Identifying Astronomical Transients in Large Scale Surveys using Gaussian Processes

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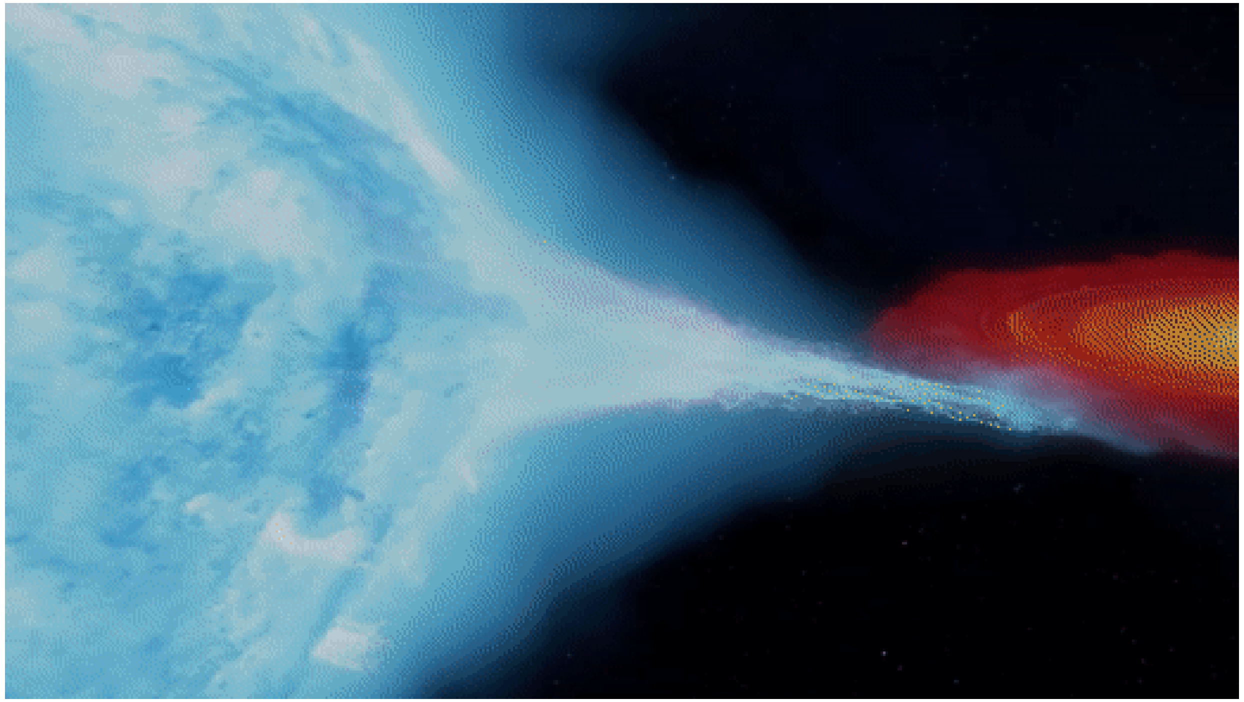
Twinkle twinkle little star…

Twinkle twinkle little star…
How I wonder what you are!

Twinkle twinkle…

A *transient* is an astrophysical phenomenon whose brightness changes over observable time.

- Supernovae
- Variable stars, e.g., pulsating, eclipsing binaries.
- Gamma-ray bursts (GRBs)
- Fast radio bursts (FRBs)
- Transiting planets
- Active galactic nuclei (AGN)
- Accreting blackholes
- and lots more…



Artist’s impression of the Cygnus X-1 system. Credit: ICRAR

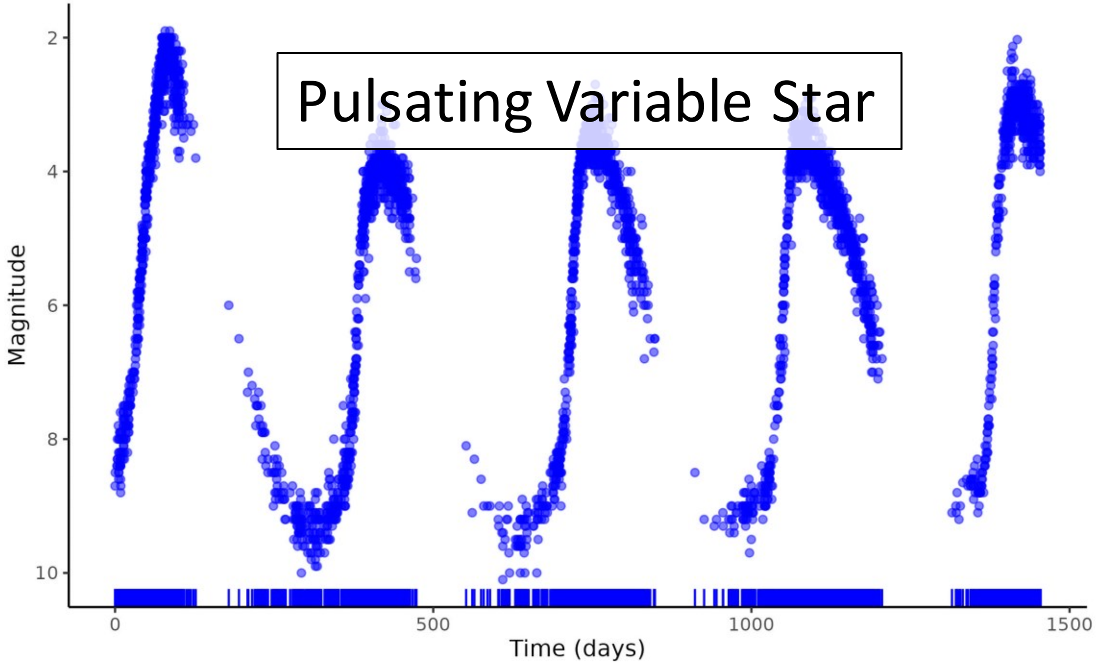
Light Curves

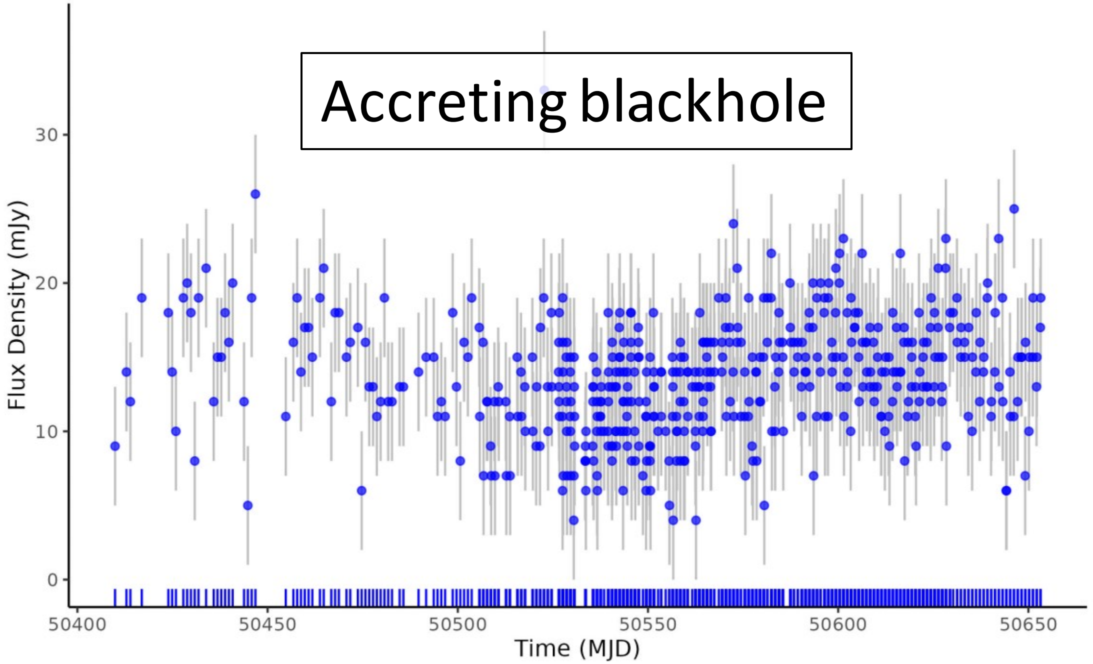
Light curves are time-series that describe the brightness of an astronomical source over time.

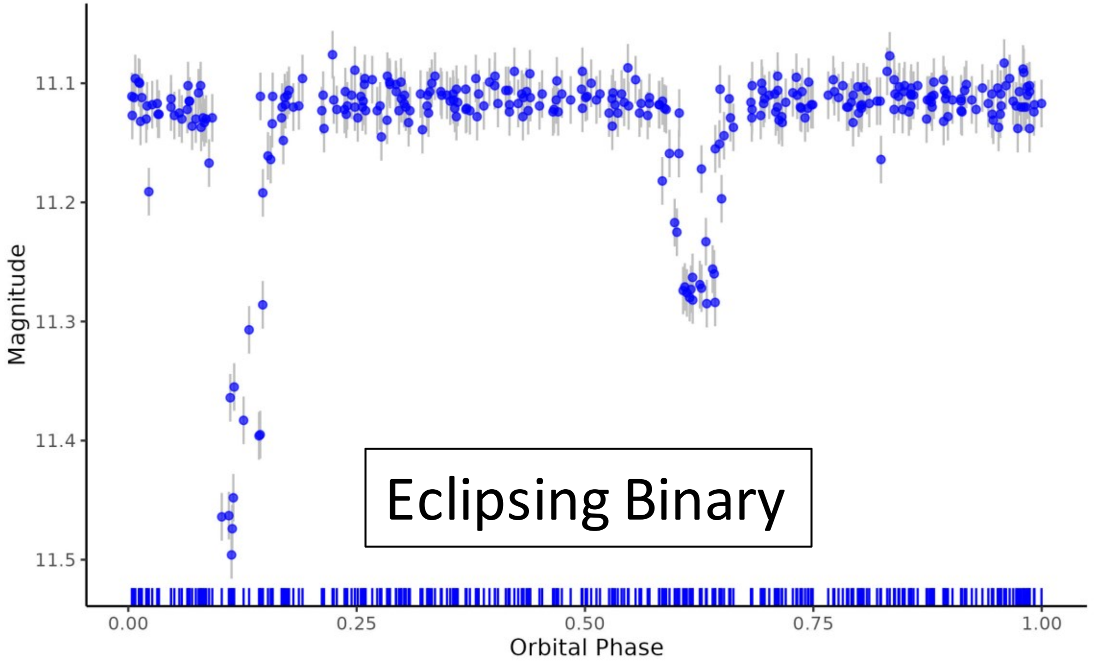
The shape of a light curve can reveal the type of phenomenon that underlies that source.

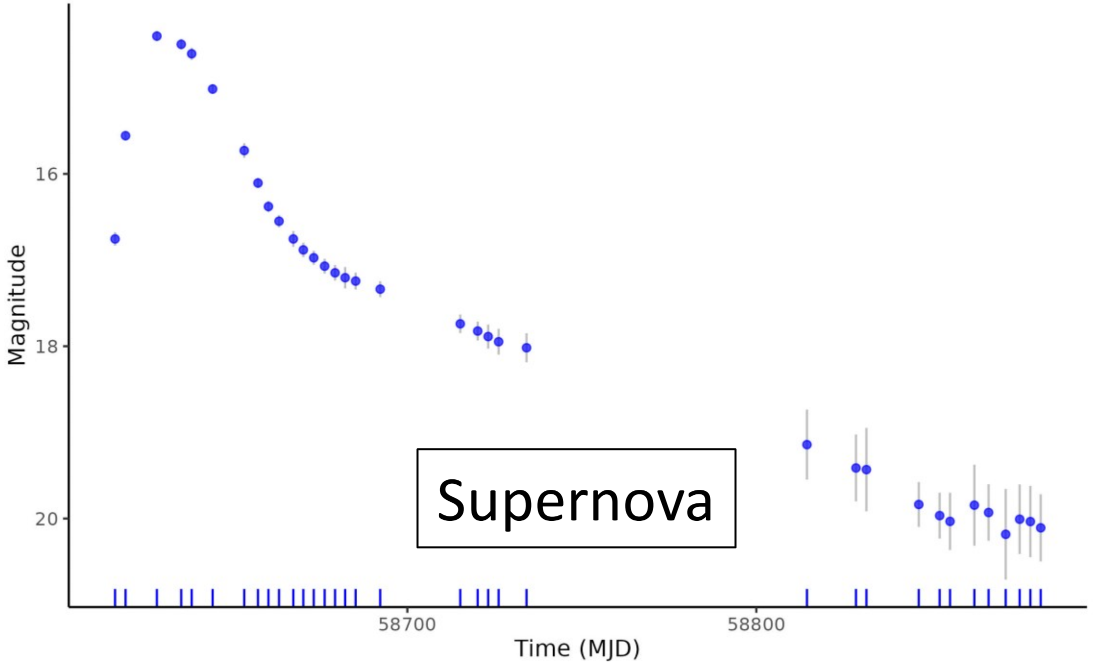
But beware!

- Sparsity of observations
- Uneven sampling rates
- Varying noise levels


Pulsating Variable Star
Magnitude
Time (days)
2
4
6
8
10
0
500
1000
1500


Accreting blackhole
Flux Density (mJy)
Time (MJD)
0
10
20
30
50400
50450
50500
50550
50600
50650


Eclipsing Binary
Magnitude
Orbital Phase
11.1
11.2
11.3
11.4
11.5
0.00
0.25
0.50
0.75
1.00

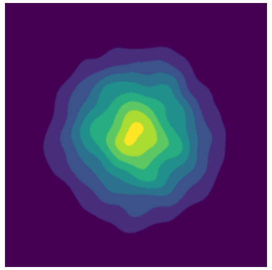

Supernova
Magnitude
Time (MJD)
16
18
20
58700
58800

Multivariate Normal $\mathbf{Y} \sim \mathrm{MVN}(\mathbf{0}, \boldsymbol{\Sigma}_{n\times n})$

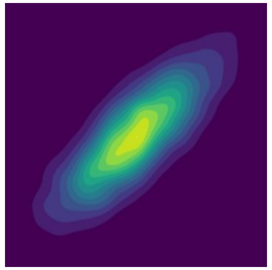
$\boldsymbol{Y}$ is a vector of n Gaussian random variables.

$$\begin{bmatrix} Y_1 \\ \vdots \\ Y_n \end{bmatrix} = \boldsymbol{Y} \sim MVN(\boldsymbol{\mu}, \boldsymbol{\Sigma}_{n\times n}),\ \boldsymbol{\Sigma}_{n\times n} = \begin{bmatrix} \Sigma_{11} & \cdots & \Sigma_{1n} \\ \vdots & \ddots & \vdots \\ \Sigma_{n1} & \cdots & \Sigma_{nn} \end{bmatrix}$$

where $\boldsymbol{\mu} = (\mu_1, \cdots, \mu_n)$ and $\boldsymbol{\Sigma}$ is a $n \times n$ covariance matrix.



$$\Sigma = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$



$$\Sigma = \begin{bmatrix} 1 & 0.8 \\ 0.8 & 1 \end{bmatrix}$$

- Symmetric, positive semi-definite matrix.
- Linear combinations of covariance matrices are also valid covariance matrices.

Gaussian Processes

Extend multivariate Gaussian to ‘infinite’ dimensions.

- Mean function, $\mu()$
- Covariance or **kernel function**, $\boldsymbol{k}()$

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \end{bmatrix} = \boldsymbol{Y} \sim GP(\boldsymbol{\mu}, \boldsymbol{\Sigma})$$

where $\boldsymbol{\mu} = \mu(t_i)$ and $\Sigma_{ij} = \boldsymbol{k}(\boldsymbol{t_i}, \boldsymbol{t_j})$, for $i, j = 1, 2, \ldots$

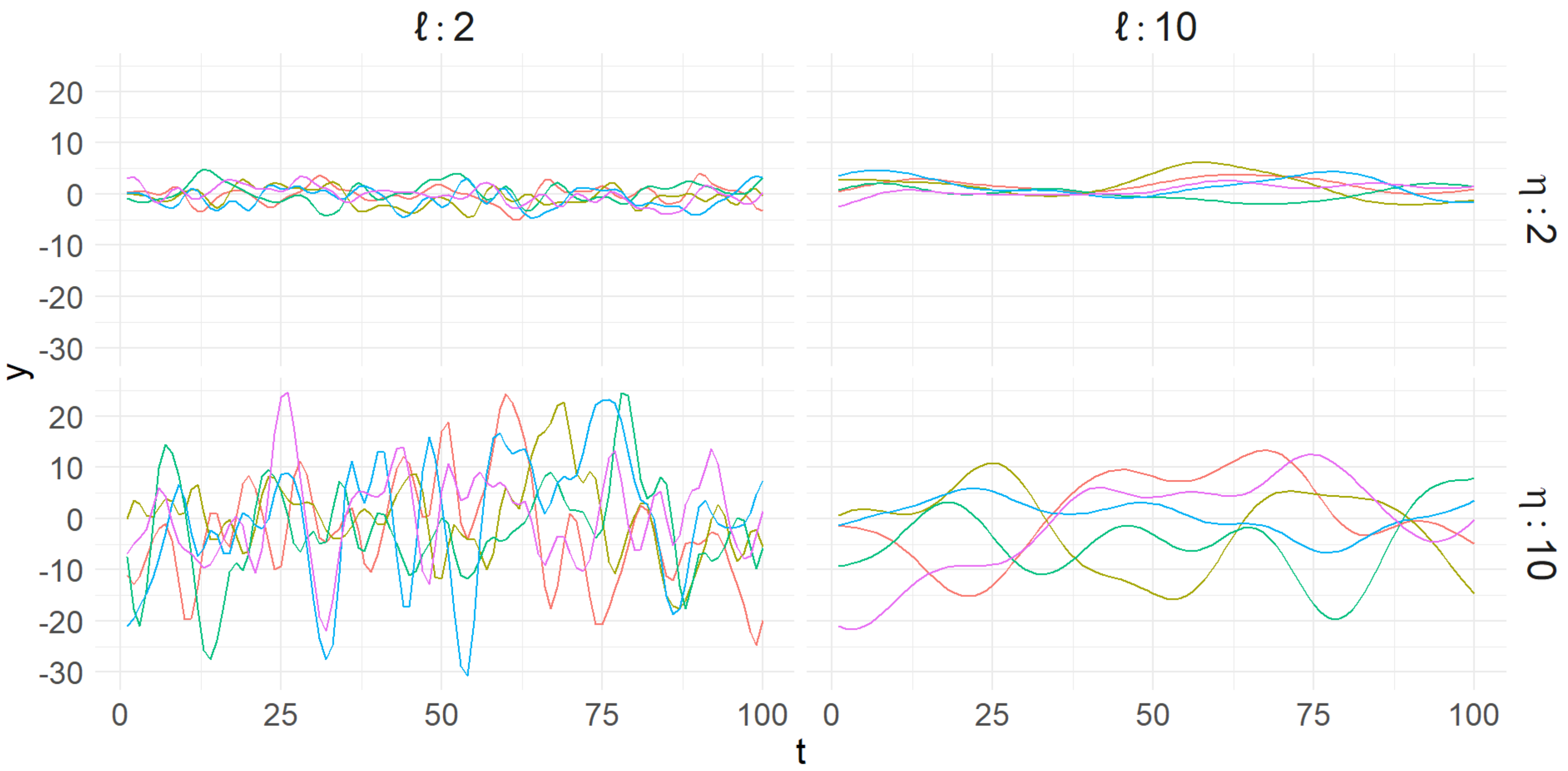
Rather than specifying a fixed covariance matrix with fixed dimensions, compute covariances using the kernel function.

Squared Exponential Kernel

$$k(\tau; \eta, \ell) = \eta \exp\left\{-\frac{1}{2\ell^2}\tau^2\right\}$$

Hyperparameters: Amplitude η, Lengthscale ℓ

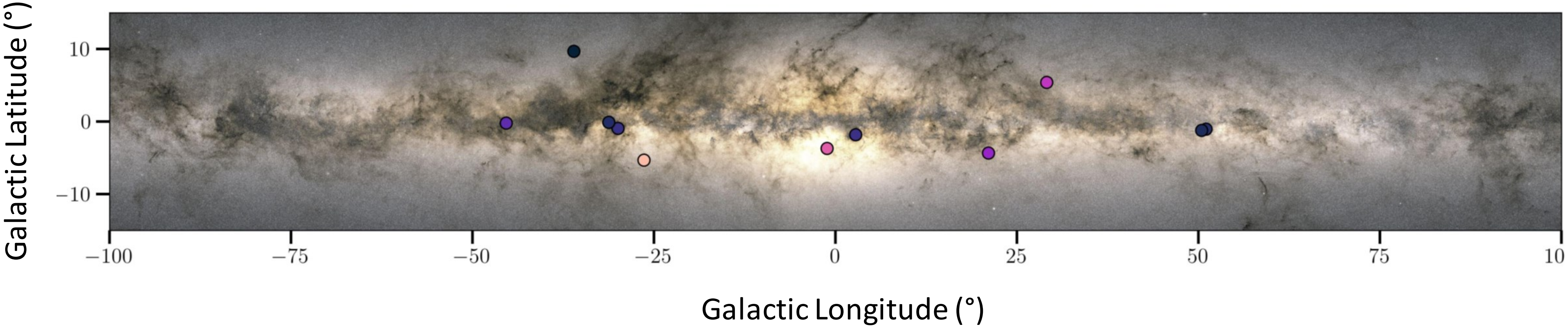
$\eta, \ell > 0, \tau = |t_i - t_j|$



ThunderKAT Survey

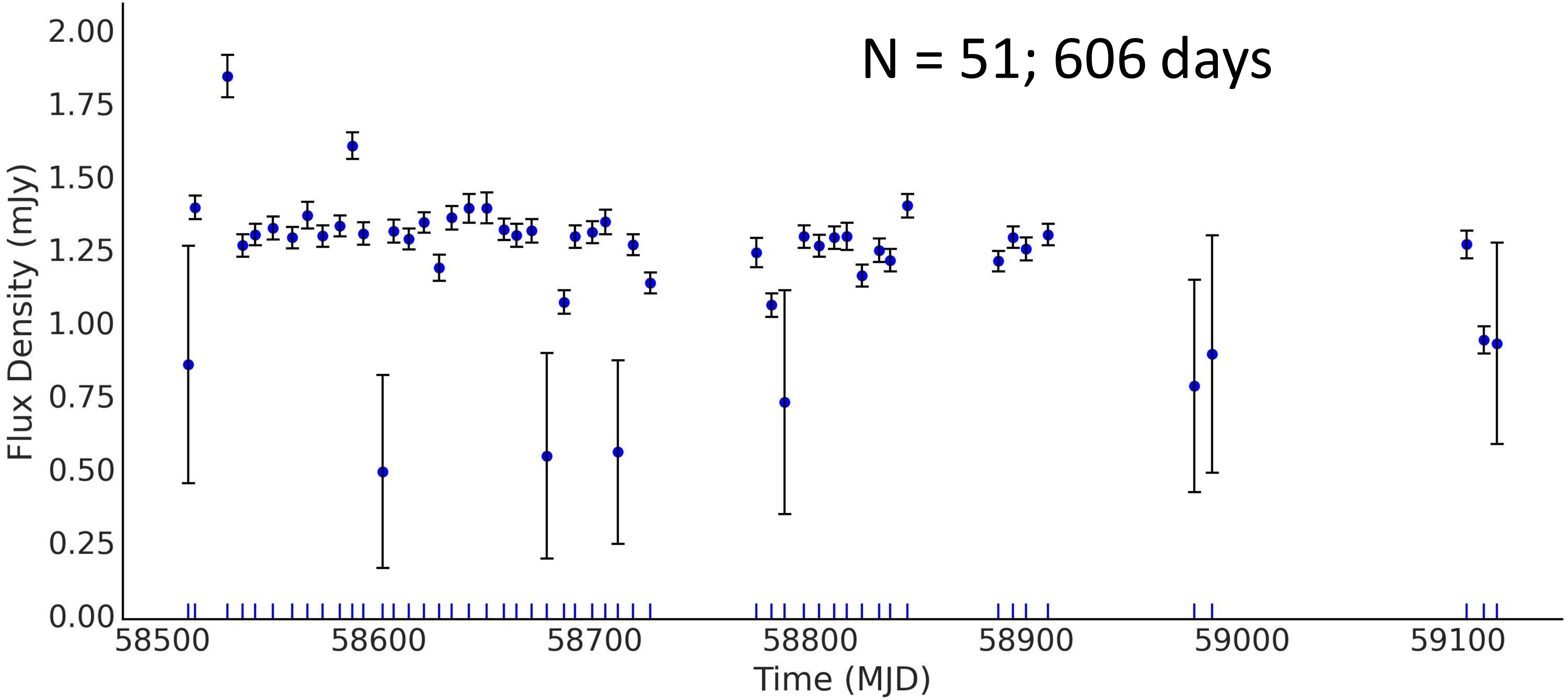
- N = 6,394 radio light curves
- Brightness measurements
- Standard errors

MeerKAT Radio Telescope (Credit: SARAO)

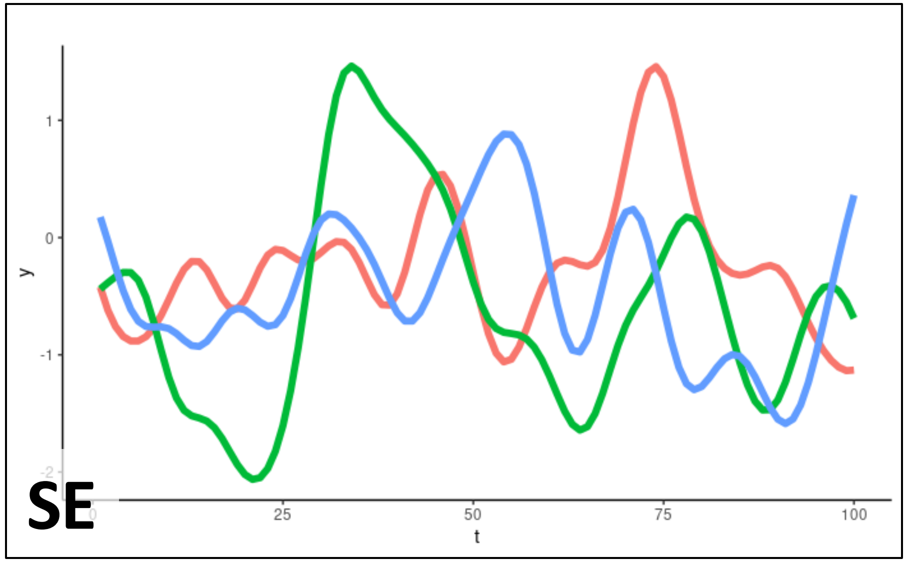


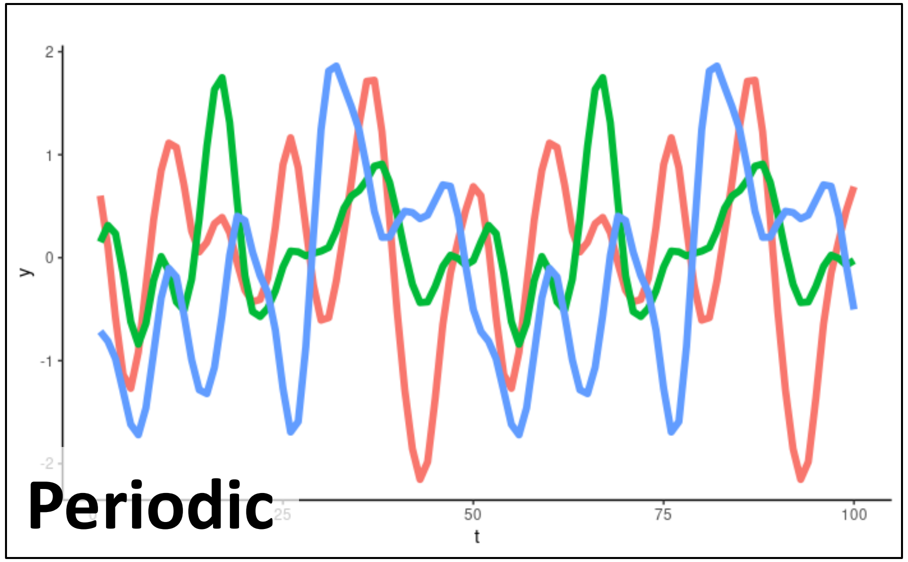
Fender et al. (2017) https://doi.org/10.48550/arXiv.1711.04132

Gaussian Process Modelling Example



Gaussian Process Model





$$Y \sim \mathrm{MVN}(f(t), \boldsymbol{\Sigma}_\varepsilon)$$

Gaussian White Noise

$$\boldsymbol{\Sigma}_\varepsilon = \hat{\boldsymbol{e}}^2 \boldsymbol{I}$$

GP Prior

$$f(t) \sim \mathrm{MVN}(\mathbf{0}, k_1(\tau) + k_2(\tau))$$

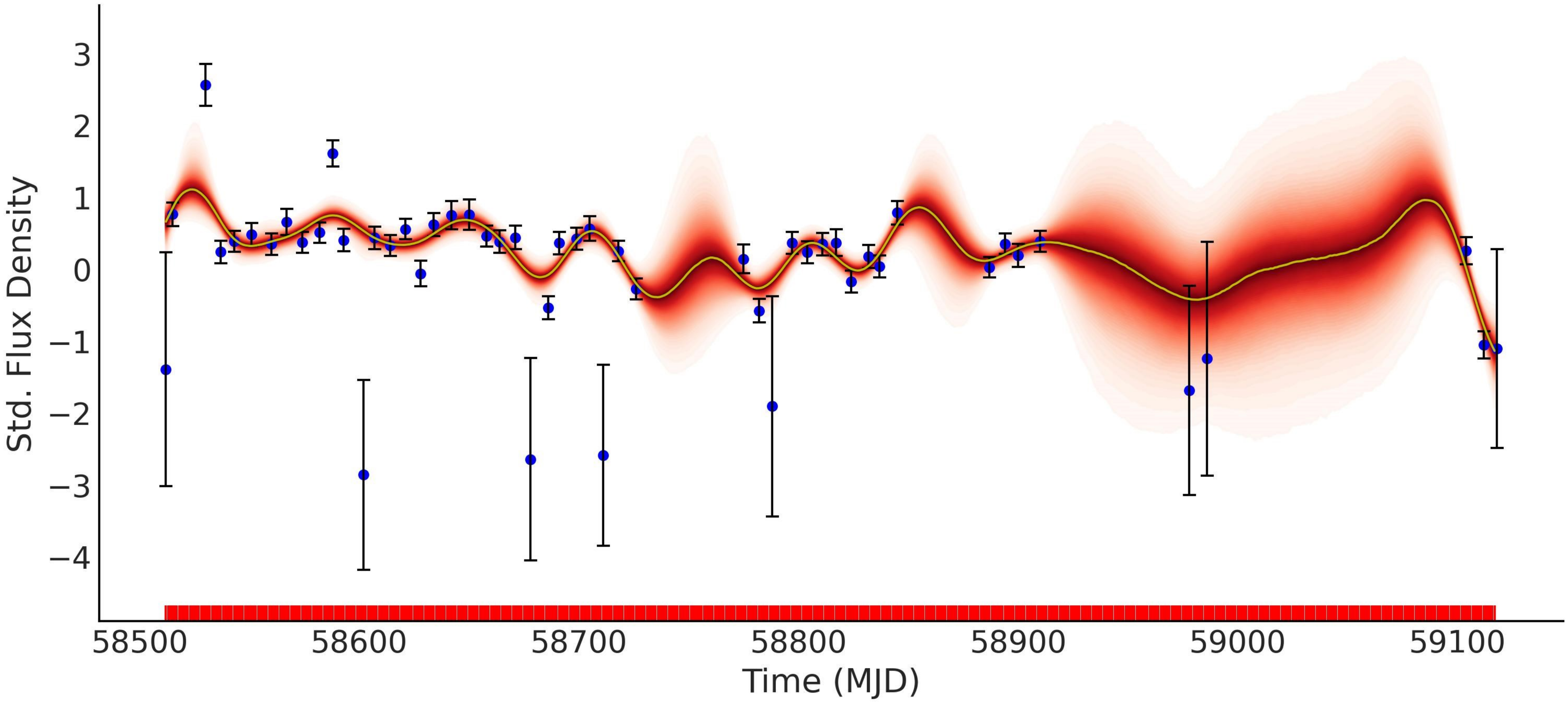
Squared Exponential Kernel

$$k_1(\tau) = \eta_{SE} \exp\left\{-\frac{1}{2\ell_{SE}^2}\tau^2\right\}$$

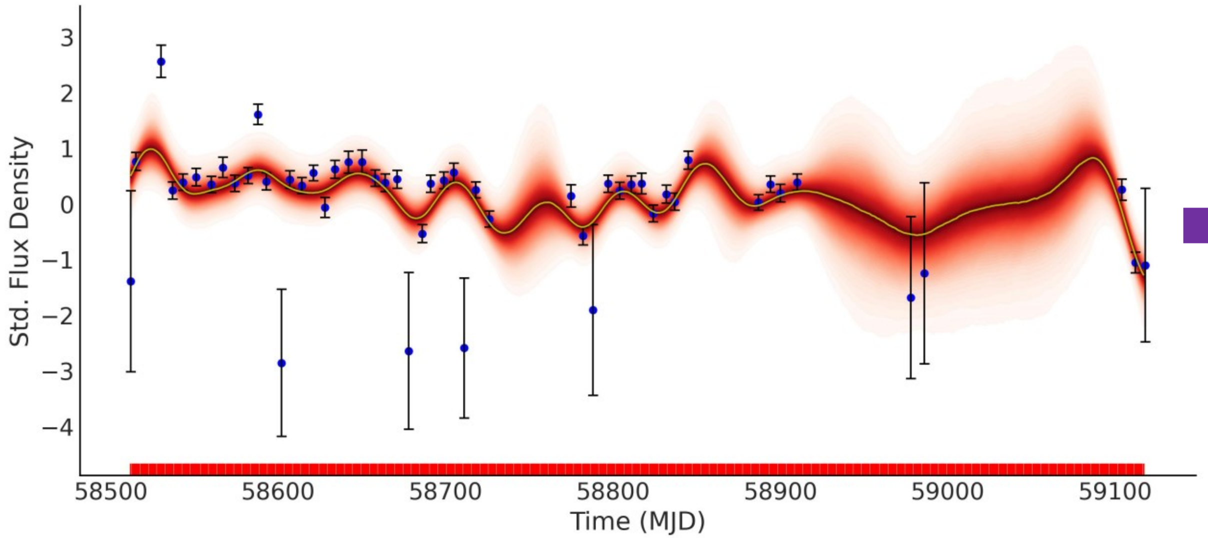
Periodic Kernel

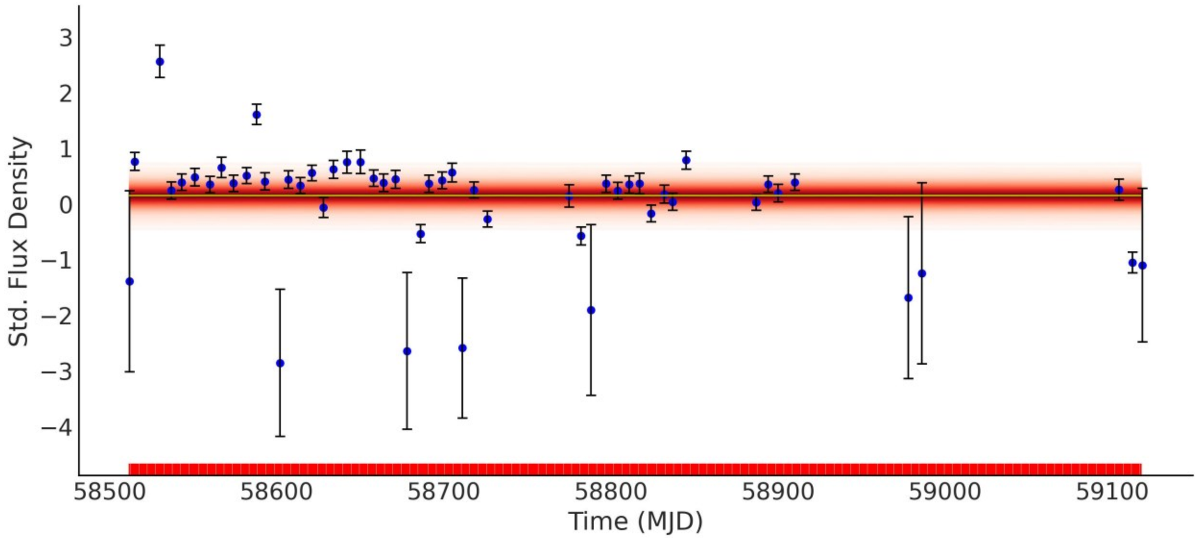
$$k_2(\tau) = \eta_{Per} \exp\left\{-\frac{1}{2\ell_{Per}^2}\sin^2\left(\pi\frac{\tau}{T}\right)\right\}$$

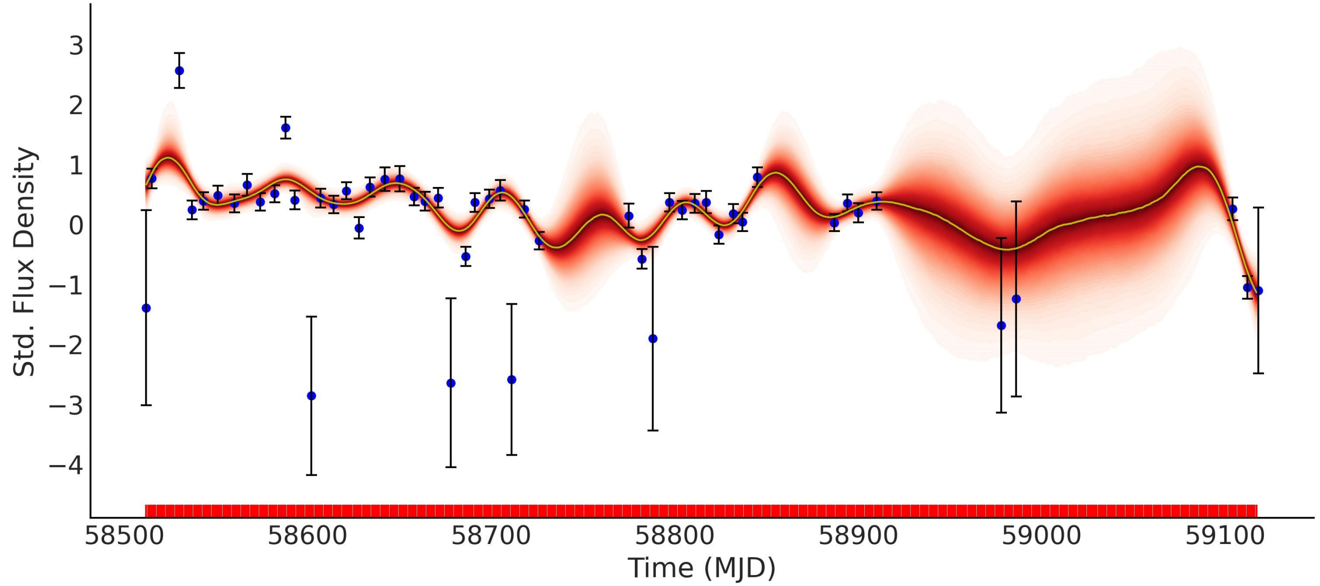
Posterior Predictive Samples



Additive Components







$\eta_{SE} = 0.74 \pm 0.37$

$\ell_{SE} = 16.0 \pm 3.3$ days

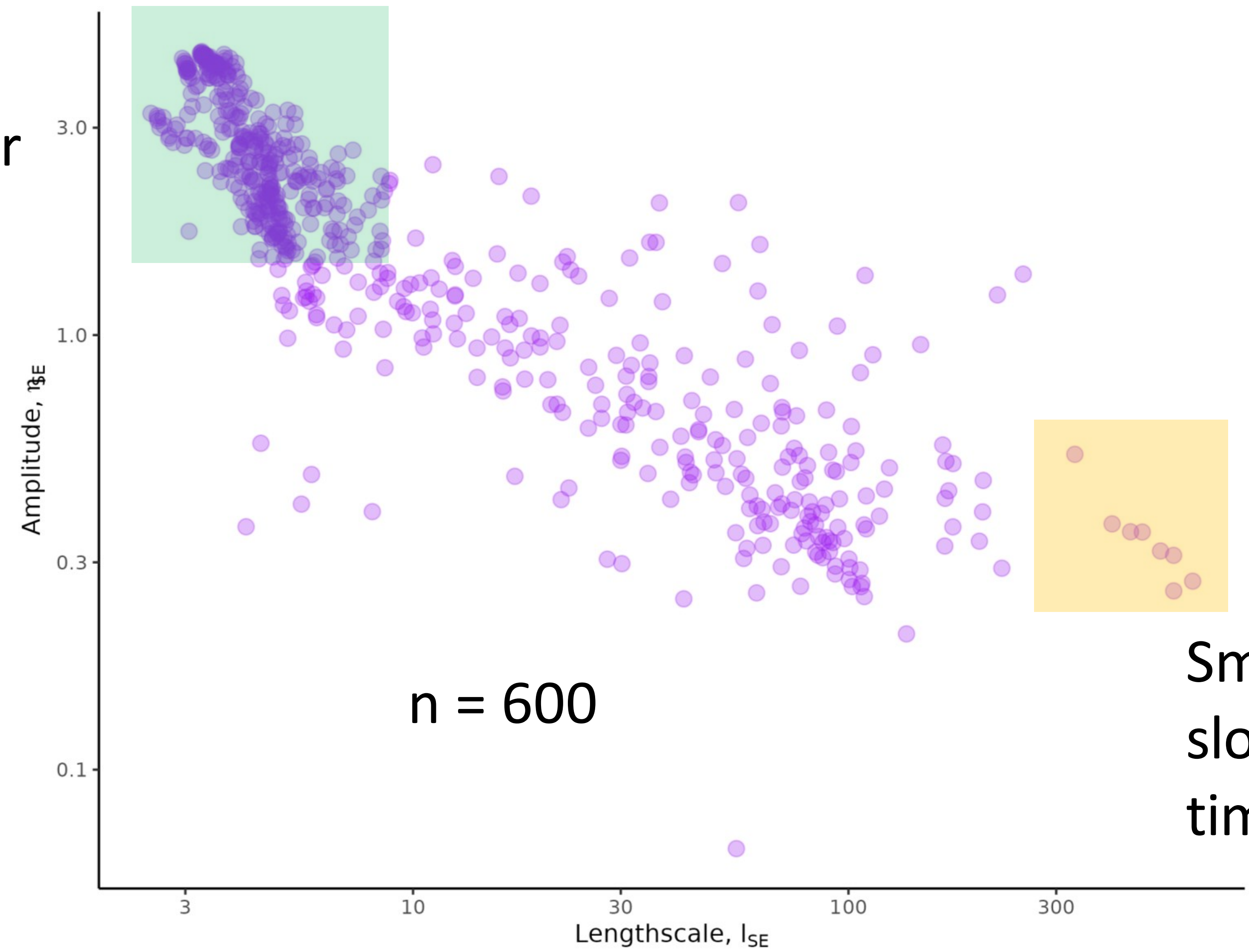
$\eta_{Periodic} = 0.59 \pm 0.51$

$\ell_{Periodic} = 149.1 \pm 150.2$ days

$T = 80.5 \pm 40.5$ days

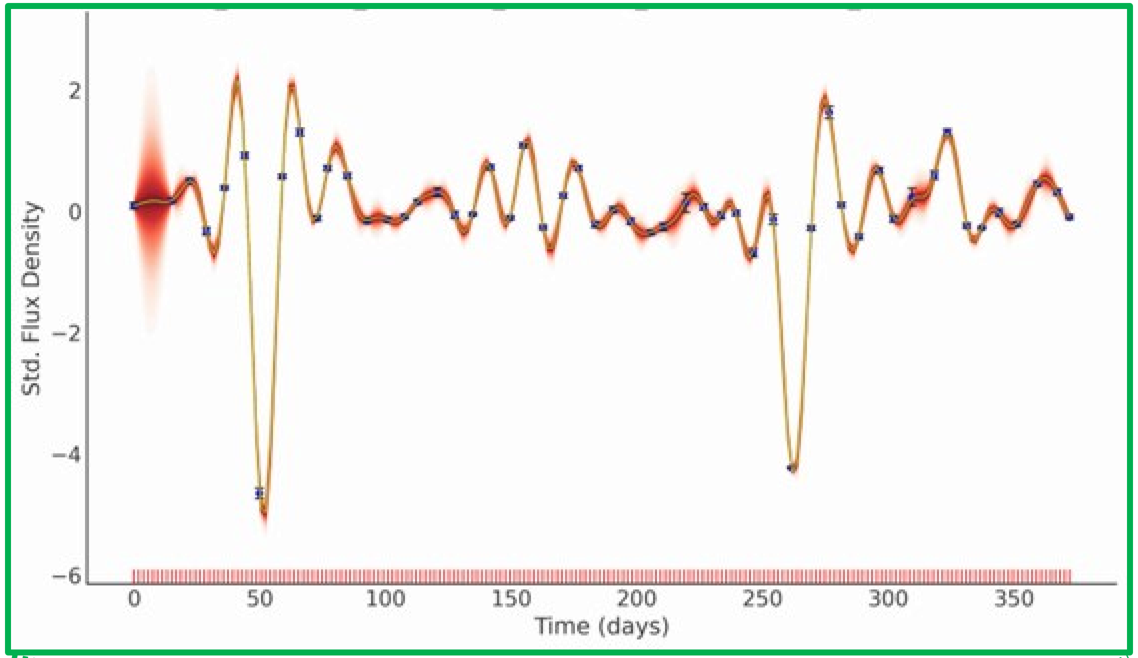
Transient Candidates

Large amplitude, rapid change over time

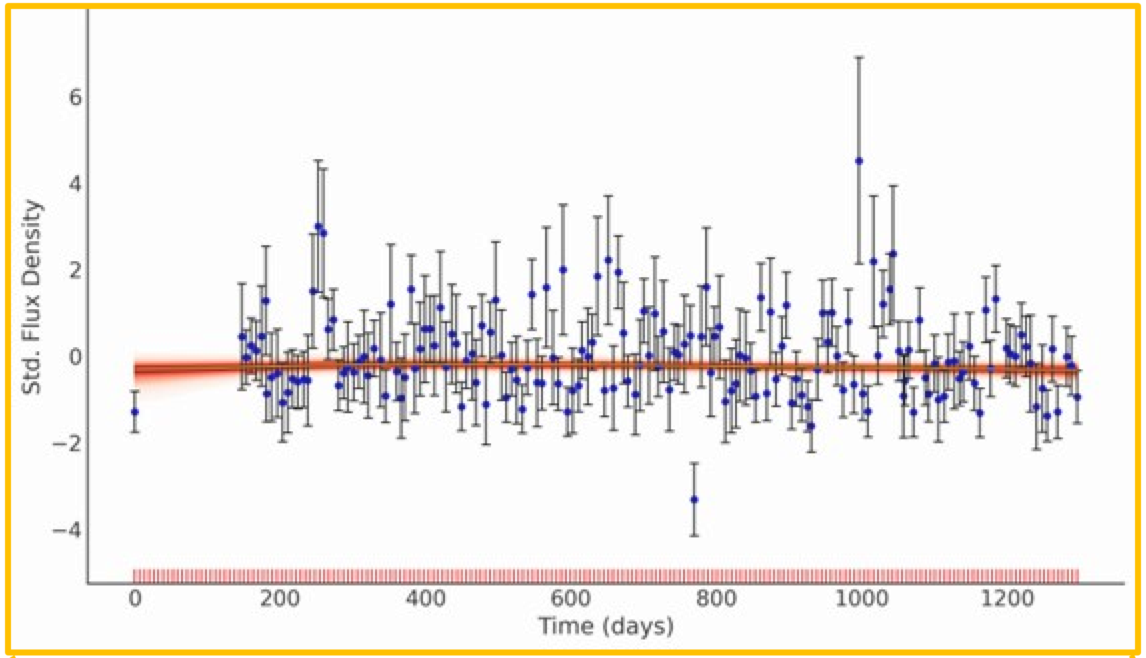


n = 600

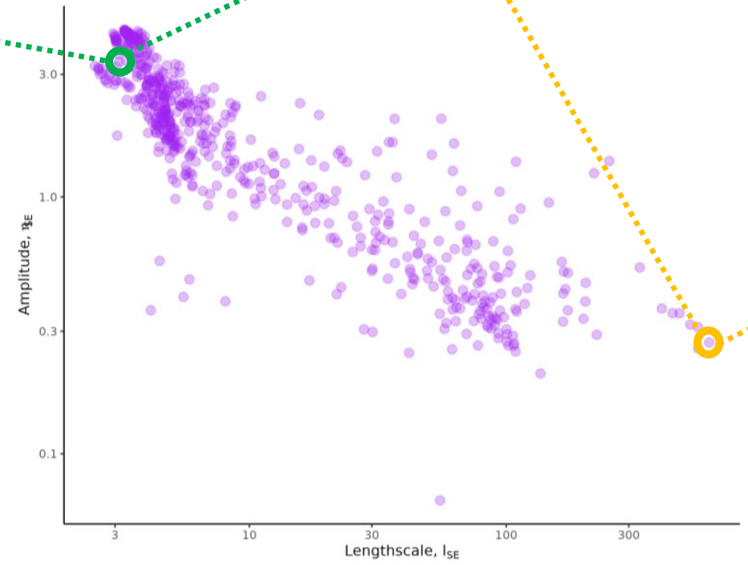
Small amplitude, slow change over time



Std. Flux Density
Time (days)

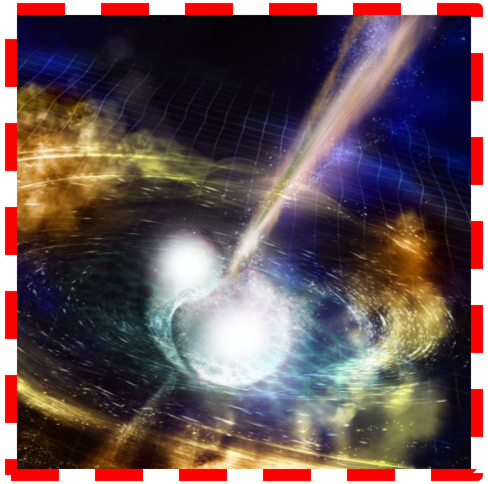


Std. Flux Density
Time (days)



Amplitude, σ_{SE}
Lengthscale, l_{SE}

Twinkle twinkle little star…



Exotic phenomena

Large-scale survey

Raw Data Processing → Identify → Classify

10^3 to 10^6 light curves

Transient candidates

Black holes, supernova, eclipsing binary, GRB, FRB, AGN, etc, …

… a Gaussian Process is what you are!