierarchy

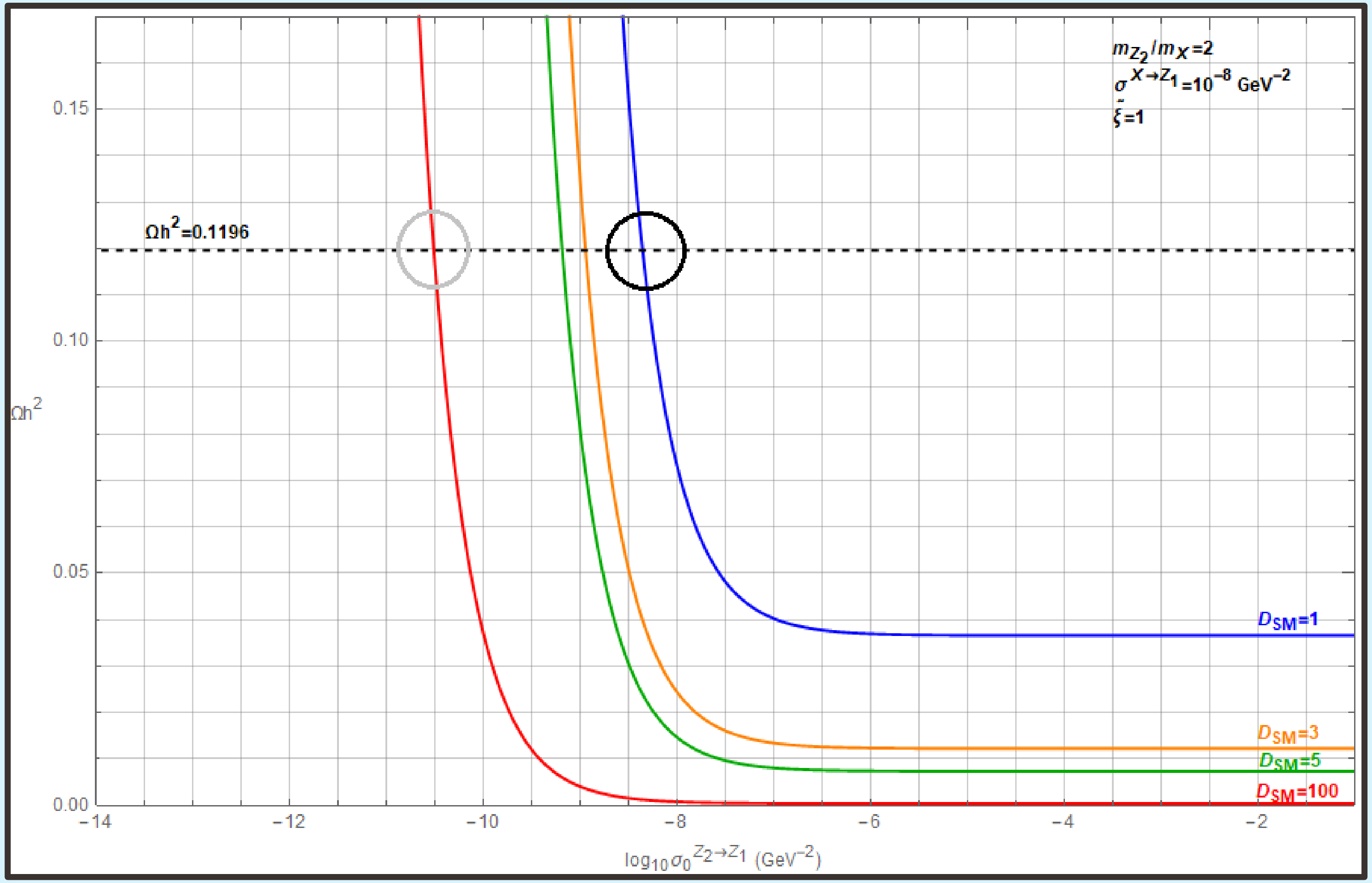
Freeze-out, Non-thermal production and Dilution

Scenario 1: Over-abundance



Freeze-out, Non-thermal production and Dilution

Scenario 2: Under-abundance



Conclusion

If a particle in the WIMP paradigm gives too **much** /too **little** energy density, can it still be a DM candidate?

- **Three-particles Dark Sector (X, Z_1, Z_2):** Dilution and NTP enhance and reduce the energy density. A model endowed by additional particles can make viable a classic WIMP that do not work.
- **Two-particles Dark Sector (X, Z_2):** cannot provide both dilution and NTP «efficiently»
- Combined effects of Dilution and NTP give **multiple** solutions to correct relic density

Outlook

Work-in progress:

- Implement the following work in a model-dependent scenario:

$$L_{dark} = g_1\phi_1\bar{\chi}\chi + g_2\phi_2\bar{\chi}\chi$$

$$L_{coupling} = \frac{\delta_1}{2}|H|^2\phi_1 - \frac{\delta_1 v^2}{4}\phi_1$$