AGN Selection and Characterization in Next-Generation *(UV/Optical)* Time-Domain Surveys

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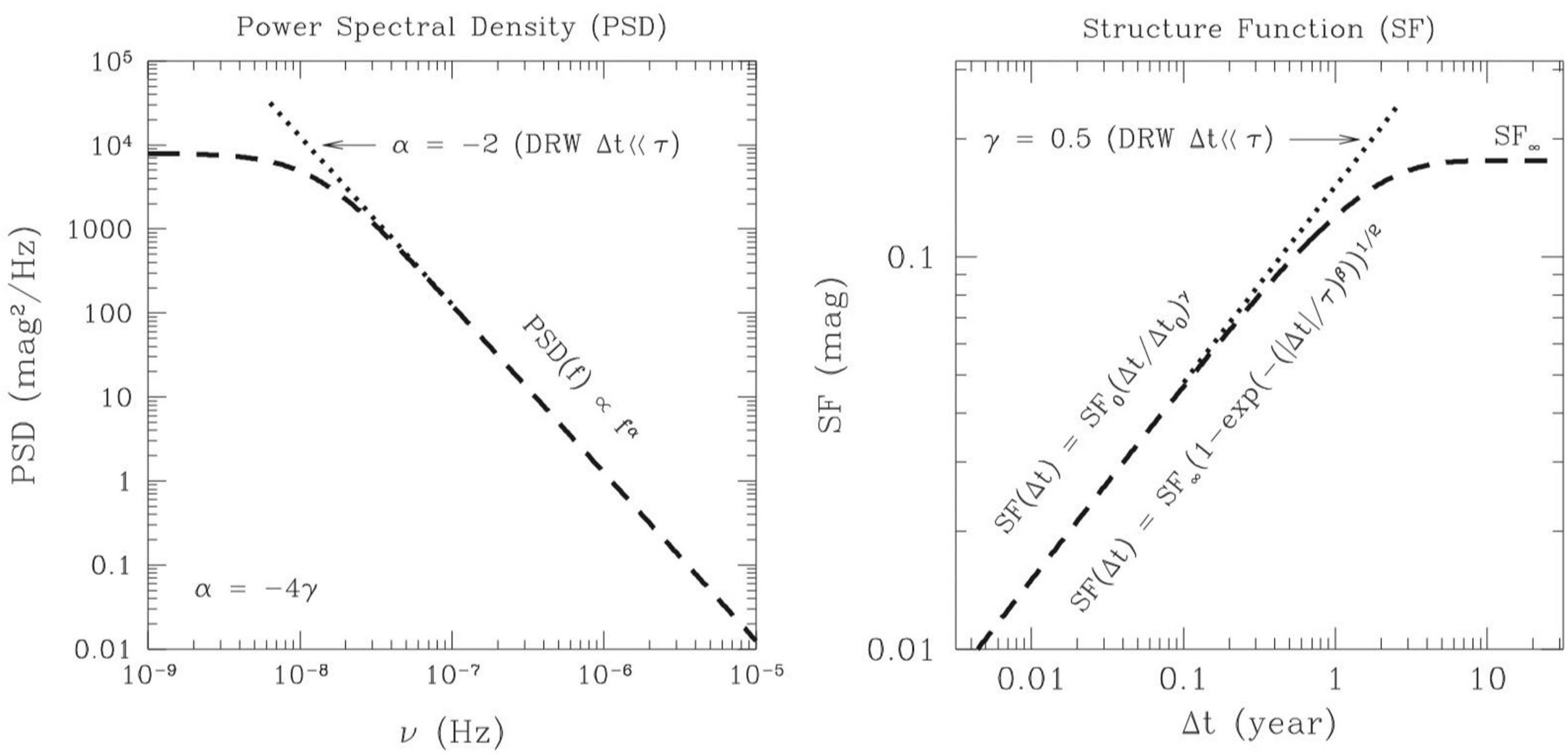
Mentors/Collaborators: Gordon Richards, Michael Vogeley, Jackie Moreno, Matthew Graham, and the entire LSST AGN Science Collaboration

AGN UV/Optical Variability

Characterization

Power Spectral Density & Structure Function

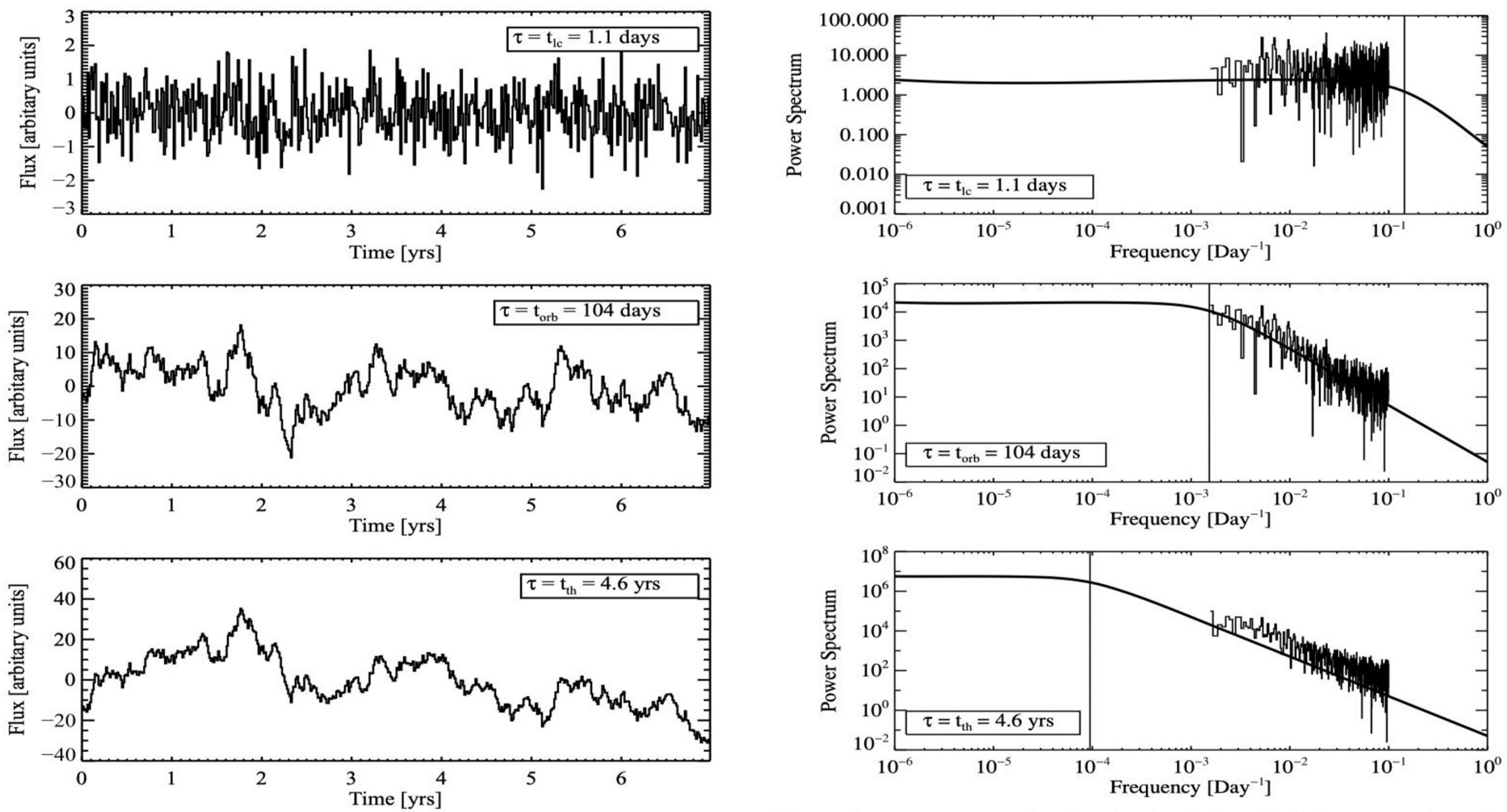


Kozlowski+16

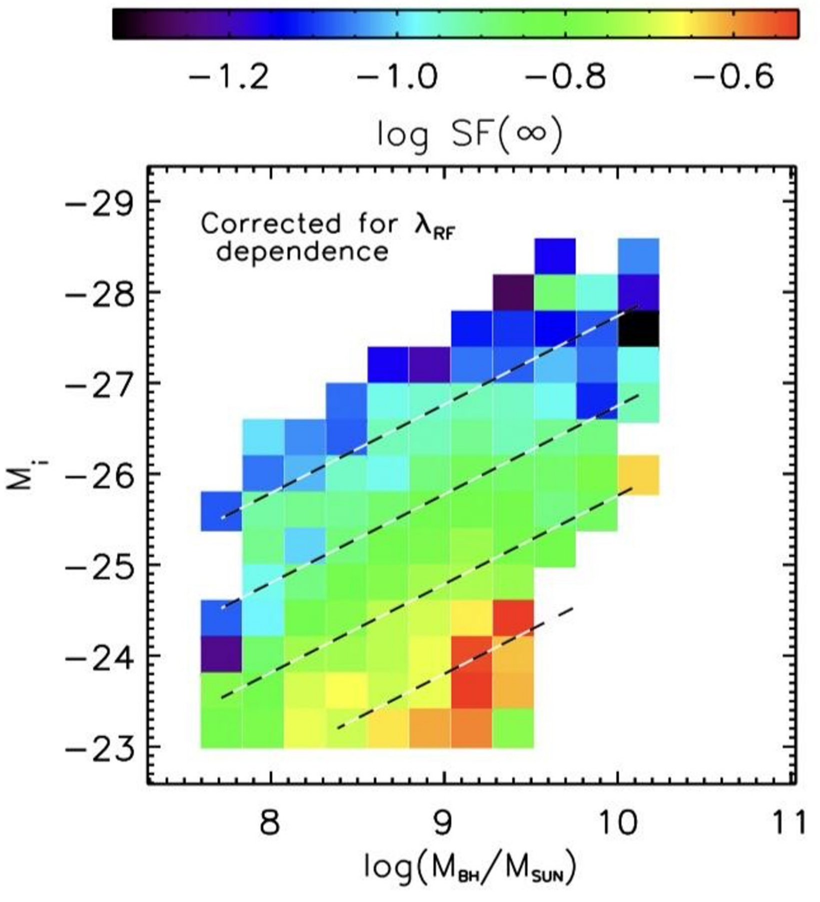
The Damped Random Walk - A Generative Process

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

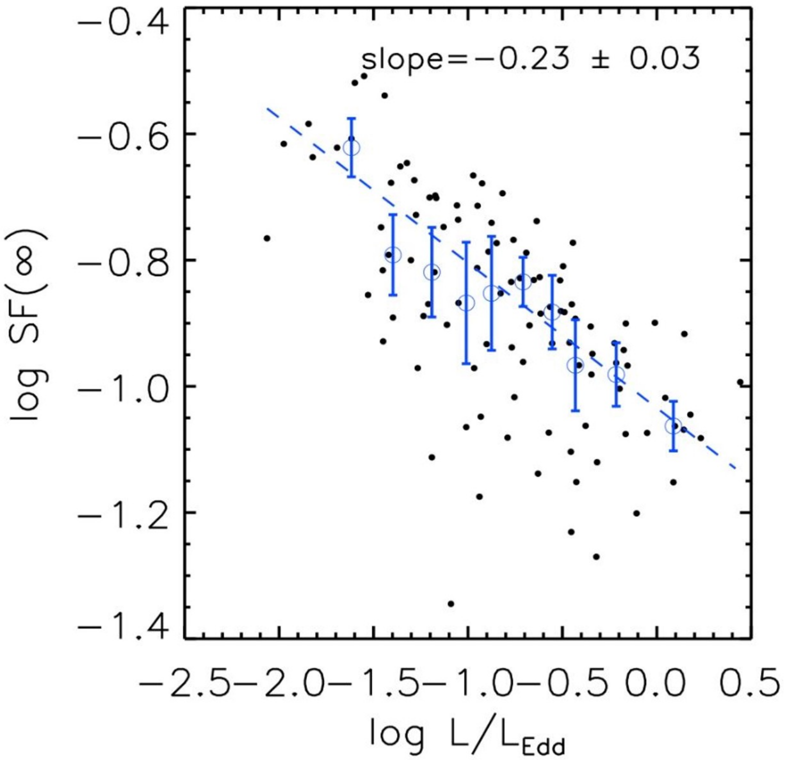
Kelly+09



SF_∞-L/L_{Edd} Correlation

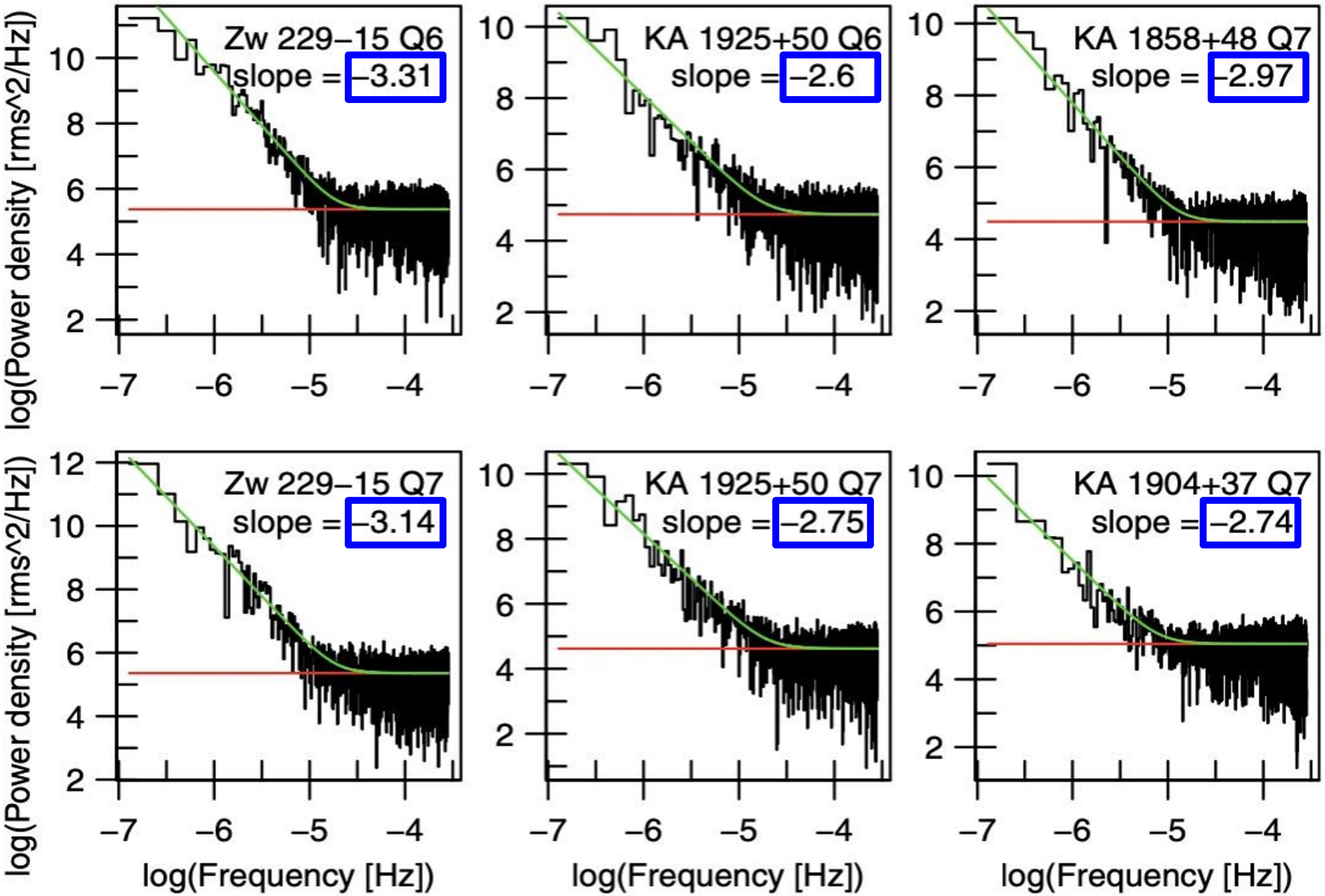


$$SF_\infty = \sqrt{2} * \sigma_{DRW}$$



MacLeod+10, Suberlak+21

Is DRW Enough?



Mushotzky+11; also Edelson+14, Kashiwal+15, Smith+18

Alternative Models?

- Continuous-Time Autoregressive Moving-Average (CARMA)

$$\mathrm{d}^p X(t) + \alpha_1 \mathrm{d}^{p-1} X(t) + \cdots + \alpha_p X(t) = \beta_0 \epsilon(t) + \beta_1 \mathrm{d}(\epsilon(t)) + \cdots + \beta_q \mathrm{d}^q(\epsilon(t))$$

Kelly+14, Kasliwal+17
Caplar+17, Goyal+18
Stone+22

❖ CARMA(1,0) => Damped Random Walk (DRW)

$$\mathrm{d}X(t) + \alpha_1 X(t) = \beta_0 \epsilon(t) \Rightarrow \mathrm{d}X(t) + \frac{1}{\tau} X(t) = \sigma\, \epsilon(t)$$

❖ CARMA(2,1) => Damped Harmonic Oscillator (DHO)

$$\mathrm{d}^2 X(t) + \alpha_1 \mathrm{d}X(t) + \alpha_2 X(t) = \beta_0 \epsilon(t) + \beta_1 \mathrm{d}(\epsilon(t))$$

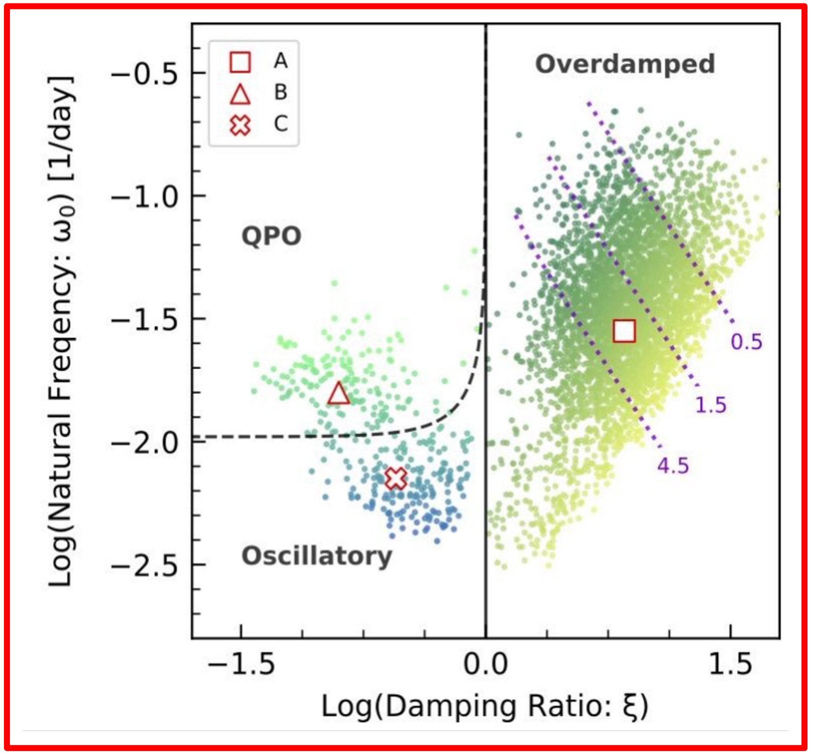
Kasliwal+17,
Moreno+19,
Yu+22

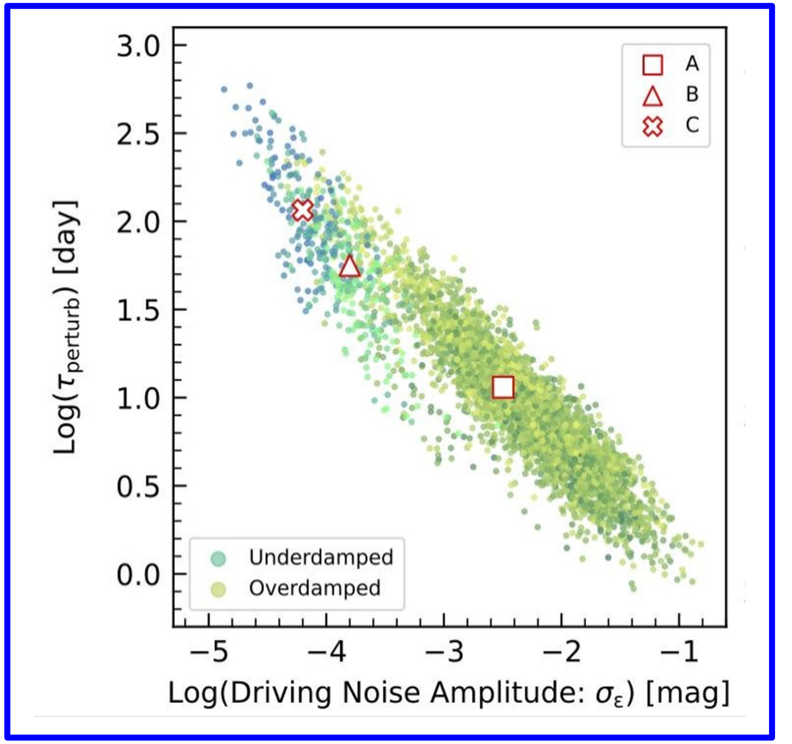
- Deep Learning

See Tachibana+20, Cvorovic-Hajdinjak+22, Sheng+22, Fagin+23

DHO & SDSS Stripe 82 Quasars

$$\mathrm{d}^2 X(t) + 2\xi\omega_0 \mathrm{d}X(t) + \omega_0^2 X(t) = \sigma_\epsilon \epsilon(t) + \sigma_\epsilon \tau_{\mathrm{perturb}}\, \mathrm{d}(\epsilon(t))$$

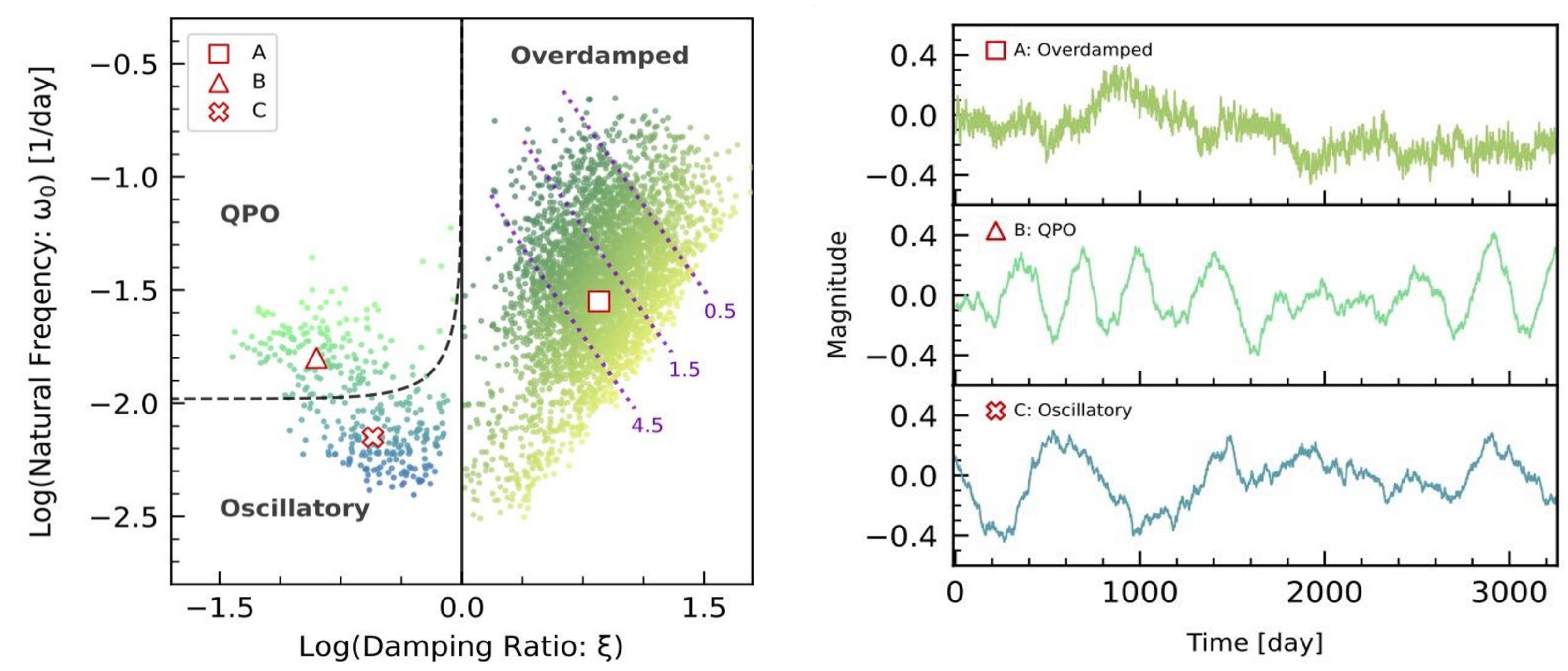




Yu+22 (ApJ, 936, 132)

AGN Stochastic Variability Captured By DHO

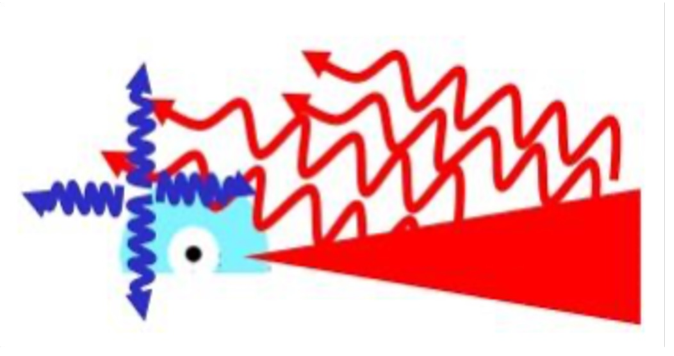
$$\mathrm{d}^2 X(t) + 2\xi\omega_0 \mathrm{d}X(t) + \omega_0^2 X(t) = \sigma_\epsilon \epsilon(t) + \sigma_\epsilon \tau_{\mathrm{perturb}}\, \mathrm{d}(\epsilon(t))$$

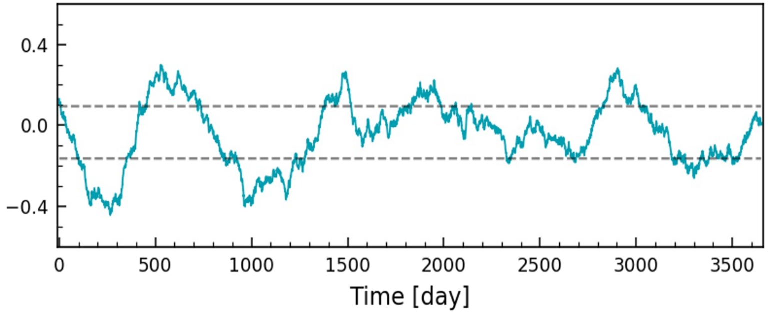


Yu+22 (ApJ, 936, 132)

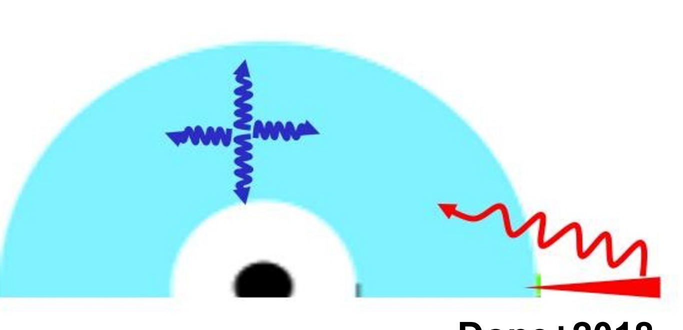
Variability & Accretion Flows

weak corona & strong disk => more disk variability

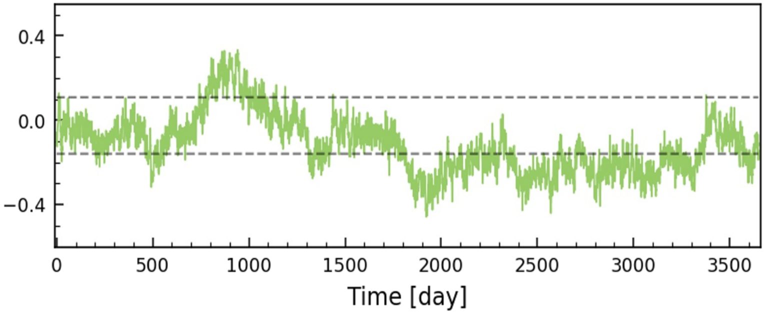




strong corona & weak disk => more X-ray variability



Done+2018

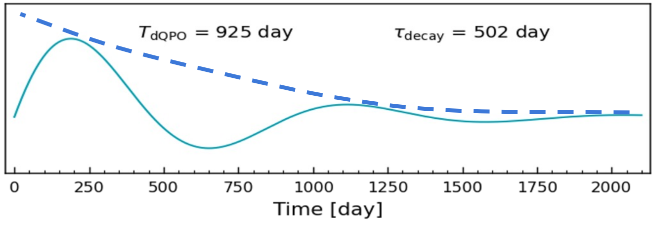


DHO in a Perturbation-Response Framework

$$\mathrm{d}^2 X(t) + 2\xi\omega_0 \mathrm{d}X(t) + \omega_0^2 X(t) = \sigma_\epsilon \epsilon(t) + \sigma_\epsilon \tau_{\mathrm{perturb}}\, \mathrm{d}(\epsilon(t))$$

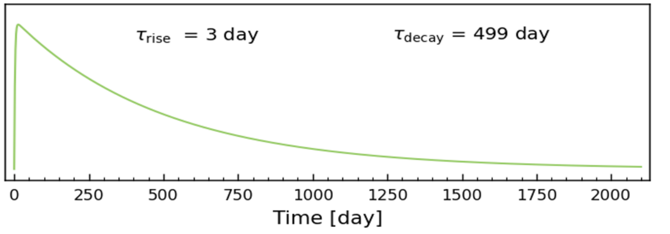
Underdamped:

- $(2\xi\omega_0)^2 - 4 * \omega_0^4 < 0$
- T_{dqpo}, $\boldsymbol{\tau}_{\mathrm{decay}}$ from LHS



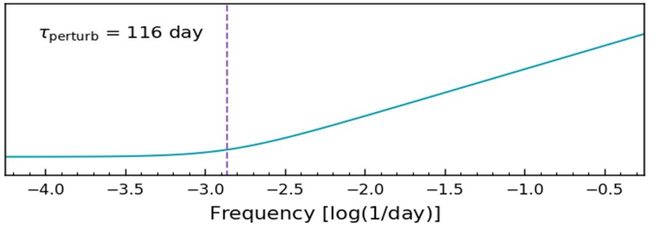
Overdamped:

- $(2\xi\omega_0)^2 - 4 * \omega_0^4 > 0$
- $\boldsymbol{\tau}_{\mathrm{rise}}$, $\boldsymbol{\tau}_{\mathrm{decay}}$ from LHS



Underdamped & Overdamped

$\boldsymbol{\sigma}_\epsilon$, $\boldsymbol{\tau}_{\mathrm{perturb}}$ from RHS



Yu+22 (ApJ, 936, 132)

Underdamped DHOs

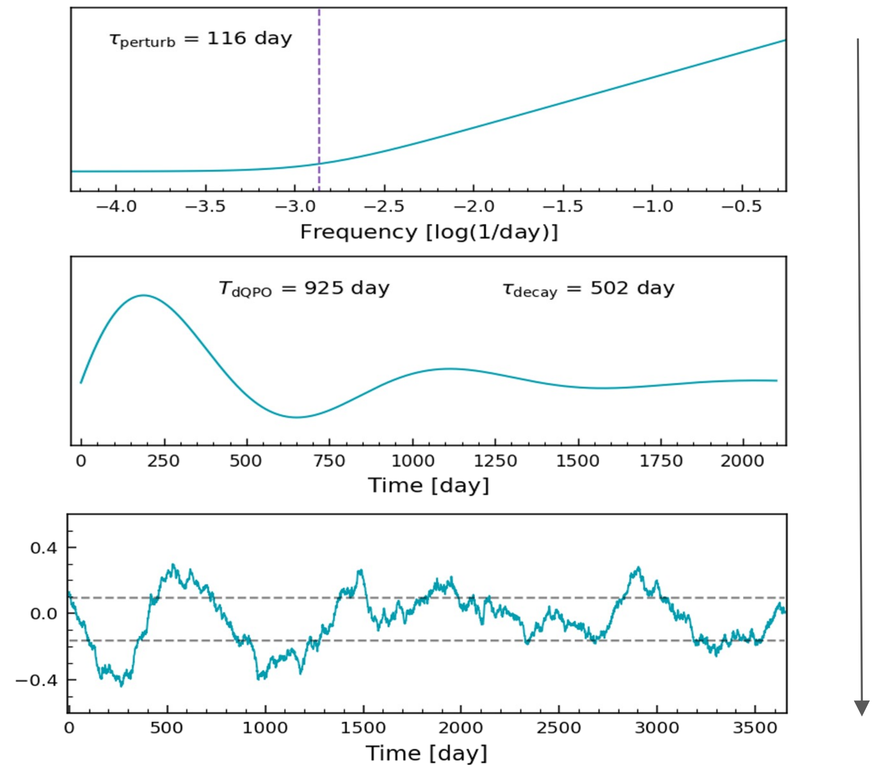
$$\mathrm{d}^2 X(t) + 2\xi\omega_0 \mathrm{d}X(t) + \omega_0^2 X(t) = \sigma_\epsilon \epsilon(t) + \sigma_\epsilon \tau_{\mathrm{perturb}}\, \mathrm{d}(\epsilon(t))$$

$$(2\xi\omega_0)^2 - 4 * \omega_0^4 = \xi^2 - 1 < 0$$

- $\boldsymbol{\sigma}_\epsilon$, $\boldsymbol{\tau}_{\mathrm{perturb}}$ from RHS
- T_{dqpo}, $\boldsymbol{\tau}_{\mathrm{decay}}$ from LHS

$$\sigma_{\mathrm{DHO}} = \sigma_\epsilon \sqrt{\frac{\omega_0^2 \tau_{\mathrm{perturb}}^2 + 1}{2\xi\omega_0^3}}$$

weak corona & strong disk



Yu+22 (ApJ, 936, 132)

Overdamped DHOs

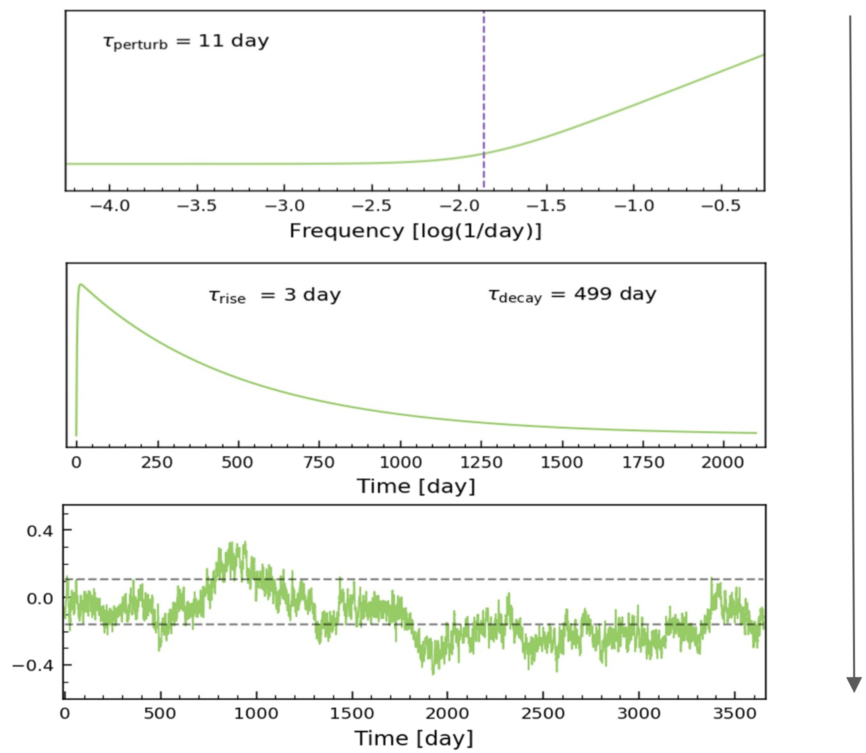
$$\mathrm{d}^2 X(t) + 2\xi\omega_0 \mathrm{d}X(t) + \omega_0^2 X(t) = \sigma_\epsilon \epsilon(t) + \sigma_\epsilon \tau_{\text{perturb}}\, \mathrm{d}(\epsilon(t))$$

$$(2\xi\omega_0)^2 - 4 * \omega_0^4 = \xi^2 - 1 > 0$$

- σ_ϵ, τ_{perturb} from RHS
- τ_{rise}, τ_{decay} from LHS

$$\sigma_{\text{DHO}} = \sigma_\epsilon \sqrt{\frac{\omega_0^2 \tau_{\text{perturb}}^2 + 1}{2\xi\omega_0^3}}$$

strong corona & weak disk



Yu+22 (ApJ, 936, 132)

Sanity Check: Are the Fits Robust?

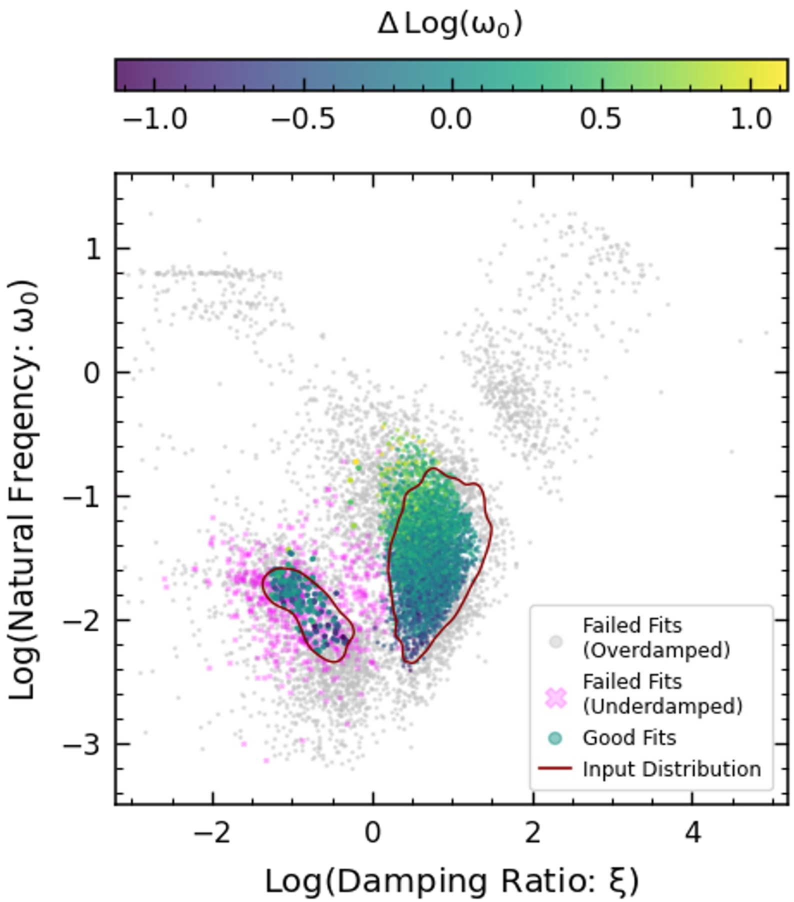


Table 1. DHO Classification Purity (Recall)

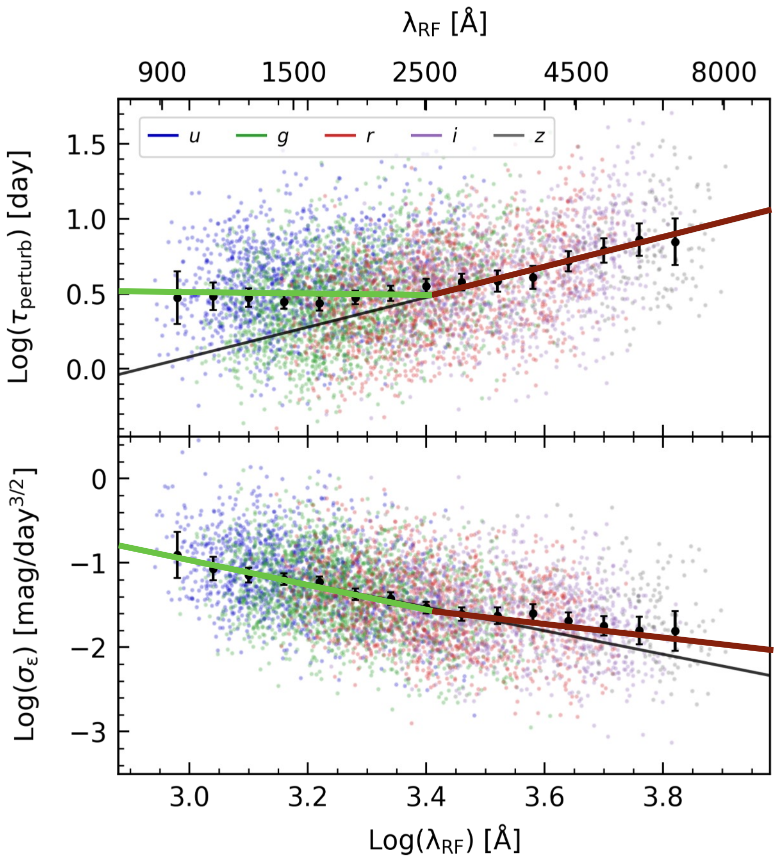
band	Underdamped DHO	Overdamped DHO
u	14.29 (100.00)	100.00 (90.65)
g	29.80 (100.00)	100.00 (97.56)
r	29.46 (92.68)	99.93 (97.90)
i	24.16 (100.00)	100.00 (96.58)
z	9.18 (100.00)	100.00 (87.85)

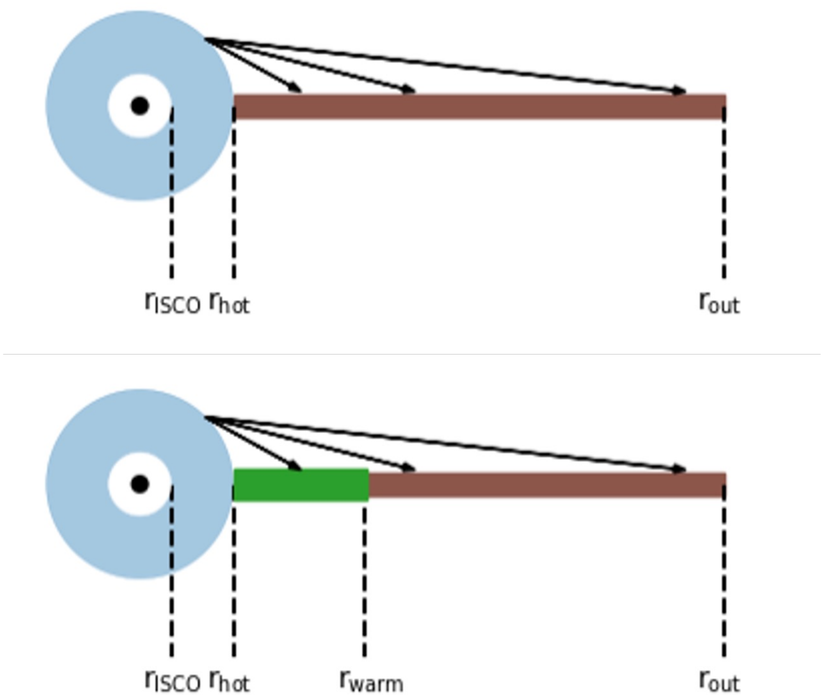
$$\mathrm{Purity(Over)} = \frac{\#\ \mathrm{True\ Overdamped}}{\#\ \mathrm{Best{-}fit\ Overdamped}}$$

$$\mathrm{Recall(Over)} = \frac{\#\ \mathrm{Best{-}fit\ Overdamped}}{\#\ \mathrm{Simulated\ Overdamped}}$$

Yu+22 (ApJ, 936, 132)

Probing Accretion Flow Geometry

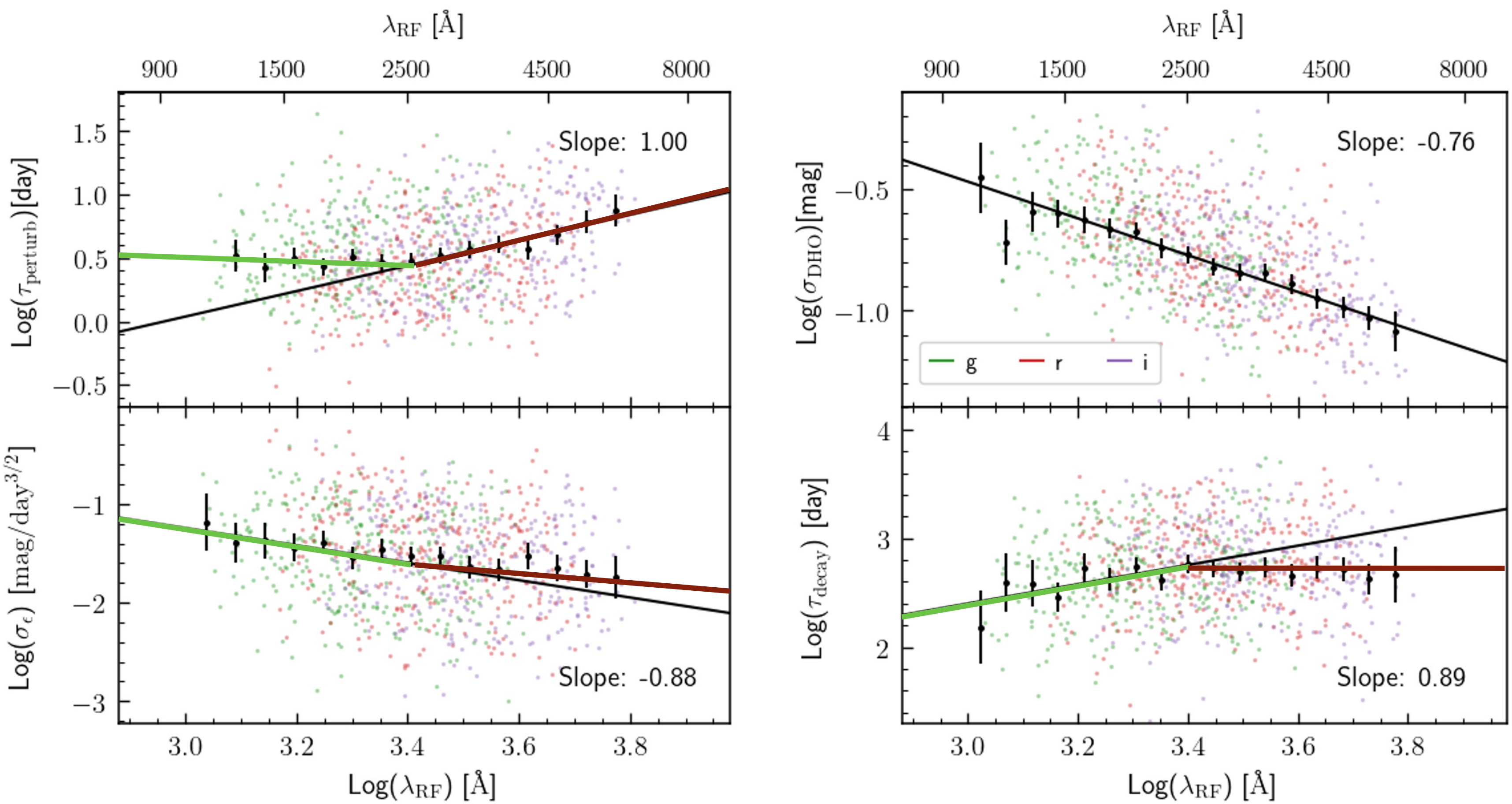




Yu+22 (ApJ, 936, 132)

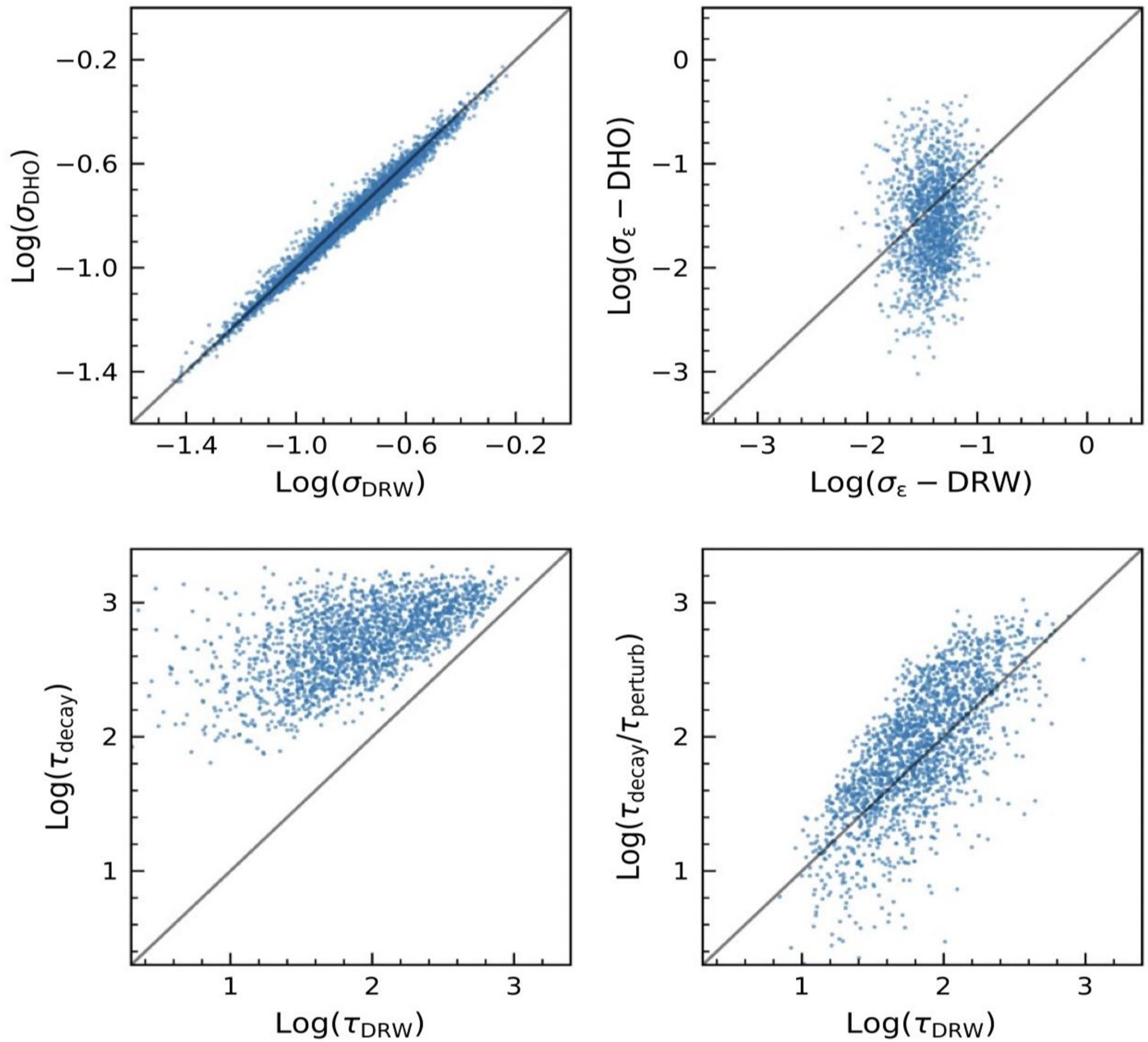
Kubota+18

SDSS-PS1 (Preliminary)



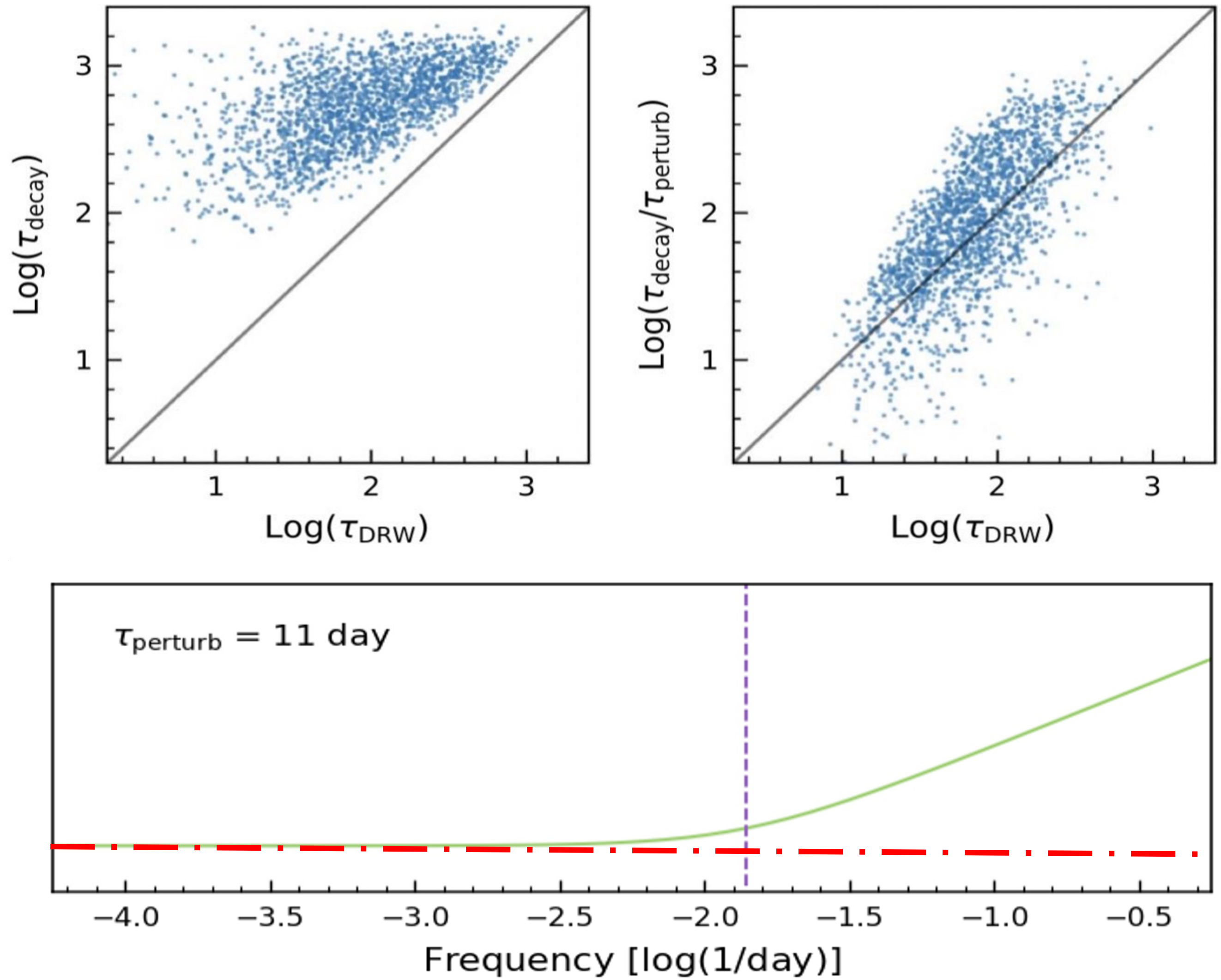
Yu+23 (in prep)

DHO vs DRW



Yu+22 (ApJ, 936, 132)

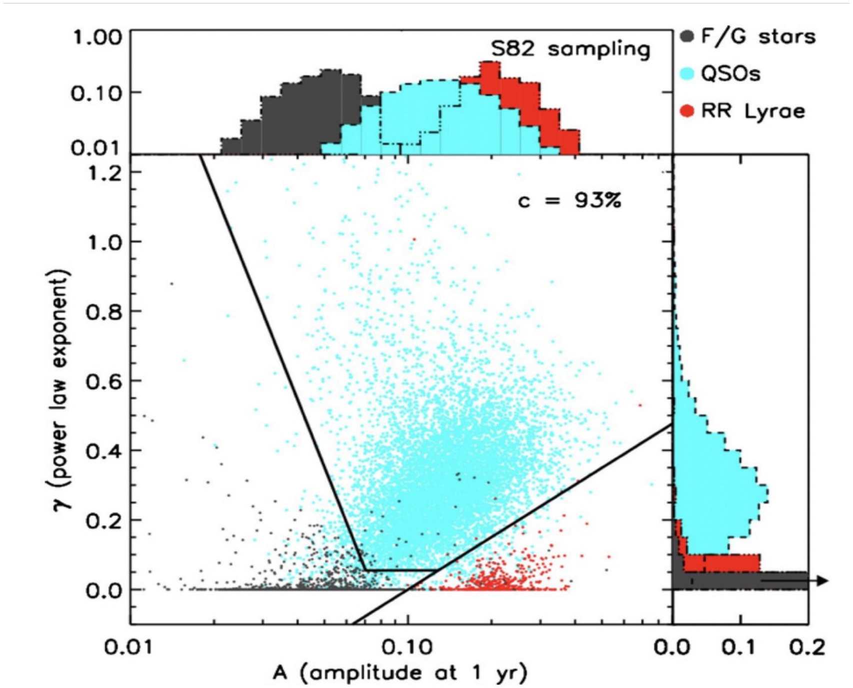
DHO vs DRW

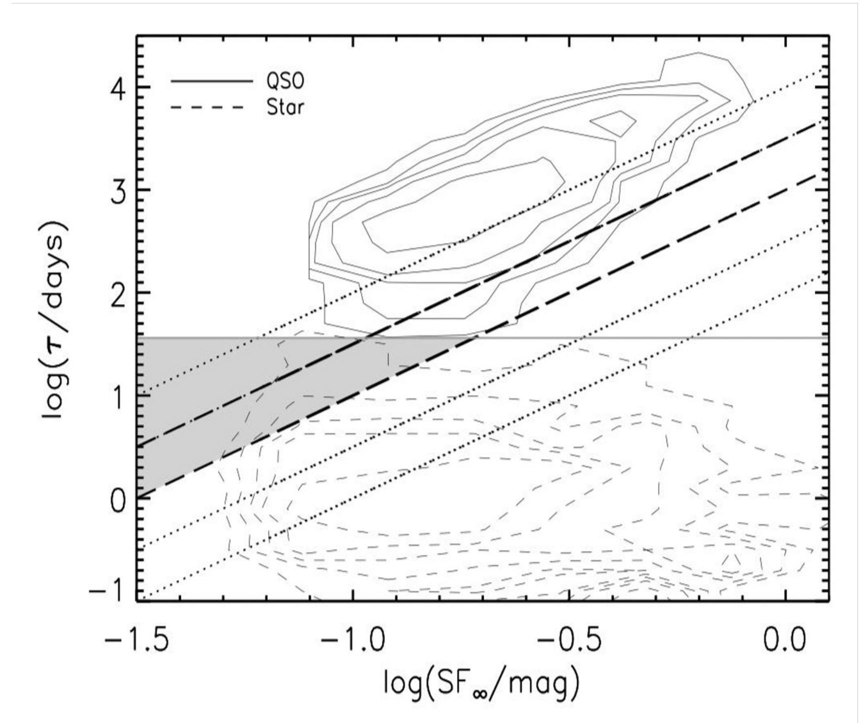


Yu+22 (ApJ, 936, 132)

AGN Selection via UV/Optical Variability

AGN Classification

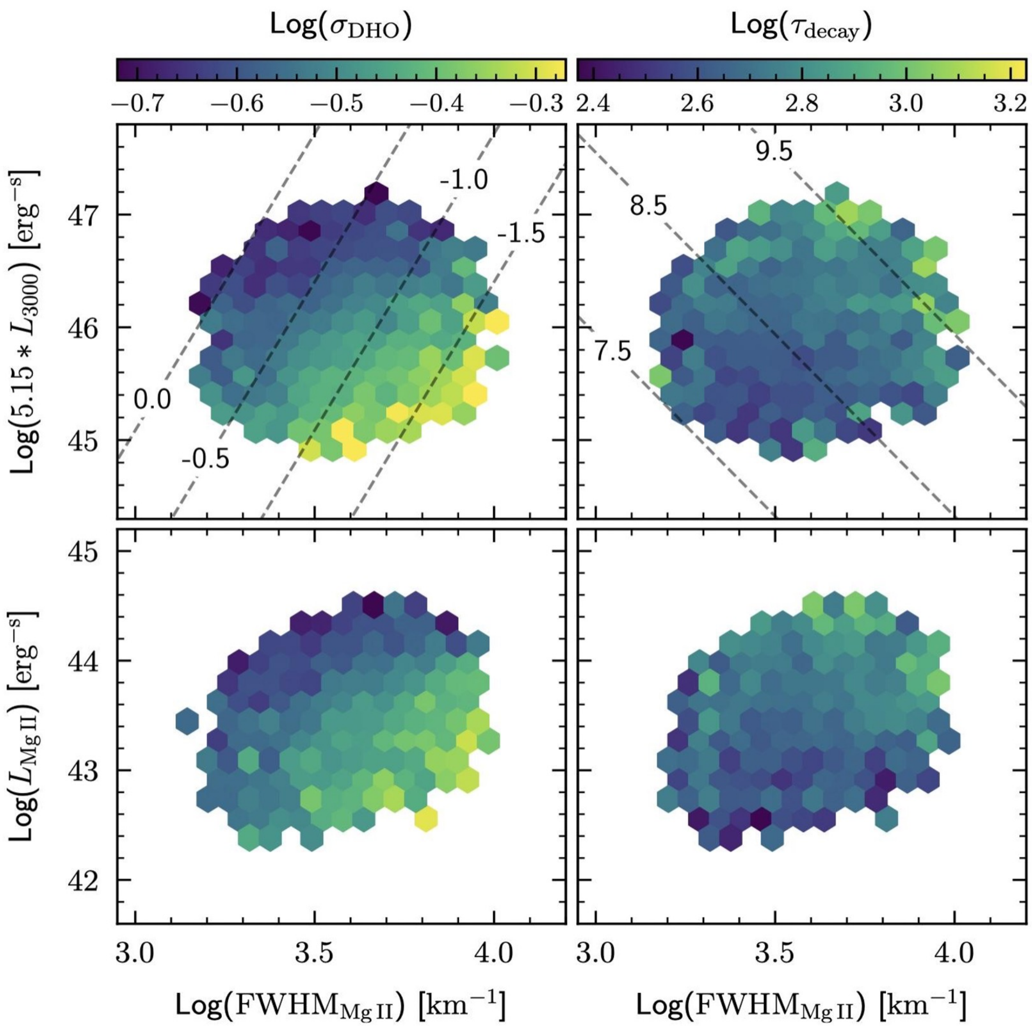




Schmidt+10 **MacLeod+11**

Also see Bulter & Bloom+11, Palanque-Delabrouille+11, Choi+14, Graham+14, Peters+15, Zinn+17, De Cicco+19.

AGN **Sub**-Classification



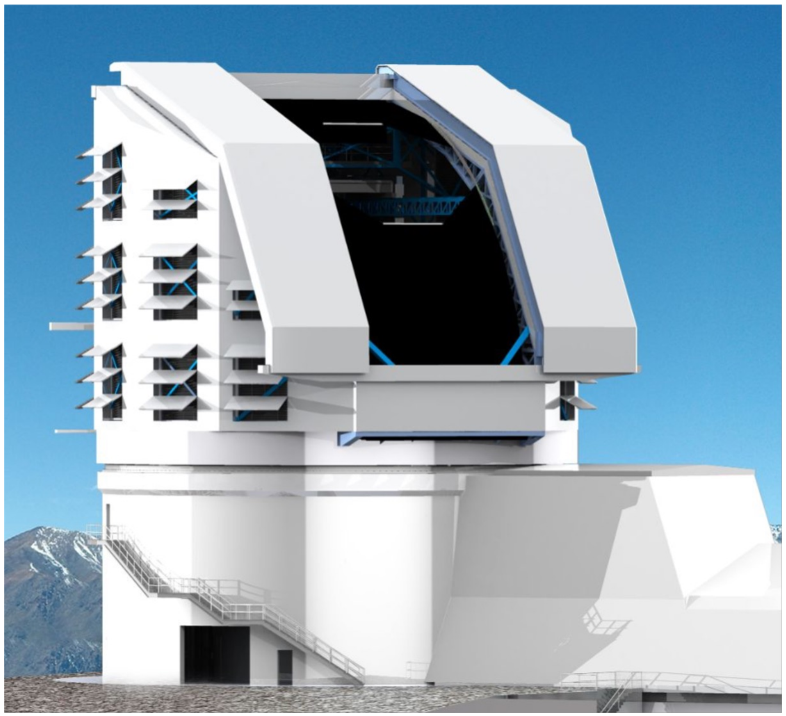
Yu+23 (in prep)

See poster from
Priscilla Behar

See talks from
Paula Sanchez Saez
Robbie Webbe
Summer McLaughlin

AGN Selection and Characterization in Next-Generation *(UV/Optical)* **Time-Domain Surveys**

Rubin Observatory LSST



- 18,000 square degrees
- 40 billion sources
- > 100 million AGNs

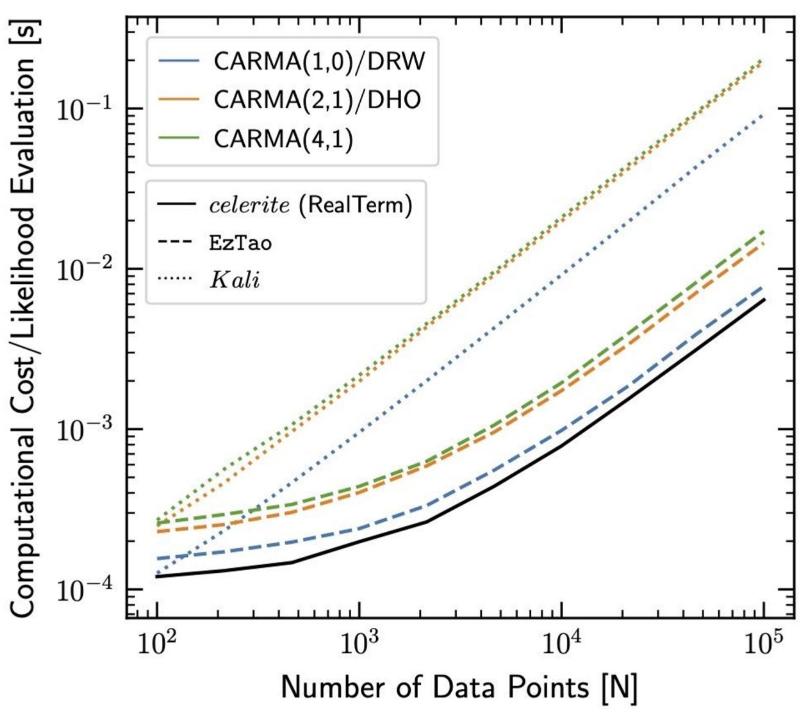
- 825 vistis over 10 years
- ugrizY bands
- 1% photometric accuracy

EzTao

tests passing | launch binder | docs passing | ascl 2201.001

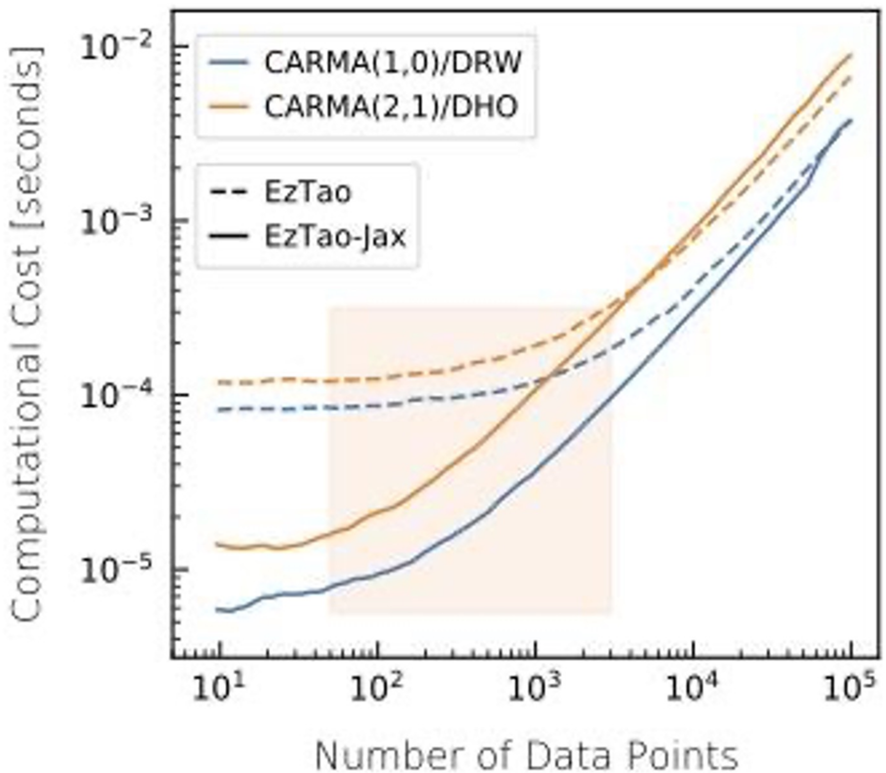
EzTao (易道)

EzTao is a toolkit for conducting AGN time-series/variability analysis, mainly utilizing the continuous-time auto-regressive moving average model (CARMA)



- A factor of 10 speed up for inference
- Fast light curve simulation
- Pip installable
- Custom optimizer
- Custom MCMC
- Unit-tested
- Documentation + tutorials

EzTao-Jax (work in progress)



- Utilizing JAX from Google
- Just-in-time (JIT) compilation
- Automatic differentiation
- A factor 5 to 10 speedup for LSST-like light curves
- Allows simultaneous fitting of CARMA and other GP kernels
- Multi-band fitting
- Integration with major DL frameworks
- …

Main Takeaways

- Direct light curve modeling is useful for AGN characterization and selection, **but** extra care should be taken when quoting the best-fit parameters obtained with maximum likelihood (*a posteriori*).
- Given the superior light curves from future time-domain surveys, we can and should go beyond the simple DRW, such as, higher-order CARMA models or deep neural networks.
- We are entering a new regime of AGN sub-classification, and more robust variability modeling will help achieve that.
- Future algorithm/tool development needs to put more weight on scalability and integrability.

Thanks!

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