



Astronomický
ústav
AV ČR

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Black Holes at different flavors

General relativistic effects at the heart of accreting Sgr A* light curve asymmetry

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Outline

- Introduction: hotspot model for Sgr a* emission
- Our Sgr a* flaring lightcurve model
- Structure functions: effects of relativity on SF2 and SF3
- Fitting of lightcurves and discussion of the results

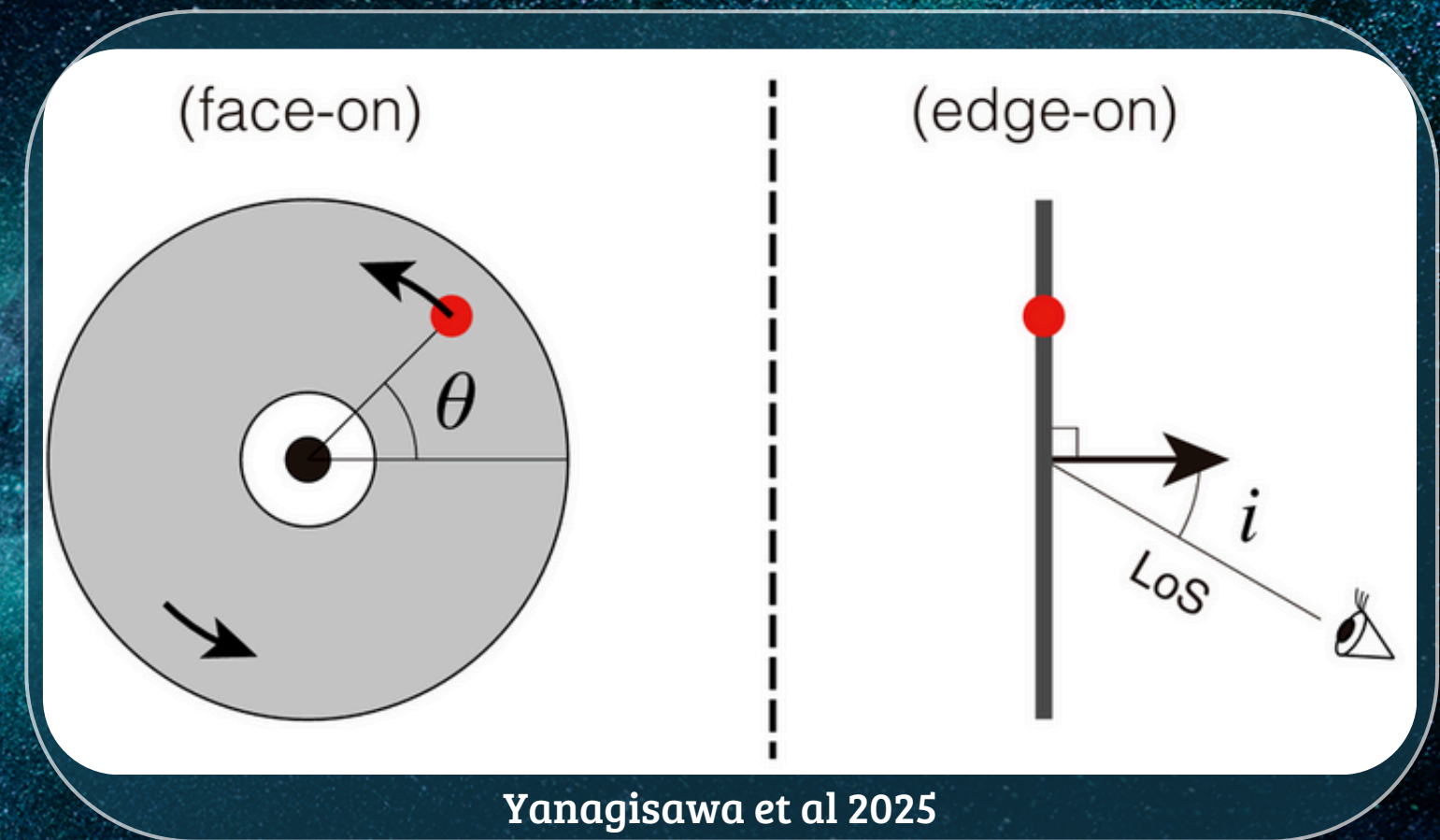
Goal:

Understand the effects of relativistic modulation on intrinsic emission.

(Von Felleberg et al. 2023, 2024)

Introducing the Hot-Spot model

- Sgr A* sometimes produces short bright IR and X-ray flares.
- Hotspot model: flares are produced by compact blobs of hot plasma orbiting near Sgr A*.



Origin of the intrinsic emission?

INFRARED:
Synchrotron emission?

X-RAYS:
High energy SSC, IC?
Magnetic reconnection?

Seem to be related

Modelling the LC

Observed emission is the result of an intrinsic emission kernel and the relativistic modulation

$$F_{obs} \approx Intrinsic(t_P, \tau_r, \tau_d) \times GRMod(\phi, \theta, R_s, k)$$

$$E(t) = \begin{cases} \exp[(t - t_p)/\tau_r], & t < t_p, \\ \exp[-(t - t_p)/\tau_d], & t > t_p, \end{cases}$$

Von Felleberg 2023

exponential rise-decay model

$$F = [p_3 \cos(\theta_0)/R_s + p_7(R_s - 1)^{2/5}] \times \{1 + \sin[2\pi(\phi + p_4 R_s - \frac{3}{5}) + \frac{1}{2}\pi]\}^z \cos^{-2/3} \theta_0 + (p_1 + p_6 R_s^{1/3}) \exp(-p_2 |\phi - \frac{1}{2}|^{9/5}) \cos^{-2} \theta_0,$$

where

$$z = p_5 \cos^{1/2} \theta_0 + p_8 \cos^{3/2} \theta_0.$$

Karas 1996

Modelling the LC: intrinsic emission

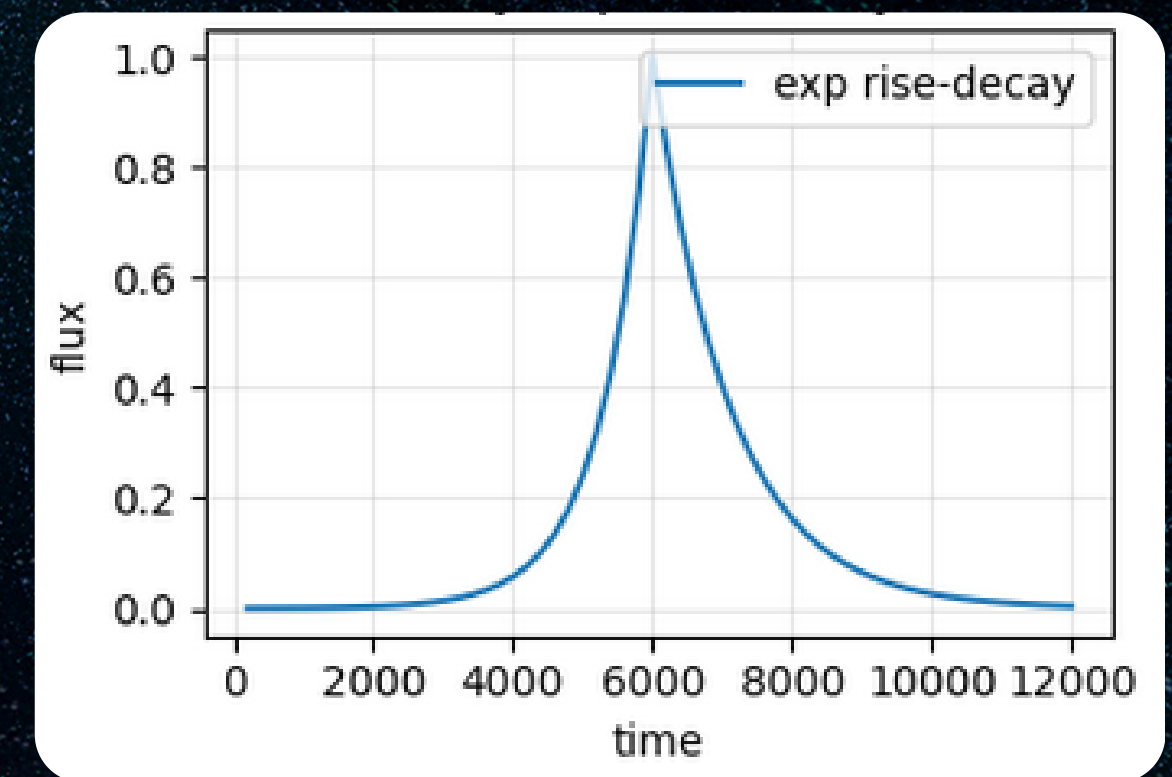
Intrinsic emission:
exponential rise-decay model

$$E(t) = \begin{cases} \exp[(t - t_p)/\tau_r], & t < t_p, \\ \exp[-(t - t_p)/\tau_d], & t > t_p, \end{cases}$$

- Each plasma blob injects energetic electrons.
- The average flare light curve in both IR and X-ray is well approximated with a double-sided exponential profile.

PARAMETERS

- Flux rises as electrons are accelerated: τ_{rise} .
- Effective fading timescale of the hotspot (by particle escape, confinement, decreased injection, unresolved cooling): τ_{decay} .



Modelling the LC: relativistic modulation

$$F_{obs} = F_0 + A \times E(t_P, \tau_r, \tau_d) \times GRMod(\phi, \theta, R_s, k) + \sigma$$

Doppler

$$F = [p_3 \cos(\theta_0)/R_s + p_7(R_s - 1)^{2/5}] \times \{1 + \sin[2\pi(\phi + p_4 R_s - \frac{3}{2}) + \frac{1}{2}\pi]\}^z \cos^{-2/3} \theta_0 + (1 + p_6 R_s^{1/3}) \exp(-p_2 |\phi - \frac{1}{2}|^{1/3}) \cos^{-2} \theta_0,$$

where

$$z = p_5 \cos^{1/2} \theta_0 + p_8 \cos^{3/2} \theta_0.$$

Lensing

- The hotspot orbits close to Sgr A*, so relativity changes the observed flux

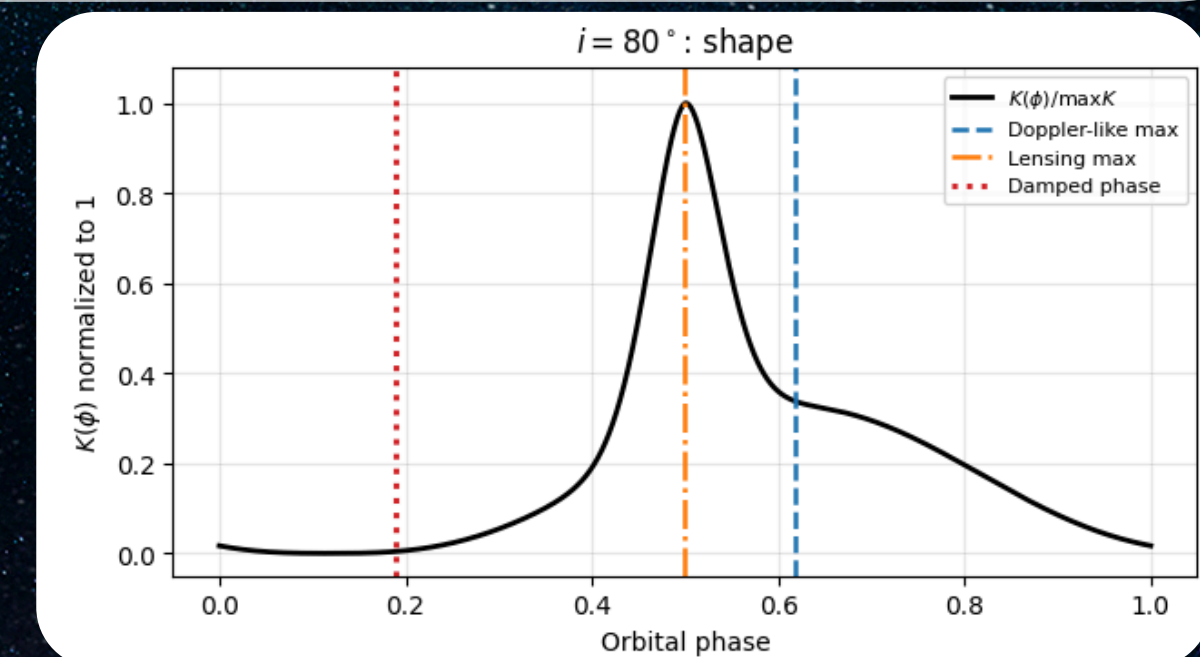
PARAMETERS

orbital radius

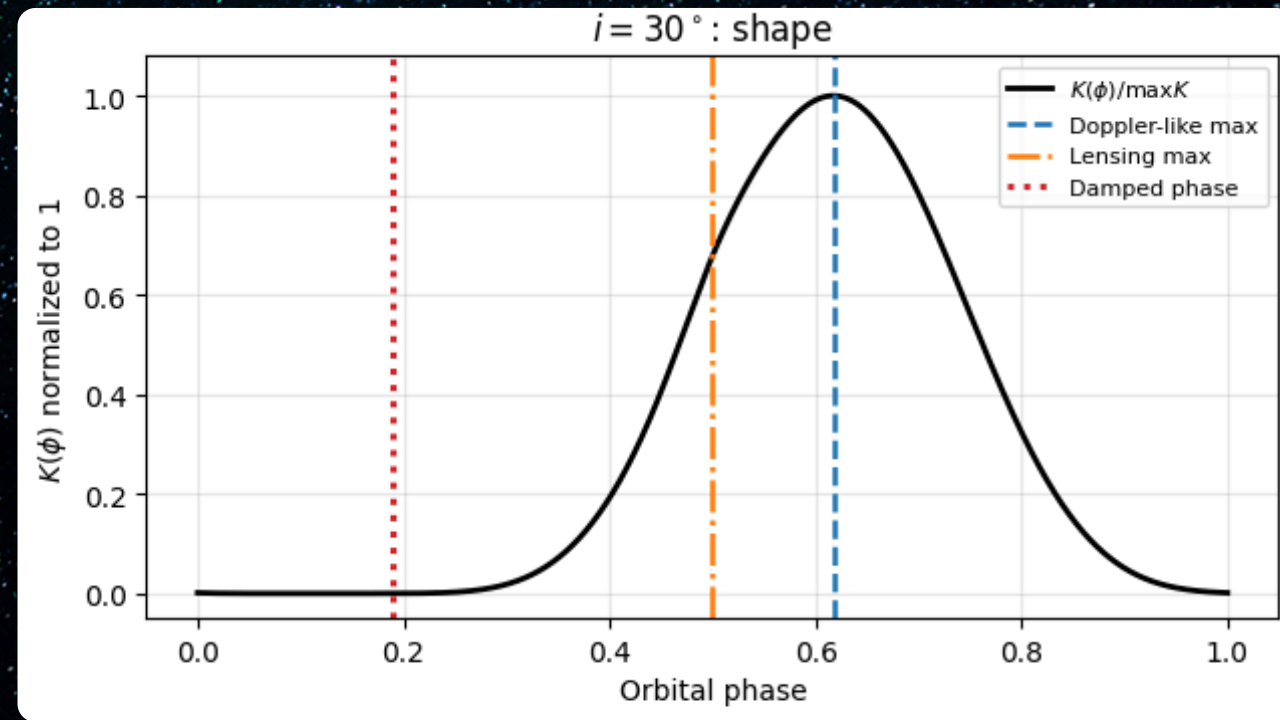
inclination

orbital factor

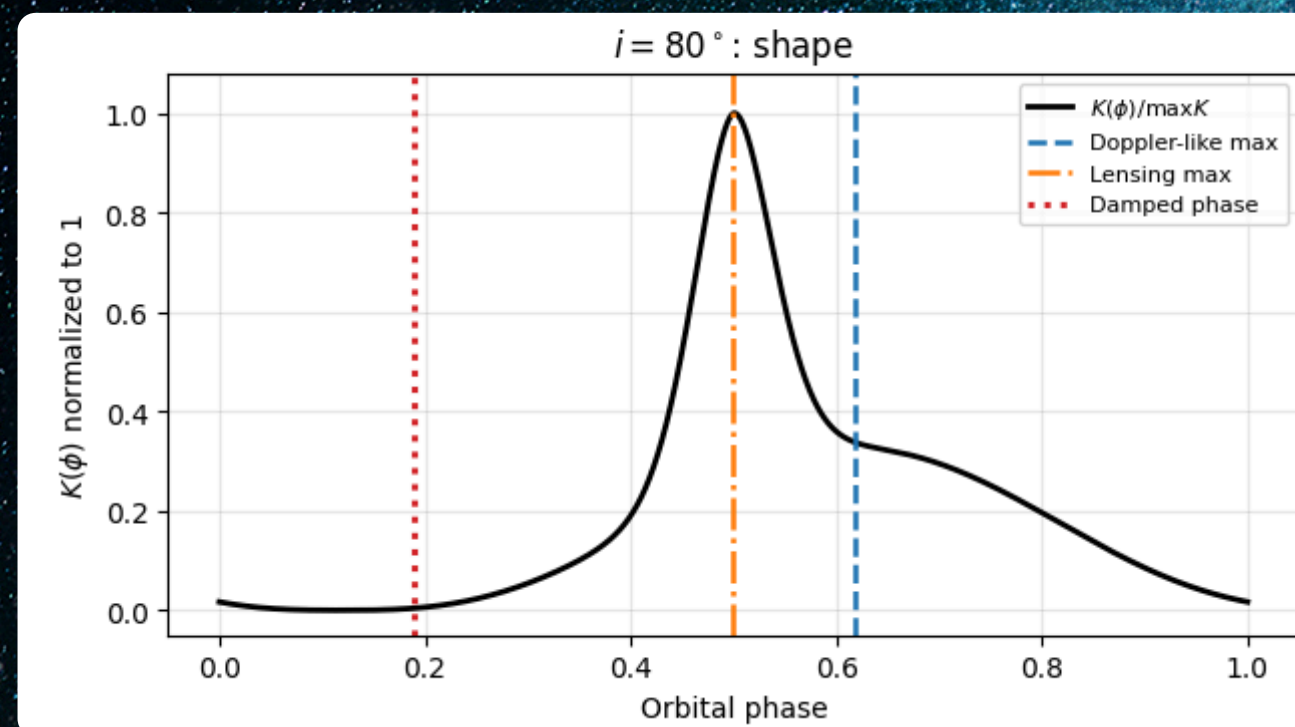
- Observed light curve = intrinsic hotspot emission* relativistic modulation



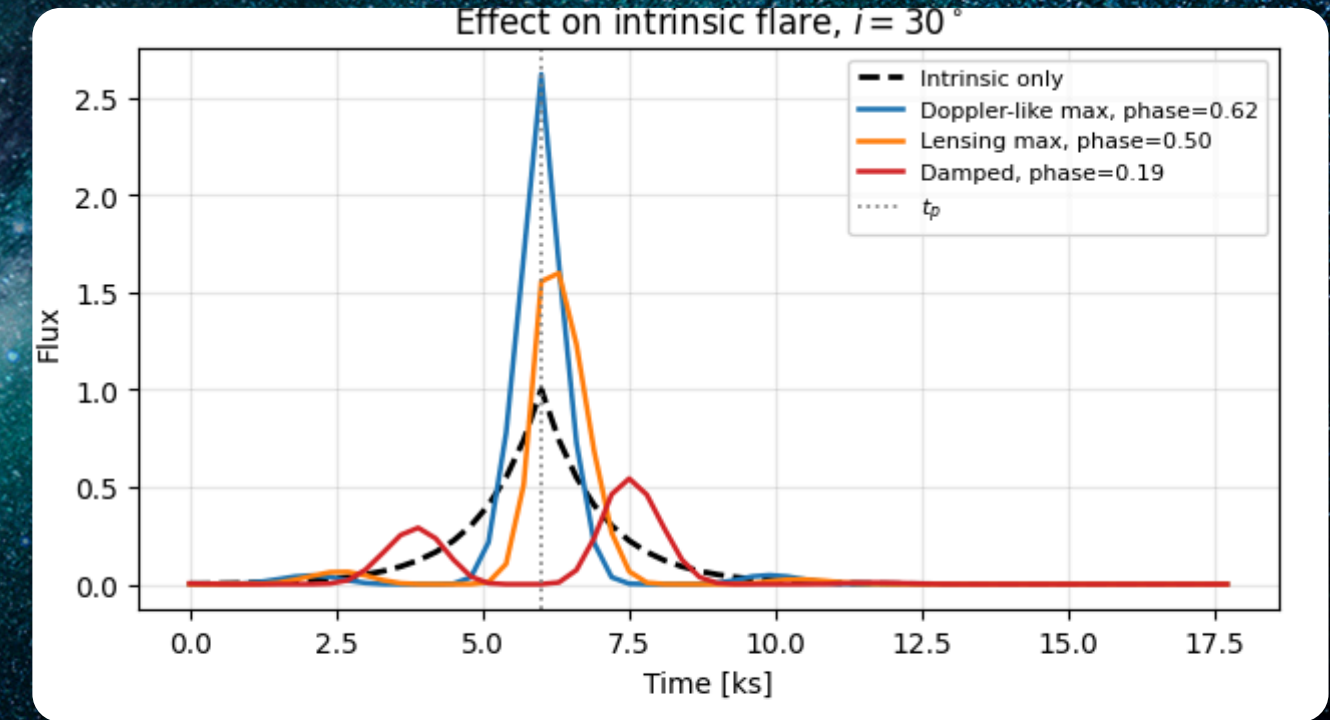
Lightcurve Model



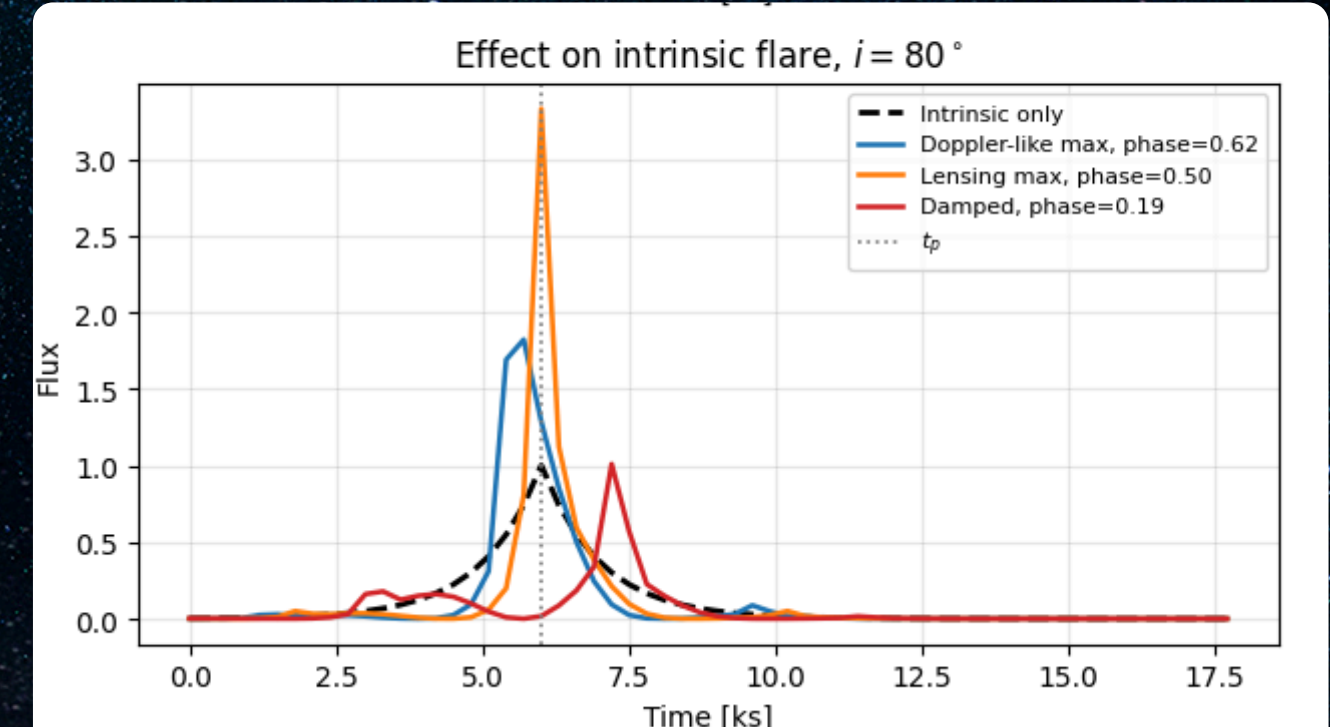
Normalized to reproduce
only shape distortions



- Magnification is phase dependent
- At high inclination the observed lightcurve looks asymmetric



Example of dependence on
phase

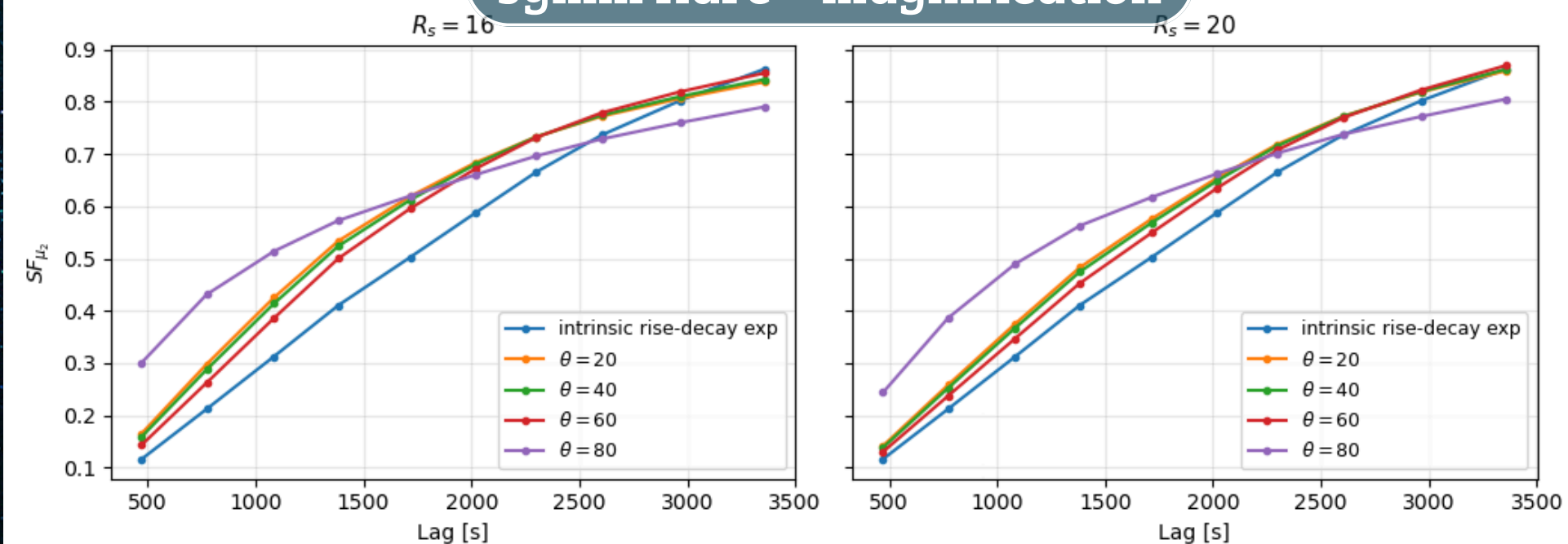
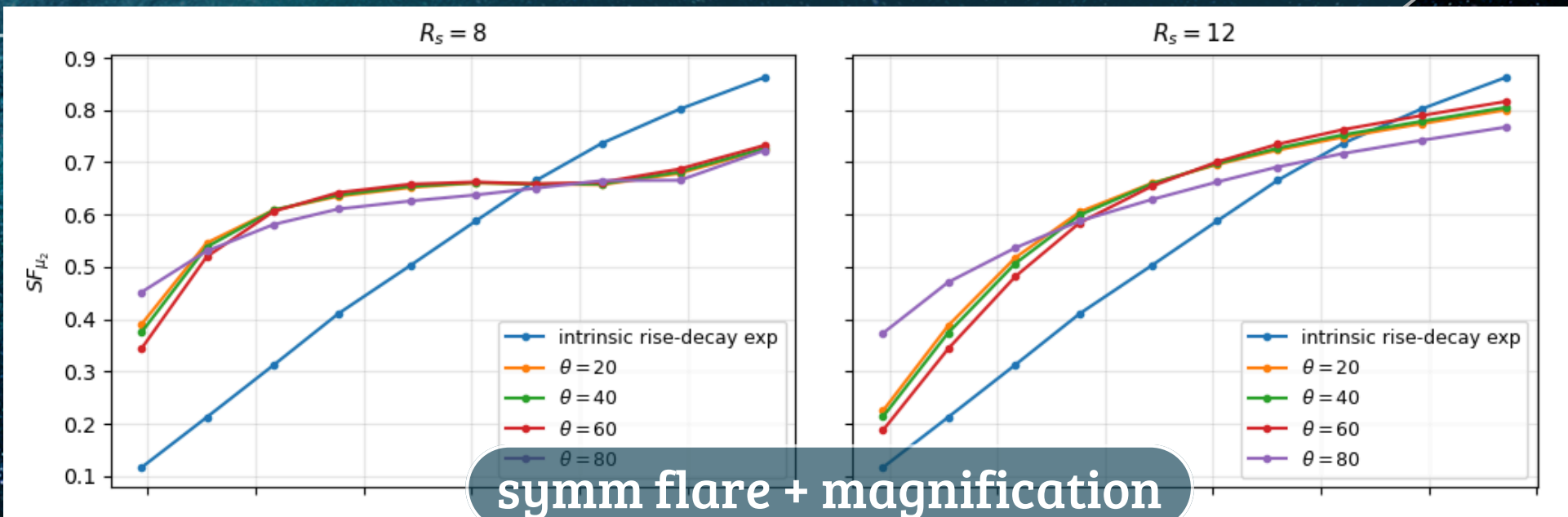
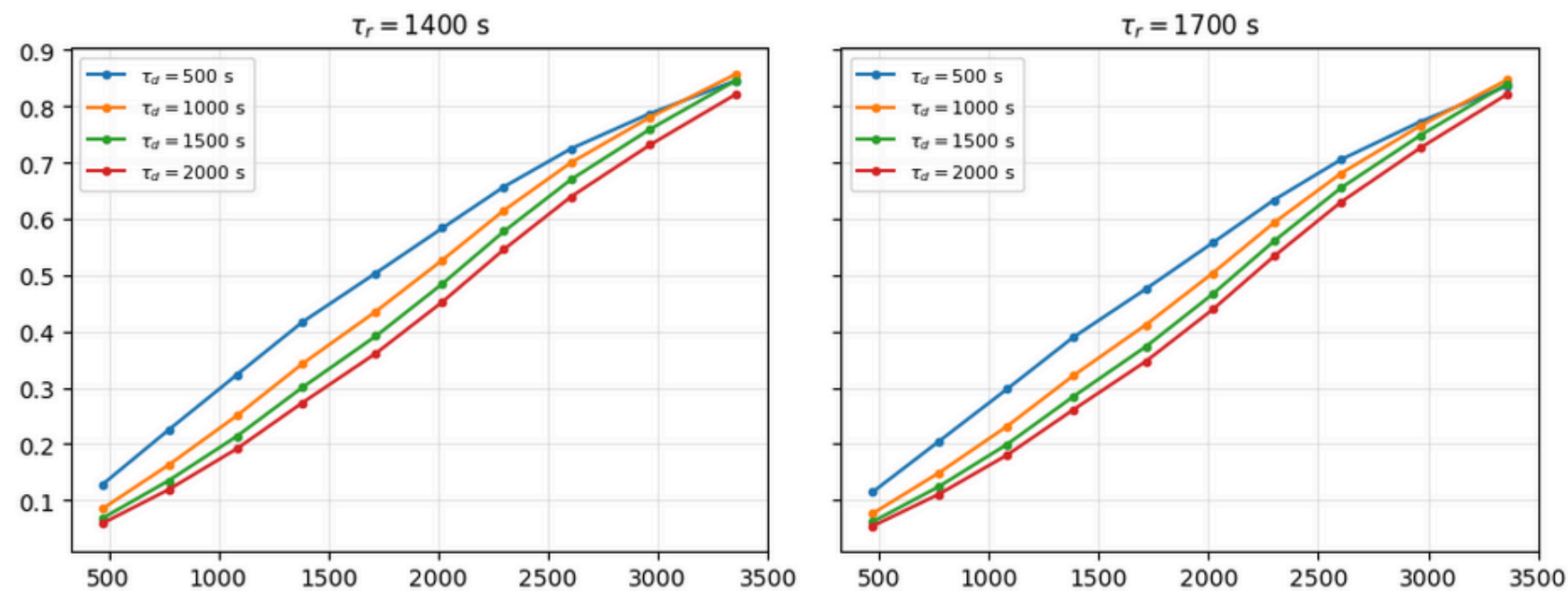
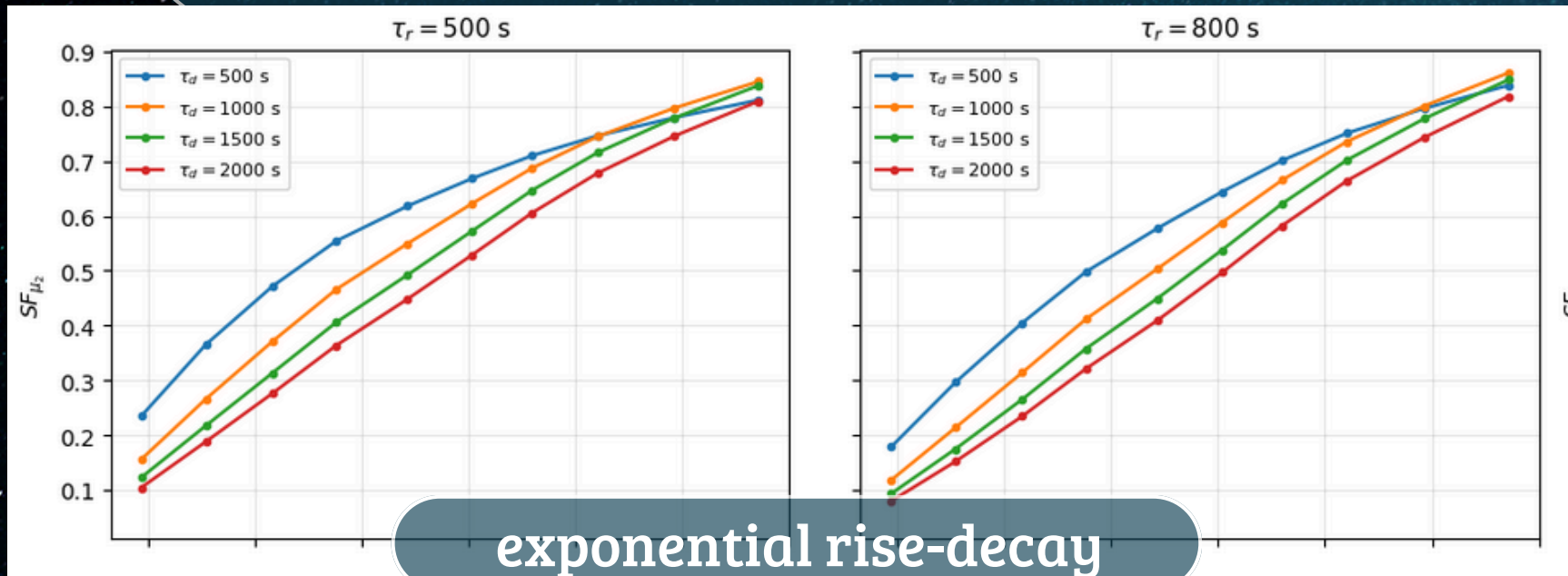


Second Moment Structure Function SF2 8/16

- Measures the strength of variability as a function of lag:

$$SF_2(\tau) \propto \langle [F(t + \tau) - F(t)]^2 \rangle$$

- Small lags $\rightarrow$ small differences $\rightarrow$ SF2 ~ 0 .
- Large lags $\rightarrow$ flux differences grow $\rightarrow$ SF2 rises and saturates.



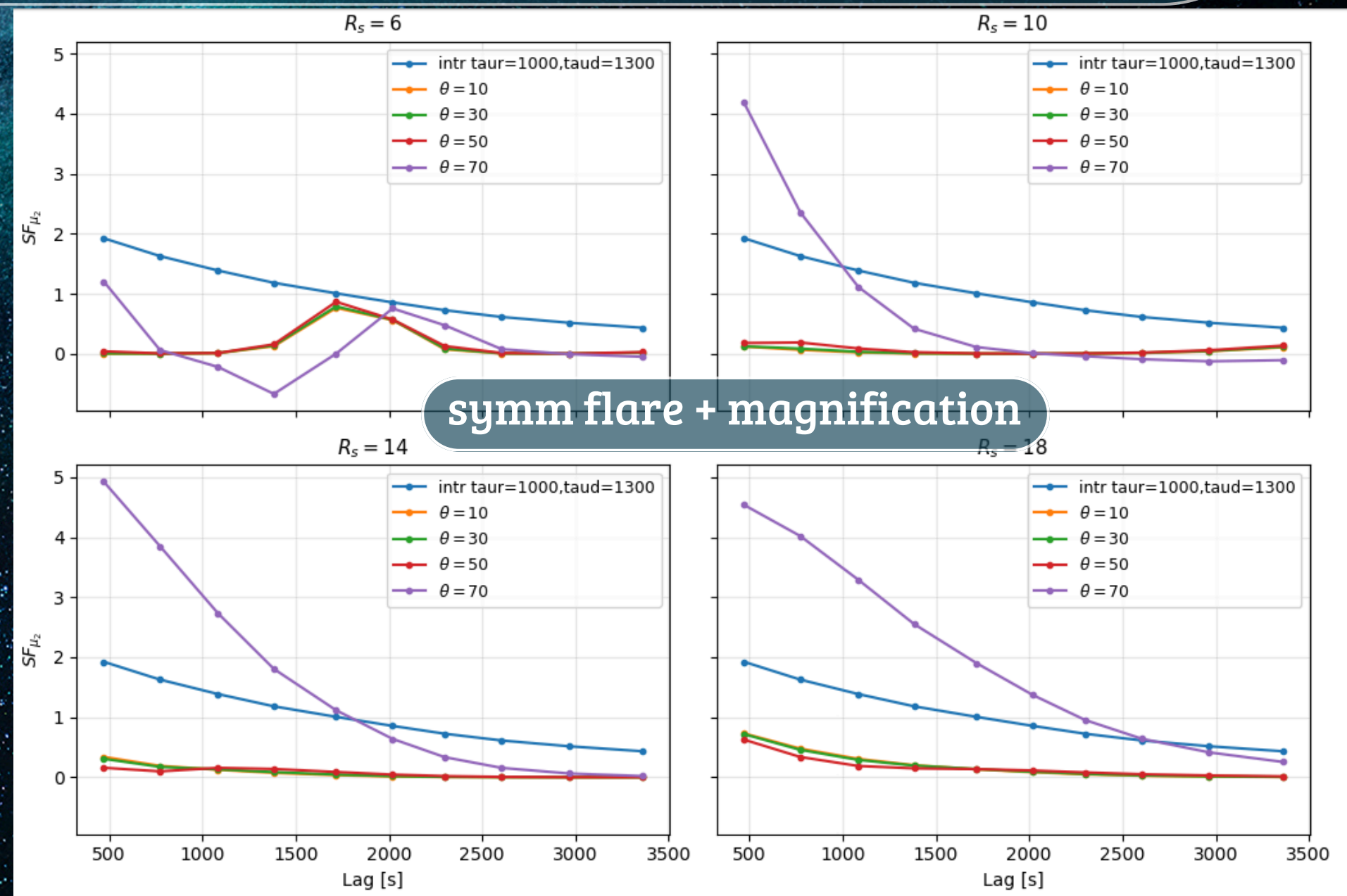
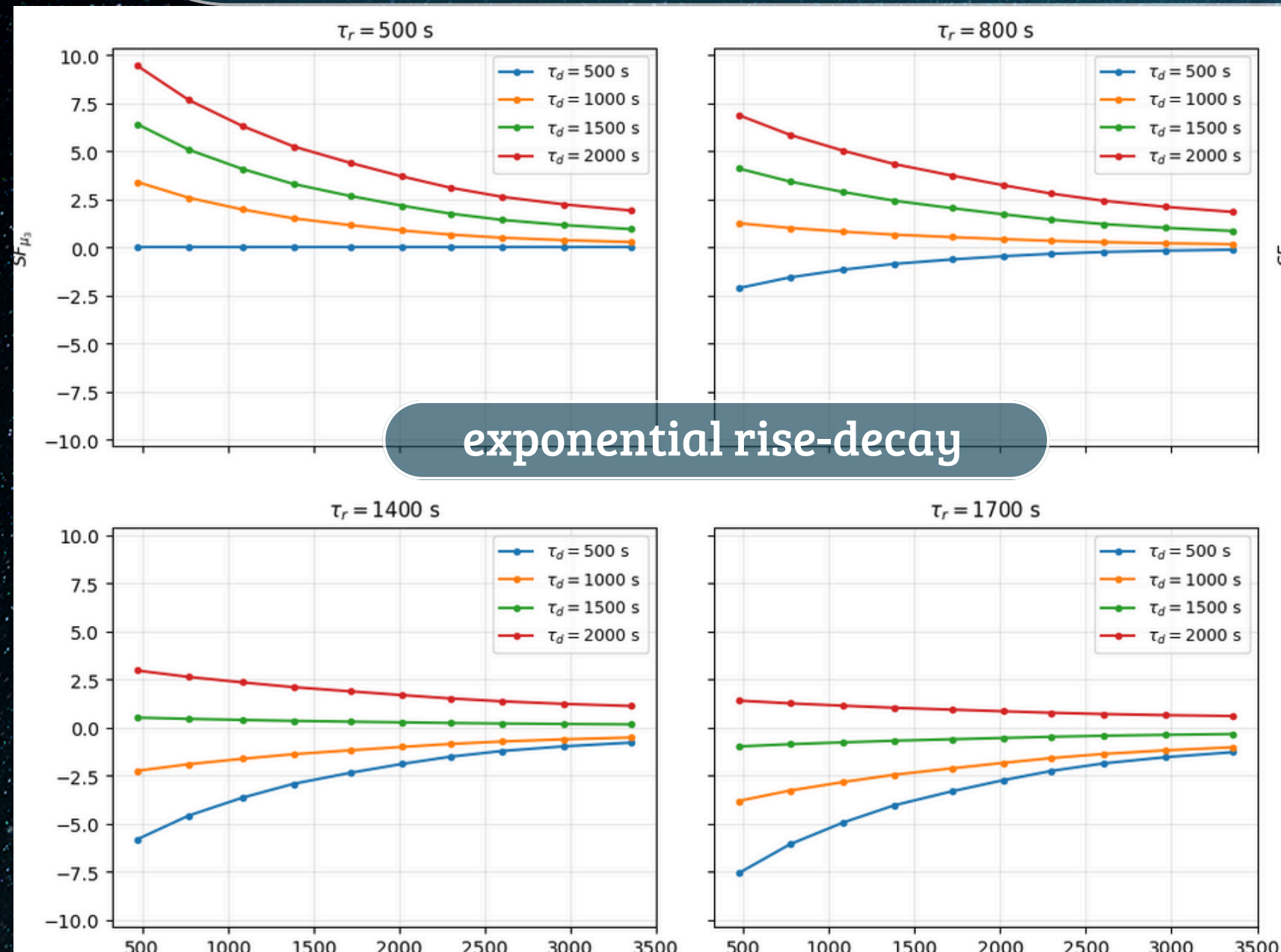
Third Moment Structure Function SF3

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- Measures time asymmetry / skewness of flux increments:

$$SF_3(\tau) \propto \langle [F(t + \tau) - F(t)]^3 \rangle$$

- To obtain independence from amplitude the SF3 will be divided by: $SF_2(\tau_i)^{1.5}$
- Positive SF3 → faster rise / slower decay; negative → opposite.
- Relativistic effects can amplify one side of the flare → SF3 can change amplitude or even sign.

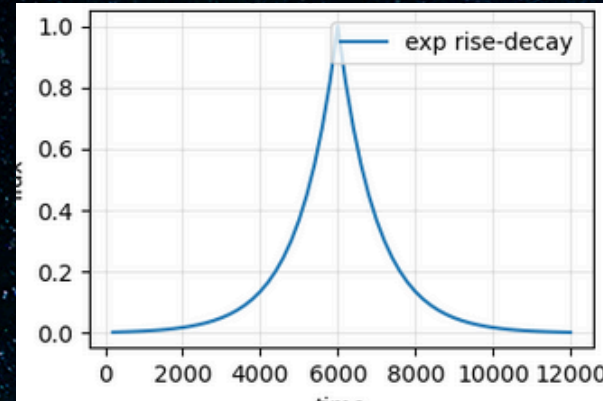


LC Parameters and their impact on SFs

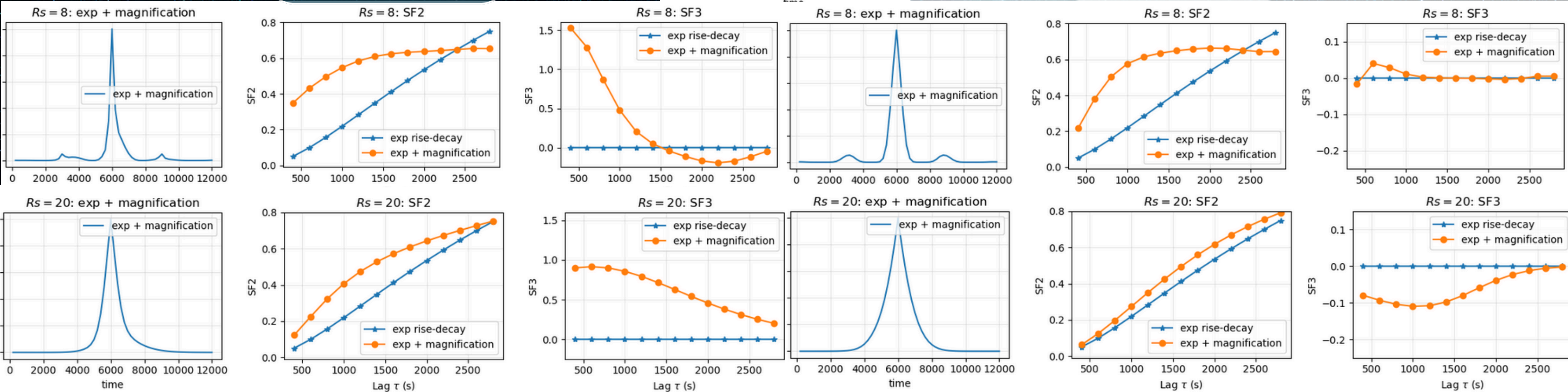
10/16

High inclination causes
observed asymmetry

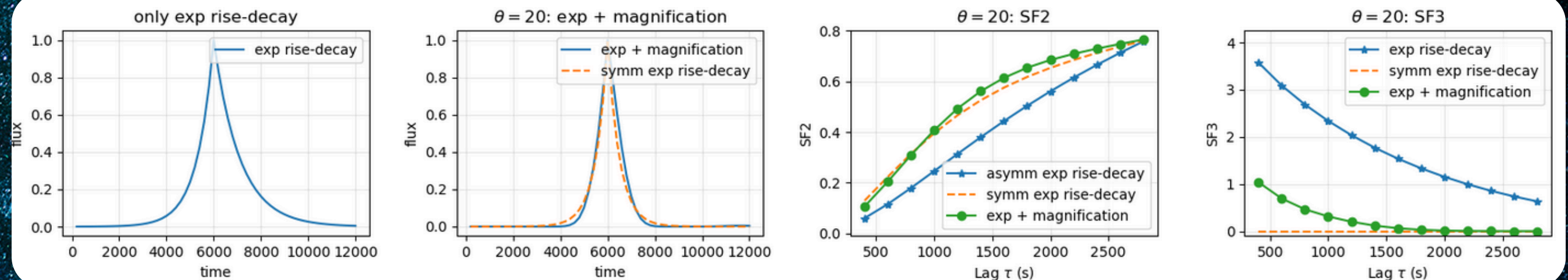
$$\theta = 80^\circ$$



$$\theta = 20^\circ$$



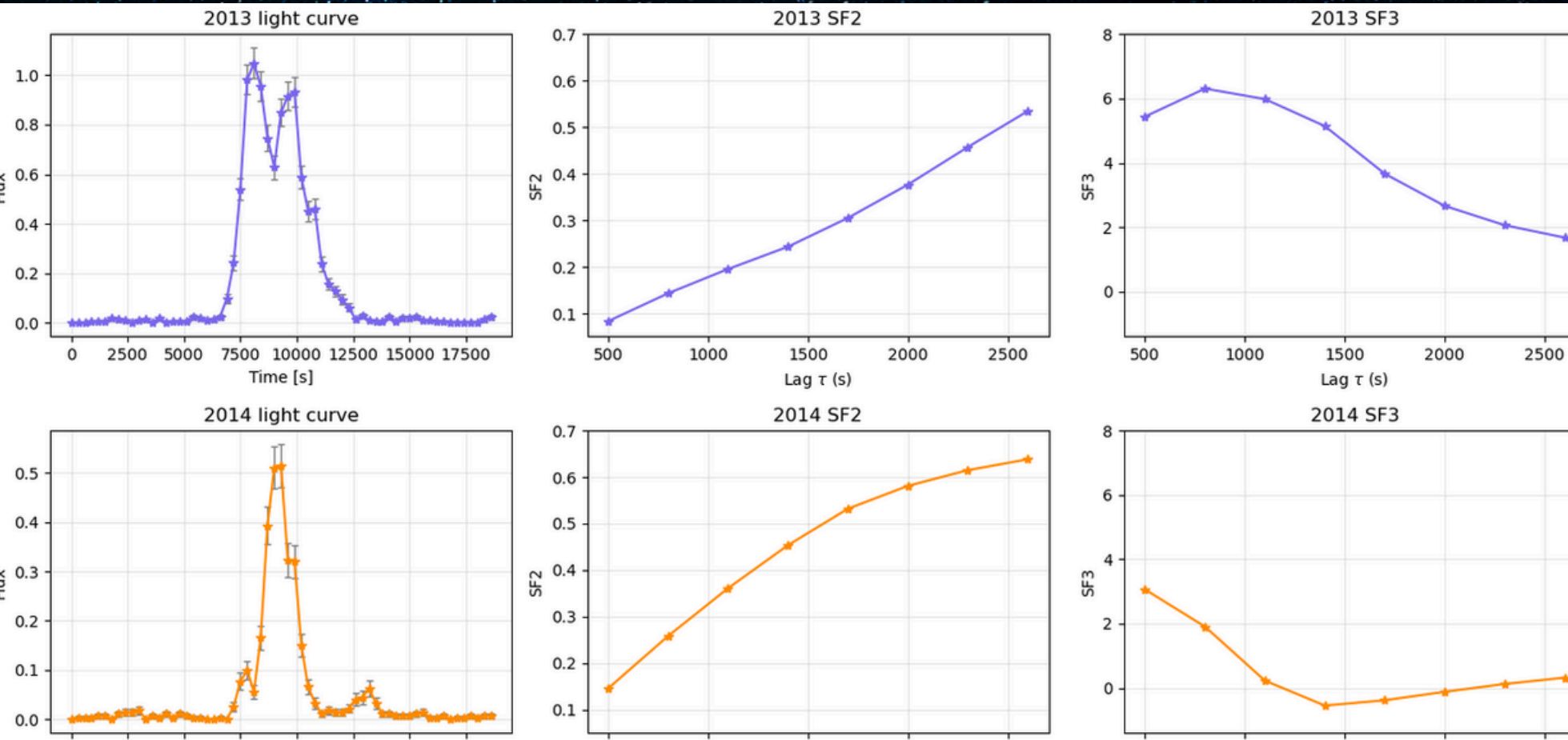
Asymmetric profile
+
Rel effect with R=12



Data Analysis

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Haggard et al.



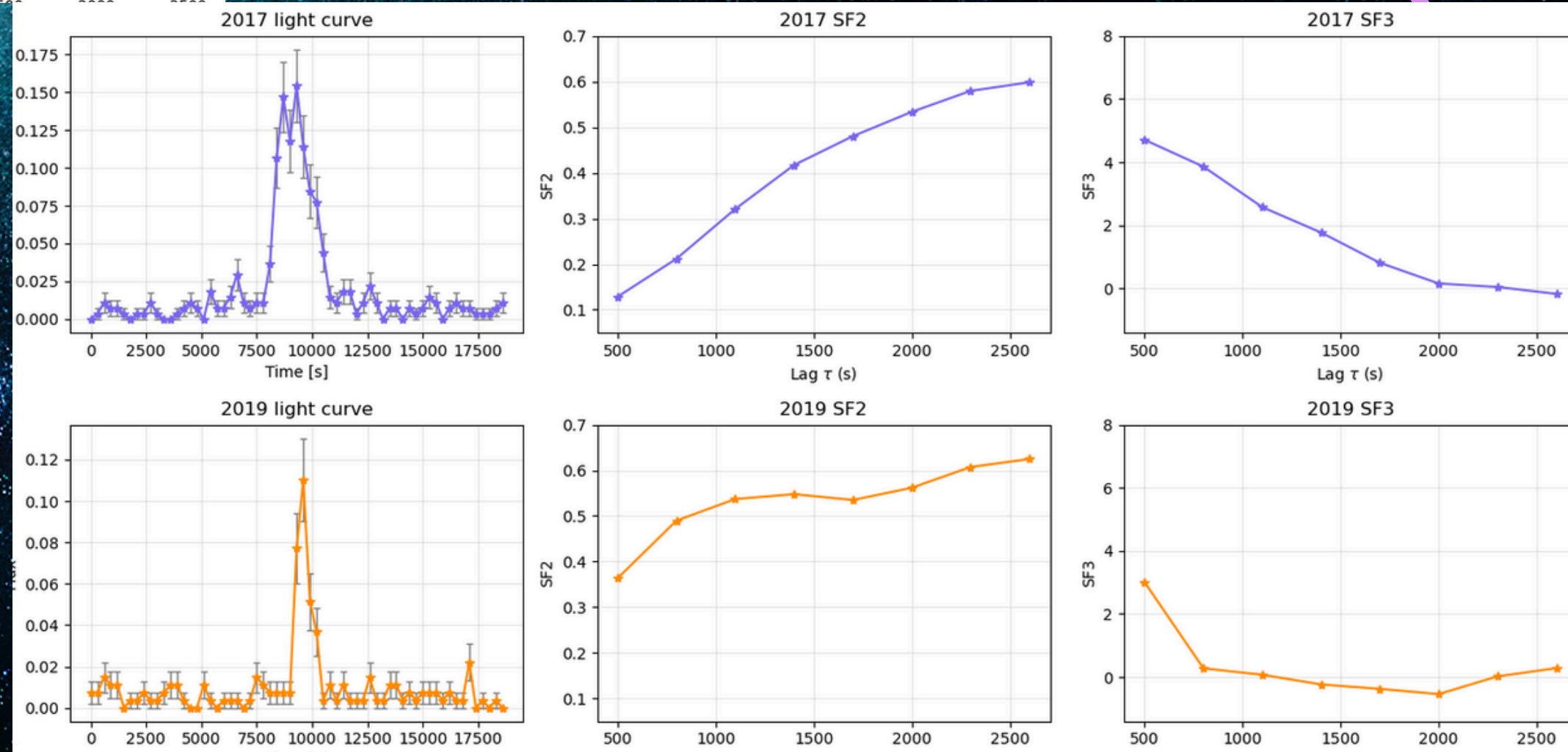
- 2013 and 2017:
- Two main peaks
- Broader flare shape
- SF3 decays slowly to zero

Ponti et al.

Haggard et al.

- 2014 and 2019:
- One main peak
- Narrower flare
- SF3 decays faster to zero

Fazio et al.



Data Analysis: PyABC

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PyABC is used for Bayesian inference with simulation-based models.

It compares the observed SFs with SFs generated by the model minimizing the distance.

Averaging the SFs at different phases averages out phase dependent relativistic effects.



Intrinsic emission time scales can be shown

The parameters are sampled from predefined prior distributions.

$$5^\circ < \theta_0 < 80^\circ$$

$$6 < R_s < 15$$

$$200 < \tau_{\text{rise}} < 2000$$

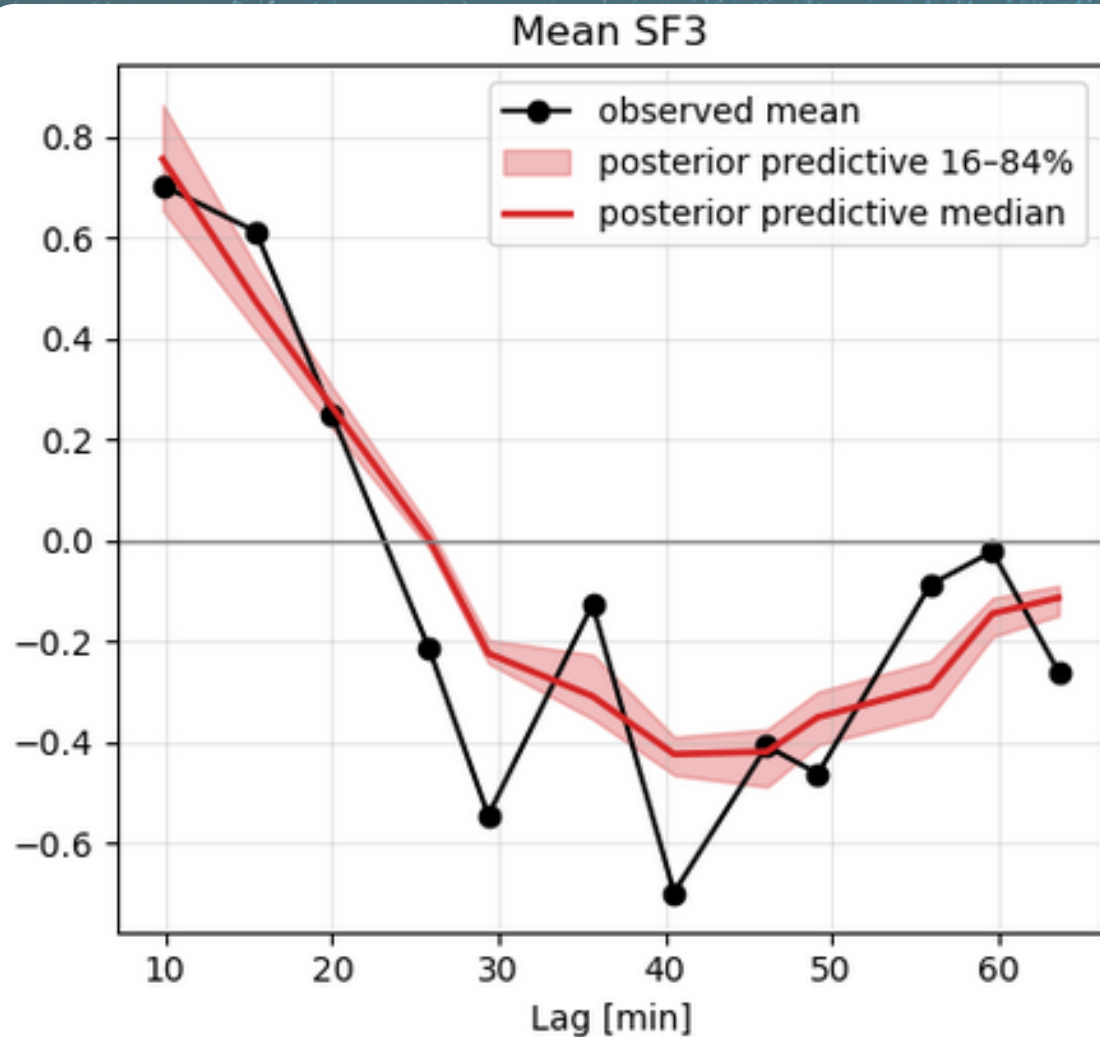
$$200 < \tau_{\text{decay}} < 2000$$

$$0.8 < k_{\text{orbit}} < 1.3$$

Fit of averaged SF2 and SF3, all flares

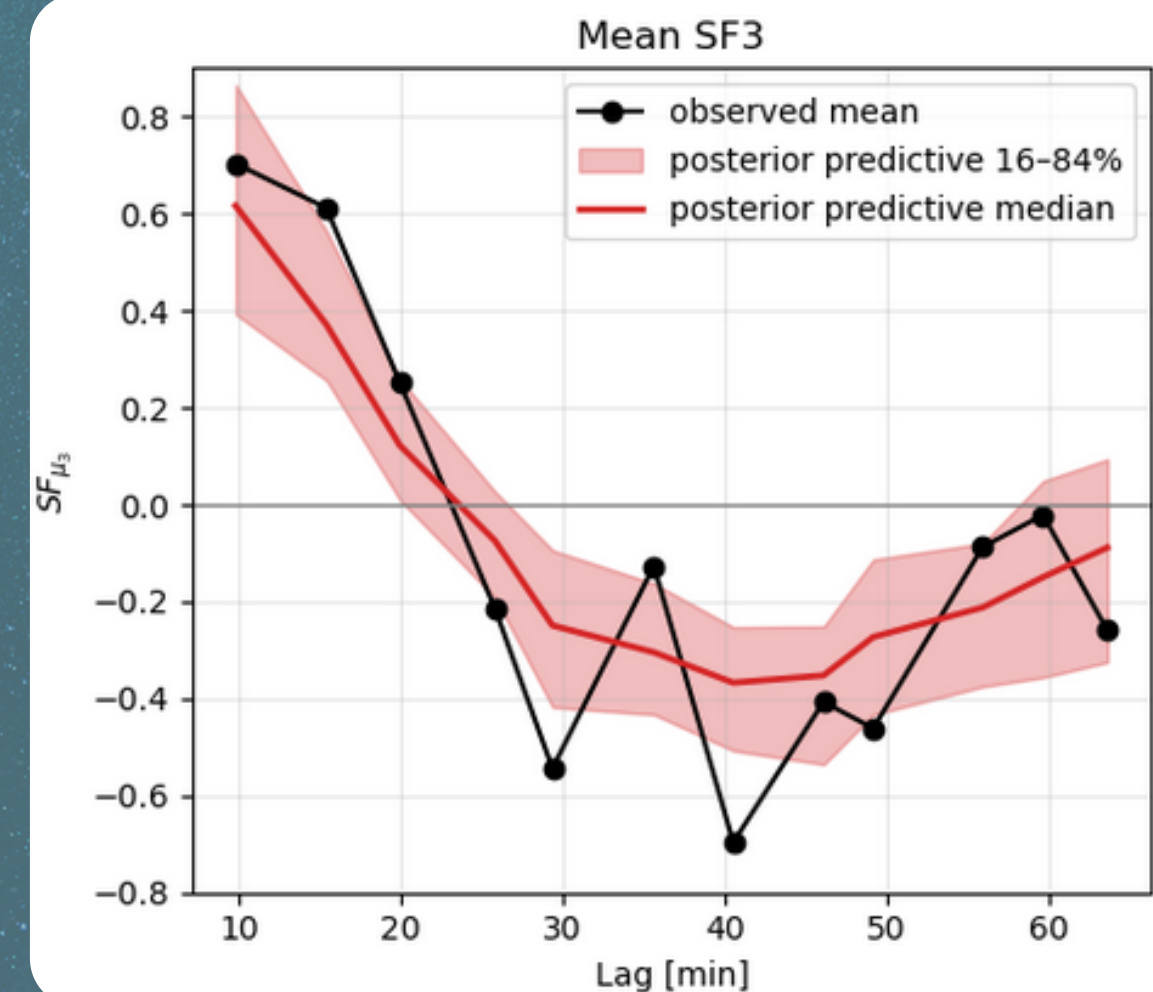
Simulated lightcurves at random tpeaks to fit the observed averaged SFs

R_s	θ_0	n_{flares}	$\tau_{\text{r,main}}$	$\tau_{\text{d,main}}$
9.5	$38.3^{+11.7}_{-16.2}$	$2.14^{+0.05}_{-0.08}$	$1073.2^{+134.5}_{-101.1}$	$1201.7^{+98.5}_{-123.6}$



53 Chandra Flares
SF3 = 0 on average
Quasi symmetric
intrinsic emission

R_s	θ_0	n_{flares}	$\tau_{\text{r,main}}$	$\tau_{\text{d,main}}$
$10.11^{+1.47}_{-1.03}$	$35.27^{+13.5}_{-16.7}$	$2.06^{+0.09}_{-0.02}$	$1110.7^{+209.7}_{-188.6}$ s	$1258.9^{+248.}_{-253.}$



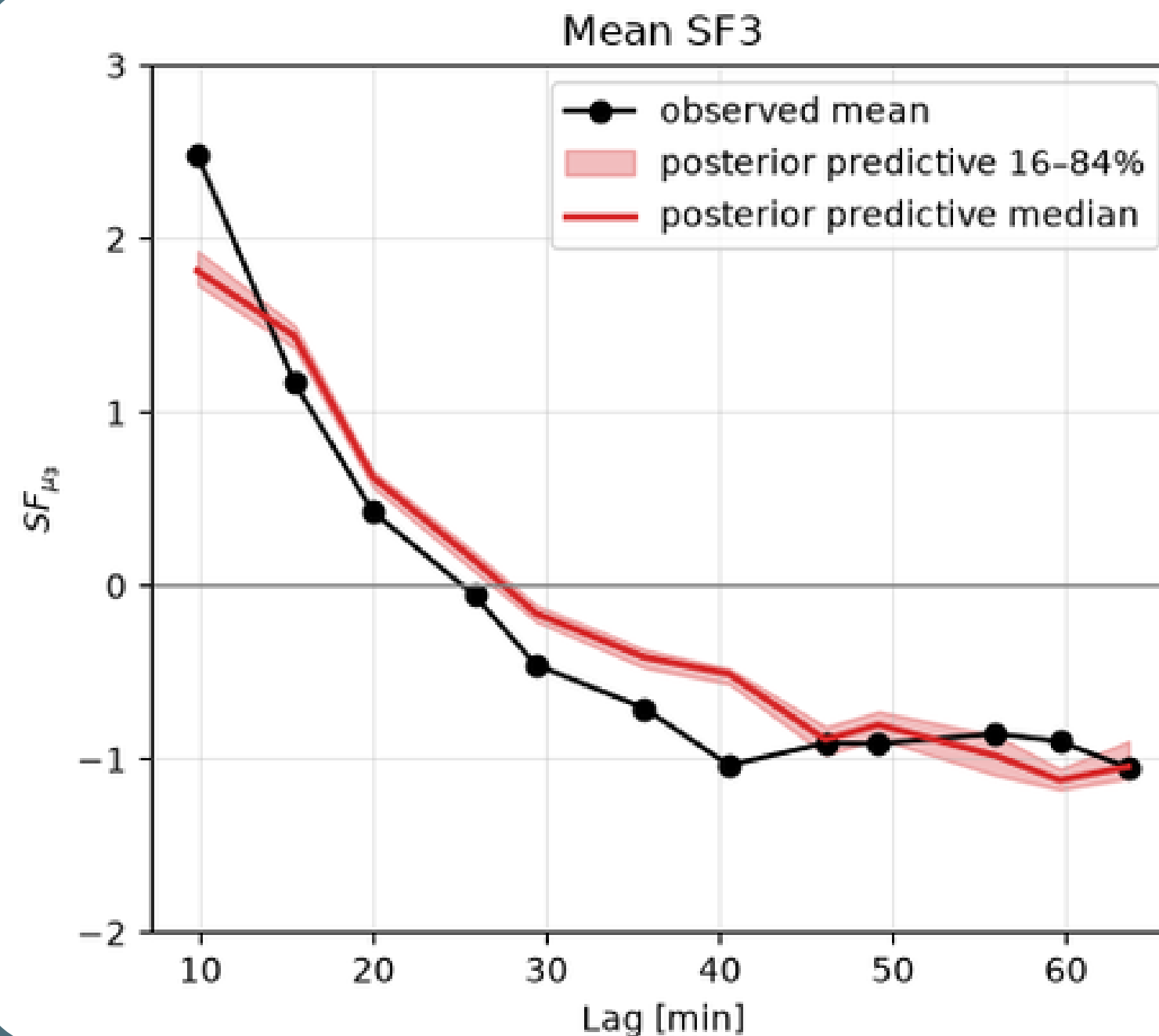
Fit of averaged SFs, brightest flares

R_s	θ_0	k_{orbit}	τ_{rise}	τ_{decay}
$11.51^{+1.665}_{-1.23}$	$31.5^{+8.158}_{-6.555}$	$1.202^{+0.1275}_{-0.0201}$	$1059^{+284.2}_{-255}$	$1394^{+163.6}_{-279.4}$

17 Chandra Flares
Counts/s at $t_p > 0.09$

This fit suggests:

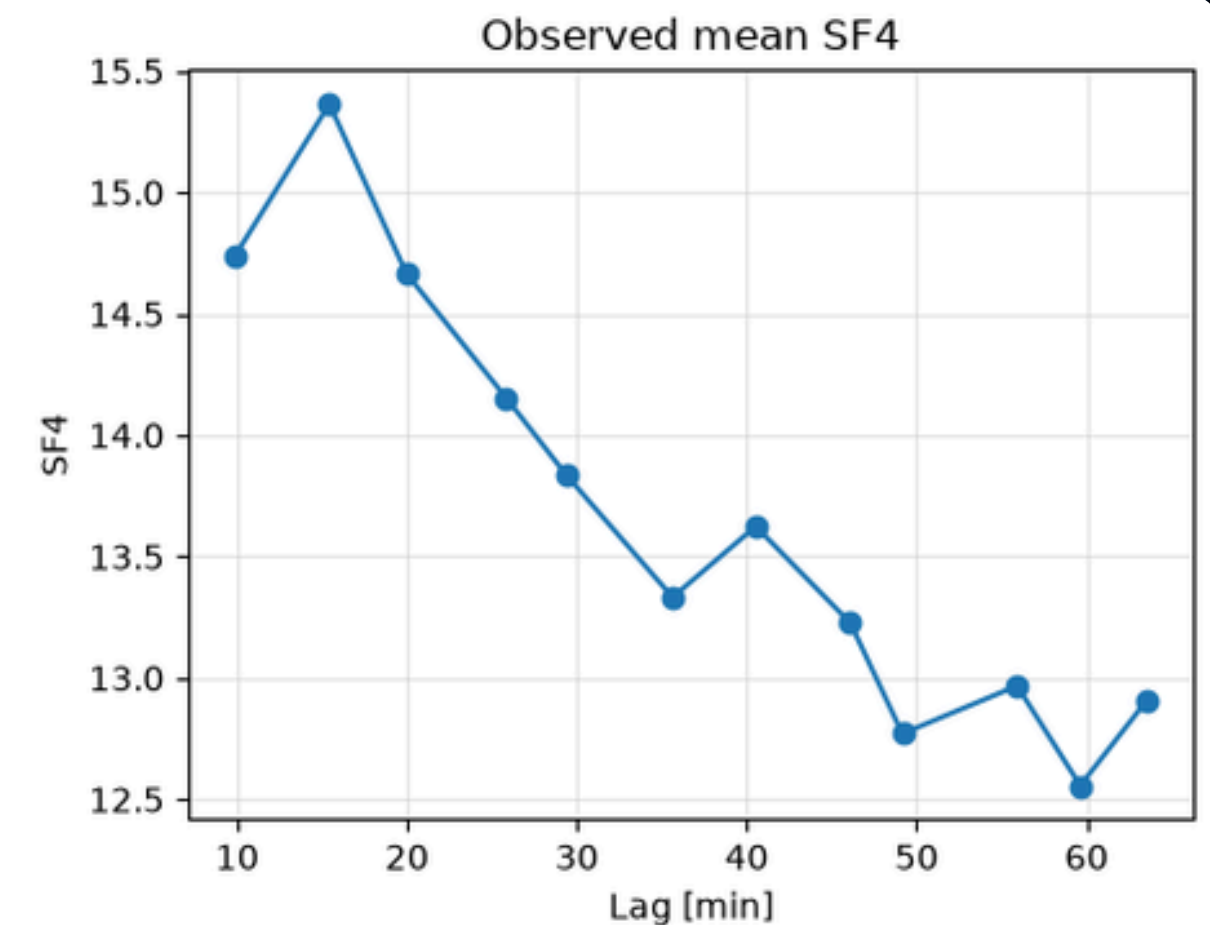
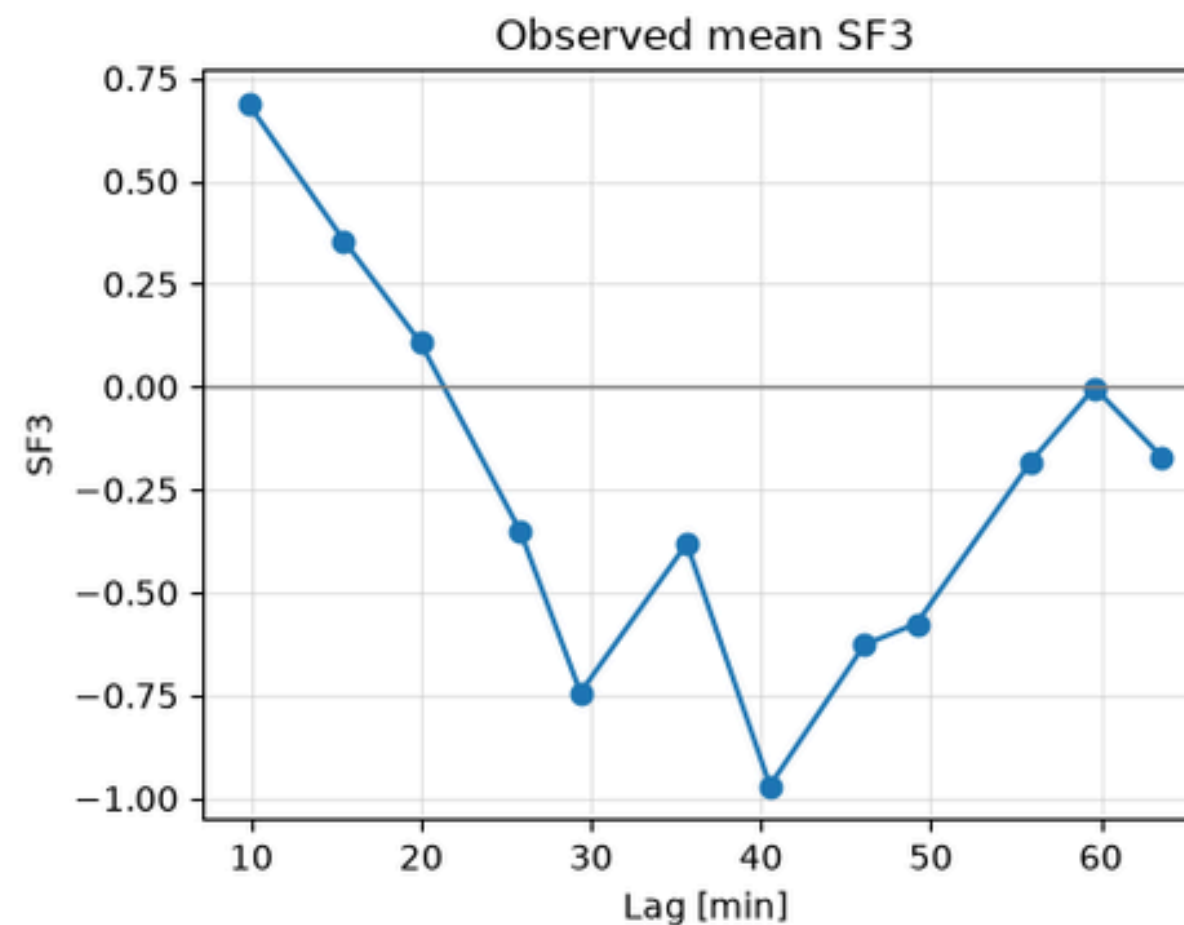
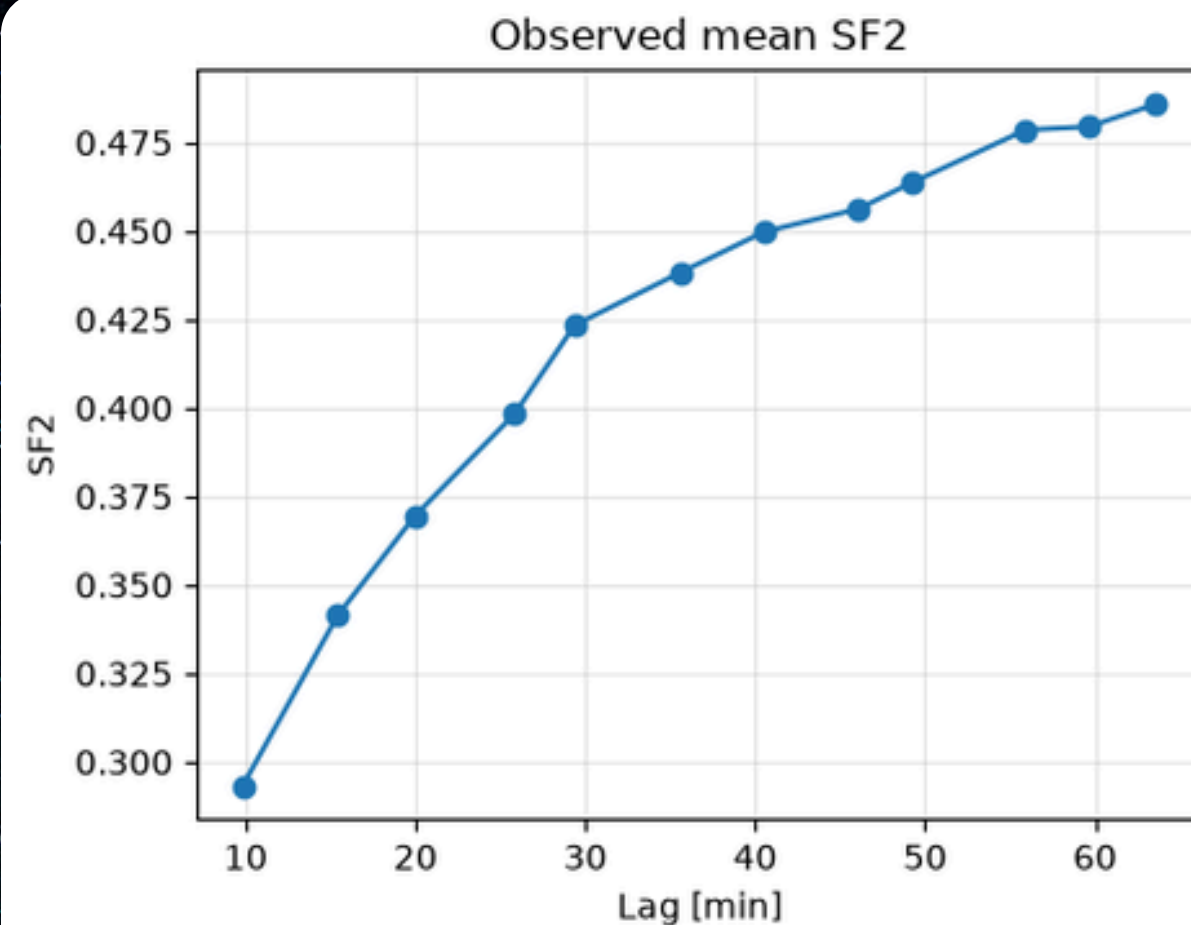
- **low intrinsic asymmetry**
- **moderate inclination.**
- **super keplerian orbit.**



Fourth Moment Structure Function SF4 15/16

- Measures the kurtosis of the flux differences as a function of lag using the fourth-order structure function.
- SF4 is more sensitive to large-amplitude variations and outliers than SF2.
- It can therefore highlight non-Gaussian and intermittent variability in the light curve.

$$SF_4(\tau) = \frac{\langle [F(t + \tau) - F(t)]^4 \rangle}{\langle [F(t + \tau) - F(t)]^2 \rangle^2}$$



Future prospects: ideas?

From Sgr A* Flares to QPEs

The Sgr A hotspot model is not directly applicable to the recurrent, quasi-periodic QPE light curves.

GOAL: model a QPE-specific light-curve model.

**Apply the same structure-function summary statistics to the QPE light curves.
Explore whether common statistical signatures can be identified between QPEs
and Sgr A* variability.**

Summary

- SF2 traces variability amplitude and characteristic timescale.
- SF3 captures temporal asymmetry direction and strength.
- Hotspot Model reproduces observations

Implications

- Flare morphology shaped by both intrinsic emission evolution and relativistic effects.
- Full sample: averaged SF3 $\approx 0 \rightarrow$ quasi-symmetric profile.

Thank you for your attention! :)

I appreciate questions and suggestions!!!

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