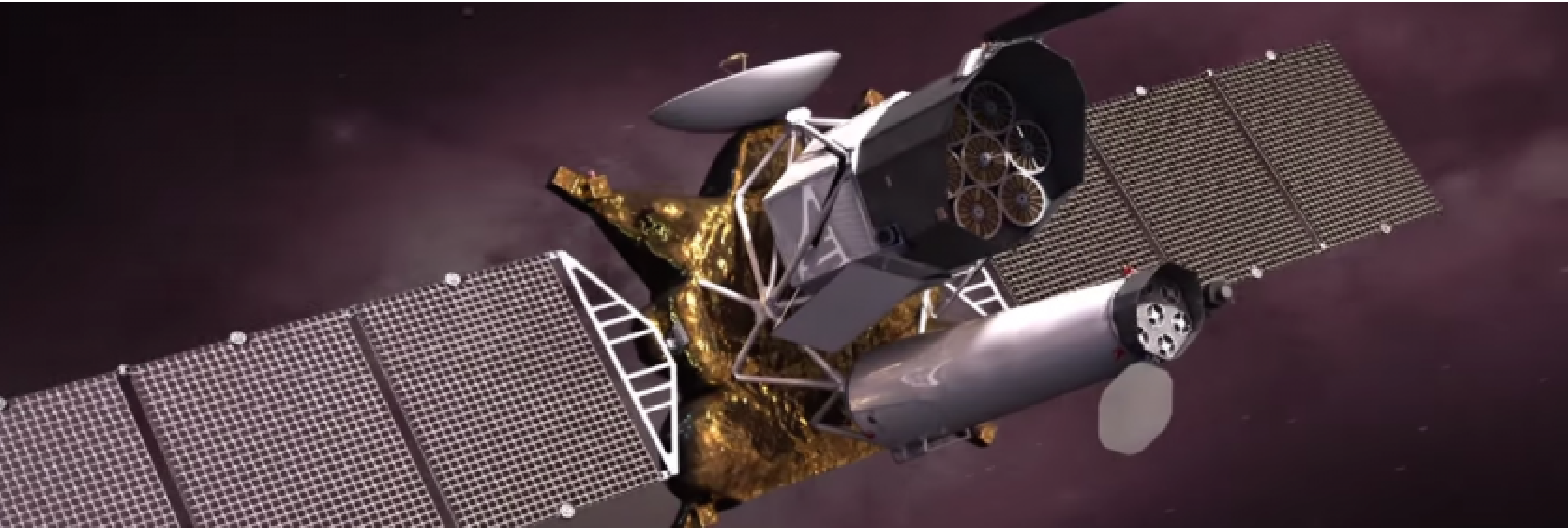
X-ray variability of SDSS quasars based on the SRG/eROSITA all-sky survey



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X-ray variability of SDSS quasars based on the SRG/eROSITA all-sky survey

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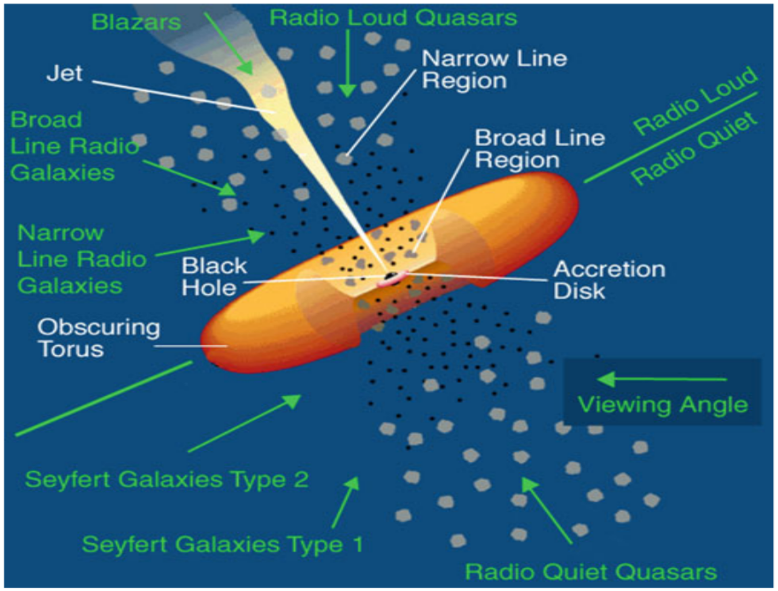
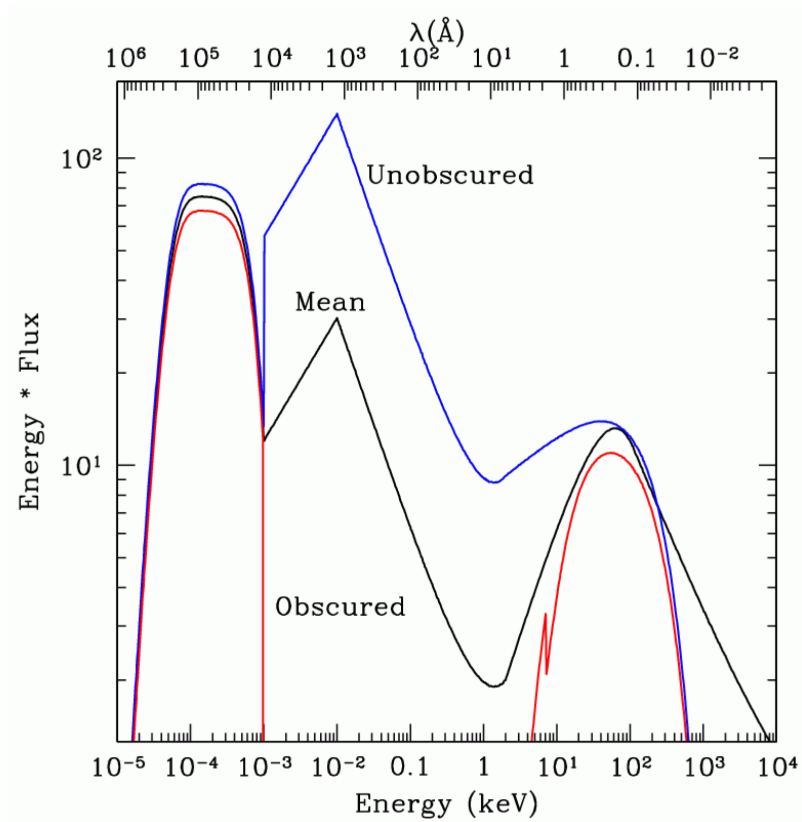
ABSTRACT

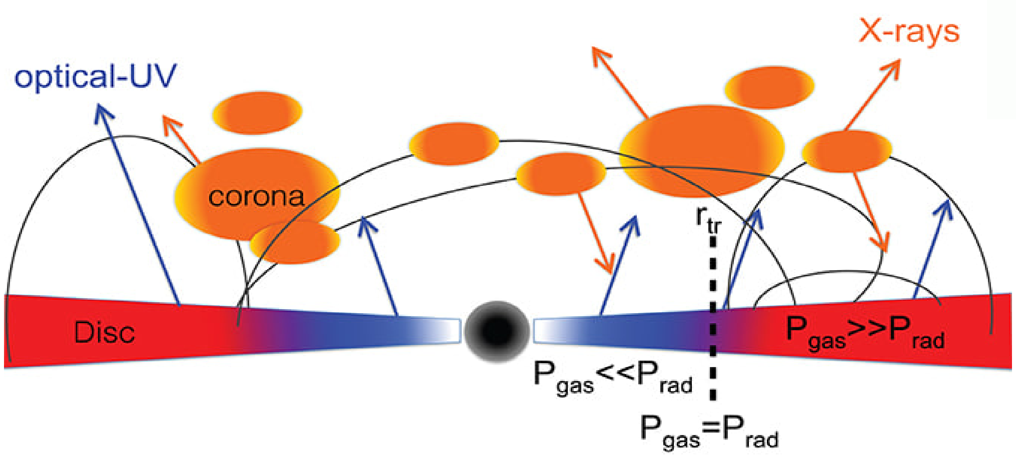
We examine the long-term (rest-frame time-scales from a few months to ∼20 yr) X-ray variability of a sample of 2344 X-ray bright quasars from the Sloan Digital Sky Survey (SDSS) data release 14 quasar (DR14Q) catalogue, based on the data of the *Spectrum-Roentgen-Gamma (SRG)*/eROSITA All-Sky Survey complemented for ∼7 per cent of the sample by archival data from the *XMM–Newton* Serendipitous Source Catalogue. We characterize variability by a structure function, $\mathrm{SF}^2(\Delta t)$. We confirm the previously known anticorrelation of the X-ray variability amplitude with luminosity. We also study the dependence of X-ray variability on black hole mass, M_{BH}, and on an X-ray-based proxy of the Eddington ratio, λ_{X}. Less massive black holes prove to be more variable for given Eddington ratio and time-scale. X-ray variability also grows with decreasing Eddington ratio and becomes particularly strong at λ_{X} of less than a few per cent. We confirm that the X-ray variability amplitude increases with increasing time-scale. The $\mathrm{SF}^2(\Delta t)$ dependence can be satisfactorily described by a power law, with the slope ranging from ∼0 to ∼0.4 for different (M_{BH}, λ_{X}) subsamples (except for the subsample with the lowest black hole mass and Eddington ratio, where it is equal to 1.1 ± 0.4).

Active Galactic Nuclei (AGN) are multi-component objects, producing radiation across the entire electromagnetic spectrum

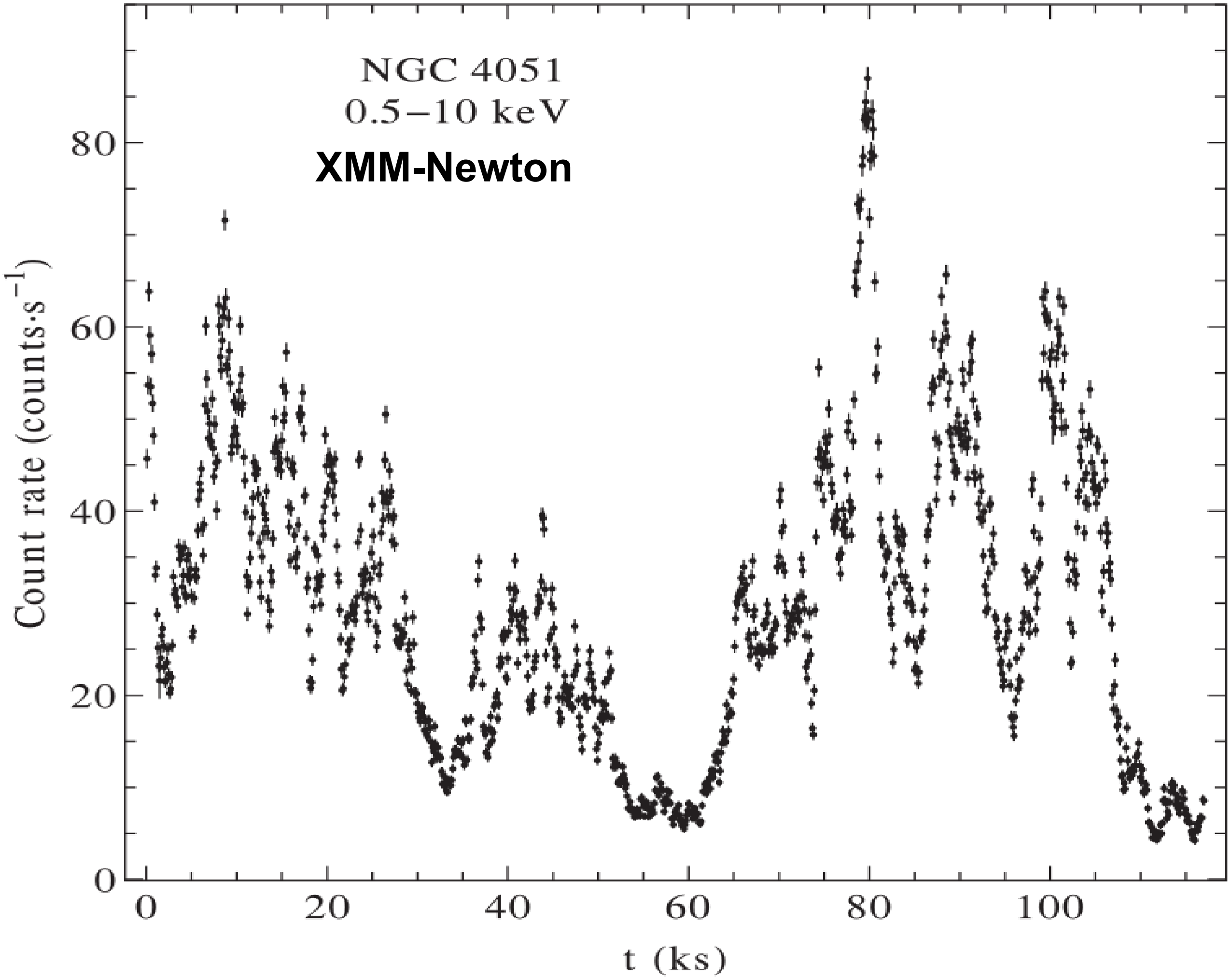




SS, Ostriker & Sunyaev 2004



AGN are variable, in particular in X-rays, on time scales from hours ...

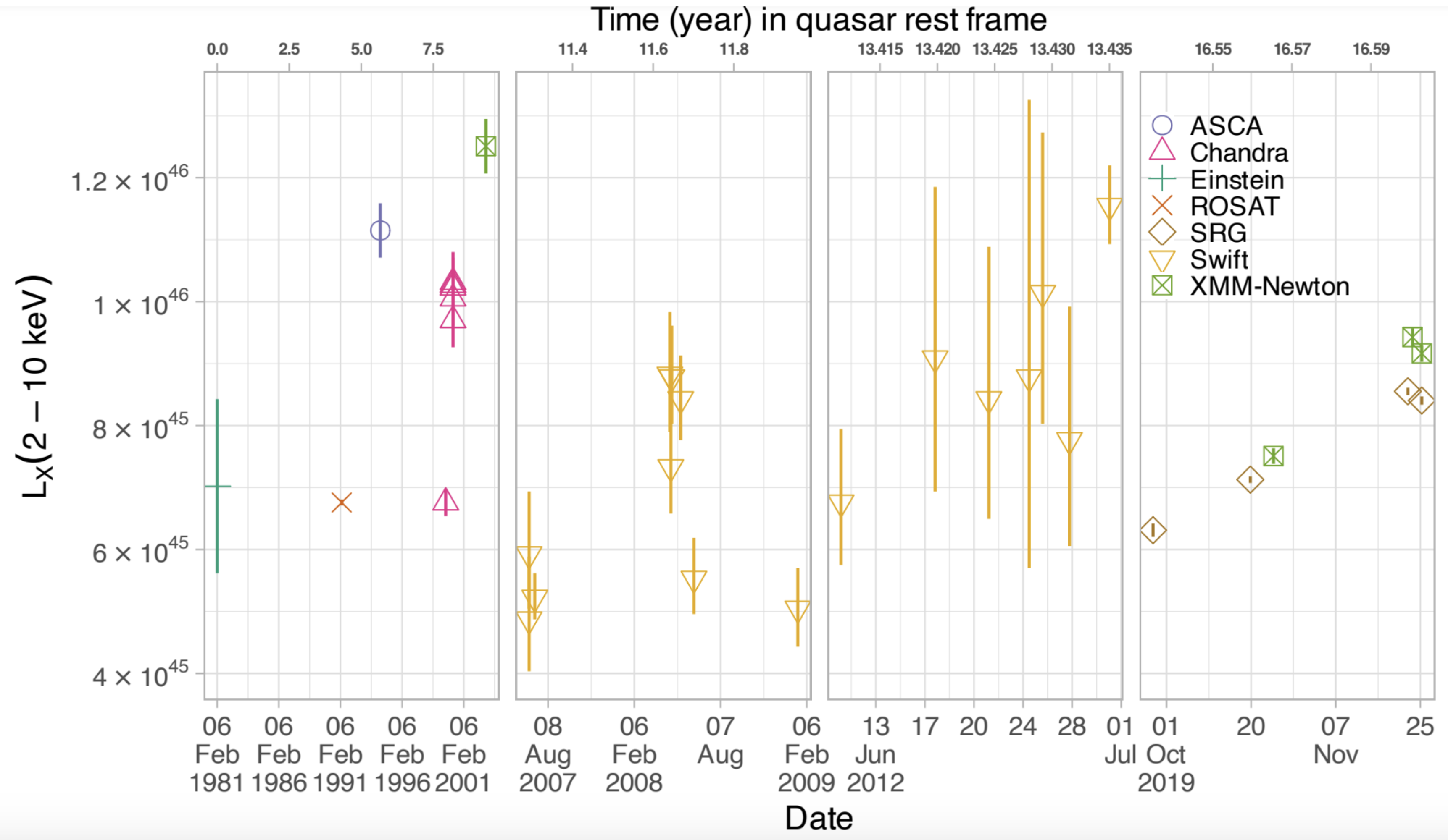


Emmanoulopoulos et al. (2013)

Seyfert 1 galaxy NGC 4051

z=0.023, M_{BH} ~ 2 10^6 M_{sun}, L_X ~ 10^{42} erg/s

… through tens of years …

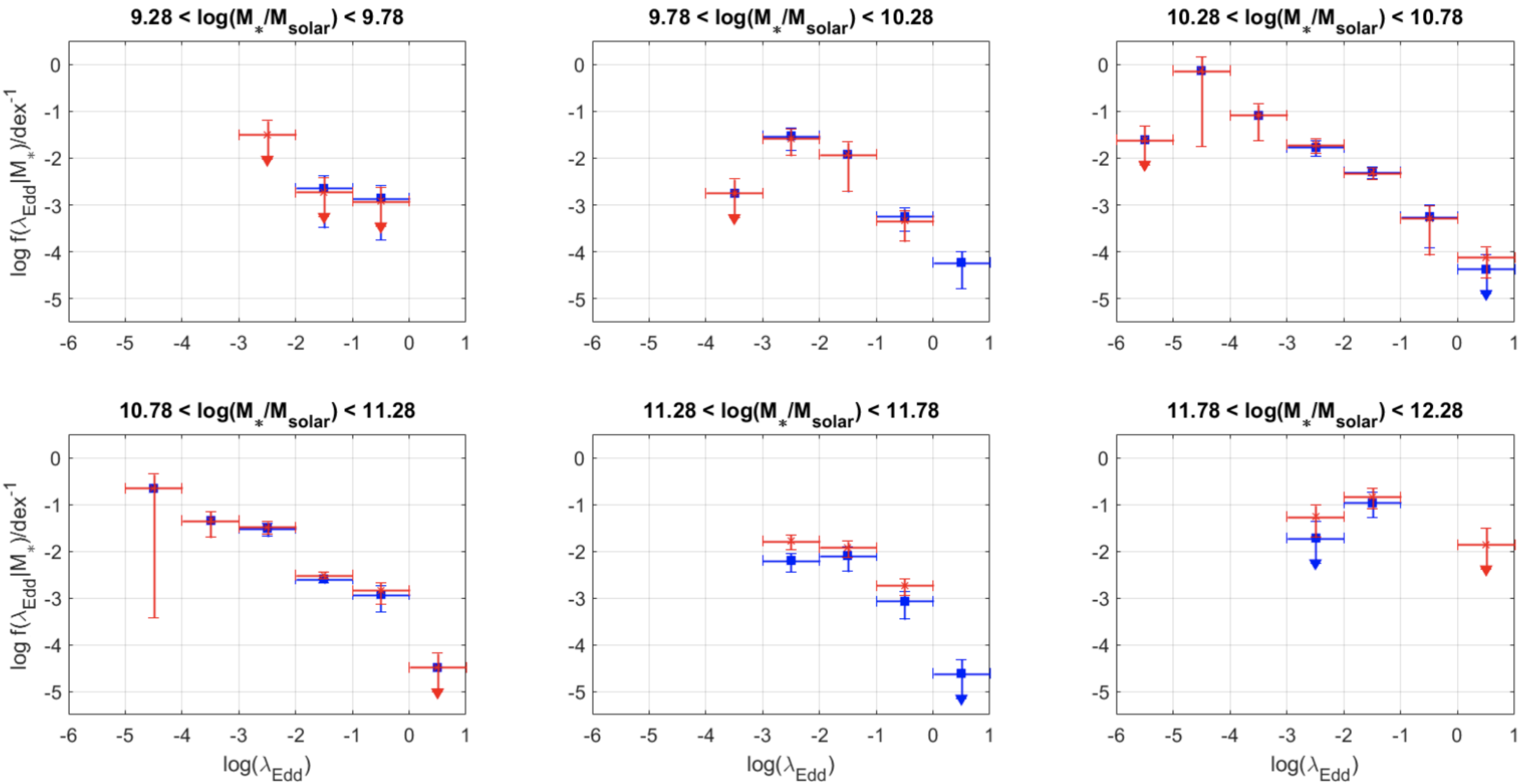


Uskov, SS et al. (2023)

Quasar PG 1634+706

z=1.337, $M_{BH} \sim 10^{10}\ M_{sun}$, $L_X \sim 10^{46}$ erg/s

… to cosmological times



Prokhorenko & SS (2021)

In the standard accretion disk paradigm, that are three characteristic times:

$$t_{\rm orb} \approx 3 \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot} \right) \left(\frac{R}{10\,R_S} \right)^{3/2} \,{\rm d}, \quad (1)$$

$$t_{\rm th} = \frac{t_{\rm orb}}{2\pi\alpha} \approx 50 \left(\frac{\alpha}{0.01} \right)^{-1} \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot} \right) \left(\frac{R}{10\,R_S} \right)^{3/2} \,{\rm d}, \quad (2)$$

$$t_{\rm visc} = \left(\frac{H}{R} \right)^{-2} t_{\rm th}, \quad (3)$$

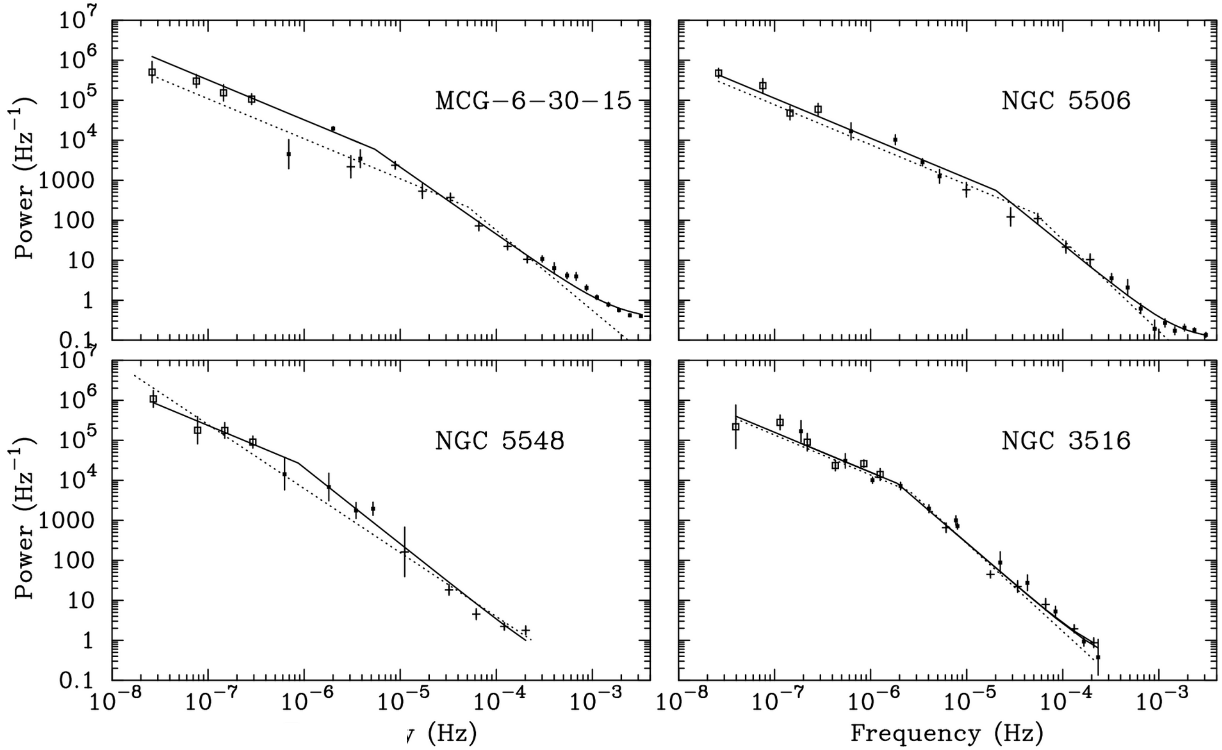
where $R_S = 2GM_{\rm BH}/c^2$ is the Schwarzschild radius of the BH, G is the gravitational constant, c is the speed of light, α is the viscosity parameter, and H is the scale height of the disc.

But how these times are reflected in AGN variability is not clear yet.

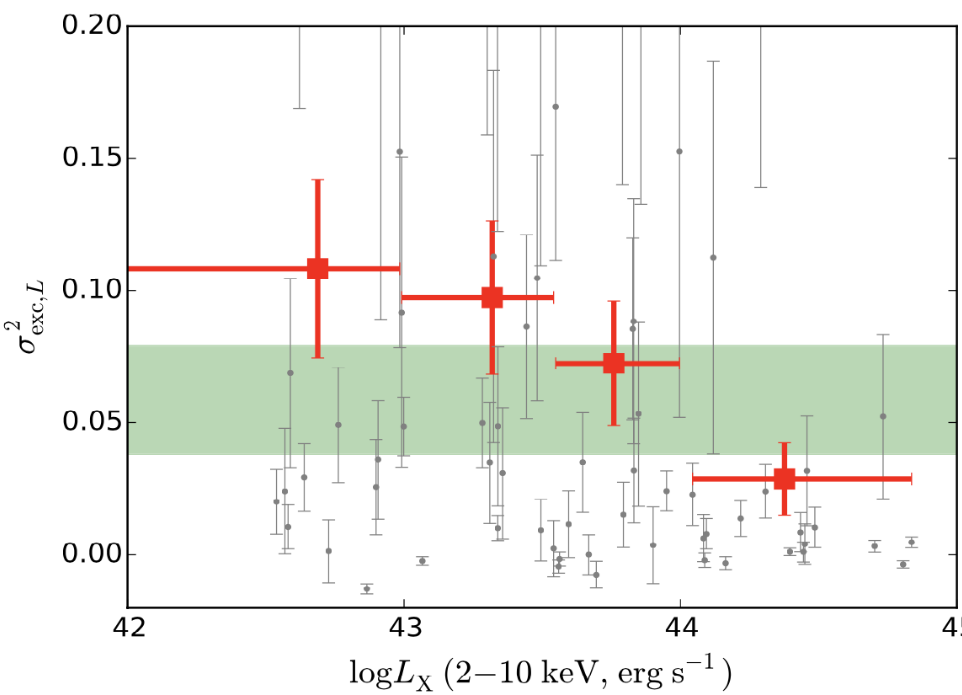
Despite the theoretical uncertainties, it is reasonable to anticipate AGN (X-ray) variability (as well as spectral) properties to mainly depend on the black hole

(1) mass
(2) accretion rate (Eddington ratio)
(3) spin

Prevous studies could not disentangle this interdependence, but clearly showed that X-ray variability increases with increasing time scale and with decreasing luminosity (at a fixed time scale).

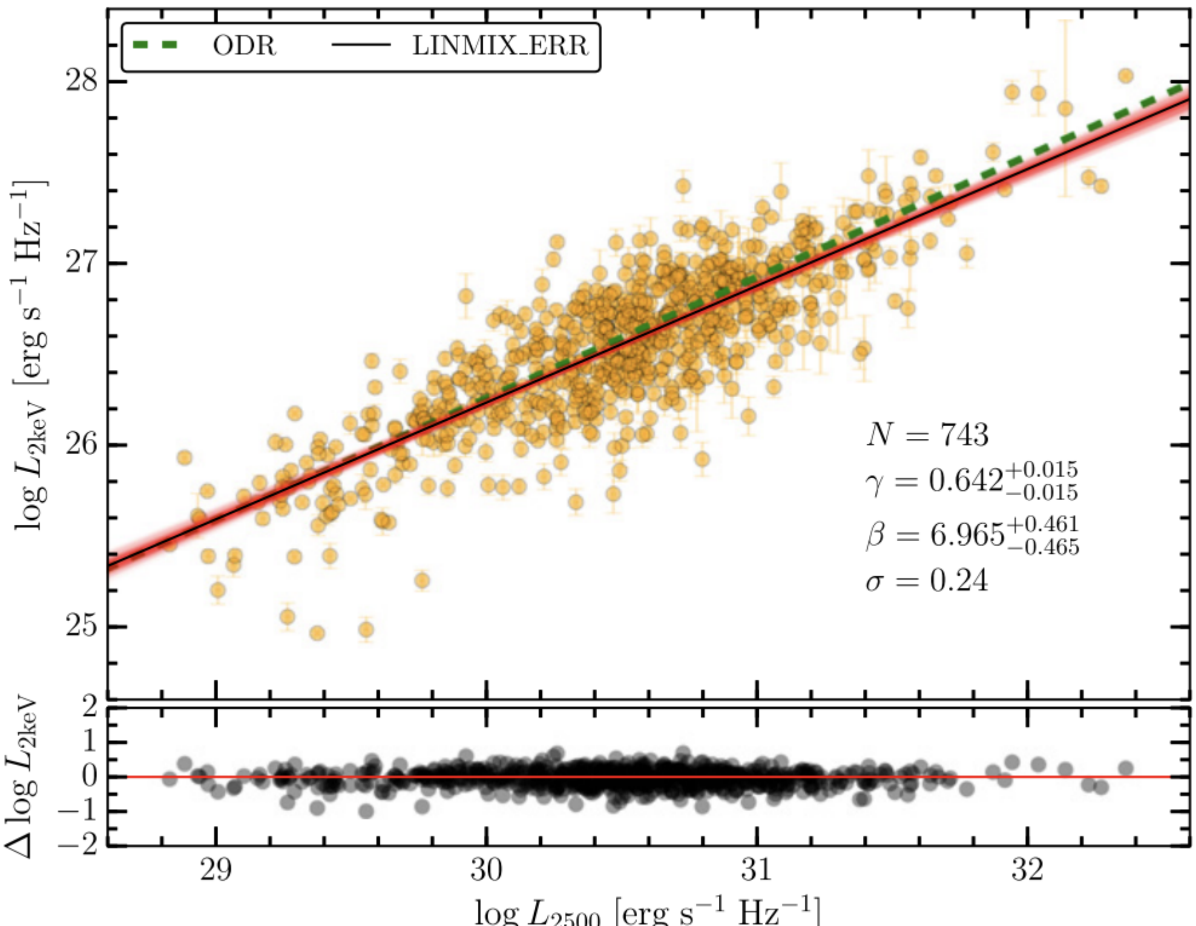


Uttley et al. (2002)



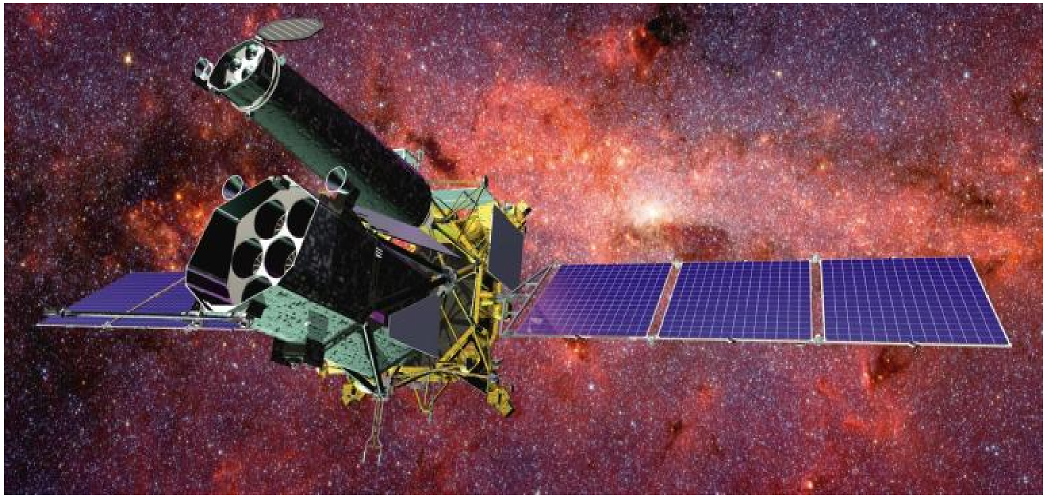
Yang et al. (2016)

Apart from importance for AGN physics, X-ray variability of AGN (in particular, quasars) should also be studied because of their potential use as standard candles in cosmology.

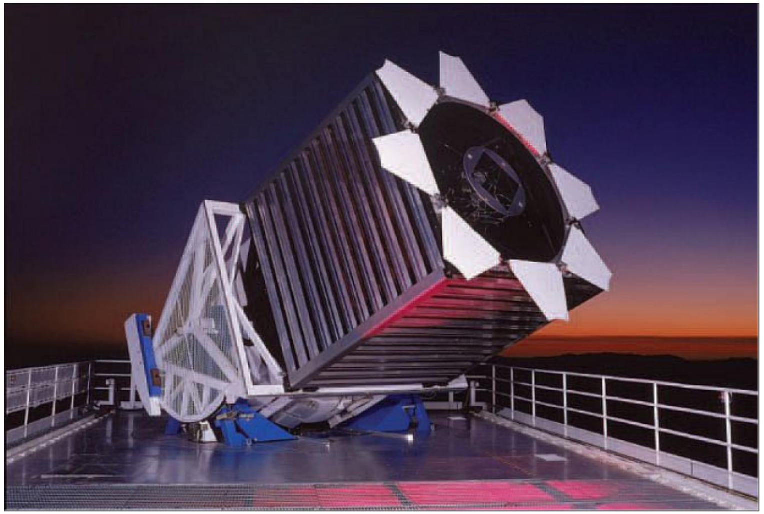


Lusso & Risaliti (2016)

SRG/eROSITA — SDSS X-ray bright quasar sample



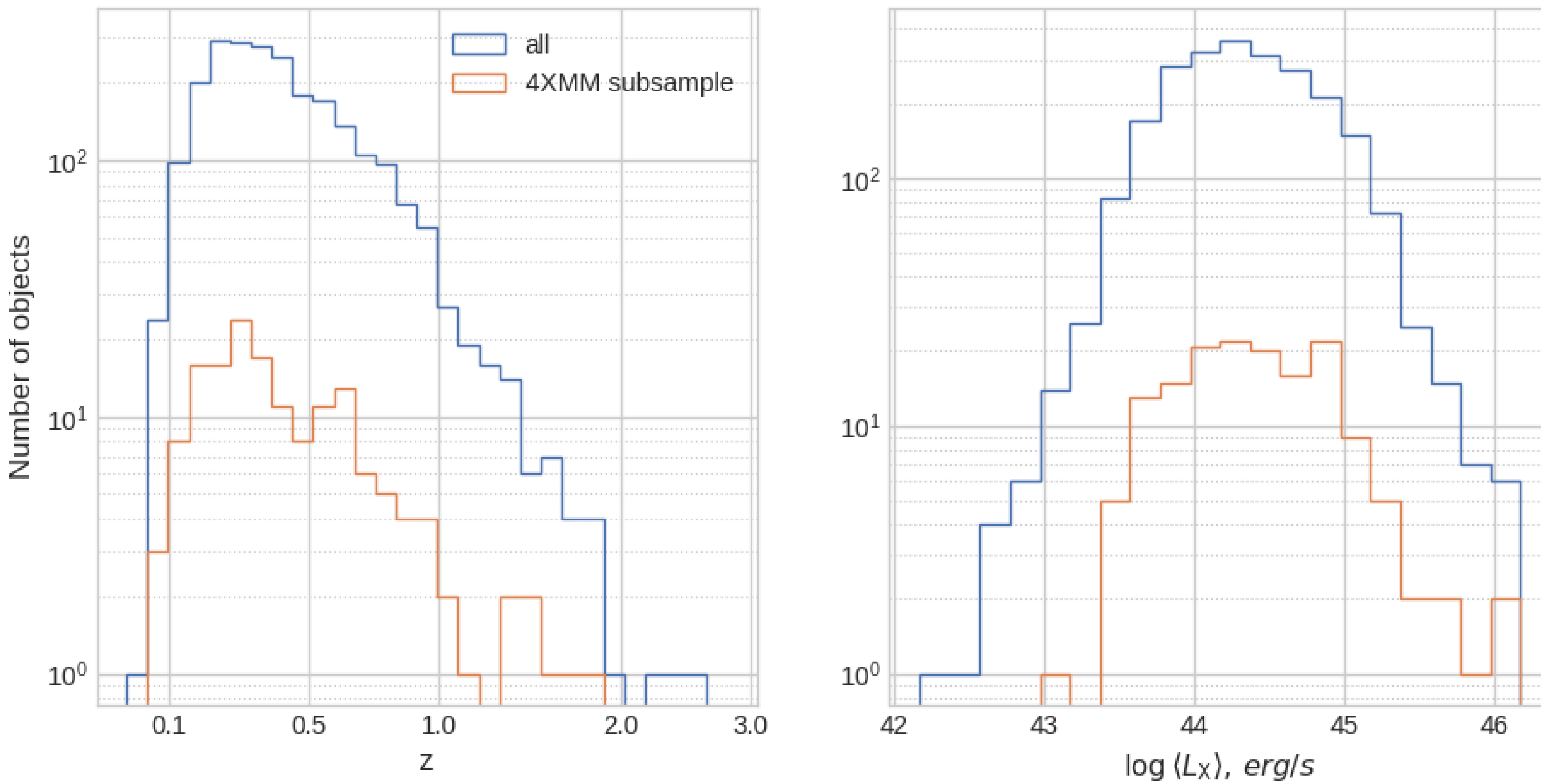
SRG/eROSITA



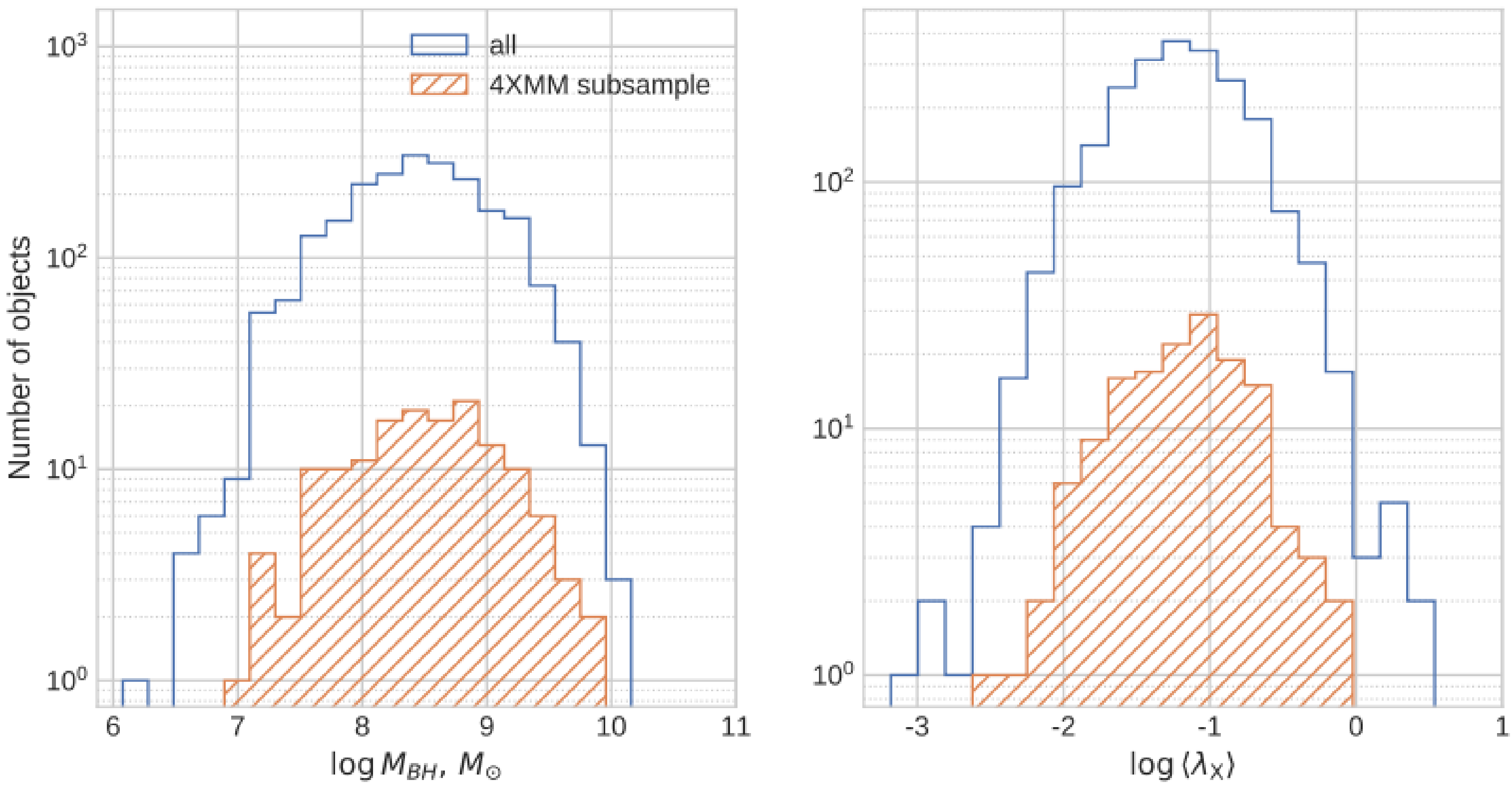
SDSS

XMM-Newton

- We started with the catalog of spectroscopically studied quasars SDSS DR14 (Paris et al. 2014).
- Cross-matched it with the catalog of bright X-ray sources (time-averaged flux $F>2\ 10^{-13}$ erg/s/cm^2, 0.3-2.3 keV) detected by eROSITA during the first 5 SRG all-sky surveys (Dec. 2019-Feb. 2022) in the Eastern Galactic hemisphere (Gilfanov et al., in prep.).
- Removed known and suspected blazars.
- This resulted in a sample of 2344 quasars.
- For 156 quasars, we added historical X-ray information (fluxes) from 4XMM DR12 (Webb et al. 2020).
- 1542 quasars from the sample are located in the footprint of the LOFAR Two-metre Sky Survey (Shimwell et al. 2022), and 1048 of them are detected in the radio.

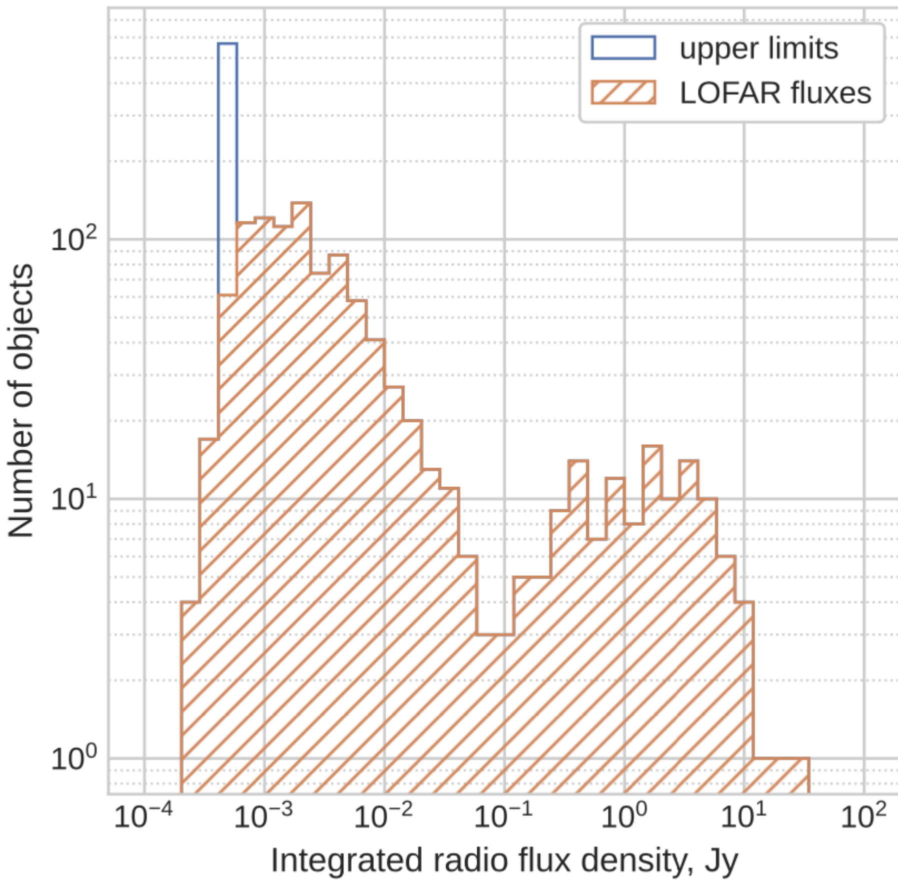


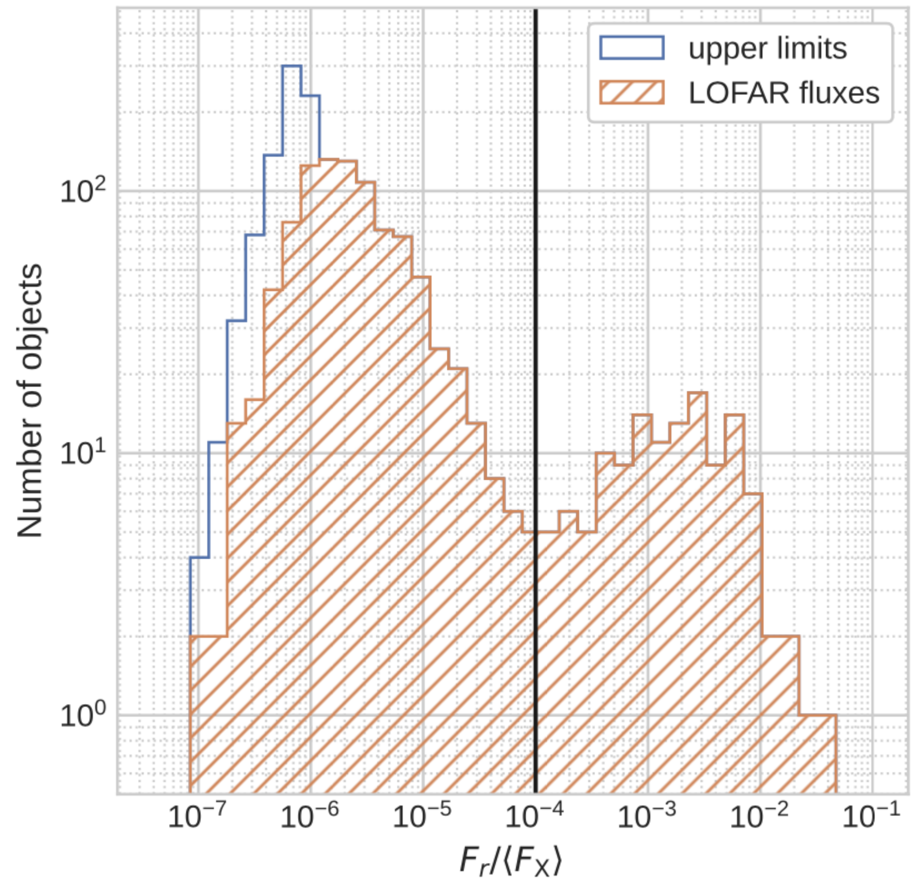
The sample effectively covers 3 decades in X-ray luminosity ...



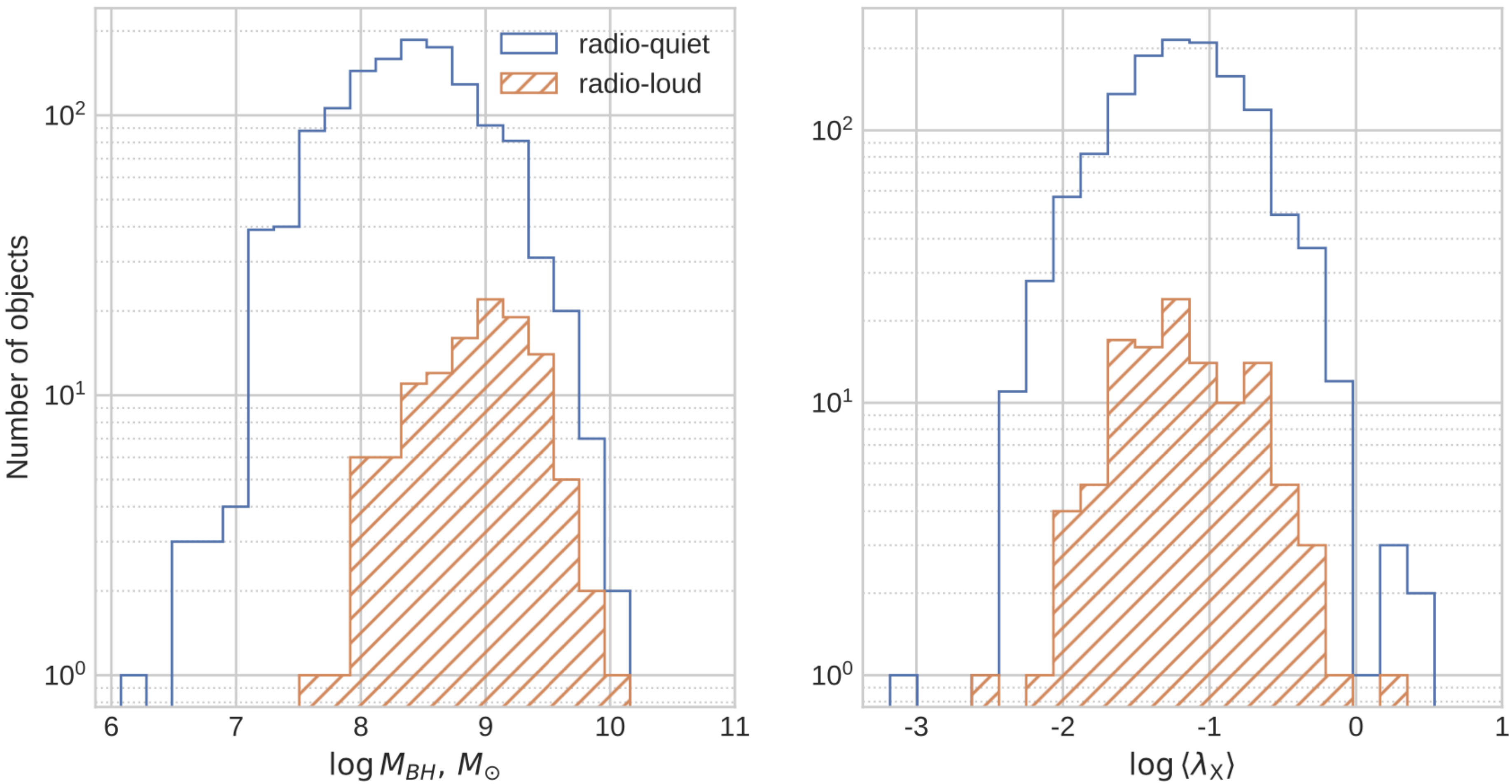
3 decades in black hole mass and 2 decades in the Eddington ratio.

- We use single-epoch BH mass estimates from Rakshit et al. (2020)
- For the Eddington ratio, we use its X-ray proxy: $\lambda_x = \dfrac{10L_X}{L_{Edd}}$



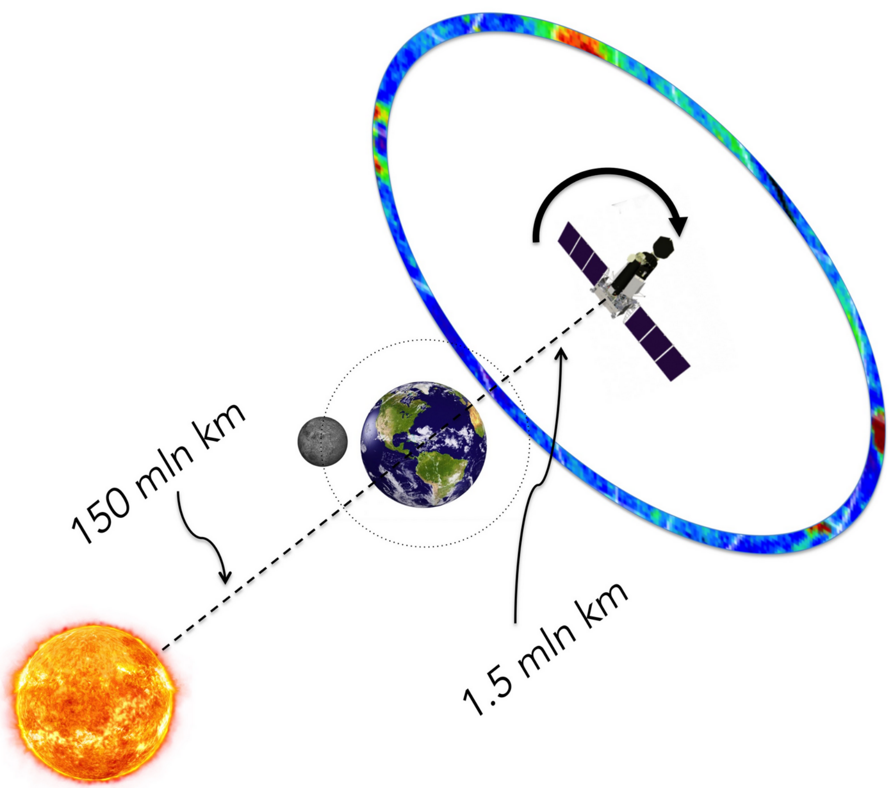


The sample exhibits the well known radio-loudness dichotomy



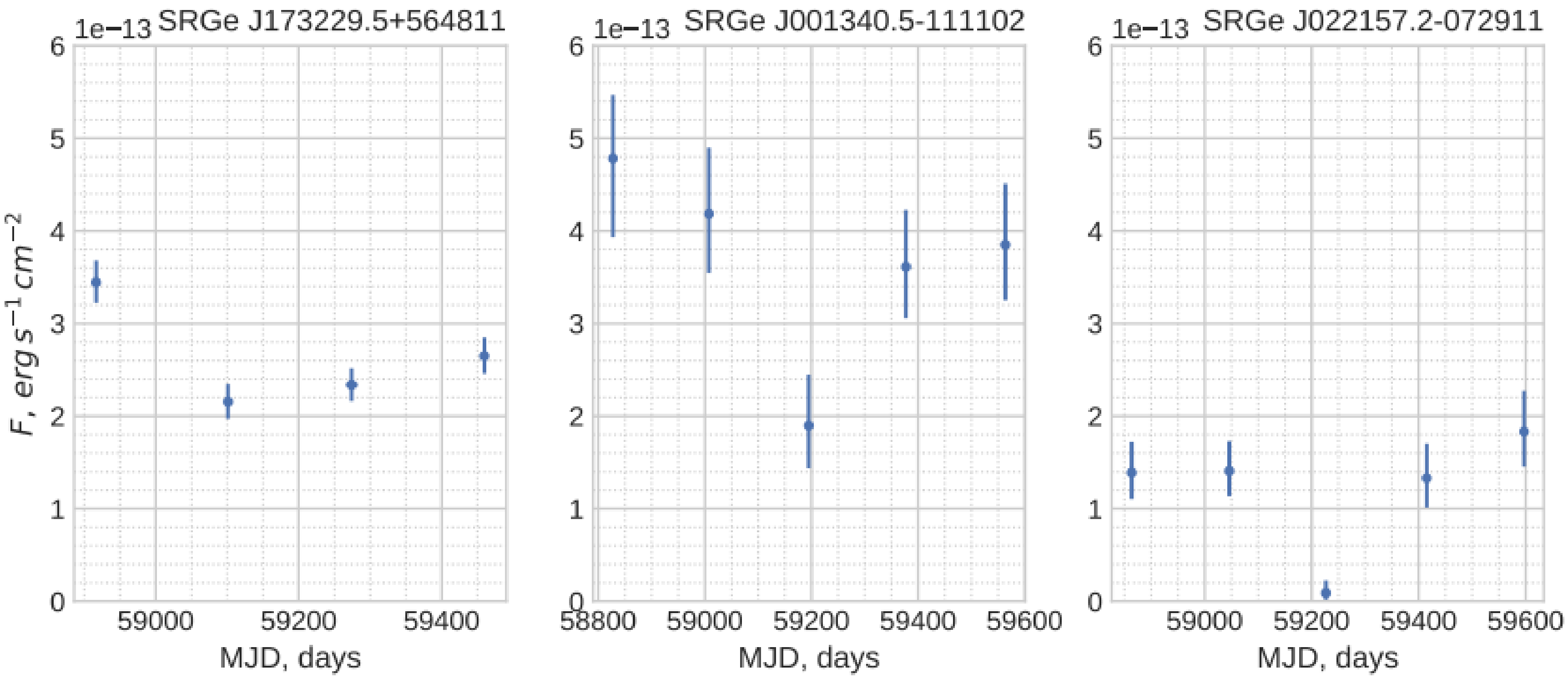
The radio-loud quasars are on average more massive than the radio-quiet ones, which is also unsurprising

SRG all-sky survey

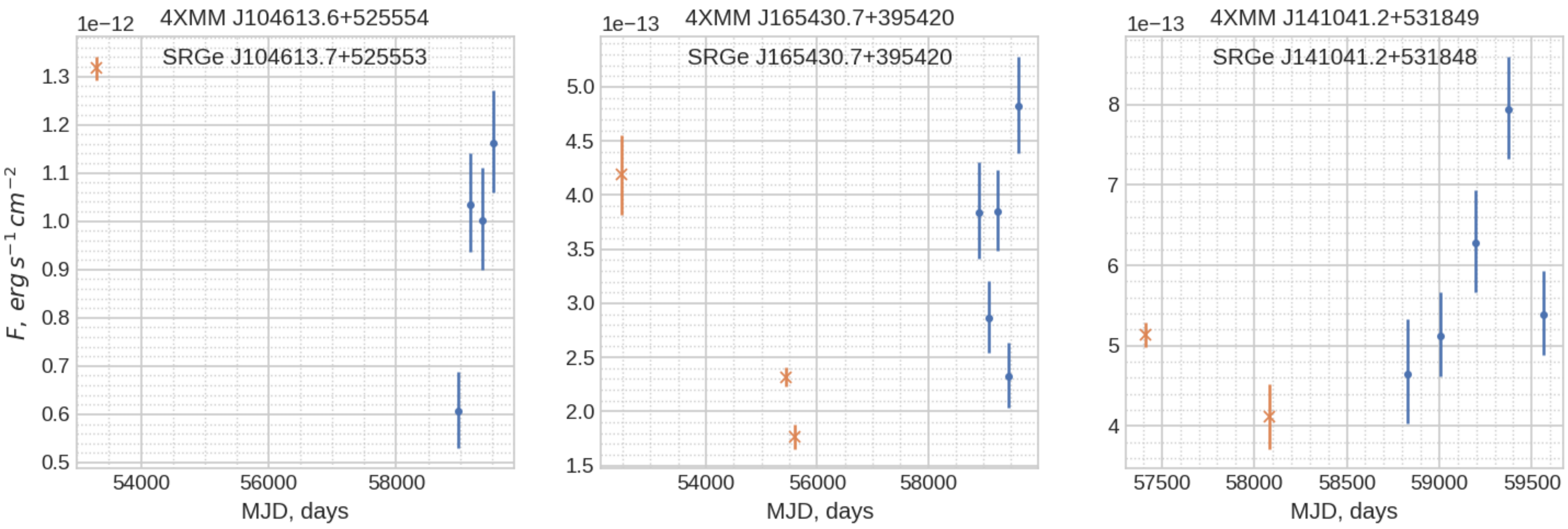


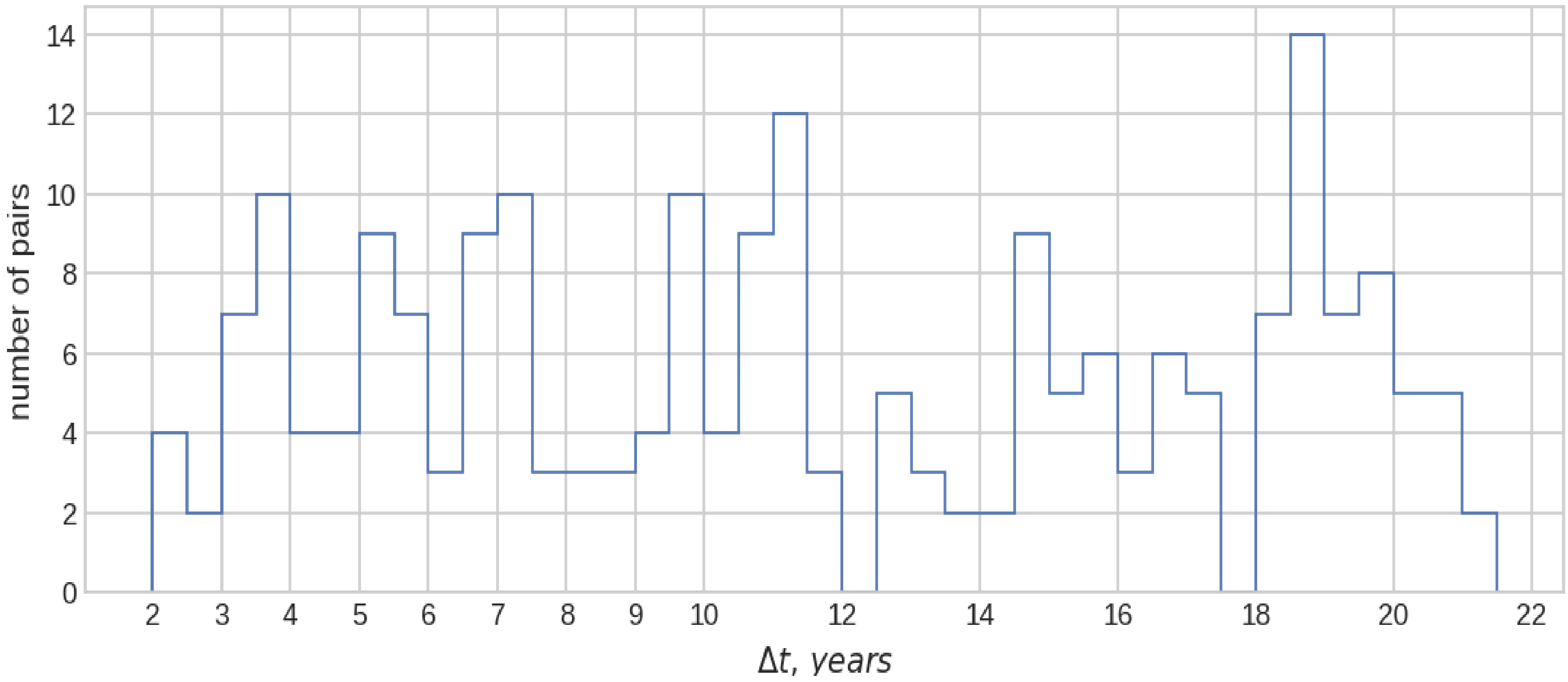
- Conducted from a halo orbit around the Sun-Earth L2 point.
- The satellite spins around its axis with a period of 4 hours. The axis is pointed at the Sun.
- A typical source is visited by eROSITA once every 6 months: 6 times for 30-40 sec every 4 hours.
- The sky is fully scanned every 6 months.
- The survey started in Dec. 2019 and eROSITA went into sleeping mode in Feb. 2022, when 40% of the 5th survey was done.

Examples of X-ray light curves obtained by SRG/eROSITA



XMM-Newton data add information on longer times scales, but are available for 7% of the sample only





Time gaps between the latest eROSITA obervation and XMM-Newton observations

X-ray variability analysis

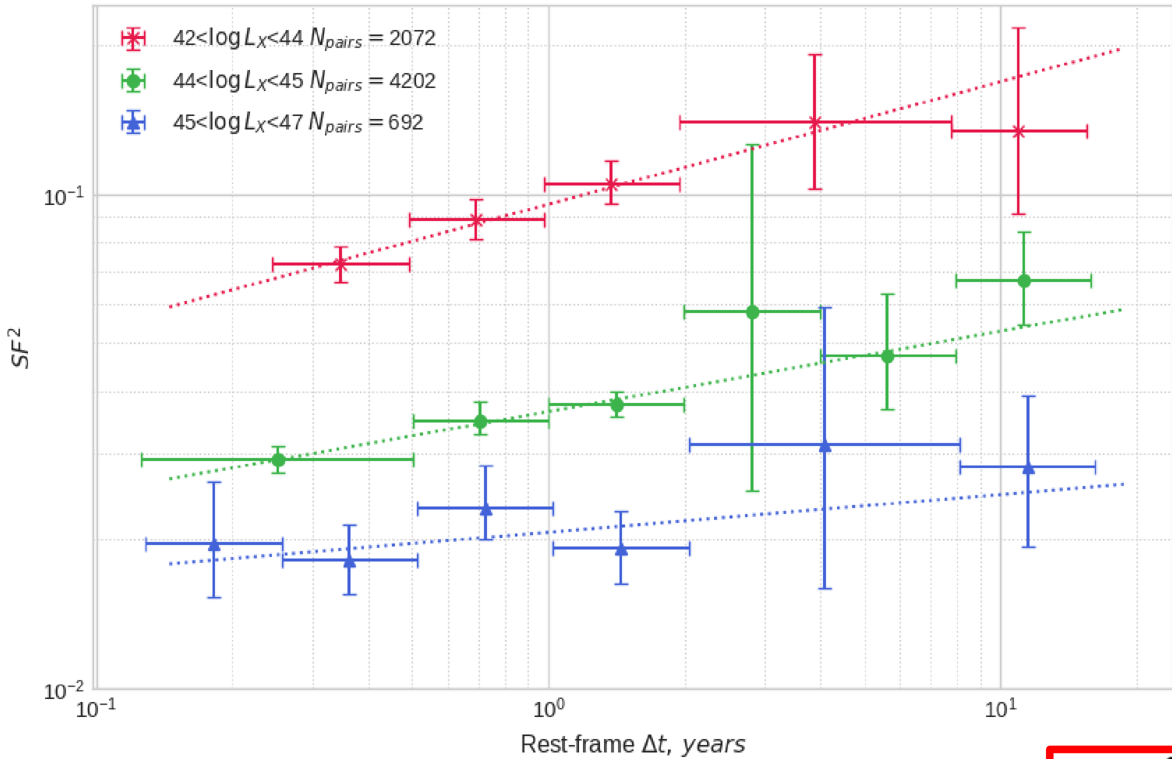
- Use the structure function (SF)

$$SF^2(\Delta t) = \left\langle \left[\log \frac{F_X(t_{obs} + \Delta t_{obs})}{F_X(t_{obs})} \right]^2 \right\rangle = \left\langle [f(t_{obs} + \Delta t_{obs}) - f(t_{obs})]^2 \right\rangle$$

$$f \equiv \log F_X \qquad \Delta t = \frac{\Delta t_{obs}}{1+z}$$

- Average SF over subsamples of quasars/flux measurements binned in rest-frame time scale (Δt) and physical quantities (luminosity, black hole mass, Eddington ratio, radio-loudness)

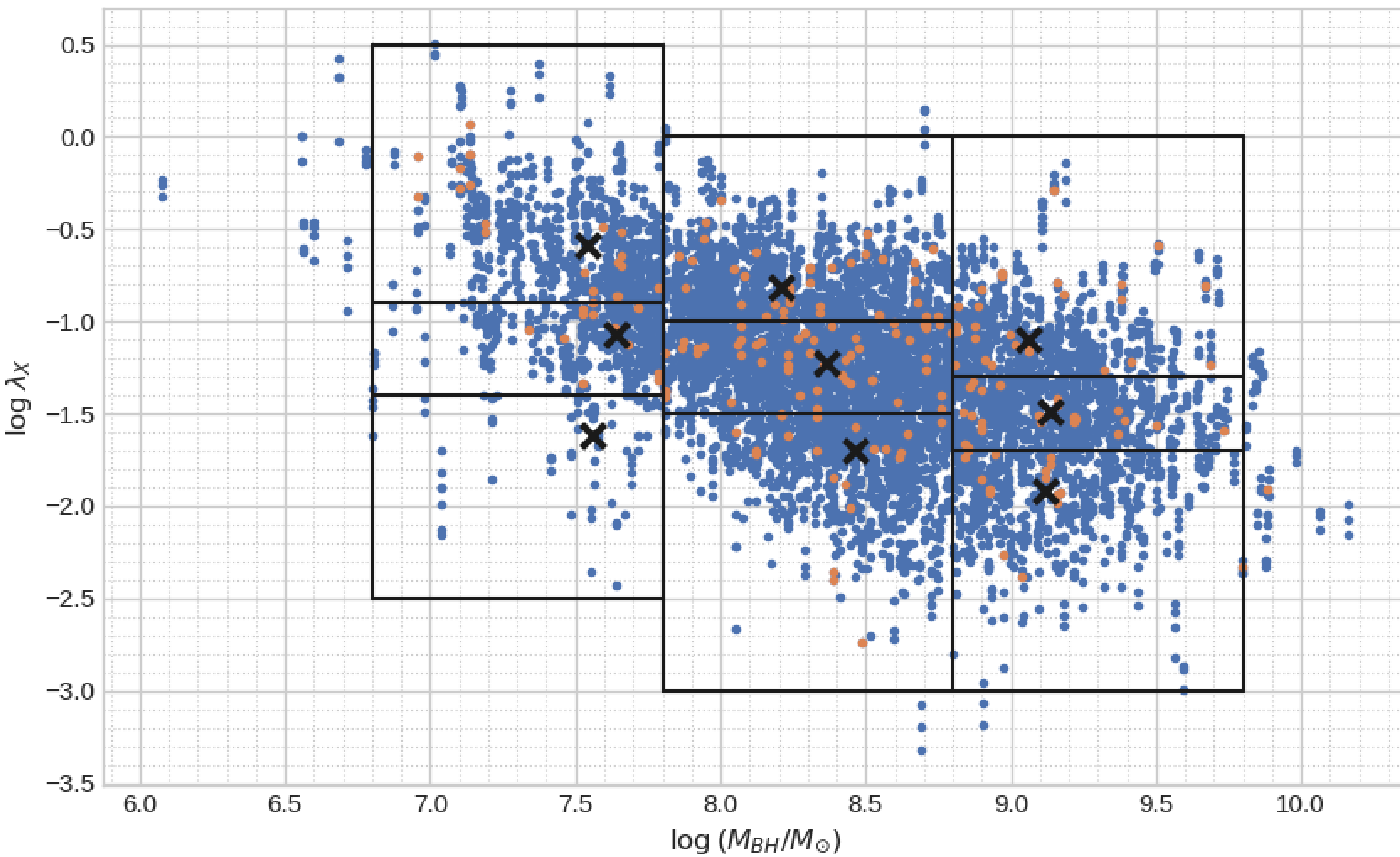
Luminosity dependence

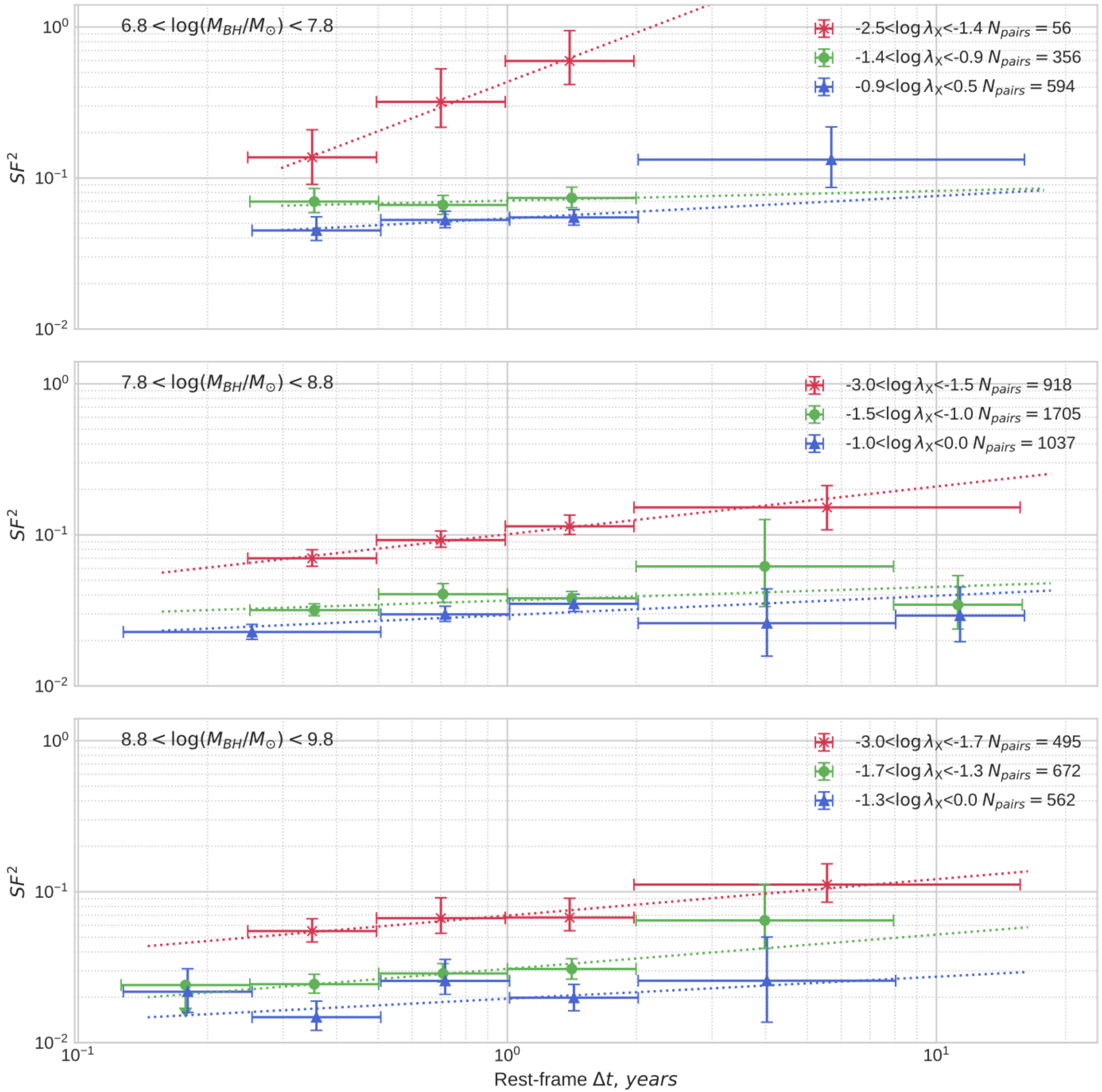


$$SF^2(\Delta t) = A^2\,(\Delta t)^{\beta}$$

$\log L_X(\mathrm{erg\,s^{-1}})$	Median $\log L_X(\mathrm{erg\,s^{-1}})$	N of Δt bins	A	β
(42, 44)	43.77	5	0.302 ± 0.015	0.25 ± 0.07
(44, 45)	44.43	6	0.191 ± 0.004	0.16 ± 0.04
(45, 47)	45.18	6	0.144 ± 0.005	0.07 ± 0.11

Dependence on BH mass and Eddington ratio



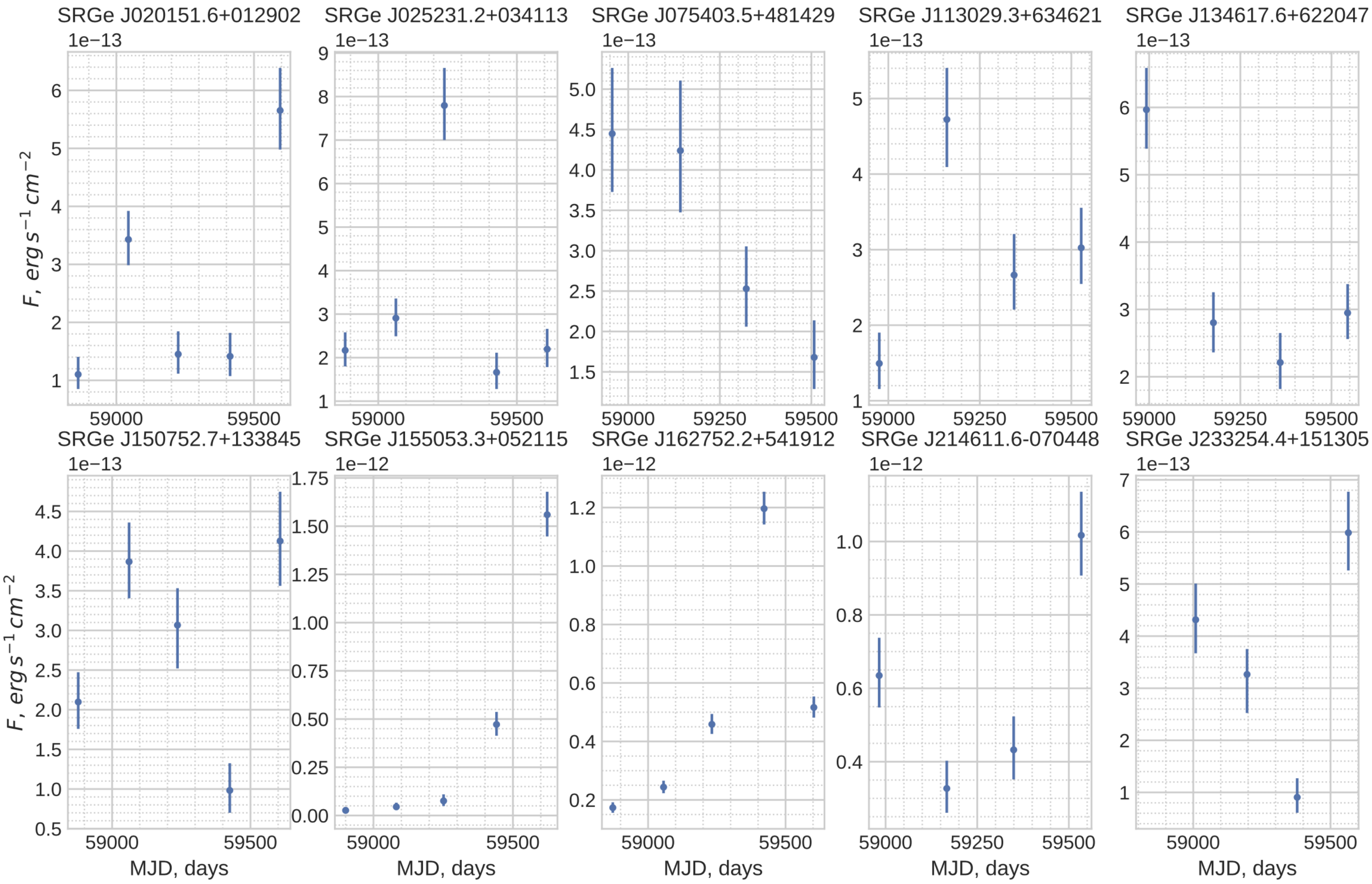


$6.8 < \log(M_{BH}/M_\odot) < 7.8$
-2.5<log λ_X<-1.4 $N_{pairs} = 56$
-1.4<log λ_X<-0.9 $N_{pairs} = 356$
-0.9<log λ_X<0.5 $N_{pairs} = 594$
$7.8 < \log(M_{BH}/M_\odot) < 8.8$
-3.0<log λ_X<-1.5 $N_{pairs} = 918$
-1.5<log λ_X<-1.0 $N_{pairs} = 1705$
-1.0<log λ_X<0.0 $N_{pairs} = 1037$
$8.8 < \log(M_{BH}/M_\odot) < 9.8$
-3.0<log λ_X<-1.7 $N_{pairs} = 495$
-1.7<log λ_X<-1.3 $N_{pairs} = 672$
-1.3<log λ_X<0.0 $N_{pairs} = 562$
SF^2
10^0
10^{-1}
10^{-2}
10^{1}
Rest-frame Δt, *years*

$\log M_{BH}(M_\odot)$	$\log \lambda_X$	Median $\log M_{BH}(M_\odot)$	Median $\log \lambda_X$	N of Δt bins	A	β
(6.8, 7.8)	(− 2.5, −1.4)	7.56	−1.62	3	0.7 ± 0.2	1.1 ± 0.2
(6.8, 7.8)	(− 1.4, −0.9)	7.64	−1.07	3	0.268 ± 0.015	0.06 ± 0.19
(6.8, 7.8)	(− 0.9, 0.5)	7.54	−0.58	4	0.232 ± 0.010	0.16 ± 0.14
(7.8, 8.8)	(− 3.0, −1.5)	8.46	−1.70	4	0.317 ± 0.013	0.32 ± 0.10
(7.8, 8.8)	(− 1.5, −1.0)	8.36	−1.23	5	0.190 ± 0.006	0.09 ± 0.07
(7.8, 8.8)	(− 1.0, 0.0)	8.21	−0.82	5	0.171 ± 0.006	0.14 ± 0.06
(8.8, 9.8)	(− 3.0, −1.7)	9.12	−1.92	4	0.264 ± 0.016	0.24 ± 0.14
(8.8, 9.8)	(− 1.7, −1.3)	9.13	−1.49	5	0.173 ± 0.008	0.22 ± 0.13
(8.8, 9.8)	(− 1.3, 0.0)	9.06	−1.09	5	0.142 ± 0.009	0.15 ± 0.15

- SF^2 increases with increasing Δt and can be satisfactorily described by a power law
- SF^2 decreases with increasing M_{BH} for fixed Δt and λ_X
- SF^2 decreases with increasing λ_X for fixed Δt and M_{BH}
- SF^2 becomes especially large for small λ_X

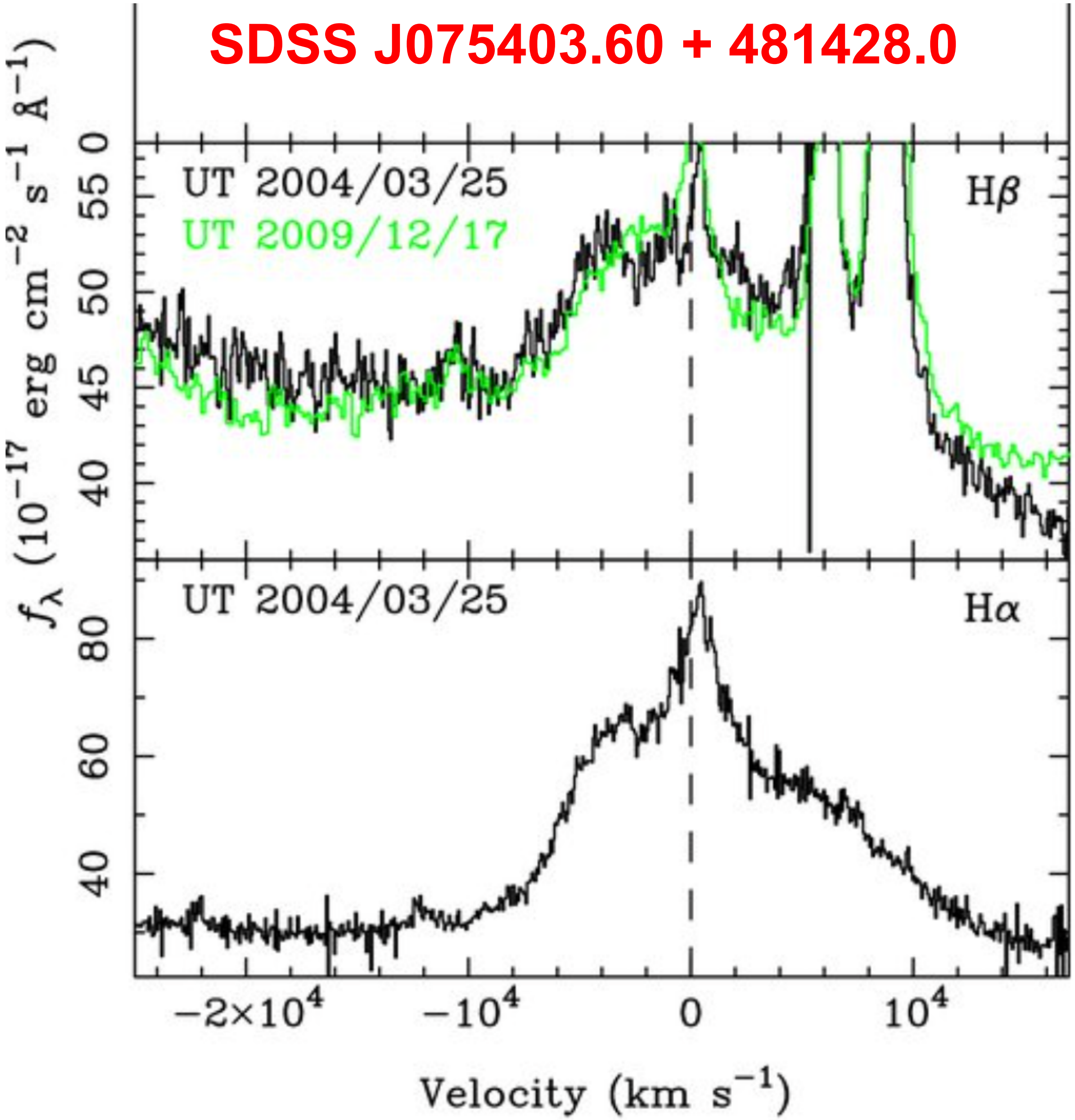
10 lowest Eddington ratio (λ_X<0.004) sources



SRGe name	SDSS name	Redshift	$\log \langle L_X \rangle$	$\log M_{BH}$ ($M_\odot$)	$\log \langle \lambda_X \rangle$	F_{max}/F_{min}	FWHM(Hα) ($1000\ km\ s^{-1}$)	FWHM(Hβ) ($1000\ km\ s^{-1}$)
J020151.6 + 012902	J020151.65 + 012902.5	0.155	43.27 ± 0.03	8.73 ± 0.12	−2.57 ± 0.13	5.1 ± 1.4	7.8 ± 0.8	9.6 ± 1.4
J025231.2 + 034113	J025231.19 + 034112.7	0.267	43.88 ± 0.03	9.18 ± 0.09	−2.42 ± 0.09	4.7 ± 1.3	9.1 ± 0.7	10.0 ± 1.0
J075403.5 + 481429	J075403.60 + 481428.0	0.276	43.88 ± 0.04	9.59 ± 0.09	−2.83 ± 0.10	2.6 ± 0.8	12.5 ± 1.4	13.7 ± 1.5
J113029.3 + 634621	J113029.48 + 634620.4	0.073	42.62 ± 0.04	8.69 ± 0.14	−3.18 ± 0.14	3.2 ± 0.9	10 ± 3	12.0 ± 1.9
J134617.6 + 622047	J134617.54 + 622045.5	0.116	43.14 ± 0.03	8.60 ± 0.03	−2.58 ± 0.04	2.7 ± 0.6	5.69 ± 0.08	7.6 ± 0.2
J150752.7 + 133845	J150752.66 + 133844.5	0.322	44.01 ± 0.03	9.566 ± 0.017	−2.68 ± 0.04	4.2 ± 1.5	13.0 ± 0.5	13.5 ± 0.3
J155053.3 + 052115	J155053.16 + 052112.1	0.110	43.11 ± 0.03	8.90 ± 0.06	−2.90 ± 0.06	60 ± 33	6.0 ± 0.4	8.5 ± 0.6
J162752.2 + 541912	J162752.18 + 541912.5	0.316	44.067 ± 0.018	9.44 ± 0.12	−2.48 ± 0.12	6.9 ± 0.8	14 ± 3	16 ± 2
J214611.6-070448	J214611.58-070449.2	0.125	43.44 ± 0.03	8.75 ± 0.02	−2.42 ± 0.04	3.1 ± 0.8	6.48 ± 0.15	8.0 ± 0.2
J233254.4 + 151305	J233254.46 + 151305.5	0.215	43.71 ± 0.04	9.039 ± 0.019	−2.44 ± 0.04	7 ± 3	8.9 ± 0.3	10.1 ± 0.2

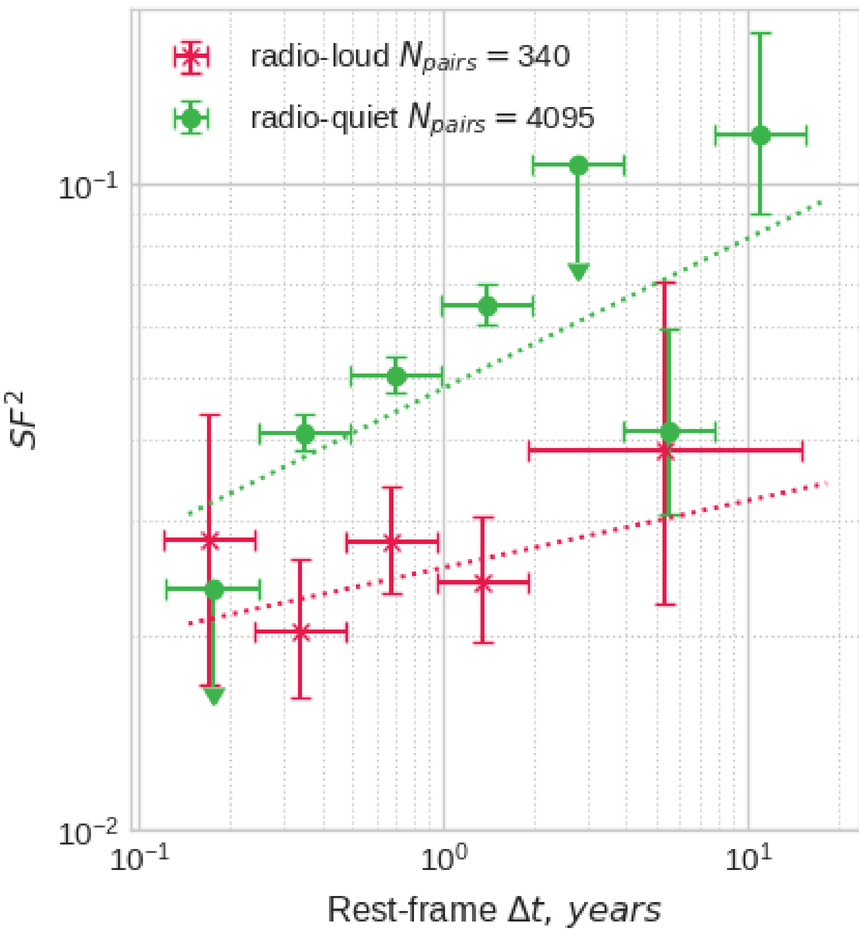
Notice the very broad Balmer lines in some of them! Moreover, these lines usually have weird profiles, as has been discussed in the literature.

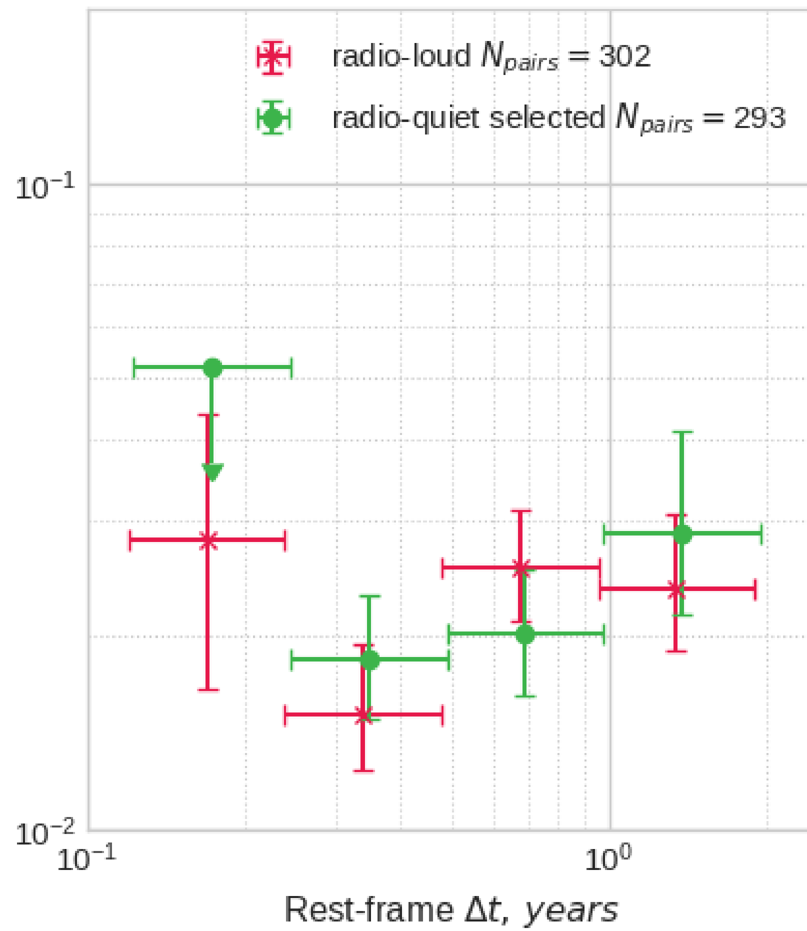
SDSS J075403.60 + 481428.0



Eracleous et al. (2012)

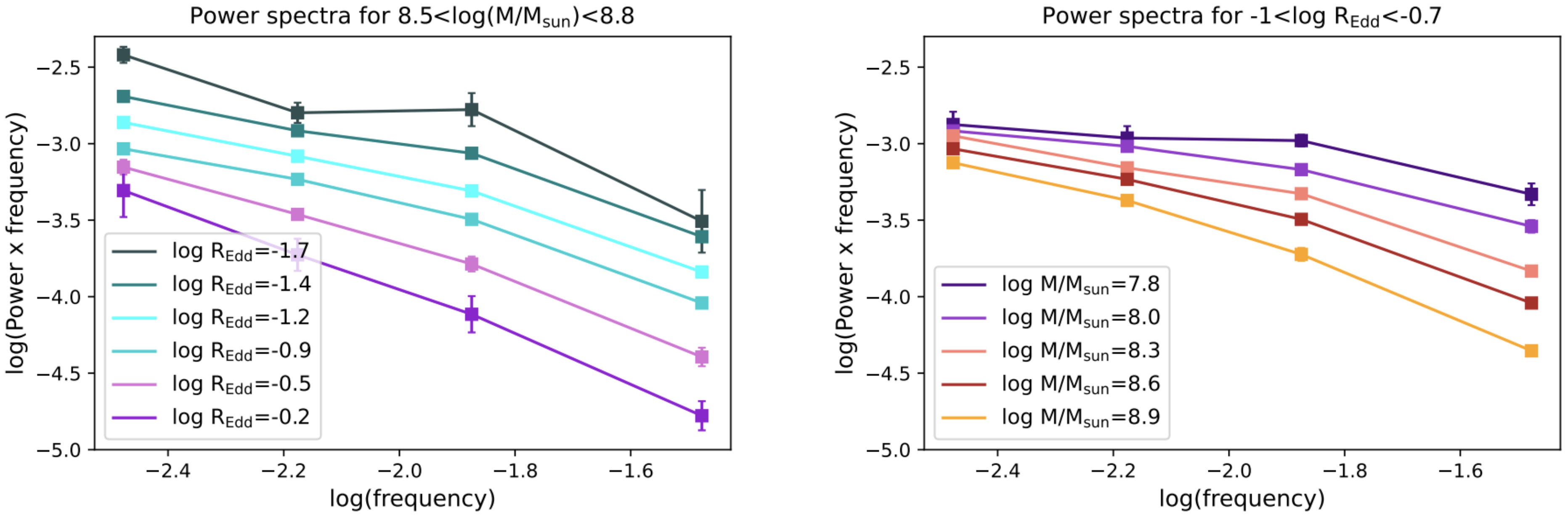
Dependence on radio-loudness





$SF^2(\Delta t)$ does not depend on radio-loudness if we take M_{BH} and λ_X into account

Similar trends are seen in the optical!



Arevalo et al. (2024)

Note, however, that their study is restricted to time scales shorter than 1 year

Conclusions

We have studied the X-ray variability of quasars on rest-frame time scales from several months to 20 years, based on a large unifrom sample with reliably measured fluxes:

- We reaffirm the anticorrelation of the X-ray variability amplitude with X-ray luminosity.
- Variability amplitude anticorrelates with both BH mass and Eddington ratio.
- There is an indication of particularly strong variability in AGN with lowest Eddington ratios.
- The dependence SF^2 on time scale is well described by a power law with a slope of ~0-1.