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CONSTRAINING THE (UNIVERSAL) FORM OF THE X-RAY AGN POWER SPECTRUM

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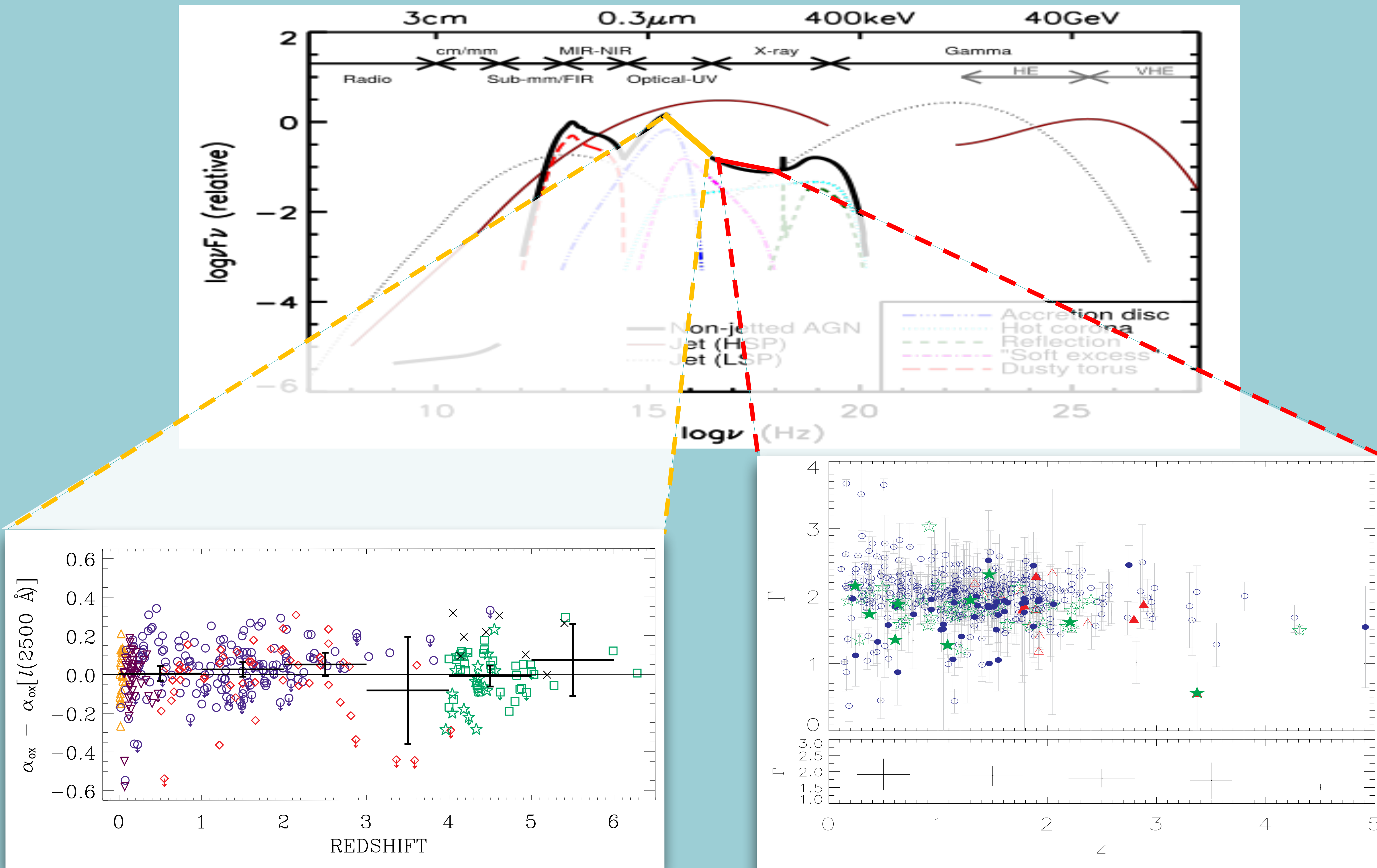
DO AGN INTRINSIC PROPERTIES EVOLVE?

Spectral properties are remarkably uniform



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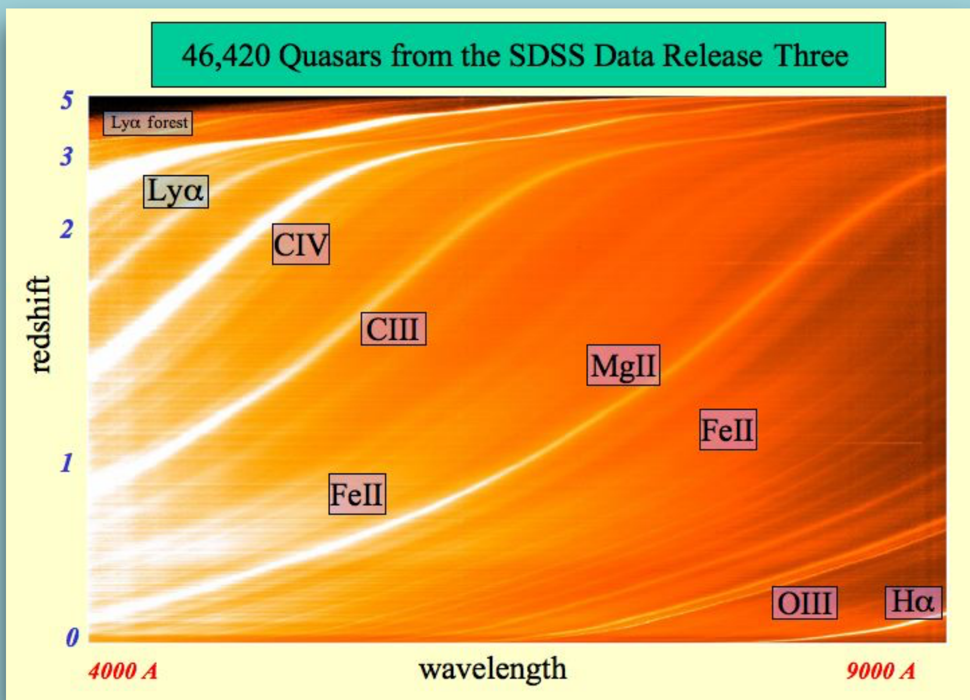
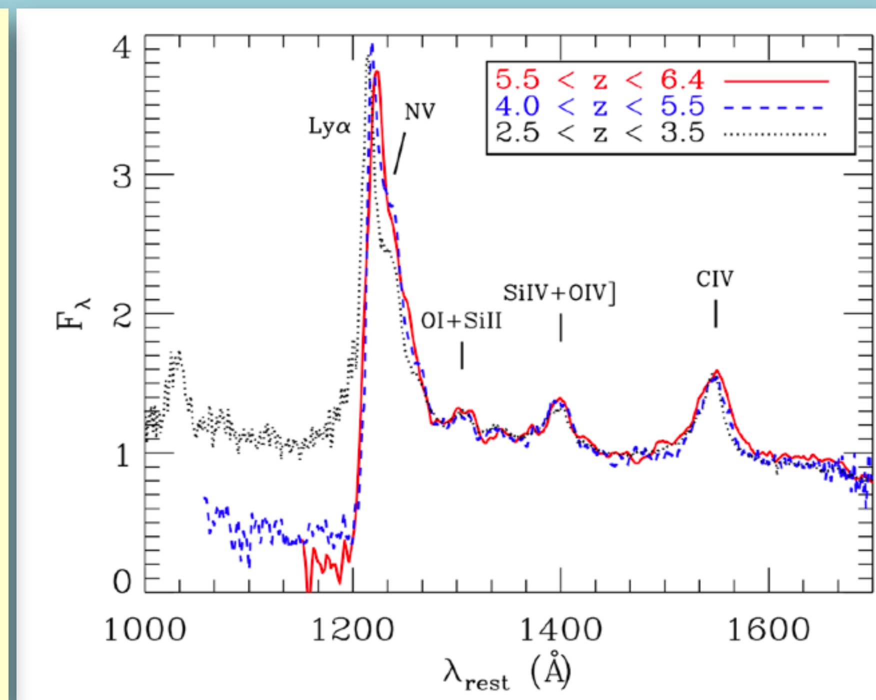
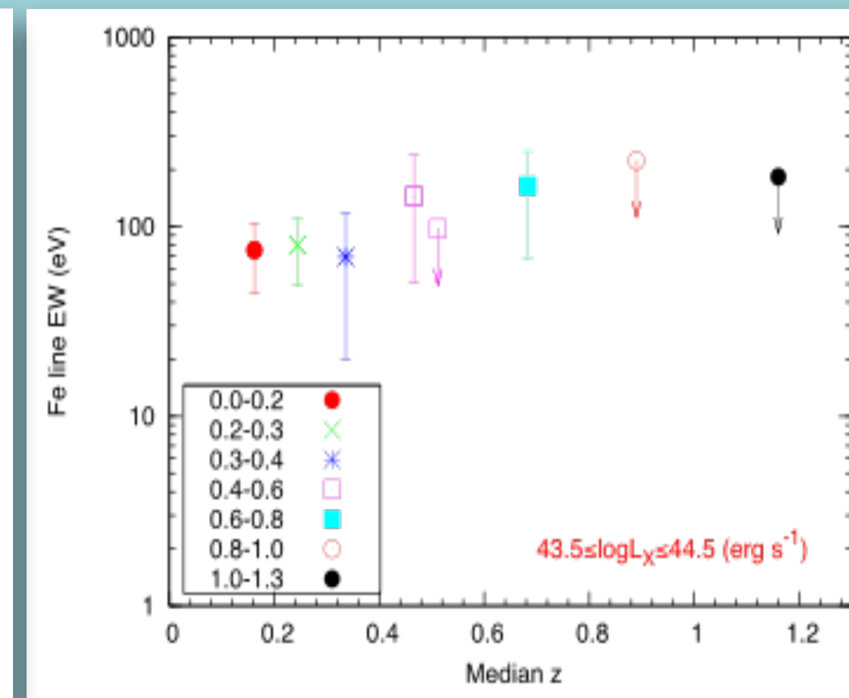
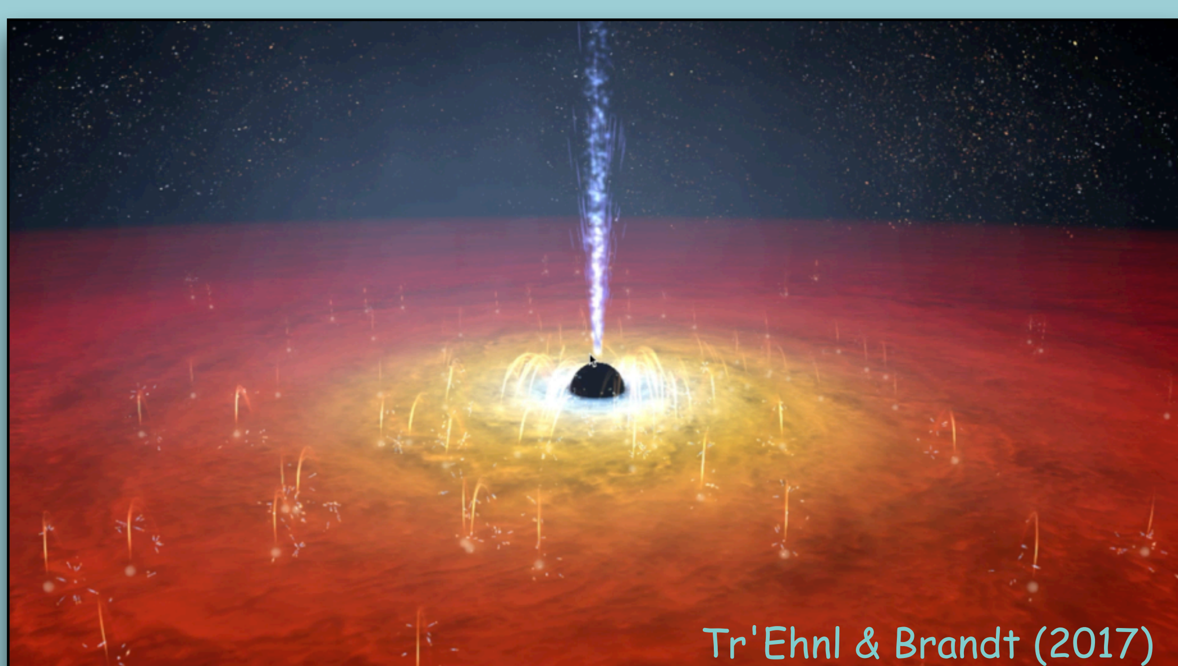
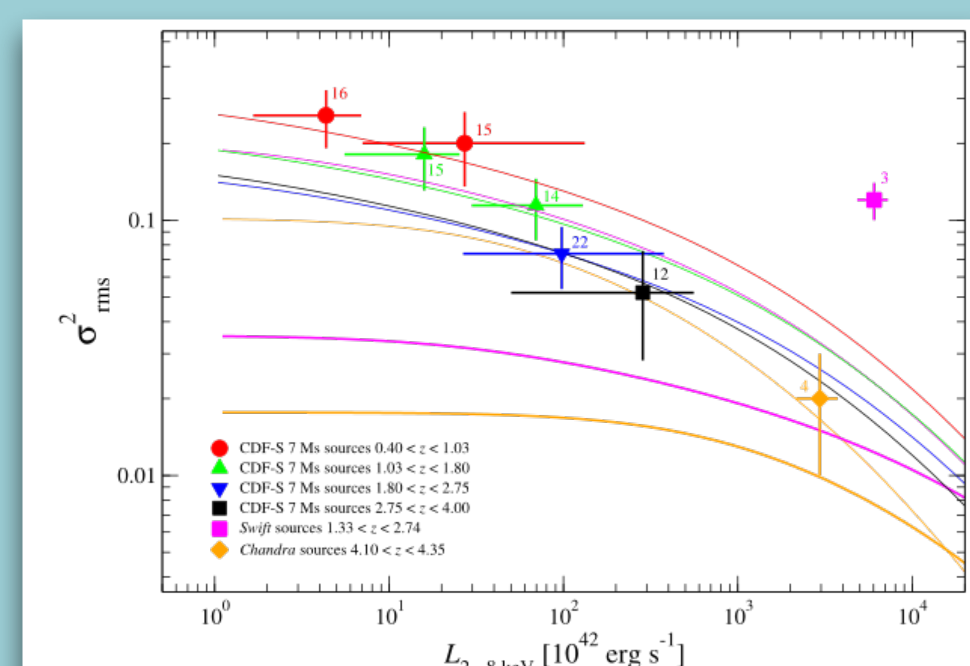




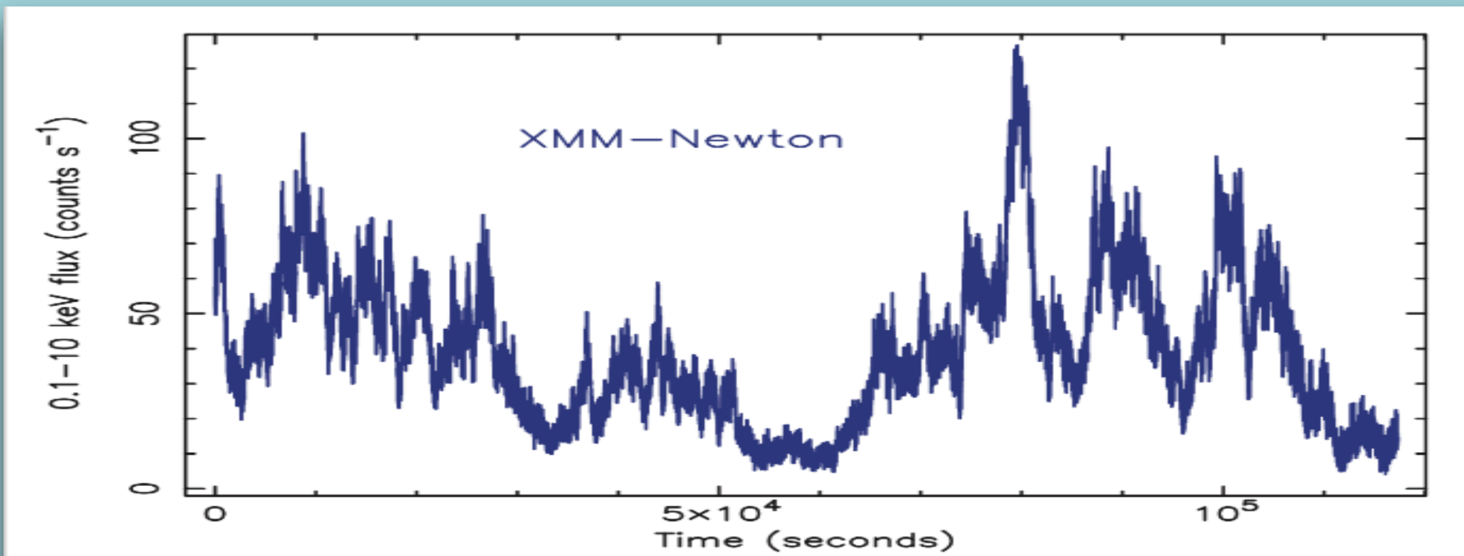


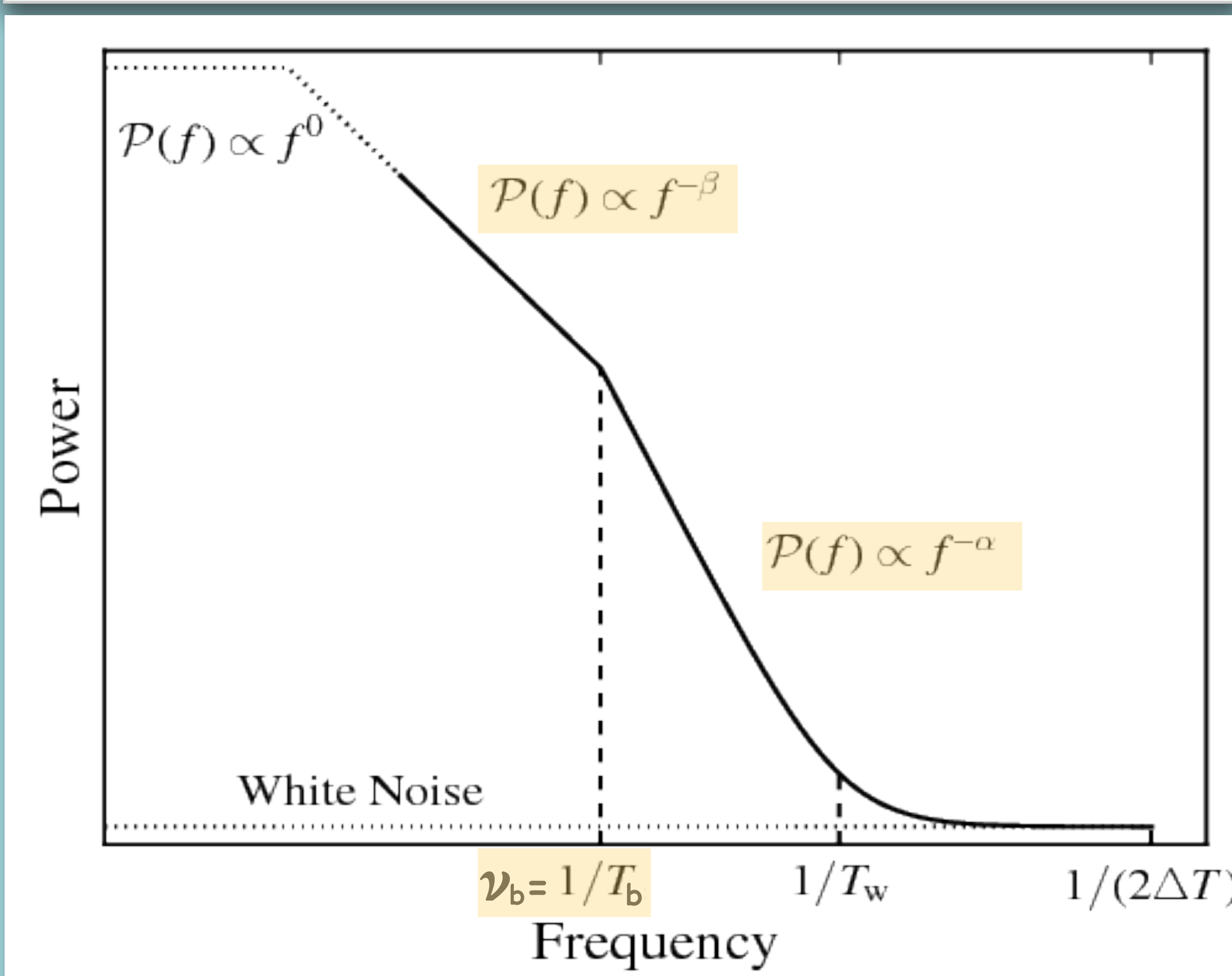
What about timing?





X-RAY VARIABILITY: POWER SPECTRAL DENSITY





$$PSD = |H(\nu)|^2 = \left| \int_{-\infty}^{+\infty} x(t) e^{-2\pi i \nu t} dt \right|^2$$

- PSD is modelled with a "bending" or "broken" power-law
- The Break Frequency represents a characteristic Break Timescale $T_b = 1/\nu_b$
- The low and high freq. slopes are commonly assumed to be $\alpha \simeq 2$ and $\beta \simeq 1$

CHARACTERISTIC TIMESCALES

- **Dynamic Timescale:** timescale to achieve the hydrodinamic equilibrium in the disk

$$T_{dyn} = 104\left(\frac{R}{100R_S}\right)^{3/2}\frac{M_{BH}}{10^8 M_{sun}}[days]$$

- **Thermal Timescale:** ratio of internal energy to the cooling or heating rate. The parameter α describe the disk viscosity.

$$T_{th} = 4{,}6\frac{\alpha^{-1}}{0{,}01}\frac{R}{100\mathrm{R}_S}^{3/2}\frac{M_{BH}}{10^8 M_{sun}}[years]$$

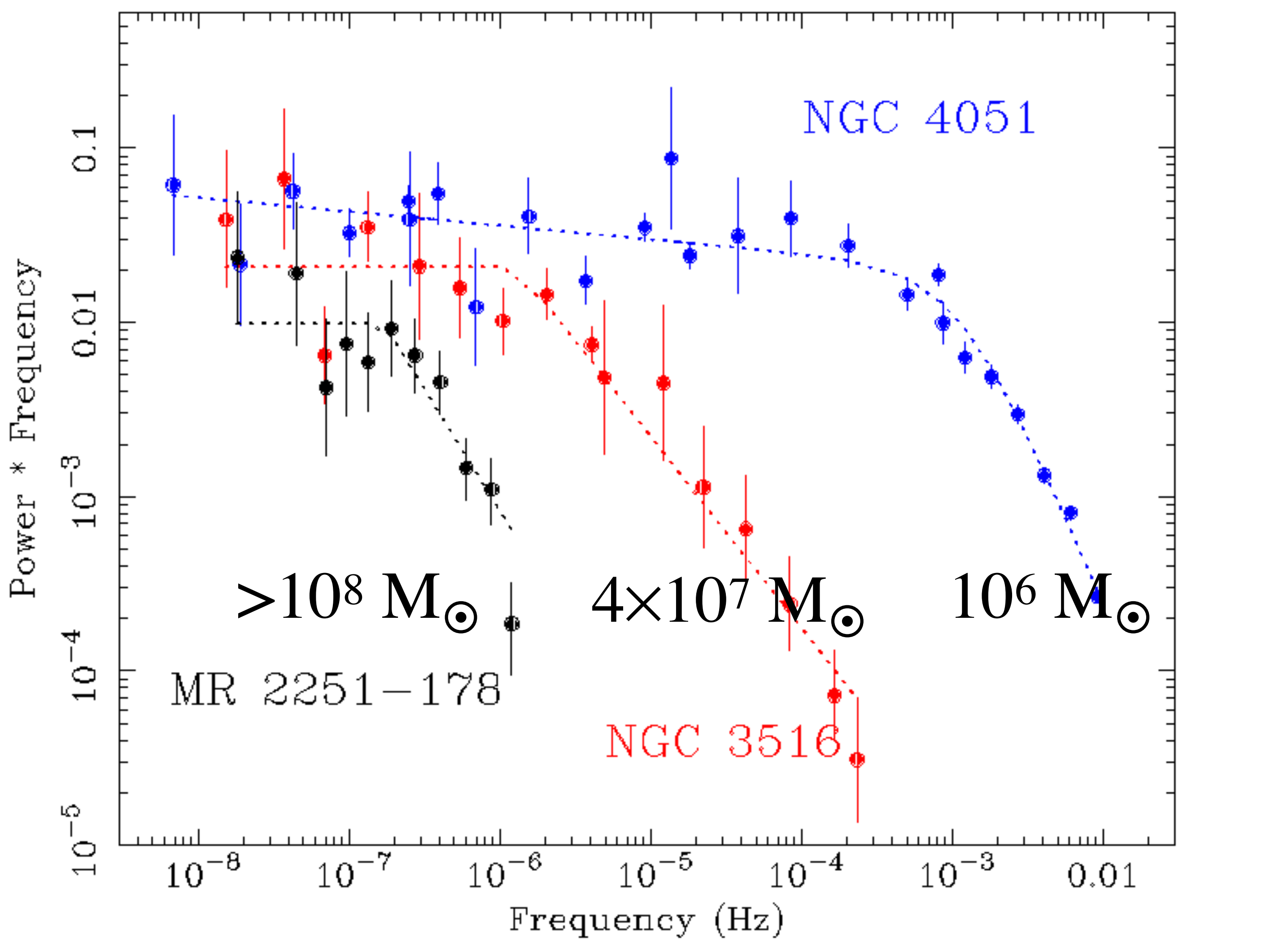
- **Viscous Timescale:** characteristic timescale of a mass flow.

$$T_{visc} = T_{th}\left(\frac{R}{H_d}\right)$$

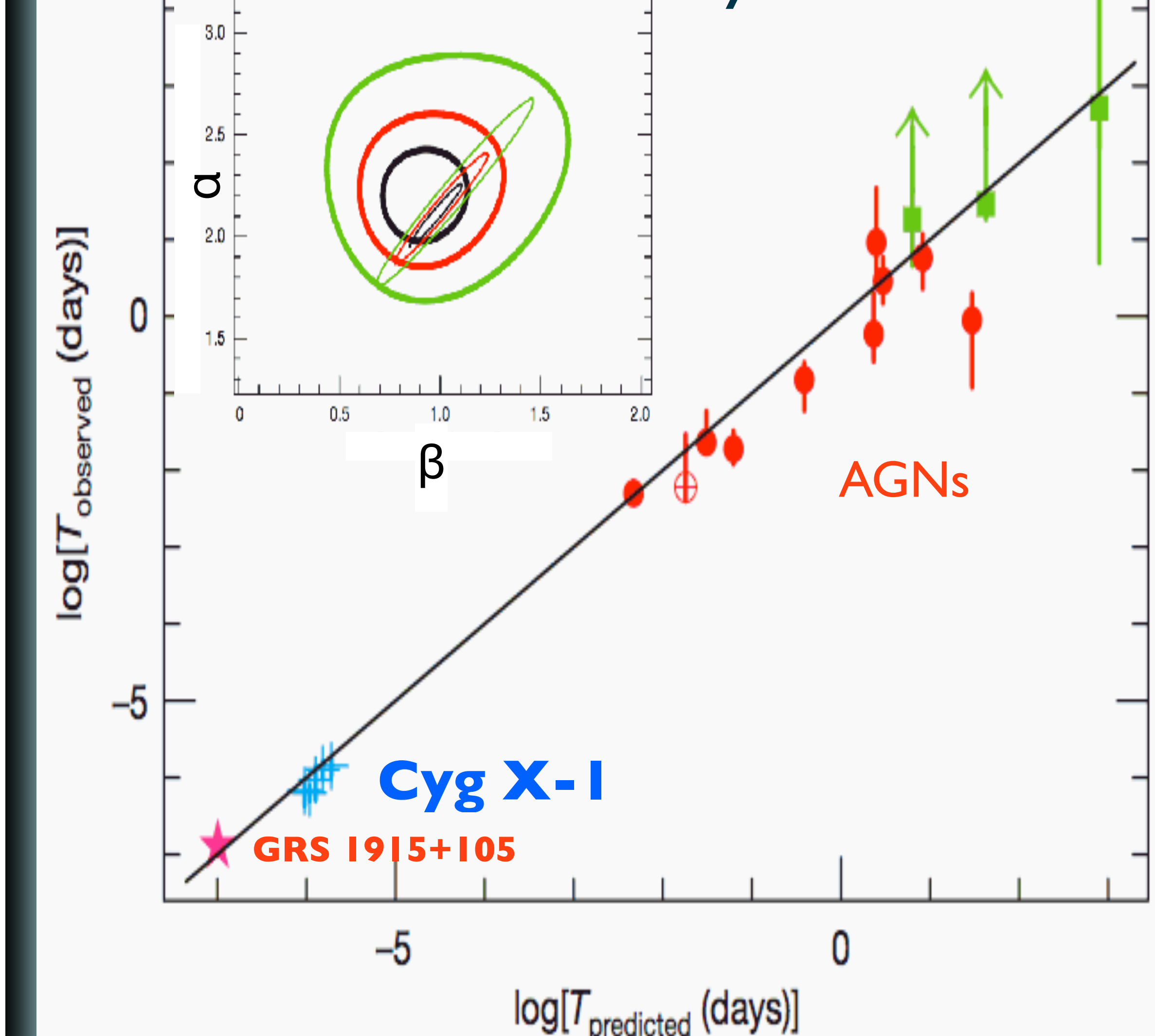
- If R/H_d <<1 ⟶ **$T_{dyn} < T_{th} < T_{vis}$**

VARIABILITY SCALING WITH BH MASS AND ACC.RATE

(courtesy of P. Uttley)



McHardy et al. 2006



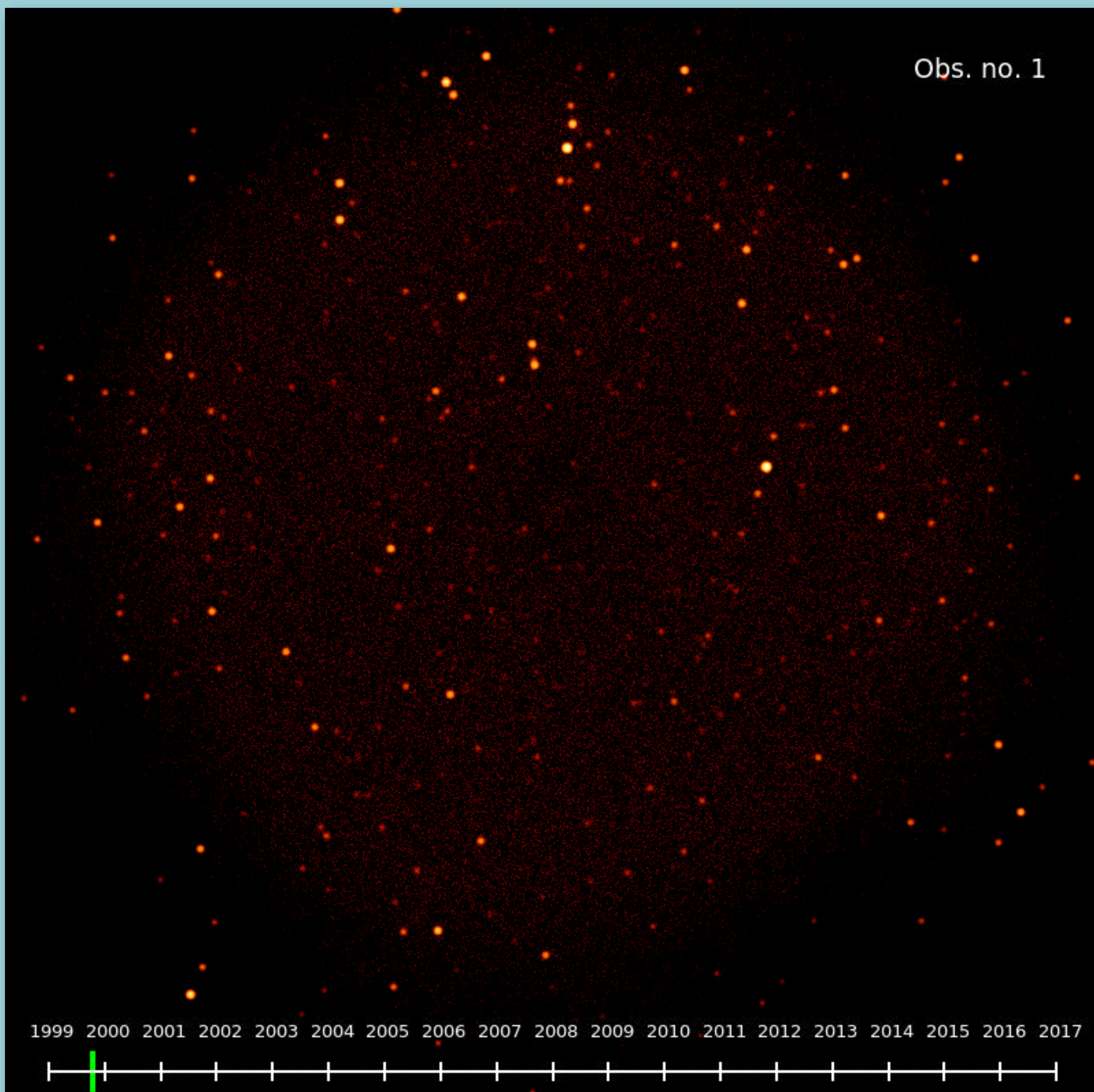
High frequency break seems to scale with BH mass and luminosity (or $\dot{m}$)

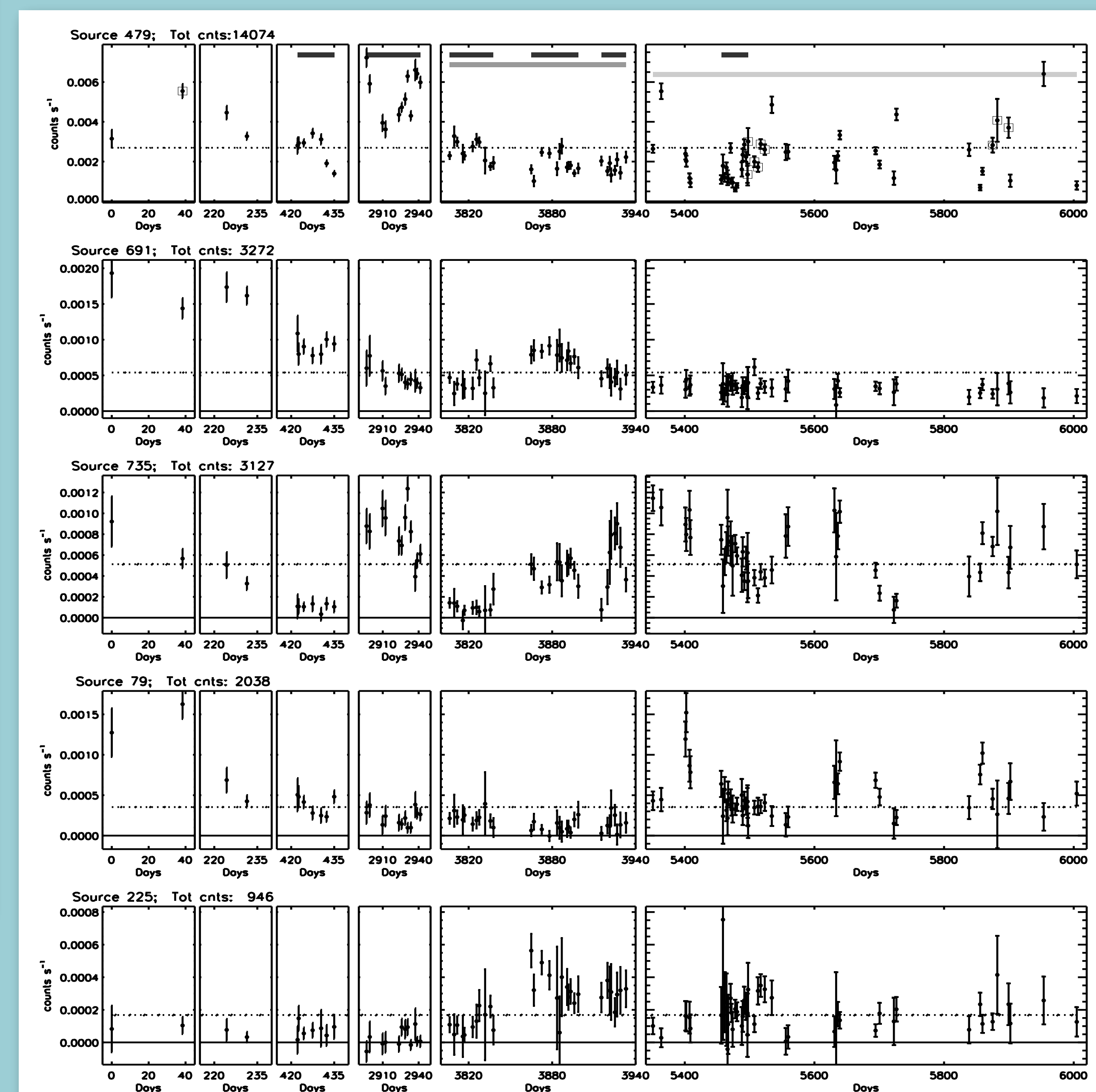
$$t_B \propto M_{BH}^{\alpha}/L_{bol}^{\beta}$$

(N.B. α and β not to be confused with PSD slope parameters)

How to test universality? 7Ms CDFS lightcurves...

(Paolillo et al. 2017, Zheng et all. 2017, Ding et al. 2018, Li-Ming et al. 2023)

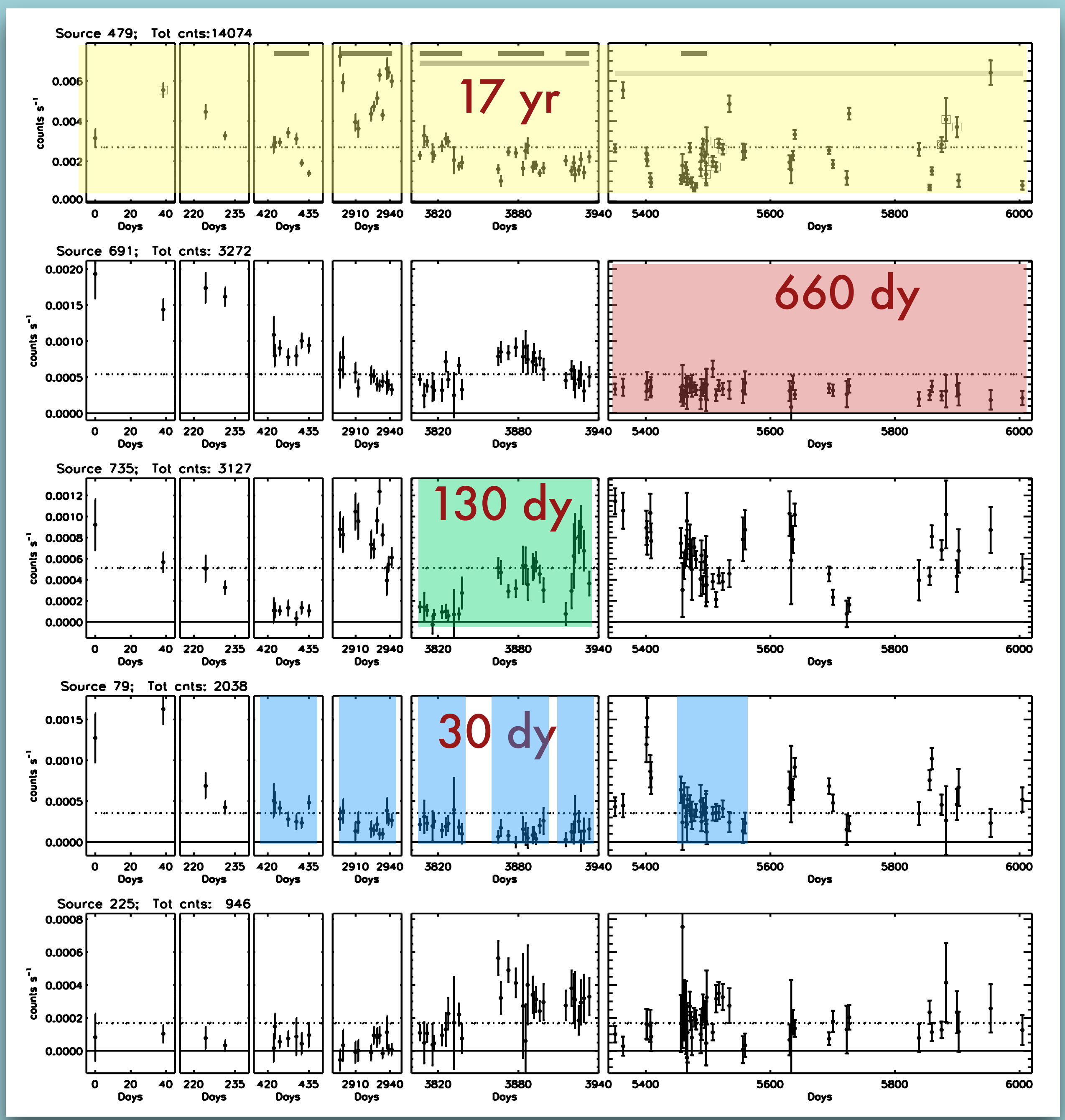


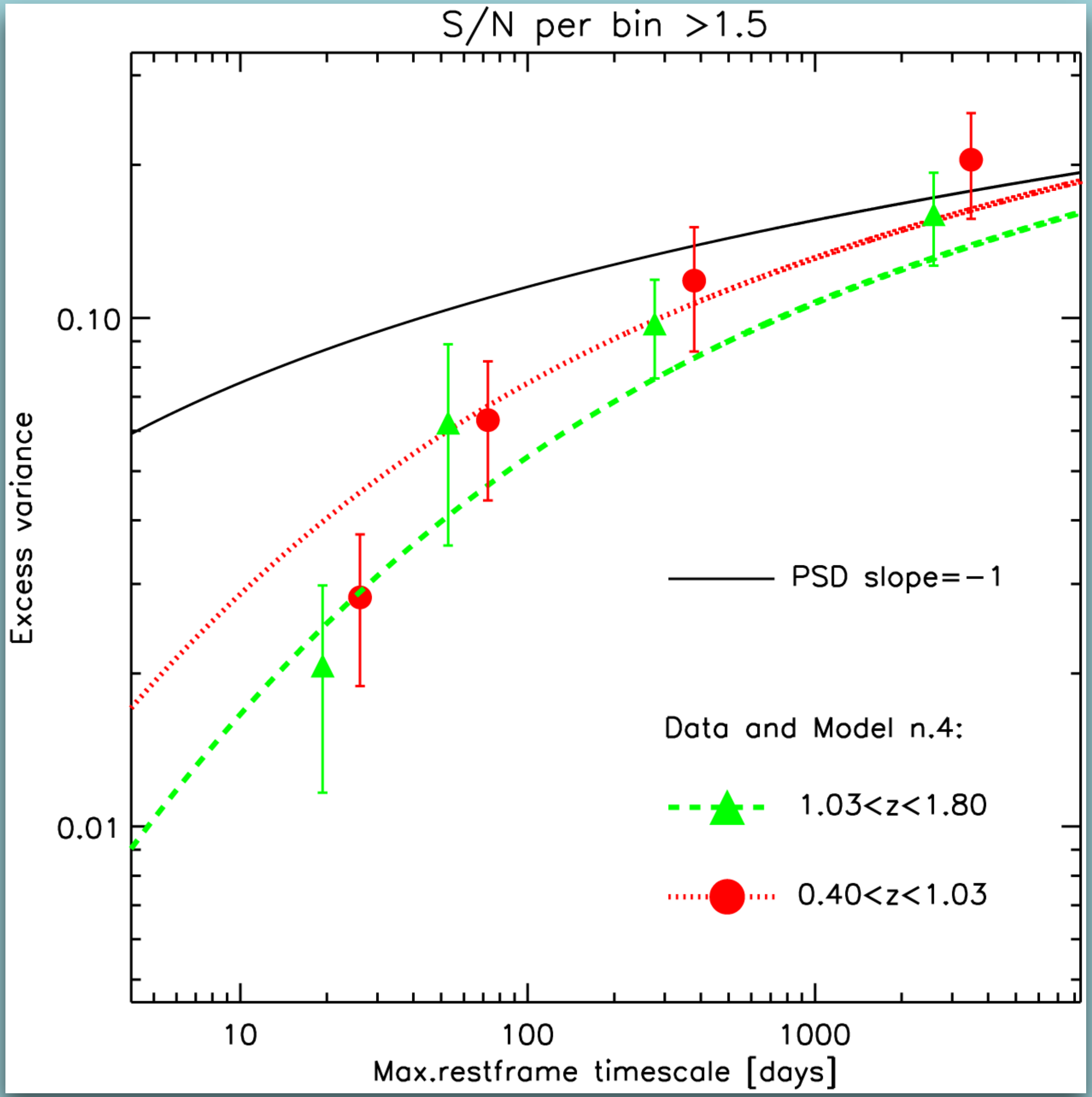


...to probe the high-z PSD

(Paolillo et al. 2017)

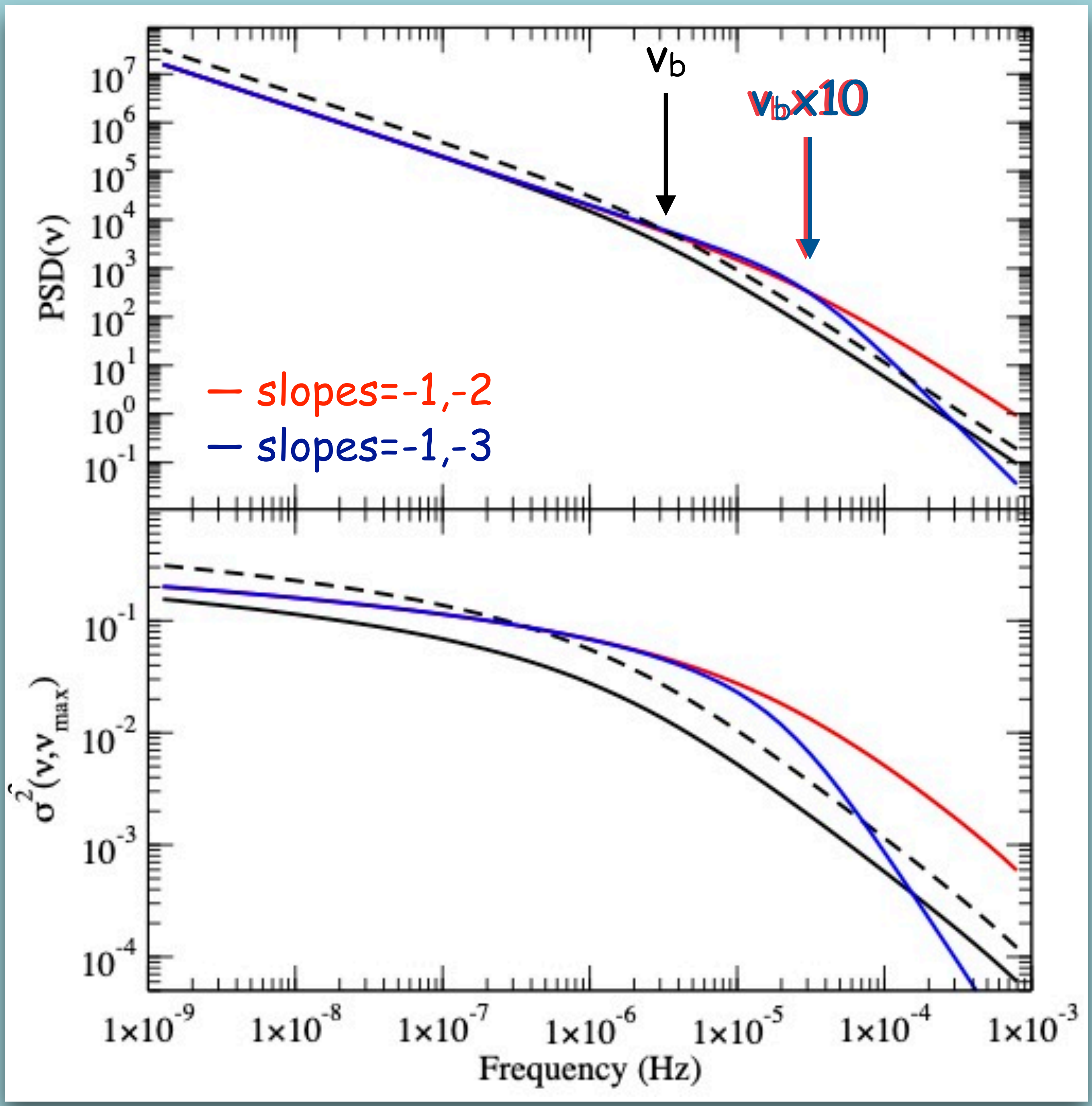
- Variability on different timescales: from a few days - 17 yrs.
- The high-z PSD must present a break as for local AGN





IMPROVING THE ANALYSIS:

THE VARIANCE-FREQUENCY PLOT (VFP)



- Assume a bending power-law PSD:

$$PSD(\nu) = A\nu^{-1}\left[1+\left(\frac{\nu}{\nu_b}\right)^s\right]^{-1}$$

where

$$\nu_b = B\left(\frac{M_{\rm BH}}{10^8 {\rm M}_\odot}\right)^{-1}$$

- The variance can be written:

$$\sigma^2(\nu_T,\nu_{max}) = \int_{\nu_T}^{\nu_{max}} {\rm PSD}(\nu)\, d\nu =$$

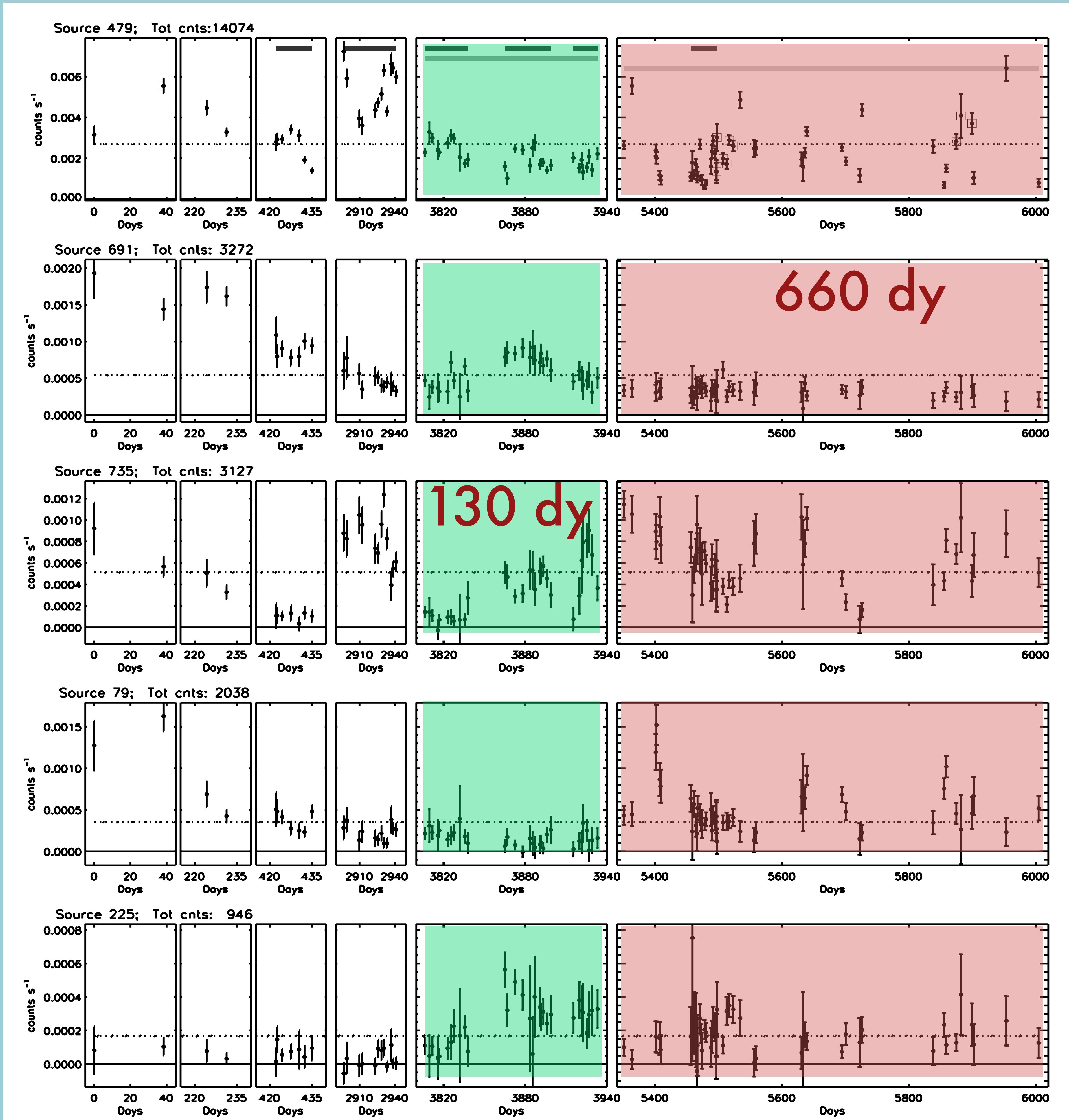
$$= A\left[\ln\left(\frac{\nu_{max}}{\nu_T}\right) - \frac{1}{s}\ln\left(\frac{\nu_b^s+\nu_{max}^s}{\nu_b^s+\nu_T^s}\right)\right]$$

Complications:

- depends on the lightcurve properties through ν_T and ν_{max}
- depends on BH mass and $\dot{m}$ through A and B

7Ms CDFS lightcurves

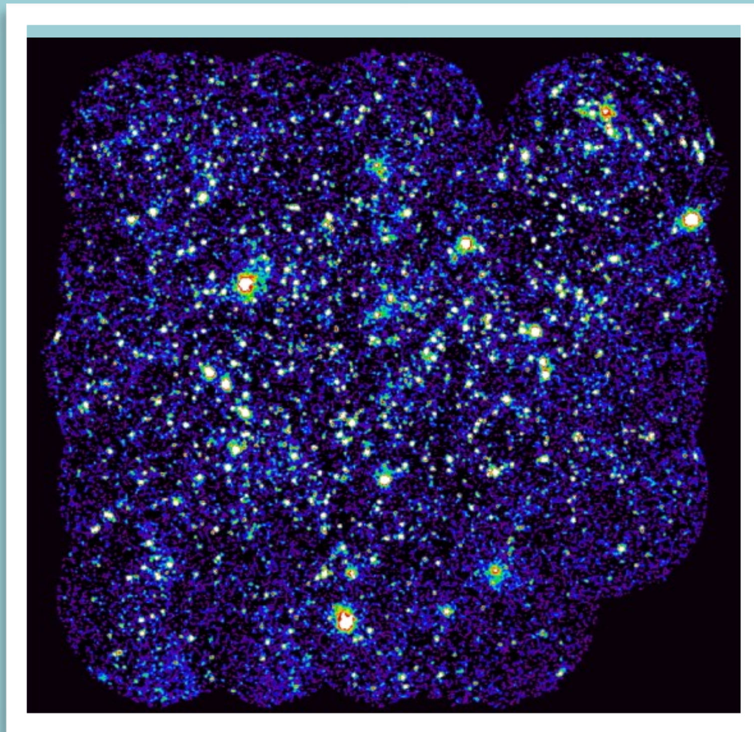
(Paolillo et al. 2022)

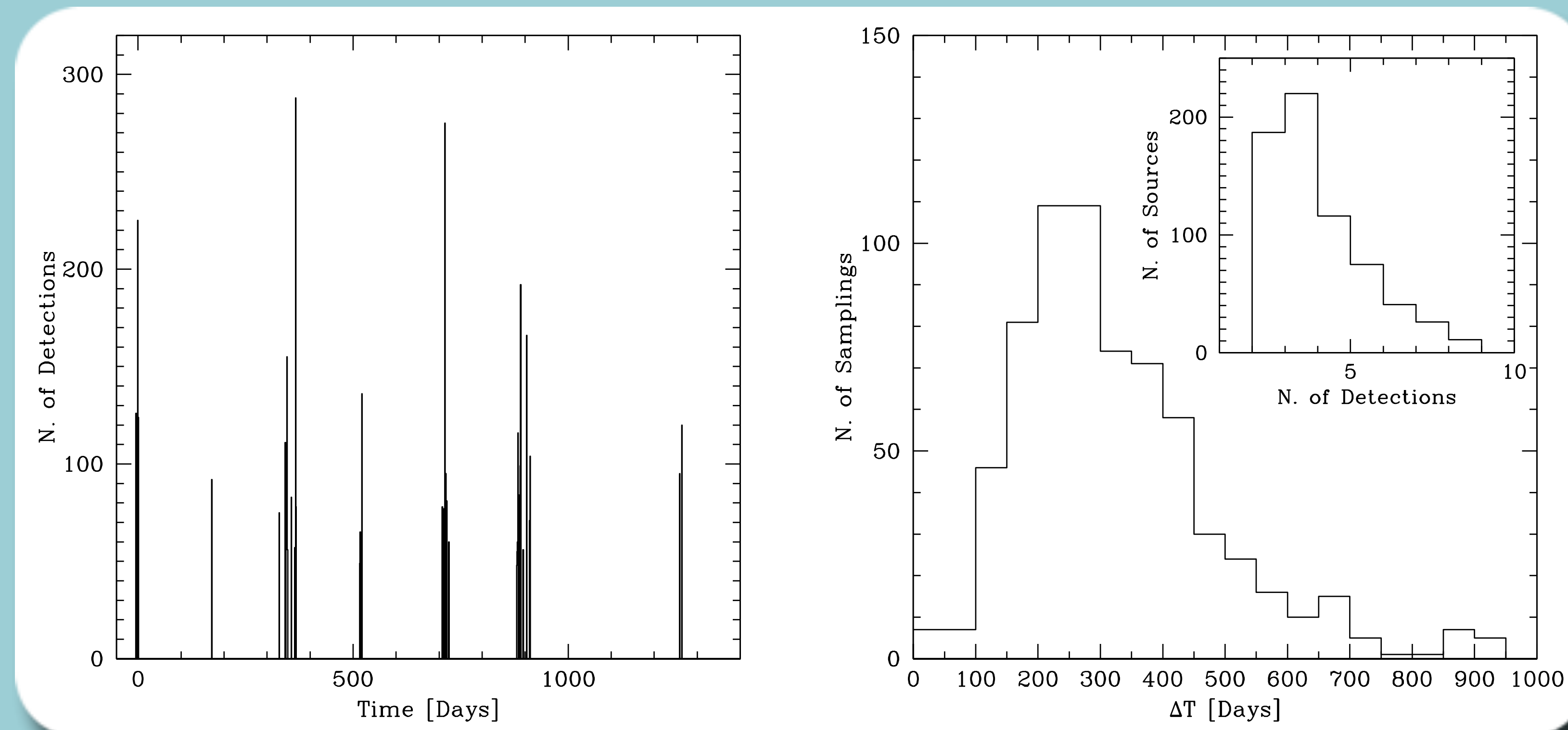


- Variability on different timescales: from a few days - 17 yrs.
- A proxy to a proper PSD analysis
- We now only use fully independent timescale

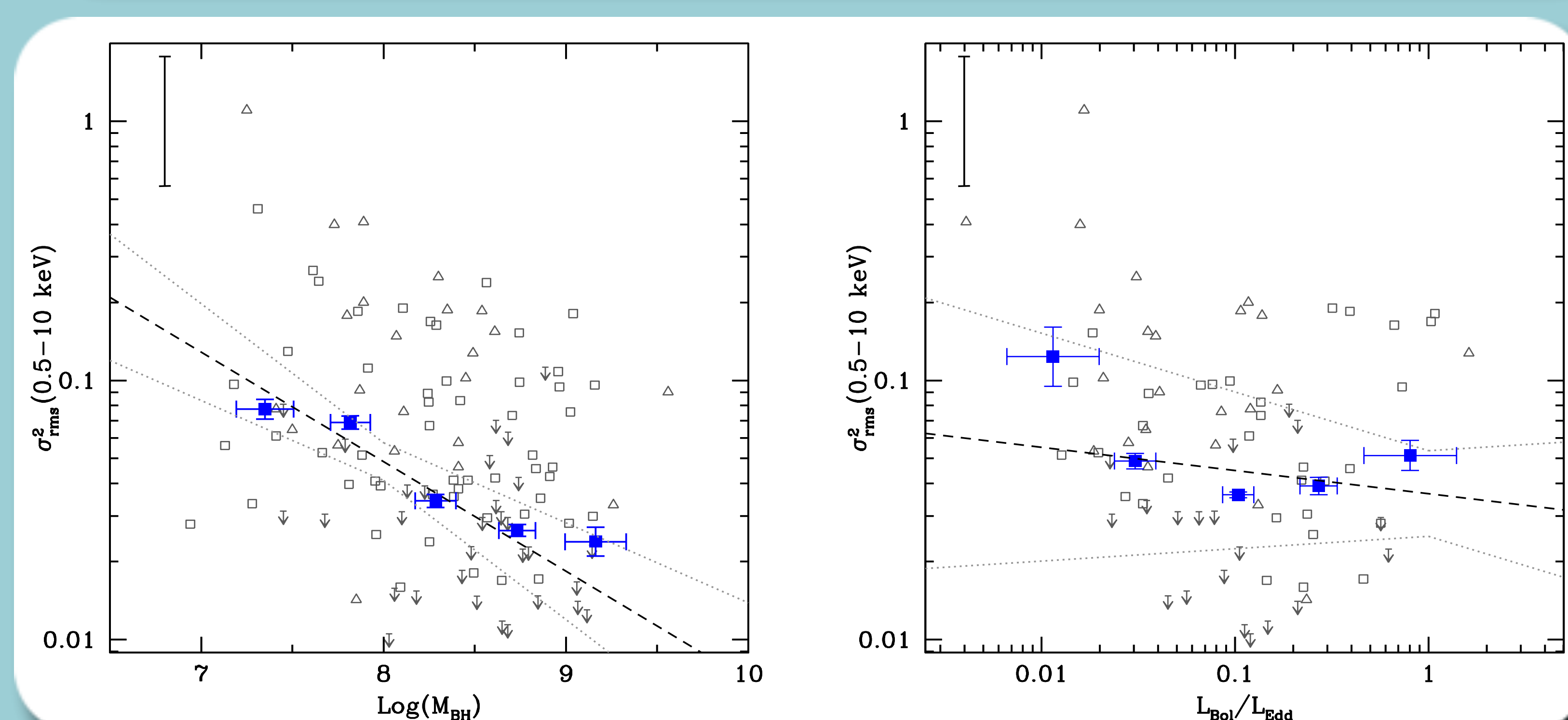
IMPROVING THE STATISTICS: COSMOS

(LANZUISI ET AL. 2014)





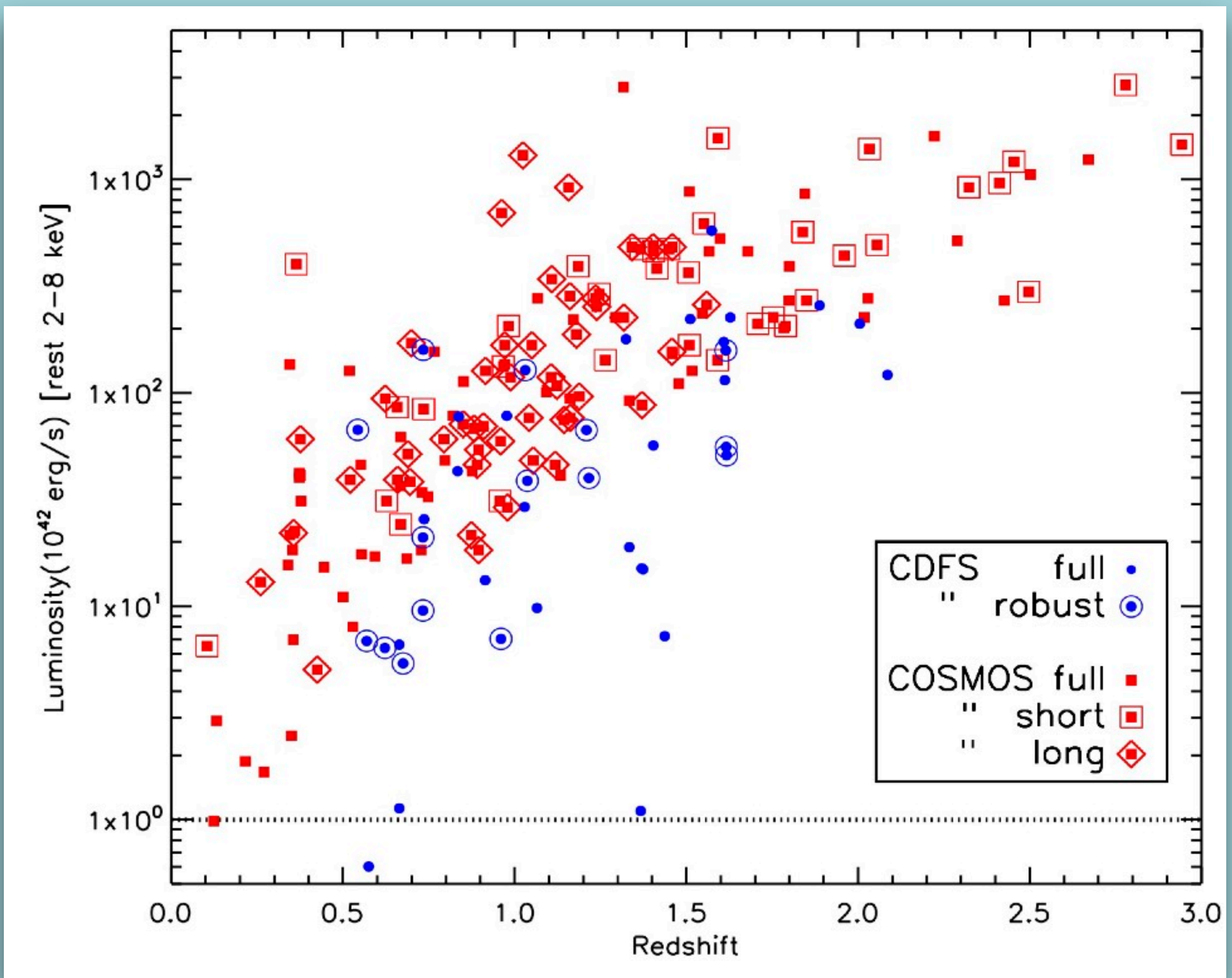
- much worse sampling but larger sample!



- In fact: clear dependence on mass, but little dependence on accretion!

EXTENDING THE TIMESCALE COVERAGE

Survey	T_{obs} (days)	$\Delta t_{min,obs}$ (days)	$\tilde{T}_{rest}$ [range] (days)	$a(T_{obs})$	$b(T_{obs})$
CDF-S	654	0.25	334[±87]	-1.07±0.12	-0.2±0.2
	128	0.95	65[±17]	-1.36±0.16	-0.3±0.3
CAIXA	0.926	0.003	0.926	-2.9±0.2	-0.71±0.16
... +TARTARUS	0.463	"	0.463	-2.98±0.14	-0.75±0.14
long-term RXTE	5110	300	5110	-1.38±0.09	-0.15±0.12
COSMOS	555	0.40	$240[^{+88}_{-107}]$	-1.36±0.10	-0.16±0.14
"	891	0.38	$413[^{+139}_{-69}]$	-1.29±0.07	-0.21±0.13
Swift+RXTE	9.45	~0.5	9.45	-1.81±0.08	-0.42±0.07



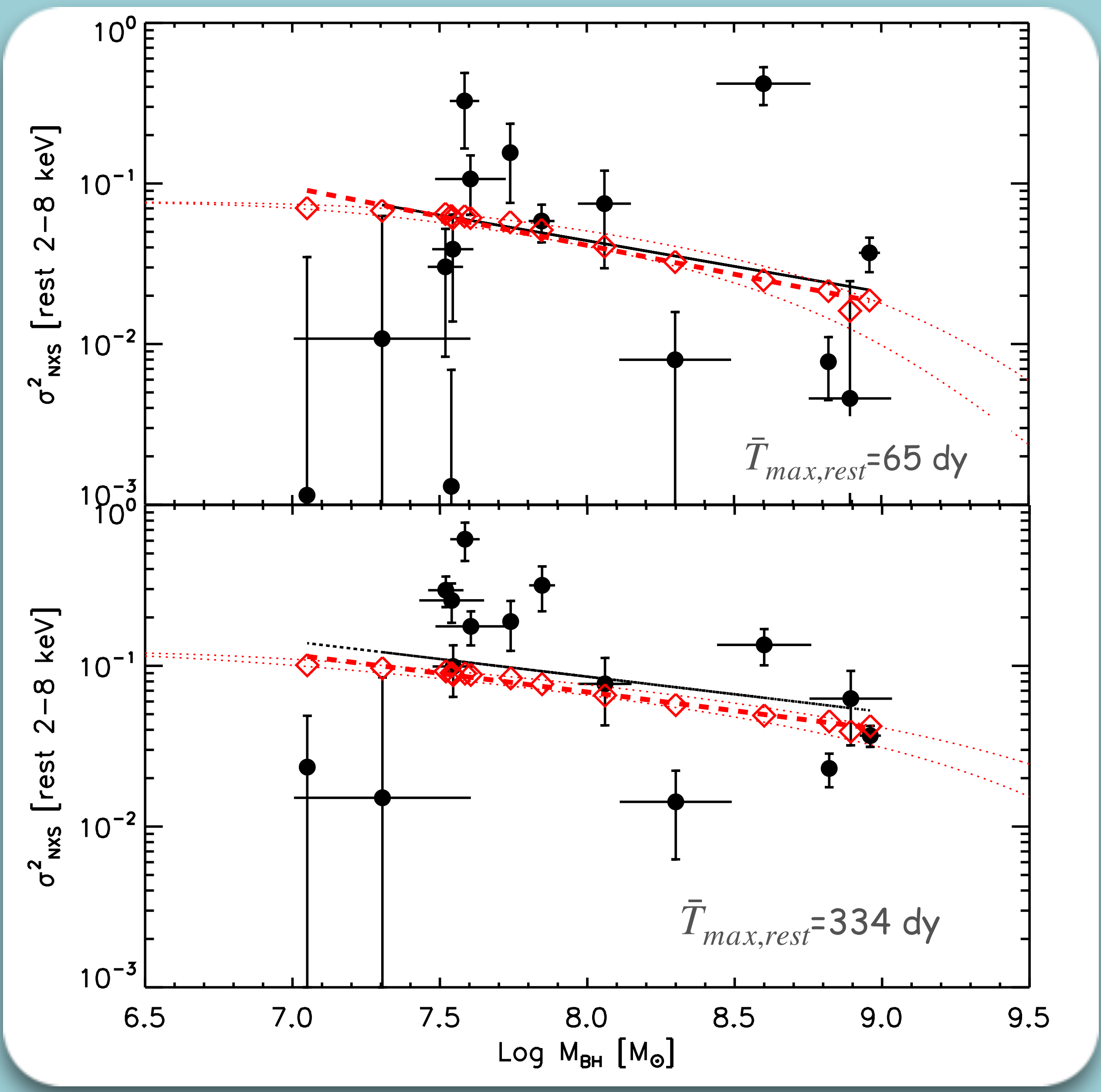
- **Local samples:**
  - 16 ASCA Tartarus sources+6 XMM CAIXA on 40 ks timescales,
  - 11 XMM CAIXA sources on 80 ks tmscl,
  - 14 RXTE+Swift sources on 10 days tmscl,
  - 27 RXTE sources on 14 years tmscl.
- **CDFS robust sample:** only 15 sources with reliable BH mass, S/N > 0.8 per epoch, >90 points in the lightcurve and regular sampling.
- **COSMOS robust samples:** 82 sources split in short (100 days ≤ T_{rest} < 330 days) and long (330 days ≤ T_{rest} < 560 days) timescales, but only 3 to 10 observations each.

WEIGHTING BLACK-HOLES:

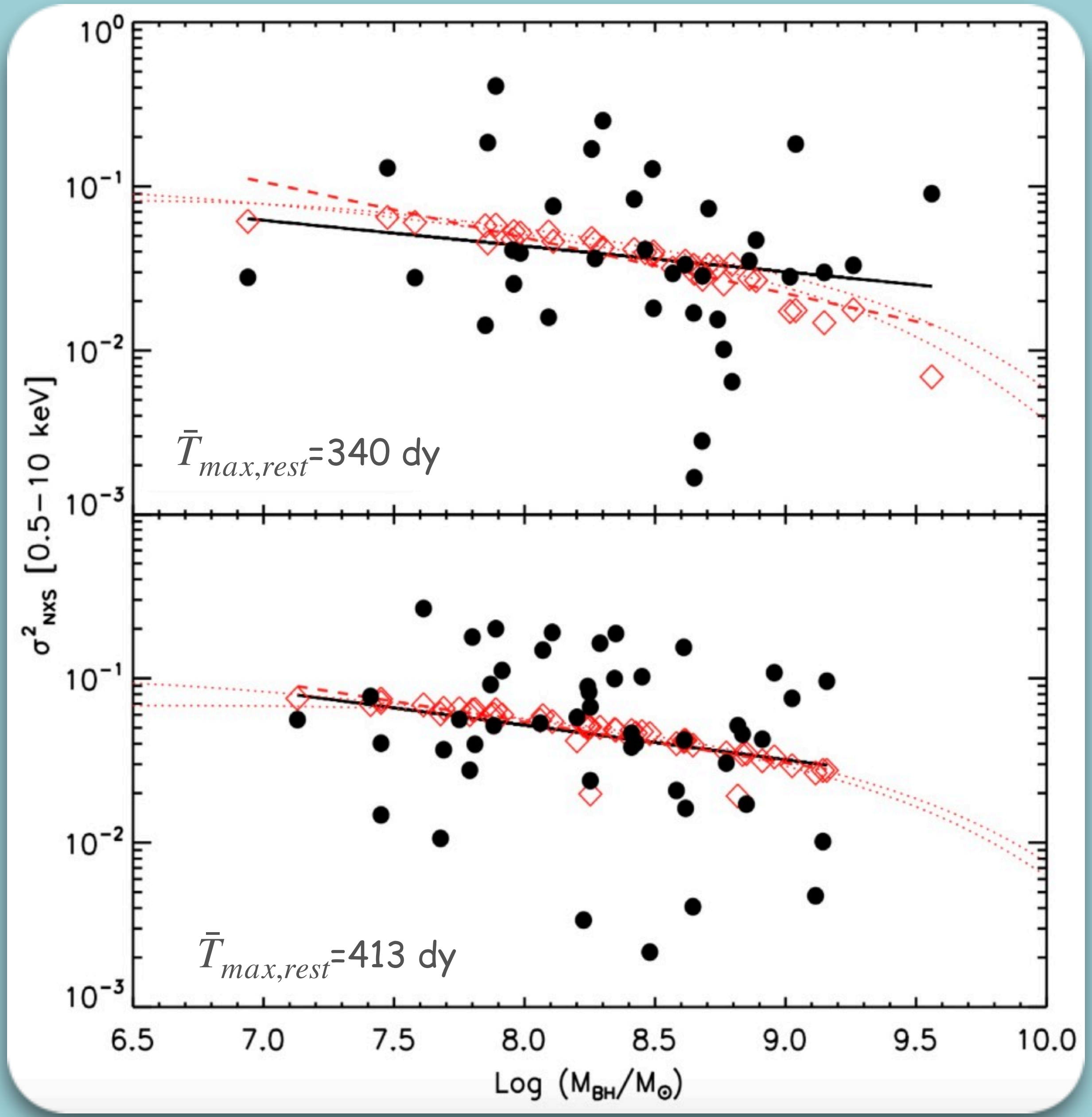
VARIANCE-MASS RELATION

- Account for different mass, redshift and sampled timescale -> normalise to a 10^8 $M_\odot$

CDFS

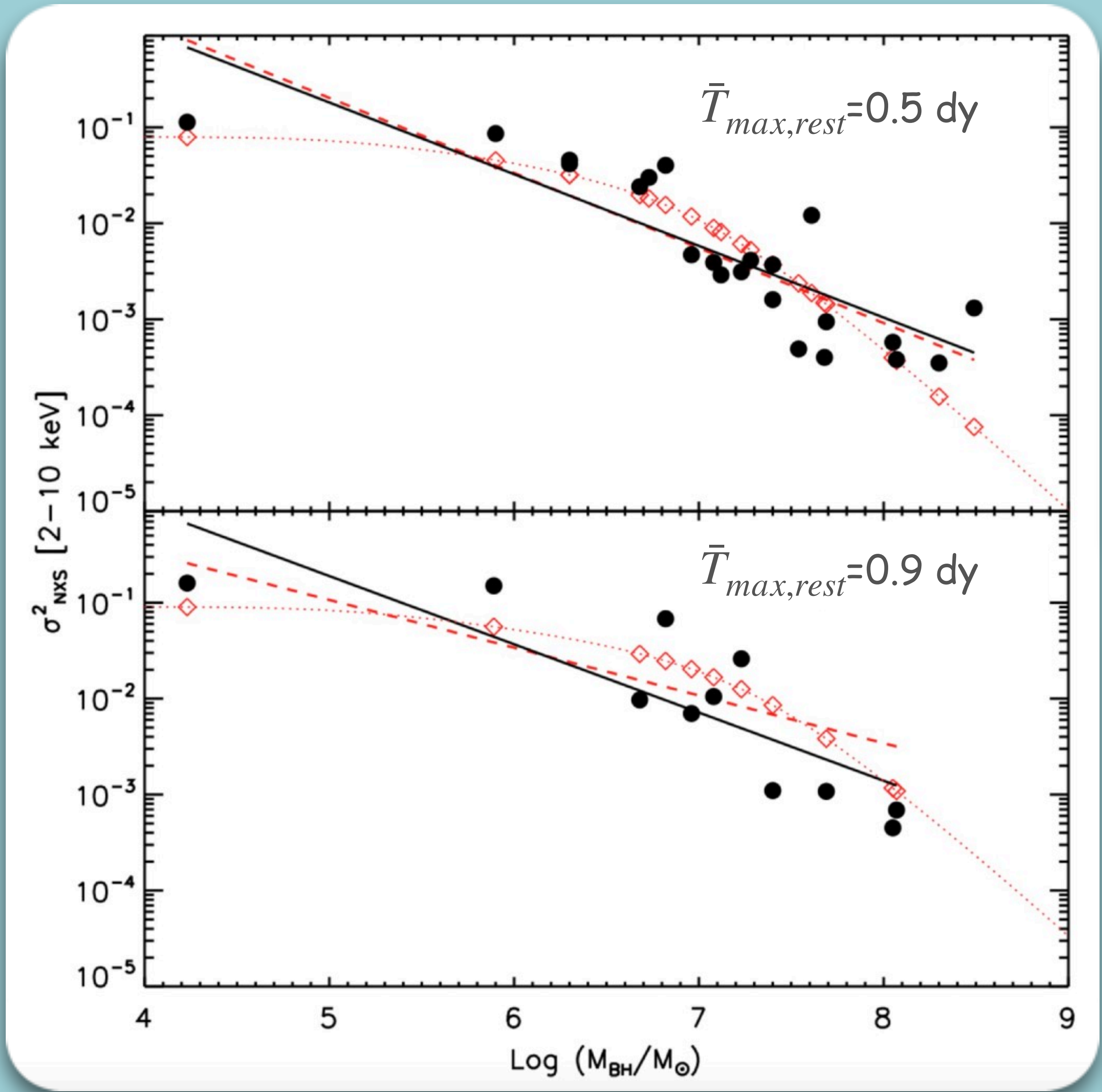


COSMOS

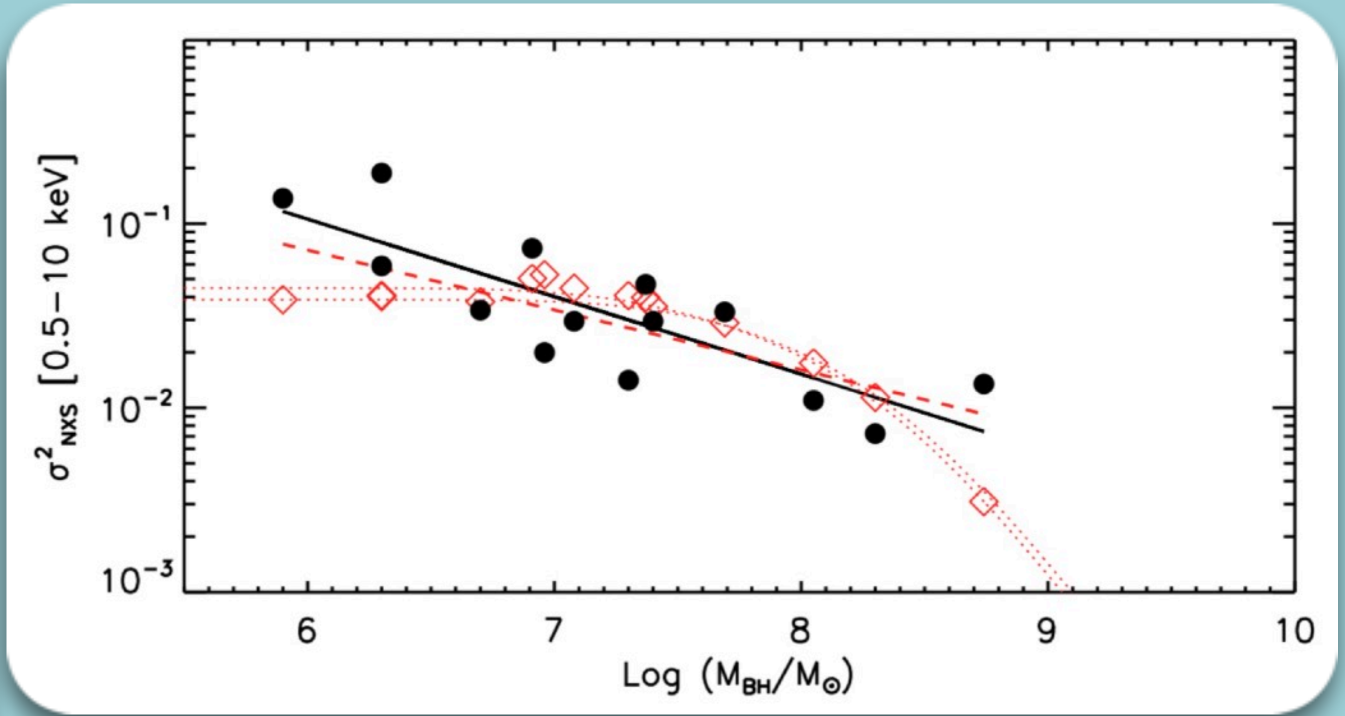


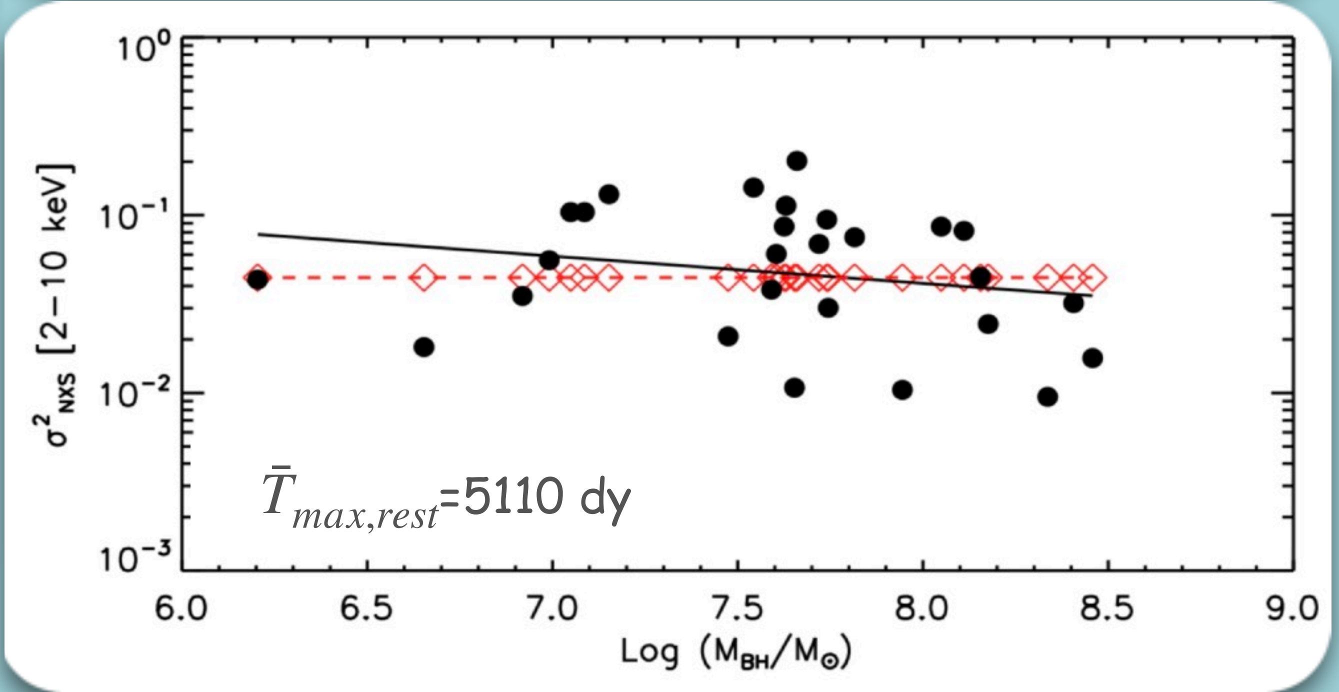
WEIGHTING BLACK-HOLES:
VARIANCE-MASS RELATION

ASCA TARTARUS+XMM CAIXA

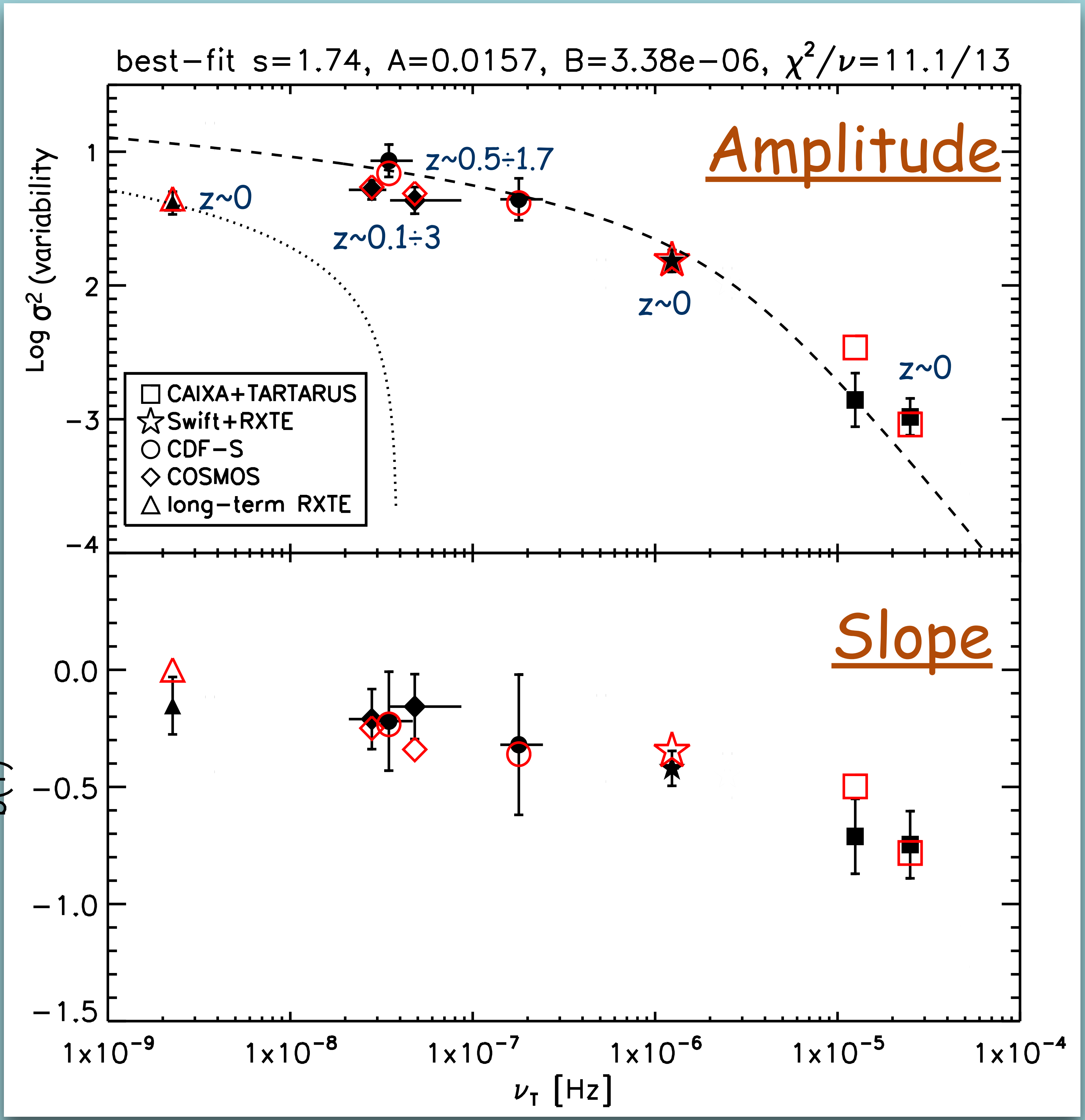


SWIFT+RXTE



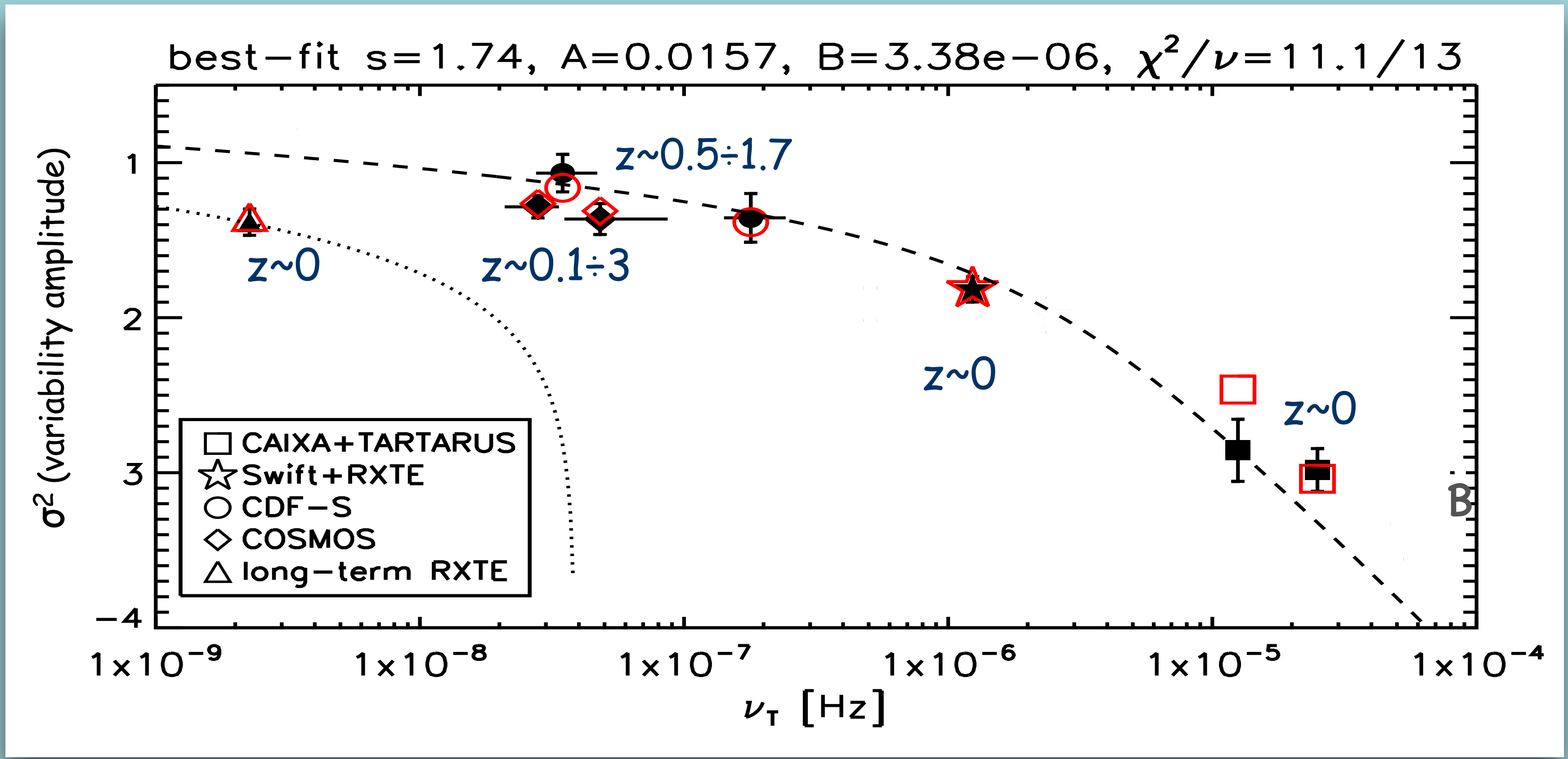


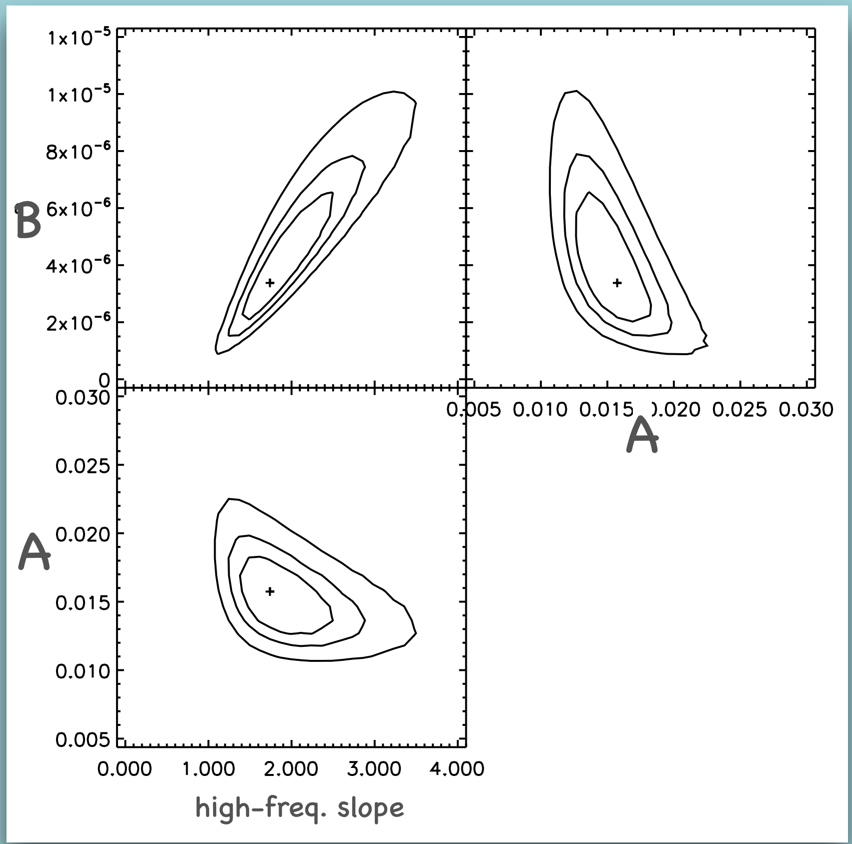
COMBINING IT ALL: THE VFP DIAGRAM OF SMBHS



- A single PSD form can fit all timescales (days to years), redshifts (0<z≲3) and masses (10^6–10^9 $M_\odot$) simultaneously
- Both amplitude and slope are reproduced!

RESULTS





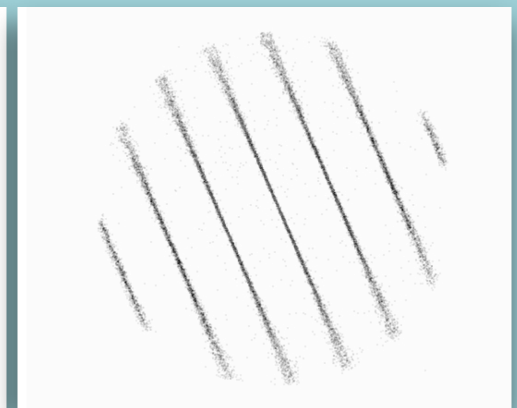
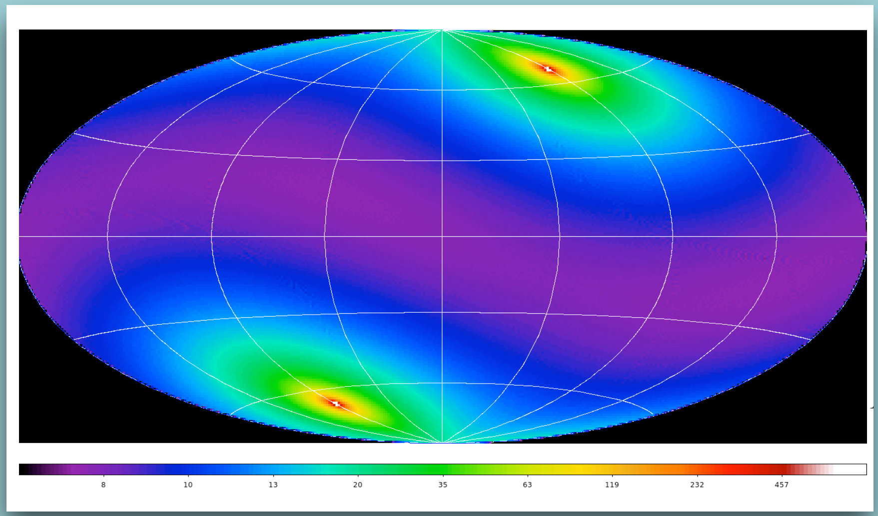
- **PSD amplitude** at the bend frequency: $\nu_b \times PSD(\nu_b) =$ $= A/2 = 0.008 \pm 0.001$ is consistent with a constant value but some dependence on accretion rate is allowed by the data.

- **PSD low frequency bend** at $\nu_b = 3.4^{+3.1}_{-1.4} \times 10^{-6} Hz$.
  This corresponds to a bend timescale of 1.8–5.8 days (90% intervals)

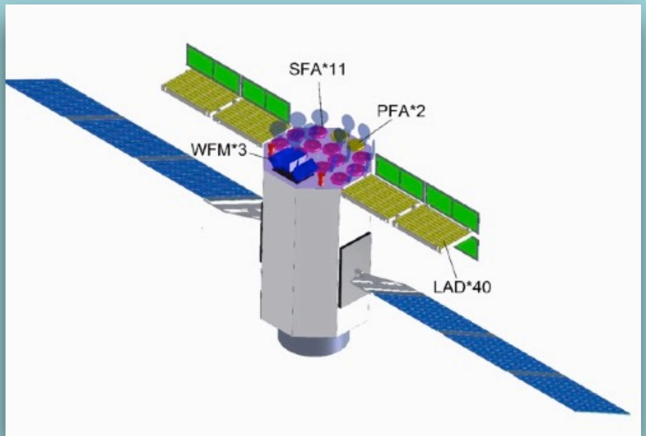
- **The high-frequency PSD slope** is -(s+1)=2.74:
  i.e. steeper than -2 usually assumed.

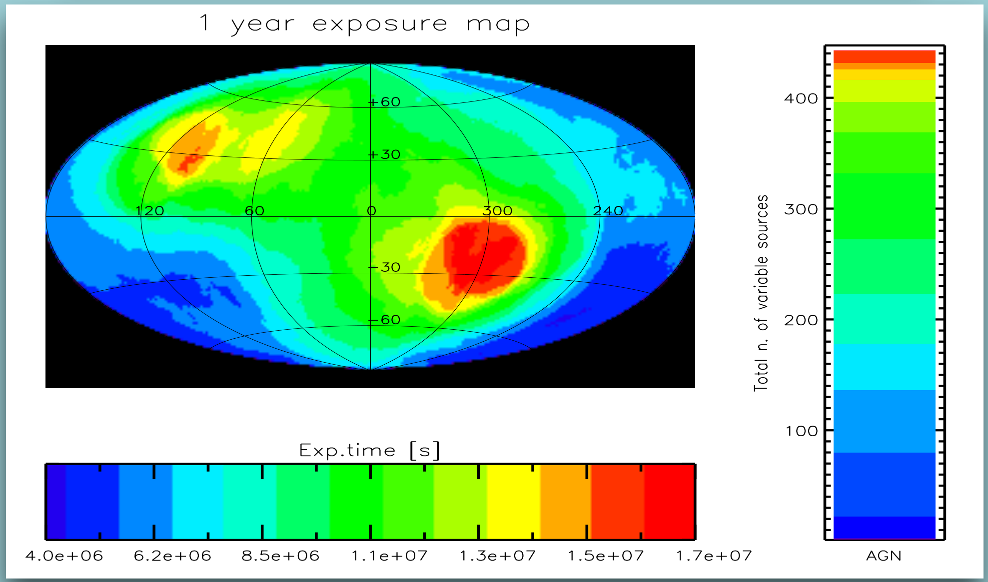
HOW TO IMPROVE? WIDE AND DEEP SURVEYS

eROSITA

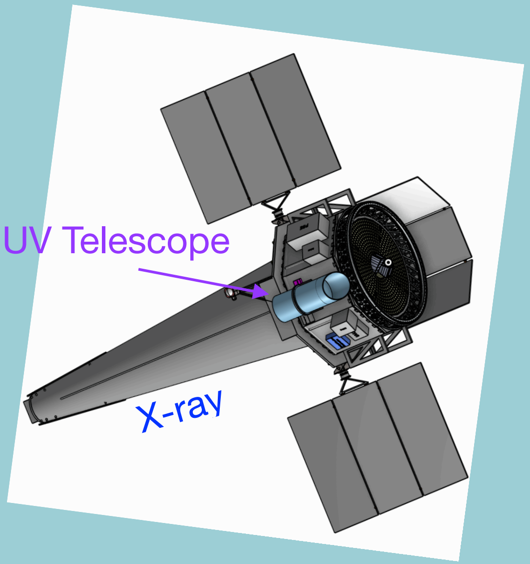




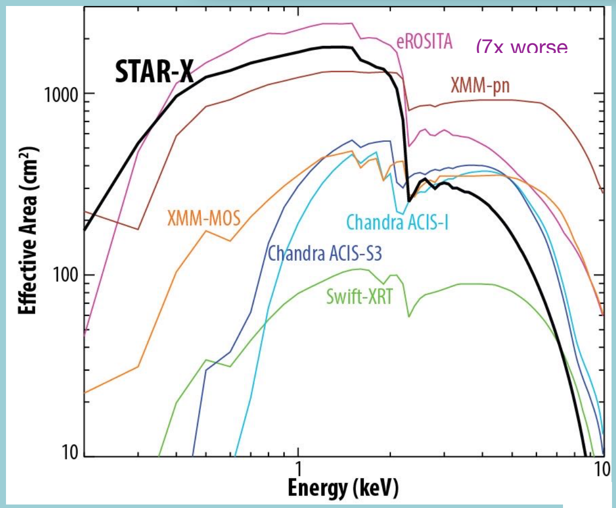
The enhanced X-ray Timing and Polarimetry mission (eXTP)

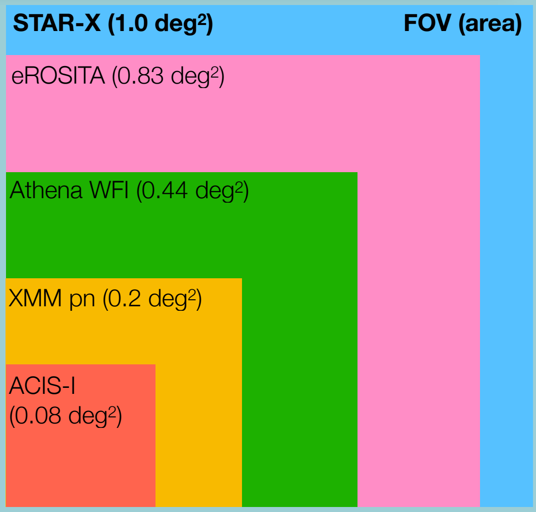




StarX (see R.Gilli talk)







But also promising applications: see A. Georgantoupoulos talk!