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ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

INAF - Arcetri

Observational evidences and demography of Black Holes

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VIII CICLO (2005 -2006): III CORSO

Dinamica delle galassie – Nuclei galattici attivi

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Outline of Lectures

- Lecture 1
  - Observational evidences for supermassive black holes and mass measurements.
- Lecture 2
  - Relations with the host galaxy and demography of local black holes.
- Lecture 3
  - Local supermassive black holes and Active Galactic Nuclei.
  - Future developments: VLT interferometry (?)

From previous lectures...

- Observational evidence for supermassive BHs (10^6-10^{10} $M_{\odot}$) in ~40 nearby galaxies.
- BH mass and structural parameters of the host spheroid (M, L, σ) are tightly correlated.
- Most (maybe all) galaxies should host a supermassive BH in their nuclei.

- Are local Black Holes consistent with expected remnants from AGNs?

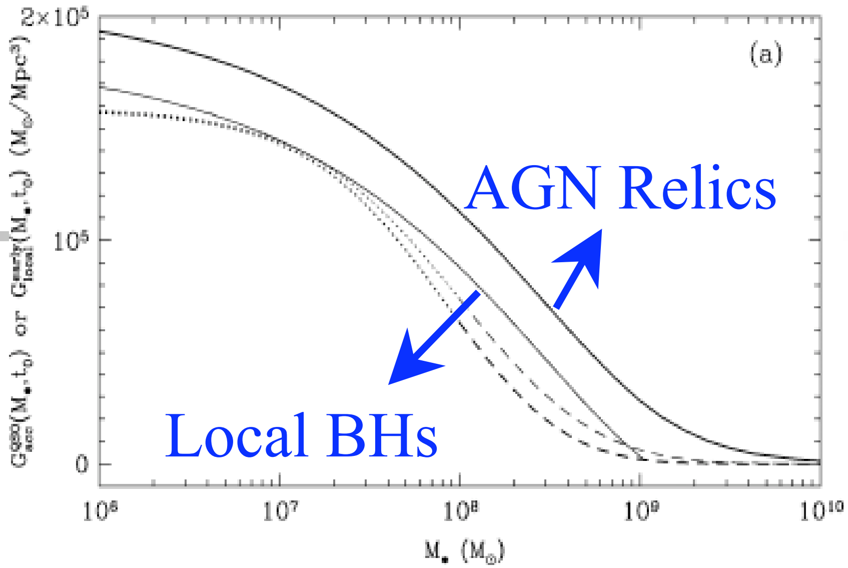
Local BHs vs AGN relics

- Compare the mass density of local BHs with that of AGN relics (e.g. Soltan 1982, Fabian & Iwasawa 1999, Elvis, Risaliti & Zamorani 2002)
  - Previous lecture: ρ(local BHs) ~ ρ(AGN relics)

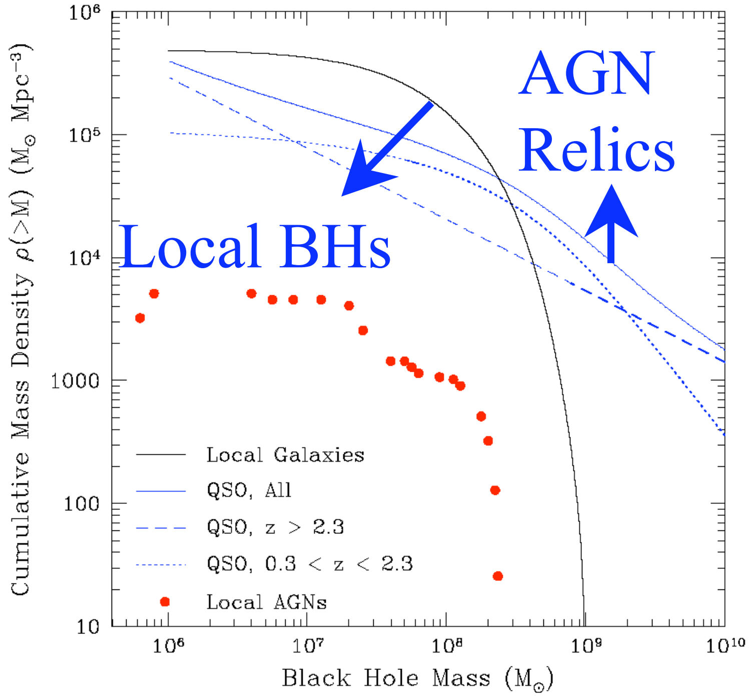
- Compare the local BH Mass Function with the mass function of relic BHs (e.g. Yu & Tremaine 2002, Ferrarese 2002, Marconi et al. 2004, Merloni 2004, Shankar et al. 2004)

Are BHs rapidly spinning?

- Yu & Tremaine 2002 and Ferrarese 2002 found that there are inconsistencies at large masses (M_{BH} >10^8 M􏰀): expected AGN relics are more numerous than local BHs.
- This result derive from assuming standard accretion efficiency _=0.1 (L= _ dM/dt c^2)
- The discrepancy can be solved if _>0.2 at high masses (⇨ less relic mass)
- Large _ imply rapidly spinning BHs!



Yu & Tremaine 2002

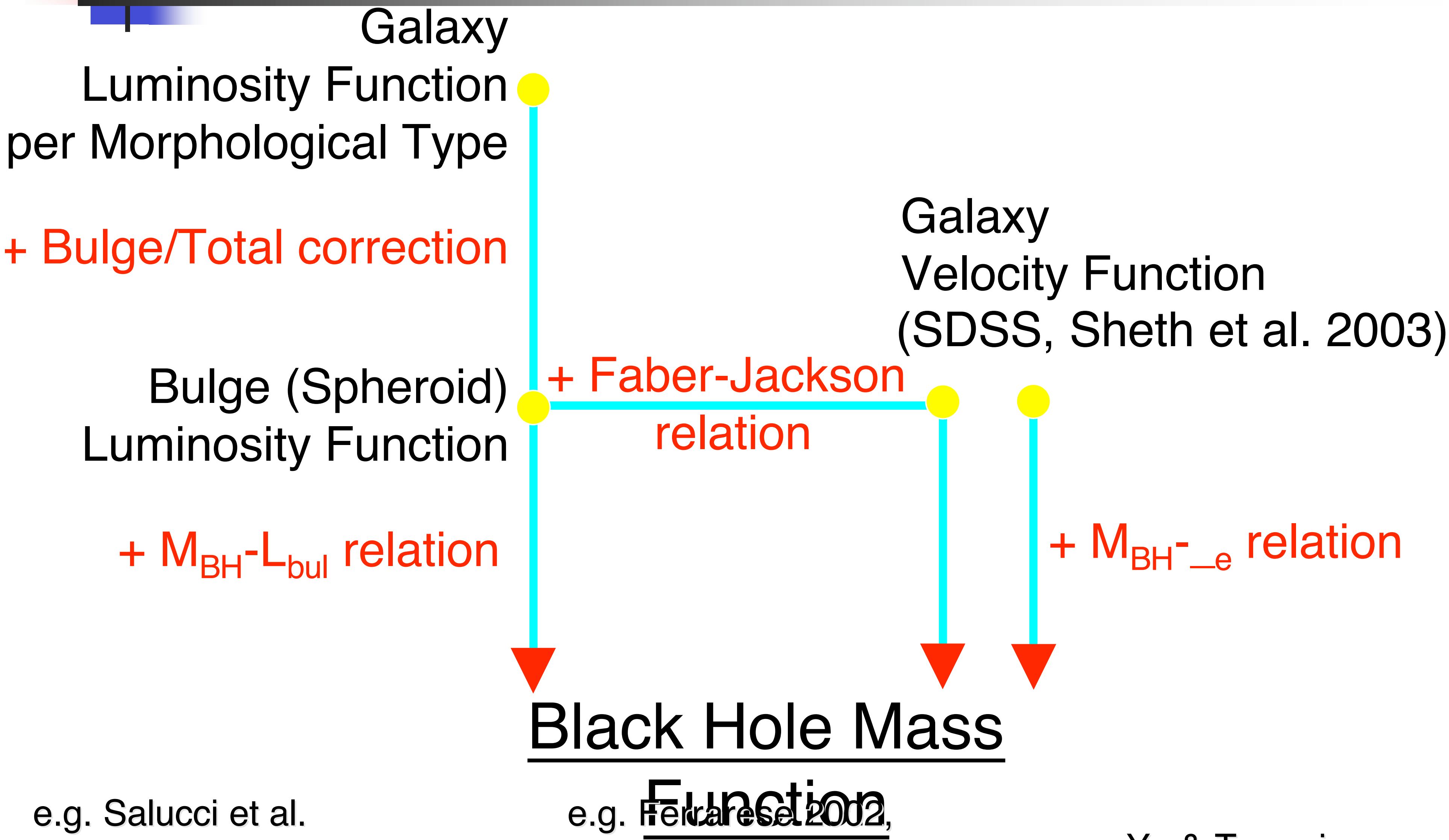


Ferrarese 2002

The Local BH Mass Function

- It can be derived combining galaxy L/_ functions with the known M_{BH}-galaxy relations.
- Critical points:
  - Correlations are not with galaxy but with spheroid structural parameters.
  - Zero point of the correlations 'a' which affect the normalization of the BHMF
    [$\log M_{BH}=a+b \log(X/X0)$, X=L/_/M]
  - Intrinsic dispersion of the correlations (i.e. the intrinsic dispersion in M_{BH} at given L/_/M)

The Local BHMF from M_{BH} – L_{bulge}/—e



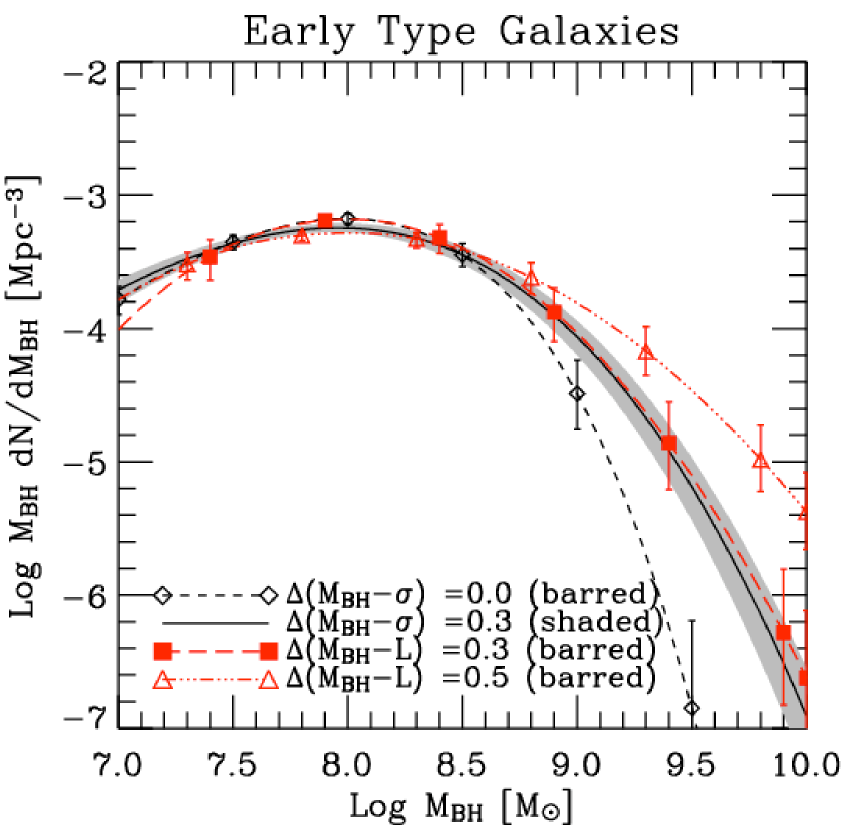
e.g. Salucci et al.
1998,
Marconi & Salvati

e.g. Ferrarese 2002,
Aller & Richstone
2003

e.g. Yu & Tremaine
2002,

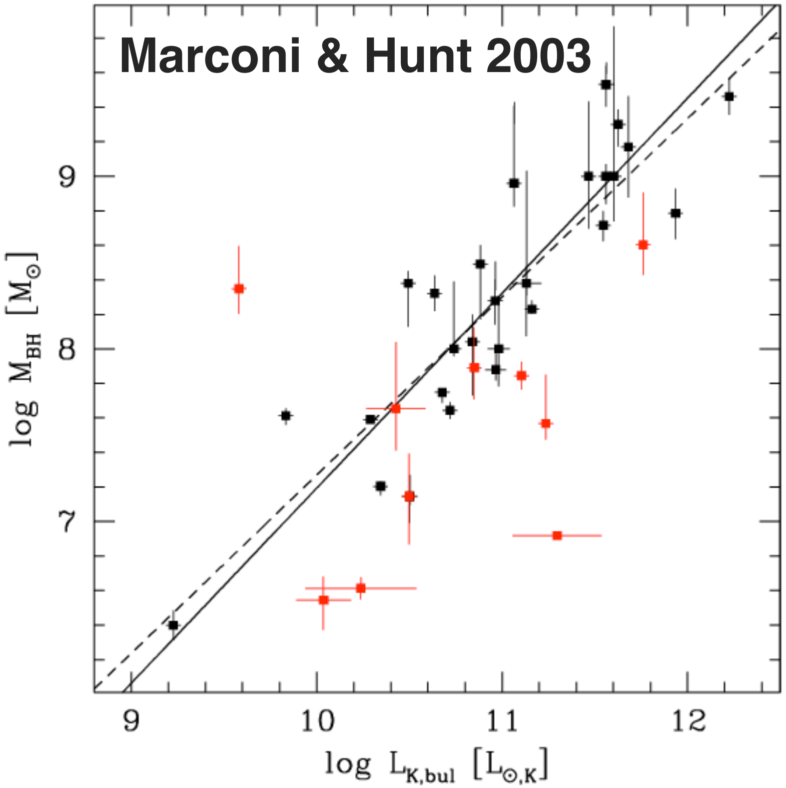
Consistency of M_{BH}-L_{bul} and M_{BH}-$\_e$

- M_{BH}-L_{bul} and M_{BH}-$\_e$ provide the same BHMF?
- Check BHMF obtained with _(_) and _(L) from the *same* sample [9000 E/S0 from SDSS; Bernardi et al, Sheth et al 2003]
- Take into account intrinsic dispersion of correlations:
  - M_{BH}-_ has *rms* ≤ 0.3 (Tremaine et al. 2002).
  - M_{BH}-_ and M_{BH}-L_{bul} have similar dispersion, *rms* ~0.3 (Marconi & Hunt 2003).
  - Also the zero points of correlations are a factor 1.5 larger when considering only galaxies with SECURE BH detections.

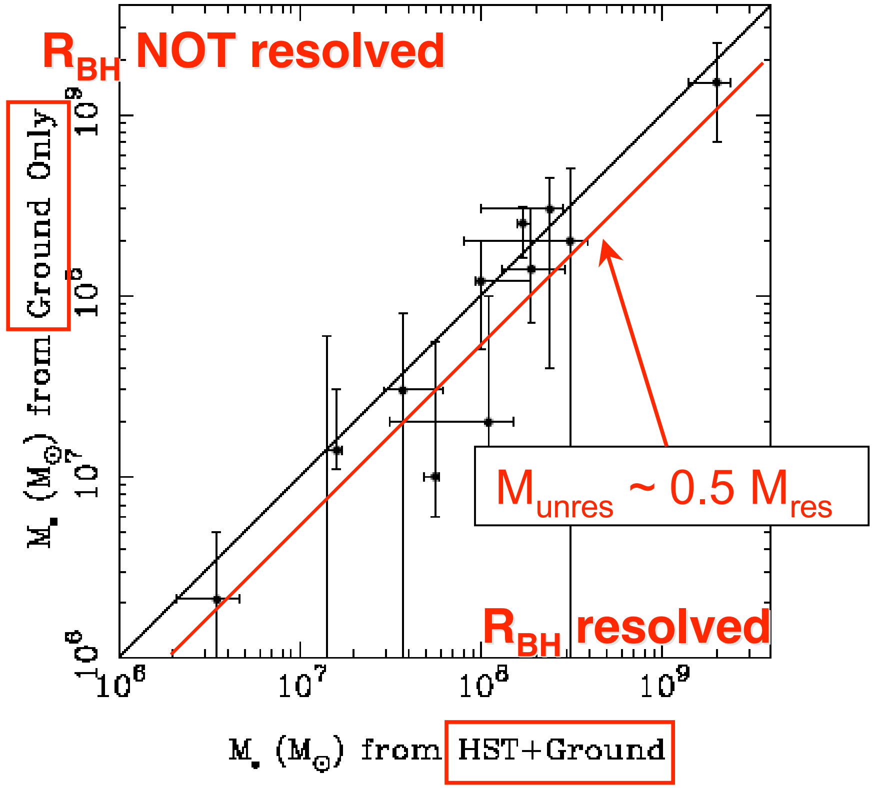


The relative shapes of _(_) and _(L) require that M_{BH}-L_{bul} and M_{BH}-$\_e$ have the same dispersion!

BH Mass vs Host Galaxy Properties



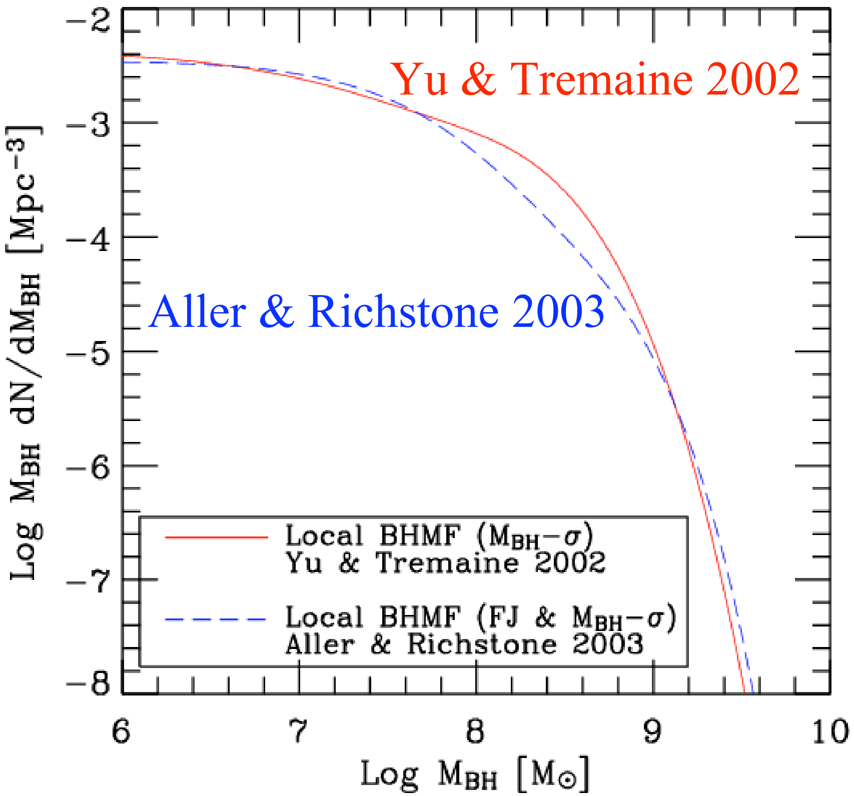
M_{BH}-$L_{K,bul}$ (*rms* 0.3 in log M_{BH})

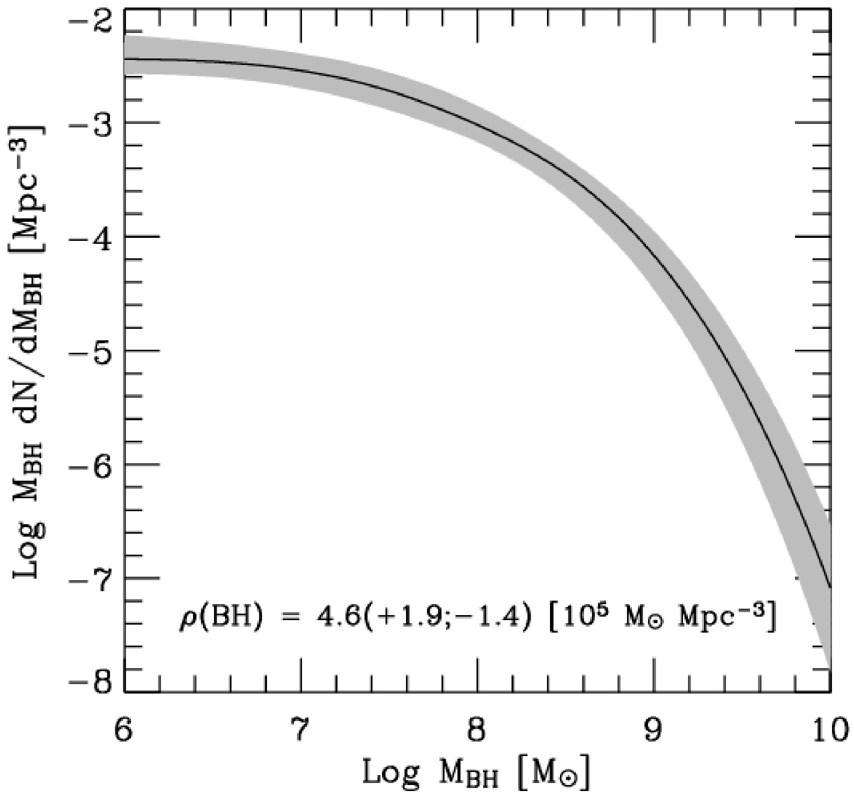


Gebhardt et al. 2003

- When considering only BHs with secure mass determination (i.e. where the BH sphere of influence R_{BH} is spatially resolved from observations) the zero points of the correlations increase by a factor ~1.5.
- Why galaxies where R_{BH} is not resolved have lower BH masses? See Gebhardt et al. 2003 …

The local Black Hole Mass Function





- Assuming PERFECT M_{BH}-galaxy correlations _$_{BH}$ _ 2.5±0.4 _10^5 M□ Mpc^{-3} (Yu & Tremaine 2002, Aller & Richstone 2003)
- _$_{BH}$ _ $4.6^{+1.9}_{-1.4}$ _10^5 M□ Mpc^{-3} (cf. Merritt & Ferrarese 2001, Ferrarese 2002, Shankar et al. 2004)
- In summary: 3-5 _10^5 M□ Mpc^{-3} (see Ferrarese & Ford 2005 review)

The AGN BH Mass Function

- Assume accretion onto BH as powering mechanism of AGN to link L_{AGN} with M_{BH}
- Use the continuity equation (Cavaliere et al. 1971) to derive the BH Mass function $N(M_{BH})$ from the AGN Luminosity function _(L)
- Critical issues:
  - _(L) is the luminosity function of ALL AGNs (observations provide _ only for a subset of AGNs)
  - L is the TOTAL accretion luminosity

The Relic BHMF: Continuity equation

- We write the continuity equation (e.g. Cavaliere et al. 1971, Small & Blandford 1992) for the BH mass function N(M,t) as

$$\frac{\partial N(M,t)}{\partial t}+\frac{\partial}{\partial M}\left[N(M,t)\left\langle \dot{M}(M,t)\right\rangle\right]=0$$

- Note that no source term is present, i.e. no merging of BHs.
- Assume that a BH with mass M at time t accretes with efficiency _ at a fraction _ of the Eddington rate (L= _ Mc^2/t_E) thus

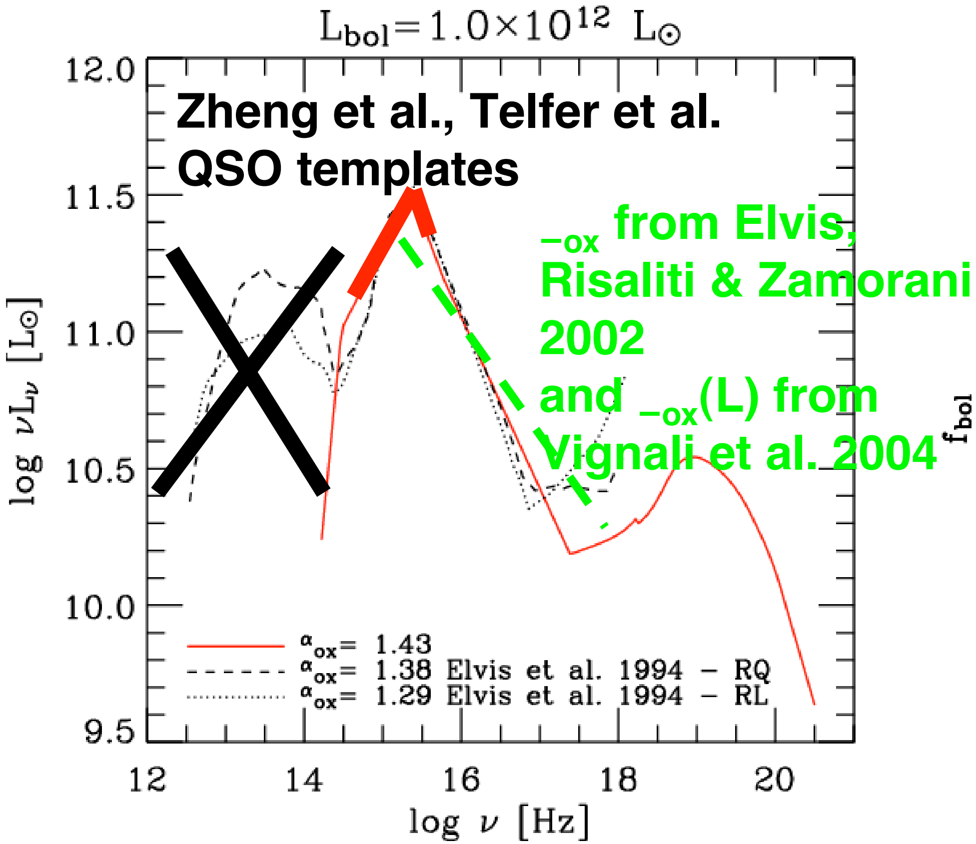
BHMF

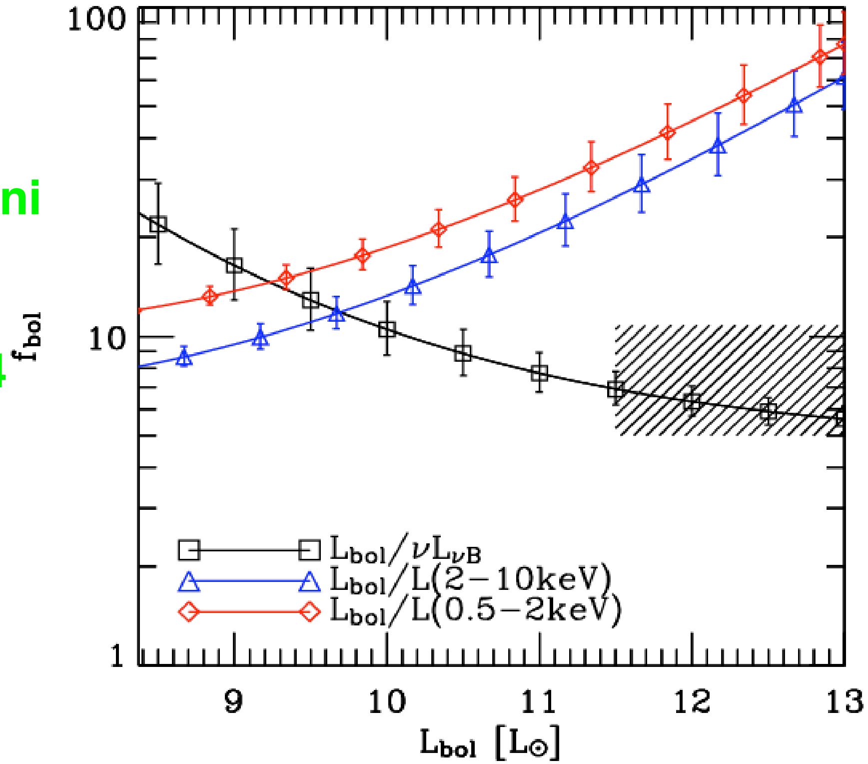
$$\frac{\partial N(M,t)}{\partial t}+\frac{(1-\varepsilon)\lambda^2 c^2}{\varepsilon t_E^2}\left(\frac{\partial \phi(L,t)}{\partial L}\right)_{L=\lambda\frac{Mc^2}{t_E}}=0$$

AGN LF

- where _(L,t) is the AGN bolometric luminosity function.
- _ and _ are assumed constant. Start integrating at z=3.

Bolometric Corrections

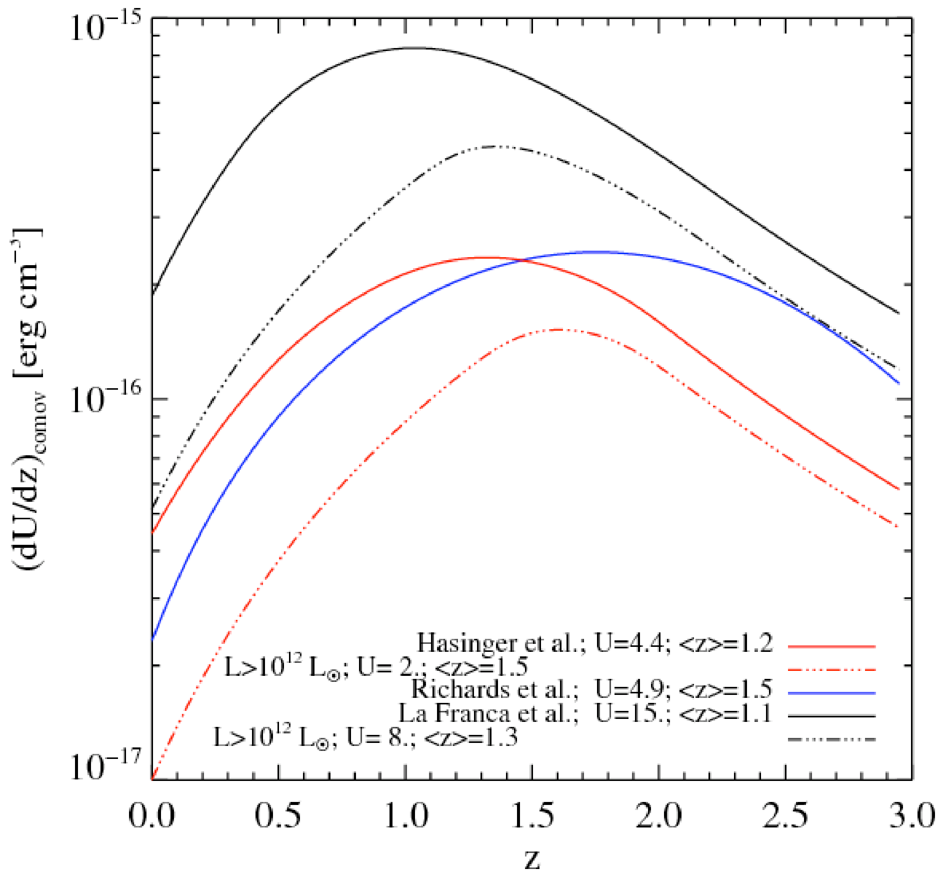




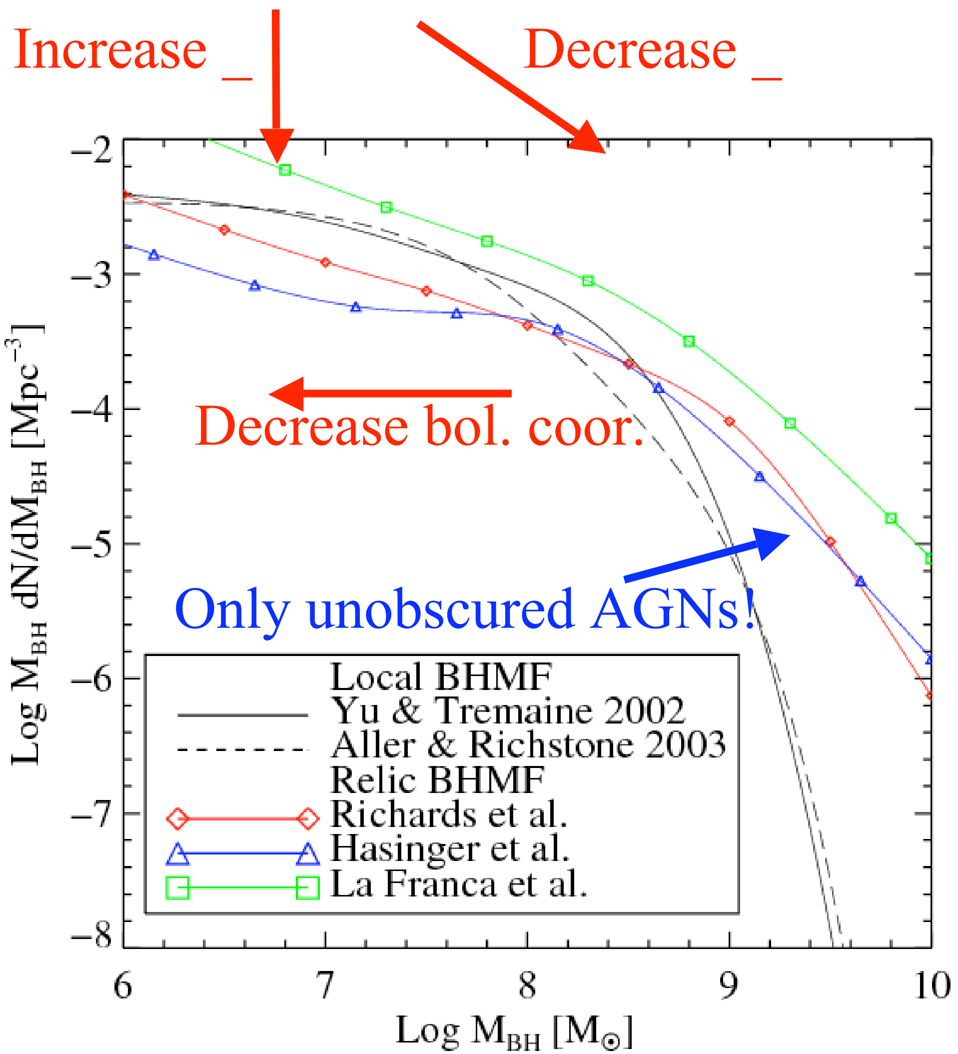
- We build spectral templates and estimate bolometric corrections.
- Our bolometric corrections are **~2/3** of commonly adopted ones (Elvis et al. 1994) because we do not consider IR radiation (reprocessed).

Luminosity Functions

- LF of optically selected quasars (Boyle et al. 2000, Richards et al. 2005)
- LF of soft X-ray selected AGNs mostly unabsorbed type 1 (Miyaji et al. 2000, Hasinger et al. 2005)
- LF of hard X-ray selected AGNs Compton-thin AGNs(Ueda et al. 2003; La Franca et al. 2005)
- New result is the different z evolution of low and high L AGNs (see also Fiore et al. 2004)
- Apply bolometric corrections from B, 0.5-2 keV and 2-10 keV to get the *bolometric* LF _(L,t) of that class of AGNs.

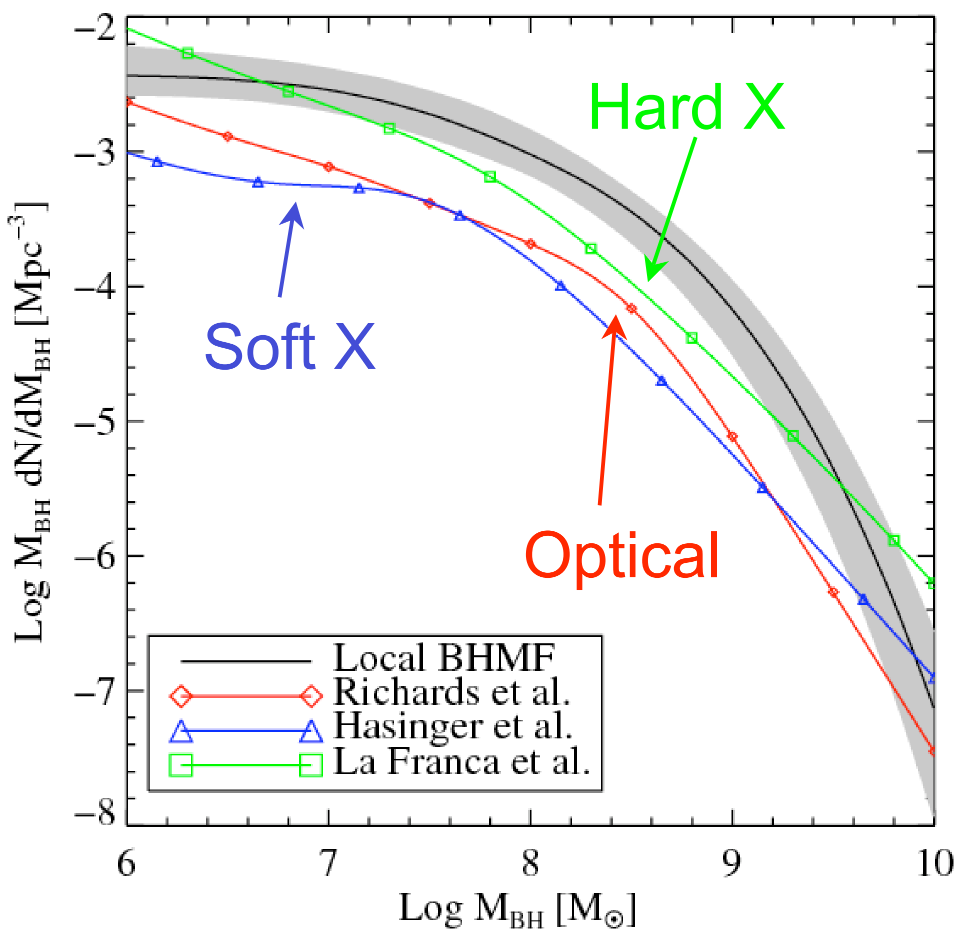


Local vs Relic BHMF



- Local BHMF with no intrinsic spread of correlations and lower zero points.
- AGN LF's from Richards et al. 2005, Hasinger et al. 2005, La Franca et al. 2005 with "standard" Bolometric Corrections.
- The relic BHMF has an excess at large masses!
- Is efficiency (_=0.1) higher?
- Yu & Tremaine (2002) conclude that high mass BHs must be rapidly rotating (_ _ 0.2-0.3).

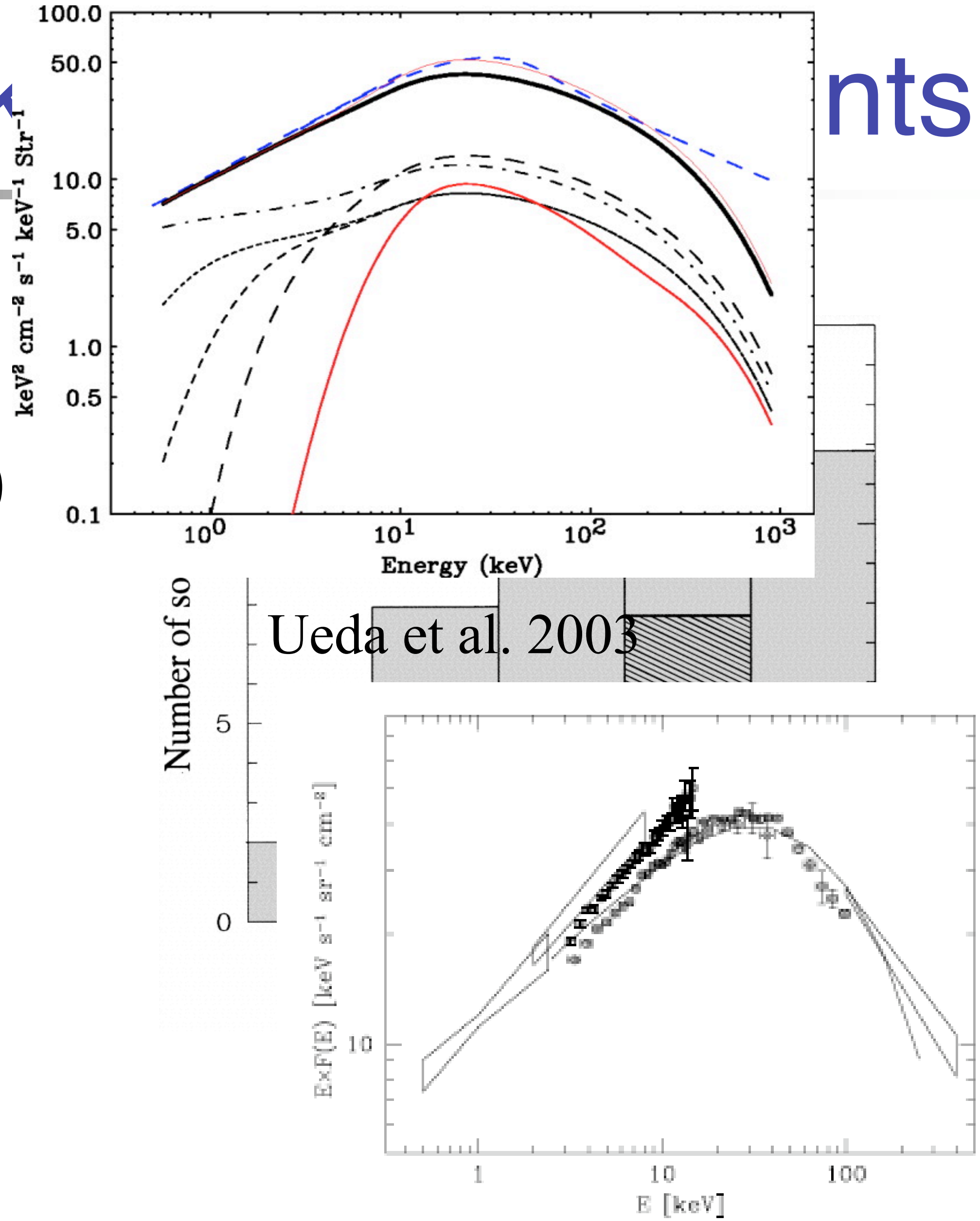
Local BHMF vs Relic BHMF



- We find no disagreement at high masses because of
  - bolometric corrections;
  - take into account intrinsic dispersion in M_{BH}-L/_;
  - larger zero points.
- The relic BHMF is only from AGN seen in the surveys (not obscured).
- How to obtain the fraction of obscured sources (Compton-thick)?
- From the X-ray background spectrum!

X-ray Back nts

- LFs from Ueda et al. 2003 and La Franca et al. 2005 (2-10 keV) are for Compton-thin AGNs.
- They extrapolate the number of Compton-thick AGNs from N_H distributions (e.g. Risaliti et al. 1999) …
- and are able to fit XRB spectrum.

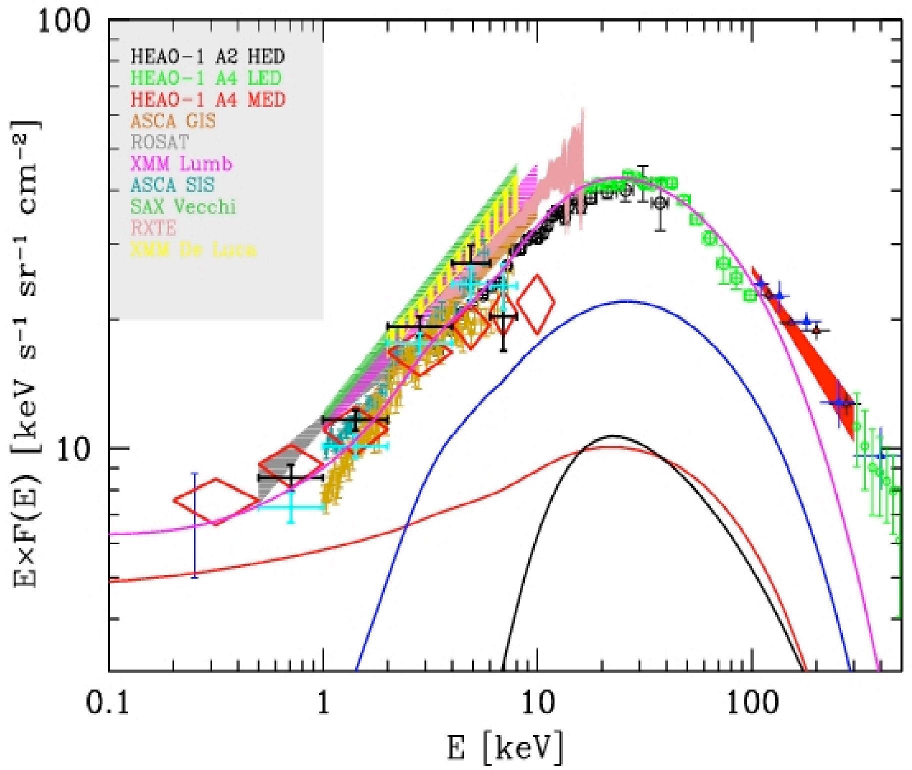


Ueda et al. 2003

La Franca et al. 2003

X-ray Background constraints

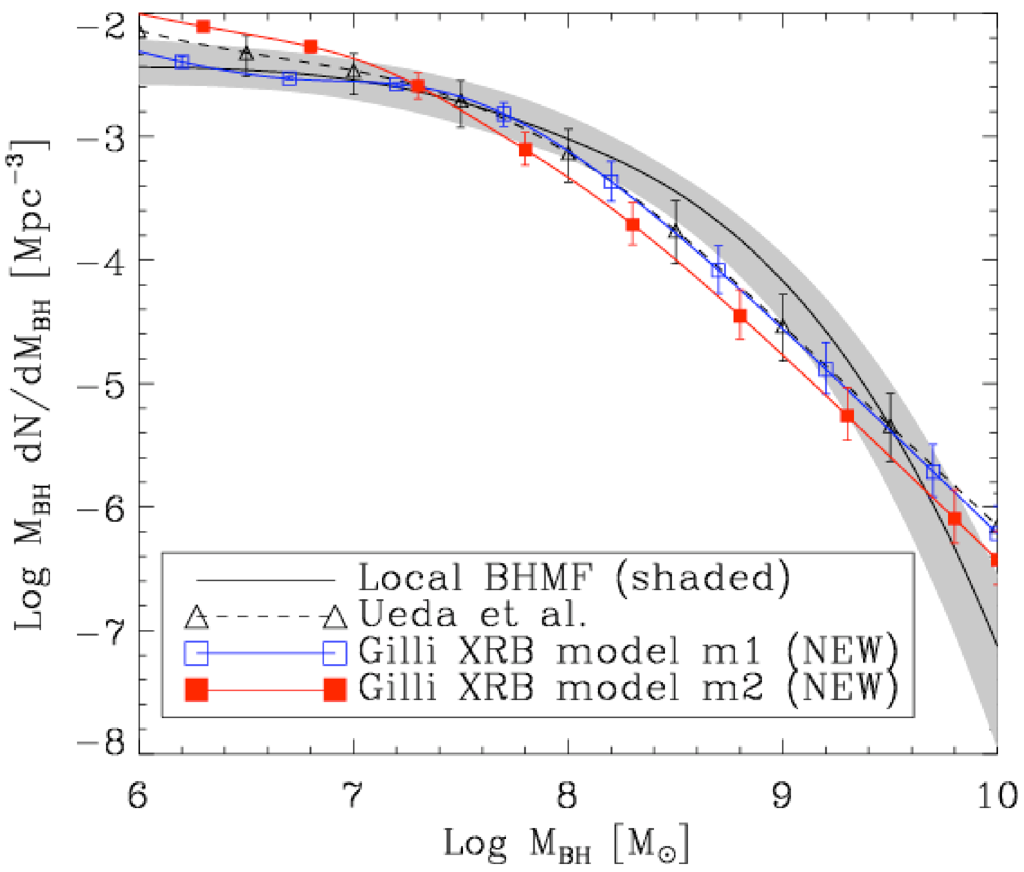
- XRB models provide the total numbers of Compton-thin + Compton-thick AGN
- Two options explored:
  - M1: R = obscured/unobscured AGN ratio = constant
  - M2: R decreasing with luminosity



Gilli, Comastri, Hasinger 2006 in prep.

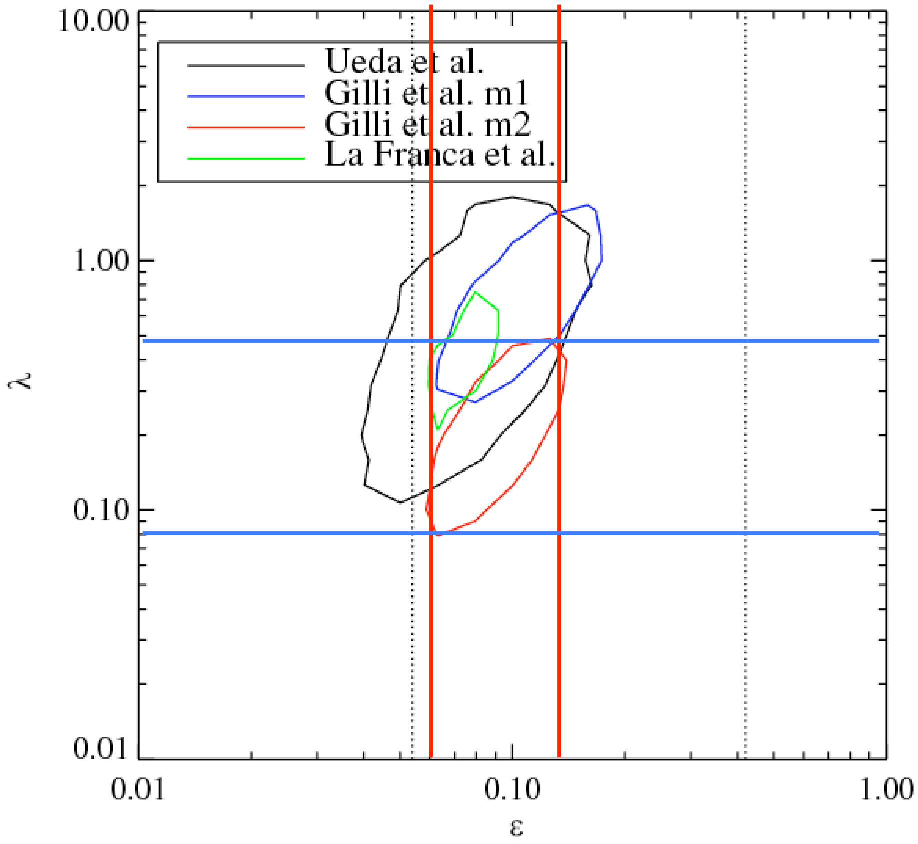
Local BHMF vs Relic BHMF

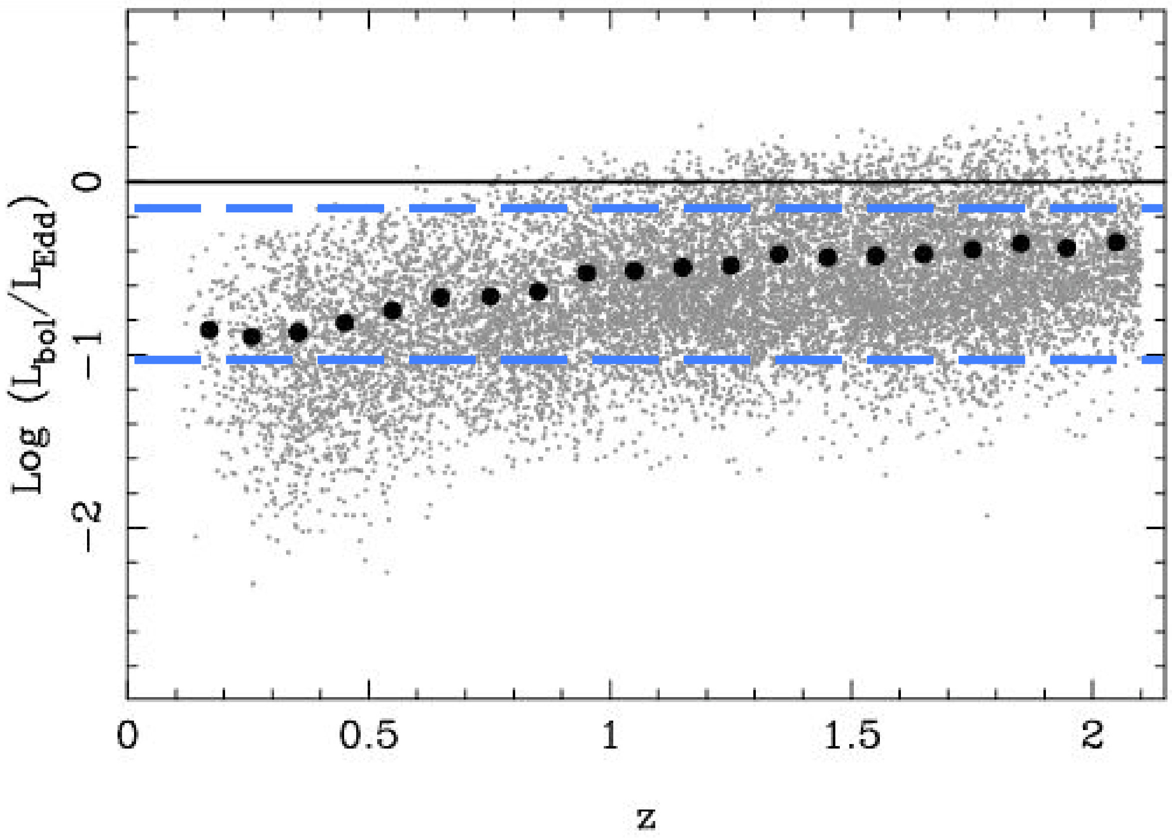
- Correction for Compton-Thick sources from XRB models ⇨ whole AGN population is considered
- The only free parameters are the accretion efficiency and Eddington ratio
- Assume:
  - _=0.1 (L= _ dM/dt c^2)
  - _=1 (L= _ L_{Edd})



Radiative Efficiency and Fraction of Eddington luminosity

- Efficiency and fraction of Eddington luminosity are the only free parameters!
- Determine locus in _-_ plane where there is the best match between local and relic BHMF!
- _=0.06-0.15 _=0.08-0.5 which are consistent with common 'beliefs' on AGNs



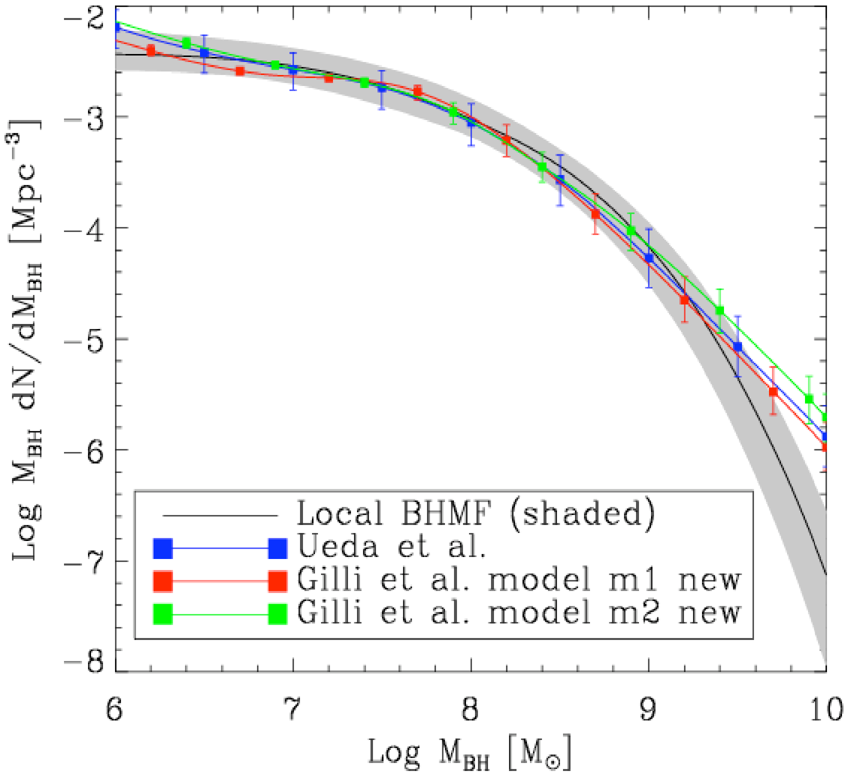


L_{bol}/L_{Edd} from the sample of SDSS quasars
(Mc Lure & Dunlop 2004)

Local BHMF vs Relic BHMF

- Local and Relic BHMFs are in agreement without considering merging.
- Either merging of BHs is negligible for z<3 or it does not modify *significantly* the BHMF (e.g. Granato et al. 2004, Menci et al. 2004, Haiman, Ciotti & Ostriker 2004).

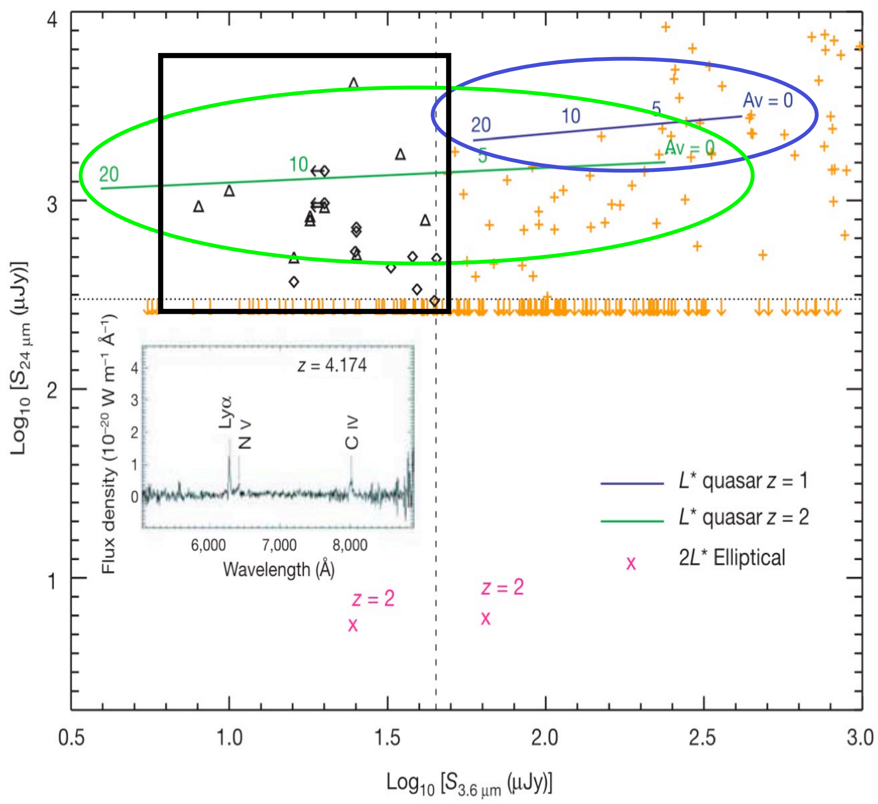
with best _ and _ values …



Missing AGNs: help from mid-IR?

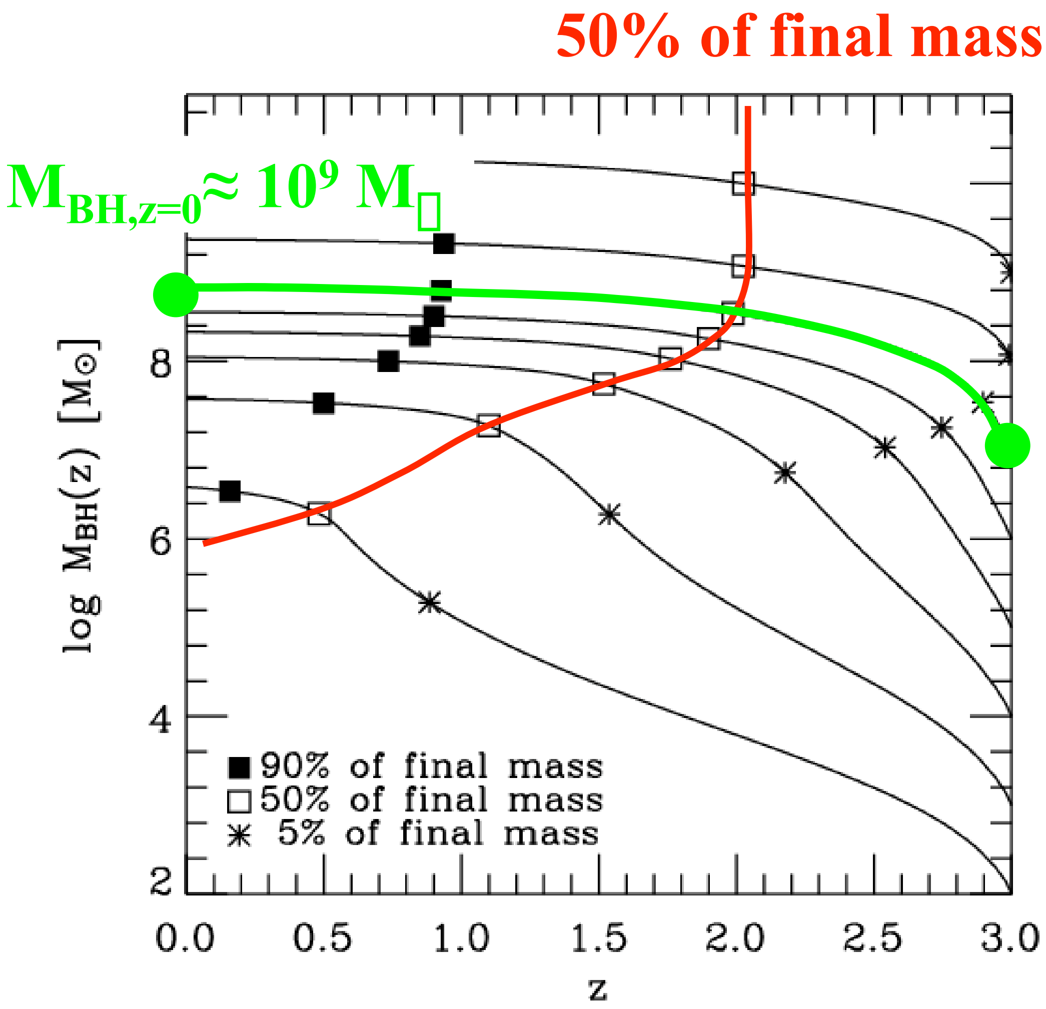
- The correction for the “missing” Compton-thick AGNs is critical.
  - One would like to quantify observationally the fraction of Compton-thick sources.
- A possibility is provided by mid-infrared observations (Spitzer).
- Martinez-Sansigre et al. (2005, 2006) used Spitzer survey data to select AGNs with QSO-like mid-IR emission but faint in near-IR. Radio flux criterion to exclude submm galaxies and radio loud AGNs.
- Half of the candidates are QSO2s. They estimate that ~50% of high luminosity QSOs are highly obscured and have been missed so far.
- However, X-ray observations are needed to establish if these are really the Compton-thick sources we are looking for.

L* quasar at z=1 (Av ⇧)
L* quasar at z=2 (Av ⇧)
Type 2 candidates



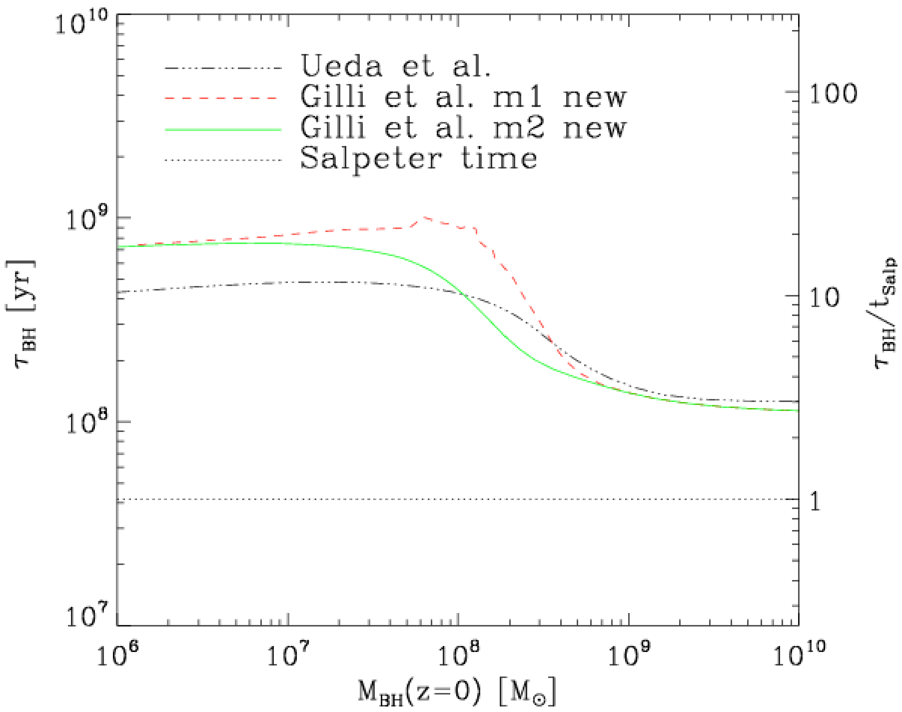
Martinez-Sansigre et al. 2005

Anti-Hierarchical BH growth



- This is *qualitatively* consistent with models of galaxy formation (e.g. Menci et al. 2003, Granato et al. 2003)
- Big BHs form in deeper ⇨ they
- Smaller BHs form in shallower potential wells and are more subjected to feedback effects (star form., AGN), ⇨ they form later and take more time to grow.
- See also Merloni 2004.

<u>Total</u> Lifetime of active BHs



_BH~2 ×10^{8} yr (>10^{9} $M_{\square}$)

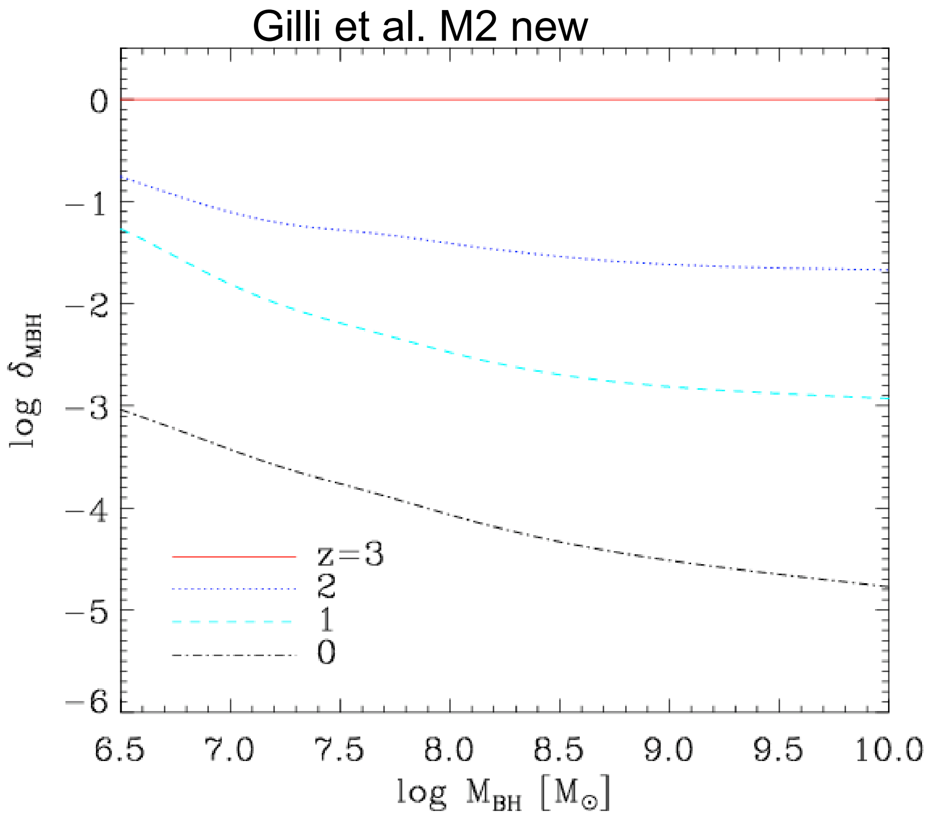
_BH~7 ×10^{8} yr (<10^{8} $M_{\square}$)

- M_{BH} e-fold time (Salpeter's):

$$t_{Salp} = \frac{\varepsilon t_E}{(1-\varepsilon)\lambda} = 4.2 \times 10^7 yr \left[\frac{(1-\varepsilon)}{9\varepsilon}\right]^{-1} \lambda^{-1}$$

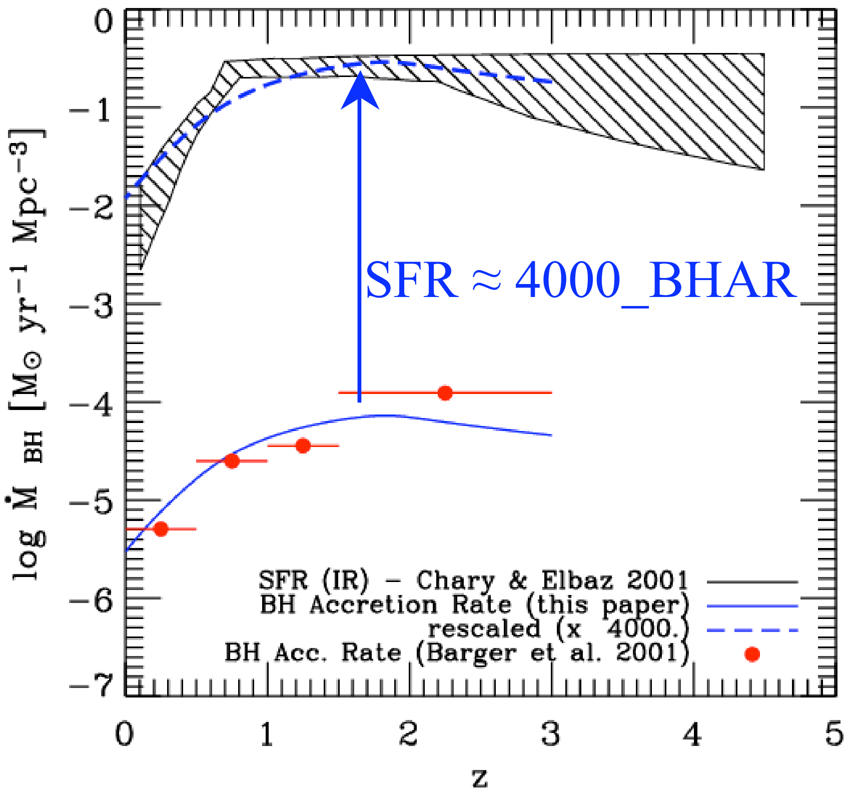
- To grow a BH SEVERAL t_{Salp} needed: 7 _ t_{Salp} 10^3 ⇨ 10^6 $M_{\square}$
  14 _ t_{Salp} 10^3 ⇨ 10^9 $M_{\square}$
- t_{Salp} independent of M_{BH}, longer _BH at lower M_{BH} indicates a more difficult growth of smaller BHs (AGN feedback!).
- Estimated AGN lifetimes range from 10^6 to 10^8 yr (AGNs from SDSS imply lifetimes > 10^8 yr; Miller et al. 2003).

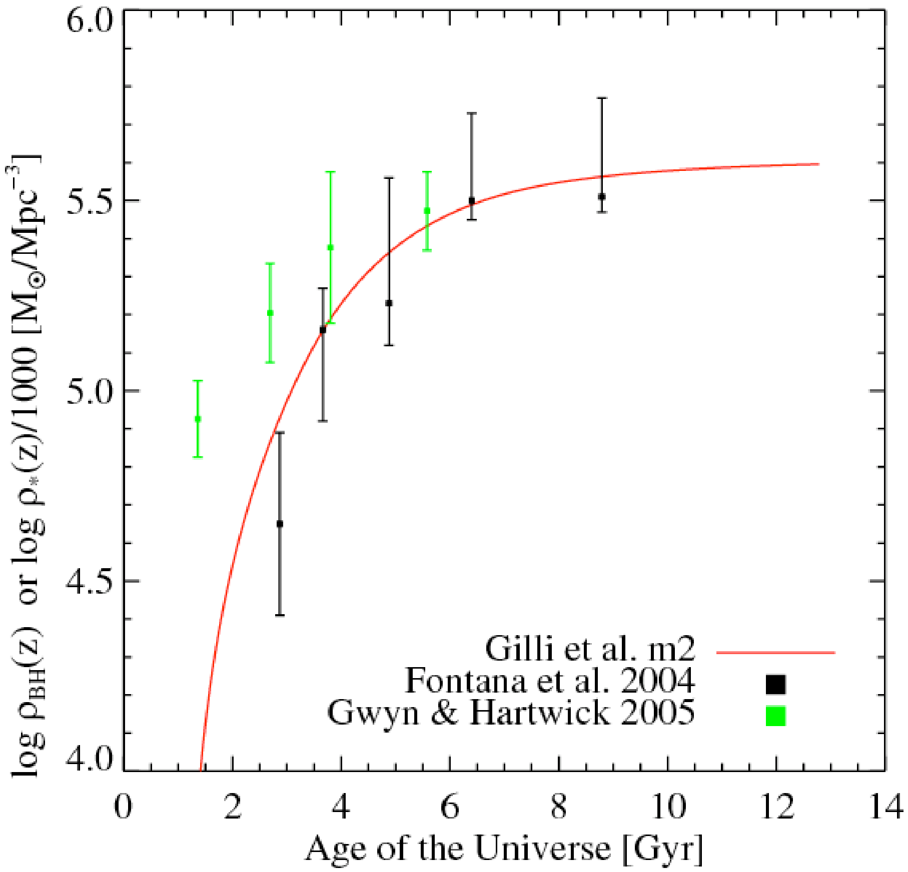
Duty cicle of active BHs



- _ is the fraction of Active BHs
- _ = _(L, t) / N(M_{BH}, t)
- _ = 1 @ z=3 is the initial condition (negligible effect on BH Mass Function at z=0)

Evolution of BH and stellar mass density

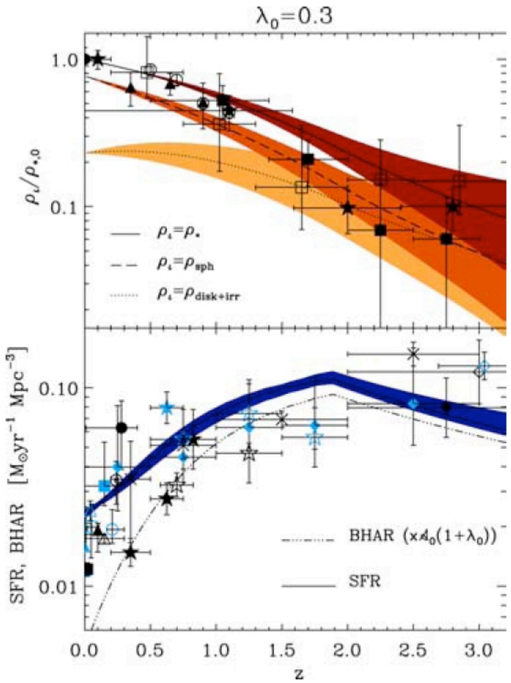


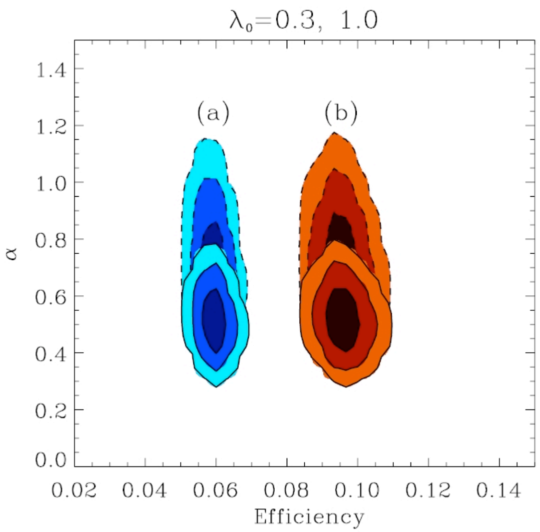


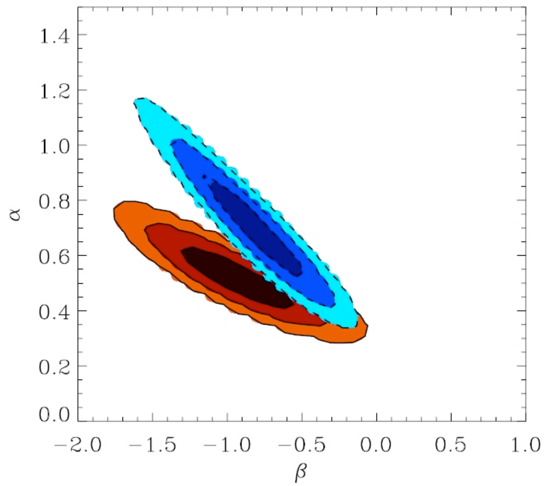
see also Merloni, Rudnick & Di Matteo 2004

Evolution of BH and stellar mass density

- Merloni, Rudnick & Di Matteo 2004:
  - Stellar Mass Density/BH mass density $(1+z)^{-}$-
  - Stellar Mass Disks+Irregulars/Spheroids $(1+z)^{-}$-
  - Compare BH mass density and accretion rate vs stellar mass density and SFR







Future Developments

- There are still “few” BH detections in nearby galaxies, many of them are at the very limit of reliability.
- It is clearly important to establish secure and accurate M_{BH}-galaxy scaling relations (see, e.g. consequences for galaxy evolutionary models).
- Need more BH mass measurements: high spatial resolution is the key point.
- Need to estimate BH masses beyond the local universe: assess reliability of virial BH mass estimates.

Future Developments

- A currently available possibility is adaptive optics near-ir assisted spectroscopy:
  - SINFONI/VLT is an integral field spectrograph now equipped with a laser guide star (extend the sky coverage up to ~50%)
- NIRSPEC/JWST will be an important instrument (> 2013)
- A possibility in the future (1-2 years) is provided by interferometry in the near-infrared.

Quick Intro on Interferometry

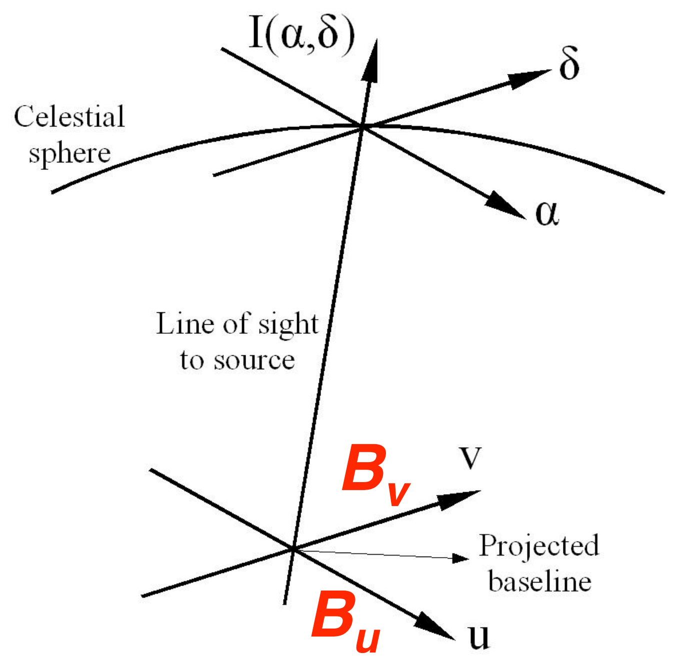
- Conventional telescope ⇨ image of the source

$$I_{\lambda,obs}(\alpha,\delta) = \iint P_\lambda(\alpha-\alpha',\delta-\delta')\, I_{\lambda,true}(\alpha',\delta')\,\mathrm{d}\alpha'\mathrm{d}\delta'$$

- 2-telescopes interferometer ⇨ complex visibility

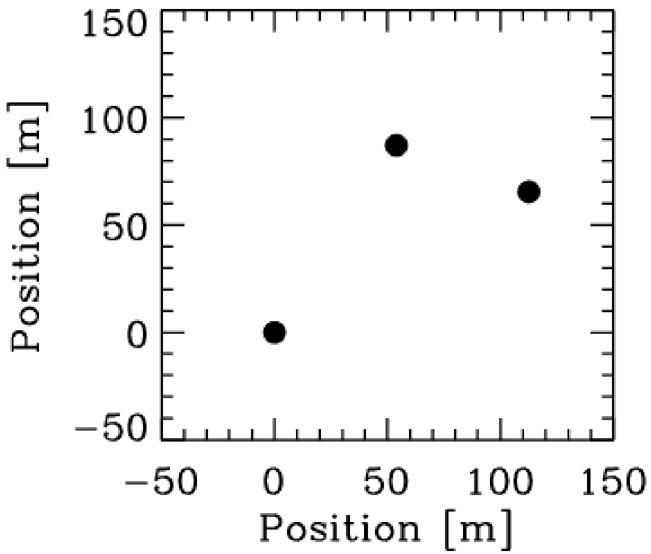
$$\upsilon_\lambda(u,v) = \iint I_{\lambda,true}(\alpha,\delta)\,\mathrm{e}^{-i2\pi(\alpha u+\delta v)}\,\mathrm{d}\alpha\mathrm{d}\delta \quad = \quad |\upsilon_\lambda(u,v)|\,\mathrm{e}^{i\phi_\lambda(u,v)}$$

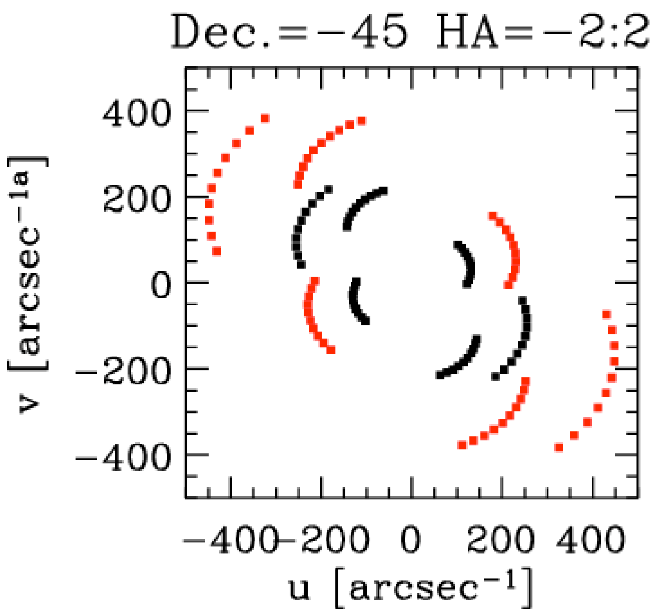
- $u=B_u/\lambda$, $v=B_v/\lambda$ spatial frequencies
- $|\upsilon_\lambda(u,v)|$ is the correlated flux;
  $|\upsilon_\lambda(0,0)|$ is the image total flux
- Often one uses the normalized visibility $V=|\upsilon_\lambda(u,v)|/|\upsilon_\lambda(0,0)|$;
  V=0/1 source is resolved/unresolved
- $\phi_\lambda(u,v)$, the phase, is VERY difficult to measure



Sampling the *u,v* plane

- 2-telescope interferometer
  =1 independent baseline ⇨ 1 indep. point in the *u,v* plane.
- N-telescopes interferometer
  = N(N-1)/2 independent baselines.
- Due to Earth rotation the projected baseline varies with time.
- Different wavelengths sample different points in *u,v* plane.
- Resolution of interferometer ~_/*B* (*B* max projected baseline).





VLT Interferometer

- 4 UT (8m) telescopes
  - max baseline 130m
  - max res 2.3 mas (J-K)

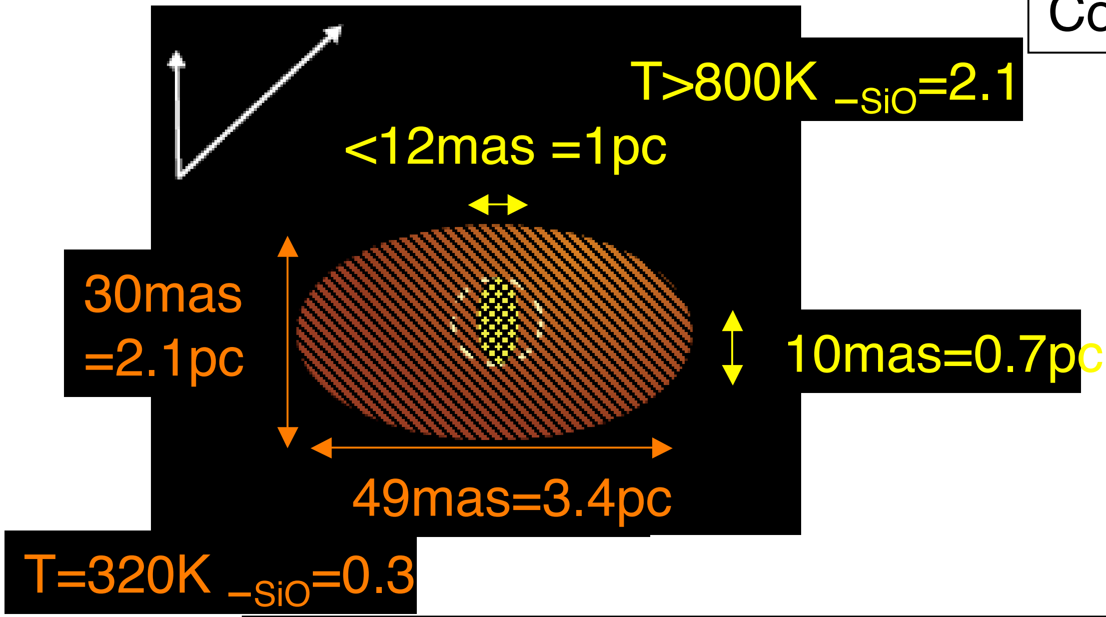
In most of cases it will not be possible to obtain a direct image of the source.

The observer will have to fit the measured visibility points with the FT of simple models of the source surface brightness as in the

- 3 AT (2m) telescopes which can be placed in 30 different stations
  - baselines 8-200m
  - max res 1-2 mas (J-K)
- MIDI
  - 8-13.5 _m, 2 beams, low spectral resolution (12/2002)
- AMBER
  - 1-2.5 _m, 3 beams, 3 spectral resolutions (100, 1000, 10000)

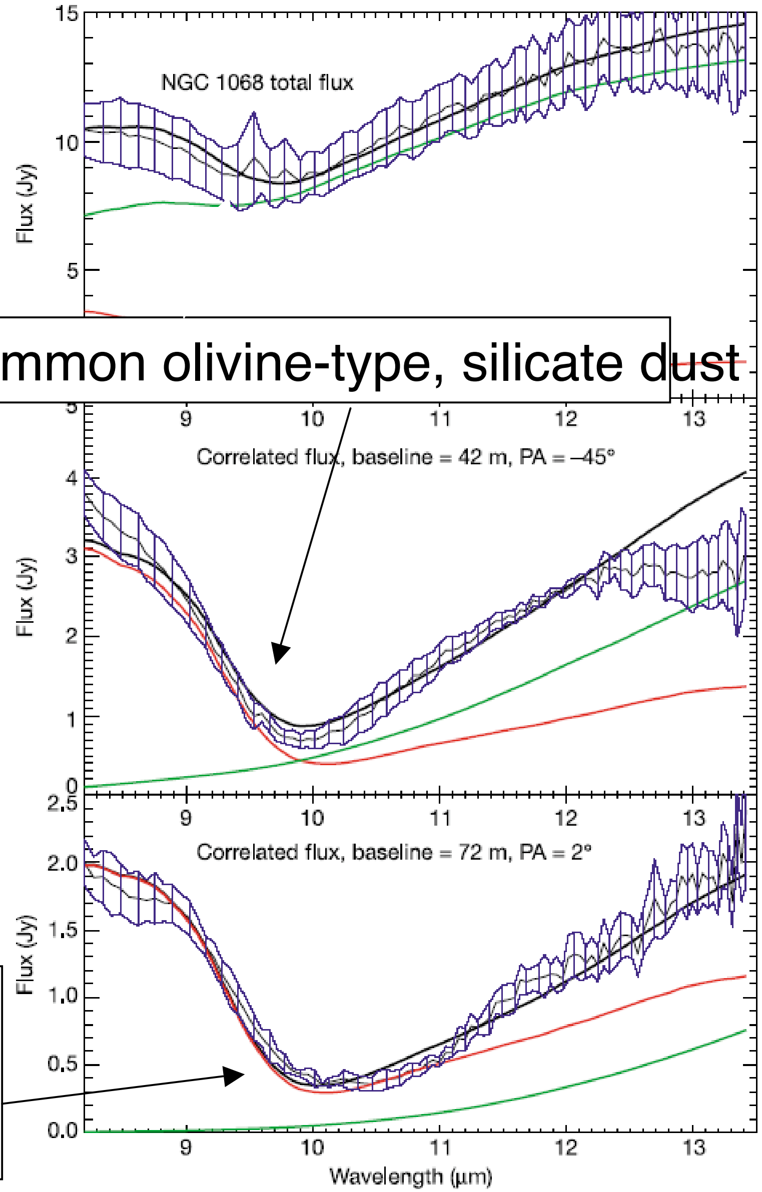
The Obscuring Torus in AGNs

- MIDI observations of NGC1068 with 2 baselines; fit with 2 gaussian comp. (Jaffe et al. 2004)



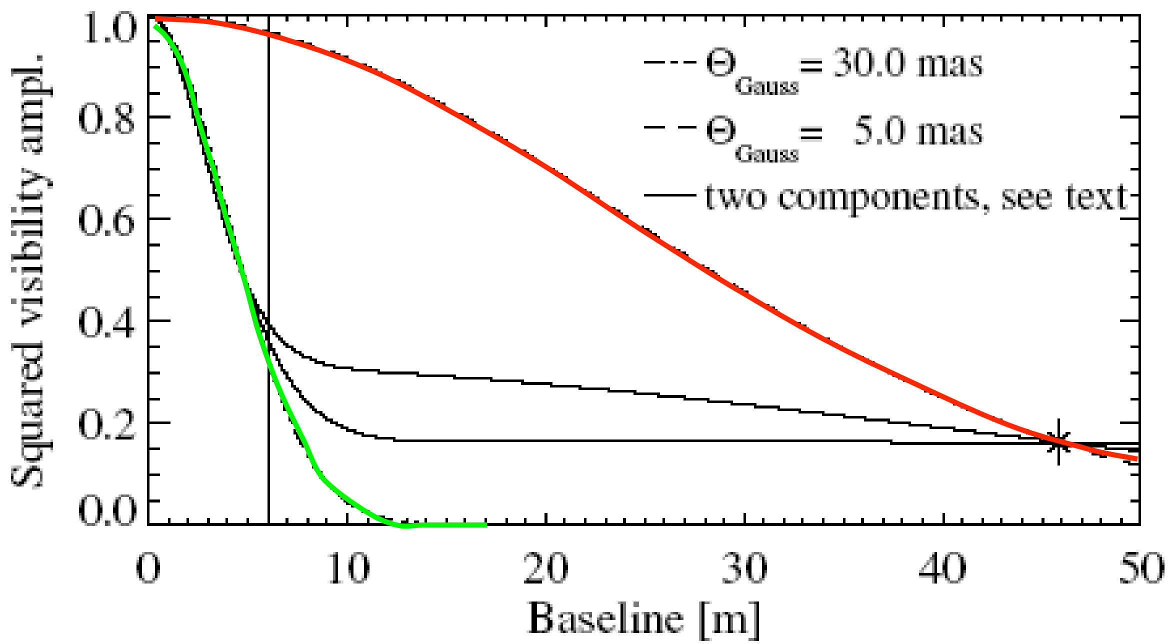
Calcium aluminum silicate (non olivine type) high T dust species found in some supergiant stars

Common olivine-type, silicate dust

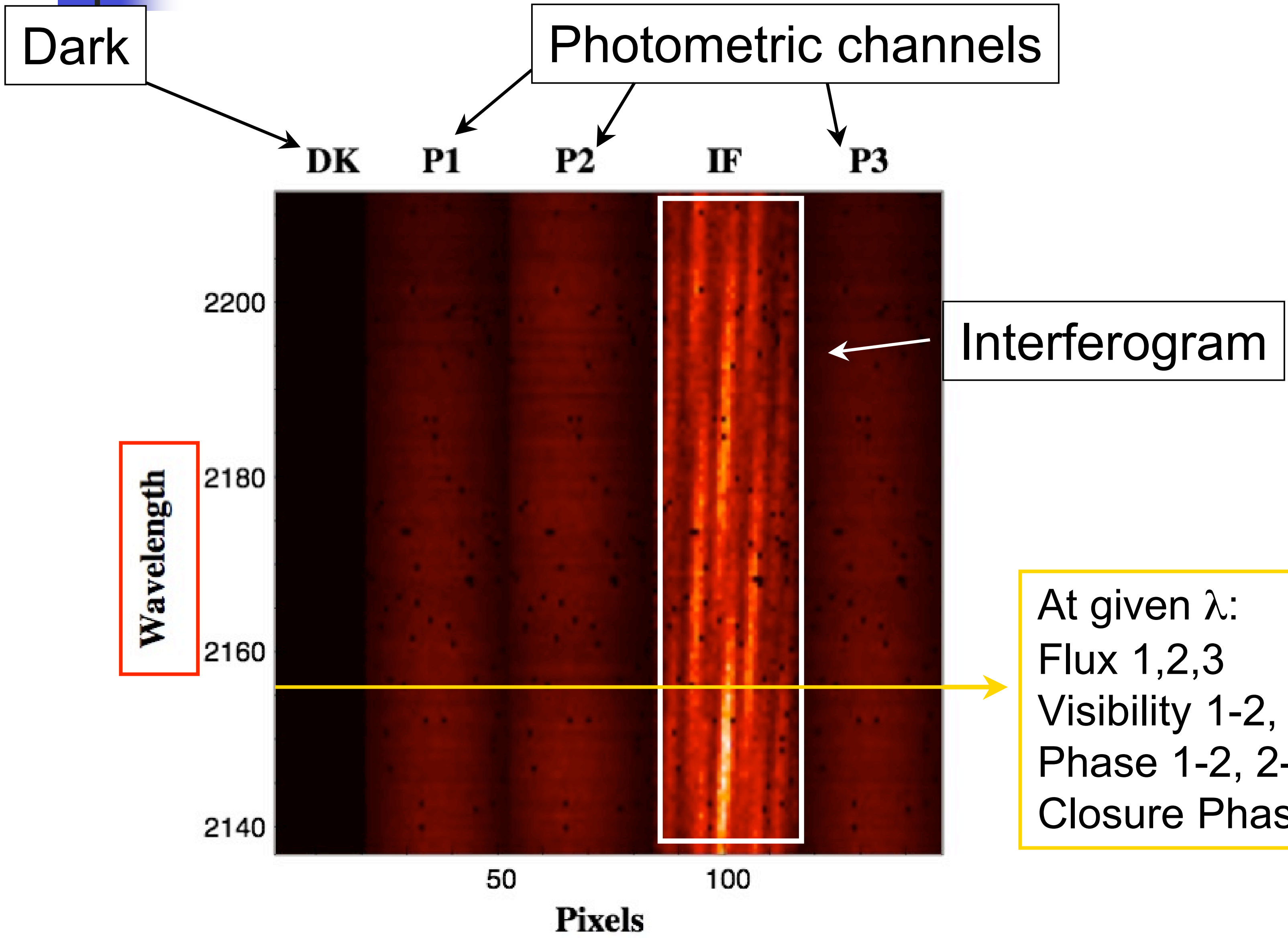


The Obscuring Torus in AGNs

- VINCI observations of NGC1068 (Wittkowski et al. 2004)
- The single visibility point can be matched with 5mas FWHM gaussian component
- Combining VINCI (B=46m) with bi-speckle interferometric data from the literature (B=6-10m), 2 components are required:
  - <5mas (0.35pc)
  - 30mas (2.1pc)

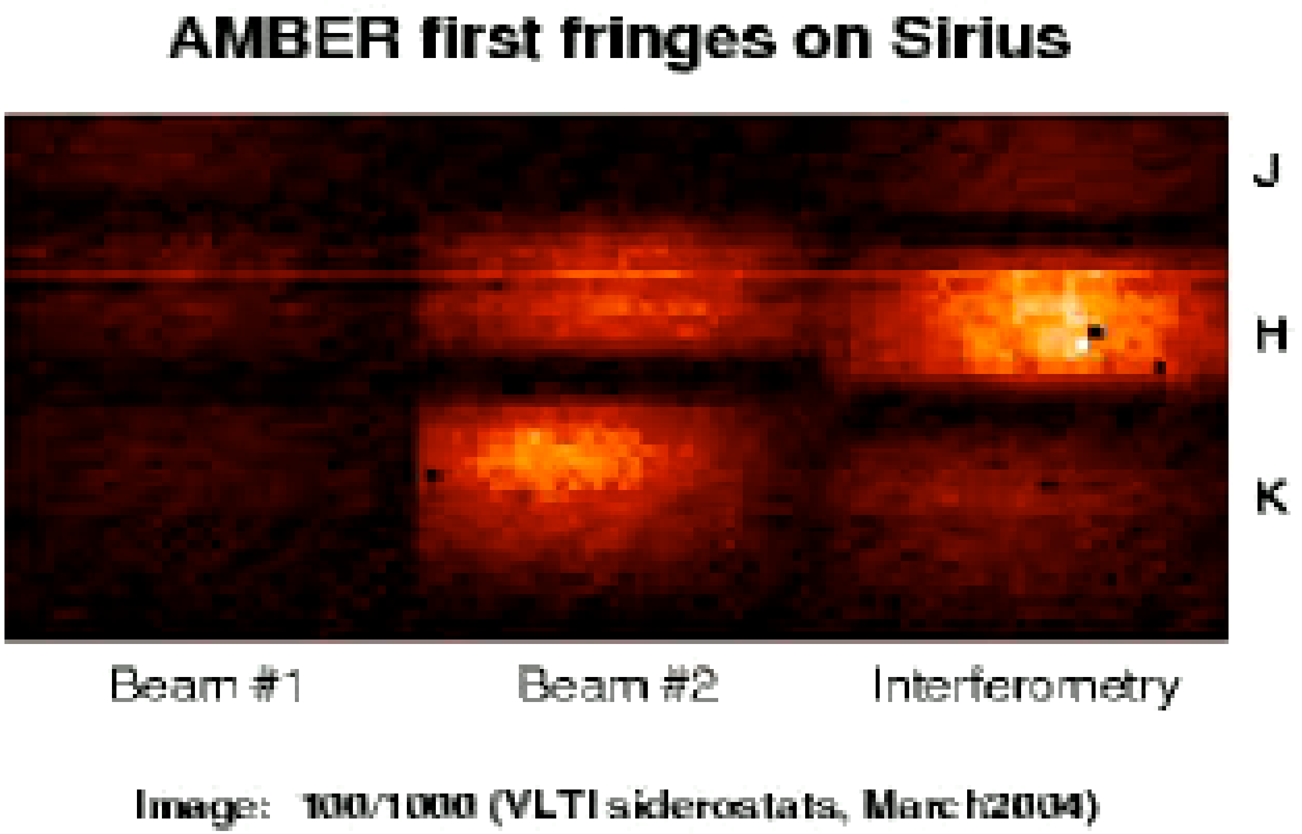


AMBER data



At given λ:
Flux 1,2,3
Visibility 1-2, 2-3, 1-3
Phase 1-2, 2-3, 1-3
Closure Phase

Atmospheric disturbance



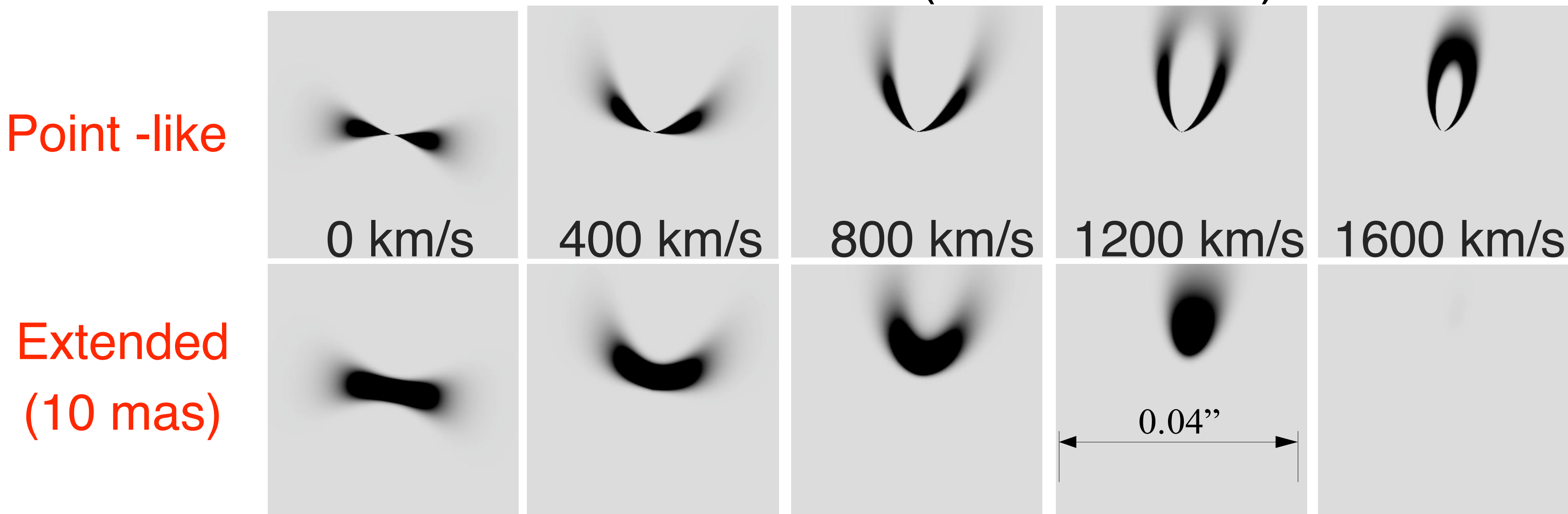
Atmospheric variations change the paths of the two beams and the fringes move on the detector. The instrument FINITO (fringe tracker) allows to integrate for long times by compensating in real time path variations.

Possible AMBER observations of AGNs/BHs

- The dusty torus in AGNs.
- Constrain spatial distribution of MDOs (*Massive Dark Objects* – alternatives to BHs).
  - Centaurus A can become the second best case for a BH after the Milky Way, better than NGC 4258.
- Size and Kinematics of the Broad Line Region in Seyfert 1 and Quasars.
  - Measure BH masses.
  - Study the R_{BLR}-L_{cont} relation (used in virial BH mass estimates).

Are MDO Black Holes?

- For example, Cen A has M_{MDO} ~2 x 10^8 $M_{□}$ (within r < 0.04” ~ 5pc) ⇒ _ ~ 10^8 $M_{□}$ 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 (2 mas sp. res.) will give _ ~ 10^{10} $M_{□}$ pc^{-3}, as good as NGC4258!
- This can be achieved using interferometric spectral information obtained with ℜ=750 (_V=400 km/s).



Unresolved source

- Unresolved source:

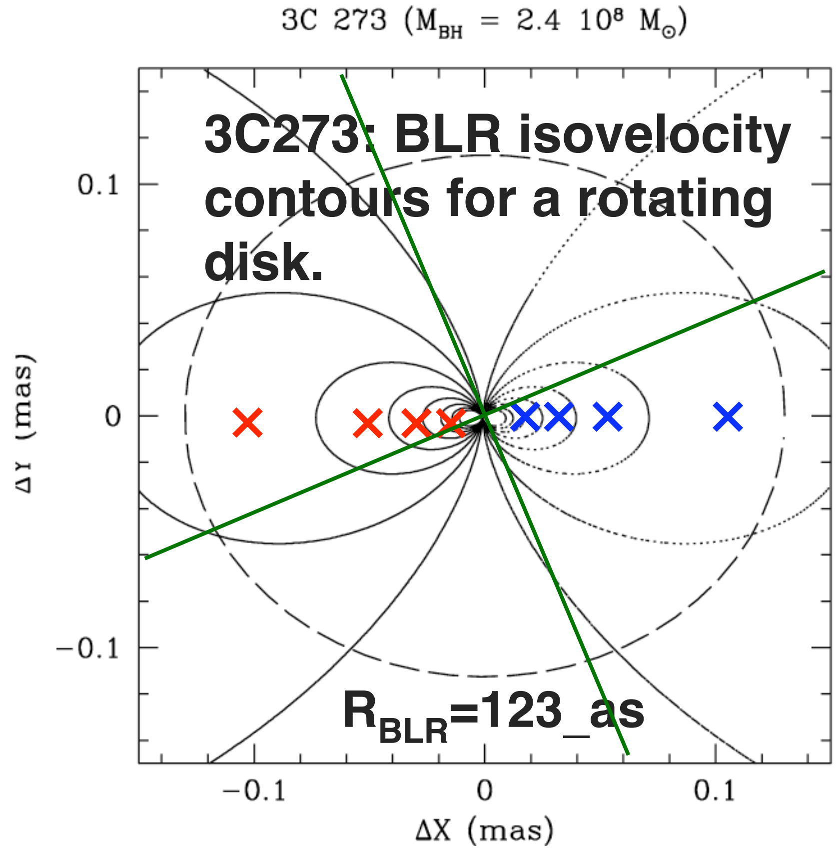
$$\upsilon_\lambda(u,v) = \iint I_{\lambda,true}(\alpha,\delta)\,\mathrm{e}^{-i2\pi(\alpha u+\delta v)}\,\mathrm{d}\alpha\,\mathrm{d}\delta \quad = \quad |\upsilon_\lambda(u,v)|\,\mathrm{e}^{i\phi_\lambda(u,v)}$$

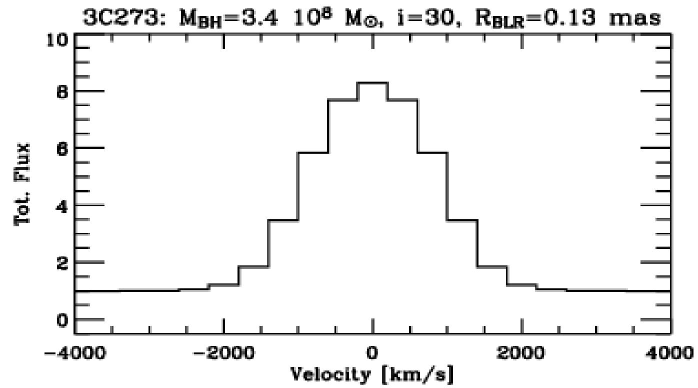
$$I_{\lambda,true}(\alpha,\delta) = \delta(\alpha-\alpha_0,\delta-\delta_0)$$

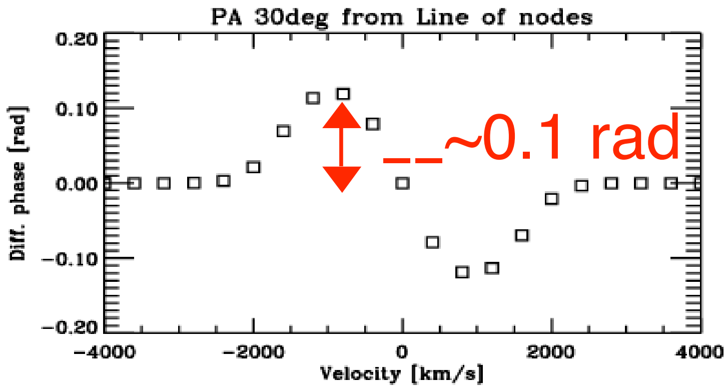
- Visibility (I amplitude I^2 of FT) is 1
- But phase depends on the position of the source on the sky plane.
- Can use phase information to measure positions at an accuracy much larger than spatial resolution.

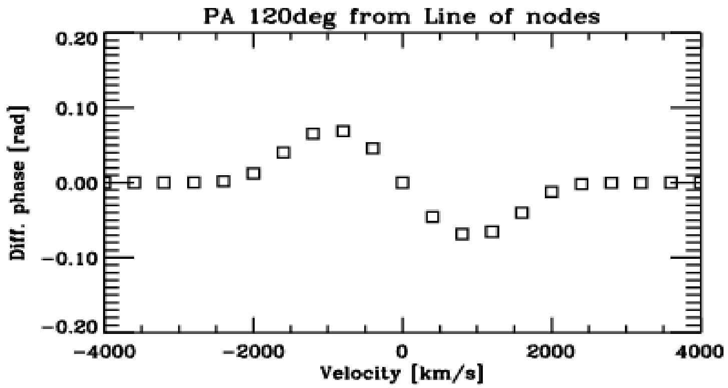
The Broad Line Region

- BLR size from reverberation mapping: from ~1 _as to ~200 _as, unresolvable with VLTI.
- The differential phase measures the position of the photocenter along a 2-tel. baseline with a few _as accuracy!

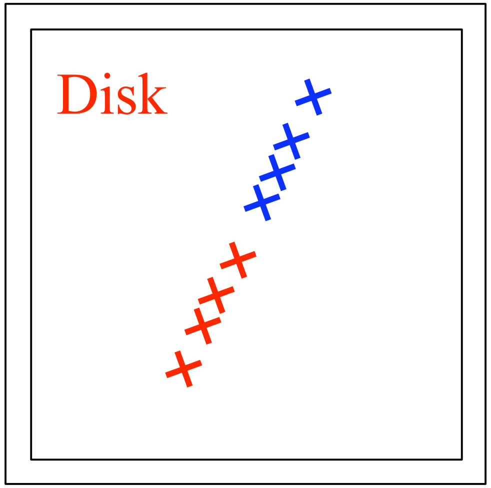


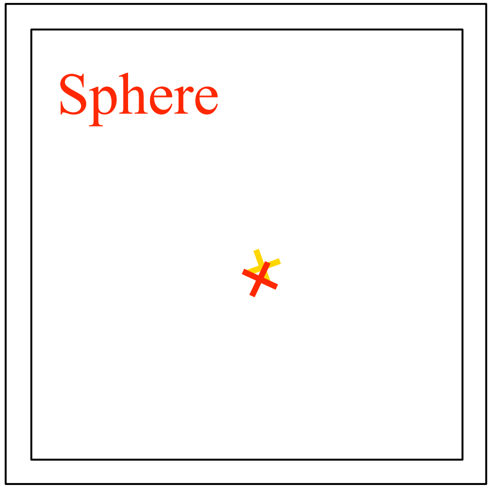


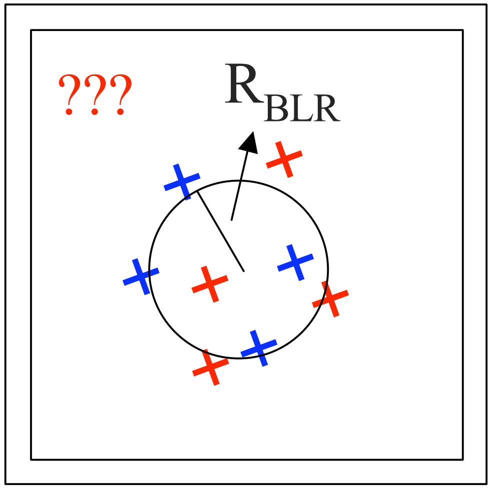




BLR geometry and kinematics



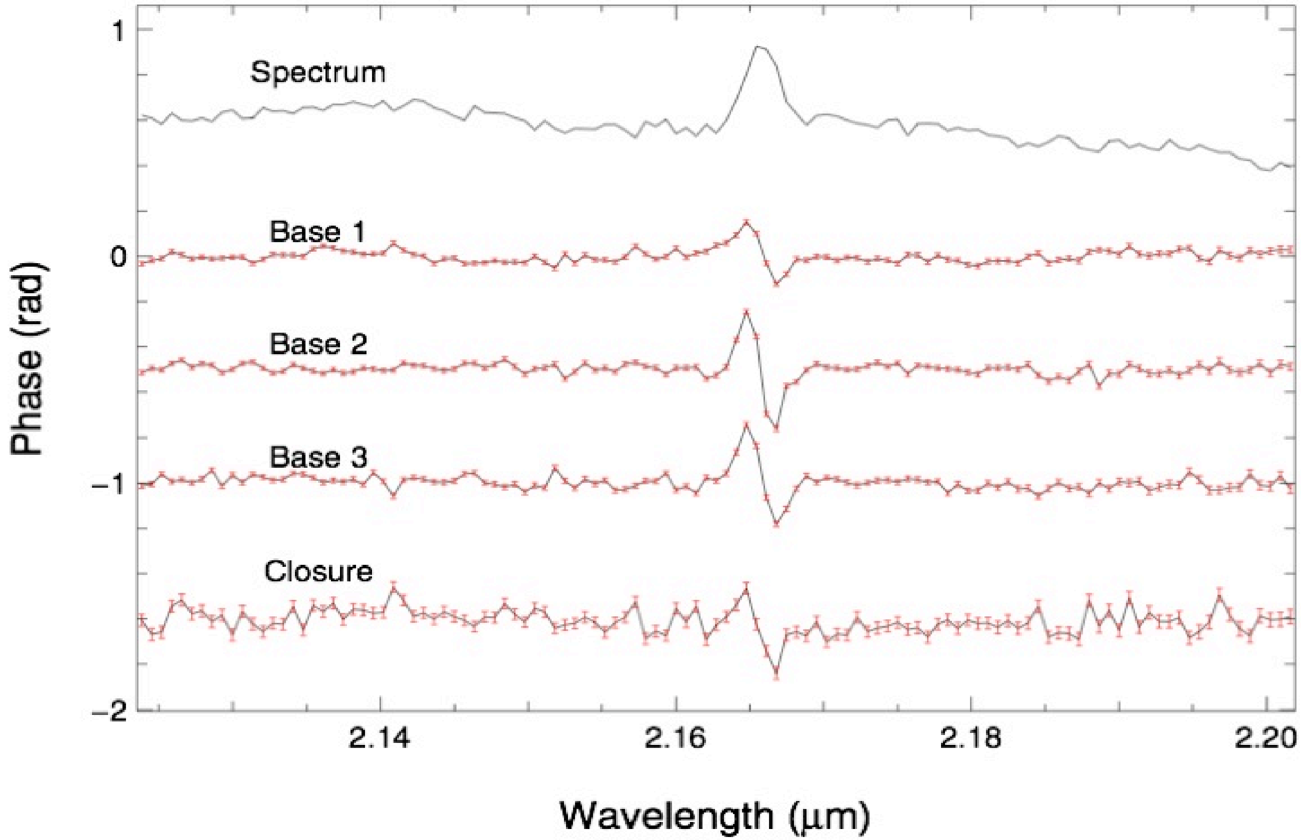




- With Differential Phase one can constrain BLR geometry and Kinematics.
- Estimate R_{BLR}.
- If BLR in a rotating disk estimate BH Mass!
- Study R_{BLR}-L relation (reliability of virial estimates of BH mass – only way to estimate MBH at high redshifts)
- Compare BLR sizes with rev. mapping we can then determine cosmological parameters, e.g. H_0 (see Elvis & Karowska 2002).

Example of differential phase

- Brγ emission line in Be star α Arae (Meilland et al. 2006)



Observational Requirements (UT)

- Reference Source for AO correction with MACAO
  - size <2.5"
  - V<15.5
  - up to 1' off axis
  - seeing <1" in V (median seeing VLT 0.65")
- Reference for Fringe Tracking with FINITO
  - point source
  - H<11
  - up to 2" off axis (20" with PRIMA)
- AGNs are ideal because the target itself can be used for AO and Fringe Tracking.
- Many quasars from 2MASS are good targets!

AMBER expected performances (3UT)

- No fringe tracking, median seeing (0.65”)

Resolution	J	H	K
R=35	8.8	10.5	11.6

- Fringe tracking (ref. sou. <2”, H<11), med. seeing

Resolution	J	H	K
R=35	18.5	20.2	19.8
R=1000	14.4	16.6	17.4
R=10000	11.9	14.1	15.1

General Conclusions

- Supermassive BHs (10^6-10^{10} $M_{\odot}$) are detected in nearby galaxies
  - although, except for the Milky Way, they could be massive dark clusters...
- M_{BH} correlates tightly with the structural parameters of the host spheroid
  - this relation is probably the consequence of AGN (=accreting BH) feedback on the host galaxy
  - this relation could be much worse than we think (or could even be an upper envelope).
- Local supermassive BHs are consistent with being remnants of AGNs.
  - accretion efficiency is about $\varepsilon \sim 0.1$
- Exciting possibilities in the next few years are offered by near-IR interferometry (BLR size ...).