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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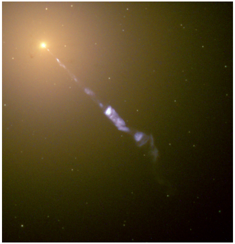
Introduction

- 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)]

Dark matter spikes at the centers of galaxies?

- 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]

$$\rho_{\rm sp}(r) \propto r^{-\gamma_{\rm sp}}, \quad \gamma_{\rm sp} \sim 7/3 \tag{1}$$

$\Rightarrow$ 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

$$t_{\rm r} \sim 2 \times 10^9 \ {\rm yr} \left(\frac{M_{\rm BH}}{4.3 \times 10^6 \ M_\odot} \right)^{1.4} \tag{2}$$

- To be compared with the age of the Universe ($\sim 10^{10}$ 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

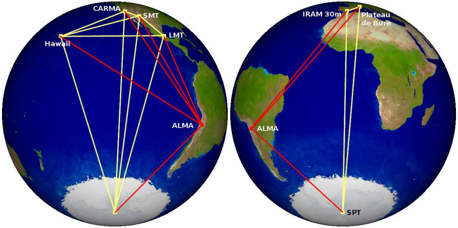
M87 ($M_{\rm BH} \approx 6 \times 10^9 \ M_\odot$) dynamically young

$\Rightarrow$ stellar heating negligible

$\Rightarrow$ **spike more likely to have survived in M87**

The Event Horizon Telescope

- 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

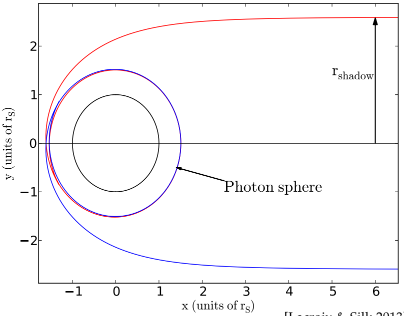


[Fish et al. 2013]

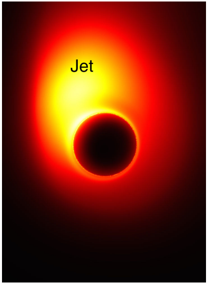
Black hole shadows

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 $\sim 8\ \mu$as, similar to Sgr A* ($\sim 10\ \mu$as)
  $\Rightarrow$ excellent target for the EHT



[Lacroix & Silk 2013]



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

Probing dark matter at the center of M87 with the Event Horizon Telescope

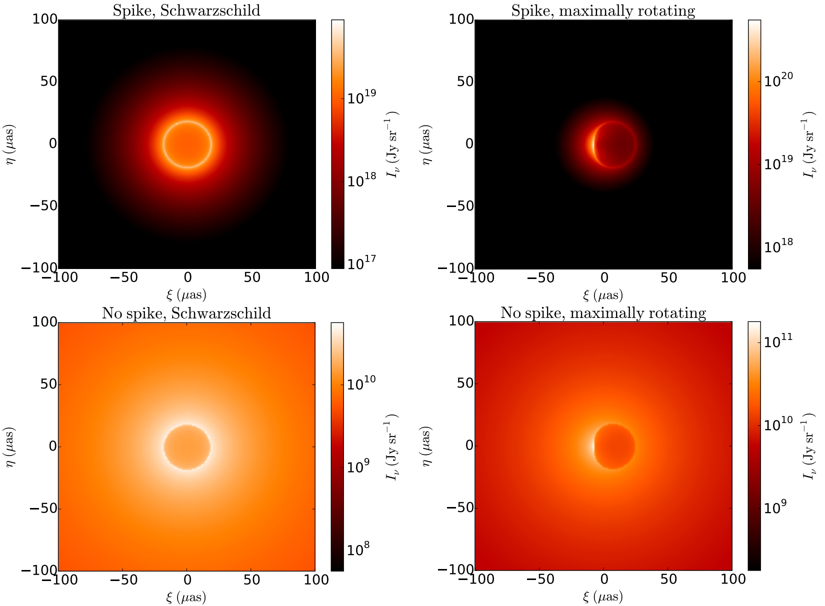
Probing the DM distribution close to the BH

- 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

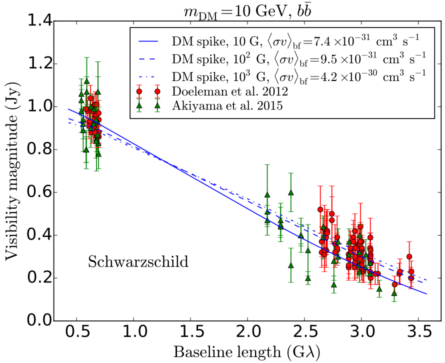


[Lacroix et al. 2016]

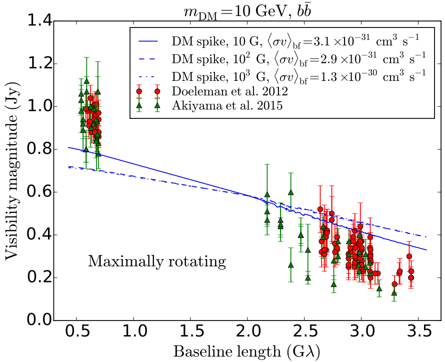
Interferometric observables

- EHT interferometer $\rightarrow$ 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)
  $\rightarrow$ closure phase (CP) from triangles of sites
- Currently only one triangle: Hawaii-California-Arizona

Visibility amplitude: DM spike



[Lacroix et al. 2016]

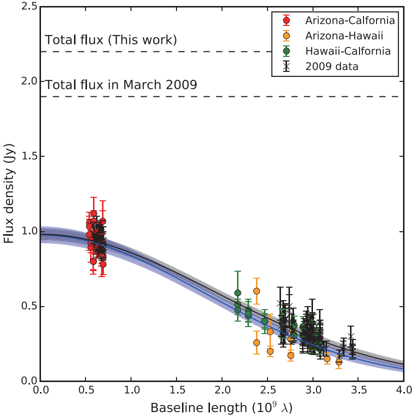


[Lacroix et al. 2016]

- 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

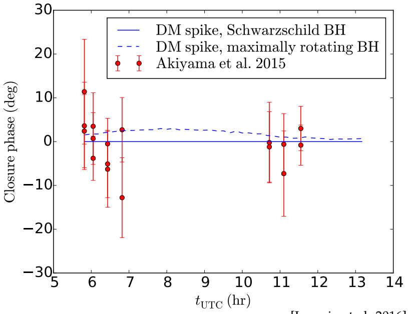


[Akiyama et al. 2015]

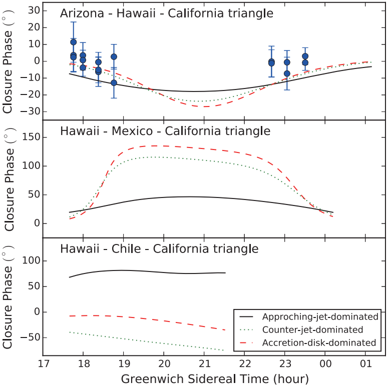
- DM may account for significant portion of mm emission from M87 core
- Potentially even more stringent constraints with jet component

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
- Additional sites ⇒ additional triangles ⇒ constraints



[Lacroix et al. 2016]



[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
  $\Rightarrow$ 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} cm^3 s^{-1} at 10 GeV)
- Jet contribution should be included
  $\Rightarrow$ energy budget
  $\Rightarrow$ potentially even stronger constraints
- Future EHT observations with additional baselines
  $\Rightarrow$ discriminate between astrophysical and DM-dominated models

Thank you for your attention!

Best-fit values

Schwarzschild

	$m_{DM} = 10$ GeV	$m_{DM} = 10^2$ GeV	$m_{DM} = 10^3$ GeV
$B = 10$ G	$\langle\sigma v\rangle_{bf} = 7.4 \times 10^{-31}$ cm^3 s^{-1}, $\chi^2_{red} = 1.4$	$\langle\sigma v\rangle_{bf} = 2.8 \times 10^{-29}$ cm^3 s^{-1}, $\chi^2_{red} = 1.4$	$\langle\sigma v\rangle_{bf} = 1.2 \times 10^{-27}$ cm^3 s^{-1}, $\chi^2_{red} = 1.4$
$B = 10^2$ G	$\langle\sigma v\rangle_{bf} = 9.5 \times 10^{-31}$ cm^3 s^{-1}, $\chi^2_{red} = 1.5$	$\langle\sigma v\rangle_{bf} = 4.4 \times 10^{-29}$ cm^3 s^{-1}, $\chi^2_{red} = 1.5$	$\langle\sigma v\rangle_{bf} = 1.8 \times 10^{-27}$ cm^3 s^{-1}, $\chi^2_{red} = 1.5$
$B = 10^3$ G	$\langle\sigma v\rangle_{bf} = 4.2 \times 10^{-30}$ cm^3 s^{-1}, $\chi^2_{red} = 1.8$	$\langle\sigma v\rangle_{bf} = 1.8 \times 10^{-28}$ cm^3 s^{-1}, $\chi^2_{red} = 1.8$	$\langle\sigma v\rangle_{bf} = 8.1 \times 10^{-27}$ cm^3 s^{-1}, $\chi^2_{red} = 1.7$

Maximally rotating

	$m_{DM} = 10$ GeV	$m_{DM} = 10^2$ GeV	$m_{DM} = 10^3$ GeV
$B = 10$ G	$\langle\sigma v\rangle_{bf} = 3.1 \times 10^{-31}$ cm^3 s^{-1}, $\chi^2_{red} = 6.5$	$\langle\sigma v\rangle_{bf} = 1.2 \times 10^{-29}$ cm^3 s^{-1}, $\chi^2_{red} = 6.0$	$\langle\sigma v\rangle_{bf} = 5.2 \times 10^{-28}$ cm^3 s^{-1}, $\chi^2_{red} = 5.8$
$B = 10^2$ G	$\langle\sigma v\rangle_{bf} = 2.9 \times 10^{-31}$ cm^3 s^{-1}, $\chi^2_{red} = 11$	$\langle\sigma v\rangle_{bf} = 1.3 \times 10^{-29}$ cm^3 s^{-1}, $\chi^2_{red} = 11$	$\langle\sigma v\rangle_{bf} = 5.6 \times 10^{-28}$ cm^3 s^{-1}, $\chi^2_{red} = 11$
$B = 10^3$ G	$\langle\sigma v\rangle_{bf} = 1.3 \times 10^{-30}$ cm^3 s^{-1}, $\chi^2_{red} = 12$	$\langle\sigma v\rangle_{bf} = 5.6 \times 10^{-29}$ cm^3 s^{-1}, $\chi^2_{red} = 12$	$\langle\sigma v\rangle_{bf} = 2.5 \times 10^{-27}$ cm^3 s^{-1}, $\chi^2_{red} = 12$