Dark matter in Higgs aligned gauge theories

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The case for minimal dark matter models:

- Small number of parameters → high predictability

- Occam's razor:

Counting of on-shell helicity states for particle physics + gravity:

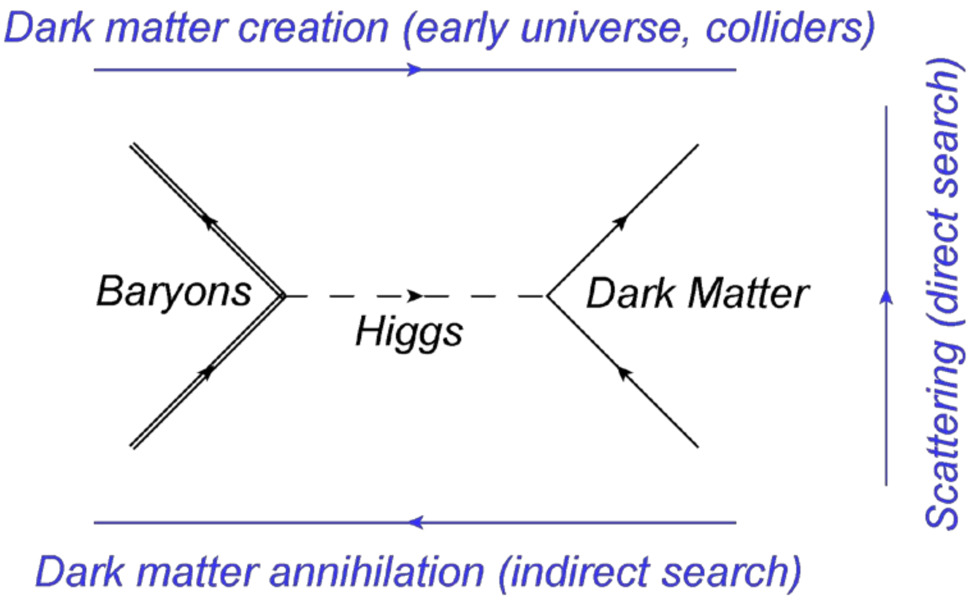
Standard model plus Einstein gravity	124 + 2 = 126
MSGSM (Minimal supergravitational SM)	264
$E_8 \times E_8$ heterotic string theory	$2 \times 3968 + 128 = 8064$ (at the Planck scale)
Minimal dark matter models	(125..132) + 2 = 127..134
"Competition": Modified gravity theories	
TeVeS	124 + 4 = 128
MOG	124 + 6 = 130

Standard Higgs Portal Models

Dark matter consists of electroweak singlets

- Higgs coupling to scalar dark matter
$$\mathcal{H} = \frac{\eta_S}{2}(H^+ \cdot H)S^2$$
- Higgs coupling to vector dark matter
$$\mathcal{H} = \frac{\eta_V}{2}(H^+ \cdot H)V_\mu V^\mu$$
- Higgs coupling to fermionic dark matter
$$\mathcal{H} = \frac{1}{2M}(H^+ \cdot H)\bar{\chi}\chi$$

Standard Higgs Portal Models



Higgs field in unitary gauge:

$$H = \frac{v_h + h}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Scalar Higgs portal model:

$$\mathcal{L}_S = -\frac{1}{2}\partial S \cdot \partial S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4}S^4 - \frac{\eta_S v_h}{2}S^2 h - \frac{\eta_S}{4}S^2 h^2$$

Vector Higgs portal model:

$$\mathcal{L}_V = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\lambda_V}{4}(V_\mu V^\mu)^2 - \frac{\eta_V v_h}{2}V_\mu V^\mu h - \frac{\eta_V}{4}V_\mu V^\mu h^2$$

$$V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$$

Standard Higgs portals lead to symmetric dark matter

What we (usually) want to know:

- Annihilation cross sections for
  - calculating abundance as a function of dark matter parameters
  - indirect signals in cosmic rays from dark matter annihilation
- Nuclear recoil cross sections for comparison with direct dark matter search experiments.
- Production cross sections for dark matter signals at colliders.

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Not for HADM!

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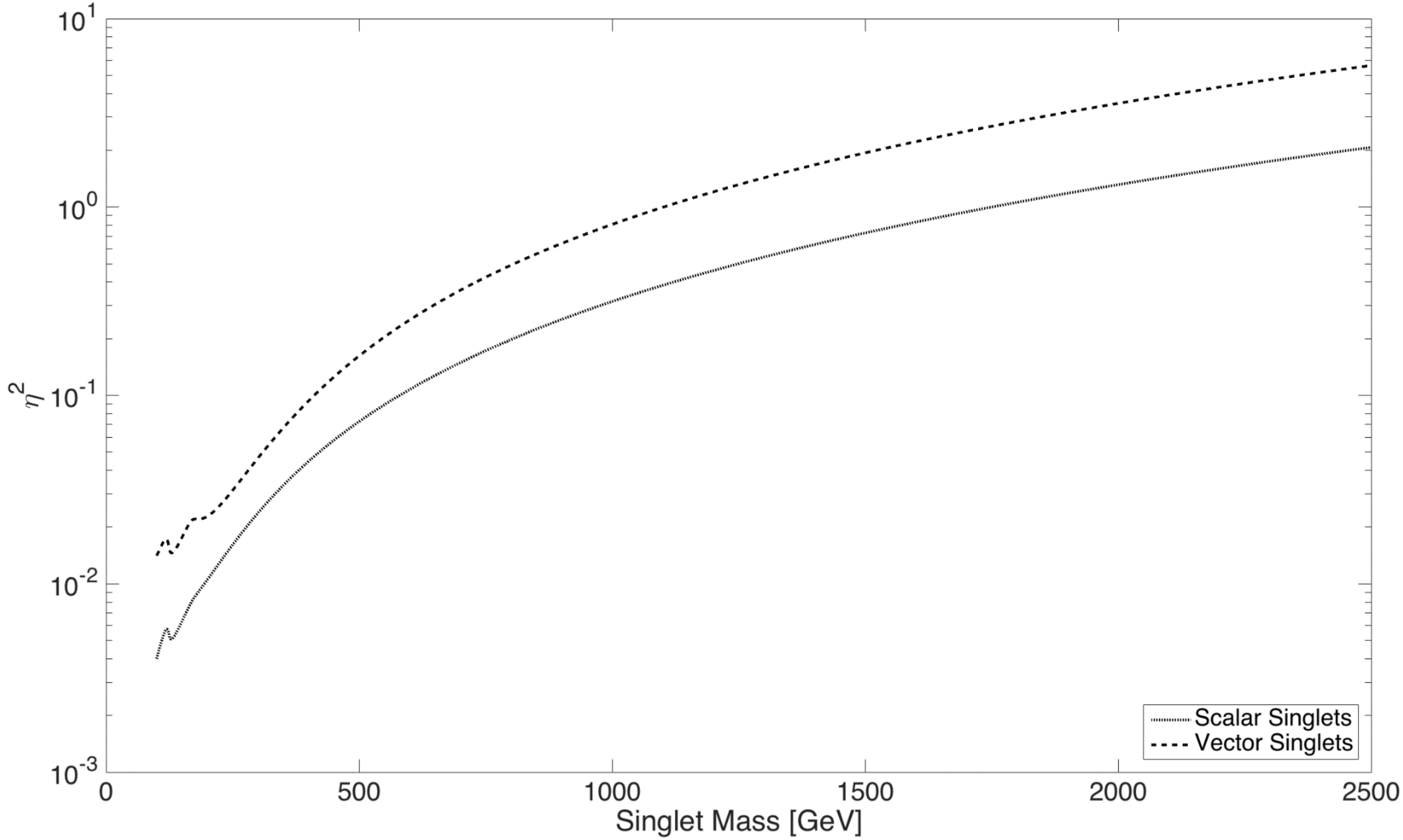
Higgs-portal couplings as a function of dark matter mass



Dark matter recoil off nucleons

The nucleon recoil cross section for bosonic Higgs portal dark matter of mass m_D is

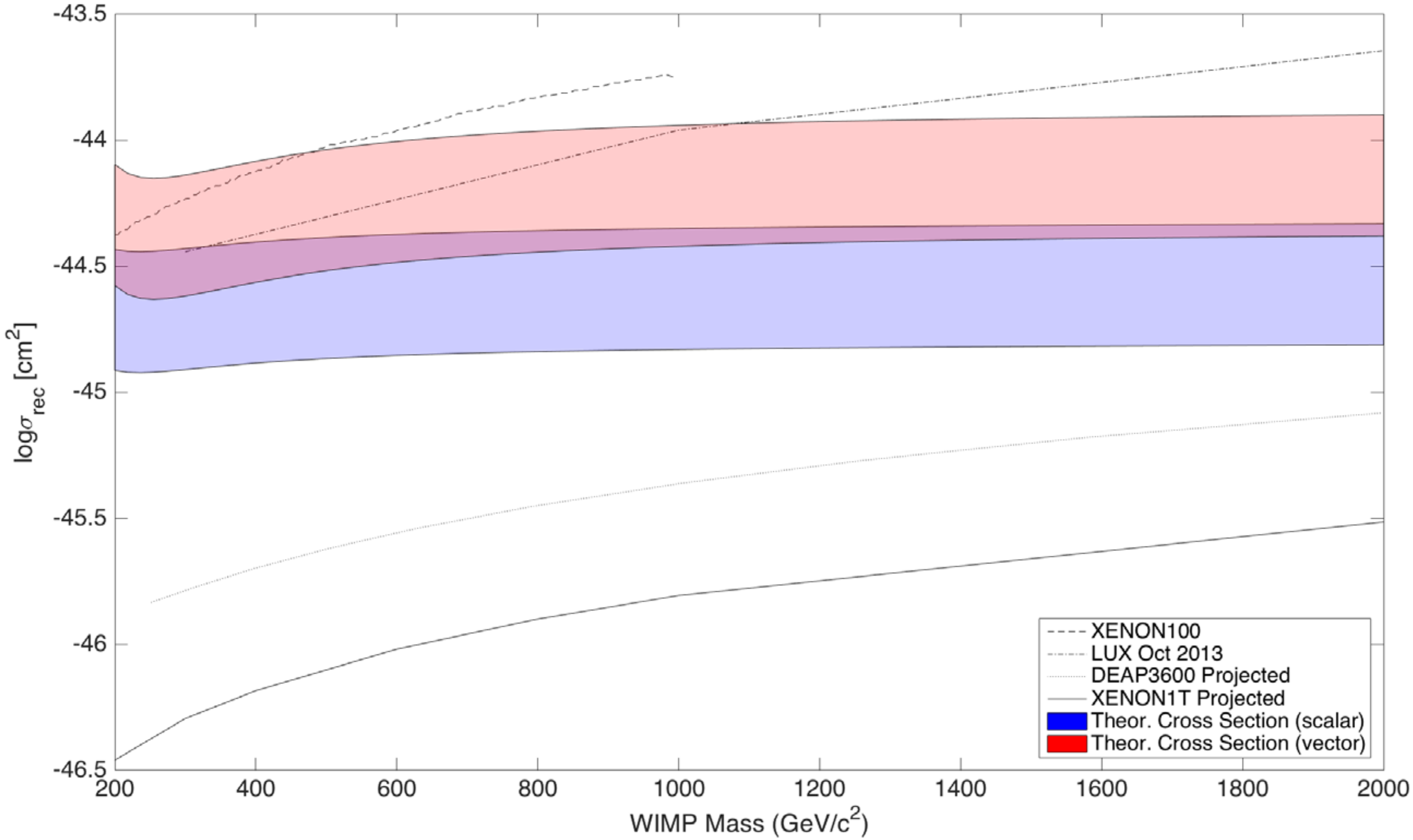
$$\sigma_{DN} = \frac{g^2 \eta_D^2 v_h^2}{4\pi m_h^4} \frac{m_N^2}{(m_D + m_N)^2}.$$

m_N is the nucleon mass

g is the coupling constant in the effective Higgs-nucleon coupling term $g\overline{N}Nh$,

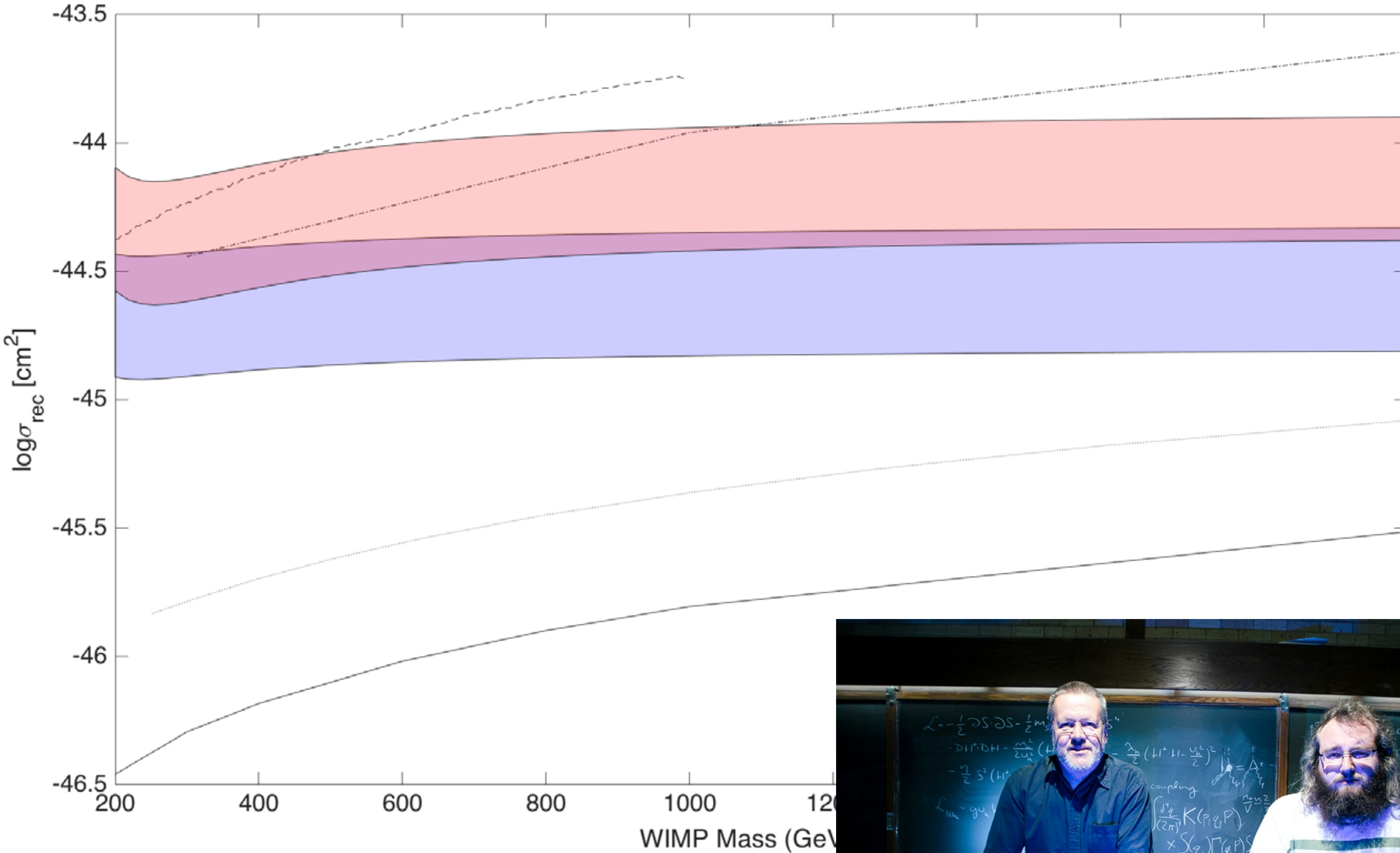
$$210\,\mathrm{MeV} \le g v_h \le 365\,\mathrm{MeV}.$$

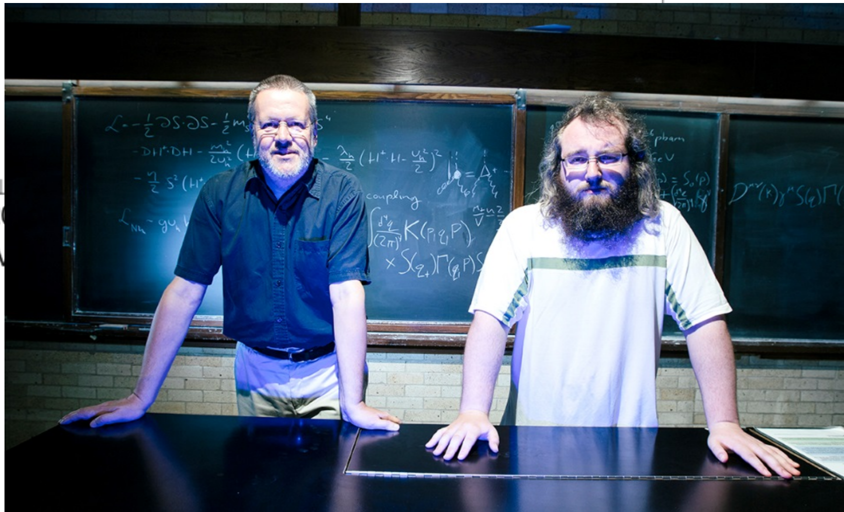
Standard Higgs portal dark matter recoil off nucleons



F. Sage & RD, Astropart. Phys. **71** (2015) 31–35.

Standard Higgs portal dark matter recoil off nucleons





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New Higgs portal models:

Higgs alignment of visible and dark gauge groups

Ψ_L is a dark left-handed doublet with charges $\frac{1}{2} \times Y'_L$ under a dark gauge group $SU'(2) \times U'(1)$.

The corresponding right-handed singlets $\psi_{i,R}$ have charges $Y'_{1,R} = Y'_L + Y_H = Y'_L + 1$ and $Y'_{2,R} = Y'_L - Y_H = Y'_L - 1$ under the dark $U'(1)$.

The coupling to the Standard Model Higgs boson

$$\mathcal{L}_{H-DM} = -\frac{\sqrt{2}}{v_h}\left(m_2 \overline{\Psi}_L \cdot H \cdot \psi_{2,R} + m_1 \overline{\Psi}_L \cdot \underline{\epsilon} \cdot H^* \cdot \psi_{1,R}\right) + h.c.$$

aligns the electroweak gauge group $SU_w(2) \times U_y(1)$ with the dark gauge group $SU'(2) \times U'(1)$ and gives masses m_1 and m_2 to the dark fermions.

→ asymmetric dark matter

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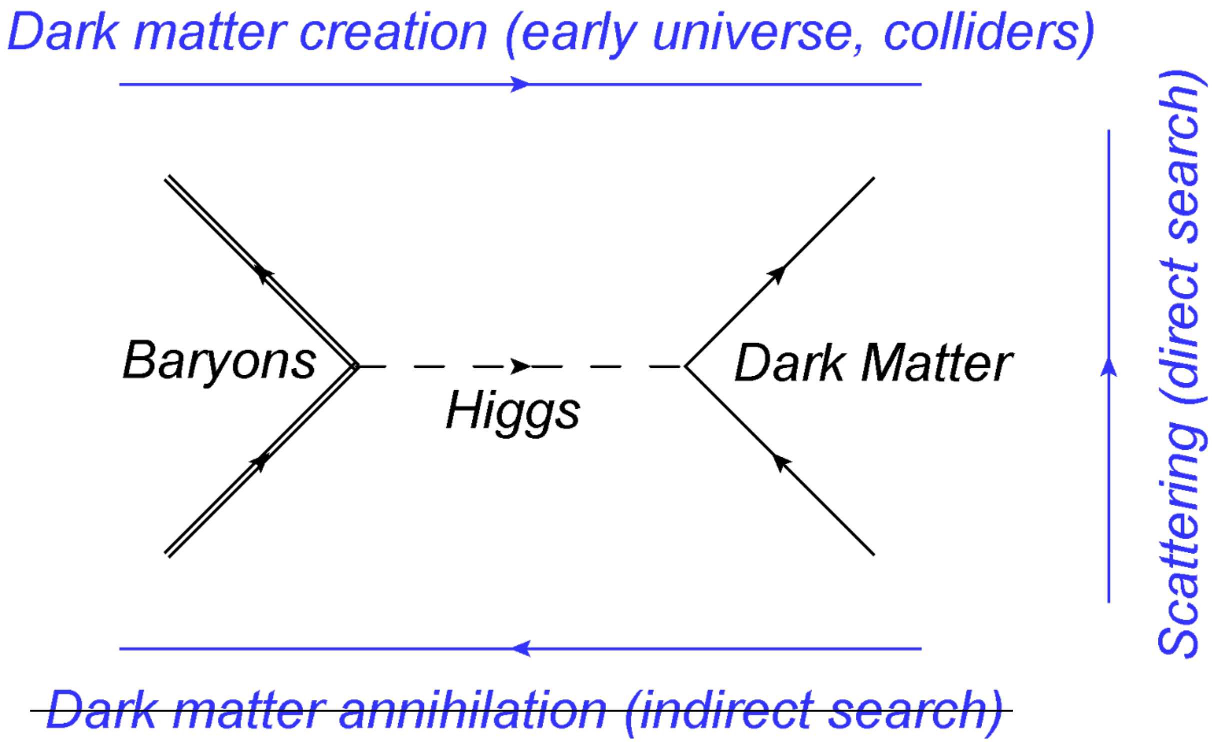
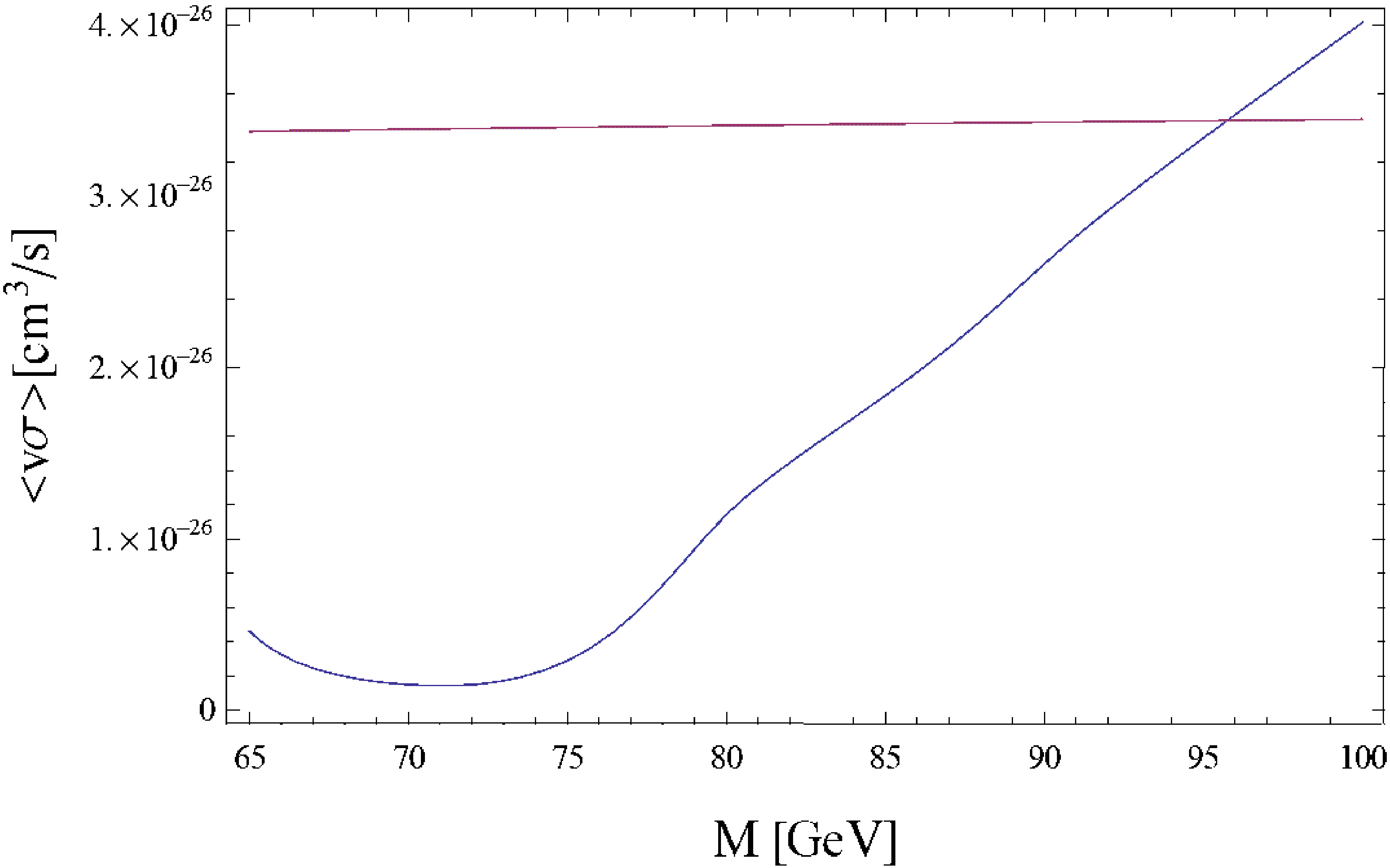
aligns the electroweak gauge group $SU_w(2) \times U_y(1)$ with the dark gauge group $SU'(2) \times U'(1) \rightarrow$ asymmetric dark matter.



However, thermal creation for a dark matter mass above $m_h/2$ yields a dark matter mass $m_D = 96$ GeV, but too large a nuclear recoil cross section $\sigma_{DN} = 1.2 \times 10^{-44}\ \mathrm{cm}^2$.



A dynamical model for alignment of visible and dark sector gauge groups can be constructed using two scalar fields $\underline{M}_i = \{M_{i,ab}\}$:

$$\mathcal{L}_{H-DM} = -\frac{\sqrt{2}}{v_h}\left(\overline{\Psi}_L \cdot \underline{M}_2 \cdot H \cdot \psi_{2,R} + \overline{\Psi}_L \cdot \underline{M}_1 \cdot \underline{\epsilon} \cdot H^* \cdot \psi_{1,R}\right) + h.c.$$

$$D_\mu \underline{M}_i = \partial_\mu \underline{M}_i - iq_2 \boldsymbol{X}_\mu \cdot \frac{\boldsymbol{\sigma}}{2} \cdot \underline{M}_i - i\frac{q_1}{2}\left(Y'_L - Y'_{i,R}\right)C_\mu \cdot \underline{M}_i$$
$$+ig_w \underline{M}_i \cdot \frac{\boldsymbol{\sigma}}{2} \cdot \boldsymbol{W}_\mu + i\frac{g_y}{2} Y_h B_\mu \cdot \underline{M}_i$$

The gauge invariant potential

$$V(\underline{M}_1, \underline{M}_2) = \frac{1}{4}\sum_{i=1}^{2} \lambda_i [\mathrm{Tr}(\underline{M}_i \cdot \underline{M}_i^+) - 2|\mathrm{Det}\underline{M}_i|]$$

yields a ground state

$$\underline{M}_i = m_i \underline{1} \text{ with } m_i \geq 0.$$

Proof: Use polar decomposition $\underline{M}_i = \underline{H}_i \cdot \underline{V}_i$ with positive semidefinite hermitian factor $\underline{H}_i$ and a unitary factor $\underline{V}_i$.

Conclusions

- Minimal bosonic Higgs portal dark matter models in the WIMP mass range below 1 TeV are ruled out now by the Xenon based experiments.
- New Higgs portal models with dynamical alignment of gauge groups are under development. They seem to favor light dark matter.
- Dark matter couplings for thermal creation increase with mass, while DEAP-3600, XENON1T, PandaX-II and LZ push (or will push) the search range to ever higher masses → We need to enhance our understanding of non-perturbatively coupled dark matter.

Annihilation cross sections for scalar singlets

$$\sigma_{SS\to hh} = \eta_S^2 \frac{\sqrt{k^2 + m_S^2 - m_h^2}}{32\pi k(k^2 + m_S^2)} \frac{(2k^2 + 2m_S^2 + m_h^2)^2}{(4k^2 + 4m_S^2 - m_h^2)^2 + m_h^2\Gamma_h^2},$$

$$\sigma_{SS\to f\bar{f}} = N_c\eta_S^2 \frac{(k^2 + m_S^2 - m_f^2)^{3/2}}{8\pi k(k^2 + m_S^2)} \frac{m_f^2}{(4k^2 + 4m_S^2 - m_h^2)^2 + m_h^2\Gamma_h^2},$$

with $N_c = 1$ for leptons and $N_c = 3$ for quarks, and

$$\sigma_{SS\to ZZ,W^+W^-} = \frac{2m_{W,Z}^4 + (m_{W,Z}^2 - 2k^2 - 2m_S^2)^2}{(4k^2 + 4m_S^2 - m_h^2)^2 + m_h^2\Gamma_h^2} \times\frac{\eta_S^2 \sqrt{k^2 + m_S^2 - m_{W,Z}^2}}{16\pi k(k^2 + m_S^2)(1 + \delta_z)},$$

where $\delta_z = 1$ for annihilation into Z bosons and $\delta_z = 0$ for annihilation into W^+W^-.

Annihilation cross sections for vector singlets

$$\sigma_{VV\to hh} = \frac{\eta_V^2 \sqrt{k^2 + m_V^2 - m_h^2}}{288\pi k(k^2 + m_V^2)} \left(\frac{2k^2 + 2m_V^2 + m_h^2}{4k^2 + 4m_V^2 - m_h^2}\right)^2 \times \frac{(2k^2 + m_V^2)^2 + 2m_V^4}{m_V^4},$$

$$\sigma_{VV\to f\bar{f}} = N_c \frac{\eta_V^2 m_f^2 (k^2 + m_V^2 - m_f^2)^{3/2}}{72\pi m_V^4 k(k^2 + m_V^2)} \times \frac{(2k^2 + m_V^2)^2 + 2m_V^4}{(4k^2 + 4m_V^2 - m_h^2)^2 + m_h^2 \Gamma_h^2},$$

and

$$\sigma_{VV\to ZZ,W^+W^-} = \frac{\eta_V^2 \sqrt{k^2 + m_V^2 - m_{W,Z}^2}}{144\pi(1 + \delta_z)k(k^2 + m_V^2)} \frac{(2k^2 + m_V^2)^2 + 2m_V^4}{m_V^4} \times \frac{(2k^2 + 2m_V^2 - m_{W,Z}^2)^2 + 2m_{W,Z}^4}{(4k^2 + 4m_V^2 - m_h^2)^2 + m_h^2 \Gamma_h^2}.$$

Dark matter coupling versus mass from thermal dark matter creation

Freeze-out happens during radiation domination

$$t = \frac{b}{T^2} \qquad\qquad b = \frac{3\hbar m_{Planck} c^2}{\pi k_B^2}\sqrt{\frac{5}{2g_*(T)}}\ :$$

Lee-Weinberg condition for freeze out temperature:

$$\exp(\xi) = \frac{2bk_B^2 m_D c^2}{(\sqrt{2\pi}\hbar c)^3}\langle\sigma v\rangle\frac{\sqrt{\xi}}{\xi - 1.5} \qquad \xi = m_D c^2/k_B T_f$$

Evolution of dark matter density to the present epoch:

$$\varrho_D^{(1)} = n(t_0)m_D c^2 = \frac{2\xi - 3}{2\xi - 1}\xi\frac{k_B\sqrt{b}}{2\langle\sigma v\rangle {t_{eq}}^{3/2} {z_{eq}}^3}$$

Elimination of $\langle\sigma v\rangle$ yields ξ (or equivalently relation $T_f(m_D)$)

Dark matter coupling versus mass from thermal dark matter creation (cont'd)

Substitution of $\xi = m_D c^2/k_B T_f$ as a function of m_D into

$$\varrho_D^{(1)} = n(t_0) m_D c^2 = \frac{2\xi - 3}{2\xi - 1}\xi \frac{k_B\sqrt{b}}{2\langle\sigma v\rangle {t_{eq}}^{3/2} {z_{eq}}^3}$$

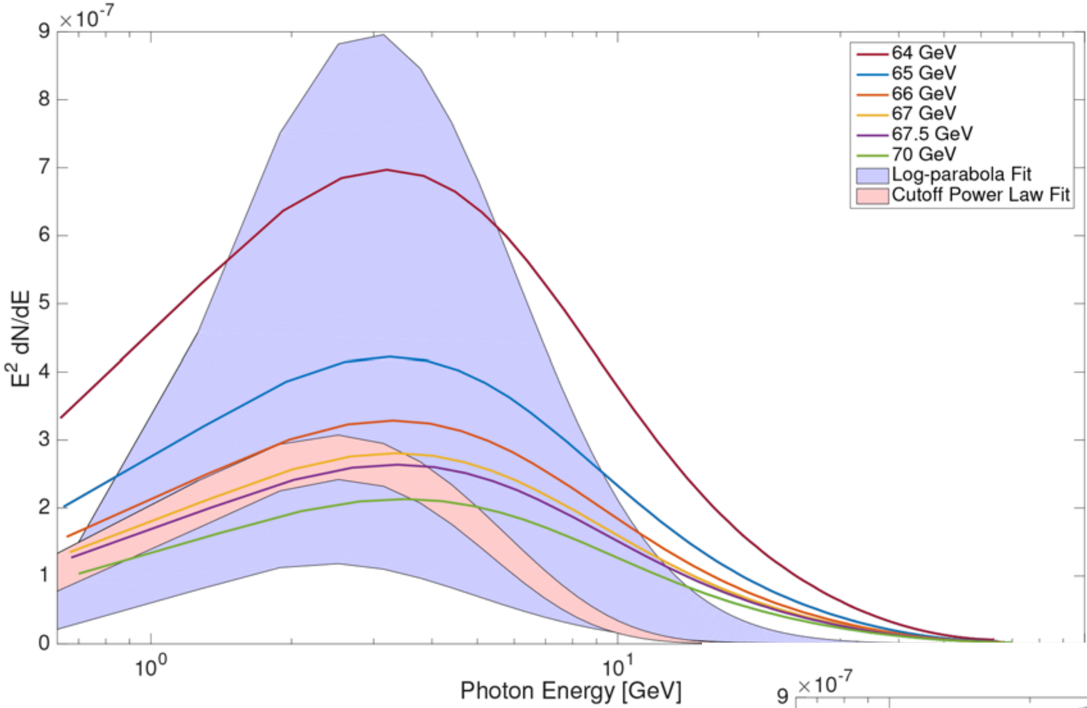
yields the required annihilation cross section $\langle\sigma v\rangle$ for thermal dark matter creation as a function of m_D.

On the other hand, Gondolo and Gelmini have taught us how to calculate thermal cross section averages if we know $\sigma(s)$

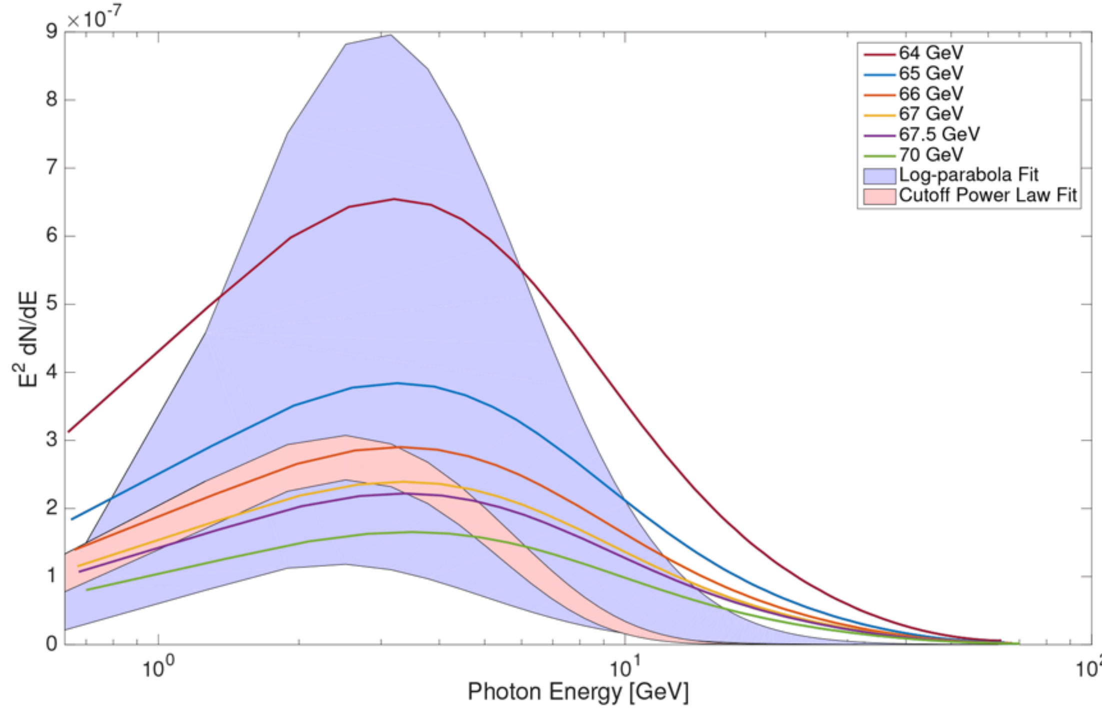
$$\langle\sigma v\rangle_{GG}(T) = \frac{1}{8m^4 T K_2^2(m/T)} \int_{4m^2}^{\infty} ds\, \sqrt{s}\left(s - 4m^2\right)\sigma(s) K_1(\sqrt{s}/T)$$

Comparison yields the dark matter coupling as a function of mass:

$$\eta^2 = \frac{\langle\sigma v\rangle(T_f)}{\langle\sigma v\rangle_{GG}(T_f)/\eta^2}.$$

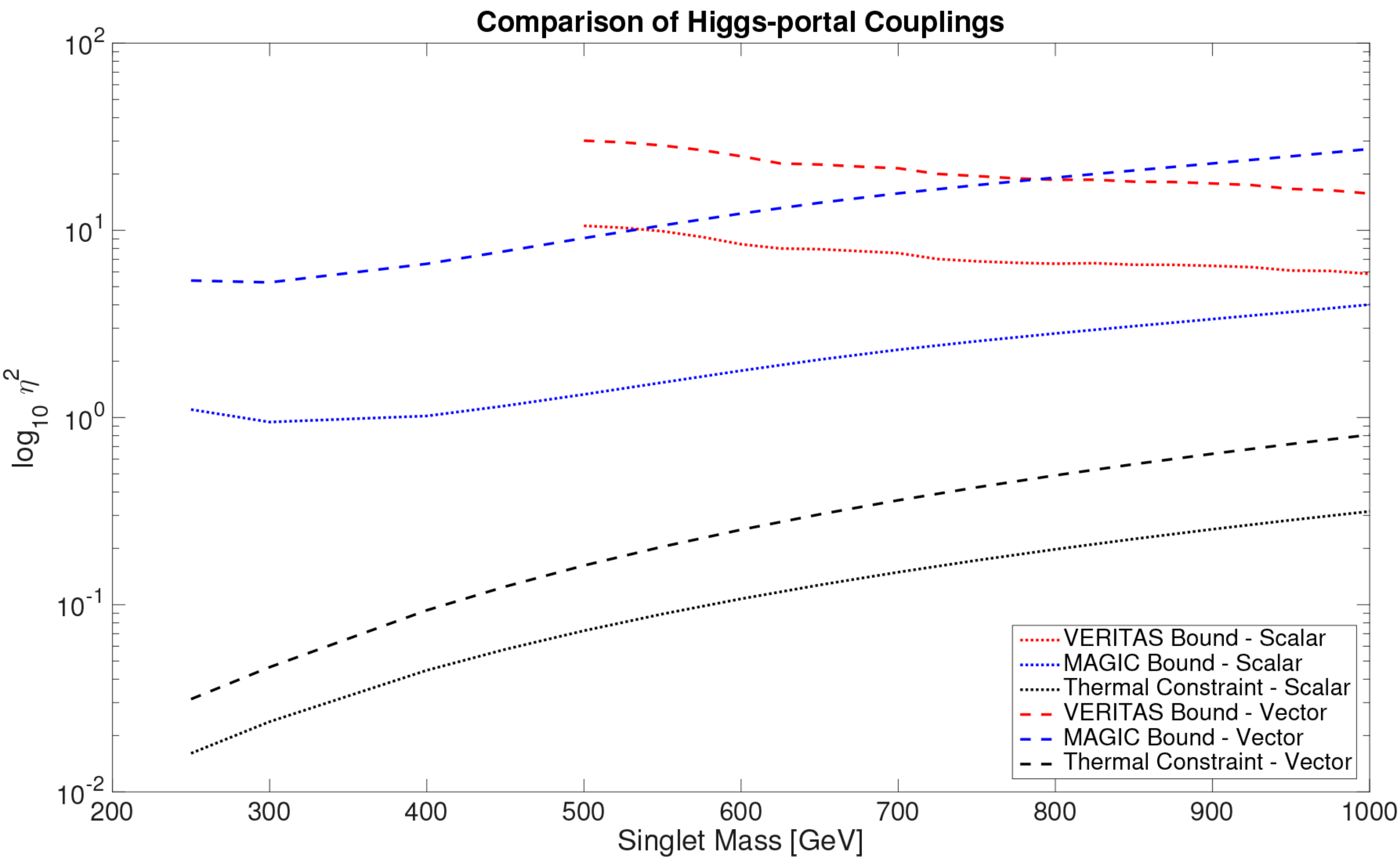


Scalar Annihilation Flux compared to GC Excess



Vector Annihilation Flux compared to GC Excess

Bounds from Segue I on Higgs portal couplings



The matter which we know is described by the Standard Model of Particle Physics

$$
\begin{aligned}
\mathcal{L} = \sum_{(\nu,e)} \Bigg[& (\overline{\nu}_L, \overline{e}_L)\, \gamma^\mu \left(\mathrm{i}\partial_\mu + \frac{e}{\sin\theta} \boldsymbol{W}_\mu \cdot \frac{\boldsymbol{\sigma}}{2} - \frac{e}{2\cos\theta} B_\mu \right) \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \overline{e}_R \gamma^\mu \left(\mathrm{i}\partial_\mu - \frac{e}{\cos\theta} B_\mu \right) e_R + \mathrm{i}\overline{\nu}_R \gamma^\mu \partial_\mu \nu_R \Bigg] \\
& + \sum_{(u,d)} \Bigg[(\overline{u}_L, \overline{d}_L)\, \gamma^\mu \left(\mathrm{i}\partial_\mu + \frac{e}{\sin\theta} \boldsymbol{W}_\mu \cdot \frac{\boldsymbol{\sigma}}{2} + \frac{e}{6\cos\theta} B_\mu + g {G_\mu}^a \frac{\lambda_a}{2} \right) \begin{pmatrix} u_L \\ d_L \end{pmatrix} \\
& \quad + \overline{d}_R \gamma^\mu \left(\mathrm{i}\partial_\mu - \frac{e}{3\cos\theta} B_\mu + g {G_\mu}^a \frac{\lambda_a}{2} \right) d_R + \overline{u}_R \gamma^\mu \left(\mathrm{i}\partial_\mu + \frac{2e}{3\cos\theta} B_\mu + g {G_\mu}^a \frac{\lambda_a}{2} \right) u_R \Bigg] \\
& - \frac{\sqrt{2}}{v_h} \sum_{(\nu,e)} \Bigg[(\overline{\nu}_L, \overline{e}_L) \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} m_e e_R + \overline{e}_R m_e \left(H^{+*}, H^{0*} \right) \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \\
& \quad + (\overline{\nu}_L, \overline{e}_L) \begin{pmatrix} H^{0*} \\ -H^{+*} \end{pmatrix} \underline{M}_\nu \nu_R + \overline{\nu}_R \underline{M}_\nu^+ \left(H^0, -H^+ \right) \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \Bigg] \\
& - \frac{\sqrt{2}}{v_h} \sum_{(u,d)} \Bigg[(\overline{u}_L, \overline{d}_L) \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \underline{M}_d d_R + \overline{d}_R \underline{M}_d^+ \left(H^{+*}, H^{0*} \right) \begin{pmatrix} u_L \\ d_L \end{pmatrix} \\
& \quad + (\overline{u}_L, \overline{d}_L) \begin{pmatrix} H^{0*} \\ -H^{+*} \end{pmatrix} m_u u_R + \overline{u}_R m_u \left(H^0, -H^+ \right) \begin{pmatrix} u_L \\ d_L \end{pmatrix} \Bigg] \\
& - \left(\partial^\mu \left(H^{+*}, H^{0*} \right) + \mathrm{i} \frac{e}{\sin\theta} \left(H^{+*}, H^{0*} \right) \boldsymbol{W}^\mu \cdot \frac{\boldsymbol{\sigma}}{2} + \mathrm{i} \frac{e}{2\cos\theta} \left(H^{+*}, H^{0*} \right) B^\mu \right) \\
& \times \left(\partial_\mu - \mathrm{i} \frac{e}{\sin\theta} \boldsymbol{W}_\mu \cdot \frac{\boldsymbol{\sigma}}{2} - \mathrm{i} \frac{e}{2\cos\theta} B_\mu \right) \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} - \frac{m_h^2}{2v_h^2} \left(H^+ H - \frac{v_h^2}{2} \right)^2 \\
& - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \boldsymbol{W}_{\mu\nu} \cdot \boldsymbol{W}^{\mu\nu} - \frac{1}{4} {G_{\mu\nu}}^a {G^{\mu\nu}}_a .
\end{aligned}
$$

Alternative proposals: Modify Einstein gravity to try to accommodate flat galactic rotation curves and stronger than expected gravitational lensing

TeVeS = Tensor-Vector-Scalar theory (motivated by MOND): Bekenstein (Milgrom) adds a constrained time-like vector field and a scalar field in the gravitational sector to modify gravity at large distances.

MOG = Modified Gravity: John Moffat (Waterloo) adds a massive vector field and three scalar fields in the gravitational sector to modify gravity at large distances.

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