Particle Dark Matter candidates

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Andreas Goudelis
LAPTh

Outline

- Introduction
- The DM abundance
- A concrete DM model example
- Summary and open questions

Ingredients for a DM model

When constructing a DM model, there are a couple of things that you might want to take into account :

- Can you explain the observed DM abundance in the universe?
  → Or at least some of it!

- Can you hide DM well enough?
  → It has only been observed through gravitational interactions!

- Can you nonetheless make the DM candidate observable in some (non-gravitational) experiment?
  → One might hope to somehow observe signatures of dark matter!

The dark matter density today

The WMAP + Planck missions give us a very precise measurement of the DM density

$$\Omega_{\rm DM} = 0.1187 \pm 0.0017$$

Rq1 : This number is valid *within ΛCDM cosmology*...

Rq2 : ...but ΛCDM is very successful so far and, well, we don't have many alternatives!

A question that follows quite naturally

→ Where does this number come from?
Can it be placed in a "historical" context?

A few assumptions

For our discussion, we shall be making the following **simplifying assumptions** :

i) DM is comprised of **one single particle species**.

→ Pretty arbitrary but doesn't qualitatively change the issues we'll discuss :)

ii) This particle is **elementary**.

→ (~) idem

iii) It does **not** interact very **strongly** with the visible sector.

→ A conclusion drawn from the non-observation of DM in non-gravitational experiments. It's a pretty safe assumption, but if it's wrong there are quite severe consequences!

Back to the main question

So we basically wish to examine the **evolution** of the **density** of some **particle species** in a homogeneous, isotropic, expanding (i.e. FLRW) **universe**.

There is a series of basic questions that we need to address :

i) Given some initial conditions, what is the possible evolution of the DM system over time and until today? What is the physics governing this evolution?

ii) What could these initial conditions be? Are there some “natural” values for the initial density of the dark matter particles?

iii) Is there an interplay among the above?

...and not addressed in this talk (guess the answer!):
iv) Are there any other factors that could complicate our computations?

The density evolution

Assume some particle species frolicking in the early universe. Four mechanisms can alter its (number) density :

→ Depletion from decays into lighter particles.

→ Production from decays of heavier particles.

Need to fix the density of the other particles and the decay rates.

→ Depletion from annihilations with other particles into yet other particles.

→ Production from annihilations of other particles.

Need to fix the annihilation rates

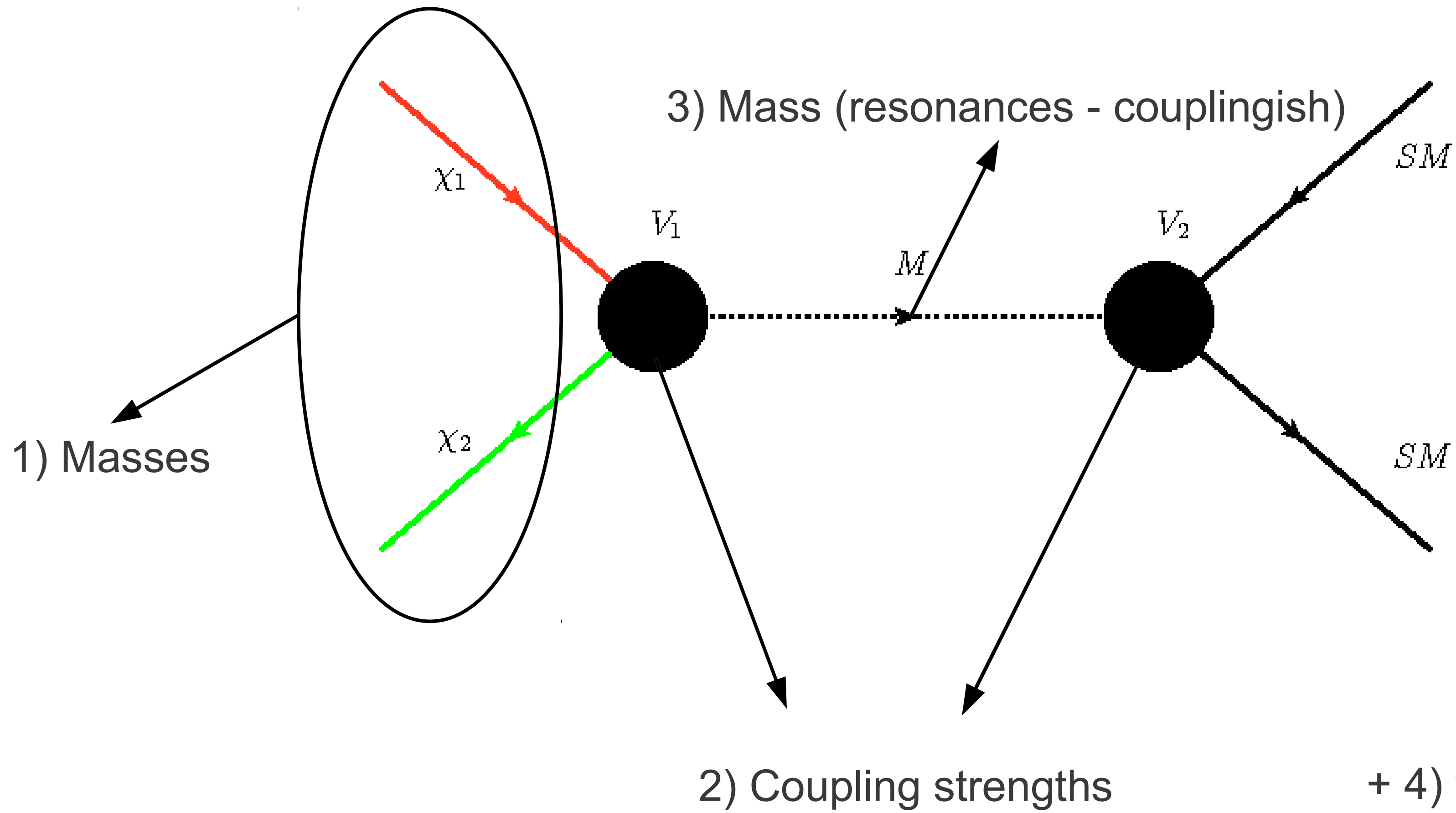
+++ Remember that the universe is expanding → Particles get diluted → Interactions become scarcer → At some point annihilations tend to “freeze”!

The most straightforward way to tackle the problem

$$\mathcal{L}[f] = \mathcal{C}[f]$$

The density evolution

In this picture, four elements govern the density evolution :



+ 4) the initial densities

So it all boils down to an interplay between masses, couplings and initial conditions...

The initial conditions

Let us again assume some particle species in the early universe.

→ Remember that the early universe is dense and hot!

The interaction rate of various particles can be quite high.
But the rate drops as the universe expands!

The various particles are very energetic (and mass is energy)
↓
heavy particles can be produced by lighter ones!

What kind of values would one expect for the initial number density of some particle species?

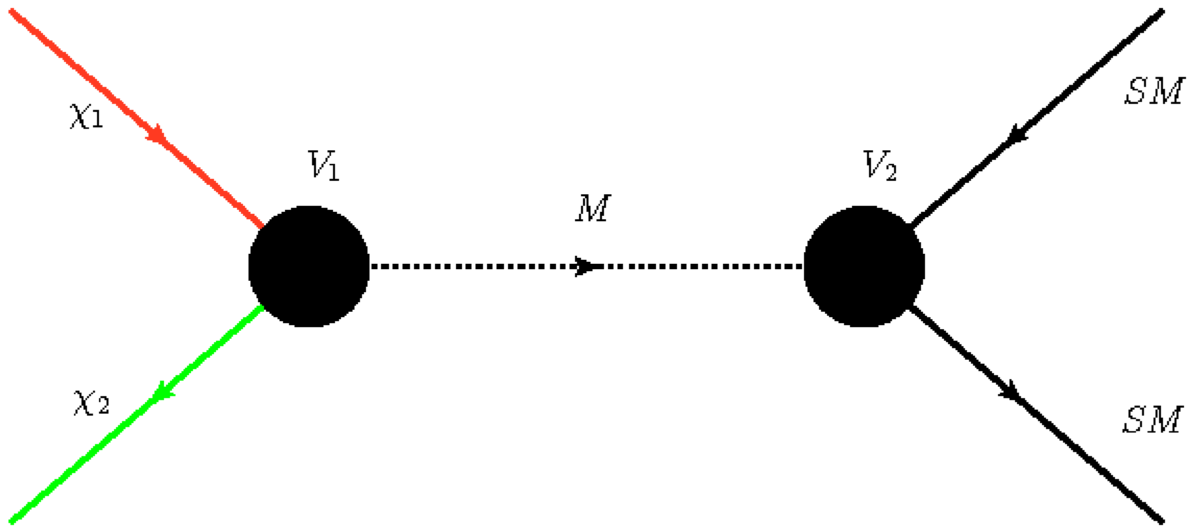
- Infinite (meh...)

- Zero (interesting... Wiped out during inflation?)

- Some density which is fixed by some external condition : some equilibrium condition?

The initial conditions

Forget about decays for the moment. Schematically :



At early times (↔ high temperatures), there are two possibilities:

→ The two sides of the reaction are initially in equilibrium. When the temperature falls below the DM mass, the density decreases asymptotically.

→ If the left-side density is zero, the density increases asymptotically.

→ For renormalizable interactions, both mechanisms are IR-dominated!

Dark matter candidates

Theorists have tried to keep busy...

- Weakly Interacting Massive Particles : neutralinos, sneutrinos, axinos, KK, minimal...

- Feably Interacting Massive Particles : pretty new, for the moment mostly minimal...

- Decaying : gravitinos, stringy moduli...

- Resulting from decays : gravitinos, axinos...

→ Symmetries to prevent (fast) decays

A very tight connexion of cosmology with particle physics. The most well-studied paradigm : WIMPs.
→ At first, DM in thermal equilibrium with SM particles.
→ As the temperature falls, WIMP production becomes inefficient.
→ As the universe expands, WIMP annihilation also becomes inefficient.

→ "Freeze-out" mechanism

Let's examine a minimal WIMP model for illustration : the Inert Doublet Model.

A WIMP model example: the IDM

Based on A.G., B. Herrmann, O. Stal, arXiv:1303.3010

One of the simplest BSM constructions yielding DM is the Inert Doublet Model :

- Gauge + spacetime symmetries : as in the SM.

- Particle content : SM + one SU(2) doublet of complex (Lorentz) scalar fields.

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + \mathrm{i}G^0\right) \end{pmatrix}, \quad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + \mathrm{i}A^0\right) \end{pmatrix}$$

- An extra Z2 discrete symmetry that protects the lightest component of the extra doublet from decaying.

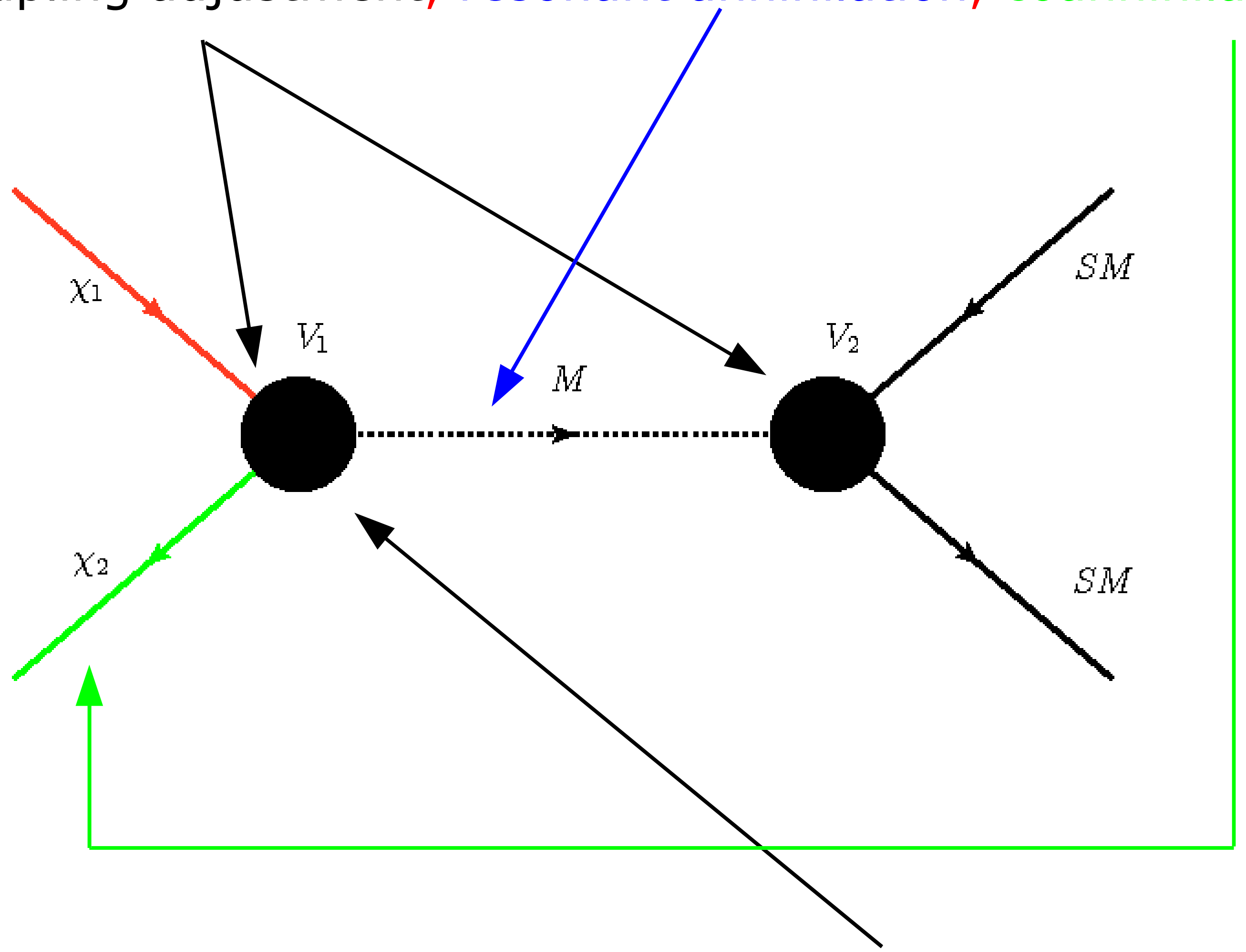
New interactions :

$$\mathcal{L}_{\rm cov} = (D_\mu H)^\dagger (D^\mu H) + (D_\mu \Phi)^\dagger (D^\mu \Phi)$$

$$V_0 = \mu_1^2 |H|^2 + \mu_2^2 |\Phi|^2 + \lambda_1 |H|^4 + \lambda_2 |\Phi|^4 + \lambda_3 |H|^2 |\Phi|^2 + \lambda_4 |H^\dagger \Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger \Phi)^2 + \mathrm{h.c.}\right]$$

The IDM : DM – relevant features

The IDM is the simplest BSM construction that can capture essentially all mechanisms that give rise to the correct DM relic density in WIMP models: coupling adjustment, resonant annihilation, coannihilation.



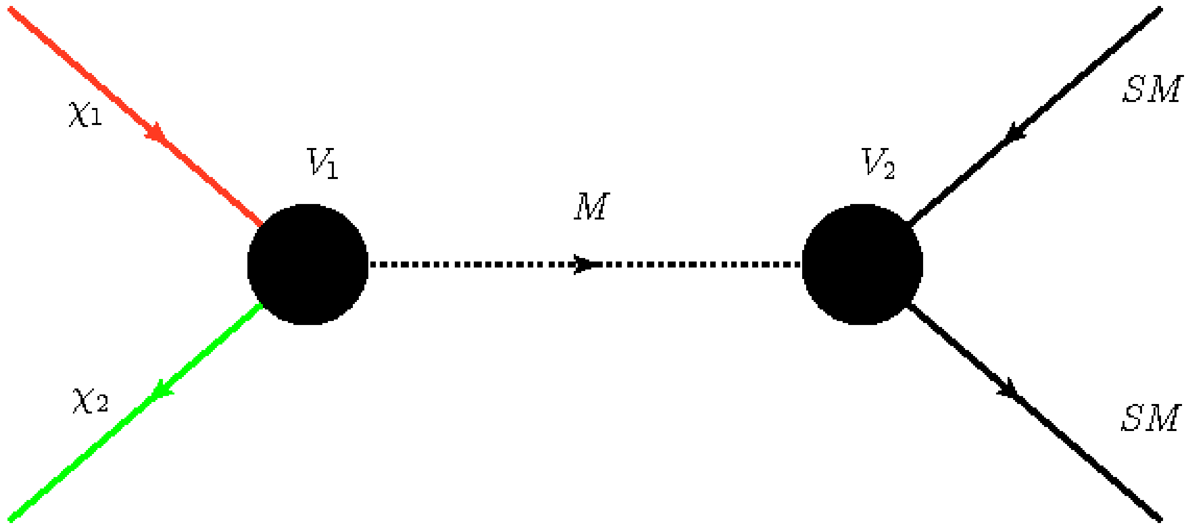
$$(\mu_1)\,,(\mu_2,\lambda_2,\lambda_3,\lambda_4,\lambda_5)\ \leftrightarrow\ (m_h),m_{H^0},m_{A^0},m_{H^\pm},\lambda_L=1/2(\lambda_3+\lambda_4+\lambda_5),\lambda_2$$

DM connection to the other sectors

Let's fix the NLOP mass to some irrelevant value to avoid coannihilations. After the (potential) Higgs boson discovery, this leaves us 2 parameters to play with :

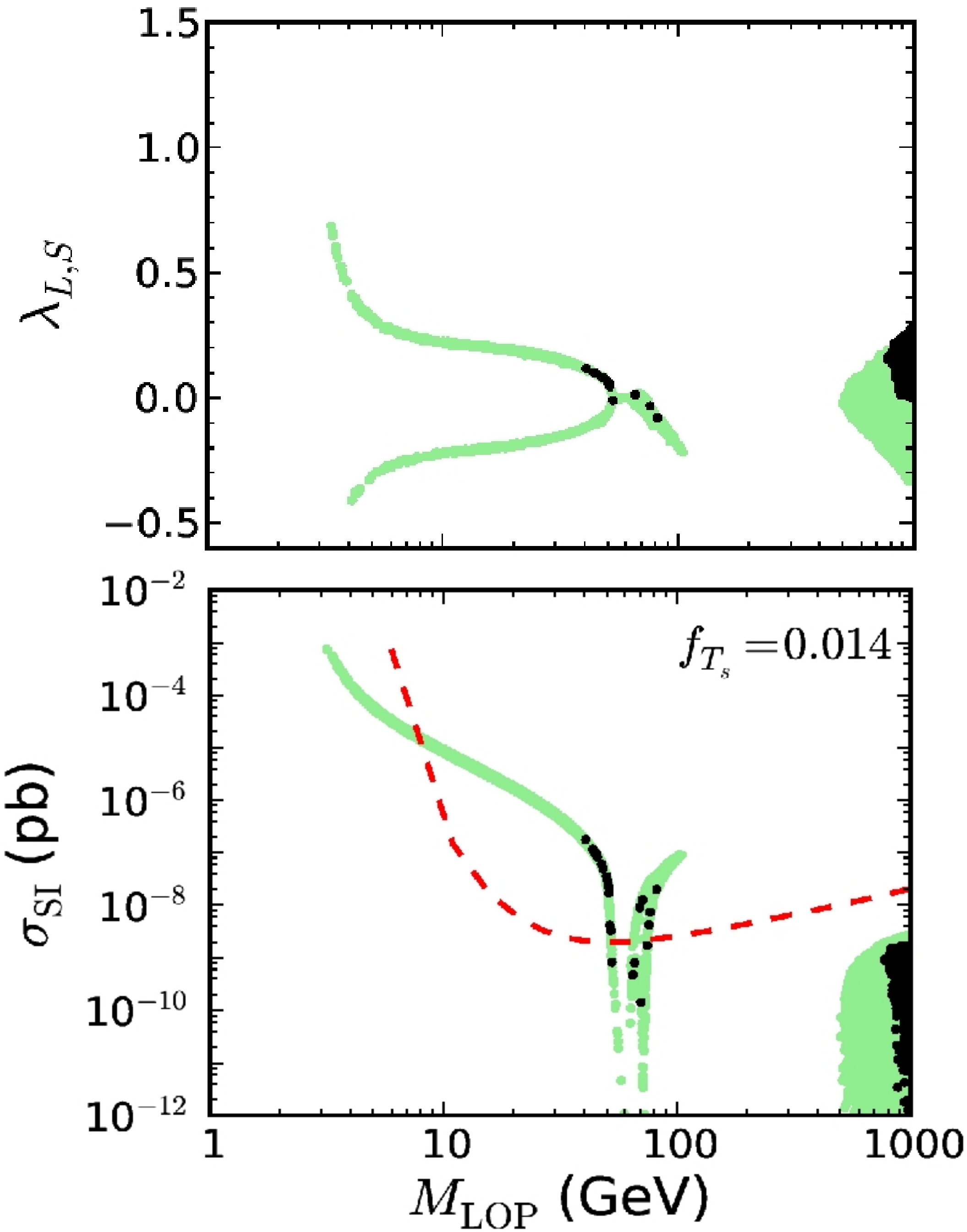
- The DM mass (as compared to the higgs and W mass)

- The strength of the DM coupling to the higgs



NB: The direct DM-DM-W-W coupling is a gauge coupling, hence fixed!

DM connection to the other sectors



The relic density requires specific values for the higgs - DM coupling :

- Approaching half the higgs mass requires reducing the coupling, taking distance requires increasing it.

- This translates directly into drastic modifications of the direct detection rates.

→ This almost 1-1 correspondence is possible only after the (possible) Higgs boson discovery! Before, many such branch regions overlapped!

Similar behaviour is observed in other models.

→ Higgs measurements could be crucial for dark matter physics!

Elements of summary

- One of the main open questions in astroparticle physics is the way the observed DM abundance can be reproduced.

- We do have candidate mechanisms for that. And more than one. But actually not that many : freeze-in, freeze-out, decay (ok, and a few more).

- DM physics is a meeting point of several different fields : cosmology, astrophysics, particle physics.

- Particle physics observables, seemingly unrelated, may have a crucial role to play for DM physics : most DM models are particle physics models!

A few open questions (highly non-exhaustive!)

- The LHC and direct/indirect detection are pushing masses upwards and couplings downwards. The WIMP region is being probed with null results (so far).

→ New mechanisms for DM generation? Will WIMPs always survive?

→ If new mechanisms, what experiments/observables?

- What are the excesses that direct + indirect detection have observed?

- Beyond ΛCDM? (Any serious reason for that?)

- DM is basically the only evidence for BSM physics. The SM has however some issues. Should we try to relate the two and how?

Merci !