A New Cosmological Distance Measure Using AGN X-Ray Variability

Stefano Bianchi

ROMA TRE
UNIVERSITÀ DEGLI STUDI

Fabio La Franca, Gabriele Ponti, Enzo Branchini, Giorgio Matt

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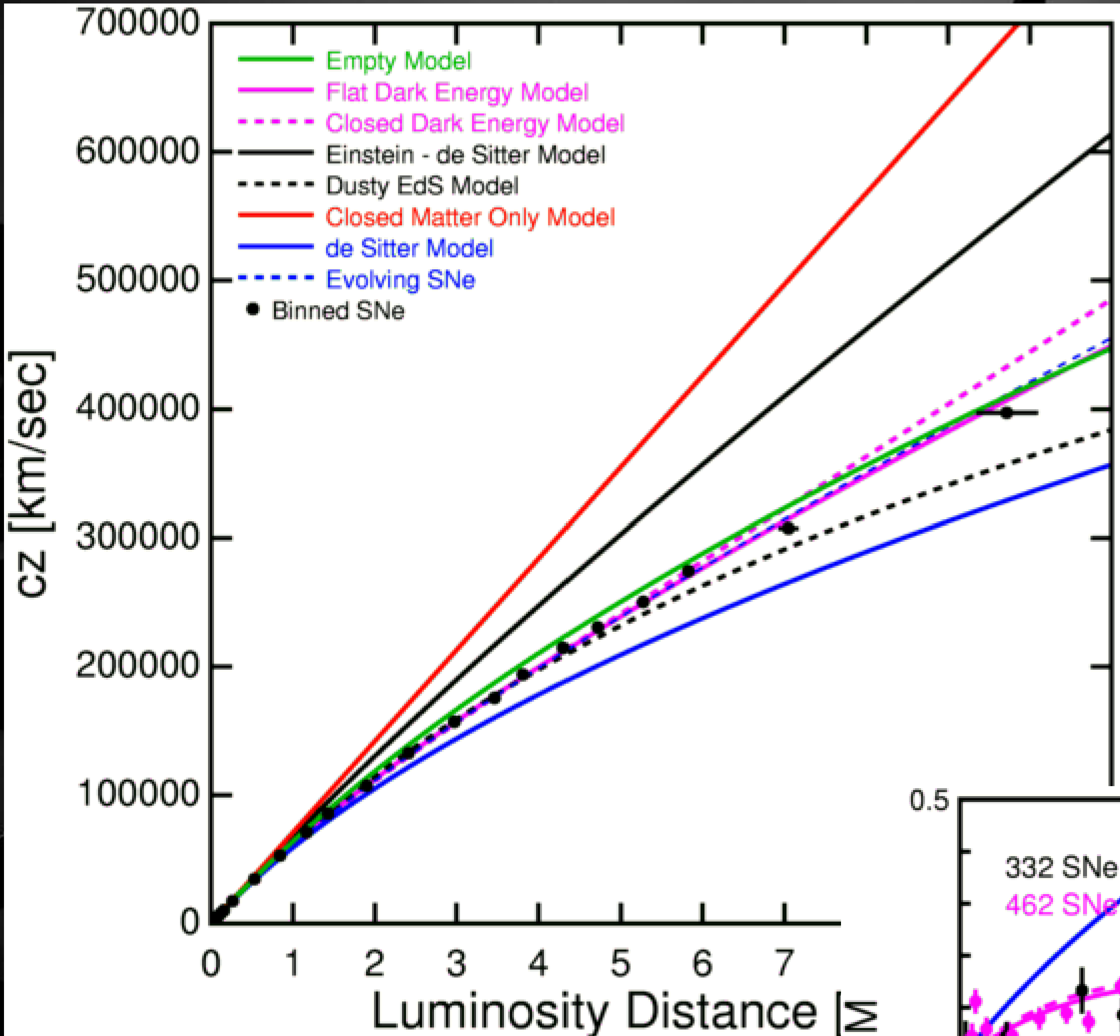
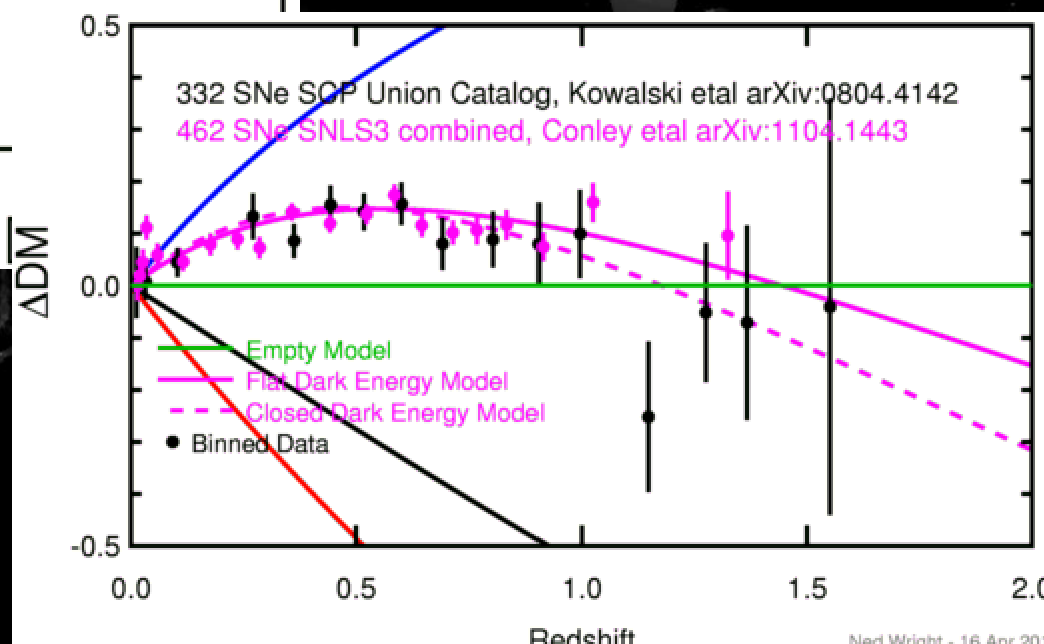


One of the most important results of observational cosmology is the discovery of the accelerating expansion of the universe, using SNeIa as standard candles

However, the use of SNeIa is difficult beyond z ~ 1 and limited up to z ~ 2



<u>**Given their high luminosities, there have been several studies on the use of AGN as standard candles**</u>

Virial BH Masses: From Reverberation Mapping to Single-Epoch Methods

The BLR in AGN is powered by photoionization from the central source. RM lags provide an estimate of its size. If we assume that the BLR is virialized and dominated by the gravitational field of the central BH, then the BH mass is

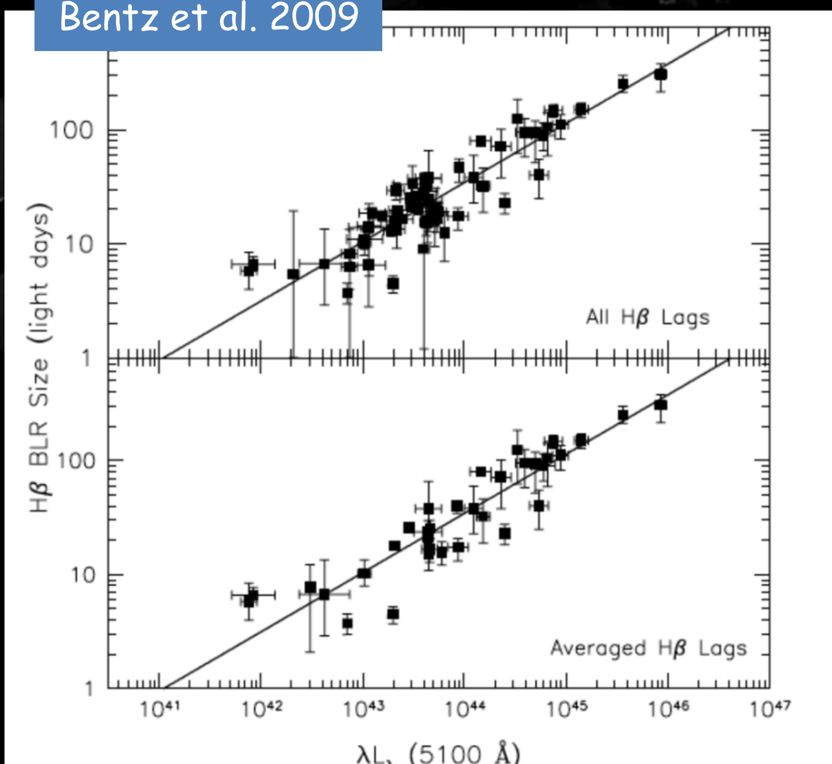
$$M_{BH} = \frac{f \Delta V^2 R}{G}$$

Geometrical Factor (f)

BLR Velocity (FWHM) (ΔV)

BLR Radius (RM lag) (R)

Bentz et al. 2009



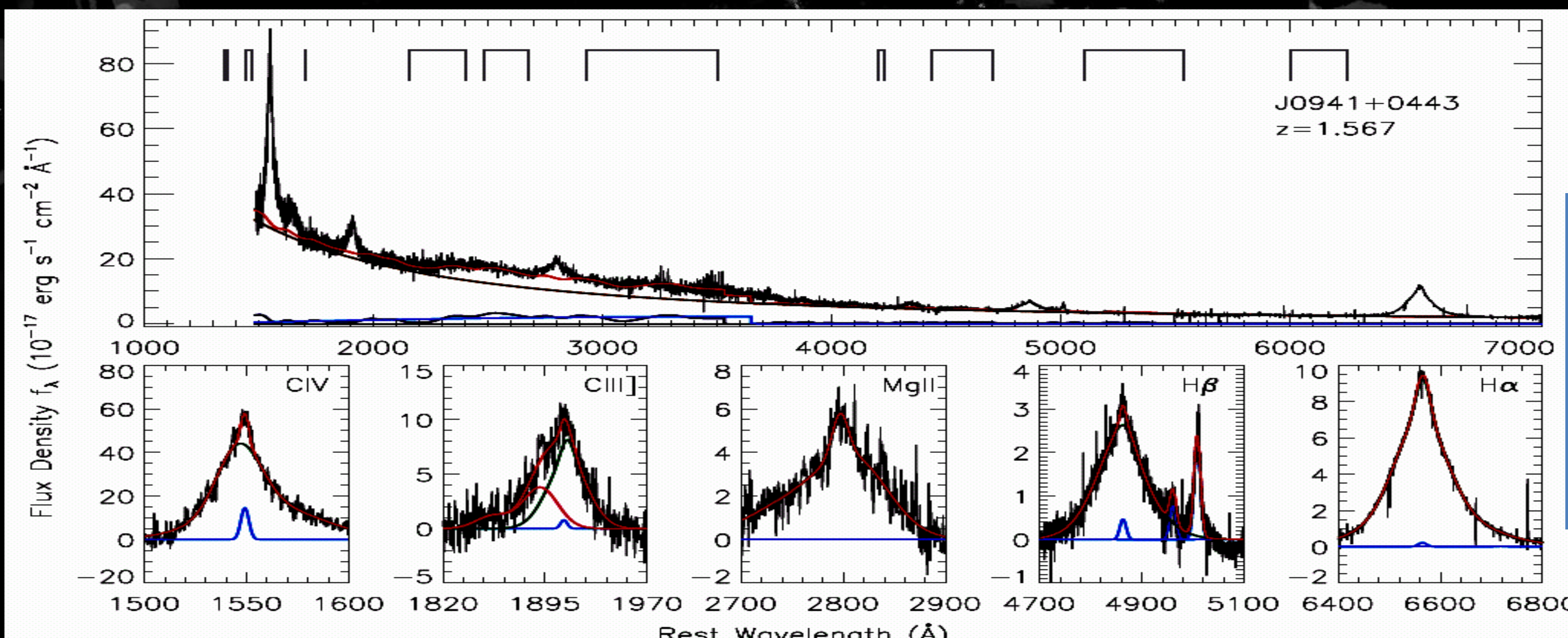
RM observations found a tight correlation between the BLR size and the optical continuum luminosity. A slope of alpha = 0.5 is found, as expected, if U and the electron density are more or less constant, and/or if the BLR size is set by dust sublimation

It was suggested to use the *R* - *L* relation (~0.15 dex) as an absolute luminosity indicator, although RM is very time consuming and still limited to local AGN

Virial BH Masses: From Reverberation Mapping to Single-Epoch Methods

The observed R-L relation provides a much less expensive way to estimate the size of the BLR, allowing a **<u>single-epoch virial BH mass estimator</u>**: from the same spectrum, one estimates the BLR size from the measured luminosity using the R-L relation, and the width of the broad emission line (typically, Hβ or MgII 2798Å or CIV 1459Å). The derived BH masses have uncertainties ~0.5 dex

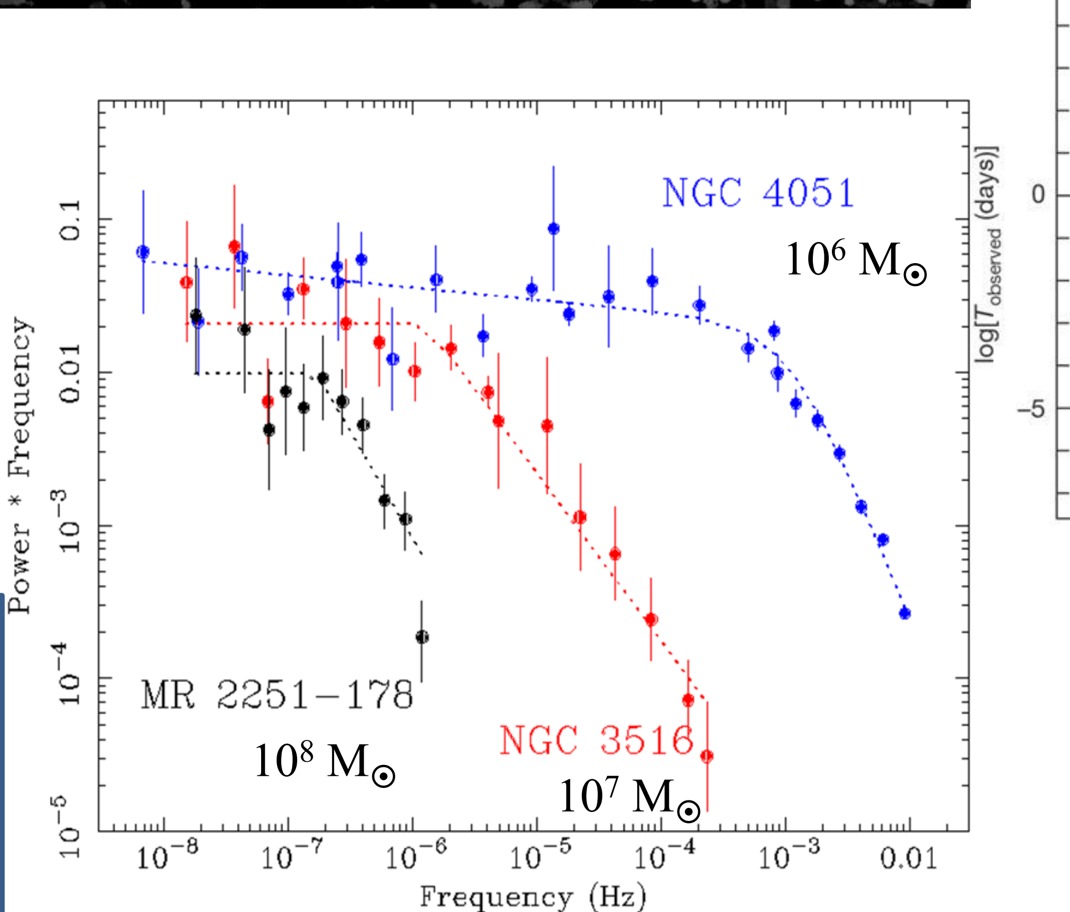
$$\log\left(\frac{M_{\rm BH,vir}}{M_\odot}\right) = a + b\log\left(\frac{\lambda L_\lambda}{10^{44}\,{\rm erg\,s^{-1}}}\right) + 2\log\left(\frac{\rm FWHM}{\rm km\,s^{-1}}\right)$$



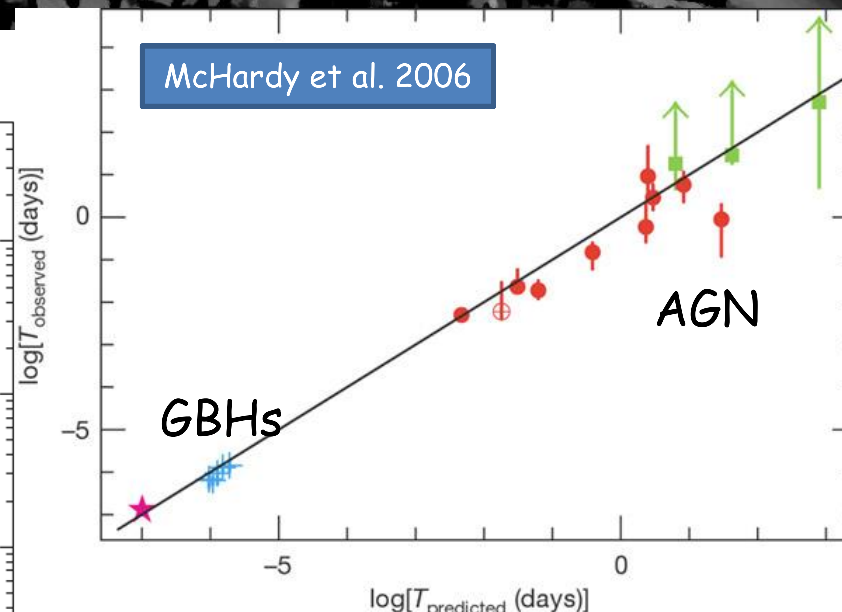
Shen & Liu 2012

BH Mass and X-ray Variability

AGN X-ray PSDs are generally well modeled by two power laws, $P(\nu) \propto 1/\nu^n$, where the PSD slope is n~1 down to a break frequency, ν_b, that scales primarily with M_{BH}, and then steepens to n~2 at larger frequencies



Uttley et al. 2005



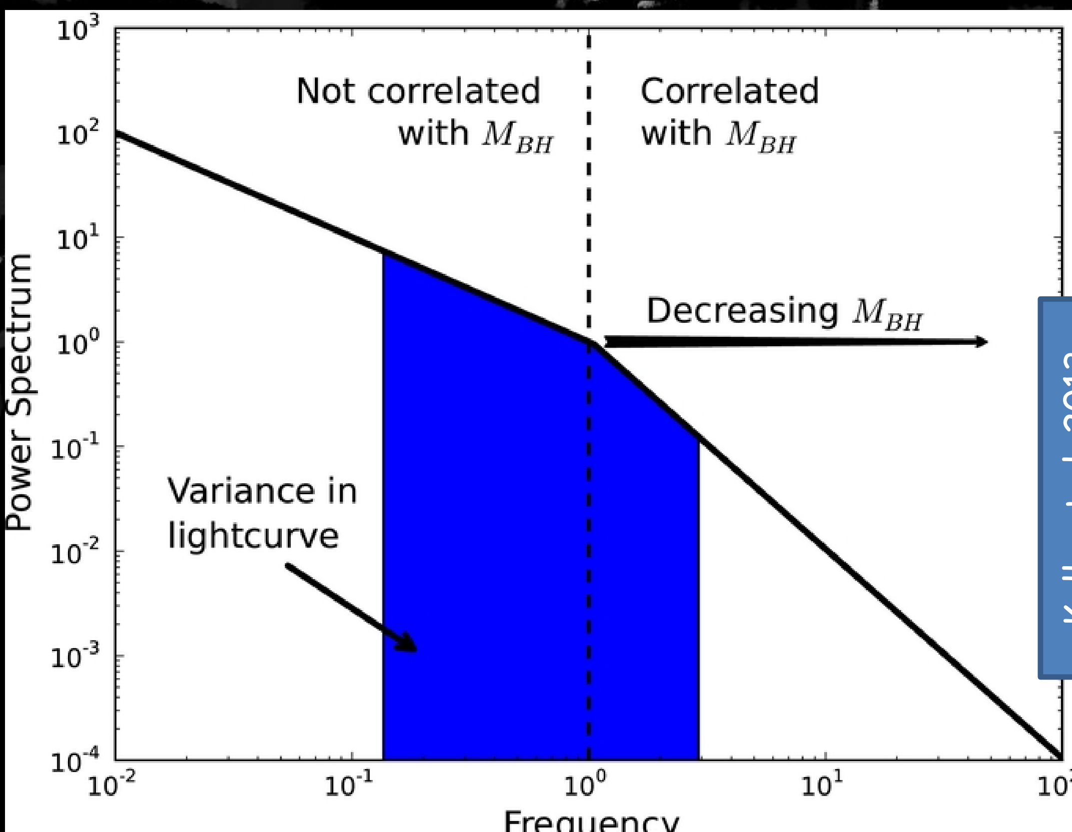
McHardy et al. 2006

The break frequency scale with M_{BH} in all accreting BHs

BH Mass and X-ray Variability

AGN X-ray PSDs are data demanding, requiring high-quality data on different timescales. On the contrary, the **excess variance** is a robust estimator as it corresponds to the integral of the PSD on the timescales probed by the data

$$\sigma_{\rm rms}^2 = \frac{1}{N\mu^2}\Sigma_{i=1}^{N}\left[(X_i-\mu)^2-\sigma_i^2\right]$$



Kelly et al. 2013

The scaling of the characteristic frequencies of the PSD with M_{BH} induces a dependence of the excess variance with M_{BH} (if computed at frequencies above ν_b)

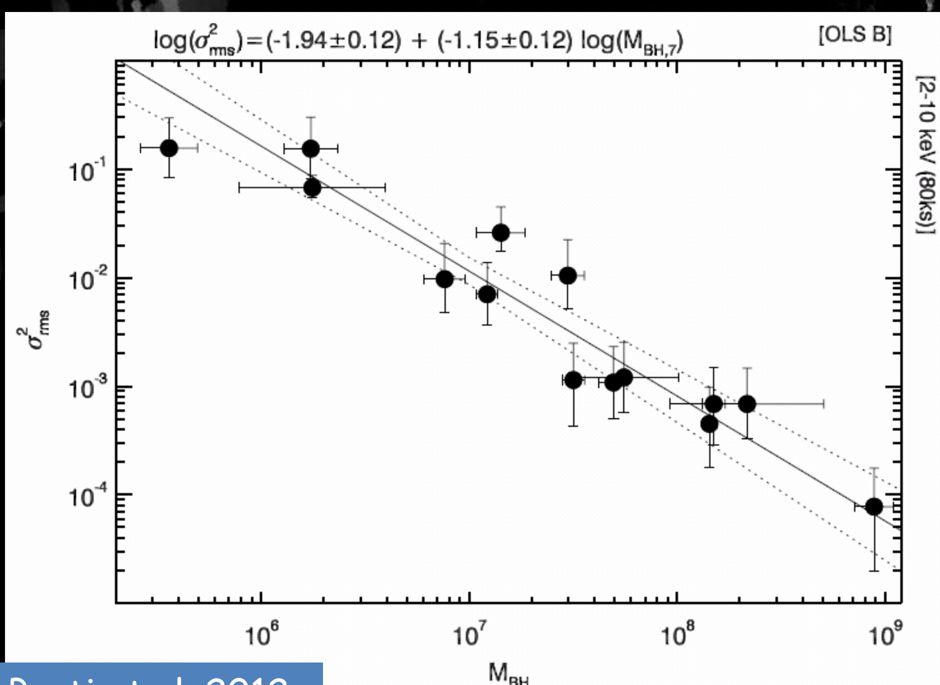
BH Mass and X-ray Variability

Several studies have indeed found a significant anti-correlation between M_{BH} and X-ray variability

(Nandra et al. 1997; Turner et al. 1999; Lu & Yu 2001; O'Neill et al. 2005; McHardy et al. 2006; Gierliński et al. 2008; Zhou et al. 2010; Ponti et al. 2012; Kelly et al. 2013)

$$\log M_{\rm BH} = -k \log \sigma^2_{\rm rms} + w$$

The constants depend on the timescale and the energy range where the variable flux is measured



Ponti et al. 2012

According to X-ray variability studies on samples of AGNs whose M_{BH} has been measured with reverberation mapping techniques, **these kinds of relationships could have spreads as narrow as 0.2–0.4 dex** (Zhou et al. 2010; Ponti et al. 2012; Kelly et al. 2013)

Single Epoch M_{BH} estimate

$$\log M_{\rm BH} = \alpha \log L + \beta \log \Delta V + \gamma$$

α~0.5 (R-L relation)
β~2 (virial motion)

+

X-ray variability M_{BH} estimate

$$\log M_{\rm BH} = -k \log \sigma^2_{\rm rms} + w$$

$$\log L = -2k \log \sigma^2 - 4 \log \Delta V + \text{const.}$$

We have a luminosity (distance) estimator!

It should be noted that in many previous studies a correlation between the AGN luminosity and X-ray variability has been measured (e.g., Ponti et al. 2012; Shemmer et al. 2014, and references therein).
Such a correlation is the projection on the L–rms plane of our proposed three-dimensional relationship among L, rms, and ΔV.
If this is the case, we should measure a more significant and less scattered relation than previously reported using only L and rms

Calibration: The Sample

CAIXA
Catalogue of AGN In the XMM-Newton Archive
(Bianchi et al. 2009, Ponti et al. 2012)

rms (2-10 keV, 20ks) with significance greater than 1.2σ

Hβ, L_{5100} OR Paβ

=

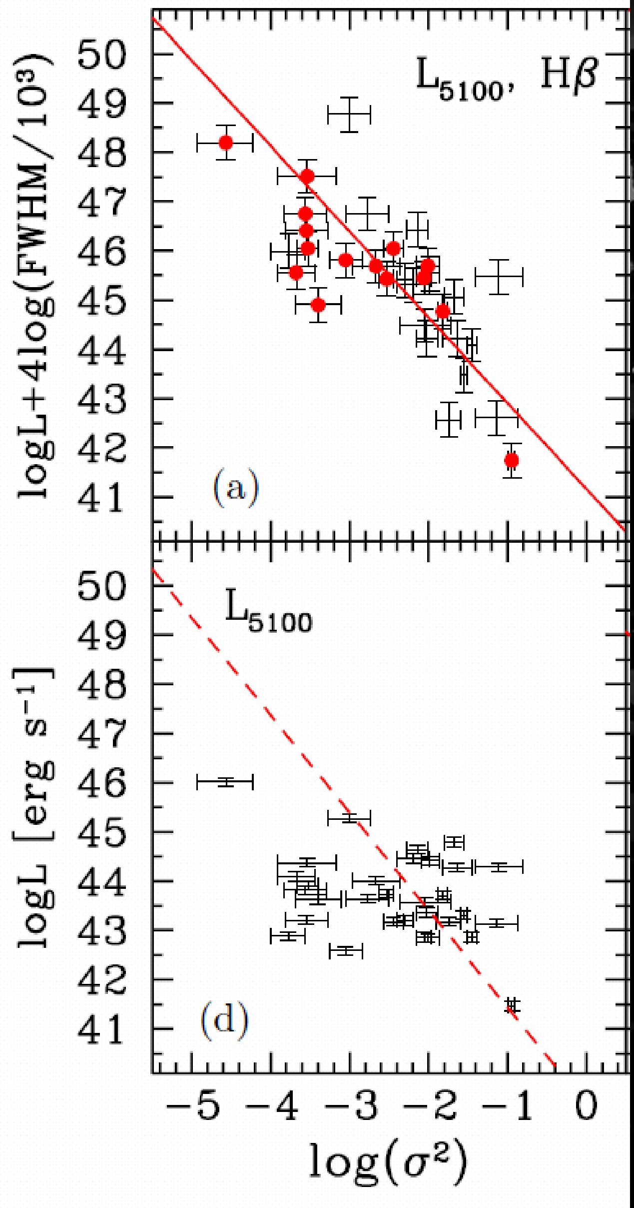
40 AGN (mostly with z<0.1)

38 with Hβ

18 with Paβ

Calibration: The Fits

$$\log \frac{L}{\mathrm{erg\,s^{-1}}} + 4\log \frac{\mathrm{FWHM}}{10^3\,\mathrm{km\,s^{-1}}} = \alpha \log \sigma^2_{\mathrm{rms}} + \beta$$



The square of the virial product, using L_{5100} and FWHM Hβ, is strongly correlated with the rms ($N=31$, $r = -0.73$, $P\sim 3\times10^{-6}$)

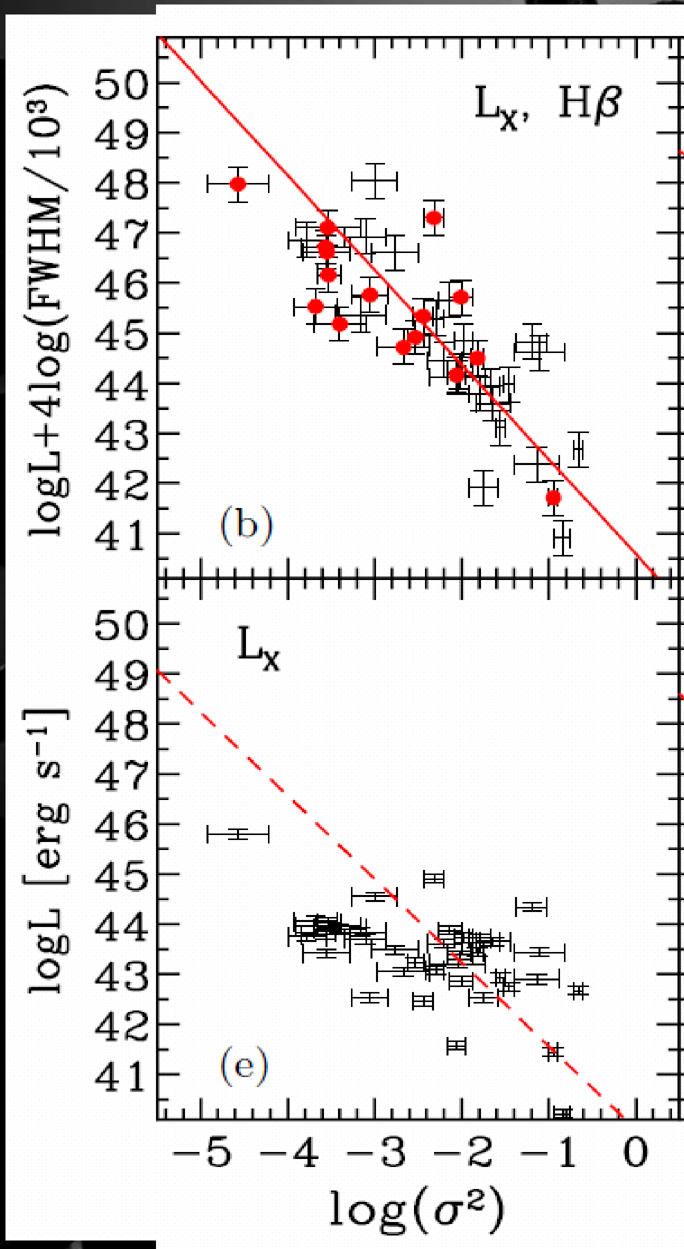
The observed and intrinsic (subtracting in quadrature the data uncertainties) spreads are 1.12 dex and 1.00 dex

If the same sample is used, the linear correlation between L_{5100} and rms has a spread of 1.78 dex, while the correlation coefficient is -0.36 ($P\sim 5\times10^{-2}$)

The virial product is significantly better correlated with the AGN variability than the luminosity alone

Calibration: The Fits

$$\log \frac{L}{\mathrm{erg\,s^{-1}}} + 4\log \frac{\mathrm{FWHM}}{10^3\,\mathrm{km\,s^{-1}}} = \alpha \log \sigma^2_{\mathrm{rms}} + \beta$$

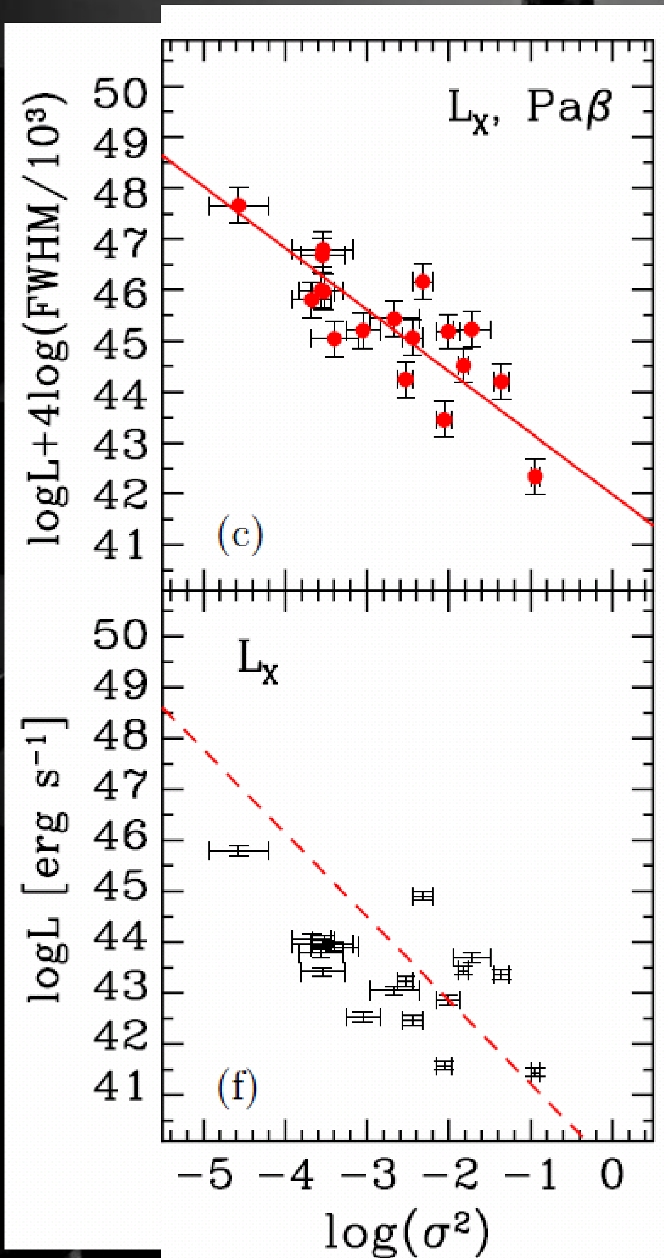


Slightly better results are obtained if the intrinsic 2–10 keV luminosity is used to compute the virial product
(N=38, r =–0.81, P~3×10^{-10})
In this case, the total and intrinsic spreads are 1.06 dex and 0.93 dex

Also in this case, the virial product is better correlated with rms than L_X alone is (r=–0.57 and spread 1.36)

Calibration: The Fits

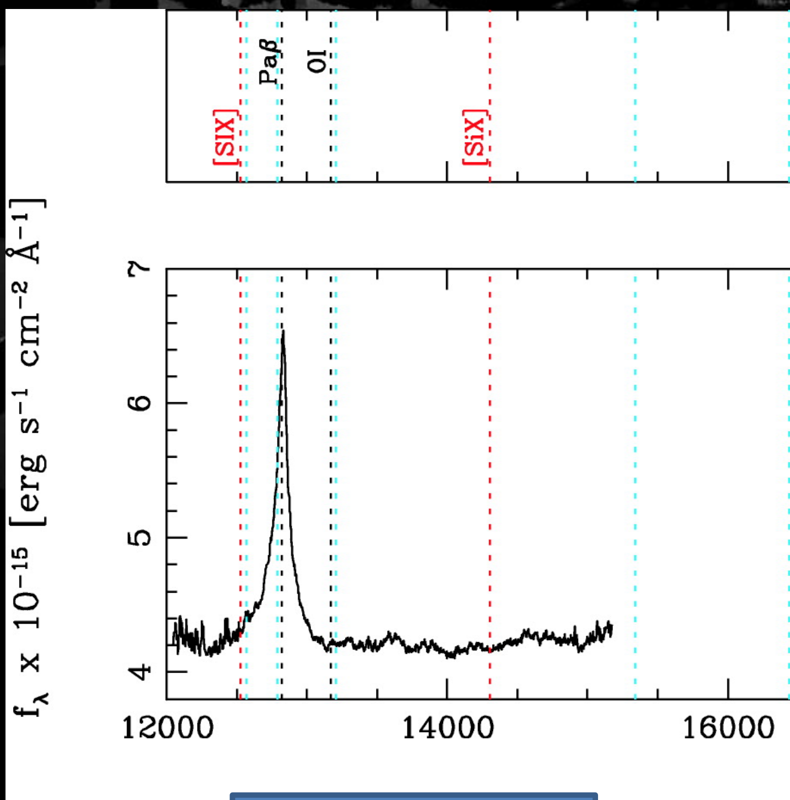
$$\log \frac{L}{\mathrm{erg\,s^{-1}}} + 4 \log \frac{\mathrm{FWHM}}{10^3\,\mathrm{km\,s^{-1}}} = \alpha \log \sigma^2_{\mathrm{rms}} + \beta$$



<u>If the virial product is computed using L_X and Paβ, the spreads considerably decrease</u> down to 0.71 dex (total) and 0.56 dex (intrinsic) (N=18, r =−0.82, P~3×10^{-5})

The correlation between L_X only and rms has instead a less significant coefficient r =−0.63 (P~4×10^{-3}) and a larger spread of 1.33 dex

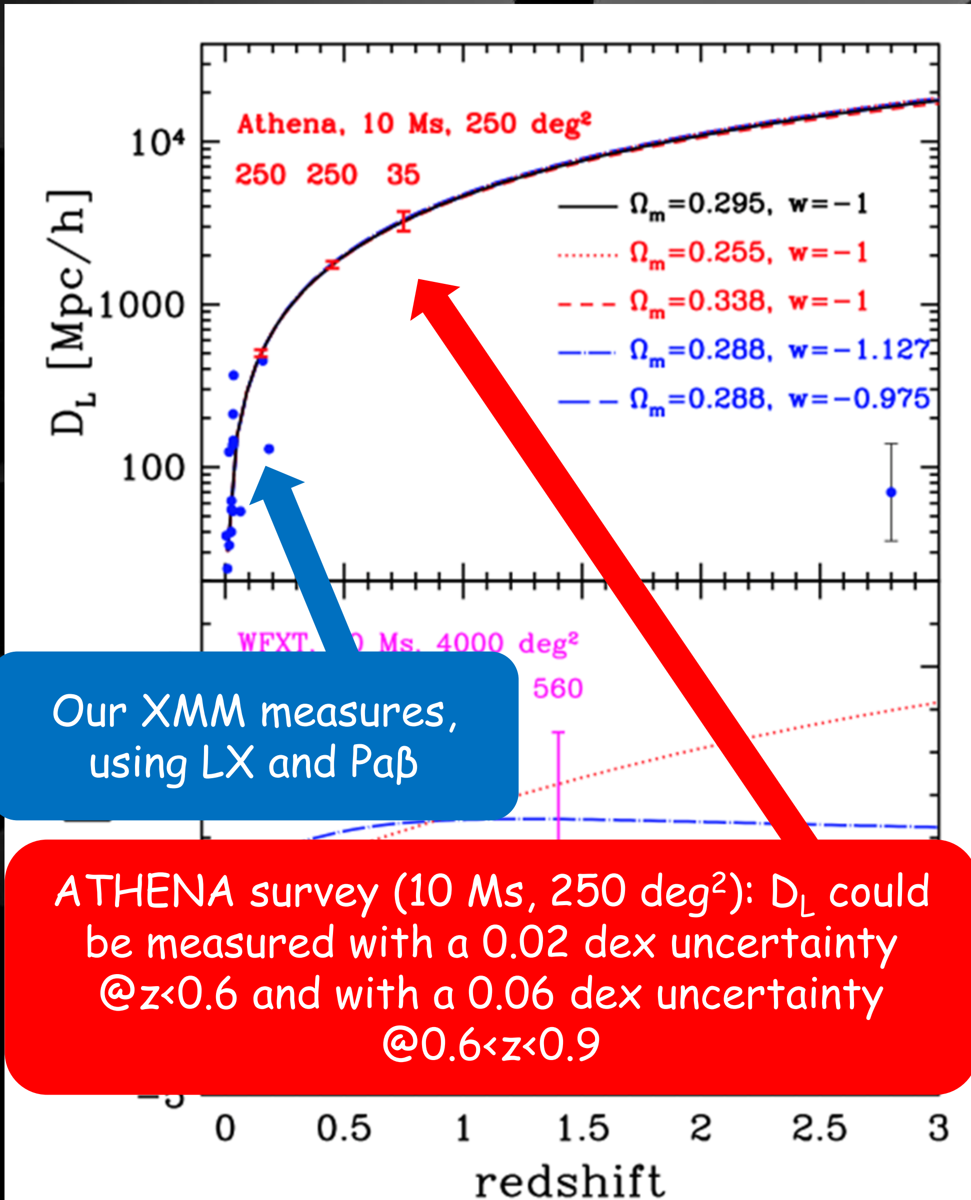
The fits described above show that highly significant relationships exist between the virial products and the AGN X-ray flux variability. **<u>These relationships allow us to predict the AGN 2–10 keV luminosities</u>**



Landt et al. 2008

The less scattered relation has a spread of 0.6–0.7 dex and is obtained when the Paβ line width is used

This could be either because the Paβ broad emission line, contrary to Hβ, is observed to be practically unblended with other chemical species or, as our analysis is based on a collection of data from public archives, the Paβ line widths, which come from the same project (Landt et al. 2008, 2013), could have therefore been measured in a more homogeneous way



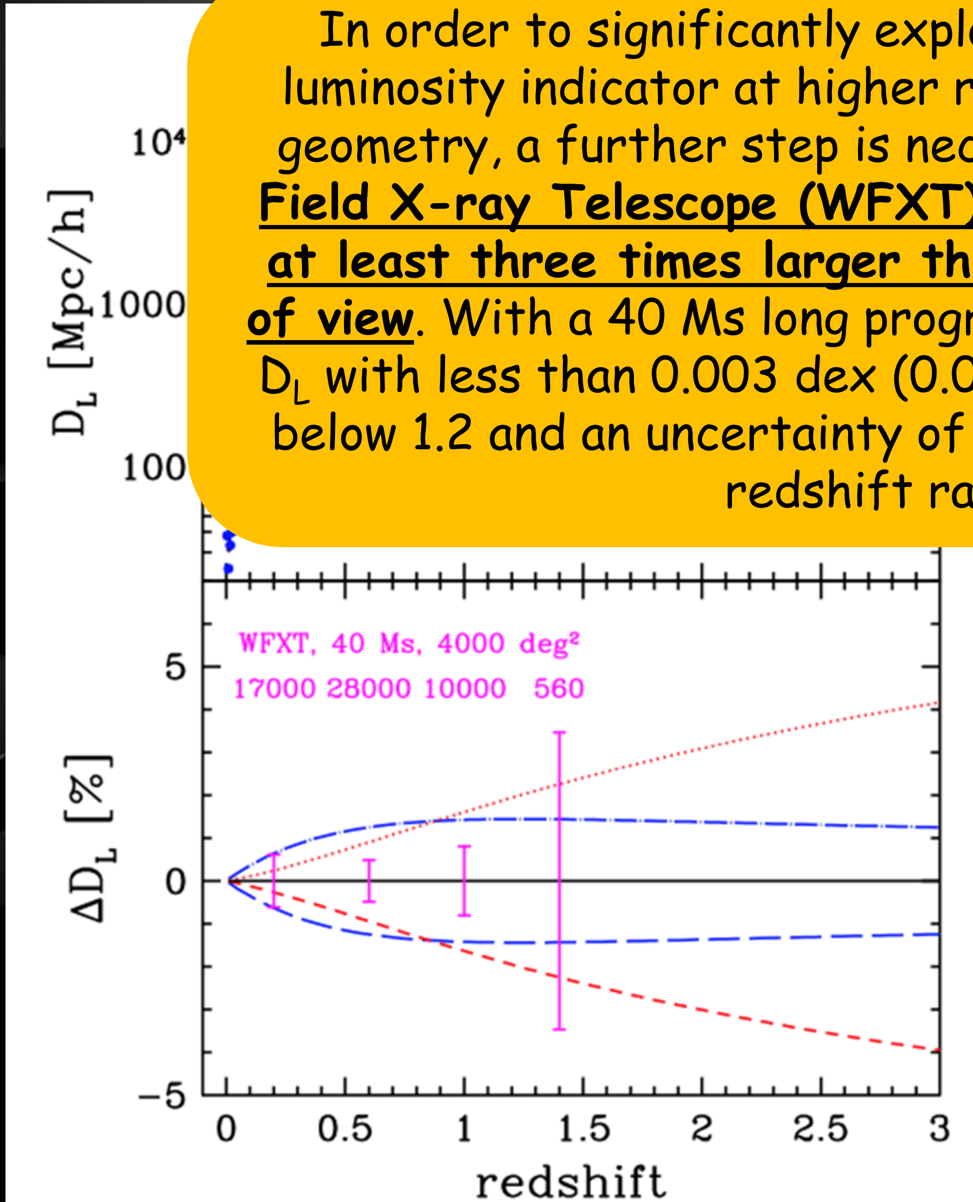
Our XMM measures, using LX and Paβ

ATHENA survey (10 Ms, 250 deg^2): D_L could be measured with a 0.02 dex uncertainty @z<0.6 and with a 0.06 dex uncertainty @0.6<z<0.9

In order to use this method to measure the cosmological distances and then the curvature of the universe, it is necessary to obtain reliable variability measures at relevant redshifts. The relations based on the Hβ line width measurement are the most promising, as they can be used up to a redshift of ~3 via NIR spectroscopic observations (e.g., with the James Webb Space Telescope)

With the proposed Athena survey, our estimator will not be competitive with SNeIa. It will, however, provide a cosmological test independent from SNeIa able to detect possible systematic errors larger than 0.1 mag @z<0.6

In order to significantly exploit our proposed rms-based AGN luminosity indicator at higher redshifts to constrain the universe geometry, a further step is necessary, such as **<u>a dedicated Wide Field X-ray Telescope (WFXT) with an effective collecting area at least three times larger than Athena and ~2deg^2 large field of view</u>**. With a 40 Ms long program, it would be possible to measure D_L with less than 0.003 dex (0.015 mag) uncertainties at a redshift below 1.2 and an uncertainty of less than 0.02 dex (0.1 mag) in the redshift range 1.2 <z < 1.6



<u>We conclude that our estimator has the prospect to become a cosmological probe even more sensitive than current SNeIa if applied to AGN samples as large as that of a hypothetical future survey carried out with a dedicated WFXT</u>