Complementary exploring low mass vector dark matter, dark photon and dark Z'

Raymundo Ramos
Institute of Physics, Academia Sinica
(Based on 2101.07115 with T.-C. Yuan y V. Q. Tran)

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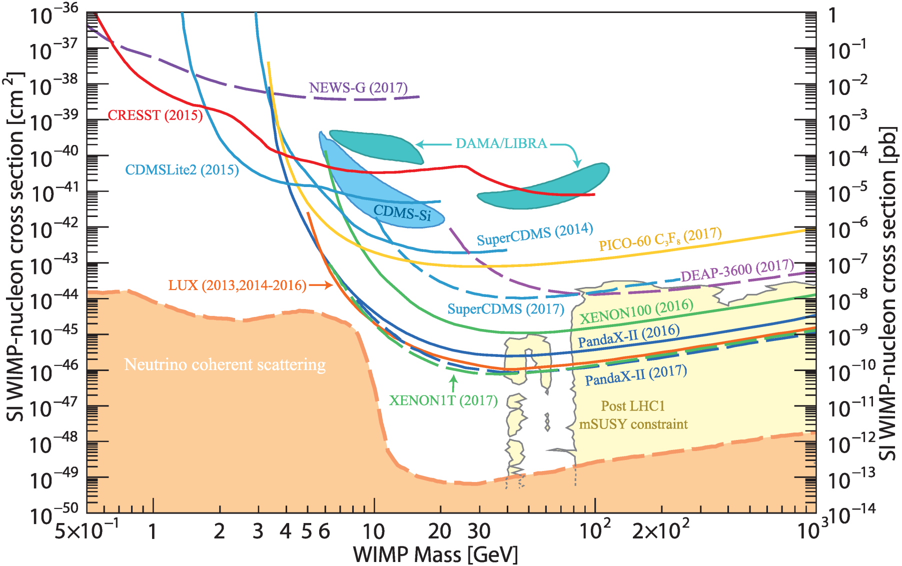
Dark matter

. . . only **indirect evidence** at the moment.



Particle Data Group

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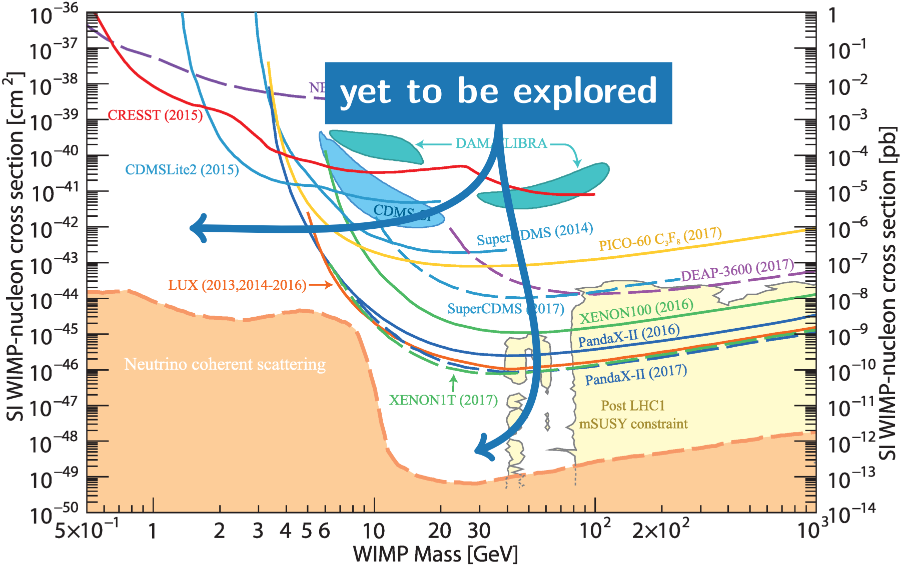

Particle Data Group

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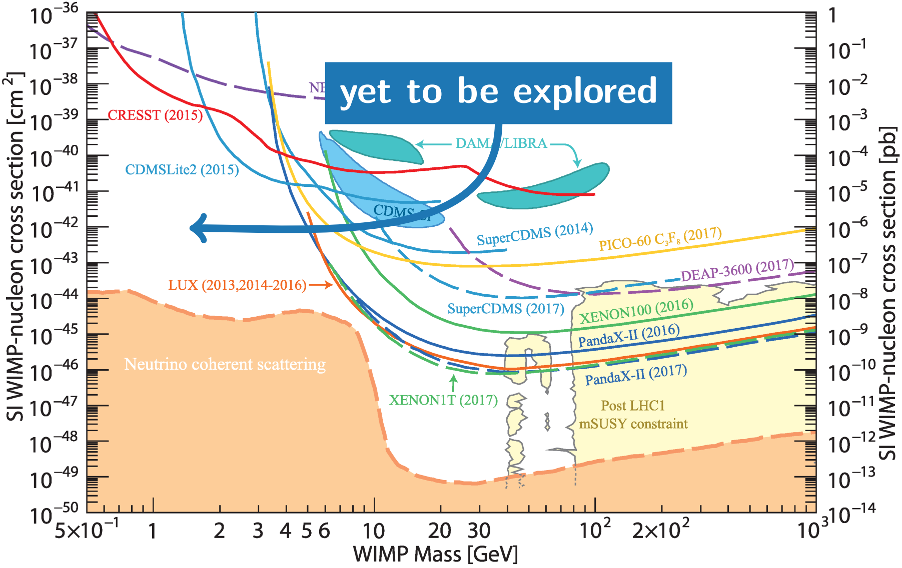

Particle Data Group

The Lee-Weinberg window (1977)

Dark matter annhilation in the WIMP paradigm:

$$\langle \sigma v \rangle \sim 10^{-26}\ \text{cm}^3/\text{s} \quad \Rightarrow \quad \Omega_{\text{DM}} \sim 0.25$$

assuming SM-DM mediators with **electroweak scale mass**

$$\sigma \propto \begin{cases} G_F^2 m_{\text{DM}}^2, & m_{\text{DM}} \ll m_W \\ 1/m_{\text{DM}}^2, & m_{\text{DM}} \gg m_W \end{cases} \quad \Rightarrow \quad \mathcal{O}(1\ \text{GeV}) < m_{\text{DM}} < \mathcal{O}(1\ \text{TeV})$$

Light mediators allow for a lower bound: down to $\mathcal{O}(1\ \text{MeV})$

$$\sigma \sim F \frac{m_{\text{DM}}^2 + 2m_f^2}{(m_{A'}^2 - 4m_{\text{DM}}^2)^2} \sqrt{1 - \frac{m_f^2}{m_{\text{DM}}^2}}, \qquad m_f < m_{\text{DM}}$$

A gauged two Higgs doublet model

We explored light vector dark matter in a gauged two Higgs doublet model

- ✓ Extended symmetry: $G_{\text{SM}} \times \text{SU}(2)_H \times \text{U}(1)_X$
- ✓ Simple potential
- ✓ **Accidental $\mathcal{Z}_2$ symmetry (h-parity)** in the potential
- ✓ Anomaly cancellation via additional heavy fermions.
- ✓ Even simpler than the original [1512.00229] by removing a triplet scalar of $SU(2)_H$

(for more details see [1512.00229] and [2101.07115])

Extended scalar and gauge sectors

Scalar fields

$$\begin{array}{ccc} SU(2)_L \text{ doublets} & & SU(2)_H \text{ doublet} \\ \downarrow \quad \downarrow & & \downarrow \\ H_1,\ H_2 & \rightarrow & H = (H_1,\ H_2)^T \end{array}$$

$SU(2)_H$ doublet: $\Phi_H = (\Phi_1,\ \Phi_2)^T$

Vector fields

- $SU(2)_H$: $W'^k_\mu,\ k = 1, 2, 3,$ coupling: g_H
- $U(1)_X$: X_μ coupling: g_X

Potential and masses for the scalars

Most general $SU(2)_L \times U(1)_Y \times SU(2)_H \times U(1)_X$ invariant potential

$$
\begin{aligned}
V = & -\mu_H^2 \left(H^{\alpha i} H_{\alpha i}\right) + \lambda_H \left(H^{\alpha i} H_{\alpha i}\right)^2 + \frac{1}{2}\lambda'_H \epsilon_{\alpha\beta}\epsilon^{\gamma\delta} \left(H^{\alpha i} H_{\gamma i}\right)\left(H^{\beta j} H_{\delta j}\right) \\
& - \mu_\Phi^2 \Phi_H^\dagger \Phi_H + \lambda_\Phi \left(\Phi_H^\dagger \Phi_H\right)^2 + \lambda_{H\Phi}\left(H^\dagger H\right)\left(\Phi_H^\dagger \Phi_H\right) \\
& + \lambda'_{H\Phi}\left(H^\dagger \Phi_H\right)\left(\Phi_H^\dagger H\right),
\end{aligned}
$$

Minimization conditions:

$$
\langle H_1 \rangle^2 = v^2 = \frac{2\left(\lambda_{H\Phi}\mu_\Phi^2 - 2\lambda_\Phi \mu_H^2\right)}{\lambda_{H\Phi}^2 - 4\lambda_H \lambda_\Phi}
$$

$$
\langle \Phi_H \rangle^2 = v_\Phi^2 = \frac{2\left(\lambda_{H\Phi}\mu_H^2 - 2\lambda_H \mu_\Phi^2\right)}{\lambda_{H\Phi}^2 - 4\lambda_H \lambda_\Phi}
$$

$$\Longrightarrow$$

$$
\mu_H^2 = \lambda_H v^2 + \frac{\lambda_{H\Phi} v_\Phi^2}{2}
$$

$$
\mu_\Phi^2 = \lambda_\Phi v_\Phi^2 + \frac{\lambda_{H\Phi} v^2}{2}
$$

Potential and masses for the scalars

Matrix basis $S = \{h, \phi_2\}$ and $S' = \{G_H^p, H_2^{0*}\}$ we get

$$\mathcal{M}_S^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\Phi} v v_\Phi \\ \lambda_{H\Phi} v v_\Phi & 2\lambda_\Phi v_\Phi^2 \end{pmatrix}, \qquad \mathcal{M}_{S'}^2 = \frac{1}{2}\lambda'_{H\Phi} \begin{pmatrix} v^2 & v v_\Phi \\ v v_\Phi & v_\Phi^2 \end{pmatrix}.$$

Mixing characterized by

$$\tan 2\theta_1 = \frac{\lambda_{H\Phi} v v_\Phi}{\lambda_\Phi v_\Phi^2 - \lambda_H v^2}\,, \qquad \tan 2\theta_2 = \frac{2 v v_\Phi}{v_\Phi^2 - v^2}\,,$$

The squared masses of the eigenstates h_1, h_2 y m_D are given by

$$m_{h_{1,2}}^2 = \lambda_H v^2 + \lambda_\Phi v_\Phi^2 \mp \sqrt{\lambda_H^2 v^4 - 2\lambda_H \lambda_\Phi v^2 v_\Phi^2 + \lambda_{H\Phi}^2 v^2 v_\Phi^2 + \lambda_\Phi^2 v_\Phi^4}\,.$$

$$m_D^2 = \frac{1}{2}\lambda'_{H\Phi}(v^2 + v_\Phi^2)\,, \quad \text{one massless state } \widetilde{G}_H^p$$

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$\det \mathcal{M}_{S'}^2 = 0$

Mixing characterized by

$$\tan 2\theta_1 = \frac{\lambda_{H\Phi} v v_\Phi}{\lambda_\Phi v_\Phi^2 - \lambda_H v^2}, \qquad \tan 2\theta_2 \; \ldots \; \frac{\ldots}{v_\Phi^2 - v^2}$$

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$$m_D^2 = \frac{1}{2}\lambda'_{H\Phi}(v^2 + v_\Phi^2), \quad \text{one massless state } \widetilde{G}_H^p$$

Massive vector fields

$SU(2)_H$ Gauge boson (h-odd) $W'^{(p,m)} = (W'^1 \pm iW'^2)/2$ receives mass from H_1 (v) and Φ_2 (v_Φ):

$$m_{W'} = \frac{1}{2} g_H \sqrt{v^2 + v_\Phi^2}$$

small $g_H \to$ **light** W'

Z^{SM} mixes with W'^3 and X (h-even)

$$\mathcal{M}_Z^2 = \begin{pmatrix} m_{Z^{SM}}^2 & -\frac{g_H v}{2} m_{Z^{SM}} & -g_X v m_{Z^{SM}} \\ -\frac{g_H v}{2} m_{Z^{SM}} & m_{W'}^2 & \frac{g_X g_H (v^2 - v_\Phi^2)}{2} \\ -g_X v m_{Z^{SM}} & \frac{g_X g_H (v^2 - v_\Phi^2)}{2} & g_X^2 (v^2 + v_\Phi^2) + M_X^2 \end{pmatrix}, \quad \begin{pmatrix} Z^{SM} \\ W'^3 \\ X \end{pmatrix} = \mathcal{O} \cdot \begin{pmatrix} Z \\ Z' \\ A' \end{pmatrix}$$

We consider the mass hierarchy: $m_Z \approx 91.19$ GeV $> m_{Z'} > m_{A'}$:

Z' and A' will play the role of **light mediators**.

Parameter space

The $\{h, \phi_2\}$ mass matrix and θ_1 mixing angle relate parameters from the potential with physical masses:

$$\lambda_H = \frac{1}{2v^2}\left(m_{h_1}^2 \cos^2\theta_1 + m_{h_2}^2 \sin^2\theta_1\right),$$

$$\lambda_\Phi = \frac{1}{2v_\Phi^2}\left(m_{h_1}^2 \sin^2\theta_1 + m_{h_2}^2 \cos^2\theta_1\right),$$

$$\lambda_{H\Phi} = \frac{1}{2vv_\Phi}\left[\left(m_{h_1}^2 - m_{h_2}^2\right)\sin\left(2\theta_1\right)\right].$$

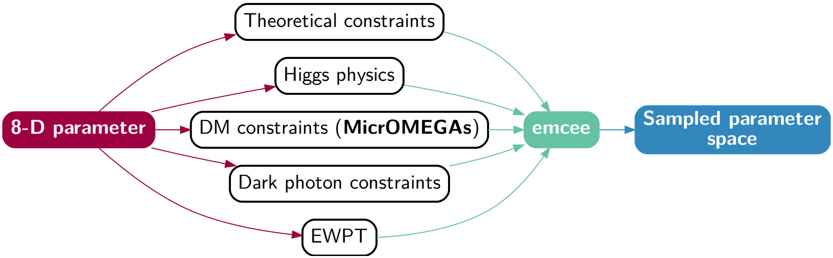
Using m_D, $m_{W'}$ y $m_{H^\pm}^2 = (\lambda'_{H\Phi} v_\Phi^2 - \lambda'_H v^2)/2$ we find

$$\lambda'_{H\Phi} = \frac{2m_D^2}{v^2 + v_\Phi^2}, \qquad \lambda'_H = \frac{2}{v^2}\left[\frac{m_D^2 v_\Phi^2}{v^2 + v_\Phi^2} - m_{H^\pm}^2\right], \qquad v_\Phi^2 = \frac{4m_{W'}^2}{g_H^2} - v^2 .$$

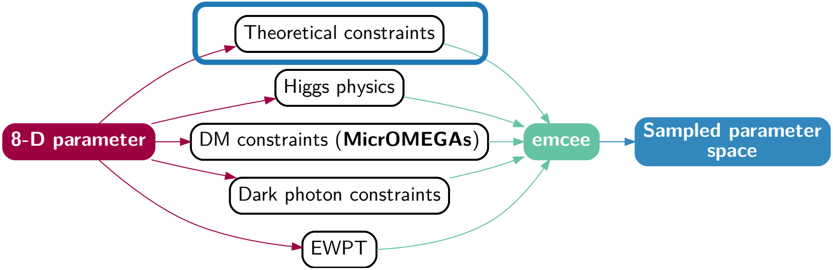
8 free parameter: m_{h_2}, m_D, $m_{H^\pm}$, $m_{W'}$, θ_1, g_X, g_H, M_X

$$m_{h_1} \approx 125 \text{ GeV}, \quad m_{f^H} = 3 \text{ TeV}$$

Sampling the parameter space



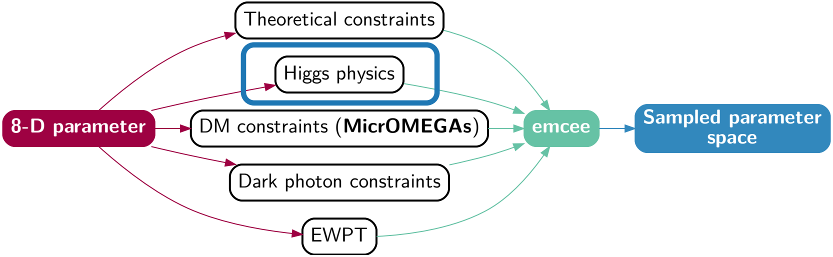
Sampling the parameter space



Theoretical constraints (pass or fail):

- Vacuum stability
- Perturbativity and unitarity

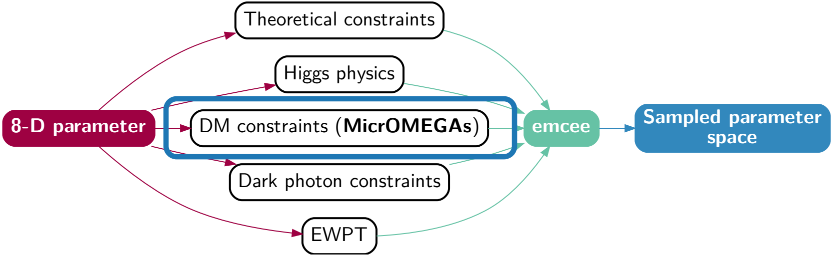
Sampling the parameter space



Higgs physics (pass/fail):

- Higgs mass
- Higgs decays
  - Higgs $\rightarrow \gamma\gamma$
  - Higgs $\rightarrow \bar{f}f$
  - Higgs $\rightarrow$ invisible

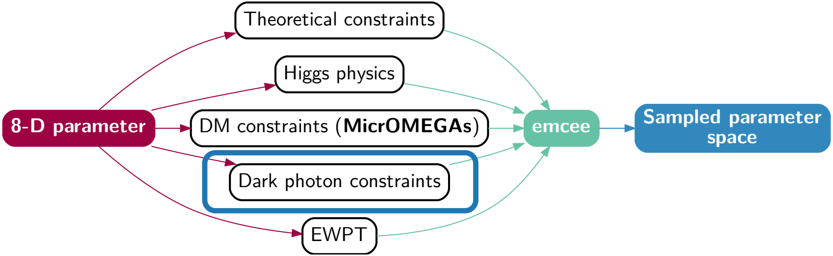
Sampling the parameter space



Dark matter (W') constraints (χ^2):

- Relic density
- Direct detection
- Indirect detection (weak constraint)
- Monojet (**Benchmark points**, weak constraint)

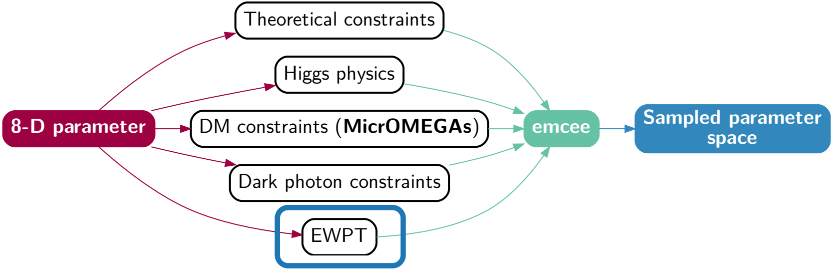
Sampling the parameter space



Dark photon (Z', A') constraints (pass/fail):
On effective $\{A', Z'\}\ell^+\ell^-$ coupling:

$$\varepsilon_\ell = \frac{1}{2 s_W c_W} \sqrt{\left(v_\ell^{\mathcal{V}}\right)^2 + \left(a_\ell^{\mathcal{V}}\right)^2 \left(\frac{1-\mu_\ell^2}{1+\mu_\ell^2/2}\right)}, \quad \mathcal{V} = A', Z', \quad \ell = e, \mu$$

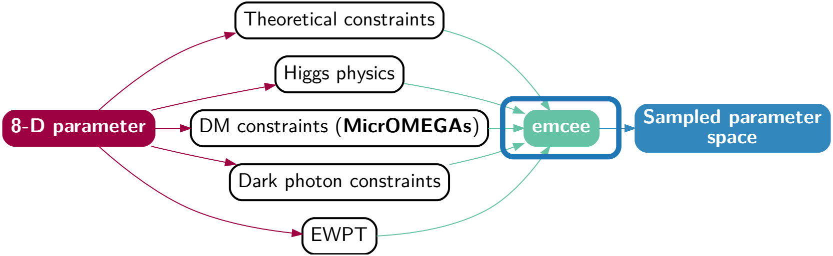
Sampling the parameter space



Electroweak precision tests (χ^2):

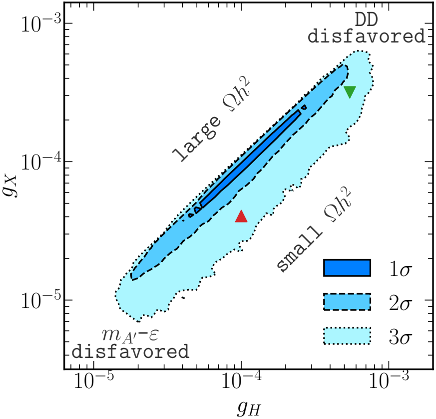
- Forward-Backward asymmetry
- Drell-Yan process
- Contact interactions ($e^+e^- \to \bar{f}f$)

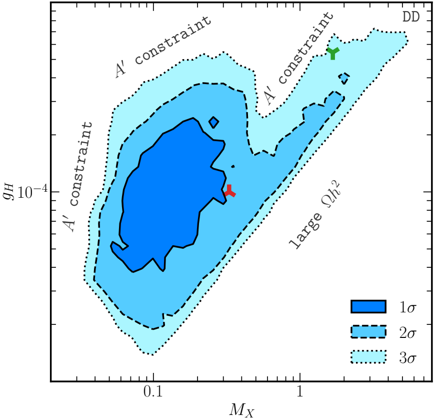
Sampling the parameter space



Sample the parameter space with `emcee`
(Markov Chain Monte Carlo)

Sampling the parameter space

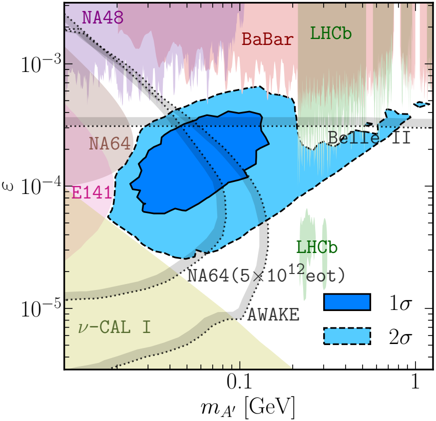


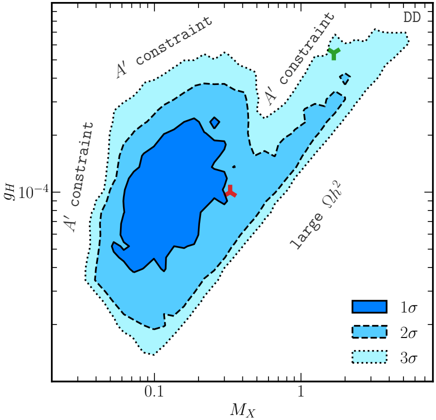


Allowed space: **dark (1σ)**, **medium (2σ)** and **light blue (3σ)** blue.

Sampling the parameter space

Dark photon





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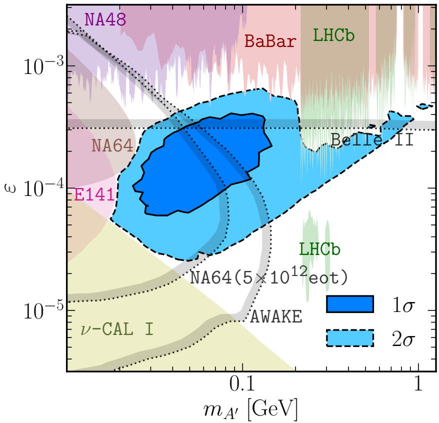
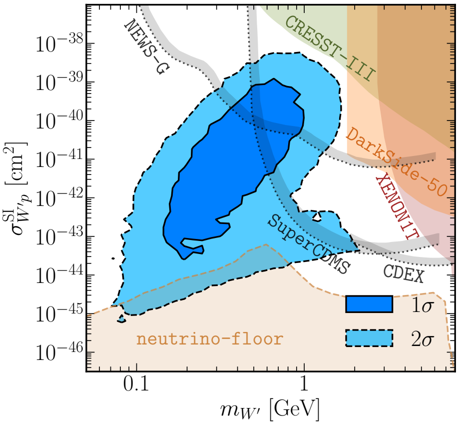
Sampling the parameter space

Dark photon



Direct detection



Allowed space: **dark (1σ)**, **medium (2σ)** and **light blue (3σ)** blue.

Summarizing. . .

- Dark matter is **very well motivated** but still undetected.
- Current observations heavily constrain the most popular options but **also** leave space for more theoretical possibilities.
- **New parameter space** $\rightarrow$ **new understanding** of the theoretical details of DM.
- We took advantage of the extended gauge sector of a **gauged 2HDM** to enhance the annihilation of the light dark matter candidate with a Z' mediator.
- The dark photon A' is crucial for direct detection of dark matter and is well placed for discovery in near future experiments.

THANKS FOR YOUR ATTENTION

BACKUP

Particle content

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$	h-parity
$Q_L = \left(u_L \ \ d_L\right)^{\mathrm{T}}$	3	2	1	1/6	0	+ +
$U_R = \left(u_R \ \ u_R^H\right)^{\mathrm{T}}$	3	1	2	2/3	1	+ −
$D_R = \left(d_R^H \ \ d_R\right)^{\mathrm{T}}$	3	1	2	−1/3	−1	− +
u_L^H	3	1	1	2/3	0	−
d_L^H	3	1	1	−1/3	0	−
$L_L = \left(\nu_L \ \ e_L\right)^{\mathrm{T}}$	1	2	1	−1/2	0	+ +
$N_R = \left(\nu_R \ \ \nu_R^H\right)^{\mathrm{T}}$	1	1	2	0	1	+ −
$E_R = \left(e_R^H \ \ e_R\right)^{\mathrm{T}}$	1	1	2	−1	−1	− +
ν_L^H	1	1	1	0	0	−
e_L^H	1	1	1	−1	0	−
$H = (H_1 \ \ H_2)^{\mathrm{T}}$	1	2	2	1/2	1	+ −
$\Phi_H = (\Phi_1 \ \ \Phi_2)^{\mathrm{T}}$	1	1	2	0	1	− +
$\mathcal{S}$	1	1	1	0	0	+