Snowmass2021 - Letter of Interest

Cosmological and Laboratory Probes of Sub-MeV Freeze-in Dark Matter

Thematic Areas:
■ (CF3) Cosmic Frontier: Dark Matter: Cosmic Probes
■ (CF1) Cosmic Frontier: Dark Matter: Particle Like
■ (TF9) Theory Frontier: Astroparticle

Contact Information:
Katelin Schutz (MIT) [kschutz@mit.edu]
Tongyan Lin (UCSD) [tongyan@physics.ucsd.edu]
Cora Dvorkin (Harvard) [cdvorkin@g.harvard.edu]

Abstract: Dark matter (DM) could be a relic of freeze-in through a light mediator, where the DM is produced by extremely feeble interactions of Standard Model particles dominantly at low temperatures. In the simplest viable models, the DM has a small effective electric charge and is born with a non-thermal, high-velocity phase space distribution. This DM candidate can cause observable departures from standard cosmological evolution. Current experiments probing the cosmic microwave background (CMB), Lyman-α forest, quasar lensing, stellar streams, and Milky Way satellite abundances can constrain freeze-in DM masses up to tens of keV. Freeze-in DM masses up to ~ 100 keV can be explored with the Hydrogen Epoch of Reionization Array and the Vera Rubin Observatory. The cosmological probes are highly complementary with proposed direct detection efforts to search for this DM candidate. In this *Letter*, we advocate for this theory of DM as a key benchmark of cosmological probes of DM and direct DM searches.

Theory Motivations: Dark matter (DM) could couple to particles in the Standard Model (SM) through a light mediator. In the limit of small DM-mediator and mediator-SM couplings, g_χ and $g_{\rm SM}$ respectively, this portal could be responsible for producing the observed DM abundance through a mechanism known as freeze-in, where DM is produced from SM particles in the thermal bath of the early Universe annihilating and decaying [1–6]. For SM temperature T, the freeze-in rate via a light mediator scales like $g_\chi^2 g_{\rm SM}^2 T$ while the Hubble expansion rate scales like $T^2/M_{\rm Pl}$. This scaling indicates that freeze-in will predominantly occur at the lowest kinematically accessible temperatures, making the relic abundance independent of UV initial conditions. Producing the observed DM relic abundance implies a tiny value for the coupling constants, which is difficult to target with accelerator searches. However, the light mediator also aids in experimental observability of this candidate in direct detection experiments, since scattering will scale like v^{-4} for velocity v, which is $v \sim 10^{-3}c$ at the Earth's location in the Milky Way (MW). Determining the requisite DM-SM couplings for the relic abundance, as we did in [7], then provides a highly predictive benchmark for direct searches for DM where the same couplings determine the relic abundance and laboratory signals.

There are strong stellar emission and fifth force constraints on many kinds of light mediators coupled to the SM [8, 9]. Therefore, the only light mediators that can be responsible for freeze-in for DM masses below 1 MeV are the SM photon or a kinetically mixed ultralight dark photon, which is not excluded by existing searches. Thus, DM made by freeze-in below 1 MeV will effectively have a small electromagnetic charge. This is the simplest allowed way to make charged DM, since the charges required for DM production via freeze-out are excluded by many orders of magnitude [10]. Charged DM has recently been the subject of keen interest in the context of the EDGES anomaly [11, 12] and can also play a role in energy loss from stellar environments [13]. The scenario involving a dark photon is also of theoretical interest, as ultralight bosons are generically expected as states in the spectrum of various string theories [14, 15].

Because of the small couplings involved, freeze-in DM never achieves a thermal number density in the early Universe. This means that freeze-in is one of the few allowed ways of making DM from the SM thermal bath with a mass below 1 MeV. Most other thermal production mechanisms below the MeV DM mass scale are excluded (there are some exceptions to this, see e.g. [16–18]) because the DM carries substantial energy and entropy density which can substantially alter $N_{\rm eff}$ and Big Bang Nucleosynthesis (BBN). Note that ultralight dark photon mediators are not produced abundantly by the SM bath in the early universe because of an in-medium suppression of the coupling [19], which means the dark photons do not affect $N_{\rm eff}$ or BBN.

Early Universe Origins: For sub-MeV dark matter, the main channels for freeze-in production are from annihilation of electrons $e^+e^- \to \chi\bar{\chi}$ and from plasmon decays $\gamma^* \to \chi\bar{\chi}$ (the decay of photons that acquire an effective in-medium plasma mass, see e.g. [20]). In [7], we found that plasmon decays are a dominant channel for DM production for sub-MeV DM masses, and including this channel leads to a significant reduction in predicted couplings and corresponding signal strength for DM searches. Accounting for production from both plasmon decays and annihilations of SM fermions, the DM is born with a highly non-thermal phase space distribution which can have typical momenta that is an O(1) fraction of the photon momenta at the freeze-in epoch (since the DM inherits the kinematic properties of the photons from which they are born). Depending on the value of g_χ, DM might be able to efficiently self-thermalize in its own secluded sector. This requires raising g_χ, which can be compensated by lowering $g_{\rm SM}$ to give the same freeze-in abundance. To avoid bounds from self interaction (for instance from merging galaxy clusters, see e.g. [21]), g_χ cannot be too large. However, there is a finite window in parameter space where the self-interaction bounds are not violated but where the DM can self-thermalize before recombination [7].

Interactions with Baryons: The portal responsible for making DM gives rise to a non-gravitational drag force between the dark matter and the photon-baryon fluid with a cross section that scales as v^{-4}. This drag force leads to a damping in the amplitude of acoustic oscillations, corresponding to a suppression of the CMB power spectrum for multipoles $\ell \gtrsim 300$ [22]. Because of the strong velocity scaling of DM-baryon scattering in this theory, the initial conditions are relevant in determining the strength of the effect. Millicharged DM with cold initial conditions, considered in previous works (e.g. [22–24]), will have the strongest effect. Meanwhile, DM with the non-thermal freeze-in phase space distribution will give a slightly weaker effect and DM with the thermalized freeze-in phase space distribution will be even weaker. Current CMB observations, for instance from *Planck* 2018, can exclude parts of the low-mass freeze-in DM parameter space, with the exact number depending on whether the DM has self-thermalized. In the future, the Simons Observatory and CMB-S4 will be able to probe freeze-in up to higher masses [25].

Effects of the Initial Velocity on Clustering: Because the phase space of freeze-in DM is initially inherited from electron-positron pairs and plasmons, sub-MeV DM is produced with a relatively high-speed phase space distribution, leading to a suppression in gravitational clustering below the free-streaming scale (in analogy to warm DM [26–28]). If the primordial phase space is preserved and the DM does not self thermalize, then the DM will stream freely through nascent cosmological structures. If DM has strong enough self couplings to thermalize, then it behaves more as a fluid with non-negligible sound speed.

Observational probes of small-scale clustering can already constrain freeze-in [25]. Recently, limits on warm DM have been set using the Lyman-α forest [29–31] and inferences about the subhalo mass function from quasar strong lensing [32, 33], stellar streams [34, 35], and MW satellite galaxies [36, 37]. Freeze-in does not yield the exact same suppression of the matter power spectrum as warm DM, but based on estimates derived from matching the point where structure is suppressed by $1/2$ (following e.g. [38]), current limits should be able to exclude part of the freeze-in parameter space, again with the exact constraints depending on whether the DM has self-thermalized. In the future, probes of small-scale clustering should considerably improve the reach. Inferences about low-mass halos from 21 cm cosmology with the Hydrogen Epoch of Reionization Array [39] and from observations of subhalos with the Vera Rubin Observatory [40] should be able to probe freeze-in masses up to ~ 100 keV. Cosmological simulations with freeze-in initial conditions should be performed to confirm these estimates, which come from the nonlinear regime of clustering.

Status as a Direct Detection Benchmark: Since the (dark) photon mediator couples to charged SM fermions, the DM can scatter off of electrons or nuclei. The detectability of the freeze-in benchmark in semiconductor or atomic targets was first pointed out in Refs. [41–43], and recently there has been an acceleration in experimental efforts to observe electron recoils in those targets with energy as low as $\sim$ eV [44–47]. These can probe halo dark matter down to about 0.5 MeV-1 MeV, limited by the available kinetic energy of the DM candidate. To access even lower mass DM and push into the sub-MeV regime, new experimental techniques and proposals are needed. There are proposals to use lower gap materials, for example Dirac materials with O(meV) electronic band gap [48–50]. The dark matter could also excite optical phonons [51–53], through the interaction of the mediator with the ions in a solid state material. Optical phonons are gapped excitations with $O(30-100)$ meV energy that are well-suited for the DM kinematics in this mass range, and could also provide a directional signal because the phonon properties depend on crystal direction. This approach would extend existing phonon-based direct detection experiments to much lower thresholds. Another recent proposal uses EM fields to induce small currents in the DM passing through the Earth, which is then observed with a shielded magnetometer [54]. These approaches will be provide complementary ways to search for sub-MeV freeze-in.

Outlook: Sub-MeV freeze-in via a light vector mediator sits at the nexus of many interesting possible DM properties. Freeze-in is the only minimal way to make millicharged DM and is one of very few ways to make sub-MeV DM from a SM thermal process in the early Universe. This DM candidate is dominantly born from the decay of plasmons (collective excitations in the primordial plasma) and has a nonthermal, high-velocity phase space distribution, making it behave somewhat like warm DM. It later can scatter with baryons either in the primordial plasma prior to recombination or in the lab, where its highly predictive signal strength makes it a key benchmark for proposed sub-MeV direct detection experiments. All of these features make this theory of great interest to the particle physics community in the near term future.

[1] T. Asaka, K. Ishiwata, and T. Moroi, Phys. Rev. **D73**, 051301 (2006), arXiv:hep-ph/0512118 [hep-ph].
[2] T. Asaka, K. Ishiwata, and T. Moroi, Phys. Rev. **D75**, 065001 (2007), arXiv:hep-ph/0612211 [hep-ph].
[3] S. Gopalakrishna, A. de Gouvea, and W. Porod, JCAP **0605**, 005 (2006), arXiv:hep-ph/0602027 [hep-ph].
[4] V. Page, JHEP **04**, 021 (2007), arXiv:hep-ph/0701266 [hep-ph].
[5] L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, JHEP **03**, 080 (2010), arXiv:0911.1120 [hep-ph].
[6] N. Bernal, M. Heikinheimo, T. Tenkanen, K. Tuominen, and V. Vaskonen, Int. J. Mod. Phys. **A32**, 1730023 (2017), arXiv:1706.07442 [hep-ph].
[7] C. Dvorkin, T. Lin, and K. Schutz, Phys. Rev. **D99**, 115009 (2019), arXiv:1902.08623 [hep-ph].
[8] S. Knapen, T. Lin, and K. M. Zurek, (2017), arXiv:1709.07882 [hep-ph].
[9] D. Green and S. Rajendran, JHEP **10**, 013 (2017), arXiv:1701.08750 [hep-ph].
[10] S. D. McDermott, H.-B. Yu, and K. M. Zurek, Phys. Rev. **D83**, 063509 (2011), arXiv:1011.2907 [hep-ph].
[11] J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen, and N. Mahesh, Nature **555**, 67 (2018).
[12] R. Barkana, N. J. Outmezguine, D. Redigolo, and T. Volansky, Phys. Rev. **D98**, 103005 (2018), arXiv:1803.03091 [hep-ph].
[13] H. Vogel and J. Redondo, JCAP **1402**, 029 (2014), arXiv:1311.2600 [hep-ph].
[14] S. A. Abel, M. D. Goodsell, J. Jaeckel, V. V. Khoze, and A. Ringwald, JHEP **07**, 124 (2008), arXiv:0803.1449 [hep-ph].
[15] M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, JHEP **11**, 027 (2009), arXiv:0909.0515 [hep-ph].
[16] S. Davidson, S. Hannestad, and G. Raffelt, Journal of High Energy Physics **2000**, 003 (2000).
[17] X.-D. Shi and G. M. Fuller, Phys. Rev. Lett. **82**, 2832 (1999), arXiv:astro-ph/9810076.
[18] A. Berlin and N. Blinov, Phys. Rev. Lett. **120**, 021801 (2018), arXiv:1706.07046 [hep-ph].
[19] H. An, M. Pospelov, and J. Pradler, Phys. Lett. **B725**, 190 (2013), arXiv:1302.3884 [hep-ph].
[20] E. Braaten and D. Segel, Phys. Rev. **D48**, 1478 (1993), arXiv:hep-ph/9302213 [hep-ph].
[21] S. Tulin and H.-B. Yu, Phys. Rept. **730**, 1 (2018), arXiv:1705.02358 [hep-ph].
[22] C. Dvorkin, K. Blum, and M. Kamionkowski, Phys. Rev. **D89**, 023519 (2014), arXiv:1311.2937 [astro-ph.CO].
[23] K. K. Boddy, V. Gluscevic, V. Poulin, E. D. Kovetz, M. Kamionkowski, and R. Barkana, (2018), arXiv:1808.00001 [astro-ph.CO].
[24] T. R. Slatyer and C.-L. Wu, Phys. Rev. **D98**, 023013 (2018), arXiv:1803.09734 [astro-ph.CO].
[25] C. Dvorkin, T. Lin, and K. Schutz, in prep.
[26] P. Bode, J. P. Ostriker, and N. Turok, The Astrophysical Journal **556**, 93 (2001).
[27] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese, and A. Riotto, Physical Review D **71**, 063534 (2005).
[28] A. Schneider, R. E. Smith, A. V. Maccio, and B. Moore, Mon. Not. Roy. Astron. Soc. **424**, 684 (2012), arXiv:1112.0330 [astro-ph.CO].
[29] V. Iršič *et al.*, Phys. Rev. **D96**, 023522 (2017), arXiv:1702.01764 [astro-ph.CO].
[30] C. Yèche, N. Palanque-Delabrouille, J. Baur, and H. du Mas des Bourboux, JCAP **1706**, 047 (2017), arXiv:1702.03314 [astro-ph.CO].
[31] J. Baur, N. Palanque-Delabrouille, C. Yeche, A. Boyarsky, O. Ruchayskiy, É. Armengaud, and J. Lesgourgues, JCAP **1712**, 013 (2017), arXiv:1706.03118 [astro-ph.CO].
[32] J.-W. Hsueh, W. Enzi, S. Vegetti, M. Auger, C. D. Fassnacht, G. Despali, L. V. Koopmans, and J. P. McKean, Monthly Notices of the Royal Astronomical Society **492**, 3047 (2020).
[33] D. Gilman, S. Birrer, A. Nierenberg, T. Treu, X. Du, and A. Benson, (2019), arXiv:1908.06983 [astro-ph.CO].
[34] N. Banik, J. Bovy, G. Bertone, D. Erkal, and T. J. L. de Boer, (2019), arXiv:1911.02662 [astro-ph.GA].
[35] N. Banik, J. Bovy, G. Bertone, D. Erkal, and T. J. L. de Boer, (2019), arXiv:1911.02663 [astro-ph.GA].
[36] E. O. Nadler, V. Gluscevic, K. K. Boddy, and R. H. Wechsler, Astrophys. J. **878**, L32 (2019), [Astrophys. J. Lett.878,32(2019)], arXiv:1904.10000 [astro-ph.CO].
[37] E. Nadler *et al.* (DES), (2020), arXiv:2008.00022 [astro-ph.CO].
[38] R. Murgia, V. Iršič, and M. Viel, (2018), arXiv:1806.08371 [astro-ph.CO].
[39] J. B. Muñoz, C. Dvorkin, and F.-Y. Cyr-Racine, Phys. Rev. **D101**, 063526 (2020), arXiv:1911.11144 [astro-ph.CO].
[40] A. Drlica-Wagner *et al.* (LSST Dark Matter Group), (2019), arXiv:1902.01055 [astro-ph.CO].
[41] R. Essig, J. Mardon, and T. Volansky, Phys. Rev. **D85**, 076007 (2012), arXiv:1108.5383 [hep-ph].

[42] R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, Phys. Rev. Lett. **109**, 021301 (2012), arXiv:1206.2644 [astro-ph.CO].
[43] R. Essig, M. Fernandez-Serra, J. Mardon, A. Soto, T. Volansky, and T.-T. Yu, JHEP **05**, 046 (2016), arXiv:1509.01598 [hep-ph].
[44] A. Aguilar-Arevalo *et al.* (DAMIC), Phys. Rev. Lett. **123**, 181802 (2019), arXiv:1907.12628 [astro-ph.CO].
[45] L. Barak *et al.* (SENSEI), (2020), arXiv:2004.11378 [astro-ph.CO].
[46] D. Amaral *et al.* (SuperCDMS), (2020), arXiv:2005.14067 [hep-ex].
[47] P. Agnes *et al.* (DarkSide), Phys. Rev. Lett. **121**, 111303 (2018), arXiv:1802.06998 [astro-ph.CO].
[48] Y. Hochberg, Y. Kahn, M. Lisanti, K. M. Zurek, A. G. Grushin, R. Ilan, S. M. Griffin, Z.-F. Liu, S. F. Weber, and J. B. Neaton, Phys. Rev. **D97**, 015004 (2018), arXiv:1708.08929 [hep-ph].
[49] R. M. Geilhufe, F. Kahlhoefer, and M. W. Winkler, Phys. Rev. D **101**, 055005 (2020), arXiv:1910.02091 [hep-ph].
[50] A. Coskuner, A. Mitridate, A. Olivares, and K. M. Zurek, (2019), arXiv:1909.09170 [hep-ph].
[51] S. Knapen, T. Lin, M. Pyle, and K. M. Zurek, (2017), arXiv:1712.06598 [hep-ph].
[52] S. Griffin, S. Knapen, T. Lin, and K. M. Zurek, (2018), arXiv:1807.10291 [hep-ph].
[53] S. M. Griffin, K. Inzani, T. Trickle, Z. Zhang, and K. M. Zurek, Phys. Rev. D **101**, 055004 (2020), arXiv:1910.10716 [hep-ph].
[54] A. Berlin, R. T. D'Agnolo, S. A. Ellis, P. Schuster, and N. Toro, Phys. Rev. Lett. **124**, 011801 (2020), arXiv:1908.06982 [hep-ph].