Multi-Component Dark Matter in a Q6-Symmetric Model

Catalina Espinoza*

IFUNAM – Cátedra SECIHTI

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Ciencia y Tecnología
Secretaría de Ciencia, Humanidades, Tecnología e Innovación

***with A. E. Cárcamo-Hernández, J.C. Gómez-Izquierdo, J. Marchant and M. Mondragón**

Outline

MOTIVATION

Motivation

Our enigmatic Universe. Recent observations of the James Webb Space Telescope could be interpreted as evidence of Dark Stars.

PNAS RESEARCH ARTICLE | ASTRONOMY OPEN ACCESS Check for updates

Spectroscopic Supermassive Dark Star candidates

Cosmin Ilie[a,1], Sayed Shafaat Mahmud[a], Jillian Paulin[b], and Katherine Freese[c,d,e,1]

Contributed by Katherine Freese; received June 2, 2025; accepted August 15, 2025; reviewed by Laura Baudis and Neelima Sehgal

Dark Stars (DSs), i.e., early stars composed almost entirely of hydrogen and helium but powered by Dark Matter (DM), could form in zero metallicity clouds located close to the center of high redshift DM halos. In 2023, three of us identified (in a PNAS work) the first three photometric DS candidates: JADES-GS-z11-0, JADES-GS-z12-0, and JADES-GS-z13-0. We report here our results of a follow-up analysis based on available NIRSpec JWST data. We find that JADES-GS-z11-0 and JADES-GS-z13-0 are spectroscopically consistent with a DS interpretation. Moreover, we find two additional spectroscopic DS candidates: JADES-GS-z14-0 and JADES-GS-z14-1, with the former being the second most distant luminous object ever observed. We furthermore identify, in the spectrum of JADES-GS-z14-0, a tentative feature ($S/N \sim 2$) indicative of the smoking gun signature of DSs: the He II λ1640 absorption line. In view of ALMA's recent identification of a probable O III nebular emission line in the spectrum of JADES-GS-z14-0, the simple interpretation of this object as an isolated DS is unlikely. If both spectral features survive follow-up observations, it would imply a DS embedded in a metal rich environment, requiring theoretical refinements of the formation of evolution of DSs, which in previous studies were assumed to form in isolation, without any companions.

stars | cosmology | Dark Matter | James Webb Space Telescope | high-z galaxies

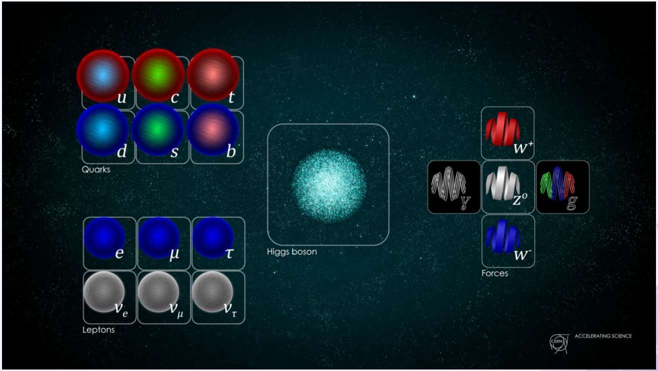
The first stars to form in the Universe, when it was roughly 200 million years old (e.g., refs. 1–7), may have been Dark Stars (DSs), composed almost entirely of hydrogen and helium from the Big Bang but powered by Dark Matter (DM) annihilation rather than by nuclear fusion (8–10). Although DM constitutes only $\lesssim$0.1% of the stellar mass, this amount is sufficient to power a DS for millions to billions of years. The relevant types of DM for heating the stars include weakly interacting massive particles (WIMPs)* and self-interacting DM (SIDM) (11). Starting from their inception at $\sim$1 $M_\odot$, DSs accrete mass from their surroundings to become supermassive stars, some even reaching masses

Significance

In 2007 Spolyar, Freese, and Gondolo proposed the idea of Dark Stars (DSs). Some of the first stars in the Universe might have been powered by Dark Matter (DM annihilations rather than nuclear fusion. They could form out of pristine Hydrogen and Helium clouds at the centers of protogalaxies, where there is a sufficient DM to serve as their heat source. They are very bright diffuse puffy objects and grow to be very massive. In 2023 three of us (C.I., J.P., and K.F.) identified the first three photometric DS candidates in the JWST NIRCam data. In this paper, we use JWST NIRSpec data and identify four spectroscopic DS candidates, one of them being the second most distant object ever observed.

Motivation

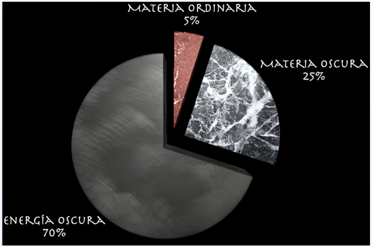
The Standard Model of Particle Physics can be regarded as one of the most important achievements of fundamental science.

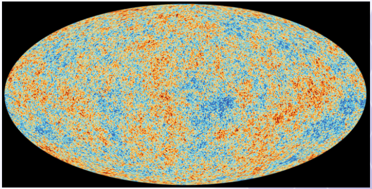


Motivation

Despite the Standard Model's outstanding successes, by now it is clear that **a more fundamental theory** is required to tackle several shortcomings and unexplained evidences such as (e.g. J. Ellis, hep-th/9812235):

- **Dark matter and dark energy**





Motivation

- Why aren't the particle masses much closer to the Planck mass (10^{19} GeV)?
- Why some particle masses are so small (m_ν) and others relatively much larger (m_t)?
- Can all the particle interactions be unified in a simple gauge group?
- What is the origin of the 6 flavours each of quarks and leptons?
- Baryon asymmetry, mixing patterns, quantization of gravity, ...

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There are many ways **to delve into** the unknown ...

- Usually: **add symmetries - or add particles - or add interactions**
- Include **all of the above simultaneously or combinations**

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  $\longrightarrow$ **Model Building**

Specifically ...

In this talk I will describe one BSM model built with the aim of:

- Provide **several** (particle) **dark matter** (DM) **candidates**.
- Generate the **mass hierarchy of quarks and leptons** through a **discrete symmetry**.

In particular, this Beyond the SM (BSM) theory has the following characteristics:

- An **extended scalar sector**.
- **DM sector** coupled through a **Higgs portal**.

However I will focus only in the description of the **scalar sector phenomenology** and its **correlations with the DM sector**.

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Q6 Symmetric Model

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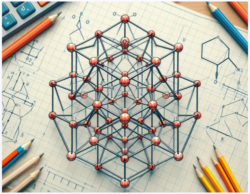
We made an analysis for a BSM model with **non-abelian Q6 discrete symmetry**:

- The discrete D_N symmetry is that of a **regular polygon of N sides**, and occurs in nature e.g. in poly-atomic molecules.
- The discrete non-abelian group Q_6 (or binary dihedral group with $N = 6$) can be seen as the **group cover of D_6** or the **double cover of S_3**, and **has pseudo-real representations** which is advantageous for chiral theories.



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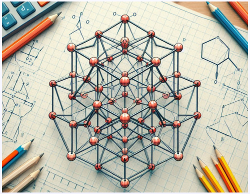

Q6 Symmetric Model

We made an analysis for a BSM model with **non-abelian Q6 discrete symmetry**:

- In this model the Q6 symmetry is **imprinted in the fermionic sector in order to predict** the mass and mixing patterns of quarks and neutrinos.

Q6 Symmetric Model

We propose a scalar sector with **3+1 Higgs Doublets** and which contains, **among other fields**:

- **3 active Higgs doublets H_1, H_2, H_3.**
- **1 inert Higgs doublet H_4.**
- **2 complex scalar singlets φ_1 and φ_2.**
- In addition, the fermion sector has **right handed heavy neutrinos.**

The **inert doublet** H_4 and the **right handed heavy neutrinos** N_{iR} have **scotogenic-like couplings** to the SM leptons.

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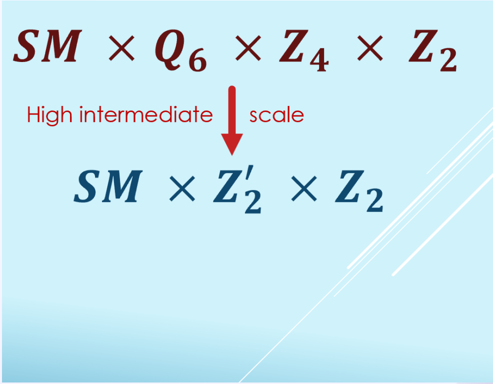
Q6 Symmetric Model

- In addition, a $Z_4 \times Z_2$ symmetry is imposed:

$$SM \times Q_6 \times Z_4 \times Z_2$$

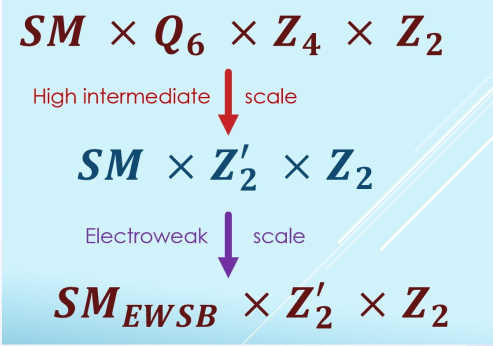
Q6 Symmetric Model

- It is assumed that at some intermediate energy scale the Q_6 symmetry is completely broken while Z_4 is broken to a remnant Z_2'.



Q6 Symmetric Model

- At low energies, we end up with the SM in the broken phase extended with the remnant $Z_2' \times Z_2$ discrete symmetries.



Q6: Particle Content

- The complete fermion content with the $SU(3)_C \times SU(2)_L \times U(1)_Y \times Q_6 \times Z_2 \times Z_4$ assignments:

	q_L	q_{3L}	u_R	u_{3R}	d_R	d_{3R}	l_{1L}	l_L	e_{1R}	e_R	N_{1R}	N_R
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$1/6$	$1/6$	$2/3$	$2/3$	$-1/3$	$-1/3$	$1/2$	$1/2$	-1	-1	0	0
Q_6	$\mathbf{2}_2$	$\mathbf{1}_{-+}$	$\mathbf{2}_2$	$\mathbf{1}_{-+}$	$\mathbf{2}_2$	$\mathbf{1}_{-+}$	$\mathbf{1}_{-+}$	$\mathbf{2}_2$	$\mathbf{1}_{-+}$	$\mathbf{2}_2$	$\mathbf{1}_{-+}$	$\mathbf{2}_2$
Z_2	0	0	0	0	0	0	0	0	0	0	1	1
Z_4	0	0	0	0	0	0	0	0	0	0	1	1

- The complete scalar content with the $SU(3)_C \times SU(2)_L \times U(1)_Y \times Q_6 \times Z_2 \times Z_4$ assignments:

	H	H_3	H_4	φ_1	φ_2	σ	ξ	ρ
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$1/2$	$1/2$	$1/2$	0	0	0	0	0
Q_6	$\mathbf{2}_1$	$\mathbf{1}_{++}$	$\mathbf{1}_{++}$	$\mathbf{1}_{++}$	$\mathbf{1}_{++}$	$\mathbf{1}_{++}$	$\mathbf{2}_1$	$\mathbf{1}_{--}$
Z_2	0	0	1	0	1	0	0	0
Z_4	0	0	1	1	2	2	2	2

Q6: Dark Sector Scalar Potential

- In the **dark sector**, the **scalar potential** contains the following terms:

$$
\begin{aligned}
V \supset\ & \mu_8^2 H_4^\dagger H_4 + \mu_9^2 \varphi_1^* \varphi_1 + \mu_{10}^2 \varphi_2^* \varphi_2 + \mu_{\mathrm{SB}}^2 (\varphi_1^2 + \mathrm{h.c.}) \\
& + \kappa_1 (\varphi_1^* \varphi_1)^2 + \kappa_2 (\varphi_2^* \varphi_2)^2 + \kappa_3 (\varphi_1^* \varphi_1)(\varphi_2^* \varphi_2) \\
& + \left[\kappa_4 (\varphi_1^2 \varphi_2^2) + \kappa_5 (H_4^\dagger H_3)(\varphi_1^* \varphi_2) + \kappa_6 (H_3^\dagger H_4)(\varphi_1 \varphi_2) + \mathrm{h.c.} \right] \\
& + \sum_{i=1}^{2} (\varphi_i^* \varphi_i) \left[\kappa_{6+i} (H_4^\dagger H_4) + \kappa_{8+i} (H_3^\dagger H_3) + \kappa_{10+i} (H^\dagger H)_{1++} \right] \\
& + \kappa_{13} (H_4^\dagger H_4)(H^\dagger H)_{1++} + \kappa_{14} (H_4^\dagger H_4)(H_3^\dagger H_3)
\end{aligned}
$$

Q6: Dark Sector

- Thanks to the $Z_2' \times Z_2$ symmetries, **the model has 3 dark sectors** with the following particle content:

Particle	Z_2'	Z_2
Reϕ_1,Imϕ_1	-1	1
Reϕ_2,Imϕ_2	1	-1
$N_{iR}, H_4^0, A_4^0, H_4^\pm$	-1	-1

- We assume that **one of the fermions is the lightest particle** the third DM sector.

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- We assume that **one of the fermions is the lightest particle** in the third DM sector.

Q6: Multi-component Dark Matter

- We end with **3 DM candidates**, 2 scalars and 1 fermion.
- The total observable **DM abundance is the sum of the 3 DM abundances**.

Two real scalars

One Majorana fermion

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Analysis Strategy

Q6: Likelihood analysis

- We present several numerical results based on a scan of the parameter space of the model where we construct **likelihood profiles** involving observables of interest by comparing predictions with experimental measurements.
- We include the information from the measured values of the **relic density** $\Omega h^2_{\text{Planck}}$ **and SM Higgs propertries** as basic Gaussian likelihoods $\mathcal{L}_{\Omega}$, $\mathcal{L}_{\text{Higgs}}$ respectively.
- We also include a likelihood function $\mathcal{L}_{DD}$ based on recent results from the **LZ Direct Detection Experiment.**

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- We then maximize over the model's parameter space **the composite log-likelihood**:

$$\log \mathcal{L} = \log \mathcal{L}_{\mathrm{DD}} + \log \mathcal{L}_{\Omega h^2} + \log \mathcal{L}_{\mathrm{Higgs}}$$

Note that in the high statistic limit, twice the negative of the composite log-likelihood approaches a χ-square function so this procedure is equivalent to minimizing such function.

$$\Delta\chi^2 = -2 \log \left(\mathcal{L}/\mathcal{L}_{\mathrm{max}}\right)$$

Numerical analysis

We implement the model in the SARAH package (Adv. High Energy Phys. **2015** (2015), 840780) and using public tools we impose hard cuts discarding points not complying with:

- **Positivity and stability of the scalar potential** (EVADE, JHEP **03** (2019), 109).
- **Exclusion limits from scalar searches** at Tevatron, LEP and LHC. (HiggsBounds, Eur. Phys. J. C **80** (2020) no.12, 1211) .
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Experimental information

We compare the predictions of the model with **publicly available data from different experiments** and implemented in diverse public tools:

- LHC for mass, couplings, ratios, etc, of the SM Higgs-like scalar (HiggsSignals, Eur. Phys. J. C **81** (2021) no.2, 145, and references therein) .
- LZ for DM direct detection limits (LZ, Phys. Rev. Lett. 131 no. 4, (2023) 041002, DDcalc, Eur. Phys. J. C **77** (2017) no.12, 831 , and references therein) .
- PLANCK for DM relic density (PLANCK, Astron. Astrophys. **641** (2020), A6) .
- We scan the parameter space of the model to construct the **likelihood profile** and find the best fit point (BFP) that maximizes the likelihood function (Diver, Eur. Phys. J. C **77** (2017) no.11, 761 , P. Scott, Eur. Phys. J. Plus **127** (2012), 138) .

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Experimental information

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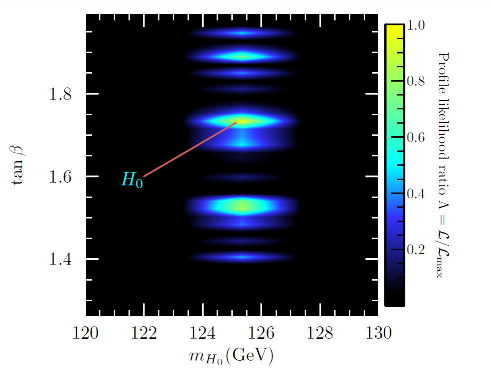
- LHC for mass, couplings, ratios, etc, of the SM Higgs-like scalar (HiggsSignals, Eur. Phys. J. C **81** (2021) no.2, 145, and references therein) .
- LZ for DM direct detection limits (LZ, Phys. Rev. Lett. 131 no. 4, (2023) 041002, DDcalc, Eur. Phys. J. C **77** (2017) no.12, 831 , and references therein) .
- PLANCK for DM relic density (PLANCK, Astron. Astrophys. **641** (2020), A6) .
- We scan the parameter space of the model to construct the **likelihood profile** and find the best fit point (BFP) that maximizes the likelihood function (Diver, Eur. Phys. J. C **77** (2017) no.11, 761 , P. Scott, Eur. Phys. J. Plus **127** (2012), 138) .

Phenomenology

Q6: Mass spectra of the scalar sector

This is the profile for **the H_0 scalar**.



- We are able to find a small region where the model correctly predicts a SM-like Higgs.
- The fit shows a preferred value of $\tan\beta = v2/v3 = 1.74$.

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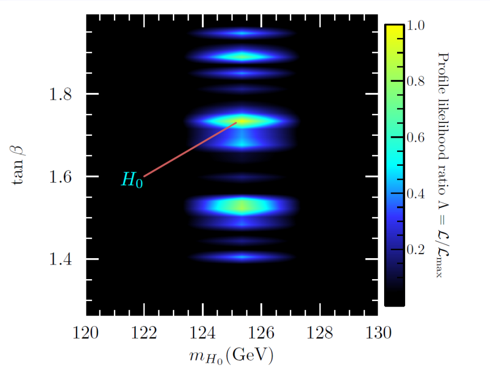

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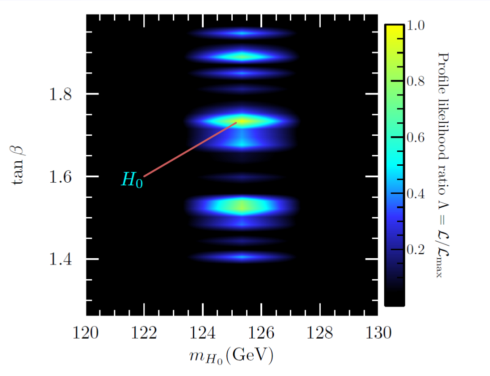

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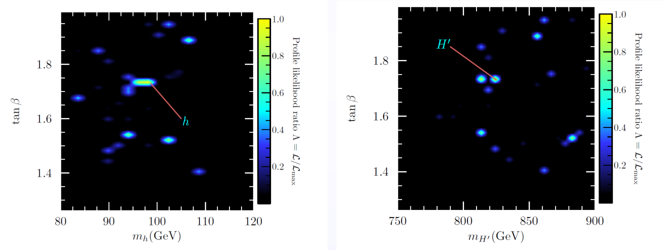
Q6: CP-even scalars

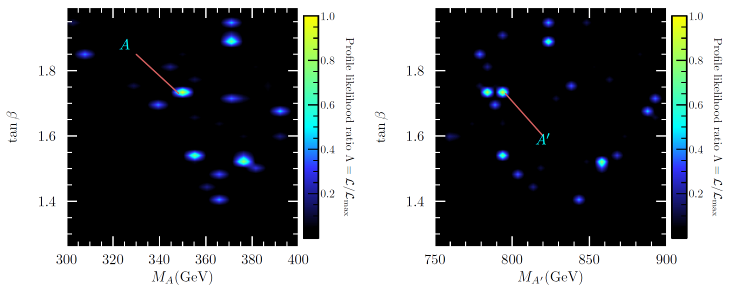
- The mass spectra contains one **light CP-even scalar** h of mass $\sim$ 98 GeV and one heavy scalar H' of mass $\sim$ 830 GeV.



This is interesting **in light of the LHC event excesses** around $\sim$ 95 GeV.

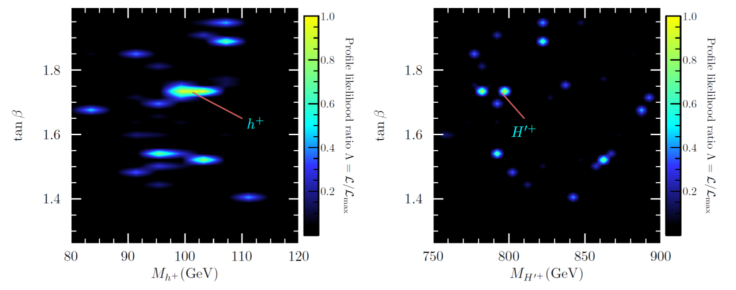
Q6: CP-odd scalars

- There are also **2 pseudo scalars** A **and** A' with masses of 350 GeV and 795 GeV respectively.



Q6: Charged scalars

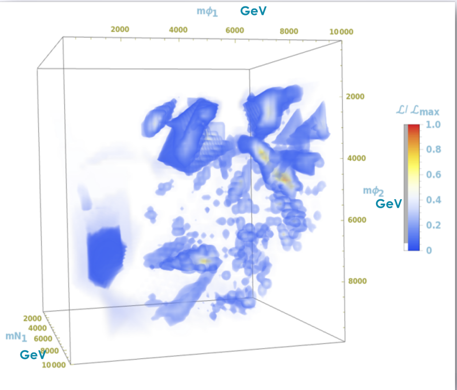
- In addition, we have 1 active **charged light scalar** h^+ of mass $\sim$ 102 GeV and one heavy charged scalar H'^+ of mass $\sim$ 800 GeV.



Multi-component Dark sector

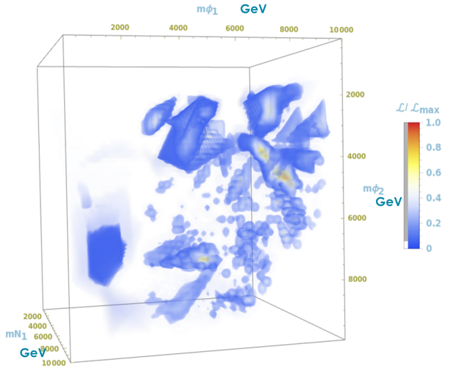
Q6: DM Abundance

Scatter plot of the masses of the DM candidates for which the model predicts a DM abundance **within the experimental interval**.



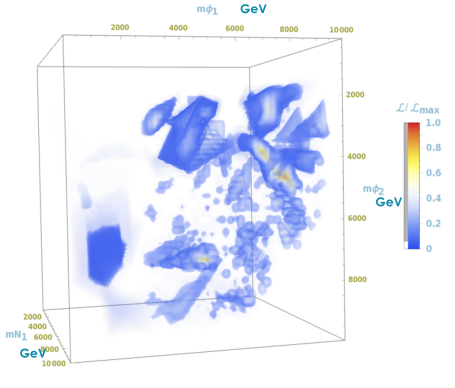
Q6: DM Abundance

Note that the **DM abundance likelihood is maximal** for these points.



Q6: DM Abundance

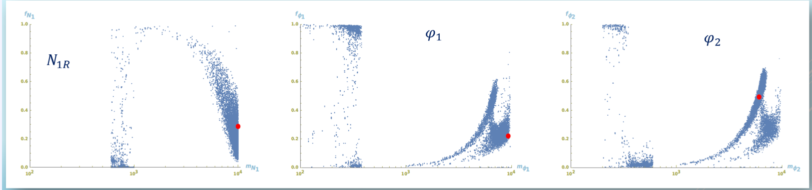
However, **only the red points are consistent with the rest of the constraints** like Direct Detection etc.



Q6: DM Abundance Fractions

- For each of the previous points the sum of the abundance fractions equals 1:

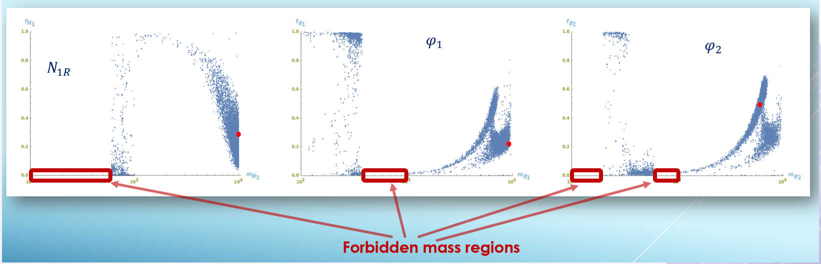
$$f_{N_{1R}} + f_{\phi_1} + f_{\phi_2} = 1$$



- Where
  $f_i = $ (Abundance of DM candidate i)/(Total DM abundance)

Q6: DM Abundance Fractions

- We can infer more information from these plots:
- For example, **in these highlighted mass regions** the model is not capable to account for the observed DM abundance.



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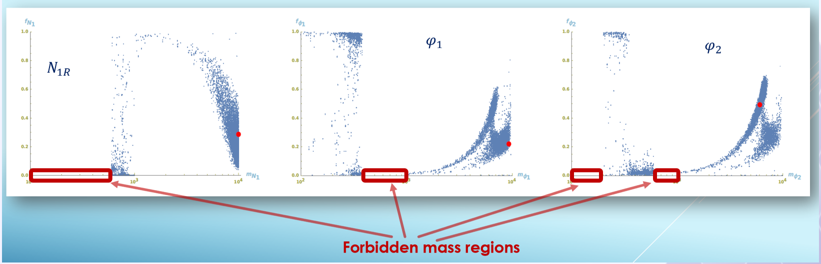
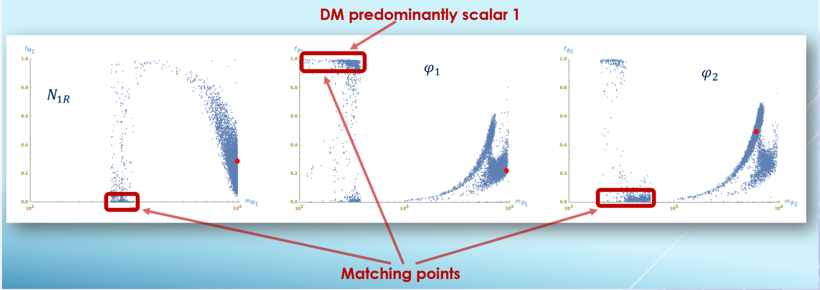


Q6: DM Abundance Fractions

- Moreover, by inspection we note points with fraction very close to unity.
- These must match with corresponding points with vanishing fractions, **here the DM is predominantly ϕ_1.**



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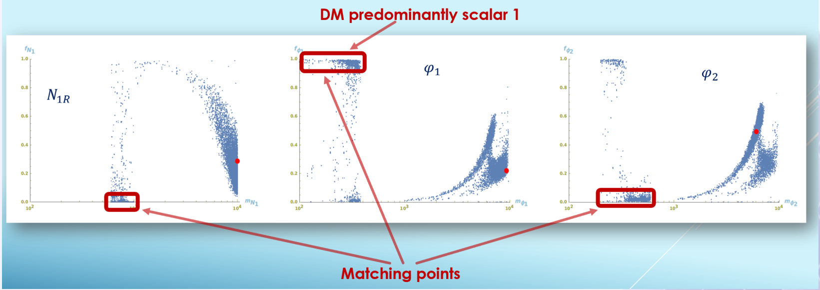
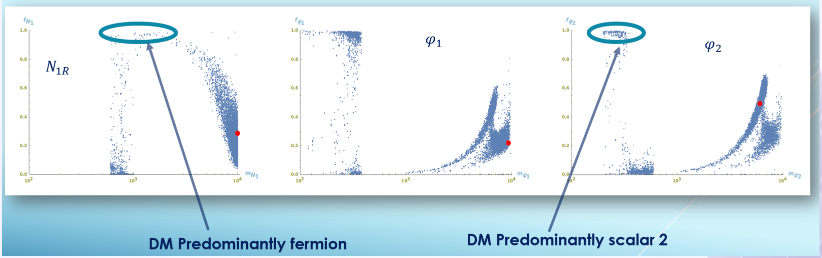


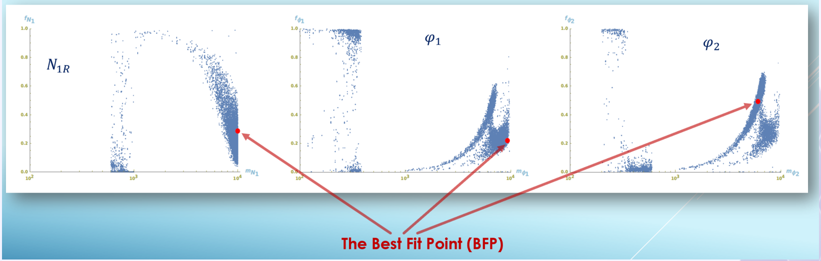
Q6: DM Abundance Fractions

- There are also regions where either the DM is predominantly the fermion or the second scalar.



Q6: DM Best Fit Point

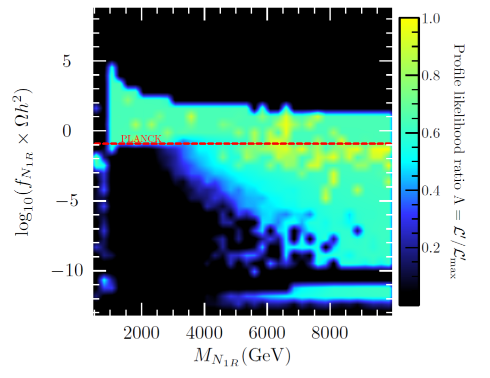
- Nevertheless, **the best fit point (BFP)** is found to be in a region of parameter space where there are **sizable contributions from the three DM candidates**.



- The BFP has masses $(m_{N_1}, m_{\phi_1}, m_{\phi_2}) = (9991, 9323, 6045)$ GeV and fractions $= (0.287, 0.22, 0.493)$.

Q6: DM Abundance Profiles

- Complementary information can be obtained with the **likelihood profiles**.
- This profile shows the **weighted fermion DM abundance** as a function of its mass.



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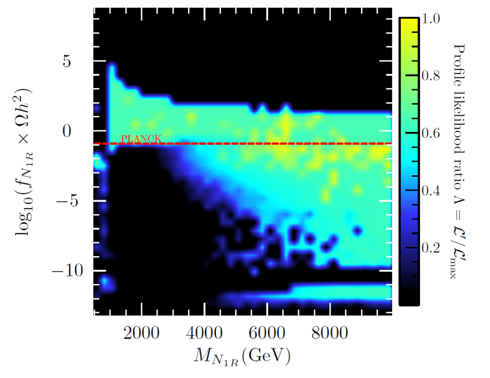
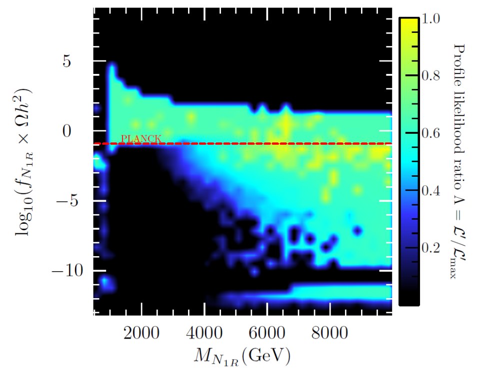


Q6: DM Abundance Profiles

- For **visual aid**, this profile is with respect to the **partial likelihood** $\mathcal{L}' = \mathcal{L} - \mathcal{L}_{\Omega h^2}$.
- **Bright spots** correspond to points where the **partial likelihood is maximal**.



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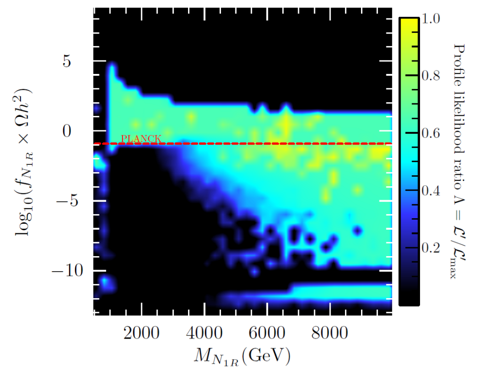
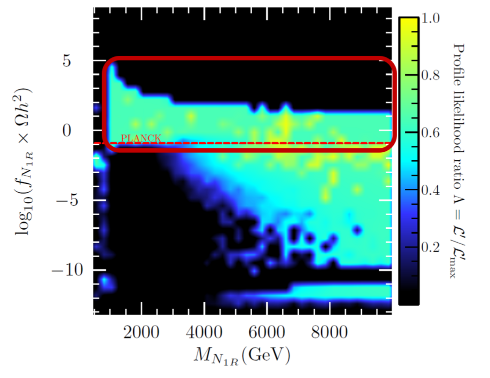


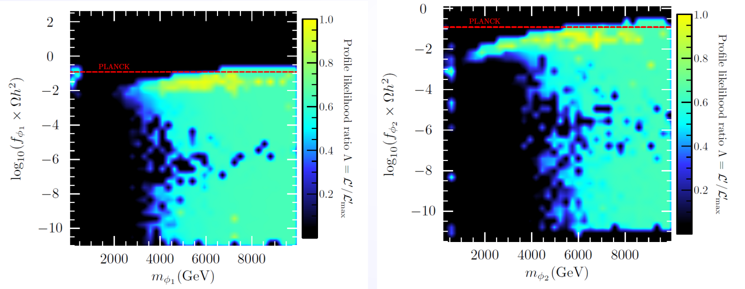
Q6: DM Abundance Profiles

- In large regions **the fermion DM candidate is overproduced** during the freeze-out epoch.



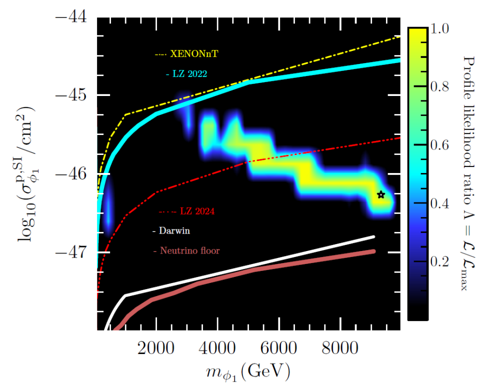
Q6: DM Abundance Profiles

- Also **for large DM masses the scalar DM particles are underproduced** during the freeze out epoch in **vast regions** of parameter space.



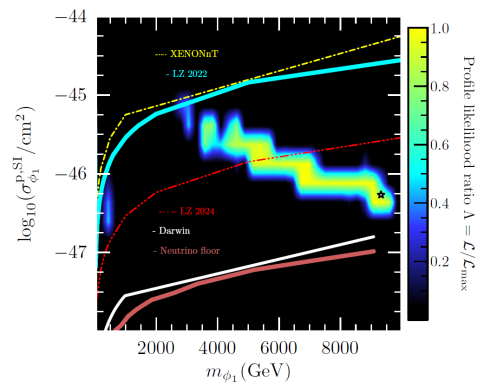
Q6: DM-nucleon Elastic Scattering Cross Section

- This profile depicts the dependence of the **total likelihood** on the **DM mass and the DM-proton spin independent (SI) cross section**, for the scalar DM candidate ϕ_1.



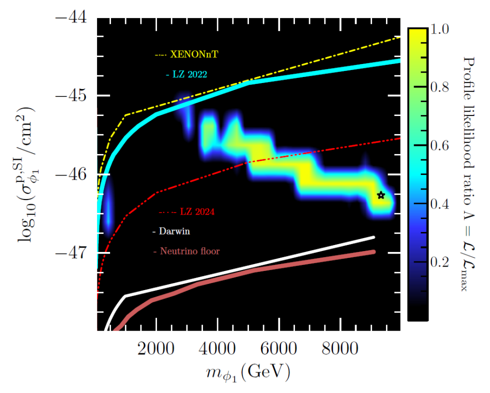
Q6: DM-nucleon Elastic Scattering Cross Section

- We also depict the 90% CL upper limit on the SI cross section from the **XENONnT and the LZ experiments**, alongside with the **DARWIN experiment** and an estimation of the **neutrino floor**.



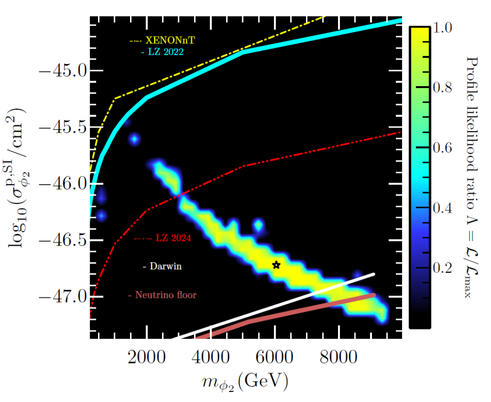
Q6: DM-nucleon Elastic Scattering Cross Section

- We can see that **LZ is already able to exclude about half** of the allowed parameter space for the case of the ϕ_1 DM candidate.



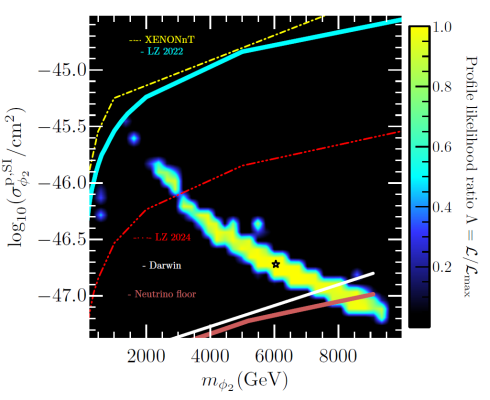
Q6: DM-nucleon Elastic Scattering Cross Section

- **For the ϕ_2 DM candidate** LZ is still is not sufficiently sensitive to strongly constrain it.



Q6: DM-nucleon Elastic Scattering Cross Section

- The **DARWIN experiment** will be able to probe around 80% of the region for ϕ_2, setting again strong constrains on the model.



CONCLUSIONS

Conclusions

- We have proposed an **extended 3 + 1 Higgs doublet model** in which the SM gauge symmetry is enlarged by the inclusion of the $Q_6 \times Z_2 \times Z_4$ discrete group, whereas the SM fermionic spectrum is augmented by the inclusion of **right-handed Majorana neutrinos**.
- In addition to the four $SU(2)$ scalar doublets, the scalar sector also includes several gauge singlet scalars. Such extended particle content and symmetries allows for a **successful implementation of a 2-loop level radiative seesaw mechanism** that yields the tiny active neutrino masses.

Conclusions

- In our proposed model, the Q_6 symmetry is spontaneously broken, whereas the Z_4 symmetry breaks spontaneously down to a **residual preserved Z_2' symmetry**. The preserved Z_2 and Z_2' discrete symmetries ensures two-loop induced masses for active neutrinos and also allow for **stable dark matter candidates**.
- We have analyzed in detail the implications of our model in the **phenomenology of the scalar and dark matter sectors**. We have found that our model successfully reproduces the low energy SM fermion flavor data and is **compatible with current dark matter constraints**.

Acknowledgments

Acknowledgments

- I would like to thank the organizers of the XIX MWPF 2025 for such a great workshop.
- I would like to thank my collaborators A.E. Cárcamo-Hernández, J.C. Gómez-Izquierdo, J. Marchant and M. Mondragón.
- I would like to thank the support of SECIHTI – Cátedra No. 341 and the Institute of Physics - UNAM.

Thank you for your attention!