Energy and Momentum Transfer Between Visible and Dark Matter Around a Supermassive Black Hole

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Active Galactic Nuclei as Dark Sector Laboratories – June 2026

Central Thesis

SMBH's are exceptional locations for testing dark matter interactions. The dark matter density could be incredibly high, and the SM objects nearby have large kinetic energies. This combination can probe dark matter models and phenomena nearly impossible to see near Earth.

Outline

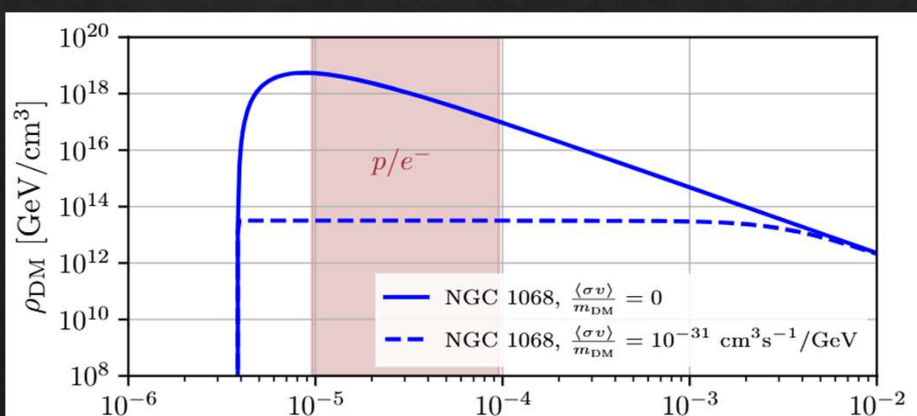
- DM Spikes around SMBH
- DM – Cosmic Ray Interactions Near Active Galactic Nuclei
  - Dark Matter Boosting
  - Cosmic Ray Cooling
  - Inelastic Dark Matter
- DM – Celestial Body Interactions Near Less-Active Galactic Nuclei
  - Orbital Degradation
  - Stellar Heating and Cooling

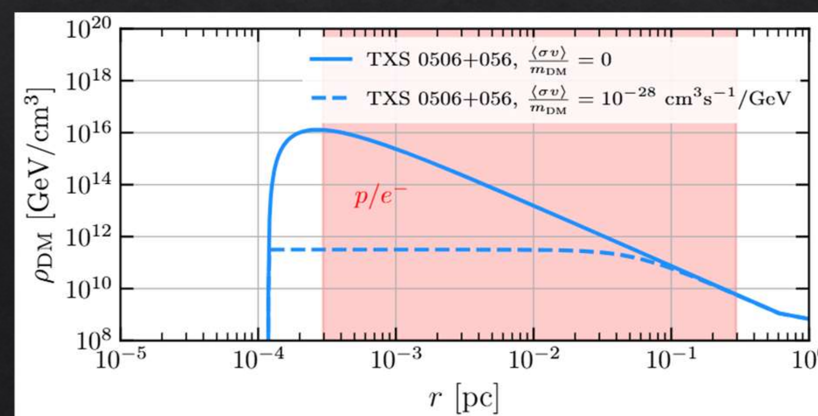
Review – DM Around SMBHs

For a SMBH adiabatically growing in a DM spike with initial power-law $\rho_i \sim r^{-\gamma_i}$, the resulting spike power-law will be

$$\gamma = \frac{9 - 2\gamma_i}{4 - \gamma_i}$$

For a typical NFW, $\gamma_i = 1 \rightarrow \gamma = 7/3$. This greatly enhances the DM density



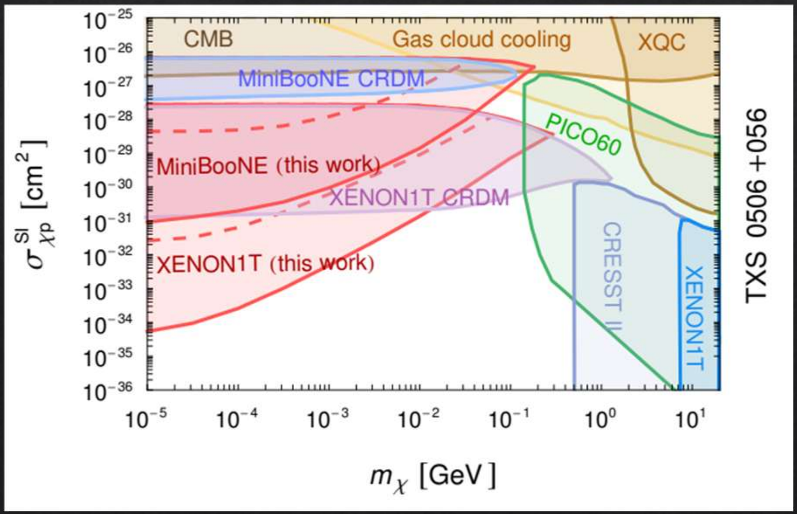


([1] Herrera, Murase : 2023)

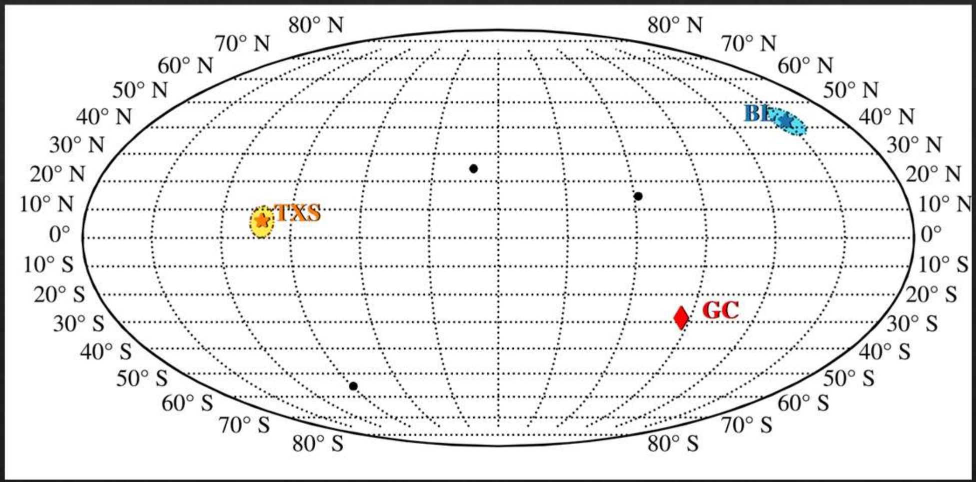
Dark Matter – Cosmic Ray Interactions Near Active Galactic Nuclei

Review – Blazar Boosted DM

- Benefits:
  - Probes low-mass dark matter by providing large kinetic energies
  - Point sources for dark matter

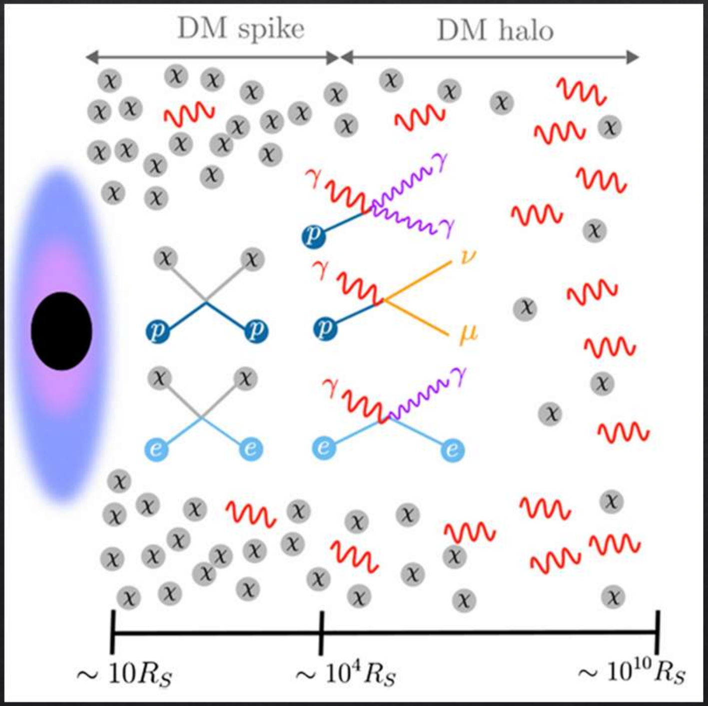


([2] Wang, Granelli, Ullio: 2021)



SK electron events, and angles expected for blazars
([3]Granelli, Ullio, Wang: 2022)

DM-Induced AGN Cooling



([1] Herrera, Murase: 2023)

- DM-electron and (elastic) DM-proton scattering steals energy from the SM sector, cooling it at a rate

$$\frac{dE}{dt} = -\frac{\langle \rho_\chi \rangle}{m_\chi} \int dT_\chi (E_{\chi f} - E_{\chi i}) \frac{d\sigma}{dT_\chi}$$

- This gives a DM-induced cooling timescale

$$\tau_{DM} = \left(\frac{-1}{E} \frac{dE}{dt} \right)^{-1}$$

- To stay consistent with neutrino and photon observations, we require

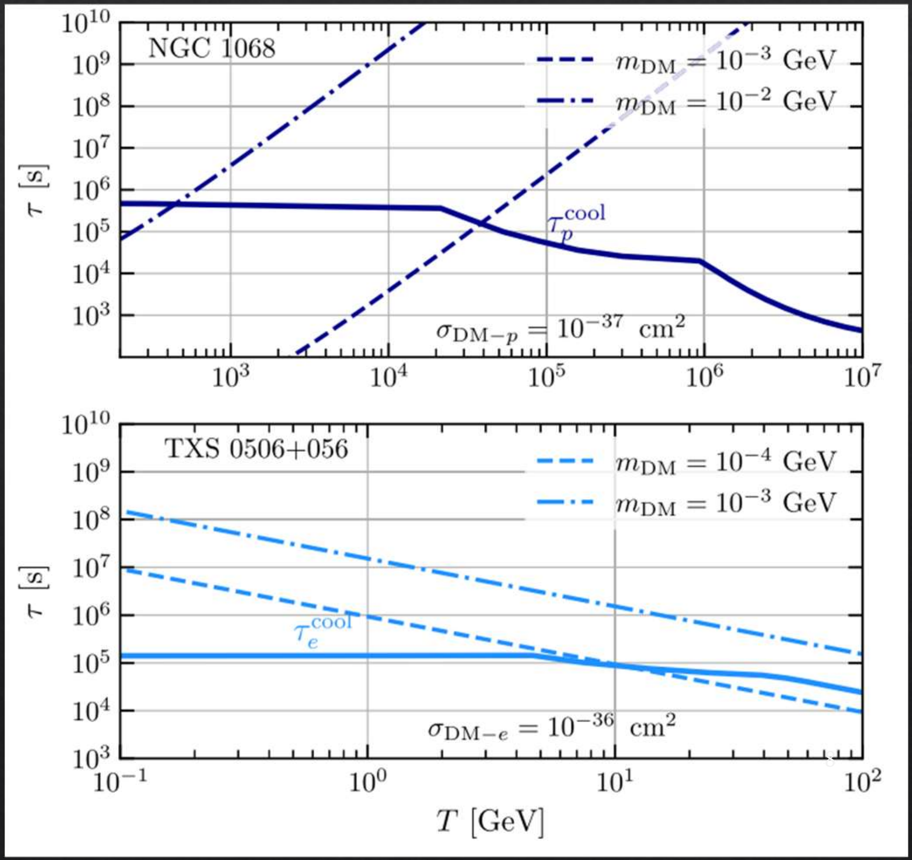
$$\tau_{DM} \geq C\, \tau_{SM}$$

with $C \sim 0.1 - 1$.

DM-Induced AGN Cooling (Cont.)

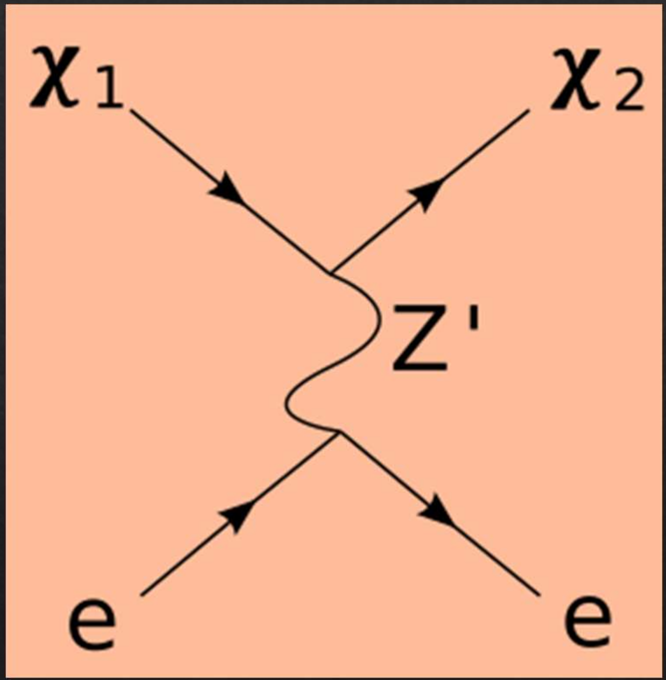
DM and SM cooling rates have different dependencies on cosmic ray energy. A DM model can be excluded if it overcools within the range of energies important for observation.

([1] Herrera, Murase: 2023)



Inelastic Dark Matter

- AGN constraints on DM are most interesting when the model requires high energies to probe
  - Examples: Light Dark Matter (previous works), Inelastic Dark Matter (my work)
- Inelastic dark matter involves a ground state χ_1 of mass m_χ which primarily scatters into an excited state χ_2 of mass $m_\chi + \delta$. Scattering must overcome a kinematic threshold
- Here we consider a vector mediator Z'



Inelastic DM Induced AGN Cooling

Recall: Cooling rate goes as

$$\frac{dE}{dt} = -\frac{\langle \rho_\chi \rangle}{m_\chi} \int dT_\chi (E_{\chi f} - E_{\chi i}) \frac{d\sigma}{dT_\chi}$$

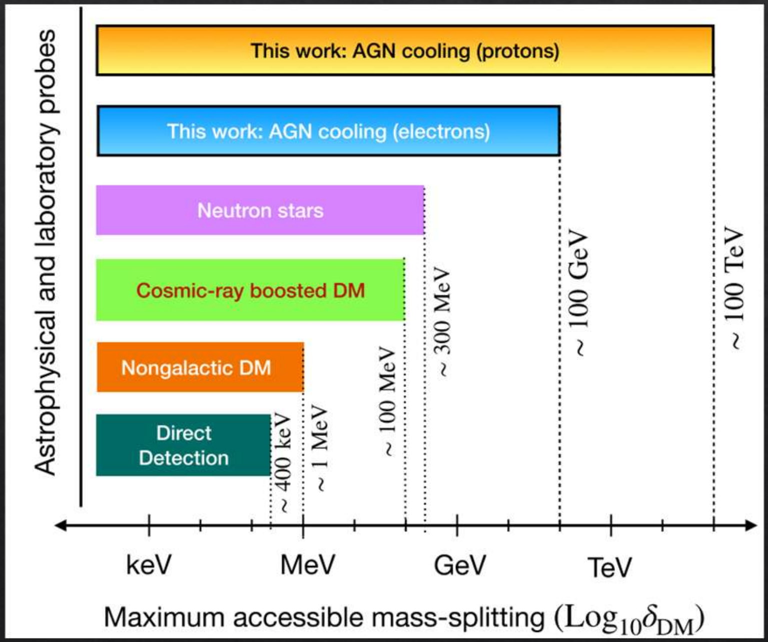
For Elastic DM:

$$E_{\chi f} - E_{\chi i} = T_\chi$$

For Inelastic DM:

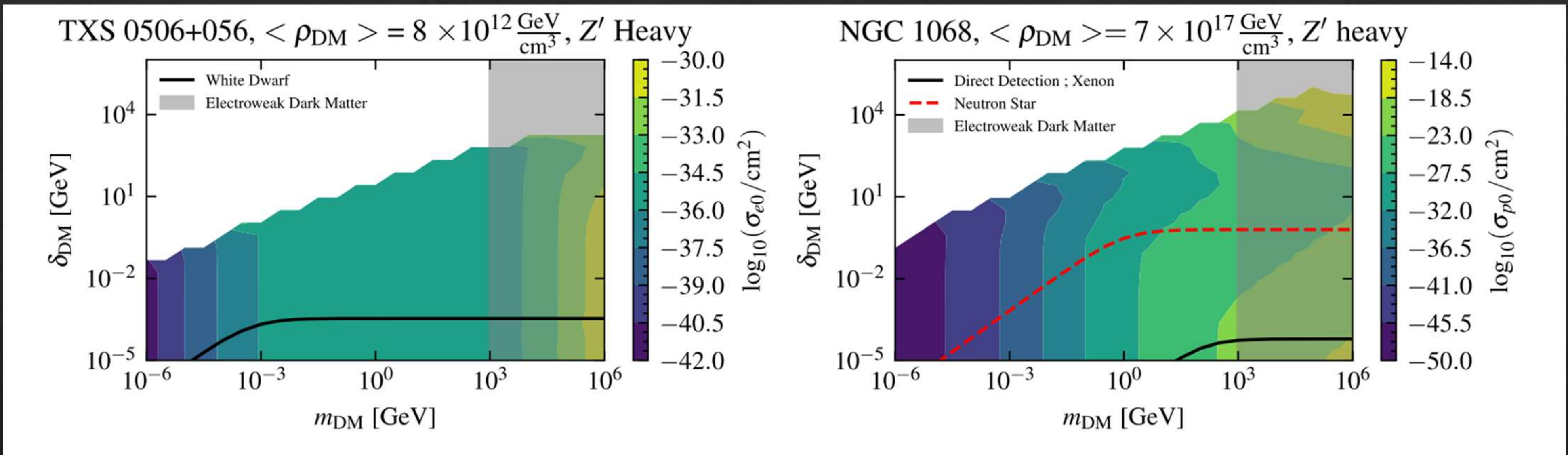
$$E_{\chi f} - E_{\chi i} = T_\chi + \delta$$

AGN are uniquely primed to probe large mass splittings AND the mass splitting provides another way to steal energy from the cosmic rays.



([4] **Gustafson**, Herrera, Mukhopadhyay, Murase and Shoemaker : 2025)

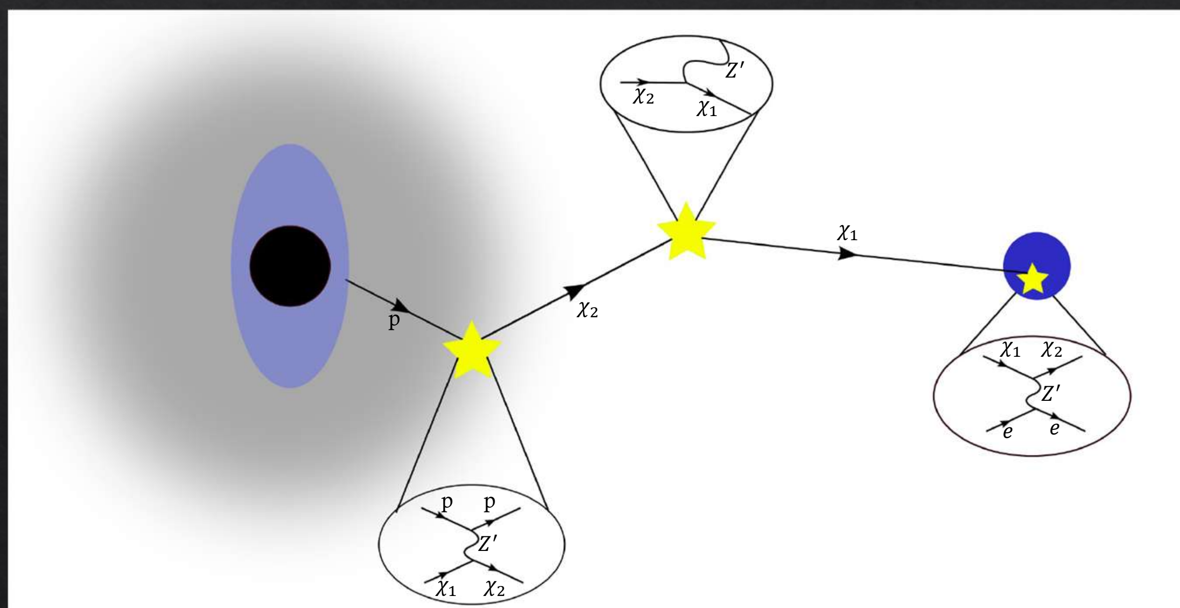
Inelastic DM-Induced AGN Cooling



([4] **Gustafson**, Herrera, Mukhopadhyay, Murase and Shoemaker : 2024)

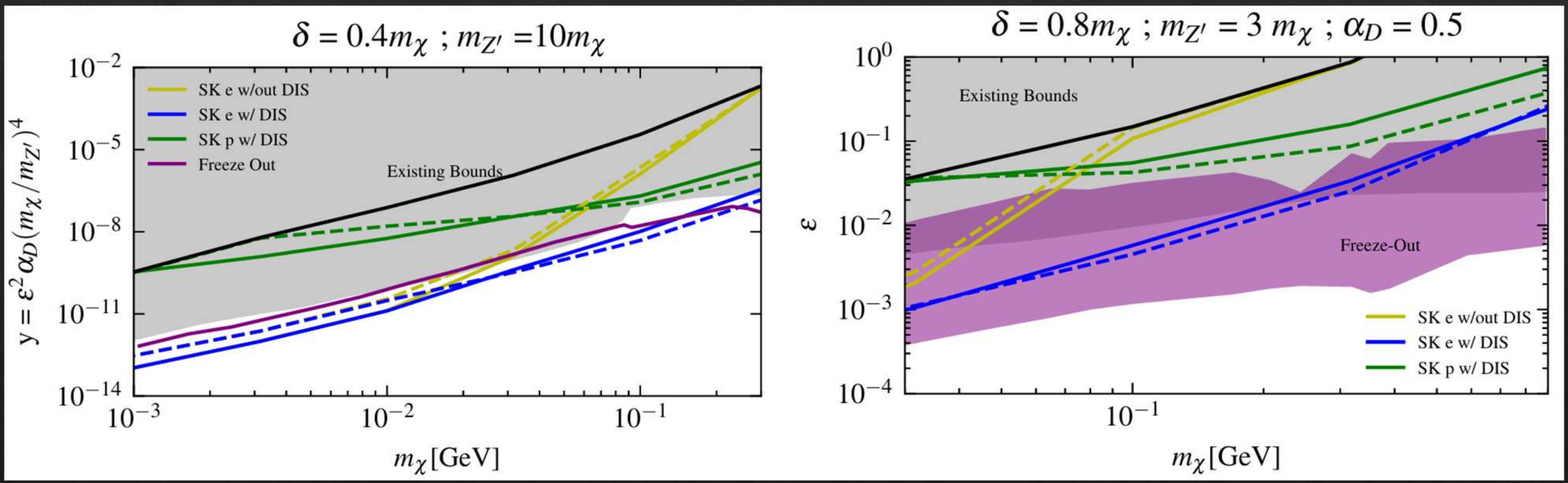
AGN Boosted Inelastic Dark Matter

- High energies are essential, as the DM must upscatter twice:
  - 1st at the source
  - 2nd at the detector



AGN Boosted Inelastic Dark Matter

- We consider different searches at Super-Kamiokande for cases with and without Deep-Inelastic Scattering between protons and DM at the AGN.

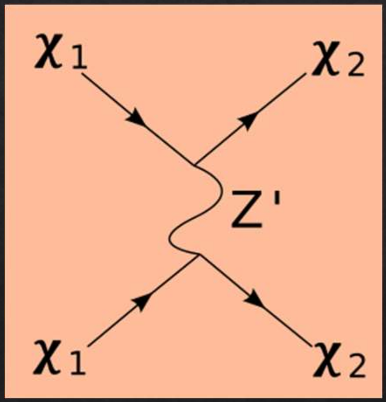


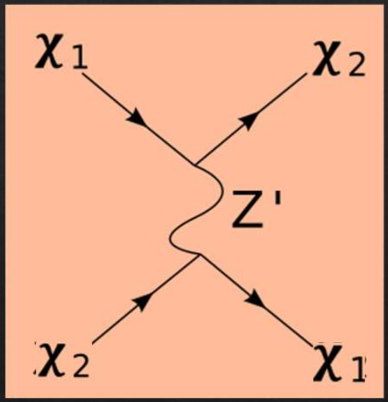
([5] **Gustafson**, Herrera, Mukhopadhyay, Murase and Shoemaker : 2025)

Looking Forward

Dark Matter Self-Interactions

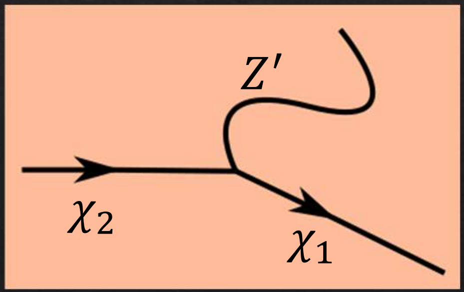
- For inelastic dark matter, energy injection is needed for self scattering to occur





Production of (Dark) Radiation

- When dark matter decays, it will induce more radiation
- If the mediator is on shell and long-lived, it is the dark radiation. Otherwise, the decay products will be the radiation.

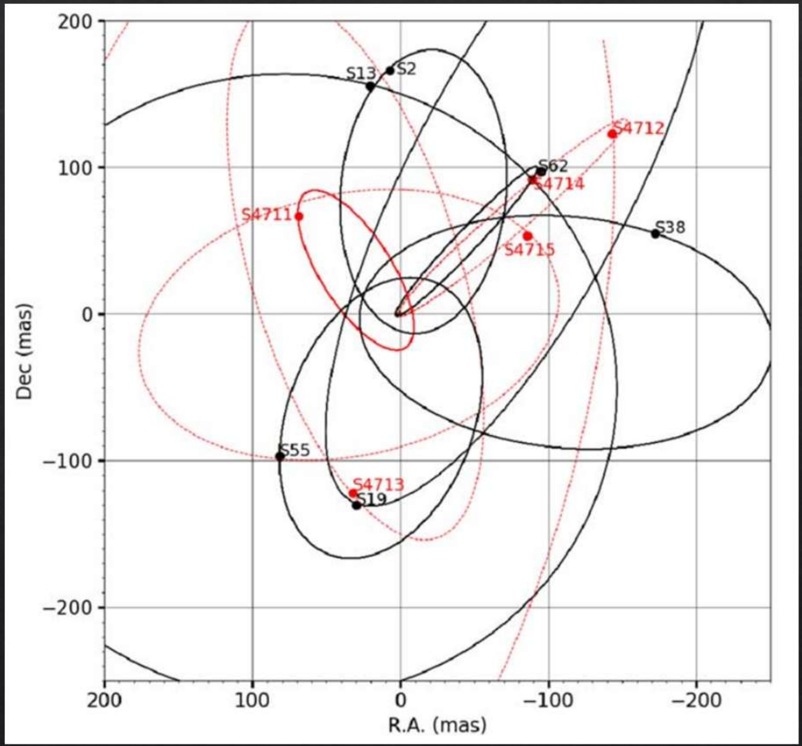


Dark Matter – Celestial Body Interactions around Less-Active Galactic Nuclei

Case Study: Milky Way Galactic Center

Milky Way Galactic Center

- The Milky Way has a SMBH at its Galactic Center: Sagittarius A* (Sgr A*)
- While Sgr A* produces very few cosmic rays, several stars orbit it with velocities up to ~few % c.
- These stars have been observed with high precision for tests of GR. These measurements might be repurposed to tell us about the DM environment.



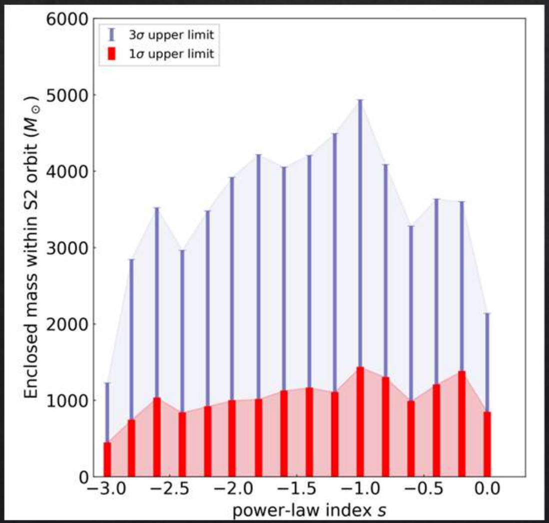
([6] Peißker, Eckart, Zajacek, Ali, and Parsa: 2020)

DM Forces on GC Objects

Extended Mass Effects

The **gravitational** potential cannot be described as that of a point mass.

Conserves orbital energy and angular momentum.



([7] GRAVITY Collaboration: 2024)

Dynamical Friction

Slowing of an object from the **gravitational** wake it produces on background particles.

Loss of orbital energy and angular momentum.

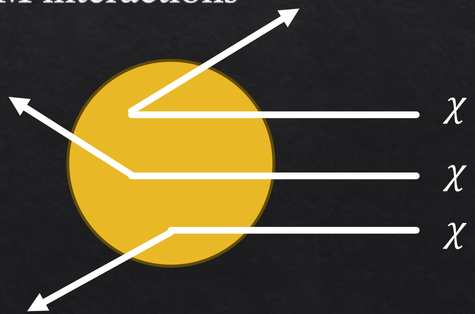
Scales as $\frac{1}{v_S^2}$ for high celestial body velocities.

Dark Drag

Slowing of the object due to DM scattering inside the object through **non-gravitational** interactions.

Loss of orbital energy and angular momentum.

Can probe the microphysics of DM-SM interactions



([8] Acevedo, Reilly, Santos-Olmsted: 2025)
([9] **Gustafson**, Shoemaker, Takhistov: 2025)

Dark Drag

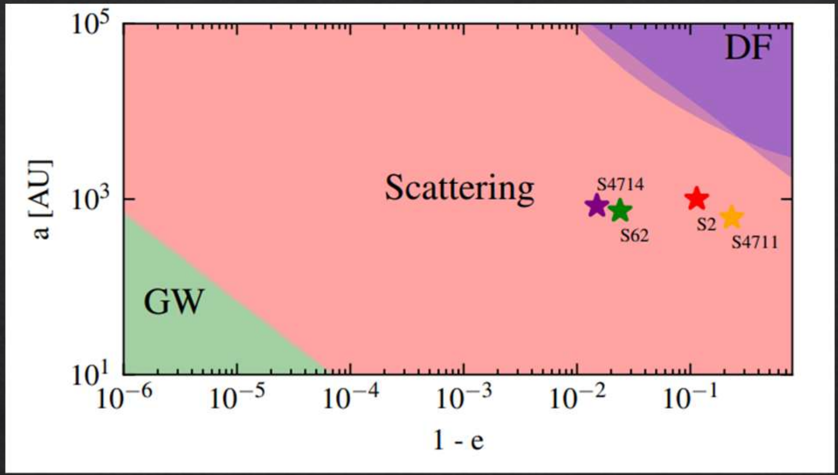
- For simplicity, consider a uniform spherical object (mass M_o, radius R_o) moving much faster than the surrounding dark matter. For low cross sections, the drag force scales as

$$F \simeq \frac{M_o\, v_s^2 \rho_\chi \sigma}{m_p + m_\chi}$$

- For high cross sections, the drag force scales as

$$F \simeq \pi\, R_o^2\, \rho_\chi\, v_s^2$$

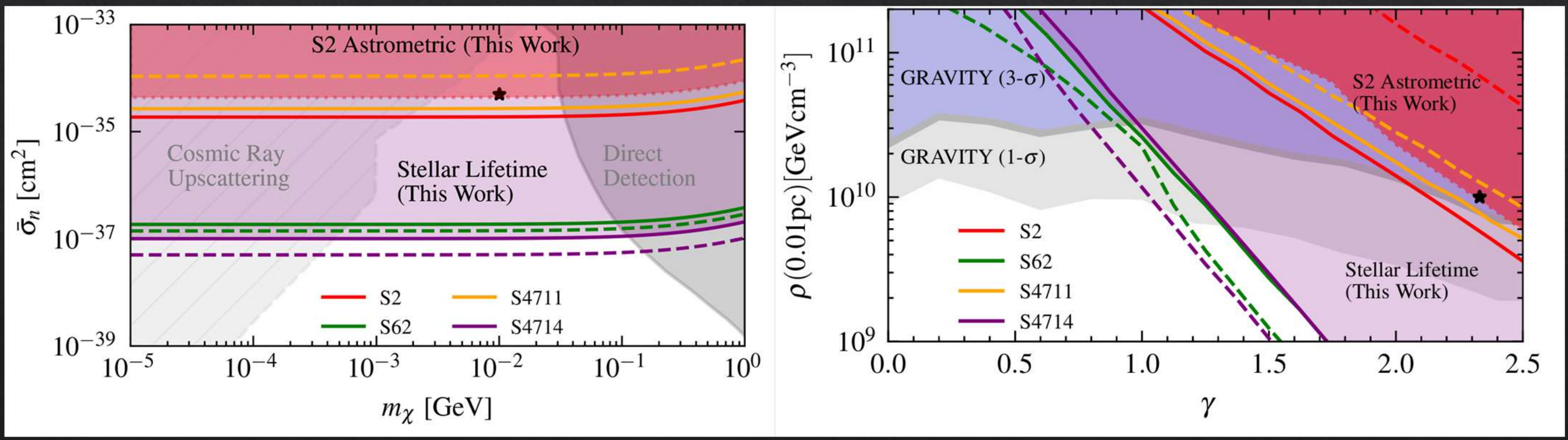
- This force can be observed through direct acceleration measurements like that of gas cloud G2 ([8] Acevedo, Reilly, Santos-Olmsted: 2025) or the degradation of stellar orbits ([9] **Gustafson**, Shoemaker, Takhistov: 2025)



Dominant Mechanism for orbital energy loss between gravitational waves, dark drag, and dynamical friction. ($\sigma = 1.3 \times 10^{-36}\ \mathrm{cm}^2$)

Dark Drag Results

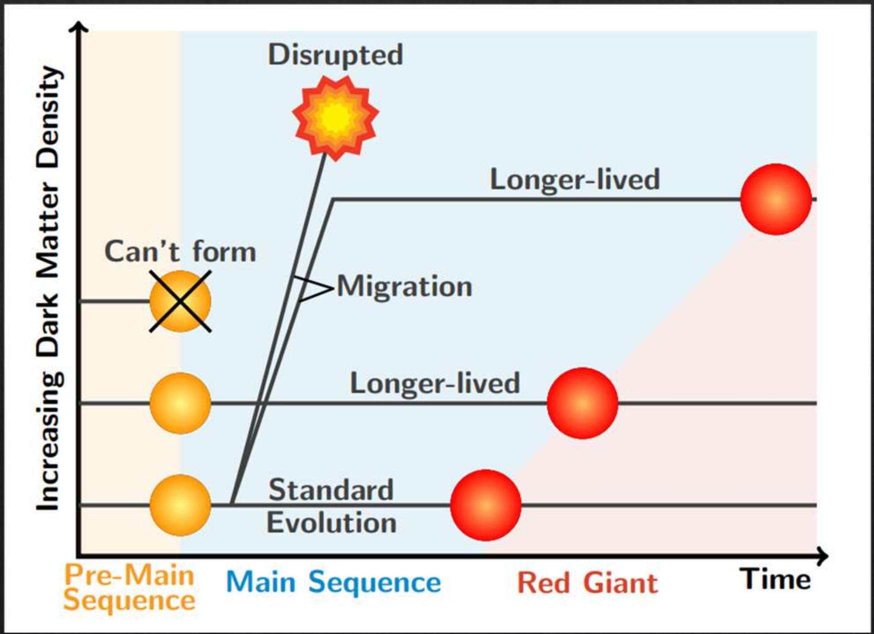
- Constraints depend on both the microphysics (cross section and DM mass) and macrophysics (DM spike parameters).



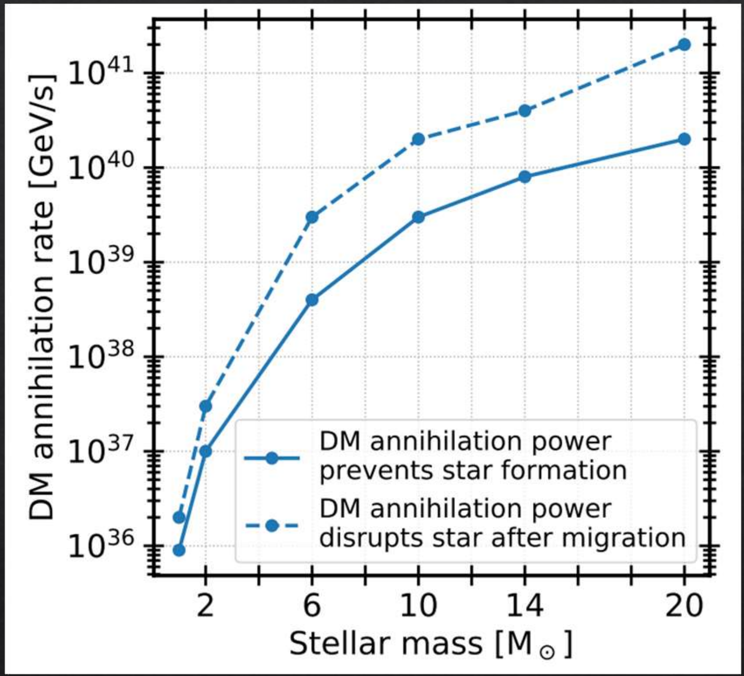
([9] **Gustafson**, Shoemaker, Takhistov: 2025)

DM Energy Injection

If dark matter injects energy into the star, the stellar evolution will be altered

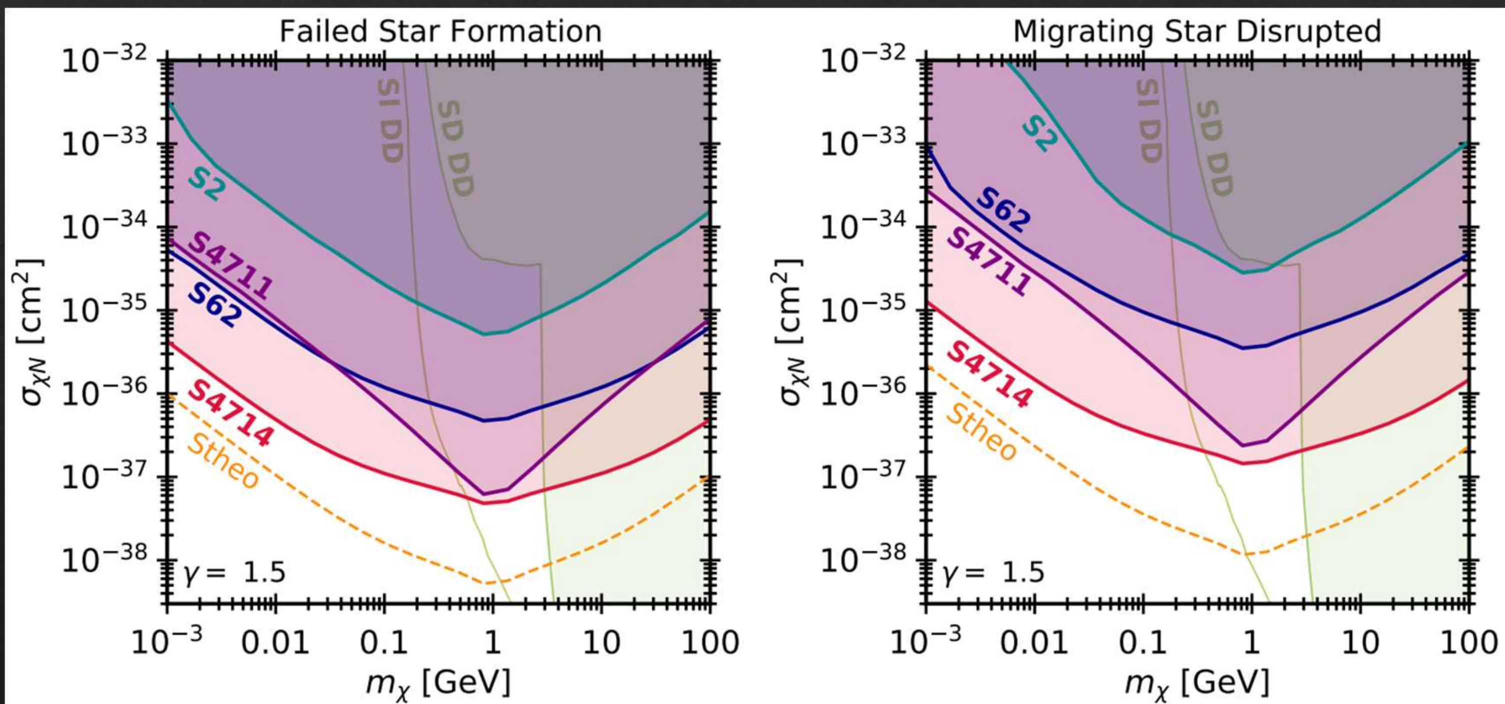


([10] Leane, Linden, John 2024)



Same for any mechanism injecting energy into the core. ($L_\odot \simeq 2 \times 10^{36} \frac{\text{GeV}}{\text{s}}$)

DM Capture and Annihilation



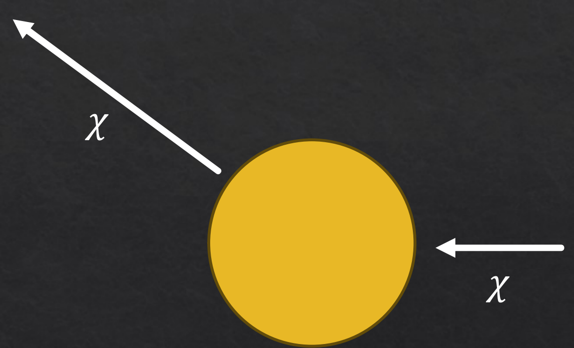
$$\rho(0.01pc) \sim 10^9 \frac{\text{GeV}}{\text{cm}^3}$$

This mechanism requires that DM annihilates into visible particles, converting all their rest mass into heat ([10] Leane, Linden, John: 2024).

DM Kinetic Energy Exchange

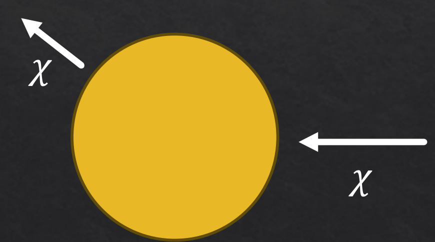
Cooling

- Occurs when $\frac{m_\chi}{2} v^2 < \frac{3T_s}{2}$
- Cooling Rate $\Gamma_C \sim \rho\, v\, T_s$



Heating

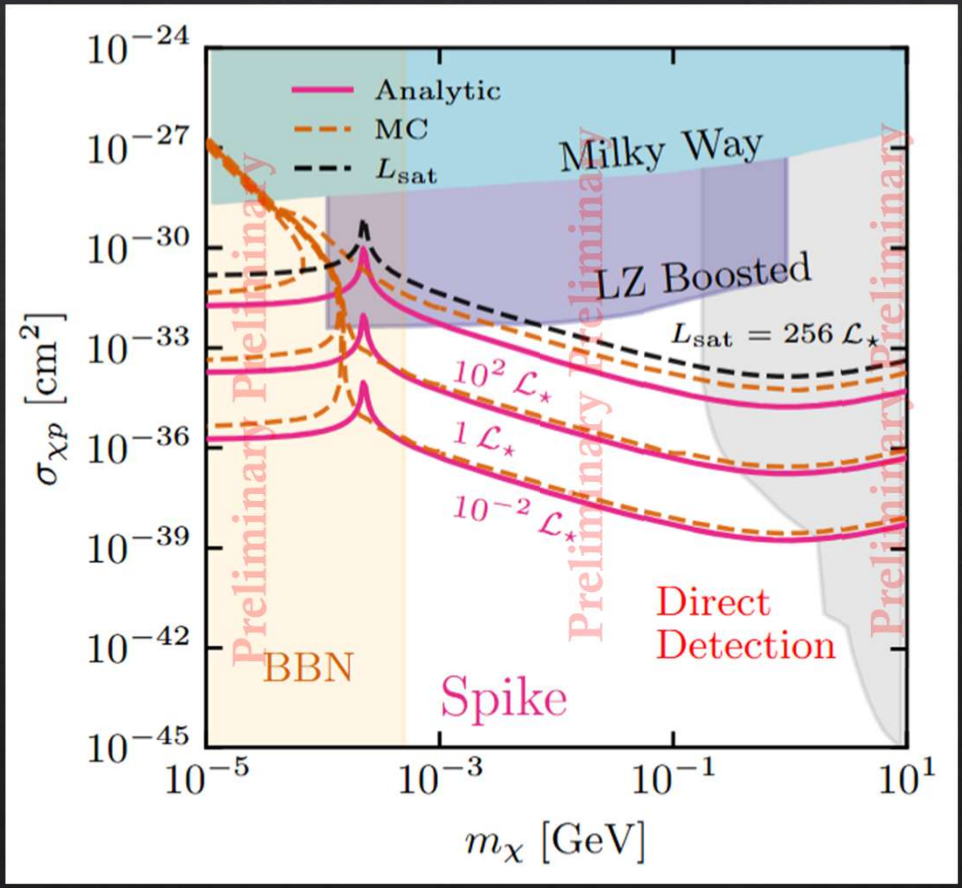
- Occurs when $\frac{m_\chi}{2} v^2 > \frac{3T_s}{2}$
- Heating rate $\Gamma_H \sim \rho\, v^3$



S4714 Preliminary Results

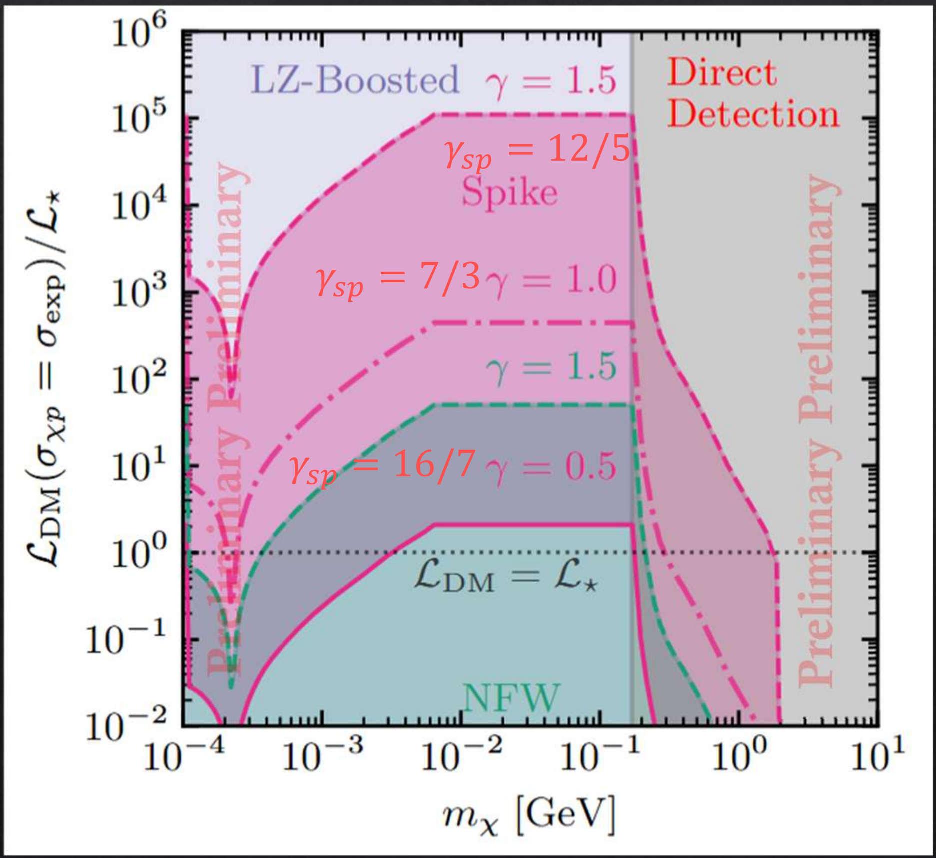
Full calculation requires a Monte Carlo, but an analytic approximation can be determined

$$L_\chi \sim f_{\text{peri}} A_s \frac{\rho(r_{\text{peri}})}{m_\chi} \, v_{\text{peri}} \, P_{scat} \, |E_{in} - E_{out}|$$



([11] Meighen-Berger, Newstead, Bell, Robles, **Gustafson**, Shoemaker: In Prep)

S4714 Possible DM-Induced Luminosities



Energy exchange rate with the cross section set to the maximum allowed by direct detection experiments. This could equal or even exceed the stellar luminosity

([11] Meighen-Berger, Newstead, Bell, Robles, **Gustafson**, Shoemaker: In Prep)

Central Thesis

SMBH's are exceptional locations for testing dark matter interactions. The dark matter density could be incredibly high, and the SM objects nearby have large kinetic energies. This combination can probe dark matter models and phenomena nearly impossible to see near Earth.

Examples

- AGN cosmic rays exchange energy with DM, leading to boosted DM and cooled cosmic rays.
  - This is most exciting for DM models which have energy thresholds to scattering
- Fast-moving stars and gas clouds at a galactic center can scatter with DM, causing a drag force and degrading the orbits
- Dark matter annihilation and kinetic energy exchange can deposit/remove substantial energy from galactic center objects, altering their evolution.

References

[1] G. Herrera and K. Murase, *Probing light dark matter through cosmic-ray cooling in active galactic nuclei*, Phys. Rev. D 110, L011701 (2024).
[2] J.-W. Wang, A. Granelli and P. Ullio, *Direct detection constraints on blazar-boosted dark matter*, Phys. Rev. Lett. 128 (2022) 221104 [arXiv:2111.13644]
[3] A. Granelli, P. Ullio and J.-W. Wang, *Blazar-boosted dark matter at Super-Kamiokande*, JCAP 07 (2022) 013 [arXiv:2202.07598]
[4] R.A. Gustafson et al., *Cosmic-ray cooling in active galactic nuclei as a new probe of inelastic dark matter*, Phys. Rev. D 111 (2025) L121303 [arXiv:2408.08947]
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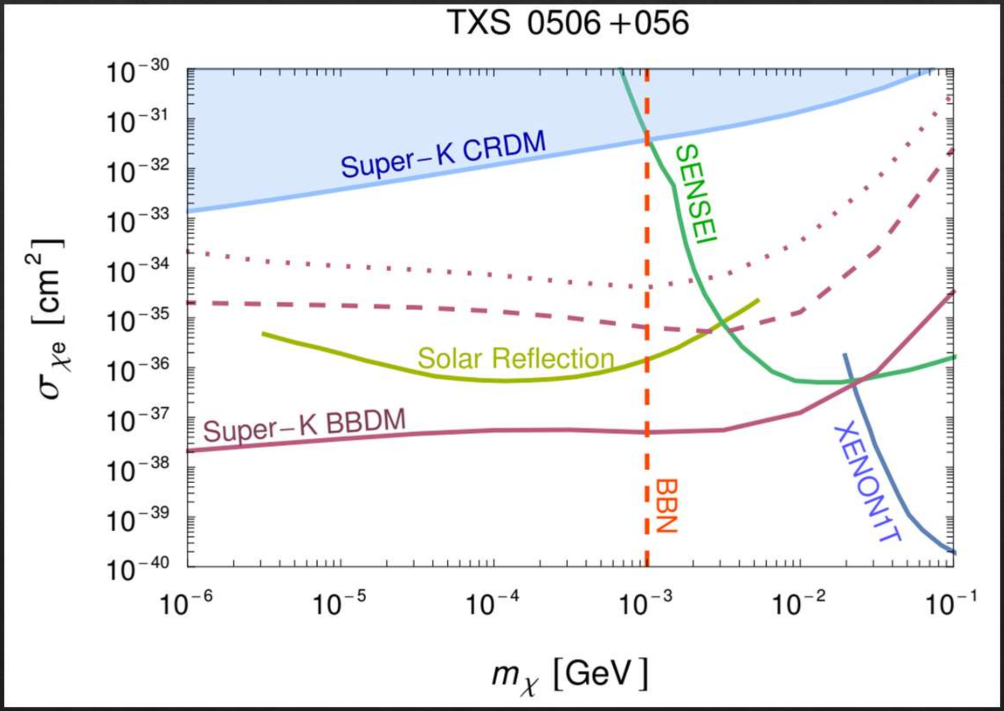
References

[7] K. Abd El Dayem et al. (GRAVITY), *Improving constraints on the extended mass distribution in the Galactic Center with stellar orbits.* Astron. Astrophys. 692, A242 (2024), arXiv:2409.12261
[8] J. F. Acevedo, A. J. Reilly, and L. Santos-Olmsted, *Dark drag around Sagittarius A*,* (2025), arXiv:2510.01320
[9] R. A. Gustafson, I. M. Shoemaker, V. Takhistov, *Probing dark matter interactions with stellar motion around Sagittarius A**, (2025), arXiv:2510.07387
[10] I. John, R. K. Leane, and T. Linden, *Dark matter scattering constraints from observations of stars surrounding Sgr A*,* Phys. Rev. D 109, 123041 (2024), arXiv:2311.16228
[11] S. Meighen-Berger, J. Newstead, N. Bell, S. Robles, R. A. Gustafson, I. M. Shoemaker, *Dark matter energy exchange in stars orbiting super-massive black holes*, (In prep)

Backup

SK Blazar Boosted DM Constraints



(Granelli, Ullio, Wang; 2022)

Dark Drag Equations

$$\sigma_T = \int dE_R \frac{d\sigma}{dE_R} \frac{m_N E_R}{\mu_{\chi N}^2 \, v_\chi^2}$$

$$\tau_T = \frac{2 \, R_s \, n_N \, \sigma_T \, m_N}{m_\chi + m_N}$$

$$\langle \mathbf{p_{SM}} \rangle = m_\chi \mathbf{v}_\chi \left(1 - 2 \frac{1 - \exp(-\tau_T)(1 + \tau_T)}{\tau_T^2} \right)$$

$$\mathbf{F_{DM}} = \pi R_S^2 \frac{\rho_\chi}{m_\chi} v_s \int \langle \mathbf{p_{SM}} \rangle \, f(\mathbf{v}_\chi) d^3 \mathbf{v}_\chi$$

Energy Equations for Kinetic Energy Exchange

$$E_{in} = \frac{4\, m_p \left(1 + \frac{K_\chi}{m_\chi}\right) \frac{K_\chi}{m_\chi}}{\left(1 + \frac{m_p}{m_\chi}\right)^2 + 2\frac{K_\chi}{m_\chi}}$$

$$E_{out} = \frac{4\, m_p \left(1 + \frac{T}{m_p}\right) \frac{T}{m_\chi}}{\left(1 + \frac{m_p}{m_\chi}\right)^2 + 2\frac{T}{m_\chi}}$$