On the cosmological bias of the excess variance for estimating quasar variability

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normalized excess variance

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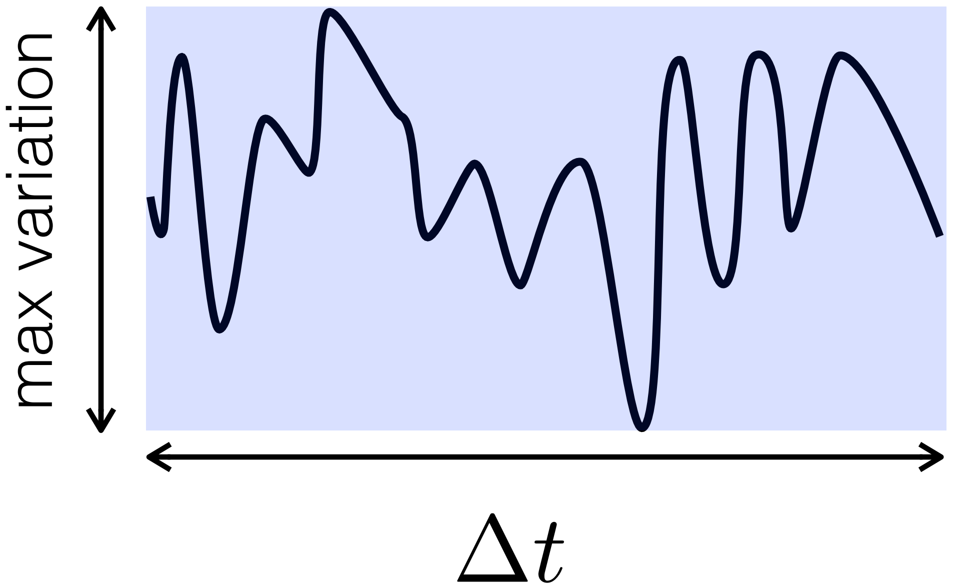
$$\sigma^2_{NXS} = \frac{S^2 - \sigma^2_n}{\overline{x}^2}$$

easy and useful variability measure, but:

it depends on the length of
the monitoring time interval



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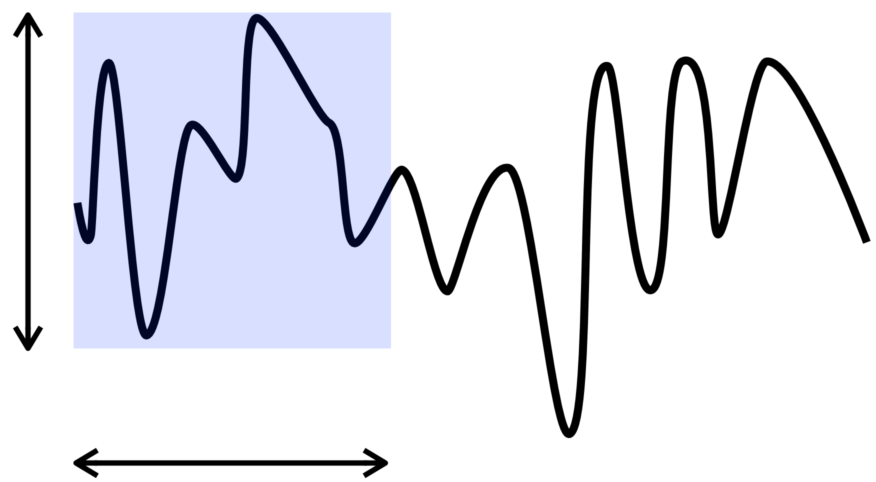

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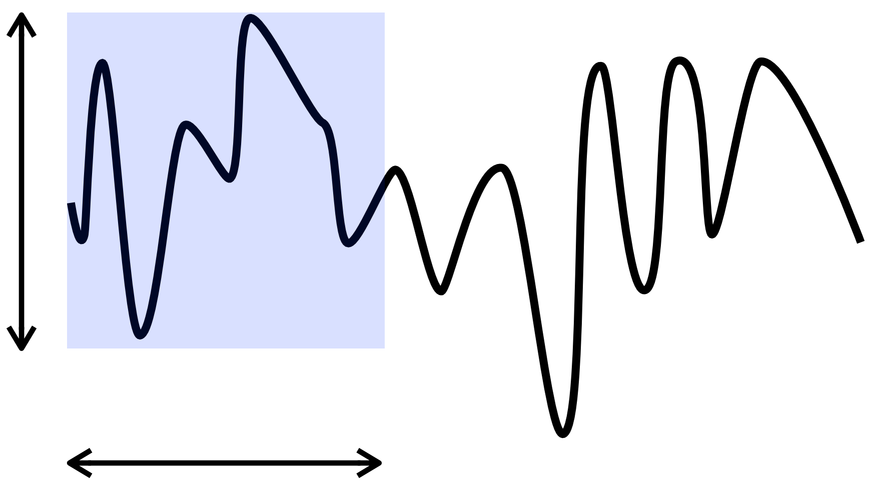

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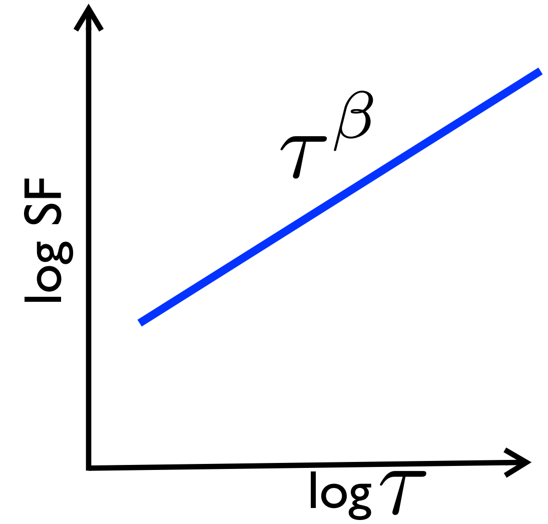
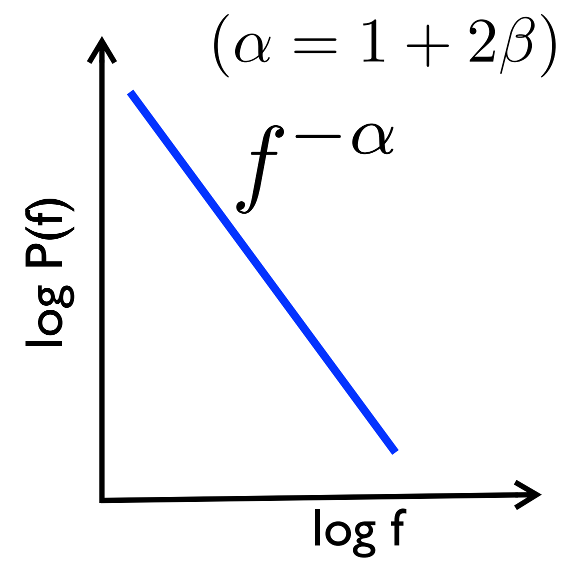
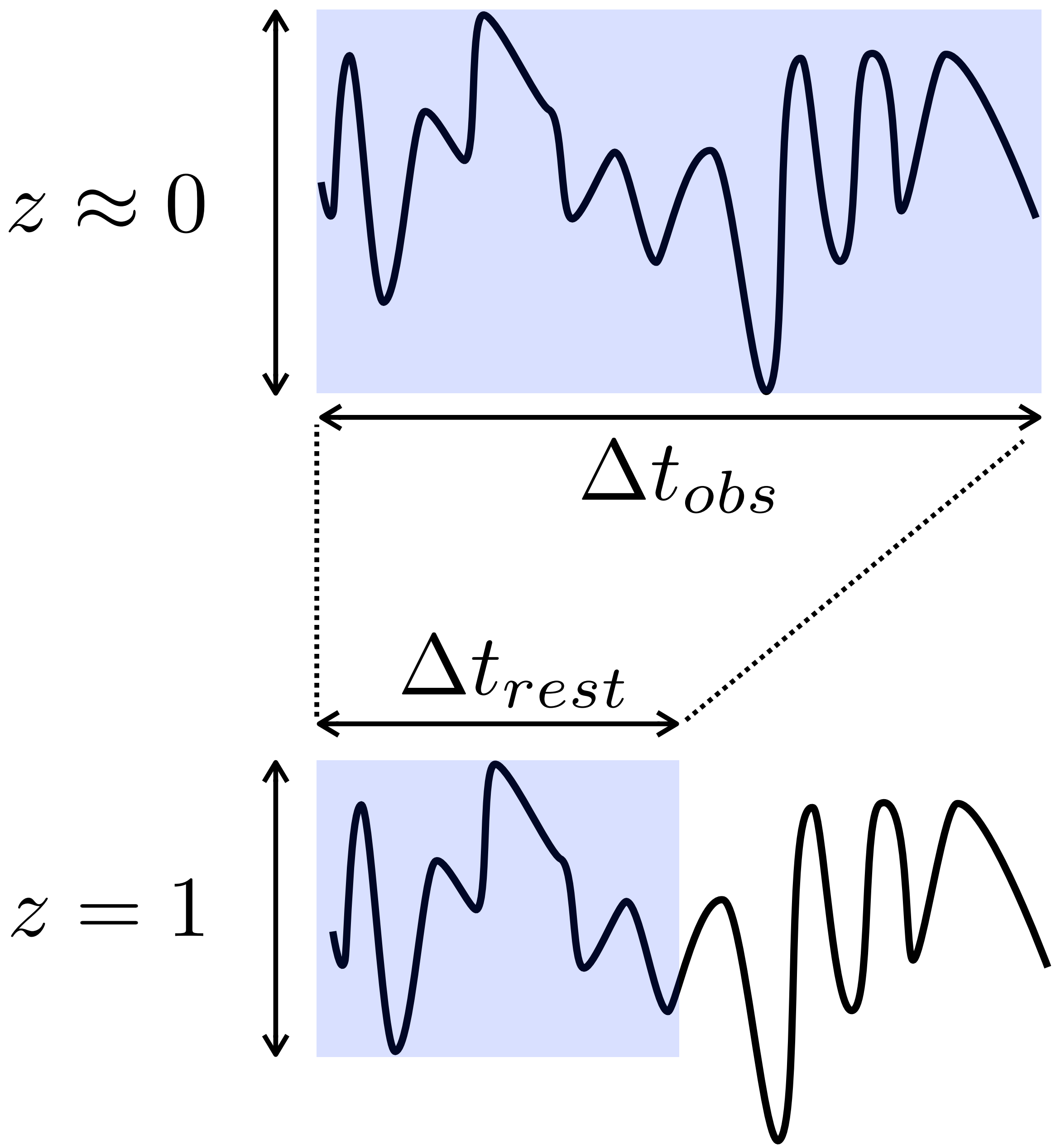
this is due to the well-known character of the AGN variability, which increases with the lag between observations, as described by the structure function (SF), or by the power spectral density (PSD)





1st order rule: ➡ **use fixed time intervals**

cosmological time dilation



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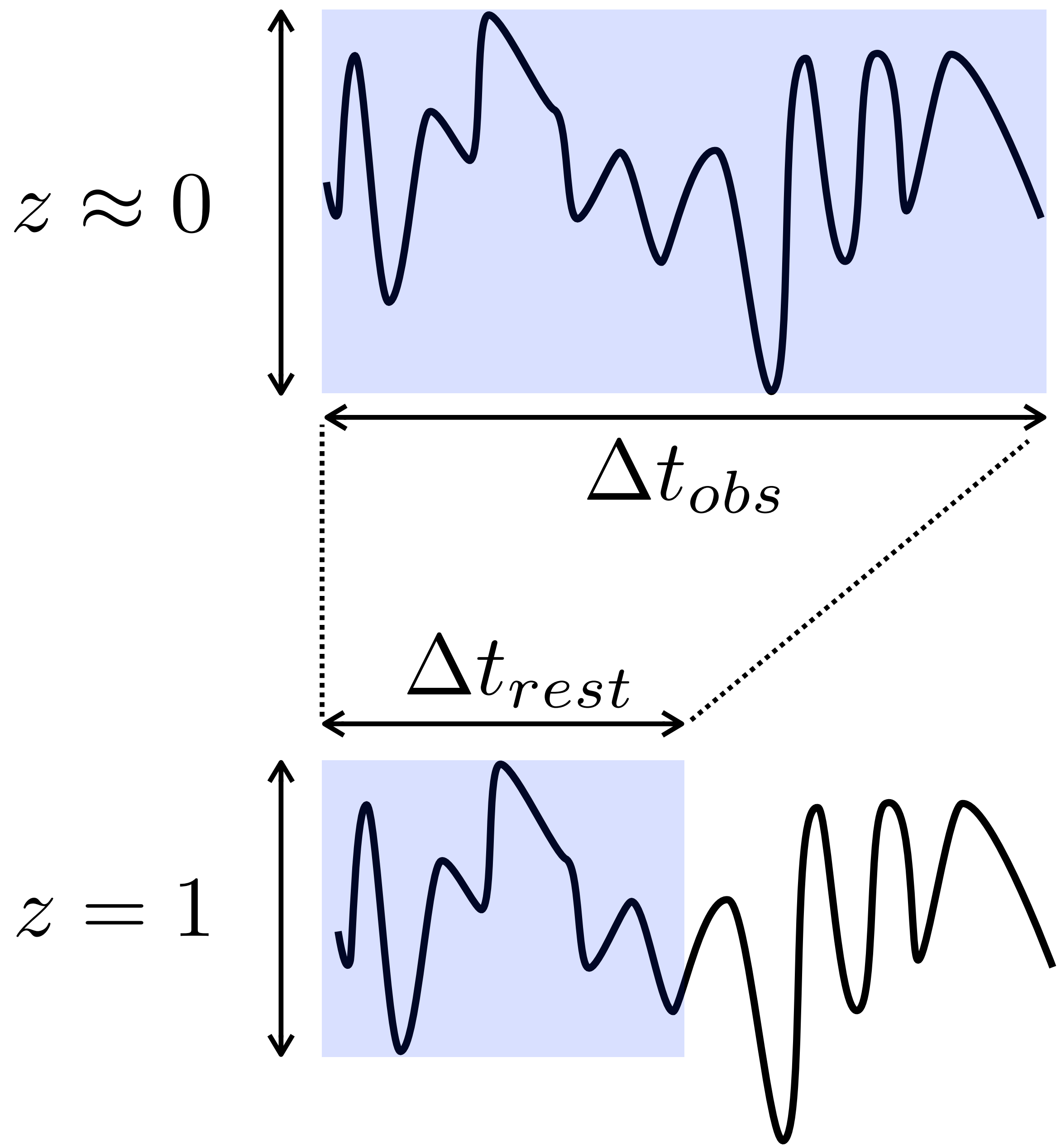

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revised rule: ➔ use fixed **rest-frame** time intervals
or **study only local AGN**
or **apply a correction**

some habits

<u>X-ray: mostly NXS and PSD</u>

- NXS is most often (but not always) used at low z, for ensemble studies of poorly sampled light-curves
- it has been shown that NXS is also biased for sampling and leakage effects, and its use is not recommended for individual light-curves (Allevato et al. 2013)
- individual, well-sampled local AGNs are typically studied with the PSD
- some authors use NXS appropriately taking care of choosing fixed time intervals (e.g. Ponti et al. 2012), at low z
- for X-ray samples including high z and L, structure function (SF) is used sometimes (e.g. Vagnetti et al. 2011)

--> a correction should be applied when using NXS at high z

<u>optical/UV: more often SF</u>

- ensemble analyses in the optical/UV are usually performed with the SF, typically in wide luminosity and redshift intervals
- SF is an appropriate tool, working in the time domain, and allowing estimate of the variability as a function of the timescale in the source rest-frame

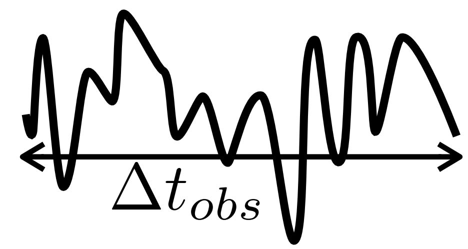
evaluate the bias

we use the SF to express the dipendence of variability on time lag:

$$SF(\tau) = \sqrt{\langle[\log f(t+\tau) - \log f(t)]^2\rangle - \cancel{\sigma_n^2}} = \sqrt{\langle(\delta \log f)^2\rangle - \cancel{\sigma_n^2}}$$

and estimate the expected value of NXS in a given time interval $(0, \Delta t_{obs})$

$$\sigma^2_{NXS} = \frac{\sigma_f^2 - \cancel{\sigma_n^2}}{\overline{f}^2} \approx \frac{\langle(\delta \log f)^2\rangle_{(0,\Delta t_{obs})}}{(\log e)^2}$$



neglecting the error, this can be expressed as

$$\longrightarrow \frac{\frac{1}{2}\langle SF^2\rangle_{(0,\Delta t_{rest})}}{(\log e)^2}$$

the factor 1/2 accounts for the 2 independent measures contributing to each flux difference

adopting a power-law SF (Vagnetti et al. 2011): $SF = k\tau^\beta$ and $\Delta t_{rest} = \Delta t_{obs}/(1+z)$

the average is computed as

$$\langle SF^2\rangle = \frac{1}{\Delta t_{rest}} \int_0^{\Delta t_{rest}} k^2 \tau^{2\beta} d\tau = \frac{[SF(\Delta t_{rest})]^2}{2\beta + 1}$$

so that: $$\sigma^2_{NXS} = \frac{k^2 \Delta t_{rest}^{2\beta}}{2(2\beta+1)(\log e)^2}$$

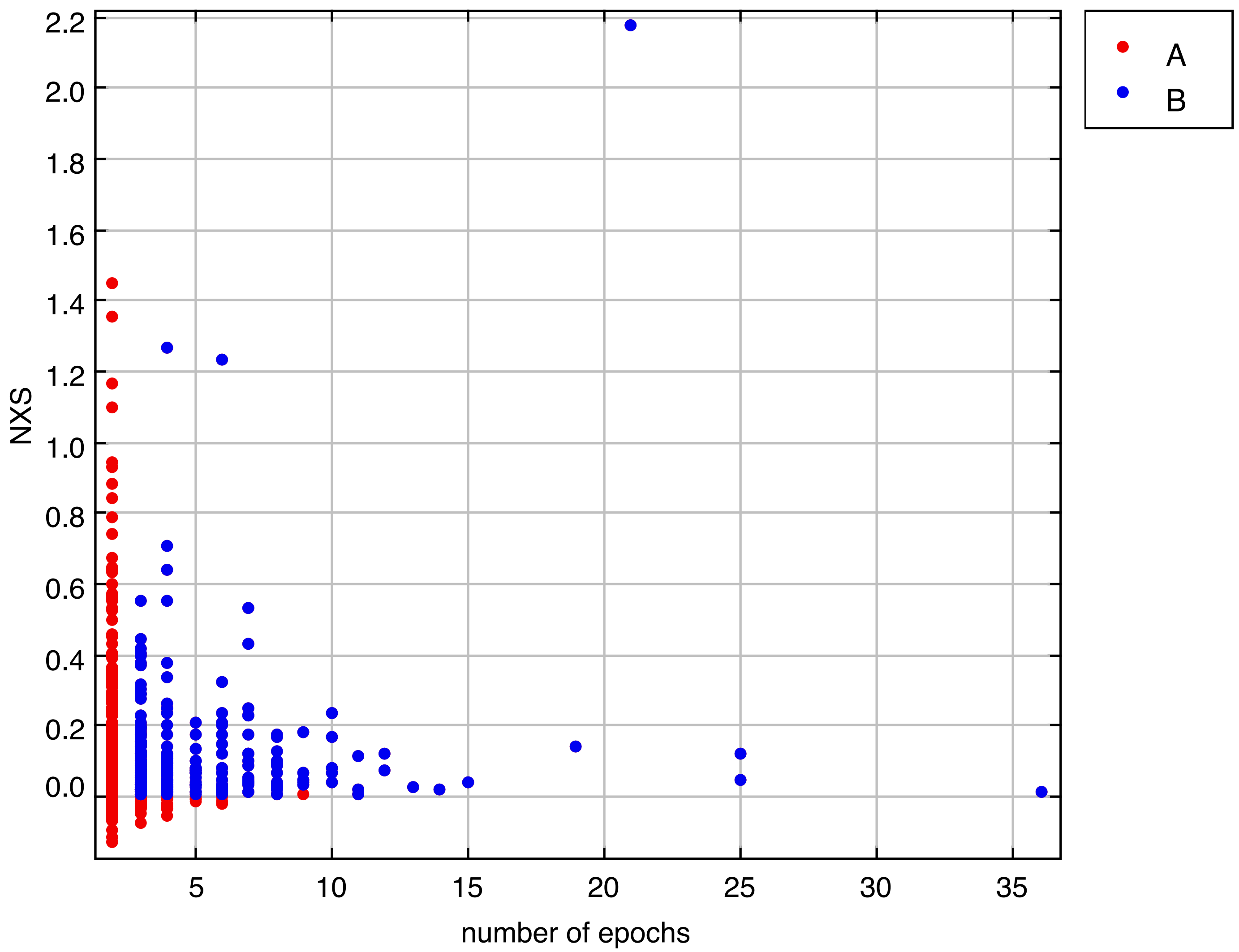
NXS dependence on the rest-frame time interval

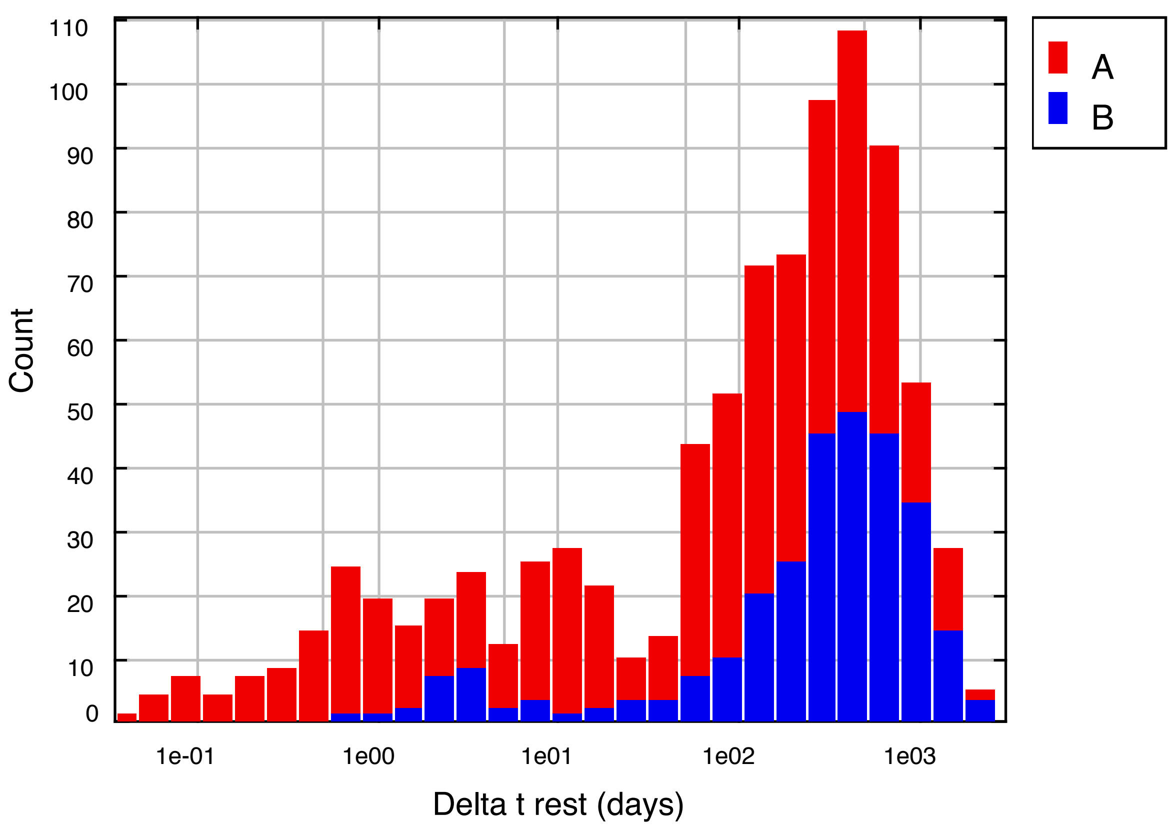
data

to test the proposed correction, we adopt the XMM-Newton Serendipitous Source Catalogue, XMMSSC-DR3 (Watson et al. 2009) already used in Vagnetti et al. 2011

here, we cross correlate XMMSSC with the SDSS/DR7Q and SDSS-III/DR10Q quasar catalogs (Schneider et al. 2010, Paris et al. 2014) to get redshifts

	number of epochs	NXS	sources	total observations
sample A	> 2	all	871	2683
sample B	> 3	> 0	284	1402





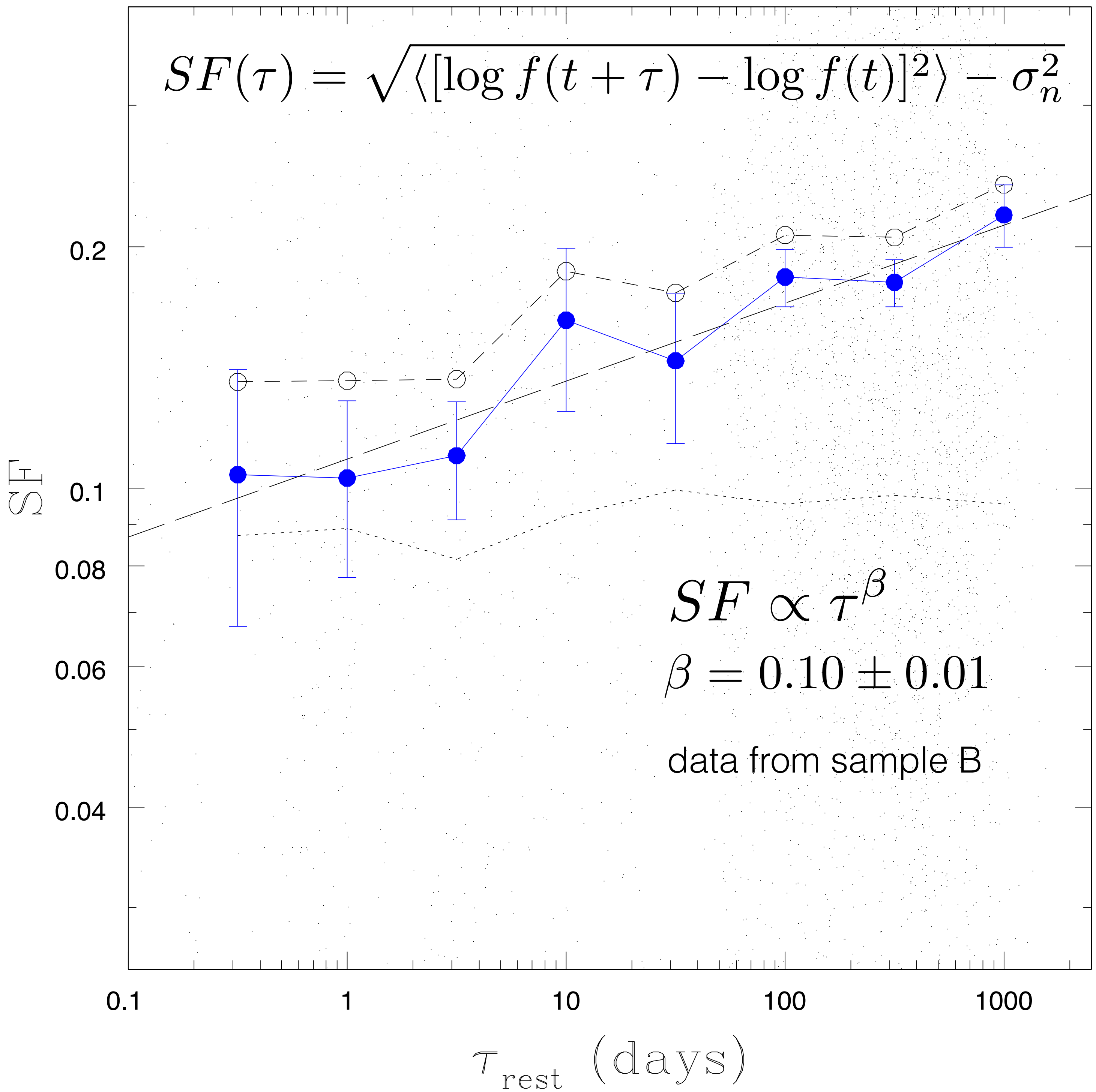
structure function

To apply the correction of the cosmological bias to the NXS values, we use the SF slope as input

for the X-ray flux, we use the XMM-Newton band EP9 (0.5-4.5 keV)

the slope found for sample B is beta=0.10±0.01, equal to the value found previously with a smaller sample (Vagnetti et al. 2011)

similar results (0.090<beta<0.105) are found for sample A and for different subsamples depending e.g. on the number of epochs and on the photometric error

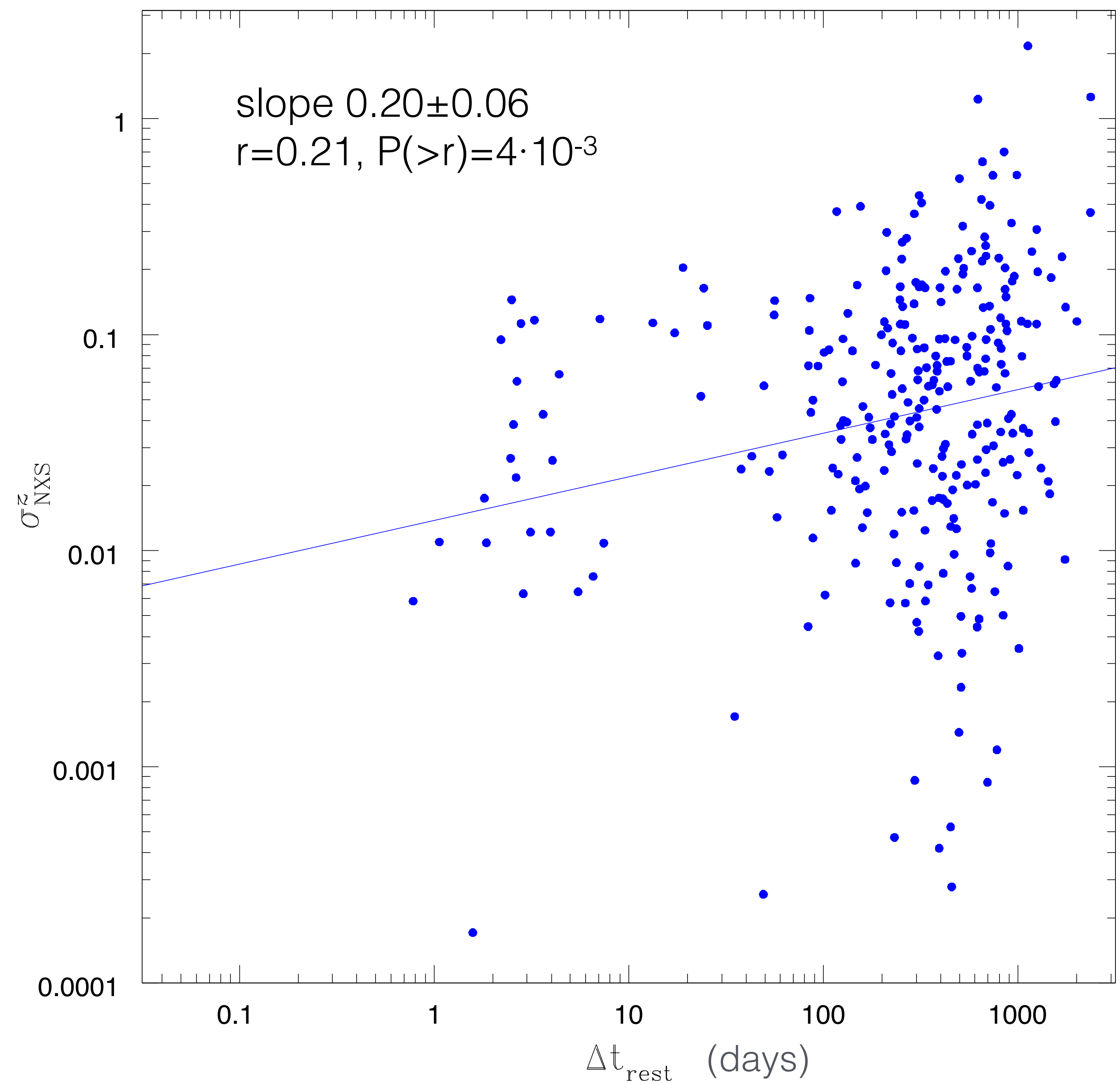


NXS trend

we then expect that NXS increases with the time interval in the rest-frame, as:

$$\sigma^2_{NXS} = \frac{k^2 \Delta t^{2\beta}_{rest}}{2(2\beta+1)(\log e)^2}$$

in fact, it is so, and the slope of the fit to the data is ~0.20



NXS correction

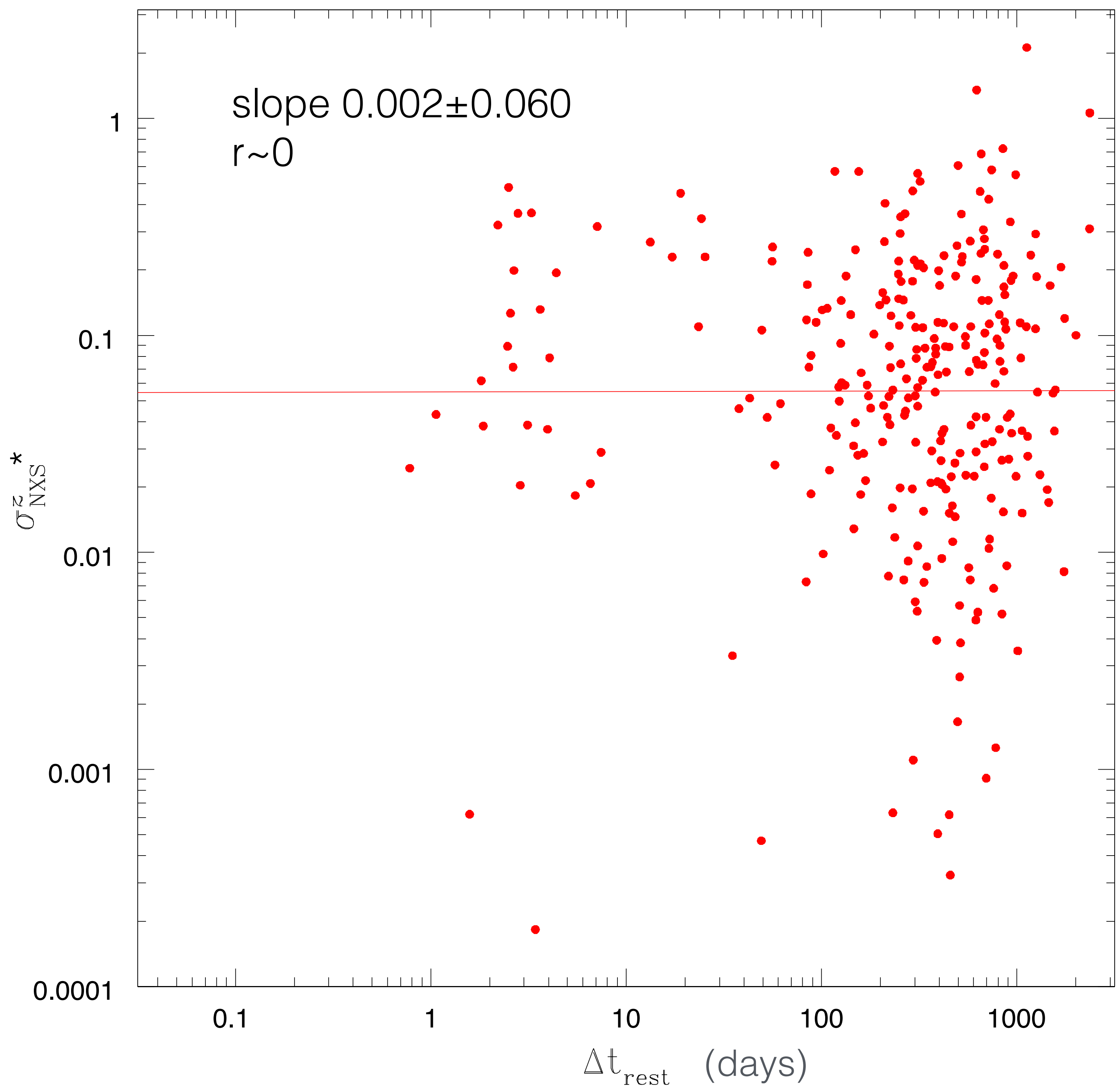
to correct for the bias, it is possible to estimate NXS for a fixed interval Δt*

$$\sigma^{2}_{NXS}{}^{*} = \sigma^{2}_{NXS}\left(\frac{\Delta t^{*}}{\Delta t_{rest}}\right)^{2\beta}$$

$$= \sigma^{2}_{NXS}\left(\frac{\Delta t^{*}}{\Delta t_{obs}}\right)^{2\beta}(1+z)^{2\beta}$$

we choose Δt*=1000 days

in this way, the small values measured for short Δt are increased to values comparable with the others

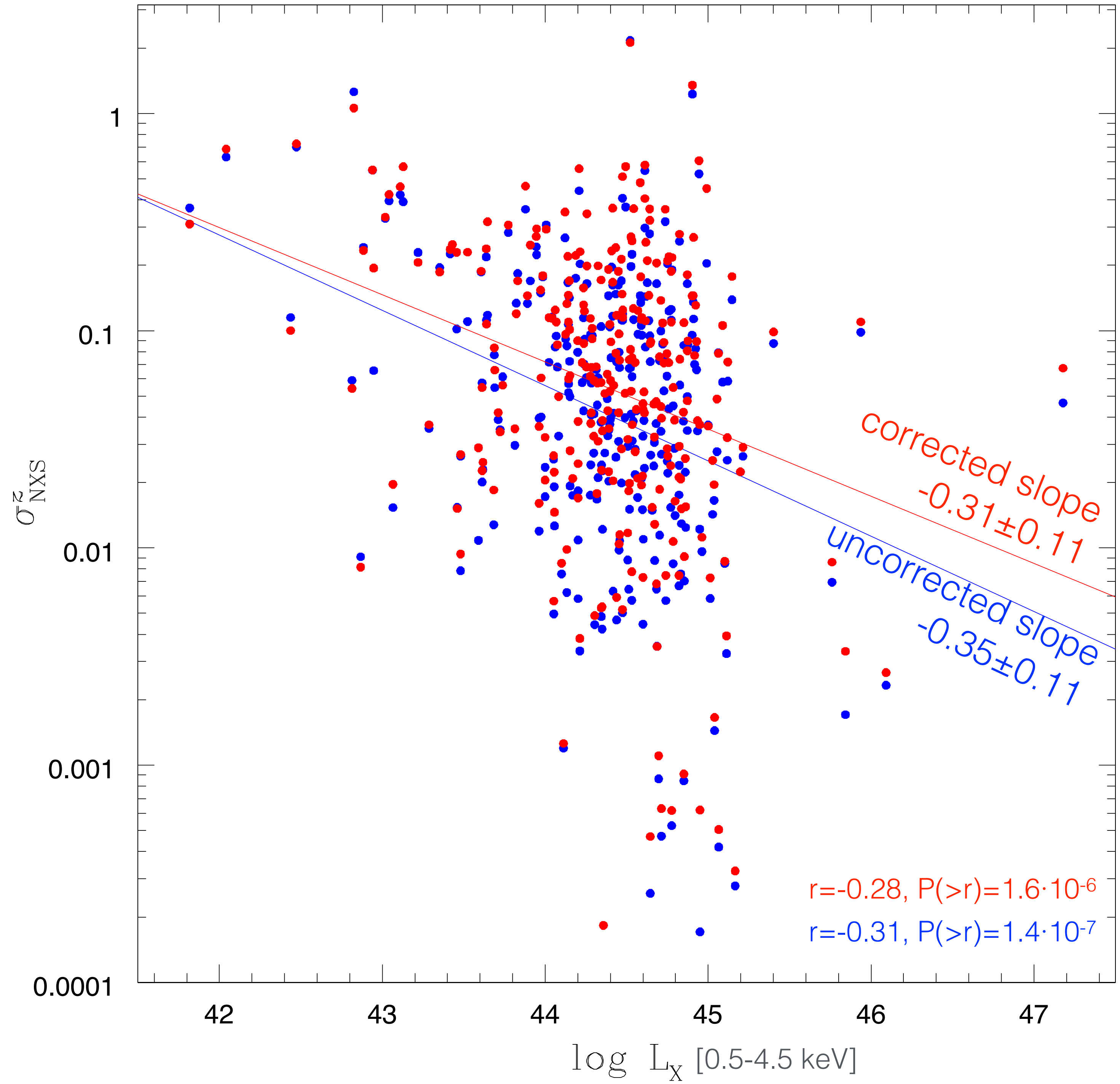


dependence on luminosity: NXS

The cosmological bias of NXS is stronger for high redshift sources, in average at higher luminosities

we expect underestimate of NXS for high L sources, which affects dependence on L

the correction results in a slight flattening of the variability-luminosity relation



summary and conclusions

- normalized excess variance NXS depends on the intrinsic length of the sampled time in the rest-frame
- NXS must be corrected whan applied at high redshift
- we verify the bias on an AGN sample extracted from the XMMSSC serendipitous source catalogue
- a trend of increasing NXS with rest-frame time interval is present $\sigma^2_{NXS} \propto \Delta t_{rest}^{0.20}$
- we propose a simple correction based on the slope of the structure function, capable of removing the bias $${\sigma^2_{NXS}}^* = \sigma^2_{NXS} \left(\frac{\Delta t^*}{\Delta t_{rest}} \right)^{2\beta}$$
- there is also an effect on the dependence of NXS on luminosity, although modest