

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

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!nterTalentum



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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
 - less model-dependent
 - e.g. probe WIMPs, ultralight DM

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

Adiabatic contraction of a DM halo

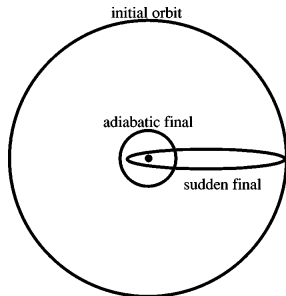
Adiabatic invariants

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

⇒ contraction of the DM halo
⇒ **"spike"** (Gondolo & Silk 1999)

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

⇒ Strong signatures



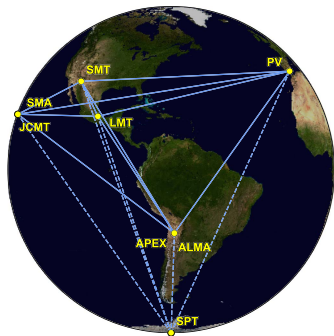
Ullio+ 2001

Theoretical uncertainties

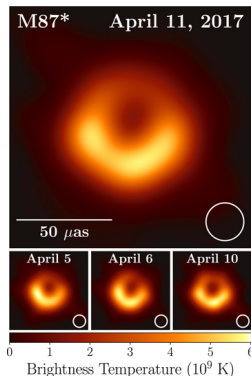
- No direct observations
- Dynamical processes
- **But** survival more likely in dynamically young galaxies (M87)

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



EHT Collaboration 2019, L1

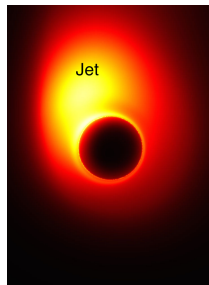
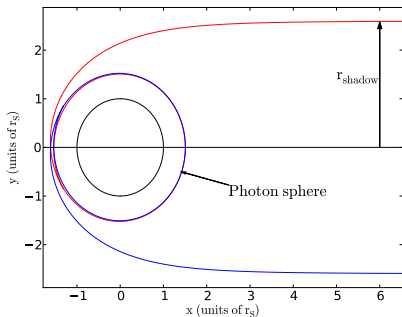


EHT Collaboration 2019, L1

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, $r_{\text{shadow}} \approx 2.6R_S$
- SMBH M87* at the center of M87:
angular diameter $\sim 40 \mu\text{s}$
 \Rightarrow prime target of the EHT



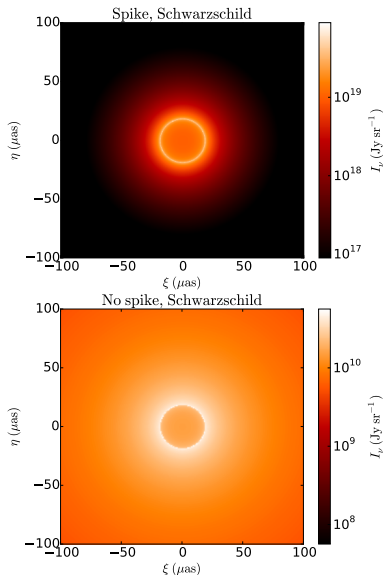
Simulation; credit: Avery E. Broderick (University of Waterloo/Perimeter Institute)

Creating simulated maps of the DM-induced synchrotron intensity

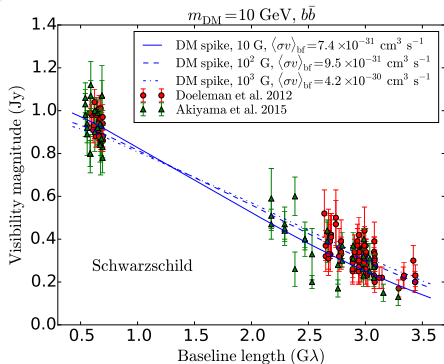
DM-induced synchrotron intensity maps

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

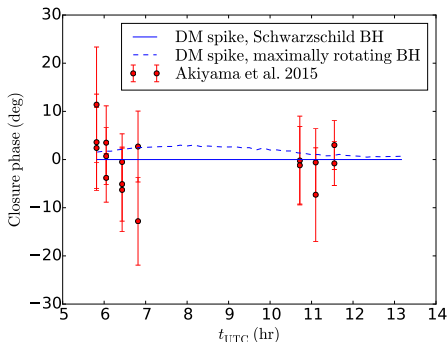
Lacroix+ 2017



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...

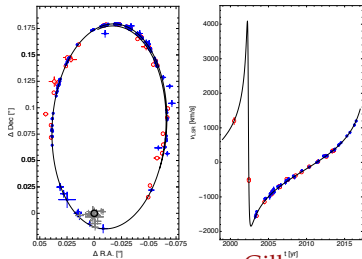
Kinematics of the S2 star at the center of the Milky Way

Quantify effect of DM spike on orbit of S2 \rightarrow Newtonian precession

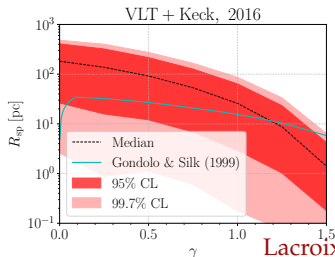
Orbit-fitting procedure

- Numerically solve equations of motion
- Reconstruct orbit as a function of time
- First direct constraints on spike parameters from S2 orbit
- Direct probe of adiabatic spike

Improvement expected with GRAVITY data



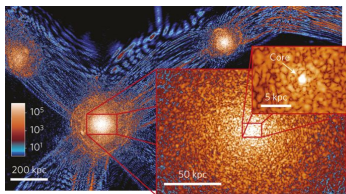
Gillessen+ 2017



Lacroix 2018

Probing ultralight DM

- Alternative to thermally produced non-relativistic massive DM candidates like WIMPs
- ULDM & challenges of CDM on galactic scales
- ULDM expected to form cored density profiles (solitons)
- Dedicated numerical (DM-only) simulations
→ CDM at large scales, cores at the centers of halos



Schive+ 2014

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

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

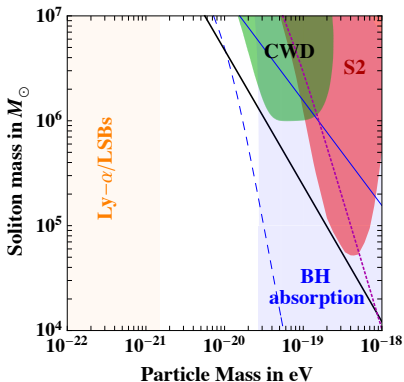
ULDM solitons: constraints from S2 orbit

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)

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 (in principle)

Going beyond standard searches

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

Thank you for your attention!

ULDM solitons: constraints from EHT data

EHT & stellar kinematics

- EHT measurement of gravitational radius of M87*

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

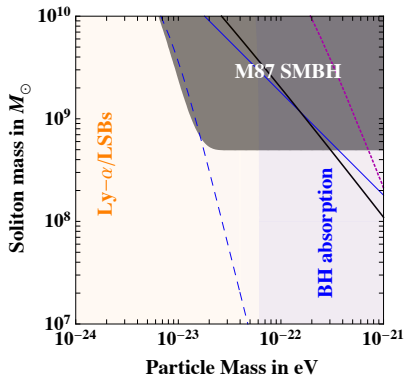
EHT Collaboration 2019, L1

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

Gebhardt+ 2011

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

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Caveats

Same as before