The Tomo-e Gozen project

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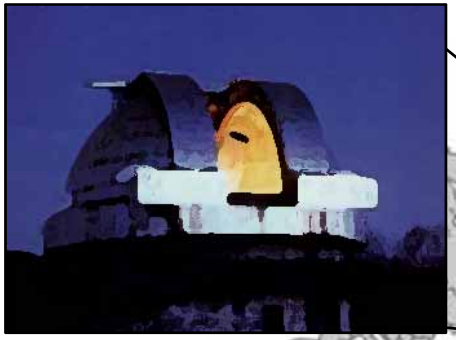
ICRR seminar, the University of Tokyo, 2019/2/27 15:30-

Institute of Astronomy, the University of Tokyo

Kiso observatory
Kiso, Nagano, Japan
1.0-m wide-field Schmidt telescope



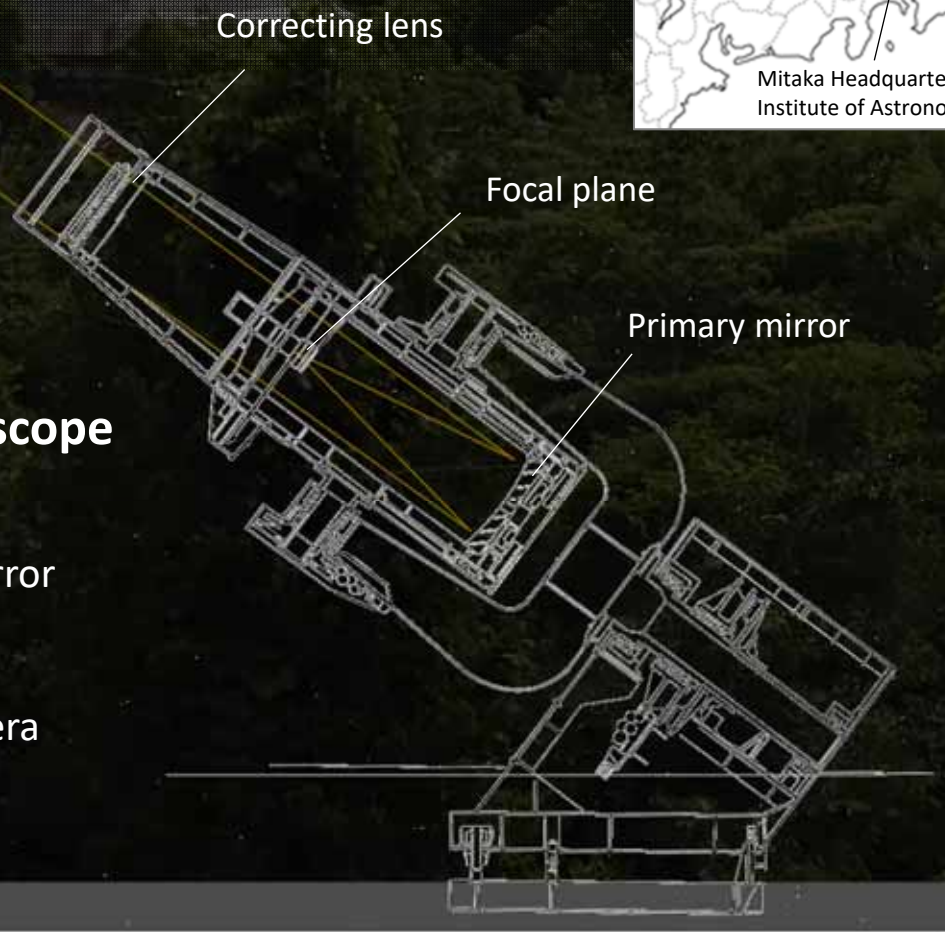
The university of Tokyo Atacama observatory (TAO)
5,600-m alt., Atacama, Chile
1.0-m mini-TAO telescope
6.5-m telescope (under construction)

Headquarter
Mitaka, Tokyo, Japan

Kiso Observatory

Kiso observatory, Institute of Astronomy, the University of Tokyo

- Established in 1974
- Dark sky, 1120-m altitude
- Accommodation, Cafeteria



Extremely wide-field Schmidt telescope

- Field of view: ϕ 9 degrees
- Primary: 150 cm spherical mirror
- Corrector : 105 cm aperture
- Focal ratio : 3.1
- Main instrument : Tomo-e Gozen camera

OUTLINE

1. **Introduction of Tomo-e Gozen**
2. Instrument and computing system
3. Survey plans and early results

Snapshot of the Sky

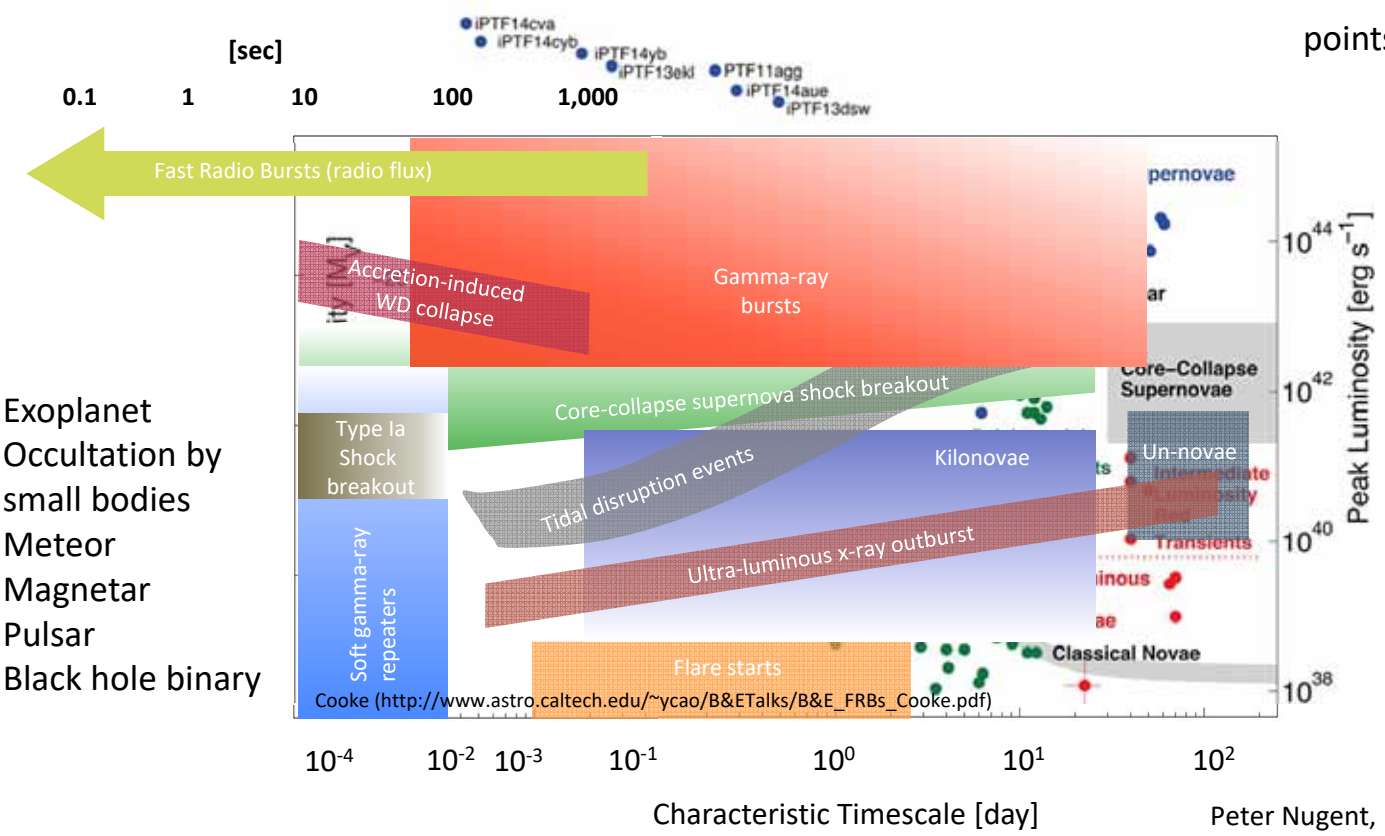
LSST Project/NSF/AURA

Time domain astronomy

The phase space of optical transients

gray: before PTF (-2009)

points: new categories discovered by PTF



- Exoplanet
- Occultation by small bodies
- Meteor
- Magnetar
- Pulsar
- Black hole binary

Peter Nugent, 13 February 2015, SPIE Newsroom

The Universe with **HOURS** time scale is less surveyed.

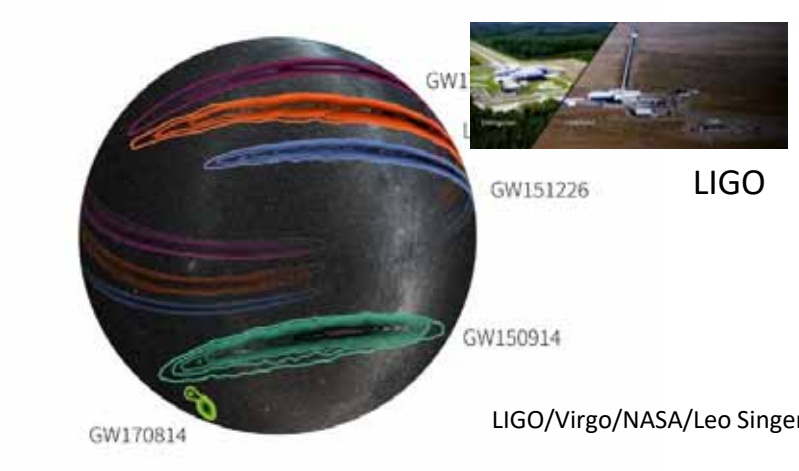
The Universe with **SECONDS** time scale is still unknown.

Multi-messenger astronomy

- Gravitational waves were detected from a black hole-black hole merger in 2015.

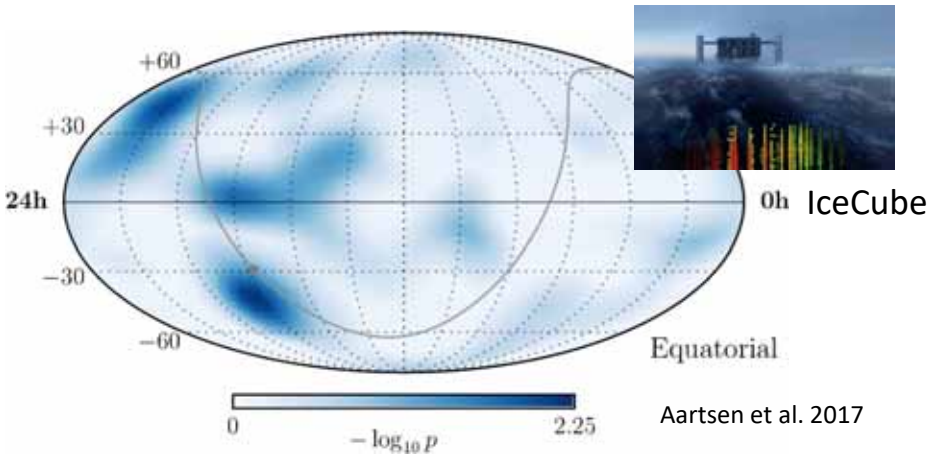
- The new astronomy with EM and non-EM radiations has begun .

GW events detected by LIGO/Virgo



Typical localization error is 10 – 100 deg^2

Neutrino cascade events detected by IceCube



Typical localization error is 10 – 100 deg^2

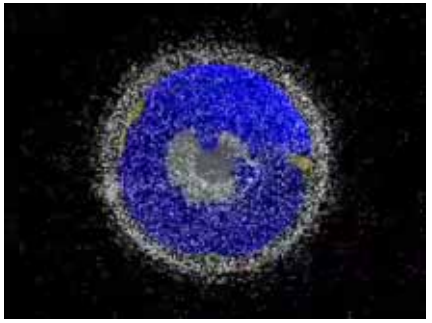
QUICK optical follow-ups with a few 10 DEG^2 are required.

Missing events in astronomy

- Most of fast-moving-objects and flash-events have been missed in surveys.

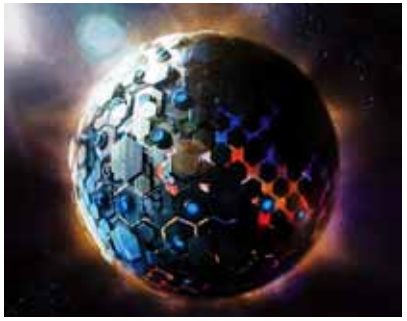
Meteors

Near earth asteroids



Space debris

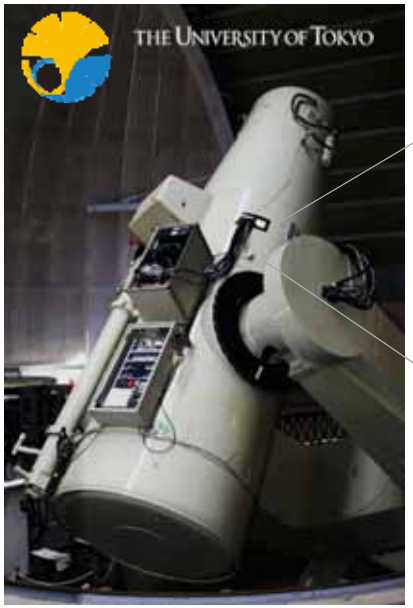
Unknown high-energy flashes



Unknown alien planets

High-speed and wide-field observations with are required.

Wide-field high-speed camera The Tomo-e Gozen



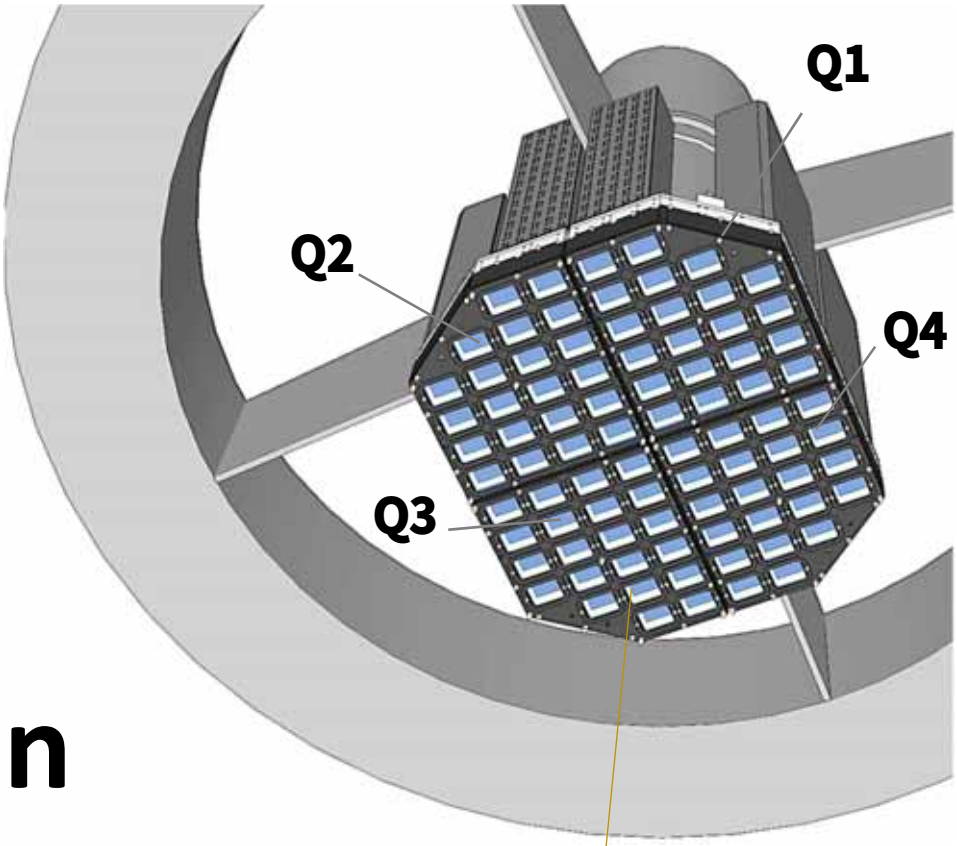
Kiso Schmidt telescope
The University of Tokyo
D=105-cm, f/3.1

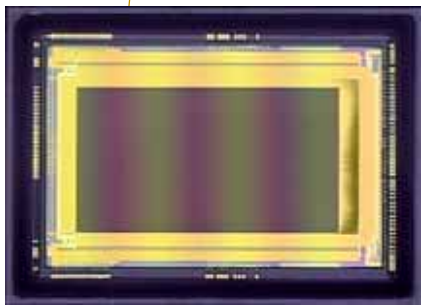
the Tomo-e Gozen with 84 CMOS sensors
FoV of 20 deg^2

The Tomo-e Gozen is named after Tomo-e Gozen (Lady Tomo-e), who is a woman warrior born in the Kiso region, Japan in the 12th century.

Image: TNM Image Archives

Sako et al. 2018, SPIE, Kojima et al. 2018, SPIE,
Sako et al. 2016, SPIE, Morii et al. 2016, ApJ, Osawa et al. 2016, SPIE





the first wide-field CMOS camera

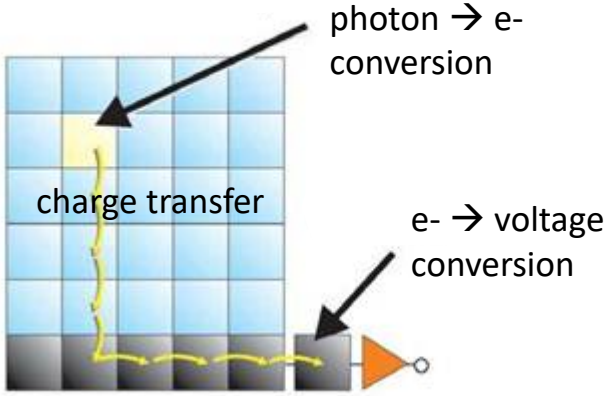
The Tomo-e Gozen

- FoV of 20 deg^2 in ϕ 9 deg
- 84 chips of CMOS, 1k x 2k pixels
- Consecutive frames at 2 fps (max)
- Big movie data of 30 TB/night (max)
- Room temperature, Non-vacuum

CCD vs CMOS sensor

CCD

Charge coupled device



◎ **Large format (< 6k x 6k)**

△ Slow readout (>10sec)

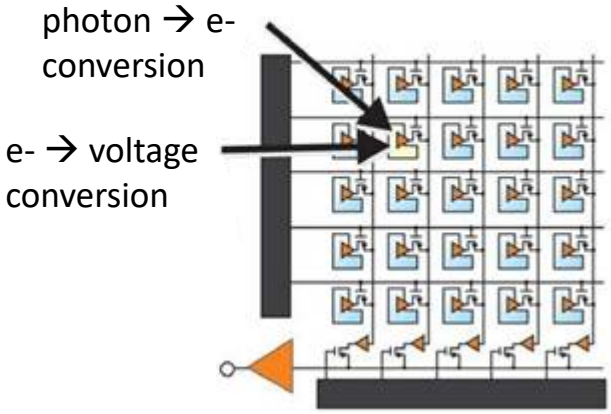
global shutter only

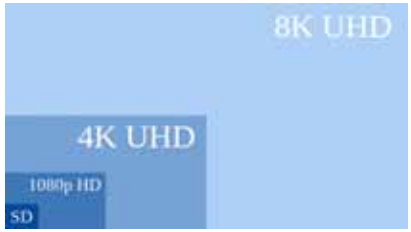
○ Simple structure

△ High voltages necessary

◎ **Backside and full-depletion technologies established**

CMOS





◎ **Large format (< 8k x 8k for commercial use)**

◎ **Fast readout (>0.1sec)**

Rolling shutter available

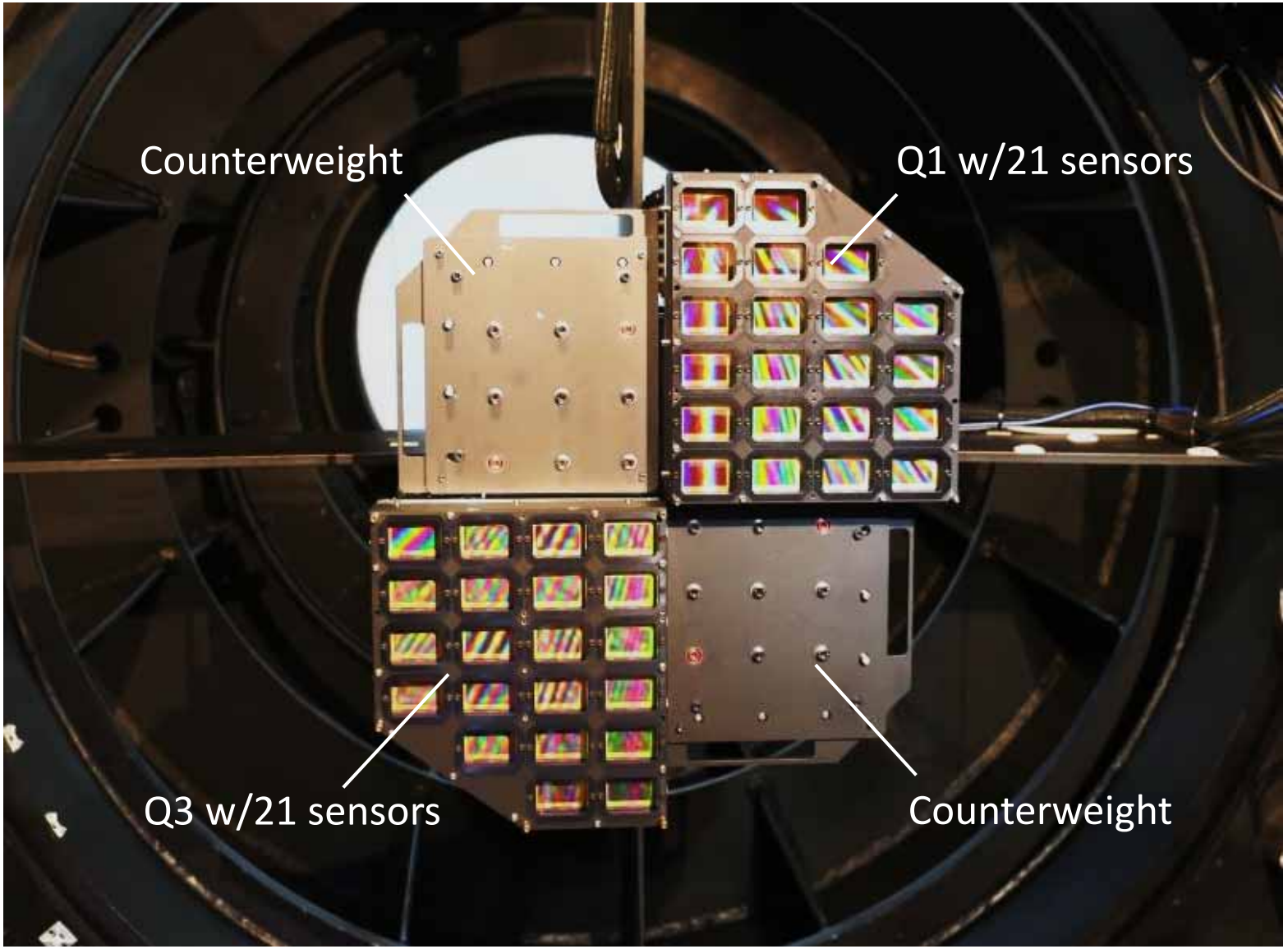
◎ **Embedded functional circuits → Low read noise**

○ Low voltages & low power

△ Backside and full-depletion (hybrid structure)

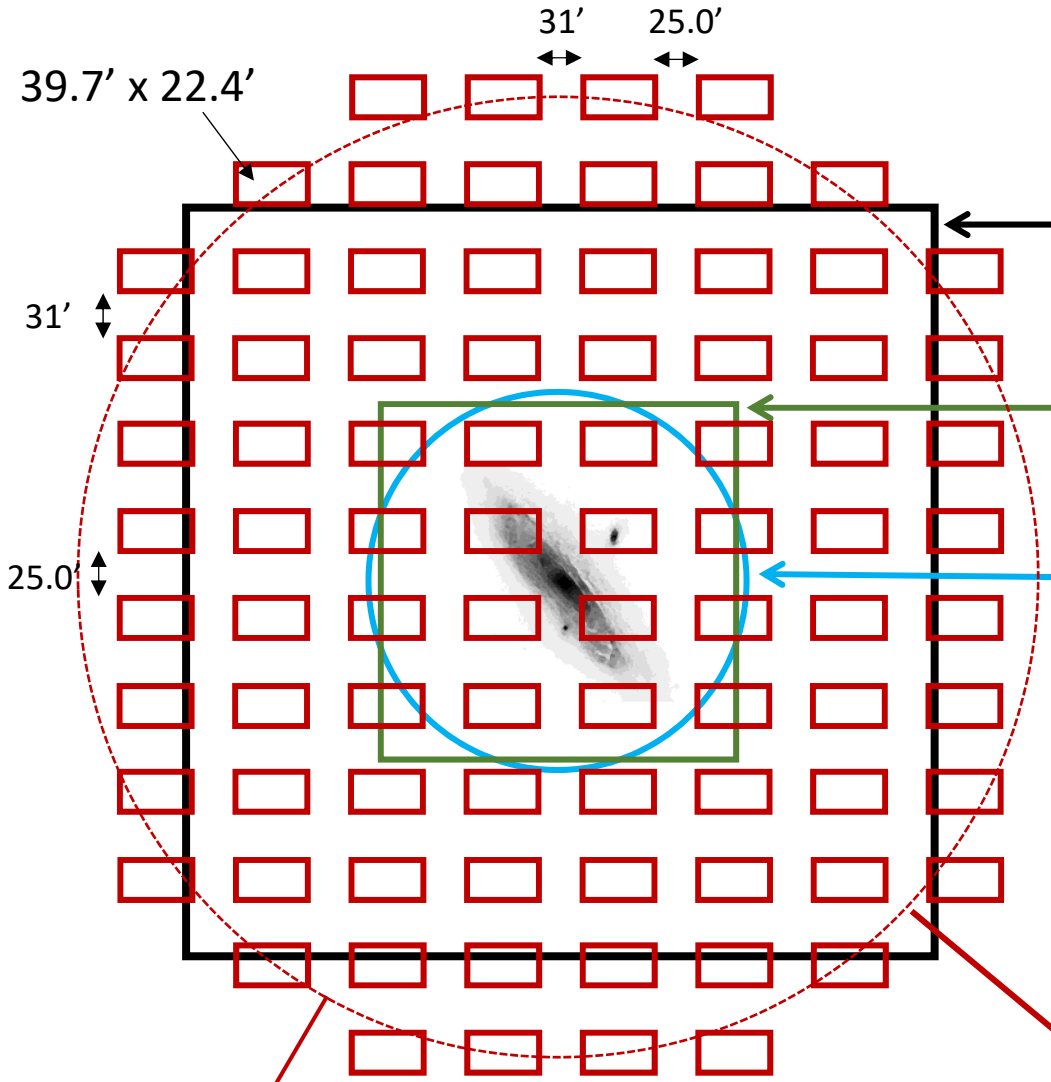
technologies under development

Image taken on Nov. 2018



The full-spec Tomo-e Gozen will be completed in April 2019

Comparison of Field-of-Views



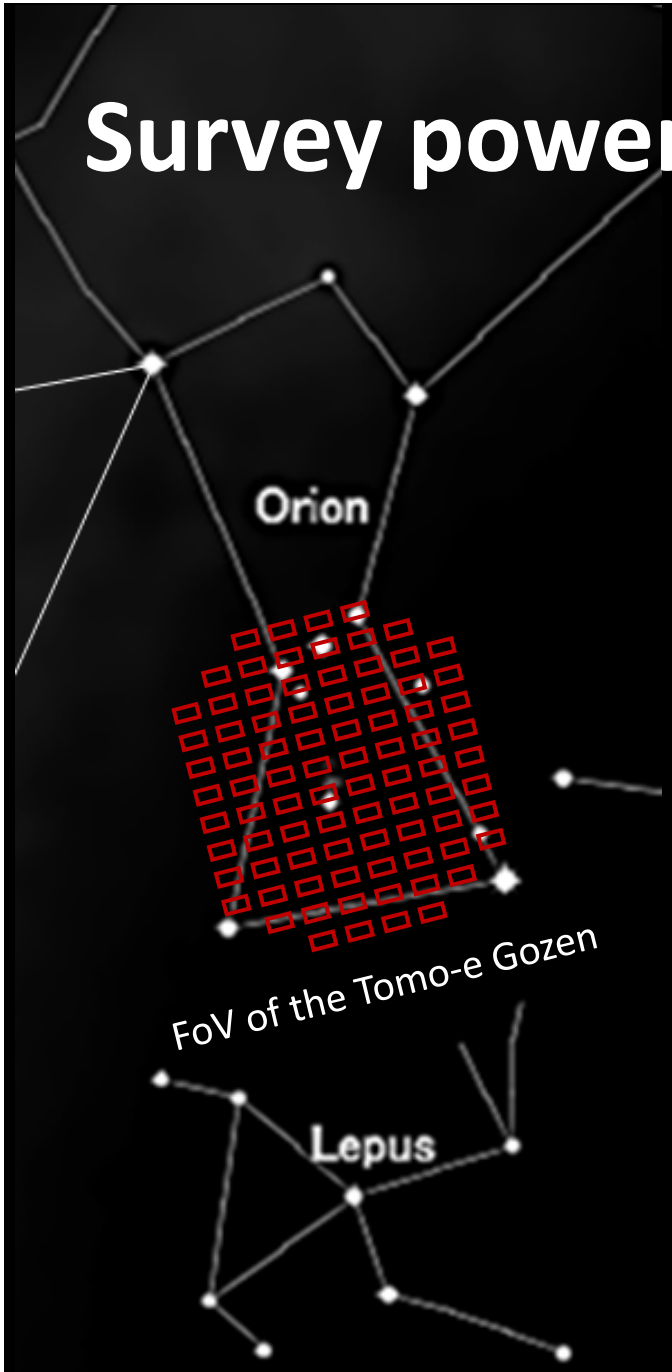
ZTF (1.2m) , 47 deg^2 , 2018-,
AΩ = 40 , Δτ ~ days, **CCD**

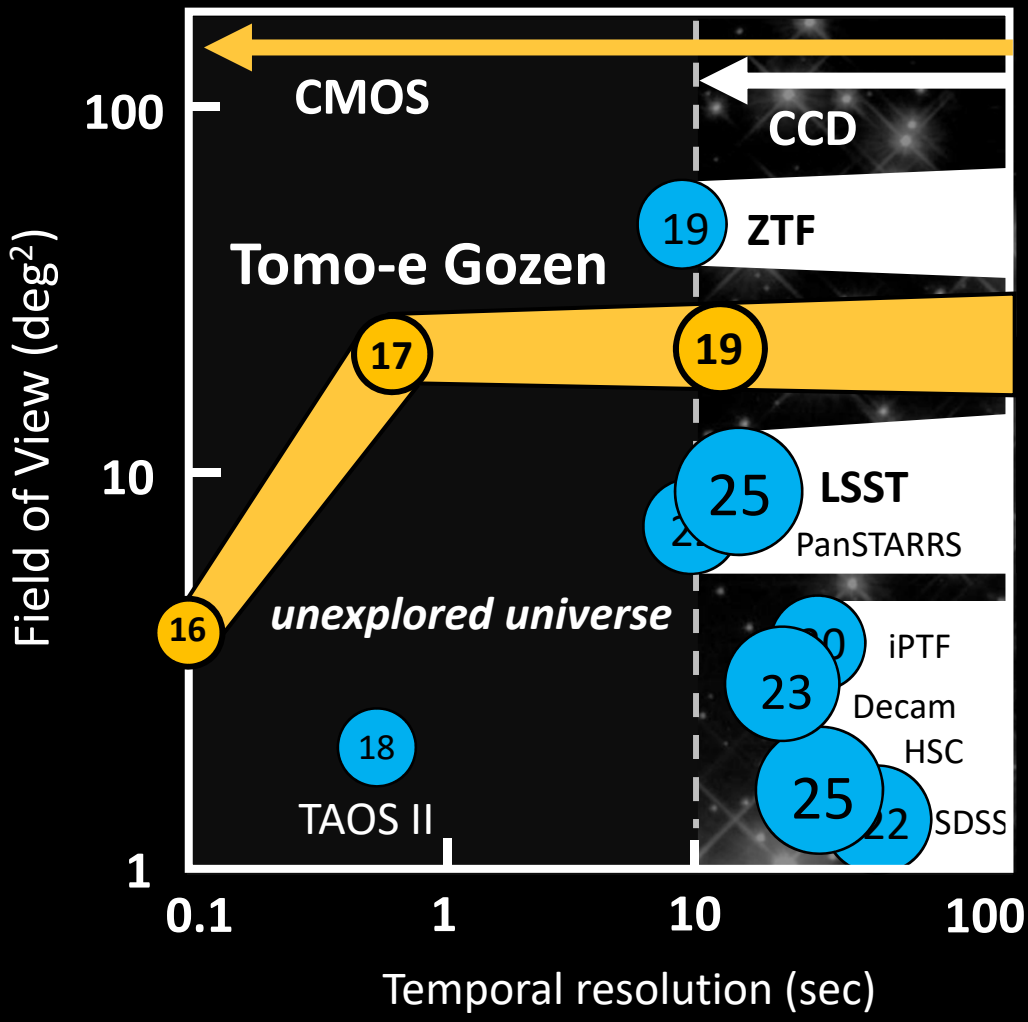
Pan-STARRS (1.8m), 9 deg^2,
AΩ = 15 , Δτ ~ days, **CCD**

LSST (8.4m), 9.6 deg^2 , 2023-,
AΩ = 320 , Δτ ~ hours, **CCD**

Tomo-e Gozen
20 deg^2 in ϕ 9 deg
AΩ = 28, Δτ ~ subsec
CMOS sensors

Survey power for transient events



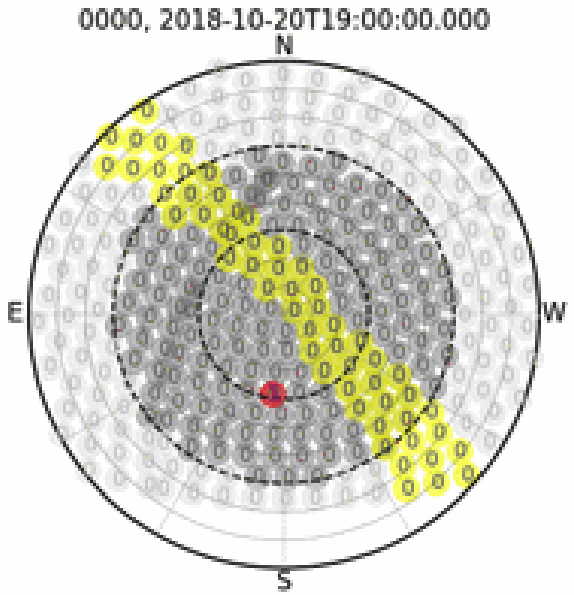


The numbers in the circles show limiting magnitudes.

Intensive Science Programs

1. Transient survey

- Elv > 40 deg (7,000 deg^2) every 2 hours
- 3 visits per night
- Record all events < 20 mag (dark clear night)
- SNs, Novae, variables



Simulation of transient survey

- Each circle: FoV with Φ9 deg
- Yellow: Milky way

2. Follow-up / Simultaneous

- GWs, neutrinos
- FRBs, NSs, BBHS, meteors, NEO,

3. Fixed FoV + high-speed

- 2-fps@ 20 deg^2 -- 200-fps@ 52” x 38”
- Occultation of TNOs, YSOs, flares, FRBs, NSs, BBHs, meteors, NEOs

Organization

You are welcome to join us!

Kiso Observatory
Institute of Astronomy, the University of Tokyo
Director: N. Kobayashi

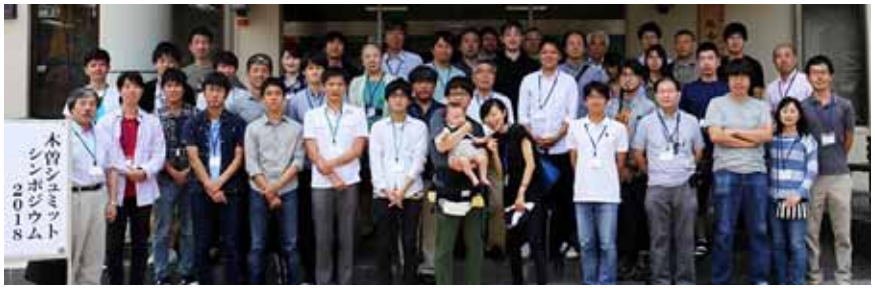
Tomo-e Gozen Project
P.I.: S. Sako

Technical Working Group†
S. Sako (reader) and 36 persons

Science Working Group†
T. Morokuma, R. Ohsawa (readers)

- Supernova
- Gravitational wave
- Planetary system
- Compact object
- AGN
- Star
- Data science

based on collaborative researches, and KAKENHI



Kiso Schmidt symposium on July 10-11 2018

† Initially, the survey data can be accessed by only Tomo-e members.

Camera development team

- Core members: ~10 persons
- U-Tokyo Mitaka staff + Kiso Observatory staff + Graduated students
- 3 Master's thesis on camera development

OUTLINE

1. Introduction
2. **Instrument and computing system**
3. Survey plans and early results

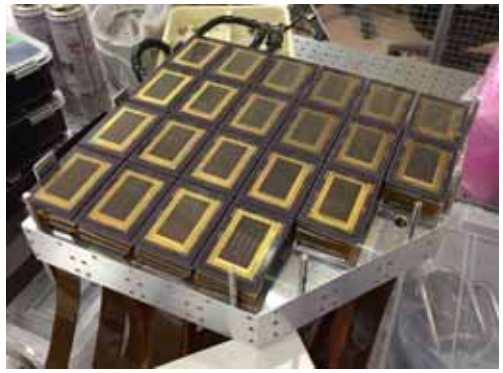
Requirements for high-speed and wide-field optical observations

0. Concept	• Simple is stable and sustainable.
1. Image sensor	• High-speed frame read without dead time • Low read noise • Low power dissipation or cooler
2. Data acquisition	• Consecutive data acquisition • High absolute time accuracy • High time stability
3. Optics	• Wide field
4. Computing	• Large storage, high-speed processing & network, data visualization
5. Operation	• Quick telescope system • Quick communication system for observers

Design concept of Tomo-e camera

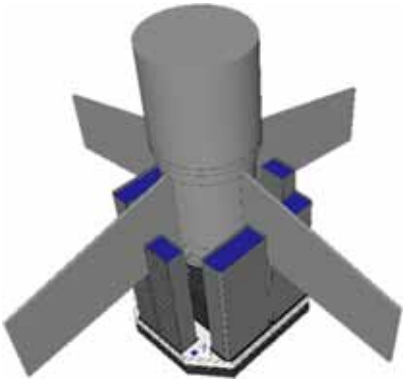
- ✓ **Discovery of transients**
- ✓ **Wide-field and high-speed**
- ✓ **Simple design**
  - ordinary temperature and pressure
  - w/o moving parts
  - easy maintenance
- ✓ **All of raw data is deleted in 7 days.**

Tomo-e Gozen Q1

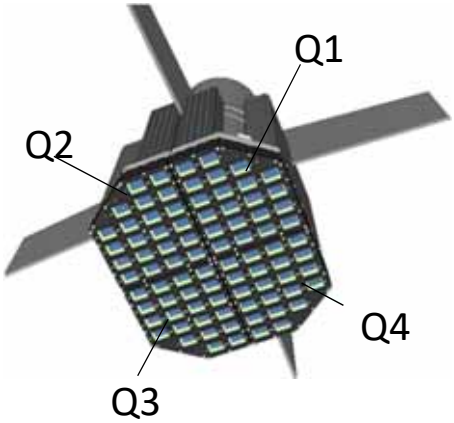


21 chips of CMOS sensors of Q1

Overview of Camera System

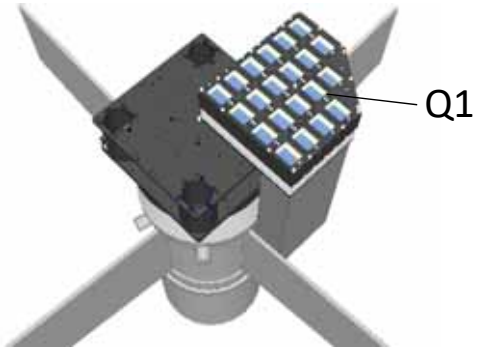


Back side view

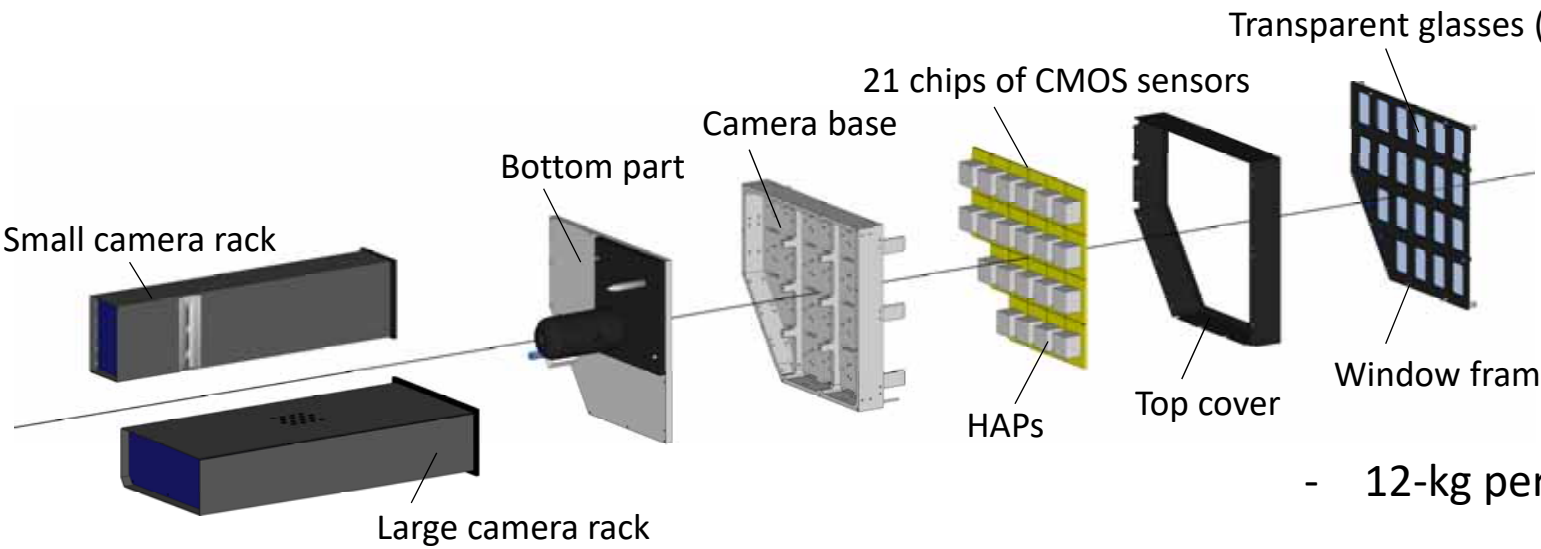


Front side view

515 x 575 x t 540 mm



Q1 unit on the focal plane interface

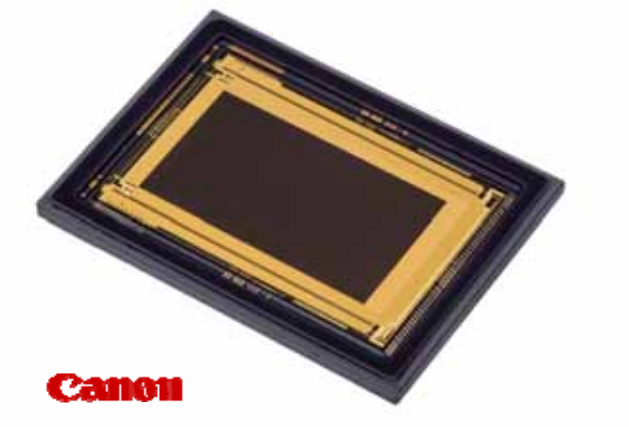


- 12-kg per camera
- 57-kg in total

Large pixel CMOS sensor

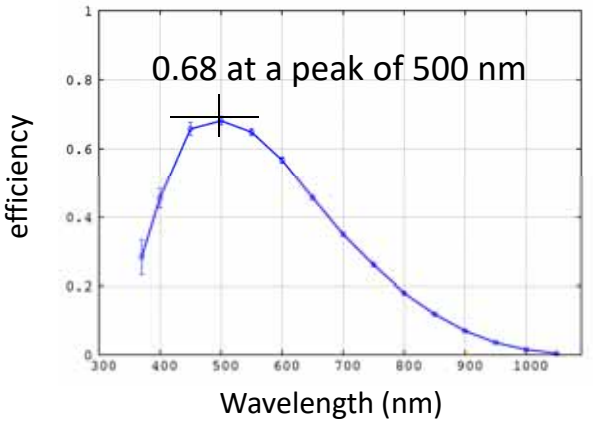
Kojima et al. 2018, SPIE

- Canon 35MMFHDXM
- 2,000 x 1,128 pixels, front side illuminated
- **19 μm pix^{-1}**
- Micro lens array + cover glass
- Rolling shutter
- Photosensitive / package = 0.35
- Analogue 16-ch outputs



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

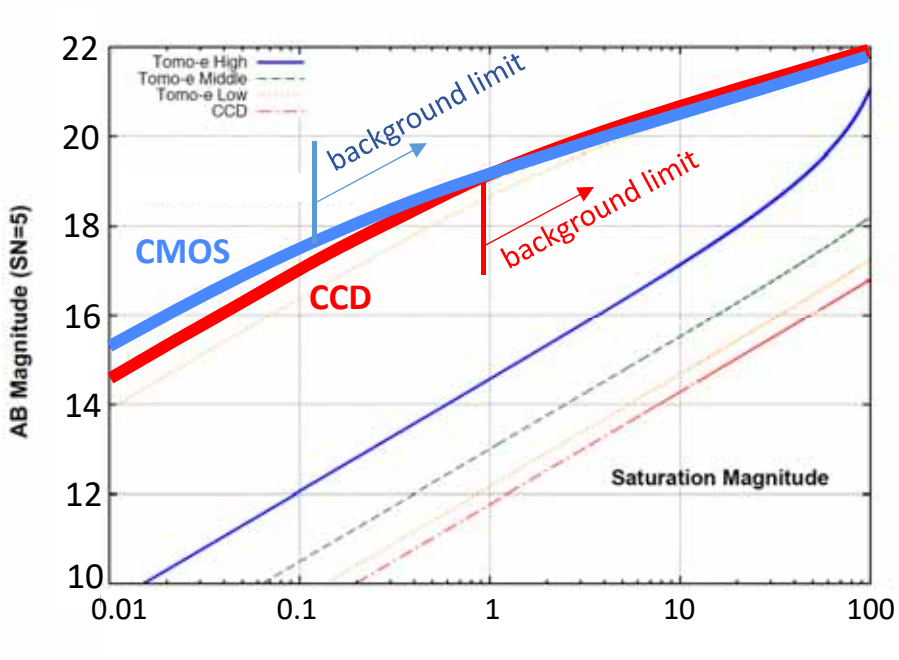
Photoelectric conversion efficiency



→ Less than sky background in dark night, 50 e$^-$ sec^{-1}, at room temperature

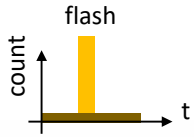
Limiting magnitude

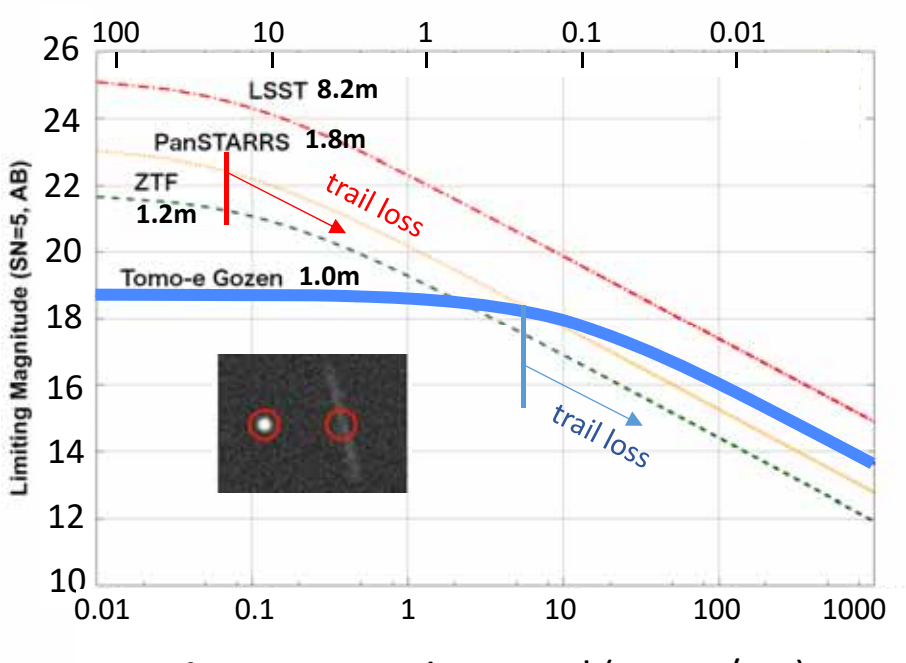
5-σ limiting magnitude



Exposure time (sec)

Duration time of flash (sec)





Apparent moving speed (arcsec/sec)

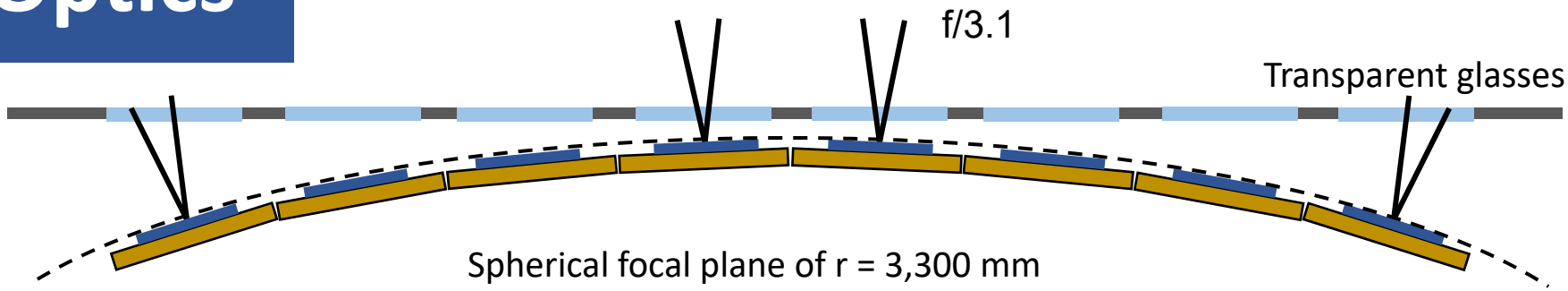
CMOS : efficiency=0.65, N_{read}=2 e-
CCD : efficiency=0.90, N_{read}=5 e-

assuming same filter-bandwidth and pixel size

Tomo-e Gozen : 0.5 sec/frame, N_{read}=2 e-
PanSTARRS, ZTF : 30 sec/frame, N_{read}=5 e-
LSST : 60 sec/frame, N_{read}=10 e-

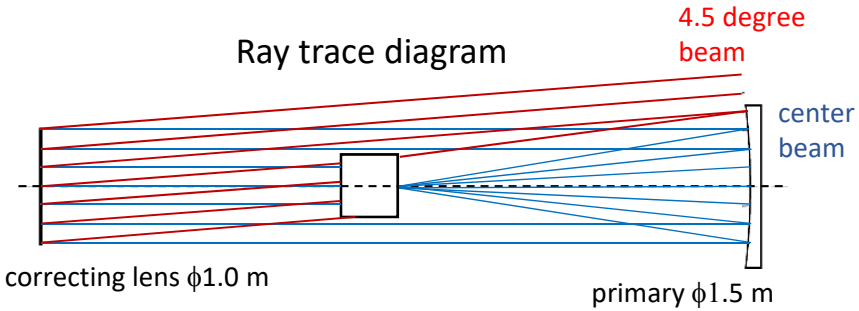
Kojima et al. 2018, SPIE

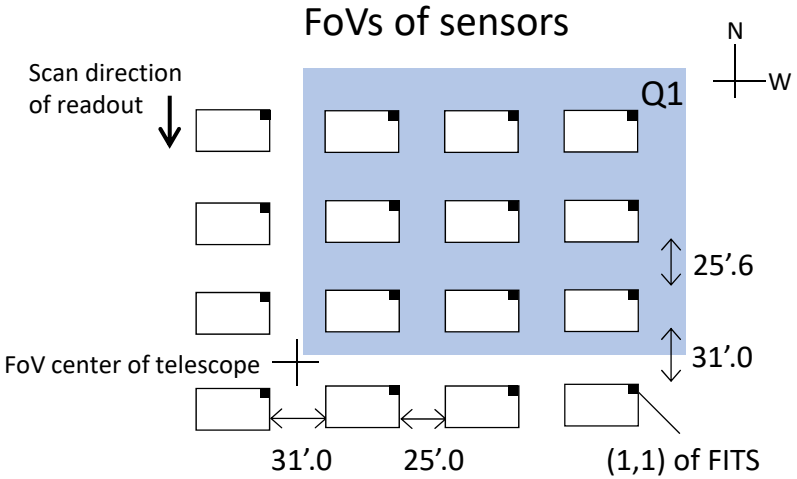
Optics

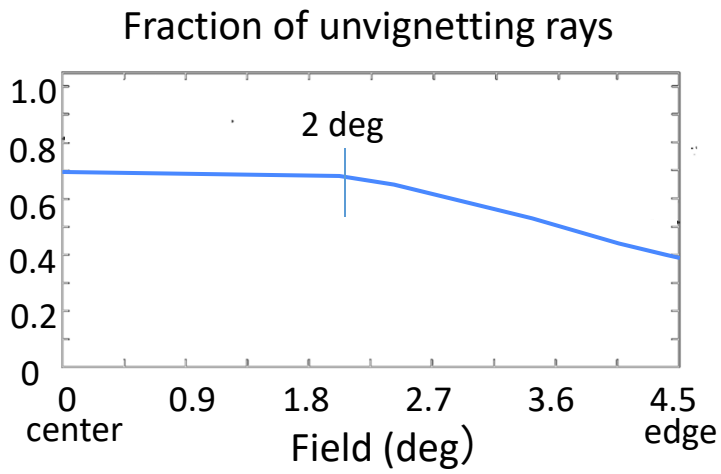


Required alignment accuracies: dz = ±60 μm, dθ = ±0.1 degree

- Pixel scale: 1. 189 " pix^{-1} (typ. seeing 3")
- FoV of sensor: 39.7' x 22.4'





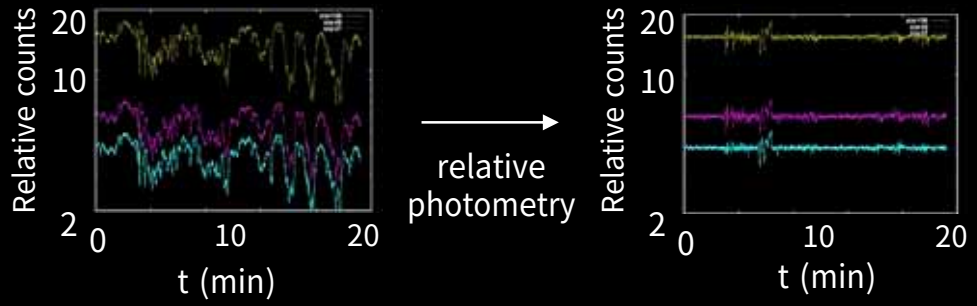


Photometry

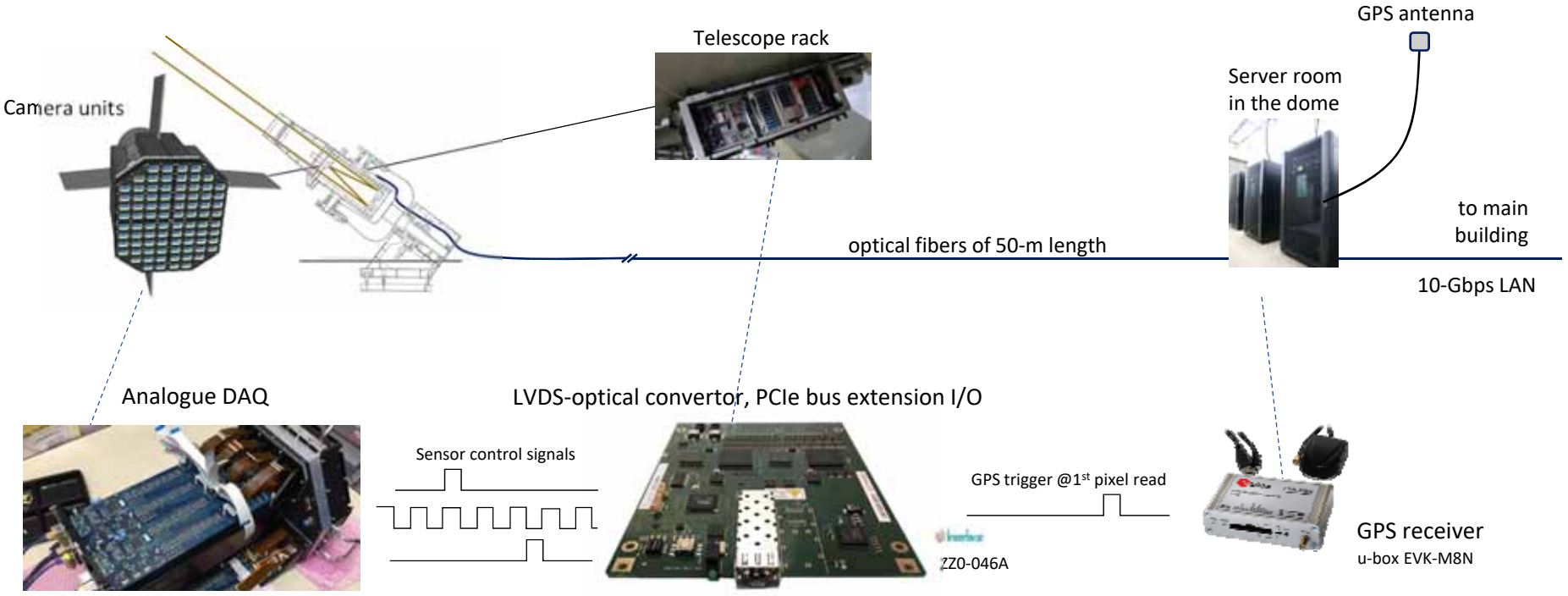
- Photometry with many reference sources
- Quick follow-ups for rapid variables

Movie obtained in 2-fps,
consecutive 6 frames every pointing

- 1 chip, FoV of 39.7' x 22.4'
- 5-σ limiting mag: 18.7 mag
- Photometric accuracy: ~10 millimag @ time scale < 5 sec



DAQ and GPS system

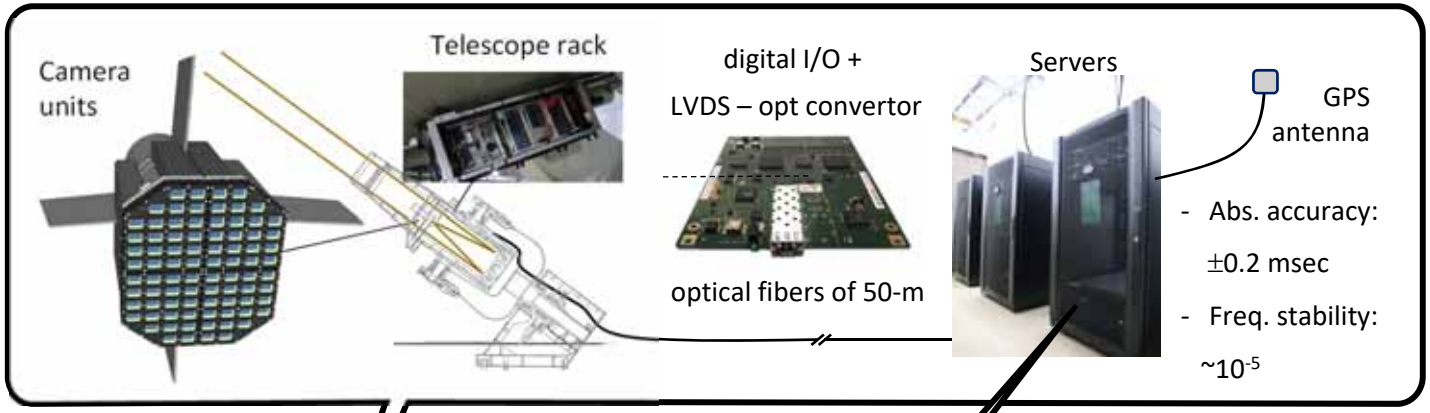


- 1,344 ch of 16-bit ADC, 400 ksps
- 9.9 Mbyte/sec/chip at 2-fps
- Synchronized with each other camera

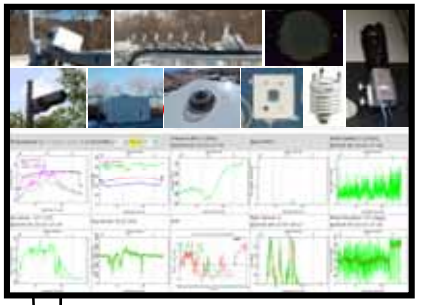
- 24 boards, 32 bits, 10 MHz, bus-master DMA
- **Consecutive data acquisition**
- **High-stability synchronization clock, ~10^{-5}**

- UTC time
- **Absolute accuracy: ±0.2 msec**

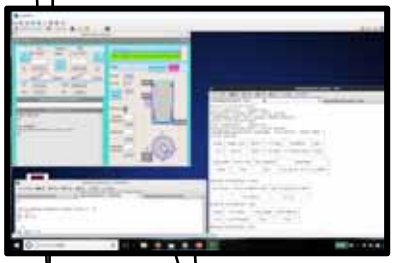
On-site computing system



Weather monitoring system



Remote operation system via VPN + VNC



Status visualization system

- Camera controllers — CPU 72 cores; Memory 640 GB; HDD 40 TB
- Buffer servers — CPU 24 cores; Memory 256 GB; HDD 384 TB
- Analysis servers — CPU 90 cores; Memory 1024 GB; HDD 96 TB
- Storage servers — CPU 12 cores; Memory 128 GB; HDD 384 TB

Telescope dome

2F control room
- Telescope controller

1F server room

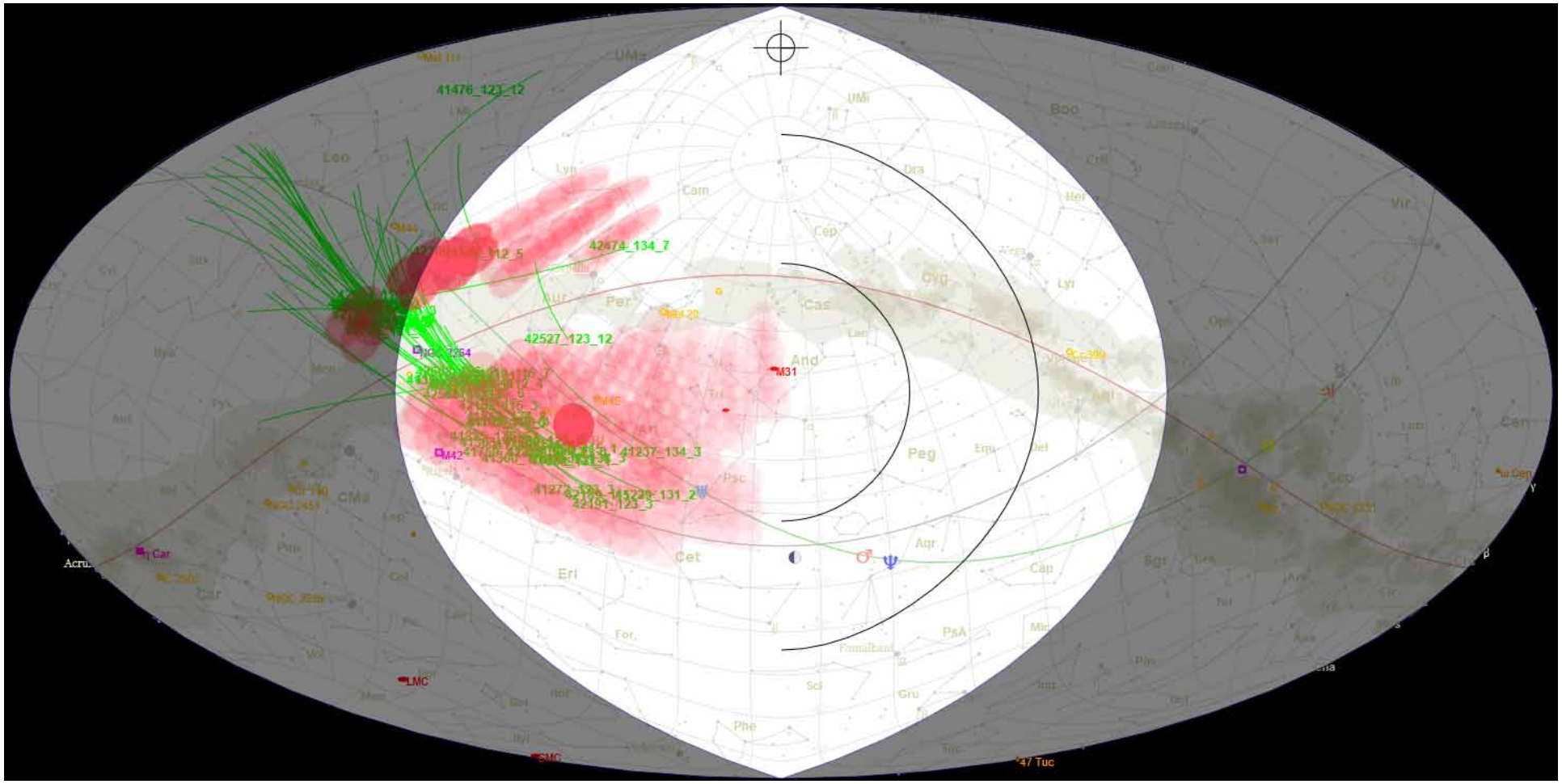
Main building

10 Gbps, fiber connection

1 Gbps, FLETs, NTT

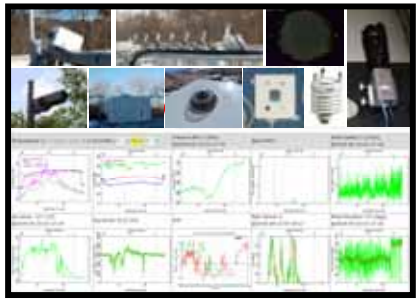
Data visualization

Tomo-e Gozen Sky map



Operation

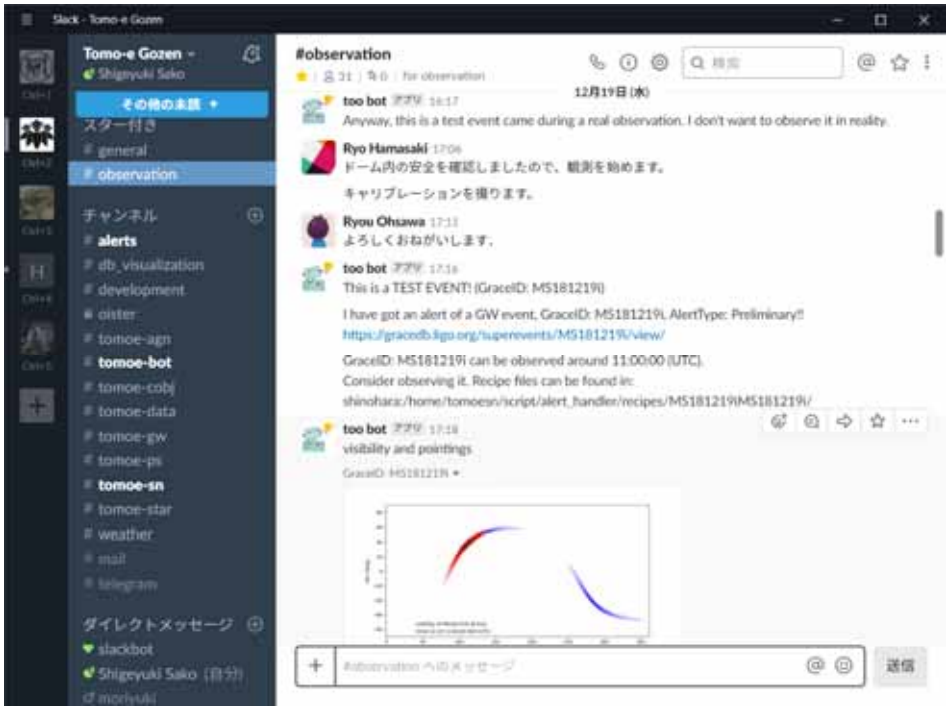
Weather monitoring system



- **Automatic observations based on Queue system**
- **Remote observations from Mitaka headquarters when needed.**
- **Quick information sharing**

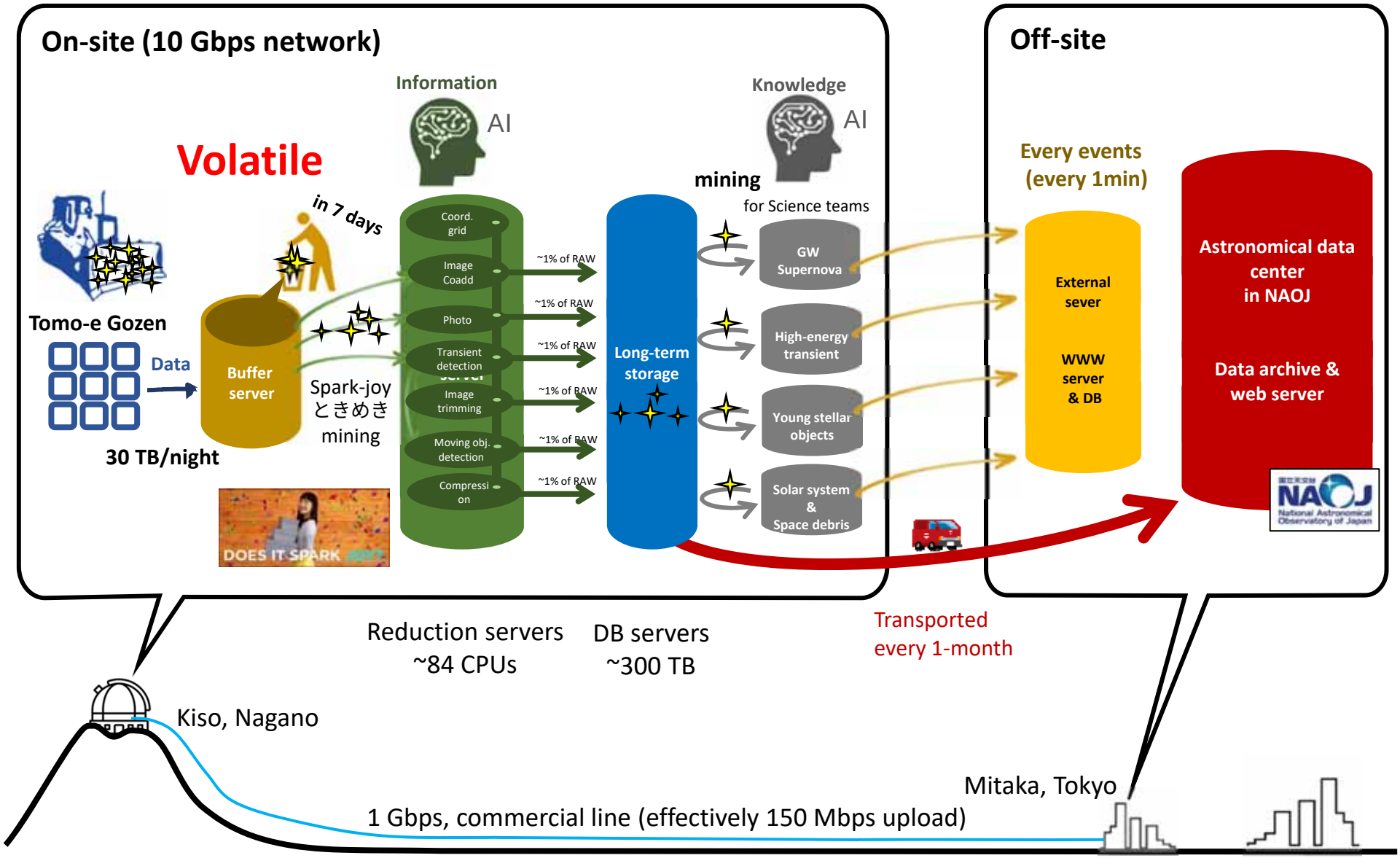
slack

https://slack.com



- LINE-like app optimized for business
- Many species of apps and bots.
- Easy and quick communication with multimedia.

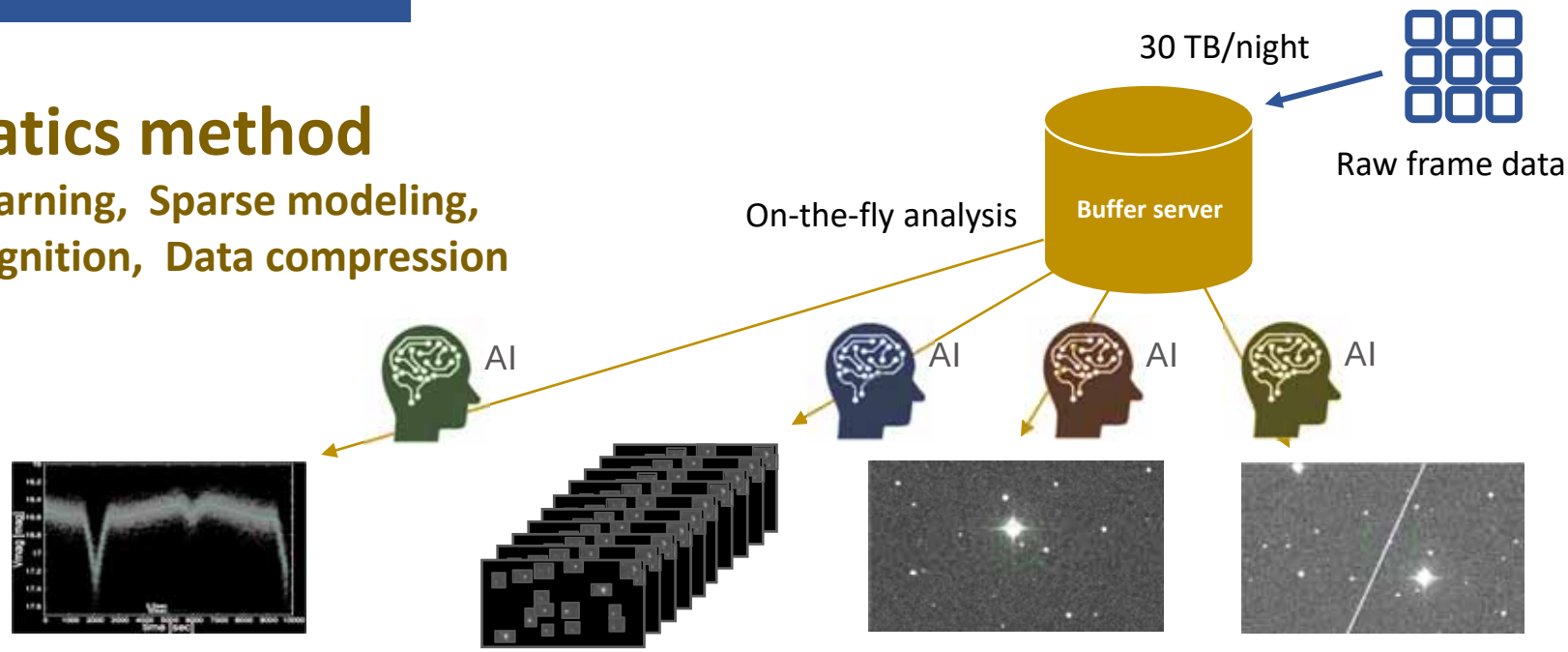
Volatile data management system



Data Analysis

Informatics method

Machine learning, Sparse modeling,
Movie recognition, Data compression



Photometry of sources detected in all frames	Detection of short timescale transient	Co-added consecutive frames	Detection of very-fast-moving objects
Text table	Masked 3D-FITS	2D-FITS	2D-FITS
Real-time	Real-time	Real-time	Day-time
Light curves of 10^5 objects	unknown	10^5 frames	10^5 frames

Monitor:	~~200 GB~~	250 GB	75 GB	500 GB (~~2x2~~ bin)
Survey:	~~30 GB~~	40 GB	500 GB	~~150~~ GB (2x2 bin)

~1 TB/night

Informatics approach

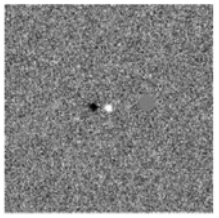
Machine learning

- Random forest classifier
- 3380 sets of training data including artificial data as NEOs

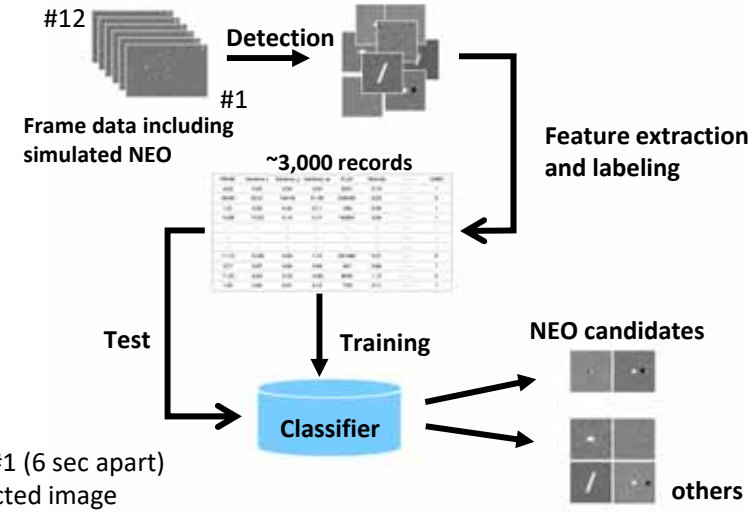
- False positive rate ~ 1%
- True positive rate ~ 99%

- Un-cataloged fast-moving-objects of ~500 events/night are being detected.

Kojima et al 2018, ASJ meeting



#12 – #1 (6 sec apart) subtracted image

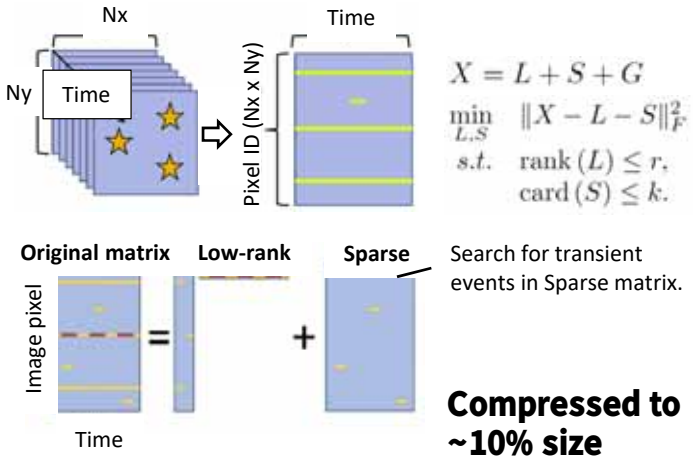


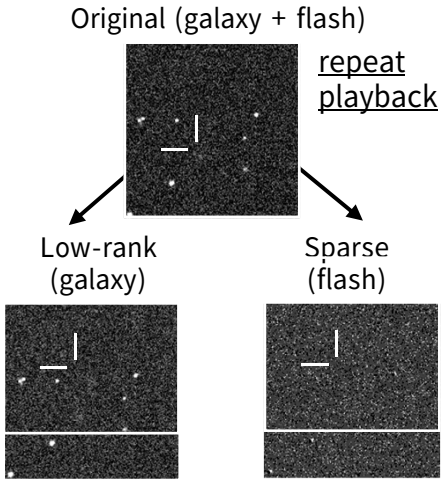
Sparse modeling

- Expressed movie frames as a matrix.

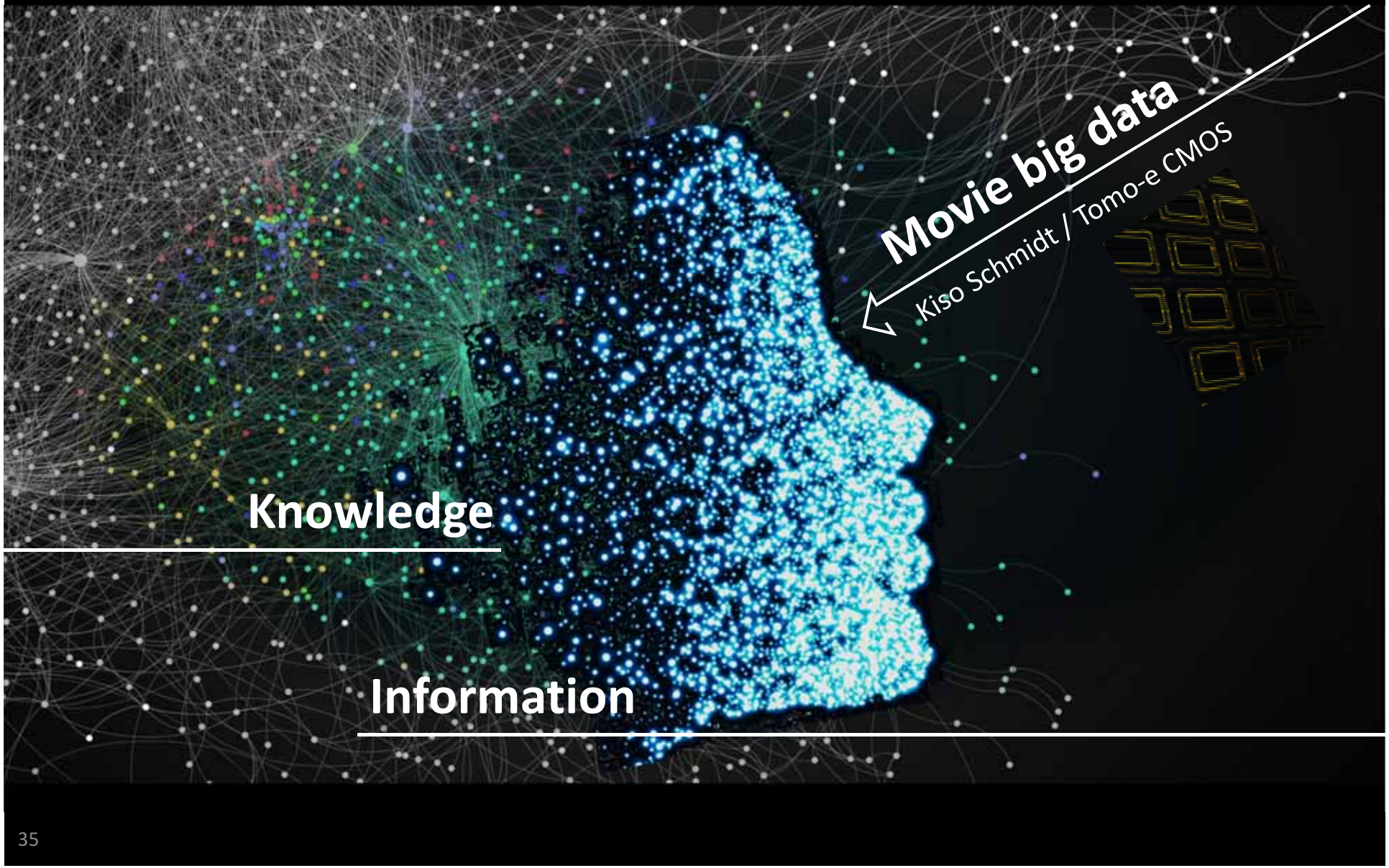
- Decomposed to Low-rank and Sparse matrixes with GoDec method.

Morii et al 2017, AJ





Cyber space of Tomo-e Gozen



OUTLINE

1. Introduction
2. Instrument and computing system
3. **Survey plans and early results**

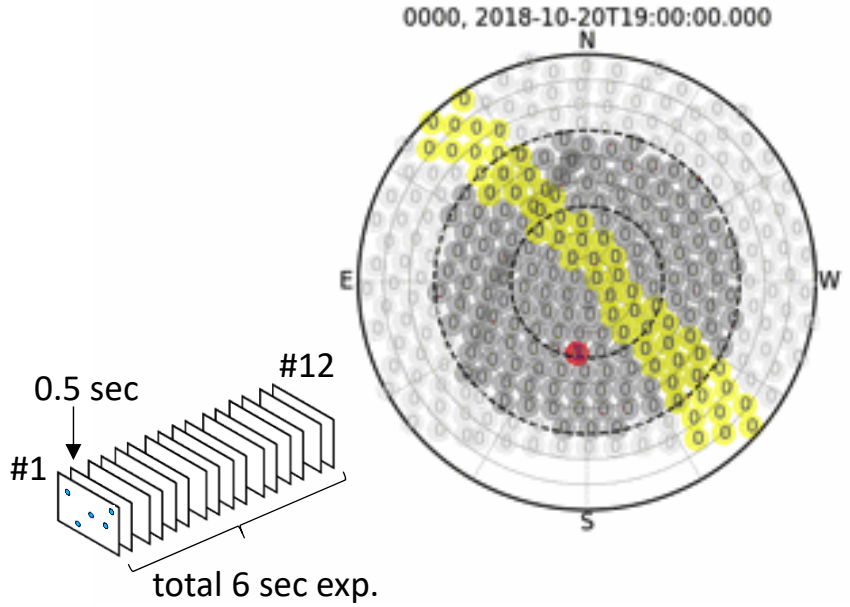
Tomo-e transient survey

All sources can be followed by spectroscopy with 1 – 3 m class telescope

First wide-field movie survey

10,000 deg^2 - 2 hr cadence - 18 mag depth

- no filter: effectively g+r (λ = 400 – 700 nm)
- [0.5 sec exposure] x 12 frames
- 6 sec exposure/visit
- ~10,000 deg^2 sky (El > 35 deg)
- 3 – 5 times visits per night



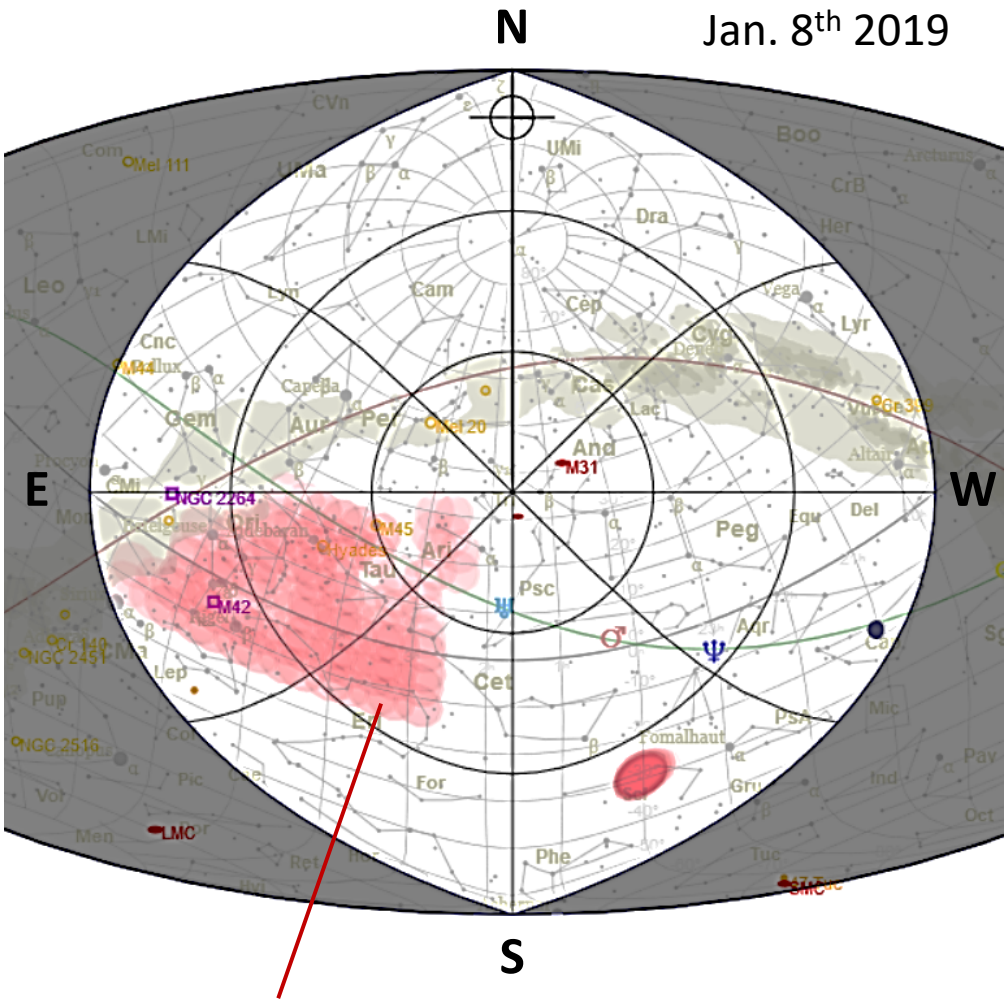
Targets

Supernovae, nova, pulsar, (GW), neutrino, comet, asteroid, meteor, occultation, NEO, debri, super-flare, dwarf star flare, CV, “Tomo-e Flash” , YSO, Ultra-Long GRB, Fast Radio Burst, AGN, X-ray transient, unknown unknown.

Tomo-e transient survey

Tests with Q1 unit

- 2,000 deg^2 survey in 2 hours
- at each pointing
  - 0.5 sec exposure x 12 frames
  - 2 x 2 dithering
- 100 beam switches
  - moving time 6-8 sec
- Limiting magnitude of 5-σ 18 mag is achieved.

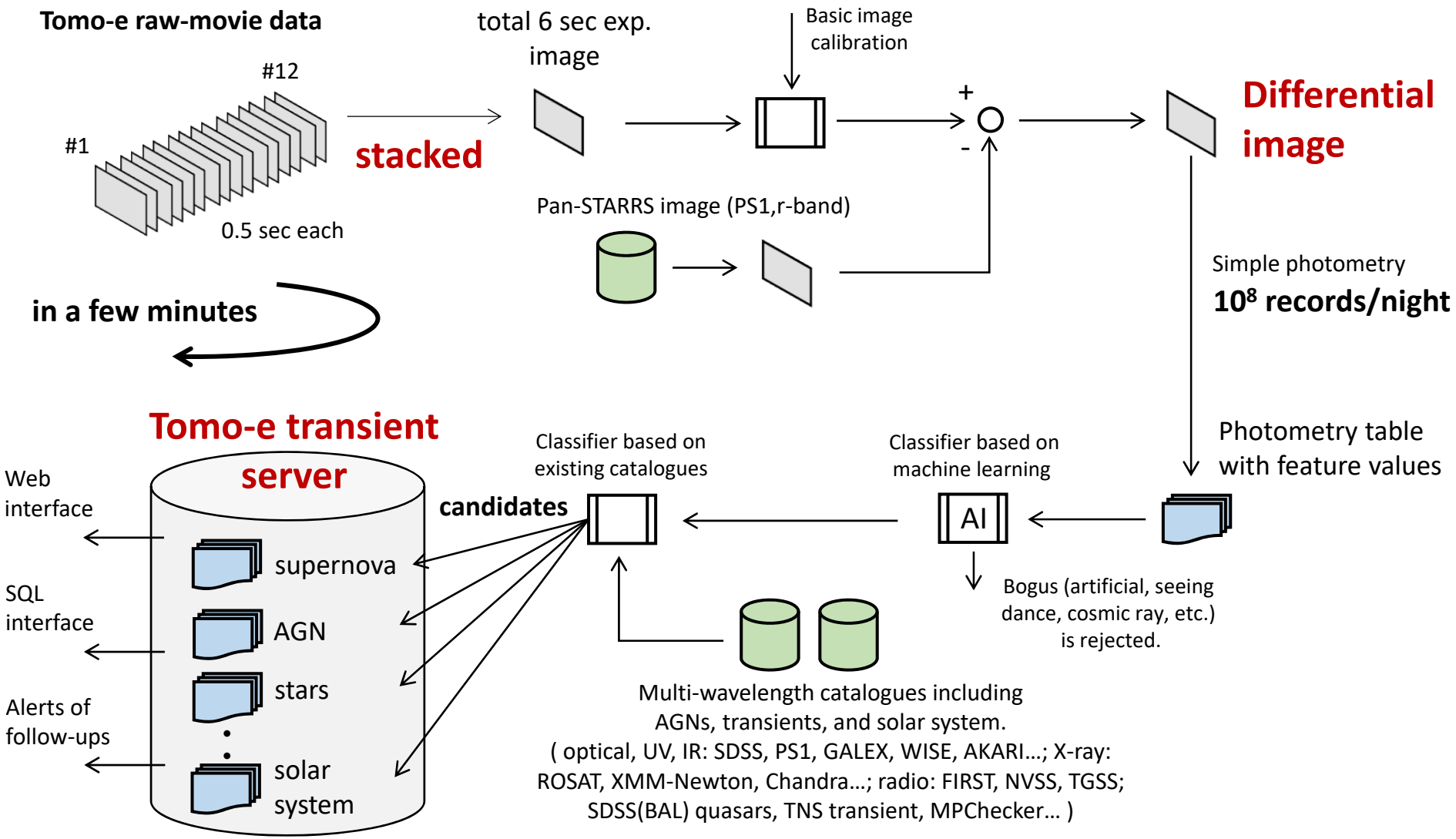


Each circle is a FoV of full Tomo-e, ϕ 9 deg

Tomo-e transient survey

Detection pipeline for transient sources

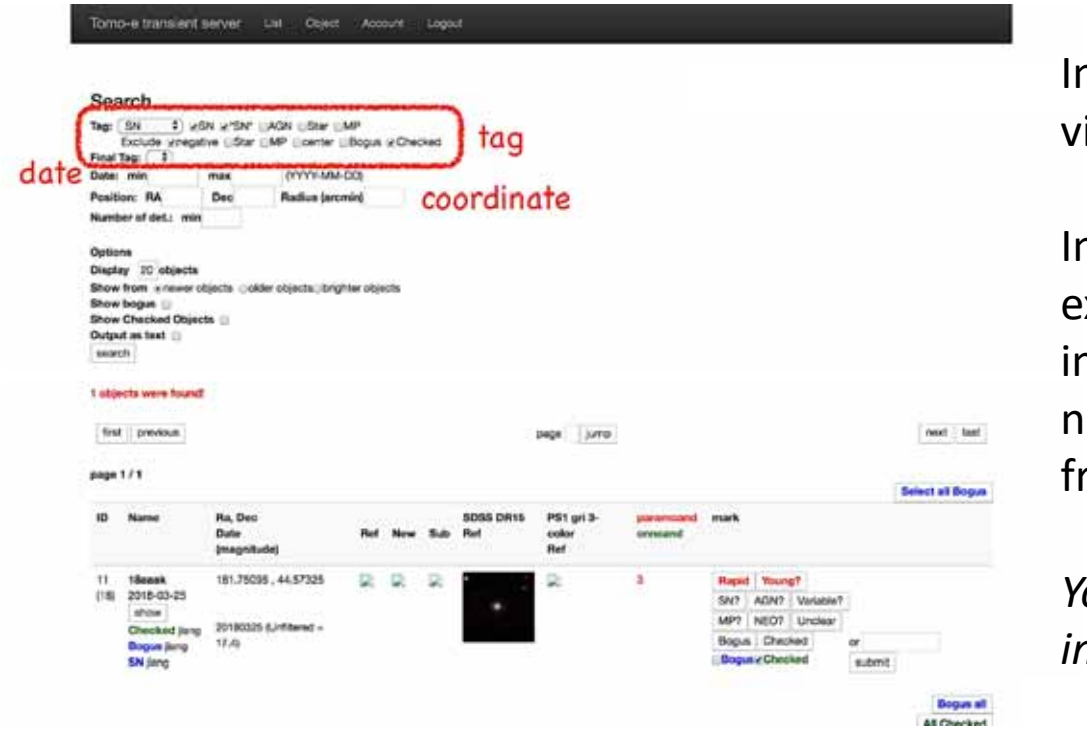
Detection for `hours timescale' events



Tomo-e transient survey

Detection pipeline for transient sources

Web and SQL interfaces for Tomo-e transient server



Initially, the data base is accessed only via VPN connection of Kiso observatory.

In near future, it will be accessed with an external rental server, but amount of information is limited because of poor network bandwidth, 150 Mbps upload from Kiso.

You are welcome to contribute improvement of network infrastructure!

Tomo-e transient survey

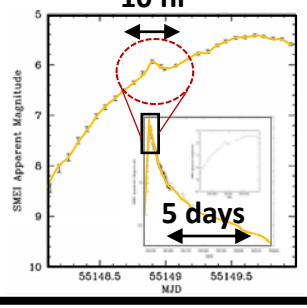
Hours timescale events

Classical novae

Hounsell+2010

Brightness at pre-maximum halt corresponds to Eddington luminosity? → use as standard candle.

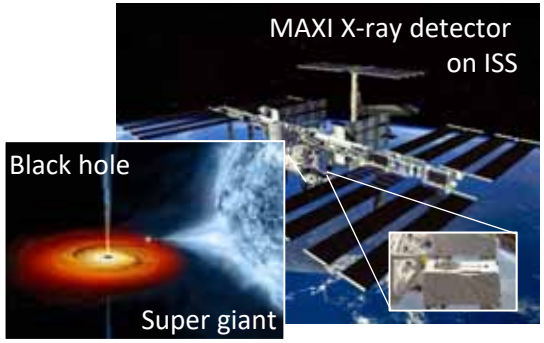
Maehara+



X-ray flares

Black hole binaries appears optical transient bursts.

MAXI team+

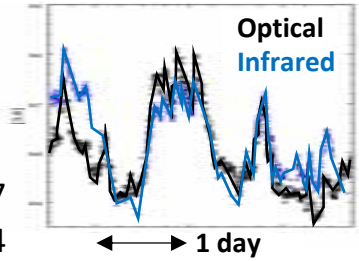


YSO flares, dust obscuration

Rapid variabilities are observed due to gas accretion and dust disk in YSO system.

Mori+

Mon567
Stauffer+2014

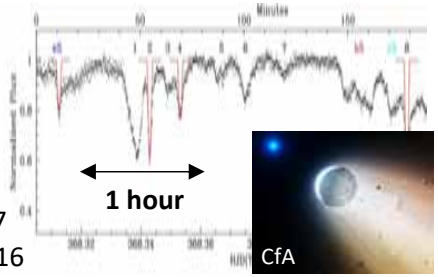


Exoplanet surrounding WD?

Broken by tidal disruption? Minutes timescale variability is detected.

Ohsawa+

WD 1145+017
Gänsicke +2016



Asteroid collisions

P/2010 A2

Search for evidences of a recent collision between two asteroids.

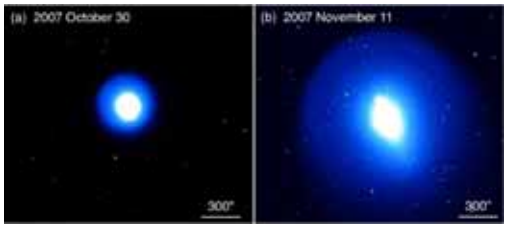
Ishiguro+

Comet outbursts

Ishiguro+2013
17P/Holmes

Fresh material is emerged from inside in outbursts.

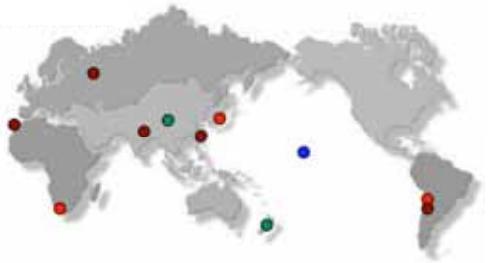
Sarugaku+



Tomo-e transient survey

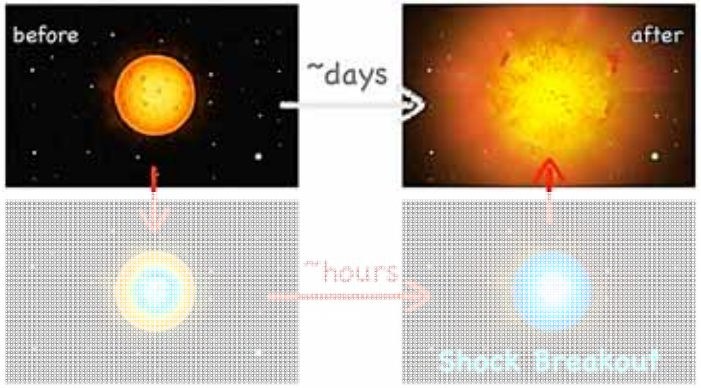
P.I. Tomoki Morokuma (U-Tokyo)

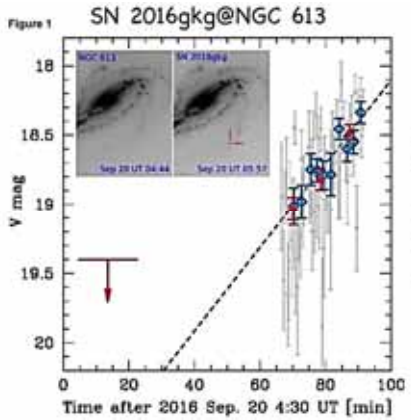
SN follow-up collaborators

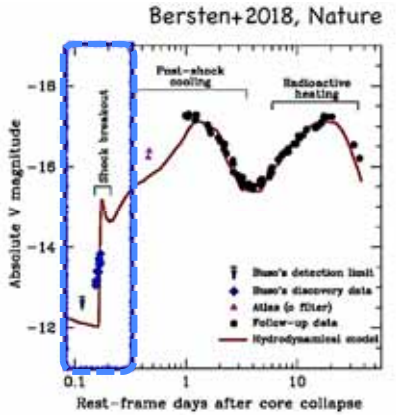


~1,000 supernovae including ~ 5 early phases could be discovered per year.

- **Very Early Phases of Core-Collapse Supernovae**



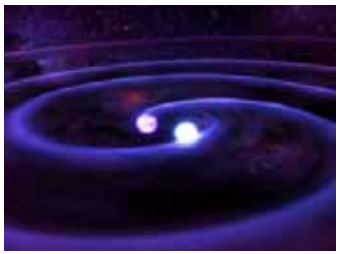


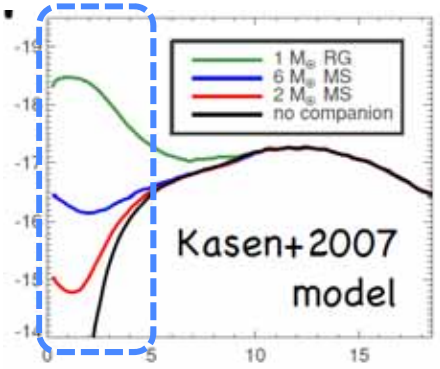


Other three candidates discovered so far.

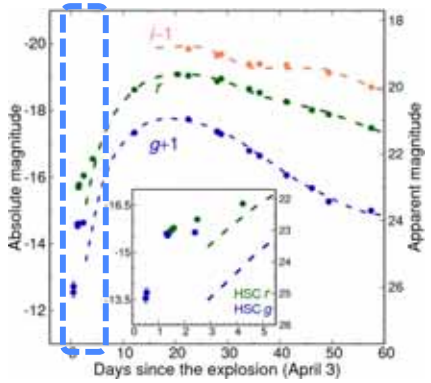
- **Very Early Phases of Type Ia Supernovae**

Single degenerate (SD) vs double degenerate (DD)





Light curve of theoretical models

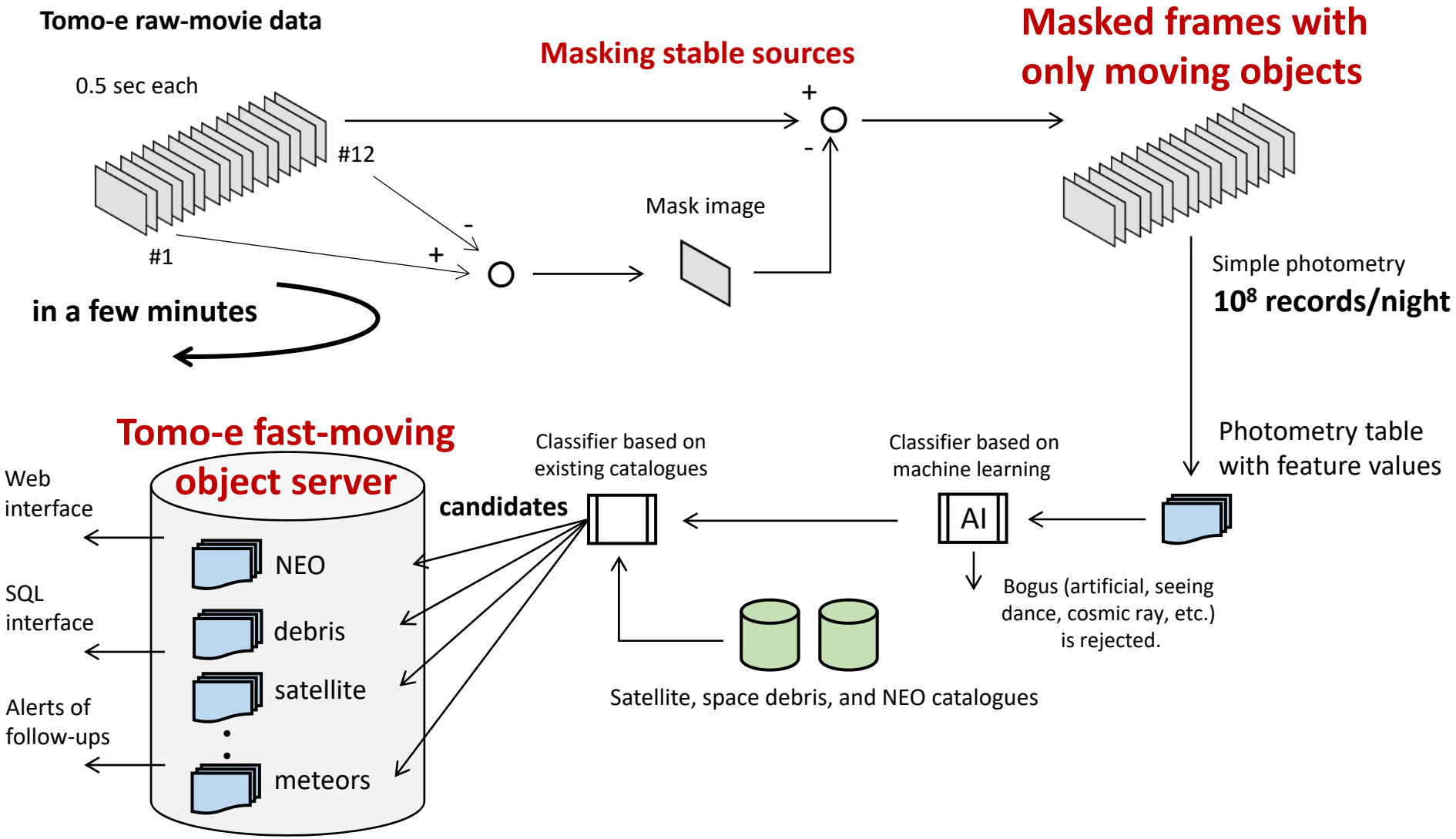


Jiang+2017, Nature, @z=0.117

Tomo-e transient survey

Detection pipeline for fast-moving sources

Detection for `v > 1 arcsec/sec' sources

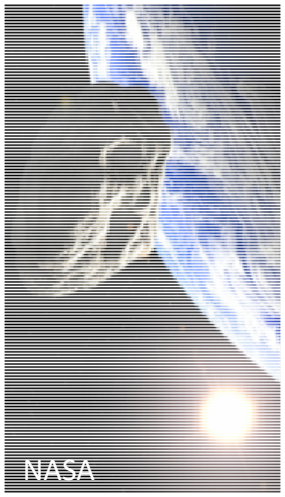


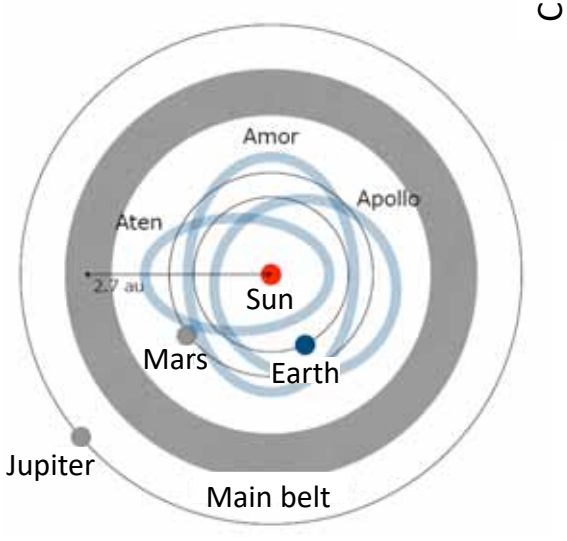
Tomo-e transient survey

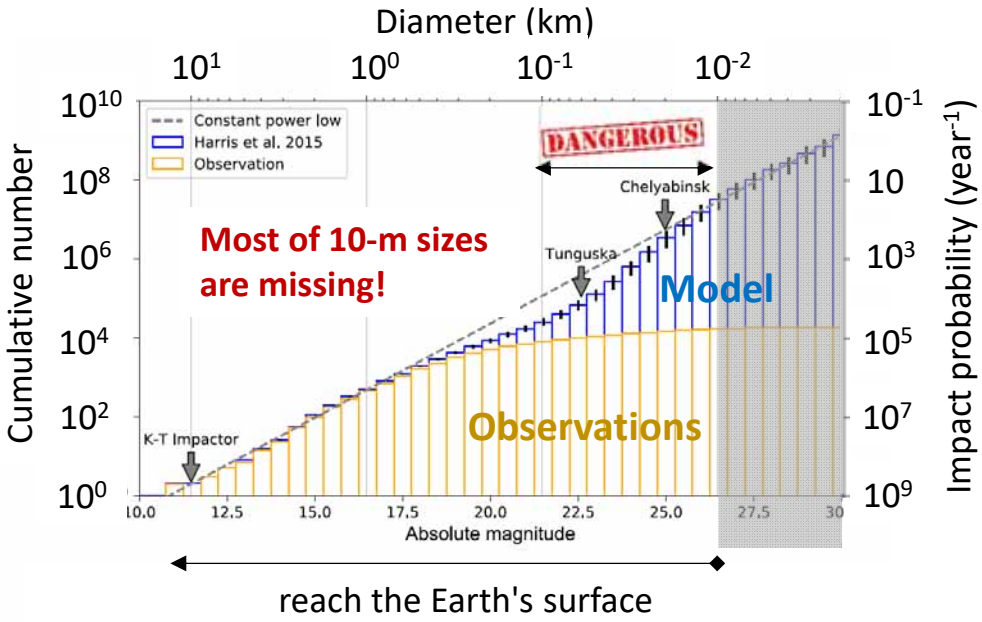
~ 100 small-NEOs could be discovered per year.

Near earth objects (NEOs)

are asteroids or comets with a closest approach to the Sun (perihelion) of < 1.3 au. Their orbits are evolved from main belts.







Tunguska event in June 1908

Chelyabinsk meteor in Feb. 2013

Planetary defense is necessary for keeping human civilization!

Tomo-e transient survey

Yuto Kojima (Master's thesis, U-Tokyo)

Trial of survey for 10-m size NEOs
= nearby fast-moving object

Bogus (artificial, seeing dance, cosmic ray, etc.) is rejected.

Raw frames

~50 TBytes in 19 days with 21 sensors

Simple detection

Fast moving objects (v > 1"/sec)

10^6 events

AI

Classifier based on Random forest machine learning

true

Catalogued artificial objects

10^3 events

2×10^3 events

Uncatalogued artificial objects with orbits similar to known artificial objects

New debris candidates

10^3 events

Others

2×10^2 events

Visual inspection

Bogus (almost seeing dance)

10^2 events

10^2 events

> 3 times detection

orbit estimation

NEO candidates

10 objects

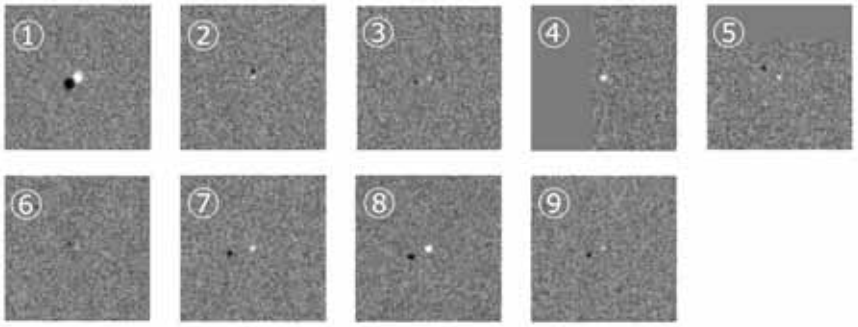
Catalogued NEO

0 events

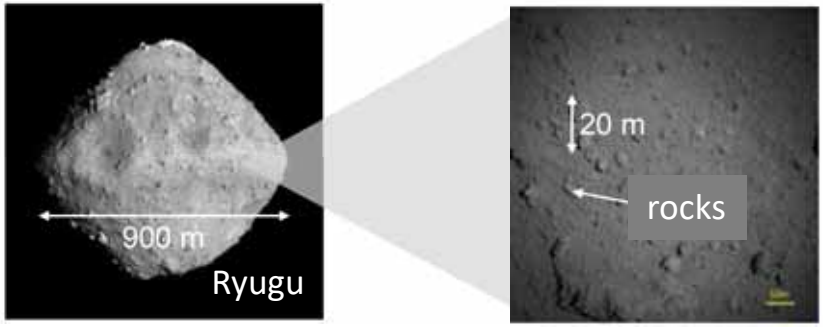
Tomo-e transient survey

Derived orbits and sizes

object	size	arc	fitting err(“)	e	P	closest distance
#1	~40 m	2.2 hr	0.79	0.37	1.96 y	0.99 au
#2	~20 m	2.6 hr	0.38	0.50	2.77 y	0.97 au
#3	~1 m	1.5 hr	1.62	0.96	89.78 d	3200 km
#4	~1 m	15.1 min	3.76	0.65	0.56 d	9900 km
#5	~0.2 m	40 min	2.44	0.51	0.93 d	20000 km
#6	~20 m	2.4 hr	0.61	0.77	0.89 d	8900 km
#7	~0.2 m	12.7 min	1.15	0.73	0.85 d	10000 km
#8	~1 m	35.7 min	5.34	0.57	0.80 d	16000 km
#9	~0.5 m	2.9 hr	1.05	0.56	1.01 d	19000 km



Heliocentric orbit

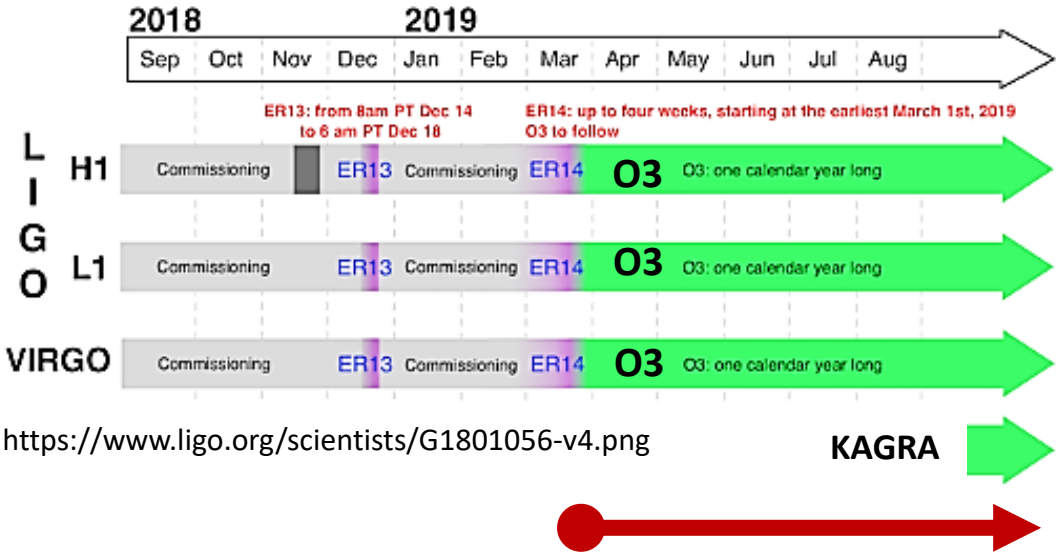


Geocentric orbit

NEO follow up network: NEOAP, APAON
NEO DB: MPC

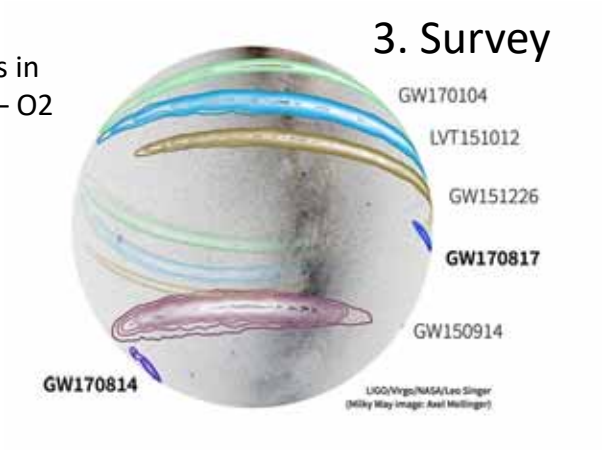
Quick follow ups in a few hours are required to confirm NEO orbits.

Tomo-e GW follow ups



https://www.ligo.org/scientists/G1801056-v4.png

KAGRA



ER14: from Mar. 4 2019

O3: from Apr. 1 2019

Tomo-e Gozen GW follow-ups: from late Mar. 2019

NS-NS sensitivity

	O2 (Mpc)		O3 (Mpc)
LIGO/Hanford (H1)	70	→	**90**
LIGO/Livingston (L1)	100	→	**135**
Virgo (V)	27	→	**55**
KAGRA			**8 - 25**

Reported on Feb. 15 2019

NS-NS event rate †

$(4 – 10) \times 10^3$ Gpc^{-3} yr^{-1} from O1-O2

→ **1 /month max, 2/year med.**

† BH-BH: 1/month - 1/week

NS-NS localization

120 – 180 deg^2 with 90% credible (med)

10 – 20% of the area is localized < 20 deg^2

Tomo-e GW follow ups

Core members:
- T. Morokuma, Y Niino (IoA, U-Tokyo)
- N. Tominaga (Konan U)
- M. Tanaka (Tohoku U)
- J-GEM members

Wide-field GW survey in O3

~100 deg^2 - 21 mag depth

- Targets: NS-NS, and BH-NS
- ~100 deg^2 sky
- on-source ~15 min exposure/pos
- [0.5 sec exposure] x 1,800 frames
- Non-galaxy-targeted survey †
- no filter: effectively g+r

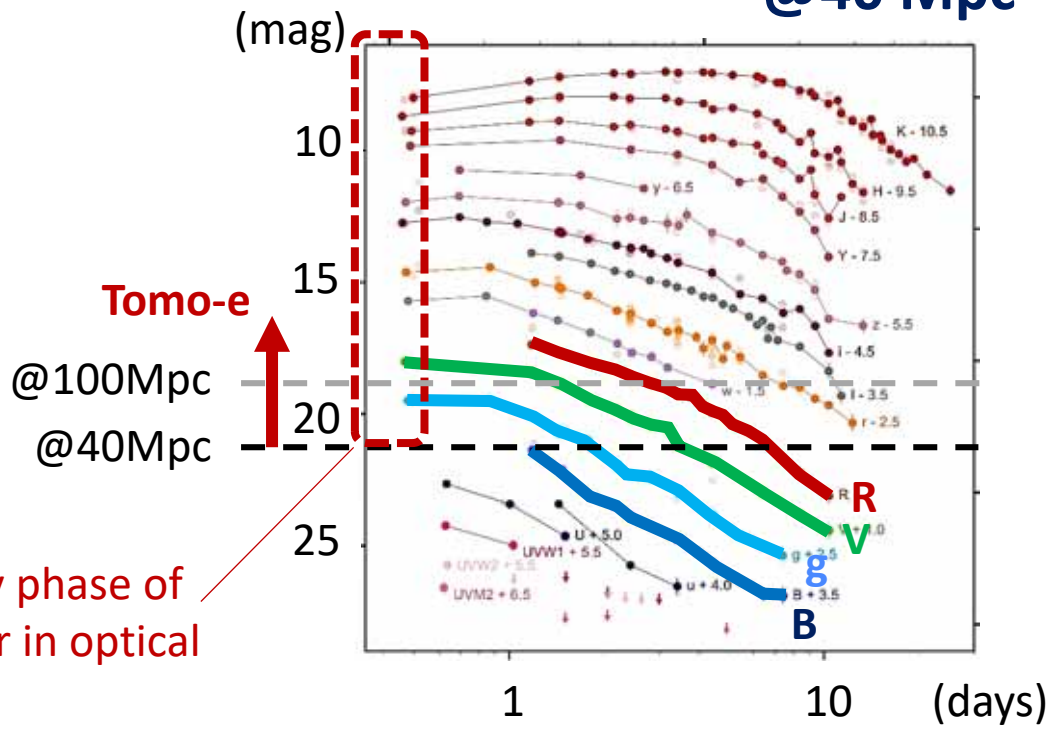
† Other telescopes of J-GEM teram will observe galaxies < 100 Mpc.

Time-resolution is selectable after getting data.

Light curves of **GW170817**

Arcavi 2018

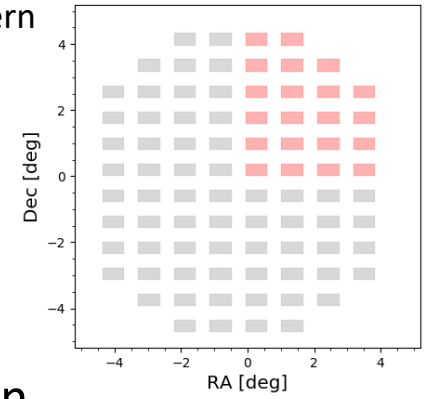
@40 Mpc



When getting GW alerts, the observation mode will be changed to the follow-up mode immediately.

Tomo-e GW follow ups

Survey pattern with Q1



Trials of GW follow-ups with Tomo-e Q1

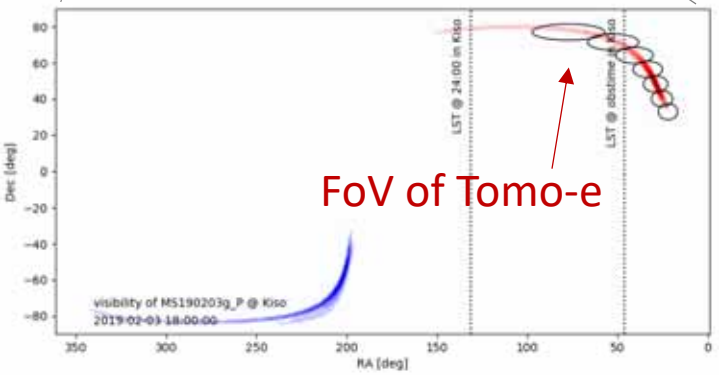
in ER13 of LIGO/VIRGO (Dec 2018)

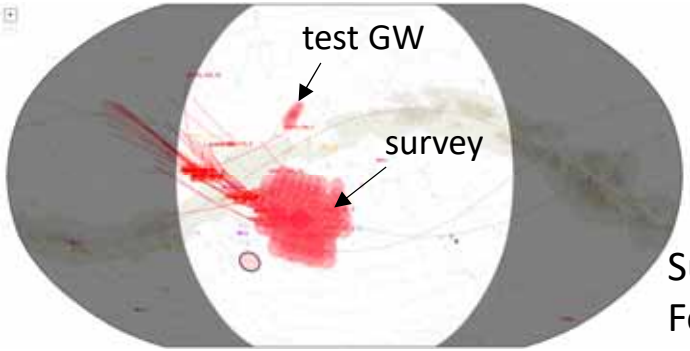
- Automatically generate localization sky-maps and observation receipt files for Tomo-e when getting ER13 test alerts.

Flow chart for ER13 tests

Slack-bot reports.

Sky map for test alerts





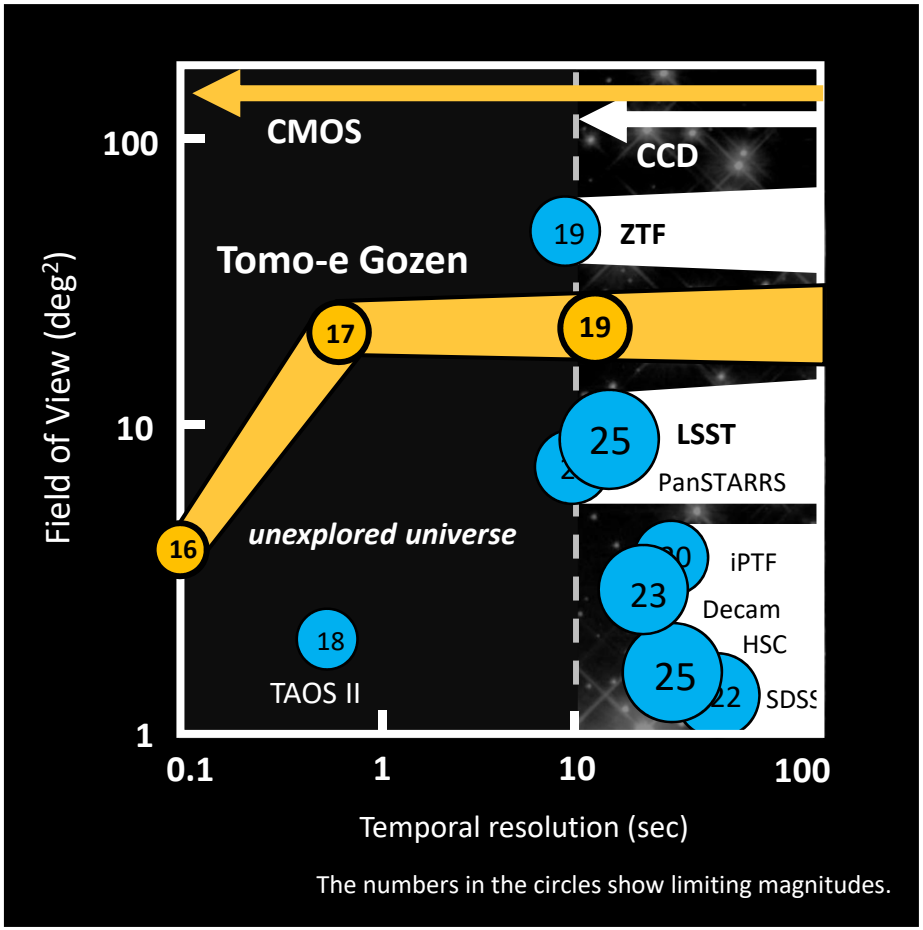
Tomo-e sky-map

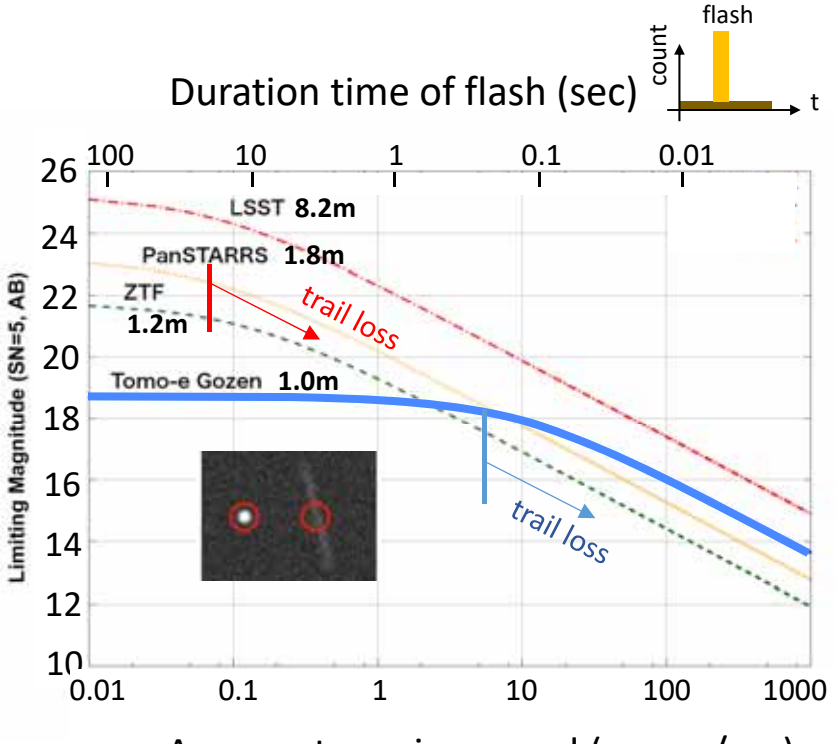
Successfully change FoV to GW areas

Tomo-e high-speed programs

2-fps wide-field movie survey

17 mag depth – 2Hz





Tomo-e Gozen : 0.5 sec/frame, N_{read}=2 e-

PanSTARRS, ZTF : 30 sec/frame, N_{read}=5 e-

LSST : 60 sec/frame, N_{read}=10 e-

Tomo-e high-speed programs

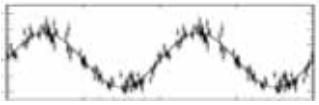
3. Survey

Seconds or shorter timescale events

Fast spinning WDs

10,000 deg^2, 2-fps survey
~300 WDs would be found.

P = 1 – 100 sec

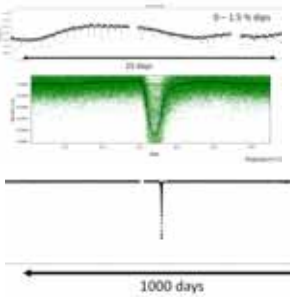


Kashiyama, Kawana+

Peculiar light curves of exoplanets

Evaporating rocky planet?
Alien's artificial planet?

Kawahara+ **t ~ 10 sec**



Keplar's light curve

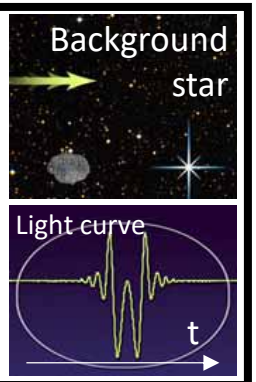
Occultations of small bodies

A few events per year

Km-size objects outer Neptune

Duration time ~ 0.3 sec

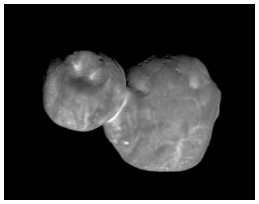
Watanabe+



Fast rotating asteroids

Phase variations on color and albedo reflects their formation history.

Urakawa+ **t ~ 1 sec**



Ultima Thule/NASA

Faint meteors

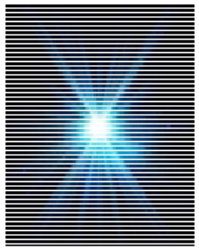
Interplanetary dust of < 1 mm
Use earth atmosphere as a detector

Ohsawa+ **t ≪ 1 sec**

from ISS /NASA

Unknown flashes

Optical counterparts of FRBs?
Unknown high-energy burst?
Unknown objects near earth?
Unknown physics? **t ≪ 1 sec**



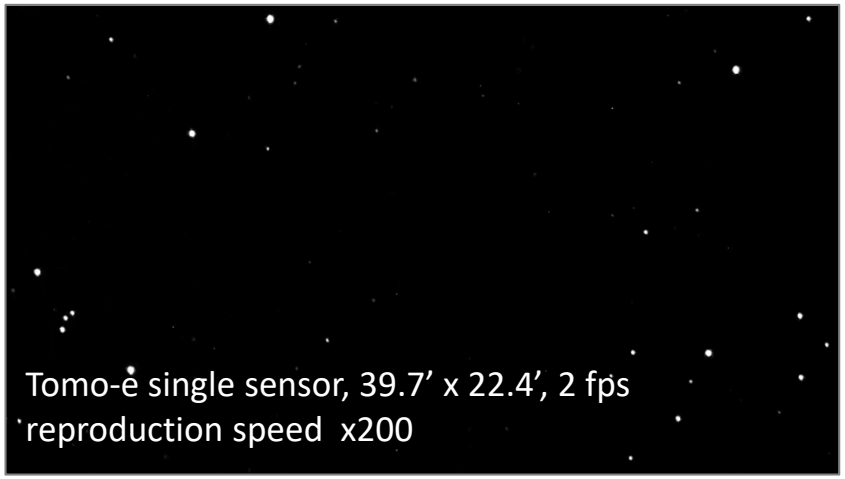
Unknown unknown

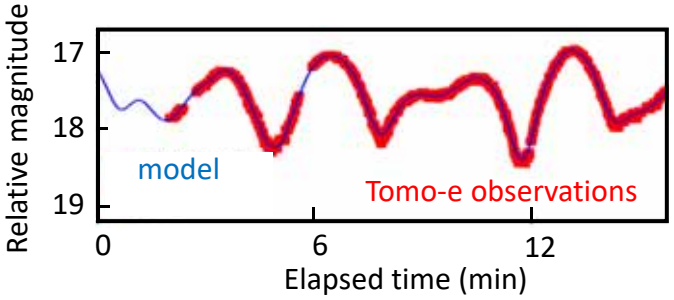
Tomo-e high-speed programs

High-speed imaging of NEO

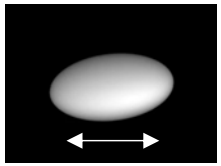
Urakawa+ 2019, AJ accepted

Near earth object 2012 TC_4





Reproduced shape and motion



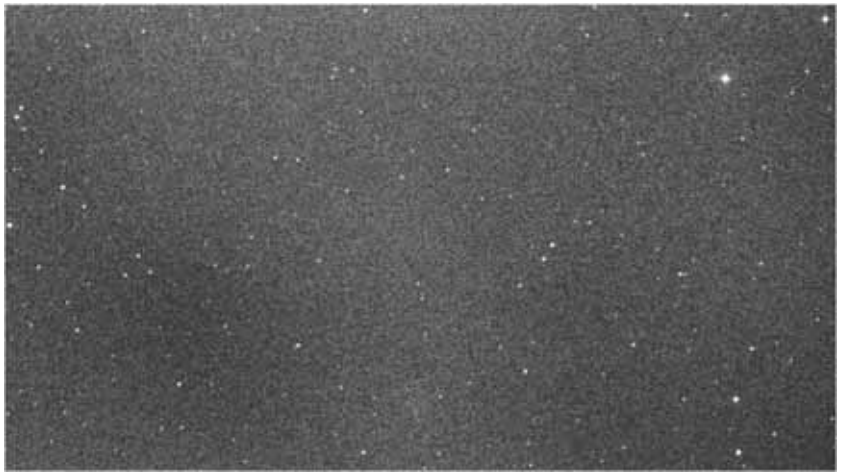
10-m size

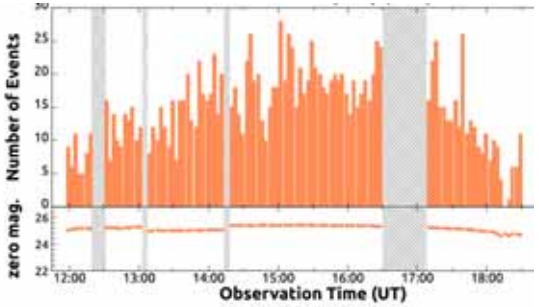
2012 TC4 was produced by impact events within ~3 x 10^5 year and has fresh surface.

First faint-meteor survey

Ohsawa+ 2019, Planetary and Space Science

Sample of bright meteor with drifting trail





Detection number of meteor

>1,500 events detected in a night. Brighter than 13 mag

Luminosity function of faint meteors is derived for the 1st time. The slope is consistent with brighter one.

Tomo-e high-speed programs

Congratulations! Hayabusa-2 touch down on Ryugu

Hayabusa-2 spaceship, JAXA

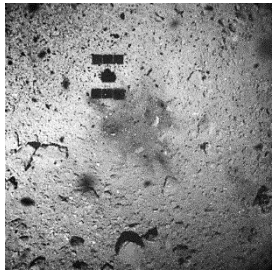
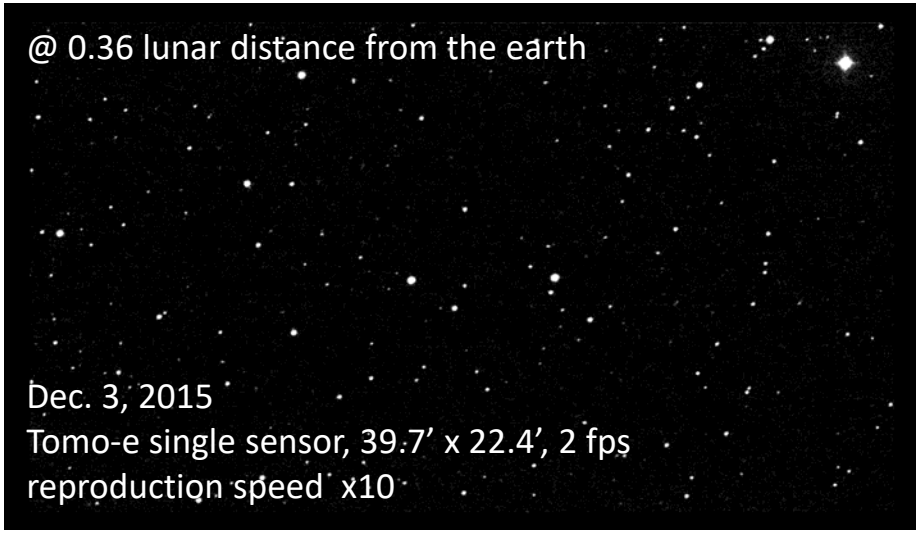


Image taken just after touch down on the surface, JAXA

Memorial picture, AFP/JAXA



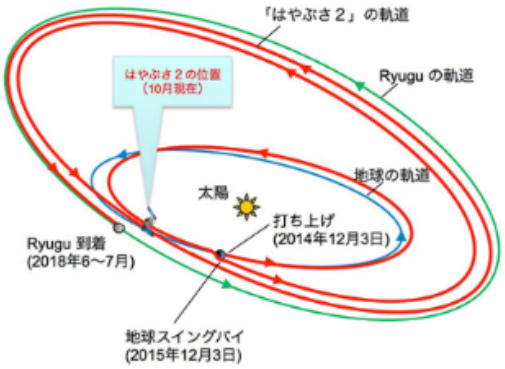


Image: JAXA

Movie of Hayabusa-2 taken by Tomo-e Gozen in the Earth swing-by

Tomo-e high-speed programs

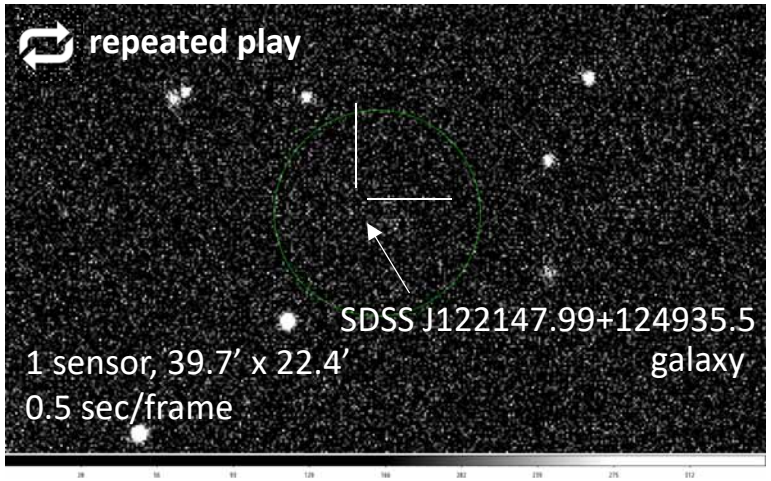
Test survey for single flash of t < 0.5 sec (= Tomo-e flash) with 8 sensors

- Data set (2 fps)

Fields	Observation time	Data size	frames
High galactic latitude	6.0 hours	1.8 TBytes	43,000
Virgo cluster	3.4 hours	1.0 TBytes	24,000

- Detection and classification

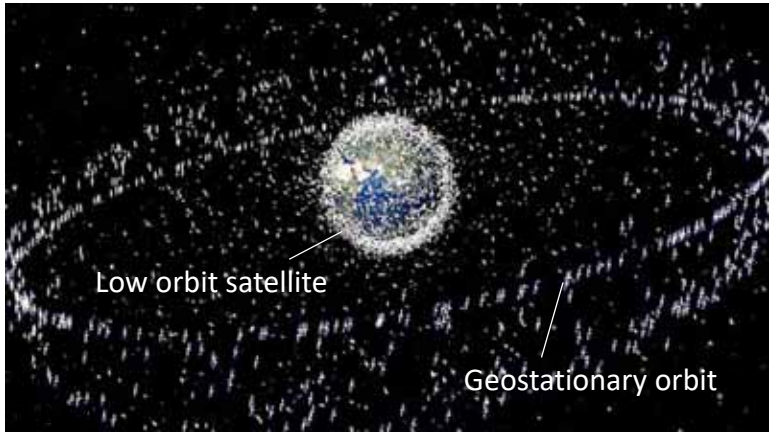
Fields	Meteor	Cosmic ray	Elec. noise	Artificial obj.	others
High galactic latitude	87	140	14	107	**7**
Virgo cluster	121	59	5	28	**3**

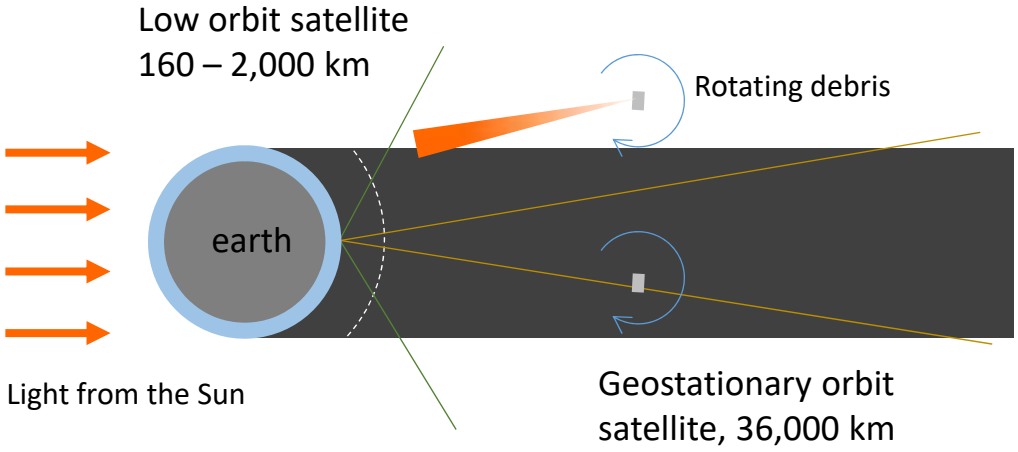


- Detected in only one frame, < 0.5 sec
- Single event (not repeated), 16-mag
- Same PSF as other sources, ~3"
- No color information obtained

Tomo-e high-speed programs

Most Tomo-e flashes would be from artificial objects





- Space debris with ϕ 10-mm on the geostationary orbit can be detected.
- In earth's shadow on the sky, no flashed are detected with Tomo-e in an additional observation run for 1 month.

But, we caught only one flash signal in the earth's shadow!

What is this signal? Space debris or Space treasures?

We will try to check again with full-Tomo-e.

Tomo-e very high-speed programs

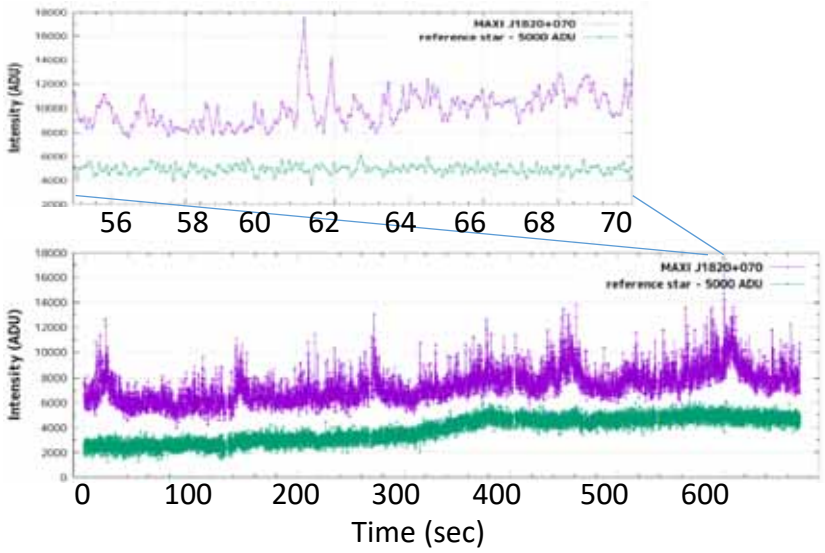
in partial read mode

Detection of 10-msec scale flares in the black-hole binary MAXI J1820+070

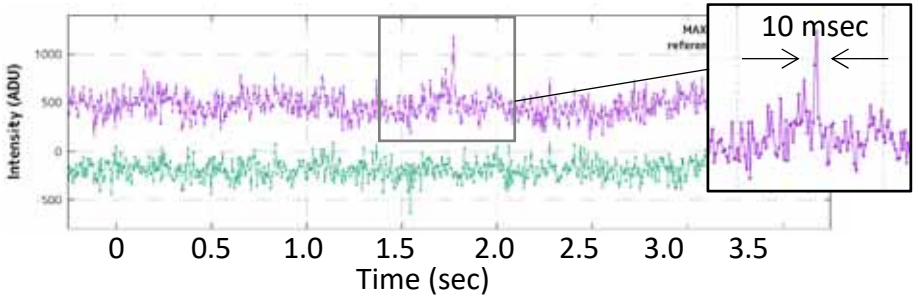
Sako et al. 2018, Atel #11426

Absolute time accuracy: ± 0.2 msec

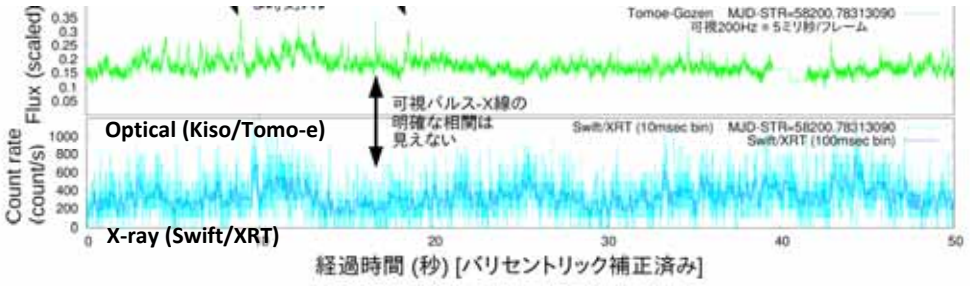
- **66.294 msec/frame,** 9.9' x 7.1‘,
  15 sets of consecutive 2,000 frames



- **6.149 msec/frame,** 1.6' x 0.79‘
  15 sets of consecutive 10,000 frames



Simultaneous observations with Optical and X-ray



Kokubo+ 2018, ASJ spring meeting

Tomo-e very high-speed programs

in partial read mode

6.45-msec resolution observations of Crab pulsar

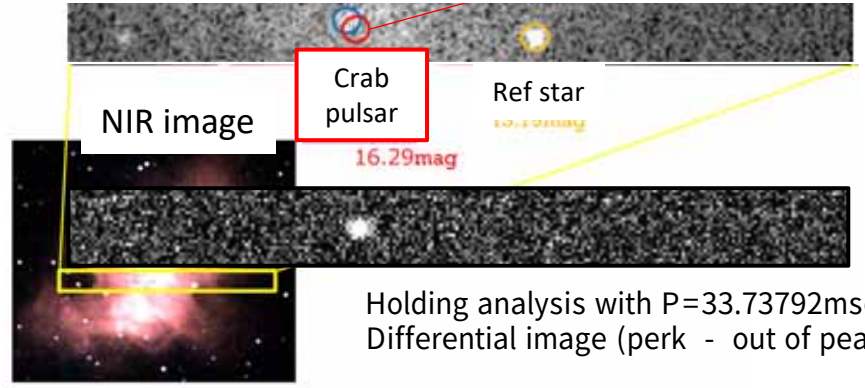
Periodic pulsations of 33.7 msec

Ichiki+2018, ASJ meeting

- Kiso/Tomo, partial readout, 299” x 29”
- UTC time synthesized by GPS（±0.2msec accuracy)
- 6.45 msec/frame, ~50,000 frames

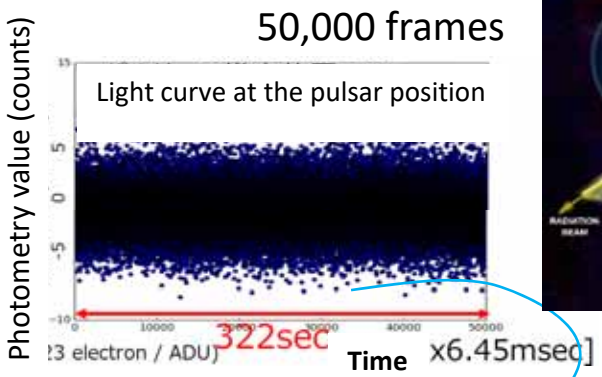
1 frame image (6.45msec exposure)

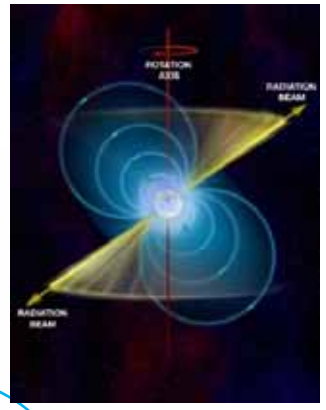
50,000 frame average image (total 322 sec exposure)

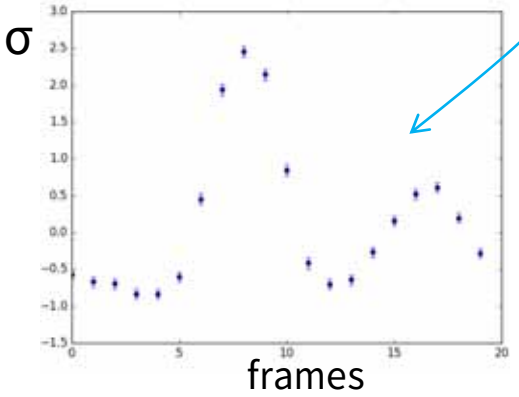


Holding analysis with P=33.73792msec
Differential image (perk - out of peak)

M1 Crab nebula (Supernova remnant)







Folding analysis
P=33.73792msec

Pulsation clearly detected

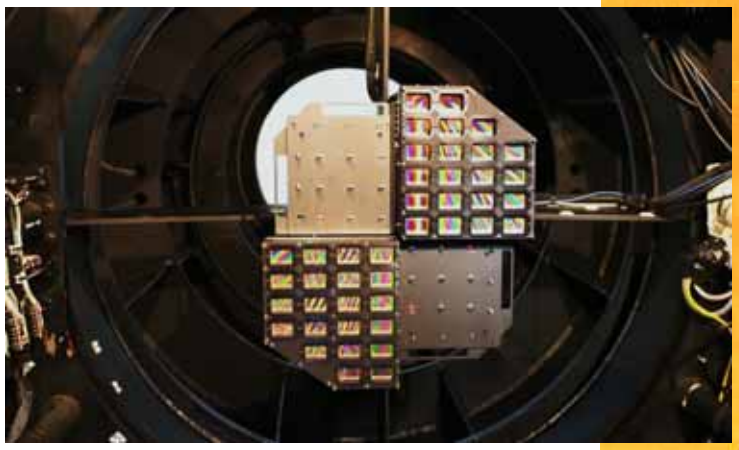
Plans

- Simultaneous observations of giant pulses of Crab pulsar with radio and X-ray telescopes.
- Optical survey for periodic pulsations in milky way fields.

SUMMARY of the Tomo-e Gozen

Instrument

- 1-m Kiso Schmidt telescope
- 20 deg^2, 2 fps
- 84 chips of 1k x 2k CMOSs
- 30 TB per night
- 19 mag @t_{exp}=0.5sec
- Optimized for discoveries of transients
- Simple system
- All of raw data is deleted in 7 days



Full Tomo-e Gozen will be completed in spring 2019

Science targets

- Tomo-e transient survey, 10,000 deg^2 every 2-3 hours
- GW optical counterparts
- Fast moving objects, high-speed monitoring