Light Dark Higgs boson in Minimal Sub-GeV Dark Matter Scenarios

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Sub-GeV Dark Matter

- Sub-GeV dark matter has been studied in a variety of scenarios particularly vector portals
- A sub-GeV dark matter with a mediator of the same mass scale behaves like a WIMP requiring $\langle \sigma v \rangle \sim 10^{-26}\text{cm}^3\text{s}^{-1}$ for the correct relic density
- We focus here on vector portal with a dark Higgs mechanism for providing mass to the vector boson
- Sub-GeV range searches for visible and invisible decays of the mediator/dark Higgs provide the most stringent constraints on such models
- For long lived scalars, BBN and CMB constraints also play an important role in constraining the parameter space

Minimal Dark Sector Scenarios

- Minimal dark sector refers to extension of SM by adding an extra $U(1)_D$ gauge group and corresponding fields
- Minimal dark sector consists of
  - $U(1)_D$ gauge boson - Dark photon V
  - Complex scalar breaking $U(1)_D$ - dark Higgs S
  - Dark matter candidate charged under $U(1)_D$ - Complex scalar or pseudo Dirac fermion χ
- $U(1)_D$ breaking leads to a massive dark photon, dark Higgs and dark matter particles
- Dark photon interacts with SM fields through kinetic mixing of $U(1)_D$ and $U(1)_Y$
- Dark Higgs interacts with the SM fields through dark photon, e.g. SV_μ^2

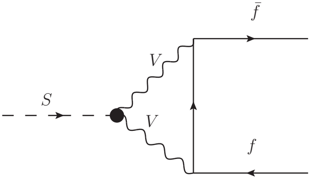
$$\mathcal{L}_V = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}\frac{\varepsilon}{\cos\theta_w}B_{\mu\nu}F'^{\mu\nu} \ ,$$

$$\mathcal{L}_S = (D^\mu S)^*(D_\mu S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4 - \frac{\lambda_{SH}}{2}|S|^2|H|^2 \ ,$$

- Focus on effect of including dark Higgs in the dark sector in addition to a dark photon
- Two models of dark matter studied - CS(complex scalar) and pDF(pseudo Dirac fermion)

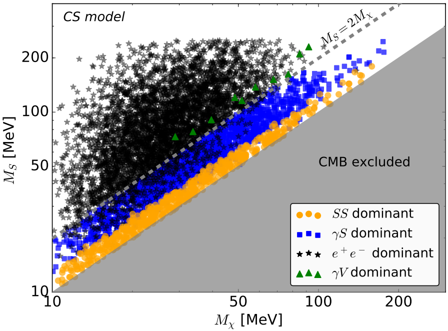
$$V_{pDF} = y_{SL} S \chi_L \chi_L + y_{SR} S \chi_R^c \chi_R^c + \text{ h.c.}$$
$$V_{CS} = \lambda_\chi |\chi|^4 + \lambda_{\chi S} |\chi|^2 |S|^2 + \lambda_{\chi H} |\chi|^2 |H|^2$$

- Parameters : $g_V, \varepsilon, M_S, M_V, m_\chi, y_{SL}$ $(\lambda_{S\chi})$ and y_{SR} (λ_χ)
- Restrict analysis to $M_S \leq 200$ MeV and $M_V \leq 500$ MeV and thereby avoid hadronic final states so as to simplify the analysis
- Only decay mode for dark Higgs is to leptons



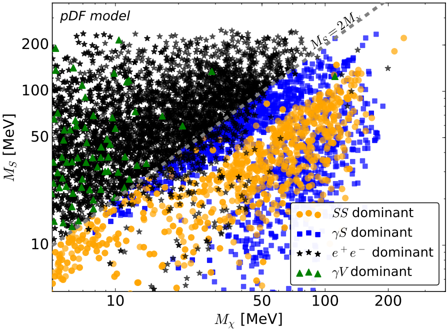
Relic Density and CMB constraints

- Relic density achieved through the freeze-out mechanism in a two-component dark matter scenario due to presence of long lived dark Higgs
- Both mediator and DM particles in the MeV mass scale requiring a annihilation cross section of $10^{-26}\text{cm}^3\text{s}^{-1}$ as in the case of a traditional WIMP
- Presence of dark Higgs provides additional annihilation channels thus modifying relic density evaluation
- Injection of charged particles and photons in the inter-galactic medium (IGM) can significantly alter the recombination history of the universe by ionizing and heating the IGM gas
- Injections from DM annihilation parametrized as $p_{ann} = f\langle\sigma v\rangle/M_\chi$
- Stringent constraints from *s*-wave DM annihilations but much more relaxed for velocity suppressed *p*-wave annihilations



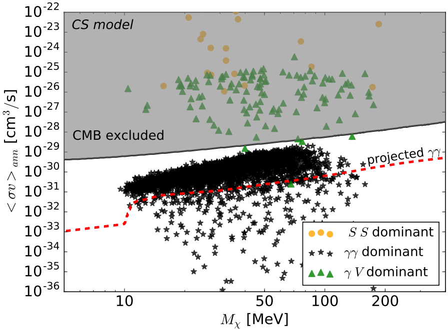
CS

- $M_S > 2M_\chi$: e^+e^- no S
- $M_S \simeq M_\chi$: SS
- $M_S \sim 2M_\chi$: $S\gamma$
- $M_S < M_\chi$: excluded



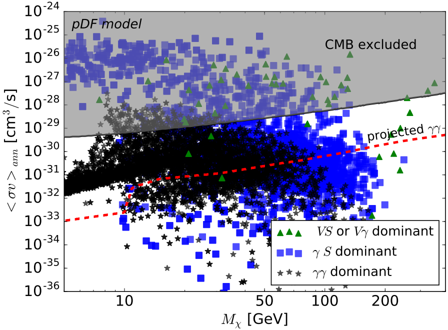
pDF

- $M_S < M_\chi$: $S\gamma$
- CMB bounds relaxed due to coannihilation channels



CS

- $M_\chi < M_V,\ M_S$ only $\gamma\gamma$ available, suppressed by ε^4
- $M_\chi > M_S$, $S\gamma$ dominates, only suppressed by ε^2

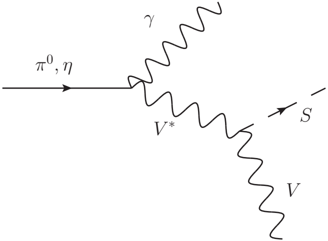


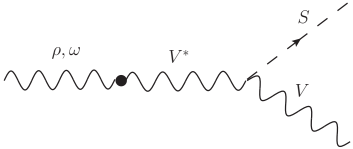
pDF

- $M_\chi > M_S$ completely excluded, no ε suppression
- $M_\chi > M_V$, channel with V in final state open

Search for Dark Higgs in Beam Dump Experiments

- Fixed target experiments well suited for detection of light dark sector particles
- High-intensity, but relatively low-energy proton or electron beam impacting target produces "dark matter beam" e.g. dark photon decay
- Proton beam-dump experiments could be practically seen as light meson factories, with around one neutral pion created for each proton on the target.
- Electron beam-dump experiments can also lead to dark sector beams through dark photon production by bremsstrahlung
- Bounds on the kinetic mixing parameter ε from electron beam dumps were found to be always significantly weaker than the current missing energy bound from BABAR, $\varepsilon < 10^{-3}$



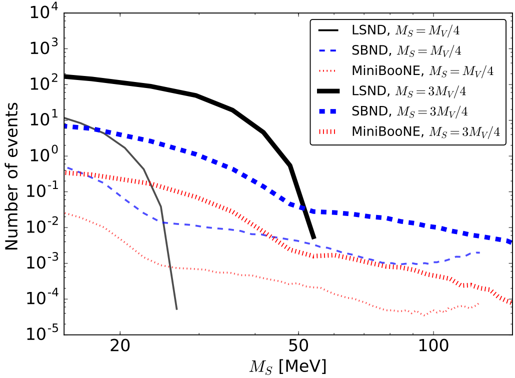


- Meson produced in proton beam dump decays into dark photon with a small probability
- Dark Higgs can be produced from an excited dark photon through a “dark” Higgstrahlung mechanism
- Scalar meson decay

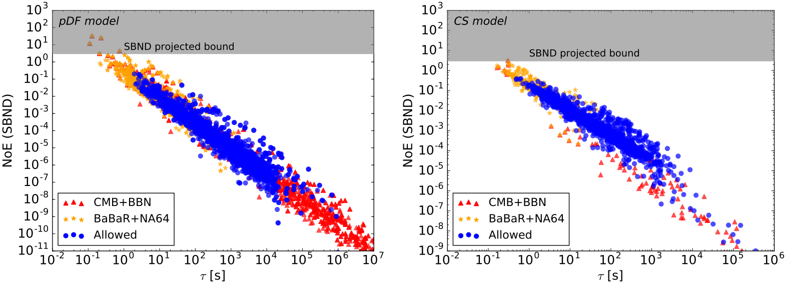
$$\pi^0, \eta \to \gamma V^*, V^* \to SV,$$

- Vector meson decay

$$\rho, \omega \to V^*, V^* \to SV.$$

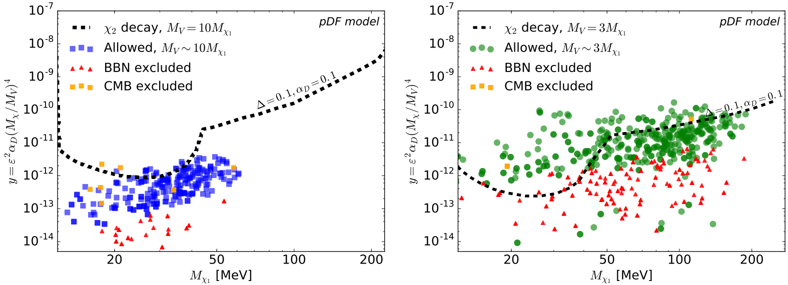


- We have chosen $\varepsilon = 0.001$ and $\alpha_D = \alpha_{\rm em}$
- SBND will improve on the miniBooNE bound by one order of magnitude



- No. of dark Higgs detected goes as ε^6 and so more sensitive to SBND compared to DM searches
- Thermal value target out of reach of beam dump experiments

Probing *CS* model through DM decay

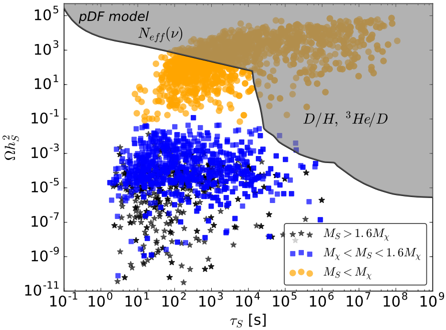


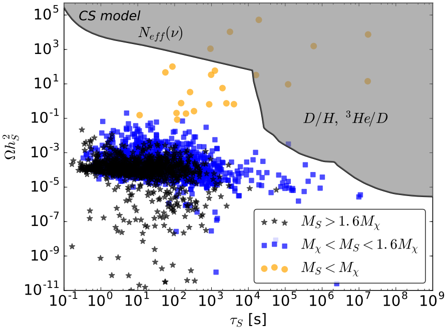
- Search at LSND recast to probe $\chi_2 \to \chi_1 e^+ e^-$
  Izaguirre etal, PRD (2017)
- Very sensitive to mass splitting, $\Delta = M_{\chi_2} M_{\chi_1}$

$$\Gamma_{\chi_2} \propto \alpha_D \varepsilon^2 \Delta^5 M_V^{-4}$$

BBN Constraints

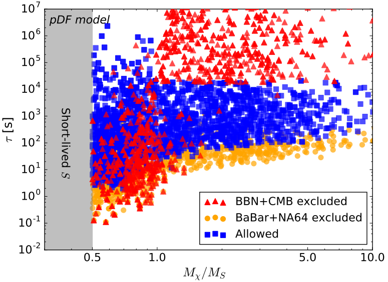
- BBN bounds arise from either early time ($t \lesssim 10$ s) injection or late time ($t > 100$ s) injection of energy from decays of long lived particles like the dark Higgs
- Early time injection constraints are obtained from n/p ratio or the effective number of neutrino species N_{eff}
- Late time injection constraints arise from primordial abundances of light nuclei (^{3}He and D)
- BBN bounds on Higgs portal models from N_{eff} limit dark Higgs lifetime to be smaller than 0.1 s
- Bounds from primordial abundances affect $\tau_S > 10^4$ s, and can be quite stringent
- These bounds are mitigated due to lepton-only decay modes of dark Higgs and efficient annhilation mechanism

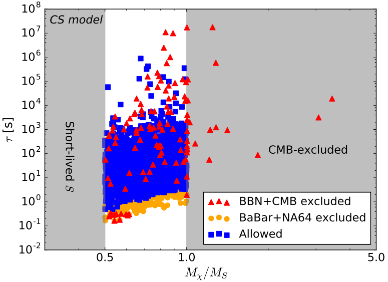




- When $M_S > M_\chi$ $SS \to \chi\chi$ decreasess abundance
- For $M_S < M_\chi$, $N_{\rm eff}$ bound rules out part of parameter space above 100 s
- Large part of parameter space ruled out above 10^4 s

Summary of Constraints





Conclusions

- We have argued that models with a massive, but light, dark vector mediator, the spectrum should naturally contain a light dark Higgs, which can substantially modify predictions
- Cosmological constraints are considerable modified due to the presence of dark Higgs and additional modes of annihilation for DM
- We particularly study a long lived, light dark Higgs boson
- The low abundance region, $M_\chi < M_S < 2M_\chi$, where bounds from BBN are weakened due to presence of dark Higgs while relic density is realized mainly from $\chi\chi \to S\gamma$ leading to a lower bound on ε
- The high abundance region, $M_S < M_\chi$, where there are relatively strong bounds from BBN-related observables and for CSmodel, this region is ruled out by CMB constraints