Light 2HDM scalars as dark matter mediators

Johannes Herms

HPNP 2025 Osaka

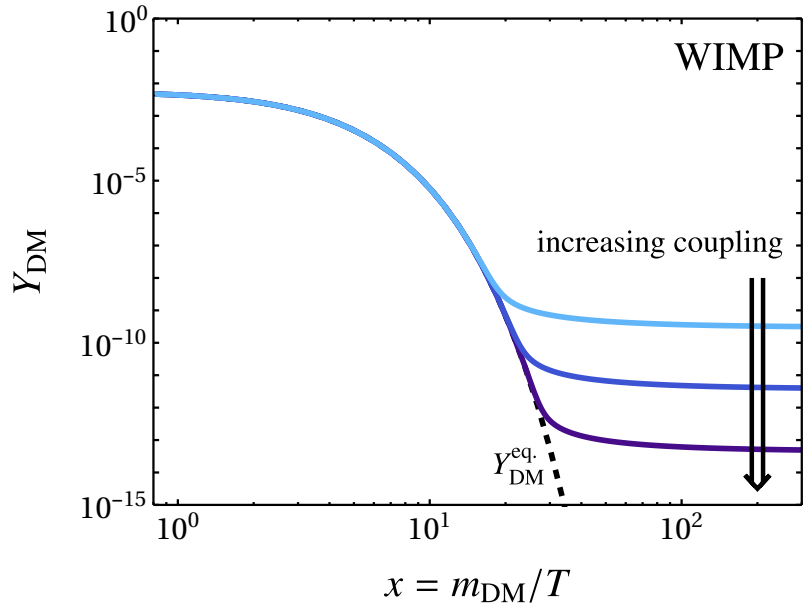
based on [PRL.129.091803] [Phys.Lett.B 845(2023)138167]

13.6.2025

Thermal relic dark matter

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

- "thermal relic" $\leftrightarrow$ was in thermal equilibrium with SM bath



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

$\Rightarrow$ simplest cosmology, generic prediction: $\langle\sigma v\rangle_{\rm fo}$

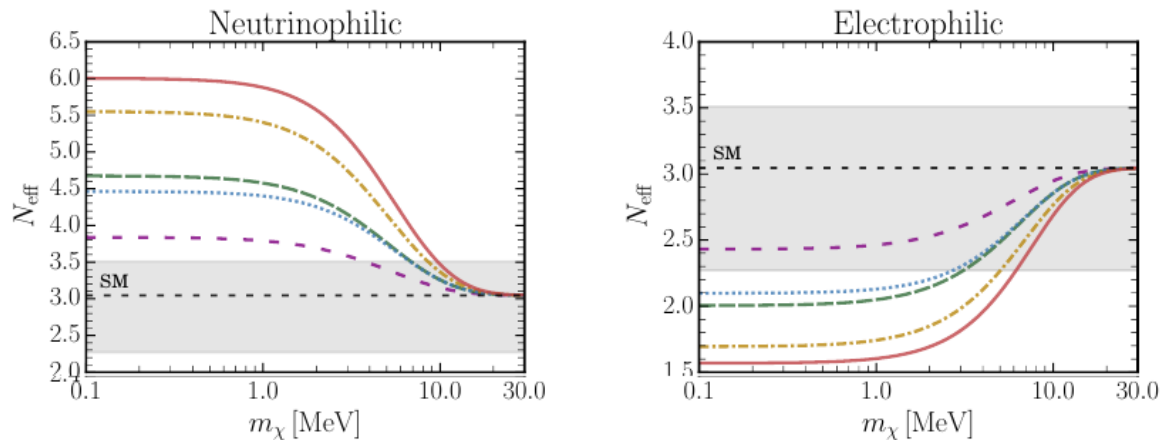
The lightest WIMP?

Lee-Weinberg and BBN

- Lee Weinberg bound

$$m_{\text{V-A } G_F \text{ WIMP}} > 2\,\text{GeV}$$

- BBN + CMB constraints
  - modified expansion history from additional $\rho_{\text{products}} \to N_{\text{eff}}$



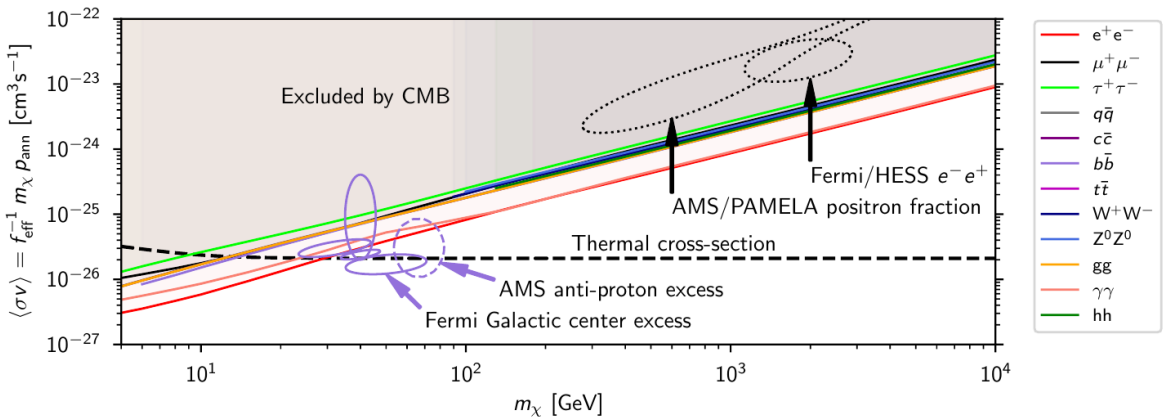
[Sabti+'20]

$$m_{\text{WIMP}} \gtrsim O(\text{few})\,\text{MeV}$$

⇒ Let's look at sub-GeV WIMPs!

Observational trouble for light WIMPs

annihilation energy injection rate $\propto m_{\rm DM}\langle\sigma v\rangle n_{\rm DM}^2 \propto \dfrac{\langle\sigma v\rangle}{m_{\rm DM}}$



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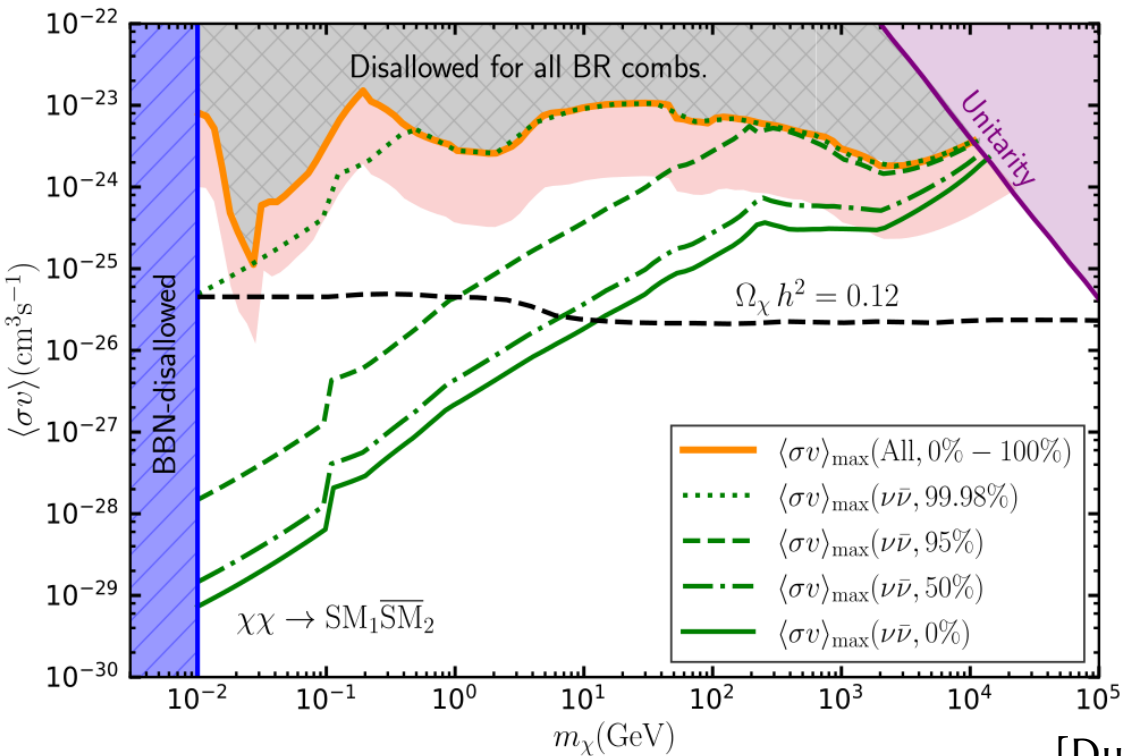

[Dutta+'2212.09795]

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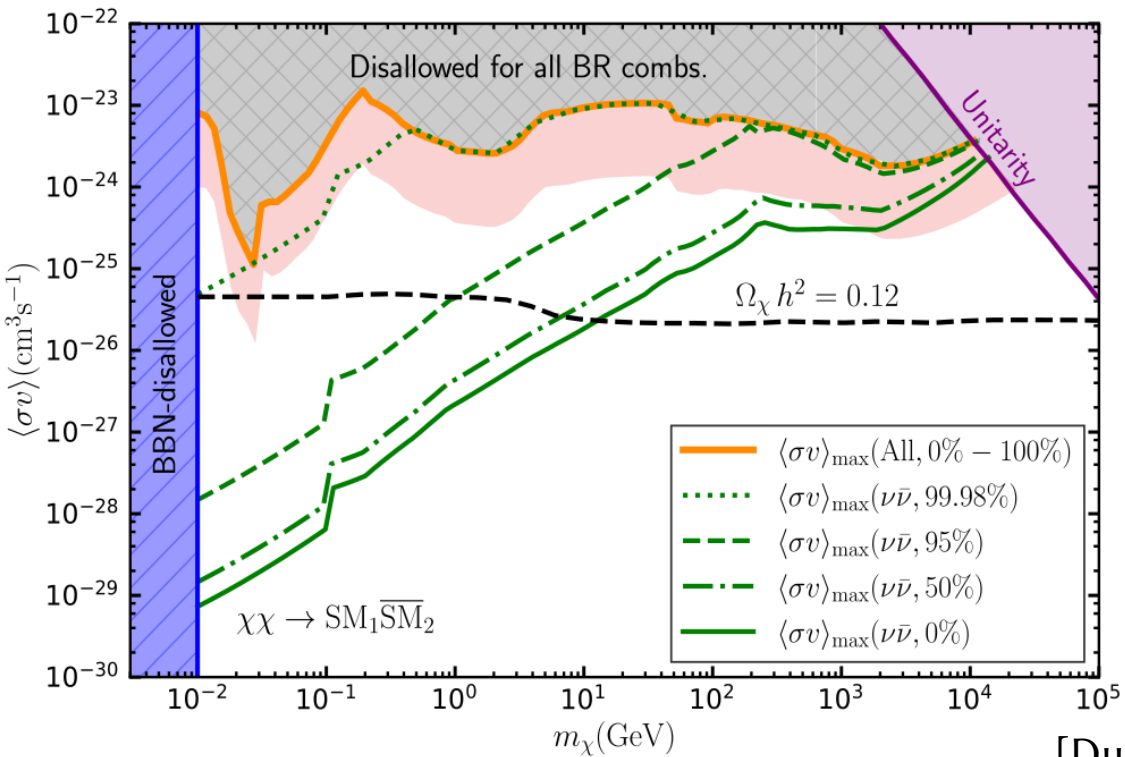

[Dutta+'2212.09795]

Sub-GeV WIMP requirement 1: $\langle\sigma v\rangle^{\rm visible}_{\rm today} \ll \langle\sigma v\rangle_{\rm freeze-out}$

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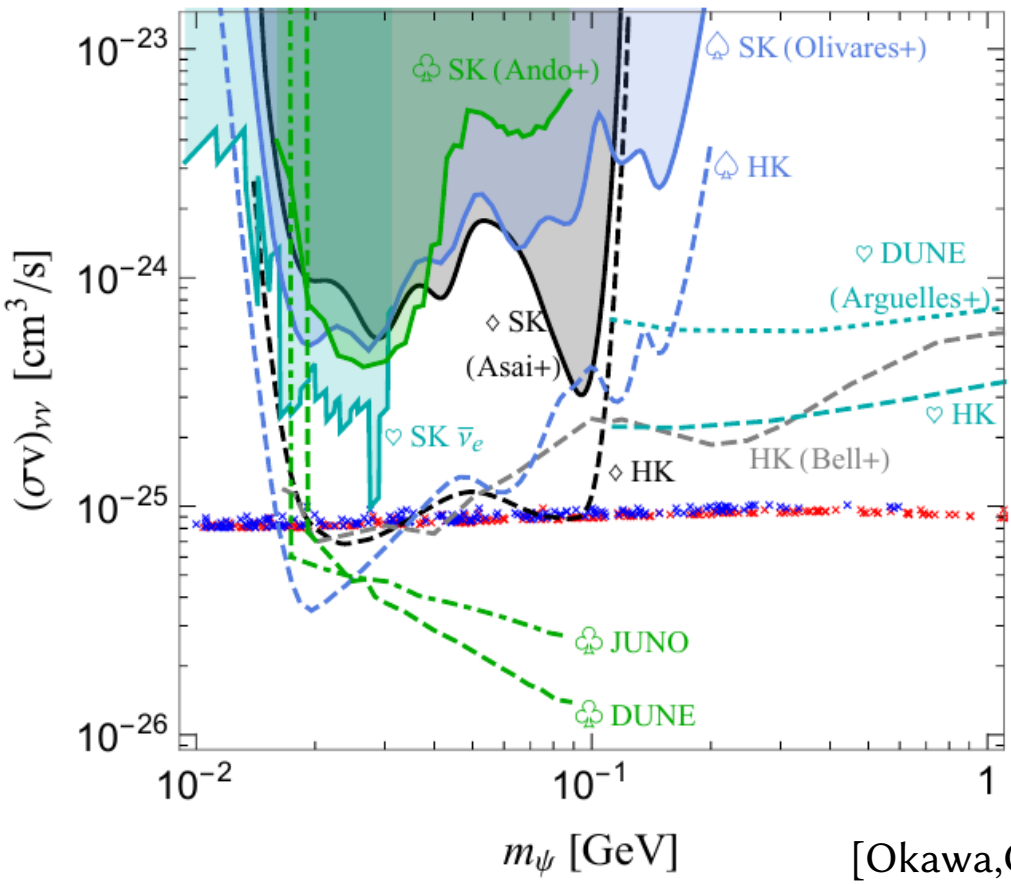
MeV prospects – neutrinos

next-gen is gonna be good!



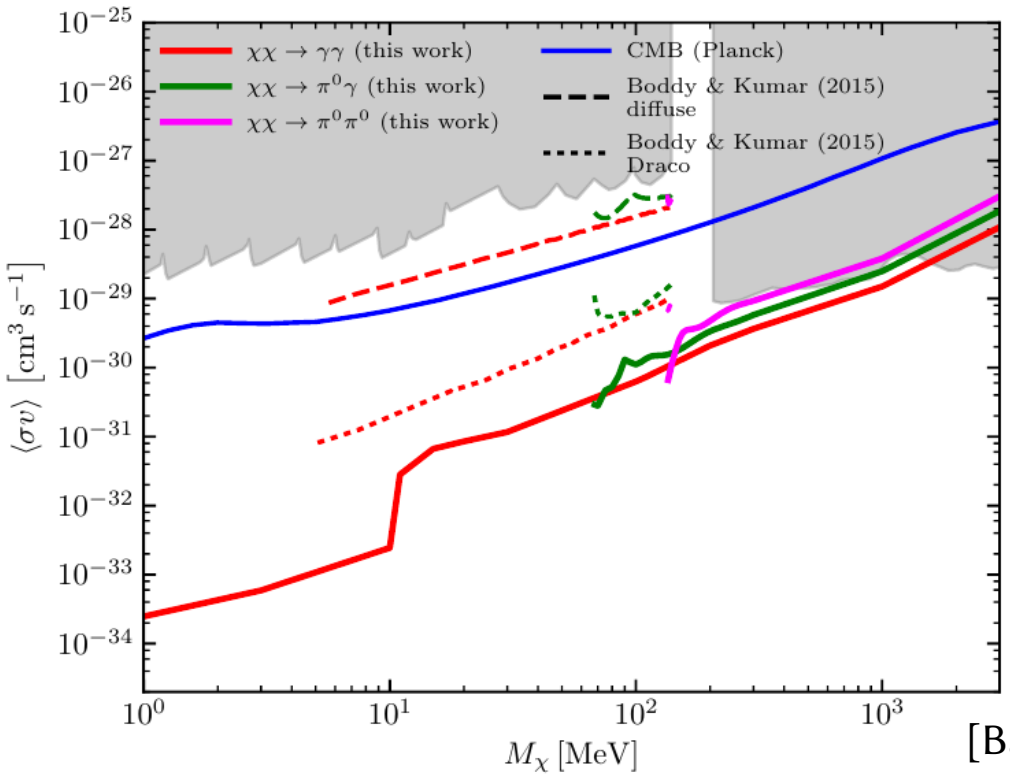
[Okawa,Omura'2011.04788]

[KlopAndo'1809.00671]

MeV prospects – photons

COSI,e-ASTROGAM, GECCO, ...

see also talks by Watanabe, Matsumoto



[Bartels+'1703.02546]

see also [Coogan+'2101.10370]

- filling the 'MeV-gap' will lead to sensitivity improvements allowing to probe velocity/radiatively suppressed $\langle\sigma v\rangle$

Theory trouble for light WIMPs

- "WIMP miracle"

$$\frac{\Omega_{\rm DM} h^2}{0.12} \sim \left(\frac{\langle \sigma v \rangle}{\text{few} \times 10^{-9}\,\text{GeV}^{-2}} \right)^{-1} \sim \left(\frac{\langle \sigma v \rangle}{m_{\rm EW}^2 G_F^2} \right)^{-1}$$

- sub-GeV DM

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

$\Rightarrow$ Sub-GeV WIMP requirement 2: light mediator!

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  $\Rightarrow$ Sub-GeV WIMP requirement 2: 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])

Light SM Particles

any sensible model of Sub-GeV thermal relics...

- needs to couple to $T \sim$ MeV SM bath

$$\gamma \qquad \nu_{1,2,3} \qquad e^{\pm} \qquad \mu^{\pm} \qquad \pi^{0,\pm} \qquad \eta, \ldots \qquad p, n \qquad \tau \qquad \ldots$$

- needs to respect chiral structure of SM

$$\gamma \qquad \nu_L \qquad e_L, e_R \qquad \mu_L, \mu_R \qquad g \qquad u_L, d_L, s_L, u_R, d_R, s_R \qquad \ldots$$

Candidate Portals

at dim 3-4

- fermions

$$y\bar{N}L\tilde{H}$$

- vectors

$$\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

$$g_{B-L,L_\mu-L_\tau}Z'_\mu\bar{f}\gamma^\mu f$$

- scalars

$$(\mu S' + \lambda_{SH}S'^2)H^\dagger H \rightarrow S\sin\theta y_f\bar{f}f$$

$$YH_2\bar{f}f$$

$$Y\tilde{H}_2\bar{N}L$$

$$\ldots ?$$

Dark Higgs

and secluded DM

eg.[Chen+'2403.02721][Coogan+'2101.10370][Pospelov+'0711.4866]

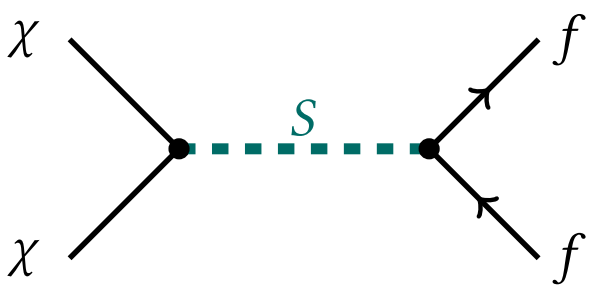
- new scalar that mixes with SM Higgs

$$\mathcal{L} \supset (\mu S' + \lambda_{SH} S'^2) H^\dagger H$$

$$\begin{pmatrix} S \\ h_{125} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} S' \\ H^0 \end{pmatrix}$$

- permits coupling to DM and light SM fermions

$$\mathcal{L} \supset -g_{\chi s} \cos\theta S \bar{\chi}\chi - \frac{m_f}{v_{\mathrm{EW}}} \sin\theta S \bar{f} f$$



→ *p-wave!* ✔

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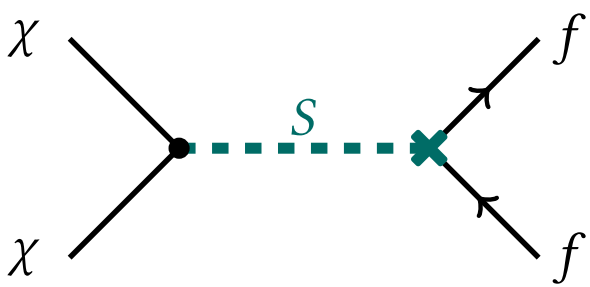

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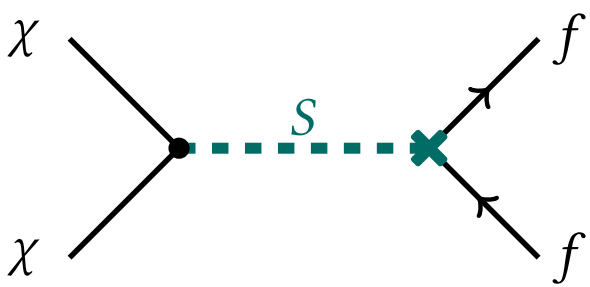

→ *resonance!* ✔

[Matsumoto+'2212.10739]

Dark Higgs

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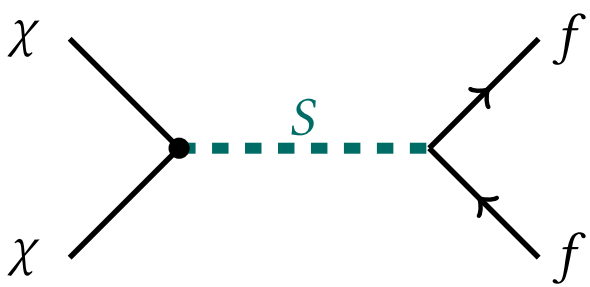
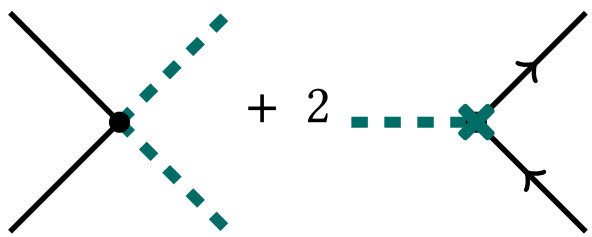


for $m_S < m_\chi$:



A light non-singlet mediator

from the 2HDM

eg. [Branco+'1106.0034]

- add a second scalar doublet to the SM

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

- alignment limit (exact if taking H_2 $\mathbb{Z}_2$-odd)

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

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- goal: $m_H \ll m_{h_{\rm SM}}, m_A^2, m_{H^\pm}^2$
  observing perturbativity, T-parameter, collider bounds on new particles

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

Scalar sector details

eg. [Branco+'1106.0034]

- work in "Higgs" basis, where only one gets a vev

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

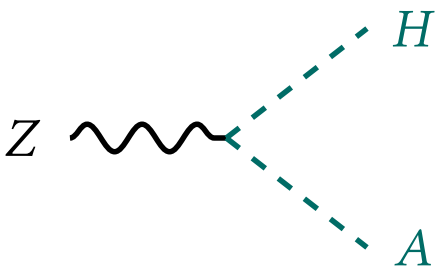
- scalar masses in alignment limit (same for inert doublet model)

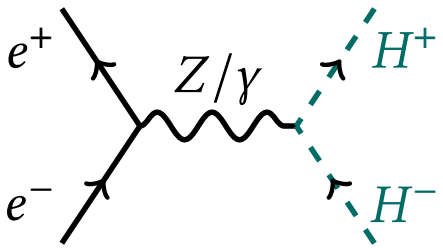
$$m_h^2 = \lambda_1 v^2,$$
$$m_H^2 = \mu_{22}^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5), \qquad \rightarrow \text{may be small}$$
$$m_A^2 = m_H^2 - v^2 \lambda_5, \qquad \rightarrow \text{may be split}$$
$$m_{H^\pm}^2 = m_H^2 - v^2 \frac{(\lambda_4 + \lambda_5)}{2} \qquad \rightarrow \text{may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

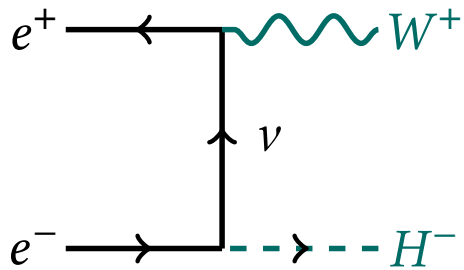
note: $-(\lambda_4 + \lambda_5) \propto m_{H^+}^2 / v^2$

Constraints

- Z-decay and LEP

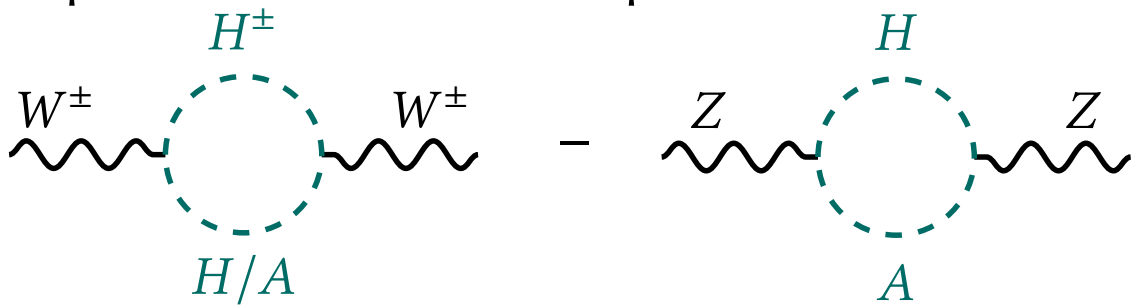






Constraints

- Z-decay and LEP
- Electroweak precision observables: T-parameter



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

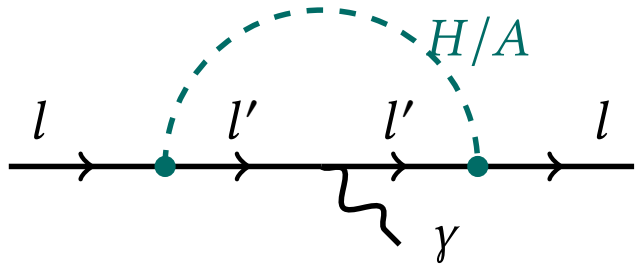
$$\text{with } \mathcal{F}(m_1^2, m_2^2) \equiv \frac{1}{2}\left(m_1^2 + m_2^2\right) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\left(\frac{m_1^2}{m_2^2}\right)$$

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

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

Constraints

- Z-decay and LEP
- Electroweak precision observables: T-parameter
- Flavor constraints



  - constrain Yukawa coupling structure

Constraints

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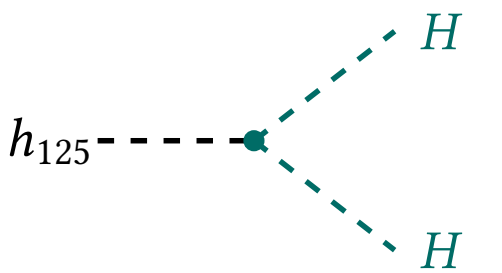
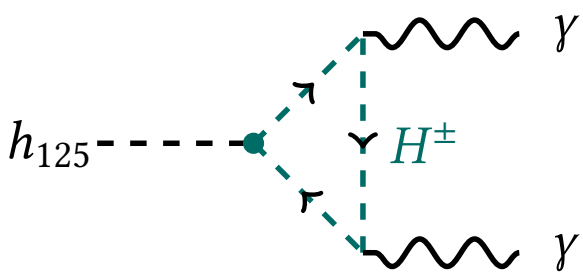
- Electroweak precision observables: T-parameter
- Flavor constraints
- Higgs decay



$$V \supset vhH^2 \frac{1}{2} \underbrace{(\lambda_3 + \overbrace{\lambda_4 + \lambda_5}^{\propto -m^2_{H^\pm}})}_{\leq 10^{-2}}$$

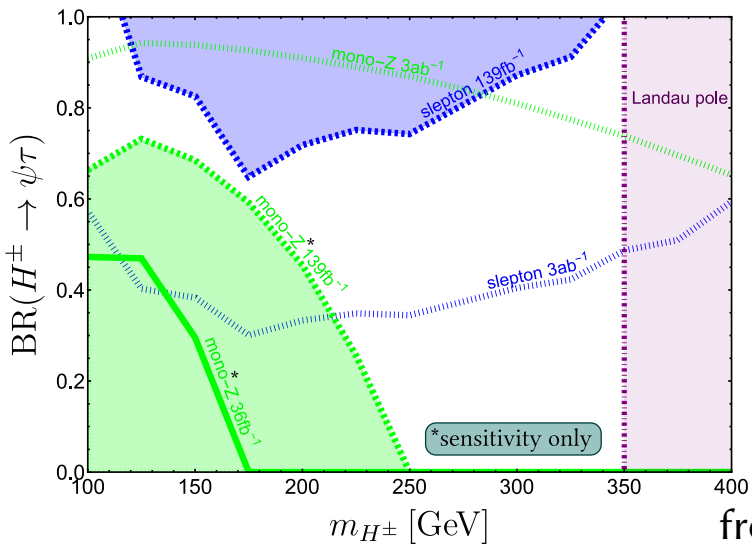


$$V \supset \lambda_3 vhH^+H^- \quad \propto m^2_{H^+}/v^2$$

negatively interferes with W-loop, predicts $R_{\gamma\gamma} < 1$; LHC data prefer $R_{\gamma\gamma} \gtrsim 1$ [Okawa,Omura'2011.04788]

Constraints

- Z-decay and LEP
- Electroweak precision observables: T-parameter
- Flavor constraints
- Higgs decay
- LHC: $H^\pm \to$ slepton searches, $H/A \to$ mono-Z



from [Iguro+'2208.05487]

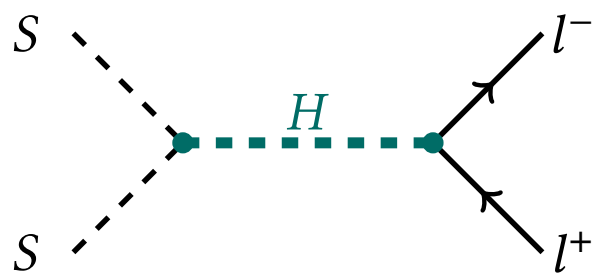
H enables light thermal DM

- coupling to light SM fermions → leptons for convenience

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

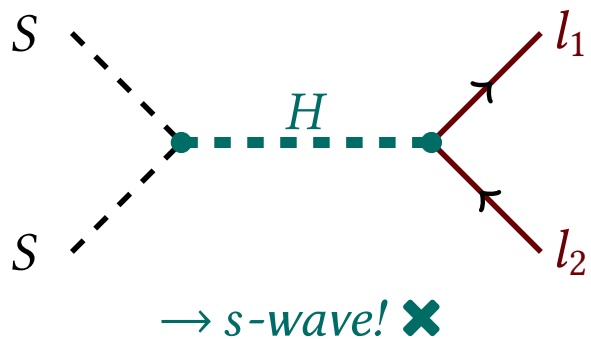
  - in alignment limit: $\widetilde{Y}_l = \text{diag}(m_e, m_\mu, m_\tau)/v$
  - Y_l → mediator coupling, DM phenomenology, flavour violation
- simplest DM candidate: real scalar S

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



Forbidden Dark Matter

[Griest,Seckel'91][DAgnolo,Ruderman'1505.07107][JH+'2203.05579][Aboubrahmin+'2306.07753]



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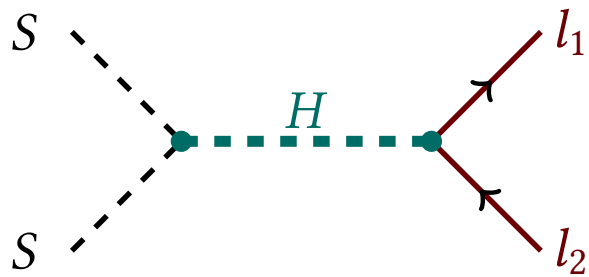


- kinematically forbidden annihilation, $2m_\chi < m_{l_1} + m_{l_2}$

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

- suppressed by mass splitting

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

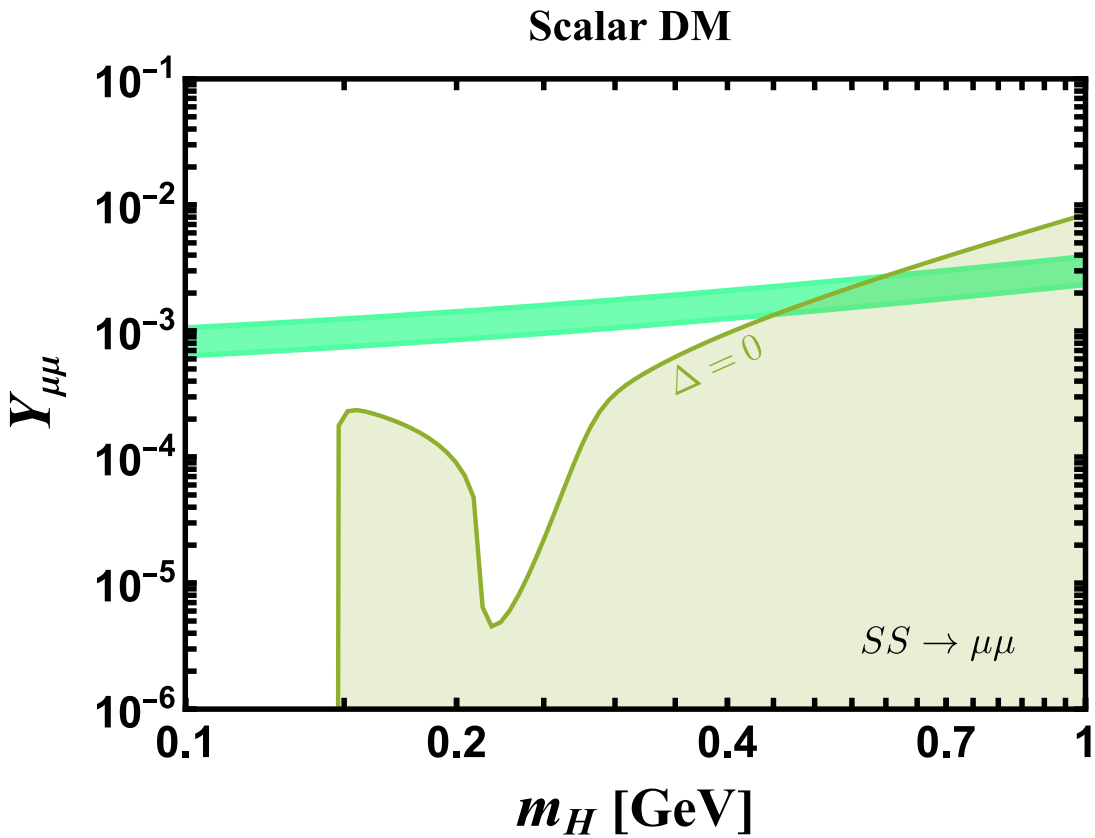
- $\langle \sigma v \rangle_{\chi\chi \to ll}$ zero at late times $T \to 0$ ✔

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

Forbidden DM results

coupling to μ for concreteness

$\kappa_{12} = 10^{-3}$



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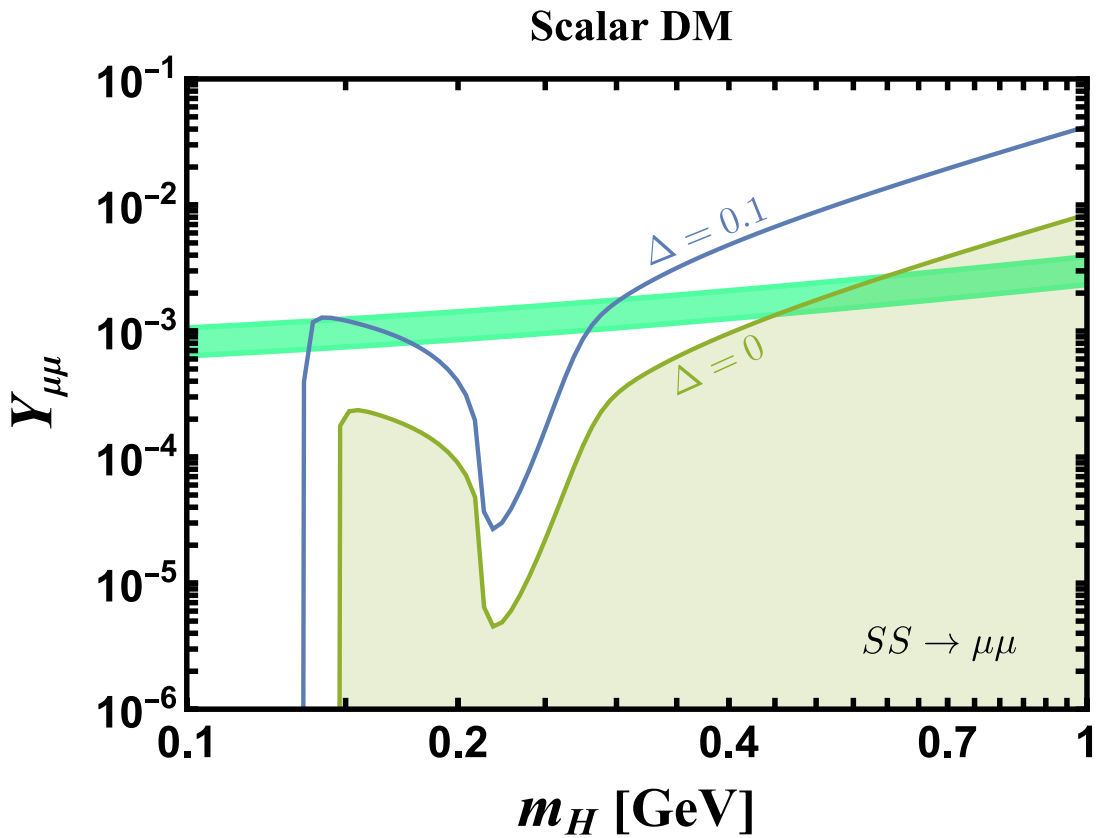

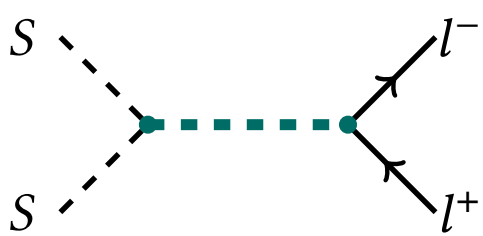

forbidden

Forbidden DM results

coupling to μ for concreteness

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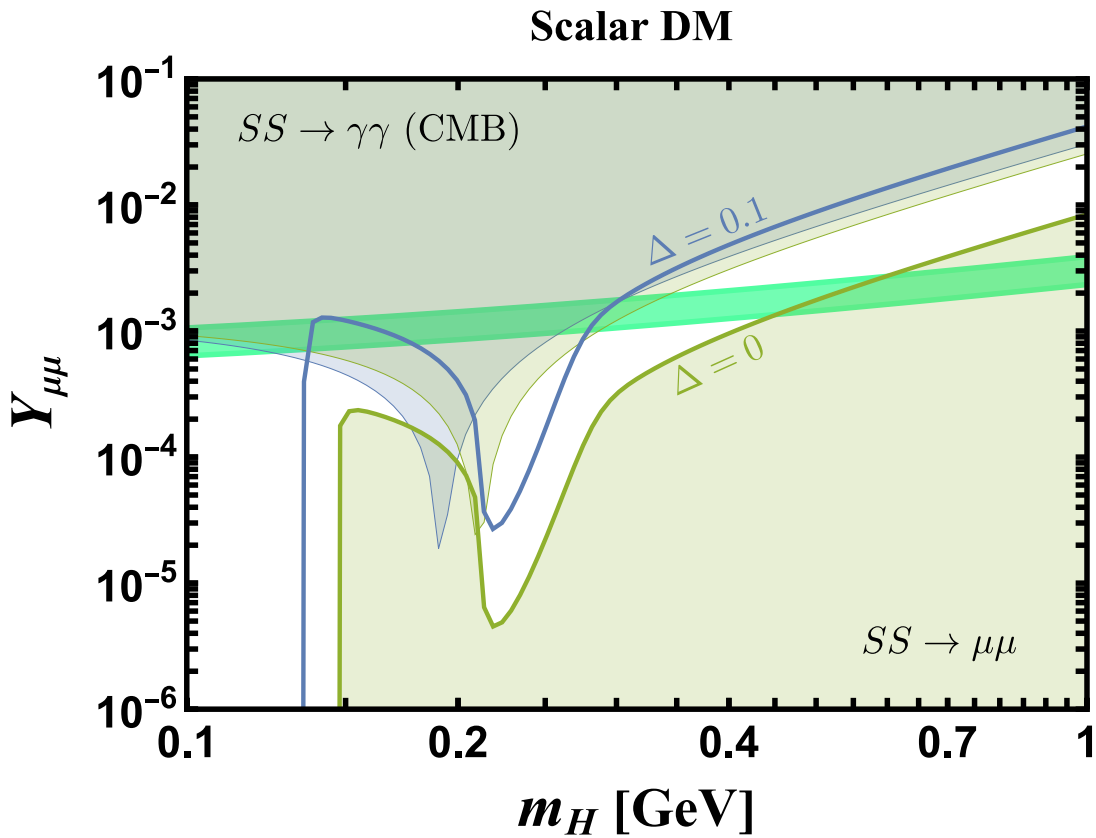

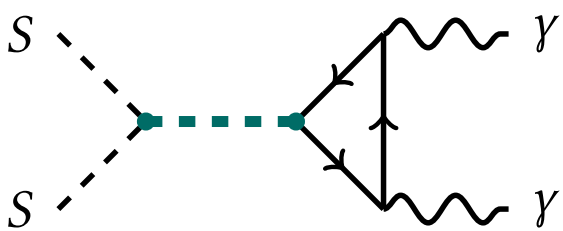

- suppressed by α^2
- enhanced by $e^{2\Delta x_f}$ wrt. $\langle\sigma v\rangle_{\rm th}^{\rm naive}$

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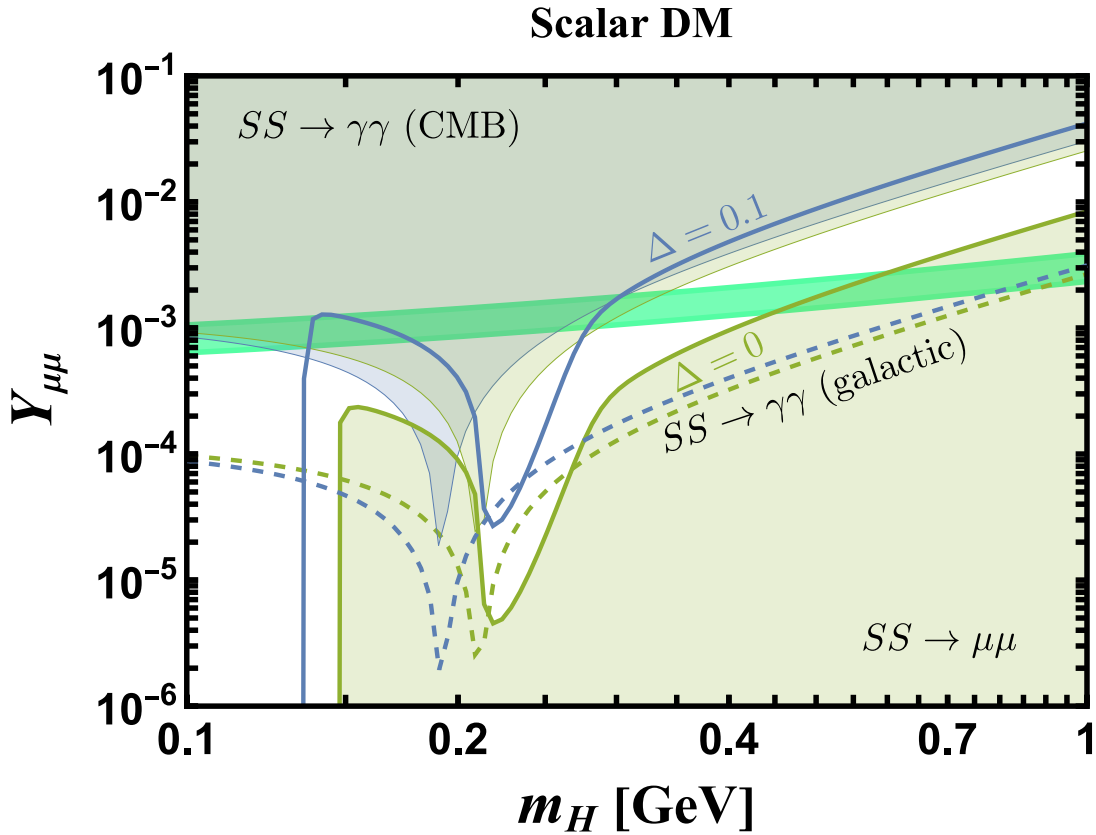
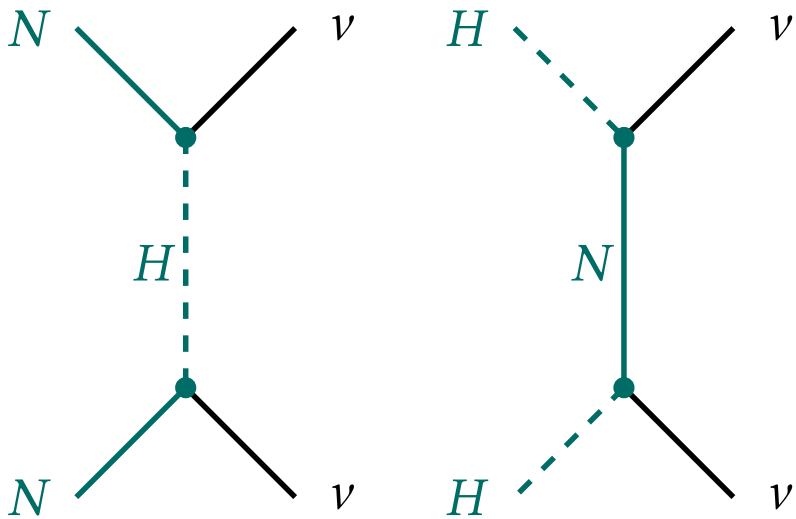


- 2 oom sensitivity boost from e-ASTROGAM/GECCO [Bartels+'1703.02546] [Coogan+'2101.10370]
- γ-ray line signal close to m_μ, m_τ as smoking-gun signal

Light scalars in the Inert Doublet model

The "scotogenic model" [Tao'hep-ph/9603309][Ma'hep-ph/0601225]



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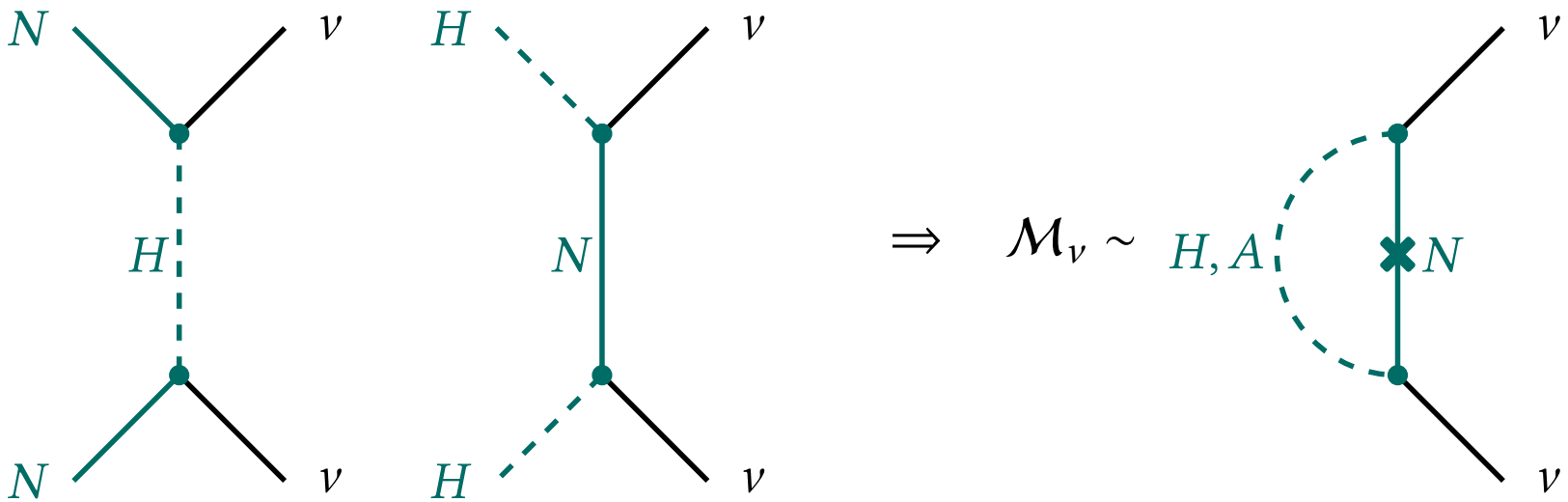

$$\mathcal{M}_\nu = \frac{Y^2}{16\pi^2} m_N \left[\frac{m_H^2}{m_H^2 - m_N^2} \log\left(\frac{m_N^2}{m_H^2}\right) - \frac{m_A^2}{m_A^2 - m_N^2} \underbrace{\log\left(\frac{m_N^2}{m_A^2}\right)}_{\text{dominant}} \right]$$

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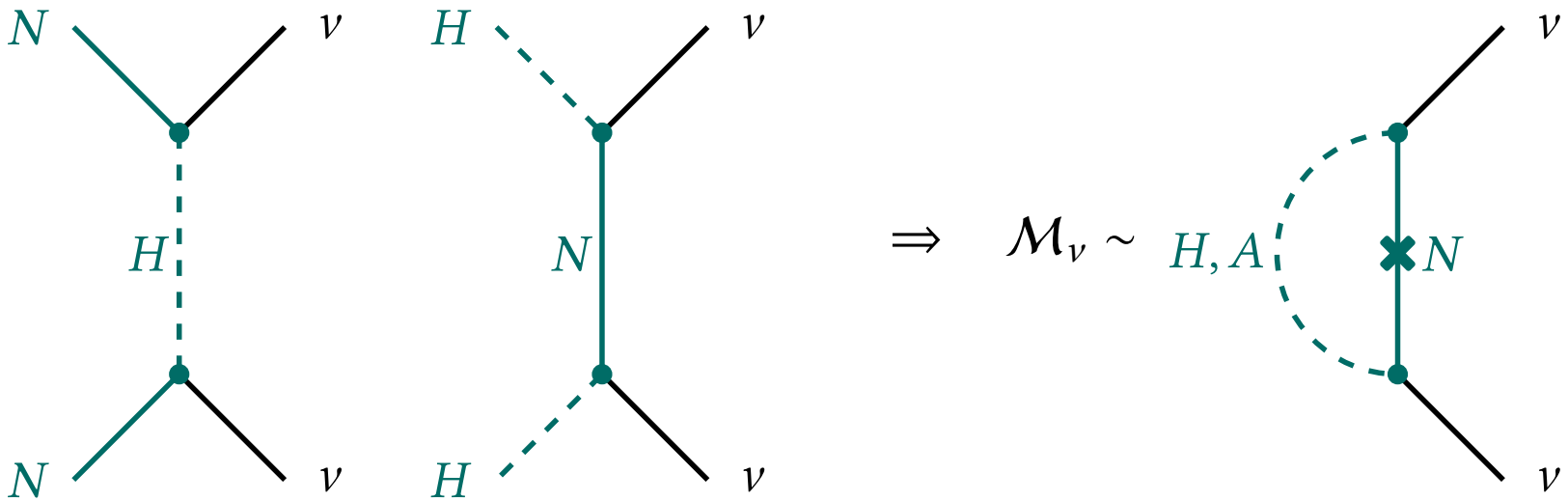

- *Scalar as LIght as an MeV (SLIM)* DM [Boehm+'hep-ph/0612228]

$$m_{\rm DM} \leq m_N = \sqrt{\frac{\mathcal{M}_\nu}{0.1\,\text{eV}} \frac{2}{1+\frac{m_{\rm med}^2}{m_{\rm DM}^2}} \frac{\log\frac{110\,\text{GeV}}{10\,\text{MeV}}}{\log\frac{m_A}{m_N}} \times \begin{cases} 1.2\,\text{MeV} & R\text{–DM} \\ 0.5\,\text{MeV} & N\text{–DM} \end{cases}} \quad \Rightarrow N_{\rm eff}^{\rm CMB} \times$$

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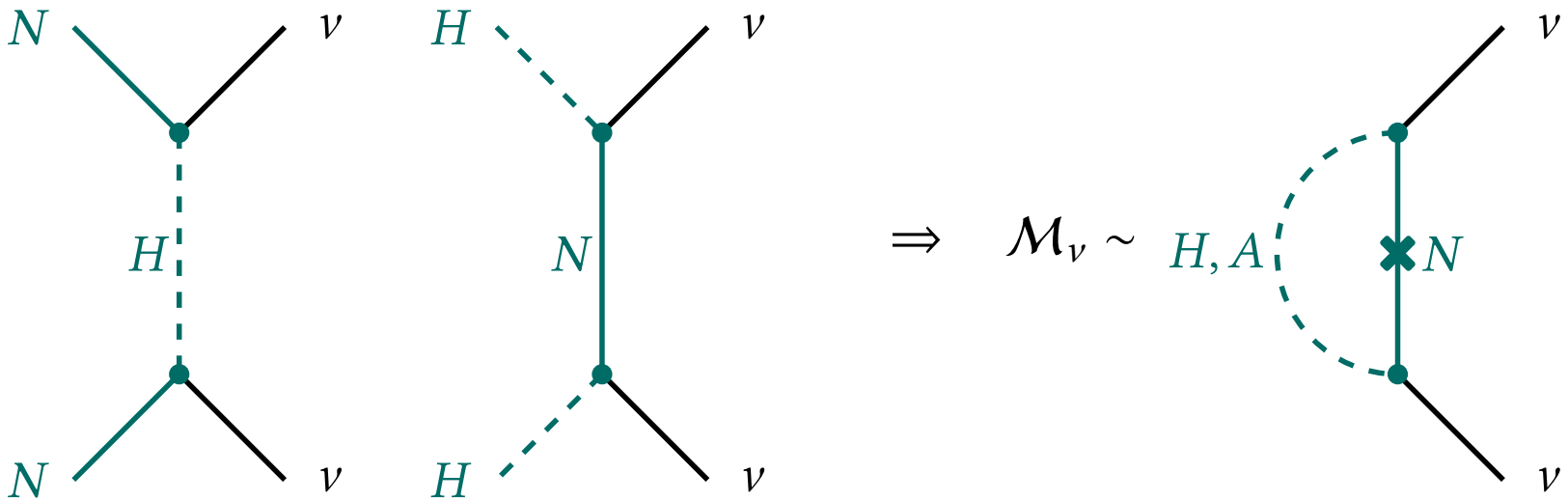

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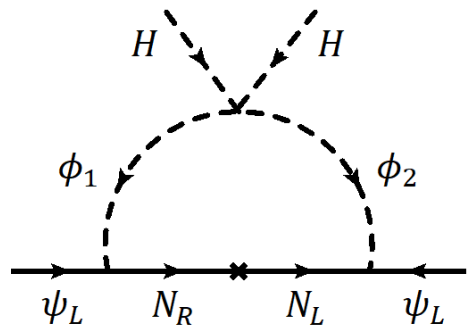
- if N is Dirac, no $\mathcal{M}_\nu$ conection → *see talk by Omura on Monday*
- Any way to have MeV-scale DM in the scotogenic $\mathcal{M}_\nu$ model?

Light neutrinophilic DM from the Scotogenic Model

[JH+'2307.15760]

- Minimal scotogenic model for $m_{3,2}$ massive [IbarraHehn'1208.3162]

$$2\,\text{RHN} + 1\,\text{ID} \quad \leftrightarrow \quad 1\,\text{RHN} + 2\,\text{ID}$$



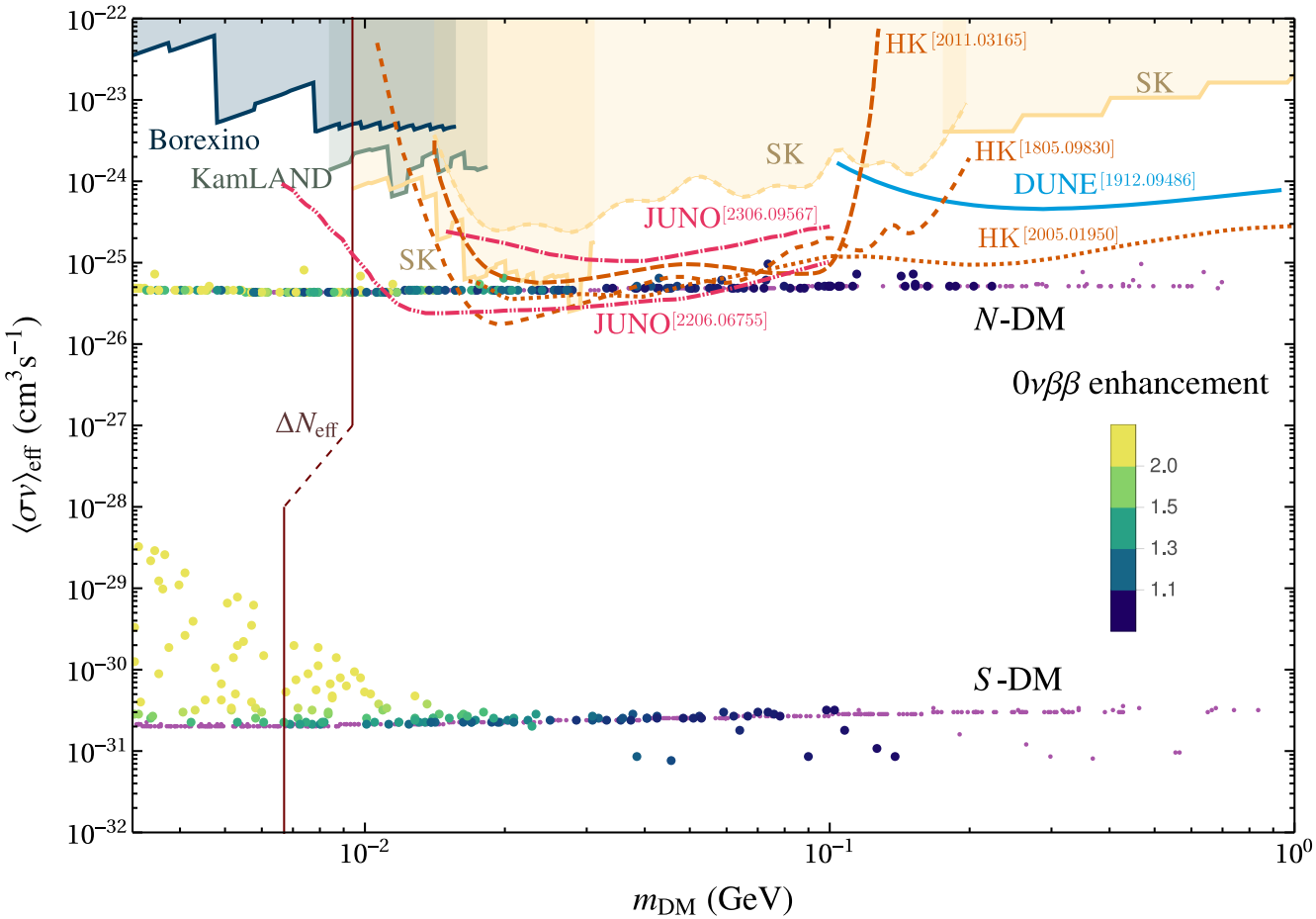
$$N_{R,L} \sim (1, 0, \omega), \quad \phi_1 \sim (1, \tfrac{1}{2}, \omega), \quad \phi_2 \sim (1, \tfrac{1}{2}, \omega^{-1})$$

$$-\mathcal{L}_{\text{Yuk}} \supset Y_1 \bar{\psi}_L \widetilde{\phi}_1 N_R + Y_2 \overline{\psi_L^c} \epsilon \phi_2 N_L + M_N \bar{N}_L N_R + h.c.$$

- couplings determined by

$$\mathcal{M}_\nu \propto Y_1 Y_2 \qquad \langle \sigma v \rangle \propto {Y_1}^4$$

MeV neutrino lines

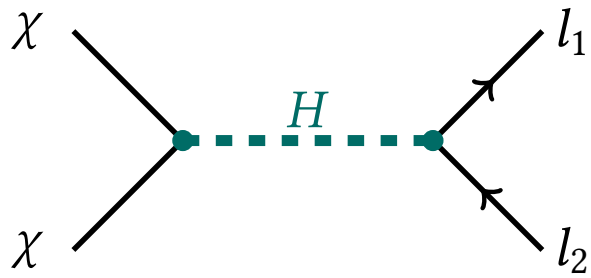


Conclusion

- Two challenges for Sub-GeV thermal relics
  1. need *light mediator* for sufficient $\langle \sigma v \rangle$
     limited options, study systematically → *don't miss the light 2HDM portal!*
  2. DM annihilation: bounds on $\langle \sigma v \rangle$
     however, velocity suppressed, radiative or neutrinophilic channels
     ⇒ *good prospects for the near future!*
- light 2HDM scalar portal
  - *light mediator from a scalar doublet*
    - enables simple sub-GeV DM models
    - pheno: much to look forward to
      DMID: MeV γ-rays, MeV neutrinos
      LHC: Higgs properties, EW-partners $A^0, H^\pm$
      Belle-II & beam dumps
  - *work in progress*
    - quarks? → benchmark models for DMDD
    - symmetries? → theory motivation for the light scalar

many thanks to my collaborators: Sudip Jana, Vishnu P.K., Shaikh Saad.

Light 2HDM portal - Fermion DM



$\longrightarrow$ *p-wave* ✔

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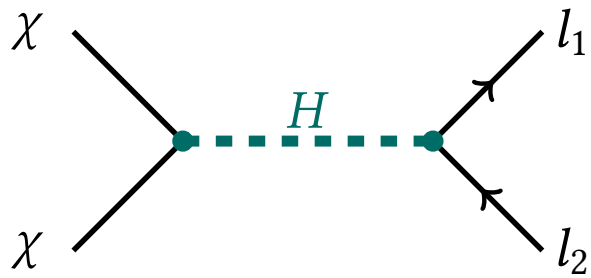
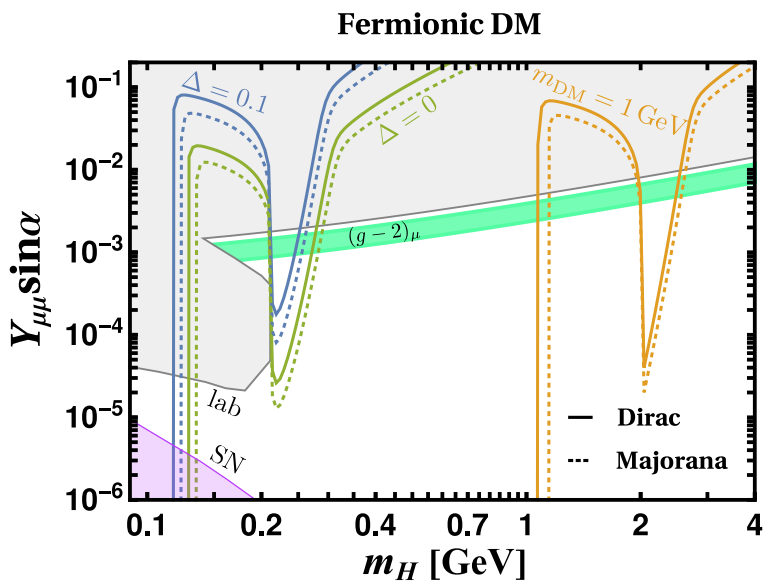


- $\bar{\chi}\chi H$ vertex?! ✖ $\rightarrow$ admix singlet $\begin{pmatrix} H \\ H' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} s \\ \phi_2^0 \end{pmatrix}$



$Y_\chi = 0.1$

Is the integrated Boltzmann equation sufficient?

no! [AboubrahminKlasenWiggering'2306.07753]

$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} = C_{\rm coll}[f_\chi] \quad \Rightarrow \quad \frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi\to \rm SM}\left(n_\chi^2 - n_\chi^{\rm eq2}\right)$$

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$$f_\chi(p) \sim f_{\text{MB}}(p, T_\chi) \quad \text{and} \quad T_\chi = T_{\text{SM}}$$

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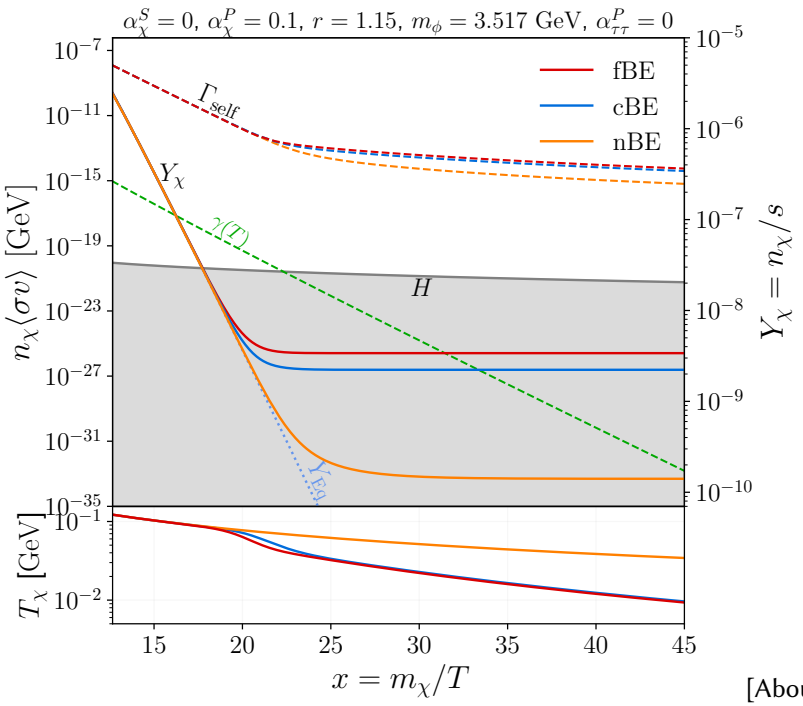

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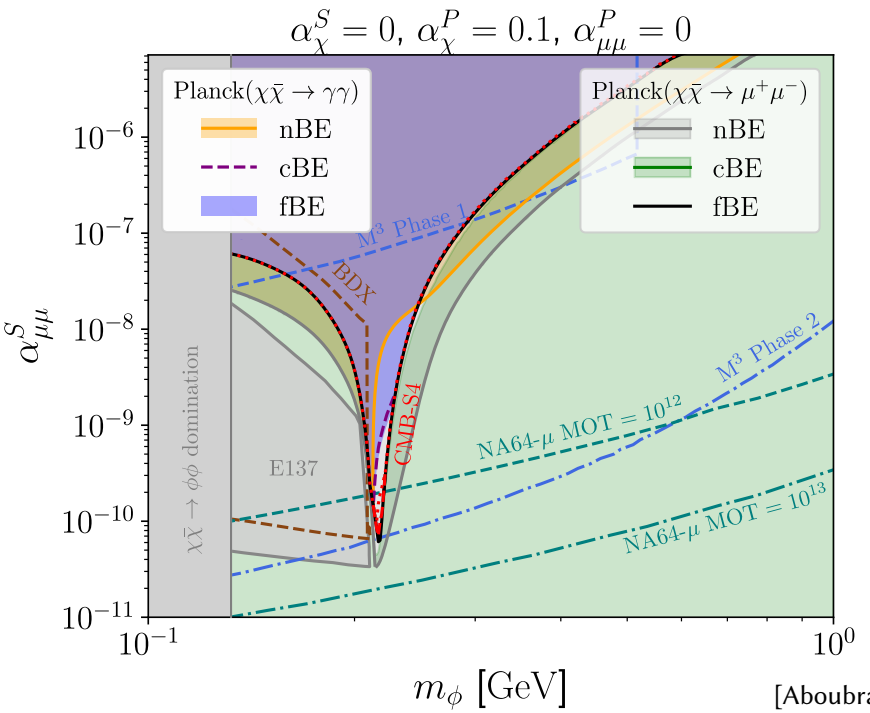
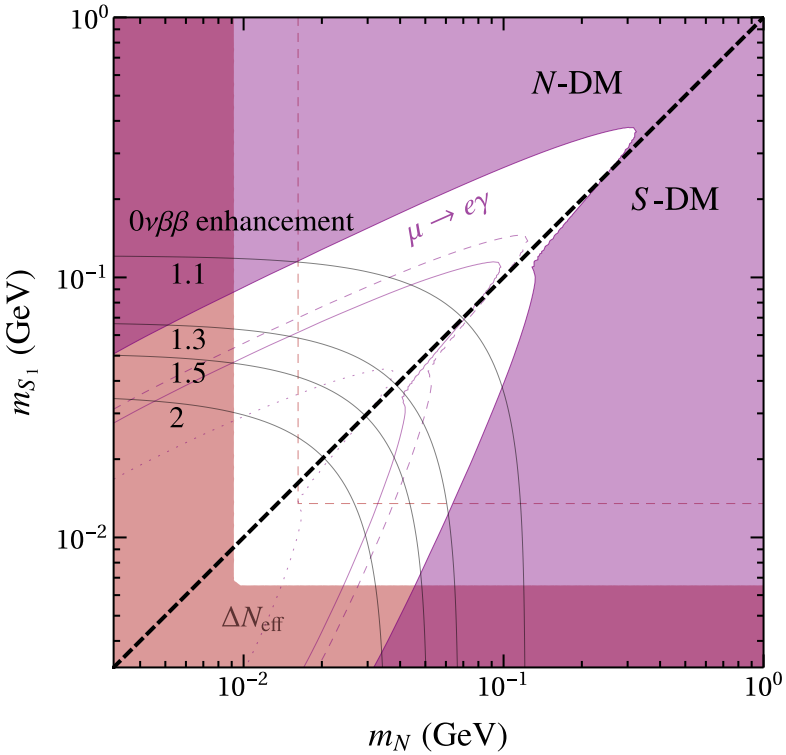


[AboubrahminKlasenWiggering'2306.07753]

Parameter space and neutrino pheno implications



- $\mu \to e\gamma$ limits rule out large couplings (masses)
- $\langle p \rangle_{\beta\beta-\text{decay}} \sim 100\,\text{MeV} \to 0\nu\beta\beta$ enhanced! [RodejohannXu'1907.12478]

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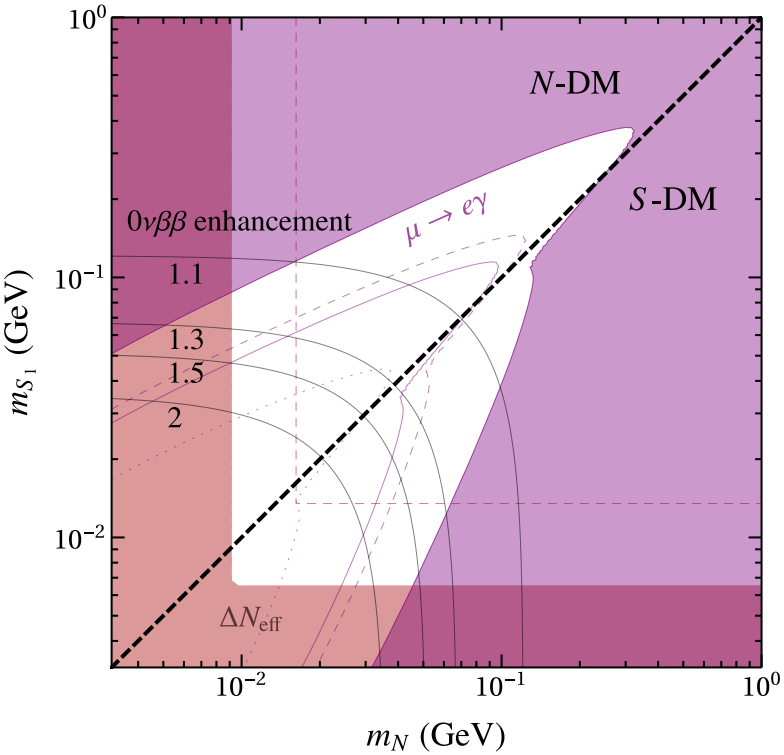

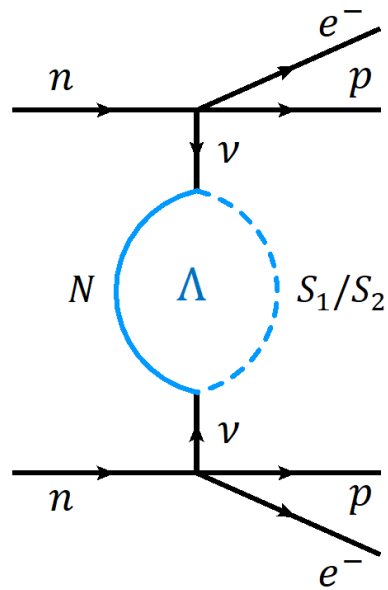

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