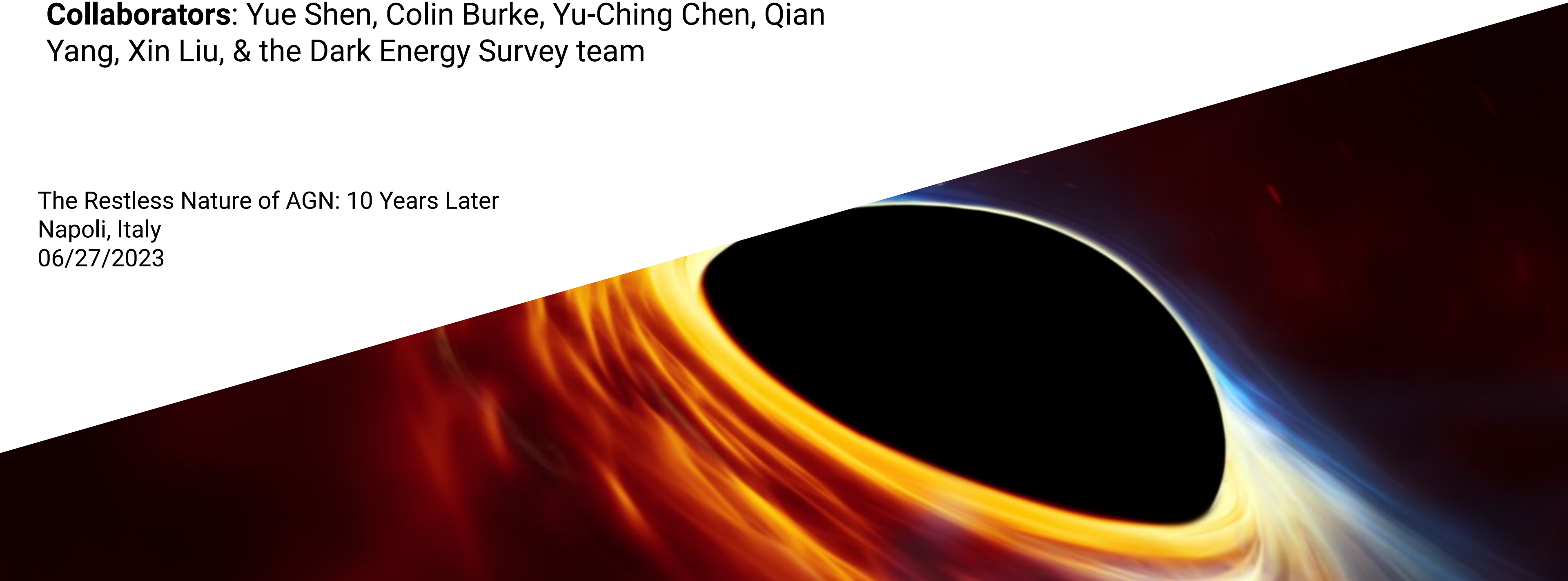
# Uncovering Optical Quasar Variability After 20 Years

Zachary Stone
UIUC Dept of Astronomy

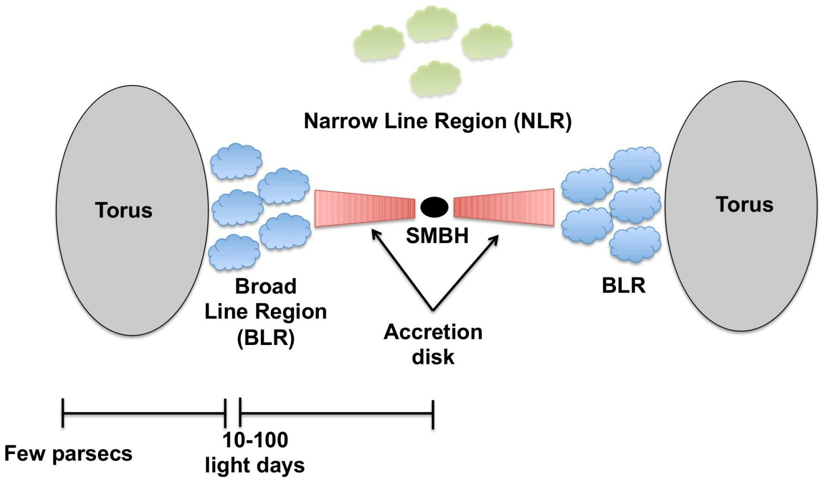
**Collaborators**: Yue Shen, Colin Burke, Yu-Ching Chen, Qian Yang, Xin Liu, & the Dark Energy Survey team

The Restless Nature of AGN: 10 Years Later
Napoli, Italy
06/27/2023



# Ensemble Quasar Variability

Claudio Ricci




Time-series data from AGN allow us to bypass high-resolution imaging

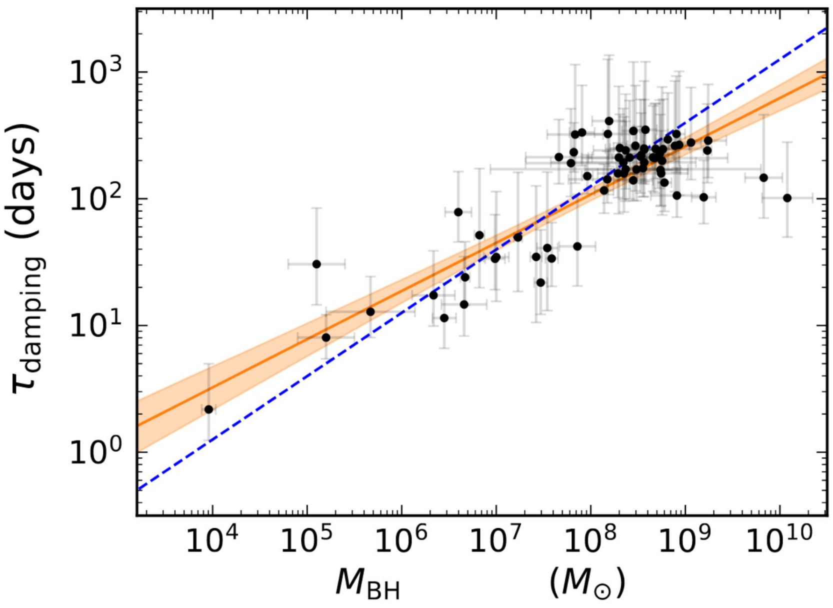
Variability tells us about the physics in the accretion disc, and the timescales on which they occur

Information in different bands tells us about:

- Reprocessing of continuum radiation
- Black hole mass
- Luminosity

# Ensemble Quasar Variability

Burke+2021

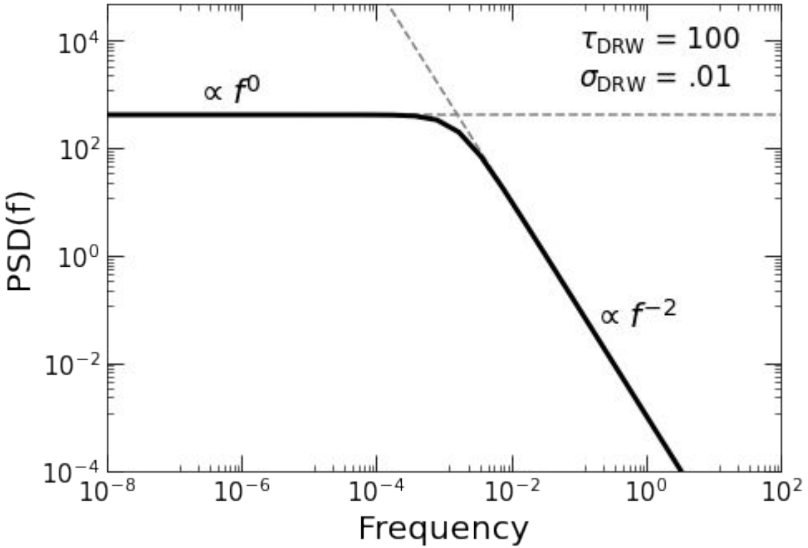



The origin of the structure of optical variability is not well understood

- What timescales of variability correspond to the disc?
- How do the timescales relate to the AGN?
- Correlations to AGN parameters?
- Correlations to disc properties?

Need to analyze the variability of ensembles of AGN to get an idea of its origin

# The Damped Random Walk (DRW) Model




$$\tau_{\mathrm{DRW}} = \frac{1}{2\pi f_{\mathrm{DRW}}} \qquad SF_{\infty} \equiv \sqrt{2}\,\sigma_{\mathrm{DRW}}$$

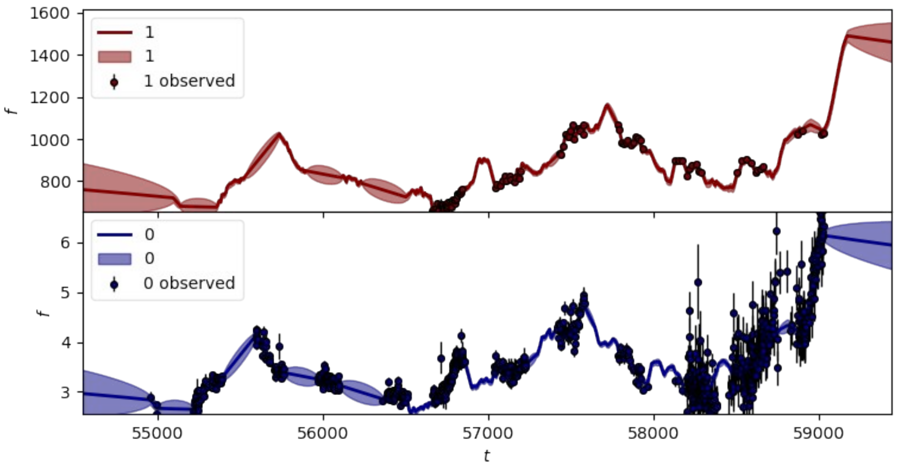
Photometric variability can be modeled well as a Damped Random Walk (DRW)

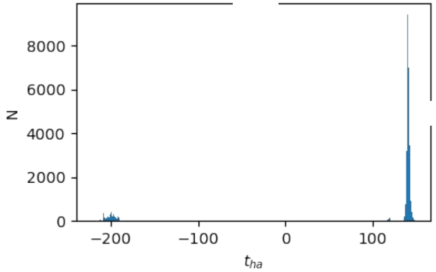
- Kelly+2009, MacLeod+2010, Suberlak+2021

Described by two parameters:

- Timescale of variability ( $\tau_{\mathrm{DRW}}$ )
- Amplitude of long-term variability ($\sigma_{\mathrm{DRW}}$ )

# The DRW Today




The DRW is assumed in many science cases, but how valid are these assumptions?

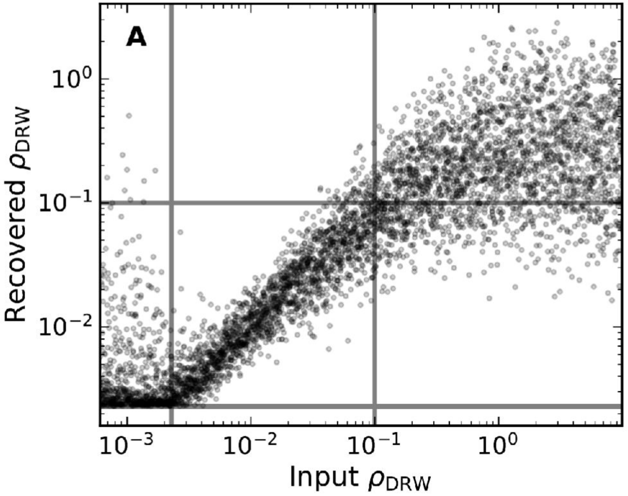
- JAVELIN
- Pancoast+2014 for dynamical modeling

Optical variability has been shown to be more complex than a DRW in the past (Simm+2016, Kelly+2014)

Need to use different models on large samples of AGN to determine how well they can be described on average

# Motivation: Saturation of $\tau_{\mathrm{DRW}}$

Burke+ 2021




$$\rho_{\mathrm{DRW}} = \frac{\tau_{\mathrm{DRW}}}{\mathrm{baseline}}$$

The fitted value for a large $\tau_{\mathrm{DRW}}$ saturates at ~20% of the total baseline of an input light curve (Kozłowski 2017, Burke+2021)

Longer baselines allow less biased values of DRW parameters

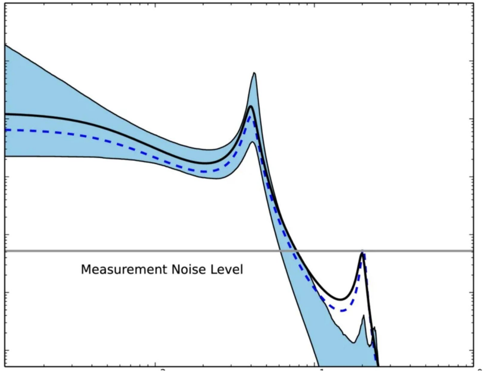
A longer baseline provides more sampling of the PSD and structure function (SF)

# CARMA Models

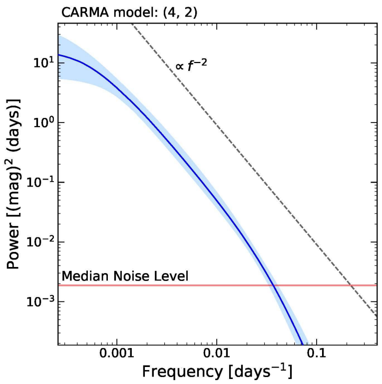
The DRW model is the simplest in a family of Gaussian processes known as Continuous Autoregressive Moving Average (CARMA) models

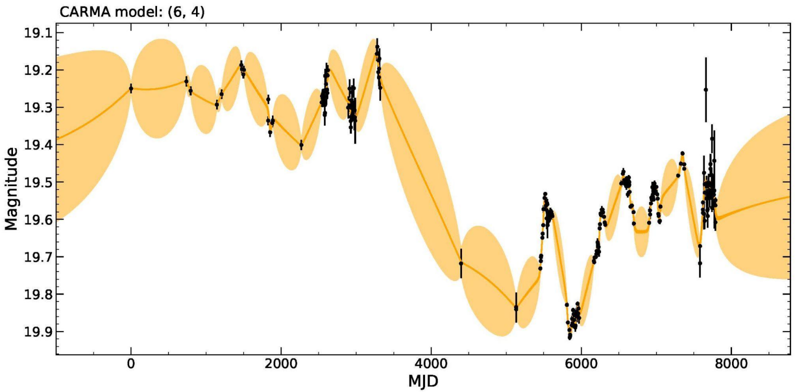
We consider these models, as a DRW might not be the most accurate model for describing quasar variability

Used this as a way to parameterize the PSD in a flexible way




Kelly+ 2014

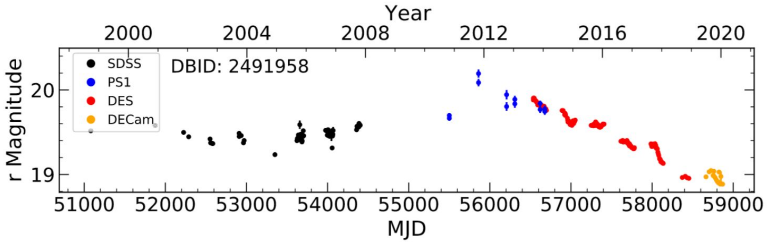


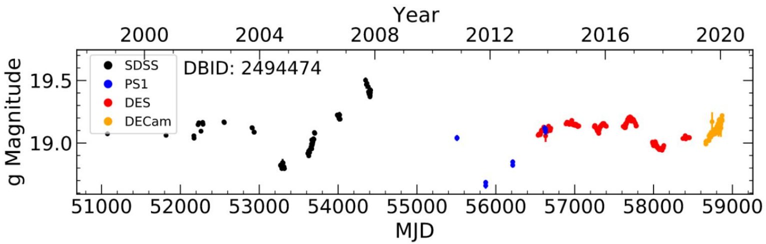



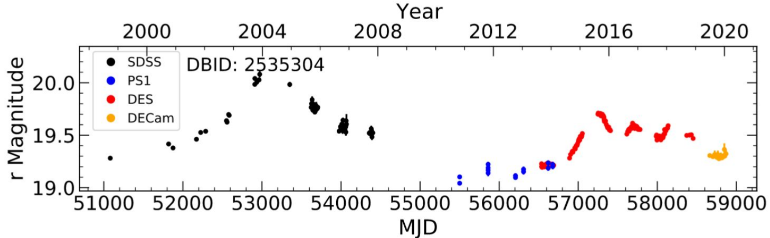
# Motivation: Validity of the DRW

We have 20 year-long baselines of light curves, over multiple surveys in *g,r,i*

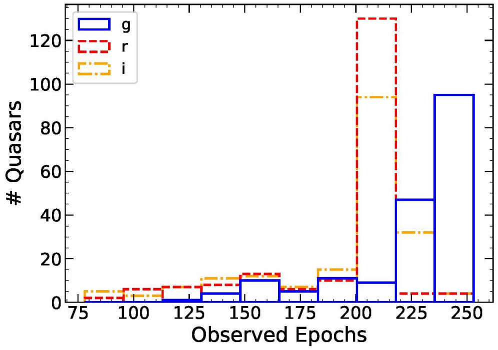
Use long-baseline light curves to test the validity of the DRW model and relations between DRW parameters and other quasar parameters

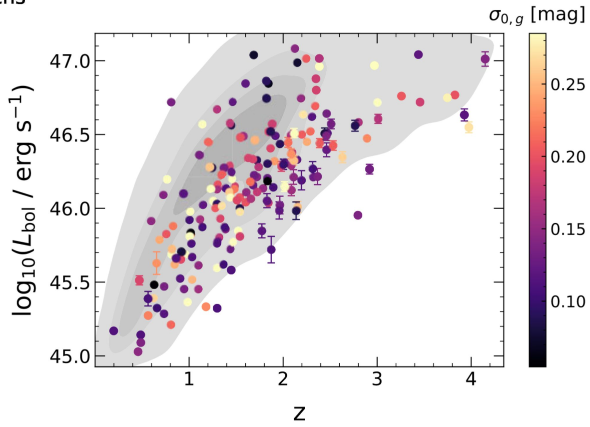


# The Quasar Sample




190 quasars with g, r, and i band light curves spanning 20 years (SDSS, PS1, DES, DECam)

Located in Stripe 82 (S82), and belong to either one of the DES-deep fields within S82

All have measured quasar properties from the known literature ($M_{BH}$ , $L_{bol}$ , z, etc.)

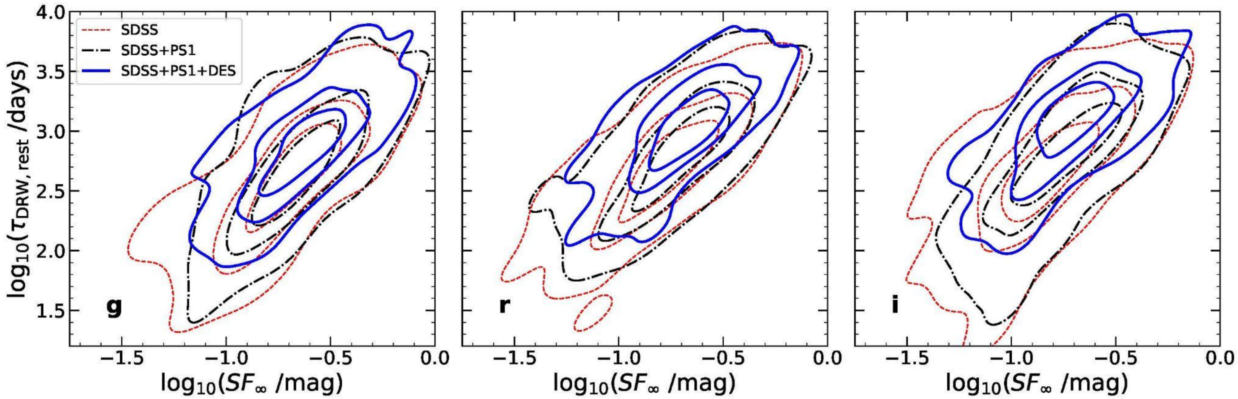
Matches the greater quasar population (compared to the Shen+2015 catalog)

# DRW Fitting Results: $\tau_{DRW}$ Convergence

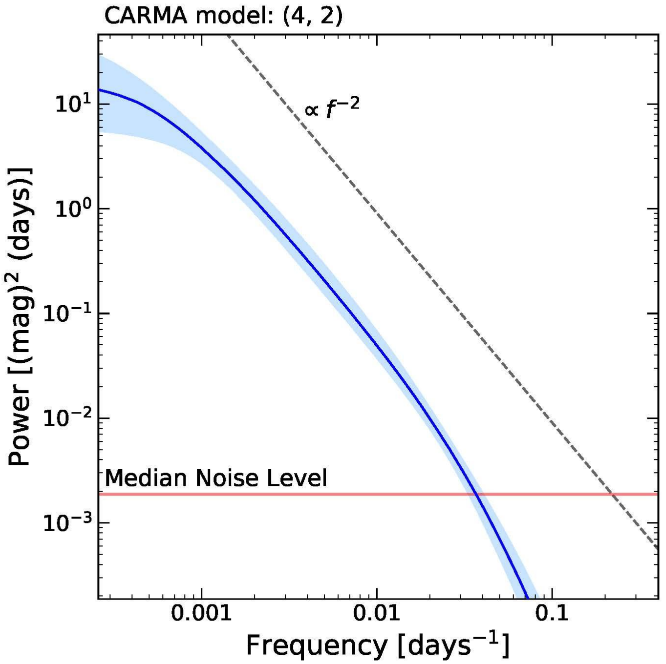
We reproduce earlier results using the shortened baselines (i.e., truncated light curves)

Our parameter values are higher than those measured previously

The measurement uncertainty and scatter in the parameters has decreased as the baseline increases



# Power Spectrum Density Fitting




Fit the light curves of each quasar to a CARMA model

Find the optimal model for a given light curve using CARMA_PACK (Kelly+ 2014)

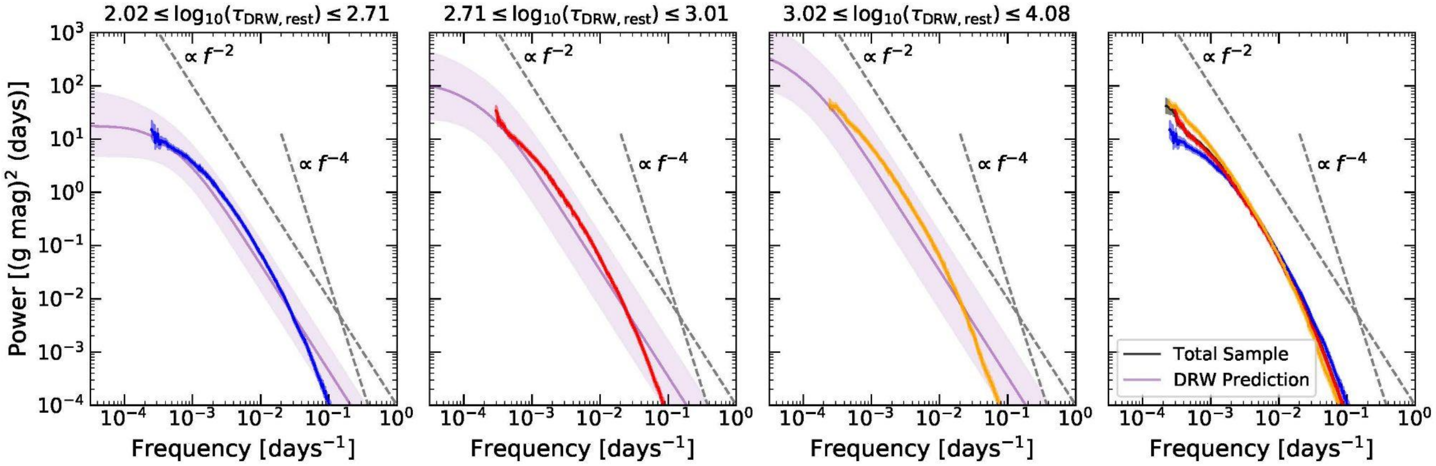
This still makes assumptions about the model and physics in the accretion disc, but it is more flexible than a DRW model fit

We construct ensemble (co-added) PSDs for different subsets of the ensemble

# PSD Results: Steepening Slope

The PSD does not follow a DRW well at large frequencies, where it is much steeper

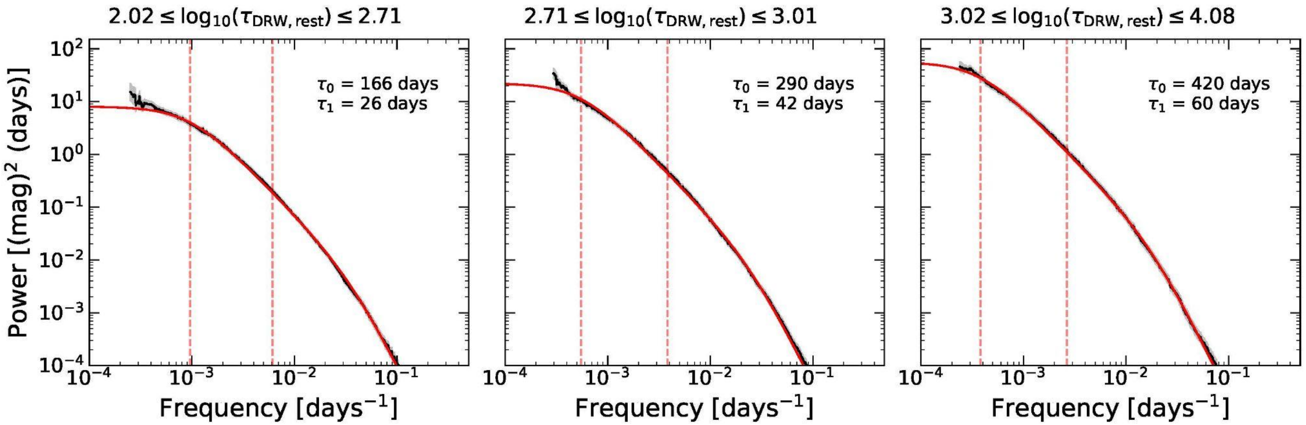
For intermediate timescales (months - years), the DRW model compares reasonably well to the measured PSD



# PSD Results: Implications

Suppressed variability at small timescales

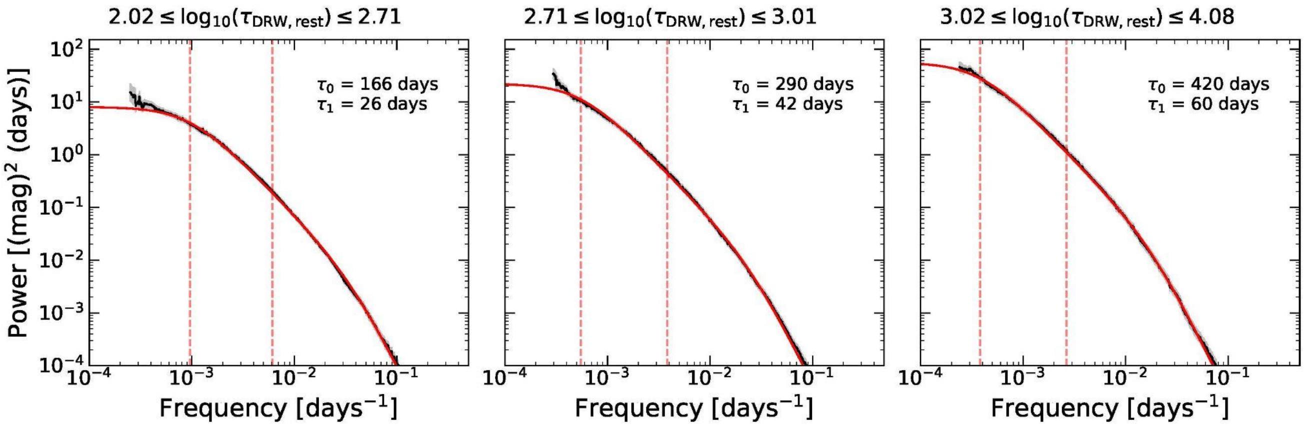
We observe that this steepening corresponds to a second break in the PSD



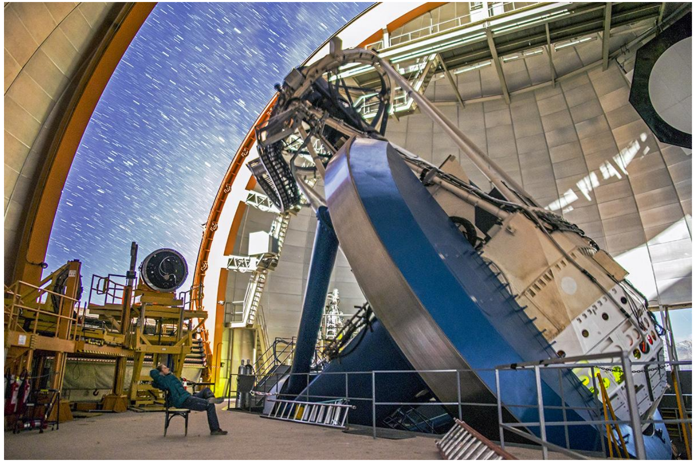
# PSD Results: Implications

Could arise from:

- Another physical timescale (scales with $\tau_{DRW}$) (e.g., Mushotzky+2011, Zu+2013)
- Averaging effect from the arrival times of radiation from different regions in the accretion disk (e.g., Neustadt & Kochanek 2022, Stone & Shen 2023)
- Smearing from central source reverberation (Tachibana+2020)



# The Future



THE DARK ENERGY SURVEY

LSST
Legacy Survey of Space and Time

# Conclusions

We recover values for $\tau_{DRW}$ and $\sigma_{DRW}$ found in previous studies when using smaller baselines

Our values for $\tau_{DRW}$ are larger, due to the increased baseline (affirms bias from a small baseline)

Recover dependences of the parameters on wavelength (ours is more positive than previous ones)

CARMA-fit PSDs show agreement to the DRW model on large timescales (months - years), but show steepening on timescales < months

- Related to averaging effects of the difference in light arrival times from different parts of the accretion disk
- Another low-frequency $\tau_{DRW}$ , corresponding to different astrophysical processes than the original timescale

Higher cadences and larger, more diverse samples with upcoming and current surveys will allow for more accurate analysis of optical variability, and test the validity of the DRW