A New Cosmological Distance Measure Using AGN X-Ray Variability

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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 $z \sim 1$ and limited up to $z \sim 2$.

Given their high luminosities, there have been several studies on the use of AGN as standard candles.
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

\[ M_{\text{BH}} = \frac{f \Delta V^2 R}{G} \]

Geometrical Factor

BLR Velocity (FWHM)

BLR Radius (RM lag)

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.
The observed R-L relation provides a much less expensive way to estimate the size of the BLR, allowing a **single-epoch virial BH mass estimator**: 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.

\[
\log \left( \frac{M_{\text{BH,vir}}}{M_\odot} \right) = a + b \log \left( \frac{\lambda L_\lambda}{10^{44} \text{ erg s}^{-1}} \right) + 2 \log \left( \frac{\text{FWHM}}{\text{km s}^{-1}} \right)
\]
**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 \( n \sim 1 \) down to a break frequency, \( \nu_b \), that scales primarily with \( M_{\text{BH}} \), and then steepens to \( n \sim 2 \) at larger frequencies.

The break frequency scale with \( M_{\text{BH}} \) in all accreting BHs.
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.

$$\sigma_{\text{rms}}^2 = \frac{1}{N \mu^2} \sum_{i=1}^{N} [(X_i - \mu)^2 - \sigma_i^2]$$

The scaling of the characteristic frequencies of the PSD with $M_{\text{BH}}$ induces a dependence of the excess variance with $M_{\text{BH}}$ (if computed at frequencies above $\nu_b$)
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).

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

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).
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 \( L - \text{rms} \) plane of our proposed three-dimensional relationship among \( L, \text{rms}, \) and \( \Delta V \). If this is the case, we should measure a more significant and less scattered relation than previously reported using only \( L \) and \( \text{rms} \).
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

- \( H\beta, L_{5100} \) OR \( Pa\beta \)

- 40 AGN (mostly with \( z<0.1 \))

- 38 with \( H\beta \)

- 18 with \( Pa\beta \)
The square of the virial product, using $L_{5100}$ and FWHM H$\beta$, is strongly correlated with the rms 
(N=31, $r = -0.73$, $P \sim 3 \times 10^{-6}$)

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 $-0.36$ ($P \sim 5 \times 10^{-2}$).

The virial product is significantly better correlated with the AGN variability than the luminosity alone.
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)
If the virial product is computed using $L_X$ and $\text{Pa}\beta$, the spreads considerably decrease down to 0.71 dex (total) and 0.56 dex (intrinsic) ($N=18, r=-0.82, P\sim3\times10^{-5}$).

The correlation between $L_X$ only and $\text{rms}$ has instead a less significant coefficient $r=-0.63$ ($P\sim4\times10^{-3}$) 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. These relationships allow us to predict the AGN 2-10 keV luminosities.

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.
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 are the most promising, as they can be used up to $z \sim 3$ via NIR spectroscopic observations (e.g., with the James Webb Space Telescope).

With the proposed Athena survey, our estimator will provide a cosmological test independent from SNeIa able to detect possible systematic errors larger than 0.1 mag @z<0.6. Significantly lower uncertainties can be reached by using all the data from the whole Athena lifetime.

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.

Our XMM measures, using LX and Paβ
In order to further exploit our proposed rms-based AGN luminosity indicator at higher redshifts to constrain the universe geometry, a dedicated X-ray telescope with a $\sim 2 \text{deg}^2$ large field of view could be used. 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 $1.2 < z < 1.6$

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 mission.