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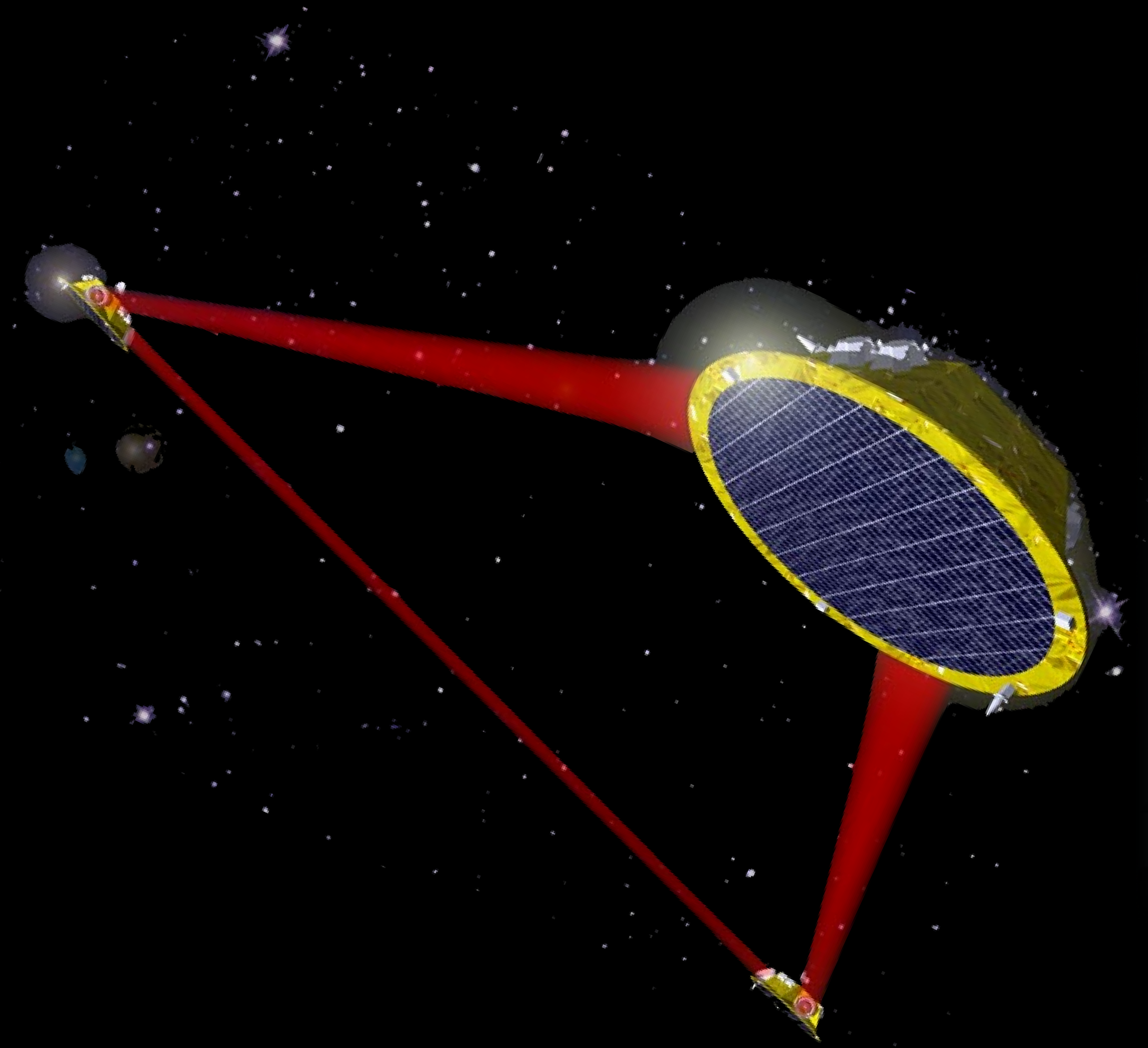
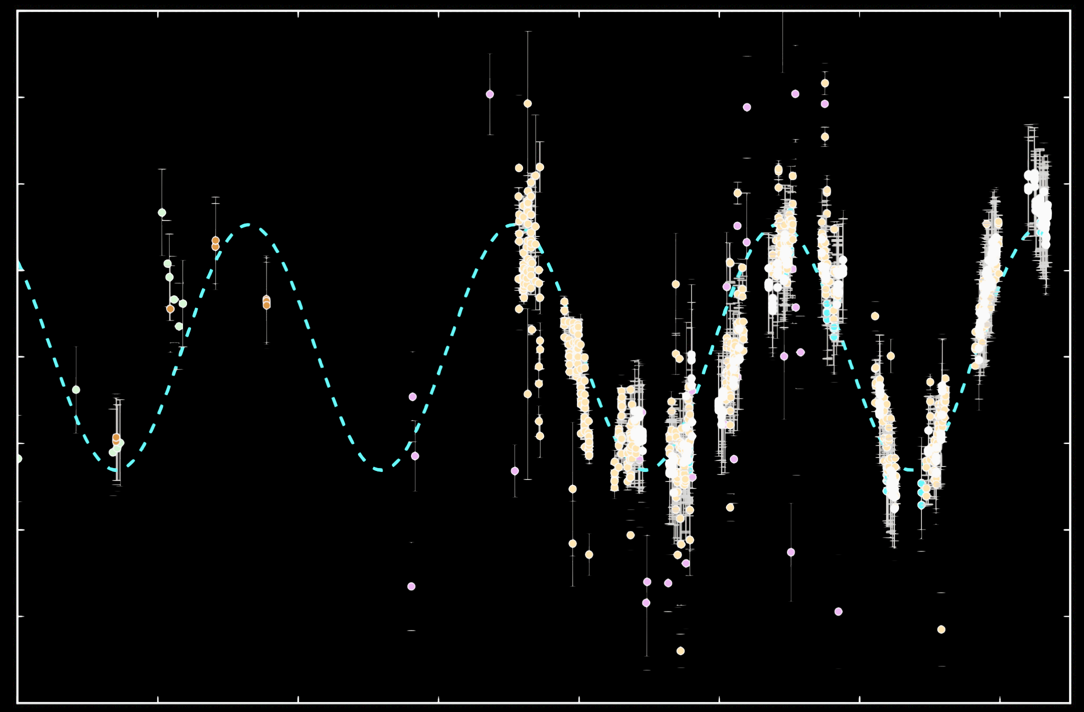
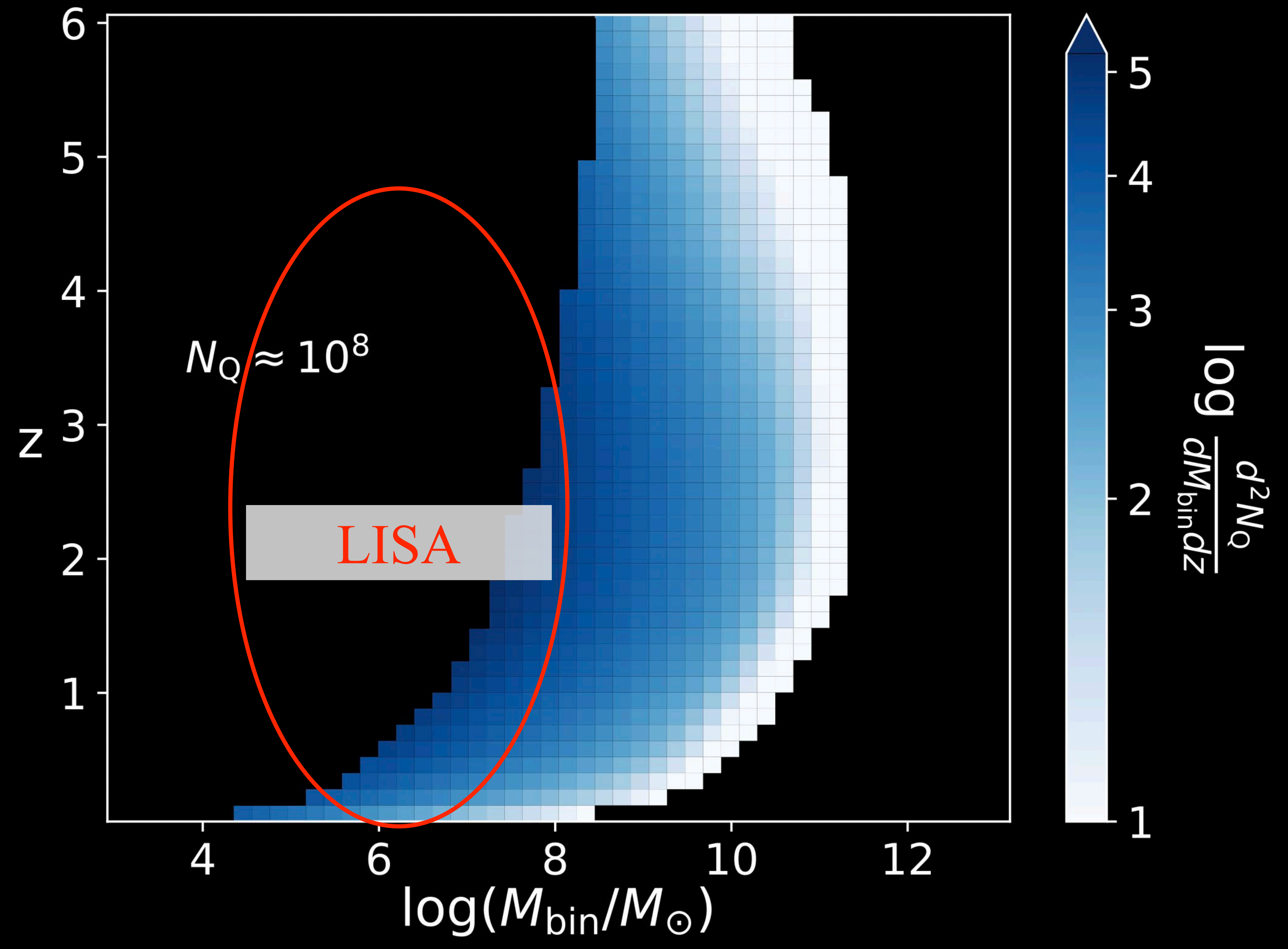
Identifying Compact SMBHBs in LSST using Bayesian Analysis



10 Years (!!) to LISA Conference (JPL) 04/01/25 — 04/03/25

Number of Quasars in LSST



1. LSST is expected to observe ~ 100 million quasars before the launch of LISA

2. **A** small fraction can be compact GW-driven SMBH binaries

   $t_m/t_Q \sim 10^{-4} - 10^{-3}$)$t_Q \sim 10^7$ years)

3. Up to 150 can be LISA binaries, assuming $t_m = 5 - 15$ years [**Xin** + Haiman 2021]

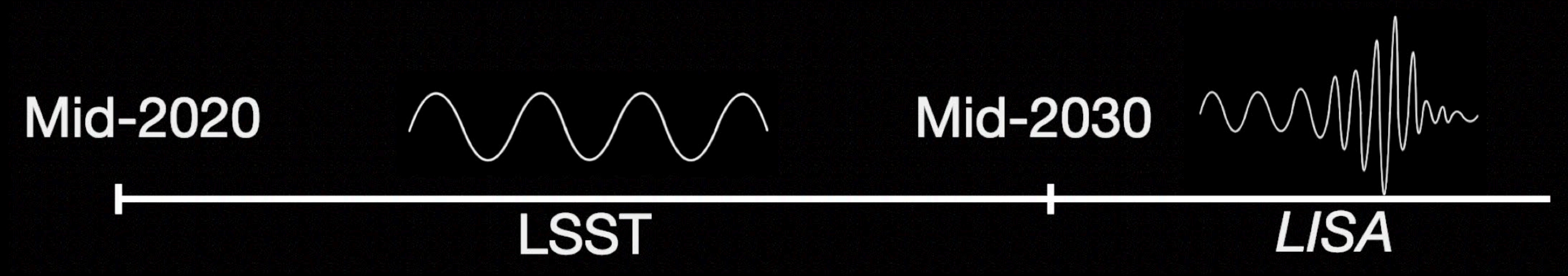
4. Orbital periods can vary from **years to days** + **"EM chirp" (Robust evidence for SMBHBs)** $\dot{f} \propto M_c^{5/3} f^{11/3}$

Identifying EM counterpart of LISA GWs

Detecting compact binaries with **"EM chirp"** will require:

(I) combining with GWs [**Xin**+Haiman 2024]

(II) **Bayesian inference:** new analysis techniques for chirping periodicity [**Xin**, Isi, Farr, Haiman 2025, in prep.]



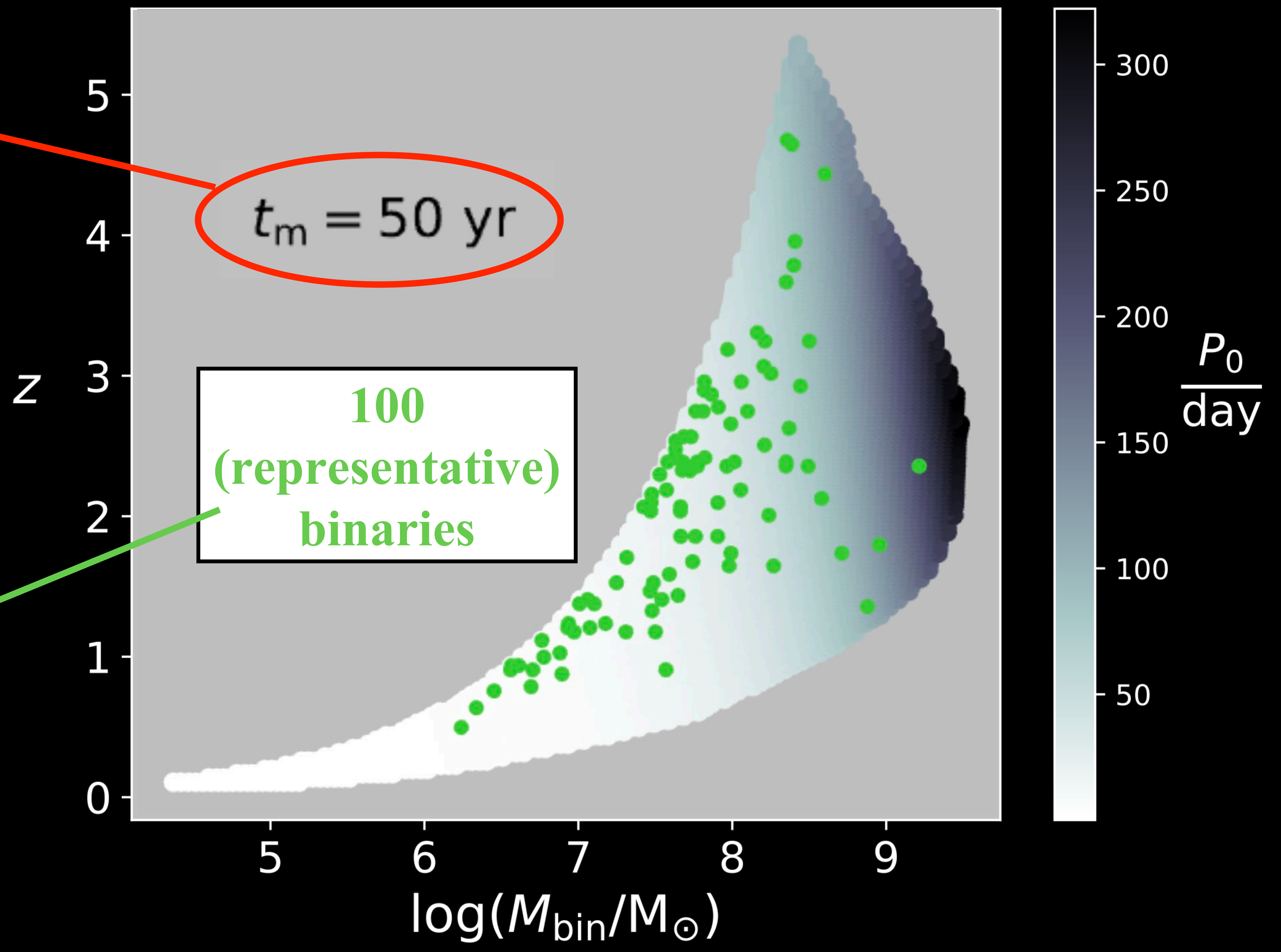
Orbital Periods of LSST Binaries with Time-to-merger t_m

Fiducial

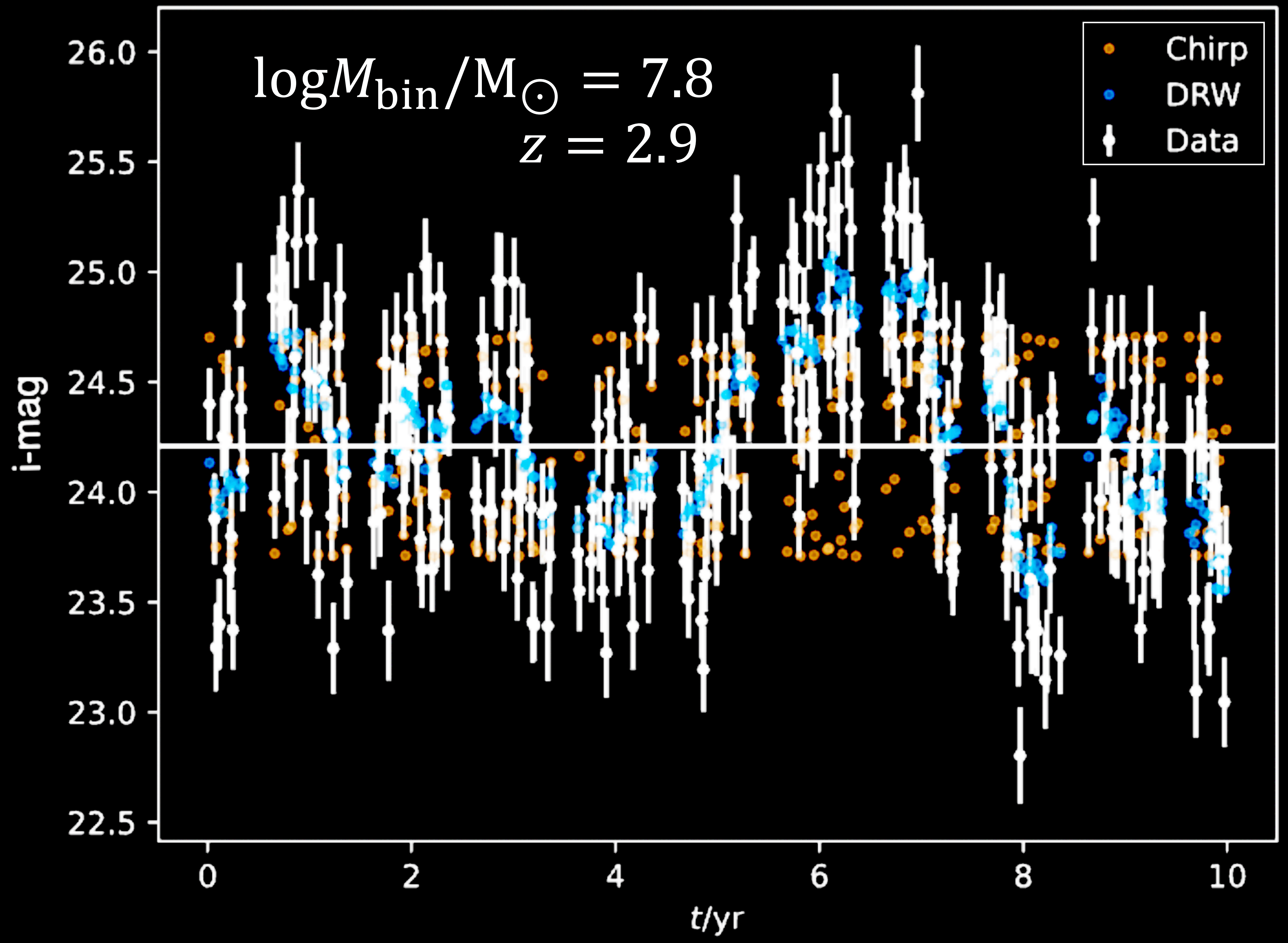
$$t_m \propto {M_{\rm bin}}^{-5/3}\left(\frac{P}{1+z}\right)^{8/3}$$

$$N_{\rm bin} = \left[\frac{t_{\rm m}}{t_{\rm Q}}\right] f_{\rm bin} N_Q \sim 500$$

Mock binary lightcurves



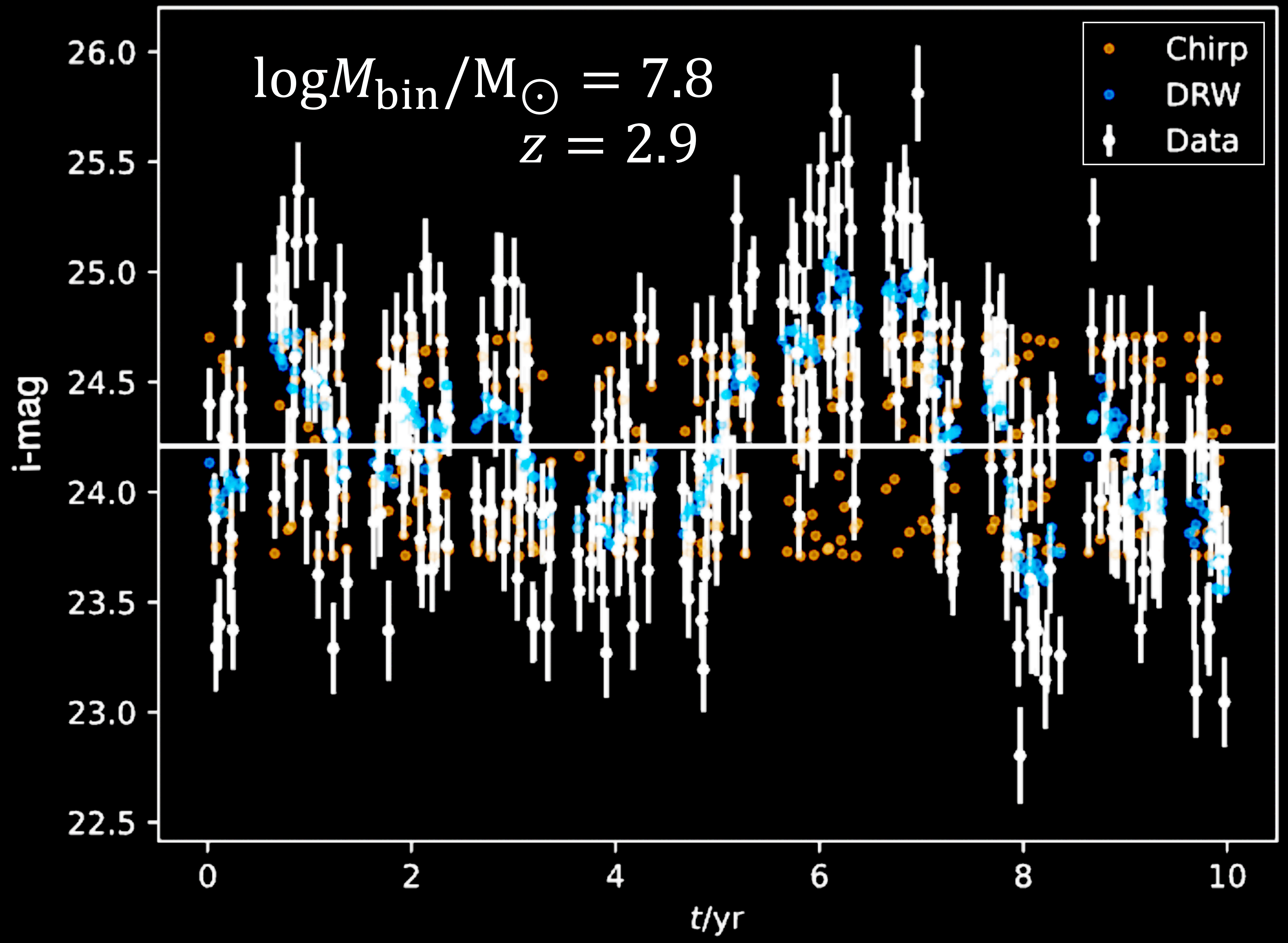
Mock LSST lightcurve



- Chirp: sinusoidal variability caused by relativistic DB — $A, \omega, \dot{\omega}, \mu, \phi$ (we assume $\ddot{\omega} = 0$; A=0.5 mag)
- DRW ("damped random walk"): stochastic AGN variability — σ, τ
- Data: **DB + DRW +** (Gaussian) **Phot. Err.**

LSST Specs: 6 d cadence and 1/3 year seasonal gaps

Mock LSST lightcurve



- Data: **DB + DRW +** (Gaussian) **Phot. Err.**

Bayesian pipeline

Measured seven DB and DRW parameters

Questions:

1. Can we detect chirp ($A \neq 0, \dot{\omega} \neq 0$ etc.)?
2. Is binary model preferred over pure DRW?
3. What is the significance that each parameter can be measured?

Bayesian Model Selection

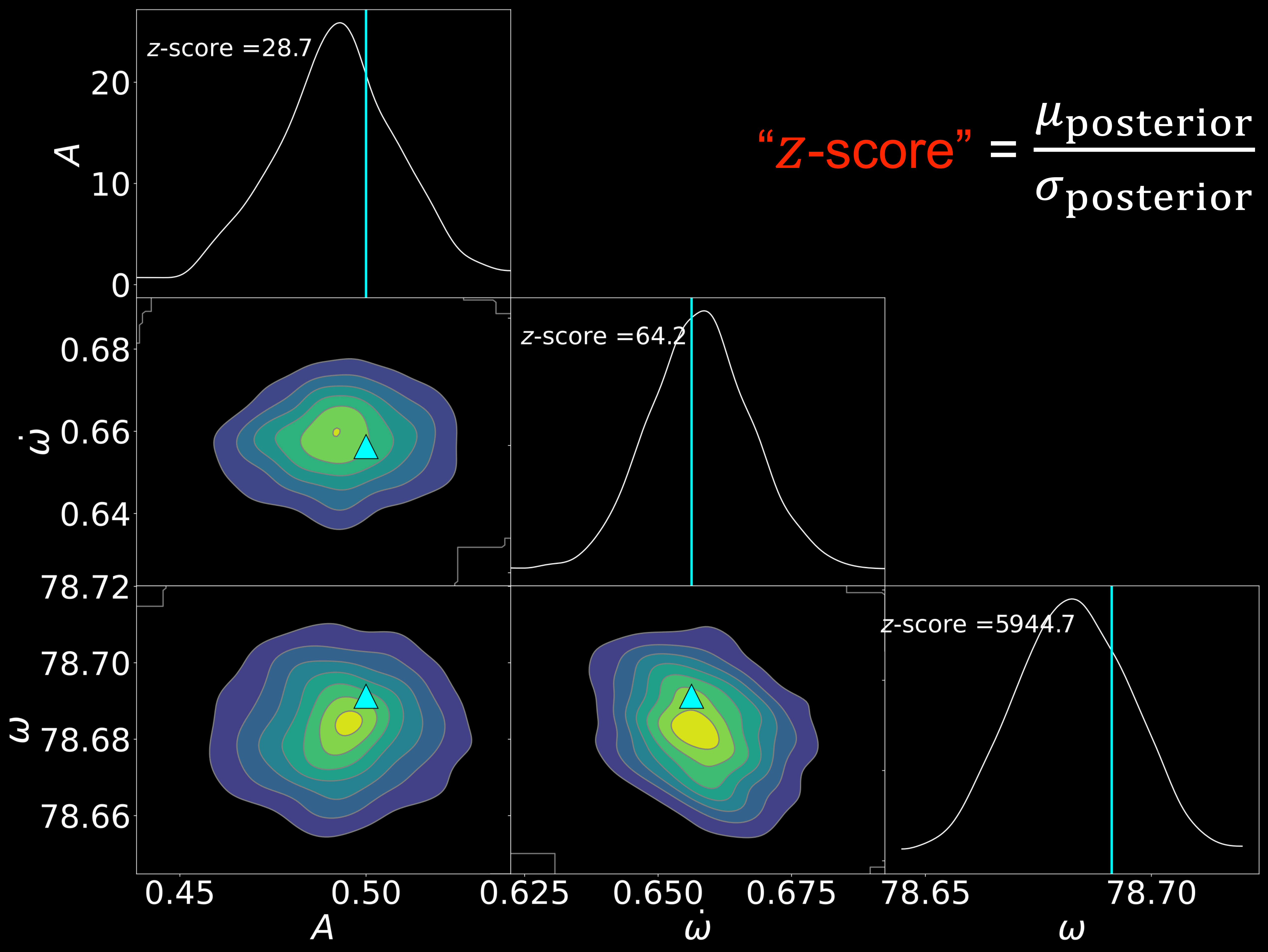
Priors given by $\Delta \log M_{\rm bh} \sim 1$

$$\frac{\Delta\omega}{\omega} = -\frac{5}{11}\frac{\Delta\mathcal{M}_c}{\mathcal{M}_c} = 0.39$$

$$\frac{\Delta\dot{\omega}}{\dot{\omega}} = \frac{5}{3}\frac{\Delta\mathcal{M}_c}{\mathcal{M}_c} = 1.43$$

$$(\dot{\omega} > 0)$$

Non-zero binary parameters, e.g. $\dot{\omega} \neq 0 \rightarrow$ chirp is detected!

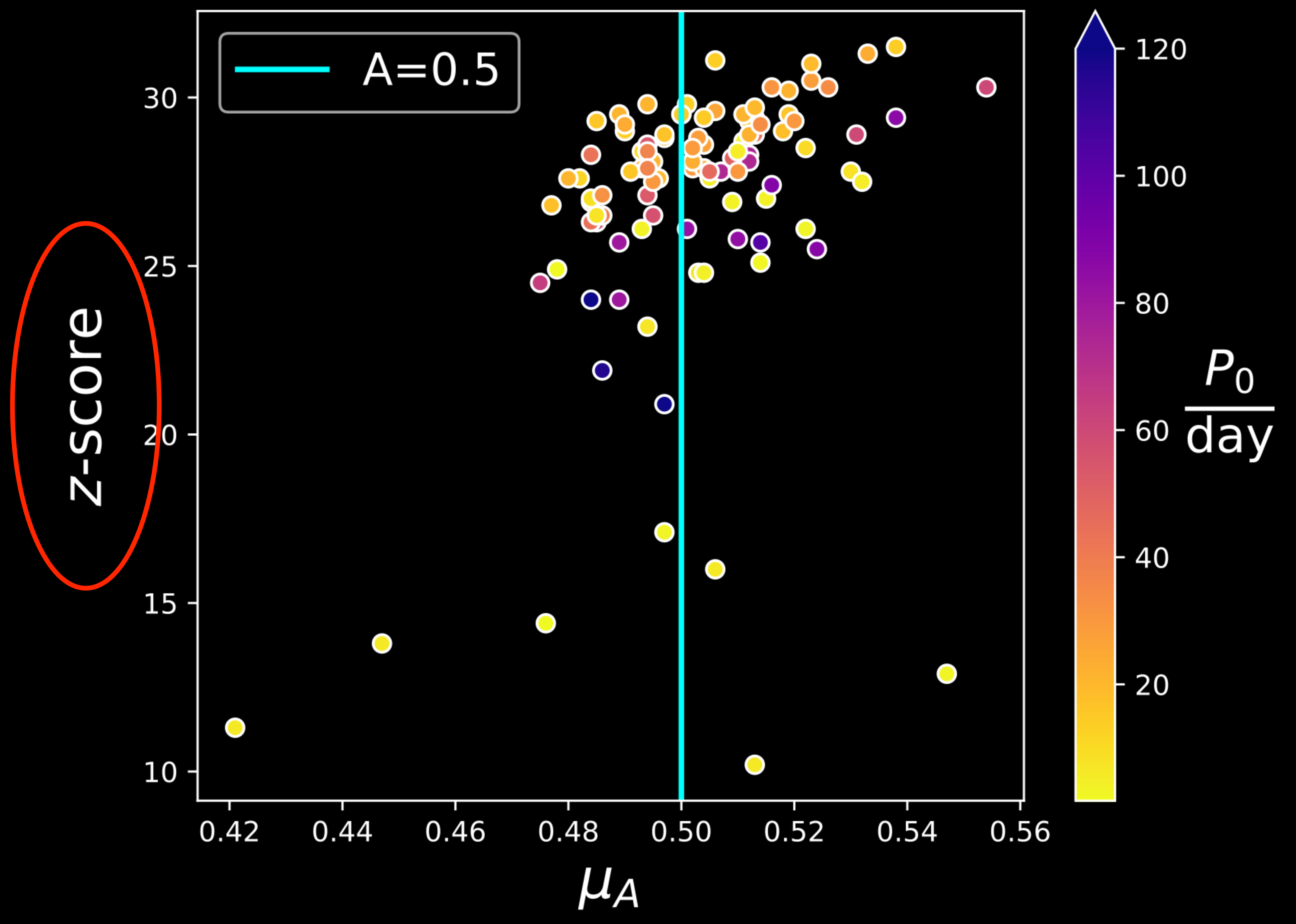


"z-score" $= \dfrac{\mu_{\rm posterior}}{\sigma_{\rm posterior}}$

Amplitude (A) detection

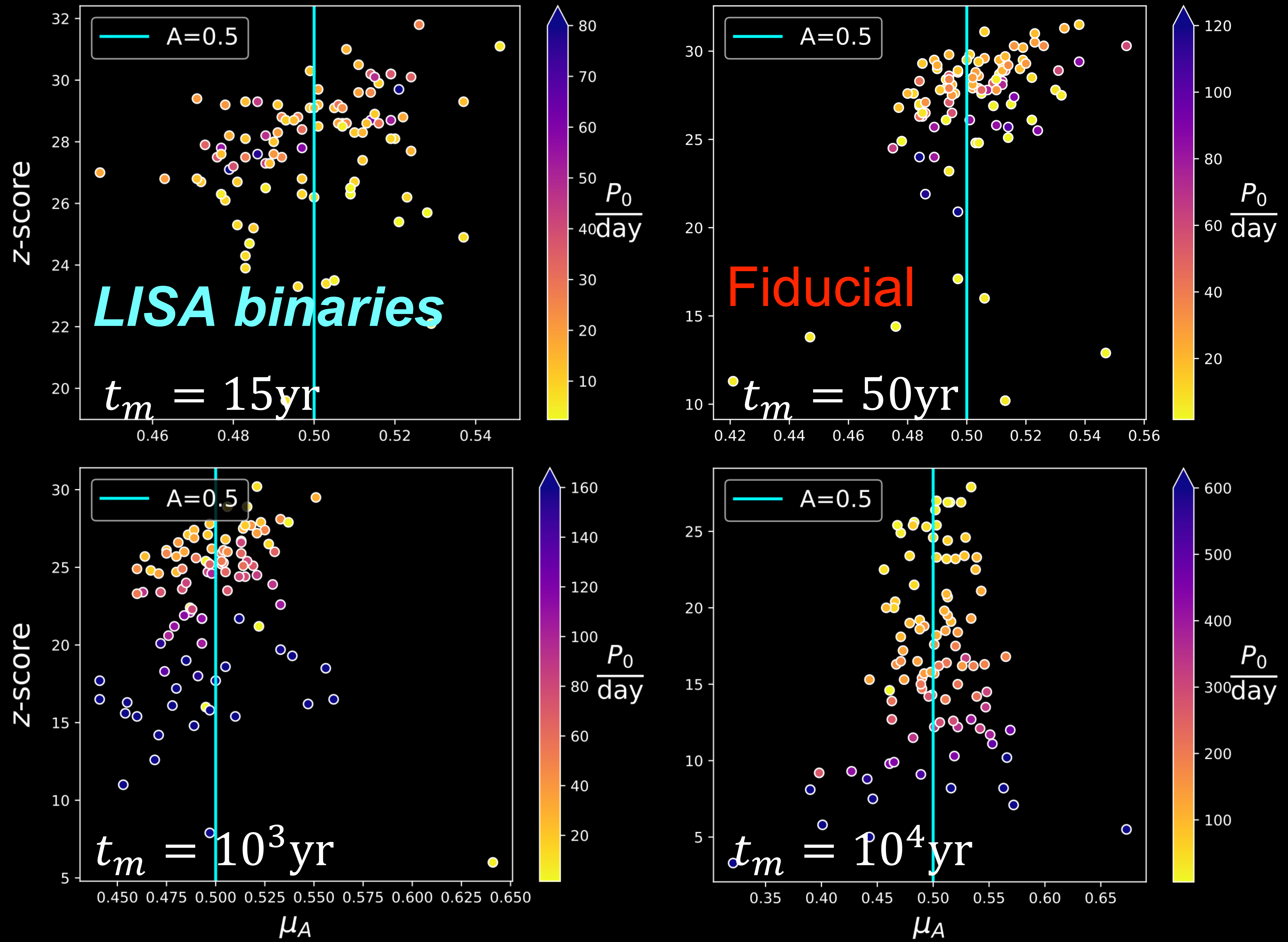
"z-score" of A for 100 LSST binaries
with $t_m = 50$ years

z-score $\gtrsim 10$!



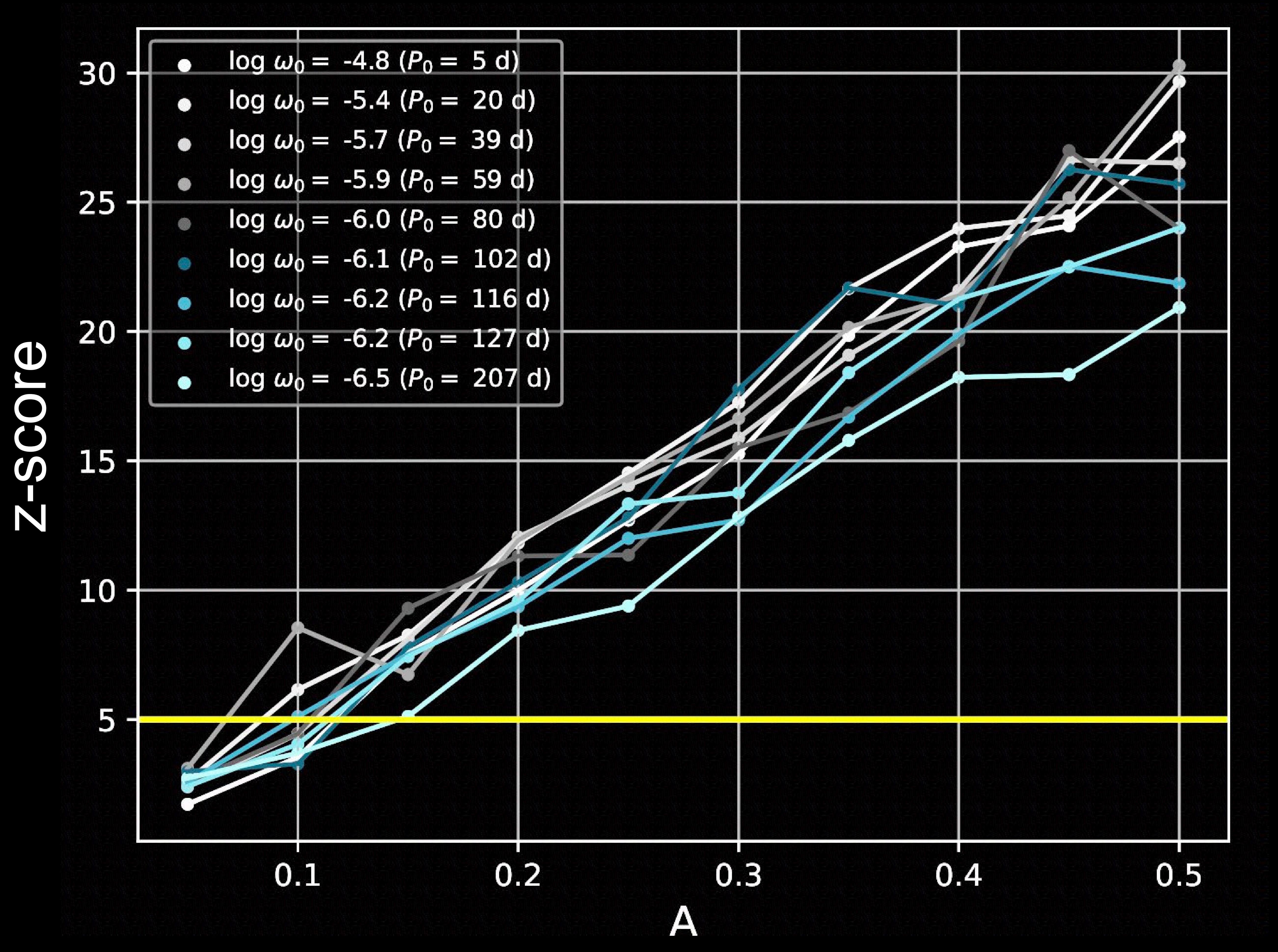
Chirp detectable using our Bayesian algorithm

Z-score of A for different t_m



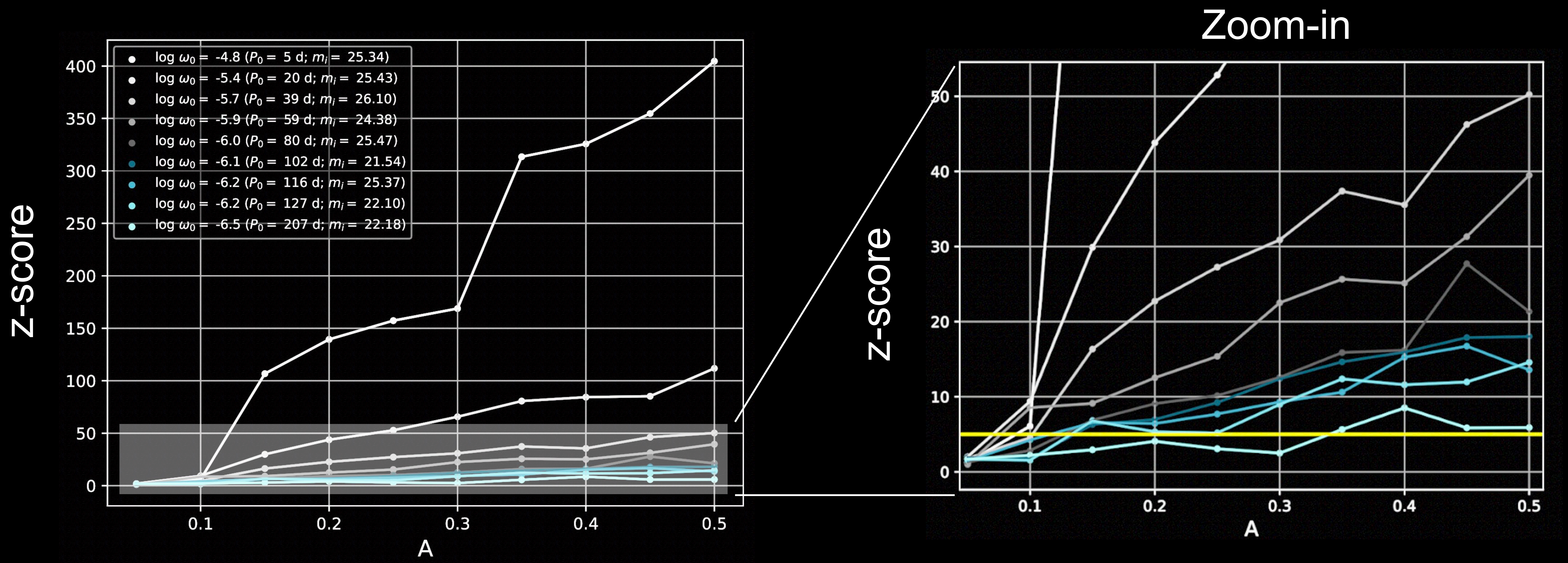
- Sampled 100 binaries for each of $t_m = 15, 50, 100, 10^3$ and 10^4 years
- Generally, z-score $\gtrsim 5$
- Z-score values are greater for smaller P $\leftarrow$ more periodic cycles in the lightcurve

Dependence of z-score on binary amplitude A



- Z-score is greater when A is larger
- Z-score $\gtrsim 5$ when $A \gtrsim 0.1$
- Z-score have weak dependence on P

Detectability of frequency chirp $\dot{\omega}$

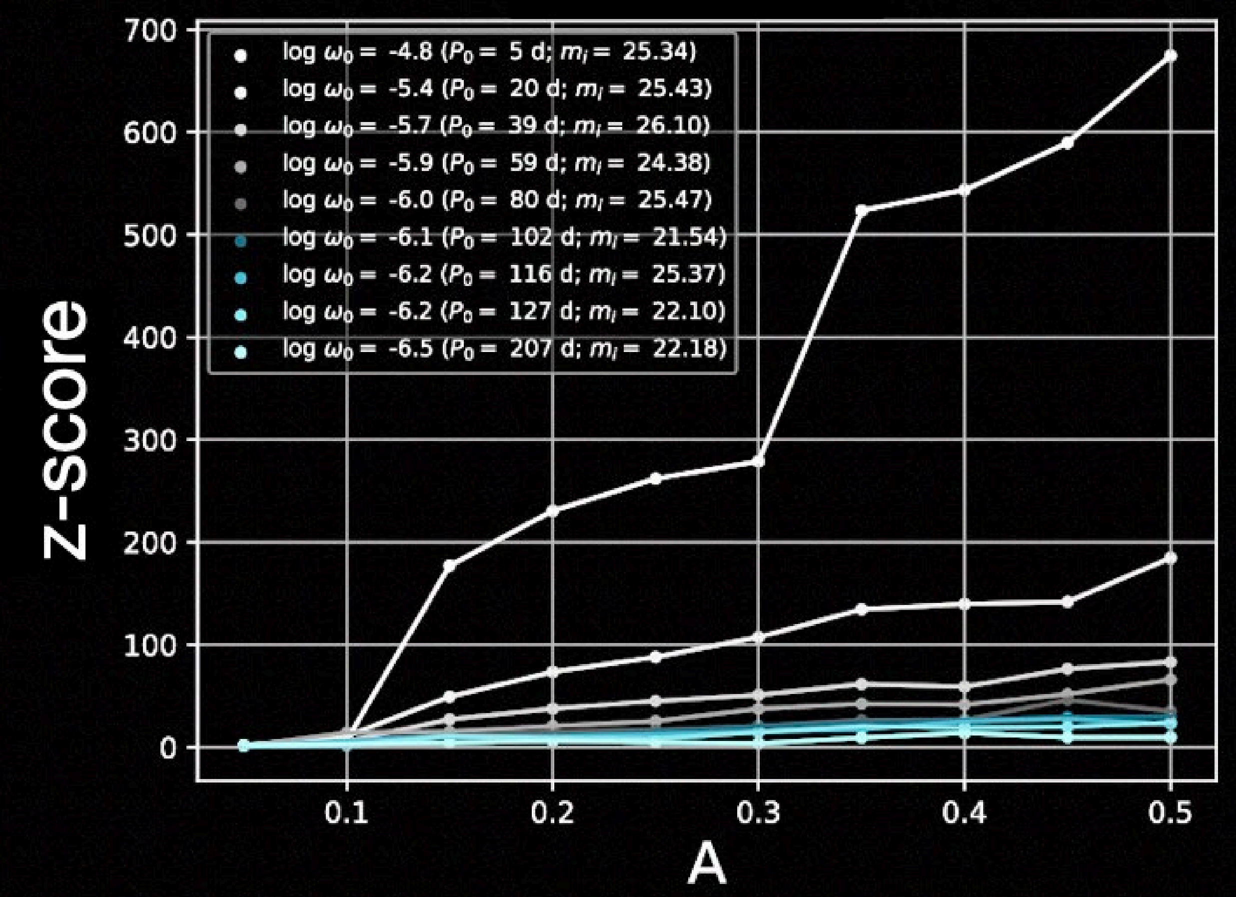


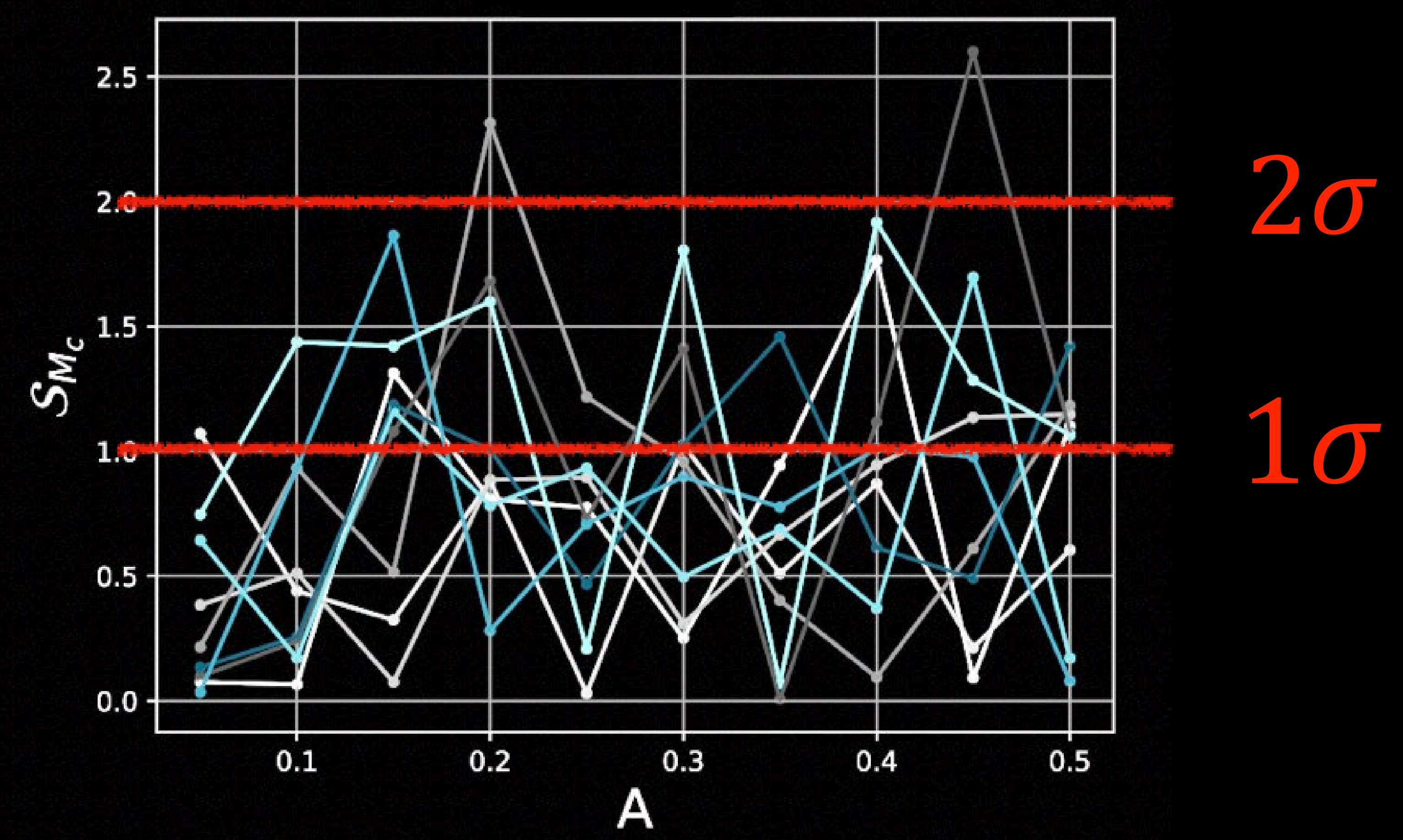
- z-score increases with true A; z-score $\gtrsim 5$ when $A \gtrsim 0.1$.
- z-score are greater when binaries have smaller P ← more cycles in the lightcurve

Physical properties: time-to-merger and chirp mass

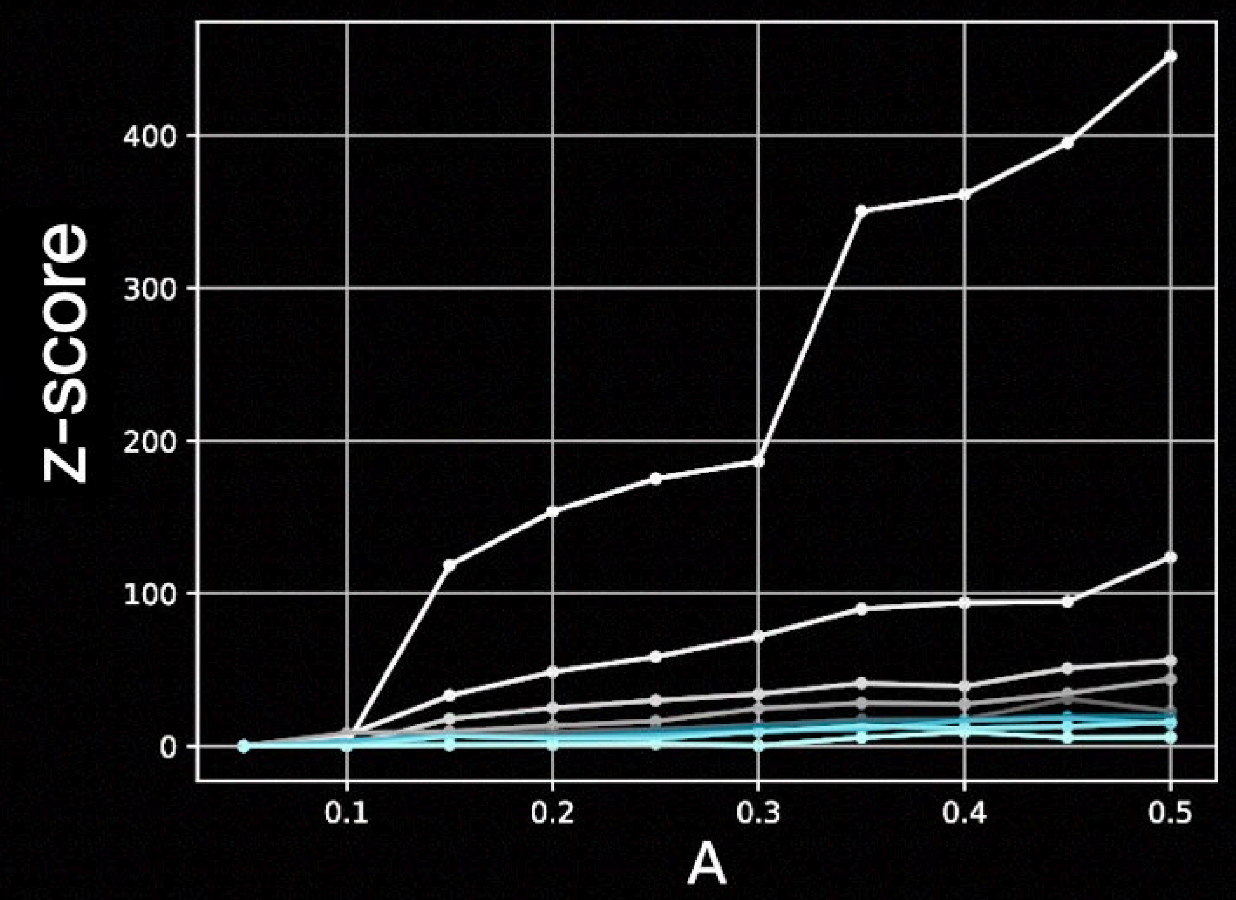
z-score | Bias

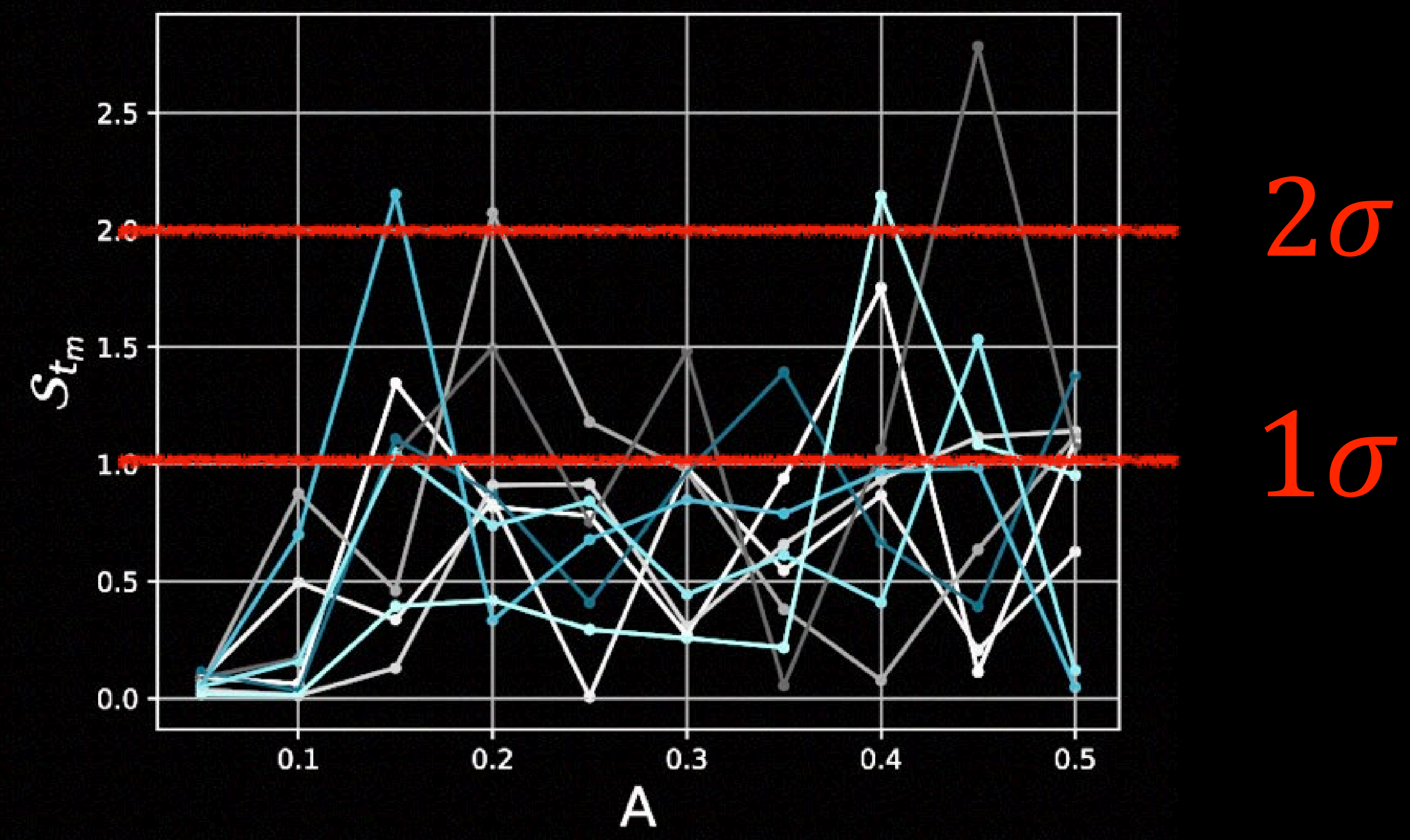
M_c





t_m





Summary and future plans

Summary

- Compact SMBH binaries ($t_m = 15 - 10^4$ years) in LSST are detectable using our Bayesian model selection pipeline, before the launch of LISA
- We measure non-zero binary parameters, including $A, \omega, \dot{\omega}$, with high significance
- Generally, z-score of binary parameters increase as a function of true A
- High z-score from measuring binary parameters compared to DRW parameters suggests that binary models are preferred over pure noise
- Chirp mass and time-to-merger can be well measured within 2σ from the truth

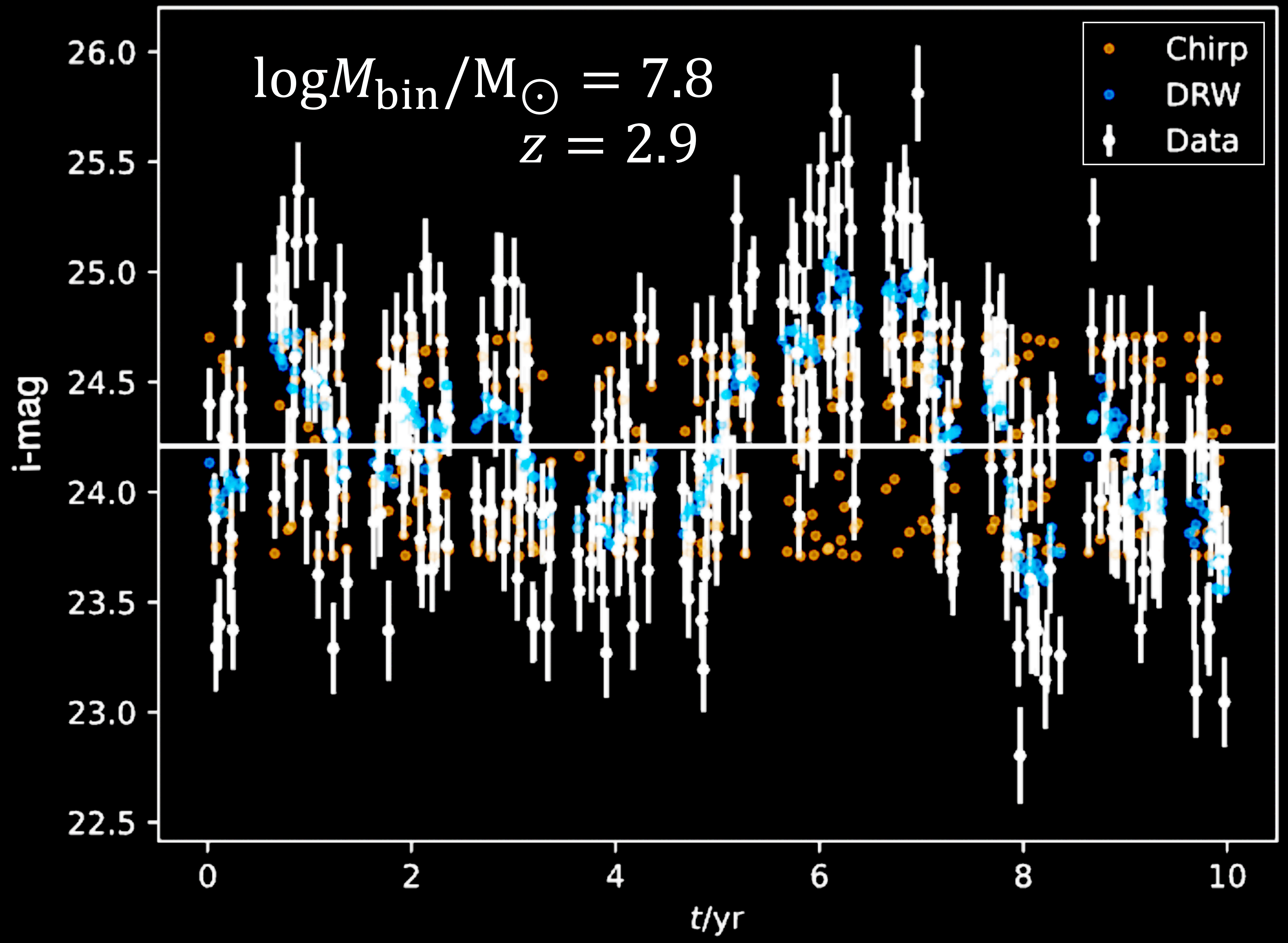
Future plans

- Testing alternative binary models (e.g. saw-tooth shaped variability from hydro-sims)
- Run analysis for SMBHB candidates from CRTS and PTF
- Apply to LSST data starting late 2025/early 2026

Back-up: Orbital Periods of LSST Binaries with Time-to-merger t_m

Frequency rate of change	$\dot{f}_{\mathrm{gw}} \propto {M_c}^{5/3} {f_{\mathrm{gw}}}^{11/3}$
Chirp Mass	${M_c}^{5/3} = \frac{q}{(1+q)^2} {M_{\mathrm{bin}}}^{5/3}$ $(q = 0.1)$
Time-to-merger	$t_{m,r} = (3/8) f_{\mathrm{gw}} / \dot{f}_{\mathrm{gw}}$
(Observed) orbital frequency	$f = 2 f_{\mathrm{gw}} (1+z)^{-1}$

Back-up: Mock LSST lightcurve



- Chirp: sinusoidal variability caused by relativistic DB

  Binary parameters (truth at $t = 0$):

  — amplitude A (0.5 mag)

  — orbital freq. f (3.7×10^{-7}Hz; $P \approx 30$ d)

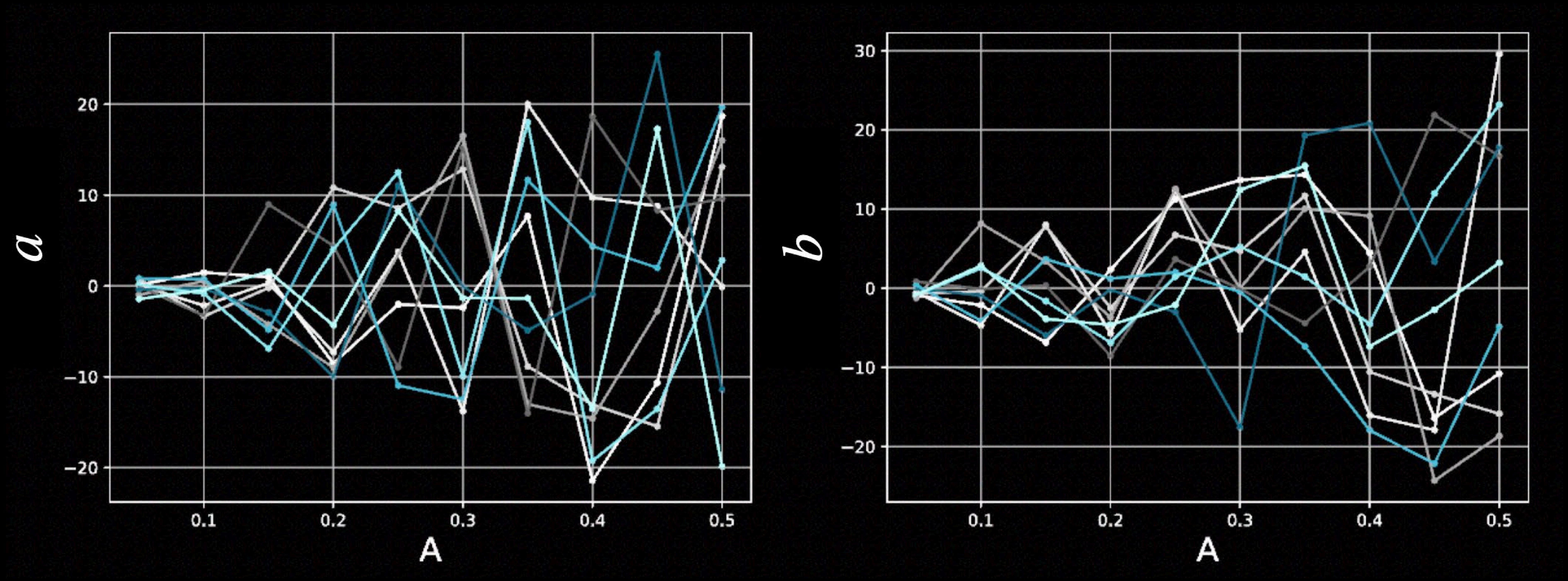
  — freq. "chirp" $\dot{f} = 0.075 f/T$ ($T = 10$ yr; $t_m = 50$ yr)

  — mean $m_i = 24.2$ mag

- DRW ("damped random walk"): intrinsic AGN variability modeled with exp. power-law with characteristic σ and τ

  <u>Typically</u>: $\sigma \sim 0.5$ mag and $\tau \sim 150$ d

Back-up: quadratures a and b z-scores



$$A = \sqrt{a^2 + b^2}$$

Back-up: runtime