

Photometric identification and spectroscopic confirmation of massive black hole binaries

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Massive Black Hole Pairs and Binaries

Galaxy Merger



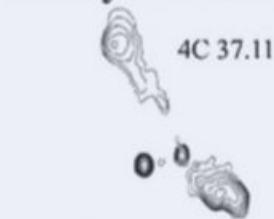
Dynamical friction drives massive objects to central positions

Stellar Core Merger



Dynamical friction less efficient as SMBHs form a binary.

Binary Formation



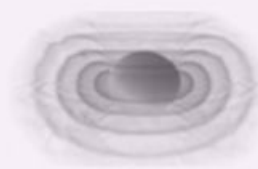
Stellar and gas interactions may dominate binary inspiral?

Continuous GWs



Gravitational radiation provides efficient inspiral. Circumbinary disk may track shrinking orbit.

Coalescence



Post-coalescence system may experience gravitational recoil.

Orbital separation

10 pc

0.1 pc

0.0001 pc

0 pc

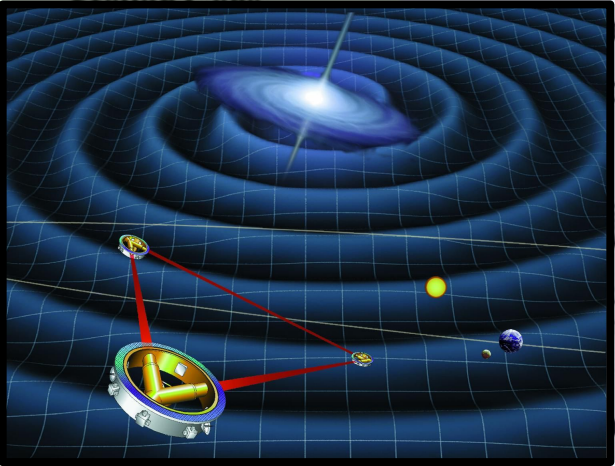
Burke-Spolaor et al. 2019

Massive Black Hole Pairs and Binaries

Galaxy Mergers



Dynamical friction drives massive objects to central positions

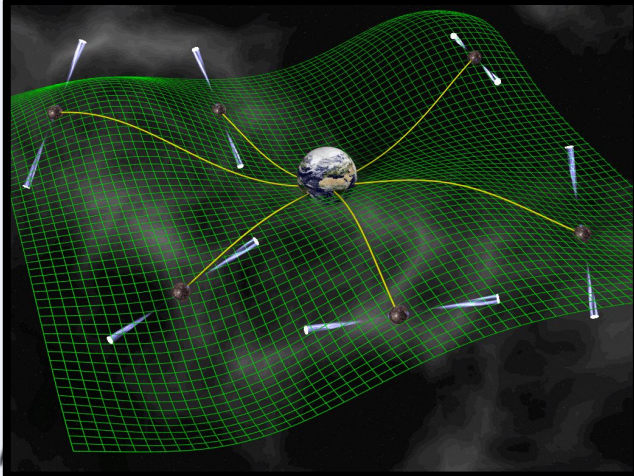


Orbital separation 10 pc

Annihilation

37.11

gas may inspiral?



0.1 pc

0.0001 pc

0 pc

rescence

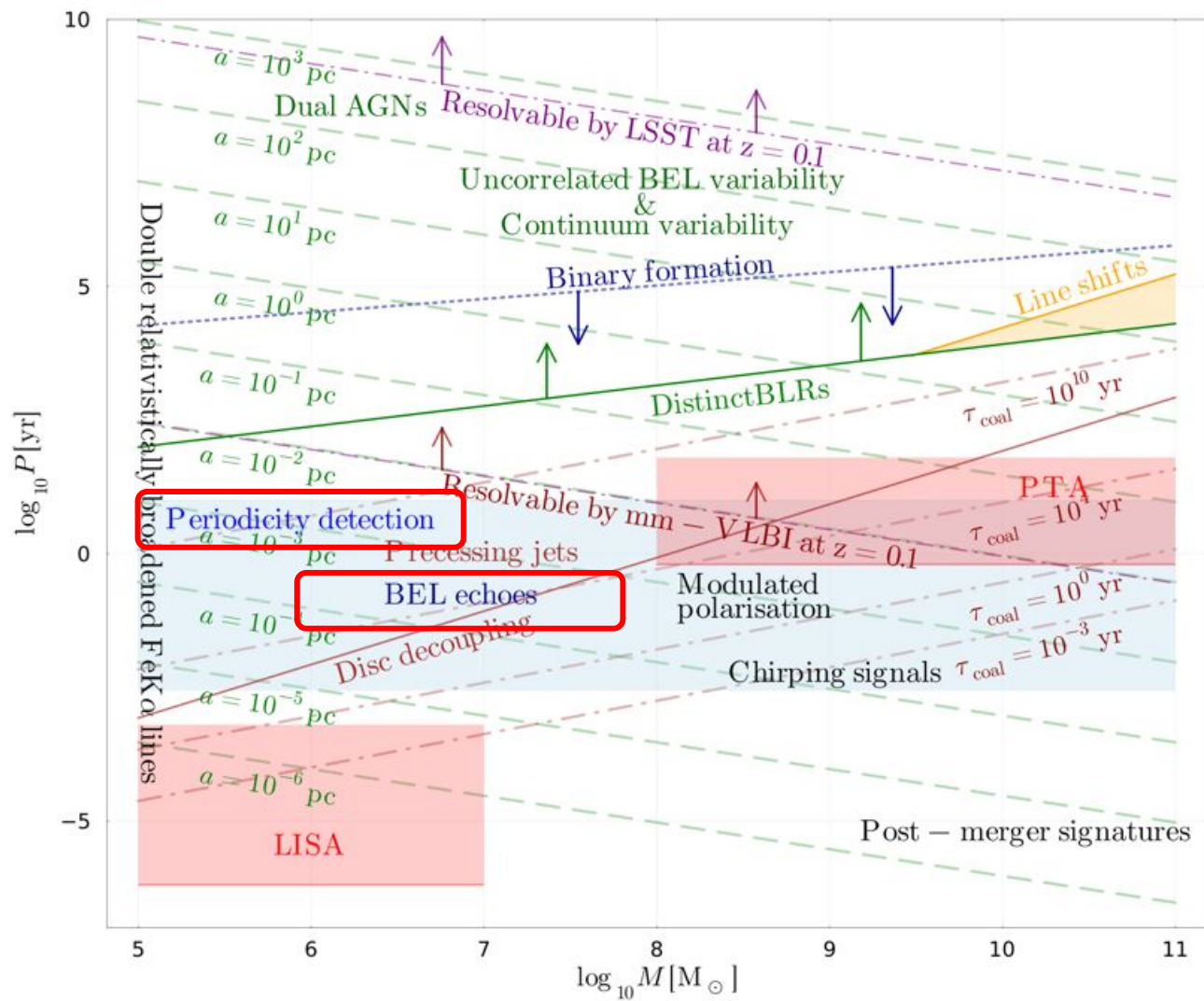
rescence system experience orbital recoil.

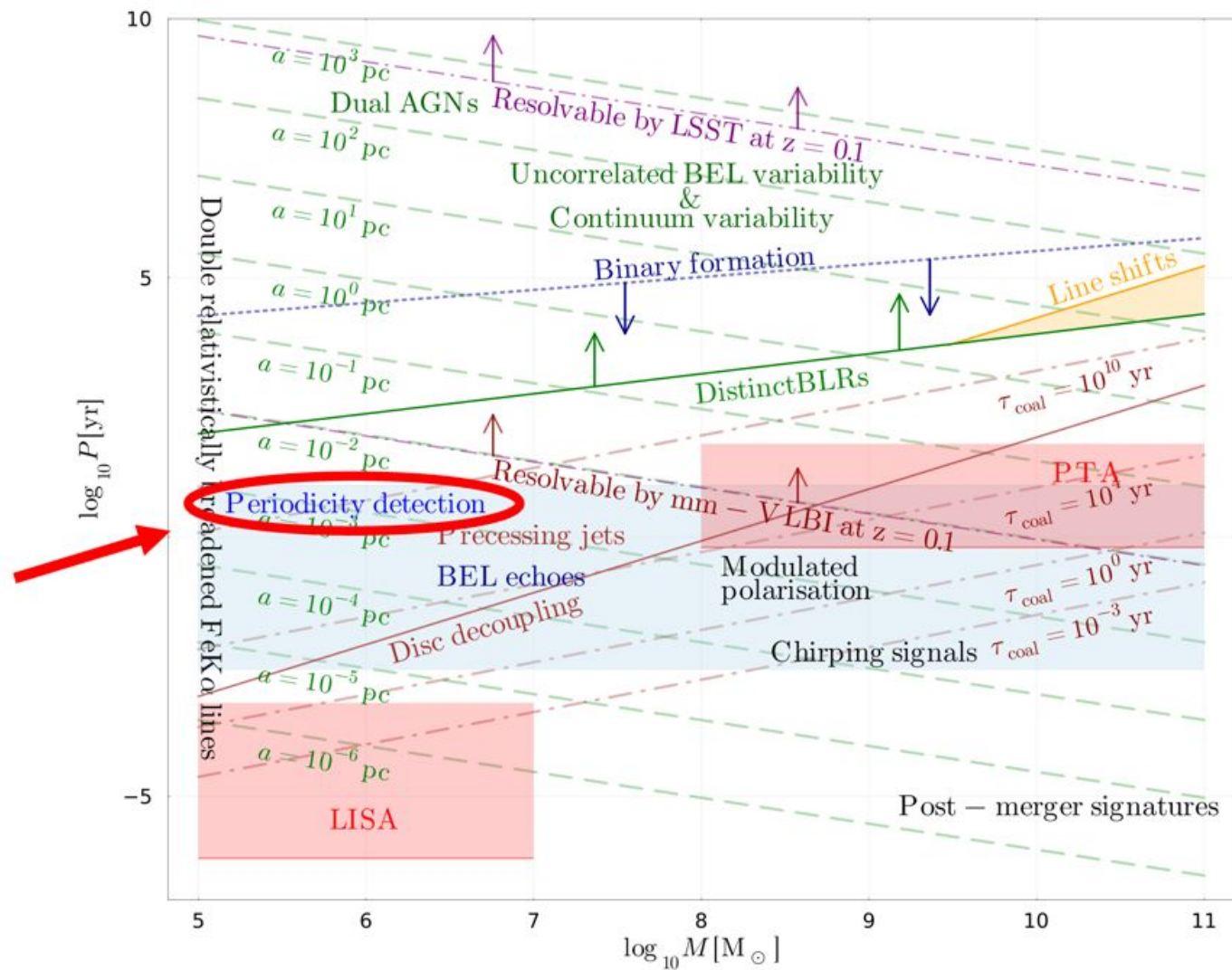
Burke-Spolaor et al. 2019

Massive Black Hole Pairs and Binaries

Electromagnetic detections will help put more constraints

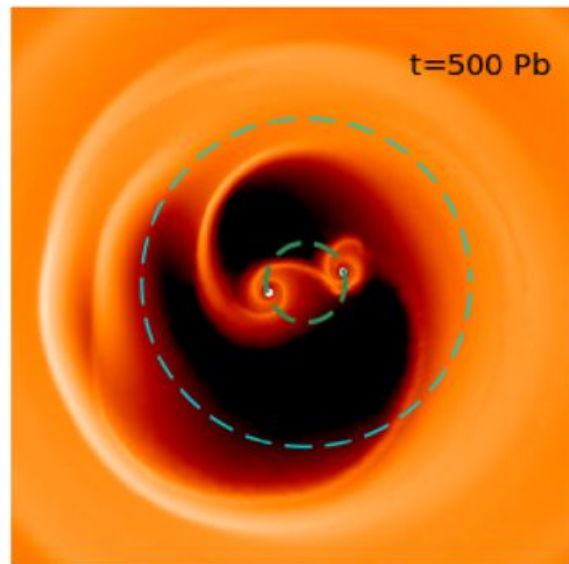
Burke-Spolaor et al. 2019





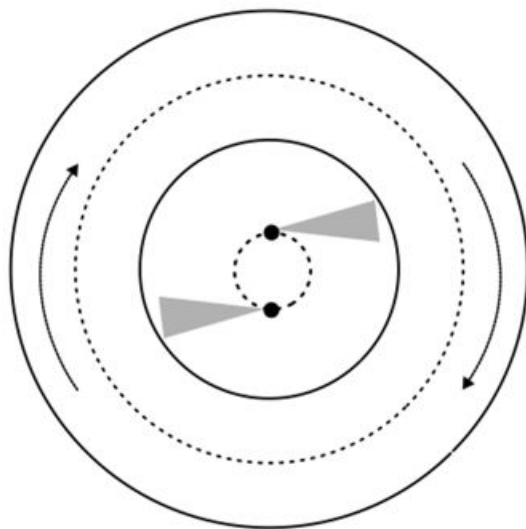
Periodic modulations

Periodic feeding



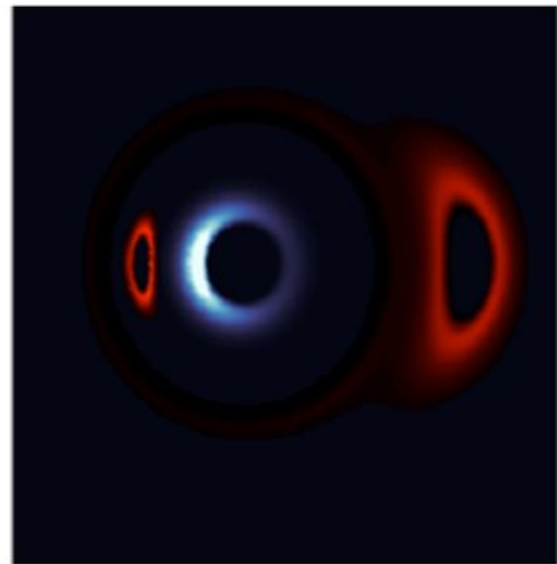
Franchini et al 2022

Doppler boost

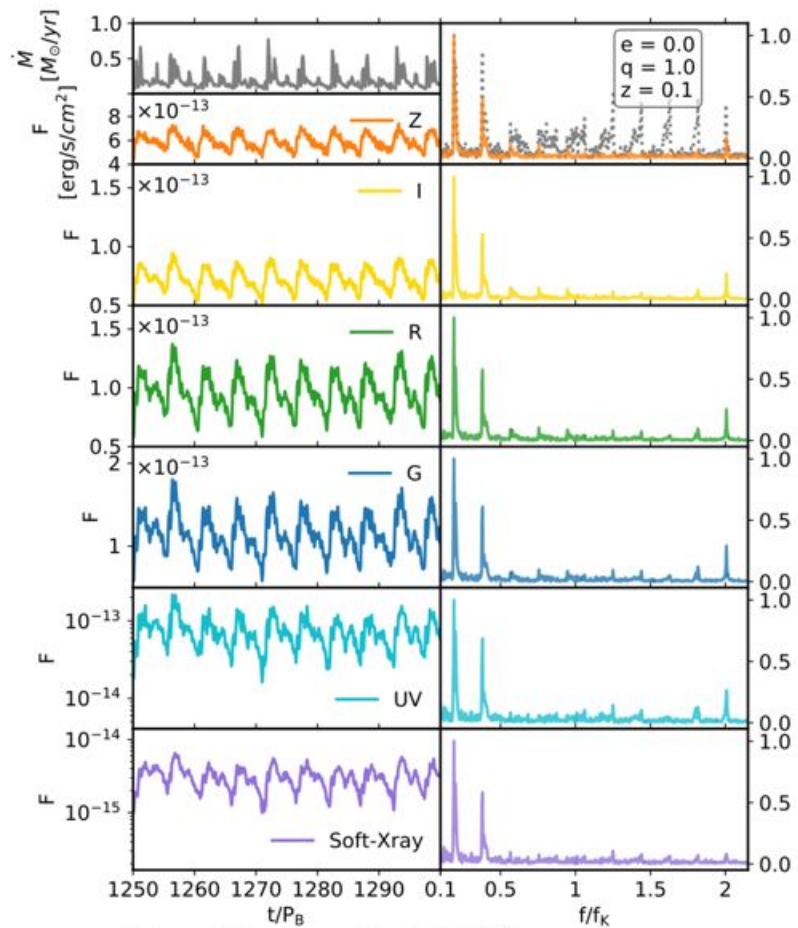


Bertassi et al 2025

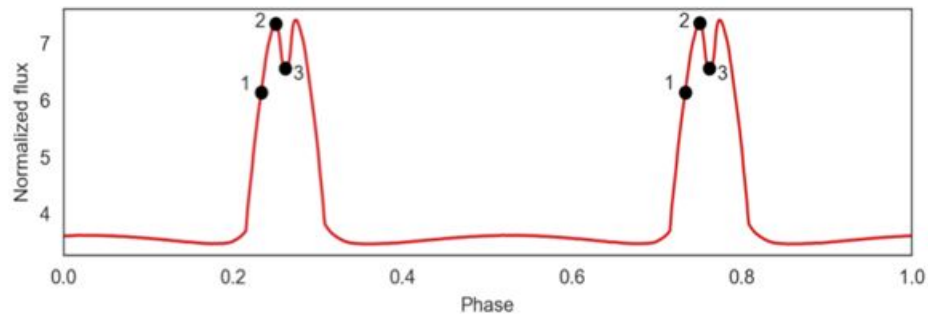
Gravitational self-lensing



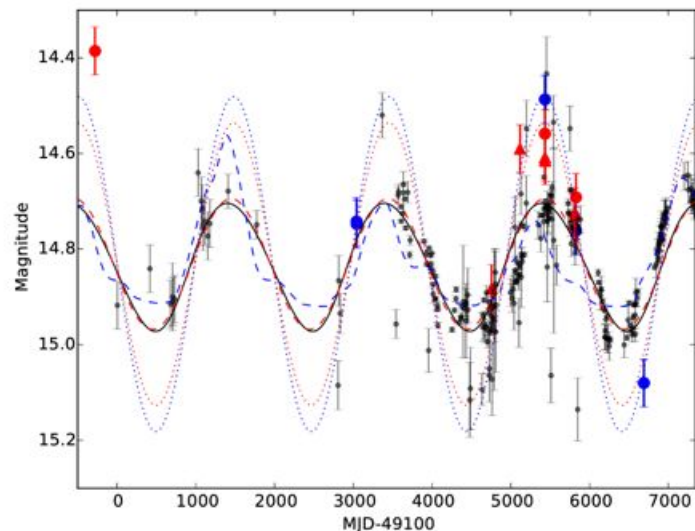
Davelaar & Haiman 2021



Cocchiararo et al. 2024

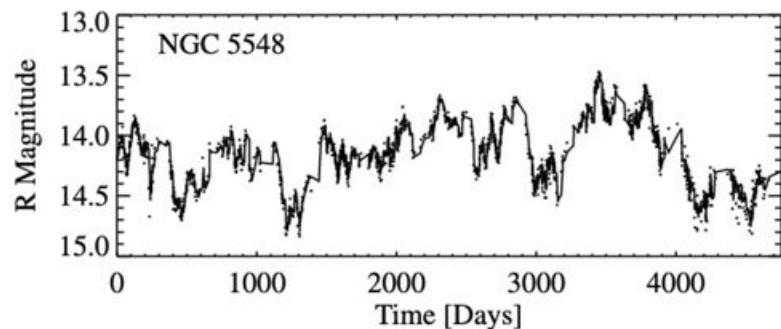


Davelaar & Haiman



D'Orazio et al 2015

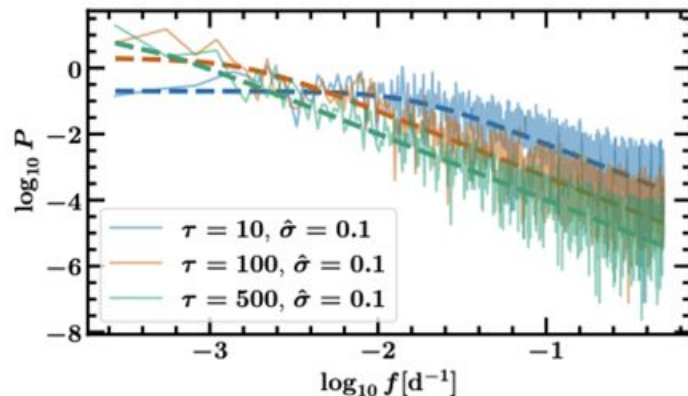
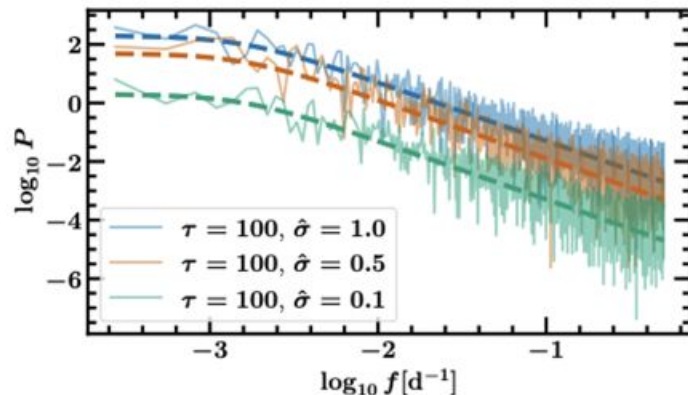
AGN intrinsic variability



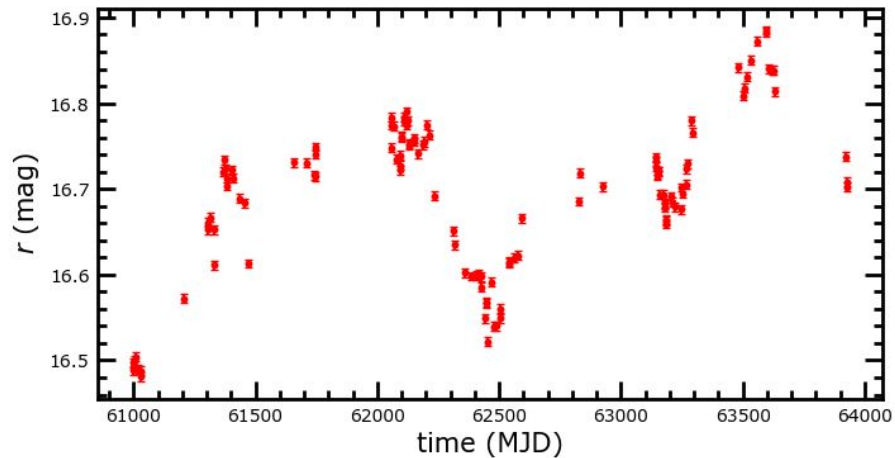
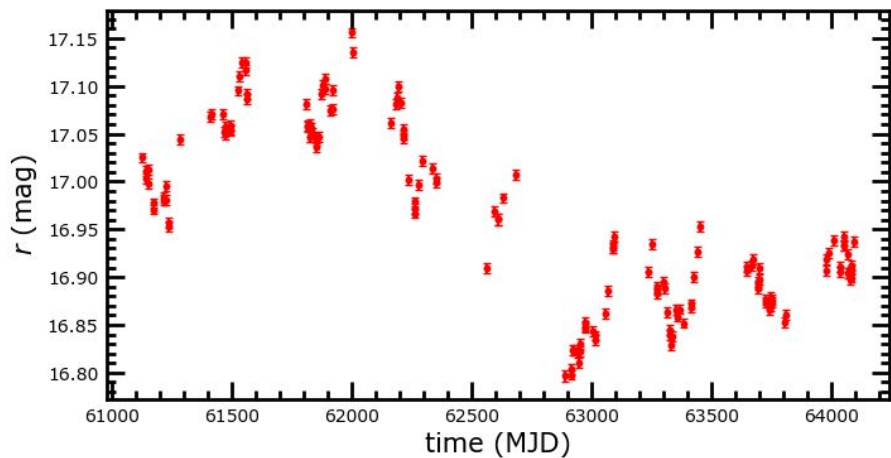
$$P(f) = \frac{2\hat{\sigma}^2\tau_0^2}{1 + (2\pi\tau_0 f)^2}$$

$$C_{ij} = \frac{1}{2}\hat{\sigma}^2\tau_0 \exp\left(-\frac{\tau_{ij}}{\tau_0}\right)$$

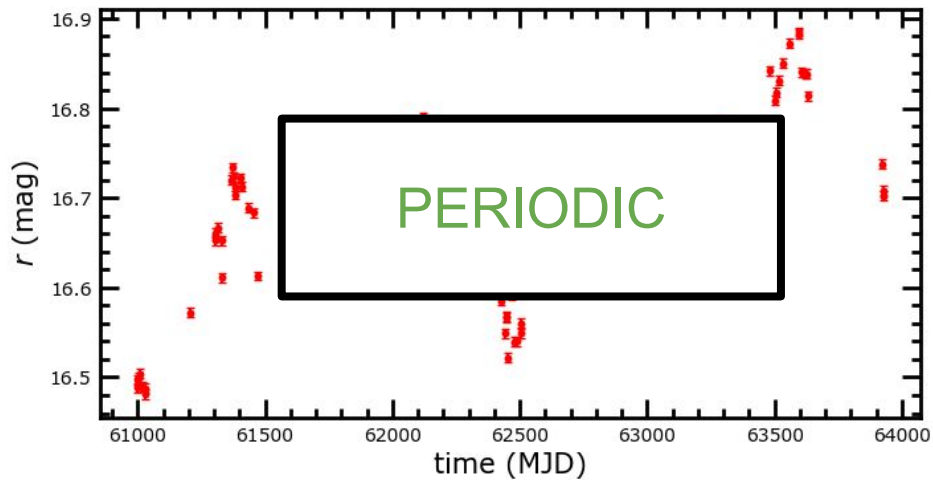
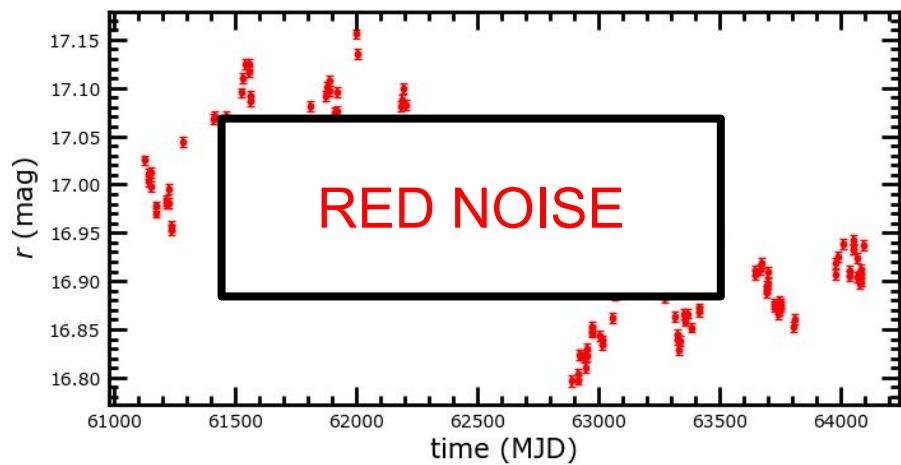
Kelly et al.2009



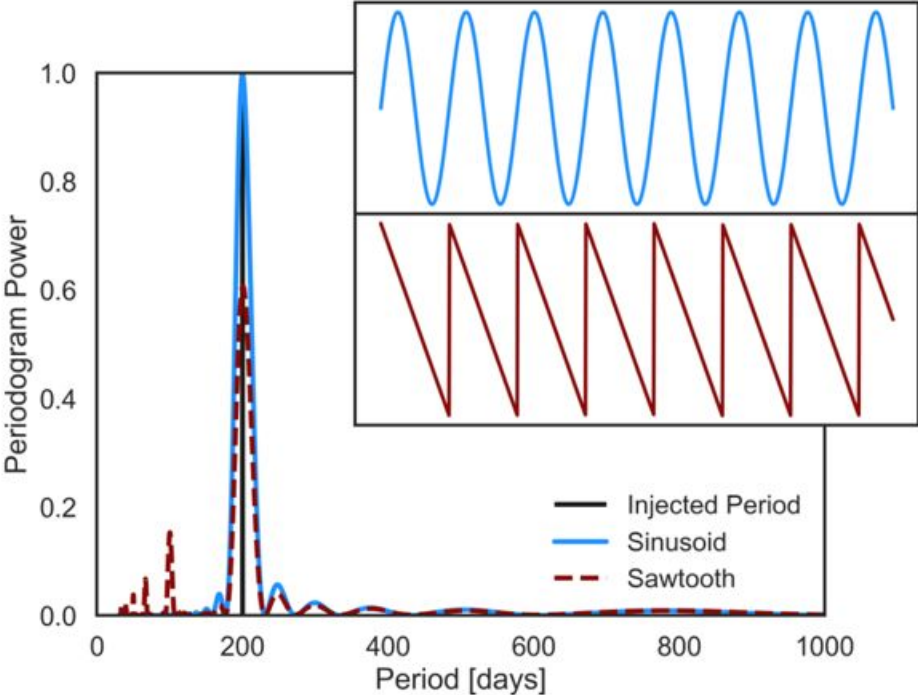
Let's play a game!



Let's play a game!



Lomb-Scargle periodogram analysis



	Sinusoid	Sawtooth
Idealized	~24%	~1%

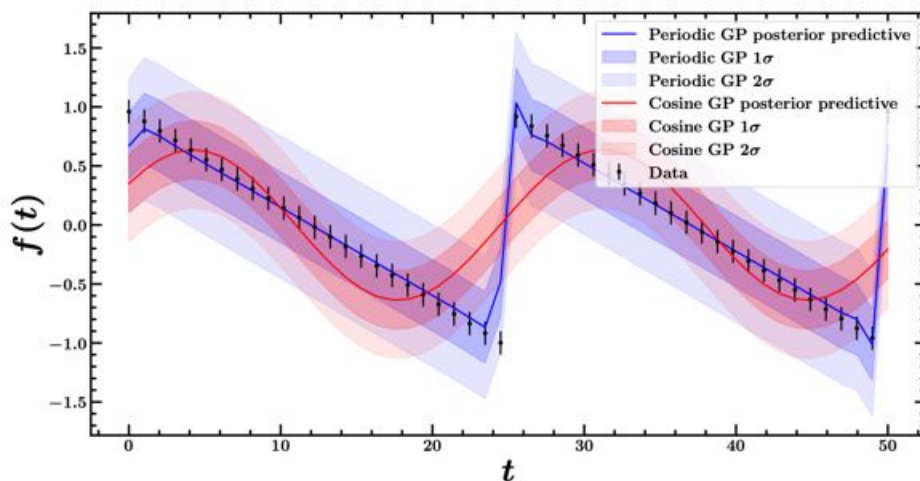
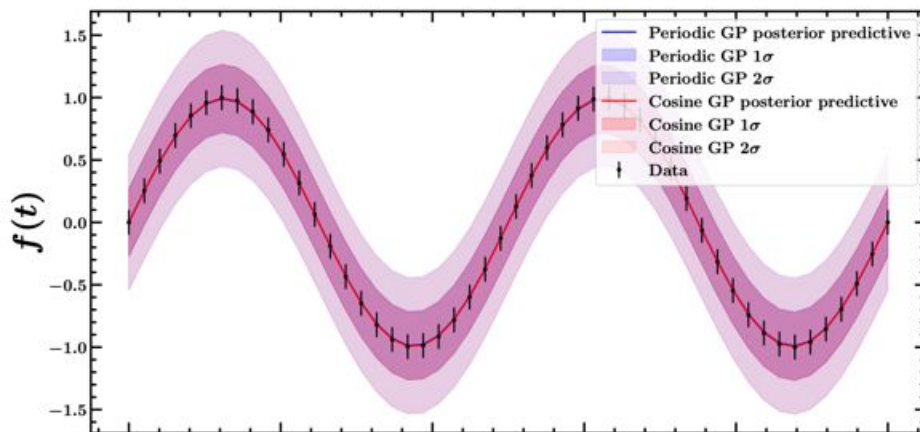
Lin et al 2026

Gaussian process kernels

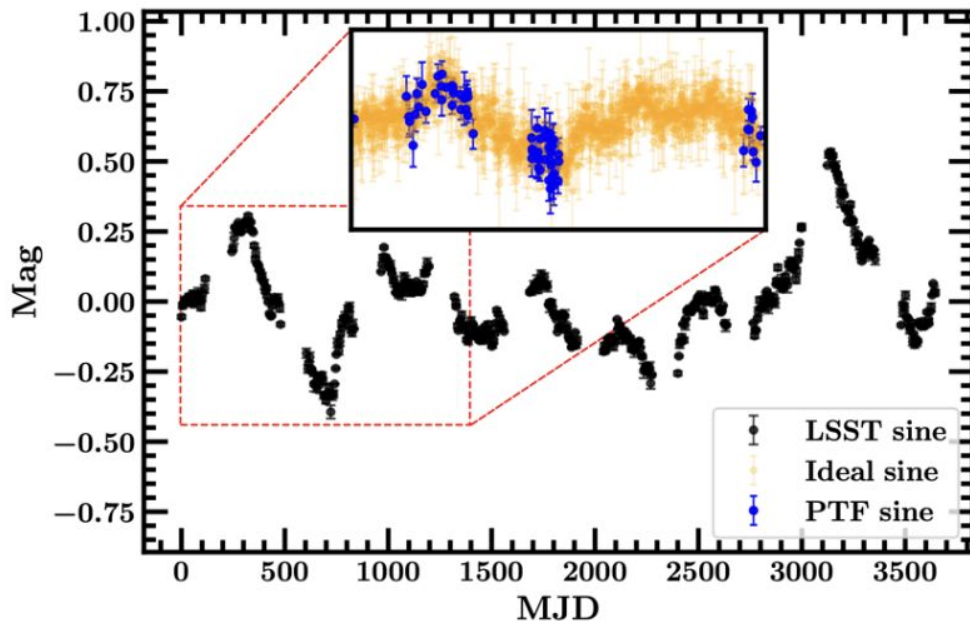
$$k_{\text{DRW}}(t_i, t_j) = \frac{1}{2} \hat{\sigma}^2 \tau \exp\left(-\frac{|t_i - t_j|}{\tau}\right)$$

$$k_{\text{cosine}}(t_i, t_j) = A^2 \cos\left(2\pi \frac{|t_j - t_i|}{P}\right)$$

$$k_{\text{periodic}}(t_i, t_j) = A^2 \exp\left(-\frac{2 \sin^2\left(\frac{\pi}{P}|t_i - t_j|\right)}{l^2}\right)$$



Retrieved fractions



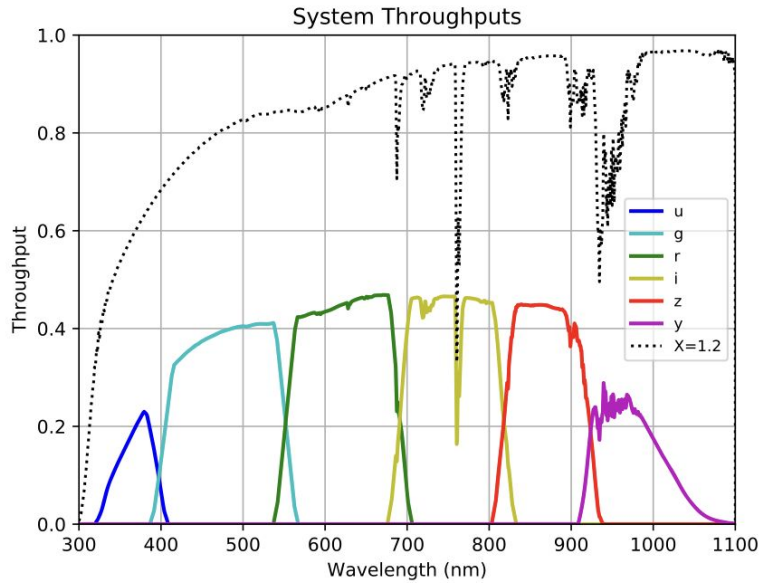
Our analysis (NS+GP)

	Sinusoid	Sawtooth
idealised	53.3%	58.1%
PTF-like	23.4%	8,9%
LSST-like	50.9%	64.5%

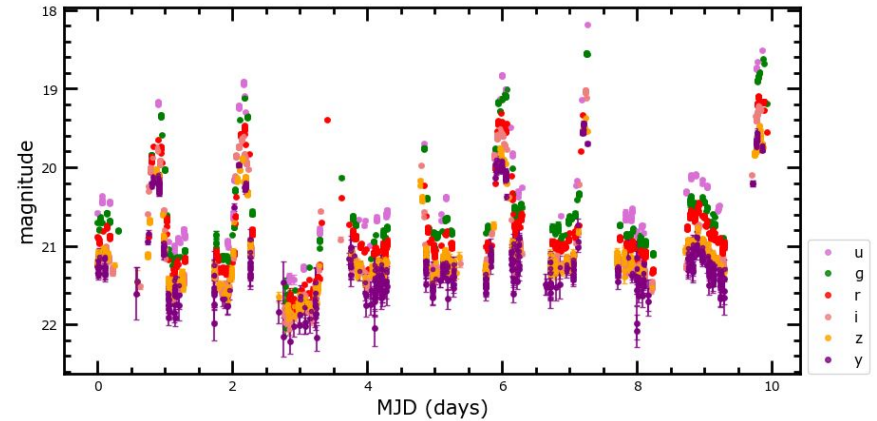
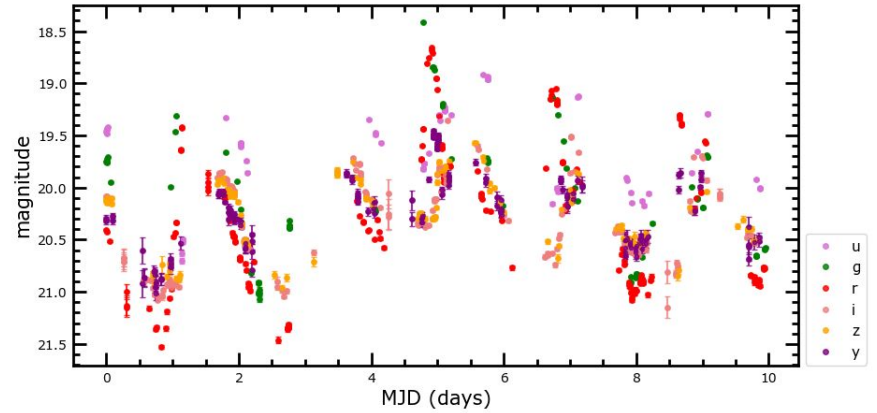
Lin et al 2026 (LSP)

	Sinusoid	Sawtooth
Idealized	~24%	~1%
PTF-like	~45%	~9%
LSST-like	~23%	~1%

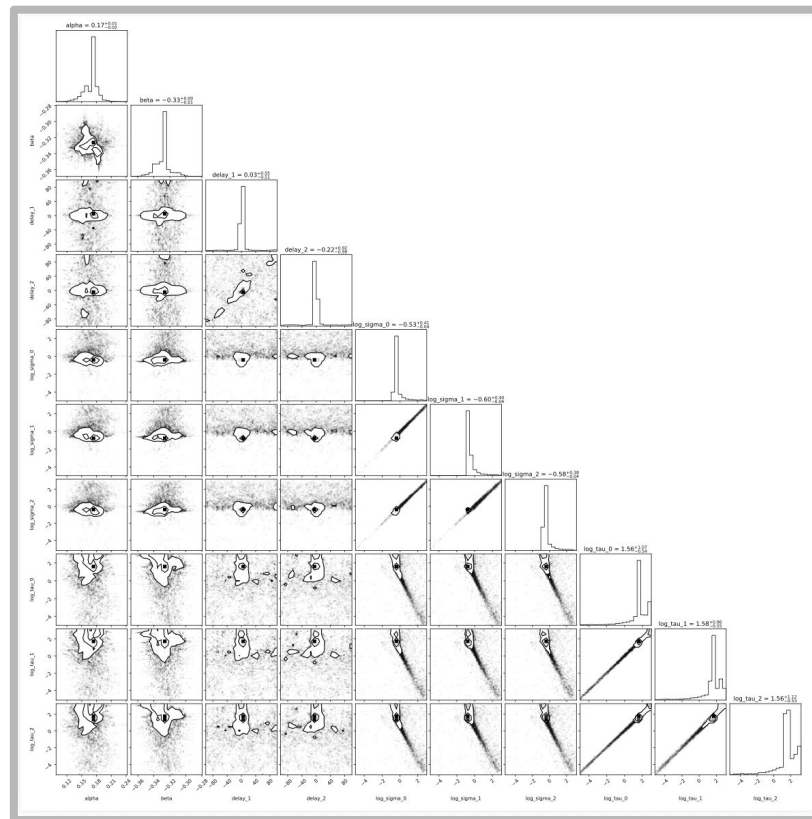
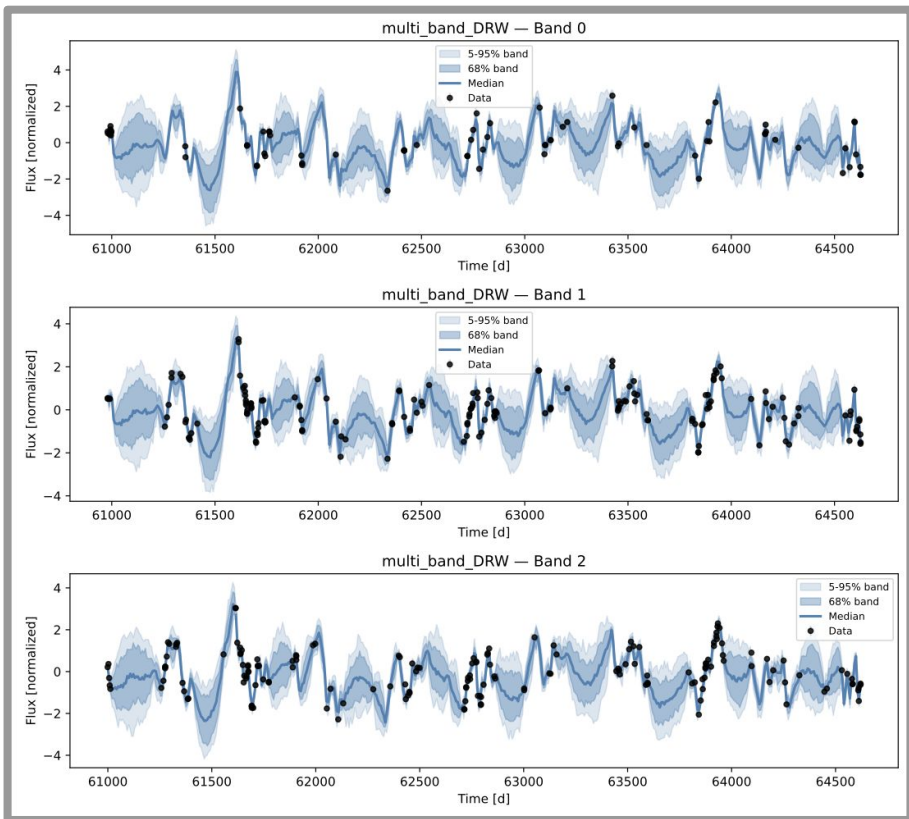
Reality is of course more complicated



Ivezić et al. 2019

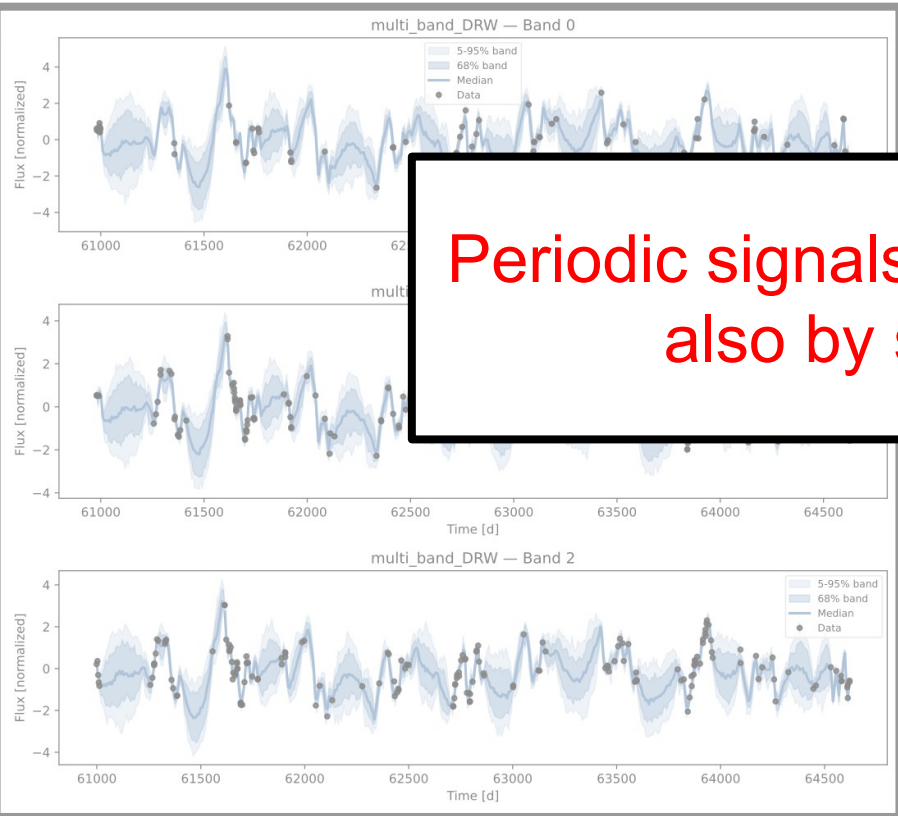


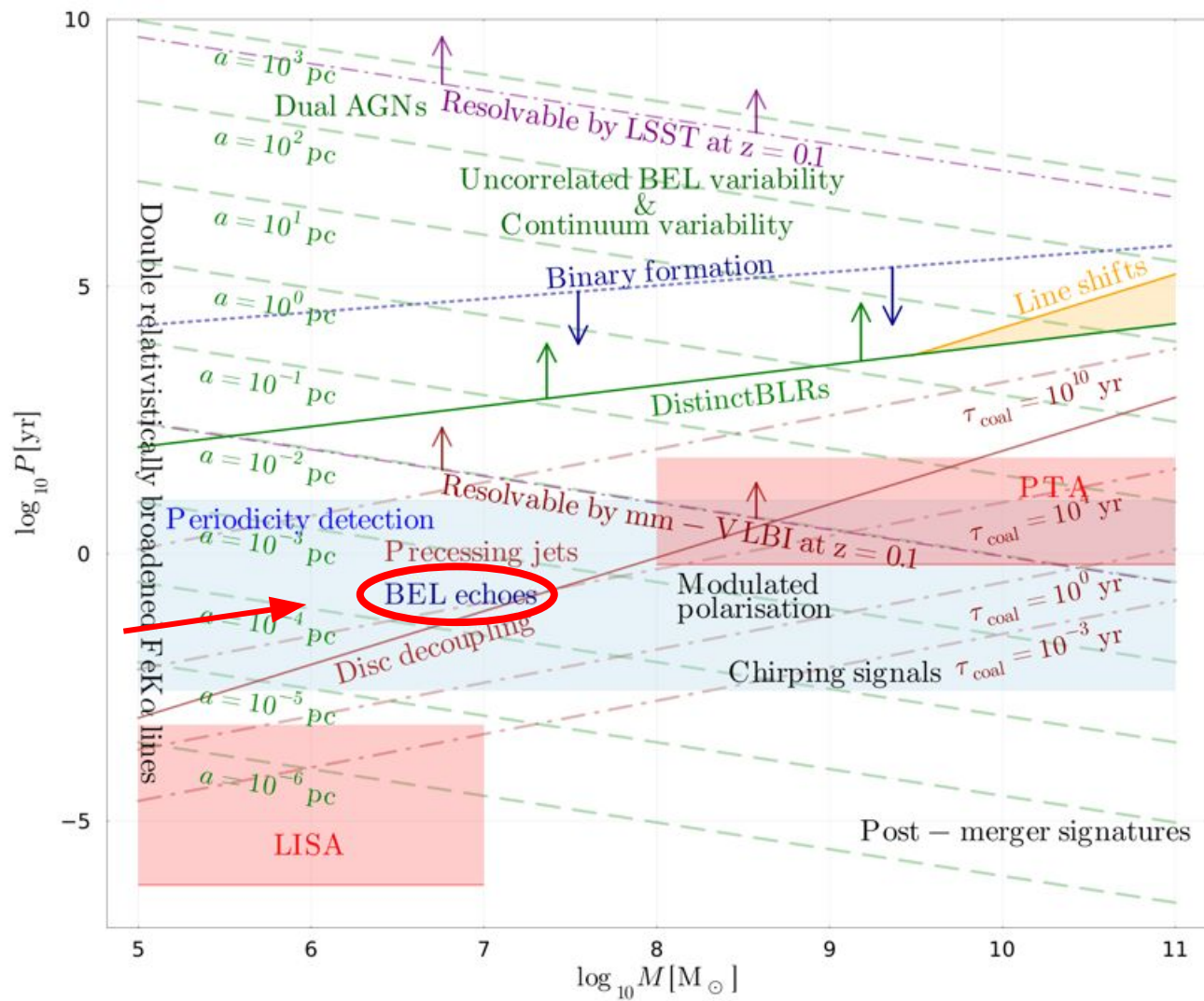
WORK IN PROGRESS



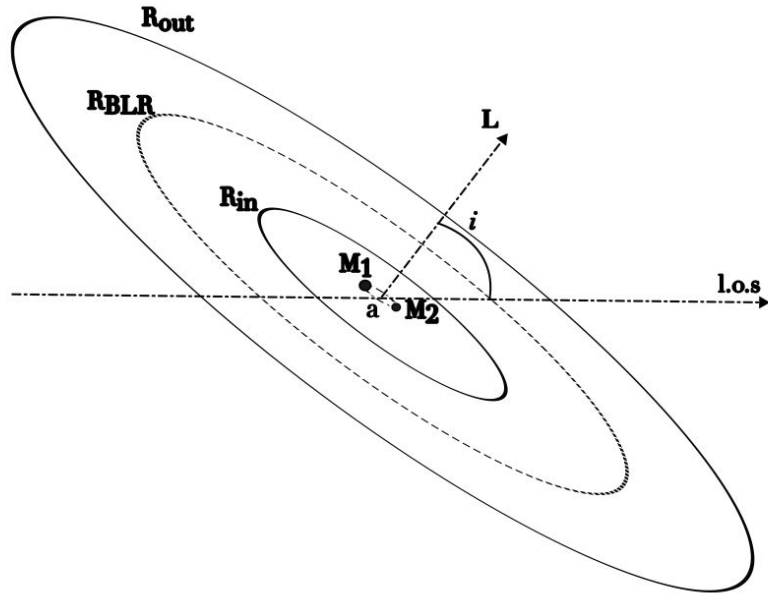
WORK IN PROGRESS

Periodic signals can be generated
also by single MBH

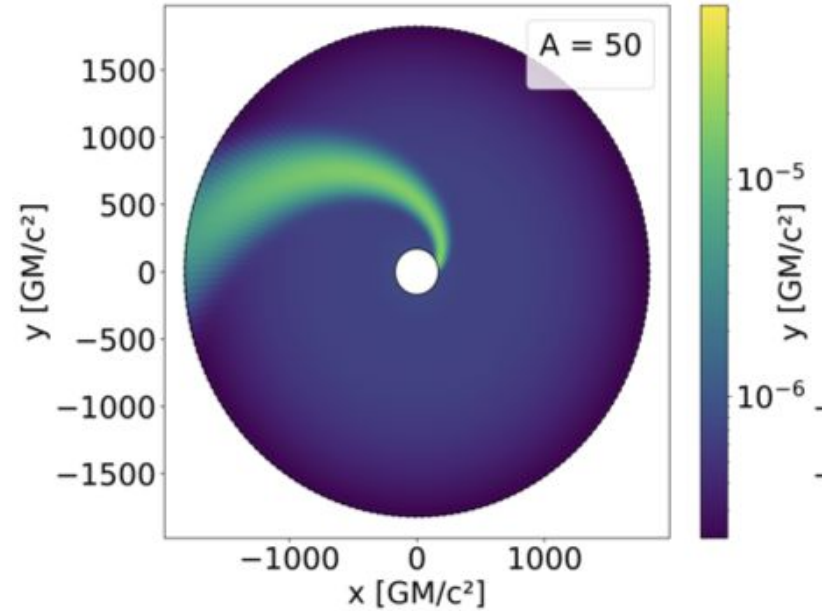




Spectroscopic confirmation



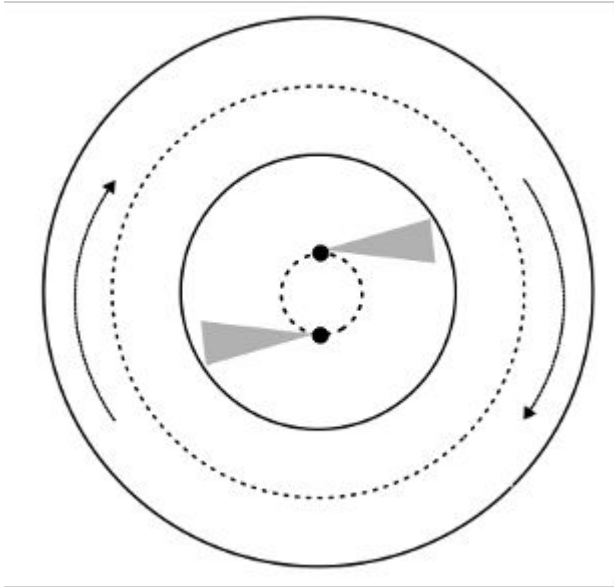
Bertassi et al 2025



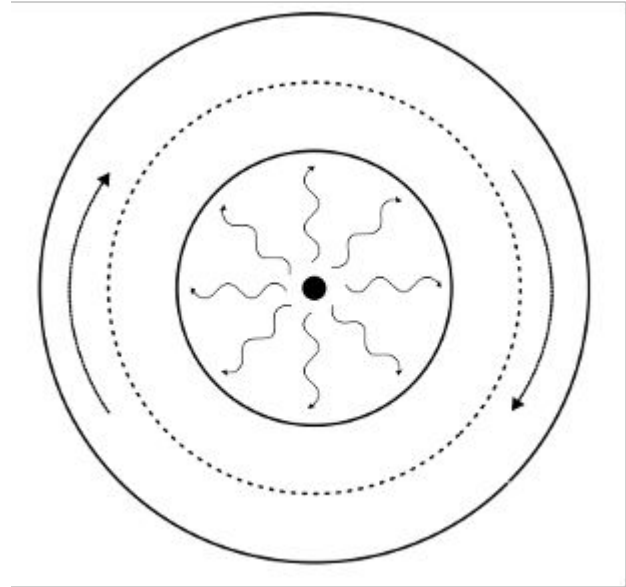
Sottocorno et al 2025

Spectroscopic confirmation

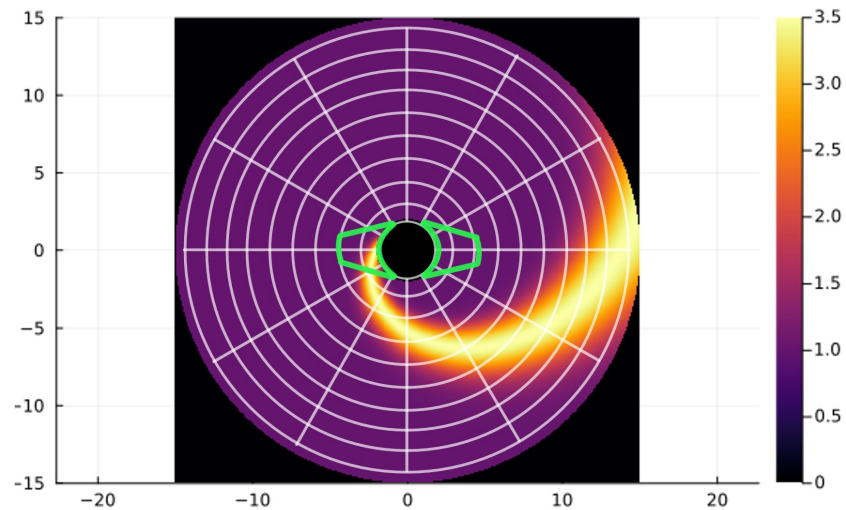
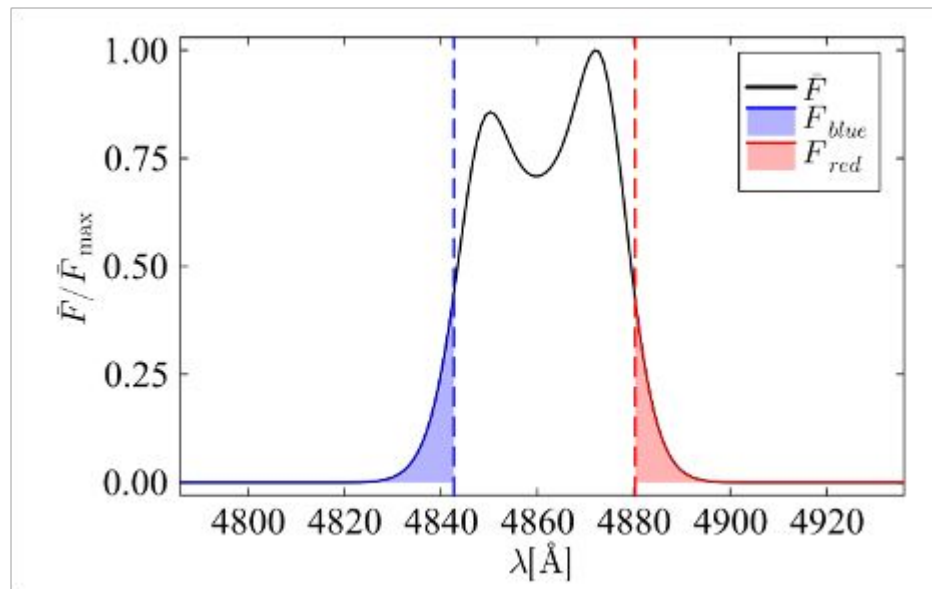
Binary scenario



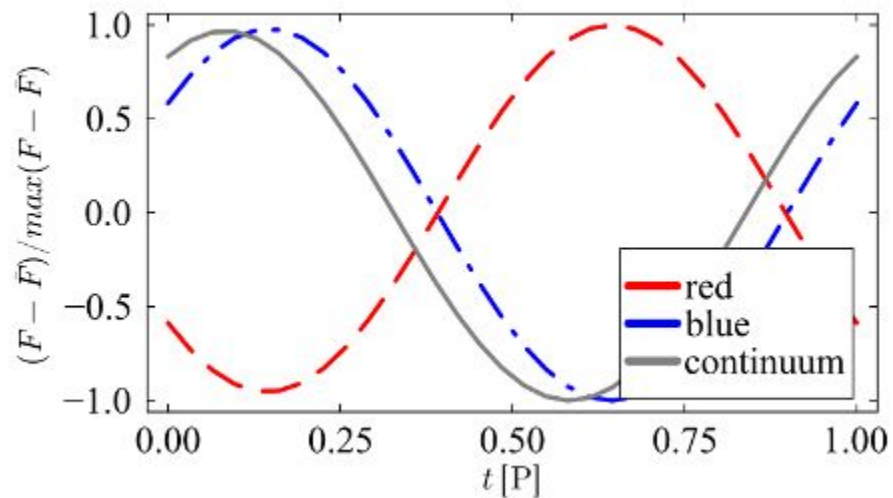
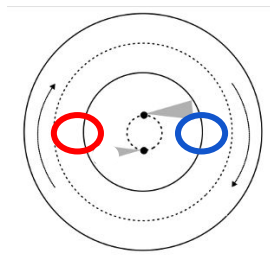
Single MBH scenario



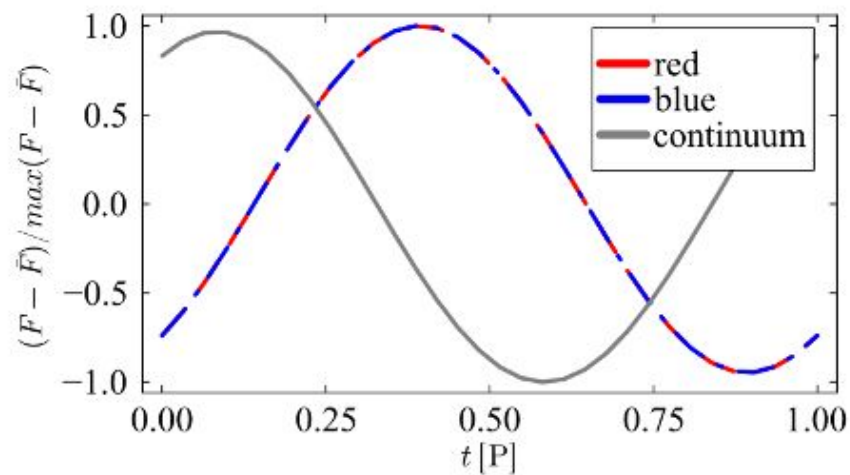
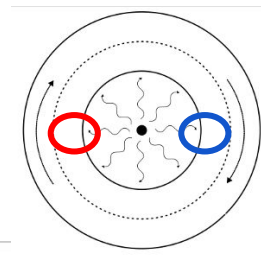
Spectroscopic confirmation



Spectroscopic confirmation



Binary scenario



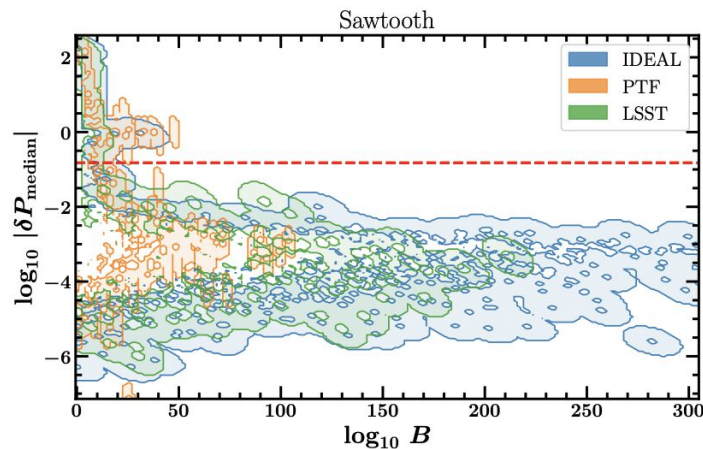
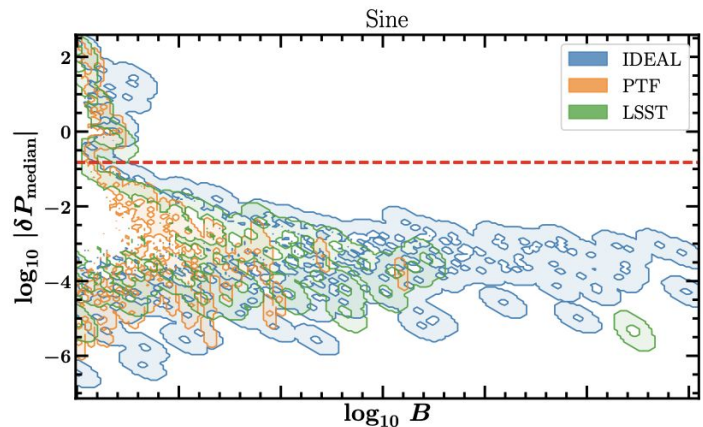
Single MBH scenario

Conclusions

- We proposed a fully Bayesian flexible method to search for periodic signals with arbitrary shapes in presence of red noise using Gaussian processes
- We proposed a possibly binary unique spectroscopic signature that can be used to confirm the nature of a periodic source



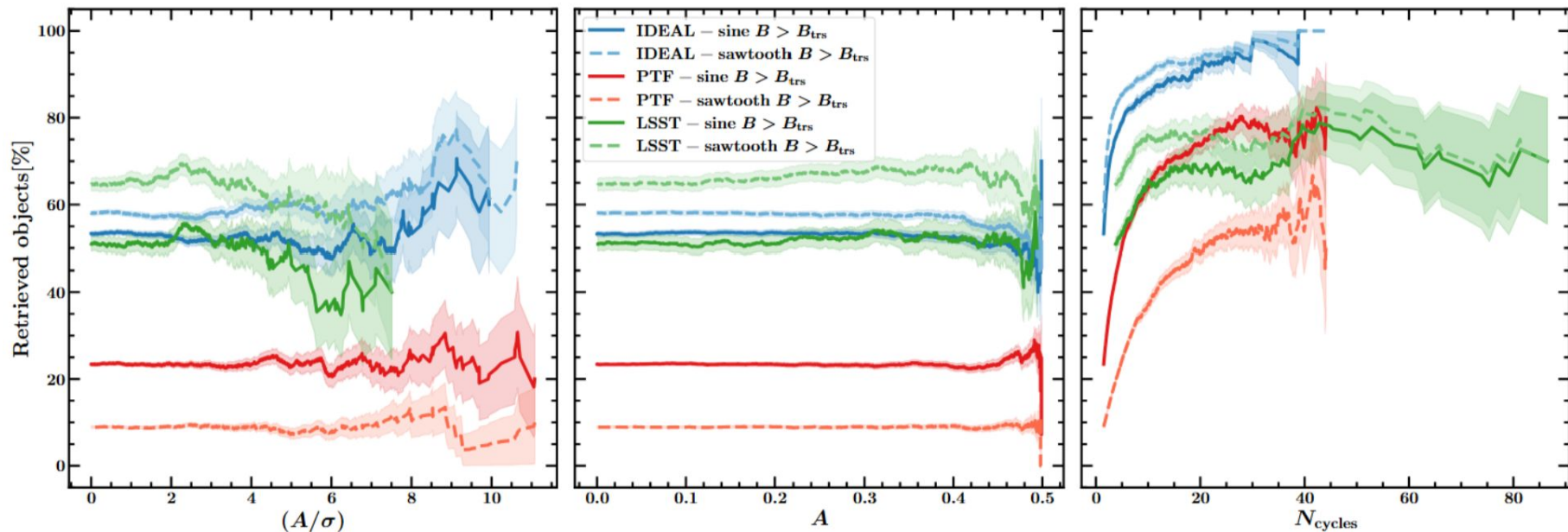
Goodness of the parameter estimation



$$\delta P = \frac{P_{\text{rec}} - P_{\text{inj}}}{P_{\text{inj}}}$$

	Sinusoid	Sawtooth
Idealised	82.3 %	99.8%
PTF-like	61.1%	69.4%
LSST-like	92.0 %	98.8%

Retrieved fraction as a function of parameters



Comparison with the cosine kernel

	True Positive	
Periodic kernel	Sine	Saw
idealised	69.7%	68.4%
PTF-like	53.4%	25.7%
LSST-like	59.3%	69.0%
Cosine kernel	Sine	Saw
idealised	55.2%	8.5%
PTF-like	17.1%	2.9%