

A Novel Approach To The Relation Between X-ray And Ultraviolet Luminosities Of Quasars Using SRG/eROSITA And SDSS Data



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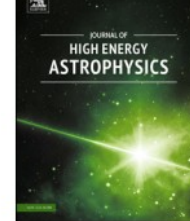
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SRG/eROSITA-SDSS view on the relation between X-ray and UV emission for quasars

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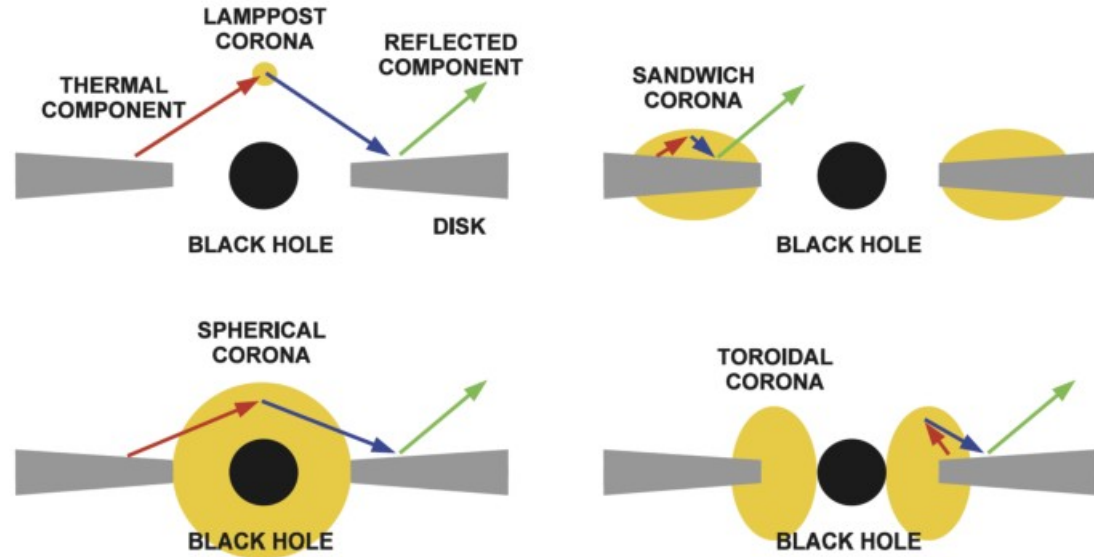
Quasars
Supermassive black holes
X-rays
Accretion discs

ABSTRACT

Motivated by the idea of using quasars as standardizable candles for cosmology, we examine the relation between X-ray (at 2 keV, $L_{2\text{keV}}$) and ultraviolet (at 2500 Å, L_{2500}) monochromatic luminosities of quasars using a sample of 2414 X-ray sources from the SRG/eROSITA all-sky survey cross-matched with the Sloan Digital Sky Survey data release 16 quasar catalogue (SDSS DR16Q), at spectroscopic redshifts between 0.5 and 2.5. These objects are bright both in X-rays and in the optical, so that the sample is characterized by nearly 100% statistical completeness. We have developed a new method for determining the $L_{2\text{keV}}-L_{2500}$ relation, which consistently takes into account (i) X-ray and UV flux limited object selection, (ii) X-ray and UV variability of quasars, and (iii) the decreasing space density of quasars with increasing luminosity. Assuming a linear relation be-

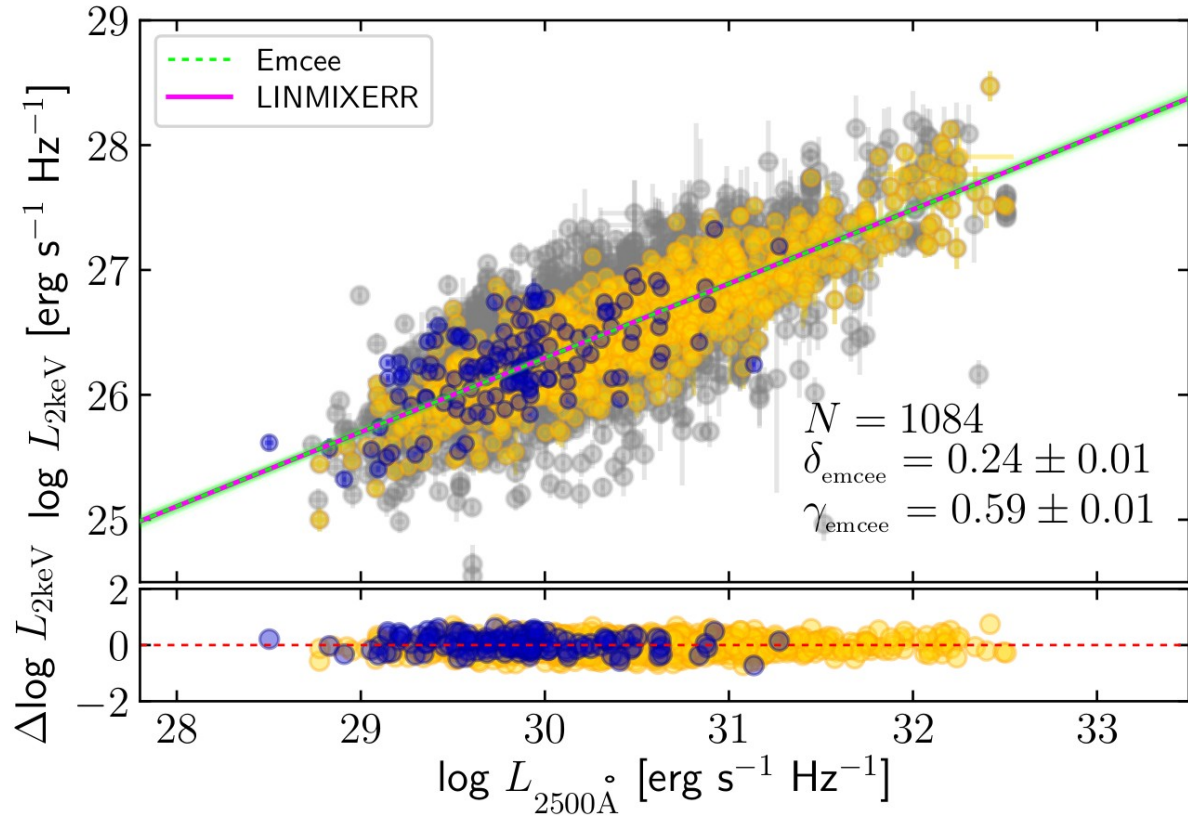
Introduction

- An **active galactic nucleus (AGN)** is a region at the center of a galaxy that emits powerful electromagnetic radiation in the range from radio to X-rays (or even gamma)
- **Quasars** are the most luminous AGNs
- The **energy source** is accretion onto a supermassive black hole.
- Accretion disk - ultraviolet (UV) radiation
- **Corona** - X-ray radiation



Results of previous work

- For more than 40 years it is known that X-ray and UV emission strongly correlate
- Disk luminosity L_{UV} at 2500\AA
- Corona luminosity L_x at 2keV
- The relation is usually sought in form $\log L_x = \gamma \log L_{UV} + \beta$
- Evaluated γ and β varied across samples and methods
- The use of quasars in cosmology as "standard candles" is being discussed (only if $\gamma \neq 1$)



Bisogni et. al. 2021

In previous works, the selection effects by fluxes were not fully taken into account

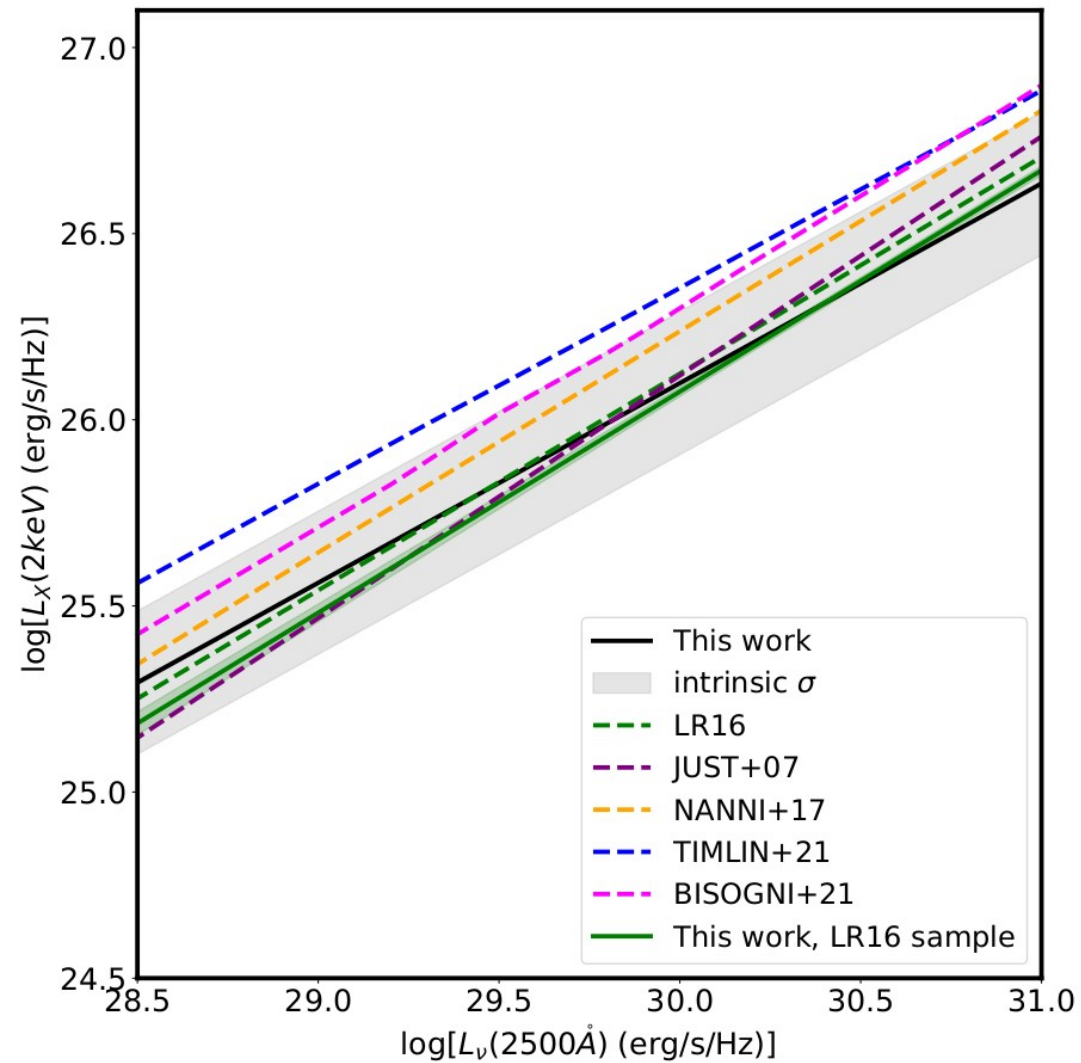


Figure from Chira et. al. 2025

In previous works, the selection effects by fluxes were not fully taken into account

Lusso & Risaliti (2016), Rankine et al. (2024), Chira et. al. (2025) took into account AGNs that were not detected in X-rays, but considered only those that were **detected in the optical**

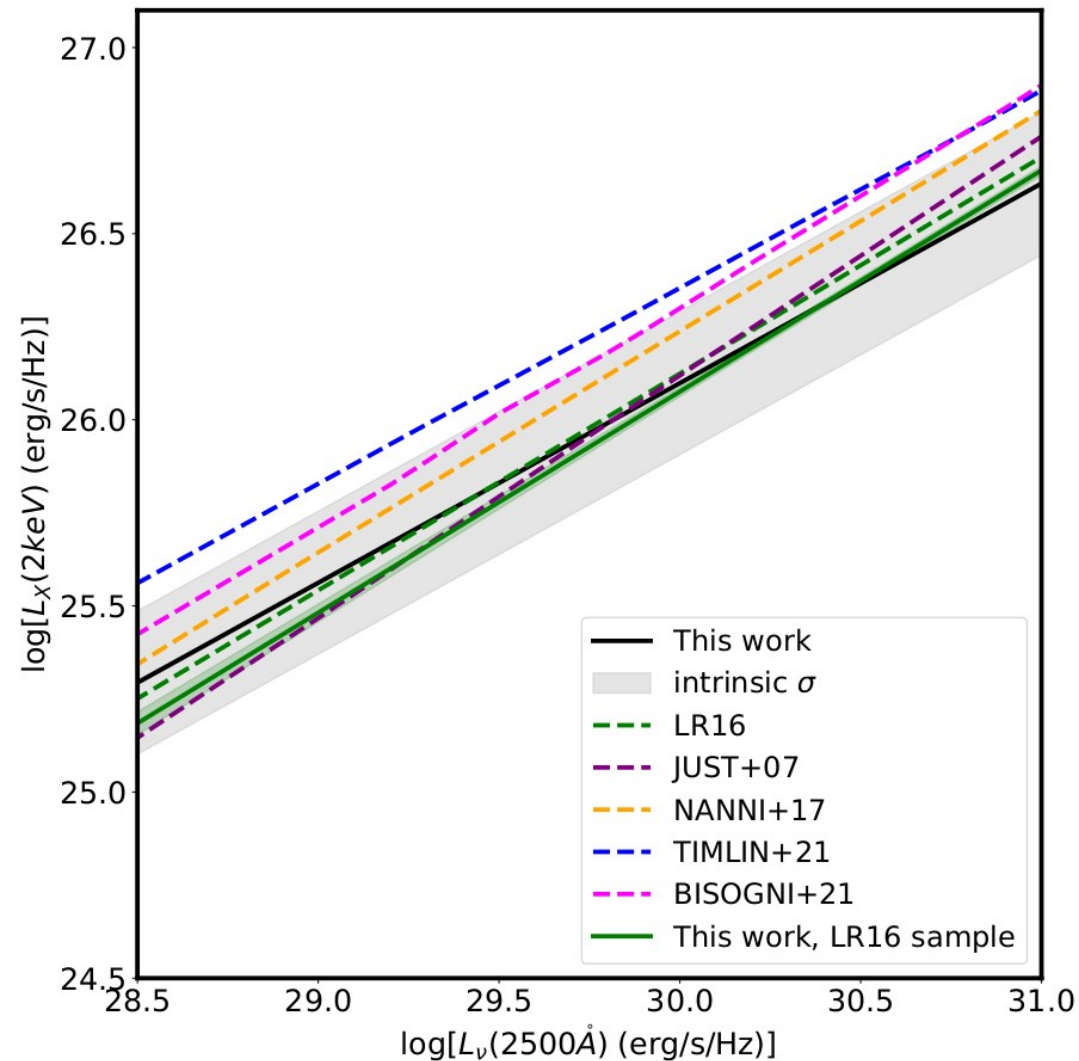


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There have been attempts to account for the change in the density of quasars with luminosity and z (Dainotti et. al. 2022, Wang et. al. 2022)

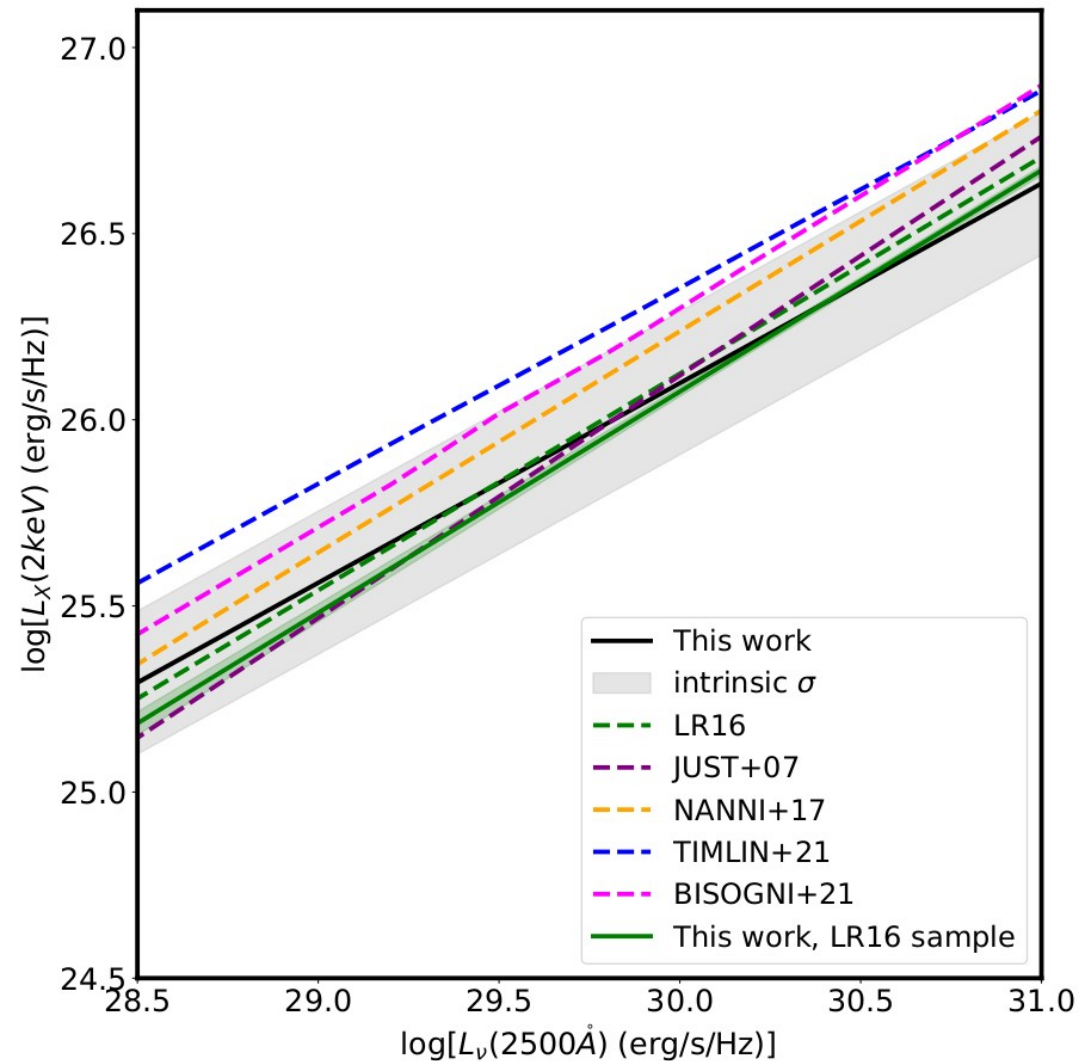


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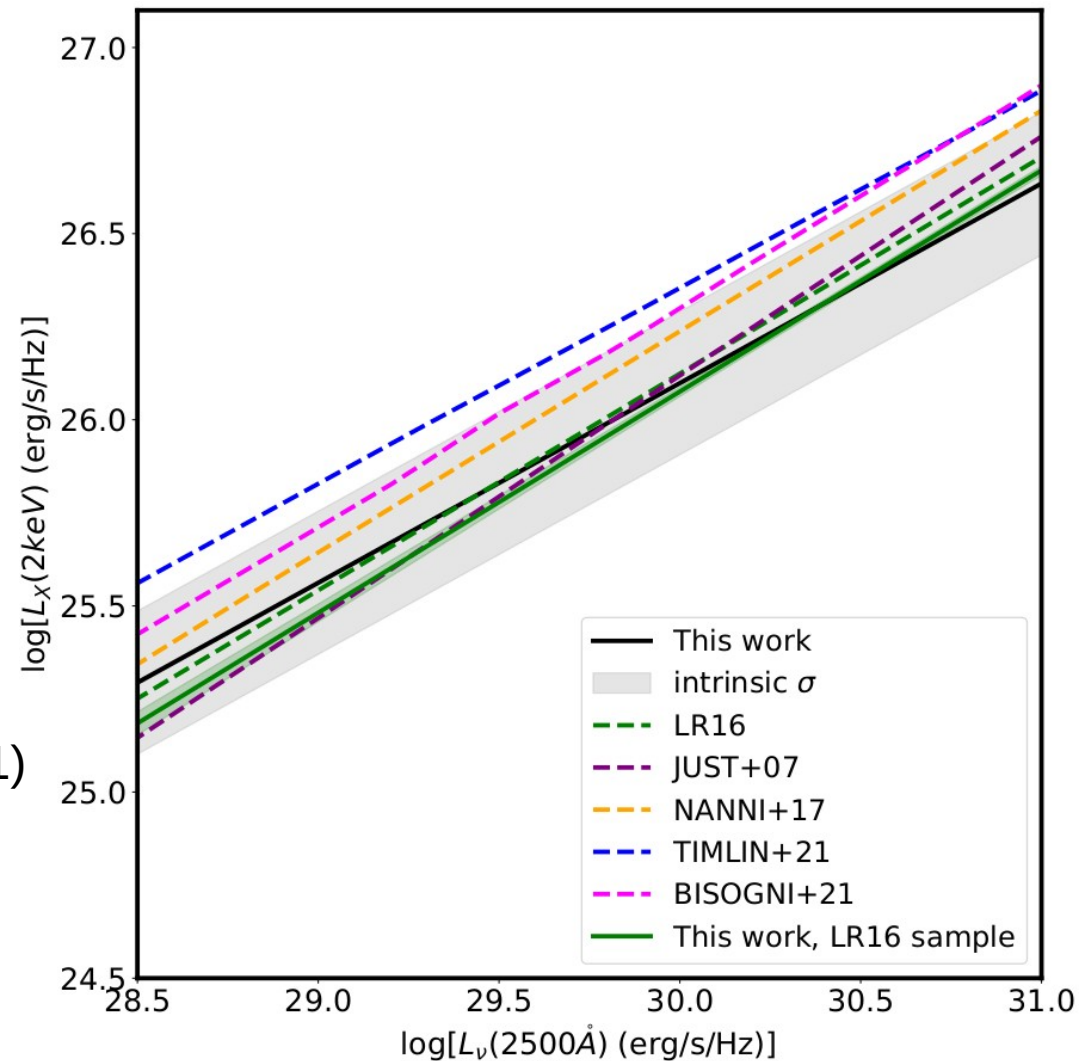


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But we presented for the first time a method for finding the relationship between L_{UV} and L_X that **self-consistently takes into account all these effects**

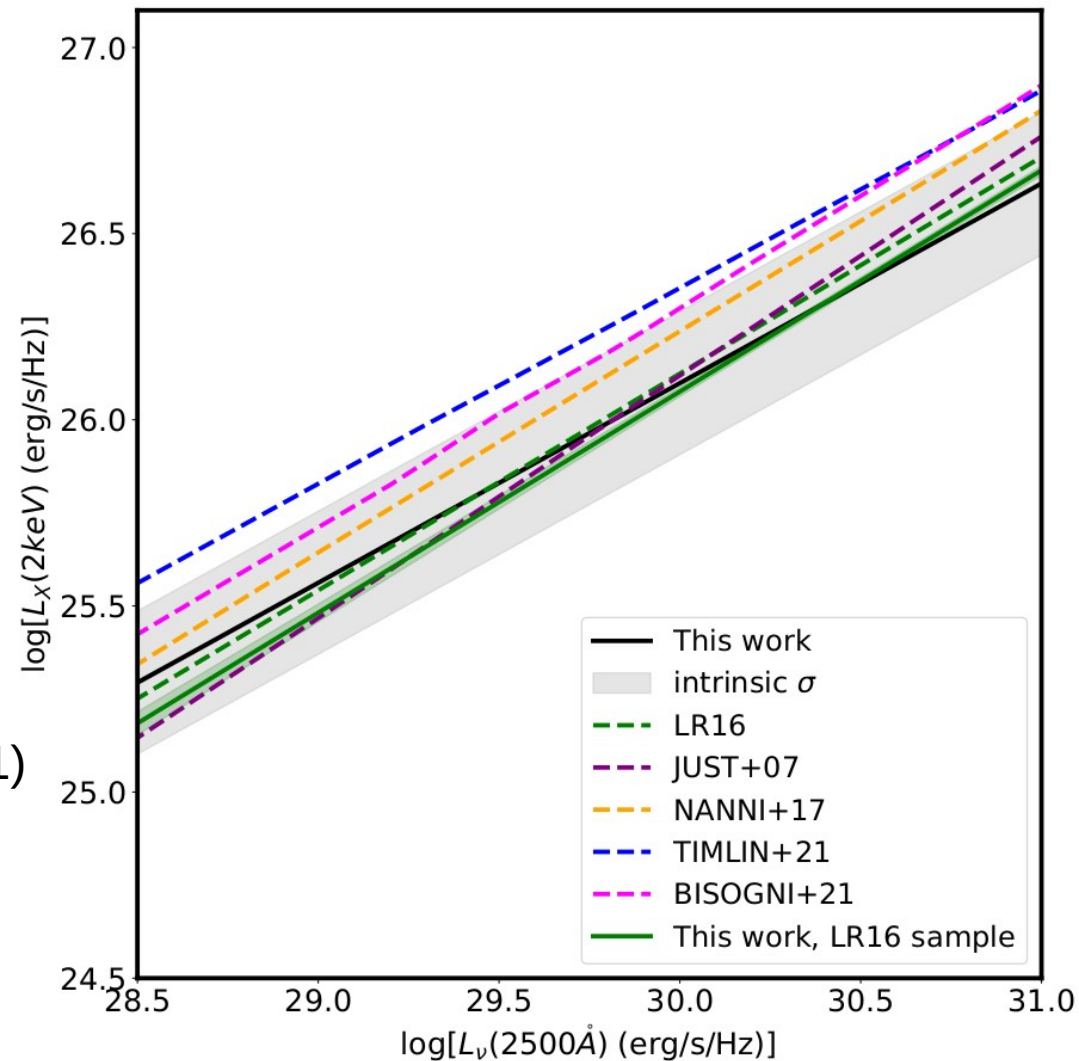
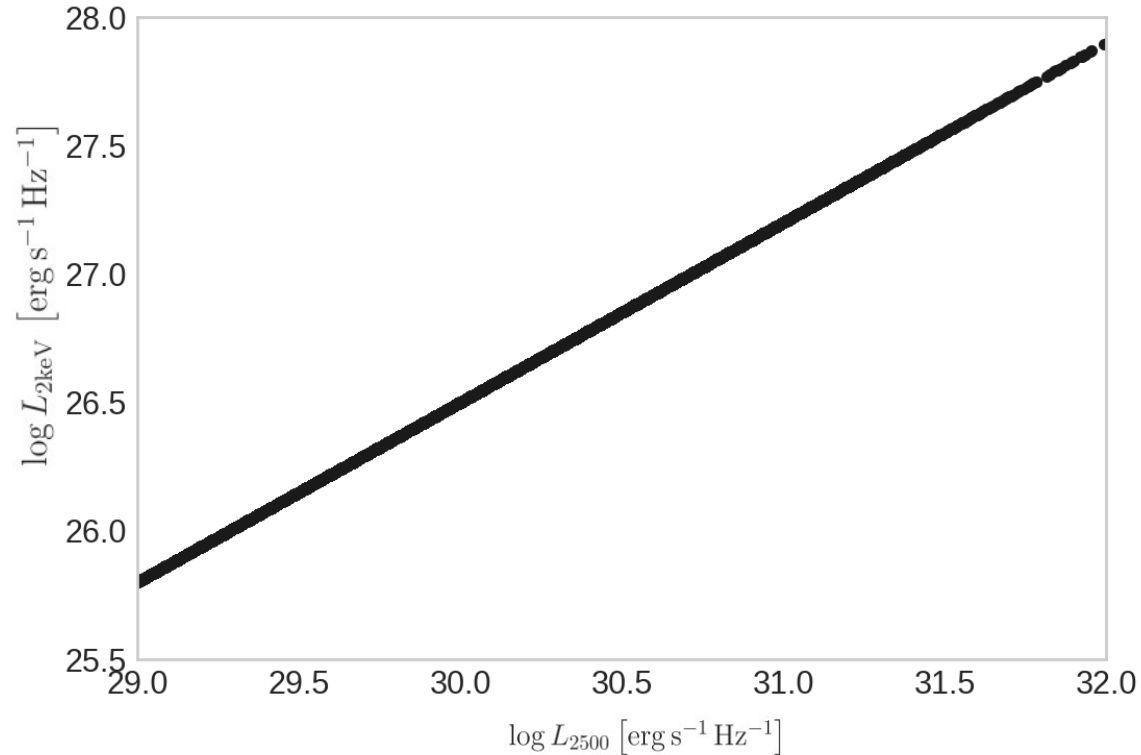


Figure from Chira et. al. 2025

Our model of the relationship between quasar luminosities

$$1) f(l_X, l_{UV}|z, \sigma_{UV}, \sigma_X) = \int \int \mathcal{N}(l_X|\tilde{l}_X, \sigma_X) \mathcal{N}(l_{UV}|\tilde{l}_{UV}, \sigma_{UV}) \times \delta(\tilde{l}_X - (\beta + \gamma\tilde{l}_{UV})) |\gamma| \tilde{L}F(\tilde{l}_X|z) d\tilde{l}_X d\tilde{l}_{UV}$$

- Primary dependence: $\tilde{l}_X = \beta + \gamma\tilde{l}_{UV}$
 $\tilde{l}_{UV} = \log \tilde{L}_{UV}$, $\tilde{l}_X = \log L_X$



$$2) f_{obs,i} = \frac{f(l_{X,i}, l_{UV,i}|z_i, \sigma_{UV,i}, \sigma_{X,i})}{\int_{l_{UVmin}(z_i)}^{\infty} \int_{l_{Xmin}(z_i)}^{\infty} f(l_X, l_{UV}|z_i, \sigma_{UV,i}, \sigma_{X,i}) dl_X dl_{UV}}$$

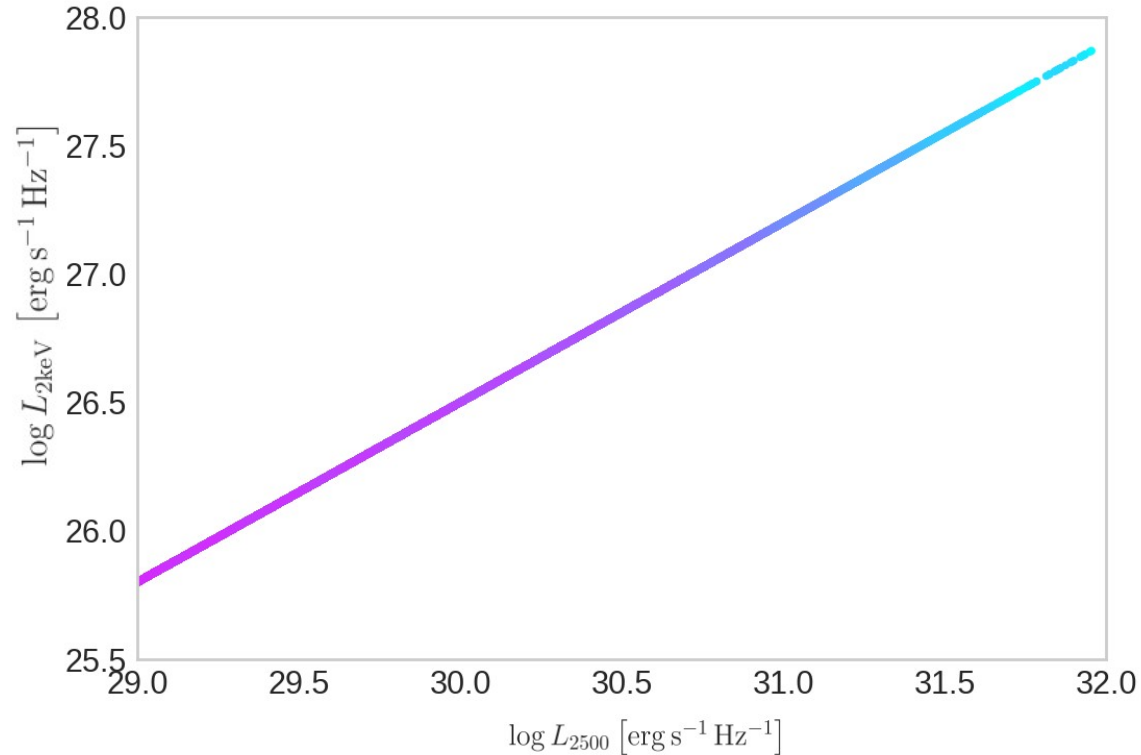


Likelihood: $\mathcal{L} = \prod_i f_{obs,i}$

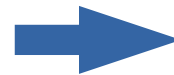
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- Primary dependence: $\tilde{l}_X = \beta + \gamma\tilde{l}_{UV}$
 $\tilde{l}_{UV} = \log \tilde{L}_{UV}$, $\tilde{l}_X = \log L_X$
- Quasars density change **along** this dependence



$$2) f_{obs,i} = \frac{f(l_{X,i}, l_{UV,i}|z_i, \sigma_{UV,i}, \sigma_{X,i})}{\int_{l_{UVmin}(z_i)}^{\infty} \int_{l_{Xmin}(z_i)}^{\infty} f(l_X, l_{UV}|z_i, \sigma_{UV,i}, \sigma_{X,i}) dl_X dl_{UV}}$$



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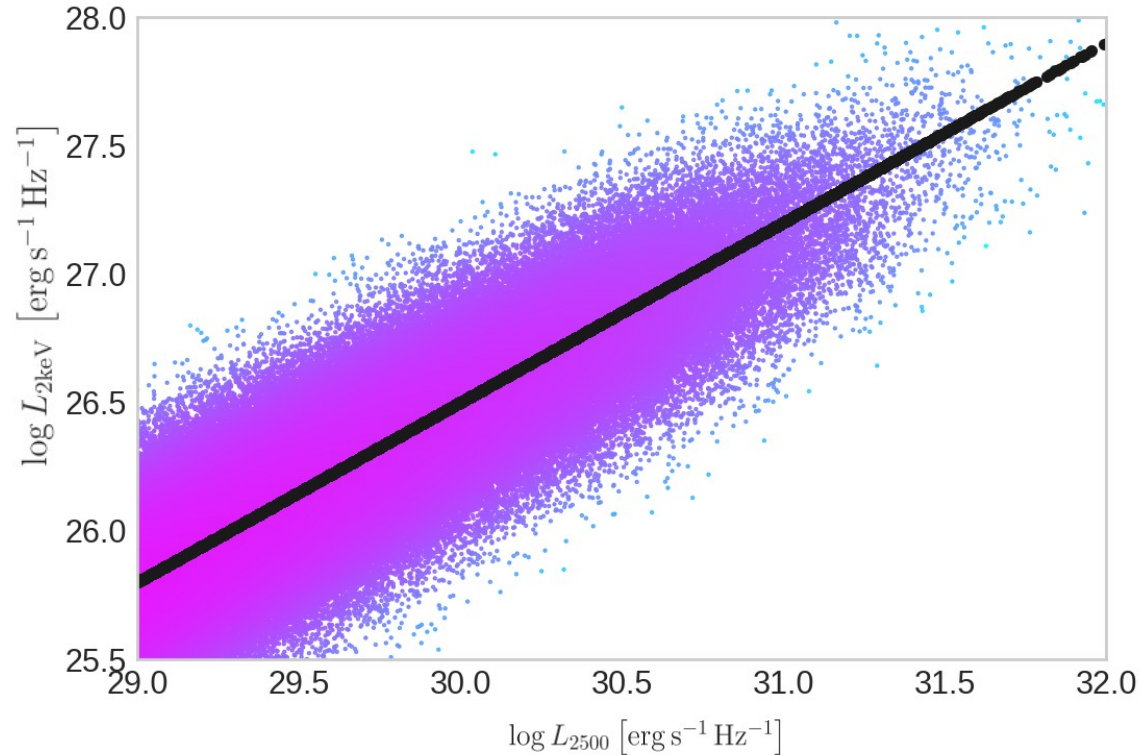
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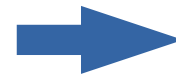
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- Quasars density change **along** this dependence
- Scatter along **both** axes with respect to the dependence consists of **independent** contributions of **measurement uncertainties**, **variability** and **intrinsic scatters**:

$$\sigma_{UV}^2 = \sigma_{errUV}^2 + \sigma_{varUV}^2 + \sigma_{intUV}^2$$

$$\sigma_X^2 = \sigma_{errX}^2 + \sigma_{varX}^2 + \sigma_{intX}^2$$



$$2) f_{obs,i} = \frac{f(l_{X,i}, l_{UV,i}|z_i, \sigma_{UV,i}, \sigma_{X,i})}{\int_{l_{UVmin}(z_i)}^{\infty} \int_{l_{Xmin}(z_i)}^{\infty} f(l_X, l_{UV}|z_i, \sigma_{UV,i}, \sigma_{X,i}) dl_X dl_{UV}}$$



$$\text{Likelihood: } \mathcal{L} = \prod_i f_{obs,i}$$

Our model of the relationship between quasar luminosities

$$1) f(l_X, l_{UV}|z, \sigma_{UV}, \sigma_X) = \int \int \mathcal{N}(l_X|\tilde{l}_X, \sigma_X) \mathcal{N}(l_{UV}|\tilde{l}_{UV}, \sigma_{UV}) \times \delta(\tilde{l}_X - (\beta + \gamma\tilde{l}_{UV})) |\gamma| \tilde{L}F(\tilde{l}_X|z) d\tilde{l}_X d\tilde{l}_{UV}$$

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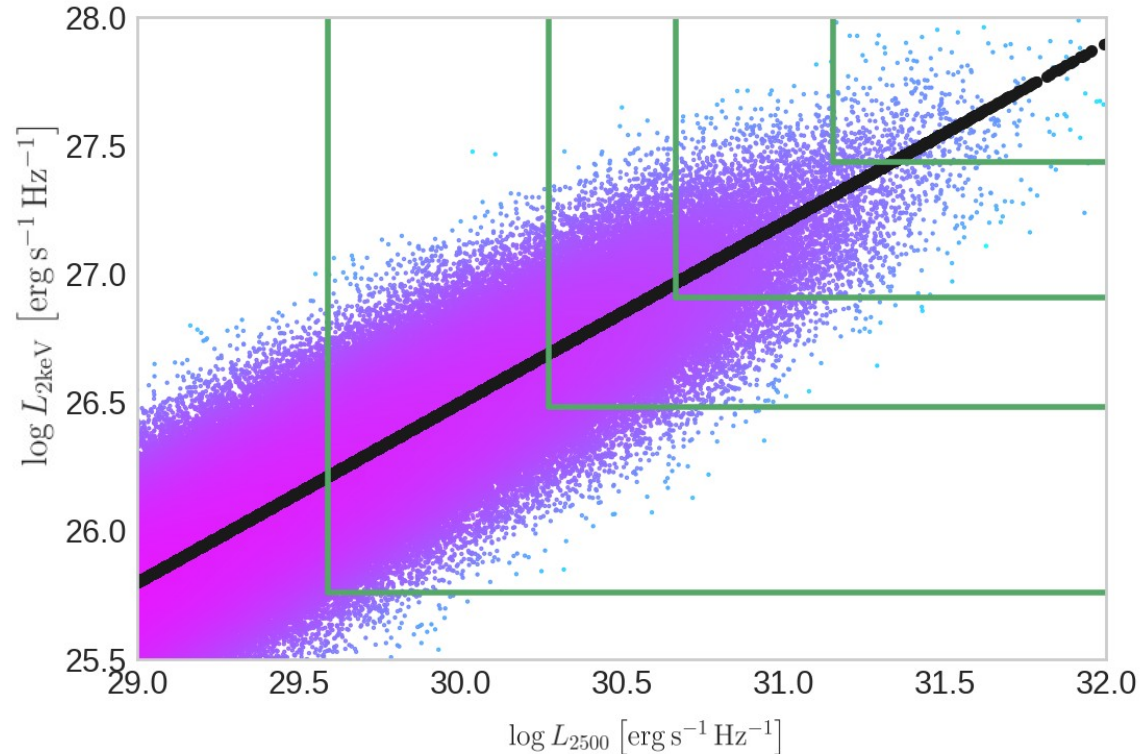
$$\sigma_X^2 = \sigma_{errX}^2 + \sigma_{varX}^2 + \sigma_{intX}^2$$

- Accounting for flux selection (selection function)

$$2) f_{obs,i} = \int_{l_{UVmin}(z_i)}^{\infty} \int_{l_{Xmin}(z_i)}^{\infty} f(l_X, l_{UV}|z_i, \sigma_{UV,i}, \sigma_{X,i}) dl_X dl_{UV}$$



$$\text{Likelihood: } \mathcal{L} = \prod_i f_{obs,i}$$



Luminosity function along the primary dependence

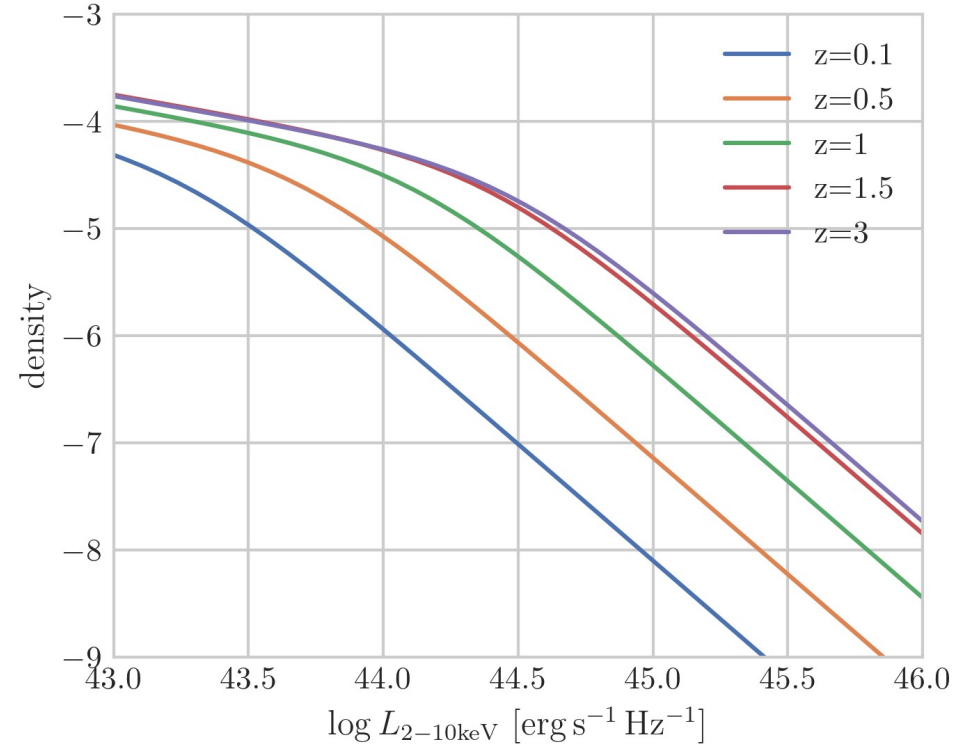
Luminosity-and-density-evolution (LADE)
from Aird et. al. 2015

$$LF(L_X, z) \propto \left[\left(\frac{L_X}{e(z)L^*} \right)^{g_1} + \left(\frac{L_X}{e(z)L^*} \right)^{g_2} \right]^{-1}$$

Our method is insensitive to
normalizations at each z

$$e(z) = \left[\left(\frac{1+z_c}{1+z} \right)^{p_1} + \left(\frac{1+z_c}{1+z} \right)^{p_2} \right]^{-1}$$

Free parameters are g_1, g_2, L^*, p_1, z_c
 $p_2 = -3.58$



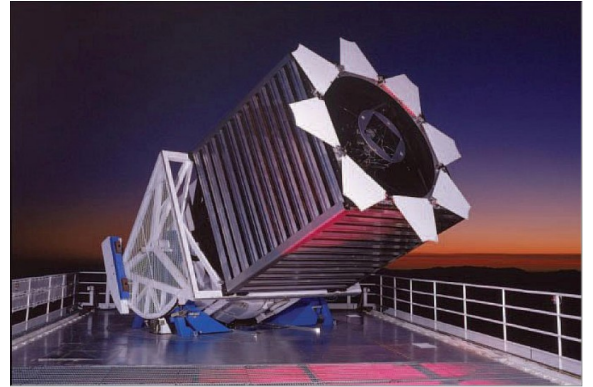
LADE LF for parameters from Aird et. al. 2015

The quasar sample we use

SDSS DR16Q catalogue of type I quasars was crossmatched with SRG/eROSITA sources.

We further use redshifts and K-corrections from the catalogue of spectral properties based on SDSS DR16Q (Wu & Shen 2022).

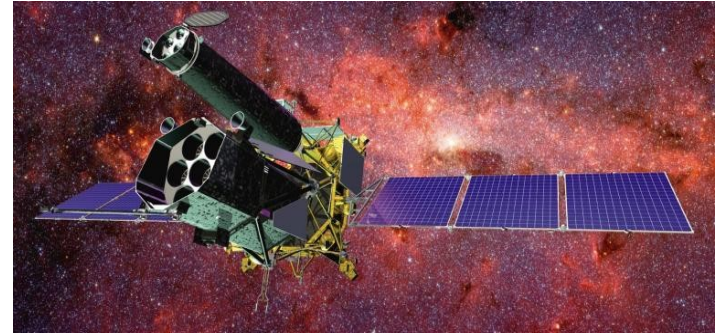
To calculate UV luminosities, we use fluxes from the SDSS photometric survey and these K-corrections.



SDSS telescope

Sampling criteria:

- At least 20 X-ray counts (mean 2-years eROSITA flux is above 6×10^{-14} erg/s/cm²)
- Apparent magnitude in the g band is <19
- From sky regions with 100% completeness in SDSS and with Galaxy absorption of $N_H < 4 \times 10^{20}$ cm⁻²

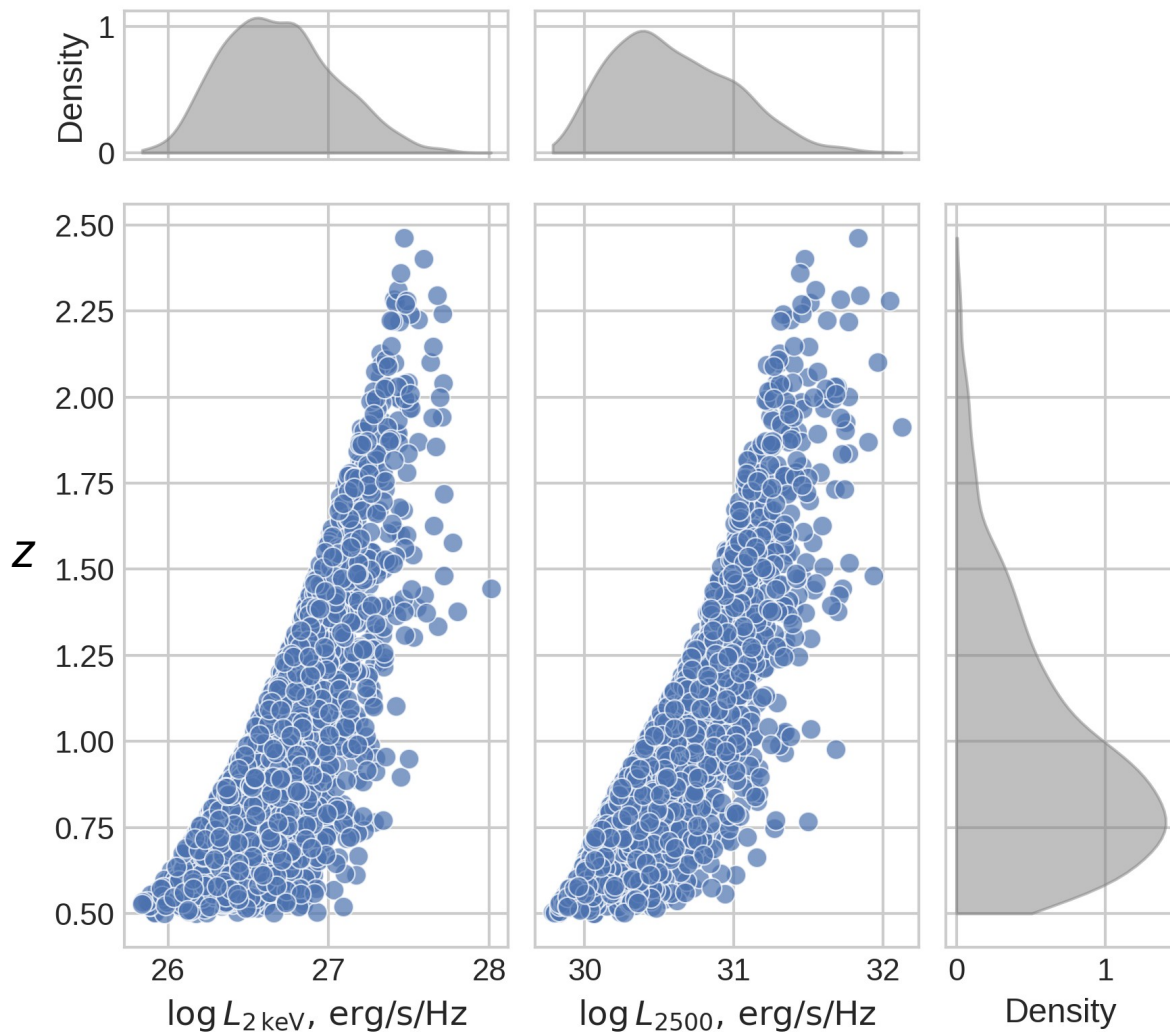


SRG observatory

The sample was further cleaned of:

- blazars
- broad-absorption-line (BAL) quasars
- lensed, dual, binary and with multiple Gaia partners in eROSITA cross-matching radius
- spectra which are outside rest-frame 2500\AA ($0.5 < z < 2.5$)

Final sample: 2414 quasars



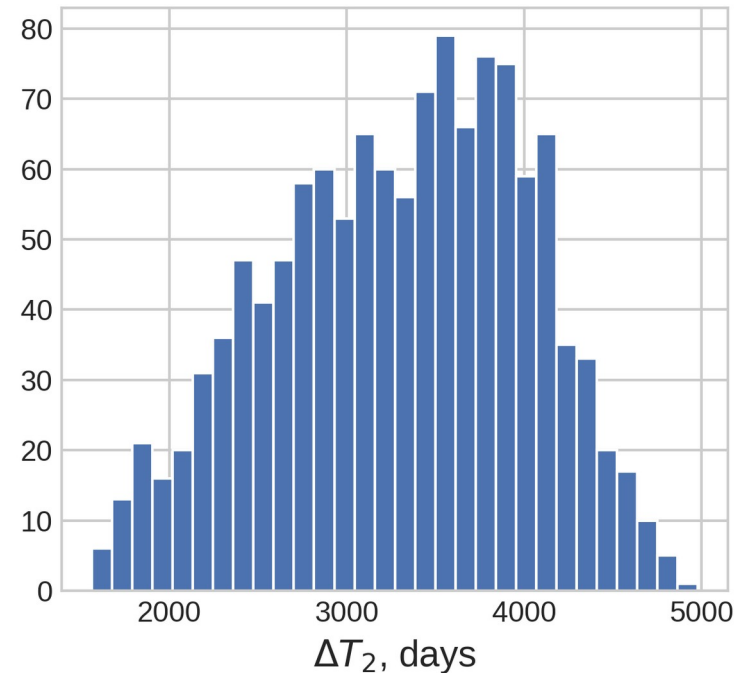
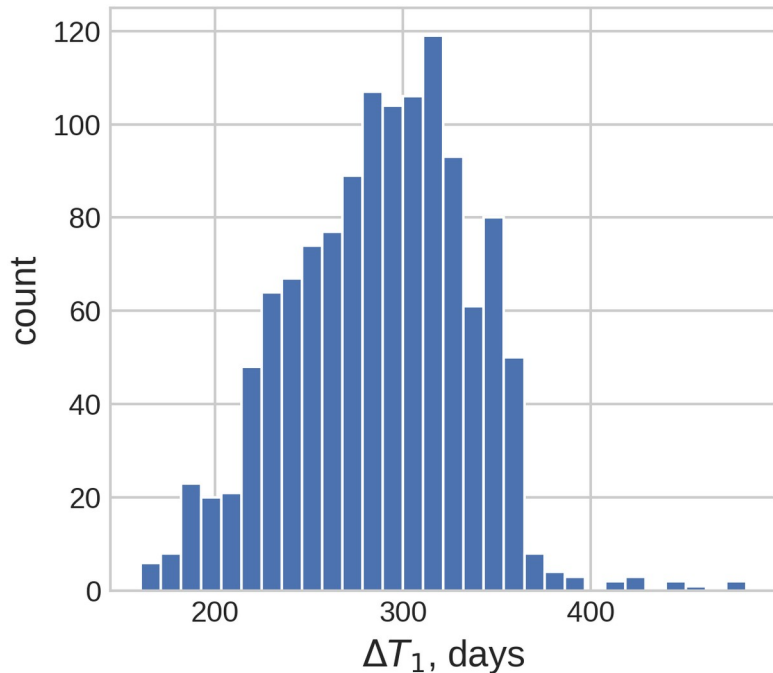
Variability consideration

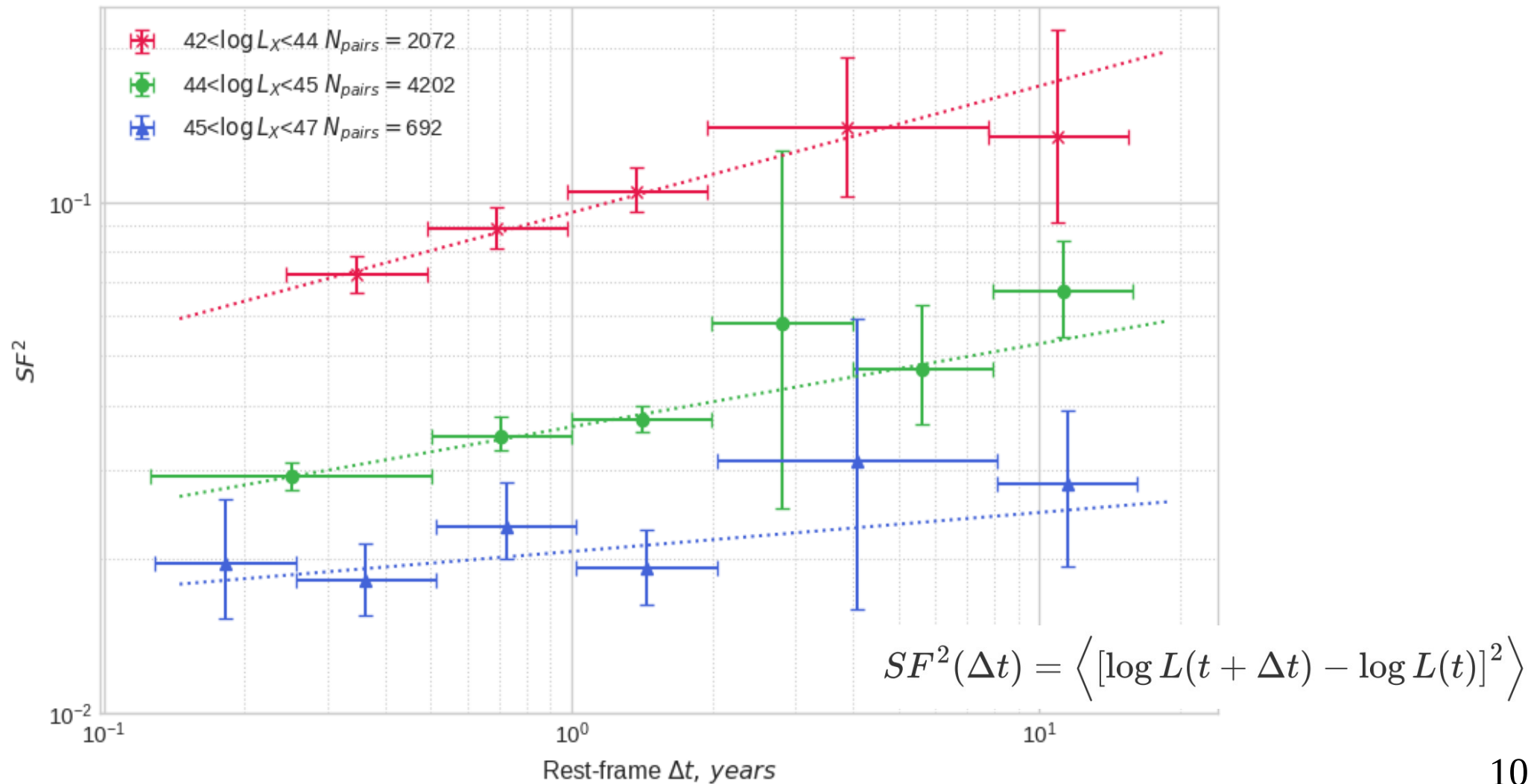
An exposure of a single SDSS photometric observation is about **a minute**

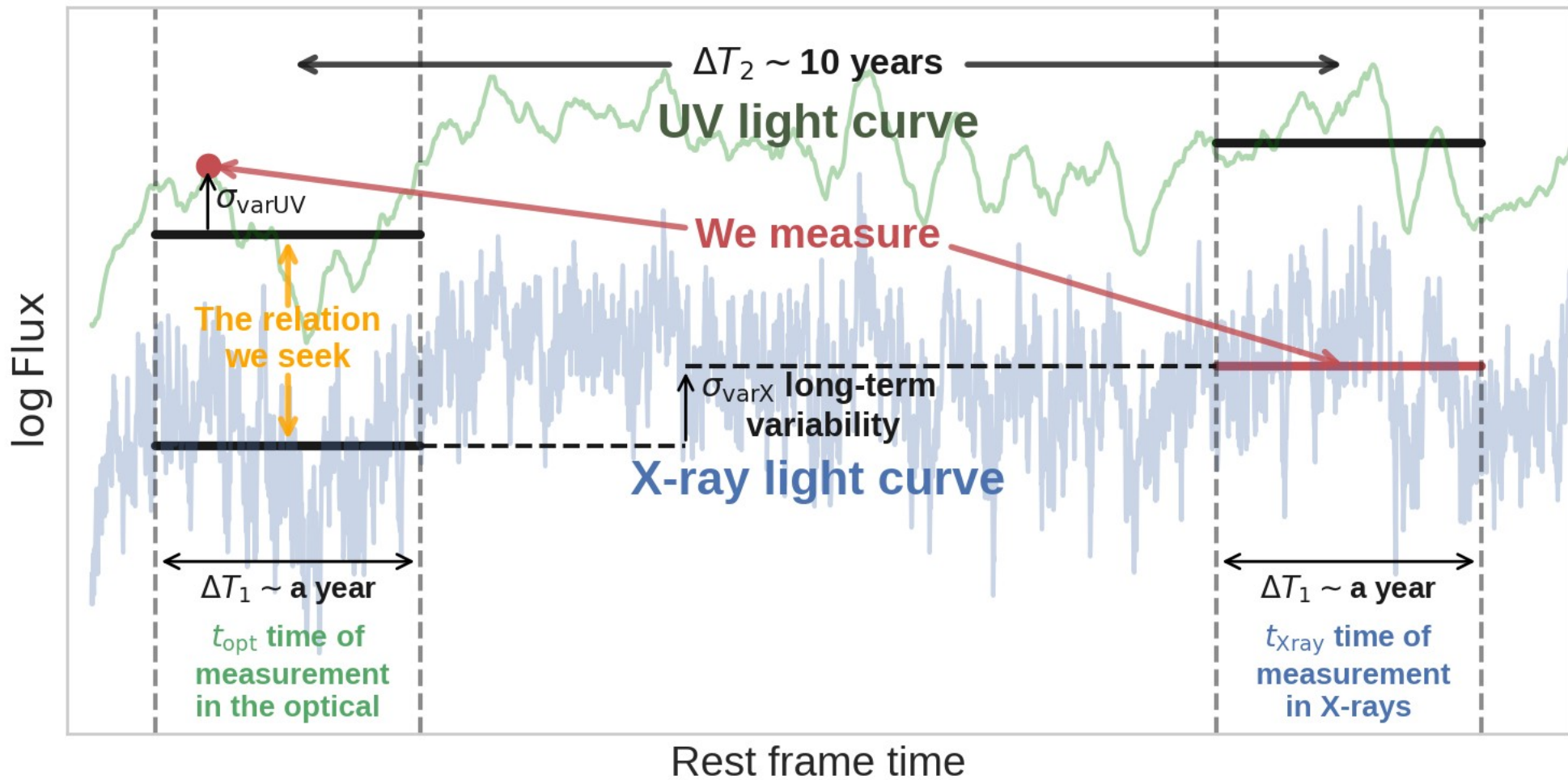
ΔT_1 — eROSITA observation time in quasar rest frame (**about a year**)

ΔT_2 — gap between the photometric SDSS measurement and the eROSITA measurement in quasar rest frame (**about 10 years**)

We used X-ray SF from our work **Prokhorenko et. al. 2024 MNRAS**, and UV SF from Li et. al. 2018

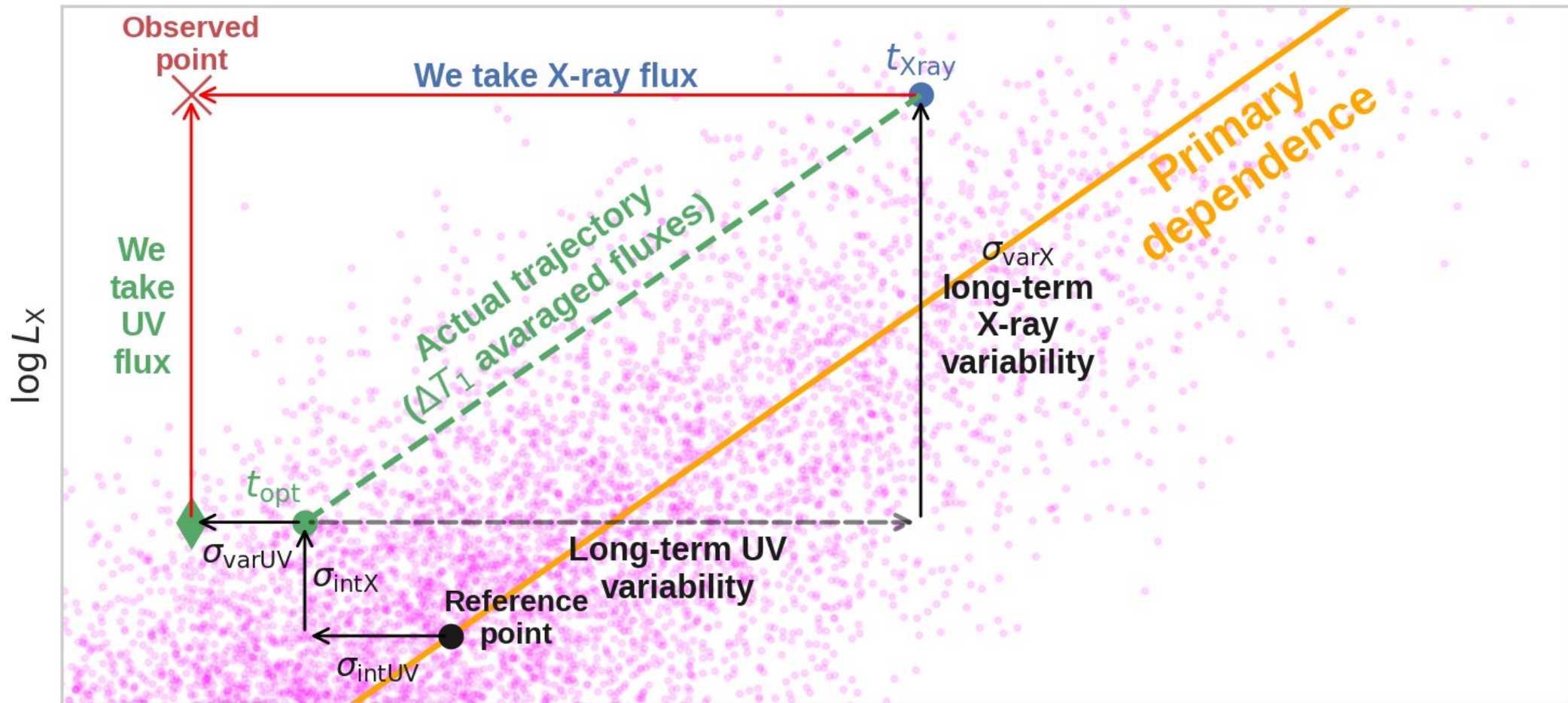






$$\sigma_{\text{varUV}}^2 = \text{Var}_{\text{UV}}(\sim 0.5 \text{ minute}, \Delta T_1)$$

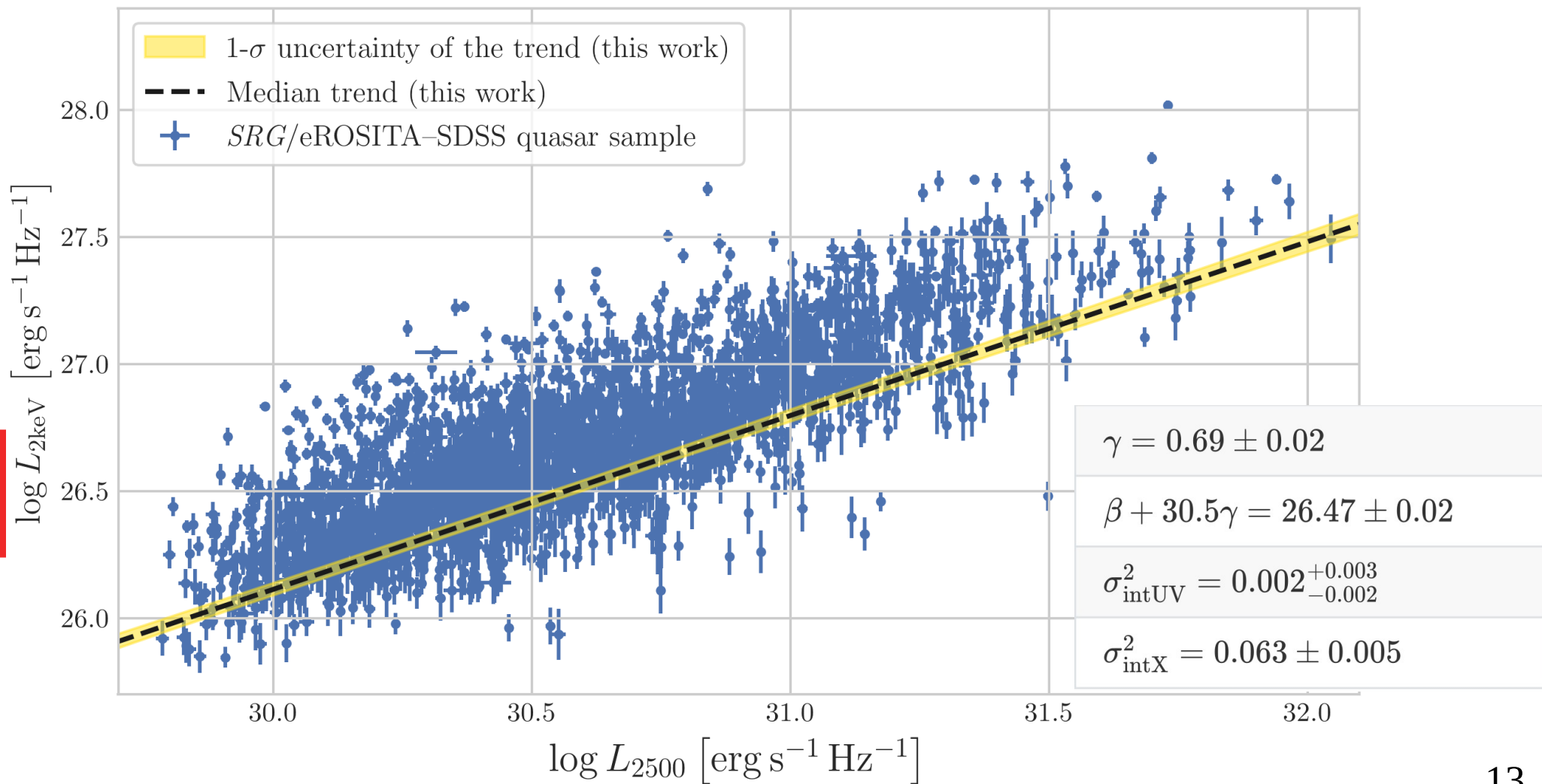
$$\sigma_{\text{varX}}^2 = \widetilde{S} F_X^2(\Delta T_1, \Delta T_2)$$

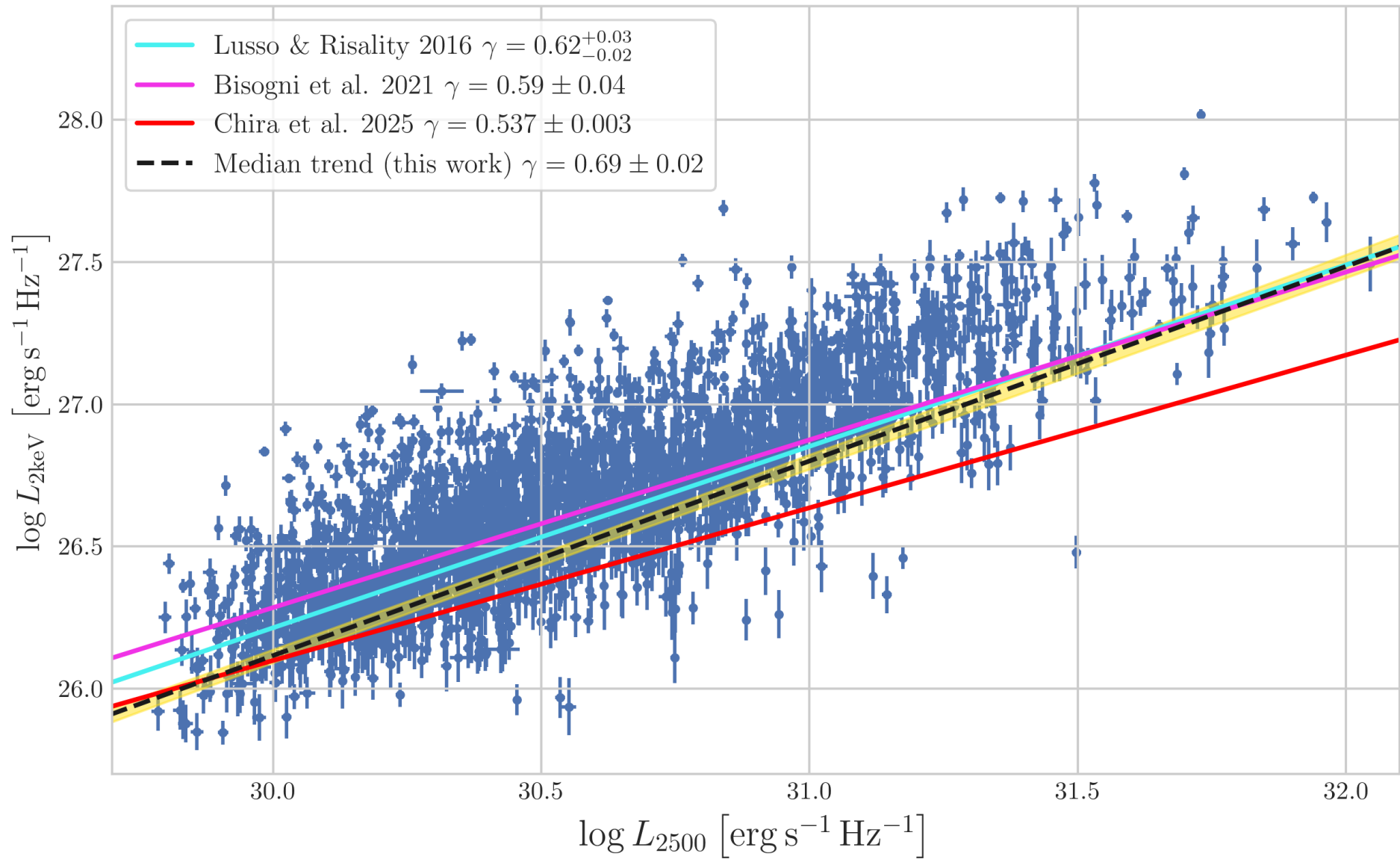


$$\sigma_{UV}^2 = \sigma_{errUV}^2 + \sigma_{varUV}^2 + \sigma_{intUV}^2$$

$$\sigma_X^2 = \sigma_{errX}^2 + \sigma_{varX}^2 + \sigma_{intX}^2$$

Results





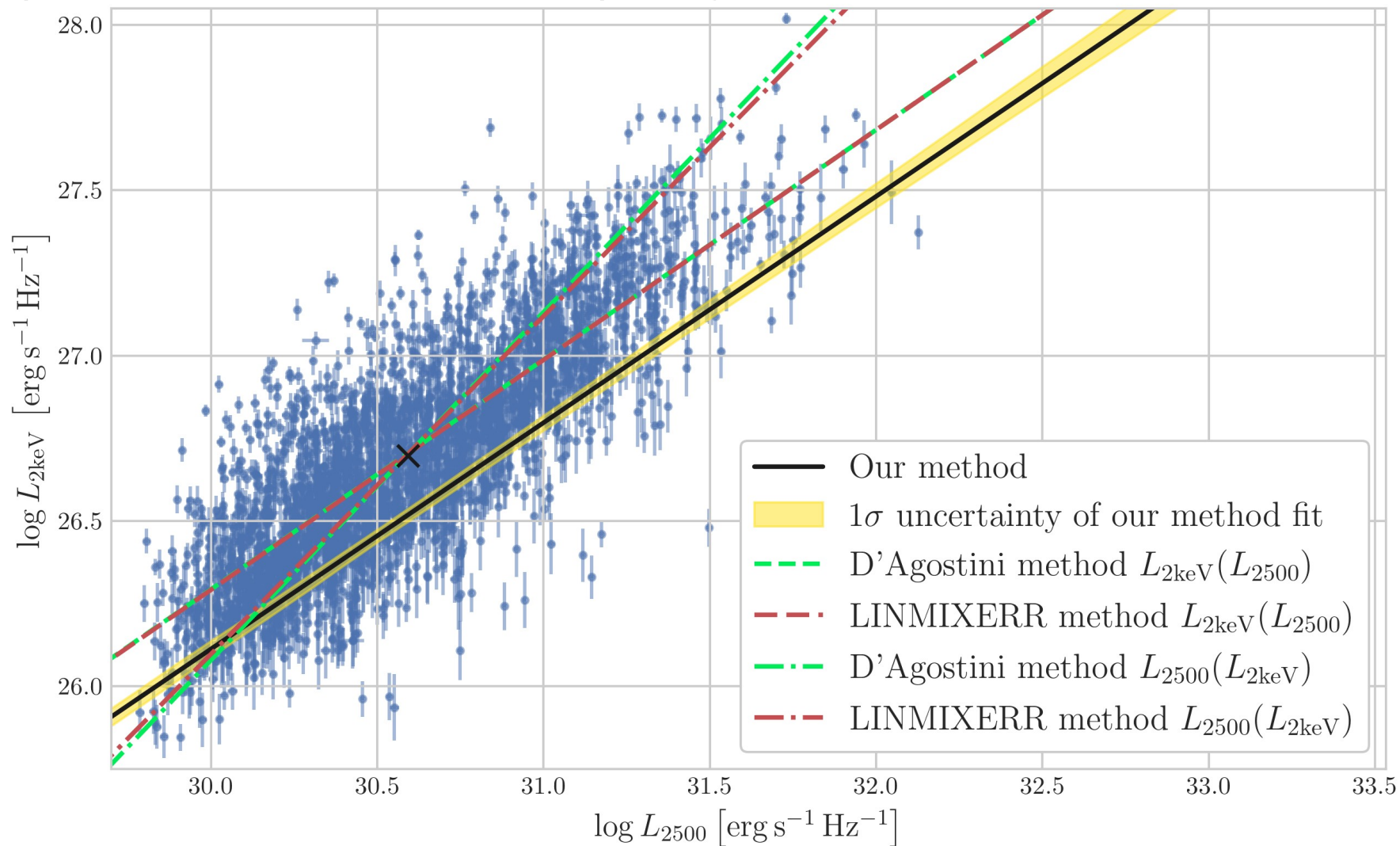
Model parameters for our baseline model

Parameter	Mean value and standard deviation	2.5% percentile	16% percentile	median	84% percentile	97.5% percentile
Baseline model						
γ	0.686, 0.020	0.65	0.67	0.69	0.71	0.73
$\beta + 30.5\gamma$	26.474, 0.021	26.43	26.45	26.47	26.49	26.52
σ_{intUV}^2	0.003, 0.003	0.000	0.000	0.002	0.005	0.011
σ_{intX}^2	0.063, 0.005	0.053	0.058	0.063	0.068	0.074
g_1	0.441, 0.020	0.40	0.42	0.44	0.46	0.48
g_2	4.33, 0.22	3.9	4.1	4.3	4.5	4.8
l^*	45.11, 0.05	45.02	45.06	45.11	45.15	45.20
p_1	3.28, 0.07	3.13	3.21	3.28	3.35	3.42
z_c	2.28, 0.07	2.14	2.21	2.28	2.34	2.41

$l^* = \log L_{2\text{keV}}^* + 17.9$ is bend luminosity in the 2-10 keV band

(the bend of LF at $\log L_{2-10\text{keV}} = 44$ erg/s corresponds to $\log L_{2\text{keV}} = 26.1$ erg/s/Hz)

Comparison of our method with simple regression



Conclusions

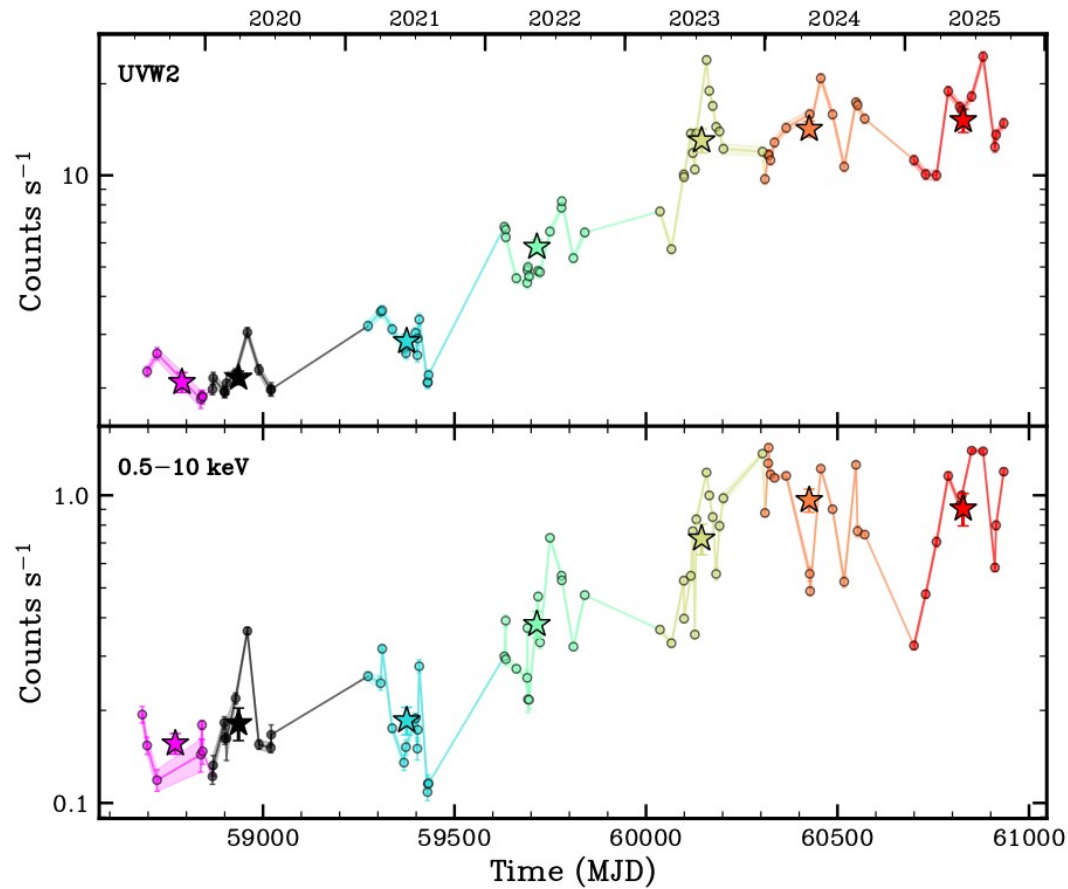
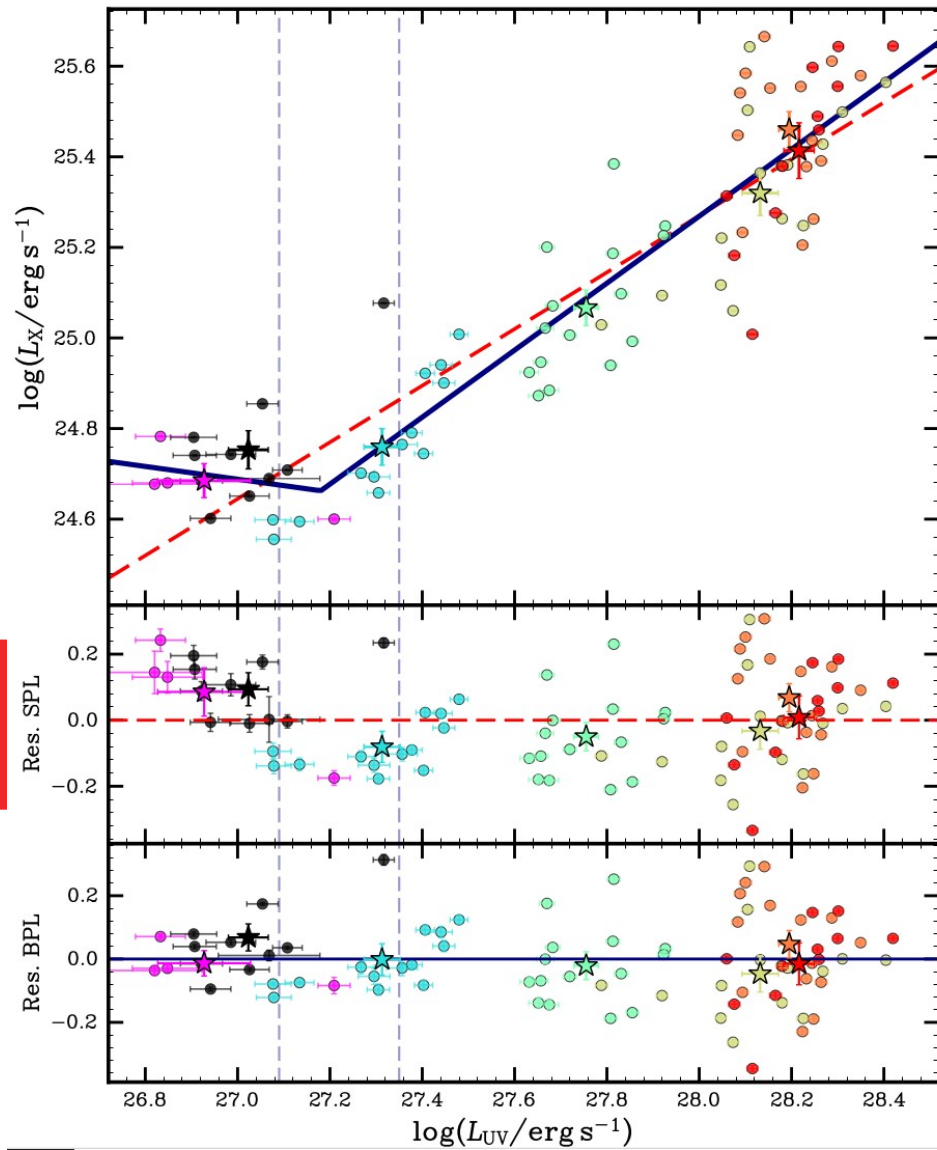
- 1) We used a new well-selected SDSS-eROSITA sample with $F_x > 6 \times 10^{-14}$ erg/s/cm² and $m_g < 19$, additionally cleaned from “bad” quasars
- 2) We constructed a model of the quasar distribution and, based on it, developed a method that takes into account selection effects, changes in the density of quasars with luminosities, and variability
- 3) We showed that ordinary regression gives incorrect results for our sample.
- 4) We applied our method to the sample and obtained the following results:
 $\gamma = 0.69 \pm 0.02$, $\beta + 30.5\gamma = 26.47 \pm 0.02$, $\sigma_{\text{intX}}^2 = 0.063 \pm 0.005$,
 $\sigma_{\text{intUV}}^2 = 0.002^{+0.003}_{-0.002}$

Thank you for your attention!



Backup slides





The figures from the preprint of Middei et. al.
2026 «Directly tracking the re-brightening of a
supermassive black hole accretion disk»
ArXiv:2605.18958v1