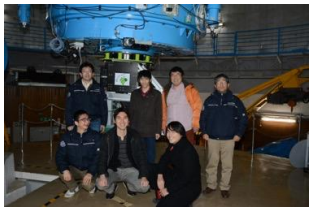
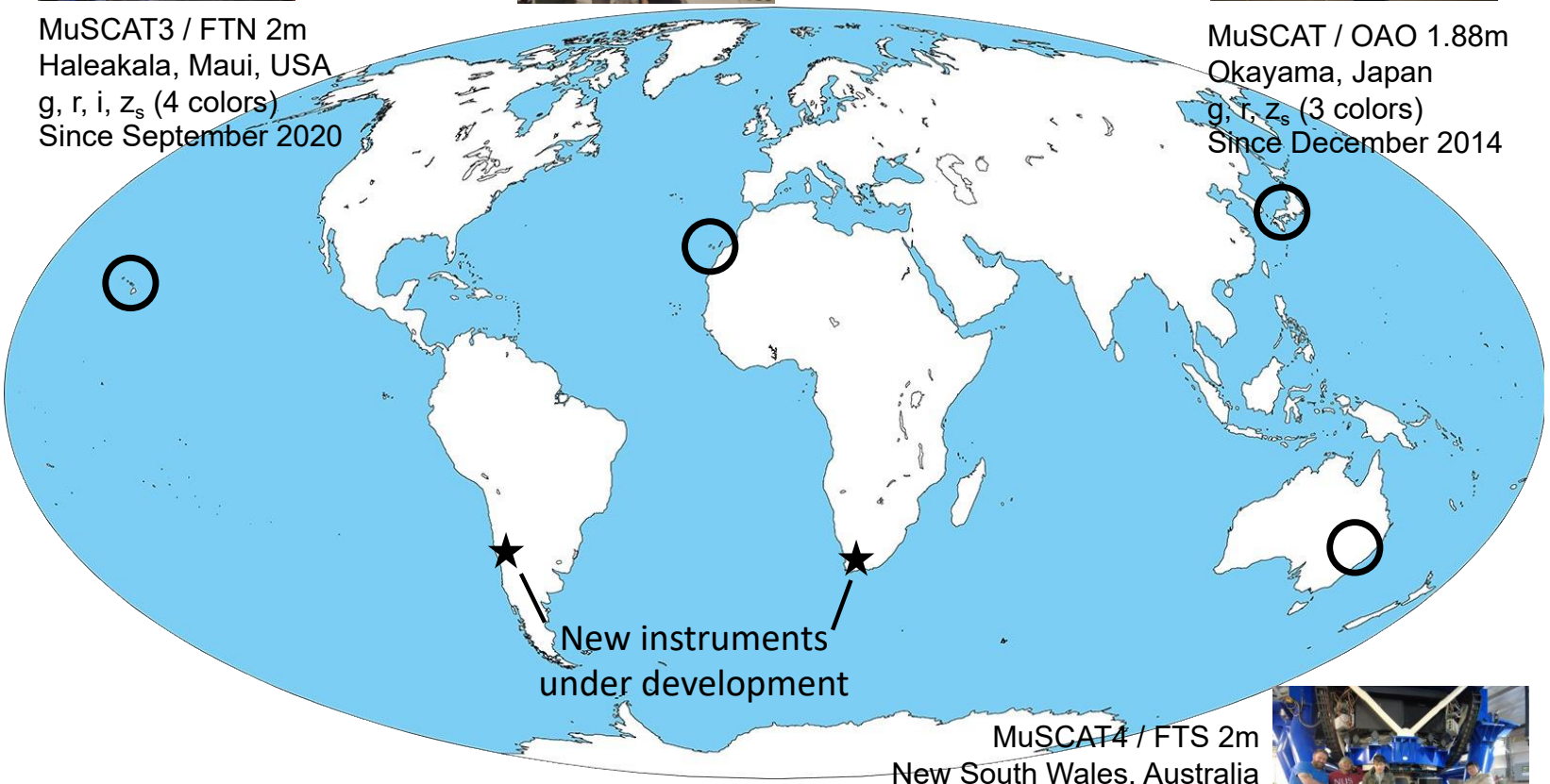
MuSCATシリーズとLCO1m望遠鏡による トランジット惑星系の観測

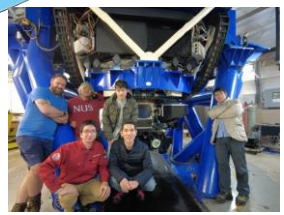
MuSCAT3 / FTN 2m
Haleakala, Maui, USA
g, r, i, z_s (4 colors)
Since September 2020

MuSCAT2 / TCS 1.52m
Teide, Tenerife, Spain
g, r, i, z_s (4 colors)
Since August 2017



MuSCAT / OAO 1.88m
Okayama, Japan
g, r, z_s (3 colors)
Since December 2014





MuSCAT4 / FTS 2m
New South Wales, Australia
g, r, i, z_s (4 colors)
Since October 2023

成田憲保（東京大学）

TESS Mission Overview

- TESS is the flagship survey mission for transiting exoplanets, proposed in 2011, approved in 2013, and launched in 2018
- All-sky survey of transiting exoplanets around nearby stars
- 2+ year observation with 4 cameras (10cm diameter) each having 24° x 24° FoV

- Currently 8th year observation is ongoing

False Positives in TESS Candidate Planets

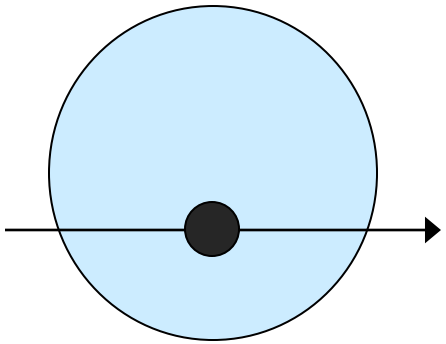
- TESS's camera has very wide field of view
  - The pixel scale is very large (21 arcsec/pixel)

- Many candidates of transiting planets are discovered by periodic dimming, but they include many false positives due to eclipsing binaries

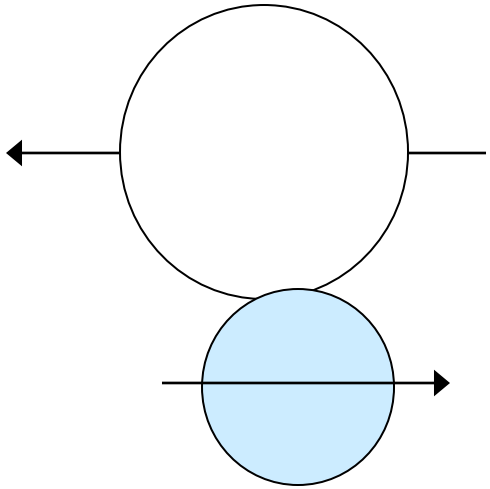
- How can we discriminate true transiting planets with eclipsing binaries?

Transiting Planets and False Positives

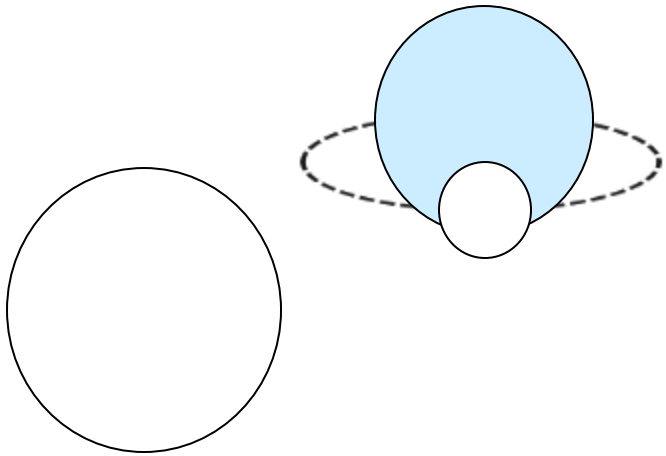
Eclipsing binaries may mimic transit-like dimming



transiting planet



grazing eclipsing binary



background/hierarchical
eclipsing binary

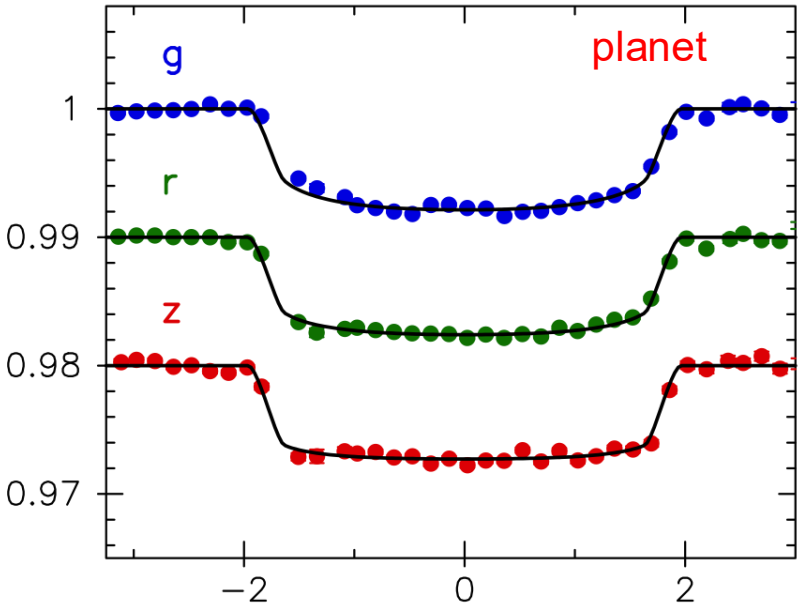
Validation/Confirmation methods

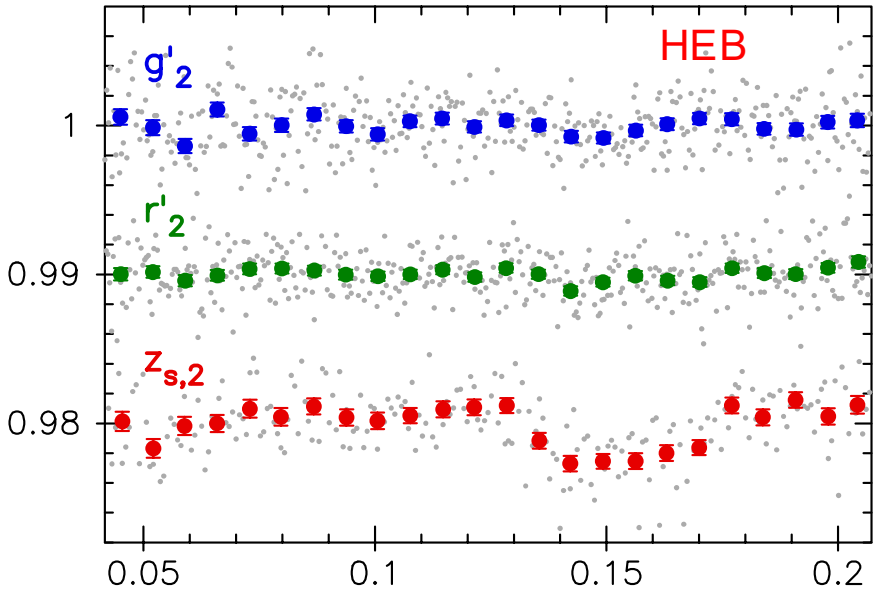
Multi-color transit photometry to see wavelength dependence

AO/speckle imaging to exclude contamination

Recon spectroscopy and RV measurements

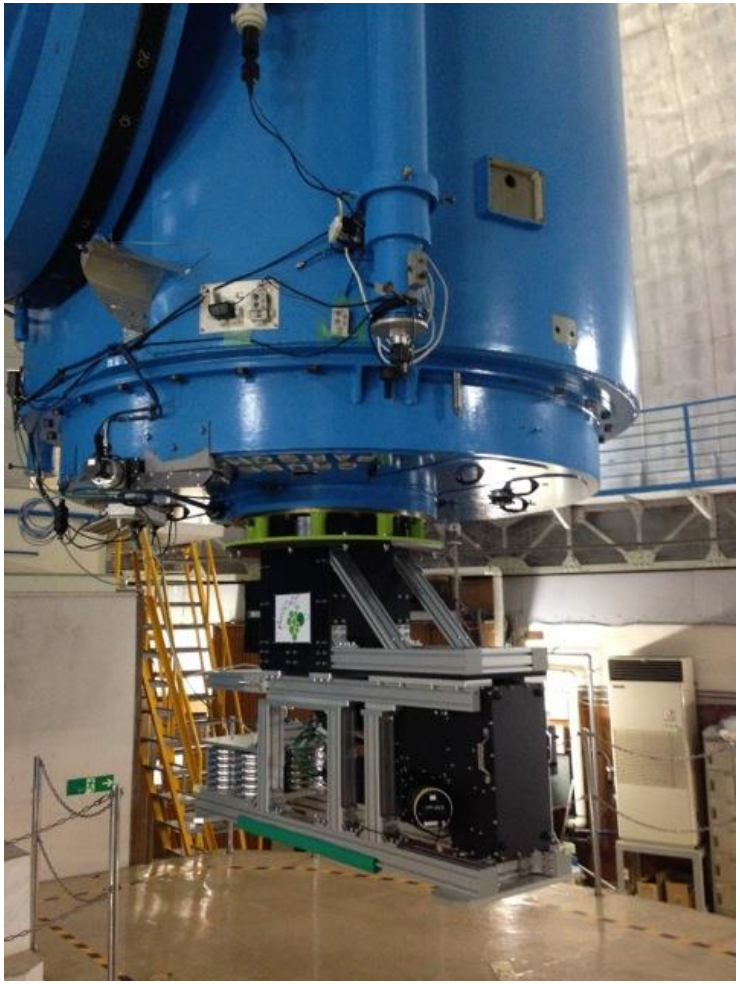
Discriminating between true planets and false positives





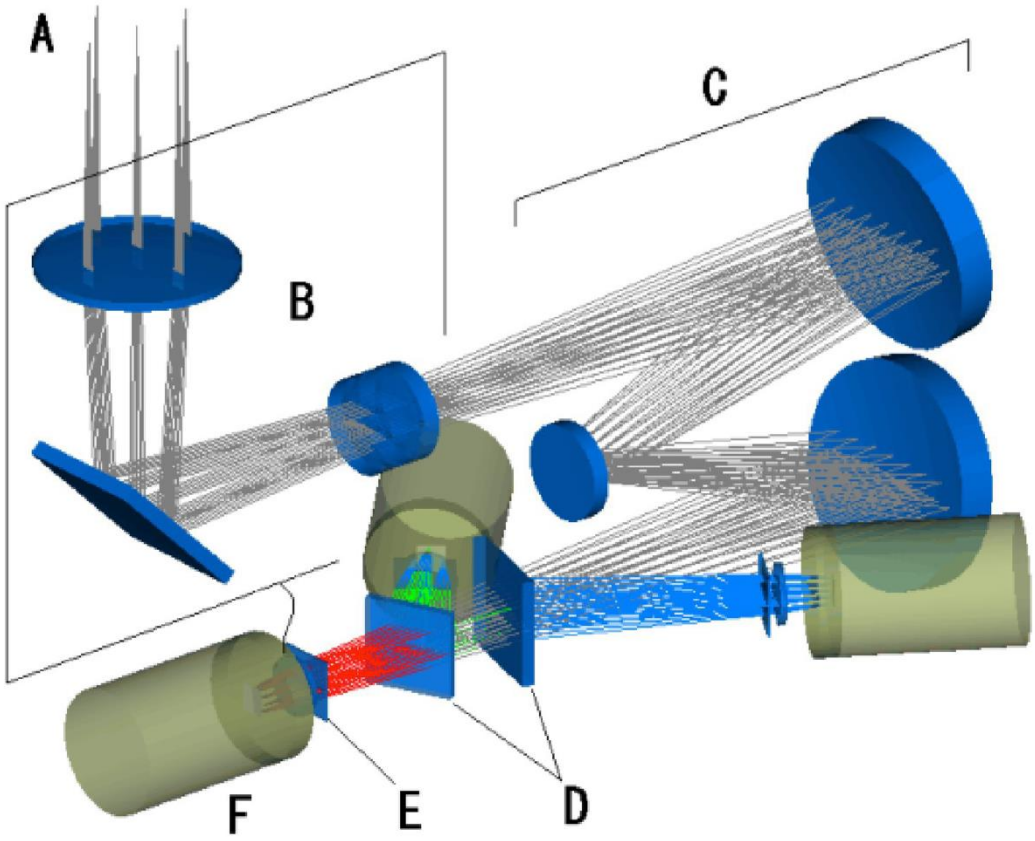
Multicolor simultaneous cameras can discriminate between true planets and false positives from a single follow-up transit observation

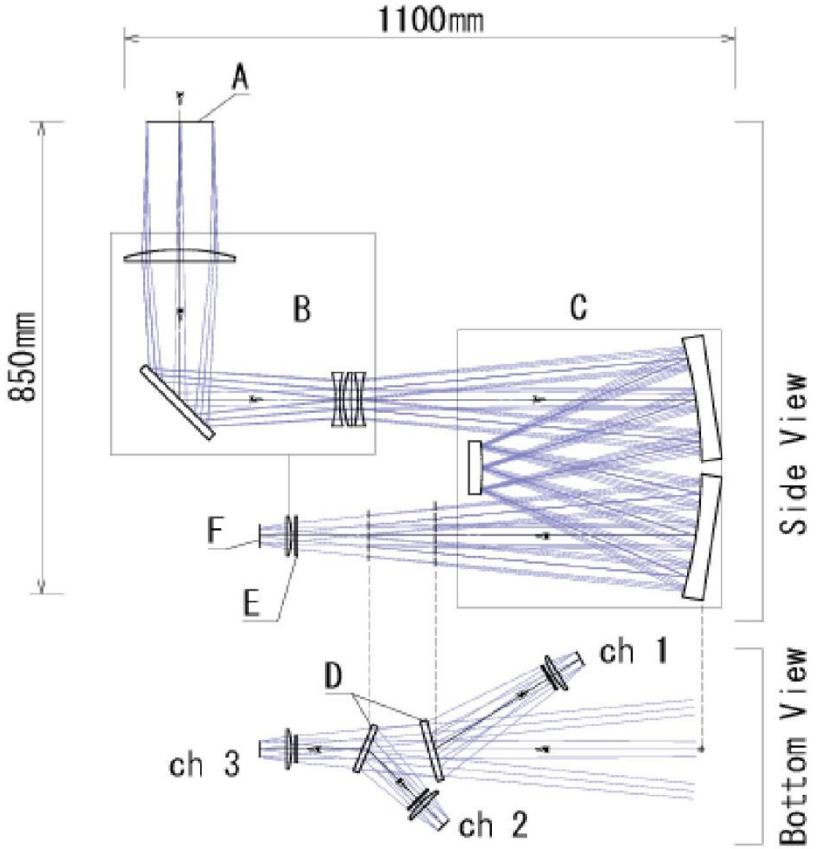
MuSCAT on Okayama 1.88m telescope



- Multicolor Simultaneous Camera for studying Atmospheres of Transiting exoplanets (MuSCAT)
- Development started since 2013, first light commissioning was done on the night of Dec 24, 2014
- Blue (g: 400-550nm)、red (r: 550-700nm)、NIR (z_s: 820-920nm) simultaneous imaging

Optical Design

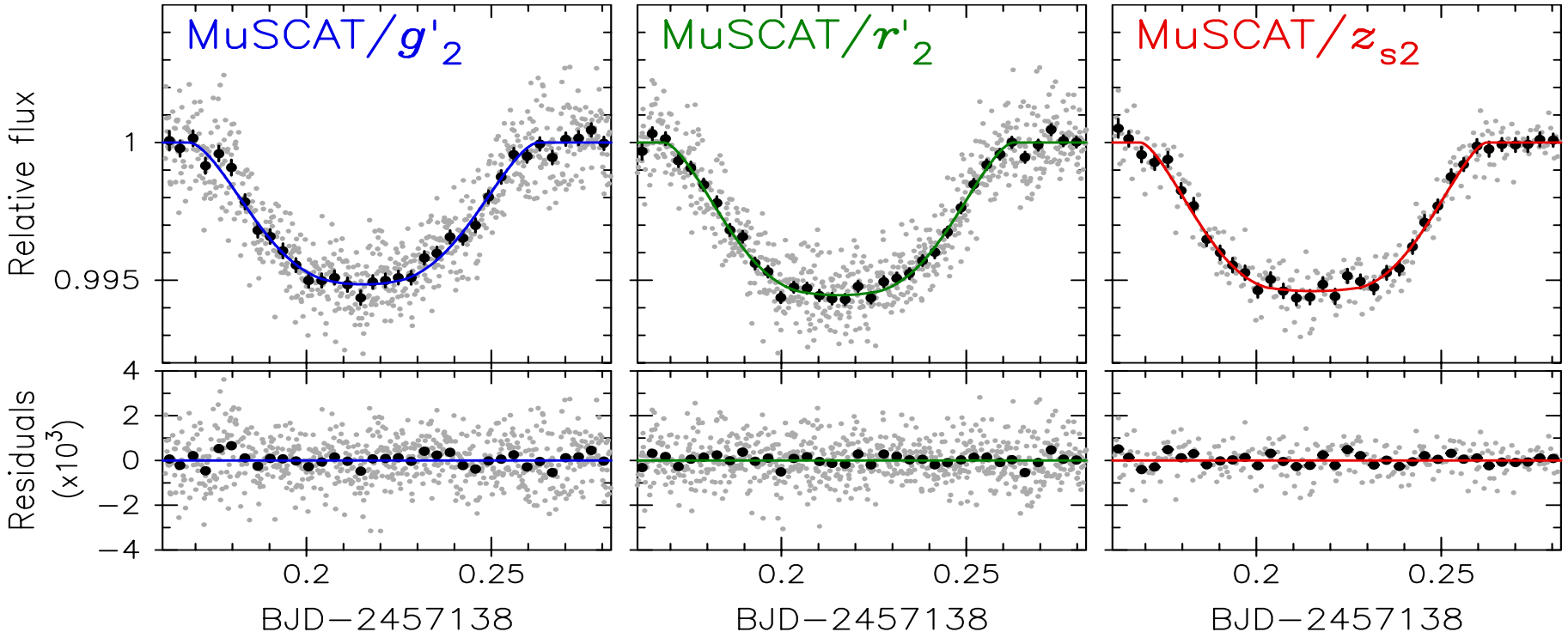




Narita et al. (2015)

Demonstration of Precision: MuSCAT

Case for HAT-P-14 (F star, V=10) : Fukui et al. (2016a)



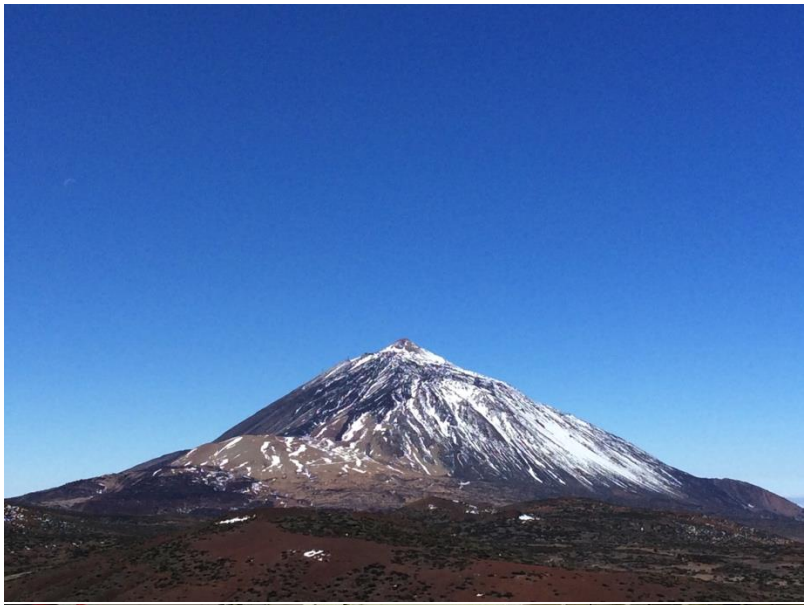
RMS(10s) = 0.10 %
RMS(1min) = **0.045 %**

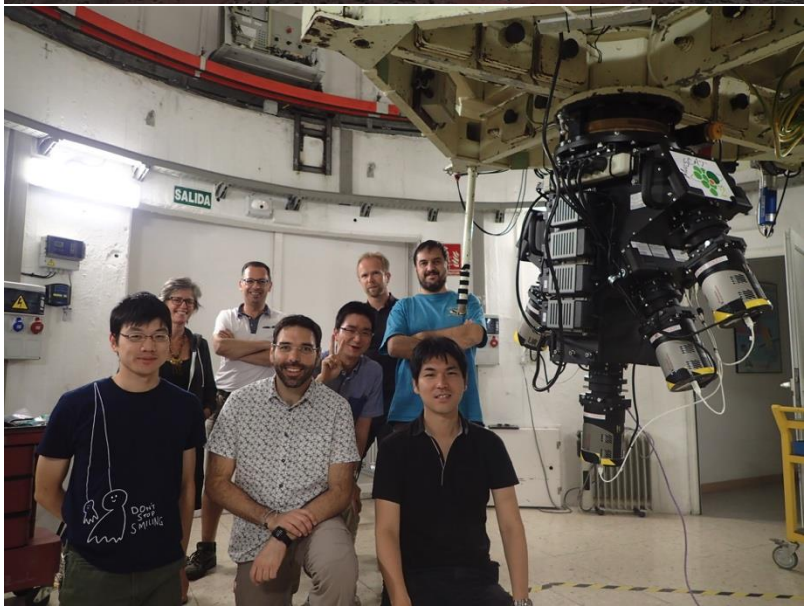
RMS(10s) = 0.091 %
RMS(1min) = **0.041 %**

RMS(30s) = 0.068 %
RMS(1min) = **0.048 %**

MuSCAT can achieve ~0.05% precision for 10th mag targets in 60 sec exposure

MuSCAT2 on TCS 1.52m@IAC

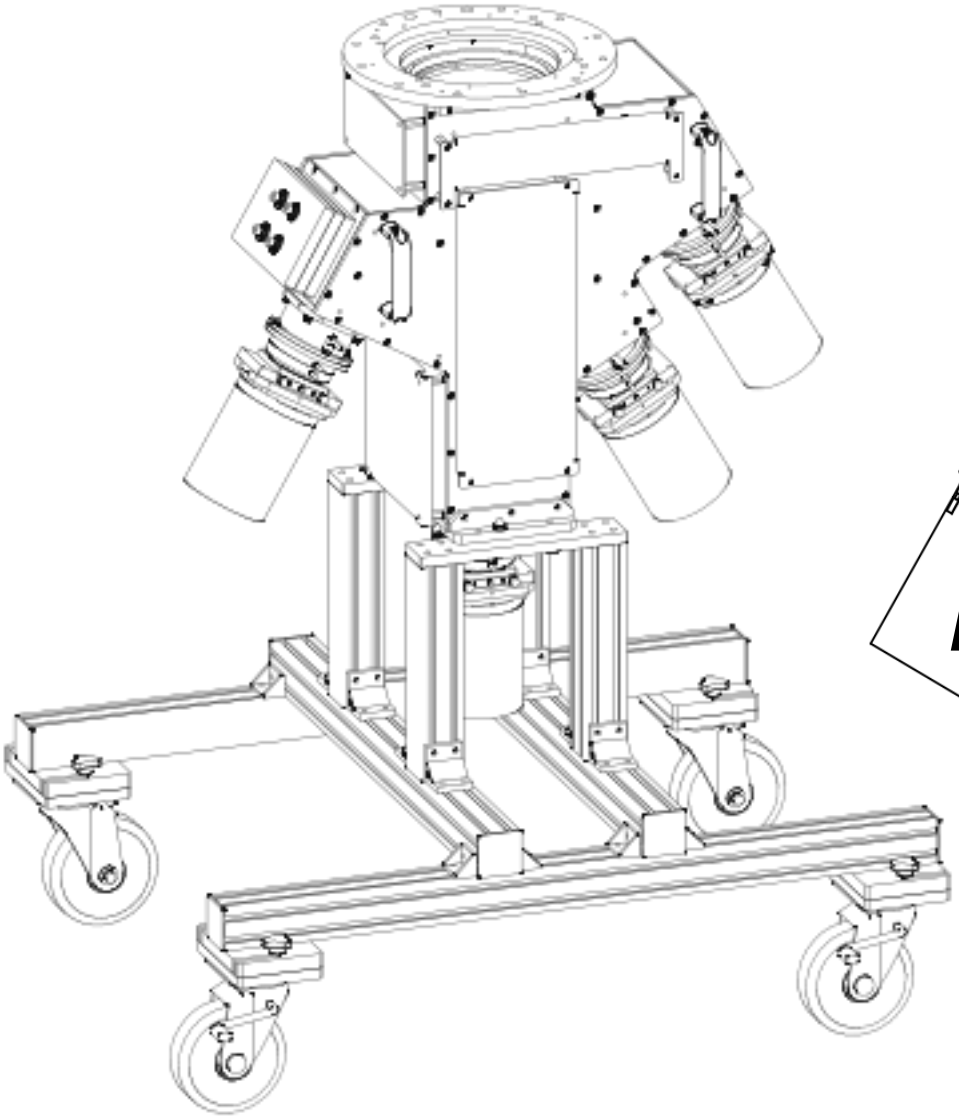


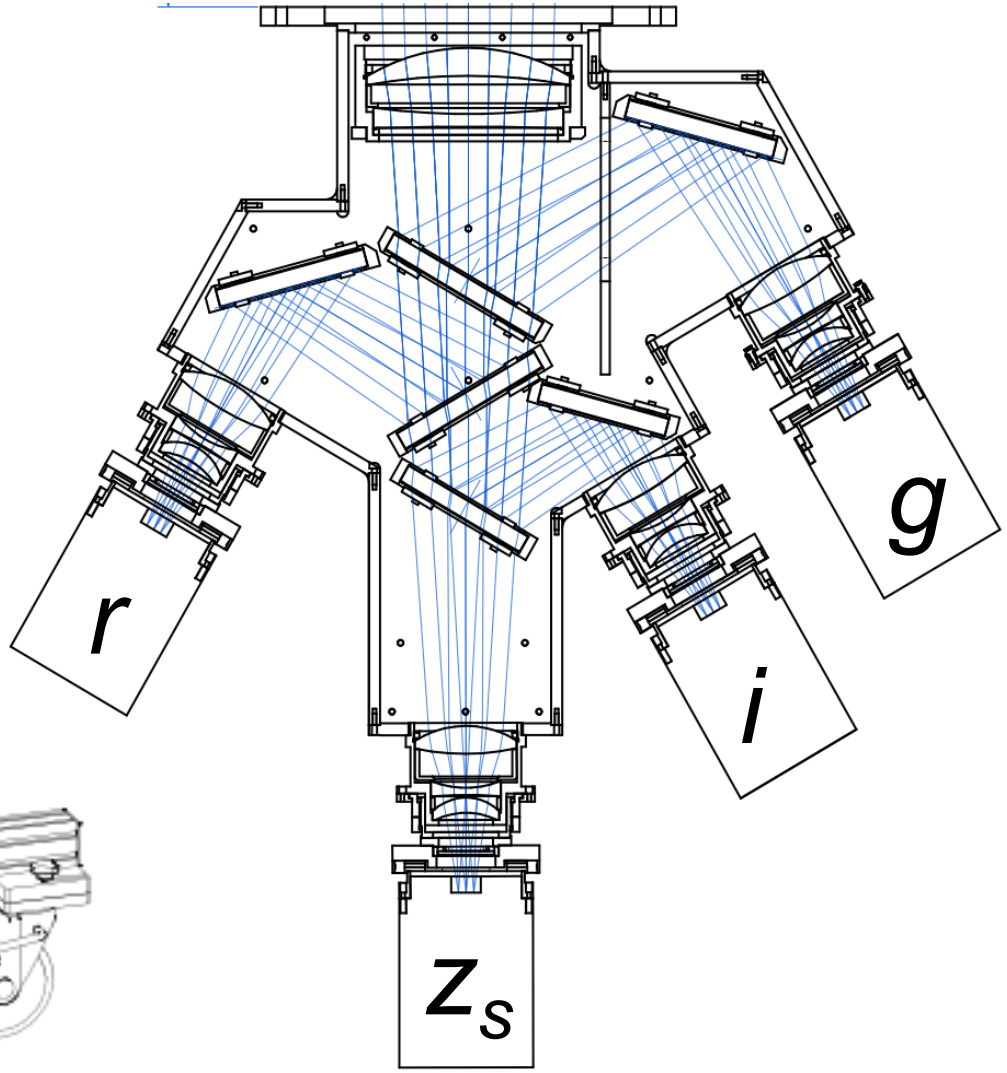


TCS 1.52m telescope
Teide observatory, Tenerife, Spain
28º 18' 01.8" N, 16º 30' 39,2" W
2386.75m
middel of Mount Teide (3718m)

First light on August 24, 2017

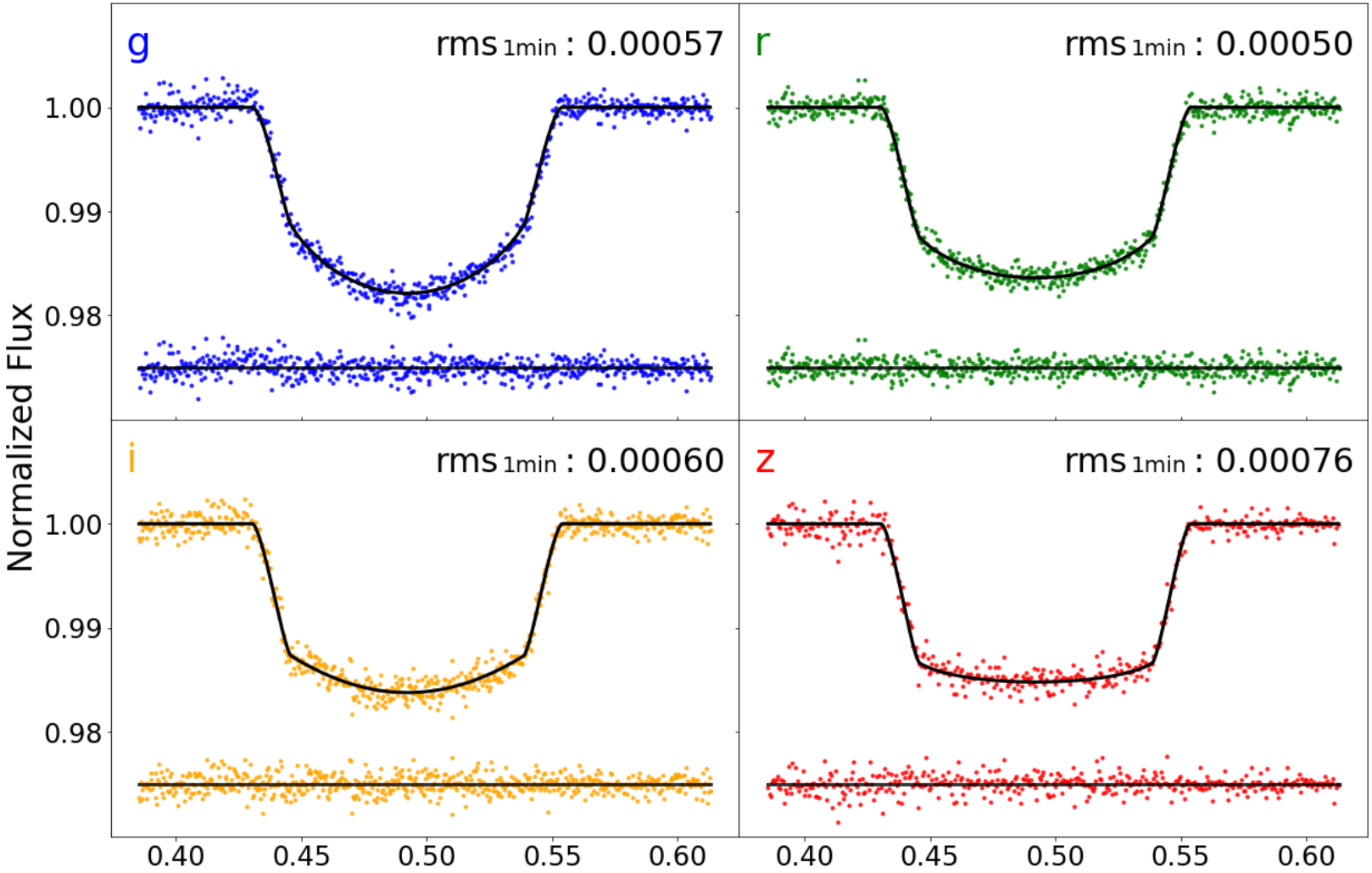
Designs of MuSCAT2





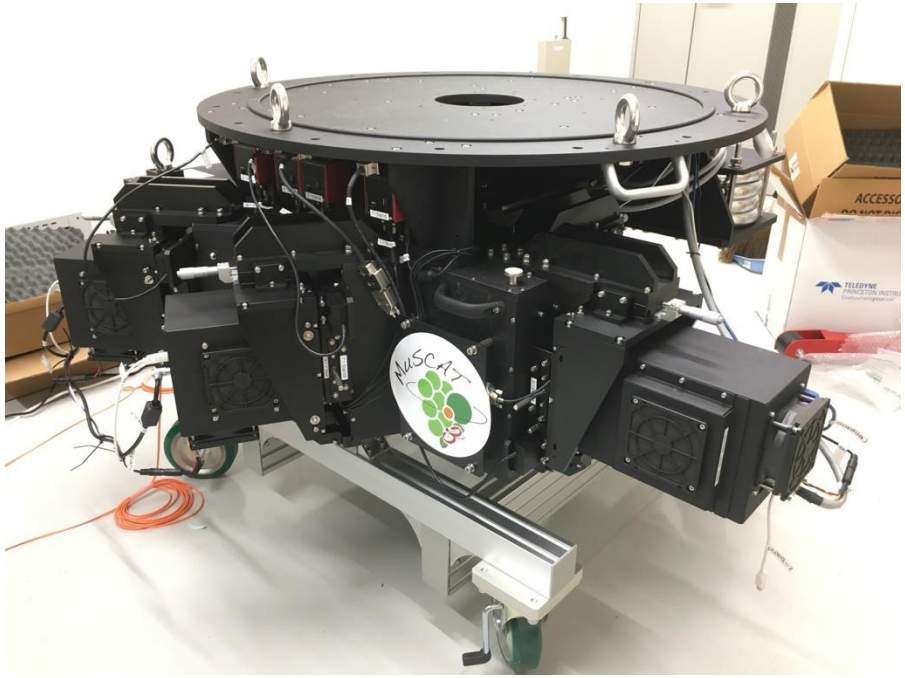
Performance of MuSCAT2: Case for WASP-12b

Achieving < 0.1% photometric precision in 4 colors simultaneously



Narita et al. (2019)

MuSCAT3 on FTN 2m@LCO



2m Faulkes Telescope North

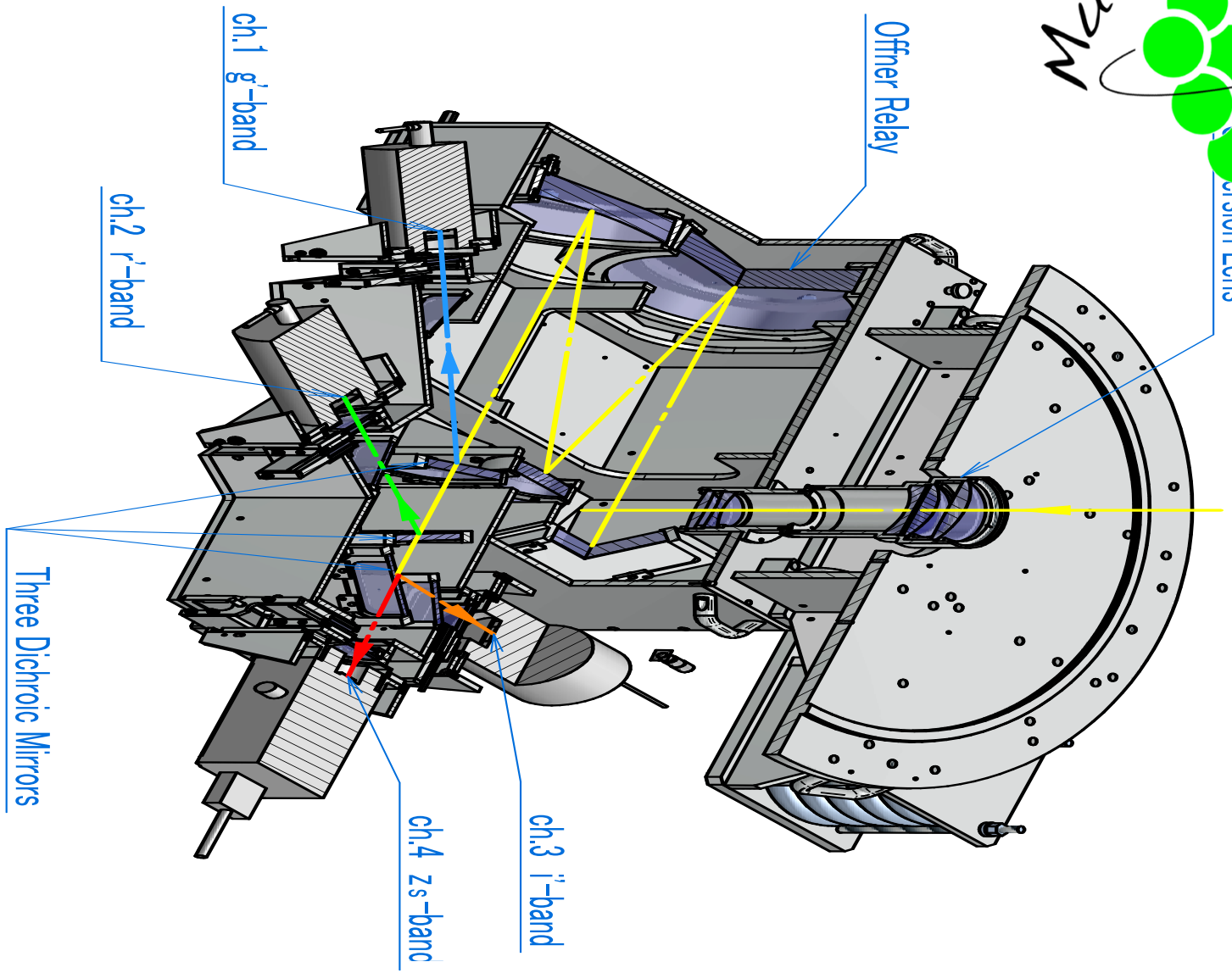
(operated by Las Cumbres Observatory)

Haleakala, Maui, USA

20º 42’ 27.0“ N, 156º 15’ 21.6” W

at the top of Haleakala (3,055m)

Design of MuSCAT3



Narita et al. (2020)

MuSCATs network for efficient planet validation

MuSCAT3 / FTN 2m
Haleakala, Maui, USA
g, r, i, z_s (4 color)
Since September 2020

MuSCAT2 / TCS 1.52m
Teide, Tenerife, Spain
g, r, i, z_s (4 color)
Since August 2017

MuSCAT / OAO 1.88m
Okayama, Japan
g, r, z_s (3 color)
Since December 2014

From MuSCAT3 to MuSCAT4

LCO got a grant from Heising-Simons Foundation, USA, to develop a copy of MuSCAT3 to the twin 2m telescope in Australia in 2022

HEISING-SIMONS FOUNDATION

Las Cumbres Observatory Global Telescope Network Inc.

to fabricate, install, and commission the MuSCAT4 imager on the Faulkes South Telescope

- **PROGRAM**: Science
- **GRANT TYPE**: Grant
- **GRANT AMOUNT**: $1,597,269
- **YEAR GRANTED**: 2022

From website of Heising-Simons Foundation

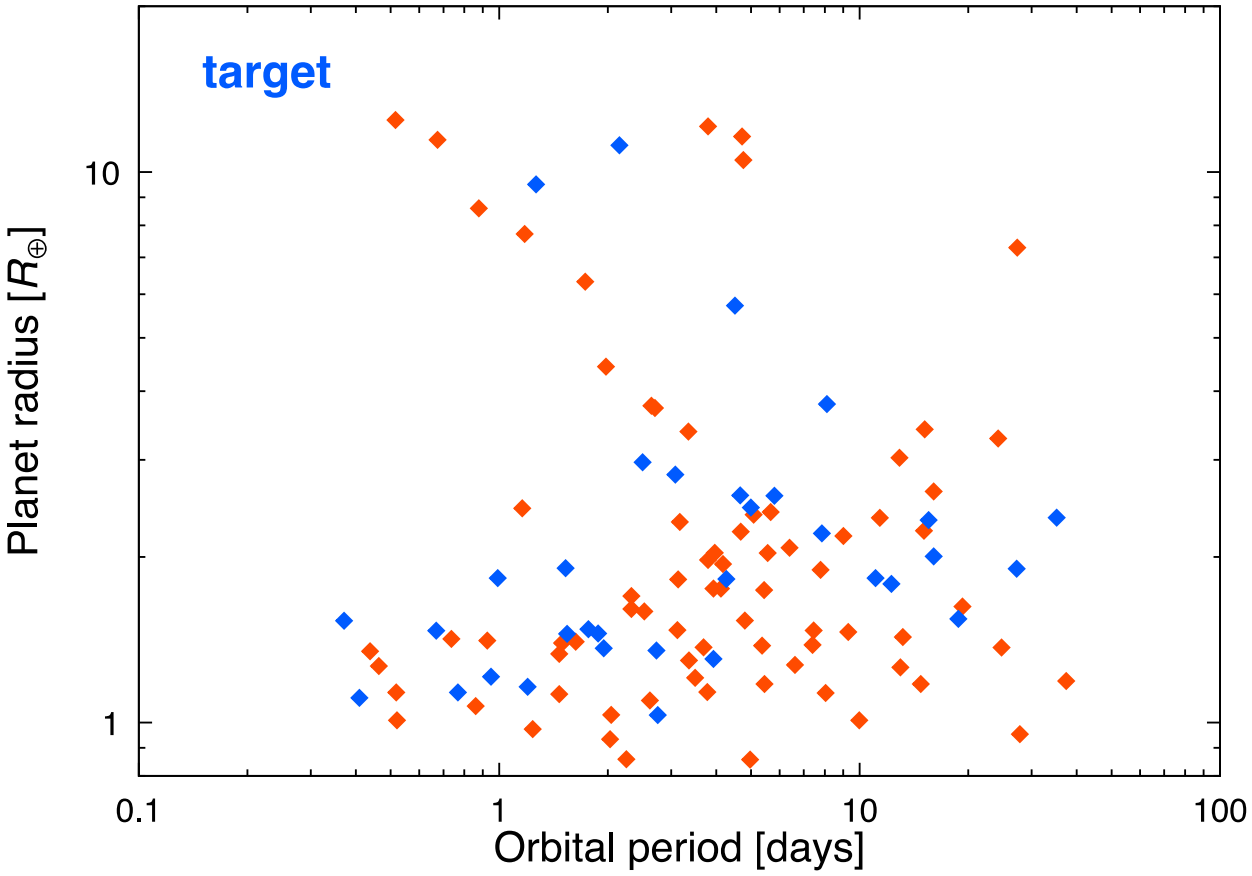
MuSCAT4 on FTS 2m@Siding Spring, Australia

We can now access southern sky

TESS candidate planets (TOIs) around stars T_{eff} < 3500K

TESS has discovered 100+ TOIs as of April 2021

50+ TOIs are observable from Maunakea with >40 deg elevation

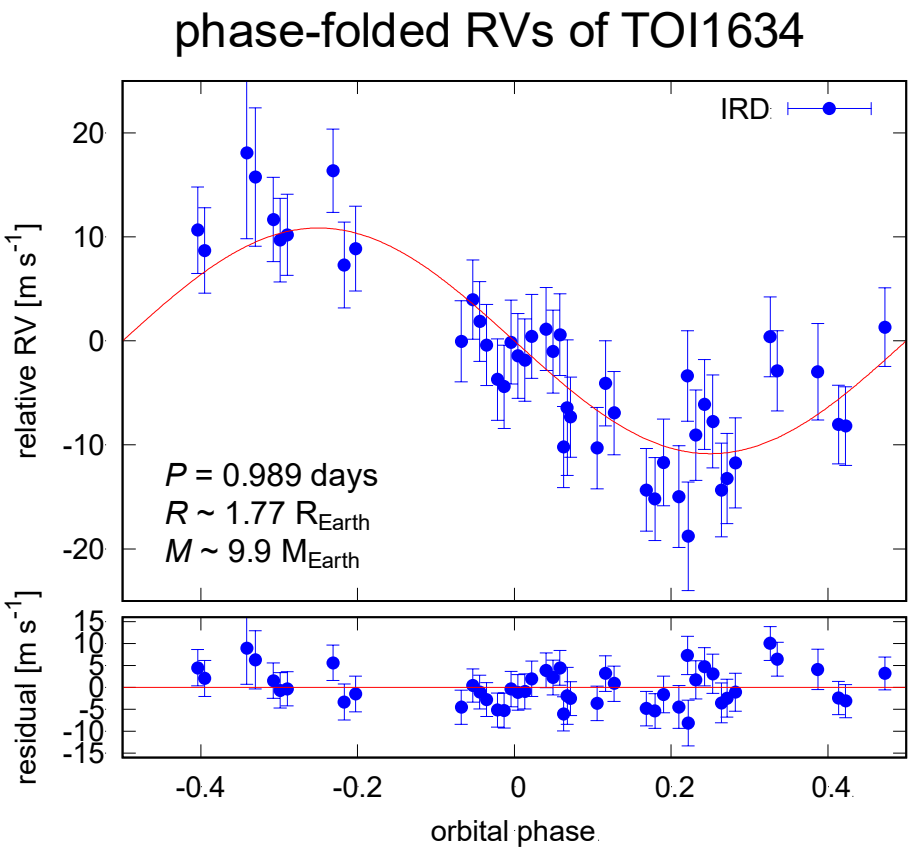


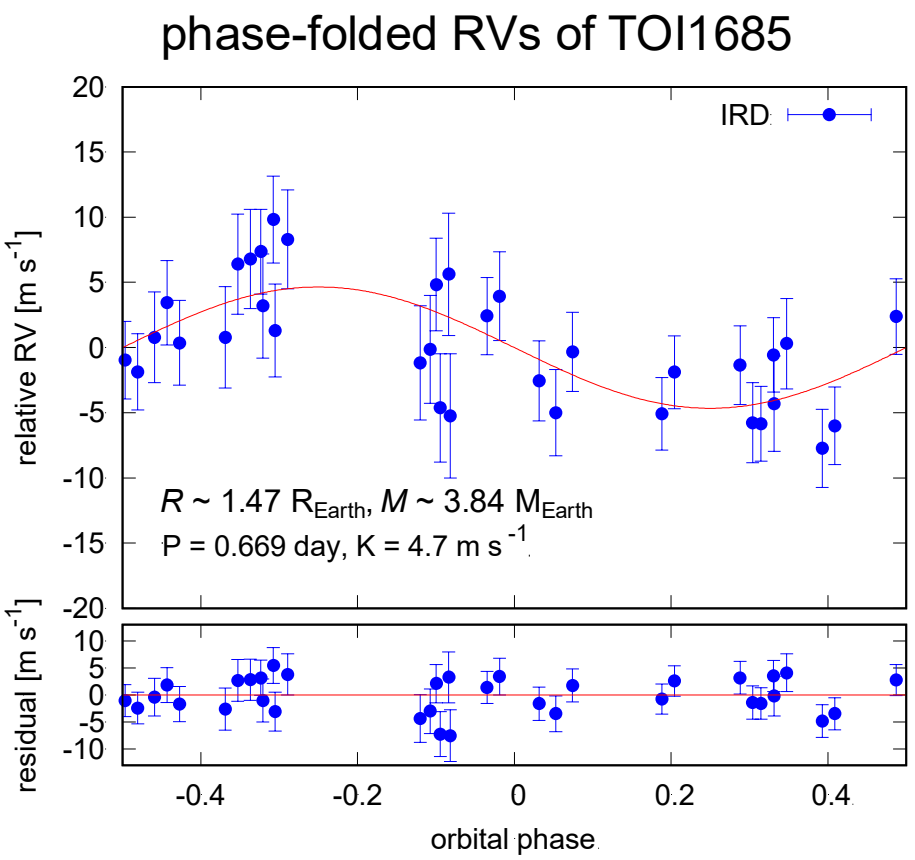
We have validated over 50 TOIs with the MuSCAT series,

and selected ~30 TOIs for further follow-up with Subaru IRD

Masses of ultra-short-period planets (USPs)

IRD measured the masses of 2 USPs validated by the MuSCAT series

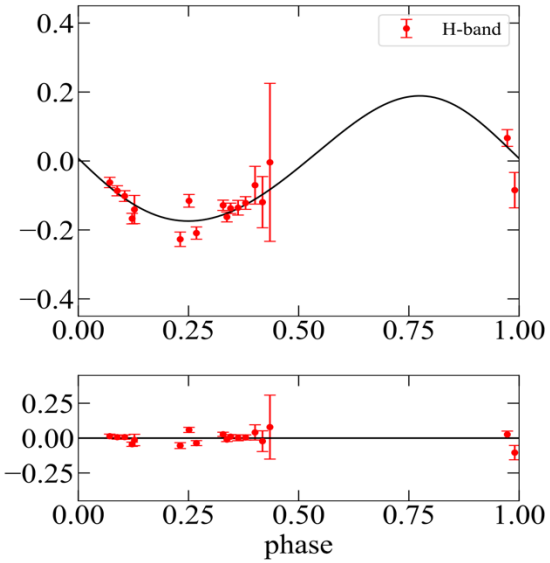


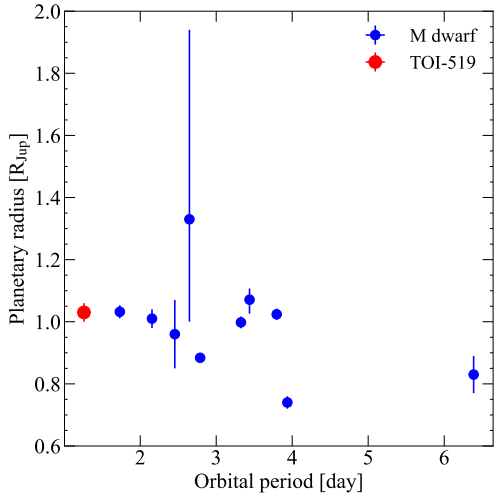


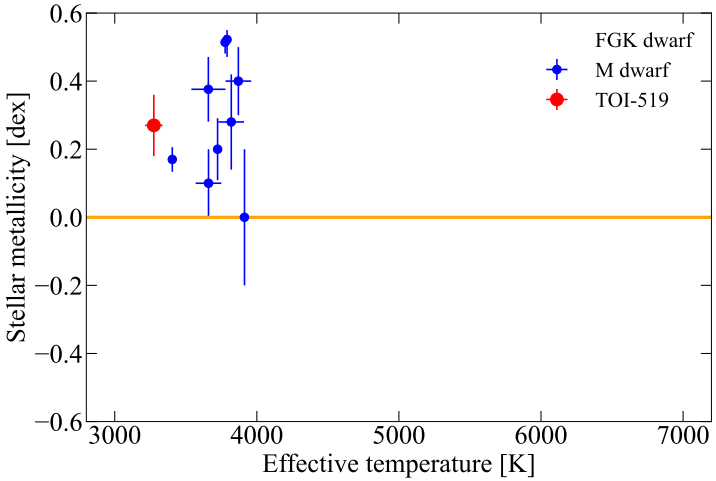
Hirano et al. (2021)

A close-in giant planet around a mid-M dwarf

We have confirmed that TOI-519 b is a giant planet from IRD RVs







$M_p = 0.463^{+0.082}_{-0.088}\ M_{\rm Jup}$

$R_p = 1.03 \pm 0.03\ R_{\rm Jup}$

$P = 1.265$ days

$[{\rm Fe/H}] = 0.27 \pm 0.09$

$T_{\rm eff} = 3275 \pm 61$ K

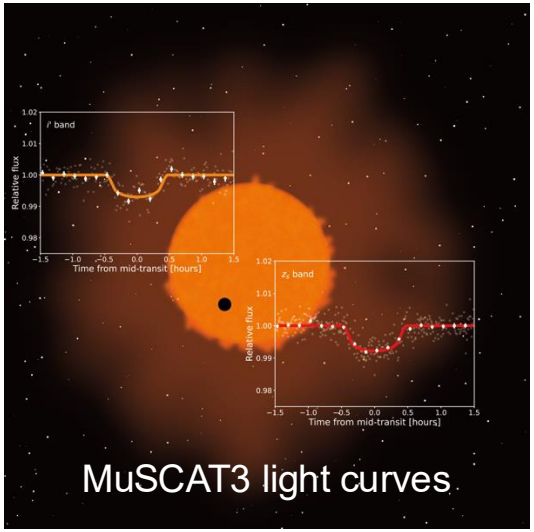
TOI-519 b is one of the short period giant planets
around one of the lowest temperature M dwarfs known so far

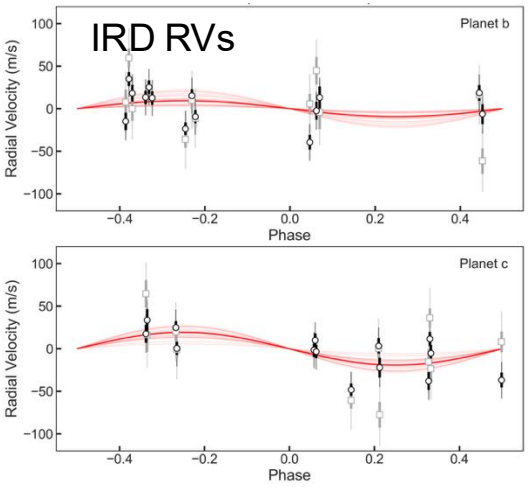
Kagetani et al. (2023)

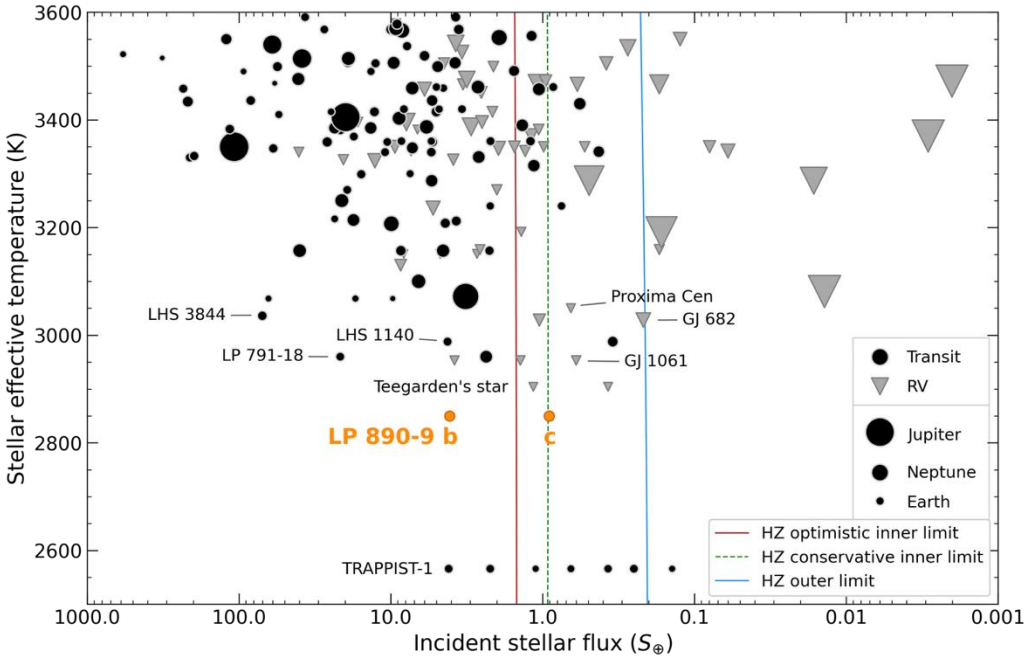
Discovery of a habitable super-Earth

We validated two super-Earths around an M6 dwarf

LP 890-9 (TOI-4306, SPECULOOS-2) at 32 pc





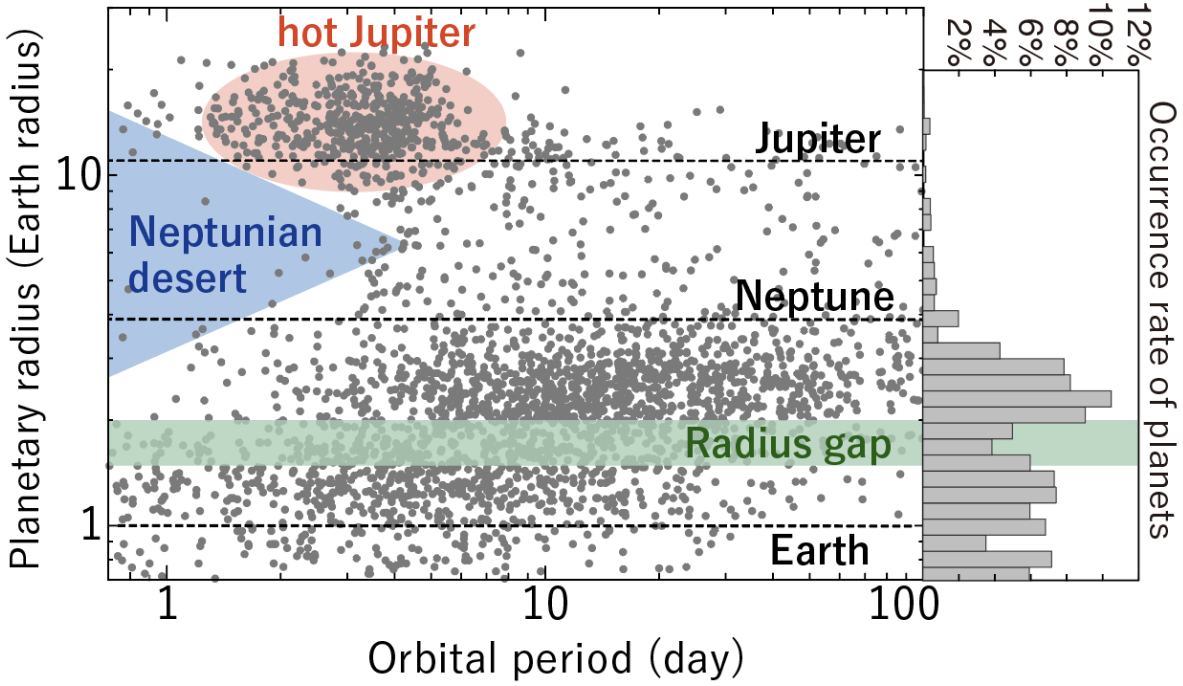


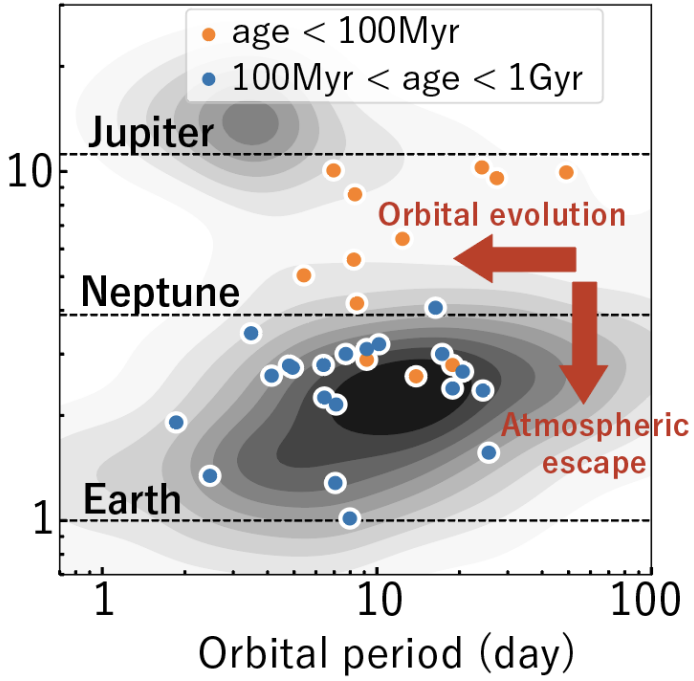
The outer one is a 1.37 R_{Earth} planet in the habitable zone

Delrez, Murray, Pozuelos, Narita et al. (2022)

New Research Topic: Young Transiting Planets

Young Transiting Planets: An Emerging Population Thanks to TESS



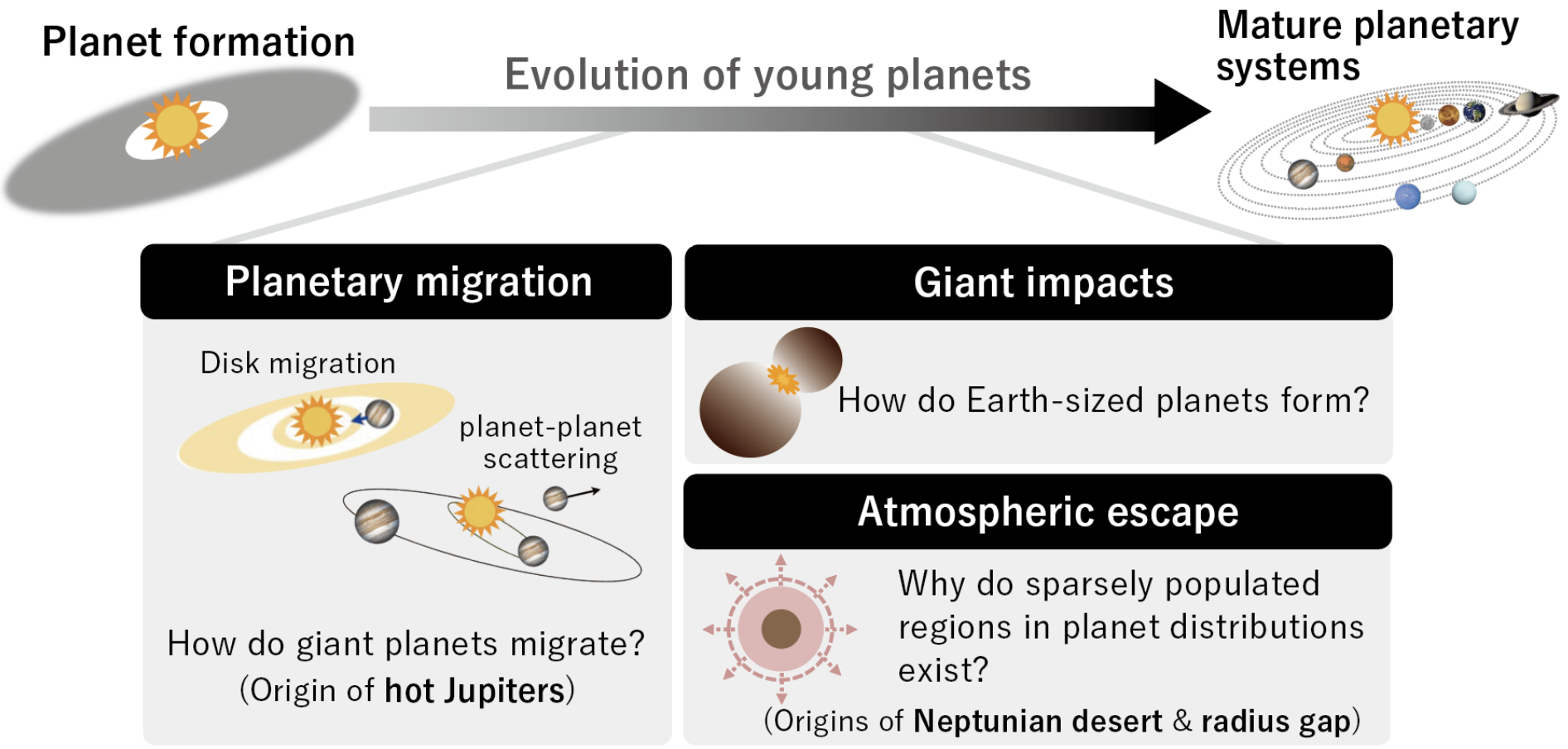


I proposed KAKENHI Kiban-S and the project started from 2024

PI: Norio Narita (UTokyo)

Co-Is: Akihiko Fukui (UTokyo), Teruyuki Hirano, John Livingston (ABC), Eiichiro Kokubo (NAOJ), Yasunori Hori (Okayama)

Why young transiting planets?



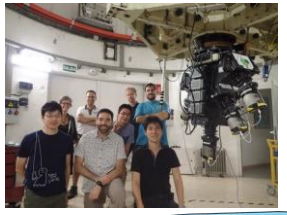
We aim to uncover how young planets and planetary systems evolve

How to achieve the goal

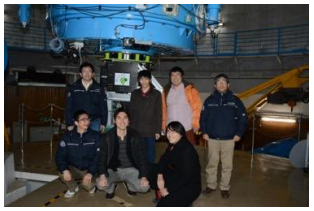
- Instrument development
  - New multi-color network in the southern hemisphere
  - Helium ultra-narrow-band filter for TAO/SWIMS
- Observational studies
  - Finding new young transiting planets
  - Monitoring TTV to determine accurate masses
  - Measuring obliquities
  - Helium transmission spectroscopy
- Theoretical studies
  - Orbital evolution
  - Atmospheric loss
  - Giant impacts

Possible future of the MuSCAT network

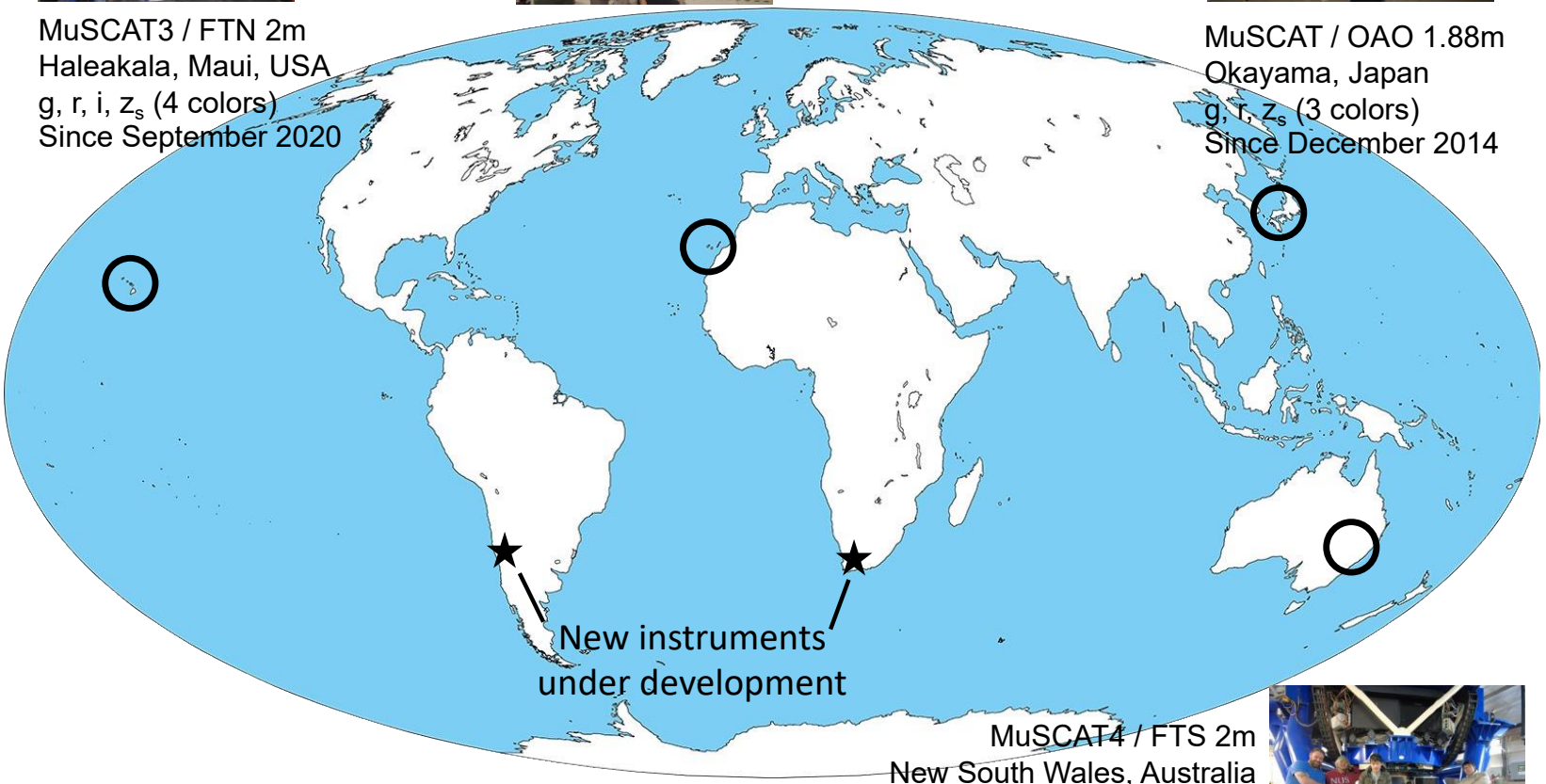
MuSCAT3 / FTN 2m
Haleakala, Maui, USA
g, r, i, z_s (4 colors)
Since September 2020



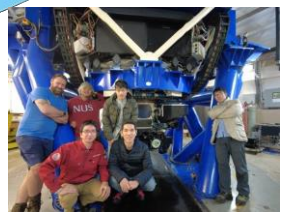
MuSCAT2 / TCS 1.52m
Teide, Tenerife, Spain
g, r, i, z_s (4 colors)
Since August 2017



MuSCAT / OAO 1.88m
Okayama, Japan
g, r, z_s (3 colors)
Since December 2014



MuSCAT4 / FTS 2m
New South Wales, Australia
g, r, i, z_s (4 colors)
Since October 2023



We are developing new instruments for LCO's 1m telescopes

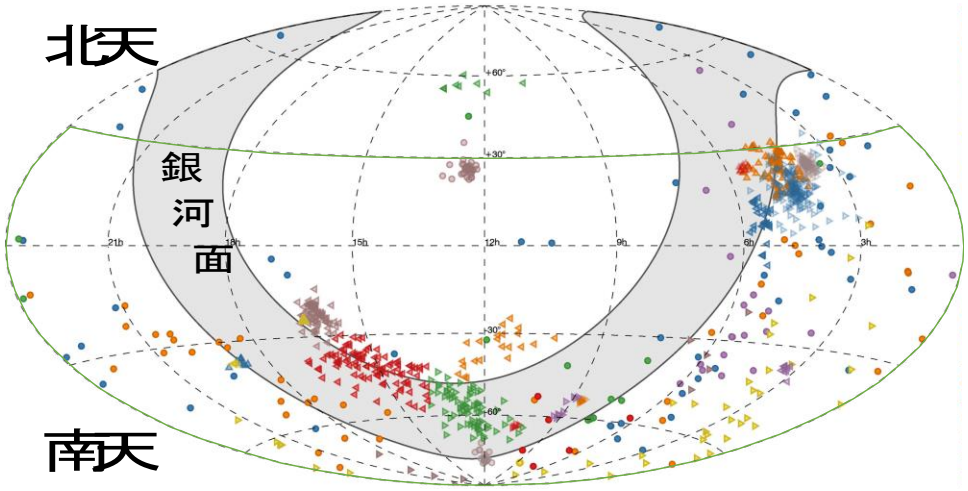
Why in the southern hemisphere?

From the southern hemisphere,

we can observe most of nearby clusters listed in Gagne et al. (2018)

Locations of LCO telescopes

Observable sky region (light green)



Sky locations of young clusters
(Gagne et al. 2018)

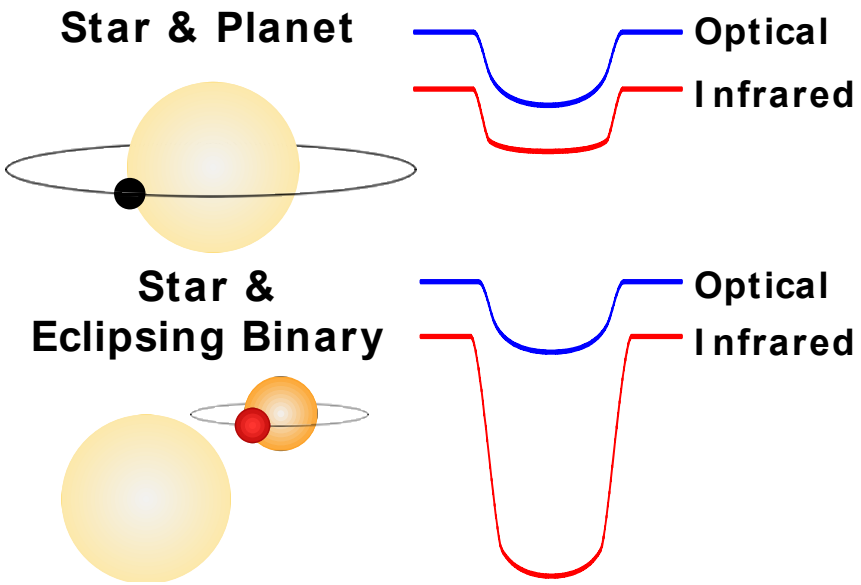
By developing multi-color network in the southern hemisphere,

we can increase new discoveries of young transiting planets

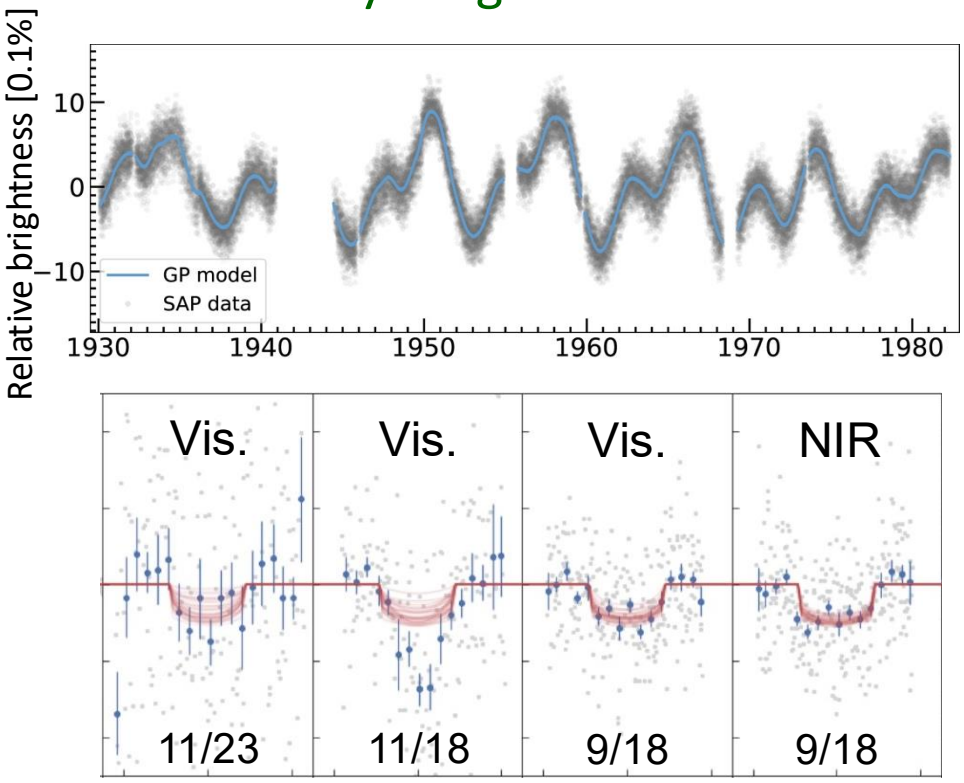
Why multi-color?

One of the major obstacles for validating new young transiting planets
Is the presence of large stellar variability of host stars

Validating new transiting planets



Example of brightness change of a young host star

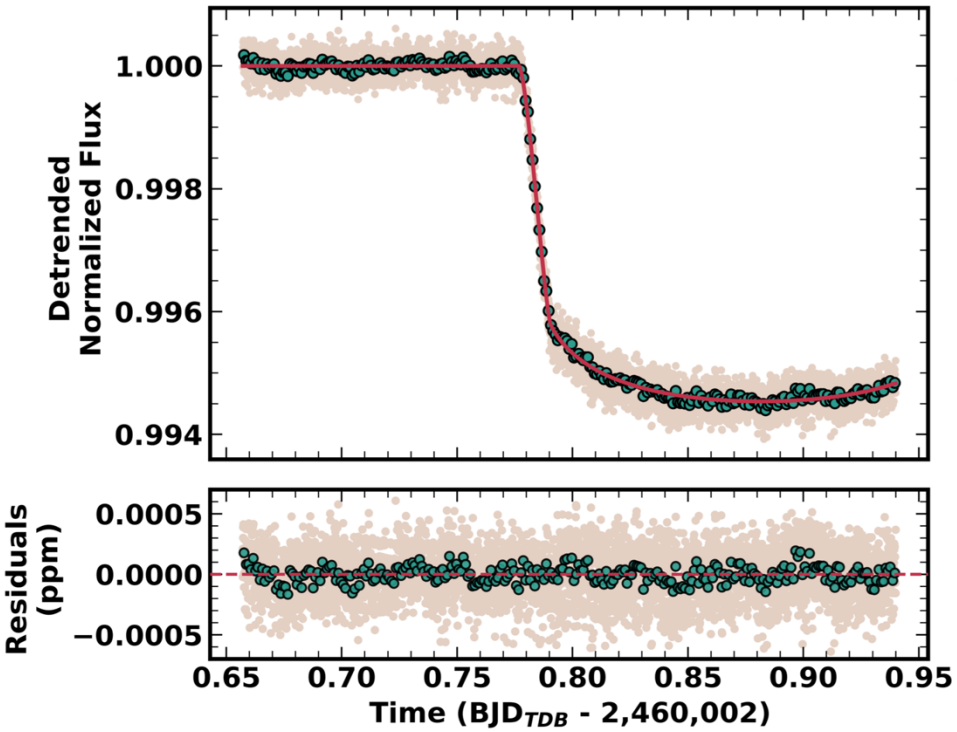


de Leon, Livingston et al. (2023)

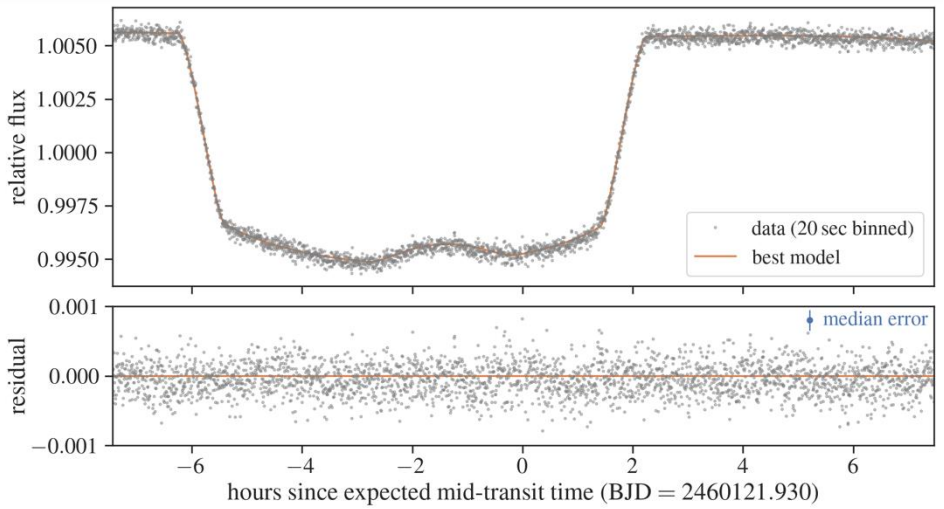
Multi-color capability helps us to check achromaticity

Need for TTV Monitoring for Young Transiting Planets

Gallery of recent JWST observations
for young (<1Gyr) transiting planets



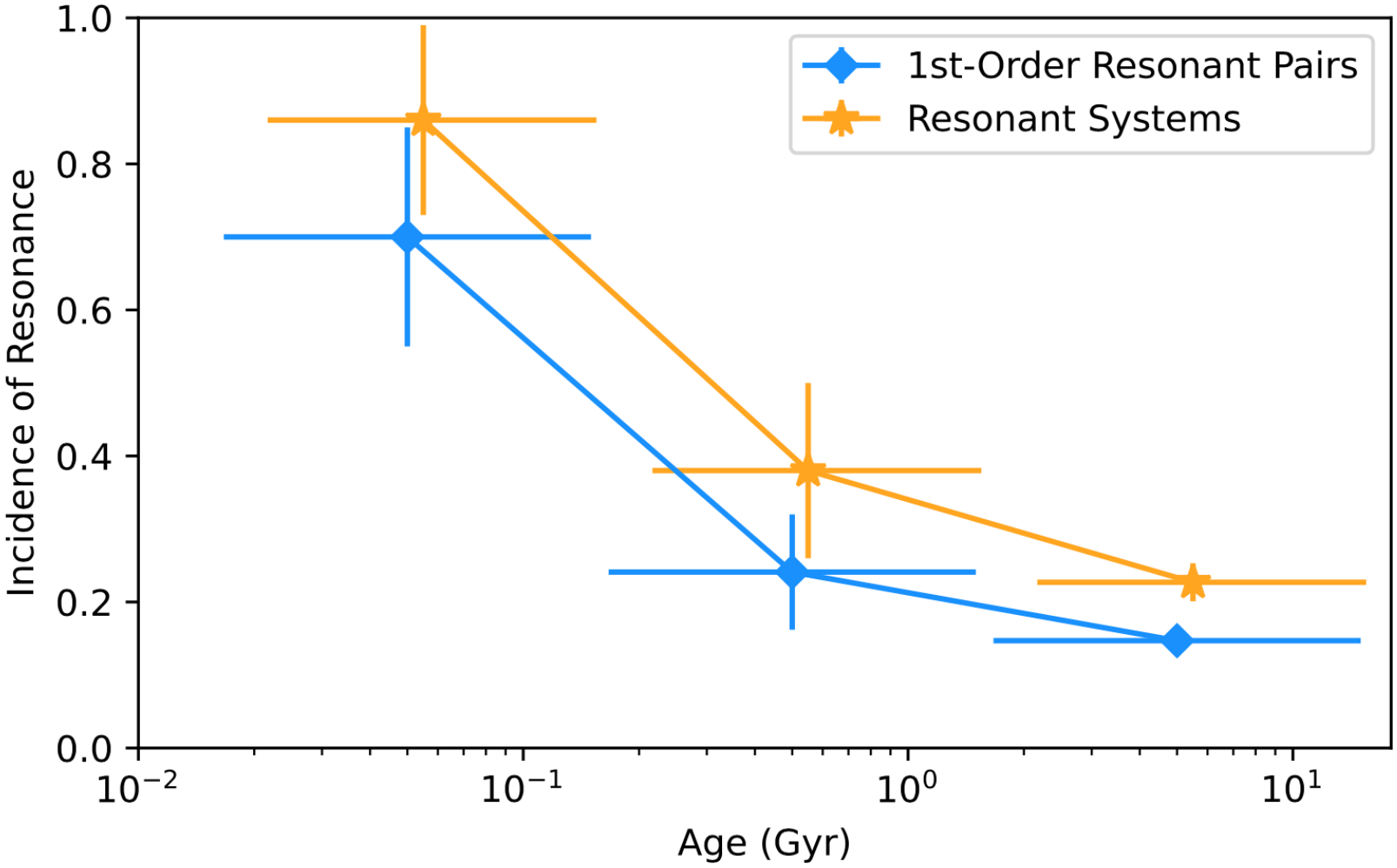
HIP 67522b: Thao et al. (2024)



Kepler-51d: Masuda et al. (2024)

MuSCAT network is useful for TTV monitoring
and ephemerides update for young transiting planets

Fractions of resonant systems with age



Dai et al. (2024)

Why TTV is important for young transiting planets

- High fraction of planet pairs in MMR
  - Identifying additional planets

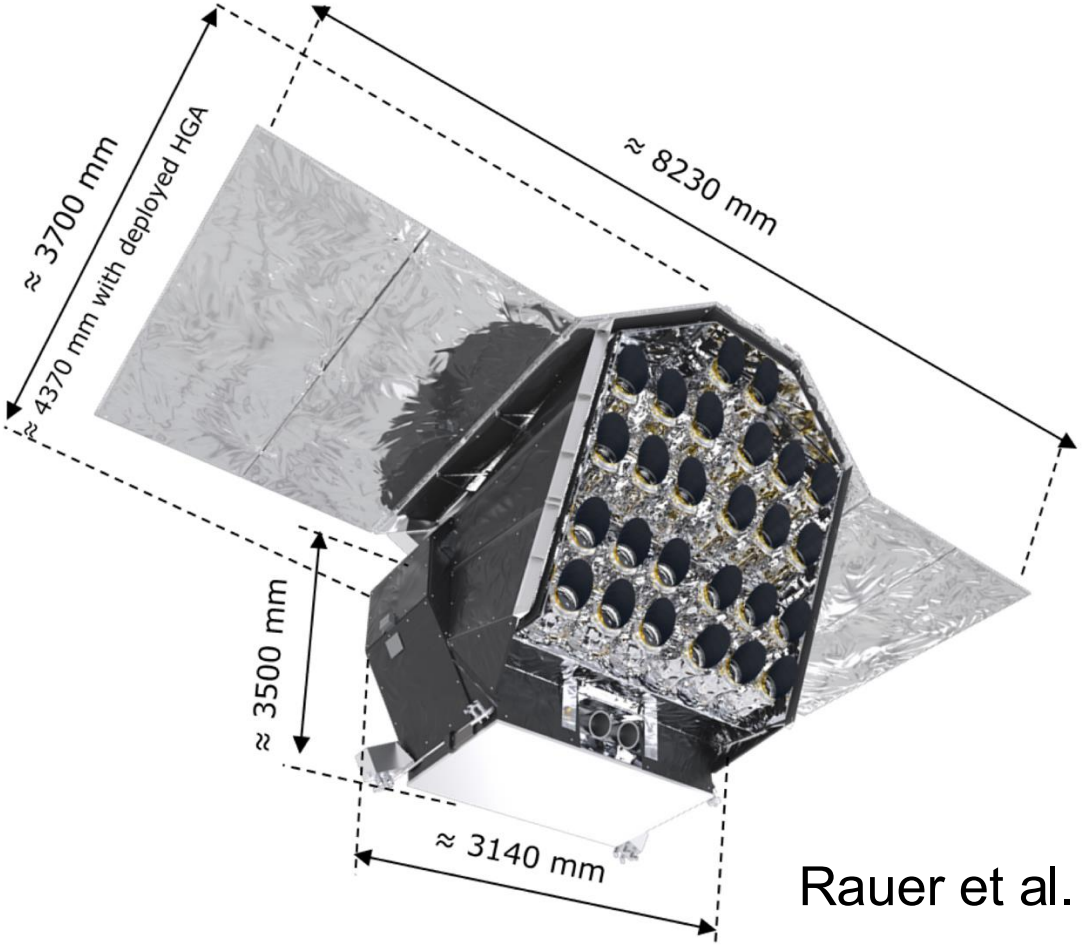
- Precise and accurate transit ephemerides
  - Continuing TTV monitoring allow us to keep TTV models and transit ephemerides updated

- Accurate and independent mass determination
  - TTVs offers mass determination independent from RVs

By developing multi-color network in the southern hemisphere, we can monitor precise TTVs of young transiting planets

Possible Next Topic

ESA's PLATO is scheduled to be launched in 2026

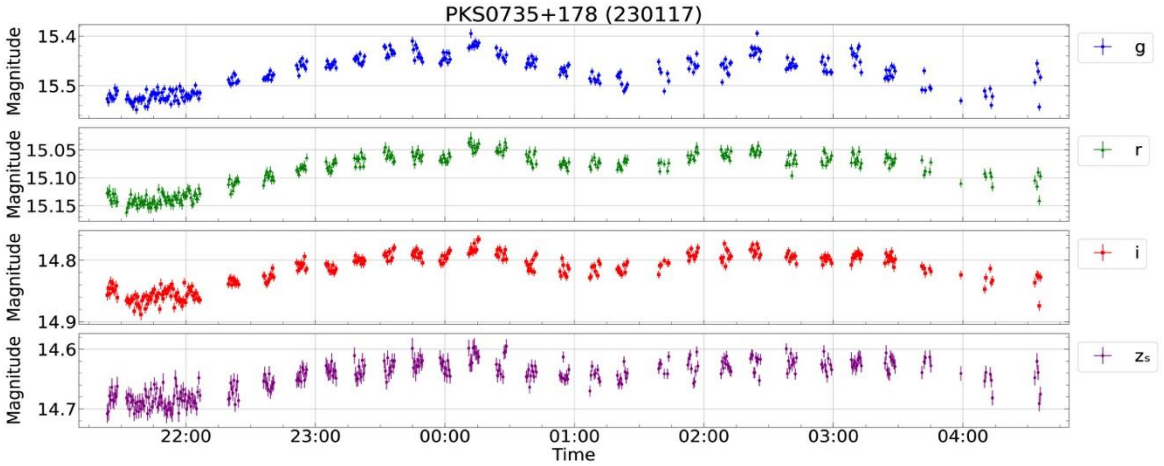


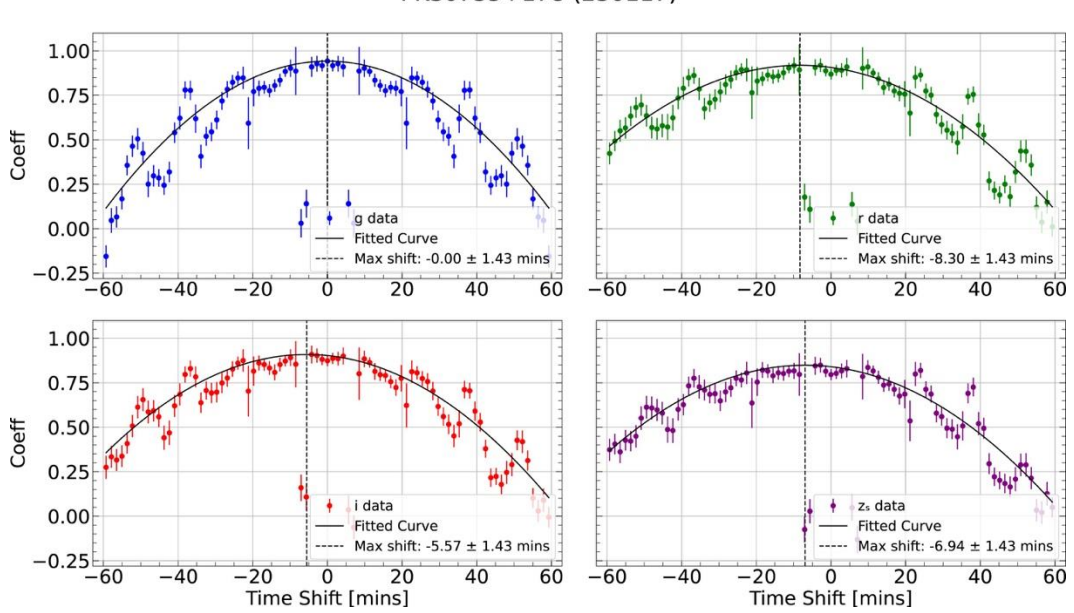
Rauer et al. (2025)

The number of long-period transiting planets will increase

Non-Exoplanetary Science with MuSCATs

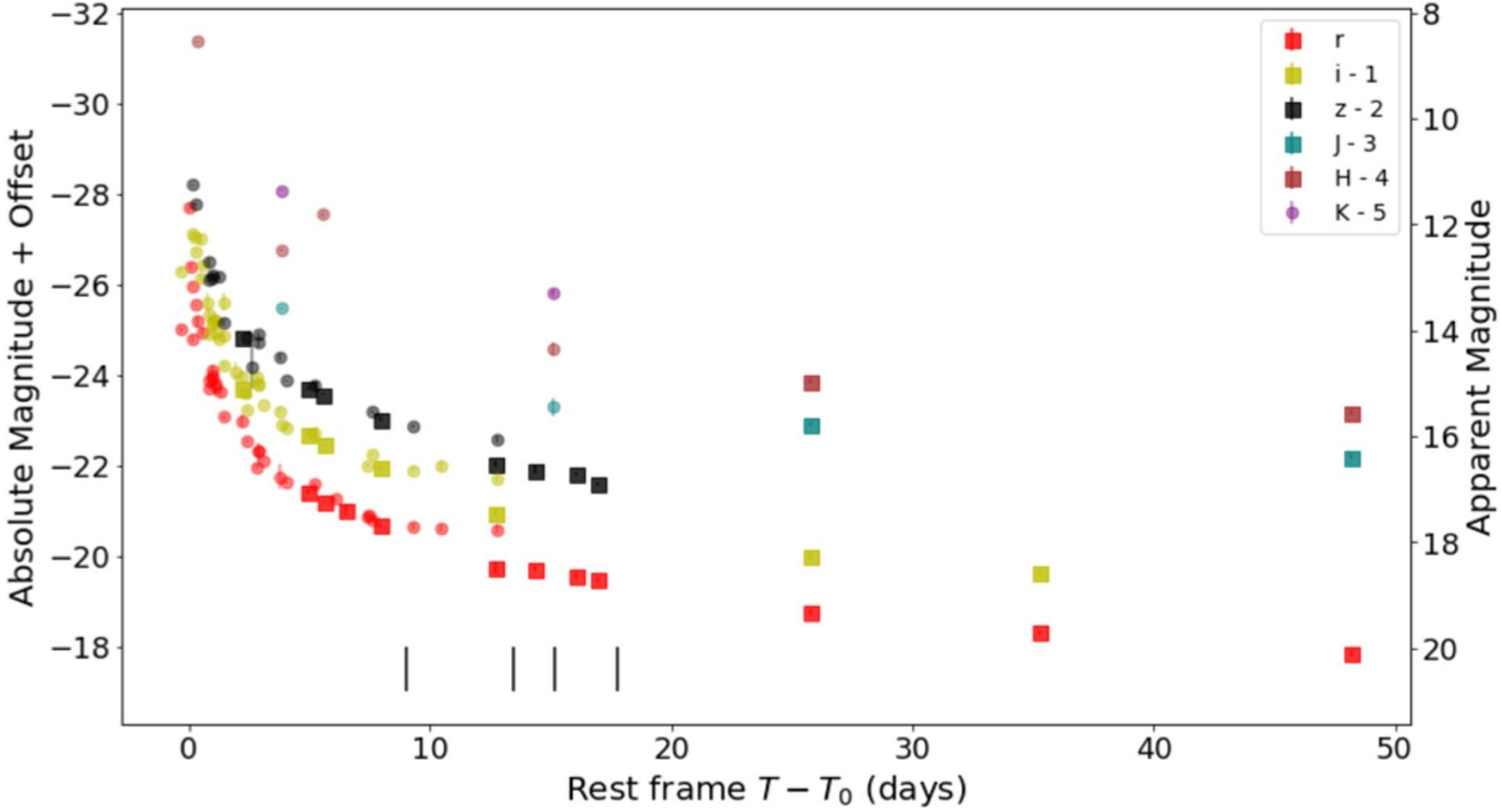
Variability of blazers (McCall et al. 2024)





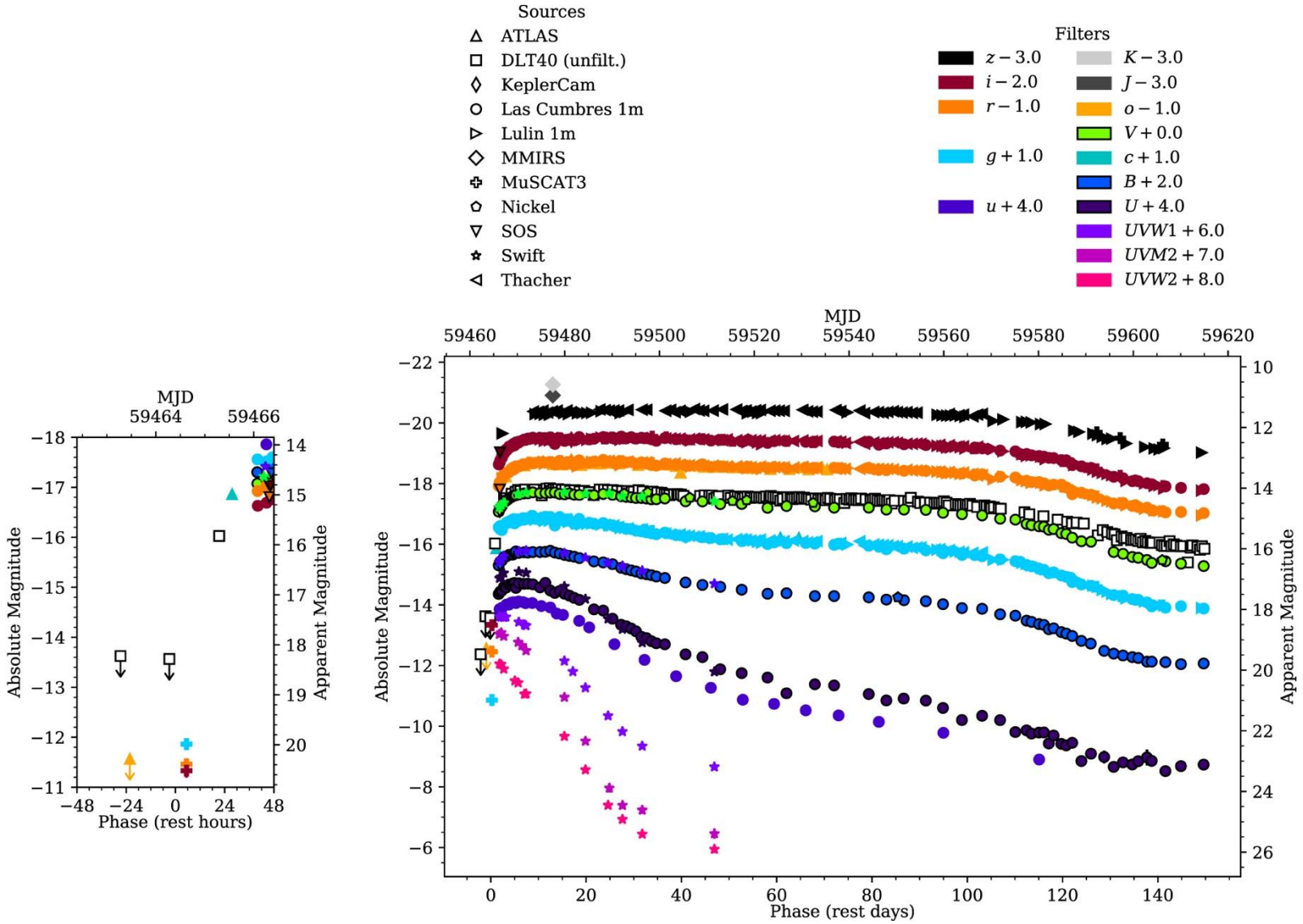
Non-Exoplanetary Science with MuSCATs

Follow-up of GRB 221009A (Shrestha et al. 2023)



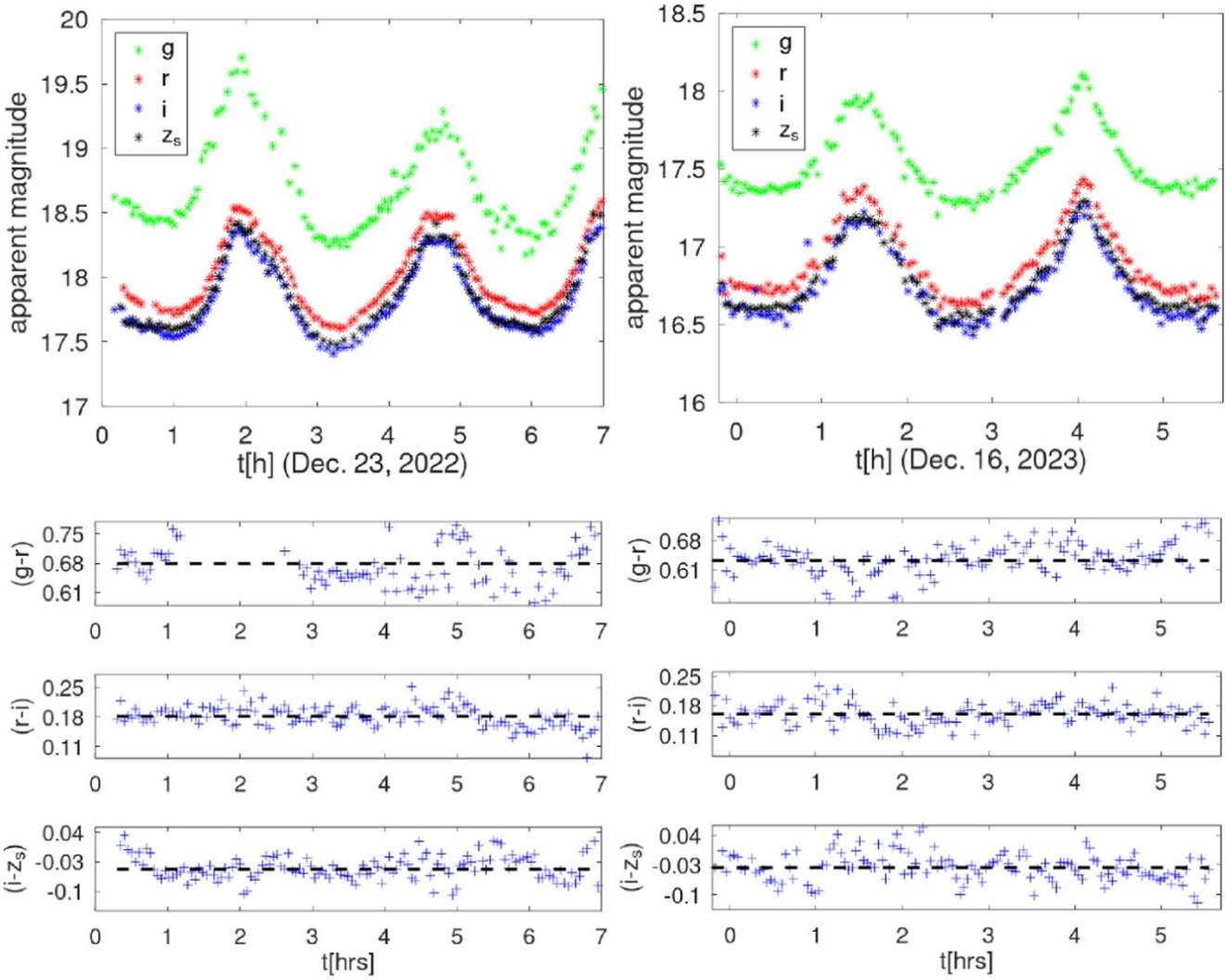
Non-Exoplanetary Science with MuSCATs

Follow-up of Type II SN 2021yja (Hosseinzadeh et al. 2022)



Non-Exoplanetary Science with MuSCATs

Monitoring of (98943) Torifune 2001 CC21 (Popescu et al. 2025)



Key Takeaways

- We have developed 4 MuSCATs and are developing 2 more in the Southern hemisphere
- We are currently focusing on young transiting planets (at least until FY2028)
  - Any collaboration for young transiting planets is more than welcome
- We also plan to observe long-period transiting planets
- MuSCATs are also useful for non-exoplanetary science including time-domain astronomy