

Probing light dark matter through cosmic-ray cooling in active galactic nuclei

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Recent observations of high-energy neutrinos from active galactic nuclei (AGN), NGC 1068 and TXS 0506 + 056, suggest that cosmic rays (CRs) are accelerated in the vicinity of the central supermassive black hole and high-energy protons and electrons can cool efficiently via interactions with ambient photons and gas. The dark matter density may be significantly enhanced near the black hole, and CRs could lose energies predominantly due to scatterings with the ambient dark matter particles. We propose CR cooling in AGN as a new probe of dark matter-proton and dark matter-electron scatterings. Under plausible astrophysical assumptions, our constraints on sub-GeV dark matter can be the strongest derived to date. Some of the parameter space favored by thermal light dark matter models might already be probed with current multimessenger observations of AGN.

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Introduction. The presence of dark matter (DM) in galaxies and clusters of galaxies is well established by astrophysical and cosmological observations [1]. However, its particle nature remains unknown [2]. A variety of experiments have aimed to detect DM particles via their scatterings off nuclei and/or electrons at Earth-based detectors, setting strong upper limits on the interaction strength of DM particles with masses in the GeV scale but leaving the sub-GeV region of the parameter space yet largely unconstrained [3–7]. Historically, DM fermions with sub-GeV masses were disfavored by the cosmological bound [8,9]. However, large parameter space still remains unexplored in more complicated but well-motivated scenarios [10–12].

Different approaches have been proposed to extend the sensitivity reach of direct detection experiments for sub-GeV DM. Some of these consider a boosted component of DM particles reaching Earth, via gravitational effects or via scatterings with protons, electrons, or neutrinos in different astrophysical environments (e.g., Refs. [13–29]).

Active galactic nuclei (AGN) are promising sources of high-energy protons and electrons. While the dominant acceleration mechanism of these cosmic rays (CRs) is still under debate, modeling of multimessenger data has placed important constraints on not only energetics of CR production, but also the emission region of the observed neutrinos that can be produced via either inelastic pp collisions or $p\gamma$ interactions [30–32]. For example, observations of high-energy neutrinos and gamma rays from NGC 1068 [33,34] suggest that the neutrino production occurs in the vicinity of the supermassive black hole (SMBH) at $R_{\text{em}} \lesssim (30\text{--}100)R_S$ (where R_S is the Schwarzschild radius), which is consistent with theoretical models [35–39], and the required proton luminosity is at least $\sim 10\%$ of the intrinsic x-ray luminosity [40,41]. Another neutrino source candidate, TXS 0506 + 056 [42–46], is known to be a jet-loud AGN, the observed spectral energy distribution in photons is mostly explained by synchrotron and inverse-Compton emission from CR electrons [45,47–51], and the proton luminosity required by IceCube observations may even exceed the Eddington luminosity [47,48].

In this work, we propose CRs produced in AGN as a new, unique probe of DM-proton and DM-electron scatterings through their multimessenger observations. Given that emission regions of neutrinos and gamma rays are constrained to be near the SMBHs, CRs also need to traverse

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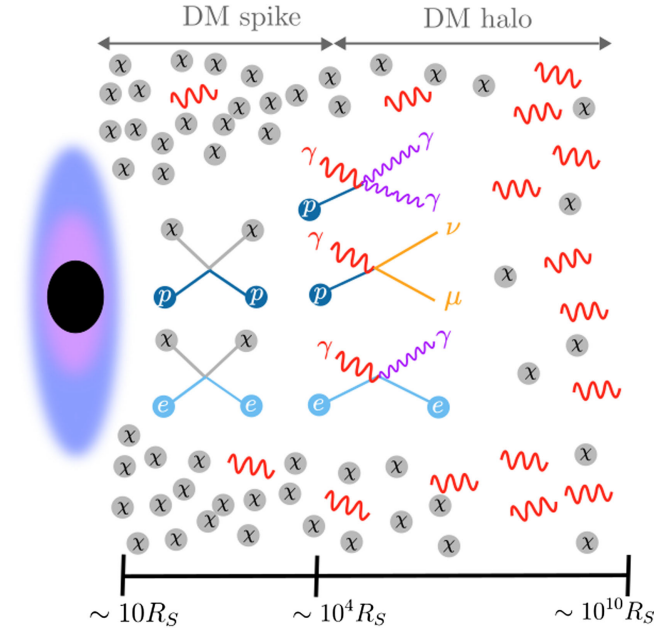


FIG. 1. Schematic picture of dark cooling of CRs due to elastic scatterings with DM particles in AGN. High-energy protons and electrons may traverse a high density of DM particles more efficiently than standard cooling processes involving neutrino and photon emission.

the DM spike around the central SMBH. If such additional cooling beyond the Standard Model (BSM) was too strong, CR energy losses are modified so that the required CR luminosity would be larger, and the neutrino and photon spectra could even be incompatible with the observations. Our work is different from previous studies on AGN probes of the DM scatterings with protons and electrons, which focused either on the boosted flux of DM particles from the source at Earth [22,52,53] or on the spectral distortions in the gamma-ray flux induced by CR scatterings off DM particles [54–59]. Instead, we focus on the impact of the DM-proton and DM-electron scatterings on the neutrino and photon fluxes or the CR power, considering for the first time the cooling of protons and electrons in the inner regions of the AGN, where a DM spike is likely to be formed (see Fig. 1).

DM distribution in AGN. The adiabatic growth of black holes may form a spike of DM particles in their vicinity [60–63]. An initial DM profile of the form $\rho(r) = \rho_0(r/r_0)^{-\gamma}$ evolves into

$$\rho_{\text{sp}}(r) = \rho_R g_\gamma(r) \left(\frac{R_{\text{sp}}}{r} \right)^{\gamma_{\text{sp}}}, \quad (1)$$

where $R_{\text{sp}} = \alpha_\gamma r_0 (M_{\text{BH}}/(\rho_0 r_0^3))^{\frac{1}{3-\gamma}}$ is the size of the spike, with numerical values α_γ provided in Ref. [62]. The cusiness of the spike is given by $\gamma_{\text{sp}} = \frac{9-2\gamma}{4-\gamma}$. Furthermore, $g_\gamma(r) \approx (1 - \frac{4R_{\text{S}}}{r})$, while ρ_R is a normalization factor, chosen to match the density profile outside of the spike, $\rho_R = \rho_0 (R_{\text{sp}}/r_0)^{-\gamma}$. This density profile vanishes at $4R_{\text{S}}$, which is, however, a conservative approximation [64,65].

We consider that the initial DM distribution follows an Navarro-Frenk-White (NFW) profile [66,67], with $\gamma = 1$, resulting in a spike with $\gamma_{\text{sp}} = 7/3$ and $\alpha_\gamma = 0.122$. The masses of the central SMBHs of the two AGN considered in this work are given in Table I. For the scale radius of both galaxies, we take $r_0 = 10$ kpc. Finally, the normalization ρ_0 is determined by the uncertainty on the SMBH mass [55,68], also provided in Table I. We have checked that these criteria yield masses of the DM halo compatible with those expected from universal relations between SMBH and galactic bulge masses [69,70]. We use Eq. (8) of Ref. [69].

If the DM particles self-annihilate, the maximal DM density in the inner regions of the spike is saturated to $\rho_{\text{sat}} = m_{\text{DM}}/(\langle\sigma v\rangle t_{\text{BH}})$, where $\langle\sigma v\rangle$ is the velocity averaged DM self-annihilation cross section and t_{BH} is the SMBH age. For TXS 0506 + 056 (NGC 1068), we take the value $t_{\text{BH}} = 10^9$ (10^{10}) yr [52,71]. Furthermore, the DM spike extends to a maximal radius R_{sp} , beyond which the DM distribution follows the initial NFW profile. The DM density profile therefore reads [62,68,72]

TABLE I. Relevant parameters considered in this work for NGC 1068 and TXS 0506 + 056, for two different sets of assumptions dubbed (I) and (II). Here, R_{em} represents the distance of the emission region from the central SMBH in NGC 1068 (TXS 0506 + 056), M_{BH} shows the SMBH mass and its uncertainty, t_{BH} is the black hole age, r_0 is the scale radius of the galaxy, $\langle\sigma v\rangle/m_{\text{DM}}$ denotes the assumed values of the effective DM self-annihilation cross section, and $\langle\rho_{\text{DM}}\rangle$ is the average density of DM particles within R_{em} .

	R_{em}	M_{BH}	t_{BH}	r_0	$\langle\sigma v\rangle/m_{\text{DM}}$	$\langle\rho_{\text{DM}}\rangle$
NGC 1068 (I)	$30R_{\text{S}}$	$(1-2) \times 10^7 M_{\odot}$	10^{10} yr	10 kpc	0	5×10^{18} GeV/cm ³
NGC 1068 (II)	$30R_{\text{S}}$	$(1-2) \times 10^7 M_{\odot}$	10^{10} yr	10 kpc	10^{-31} cm ³ s ⁻¹ /GeV	4×10^{13} GeV/cm ³
TXS 0506 + 056 (I)	$10^4 R_{\text{S}}$	$(3-10) \times 10^8 M_{\odot}$	10^9 yr	10 kpc	0	8×10^{12} GeV/cm ³
TXS 0506 + 056 (II)	$10^4 R_{\text{S}}$	$(3-10) \times 10^8 M_{\odot}$	10^9 yr	10 kpc	10^{-28} cm ³ s ⁻¹ /GeV	4×10^{11} GeV/cm ³

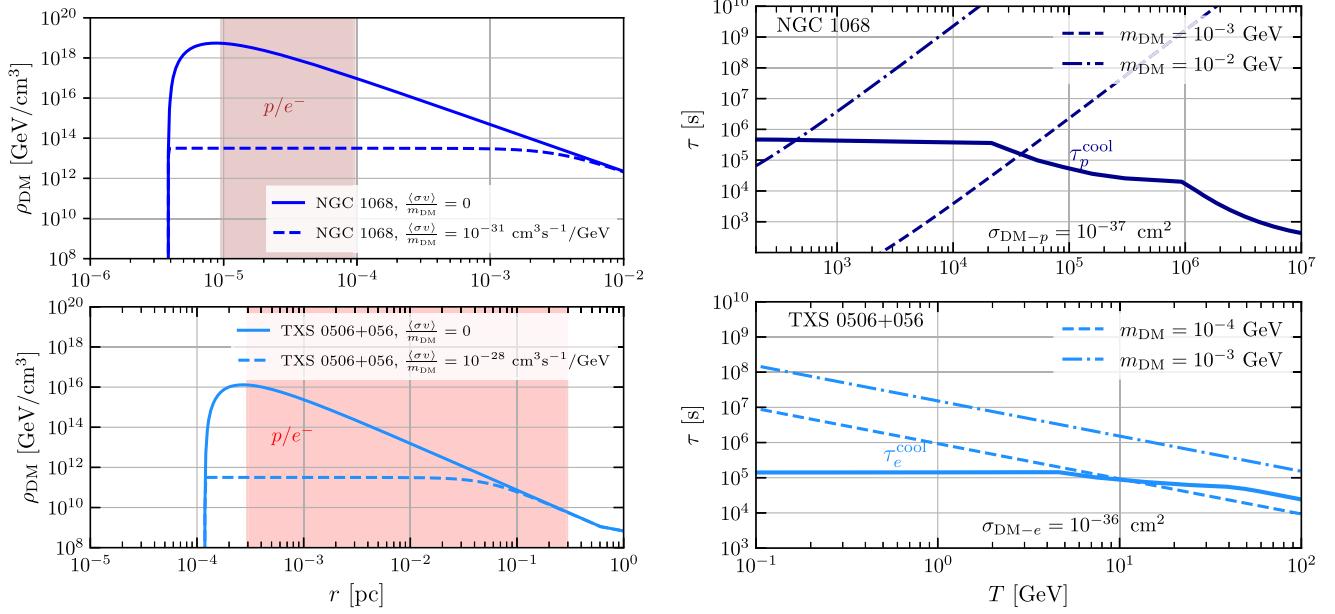


FIG. 2. Left panel: DM distribution around the SMBHs of TXS 0506 + 056 and NGC 1068, for different values of the DM self-annihilation cross section over its mass. The red (brown) shaded region indicates the region where the production of high-energy particles is expected to take place in TXS 0506 + 056 (NGC 1068). Right panel: In solid lines, we show the cooling timescales of protons (electrons) in NGC 1068 (TXS 0506 + 056). In dashed and dot-dashed lines, we show the timescales due to elastic DM proton and DM-electron scatterings [40,45].

$$\rho(r) = \begin{cases} 0 & r \leq 4R_S, \\ \frac{\rho_{\text{sp}}(r)\rho_{\text{sat}}}{\rho_{\text{sp}}(r)+\rho_{\text{sat}}} & 4R_S \leq r \leq R_{\text{sp}}, \\ \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left(1 + \frac{r}{r_0}\right)^{-(3-\gamma)} & r \geq R_{\text{sp}}. \end{cases} \quad (2)$$

The DM profiles in TXS 0506 + 056 and NGC 1068 are shown in the left panel in Fig. 2 for two values of $\langle\sigma v\rangle/m_{\text{DM}}$ allowed for sub-GeV DM [73–75]. We find that the DM density is extremely high in the region where high-energy particles are produced.

BSM cooling of CRs in AGN. Neutrinos and photons from AGN can be explained by emission from high-energy protons and electrons through purely SM mechanisms. Energy-loss mechanisms include scatterings with other SM particles in the plasma or synchrotron radiation as well as adiabatic losses. In addition, there are escape losses due to advection or diffusion via magnetic fields. The presence of DM coupling to protons and electrons in the vicinity of SMBHs would introduce additional scattering timescales, leading to the suppression of the observed neutrino and gamma-ray fluxes in certain energy ranges, if the BSM cooling timescales of CRs were shorter than the standard cooling timescales. For example, at $m_{\text{DM}} \sim 10^{-3} \text{ GeV}$, the currently allowed maximum DM-proton cross section stems from CR-boostered DM at the Super-Kamiokande experiment [76], with a value of $\sigma_{\text{DM}-p} \sim 10^{-35} \text{ cm}^2$. As

discussed in the previous section, the average density of asymmetric DM particles in the coronal region of NGC 1068 is $\langle\rho_{\text{DM}}\rangle \sim 5 \times 10^{18} \text{ GeV}/\text{cm}^3$. Thus, if the corresponding cross section for CR protons is comparable to $\sigma_{\text{DM}-p}$ (although this is not the case, in general), the BSM cooling timescale for the currently allowed values in the literature is $\tau_{\text{DM}-p} \sim 1/(\langle n_{\text{DM}}\rangle\sigma_{\text{DM}-p}c) \sim 7 \times 10^3 \text{ s}$, which is well below the proton cooling time inferred by observations of NGC 1068. This simple estimate clearly suggests that CRs in AGN can provide a powerful probe of these interactions.

More quantitatively, the BSM cooling timescale due to elastic DM scattering off CRs is given by [59]

$$\tau_{\text{DM}-i}^{\text{el}} = \left[-\frac{1}{E} \left(\frac{dE}{dt} \right)_{\text{DM}-i} \right]^{-1}, \quad (3)$$

with

$$\left(\frac{dE}{dt} \right)_{\text{DM}-i} = -\frac{\langle\rho_{\text{DM}}\rangle}{m_{\text{DM}}} \int_0^{T_{\text{DM}}^{\text{max}}} dT_{\text{DM}} T_{\text{DM}} \frac{d\sigma_{\text{DM}-\text{CR}i}}{dT_{\text{DM}}}, \quad (4)$$

where $\langle\rho_{\text{DM}}\rangle$ is the average density of DM particles in the region of CR production. See Table I for the specific values that we use for NGC 1068 and TXS 0506 + 056. Also, $d\sigma_{\text{DM}-\text{CR}i}/dT_{\text{DM}}$ is the differential elastic DM-proton or DM-electron cross section, and $T_{\text{DM}}^{\text{max}}$ is the maximal allowed value for T_{DM} in a collision with a particle i with kinetic energy $T = E - m_i$, which is

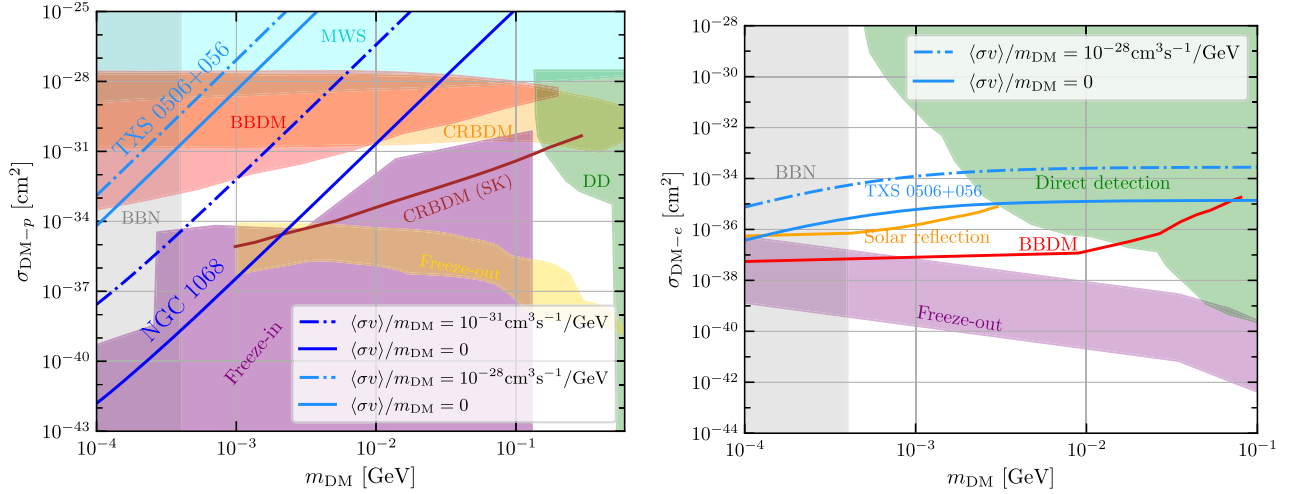


FIG. 3. Left panel: upper limits on the DM-proton cross section vs DM mass, derived from the requirement that the required proton luminosity is substantially larger due to scatterings off DM particles in NGC 1068 and TXS 0506 + 056. Complementary constraints from different searches are shown for comparison. We also show values of the DM-proton scattering cross section that can produce the observed DM relic abundance via freeze-in (purple) [80,81] and via freeze-out (gold) [82,83]. Right panel: analogous upper limits on the DM-electron cross section, for TXS 0506 + 056. We also display values of the DM-electron cross section vs DM mass compatible with thermal production of light DM [84]. This band shows the range of values compatible with thermal production in different models (scalar dark matter [85], asymmetric dark matter [73], strongly interacting massive particles [12,86], and elastically decoupling relics [87]). Note that we do not have constraints from NGC 1068, because the observed gamma rays may be purely hadronic [34].

$$T_{\text{DM}}^{\text{max}} = \frac{2T^2 + 4m_i T}{m_{\text{DM}}} \left[\left(1 + \frac{m_i}{m_{\text{DM}}} \right)^2 + \frac{2T}{m_{\text{DM}}} \right]^{-1}. \quad (5)$$

We consider fermionic DM which elastically interacts with protons and electrons via a heavy scalar mediator. The differential cross section reads [77]

$$\frac{d\sigma_{\text{DM}-i}}{dT_{\text{DM}}} = \frac{\sigma_{\text{DM}-i}}{T_{\text{DM}}^{\text{max}}} \frac{F_i^2(q^2)}{16\mu_{\text{DM}-i}^2 s} (q^2 + 4m_i^2)(q^2 + 4m_{\text{DM}}^2), \quad (6)$$

where $\sigma_{\text{DM}-i}$ is the DM-proton or DM-electron cross section at the zero center-of-mass momentum, $\mu_{\text{DM}-i}$ is the reduced mass, s is the square of center-of-mass energy, and $q^2 = 2m_{\text{DM}}T_{\text{DM}}$ is the momentum transfer of the process. The quantity F_i is either the proton form factor [78] or equal to 1 for electrons.

In the right panel in Fig. 2, the solid lines represent the total standard energy-loss timescales as a function of energy for protons in NGC 1068 [40] and for electrons in TXS 0506 + 056 [79]. CR protons in NGC 1068 are almost depleted, and the dominant cooling mechanisms at increasing energies are inelastic pp interactions, Bethe-Heitler pair production, and $p\gamma$ interactions [35]. CR protons do not cool efficiently in TXS 0506 + 056, and the fate is governed by a dynamical timescale of $\sim 10^5$ s in the SMBH frame [79]. For electrons in TXS 0506 + 056, the dominant cooling mechanisms are inverse Compton scattering and synchrotron radiation. The breaks in the solid lines of the

plots reflect the energies at which the transition of dominant processes occurs.

For comparison, we also show BSM cooling timescales due to elastic DM scatterings with protons and electrons. The dot-dashed line corresponds to values of the DM mass and cross section that would induce a contribution smaller than the proton and electron energy losses due to the SM processes. On the other hand, the dashed line shows values of the parameters that would induce larger energy losses than in the SM at relevant energies. It is important to point out that inelastic DM-proton scatterings are expected to dominate over the elastic channel at energies $E \gtrsim m_p^2/2m_{\text{DM}}$. For simplicity, we restrict our analysis to the elastic channel.

For the purpose of constraining the interaction strength, we find for each m_{DM} the largest DM-proton (electron) cross section yielding a timescale equal or larger to the cooling timescales determined with models at relevant energies. In particular, we use

$$\tau_{\text{DM}-i}^{\text{el}} \geq C\tau_i^{\text{cool}}. \quad (7)$$

The coefficient C is a model-dependent factor, and we use $C = 0.1$ in this work. In other words, we find the maximum DM-proton (electron) cross section that would have an $\mathcal{O}(10)$ or less impact on the proton (electron) cooling timescale. This is reasonable and may be even conservative from the energetics requirement of neutrino-emitting AGN. For NGC 1068, the proton luminosity

would be $10^{43} \text{ erg s}^{-1} \lesssim L_p \lesssim L_X \lesssim 10^{44} \text{ erg s}^{-1}$ [35,40], justifying $C \sim 0.1$ – 1 . For TXS 0506 + 056, the proton luminosity in the single-zone model already violates the Eddington luminosity L_{Edd} [47], so our choice is conservative. This is also reasonable for electrons because of $L_e \sim 8 \times 10^{47} \text{ erg s}^{-1} \sim 20L_{\text{Edd}}$ [79]. In principle, if the CR acceleration mechanism is understood, spectral modification due to BSM cooling may allow us to improve constraints and $C \sim 1$ is possible. For proton energies of interest, we use 10–300 TeV for NGC 1068 [33], which is required to match the IceCube data [40]. For protons in TXS 0506 + 056, we use 0.1–20 PeV [43], and for electrons we use 50 GeV–2 TeV, following Ref. [79].

Applying the condition of Eq. (7) for NGC 1068 and TXS 0506 + 056, we set constraints on the DM-proton and DM-electron cross sections via a heavy mediator (see Fig. 3). The solid lines correspond to scenario I, and the dashed lines correspond to scenario II (see Table I). We find that our constraints become stronger at lower DM masses, due to the fact that the number density of DM particles increases, and the cross section needed to induce energy losses becomes smaller. However, for protons the dependence of the constraint on the DM mass is more pronounced than for electrons, since the elastic DM-proton cross section decreases with reference to its maximum value for $E \gtrsim m_p^2/2m_{\text{DM}}$.

For comparison, we show complementary constraints from other methods. The green region is excluded by DM direct detection experiments [88–94]. The cyan region is constrained by Milky Way satellite galaxy counts [95], and the gray region is constrained by big bang nucleosynthesis (constraints can be stronger by a factor as large as ~ 3 depending on the details of the model) [96–99]. The orange region is constrained by CR-boosted DM at XENON1T [19], and the red regions are excluded when considering the blazar-boosted DM flux from TXS 0506 + 056 [22,52]. Finally, values above the brown line are constrained by CR-boosted DM at the Super-Kamiokande experiment [76]. Further, for DM-electron scatterings, we include constraints from the solar reflection [100], and the region of values where light thermal DM acquires its relic abundance via various mechanisms [12,87,101]. From Fig. 3, one sees that our constraints for light DM coupling to protons are stronger than complementary bounds for $m_{\text{DM}} \lesssim 10^{-3} - 10^{-2} \text{ GeV}$. Additional constraints from colliders may also apply; see, e.g., Ref. [102] for constraints on dark matter with masses above $m_{\text{DM}} \gtrsim 0.1 \text{ GeV}$, assuming a mediator of mass $m_\phi \sim 1 \text{ GeV}$ and a direct coupling to quarks. If the mediator were more massive, or if it couples to gluons, those constraints could be weaker.

For DM-electron scatterings, our constraints are stronger than direct detection bounds at masses below $m_{\text{DM}} \lesssim 5 \times 10^{-3} \text{ GeV}$. In addition, for DM-electron interactions, AGN data allow one to probe the parameter space favored for DM models with $m_{\text{DM}} \lesssim 10^{-4} \text{ GeV}$. Effects of

different assumptions on the DM distribution and constraints in a concrete model of DM-proton interactions are discussed in Supplemental Material [103].

Summary and discussion. Recent multimessenger measurements of AGN have indicated that high-energy particles, in particular, CR protons and secondary neutrinos, are produced in the vicinity of SMBHs. CR cooling could be significantly enhanced by BSM interactions with DM, thanks to a large DM density around the central SMBH. We demonstrated that neutrino-emitting AGN, NGC 1068 and TXS 0506 + 056, allow us to set strong constraints on sub-GeV DM coupled to protons and/or electrons. The new constraints on light DM coupling to protons are stronger than other complementary bounds for $m_{\text{DM}} \lesssim 10^{-3} - 10^{-2} \text{ GeV}$. For DM-electron scatterings, our constraints are stronger than direct detection bounds at masses below $m_{\text{DM}} \lesssim 5 \times 10^{-3} \text{ GeV}$, which potentially allows us to probe the parameter space favored for thermal DM models with $m_{\text{DM}} \lesssim 10^{-4} \text{ GeV}$.

Remarkably, our method based on CR cooling is unique and different from previous AGN constraints from boosted DM [22] and those on neutrino-DM interactions [65,104–109], in that the results are largely insensitive to CR and neutrino spectra. Regarding uncertainties in CR cooling timescales, we stress that our constraints are robust and conservative for NGC 1068. This is because the neutrino production efficiency of CR protons has to be nearly maximal to explain the neutrino flux [40], and relaxing assumptions (e.g., with longer CR cooling timescales and/or softer CR spectra) will make the limits stronger. Future multimessenger observations and astrophysical modeling will allow us to better understand the sources and reduce uncertainties, and the resulting limits on the

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