[J.Phys.G 49 (2022) 6, 065001]

Revisiting the scotogenic model with scalar dark matter

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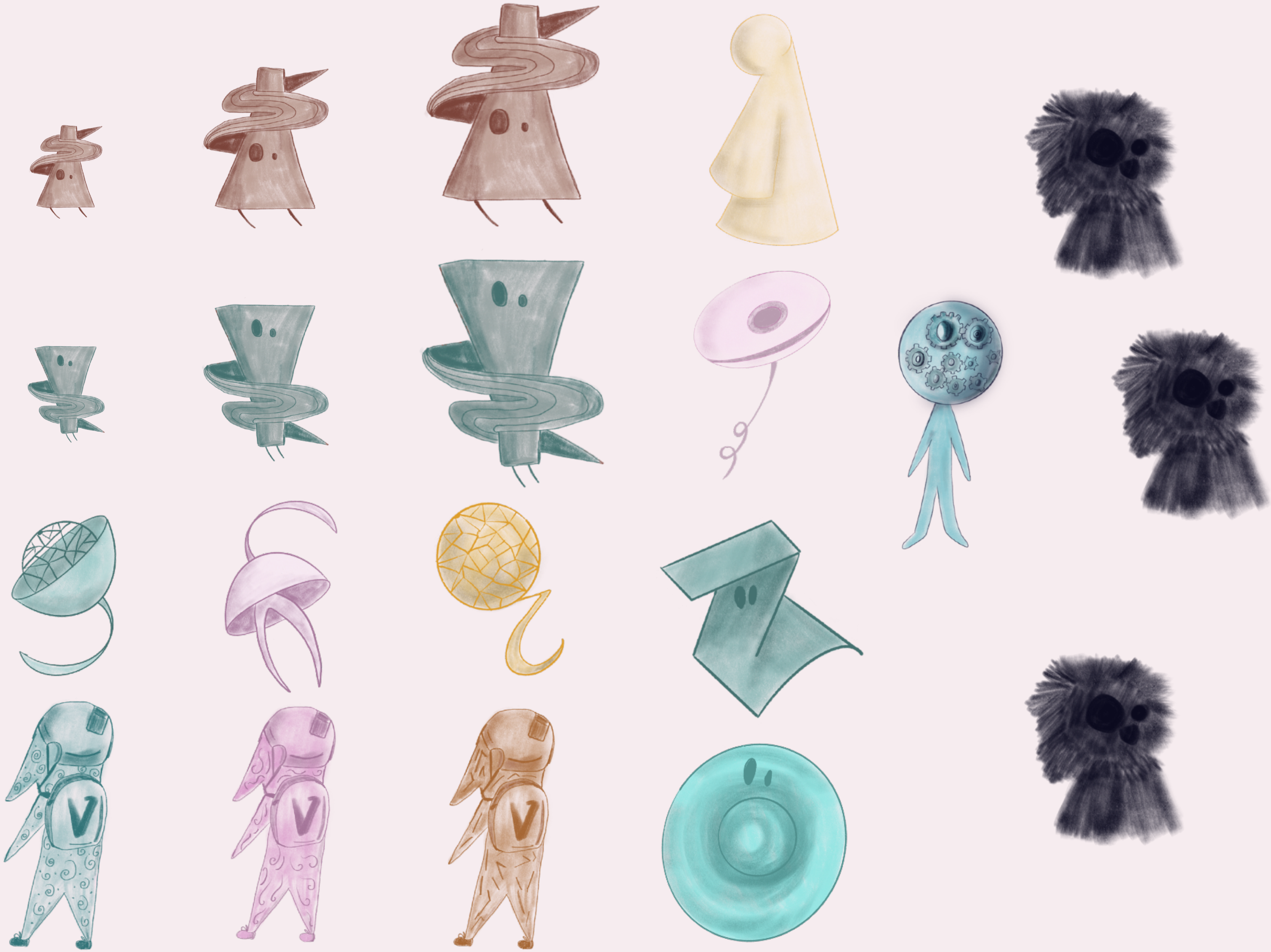
BEYOND THE STANDARD MODEL



BORN FROM THE DARK

- The idea of the Scotogenic Model was proposed by Ernest Ma [1] In 2006. It is a simple model, similar to the Inert Higgs doublet model, that can solve some of the open questions in physics.

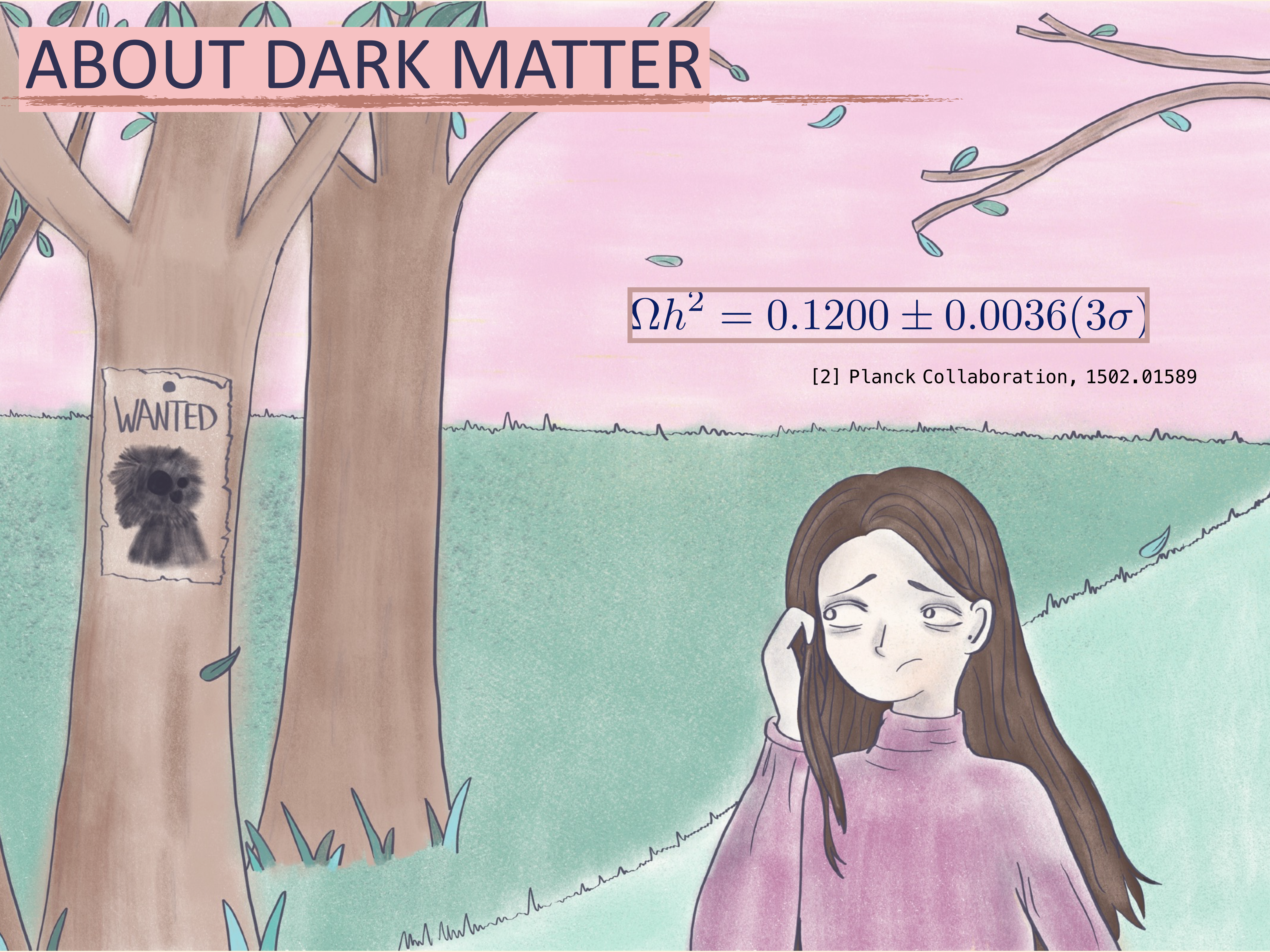
- The Scotogenic model introduce new fields:
  - An inert scalar
  - Three new fermions

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

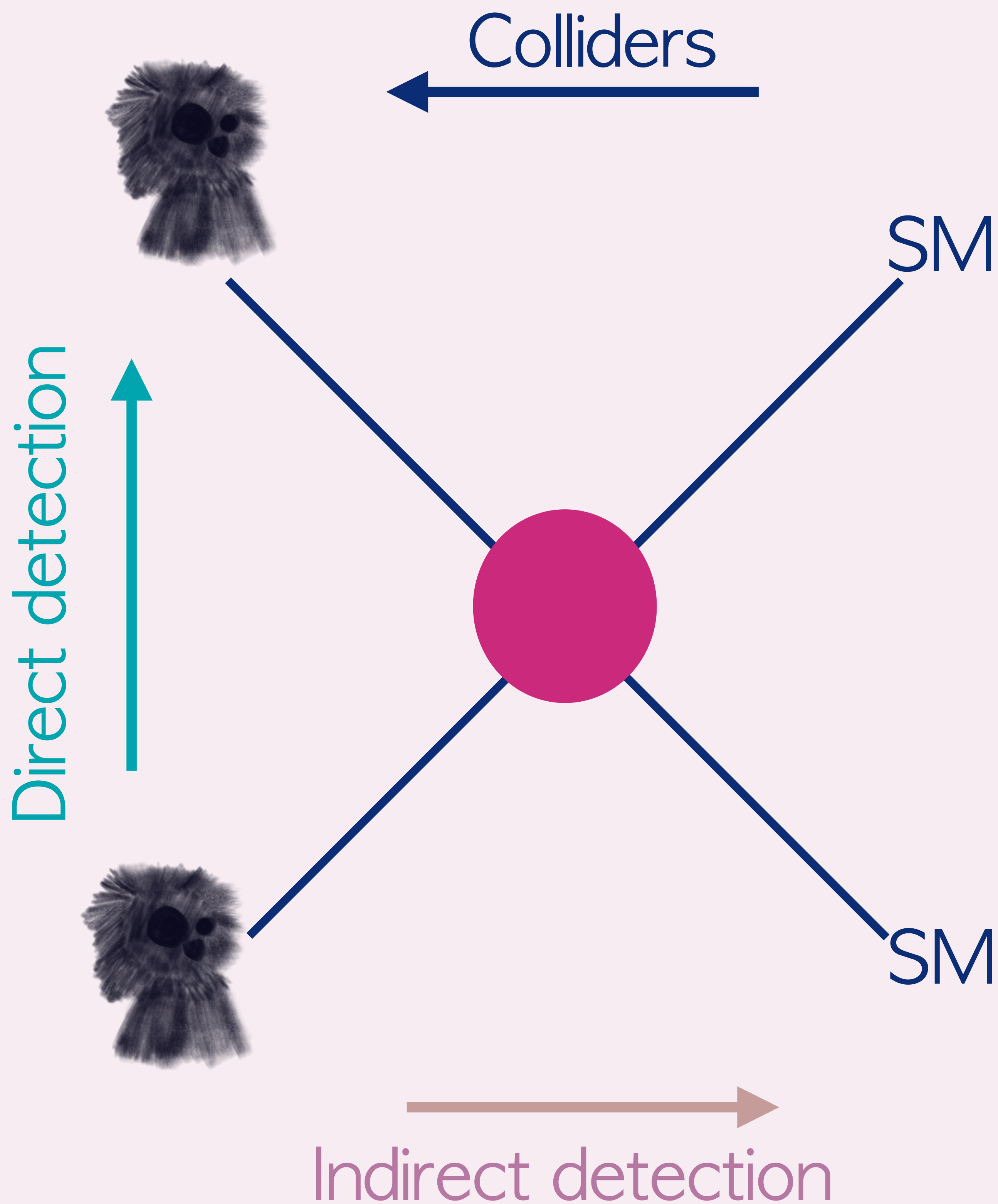
ABOUT DARK MATTER

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

[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

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

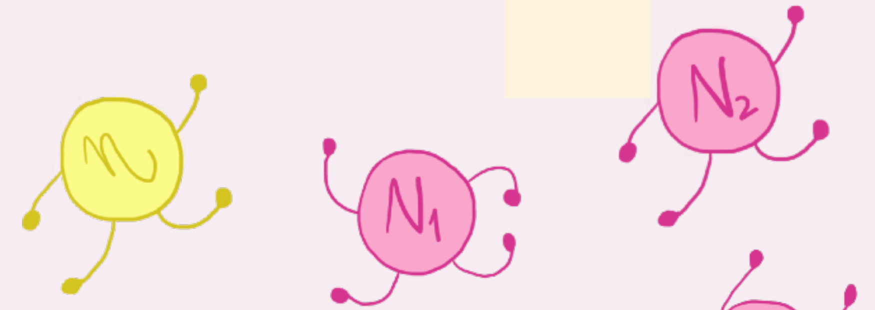
WIMPs manifest at colliders as missing transverse momentum. Searches at colliders try to find mono-X signals.
New searches for LLP.

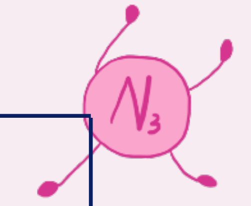
NEUTRINOS

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

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

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

Fermionic Dark Matter

[JHEP 11, 103 (2018)]

[JHEP 01, 100 (2017)]

[JHEP 09, 136 (2020)]

DM candidate

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

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

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

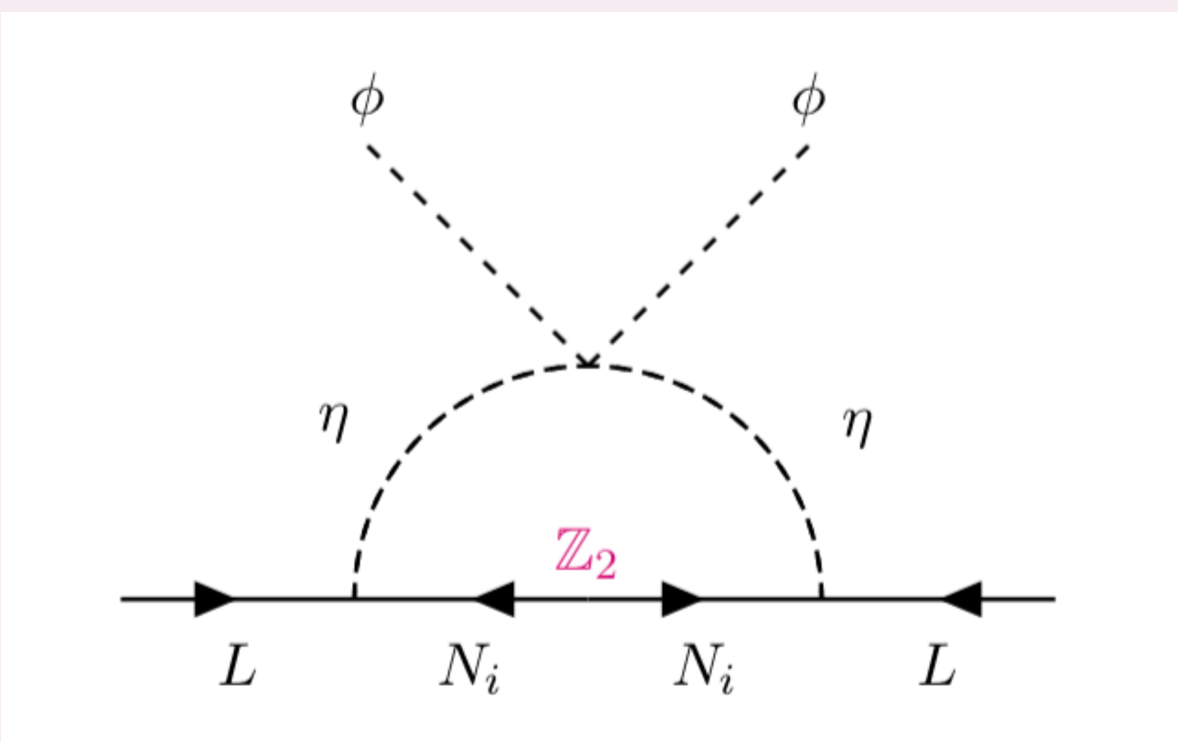
$$m_{\eta_I}^2 = m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5)\,\frac{v^2}{2}.$$

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

[J.Phys.G 49 (2022) 6, 065001]

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

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

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

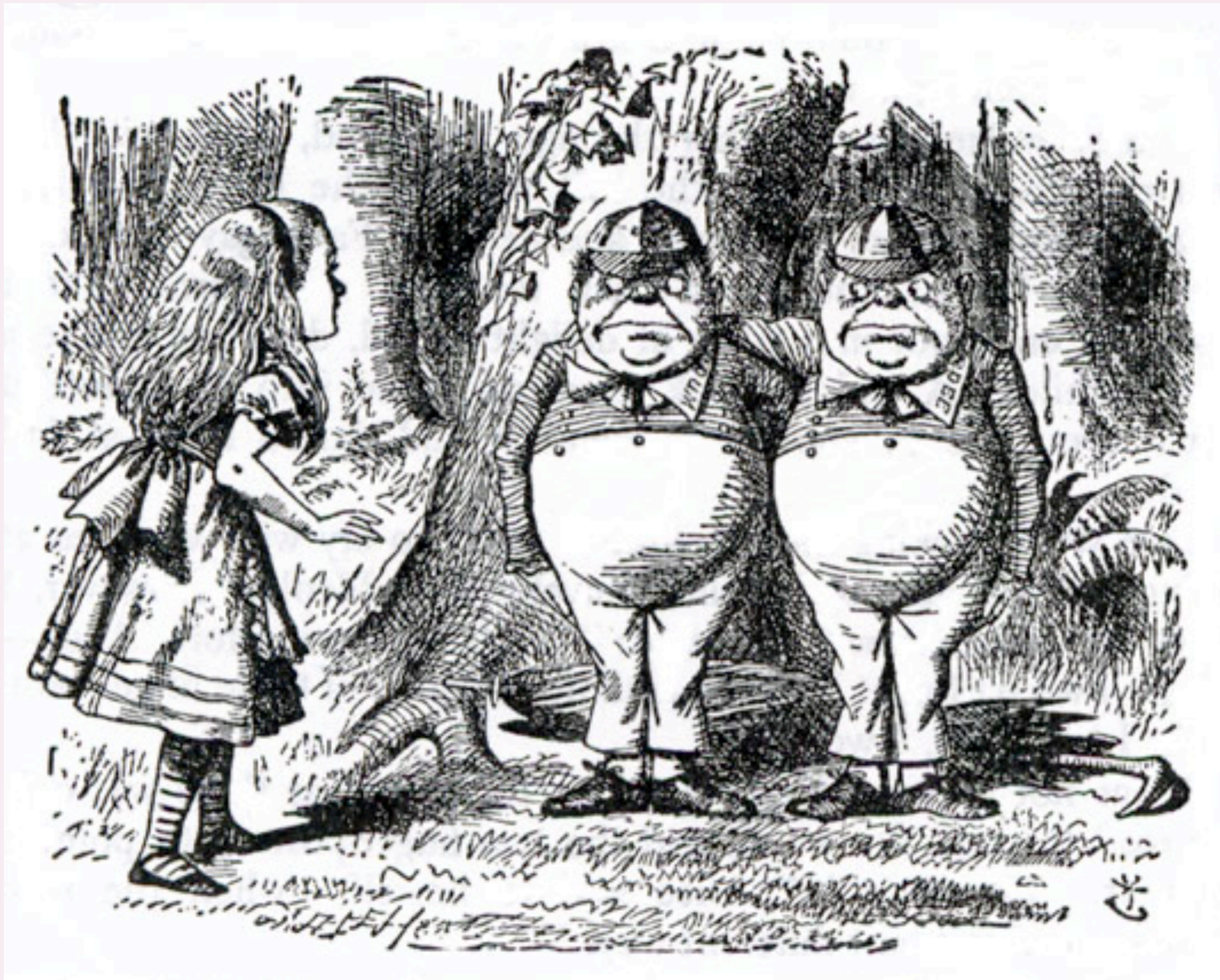
$$BR(h^0 \to \gamma\gamma)/BR(h^0 \to \gamma\gamma)_{\mathrm{SM}} \lesssim 1.41$$

- Colliders

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

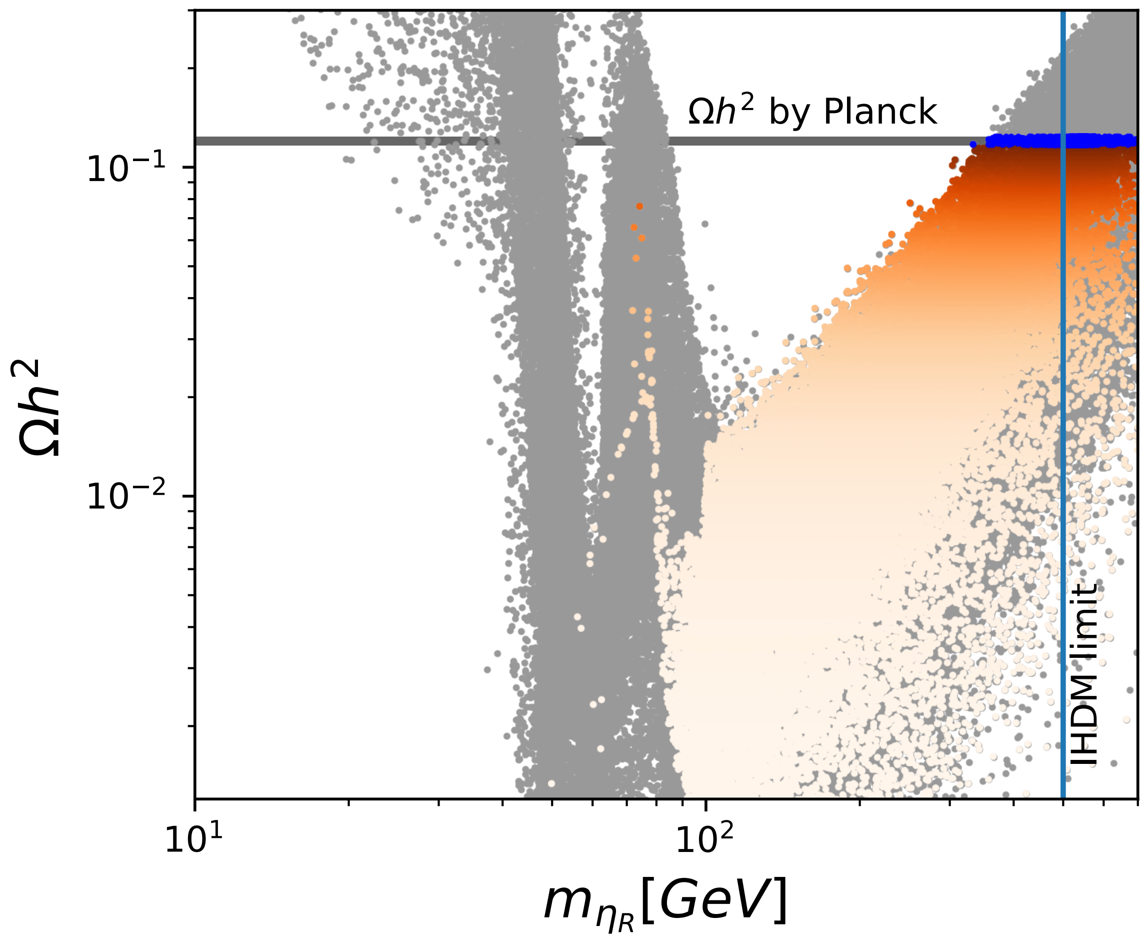
$$122\ \mathrm{GeV} \leq m_{h^0} \leq 128\ \mathrm{GeV}$$

IHDM VS SCOTOGENIC

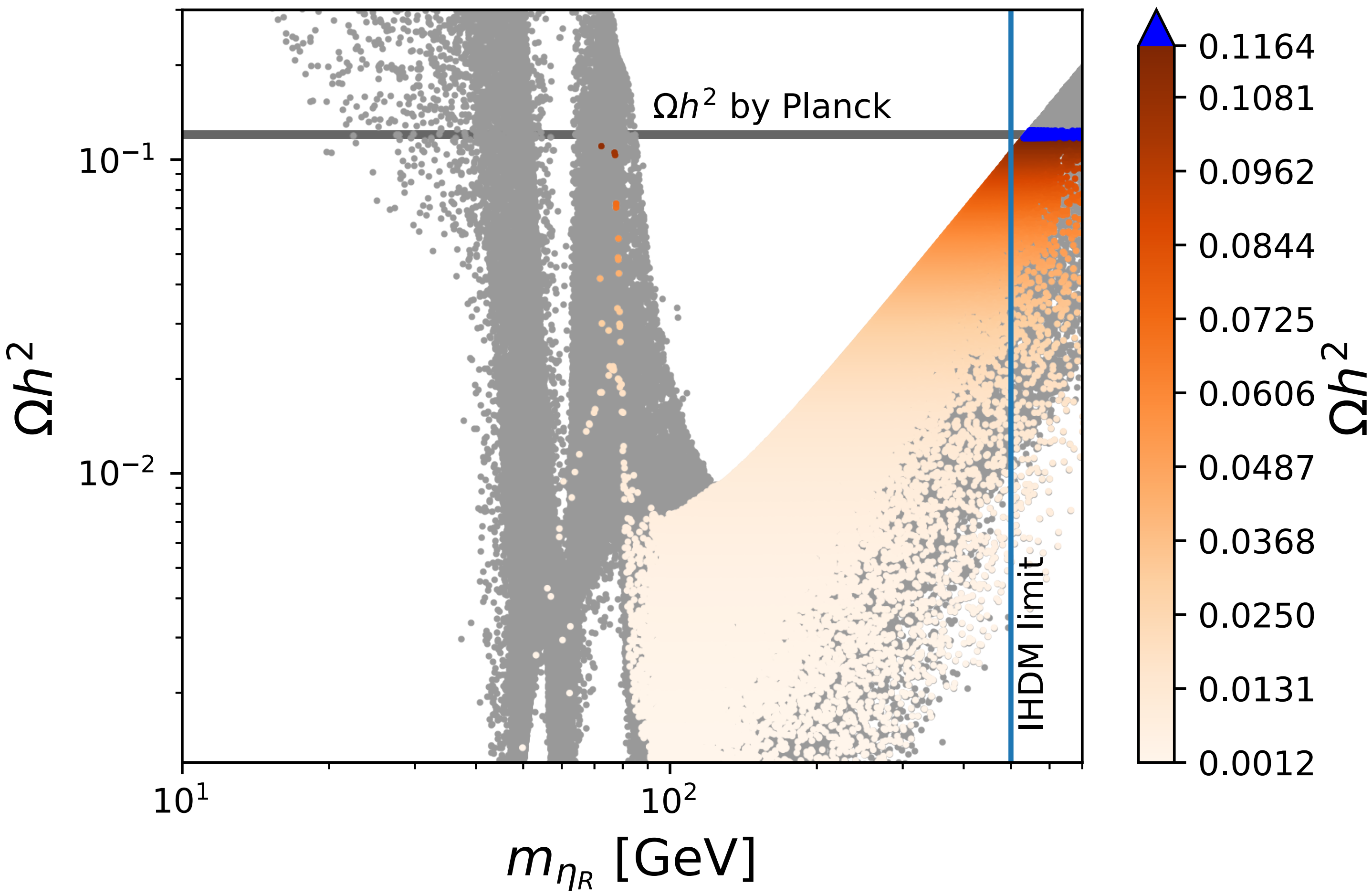


RELIC DENSITY

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

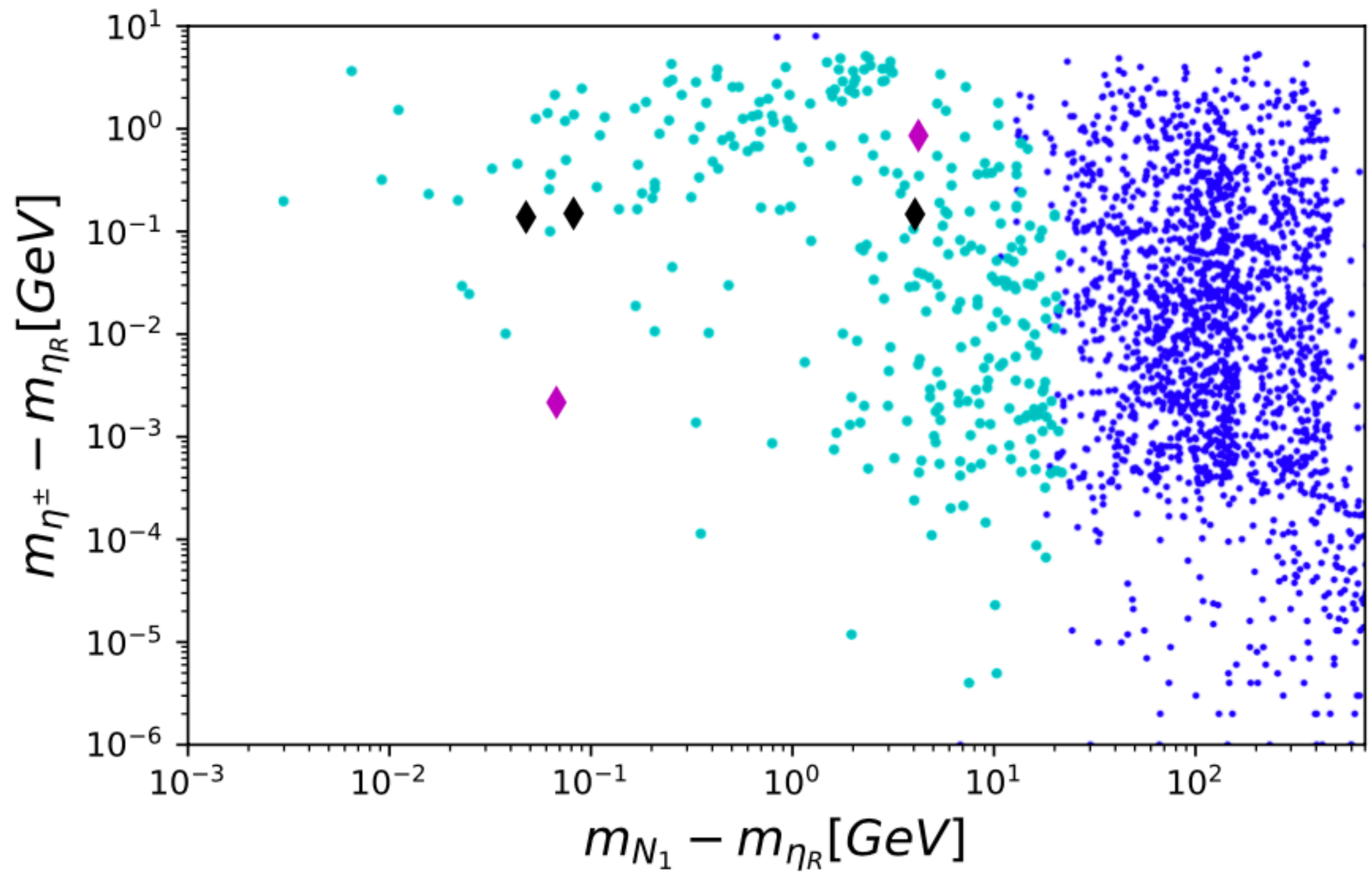
Parameter	Scanned range
λ_1	$[10^{-8}\ ,\ 1]$
λ_2	$[10^{-8}\ ,\ 1]$
λ_3	$\pm[10^{-8}\ ,\ 1]$
λ_4	$\pm[10^{-8}\ ,\ 1]$
λ_5	$\pm[10^{-8}\ ,\ 1]$
m_η [GeV]	$[10\ ,\ 1000]$
M_{N_1} [GeV]	$[50\ ,\ 5000]$
M_{N_2} [GeV]	$[5\times10^3\ ,\ 2\times10^6]$
M_{N_3} [GeV]	$[5\times10^3\ ,\ 3.5\times10^6]$

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

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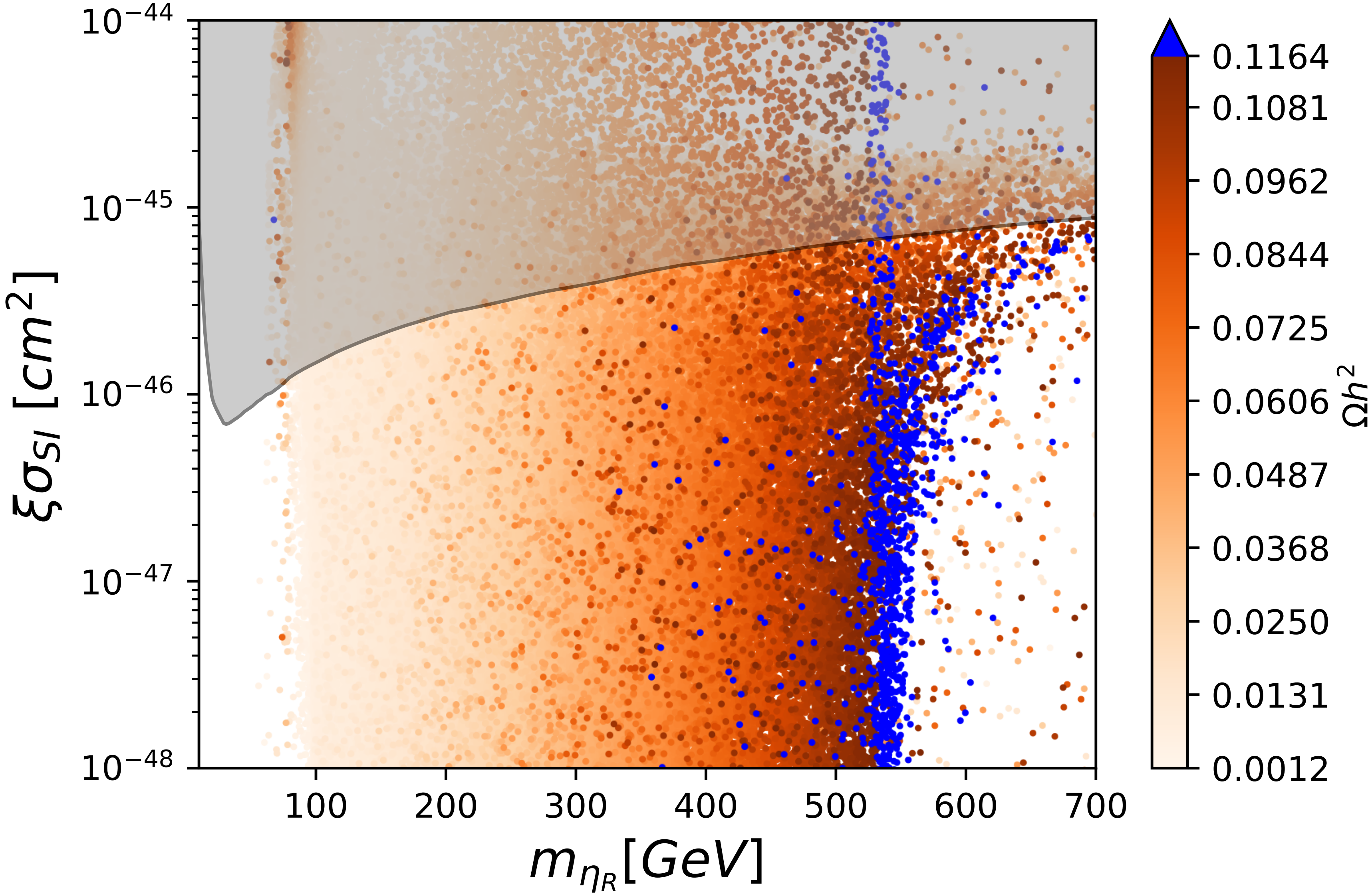
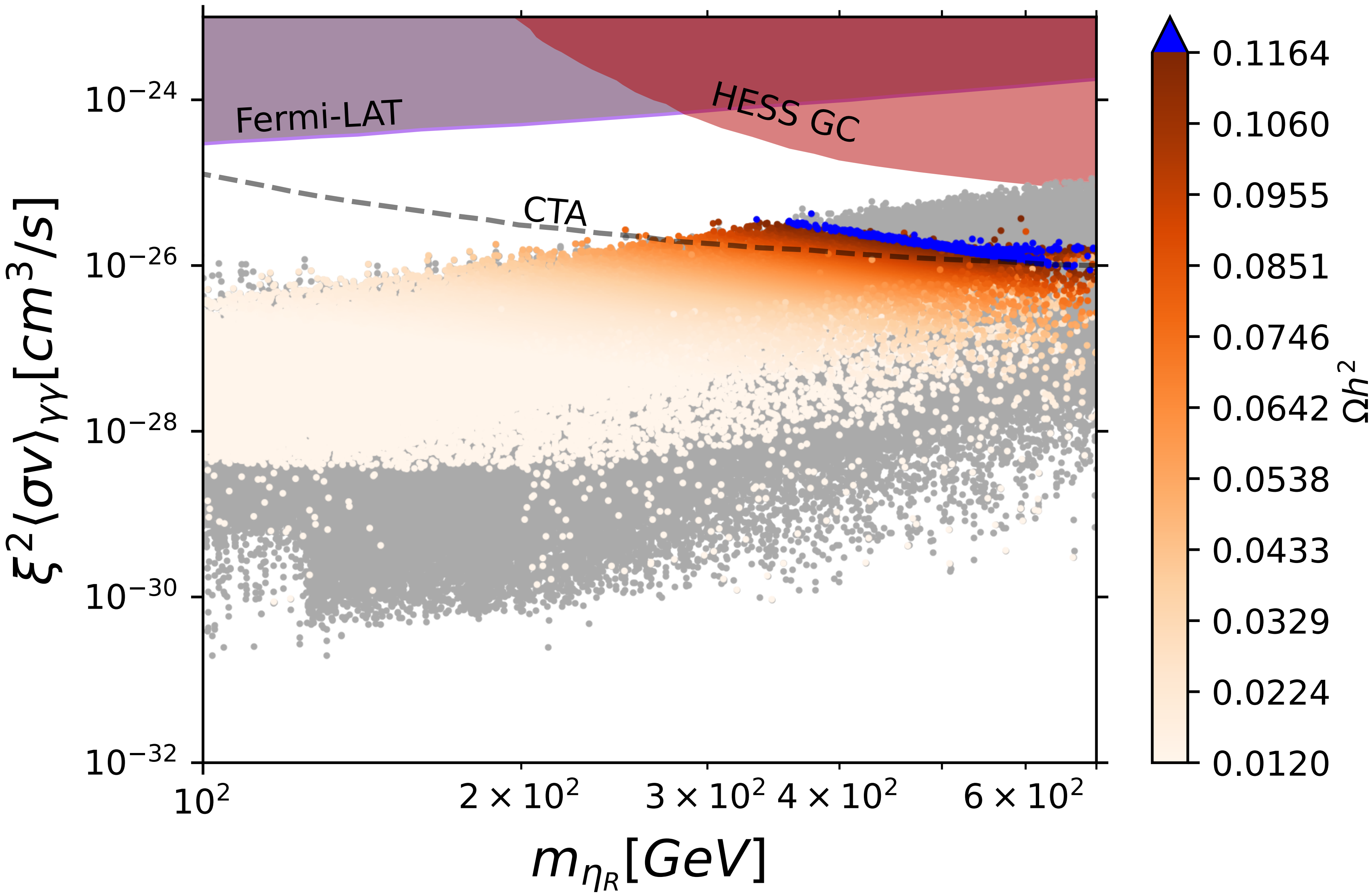


ηR-nucleon spin independent elastic scattering cross- section as a function of mηR . The dark grey line denotes the upper bound from XENON1T

INDIRECT DETECTION

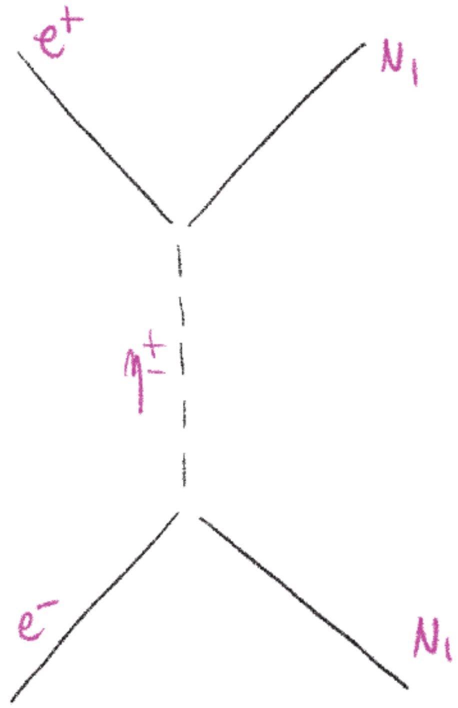


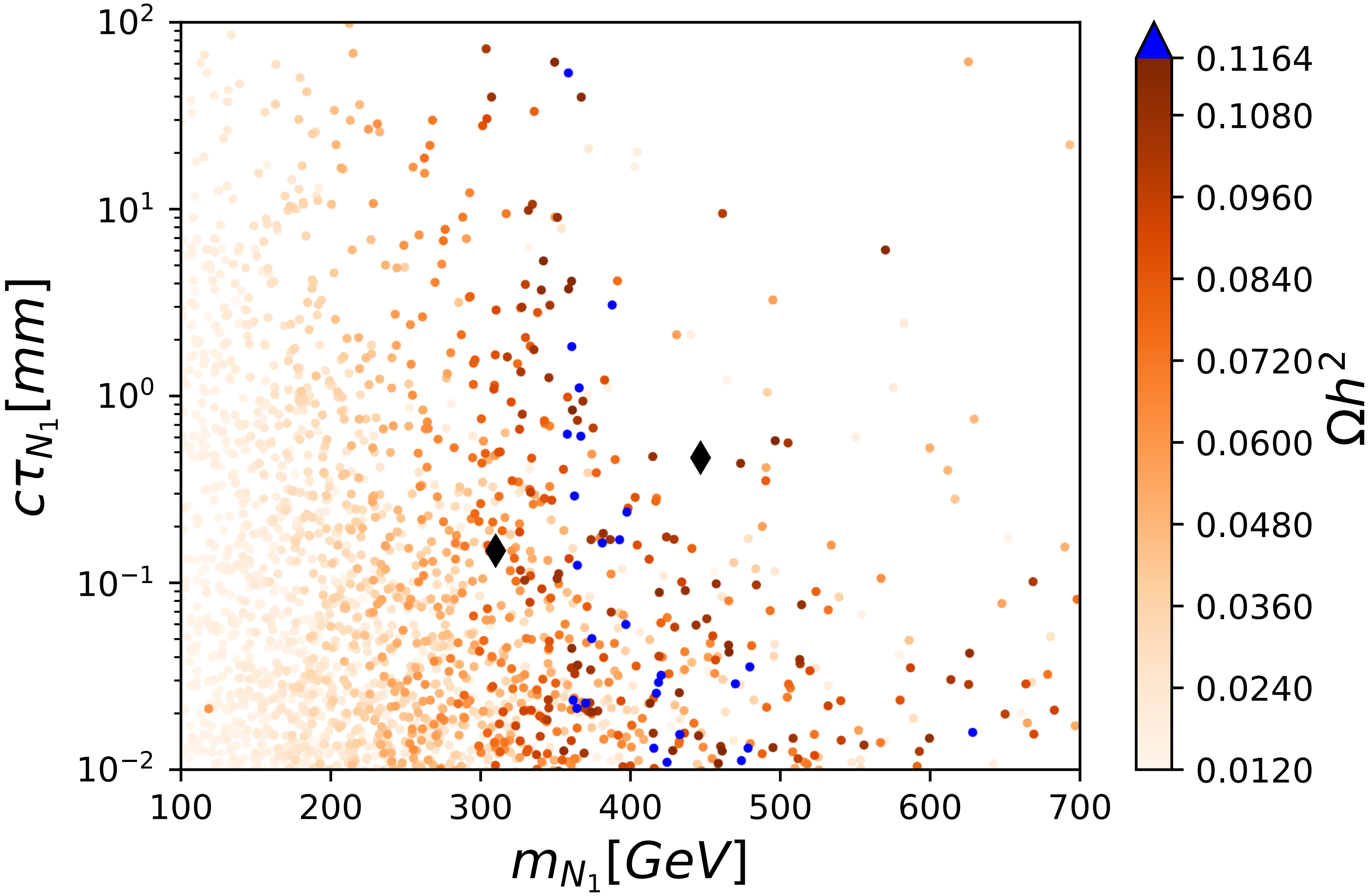
Dark matter annihilation cross section into γ rays, for annihilation to W^+W^-. Dark purple and dark red regions represent the upper limit by Fermi-LAT and H.E.S.S at 95% C.L, respectively. The black dashed curve shows a sensitivity projection for CTA

LONG-LIVED SEARCHES

[JHEP 01, 100 (2017)]

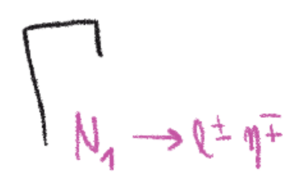
LONG-LIVED N_1





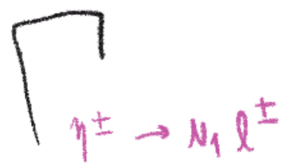
Proper decay distance of N1 as a function of mass, for different values of the relic density $\Omega\eta\ h^2$.

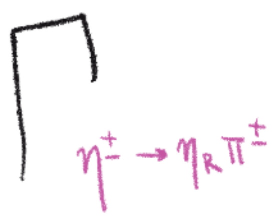
Parameter	B1	B2
λ_3	-2.809×10^{-4}	2.322×10^{-8}
λ_4	1.16×10^{-5}	-1.538×10^{-5}
λ_5	-2.511×10^{-2}	-2.878×10^{-5}
m_η^2 [GeV]	1.966×10^5	9.608×10^4
m_{η_R} [GeV]	442.535	309.961
$m_{\eta^\pm}$ [GeV]	443.394	309.964
m_{N_1} [GeV]	446.754	310.028
$c\tau_{N_1}$ [mm]	0.467	0.149
$\sigma(e^+e^- \to N_1 N_1)$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

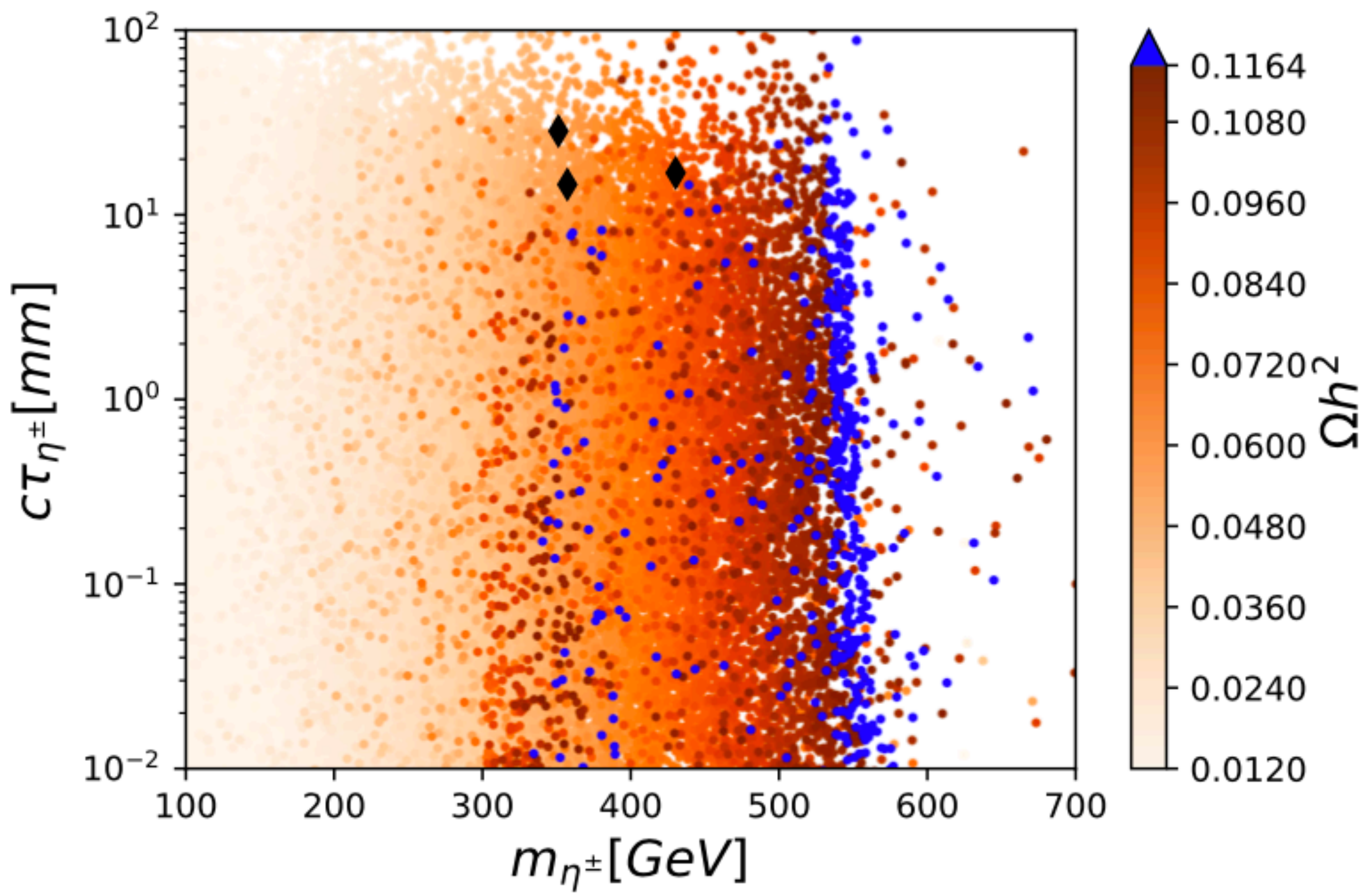


Displaced vertex signal

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







Disappearing charged track strategy [JHEP 01, 198 (2021)]

Parameter	B3	B4	B5
λ_3	-2.392×10^{-5}	3.305×10^{-6}	4.447×10^{-5}
λ_4	-6.923×10^{-7}	-1.46×10^{-3}	-3.293×10^{-6}
λ_5	-4.177×10^{-3}	-2.07×10^{-3}	-3.191×10^{-3}
m_η^2 [GeV]	1.851×10^5	1.276×10^5	1.234×10^5
m_{η_R} [GeV]	430.141	357.093	351.087
m_{η_I} [GeV]	430.435	357.269	351.362
$m_{\eta^{\pm}}$ [GeV]	430.288	357.243	351.224
m_{N_1} [GeV]	434.197	357.175	351.134
$c\tau_{\eta^{\mp}}$ [mm]	16.859	14.587	28.412
$\sigma(pp \to \eta\eta j)$ [fb]	2.525	5.44	5.81
$N = \sigma \times BR \times \mathcal{L} \times \epsilon$	19.392	33.474	77.811
Ωh^2	0.121	0.121	0.119

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

Disappearing charge track

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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