Dark matter and black holes at the centers of galaxies: from gravitational dynamics to particle phenomenology

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Introduction

Why cores of galaxies?

- Large DM abundance expected
- But density profile poorly constrained
- (Spatial) distribution of DM around supermassive black holes (SMBHs)?

Using astrophysical observations of SMBH environments

- Probing WIMP annihilation around M87* with the Event Horizon Telescope
- Gravitational dynamics: kinematics of S2 star and dark mass
  $\rightarrow$ less model-dependent
  $\rightarrow$ e.g. probe WIMPs, ultralight DM

DM profiles at the centers of galaxies: impact of the central BH?

Adiabatic contraction of a DM halo

Adiabatic invariants

$$L_f = L_i,\ f_f = f_i,\ J_{r,f} = J_{r,i}$$

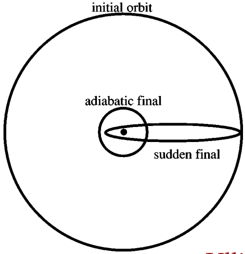
$\Rightarrow$ contraction of the DM halo
$\Rightarrow$ **"spike"** (Gondolo & Silk 1999)

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

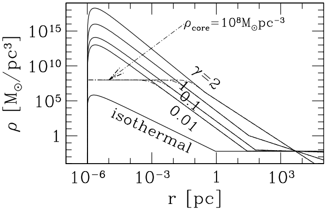
$\Rightarrow$ Strong signatures

Theoretical uncertainties

- No direct observations
- Dynamical processes



Ullio+ 2001



Gondolo & Silk 1999

A DM spike in dynamically young galaxies?

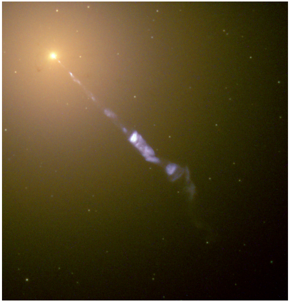
Negligible effect of heating by stars in dynamically young galaxies

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

M87 ($M_{BH} \approx 6.4 \times 10^9 \, M_\odot$) dynamically young

$\Rightarrow$ Dynamical heating of the core negligible

$\Rightarrow$ **Survival of a spike more likely**



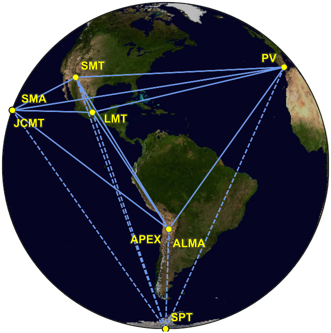
M87

Source : NASA and The Hubble Heritage Team (STScI/AURA)

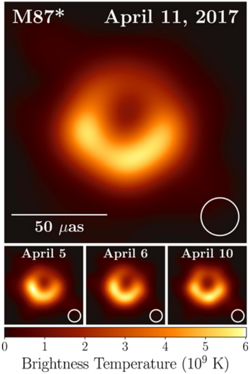
Probing DM at the center of M87 with the Event Horizon Telescope

- Spatial morphology of the annihilation signal around M87*
- How much DM-induced signal can hide there?
- Very Long Baseline Interferometry (1.3 mm)

$\Rightarrow$ angular resolution $\sim \frac{\lambda}{D}$: a few μas



EHT Collaboration 2019, L1

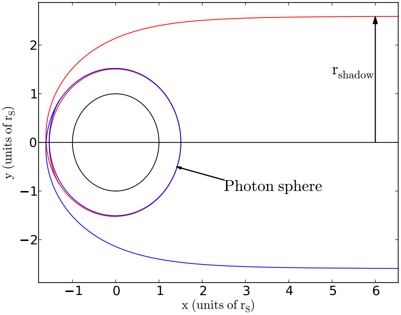


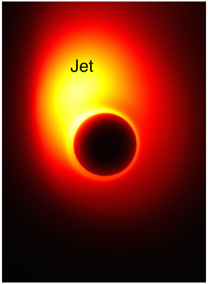
EHT Collaboration 2019, L1

Shadow of a BH

Shadow of the BH at the center of M87

- Shadow: locally dark disk surrounded by a bright ring due to gravitational lensing, $r_{\text{shadow}} \approx 2.6 R_S$
- SMBH M87* at the center of M87:
  angular diameter $\sim 40\ \mu$as
  $\Rightarrow$ prime target of the EHT





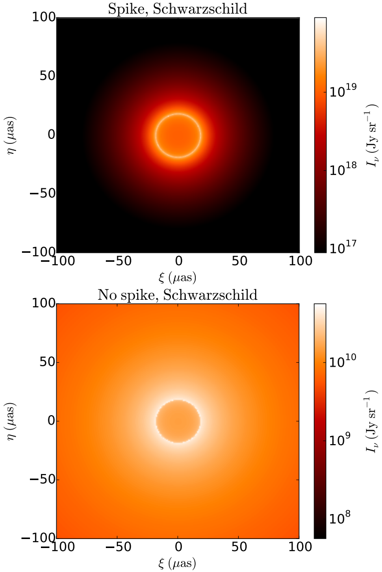
Simulation; credit: Avery E. Broderick (University of Waterloo/Perimeter Institute)

Creating simulated maps of the DM-induced synchrotron intensity

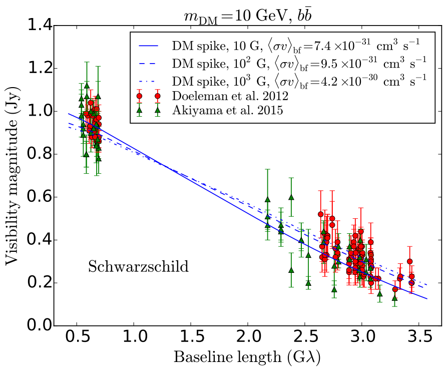
DM-induced synchrotron intensity maps

- $e^{\pm}$ propagation: synchrotron + advection $\Rightarrow$ Emissivity j_{syn}
- Ray-tracing scheme for radiative transfer in strong gravitational field (Broderick 2006; Broderick & Loeb 2006) $\Rightarrow I_{\mathrm{syn}}$ @ $\lambda = 1.3\,\mathrm{mm}$

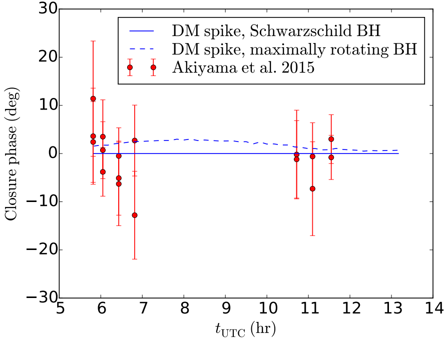
Lacroix+ 2017



Fitting 2015 EHT data



Lacroix+ 2017



Lacroix+ 2017

- Interferometric observables: complex visibilities
- DM spike $\Rightarrow$ ring around shadow amplified
- EHT data can be accounted for with a spike
- **But**: degeneracies with astrophysical components
- How much room for DM with 2019 data? Work in progress...

Kinematics of the S2 star at the center of the Milky Way

Quantify effect of DM spike on orbit of S2 → Newtonian precession

Orbit-fitting procedure

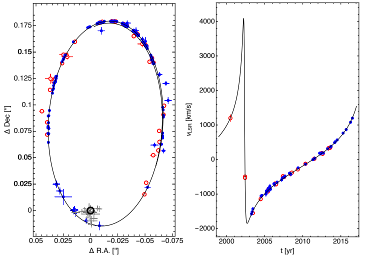
- Numerically solve equations of motion

$$\ddot{r} - \frac{L^2}{r^3} = -\frac{GM_{\rm BH}}{r^2} - \frac{{\rm d}\Phi_{\rm S}}{{\rm d}r} - \frac{{\rm d}\Phi_{\rm DM}}{{\rm d}r}$$

$$\theta(t) = \theta_0 + \int_{t_0}^{t} \frac{L}{r(t')^2}\,{\rm d}t'$$

- Reconstruct orbit as a function of time
- 12 + 1 (16 + 1) free parameters

$$\gamma_{\rm sp} = (9-2\gamma)/(4-\gamma)$$

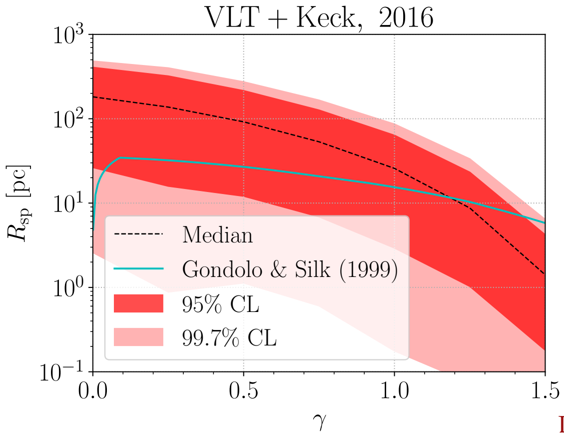


Gillessen+ 2017

$$\rho(r) = \begin{cases} 0, \; r < 2R_{\rm S} \\ \rho_0 \left(\dfrac{r}{R_{\rm sp}}\right)^{-\gamma_{\rm sp}}, \; 2R_{\rm S} \leqslant r < R_{\rm sp} \\ \rho_{\rm h}(r), \; r \geqslant R_{\rm sp} \end{cases}$$

Direct dynamical constraints on a spike at the center of the Milky Way

- First direct constraints on spike parameters from S2 orbit
- Direct probe of adiabatic spike

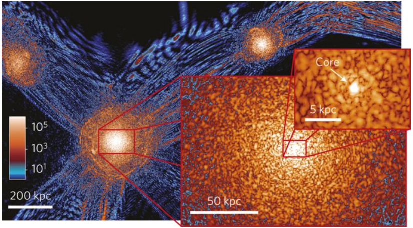


Lacroix 2018

Improvement expected with GRAVITY data

Probing ultralight DM

- Alternative to thermally produced non-relativistic massive DM candidates like WIMPs
- ULDM & challenges of CDM on galactic scales
- Constraints from astrophysics & cosmology (e.g. Ly-α forest)
  $\Rightarrow$ Tension for $m \lesssim 10^{-21}$ eV
- ULDM expected to form cored density profiles (solitons)
- Dedicated numerical (DM-only) simulations
  $\rightarrow$ CDM at large scales, cores at the centers of halos



Schive+ 2014

Ultralight DM and SMBHs

- Soliton-host halo mass relation from ULDM-only simulations

$$M_{\rm sol} \approx 6.5 \times 10^8 M_\odot \left(\frac{m}{10^{-22}\ {\rm eV}}\right)^{-1} \left(\frac{M_{\rm h}}{10^{11}\ M_\odot}\right)^{\frac{1}{3}}$$

Schive+ 2014

- Solving Schrödinger-Poisson system semi-analytically

$$\left.\frac{K}{M}\right|_{\rm soliton} \approx \left.\frac{K}{M}\right|_{\rm halo}$$

Bar+ 2018

- Naive extrapolation to larger masses
  $\Rightarrow M_{\rm sol} \sim M_{\rm BH}$ for $m \sim (10^{-20}\text{-}10^{-19})$ eV
  $\Rightarrow$ stellar kinematics around SMBHs good probe

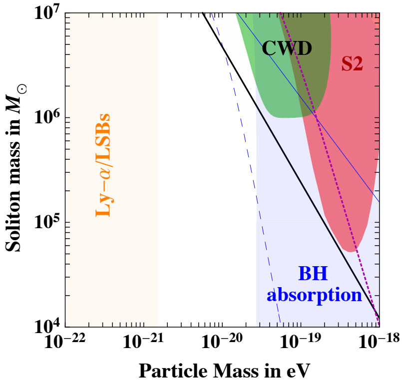
ULDM solitons: constraints from S2 orbit

Accounting for BH potential

- M_{sol} independent parameter
- Extended mass profile $M^{\text{ext}}(r; M_{\text{sol}}, m)$

Upper limits in (m, M_{sol}) plane

- Exclude naive extrapolation of soliton-host mass relation
- Soliton-halo relation tested in a new range



Bar+ 2019

Caveats

- Dynamical relaxation
- Absorption by the BH

→ Dedicated numerical simulations called for (w/ BH, large m)

ULDM solitons: constraints from EHT data

EHT & stellar kinematics

- EHT measurement of gravitational radius of M87*

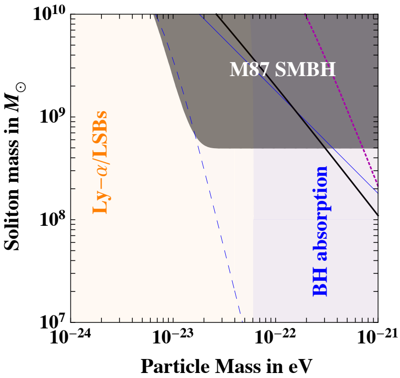
$$\theta_g = \frac{GM_{BH}}{c^2 D} = (3.8 \pm 0.4)\ \mu\text{as}$$

EHT Collaboration 2019, L1

- Combine with stellar kinematics at $\theta_* = (2.5'' - 11'')$
  Gebhardt+ 2011

$$\frac{\delta M(\theta_*)}{M_{BH}} = -0.04 \pm 0.11$$

Bar+ 2019



Bar+ 2019

Caveats

Same as before

Summary: observations of vicinity of SMBHs

EHT and M87*: new probe of WIMP-like DM

- Spatial morphology of 1.3 mm signal from the vicinity of M87*
- Fraction of observed signal from WIMP-induced synchrotron signal?

Stellar orbit reconstruction in the Milky Way (S2)

- Direct constraints on models of spiky DM profiles at the Galactic center
- Good probe of soliton cores of ULDM

Going beyond standard searches

- Gravitational probes (e.g. stellar kinematics)
  $\rightarrow$ Robust, model-independent constraints
- State-of-the-art experiments (EHT, GRAVITY)
  $\rightarrow$ New avenues for DM searches

Thank you for your attention!