

Introduction to The 7-Dimensional Telescope: Eyes of Multi-Messenger Astronomy



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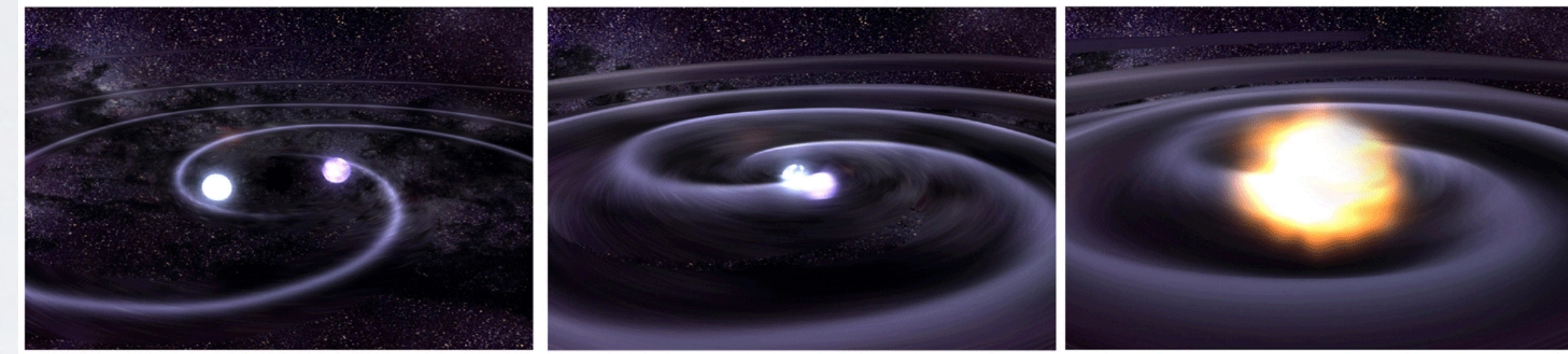
November 20 2025

KHEP Workshop @ Gwangju

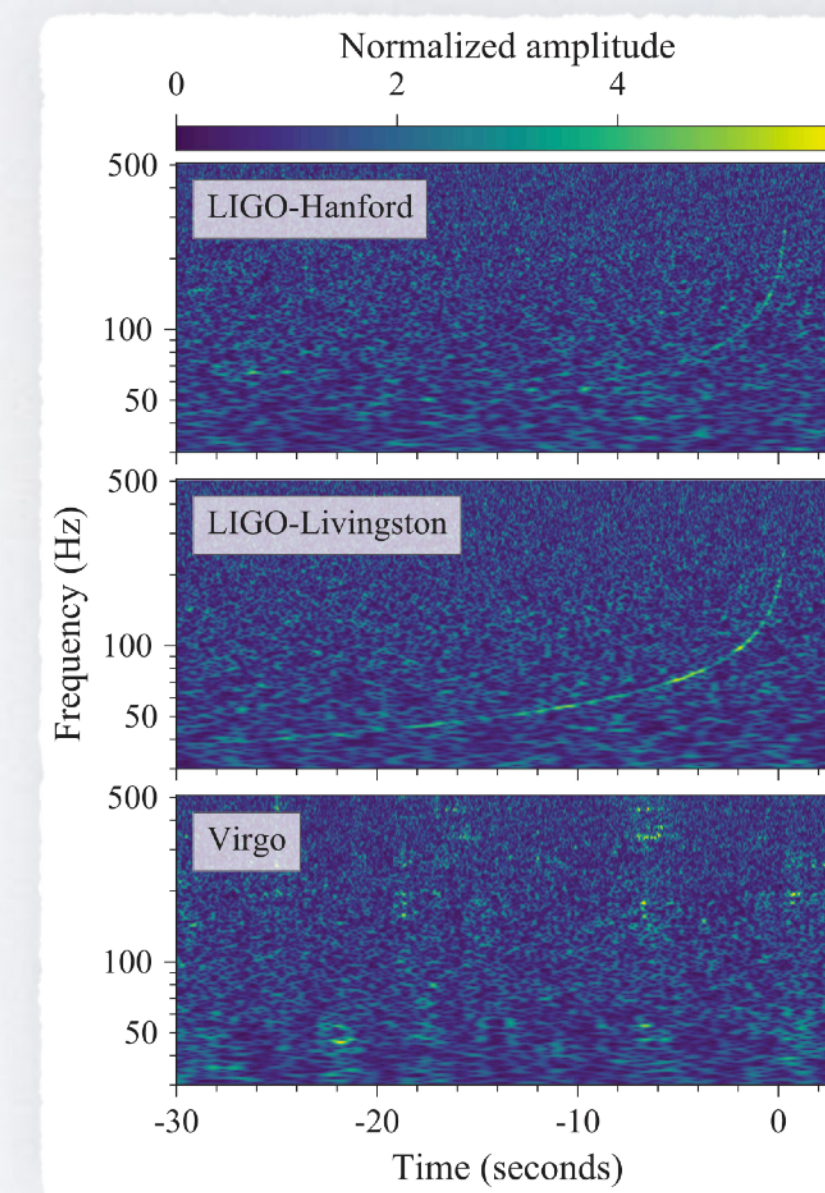


Multi-Messenger Astronomy

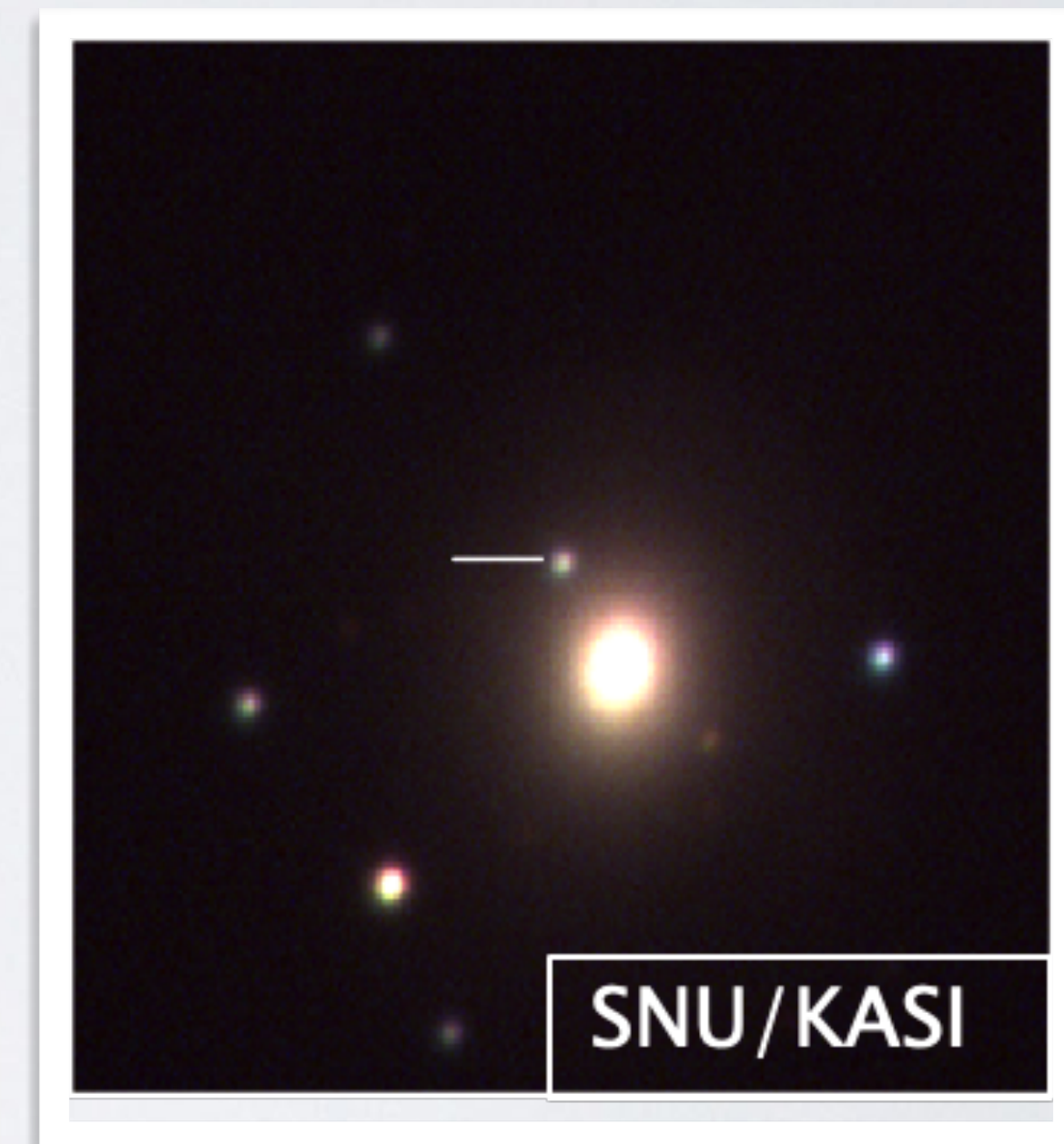
- 4 messengers: *photons* (electromagnetic waves), *cosmic rays* (protons and atomic nuclei), *neutrinos*, and *gravitational waves*.
- *Gravitational Wave Astronomy*
 1. Binary Black Hole Merger
 2. Binary Neutron Star Merger
 3. Violent Events, such as Supernovae
 4. Epoch Before Recombination
 5. The Properties of GW Sources: mass and distance
- *GW170817: a binary neutron star merger*



An artistic rendition of binary neutron star merger (image credit : NASA)



Time-frequency representations of data containing the gravitational-wave event, GW170817 observed by LIGO.



Challenges and Needs for Kilonova Hunting

- 3 Challenges to EM Counterpart Identification

1. Wide Localization Area:

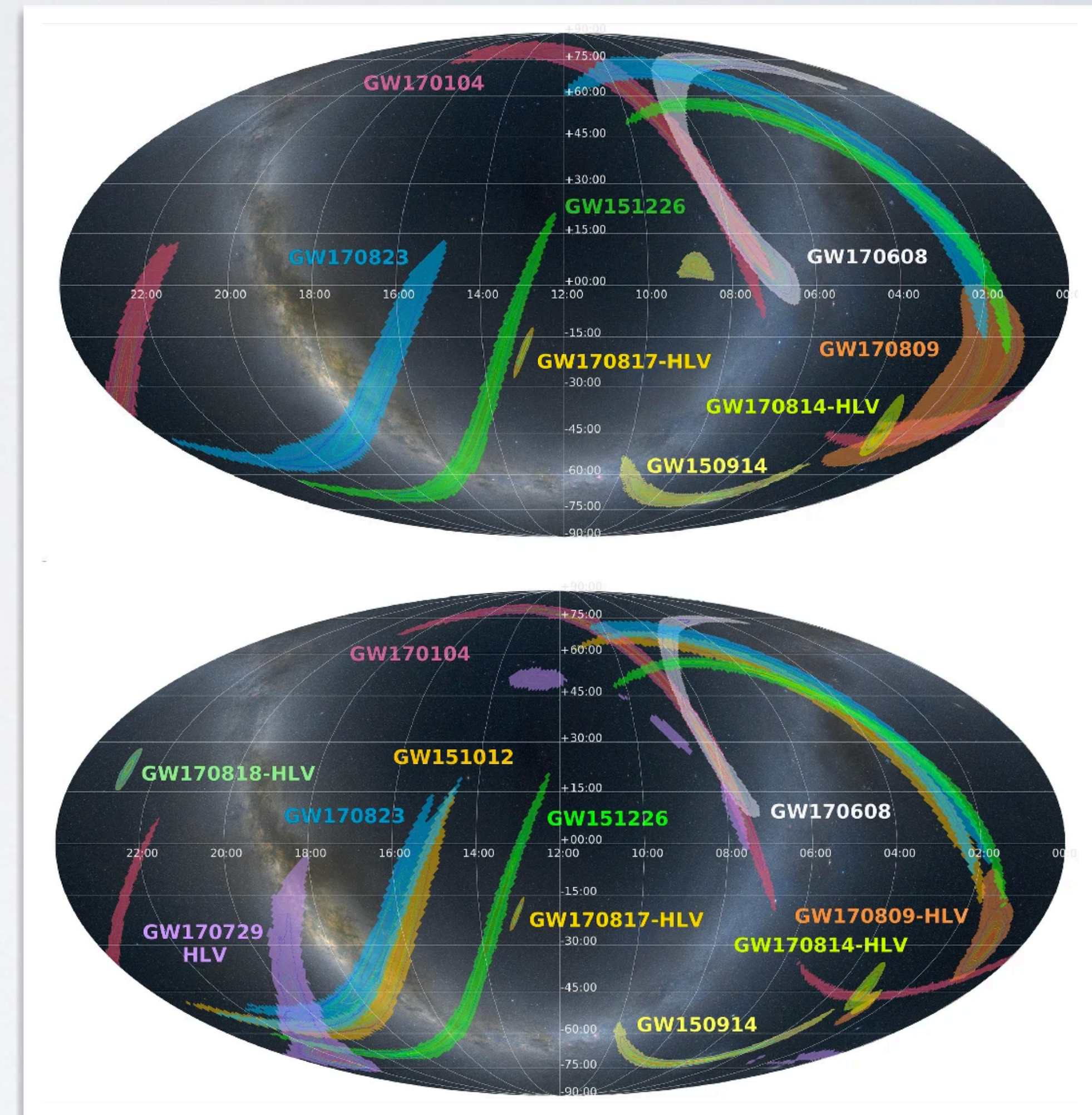
- a few 100's square degrees for O3
- a few 10's of square degrees for O4?

2. Faint, Fast-declining Transients (kilonova):

- Peak apparent magnitudes are $R = 17 \sim 22.5$ mag.
- They become a few mag fainter in several days.

3. Numerous Transients and Bogus Signals in large FoVs:

- a few 100's transients and/or variable objects in 10 square degrees
- a few 10^5 's artifacts in 10 square degrees



Sky locations of GW events confidently detected in O1 and O2
(Fig 5 of Abbot et al. 2020)

Challenges and Needs for Kilonova Hunting

- 3 Challenges to EM Counterpart Identification

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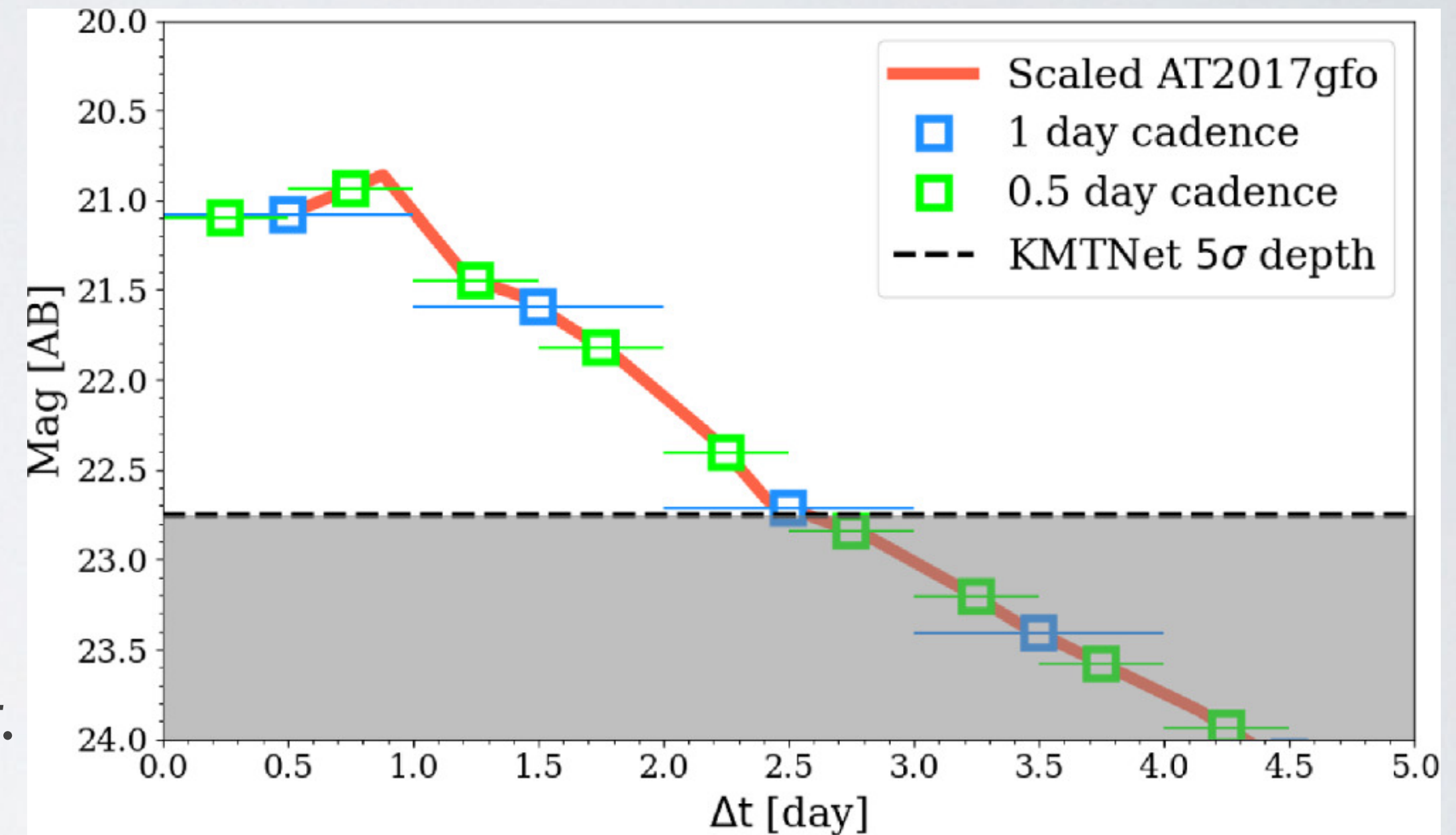
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- Peak apparent magnitudes are $R = 17 \sim 22.5$ mag.
- They become a few mag fainter in several days.

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- ~ 100 's transients and/or variable objects in 10 square degrees
- $\sim 10^5$ artifacts in 10 square degrees



G. Paek, Im, et al. (2025)

Multi-Messenger Astronomy

- 3 Challenges to EM Counterpart Identification

1. Wide Localization Area

- ~100's square degrees for O3
- ~10's of square degrees for O4?

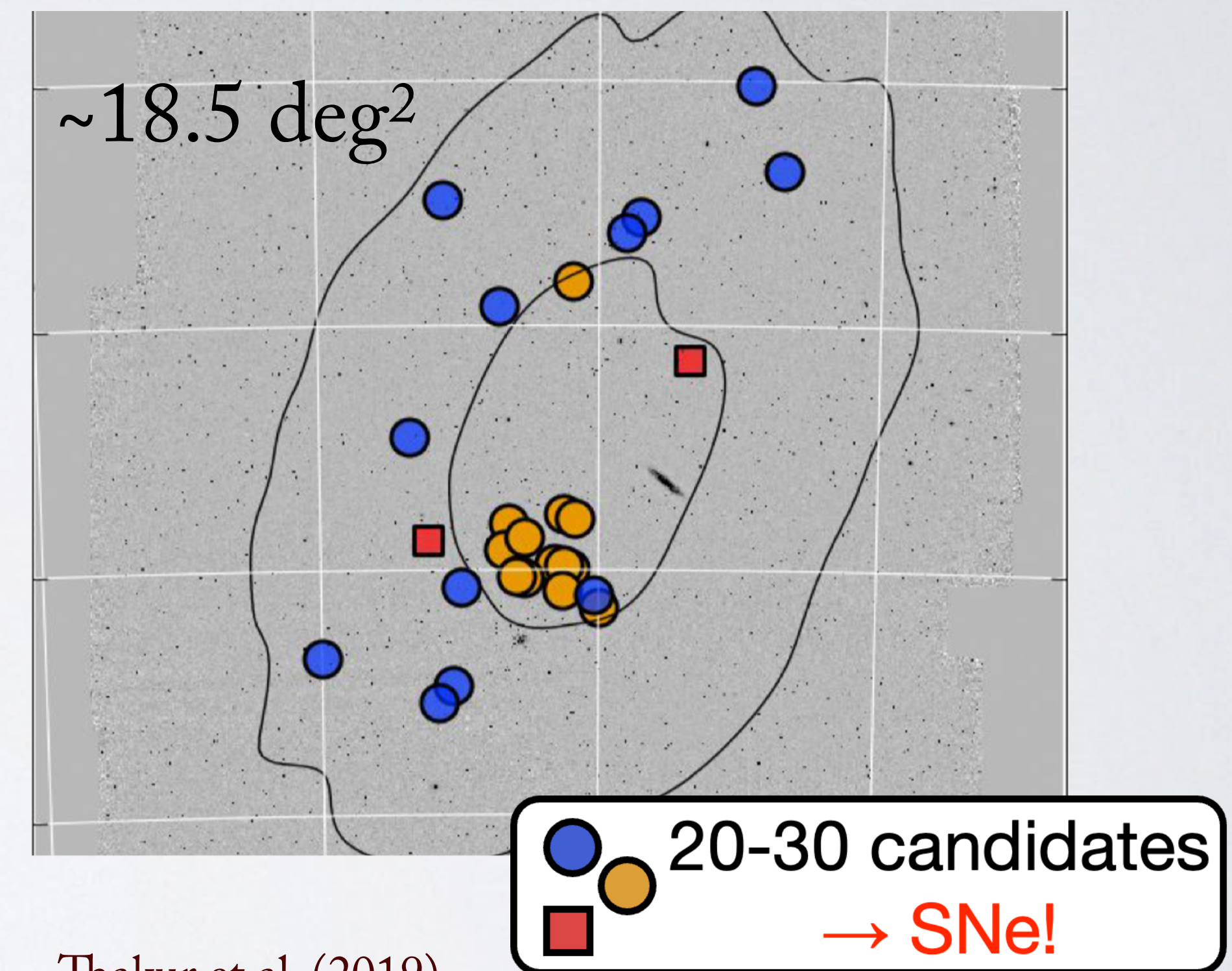
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- ~ 10^5 artifacts in 10 square degrees

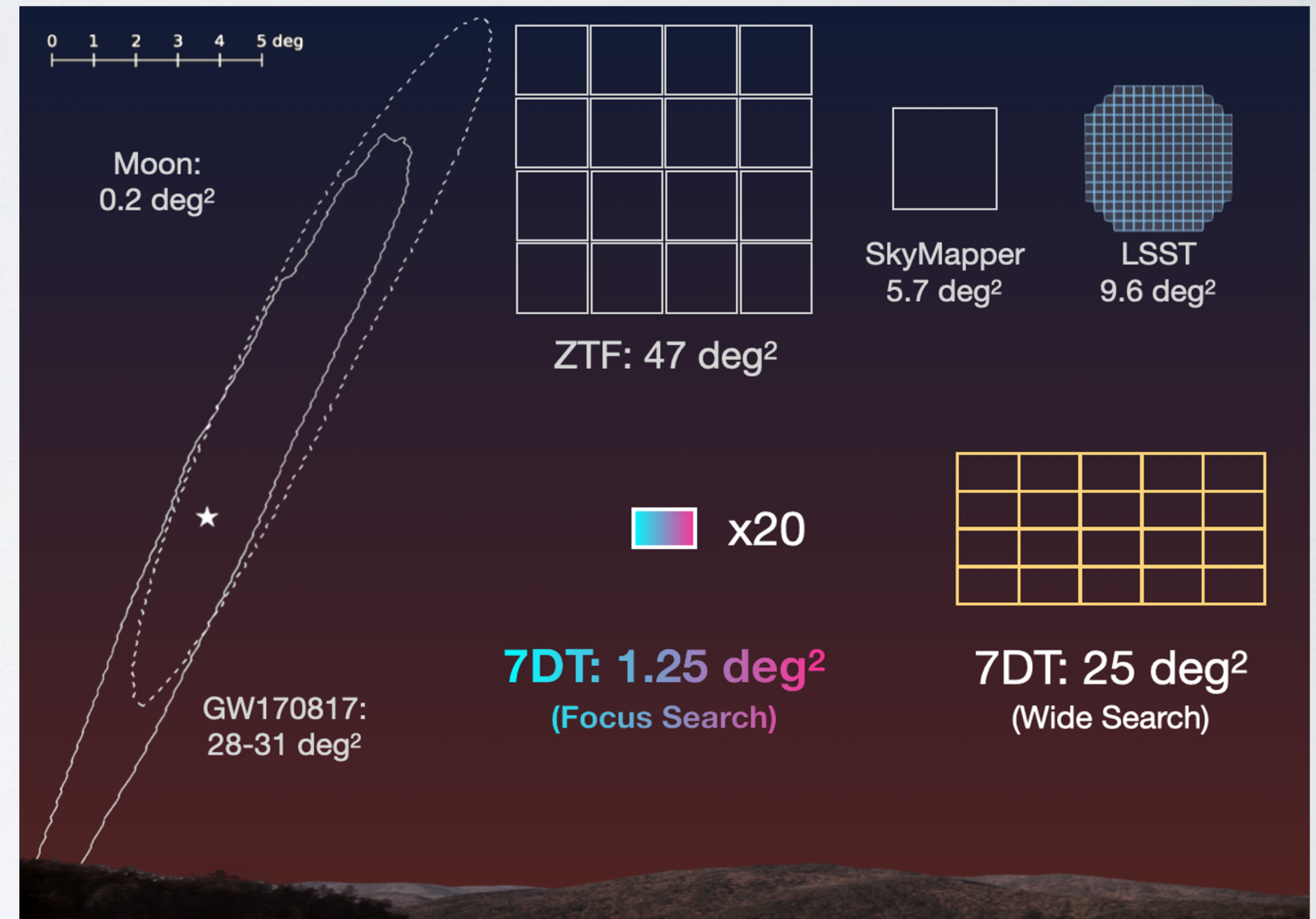
GW 190814 , NSBH (O3)



Thakur et al. (2019)

What do we need?

1. Large localization areas: a few hundred square degrees
 - **Large FOV**
2. Faint, fast-declining transients: 3~4 mag fainter than SN Ia and becoming fainter very rapidly
 - **Flexible operation**
3. Too many transients with large FoVs: a few hundred of transients in 10 square degrees
 - **Spectroscopy even with low-R**
 - Real-time data reduction
 - Real-time data analysis



7-Dimensional Telescope in a Nutshell

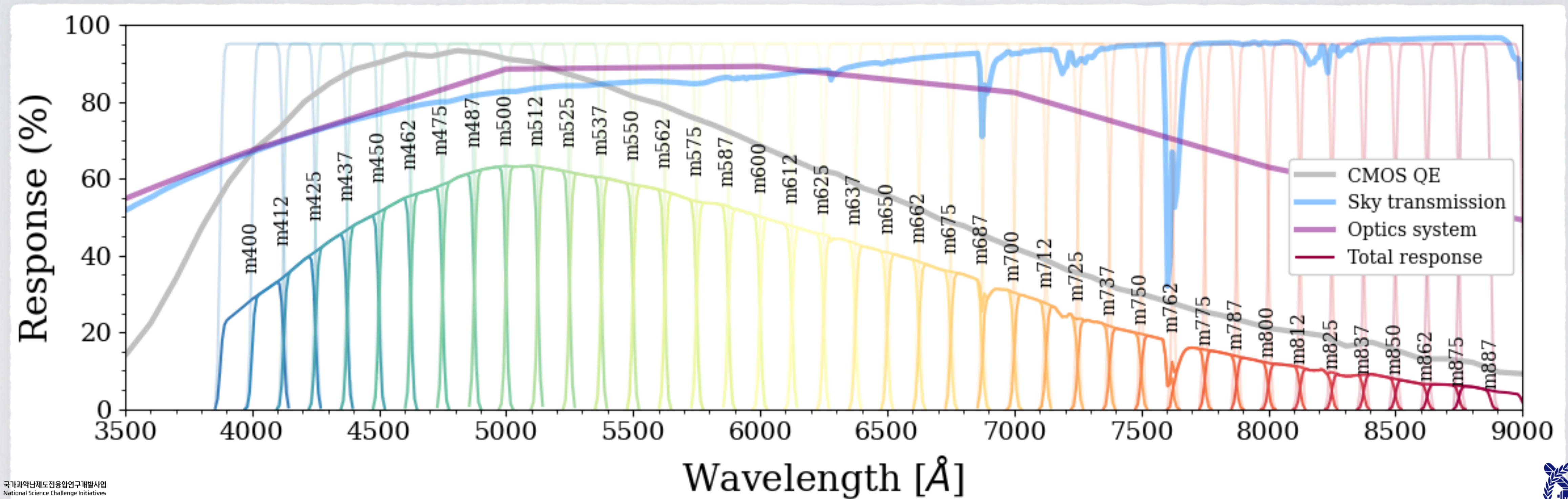
- $20 \times 50\text{-cm}$ commercial off-the-shelf astrograph
- $40 \times 25 \text{ nm}$ medium band filters + Sloan Broad-band filters
- IFU-style data for a *large FoV* (~ 1.2 square degrees with R of 30~70)
- Hosted by ObsTech at Observatorio El Sauce situated in the Río Hurtado Valley in Chile.
- **Fully remote observation** accommodating automated survey, alert brokers, GW follow-up rankings, etc.



- altitude: 1700 m
- more than 300 clear nights (up to 320 nights)
- the median seeing: $1.3''$
- the mean sky brightness: $\sim 22 \text{ mag/''}^2$

Filter

1. 40 medium-band filters with FWHM of 25nm from 400 nm through 900 nm with gaps of 12.5 nm.
2. Currently, 2 sets of 20 medium-band filters with gaps of 25 nm are ready.
3. Sloan u-, g-, r-, i-, and z-band filters: g-, r-, and i-bands for every unit

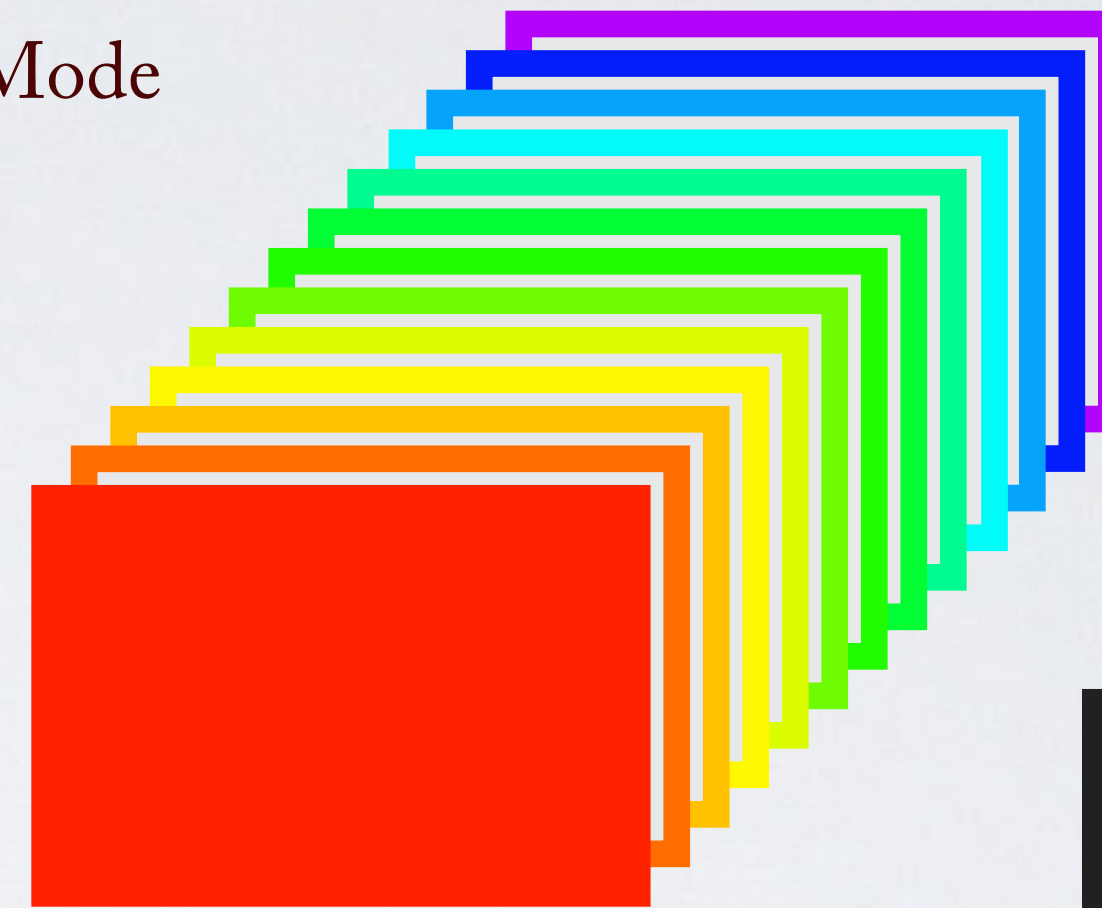


Observation Mode

1. Spec Mode - Color Mode:

- One pointing with 40 medium-band filters
- FoV: ~ 1.2 square degrees
- Spectral maps of the entire FoV ($R = 30 \sim 70$)

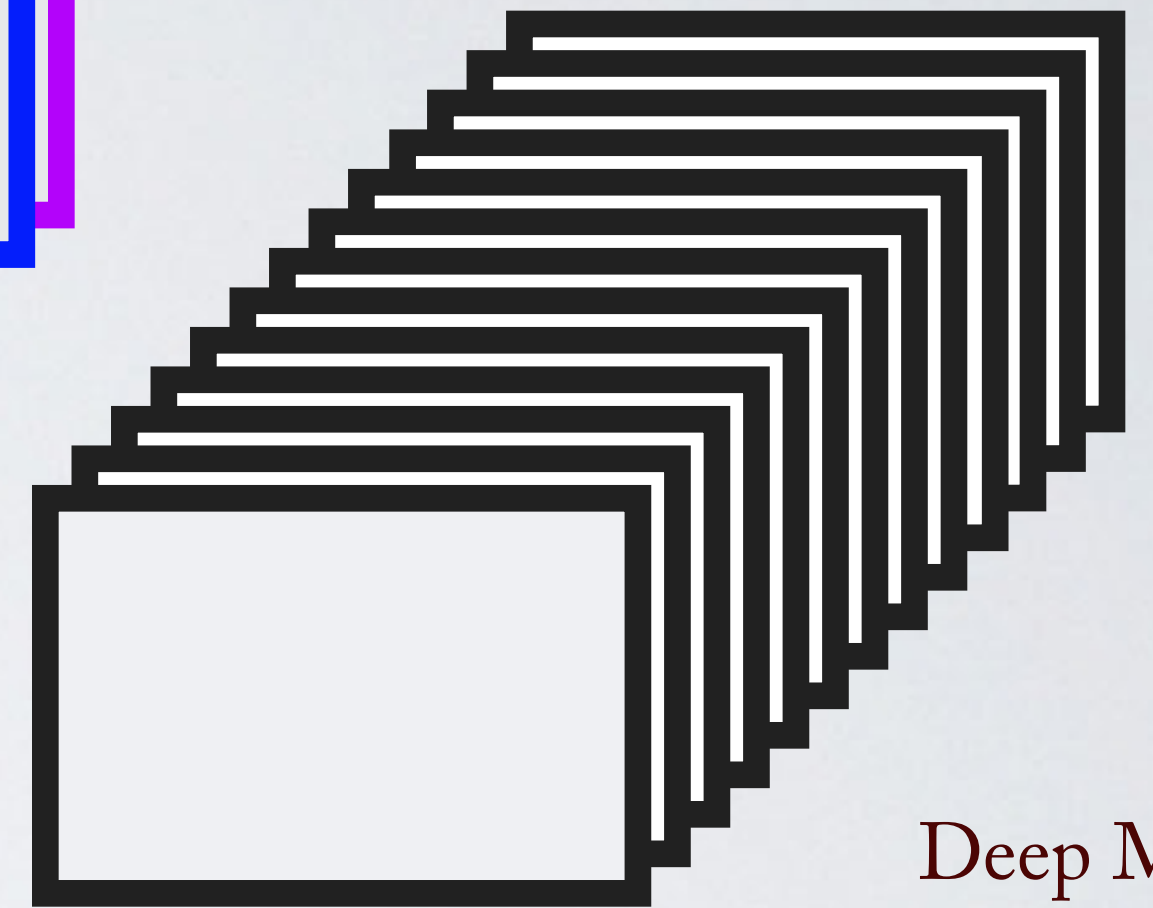
Spec Mode



2. Deep Mode:

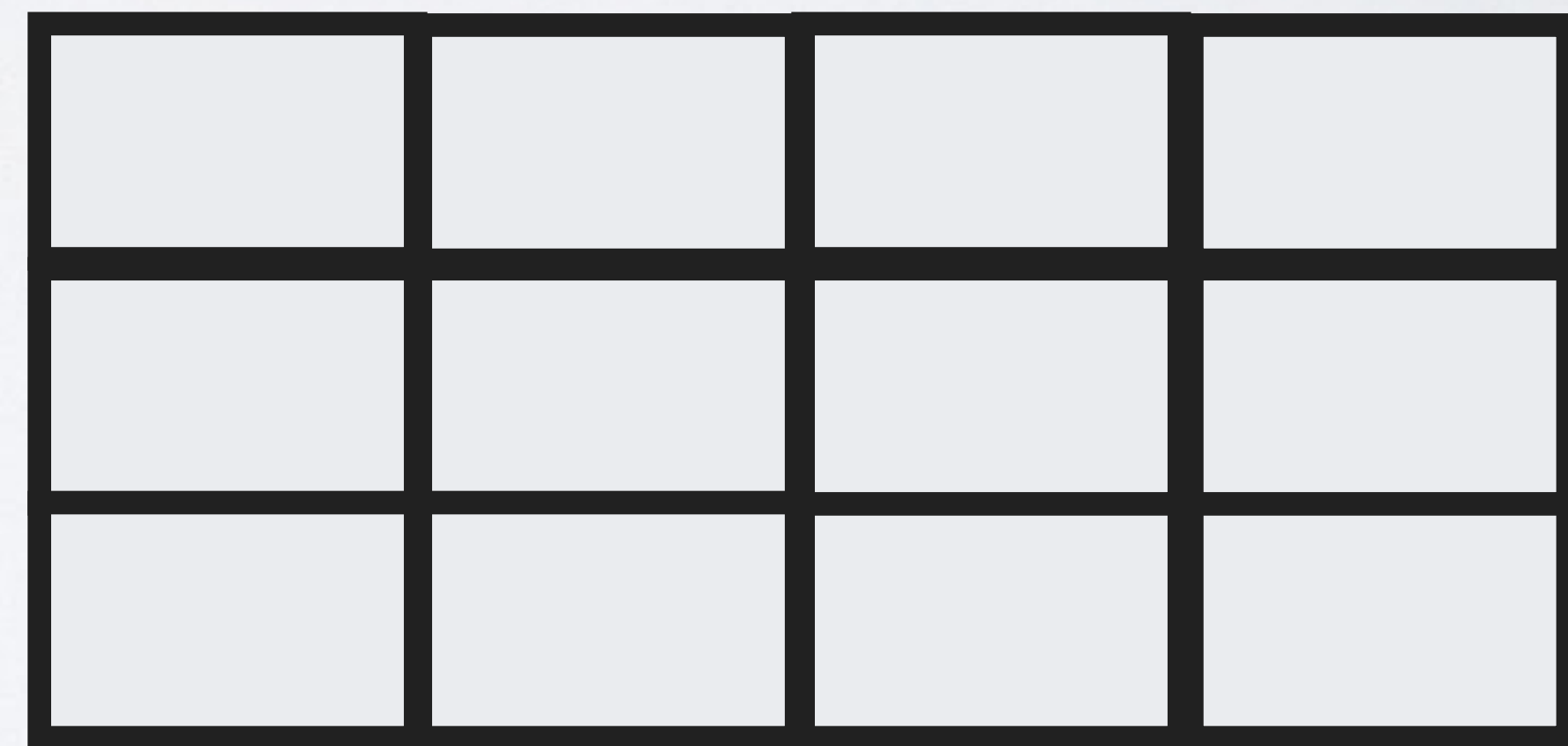
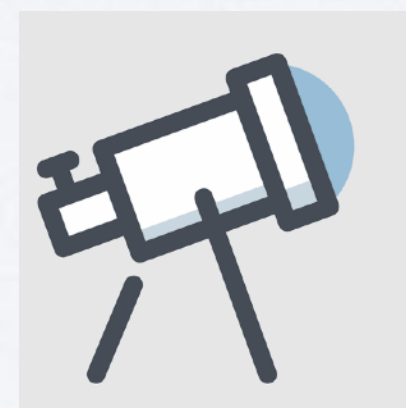
- One pointing with one broadband filter
- FoV: ~ 1.2 square degrees

Deep Mode



3. Search Mode:

- 20 pointings with one broadband filter
- FoV: ~ 25 square degrees



Search Mode

Current Status: Facility

- *16 units* are installed.
- *20 × 25nm* medium band filters + Sloan broadband filters
- A new set of 15 medium-band filters
- A data storage server of 2 PB, **Lyman**, is ready, and we are incrementing the storage volume by 1 PB.
- A new data storage server of 2 PB, **Balmer**, is being purchased.
- A GPU-based data process server with 2 NVIDIA A100 cards, **Proton**, is carrying out the data reduction pipeline.

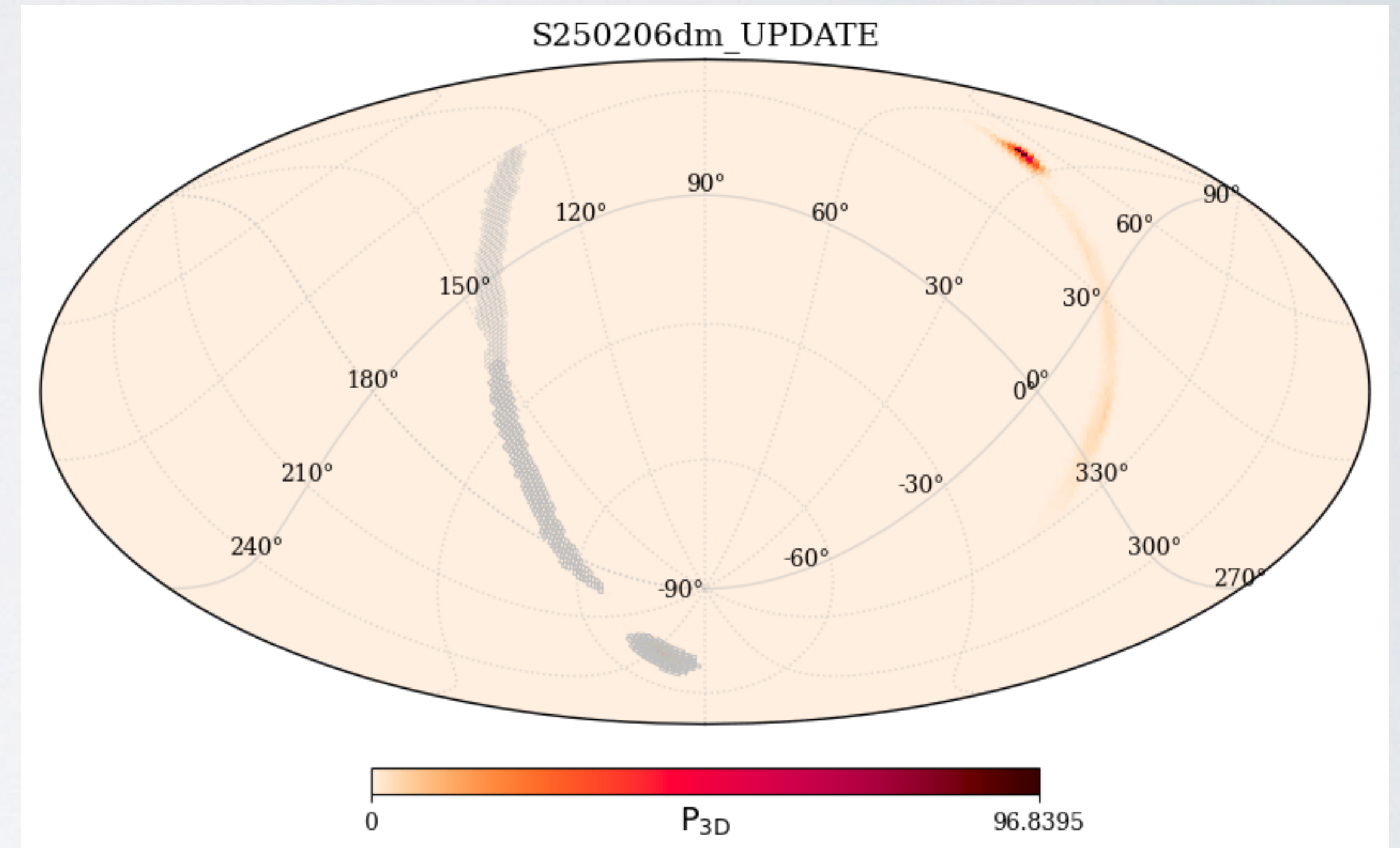
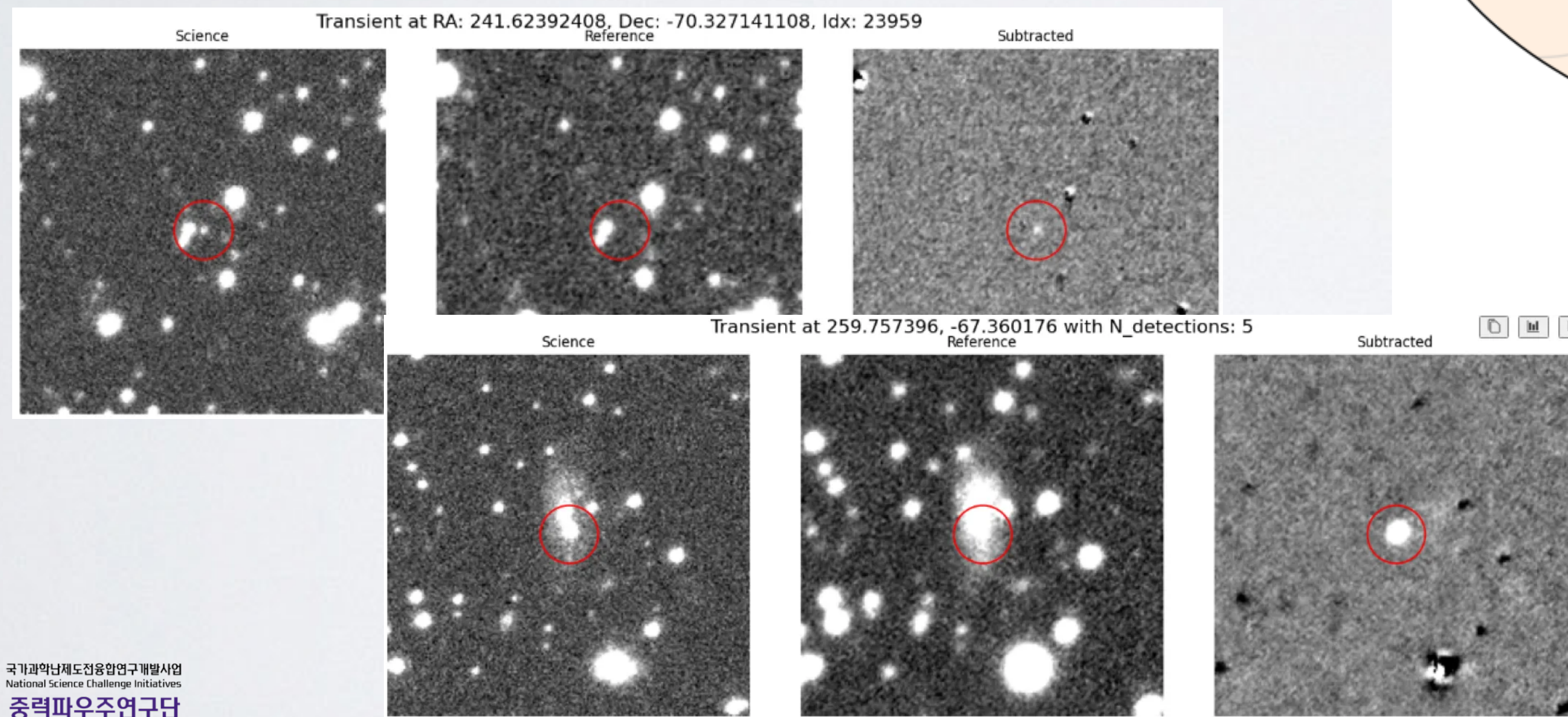


GW Follow-up Observations during O4 Run

Event name	Localization (90%, deg ²)	Observation by 7DT (deg ²)	Obsmode	Exptime
S240422ed	258.6	207.6	Search (r)	360s
S240910ci	393.6	39.6	Spec	600s
S240915b	18	18	Spec	1800s
S240925n	13.8	13.8	Spec	300s
S250206dm	909.8	590	Search (g,r)	300s
S250328ae	14.2	14.2	Spec	1800s
S250725j	18.6	18.6	Spec	1800s
S250830bp	3.7	3.7	Spec	7200s

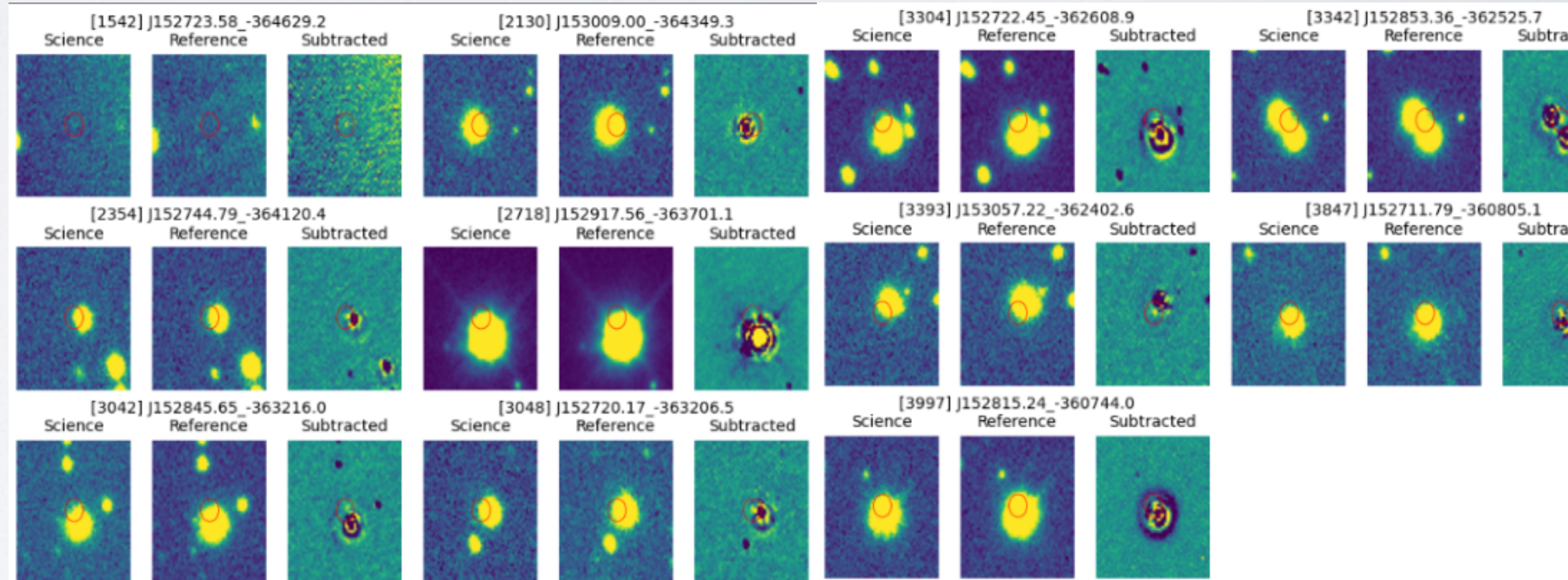
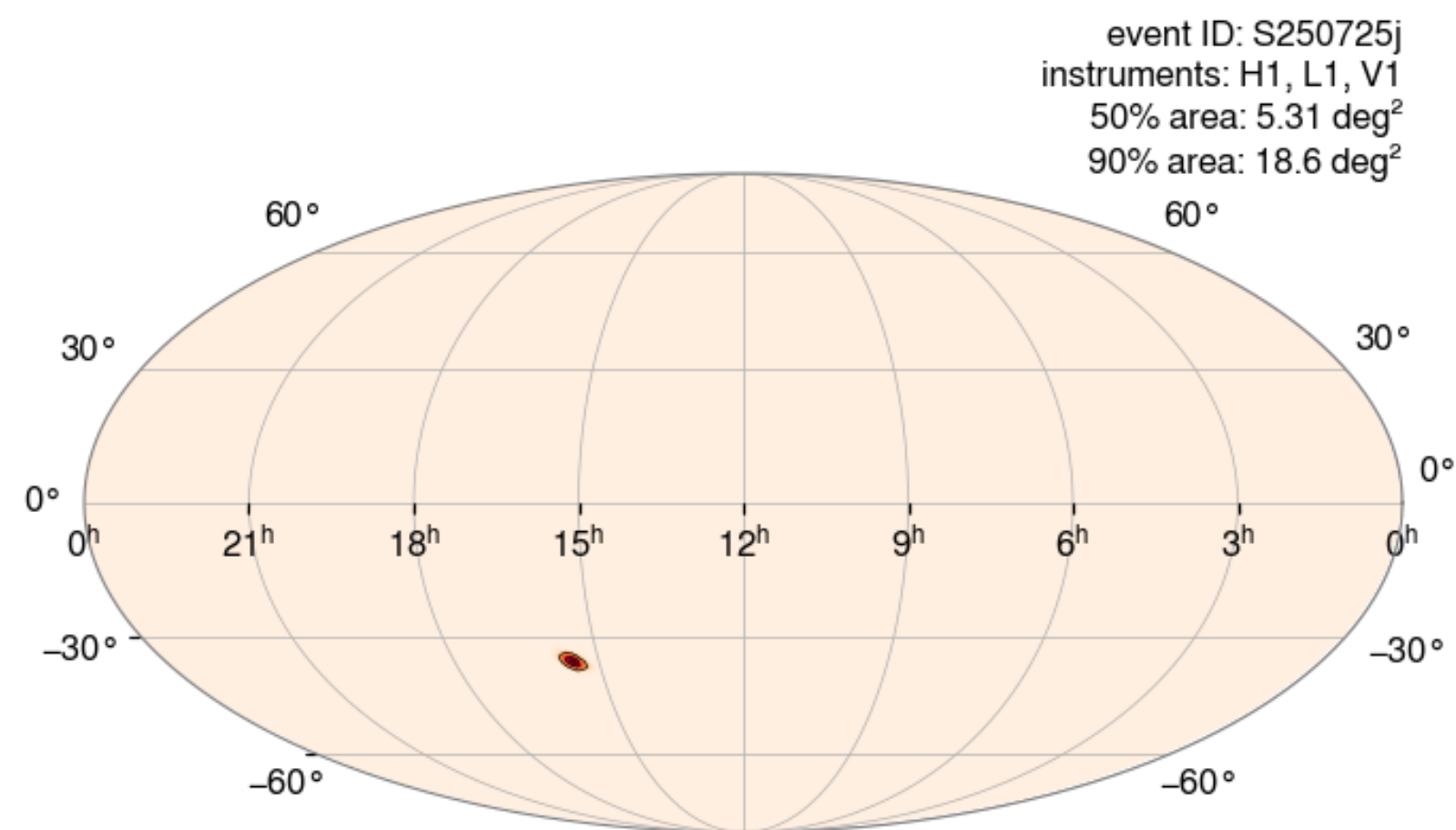
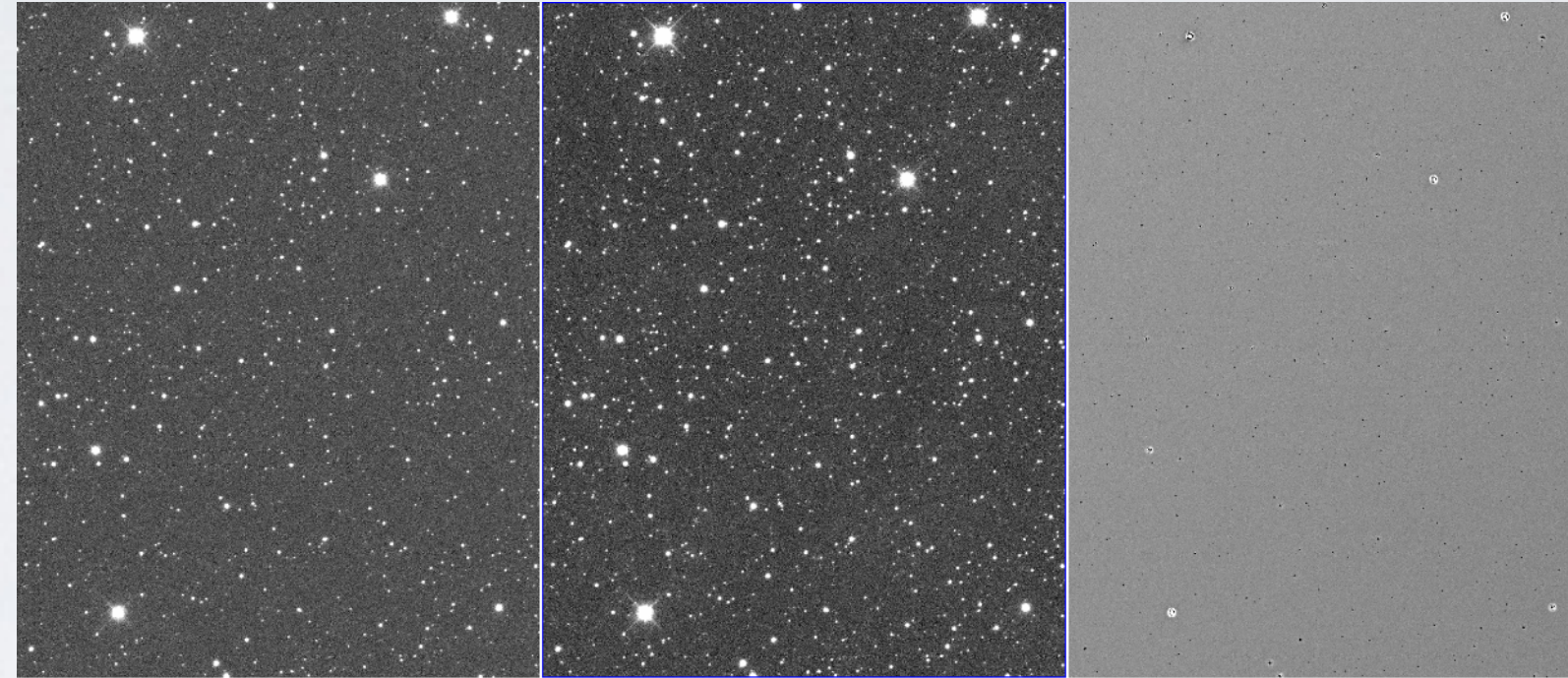
GW Follow-up Observations during O4 Run

- *S250206dm*
- *Localization area: ~910 square degrees*
- *Total observed area: ~90 square degrees*



GW Follow-up Observations during O4 Run

- *S250725j*
- *Localization area: ~ 19 square degrees are all observed.*



Science beyond Gravitational-wave Astronomy

Subject	Now	7DS	Scientific Value
Time-series Spectra of Quasars	~1000	>30,000	Complete Census of SMBH AGN Variability
RM Measurement of SMBH Mass	~100	10,000	Growth History of SMBHs
Velocity Maps of Galaxies	~10,000	50,000,000	Galaxy Evolution
Galaxy Clusters	100,000	100,000	Cosmology, Galaxy Evolution
Early Spectra of SNe	~10	>1,000	Physical Mechanism of SNe
Time-series Spectra of Stellar Objects	1,000,000	10^9	Stellar Evolution
Time-series Spectra of Small Bodies of the Solar System	100	>10,000	Origin of the Solar System, Census of Asteroids/Comets

Survey Plan: the 7-Dimensional Sky Survey (7DS)

1. Reference Imaging Survey (RIS): >30% completion

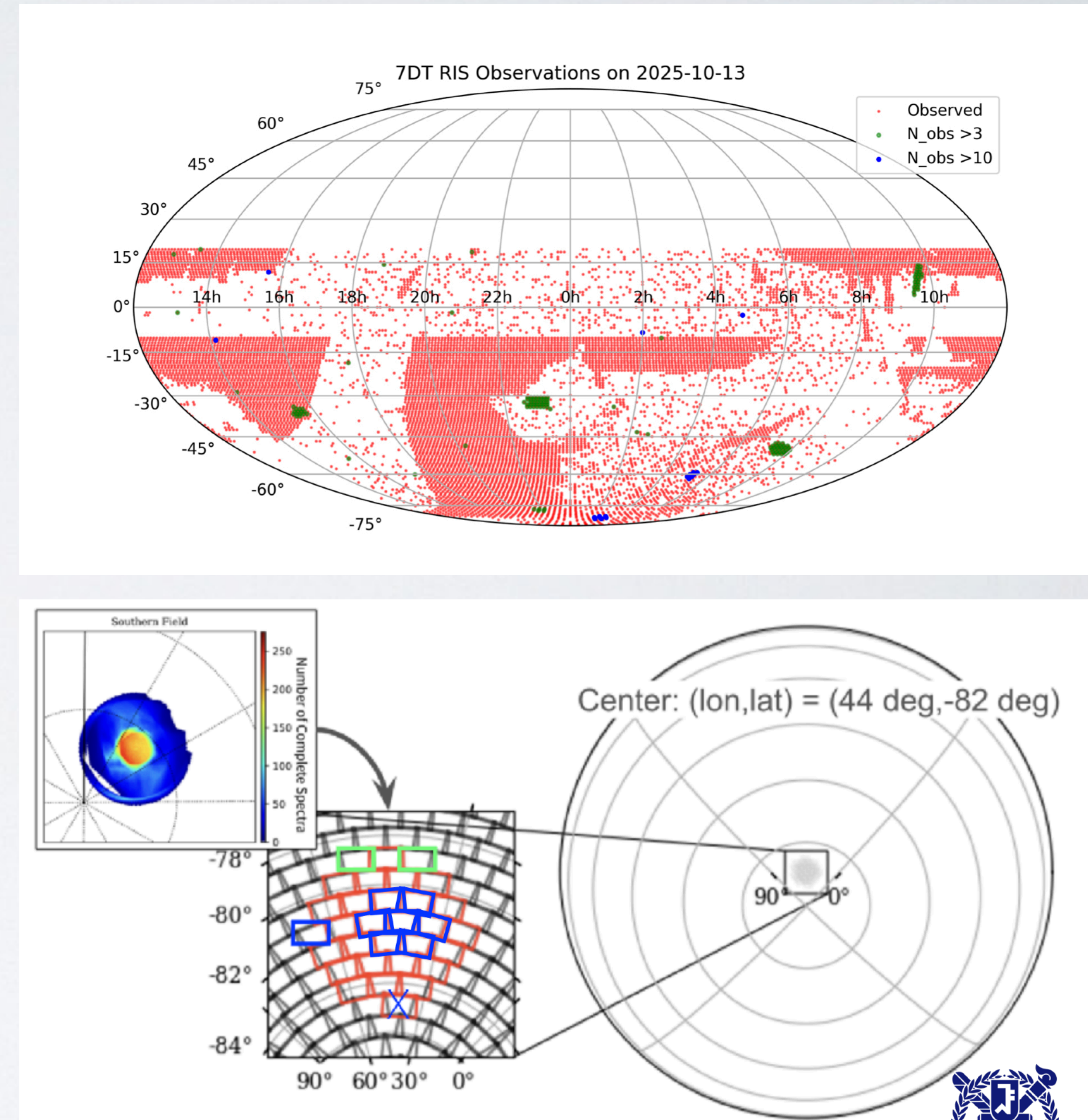
- 1 visit with 5 minutes total exposure
- the Southern Hemisphere (Dec < 20°, ~23,000 square degrees)

2. Wide-Field Time-Domain Survey (WTS)

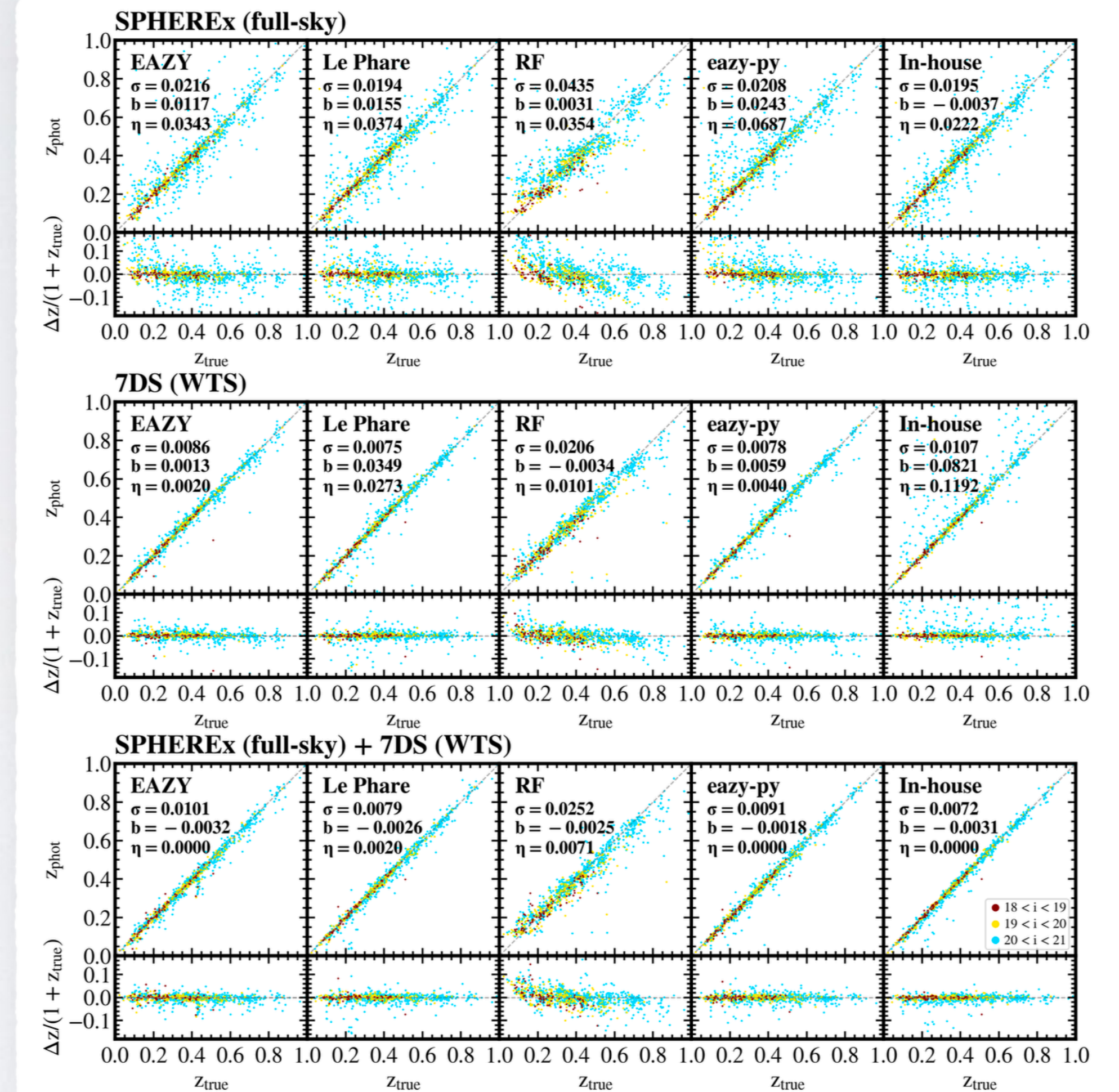
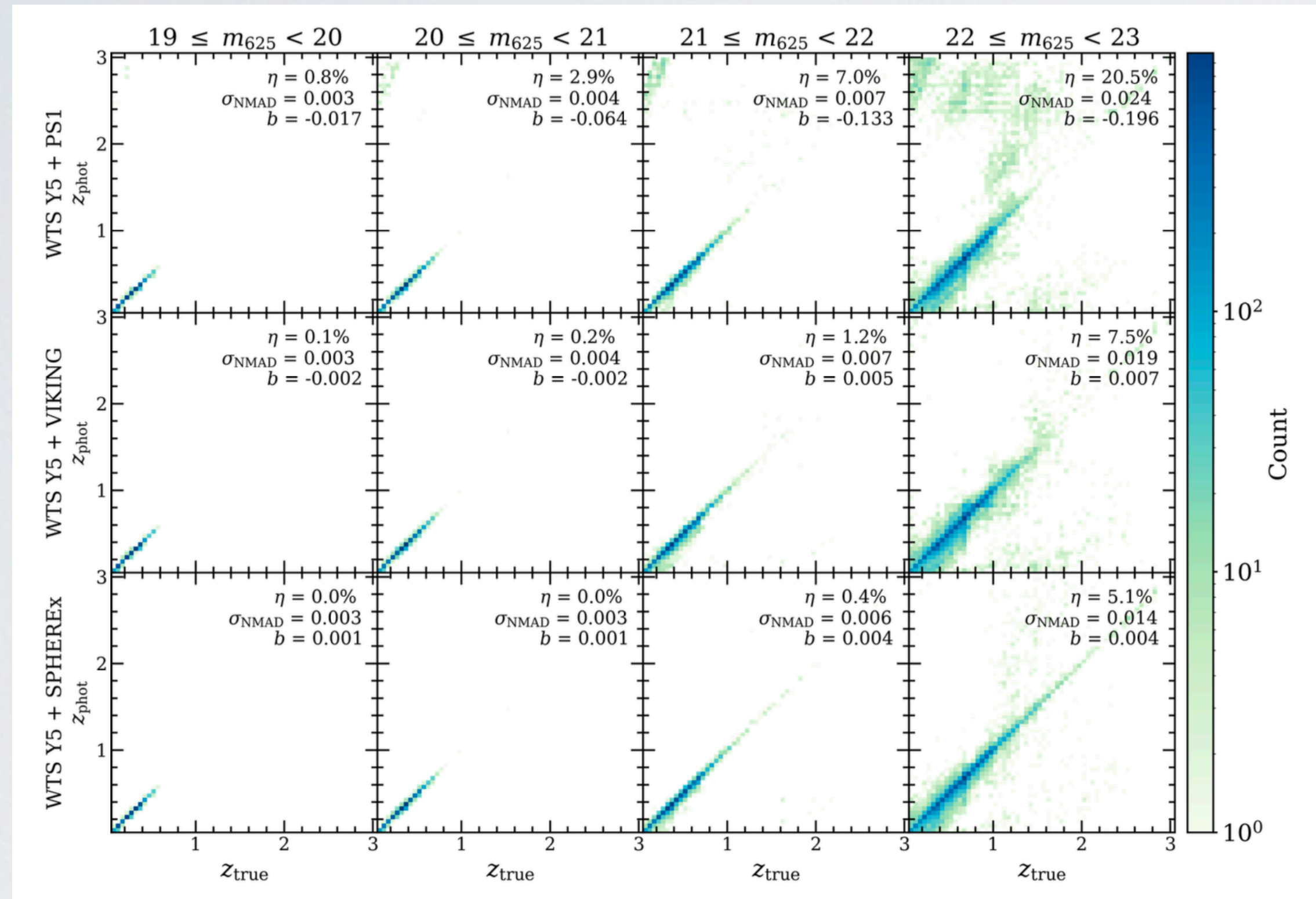
- 1 visit per 10 ~ 14 days; 80 ~ 100 minutes per year; up to 6.5 hours for 5-year operation
- Target field candidates: Rubin's Deep Drilling Fields, VIKING, VIDEO, etc.

3. Intensive Monitoring Survey (IMS):

- AKARI Deep Field South (~8 square degrees)
- 1 visit per day; 1,200 ~ 1,500 minutes per year; up to 65 hours for 5-year operation

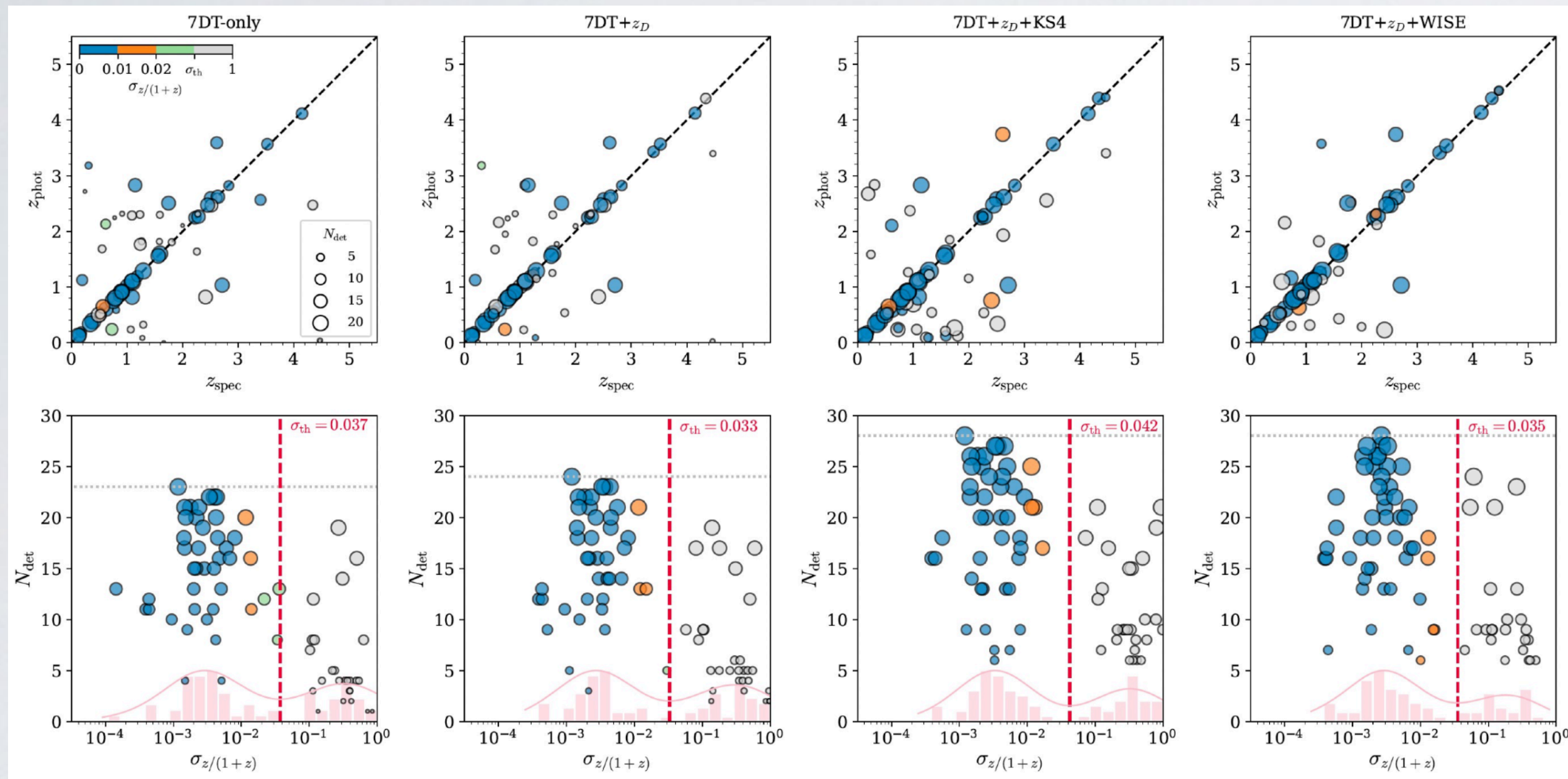


Science beyond Gravitational-wave Astronomy: Photometric Redshift Measurement

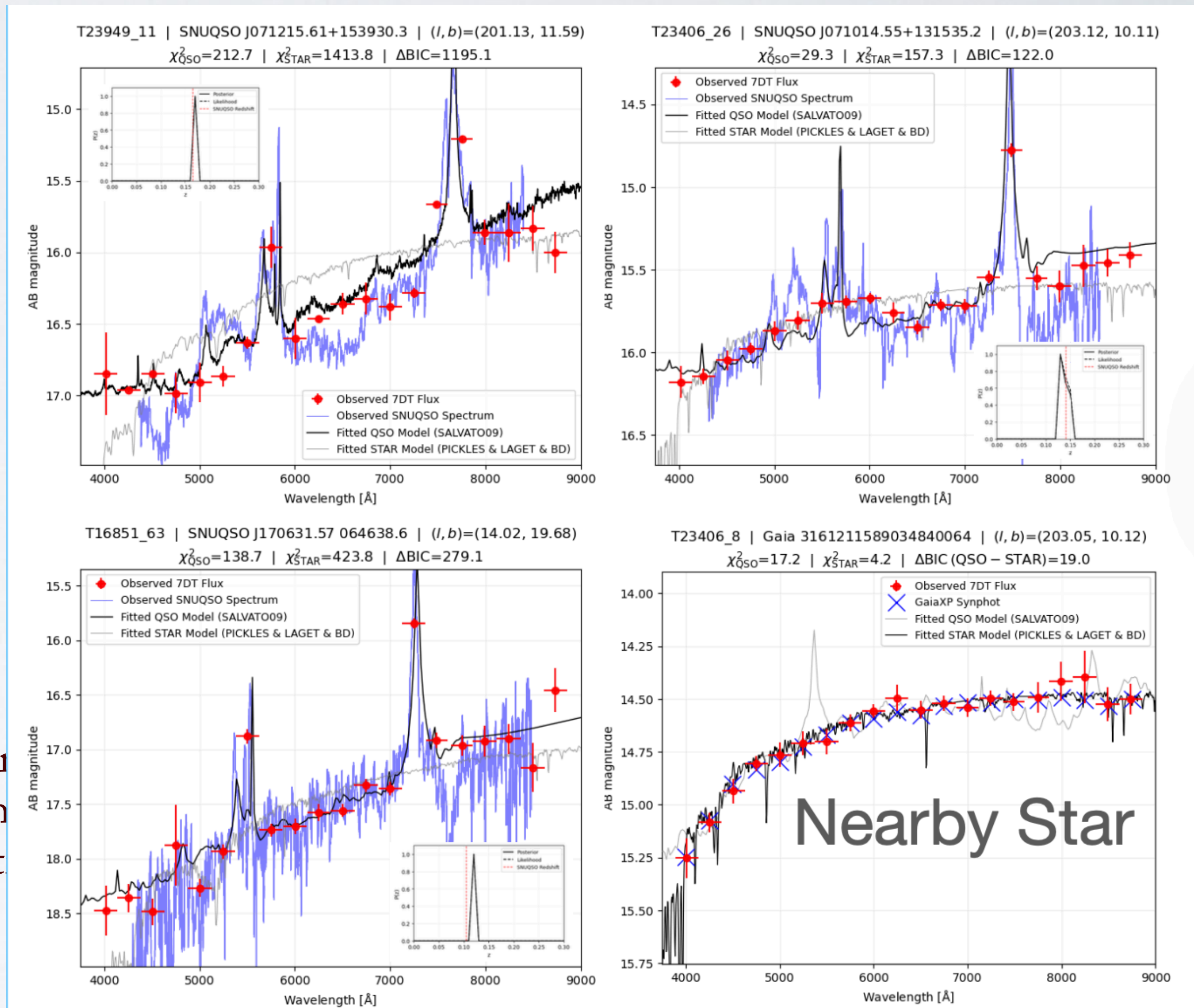


Comparison between spectroscopic redshifts with photometric redshifts. Left: Comparison based on year 5 data of WTS combined with PS1, VIKING, and SPHEREx depending on objects' magnitude. (Ko et al. ApJ, *Accepted*) Right: Comparisons based on WTS, or SPHEREx, or both. (Bae et al. ApJ, *Submitted*)

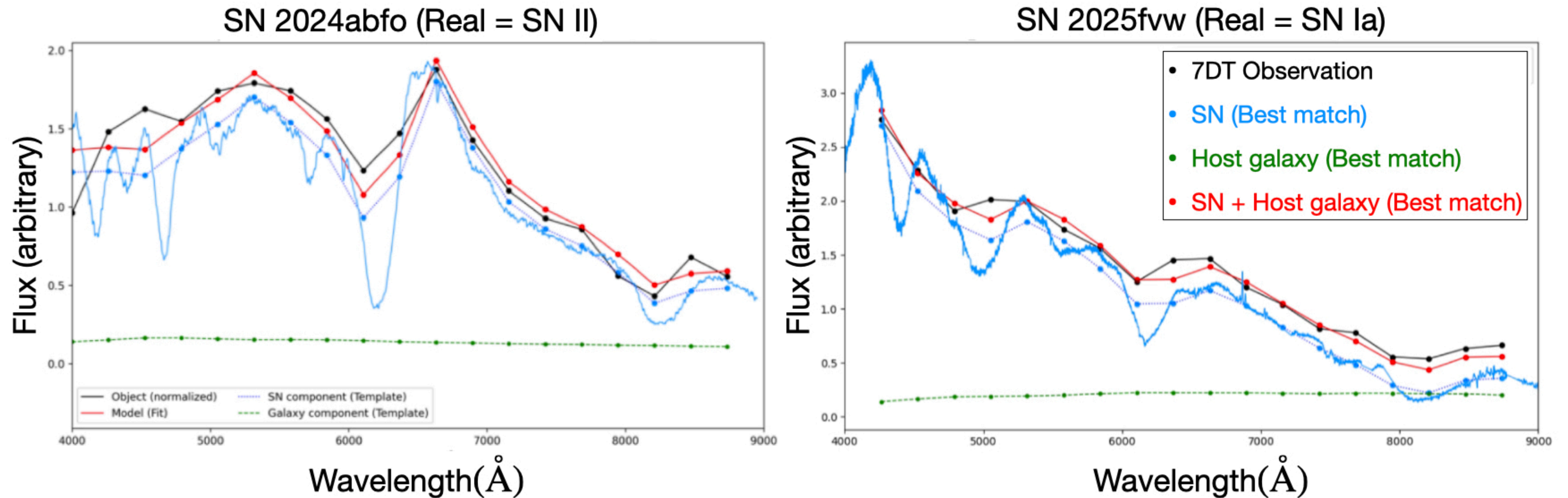
Science beyond Gravitational-wave Astronomy: Discovery of Quasars and Galaxies in the Southern Sky



Left: Performance analysis of photometric redshifts based on 7DT and ancillary data for the quasars confirmed in the southern sky. Courtesy of Y. Kim. Right: Spectral energy distribution fitting of quasar candidates in the low galactic latitude regions obtained by 7DS. Courtesy of D. Seol.



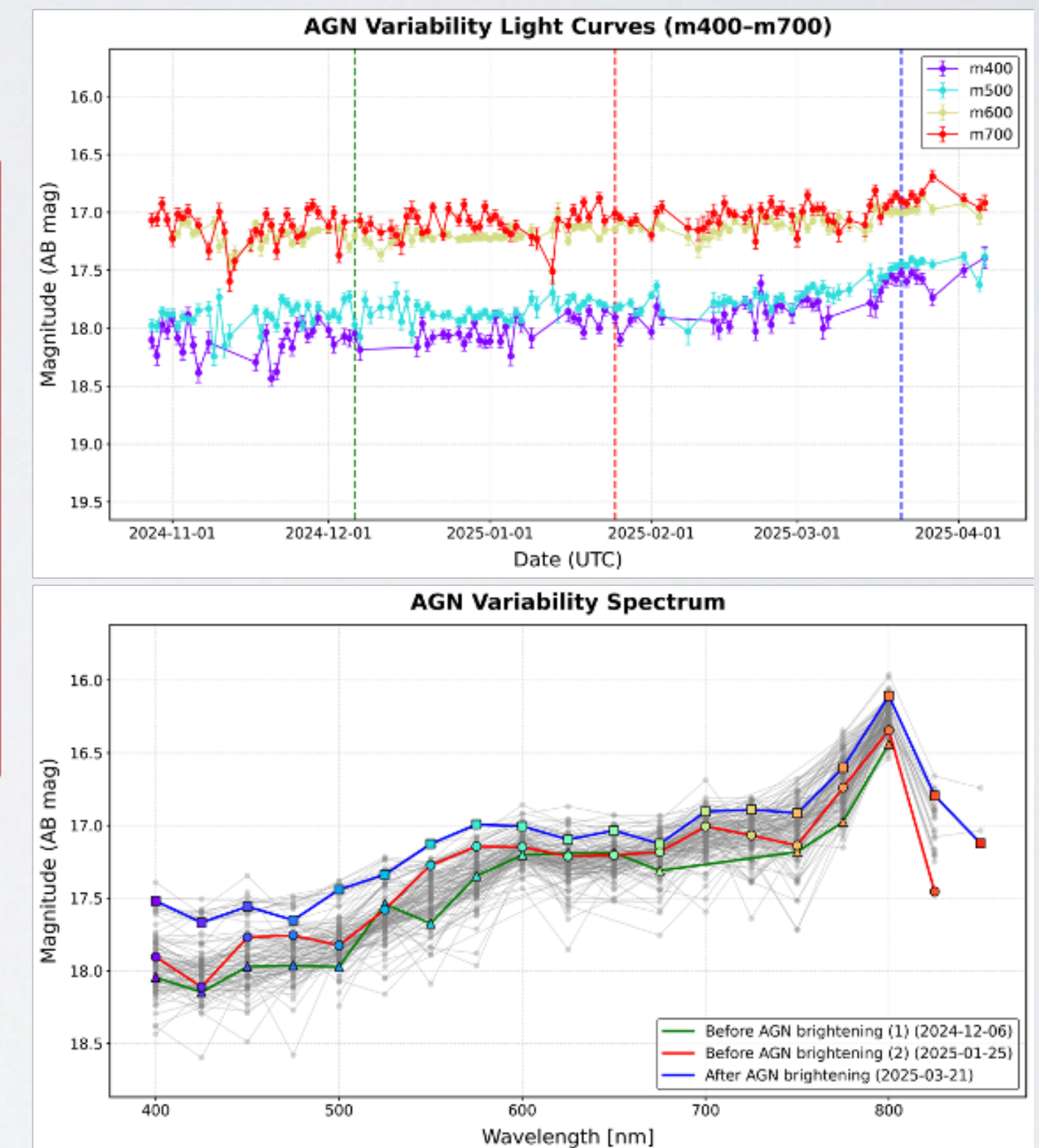
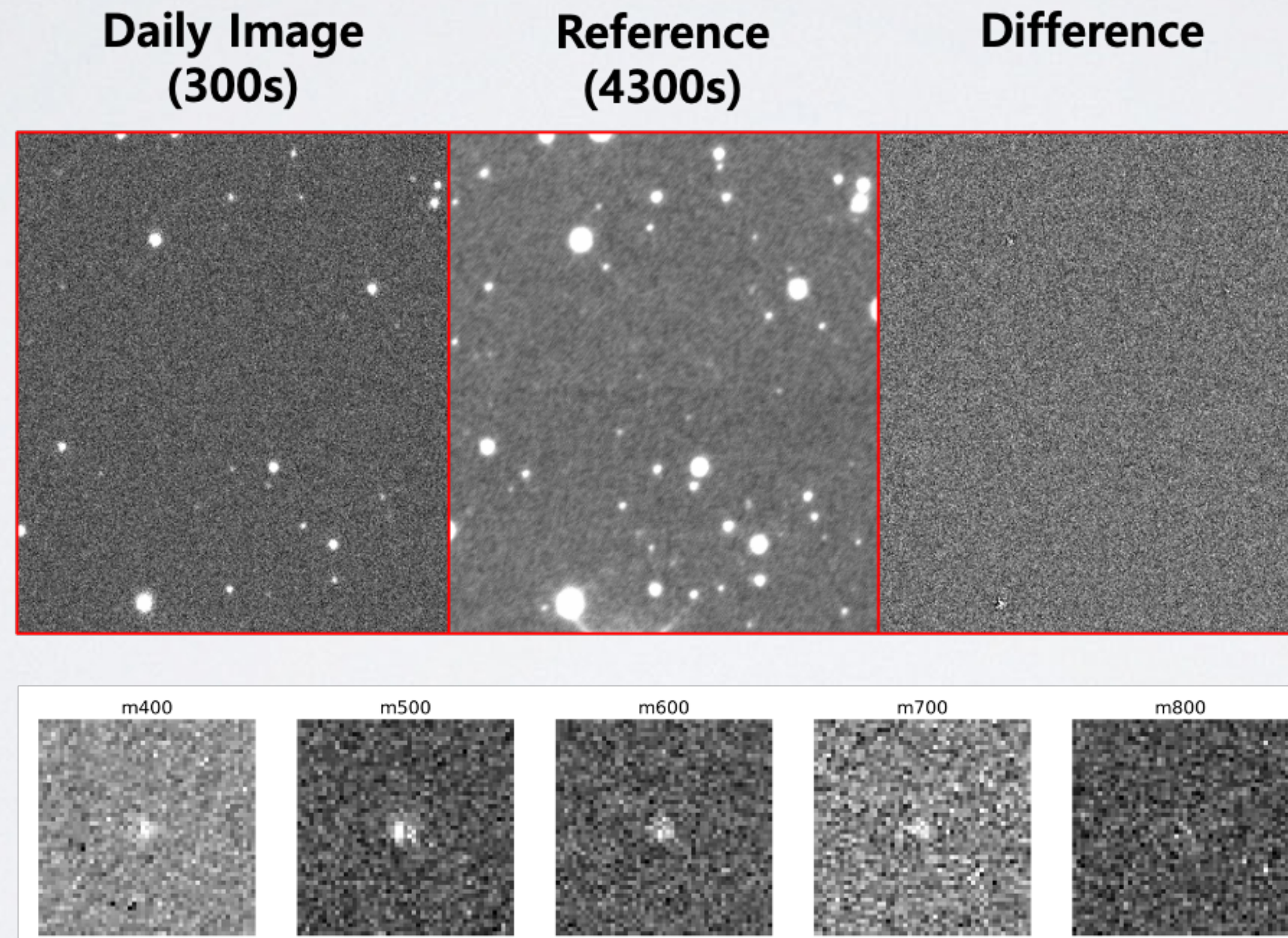
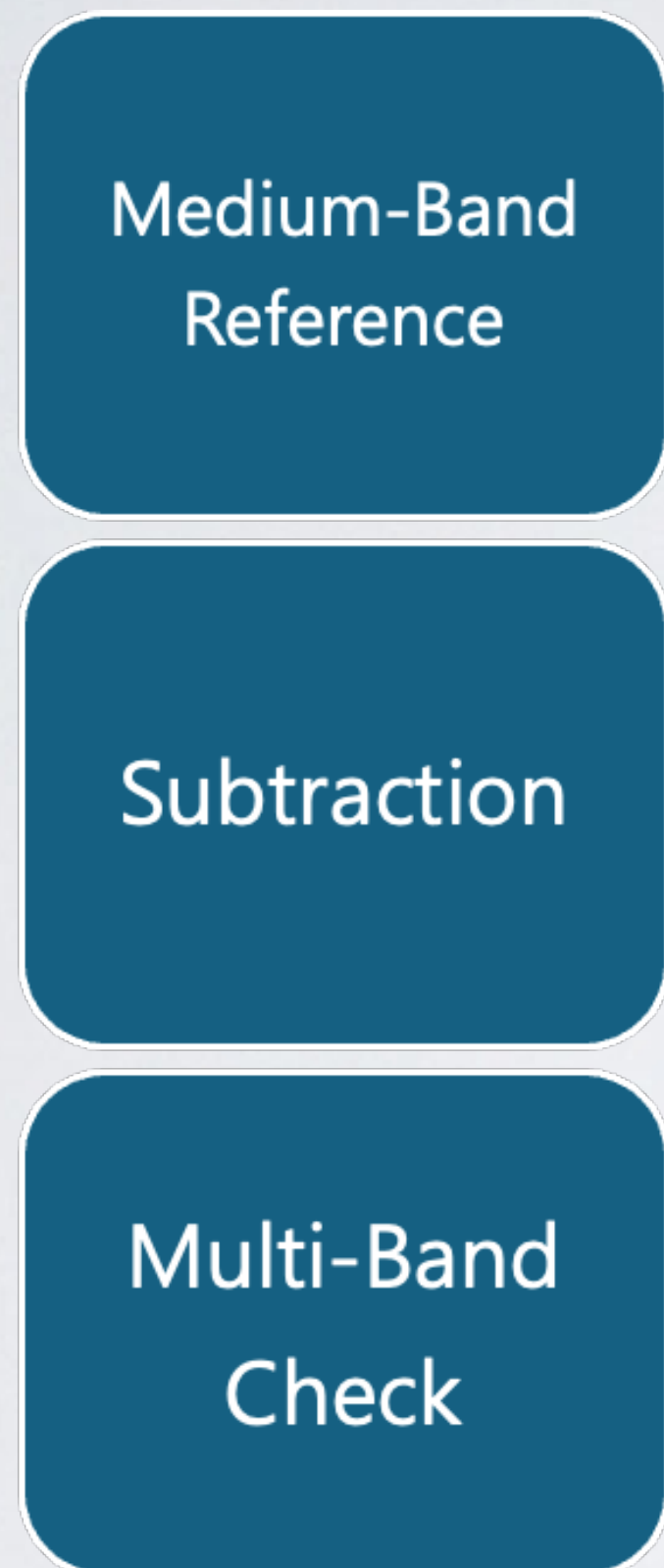
Science beyond Gravitational-wave Astronomy: Transient Follow-up Observation



Next Generation SuperFit (NGSF)

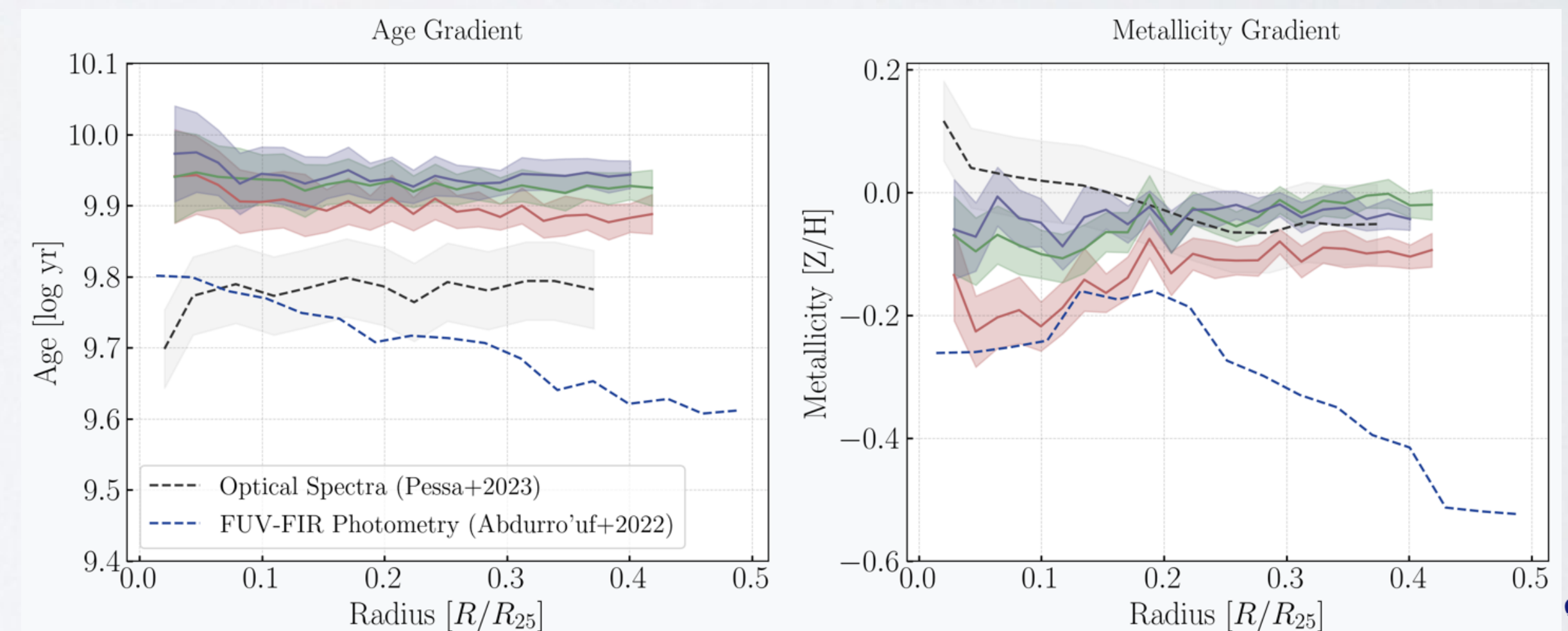
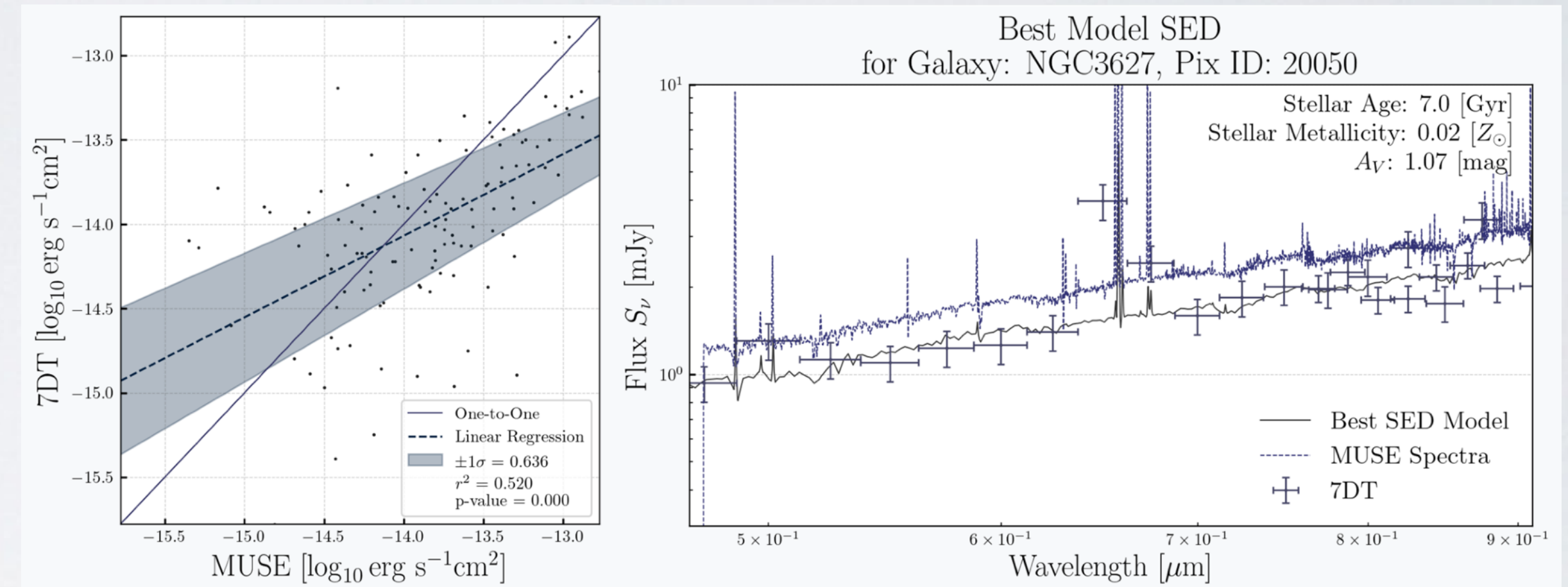
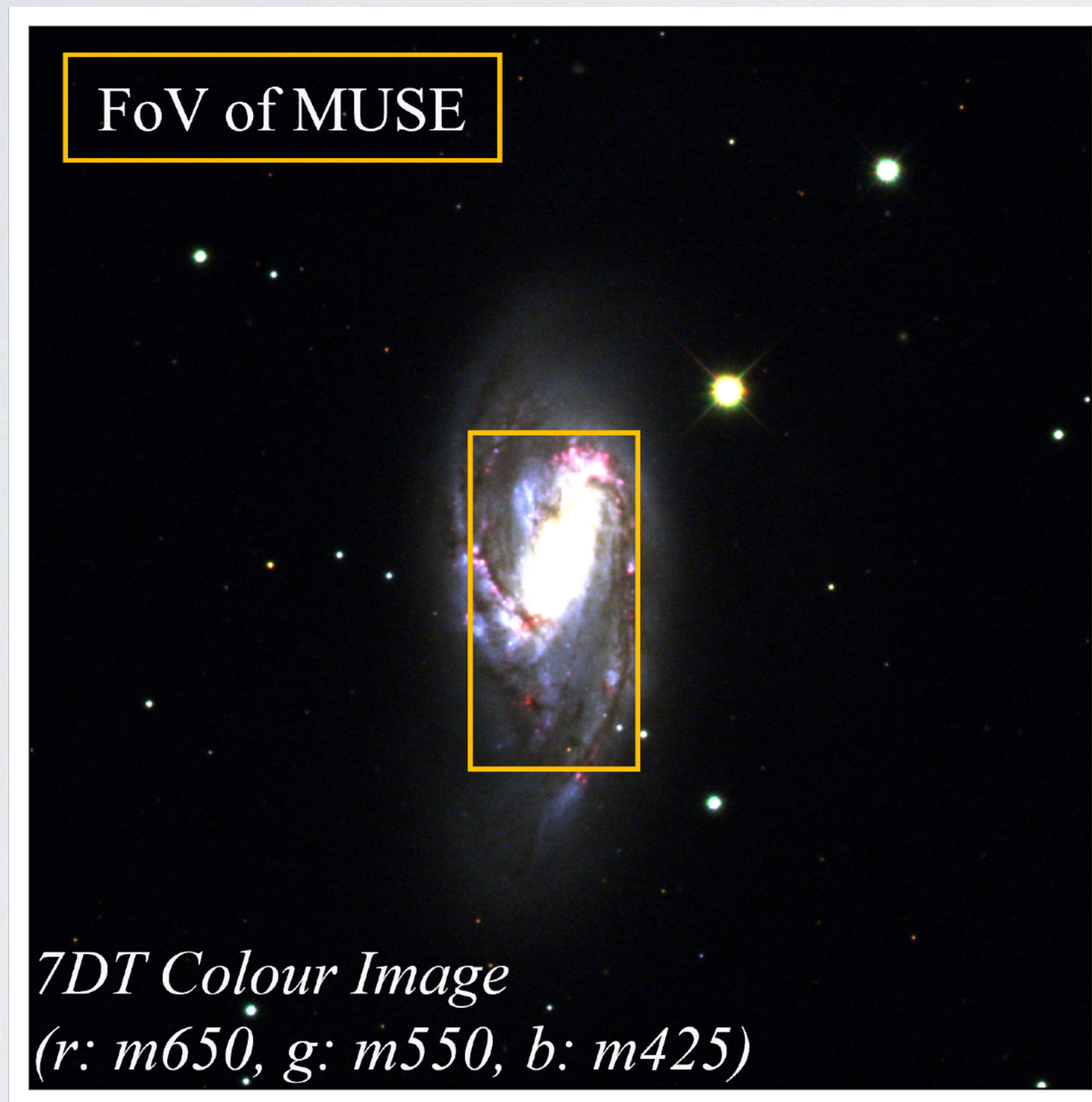
- *Template-based fitting: Host galaxy template + Supernova template = Composite spectrum*

Science beyond Gravitational-wave Astronomy: Transient Search in Multi-epoch Data



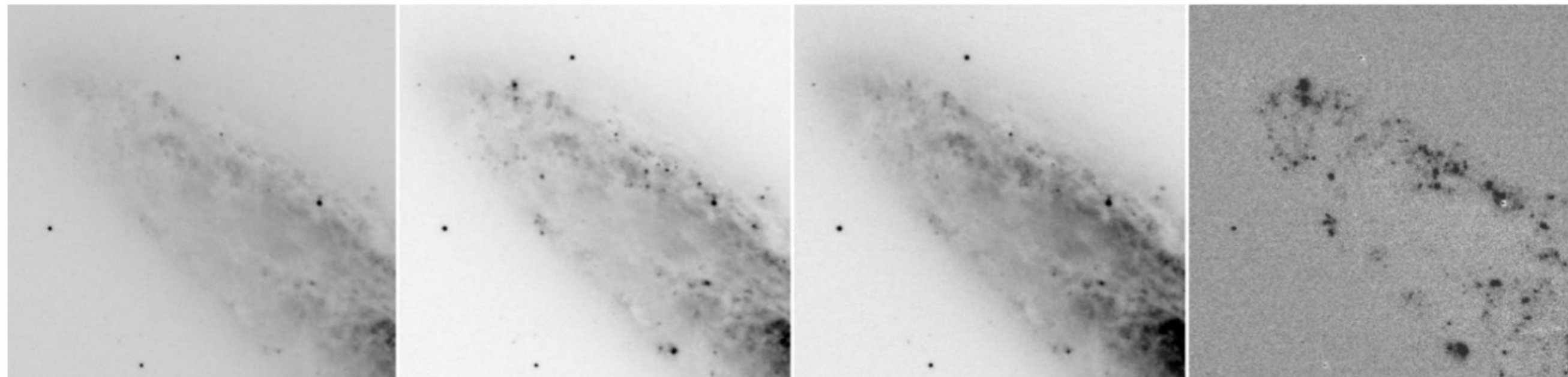
Left: Schematic flow for transient detection. Middle: Sample images to show how the differential imaging analysis processes. Right: An AGN candidate discovered within 7DT Time-Domain Verification Field

Science beyond Gravitational-wave Astronomy: Resolved Stellar Populations in Nearby Galaxies



Left: Fov of MUSE, Right Top: Example of the best SED model, Right Bottom: Stellar age and metallicity gradients of NGC 3627

Science beyond Gravitational-wave Astronomy: Resolved Stellar Populations in Nearby Galaxies



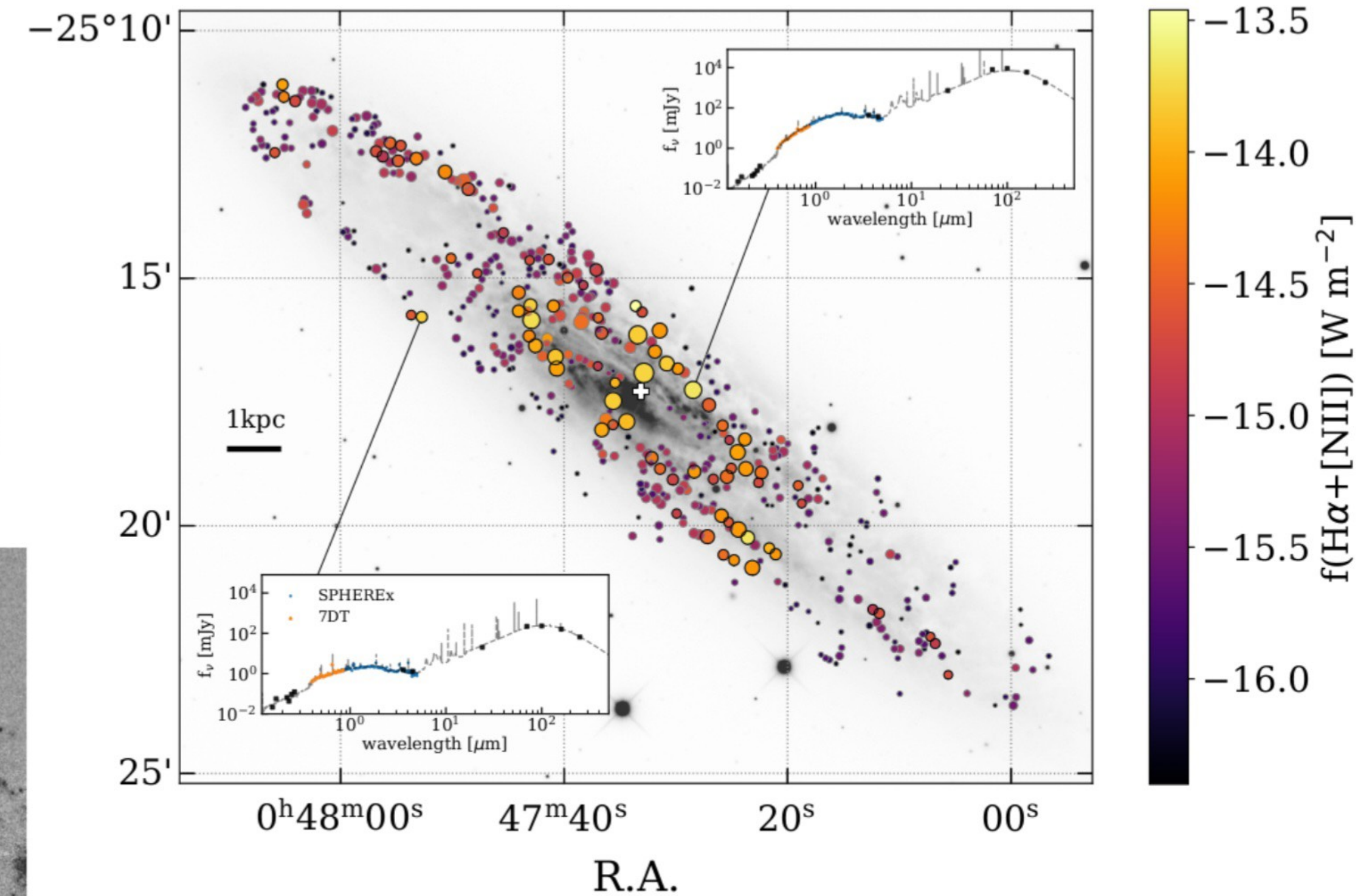
m625

m650

m675

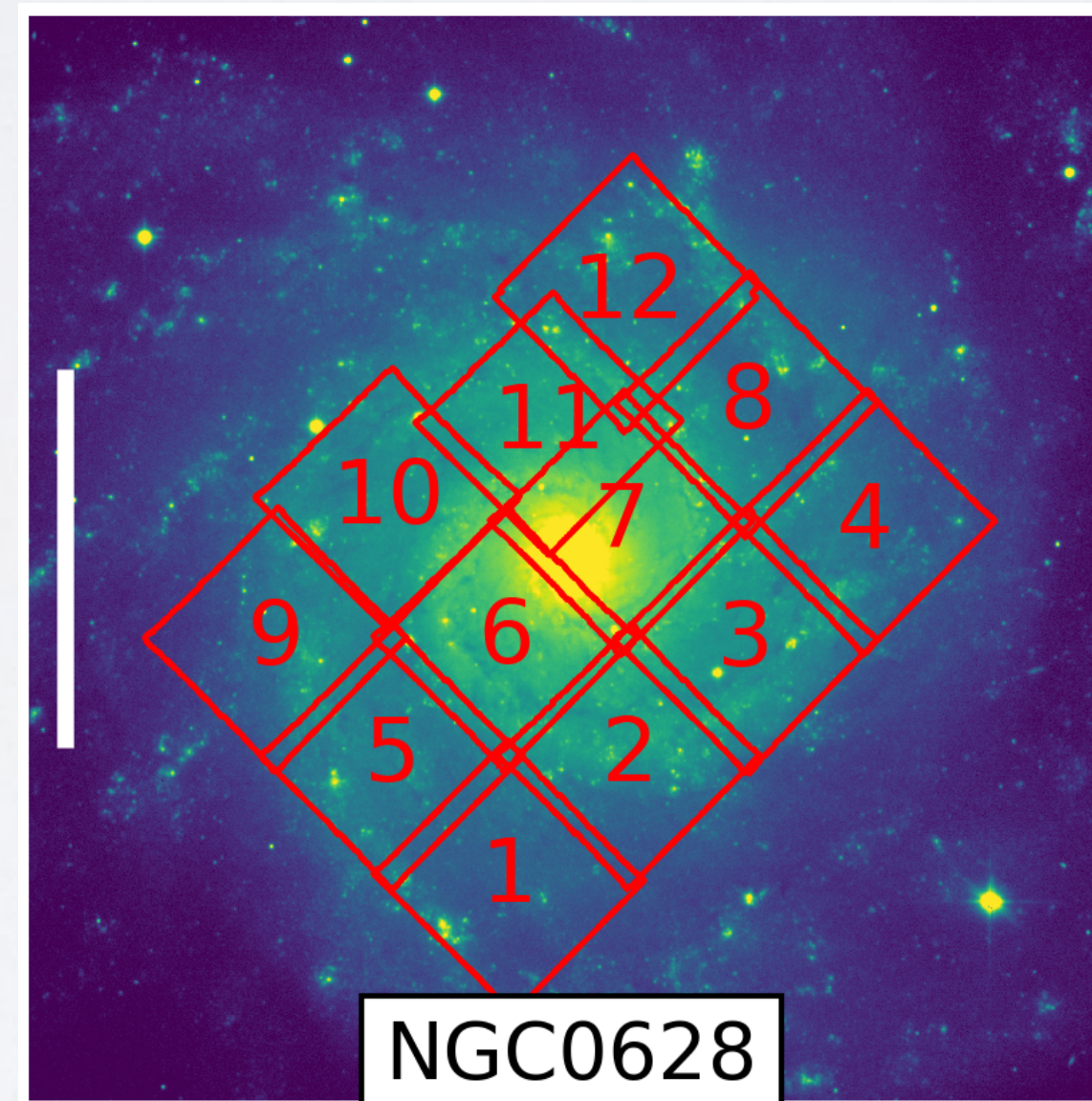
m650-(c₁m625+c₂m675)

Decl.

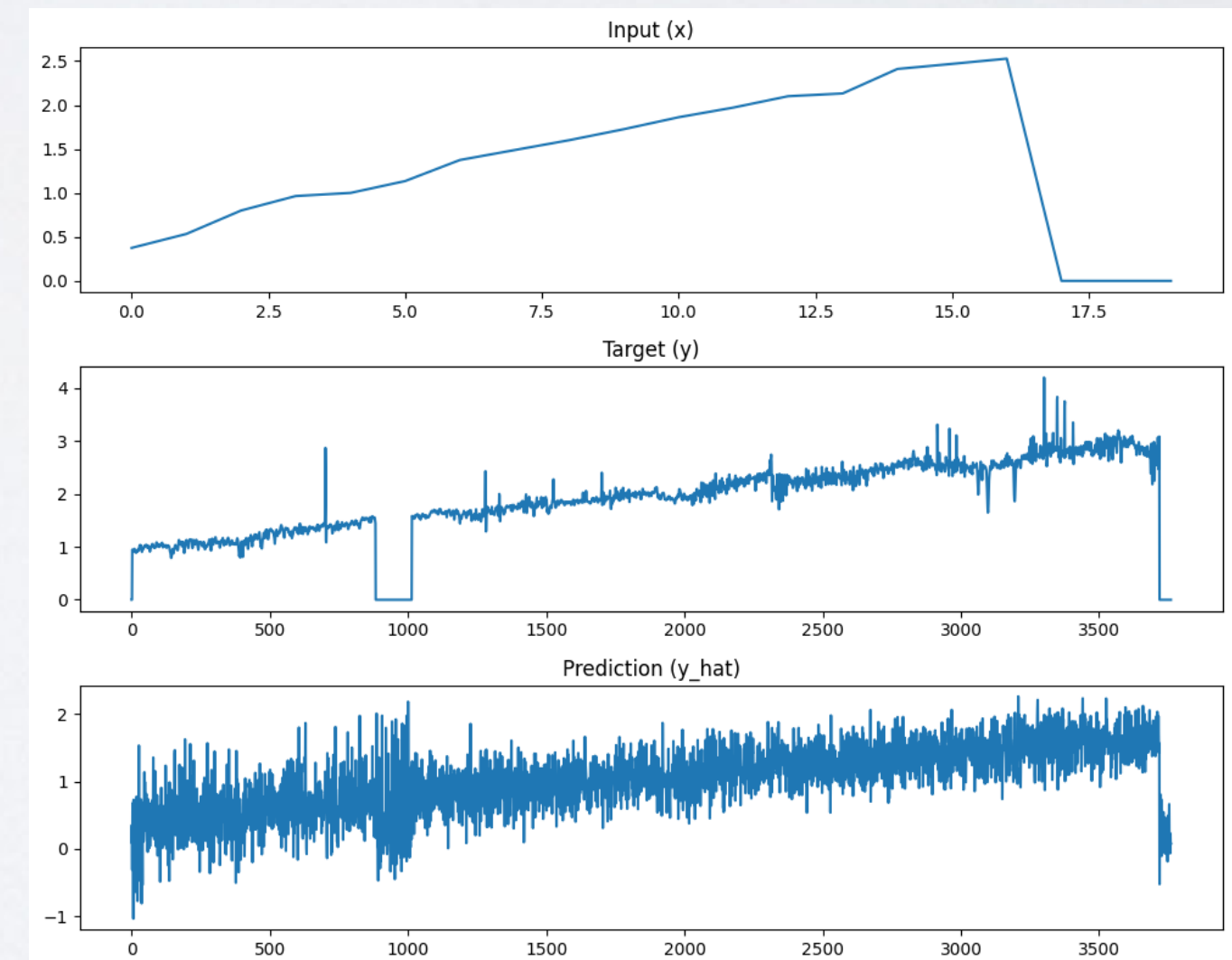
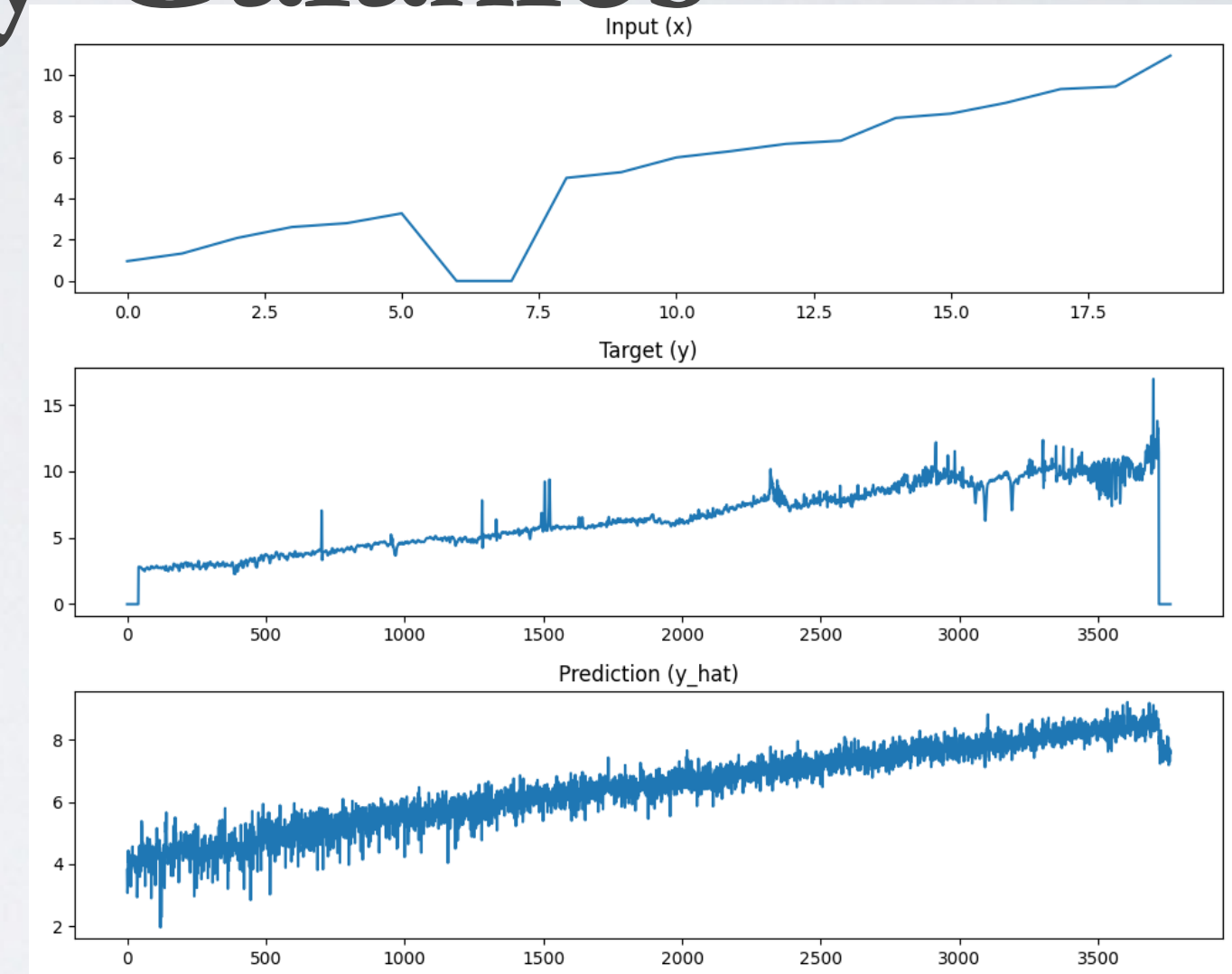


Science beyond Gravitational-wave Astronomy: Resolved Stellar Populations in Nearby Galaxies

We can train a machine-learning algorithm on low-resolution spectra from 7DS and high-resolution spectra from MUSE. Eventually, this trained algorithm will enhance the spectral resolution of 7DS spectral mapping of nearby galaxies.



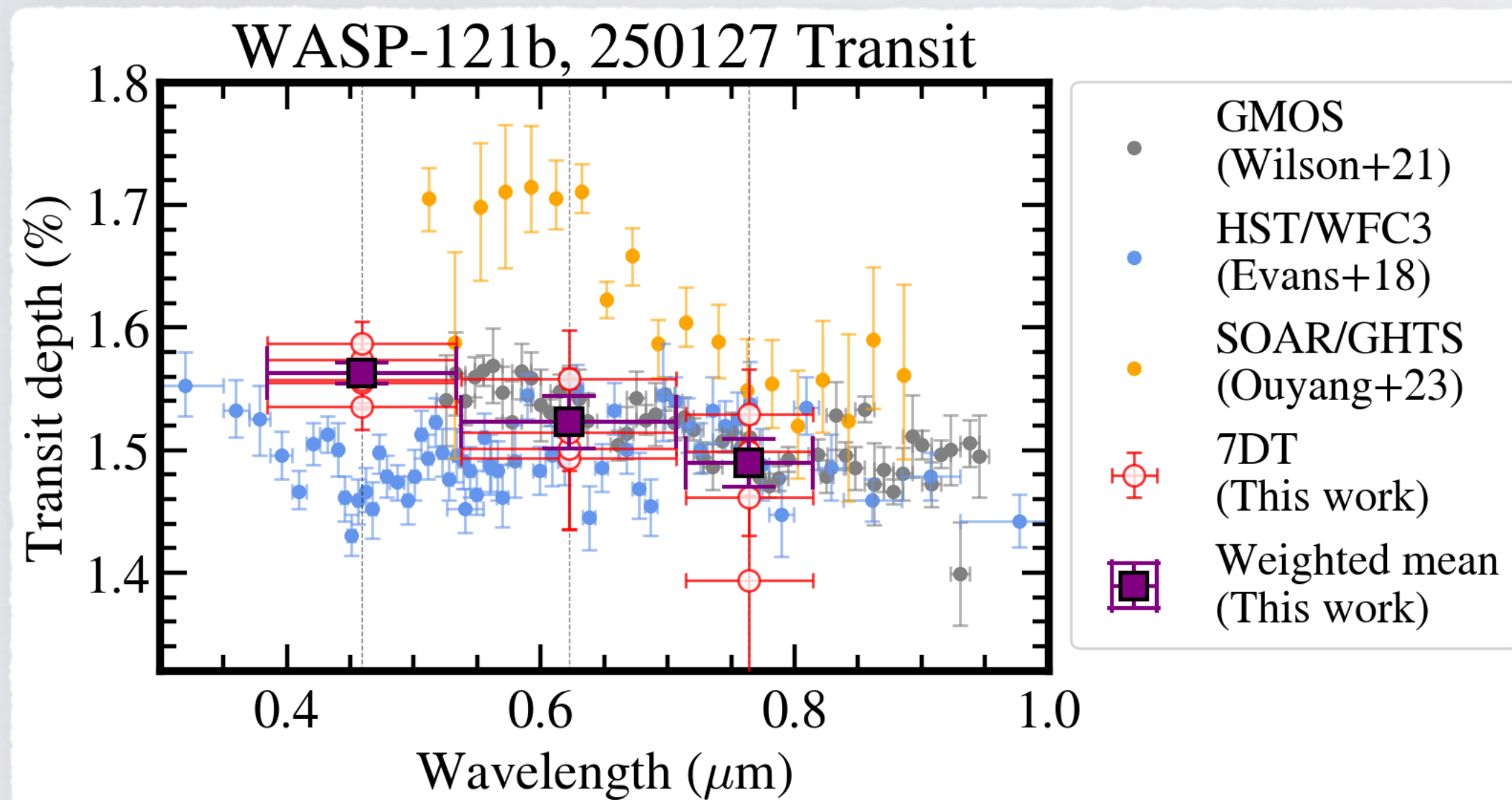
Left: A three color image of NGC 628 based on 7DT images. Right: The schematic view of PHANGS-MUSE tiles for NGC 628.



Science beyond the Originally Sought-after Projects

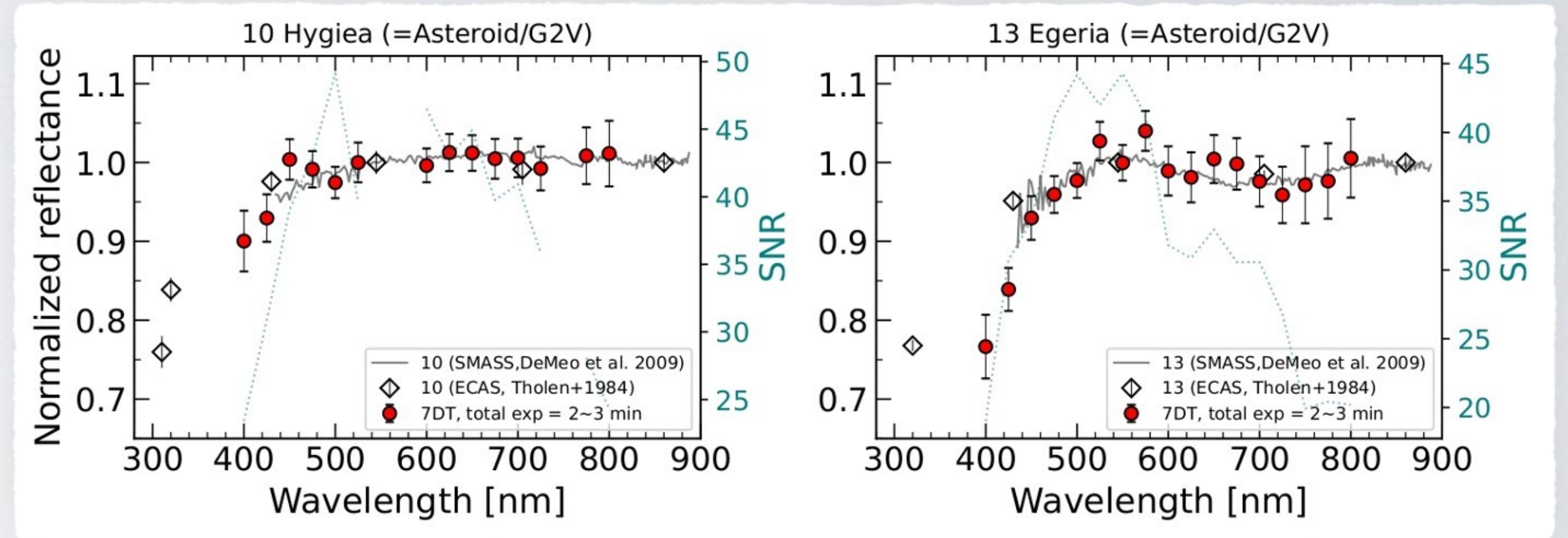
- Composition of Exoplanet Atmosphere

- Ultra-hot Jupiter with $T_{eq} \sim 2400$ K
- Temporal variation
- Presence of TiO/VO



Transition Depth of WASP-121b

- Composition of Asteroids



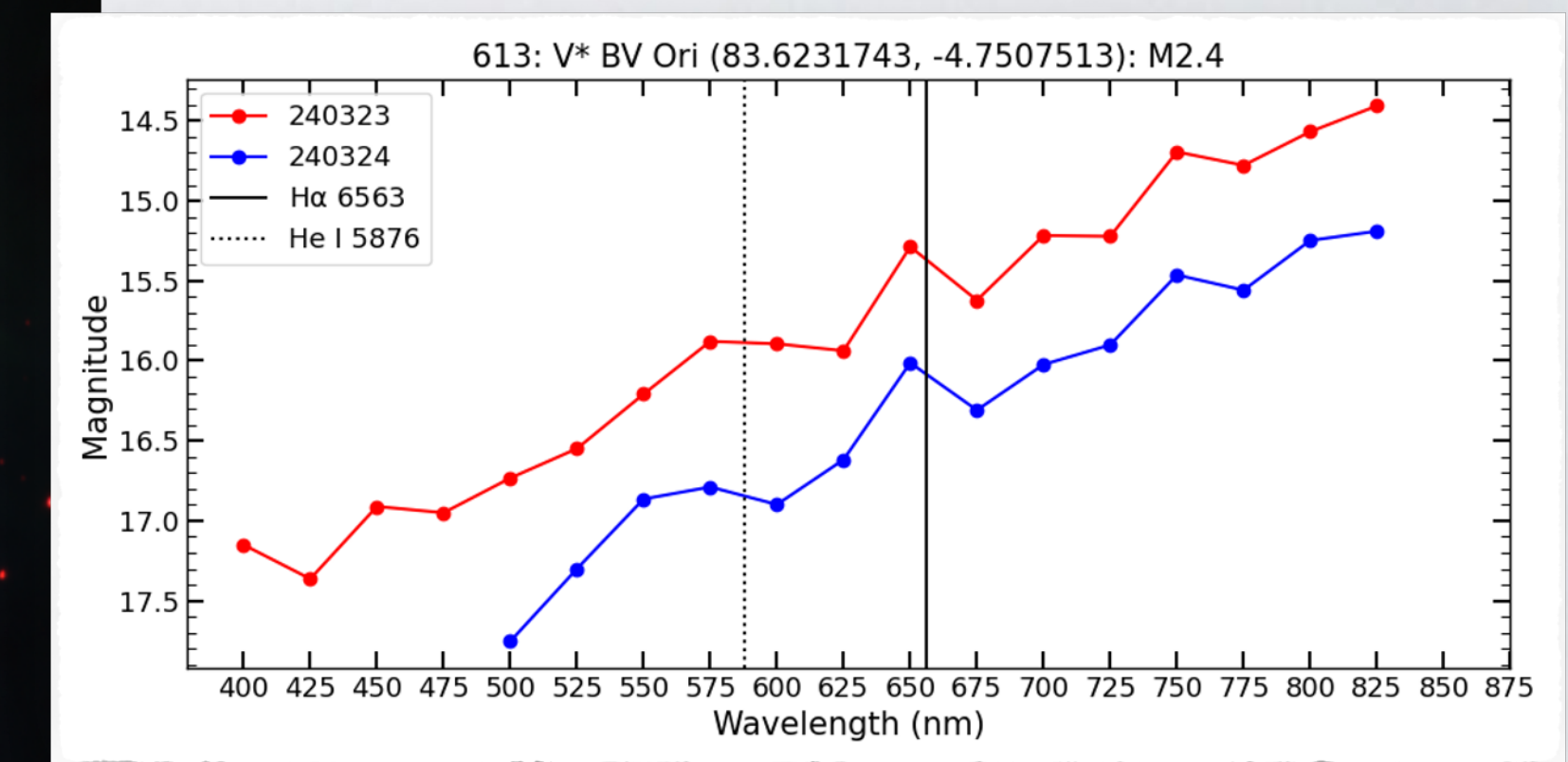
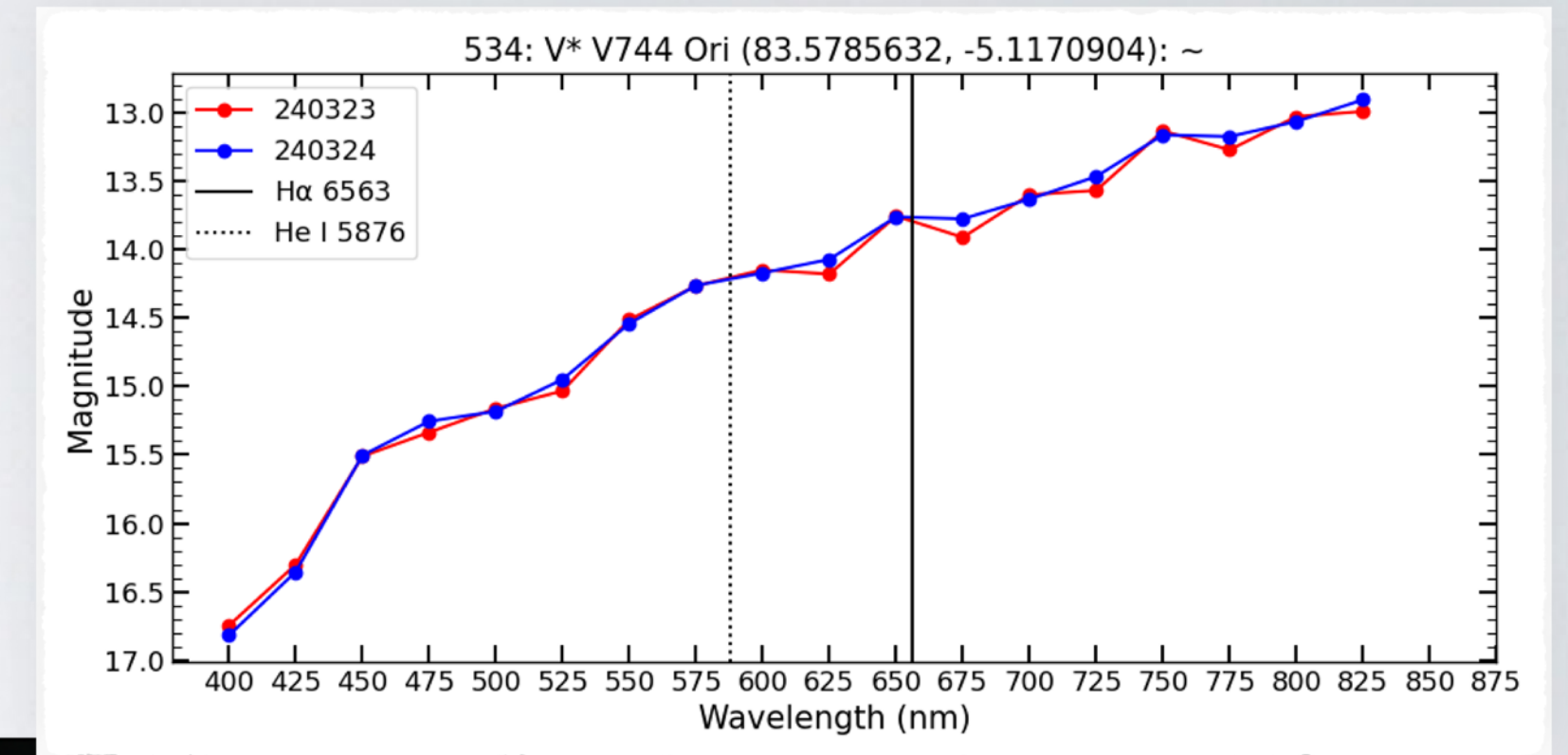
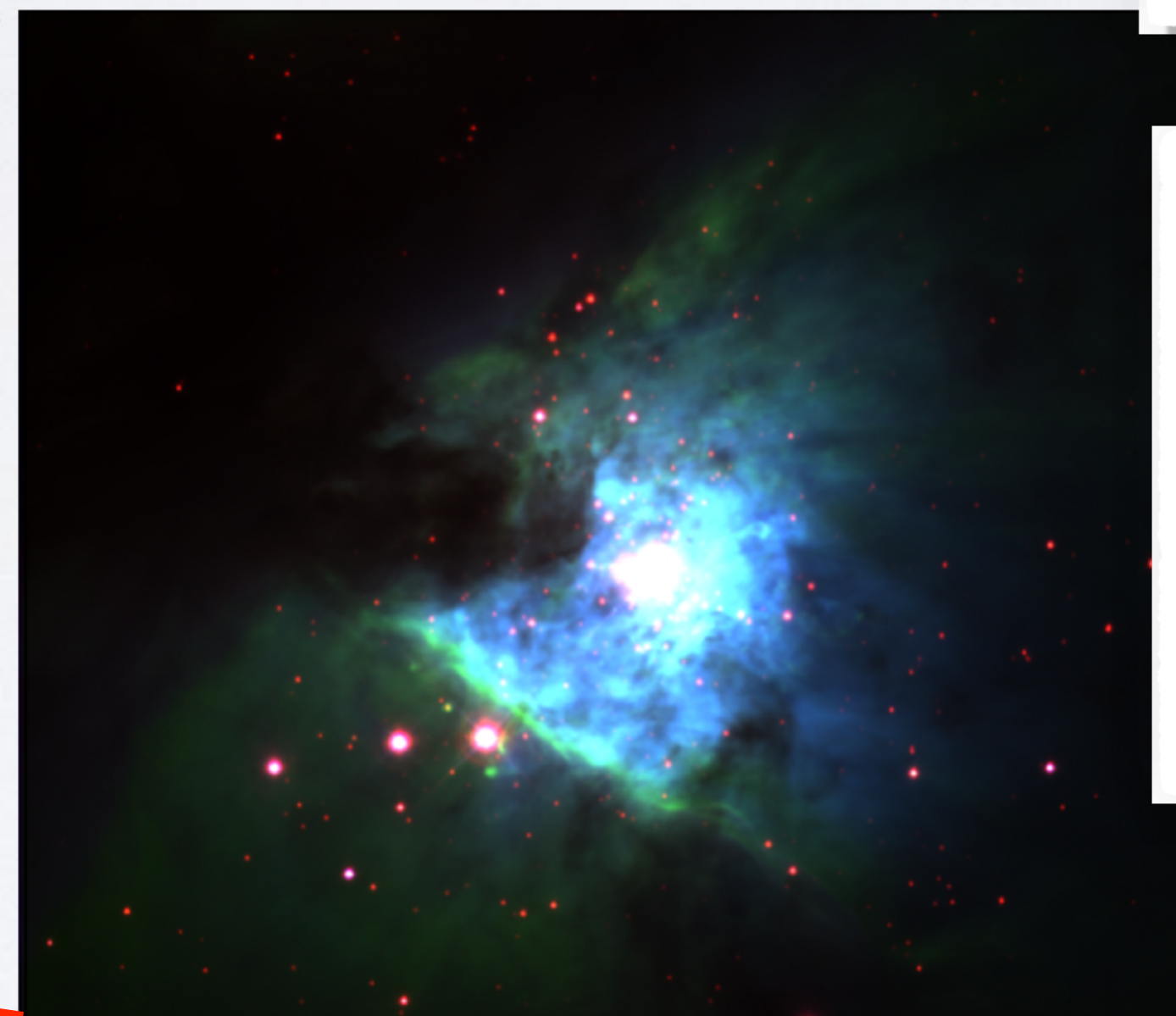
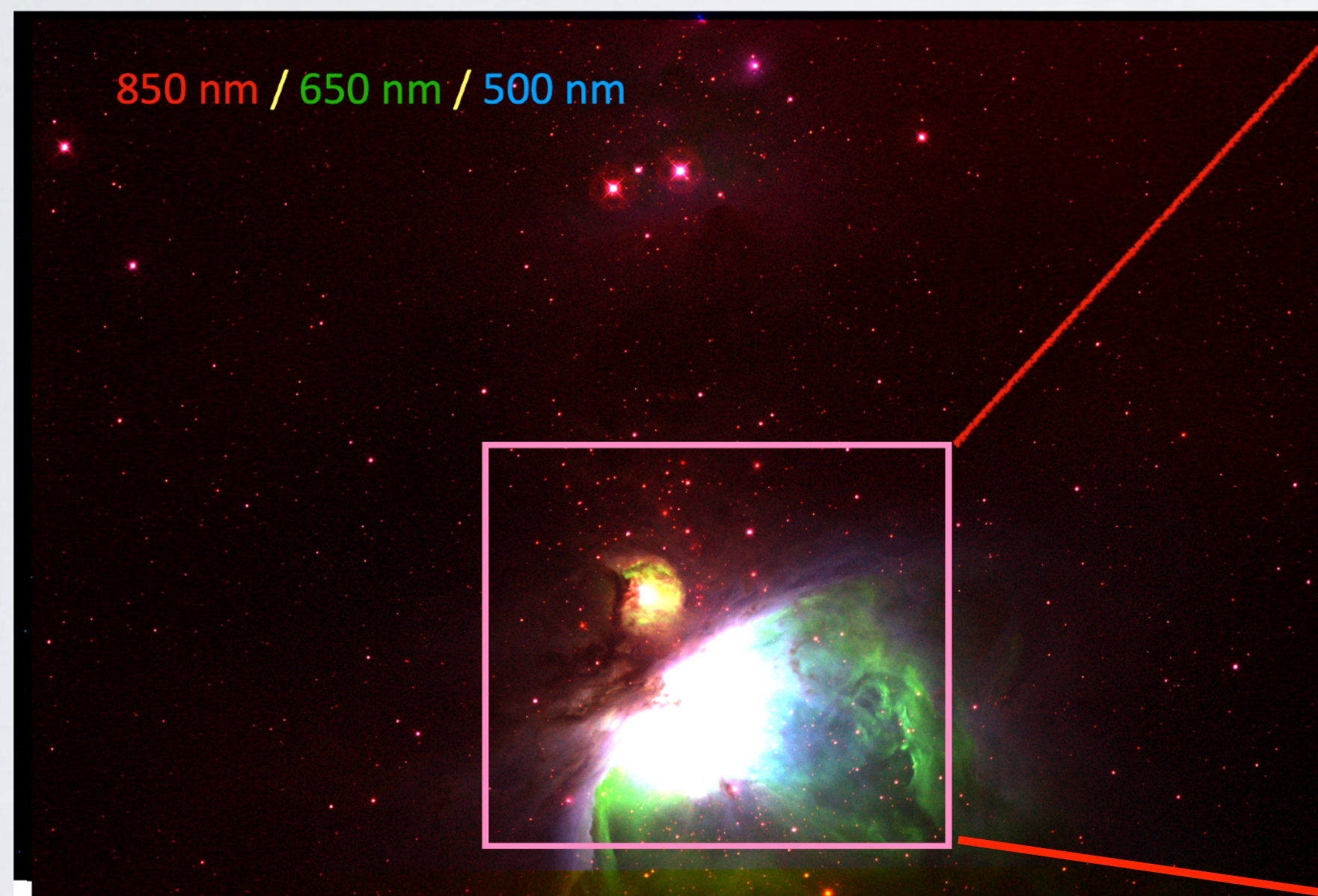
7DT spectra of 10 Hygiea and 13 Egeria provided by J. Geem

- $0.7\mu\text{m}$ absorption feature of hydrated asteroids
- Constraints on thermal evolution on the asteroids

Science beyond the Originally Sought-after Projects

- *Discovery of YSOs, T-Tauri Stars*

- *Detection of uncataloged T-Tauri stars*
- *Variability of H- α emission*

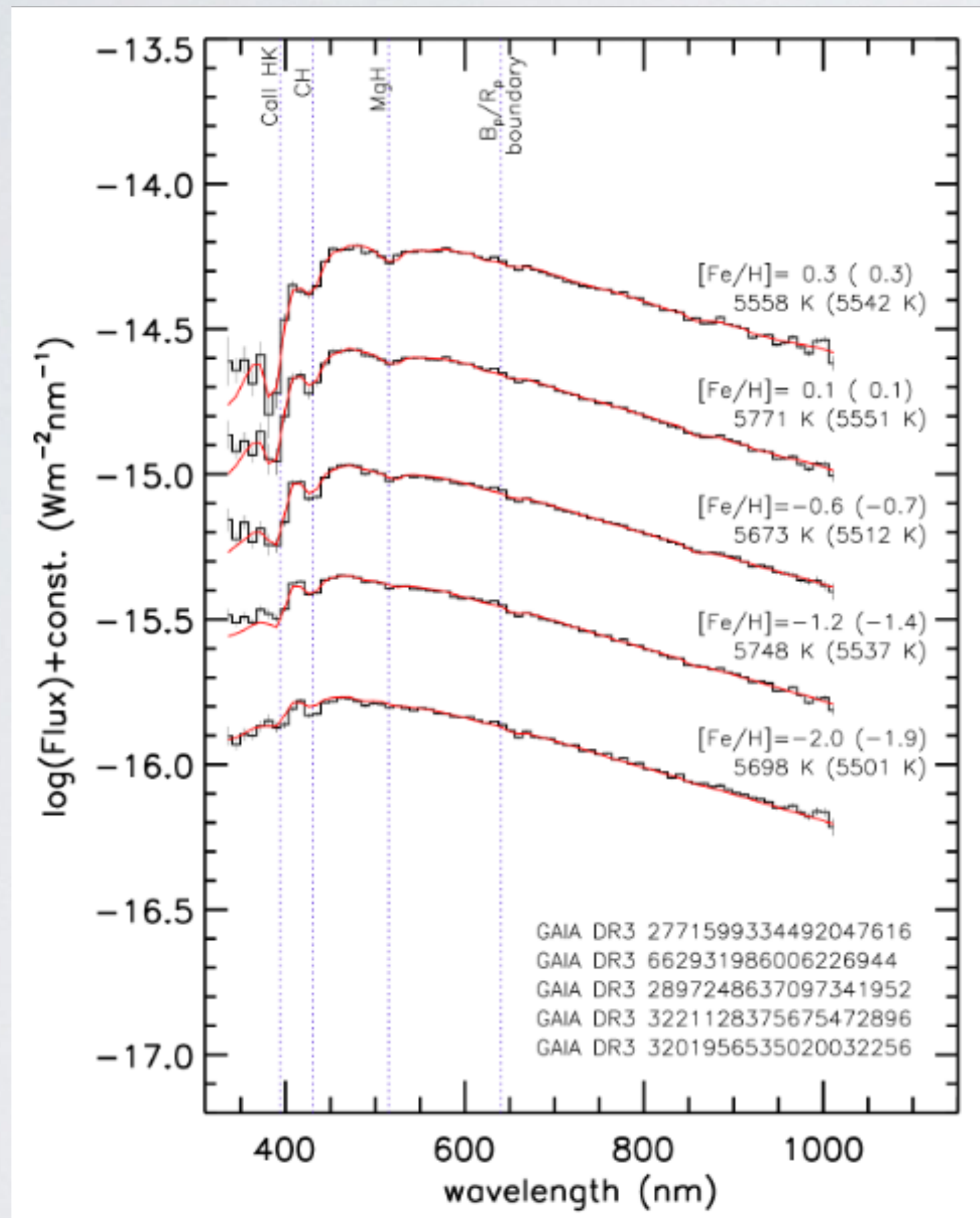


Various spectra of T-Tauri stars obtained by 7DT

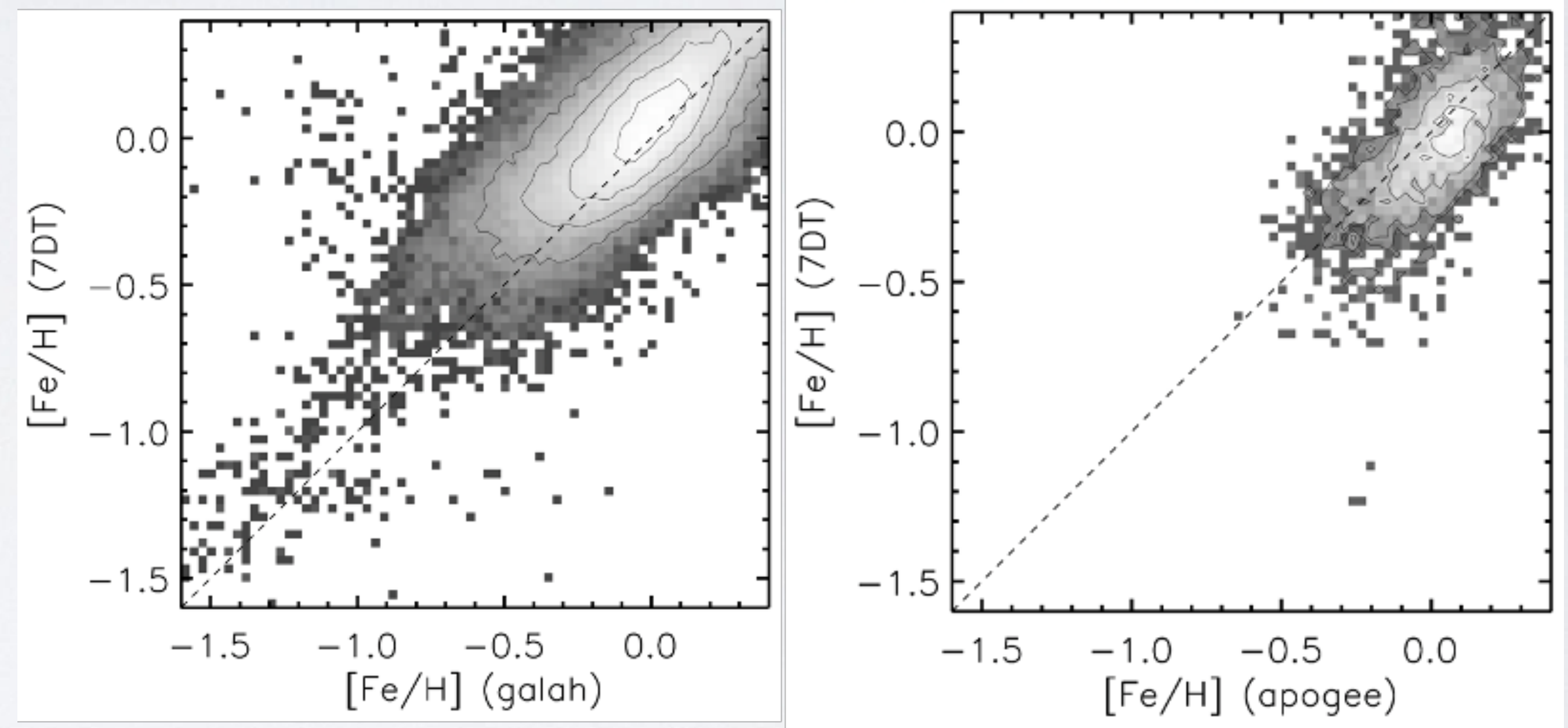
Composite images of the Orion Nebula obtained by 7DT (Courtesy of M. Kim)

Science beyond the Originally Sought-after Projects

Comparison of synthetic models to Gaia XP spectra ($30 < R < 100$; De Angeli et al. 2023).



Low-resolution spectra, such as those from 7DS, can be used to accurately determine key stellar parameters, including effective temperature, distance, metallicity, and foreground extinction.



Comparison between high-resolution spectroscopic metallicity and that derived from the mock 7DS catalog generated using Gaia XP spectra. (Courtesy of An and Lee)

Summary

- *7DT is a multi-telescope array with 20 50-cm astrographs; now 16 of the planned telescopes are operational.*
- *Equipped with 40 25-nm medium-band filters, 7DT provides IFU-like data with low spectral resolution for a FoV of 1.25 square degrees.*
- *7DS consists of 3 layers: RIS, WFS, and IMS.*
- *Beyond the detection of GW electromagnetic counterparts, 7DT/7DS provides spectral mapping data for a wide range of scientific goals.*
- *We have been conducting commissioning procedures: performance evaluation and science capability verification, including photometric calibration, photometric redshift estimation, etc.*
- *We are open to more scientific collaboration!*

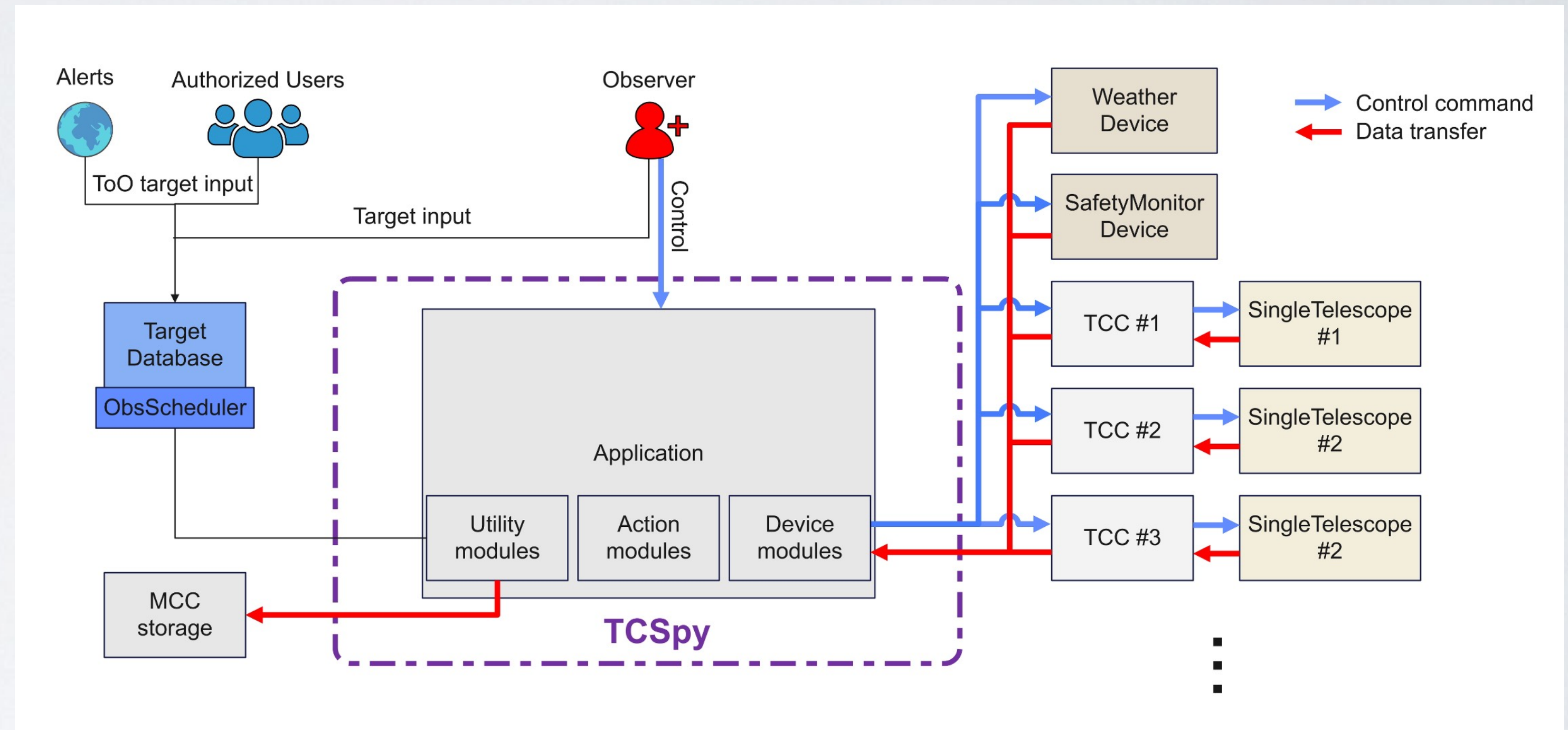
Instruments

- *Delta-Rho 500 by PlaneWave Instruments*
 1. Primary mirror diameter: 508 mm
 2. Effective focal ratio: $f/3.0$
 3. Optical field of view: 70 mm diameter
- *C3-61000 Pro by Moravian Instruments*
 1. Sony IMX455 CMOS Sensor
 2. Sensor dimension: 9576 x 6388
 3. Pixel scale: 0.5 arcseconds (seeing limited)
 4. Field of view: 1.3 by 0.9 ~ 1.2 square degrees
 5. 9-slot filter wheel



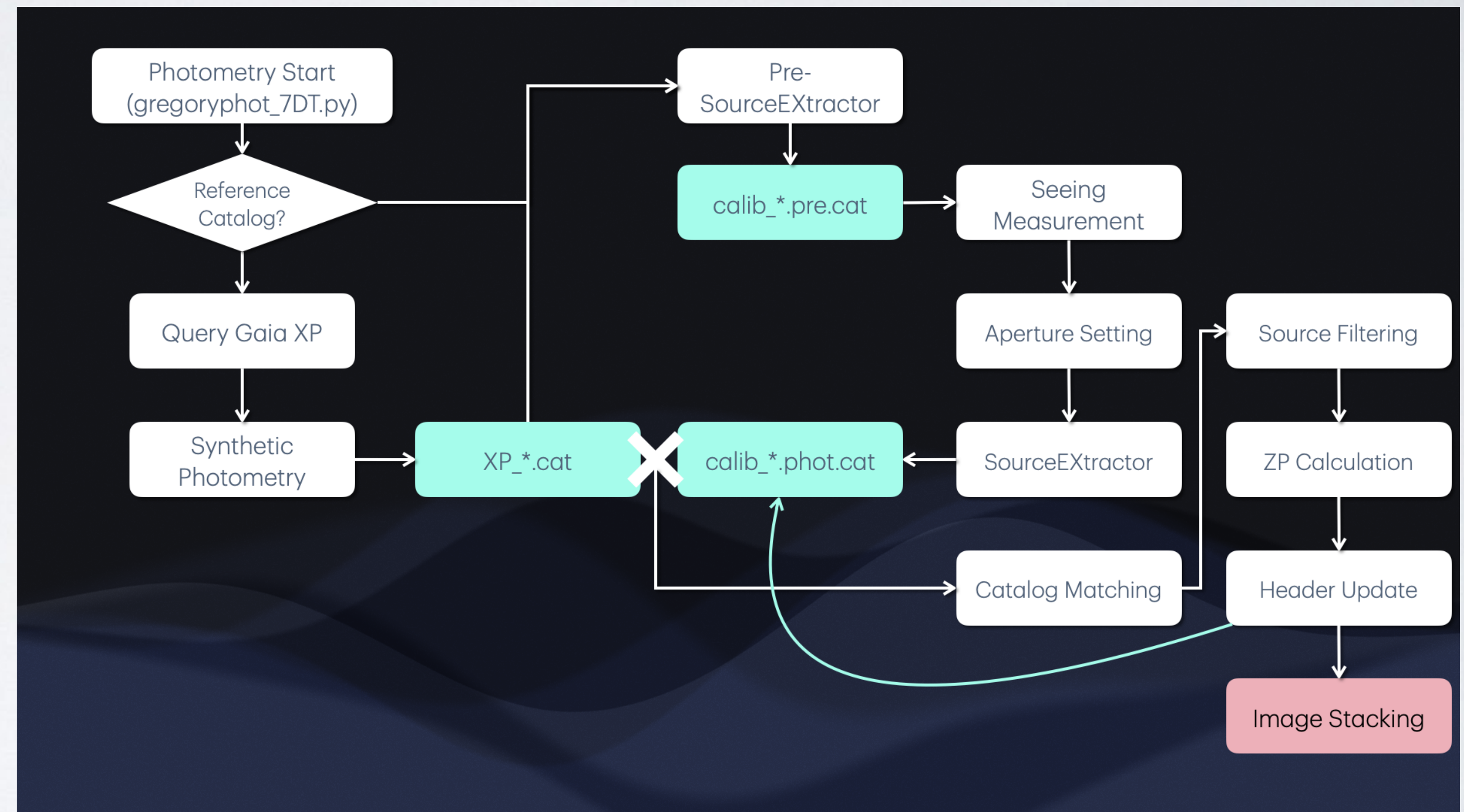
Controller/Scheduler

- TCSpy
- AlpacaPi suite and PWI4
- 3 observation modes:
 1. Spec mode: 1 FoV w/ 20 bands
 2. Deep mode: 1 FoV w/ 1 band
 3. Search mode: 20 FoVs
- MySQL-based DB and scheduling system
- arxiv.org/abs/2407.13315 for more information



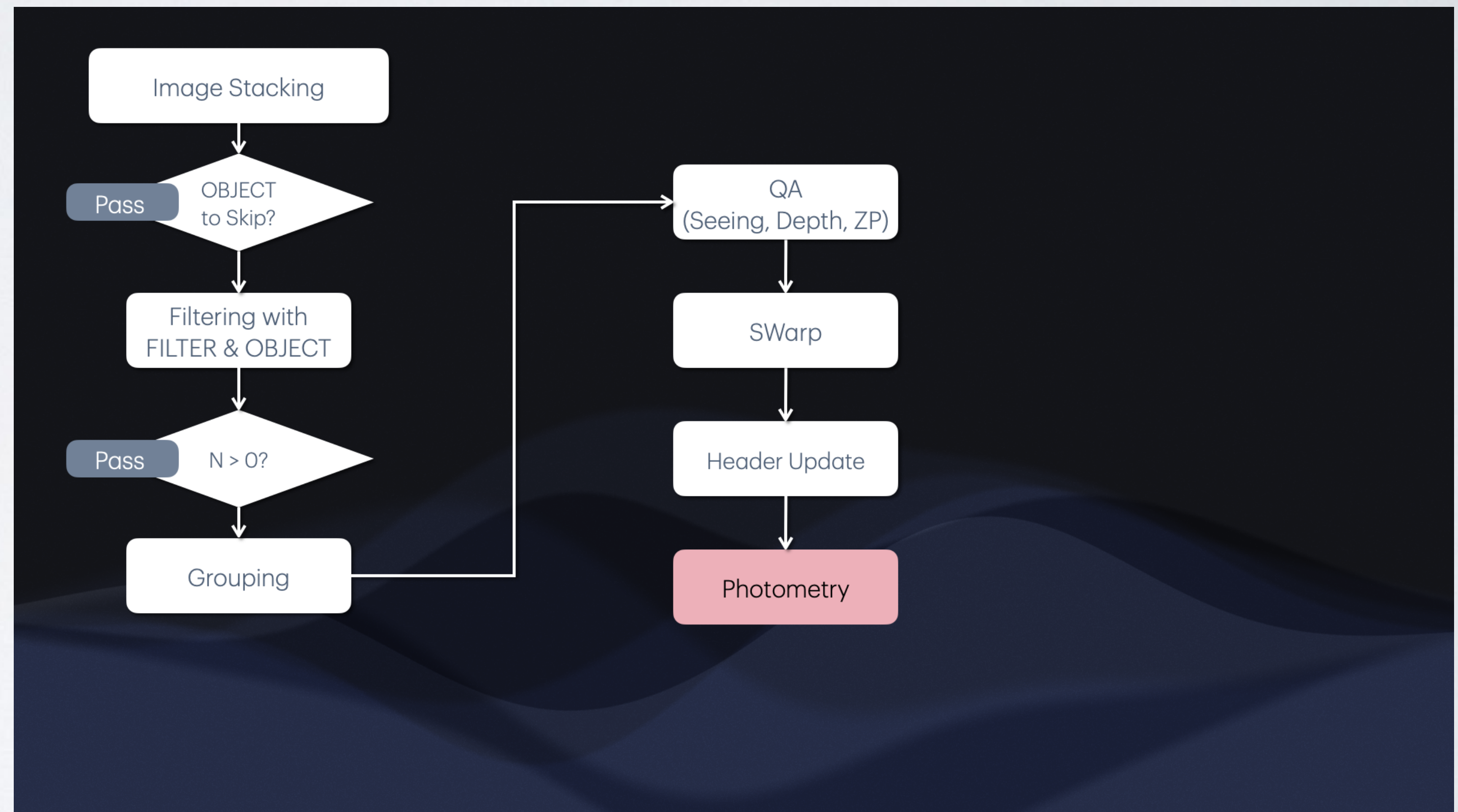
Data Reduction Pipeline

- the modified gpPy (gpPy+GPU)
- Utilizing a GPU-accelerated library
- The original gpPy is an automatic data reduction package that handles images for transient searches.
- 3 steps:
 1. Single frame reduction
 2. Basic photometry
 3. Stacking frames
- <https://github.com/SilverRon/gppy>



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Commissioning Procedures: Science Verification

- NGC 253, NGC 1097, NGC 6514
- PHANGS (*Physics at High Angular Resolution in Nearby Galaxies*, PI: J. Lee)
 - ALMA, HST, and MIRI of JWST
 - 74 sample galaxies with ALMA
 - 40 sample galaxies were observed with 7DT so far.
- The Ultra-Deep Survey (UDS) field
 - Photo-z test, cross-check with available spectra
 - 800 ~ 3000 sec exposures per filter
- SPT-CL_J2017-6258 & SPT-CL_J2020-6314
- M44, SDSS J0228-0901, GRB231117A, Orion Molecular Clouds 2/3, 13 Egeria, 10 Hygiea, etc.

Photometric Redshift Estimation

Photo-z analysis by J. Bae

- Data:

- 7DT simulated catalog from COSMOS2020 SED data (Feder et al. 2024)
- Synthetic photometry with empirical filter response curves

- Fitting software: EAZY (C version)

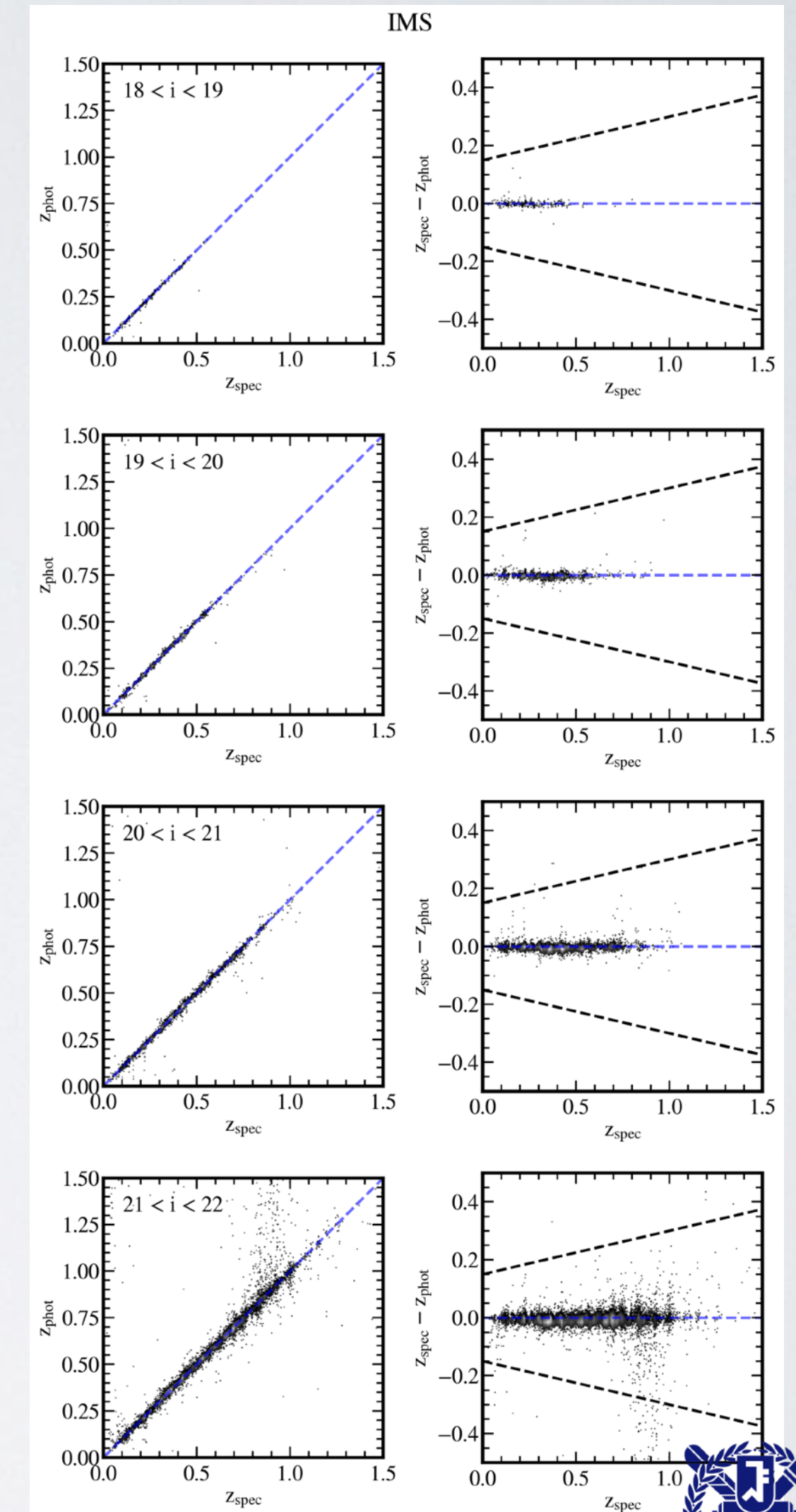
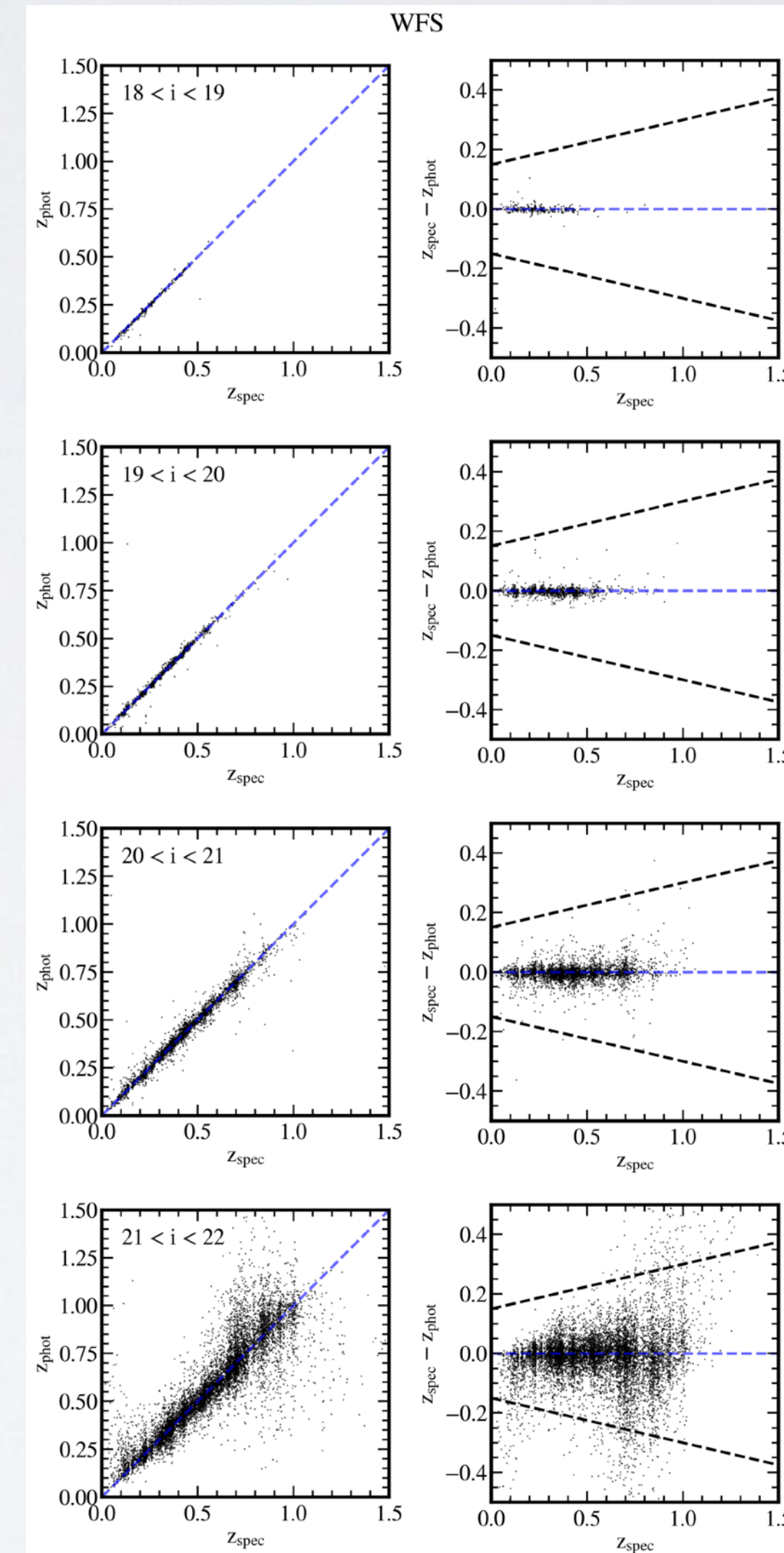
- Fitting results:

1. WFS

- $\text{bias} > -0.01$, $\sigma_{\text{nmad}} < 0.04$, $\text{RMS} < 0.08$, $f_{\text{cata}} < 0.06$ for $i < 22$ objects

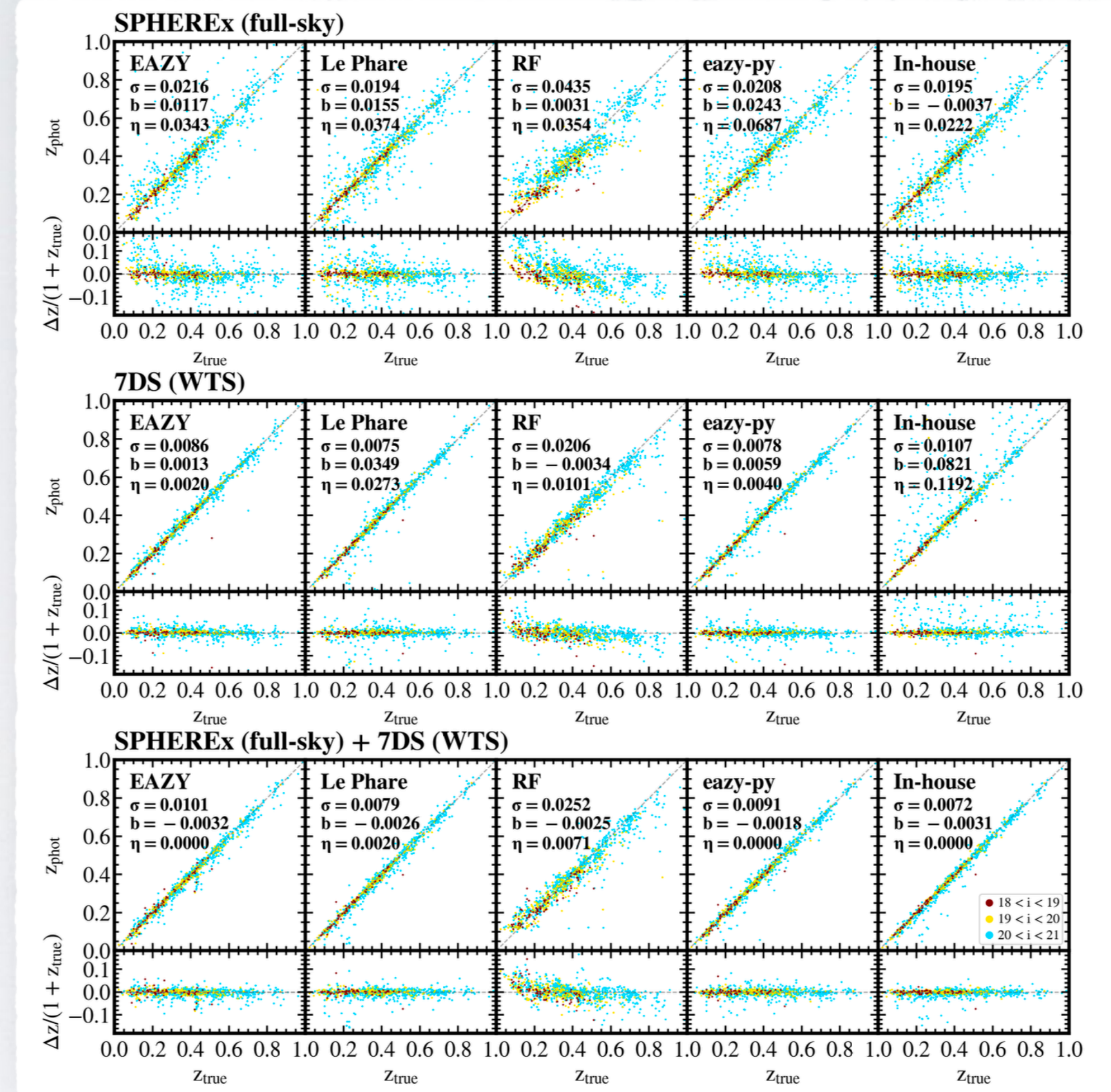
2. IMS

- $\text{bias} > -0.009$, $\sigma_{\text{nmad}} < 0.01$, $\text{RMS} < 0.08$, $f_{\text{cata}} < 0.02$ for $i < 22$ objects



Science beyond Gravitational-wave Astronomy

- Time-series spectra of quasars
- Reverberation mapping measurement of SMBH mass
- Spectral mapping of nearby galaxies
 - Dynamics, stellar populations, metallicity, etc.
- High-redshift objects
 - Galaxy clusters, large-scale structures, etc.
- Early phase spectra of SNe
- Time-series spectra of stellar objects
- Time-series spectra of small bodies of the solar system



Estimated photo-z based on 7DS, SPHEREx, and both datasets from Bae et al. (*in prep*)