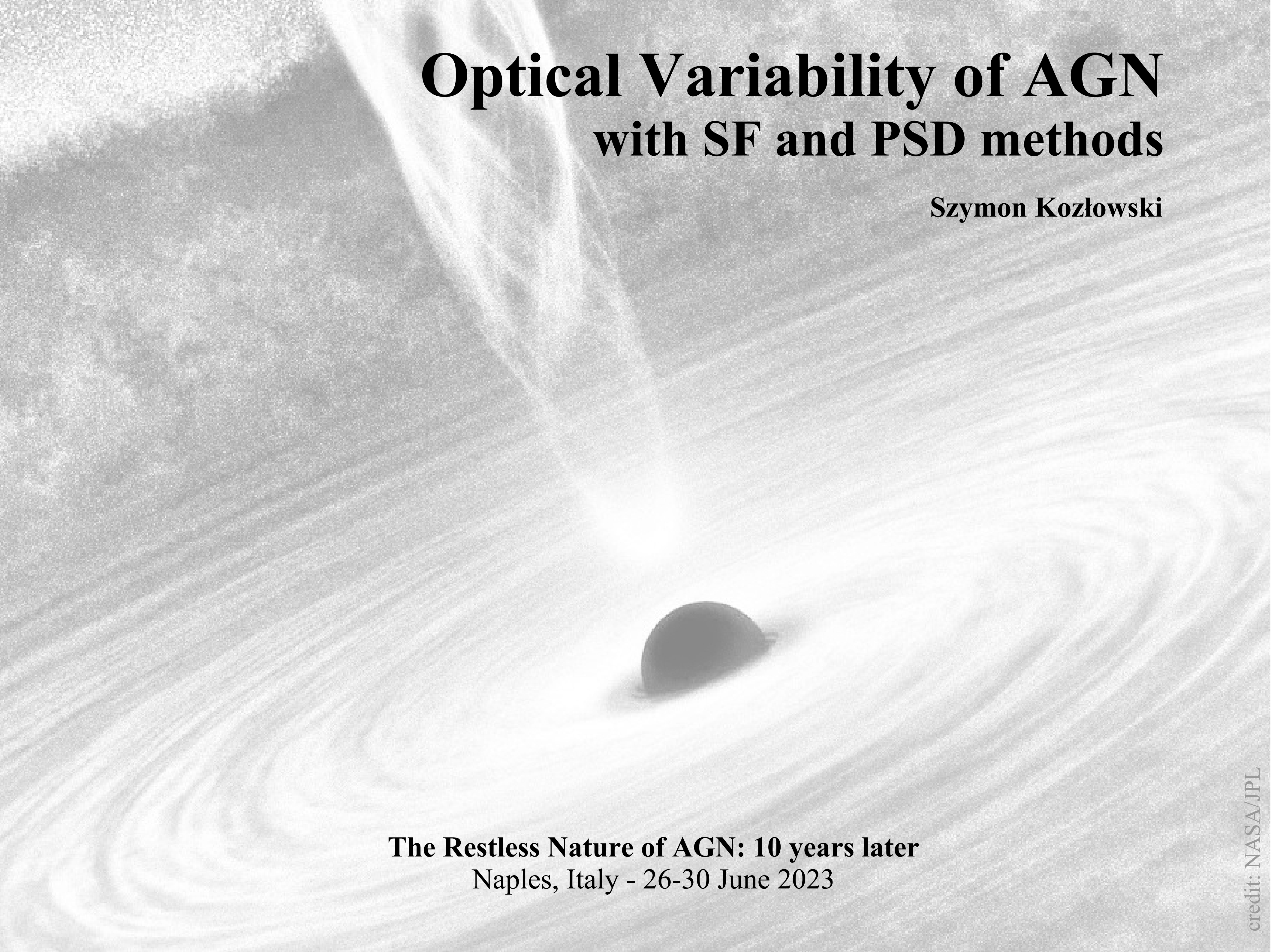


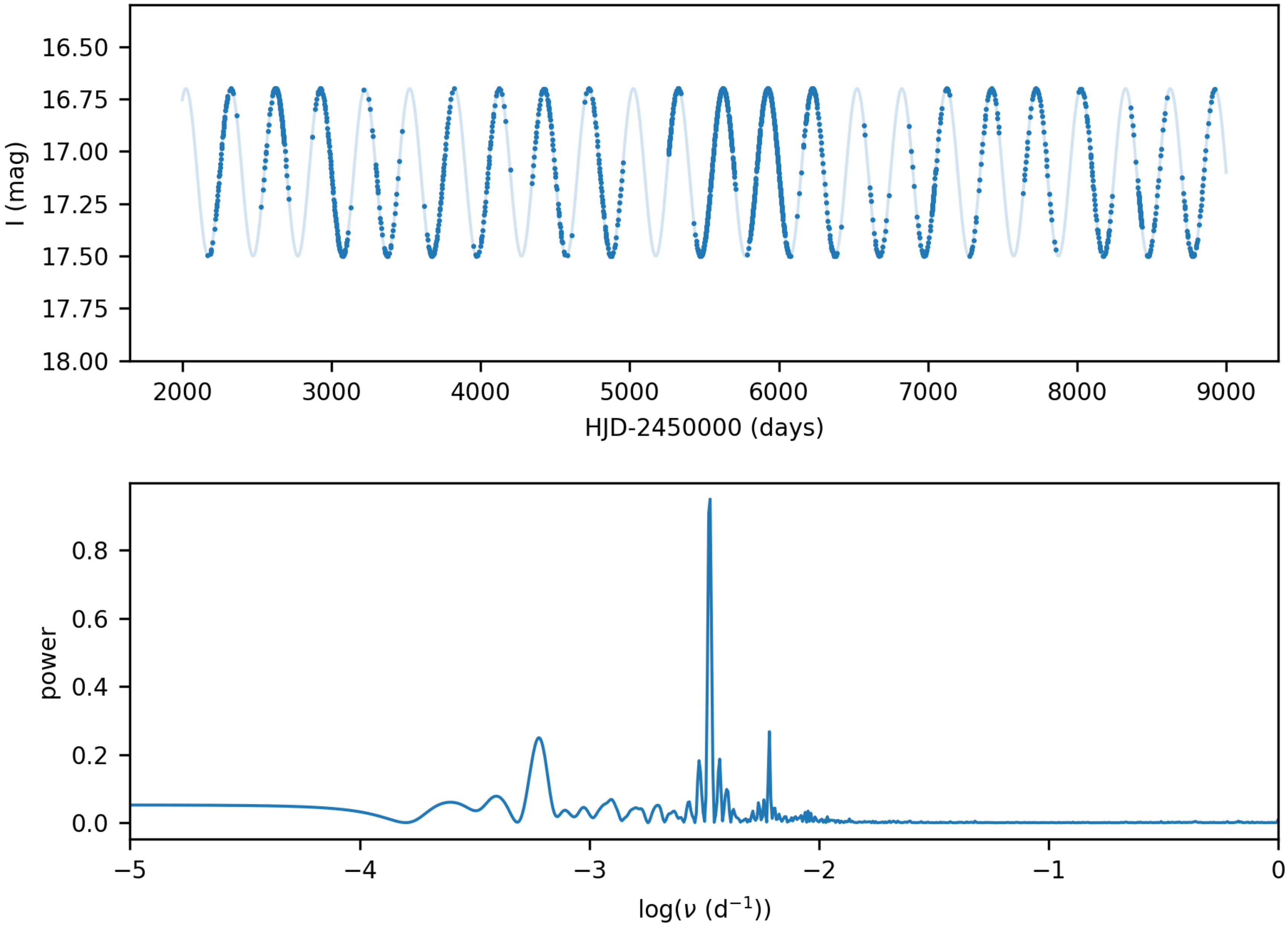
Optical Variability of AGN
with SF and PSD methods

Szymon Kozłowski

The Restless Nature of AGN: 10 years later
Naples, Italy - 26-30 June 2023

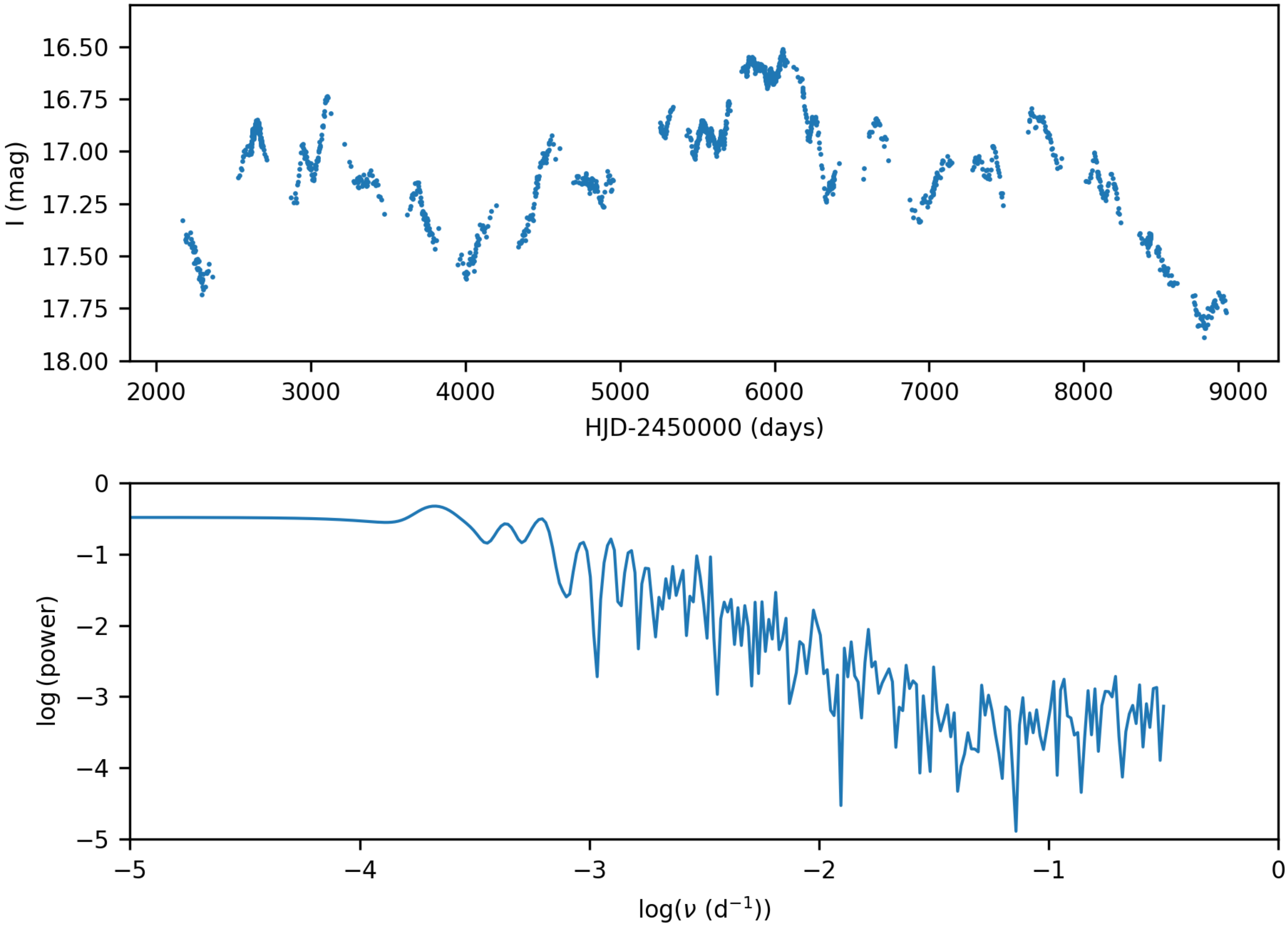
credit: NASA/JPL

Periodic objects



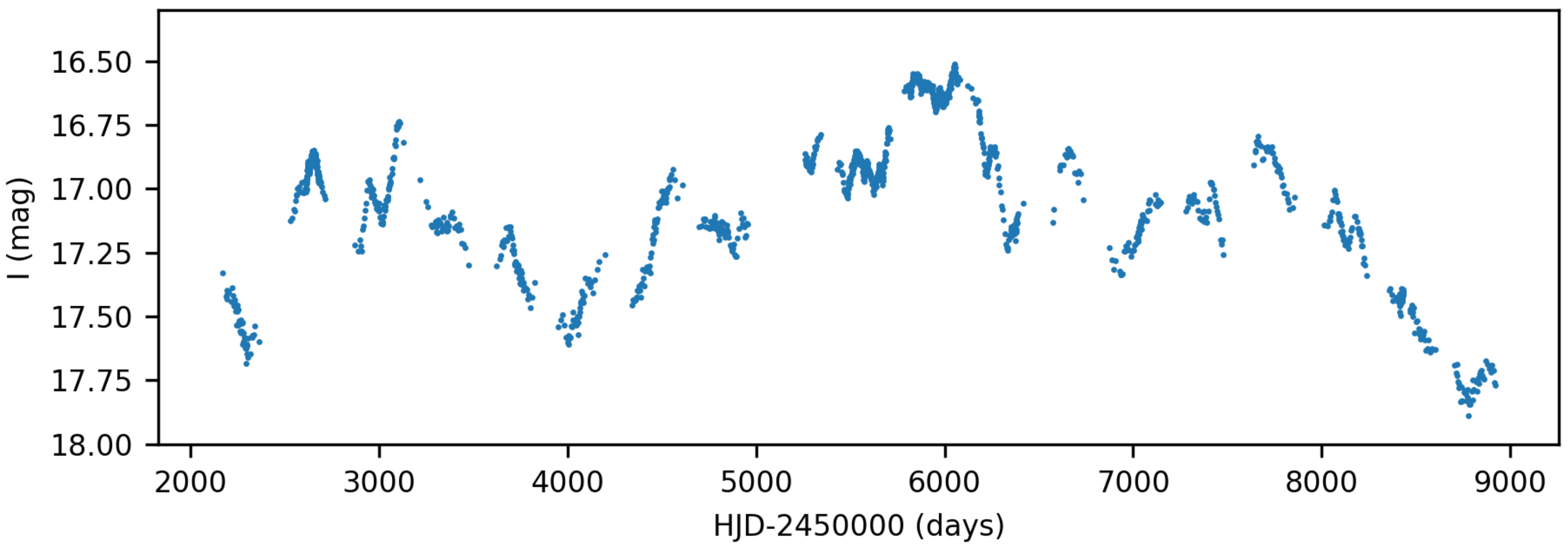
Understanding the Lomb–Scargle Periodogram – VanderPlas, 2018, ApJS, 236, 16

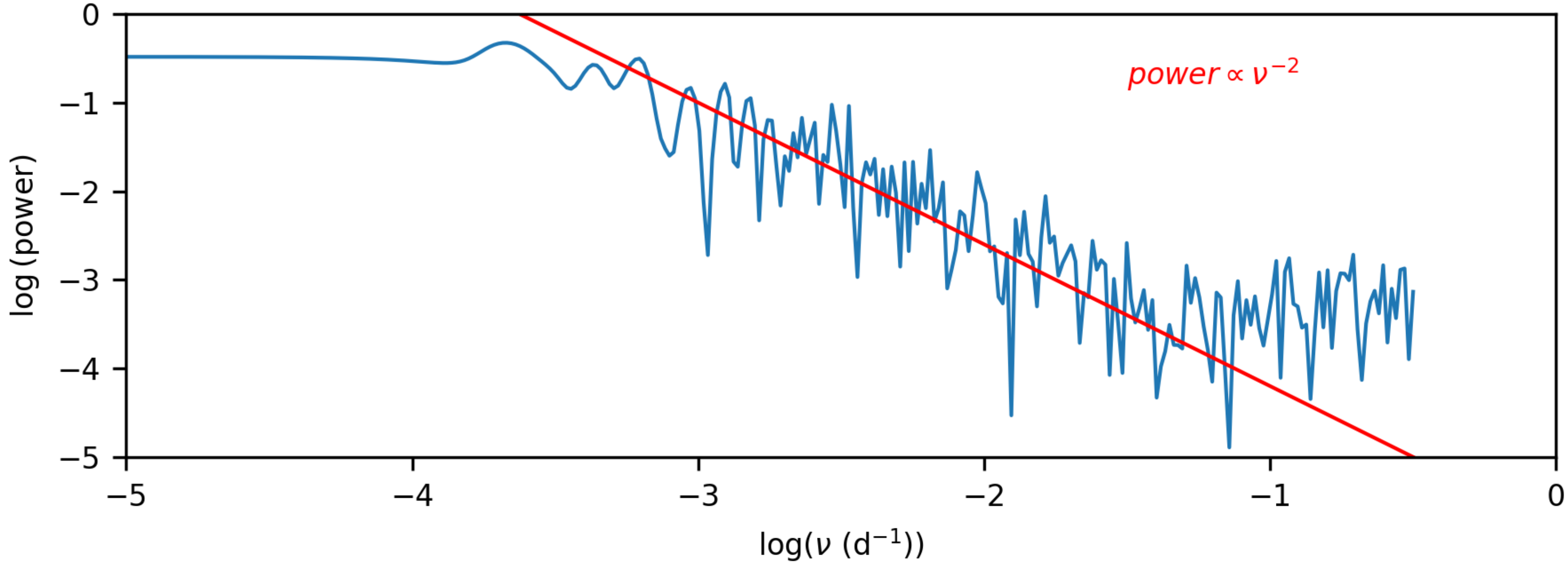
Non-periodic objects



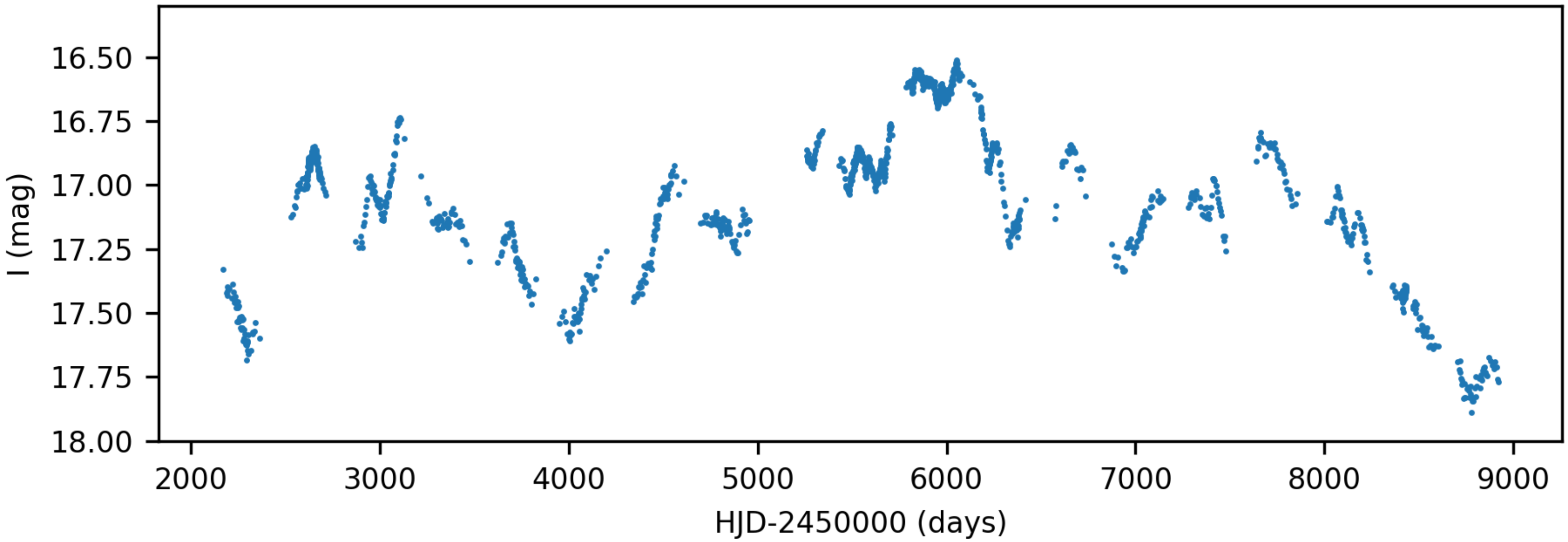
Stochastic Modeling Handbook for Optical AGN Variability – Moreno et al. 2019, PASP, 131, 1000

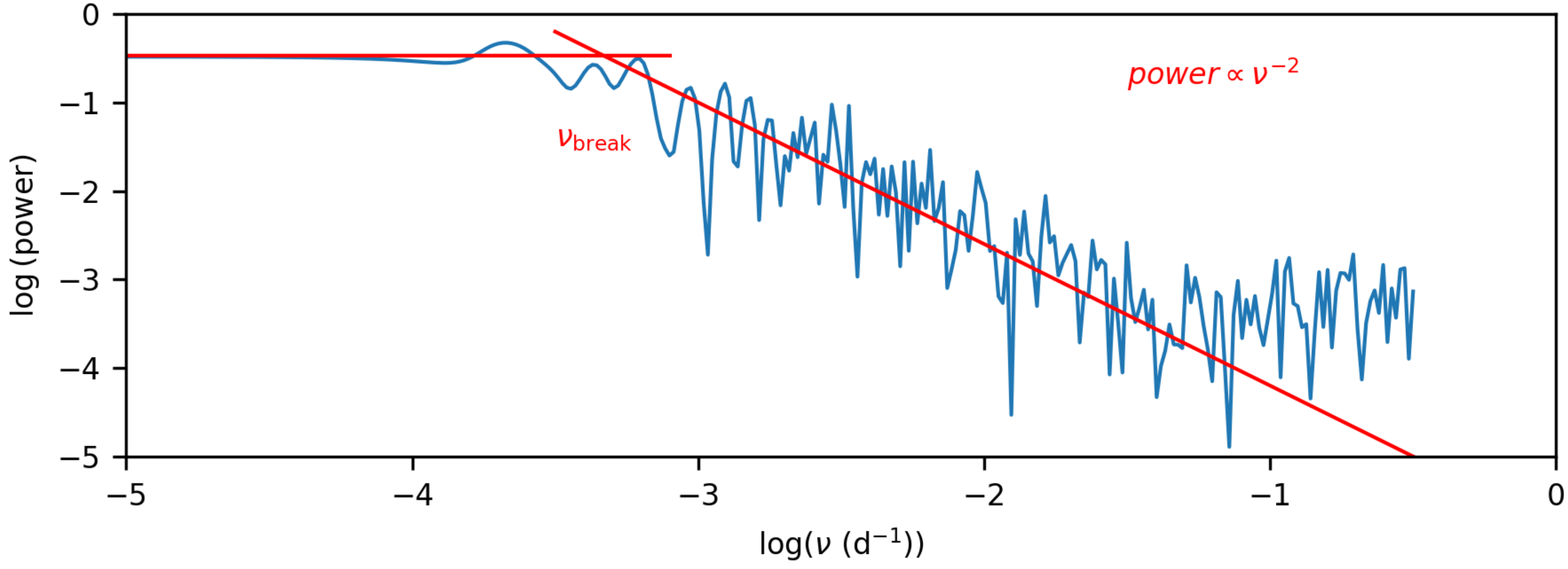
Non-periodic objects



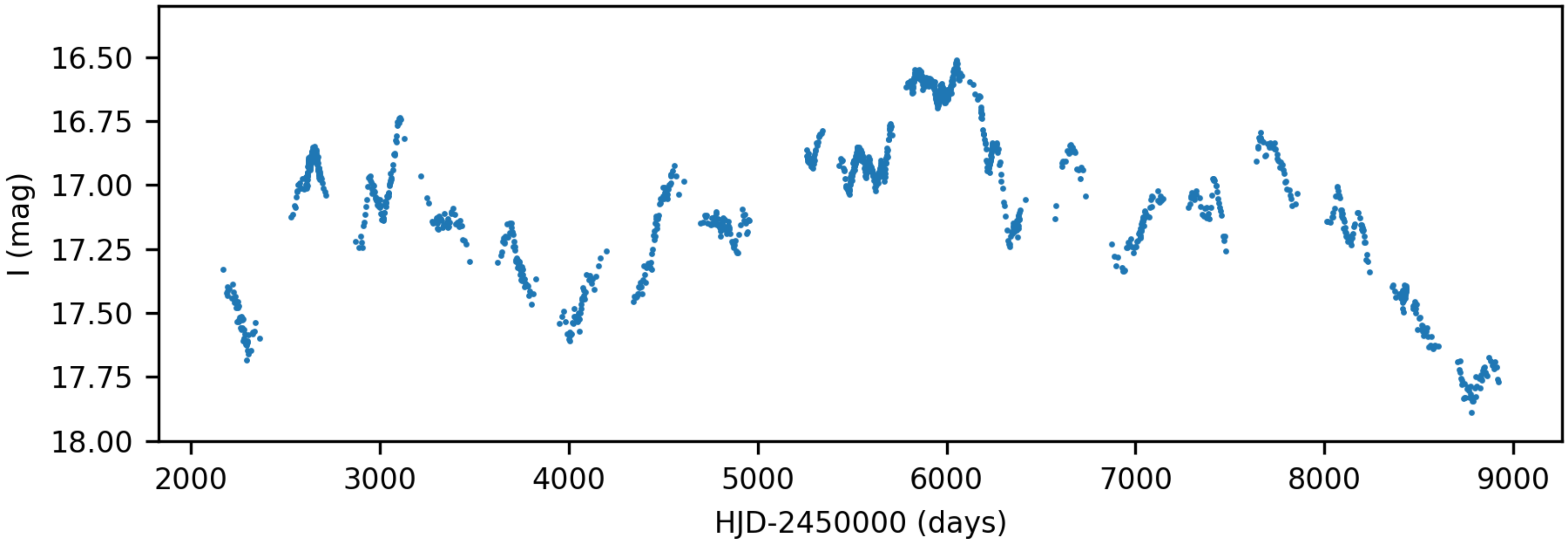


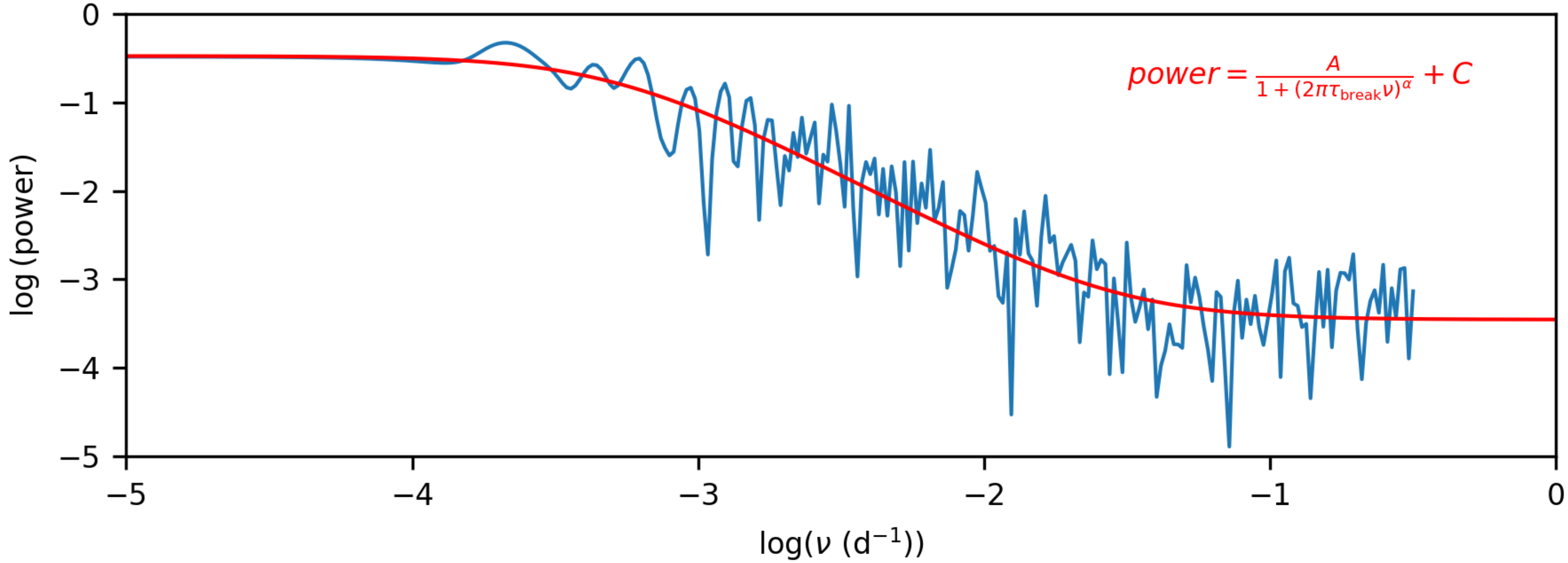
Non-periodic objects





Non-periodic objects





AGN from Kepler

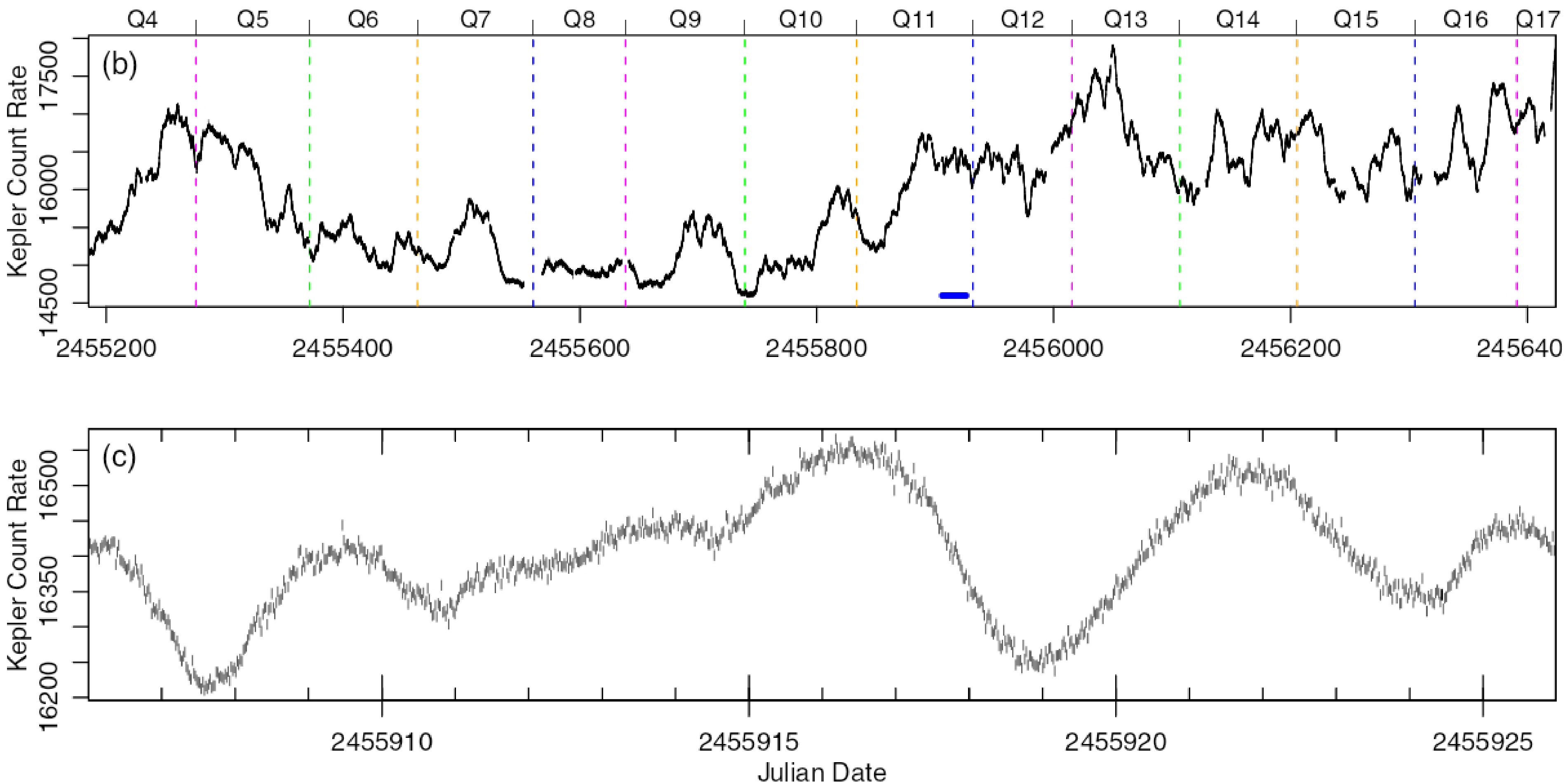
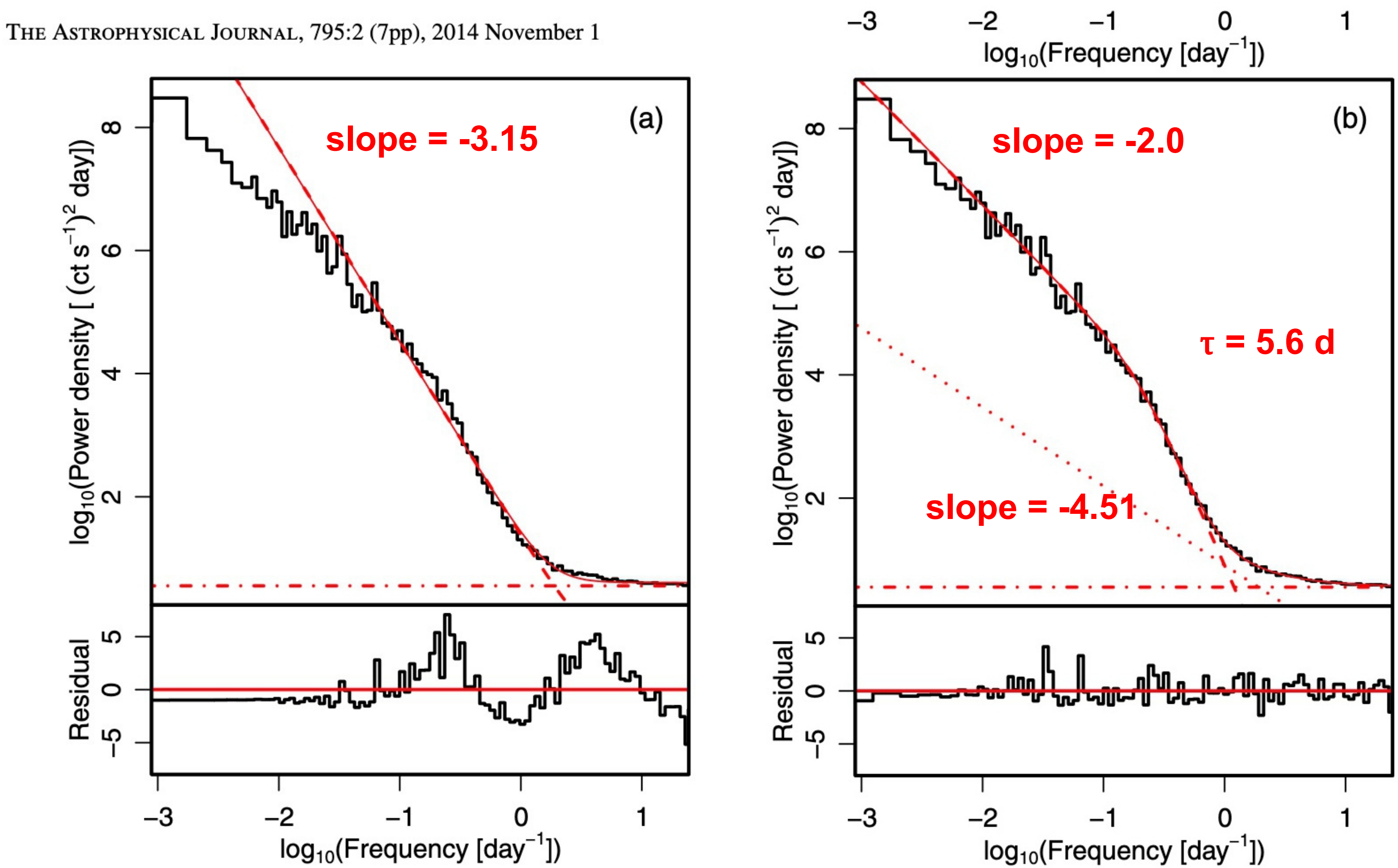


Figure 2. (a) Uncorrected light curve. Bad data (in red) were eliminated and seasonal jumps were corrected as discussed in the text. (b) Corrected light curve. (c) Twenty day (960 cadence) snippet from Q11, showing the quality of the *Kepler* data. This time range is shown with a horizontal blue line in panel (b).

(A color version of this figure is available in the online journal.)

Edelson et al. 2014, ApJ, 795, 2

AGN from Kepler



Edelson et al. 2014, ApJ, 795, 2

AGN from Pan-STARRS1

A&A 585, A129 (2016)
DOI: 10.1051/0004-6361/201527353

Astronomy & Astrophysics

Pan-STARRS1 variability of XMM-COSMOS AGN

II. Physical correlations and power spectrum analysis

T. Simm[1], M. Salvato[1], R. Saglia[1,2], G. Ponti[1], G. Lanzuisi[3,4] B. Trakhtenbrot[5,⋆], K. Nandra[1], and R. Bender[1,2]

Results. We observe that the excess variance and the PSD amplitude are strongly anticorrelated with wavelength, bolometric luminosity, and Eddington ratio. There is no evidence for a dependency of the variability amplitude on black hole mass and redshift. These results suggest that the accretion rate is the fundamental physical quantity determining the rest-frame UV/optical variability amplitude of quasars on timescales of months and years. The optical PSD of all of our sources is consistent with a broken power law showing a characteristic bend at rest-frame timescales ranging between ~100 and ~300 days. The break timescale exhibits no significant correlation with any of the fundamental AGN parameters. The low-frequency slope of the PSD is consistent with a value of −1 for most of our objects, whereas the high-frequency slope is characterized by a broad distribution of values between ~−2 and ~−4. These findings unveil significant deviations from the simple damped random walk model that has frequently been used in previous optical variability studies. We find a weak tendency for AGNs with higher black hole mass to have steeper high-frequency PSD slopes.

90 X-ray selected AGN, observed by Pan-STARRS (optical - griz)

Simm et al. 2016, A&A, 585, A129

AGN from XMM-Newton

O. González-Martín and S. Vaughan: X-ray variability of 104 active galactic nuclei

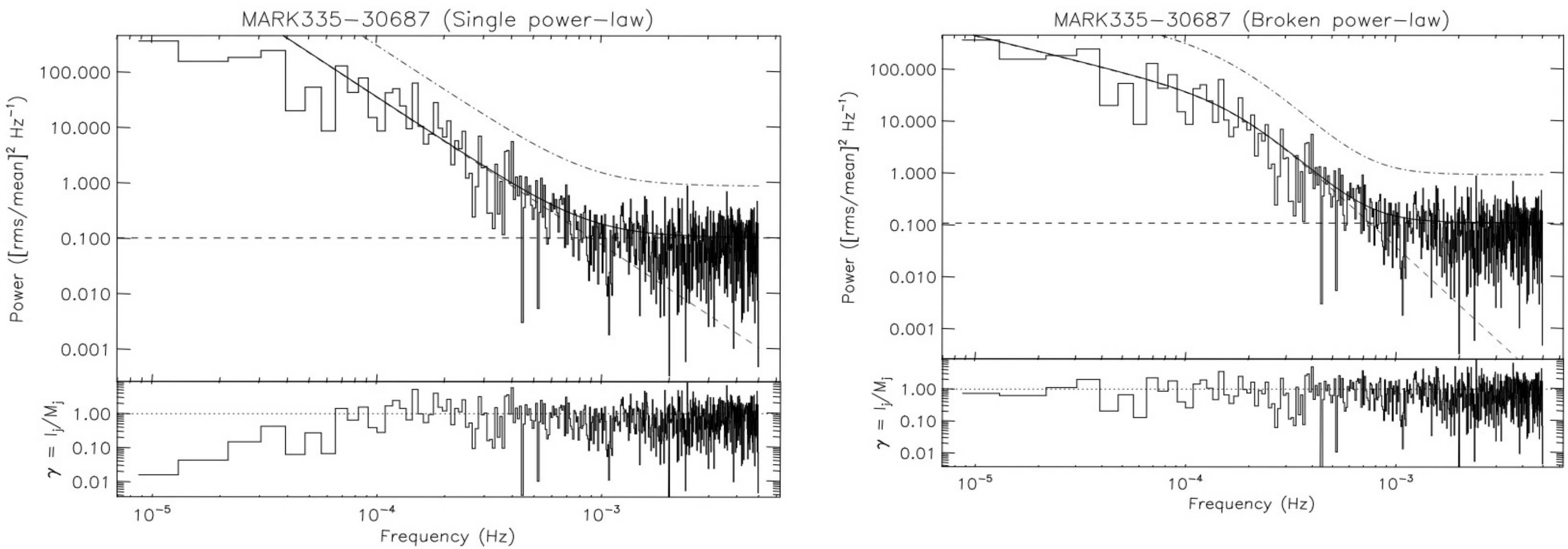


Fig. 1. PSDs fits (continuous line) to Model A (*left*) and Model B (*right*) for the Mrk 335 data (ObsID 306870101) using the broad (0.2−10 keV) energy band. The dashed lines shows the two components of the model: constant Poisson noise and the source PSD model (power-law, *left*; bending power-law, *right*). The dot-dashed line shows the "global" 90% confidence limit use to flag QPO candidates. Appendix B shows the corresponding figures for the complete sample.

Majority of PSDs: single power-law with slopes α=-2.01±0.01;
15 AGN: broken power-law with slopes α=-3.08±0.04

Gonzales-Martin & Vaughan 2012, A&A, 544, A80

Damped Random Walk (DRW)

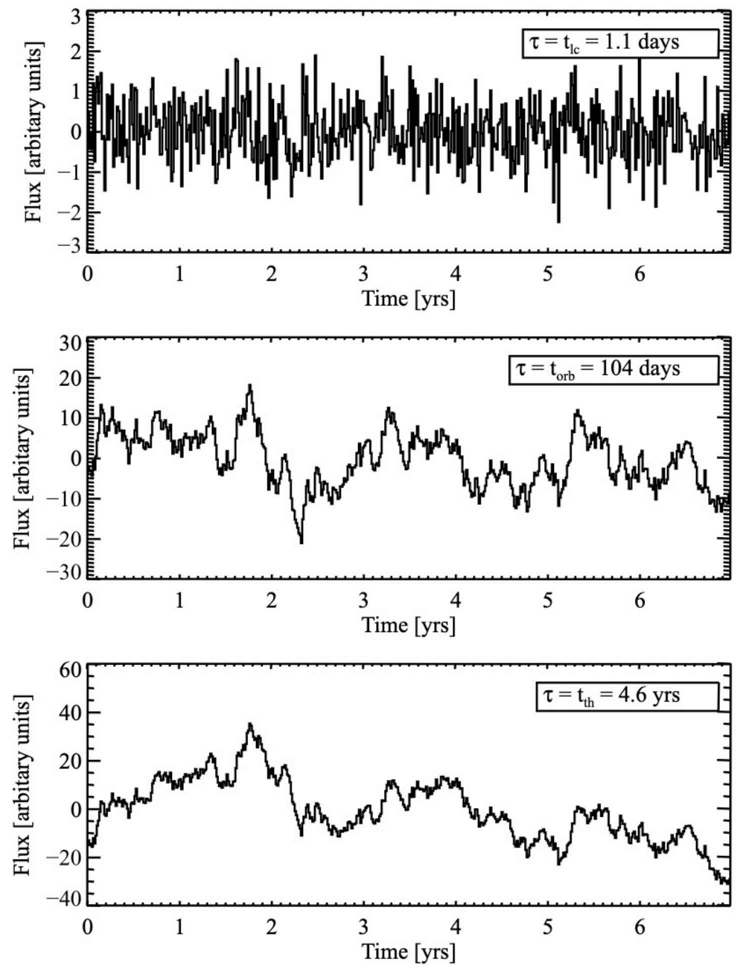


Figure 2. Light curves simulated from a CAR(1) process for three different characteristic timescales, assuming typical parameters for quasars ($M_{\rm BH} = 10^8\ M_\odot$, $R_s = 100, \alpha = 0.01$; see Equation (3)–(5)). From top to bottom, these are the light crossing time, $\tau = 1.1$ days, the disk orbital timescale, $\tau = 104$ days, and the disk thermal timescale, $\tau = 4.6$ yr. The stochastic nature of the CAR(1) process is apparent, and the light curve exhibits more variability on longer timescales as the characteristic timescale increases.

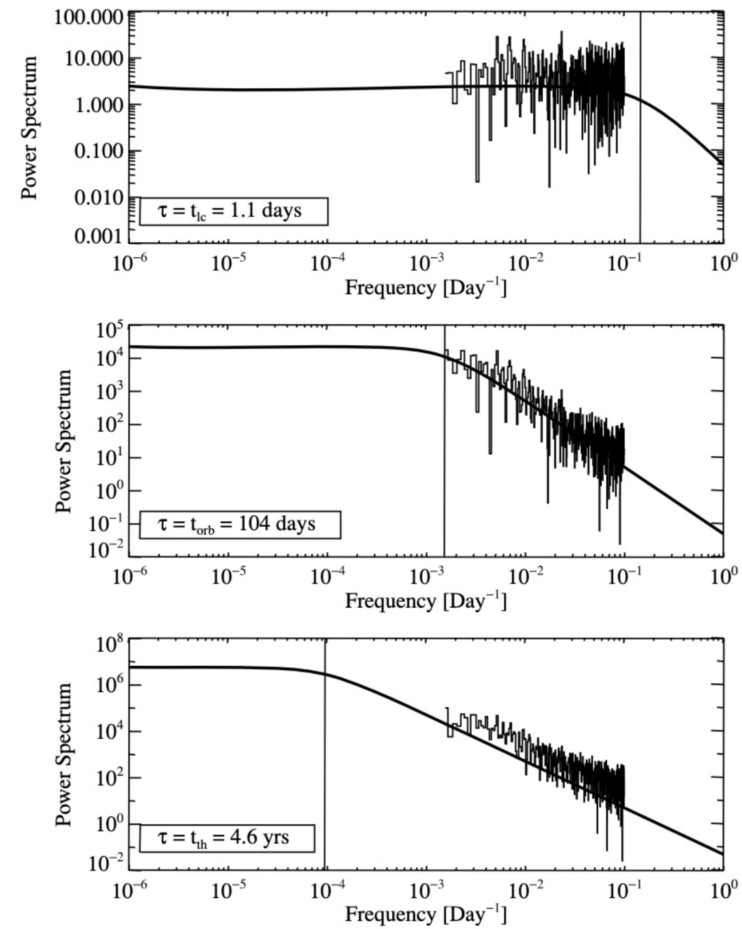


Figure 3. Power spectra for the simulated CAR(1) light curves shown in Figure 2. The actual power spectra are shown with a solid line, and the empirical power spectra estimated directly from the light curves are the noisy curves. The power spectra are flat on the "white noise" part of the curve, corresponding to frequencies $f \lesssim (2\pi\tau)^{-1}$, and fall off as $1/f^2$ on the "red noise" part of the curve, $f \gtrsim (2\pi\tau)^{-1}$. As τ increases, the break in the power spectra, marked with a vertical line, shifts toward smaller frequencies. For the CAR(1) process with $\tau = t_{\rm th}$, red noise leak biases the power spectrum estimated directly from the simulated light curve.

Kelly, Bechtold & Siemiginowska 2009, ApJ, 698, 985

Damped Random Walk (DRW)

THE ASTROPHYSICAL JOURNAL, 708:927–945, 2010 January 10
doi:10.1088/0004-637X/708/2/927

QUANTIFYING QUASAR VARIABILITY AS PART OF A GENERAL APPROACH TO CLASSIFYING CONTINUOUSLY VARYING SOURCES

SZYMON KOZŁOWSKI[1], CHRISTOPHER S. KOCHANEK[1,2],
AND
A. UDALSKI[3], Ł. WYRZYKOWSKI[3,4], I. SOSZYŃSKI[3], M. K. SZYMAŃSKI[3], M. KUBIAK[3], G. PIETRZYŃSKI[3,5], O. SZEWCZYK[3,5], K. ULACZYK[3], AND R. POLESKI[3]
(THE OGLE COLLABORATION)
[1] Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA;
simkoz@astronomy.ohio-state.edu, ckochanek@astronomy.ohio-state.edu
[2] The Center for Cosmology and Astroparticle Physics, Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA
[3] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warsaw, Poland
[4] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[5] Universidad de Concepción, Departamento de Fisica, Casilla 160-C, Concepción, Chile
Received 2009 September 7; accepted 2009 November 13; published 2009 December 16

ABSTRACT

Robust fast methods to classify variable light curves in large sky surveys are becoming increasingly important. While it is relatively straightforward to identify common periodic stars and particular transient events (supernovae, novae, microlensing events), there is no equivalent for non-periodic continuously varying sources (quasars, aperiodic stellar variability). In this paper, we present a fast method for modeling and classifying such sources. We demonstrate the method using ~86,000 variable sources from the OGLE-II survey of the LMC and ~2700 mid-IR-selected quasar candidates from the OGLE-III survey of the LMC and SMC. We discuss the location of common

of quasars with multi-year light curves. Physically, the model is a damped random walk, and it has a broken power law structure function consistent with studies of quasar structure functions. Unfortunately, there are few large samples of quasars with extensive monitoring data. To our knowledge, there are the quasars in the SDSS equatorial strip, with roughly 60 epochs over ~six years (Sesar et al. 2007; Bramich et al. 2008), the QUEST survey (Rengstorf et al. 2004b), whose light curves are

et al. 2004a), eclipsing binaries[8] (ECL; Wyrzykowski et al. 2003), ellipsoidal variable red giants[9] (ELL; Soszyński et al. 2004b), long secondary period variables (LSPs; Soszyński 2007), and long period variables (Miras, LPVs, and other semiregular variables; Soszyński et al. 2005) in the LMC. We separately extracted the OGLE-II light curves of Be stars from Keller et al. (2002), and ~300 OGLE-II and ~2700 OGLE-III light curves of the mid-IR-selected quasar candidates from

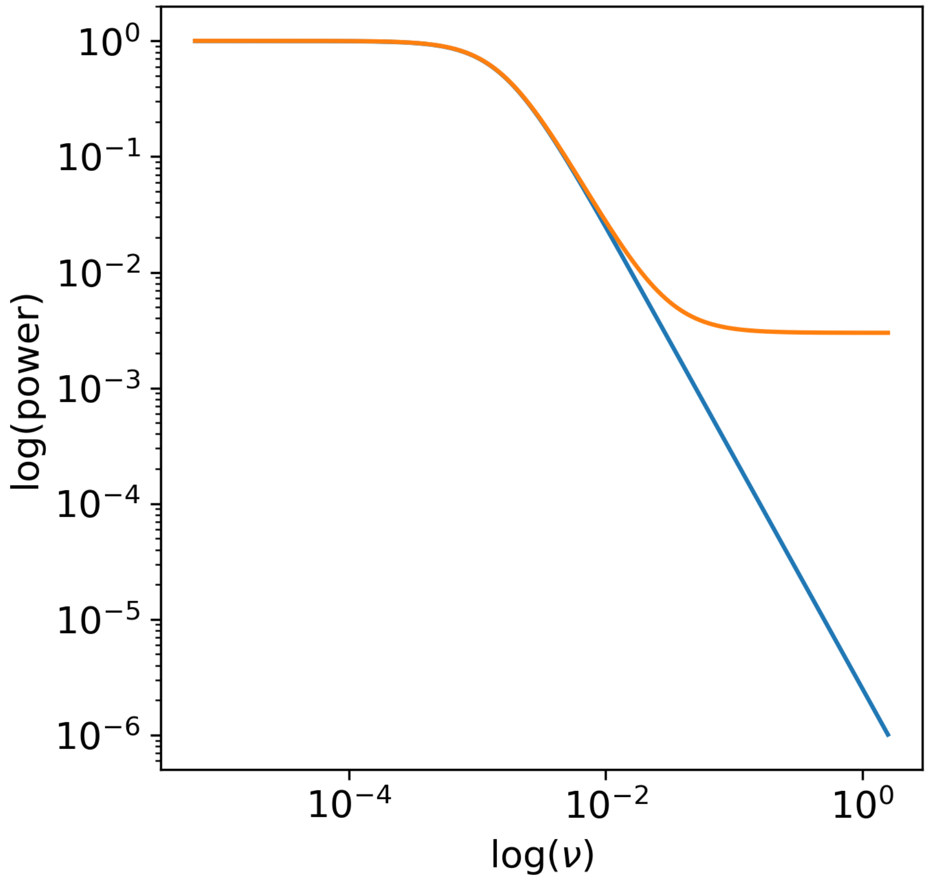
Power Spectral Density (PSD)
and
Auto-Correlation Function (ACF)

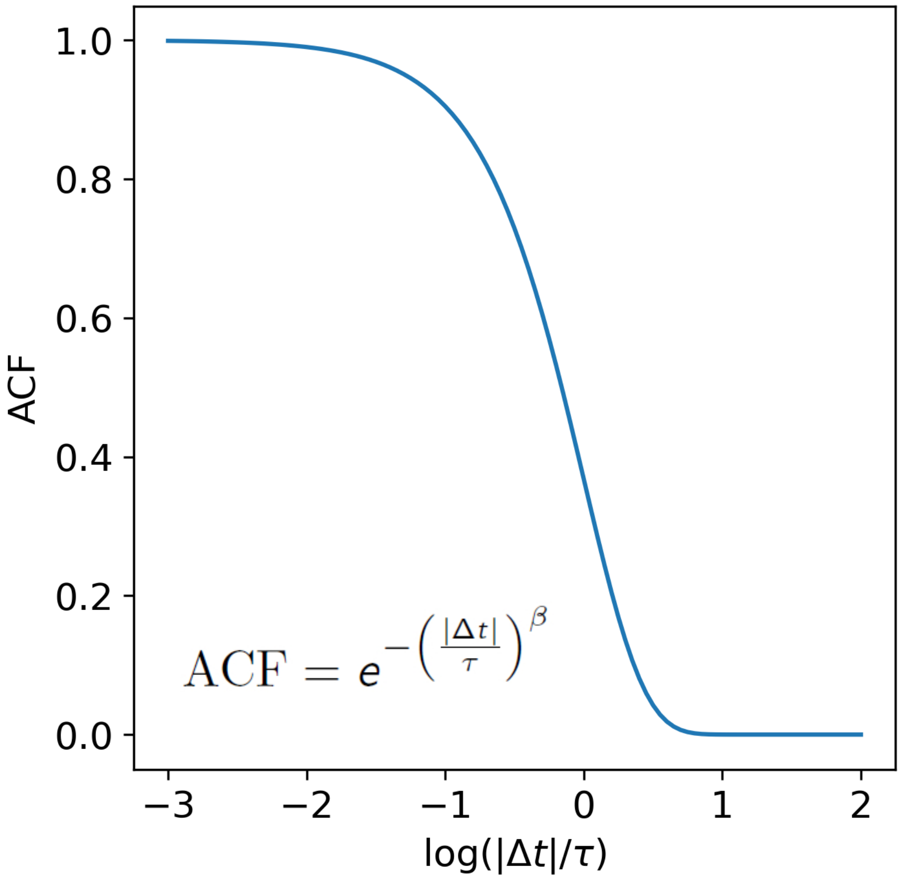
$$\mathrm{PSD}(\nu) = \int_{-\infty}^{\infty} \mathrm{ACF}(t)\, e^{-2\pi i \nu t}\, dt$$

$$\mathrm{ACF}(t) = \int_{-\infty}^{\infty} \mathrm{PSD}(\nu)\, e^{2\pi i \nu t}\, d\nu$$

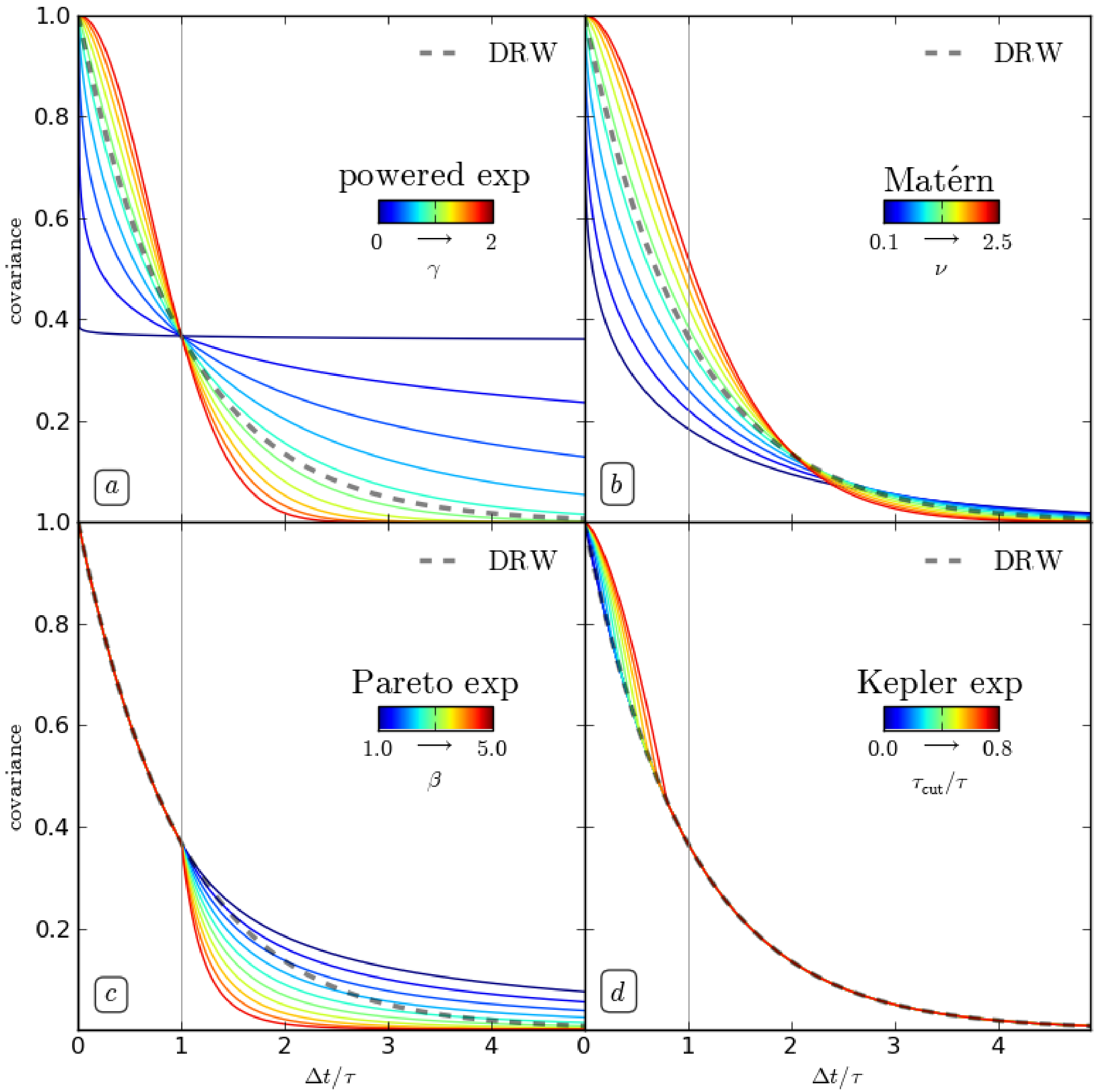
Wiener–Khinchin theorem

Power Spectral Density (PSD)
and
Auto-Correlation Function (ACF)



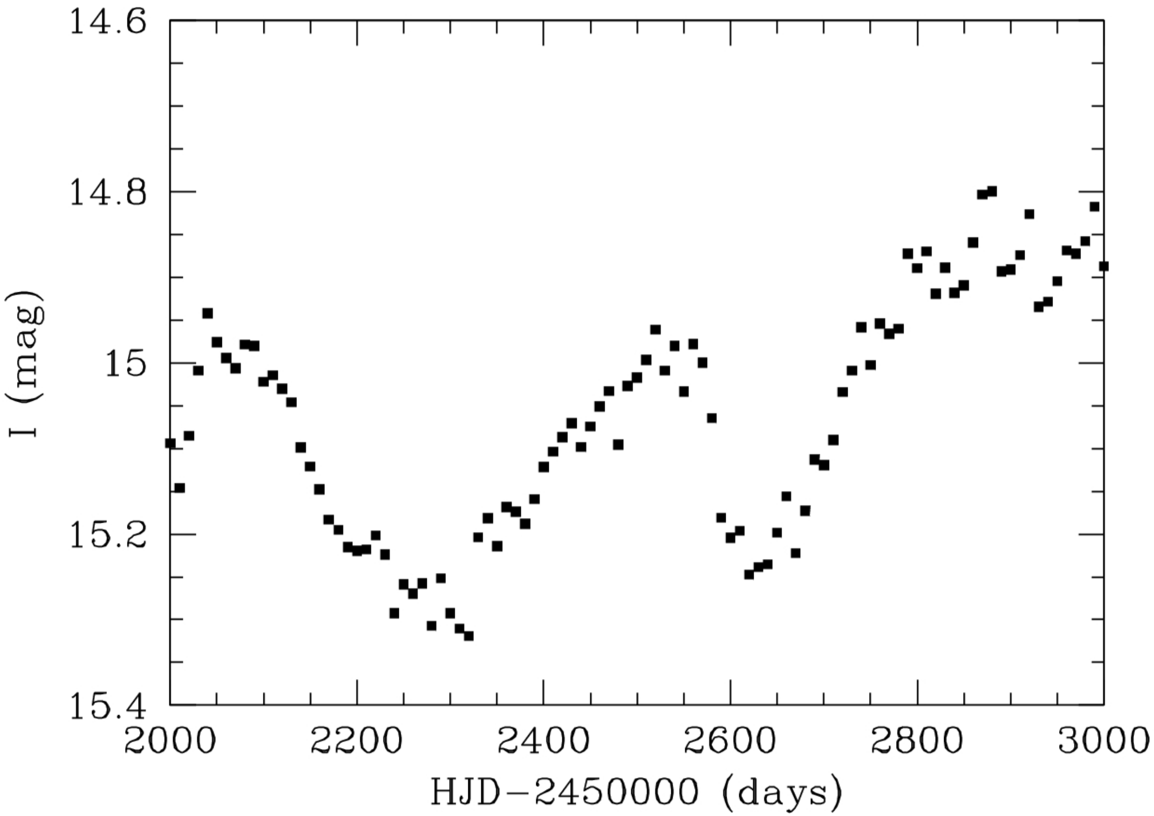


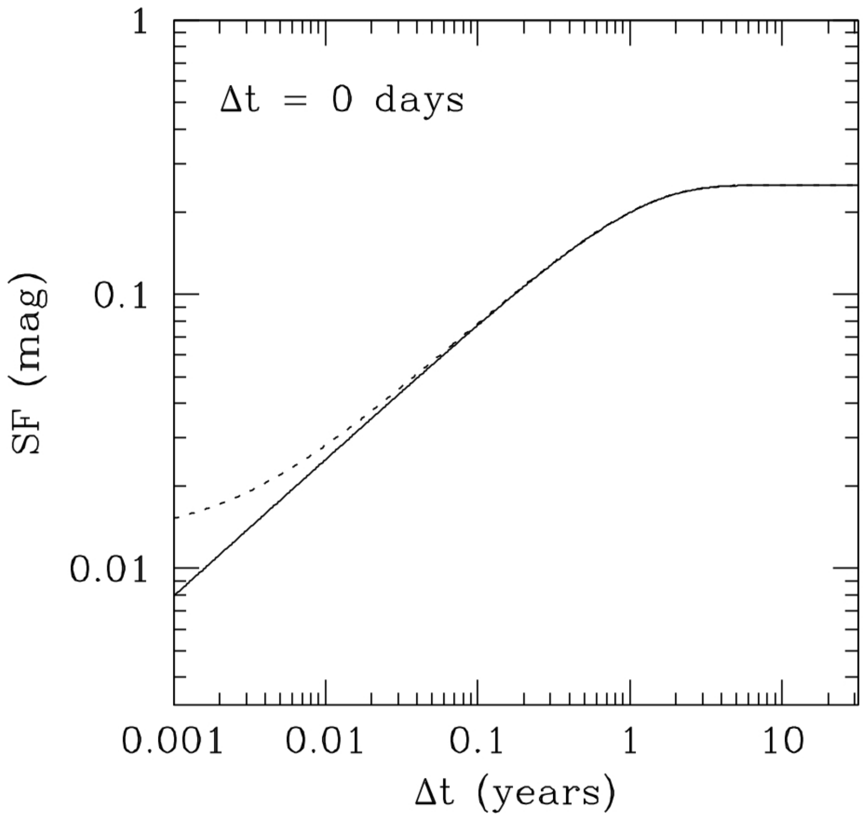
Auto-Correlation Function (ACF)



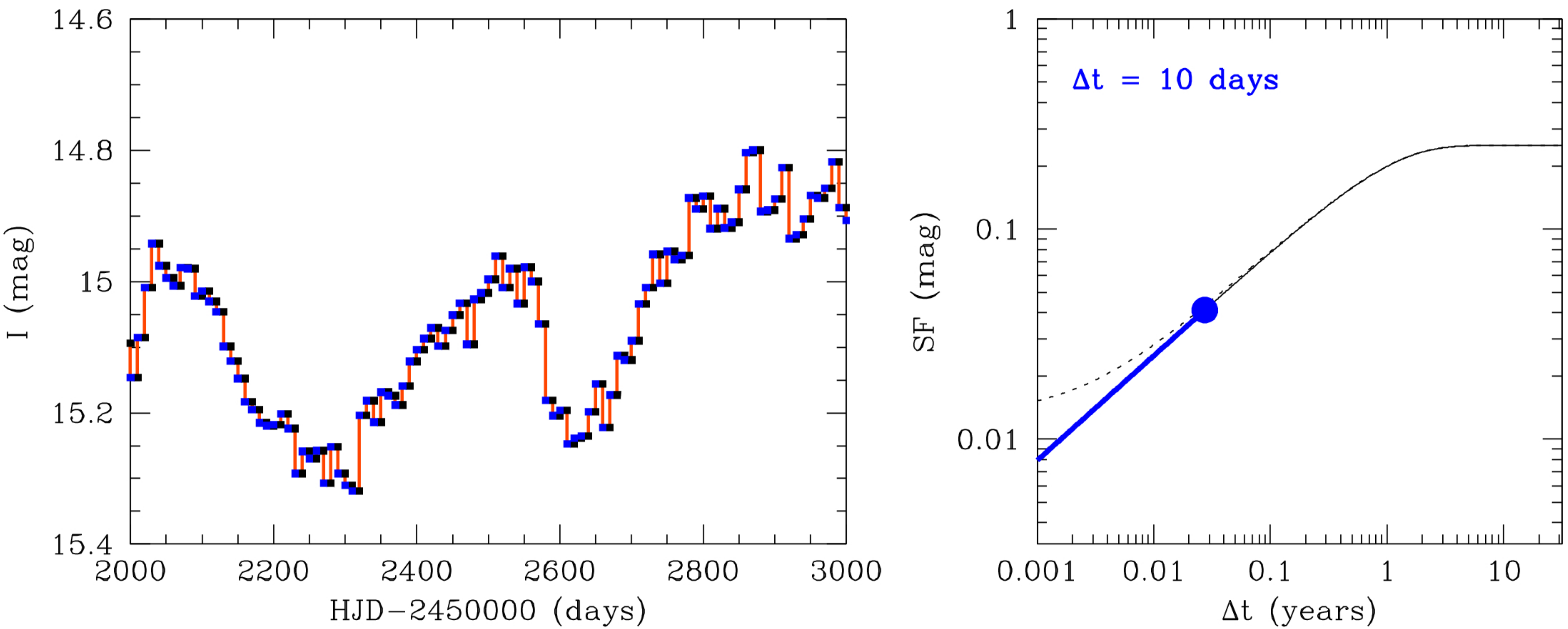
Javelin – Zu et al. 2013, ApJ, 765, 106

Structure Function

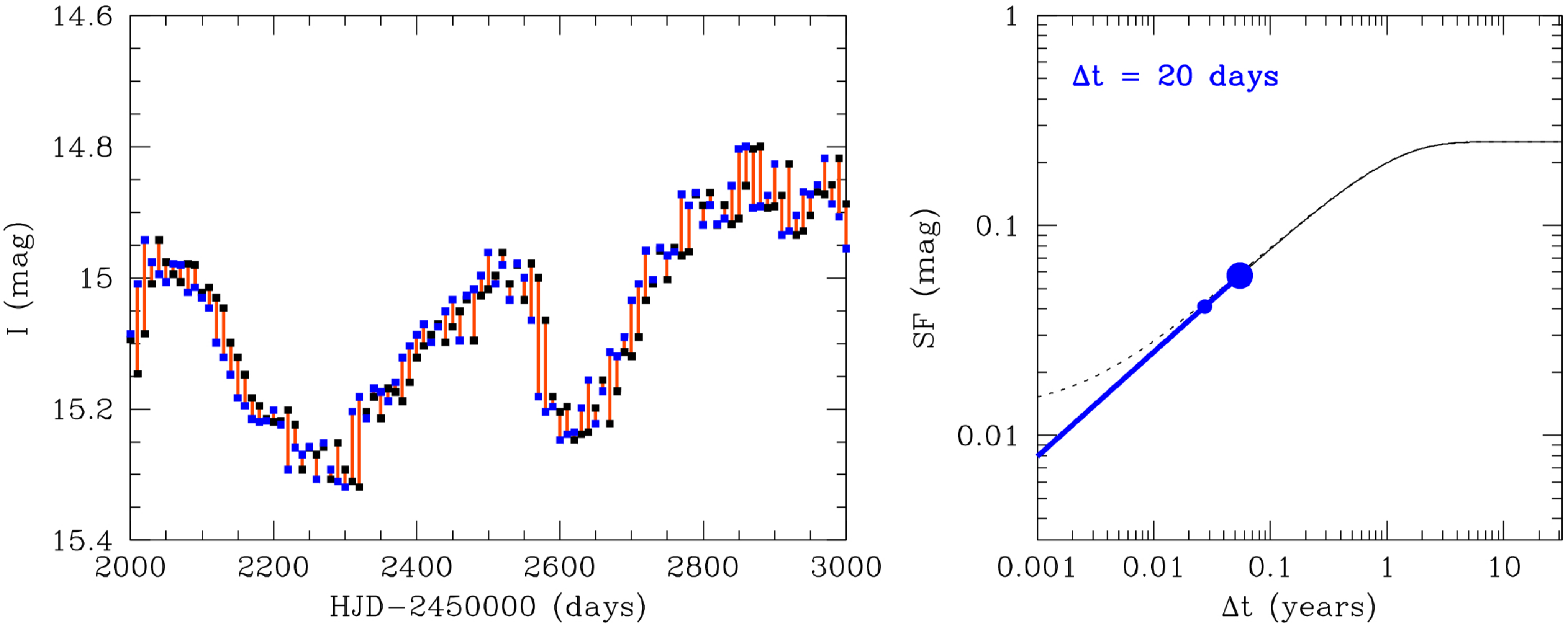




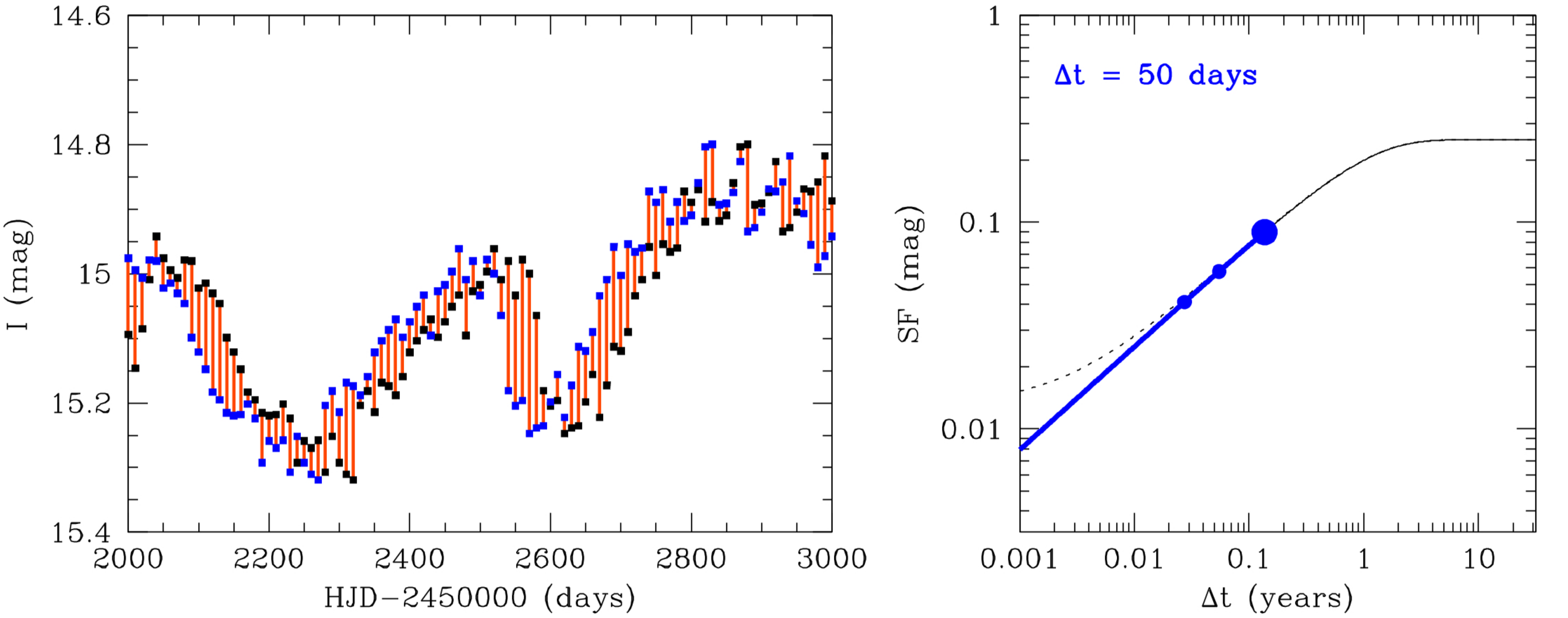
Structure Function



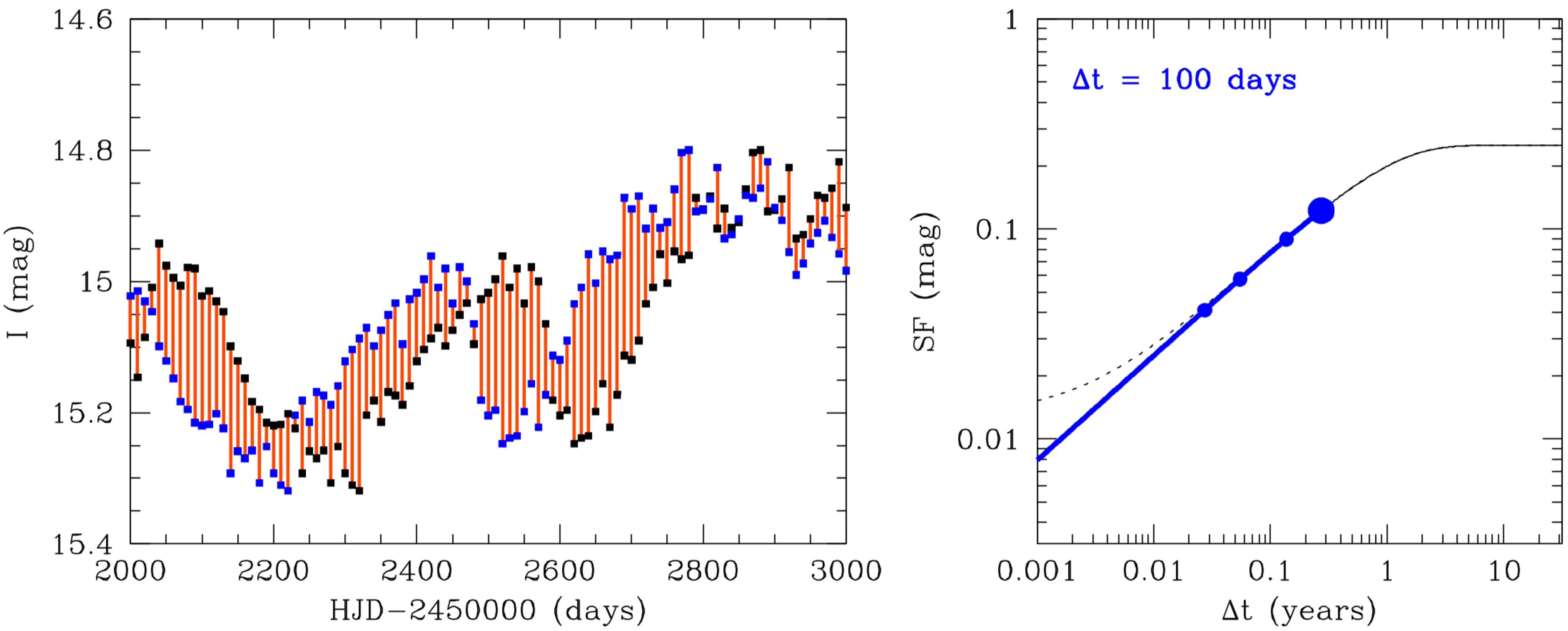
Structure Function



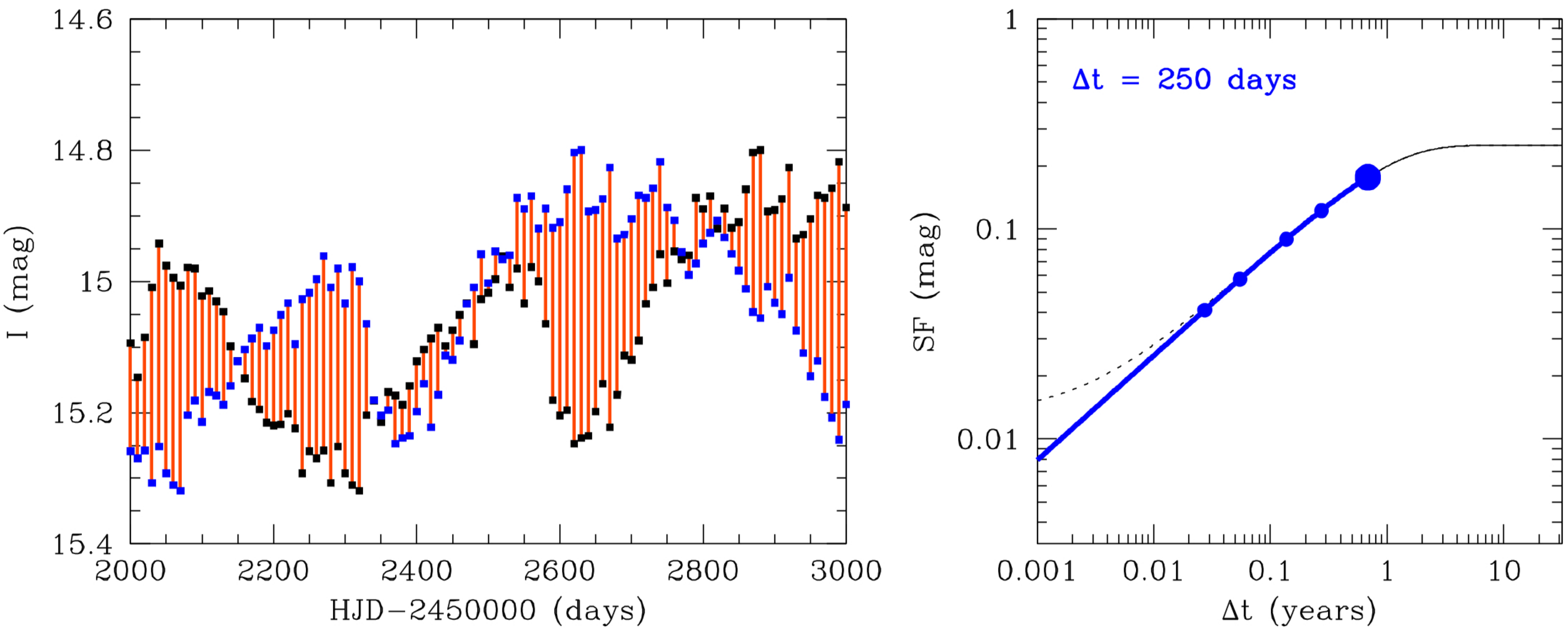
Structure Function



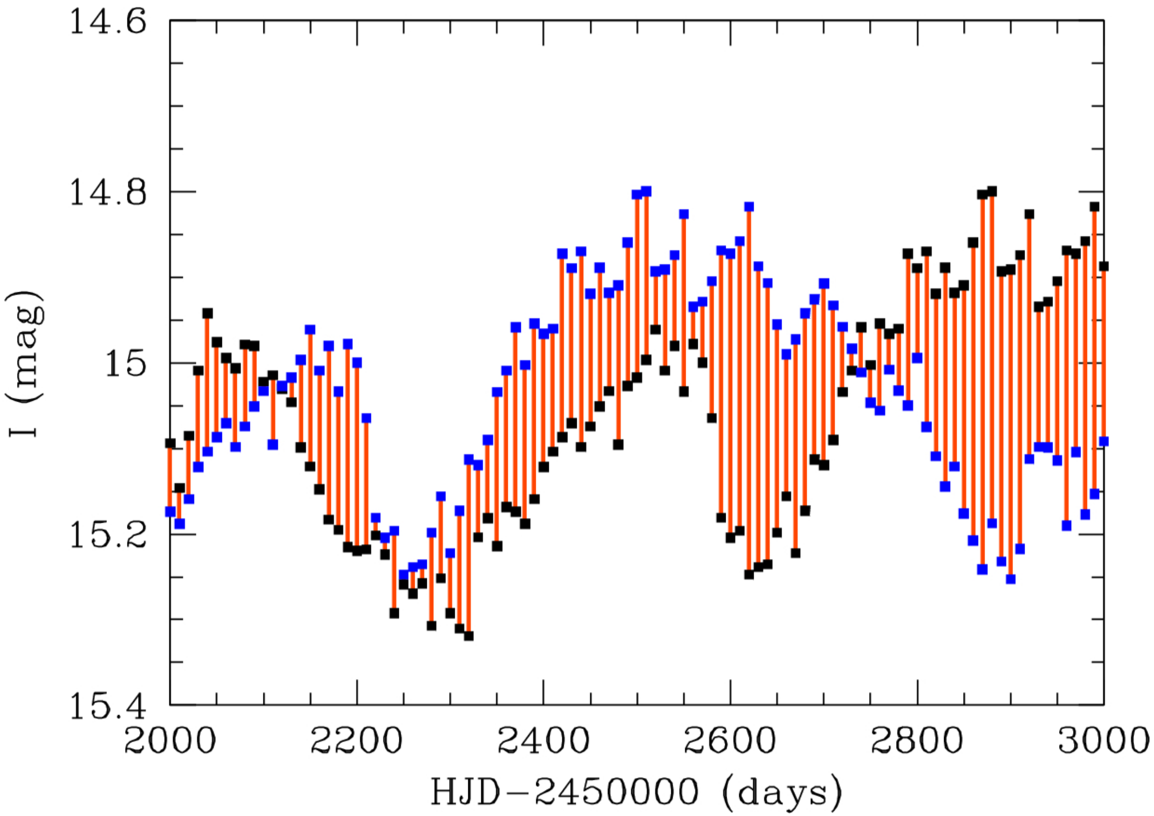
Structure Function

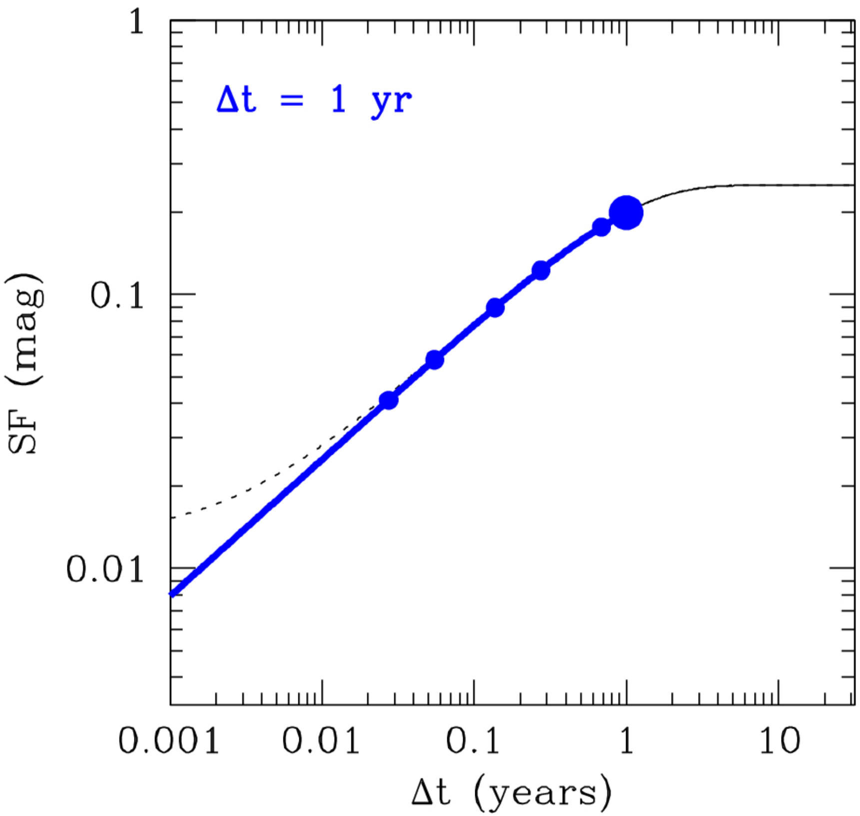


Structure Function

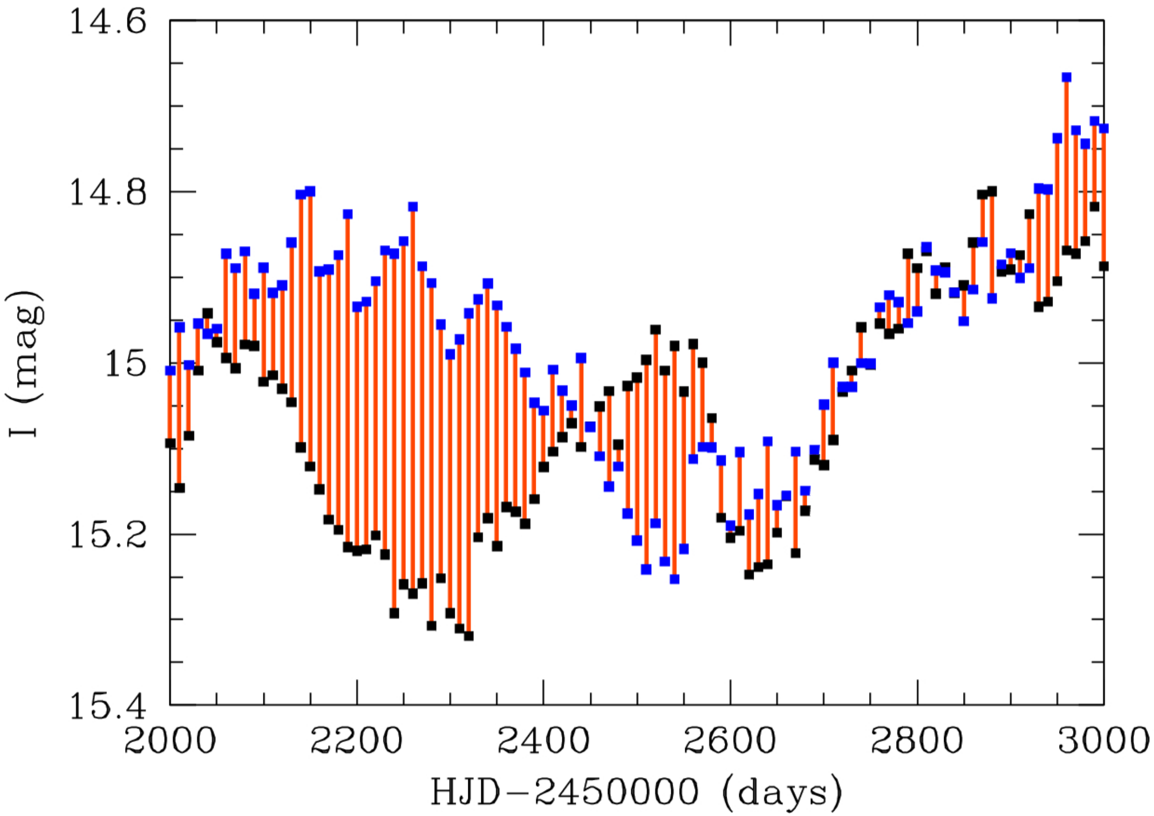


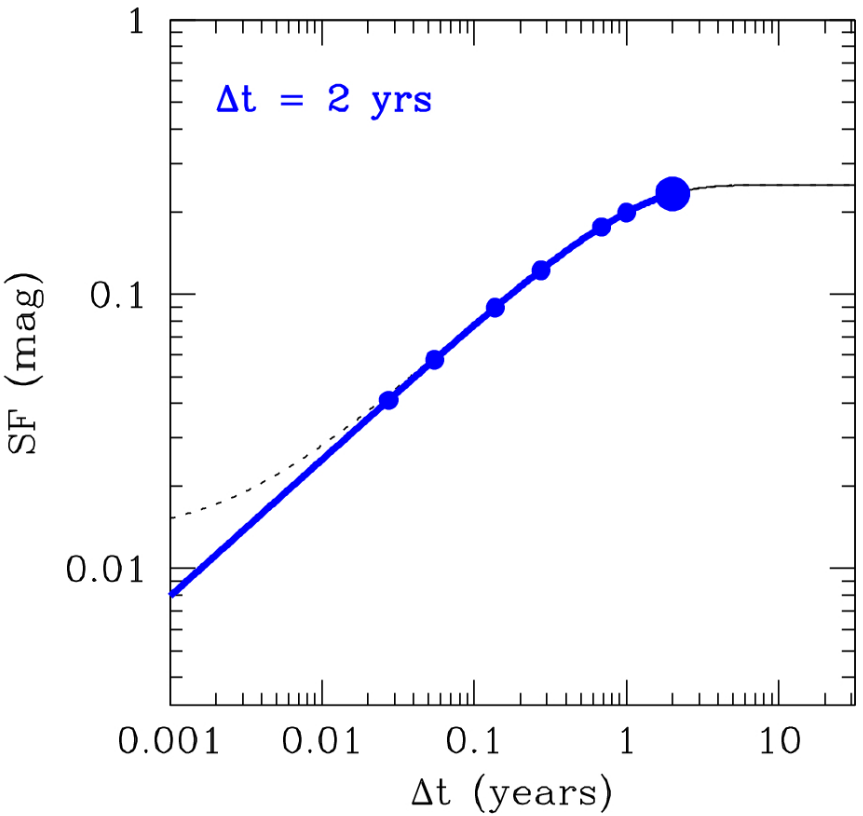
Structure Function



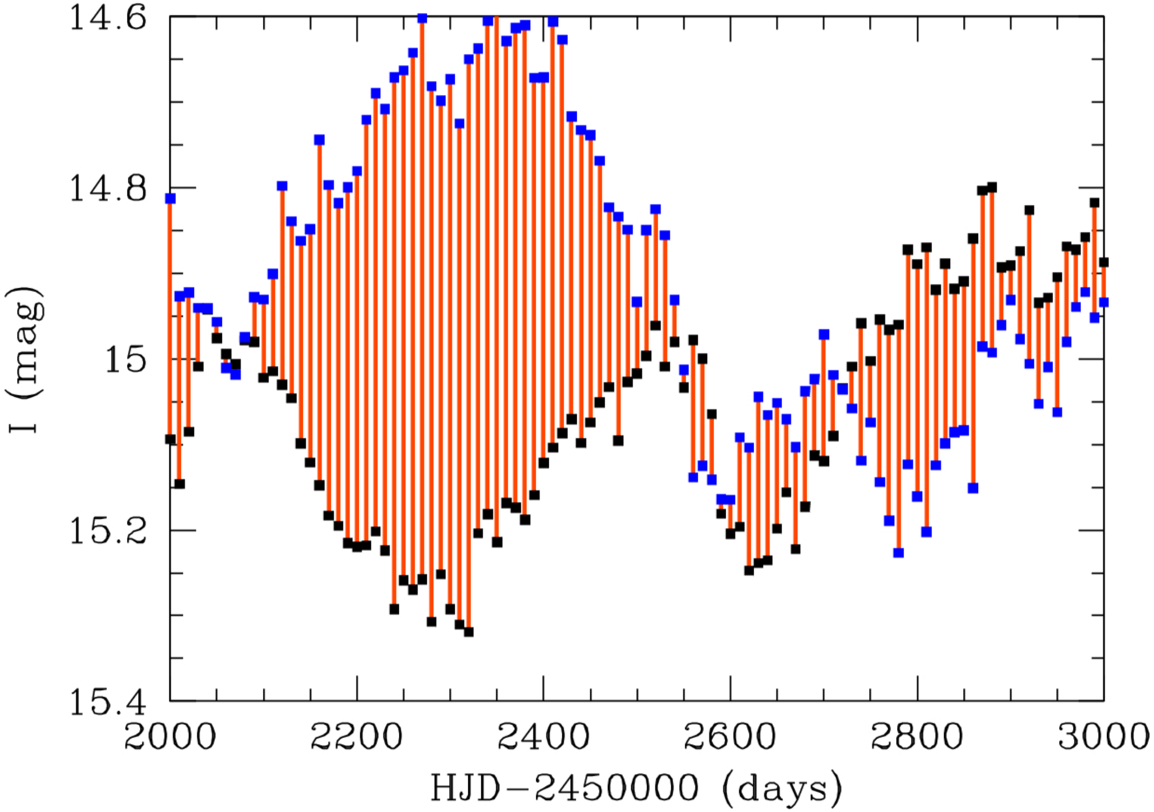


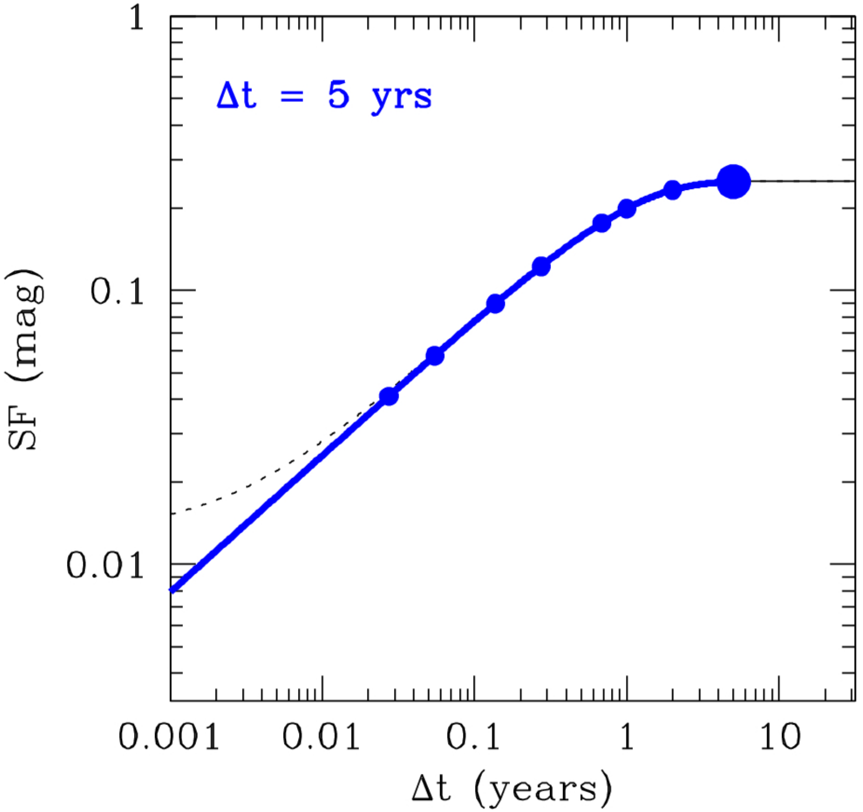
Structure Function





Structure Function





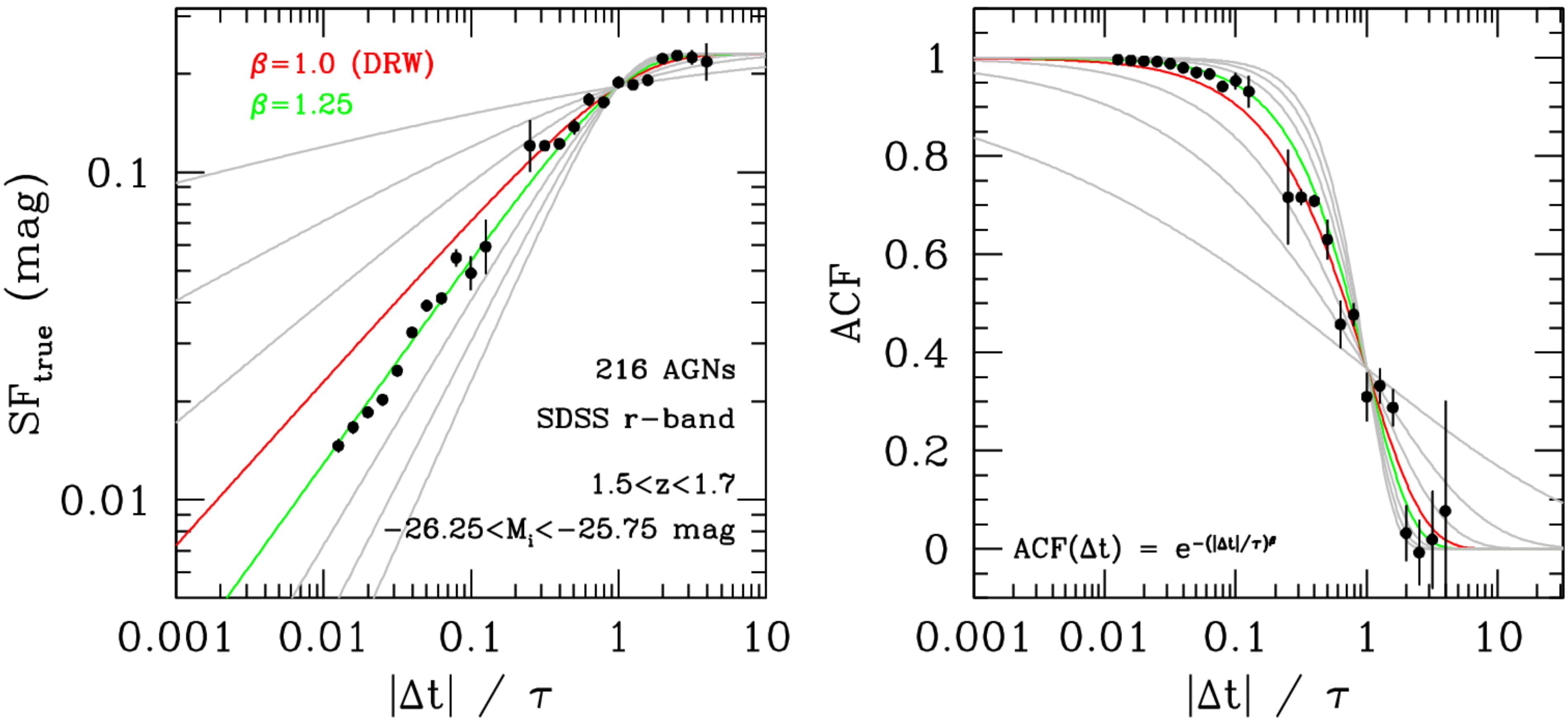
Structure Function

$$\mathrm{cov}(y_i, y_j) \equiv \mathrm{var}(y_i) - V(y_i, y_j)$$

$$V(y_i, y_j) = \frac{1}{2}\langle (y_i - y_j)^2 \rangle$$

$$SF = \sqrt{2V}$$

Structure Function and ACF



$$\mathrm{SF} = \sqrt{\mathrm{SF}_{\infty}^{2}\left(1 - \mathrm{ACF}\right) + 2\sigma_{n}^{2}}$$

$$\mathrm{ACF} = e^{-\left(\frac{|\Delta t|}{\tau}\right)^{\beta}}$$

Kepler - Zw229-15

2078 *V. P. Kasliwal et al.*

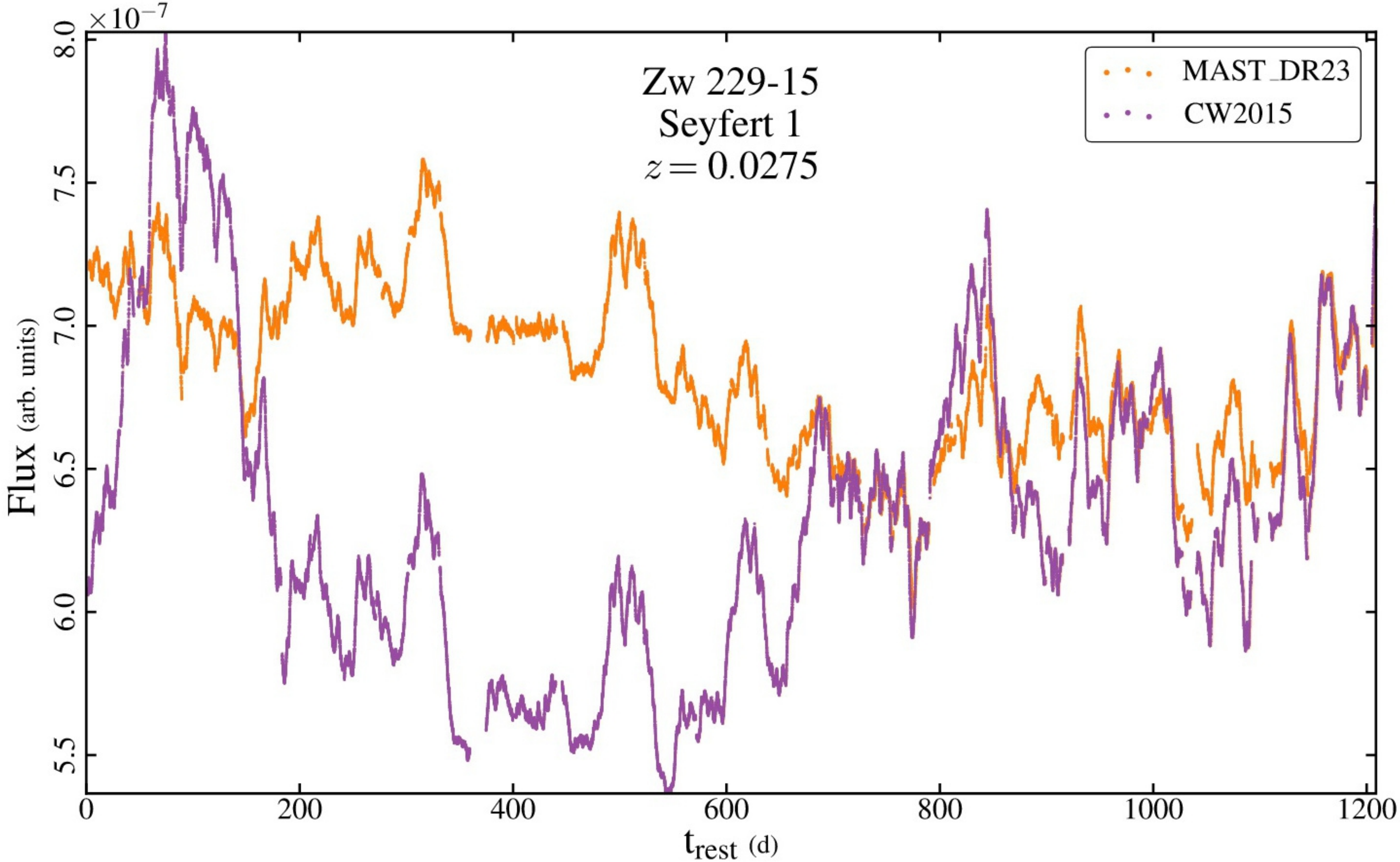


Figure 2. The *MAST_DR23* and *CW2015* light curves of Zw 229-15.

Kasliwal et al. 2015, MNRAS, 453, 2075

Kepler - Zw229-15

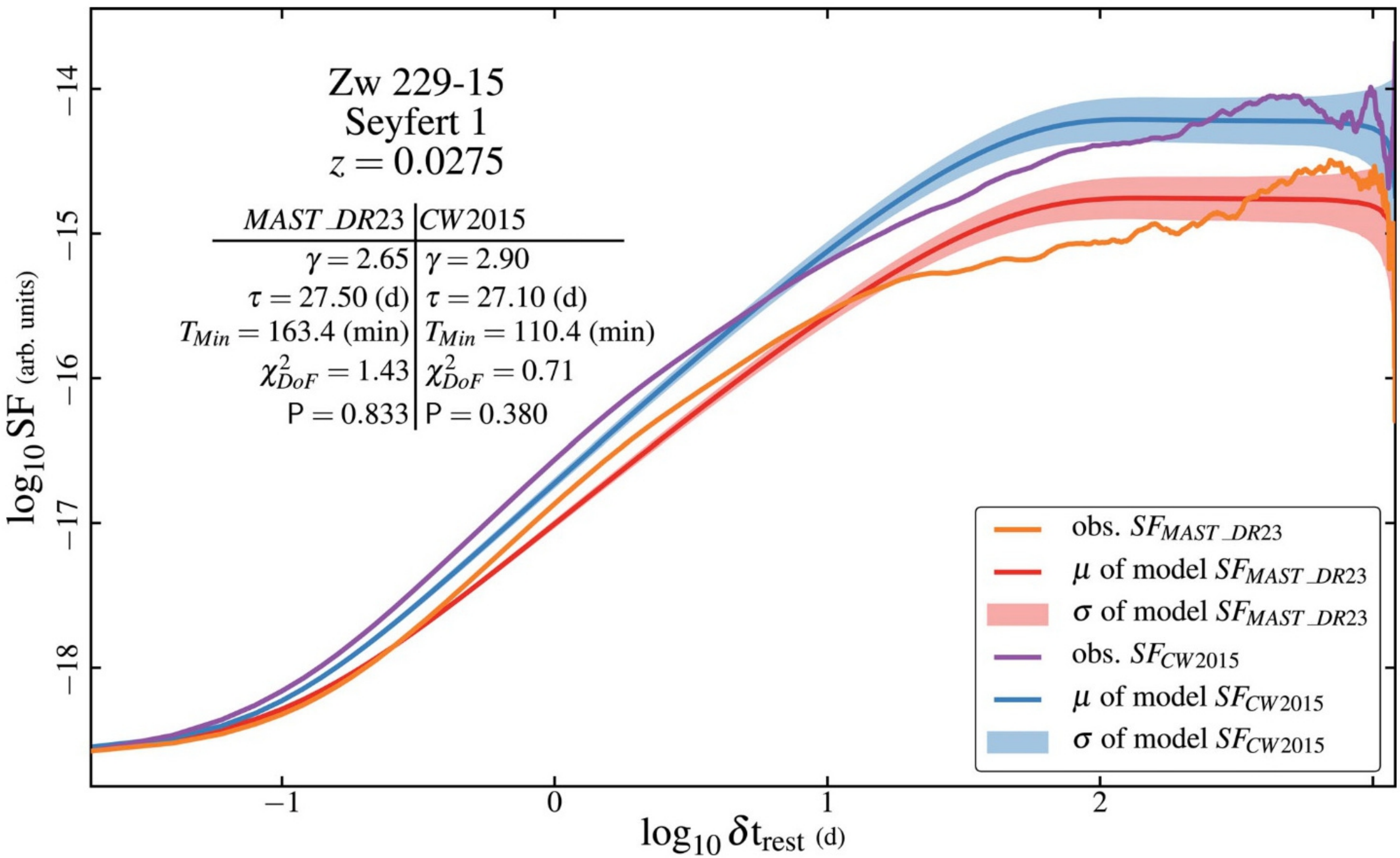


Figure 3. Structure functions of the *MAST_DR23* and *CW2015* light curve of Zw 229-15.

Kasliwal et al. 2015, MNRAS, 453, 2075

Correlations

The Astrophysical Journal, 864:87 (20pp), 2018 September 1 https://doi.org/10.3847/1538-4357/aad7f9

CrossMark

The QUEST–La Silla AGN Variability Survey: Connection between AGN Variability and Black Hole Physical Properties

P. Sánchez-Sáez[1,2], P. Lira[1], J. Mejía-Restrepo[1,2], L. C. Ho[3,4], P. Arévalo[5], M. Kim[6,7], R. Cartier[8], and P. Coppi[9]

[1] Departamento de Astronomia, Universidad de Chile, Casilla 36D, Santiago, Chile
[2] European Southern Observatory, Casilla 19001, Santiago 19, Chile
[3] Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People's Republic of China
[4] Department of Astronomy, School of Physics, Peking University, Beijing 100871, People's Republic of China
[5] Instituto de Fisica y Astronomia, Facultad de Ciencias, Universidad de Valparaiso, Gran Bretana No. 1111, Playa Ancha, Valparaiso, Chile
[6] Korea Astronomy and Space Science Institute, Daejeon 305-348, Republic of Korea
[7] Department of Astronomy and Atmospheric Sciences, Kyungpook National University, Daegu 702-701, Republic of Korea
[8] Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile
[9] Yale Center for Astronomy and Astrophysics, 260 Whitney Avenue, New Haven, CT 06520, USA

Received 2018 May 18; revised 2018 July 30; accepted 2018 August 1; published 2018 September 4

Abstract

We present our statistical analysis of the connection between active galactic nucleus (AGN) variability and physical properties of the central supermassive black hole (SMBH). We constructed optical light curves using data from the QUEST–La Silla AGN variability survey. To model the variability, we used the structure function, among the excess variance and the amplitude from Damp Random Walk (DRW) modeling. For the measurement of SMBH physical properties, we used public spectra from the Sloan Digital Sky Survey (SDSS). Our analysis is based on an original sample of 2345 sources detected in both SDSS and QUEST–La Silla. For 1473 of these sources we could perform a proper measurement of the spectral and variability properties, and 1348 of these sources were classified as variable (91.5%). We found that the amplitude of the variability (A) depends solely on the rest-frame emission wavelength and the Eddington ratio, where A anticorrelates with both $\lambda_{\rm rest}$ and $L/L_{\rm Edd}$. This suggests that AGN variability does not evolve over cosmic time, and its amplitude is inversely related to the accretion rate. We found that the logarithmic gradient of the variability (γ) does not correlate significantly with any SMBH physical parameter, since there is no statistically significant linear regression model with an absolute value of the slope higher than 0.1. Finally, we found that the general distribution of γ measured for our sample differs from the distribution of γ obtained for light curves simulated from a DRW process. For 20.6% of the variable sources in our sample, a DRW model is not appropriate to describe the variability, since γ differs considerably from the expected value of 0.5.

Sanchez-Saez et al. 2018, ApJ, 864, 87

Correlations

8 *M. Laurenti et al.*

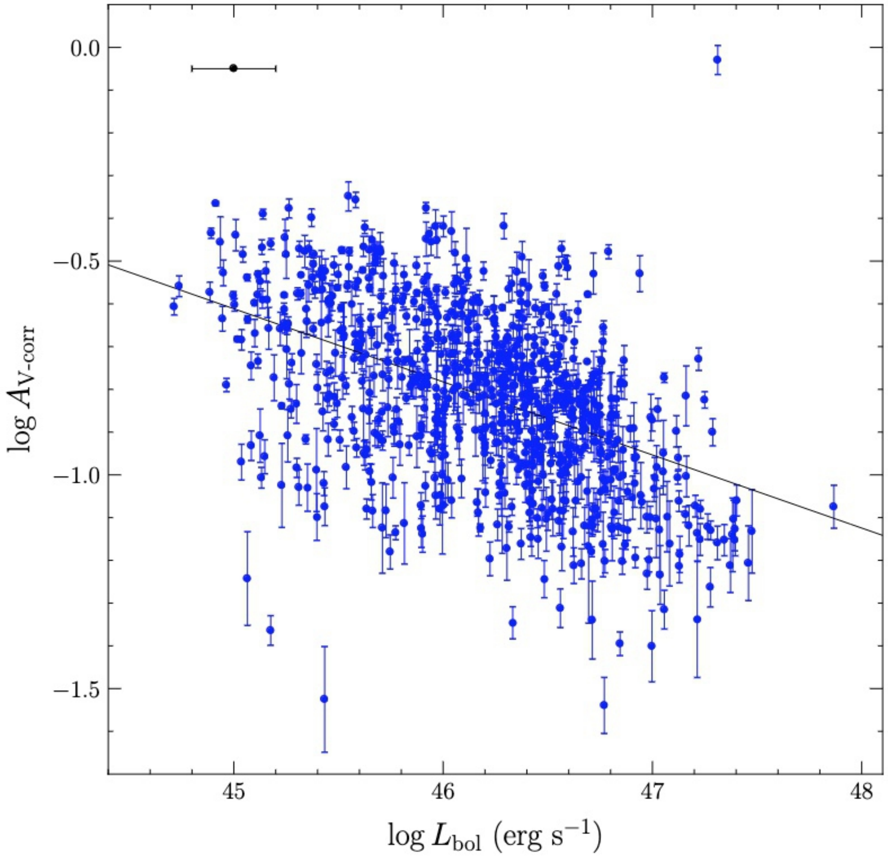


Figure 9. Variability amplitude is negatively correlated with the bolometric luminosity. The typical error bar of log L_{bol} is indicated in black in the upper-left corner. The Spearman's correlation coefficient is $\rho_s = -0.48$, with null probability $p(>|\rho_s|) < 10^{-10}$. The black solid line describes the best-fit relation.

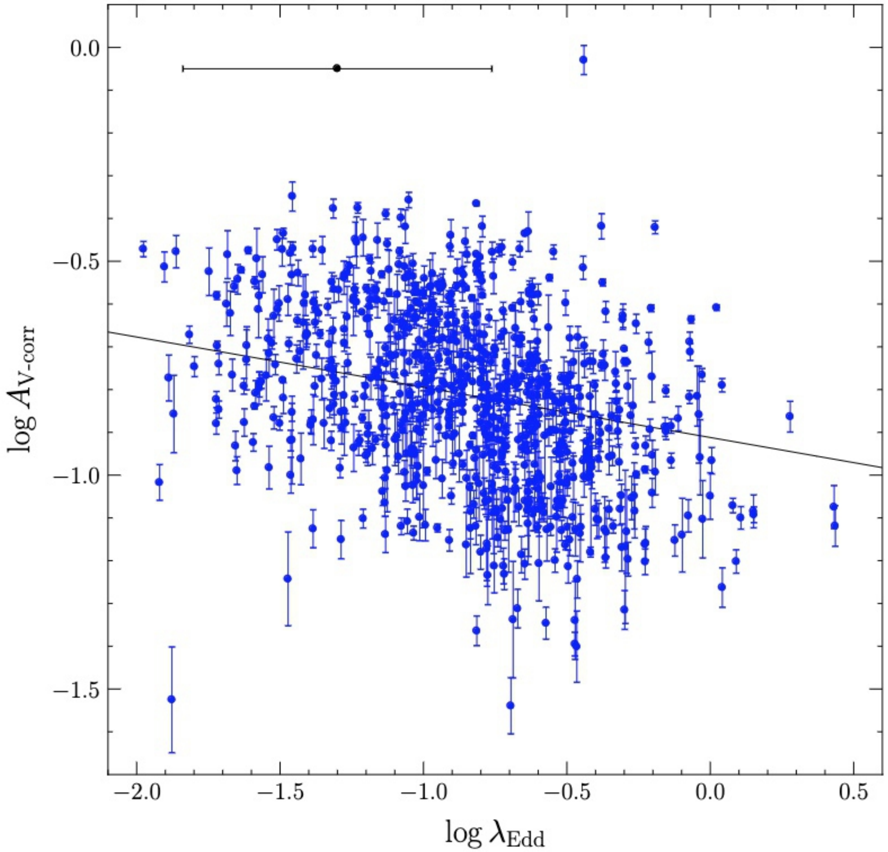


Figure 10. Variability amplitude is anti-correlated with the Eddington ratio. The typical error bar of log λ_{Edd} is indicated in black in the upper-left corner. The Spearman's correlation coefficient is $\rho_s = -0.30$, with null probability $p(>|\rho_s|) < 10^{-10}$. The black solid line describes the best-fit relation.

~800 AGN from Catalina (10 yrs) and MEXSAS2 (XMMN)

Laurenti et al. 2020, MNRAS, 499, 6053

Correlations

A&A 664, A117 (2022)
https://doi.org/10.1051/0004-6361/202142750

Astronomy & Astrophysics

A structure function analysis of VST-COSMOS AGN⋆,⋆⋆

D. De Cicco[1,2,3], F. E. Bauer[1,2,4], M. Paolillo[3,5,6], P. Sánchez-Sáez[7,2,1], W. N. Brandt[8,9,10], F. Vagnetti[11,12], G. Pignata[13,2], M. Radovich[14], and M. Vaccari[15,16,17]

ABSTRACT

Context. We present our sixth work in a series dedicated to variability studies of active galactic nuclei (AGN), based on the survey of the COSMOS field by the VLT Survey Telescope (VST). Its 54 r-band visits over 3.3 yr and single-visit depth of 24.6 r-band mag make this dataset a valuable scaled-down version that can help forecast the performance of the Rubin Observatory Legacy Survey of Space and Time (LSST).
Aims. This work is centered on the analysis of the structure function (SF) of VST-COSMOS AGN, investigating possible differences in its shape and slope related to how the AGN were selected, and explores possible connections between the AGN ensemble variability and the black-hole mass, accretion rate, bolometric luminosity, redshift, and obscuration of the source. Given its features, our dataset opens up the exploration of samples ~2 mag fainter than most literature to date.
Methods. We identified several samples of AGN – 677 in total – obtained through a variety of selection techniques partly overlapping. Our analysis compares the results for the various samples. We split each sample in two based on the median of the physical property of interest, and analyzed the differences in the SF shape and slope, and their possible causes.
Results. While the SF shape does not change with depth, it is highly affected by the type of AGN (unobscured or obscured) included in the sample. Where a linear region can be identified, we find that the variability amplitude is anticorrelated to the accretion rate and bolometric luminosity, consistent with previous literature on the topic, while no dependence on black-hole mass emerges from this study. With its longer baseline and denser and more regular sampling, the LSST will allow for an improved characterization of the SF and its dependencies on the mentioned physical properties over much larger AGN samples.

De Cicco et al. 2022, A&A, 664, A117

Correlations

The Astrophysical Journal, 826:118 (16pp), 2016 August 1
doi:10.3847/0004-637X/826/2/118

CrossMark

REVISITING STOCHASTIC VARIABILITY OF AGNs WITH STRUCTURE FUNCTIONS

Szymon Kozłowski
Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland; simkoz@astrouw.edu.pl
Received 2016 March 12; revised 2016 May 12; accepted 2016 May 16; published 2016 July 26

ABSTRACT

Discrepancies between reported structure function (SF) slopes and their overall flatness as compared to the expectations from the damped random walk (DRW) model, which generally well describes the variability of active galactic nuclei (AGNs), have triggered us to study this problem in detail. We review common AGN variability observables and identify their most common problems. Equipped with this knowledge, we study ~9000 *r*-band AGN light curves from Stripe 82 of the Sloan Digital Sky Survey, using SFs described by stochastic processes with the power exponential covariance matrix of the signal. We model the "subensemble" SFs in the redshift–absolute magnitude bins with the full SF equation (including the turnover and the noise part) and a single power law (SPL; in the "red noise regime" after subtracting the noise term). The distribution of full-equation SF (SPL) slopes peaks at $\gamma = 0.55 \pm 0.08$ (0.52 ± 0.06) and is consistent with the DRW model. There is a hint of a weak correlation of γ with the luminosity and a lack of correlation with the black hole mass. The typical decorrelation timescale in the optical is $\tau = 0.97 \pm 0.46$ year. The SF amplitude at one year obtained from the SPL fitting is $SF_0 = 0.22 \pm 0.06$ mag and is overestimated because the SF is already at the turnover part, so the true value is $SF_0 = 0.20 \pm 0.06$ mag. The asymptotic variability is $SF_\infty = 0.25 \pm 0.06$ mag. It is strongly anticorrelated with both the luminosity and the Eddington ratio and is correlated with the black hole mass. The reliability of these results is fortified with Monte Carlo simulations.

Kozłowski 2016, ApJ, 826, 118

Correlations

The Astrophysical Journal, 849:110 (17pp), 2017 November 10 https://doi.org/10.3847/1538-4357/aa9188

CrossMark

Near-infrared Variability of Obscured and Unobscured X-Ray-selected AGNs in the COSMOS Field

P. Sánchez[1], P. Lira[1], R. Cartier[2,3], V. Pérez[1], N. Miranda[4], C. Yovaniniz[1], P. Arévalo[5], B. Milvang-Jensen[6], J. Fynbo[6], J. Dunlop[7], P. Coppi[8], and S. Marchesi[9]
[1] Departamento de Astronomía, Universidad de Chile, Casilla 36D, Santiago, Chile
[2] Department of Physics and Astronomy, University of Southampton, Southampton, Hampshire, SO17 1BJ, UK
[3] Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile
[4] Departamento de Ciencias de la Computación, Universidad de Chile, Santiago, Chile
[5] Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Gran Bretana No. 1111, Playa Ancha, Valparaíso, Chile
[6] Dark Cosmology Centre, Niels Bohr Institute,University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark
[7] Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK
[8] Yale Center for Astronomy and Astrophysics, 260 Whitney Avenue, New Haven, CT 06520, USA
[9] Department of Physics & Astronomy, Clemson University, Clemson, SC 29634, USA
Received 2017 March 9; revised 2017 September 13; accepted 2017 October 3; published 2017 November 7

Abstract

We present our statistical study of near-infrared (NIR) variability of X-ray-selected active galactic nuclei (AGNs) in the COSMOS field, using UltraVISTA data. This is the largest sample of AGN light curves in $YJHK_s$ bands, making it possible to have a global description of the nature of AGNs for a large range of redshifts and for different levels of obscuration. To characterize the variability properties of the sources, we computed the structure function. Our results show that there is an anticorrelation between the structure function A parameter (variability amplitude) and the wavelength of emission and a weak anticorrelation between A and the bolometric luminosity. We find that broad-line (BL) AGNs have a considerably larger fraction of variable sources than narrow-line (NL) AGNs and that they have different distributions of the A parameter. We find evidence that suggests that most of the low-luminosity variable NL sources correspond to BL AGNs, where the host galaxy could be damping the variability signal. For high-luminosity variable NL sources, we propose that they can be examples of "true type II" AGNs or BL AGNs with limited spectral coverage, which results in missing the BL emission. We also find that the fraction of variable sources classified as unobscured in the X-ray is smaller than the fraction of variable sources unobscured in the optical range. We present evidence that this is related to the differences in the origin of the obscuration in the optical and X-ray regimes.

Sanchez et al. 2017, ApJ, 849, 110

Correlations

THE ASTROPHYSICAL JOURNAL, 834:111 (20pp), 2017 January 10 doi:10.3847/1538-4357/834/2/111

CrossMark

OPTICAL VARIABILITY OF AGNs IN THE PTF/iPTF SURVEY

NEVEN CAPLAR, SIMON J. LILLY, AND BENNY TRAKHTENBROT[1]
Institute for Astronomy, Department of Physics, ETH Zurich, Wolfgang-Pauli-Strasse 27, 8093, Zurich, Switzerland; neven.caplar@phys.ethz.ch
Received 2016 August 22; revised 2016 November 3; accepted 2016 November 8; published 2017 January 6

ABSTRACT

We characterize the optical variability of quasars in the Palomar Transient Factory and intermediate Palomar Transient Factory (PTF/iPTF) surveys. We re-calibrate the *r*-band light curves for ~28,000 luminous, broad-line active galactic nuclei from the SDSS, producing a total of ~2.4 million photometric data points. We utilize both the structure function (SF) and power spectrum density (PSD) formalisms to search for links between the optical variability and the physical parameters of the accreting supermassive black holes that power the quasars. The excess variance (SF^2) of the quasar sample tends to zero at very short time separations, validating our re-calibration of the time-series data. We find that the the amplitude of variability at a given time-interval, or equivalently the timescale of variability to reach a certain amplitude, is most strongly correlated with luminosity with weak or no dependence on black hole mass and redshift. For a variability level of $SF(\tau) = 0.07$ mag, the timescale has a dependency of $\tau \propto L^{0.4}$. This is broadly consistent with the expectation from a simple Keplerian accretion disk model, which provides $\tau \propto L^{0.5}$. The PSD analysis also reveals that many quasar light curves are steeper than a damped random walk. We find a correlation between the steepness of the PSD slopes, specifically the fraction of slopes steeper than 2.5, and black hole mass, although we cannot exclude the possibility that luminosity or Eddington ratio are the drivers of this effect. This effect is also seen in the SF analysis of the (i)PTF data, and in a PSD analysis of quasars in the SDSS Stripe 82.

Caplar, Lilly & Trakhtenbrot 2017, ApJ, 834, 111

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Correlations

MNRAS **514,** 164–184 (2022)
Advance Access publication 2022 May 18
https://doi.org/10.1093/mnras/stac1259

Optical variability of quasars with 20-yr photometric light curves

Zachary Stone,[1★] Yue Shen,[1,2★] Colin J. Burke,[1,3] Yu-Ching Chen,[1,3] Qian Yang,[1,4] Xin Liu,[1,2] R. A. Gruendl,[1,3] M. Adamów,[3] F. Andrade-Oliveira,[5,6] J. Annis,[7] D. Bacon,[8] E. Bertin,[9,10] S. Bocquet,[11] D. Brooks,[12] D. L. Burke,[13,14] A. Carnero Rosell,[6] M. Carrasco Kind,[1,3] J. Carretero,[15,16] L. N. da Costa,[6,17] M. E. S. Pereira,[19] J. De Vicente,[20] S. Desai,[21] H. T. Diehl,[7] P. Doel,[12] I. Ferrero,[22] D. N. Friedel,[3] J. Frieman,[7,13] J. García-Bellido,[23] E. Gaztanaga,[24,25] D. Gruen,[26] G. Gutierrez,[7] S. R. Hinton,[27] D. L. Hollowood,[28] K. Honscheid,[29,30] D. J. James,[4] K. Kuehn,[31,32] N. Kuropatkin,[7] C. Lidman,[33,34] M. A. G. Maia,[6,17] F. Menanteau,[1,3] R. Miquel,[35,36] R. Morgan,[37] F. Paz-Chinchón,[3,38] A. Pieres,[6,17] A. A. Plazas Malagón,[39] M. Rodriguez-Monroy,[20] E. Sanchez,[20] V. Scarpine,[7] S. Serrano,[24,25] I. Sevilla-Noarbe,[20] M. Smith,[40] E. Suchyta,[41] M. E. C. Swanson,[42] G. Tarlé,[18] and C. To[29] (DES Collaboration)

ABSTRACT

We study the optical *gri* photometric variability of a sample of 190 quasars within the SDSS Stripe 82 region that have long-term photometric coverage during ∼1998−2020 with SDSS, PanSTARRS-1, the Dark Energy Survey, and dedicated follow-up monitoring with Blanco 4m/DECam. With on average ∼200 nightly epochs per quasar per filter band, we improve the parameter constraints from a Damped Random Walk (DRW) model fit to the light curves over previous studies with 10–15 yr baselines and $\lesssim 100$ epochs. We find that the average damping time-scale $\tau_{\rm DRW}$ continues to rise with increased baseline, reaching a median value of ∼750 d (*g* band) in the rest frame of these quasars using the 20-yr light curves. Some quasars may have gradual, long-term trends in their light curves, suggesting that either the DRW fit requires very long baselines to converge, or that the underlying variability is more complex than a single DRW process for these quasars. Using a subset of quasars with better-constrained $\tau_{\rm DRW}$ (less than 20 per cent of the baseline), we confirm a weak wavelength dependence of $\tau_{\rm DRW} \propto \lambda^{0.51 \pm 0.20}$. We further quantify optical variability of these quasars over days to decades time-scales using structure function (SF) and power spectrum density (PSD) analyses. The SF and PSD measurements qualitatively confirm the measured (hundreds of days) damping time-scales from the DRW fits. However, the ensemble PSD is steeper than that of a DRW on time-scales less than ∼ a month for these luminous quasars, and this second break point correlates with the longer DRW damping time-scale.

Stone et al. 2022, MNRAS, 514, 164

Correlations

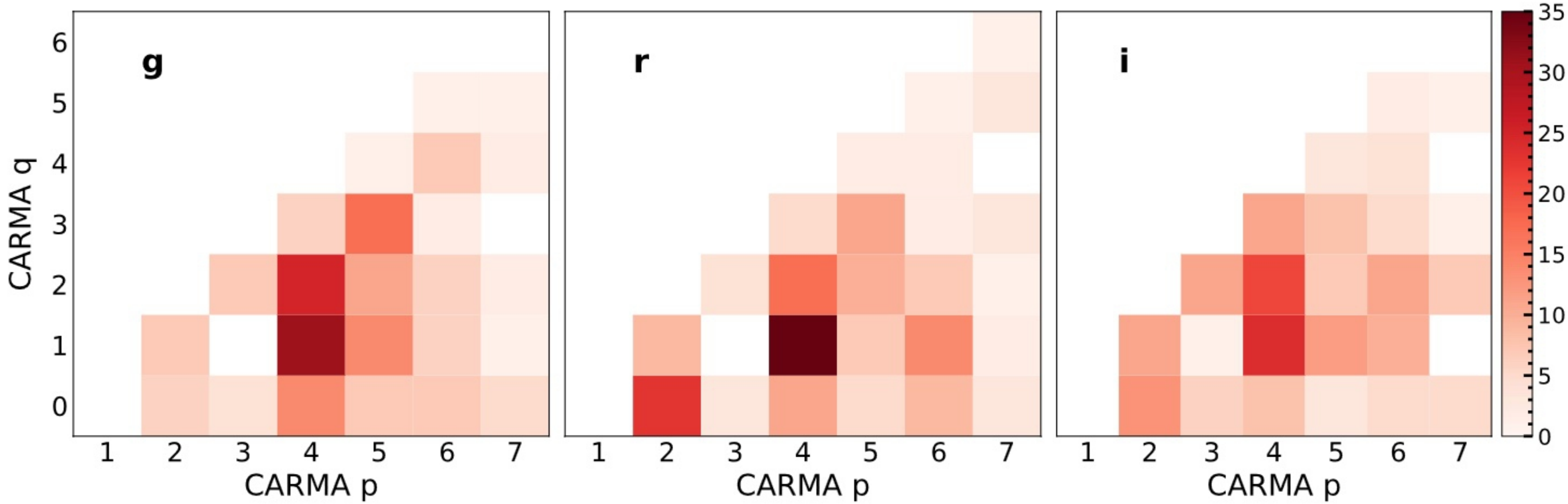


Figure 12. The distribution of best-fitting CARMA (p, q) parameters when fitting our quasar light curves to a generalized CARMA model (requiring $q < p$ for stationary processes). The best-fitting order for the CARMA model for a given quasar light curve was chosen as the fit with the minimum value for the AICc. The AIC (Akaike Information Criterion, Akaike 1973) is a statistic measuring an estimate of information loss due to assuming a particular model generates a certain set of data, which can be corrected for a finite sample size to give the AICc (Hurvich & Tsai 1989) (discussed further in A3). Darker colours indicate higher incidence. There is a tendency of clustering of quasars around $(p, q) \approx (4, 2)$.

Stone et al. 2022, MNRAS, 514, 164

Correlations

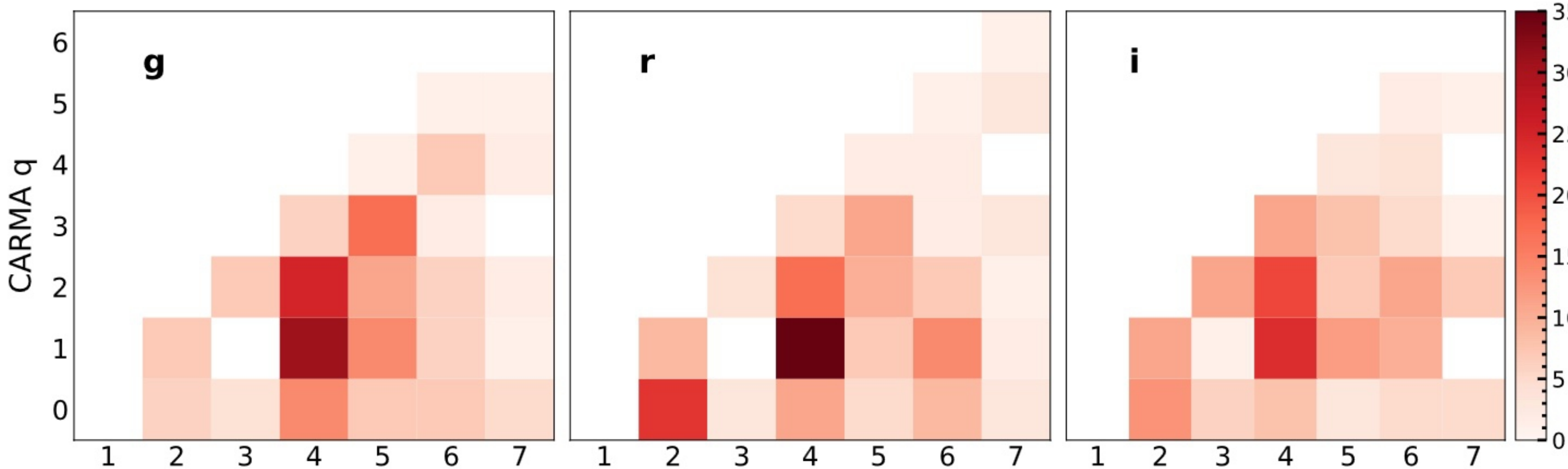
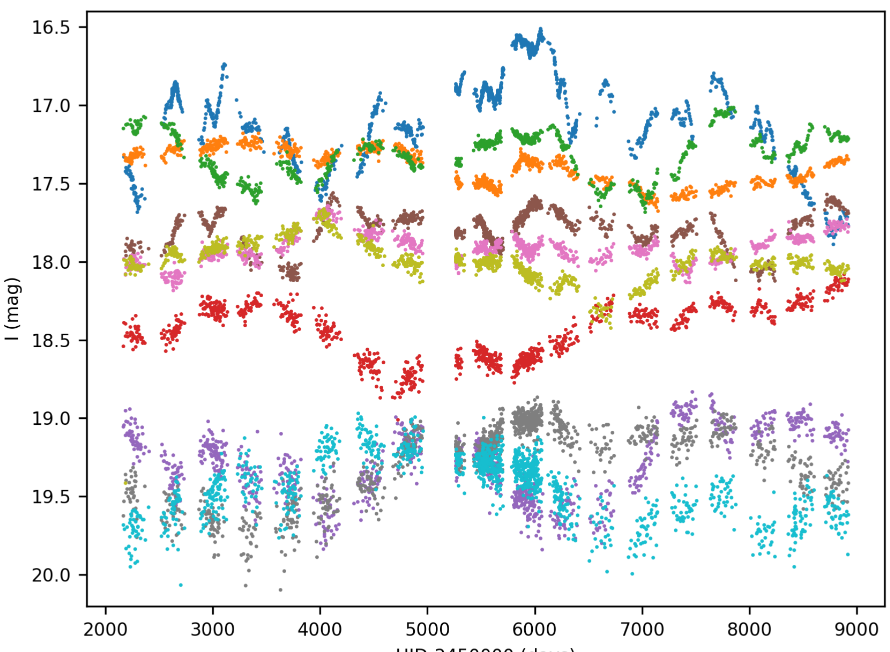
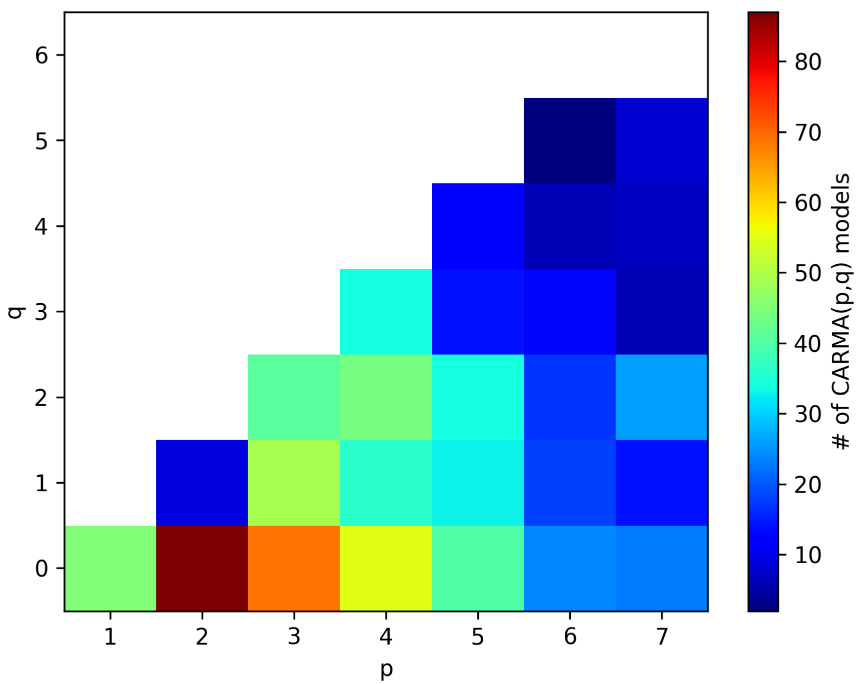


Fig
sta
Th
cer
hig





Thank you!

Revisiting Stochastic Variability of AGNs with Structure Functions
Kozłowski Szymon, 2016, The Astrophysical Journal, 826, 118

A degeneracy in DRW modelling of AGN light curves
Kozłowski Szymon, 2016, MNRAS, 459, 2787

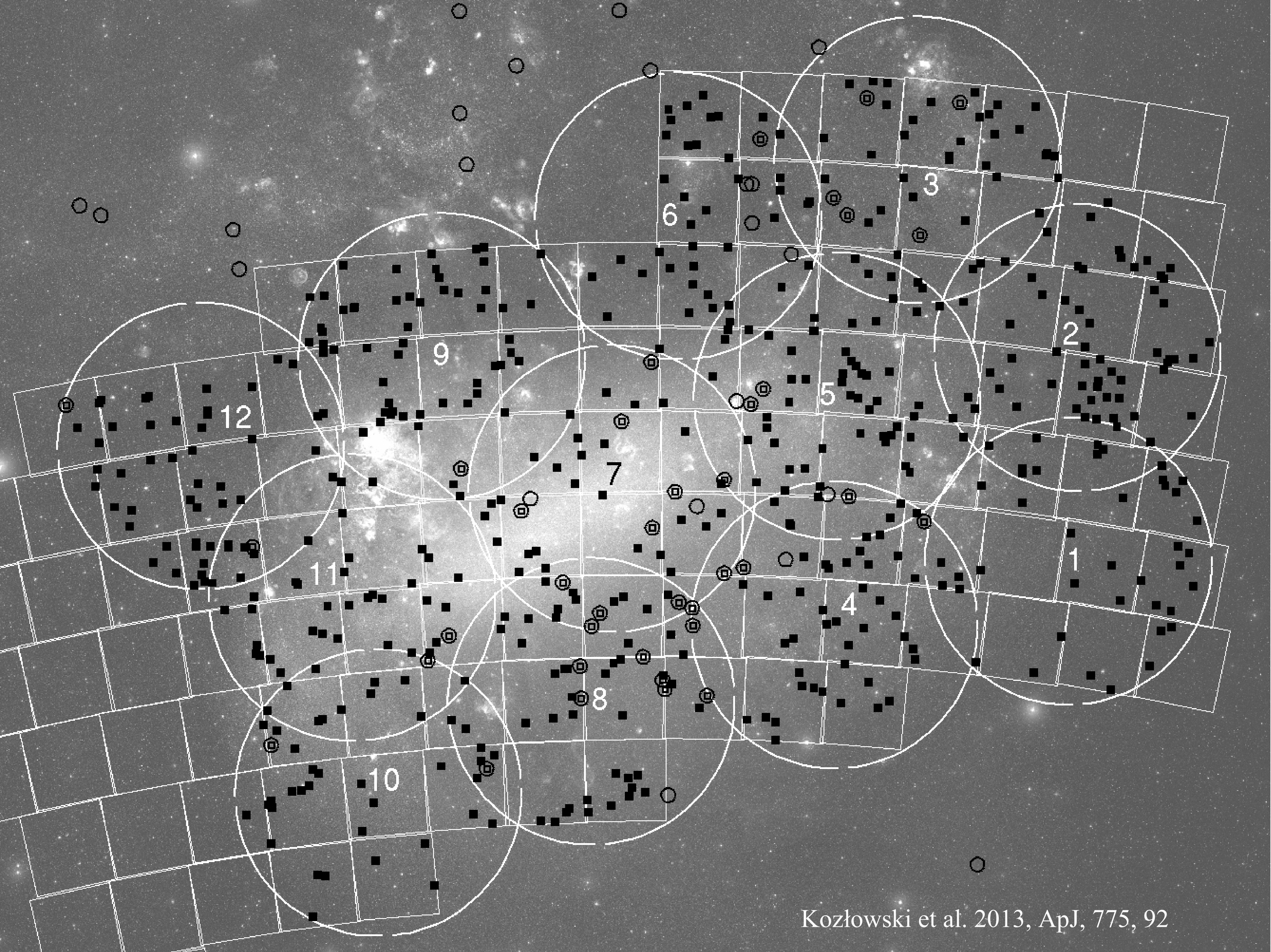
Limitations on the recovery of the true AGN variability parameters using damped random walk modeling
Kozłowski Szymon, 2017, A&A, 597, 128

A Method to Measure the Unbiased Decorrelation Timescale of the AGN Variable Signal from Structure Functions
Kozłowski Szymon, 2017, The Astrophysical Journal, 835, 250

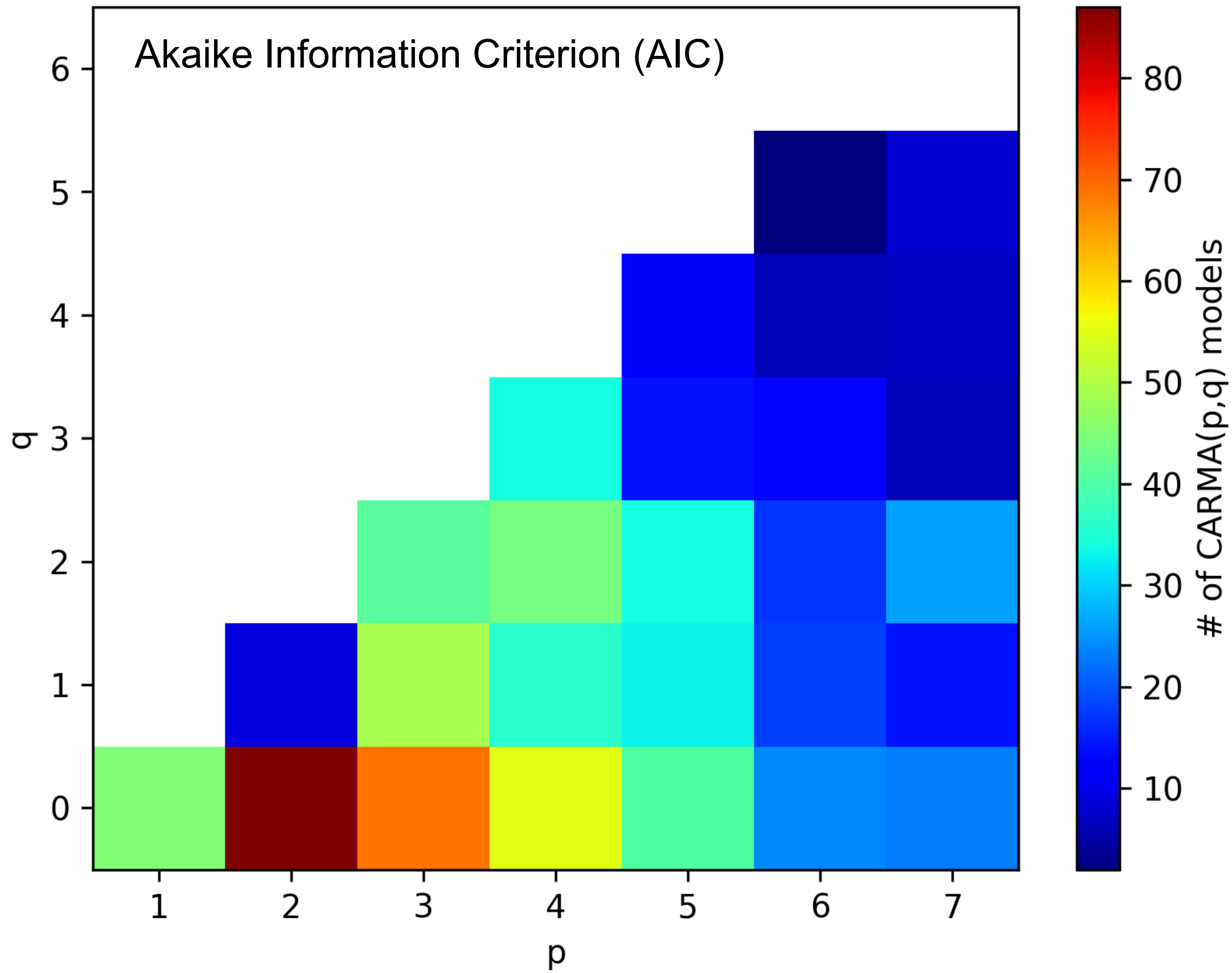
A Survey Length for AGN Variability Studies
Kozłowski Szymon, 2021, Acta Astronomica, 71, 103

Optical Gravitational Lensing Experiment (OGLE)

Udalski et al. 2015, Acta Astronomica, 65, 1

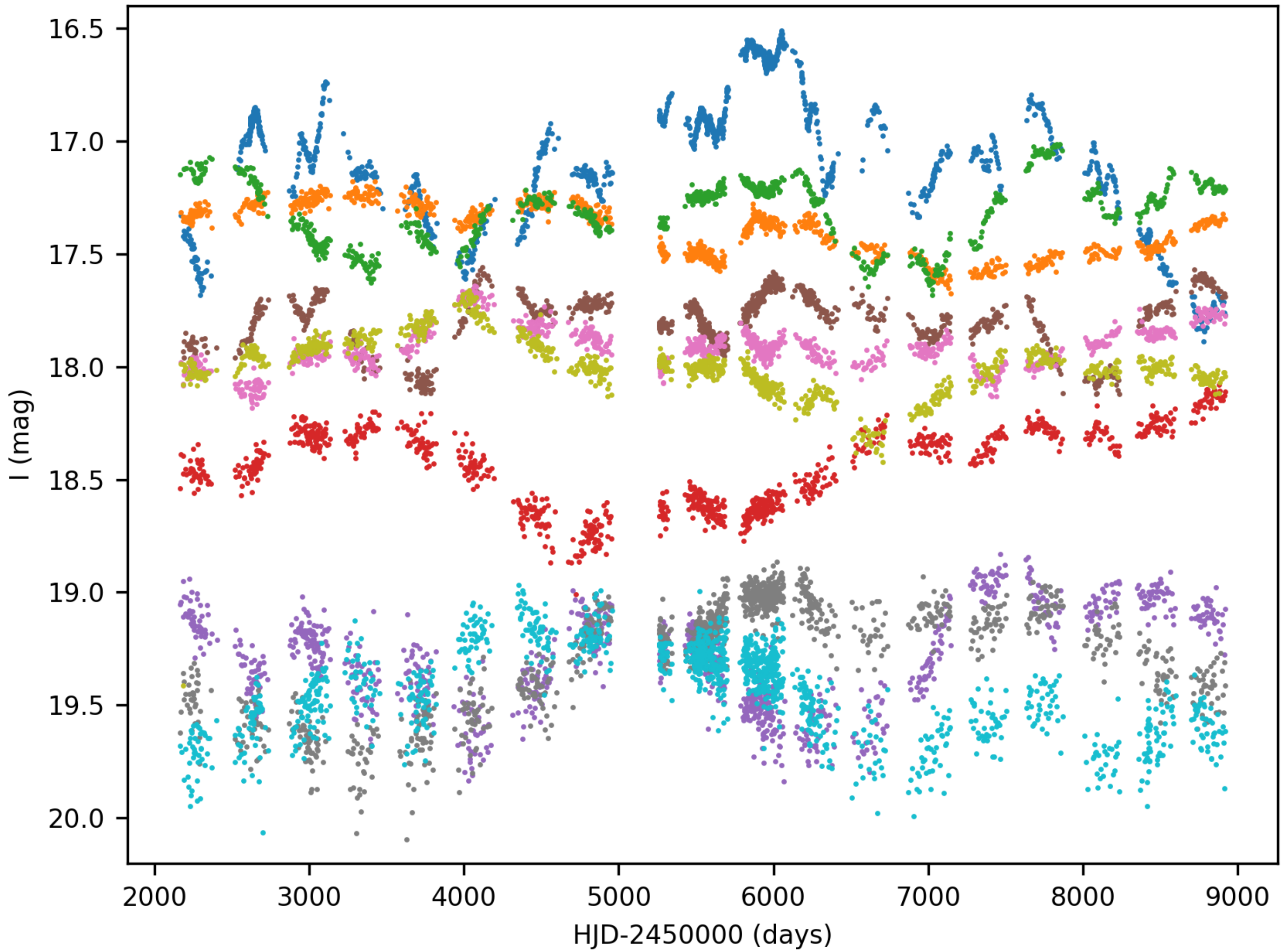

1
2
3
4
5
6
7
8
9
10
11
12
Kozłowski et al. 2013, ApJ, 775, 92

CARMA for ~800 OGLE AGN

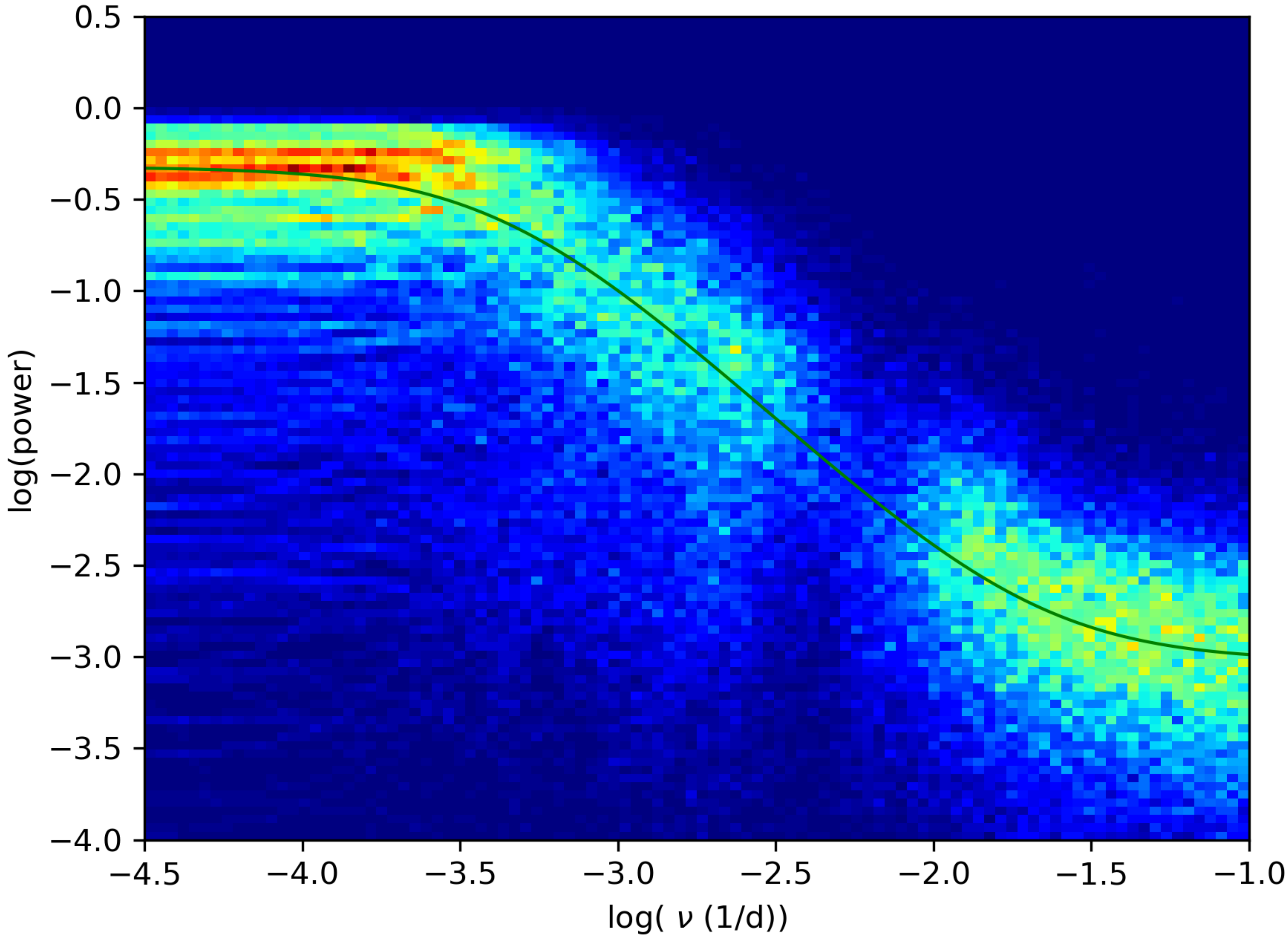


CARMA code: Kelly et al. 2014, ApJ, 788, 33

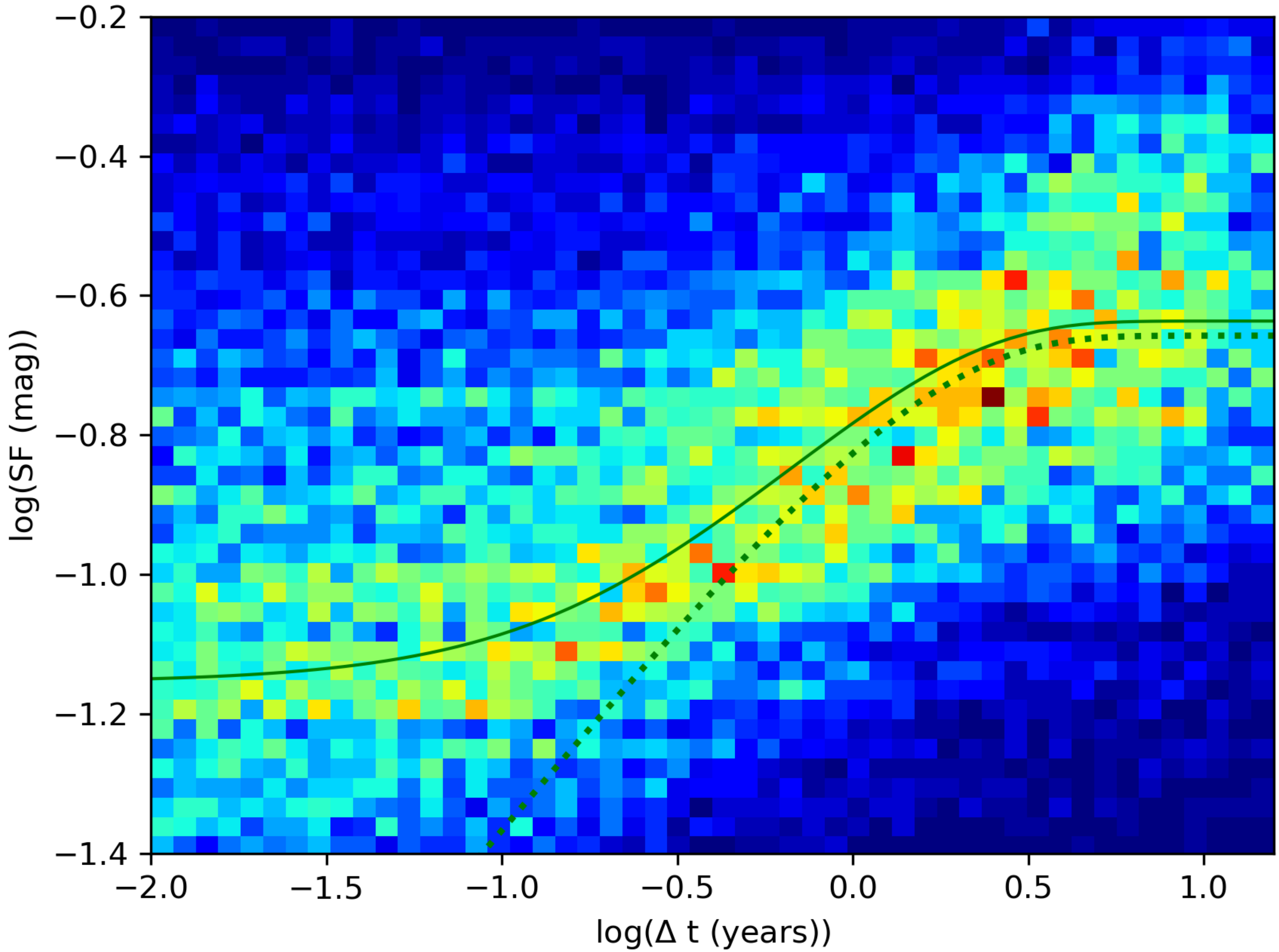
AGN Variability in OGLE



PSD for ~800 OGLE AGN



Structure Function for ~800 OGLE AGN



AGN in mid-IR (Spitzer)

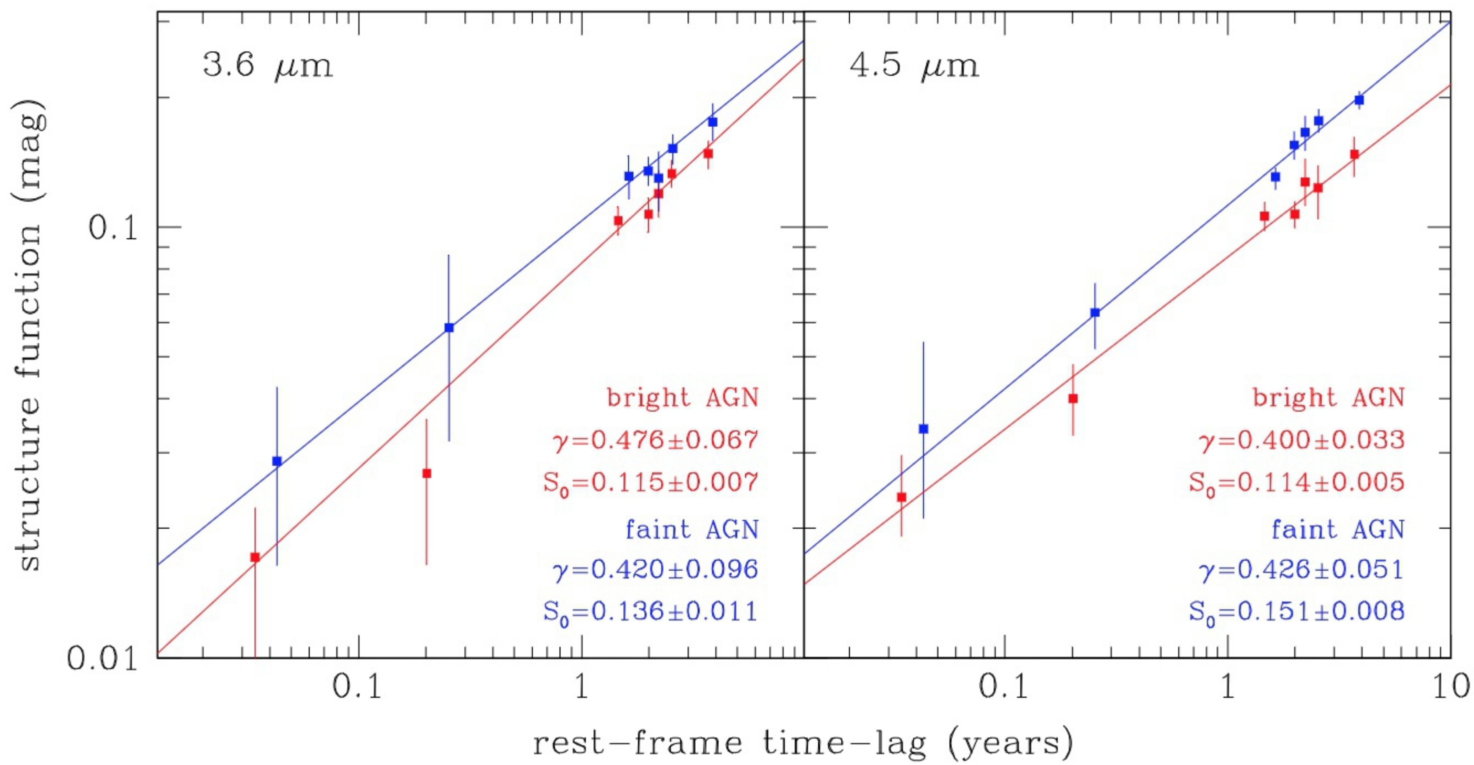
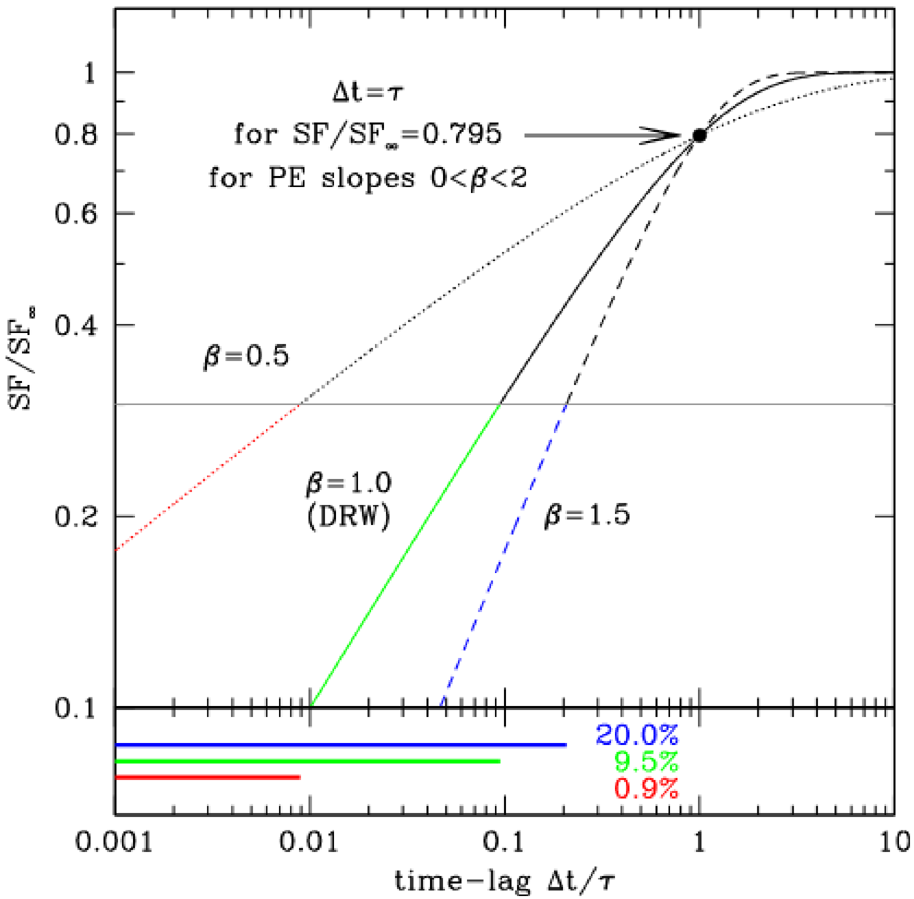


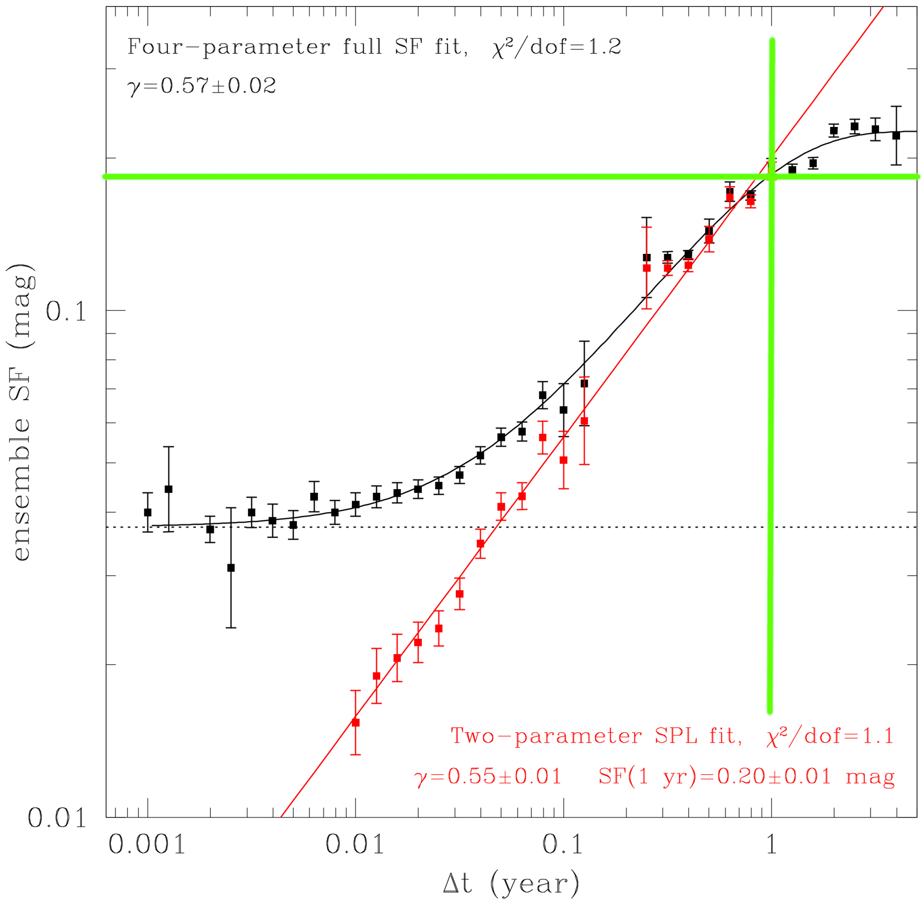
Figure 10. Rest-frame mid-IR AGN structure functions for the $0.5 < z < 2$ AGES quasars brighter than $[3.6] < 18$ mag. We divide the sample of 1000 AGNs in half after sorting them by their absolute magnitudes and calculate SF for the brighter half (red) and the fainter half (blue). It is clear that fainter AGN show higher amount of variability then the brighter ones.

Kozłowski et al. 2016, ApJ, 817, 119

Unbiased timescale



Kozłowski 2017, ApJ, 835, 250



Kozłowski 2016, ApJ, 826, 118