Probing AGN Accretion Physics through AGN Variability: Insights from Kepler

Dissertation Defense
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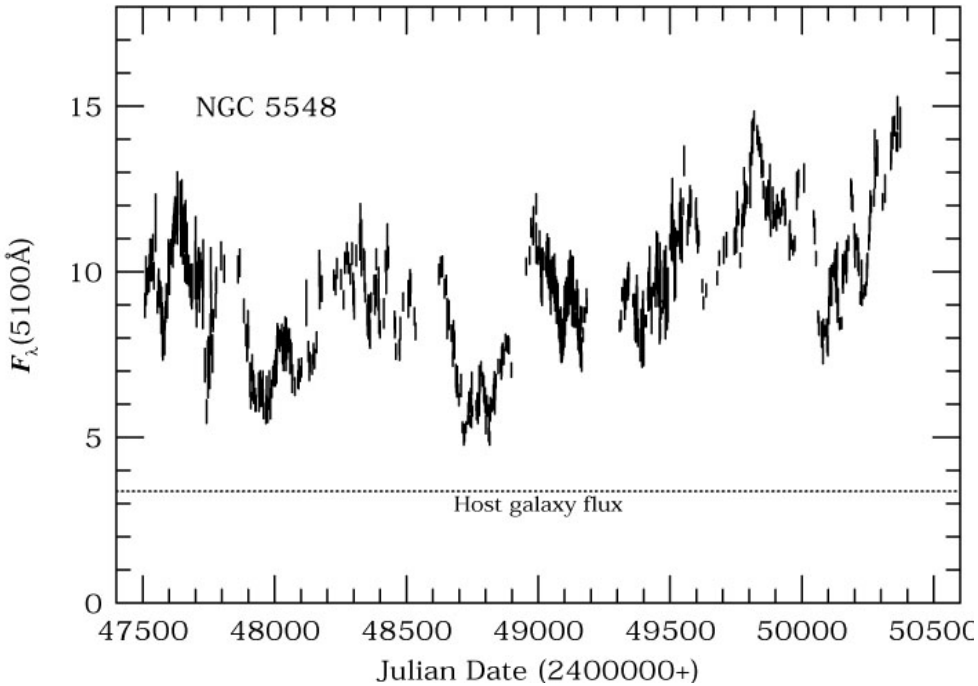
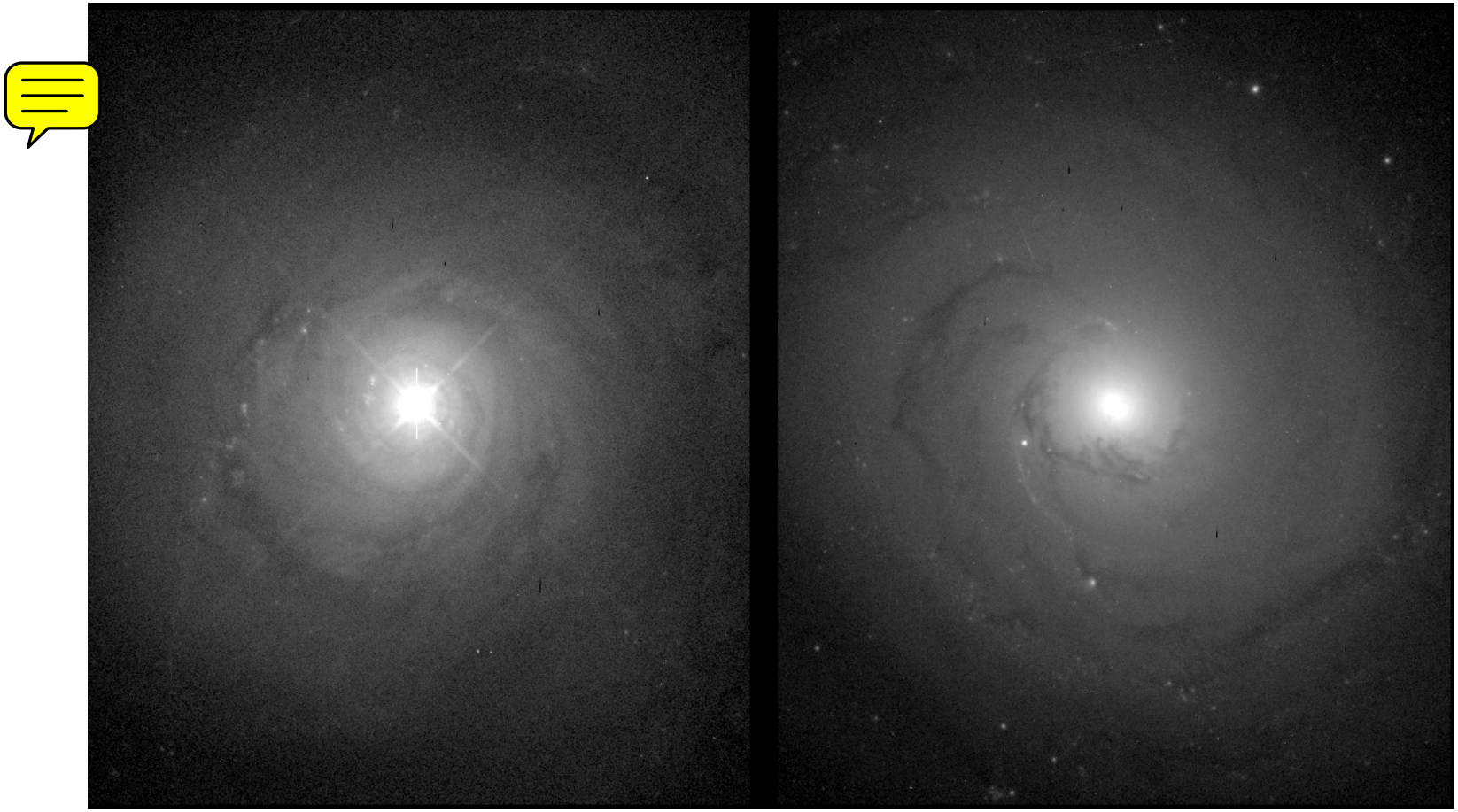
AGN Exhibit Rapid, Stochastic, Luminosity Variations (and we do not know why!)



(Peterson et al. 1999)

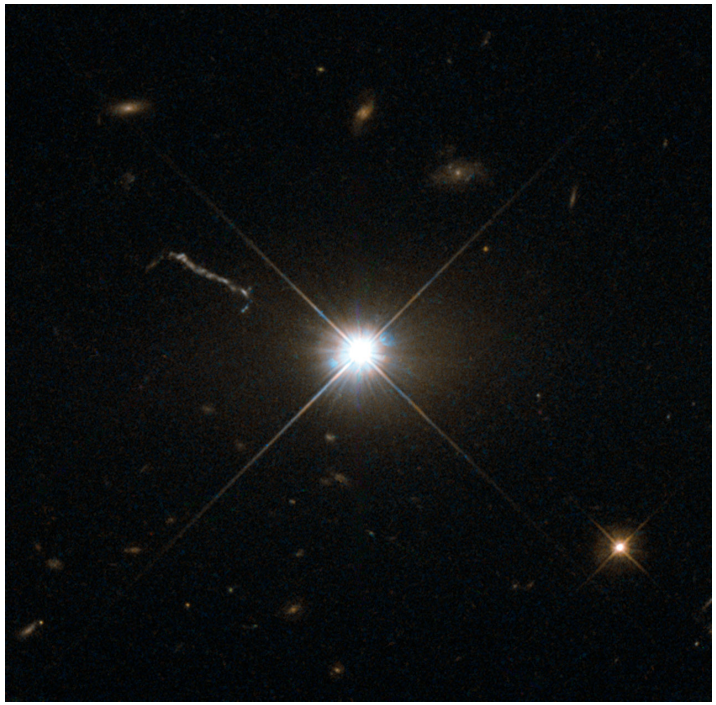
- ~ 90 % vary (Sesar et al. 2007)
- Pan-spectral: shorter $\lambda \Rightarrow$ stronger variability
- Stochastic! (Peterson 1997)
- longer λ lag shorter λ

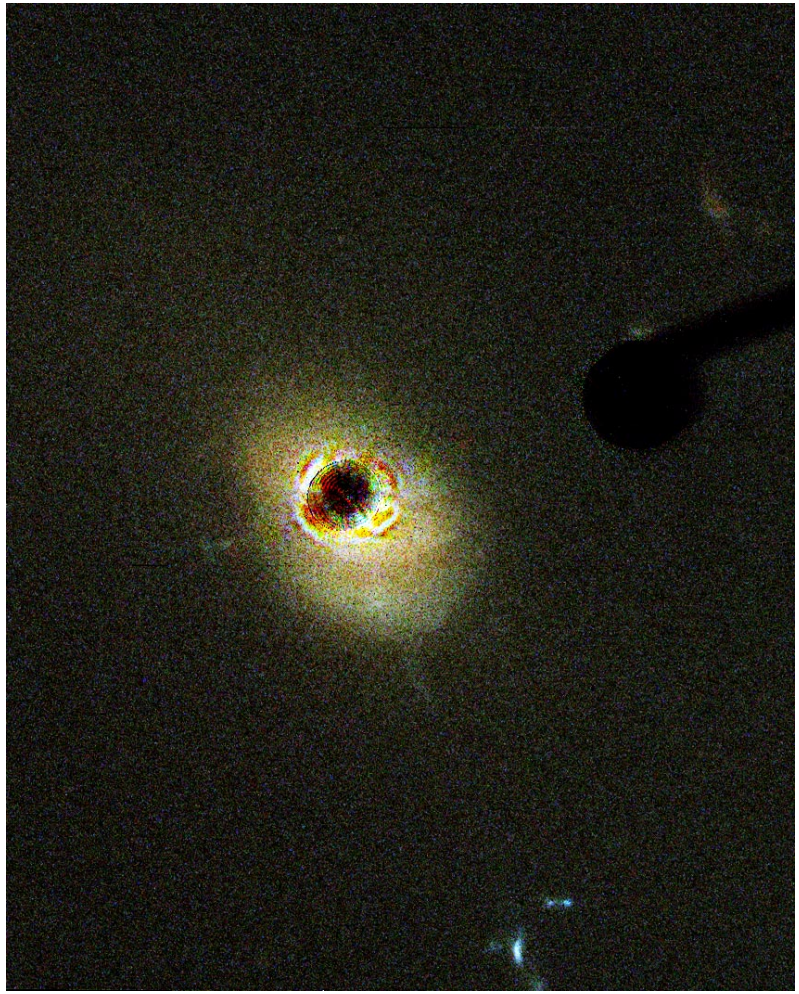
Are these galaxies different?



NGC 5548 (AGN Host) v/s NGC 3277 (non-AGN Host)

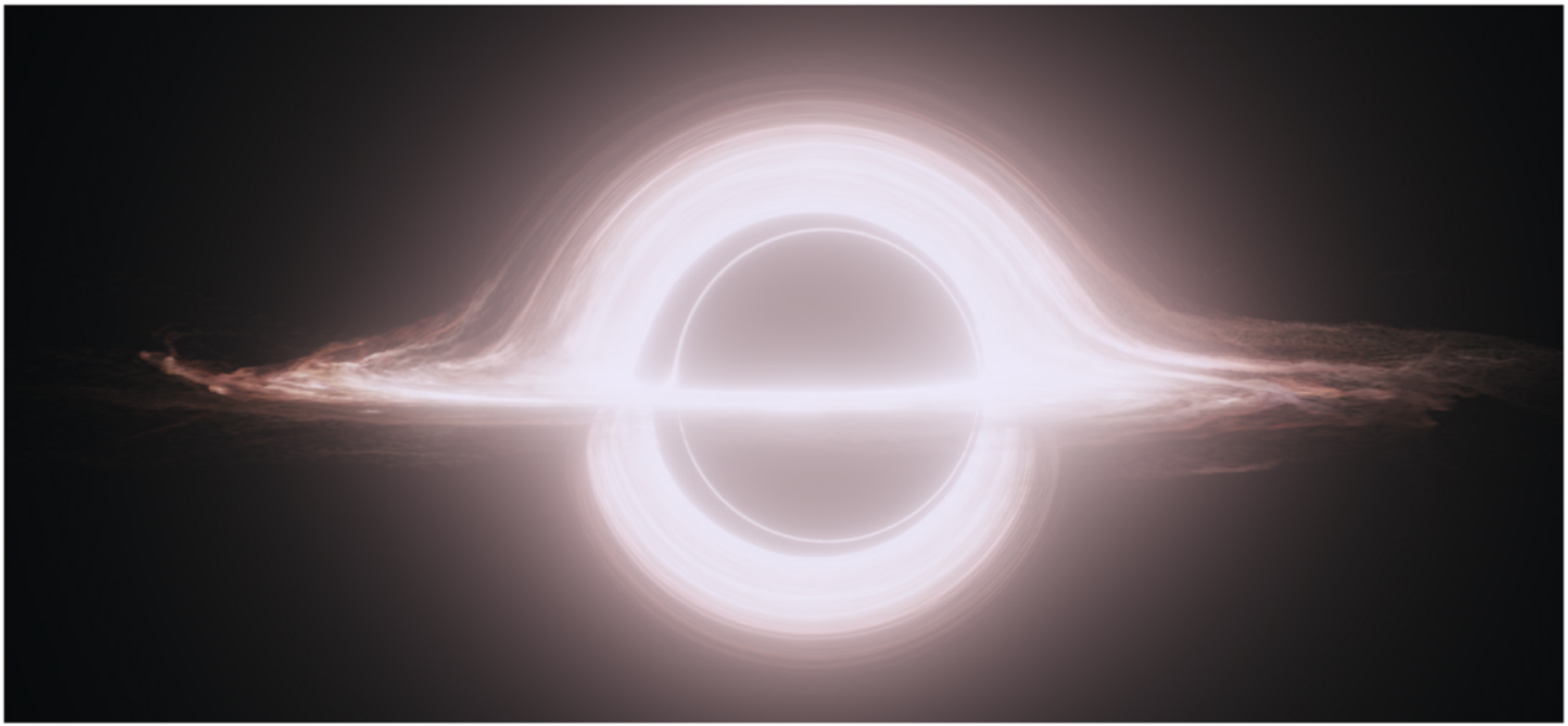
How bright can AGN be?





3C 273 Completely Outshines Its Host Galaxy!

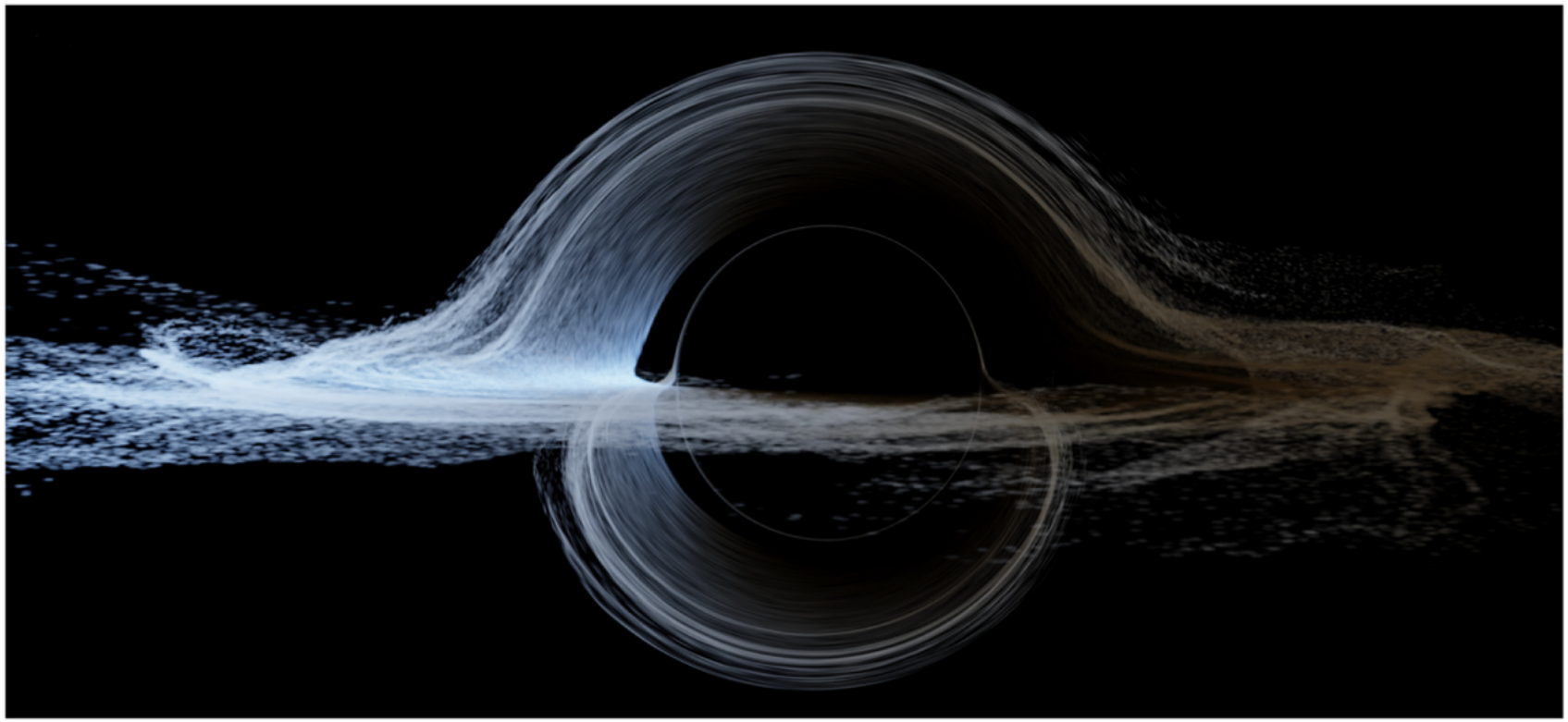
So what is an AGN?
In a nutshell...



James, von Tunzelmann, Franklin, & Thorne (2015)

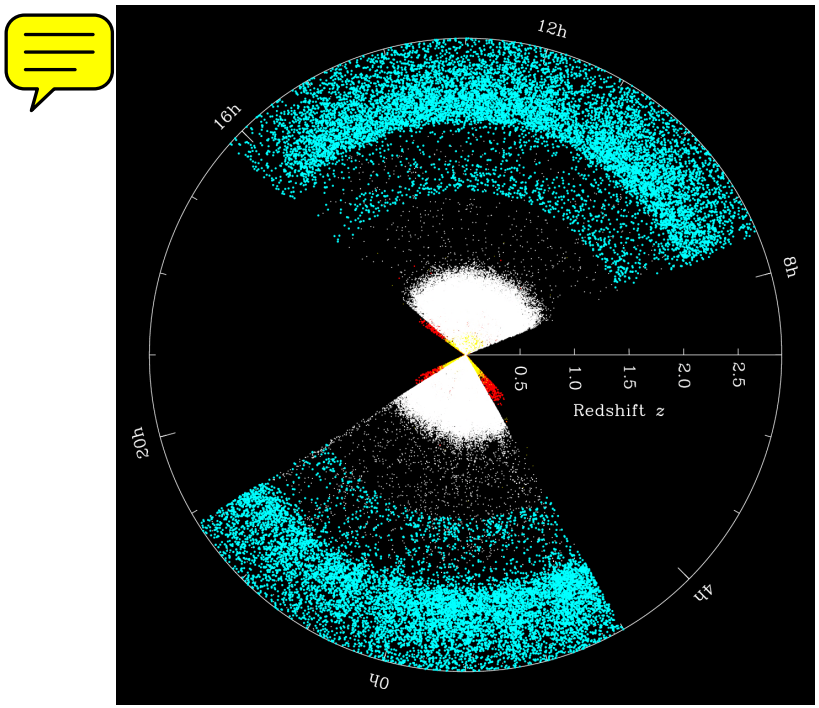
... but a lot less anemic!

More realistically...



James, von Tunzelmann, Franklin, & Thorne (2015)

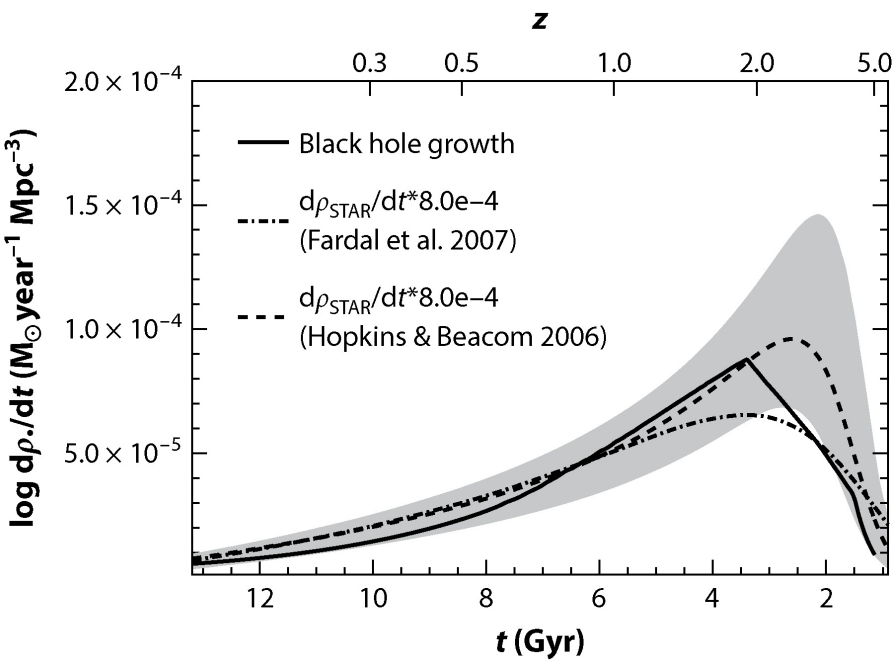
How common are AGN?

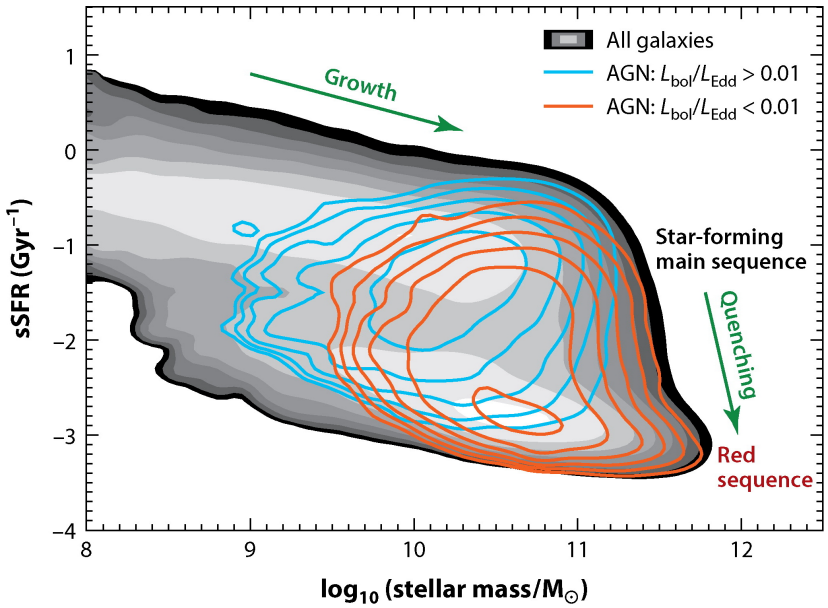


SDSS-III

- 1 in 50 in local Universe.
- $\sim$ 120 deg^2 at SDSS limit
- $\sim$ 10000 deg^{-2} in *Chandra* 4Ms Survey (Netzer 2013)
- 1 in 4 including LINERS

Do AGN dictate the evolution of galaxies?

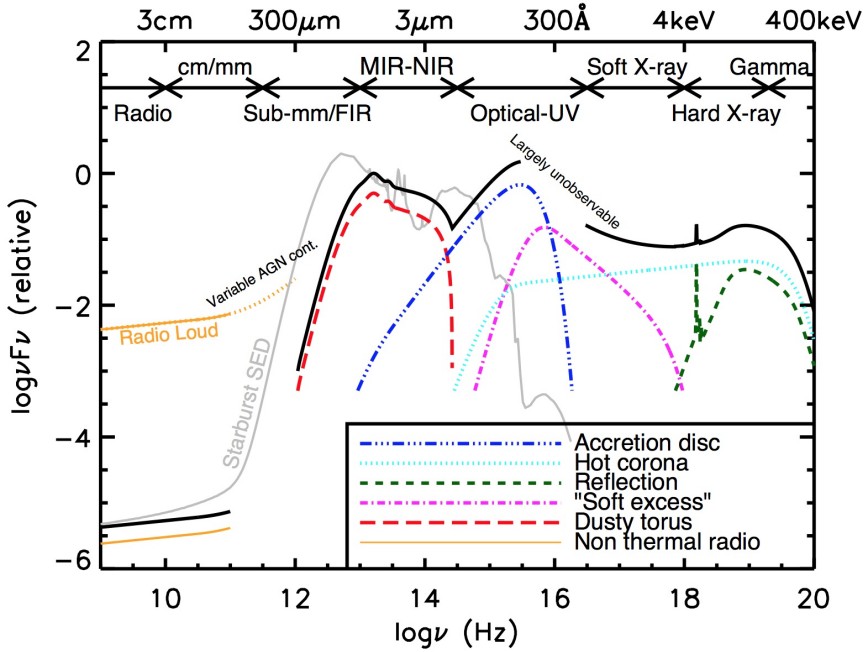




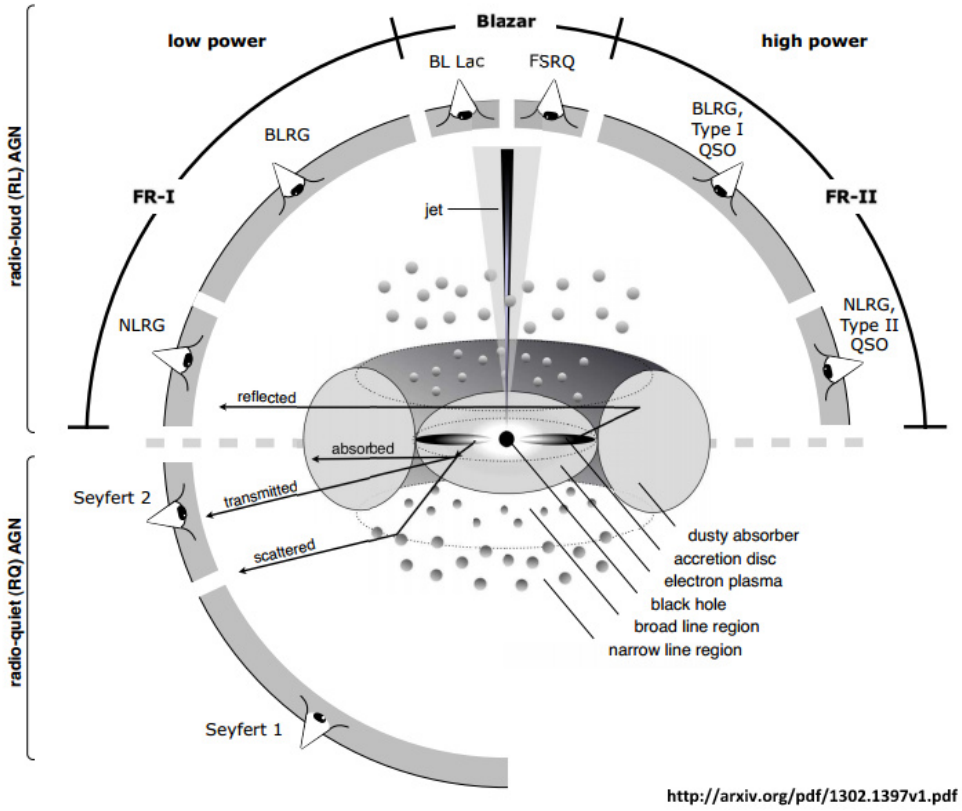
Heckman & Best (2014)

AGN quench star formation in galaxies!

AGN Morphology: Continuum Variations → Origin in Accretion Disk

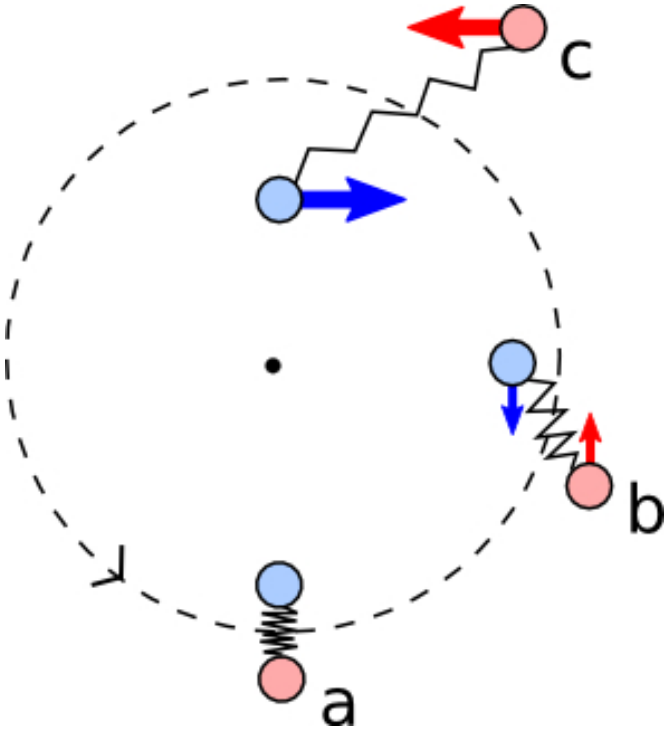


Chris Harrison

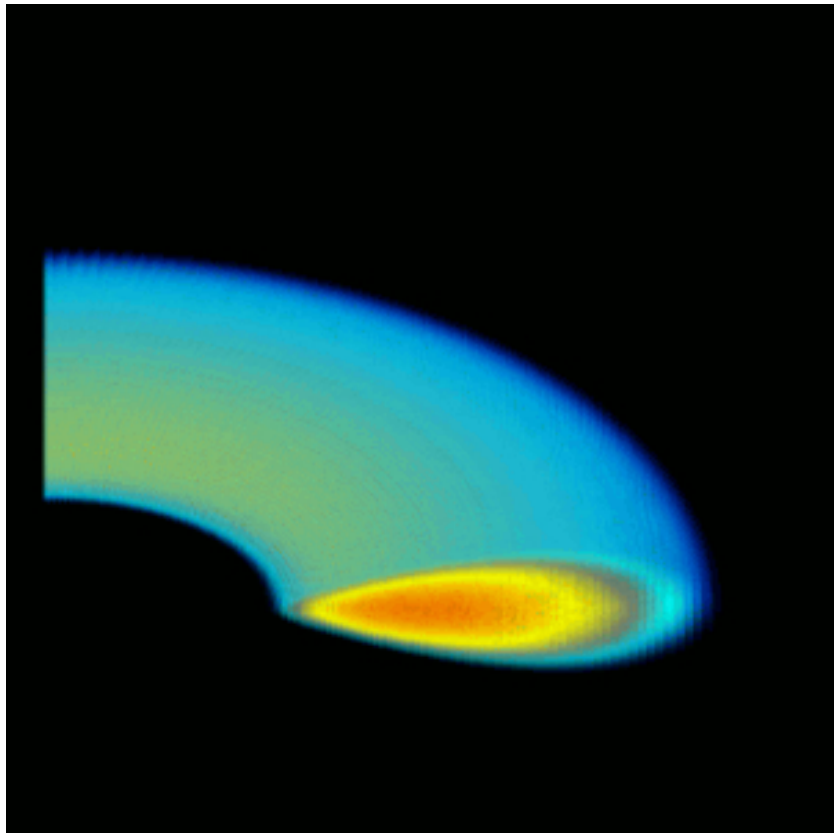


http://arxiv.org/pdf/1302.1397v1.pdf

Accretion Mechanism: The MRI

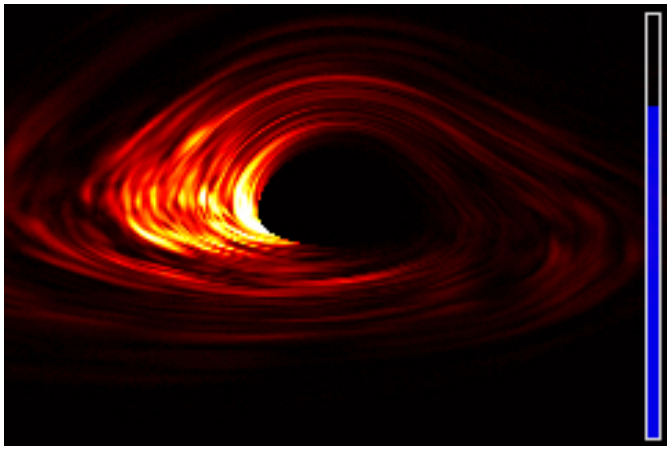


Harvard Astronomy Dept



Hawley & Krolik (2002)

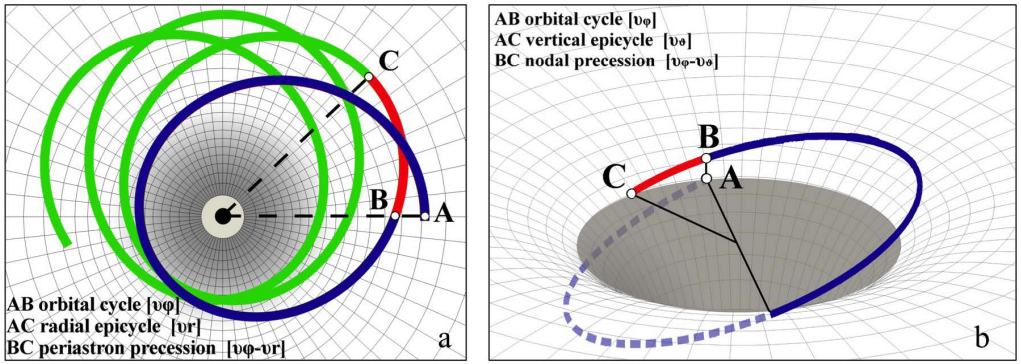
Sources of variability



Armitage & Reynolds (2003)

- λ dependent (X-Ray partially drives Optical) (Uttley & Casella 2014)
- Shot noise models unlikely (Uttley et al. 2005)
- MHD turbulence responsible (Nowak & Wagoner 1995)
- Coronal X-Ray flares possible (Poutanen & Fabian 1999)
- Propagating fluctuations (Lyubarskii 1997)
- Coronal accretion (Janiuk & Czerny 2007)

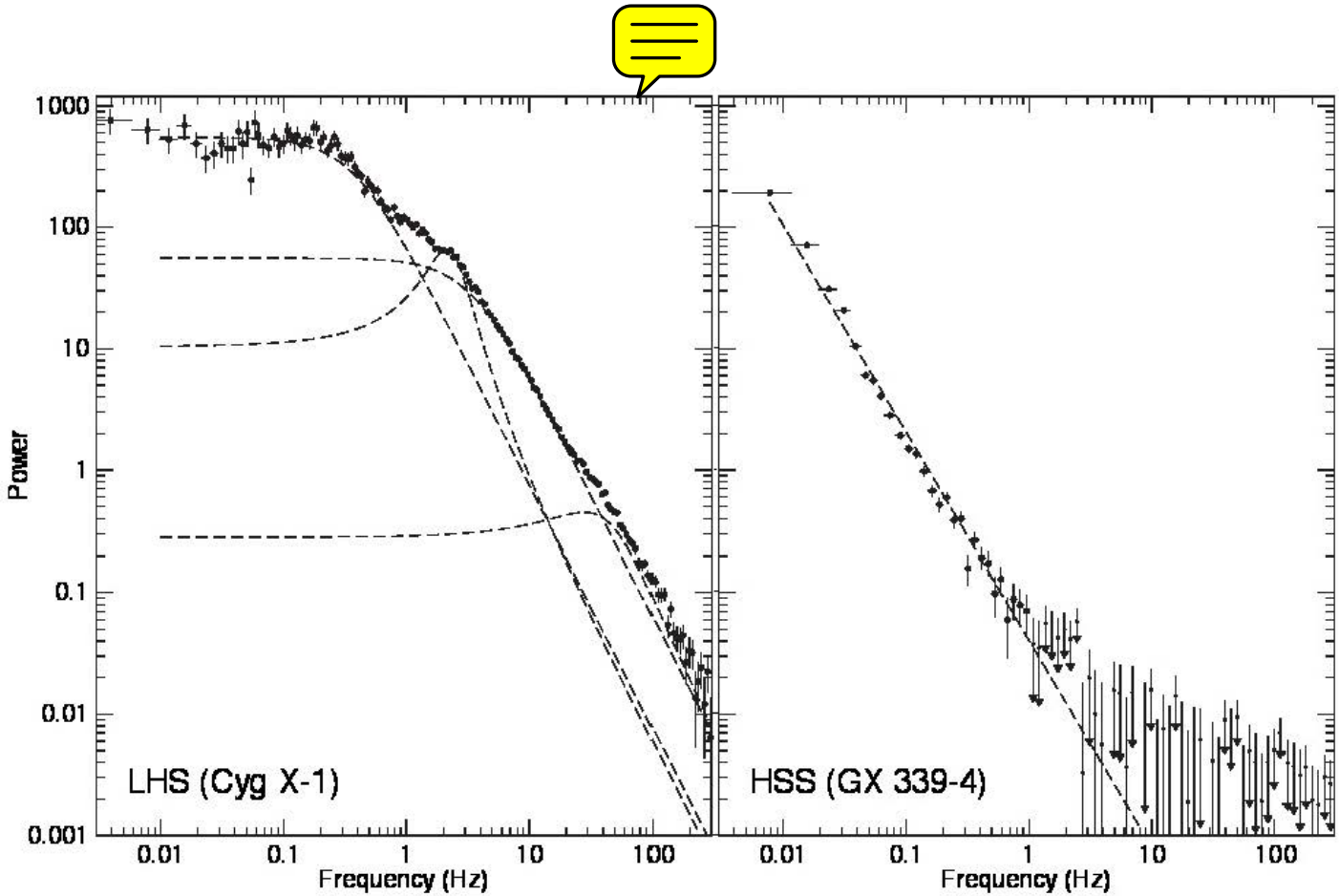
Timescales that *may* be found in AGN



Belloni & Stella (2014)

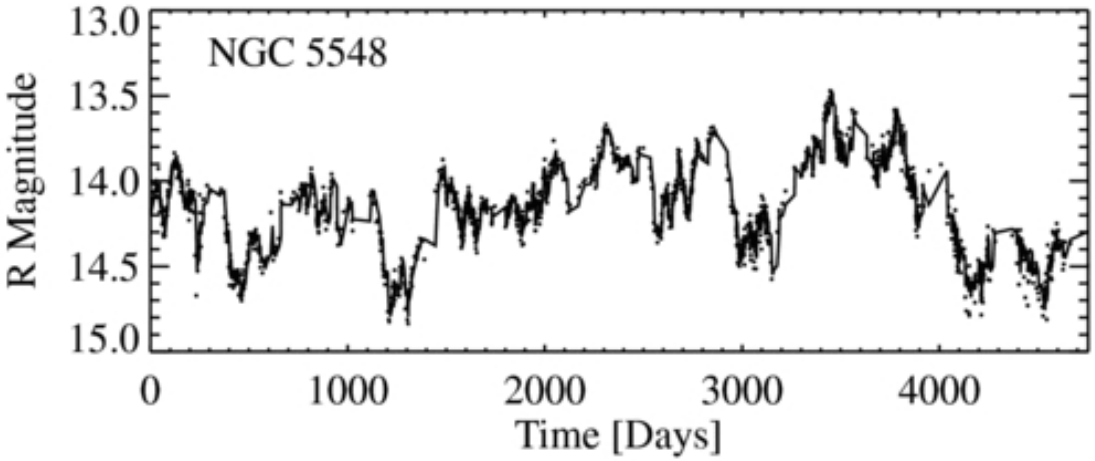
- $t_{\rm dyn} = \sqrt{\frac{r^3}{GM_{\rm BH}}} \sim$ 1-1500 d
- $t_{\rm therm} = \frac{t_{\rm dyn}}{\alpha} \sim$ 1 d - 5 yr
- $t_{\rm visc} = \frac{t_{\rm dyn}}{\alpha (H/r)^2} \sim$ 1-10 yr

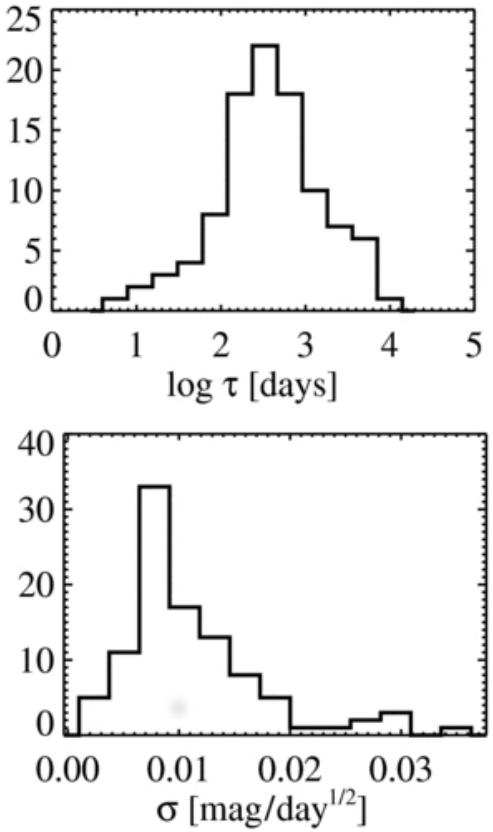
Search for timescales in PSD



Belloni & Stella (2014)

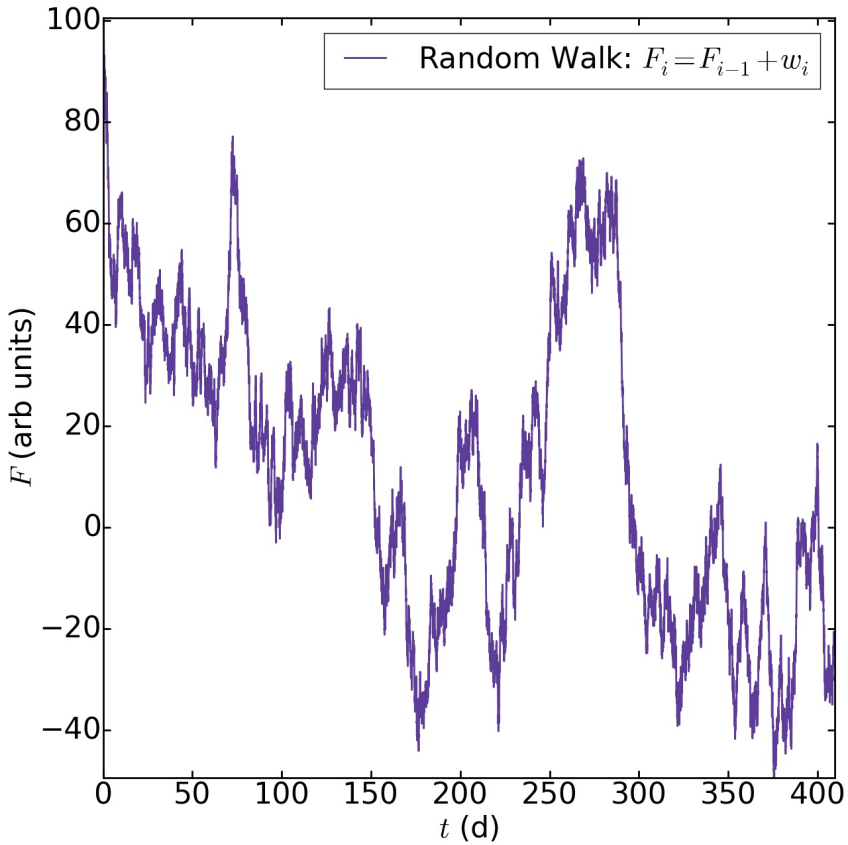
Kelly et al. (2009): Model variability as DRW





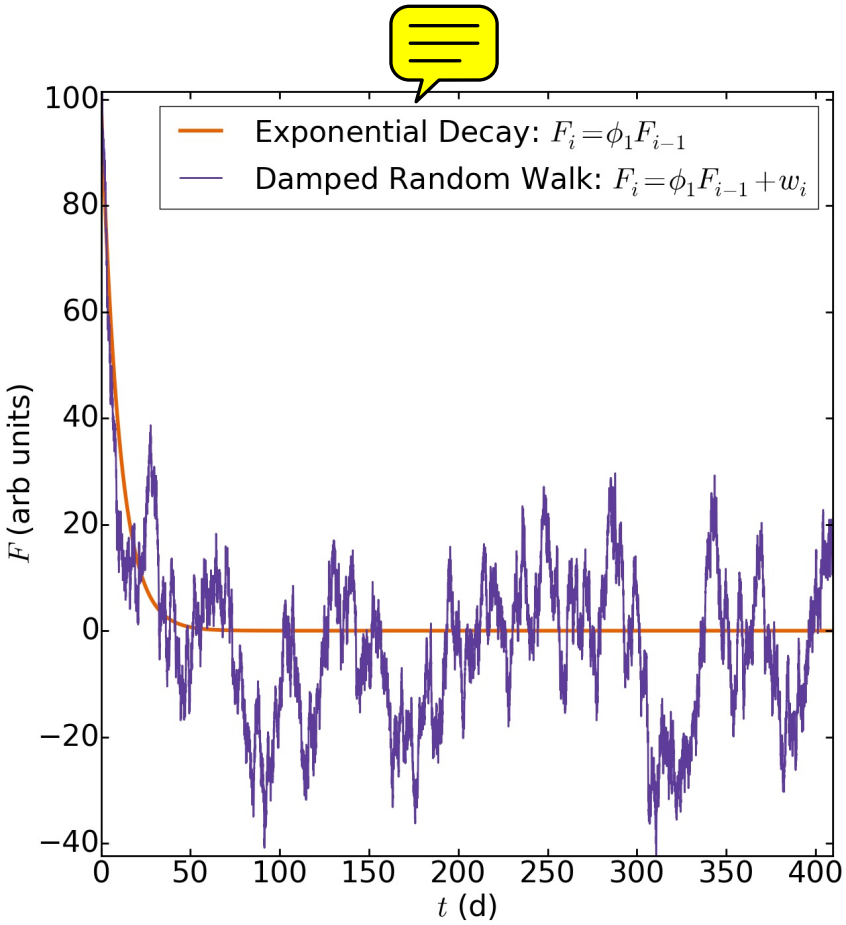
- Dynamical or thermal processes responsible for variability
- $\tau \propto M_{BH}$ & L_{AGN} but $\sigma \propto 1/M_{BH}$ & $1/L_{AGN}$

Random Walks



- Accretion disk: MHD 'Hot-spots'
- Random 'disturbances'
  - $w_i \sim \mathcal{N}(0, \sigma^2)$
- $F_{i+1} = F_i + w_i$
- Not stationary - flux 'walks away'

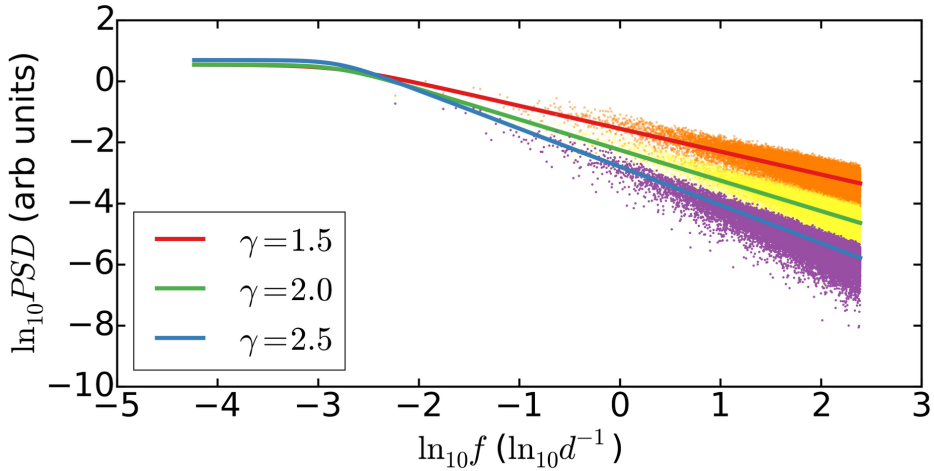
The Damped Random Walk

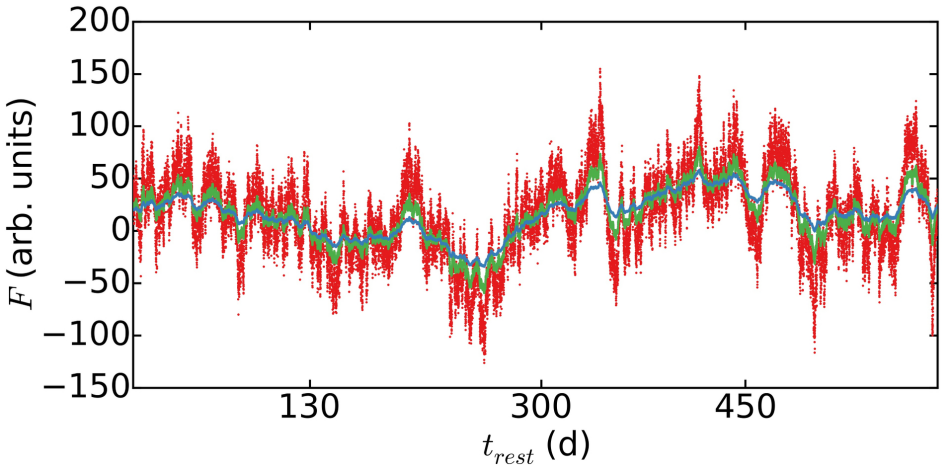


$\tau = 1$ d.

- Exponential decay
  - $F_i = \phi_1 F_{i-1}$
  - $\phi = e^{-\frac{\delta t}{\tau}} < 1$
  - Decays to asymptotic flux level
- Damped Random Walk
  - $F_i = \phi_1 F_{i-1} + w_i$
  - 'Walks around' exponential decay
- Exponential decay driven by Gaussian noise
- 1^{st}-Order Linear Stochastic-DE

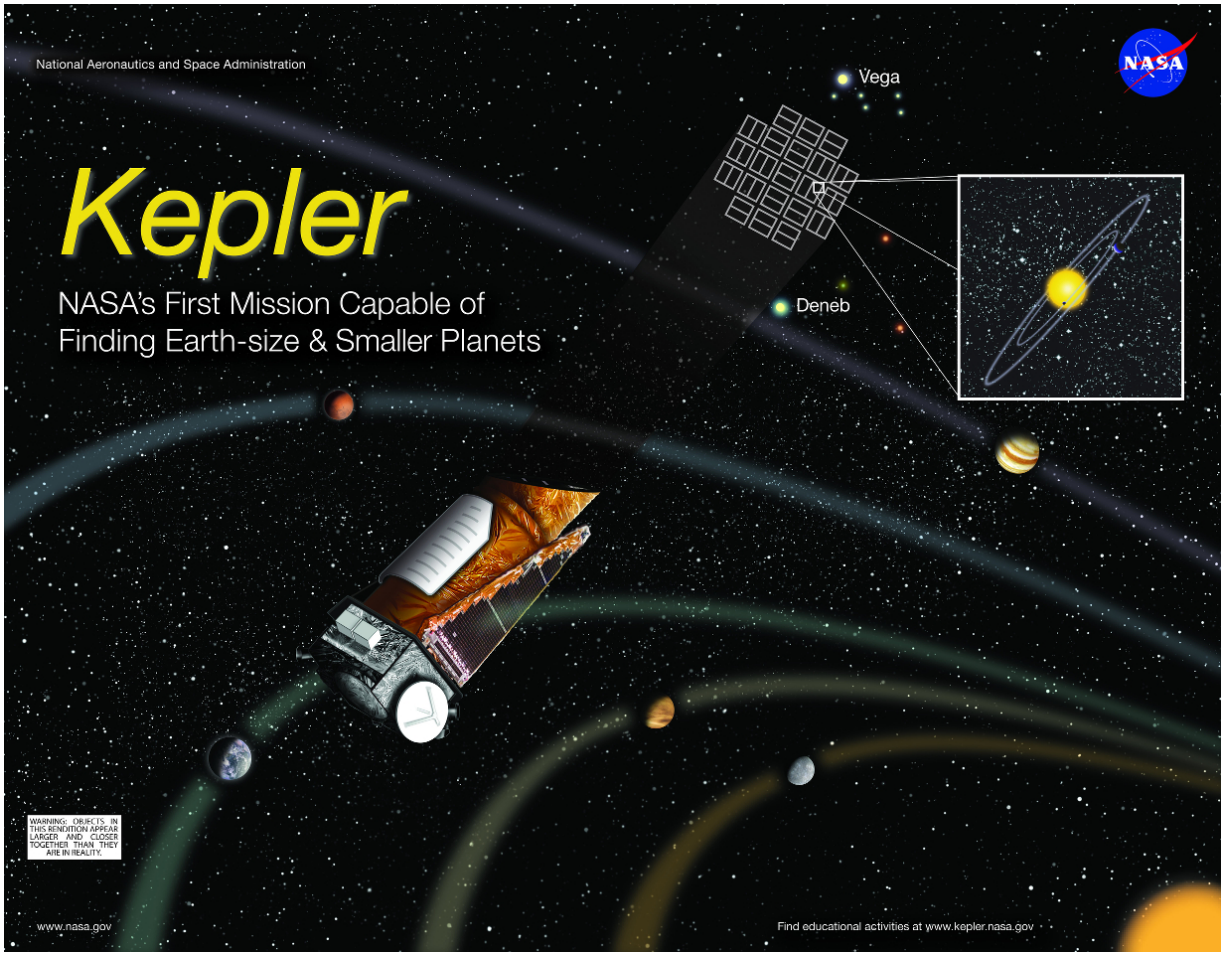
PSD of the Damped Random Walk



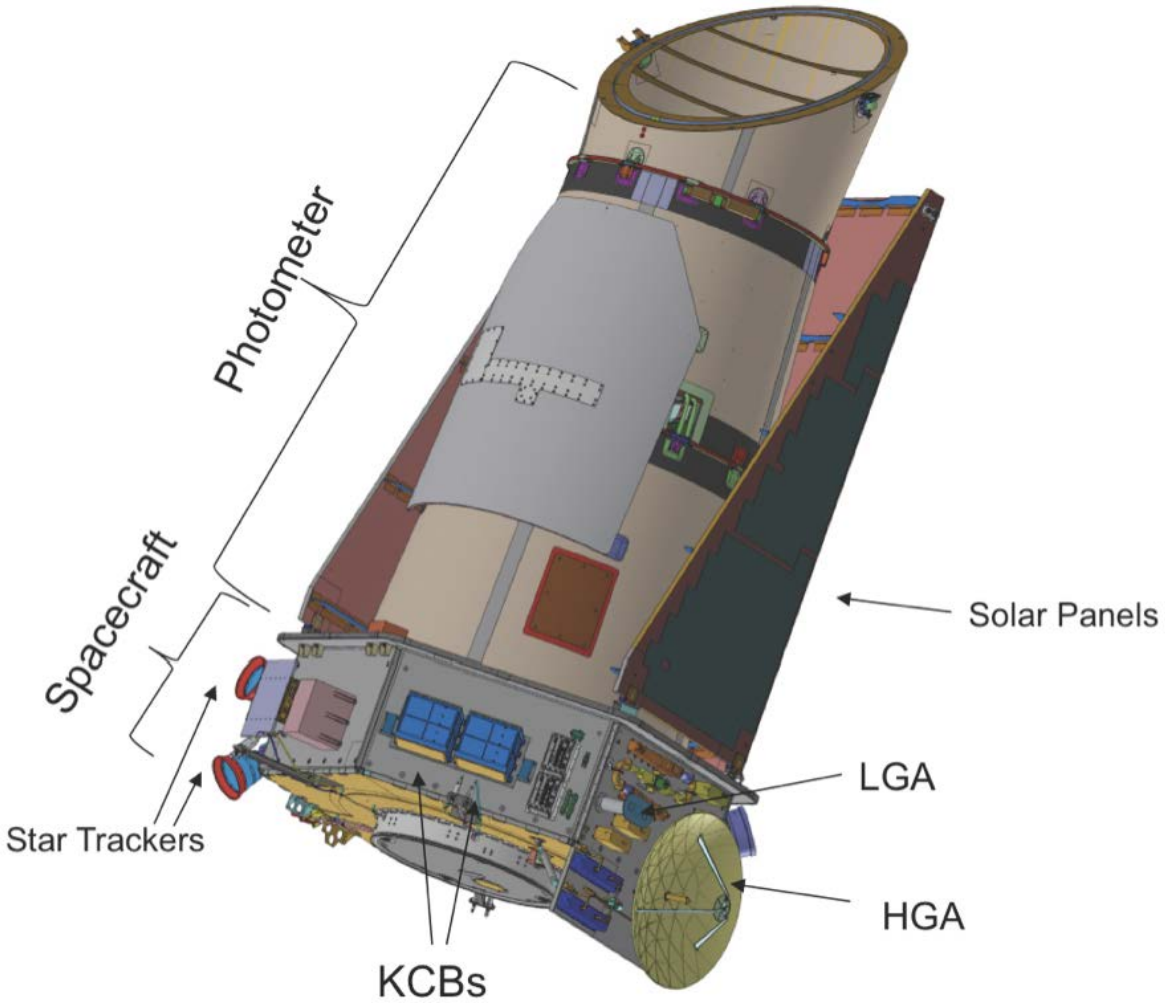


- $PSD \propto \frac{1}{f^2}$ on short timescales
- $PSD \propto \frac{1}{f^b} \Rightarrow \sigma_{\alpha-fluc} \propto r^b$ (Lyubarskii 1997)
- DRW: b is fixed - is this true?
- Generalize: $PSD \propto \frac{1}{f^\gamma}$ (McHardy et al. 2004)
- Test with data!

Serendipitous AGN science with Kepler

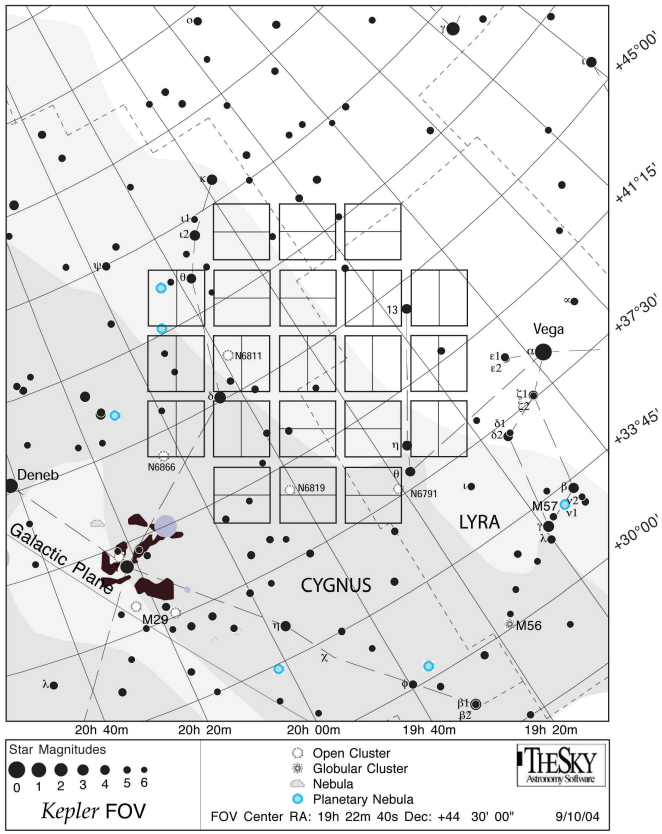


Kepler Instrument Design



- Schmidt camera
- 0.95 m clear aperture
- Fast f/1.473 optics
- Plate scale
  3.98 arcsec/pixel
- PSF: 95-percent EED
  ~ 6.4 pixel
- Photometric Precision: 35 ppm (mag 12 star)

What can we learn from Kepler?

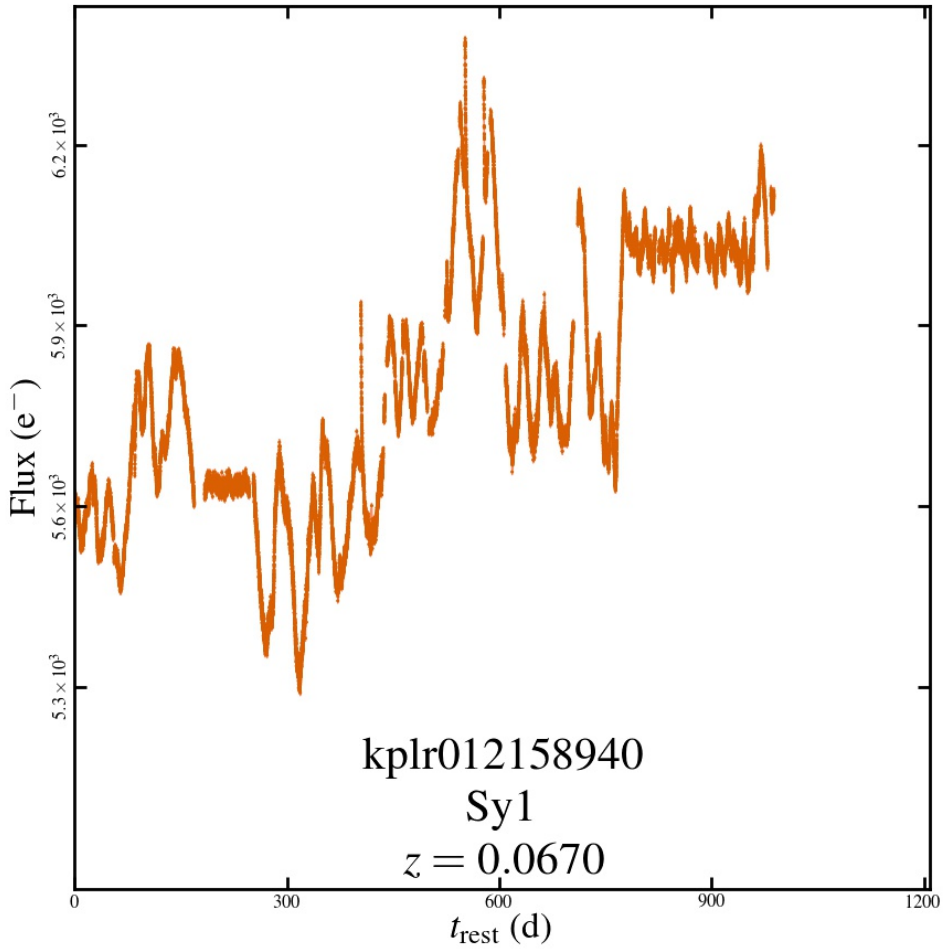


Van Cleve & Caldwell (2009)

- Very precise: S/N $\sim 10^5$
- Long baseline: $T = 3.5$ yr
- Rapid sampling: $\delta t_{\rm obs} = 29.4$ min
- 110 deg^2 FOV
- $\sim$ 80 AGN

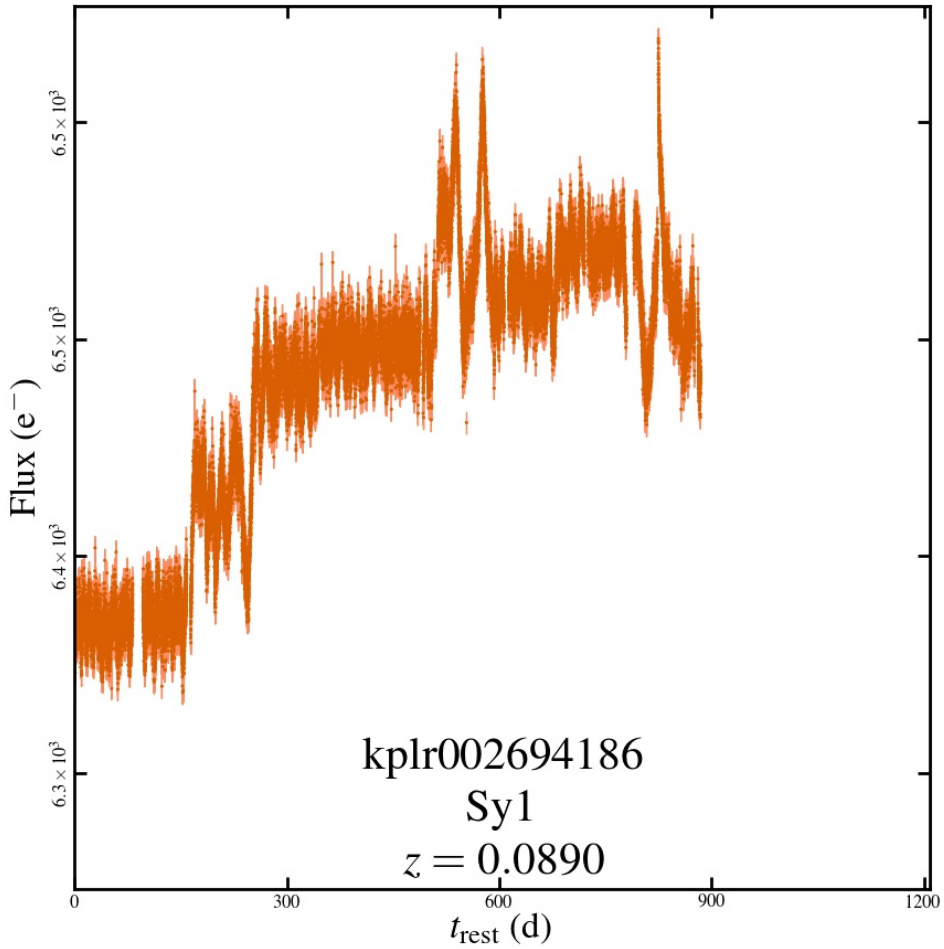
(Mushotzky et al. 2011; Edelson & Malkan 2012; Carini & Ryle 2012; Wehrle et al. 2013; Shaya et al. 2015)

AGN sample



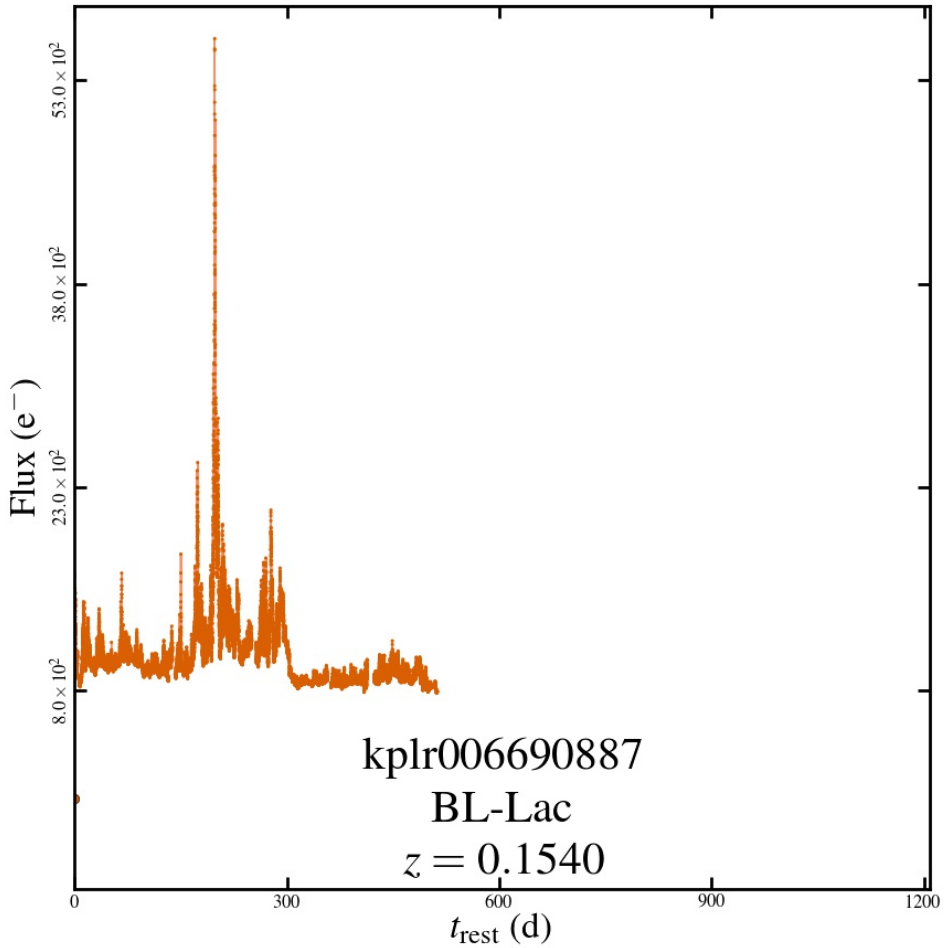
- Seyfert 1
- $\delta t_{rest} \sim 27.5$ min
- $N \sim 50$k
- Stationary?

AGN sample



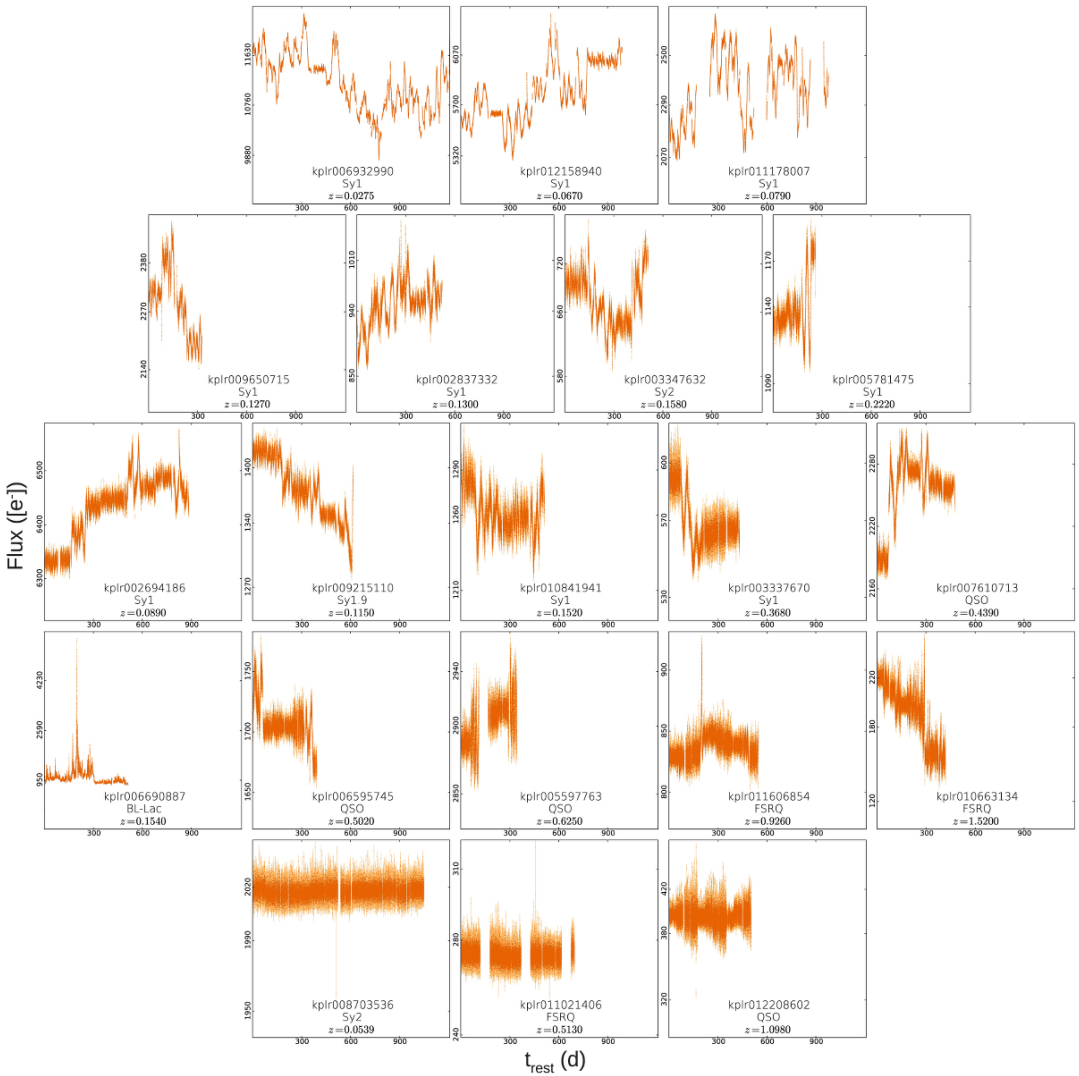
- Seyfert 1
- $\delta t_{\rm rest} \sim 27.0$ min
- $N \sim 44$k
- QPO?

AGN sample



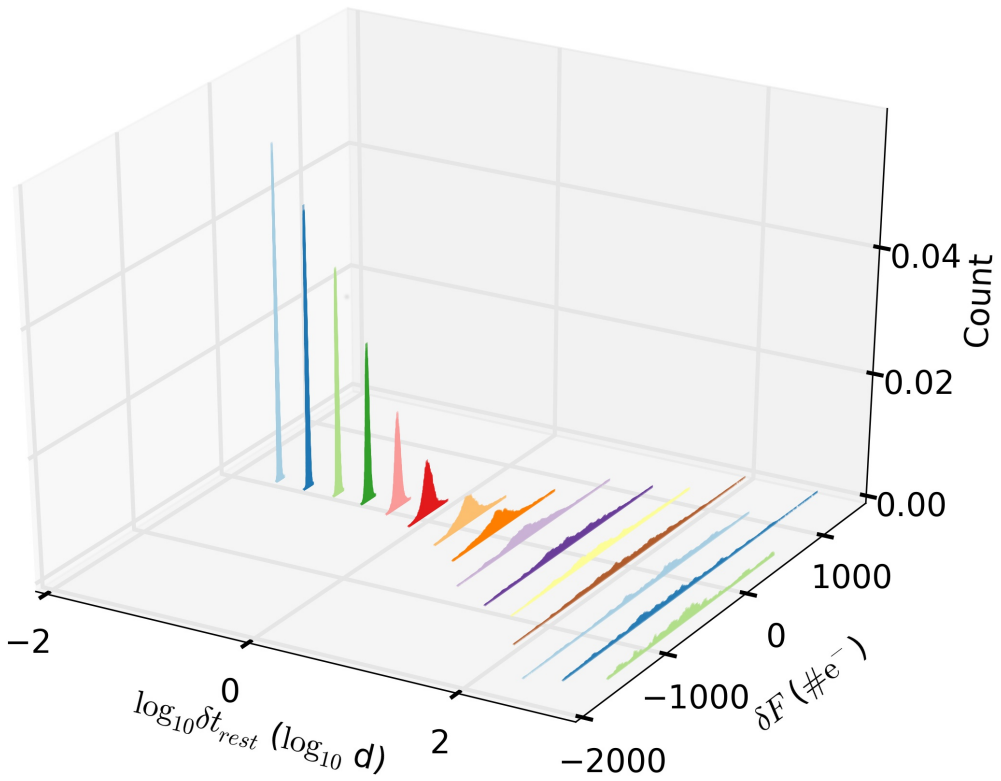
- BL Lacertae object
- $\delta t_{\rm rest} \sim 25.5$ min
- $N \sim 28$k
- Flares!

Full AGN sample



- $z \sim 0.02$-1.5
- $\delta t_{\rm rest} \sim$ 14-28 min
- $N \sim$ 16k-60k
- Wide variety of behavior!

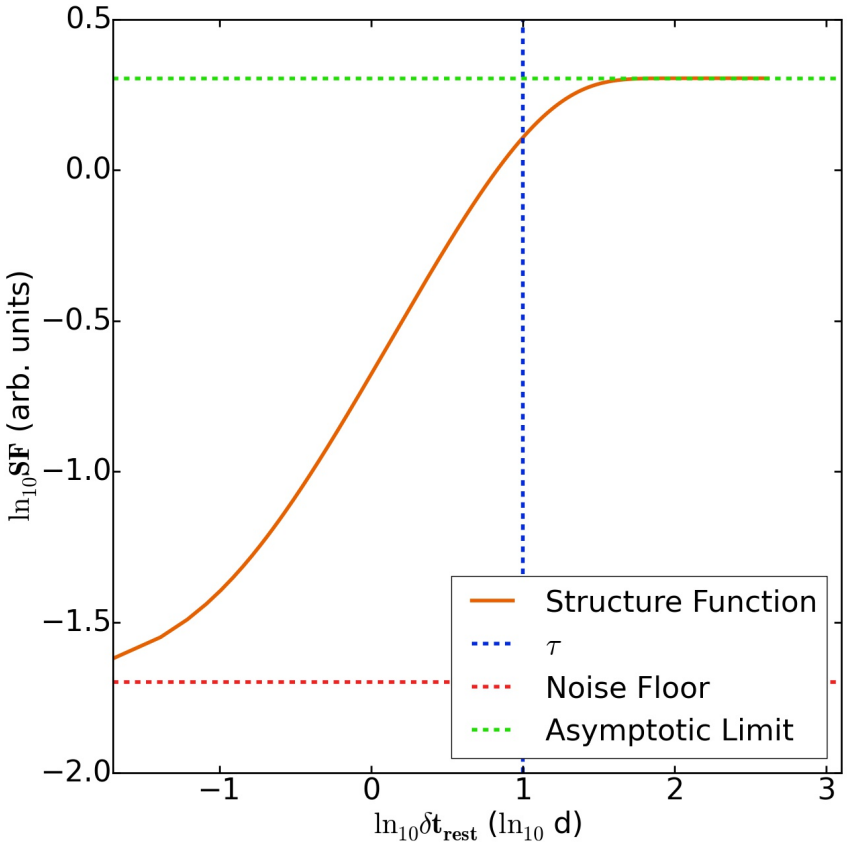
Structure functions



How does variance of δF vary with δt?

- $\delta F = F(t + \delta t) - F(t)$
- $SF(\delta t) = \langle |\delta F|^2 \rangle_t$
- Insensitive to edge-effects, aliasing etc...

Structure functions

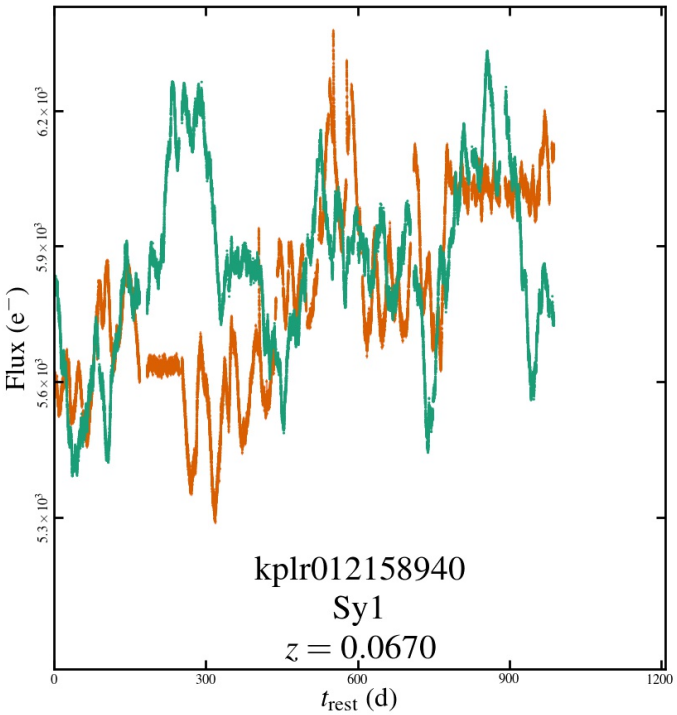


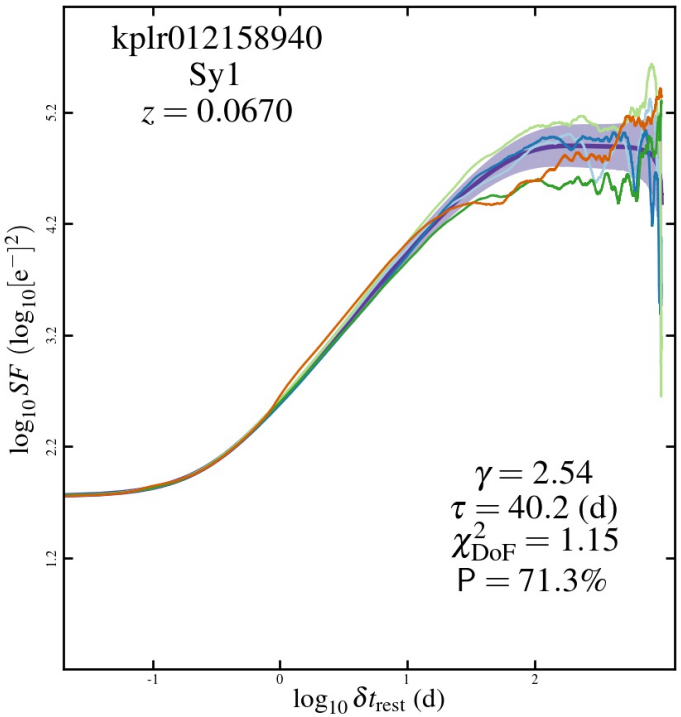
Features in the Structure Function

- Short δt: 'Noise floor'
- Slope $\sim \gamma$
- Long δt: Turnover
- Spurious breaks & features

(Emmanoulopoulos et al. 2010)

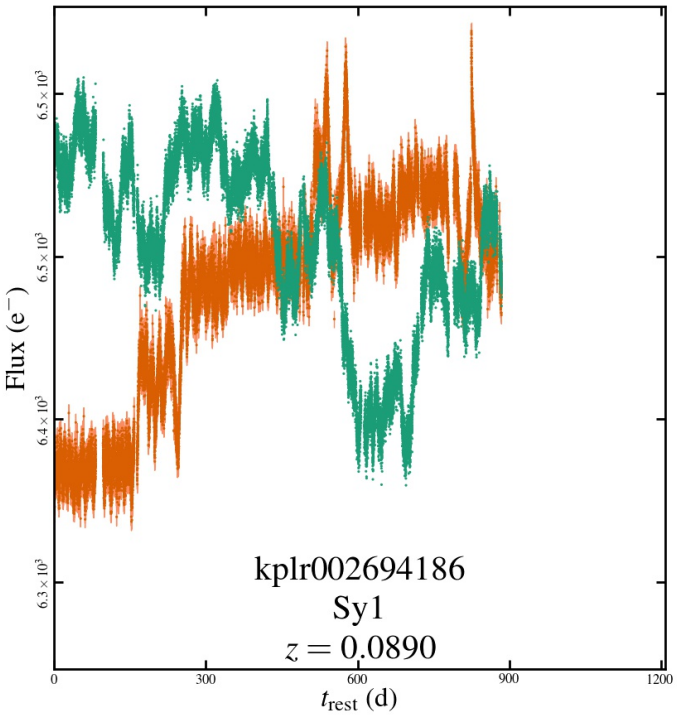
Monte-Carlo simulations

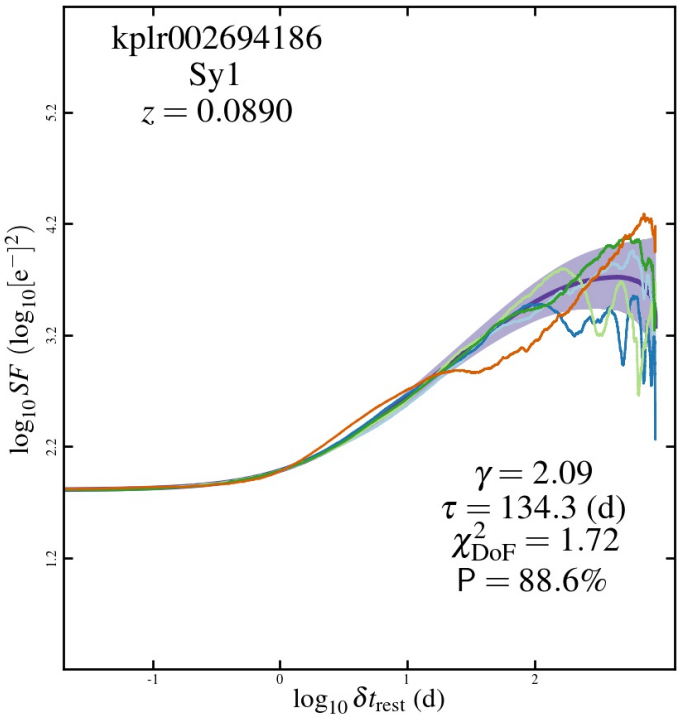




- Best-fit Parameters: $\gamma = 2.54$ & $\tau = 40.2$ d
- Inconsistent with DRW ($\gamma_{DRW} = 2$)
- χ^2 of best-fit PSD model > 71.3% of mocks

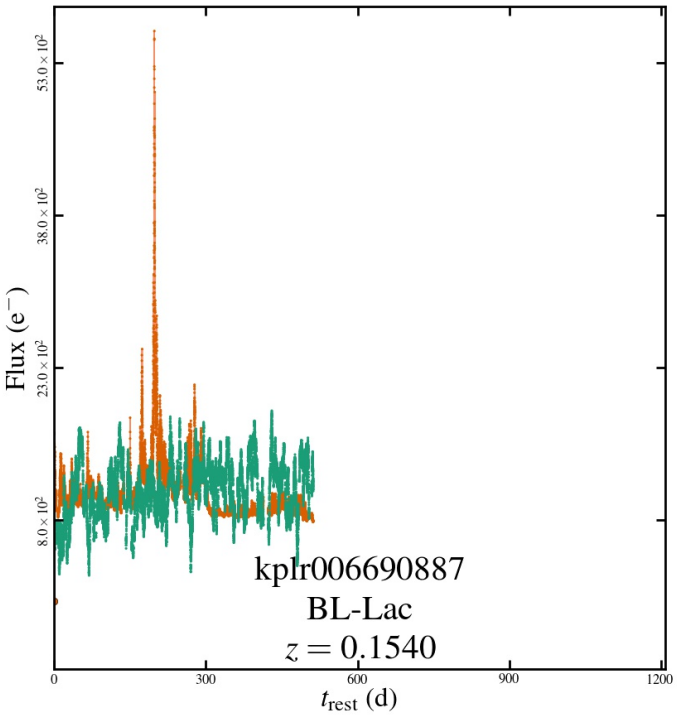
Monte-Carlo simulations

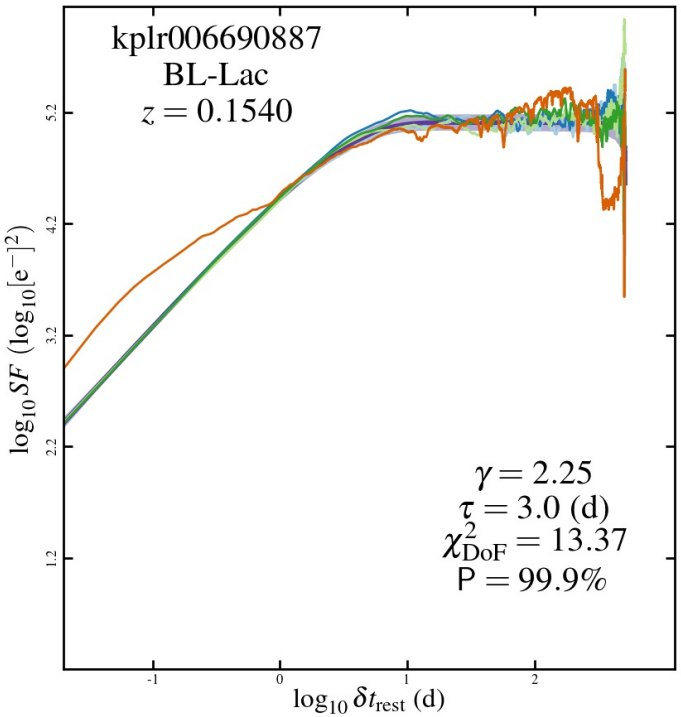




- Best-fit Parameters: $\gamma = 2.09$ & $\tau = 134.3$ d
  - Consistent with DRW ($\gamma_{DRW} = 2$)
- χ^2 of best-fit PSD model > 88.6% of mocks

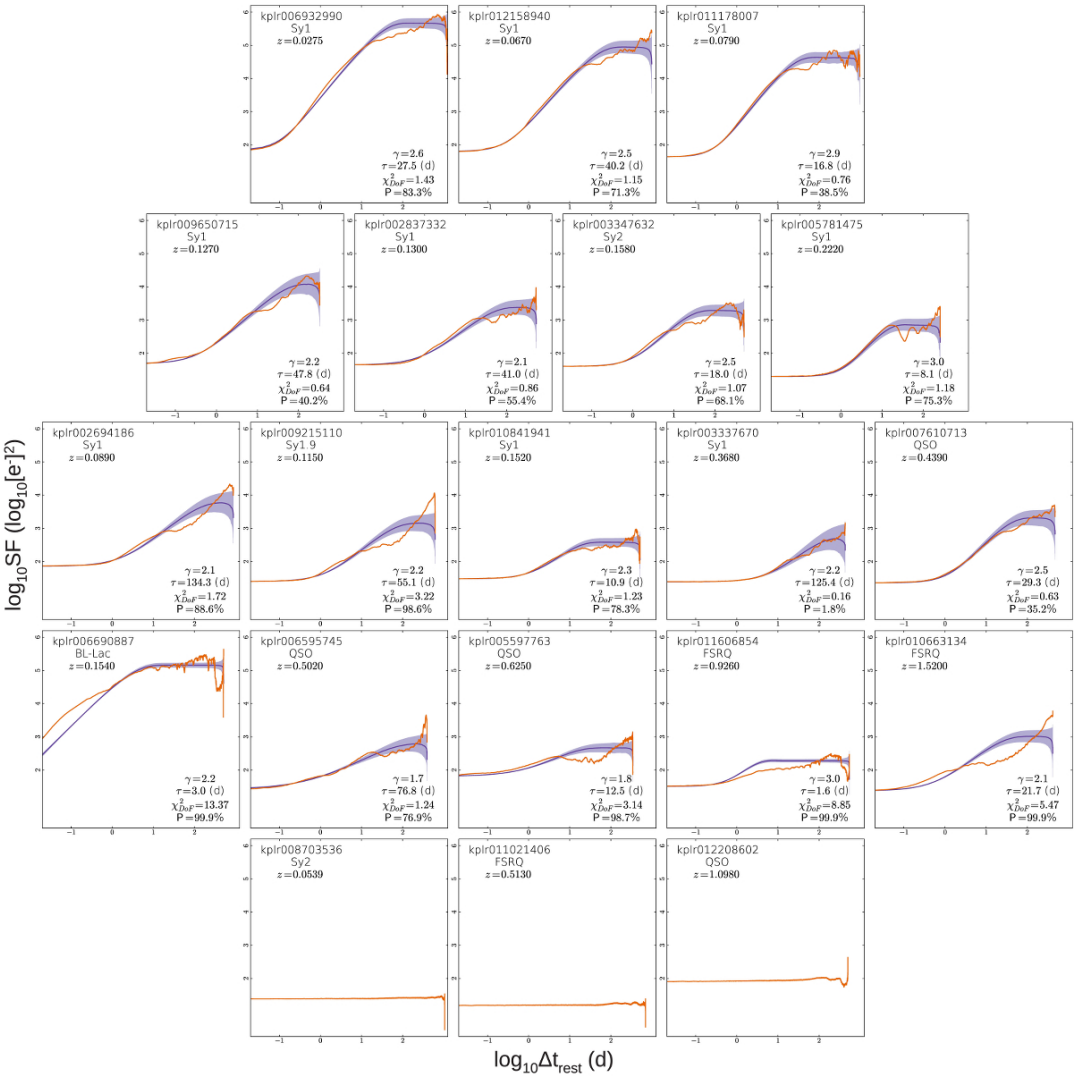
Monte-Carlo simulations





- Best-fit Parameters: $\gamma = 2.25$ & $\tau = 3.0$ d
- Not well-modelled by a DRW ($\gamma_{DRW} = 2$)
- χ^2 of best-fit PSD model > 99.9% of mocks

Structure function fits



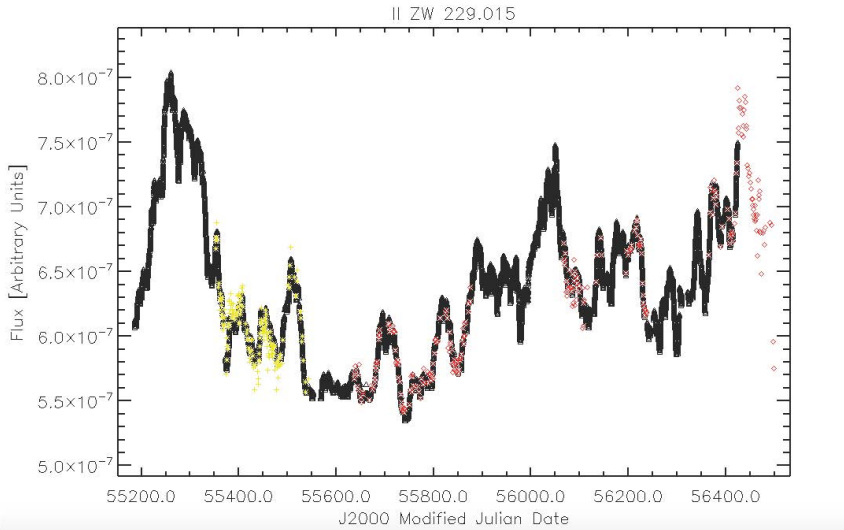
- Not all AGN ~ DRW
- PSD model too simple
- Variability onsets over ~ 1 hr to ~ 1 d


Are the variability properties of the *Kepler* AGN light curves consistent with a damped random walk?

Vishal P. Kasliwal,* Michael S. Vogeley and Gordon T. Richards

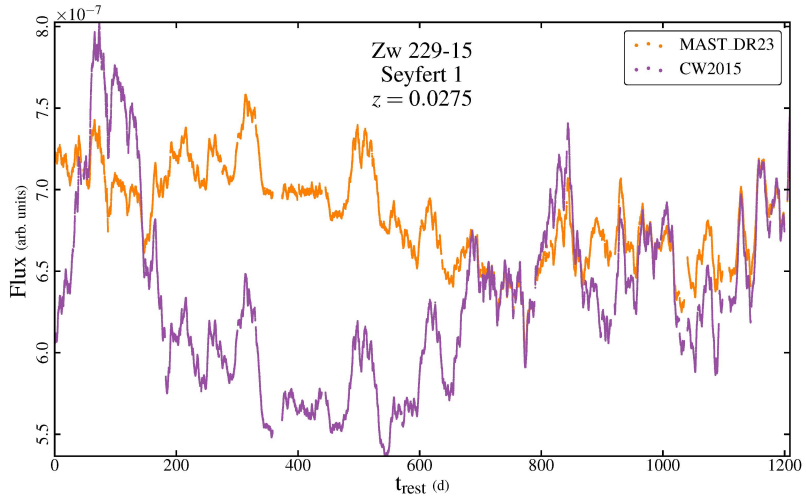
Kasliwal, Vogeley, & Richards (2015a)

Are the MAST light curves accurate?



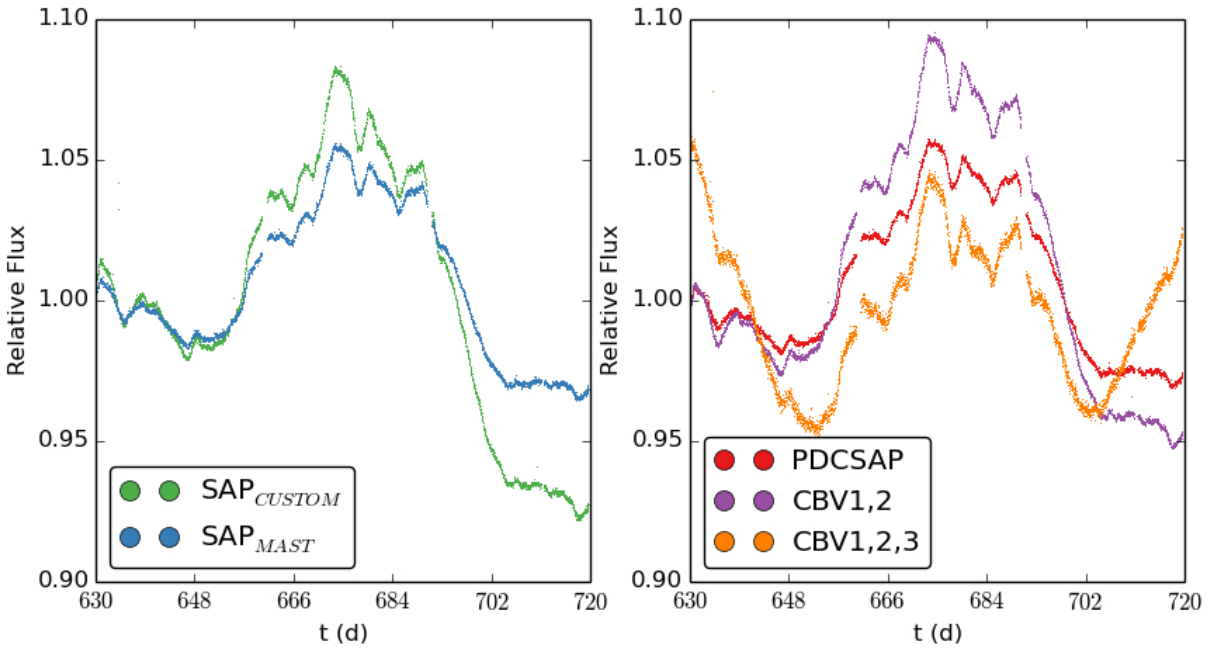
Williams & Carini (2015)

- Spacecraft induced systematics



- Incorrect photometric aperture

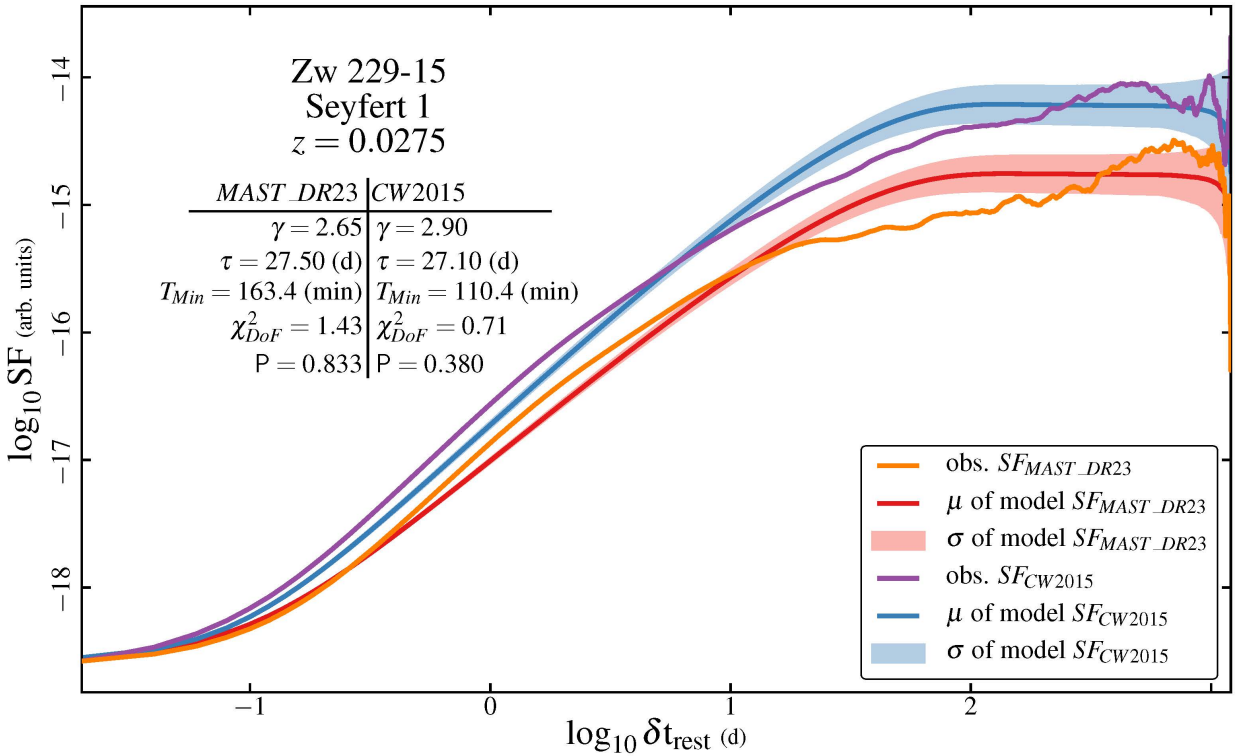
Photometric aperture definition & de-trending



Jackeline Moreno

- Flux re-extraction possible
- De-trending can be re-done

Effect on Structure Functions Analysis

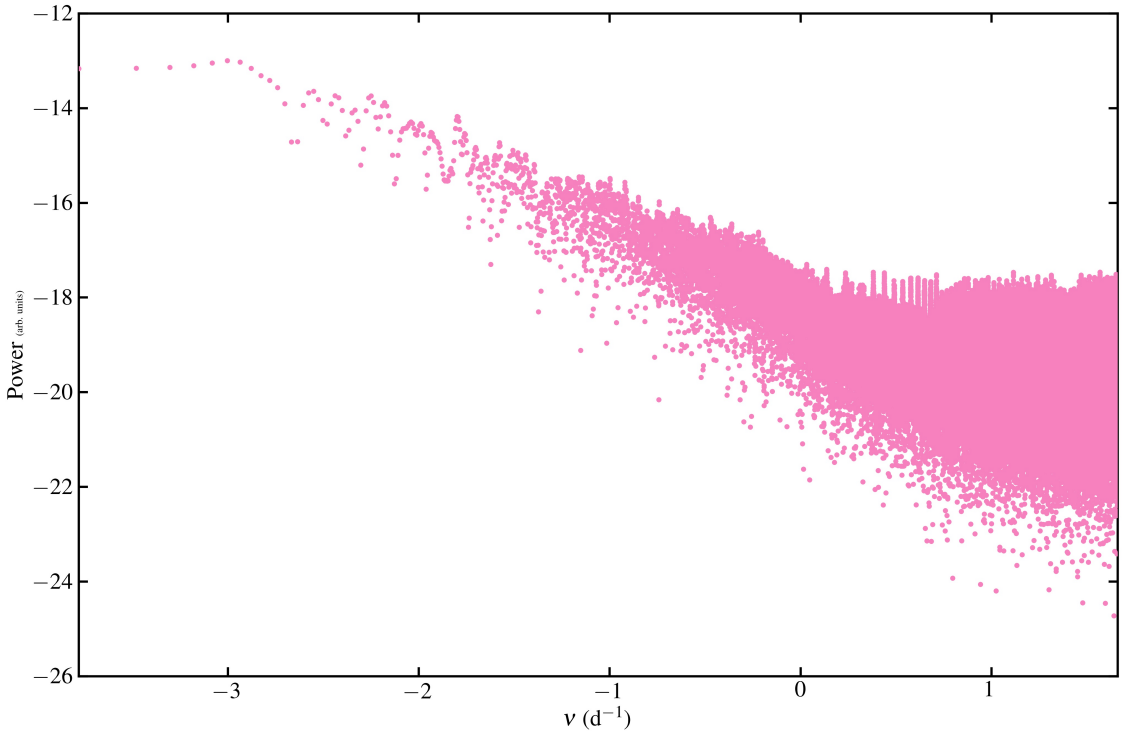


- Instrumentation not responsible for non-DRW behavior
- Ground-based supplementary data crucial


Do the *Kepler* AGN light curves need reprocessing?

Kasliwal, Vogeley, Richards, Williams, & Carini (2015b)

Periodogram of Zw 229-15
What model to use?



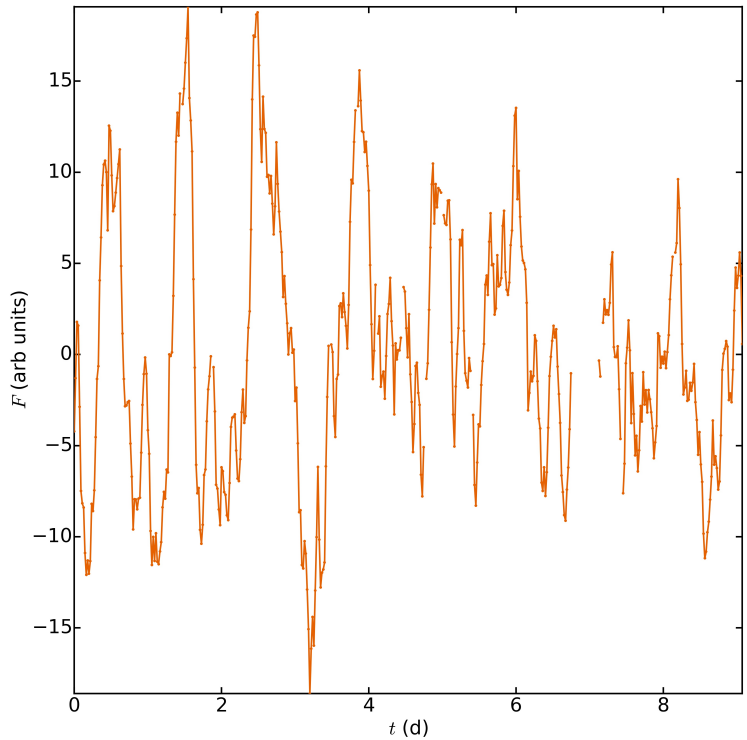
- Stochastic model must be flexible
- Amenable to physical interpretation

ARMA Stochastic Processes

$$w_k \sim \mathcal{N}(0, \sigma^2)$$

$$F_k = \phi_1 F_{k-1} + \ldots + \phi_p F_{k-p} + w_k + \theta_1 w_{k-1} + \ldots + \theta_q w_{k-q}$$

- Auto-Regressive Moving Average process Brockwell & Davis (2010)
- PSD: rational function - arbitarily complex
- Not continuous!
- $F_i = 1.25F_{i-1} - 0.3F_{i-2} + w_i$, $w \sim \mathcal{N}(0, 2)$

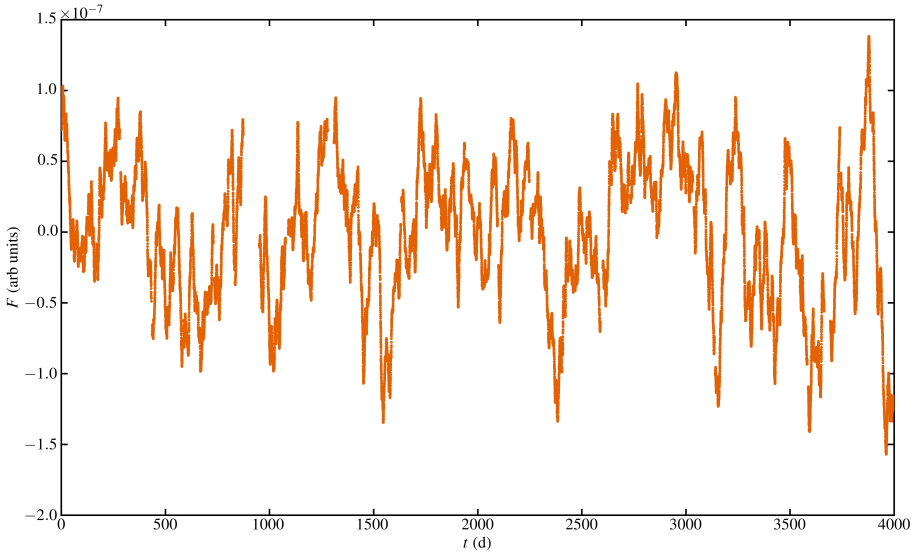


Continuous-time ARMA Processes

$$\mathrm{d}W \sim \mathcal{N}(0, \mathrm{d}t)$$

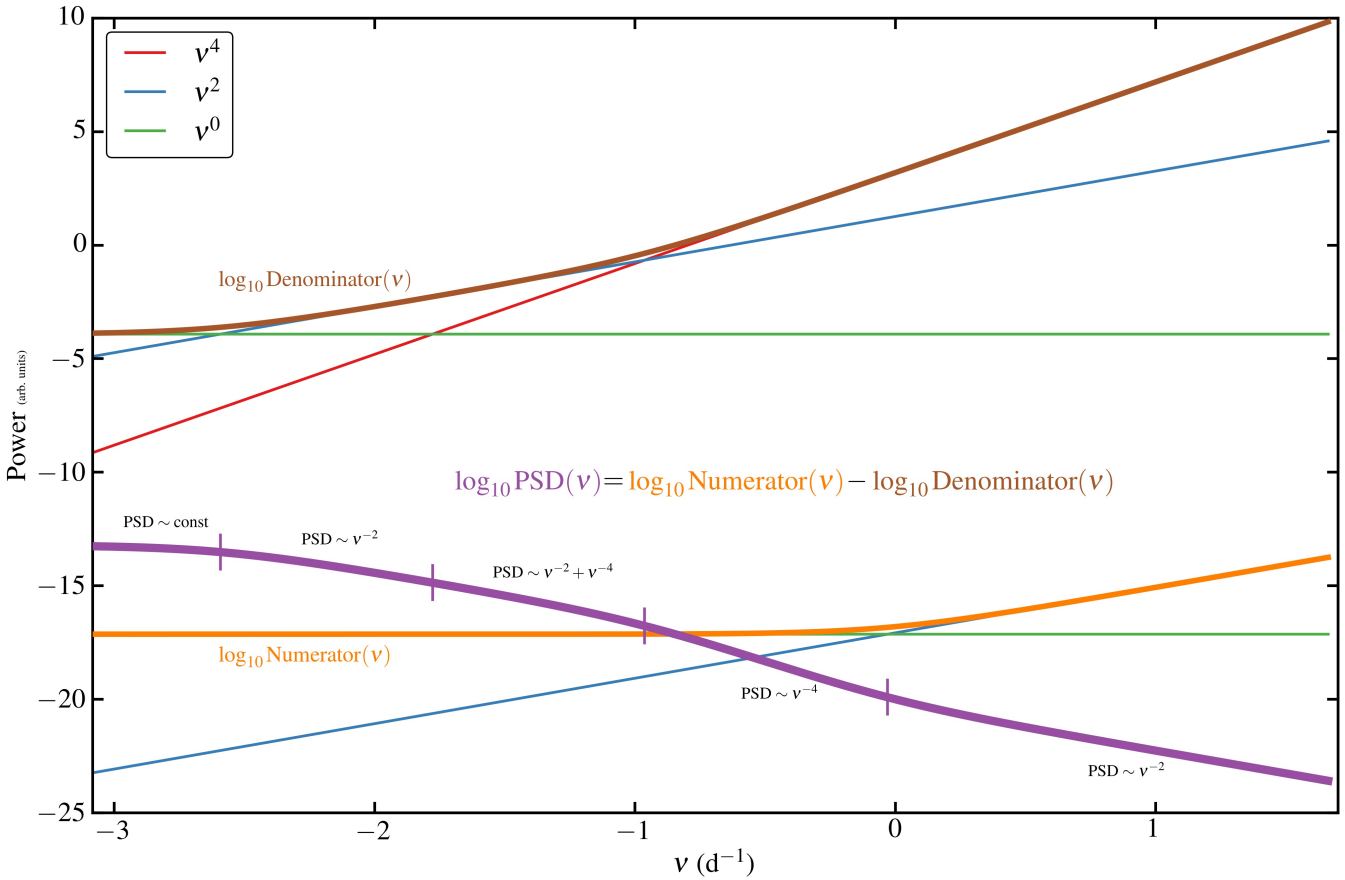
$$\mathrm{d}^p x + \alpha_1 \mathrm{d}^{p-1} x + \ldots + \alpha_{p-1} \mathrm{d}x + \alpha_p x = \beta_1 \mathrm{d}^{p-1}(\mathrm{d}W) + \ldots + \beta_p (\mathrm{d}W)$$

- Uses Itō calculus Brockwell (2014); Davis (2002); Kelly et al. (2014)
- Linear perturbations of non-linear DE $\rightarrow$ LHS
- C-ARMA $\rightarrow$ ARMA via sampling
- $\mathrm{d}^2 x + 0.7 \mathrm{d}x + 0.011 x = 7 \times 10^{-9} \mathrm{d}(\mathrm{d}W) + 1.2 \times 10^{-9} (\mathrm{d}W)$

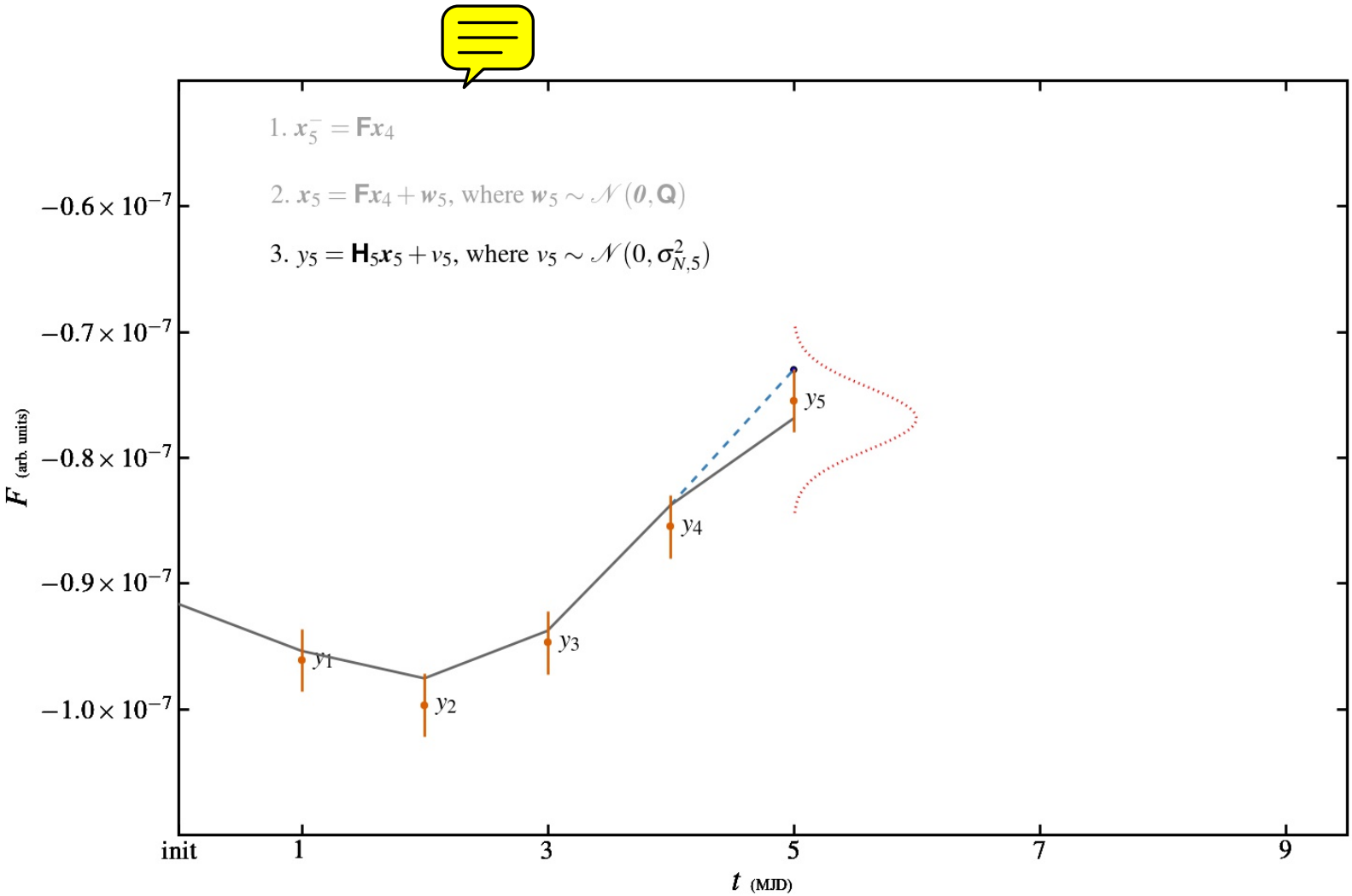


Power Spectral Density
C-ARMA(2,1) case

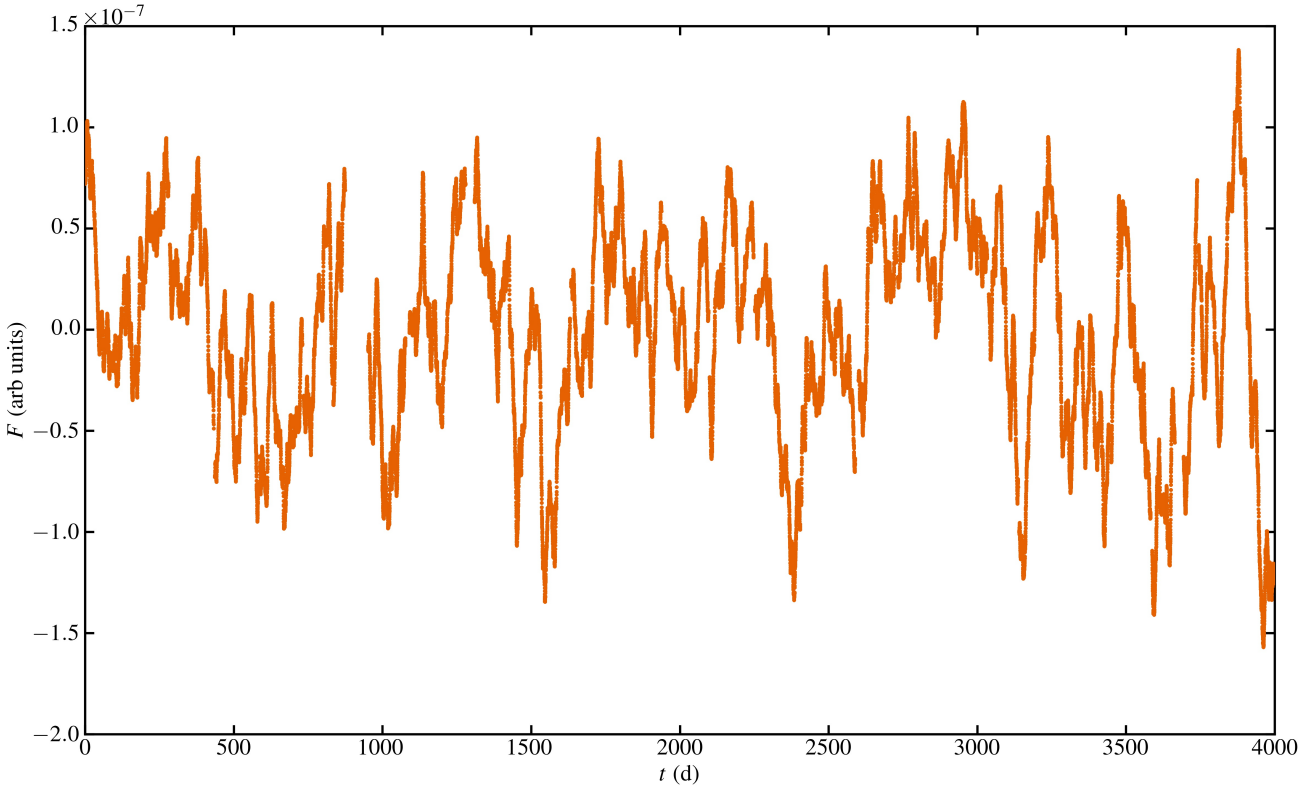
$$\mathrm{d}^2x + 2\omega\zeta \mathrm{d}x + \omega^2 x = \beta_1 \mathrm{d}(\mathrm{d}W) + \beta_2(\mathrm{d}W)$$



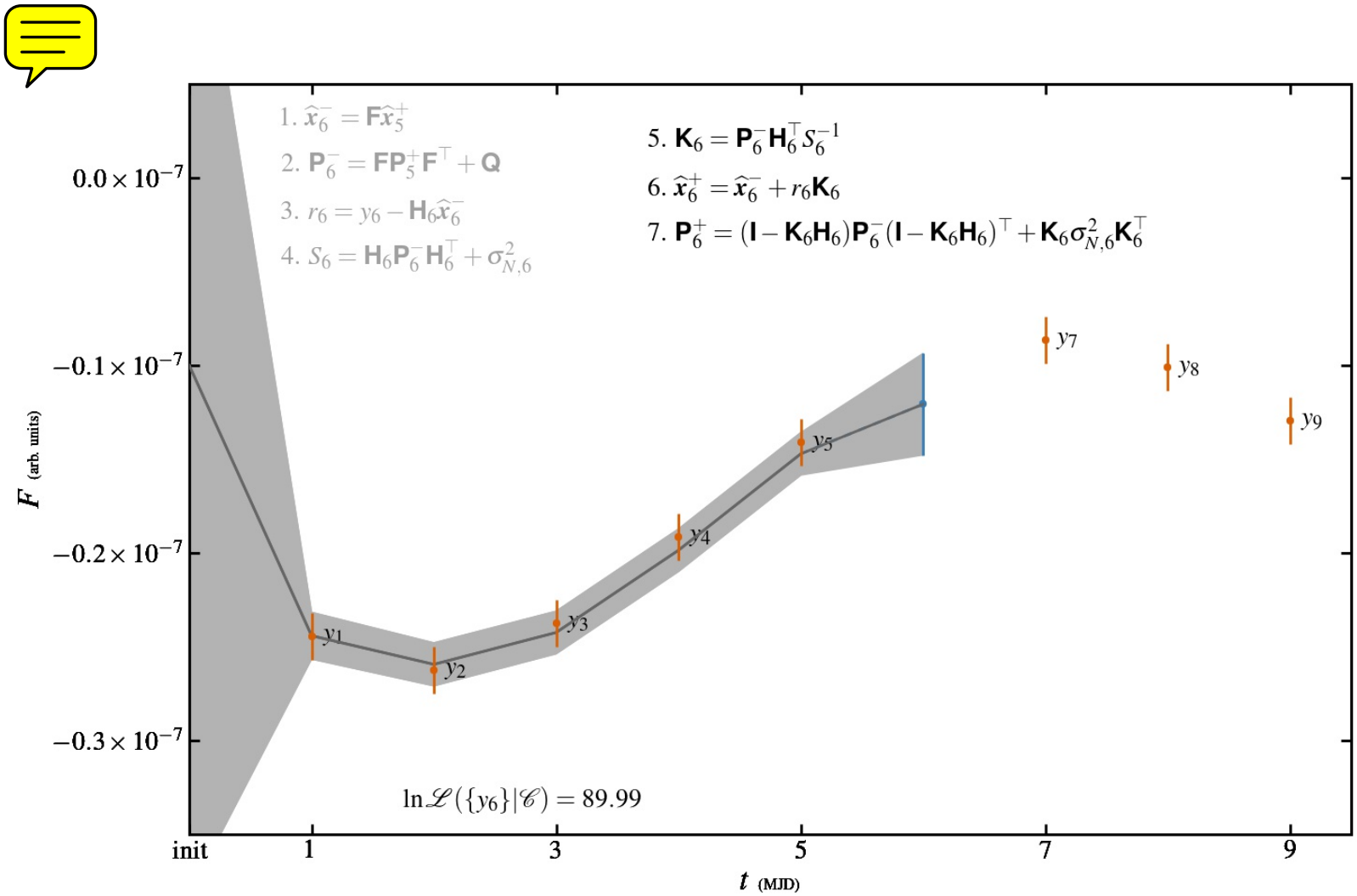
Evolution & observation of light curve state



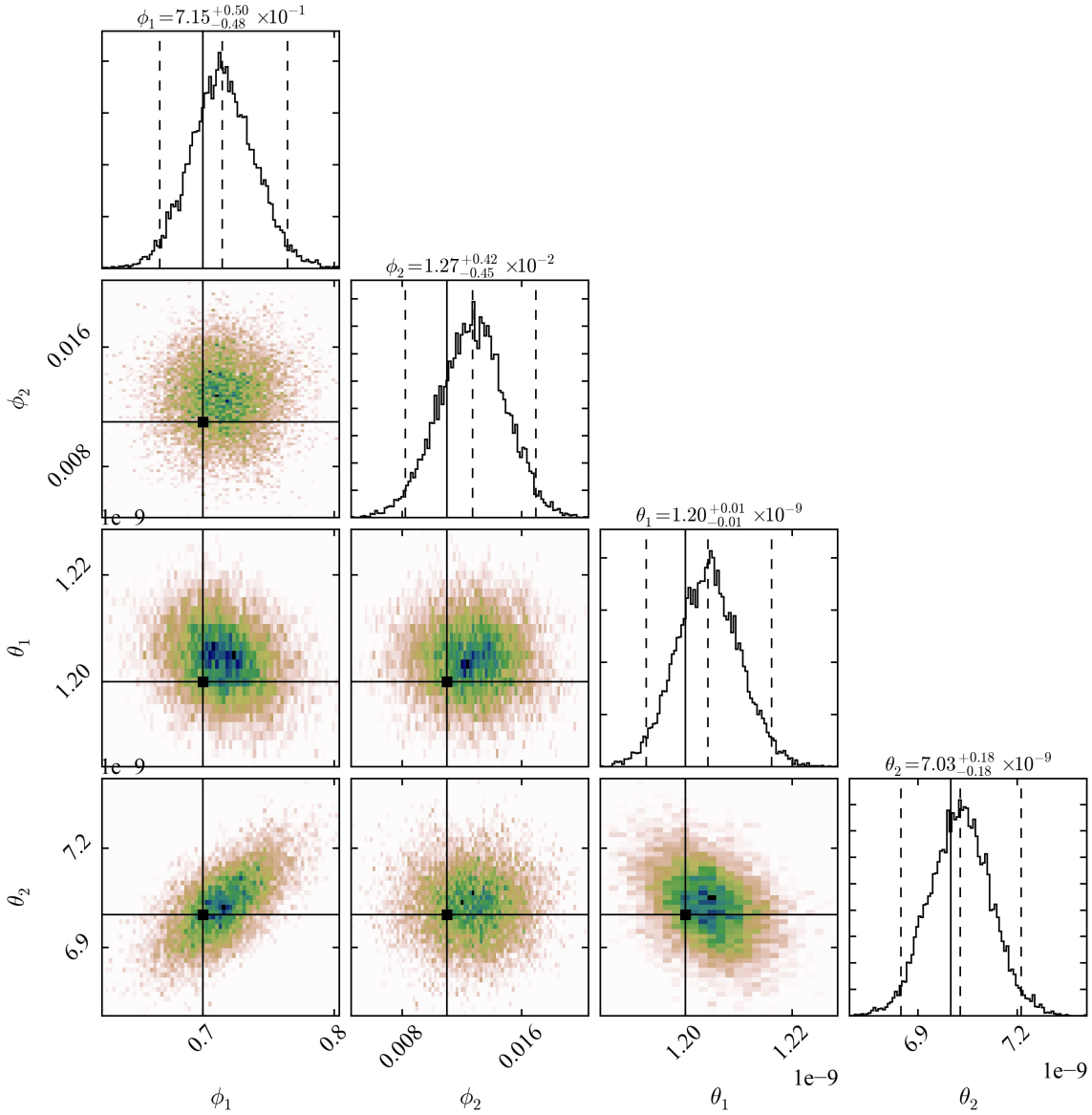
A C-ARMA(2,1) light curve



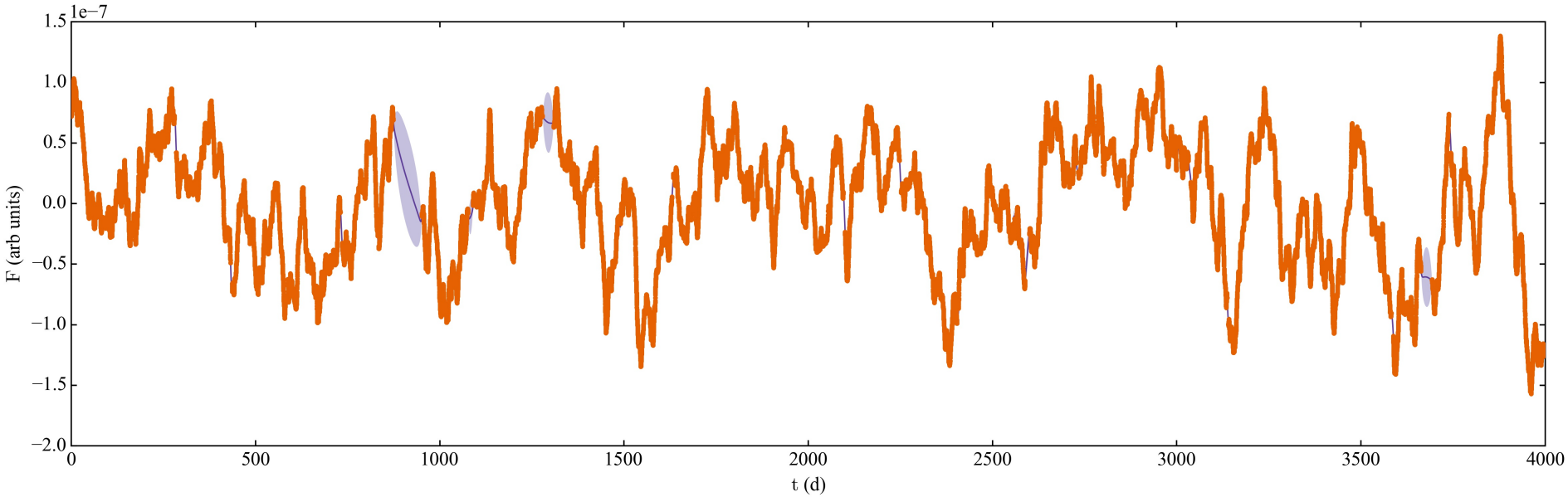
$\ln \mathcal{L}$ via Kalman filter



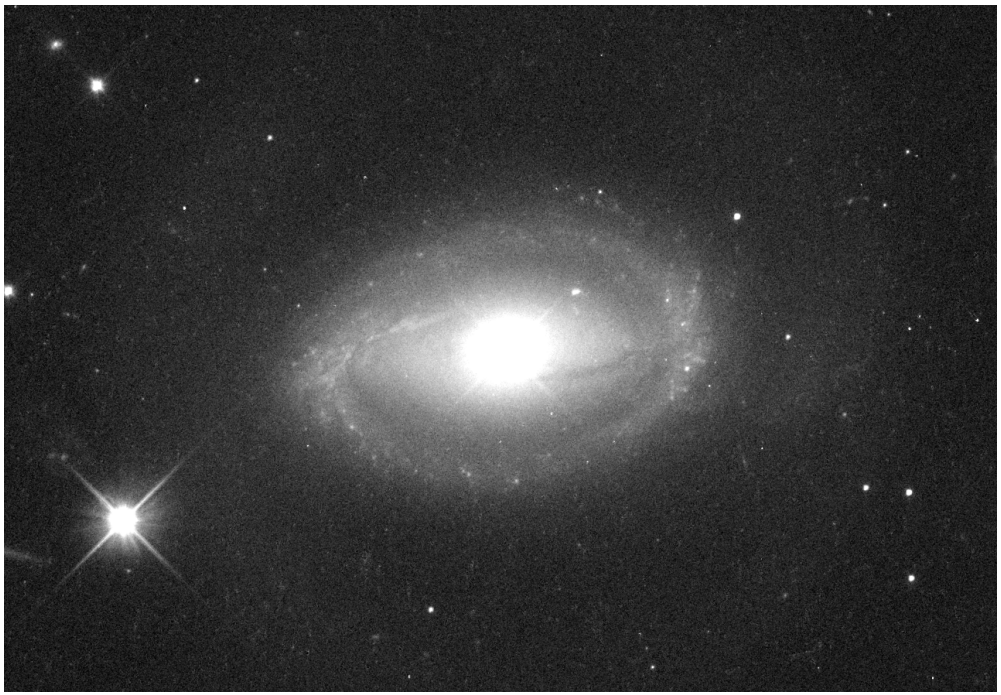
Confidence Interval Estimates



Smoothed Light Curve



Zw 229-15 (kplr006932990)

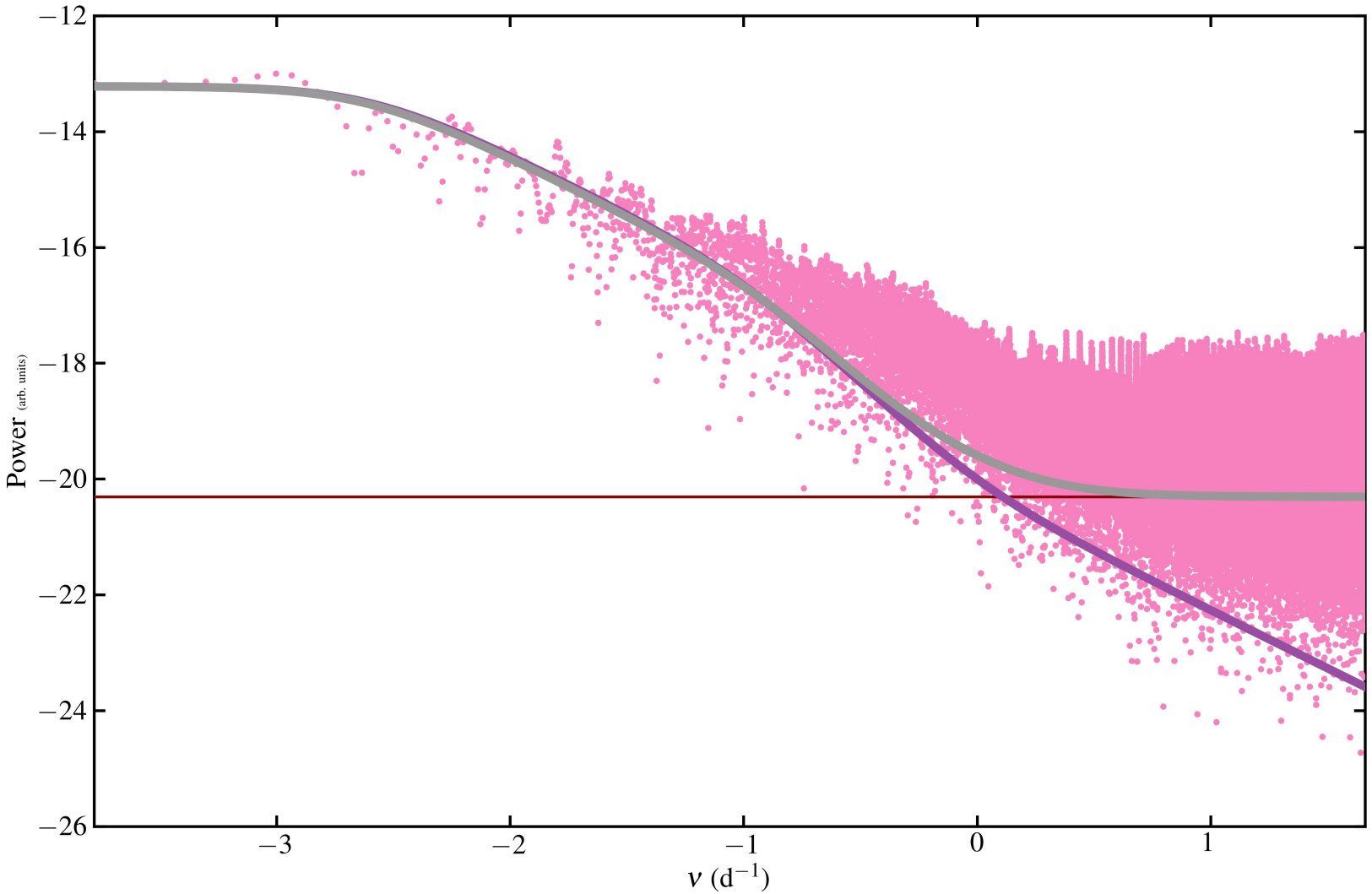


HST Image

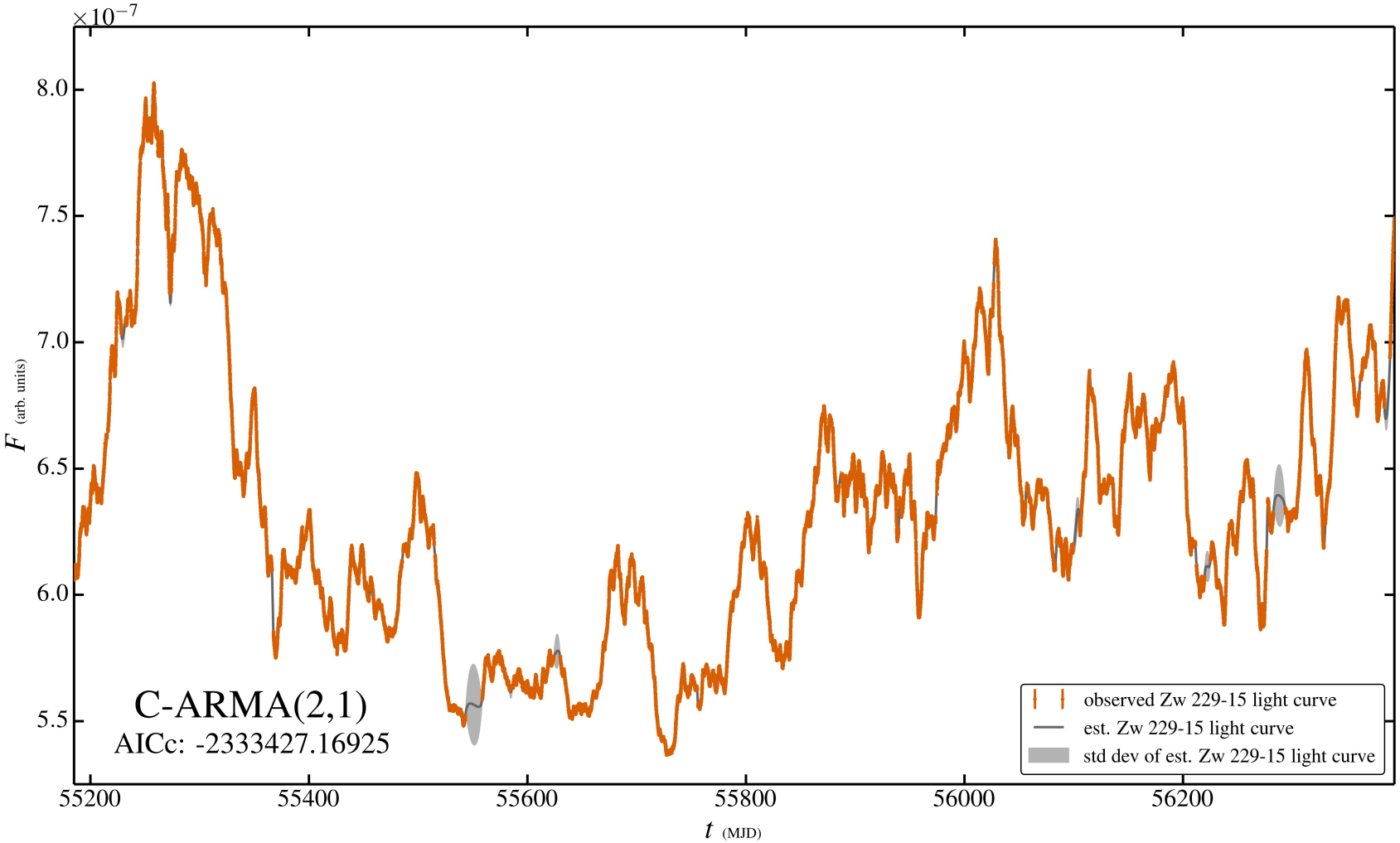
- Sy 1 in Lyra
- $\Delta T_{H\beta} = 3.86^{+0.69}_{-0.90}$ d
- mag 15.4
- $M_{BH} = 1.00^{+0.19}_{-0.24} \times 10^7 M_\odot$

(Barth et al. 2011)

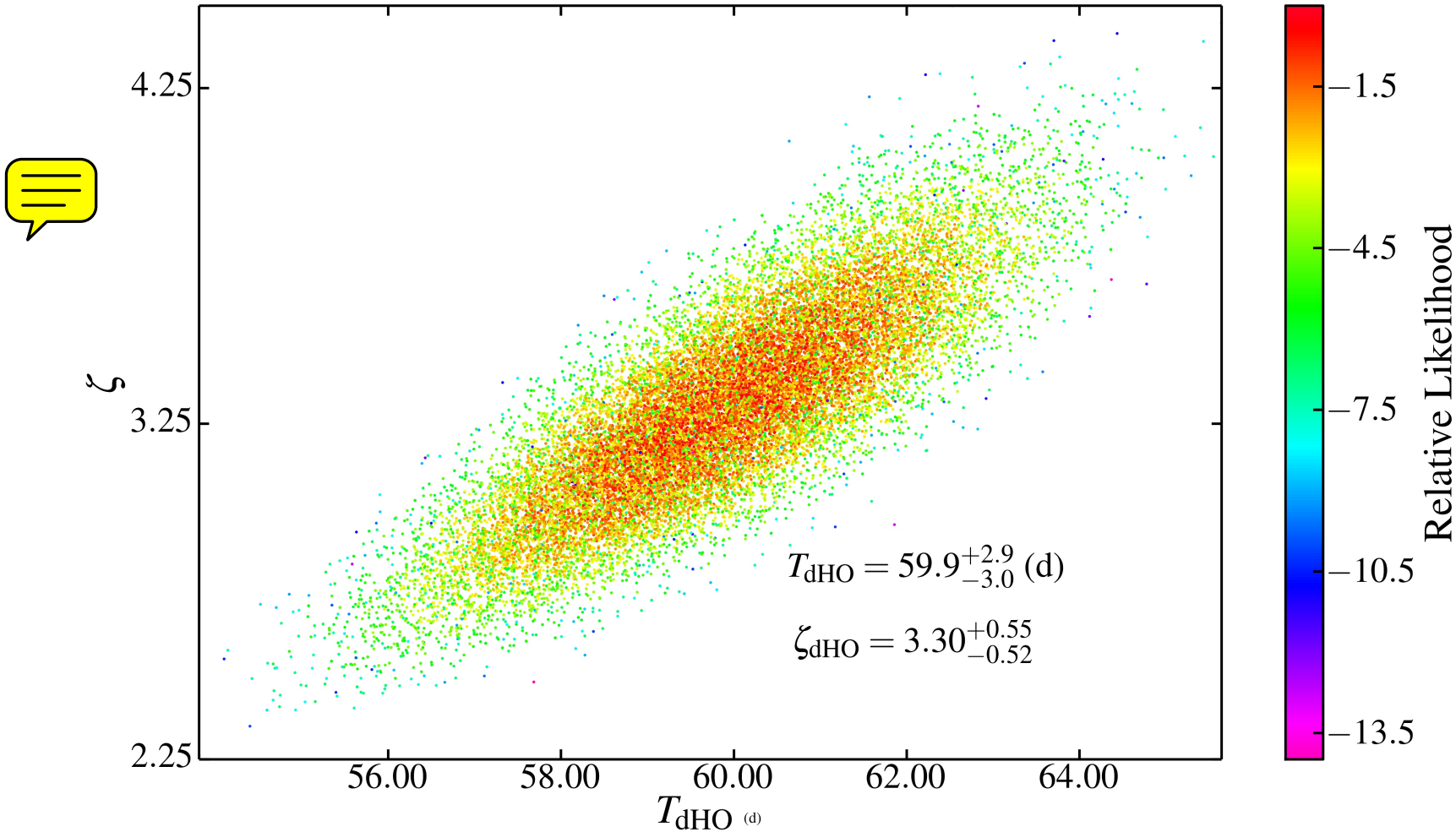
C-ARMA(2,1) model of Zw 229-15
PSD of the light curve



C-ARMA(2,1) model of Zw 229-15
Smoothed light curve

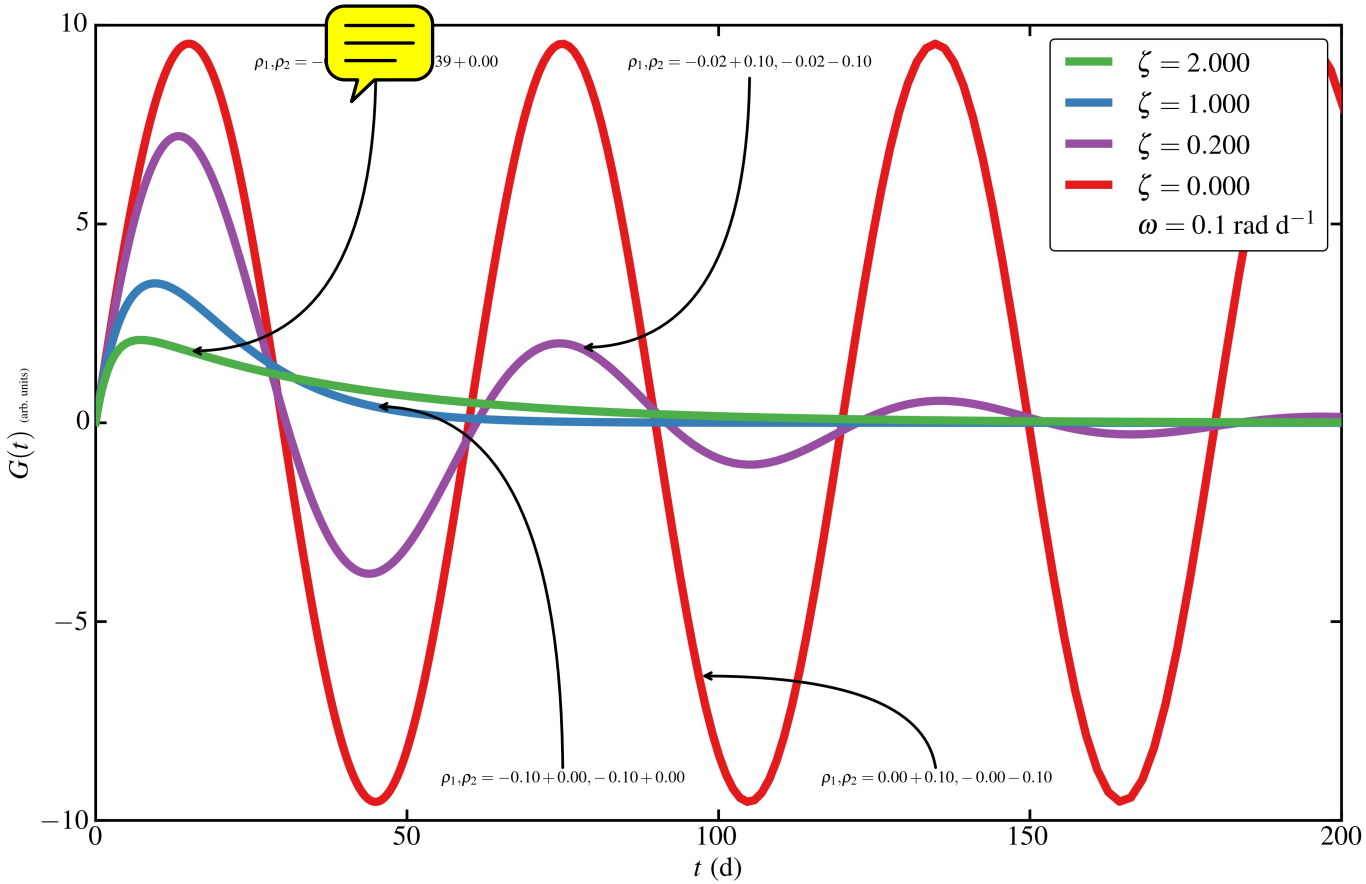


C-ARMA(2,1) model of Zw 229-15
Damped Harmonic Oscillator

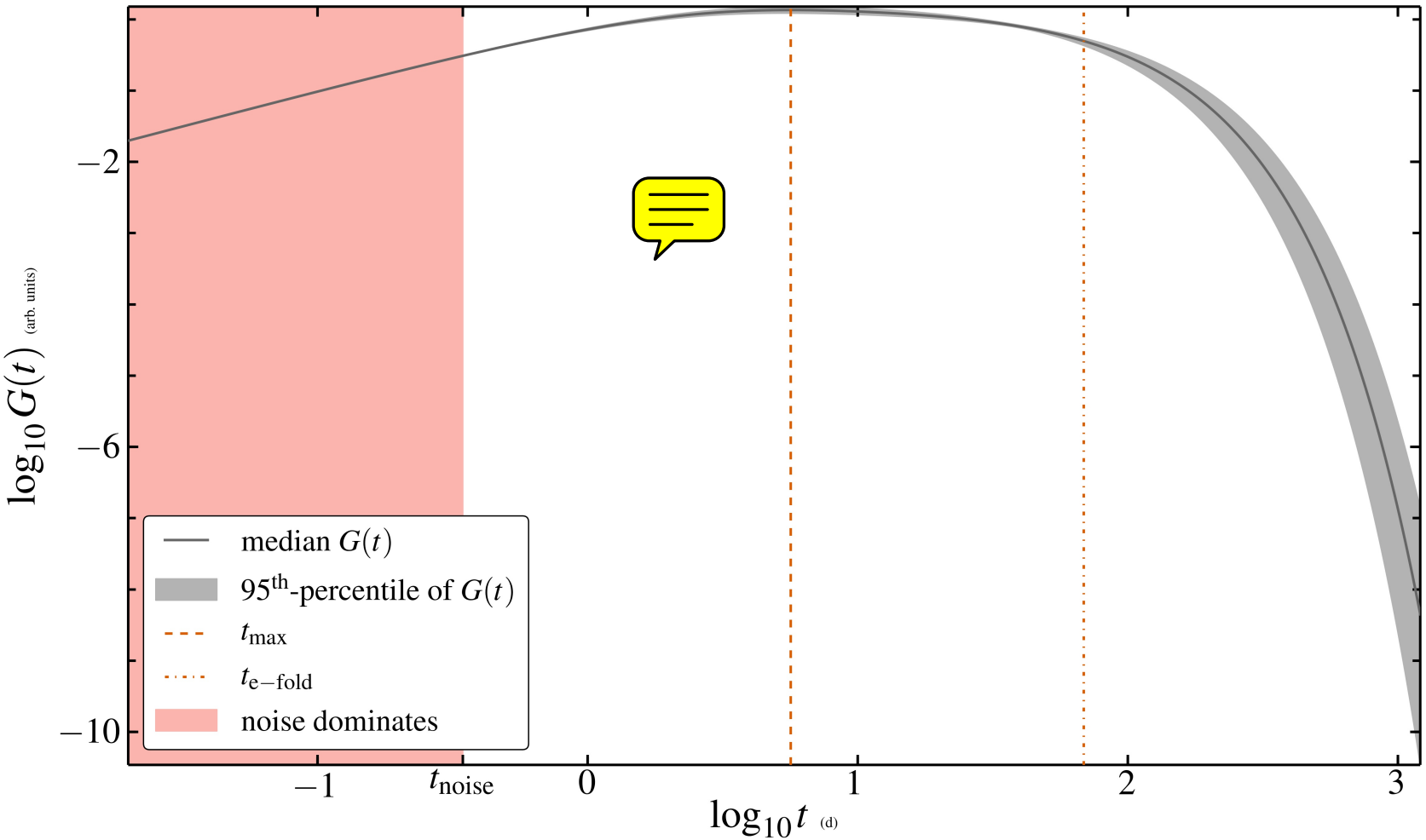


Green's Function
C-ARMA(2,1) case

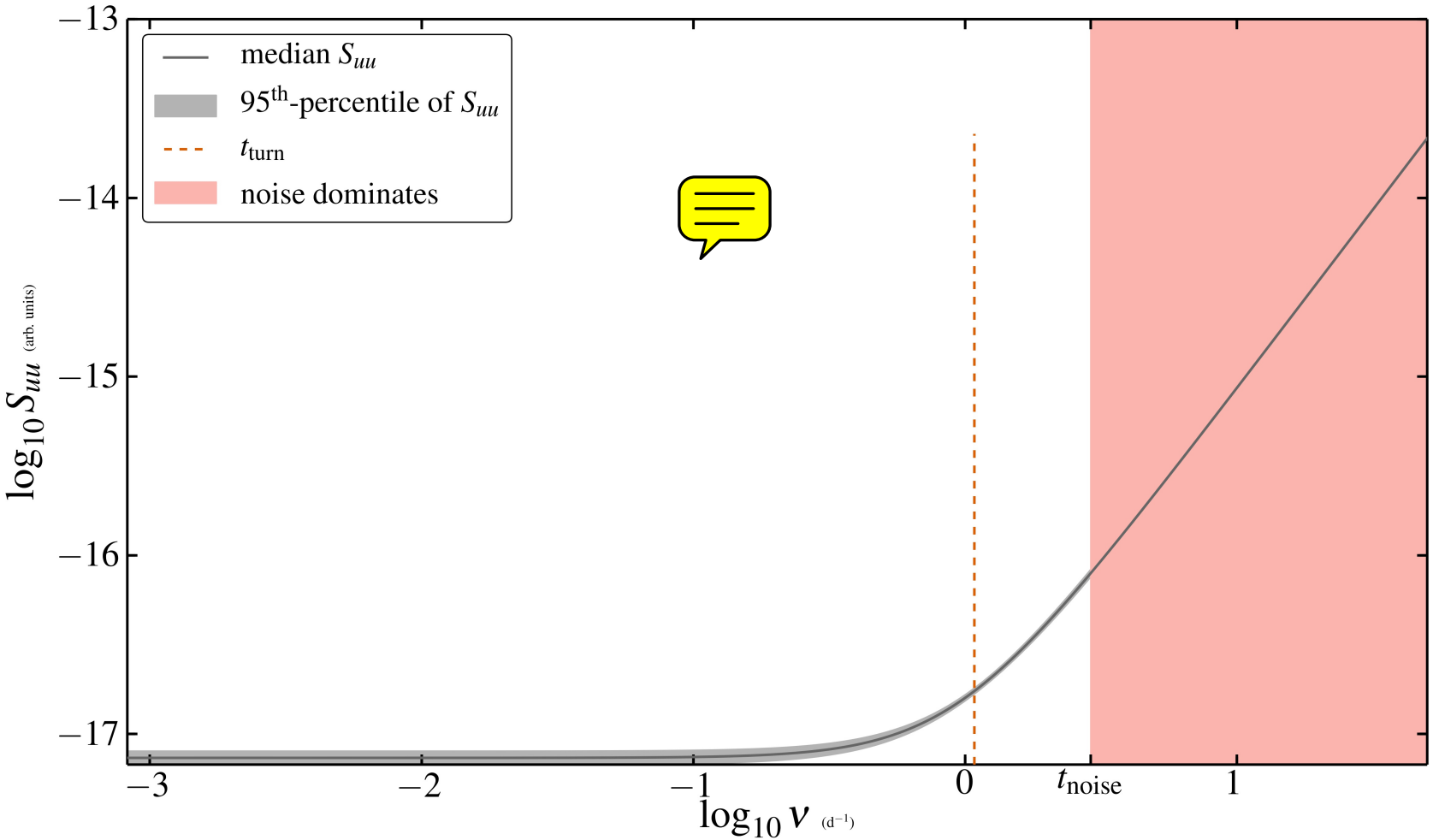
$$\mathrm{d}^2G + 2\omega\zeta \mathrm{d}G + \omega^2 G = \delta(0)$$



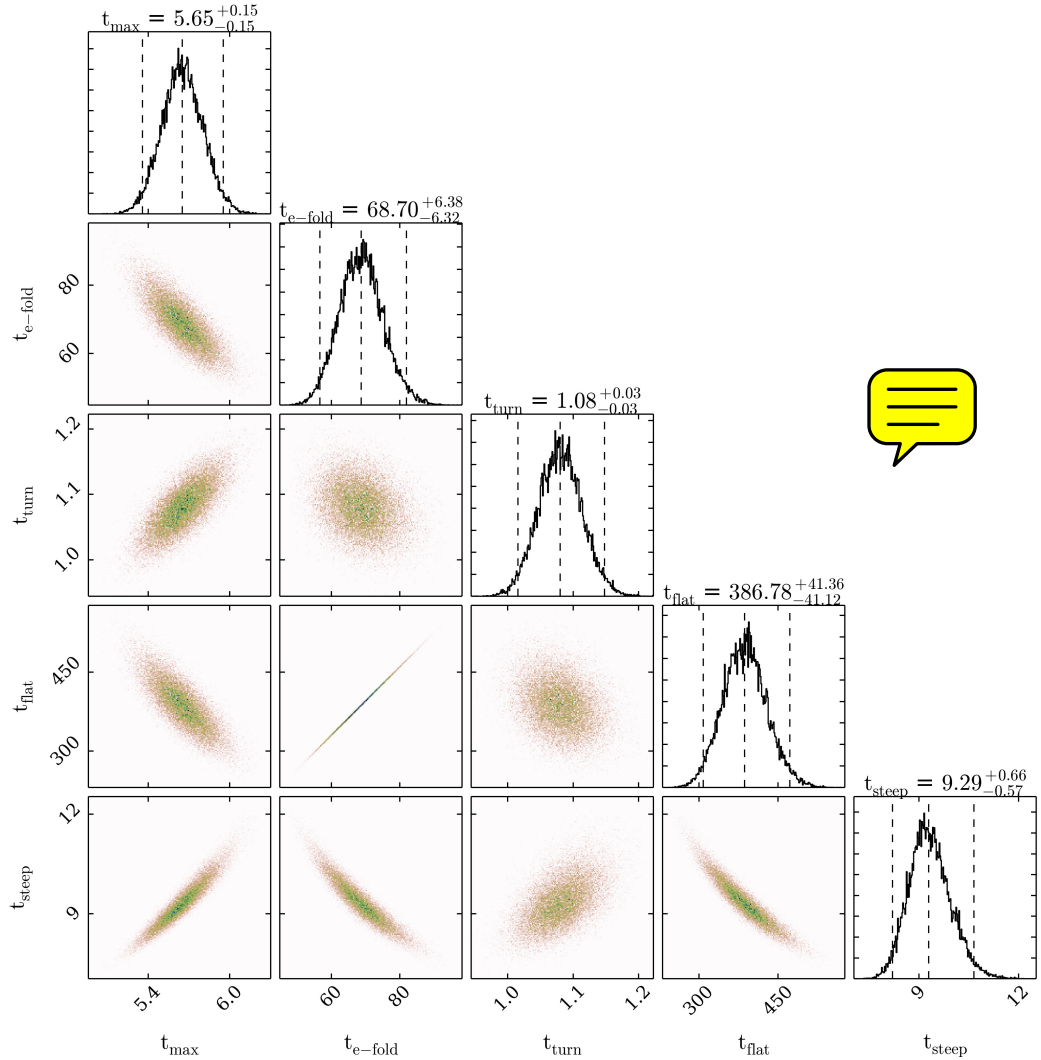
C-ARMA(2,1) model of Zw 229-15
Green's Function



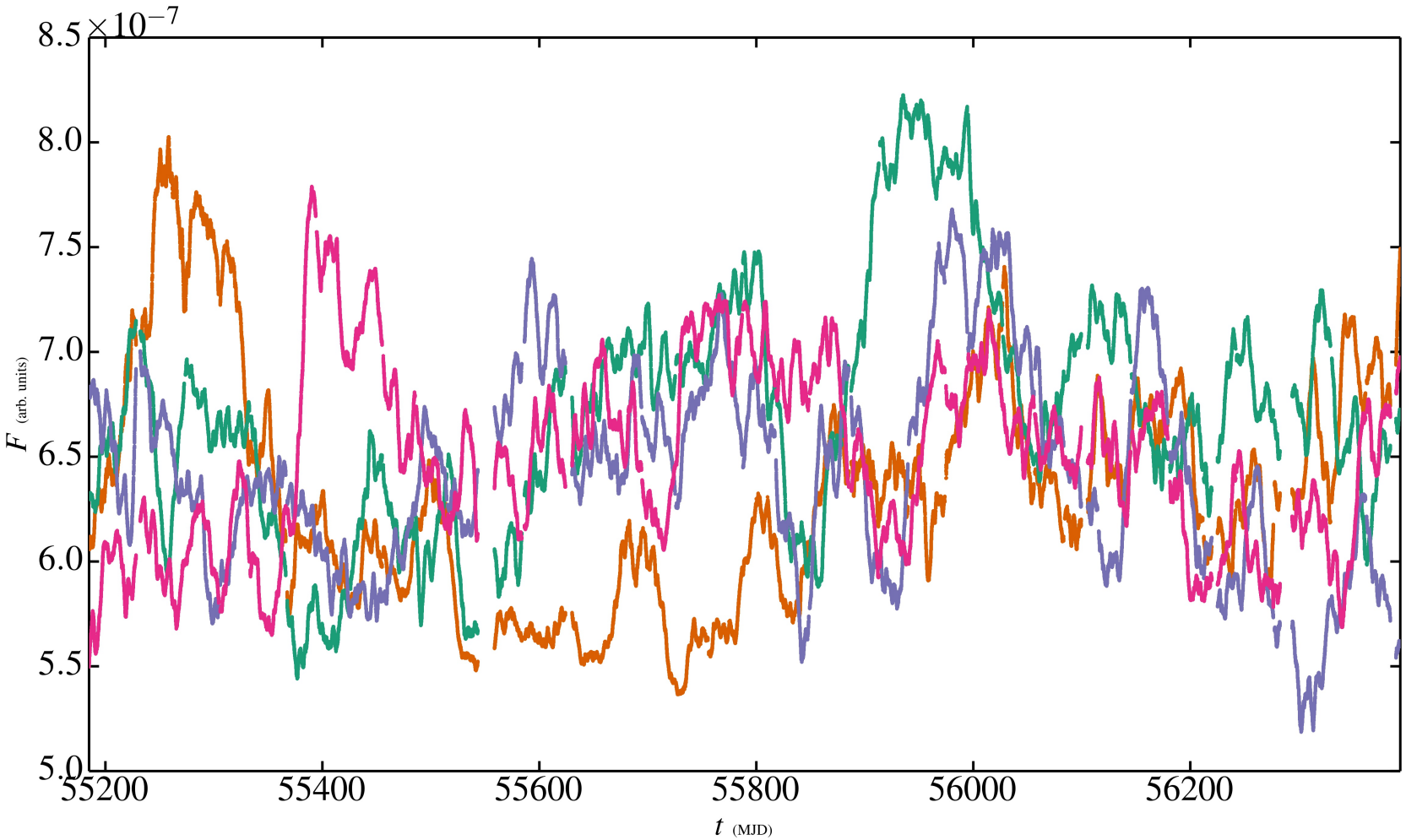
C-ARMA(2,1) model of Zw 229-15
Disturbance PSD



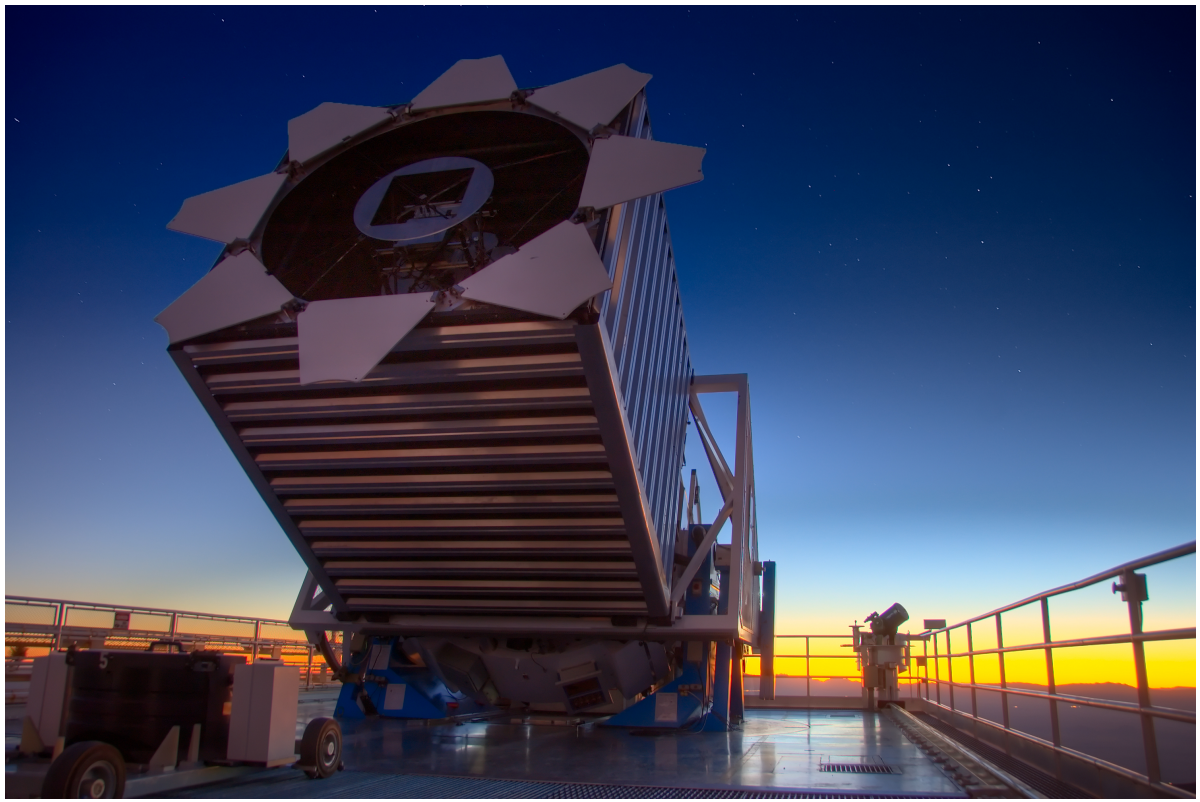
C-ARMA(2,1) model of Zw 229-15
Timescales



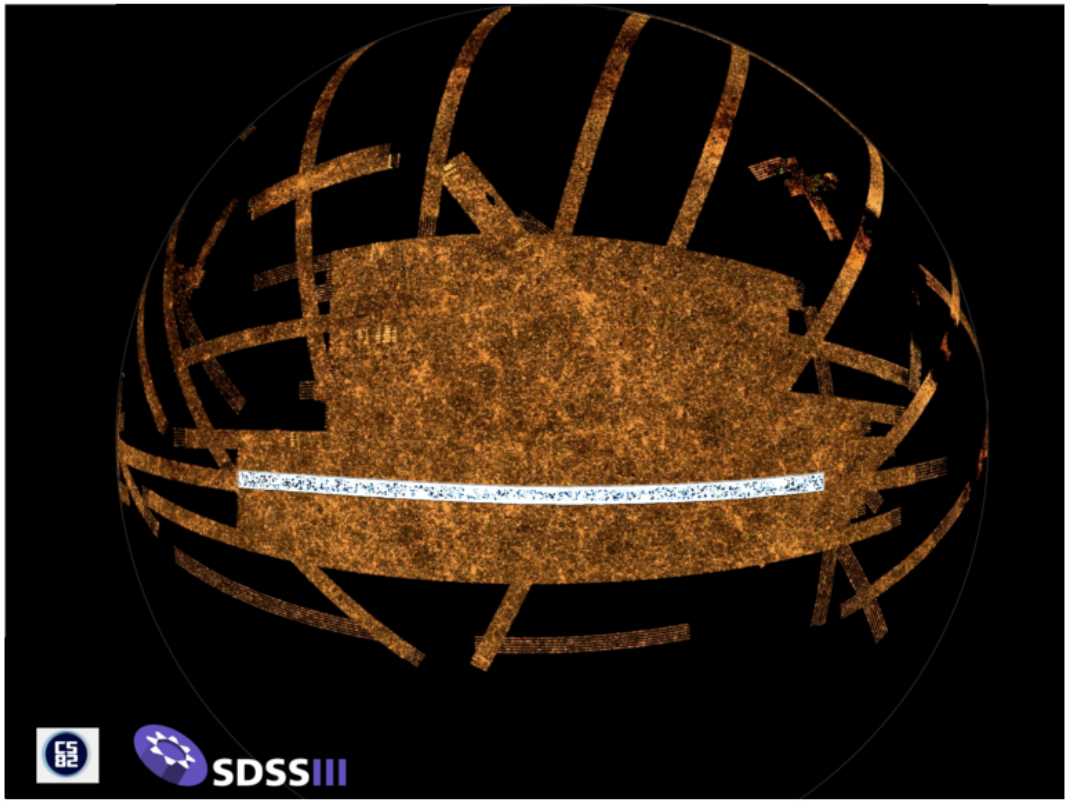
C-ARMA(2,1) model of Zw 229-15
Which is the real light curve?



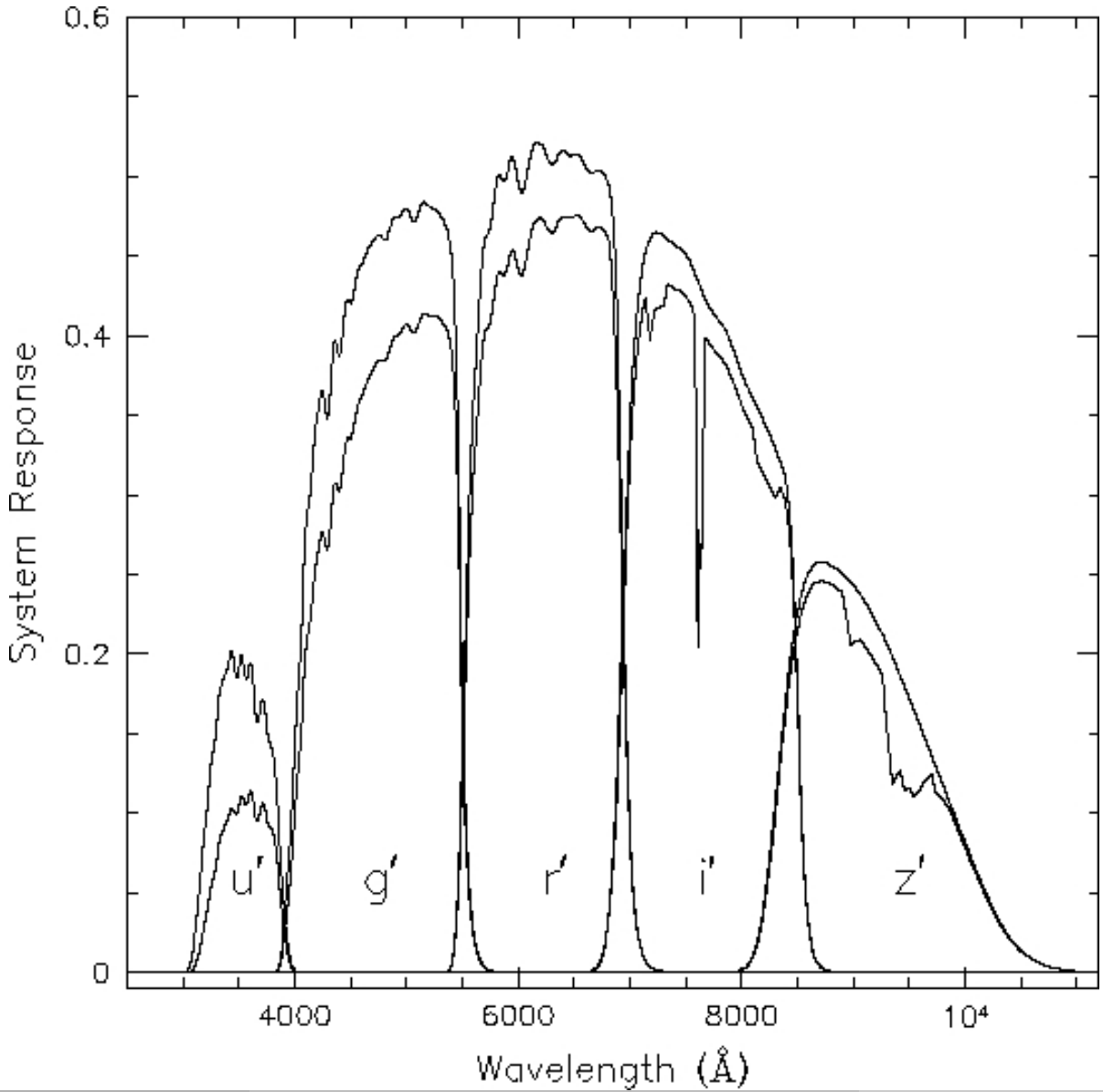
The Sloan Digital Sky Survey (SDSS)



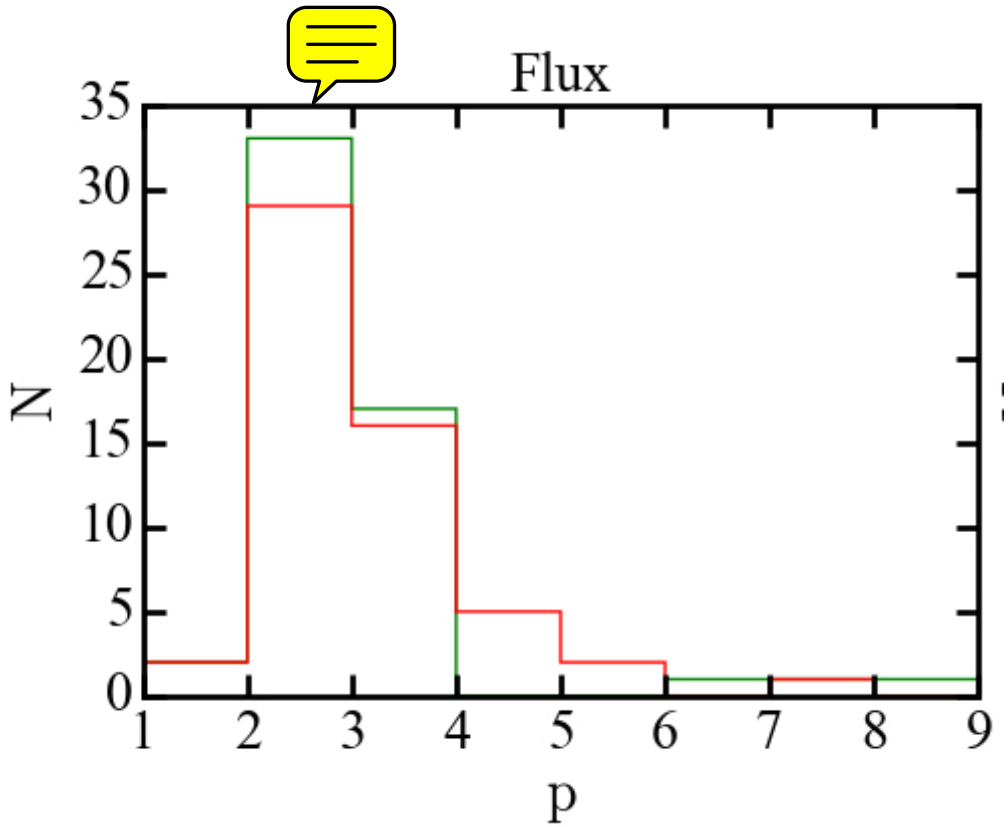
Massive dataset from Stripe82



SDSS Photometric System

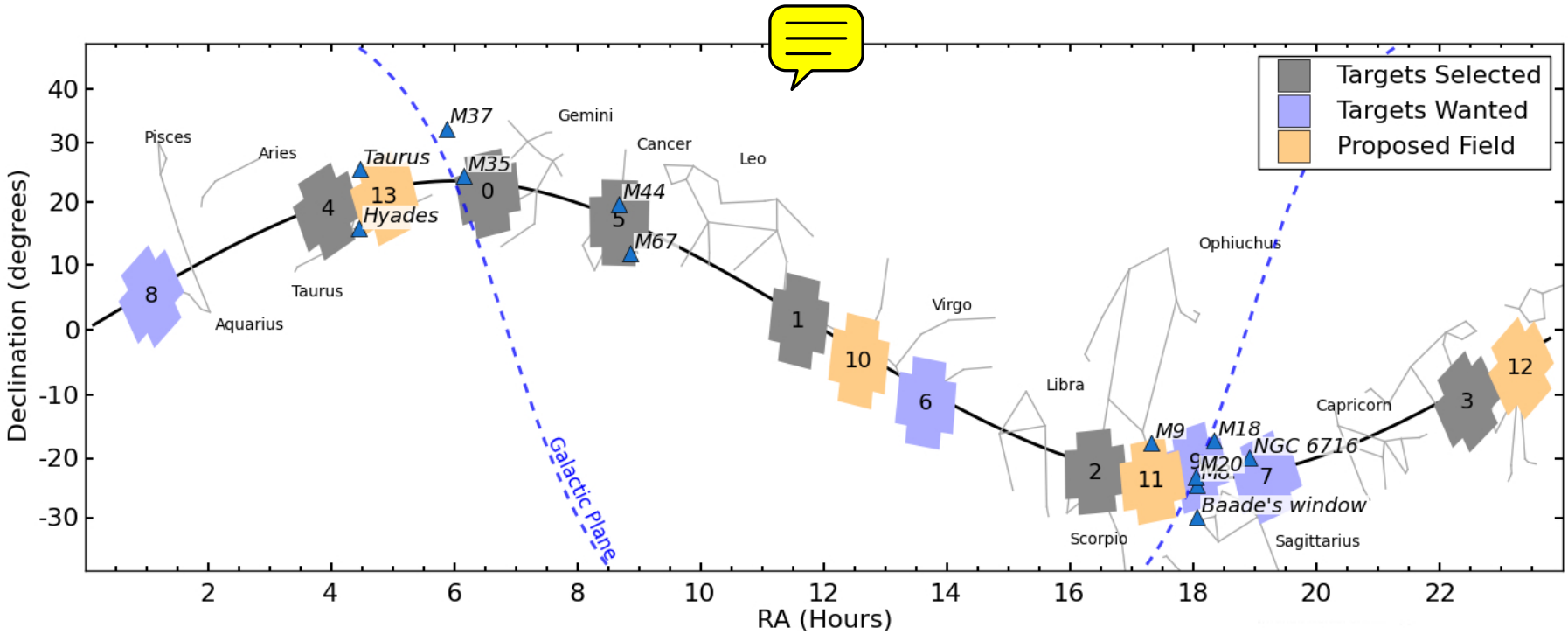


Stripe 82 QSO C-ARMA fits

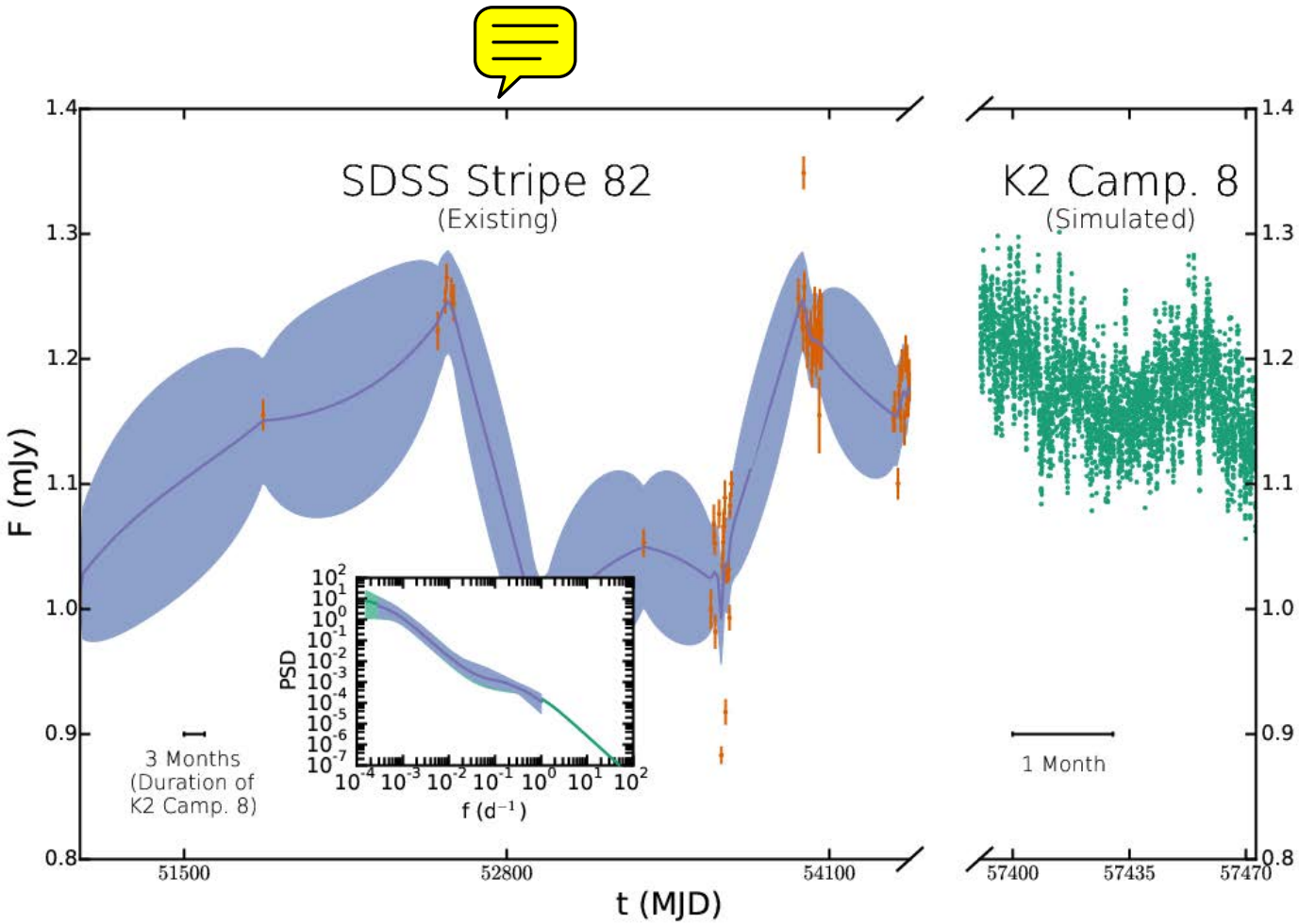


Jack O'Brien

Work in Progress
K2 campaigns

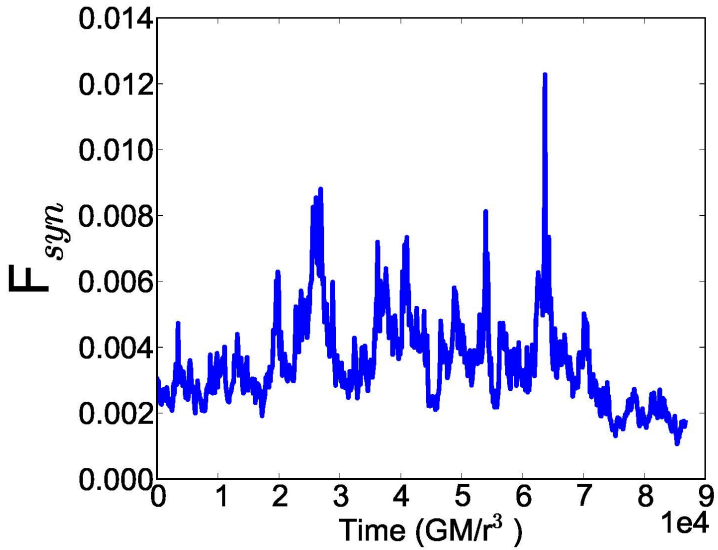


Work in Progress
K2 observations of Stripe 82 QSOs



Work in Progress

- SDSS Stripe 82 + K2 QSO variability
- Connection between AGN sub-type and variability
- Stationarity of AGN light curves
- More sophisticated time series models
- Comparing simulations with observations
- Cadence and periodicity requirements of LSST
- Multi-wavelength variability



J. Drew Hogg

Conclusions

- Kepler AGN exhibit a **wide variety** of behavior (flares & possibly QPOs)
- DRW does **not work** for all AGN
- Instrumentation **not responsible** for non-DRW behavior
- AGN variability can be modelled as a C-ARMA process
- Kalman filter can be used to infer C-ARMA parameters
- C-ARMA(2,1) process is an **appropriate model** of accretion disk variability
- AGN act like a **Damped Harmonic Oscillator Driven by Colored Noise**

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- Collaborator: Dr. Michael T. Carini

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- Jack O'Brien
- Dr. Michel Vallières
- Dr Stephen McMillan
- Dr. Dave Goldberg
- (Dr.) Frank Jones

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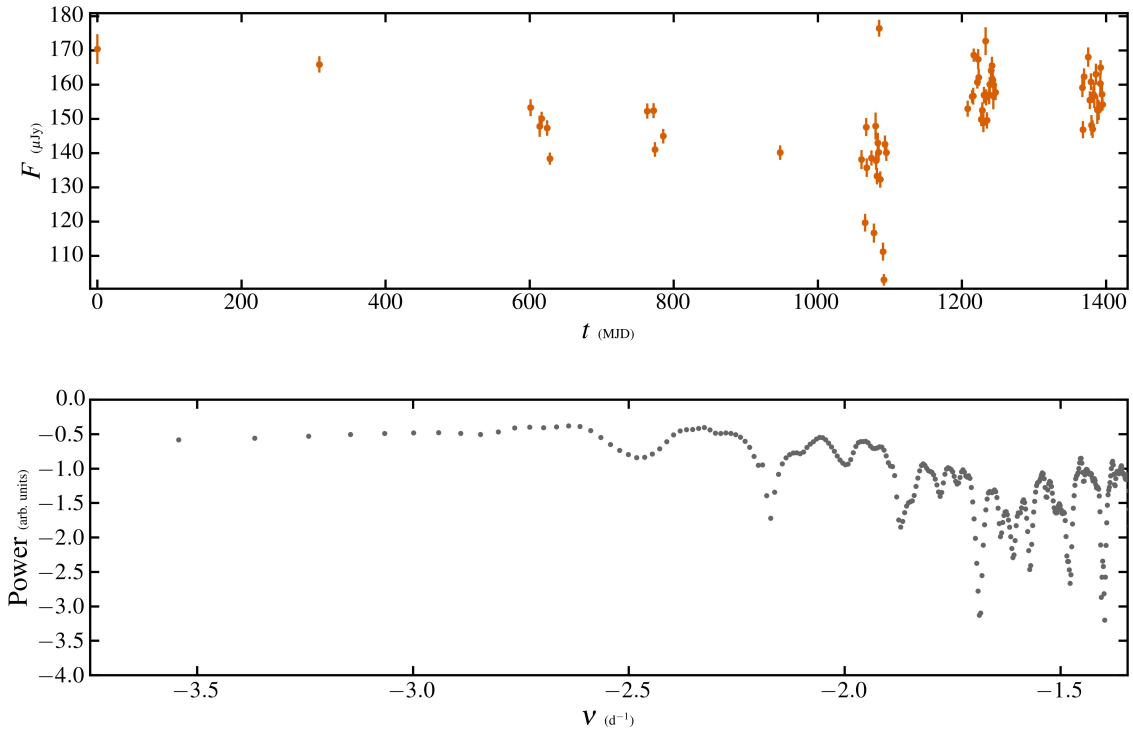
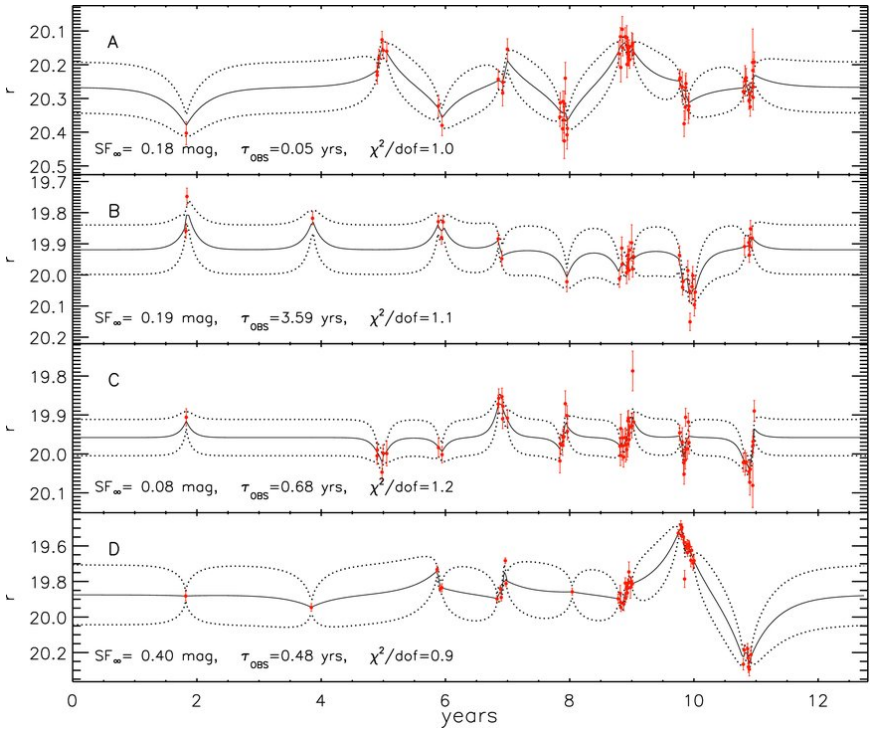
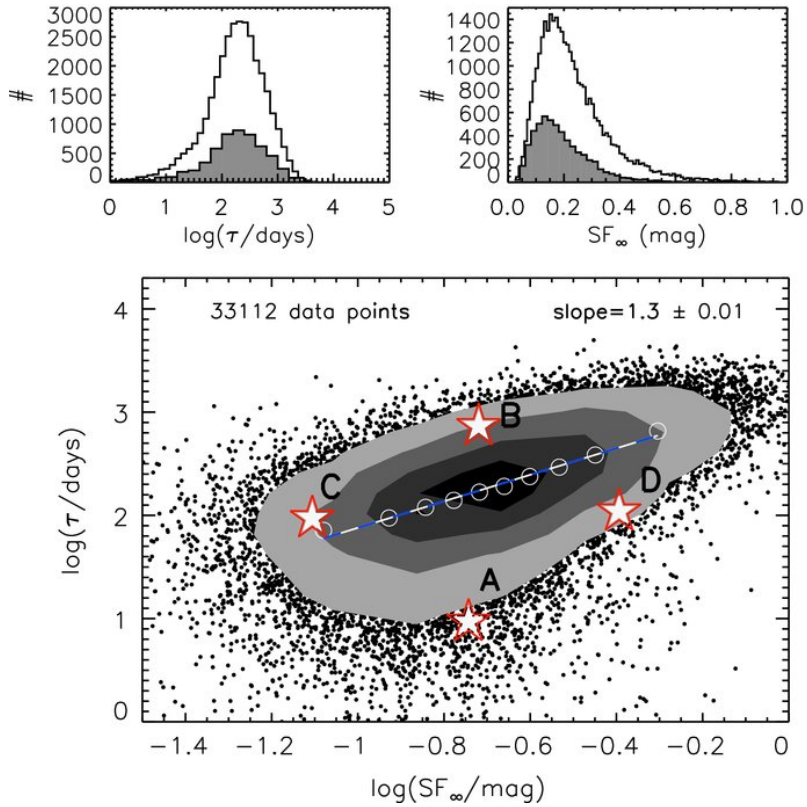
SDSS light curves



- Large dataset (~ 10000 AGN)
- Well-characterized photometry
- Long temporal baseline (~ 10 yr)
- Sparse sampling

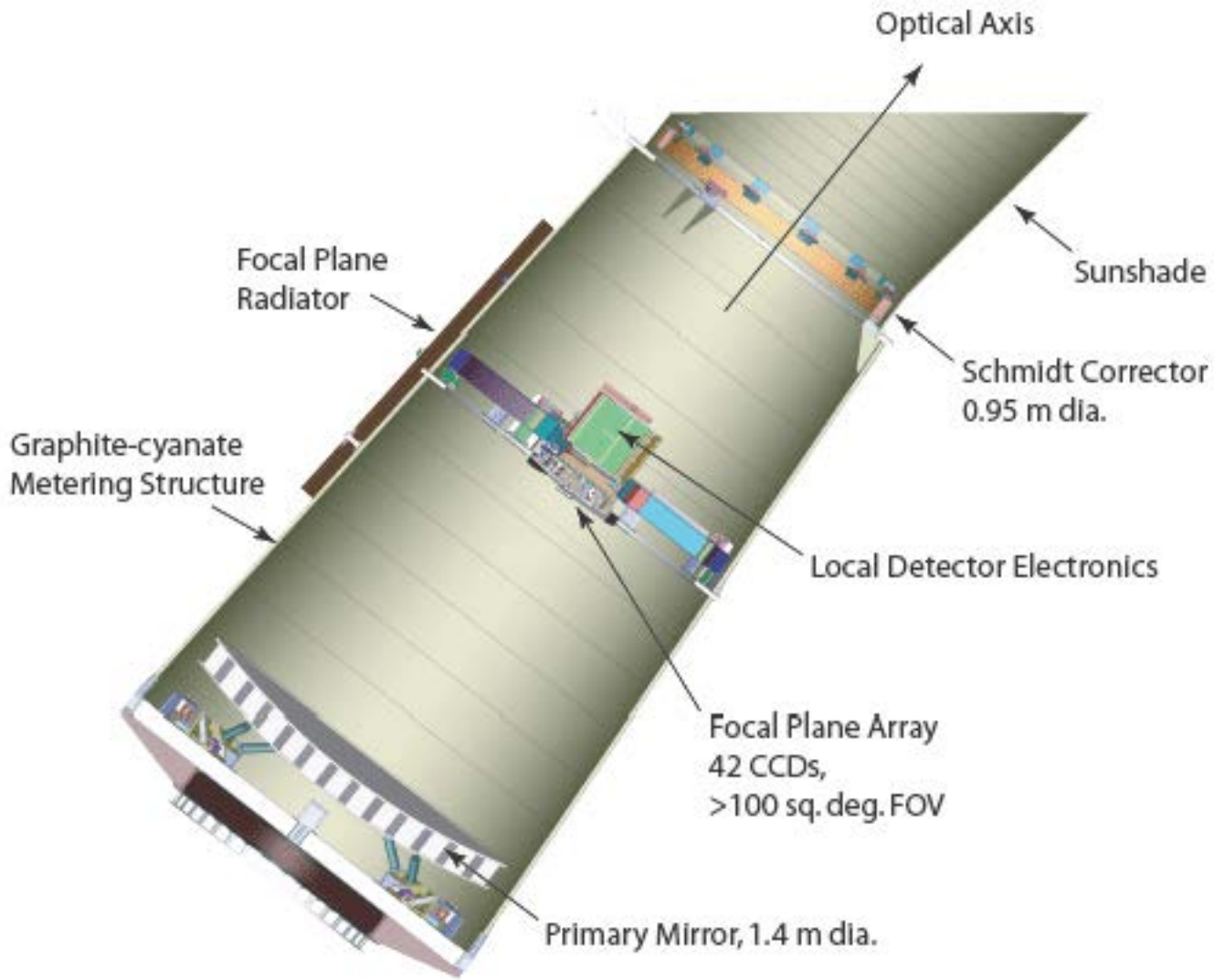
MacLeod et al. (2010): Apply DRW to SDSS QSOs



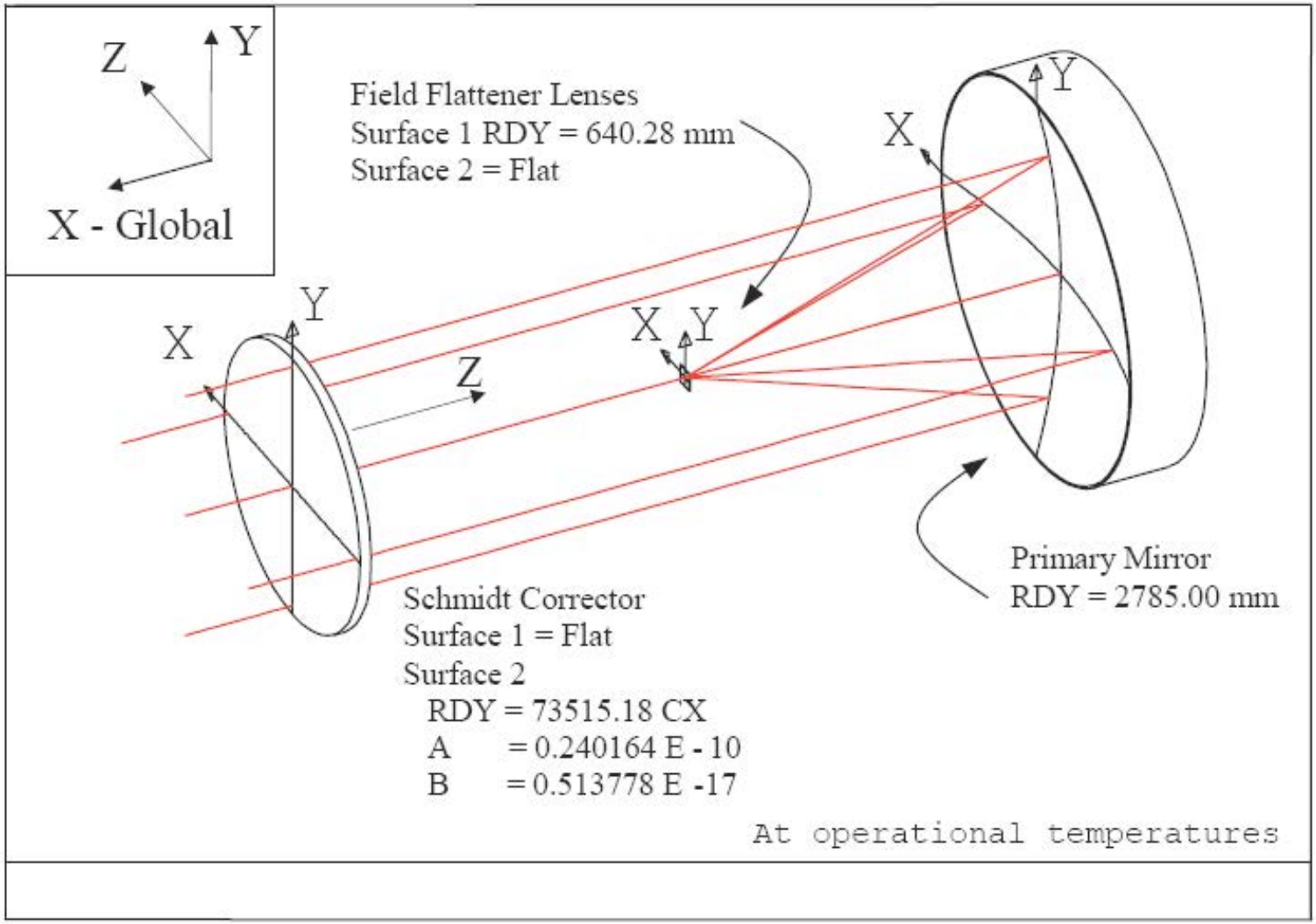


- Thermal processes responsible for variability
- No 'evolution' over cosmic time.
- $\tau \sim M_{BH}$ but not L_{AGN}

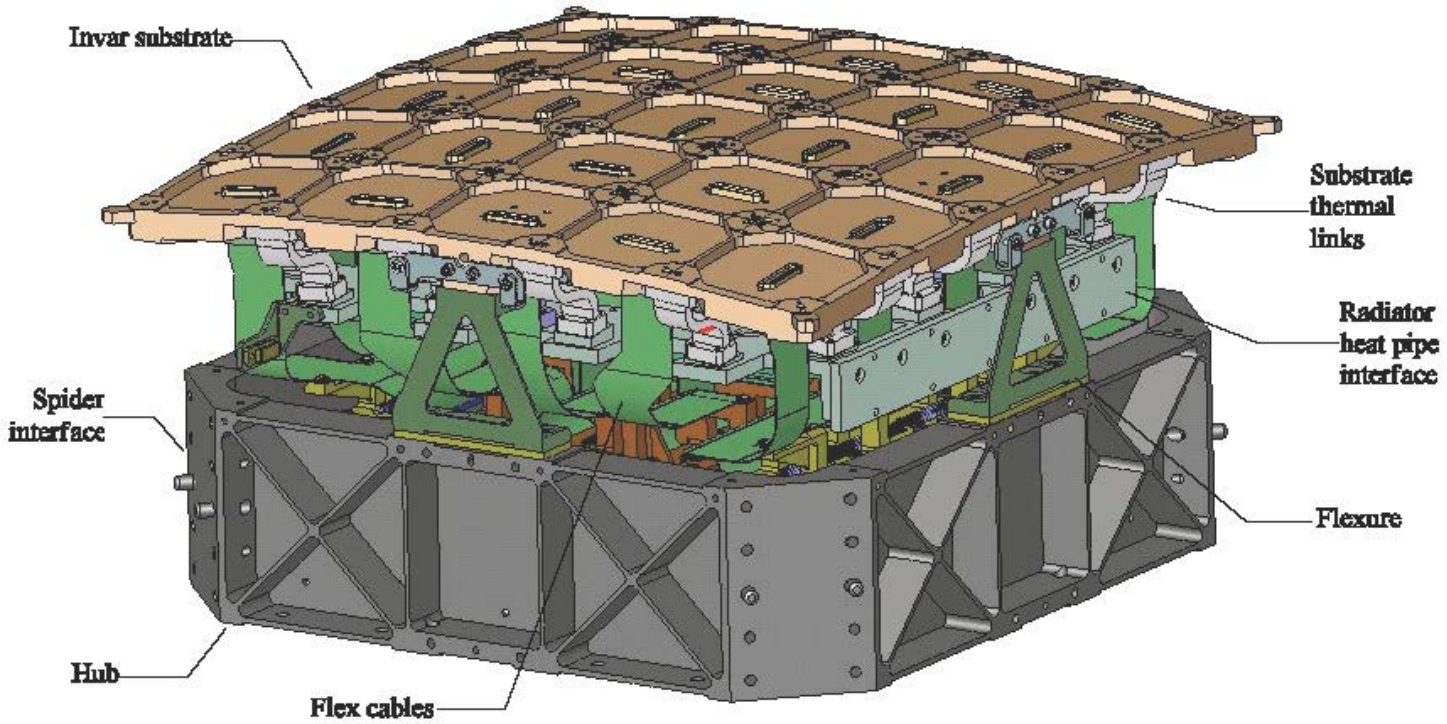
Photometer Design



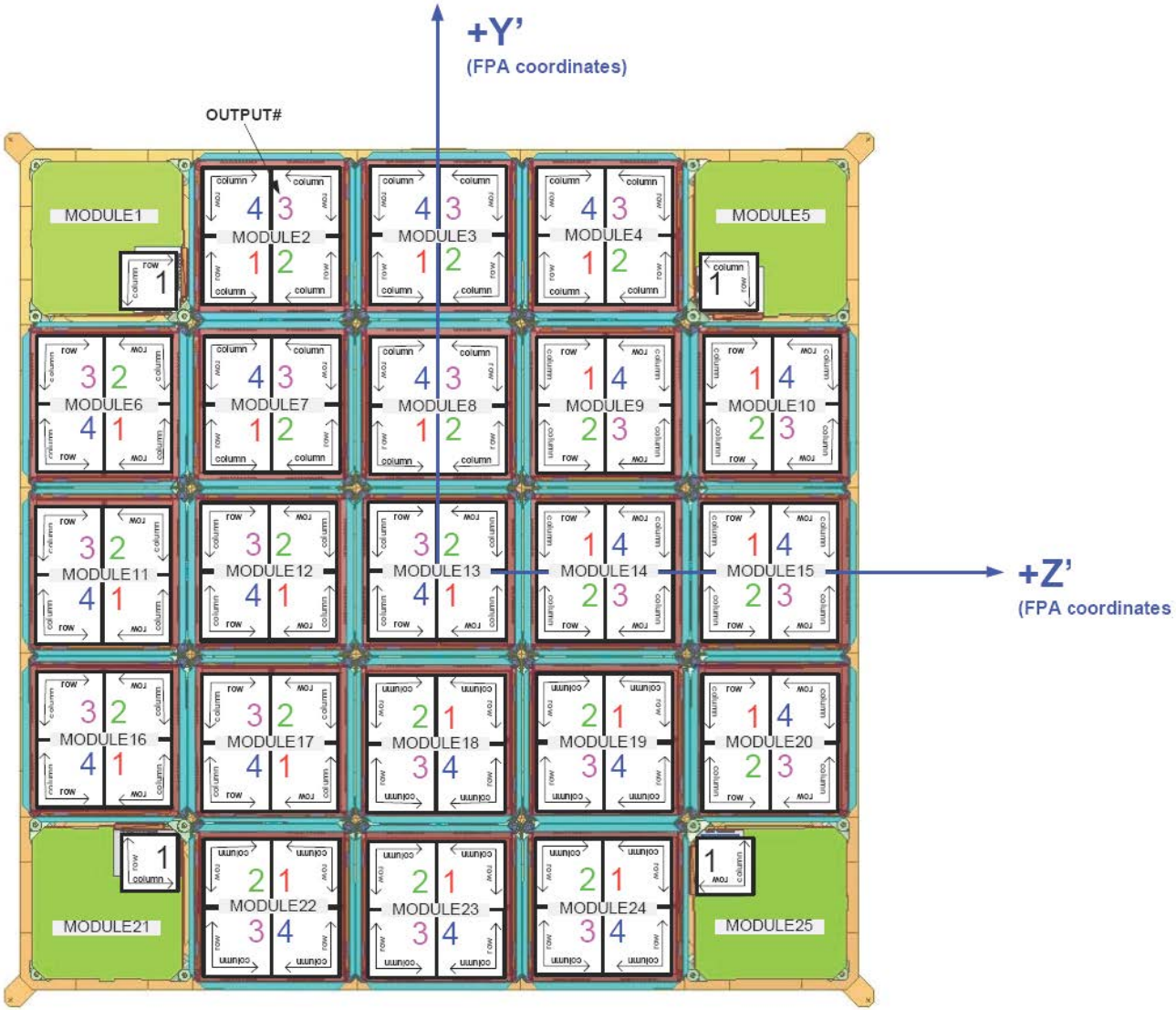
Optical Layout



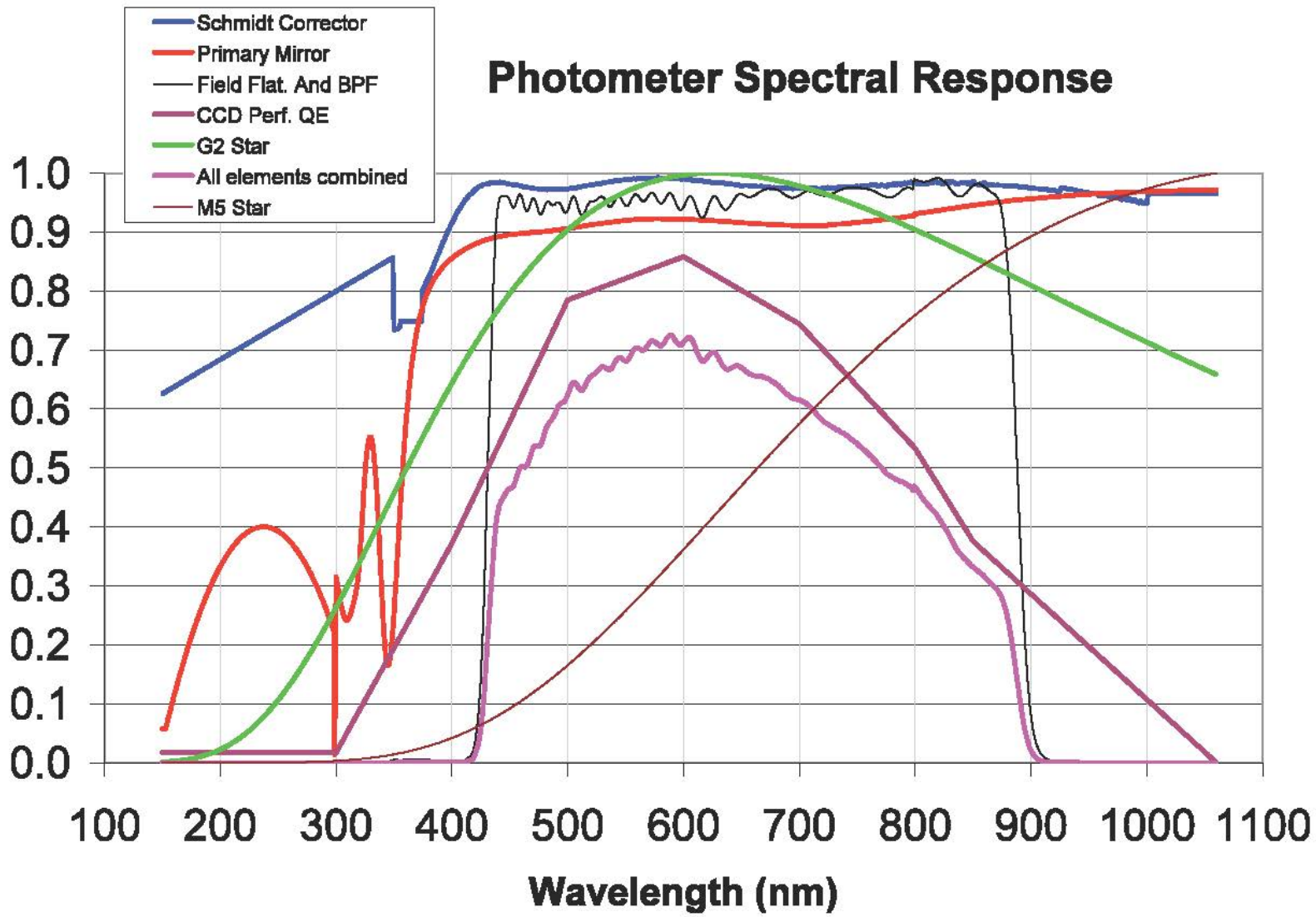
Kepler Focal Plane



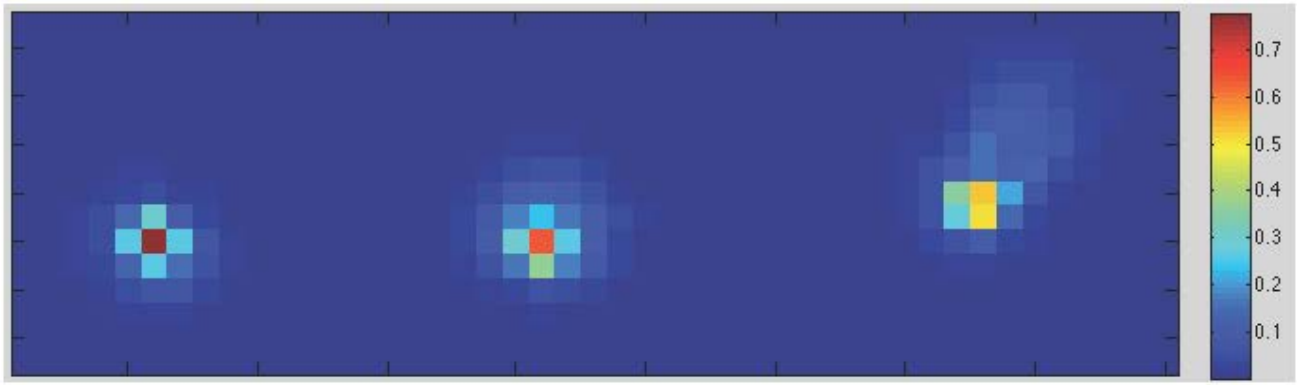
Kepler Focal Plane Layout

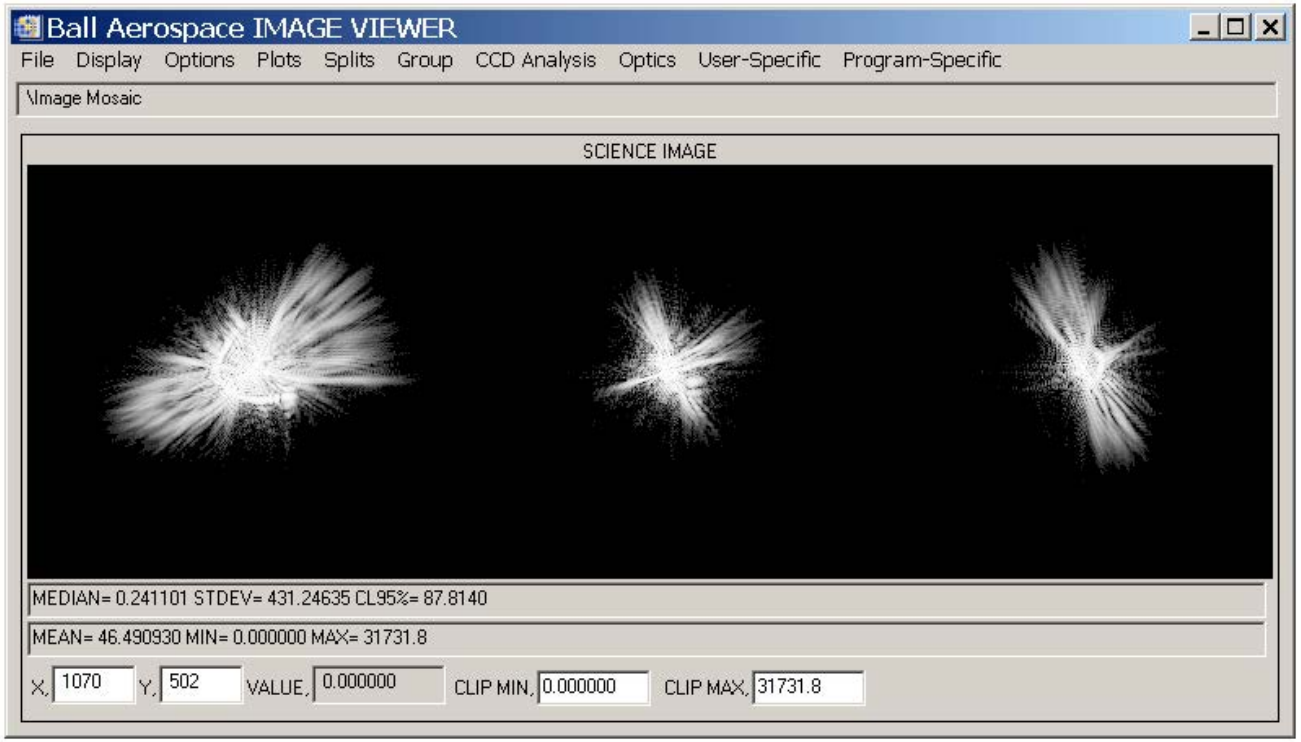


Kepler Bandpass

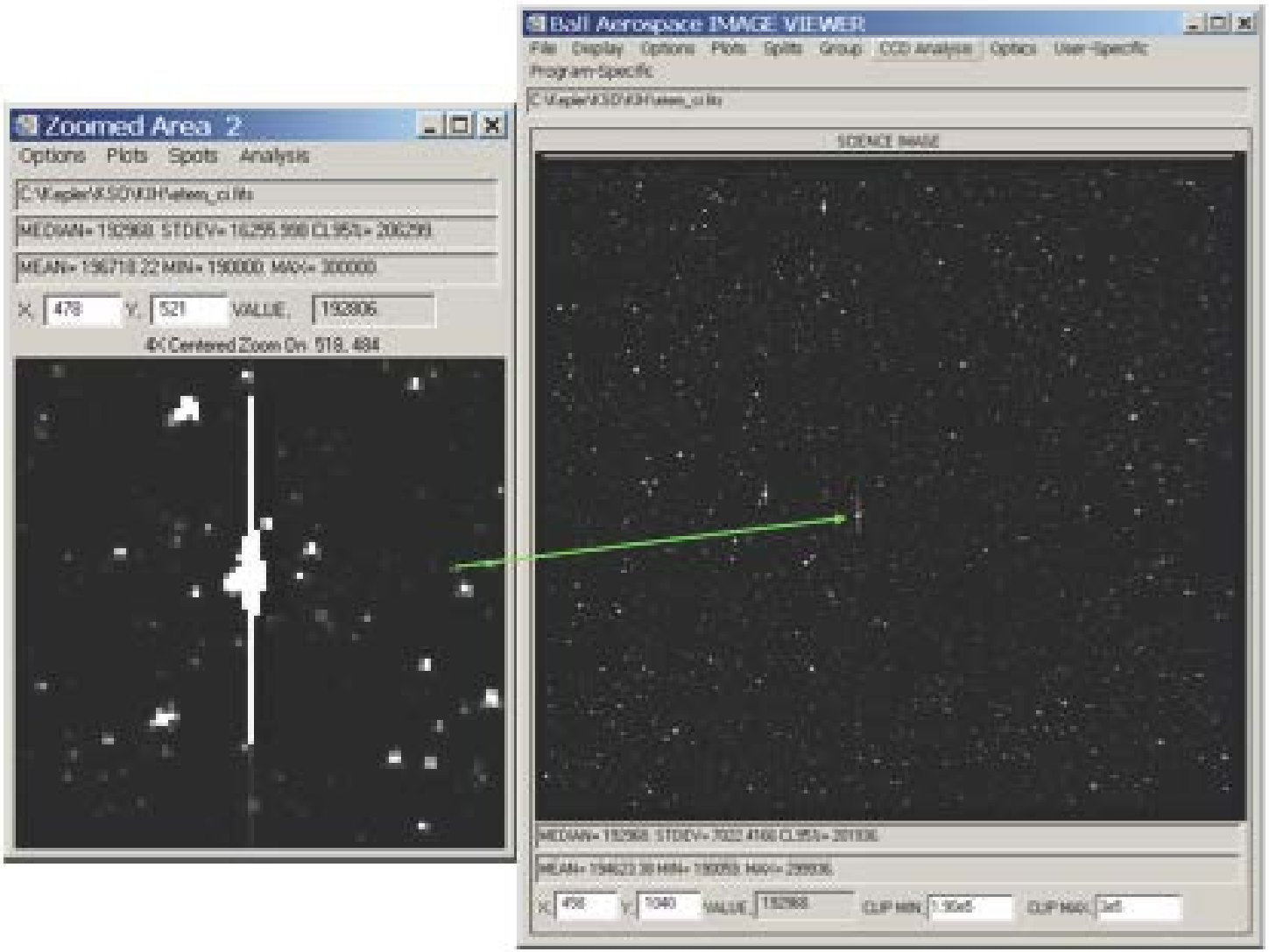


Kepler PRF & Chromatic aberration

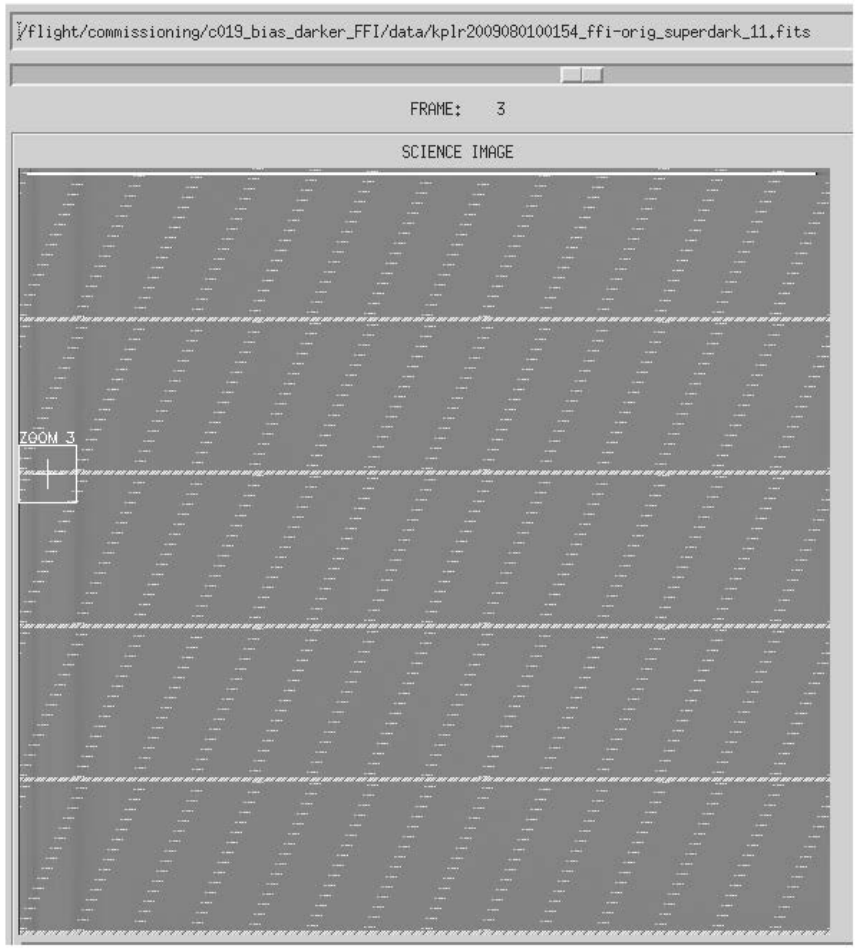




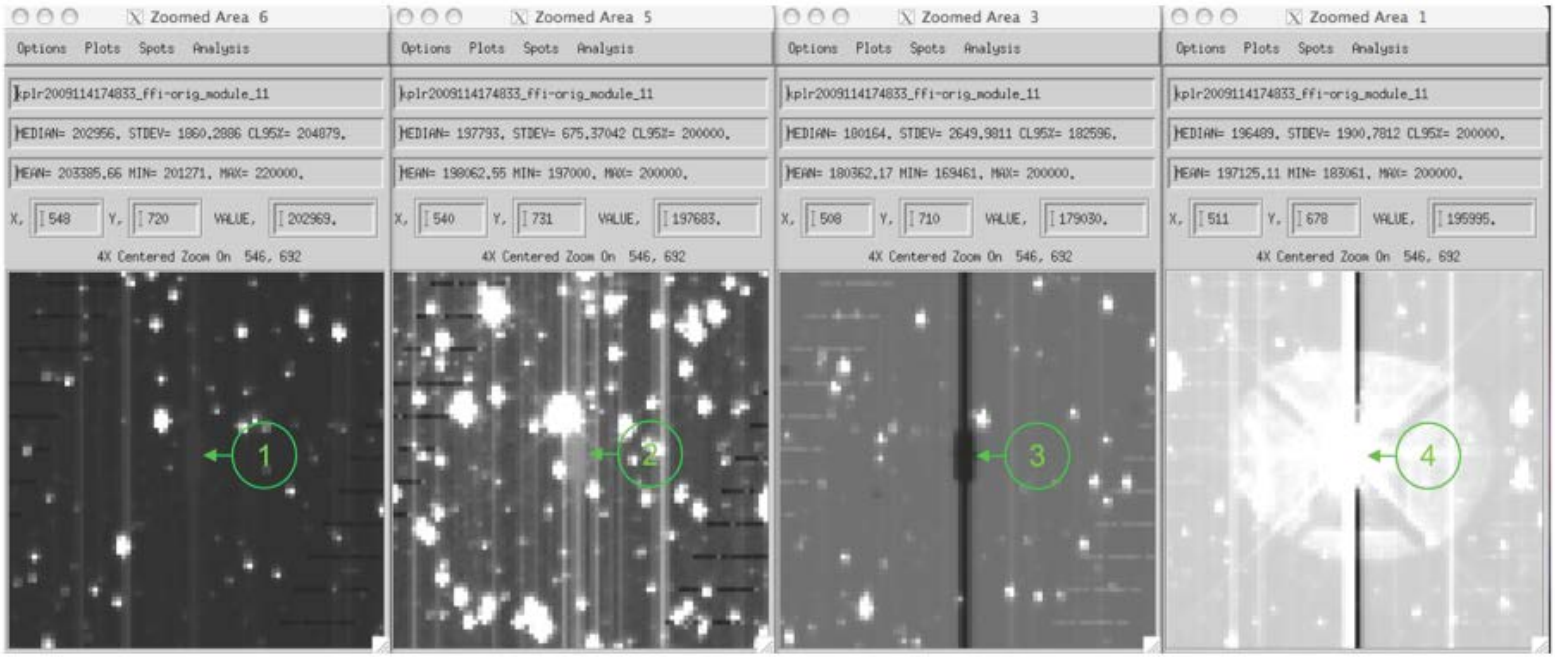
Kepler Image Quality



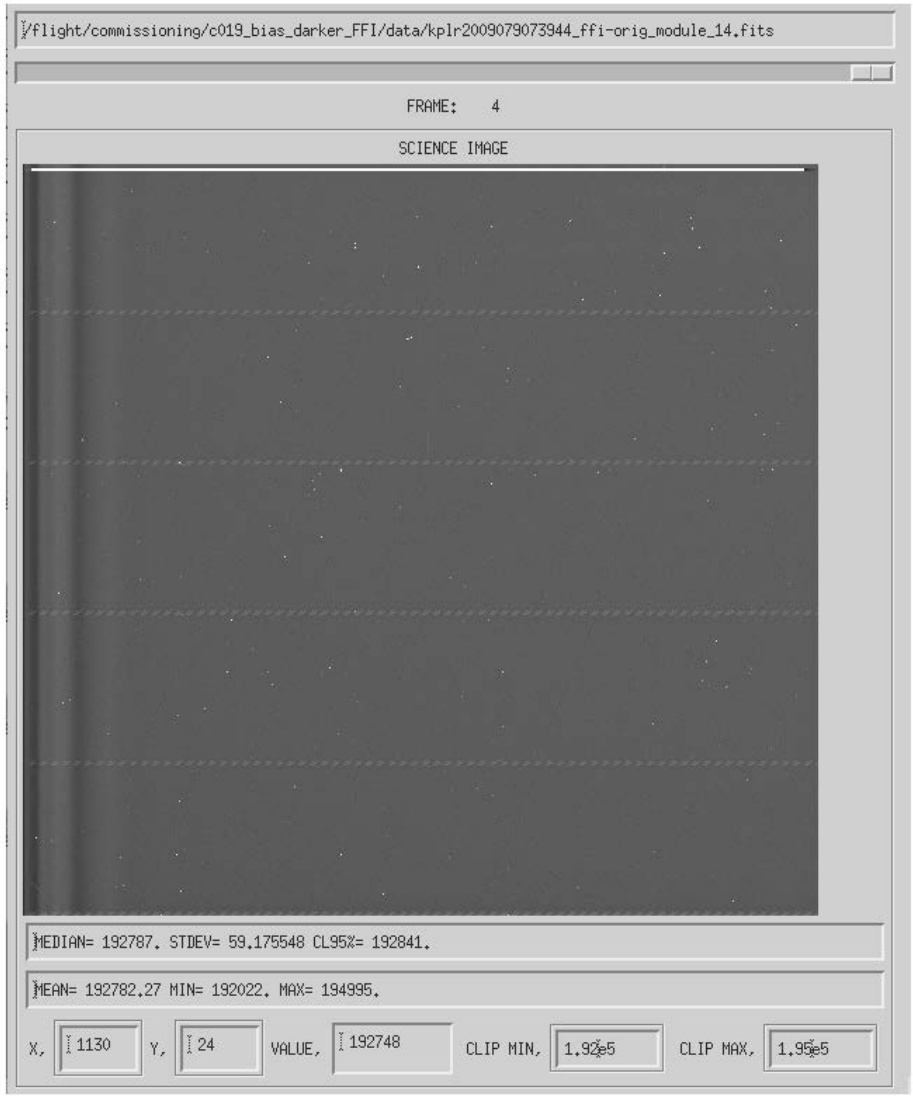
Artifact: FGS Crosstalk (Dark)



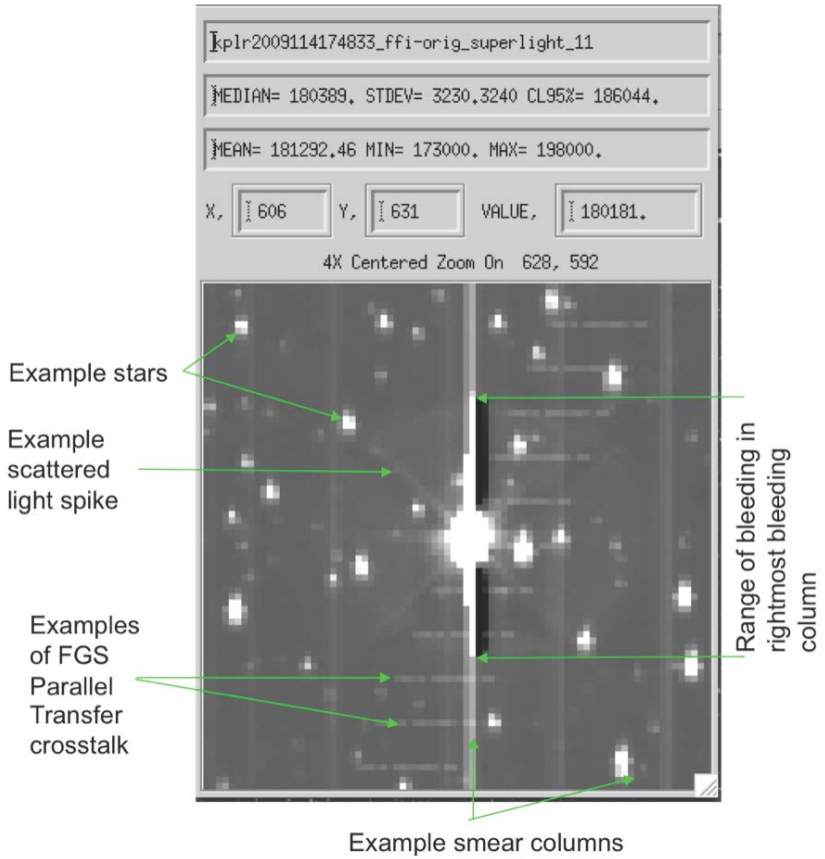
Artifact: Video Crosstalk



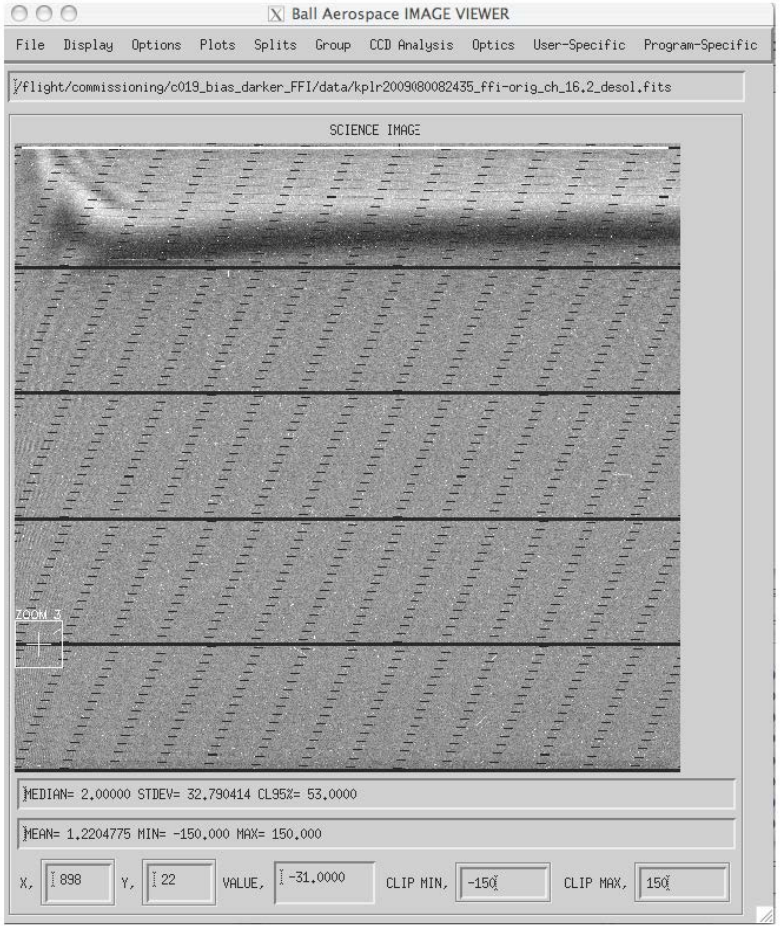
Artifact: Start-of-Line Ringing (SOLR)



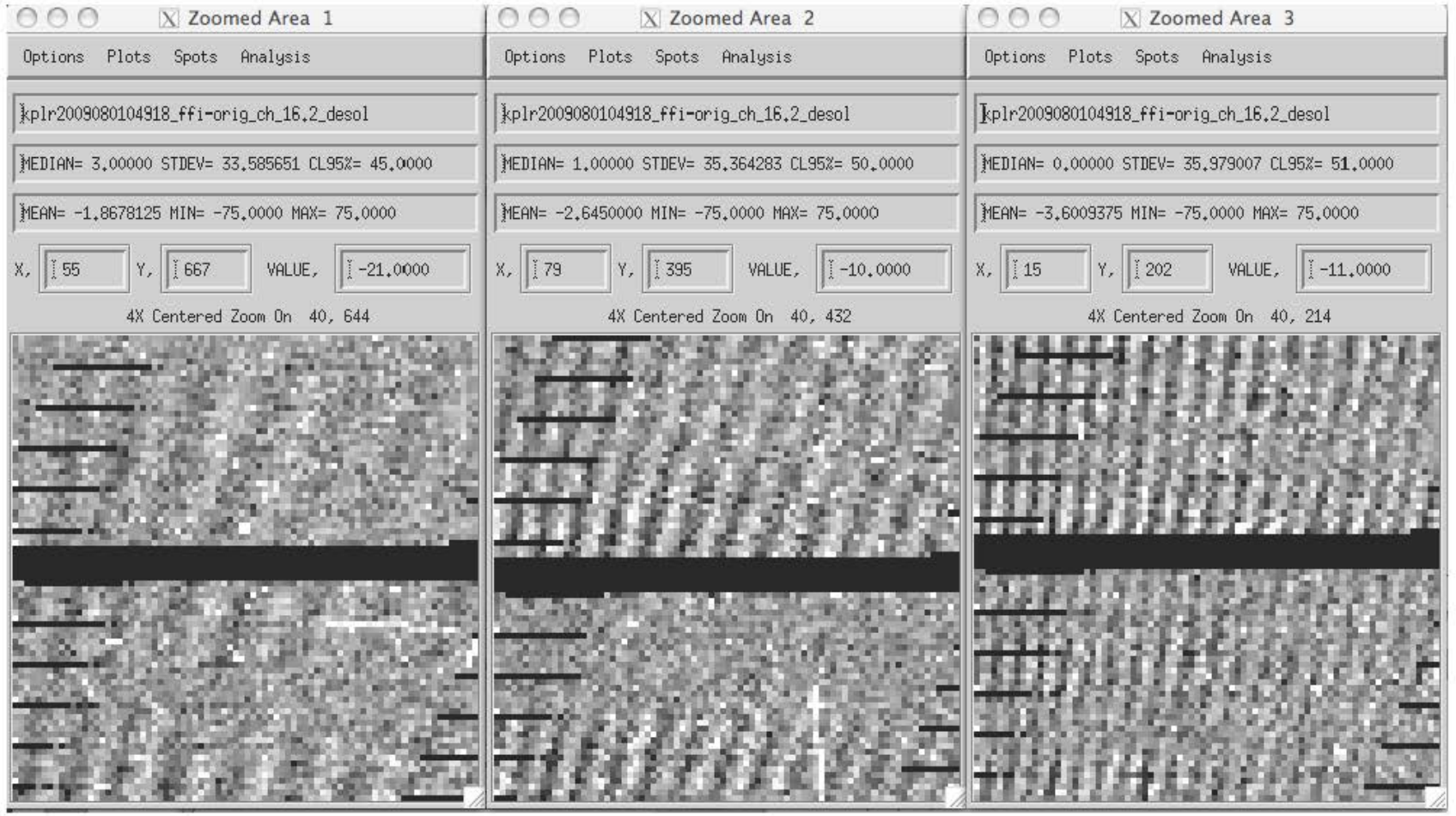
Artifact: Undershoot



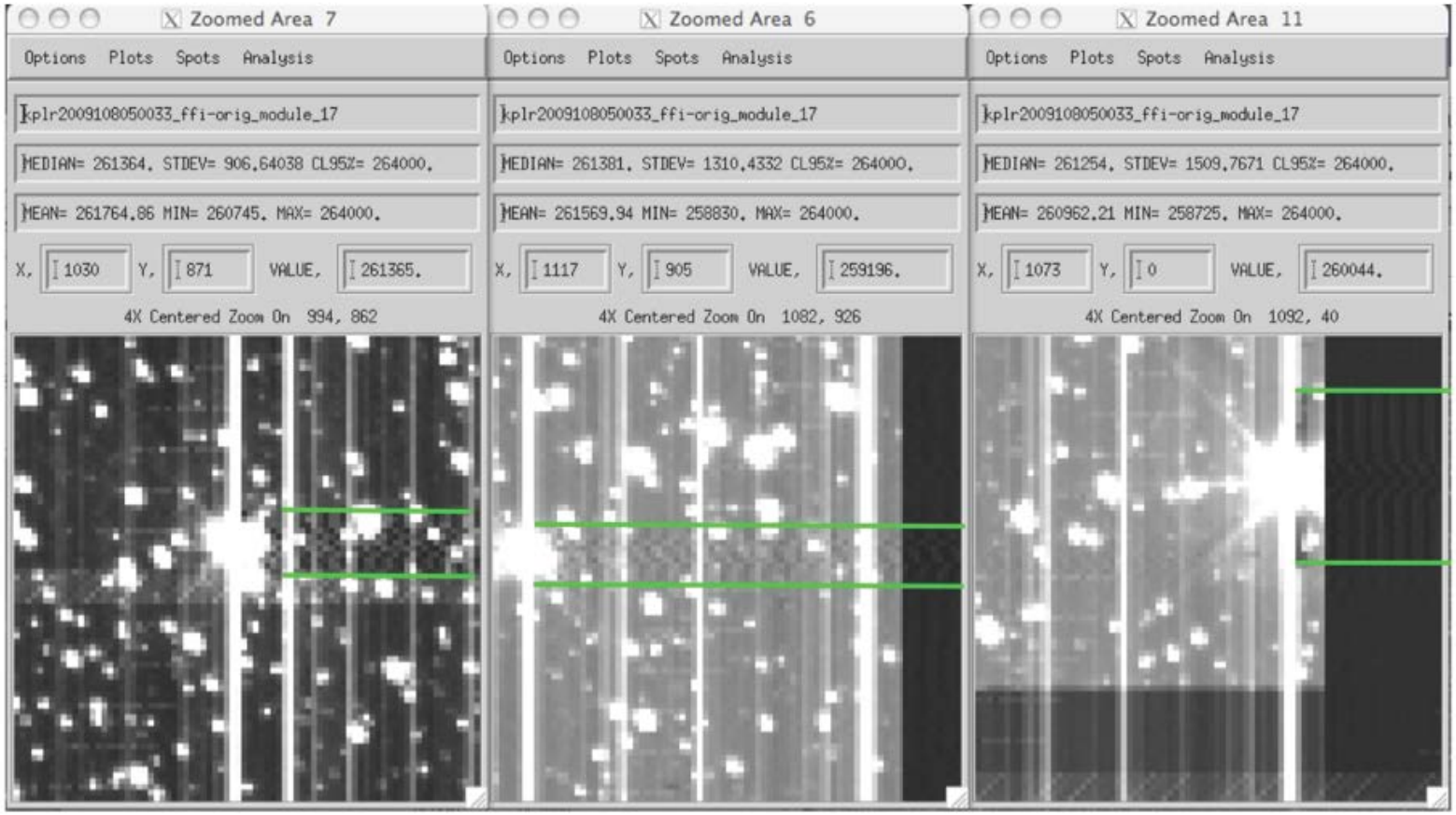
Artifact: Rolling Bands



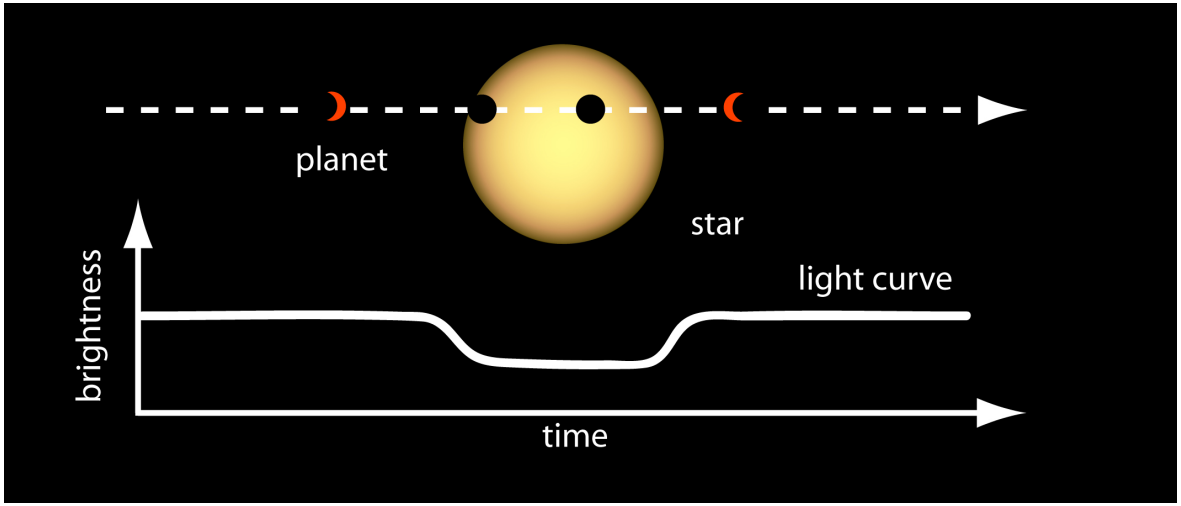
Artifact: Moire Pattern Drift (MPD)



Artifact: Bright Star Induced MPD



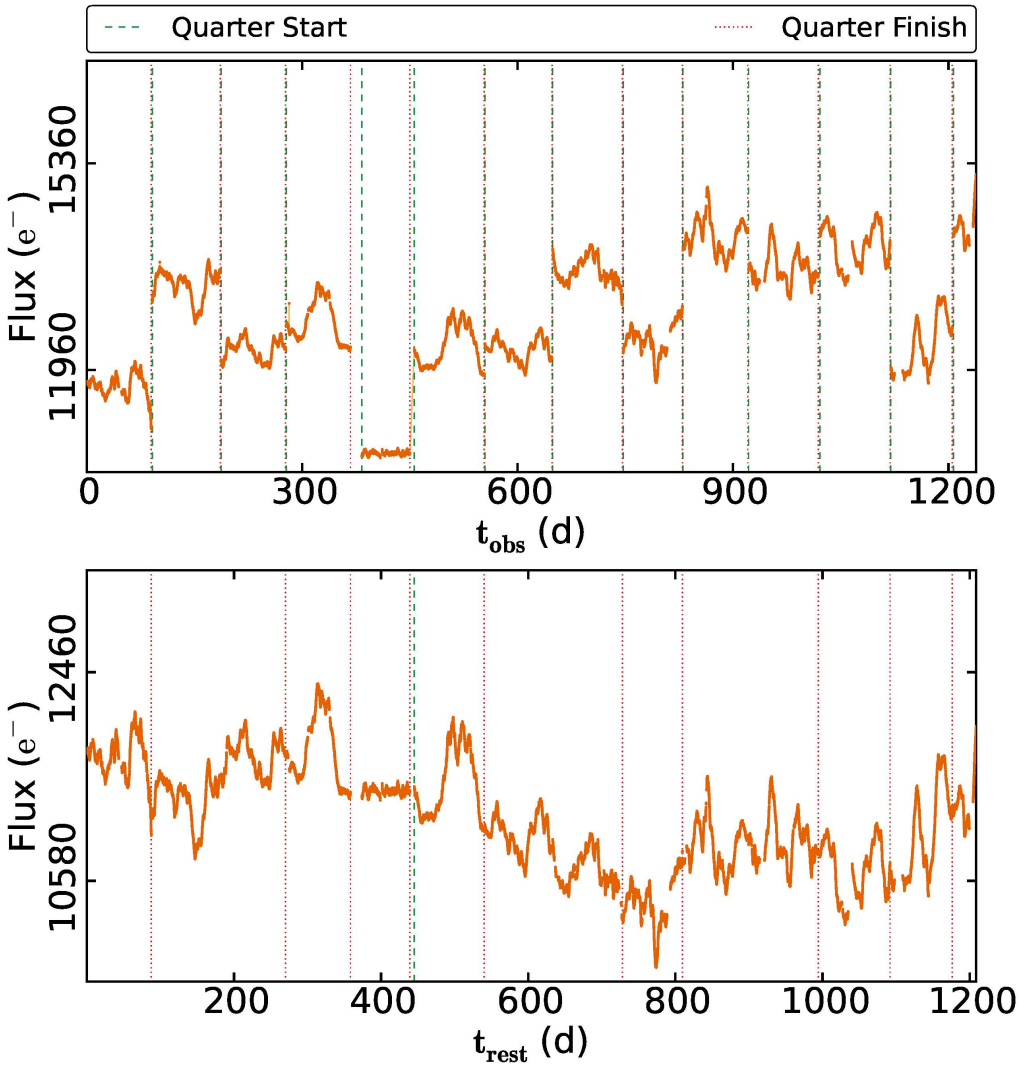
Kepler Mission



- Required precision ~ 20 ppm
- Desired lifetime ~ 4 yr
- Achieved precision ~ 35 ppm
- Actual lifetime ~ 3.5 yr

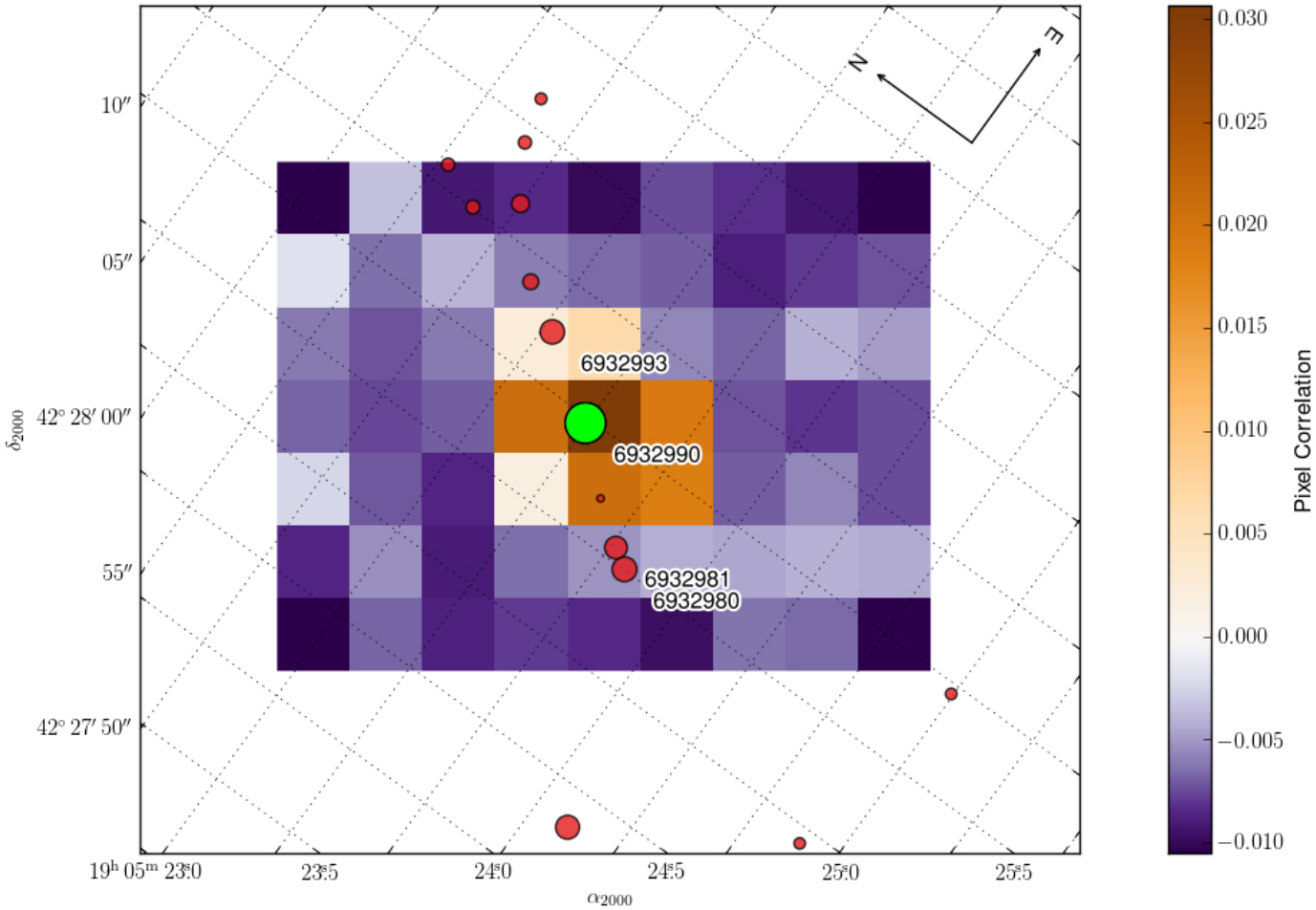
Gilliland et al. (2011); Thompson et al. (2015)

Offsets



- Inter-quarter
- Photometric aperture re-definition
- Stitching: End-match mean (100 obs)

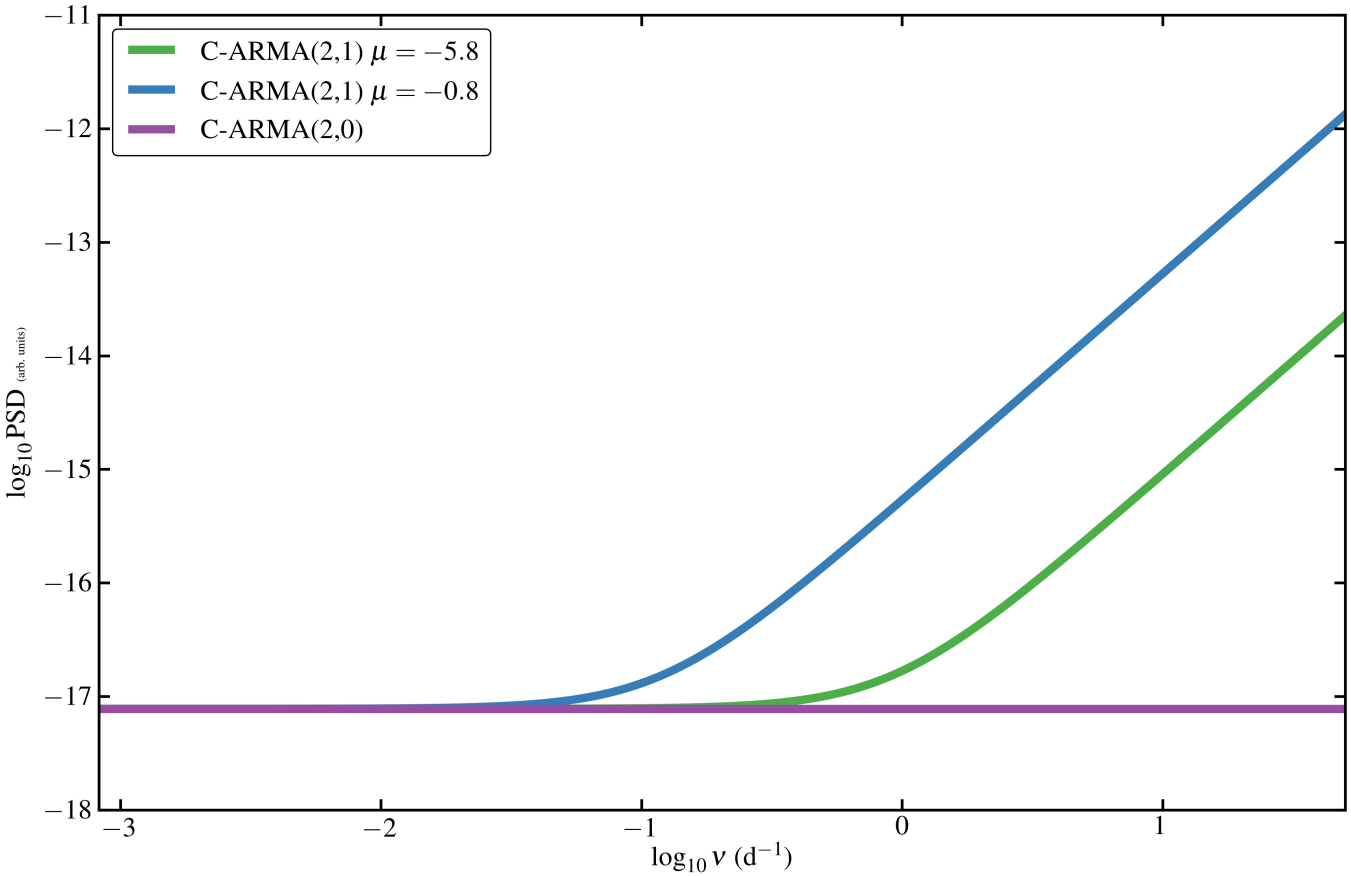
Crowding



Jackeline Moreno

Disturbance PSD
C-ARMA(2,1) case

$$u = \beta_1 \mathrm{d}(\mathrm{d}W) + \beta_2(\mathrm{d}W)$$



State Space Representation

State equation:

$$\boldsymbol{x}_{k+1} = \mathbf{F}\boldsymbol{x}_k + \boldsymbol{w}_k$$

Observation equation:

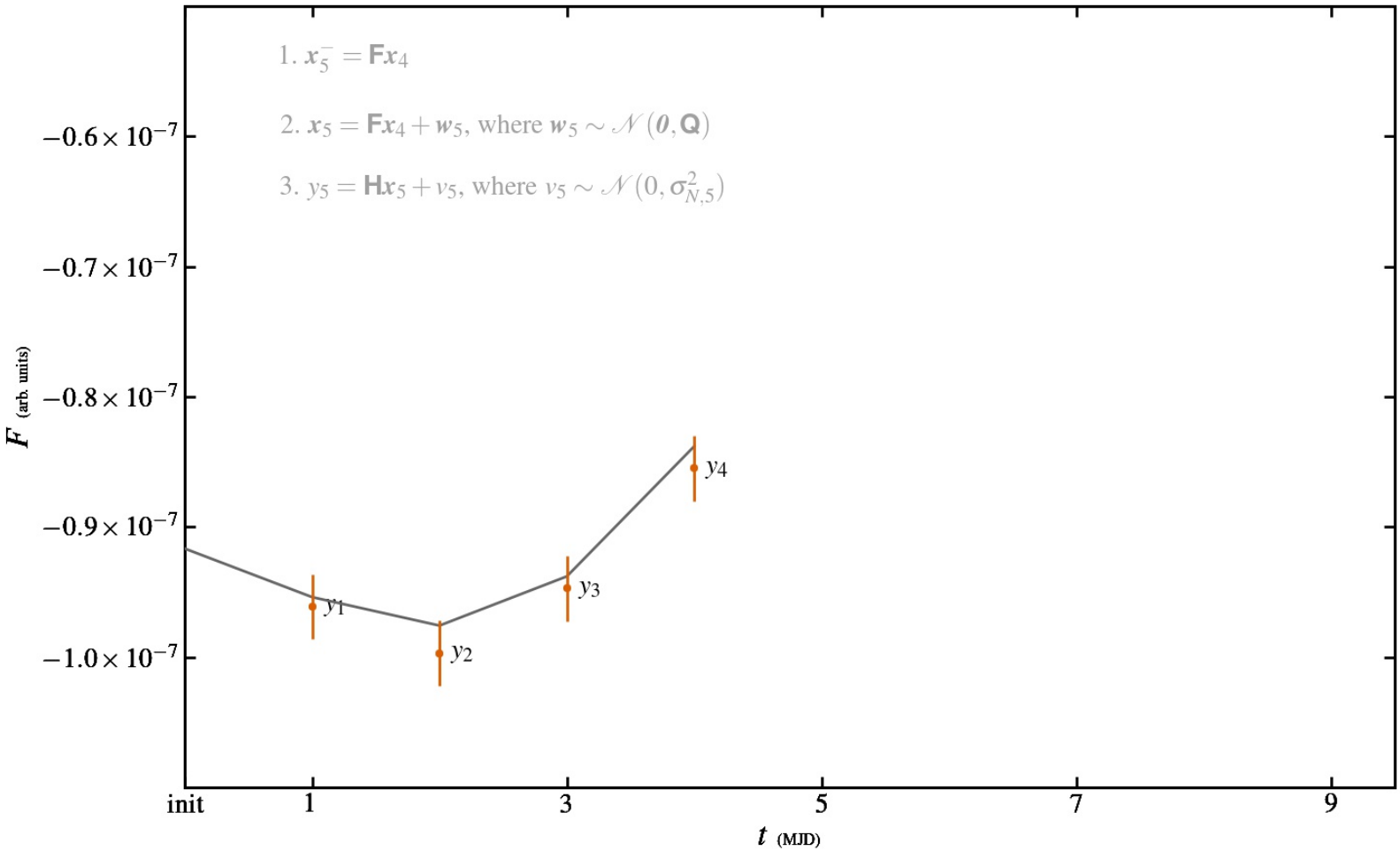
$$y_k = \mathbf{H}_k\boldsymbol{x}_k + v_k$$

Disturbance & noise properties

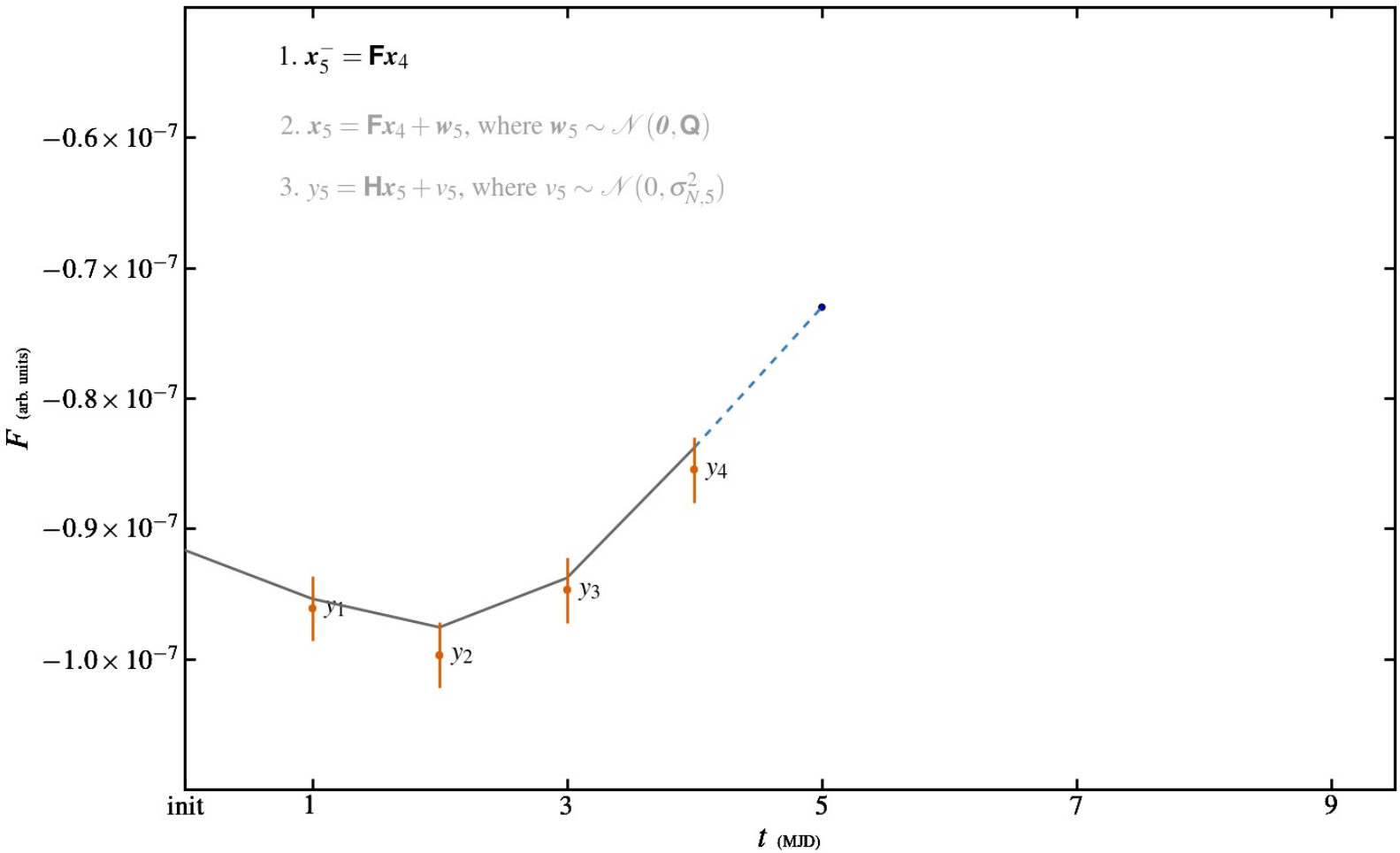
$$\boldsymbol{w}_k \sim \mathcal{N}(\boldsymbol{0}, \mathbf{Q})$$

$$v_k \sim \mathcal{N}(0, \sigma^2_{N,k})$$

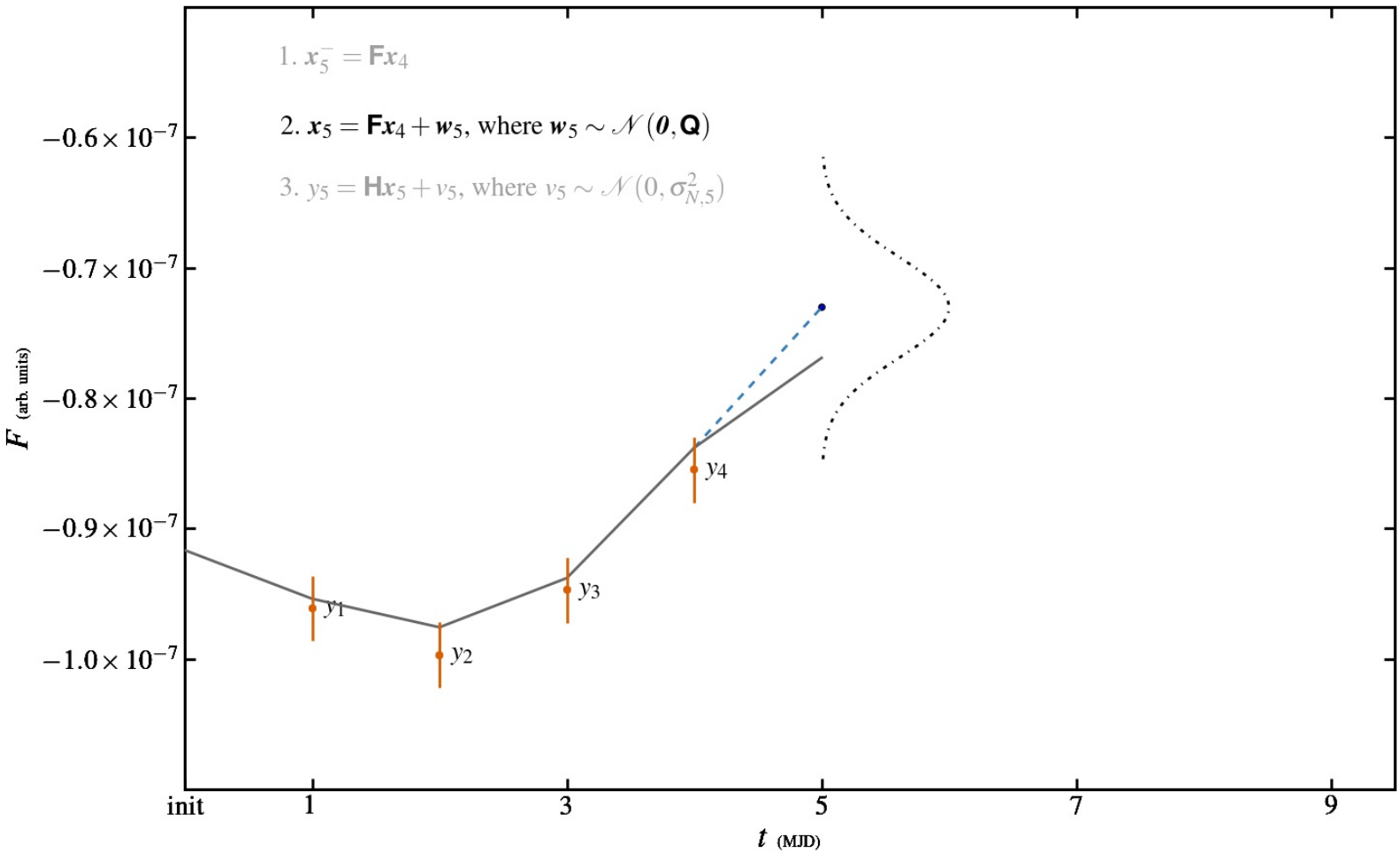
Evolution & observation of light curve state



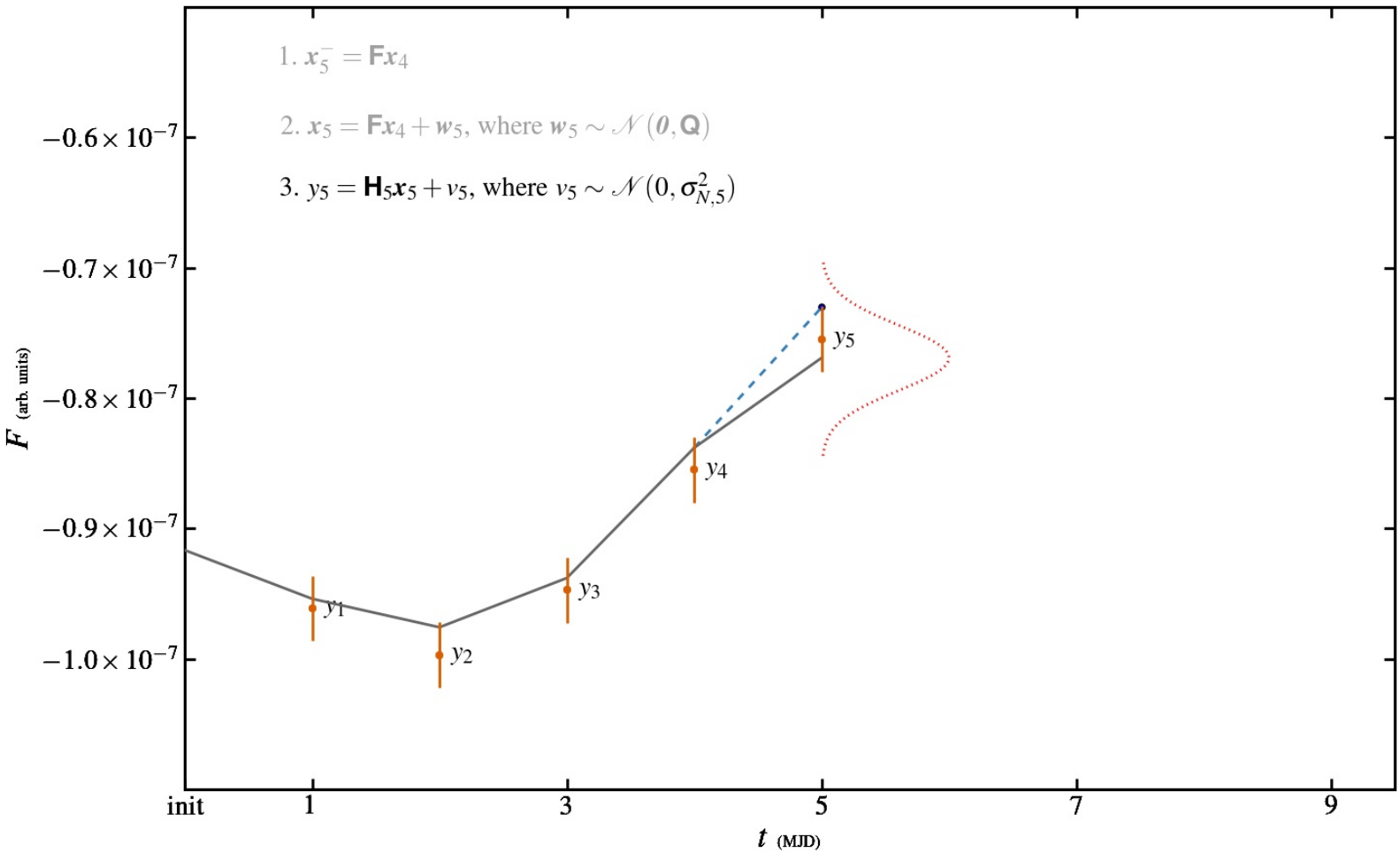
Evolution & observation of light curve state
Evolution without disturbance



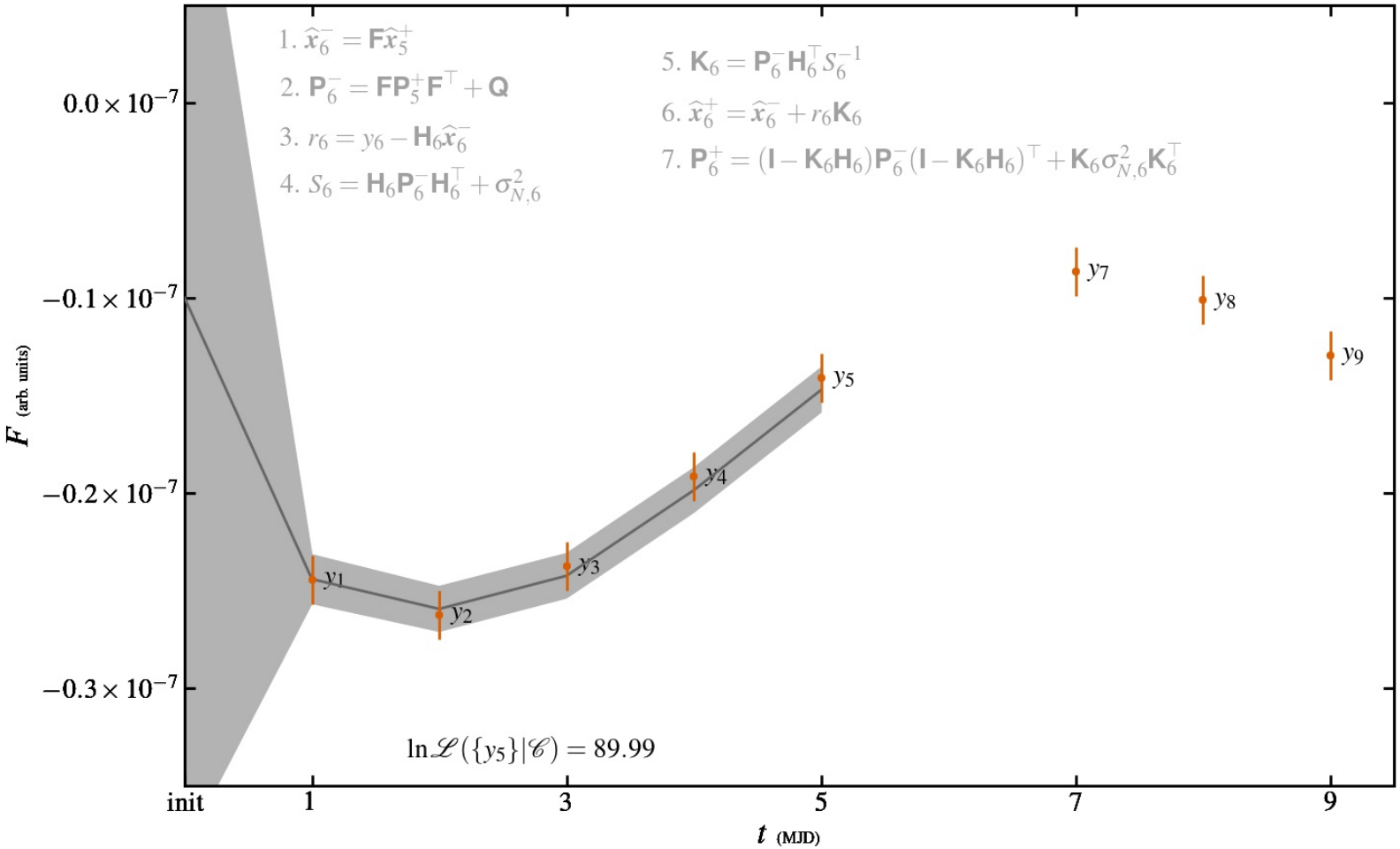
Evolution & observation of light curve state
Effect of the disturbance



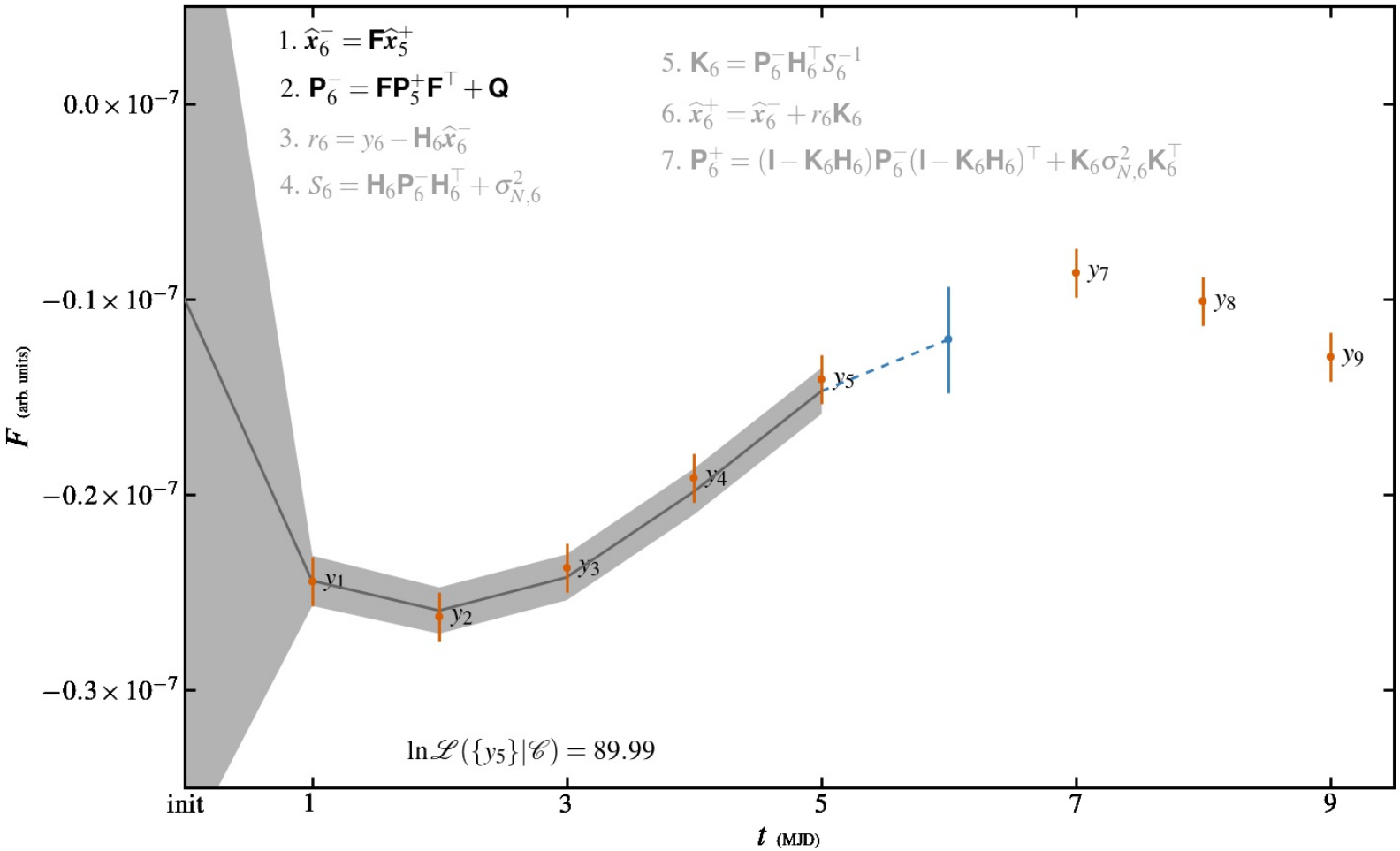
Evolution & observation of light curve state
Observing the AGN



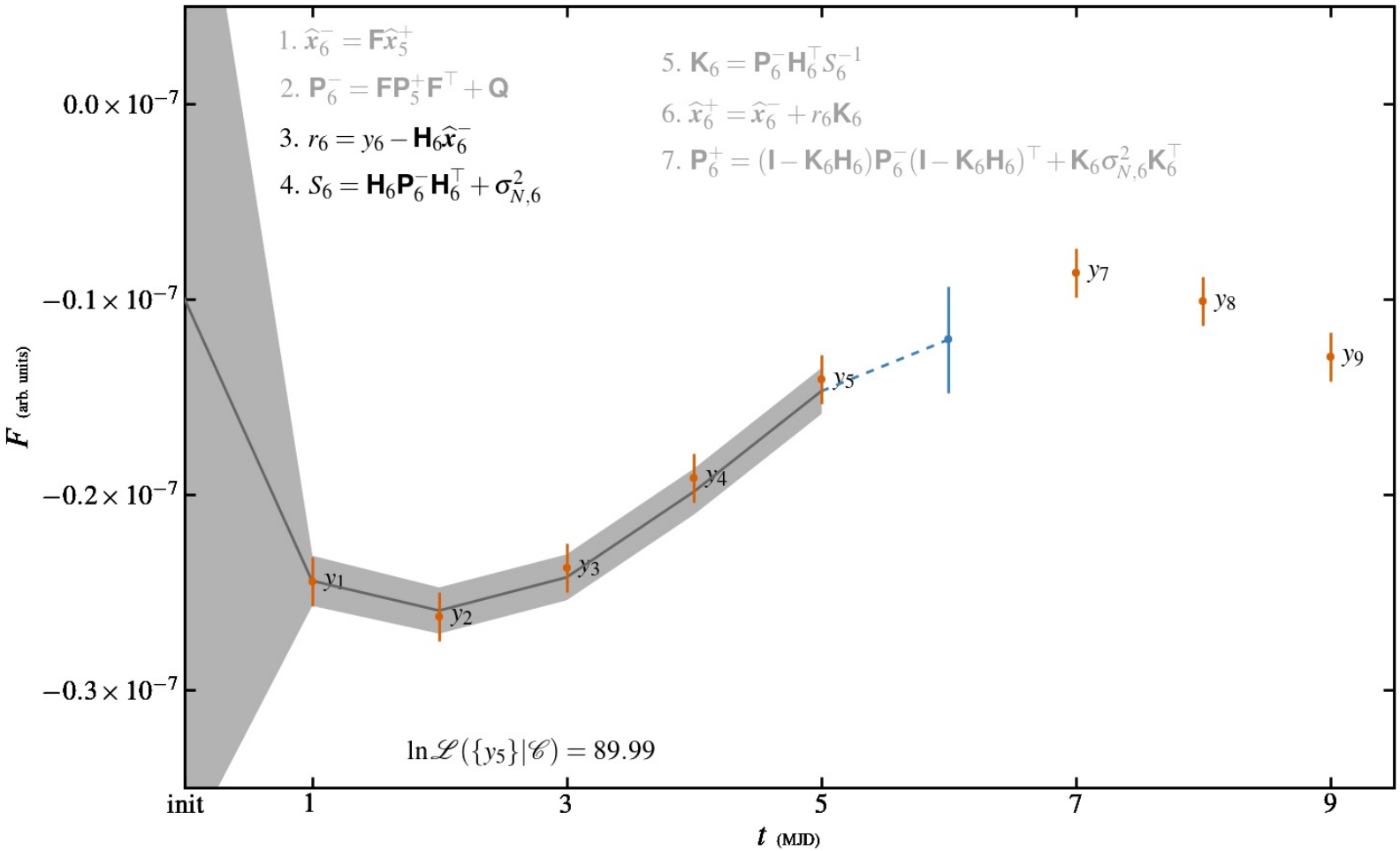
$\ln \mathcal{L}$ via Kalman filter



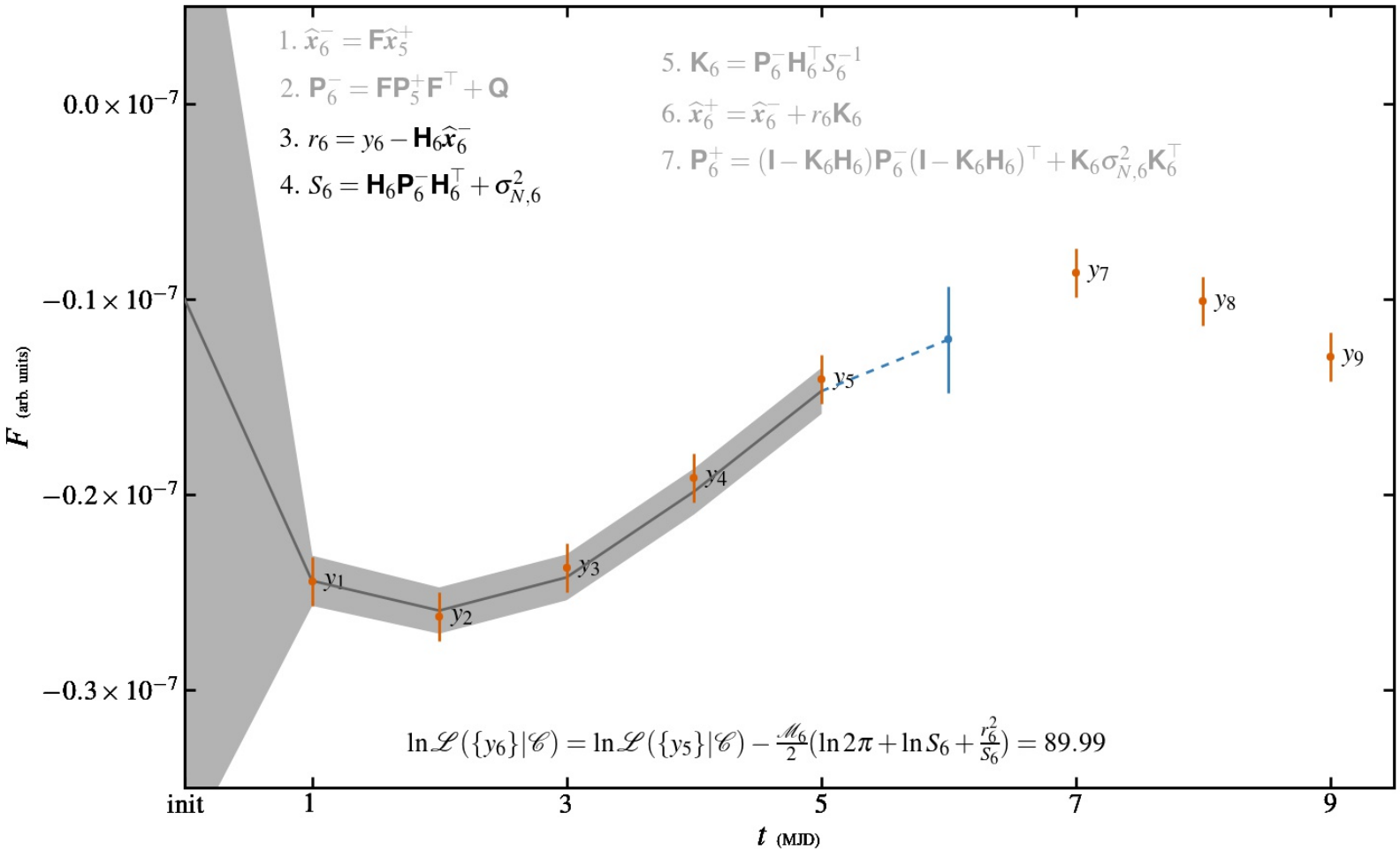
$\ln \mathcal{L}$ via Kalman filter
Predict Step



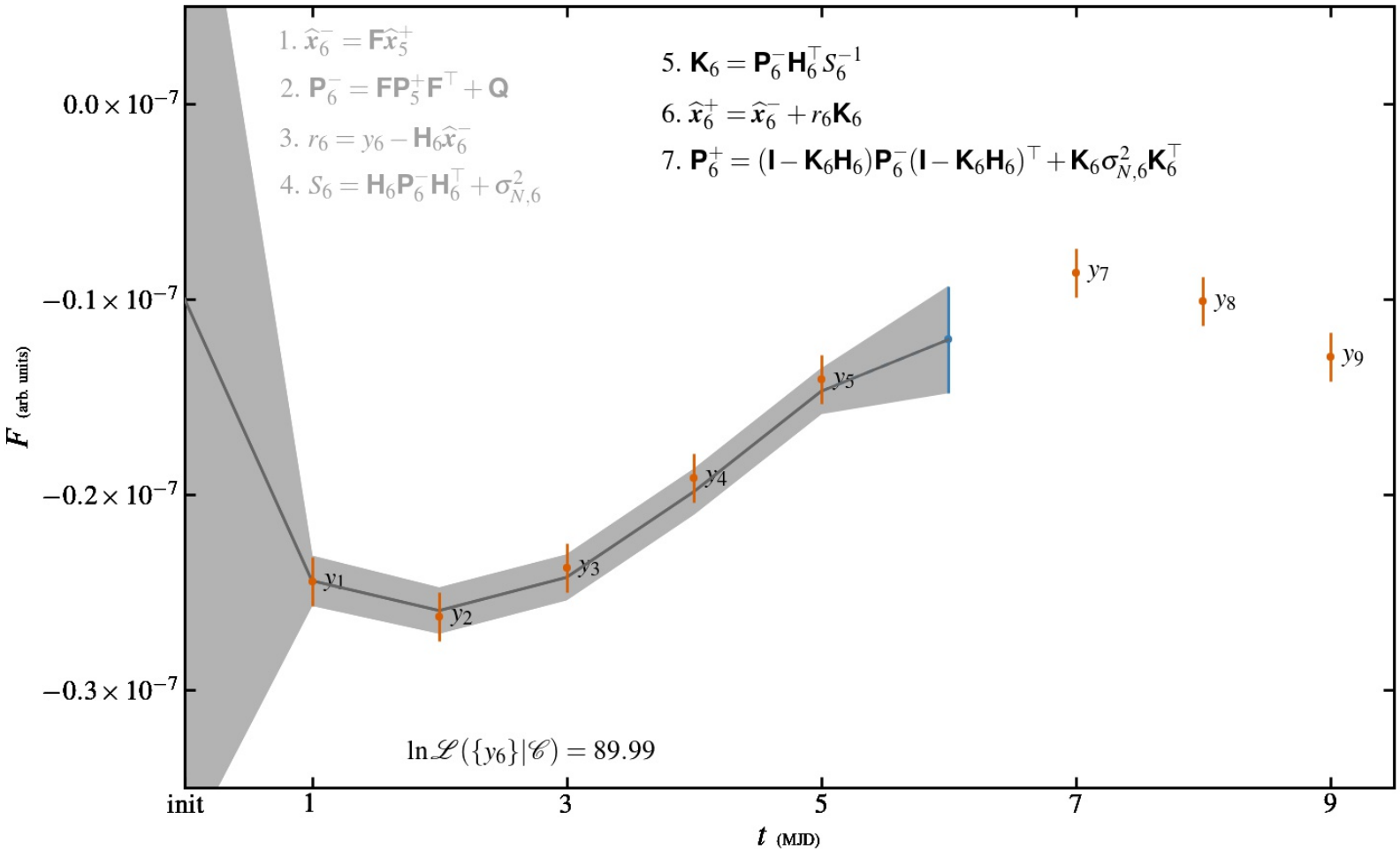
$\ln \mathcal{L}$ via Kalman filter
Innovation calculation



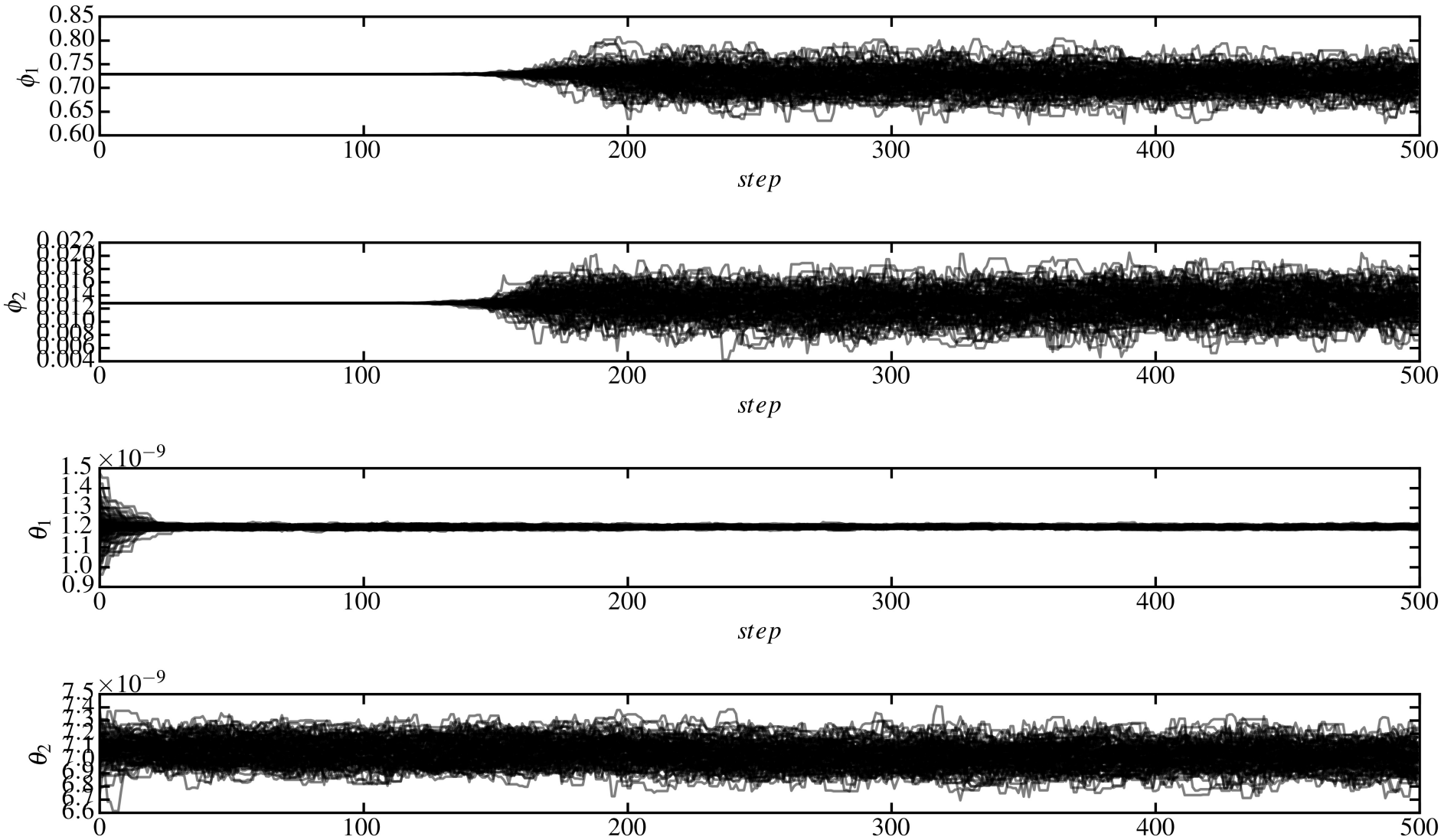
$\ln \mathcal{L}$ via Kalman filter
Update $\ln \mathcal{L}$



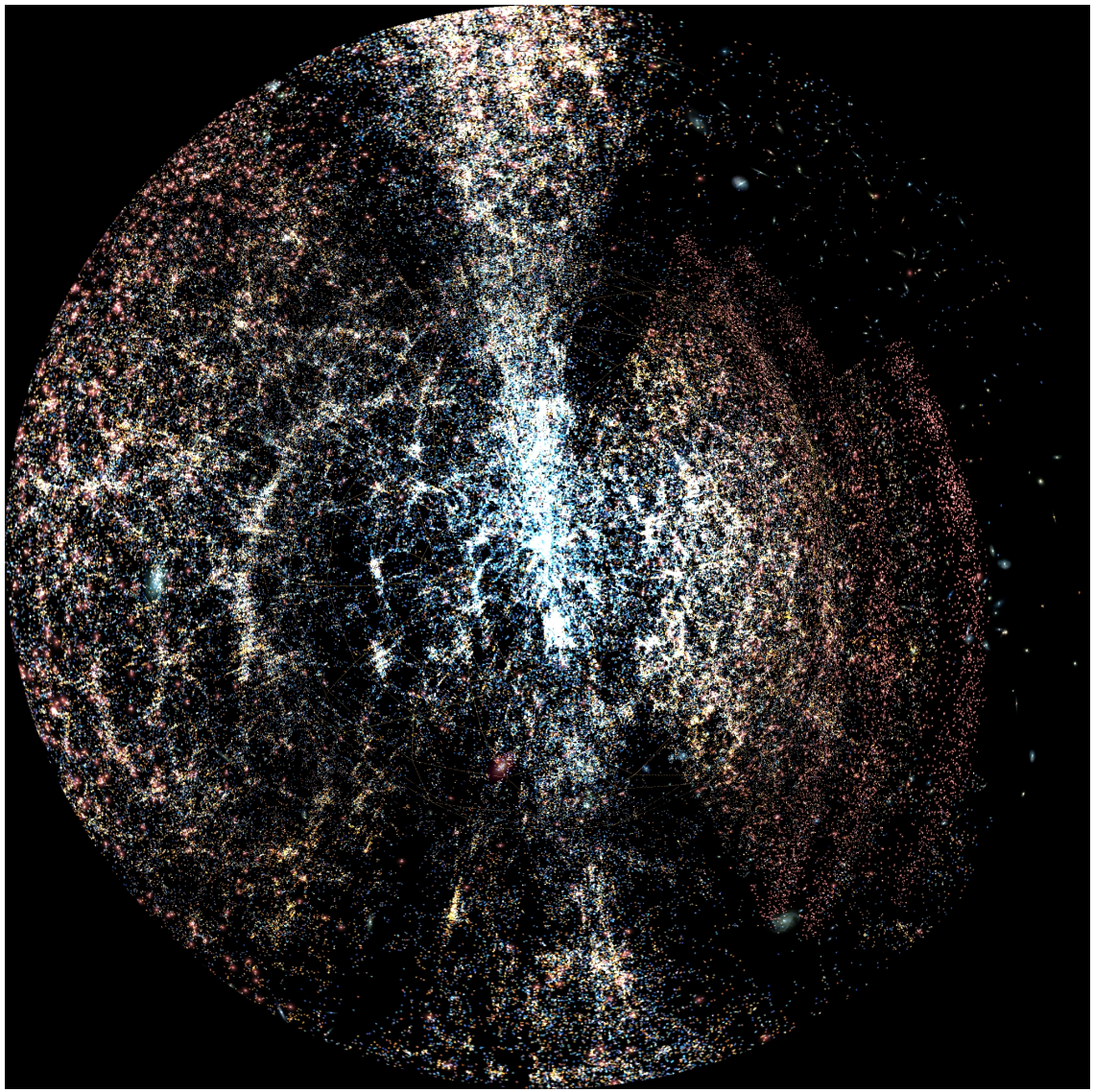
$\ln \mathcal{L}$ via Kalman filter
Correct Step



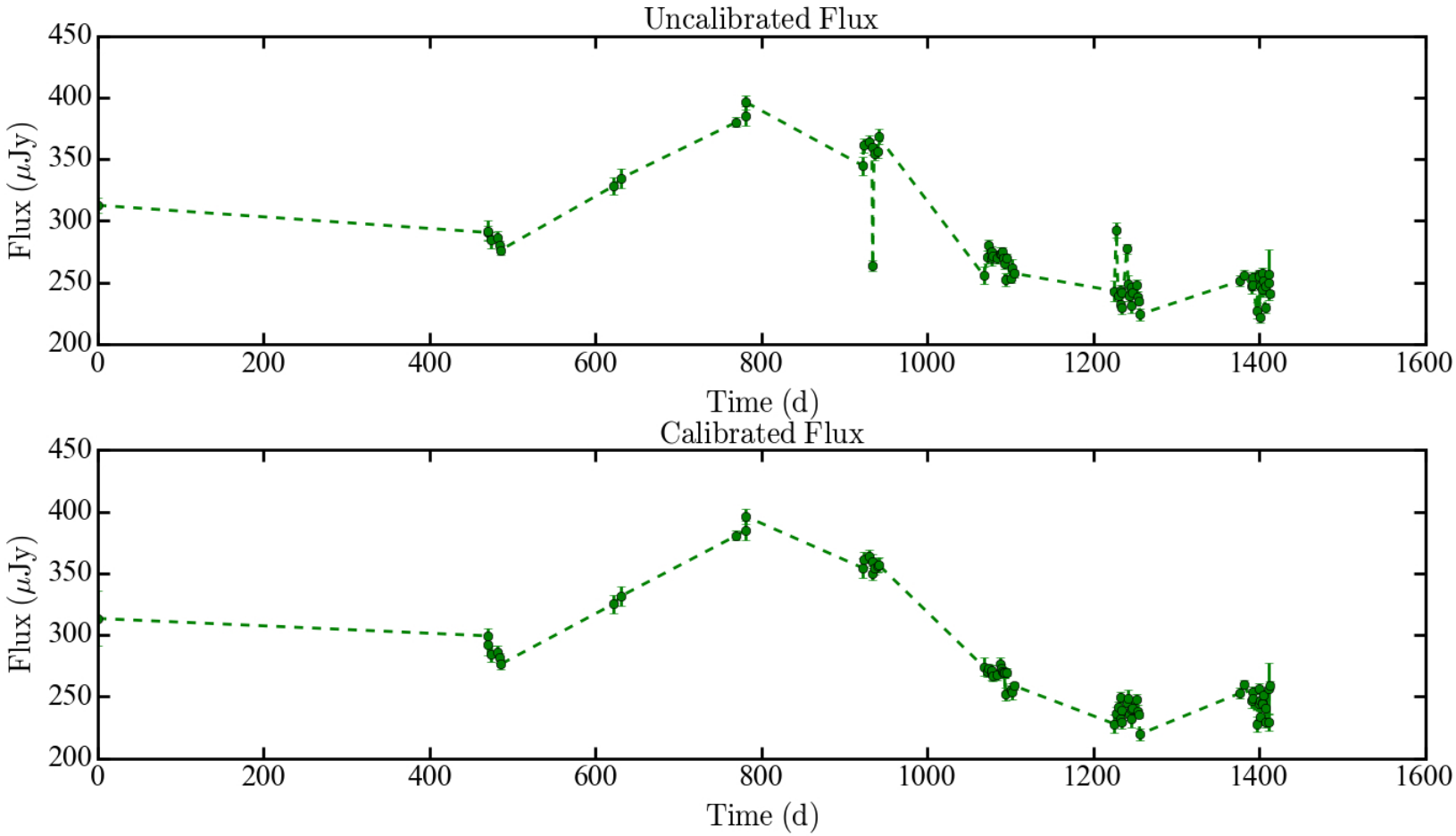
MCMC Estimation



Large Scale Structure of the Universe



Ivezić Stripe 82 Calibration



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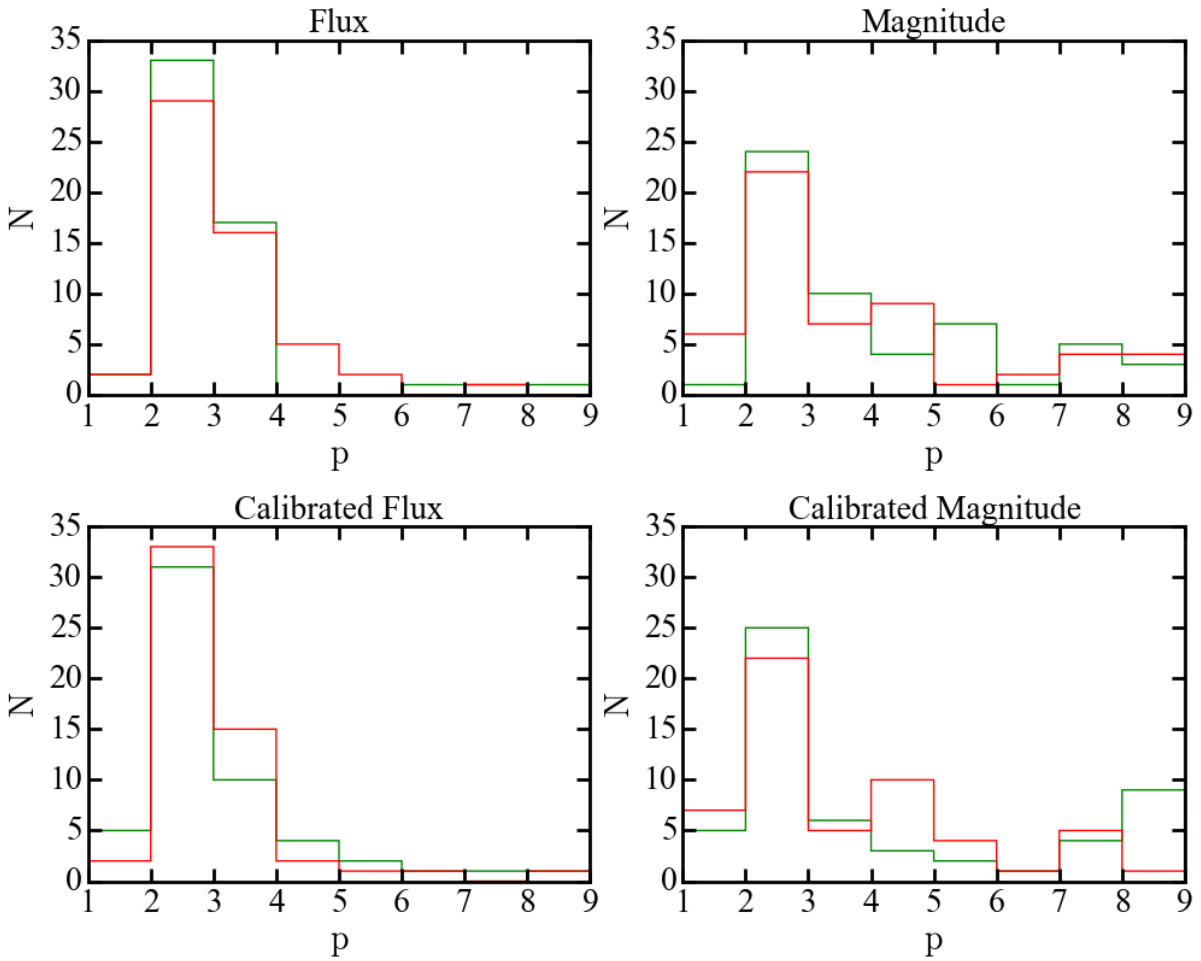
Stripe 82 QSO C-ARMA fits



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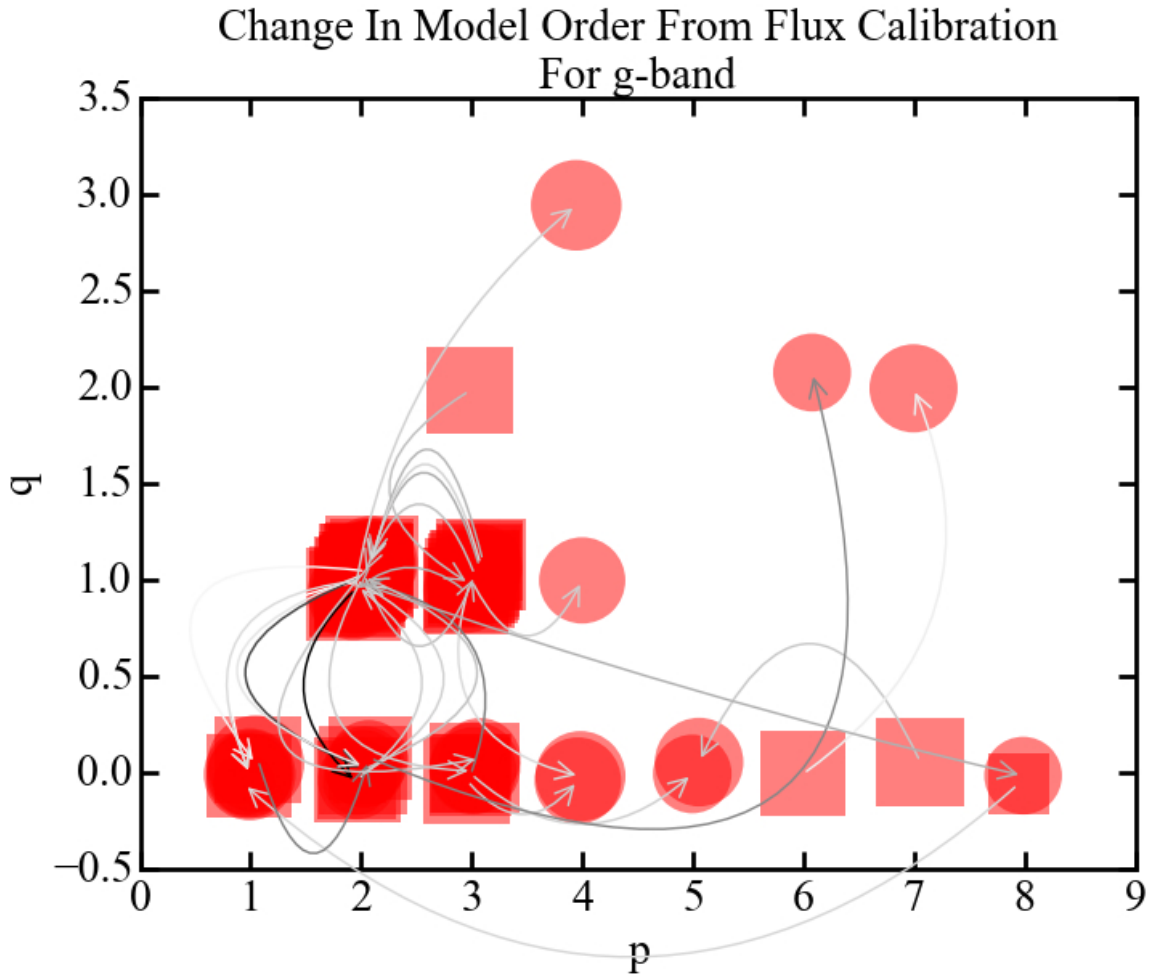
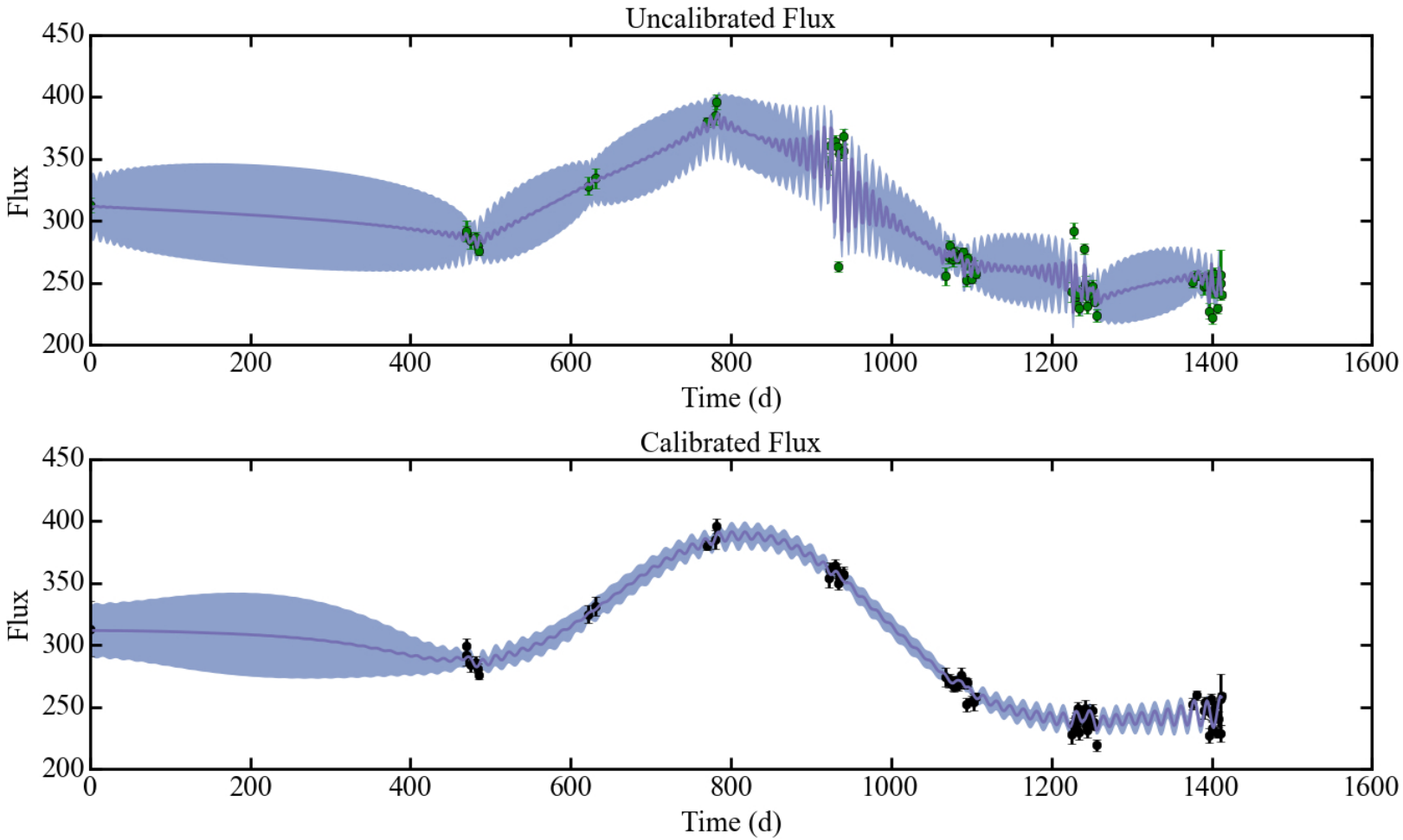
Stripe 82 QSO
Effect of Ivezić calibration



Stripe 82 QSO light curve C-ARMA fit



C-ARMA(3,1) → C-ARMA(2,1)

Jack O'Brien

Work in Progress
K2