Variability of Local X-ray Selected AGN

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Background

- AGN show intrinsic stochastic variability at all wavelengths. Their light curves are often modeled as damped random walk or harmonic oscillator processes, although the underlying physical mechanisms that generate such variability remain unclear (e.g., Cackett+21).
- Many past studies (e.g., MacLeod+10; Kelly+14; Sartori+18; Yu+22) argued that the optical variability properties of AGN (timescale and amplitude) are likely tied to AGN accretion rate (L/L_{Edd}) and more tentatively black hole mass (M_{BH}). A M_{BH} dependence may only appear on certain timescales (e.g., Arévalo+23). However, statistical studies primarily focused on large samples of bright optically selected QSOs with $M_{BH} \gtrsim 10^{7.5\text{-}8}\ M_{\odot}$, and extrapolations to more common AGN remain more poorly explored/constrained due in part to host contamination.

Objectives and Research Questions

- Systematically characterize ≲5yr optical variability for a complete sample of 607 local non-beamed AGN (hard X-ray selection via BAT 105-month sample; Oh+2018) using ZTF's *gri* bands (Masci+18).
- Compare and extend results obtained for more massive central engines and explore correlations between fundamental parameters (e.g., black hole mass, accretion rate, λ-dependence).
- Explore observables and place constraints on possible driving mechanisms for AGN variability in well-characterized local sample (see Fig. 1).

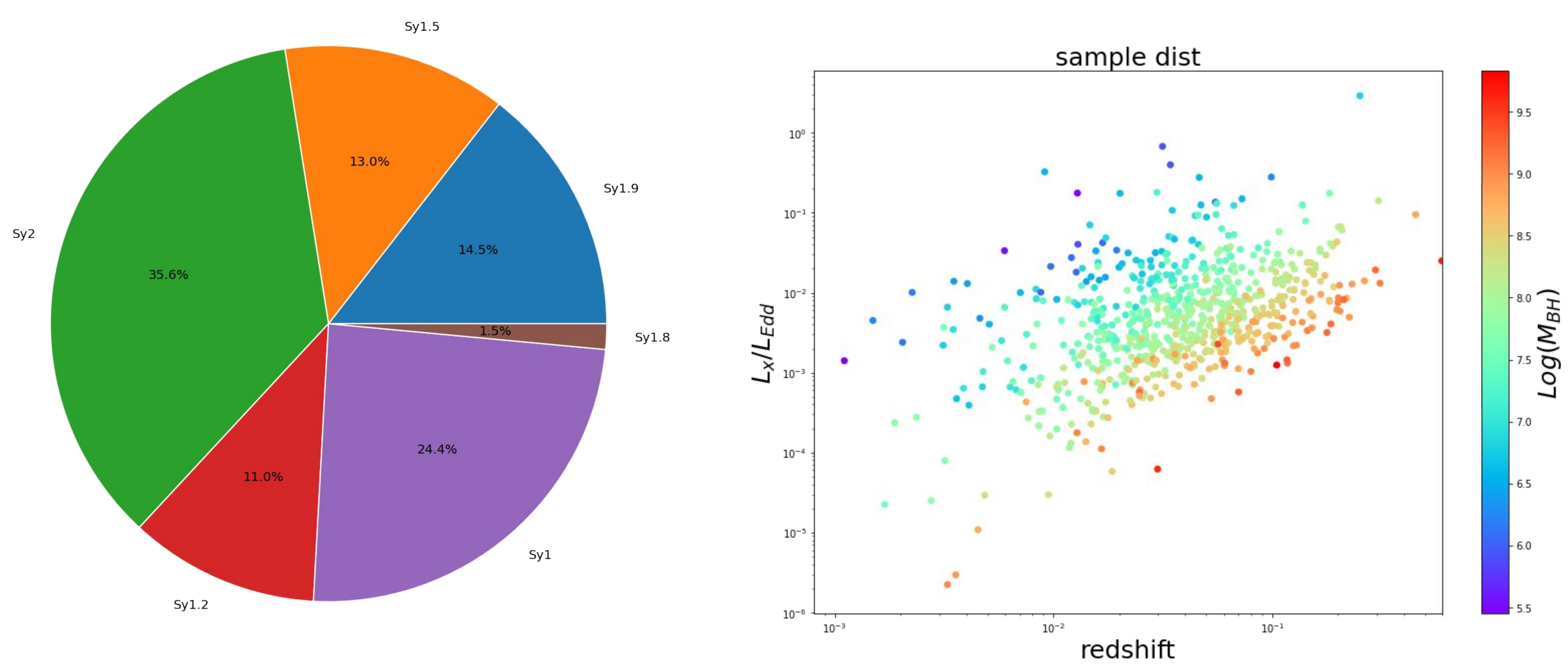


Fig 1: (*left*) AGN type, (*right*) redshift, Eddington rate and black hole mass (M_{BH}) distributions for sample, from Koss+22.

Methods

- We extracted forced photometry *gri* light curves from ZTF for BASS DR2 AGN. The data were cleaned and errors re-calibrated using ZTF DR12 data and querying for nearby non-variable stars in a 3.0 arcmin radius for every epoch.
- We study light curves with more than 30 epochs (557 in g, 549 in r, and 380 in i)
- To model variability, we considered basic statistical estimates, the structure function (SF) and Continuous-Time Auto-Regressive Moving Average (CARMA) (2,1) models (Brockwell+01).

CARMA(2,1) Mode Analysis

- The best-fit CARMA (2,1) parameters and error distributions were obtained using the Eztao code (Yu+Richards22). We retrieve characteristic damping timescales ($\boldsymbol{\tau}_{perturb}$) and amplitudes ($\boldsymbol{\sigma}_{\varepsilon}$) of the variability and study their correlation to black hole mass, accretion rate, and other parameters (Fig. 2). Normalizing $\boldsymbol{\tau}_{perturb}$ by the gravitational radius and multiplying by the light speed, we have $\mathbf{r}_{perturb}$.
- A significant number of corner plots are distinguished by strong bimodal behavior (see Fig. 3). These could represent contributions from over and under-damped regimes (Yu+Richards22), although we see dependencies with variations in light curve errors, number of epochs, baseline, and cadence used in the fits, suggesting systematic effects at play (e.g., Kozlowski17). We distinguish between well-behaved and bimodal fits in Fig. 2, where the latter comprise >35% (based on large errors, and >50% from visual inspection) of the type I AGN model fits.

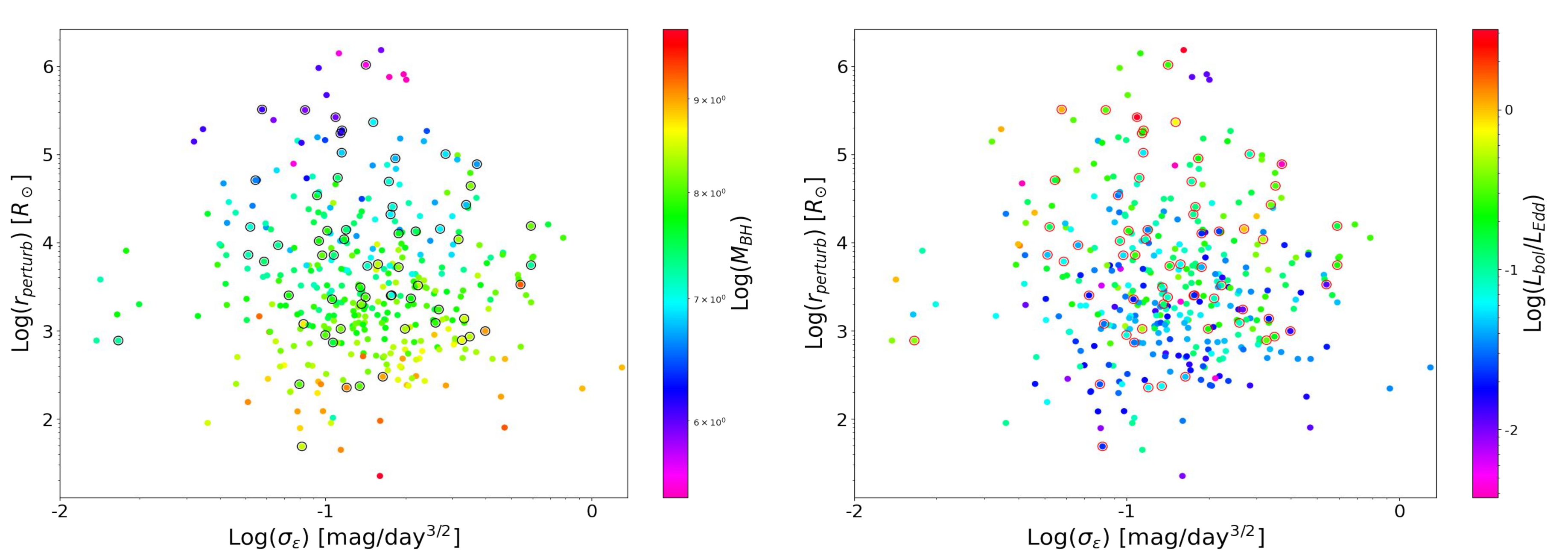


Fig 2: Best-fitted CARMA (2,1) parameters $r_{perturb}$ vs $\boldsymbol{\sigma}_{\varepsilon}$, color coded by M_{BH} (left) and L/L_{Edd} (right) for the BASS AGN. AGN with clearly bimodal MCMC fits are denoted by open circles.

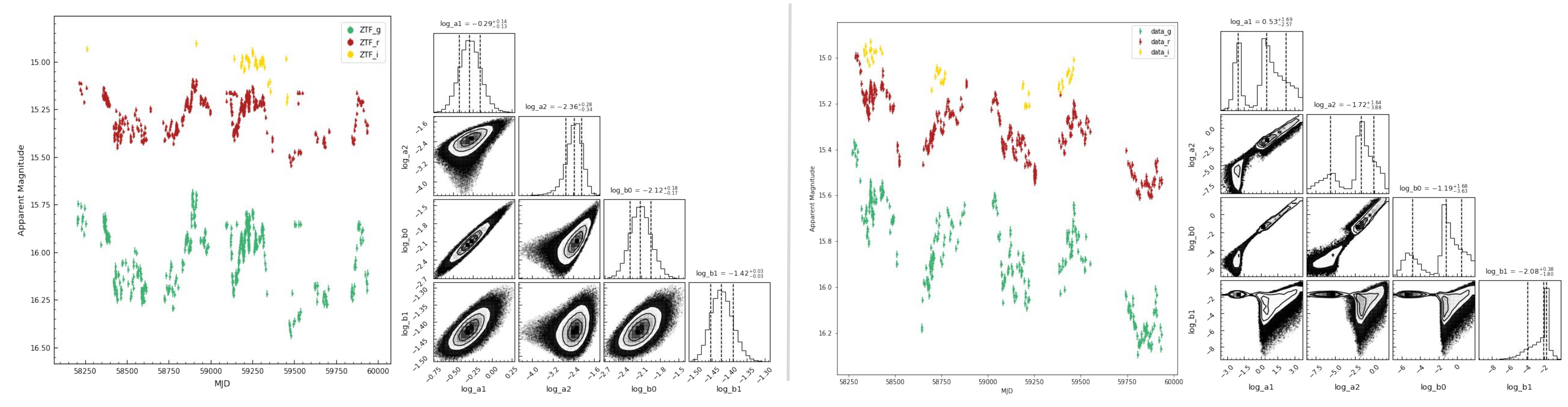


Fig 3: Example forced photometry ZTF light curves and CARMA(2,1) model fit parameter corner plots for Markarian 10 in the r band (left; well-behaved) and Markarian 705 in the g band (right; bimodal).

Structure Function Analysis

- We estimated SF features SF_{∞} and gamma (SF_{∞} vs. Δt slope) using the lc_classifier pipeline (Sánchez-Sáez+20), comparing to AGN type, M_{BH}, L/L_{Edd}.

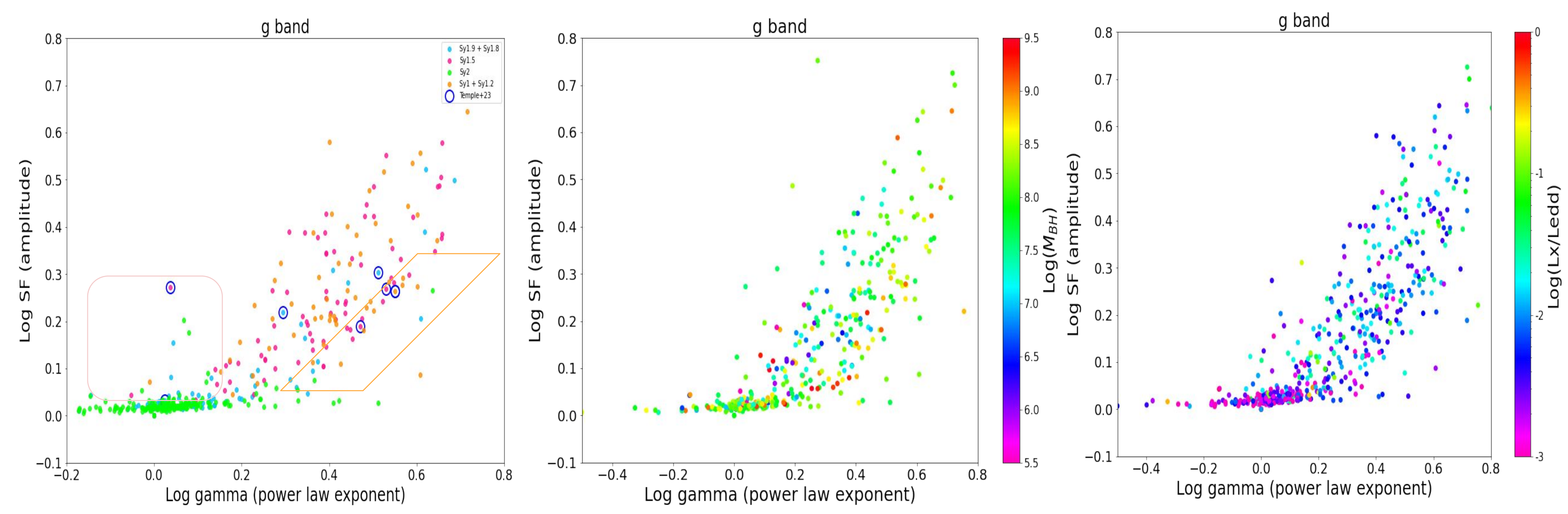
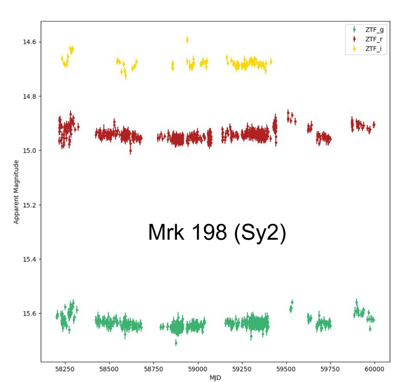


Fig 4: g-band SF distinguished by AGN type (left) and black hole mass (right). The blue open circles on the left denote Changing-State AGNs (CSAGN) from Temple+23. Are there other CSAGN in orange regions?

Preliminary Results

- Out of 557 targets with ≥30 epochs in any band, based on a significant positive excess variance, we find that:
  - 97%(271) of Sy1-Sy1.5s appear variable, consistent with expectations, while 13%(10) and 30%(55) of Sy1.8-1.9s and Sy2s, respectively, are variable.
  - 8.9%(6) of $\log(M_{BH}/M_{\odot}) < 7$, 39.2%(103) of $\log(M_{BH}/M_{\odot})$ between the range of 7-8, 38.4%(99) for the 8-9 bin, and 2.8%(1) of those >9 appear variable.
- SF amplitude and slope (gamma) show trends with AGN type, M_{BH} and L/L_{Edd} (Fig. 2), consistent with past studies (e.g., De Cicco+22). Sy1-1.5s strongly overlap in parameter space, while Sy 1.8-1.9 and Sy2s appear strongly damped.
- Considering the 17 confirmed BAT Changing-State AGN from Temple+23, only 1 out of the 7 well-observed by ZTF shows extreme variability in SF parameters which might easily identify it. There are a handful of BAT AGN (orange regions, including several Sy2s) which show similar characteristics and may warrant dedicated monitoring.



- Based on CARMA (2,1) modeling, the BASS AGN appear to occupy an adjacent parameter range compared to the Stripe 82 QSOs from Yu+22. <u>However</u>, a large fraction of the sample show bimodality in their MCMC results; this does not seem to affect their distributions compared to more well-behaved sources. Moreover, we see a large spread to higher $\boldsymbol{\tau}$ and $\mathbf{r}$ values, which remain to be fully understood (fits being stuck in local minima? errors being incorrectly estimated?).

Discussion

- ZTF forced photometry light curves allow us to minimize substantial host contamination, enabling studies for a large and statistically well characterized sample of local BAT AGN. The properties of these light curves highlight various intriguing trends and outliers which warrant further investigation.
- In terms of basic statistics, if we extrapolate to what LSST will ultimately observe (future work), we should expect to detect significant variability not only from the vast majority of type I AGN, but also for substantial fractions of the Sy1.8-Sy2 populations.
- However, given the similarity in cadence between ZTF and LSST, it will be important to understand the origins of the bimodality seen for a significant fraction of AGNs. Will this also be a problem for LSST?
- More detailed investigations are necessary to make sense out of the CSAGNs in terms of their variability properties: e.g., why so few stand out?; are there additional candidates of CSAGN in the BAT sample awaiting confirmation?

References: Arevalo+23, Brokwell+01, Cackett+21, De Cicco+22, Kelly+14, Koss+22, Kozlowski17, MacLeod+10, Masci+18, Oh+18, Sanchez-Saez+20, Sartori+18, Temple+23, Yu+Richards22, Yu+22,

We acknowledge funding support from ANID FONDECYT Regular #1200495 and CATA FB210003, UC-VRI