SUZANNE AIGRAIN (OXFORD)

KEPLER LIGHT CURVES
AS STELLAR VARIABILITY TEMPLATES FOR PLATO

PLATO STESCI II, MILAZZO, MAY 2018

transits

transits

phase variations

transits

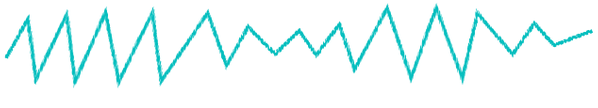
phase variations

stellar pulsations

transits

phase variations

stellar pulsations

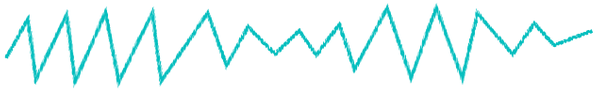


granulation

transits

phase variations

stellar pulsations



granulation

rotation / activity

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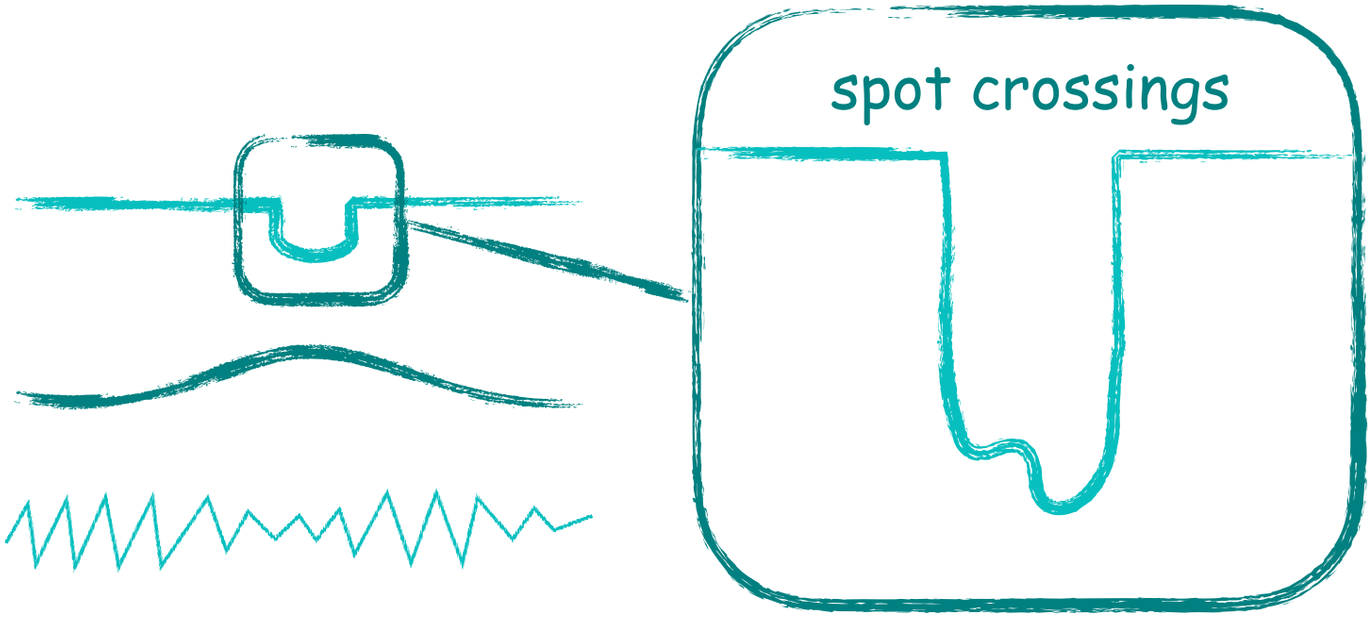

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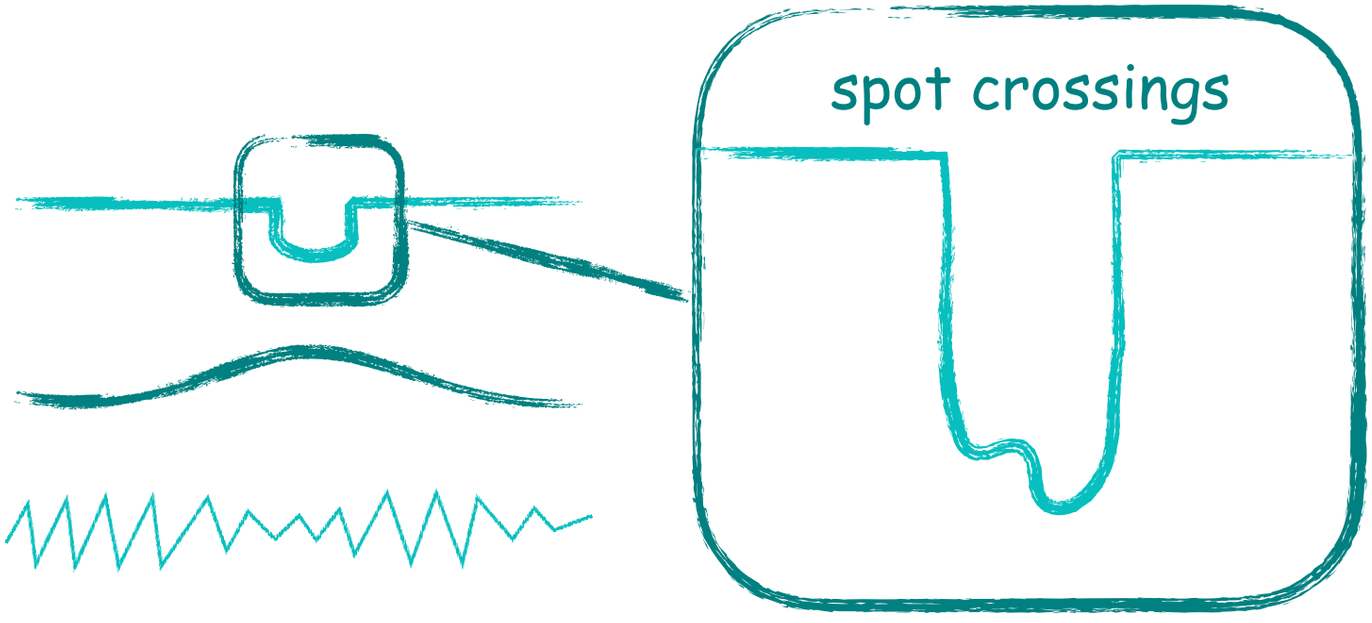
rotation / activity

flares



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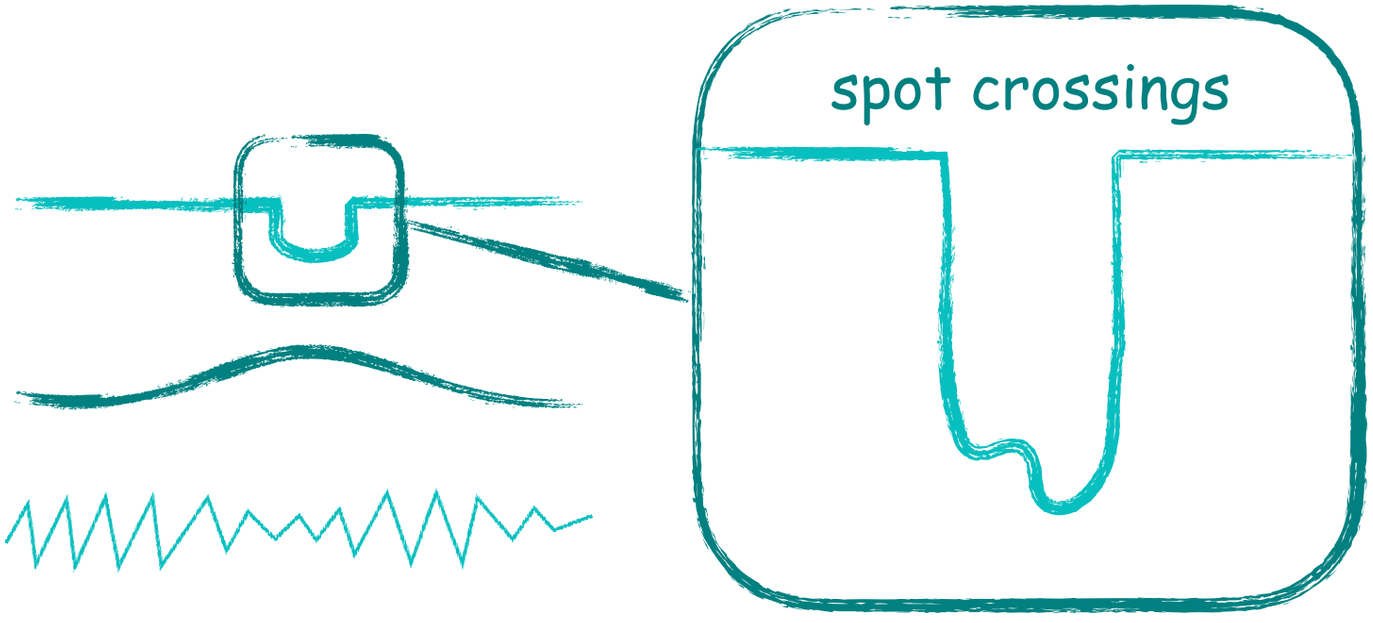
new stuff???



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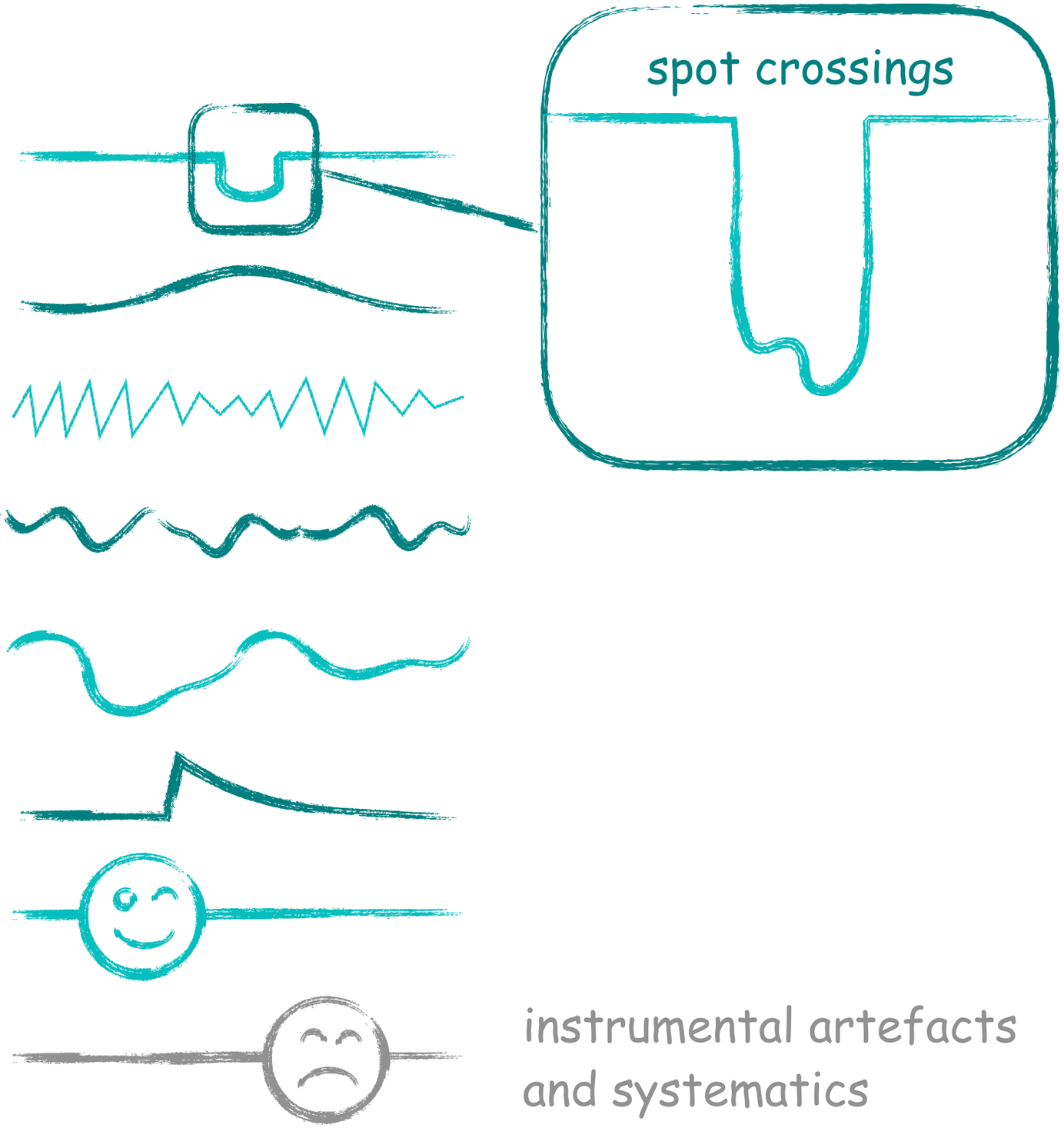

instrumental artefacts
and systematics

transits

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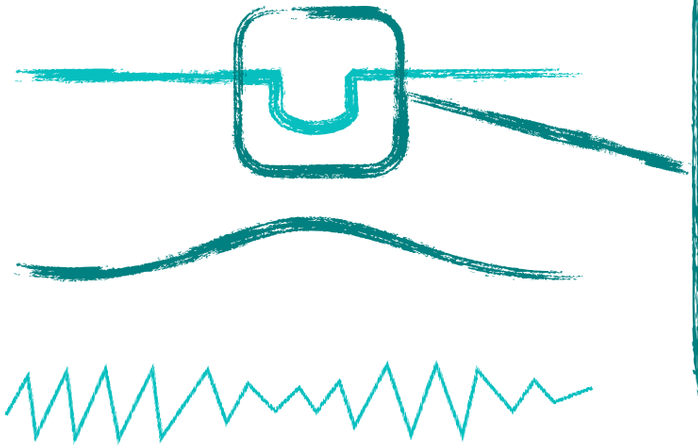

spot crossings

this talk

instrumental artefacts
and systematics

WHY?

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- test ability to measure parameters of rotation, activity, etc…
- one of many ingredients in simulations also including instrumental effects, pulsations, etc….

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- physical models (e.g. spot models)?
  - can be slow
  - have we got the model right?

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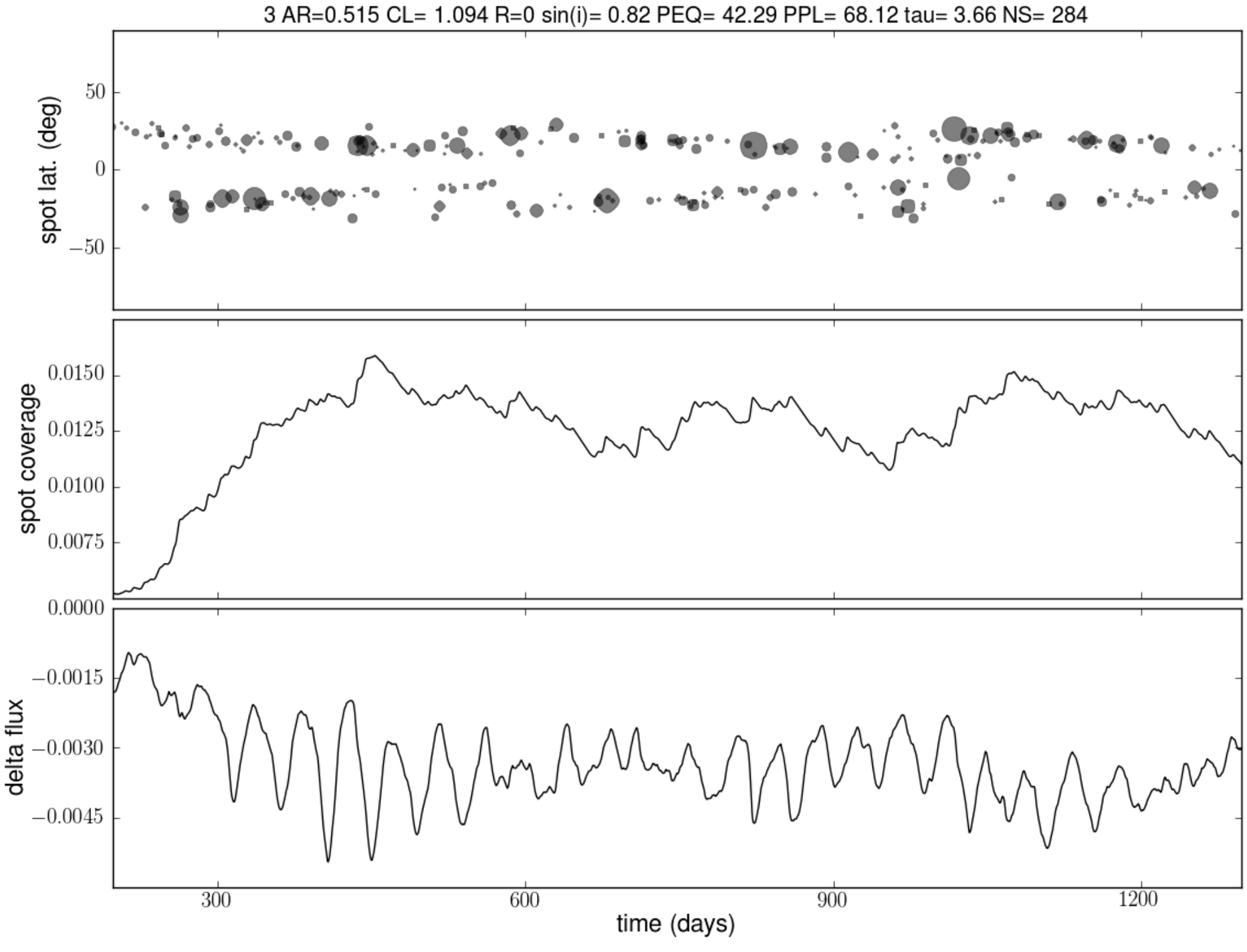
- physical models (e.g. spot models)?
  - can be slow
  - have we got the model right?
- use Kepler light curves as templates
  - multiple physical (and instrumental) effects mixed
  - no ground truth!

SPOT MODELS

Aigrain, Llama et al. (2015)



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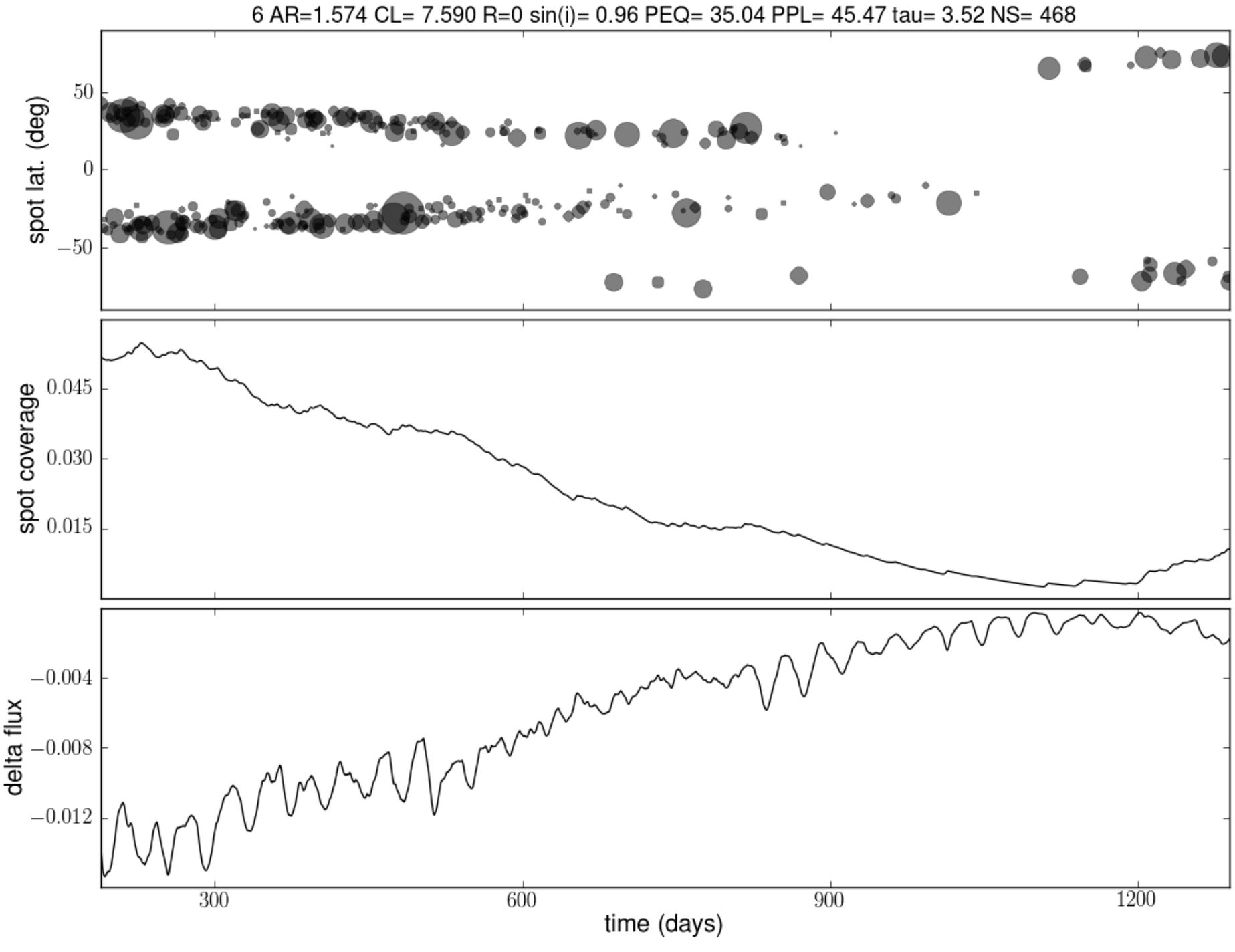

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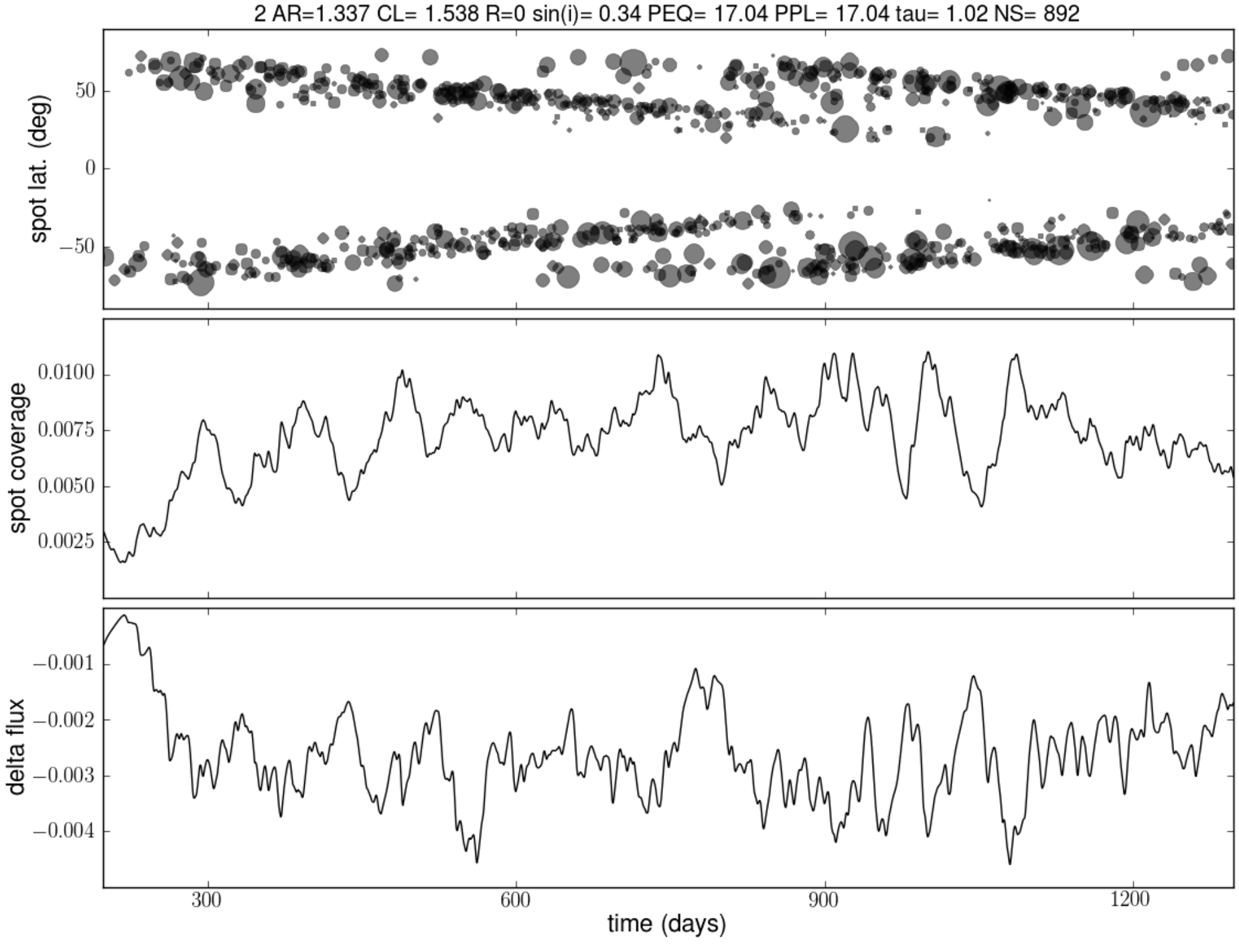
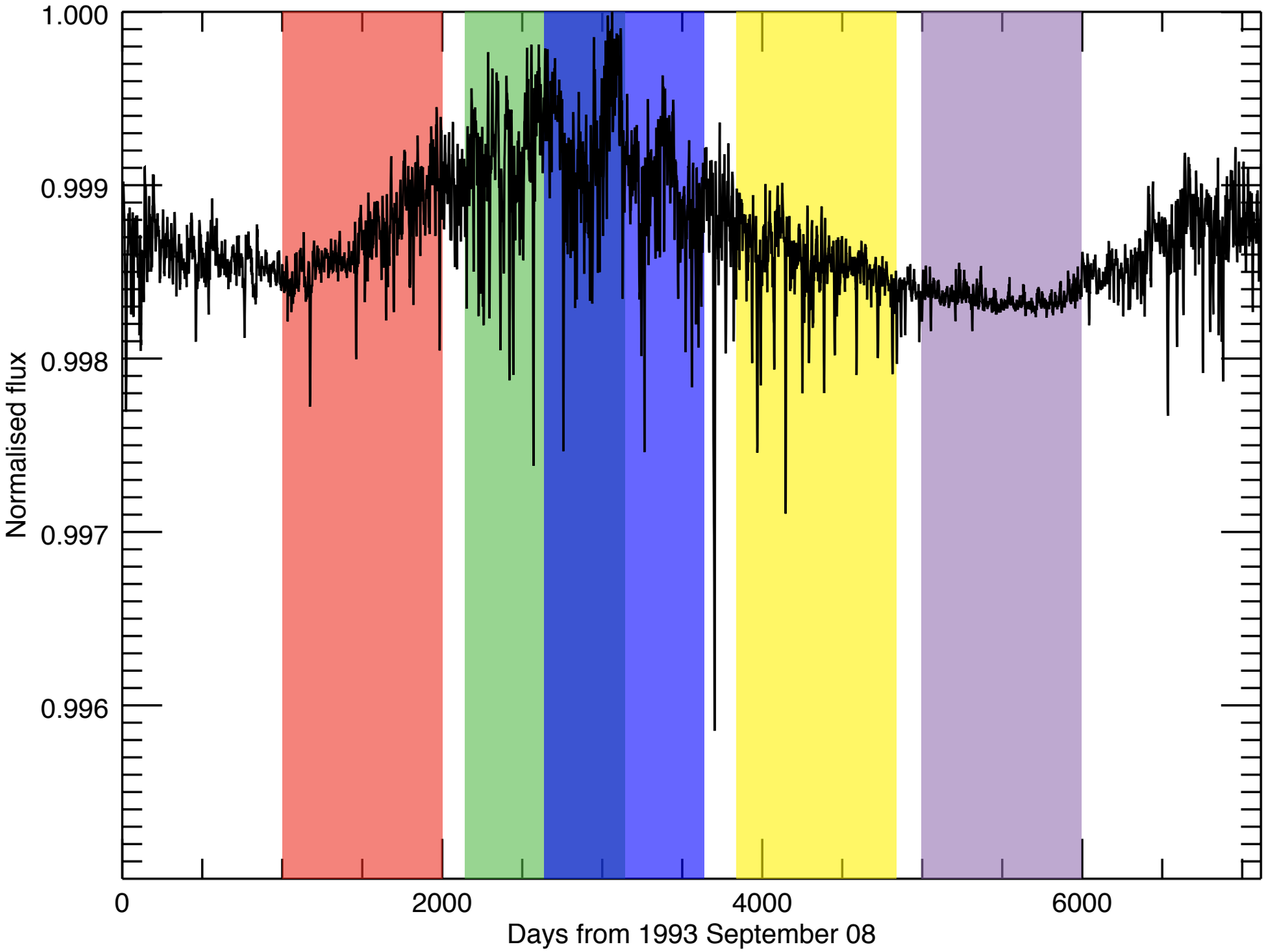
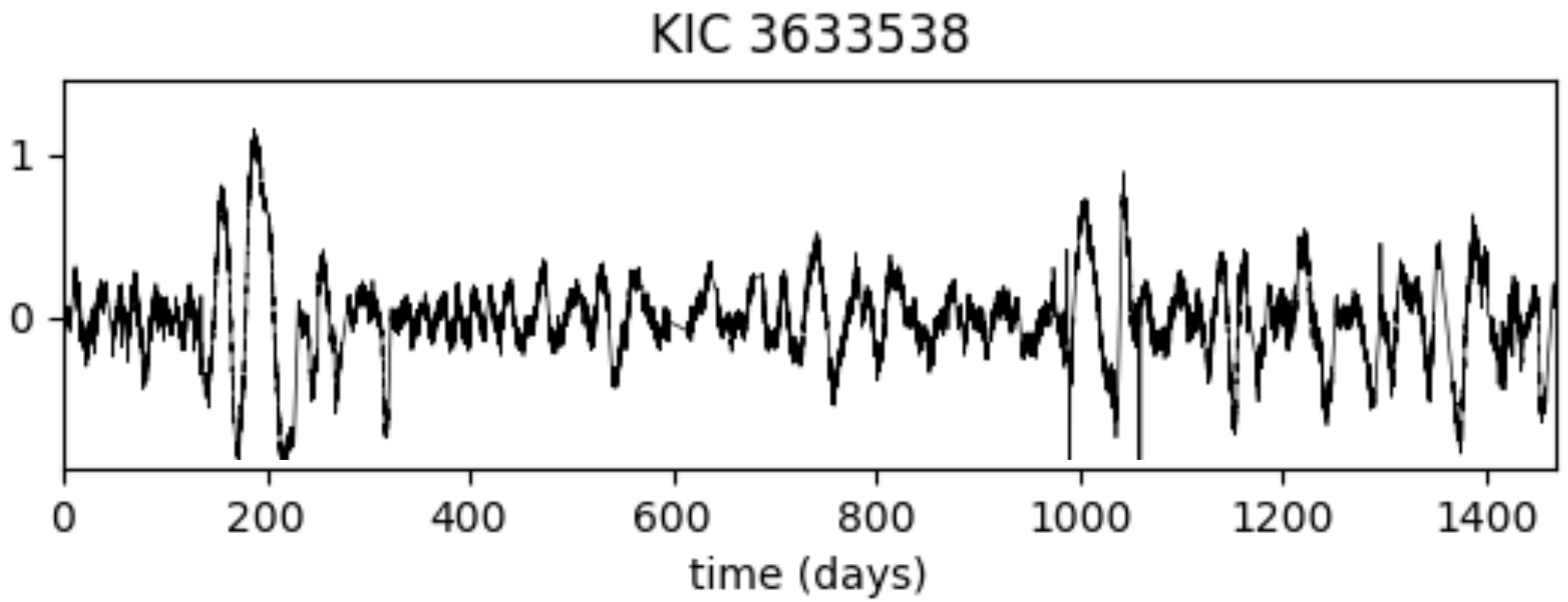


THE SUN


1.000
0.999
0.998
0.997
0.996
Normalised flux
0
2000
4000
6000
Days from 1993 September 08

KEPLER LIGHT CURVES



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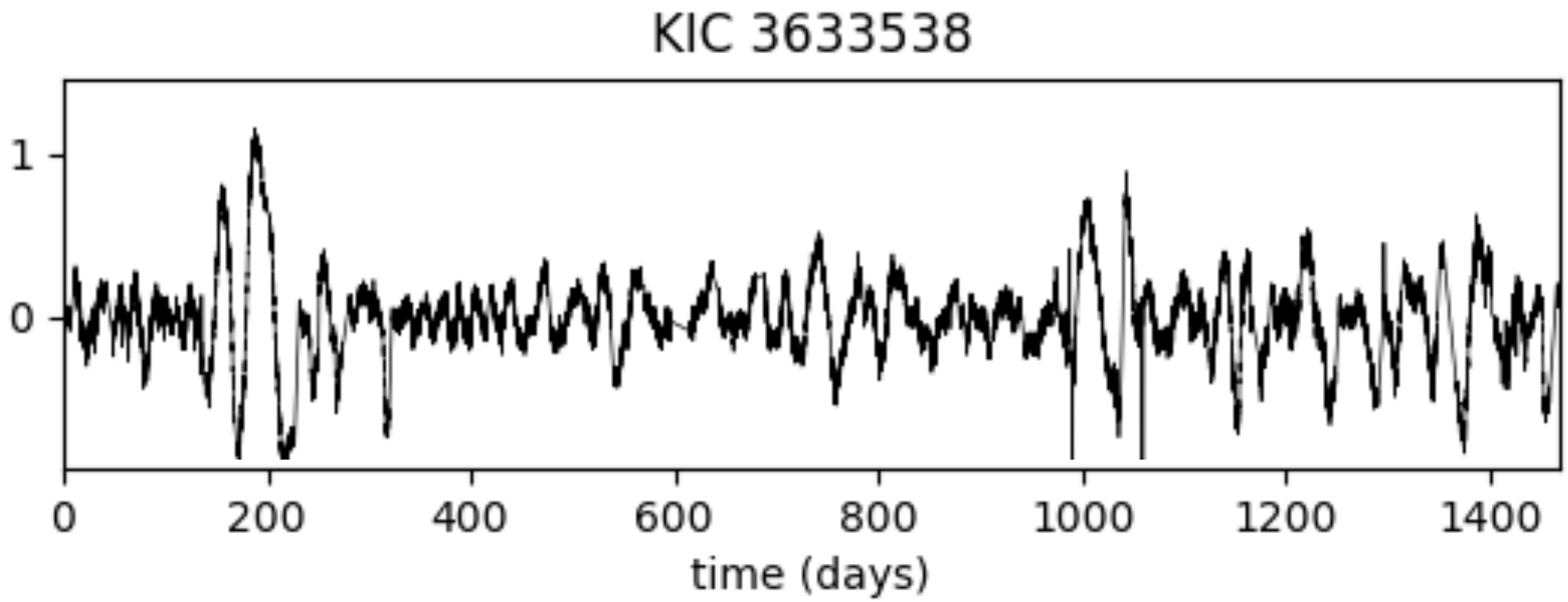
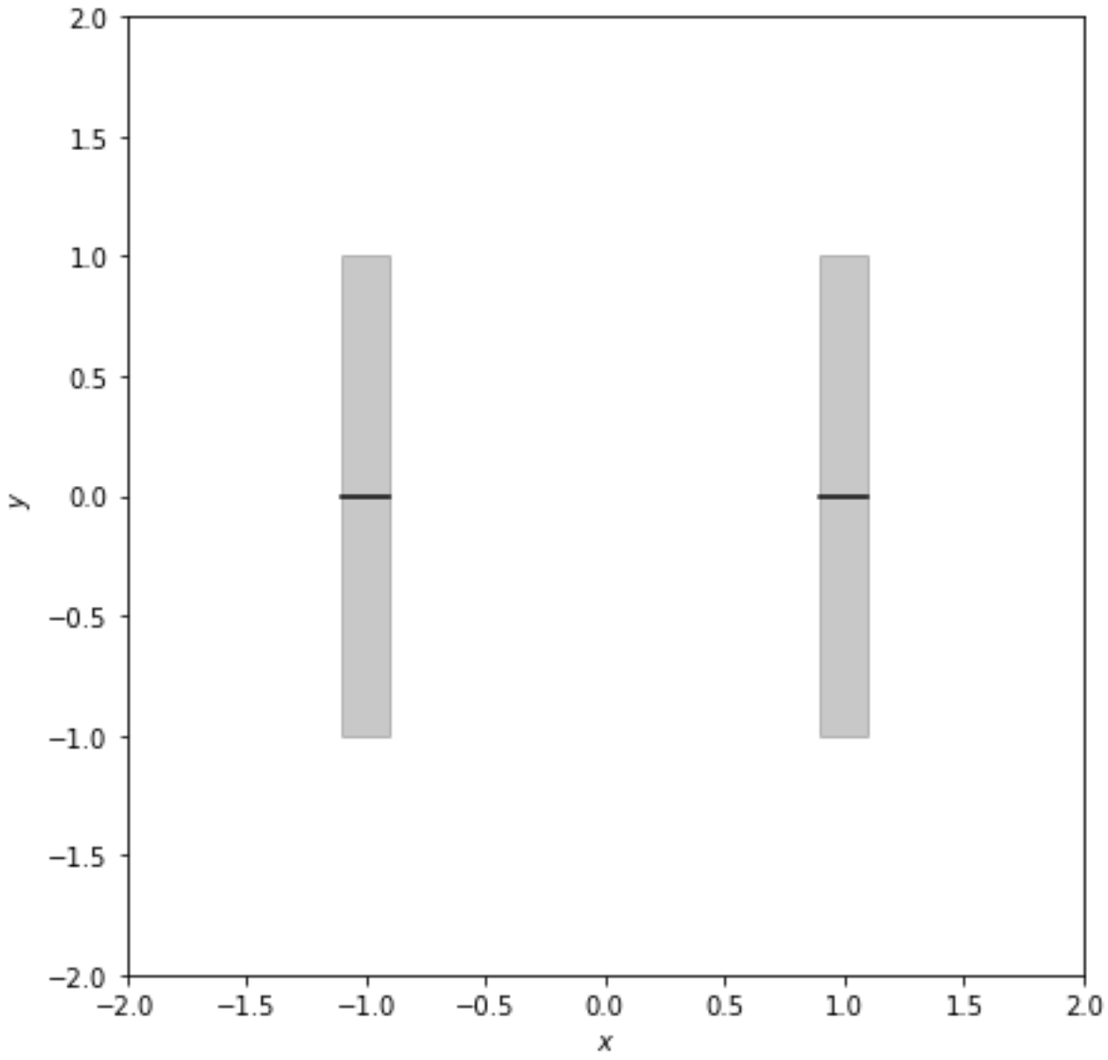


- problems:
  - sparser time-sampling (512s vs 2.5s)
  - different noise properties
  - quarter-to-quarter discontinuities
  - residual systematics

GAUSSIAN PROCESSES

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}, \begin{bmatrix} \sigma_1^2 & C \\ C & \sigma_2^2 \end{bmatrix}\right),$$



$$p(y_1) = \mathcal{N}(\mu_1, \sigma_1^2).$$

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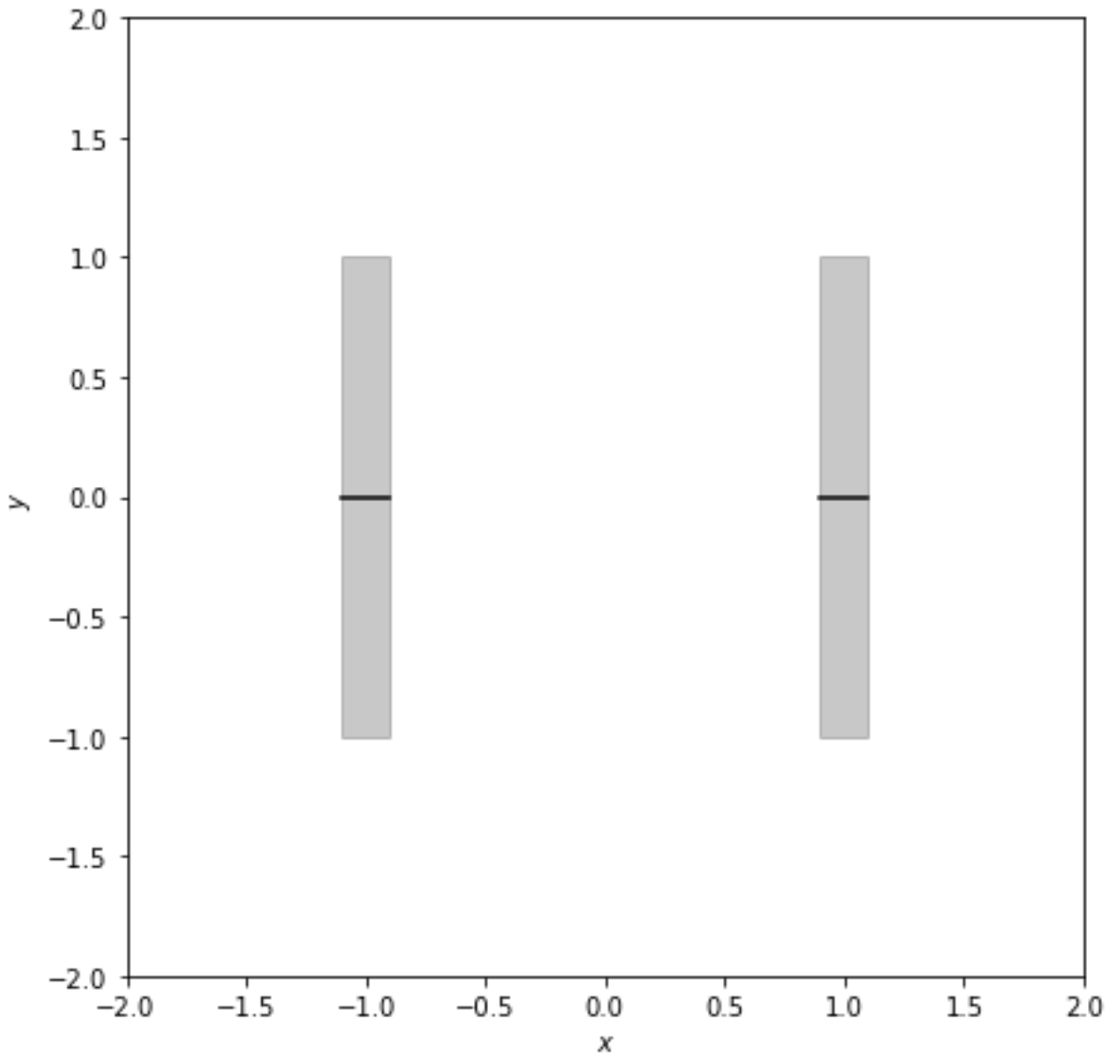
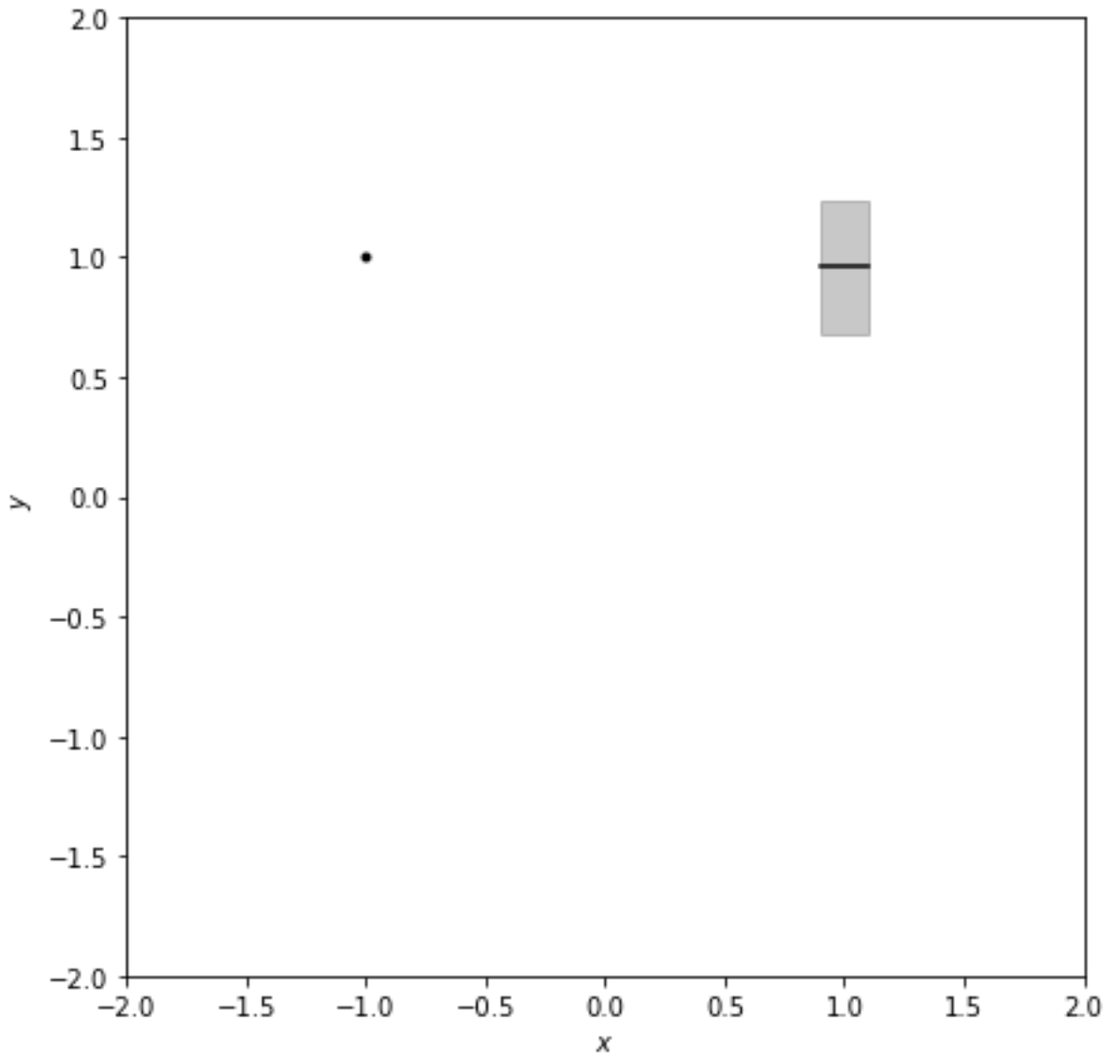




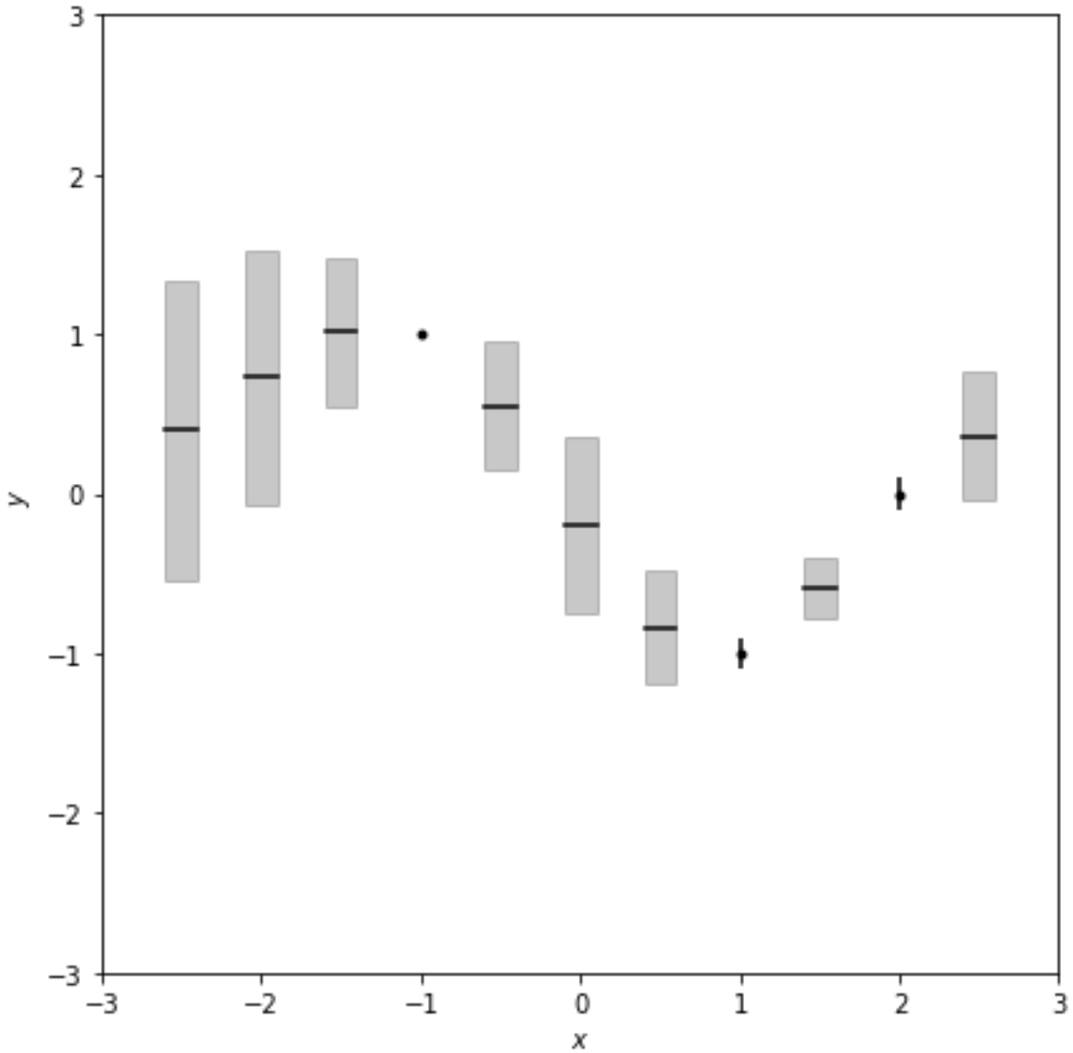
$$p(y_1) = \mathcal{N}(\mu_1, \sigma_1^2).$$

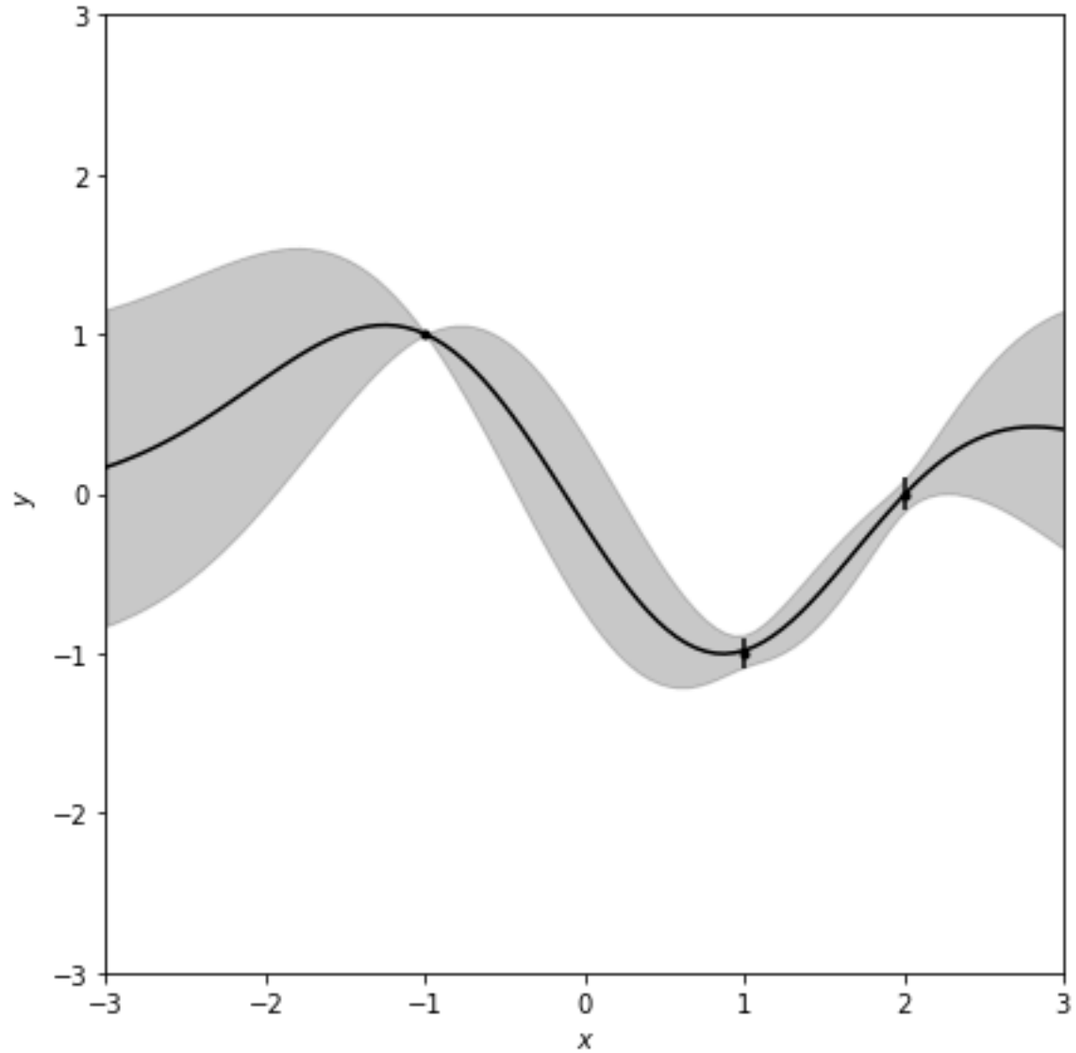
$$p(y_1 \mid y_2) = \mathcal{N}\left(\mu_1 + C(y_2 - \mu_2) / \sigma_2^2,\ \sigma_1^2 - C^2\sigma_2^2\right).$$

GAUSSIAN PROCESSES

$$\mathbf{y} \sim \mathcal{N}(\mathbf{m},\, K)$$

$$K_{ij} = k(x_i,\, x_j) = A\exp\Big[-\Gamma(x_i - x_j)^2\Big],$$





predictive distribution $\mathrm{p}(\mathbf{y}_* \,|\, \mathbf{y},\, k) = \mathcal{N}(K_*^T K^{-1}\mathbf{y},\, K_{**} - K_*^T K^{-1} K_*).$

likelihood $\mathrm{p}(\mathbf{y} \,|\, \mathbf{x}) = \mathcal{N}(\mathbf{y} \,|\, \mathbf{0},\, K + \sigma^2 \mathbb{I}).$

FAST, PHYSICALLY MOTIVATED GP FOR STELLAR LIGHT CURVES

- celerite Gaussian process code (Foreman-Mackey et al. 2017, `celerite.readthedocs.io`)

$$k_j(\tau_{nm}) = a_j \, \exp\left(-c_j \, \tau_{nm}\right) \cos\left(d_j \, \tau_{nm}\right)$$

$$S_j(\omega) = \frac{1}{\sqrt{2\,\pi}} \frac{a_j}{c_j} \left[\frac{1}{1 + \left(\frac{\omega - d_j}{c_j}\right)^2} + \frac{1}{1 + \left(\frac{\omega + d_j}{c_j}\right)^2} \right]$$

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stochastically driven, damped simple harmonic oscillator

$$\left[\frac{\mathrm{d}^2}{\mathrm{d}t^2} + \frac{\omega_0}{Q}\frac{\mathrm{d}}{\mathrm{d}t} + \omega_0^2\right] y(t) = \epsilon(t)$$

$$S(\omega) = \sqrt{\frac{2}{\pi}} \frac{S_0\,\omega_0^4}{(\omega^2 - \omega_0^2)^2 + \omega_0^2\omega^2/Q^2}$$

$$\begin{aligned} a_j &= S_0\,\omega_0\,Q \\ b_j &= \frac{S_0\,\omega_0\,Q}{\sqrt{4\,Q^2 - 1}} \\ c_j &= \frac{\omega_0}{2\,Q} \\ d_j &= \frac{\omega_0}{2\,Q}\sqrt{4\,Q^2 - 1} \end{aligned}$$

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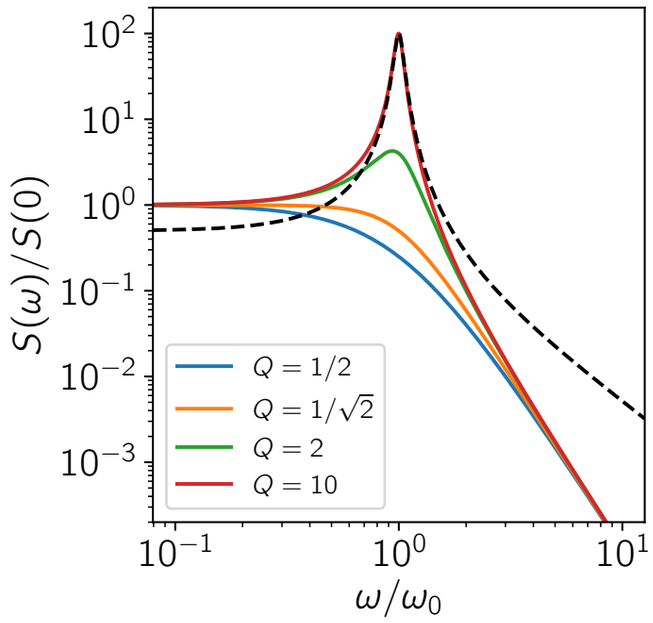
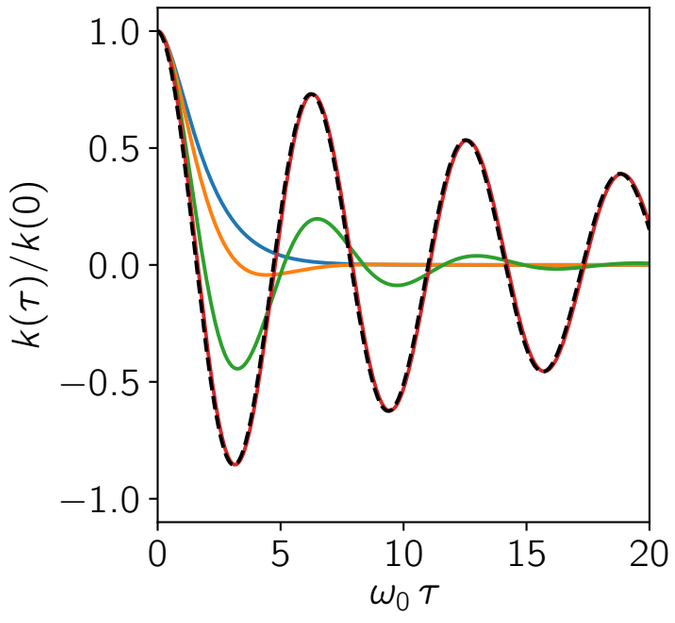
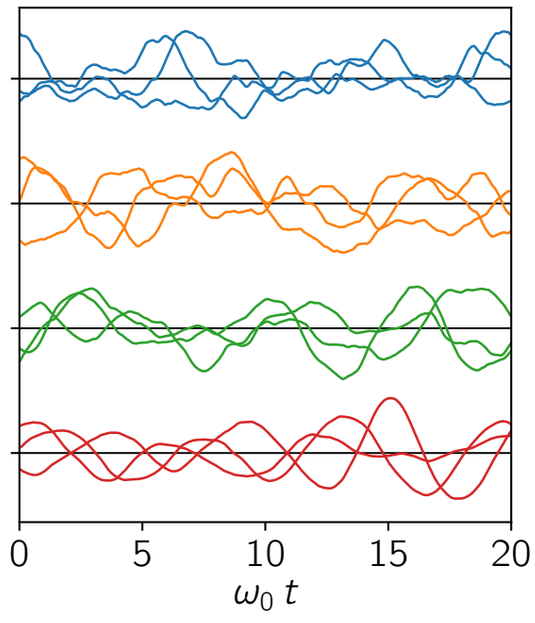
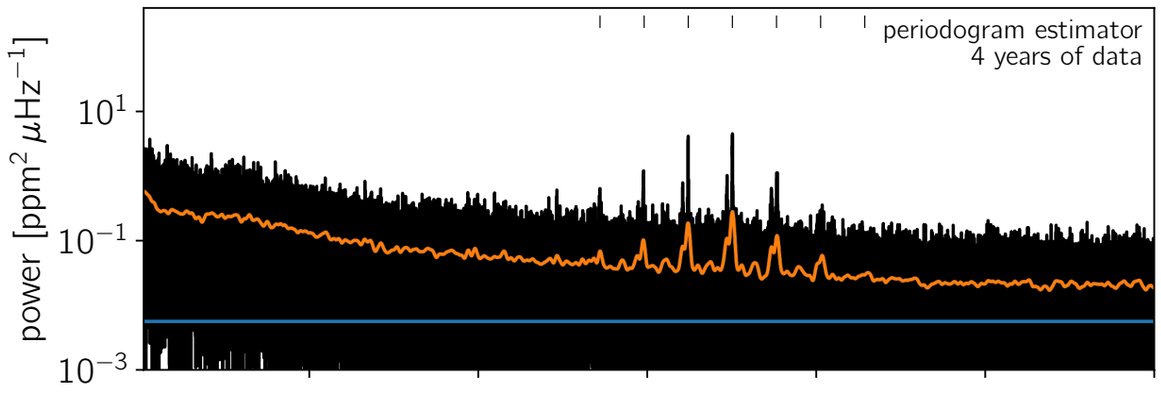






ASIDE: TIME-DOMAIN ASTEROSEISMOLOGY



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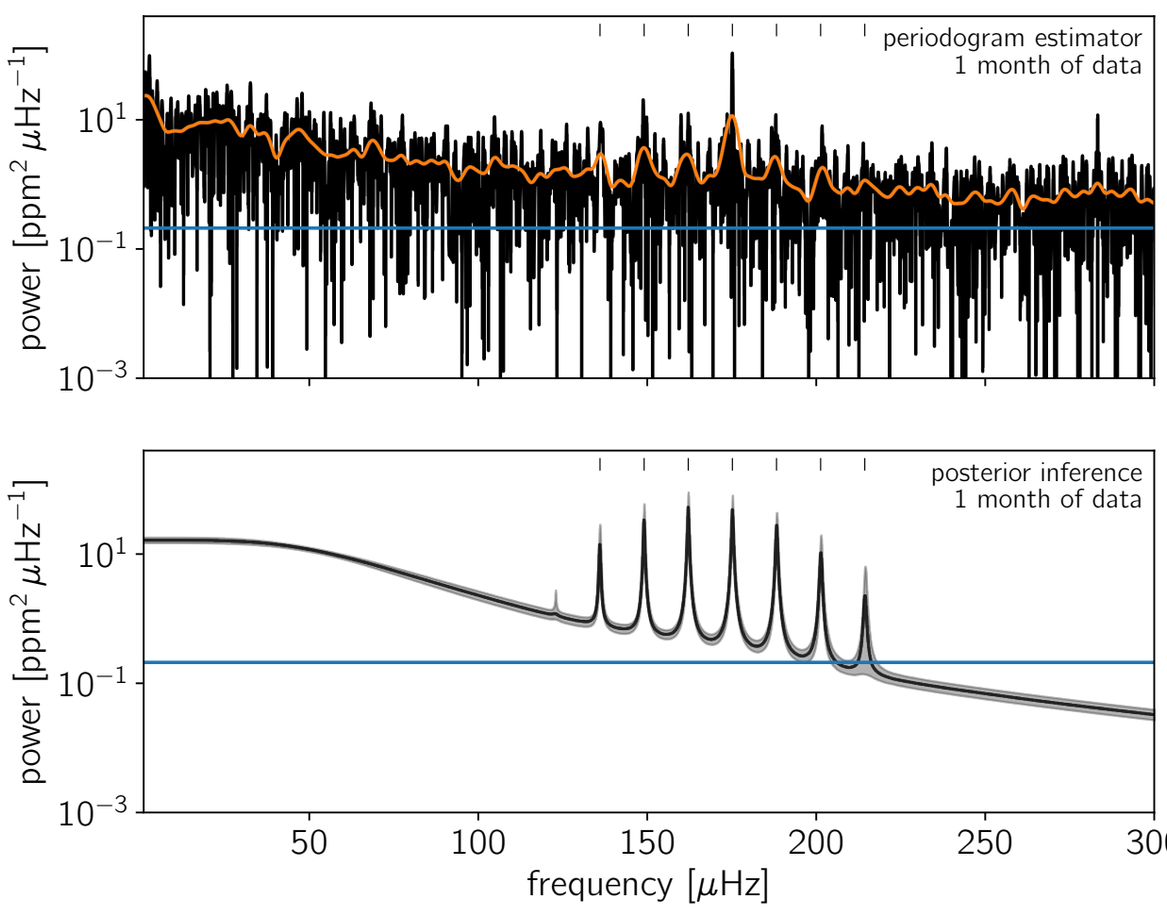
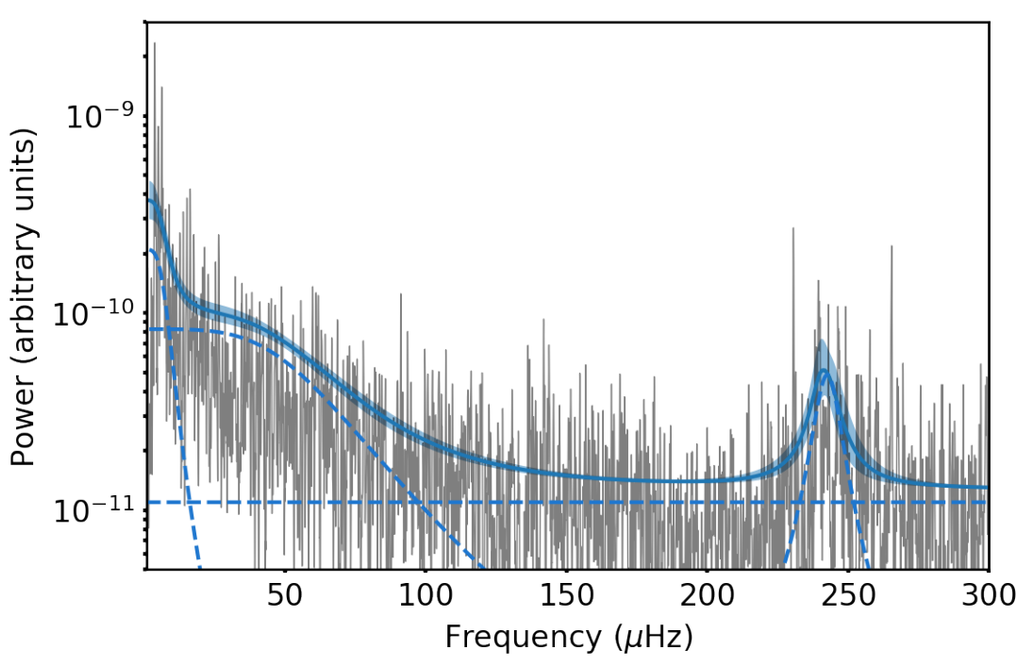
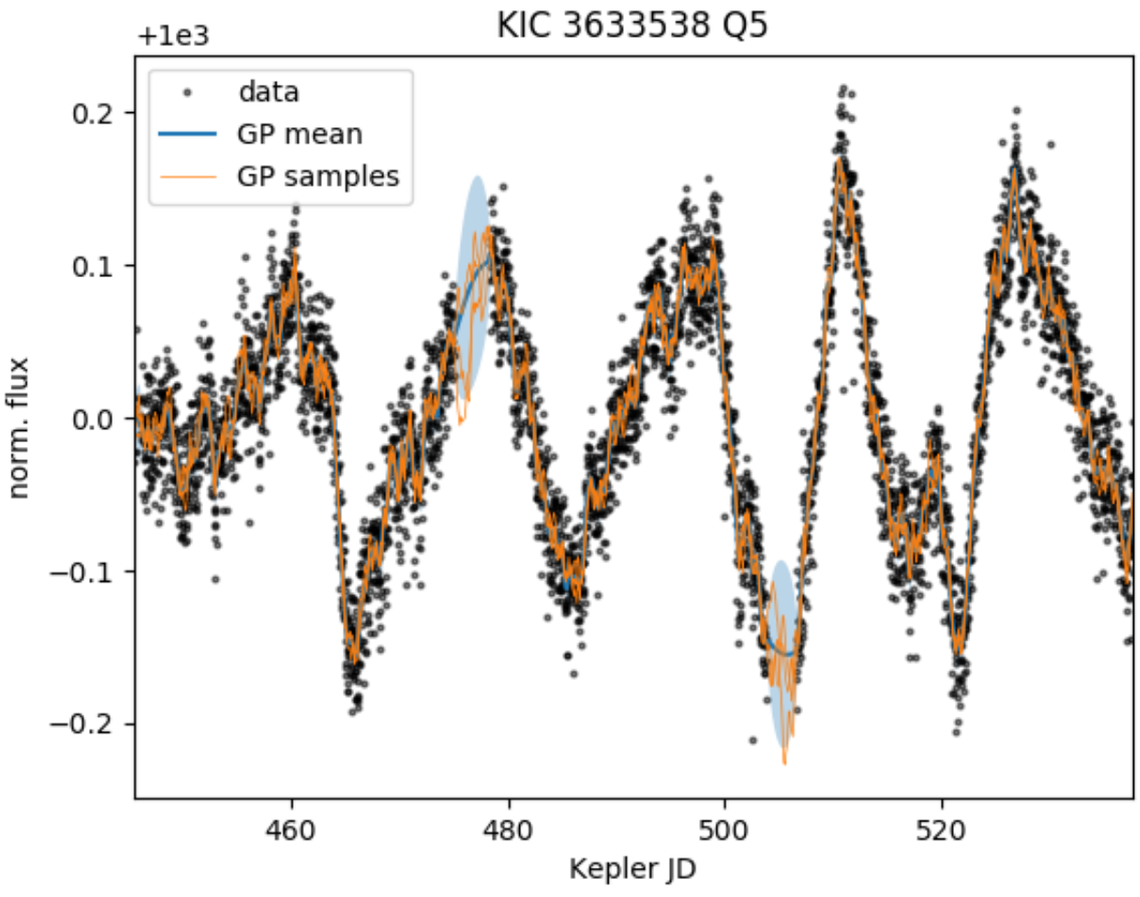
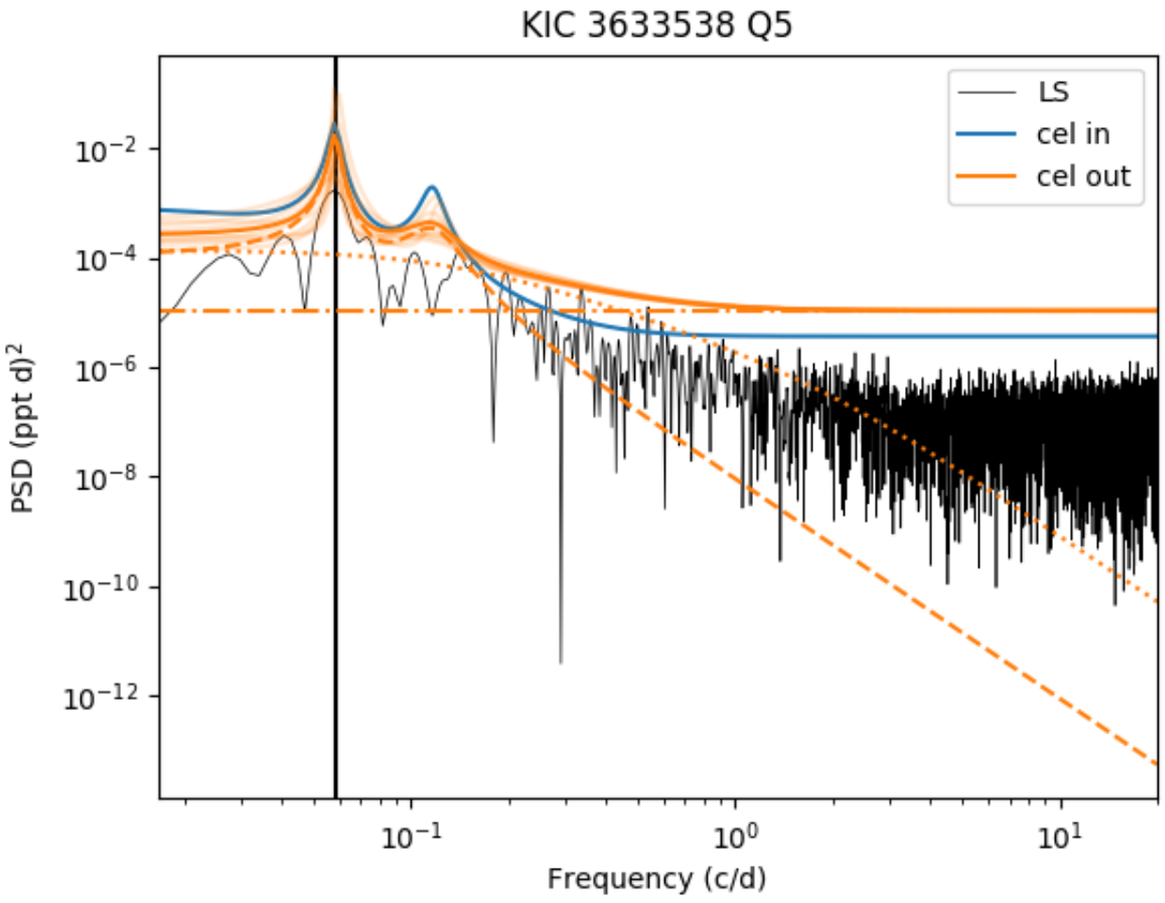


Grunblatt et al. (2018)



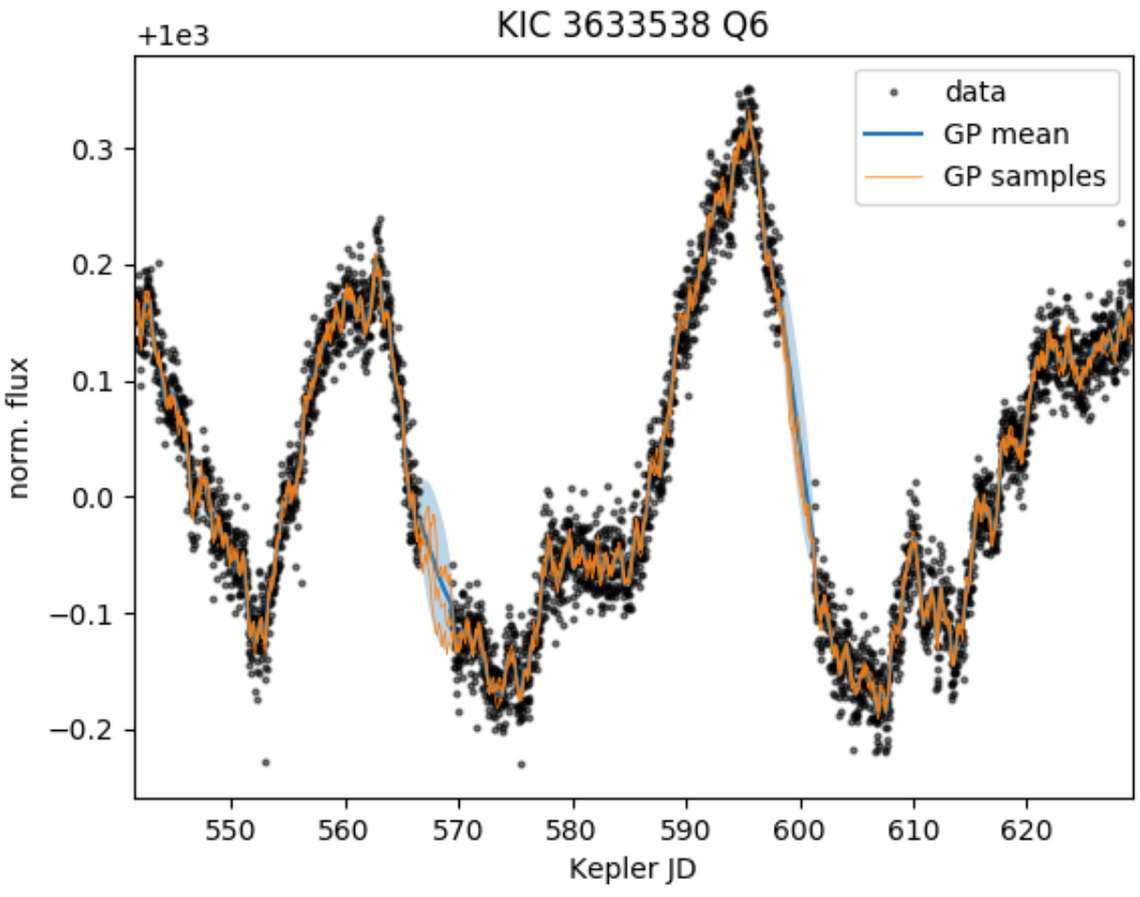
CELERITE MODEL FOR ACTIVITY VARIABILITY

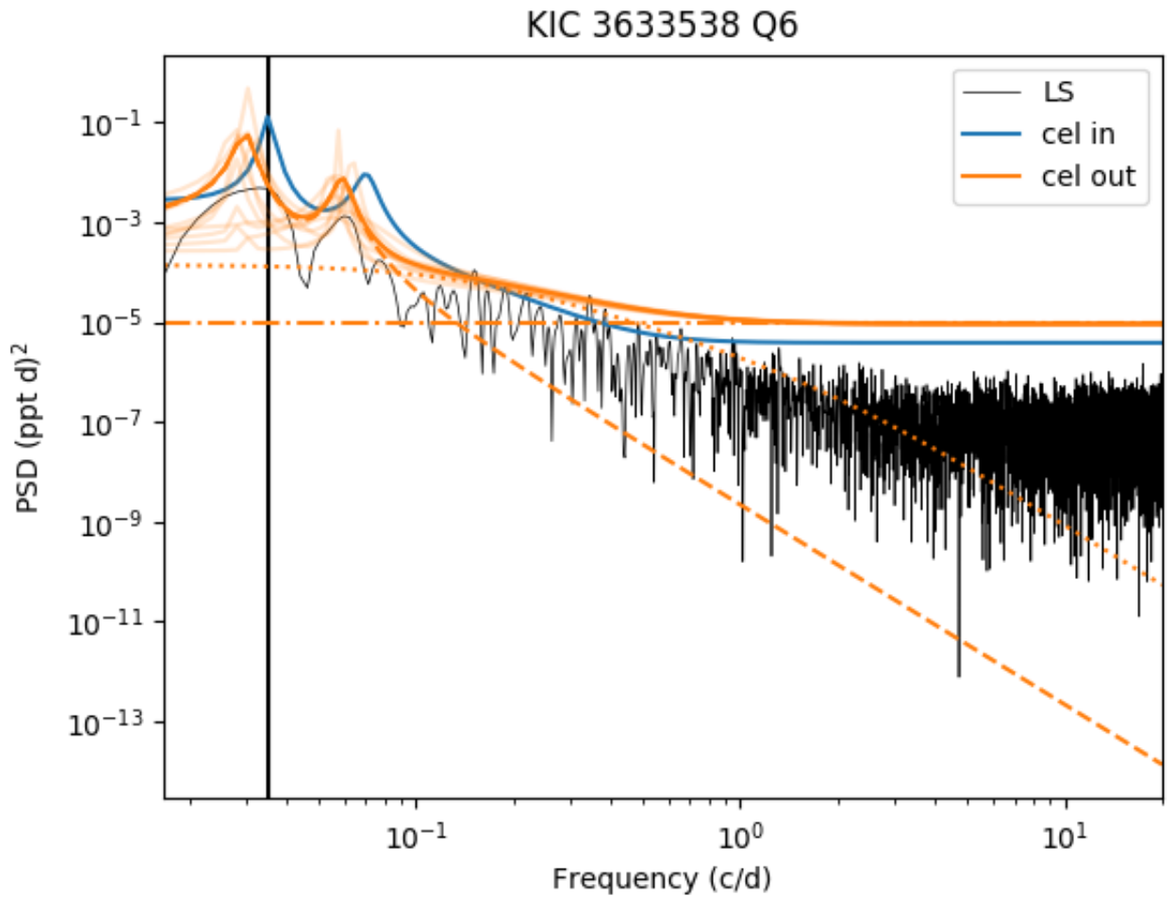




- sum of 2 high-Q SHOs, one at P and one at P/2
- SHO w. Q=1/sqrt(2) to represent granulation (unresolved for MS stars at Kepler long cadence)
- additional white noise term to account for any extra noise

CELERITE MODEL FOR STARSPOT VARIABILITY





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SIMULATING PLATO LCS

- fit all available quarters for a Kepler target
- obtain weighted mean of GP model parameters from all quarters
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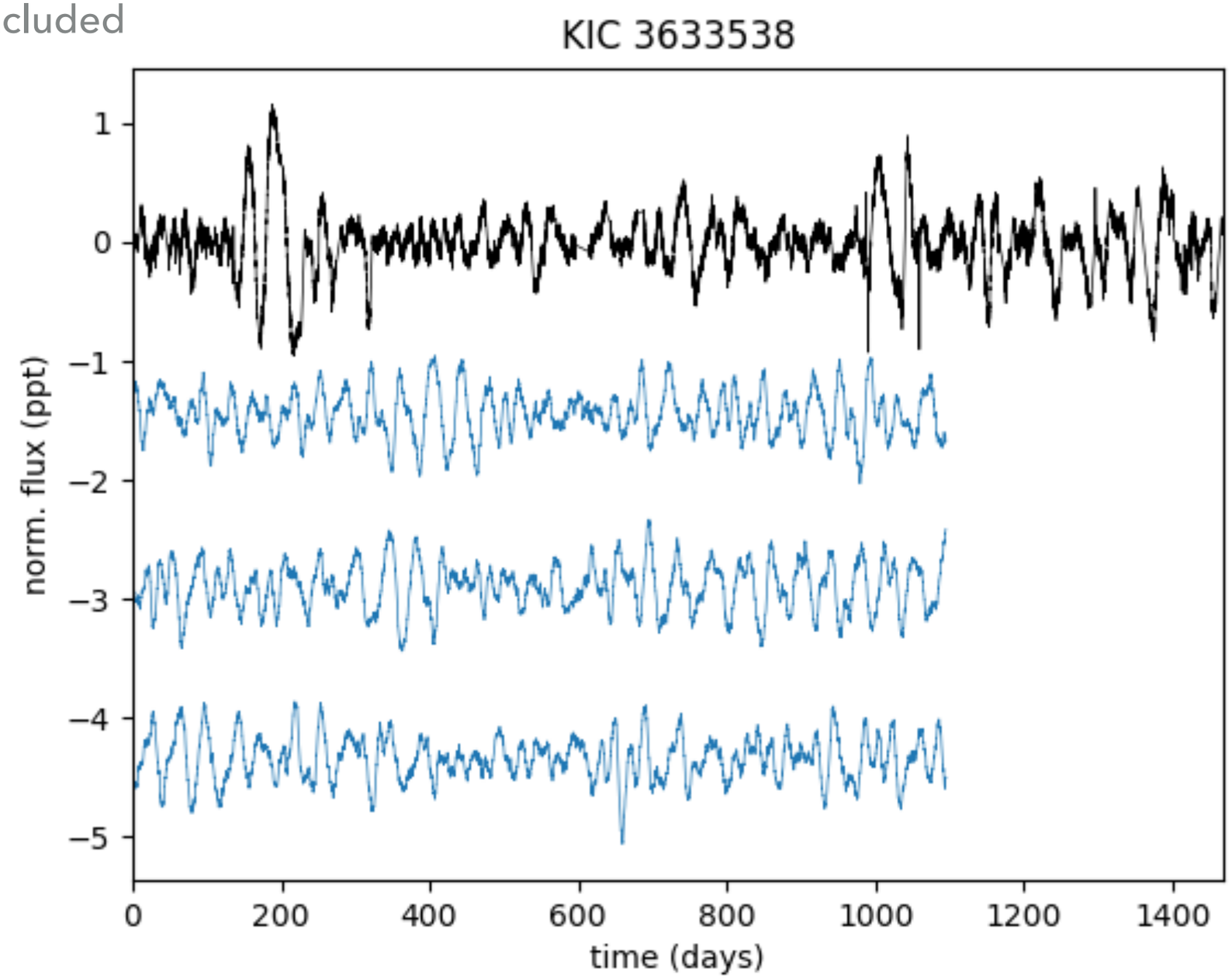

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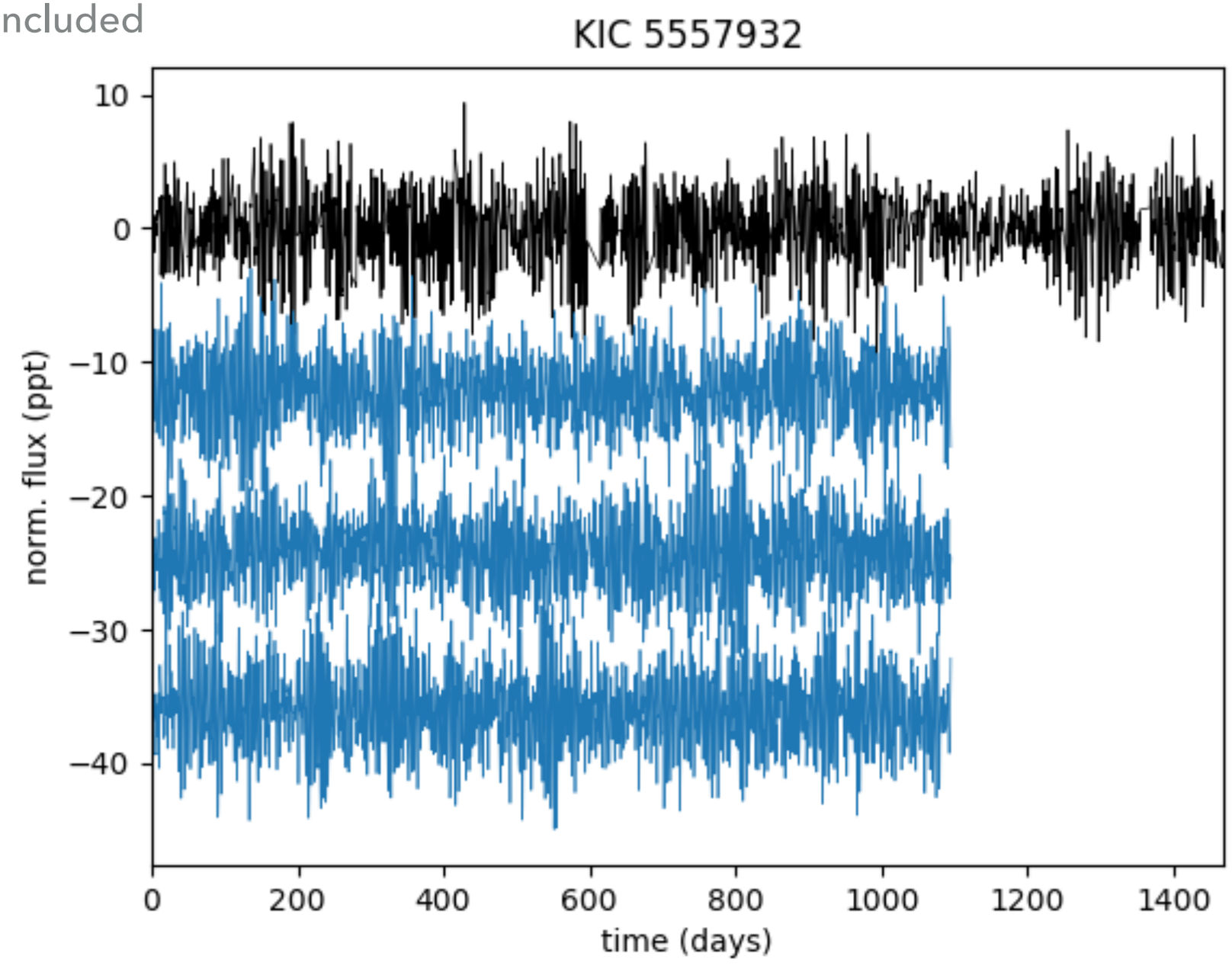

WHICH KEPLER STARS?

- so far I've used brightest ~50 MS & sub giant stars from KIC in each 200K T_{eff} bin (*log g* cut of Ciardi et al. 2010)
- could use APOKASC or CKS samples instead
  - better stellar parameters, but other issues
  - input welcome!
- will make available in coming month
  - light curves (via Oxford or PSM website)
  - code (via GitHub)
  - email suz@astro.ox.ac.uk if interested

RELATION BETWEEN GP AND STELLAR PARAMETERS?

"granulation"

extra white noise

"rotation"