The ScotoSinglet Model

Based on: *AB, J. H-García, N. Leerdam, M. White & A. G. Williams*
[arXiv:2010.05937]

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When the M meets the P

(20-21 January, 2021)

Overview

- Motivation
- The ScotoSinglet Model (ScSM)
  - Model details
  - Analysis
  - Results
- Summary

Motivation

- Two unsolved puzzles of the Standard Model (SM):
  1) Neutrino masses;
  2) Dark Matter (DM).
- Possible beyond the SM extensions:
  - Radiative neutrino mass models;

[S. M. Boucenna, S. Morisi and J. W. Valle, *Adv. High Energy Phys.* (2014), **arXiv:1404.3751**]
[Y. Cai et al. , *Front. In Phys.* (2017), **arXiv:1706.08524**]

  - Weakly Interacting Massive Particles (WIMPs).

[J. L. Feng, *Ann. Rev. Astron. Astrophys.* (2010)]

- The Scotogenic Model (ScM) can addresses both puzzles *simultaneously*.

[E. Ma, *Phys. Rev. D. (2006)*, **hep-ph/0601225**]
[J. Kubo, E. Ma and D. Suematsu, *Phys. Lett. B.* (20016), **hep-ph/0604114**]

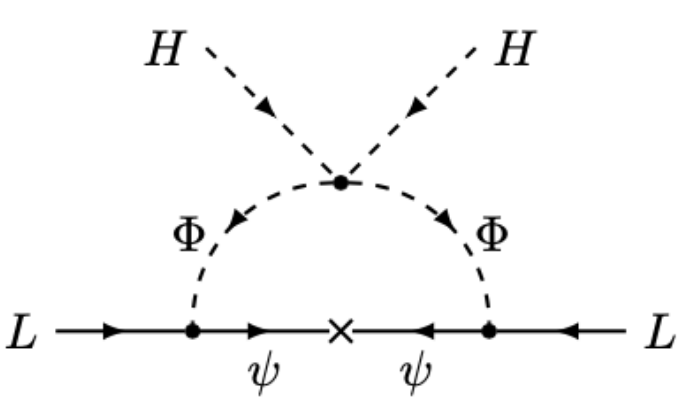
The Scotogenic Model (ScM)

Add a scalar doublet Φ and new Majorana singlets ψ_i $(i \geq 2)$.

All fields charged under $\mathbb{Z}_2$ symmetry: $\Phi \to -\Phi$ and $\psi_i \to -\psi_i$.

- Neutrino masses generated at 1-loop level.

- DM can be either the lightest ψ_i, or lightest component of Φ (CP-odd or CP-even.



Neutrino mass generation in the Scotogenic model at 1-loop level.

Strong constraints from ν masses, electroweak precision tests, direct detection & lepton flavour violation (LFV) processes $\implies$ non-trivial to saturate the observed DM abundance.

[C. Hagedorn et al., *JHEP* (2018), **arXiv:1804.04117**]

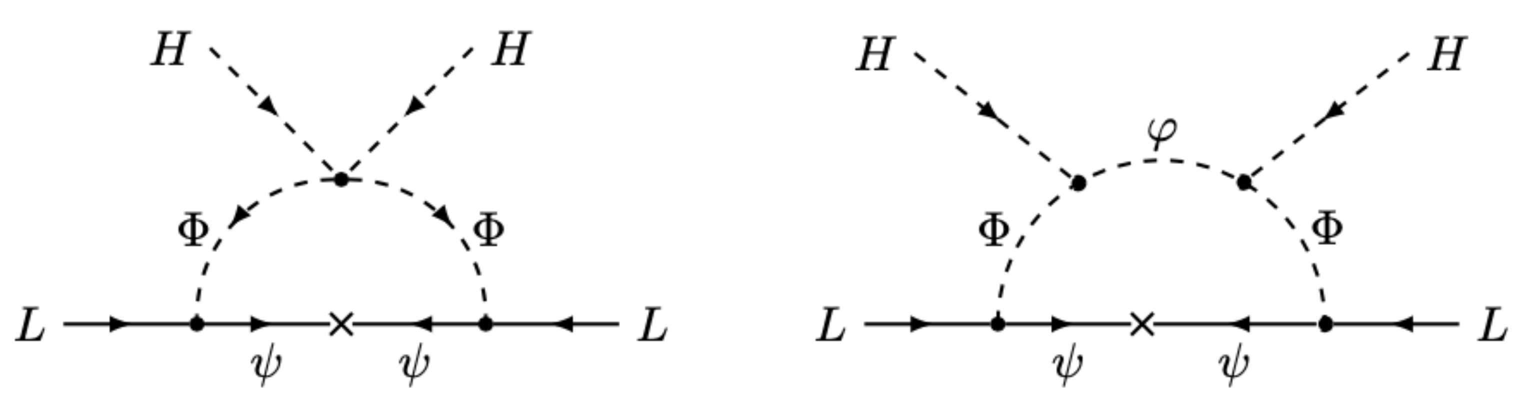
The ScotoSinglet Model (ScSM)

ScotoSinglet: Scotogenic model with an extra scalar singlet.

Simplest extension of the Scotogenic Model.

Interesting features:

- New contribution to neutrino masses;
- 3 potential DM candidates;
- Possibility of maintaining $\mathbb{Z}_2$ symmetry up to high-energy scales.



Neutrino masses in the ScSM at the 1-loop level. *Left panel*: contribution in the ScM. *Right panel*: new contribution in the ScSM.

The ScotoSinglet Model (ScSM)

Model details

Fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Real φ	1	1	0	$-$
Φ	1	2	1/2	$-$
ψ_k	1	1	0	$-$

Particle contents of the ScSM. Here $k = 1, 2$.

See arXiv:2010.05937 for more details.

Majorana fermion Lagrangian

$$\mathscr{L}_\Psi = \frac{1}{2}\overline{\Psi}(i\partial\!\!\!/ - M_\Psi)\Psi - \overline{\Psi}\,\mathbf{y}_\Psi\,\tilde{\Phi}^\dagger\,L\;+\;\mathrm{H.c.}\,,$$

$\mathbf{y}_\Psi = 2 \times 3$ matrix of complex Yukawa couplings

Scalar potential

$$\begin{aligned} V = &-\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Phi^2 \Phi^\dagger\Phi + \lambda_\Phi (\Phi^\dagger\Phi)^2 + \frac{1}{2}m_\varphi^2\varphi^2 + \frac{1}{4}\lambda_\varphi\varphi^4 \\ &+ \lambda_{H\Phi,1}(H^\dagger H)(\Phi^\dagger\Phi) + \lambda_{H\Phi,2}(H^\dagger\Phi)(\Phi^\dagger H) + \frac{1}{2}\left[\lambda_{H\Phi,3}(H^\dagger\Phi)^2 + \mathrm{H.c.}\right] \\ &+ \frac{1}{2}\lambda_{H\varphi}H^\dagger H\varphi^2 + \frac{1}{2}\lambda_{\Phi\varphi}\Phi^\dagger\Phi\varphi^2 + \left[\kappa\,\Phi^\dagger H\,\varphi + \mathrm{H.c.}\right]. \end{aligned}$$

$$\Phi \equiv \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\phi_R + iA) \end{pmatrix}.$$

The ScotoSinglet Model (ScSM)

Model details

After electroweak symmetry breaking & mass-diagonalisation in (ϕ_R, φ) basis, namely

$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi_R \\ \varphi \end{pmatrix}$$

$\Longrightarrow$ **21 parameters** (12 free + 9 nuisance parameters):

$$\text{5 masses (1 mixing angle)}: \quad \{m_{\psi_1},\, m_{\psi_2},\, m_{\eta_1},\, m_{\eta_2},\, m_A,\, \theta\}\,, \qquad (3.1a)$$

$$\text{6 couplings:} \quad \{\lambda_\Phi,\, \lambda_\varphi,\, \lambda_{H\Phi,1},\, \lambda_{H\Phi,2},\, \lambda_{H\varphi},\, \lambda_{\Phi\varphi}\}\,. \qquad (3.1b)$$

6 complex Yukawas $\mathbf{y}_\Psi$ (9 nuisance parameters) fixed using Casas-Ibarra parametrisation.

[J. A. Casas & A. Ibarra, *Nucl. Phys. B.* (2001), **hep-ph/0103065**]

The ScotoSinglet Model (ScSM)

Analysis

- Use MultiNest 3.10.0 to sample the 21-dimensional parameter space.

[F. Feroz, M. Hobson & M. Bridges, *Mon. Not. Roy. Astron.* (2009), **arXiv:0809.3437**]

- Perform a frequentist analysis, specifically *Profile Likelihood Ratio (PLR)*.

$$\ln \mathcal{L}_{\text{total}}(\boldsymbol{\theta}) = \ln \mathcal{L}_{\kappa}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\text{EWPT}}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\mathcal{R}_{\gamma\gamma}}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\text{LFV}}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\Omega h^2}(\boldsymbol{\theta}) + \ln \mathcal{L}_{\text{DD}}(\boldsymbol{\theta})$$

Constraints include:

1) Perturbativity and naturalness;
2) Electroweak Precision Tests (EWPT);
3) $\mathscr{R}_{\gamma\gamma} \equiv \Gamma(h \to \gamma\gamma)_{\text{ScSM}} / \Gamma(h \to \gamma\gamma)_{\text{SM}}$;
4) Lepton Flavour Violation (LFV) processes;
5) DM Relic density (Ωh^2);
6) Direct Detection (DD).

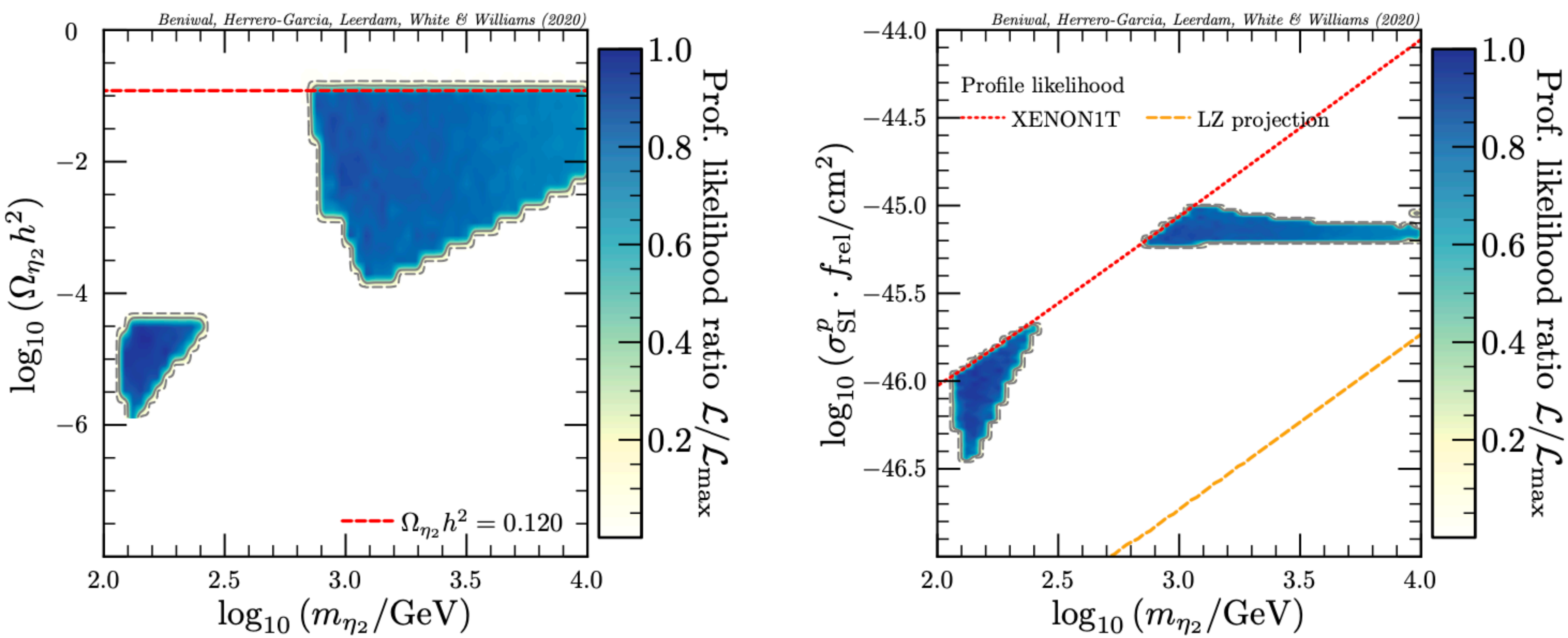
	Ranges	Priors
Model parameters		
$\{m_{\psi_1}, m_{\psi_2}\}$ (GeV)	$[10,\ 10^6]$	Log
m_{η_2} (GeV)	$[100, 10^4]$	Log
$\delta_1 \equiv m_{\eta_1} - m_{\eta_2}$ (GeV)	$[10^{-3},\ 10^4]$	Log
$\delta_A \equiv m_A - m_{\eta_2}$ (GeV)	$[-10^4,\ -10^{-3}] \cup [10^{-3}, 10^4]$	Log |value|
θ (rad.)	$[0,\ \pi]$	Flat
$\{\lambda_\Phi,\ \lambda_\varphi\}$	$[10^{-3},\ 4\pi]$	Log
$\{\lambda_{H\Phi,1},\ \lambda_{H\Phi,2},\ \lambda_{H\varphi},\ \lambda_{\Phi\varphi}\}$	$[-4\pi,\ -10^{-3}] \cup [10^{-3}, 4\pi]$	Log |value|
Nuisance parameters		
$\sin^2\theta_{12}$	$[0.275,\ 0.350]$	Flat
$\sin^2\theta_{13}$	$[0.02044,\ 0.02435]$ (NO) $[0.02064,\ 0.02457]$ (IO)	Flat
$\sin^2\theta_{23}$	$[0.433,\ 0.609]$ (NO) $[0.436,\ 0.610]$ (IO)	Flat
$\frac{\Delta m^2_{21}}{10^{-5}\,\text{eV}^2}$	$[6.79,\ 8.01]$	Flat
$\frac{\Delta m^2_{3l}}{10^{-3}\,\text{eV}^2}$	$[2.436, 2.618]$ (NO) $[-2.601, -2.419]$ (IO)	Flat
δ_{CP} $(^\circ)$	$[144,\ 357]$ (NO) $[205,\ 348]$ (IO)	Flat
α (rad.)	$[0,\ 2\pi]$	Flat
$\{\zeta_1,\ \zeta_2\}$	$[10^{-3},\ 10^3]$	Log

Parameter ranges and priors used in our analysis.

The ScotoSinglet Model (ScSM)

Results

Case 1: $\theta = 0 \implies \eta_2 =$ scalar <u>singlet</u>



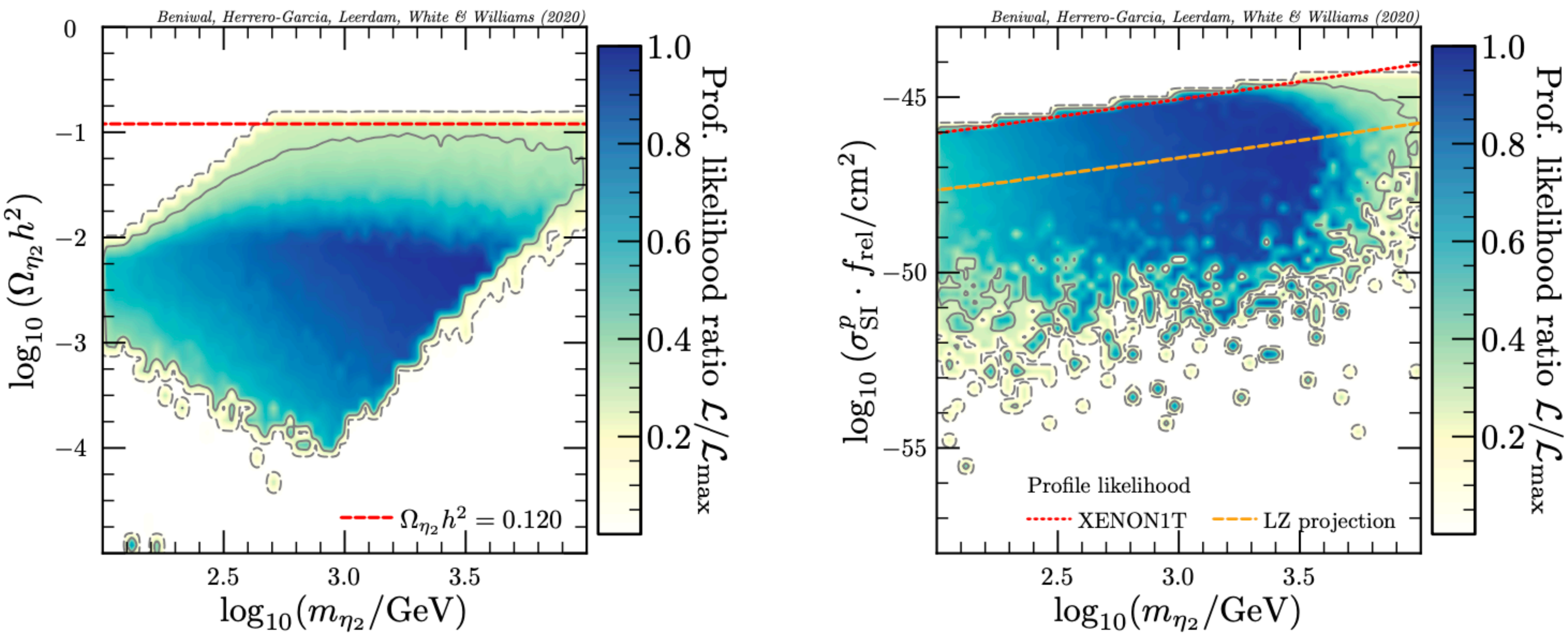
Left panel: relic density vs η_2 mass. *Right panel*: effective spin-independent η_2-proton cross-section vs η_2 mass.

[P. Athron et al., *Eur. Phys. J. C.* (2018), **arXiv:1806.11281**]
[P. Athron et al., *Eur. Phys. J. C.* (2019), **arXiv:1808.10465**]

The ScotoSinglet Model (ScSM)

Results

Case 2: $\theta = \pi/2 \Longrightarrow \eta_2 =$ scalar <u>doublet</u>

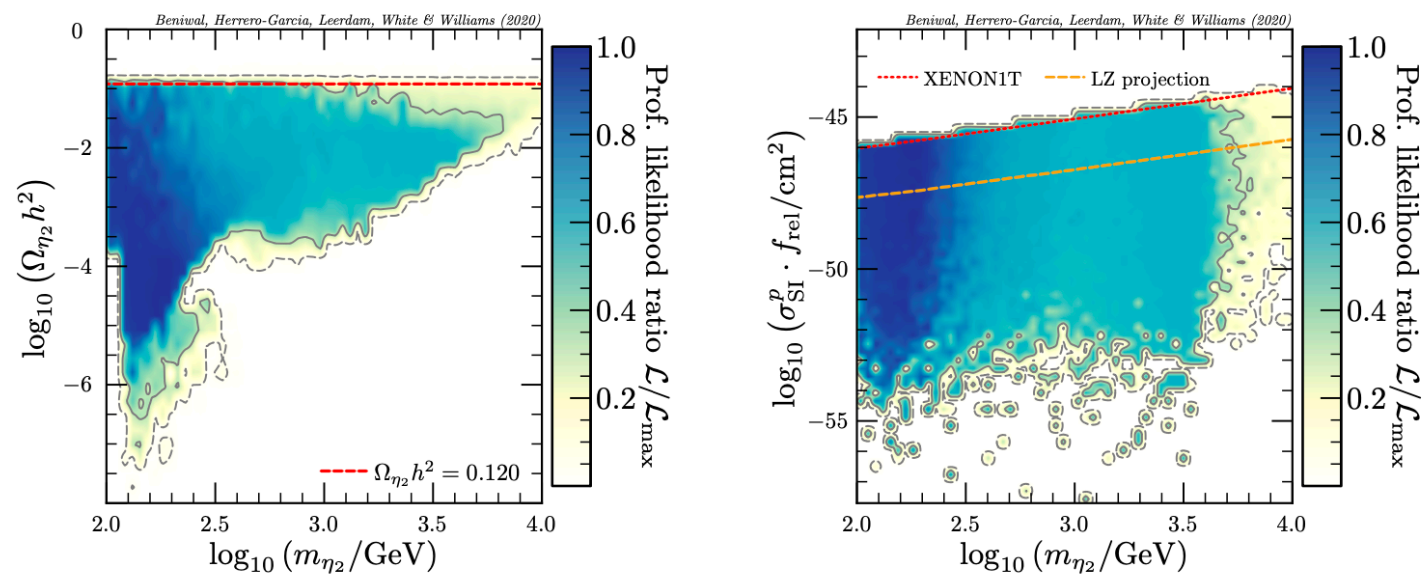


Left panel: relic density vs η_2 mass. *Right panel*: effective spin-independent η_2-proton cross-section vs η_2 mass.

[L. L. Honorez et al., *JCAP* (2007), **hep-ph/0612275**]

The ScotoSinglet Model (ScSM)

Results



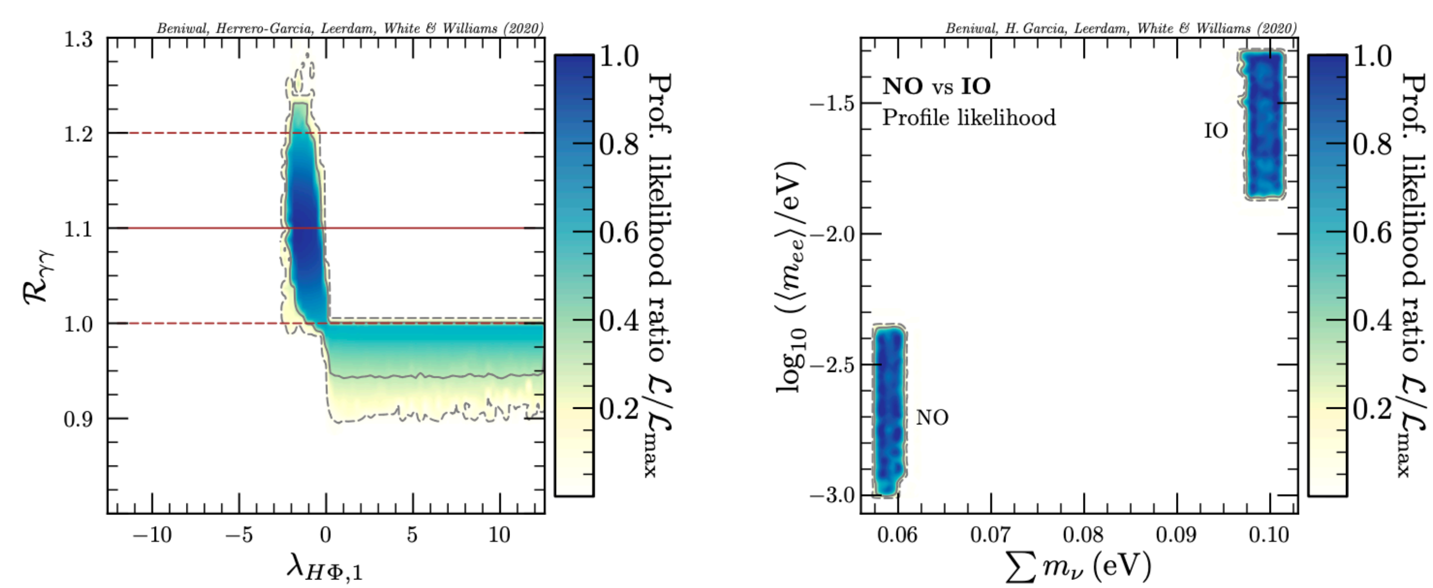
Case 3: Non-zero mixing

$(\theta \neq 0, \pi/2)$

Left panel: relic density vs η_2 mass. *Right panel*: effective spin-independent η_2-proton cross-section vs η_2 mass.

$$\mathscr{R}_{\gamma\gamma} \equiv \frac{\Gamma(h \to \gamma\gamma)_{\text{ScSM}}}{\Gamma(h \to \gamma\gamma)_{\text{SM}}} = \left| 1 + \frac{\lambda_{H\Phi,1}\, v^2}{2m^2_{\phi^+}} \frac{A_0(\tau_{\phi^+})}{A_1(\tau_W) + \frac{4}{3} A_{1/2}(\tau_t)} \right|^2$$

$$\langle m_{ee} \rangle \equiv \sum | U^2_{ei} m_i |$$



Left panel: $\mathscr{R}_{\gamma\gamma}$ vs $\lambda_{H\Phi,1}$. *Right panel*: $\langle m_{ee} \rangle$ vs $\sum m_\nu$

Summary

- Proposed a simple variant of the ScM, namely ScSM.
- Interesting features of ScSM:
  - Scalar DM (CP-even or CP-odd) with suppressed direct detection rates **and** correct DM abundance;
  - Two contributions to ν masses: usual scotogenic one ($\propto \lambda_{H\Phi,3}$) + new singlet one ($\propto \kappa^2$).
  - Singlet improves the $\mathbb{Z}_2$ symmetry at high-energy scales.

For more details, see arXiv:2010.05937.

Thank you!

Backup slides

Dependent parameters

$$m_\Phi^2 = m_{\eta_1}^2 \cos^2\theta + m_{\eta_2}^2 \sin^2\theta - \frac{1}{2}\left(\lambda_{H\Phi,1} + \lambda_{H\Phi,2} + \lambda_{H\Phi,3}\right) v^2\,, \tag{3.2a}$$

$$m_\varphi^2 = m_{\eta_1}^2 \sin^2\theta + m_{\eta_2}^2 \cos^2\theta - \frac{1}{2}\lambda_{H\varphi} v^2\,, \tag{3.2b}$$

$$m_{\phi^+}^2 = m_\Phi^2 + \frac{1}{2}\lambda_{H\Phi,1} v^2\,, \tag{3.2c}$$

$$\lambda_{H\Phi,3} = \frac{1}{v^2}\left(m_{\eta_1}^2 \cos^2\theta + m_{\eta_2}^2 \sin^2\theta - m_A^2\right)\,, \tag{3.2d}$$

$$\kappa = \frac{1}{v}(m_{\eta_1}^2 - m_{\eta_2}^2)\sin\theta\cos\theta\,. \tag{3.2e}$$