Massive Black Holes & Galaxies: Experimental Evidence & Cosmic Evolution

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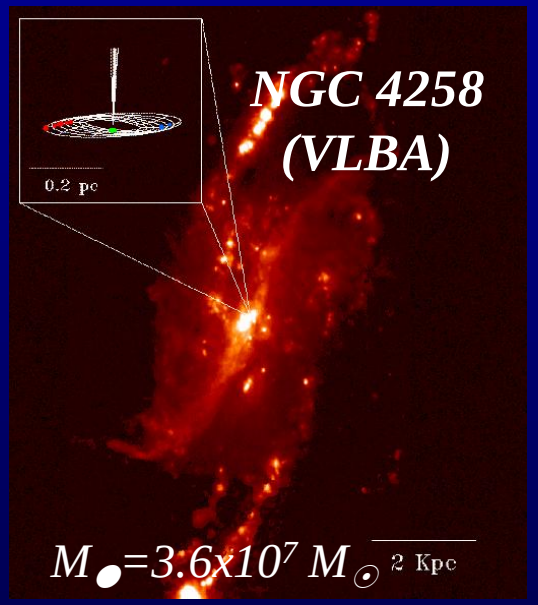
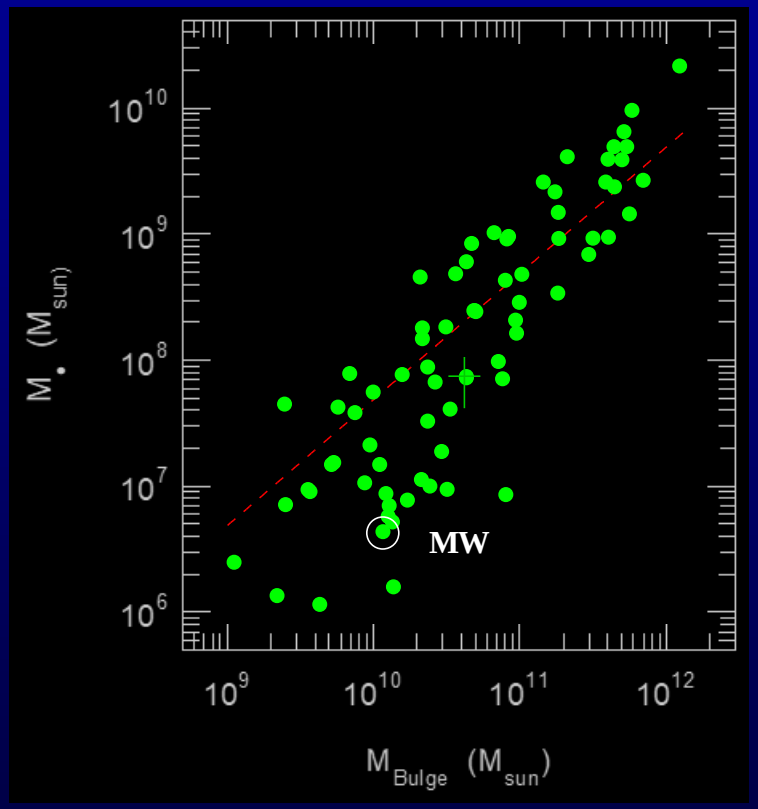
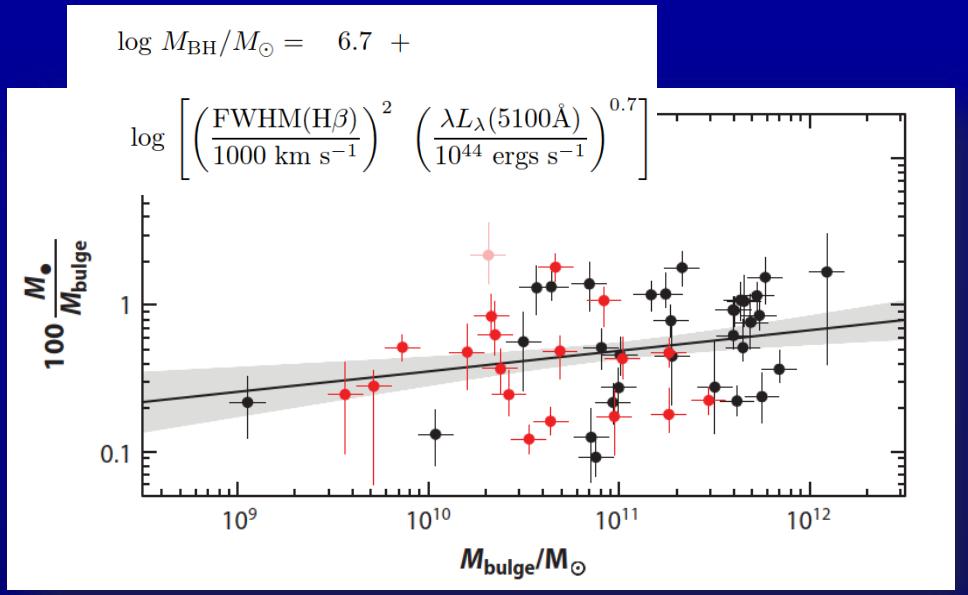
MPE, UCB & LMU

Conference in honor of my long-time colleague, friend and collaborator, Thijs de Grauuw

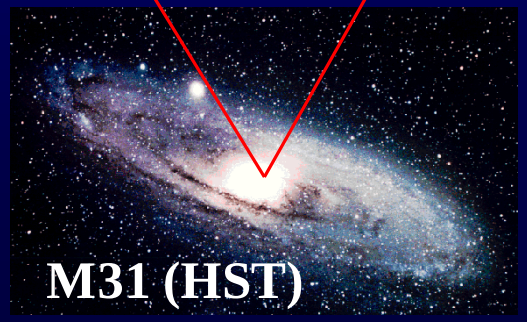
Demographics of central mass concentrations in wxternal galaxies/AGN





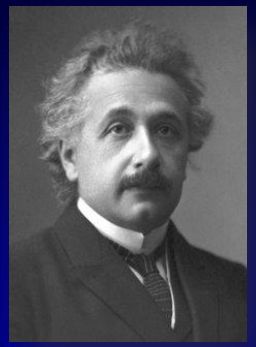


$M_\bullet/M_{bulge} \sim 2\text{-}5 \times 10^{-3}$



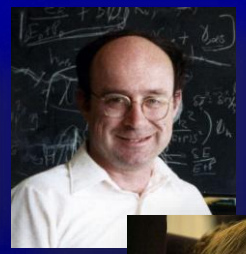
Bender, Faber, Fabian, Ferrarese, Filippenko, Ford, Gebhardt, Greene, Greenhill, Ho, Kormendy, Nandra, Ma, McConnell, Moran, Merritt, Myoshi, Saglia, Thomas, Tanaka, Tremaine 1995-2023

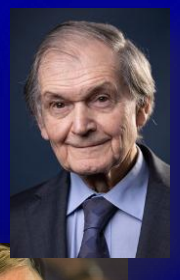
What if not a Black Hole?

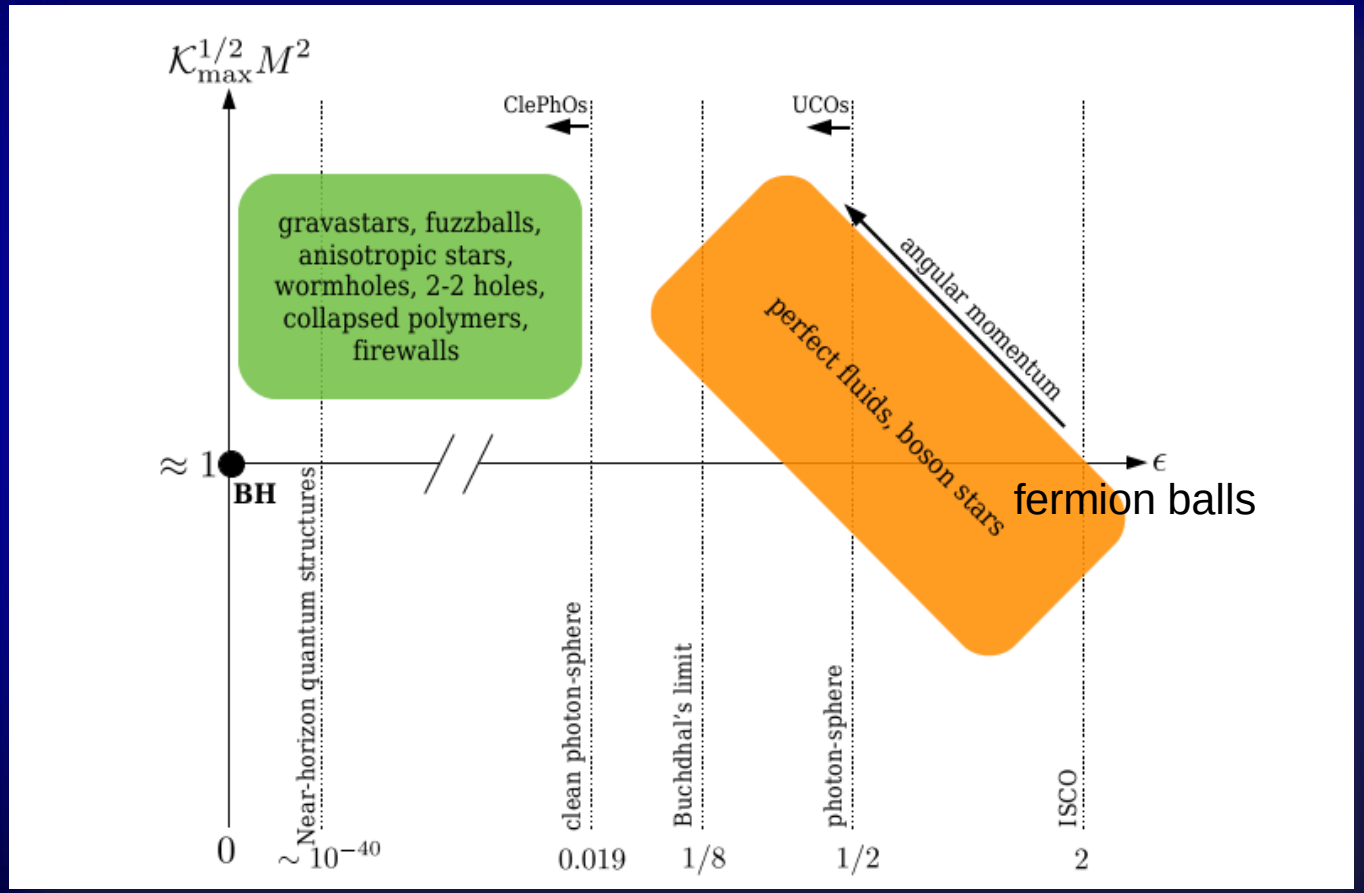


measure of compactness

$$\varepsilon_{\text{spherically symmetric}} = \left[1 - \left(\frac{2GM}{Rc^2}\right)\right]$$



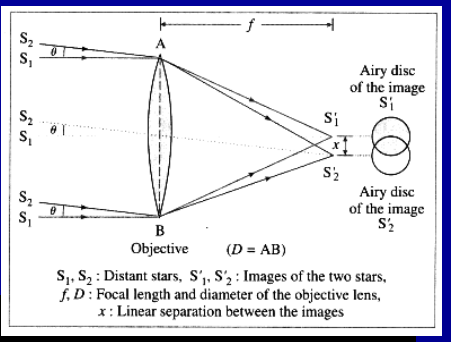


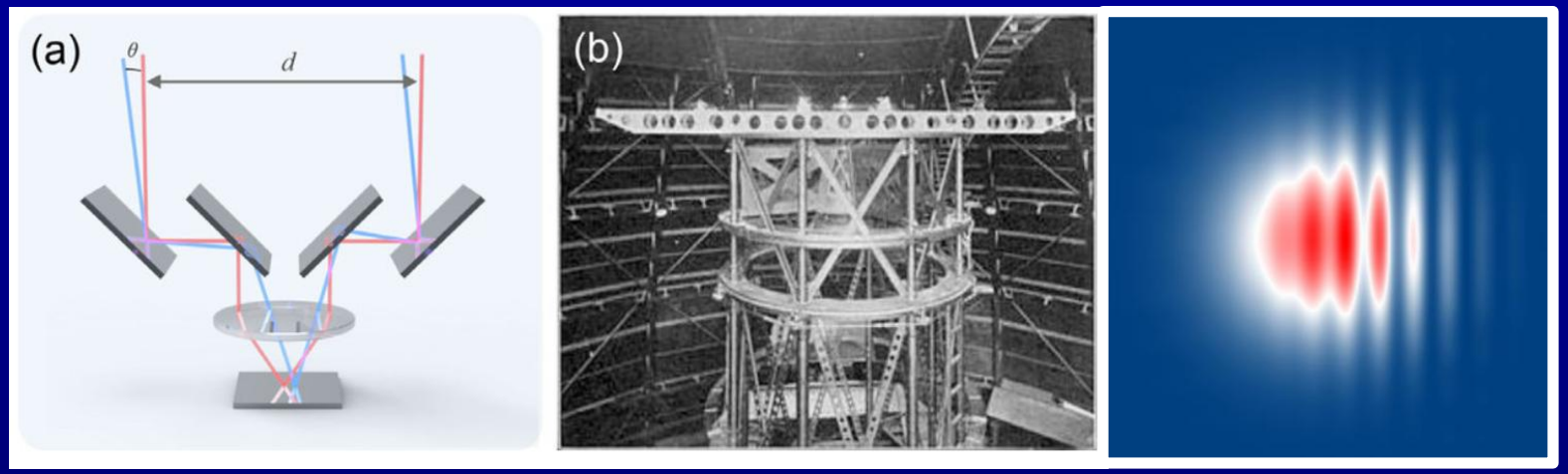


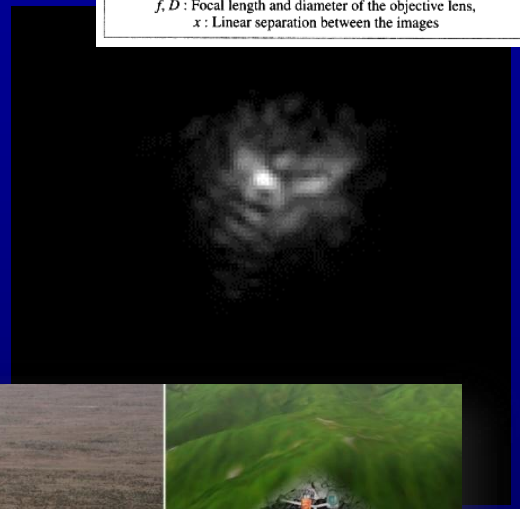
***spherical**: Schwarzschild 1916, **spin**: Kerr 1963, critical curvature: Penrose 1965, **charge**: Newman 1965, **no hair**: Israel, Carter, Robinson, Wheeler & Bekenstein 1965-1967, **photon orbit:** Bardeen 1972, Cardoso & Pani 2019, Psaltis 2023, Arguelles et al. 2018, 2023*

Interferometry & Adaptive Optics

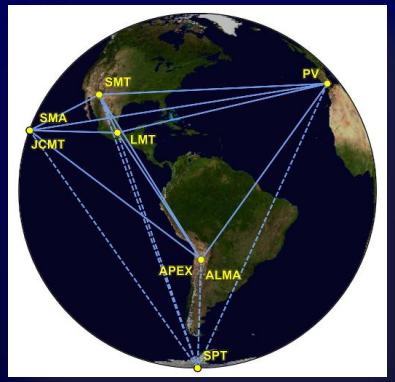
$\Theta \sim \lambda/D$







Young 1804, Michelson & Morley 1887, Michelson & Pease 1922, Thompson et al. 1980

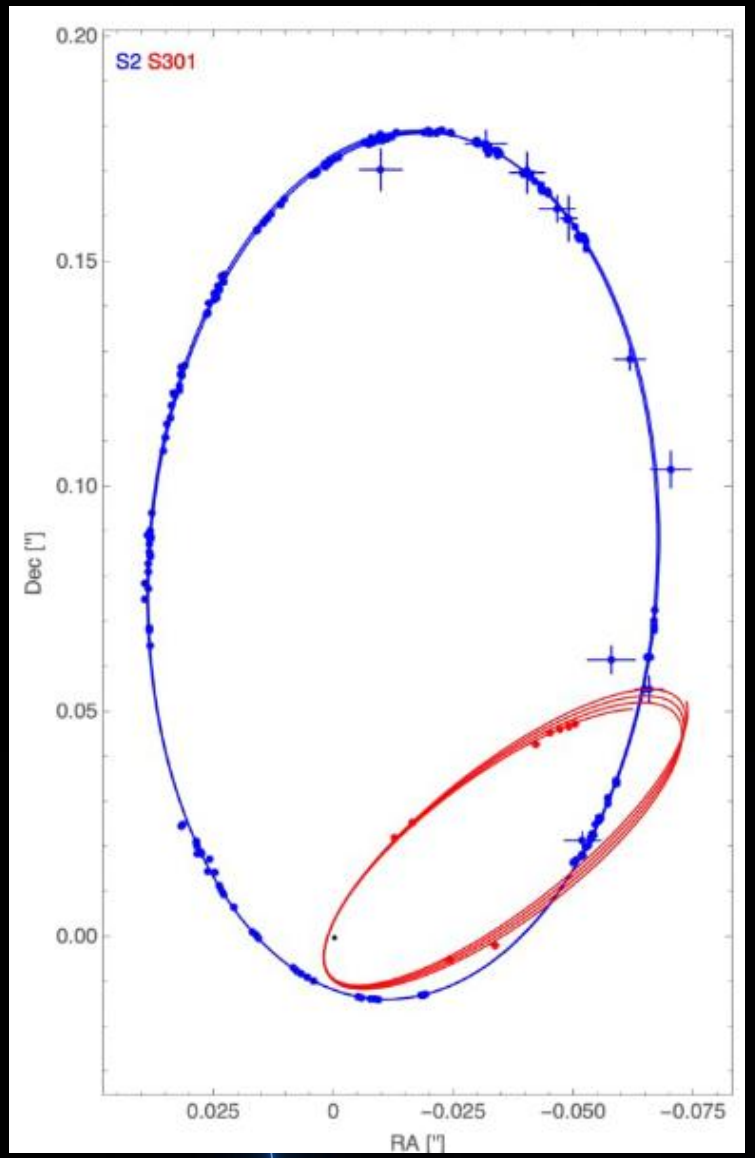


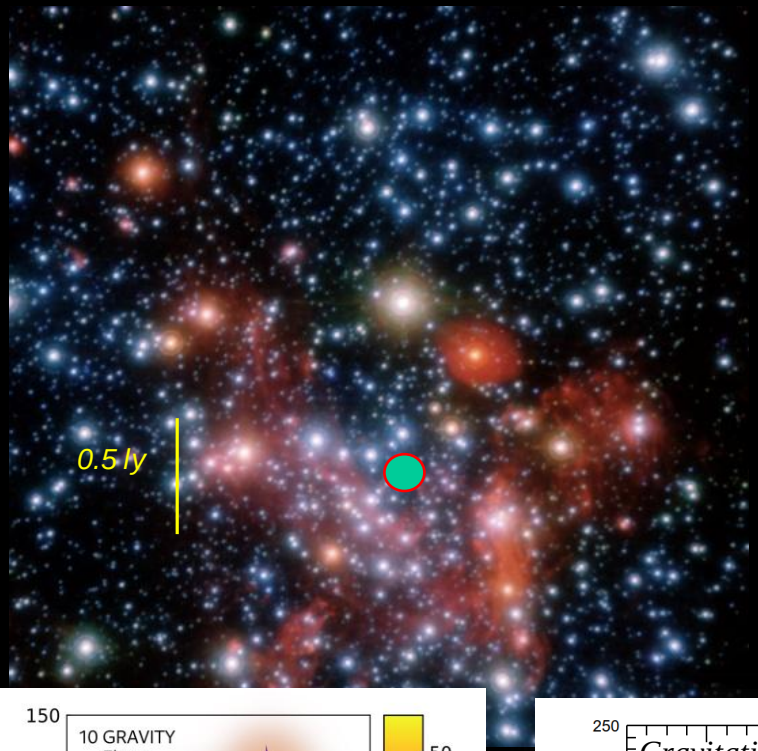
The Event Horizon VLBI Telescope (1mm, L=10,000 km/s resolution 25μarcsec)

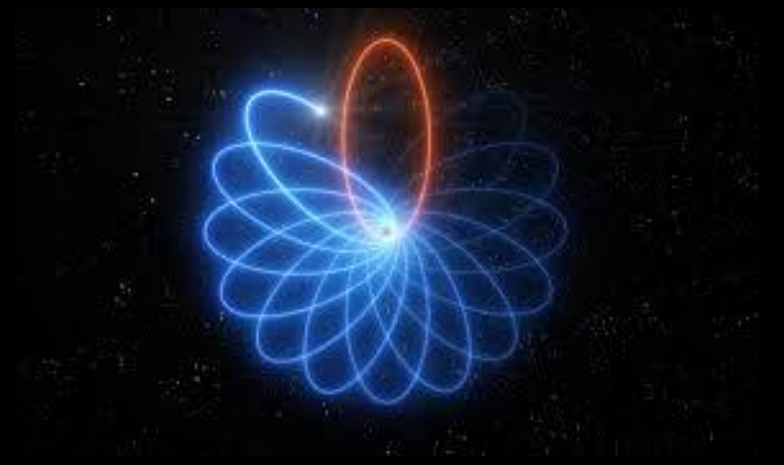
GRAVITY @ ESO VLT-Interferometer (2μm) (L=130 m, astrometric precision 10μarcsec)

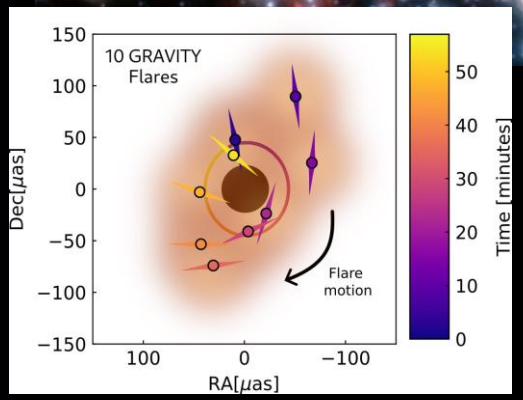
The LIGO-VIRGO-KARGA Gravitational Observatories

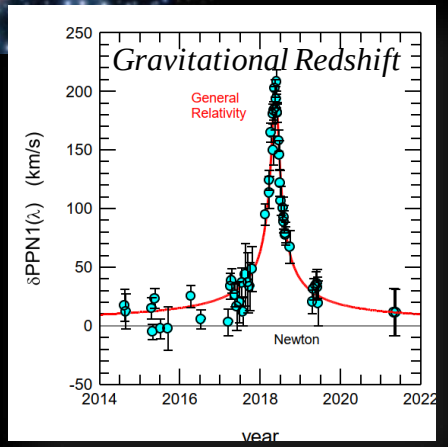
The Galactic Center Laboratory

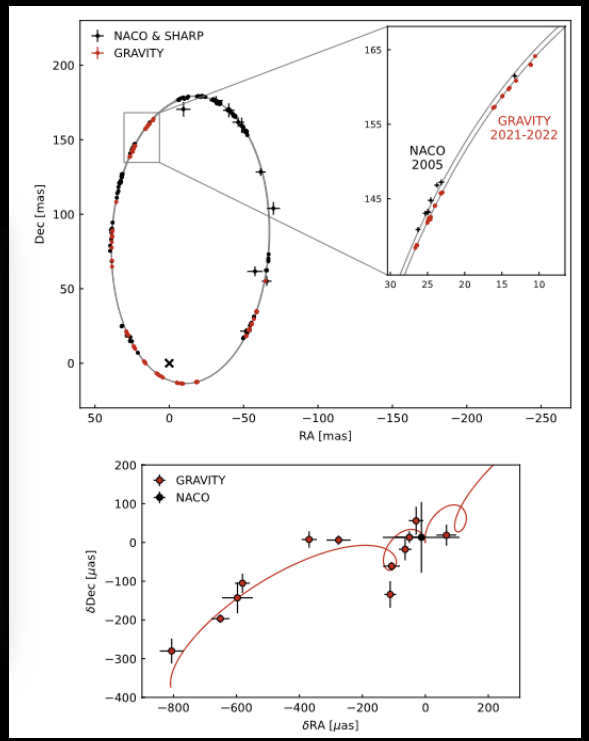










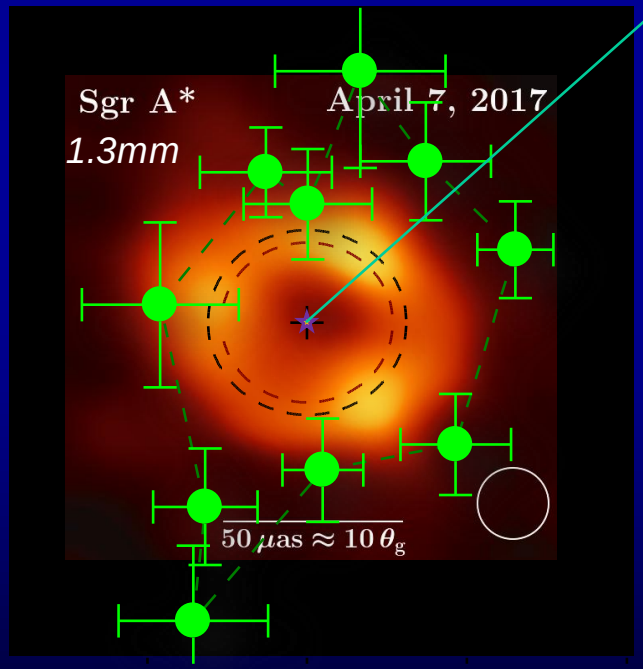


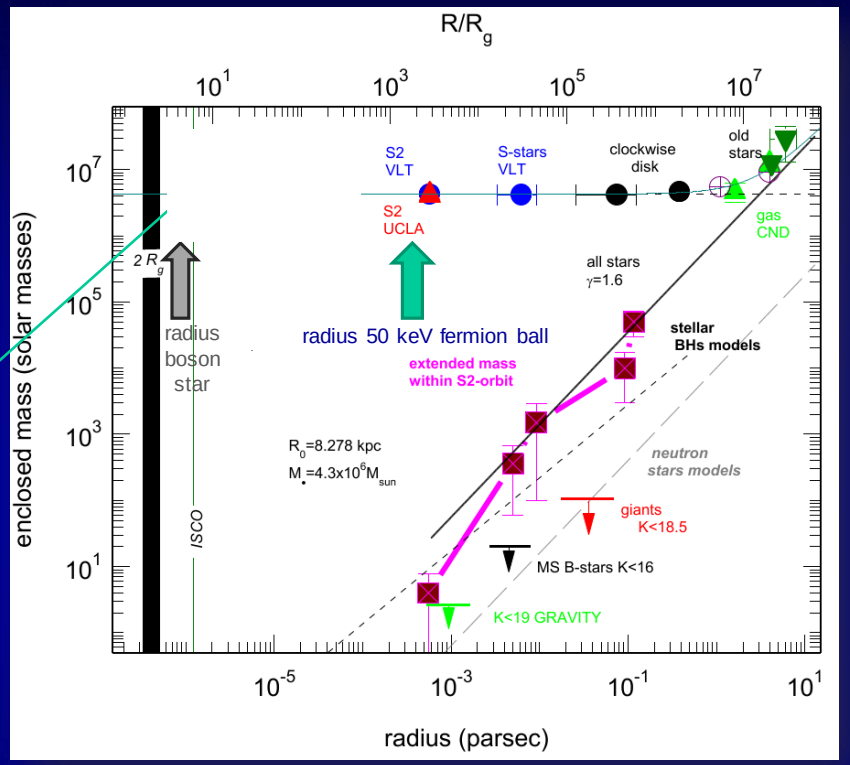
Schoedel et al. 2003, Ghez et al. 2003, 2008, Gillessen et al. 2009, 2017, Boehle et al. 2016, GRAVITY collaboration 2019a, 2020, 2022b, 2023b, 2024, Do et al. 2019, UCLA 2024 in prep.

Derived Mass Distribution: BH or DM-Ball?

MPE- (SHARP@NTT (1992-2002), NACO&GRAVITY@VLT) (2001-2023) NIRC&OSIRIS @ Keck

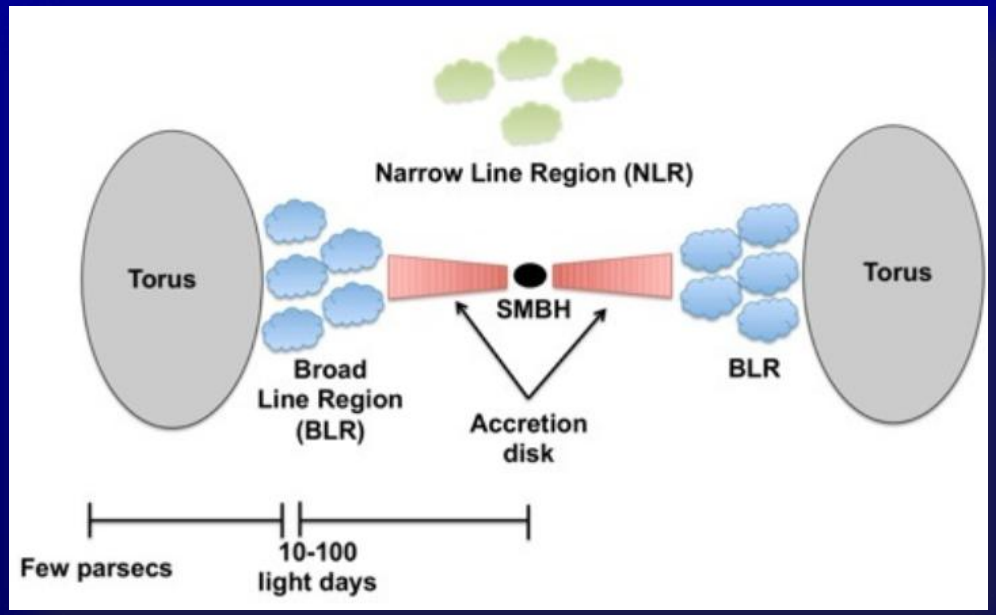
$M_\bullet$=4.299 (±0.012, ±0.020)×10^6 $M_\odot$
R_0=8275 (±8, ±15) pc





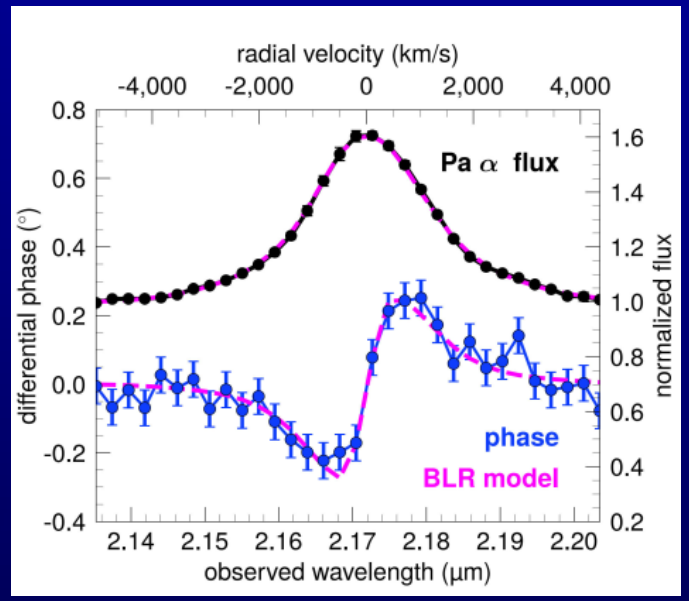
Genzel et al. 2010, Gillessen et al. 2019, Do et al. 2019, GRAVITY Collaboration 2022, 2023, 2024a,b , EHT Collaboration 2022, Sadun Bordoni et al. 2025

Resolved MBH Studies of AGN



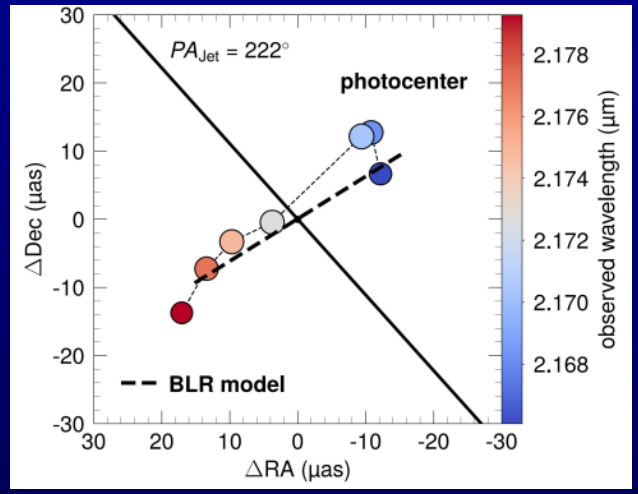
AGN MBH mass measurements:
Reverberation mapping & calibration
L_{5000}-$\Delta v \rightarrow M_{BH}$

3C 273 z=0.16



R_{BLR} =0.18 pc (46 μas)

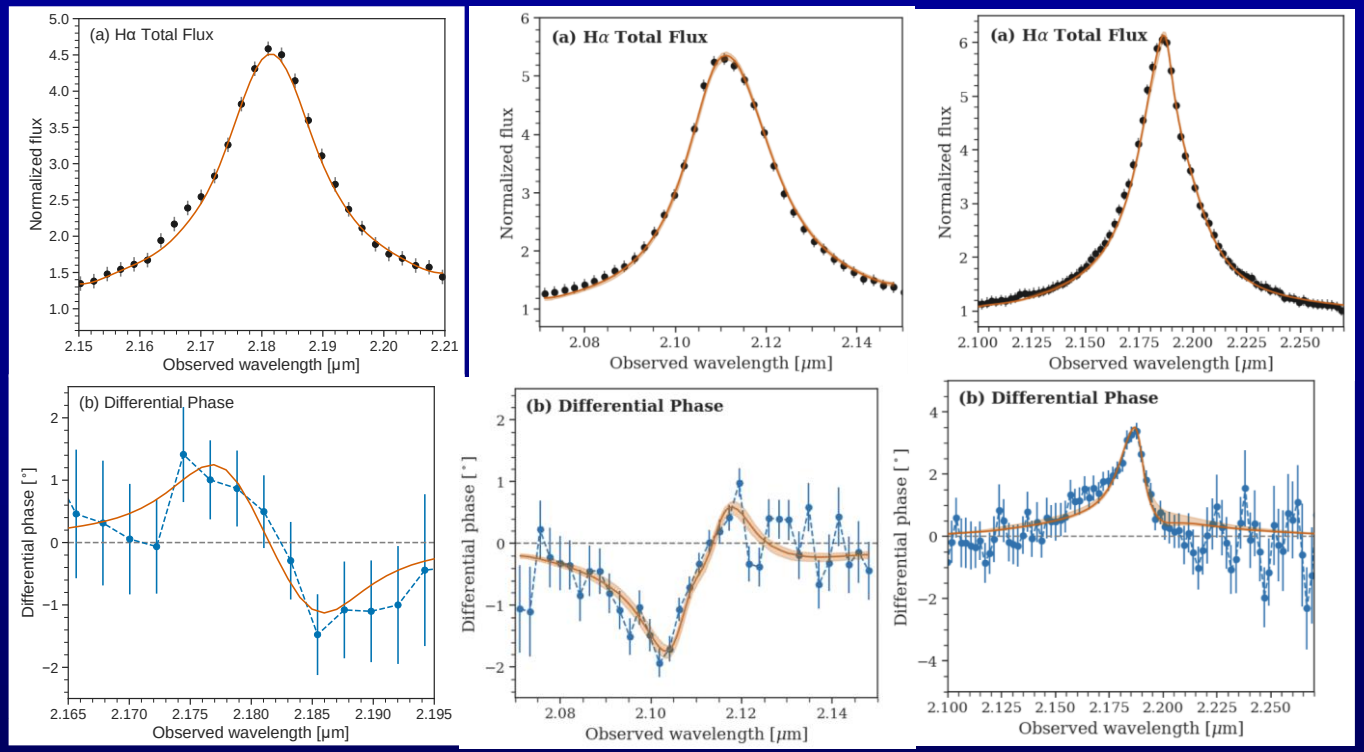
Spatially resolved Spectoscopy with Interferometry

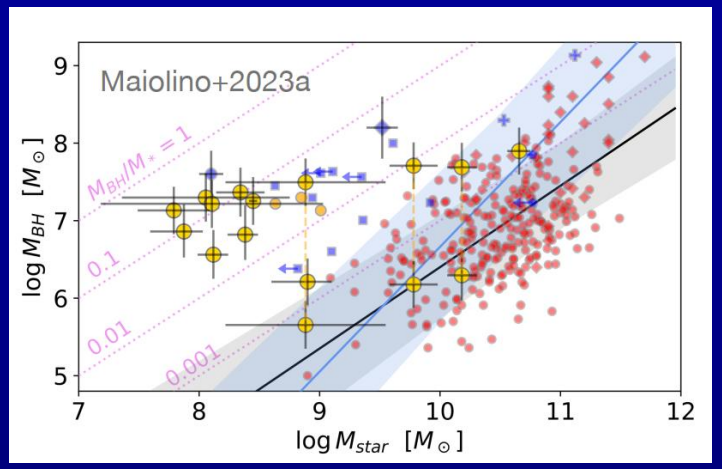


$\log M_{BH} = 8.41 \pm 0.18\ M_{\odot}$

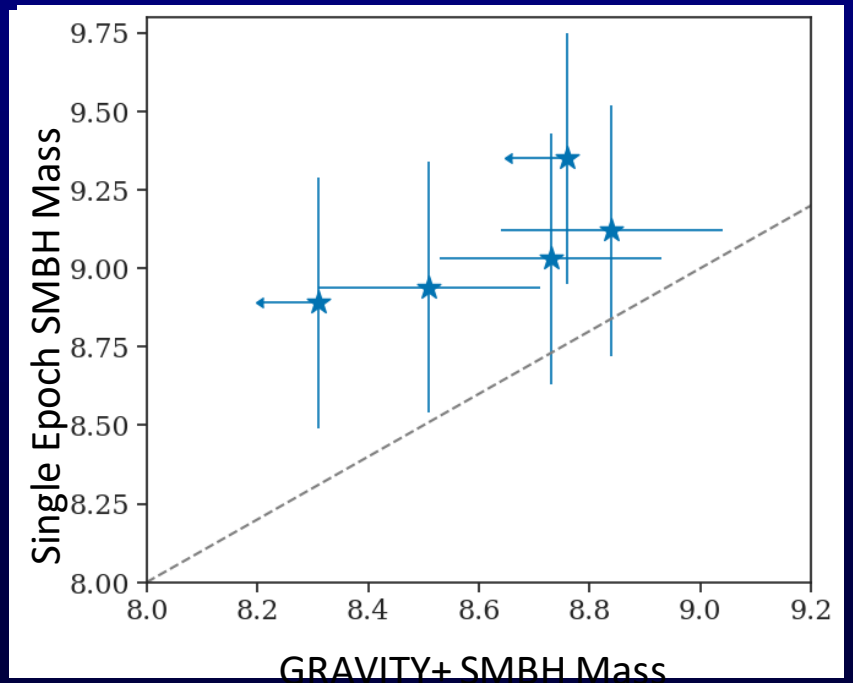
Blandford & McKee 1982, Kaspi et al. 2000, Vestergaard 2004, 2008, Bentz et al. 2099, 2011, 2013, Gebhardt et al. 2001, Ferrarese & Merritt 2001, Alexander & Hickox 2012, Kormendy & Ho 2013, McConnell & Ma 2013, Peterson et al. 2014, Saglia et al. 2016,GRAVITY Collaboration 2018c, 2024

Dynamical SMBH masses at high z with JWST & GRAVITY+



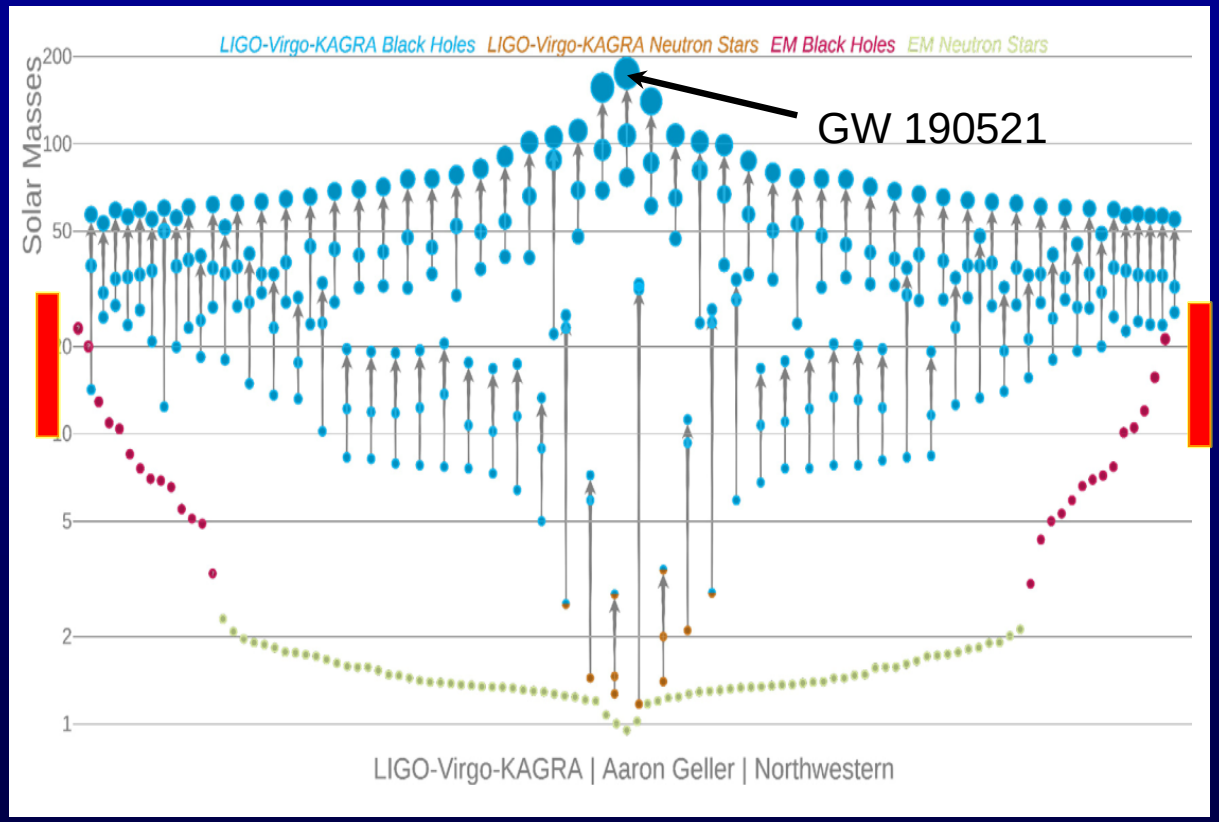


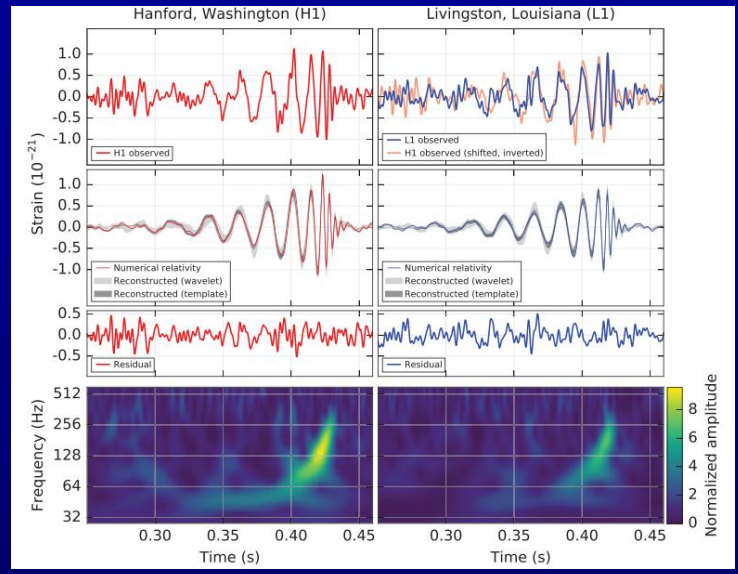
- 5 deep observations of z ~ 2 quasars with GRAVITY+ with 3 significant detections



Abuter et al. (2024), GRAVITY+ Collaboration et al. (in prep, Shimizu, Shanguang)

Intermediate & Stellar BHs: LIGO-VIRGO-GWTC-3-Status Binary In-spirals 2021

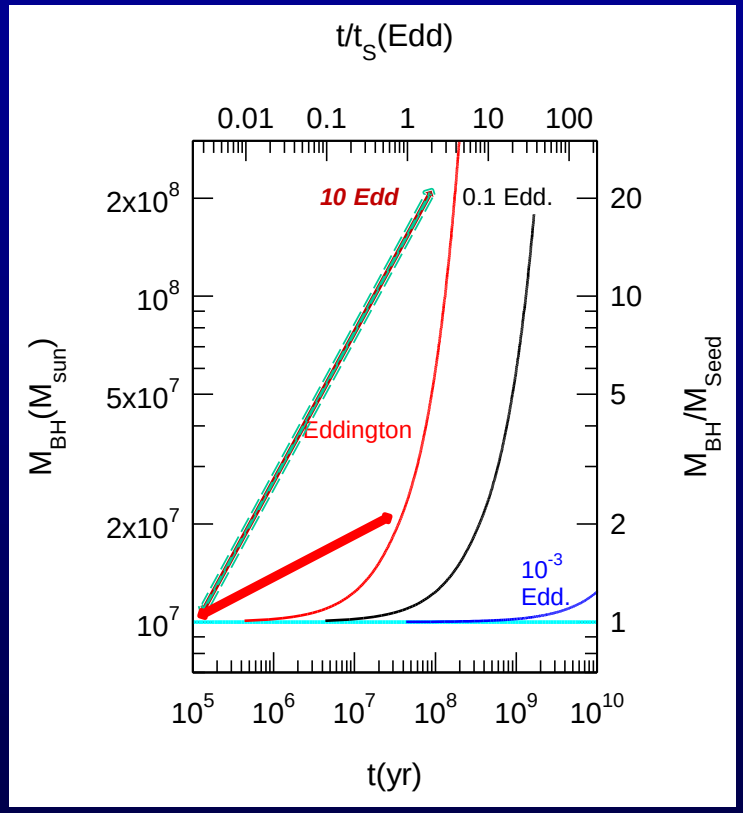




- Multiple SBH mergers in dense environments
- Growth by accretion as in MBH-AGN
- Primordial -IMBH

Abbott et al. 2020, 2021, Woosley 2017, Woosley & Heger 2021, Carr et al. 2024

The Riddle of Early Growth



Eddington limited, radiatively efficient accretion:

$M_0=10^2 M_\odot$, $M=10^9 M_\odot$, $\eta=0.2$, $L=L_{edd}$

$\rightarrow t_M=1.8\times10^9$ yr, $z < 3$-4 !

$>10^8\ M_\odot$ MBHs at z>4…..12

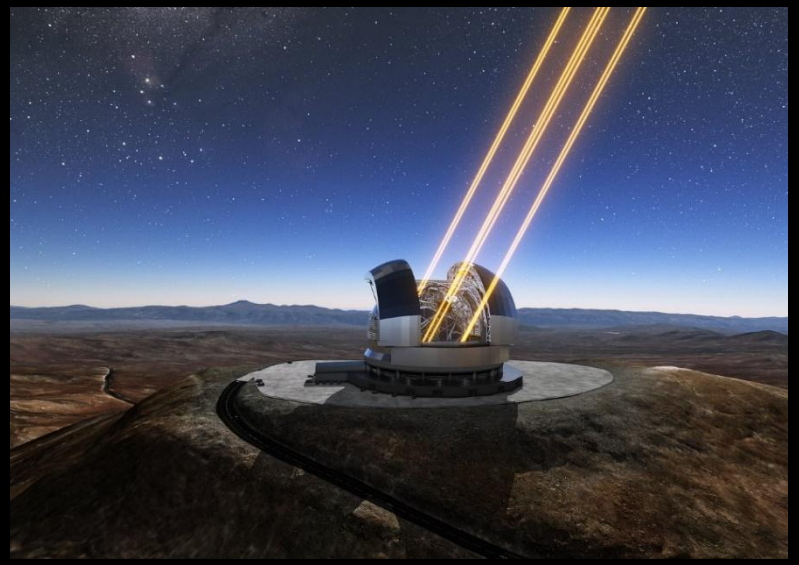
→ heavy seeds (quasi-stars), very low metallicity Pop III stars

→ super-Eddington accretion

→ low radiation efficiency

→ enhanced tidal stellar disruption

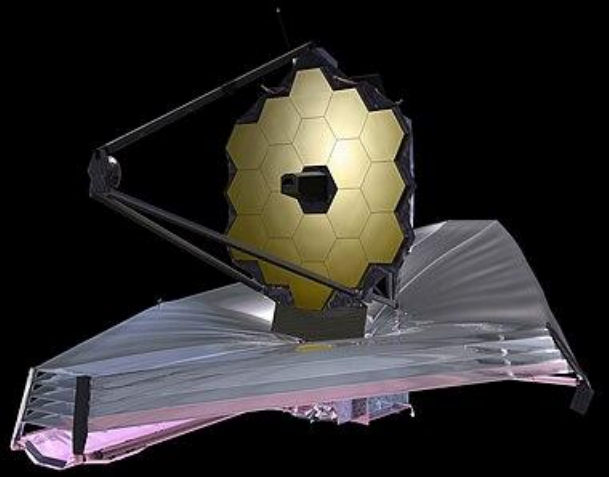
Maiolino et al. 2023, 2024



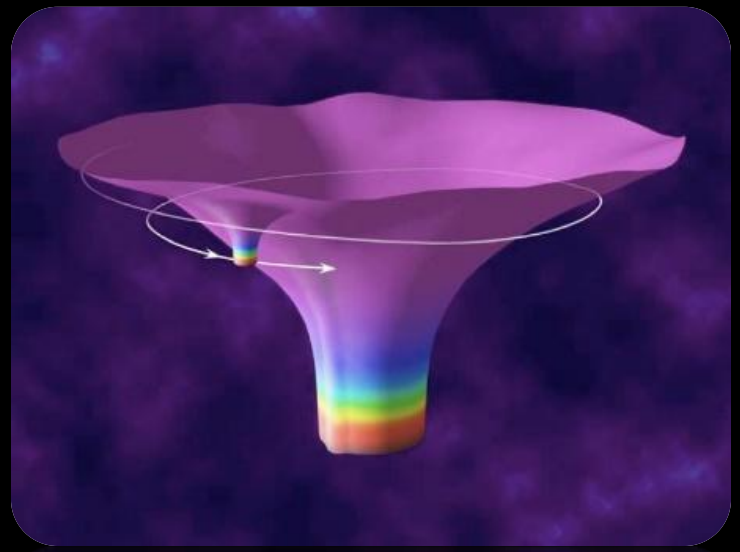
ESO's ELT

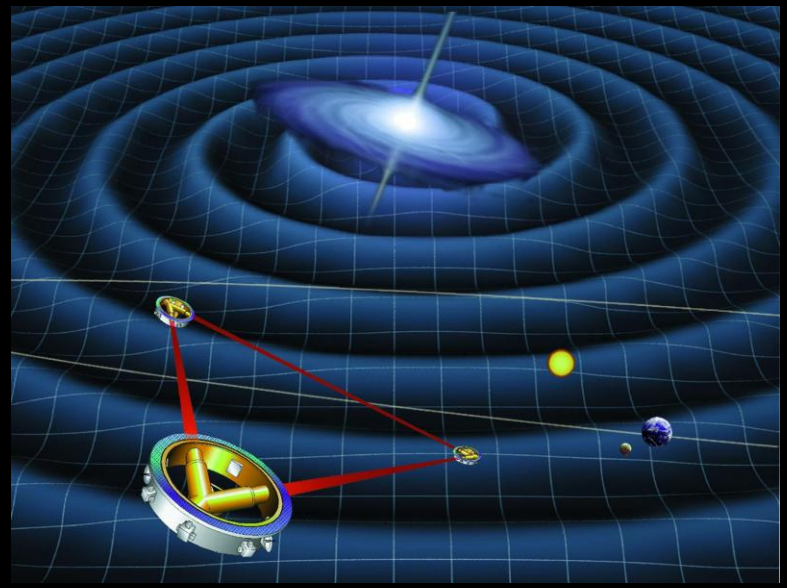
What about the Future?

$$\left(\frac{q}{M}\right) = -a^2 \quad \text{(no hair)}$$



James Webb Telscope NASA





LISA Mission of ESA

Apropos: can someone explain what these black holes are good for?

P.Samson & O. Williams, Best Short Film, Cannes 2008