Supermassive Black Holes: from Conventional Telescopes to Interferometers

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In collaboration with:
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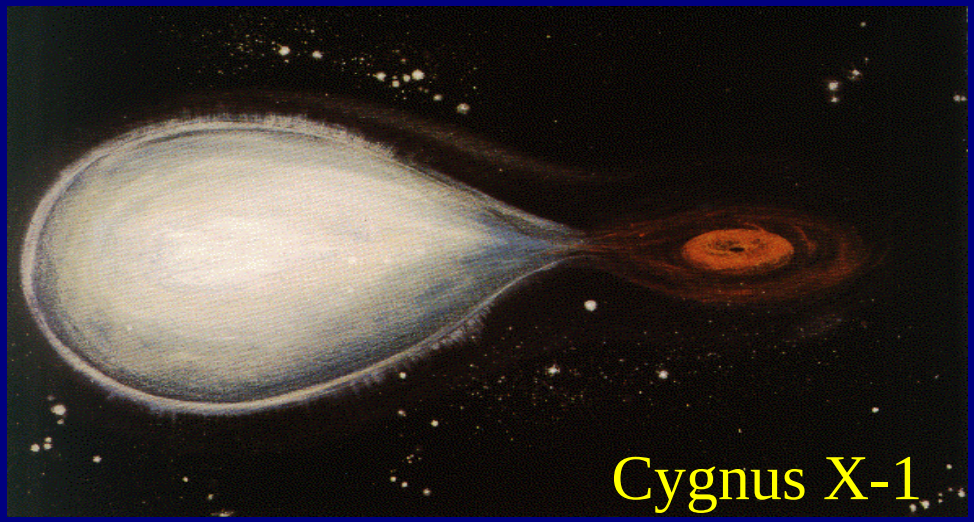
What types of BHs?

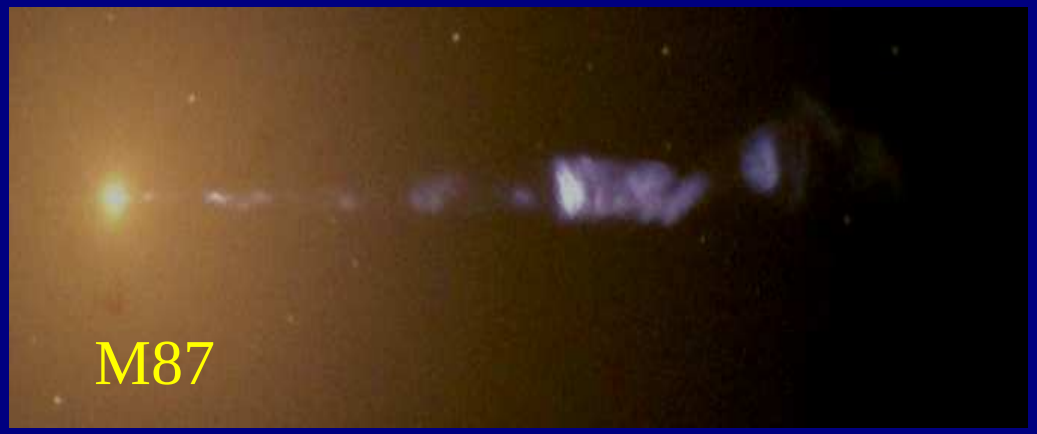
Stellar mass Black Holes

(~1-10 $M_\odot$)

- endpoints of the life of massive stars



Intermediate Mass Black Holes (~10^2-10^5 $M_\odot$) ???



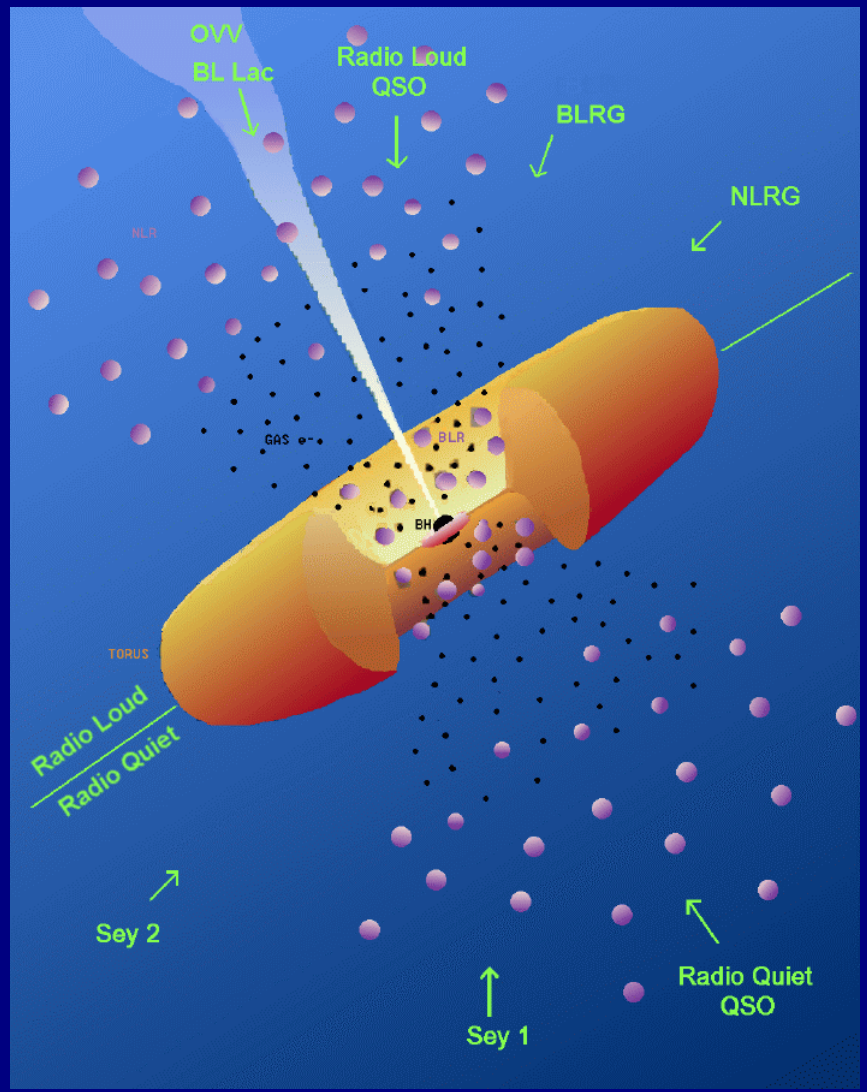
Supermassive Black Holes

(~10^6-10^9 $M_\odot$)

- in galactic nuclei

Why Supermassive Black Holes (10^6-10^9 $M_\odot$) in Galactic Nuclei?

- Accretion onto a massive BH is the powering mechanism of Active Galactic Nuclei (e.g. Salpeter 1964, Zel'dovich 1964)
- Observed evolution of AGNs (at z~2-3 luminous quasars where ~2 orders of magnitude more numerous than they are now)
- Significant fraction of quiescent luminous galaxies should host a BH in their nuclei as a relic of AGN activity.

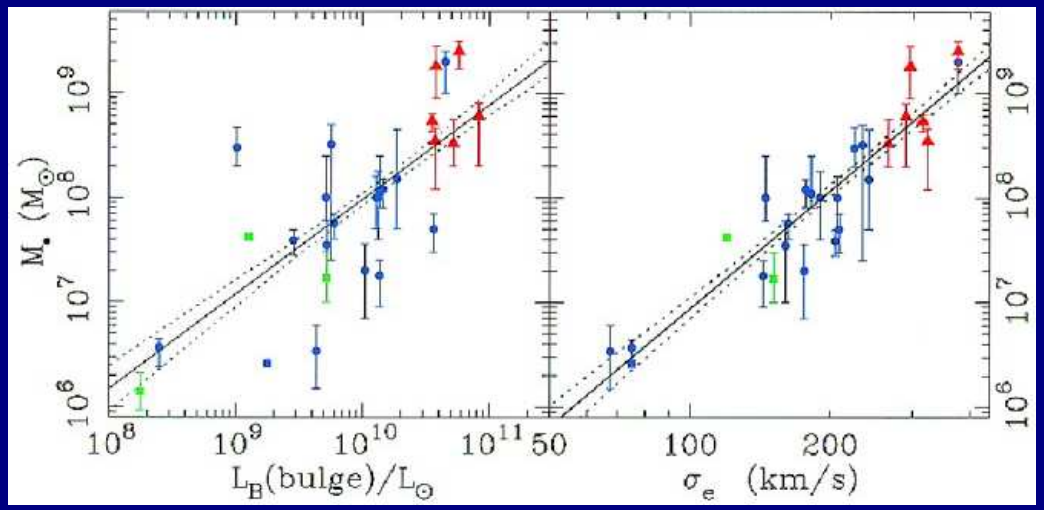


Overview of current status

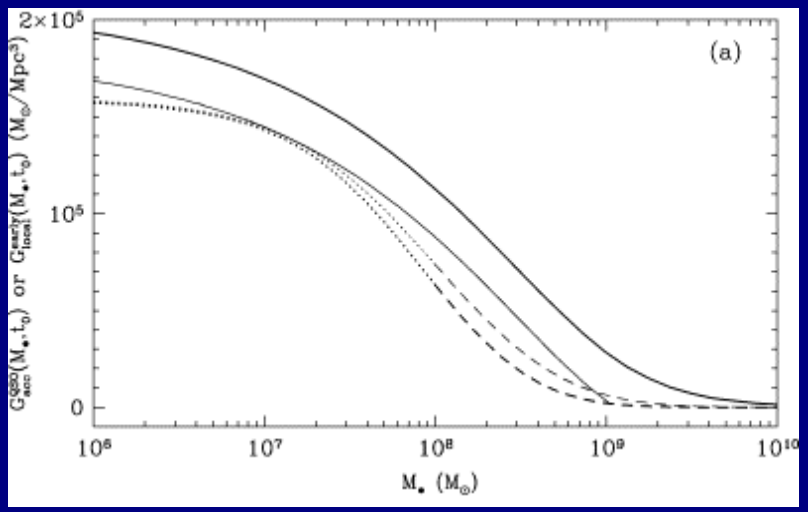
1) Current Observational Evidence is consistent with the hypothesis that Massive Black Holes are present in all galaxies but only ~30-40 BH's are detected (e.g. Kormendy & Gebhardt 2001, Merritt & Ferrarese 2001).

2) M_{BH} correlates with spheroid (bulge) luminosity/mass and, more tightly, with the stellar velocity dispersion (Kormendy & Richstone 1995, Ferrarese & Merritt 2000, Gebhardt et al. 2000, Tremaine et al. 2002)

3) There is apparently a discrepancy between the massive local BH's and what is expected from AGN activity (Yu & Tremaine 2002, Ferrarese 2002)



Gebhardt et al. 2000



Yu & Tremaine 2002

Research on Supermassive BHs in Arcetri

1) Detection and Measurement of BH masses

   (Several ongoing programs with HST/STIS and VLT/ISAAC/FORS).

2) Relations BH Mass – Host galaxy properties.

3) Demography of BH's and Relation with AGN activity.

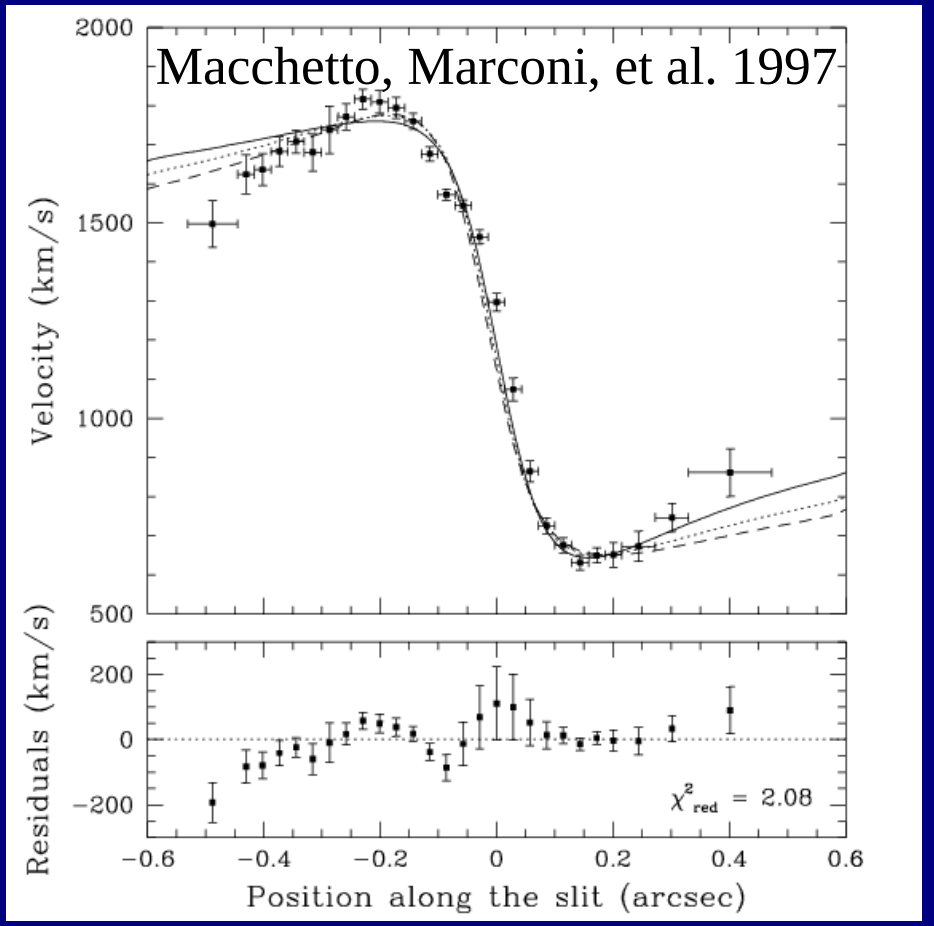
4) Future developments: Optical Interferometry

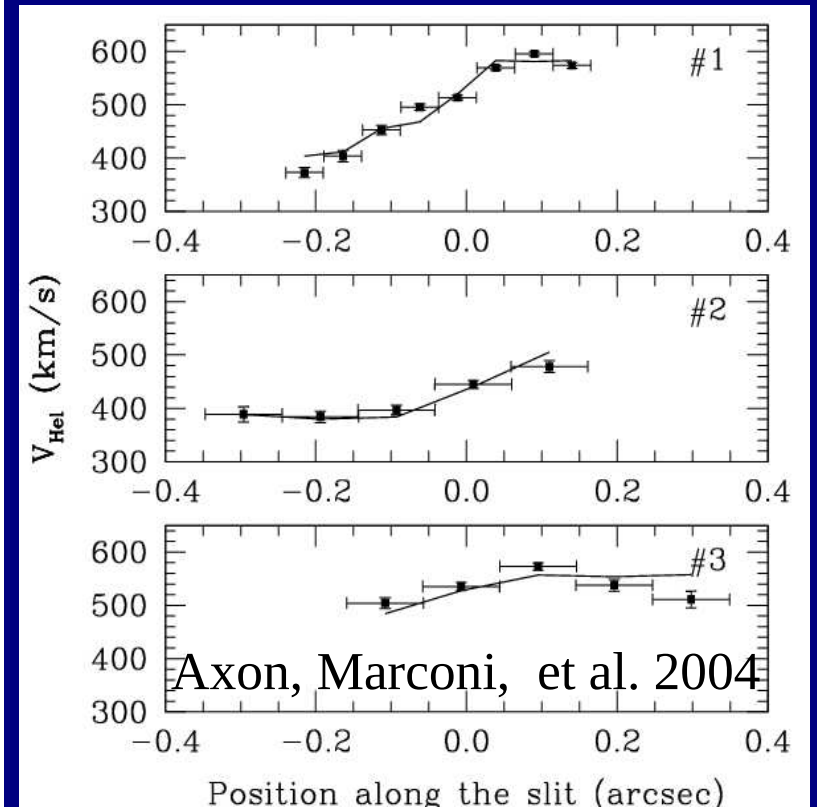
   (GTO with VLTI/AMBER, LBT).

1) Detection of BH's in galactic nuclei and measurement of their masses with gas kinematics.

Highlights from HST

M87: first longslit spectrum from HST (FOC); $M_{BH}=(3.2 \pm 0.9) \times 10^9 M_\odot$





NGC 4258: 2° best case for a BH (kin. of H_2O masers $M_{BH} = 4\times10^7 M_\odot$; Miyoshi et al. 1995) is a crucial test for the gas kinematical method! Our HST observations find $M_{BH}= 4^{+4}_{-2} \times10^7 M_\odot$ in agreement with maser data!

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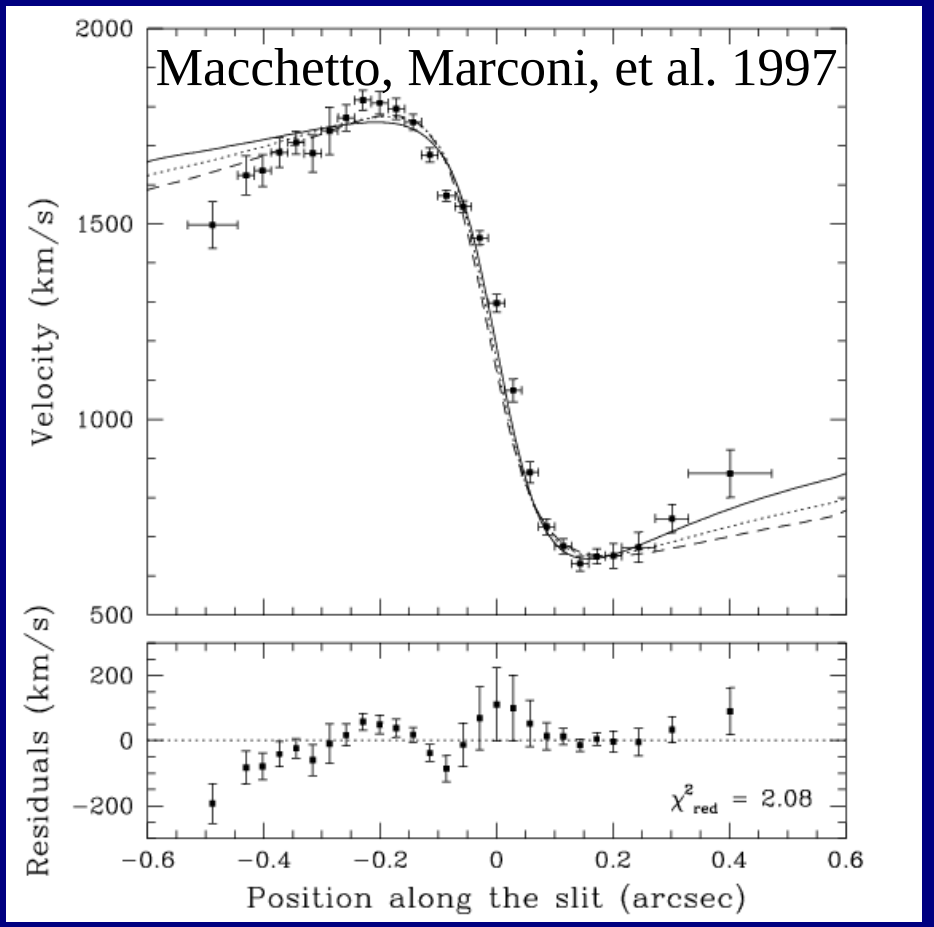
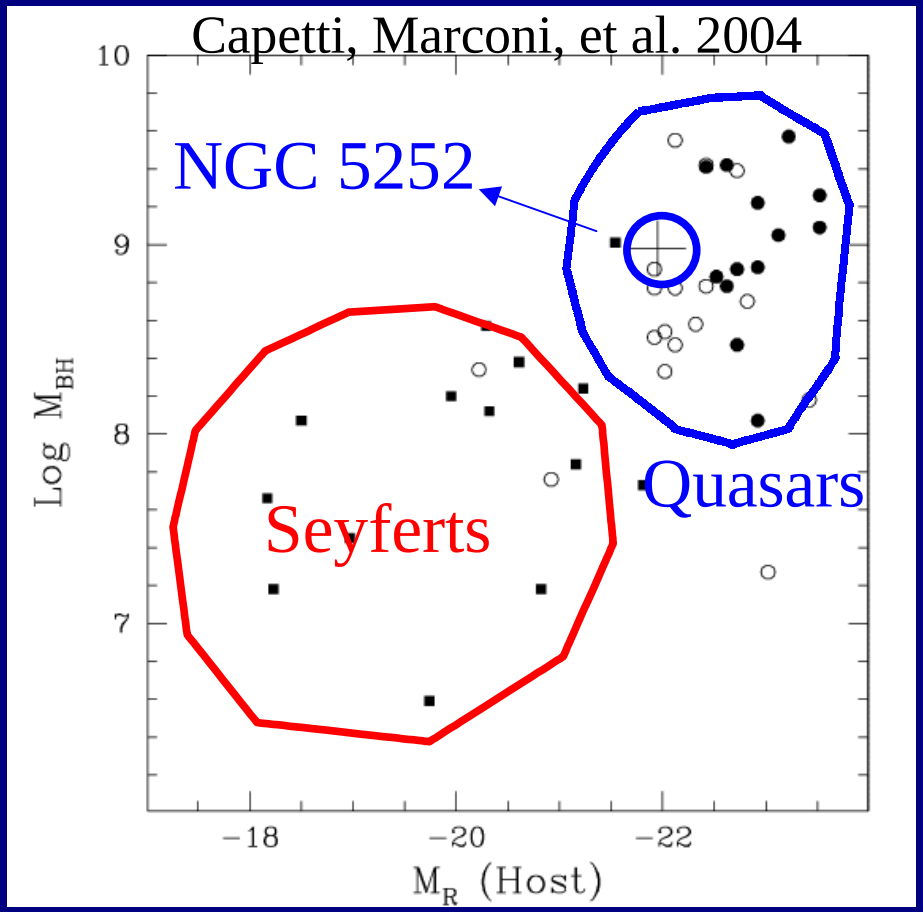


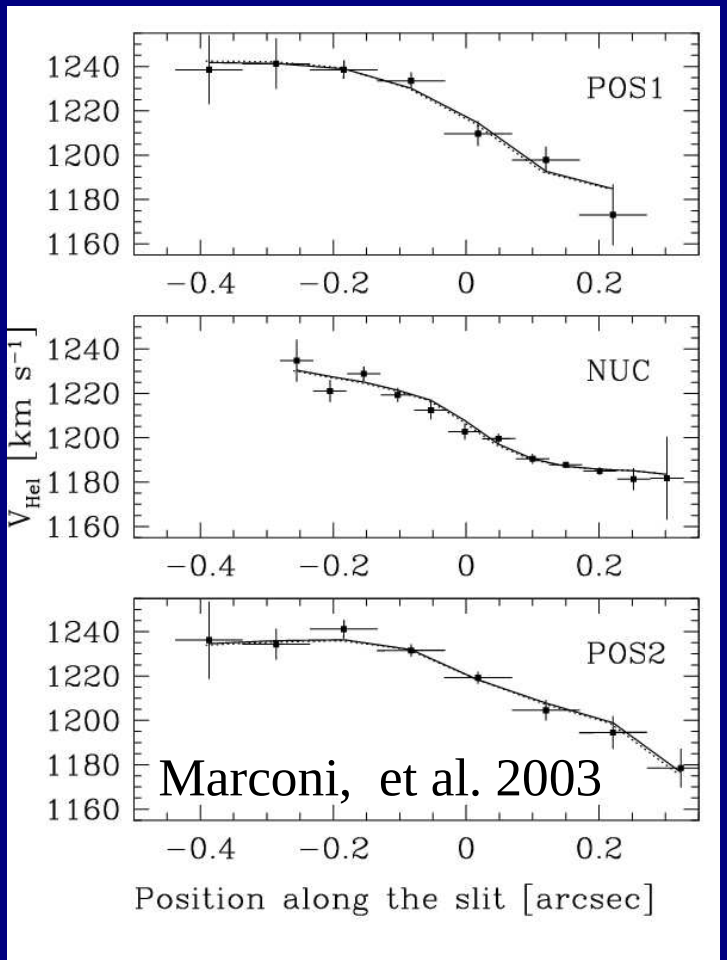


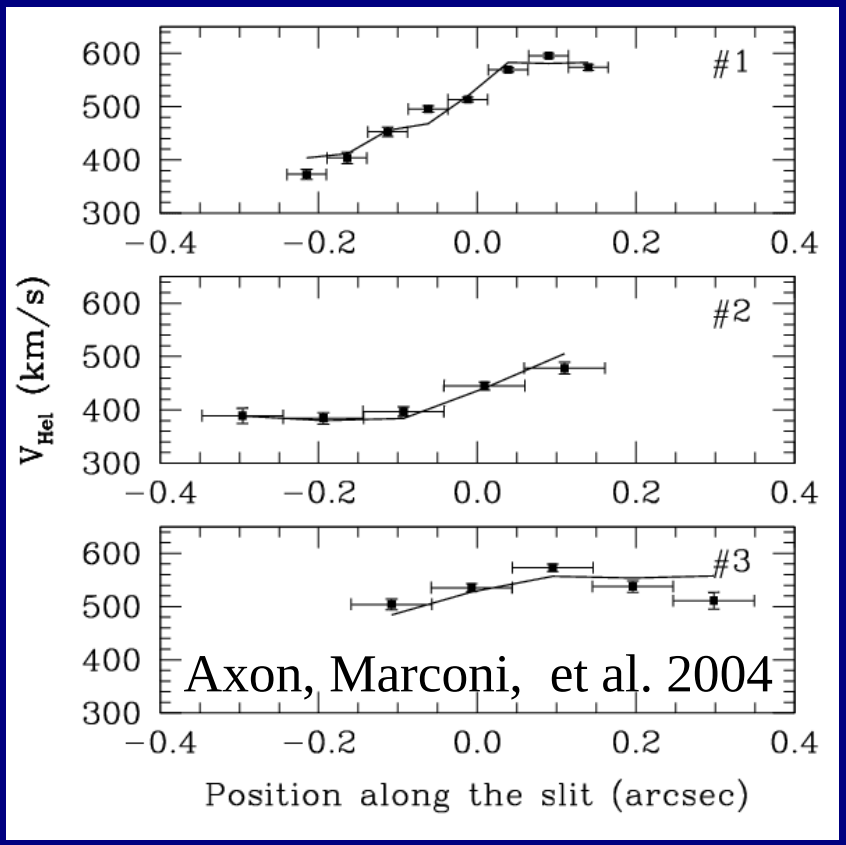
NGC 5252: pure Seyfert 2 but hosting a quasar relic (big BH but low L output)

$M_{BH} = 1\ ^{+1.5}_{-0.4} \times 10^9 M_\odot$ (HST+STIS)

Highlights from HST

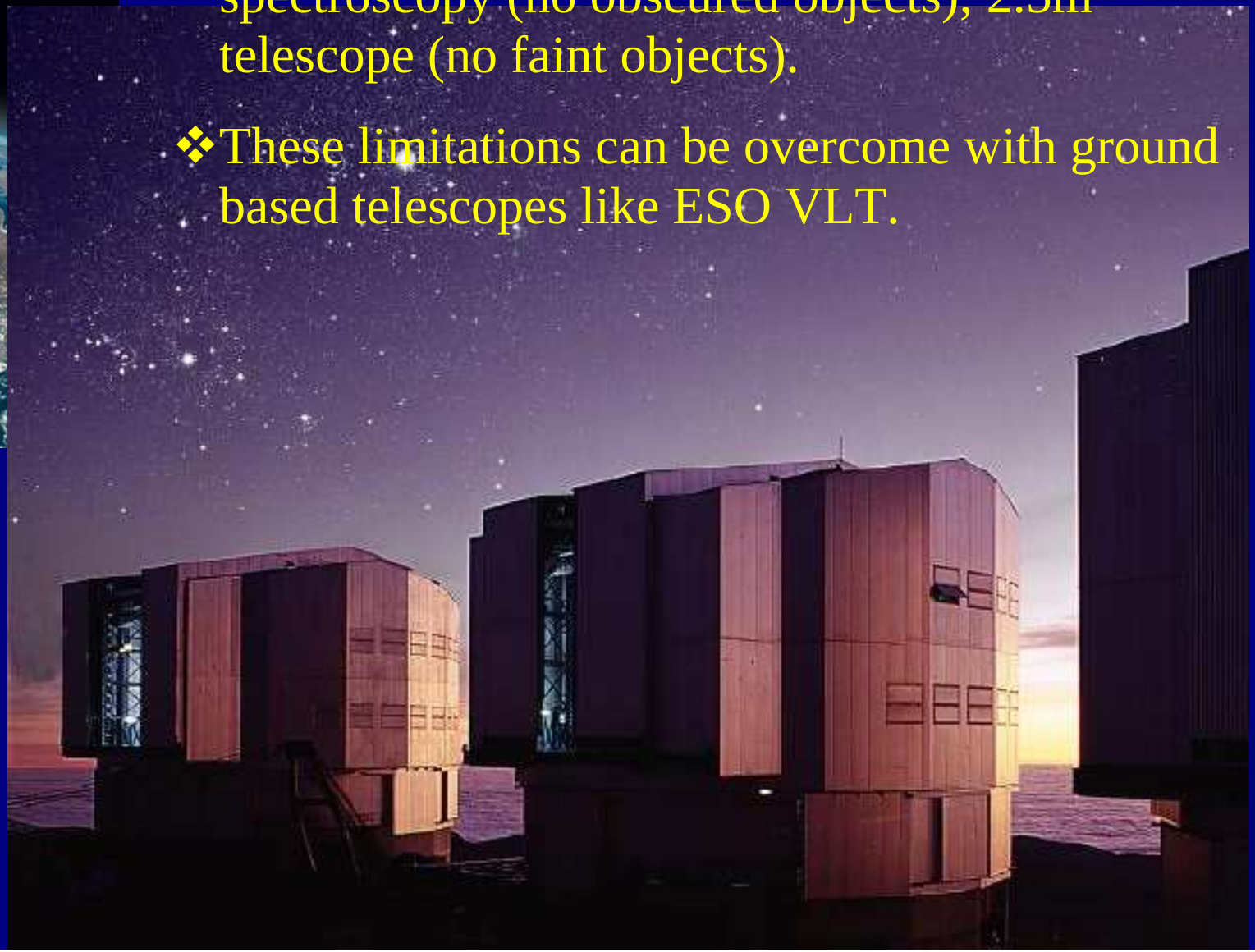
NGC 4041: pushing STIS to the limits in a Sbc galaxy with *small* bulge $M_{BH}<2\times10^7\ M_\odot$





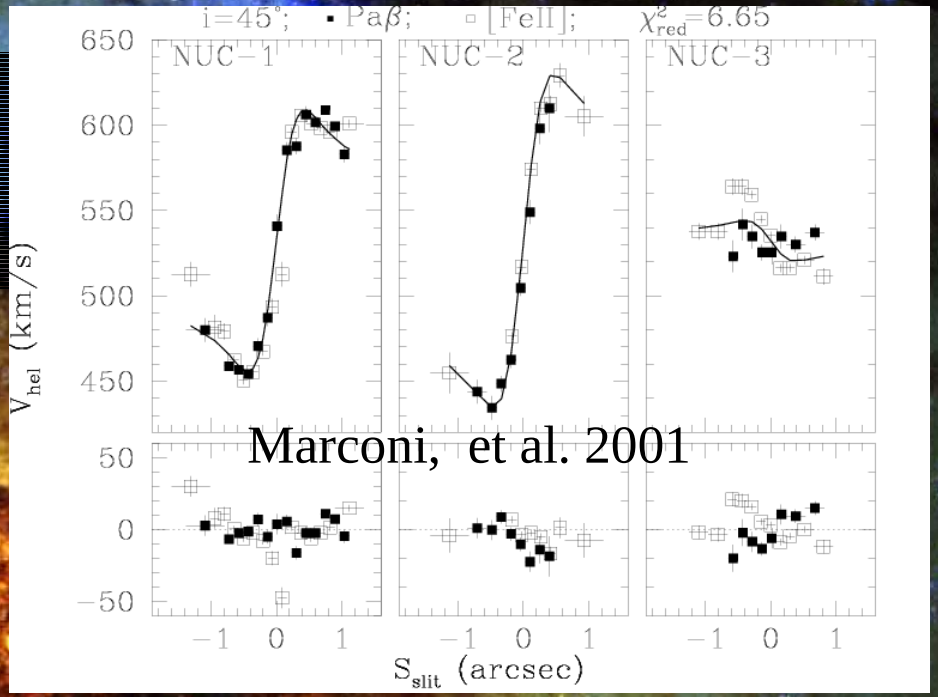
NGC 4258: 2° best case for a BH (kin. of H_2O masers $M_{BH} = 4\times10^7\ M_\odot$); crucial test for the gas kinematical method! Our HST obs. find $M_{BH}= 4^{+4}_{-2}\times10^7\ M_\odot$ in agreement with maser data!

- HST has produced a major breakthrough in the field of supermassive BH's.
- However it has limitations: no near-IR spectroscopy (no obscured objects); 2.5m telescope (no faint objects).
- These limitations can be overcome with ground based telescopes like ESO VLT.

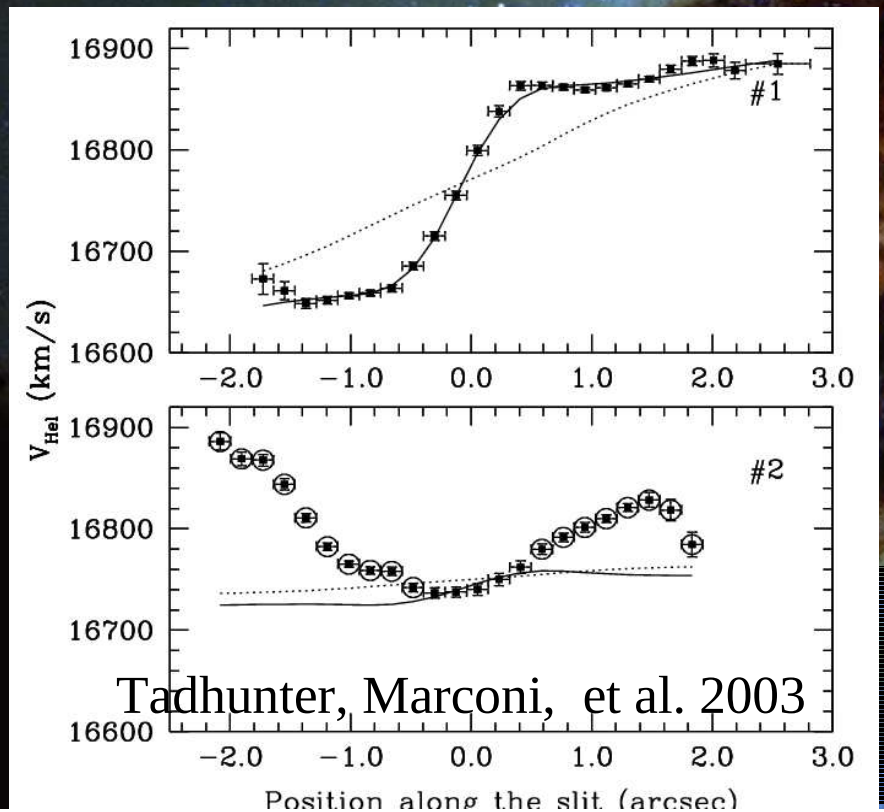


Highlights from ESO VLT

Centaurus A: first extragalactic BH detection in the near-IR (VLT/ISAAC) $M_{BH} \sim 2 \times 10^8 M_\odot$



Marconi, et al. 2001



Tadhunter, Marconi, et al. 2003

Cygnus A: first detection of a BH in AGN with Quasar-like Luminosity (Keck/NIRSpec) $M_{BH} \sim 3 \times 10^9 M_\odot$

1) Detection of BH's in galactic nuclei and measurement of their masses with gas kinematics.

Ongoing programs from HST:

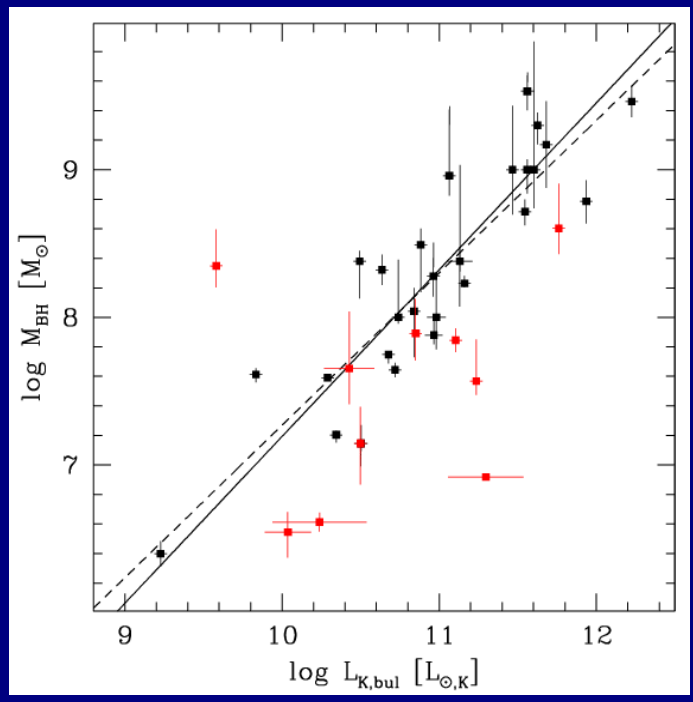
- BH masses in a large sample of spiral galaxies (PI Axon)
- BH masses in Double Humped Active Galactic Nuclei (PI Axon)

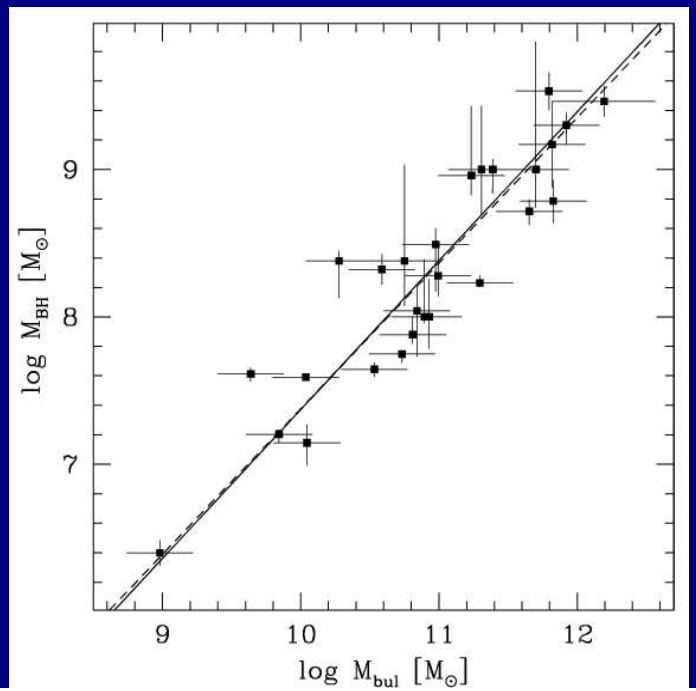
Ongoing programs with ESO / VLT:

- BH masses from reverberations mapping of high-z Quasars – long term program (PI Marconi)
- BH masses in nearby obscured Seyfert galaxies (PI Marconi)
- Hypermassive BHs in CD galaxies (PI Marconi) – Just Accepted!

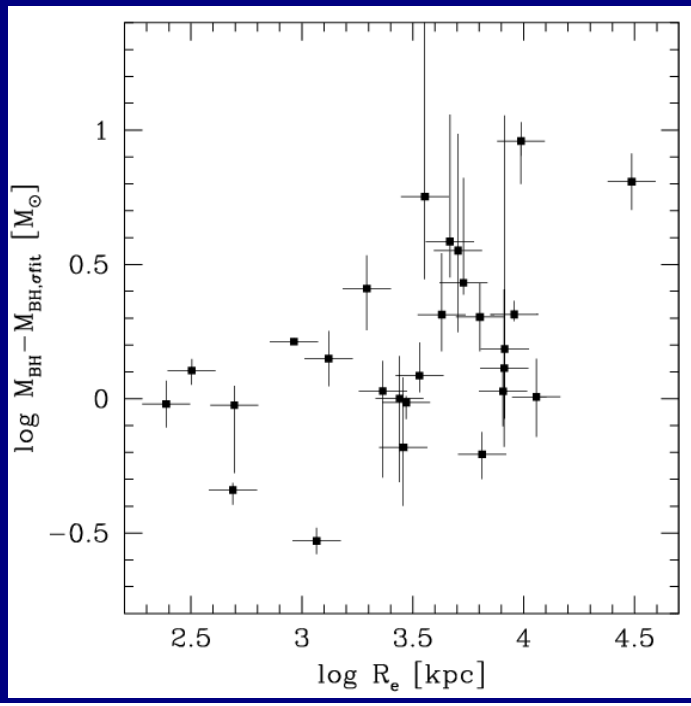
2) Relations between BH Mass and Host Galaxy Properties.

- M_{BH}-σ_e is believed to be tighter than M_{BH}-L_{bul} and Marconi & Hunt (2003) studied the M_{BH}-L_{bul} relation in the near-IR.
- Sample is composed of ALL galaxies with DIRECT BH mass determination. Galaxy structural params from J, H, K 2MASS images.



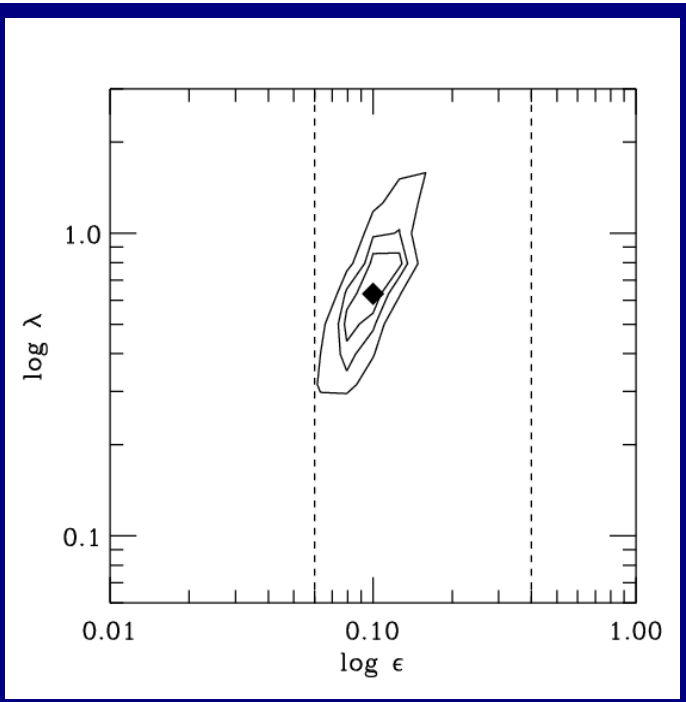


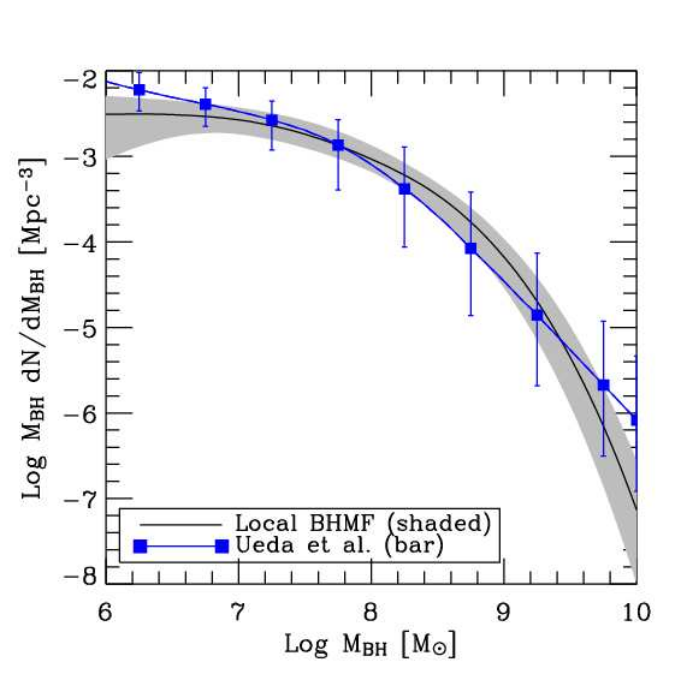
- M_{BH} correlates tightly with $L_{NIR,bul}$ (as good as M_{BH}-σ_e).
- M_{bul} ($\sigma_e{}^2$ R_e) tightly correlates with M_{BH} (M_{BH}/M_{bul}~0.002).
- M_{BH} depends on both σ_e and R_e in a relation like the Fundamental Plane of Elliptical Galaxies.



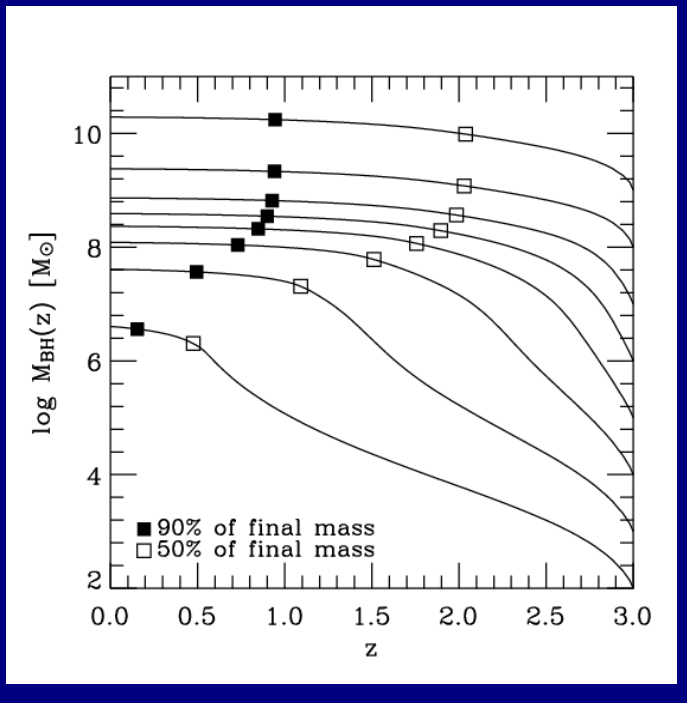
3) Demography of local BH's and their relation with AGN activity.

- AGN Relics: BH's grown exclusively by mass accretion during AGN phases
- To verify the hypothesis the local BH's are AGN relics, one needs to compare the local BH mass function with the mass function of AGN relics.
- Mass of Local BH's vs Energy Budget of AGN's (Marconi et al. 2004).





- The Mass Function of AGN relics consistent with that of Local BHs.
- Permitted Locus in ε-λ plane.
- Anti-hierarchical growth of BH's (consequence of AGN LF).



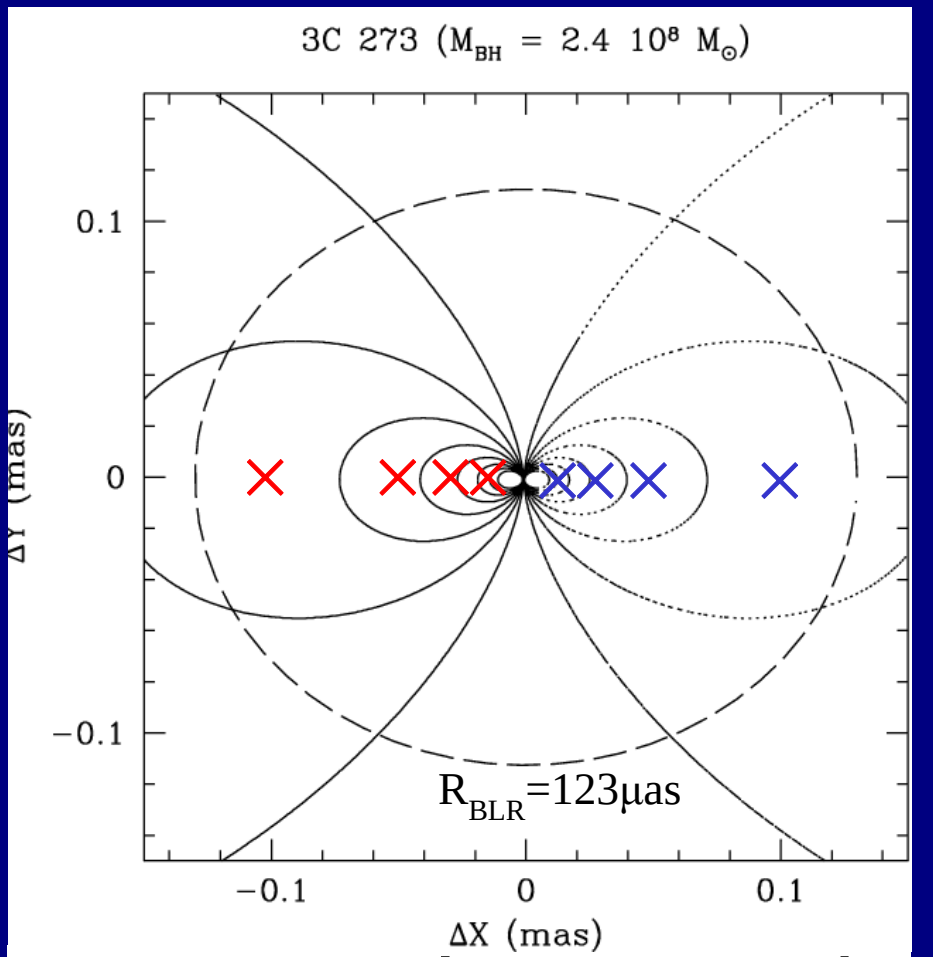
4) Future developments: optical interferometry with VLTI/AMBER.

FUTURE: ESO VLTI+AMBER

- AMBER is a near-IR spectrograph that combines up to 3 beams from VLTI.
- Built by a consortium [Arcetri, LAOG (F), OCA (F), UNSA (F), MPIfR (D)]
- It provides fringes dispersed at 3 spectral resolutions: $\Re$= 35, 750, 10000 in the 1-2.5 μmrange.
- Maximum Spatial Resolution: ~ 1 mas in J, ~ 2 mas in K

GTO Program: the size of the Broad Line Region of Quasars and Seyfert Galaxies

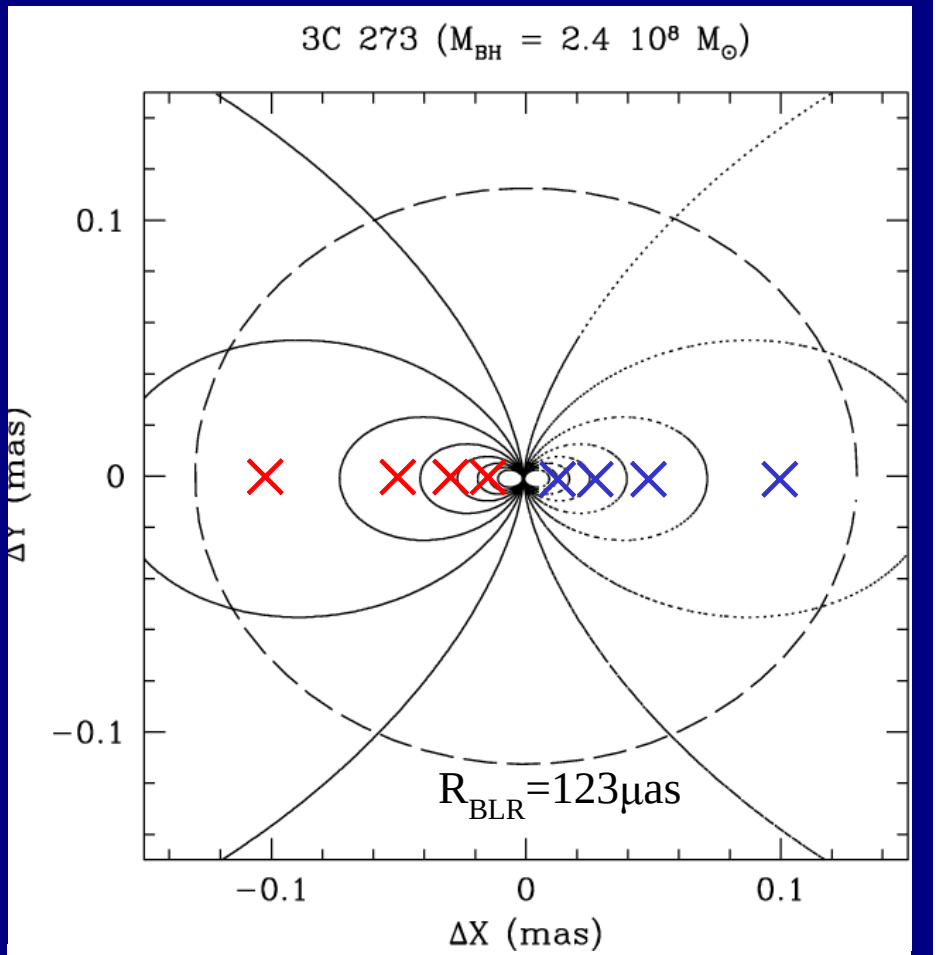
- BLR sizes were estimated with reverberation mapping (a few light days, i.e. from ~1 μas to ~200 μas on the sky), apparently unresolvable with the VLTI.
- However one can measure the position of the photocenter along a 2-telescopes baseline with an accuracy of a few μas!
- With 2 perpendicular baselines one can obtain a map of the photocenter positions on the sky.
- For instance, one can get the photocenter of a Broad Emission Line (e.g. Paα, Paβ) per velocity (wavelength) bin.



3C 273: BLR isovelocity contours in the case of a rotating Keplerian disk.
(M_{BH} =2.4 × 10^8 $M_\odot$; i=30 deg)

GTO Program: the size of the Broad Line Region of Quasars and Seyfert Galaxies

- BLR sizes have been estimated with reverberation mappings (a few light days, i.e. from ~1 μas to ~200 μas on the sky).
- BLR is unresolved from the VLTI, however one can measure the position of the photocenter with an accuracy much higher than spatial resolution.
- The *Differential Phase* across the broad line $\varphi(\lambda)$ provides the photocenter position of the BLR along the baseline as a function of λ (velocity): $\varepsilon(\lambda)$
- Example: 3C 273. From rev. mapping R_{BLR}~390 lt-days $\Rightarrow$ 123 μas.
- With 1h observation of Paα with AMBER ($\Re$=750) one can measure $\varepsilon(\lambda)$ with an accuracy $\Delta\varepsilon$ ~ 6 μas and with two perpendicular baselines one gets the XY position of the photocenter.



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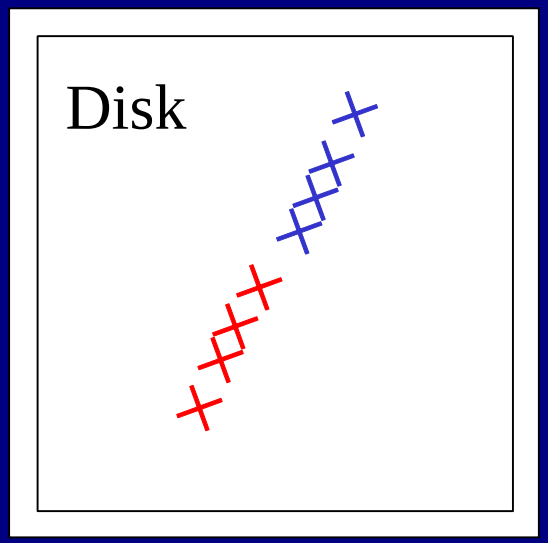
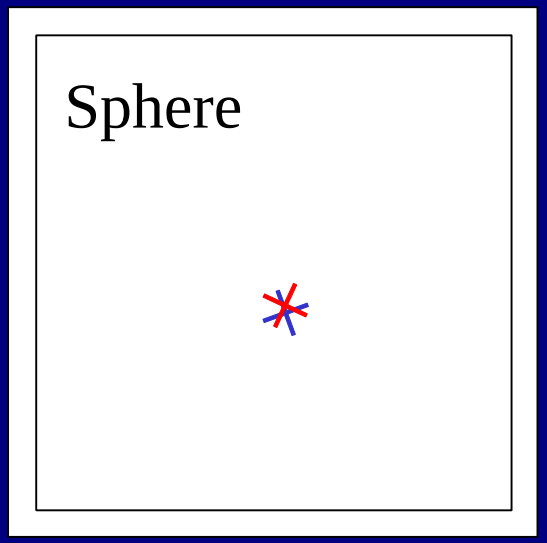
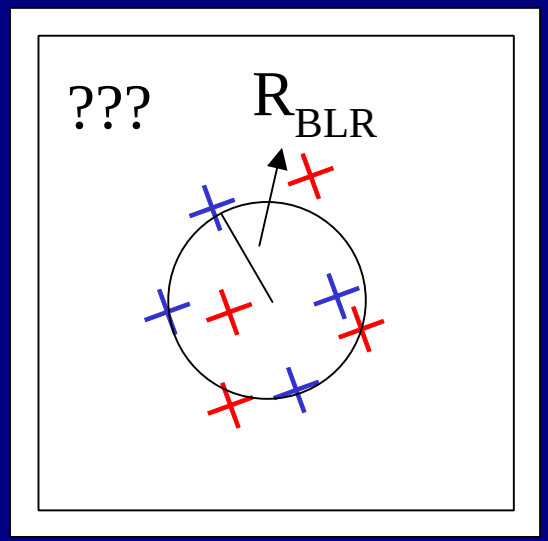
BLR geometry and kinematics



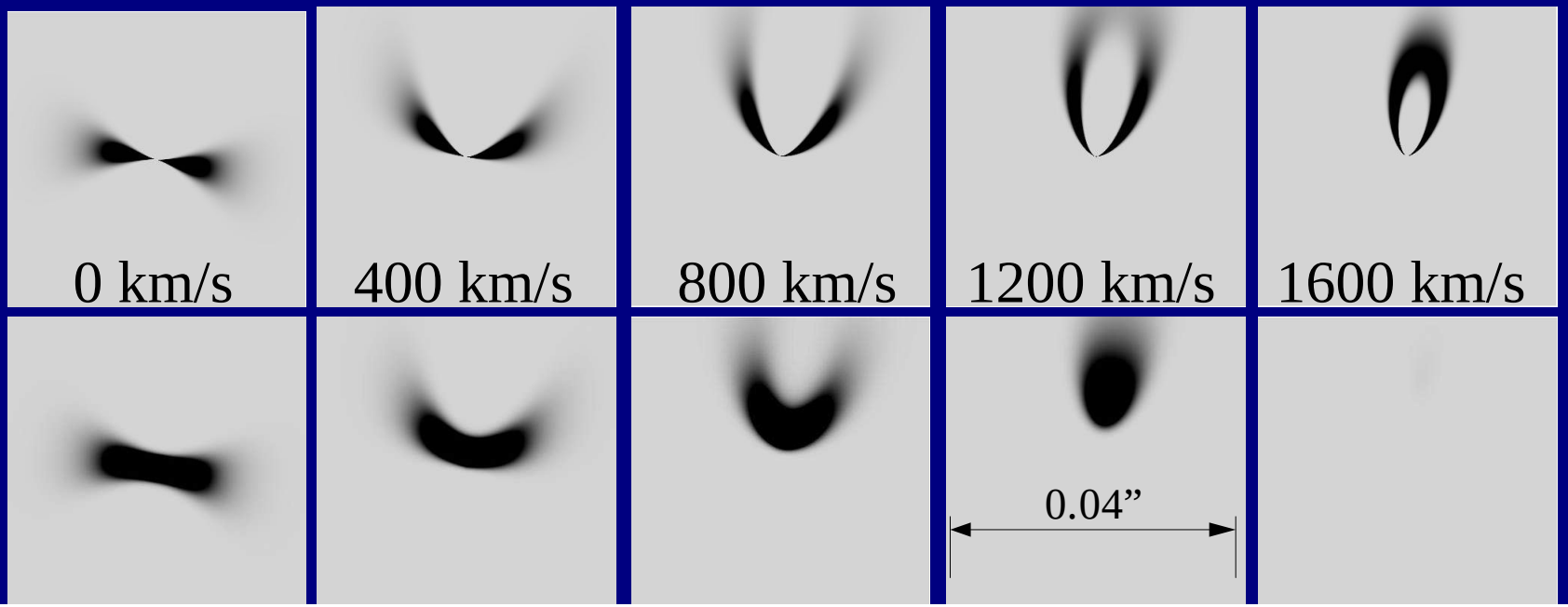




- With Differential Phase one can constrain BLR geometry and Kinematics.
- Estimate R_{BLR}.
- If BLR in a rotating disk estimate BH Mass!
- Study R_{BLR}-L relation.
- Compare BLR sizes with rev. mapping we can then determine cosmological parameters, e.g. H_0.

GTO Program: are MDO Black Holes?

- For example, Cen A has M_{MDO} ~2 x 10^8 $M_\odot$ (within r < 0.3” ~ 5pc) ⇒ ρ ~ 4x10 ^{5} $M_\odot$ pc^{-3} compatible with a cluster of dark objects (neutron stars, stellar mass BHs, etc.)
- Constraining the size of the dark matter distribution within AT LEAST 10 mas willgive ρ ~ 10 ^{10} $M_\odot$ pc^{-3}, as good as NGC 4258!
- This can be achieved using interferometric spectral information obtained with ℜ=7500 (ΔV=40km/s).



Conclusions

- We have several ongoing programs (from HST and VLT) aimed at measuring BH masses in nearby galaxies.

  Gas Kinematics is a reliable method to measure M_{BH}.

- We are using our own measurements of BH masses and data from the literature to study the correlations between BH mass and host galaxy properties.

  M_{BH}-L_{bul} is as good as M_{BH} - σ_e. M_{BH} depends on σ_e^2 R_e.

- We are studying the relation between local BH's and past Active Galactic Nuclei to test the hypothesis that local BH's are AGN relics. We are using the results from the previous point and AGN LF's from literature.

  Local BH's are AGN relics. BH's grow anti-hierarchically.

- We are waiting for our GTO observations with VLTI/AMBER.