A unique probe of dark matter in the core of M87 with the Event Horizon Telescope

Based on Lacroix et al. 2016 [arXiv:1611.01961]

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Introduction

- Cores of galaxies extremely interesting: interplay of high-energy processes, jets, putative DM annihilation...
- Difficult to probe: high angular resolution needed
- Inner DM density profile critical for indirect searches but poorly constrained
- Probe DM at horizon scales with the Event Horizon Telescope (EHT)
- Focus on M87, a primary target of the EHT

[Credit: NASA and The Hubble Heritage Team (STScI/AURA)]
- DM density profile very uncertain below parsec scales
- Can be significantly affected by supermassive black holes (SMBH)
- Adiabatic (slow) growth of SMBH at the center of DM halo
  \( \Rightarrow \) **spike**: strong enhancement of the DM density in the inner region [Gondolo & Silk 1999]

\[
\rho_{sp}(r) \propto r^{-\gamma_{sp}}, \quad \gamma_{sp} \sim 7/3
\]  

\( \Rightarrow \) strong annihilation signals

- Adiabatic spikes not observed yet
Dark matter spikes affected by competing dynamical processes

Disruptive dynamical effects

- Instantaneous BH growth [Ullio et al. 2001]
- Off-centered BH formation [Nakano & Makino 1999; Ullio et al. 2001]
- Halo mergers [Merritt et al. 2002]
- Stellar dynamical heating [Gnedin & Primack 2004; Merritt 2004]

Dynamical effects strengthening the case for DM spikes

- Core-collapse from DM self-interactions [Ostriker 2000]
- Efficient replenishment of the loss cone from steep stellar cusp [Zhao et al. 2002]
- Triaxiality of DM halo $\Rightarrow$ enhanced DM accretion [Merritt & Poon 2004]
Additional motivation for spike in M87

Dynamical relaxation time in the core of a galaxy

\[ t_r \sim 2 \times 10^9 \text{ yr} \left( \frac{M_{\text{BH}}}{4.3 \times 10^6 M_\odot} \right)^{1.4} \]  

- To be compared with the age of the Universe (\( \sim 10^{10} \text{ yr} \))
- Stellar dynamical heating potentially relevant for the Milky Way
- Negligible for galaxies with sufficiently massive central BHs

Negligible effect of stellar heating in dynamically young galaxies

M87 (\( M_{\text{BH}} \approx 6 \times 10^9 M_\odot \)) dynamically young
\[ \Rightarrow \text{stellar heating negligible} \]
\[ \Rightarrow \text{spike more likely to have survived in M87} \]
- Idea: exploit the morphology of the DM-induced synchrotron signal in the vicinity of the central SMBH
- Previously lack of angular resolution of existing facilities
- Event Horizon Telescope (EHT): game changer
- Network of mm/submm telescopes
- Very long baseline interferometry $\Rightarrow$ Earth-sized telescope
  $\Rightarrow$ micro-arcsecond-scale angular resolution

![EHT Network Diagram]

[Fish et al. 2013]
Black hole shadows

Observing the shadow of the SMBH in M87

- Shadow: disk of local darkness surrounded by brighter photon ring from gravitational lensing
- SMBH at the center of M87: angular Schwarzschild radius $\sim 8 \, \mu\text{as}$, similar to Sgr A* ($\sim 10 \, \mu\text{as}$)
  $\Rightarrow$ excellent target for the EHT

[Simulation; credit: Avery E. Broderick (University of Waterloo/Perimeter Institute)]

[Lacroix & Silk 2013]
Probing dark matter at the center of M87 with the Event Horizon Telescope

Probing the DM distribution close to the BH

- EHT can probe the vicinity of the BH at the center of M87
- Observe shadow of the SMBH in the DM annihilation-induced synchrotron signal at 230 GHz

DM-induced synchrotron intensity

- Synchrotron radiation + advection of $e^\pm$ towards the BH
- $b\bar{b}$ annihilation channel for illustration
- Ray-tracing scheme to model radiative transfer in the vicinity of the BH  
  [Broderick 2006; Broderick & Loeb 2006]
BH shadow in DM-induced synchrotron signal

FIG. 1. Simulated maps of the synchrotron intensity at 230 GHz from a spike of 10 GeV DM annihilating into $b\bar{b}$, accounting for the strong gravitational lensing induced by the central BH, for a Schwarzschild BH (left panel) and a maximally rotating BH (right panel), in the presence (upper panels) and absence (lower panels) of a spike in the DM profile. Note that considering the wide range of intensities, we use different color scales, but with the same dynamic range spanning three orders of magnitude for comparison. The angular coordinates $\xi$ and $\eta$ correspond to the directions respectively perpendicular and parallel to the spin of the BH. For the spike cases, the slope of the DM spike is $g_{sp} = 7/3$, and the annihilation cross-sections correspond to the best fit to EHT observations (see text for details), namely $7.4 \times 10^{-31}$ cm$^3$ s$^{-1}$ for the Schwarzschild case and $3.1 \times 10^{-31}$ cm$^3$ s$^{-1}$ for the maximally rotating case. In the absence of a spike, the intensity is computed for the thermal s-wave cross-section of $3 \times 10^{-26}$ cm$^3$ s$^{-1}$. For all the simulated maps the magnetic field is 10 G.

Detectable with the EHT, as discussed in the following. The presence of a photon ring introduces small-scale structure into the signal, readily observable with the EHT on long baselines. For a static BH the shadow is exactly circular. For all but the most rapidly rotating BHs it is also very nearly circular [31, 32]. For a maximally rotating Kerr BH viewed from the equatorial plane the photon ring is flattened in the direction aligned with the BH spin.

At scales above 25 $\mu$as the DM spike-induced emission produces a diffuse synchrotron halo whose intensity falls with radius as a power law with index $\pi/3$. This is generic, occurring independently of the BH spin and is present even when gravitational lensing is ignored. The extended nature of this component ensures that it is subdominant on Earth-sized baselines. In the absence of a spike, the profile is much flatter, and falls with radius as a power law with index $\pi/1.5$. Fig. 1 also illustrates the fact that the intensity is significantly enhanced in the presence of a DM spike with respect to the no-spike case. To better stress this enhancement, we show the maps for the spike case computed for very small annihilation cross-sections of a few $10^{-31}$ cm$^3$ s$^{-1}$—corresponding to the best fits to the EHT data, as discussed below—, while in the absence of a spike we use the thermal s-wave cross-section of $3 \times 10^{-26}$ cm$^3$ s$^{-1}$.

Shown in the blue solid line in Fig. 2 is the visibility amplitude at 230 GHz as a function of baseline length for the current EHT triangle, for the simulated DM-induced synchrotron signal, computed with a cross-section that gives the best fit to the EHT measurements from Refs. [13, 14]. The left panel corresponds to the Schwarzschild case and the right panel to the...
Interferometric observables

- EHT interferometer → complex visibilities (Fourier transform of the image)
- Currently sampling of the spatial-frequency plane too sparse to directly reconstruct image
- Visibility amplitude
- Phase more difficult to obtain (atmospheric delays) → closure phase (CP) from triangles of sites
- Currently only one triangle: Hawaii-California-Arizona
Visibility amplitude: DM spike

Photon ring around BH shadow ⇒ observable small-scale structure for the EHT

Adequate fit to EHT data with spike of annihilating DM

Very stringent constraints on annihilation cross-section: a few $10^{-31}$ cm$^3$ s$^{-1}$ at 10 GeV and $\sim 10^{-27}$ cm$^3$ s$^{-1}$ at 1 TeV
Visibility amplitude: astrophysical contribution

But astrophysical component should be included → degeneracy

DM may account for significant portion of mm emission from M87 core

Potentially even more stringent constraints with jet component
Closure phase

- CP of DM-induced emission consistent with low values observed
- Small CPs also typical of astrophysical models on the Hawaii-California-Arizona triangle

[Diagram showing closure phase versus UTC time with data points and lines representing different models.]
Improvements with additional sites

- Better image reconstruction
- In particular phase better constrained

[EHT Collaboration]
Improvements with additional sites

- Better image reconstruction
- In particular phase better constrained

[Diagram showing data points labeled SMA+JCMT, SMT, CARMA, ALMA with corresponding u (G\(\lambda\)) and v (G\(\lambda\)) axes.]

[EHT Collaboration]
Improvements with additional sites

- Better image reconstruction
- In particular phase better constrained

[EHT Collaboration]
Improvements with additional sites

- Better image reconstruction
- In particular phase better constrained
Constraining the various scenarios with more sites

Additional sites ⇒ additional triangles ⇒ better constraints

[Figure showing closure phases for different triangles with models indicating different scenarios: approaching-jet-dominated, counter-jet-dominated, and accretion-disk-dominated.]

[Figure notes: Akiyama et al. 2015]
Conclusion

- First model of synchrotron emission from spike of annihilating DM at horizon scale with BH lensing
- DM-induced emission should be readily visible in EHT images
- DM spike enhances the photon ring surrounding the BH shadow
  ⇒ observable small-scale feature for the EHT
- Adequate fit to current EHT data with DM spike
- Stringent upper limits on DM annihilation cross-section (a few $10^{-31} \text{ cm}^3 \text{ s}^{-1}$ at 10 GeV)
- Jet contribution should be included
  ⇒ energy budget
  ⇒ potentially even stronger constraints
- Future EHT observations with additional baselines
  ⇒ discriminate between astrophysical and DM-dominated models
Thank you for your attention!
Schwarzschild

<table>
<thead>
<tr>
<th>$m_{\text{DM}} = 10 \text{ GeV}$</th>
<th>$m_{\text{DM}} = 10^2 \text{ GeV}$</th>
<th>$m_{\text{DM}} = 10^3 \text{ GeV}$</th>
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<tbody>
<tr>
<td>$B = 10 \text{ G}$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 7.4 \times 10^{-31} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 1.4$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 2.8 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 1.4$</td>
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<td>$B = 10^2 \text{ G}$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 9.5 \times 10^{-31} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 1.5$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 4.4 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 1.5$</td>
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<tr>
<td>$B = 10^3 \text{ G}$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 4.2 \times 10^{-30} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 1.8$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 1.8 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 1.8$</td>
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Maximally rotating

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<th>$m_{\text{DM}} = 10 \text{ GeV}$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$B = 10 \text{ G}$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 3.1 \times 10^{-31} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 6.5$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 1.2 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 6.0$</td>
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<tr>
<td>$B = 10^2 \text{ G}$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 2.9 \times 10^{-31} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 11$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 1.3 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 11$</td>
</tr>
<tr>
<td>$B = 10^3 \text{ G}$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 1.3 \times 10^{-30} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 12$</td>
<td>$\langle \sigma v \rangle_{\text{bf}} = 5.6 \times 10^{-29} \text{ cm}^3 \text{ s}^{-1}, \chi^2_{\text{red}} = 12$</td>
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