PHOTOMETRIC VARIABILITY AND DETECTABILITY OF SUPERMASSIVE BLACK HOLE BINARIES ON SUB-PARSEC SCALES

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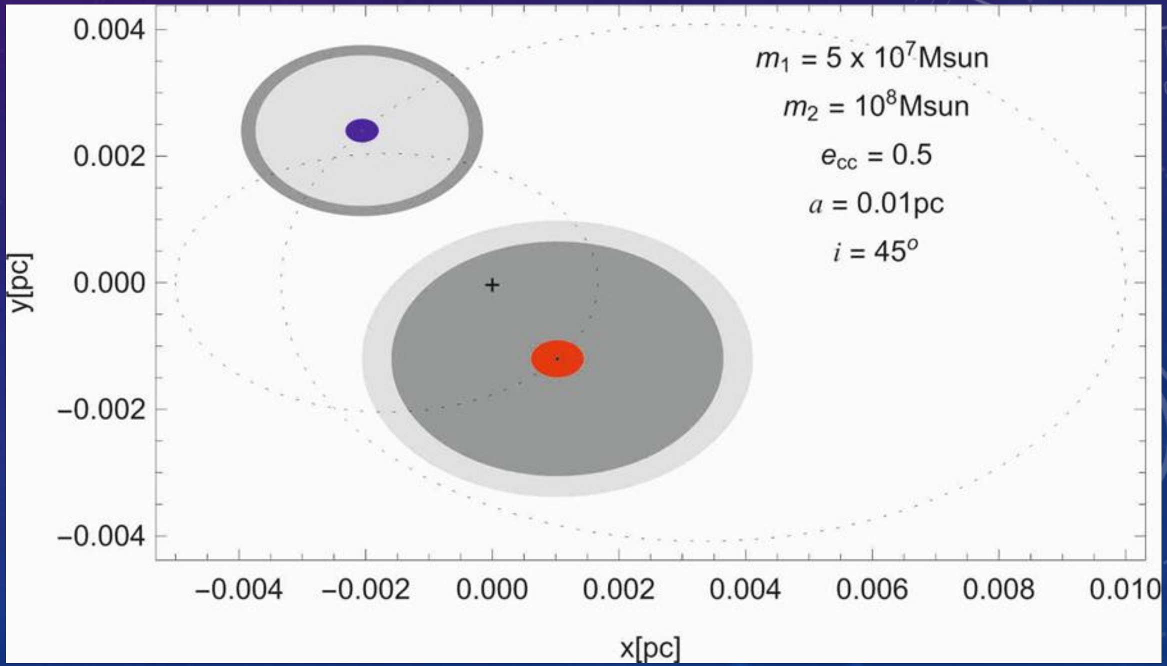
22. July 2026.

MOTIVATION

- Supermassive black hole binary systems
- kpc vs sub-pc
- Gravitational waves
- Periodicity in light-curves is expected

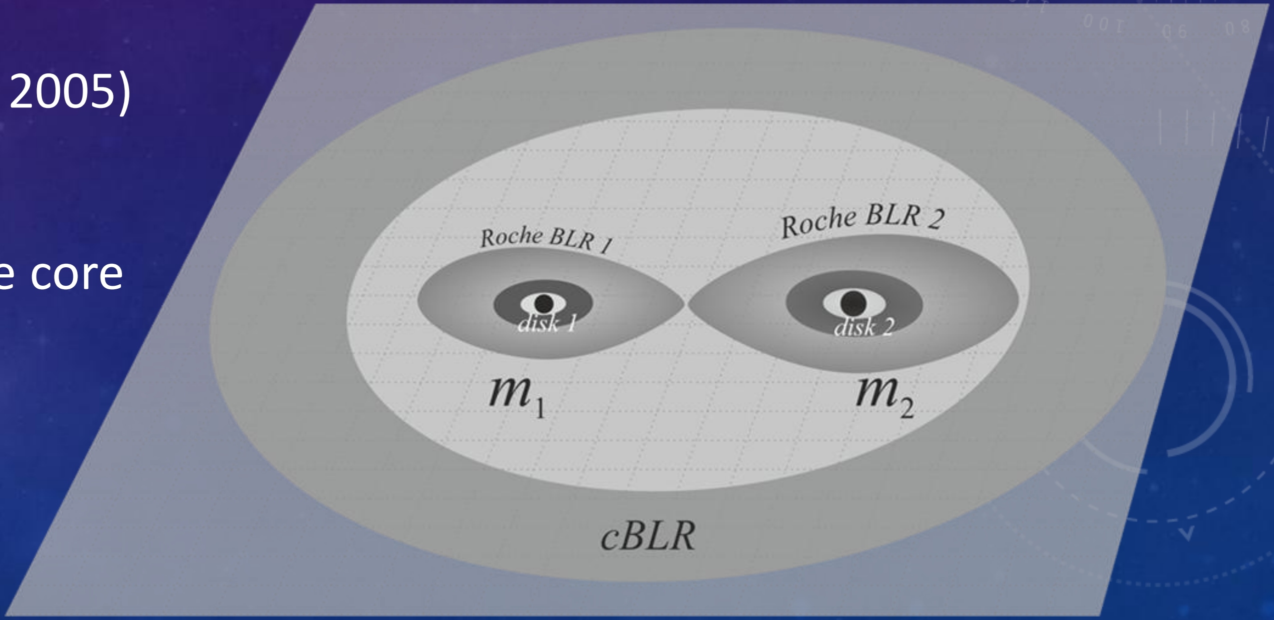
POSKI MODEL

- Authors: Popović, Simić, Kovačević and Ilić
- Two supermassive black holes
- Accretion disks
- Three Broad-Line Regions (BLR1, BLR2 and cBLR)
- Gravitationally bound BLR
- Relativistic beaming incorporated
- Gravitational perturbation of accretion disk
- Variable accretion rate



MODEL CHARACTERISTICS

- Blackbody spectrum of the accretion-disk elements
- Dimensions are determined using R-L relation (Kaspi 2005)
- BLR1 and BLR2 are moving together with black holes
- cBLR is stationary and is responsible for emission-line core
- Roche lobes



PARAMETERS

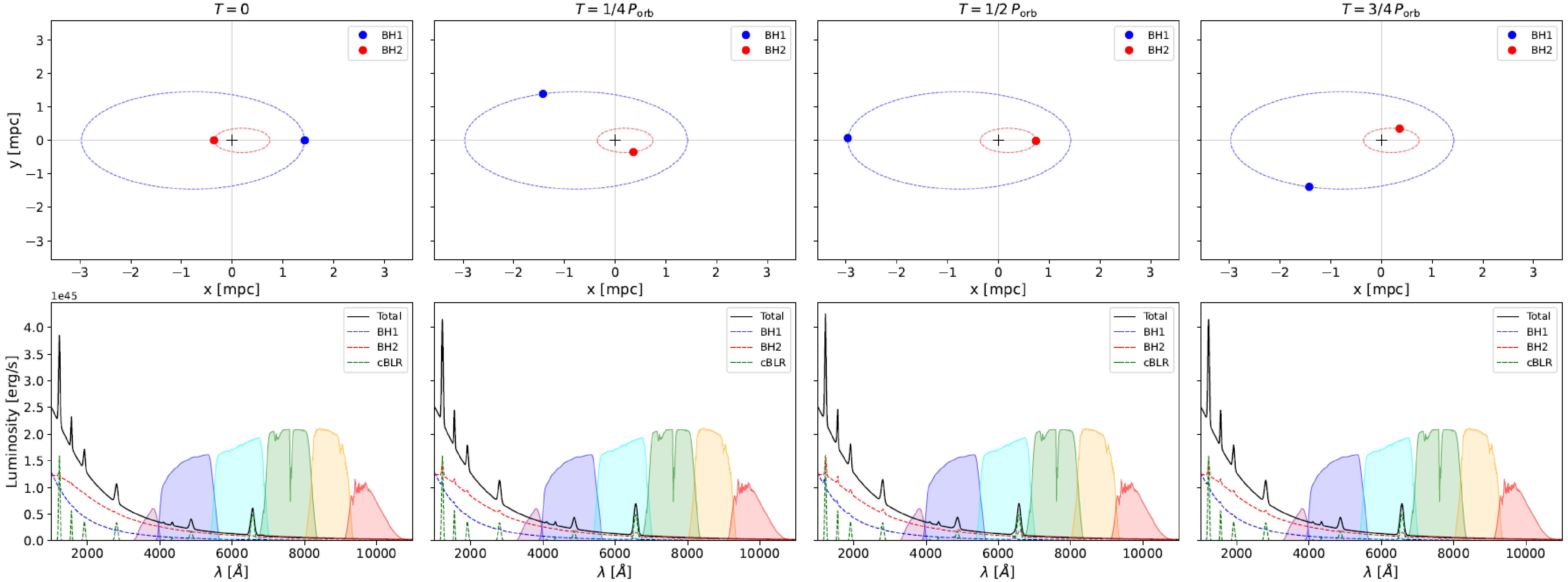
Parameter	Value	N
Primary black hole mass	$10^7, 5 \cdot 10^7, 10^8, 5 \cdot 10^8, 10^9$	5
Mass ratio q	0.1, 0.25, 0.5, 0.75, 1	5
Secondary black hole mass	$m_2 = q\, m_1$	
R	1 mpc and 2.5 – 10 mpc, in steps 0.25 mpc	32
e	0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75	7
z	0.1, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 4	10
SNR	5, 10, 15, 20, 25, 30, 40, 50	8

COMPUTATION RESOURCES

- Data center, Kragujevac, Serbia
- 1 core $\leftrightarrow$ 1 set of simulation parameters
- 160 cores $\leftrightarrow$ $t \sim 7200\ \mathrm{s}$
- $N = 5 \cdot 5 \cdot 32 \cdot 7 \cdot (8 \cdot 10) = 5600\ (448\,000)$
- $1.3\ \mathrm{s/sim}\ (16\ \mathrm{ms/sim})$

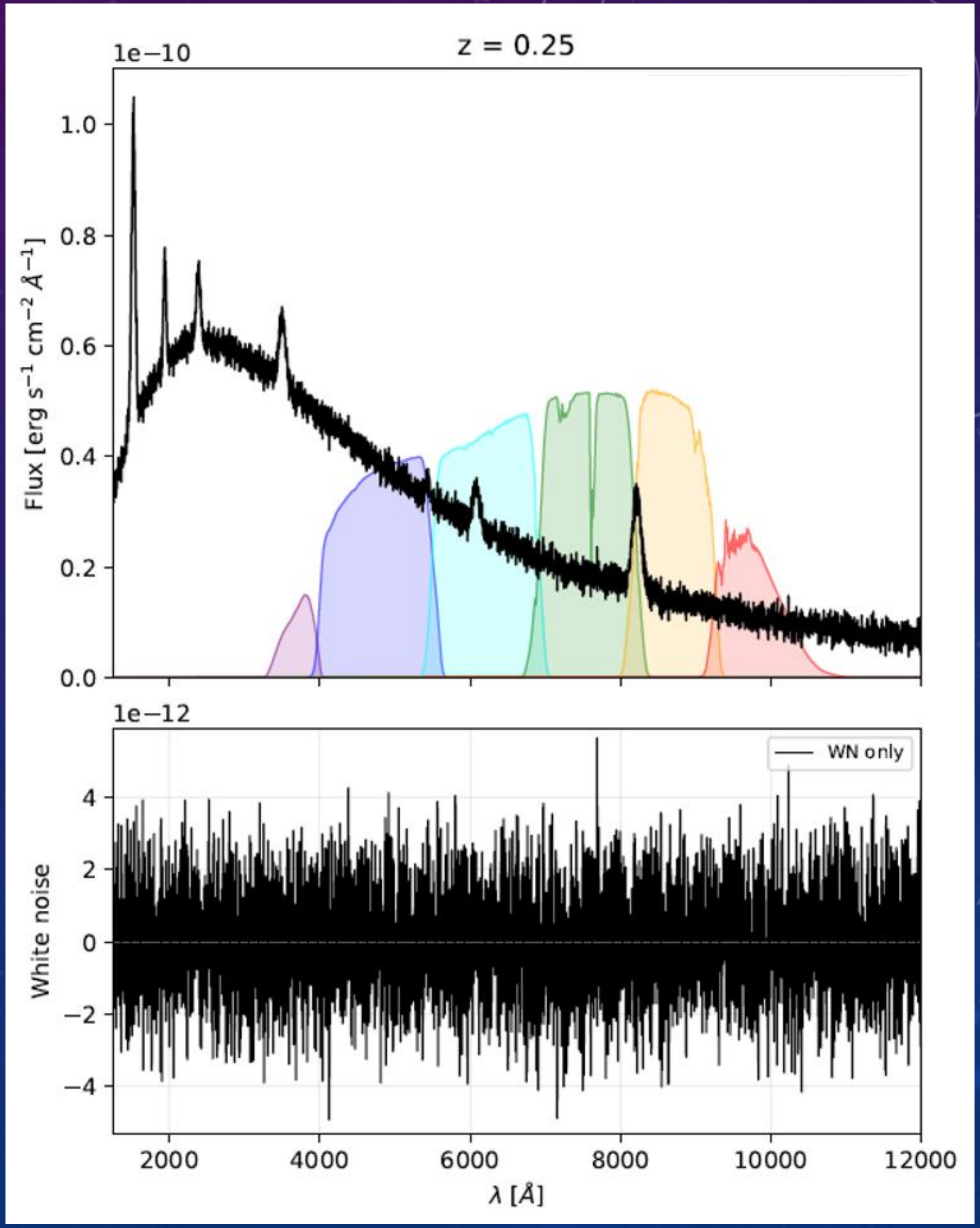
SPECTRUM SIMULATION

$m_1 = 2.5 \cdot 10^7\ \mathrm{M}_\odot$ $\quad$ $m_2 = 10^8\ \mathrm{M}_\odot$ $\quad$ $R = 2.75\ \mathrm{mpc}$ $\quad$ $e = 0.15$



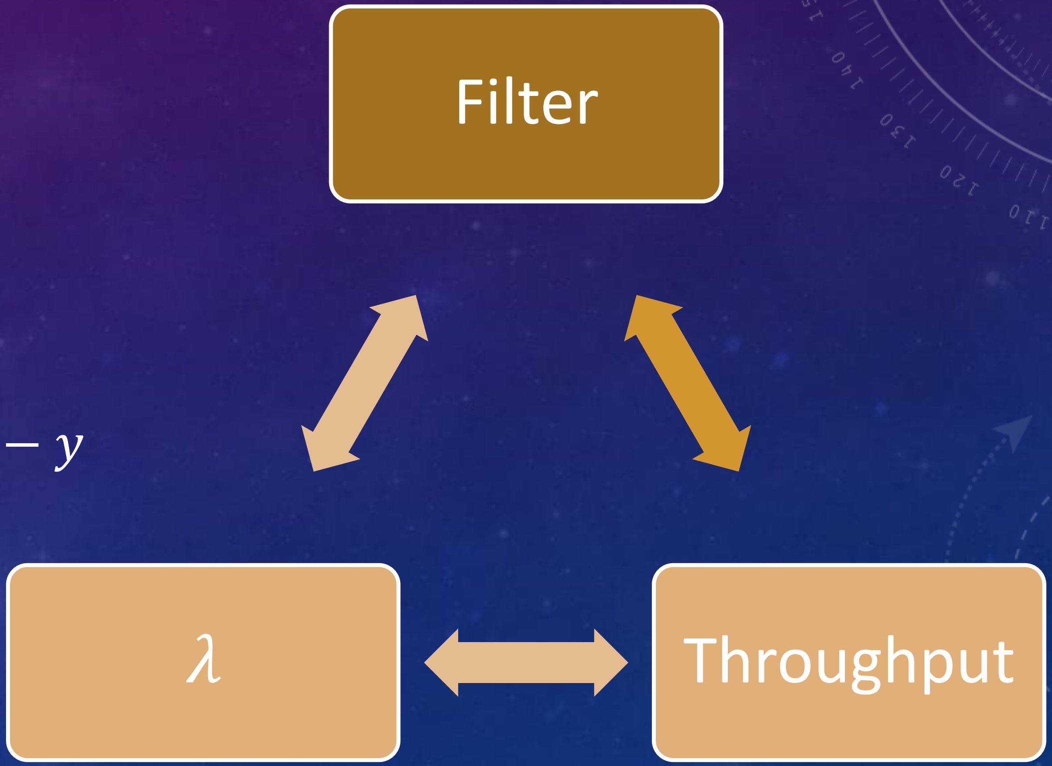
WHITE NOISE

- Gaussian white noise:
- $\sigma_{wn} = \frac{\langle F_\lambda \rangle}{SNR}$



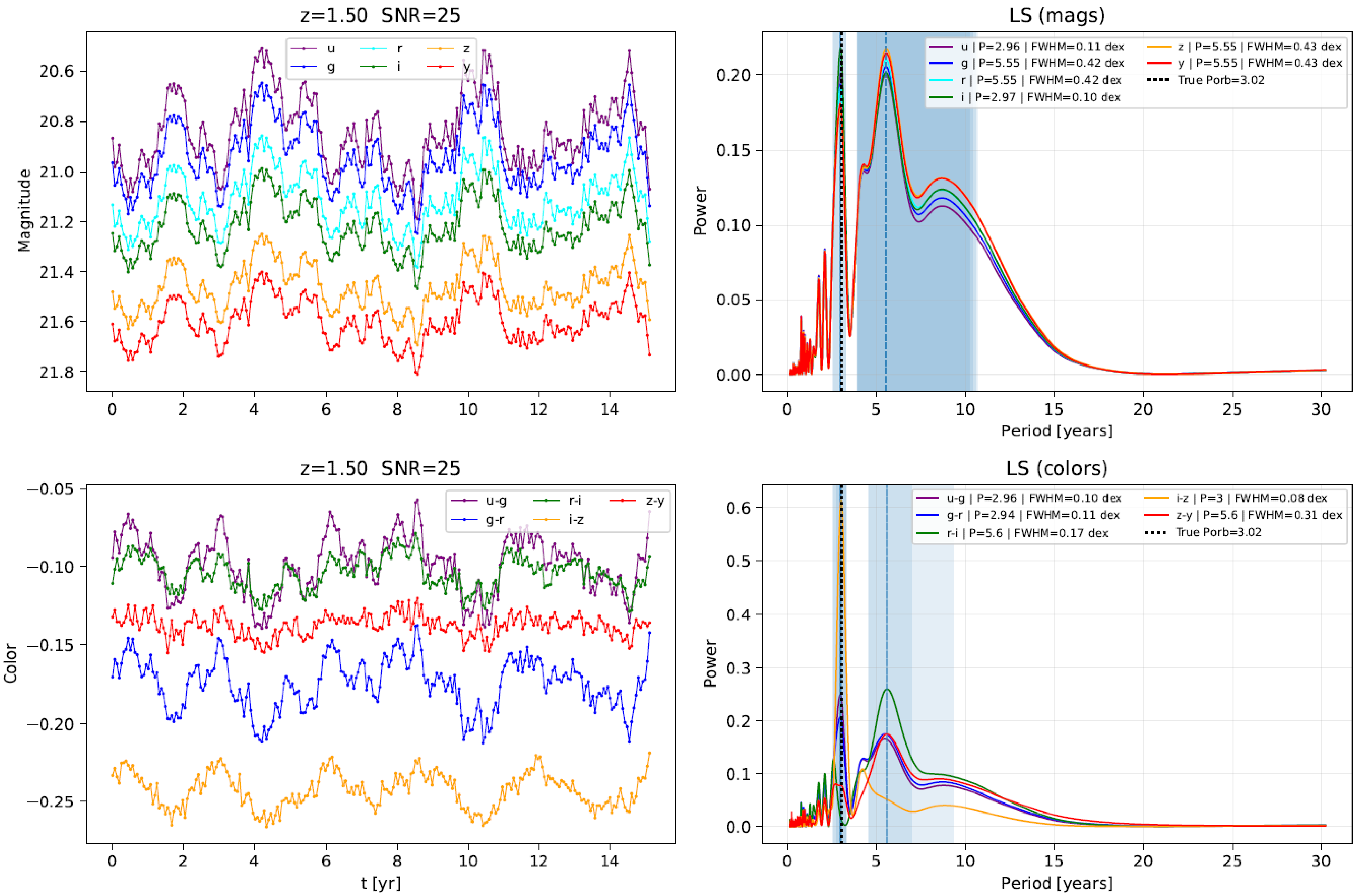
UGRIZY FILTERS

- LSST GitHub
- Flux integration through each filter
- 6 magnitudes
- 5 color indices: $u-g,\ \ g-r,\ \ r-i,\ \ i-z,\ \ z-y$
- Zhang 2025.



RED NOISE

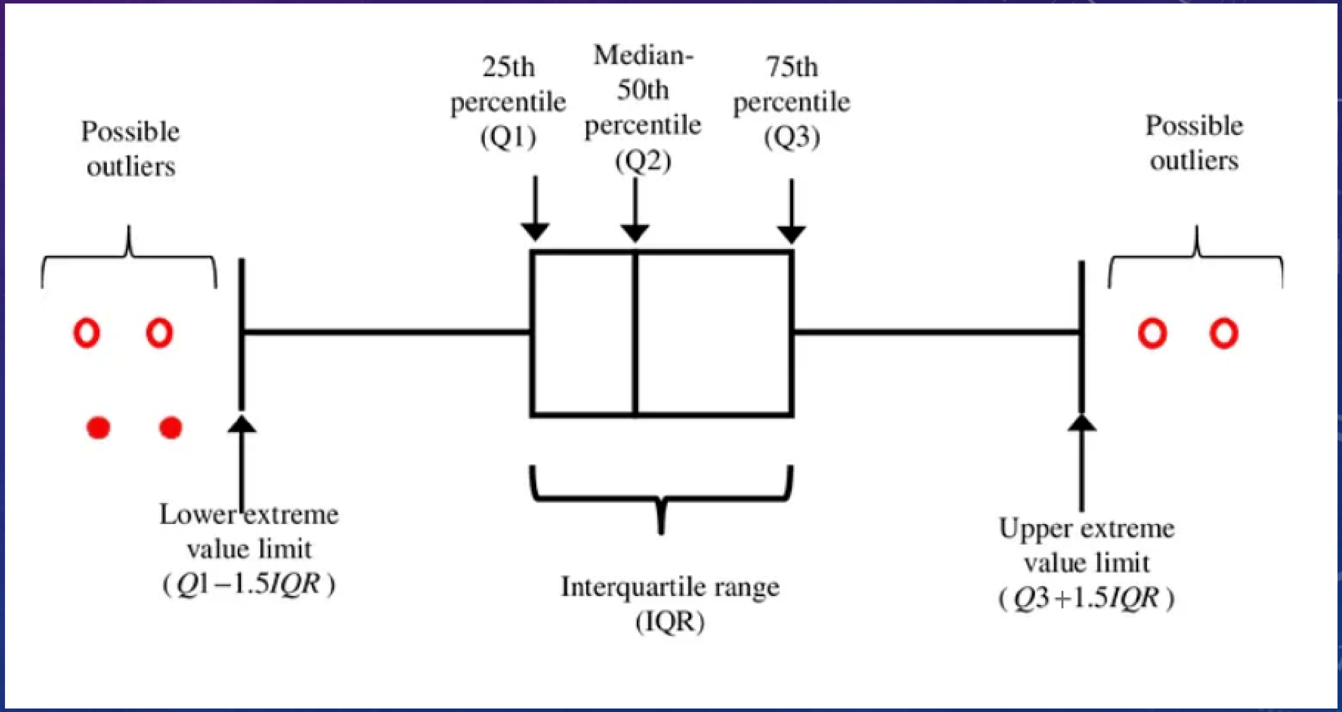
- Damped Random Walk - DRW (MacLeod 2010):
- Characteristic timescale: τ
- Asymptotic variability amplitude: SF_∞
- $\log_{10}\tau = 2.4 + 0.17\log_{10}\left(\frac{\lambda_{RF}}{4000\ \text{Å}}\right) + 0.03(M_i + 23) + 0.21\log_{10}\left(\frac{M_{BH}}{10^9 M_\odot}\right)$
- $\log_{10} S\,F_\infty = -0.51 - 0.479\log_{10}\left(\frac{\lambda_{RF}}{4000\ \text{Å}}\right) + 0.131(M_i + 23) + 0.18\log_{10}\left(\frac{M_{BH}}{10^9 M_\odot}\right)$
- $\sigma = \frac{SF_\infty}{\sqrt{2}}$



z=1.50 SNR=25
LS (mags)
u | P=2.96 | FWHM=0.11 dex
g | P=5.55 | FWHM=0.42 dex
r | P=5.55 | FWHM=0.42 dex
i | P=2.97 | FWHM=0.10 dex
z | P=5.55 | FWHM=0.43 dex
y | P=5.55 | FWHM=0.43 dex
True Porb=3.02
Magnitude
Power
Period [years]
z=1.50 SNR=25
LS (colors)
u-g | P=2.96 | FWHM=0.10 dex
g-r | P=2.94 | FWHM=0.11 dex
r-i | P=5.6 | FWHM=0.17 dex
i-z | P=3 | FWHM=0.08 dex
z-y | P=5.6 | FWHM=0.31 dex
True Porb=3.02
Color
t [yr]
Power
Period [years]

PERIOD ESTIMATION

- $FWHM < 0.2$ dex
- NORMAL vs IQR vs MAD
- MAD (median absolute deviation):
- $MAD = median(|P_i - median(P_i)|)$
- $\sigma = 1.4826\ MAD\ (\pm 3\sigma)$



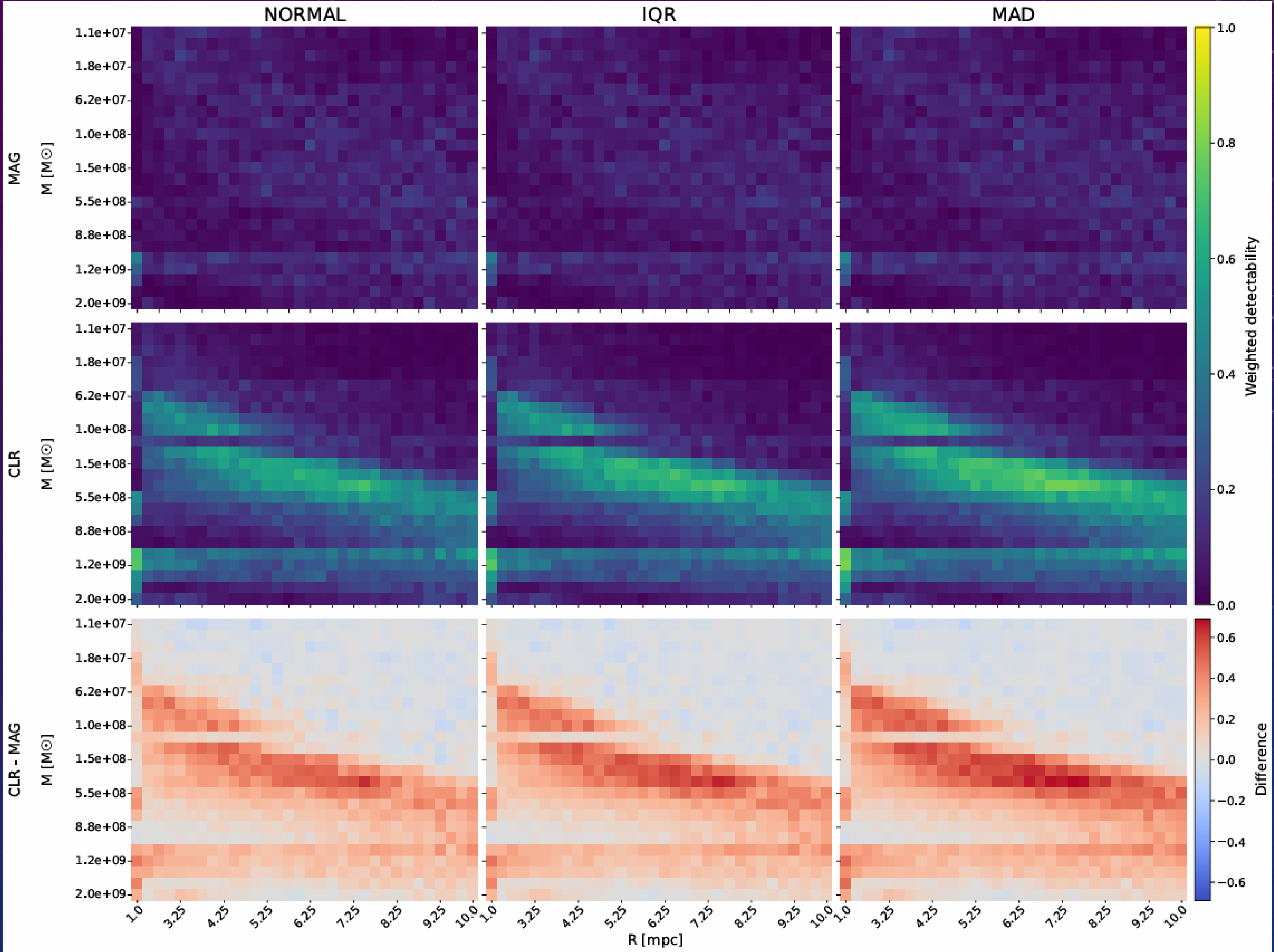
DETECTABILITY MAPS

- $D = \begin{cases} 1, & \left|\frac{P_{obs}-P}{P}\right| < 0.1 \\ 0, & \left|\frac{P_{obs}-P}{P}\right| \geq 0.1 \end{cases}$
- $D_w = \frac{m}{n} \cdot D$
- $\langle D_w(X,Y) \rangle = \frac{1}{N} \sum D_{w,i}(X,Y)$

- Separation by SNR-regime is possible
- Magnitude versus color comparison is possible (Zhang 2025)

OVERVIEW

Peak selection		$FWHM < 0.2$ dex	
Period estimate	Mean value	IQR	MAD
Binary detectability (D)	Pobs/P	Pobs/P	Pobs/P
Scaling and averaging	Dw	Dw	Dw



NORMAL
IQR
MAD
MAG
CLR
CLR - MAG
M [M☉]
1.1e+07
1.8e+07
6.2e+07
1.0e+08
1.5e+08
5.5e+08
8.8e+08
1.2e+09
2.0e+09
1.0
3.25
4.25
5.25
6.25
7.25
8.25
9.25
10.0
R [mpc]
Weighted detectability
0.0
0.2
0.4
0.6
0.8
1.0
Difference
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6

MAGNITUDE VS COLOR

Fraction of simulated objects with $D_w \geq 0.75$

$D_w \geq 0.75$		
Method	MAG [%]	COLOR [%]
Normal	6.7	10.7
IQR	6.5	10.7
MAD	6.6	11.2

Fraction of simulated objects for which one method correctly predicts the orbital period while the other does not

Method	MAG [%]	COLOR [%]
Normal	5.6	24.5
IQR	6.5	27.6
MAD	6.3	31.2

THANK YOU FOR YOUR ATTENTION!