Enhanced Cosmic-Ray Cooling in AGN from Dark Matter Deep Inelastic Scattering

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References: Phys.Dark Univ. 49 (2025) 102050 (2504.03409 [hep-ph]),
2509.11906 [hep-ph].

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What are active galactic nuclei (AGN)?

- Active galactic nuclei (AGN) are galaxies that release an incredible amount of energy from their cores.
- Formation of AGN:

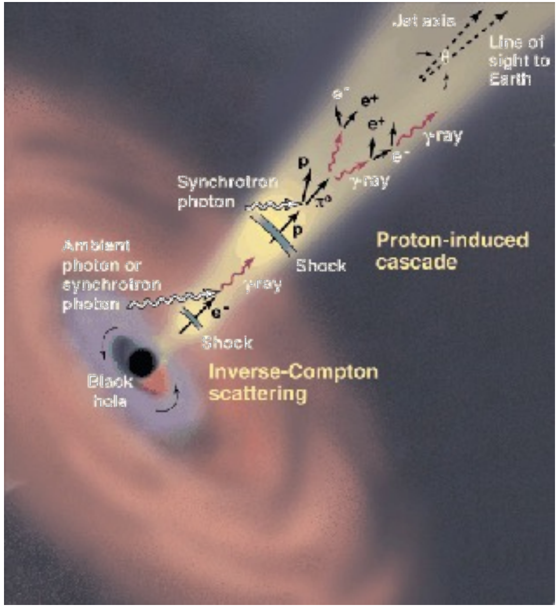
(1) At the center of most galaxies, there's a **massive black hole**;

(2) They have mass of **millions or even billions** of Suns;

(3) The black hole accretes gas, dust, and stellar debris around it;

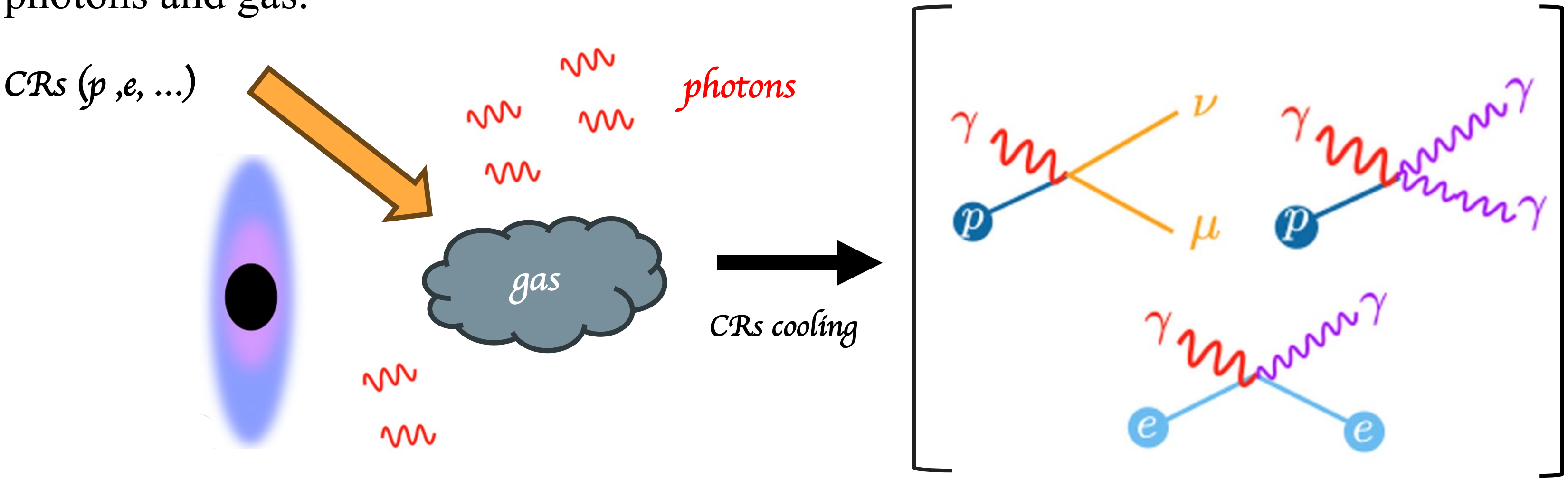
(4) Their gravitational energy gets converted to light forming AGN;

(5) **15%** of AGN emit **charged particles** called **jets** travelling at **speeds close to the speed of light**.



Multi-messenger observations

- Recent observations of high-energy neutrinos from AGN, **NGC 1068** and **TXS 0506+056**, suggest that CRs are accelerated in the vicinity of the central SMBH and high-energy protons and electrons can cool efficiently via interactions with ambient photons and gas.



Multi-messenger observations

- We propose CR cooling in AGN as a new probe of DM-proton (electron) scatterings for sub-GeV DM.

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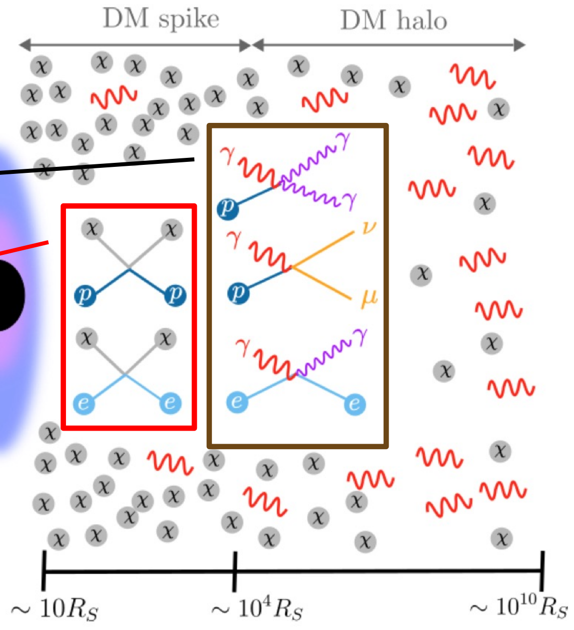
Standard SM cooling

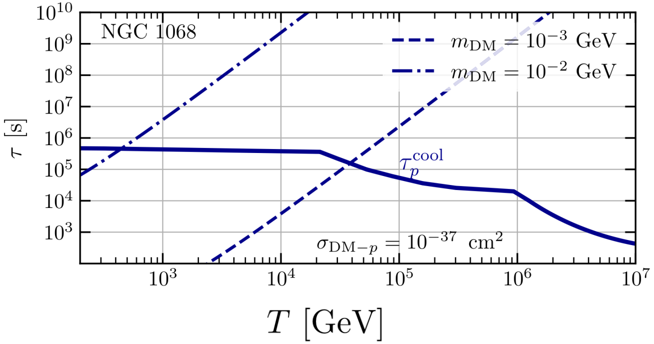
BSM cooling:
DM-proton(electron) scattering
thanks to DM spike



DM density may be significantly enhanced near the adiabatic growth of SMBH

A taste of BSM cooling of CRs in AGN

- Based on the Super-Kamiokande experiment [*Phys. Rev. Lett. 130, 031802 (2023)*], for $m_{DM}{\sim}10^{-3}\ GeV$, $\sigma_{DM-p} \lesssim 10^{-35}\ cm^2$
- The average asymmetric DM density of NGC 1068 is $< \rho_{DM} >{\sim}\ 5{\times}10^{18}\,\frac{GeV}{cm^3}$.
- The BSM cooling timescale is estimated as $\tau_{DM-p} \sim \frac{1}{<n_{DM}>\sigma_{DM-p}c} \sim 7{\times}10^3 s$.



This is well below the proton cooling time inferred by observations of NGC 1068!

DM density profile and relevant parameters

- The DM density profile:

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

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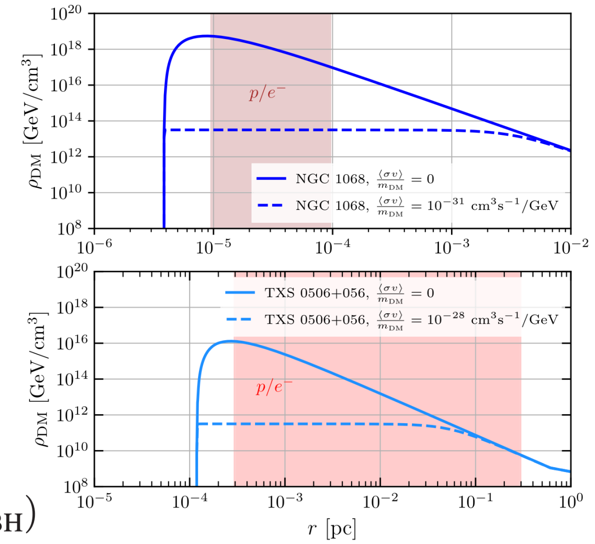
$$\rho_{sat} = m_{DM}/(\langle\sigma v\rangle t_{BH})$$



Shaded regions: The production of high-energy particles is expected to take place.

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

More concrete calculations

- The cooling timescale due to DM-CRs scattering:

$$\tau_{\chi-i}^{\text{cool}} = \left[-\frac{1}{E} \left(\frac{dE}{dt} \right)_{\chi i} \right]^{-1},$$

energy of CRs

energy loss rate during CR and DM collisions

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

Model-dependent

DM final kinetic energy

the differential cross-section between DM–proton(electron)

More concrete calculations

- The kinematics of energy transfer differ fundamentally between **elastic** and **deep inelastic scattering (DIS)** processes:
- In the context of elastic scattering, the maximum kinetic energy imparted to the DM particle is derived using the 4-momentum conservation as

$$T_{\chi,el}^{\max} = \frac{2T^2 + 4m_p T}{m_\chi} \left[\left(1 + \frac{m_p}{m_\chi}\right)^2 + \frac{2T}{m_\chi} \right]^{-1},$$

  where $T = E - m_p$ is the proton kinetic energy.
- For DIS of CR-DM, final-state hadronization has been shown to relax momentum constraints, thereby **enabling full energy transfer to DM**.
  Consequently, $\boldsymbol{T_{\chi,DIS}^{max} = T}$.

Sub-GeV Gauged U(1) DM models

$$\mathcal{L} = g_\chi \bar{\chi}\gamma^\mu \chi A'_\mu + \sum_q g_q \bar{q}\gamma^\mu q A'_\mu$$

Dirac fermion DM (χ), dark photon mediator (A')

where q for quarks, with coupling constants g_χ (DM-dark photon) and $g_q = Q_q e\epsilon$ (quarks-dark photon).

DM-p elastic scattering

$$\frac{d\sigma_{\chi i}}{dT_\chi} = g_i^{A'^2} g_\chi^{A'^2} F_i^2(q^2) \times \frac{2m_\chi (m_i + T_i)^2 - T_\chi \left\{ (m_i + m_\chi)^2 + 2m_\chi T_i \right\} + m_\chi T_\chi^2}{4\pi (2m_i T_i + T_i^2)(2m_\chi T_\chi + m_{A'}^2)^2},$$

$F_i^2(q^2)$ → form factor →

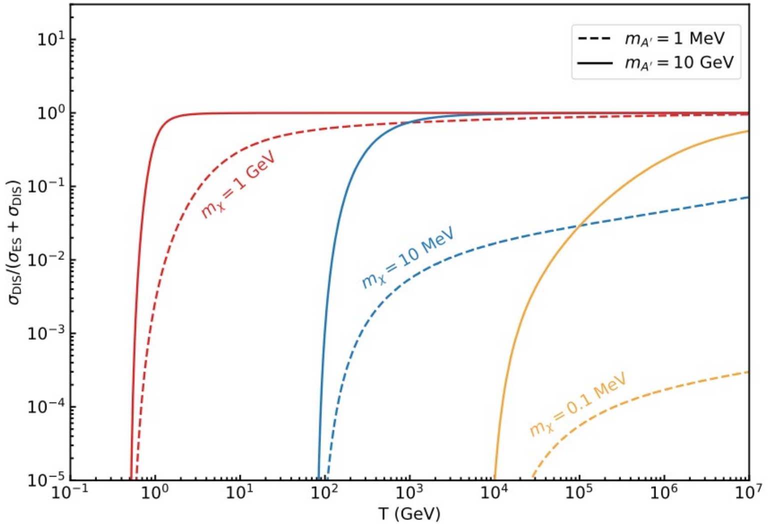
For protons,

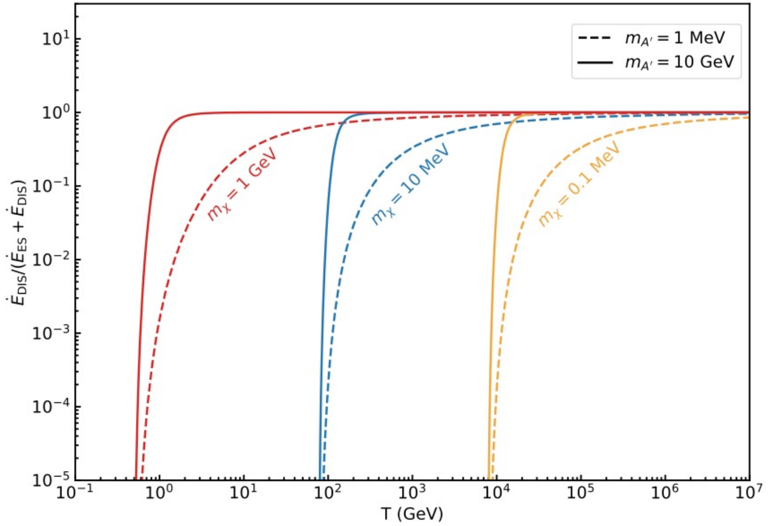
$$F(q^2) = \frac{\Lambda^2}{q^2 + \Lambda^2},$$

where $\Lambda = 770\ GeV$.

Deep Inelastic Scattering (DIS)

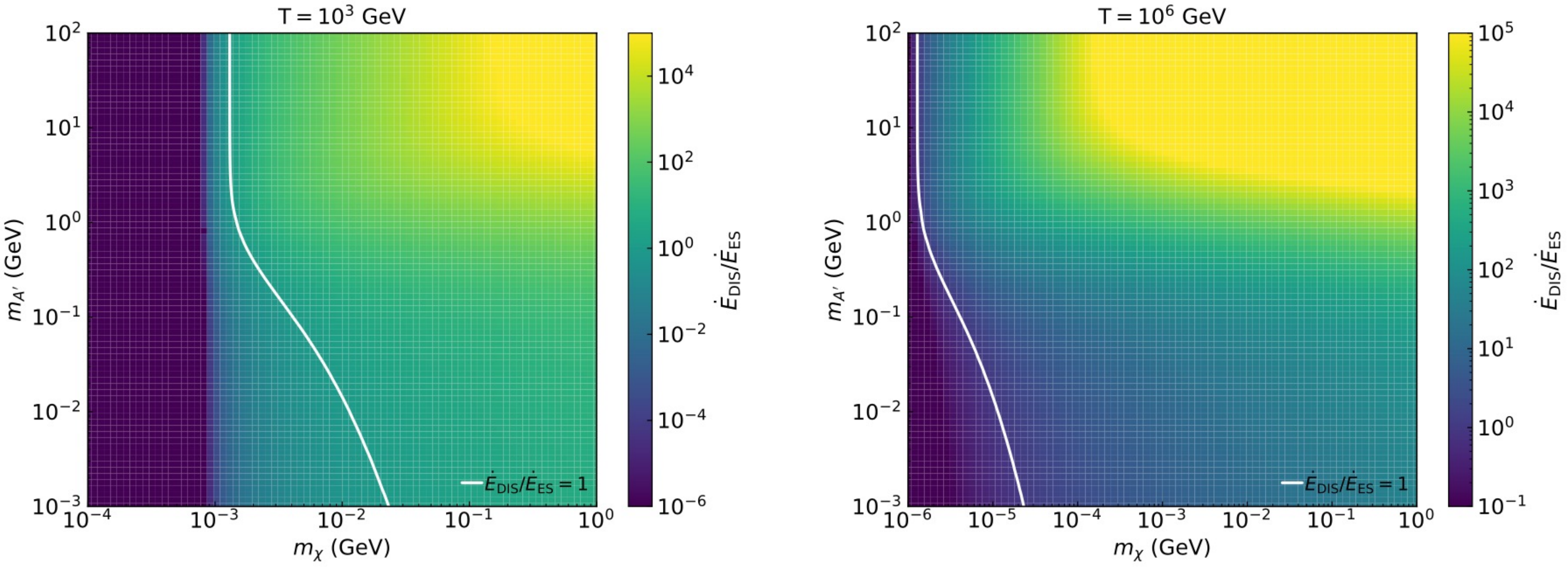
- During the DM scattering with the protons, whenever $E \geq m_p^2/2m_\chi$, inelastic scattering will dominate over the elastic case.



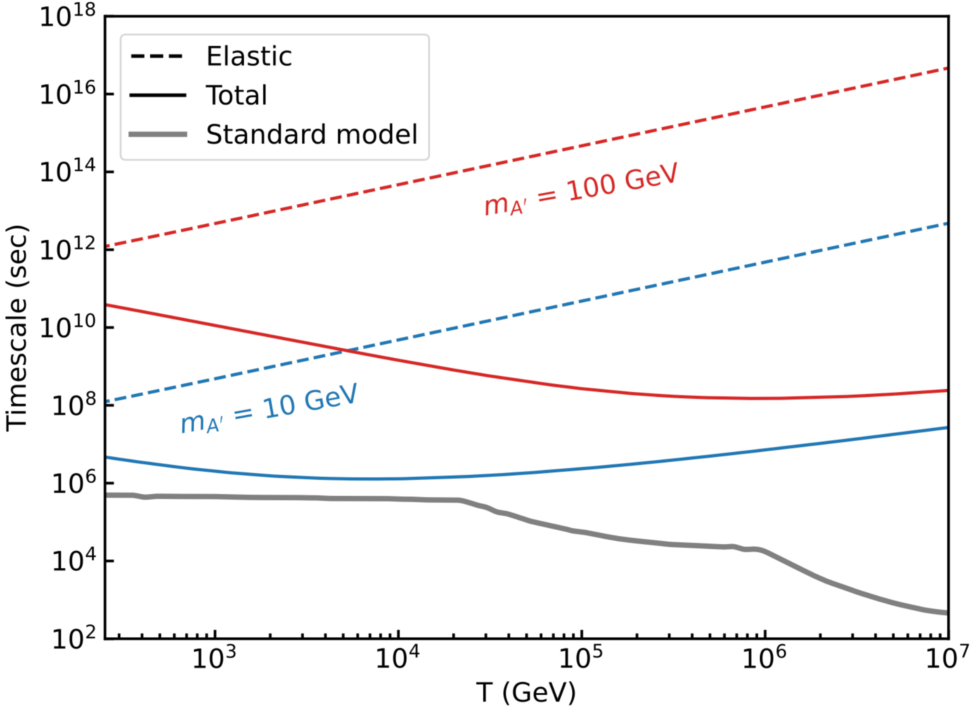


Ratio of inelastic to elastic scattering energy loss rate

$g_\chi = g_p = 0.1$



Cooling timescale for CRs interacting with DM

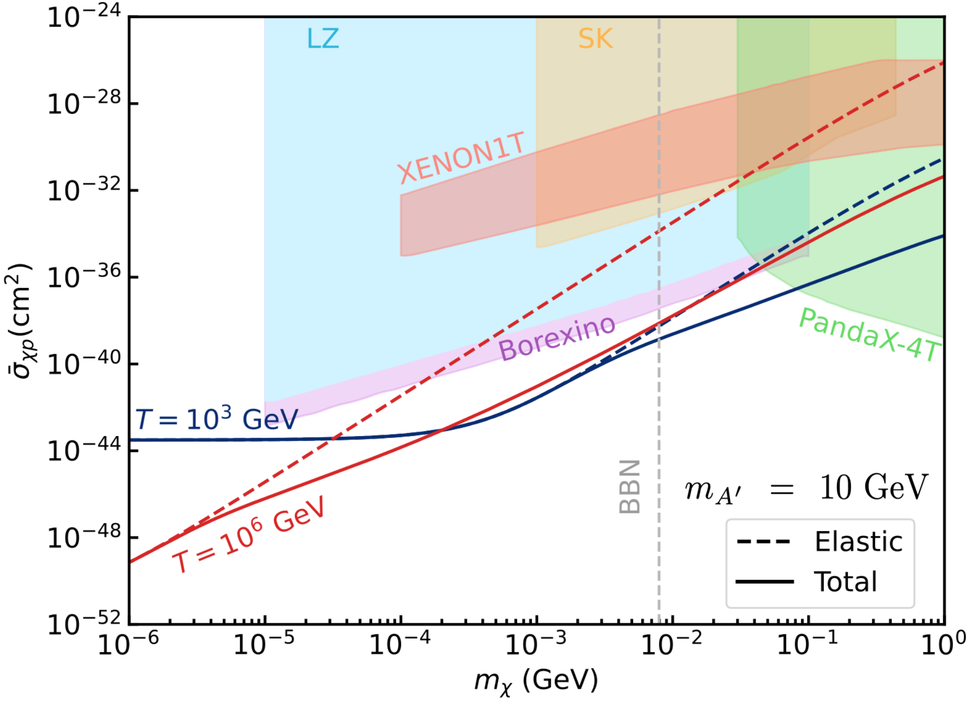


$$g_\chi = g_p = 0.1$$

$$m_\chi = 0.1 \text{ GeV}$$

As increasing of $m_{A'}$ and T, the DIS contribution becomes more and more dominant.

Constraints on the DM-proton elastic and DIS cross-section from the CR cooling effect



CR cooling condition:

$$\tau_{\chi-i}^{\mathrm{cool}} \leq C\ \tau_{\mathrm{SM}}^{cool}$$

$$C = 0.1$$

$$\bar{\sigma}_{\chi p} = (g_p^2 g_\chi^2 \mu_{\chi p}^2)/(\pi m_{A'}^4)$$

where $\mu_{\chi p}$ is the reduced DM-proton mass

Conclusion

- High-energy particle (TeV-PeV) emission from AGN provides us with a powerful probe of DM scatterings with CR protons.
- For elastic DM-p scattering, lowering the DM or mediator mass enhances the BSM cooling rate compared to the SM one.
- For DM-p DIS, our analysis of NGC 1068 shows that for heavier mediators ($m_{A'} \gtrsim$ 1 GeV) at higher energies, the DIS process enhances the cross-section, shortening the CR cooling timescale by orders of magnitude compared to elastic scattering.

Thank you
for your attention

Back-up Slides

Cooling of CRs in AGNs from multi-messenger high-energy neutrino and electromagnetic observations

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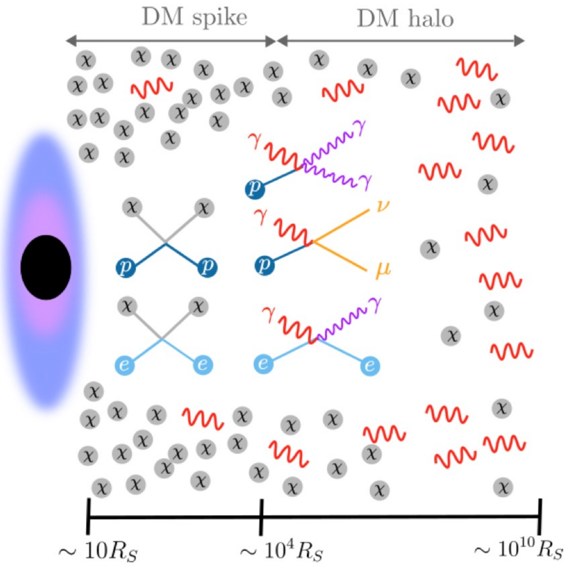

Source: NGC 1068
ICECUBE, *neutrino*,
Science 378, 538 (2022);
FERMI-LAT, *photon*,
Astrophys.J. 954 (2023) L49.

Source: TXS 0506+056
ICECUBE, ICECUBE-PINGU, FERMI-LAT, MAGIC, AGILE, ASAS-SN, HAWC, HESS, INTEGRAL, VERITAS,
neutrino & photon,
Science 361 (2018) 6398, eaat1378.

Relevant uncertainties

- The method to probe DM-proton(electron) scatterings through CR cooling in AGN are <u>not sensitive to uncertainties in CR spectra</u>, and **the major uncertainty comes from the DM density profile**.
- The **major merger process may disrupt the DM spike**, but NGC 1068 is morphologically similar to a normal spiral galaxy even though a minor merger happened in the past, and **NGC 1068 is effectively regarded as a nonmerger object**.
- With some estimations, **NGC 1068 is well within the adiabatic growth regime**.
- Moreover, **NGC 1068 is a jet-quiet AGN** which would not cause additional disrupting processes that may alter the structure of the DM spike.

Relevant uncertainties

- TXS 0506+056 is a **blazar**, and the merger history of the host galaxy is more uncertain.
- TXS 0506+056 is usually classified as a **BL Lac object**, in which the accretion rate is expected to be much lower than the Eddington accretion rate. Thus, we still find that **the adiabatic growth holds within these uncertainties**.
- TXS 0506+056 is a blazar with a relativistic jet, which may affect the structure of the spike especially if a DM-proton coupling is present.
- More details about the DM spike formation and uncertainties for TXS 0506+056 can be found in the Supplementary Material of "*Phys.Rev.D 110 (2024) 1, L011701*".

The DM density profile

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

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We consider that the initial DM distribution follows an NFW profile, with $\gamma = 1$, resulting in a spike with $\gamma_{sp} = 7/3$ and $\alpha_\gamma = 0.122$. Here, we take $r_0 = 10$ kpc.

$$\gamma_{sp} = \frac{9-2\gamma}{4-\gamma}.$$

the cuspiness of the spike

a normalization factor

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

$$R_{sp} = \alpha_\gamma r_0 (M_{BH}/(\rho_0 r_0^3))^{\frac{1}{3-\gamma}}$$

the size of the spike

$$g_\gamma(r) \approx (1 - \frac{4R_S}{r})$$

If the DM particles self-annihilate, the maximal DM density in the inner regions of the spike is saturated to

$$\rho_{sat} = m_{DM}/(\langle\sigma v\rangle t_{BH})$$

Relevant parameters considered in this work

	$R_{\rm em}$	$M_{\rm BH}$	$t_{\rm BH}$	r_0	$\langle\sigma v\rangle/m_{\rm DM}$	$\langle\rho_{\rm DM}\rangle$
NGC 1068 (I)	$30R_S$	$(1–2)\times10^7 M_\odot$	10^{10} yr	10 kpc	0	5×10^{18} GeV/cm^3
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TXS 0506 + 056 (I)	10^4R_S	$(3–10)\times10^8 M_\odot$	10^9 yr	10 kpc	0	8×10^{12} GeV/cm^3
TXS 0506 + 056 (II)	10^4R_S	$(3–10)\times10^8 M_\odot$	10^9 yr	10 kpc	10^{-28} cm^3 s^{-1}/GeV	4×10^{11} GeV/cm^3

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- R_{em} represents the distance of the emission region from the central SMBH in NGC 1068 (TXS 0506+056).
- r_0 is the scale radius of the galaxy.
- R_S is the Schwarzschild radius.

Deep Inelastic Scattering (DIS)

- As the momentum transfer increases, the internal structure of the nucleon becomes progressively relevant.
- In this region, the effective DM-proton interaction Lagrangian can be defined by the electromagnetic form factors $F_1(Q^2)$ and $F_2(Q^2)$:

$$\langle N(p')| \sum_q g_q \bar{q} \gamma^\mu q A'_\mu |N(p)\rangle = g_p A'_\mu \bar{N} \Gamma^\mu N,$$

$$\text{with} \quad \Gamma^\mu = \gamma^\mu F_1\left(Q^2\right) + \frac{i}{2m_p} \sigma^{\mu\nu} q_\nu F_2\left(Q^2\right),$$

where $g_p = \epsilon e$ denotes the coupling between the dark photon and the proton in the secluded dark sector.

Deep Inelastic Scattering (DIS)

- The squared momentum transfer is given by $Q^2 = -q^2 = -(p - p')^2$, where p and p' are the 4-momenta of the initial and fianl protons.

- For high momentum transfers ($Q^2 \gtrsim 1\ GeV^2$), DM–proton scattering is dominated by DIS. In this regime, the process can be reduced to an **incoherent sum of DM-quark elastic scatterings**, $\chi(k) + q(xp) \rightarrow \chi(k') + q(p')$, where x denotes the quark momentum fraction.

Deep Inelastic Scattering (DIS)

- In the DM rest frame, the differential cross-section of DM-proton DIS can be expressed as

$$\frac{\mathrm{d}\sigma_{\chi p}}{\mathrm{d}T_\chi} = \frac{\left|\vec{k}'\right|}{16\pi m_\chi Q^2 \sqrt{E_p^2 - m_p^2}} \times \sum_{q=u,d} \int_{\cos\theta_{\min}}^{1} f_q\left(x, Q^2\right) \overline{|\mathcal{M}(x)|^2}\, \mathrm{d}\cos\theta,$$

  where the momentum fraction $x = Q^2/(-2p\cdot q)$ is the function of $Q^2 = 2m_\chi T_\chi$.
- In this work, we focus on the partonic contributions from up and down quarks. Their parton distribution functions (PDFs), $f_q(x, Q^2)$, are taken from the results of CT10nlo.