UNIVERSIDAD ADOLFO IBÁÑEZ

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Revisiting the scotogenic model with scalar dark matter

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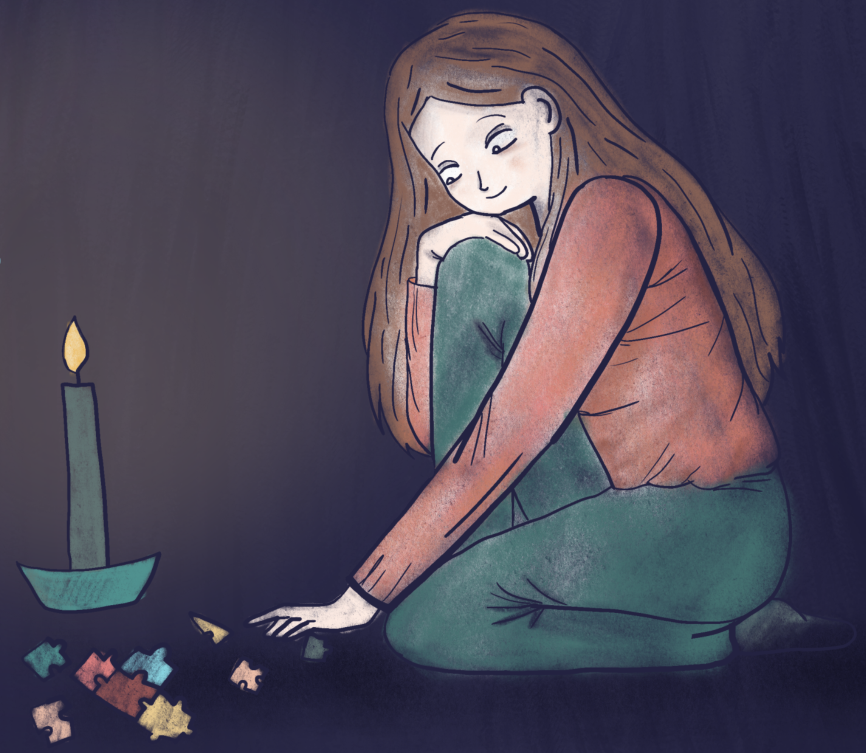

November, 2021

Searching for new physics

The Standard Model is the best theory that explain the electroweak and strong interaction at present. But there are some phenomena in physics that are not possible to understand with it.

- Higgs Boson
- Matter and Antimatter
- GUT
- Neutrino masses
- Dark Matter

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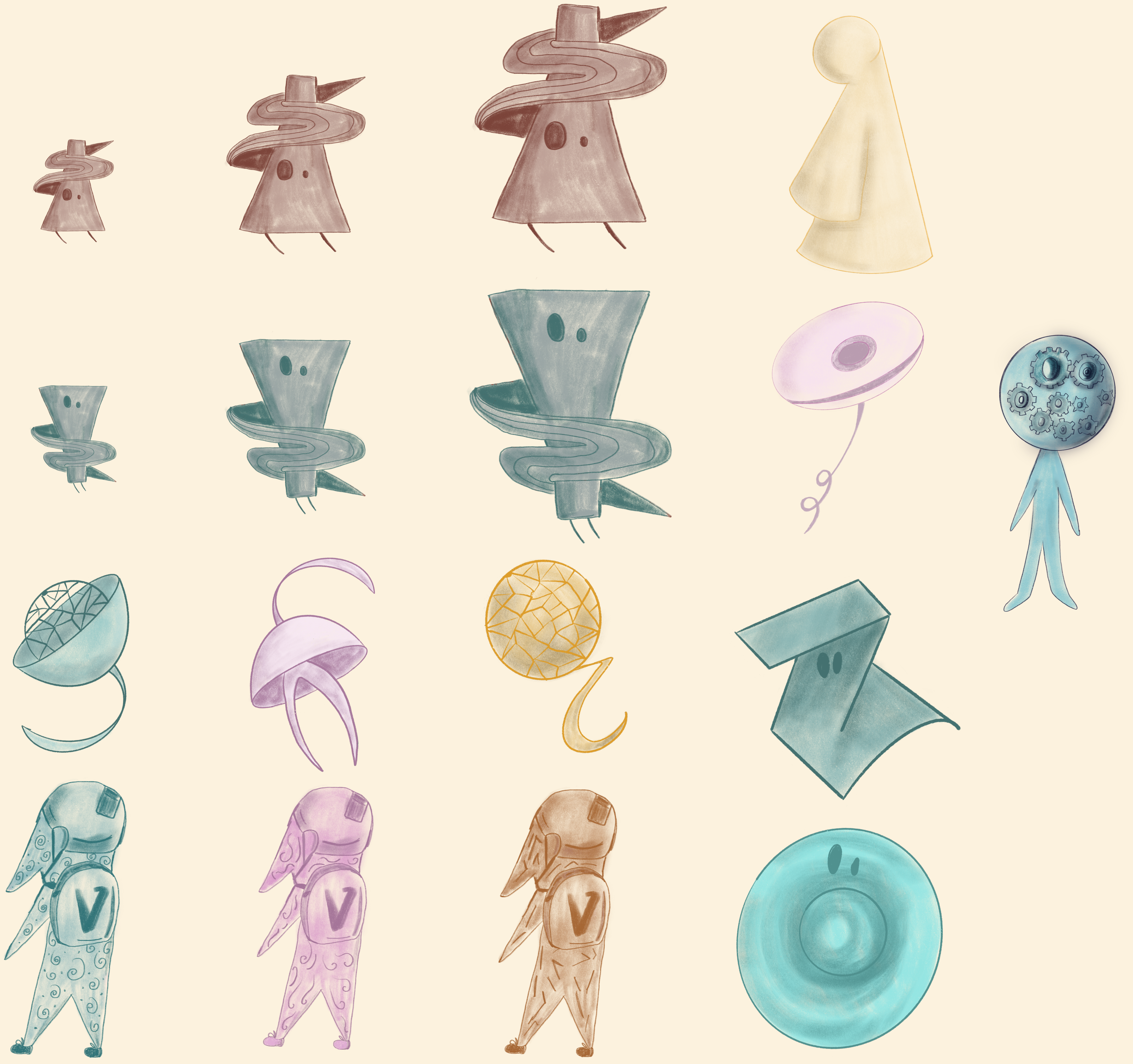
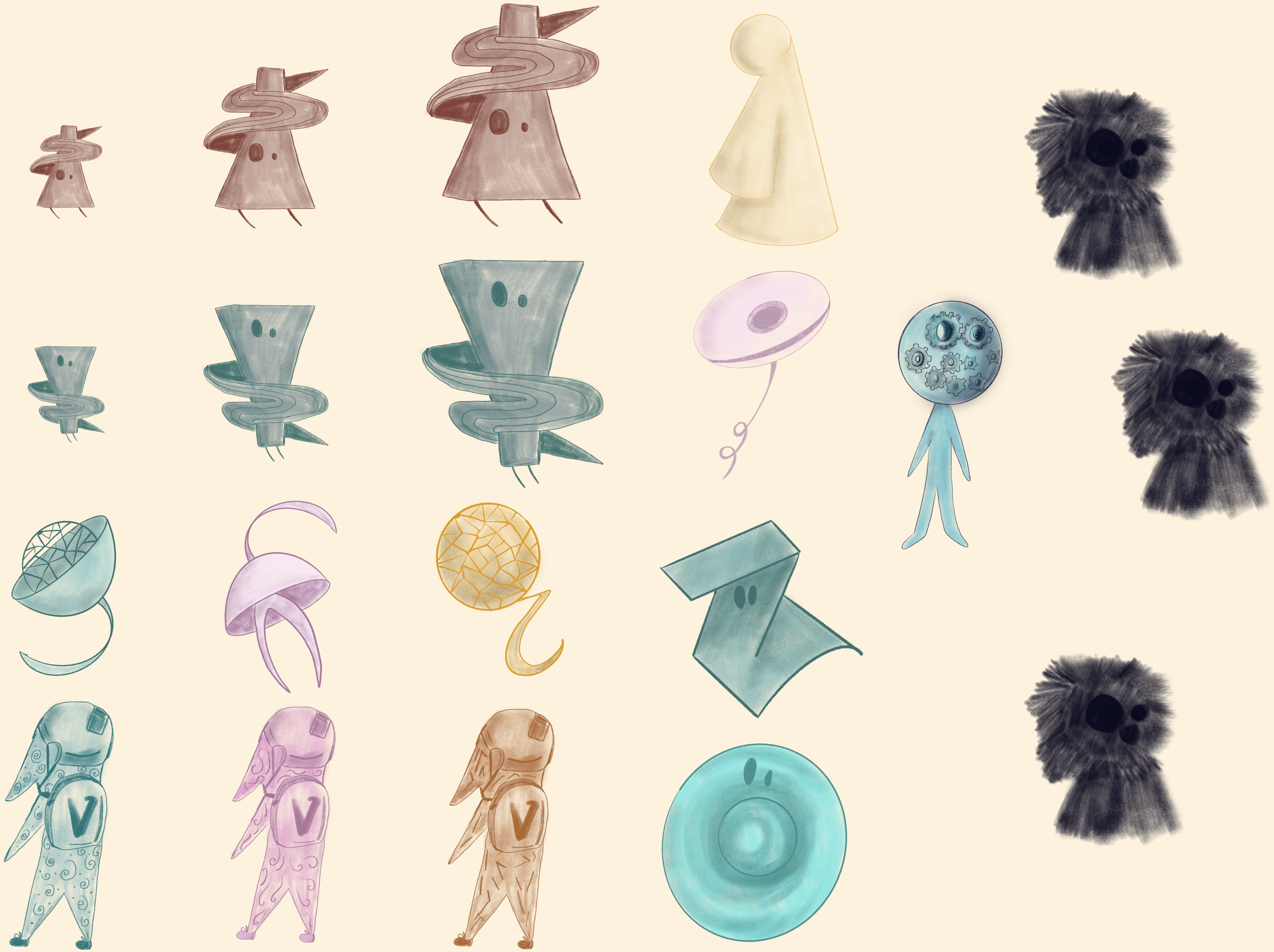
→ in this work!

THE STANDARD MODEL



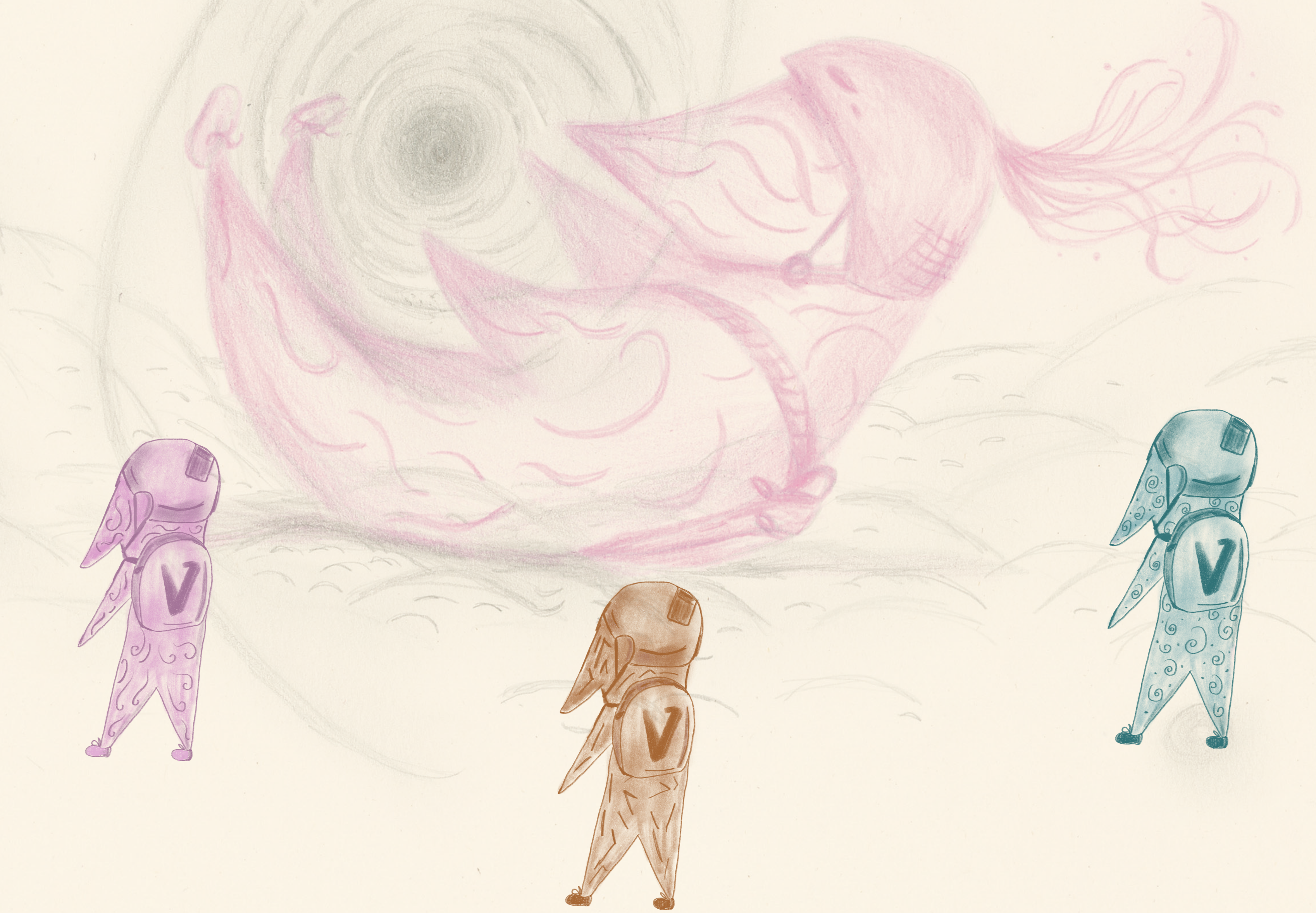
BEYOND THE STANDARD MODEL



ABOUT NEUTRINOS

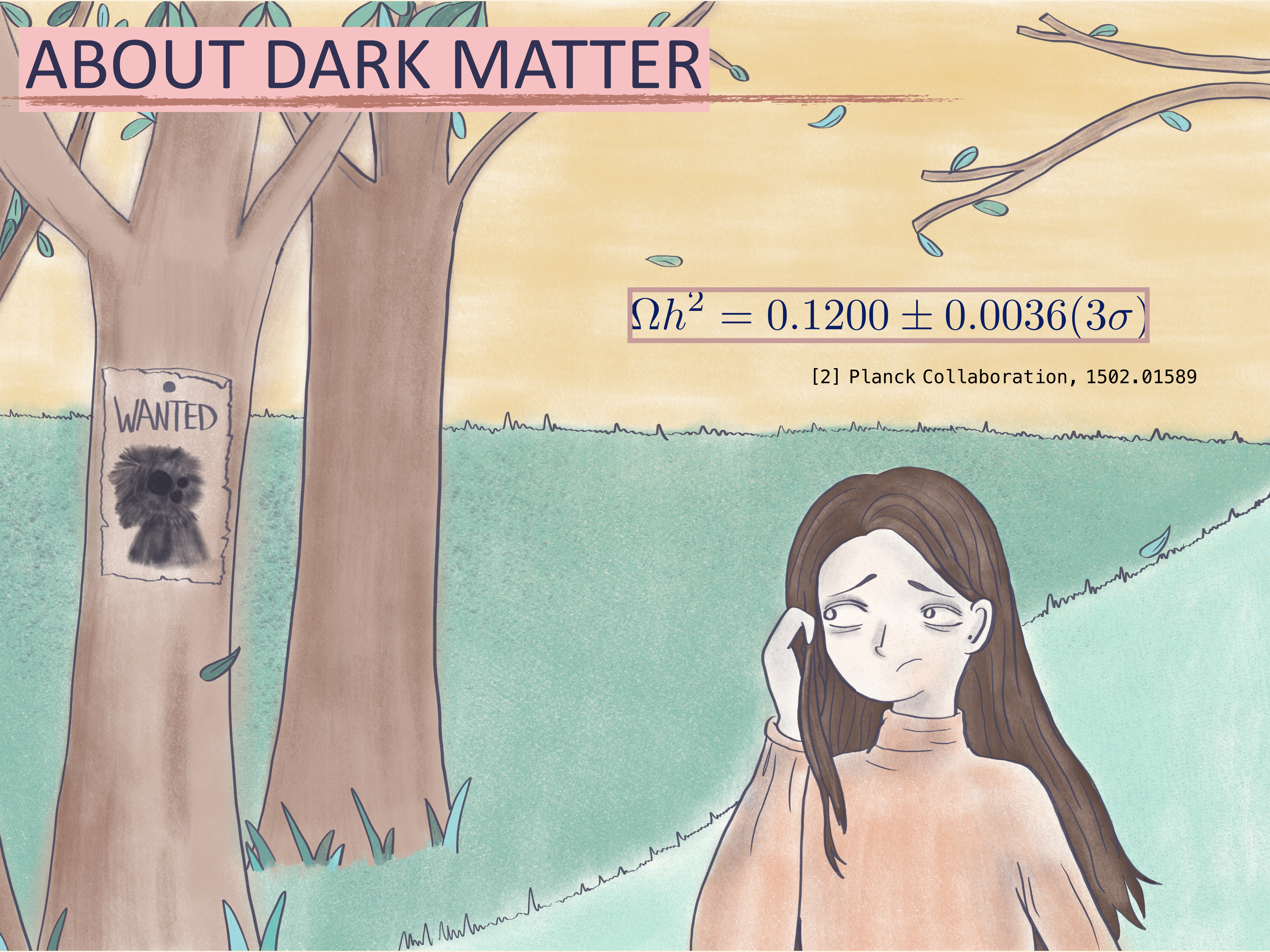
Neutrinos are particles with a mass different from zero [1]. The actual Standard Model cannot explain these results by itself

→ Many theoretical models try to explain it



[1] Fukuda, Y.; et al. Phys. Rev.Let. 81 (8): 1562–1567 (1998)

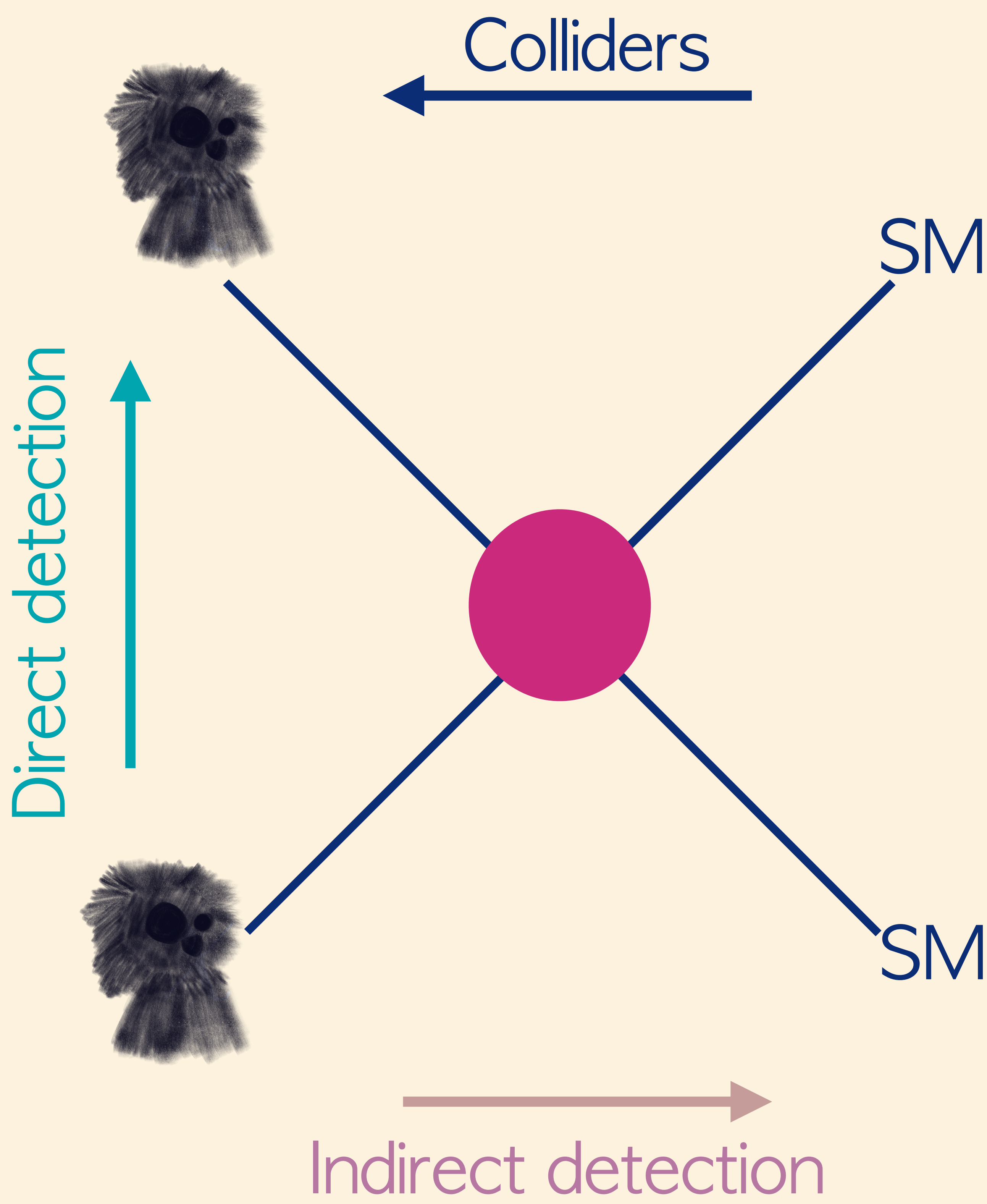
ABOUT DARK MATTER



$$\Omega h^2 = 0.1200 \pm 0.0036 (3\sigma)$$

[2] Planck Collaboration, 1502.01589

WIMP-like DM searches



DM halos. DD experiments aim at detecting DM through scattering off nuclei.
DD experiments mesure the nuclear recoil imparted by the scattering of a WIMP.

Observation of SM products of annihilation. Detection of the byproducts of DM WIMPs annihilation over the expected background at galactic or extra galactic scales

$$\chi + \chi \to q\bar{q}, W^+W^-, ... \to \bar{p}, \gamma, e^+, e, \nu...$$

WIMPs manifest at colliders as missing transverse momentum. Searches at colliders try to find mono-X signals.
New searches for LLP.

BORN FROM THE DARK

- To generate neutrino masses at tree level, a dim-5 operator can be introduced via the seesaw mechanism [1] [2] [3]. Neutrino masses can be generated at loop level.
- The idea of the Scotogenic Model was proposed by Ernest Ma [4]
  - His model introduced the possibility of giving mass to neutrinos at One-Loop
  - Also a WIMP-like Dark Matter (DM) candidate appears which can be either scalar or fermionic.

    → The stability of the DM particle is ensured by the same Z_2 symmetry that leads to the radiative origin of neutrino masses.

The Scotogenic Model has been generalized in different ways [5] [6]

[1] R. N. Mohapatra et al Phys. Rev. Lett. 44 (1980) 912.

[2] J. Schechter, José W. F. Valle (1980). Phys. Rev. 22 (9): 2227–2235

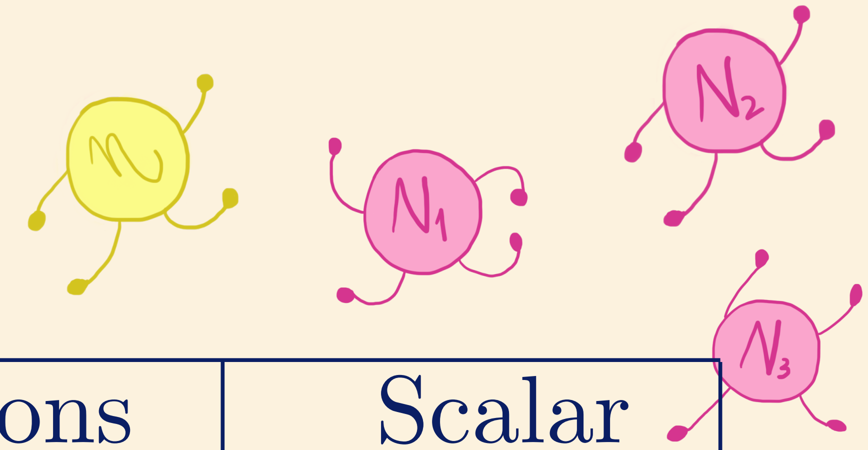
[3] B. Bajc and G. Senjanovic, JHEP 0708 (2007) 014

[4] E. Ma, Phys.Rev. D73, 077301 (2006), hep-ph/0601225.

[5] R. Foot et al., Z.Phys. C44 (1989) 441.

[6] M. Hirsch et al., JHEP 1310, 149 (2013), 1307.8134.

SIMPLE SCOTOGENIC MODEL



	Standard Model			Fermions	Scalar
	L	e	ϕ	N	η
$SU(2)_L$	2	1	2	1	2
Y	-1	-2	1	0	1
$\mathbb{Z}_2$	$+$	$+$	$+$	$-$	$-$
l	1	1	0	0	0

The new interaction terms presented in the Lagrangian are

$$\mathcal{L}_{int} \subset -Y_N^{\alpha\beta} \bar{N}_\alpha \tilde{\eta}^\dagger L_\beta - \frac{1}{2} \bar{N}^\alpha M_{\alpha\beta} N^{\beta\, c} + h.c.$$

Scalar sector

The scalar fields presented in the model can be written as follows

$$\eta = \begin{pmatrix} \eta^+ \\ (\eta_R + i\eta_I)/\sqrt{2} \end{pmatrix} \qquad \phi = \begin{pmatrix} \varphi^+ \\ (h_0 + v_\phi + i\psi)/\sqrt{2} \end{pmatrix}$$

The masses for the scalars are

$$\begin{cases} m_\phi^2 = 2\lambda_1 v^2, \\ m_{\eta^\pm}^2 = m_\eta^2 + \dfrac{\lambda_3}{2} v^2, \\ m_{\eta_R}^2 = m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5)\dfrac{v^2}{2}, \\ m_{\eta_I}^2 = m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5)\dfrac{v^2}{2}. \end{cases}$$

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The masses for the scalars are

DM candidate

$$m_\phi^2 = 2\lambda_1 v^2,$$

$$m_{\eta^\pm}^2 = m_\eta^2 + \frac{\lambda_3}{2} v^2,$$

$$m_{\eta_R}^2 = m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5)\,\frac{v^2}{2},$$

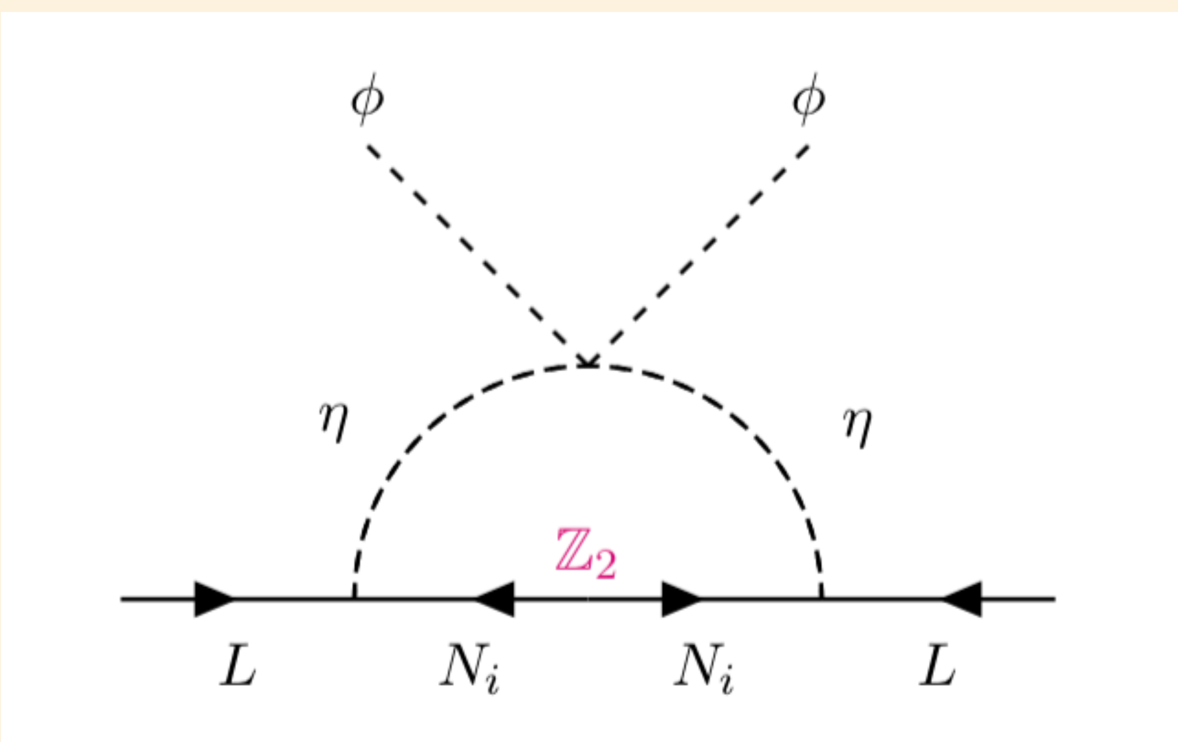
$$m_{\eta_I}^2 = m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5)\,\frac{v^2}{2}.$$

NEUTRINO MASS GENERATION IN THE SCOTOGENIC MODEL

$$m_{\nu,\alpha\beta} = \frac{Y^N_{\alpha k} Y^N_{\beta k}}{32\pi^2} m_{N_k} \left[\frac{m^2_{\eta_R}}{m^2_{\eta_R} - m^2_{N_k}} ln\left(\frac{m^2_{\eta_R}}{m^2_{N_k}}\right) - \frac{m^2_{\eta_I}}{m^2_{\eta_I} - m^2_{N_k}} ln\left(\frac{m^2_{\eta_I}}{m^2_{N_k}}\right) \right]$$

$$\Lambda_i = \frac{N_i}{32\pi^2} \left[\frac{m_R^2}{m_R^2 - N_i^2} \ln\left(\frac{m_R^2}{N_i^2}\right) - \frac{m_I^2}{m_I^2 - N_i^2} \ln\left(\frac{m_I^2}{N_i^2}\right) \right]$$

$$\Lambda = \begin{pmatrix} \Lambda_1 & 0 & 0 \\ 0 & \Lambda_2 & 0 \\ 0 & 0 & \Lambda_3 \end{pmatrix}.$$



$$Y^N = \sqrt{\Lambda^{-1}} \rho \sqrt{m_\nu} U_\nu^\dagger.$$

[J. A. CASAS AND A. IBARRA, NUCL. PHYS. B618, 171 (2001),HEP-PH/0103065]

Constraints

For our analysis the following constraints have been considered

- Lepton Flavor Violation

$$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$$ [Baldini+ (MEG), EPJC 2016]

$$BR(\mu \to eee) < 1. \times 10^{-12}$$ [Bellgardt+ (SINDRUM), NPB 1988]

$$CR(\mu^-, \mathrm{Au} \to e^-, \mathrm{Au}) < 7 \times 10^{-13}$$ [Bertl+ (SINDRUM II), EPJC 2006]

- Neutrino oscillation parameters [de Salas+ PLB, 2018]

- Electroweak precision tests $$-0.00022 \leq \delta\rho \leq 0.00098$$

- DM and cosmological observations

- Invisible Higgs decay of the Higgs boson

$$BR(h^0 \to \mathrm{inv}) \leq 19\%$$

$$BR(h^0 \to \gamma\gamma)/BR(h^0 \to \gamma\gamma)_{\mathrm{SM}} \gtrsim 0.84$$

$$BR(h^0 \to \gamma\gamma)/BR(h^0 \to \gamma\gamma)_{\mathrm{SM}} \lesssim 1.41$$

- Colliders

$$m_{\eta^\pm} \geq 100\,\mathrm{GeV}$$

$$122\ \mathrm{GeV} \leq m_{h^0} \leq 128\ \mathrm{GeV}$$

Tools

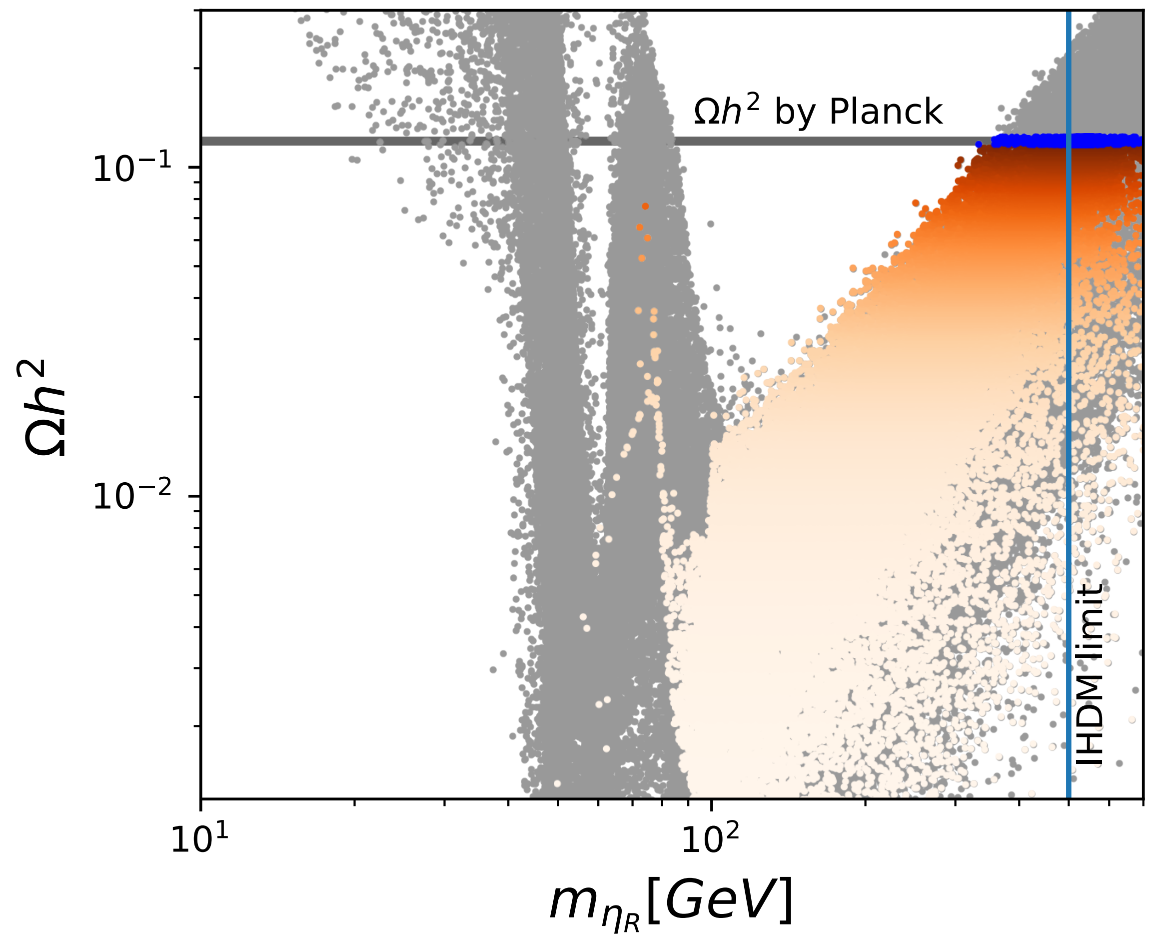
For the montecarlo simulation we develop our own python code.

For our analysis we use numerical tools.

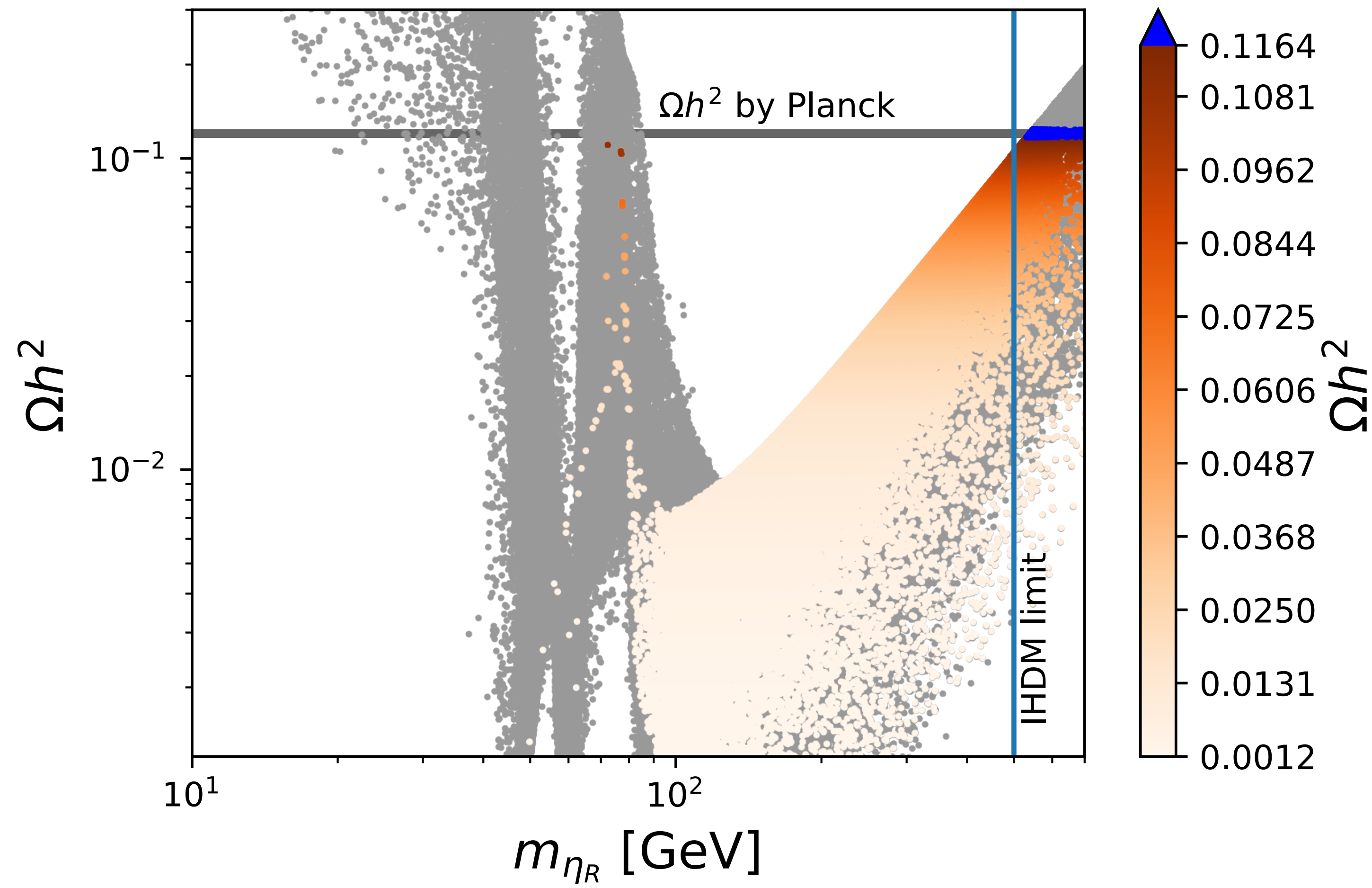
- SARAH: model implementation, computation off all the vertices, mass matrices, one loop correction for tadpole and self-energies.
- SPHENO: computation of the physical particle spectrum and low energy observables
- MicrOMEGAs: computation of the thermal component to the DM relic abundance and the DM-nucleon scattering cross section.
- MadGraph: computation of the cross section.

RELIC DENSITY

SCOTOGENIC MODEL



IHDM MODEL



Relic density as a function of the DM mass, for the scotogenic model and the IHDM. Grey points are results that are excluded when applying the constraints described

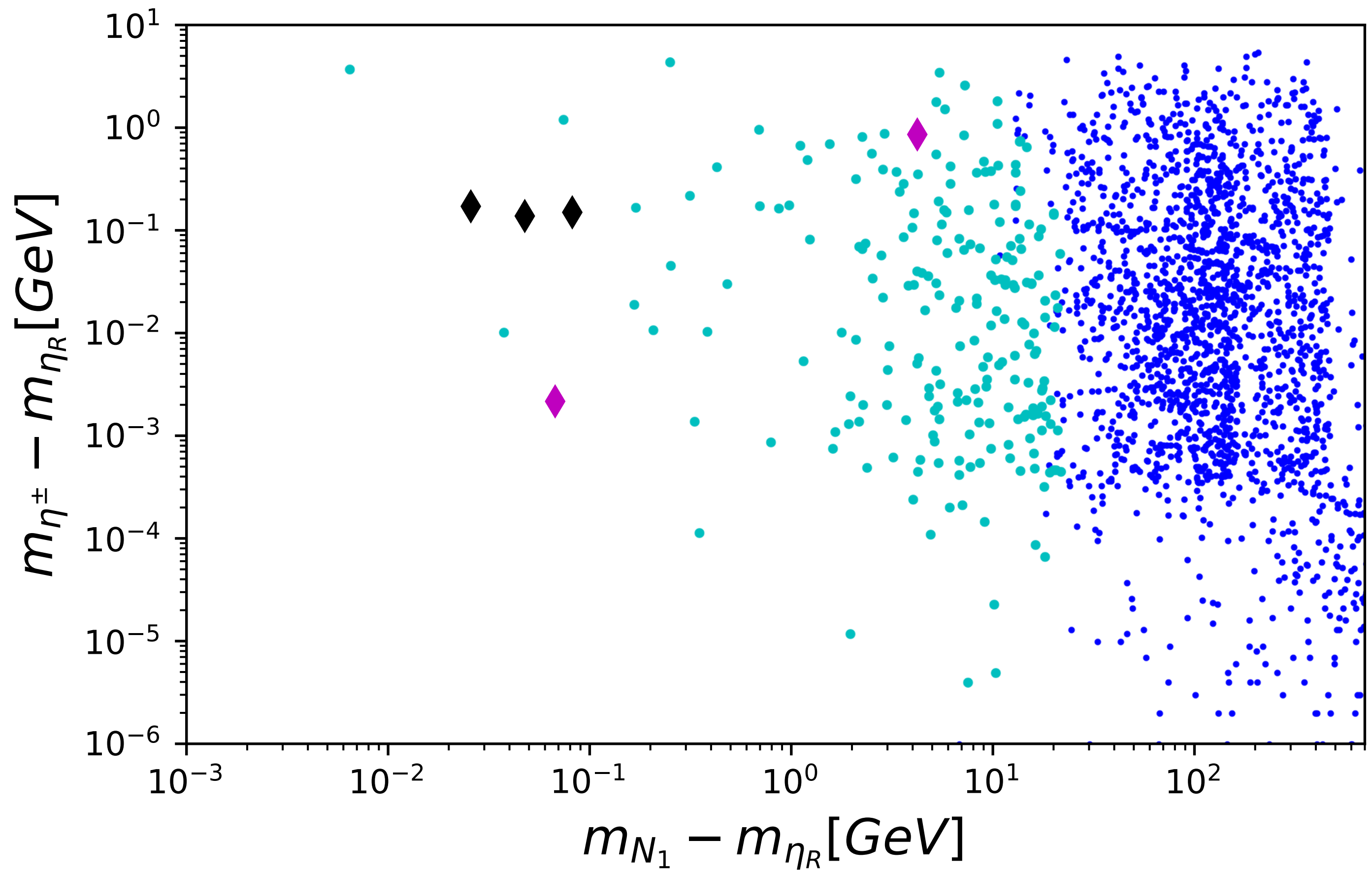
Parameter	Scanned range
λ_1	$[10^{-8}\ ,\ 1]$
λ_2	$[10^{-8}\ ,\ 1]$
λ_3	$\pm[10^{-8}\ ,\ 1]$
λ_4	$\pm[10^{-8}\ ,\ 1]$
λ_5	$\pm[10^{-8}\ ,\ 1]$
m_η [GeV]	$[10\ ,\ 1000]$
M_{N_1} [GeV]	$[50\ ,\ 5000]$
M_{N_2} [GeV]	$[5 \times 10^3\ ,\ 2 \times 10^6]$
M_{N_3} [GeV]	$[5 \times 10^3\ ,\ 3.5 \times 10^6]$

We explore a mass region for the dark matter candidate below 500 GeV. As opposed to the Inert Higgs Doublet model (IHDM) the scotogenic model has extra contributing annihilation channels involving new fermions, allowing to decrease the relic density value. This scenario was study first by M. Klasen et al. [JCAP 04, 044 (2013)]

$$\Omega_{\rm DM} = \left[\frac{4\pi^3 G g_*(m)}{45}\right]^{1/2} \frac{x_F T_0^3}{3 - \langle \sigma v \rangle \rho_{\rm cr}}$$

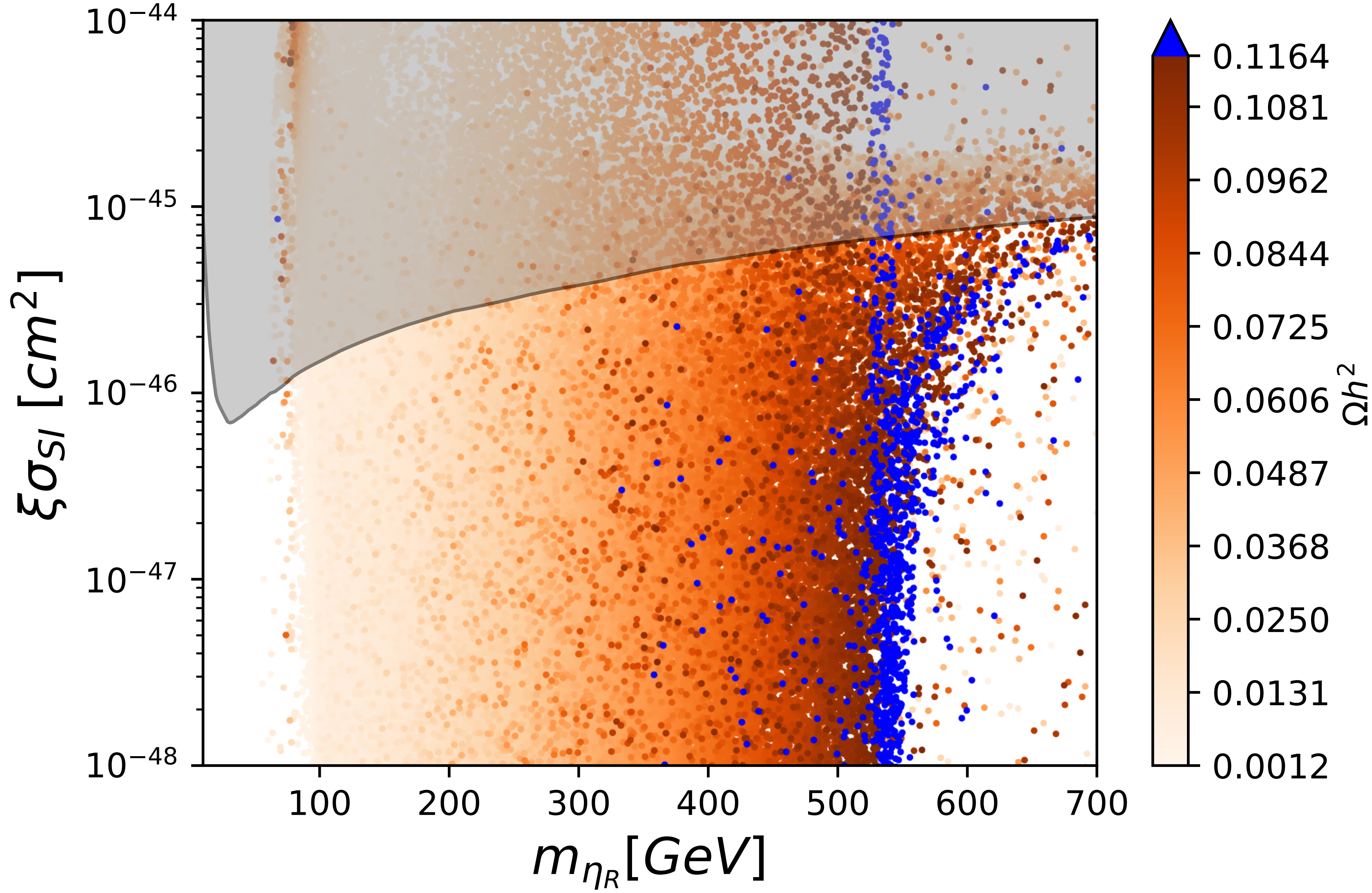
$$g_* = \sum_{bosons} g_i \frac{T_i^4}{T^4} + \frac{7}{8} \sum_{fermions} g_i \frac{T_i^4}{T^4} + g_{*,NR}$$

$$g_{*,\rm NR} \propto \sum_i g_i e^{-m_i/T_i} \frac{m_i}{T_i}$$



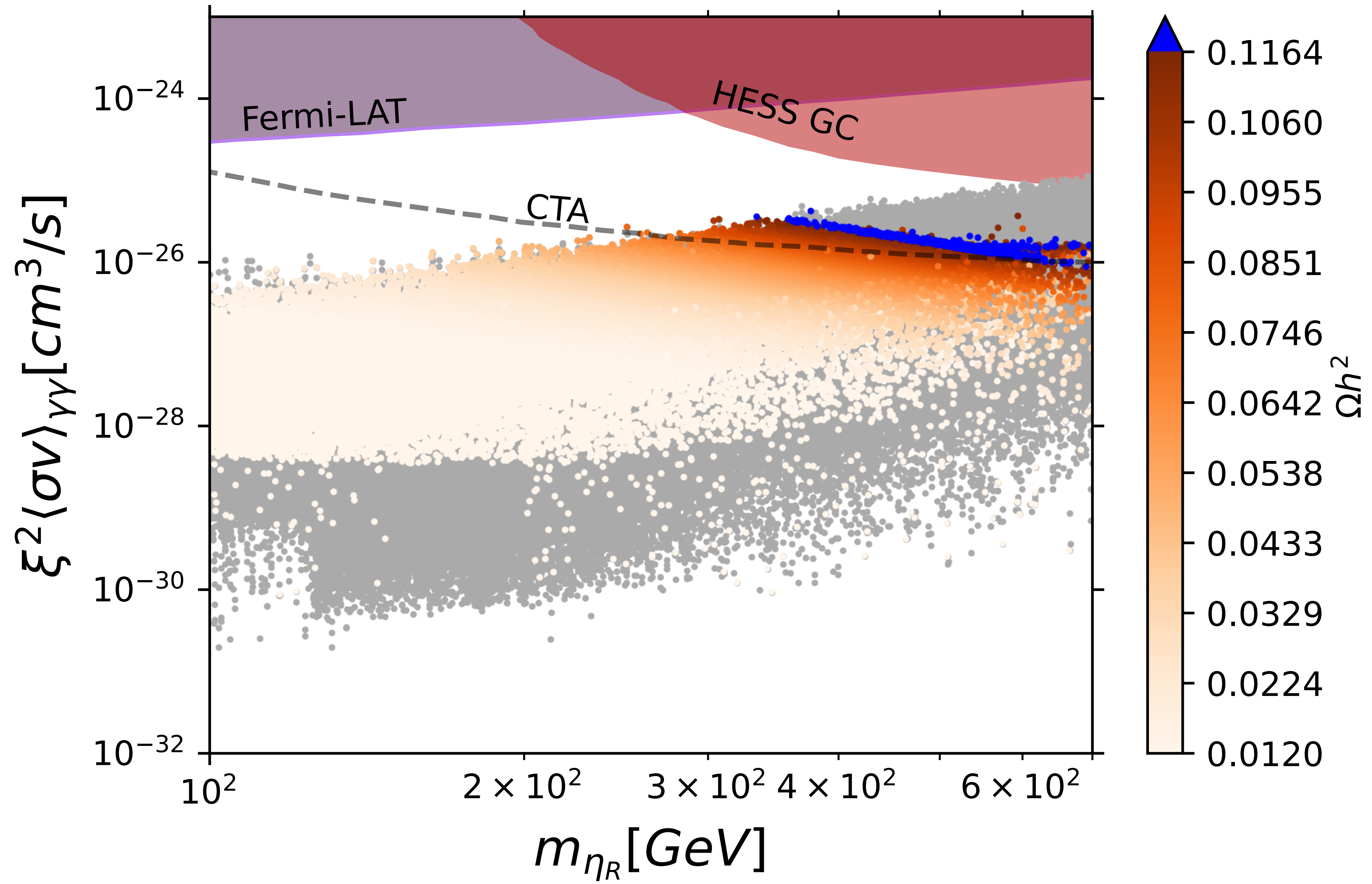
Blue points correspond to mass differences when fixing $m_{\eta R}$ > 500 GeV, while cyan ones correspond to $m_{\eta R}$ < 500 GeV. Diamonds correspond to the benchmarks B1 and B2 in magenta and B3, B4 and B5 in black

DIRECT DETECTION



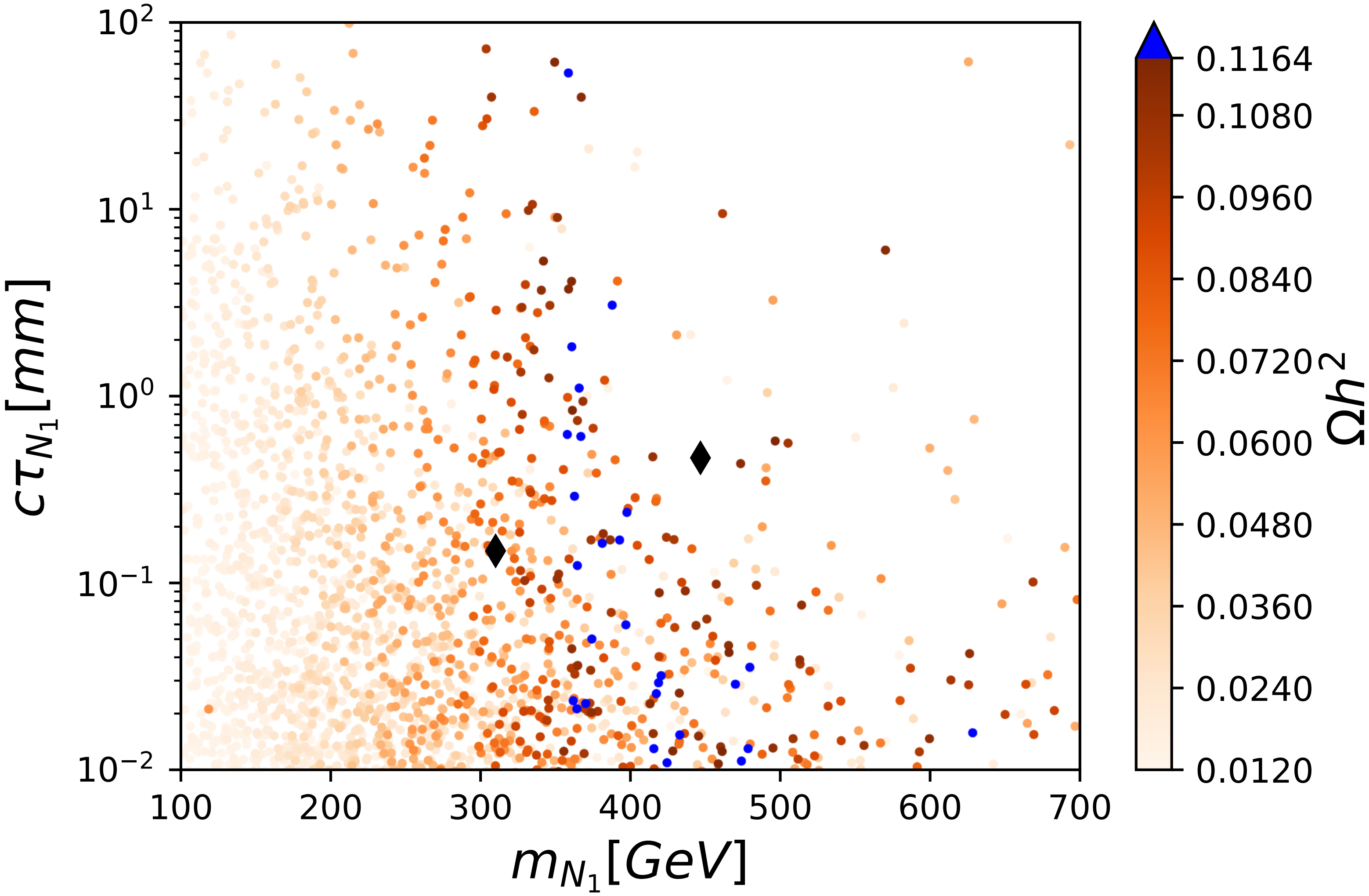
ηR-nucleon spin independent elastic scattering cross- section as a function of $m_{\eta R}$. The dark grey line denotes the upper bound from XENON1T

INDIRECT DETECTION



Dark matter annihilation cross section into γ rays, for annihilation to W^+W^-. Dark purple and dark red regions represent the upper limit by Fermi-LAT and H.E.S.S at 95% C.L, respectively. The black dashed curve shows a sensitivity projection for CTA

LONG-LIVED N_1



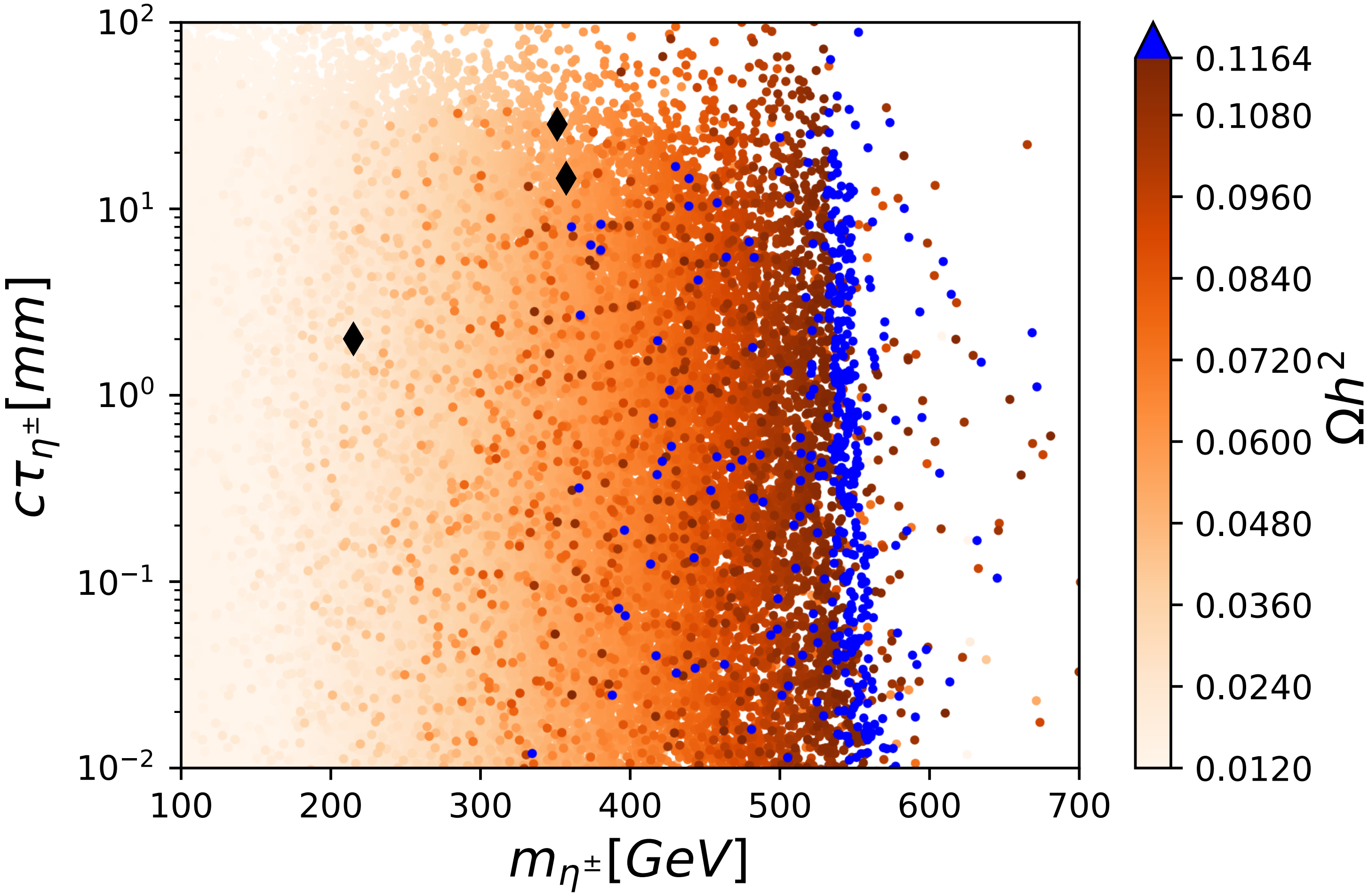
Proper decay distance of N1 as a function of mass, for different values of the relic density Ω_η h^2.

$$\Gamma_{N_k \to l_j^\pm \eta^\mp} = \frac{|Y_{jk}|^2 (m_{N_k}^2 + m_{l_j}^2 - m_{\eta^+}^2)}{32\pi m_{N_k}^3} \times \sqrt{(m_{N_k}^2 - m_{l_j}^2 - m_{\eta^+}^2)^2 - 4 m_{l_j}^2 m_{\eta^+}^2}$$

$$\Gamma_{N_k \to \nu_j \eta_\alpha} = \Sigma_j \frac{|Y_{jk}|^2}{32\pi m_{N_k}^3} (m_{N_k}^2 - m_{\eta_\alpha}^2)^2.$$

Parameter	B1	B2
λ_3	-2.809×10^{-4}	2.322×10^{-8}
λ_4	1.16×10^{-5}	-1.538×10^{-5}
λ_5	-2.511×10^{-2}	-2.878×10^{-5}
m_η^2 [GeV]	1.966×10^5	9.608×10^4
m_{η_R} [GeV]	442.535	309.961
$m_{\eta^\pm}$ [GeV]	443.394	309.964
m_{N_1} [GeV]	446.754	310.028
$c\tau_{N_1}$ [mm]	0.467	0.149
$\sigma(e^+e^- \to N_1 N_1)$ [fb]	9.89×10^{-20}	1.68×10^{-11}
Ωh^2	0.122	0.092

LONG-LIVED $\eta^{\pm}$



Proper decay distance of $\eta^{\pm}$ as a function of mass, for different values of the relic density $\Omega_{\eta R}\, h^2$.

$$\Gamma_{\eta^\pm \to N_1 l^\pm} = \frac{Y_{l1}^2 (m_{\eta^\pm}^2 - (m_{N_1} + m_l)^2)}{8 m_{\eta^\pm} \pi} \times \sqrt{1 - \left(\frac{m_{N_1} - m_l}{m_{\eta^\pm}}\right)^2} \sqrt{1 - \left(\frac{m_{N_1} + m_l}{m_{\eta^\pm}}\right)^2}$$

$$\Gamma_{\eta^\pm \to \eta_R \pi^\pm} = \frac{f_\pi^2 g^4}{m_W^4} \frac{(m_{\eta^\pm}^2 - m_{\eta_R}^2)^2}{512 m_{\eta^\pm} m_\pi} \times \sqrt{1 - \left(\frac{m_{\eta_R} - m_\pi}{m_{\eta^\pm}}\right)^2} \sqrt{1 - \left(\frac{m_{\eta_R} + m_\pi}{m_{\eta^\pm}}\right)^2}$$

Parameter	B3	B4	B5
λ_3	-1.686×10^{-6}	3.305×10^{-6}	4.447×10^{-5}
λ_4	2.112×10^{-3}	-1.46×10^{-3}	-3.293×10^{-6}
λ_5	-4.542×10^{-3}	-2.07×10^{-3}	-3.191×10^{-3}
m_η^2 [GeV]	4.627×10^4	1.276×10^5	1.234×10^5
m_{η_R} [GeV]	214.938	357.093	351.087
$m_{\eta^\pm}$ [GeV]	215.11	357.243	351.224
m_{N_1} [GeV]	214.964	357.175	351.134
$c\tau_{\eta^\mp}$ [mm]	2.006	14.587	28.412
$\sigma(pp \to \eta\eta j)$ [fb]	36.830	5.44	5.81
Ωh^2	0.04	0.121	0.119

CONCLUSIONS

- We find a regions in model parameter space where a correct DM relic abundance can be satisfied where the tiny mass splitting is connected to the possibility to find long lived particles.
- A long-lived charged scalar could give rise to disappearing charged track signatures from its decay to dark matter and a soft pion. This scenario could be tested within the reach of the LHC.

Thanks!

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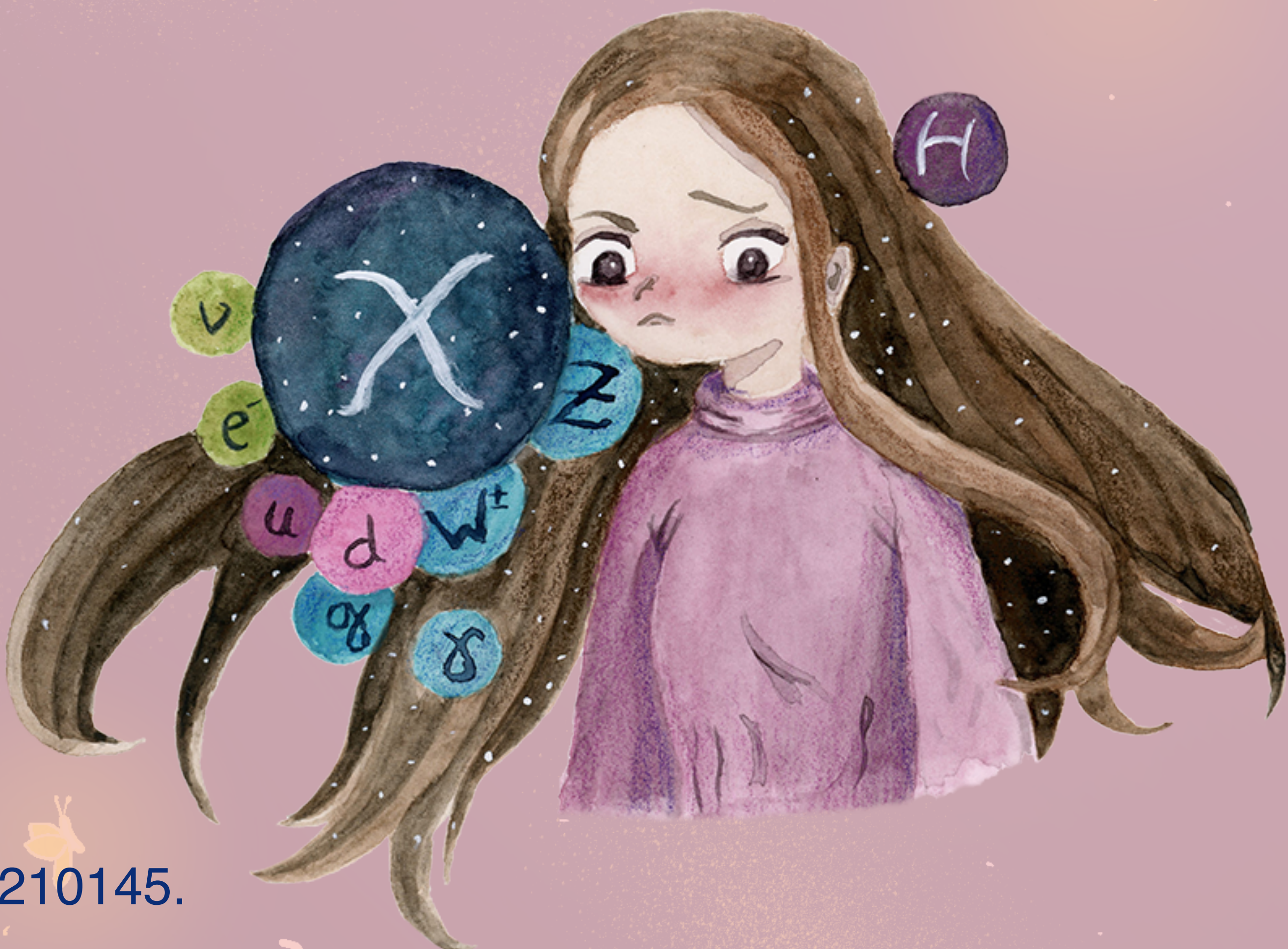

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