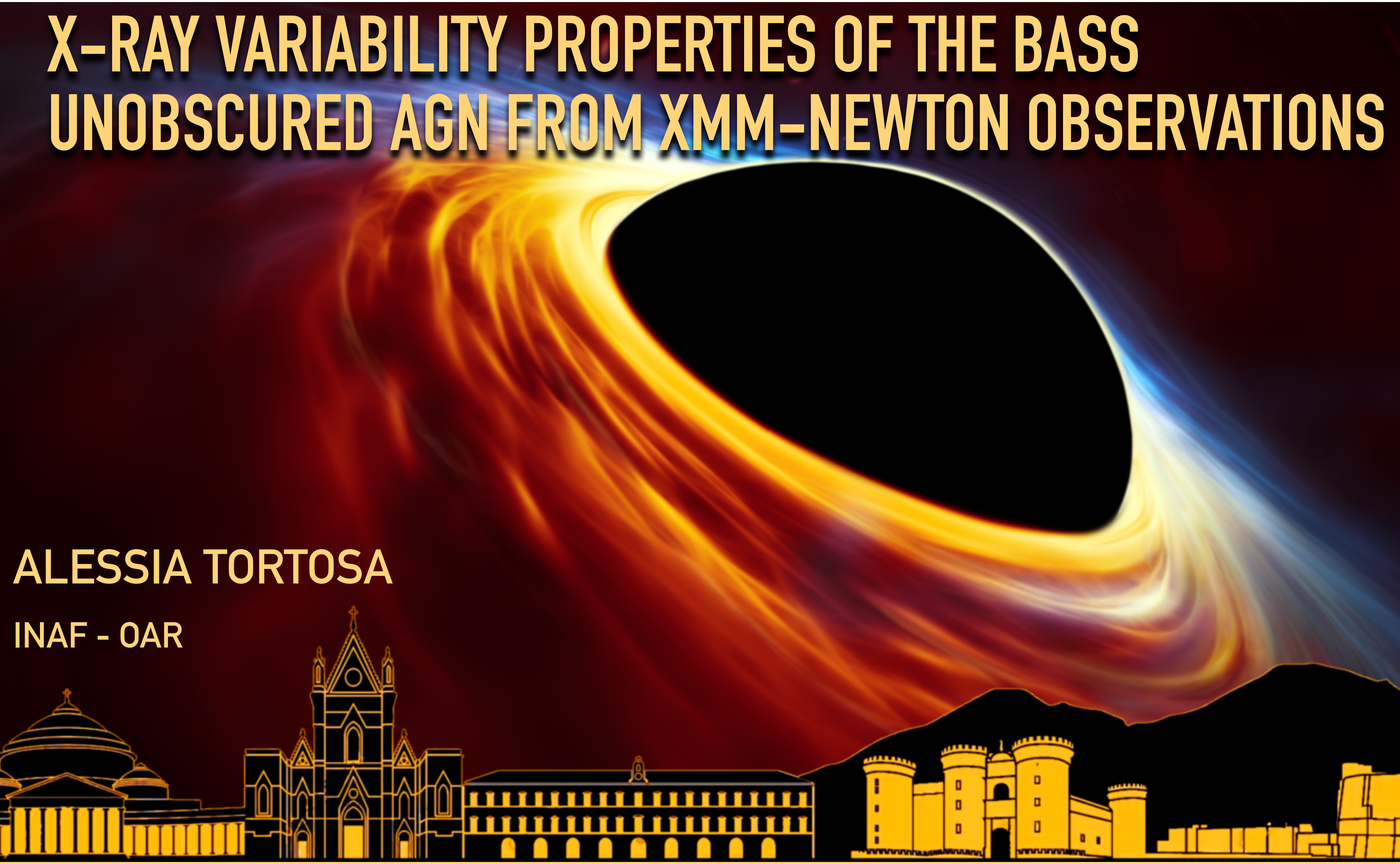
X-RAY VARIABILITY PROPERTIES OF THE BASS UNOBSCURED AGN FROM XMM-NEWTON OBSERVATIONS



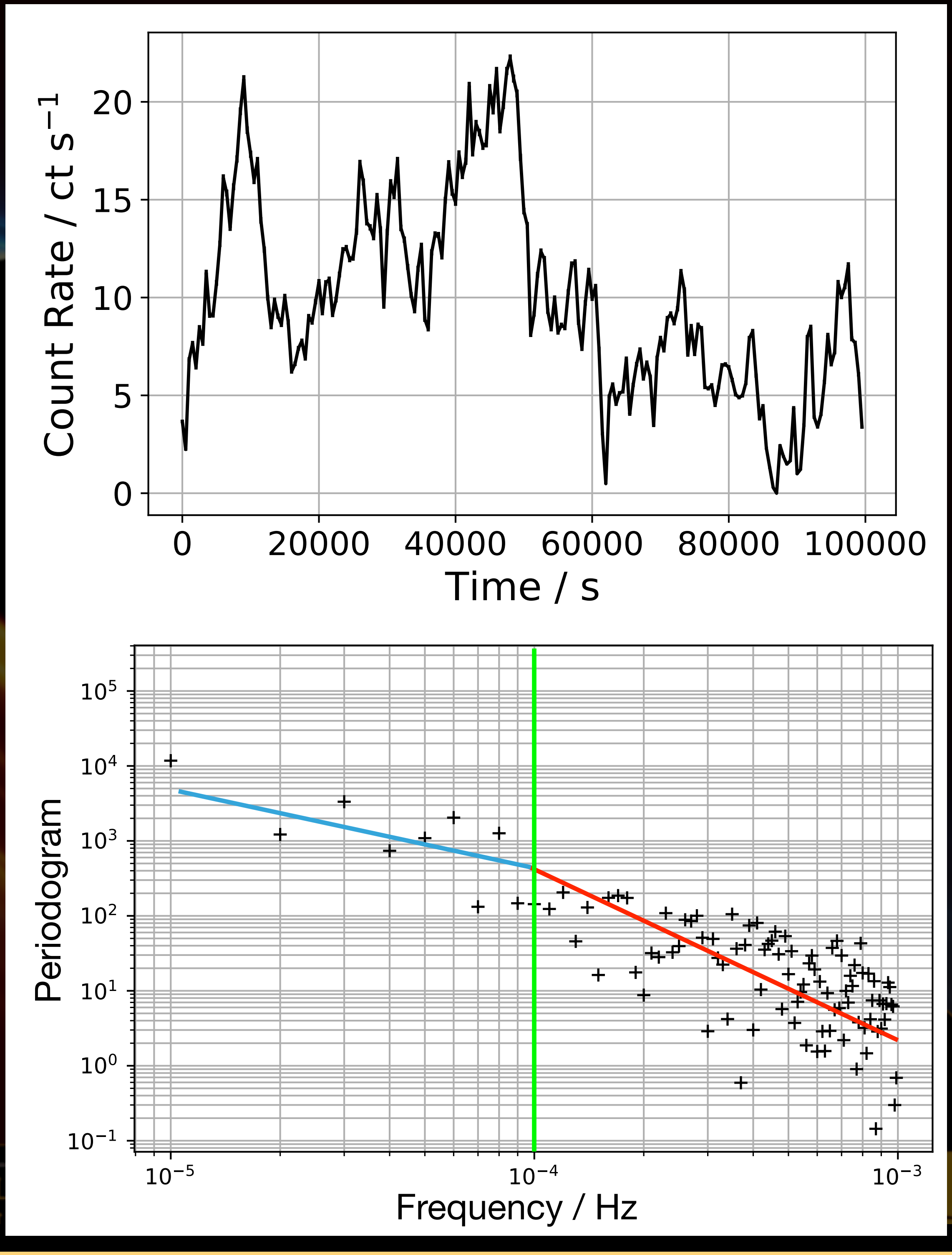
ALESSIA TORTOSA

INAF - OAR

TIMING VARIABILITY

$t < T_B \; \alpha \sim -1 \quad t > T_B \; \alpha \sim -2$

- Variability: common feature shared by all classes of AGN;
- Power Spectral Density (PSD) analysis: $P_\nu \propto \nu^\alpha$;
- Rapid variability (time-scales < 10^3 s): $\alpha \sim -2$
- Long-term variability (time-scales ~ years): $\alpha \sim -1$
- Break time scale related to AGN properties and AGN-BH connections;
- Accurate power spectra for AGN requires high-quality data.



NORMALISED EXCESS VARIANCE

- σ^2_{NXS} ;
- Quantify the X-ray variability of AGN;
- Describe the variability amplitude;
- Difference between the total variance of a light curve and the mean squared error, normalised for the average of the N flux measurements square:

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

Sample variance:

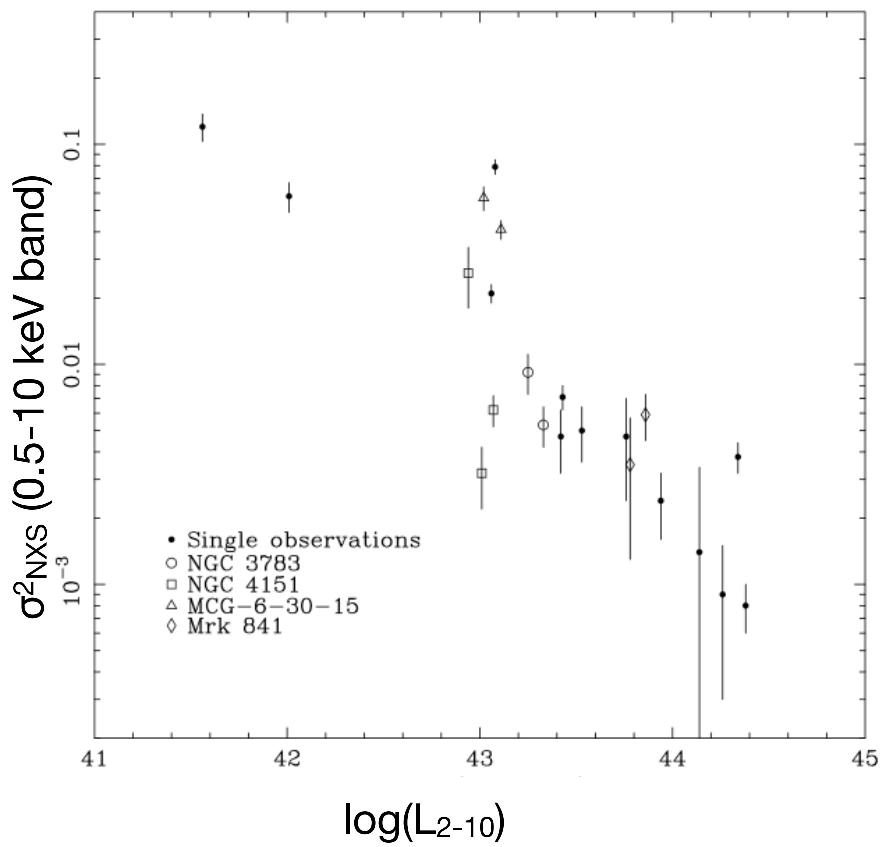
$$S^2 = \frac{1}{N-1} \sum_{i=1}^{N} [(x_i - \overline{x_i})^2]$$

Mean square error:

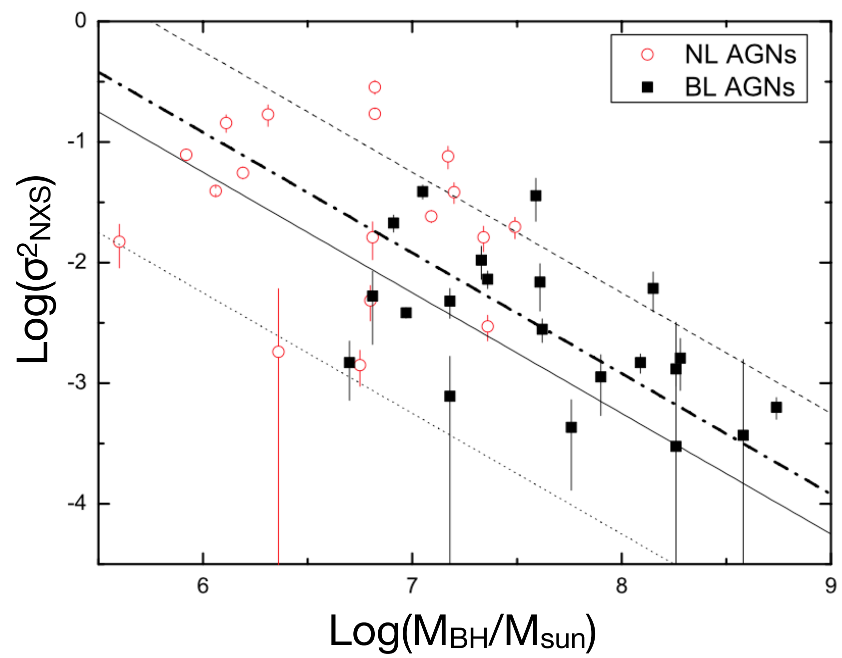
$$\overline{\sigma^2} = \frac{1}{N} \sum_{i=1}^{N} [\sigma_i^2]$$

SCALING RELATIONS FROM EXCESS VARIANCE IN THE LITERATURE:

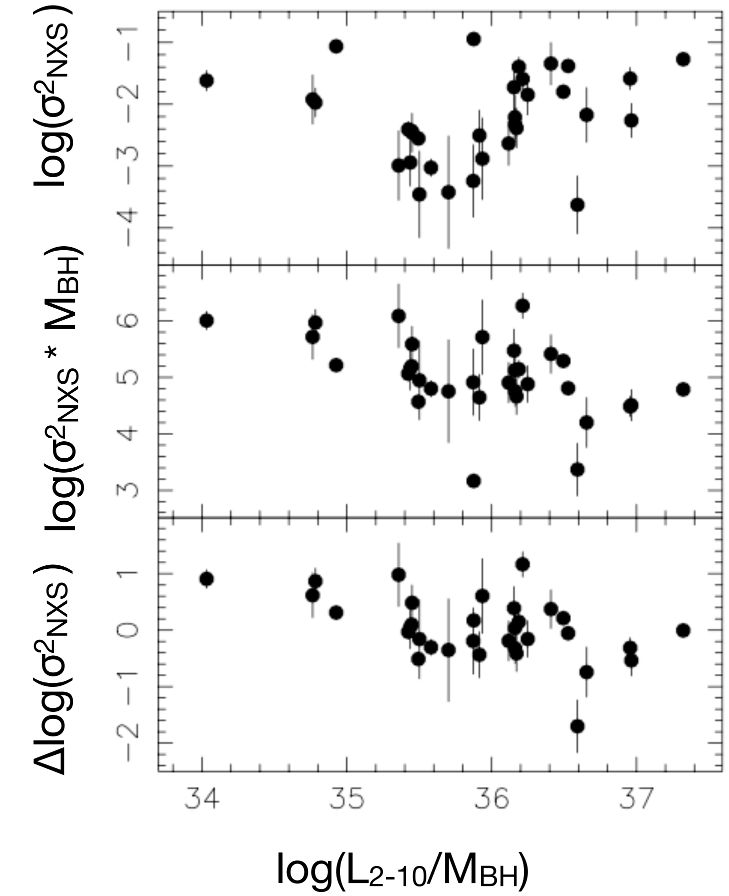
Nandra + 1997



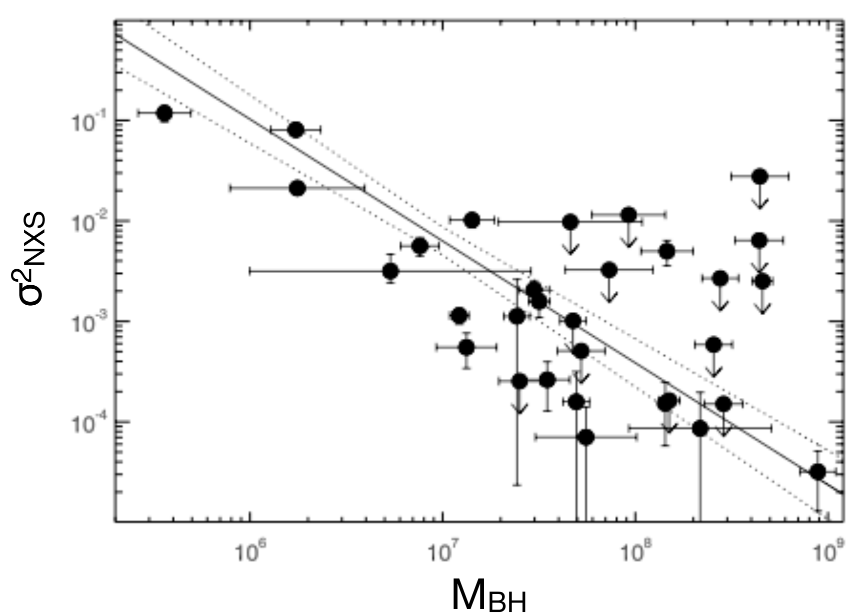
Bian & Zhao 2003

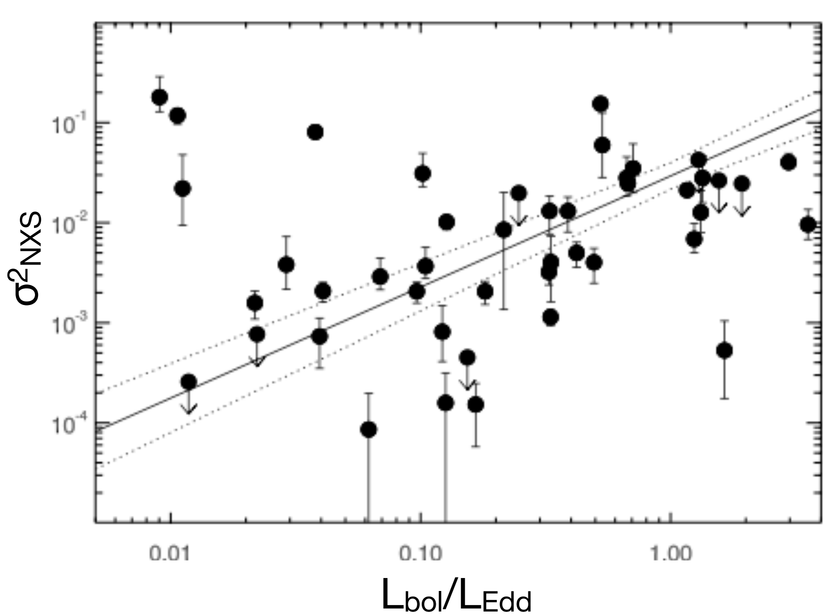


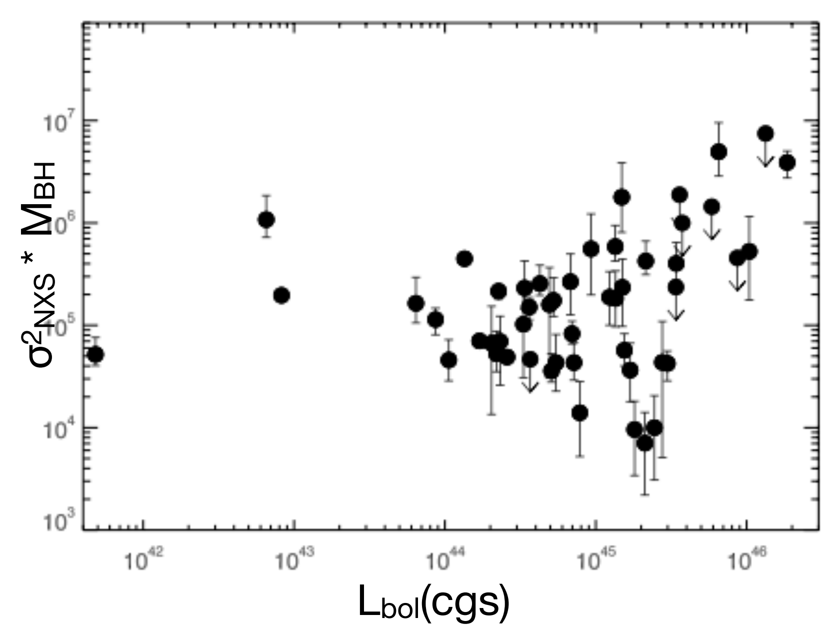
O'Neil 2005



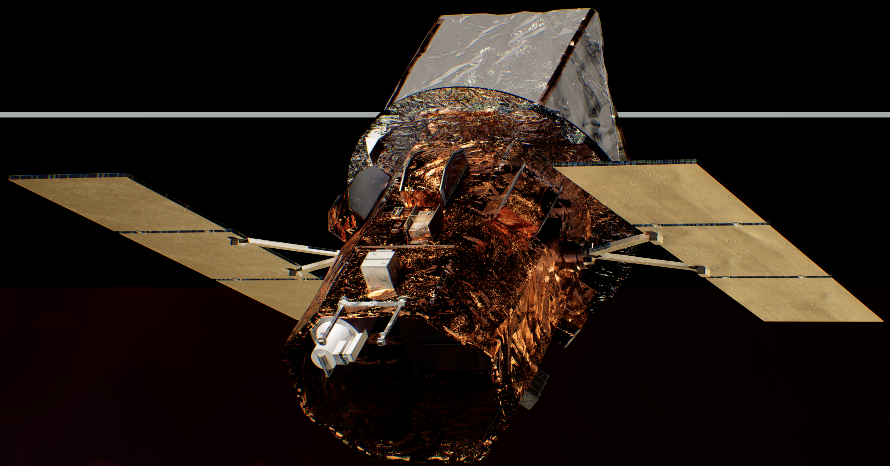
First XMM-Newton systematic "excess variance" study: CAIXAvar, Ponti + 2012







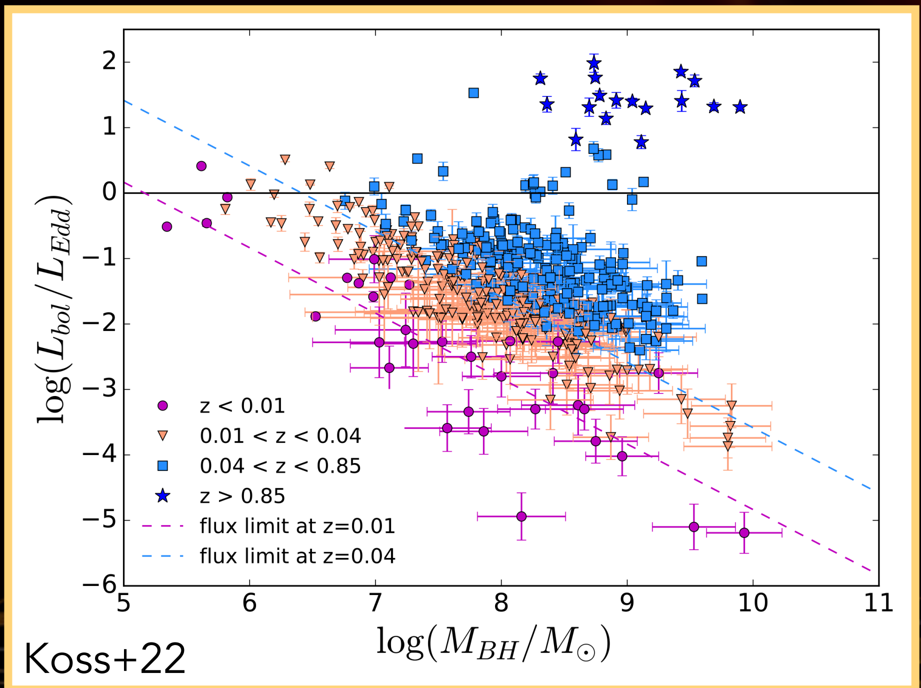
THE SAMPLE



- AGN belonging to the **BASS sample**

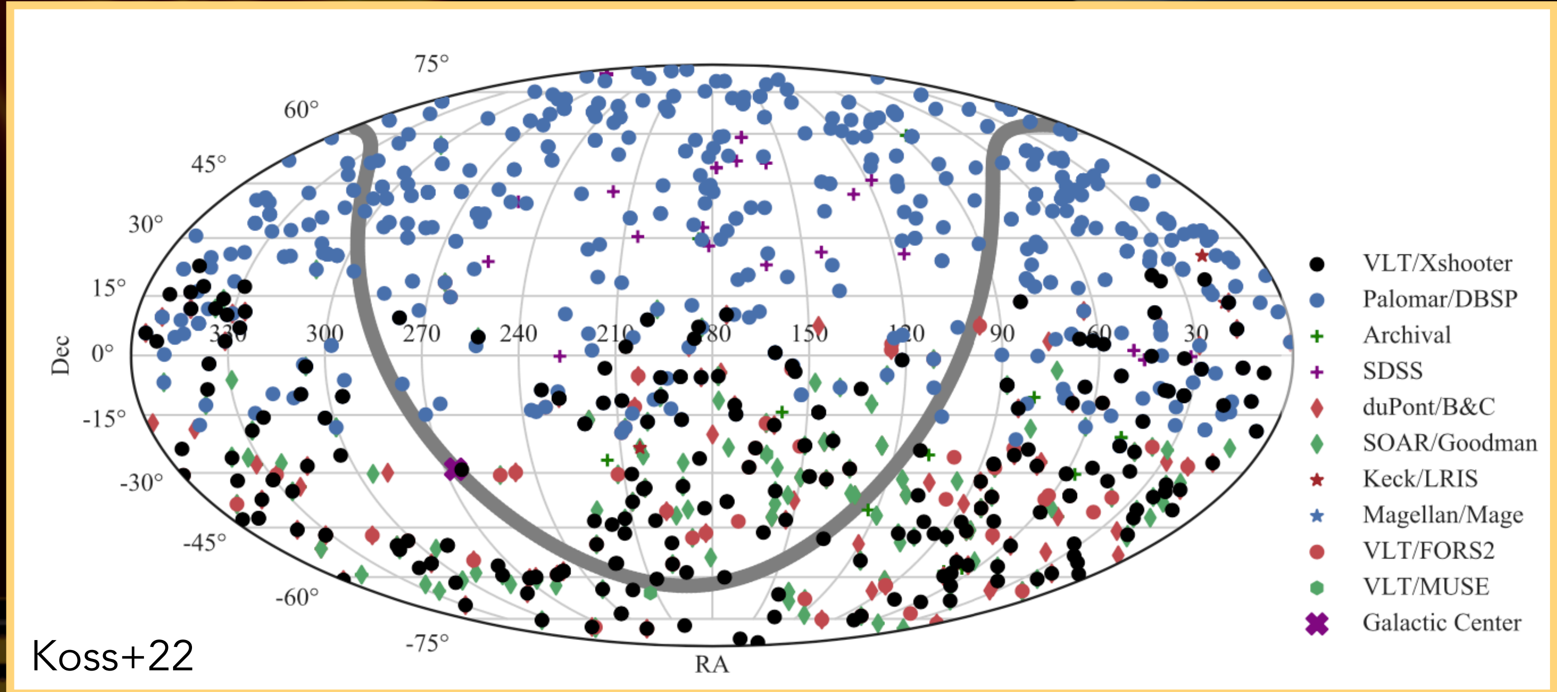
- ✦ BAT AGN Spectroscopic Survey (BASS) is a large (>1000) survey of hard X-ray selected AGN with optical spectroscopy;
- ✦ High quality data across the full SED for nearby AGN;
- ✦ 70-month 858 AGN, (2005-2010 Sept);
- ✦ 105-month 1182 AGN, (2005-2013 Aug).

Distribution of M_{BH} and λ_{Edd} for the BASS AGNs



Koss+22

BASS DR2 optical spectroscopy

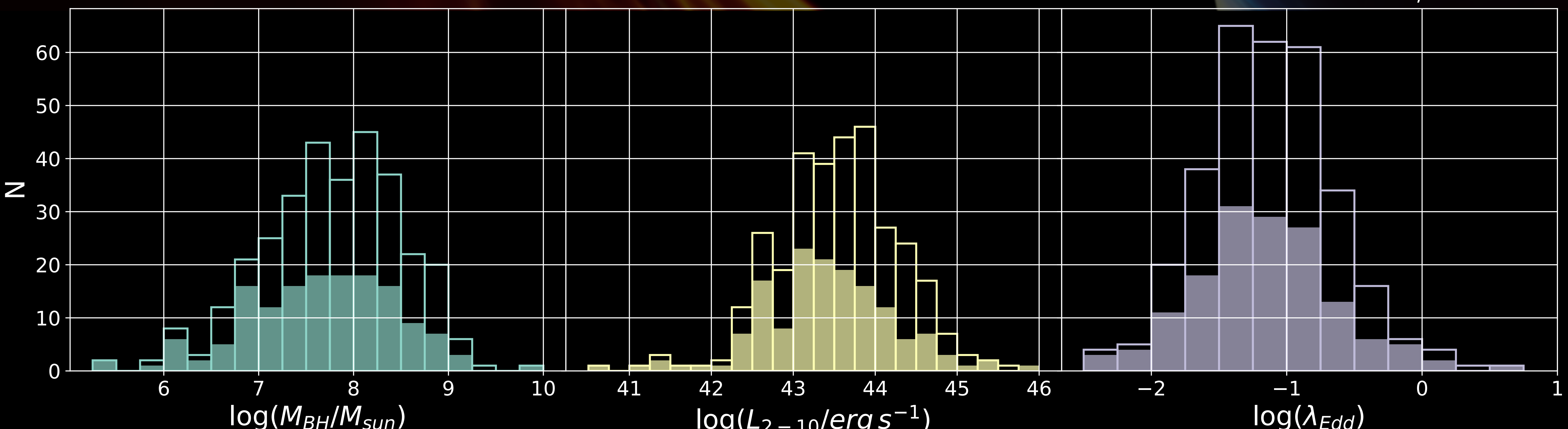


Koss+22

THE SAMPLE

- AGN belonging to the **BASS sample**;
- Unobscured ($N_H < 10^{22}$ cm^{-2}) with public XMM-Newton observations;
- Clean exposure time > 10ks;
- At least 10 counts in the 0.2-10 keV energy band;
- 151 sources with XMM-Newton observations (December 2022);
- 27 Ms of exposure time;
- $z_{med} = 0.035$

Tortosa+23, submitted

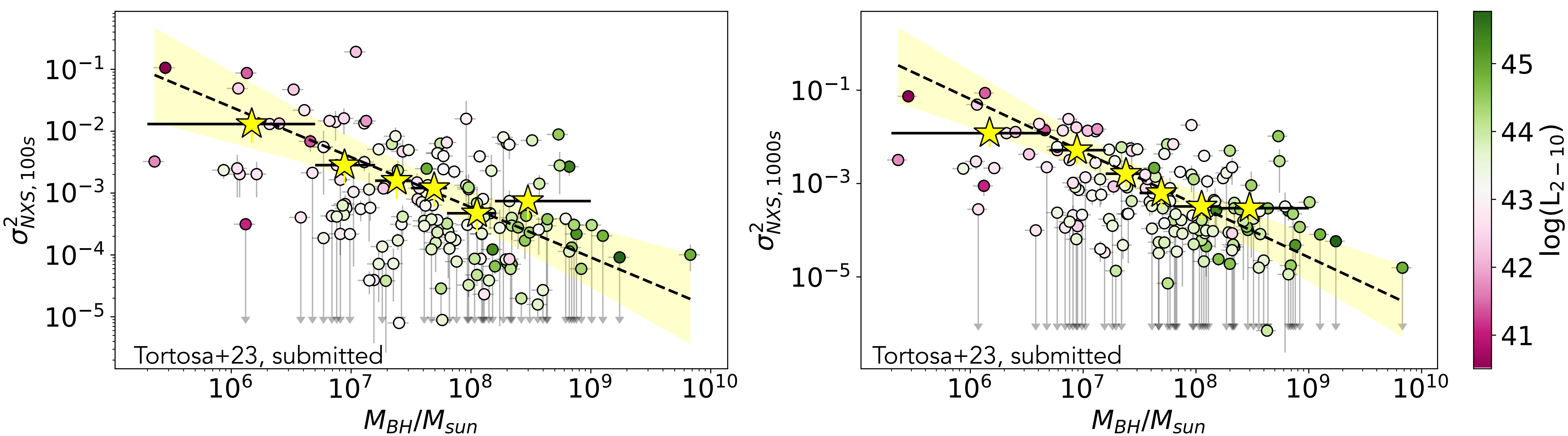


METHOD:

- Light curves length: 10ks, binned with 100s and 1000s;
- If T_{exp} > 10 ks –> Median of σ^2_{NXS} if chunks of 10 ks;
- Median of σ^2_{NXS} for multiple obs;
- Survival analysis: Kaplan-Meier product-limit (scikit-survival package);
- Linear fitting (linmix package - hierarchical Bayesian model for fitting a straight line).

SCALING RELATIONS: $\sigma^2_{\rm NXS}$ *vs* $M_{\rm BH}$

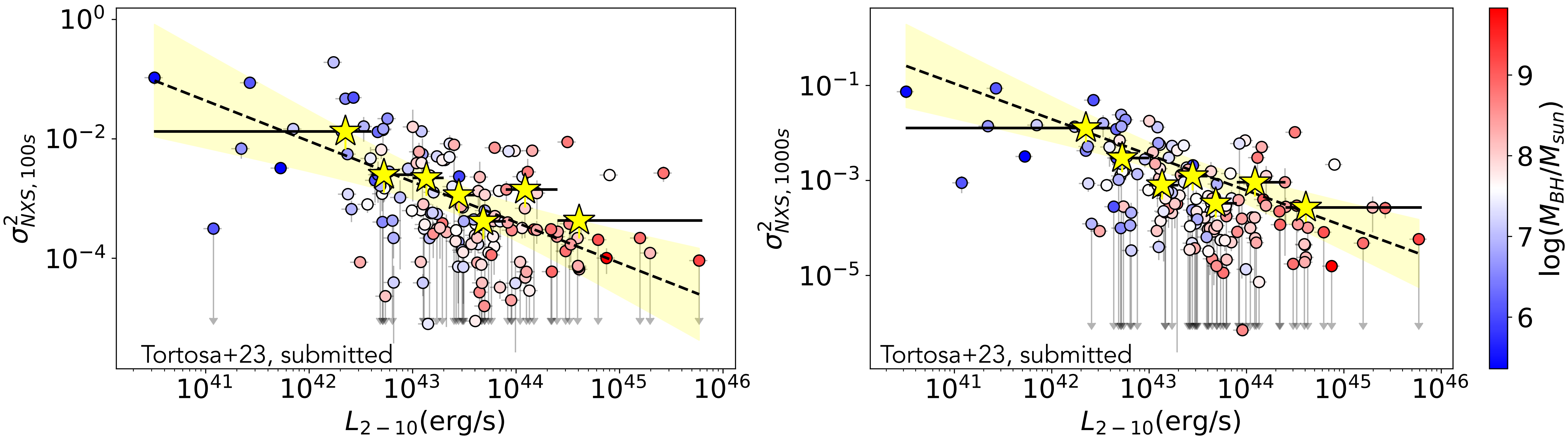
Relation	$\Delta(t)$	Intercept	Slope	Pearson	$1 - P_{\rm value}$
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH}$	100	2.99 ± 1.79	-0.77 ± 1.13	-0.94	0.99
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH}$	1000	5.54 ± 2.11	-1.12 ± 1.18	-0.96	0.99



RESULTS:

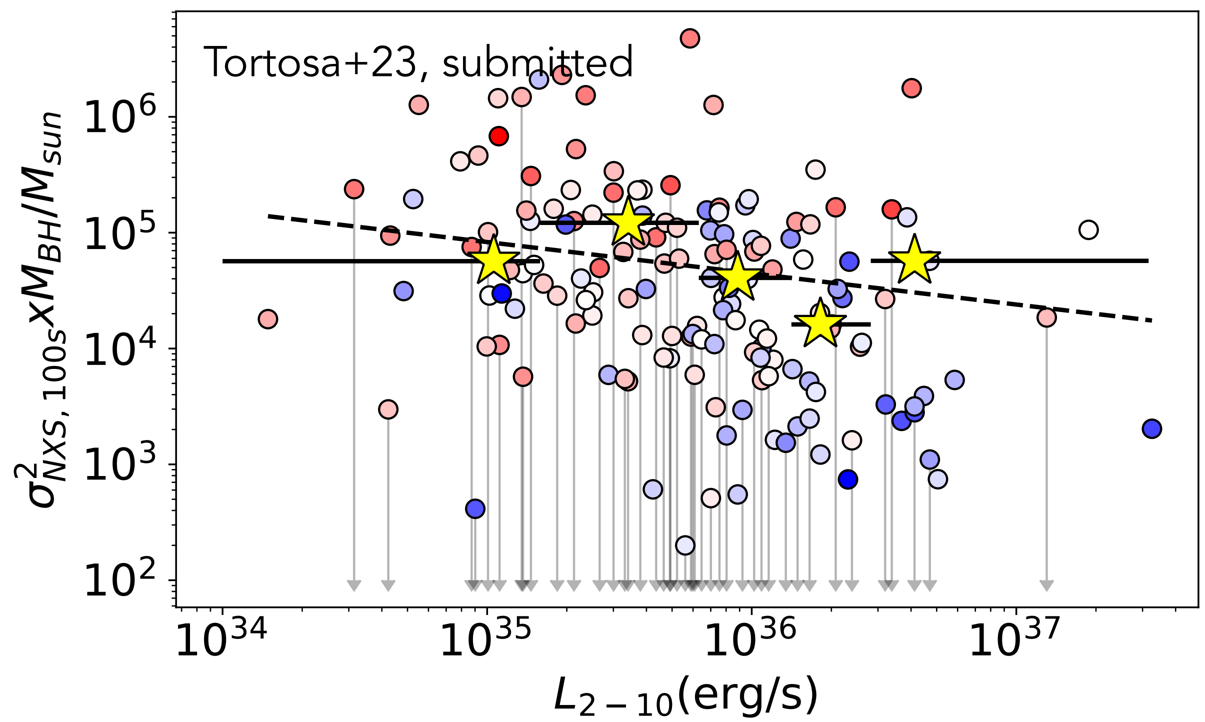
SCALING RELATIONS: $\sigma^2_{\mathrm{NXS}}\ vs\ \mathrm{L}_{2-10}$

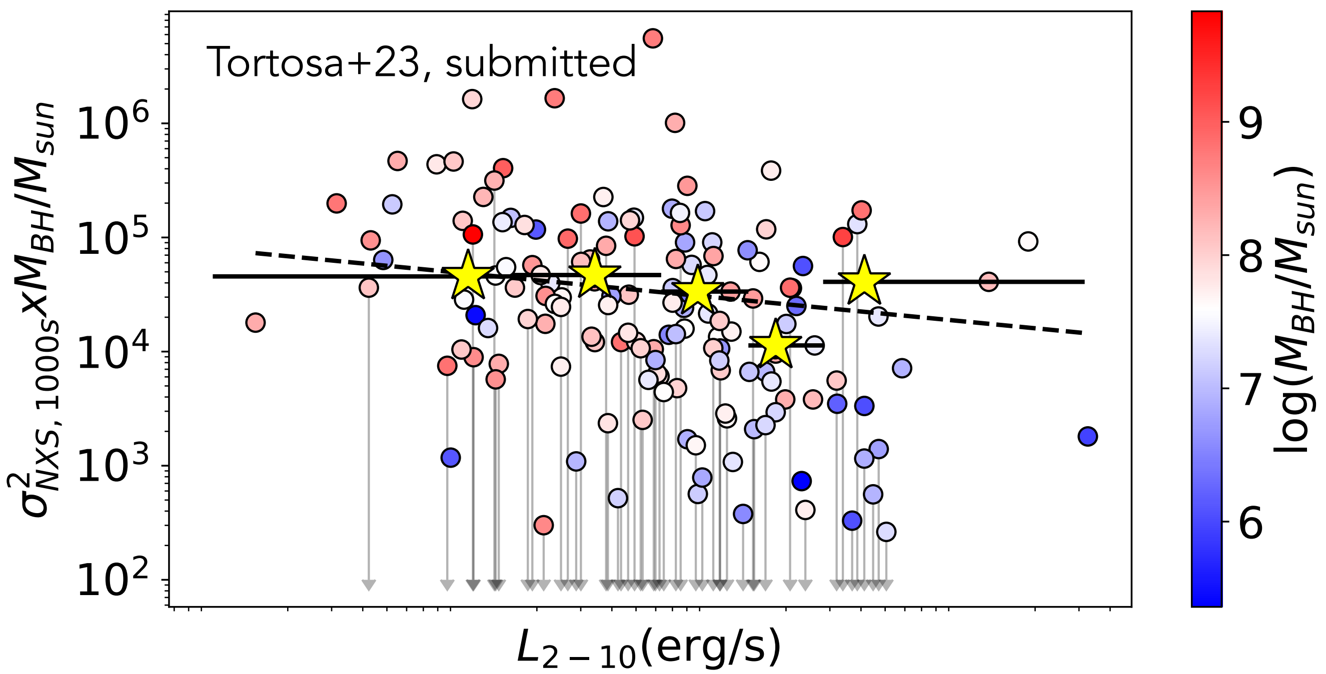
Relation	$\Delta(t)$	Intercept	Slope	Pearson	$1-P_{\mathrm{value}}$
σ^2_{NXS} vs L_{2-10}	100	26.29 ± 25.29	-0.67 ± 0.58	-0.84	0.95
σ^2_{NXS} vs L_{2-10}	1000	29.84 ± 36.41	-0.76 ± 0.60	-0.85	0.96



CORRECTION FOR THE M_{BH}:

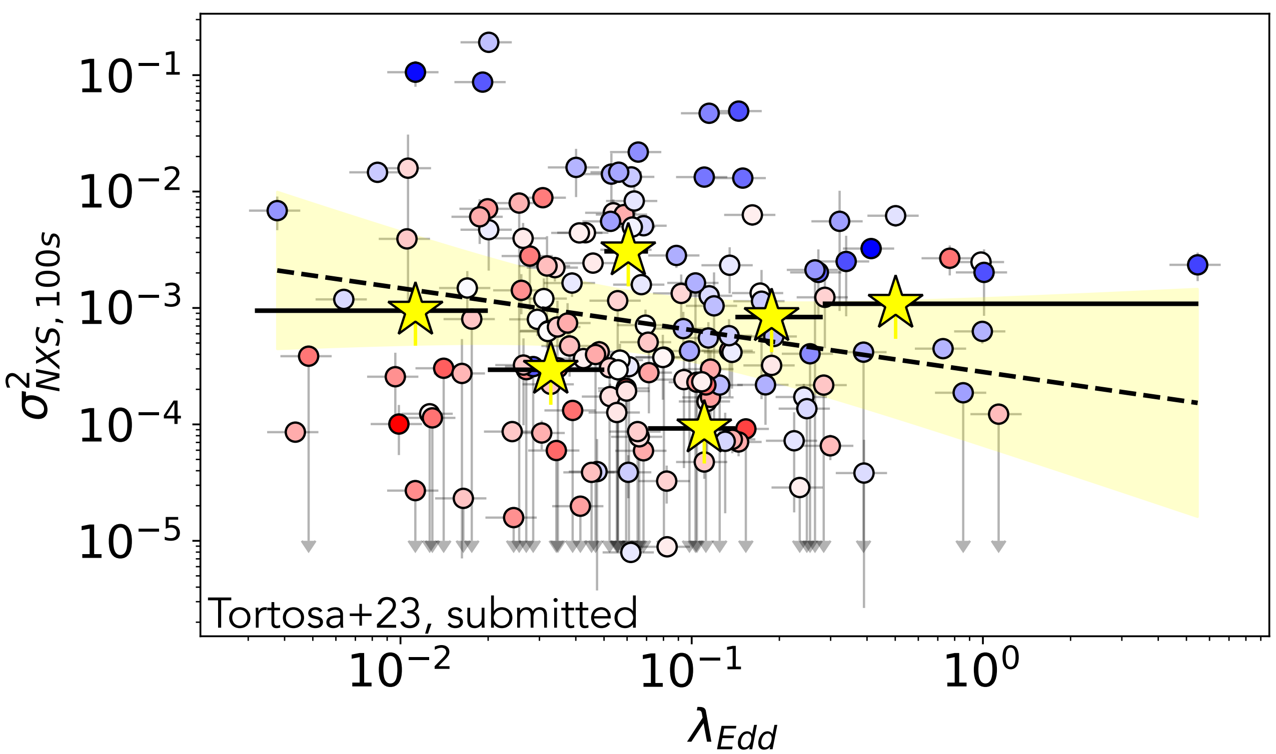
Relation	$\Delta(t)$	Intercept	Slope	Pearson	$1-P_{\text{value}}$
$\sigma^2_{\text{NXS}} \times M_{\text{BH}}$ vs L_{2-10}	100	-0.30 ± 0.79	-0.39 ± 0.11	0.23	0.43
$\sigma^2_{\text{NXS}} \times M_{\text{BH}}$ vs L_{2-10}	1000	0.66 ± 1.07	-0.54 ± 0.14	0.89	0.97

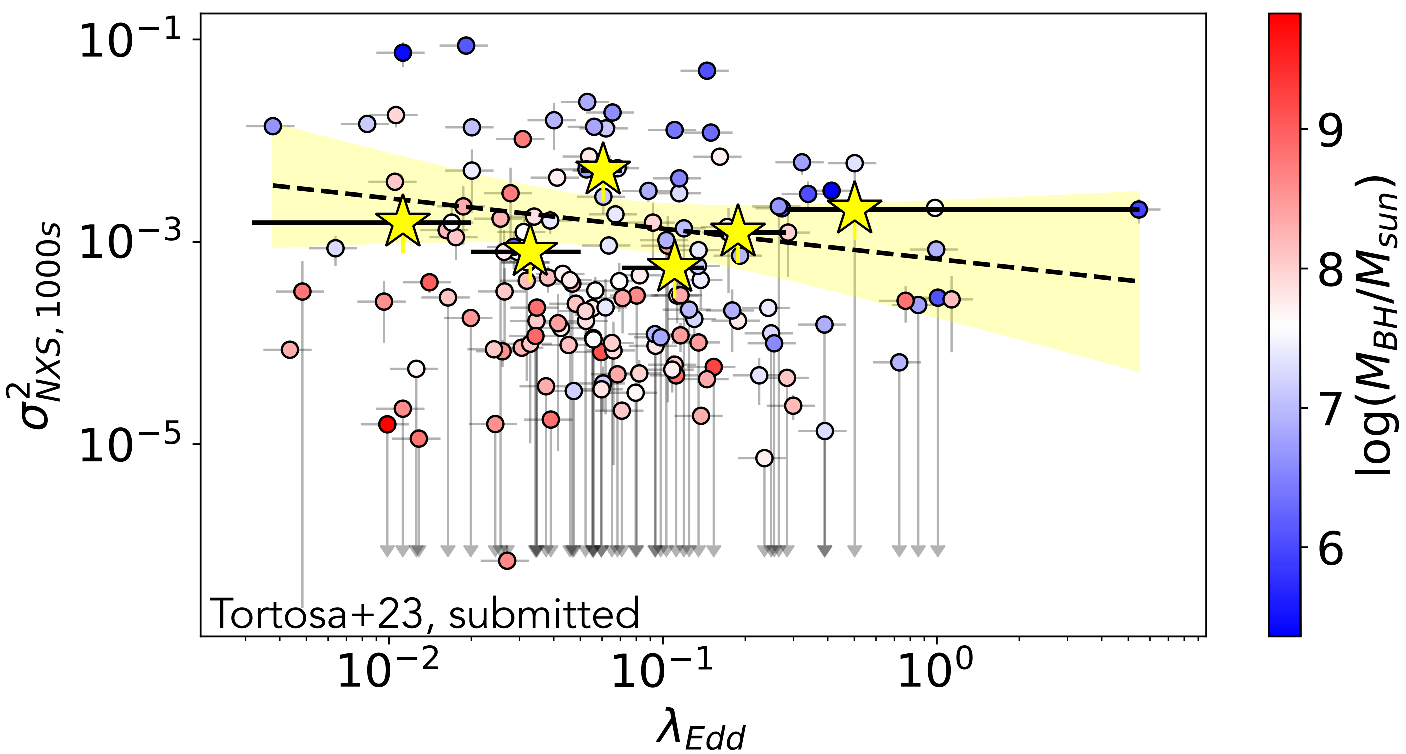




SCALING RELATIONS: $\sigma^2_{\rm NXS}$ vs $\lambda_{\rm Edd}$

Relation	$\Delta(t)$	Intercept	Slope	Pearson	$1 - P_{\rm value}$
$\sigma^2_{\rm NXS}$ vs $\lambda_{\rm Edd}$	100	-3.77 ± 2.27	-0.94 ± 1.61	-0.52	0.35
$\sigma^2_{\rm NXS}$ vs $\lambda_{\rm Edd}$	1000	-3.11 ± 3.19	-0.24 ± 1.59	-0.12	0.25



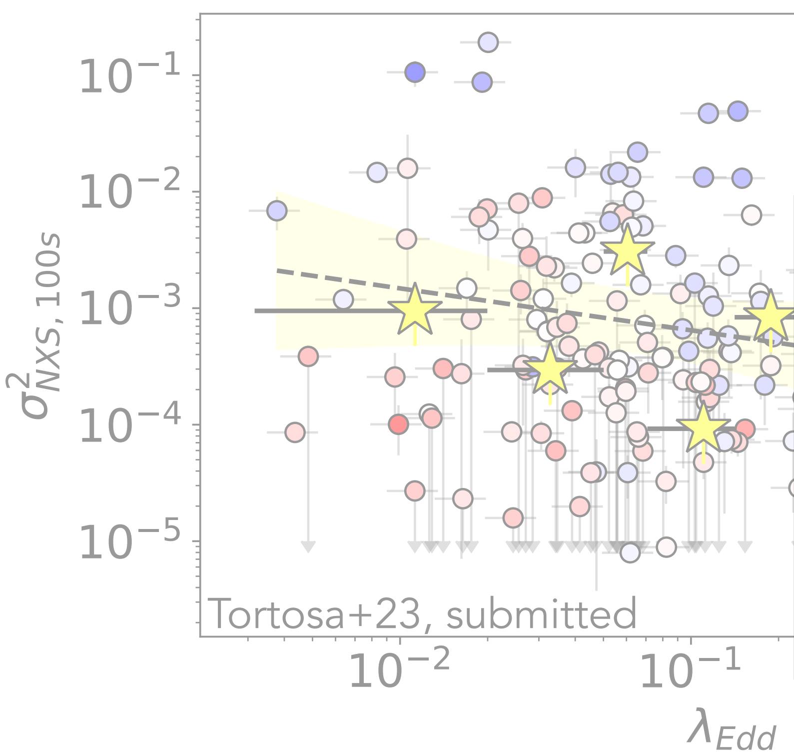


SCALING RELATIONS:

$\sigma^2_{\rm NXS}$ *vs* $\lambda_{\rm Edd}$

	Slope	Pearson	$1 - P_{\rm value}$
	94 ± 1.61	-0.52	0.35
	24 ± 1.59	-0.12	0.25

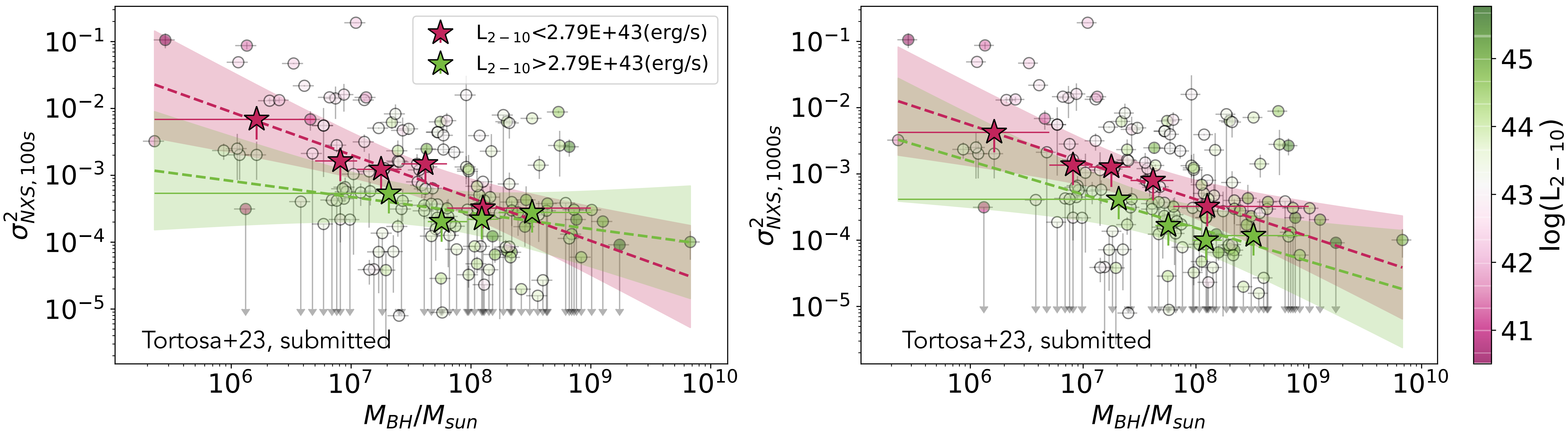
No correlation between $\nu_{\rm break}$ and $\lambda_{\rm Edd}$ (González-Martín & Vaughan 2012)



$\nu_{\rm break}$ scales with $M_{\rm BH}$ and the normalisation of the PSD scales with $\lambda_{\rm Edd}$ (McHardy+2006)

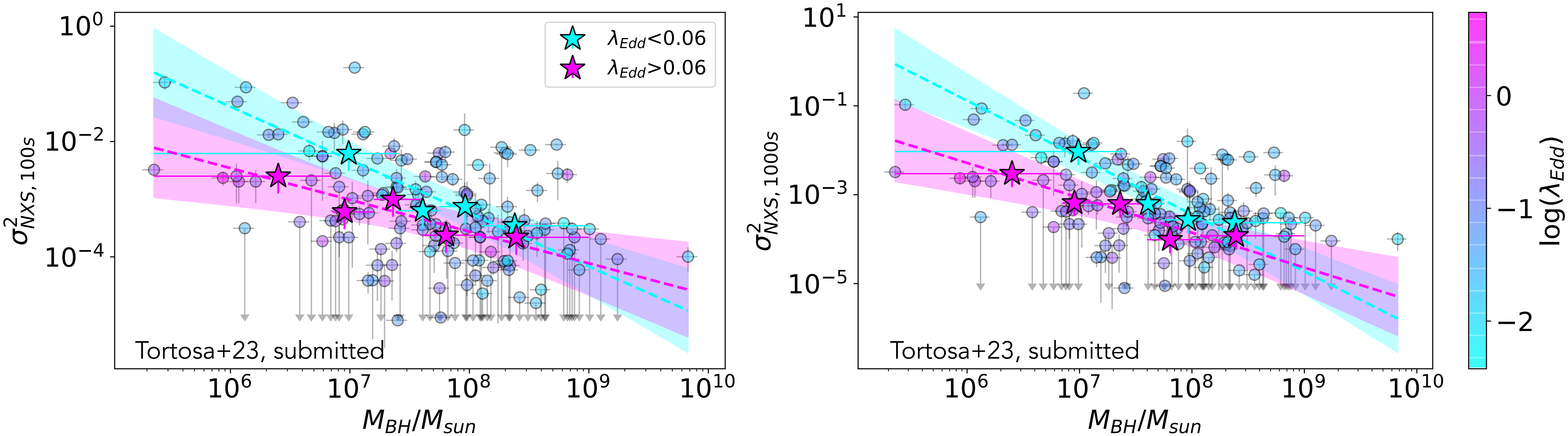
SUB-SAMPLES:

Relation	$\Delta(t)$	Intercept	Slope	Pearson	$1-P_{\text{value}}$
σ^2_{NXS} vs $M_{\text{BH}}(L_{2-10} < L_{2-10,\text{med}})$	100	0.36 ± 0.51	-0.43 ± 0.06	-0.89	0.97
σ^2_{NXS} vs $M_{\text{BH}}(L_{2-10} < L_{2-10,\text{med}})$	1000	0.16 ± 0.38	-0.37 ± 0.04	-0.99	0.99
σ^2_{NXS} vs $M_{\text{BH}}(L_{2-10} > L_{2-10,\text{med}})$	100	-2.45 ± 0.48	-0.14 ± 0.06	-0.30	0.38
σ^2_{NXS} vs $M_{\text{BH}}(L_{2-10} > L_{2-10,\text{med}})$	1000	-1.71 ± 0.41	-0.26 ± 0.05	-0.895	0.97



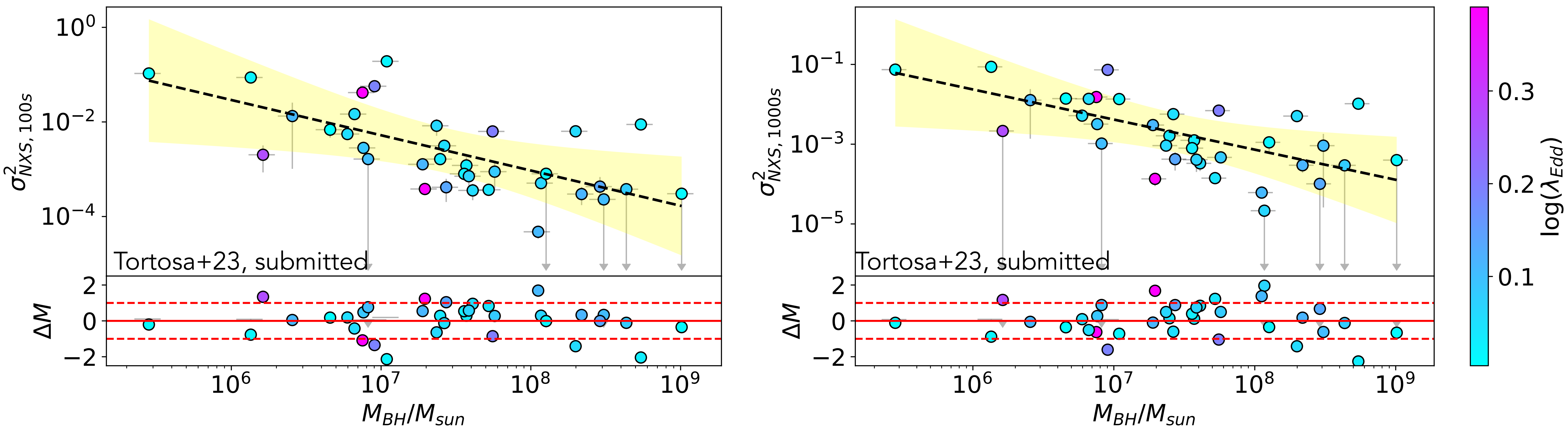
SUB-SAMPLES:

Relation	$\Delta(t)$	Intercept	Slope	Pearson	$1-P_{\rm value}$
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH}(\lambda_{\rm Edd} < \lambda_{\rm Edd,med})$	100	0.69 ± 0.76	-0.48 ± 0.09	-0.89	0.97
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH}(\lambda_{\rm Edd} < \lambda_{\rm Edd,med})$	1000	1.46 ± 1.32	-0.55 ± 0.16	-0.89	0.97
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH}(\lambda_{\rm Edd} > \lambda_{\rm Edd,med})$	100	0.16 ± 0.83	-0.42 ± 0.13	-0.89	0.97
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH}(\lambda_{\rm Edd} > \lambda_{\rm Edd,med})$	1000	2.35 ± 0.88	-0.71 ± 0.11	-0.89	0.97

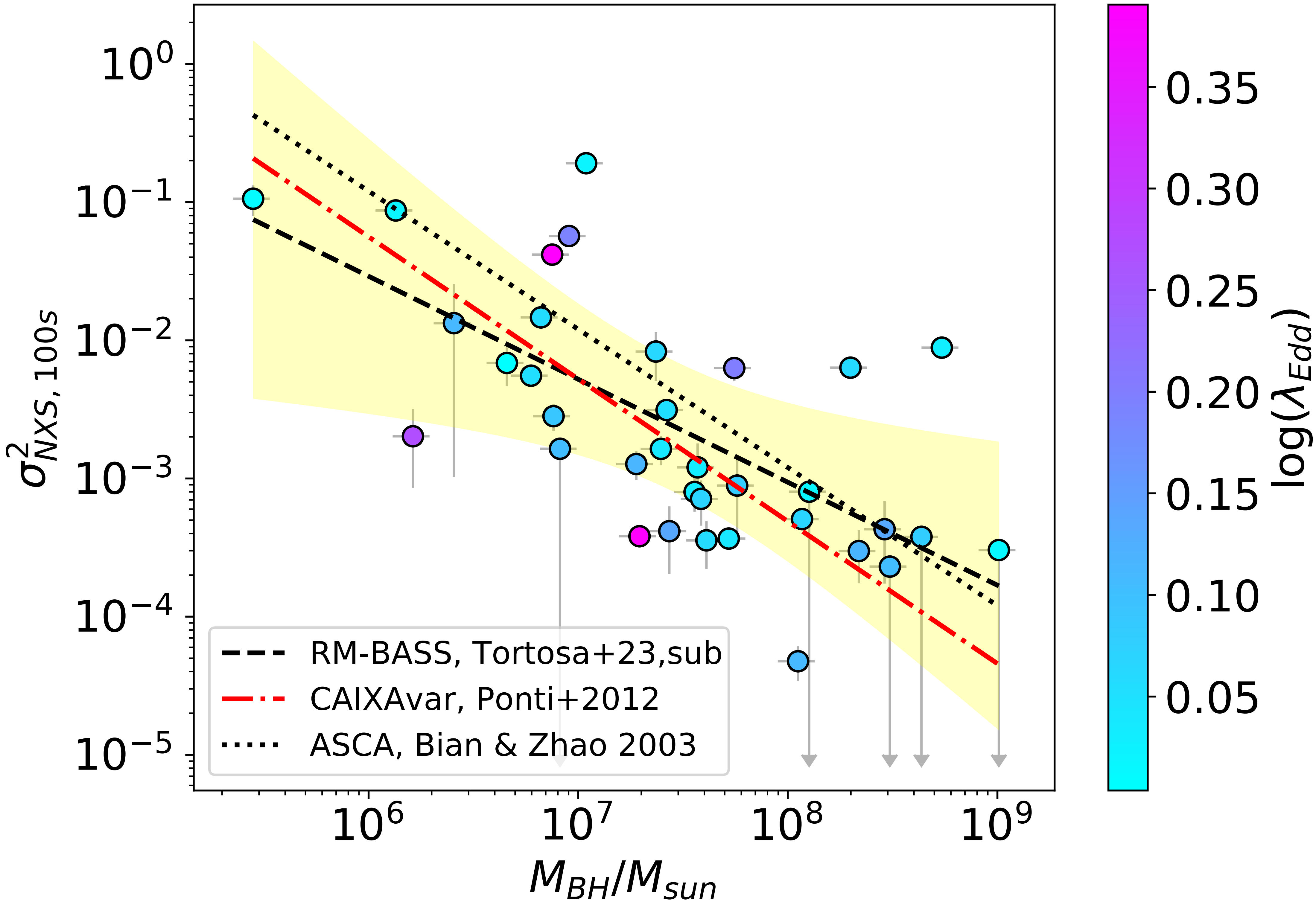


REVERBERATION MAPPING:

Relation	$\Delta(t)$	Intercept	Slope	Pearson	$1 - P_{\rm value}$
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH,rev}$	100	2.94 ± 0.29	-0.75 ± 0.20	-0.66	0.75
$\sigma^2_{\rm NXS}$ vs $M_{\rm BH,rev}$	1000	2.91 ± 0.34	-0.76 ± 0.41	-0.67	0.79



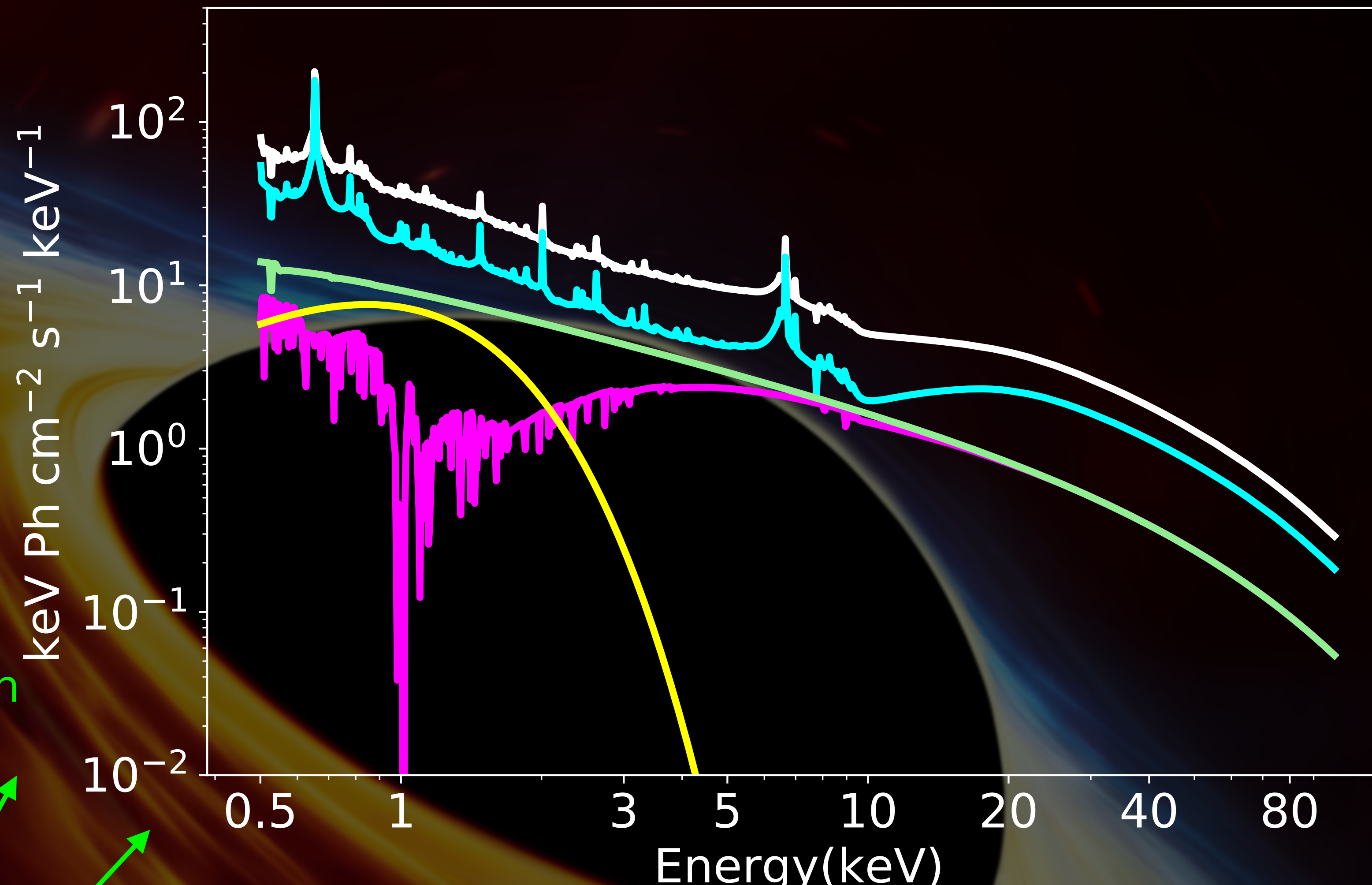
REVERBERATION MAPPING:

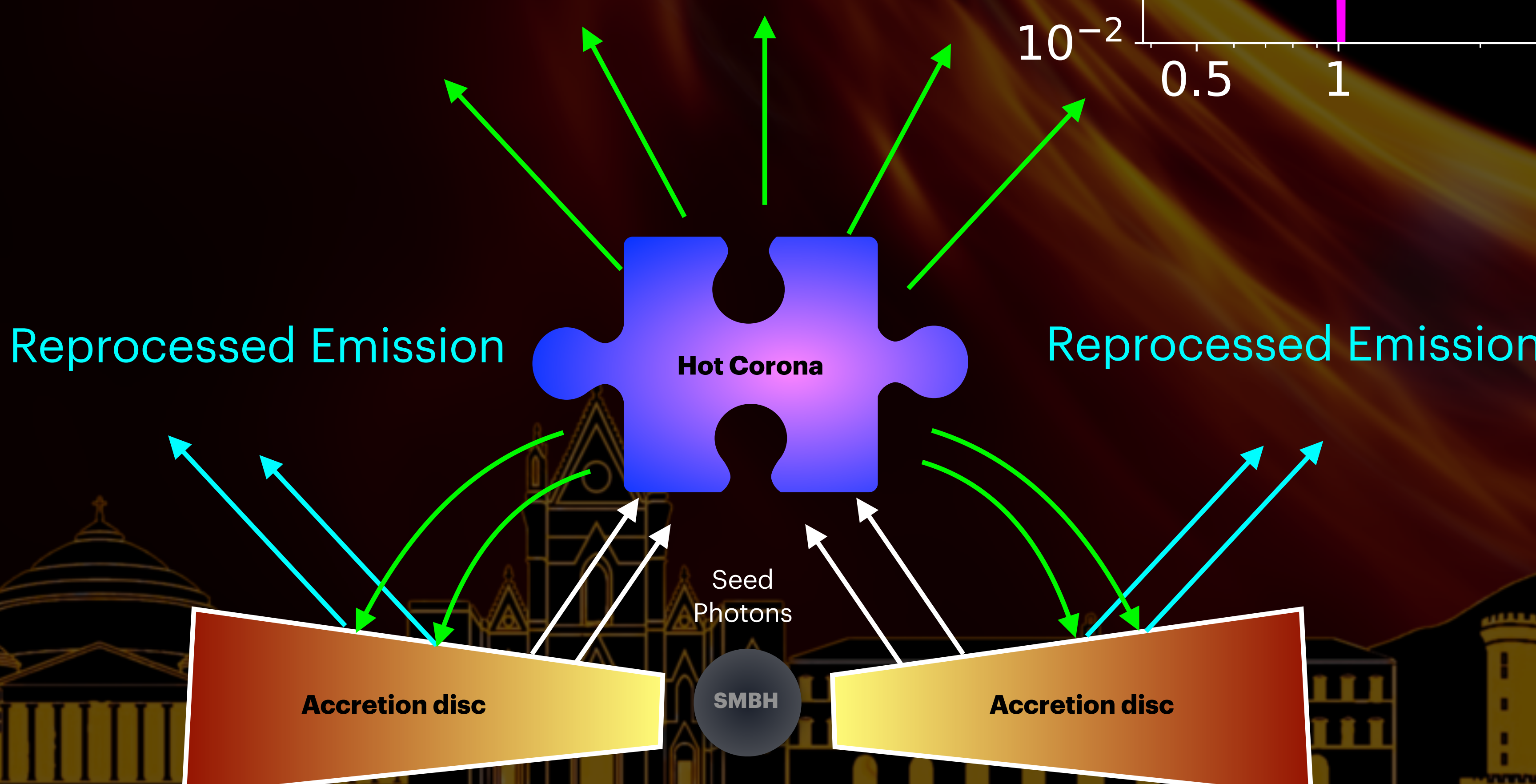


X-RAY EMISSION OF AGN:

Soft - Medium energy band
(0.3-3 keV)

- Absorbing features;
- Soft-excess.



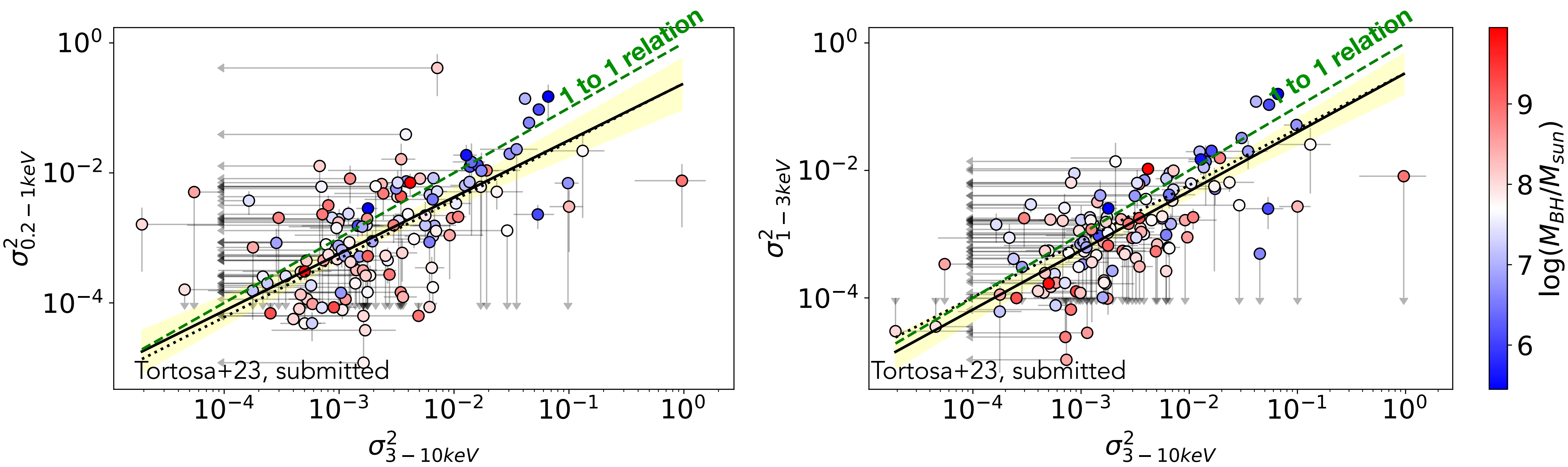


Hard energy band
(3-10 keV)

- Primary emission;
- Reprocessed emission.

SOFT, MEDIUM AND HARD ENERGY BANDS:

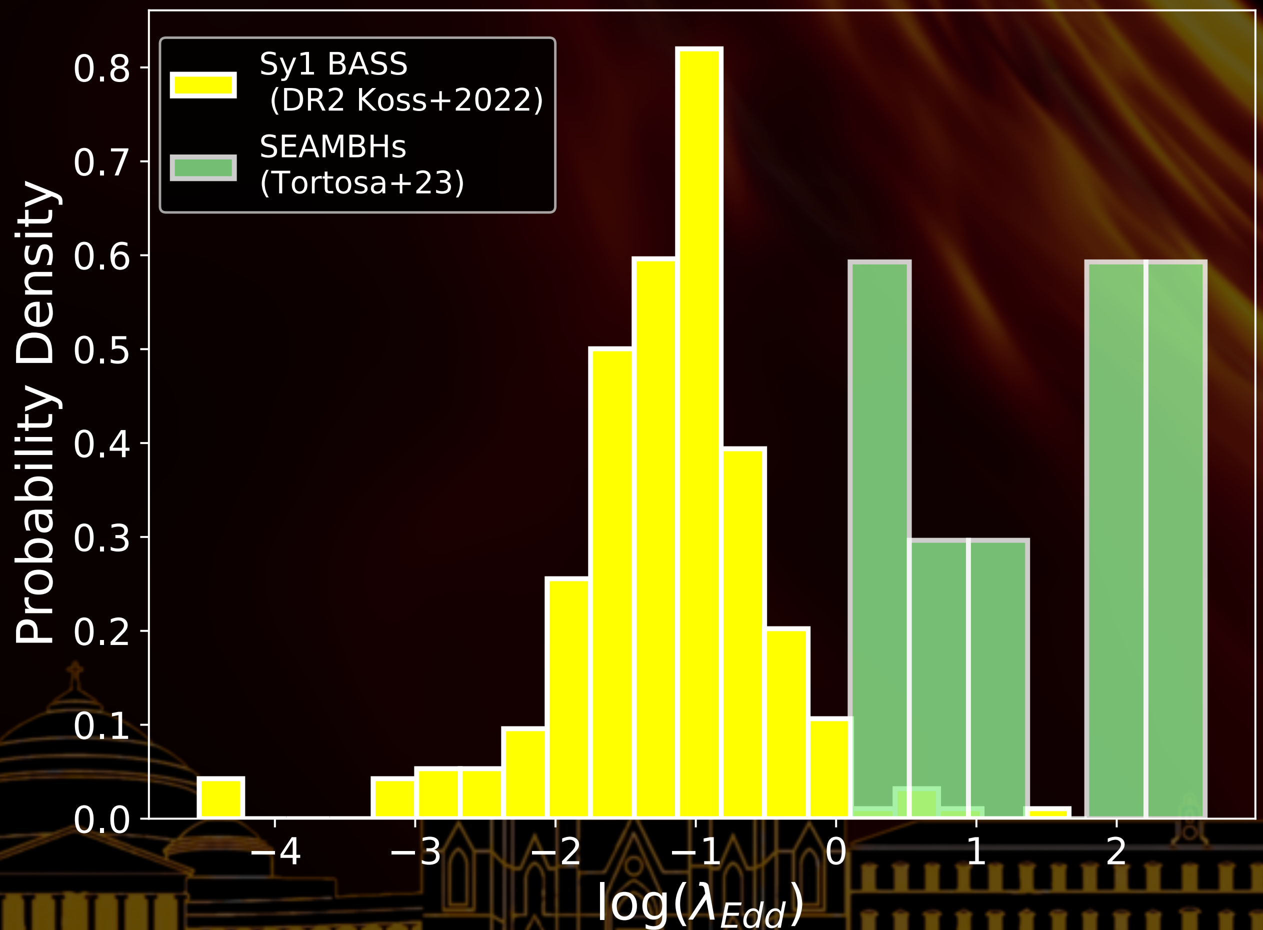
Relation	Intercept	Slope	Pearson	$1 - P_{\rm value}$
$\sigma^2_{\rm NXS,hard}$ vs $\sigma^2_{\rm NXS,soft}$	-1.53 ± 0.24	0.54 ± 0.08	0.59	0.99
$\sigma^2_{\rm NXS,hard}$ vs $\sigma^2_{\rm NXS,med}$	-1.38 ± 0.22	0.60 ± 0.07	0.68	0.99

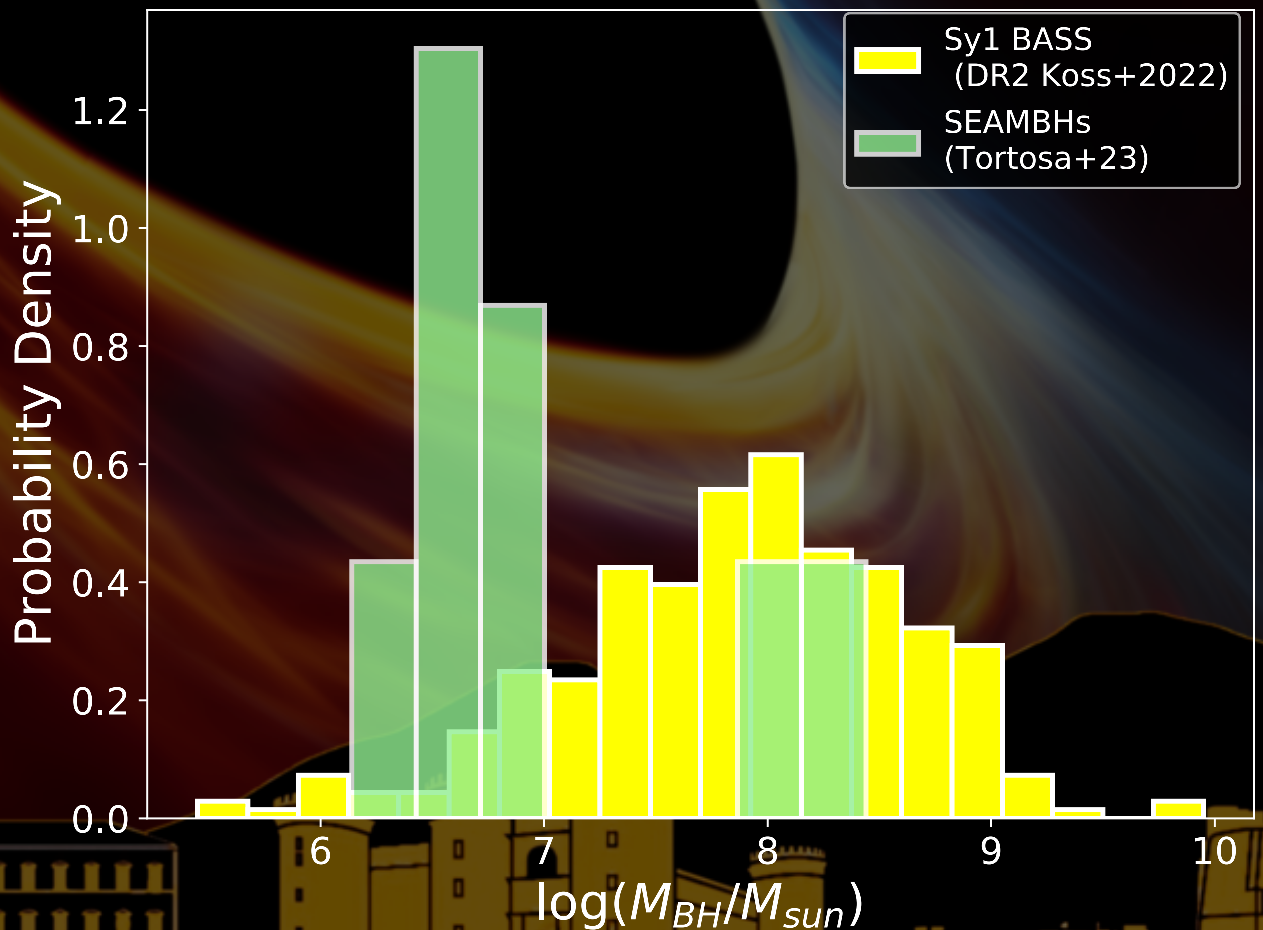


SEAMBHS:

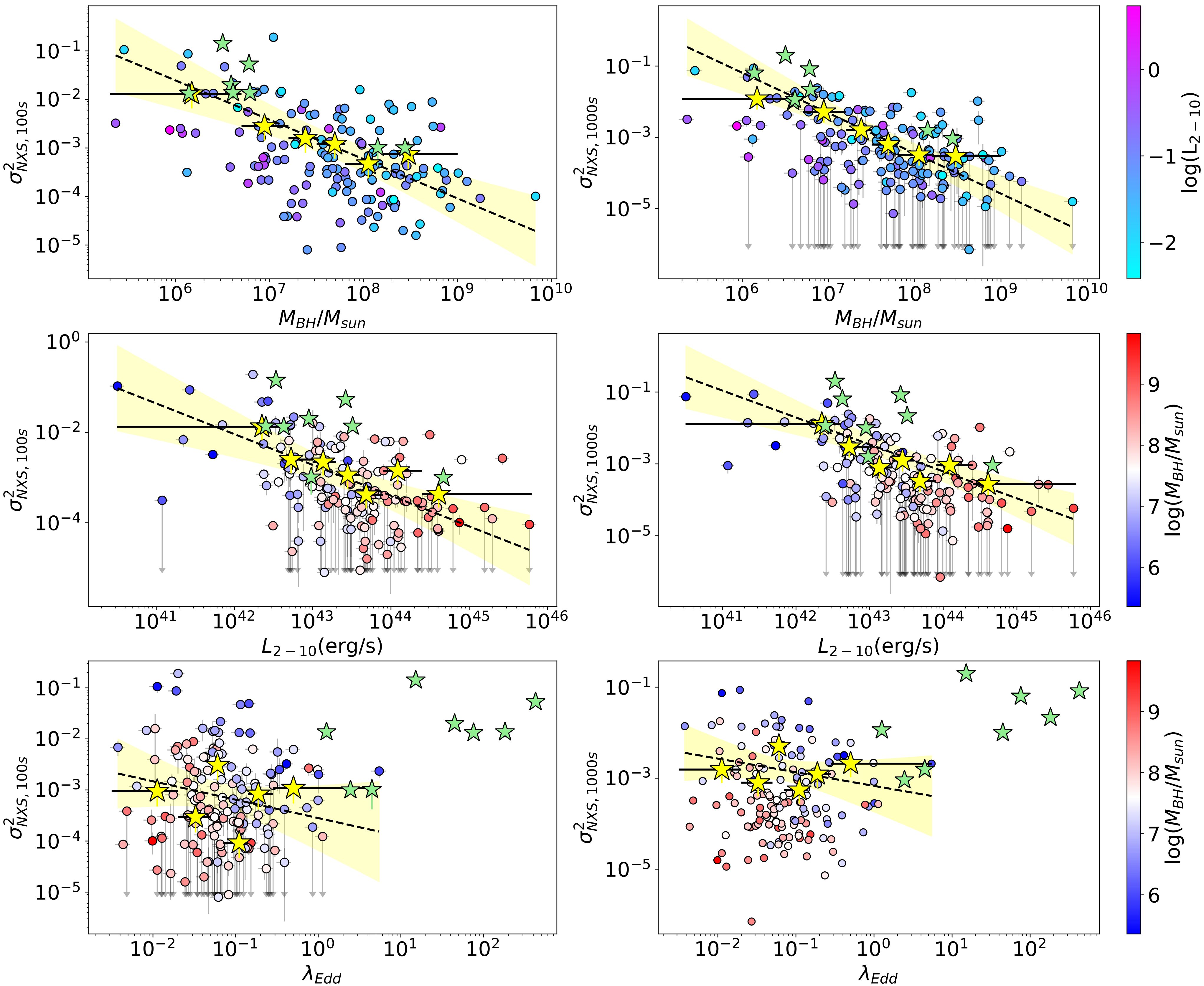
Super Eddington Accreting Massive Black Hole sample (Du et al. 2014; Wang et al. 2014; Du et al. 2015); M_{BH} estimated via reverberation mapping.
NLS1 with NuSTAR + XMM-Newton observations.

More infos here: Tortosa+2023 doi.org/10.1093/mnras/stac3590





BONUS TRACK:



$\sigma^2_{NXS,100s}$
$\sigma^2_{NXS,1000s}$
M_{BH}/M_{sun}
L_{2-10}(erg/s)
λ_{Edd}
log(L_{2-10})
log(M_{BH}/M_{sun})

TAKE HOME MESSAGES:

- Strong and highly significant σ^2_{NXS} vs. M_{BH} correlation;
- Marginally significant σ^2_{NXS} vs. λ_{Edd} correlation:
  - no correlation between T_{break} and λ_{Edd} (González-Martín & Vaughan 2012);
  - on timescales < 10ks, T_{break} scales with M_{BH} and the normalisation of the PSD scales with λ_{Edd} (McHardy+2006).
- σ^2_{NXS} vs. L_{2-10} is a secondary correlation;
- Detected lower variability for sources with higher L_{2-10} (M_{BH});
- Primary continuum and/or of reflection component increasingly more variable than spectral components dominating other energy bands on timescales < 10 ks.


Thank You!

NXS CALCULATION

- Light curves length: 10ks;
- Light curved binned with 100s and 1000s;
- z_{med}= 0.035 —> the impact of redshift is negligible;
- 10 ks-long independent light curve section to take into account the red-noise;
- For the sources with cleaned exposure time that lasted for a multiple of 10 ks, we took the median of the excess variances of all these independent sections in each energy band;
- For the sources with more than one observation, we used the median value of the NXS in both the cases of the light curves with 100 s and 1000 s time bin in each energy band.

SURVIVAL ANALYSIS

- We divided the M_{BH} into 6 bins and the L_{2-10} and λ_{Edd} into 7 bins.
- The bins are not symmetrical since in each bin there must be at least 15 values.
- We extrapolated the median (using the Kaplan-Meier product-limit) and the error of the normalized excess variance in each M_{BH}, L_{2-10} and λ_{Edd} bin using survival analysis (scikit-survival).
- We fitted the data obtained from the SA with the linmix package (hierarchical Bayesian model for fitting a straight line).

CENSORED FITTING

- Large number of least square fits on a set of Monte-Carlo simulated data derived from the experimental points.

- Each detection is substituted by a random Gaussian distribution, whose mean is the best-fit measurement and whose standard deviation is its statistical uncertainty.

- Each upper limit U was substituted by a random uniform distribution in the interval [A,U], where A is an arbitrary value $A \ll U$.