PSD, Structure Function, and CARMA Analysis of AGN Variability

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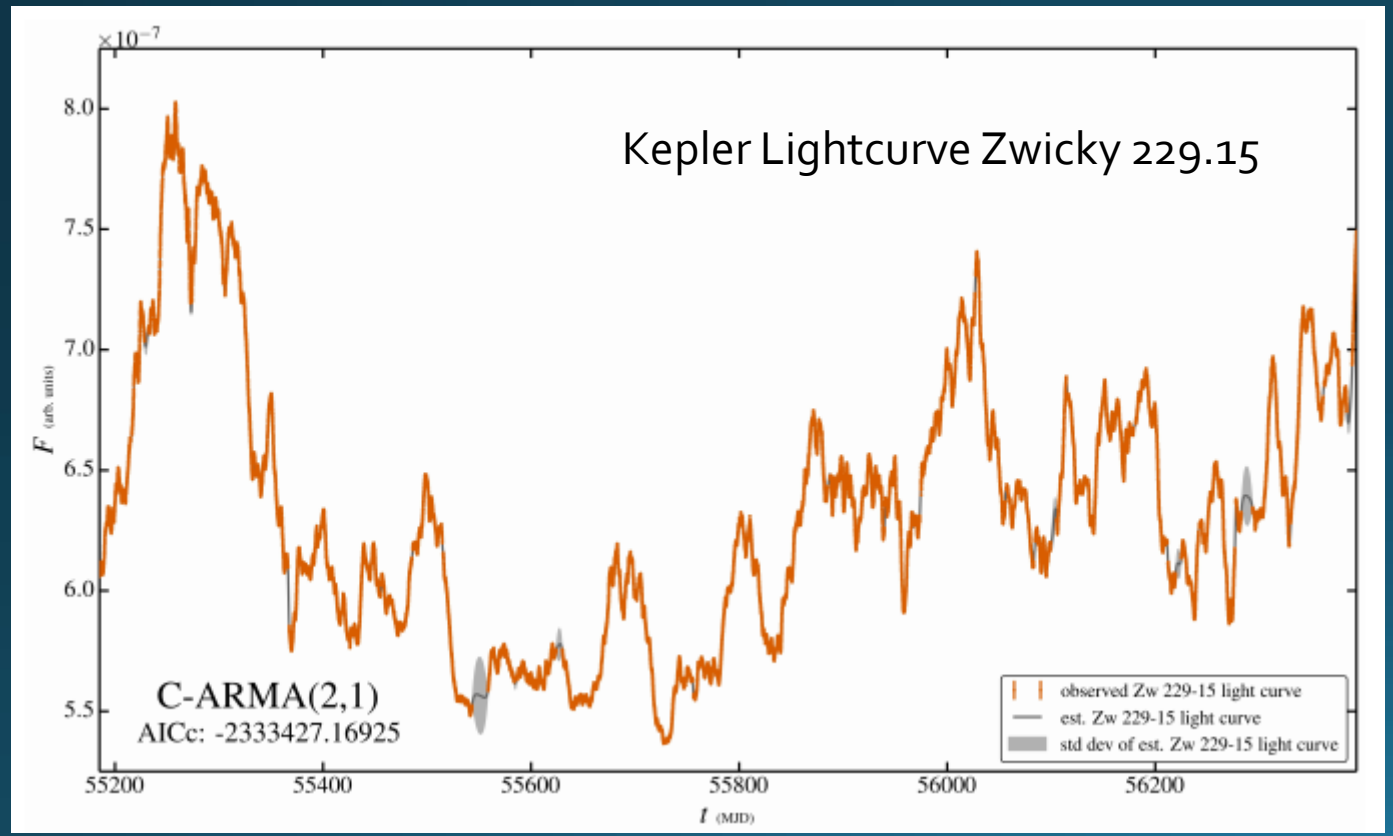
Outline

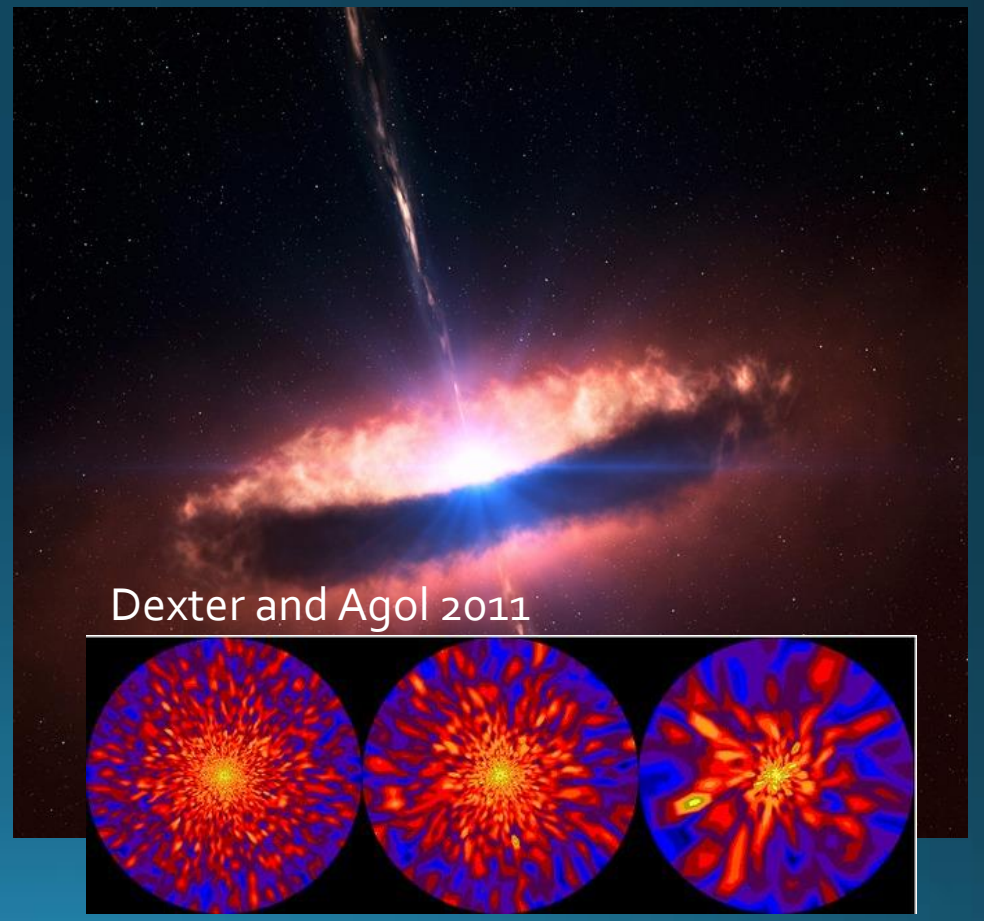
- Structure Functions and Damped Random Walk Models
- Sparse Cadences affect how well we infer parameters and model complexity
- CARMA description using the roots and the power spectrum

AGN Variability

- What information can we learn from AGN lightcurves?

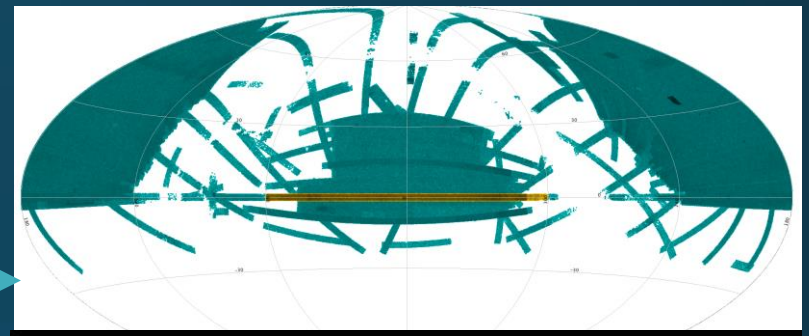


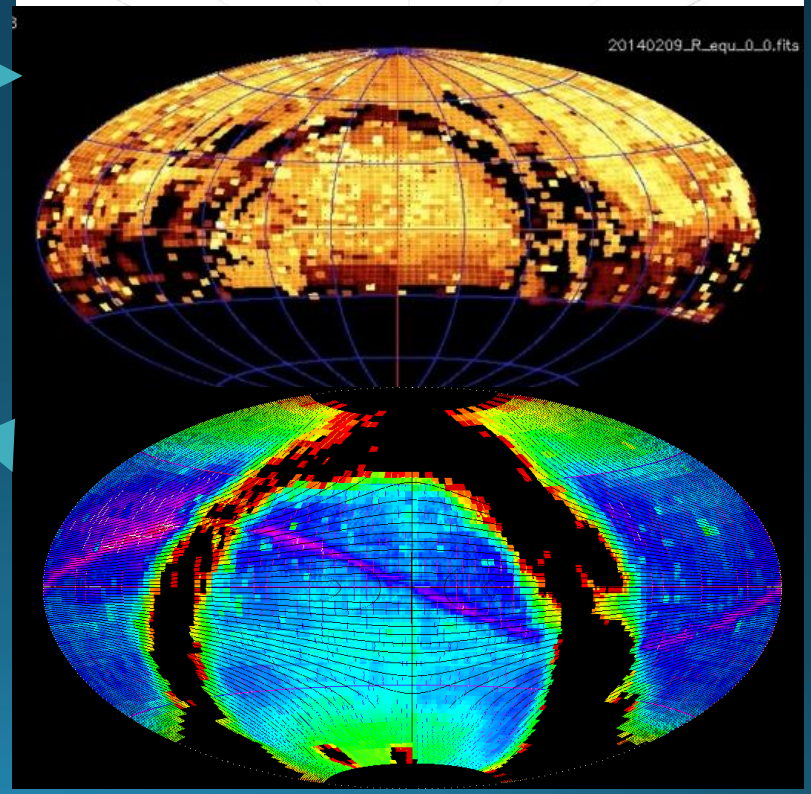
Kasliwal et al. 2016



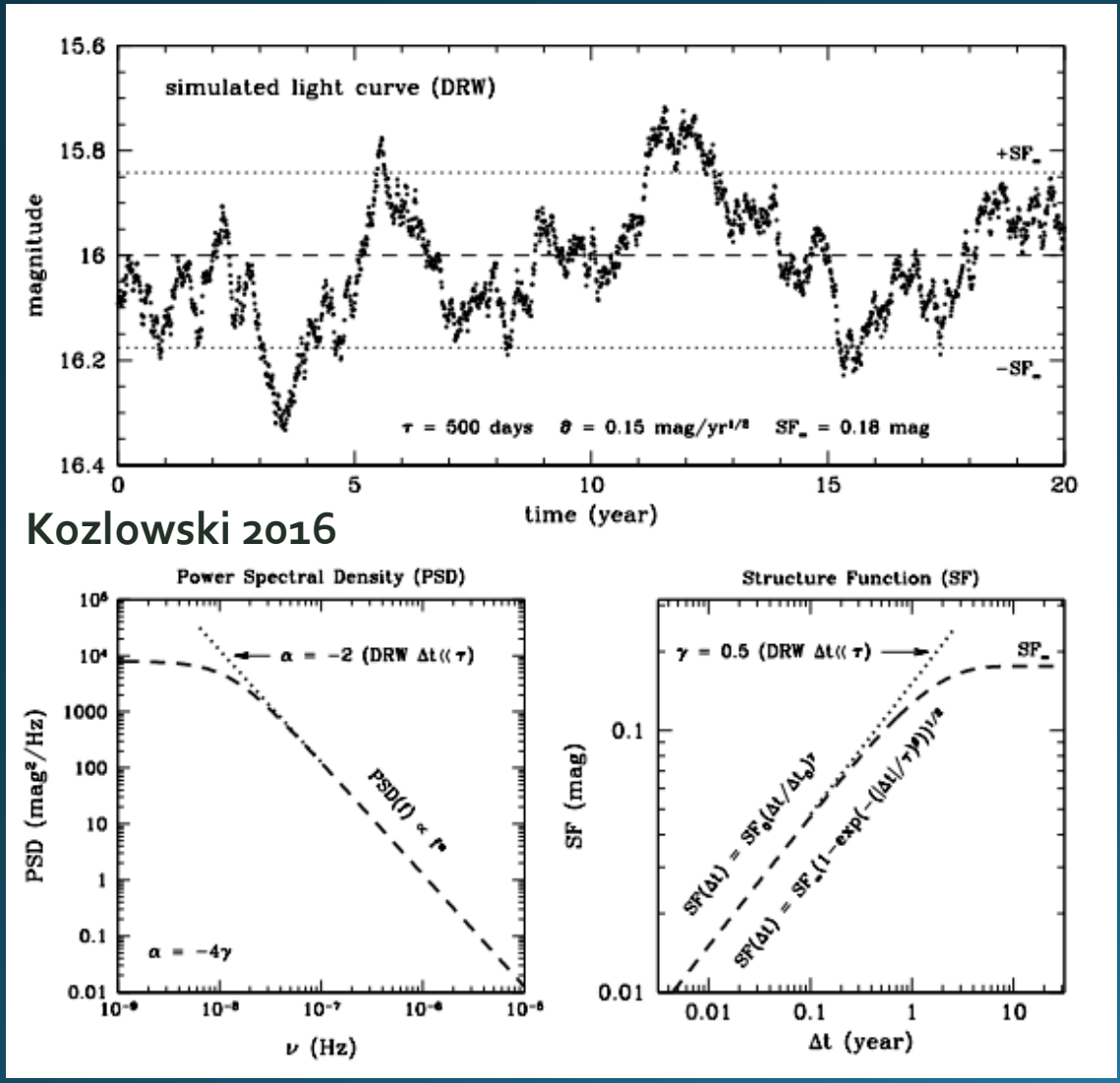
Surveys and Quasar Variability

Survey	QSO Lightcurves	A Few References
SDSS	~9000	MacLeod et al. 2010
CRTS	~200,000	Graham et al. 2014
PTF & iPTF	~28,000	Caplar et al 2017
OGLE	~1,000	Kozlowski et al. 2010, 2013
MACHO	-	Pichara et al. 2012
Pan-STARRS	-	Simm et al. 2016





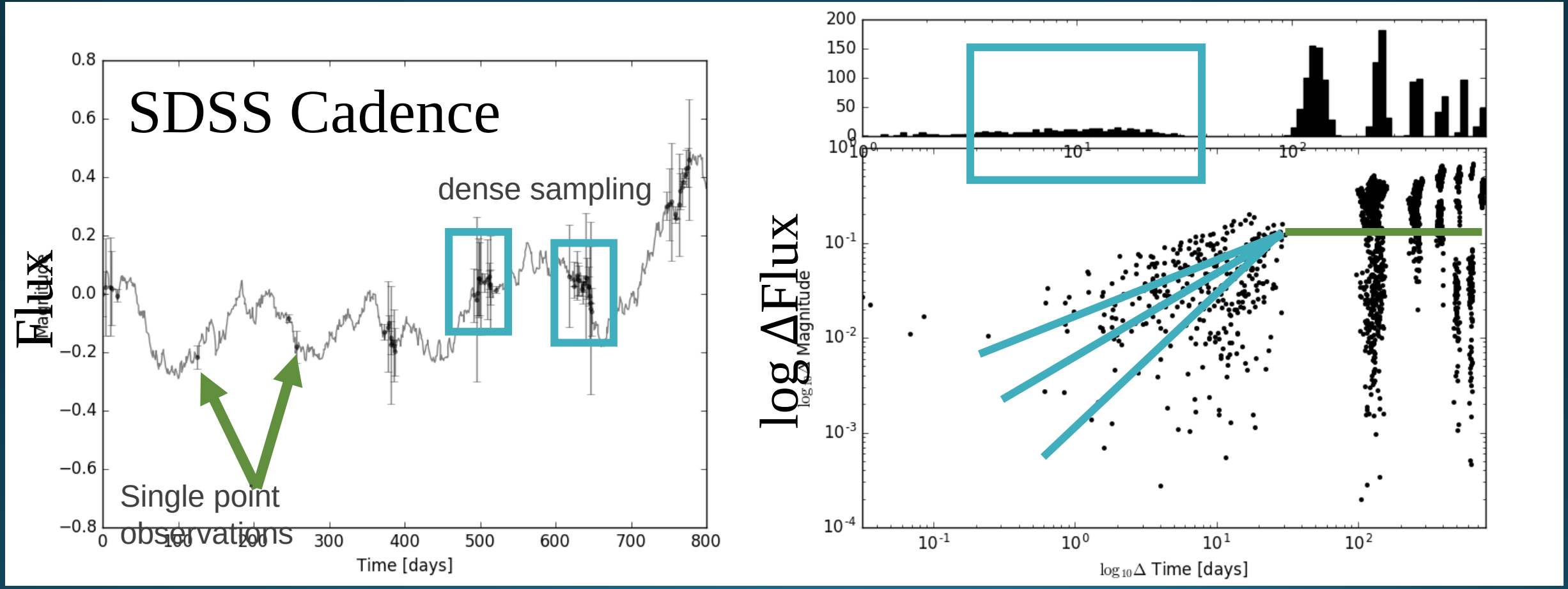
Lightcurves and Characterization



Kozlowski 2016

- SF and DRW parameters are used for classification (MacLeod et al. 2010, Graham et al. 2014, Pichara et al. 2012, Kozlowski 2010,2013)
- SF, PSD and Auto-regressive model parameters used to probe physics (Simm et al 2016, Caplar et al. 2017)

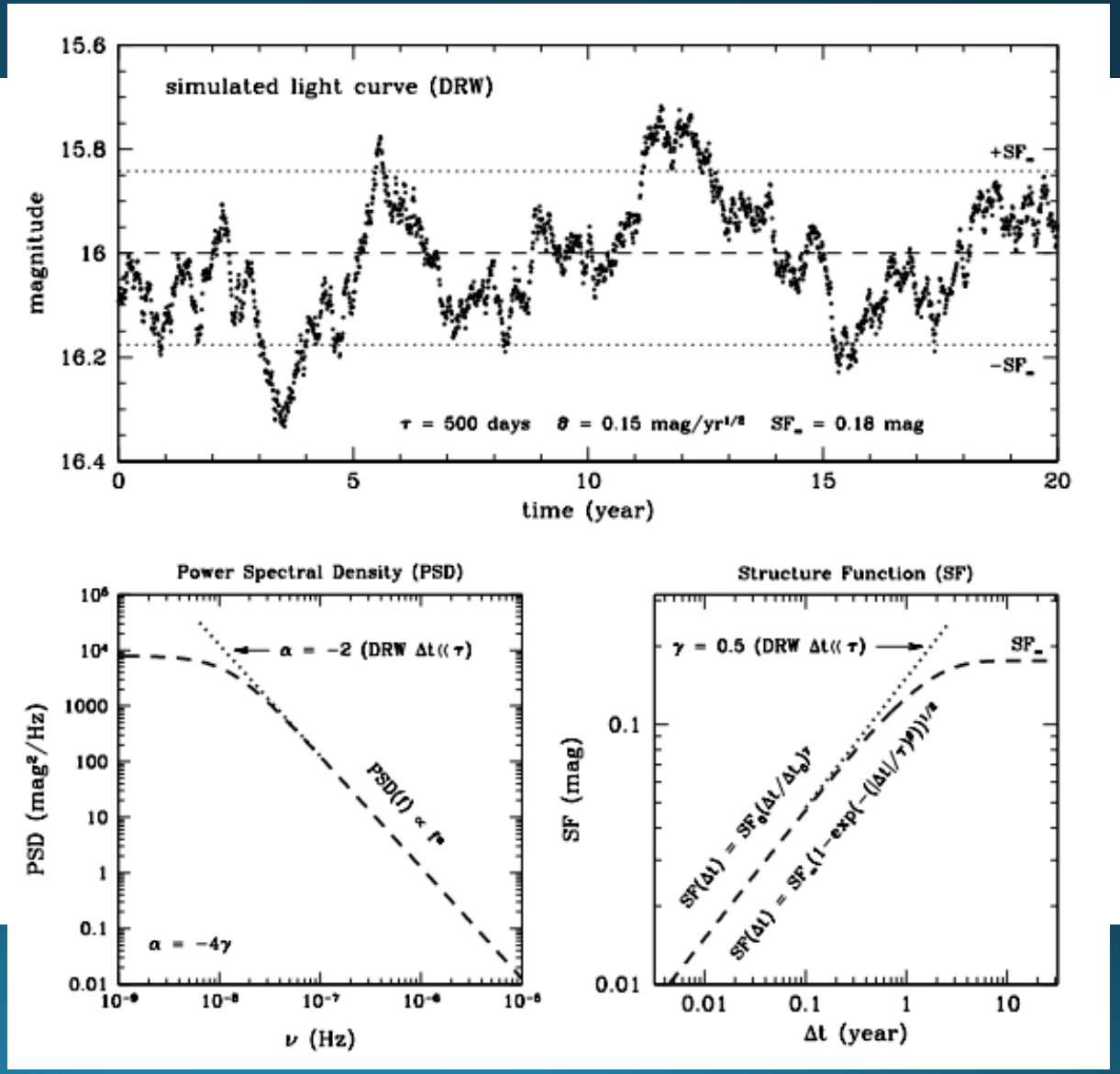
Lightcurves and Characterization



Credit: Tina Peters

Lightcurves and Characterization

- Studies find deviations from DRW models (Mushotsky 2011, Graham et al 2014, Kasliwal et al. 2015)
- Kelly et al. 2014 introduces CARMA models to time domain astronomy as more flexible and scalable to massive data sets



CARMA process (Kelly et al. 2014)

$$d^p F(t) + \alpha_{p-1} d^{p-1} F(t) + \cdots \alpha_0 F(t) = \epsilon(t) + \beta_q d^q \epsilon(t) + \ldots$$

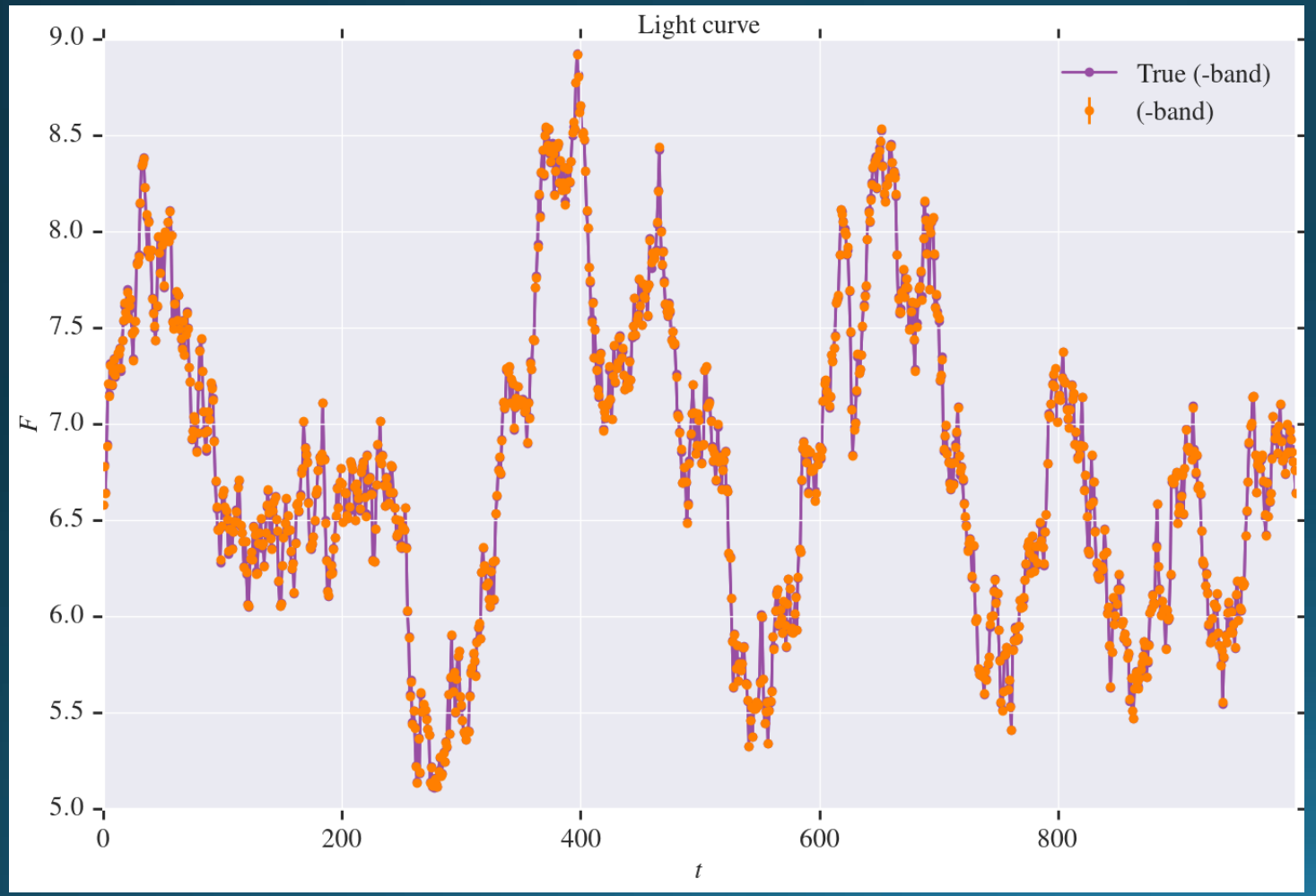
AR Coeffs → $\alpha_0 \ldots . \alpha_{p-1}$

$\beta_1 \ \ldots \beta_q$ ← MA Coeffs.

$$\alpha_0 + \alpha_1 z^1 + \cdots + \alpha_{p-1} z^{p-1} = 0$$

The roots are more physically intuitive…

CAR(1) = DRW



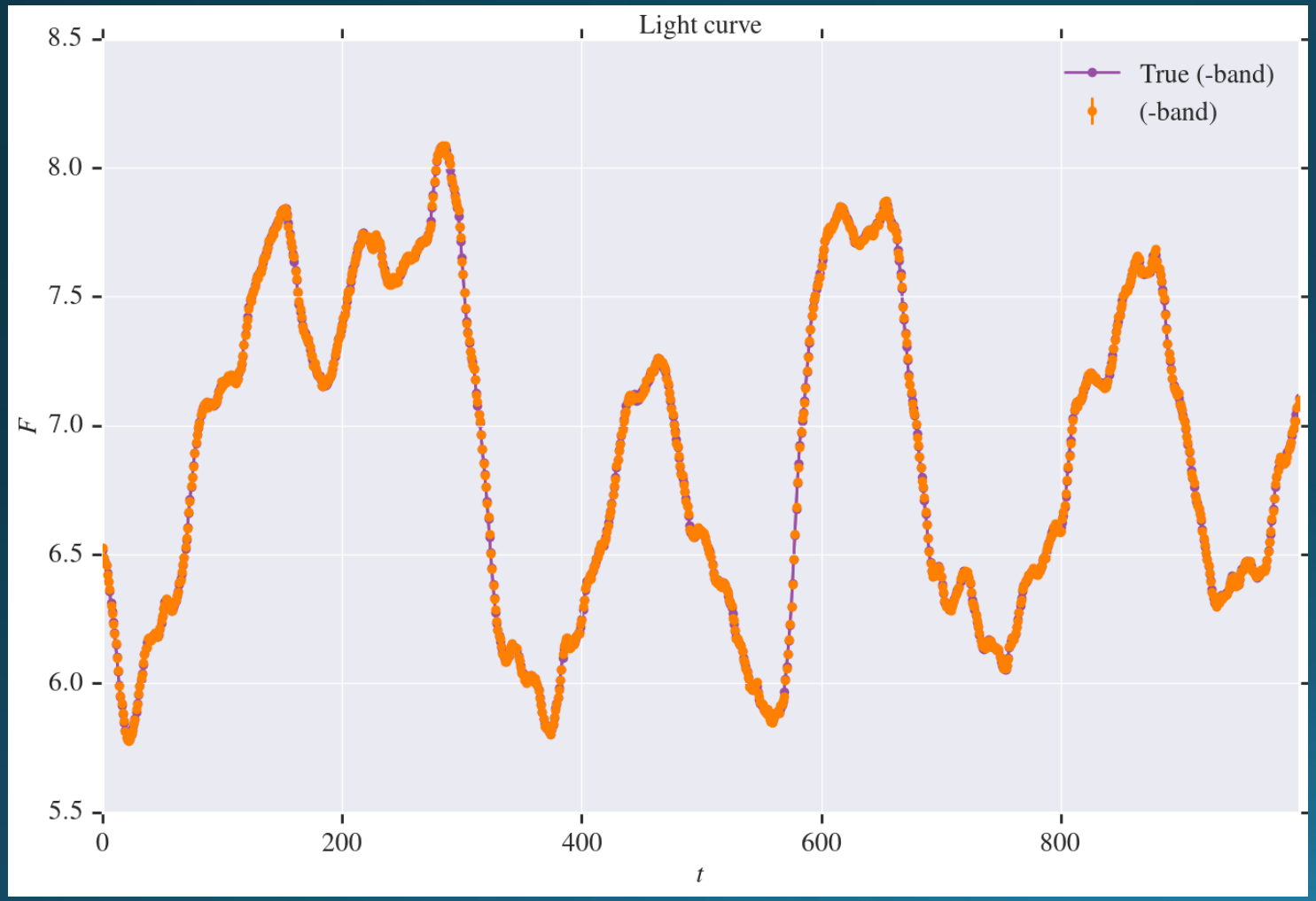
$$F_i = e^{\rho|t_i - t_{i-1}|}F_{i-1} + kick + I$$

$$\rho = \frac{-1}{timescale}$$

Kick from a Gaussian ($\sigma = 1, \mu = 0$)

I = *Stochastic Ito Integral*

CAR(2)

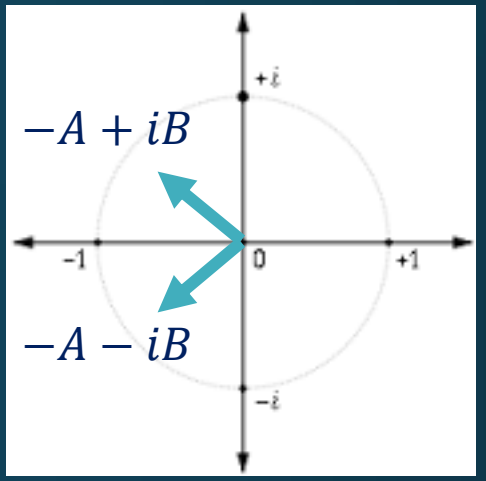


$$F_i = \sum_{j=1}^{p=2} e^{\rho_j |t_i - t_{i-1}|} F_{i-1} + kick + I$$

$$\rho = \begin{cases} 2\ real, negative \\ complex\ conjugate\ pair \end{cases}$$

Kick from a Gaussian $(\sigma = 1, \mu = 0)$

CAR(2) with Complex roots



- Second order process with complex roots

$$F_{i-1}e^{(-A+iB)\delta t} + F_{i-1}e^{(-A-iB)(\delta t)}$$

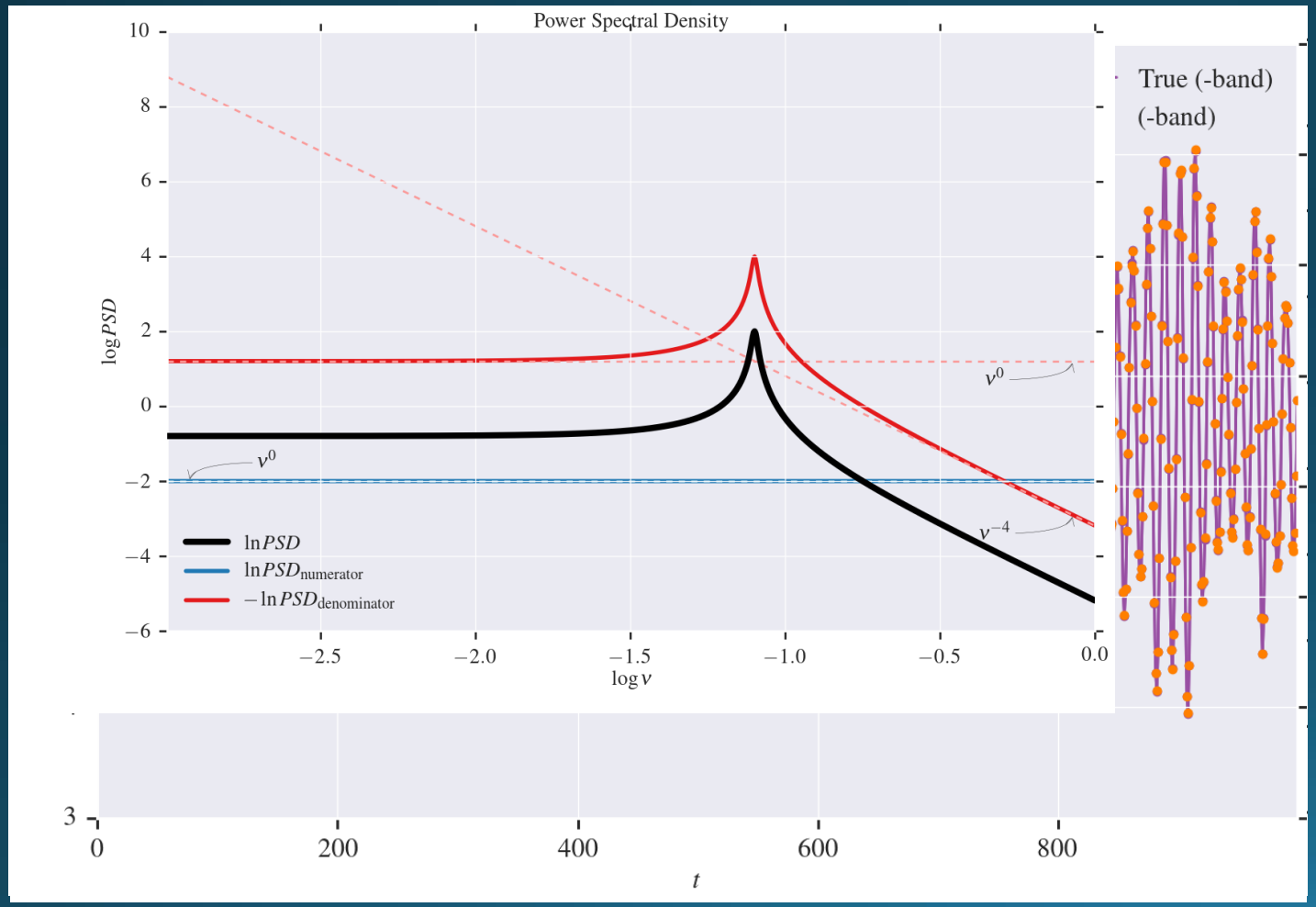
$$=\mathrm{F}e^{-A\delta t}\{(\cos(B\delta t) + isin(B\delta t) + (\cos(B\delta t) - isin(B\delta t))\}$$

$$=2\mathrm{F}e^{-A\delta t}\cos(B\delta t)$$

Physical behavior looks like damped harmonic oscillator

$\sim e^{-A\delta t}\cos(B\delta t)$ + kick

CAR(2) $\sim 2e^{\rho_2 \delta t} \cos \delta t$ + kick

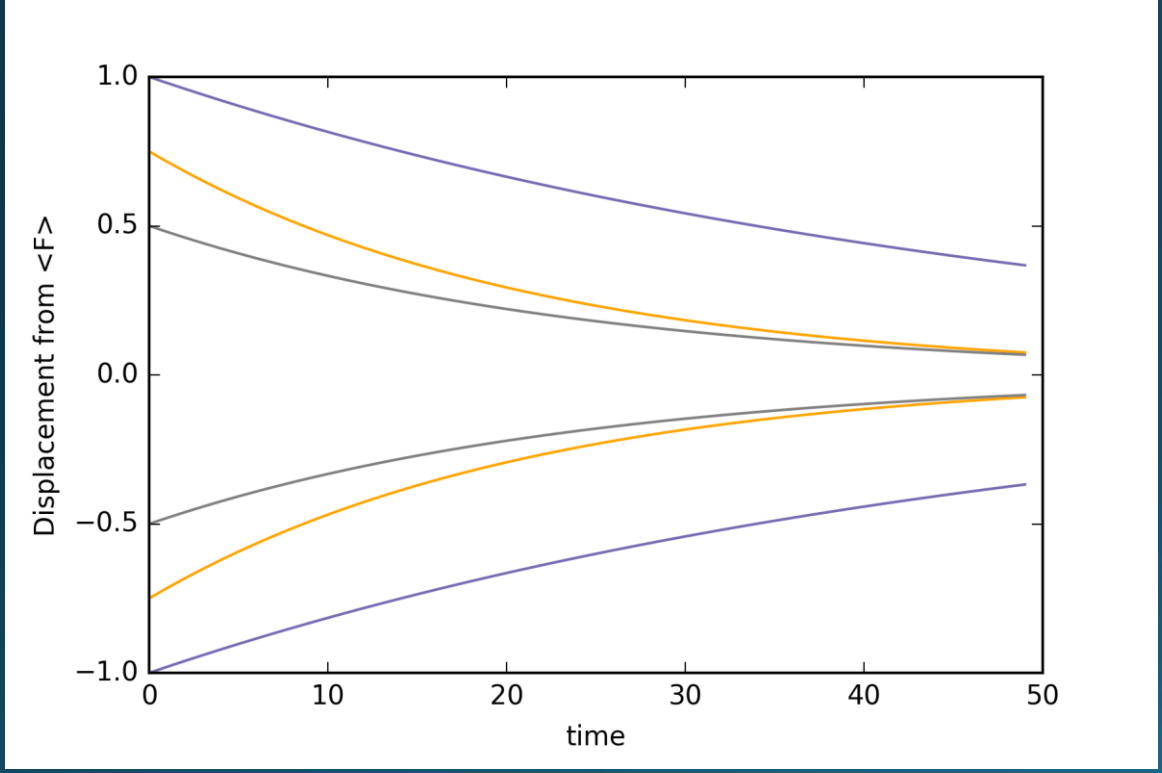


$$F_t = \sum_{j=1}^{p=2} e^{\rho_j |t_i - t_{i-j}|} F_{i-j} + kick + I$$

$$\rho = \begin{cases} 2\ real, negative \\ complex\ conjugate\ pair \end{cases}$$

Kick from a Gaussian
$(\sigma = 1, \mu = 0)$

Higher order models?



CAR(3)

$$\rho = \begin{cases} 3\ real, negative \\ 1\ real + complex \\ conjugate\ pair \end{cases}$$

CAR(4)

$$\rho = \begin{cases} 4\ real, negative \\ 2\ complex \\ conjugate\ pairs \end{cases}$$

What about Moving Average (MA) terms?

CARMA process (Kelly et al. 2014)

$$d^p F(t) + \alpha_{p-1} d^{p-1} F(t) + \cdots \alpha_0 F(t) =$$
$$\epsilon(t) + \beta_q d^q \epsilon(t) + \ldots$$

AR Coeffs → $\alpha_0 \ldots . \alpha_{p-1}$

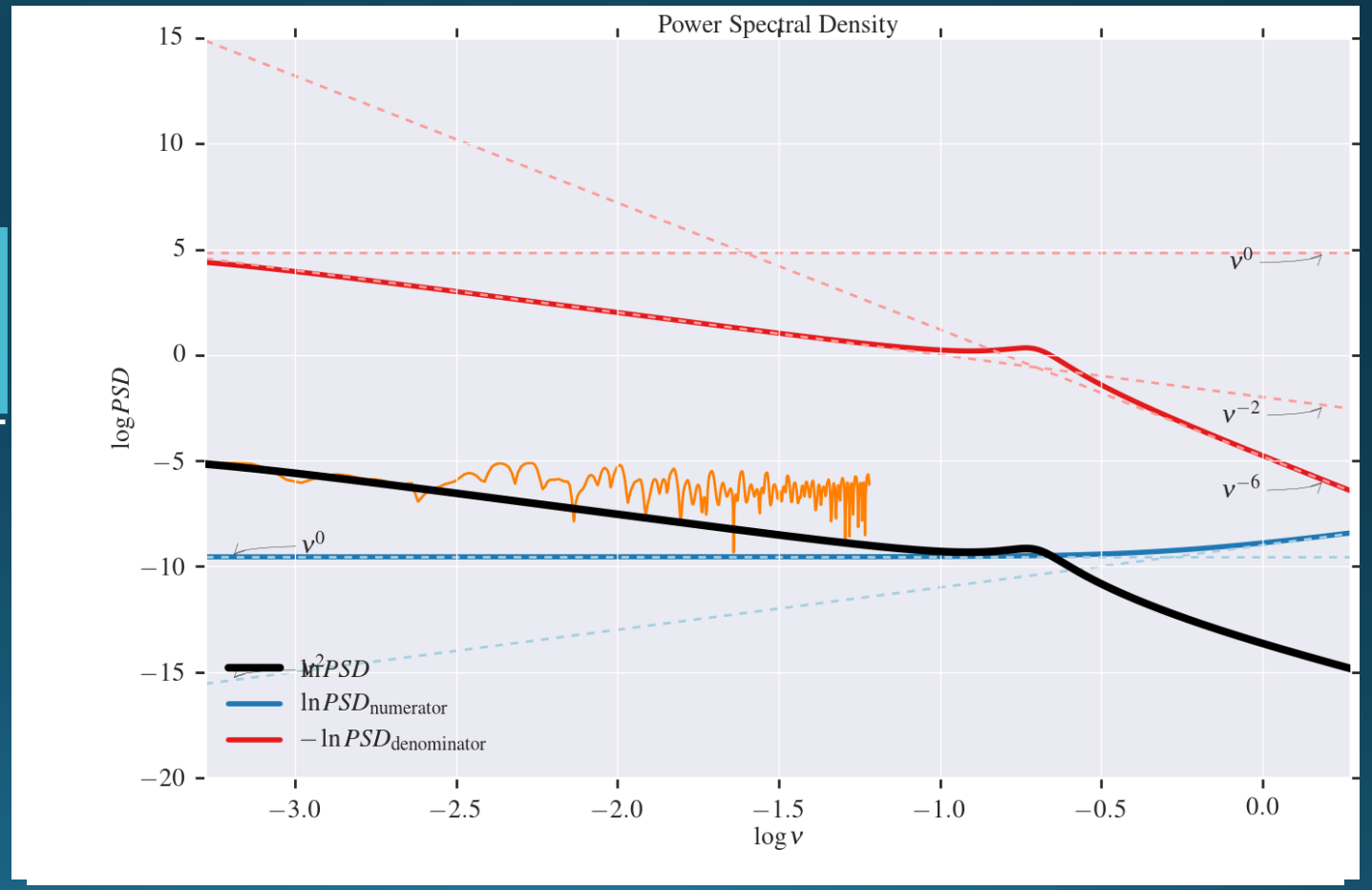
MA Coeffs. → $\beta_1 \ \ldots \beta_q$

Power Spectrum of Moving Average terms

MA terms stochastically drive the system at different frequencies!

$$PSD = \frac{\sigma^2 \left| \sum_{j=0}^{q} B_j (2\pi i \nu)^j \right|^2}{\left| \sum_{k=0}^{p} \alpha_k (2\pi i \nu)^k \right|^2}$$

+ slopes drive
- slopes decay



Challenge

- To explore and quantify how gaps in cadence affect CARMA modelling

1. By using an ensemble of variability techniques

2. By finding ways to combine data sets or finding overlaps in parameters space to catch discrepancies due to cadence

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