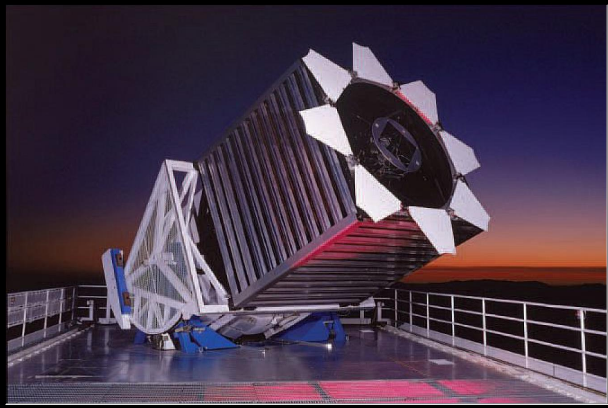


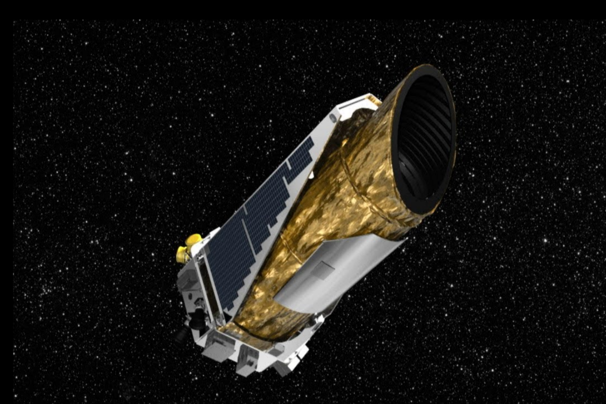

AGN Optical/UV Variability: Pleasures and Pains

INSTITUTO MILENIO DE ASTROFÍSICA

LSST AGN Science Collaboration

Demetra De Cicco

University of Napoli "Federico II"

20 Years Ago…

- What are the timescales of variability?
- How is the variability amplitude related to the timescales?
- What is the variability amplitude in different wavebands?
- Is variability periodic?
- Is there evidence for non-linear behavior?
- How is the variability of the various continua related?
- How does variability vary with luminosity?
- Can the variability properties of an AGN change with time?

VARIABILITY OF ACTIVE GALACTIC NUCLEI FROM THE OPTICAL TO X-RAY REGIONS

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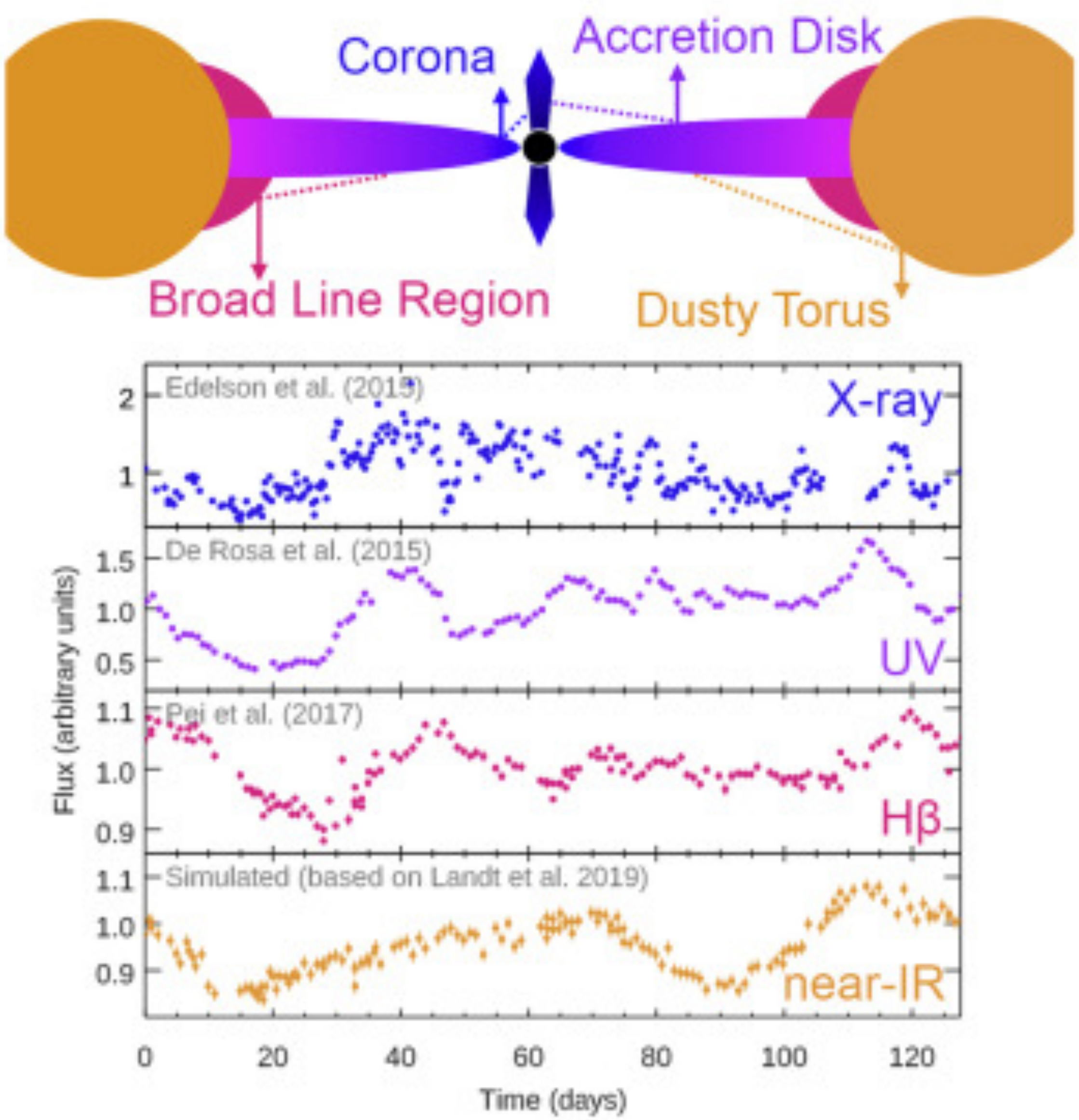
(Received: 28 May 2003)

AGN Variability Overview



Cackett+21

ubiquitous: detected at all wavelengths, timescales, in continuum emission and in emission lines

erratic, aperiodic, red-noise type
>20 orders of magnitude in frequency, from radio to γ rays

timescales: from minutes to years, depending on wavelength, viscosity, disk height

correlations among different wavebands

origin: instability in the accretion flow, variations of the accretion rate, shocks or bulk injection of new particles (jet variability)

information about the physics of the central black hole and the AGN emission mechanism; probe connection with the host

The Beginning of Pains: Origin of Optical Variability

Reprocessing of X-ray emission

optical/UV lags behind X-rays (lag = light travel time, ~hours)

- explains the observed short-term lags among different bands
- does not explain long-term X-rays vs. optical variation amplit

Yesterday's talks

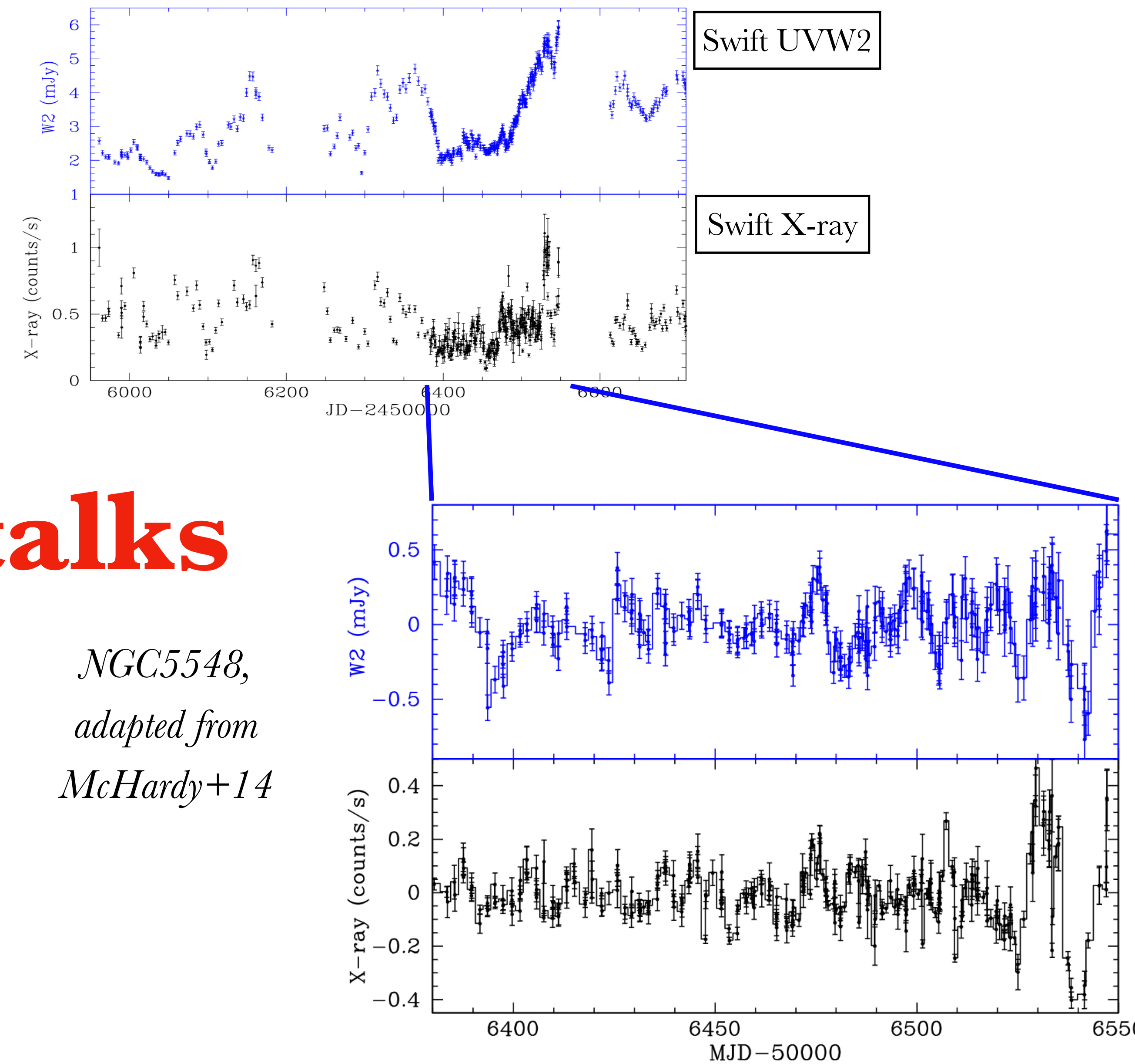
Intrinsic variability

optical/UV emission => inverse Compton scattering in the corona => X-rays will lag behind optical/UV

OR

inwardly propagating variations (lag ~ viscous timescale, years)

- observed also on short timescales => conflict with the standard accretion disk model?
- correlations observed among different bands => who leads?



NGC5548, adapted from McHardy+14

the observed emission is very likely intrinsic + reprocessed emission

McHardy+16, Arévalo+08, Uttley+03, and references therein

Nearby AGN: An Asset for Variability Monitoring

The study of individual sources in multi-wavelength campaigns proved crucial

NGC 4151: photographic + photoelectric observations, 1906-1984, ~1000 measurements in total

- two component: fast flares (10-100 d) + slower variations (4-14 yr)
- no periodicity
- pulsating accretion disk?
- correlation between UV and optical variability
- correlation between continuum and emission line-variability

Luytyi&Oknianskii87, Ulrich+91

3C 273: IUE observations, 1978-1992

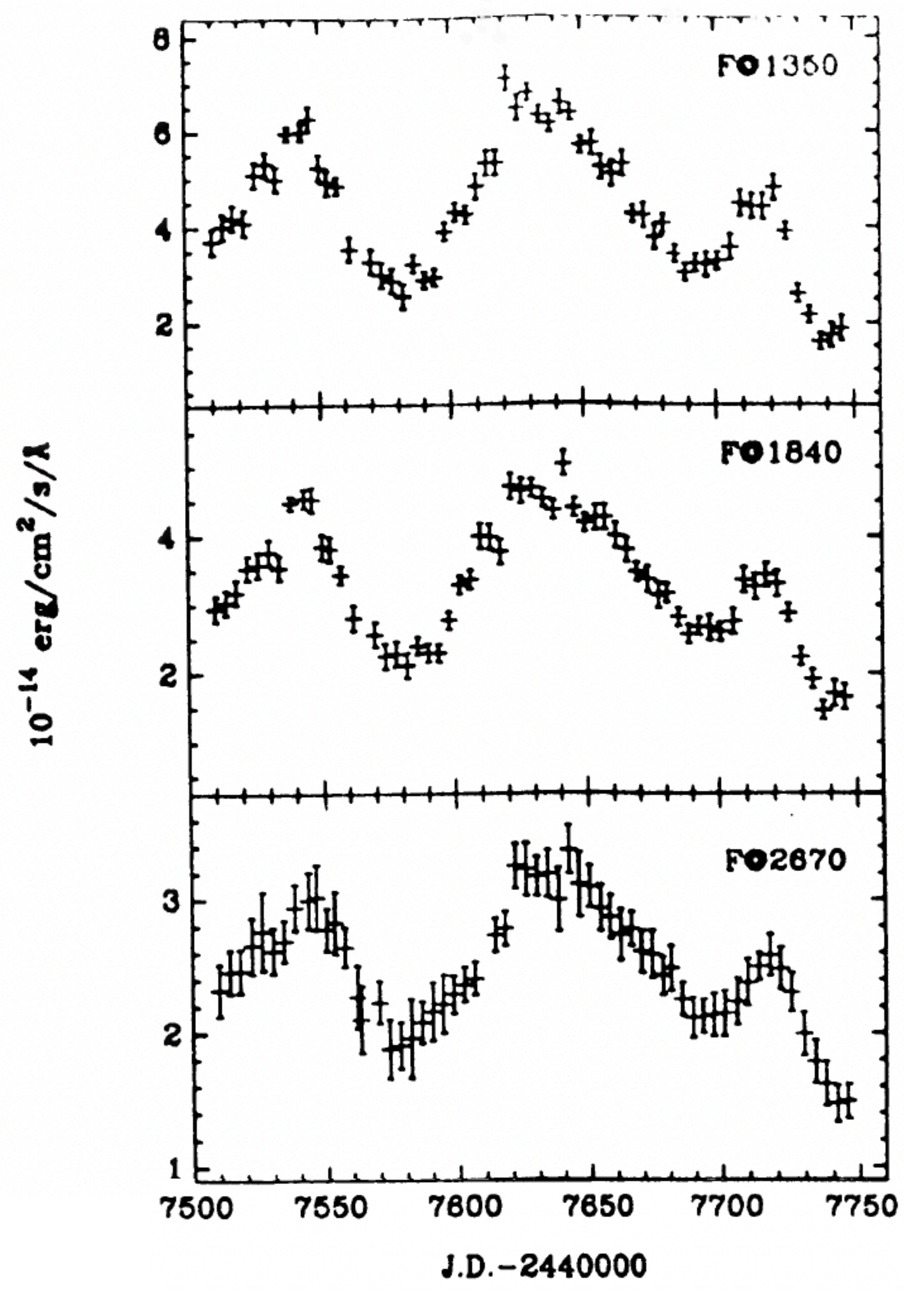
- variation by a factor of 1.5-2

Ulrich+93

NGC 5548: IUE observations, Dec. 1988-Aug. 1989, 4 d cadence

- variability amplitude decreases with wavelength
- continuum variations are simultaneous in the 4 UV/optical bands tested

Clavel+91



Light curves of NGC 5548 at 1350, 1840, and 2670 Å. Adapted from Clavel+91.

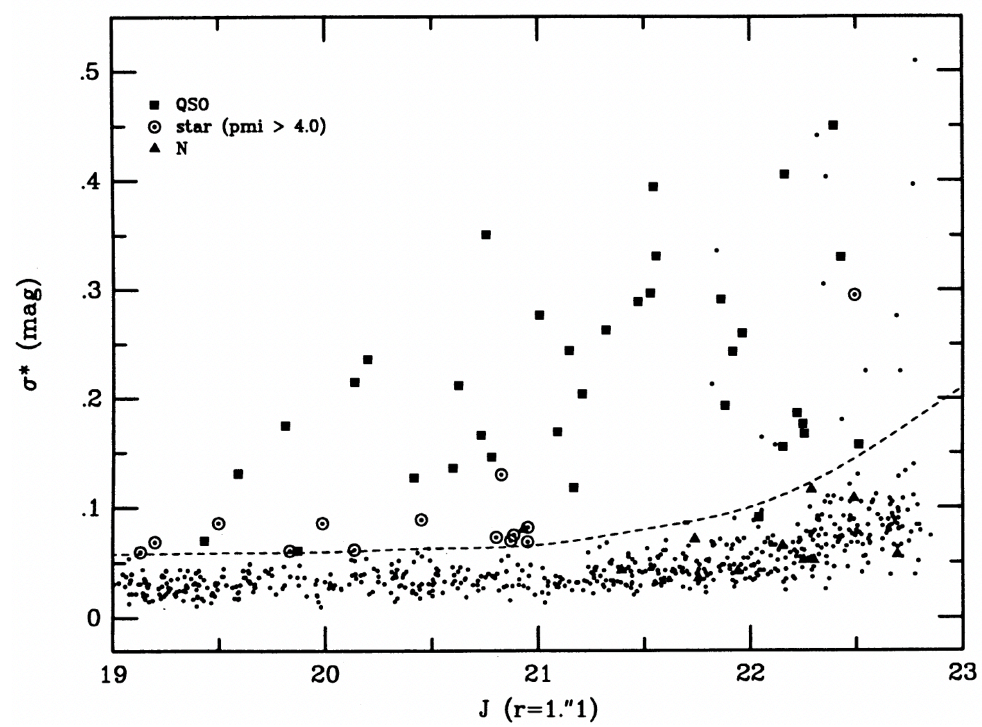
The First Ensemble Studies

Series of studies **identifying and characterizing faint QSOs** in the Selected Area 57, based on plates from the Mayall telescope at KPNO:

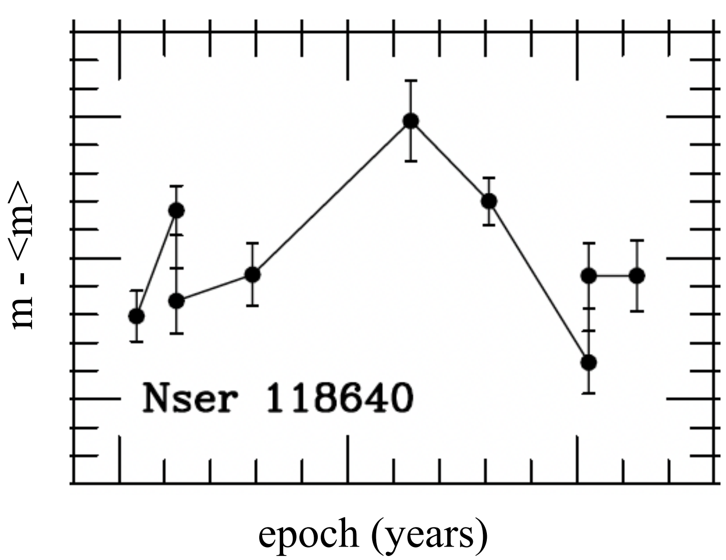
- color selection and magnitude distribution analysis
- identification of stellar objects lacking detectable proper motion

Kron80, Kron&Chiu81, Koo+86, Koo&Kron88b

Trevese+94



Selection of variable AGN candidates from multiple images: 9 Mayall plates covering an 11 yr-baseline, down to B = 22.6 mag, then extended to 11 observations covering 15 yr (*Trevese+89, 94*)



Bershady+98

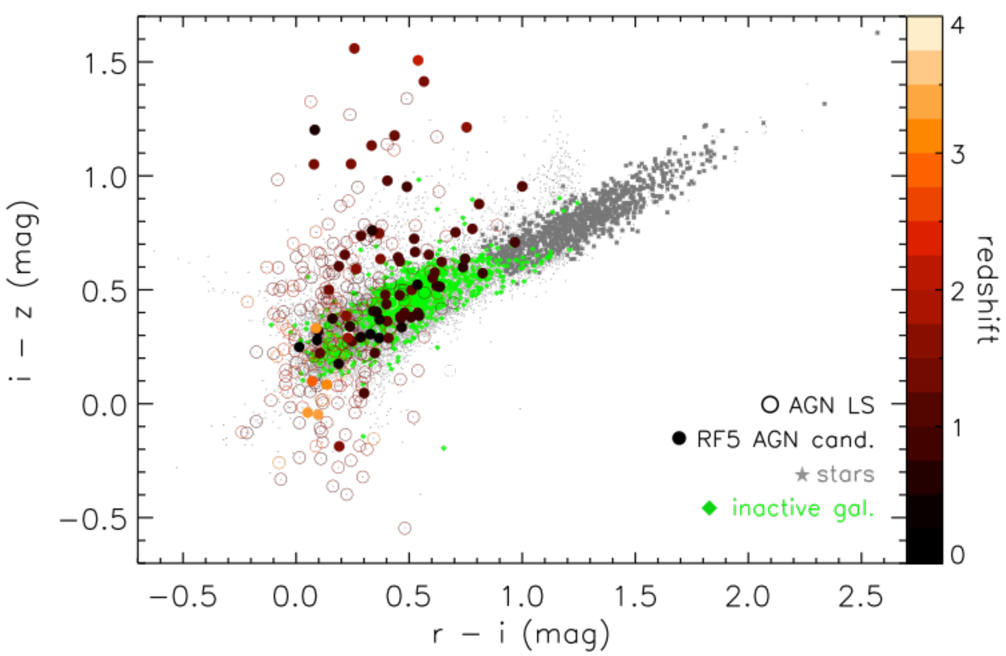
Selected Area 57, extension of the search to low-luminosity AGN with extended light profiles: **at least 10% of the AGN population consists of extended AGN** (14 candidates/0.284 sq. deg., B_J = 22.5 mag)

Bershady+98

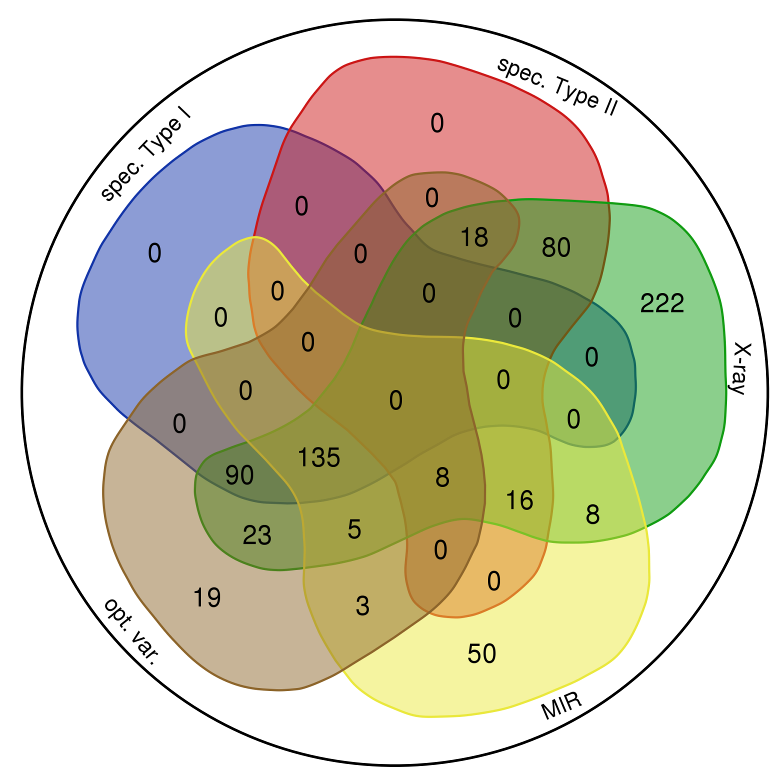
Optical Variability Selection of AGN: Pleasures…

large source samples from SDSS, PanSTARRS, ZTF, etc. → good characterization

- allows **exploration of large areas**
- identifies **AGN missed by X-ray surveys** (*Villforth+12*)
- does not miss **host-dominated AGN** (*Sarajedini+03*)
- **identifies low-luminosity AGN** (*Barr&Mushotzky86*, *Cristiani+96; Villfort+12*)
- returns **higher AGN surface density** than estimated via other selection methods (*Sarajedini+03*)
- allows **completeness studies** (*Trevese+08, Boutsia+09*)
- **lower costs** compared to space-based surveys



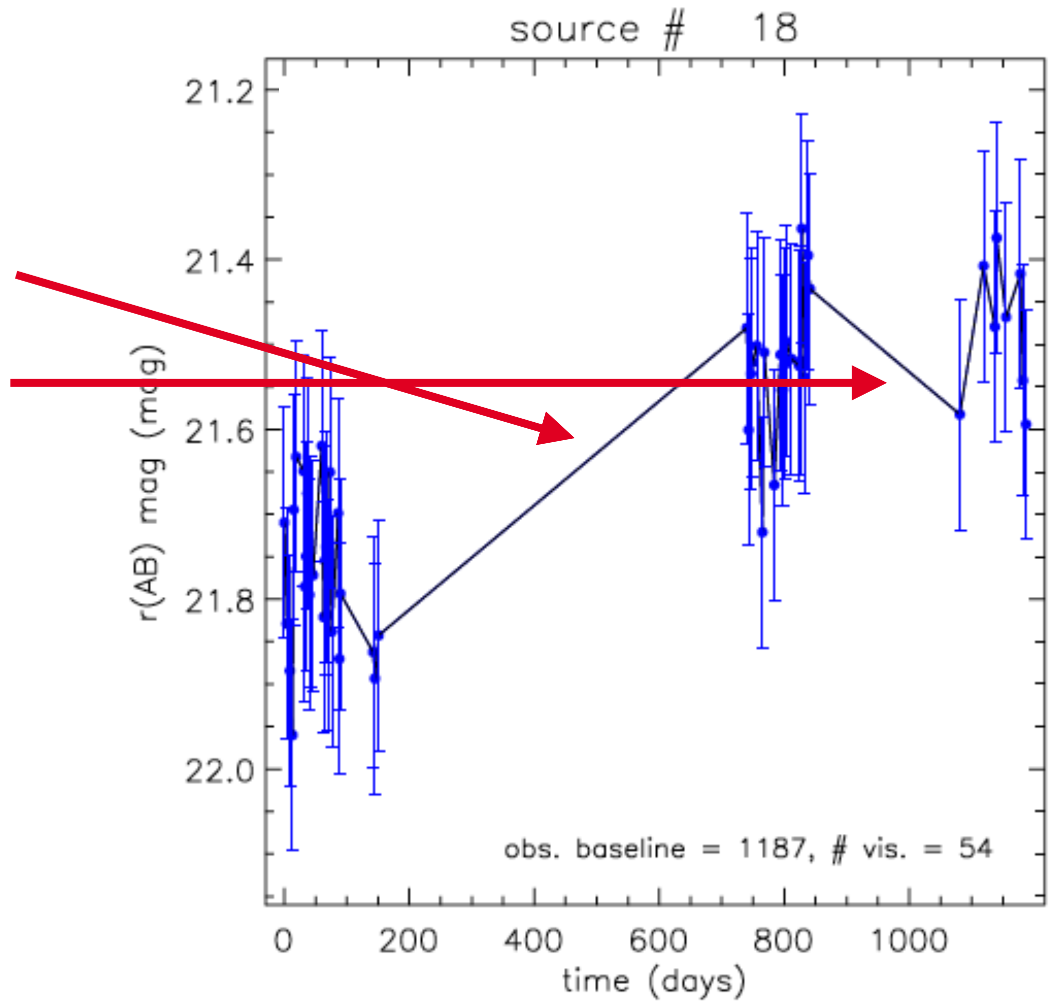
De Cicco+21



…and Pains: Irregular Sampling

1 yr 7 months-gap
+
8month-gap

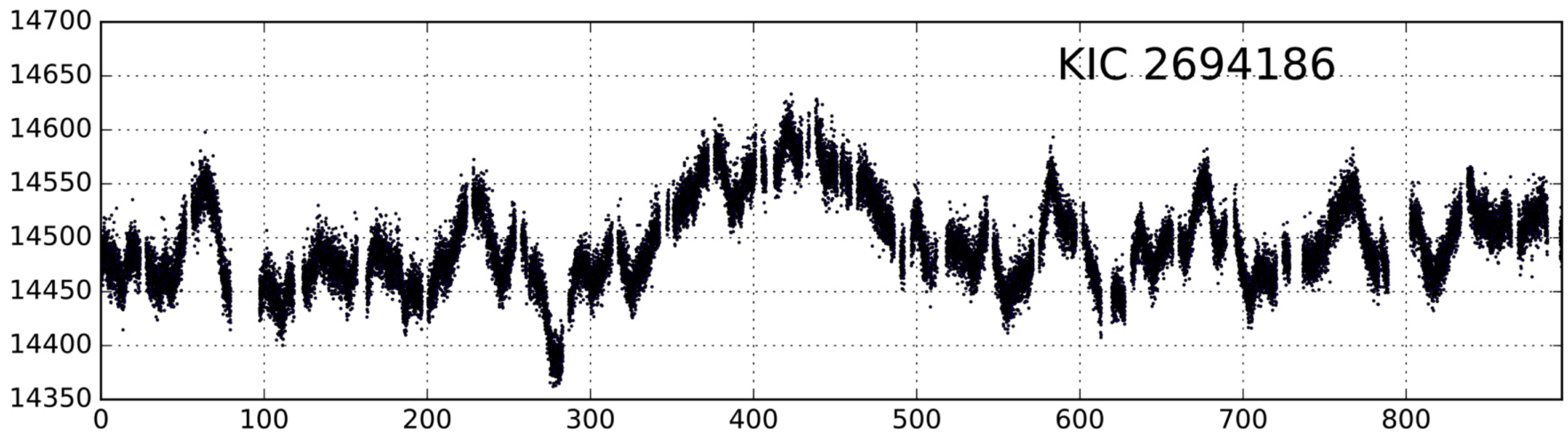
=



example of VST-COSMOS AGN light curve

from De Cicco+19 dataset

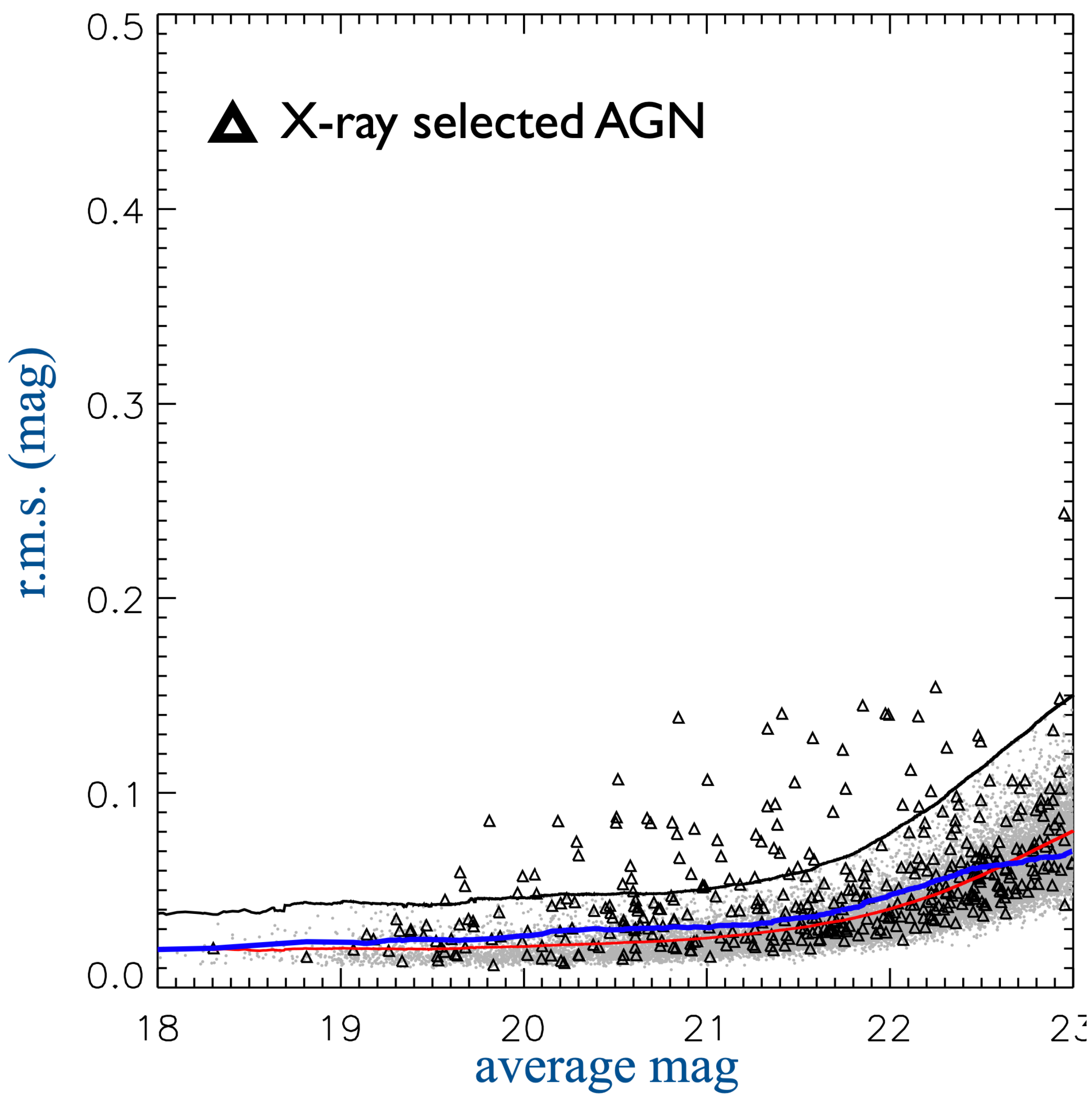
…but less sampling pains when you have a space telescope!



Smith+18

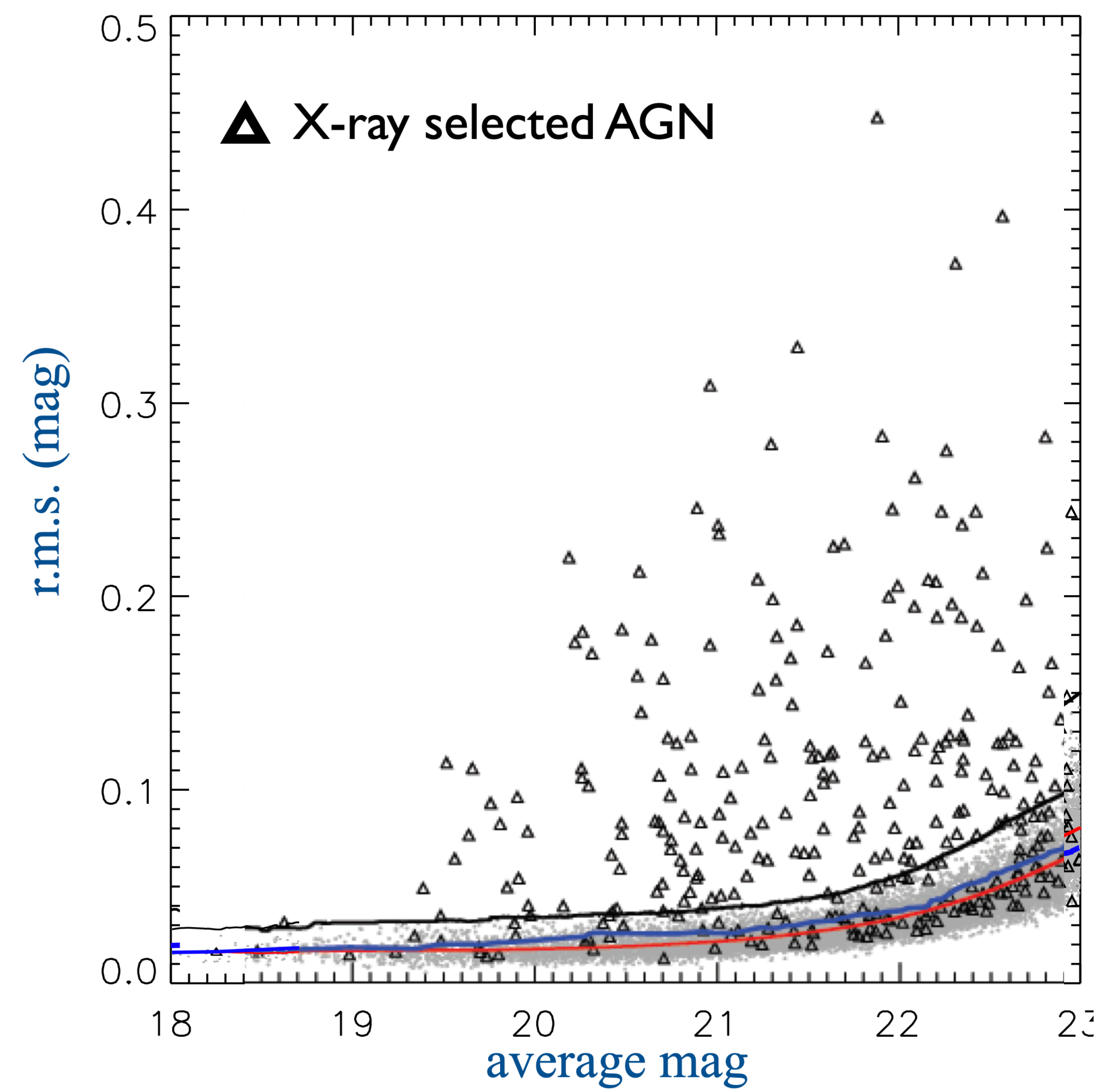
Further Pains: Baseline Dependence

5 month baseline



15% above threshold

3.3 yr baseline

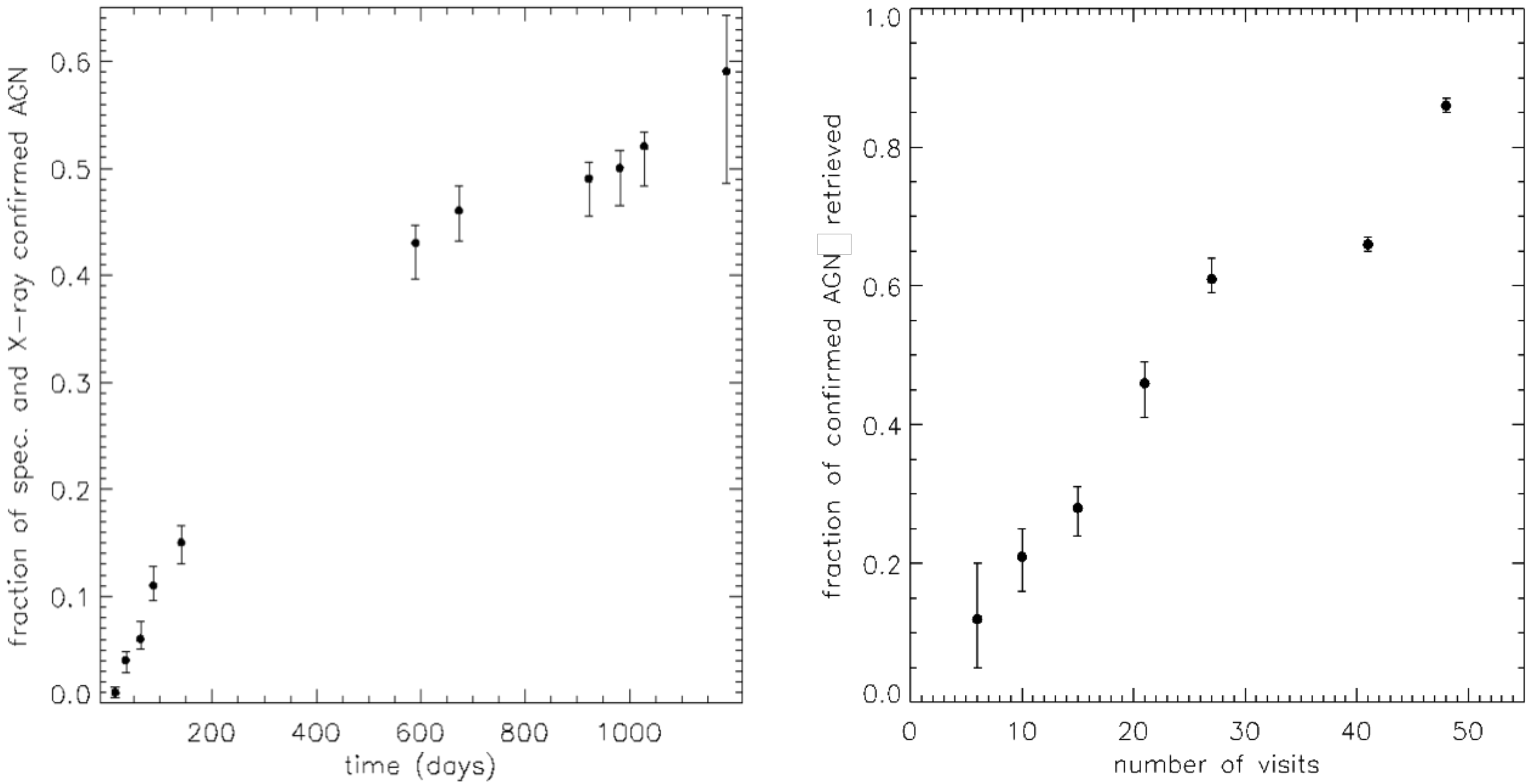


59% above threshold

De Cicco+15, 19

More Pains: Baseline and Cadence Dependence

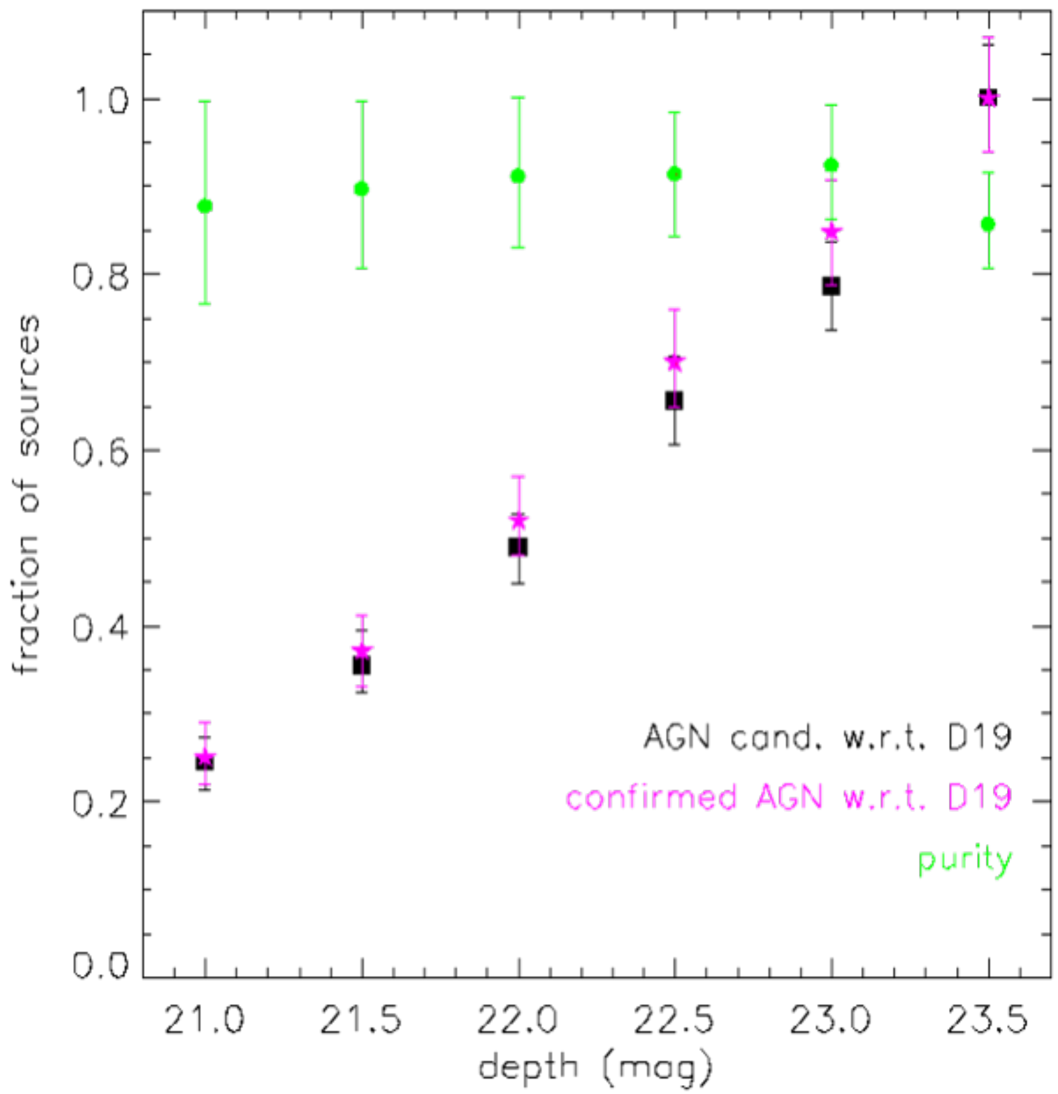
~90% / 50% / 20% visits:
~15% / 40% / 80% of the AGN missed



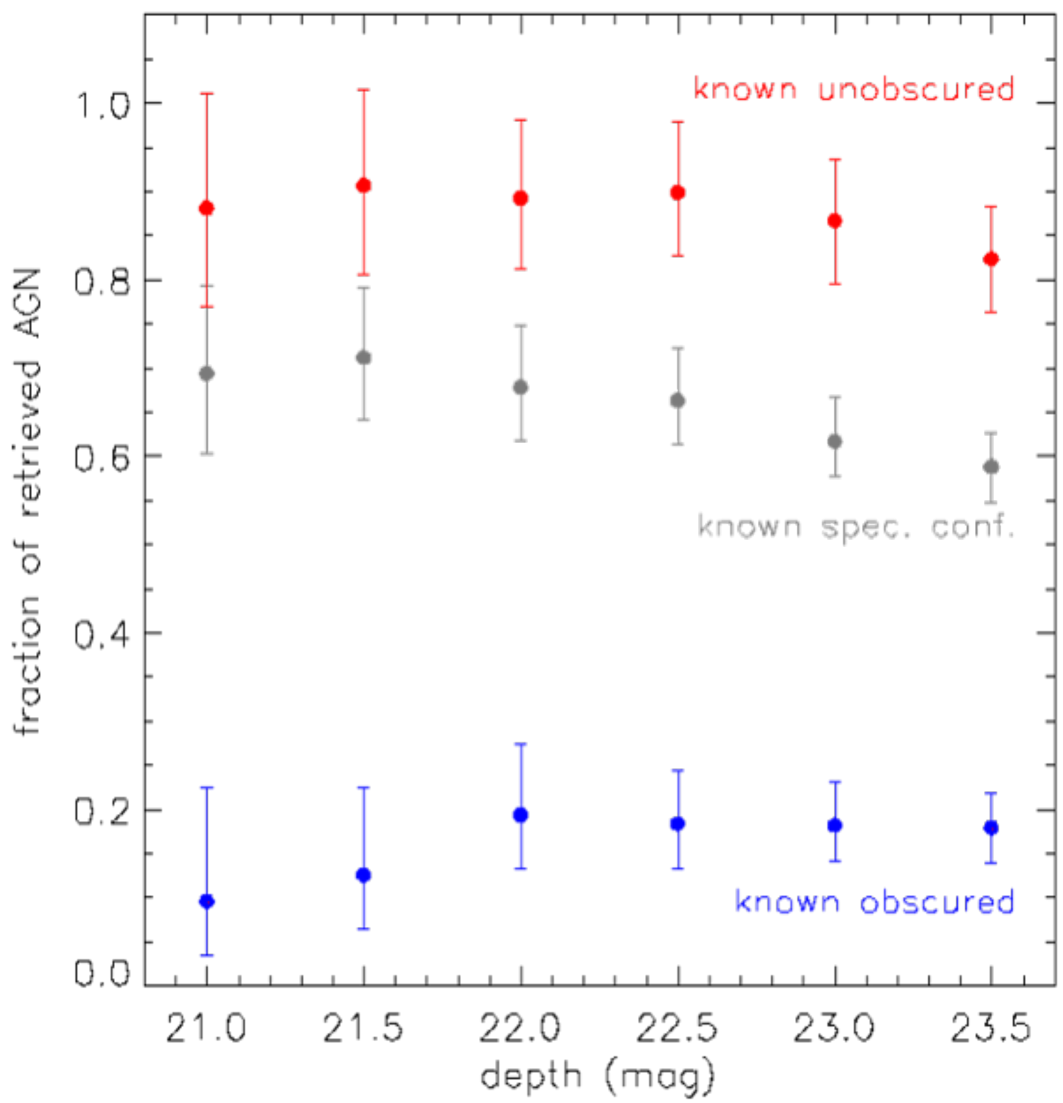
De Cicco+19

Additional Pains: Depth Dependence

retrieved sources and purity



completeness w.r.t. spec. confirmed AGN



each point represents the fraction of sources retrieved if the sample is cut to the corresponding depth (x axis)

The Current VST-COSMOS Data Set

visit	obs. date	seeing (FWHM) (arcsec)
1	2011-Dec-18	0.64
2	2011-Dec-22	0.94
3	2011-Dec-27	1.04
4	2011-Dec-31	1.15
5	2012-Jan-02	0.67
6	2012-Jan-06	0.58
7	2012-Jan-18	0.62
8	2012-Jan-20	0.88
9	2012-Jan-22	0.81
10	2012-Jan-24	0.67
11	2012-Jan-27	0.98
12	2012-Jan-29	0.86
13	2012-Feb-02	0.86
14	2012-Feb-16	0.50
15	2012-Feb-19	0.99
16	2012-Feb-21	0.79
17	2012-Feb-23	0.73
18	2012-Feb-26	0.83
19	2012-Feb-29	0.90
20	2012-Mar-03	0.97
21	2012-Mar-13	0.70
22	2012-Mar-15	1.08
23	2012-Mar-17	0.91
24	2012-May-08	0.74
25	2012-May-11	0.85
26	2012-May-17	0.77
27	2013-Dec-27	0.72
28	2013-Dec-30	1.00
29	2014-Jan-03	0.86
30	2014-Jan-05	0.81
31	2014-Jan-12	0.73
32	2014-Jan-21	1.18
33	2014-Jan-24	0.80
34	2014-Feb-09	1.28
35	2014-Feb-19	0.89
36	2014-Feb-21	0.93

visit	obs. date	seeing (FWHM) (arcsec)
37	2014-Feb-23	0.81
38	2014-Feb-26	0.81
39	2014-Feb-28	0.77
40	2014-Mar-08	0.91
41	2014-Mar-21	0.96
42	2014-Mar-23	0.92
43	2014-Mar-25	0.66
44	2014-Mar-29	0.89
45	2014-Apr-04	0.58
46	2014-Apr-07	0.61
47	2014-Dec-03	1.00
48	2015-Jan-10	0.71
49	2015-Jan-28	0.90
50	2015-Jan-31	0.73
51	2015-Feb-15	0.70
52	2015-Mar-10	0.80
53	2015-Mar-14	0.84
54	2015-Mar-19	1.00
55	2021-Dec-06	0.94
56	2021-Dec-28	0.57
57	2022-Jan-05	0.58
58	2022-Jan-13	0.69
59	2022-Jan-25	0.71
60	2022-Feb-03	0.96
61	2022-Feb-10	0.62
62	2022-Feb-24	0.56
63	2022-Mar-04	0.58
64	2022-Mar-11	0.75
65	2022-Mar-24	0.68
66	2022-Mar-31	0.70
67	2022-Nov-23	0.91
68	2022-Dec-10	0.56
69	2022-Dec-31	1.07
70	2023-Jan-02	–
71	2023-Jan-03	0.84
stacked	-	0.67

Season 1 (visits 1–27)

1 yr 7 month-gap

Season2 (visits 28–46)

8 month-gap

Season 3 (visits 47–54)

6 yr 9 month-gap

Season 4 (visits 55–66)

8 month-gap

Season 5 (visits 67–71)

more visits now being reduced

> 11 yr baseline

Light Curve Analysis: Structure Function

Analyzes the amplitude of variability as a function of the time lag between each pair of observations; model-independent; non affected by irregularity of sampling

$$SF(\Delta t) = \frac{1}{N}\sum_{i=1}^{N}(\Delta m_{ij})^2$$ (Simonetti+84)

$$SF(\Delta t) = \left\langle \sqrt{\frac{\pi}{2}}|\Delta m_{ij}| - \langle \sigma^2 \rangle \right\rangle$$ (Vanden Berk+04)

$$SF(\Delta t) = \mathrm{med}(\Delta m_{ij}^2)$$ (Sumi+05)

$$SF(\Delta t) = \left\langle \sqrt{\frac{\pi}{2}}|\Delta m_{ij}| - \sqrt{\sigma_i^2 + \sigma_j^2} \right\rangle$$ (Schmidt+10)

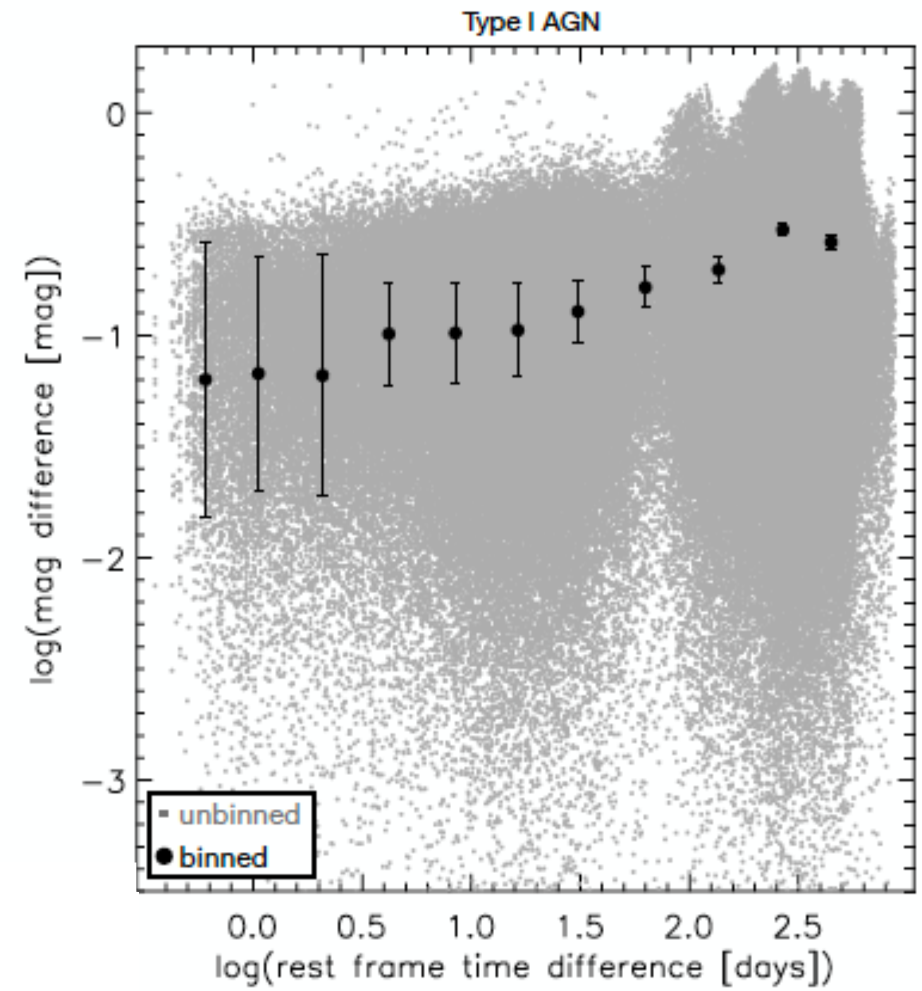
$$SF(\Delta t) = 0.74(IQR)/\sqrt{N-1}$$ (MacLeod+12)

$$SF(\Delta t) = \sqrt{\langle \Delta m_{ij}^2 \rangle - \langle \sigma^2 \rangle}$$ (Bauer+09)

$$SF(\Delta t) = \sqrt{\left\langle \frac{\pi}{2}\Delta m_{ij} \right\rangle^2 - \langle \sigma^2 \rangle}$$ (Bauer+09)

Graham+14

$$SF(\Delta t) = \sqrt{\frac{\pi}{2}\langle |m(t_j) - m(t_i)| \rangle^2 - \langle \sigma^2_{noise} \rangle}$$ (Di Clemente+96)

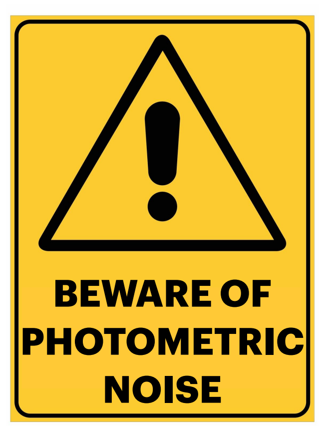


based on data in De Cicco+22

$$SF(\Delta t) = SF_0\left(\frac{\Delta t}{\Delta t_0}\right)^{\gamma}$$

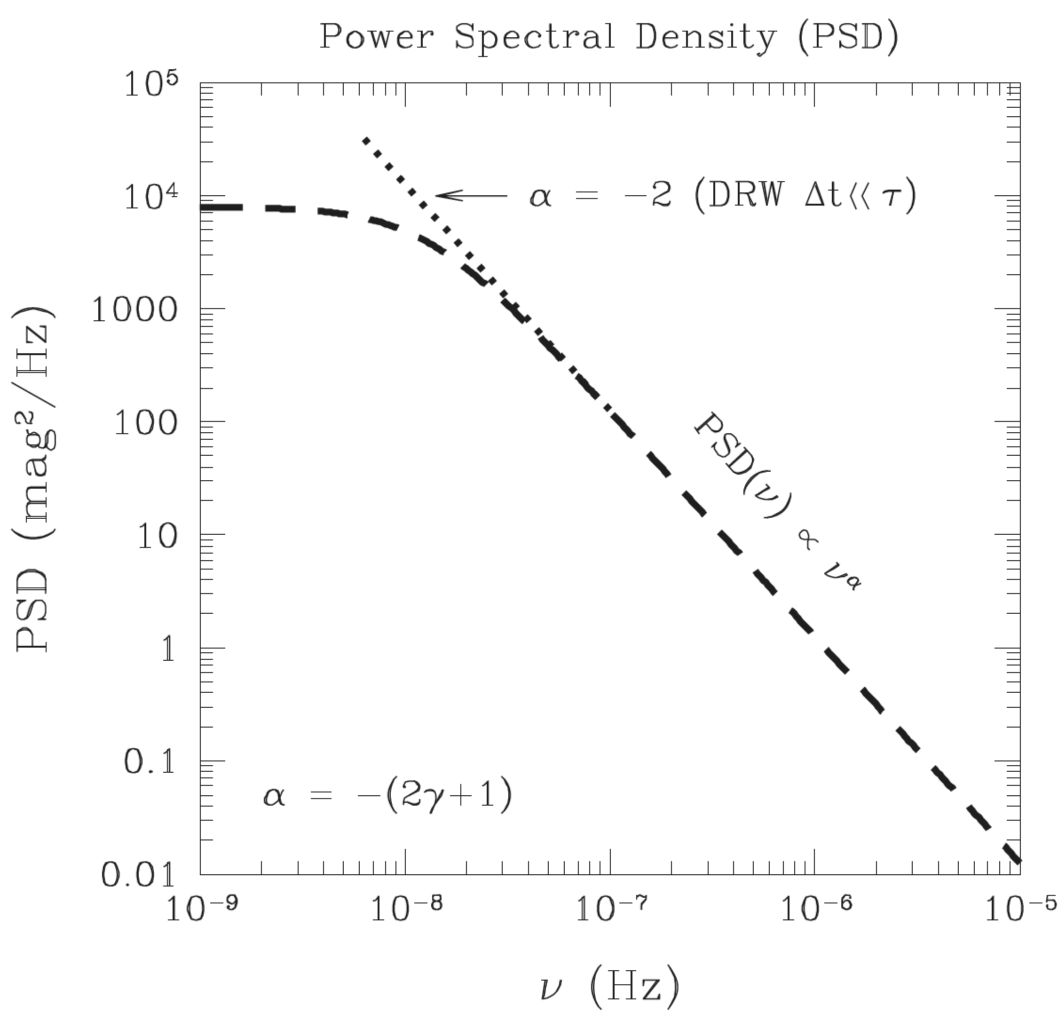
$$SF(\Delta t) = SF_\infty(1 - e^{-|\Delta t|/\tau})^{1/2}$$

Szymon Kozłowski's talk after the break



Light Curve Analysis: Power Spectral Density

Kozłowski16 and references therein



$$\text{total power} = \int_{-\infty}^{\infty} |y(t)|^2 dt = \int_{-\infty}^{\infty} |Y(\nu)|^2 d\nu$$

time series — PSD

Aperiodic variability => spectra are well fitted by a broken power law (PSD ~ ν^{-2}, i.e., red-noise type)

No correlation among the points, well-constrained statistical properties, but issues with irregular sampling

The variability of a light curve can be estimated via continuous-time autoregressive moving average (CARMA) models; first-order => damped random walk (*Kelly+09, MacLeod+10, Kelly+14, Kozłowski16, Burke+21*)

variability amplitude (t << τ)

$$dX(t) = -\frac{1}{\tau}X(t)dt + \sigma\sqrt{dt}\,\epsilon(t) + b\,dt, \quad \tau, \sigma, t > 0.$$

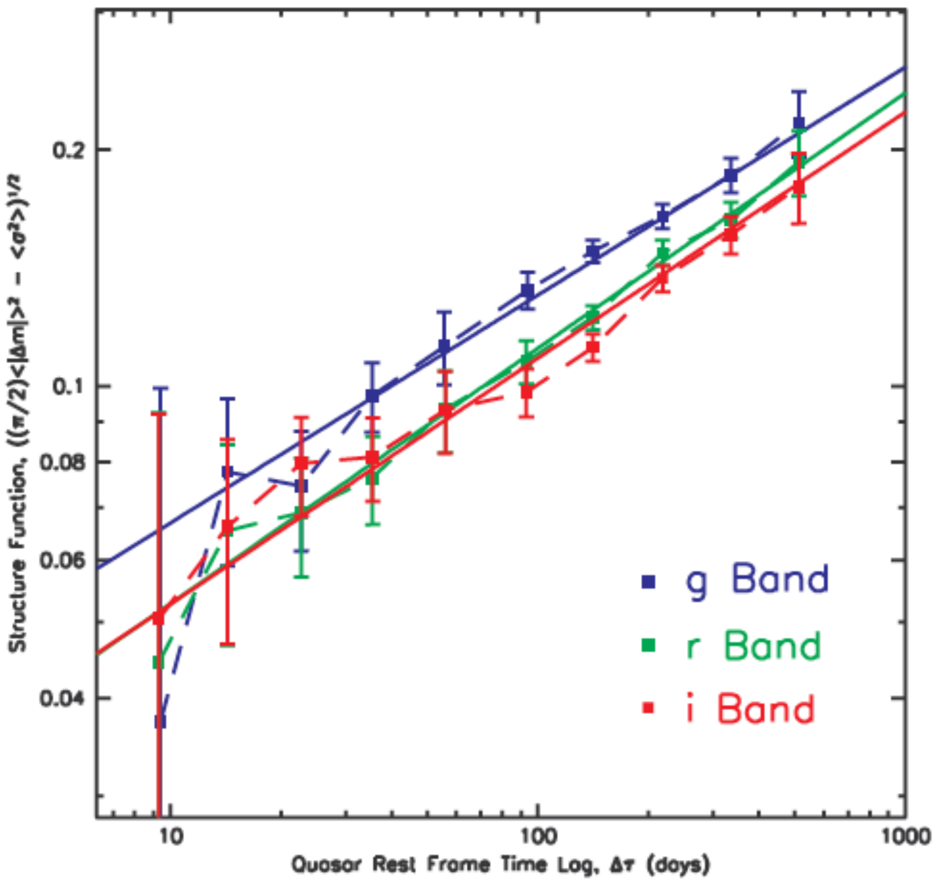
relaxation time **AGN flux** **white-noise process**

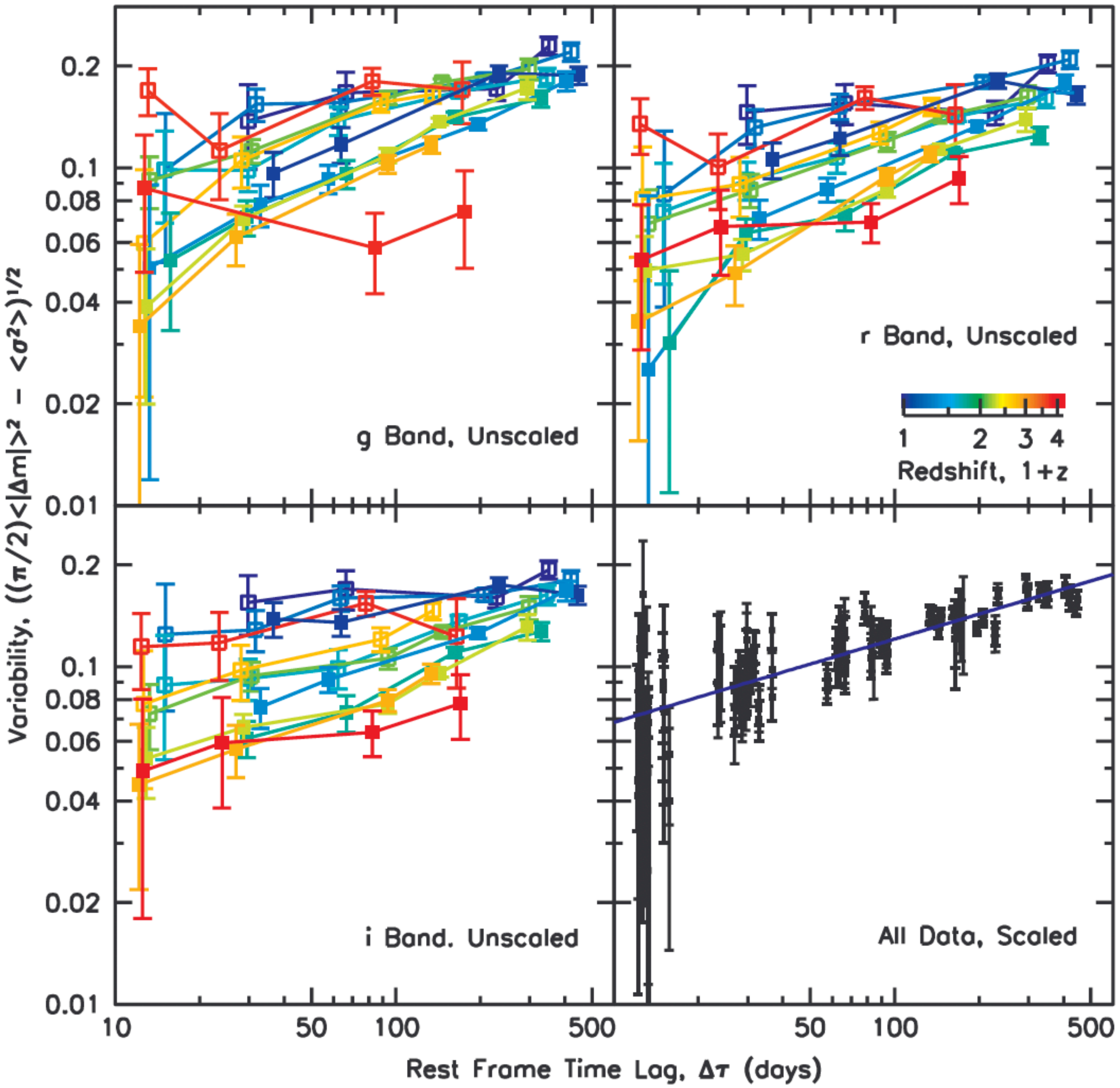
also Vincenzo Petrecca's talk, Weixiang Yu's talk & Priscilla Behar's poster

Variability Amplitude Properties

- increases with time lag
- decreases with increasing wavelength and with luminosity
- high correlation among different bands

min. timescales: days – months
amplitude: $10^{-2} - 10^{-1}$ mag





(e.g., Vanden Berk+ 2004 (both figures up here), de Vries+03, MacLeod+10)

Connections with the Central Engine

Variability amplitude and timescales are connected to rest-frame wavelength as well as to some properties (e.g., M_{BH}, λ_E, L_{bol}; e.g., *McHardy+06*, *Gonzalez-Martín & Vaughan12*, *Paolillo+17*) of the central black hole => can be used to characterize and estimate these properties, especially in the era of wide-field surveys

Conflicting results for BH mass dependence;

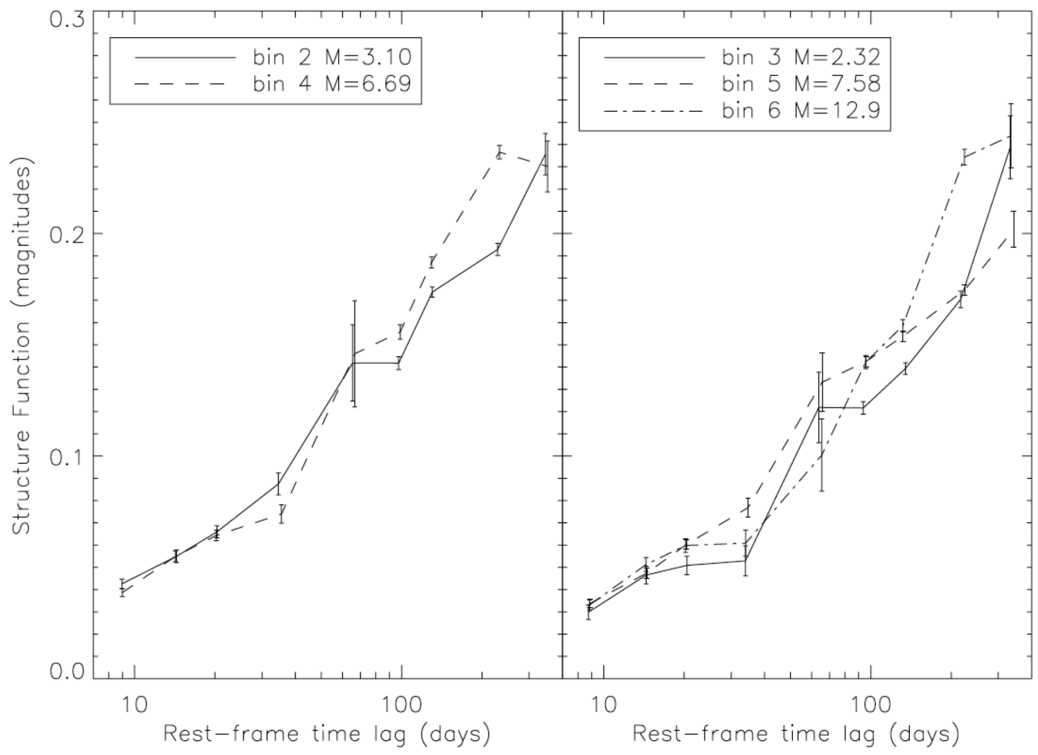
evidence for anti-correlation of variability amplitude with λ_E and L_{bol}

Publication	Measure of Amplitude/Timescale		A vs.			τ vs.	
		M_{BH}	f_{Edd}	L_{Bol}	M_{BH}	f_{Edd}	L_{Bol}
Wilhite et al. (2008)	SF (ensemble study)	+	–	–	x	x	x
Kelly et al. (2009)	DRW: τ-decorrelation timescale, σ	···	0	!–	+	x	~+
(M10)	DRW: τ, σ	+	!–	!–	+	x	~+
Morganson et al. (2014)[a]	SF: A, γ	x	x	–	x	x	+
Kozłowski et al. (2016)	DRW: τ, σ	x	x	!–	+	x	~+
Simm et al. (2016)[b]	EV, and PSD (break timescale)	0	···	···	0	0	0
Caplar et al. (2017)	SF: τ, σ	~	x	!–	x	x	+
Rakshit & Stalin (2017)[c]	DRW: τ, σ	+	!–	~+	x	x	x
Sun et al. (2018)[d]	SF: τ, σ	x	x	!–	x	+	!+
Li et al. (2018)[e]	SF: A, γ	~+	···	···	+	x	+
Sánchez-Sáez et al. (2018)[f]	SF: A	0	···	x	x	x	x
This work - Suberlak et al. (2021)	DRW: τ-decorrelation timescale, σ	+	!–	+	+	x	~+
Laurenti et al. (2020)	SF: A	0	-	!-	x	x	x
De Cicco et al. (2022)	SF: A	0	-	-	x	x	x

+	corr.	x	not studied
–	anticorr.	!	strong
0	no rel.	~	weak

adapted from *Suberlak+21*

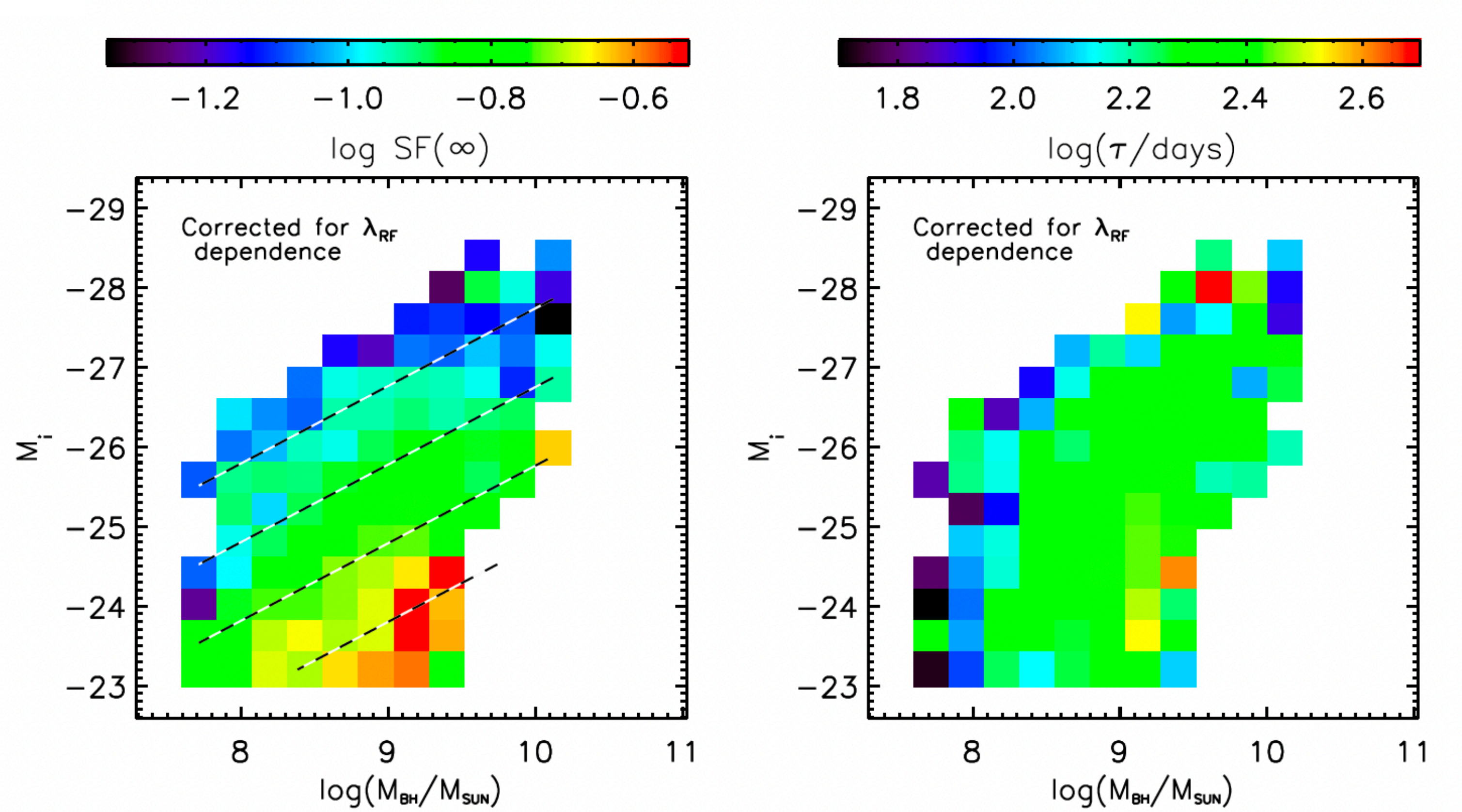
Black-Hole Mass Dependence: Correlation…



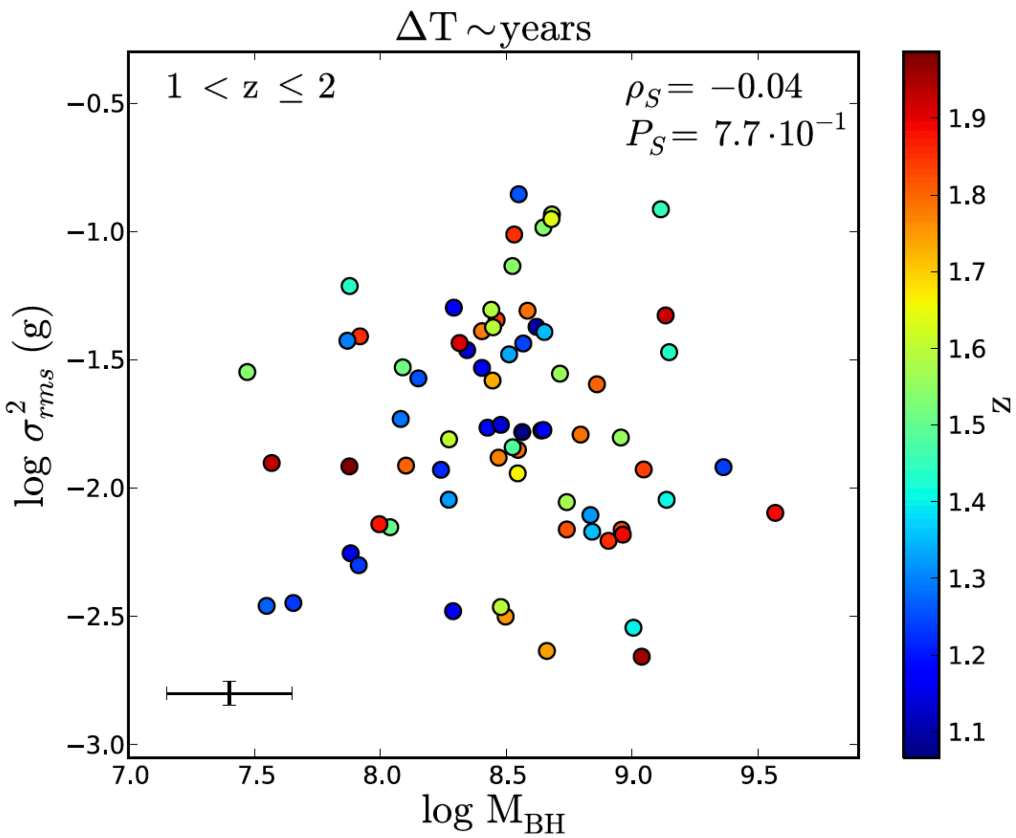
Wilhite+08: SDSS Equatorial Stripe,
~8,000 spectroscopically confirmed quasars,
8 to 12 visits per source

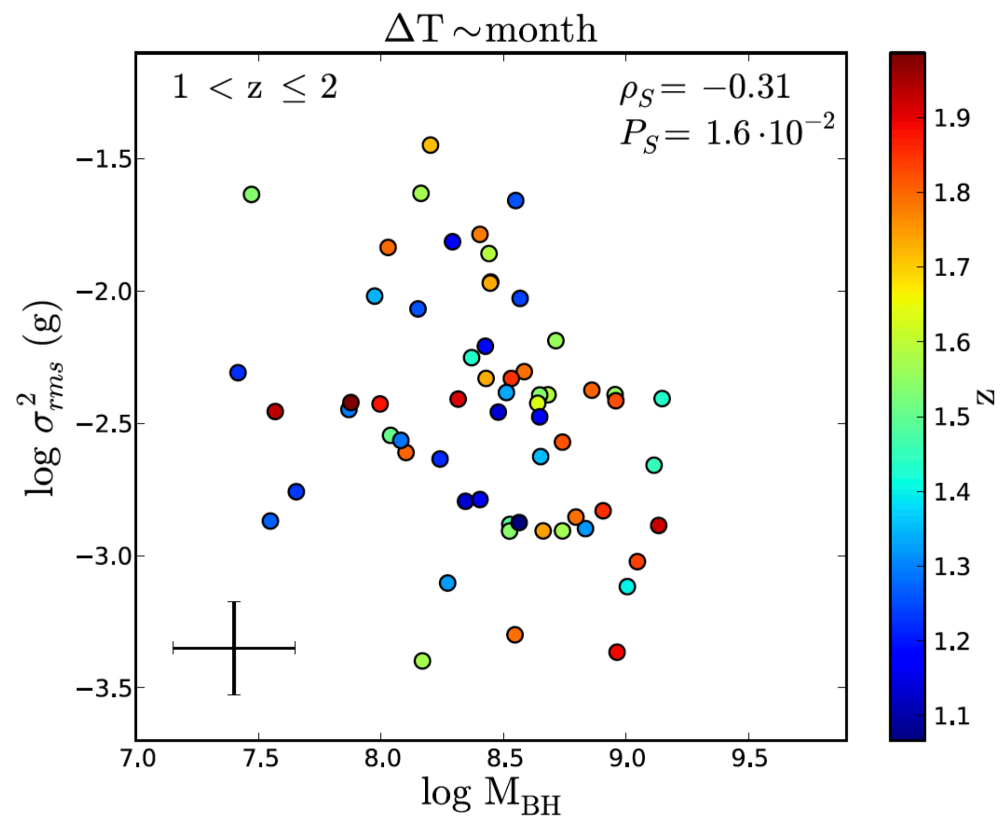
g band; M x10^8 M_{Sun}

MacLeod+10: SDSS Stripe 82,
~9,000 spectroscopically confirmed quasars,
> ~10 yr baseline, 60 visits per source



…Or Not?





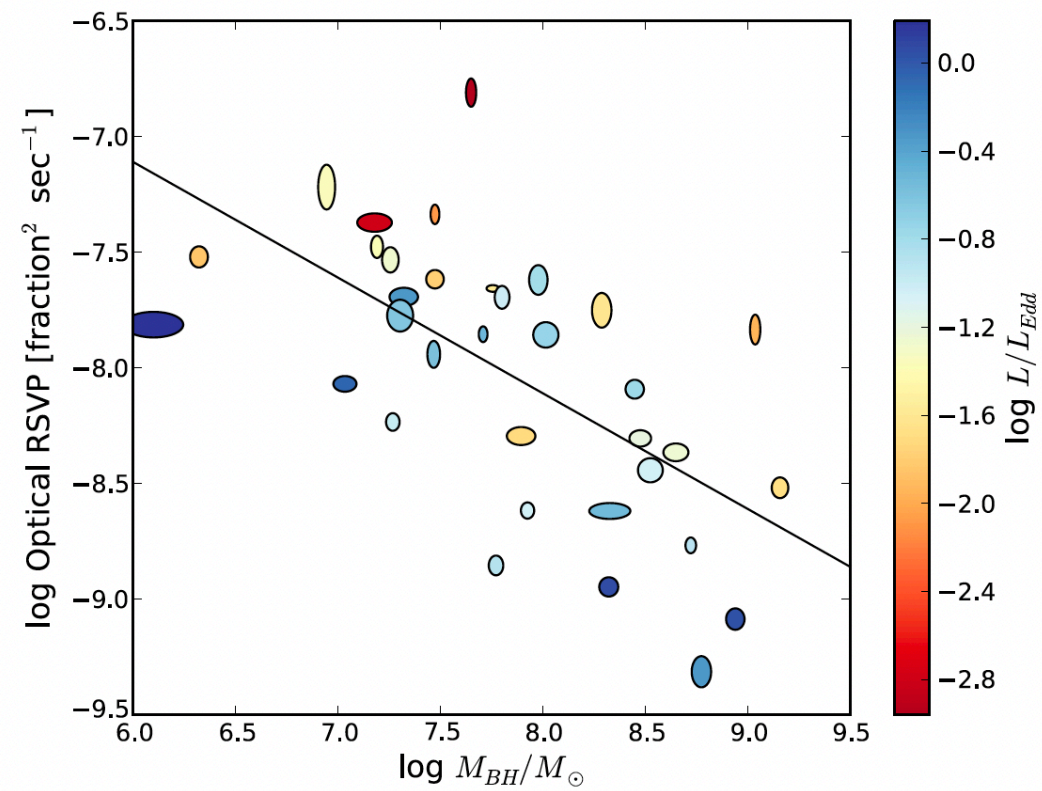
Simm+16: optical variability via PanSTARRS1 for ~90 XMM-COSMOS AGN; 4 yr, gaps => 2 baselines: 1-3 months, 1-3 yr

~70 - 80 visits (10 – 20 points over ~ 3 months)

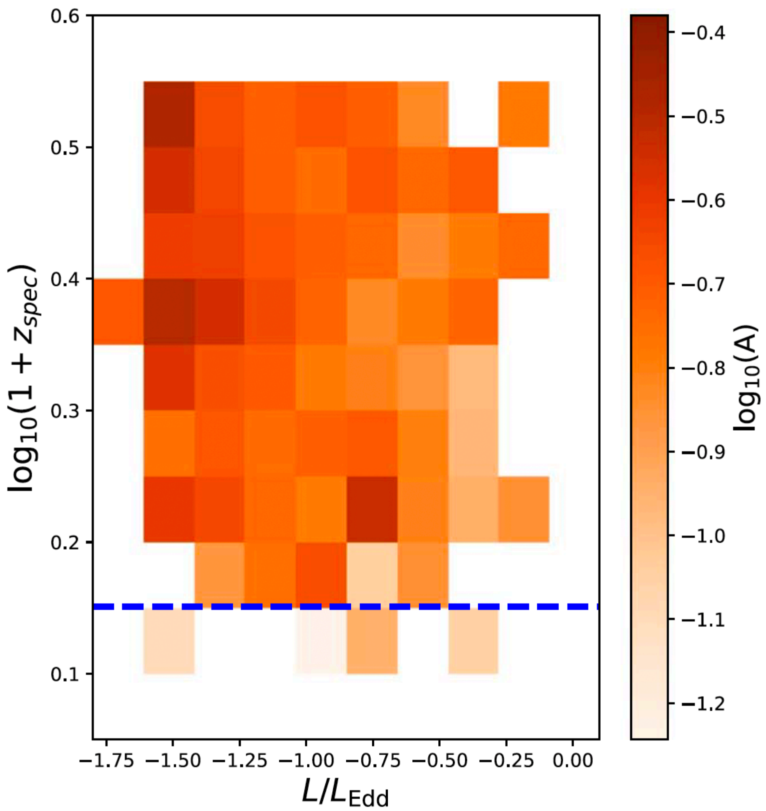
no correlation with M_{BH}

Kelly+13: analysis of the dependence of the PSD on M_{BH} for 39 AGN

the optical rate of stochastic variability power anti-correlates with M_{BH}



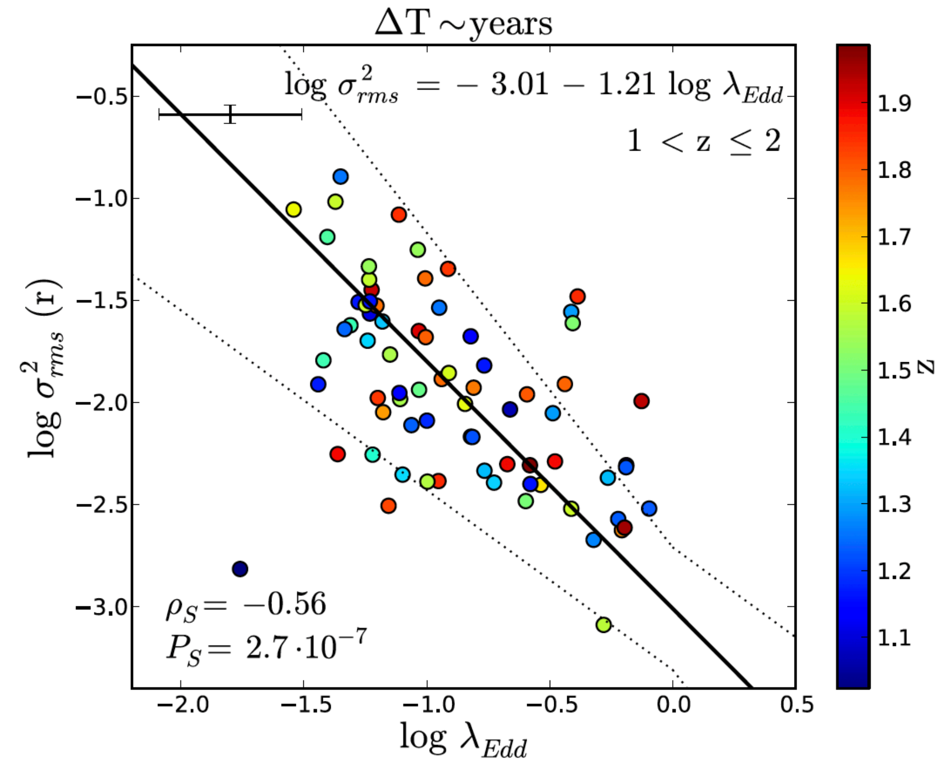
Accretion Rate Dependence



Simm+16 →

best-fit power law

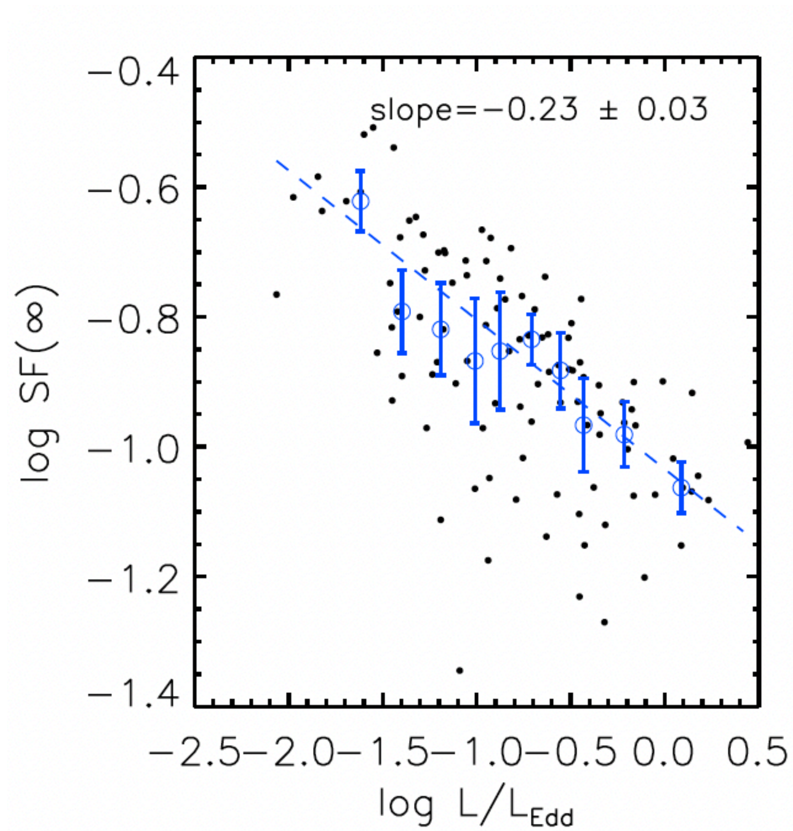
1σ errors

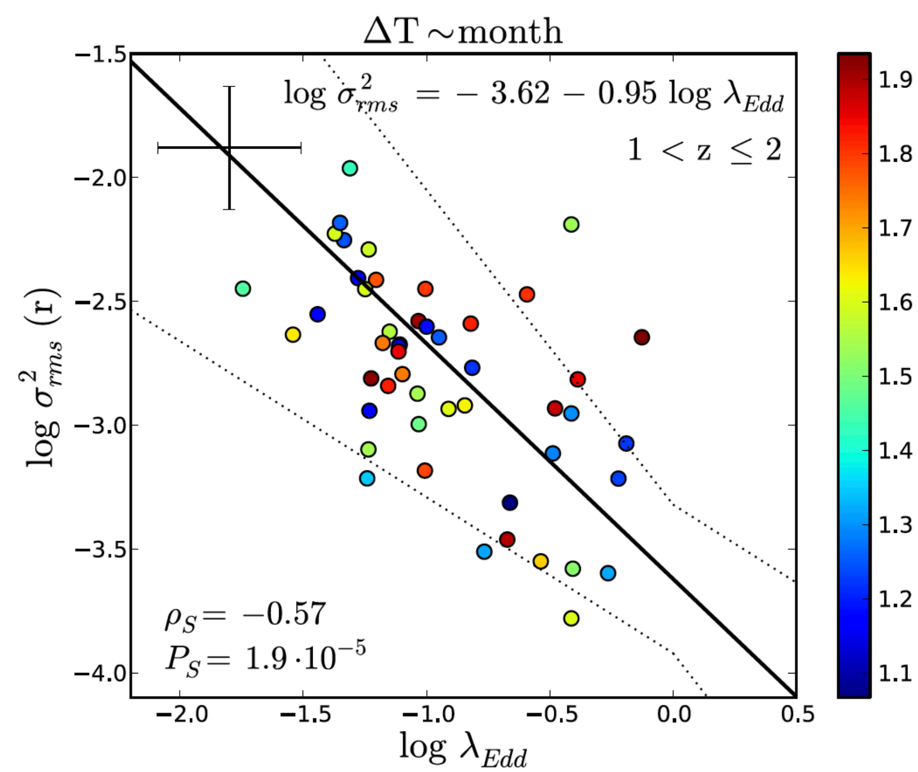


MacLeod+10 ↓

medians in each bin

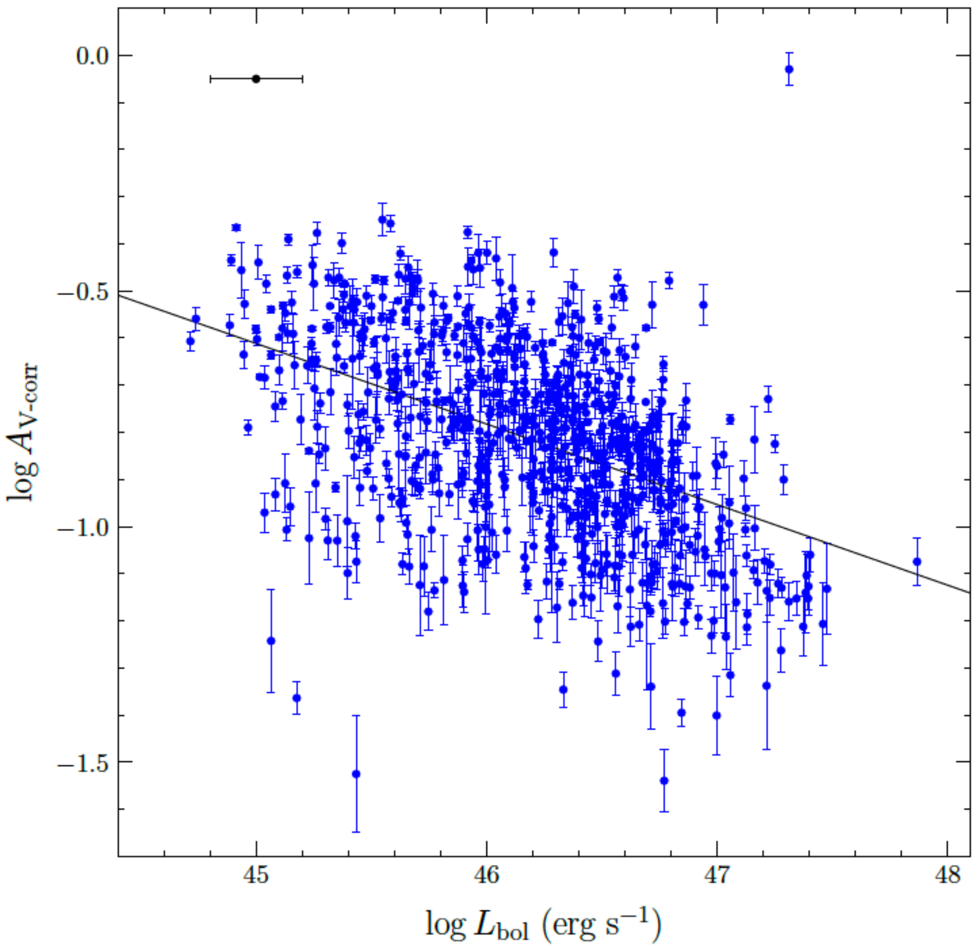
Sánchez-Sáez+18: 2,345 QUEST-La Silla ∩ SDSS AGN variability amplitude anti-correlates with λ_E ↑

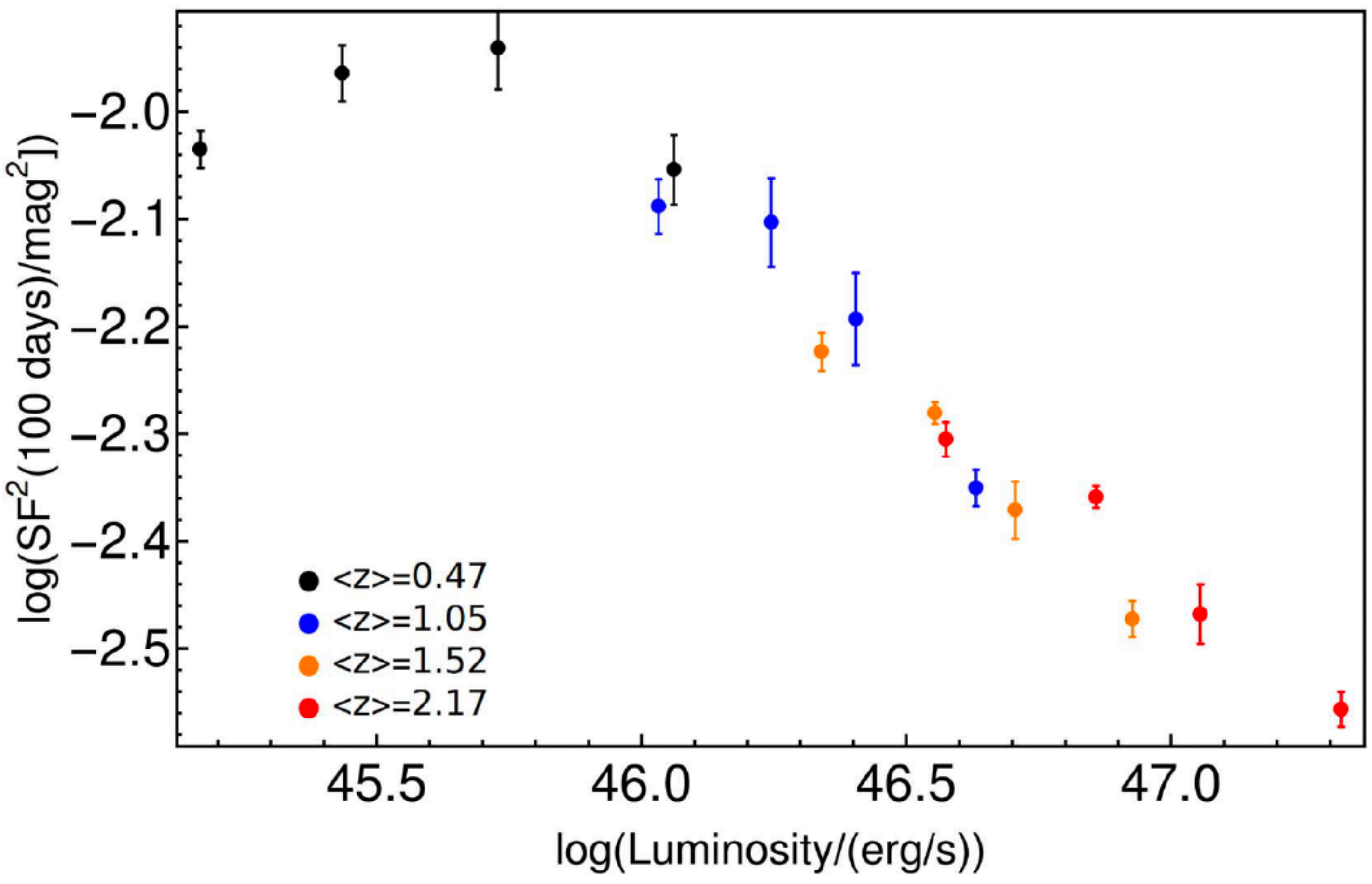




Luminosity Dependence

Laurenti+18: individual optical variability properties of 795 MEXAS2 AGN: variability amplitude anti-correlates with L_{bol}





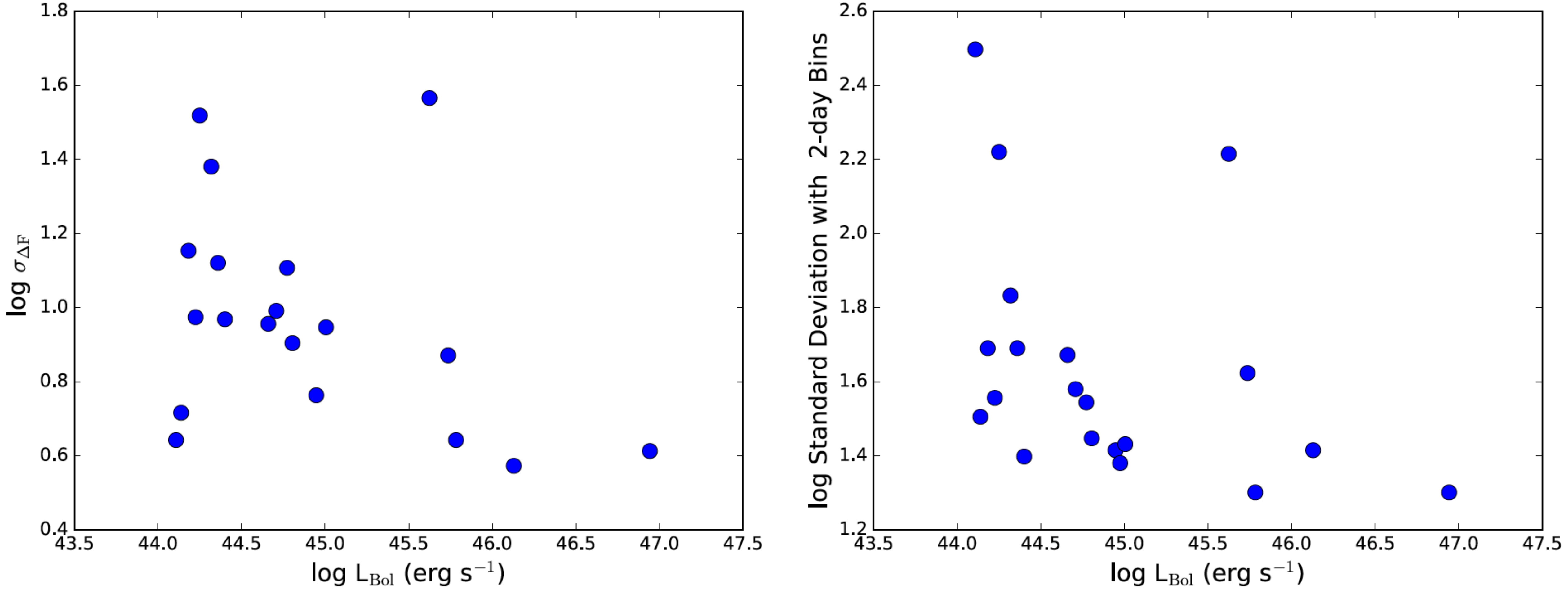
Caplar+17: 28,000 PTF/iPTF BLAGN, *r*-band variability amplitude anti-correlates with L_{bol}, no obvious dependence on z

Luminosity Dependence

Smith+18: Kepler light curves for 21 Type 1 AGN, selected via IR and spectroscopic properties

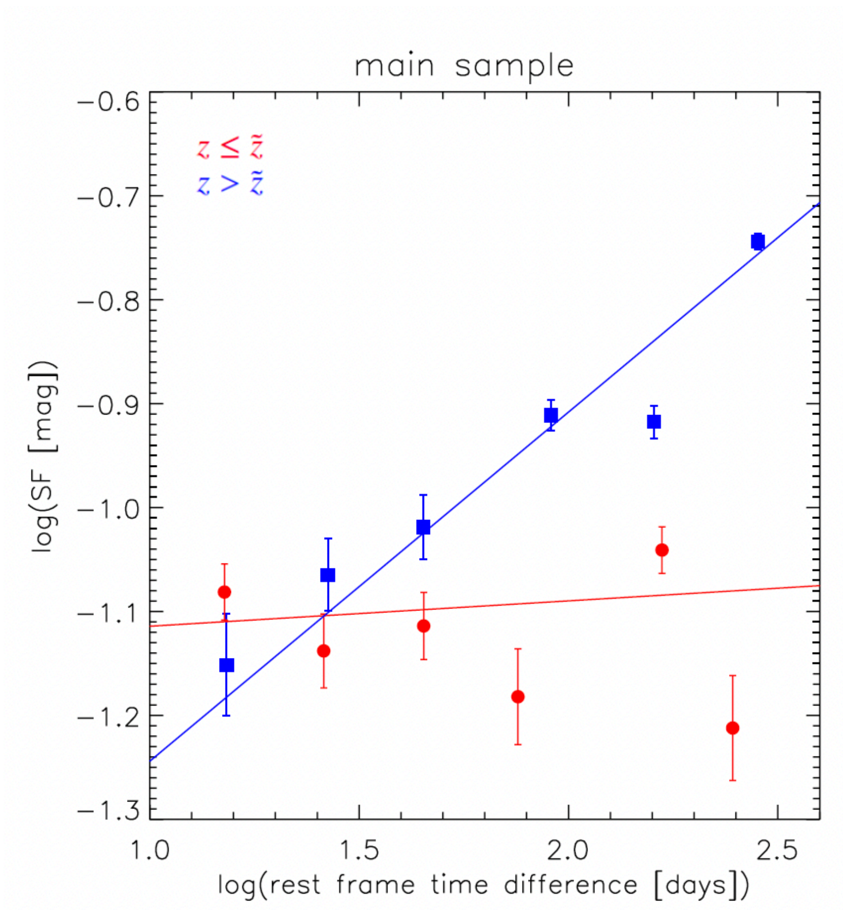
Each LC is re-binned into 2 d bins, to reduce the effect of noise and gaps

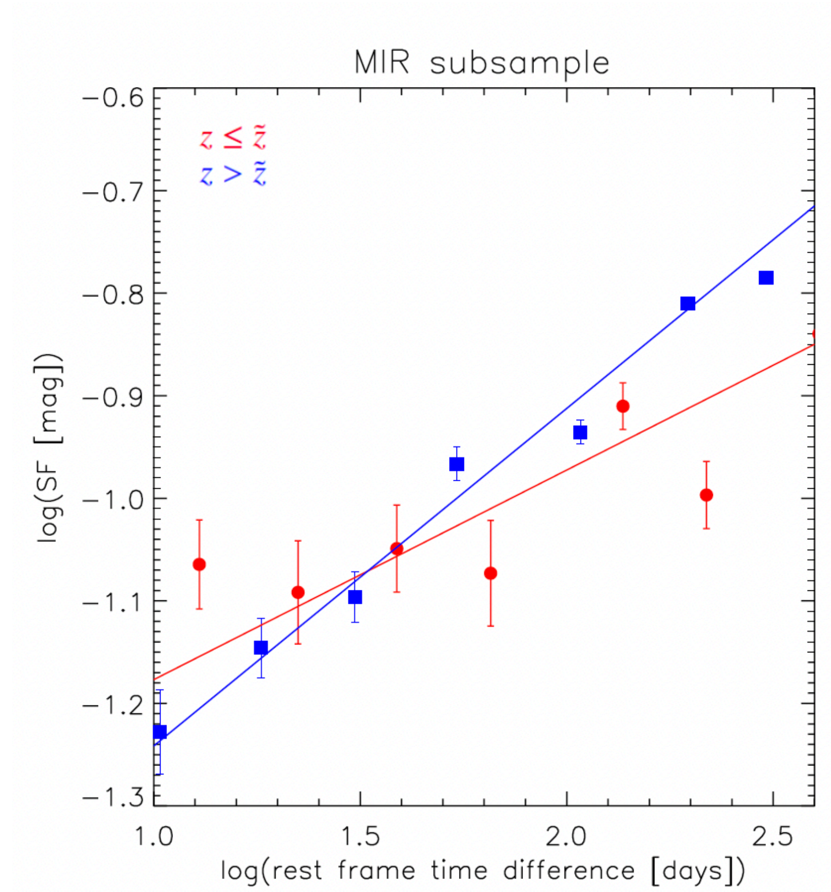
ΔF = flux difference between
two subsequent measurements

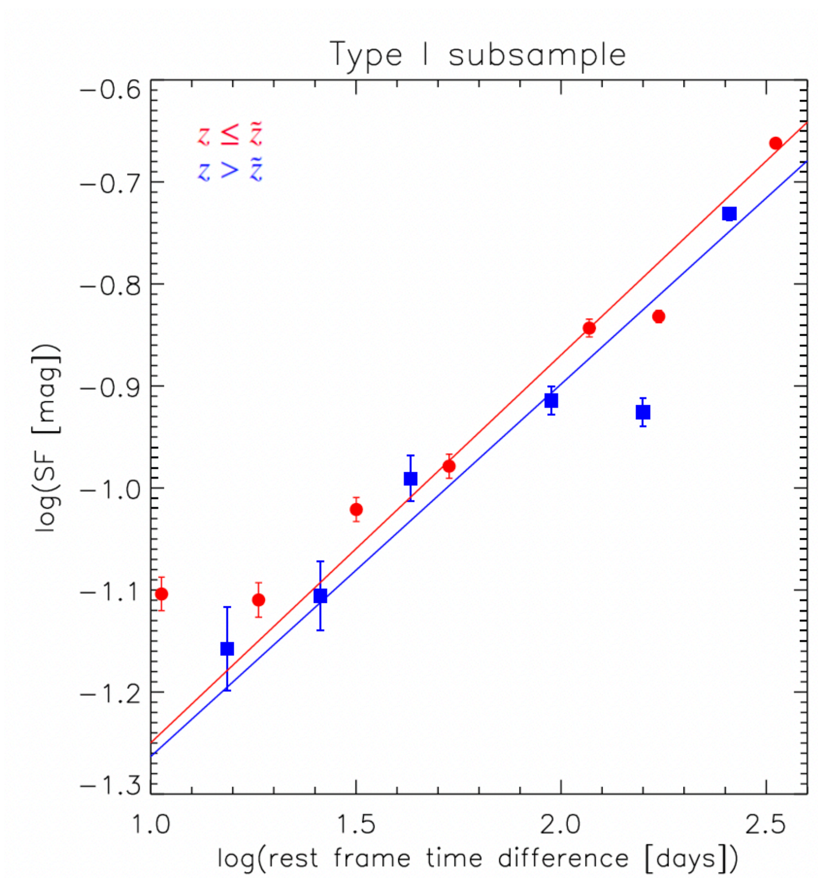


Redshift Dependence

De Cicco+22: the observed correlation with z is actually related to the fraction of obscured AGN







≥ 33% spec. Type I AGN,
≥ 18% spec. Type II AGN

≥ 60% spec. Type I AGN,
≥ 11% spec. Type II AGN

100% spec. Type I AGN
by construction

Optical Variability Timescales

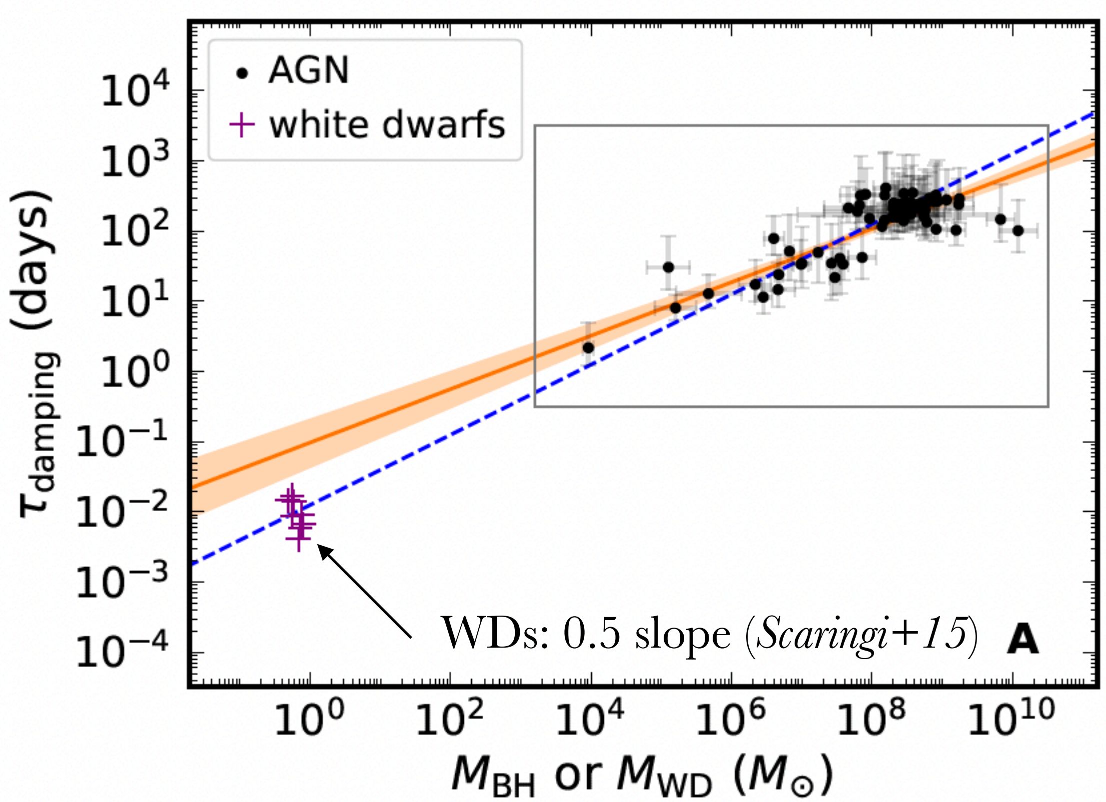
$\tau \sim 10^2$ days for quasars (*MacLeod+10*, *Suberlak+21*); no clear physical origin; dependence on M_{BH} and/or L_{bol}? difficult to assess due to limited timescales and M_{BH} ranges, low S/N (*Kozłowski17*, *Burke+21*)

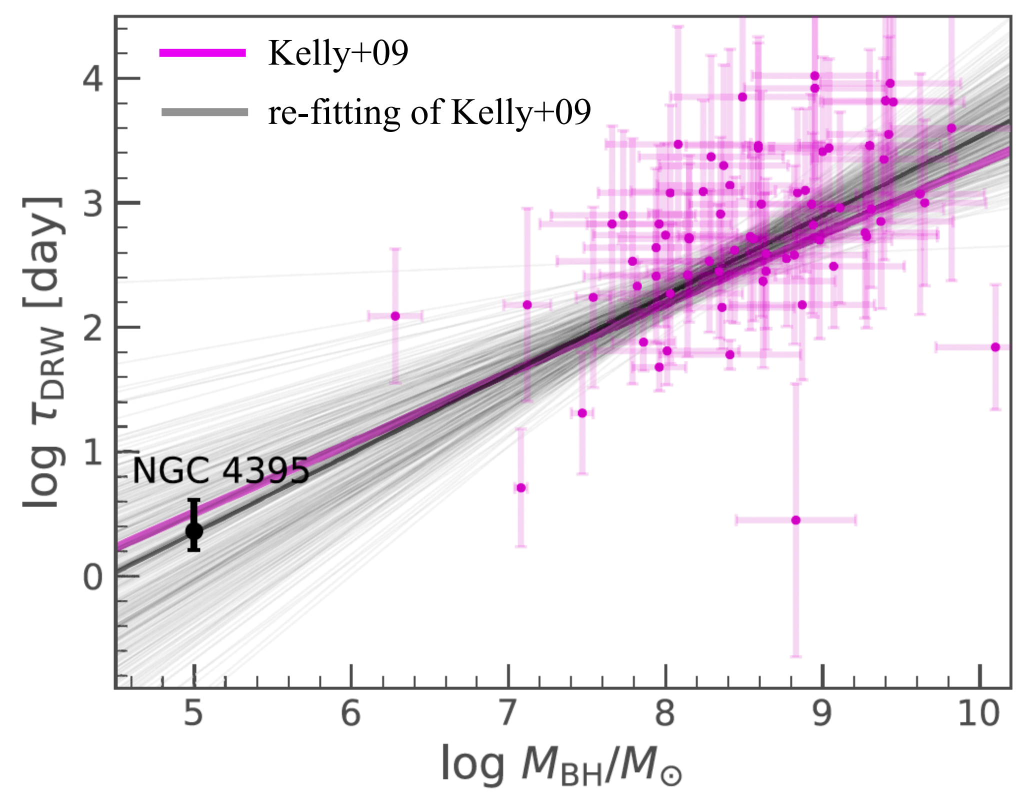
important for, e.g., LSST-related studies!

Burke+21: 67 AGN,

10^4 M_{Sun} < M_{BH} < 10^{10} M_{Sun}

Burke+20: NGC 4395, 10^5 M_{Sun} SMBH in its center; observed with TESS, month-long baseline, 30 min-cadence





Krzysztof Suberlak, Zachary Stone, and Ernesto Camacho's talks

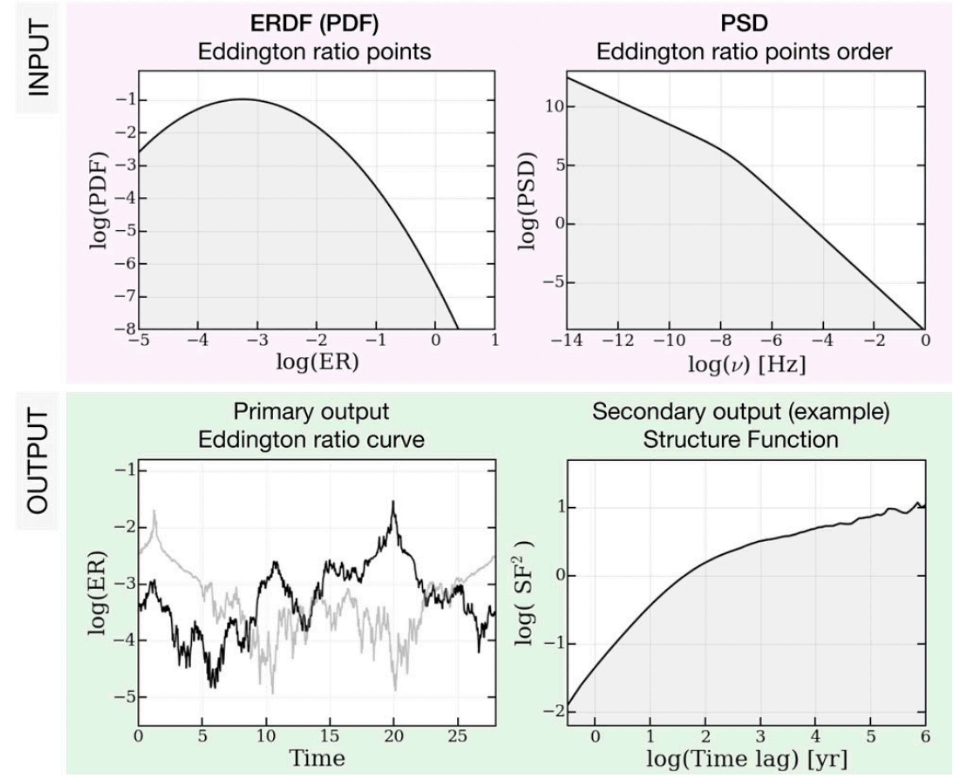
A Model for Multiple Timescales

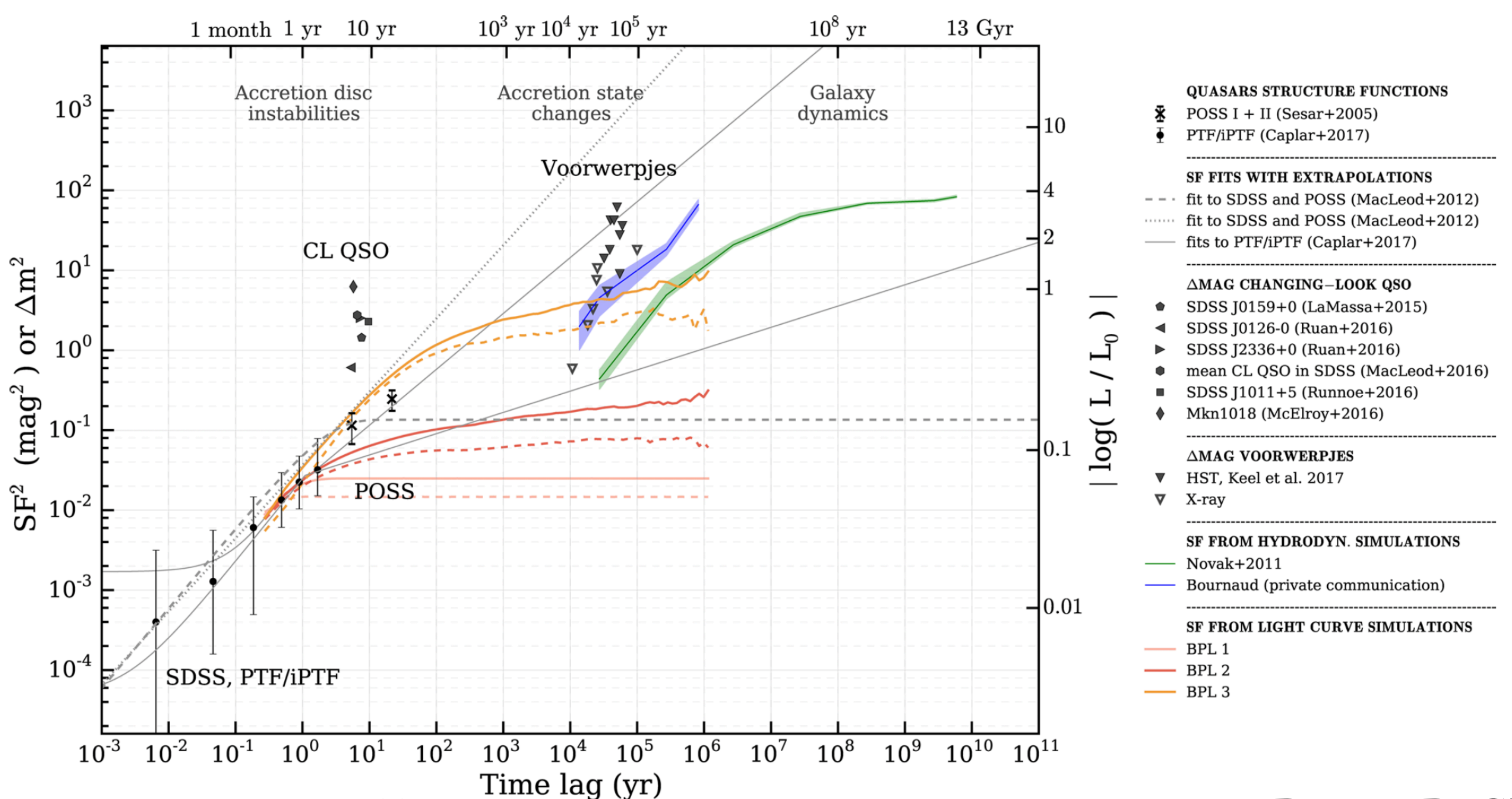
Modeling of AGN variability for different types of objects and timescales, based on the λ_E distribution of the AGN population and its evolution with time. Simulations use the variability observed in iPTF light curves to build longer ones.

↓

Define a "general" AGN behavior, constrain intrinsic variability, merge data sets from different surveys

Sartori+18b, 19





…and 60 Years Ago

1960-1961: first detection of optical variability in the "stellar object" 3C 48

"Optical photometry of 3C 48 continued sporadically during 1961, with the results given in Table 1. The most striking feature of these data is that the optical radiation varies!"

Matthews&Sandage63

"Photometric observations of the 3C 48 optical object confirm its peculiar nature."

"colors which are similar to, but not identical with, old novae (Walker 1957) and to some white dwarfs (Greenstein 1958), but are quite different from ordinary stars and galaxies."

TABLE 1

PHOTOMETRIC DATA FOR THE THREE RADIO STARS

Object	Date	V	$B-V$	$U-B$	Remarks
3C 48	Oct. 23/24, 1960	16 06	0 38	−0 61	
	Nov. 19/20, 1960	16 02	48	− 61	60-inch
	Jan 12/13, 1961	16 11	.42	− 61	
	Jan. 13/14, 1961	16 13	.39	− 61	
	Jan. 14/15, 1961	16 02	49	− 60	
	Jan. 16/17, 1961	16 13	40	− .59	
	Aug. 17/18, 1961	16 31	40	− 52	
	Oct 11/12, 1961	16 333	340	− 579	Taken 15 minutes apart
	Oct. 11/12, 1961	16 289	393	− 555	
	Dec. 4/5, 1961	16 44	35	− 57	Obs. by Baum
	Dec 5/6, 1961	16 40	42	− .64	Obs. by Baum
3C 196	Mar. 31/1, 1962	17 79	57	−. 43	
3C 286	June 2/3, 1962	17 25	0 26	−0 91	

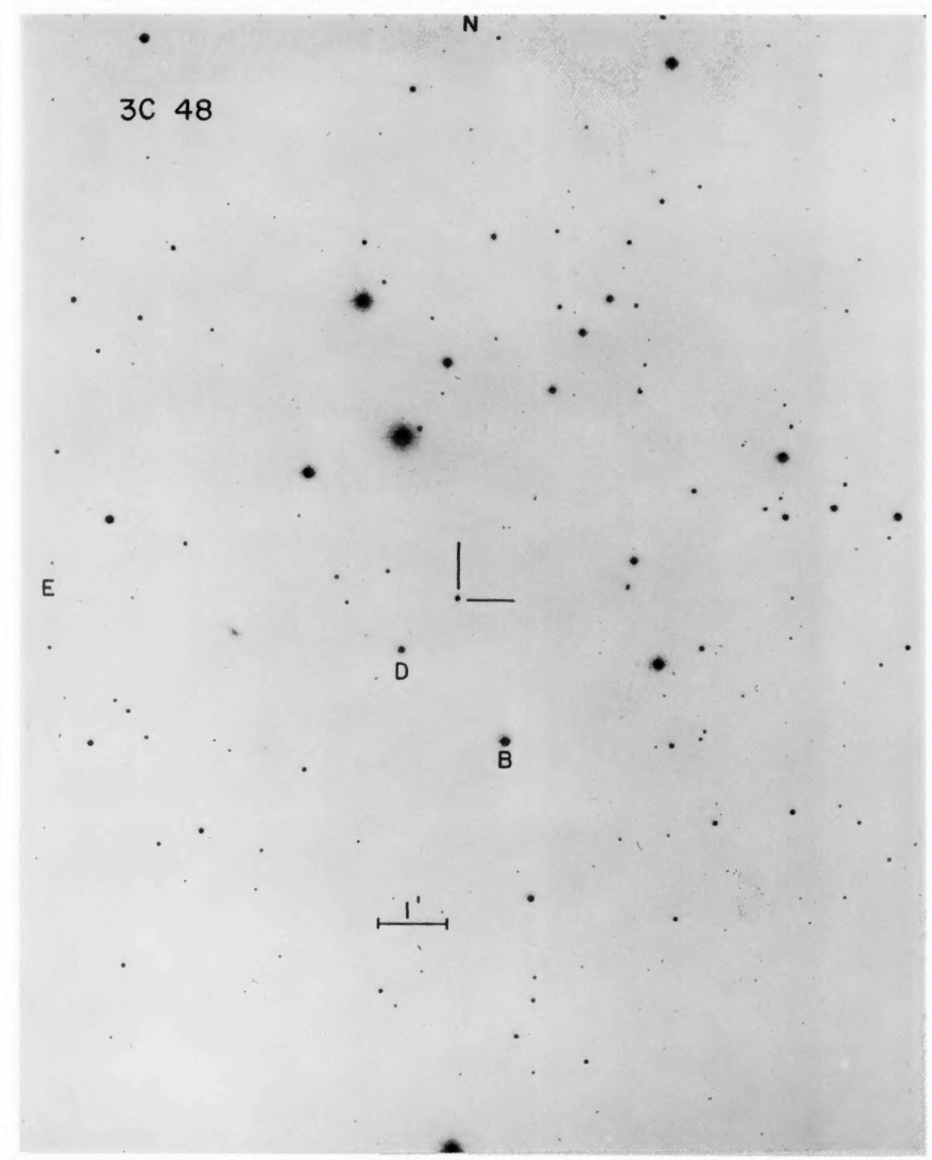


FIG. 2.—Finding chart for 3C 48 taken from a 10-minute exposure with the 200-inch. Local photometric standard stars B and D are marked. The data are $V = 13.53$, $B - V = 0.50$, $U - B = 0.00$ for star B; $V = 14.54$, $B - V = 0.66$, and $U - B = 0.05$ for star D. The plate used was a 103a-O + GG 13.