the 17th ACHEC meeting,
Hotel Fukuracia Osaka Bay, Osaka, Japan
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The Tomo-e Gozen wide-field CMOS camera

Shigeyuki Sako (Institute of Astronomy, the University of Tokyo)

Shigeyuki Sako

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Affiliation

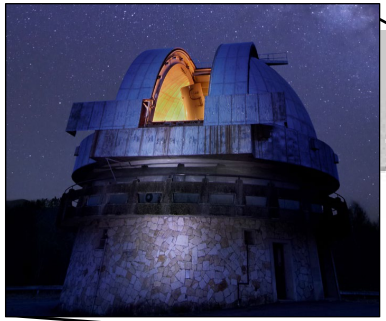
- Institute of Astronomy, the University of Tokyo
- Kiso Observatory
- The University of Tokyo Atacama Observatory (TAO)

Research fields

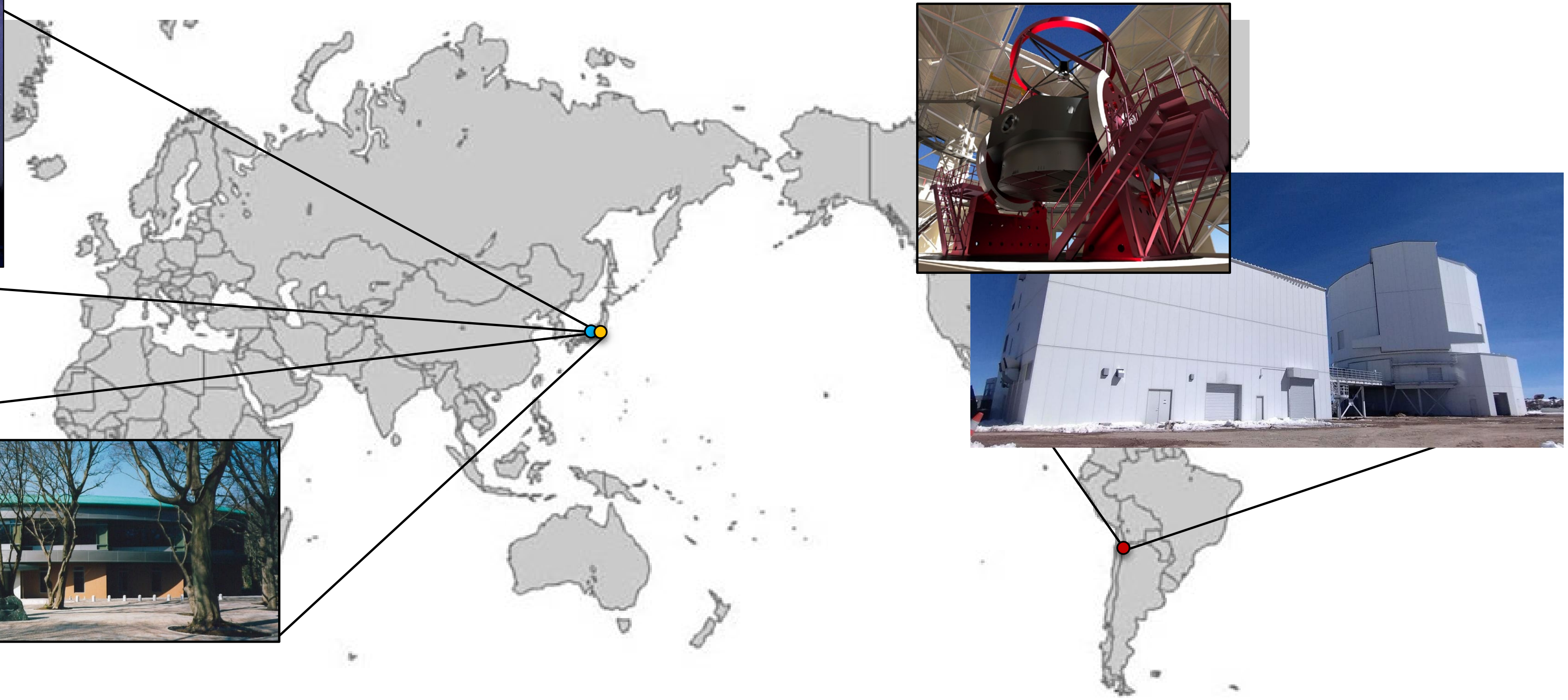
- Optical-and-infrared astronomy
- Time-domain astronomy (meteors, near-Earth asteroids … SNe, FRBs)
- Instrumentation
- P.I. of the Tomo-e Gozen project

Institute of Astronomy, the University of Tokyo

Kiso Observatory
Kiso, Nagano
1.0m Schmidt telescope



UTokyo Atacama Observatory (TAO)
Atacama, Chile at 5,640 m
6.5 m opt-infrared telescope
(It will be completed in 2026)

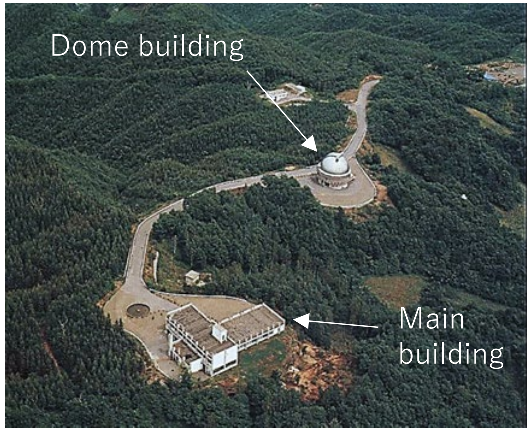


Headquarters
Mitaka, Tokyo

Institute of Astronomy, the University of Tokyo
Kiso Observatory

Facility

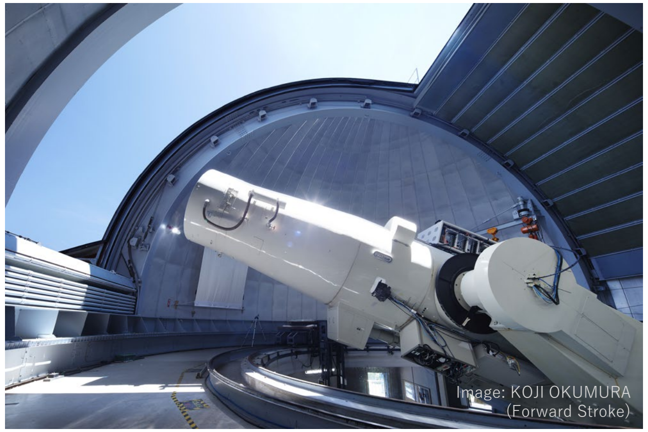
- Established in 1974
- Dark night, 1132-m altitude
- Laboratories, experiment rooms
- Accommodation



1 m Schmidt telescope

- **Wide field-of-view (ϕ 9 deg)**
- Primary mirror: ϕ 1.5 m spherical
- Corrector lens: ϕ 1.05 m
- F-ratio: 3.1

Dome building



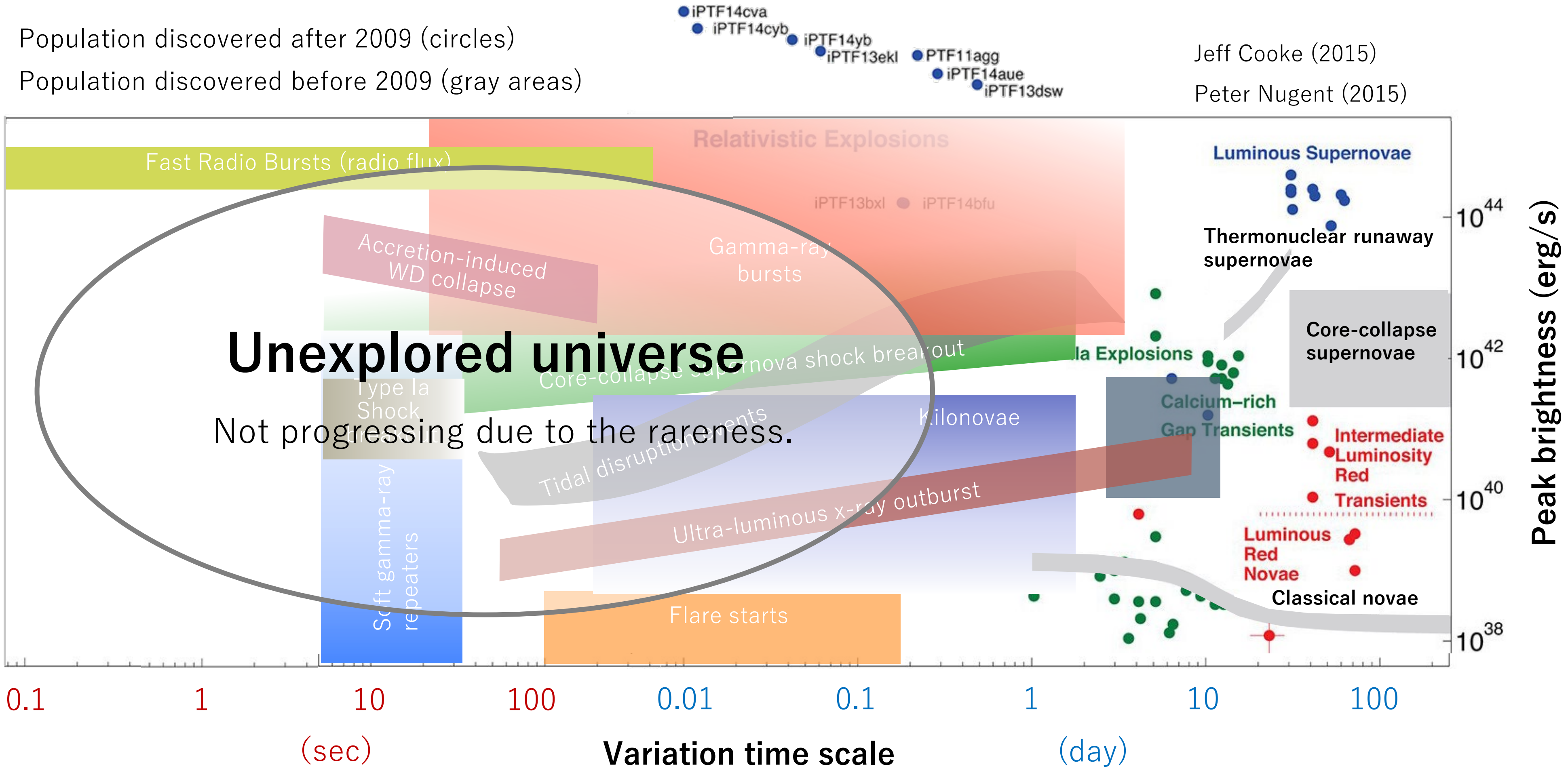
1 m Schmidt telescope

Outline

1. Tomo-e Gozen project
2. Scientific results
3. Hardware and calibration

1. Tomo-e Gozen Project

Optical Transient in Short-time Scales



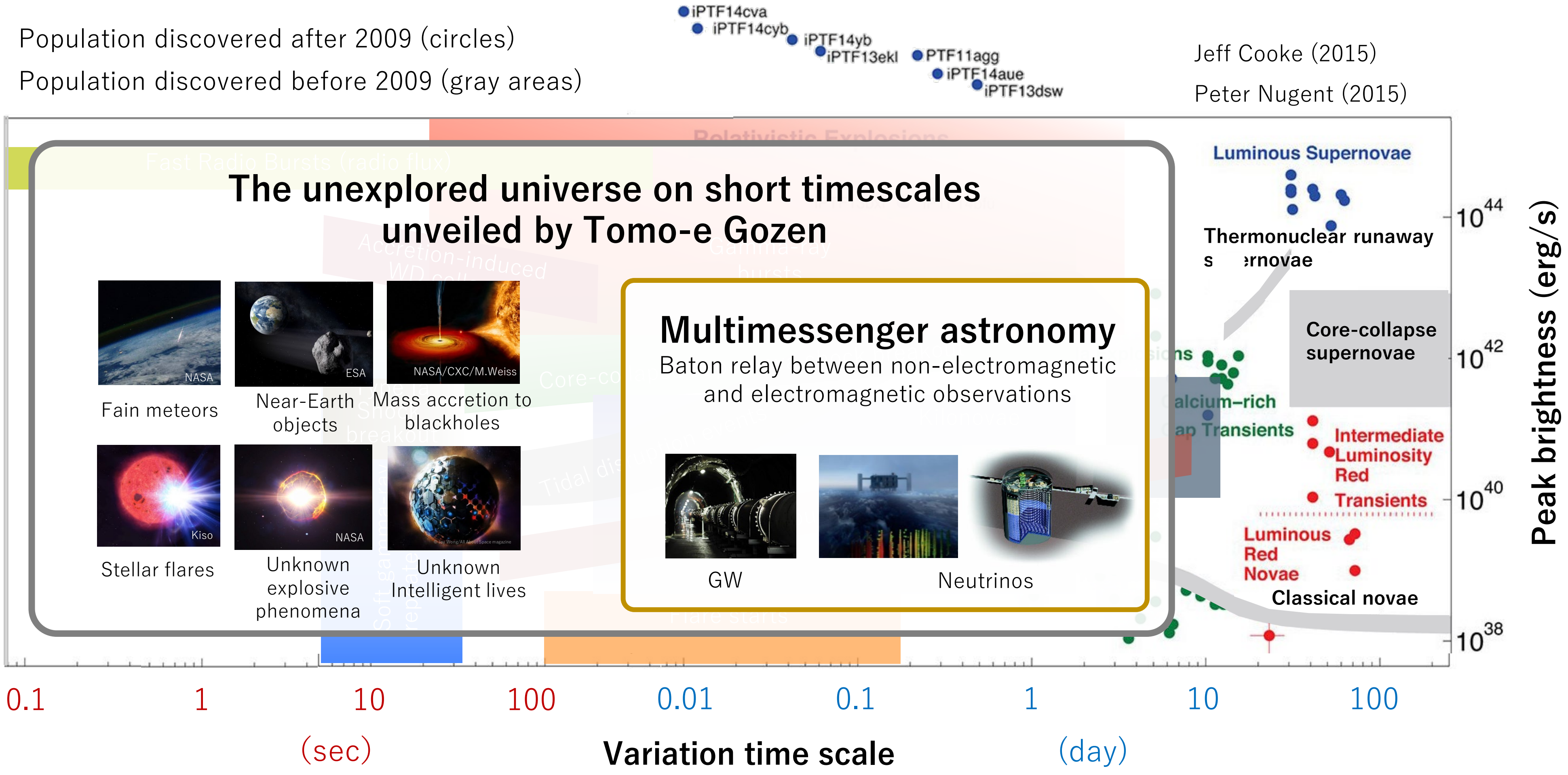
Optical Transient in Short-time Scales

Population discovered after 2009 (circles)

Population discovered before 2009 (gray areas)

Jeff Cooke (2015)

Peter Nugent (2015)



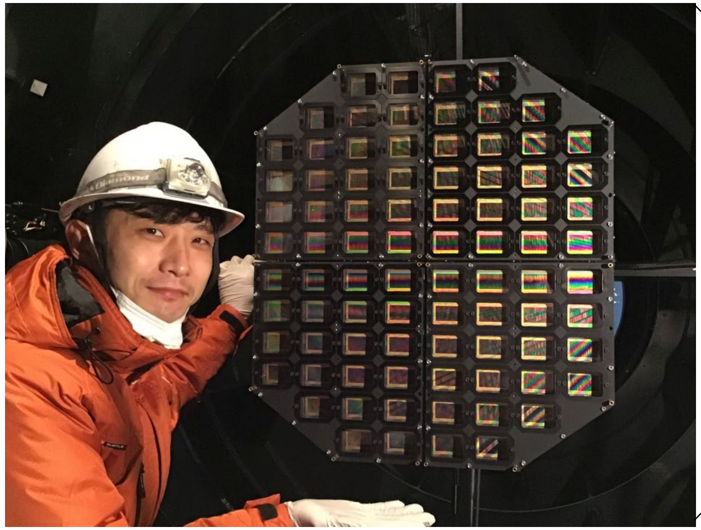
The world's first high-speed survey using a wide-field video camera.

TOMO-E GOZEN

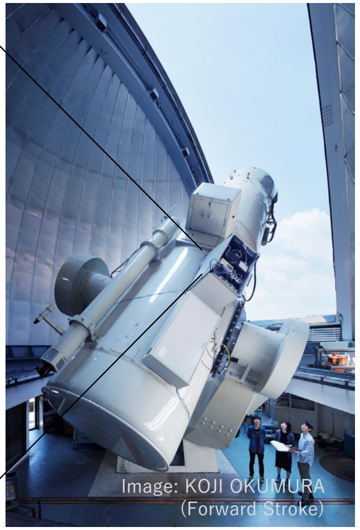
Sako et al. 2018

Camera instrument

- Field of view: 20 deg^2
- 84 chips of CMOS image sensors (190 M pixels)
- Video data at 2 frames/sec (max)
- Single band in optical (λ = 380 – 710 nm)
- Started observations in 2019



Tomo-e Gozen camera on the telescope's focal plane, features an array of 84 CMOS sensors.



1 m Schmidt telescope at Kiso Observatory

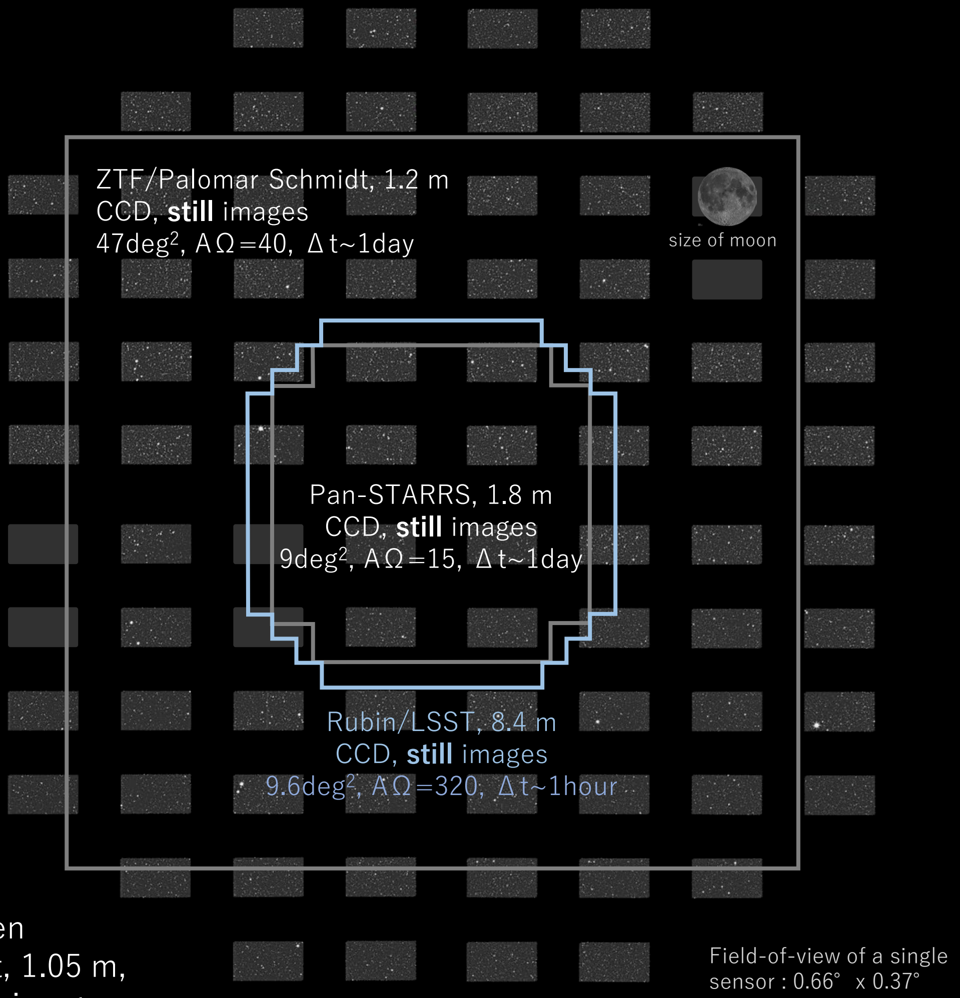
Tomo-e Gozen (Tokyo National Museum collection Image: TNM Image Archives)

Data output and data processing

- Video frames of 30 TB per night (max)
- On-site computing system directly connected to the camera.
- CPU: 200 cores, Storage: 1 PB
- Real-time processing and alert generation based on ML and optimization algorithms.
- Connected to the high-speed network SINET6.

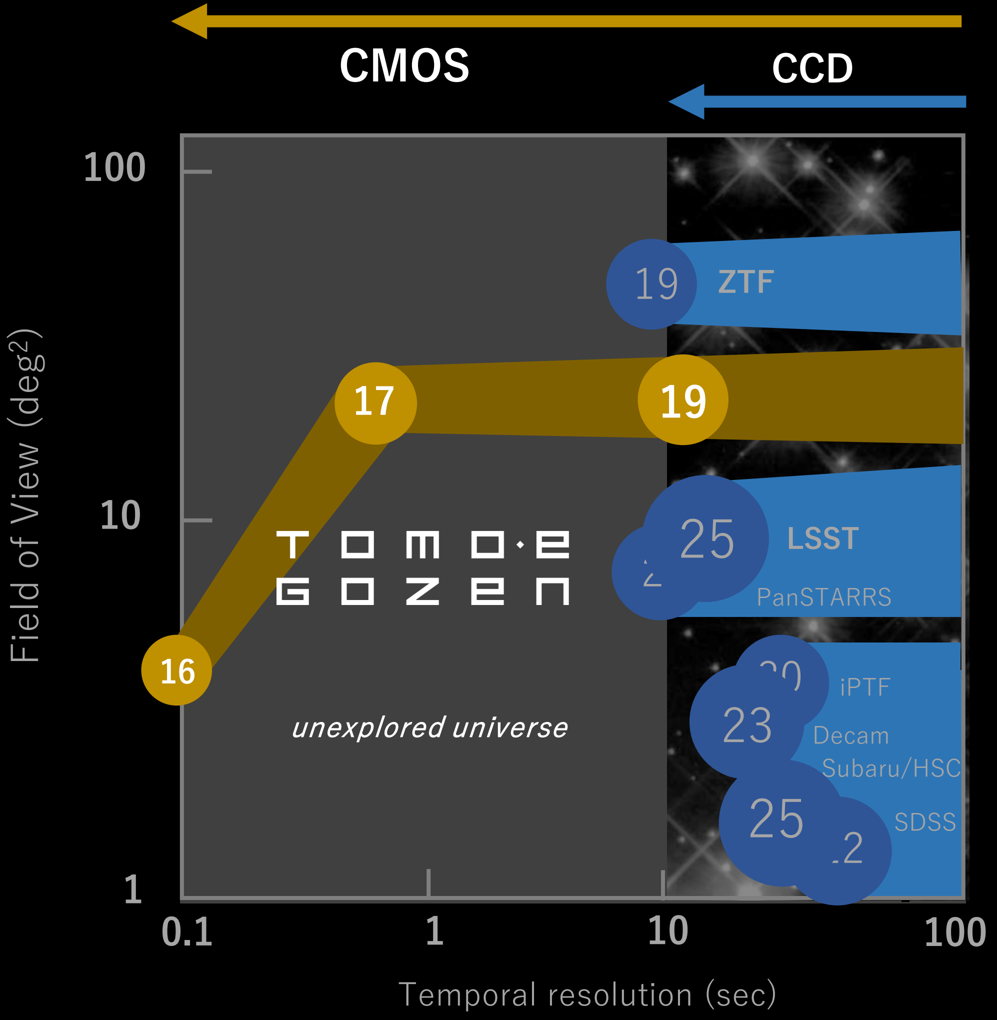
Research members of the Tomo-e Gozen project

FoVs of wide-field cameras



Tomo-e Gozen
Kiso Schmidt, 1.05 m,
CMOS, **video** images
20deg^2, AΩ=28, Δt>sub-sec

Survey power of transients



The numbers in the circles show limiting magnitudes.

All-Sky Video Survey at Second-Scale Cadence with Tomo-e Gozen

Data Acquisition

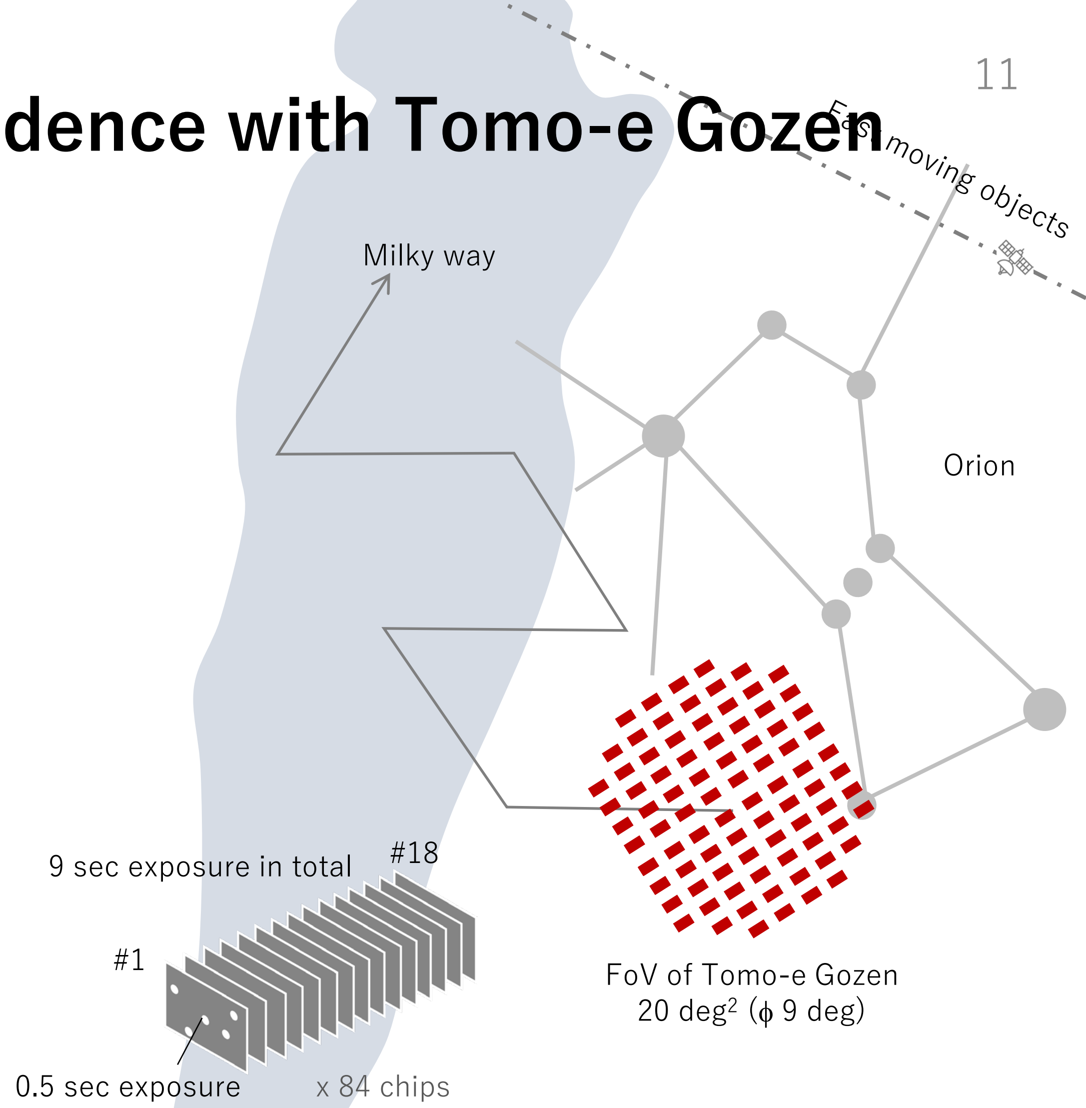
- Autonomous scheduling and self-operated observing, based on real-time assessment of weather conditions
- 20 deg^2 per pointing, 18 frames at 0.5-sec intervals
- Almost every clear night (~100 nights/year)

Survey Area

- 12,000 deg^2 (entire sky, > 35 deg alt.): once per night, in 3 hrs
- 3,000 deg^2 (high cadence): up to 10 passes per night

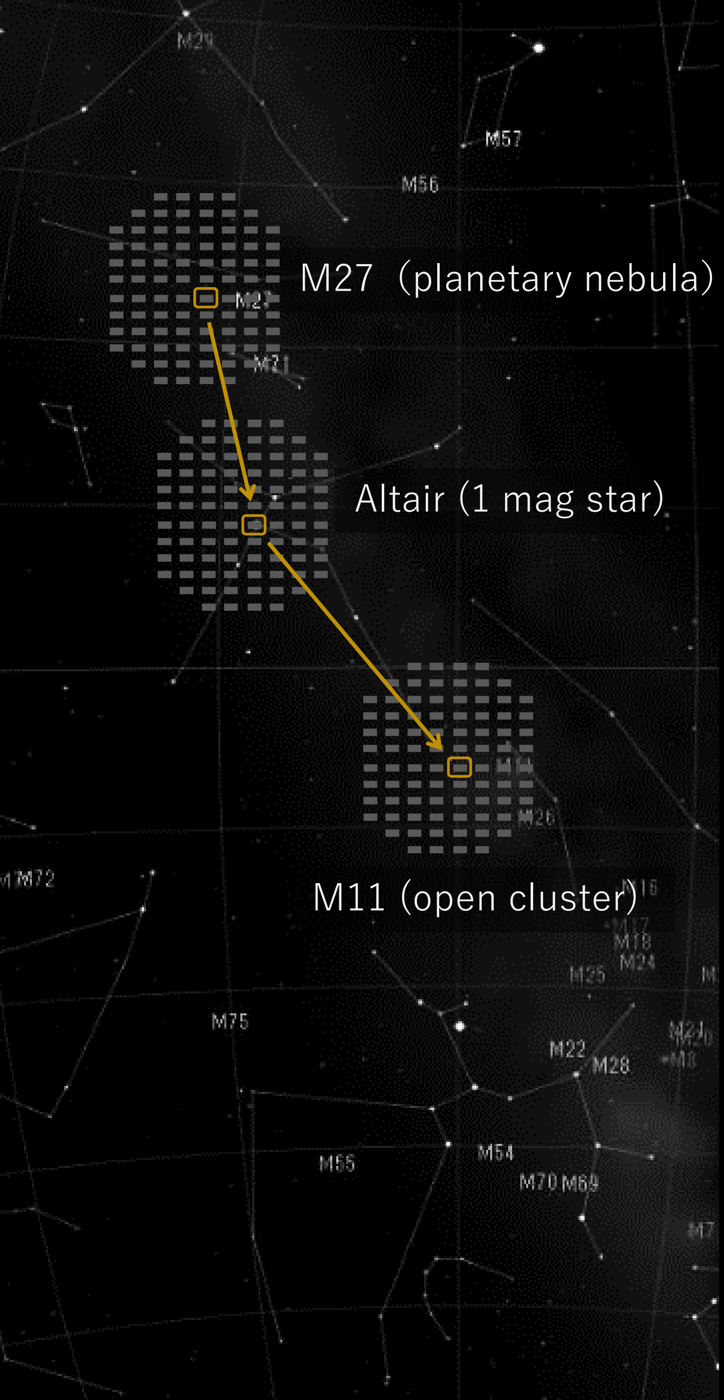
Sensitivity and Performance

- < 17 mag, < 18 mag (in 9 frames stacked), 3” resolution (seeing limited)
- **~100 million objects detected** per full-sky scan



This is the world's only dataset that continuously monitors the night sky over a wide field of view in high sensitivity and high-resolution video.

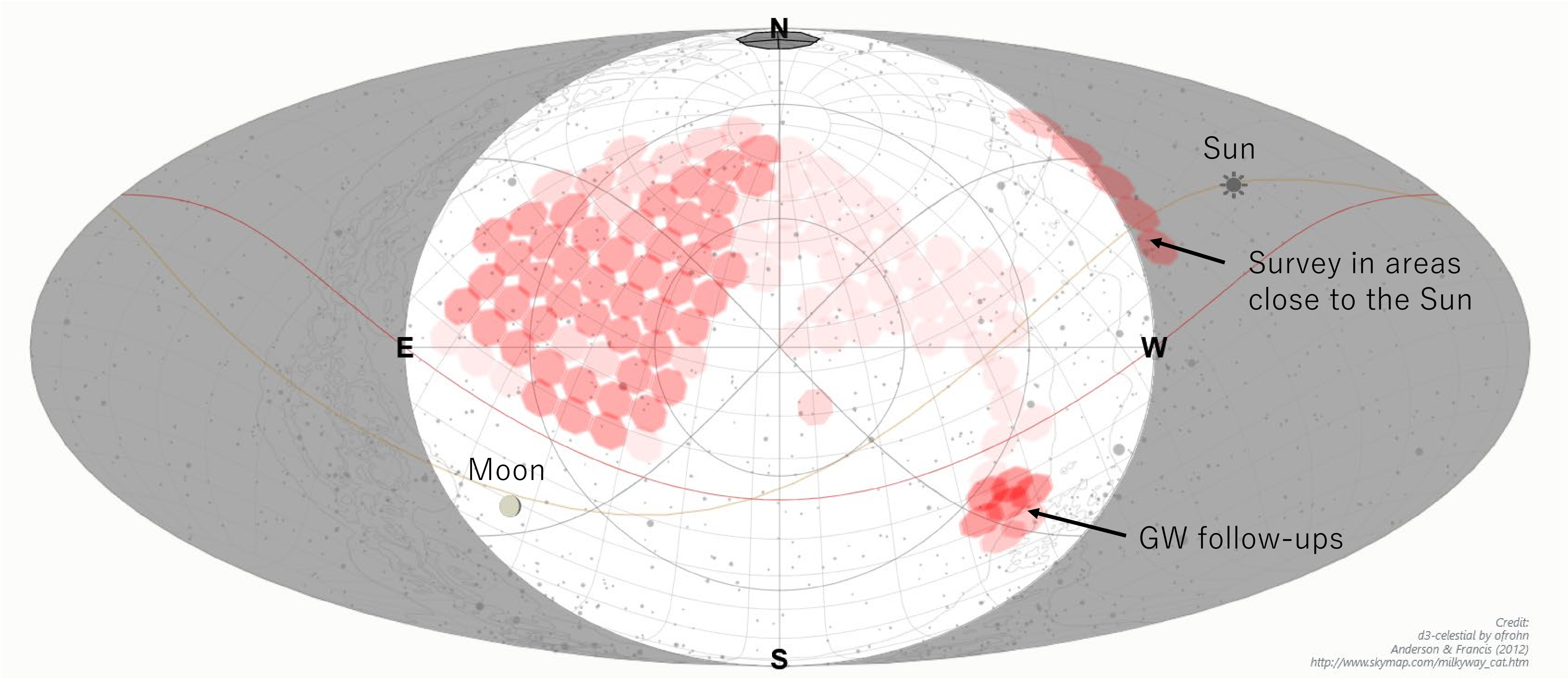
Video frames obtained with a single CMOS sensor, 2 frames/sec



ckground image : Stellar navigator

39.7 arcmin x 22.4 arcmin

Footprints of the Tomo-e Gozen survey on Apr. 25, 2024



Observer Interface and System Integration

- Commands to the telescope and instruments are issued via a queue + scheduler system.
- The default is autonomous observation, but observers can override the commands when necessary.
- Information is shared via a web browser and social media platforms.

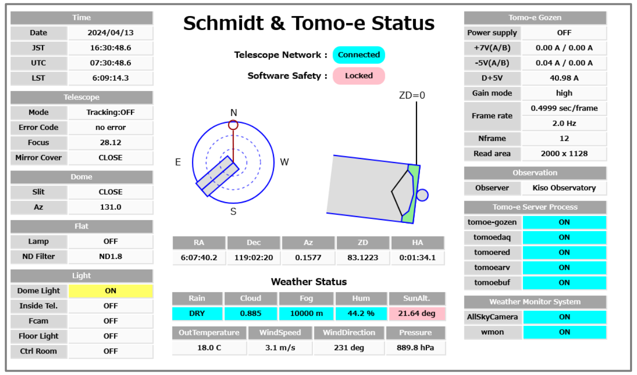
Automated observation via queue and scheduler system

Control and status monitoring of software processes

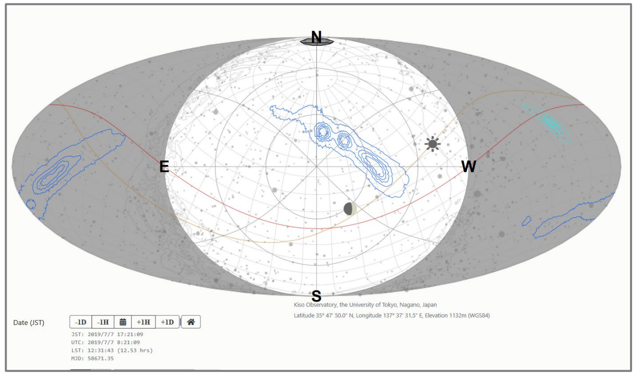
Exposure Log

DATE(JST)	Exp ID	Object	Observer	Project	(RA, DEC)	Frame Size	N_{frame}	Gain	T_{int}	FPS	ZD
2019-07-07 20:17:46	129850	FLAT	Kiso Staff	Sample Recipe	(15:28:21.7, 115:56:18)	2000×1128	90	high	1.0000	1.0000	79.99
2019-07-07 20:13:09	129849	DARK	Kiso Staff	Sample Recipe	(15:23:44.9, 115:56:24)	2000×1128	360	high	0.5000	2.0000	79.99
2019-07-07 20:07:04	129848	DARK	Kiso Staff	Sample Recipe	(15:17:39.8, 115:56:32)	2000×1128	360	high	1.0000	1.0000	79.99
2019-07-07 19:57:59	129847	DARK	Kiso Staff	Sample Recipe	(15:08:34.7, 115:56:43)	400×240	4500	high	0.0410	24.4057	79.99
2019-07-07 19:51:51	129846	DARK	Kiso Staff	Sample Recipe	(15:02:25.9, 115:56:50)	400×24	40000	high	0.0055	181.0610	79.99
2019-07-07 19:38:02	129845	DARK	Kiso Staff	Sample Recipe	(14:48:35.8, 115:56:54)	400×24	40000	high	0.0055	181.0610	79.99

Access to observation logs and processed image data.



Monitoring of telescope and camera status.



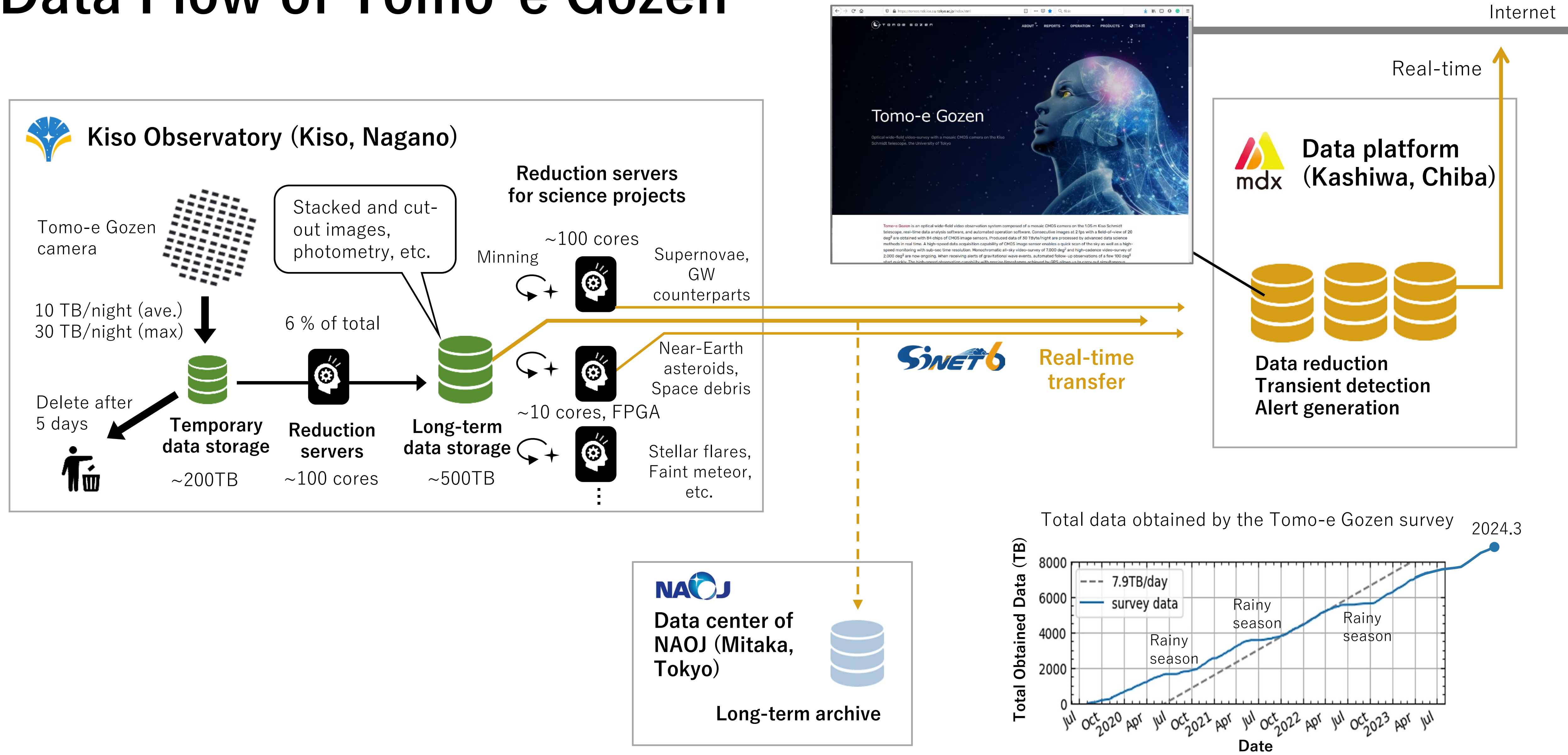
Monitoring of survey observation progress.

Slack is actively used for real-time information sharing

Data Flow of Tomo-e Gozen

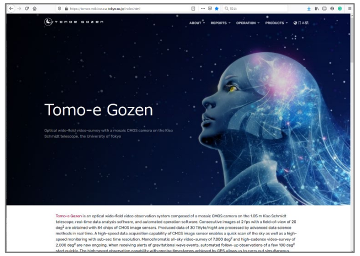
Partial data release (full access immediately to collaborators)

https://tomoe.mtk.ioa.s.u-tokyo.ac.jp/



Data will be released sequentially starting 3 years after acquisition.

Tomo-e Gozen Data Release



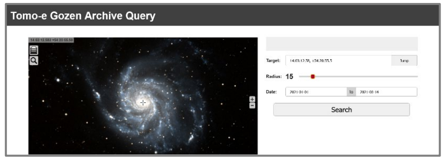
1. Via the mdx data platform (Kashiwa Campus)

https://tomoe.mtk.ioa.s.u-tokyo.ac.jp/

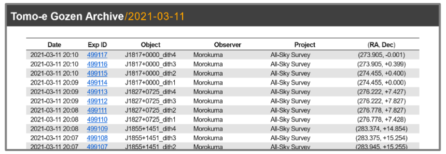
Open Data Access

- **Co-added Image Data**
  - Calibrated scientific data (FITS)
  - Released sequentially starting 6 months after acquisition
  - Partially blocked in pos. and period.
- **Sky Atlas (for education)**
  - Calibrated image data (PNG)
  - Interactive web interface
  - All survey data are available immediately

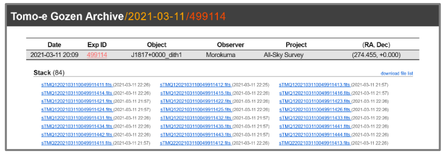
Search interface



Observation log



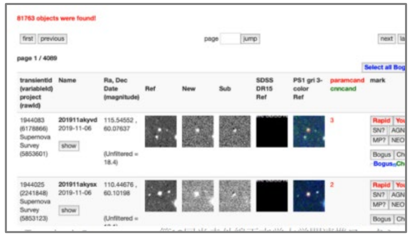
File list

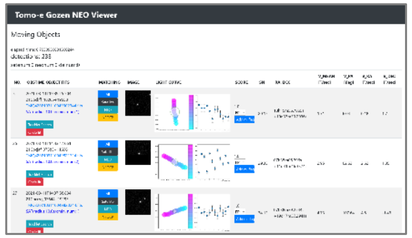


Collaborative Research Data

Available to official collaborators of the Tomo-e Gozen project

- **Co-added Image Data**
  - Calibrated scientific data (FITS)
  - All survey data released immediately
- **Extracted Scientifically Valuable Information**
  - Transient object database
  - Fast-moving object database
- **Industry-Academia Collaboration Data**
  - Information related to artificial satellites, etc.

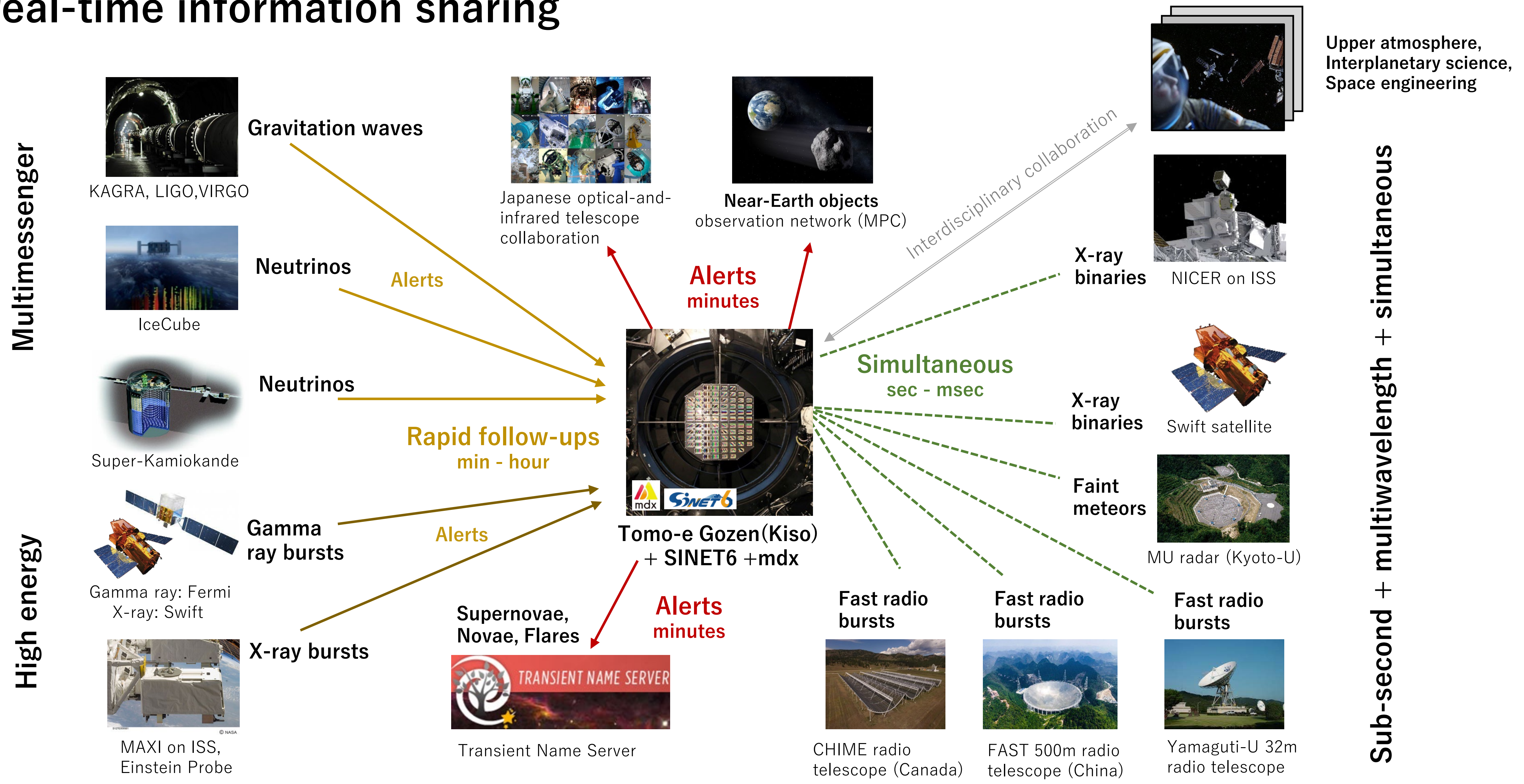




2. Via the NAOJ data center – SMOKA service

- **Co-added Image Data**
  - Calibrated scientific data (FITS)
  - Released sequentially starting 3 years after acquisition

Collaborations of time-domain observations through real-time information sharing



2. Scientific Results by Tomo-e Gozen

Key scientific publications from the Tomo-e Gozen project

No.	Publication	Topic
1.	Urakawa et al. `*Shape and Rotational Motion Models for Tumbling and Monolithic Asteroid 2012 TC4 : High Time Resolution Light Curve with the Tomo-e Gozen Camera*' The Astronomical Journal, Volume 157, Issue 4, article id. 155, 13 pp. (2019).	Near-Earth asteroid
2.	Arimatsu et al. `*New Constraint on the Atmosphere of (50000) Quaoar from a Stellar Occultation*' The Astronomical Journal, Volume 158, Issue 6, article id. 236, 7 pp. (2019).	Trans-Neptunian objects
3.	Richmond et al. `*An optical search for transients lasting a few seconds*' Publications of the Astronomical Society of Japan, Vol 72, 1, id.3 (2020)	Searching for unknow flashes
4.	Ohsawa et al. `*Relationship between Radar Cross Section and Optical Magnitude based on Radar and Optical Simultaneous Observations of Faint Meteors*' Planetary and Space Science, Vol 194, id. 105011 (2020)	Faint meteors
5.	Morokuma et al. `*Follow-up observations for IceCube-170922A: Detection of rapid near-infrared variability and intensive monitoring of TXS 0506+056' Publications of the Astronomical Society of Japan*, Vol 73, 1, pp.25-43 (2021)	Neutrino
6.	Sasada et al. `*J-GEM optical and near-infrared follow-up of gravitational wave events during LIGO's and Virgo's third observing run*' Progress of Theoretical and Experimental Physics, Vol 2021, 5, id.05A104, 23 pp. (2021)	Gravitational wave
7.	Jiang et al. `*Discovery of the Fastest Early Optical Emission from Overluminous SN Ia 2020hvf: A Thermonuclear Explosion within a Dense Circumstellar Environment*' The Astrophysical Journal Letters, Vol 923, 1, L8 (2021)	Supernova
8.	Nishino et al. `*Detection of highly correlated optical and X-ray variations in SS Cygni with Tomo-e Gozen and NICER*' Publications of the Astronomical Society of Japan, Volume 74, Issue 3, 6 pp (2022)	Dwarf nova
9.	Niino et al. `*Deep simultaneous limits on optical emission from FRB 20190520B by 24.4 fps observations with Tomo-e Gozen*' The Astrophysical Journal, Volume 931, Issue 2, id.109, 7 pp. (2022)	Fast radio bursts
10.	Beniyama et al. `*Video observations of tiny near-Earth objects with Tomo-e Gozen*' Publications of the Astronomical Society of Japan, Volume 74, Issue 4, 27 pp. (2022)	Near-Earth asteroids
11.	Aizawa et al. `*Fast optical flares from M dwarfs detected by a one-second-cadence survey with Tomo-e Gozen*' Publications of the Astronomical Society of Japan, Volume 74, Issue 5, pp.1069-1094 (2022)	M-dwarf flares

Improving the accuracy of transient detection using ML models.

Detection of transient events via comparison with archival survey

Challenge

- Although the wide-field survey data typically contain **~10 transients** per night, they also produce up to **~10^6 false positives**.

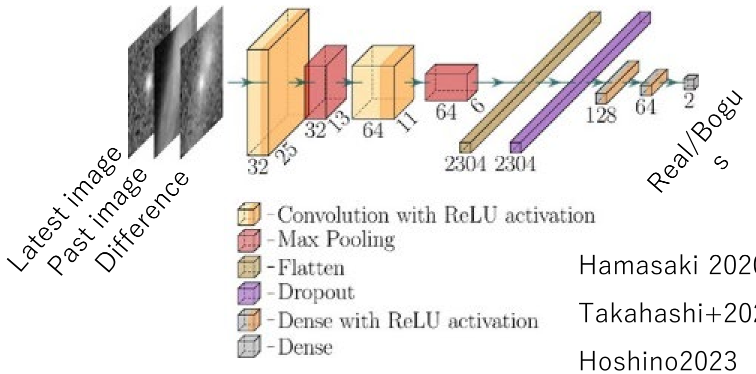
Solutions

- Real/Bogus classification using ML models (CNN, VAT) with **images**:
  → Reduced false positives to **~10^2 per night**.
- Enhanced accuracy using additional features from **astronomical catalogs**
  → Applied Random Forest models to improve classification performance further.

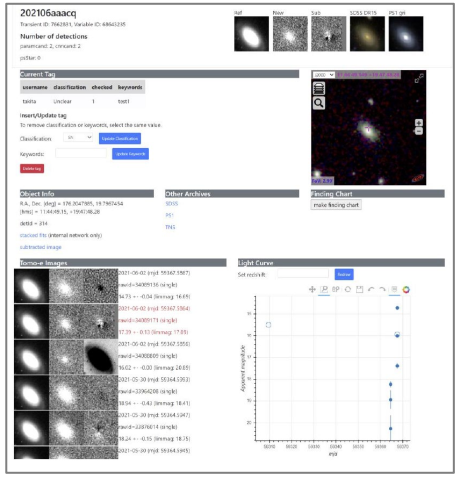
Example: detection of SN

Latest image − Past image = Difference

Real/Bogus classification powered by Convolutional Neural Networks (CNN)

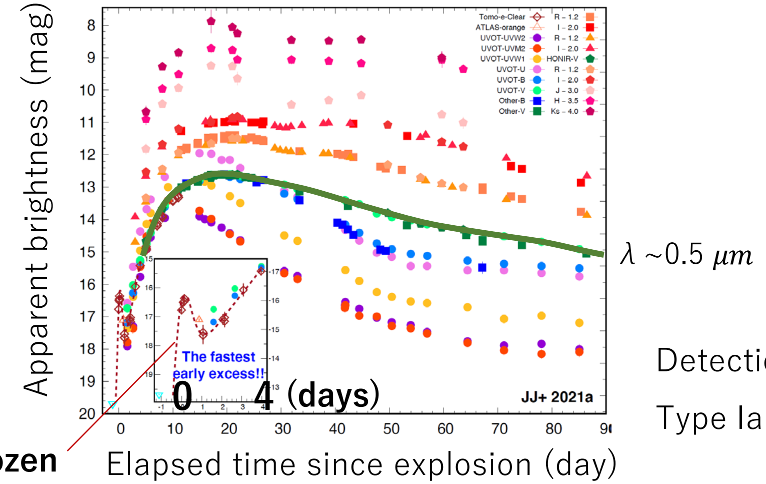


Hamasaki 2020, Takahashi+2022, Hoshino2023



Web viewer for transient candidate inspection

Light curve of SN 2020hvf



Tomo-e Gozen

Detection of early light curve from Type Ia SNe (Jiang et al. 2021)

Simulated image of SN 2020hvf

Improving the accuracy of fast-moving object detection using ML models

Detection of moving objects with 1 – 50 arcsec/sec speed in survey video data

Challenge

- Each night, the survey contains ~1,000 fast-moving objects, but generates ~1 million false positives.

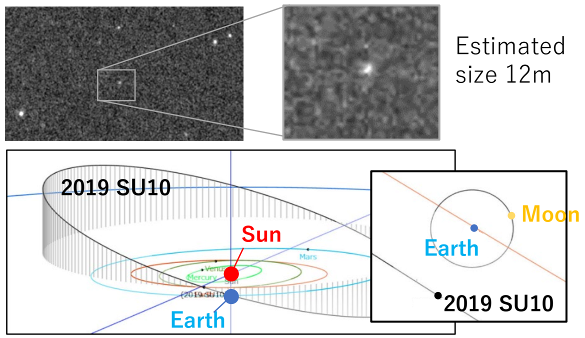
Solutions

- **A feature-based ML classifier was developed to distinguish real/bogus detections.**

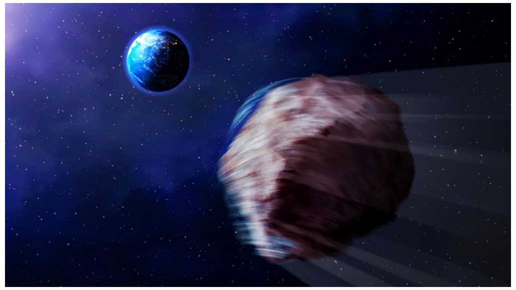
  → False positives reduced to ~100 per night.

- Candidate is made publicly available within minutes after observation.

Orbit of 2019 SU10, discovered by Tomo-e



Beniyama et al. 2022

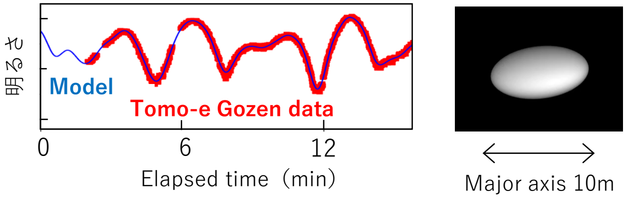


Artist's impression of NEO (UTokyo)

Detection and tracking of near-Earth Objects (NEOs)

- Cross-matched with artificial object catalogs.
  - ~99.9% are artificial satellites or debris.
  - **~0.1% are identified as NEOs.**
- Immediately follow up to determine the orbit and rotational characteristics.

Light curve of 2012 TC_4 and estimated shape



Urakawa et al. 2019

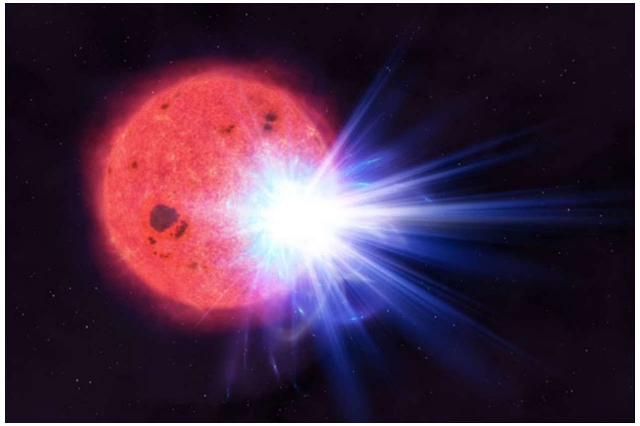
49 NEOs discovered by Tomo-e have been officially registered with the IAU.

#	Name	Discovery date	Estimated diameter
49	2022 YF6	2022-12-27	16m
:	:	:	:
17	2020 VH5	2020-11-13	5m
16	2020 VR1	2020-11-09	5m
15	2020 VJ1	2020-11-09	15m
14	2020 UQ6	2020-10-20	94m
13	2020 QW	2020-08-17	28m
12	2020 PW2	2020-08-14	6m
11	2020 HT7	2020-04-27	14m
10	2020 HU3	2020-04-21	21m
9	2020 GY1	2020-04-02	16m
8	2020 FA2	2020-03-18	10m
7	2020 EO	2020-03-12	21m
6	2019 XL3	2019-12-15	13m
5	2019 XT2	2019-12-08	17m
4	2019 XM2	2019-12-05	16m
3	2019 VD3	2019-11-05	21m
2	2019 SU10	2019-09-25	12m
1	2019 FA	2019-03-16	6m

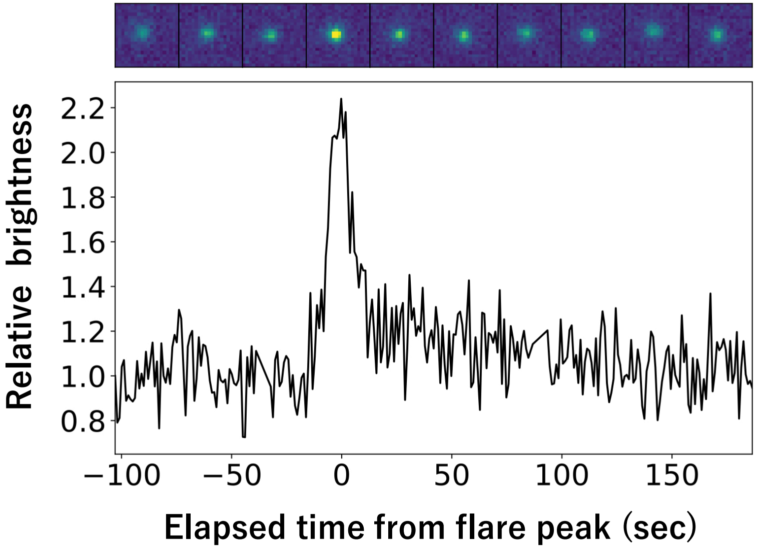
Exploring Second-Scale Flares from M Dwarfs

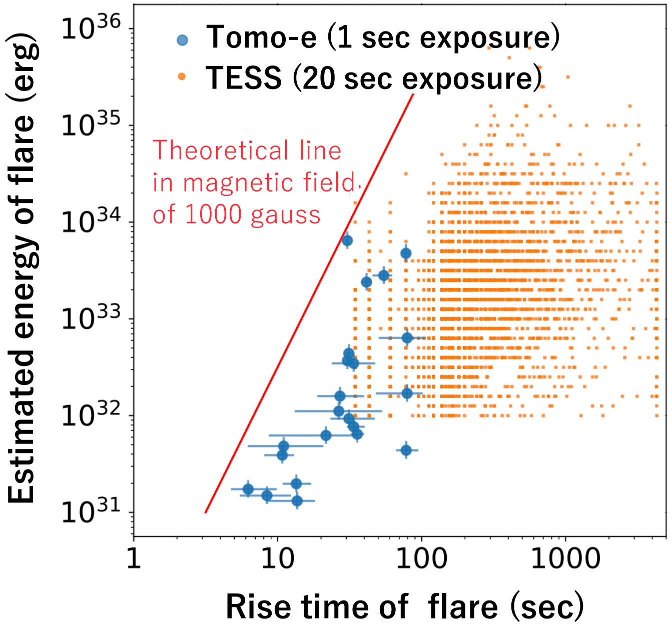
Aizawa et al. 2022, PASJ

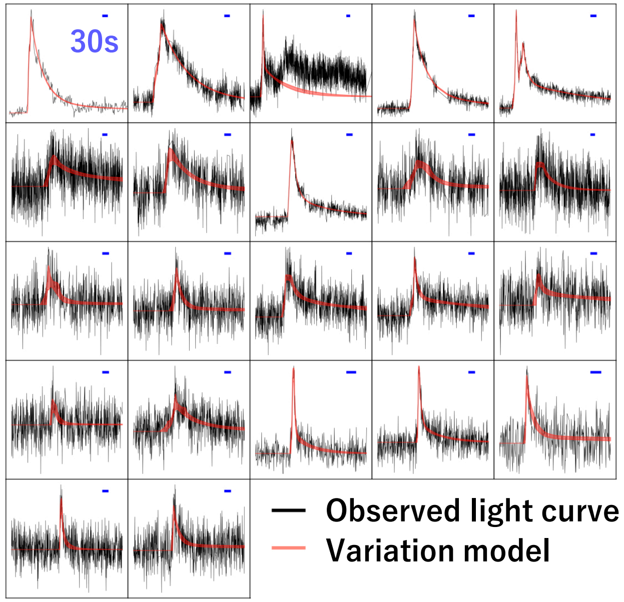
- Continuous 2 fps fixed-field monitoring observations of ~5,700 M dwarfs.
  Total data: 10 hours, 30 TB
- Flare detection rate: 3 – 4 flares per 200 deg² · hr
- Identified 22 flares exhibiting significant brightening over short timescales of several tens of seconds.
- Suggest that energetic flares with rapid rise times occur on active M dwarfs at an average rate of once per day.



Artist's impression of short-duration flares on an M dwarf © UTokyo





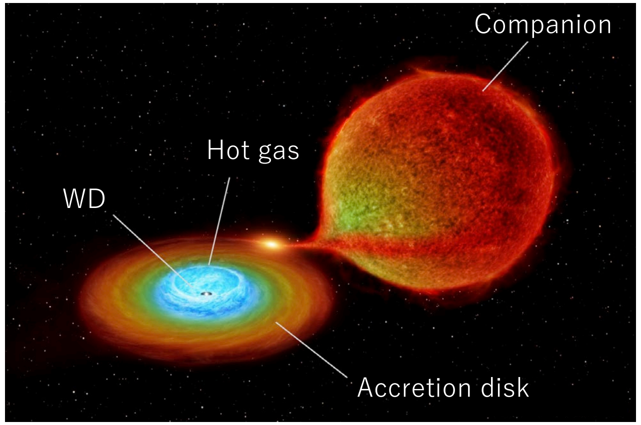


Press release from UTokyo, Aizawa et al.

Sub-Second Optical–X-ray Simultaneous Observations of a Dwarf Nova

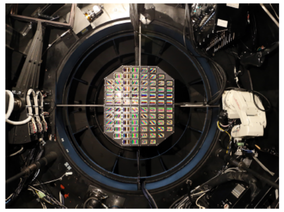
Nishino et al. 2022, PASJ

- Conducted high-speed, sub-second resolution simultaneous observations in optical and X-ray wavelengths of the dwarf nova SS Cyg.
- Discovered that brightness variations in the optical and X-ray bands are correlated.
- This is thought to be caused by X-rays emitted from hot gas located near the WD, which in turn illuminate the surrounding accretion disk and the companion star.



Artist's impression of SS Cyg (UTokyo)

Tomo-e Gozen



Optical 400 – 700 nm

Wide-field, high-sensitivity

Video data by CMOS

Time accuracy: < 1 msec

NICER

Soft X-ray 0.2 – 12 keV

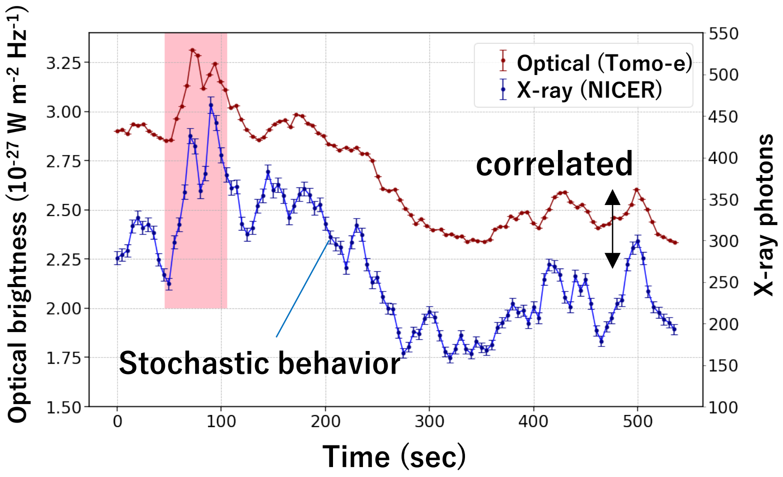
Large effective area (Silicon Strip Detector)

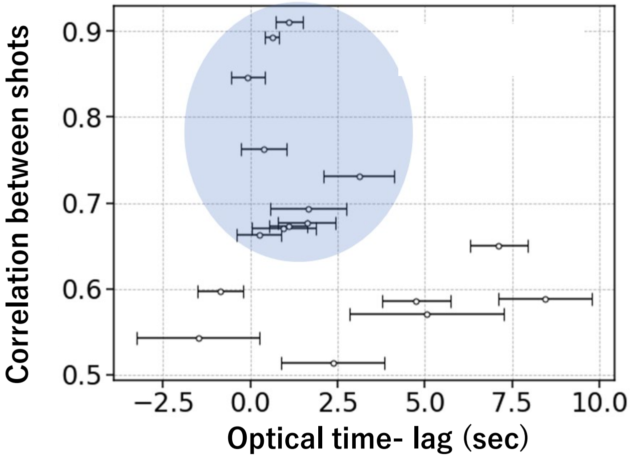
Video data by CMOS

Sub-sec scale resolution

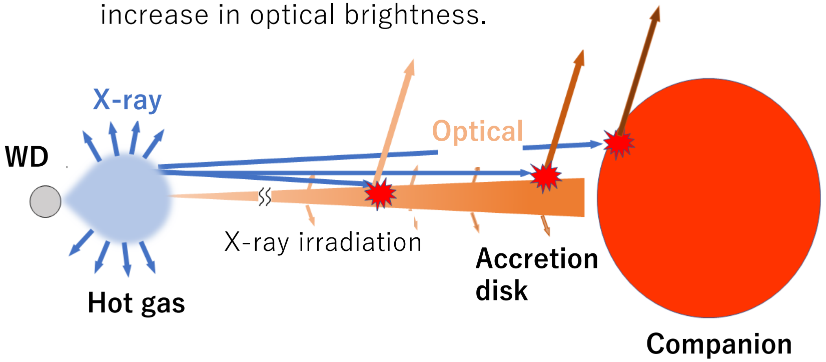
Time accuracy: < 0.1 msec

Gendreau, Keith C et al. 2016





X-rays temporarily heat the disk, causing an increase in optical brightness.



Press release from UTokyo, Nishino et al.

Simultaneous Observations of Fast Radio Bursts (FRBs) with Tomo-e Gozen and Radio Telescopes

To put constraints on the radio–optical SED.

Monitoring of Known Repeating FRBs

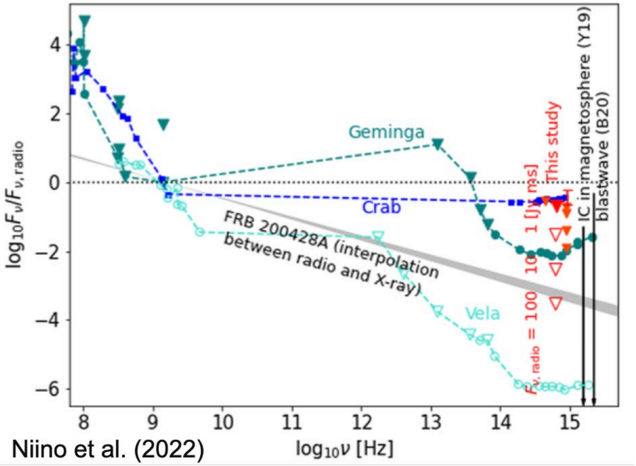
- Simultaneous optical–radio monitoring in coordination with FAST 500 m (China)
- During active phases, >10 radio bursts can be observed within a few hours.
- **No optical emission has been detected so far.**
- Observations are ongoing.

Wide-Field Monitoring of Non-Repeating FRBs

- Wide-field monitoring the same field-of-view as CHIME (Canada) in optical.
- Expected event rate: ~1 per 240 hours.
- **No optical emission has been detected so far.**
- Observations are ongoing.

Known Repeating FRBs

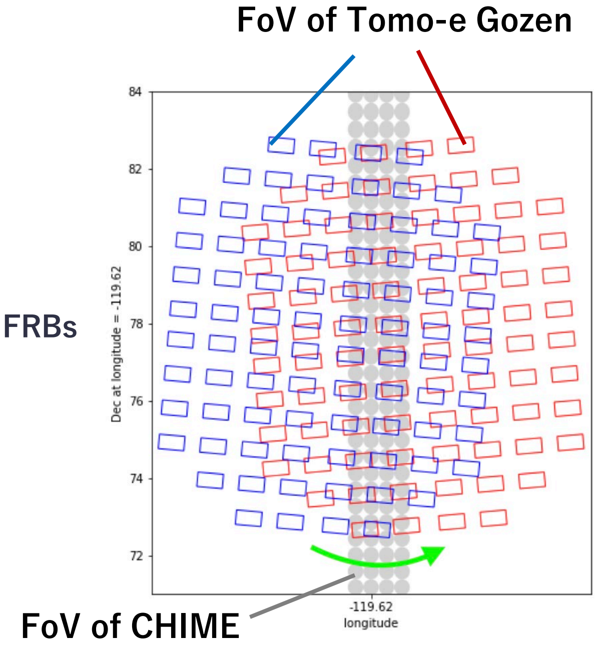
Simultaneous



Tomo-e Gozen

Simultaneous

Wide-Fileld Non-Repeating FRBs

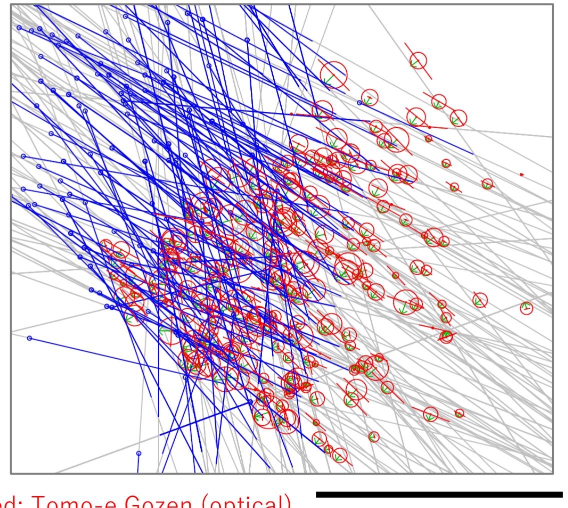


Simultaneous Optical–Radar Observations of Faint Meteors (Interplanetary Dust)

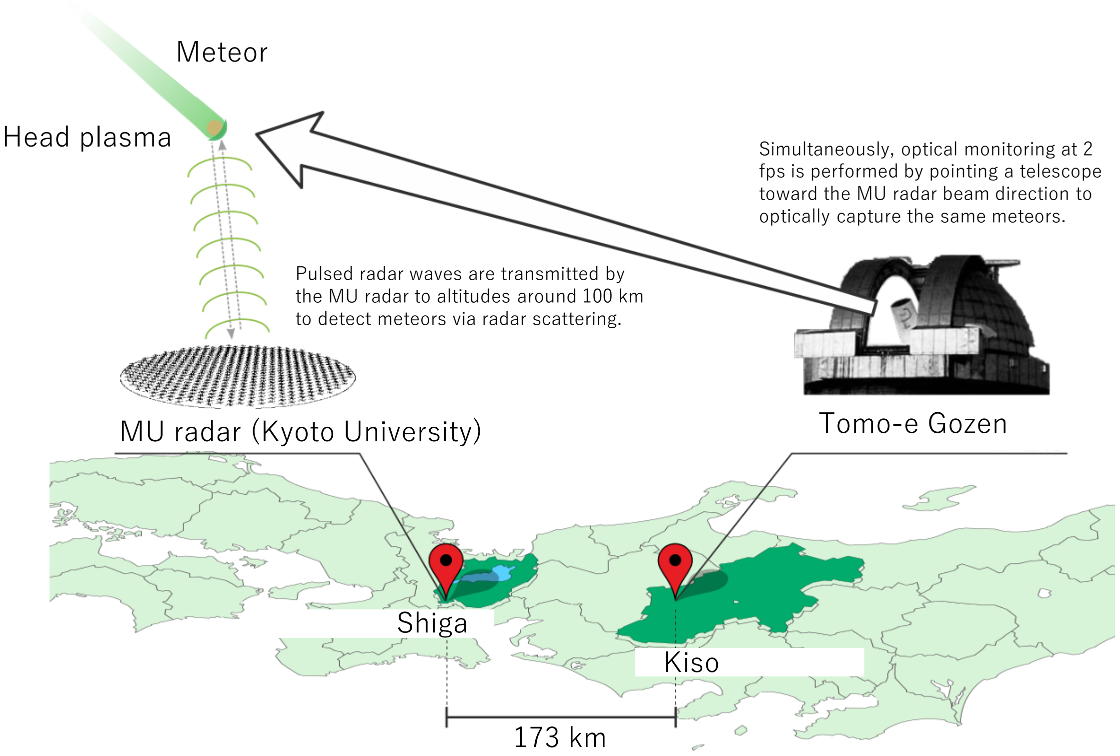
- Simultaneous observations of faint meteors using Tomo-e Gozen (Kiso) and MU radar of Kyoto University (Shiga)
- Achieved simultaneous detections of faint meteors
- Derived a conversion factor between radar cross section and optical brightness/mass of tiny meteoroids.

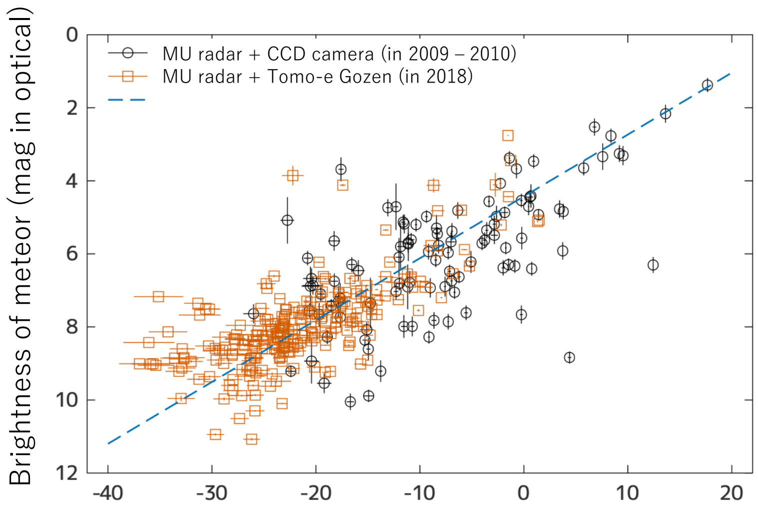
Ohsawa+ 2020

0.01 mg -- 1 g



red: Tomo-e Gozen (optical)
blue: MU radar (radio)





The radar cross section (RCS) is measured in dB relative to 1 m².

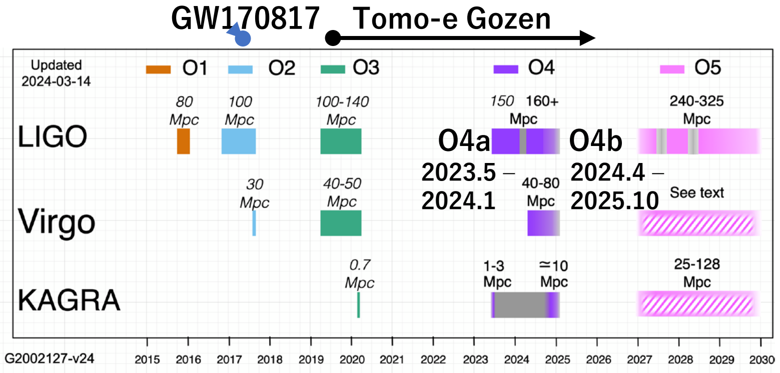
Press release from UTokyo, Ohsawa et al.

Search for Optical Counterparts of Gravitational Wave Events

Rapid Follow-ups with Tomo-e Gozen

- Wide field-of-view (20 deg^2) and fast response capability (< 20 mag).
- Transient detection pipeline can identify candidates for GW counterparts.
- Particularly advantageous when GW localization uncertainties are large.
- For BNS mergers, detections are feasible for events within ~100 Mpc.

Operation schedule of LVK



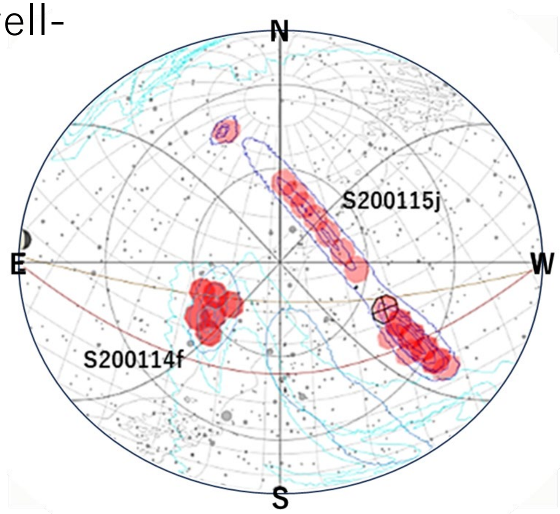
https://observing.docs.ligo.org/plan/

Tomo-e Gozen Follow-up in GW Observing Runs O3 – O4a

- Responded to 43 GW alerts, targeting high-confidence, well-localized, and nearby events (BNS, NS-BH, BBH).
- **No optical counterparts were detected.**

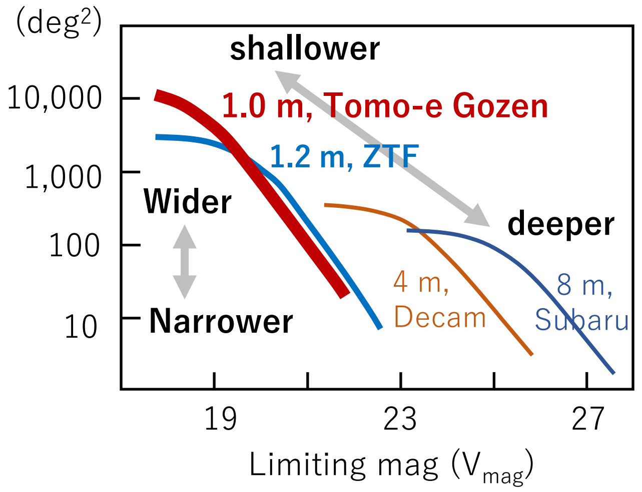
Observing Runs O4b

- Currently ongoing since April 2024
- **No optical counterparts were detected.**



Sample of GW follow-ups
(Jan. 15, 2020)

Sky area observable within 1 hour



3. Hardware of Tomo-e Gozen

Schmidt Telescope (Spherical Primary + Corrector Lens)

Advantages: Extremely wide field of view

- Free from spherical aberration, astigmatism, and coma across the entire focal plane
- Bright optical system

Disadvantages: High construction cost

- Long focal length
- Requirement for a large corrector lens
- Need for a larger-than-normal primary mirror

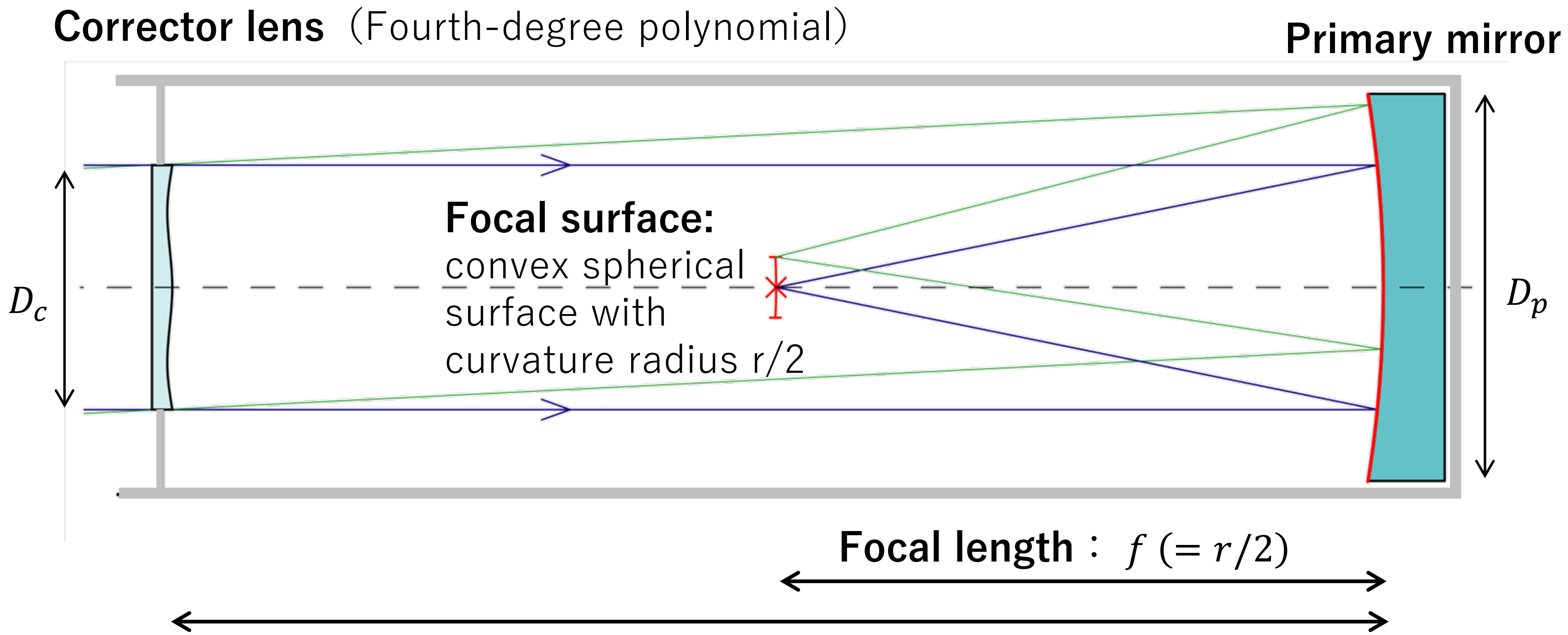
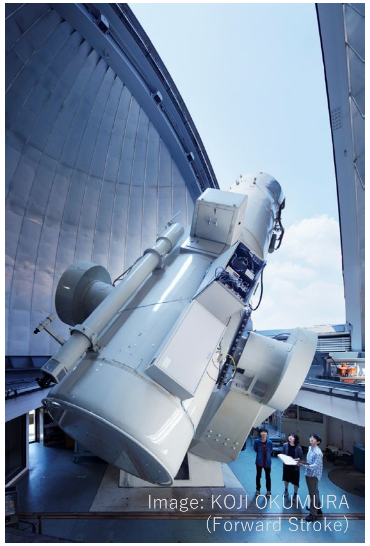


Image Wikipedia



Kiso 1.05 m Schmidt telescope

$D_c = 1050\ mm, D_p = 1500\ mm$

$F/3.1,\ f = 3300\ mm,\ 16\ \mu m/arcsec$

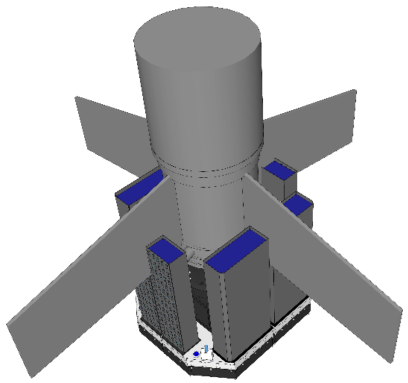
Third-largest Schmidt telescope in the world

Design Concept of the Tomo-e Gozen Camera

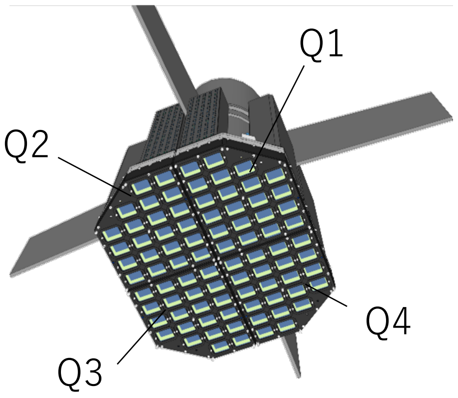
Key Features

- **Wide FoV** and **high-speed consecutive** (**video**) observation
- **Simplified system**
  - At room temperature and ordinary pressure
  - No moving parts
  - Easy maintenance

  } Realize a large-scale and highly stable system
- **Raw data are automatically deleted after 5 days**

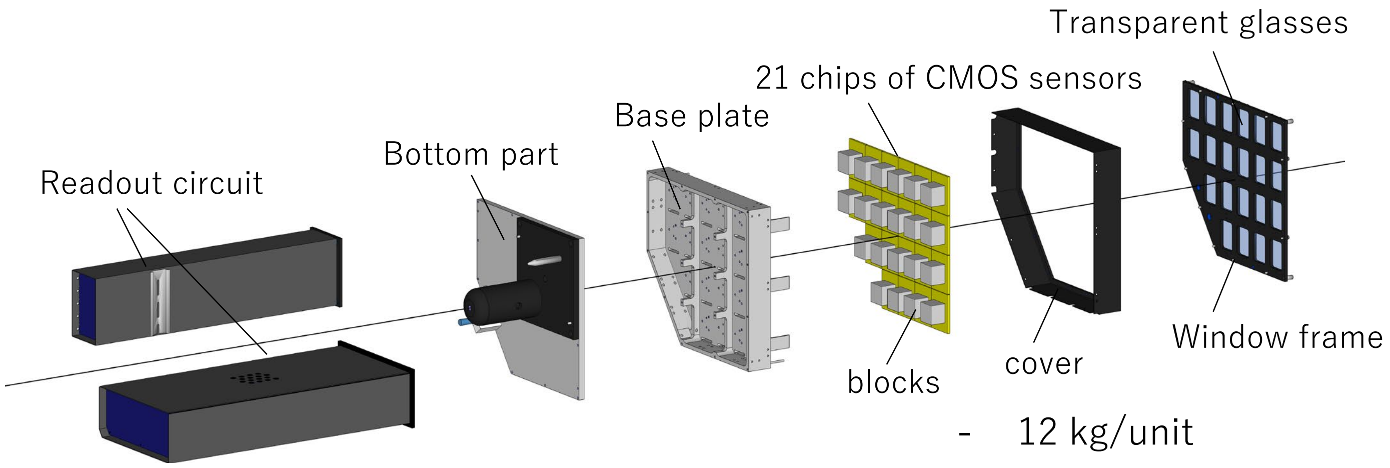


Rear view



Front view

515 x 575 x t = 540 mm



- 12 kg/unit
- Total weight 57 kg

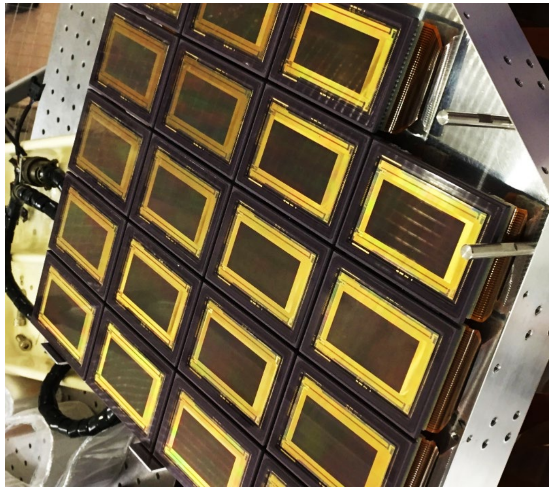
Large pixel CMOS image sensor

- Canon 35MMFHDXM
- 2,000 x 1,128, $\mathbf{19}\ \boldsymbol{\mu m/pix}$,
- Front-side illuminated
- Microlens array + protective glass
- Rolling shutter read, 16ch analog output
- Photosensitive area / package = 0.35

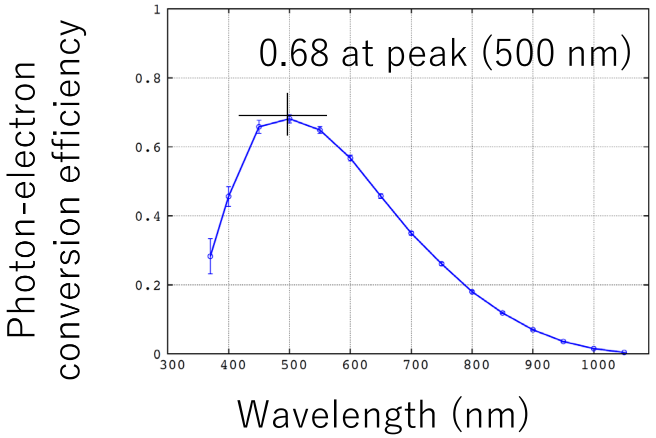
The typical seeing size on the telescope focal plane is $60\ \mu m$ (= 4")

- Sensitivity range: 370 – 730 nm
- Power consumption: 230 mW $chip^{-1}$ @ 2 fps
- Full well : 6,000 e^-, 53,000 e^- @ G = x16, x1.7
- **Read out noise : 2.0 e^-**, 9.2 e^- @ G = x16, x1.7
- **Dark current : 6 e^- sec^{-1} @ 305K**

→ Less than dark-sky background level (< 50 e^-/sec) even at room temperature

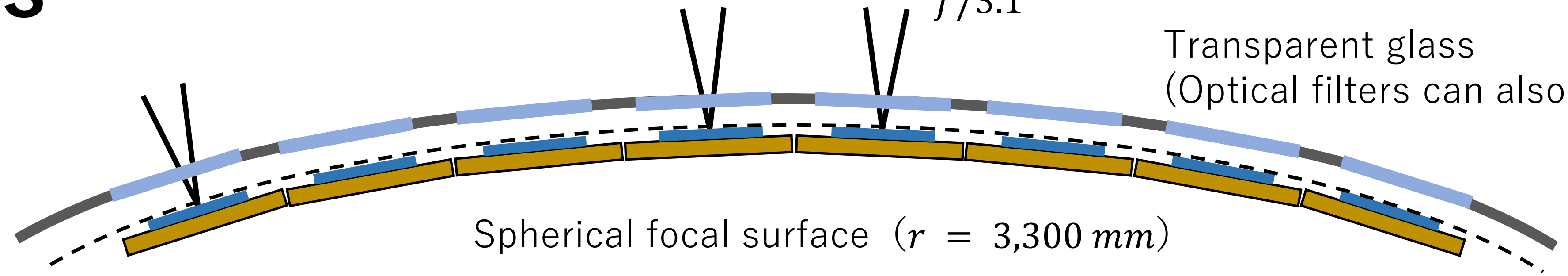


CMOS image sensors arranged along a spherical focal surface



Kojima et al. 2018

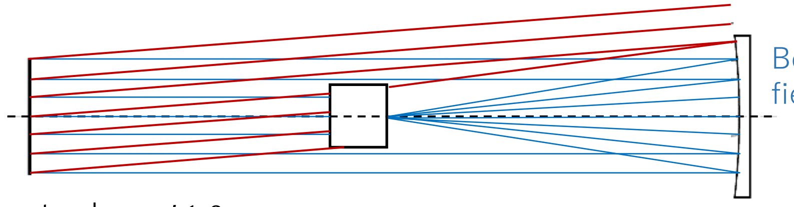
Optics



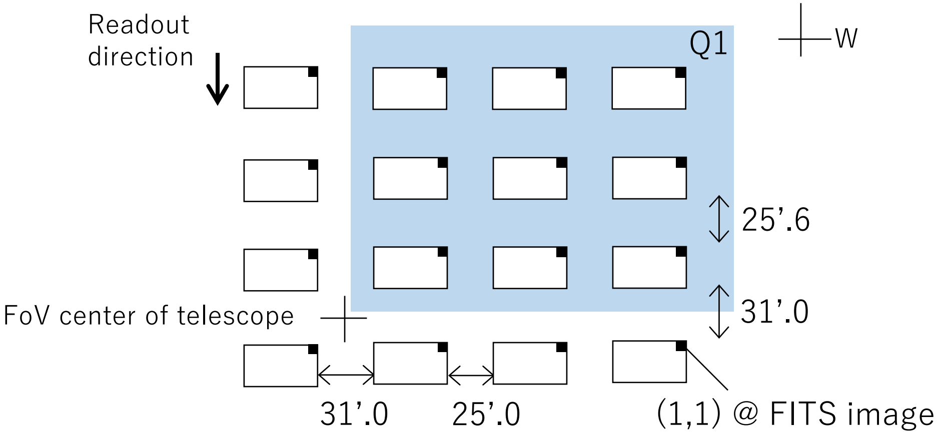
Alignment tolerance: $dz = \pm 60\ \mu m$, $d\theta = \pm 0.1°$

- Picel scale : $1.189\,''\,pix^{-1}$ (typical seeing size 3")
- FoV of 1 chip : $39.7' \times 22.4'$

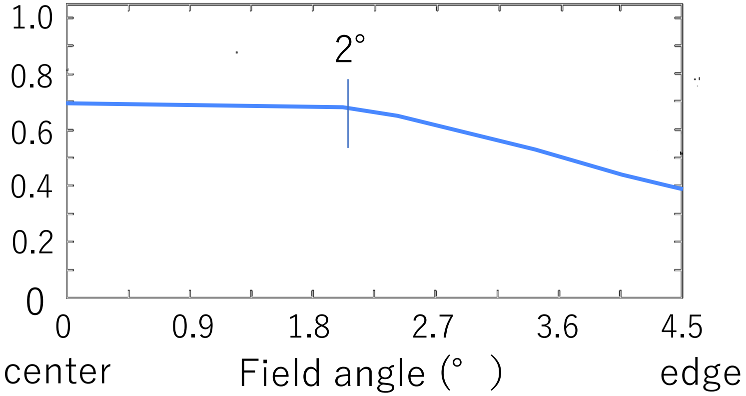
Lay trace



Sensor layout



Vignetting ratio

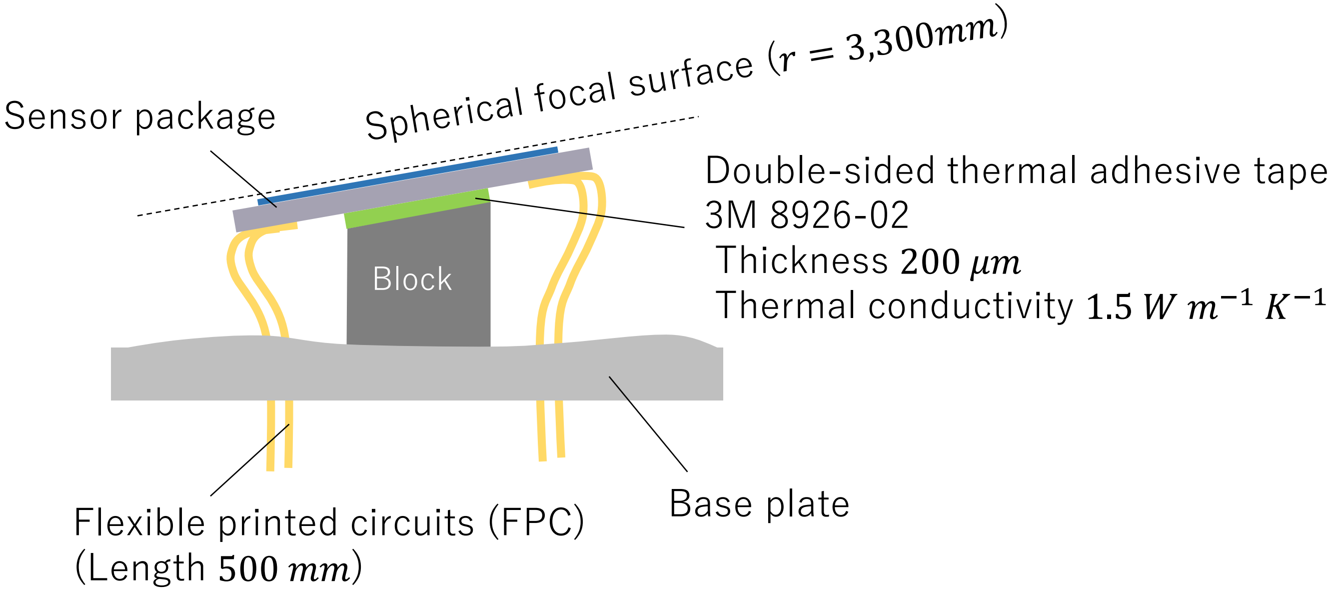


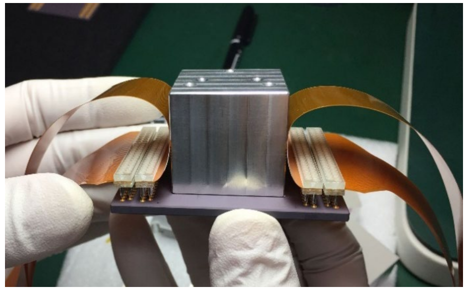
Camera Housing Fabrication and Assembly

By manufacturing the base plate with high precision, sensor alignment work was eliminated.

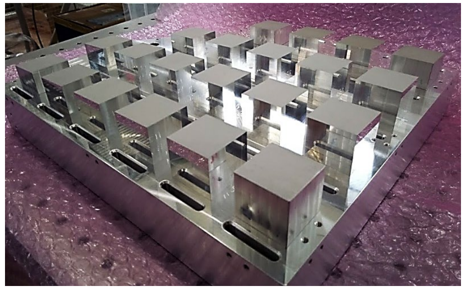
(1) High-precision measurement of the base geometry

(2) Each block was precisely machined to cancel out the height error of the base plate.



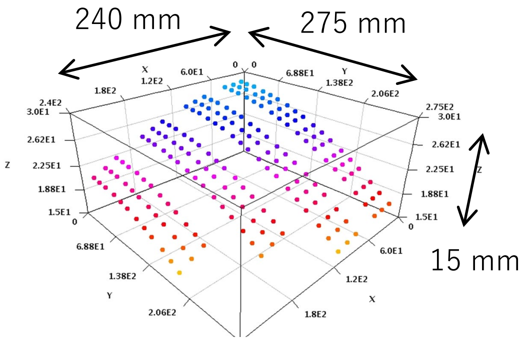


Blocks adhered to the back of each sensor



21 blocks installed on the base plate

336 FPCs connected to 84 CMOS sensors



Top surface positions of the blocks measured precisely.

Achieved an alignment error of 60 μm peak-to-valley relative to the spherical focal surface.

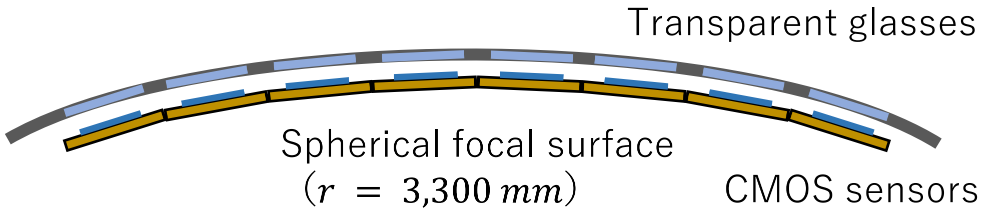
Fabrication of Curved Window Frames

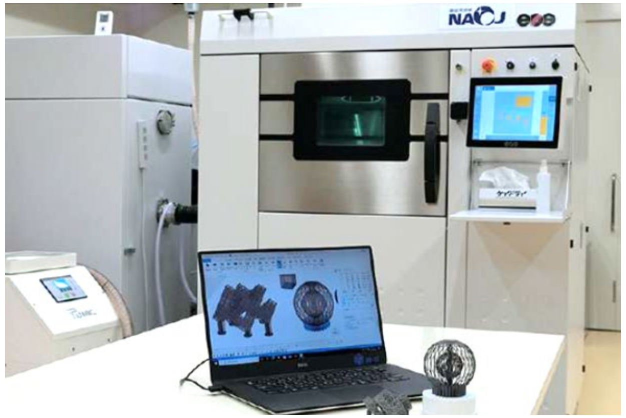
- Manufactured using a metal 3D printer, followed by surface finishing with a milling machine.

Material : AlSi10Mg

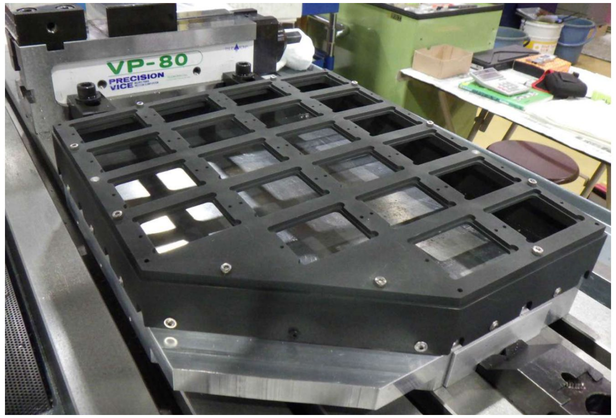
Size : $254 \times 284 \times 10 \sim 50\ mm$

Build time: 74 hours per unit

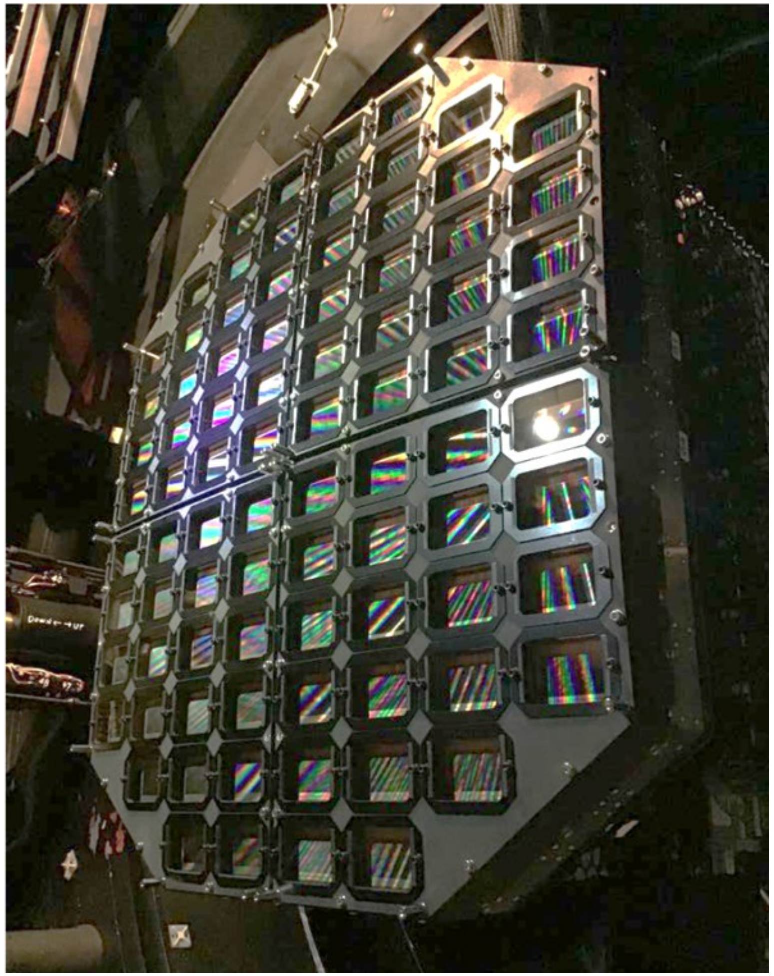




Metal 3D Printer: EOS M290
(Advanced Technology Center, NAOJ)



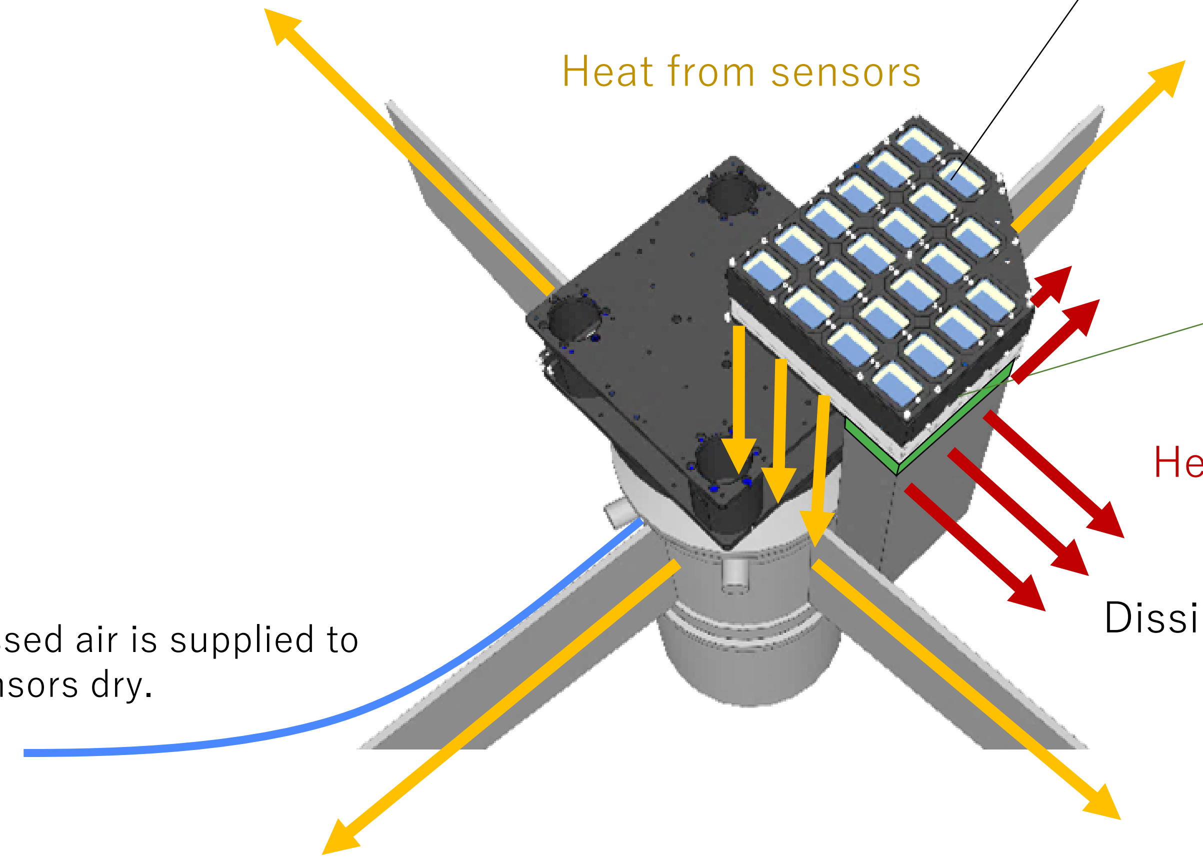
Fabricated curved window frames



Installed on the Tomo-e Gozen camera

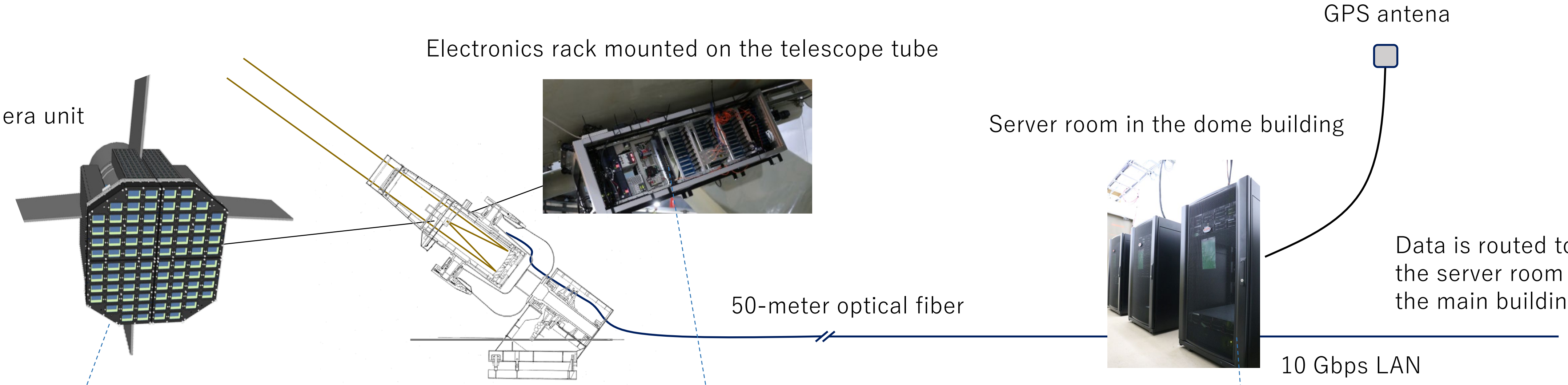
Thermal Design

Non-vacuum, passive cooling system (no forced cooling)

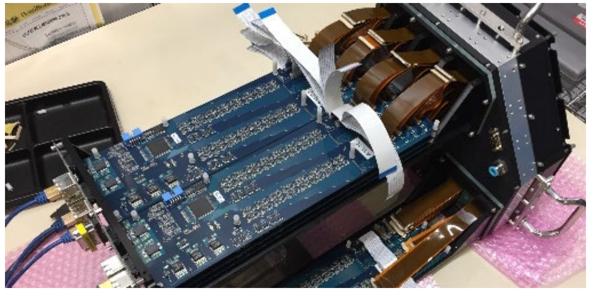


Sensor temperature remains at an offset of ~1.5 K above ambient air temperature
(No active temperature control is applied)

Data Acquisition System



Analog front-end (mounted on the focal plane)



- 1,344 channels, 16-bit ADC, 400 ksps
- 9.9 MB/sec per chip @ 2 fps
- Readout from 4 camera units is synchronized.

Digital I/O boards connected via PCIe bus extenders

Interface ZZ0-046A

- 32-bit I/O, 10 MHz, 24 boards in total
- LVDS-to-optical fiber conversion boards
- Supports bus-master

GPS receiver

u-box EVK-M8N

- UTC timestamping
- Absolute timing precision: ±0.2 ms
- Frame rate stability: $\sim 10^{-5}$

Environmental Monitoring to Supporting Autonomous Observations

• Weather Monitoring Instruments

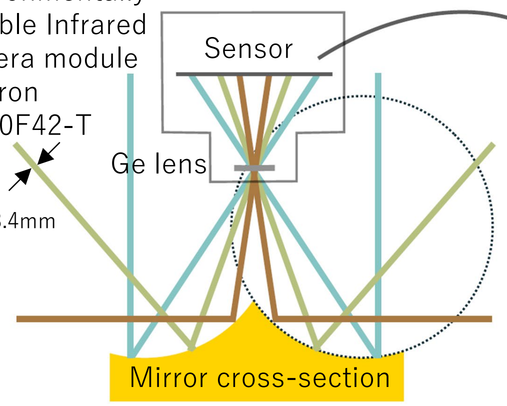
Rooftop of the main building at Kiso Observatory

- Infrared all-sky camera
- Visible-light all-sky camera
- Radiation thermometer (single-pixel, for cloud detection)
- Fog sensor
- Rain sensor (wetness detection)
- Weather station (temperature, humidity, wind direction and speed, raindrops)

• Infrared All-Sky Camera for Cloud Monitoring

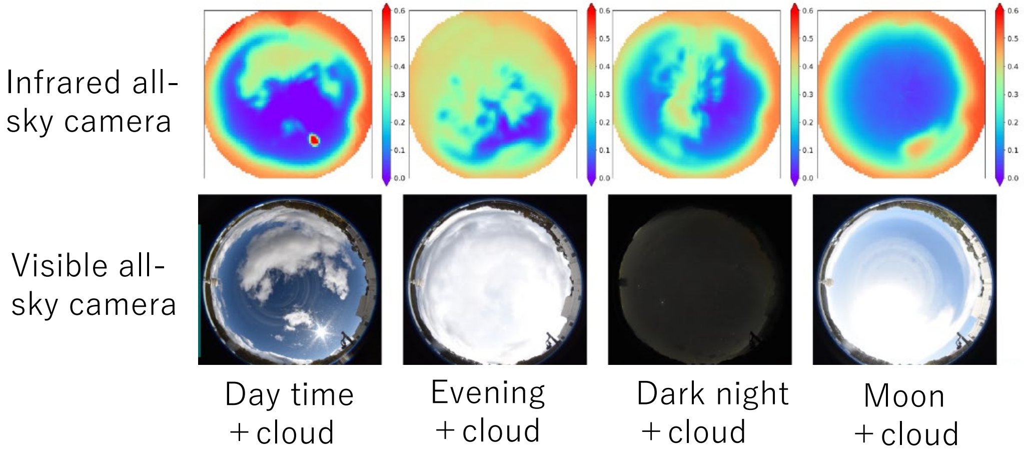
Tsutsuki et al. 2024, SPIE

Overview of the infrared all-Sky camera



Principle of the reflective all-sky camera

Fabricated field-expanding mirror



Enables accurate cloud distribution mapping regardless of day/night conditions, moonlight, and urban lights)

Performance Verification of Camera Instrument in Laboratory

Electronics

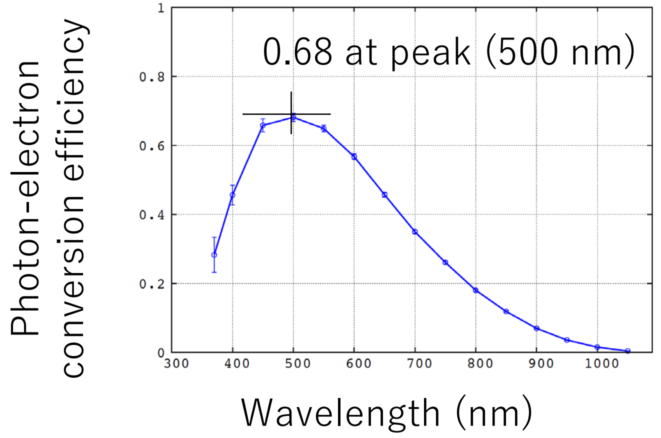
- Quantum efficiency, dark current, readout noise, and full well
- Those temperature and pixel dependence

Optics

- Pixel scale, field-of-view
- Efficiency of optical elements.
- Vignetting of the incoming beam

Thermal

- Daily temperature variation



Kojima et al. 2018

These verified characteristics are utilized to estimate observational performance.

Basic Calibration

The following basic calibrations are performed for each frame.

- **Remove zero offsets of CMOS sensor**

  Dark frames are obtained before starting observations (every evening).

- **Uniformize sensitivity difference in pixel-to-pixel, caused by sensor and optics**

  Flat frames are obtained before starting observations (every evening).

- **Correct image distortion and pixel scale**

  1. Measure the centroid positions of stellar objects detected in the same frame.
  2. Compare the position values and the Gaia catalog.

- **Calibrate the efficiency of sensor, optics, and atmospheric transmittance**

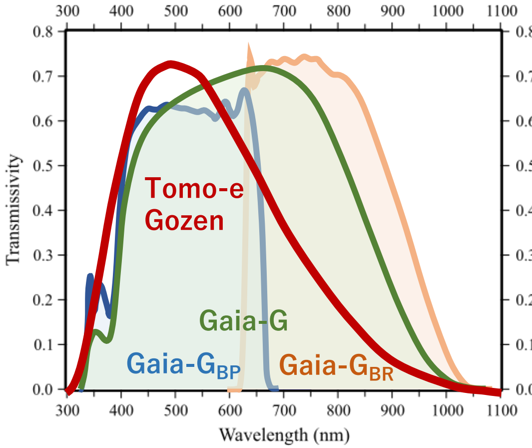
  Transform from the photometric values (ADU) to the photon number.

  Perform **relative photometry** using the Gaia catalog.

  Color correction is also performed.

Color correction factors are empirically derived from Tomo-e Gozen photometric values and linear combinations of Gaia G, G_{BP}, and G_{BR} values.

Efficiency of Tomo-e Gozen and Gaia



High-Accuracy Calibration

The following calibrations can improve the quality of the reduced data. **However, we DO NOT apply these reductions because the Tomo-e Gozen project prioritizes the detection of transient and fast-moving phenomena, and computing resources are limited**.

- **Temperature dependence of dark current, pix-to-pix uniformity of efficiency (flat pattern).**
- **Gradient of the efficiency within the frame.**
- **Time variation of the color correction factors due to characteristics changes of the earth's atmosphere**

Summary

Tomo-e Gozen project

- A wide-field survey project designed to capture short-timescale transient phenomena.
- Video observations of a 20 deg^2 field at up to 2 fps.
- Operates autonomously, surveying over 10,000 deg^2 per night.

Exploration of rapid variability down to the second timescale

- Utilizes ML models to identify transient phenomena and fast-moving objects.
- Successfully detected stellar flares with second time-scales.
- Ongoing simultaneous optical–X-ray observations of accretion disks.

Tomo-e Gozen camera

- Equipped with 84 CMOS sensors, with a high-performance computing system directly connected to the camera.
- Simplified system
  - At room temperature and atmospheric pressure, no moving parts, easy maintenance
  - Minimal data processing is performed.
- Raw data are automatically deleted after 5 days