Minimal realization of light thermal Dark Matter

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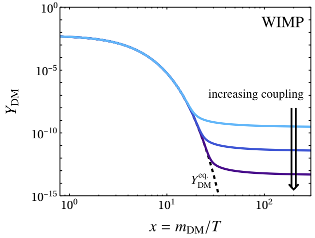
Thermal relic dark matter

suppose there exists a stable neutral particle beyond the Standard Model...

- thermal relic ↔ was in thermal equilibrium with SM bath
- relic abundance from cosmic expansion and particle properties

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi\to\mathrm{SM}}\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$



$$\Omega_\chi \propto \frac{1}{\langle\sigma v\rangle_{\mathrm{fo}}}, \qquad \Omega_{\mathrm{DM}}h^2 = 0.12 \quad \Longrightarrow \quad \langle\sigma v\rangle_{\mathrm{fo}} \sim 2\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$$

⟹ general framework, simplest cosmology, useful prediction

Light thermal Dark Matter

Issue 1: needs a new mediator?

- "WIMP miracle"

$$\frac{\Omega_{\mathrm{DM}} h^2}{0.12} \sim \frac{\text{few} \times 10^{-9}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \sim \frac{m_{\mathrm{EW}}^2 G_F^2}{\langle \sigma v \rangle}$$

- sub-GeV DM

$$\langle \sigma v \rangle \sim \frac{m_\chi^2 g^4}{M^4}, \qquad m_\chi \sim 100\,\mathrm{MeV} \Rightarrow \begin{cases} 100\,\mathrm{GeV}\ \text{mediator},\ g = 1 \\ 100\,\mathrm{MeV}\ \text{mediator},\ g = 10^{-3} \end{cases}$$

$\Rightarrow$ need new light mediator!

Light thermal Dark Matter

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$\Rightarrow$ need new light mediator!

- conclusion in principle relaxed in SIMP scenarios [Hochberg+'1402.5143], [Kuflik+'1512.04545]
  - everyone still introduces light mediators (eg. [Hochberg+'1512.07917], [Choi+'1707.01434], [Hochberg+'1806.10139])

Possible light ($\lesssim$ GeV) mediators

requirements:

- need to couple to light SM dof
- need to couple to DM singlets

popular options:

- dark photon $U(1)_D$, kinetically mixed with $U(1)_Y$
- $U(1)_{L_\mu - L_\tau}$ Z'
- scalar singlet, $\phi(H^\dagger H)$
- purely phenomenological, eg. $\frac{1}{M}\phi_{\text{med}} H \bar{f}_L f_R$

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this talk:

light mediator $\in H_2$, second Higgs doublet

The two-Higgs-Doublet model

Scalar potential

- add a second scalar doublet to the SM

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2^0 + iA) \end{pmatrix}$$

- phyiscal states in alignment limit

$$h_{\mathrm{SM}} \simeq \phi_1^0,\ H_{\mathrm{new}} \simeq \phi_2^0,\ A,\ H^\pm$$

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- scalar potential

$$\begin{aligned} V(H_1,H_2,S) &= \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 - \{\mu_{12}^2 H_1^\dagger H_2 + \text{h.c.}\} \\ &+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &+ \left\{\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \text{h.c.}\right\} + \left\{\left[\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \text{h.c.}\right\} \end{aligned}$$

Light scalars in the 2HDM

- scalar masses in alignment limit:

$$\begin{aligned} m_h^2 &= \lambda_1 v^2, \\ m_H^2 &= \mu_{22}^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5), && \rightarrow \text{may be small} \\ m_A^2 &= m_H^2 - v^2 \lambda_5, && \rightarrow \text{may be split} \\ m_{H^\pm}^2 &= m_H^2 - v^2 \frac{(\lambda_4 + \lambda_5)}{2} && \rightarrow \text{may be split} \end{aligned}$$

- choose $m_H \ll m_A^2, m_{H^\pm}^2$, and for simplicity $m_A^2 \sim m_{H^\pm}^2$
- perturbativity: $|\lambda| < \sqrt{4\pi} \Rightarrow m_A, m_{H^\pm} \lesssim 460\,\text{GeV}$

we can have a sub-GeV scalar $H \in$ 2HDM

Electroweak precision observables

... is there a hint already?

- mass splittings between members of an electroweak multiplet contribute to EW oblique parameters

$$T = \frac{1}{16\pi s_W^2 M_W^2}\left(\mathcal{F}(m_{H^\pm}^2, m_H^2) + \mathcal{F}(m_{H^\pm}^2, m_A^2) - \mathcal{F}(m_H^2, m_A^2)\right)$$

$$\text{with } \mathcal{F}(m_1^2, m_2^2) \equiv \frac{1}{2}\left(m_1^2 + m_2^2\right) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\left(\frac{m_1^2}{m_2^2}\right)$$

- $m_{A,H^\pm} \lesssim 250\,\mathrm{GeV}$ easy; if larger need $m_A^2 \sim m_{H^\pm}^2$

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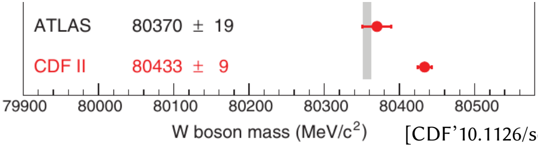
→ *CDF II M_W indications for $T > 0$?!*

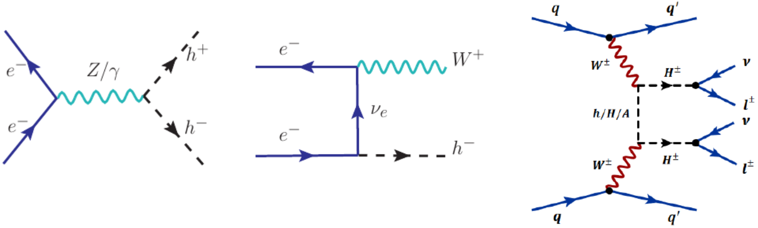


[CDF'10.1126/science.abk1781]

New Scalars at Colliders

direct constraints on the mass spectrum

- existing constraints
  - $m_A > m_Z - m_H \sim 90\,\text{GeV}$ to forbid $Z \to HA$
  - charged scalar production: $m_{H^\pm} \gtrsim 110\,\text{GeV}$ from LEP $W \to \nu l$ universality
  - LHC constraints evaded for substantial $\text{Br}_{\nu\tau}$
- signature processes
  - $pp \to H^\pm H^\pm jj \to l^\pm_\alpha l^\pm_\beta jj + \not{E}_T$



[1907.09498][2003.03386]

SM Higgs properties

- alignment limit: h mostly SM-like
- $h \to HH \to l^+l^-l^+l^-$ / invisible

$$V \supset vhH^2 \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) \qquad \to \lambda_3 \simeq -(\lambda_4 + \lambda_5) \quad \propto m_{H^+}^2/v^2$$

- $h \to \gamma\gamma$

$$V \supset \lambda_3 vhH^+H^-$$

negatively interferes with t-loop, predicts $R_{\gamma\gamma} < 1$; LHC data prefer $R_{\gamma\gamma} \gtrsim 1$ [Okawa,Omura'2011.04788]

H enables light thermal DM

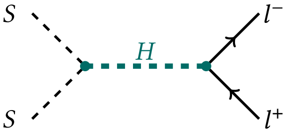
- coupling to light SM fermions → leptons for convenience

$$-\mathcal{L}_Y \supset \widetilde{Y}_l \bar{\psi}_L H_1 \psi_R + Y_l \bar{\psi}_L H_2 \psi_R + \text{h.c.}$$

  - in alignment limit: $\widetilde{Y}_l = \text{diag}(m_e, m_\mu, m_\tau)/v$
  - Y_l → mediator coupling, DM phenomenology, flavour violation

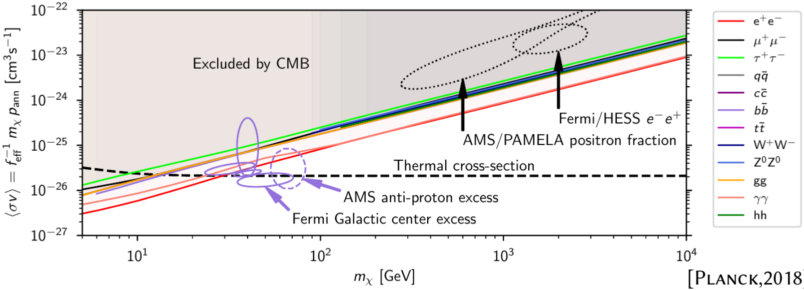
- simplest DM candidate: real scalar S

$$-\mathcal{L}_S \supset \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4 + \frac{\kappa_1}{2} S^2 (H_1^\dagger H_1) + \frac{\kappa_2}{2} S^2 (H_2^\dagger H_2) + \left\{ \frac{\kappa_{12}}{2} S^2 (H_1^\dagger H_2) + h.c. \right\}$$



Light thermal Dark Matter

Issue 2: annihilation constraints



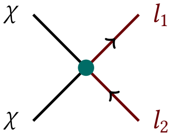
[Planck,2018]

- WIMPs with $m_{\rm WIMP} \lesssim 10\,{\rm GeV}$ require

$$\langle\sigma v\rangle_{\rm today} \ll \langle\sigma v\rangle_{\rm freeze-out}$$

Forbidden Dark Matter

[Griest,Seckel'91][DAgnolo,Ruderman'1505.07107]



- kinematically forbidden annihilation, $2m_\chi < m_{l_1} + m_{l_2}$

$$\langle \sigma v \rangle_{\chi\chi \to ll} = \langle \sigma v \rangle_{ll \to \chi\chi} e^{-2\Delta (m_\chi / T)}$$

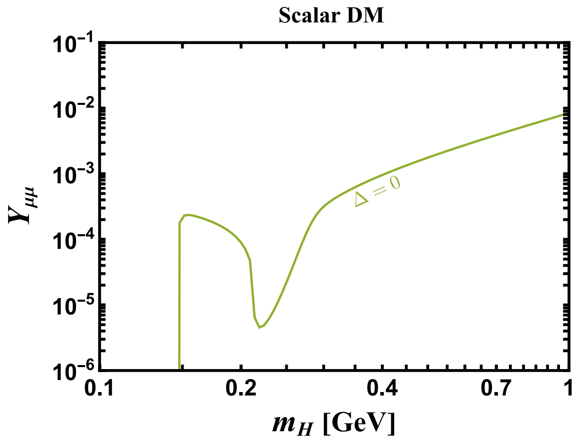
- suppressed by mass splitting

$$\Delta = (m_{l_1} + m_{l_2} - 2m_\chi)/2m_\chi$$

- $\langle \sigma v \rangle_{\chi\chi \to ll}$ zero at late times $T \to 0$

$\to$ spoiler: $\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma}$ allowed!

Relic abundance – $\mu\mu$



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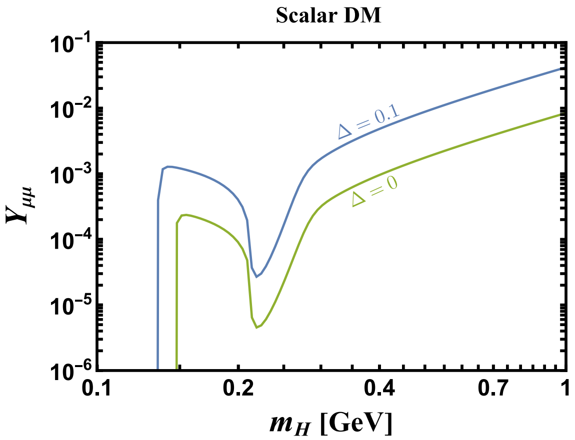
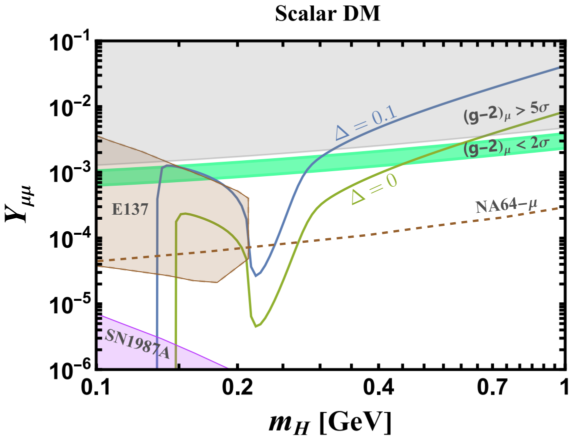
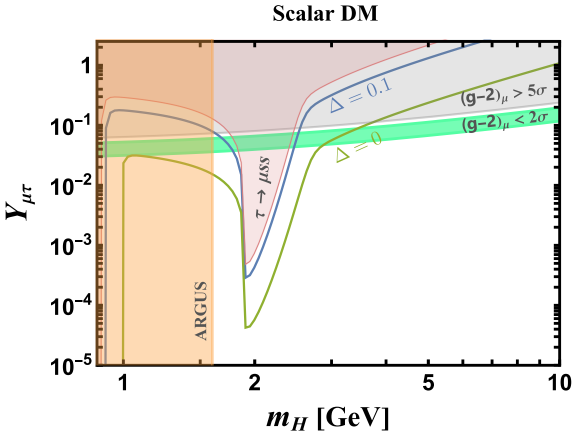


Relic abundance results - $\mu\mu$ $\kappa_{ij} = 10^{-3}$ fixed



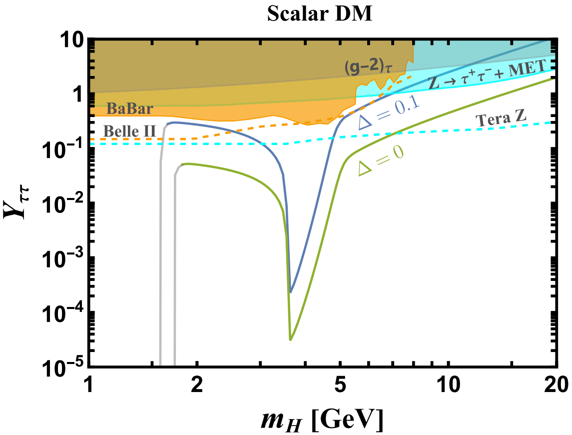
- $(g-2)_\mu$ [FNAL'2104.03281][Jana+'2003.03386]
- E137 beam dump [Bjorken+'88][Batell+'1712.10022]
- SN energy loss [Croon+'2006.13942]

Relic abundance results - $\mu\tau$ $\kappa_{ij} = 10^{-3}$ fixed



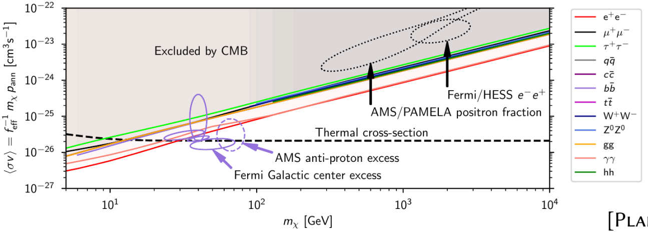
- $(g-2)_\mu$ [FNAL'2104.03281][Jana+'2003.03386]
- $\tau \longrightarrow \mu H$ LFV 2-body decay [ARGUS'95] $\Rightarrow m_H > m_\tau - m_\mu$
- $\tau \longrightarrow \mu SS$ adds to expt. $\Gamma(\tau \longrightarrow \mu\bar{\nu}_\mu\nu_\tau)$ $\Rightarrow m_{\mathrm{DM}} > (m_\tau - m_\mu)/2$

Relic abundance results - $\tau\tau$ $\kappa_{ij} = 10^{-3}$ fixed

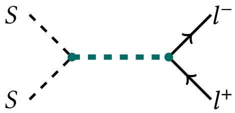


- $e^+e^- \to \gamma H$, with $H \to$ dark
  [BaBaR'1702.03327][Dolan+'1709.00009][DAgnolo+'2012.11766]
- $Z \to \bar{\tau}\tau H$ adds to expt. $\mathrm{Br}(Z \to \bar{\tau}\tau)$ [Chen+'1807.03790]

Radiative annihilation probes forbidden DM



[Planck,2018]



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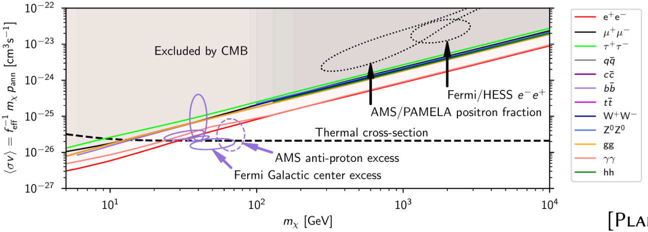

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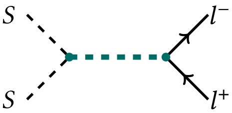
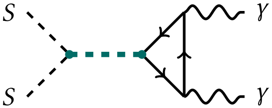


forbidden



{ suppressed by α^2
enhanced by $e^{2\Delta x_f}$ wrt. $\langle\sigma v\rangle_{\rm th}^{\rm naive}$

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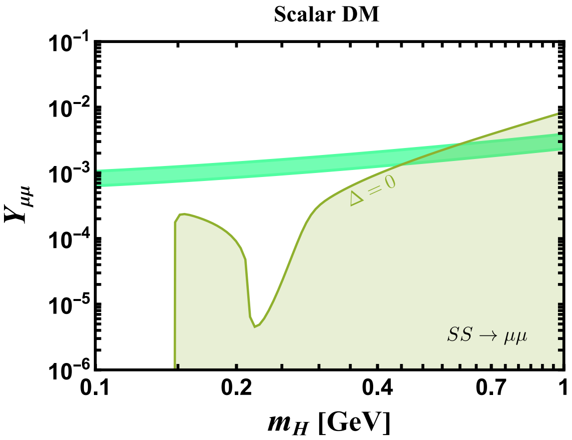

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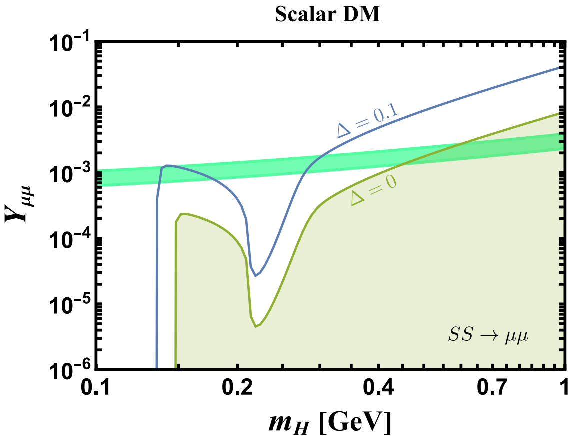

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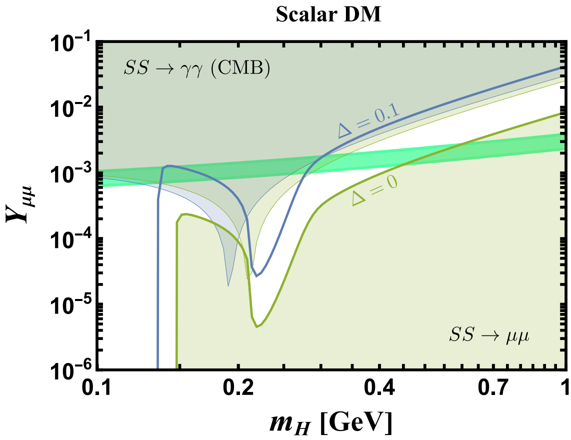

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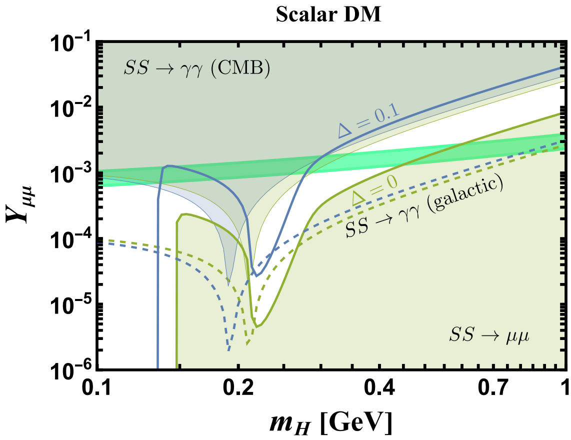


- 2 oom sensitivity boost from proposed telescopes [Bartels+'1703.02546]
- γ-ray line signal close to m_μ, m_τ as smoking-gun signal

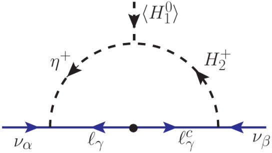
Neutrino masses?

purely scalar model for DM and M_ν: Zee model

- introduce a charged scalar singlet $\eta^+ \sim (1,1,1)$

$$-\mathcal{L}_Y \supset f_{ij} L_i \epsilon L_j \eta^+ + \text{h.c.}$$

$$-V \supset \mu H_1 \epsilon H_2 \eta^- + \text{h.c.}$$



- leads to neutrino masses

$$M_\nu \propto \left(f m_E Y_l - {Y_l}^T m_E f \right)$$

- DM constraints
  - non-forbidden channels must have negligible coupling → Y_l texture
- LFV
  - $\mu \to e\gamma, \tau \to e\gamma$, and $\tau \to \mu\gamma$ at one-loop

⇒ $\mu\tau$ coupled scenario works out! predicts $\mu \to e\gamma$ at reach of MEG-II

Light 2HDM Portal to general Dark Sectors

- 2HDM provides light scalar mediator
  - loads of accessible phenomenology!
  - first hints in $(g-2)_\mu$, T-parameter?
- DMID problem of light thermal DM circumvented
  - minimal realisation of forbidden DM
  - radiative annihilation → positive identification
- neutrino masses & light thermal DM, purely scalar

looking forward to your comments!

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Fermionic forbidden DM

- Yukawa Lagrangian

$$-\mathcal{L}_Y \supset \psi_R + Y_l \bar{\psi}_L H_2 \psi_R + Y_\chi S \bar{\chi}\chi + m_\chi \bar{\chi}\chi + h.c.,$$

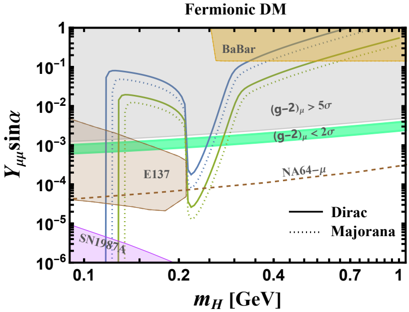
- scalar potential

$$V_{\{H_1,H_2,S\}} \supset \mu_{12S} S(H_1^\dagger H_2) + \frac{\kappa_{12}}{2} S^2 (H_1^\dagger H_2) + h.c..$$

- scalars $\phi_1^0 \sim h$, while other CP-even scalars $\phi_2^0 \in H_2$, $\omega \in S$ mix

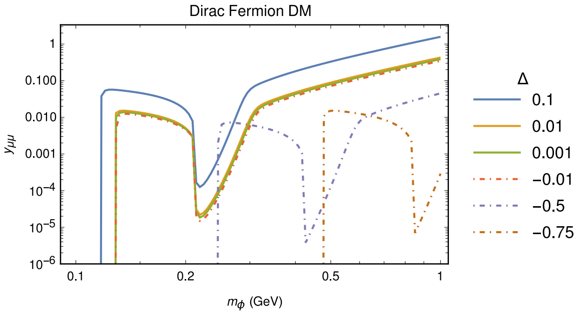
$$H = \cos\alpha\ \omega + \sin\alpha\ \phi_2^0,$$
$$H' = -\sin\alpha\ \omega + \cos\alpha\ \phi_2^0,$$

Light 2HDM Portal to general Dark Sectors – Fermion DM



- similar at first sight to scalar DM

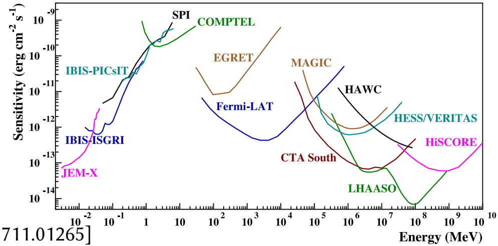
Light 2HDM Portal to general Dark Sectors – Fermion DM



- similar at first sight to scalar DM
- but: non-forbidden mass spectra allowed (velocity suppressed DMID)
- less tuned? less predictive?

Future MeV γ-ray missions

AMEGO, e-ASTROGAM, GECCO, ...



[e-ASTROGAM'1711.01265]

Johannes Herms

Future MeV γ-ray missions

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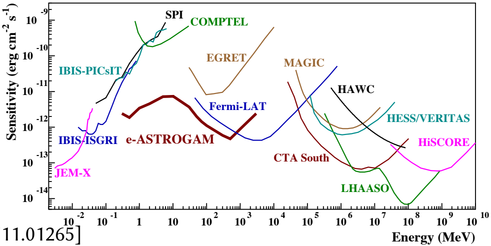

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Future MeV γ-ray missions

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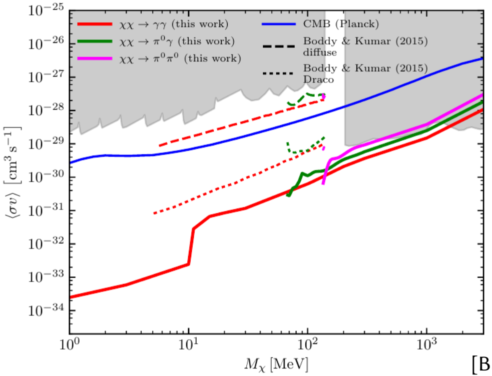

[Bartels+'1703.02546]

- γ-ray line signal close to m_μ, m_τ as smoking-gun signal

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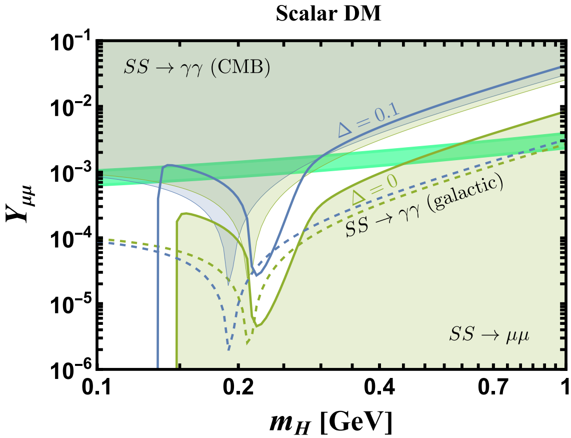

- γ-ray line signal close to m_μ, m_τ as smoking-gun signal

Neutrino masses – details

we provide a benchmark

$$M_\nu = a_0 \left(f m_E Y_l - Y_l^T m_E f \right)$$

$$a_0 = \frac{\sin 2\omega}{16\pi^2} \ln \left(\frac{m_{h^+}^2}{m_{H^+}^2} \right); \quad \sin 2\omega = \frac{\sqrt{2} v \mu}{m_{h^+}^2 - m_{H^+}^2},$$

$$Y_l = 10^{-4} \begin{pmatrix} 0 & 0 & 3.494 \times 10^{-4} \\ 0 & 0 & 5 \\ -10^{-3} & -0.382 & 0.542 \end{pmatrix},$$

$$a_0 \cdot f = 10^{-7} \begin{pmatrix} 0 & 2.135 & 0 \\ -2.135 & 0 & 2.266 \\ 0 & -2.266 & 0 \end{pmatrix}.$$

Neutrino observables associated with this fit yield,

$$\Delta m_{21}^2 = 7.486 \times 10^{-5} eV^2, \ \Delta m_{31}^2 = 2.511 \times 10^{-3} eV^2,$$
$$\theta_{12} = 34.551^\circ, \ \theta_{23} = 47.830^\circ, \ \theta_{13} = 8.545^\circ.$$