

# Rubin/LSST時代の 突発天体観測

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第16回光赤外線天文学大学間連携 (OISTER) ワークショップ

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  - Multi-messenger astronomy
- Rubin/Legacy Survey of Space and Time (LSST)
  - Observation plan
  - Realtime alerts
  - Target-of-opportunity observations
- What can we do in the Rubin/LSST era?

# Time-domain astronomy

## Targets

- Variables

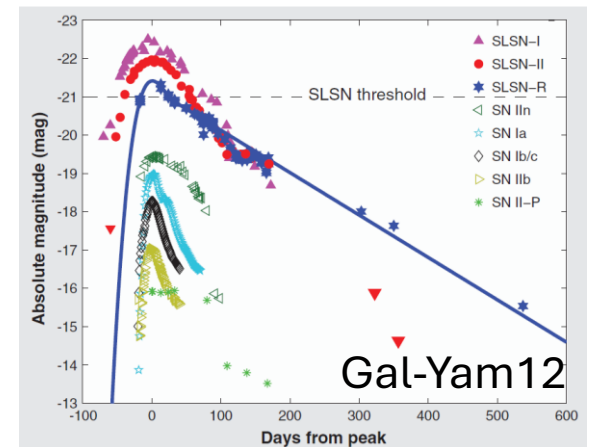
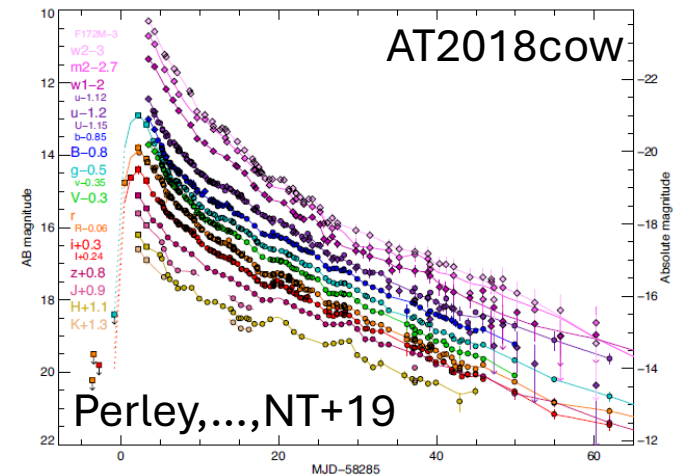
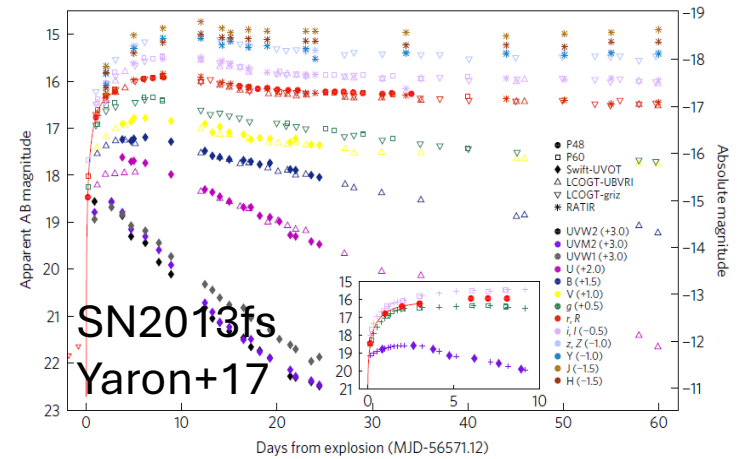
- Variable stars
  - Cepheids
  - Mira variables
- Flares of dwarf stars
- Cataclysmic variables
- Recurrent novae

- Transients

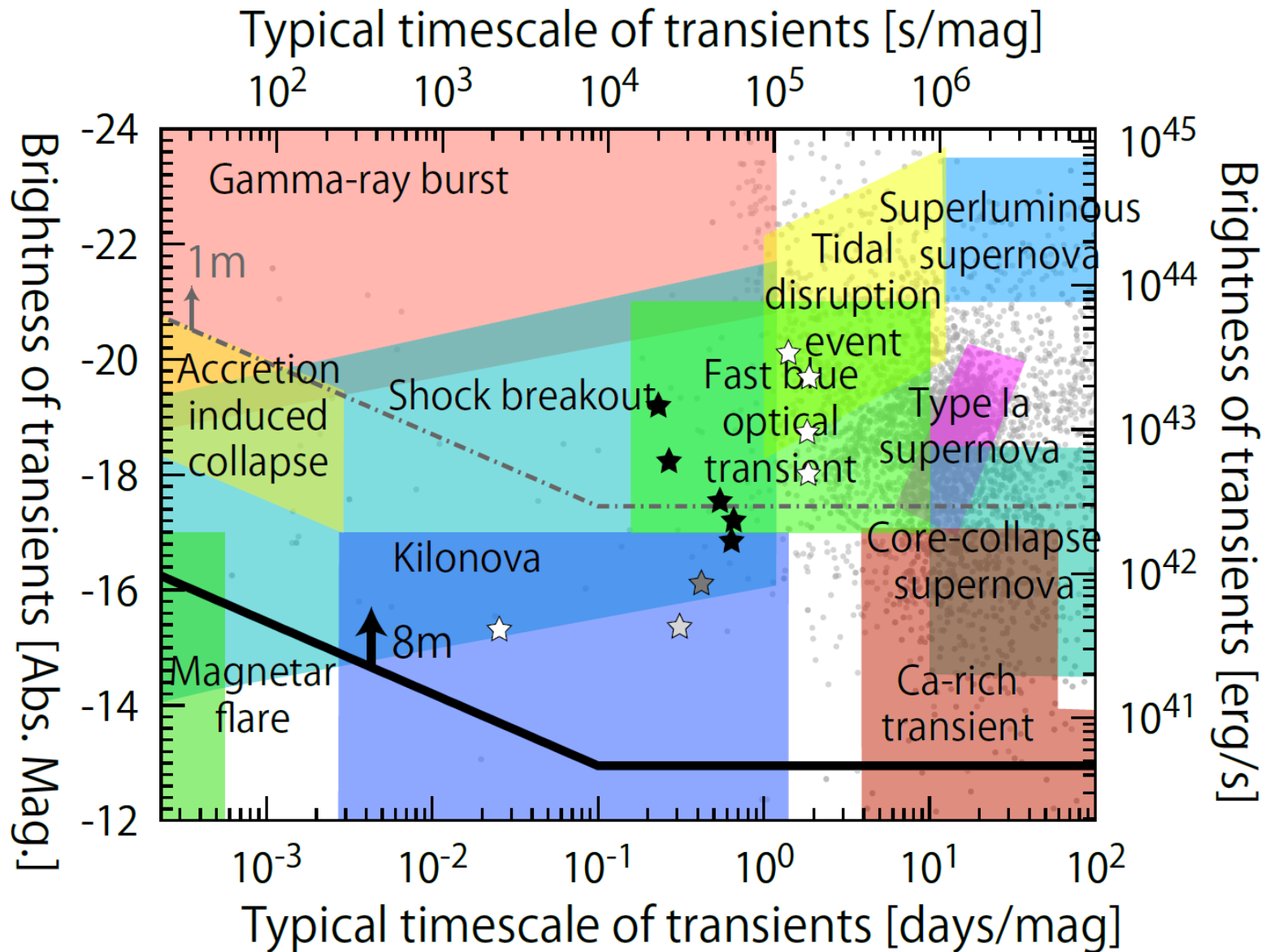
- Supernovae
- Kilonovae/Macronovae
- Gamma-ray bursts
- Fast radio bursts?

# Topics

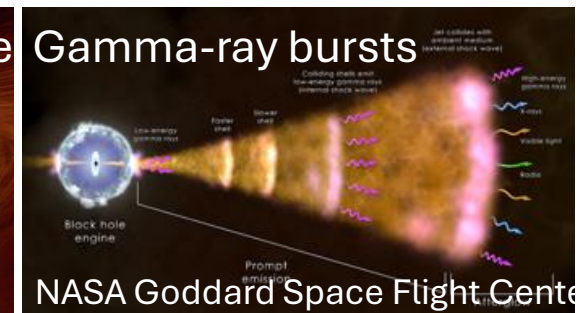
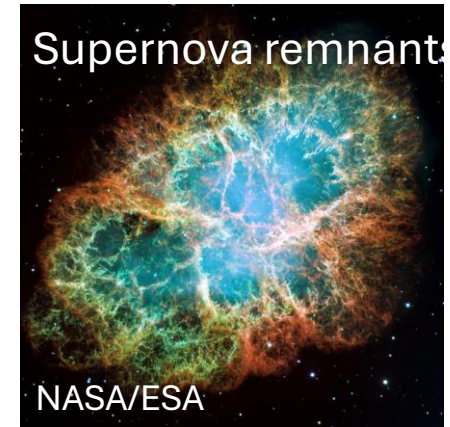
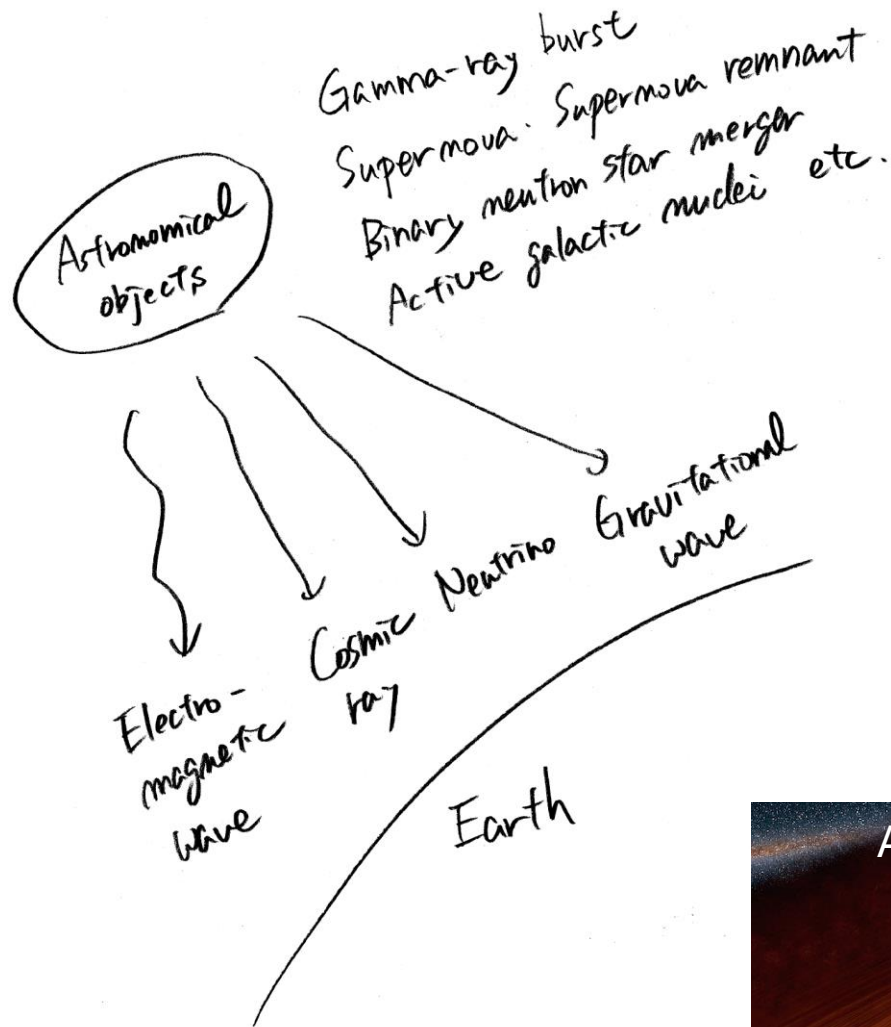
- Early supernovae
  - Last moment of massive stars
  - Progenitor system of SNeIa
- Rapid transients
  - Ultra-stripped SNe?
  - Accretion disk around BHs?
- Superluminous supernovae
  - Energy source?
  - Magnetar, CSM interaction, or radioactivity



# Census of transients

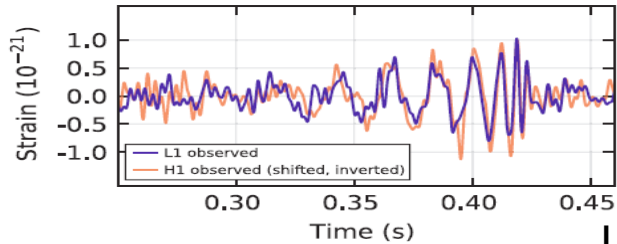


# Multi-messenger astronomy



# Various messengers

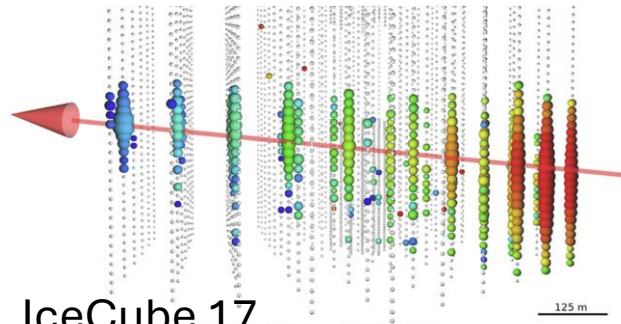
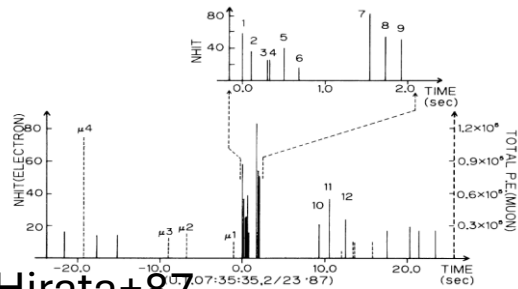
- Gravitational waves



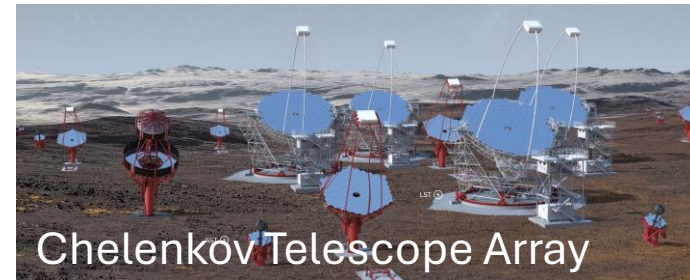
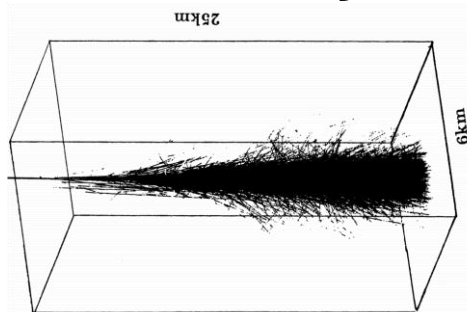
LIGO 16



- Neutrinos

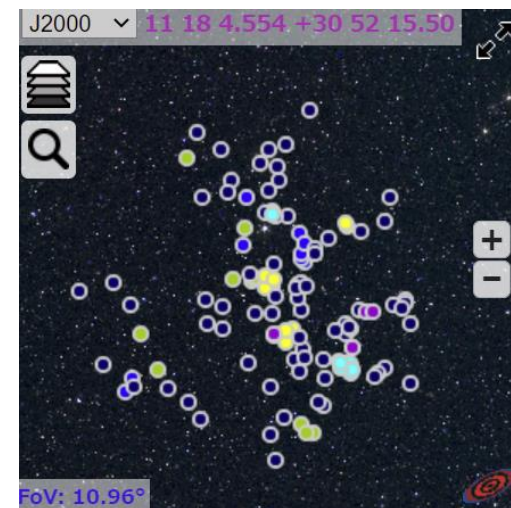
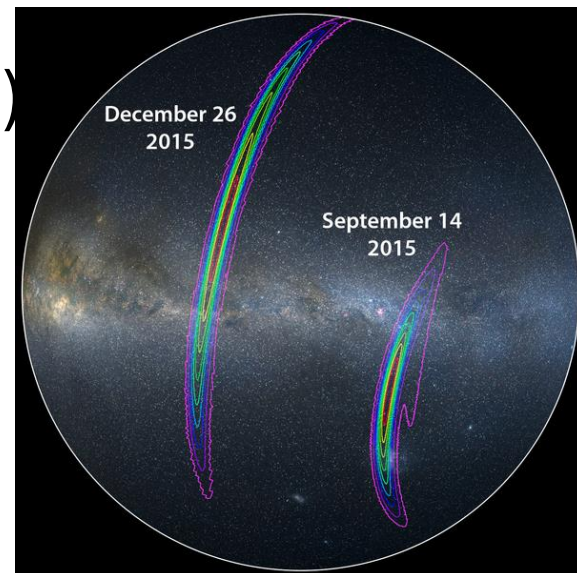


- Cosmic rays / gamma rays



# Multi-messenger astronomy

- Gravitational waves ( $\sim 10\text{-}100\text{deg}^2$ )
- Neutrinos ( $\sim \text{several deg}^2$ )
- Flowchart
  1. Alert
    - Poor localization
  2. Follow-up in  $<1\text{day}$ 
    - Galaxies in the (3D) localization
  3. Data reduction and analysis
    - Redshift, etc.
  4. Report in  $<1\text{day}$



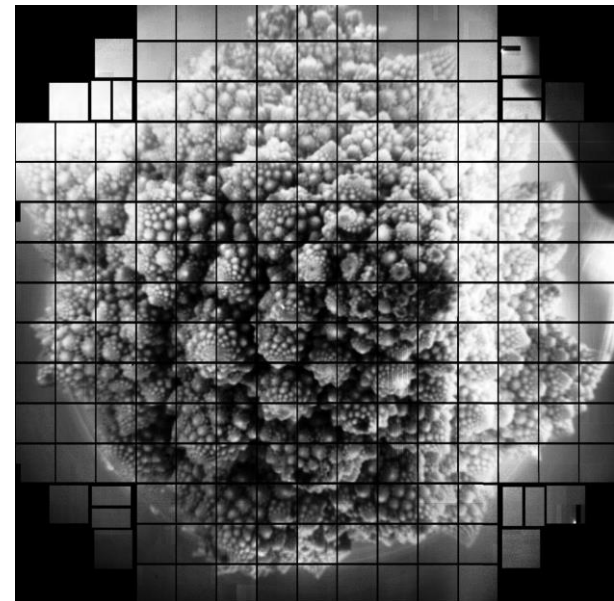
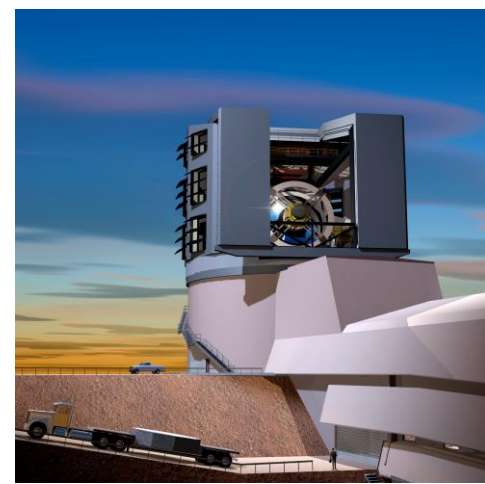
# Rubin/Legacy Survey of Space and Time (LSST)

# Rubin/Legacy Survey of Space and Time (LSST)

Effective aperture: 6.5m, FoV: 9.6deg<sup>2</sup>

## Science goals

- Probing dark energy and dark matter.
- Taking an inventory of the solar system.
- Exploring the transient optical sky.
- Mapping the Milky Way.



# A main survey Wide-Fast-Deep (WFD)

- 10years, 6 filters (ugrizy)
- **18,000deg<sup>2</sup>** (825 visits x 15s x 2)

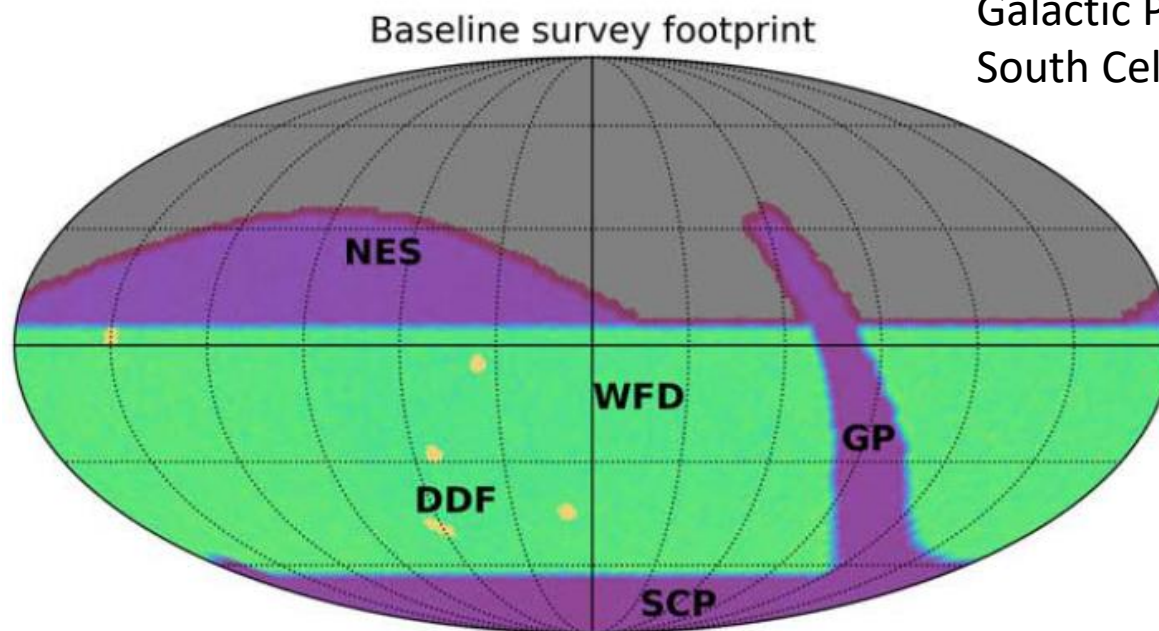
Others

Deep Drilling Fields (DDFs)

North Ecliptic Spur (NES)

Galactic Plane (GP)

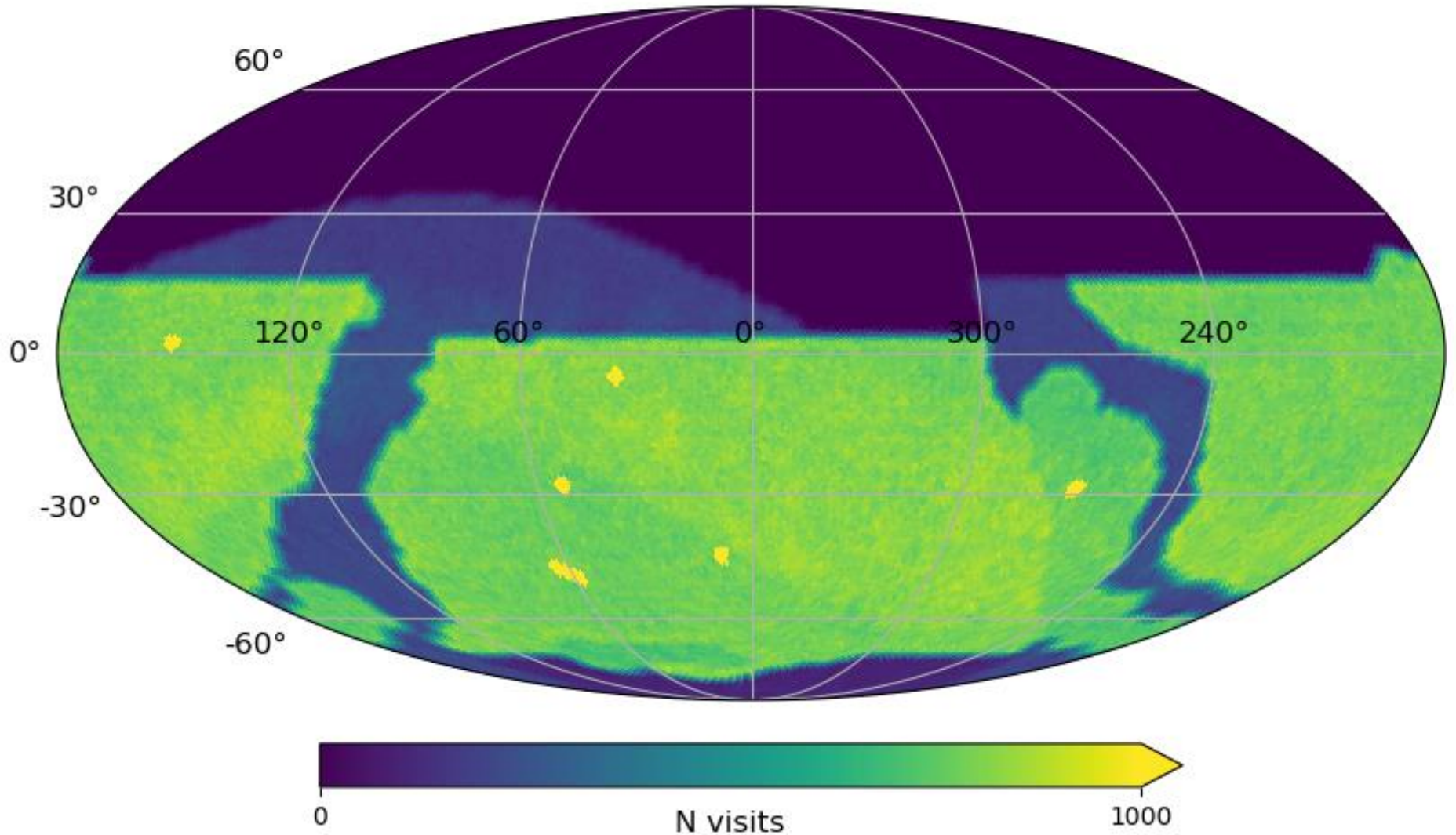
South Celestial Pole (SCP)



# Observation plan

# Footprints

[https://usdf-maf.slac.stanford.edu/sims\\_featureScheduler\\_runs4.3/ddf\\_ocean/ddf\\_ocean\\_ocean6\\_v4.3.5\\_10yrs.db](https://usdf-maf.slac.stanford.edu/sims_featureScheduler_runs4.3/ddf_ocean/ddf_ocean_ocean6_v4.3.5_10yrs.db)





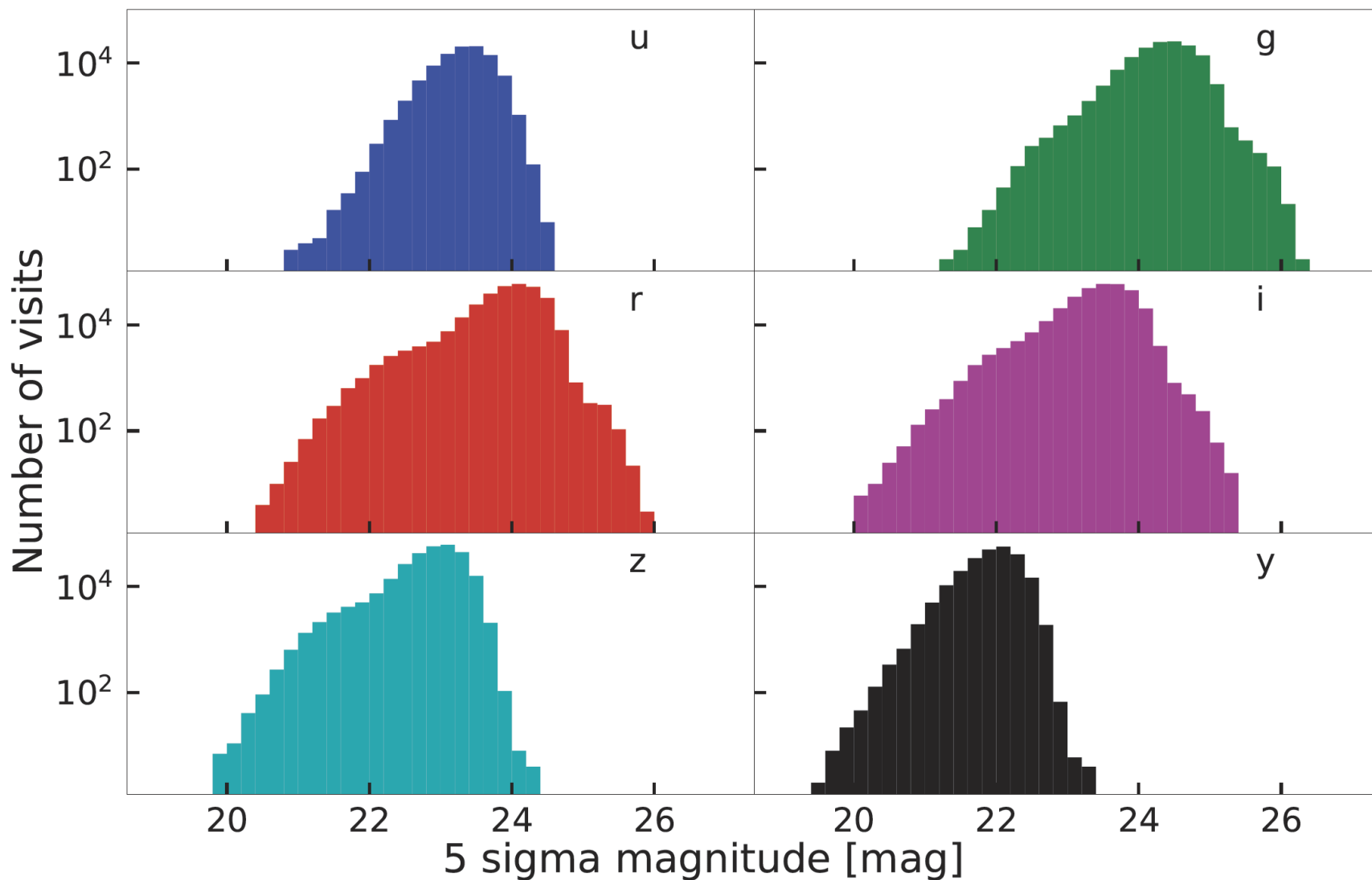
# Depth

Depth (saturation, single, all)

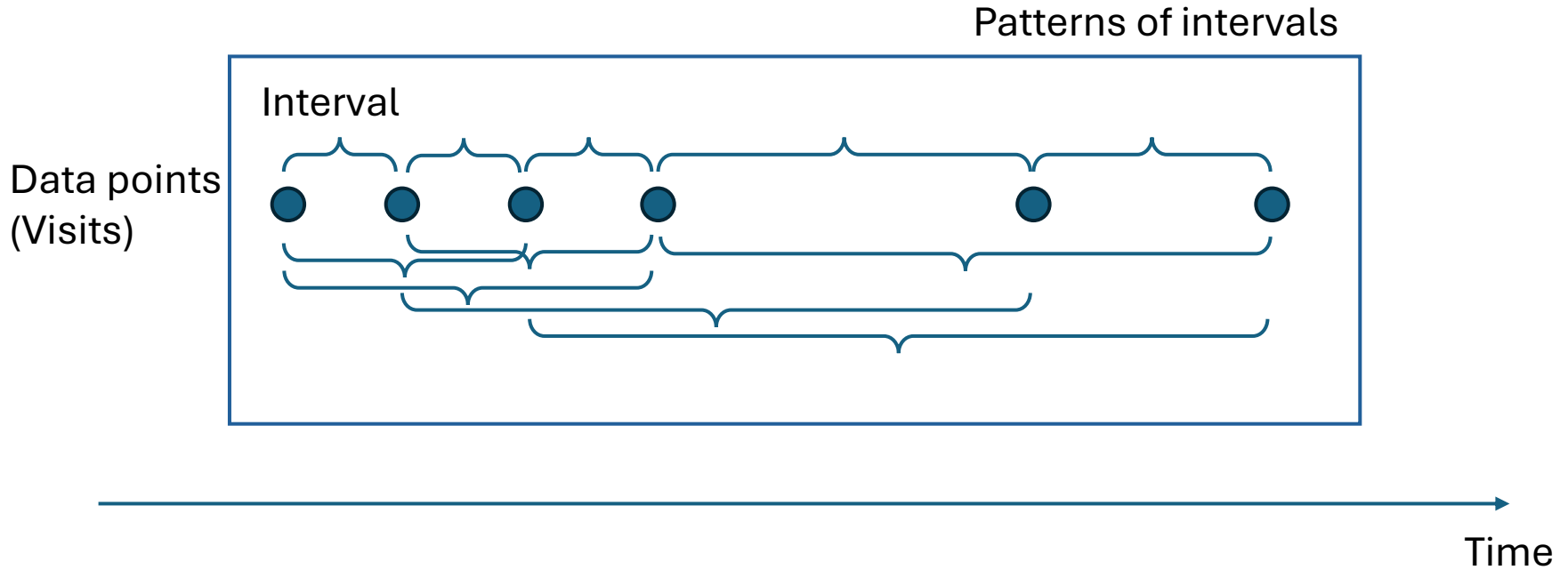
u : 14.7, 23.8, 25.6    i : 15.8, 23.41, 26.4

g : 15.7, 24.5, 26.9    z : 15.3, 22.74, 25.6

r : 15.8, 24.03, 26.9    y : 13.9, 22.96, 24.8

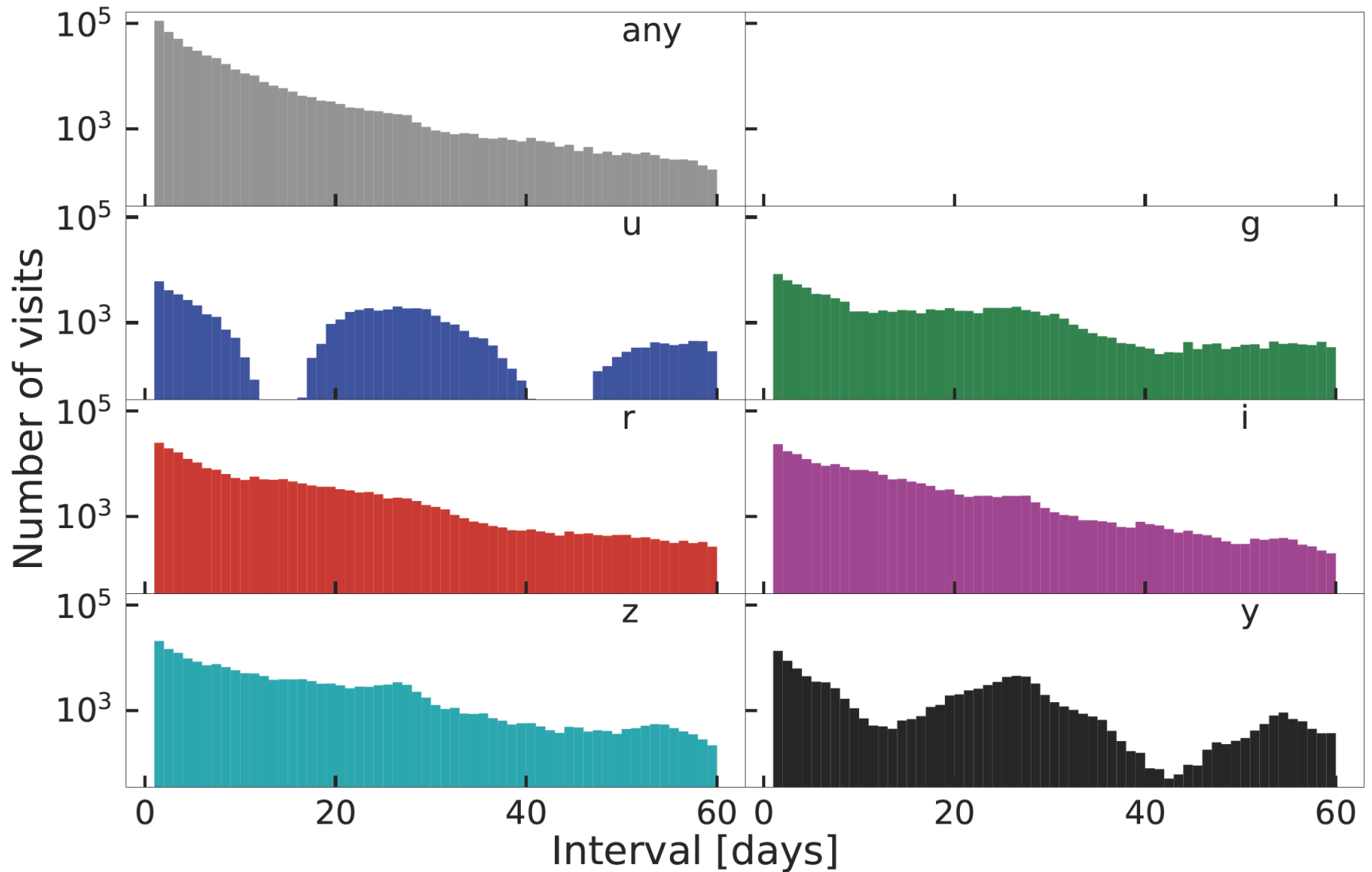


# Terminology

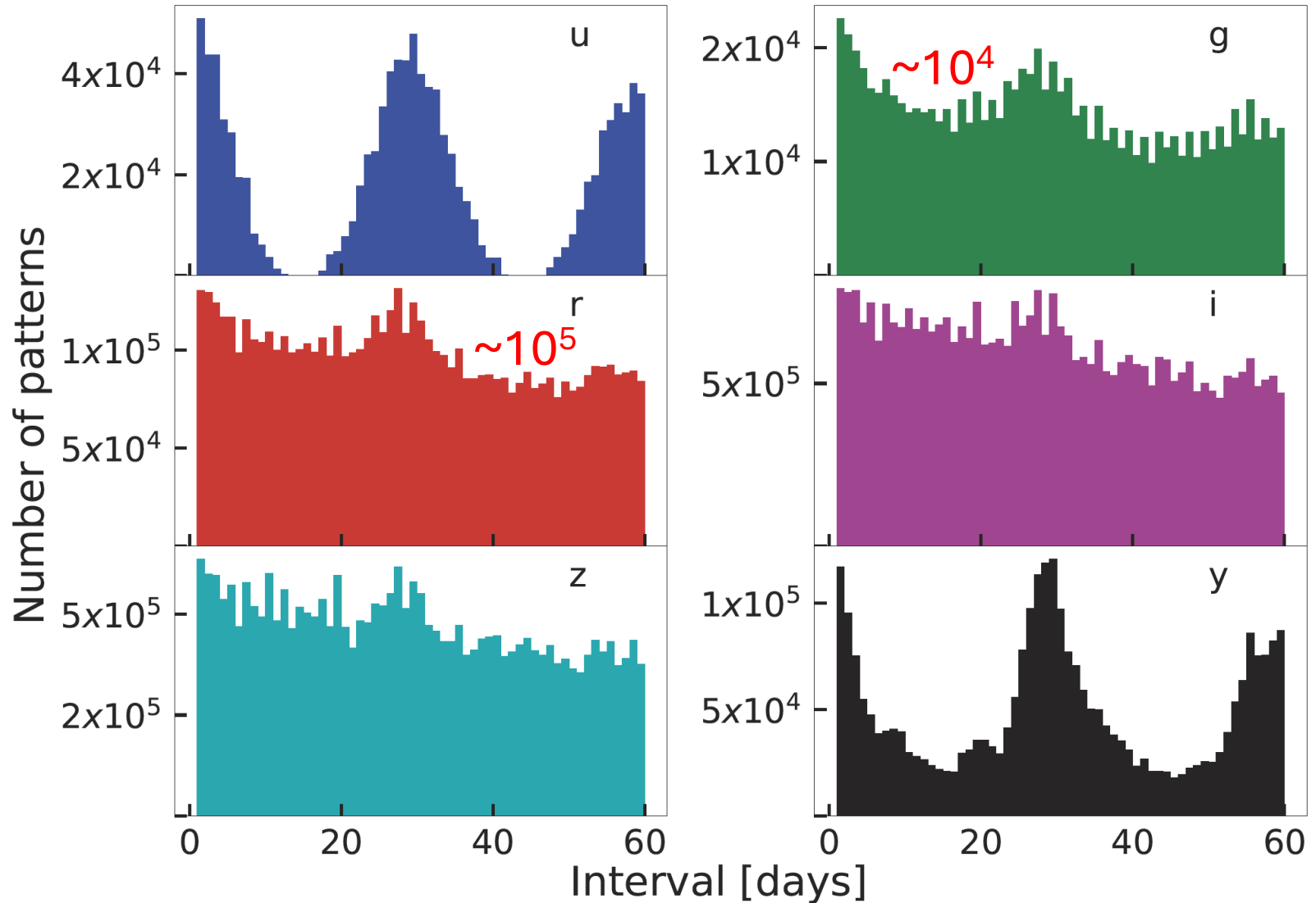


- Visits: exposures
- Patterns: combination of exposures

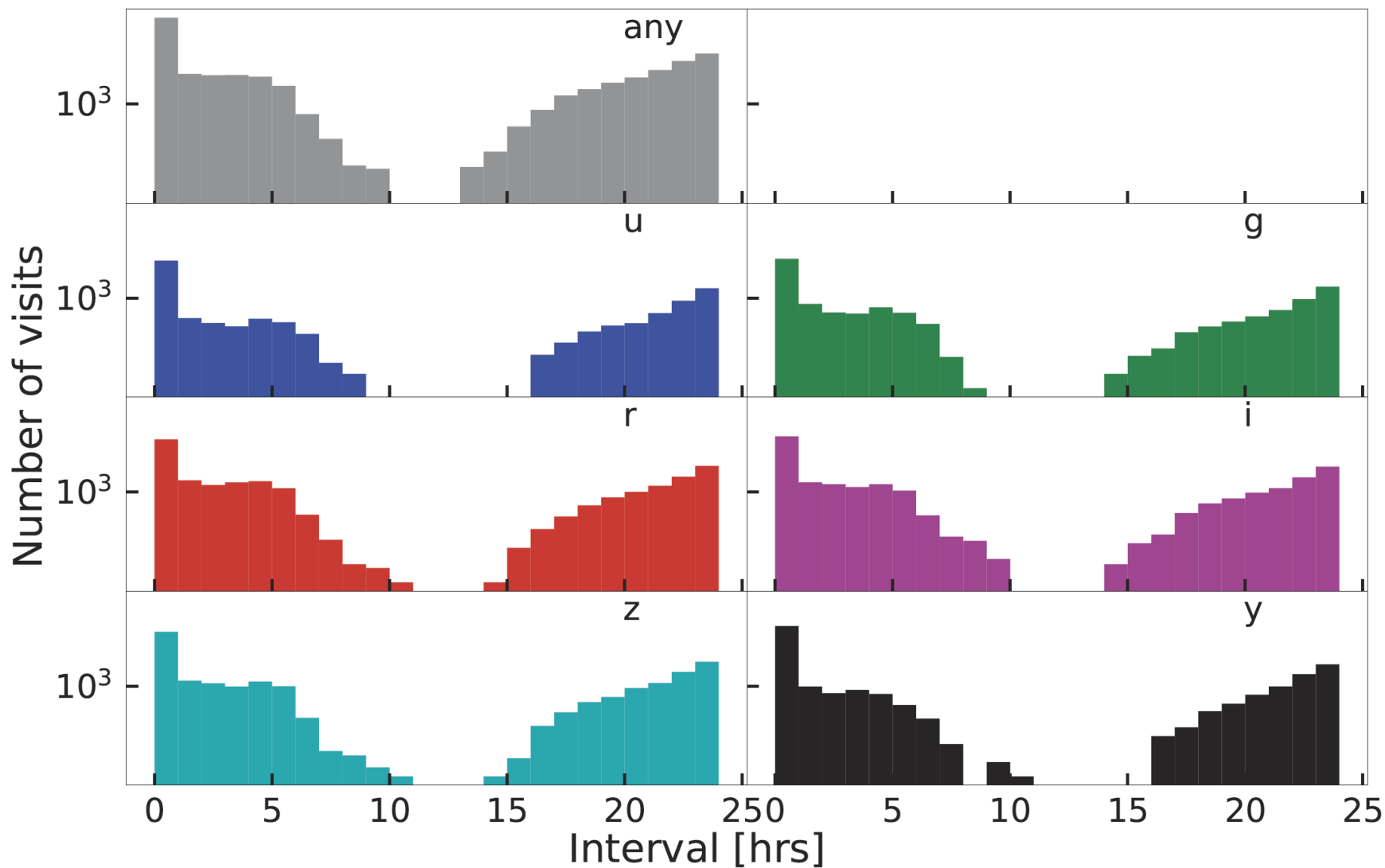
# Daily intervals



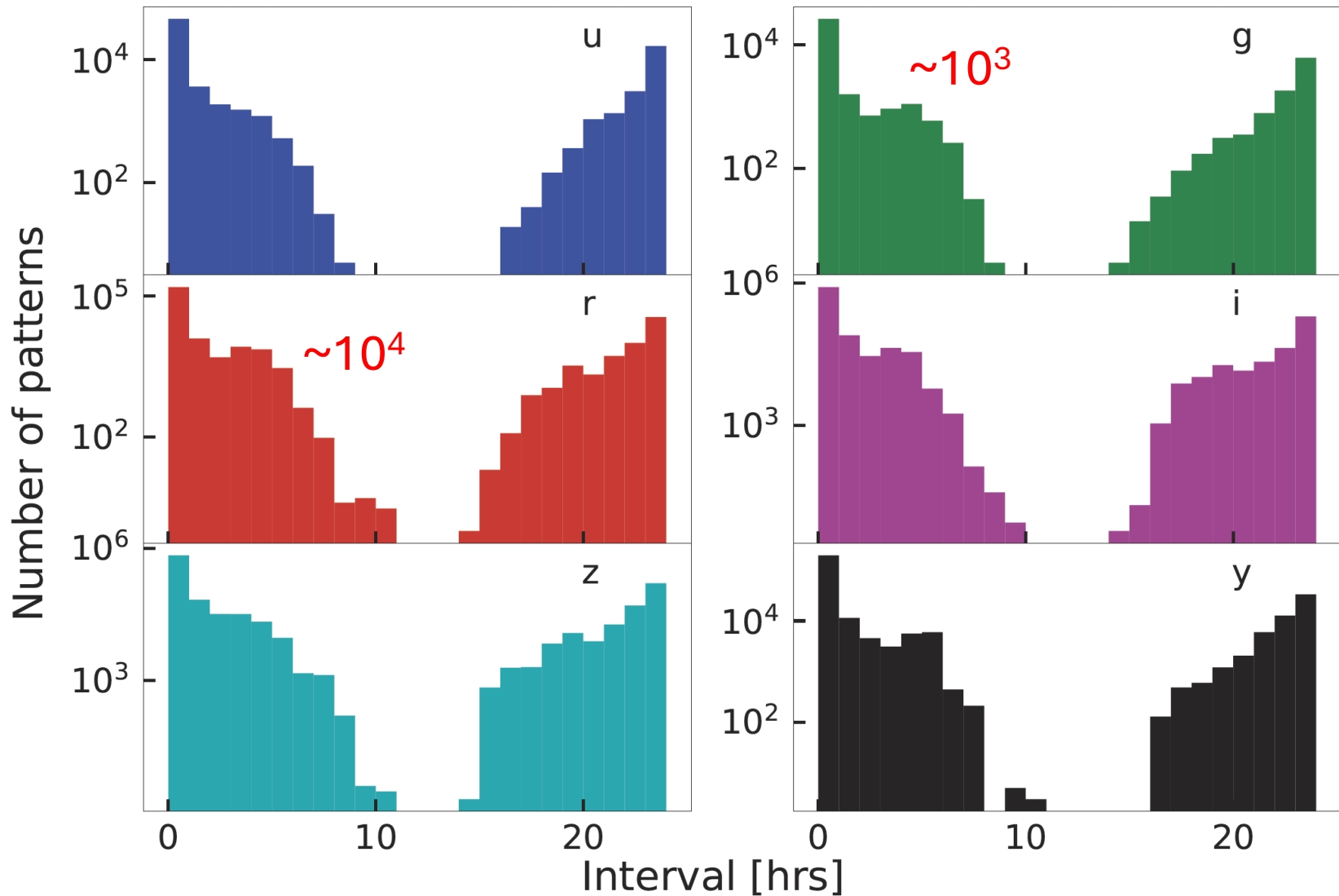
# Patterns of daily intervals



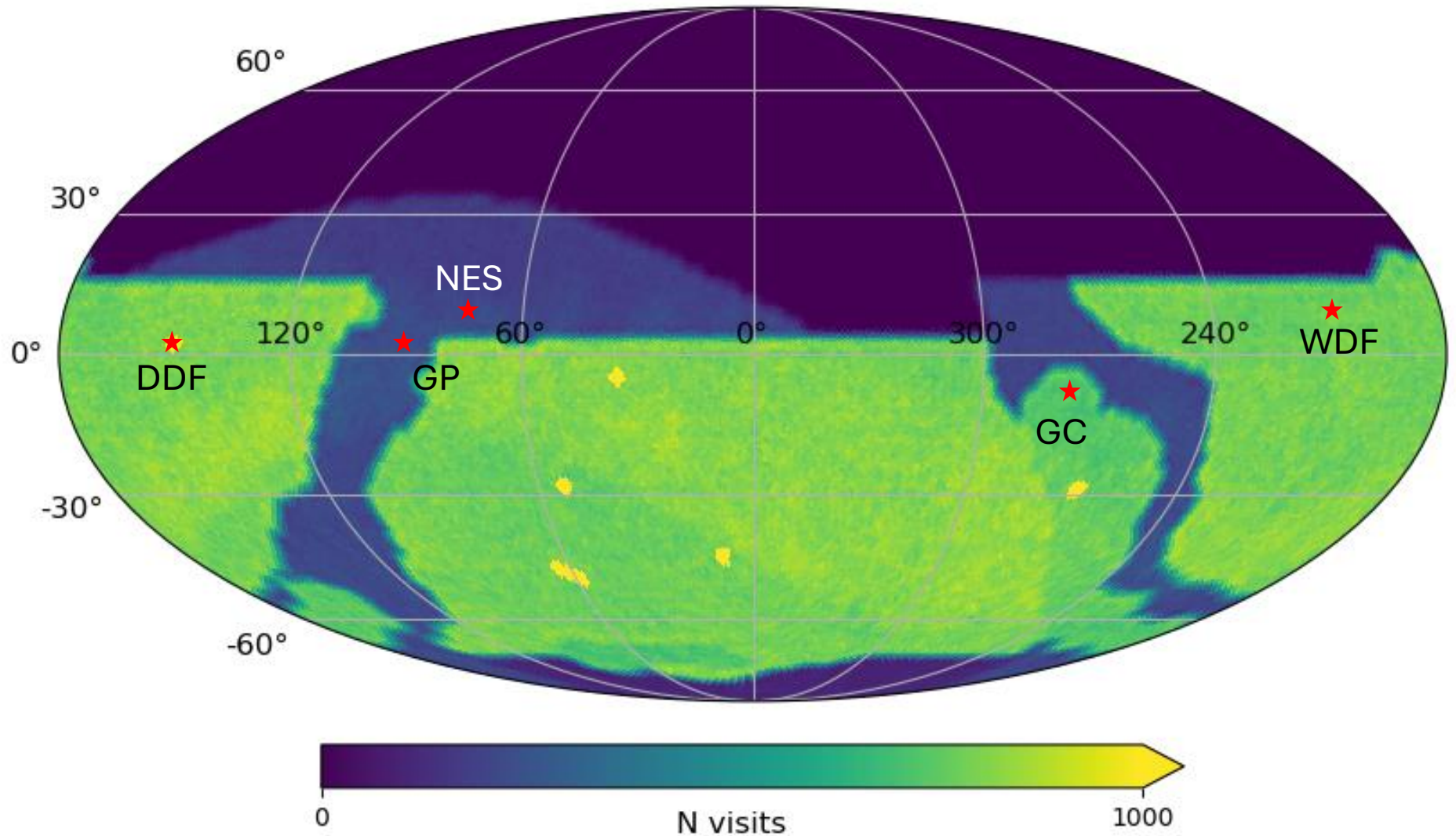
# Intranight intervals



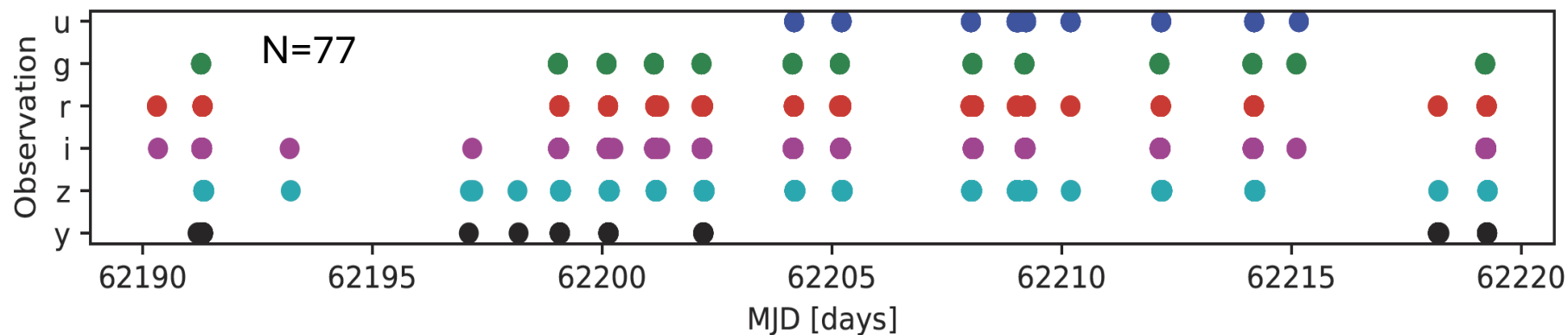
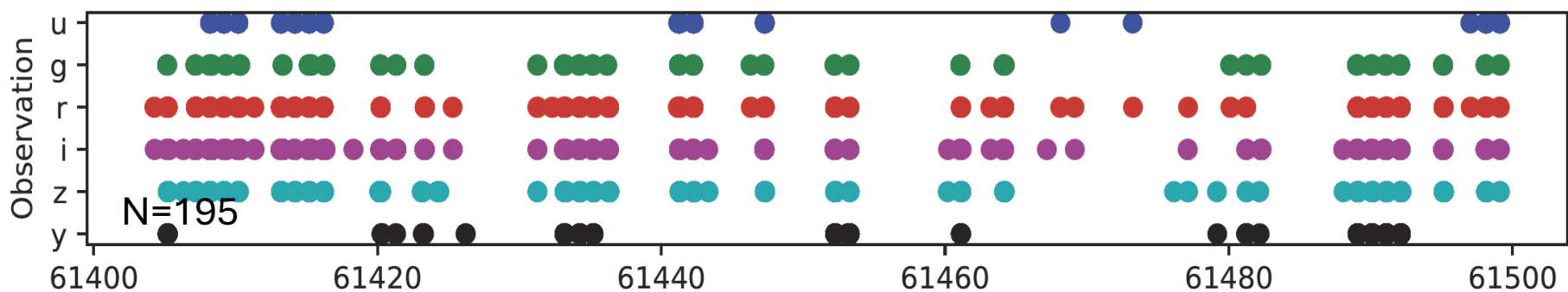
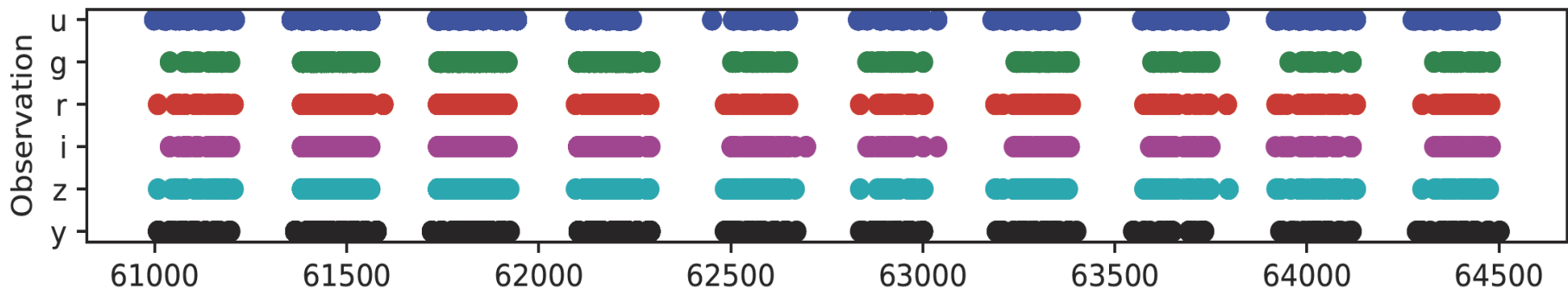
# Patterns of intranight intervals



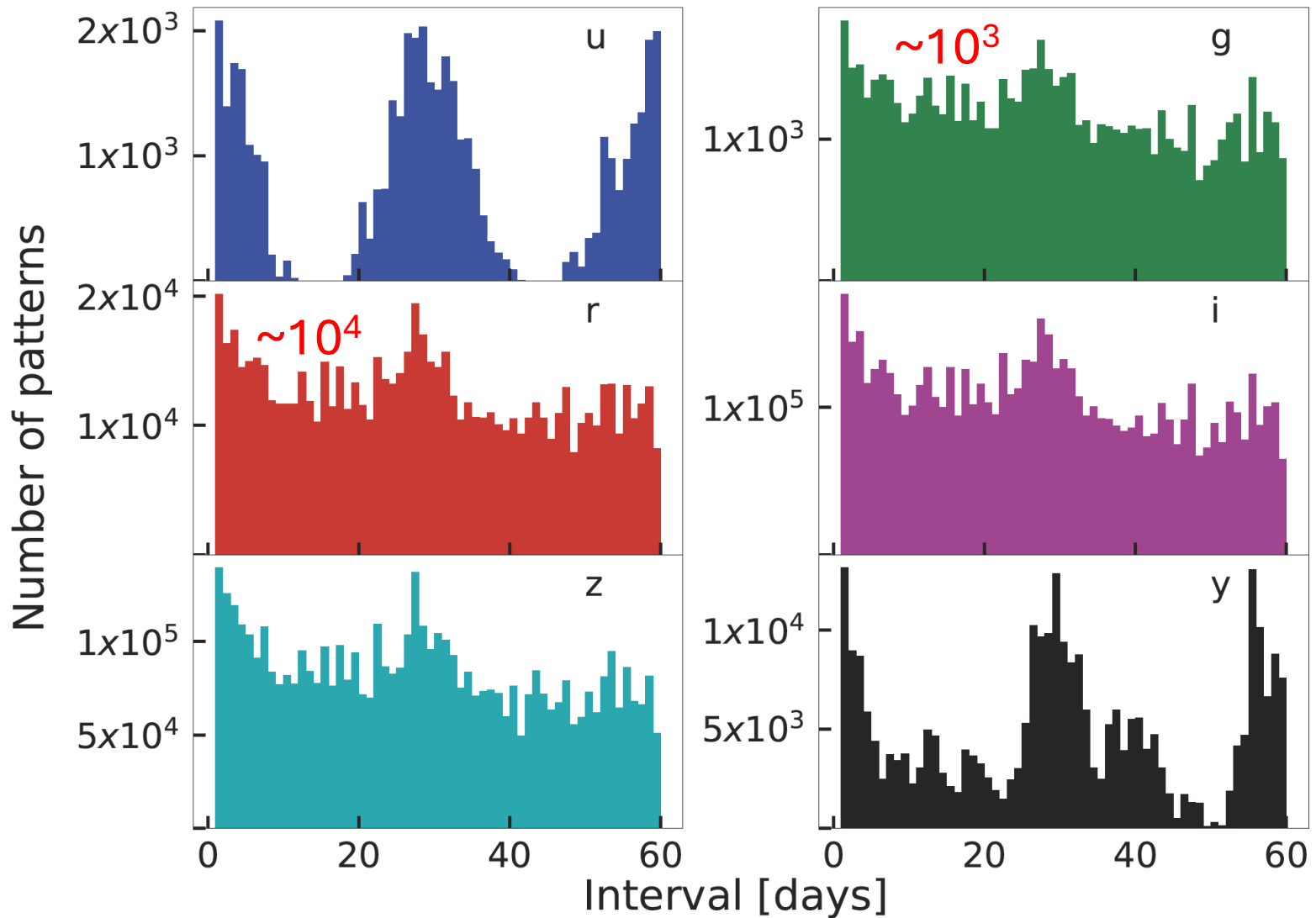
# Footprints



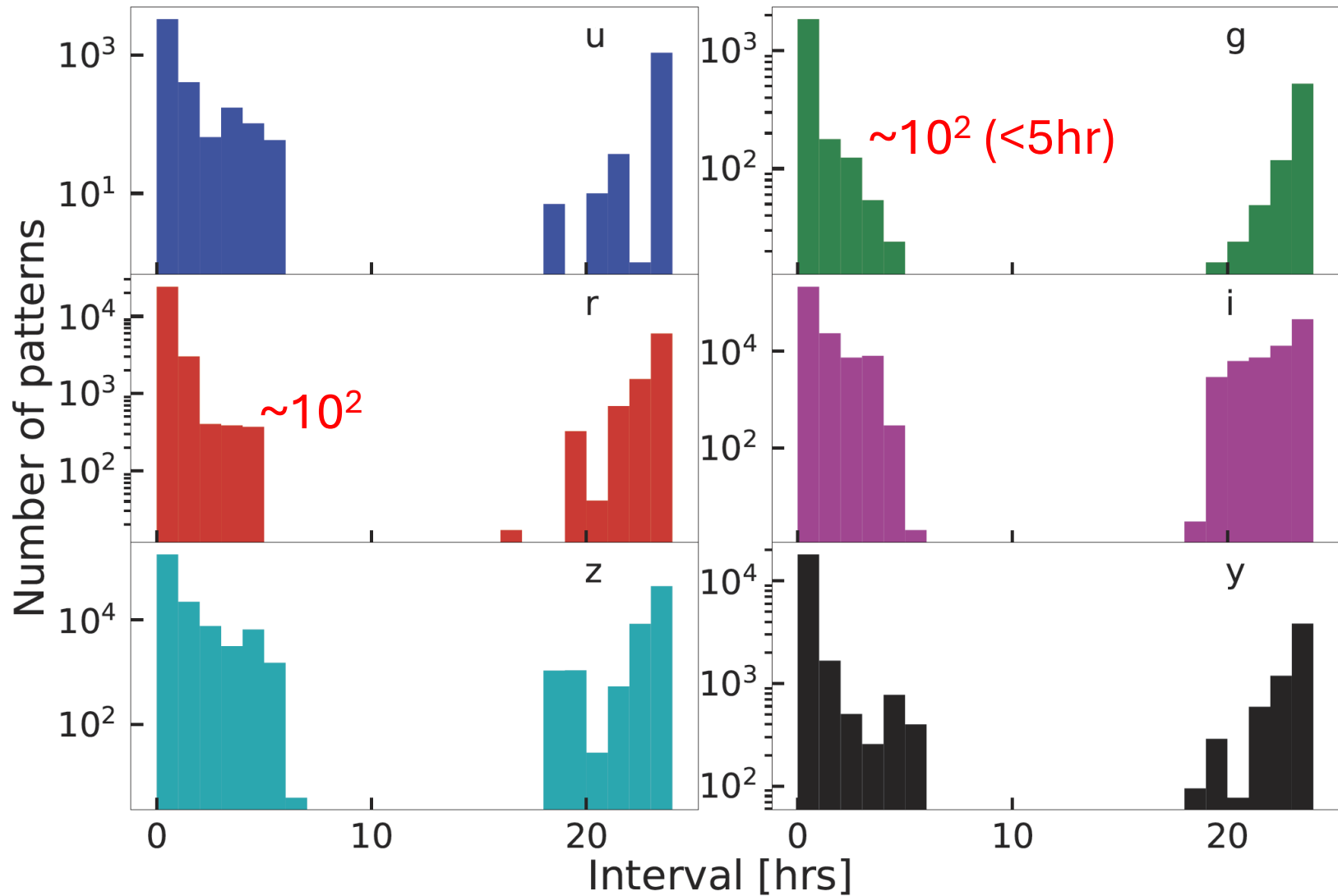
# Observation – DDF (N=23921)



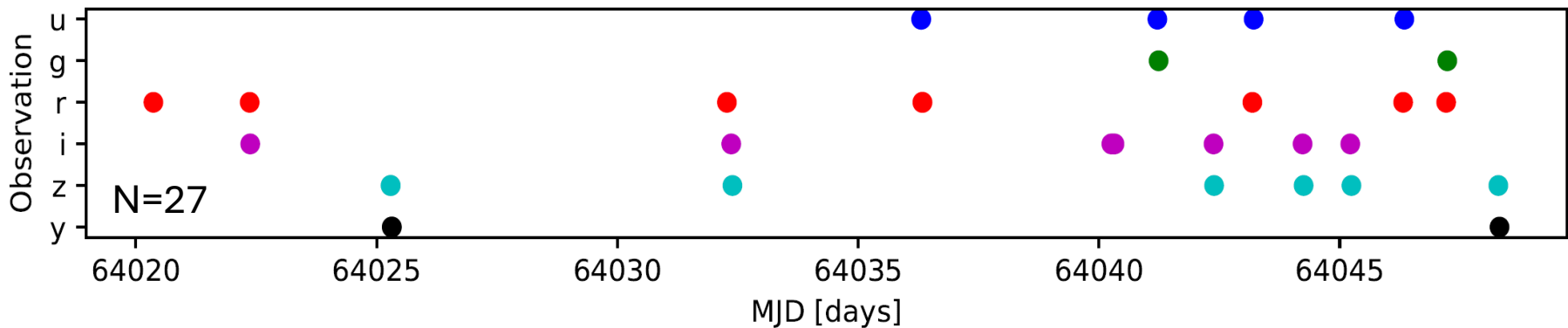
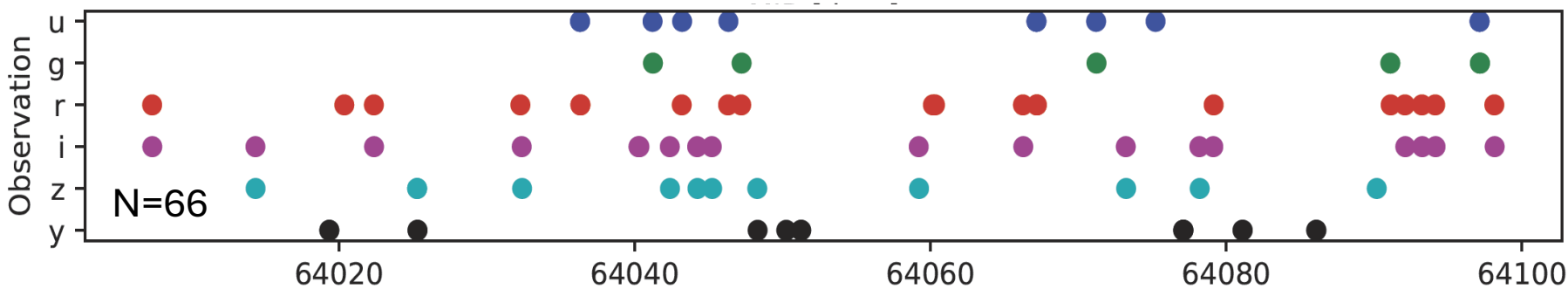
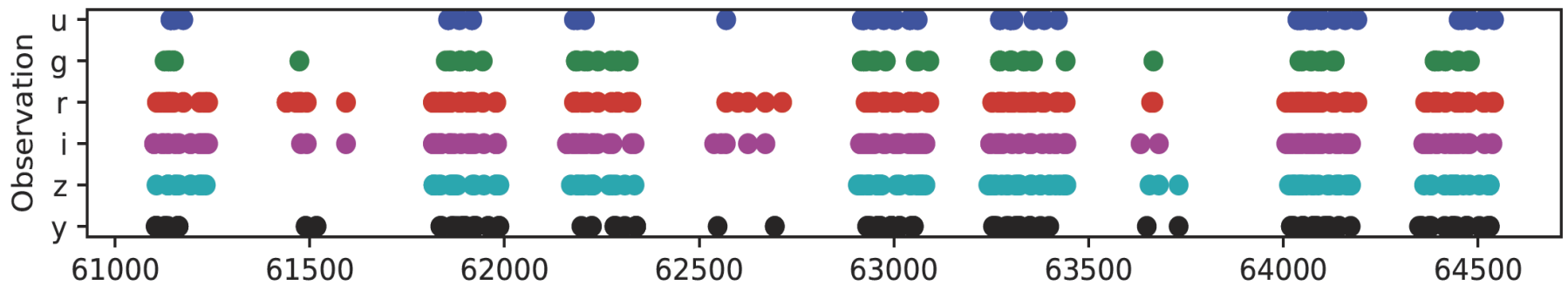
# Patterns of daily intervals



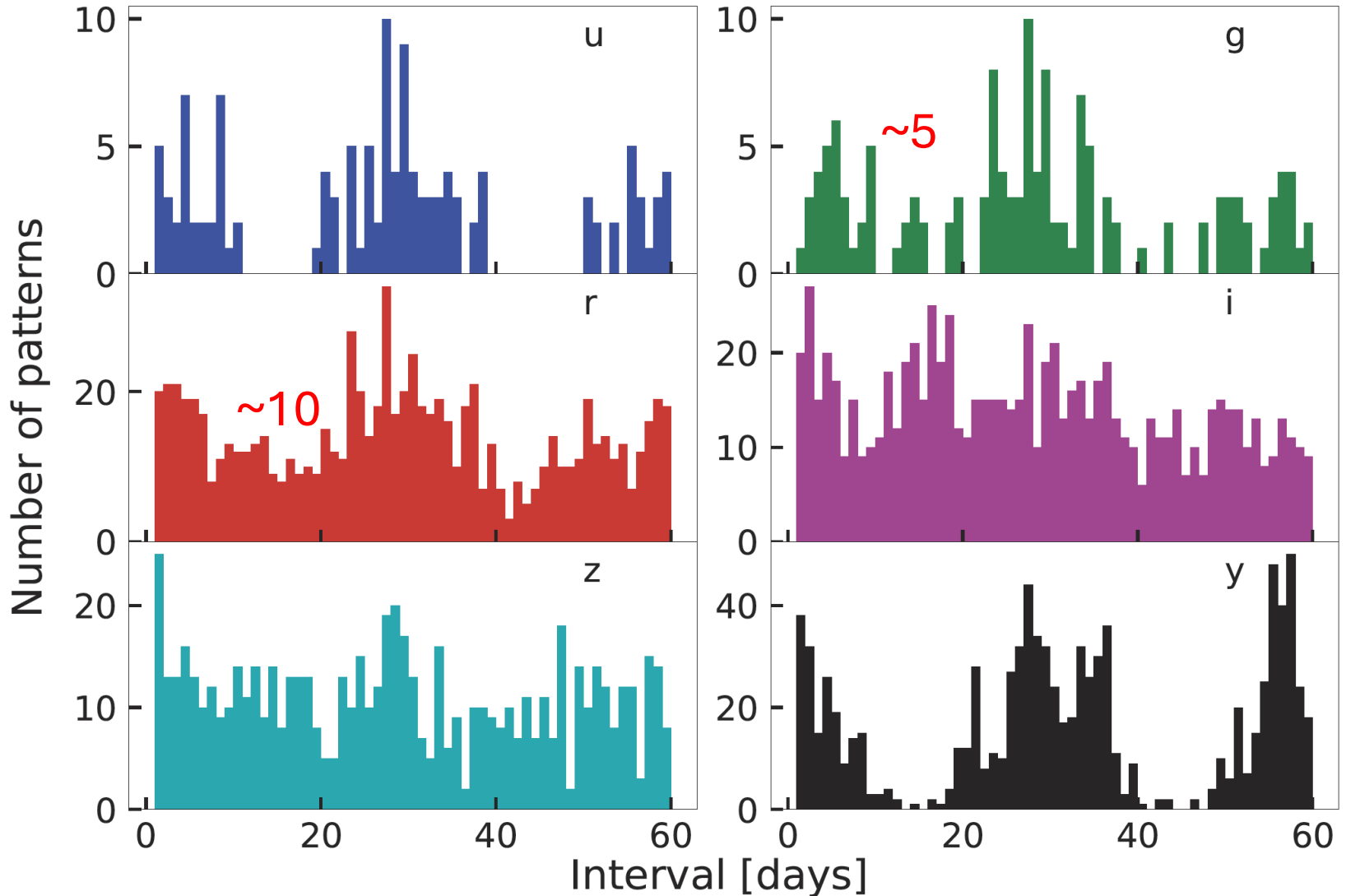
# Patterns of intranight intervals



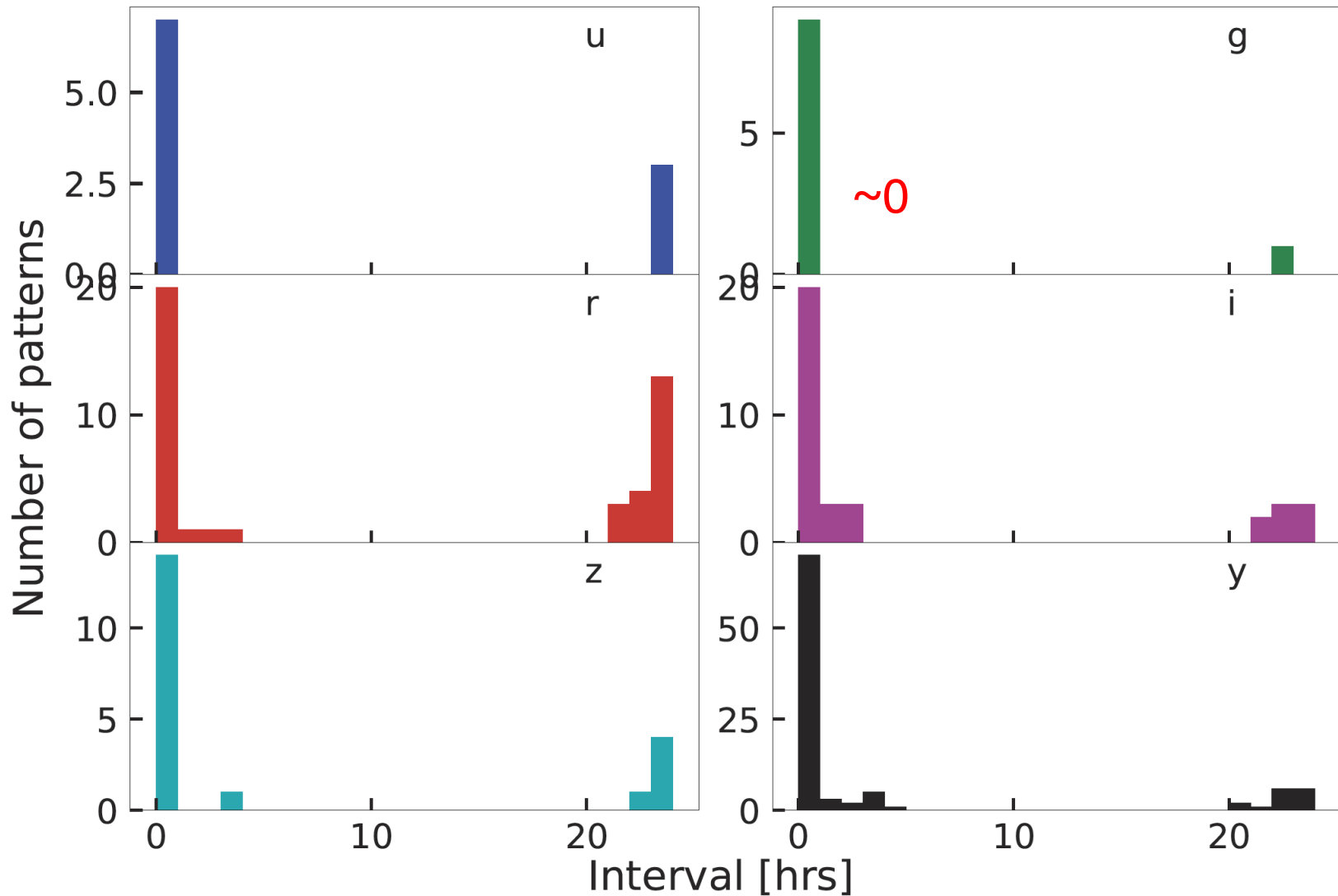
# Observation – WDF (N=724) & GC



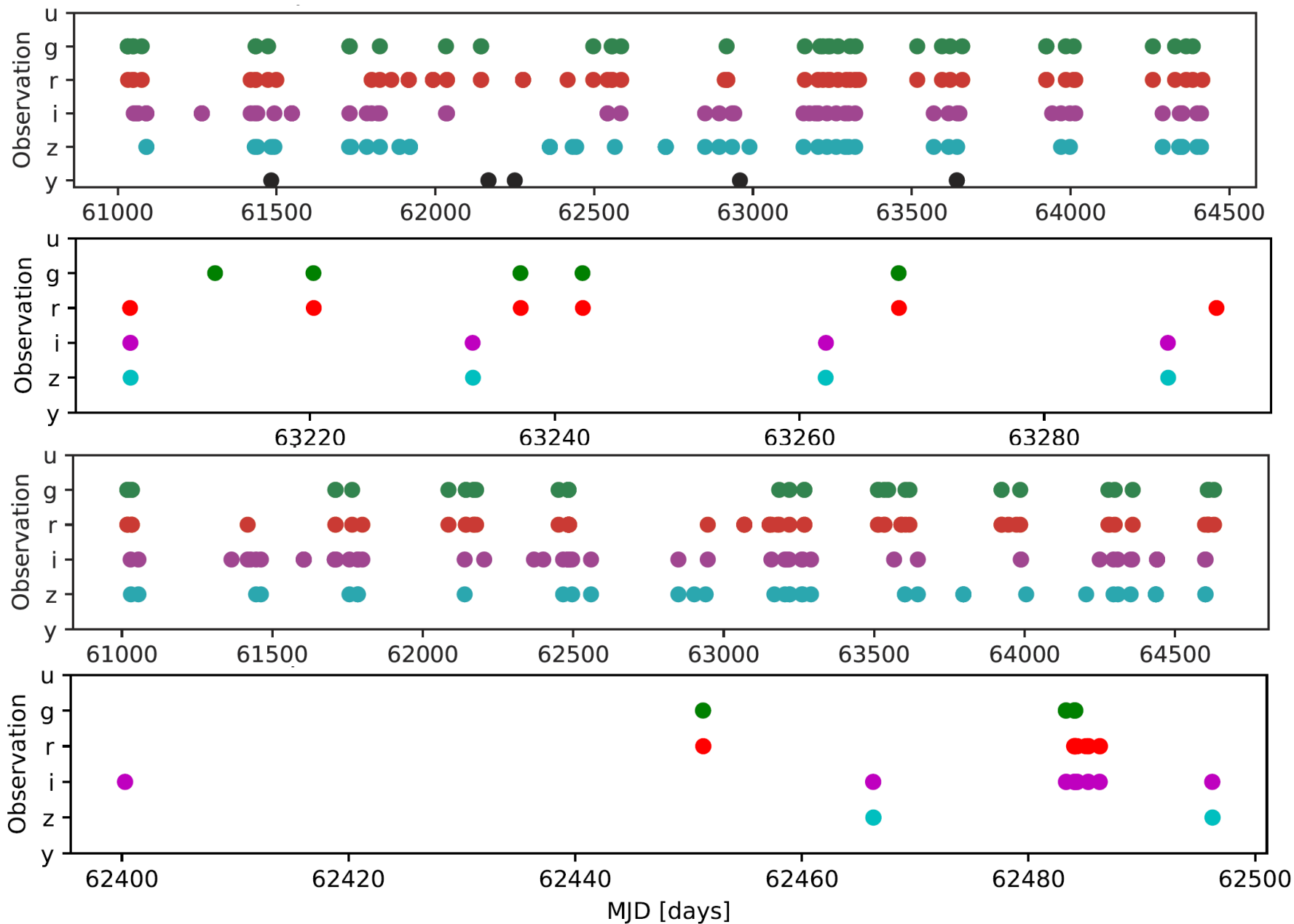
# Patterns of daily intervals



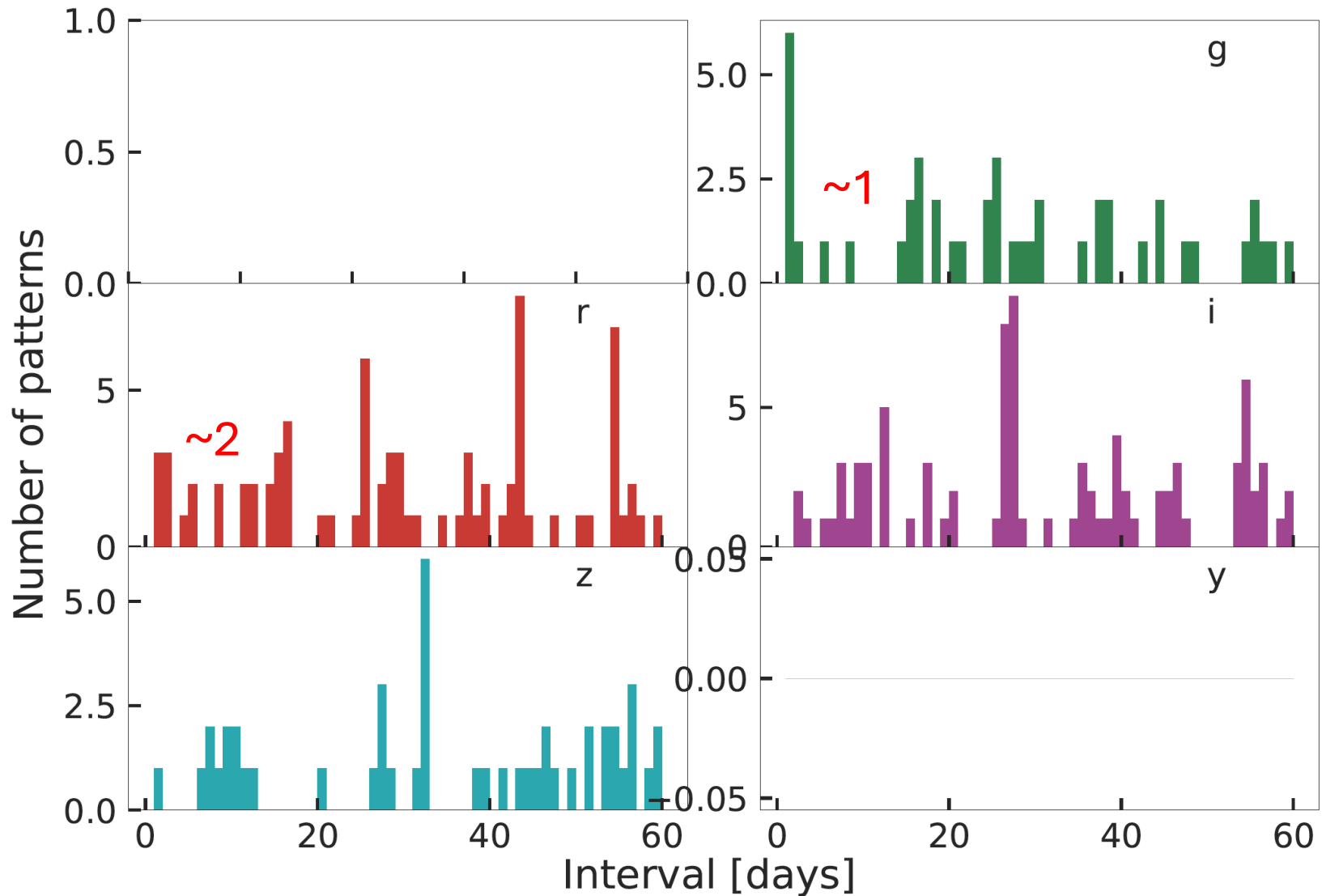
# Patterns of intranight intervals



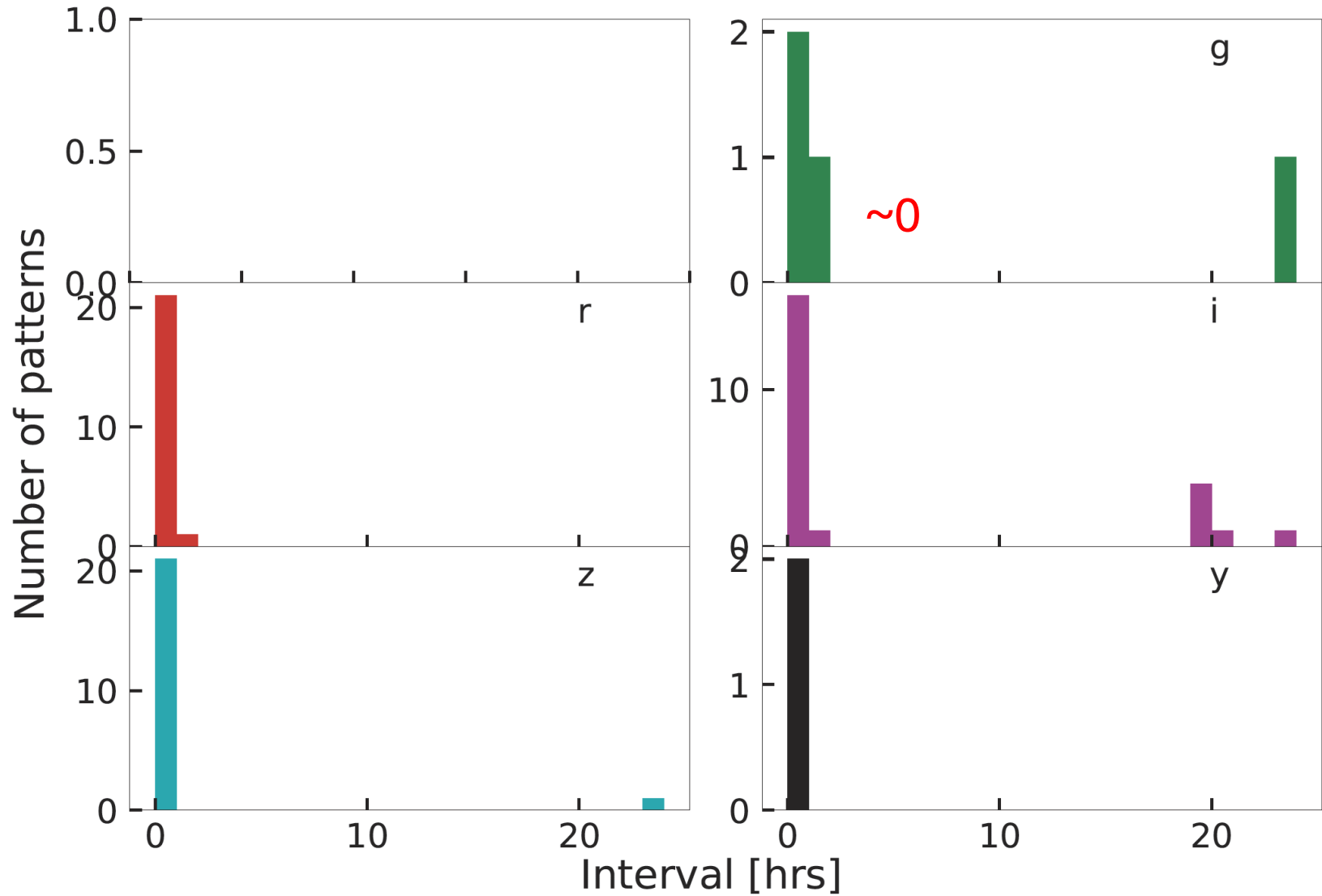
# Observation – GP&NES (N=221,207)



# Patterns of daily intervals



# Patterns of intranight intervals



# Summary of observation plan

- All
  - $>10^4$  patterns of daily intervals (1-60days)
  - $\sim 10^3(\text{g})-\sim 10^4(\text{riz})$  patterns of hourly intervals (<5hr)
- DDF
  - $>10^3$  patterns of daily intervals (1-60days)
  - $\sim 100(\text{gr})-\sim 10^3(\text{iz})$  patterns of hourly intervals (<5hr)
- WDF & GC
  - $\sim 10$  patterns of daily intervals (1-60days)
  - $<\sim 1$  patterns of hourly intervals
- GP & NES
  - $\sim \text{several}$  patterns of daily intervals (1-60days)
  - $<\sim 1$  patterns of hourly intervals

# Alert stream

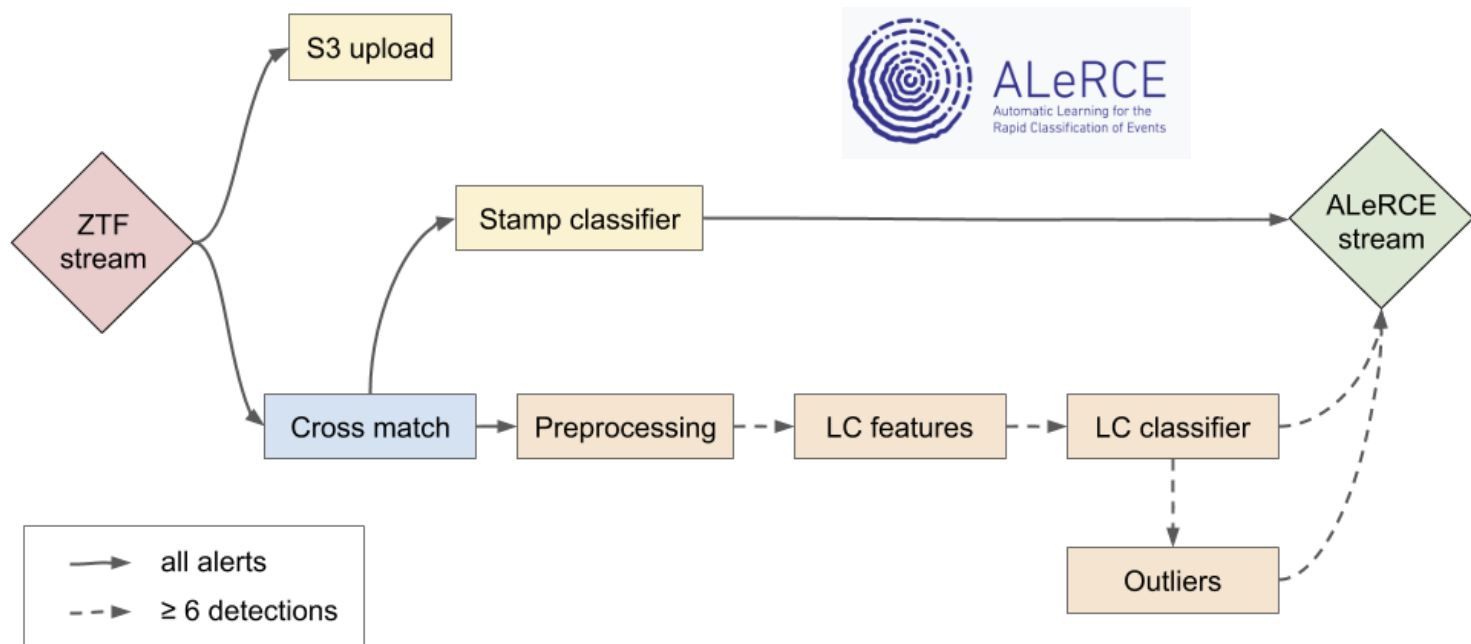


- Full alert stream is accessible only from community brokers. (**Filtered alert stream** may be received by the LSST users.)
- Latency: **<60sec** after image readout
- Rate: **<10<sup>7</sup> alerts/night** (2x10<sup>4</sup> for the filtered alerts)
- Alerts include
  - ID, filter name
  - Coordinate, proper motion, parallax, flux, error
  - Nearby object in catalog
  - 12 months history
  - Cutout images (stamps)

# Alert brokers

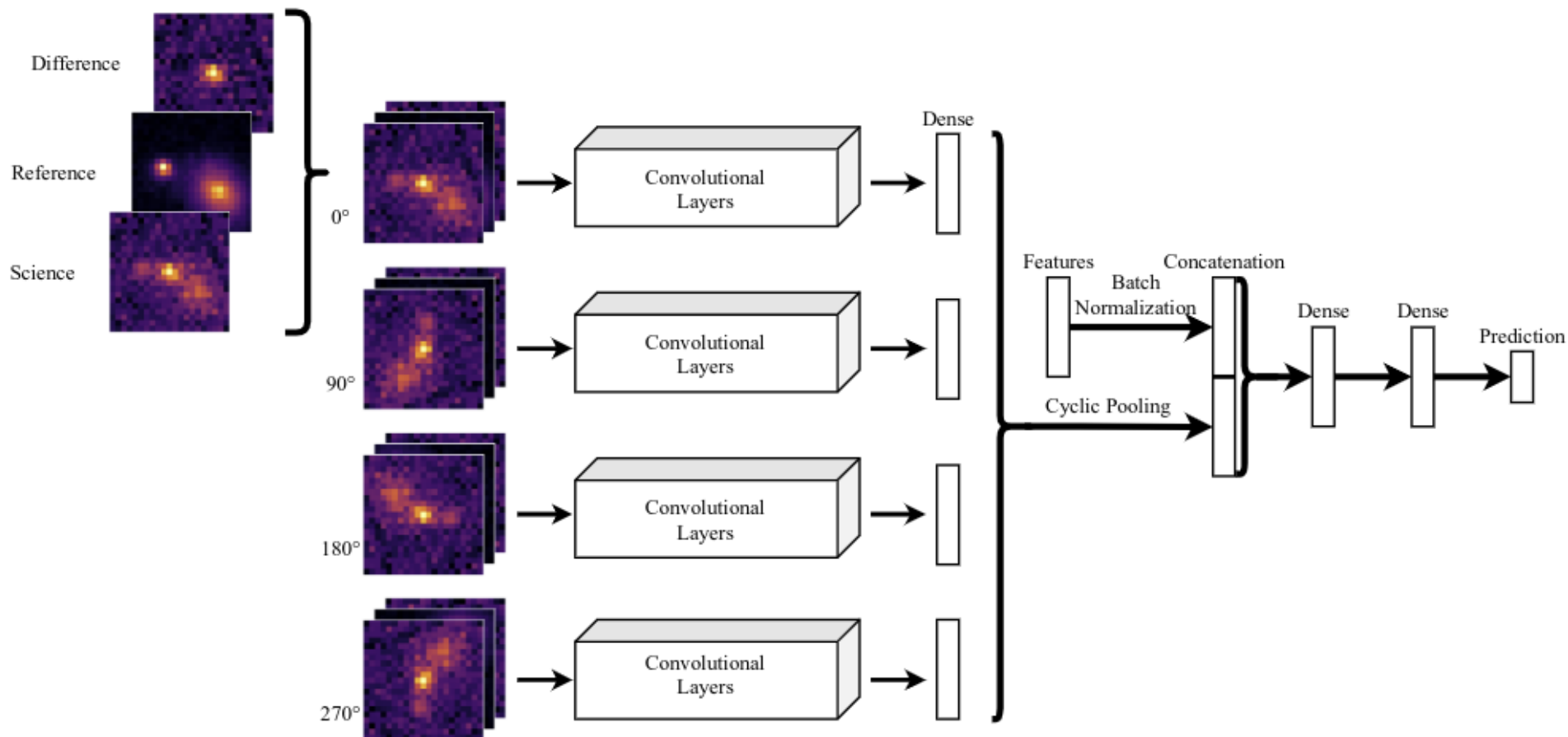
<https://www.lsst.org/scientists/alert-brokers>

- 7 full stream brokers, 2 downstream brokers
- They provide alerts with additional information such as **classification** and **filtering**, and a public database of full stream.

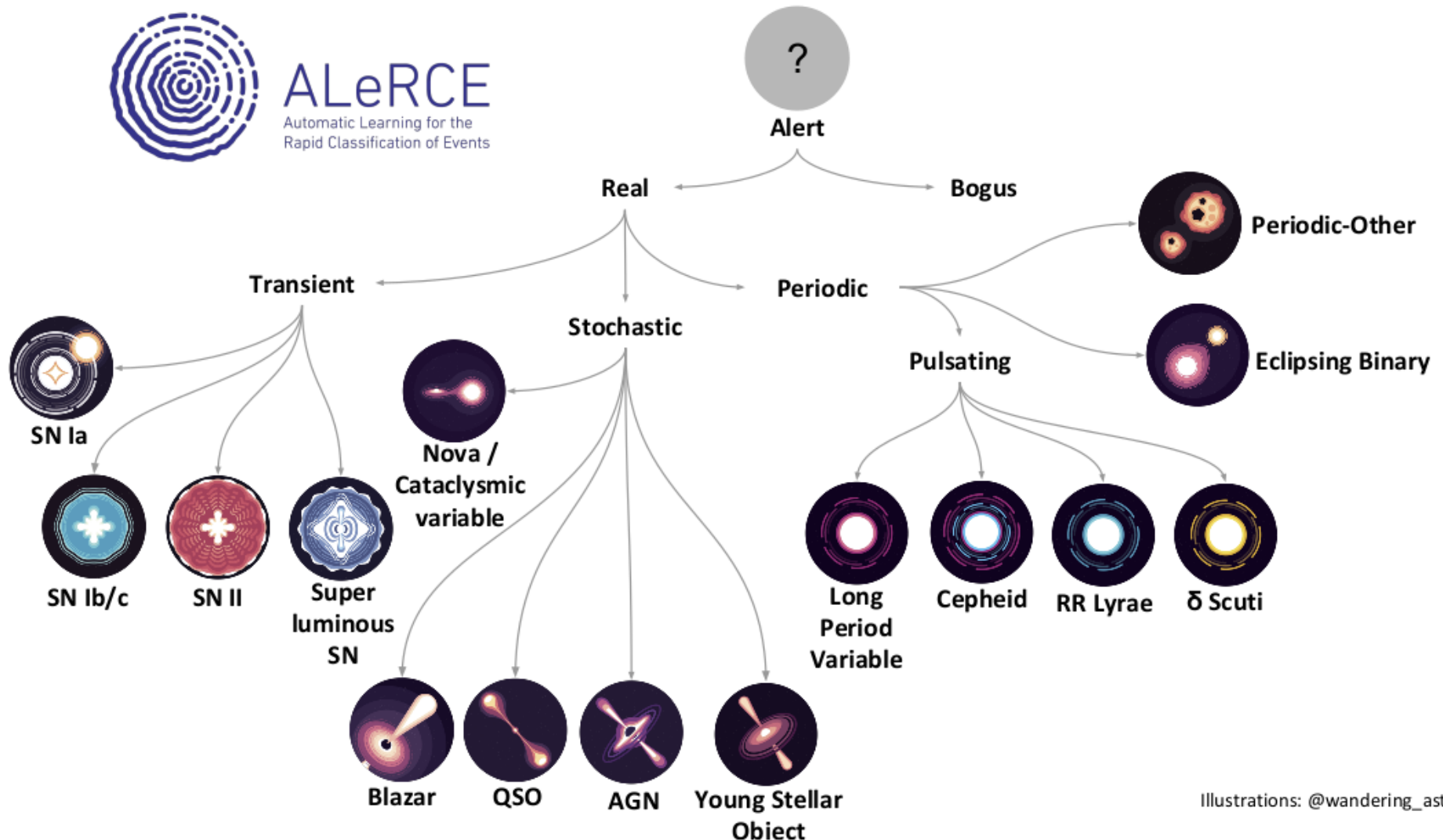


# Stamp classification

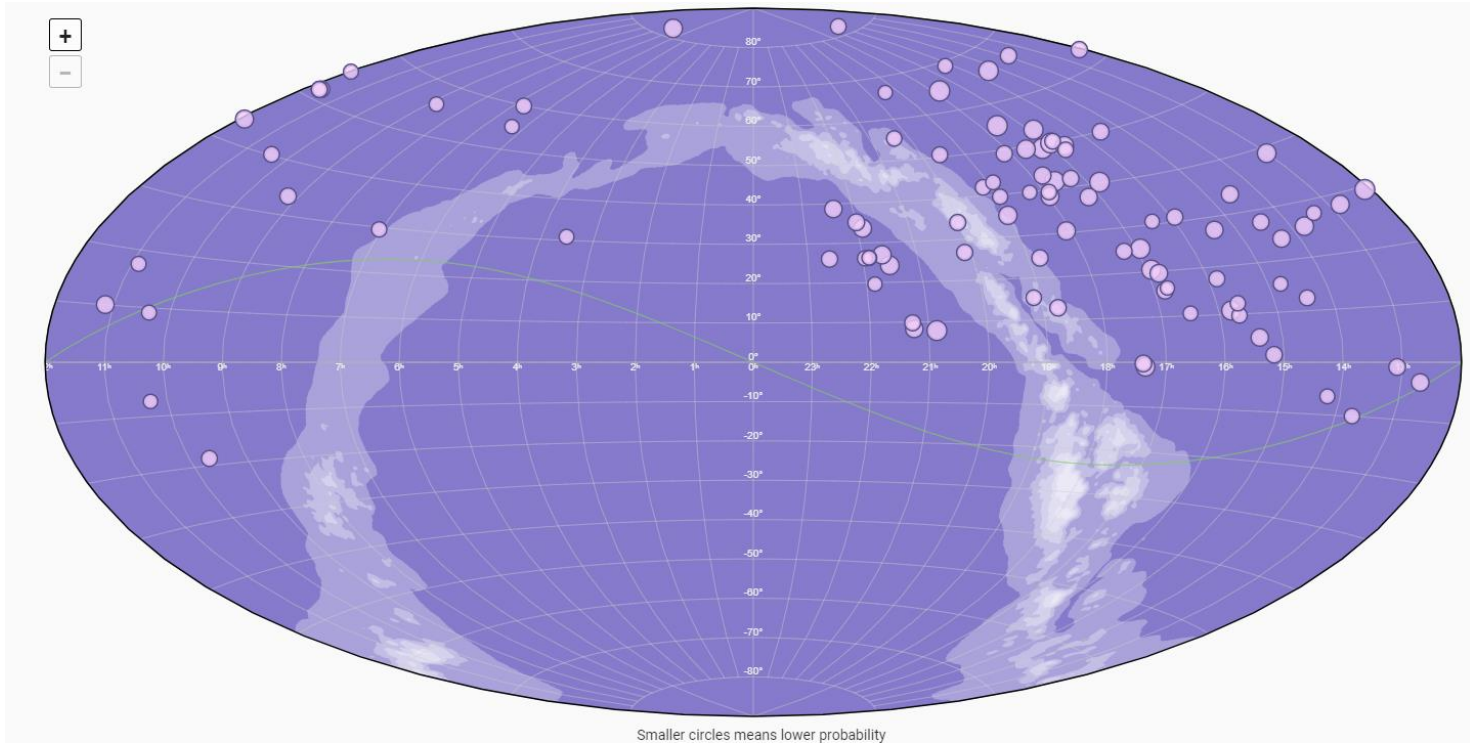
- Classification among **supernova**, **active galactic nuclei**, **variable star**, **asteroid**, and **bogus**



# Light curve classification



# ALeRCE SN Hunter



SN Candidate First Detection Information

## ZTF24aahestt

First Detection Information

RA: 236.8370589  
DEC: 10.7826494

Band: **g**

★ Mag: 19.656  
MJD: 60389.46170140011

PanSTARRS X-Match Information

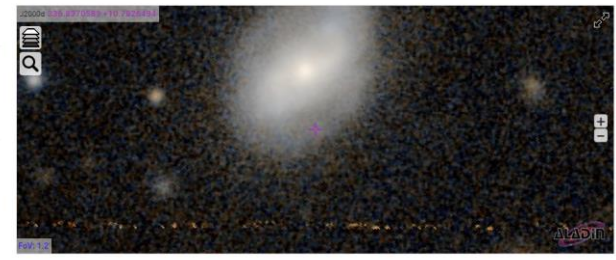
ObjectID : 120942368370561170

Distance : 4.457 arcsec

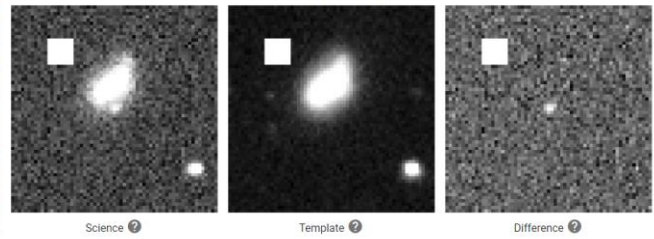
Star Galaxy Score : 0.500

- ALeRCE
- NED
- TNS
- SIMBAD

FULL ALERT INFORMATION



### Discovery Stamps

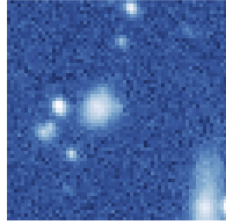


# Fink

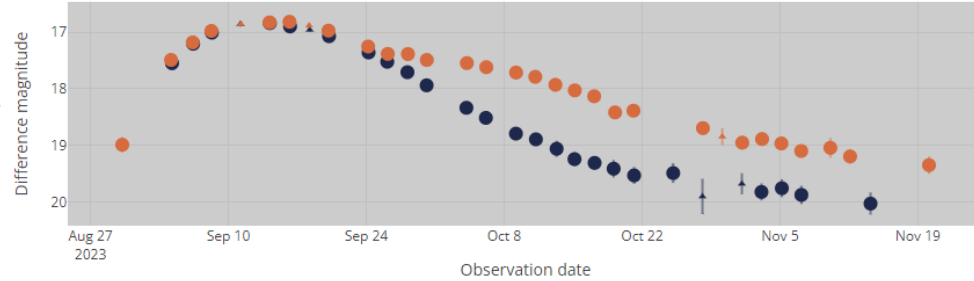


## ZTF23abanqhu

SN CANDIDATE ZTF: 5.4" PS1: 5.8" GAIA: 17.1"

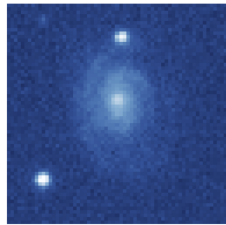


92 detection(s) in 83.9 days  
 First: 2023-08-28 06:29:20  
 Last: 2023-11-20 03:11:16  
 Equ: 20 55 33.45 +16 41 40.1  
 Gal: 63.2936 -17.9658  
 RealBogus: 0.76  
 Anomaly score: -0.38

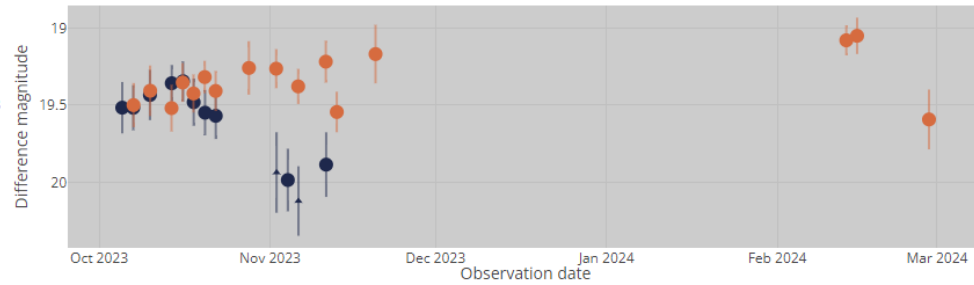


## ZTF23abiacak

UNKNOWN VSX: NAN ZTF: 2.9" PS1: 3.4" GAIA: 21.8"

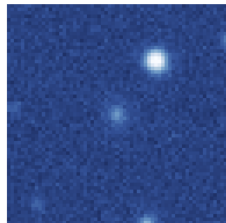


30 detection(s) in 146.3 days  
 First: 2023-10-05 04:45:43  
 Last: 2024-02-28 12:44:23  
 Equ: 18 53 36.42 +66 13 52.3  
 Gal: 96.6534 24.4508  
 RealBogus: 0.85  
 Anomaly score: -0.01

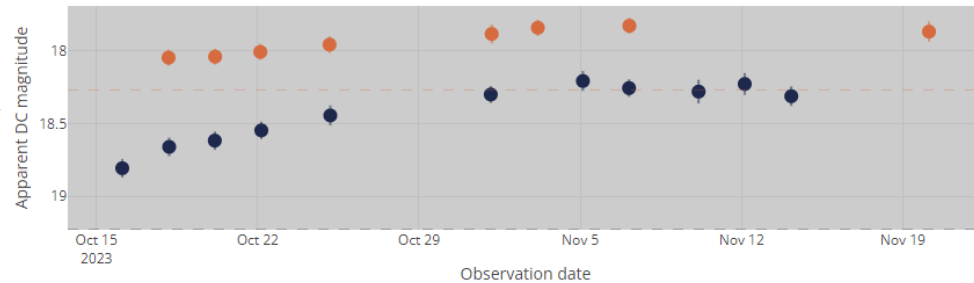


## ZTF23abkixdb

SN CANDIDATE ZTF: 0.5" PS1: 0.5" GAIA: 16.9"



23 detection(s) in 40.9 days  
 First: 2023-10-10 04:49:15  
 Last: 2023-11-20 03:19:26  
 Equ: 18 25 20.90 +30 11 21.1  
 Gal: 58.0585 18.4621  
 RealBogus: 0.64  
 Anomaly score: -0.37



# Target of opportunity observation

## Rubin ToO 2024: Envisioning the Vera C. Rubin Observatory LSST Target of Opportunity program

UC Berkeley, March 18-20, 2024

- 3% of LSST sky time (9 nights/year)
- Targets
  - Gravitational waves
  - High-energy neutrinos
  - Galactic supernovae (MeV neutrinos)
  - Solar system objects

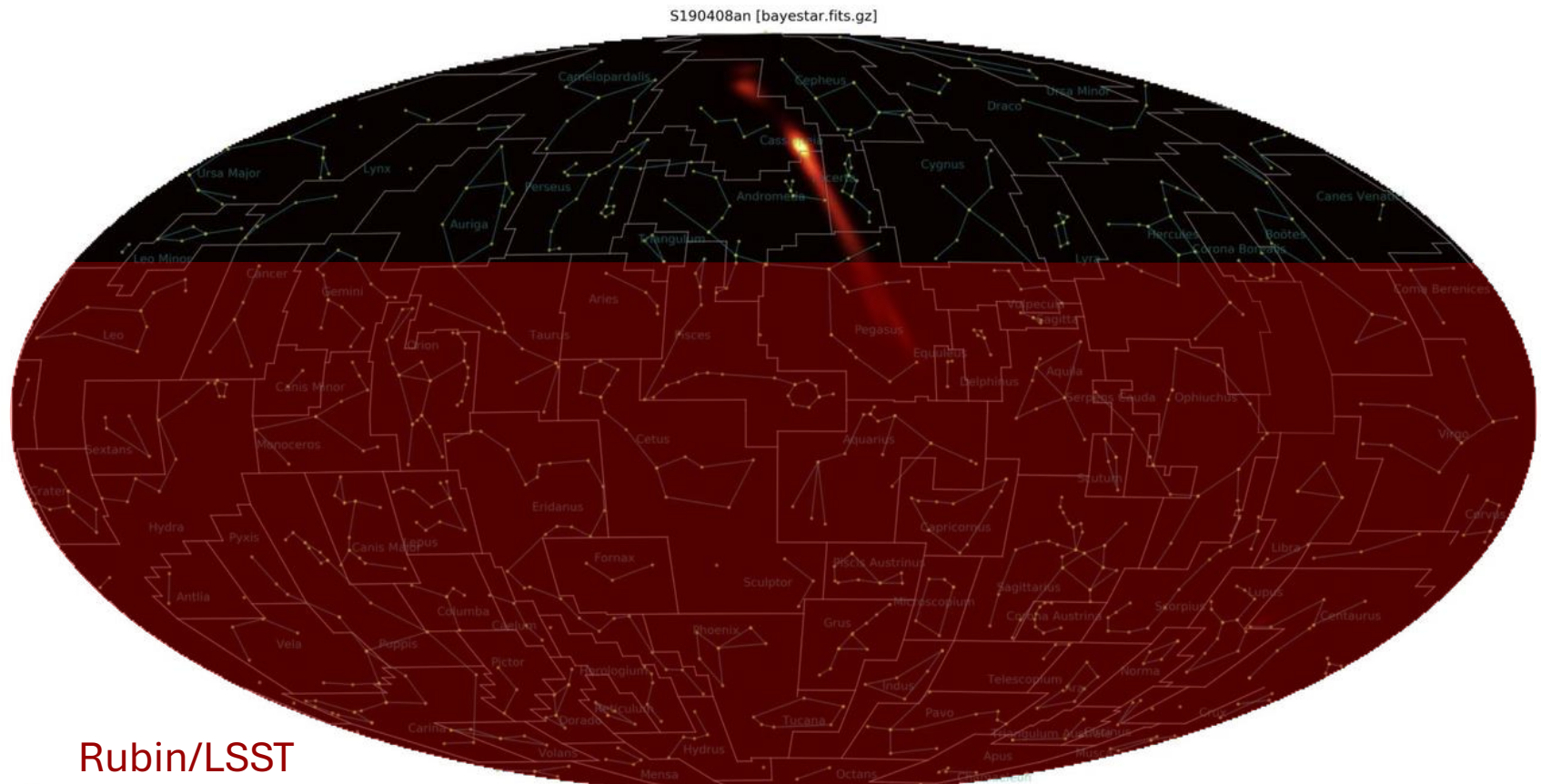
What can we do in the  
era of Rubin/LSST?

Competition or  
cooperation?

# Northern sky

## Rubin/LSST cannot reach

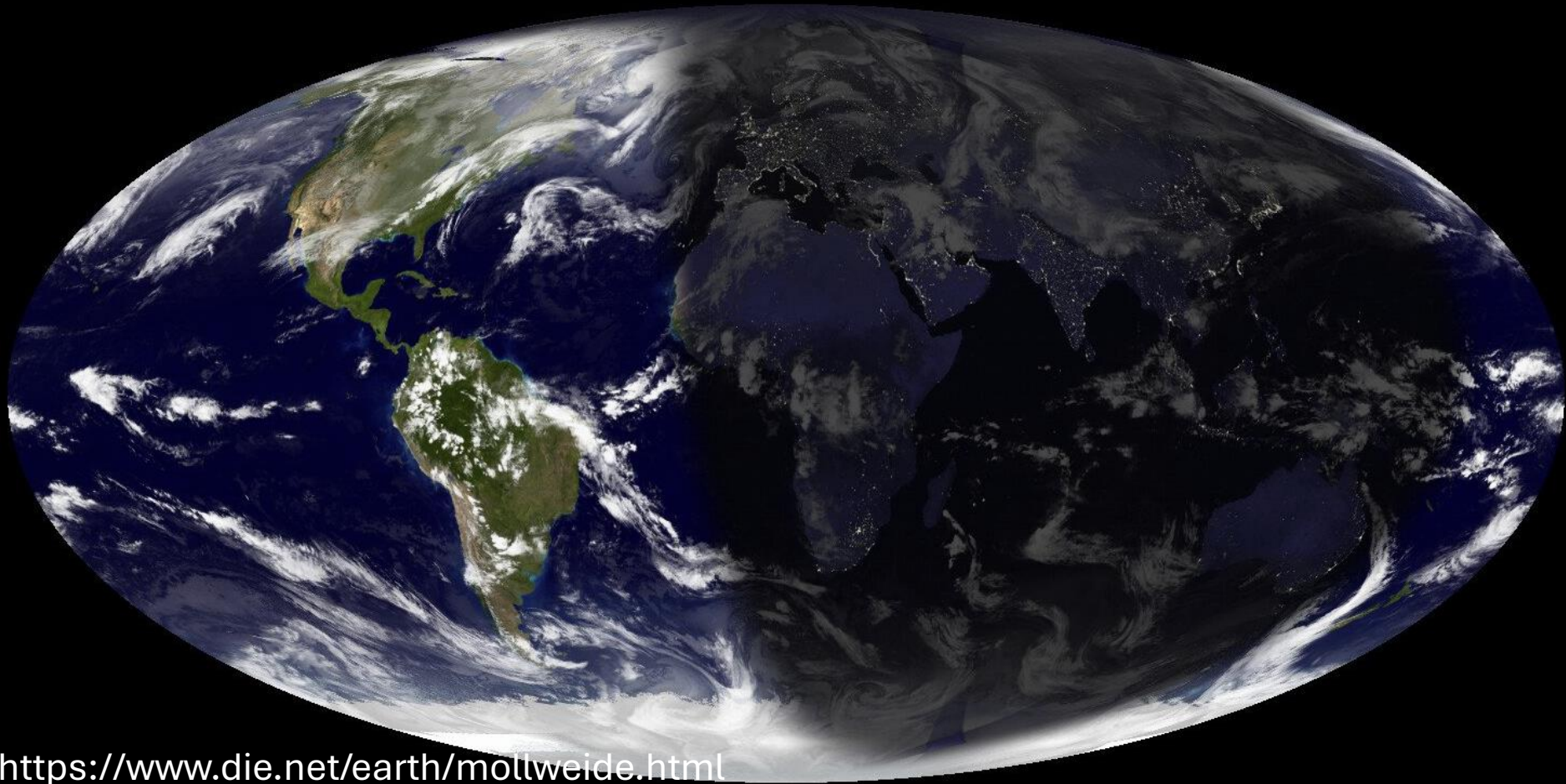
- Rare transients: MMA sources



# Time difference

## Rubin/LSST cannot observe

- Rapid transients: early SNe, intranight transients

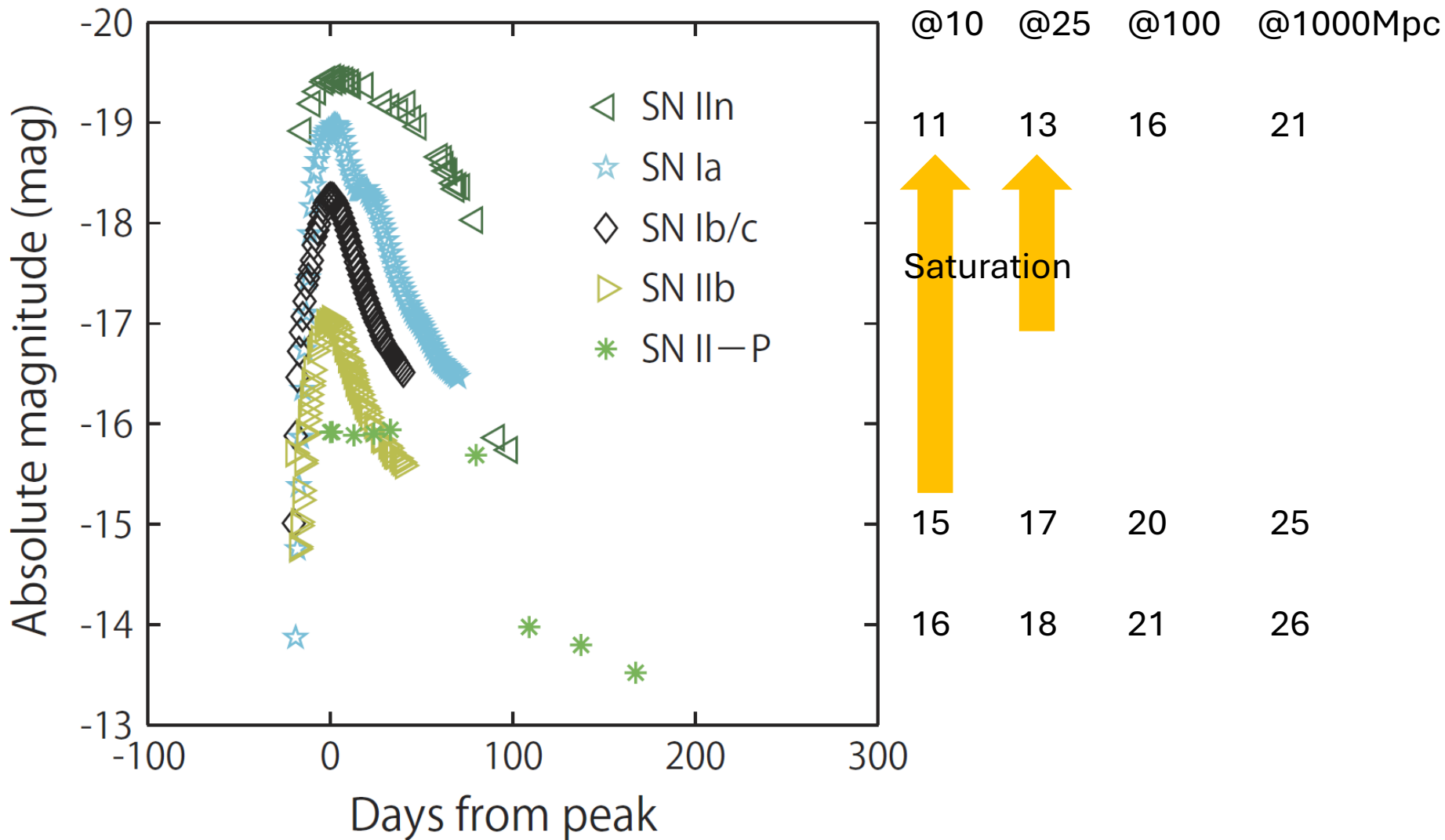


# Intranight transients

- ~1000 patterns over 10 years (g, Rubin/LSST)
  - $N A \Omega = 3 \times 10^5$  pattern deg<sup>2</sup> m<sup>2</sup> for intranight transients with a given timescale
- Tomo-e Gozen Camera
  - $A \Omega = 15.7$  deg<sup>2</sup> m<sup>2</sup>
  - $N = 2000$  pattern
  - 500 patterns will be obtained if  $10^4$ deg<sup>2</sup> (~3-4hr) is surveyed twice.

# Nearby transients

Depth (saturation, single, all)  
 u : 14.7, 23.8, 25.6 i : 15.8, 23.41, 26.4  
 g : **15.7, 24.5, 26.9** z : 15.3, 22.74, 25.6  
 r : 15.8, 24.03, 26.9 y : 13.9, 22.96, 24.8

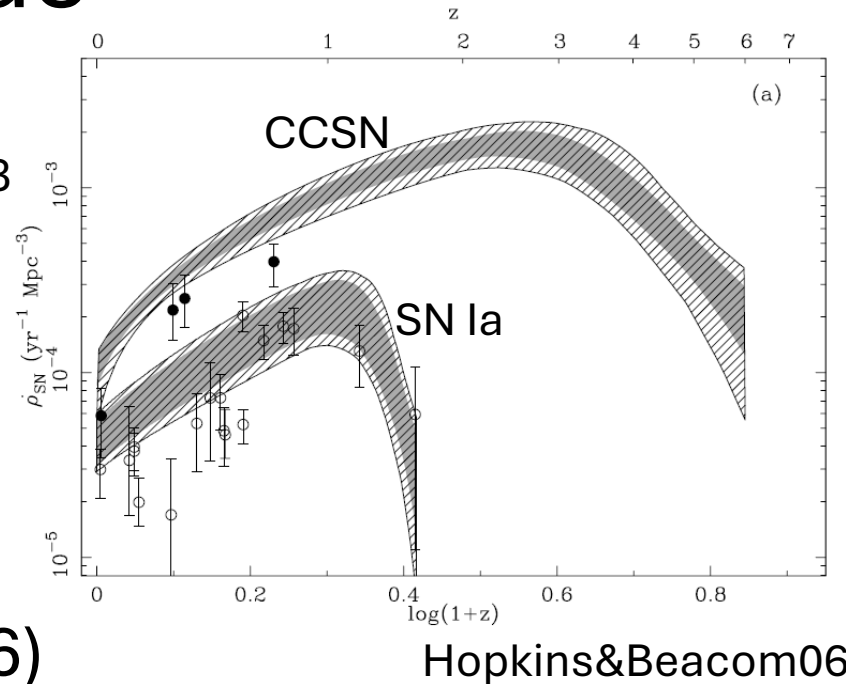


# Number of supernovae

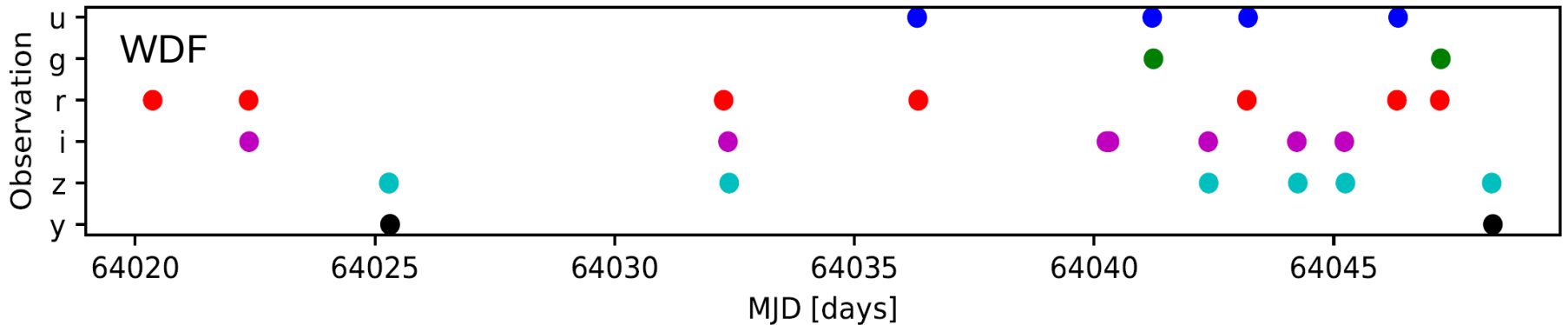
- CCSN rate:  $10^{-4}$  SN/yr/Mpc<sup>3</sup>
  - 0.5 (**0.25**) SN/yr @ <10Mpc
  - 8 (**4**) SN/yr @ <25Mpc
  - 50 (**25**) SN/yr @ <100Mpc

Detection by the Rubin/LSST

- SLSN: 0.1 % of SN (Prajs+16)
- FBOT: 0.1% of SN (Ho+23)
- GRB: 0.01% of SN (Finke+24)
  - Low-luminosity GRB: 0.1% of SN (Virgili+09)

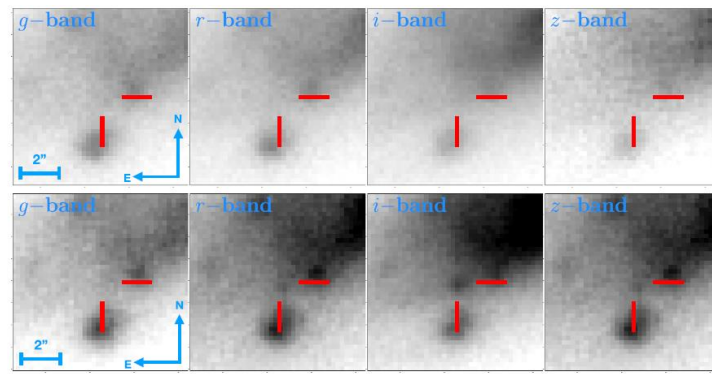


# Multi-color light curves

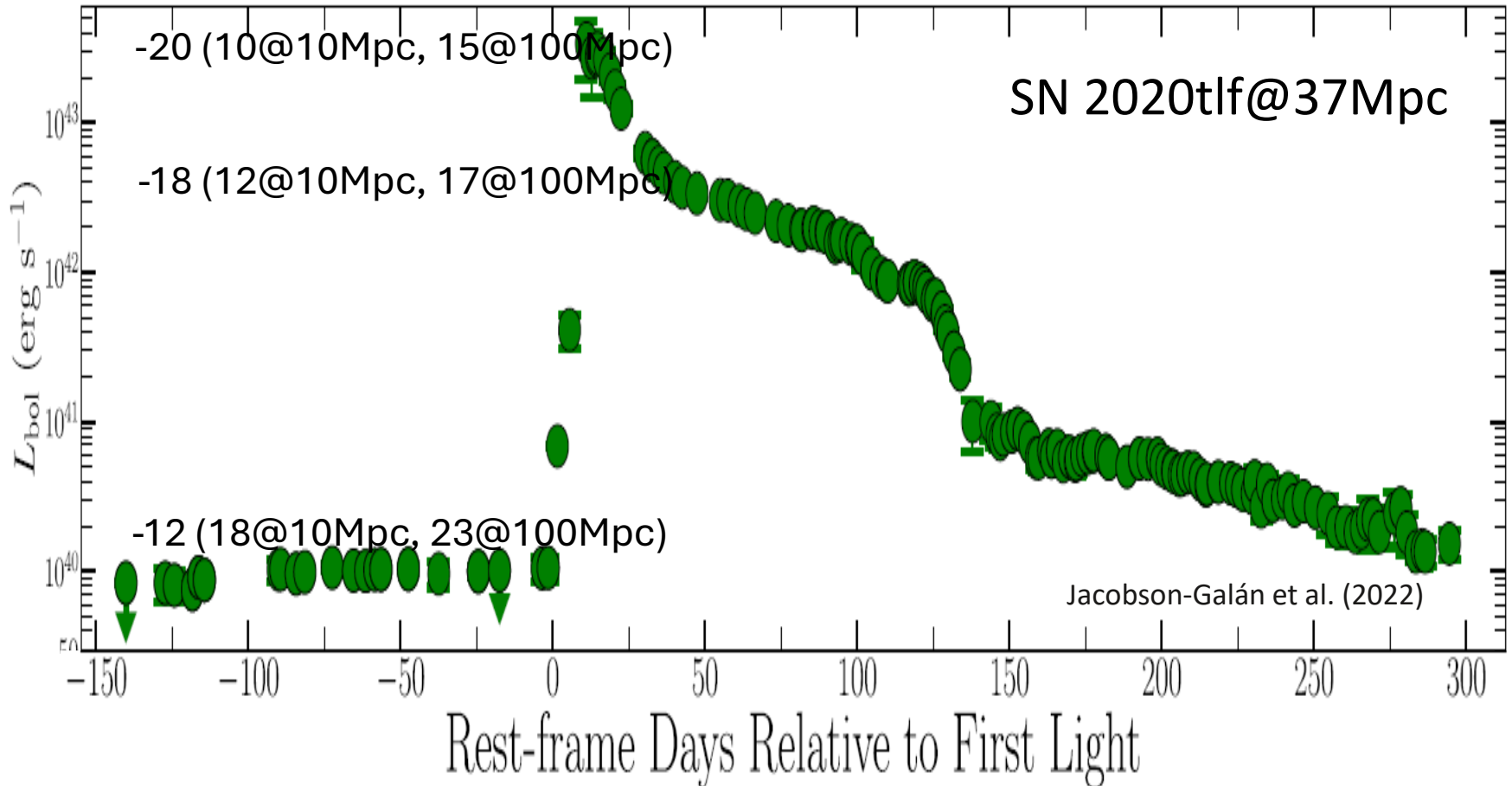


- **Multi-color light curve** data is not sufficient only with the Rubin/LSST WDF layer.
- **Multi-wavelength data** (gamma-ray, X-ray, UV, IR, radio) is not available.
- Rubin/LSST alerts of nearby transients -> **multi-color continuous/multi-wavelength follow-ups**

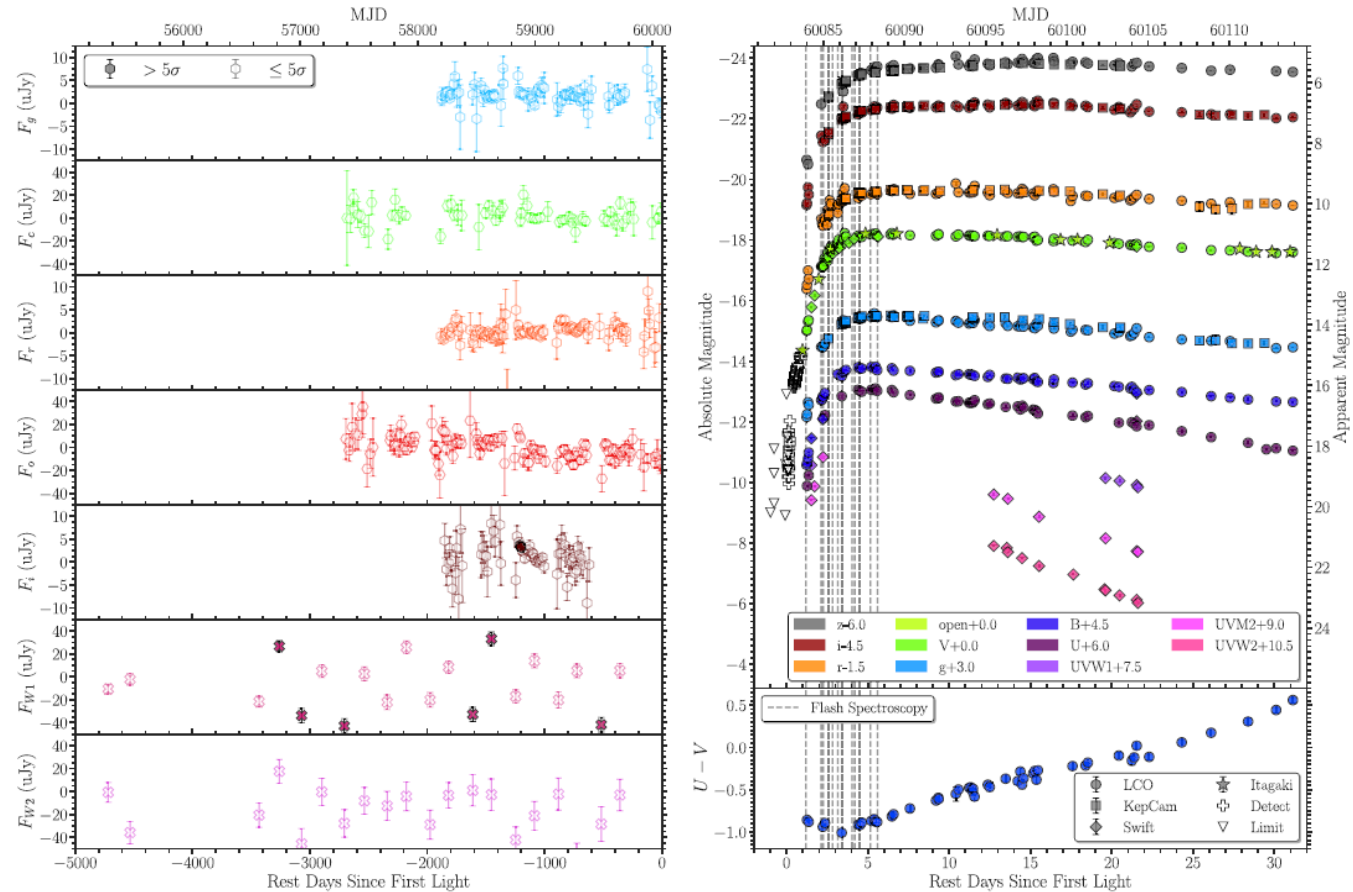
# Progenitor



- Red supergiants:  $M_{\text{bol}} \sim -5$  (25 @10Mpc)



# Variability of progenitor SN2023ixf



Hiramatsu+23; Kilpatrick+23; Soraisam+23; Jencson+23

- (Multi-wavelength) detection -> **archive search** and forced photometry of the Rubin/LSST data

# Science platform



## Large file servers

Data taken with HSC, PFS, Next generation large surveys

## Rapid database

Multi-wavelength database  
Multi-color photometry

Time-series database  
Time-domain information

Search query

Rapid data retrieve

## Science platform

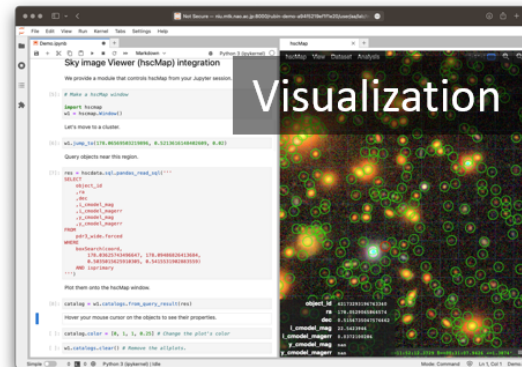
### Sufficient environment

- Rapid access to database and images
- High computing power
- Flexible interface

Science-ready data

## Optimized tools

### Visualization tool



### Data analysis tool

- Physical parameters of transients
- Identification of distant transients
- Discoveries of unknown unknowns



Researchers

基盤研究 (S) 次世代大規模探査を用いた突発天体観測で明らかにする宇宙の進化 (FY2024-2028)

# Summary

- Rubin/LSST will come soon (Nov-Dec 2025).
  - Saturation: 15.5; Single depth: 24; Full depth: 26.5
  - $>10^4$  patterns of daily intervals (1-60days)
  - $\sim 10^3$ (g)- $\sim 10^4$ (riz) patterns of hourly intervals (<5hr)
  - ToO observation (9 nights/year)
  - Alerts will be sent in 60sec after the exposure.
- What can we do in the Rubin/LSST era?
  - Northern sky: rare transients, MMA sources
  - Time difference: rapid transients, early SN, intranight transients
  - Nearby transients
    - Rubin/LSST alerts -> Multi-color continuous/multi-wavelength follow-ups
    - (Multi-wavelength) detection -> Archive search and forced photometry
- Science platform