We study a dark matter production mechanism based on decays of a messenger WIMP-like state into a pair of DM particles that are self-interacting via exchange of a light mediator. Its distinctive thermal history allows the mediator to be stable and therefore avoid strong limits from the cosmic microwave background and indirect detection. A natural by-product of this mechanism is a possibility of a late time transition to a dominant dark radiation component which can help alleviate the $H_0$ tension. We provide a simple realization of the mechanism in a Higgs portal dark matter model. We find a significant region of the parameter space that leads to a mild relaxation of the Hubble tension while simultaneously having the potential of addressing small-scale structure problems of $\Lambda$CDM. In addition, the light mediator lying in cosmologically preferred region we considered was recently shown to provide one of most promising explanations of XENON1T electronic recoils excess.

**Shortcomings of $\Lambda$CDM model**

- small-scale problems
  - too big to fail
  - missing satellites
  - core-cusp
- early-late Universe tensions
  - $H_0$, $\sigma_8$ tension
  - $\Omega_m$ tension ($\Omega_m$)

**Model**

- Consider a dark sector comprised of a Dirac fermion $\chi$ charged under new gauged $U(1)_{S}$ broken spontaneously at some higher scale resulting in massive vector $A^0$.
- The dark sector part of the Lagrangian after the $U(1)_{S}$ breaking reads:
  $$\mathcal{L}^{\text{DM}} = \frac{1}{2}(D_{\mu}S)(D^{\mu}S) + \frac{1}{2}S^2 \left( 2 \lambda H^2 + 2 \mu_1 S \chi^2 + \mu_2 S^2 \right)$$
- Massless fermion $\chi$.

**Cosmological scan**

- We used public MCMC code Mamba/Python with combined datasets from Planck, BAO data from the BOSS survey, the galaxy cluster counts from Planck catalogue and local measurement of the Hubble constant to constrain decaying DM model and compare with standard $\Lambda$CDM cosmology.

**Thermal history**

![Thermal history diagram](image)

- The illustration of the thermal history of $S$ (blue), $\chi$ (black) and $A^0$ (orange) with example parameter choices leading to early (regime A, solid lines), late (regime B, dashed) and very early (regime C, dotted) decay of $S$.
- Parametrizing the symmetry breaking by a small parameter $\epsilon$ one can distinguish four regimes:
  - $\text{O)}$ weak $\leq \epsilon$: usual thermal self-interacting model subject to strong limits
  - $\text{A)}$ very weak $\leq \epsilon \leq \text{weak}$: viable regime for self-interacting DM
  - $\text{B)}$ ultra weak $\leq \epsilon \leq \text{very weak}$: regime for self-interacting DM with an impact on the $H_0$ tension
  - $\text{C)}$ ultra weak: regime potentially addressing the $H_0$ tension and providing an uSIDM candidate.

**SIDM regime - early decays**

- We found two preferred lifetime regimes:
  - short (regime B): $\tau \sim 1\text{Myr}$ while fraction of dark radiation is strongly constrained to by below $\sim 1\%$
  - long (regime C): $\tau \sim 3\text{Gyr}$ while fraction of dark radiation is allowed to be as big as $\sim 10\%$.

**uSIDM regime - late decays**

- $\text{Regime B:}$ SIDM originating from $S$ decays taking place after recombination. Color coding denotes the value of the coupling $\alpha$ for the points that satisfy the condition $\sigma/m_{\chi} < (1 \pm 10\%)\text{ cm}^2/\text{g}$. Dark green shade denotes the regime at the 1σ level around the mean values of $\Lambda$CDM parameters, which relax Hubble tension in the short lifetime scenario. Gray pluses overlay points that have $\tau > 0.1\text{Gyr}$ which are in this model in tension with the structure formation.

**Takeaway**

- SIDM production by late decays of WIMP-like messenger
- Mechanism exemplified in a Higgs portal DM model
- Well-motivated mechanism deserving further model building

**Based on:** hep-ph/2006.16139. See also Andrzej’s talk on Friday, 12:40.

**Supported by:** NCS grant No. 2015-18-A-ST2/0078 and No. 2018/14/D/ST2/00813.

**National Centre for Nuclear Research, Poland**