Lecture 4 Notes (VSOP 2026): Models and Searches for Thermal Dark Matter

Tracy R. Slatyer[1, *]

[1] *Center for Theoretical Physics – a Leinweber Institute, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

I. AFTER FREEZE-OUT: COSMOLOGICAL CONSEQUENCES OF RESIDUAL ANNIHILATION

In the simplest baseline scenario, what happens after freeze-out? The fraction of dark matter that annihilates per Hubble time is $n\langle\sigma v\rangle H^{-1}$. During radiation domination, $n \propto T^3$ for a decoupled non-relativistic species, while $H^{-1} \propto T^{-2}$. Thus $n\langle\sigma v\rangle H^{-1} \propto T$, for a velocity-independent $\langle\sigma v\rangle$ (this is characteristic of models where there is no particular source of velocity dependence in the interaction). At freeze-out, $n\langle\sigma v\rangle \sim H$, so at later times we can write $n\langle\sigma v\rangle H^{-1} \sim \frac{T}{T_f}$. The energy injected per baryon over a Hubble time by dark matter annihilation is therefore roughly ~ 5 GeV $\left(\frac{T}{T_f}\right)$. If $T_f \sim 5$ GeV, corresponding to $m_{\rm DM} \sim 100$ GeV, we see that this value is $\sim T$: thus a classic WIMP's ongoing annihilations inject enough power to change the baryon temperature at order-one level through radiation domination, albeit often with this energy diluted by the photons.

Considering the cosmological epochs discussed previously:

- **BBN:** dark-matter annihilation can modify nuclear reactions. If dark matter is annihilating into dark radiation, it modifies $N_{\rm eff}$. Annihilation to photons versus neutrinos can heat one bath relative to the other, again modifying $N_{\rm eff}$.

  Detailed analyses find that thermal relic dark matter below roughly 4–14 MeV can be constrained, depending on its spin and annihilation channel [1, 2]. This is a general limit on thermal freeze-out; it is not constraining for freeze-in.

- **CMB:** at $T \sim 0.2$ eV, changing the matter temperature by an order-one factor corresponds to having enough power to ionize an order-percent fraction of all hydrogen. The CMB constrains changes to the post-recombination ionization history at roughly the 10^{-3} level. A detailed calculation implies that a thermal annihilation cross section to any Standard Model final state except neutrinos is ruled out for dark matter lighter than about 10 GeV [3]. This is a strong mass limit, but it is not too hard to evade in specific models: loopholes include annihilating nearly 100% to neutrinos, or suppressing annihilation at late times.

- **Structure formation:** the free-streaming scale bounds discussed previously constrain thermal dark matter below roughly the 10 keV scale. This also works for freeze-in and does not require that dark matter ever reached equilibrium. It is the weakest, but most general, mass limit on species sourced from Standard Model interactions.

Thus low masses are constrained by cosmology; in contrast, the limit on high masses is primarily a theoretical one, that it becomes hard to obtain the required annihilation cross section.

* tslatyer@mit.edu

II. UNITARITY AND THE HIGH-MASS LIMIT ON THERMAL RELICS

Unitarity, or probability conservation, sets an upper limit on the annihilation cross section for each partial wave. For total angular momentum J,

$$(\sigma v_{\rm rel})^J_{\rm total} < (\sigma v)^J_{\rm max} = \frac{4\pi(2J+1)}{m_{\rm DM}^2 v_{\rm rel}}. \tag{1}$$

Equivalently, obtaining the observed abundance requires

$$m_{\rm DM}^2 < \frac{4\pi(2J+1)}{v_{\rm rel}(\sigma v_{\rm rel})^J_{\rm total}}. \tag{2}$$

The relative velocity is determined by the freeze-out temperature. For standard thermal freeze-out, as we discussed, the kinetic energy at freezeout is set by $T_f \sim m_\chi/25$, so a typical velocity is $v \sim 0.3$. If only a few partial waves dominate, then inserting our previous estimate $\sigma v \sim 10^{-9}\text{GeV}^{-2}$ gives

$$m_{\rm DM} \lesssim \sqrt{\frac{4\pi 10^9 \text{GeV}^2}{0.3}} \sim 200 \text{ TeV}. \tag{3}$$

One can go higher if many partial waves contribute, although there is still a limit around the PeV scale [4]. There are also loopholes if the cosmological history is modified. For example, a first-order phase transition can allow non-thermal production of heavy dark matter.

Putting these considerations together, the rough thermal window is

$$m_{\rm DM} \sim 10 \text{ MeV–}100 \text{ TeV}. \tag{4}$$

This can extend down to roughly 10 keV with freeze-in. For thermal relics lighter than roughly 10 GeV, late-time annihilation to non-neutrino Standard Model particles must be suppressed.

The natural next question is: what models populate this space?

III. MODELS THAT POPULATE THE THERMAL WINDOW

One useful way to classify thermal-relic models is by asking what physics governs the annihilation cross section. The most classic version of the Weakly Interacting Massive Particle (WIMP) scenario is motivated by the fact that weak-scale masses and couplings naturally give a cross section of the right order. Suppose the dark matter is lighter than the Z boson and annihilates through a diagram with a weak-scale mediator (coupled to the dark matter with strength α_D), schematically

$$\chi\chi \to Z^* \to \text{SM particles}. \tag{5}$$

Then the annihilation cross section is parametrically

$$\langle \sigma v \rangle \sim \alpha_W \alpha_D \frac{m_{\rm DM}^2}{m_Z^4} \sim 10^{-9} \text{ GeV}^{-2}, \tag{6}$$

where the last step indicates the value required for the thermal relic abundance. This gives

$$\frac{m_{\rm DM}^2}{m_Z^4} \gtrsim \frac{10^{-9} \text{ GeV}^{-2}}{\alpha_W}, \qquad \left(\frac{m_{\rm DM}}{m_Z}\right)^2 \gtrsim 10^{-4}, \tag{7}$$

and hence a lower bound of order

$$m_{\rm DM} \gtrsim \text{GeV}. \tag{8}$$

This is the Lee–Weinberg bound in its simplest form [5].

Thus sub-GeV dark matter produced by freeze-out generally needs a new mediator between the Standard Model and dark matter. For classic WIMPs above roughly 10 GeV, annihilation need not be suppressed during the CMB epoch; the mediator can be the W, Z, Higgs, or a new particle; and model-building is relatively unconstrained. Direct detection and collider searches can then be powerful, as we will discuss.

A long-standing idea is that dark matter could be the lightest supersymmetric particle (LSP). In supersymmetry (SUSY), every Standard Model particle has a superpartner: fermions have bosonic partners and bosons have fermionic partners. Superpartners cancel large corrections to the Higgs mass and help ensure unification of Standard Model couplings at high energies, motivating SUSY independently of dark matter. A standard reference is Martin's supersymmetry primer [6].

However, generic supersymmetry would imply proton decay through diagrams involving squarks and sleptons. The usual approach is to impose a symmetry called R-parity:

- superpartners have $R = -1$;
- ordinary Standard Model particles have $R = +1$;
- the product of R-parities before and after an interaction is conserved.

The lightest particle with $R = -1$ therefore cannot decay, since all possible final-state particles would have $R = +1$. If this "lightest supersymmetric particle" (LSP) is electrically neutral, it can be a good dark matter candidate.

In the Minimal Supersymmetric Standard Model, the standard neutral dark matter candidates are neutralinos, admixtures of the fermionic superpartners of neutral bosons. They are usually labeled the wino, bino, and higgsino, i.e. the partners of the $SU(2)$ gauge boson, the $U(1)$ gauge boson, and the Higgs. The space of neutralino candidates is large and multi-dimensional. Large regions are constrained by collider searches, underground direct-detection experiments, and telescopes, but viable regions remain (see recent analyses such as Ref. [7] and the older comprehensive analysis of Ref. [8]). For example, nearly pure higgsino dark matter remains hard to constrain and can obtain the correct relic density for $m_{\rm DM} \sim 1$ TeV.

"Minimal dark matter" provides a related but more economical approach: instead of adding a whole supersymmetric spectrum, one adds multiplets of the Standard Model $SU(2)_L$ gauge group [9]. The higgsino can be viewed as adding an $SU(2)$ doublet fermion. In minimal dark matter, the interactions are fixed by the gauge structure, and the mass can be chosen to give the correct relic density. The correct relic density is obtained for a dark matter mass of ~ 1 TeV for a fermionic doublet (akin to the higgsino), ~ 3 TeV for a fermionic triplet (akin to the wino), and ~ 14 TeV for a fermionic quintuplet. The resulting models are simple and predictive, and none have yet been tested by collider or direct-detection experiments [10, 11], although some of the lower multiplets can be probed via annihilation signals [12].

Below the GeV scale, because of the Lee-Weinberg bound, the focus is usually on dark sectors containing at least one extra new particle beyond the dark matter, typically a mediator coupling dark matter to the Standard Model. Thermal freeze-out is a key benchmark for such dark sectors, but not the only possibility for obtaining the correct relic density. Such scenarios typically imply dark-matter self-interactions, which are constrained by observations such as the Bullet Cluster and similar systems; these limits can be strong for sufficiently light dark matter.

A common language is to classify the model by the quantum numbers of the mediator. If we assume the mediator does not transform under the Standard Model gauge symmetries (it is a "gauge singlet"), we can ask what renormalizable Lagrangian terms can be constructed from the mediator and a gauge-singlet combination of Standard Model fields [13]. That list is rather short:

1. **Vector portal:** a new Abelian vector boson V_μ with interaction
$$-\,\epsilon F'_{\mu\nu} B^{\mu\nu}, \tag{9}$$
where $F'_{\mu\nu}$ is the dark-sector field strength and $B^{\mu\nu}$ is the hypercharge field strength.
2. **Scalar portal:** a scalar mediator S with interaction
$$(\mu S + \lambda S^2) H^\dagger H. \tag{10}$$

3. **Heavy neutral lepton/neutrino portal:** a neutral fermion mediator N with interaction

$$y_N LHN. \tag{11}$$

Allowing for higher-dimension operators opens up the possibilities further, but we generically expect such interactions to be suppressed by a heavy mass scale.

The CMB bounds discussed above, which become important below ~ 10 GeV, require late-time annihilation to be suppressed for annihilation into non-neutrino Standard Model final states. There are many viable examples. For instance, scalar dark matter annihilating to Standard Model particles via a vector mediator, or fermion dark matter annihilating to two scalar mediators, can have p-wave suppression, with

$$\langle \sigma v \rangle \propto v^2, \tag{12}$$

which makes late-time annihilation safe from CMB constraints [14][1]. Another possibility is pseudo-Dirac dark matter: two slightly split states χ and χ^* annihilate through a vector mediator, but annihilation is suppressed in the late universe once the excited state has decayed away. (This is one variant of *coannihilation* where the freezeout involves a partner particle which is absent at later times.) A neutrino-portal construction can arrange for the dominant annihilation to be to neutrinos, which are much less constrained (e.g. [16]).

IV. EXPERIMENTAL PROBES OF THESE MODELS

Beyond annihilation, we can consider other possible interactions between dark matter and visible particles. Schematically, in terms of the direction of time, we can distinguish

- annihilation, DM + DM → SM + SM, which "breaks" the dark matter;
- scattering, DM + SM → DM + SM, which "shakes" the target;
- production, SM + SM → DM + DM, which "makes" the dark matter.

A. Indirect detection (DM + DM → SM + SM)

We already discussed CMB bounds on dark-matter annihilation. Beyond these homogeneous effects, we can look for the particles produced by annihilation in regions of high dark-matter density, for example the center of the Milky Way, clumps of dark matter in the Milky Way halo such as dwarf satellite galaxies, galaxy clusters, and so on.

For photon and neutrino searches, because the (uncharged) particles follow straight lines, we can trace the particles back to their source locations. For charged particles, we instead measure an approximately isotropic flux, which requires modeling of propagation in Galactic magnetic fields. This introduces extra systematic uncertainties, but can still set powerful constraints, testing the thermal relic cross section up to dark-matter masses of order hundreds of GeV; see for example Refs. [17, 18].

The optimal target region on the sky can depend on the final-state particles of the annihilation process. Broadly speaking, there are three types of signal spectrum (see Ref. [18] and references therein):

- Final states such as quarks and τ's hadronize or decay to produce π^0's, which then decay to $\gamma\gamma$. This gives a photon-rich continuum spectrum with a characteristic scale associated with the dark matter mass. Gamma-ray and antiproton searches give the strongest limits for these channels. Astrophysical backgrounds are a concern, as there are astrophysical sources that produce similar spectra, but robust limits from dwarfs test the thermal relic cross section up to masses around $m_{\mathrm{DM}} \sim 100$ GeV for such channels, e.g. [19].

[1] Ref. [15] is a useful reference on which interaction structures give rise to suppressed annihilation, scattering, etc

- Final states such as $e^\pm$ and $\mu^\pm$ produce copious charged leptons, and possibly neutrinos and photons from three-body final states such as $e^+e^-\gamma$, as well as from cooling of the $e^\pm$. The strongest limits usually come from positron searches with AMS-02. The thermal relic cross section for such models can be probed up to masses $\sim$ 60–380 GeV, e.g. [20].
- The $\gamma\gamma$ final state gives direct annihilation to line photons. This is a clean signal with no known backgrounds in gamma rays, but the rate is expected to be small (since the dark matter cannot have an unsuppressed coupling to photons in order to be dark, so this process usually arises first at one-loop level), so it is usually optimal to look at the targets with the highest expected signal (even if there are also substantial backgrounds).

For dark-matter decays, galaxy clusters and the Milky Way Galactic halo typically give the strongest limits. To evade these bounds, lifetimes need to satisfy $\tau \gtrsim 10^{27}$–10^{28} s for most final states and for keV $\lesssim m_{\rm DM} \lesssim$ EeV; see for example Refs. [21, 22].

For dark-matter annihilation, the largest signal is typically expected from the Galactic Center, but it also has the highest backgrounds. Dwarf galaxies provide a good low-background target for less distinctive channels. Current robust limits for thermal relic dark matter are around the tens to hundreds of GeV, depending on the channel. There are prospects for extending sensitivity up to the tens of TeV range with large ground-based γ-ray telescopes, for example CTAO, LACT, and SWGO [23]. These searches will test the benchmark $SU(2)_W$ dark-matter models discussed earlier.

B. Direct detection (DM + SM → DM + SM)

Direct detection focuses on the second possibility, where dark matter elastically scatters on a Standard Model target. Variations also include absorption of dark matter onto Standard Model targets, instead of scattering. The basic idea is to observe the recoil of a target, such as an atomic nucleus or electron, via ionization, phonons, scintillation, excitation, or a similar observable. Direct-detection experiments have sensitivity to extremely tiny cross sections, as small as $\sigma \approx 10^{-48} - 10^{-47}$ cm^2 [24]. Direct-detection experiments are typically underground and heavily shielded to reduce backgrounds. They are often also cooled to low temperatures.

In principle, the recoil signal is both directional and time-dependent. Due to the motion of the Sun through the Galaxy, dark matter has a preferred direction in the solar frame, the "WIMP wind." The direction of this wind relative to the laboratory varies over a one-day period. The dark-matter flux is also enhanced when the Earth and Sun move in the same direction relative to the dark-matter wind, and suppressed when the opposite is true. This leads to an annual modulation of the signal.

As you will explore on the problem set, classic direct detection experiments lose sensitivity when the dark matter mass is much smaller than the mass of the target atoms. To access lower-mass dark matter, one can use several strategies. One is to search for electron recoils rather than nuclear recoils. This drops the scale at which the recoil energy is badly suppressed (due to the reduced mass dropping well below the target mass) from $\mathcal{O}$(10 GeV) to $\mathcal{O}$(MeV). Example experiments include SENSEI and DAMIC-M [25] – in particular, DAMIC-M is able to test some freeze-in benchmarks. Another possibility is to look for photons or electrons produced in conjunction with nuclear recoils through the Migdal effect. This effect has recently been observed in the laboratory using a neutron beam [26]. A further possibility is to look for accelerated higher-velocity dark matter, for example solar-reflected dark matter [27]. One can also study special systems with tiny masses or gaps, and hence sensitivity to tiny energy depositions. In such systems, collective and in-medium effects often dominate. A useful review article on these strategies is the Snowmass report of Ref. [28].

C. Collider/accelerator searches (SM + SM → DM + DM)

We now turn to collider searches. In a first approximation, we might look for Standard Model particles producing a pair of dark-matter particles. However, dark matter is very long-lived, so if it is produced by a collision, it will escape the detector. Thus we need other particles in the final state, so we can look for visible particles recoiling against invisible dark matter. The dark matter appears as missing energy or missing momentum.

If we look for just one visible particle or jet, we call such searches "mono-X" searches, for example mono-Higgs, mono-jet, or mono-photon searches. We can also look for more than one particle, for example dijet searches. Production of visible particles can occur via radiation from the Standard Model part of the interaction, or by production of unstable partners which decay into dark matter plus visible particles. An overview of various dark matter searches at the LHC can be found in (for example) Ref. [29].

In specific models, searches for new physics related to dark matter may beat dark-matter-focused searches. For example, in supersymmetric models the dark matter often comes with charged partners, and one can search for those. In some exotic scenarios, dark matter could form bound states that decay to Standard Model particles. In dark sectors with new mediators, it is often more efficient to look for the mediator itself than the dark matter particle; because the mediator need not be stable, we can search for its decays after production. Especially for lighter dark matter and mediators, high-intensity but lower-energy accelerators may be able to surpass the LHC. One idea is to use existing accelerators, including the LHC, as a source of long-lived new particles, and search for their displaced decays with additional detectors, for example FASER, CODEX-b, and MATHUSLA. Aspects of this program are described in the Snowmass reports of Refs. [30, 31].

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[1] Nashwan Sabti, James Alvey, Miguel Escudero, Malcolm Fairbairn, and Diego Blas, "Refined Bounds on MeV-scale Thermal Dark Sectors from BBN and the CMB," JCAP **01**, 004 (2020), arXiv:1910.01649 [hep-ph].

[2] Rui An, Vera Gluscevic, Erminia Calabrese, and J. Colin Hill, "What does cosmology tell us about the mass of thermal-relic dark matter?" JCAP **07**, 002 (2022), arXiv:2202.03515 [astro-ph.CO].

[3] N. Aghanim *et al.* (Planck), "Planck 2018 results. VI. Cosmological parameters," Astron. Astrophys. **641**, A6 (2020), [Erratum: Astron.Astrophys. 652, C4 (2021)], arXiv:1807.06209 [astro-ph.CO].

[4] Juri Smirnov and John F. Beacom, "TeV-Scale Thermal WIMPs: Unitarity and its Consequences," Phys. Rev. D **100**, 043029 (2019), arXiv:1904.11503 [hep-ph].

[5] Benjamin W. Lee and Steven Weinberg, "Cosmological Lower Bound on Heavy Neutrino Masses," Phys. Rev. Lett. **39**, 165–168 (1977).

[6] Stephen P. Martin, "A Supersymmetry primer," Adv. Ser. Direct. High Energy Phys. **18**, 1–98 (1998), arXiv:hep-ph/9709356.

[7] Rahool Kumar Barman, Genevieve Belanger, Biplob Bhattacherjee, Rohini Godbole, and Rhitaja Sengupta, "Current status of the light neutralino thermal dark matter in the phenomenological MSSM," Phys. Rev. D **111**, 015014 (2025), arXiv:2402.07991 [hep-ph].

[8] Joseph Bramante, Nishita Desai, Patrick Fox, Adam Martin, Bryan Ostdiek, and Tilman Plehn, "Towards the Final Word on Neutralino Dark Matter," Phys. Rev. D **93**, 063525 (2016), arXiv:1510.03460 [hep-ph].

[9] Marco Cirelli, Nicolao Fornengo, and Alessandro Strumia, "Minimal Dark Matter," Nucl. Phys. B **753**, 178–194 (2006), arXiv:hep-ph/0512090.

[10] Salvatore Bottaro, Dario Buttazzo, Marco Costa, Roberto Franceschini, Paolo Panci, Diego Redigolo, and Ludovico Vittorio, "Closing the window on wimp dark matter," The European Physical Journal C **82** (2022), 10.1140/epjc/s10052-021-09917-9.

[11] Salvatore Bottaro, Dario Buttazzo, Marco Costa, Roberto Franceschini, Paolo Panci, Diego Redigolo, and Ludovico Vittorio, "The last complex wimps standing," The European Physical Journal C **82** (2022), 10.1140/epjc/s10052-022-10918-5.

[12] Benjamin R. Safdi and Weishuang Linda Xu, "Wino and real minimal dark matter excluded by fermi gamma-ray observations," (2025), arXiv:2507.15934 [hep-ph].

[13] Marco Cirelli, Alessandro Strumia, and Jure Zupan, "Dark Matter," SciPost Phys. Rev. **1** (2026), 10.21468/SciPostPhysRev.1, arXiv:2406.01705 [hep-ph].

[14] Marco Battaglieri *et al.*, "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report," (2017), arXiv:1707.04591 [hep-ph].

[15] Jason Kumar and Danny Marfatia, "Matrix element analyses of dark matter scattering and annihilation," Phys. Rev. D **88**, 014035 (2013), arXiv:1305.1611 [hep-ph].

[16] Nicole F. Bell, Matthew J. Dolan, Avirup Ghosh, and Michael Virgato, "Neutrino portals to MeV WIMPs with s-channel mediators," Phys. Rev. D **111**, 055020 (2025), arXiv:2412.02994 [hep-ph].

[17] Alessandro Cuoco, Jan Heisig, Michael Korsmeier, and Michael Krämer, "Constraining heavy dark matter with cosmic-ray antiprotons," JCAP **04**, 004 (2018), arXiv:1711.05274 [hep-ph].

[18] Rebecca K. Leane, Tracy R. Slatyer, John F. Beacom, and Kenny C. Y. Ng, "GeV-Scale Thermal WIMPs: Not

Even Slightly Dead," Phys. Rev. D **98**, 023016 (2018), arXiv:1805.10305 [hep-ph].

[19] S. Abdollahi *et al*, "Combined dark matter search towards dwarf spheroidal galaxies with fermi-lat, hawc, h.e.s.s., magic, and veritas," Journal of Cosmology and Astroparticle Physics **2026**, 035 (2026).

[20] Isabelle John and Tim Linden, "Cosmic-ray positrons strongly constrain leptophilic dark matter," Journal of Cosmology and Astroparticle Physics **2021**, 007 (2021).

[21] Timothy Cohen, Kohta Murase, Nicholas L. Rodd, Benjamin R. Safdi, and Yotam Soreq, "Gamma-ray Constraints on Decaying Dark Matter and Implications for IceCube," Phys. Rev. Lett. **119**, 021102 (2017), arXiv:1612.05638 [hep-ph].

[22] Rouven Essig, Eric Kuflik, Samuel D. McDermott, Tomer Volansky, and Kathryn M. Zurek, "Constraining Light Dark Matter with Diffuse X-Ray and Gamma-Ray Observations," JHEP **11**, 193 (2013), arXiv:1309.4091 [hep-ph].

[23] SWGO Collaboration, "Science prospects for the southern wide-field gamma-ray observatory: Swgo," (2025), arXiv:2506.01786 [astro-ph.HE].

[24] J. Aalbers *et al*, "Dark matter search results from 4.2 tonne-years of exposure of the lux-zeplin (lz) experiment," Physical Review Letters **135** (2025), 10.1103/4dyc-z8zf.

[25] K. Aggarwal *et al*, "Probing benchmark models of hidden-sector dark matter with damic-m," Physical Review Letters **135** (2025), 10.1103/2tcc-bqck.

[26] Difan Yi *et al.*, "Direct observation of the Migdal effect induced by neutron bombardment," Nature **649**, 580–583 (2026).

[27] Haipeng An, Maxim Pospelov, Josef Pradler, and Adam Ritz, "Directly Detecting MeV-scale Dark Matter via Solar Reflection," Phys. Rev. Lett. **120**, 141801 (2018), arXiv:1708.03642 [hep-ph].

[28] Rouven Essig *et al.*, "Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade," in *Snowmass 2021* (2022) arXiv:2203.08297 [hep-ph].

[29] Cristiano Alpigiani, "Searches for Dark Matter in ATLAS," in *5th Large Hadron Collider Physics Conference* (2017) arXiv:1708.09674 [hep-ex].

[30] Stefania Gori, Mike Williams, Phil Ilten, Nhan Tran, Gordan Krnjaic, Natalia Toro, Brian Batell, Nikita Blinov, Christopher Hearty, Robert McGehee, Philip Harris, Philip Schuster, and Jure Zupan, "Dark Sector Physics at High-Intensity Experiments," in *Snowmass 2021* (2022) arXiv:2209.04671 [hep-ph].

[31] Brian Batell, Nikita Blinov, Christopher Hearty, and Robert McGehee, "Exploring dark sector portals with high intensity experiments," (2022), arXiv:2207.06905 [hep-ph].