Insights into the Supermassive Black-Hole Accretion Process from X-ray and Optical Time-Domain Surveys

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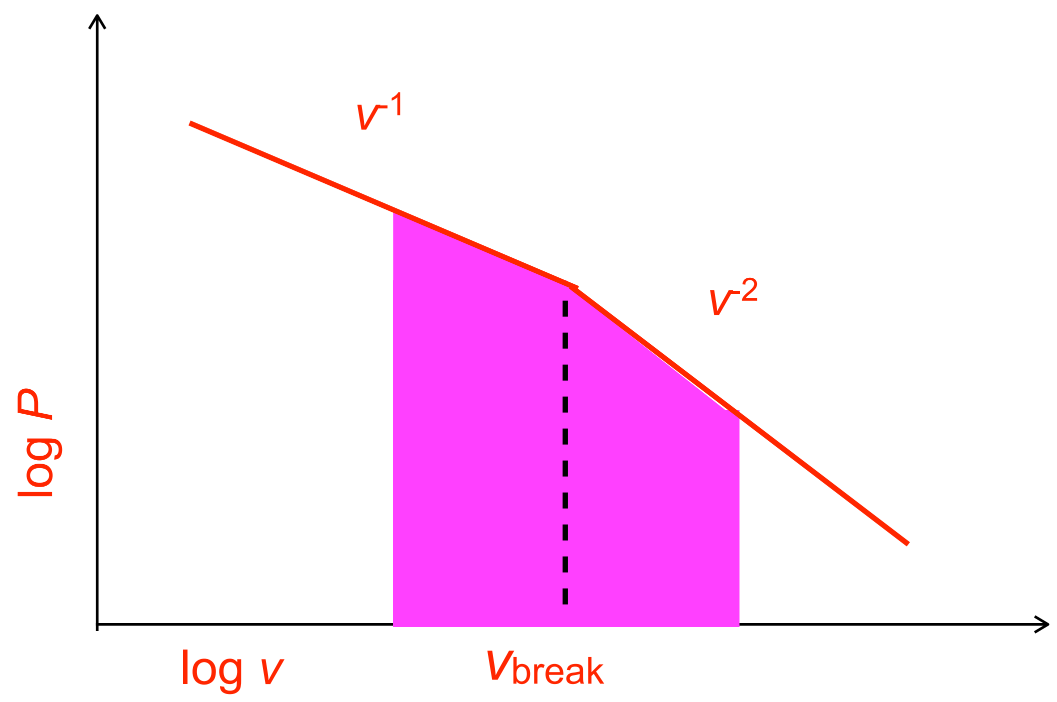
Part I

AGN Variability in X-ray Surveys

Why X-ray?

X-ray variations are typically faster and stronger relative to those in the optical.
X-ray monitoring: more efficient for studying continuum variations in distant AGN.

X-ray variability depends on L and $M_{\rm BH}$ in a complicated way.



$$\mathrm{PSD}(\nu) = A\nu^{-1}\left(1+\frac{\nu}{\nu_{\rm b}}\right)^{-1}$$

$$\nu_{\rm break} \propto \frac{\eta(L/L_{\rm Edd})}{M_{\rm BH}}$$

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

Broken (or bending) power-law model for the power spectral density (PSD) of AGN X-ray variability; analogous to X-ray binaries (e.g., Markowitz et al. 2003; Done & Gierliński 2005; McHardy 2006). The PSD normalization may depend on $L/L_{\rm Edd}$ (e.g., Ponti et al. 2012).

What we measure is the **Excess Variance** (e.g., Nandra et al. 1997; Turner et al. 1999):

$$\sigma_{\rm rms}^2 = \frac{1}{N_{\rm obs}\langle f\rangle^2}\sum_{i=1}^{N_{\rm obs}}\left[(f_i-\langle f\rangle)^2-\sigma_i^2\right]$$

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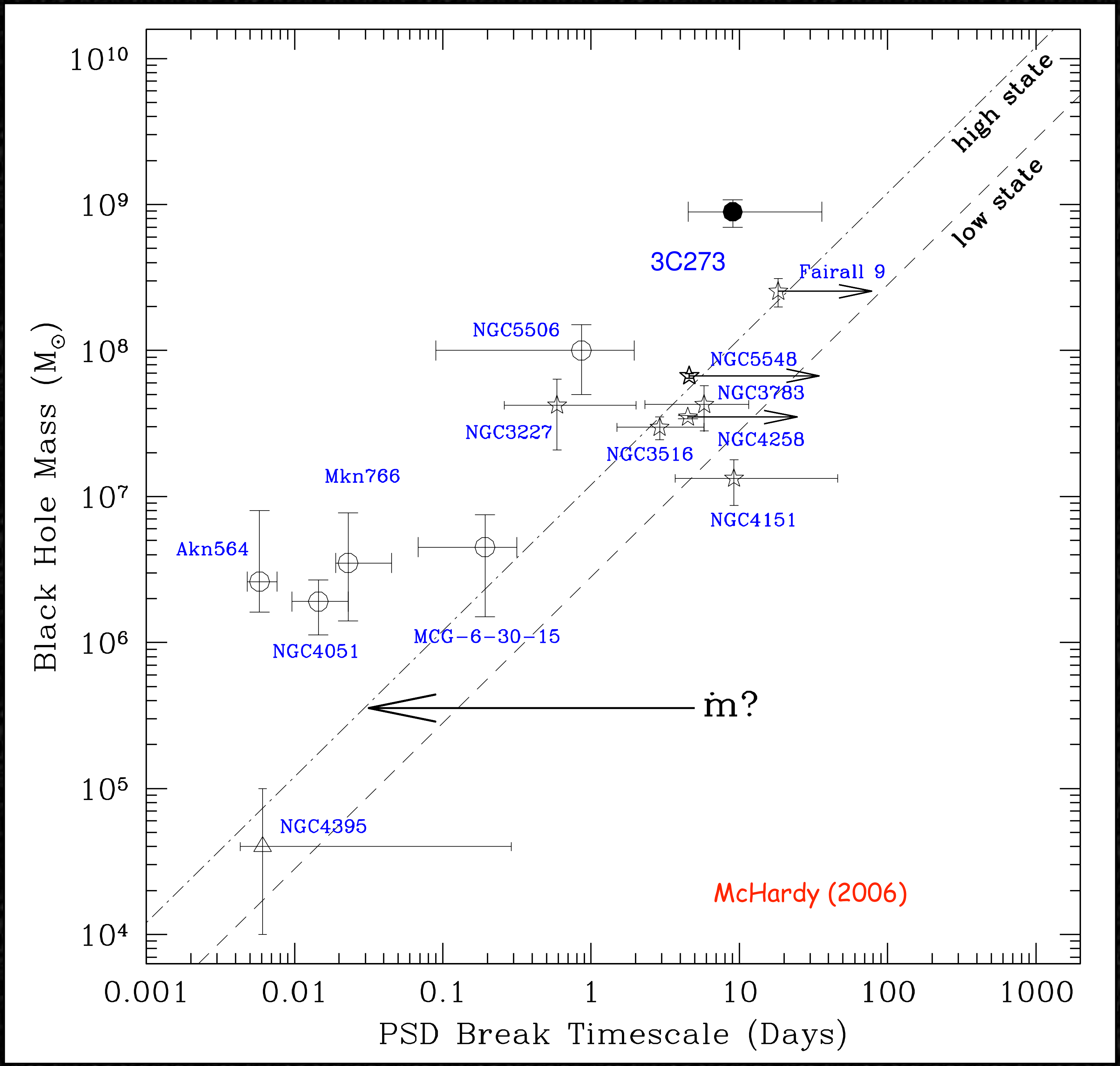
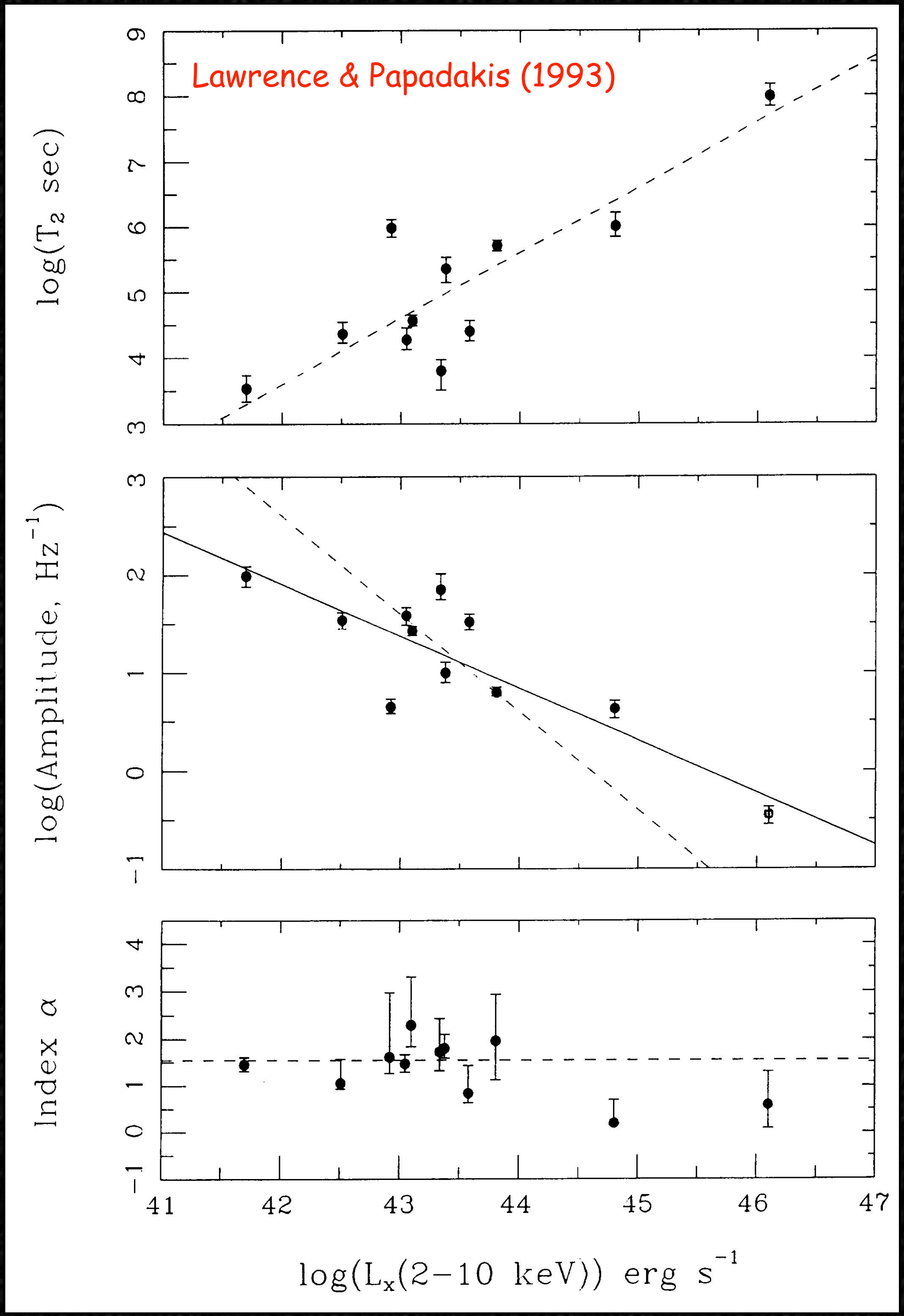
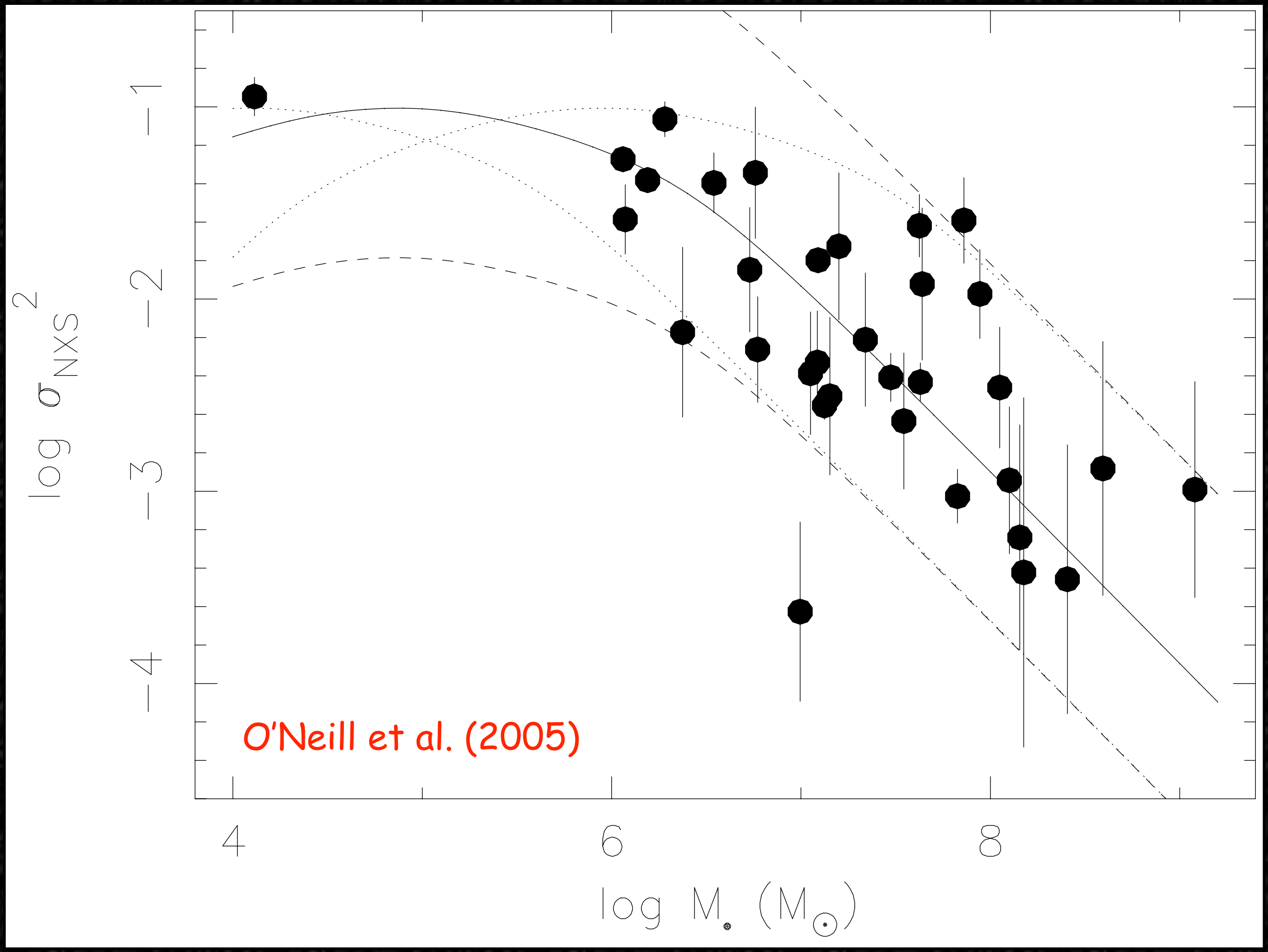


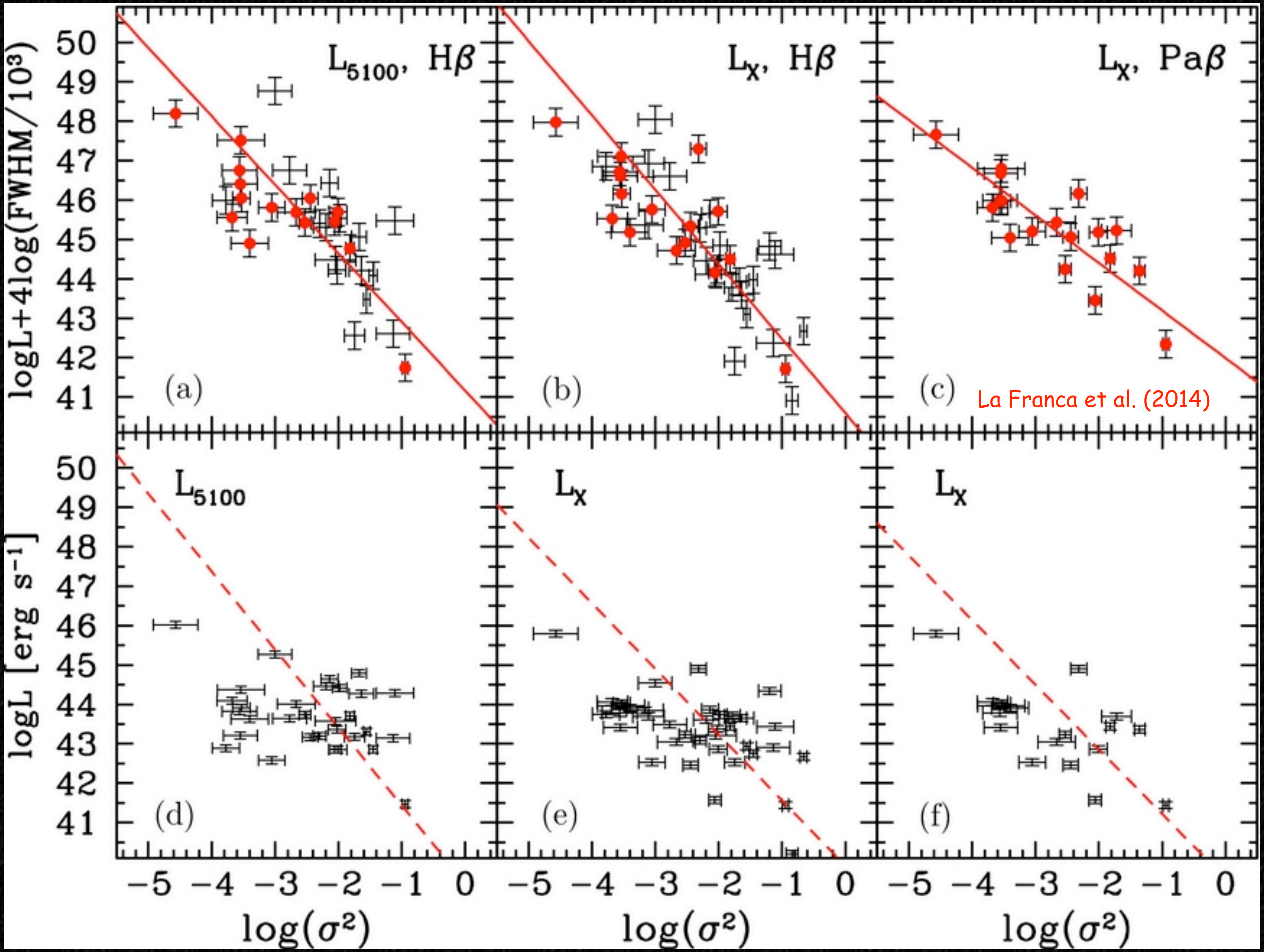
X-ray Variability Dependence on L, M_{BH}





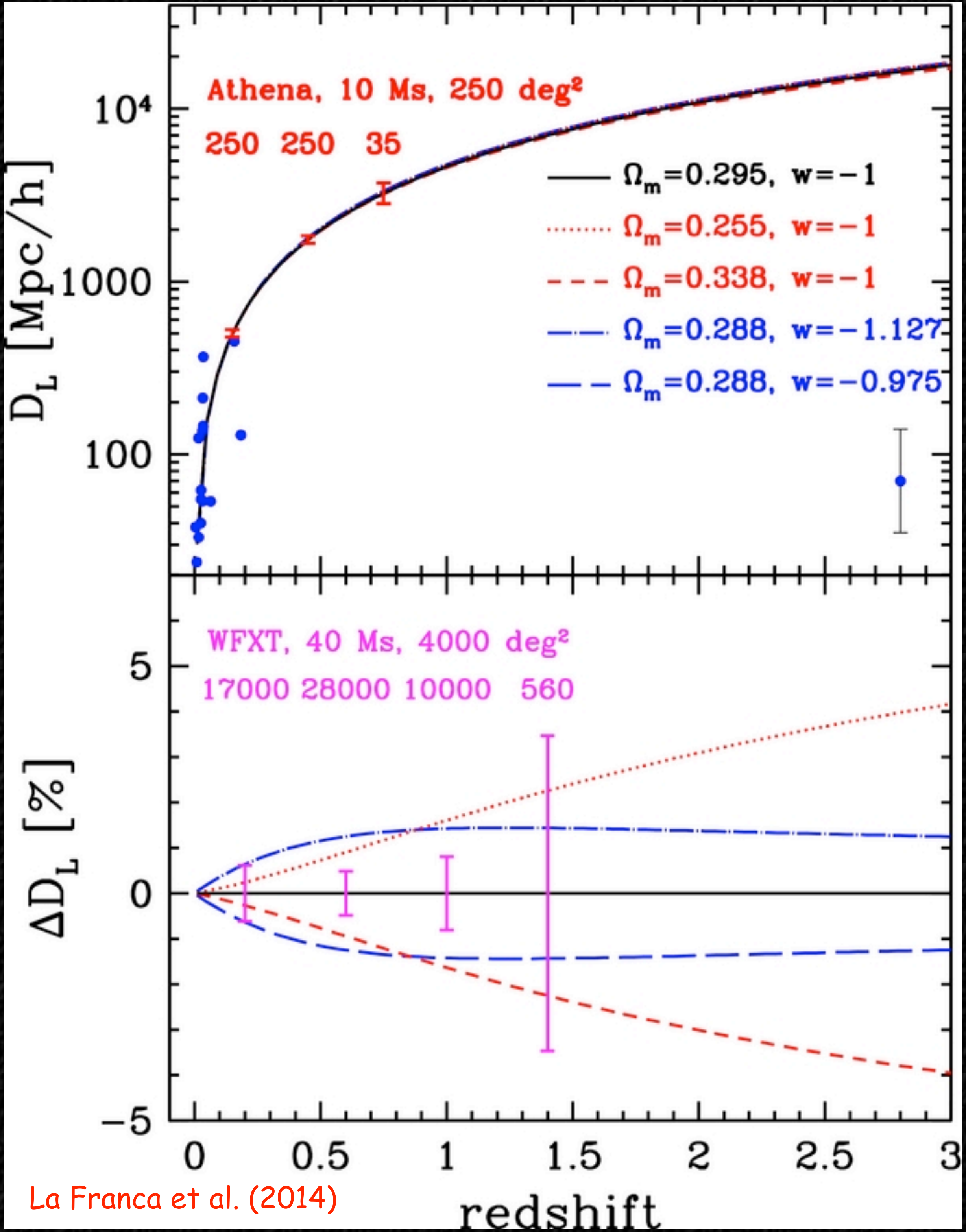
Luminous AGN show milder and slower X-ray variations with respect to lower luminosity sources. Primary driver could be M_{BH}.

X-ray Variability as a Cosmological Probe?



The hope is to use X-ray variability as a luminosity/distance indicator

X-ray Variability as a Cosmological Probe?



La Franca et al. (2014)

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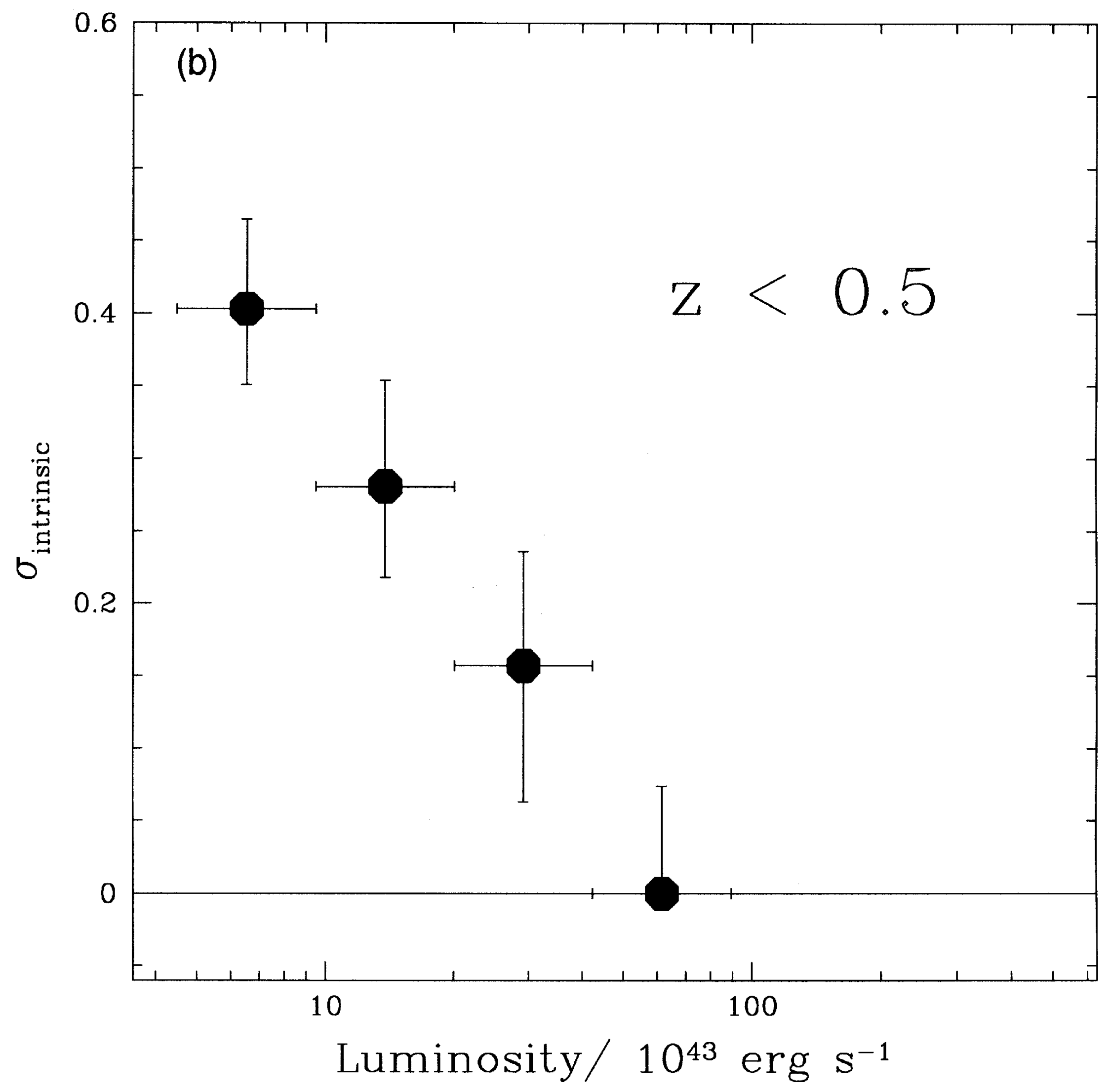
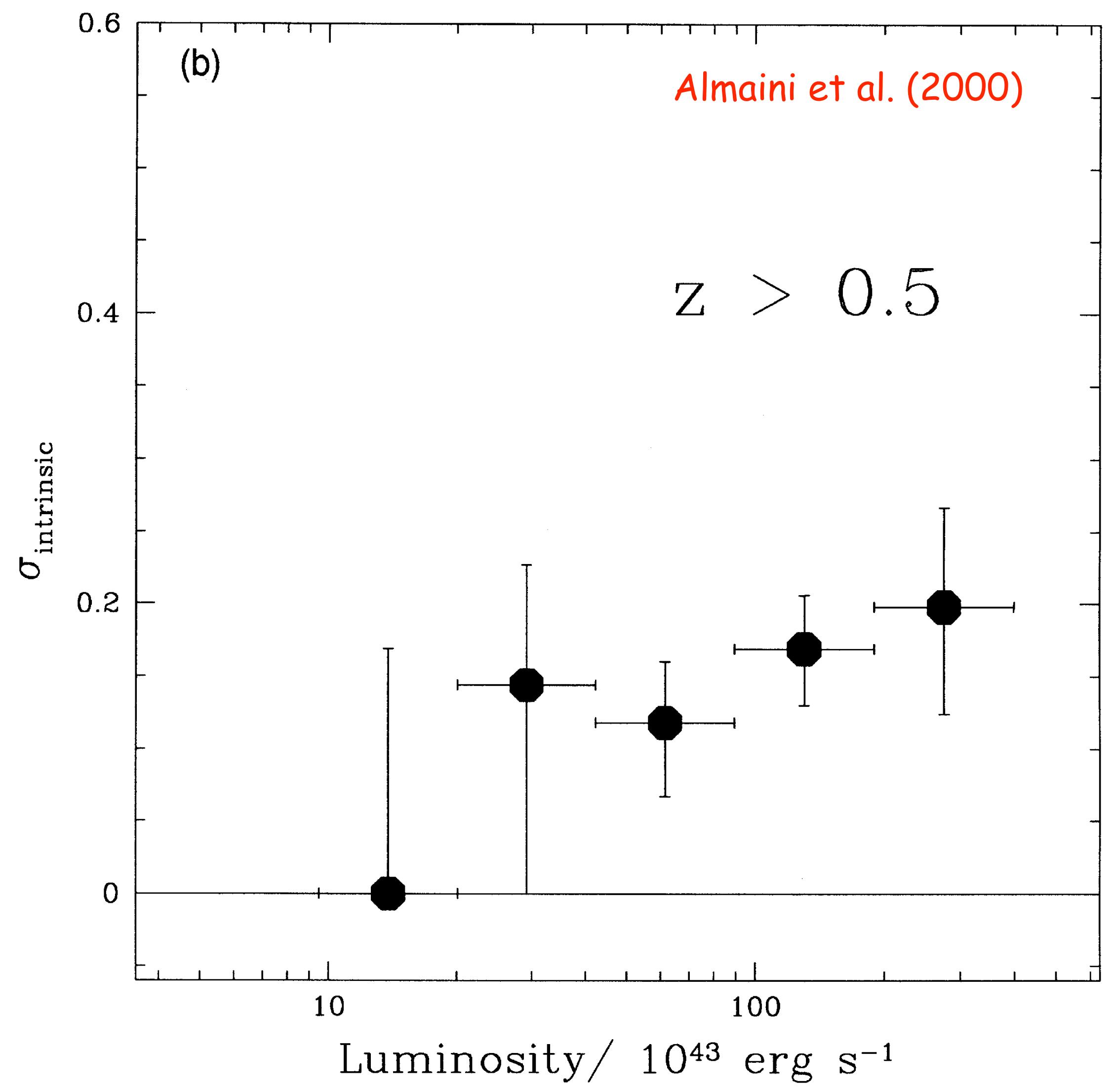
Were Quasars More X-ray Variable in the Early Universe?

Early, tentative indications for increased X-ray variability at high redshift:





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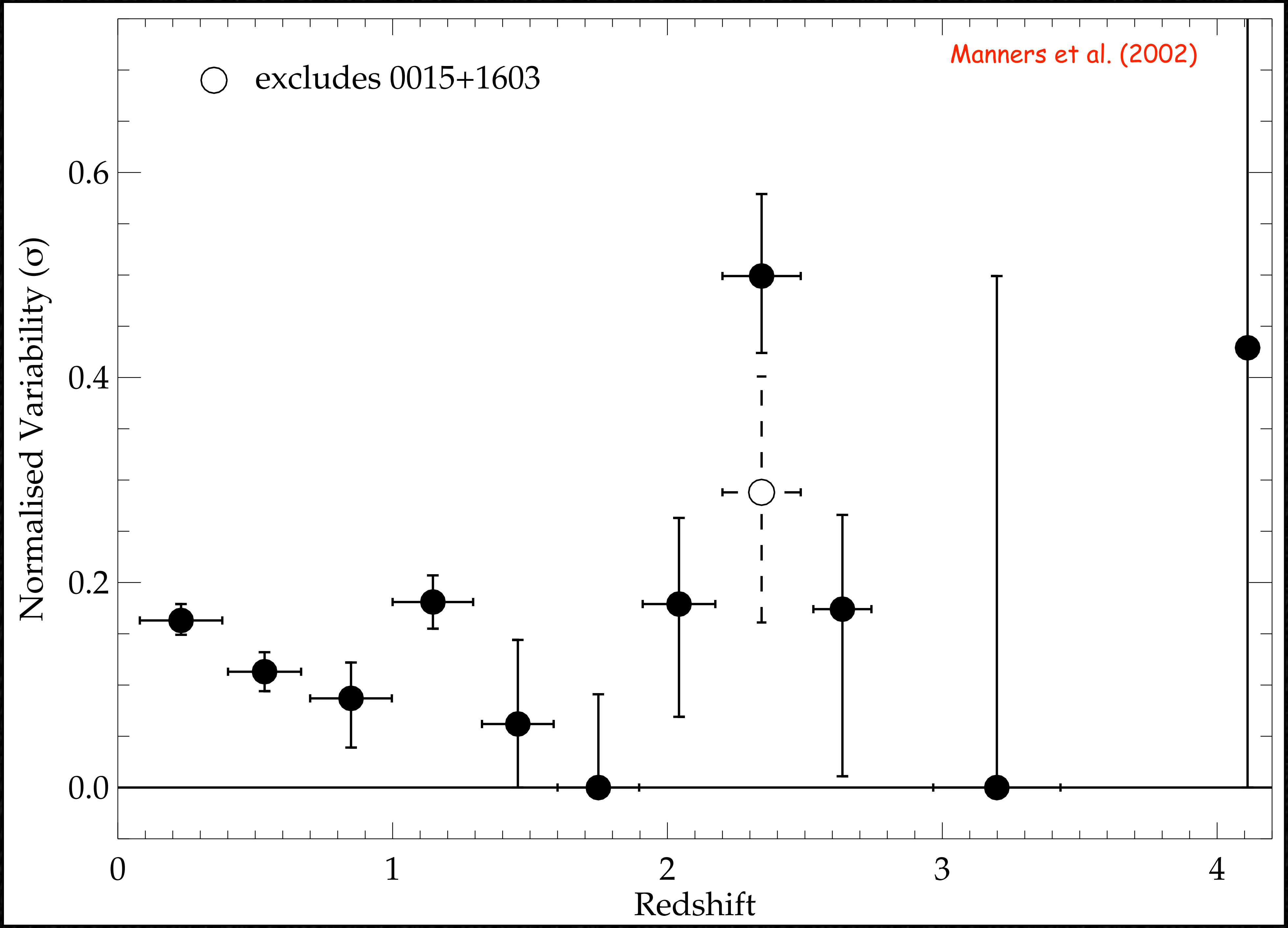

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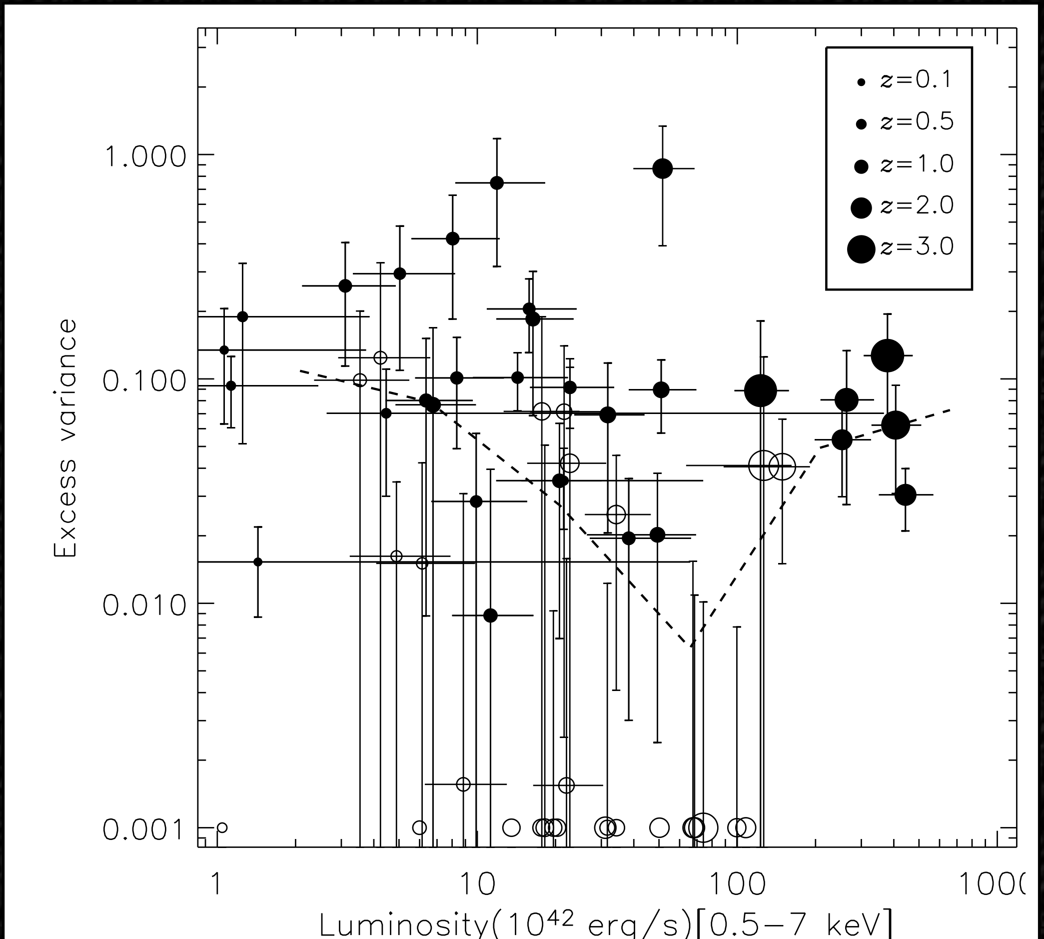


Paolillo et al. (2004)

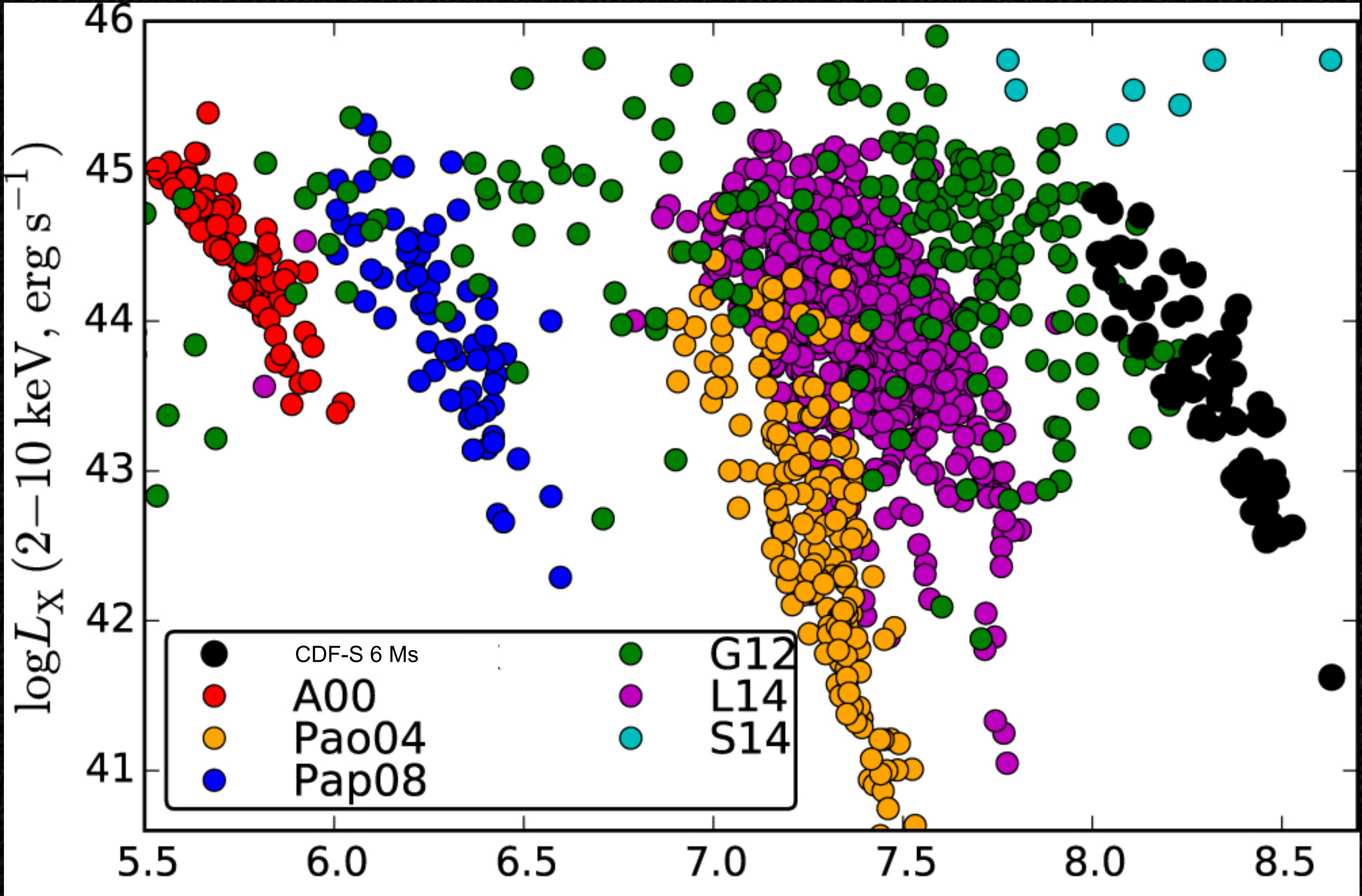
Perplexing result, leading to conflicting interpretations (e.g., Papadakis et al. 2008; Ponti et al. 2012; Lanzuisi et al. 2014). Mainly because:

- ✳ distant AGN are more luminous (and thus have larger central engines) → their X-ray variations are expected to be slower and suppressed.
- ✳ AGN X-ray spectral properties have not evolved significantly.

If real, may indicate evolution of:

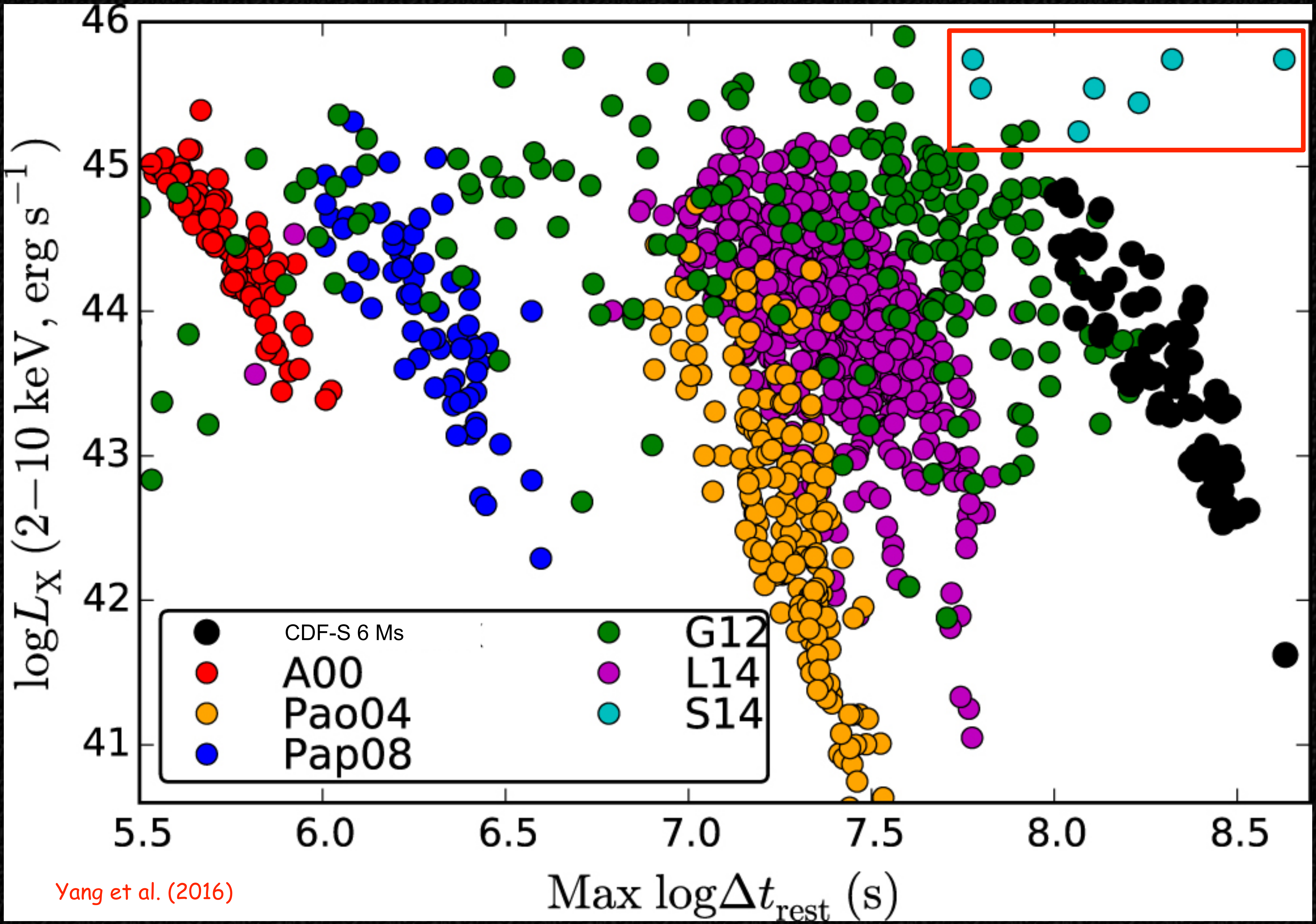
- ✳ The X-ray variability mechanism
- ✳ The X-ray emitting region size
- ✳ The accretion rate/mode/efficiency

Insights from X-ray Surveys



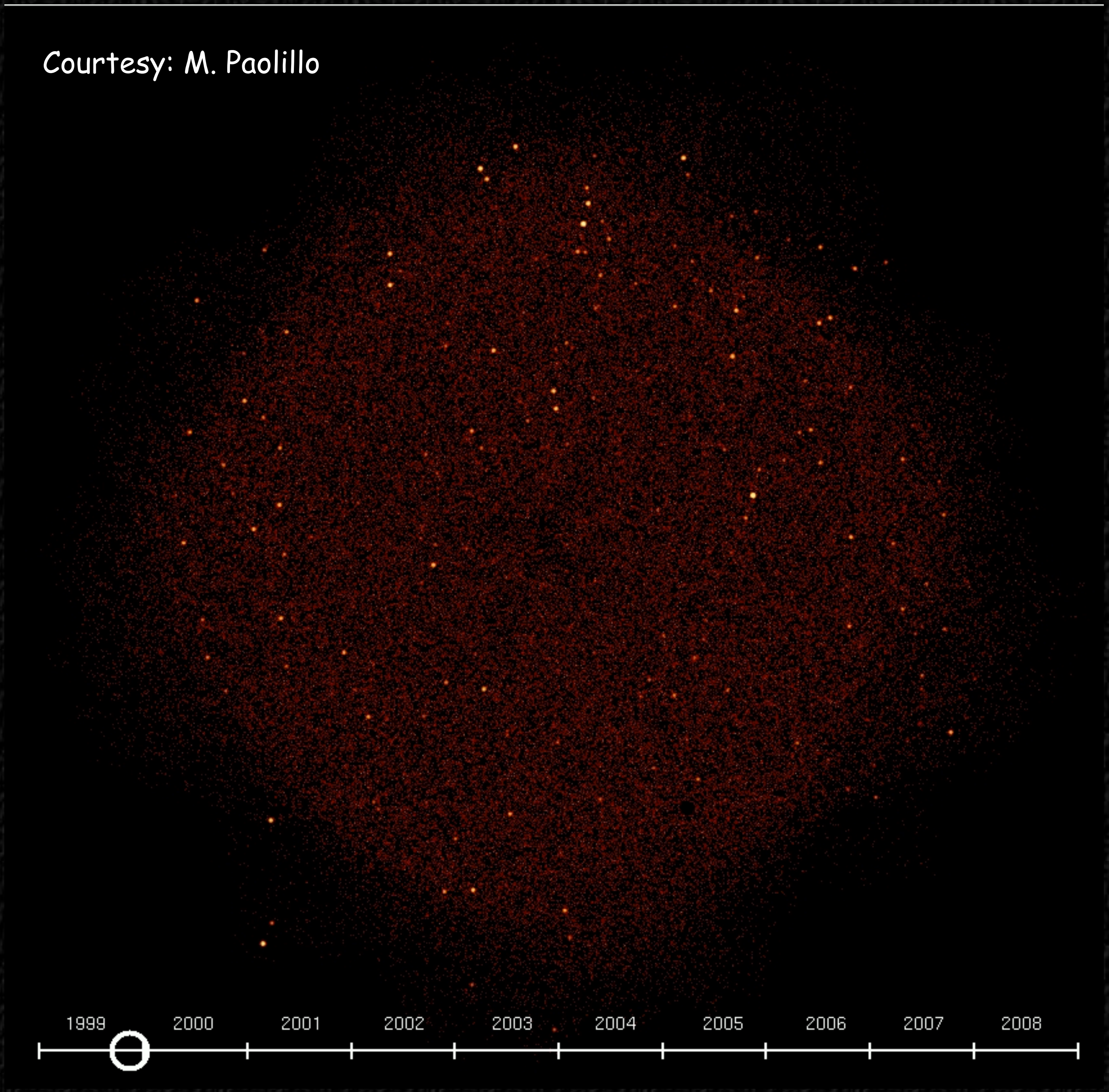
Yang et al. (2016)

Insights from X-ray Surveys



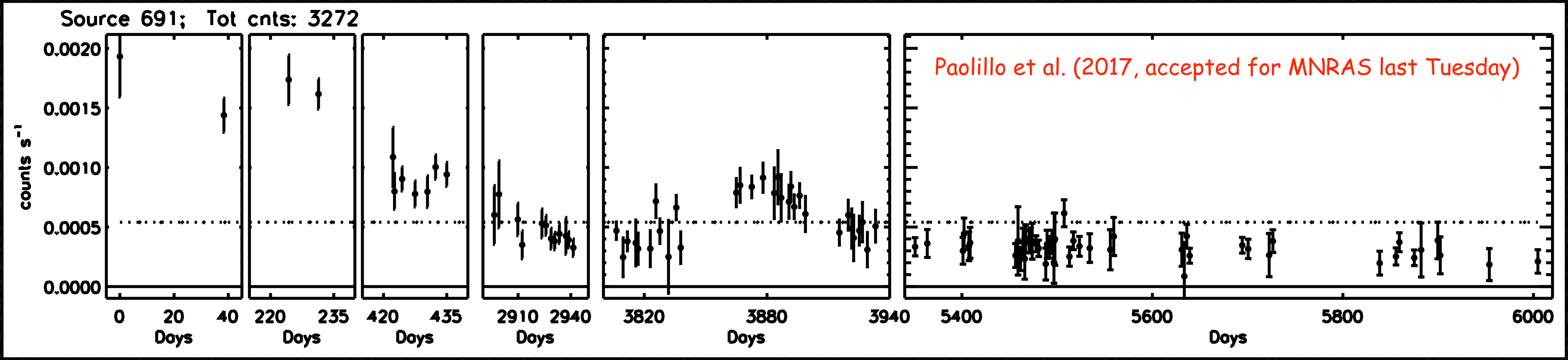
Yang et al. (2016)

Insights from the Deepest X-ray Survey



The *Chandra* Deep Field-South: 7 Ms exposure covering 17 years; ~1000 X-ray sources (Luo et al. 2017).

Insights from the Deepest X-ray Survey

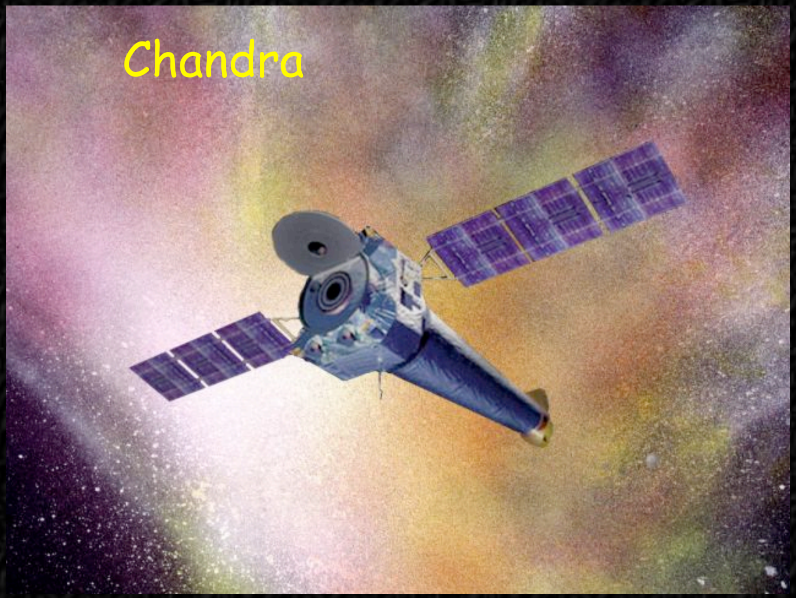


1. Flux-limited survey: low-L (low-$L/L_{\rm Edd}$) sources underrepresented at high redshift.
2. Fixed temporal baseline: high-redshift sources not probed sufficiently long (e.g., Papadakis et al. 2008).

X-ray Monitoring of Luminous Distant Quasars

Need a complementary approach to the survey strategy:

Long-term X-ray monitoring of a carefully-selected sample of luminous radio-quiet quasars (RQQs) at high redshift while breaking the strong *L*-*z* dependence.



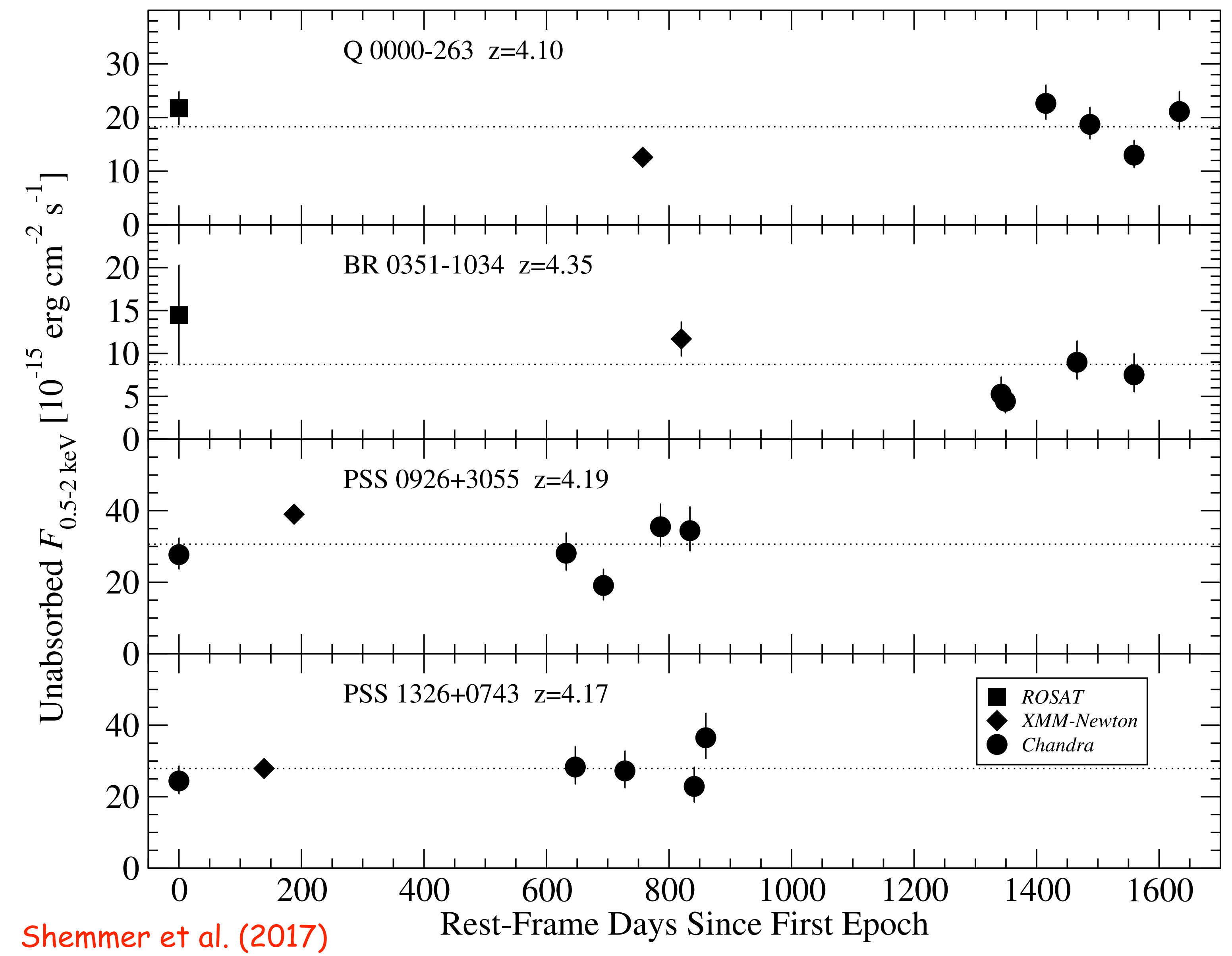
log $L_x \sim 46$

Four RQQs at $z \sim 4.2$

Three RQQs at $z \sim 1.3 - 2.7$

X-ray Monitoring of Luminous Distant Quasars

Long-term X-ray monitoring of a carefully-selected sample of luminous RQQs at high redshift while breaking the strong *L*-*z* dependence.



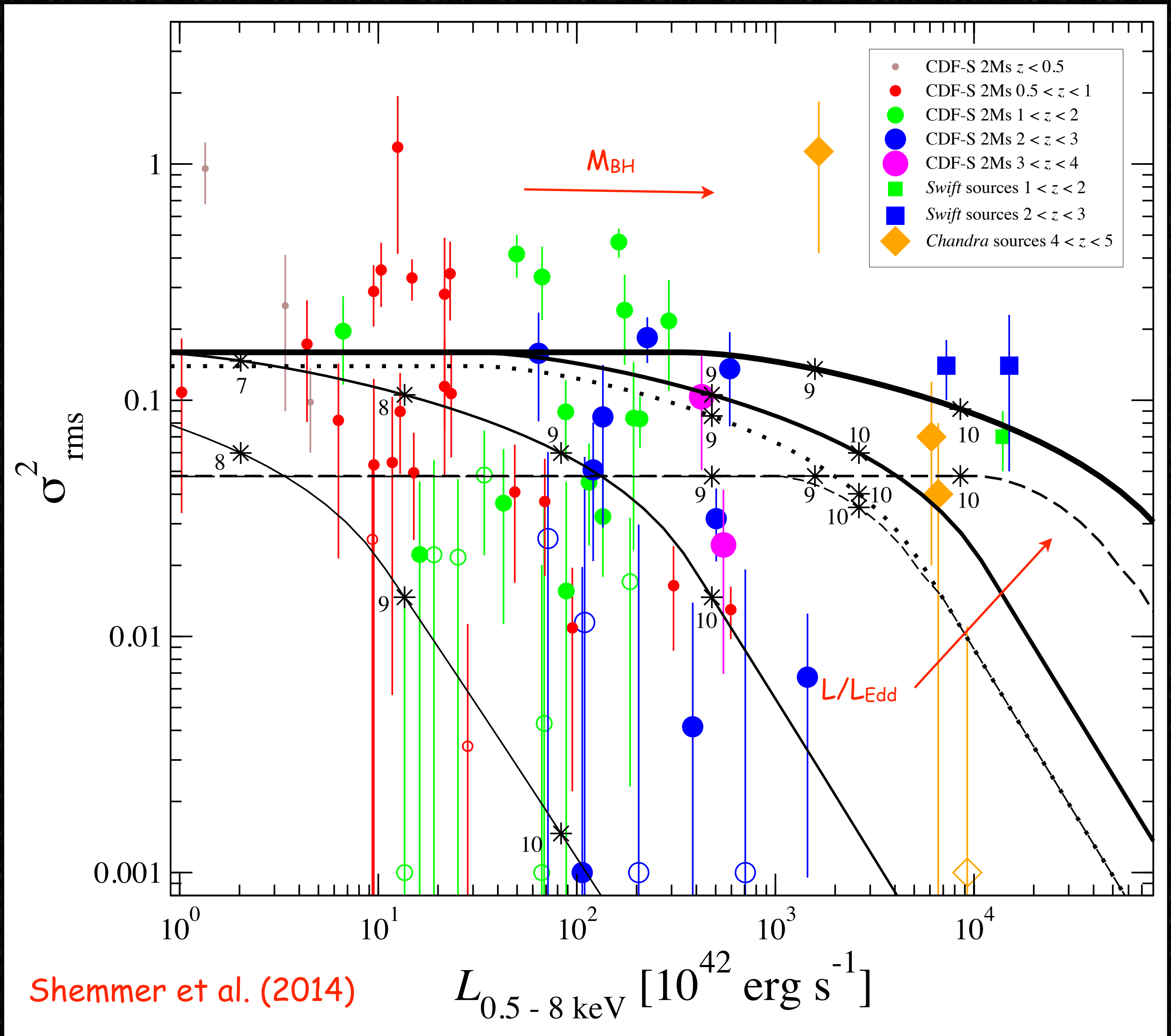
Shemmer et al. (2017)

X-ray light curves of RQQs at $z \sim 4.2$
(continued *Chandra* monitoring during Cycles 19 - 21)

X-ray Monitoring of Luminous Distant Quasars

Long-term X-ray monitoring of a carefully-selected sample of luminous RQQs at high redshift while breaking the strong *L*-*z* dependence.

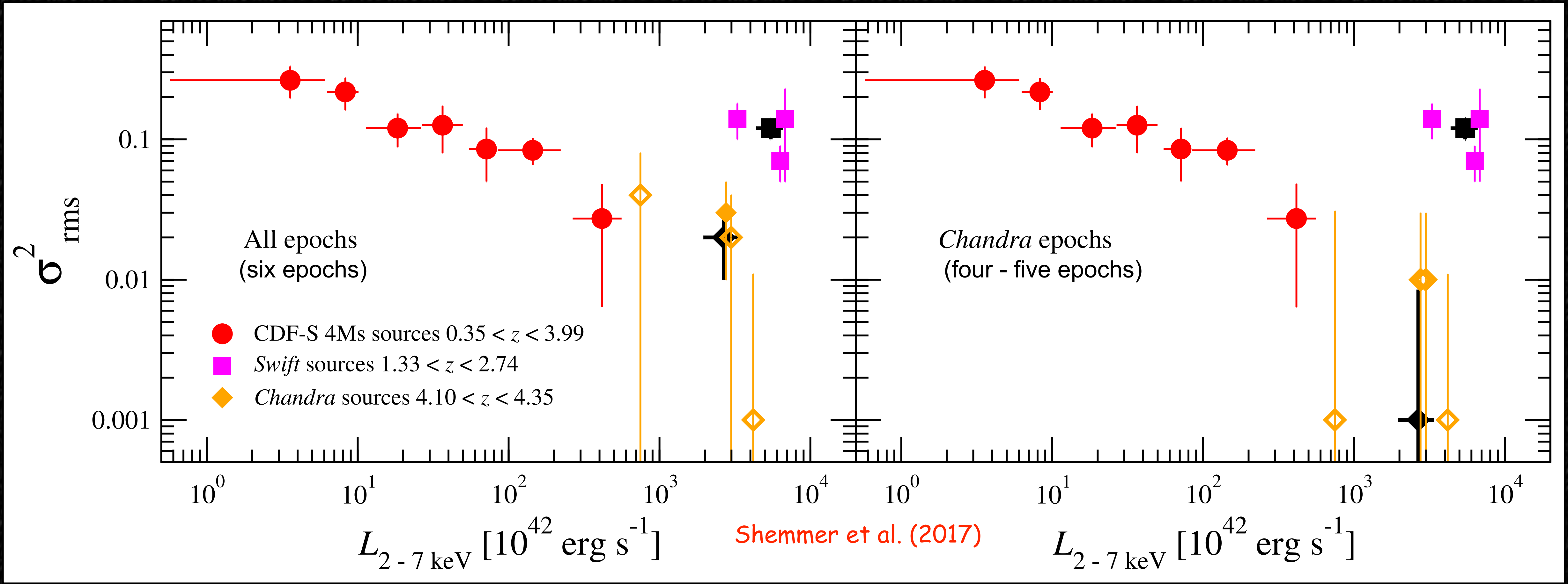
Comparison between: entire light curves of the *z* ~ 1.3 - 2.7 sources, four-epoch light curves of the *z* ~ 4.2 sources, and the *Chandra* Deep Field-South 2 Ms exposure.



Extended the *Chandra* Deep Field-South parameter space by $\Delta z \sim 1$ and by an order of magnitude in *L*

X-ray Monitoring of Luminous Distant Quasars

Comparisons with the *Chandra* Deep Field-South 4 Ms exposure.



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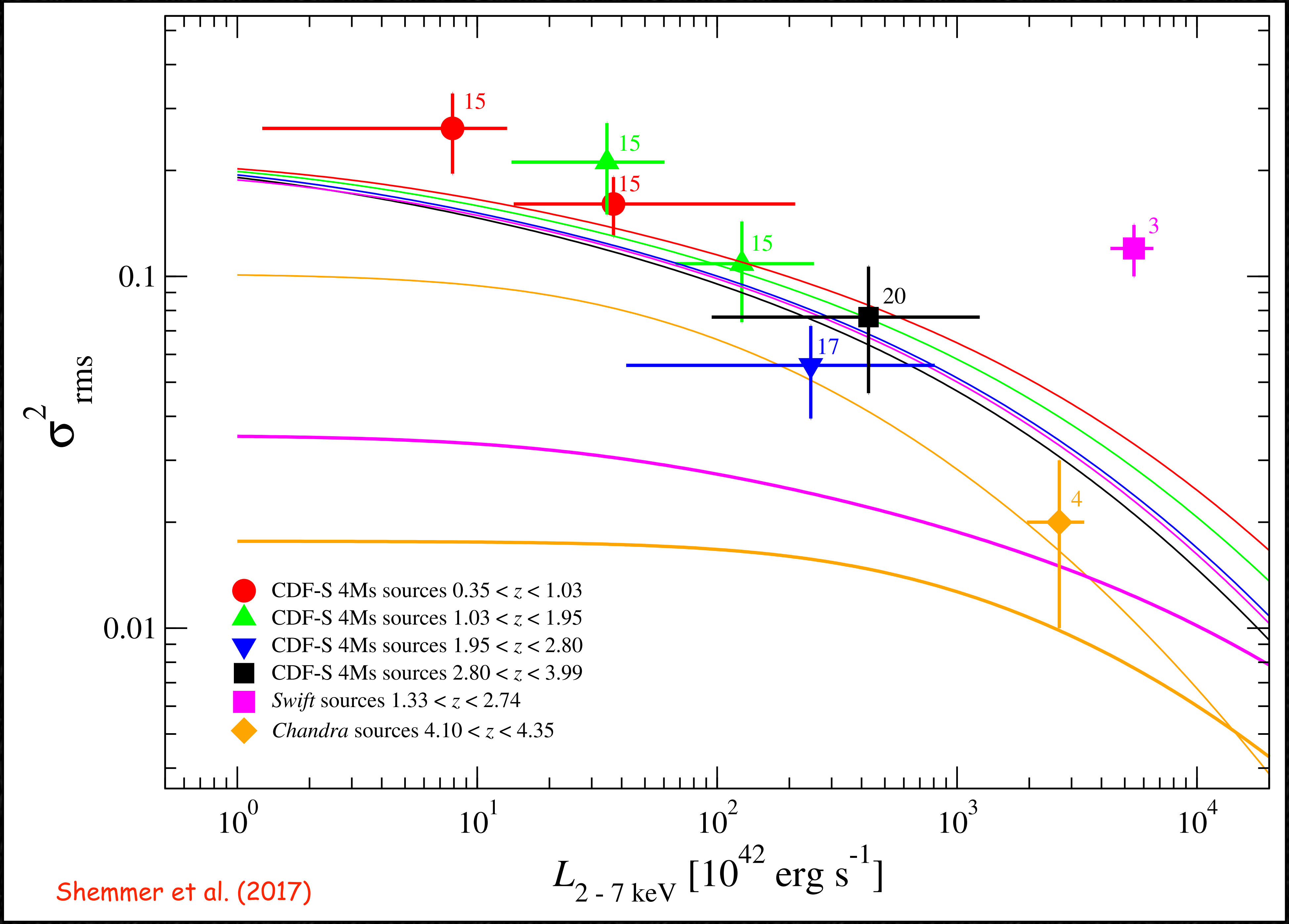
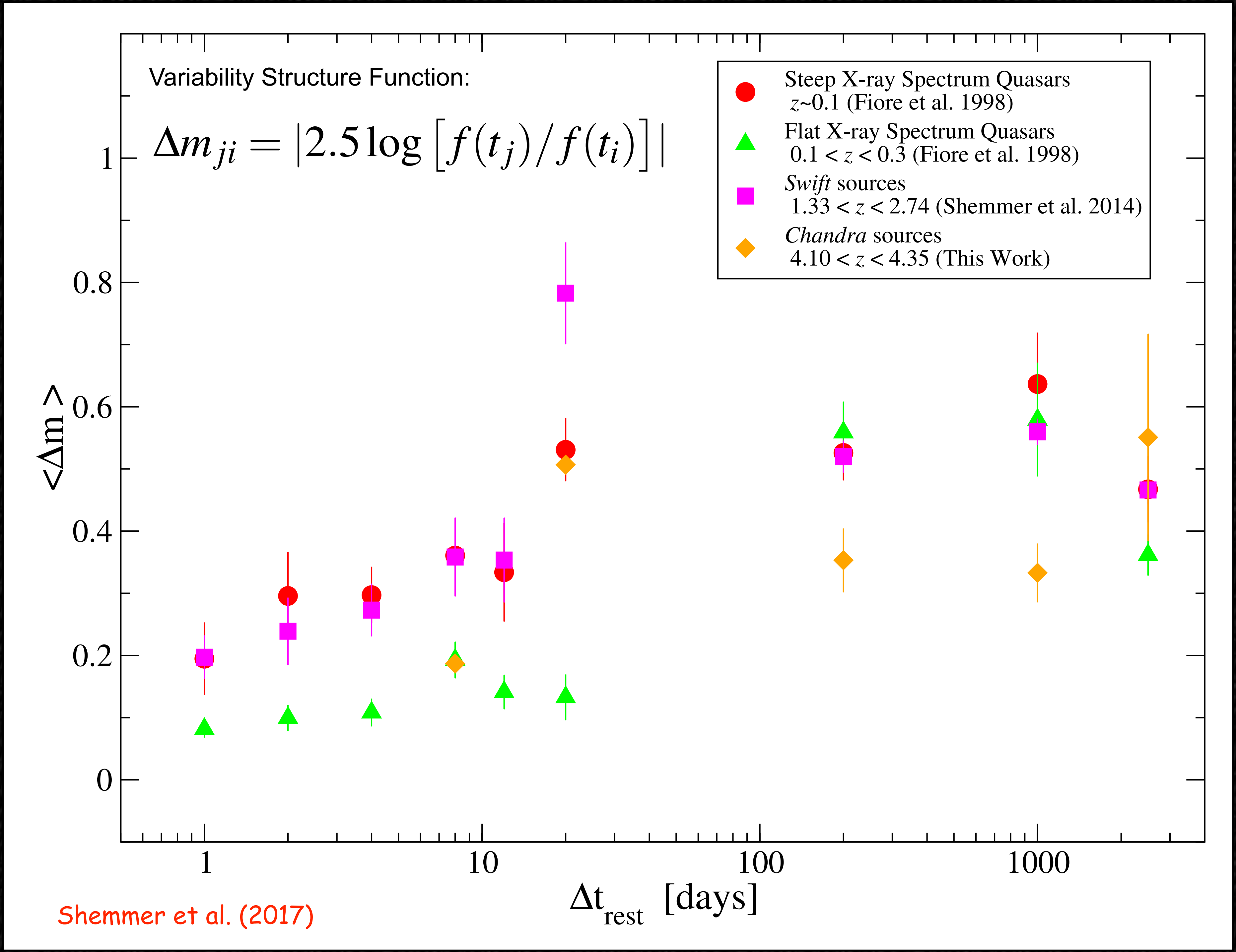


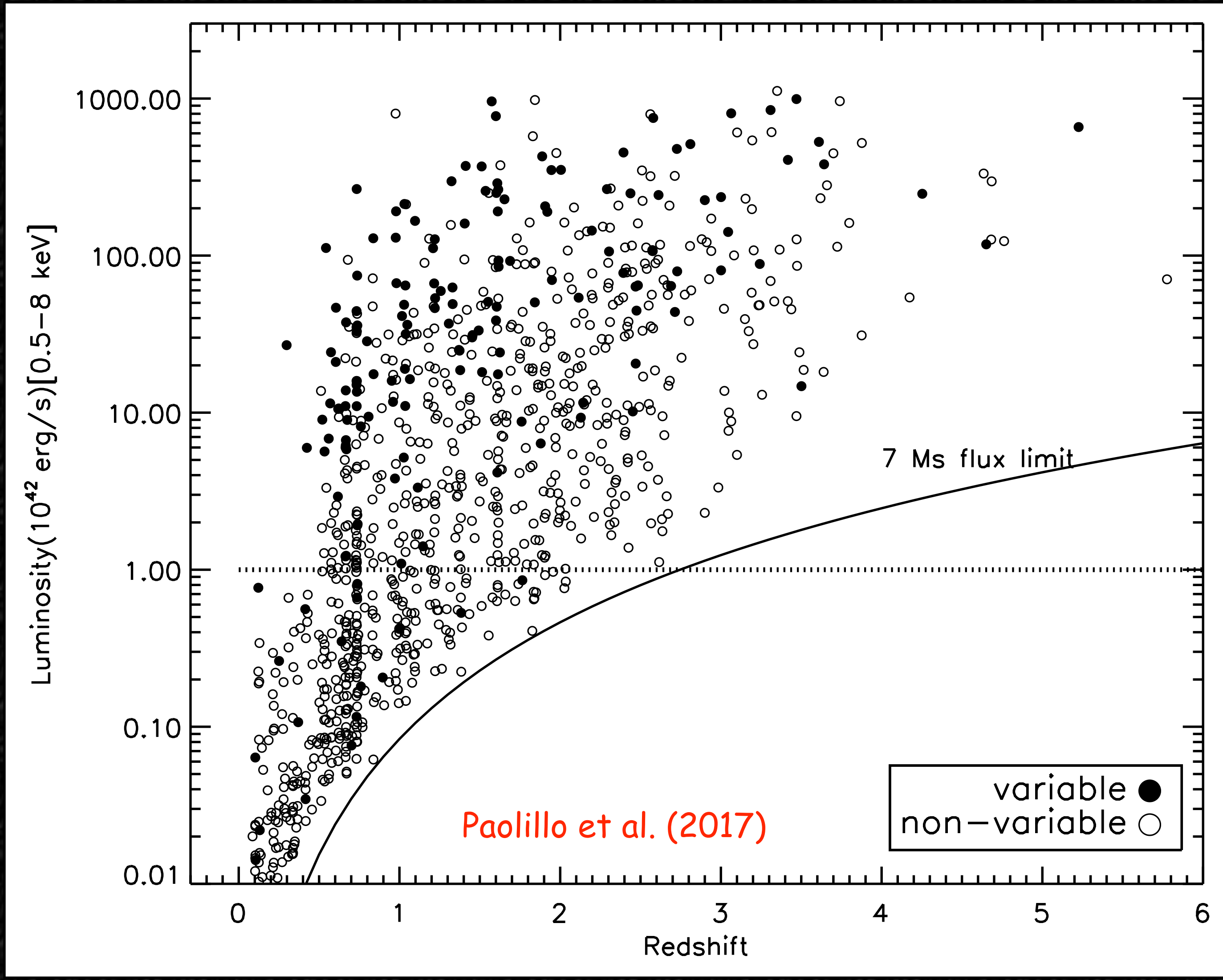
X-ray variability: no evidence for evolution; complex dependence on L/L_{Edd}.

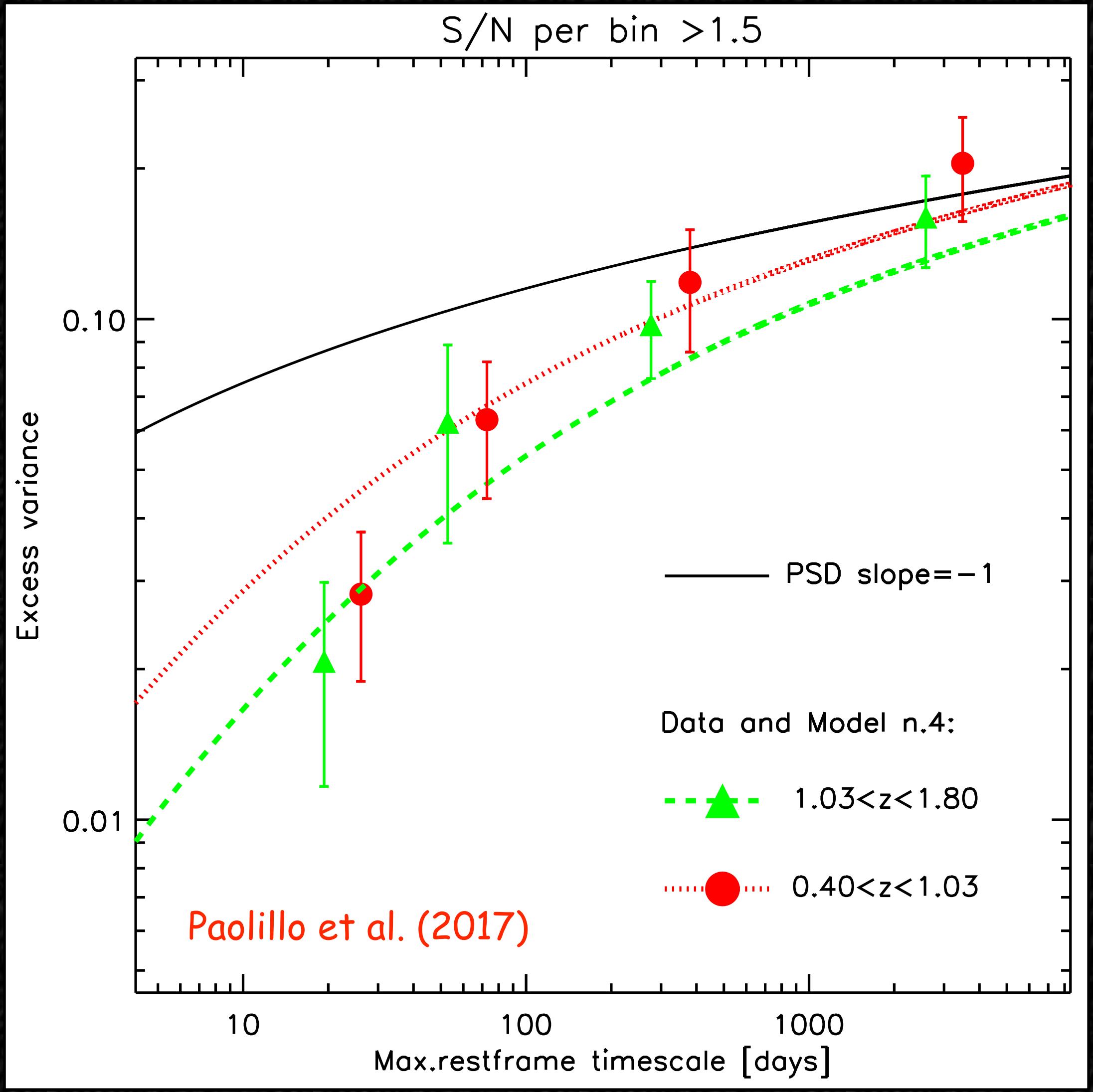
X-ray Monitoring of Luminous Distant Quasars



Structure function of luminous, high-redshift quasars is similar to that of nearby, steep-X-ray spectrum (also high-L/L_{Edd}) sources. X-ray variability is stronger on longer timescales.

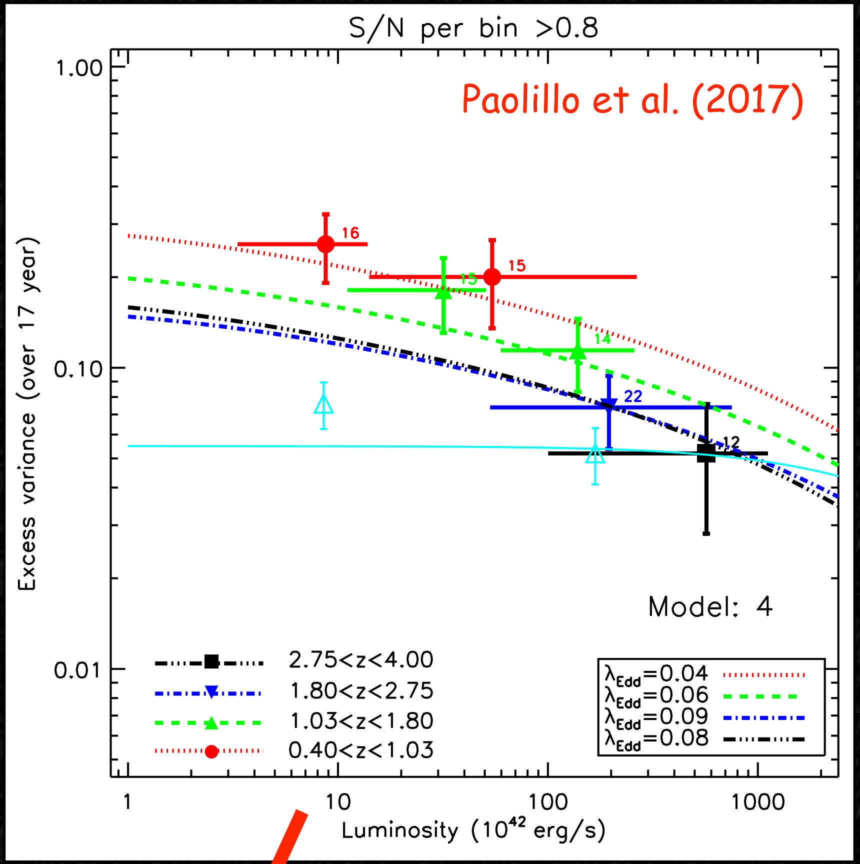
Results from the Chandra Deep Field-South 7 Ms Exposure

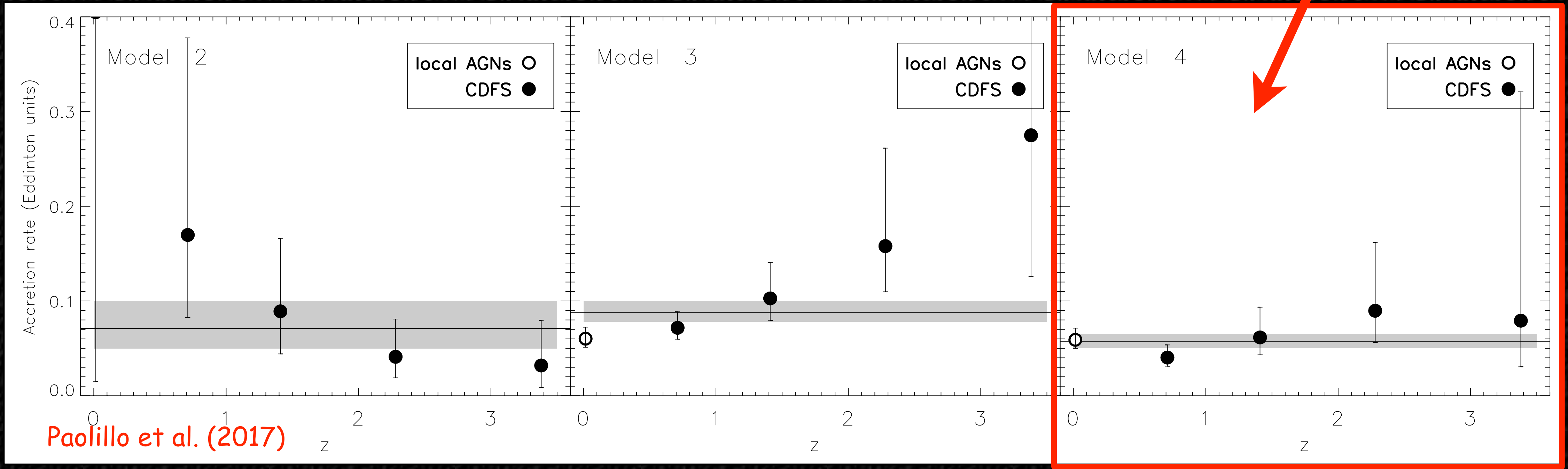




Results from the Chandra Deep Field-South 7 Ms Exposure

- The PSDs of high-redshift AGN are similar to those of local AGN.
- The break frequency depends on M_{BH} and L/L_{Edd}, and the PSD normalization most likely depends on L/L_{Edd}.
- The Eddington ratio is consistent with a constant value up to z~3.

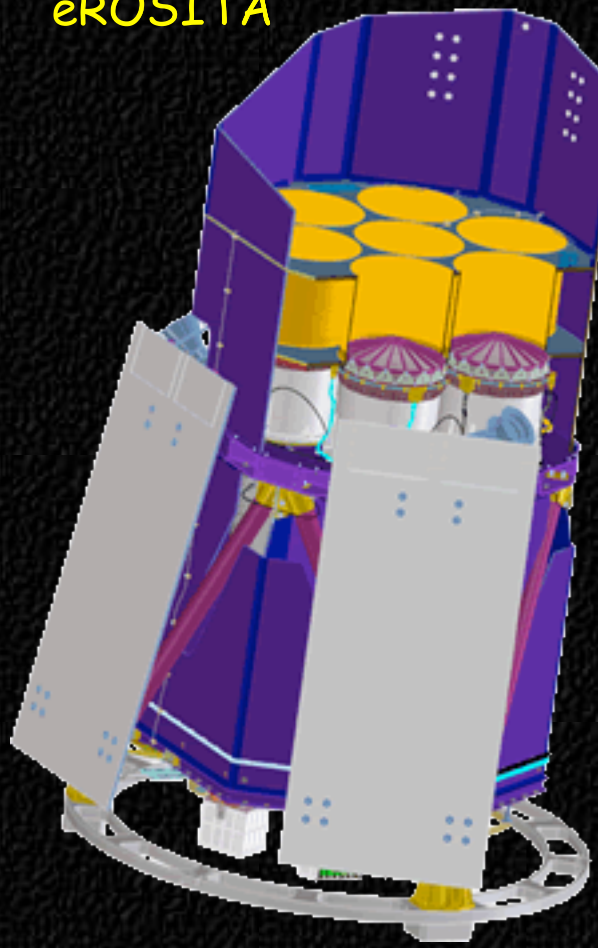




What the Future Holds for AGN X-ray Variability

(X-ray) variability of the most distant quasars: uncharted territory.

eROSITA



WFXT

X-ray monitoring of millions of AGN up to z~6

Summary - Part I

- ✳ AGN X-ray variability depends on the temporal baseline and on M_{BH} and L in a complicated way.
- ✳ No evidence for evolution of X-ray variability up to $z \sim 4$.
- ✳ Currently, no evidence for evolution in accretion rate up to $z \sim 3$.
- ✳ Prospects for constraining evolution of accretion rate with next-generation X-ray observatories.

Part II

AGN Variability Science in the LSST Era

See also the AGN chapters in the LSST Science Book and LSST Observing Strategy White Paper:

http://www.lsst.org/sites/default/files/docs/sciencebook/SB_10.pdf

https://github.com/LSSTScienceCollaborations/ObservingStrategy/

For more information, contact: **lsst-agn@lsstcorp.org**

AGN Selection by LSST

- Magnitude range: $15.7 < i < 26.3$, $M_i \le -20$
- Redshift range: $0 < z < 7.5$ (and beyond), using photometric redshift probability distribution functions
- Classification and characterization based on joint likelihood distribution using:
  1. Colors
  2. Variability
  3. Astrometry
  4. Multiwavelength matching
- Obscuration and host-galaxy dilution will hinder AGN selection

Background: LSST image simulation spanning ~0.03 deg^2

AGN Selection by LSST

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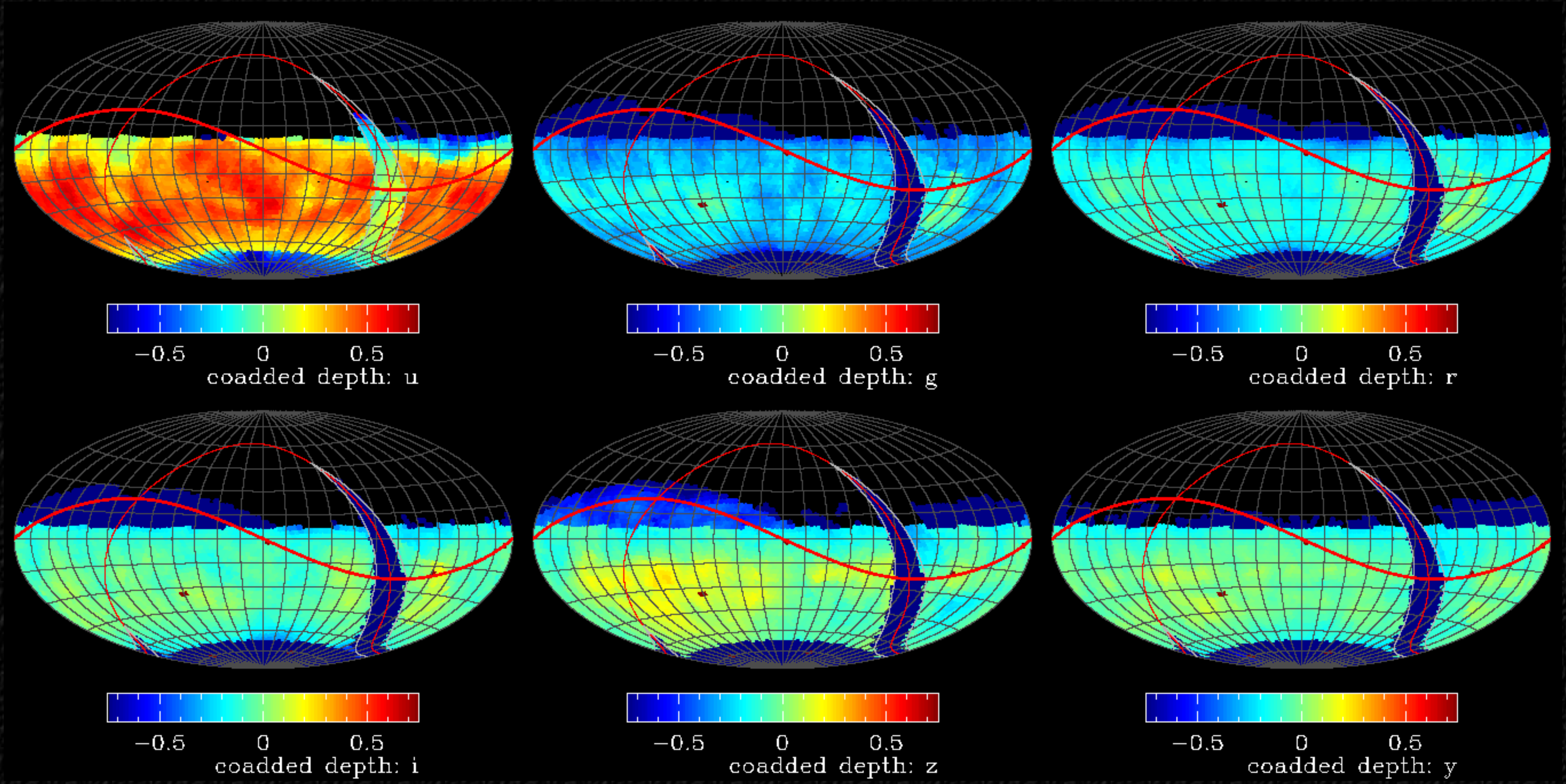
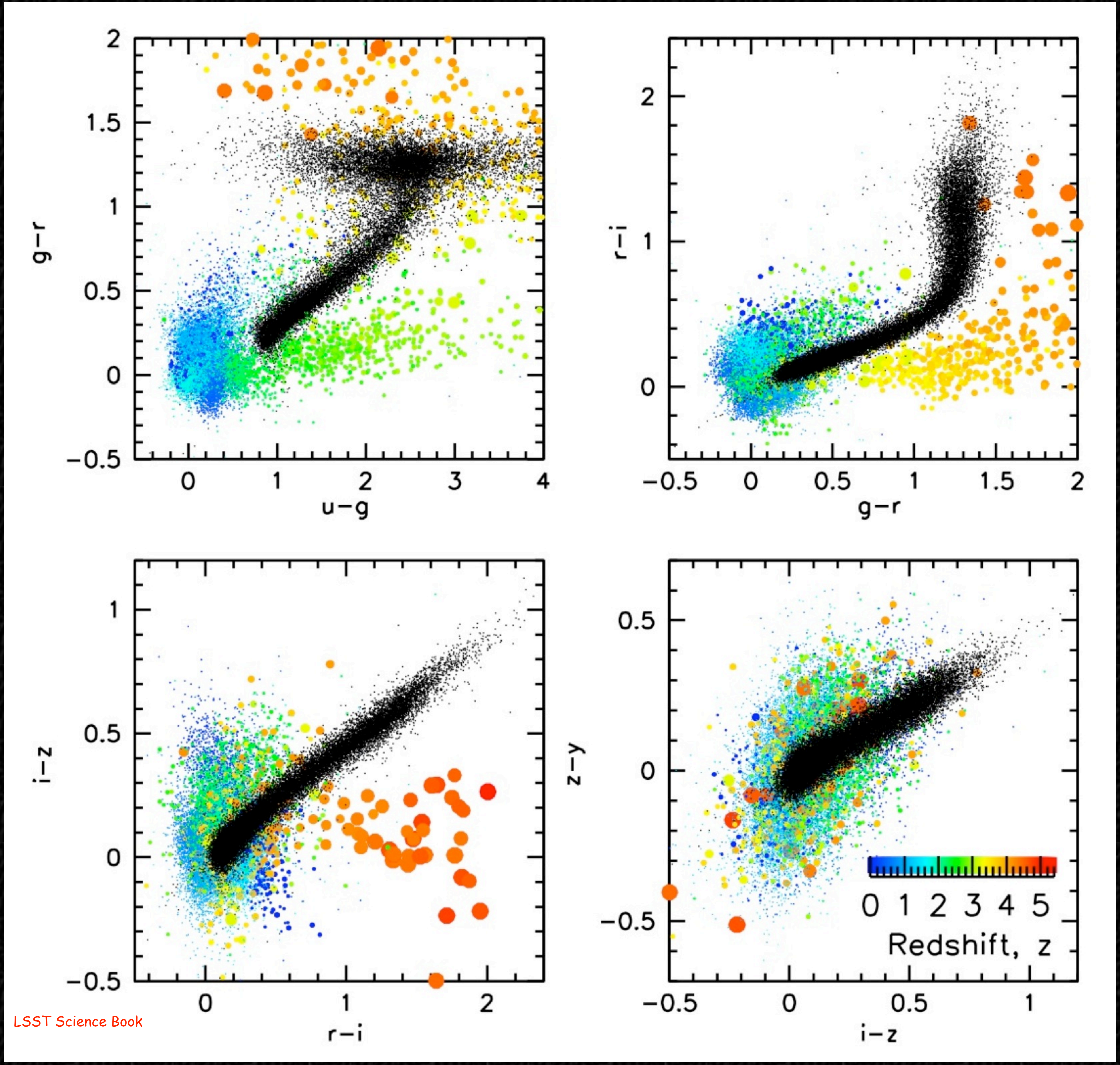
Background: LSST image simulation spanning ~0.03 deg^2

LSST Observing Strategy and the Operations Simulator



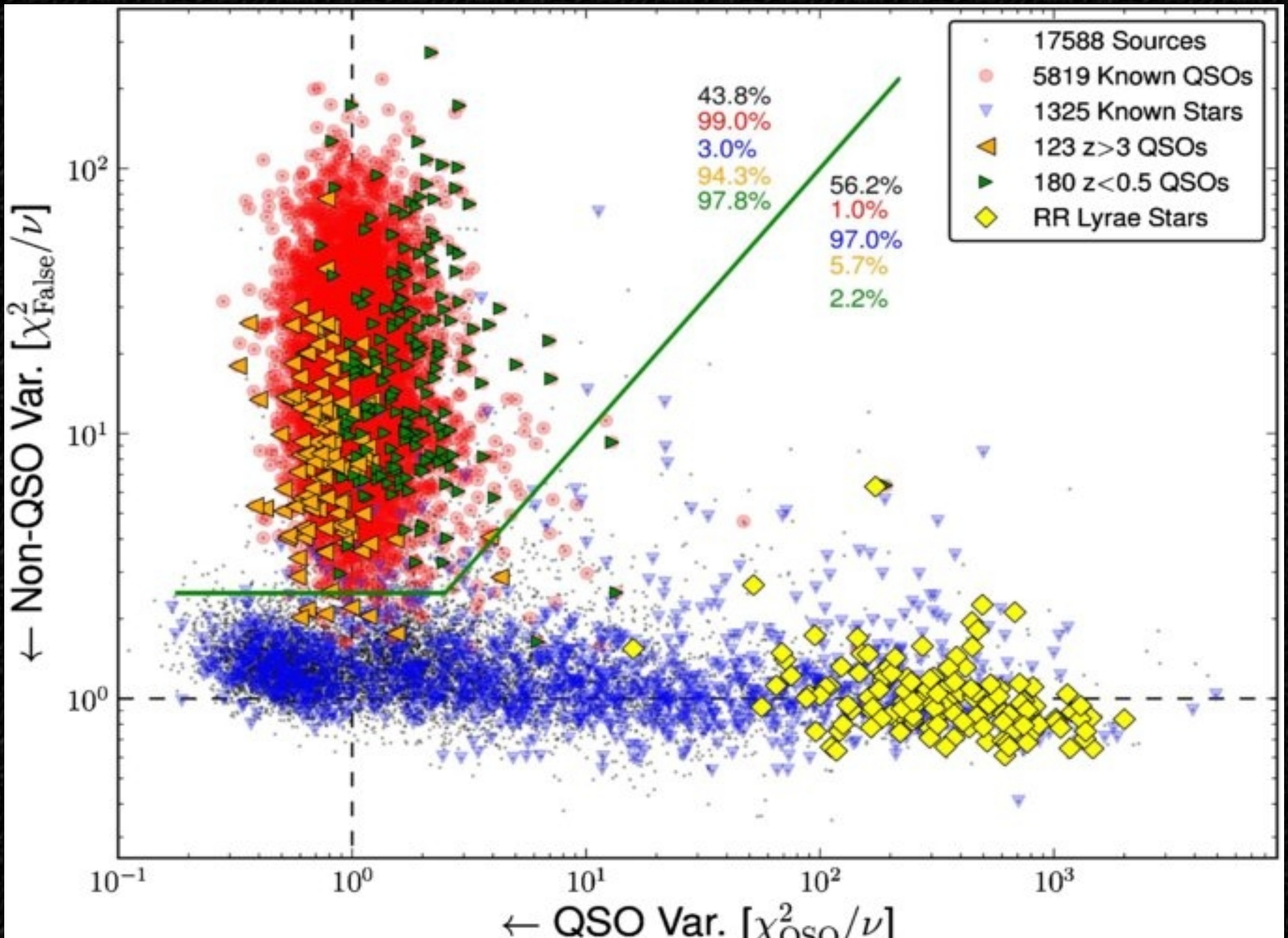
AGN Selection by LSST

Multicolor selection: employing the six LSST bands, *ugrizY*



AGN Selection by LSST

Variability: AGN have variability patterns distinct from those of variable stars



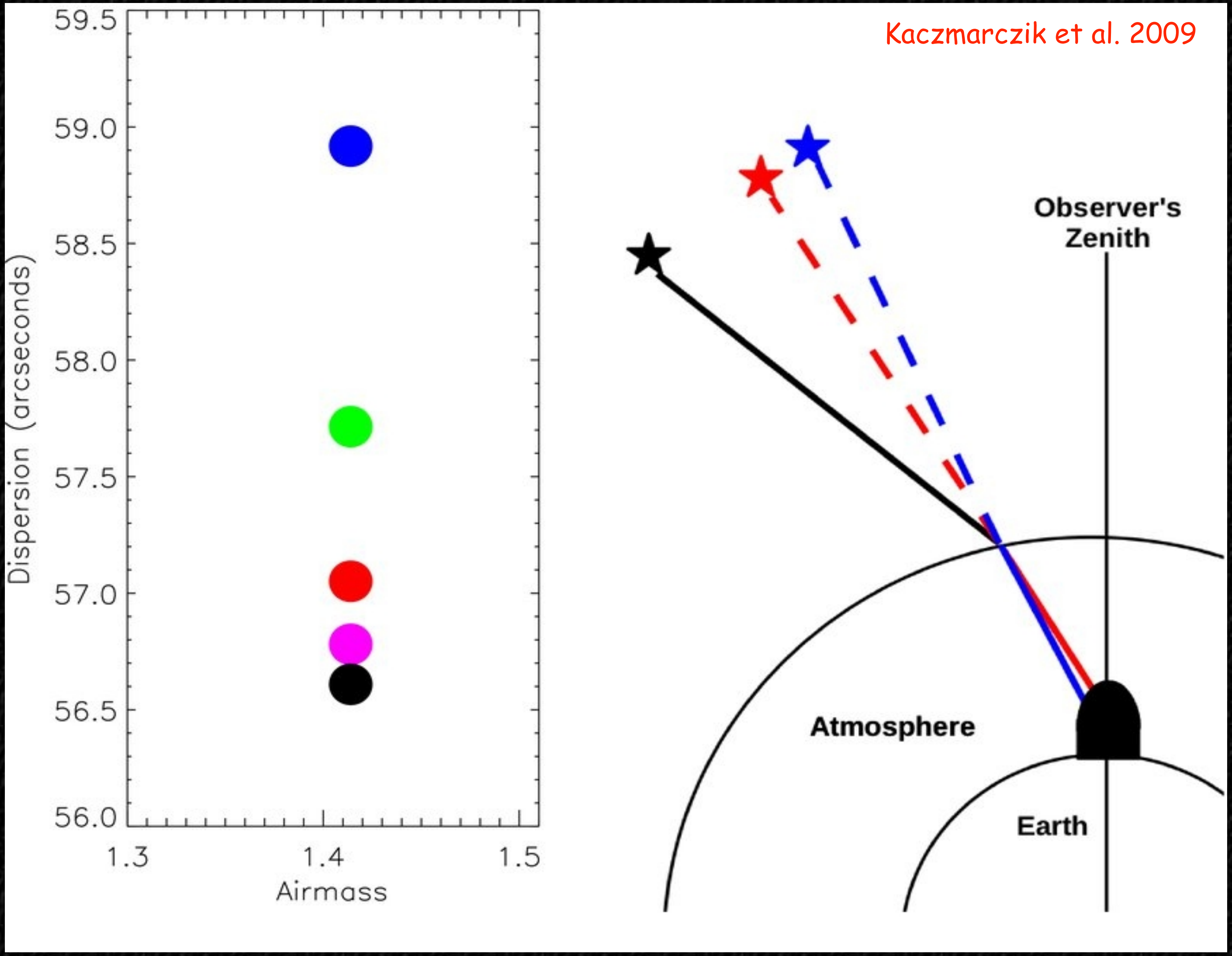
Butler & Bloom (2011)

AGN Selection by LSST

Astrometry:

1) Lack of proper motion (down to ~1 mas yr^{-1} at r ~ 24)

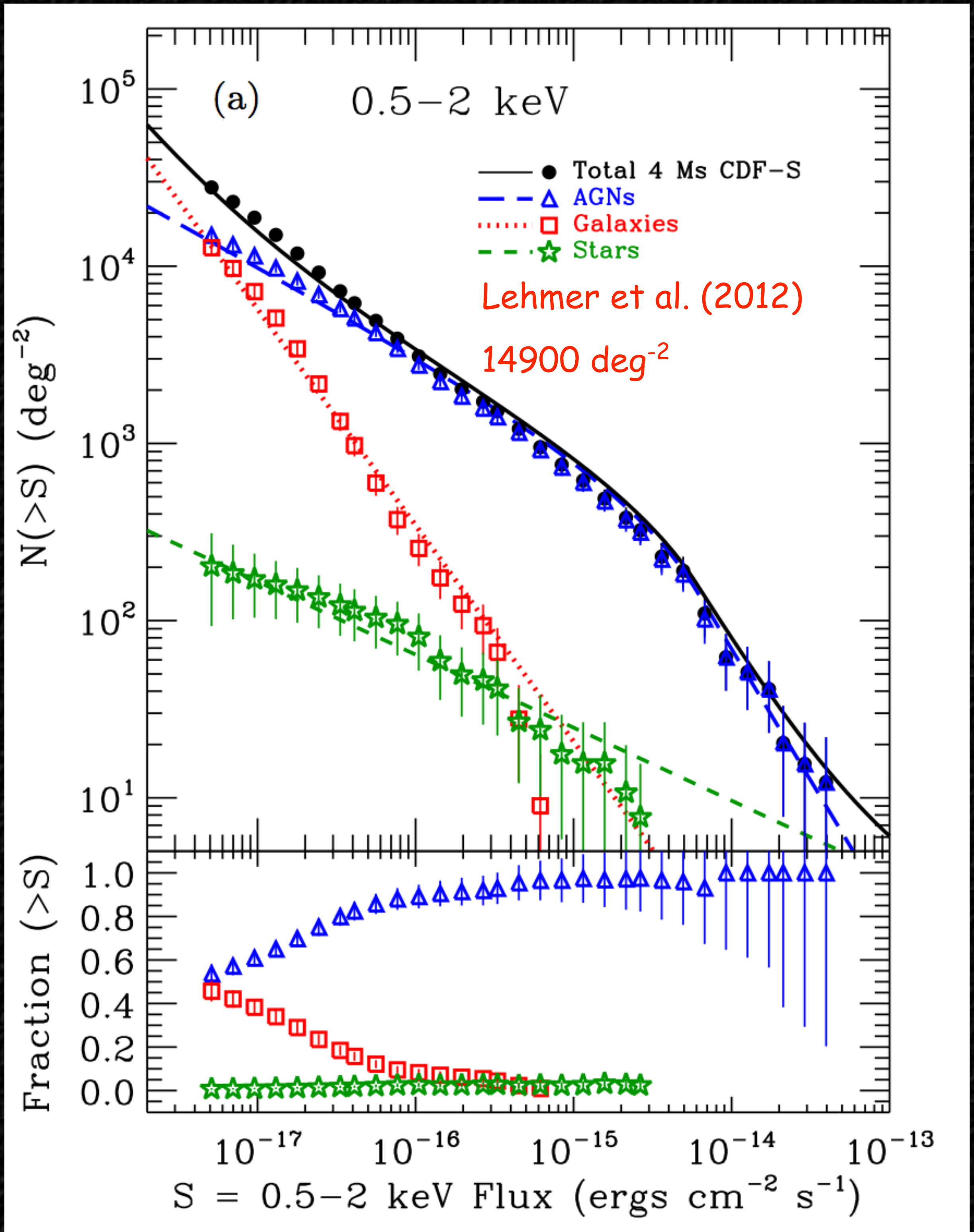
2) Differential chromatic refraction (change in band λ_{eff} with z): "astrometric redshifts"



AGN Selection by LSST

Multiwavelength matching: cross-correlating source positions with LSST data

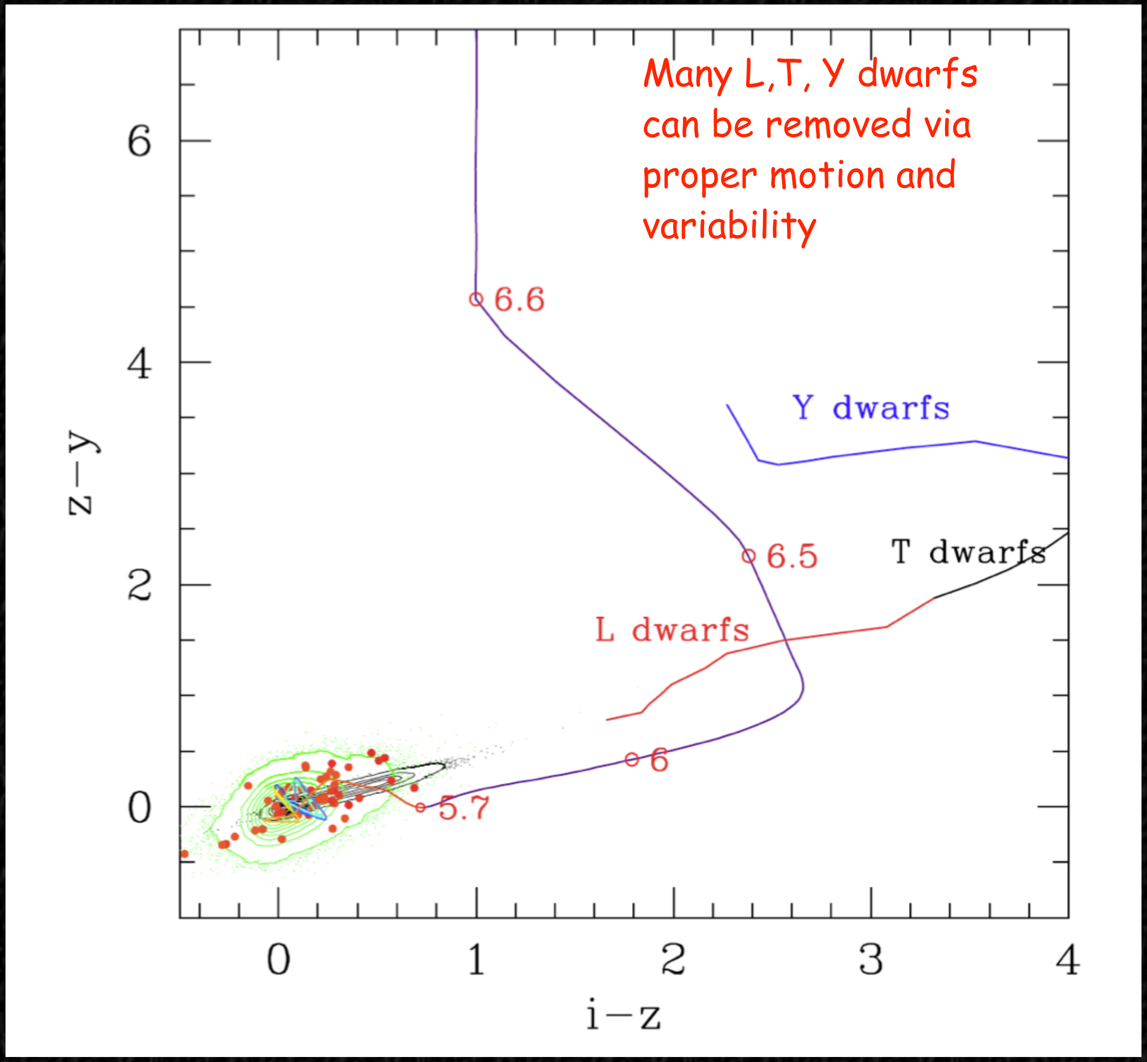
AGN by the Numbers



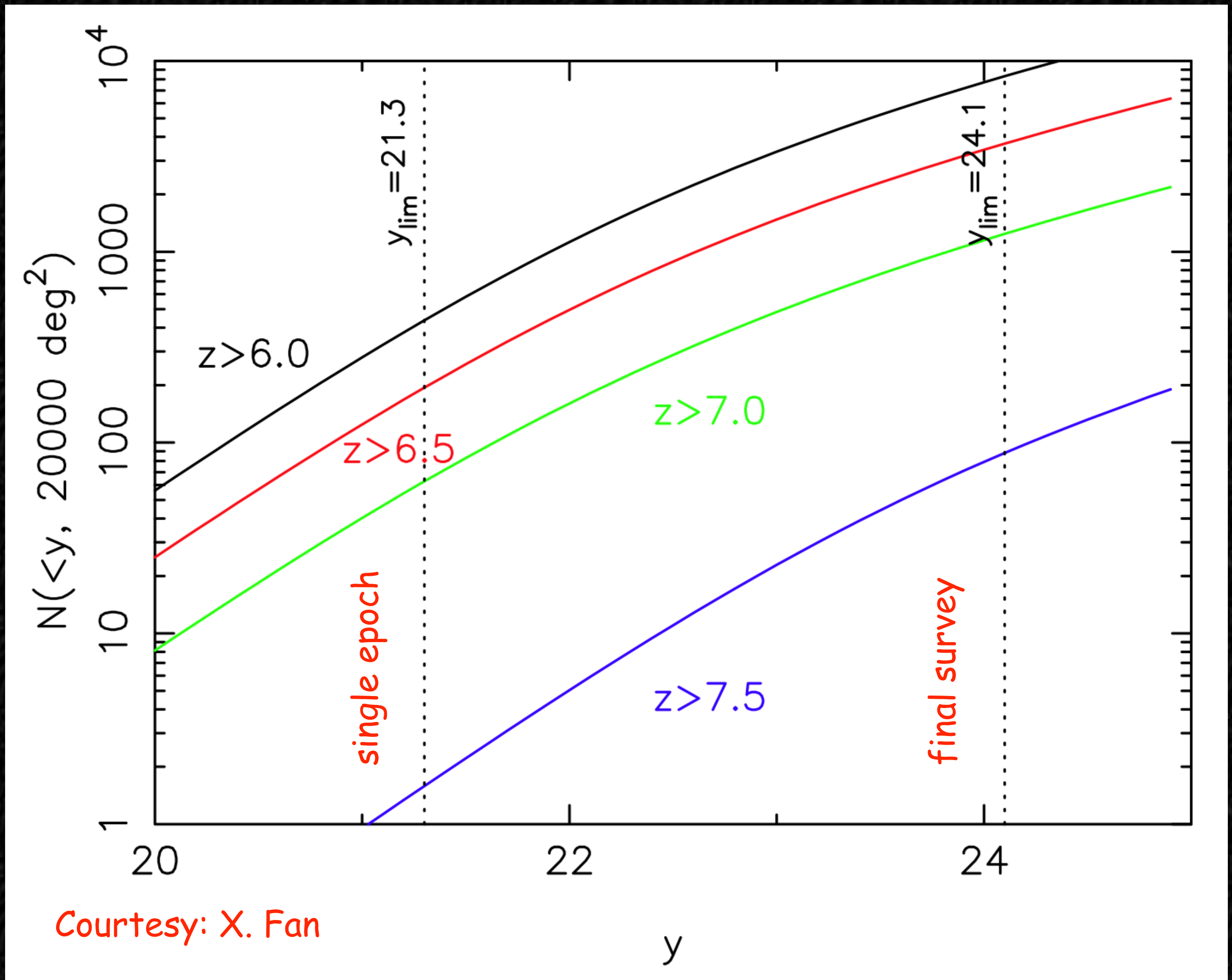
Chandra Deep Field-South Number Counts

- ✳ Expect ≈10^8 AGN detected in ≈10^4 deg^2 main LSST survey.
- ✳ Additional detections of ~40000 (ultrafaint) AGN expected in ~200 deg^2 of Deep Drilling Fields (DDFs).
- ✳ Expected discovery of ~8000 gravitationally lensed quasars including ~1000 systems with measurable time delays.
- ✳ Expected discovery of at least 1000 AGN at $z > 6.0$ down to L_{opt} ~10^{44} erg s^{-1}.

Quasars at the End of the Dark Ages



Colors of high-redshift quasars



Expected numbers of *z* > 6 quasars

1) Between redshifts of 6.0 and 7.5: *i*- and *z*-band dropouts.

2) Above redshift 7.5, *Y*-band dropouts having multiwavelength detections.

AGN Variability Studies with LSST

Millions of AGN light curves with ~55-185 samplings per band (main survey) and ≈10^3 samplings per band (DDFs) over 10 years spanning a temporal baseline of minutes-to-years.

- ✳Variability amplitude and timescale as a function of L, z, $\lambda_{\rm eff}$, color, multiwavelength and spectroscopic properties (where available).
- ✳Photometric reverberation mapping (e.g., black-hole mass estimates).
- ✳Power density spectra (black-hole mass estimates, accretion flow probe).
- ✳Searching for binary supermassive black holes.
- ✳Accretion disk size and structure using gravitational microlensing.
- ✳Time delays in gravitationally lensed quasars (cosmology).
- ✳Unresolved lensed-quasar candidates (cosmology).

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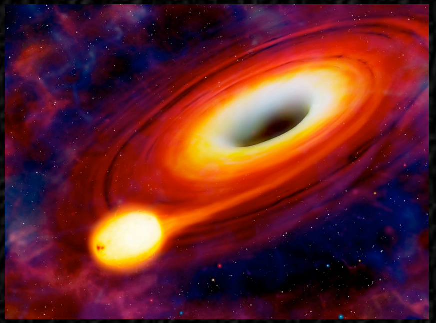
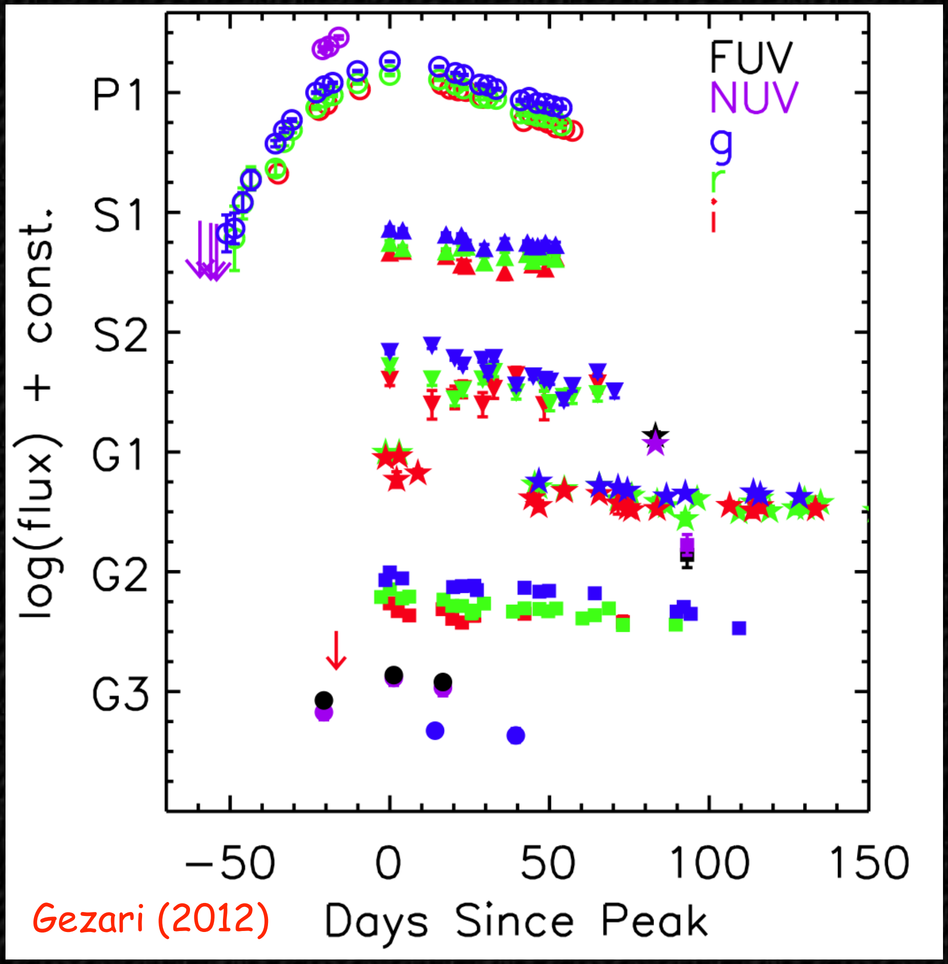
Transient AGN

Transient outbursts from galactic nuclei lasting over a month or more can occur when a star, a planet, or a gas cloud is tidally disrupted and partially accreted by the supermassive black hole.





Light curves of tidal disruption event candidates discovered in UV and optical surveys

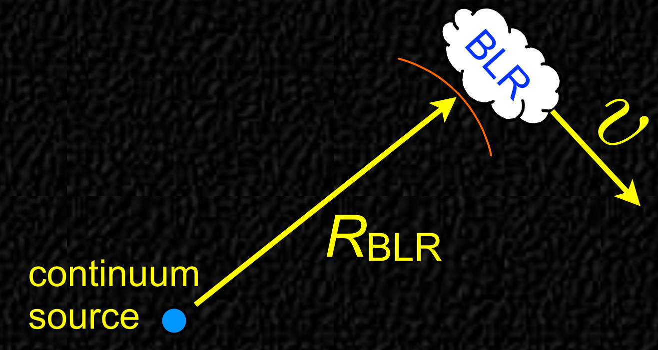
- LSST is expected to discover and monitor ~1000 events per year.
- LSST can trigger prompt multiwavelength follow-up.
- Provide tight constraints on the contribution of transient AGN to the faint end of the AGN luminosity function.
- Frequent monitoring and large area covered by LSST may allow detection of faint and rapid outbursts associated with intermediate-mass black holes in nuclei of nearby galaxies.

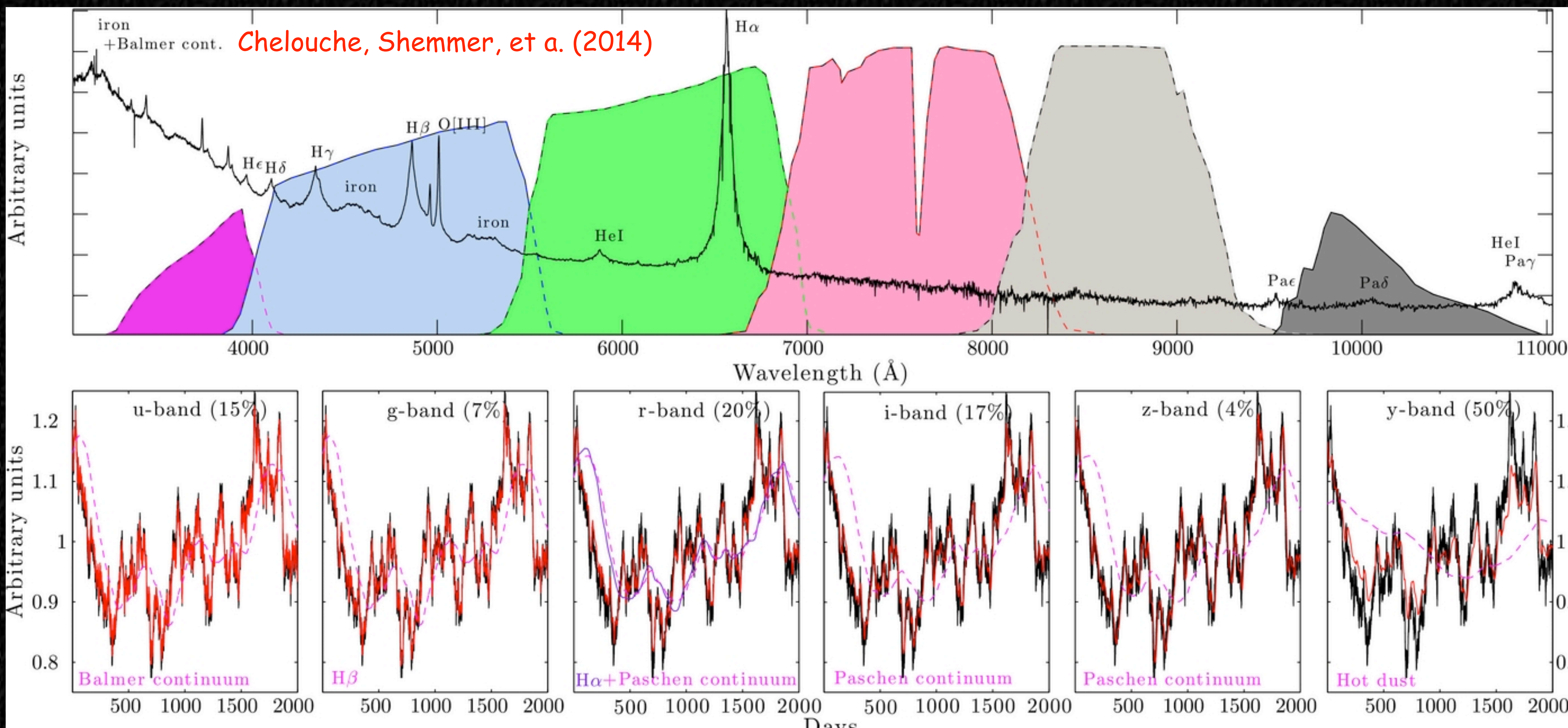
Photometric Reverberation Mapping with LSST

Assuming Keplerian motion of the BLR clouds: $M_{BH} \propto R_{BLR} V^2$

From photoionization: $R_{BLR} \propto L^{0.5}$

Single-epoch BH mass estimate: $M_{BH} \propto L^{0.5}$ FWHM(BLR line)^2





Photometric reverberation mapping: estimating R_{BLR} and M_{BH} in ~10^5 quasars

Summary - Part II

- First light coming soon - stay tuned!