Tomo-e Gozen計画

東京大学大学院理学系研究科附属天文学教育研究センター
酒向 重行

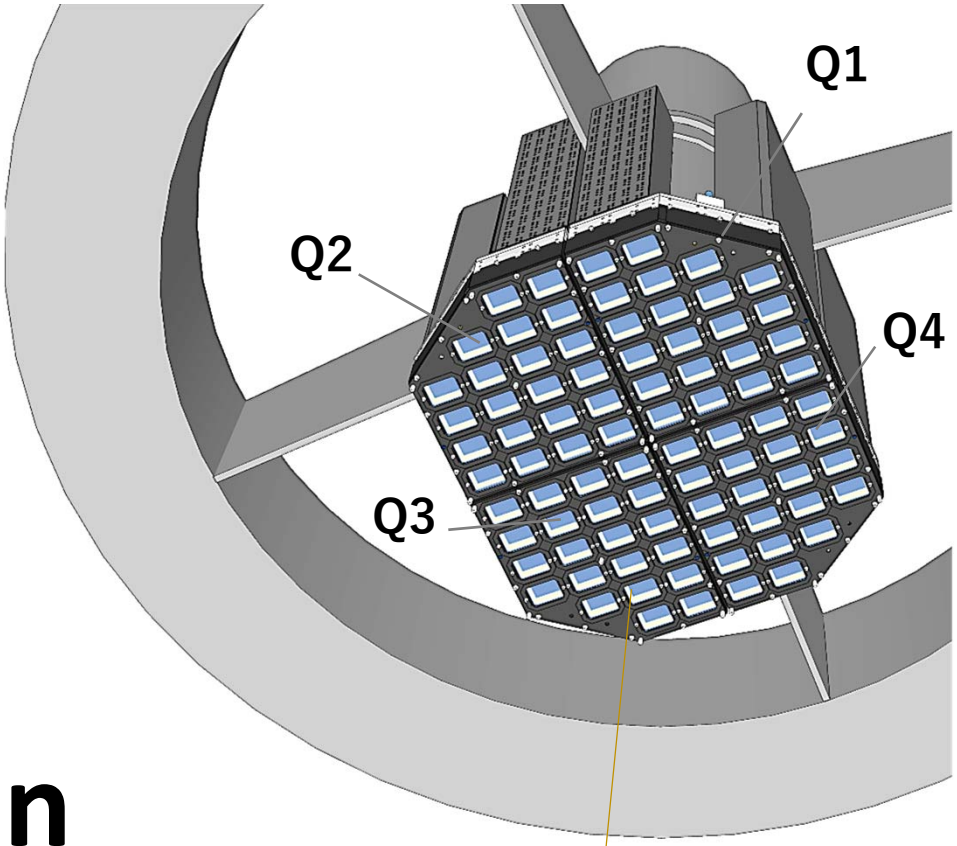
2018/7/10-11,シュミットシンポ2018,上松町ひのきの里総合文化センター

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

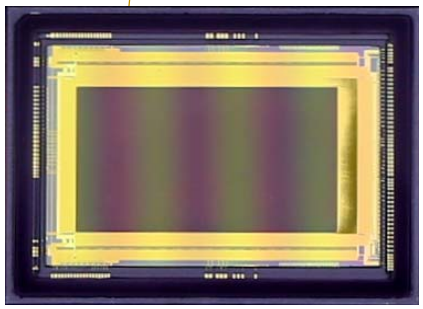
Overview of Tomo-e Gozen

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



the first wide-field CMOS camera

The Tomo-e Gozen

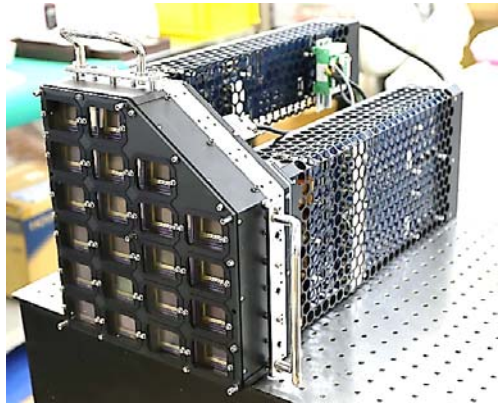


Canon

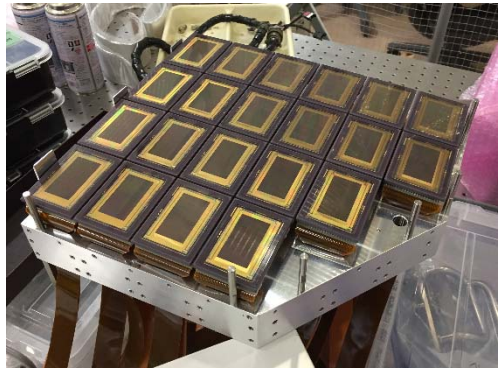
- FoV of 20 deg^2 in ϕ 9 deg
- 84 chips of CMOS, 1k x 2k pixels
- Consecutive frames in 2 fps (max)
- Big movie data of 30 TB/night (max)

Design concept

- ✓ **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.**

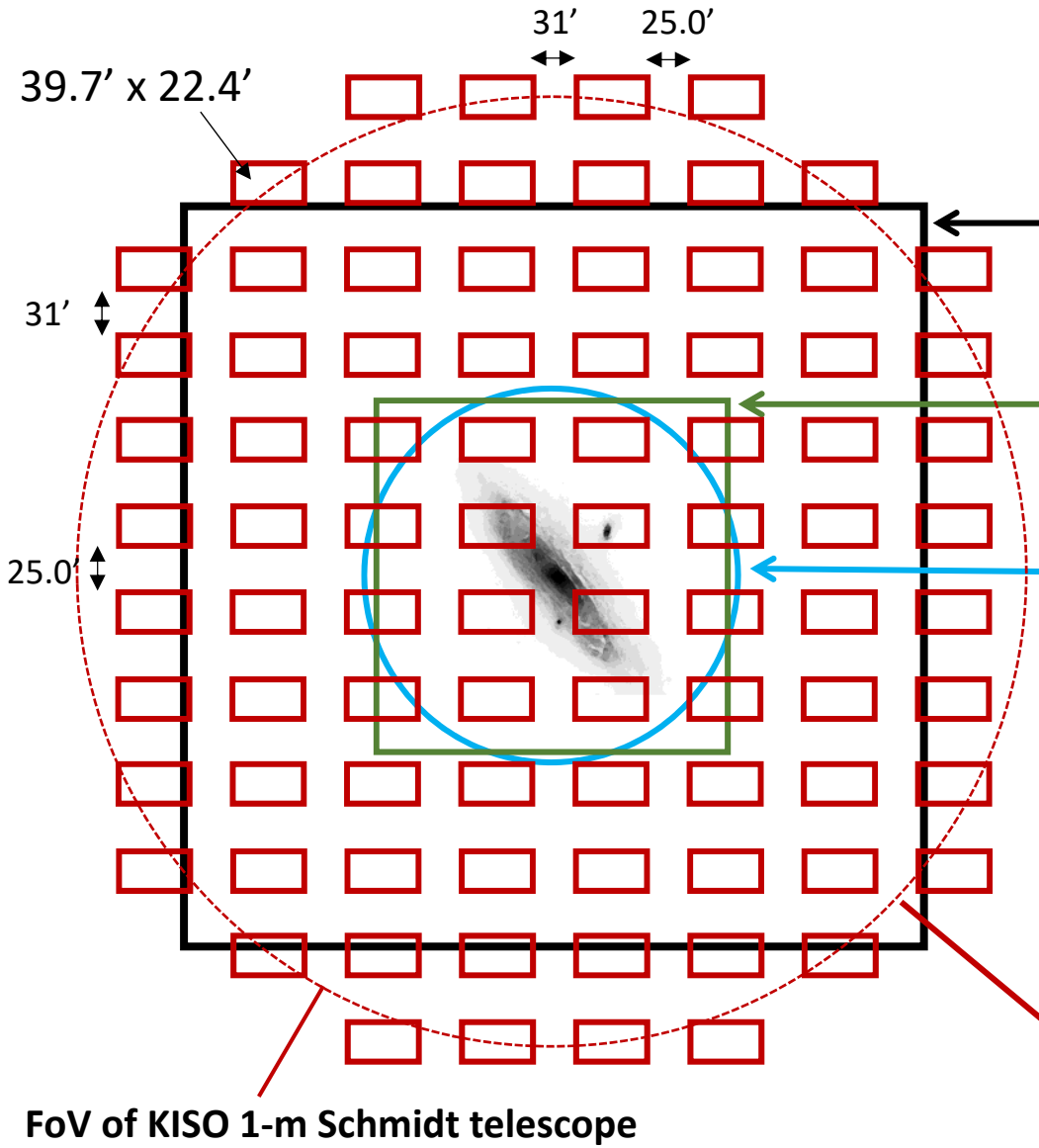


Tomo-e Gozen Q1



21 chips of CMOS sensors of Q1

Comparison of Field-of-Views



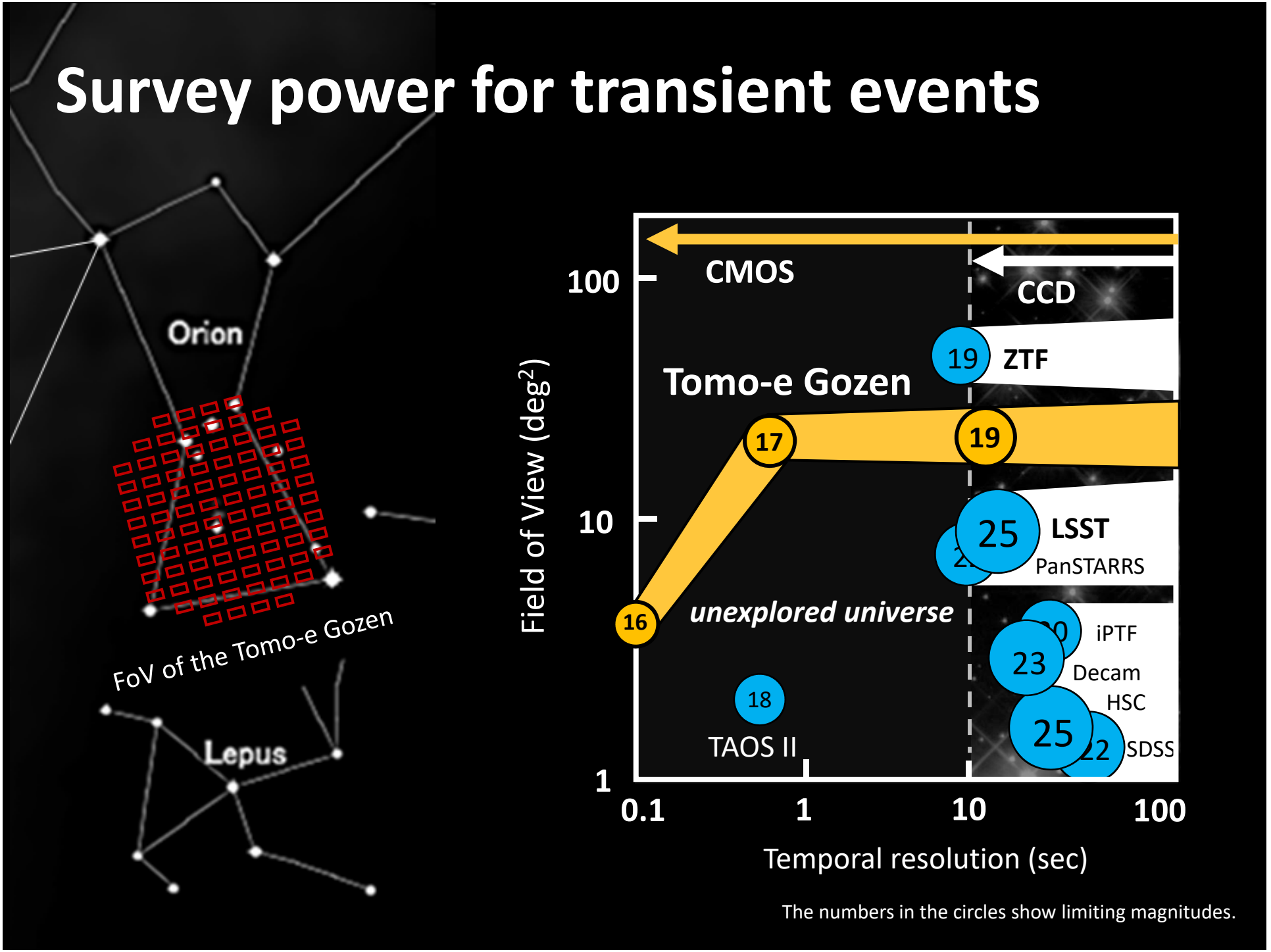
ZTF (1.2m) , 47 deg^2 , 2018-,
AΩ = 40 , Δτ ~ days, **CCD**

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

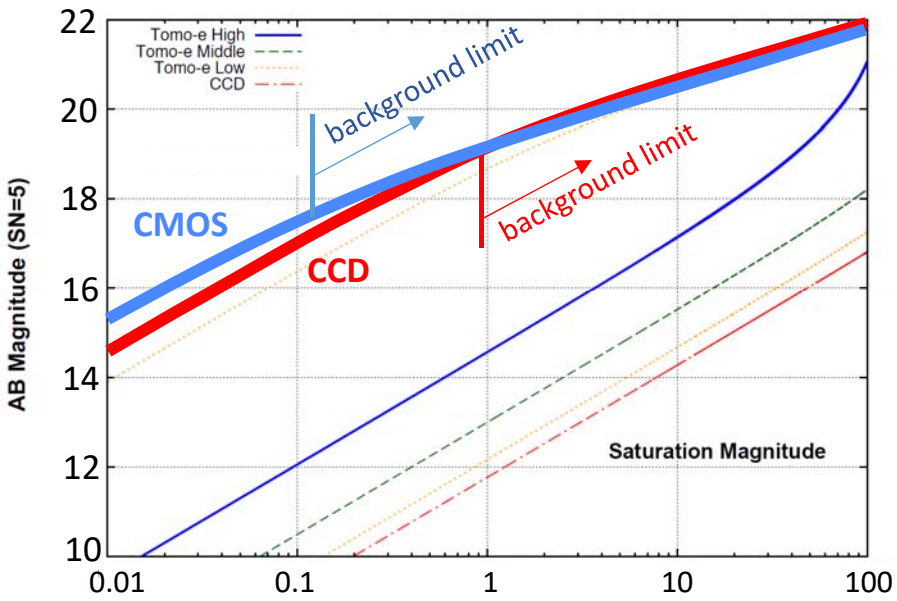
Survey power for transient events



The numbers in the circles show limiting magnitudes.

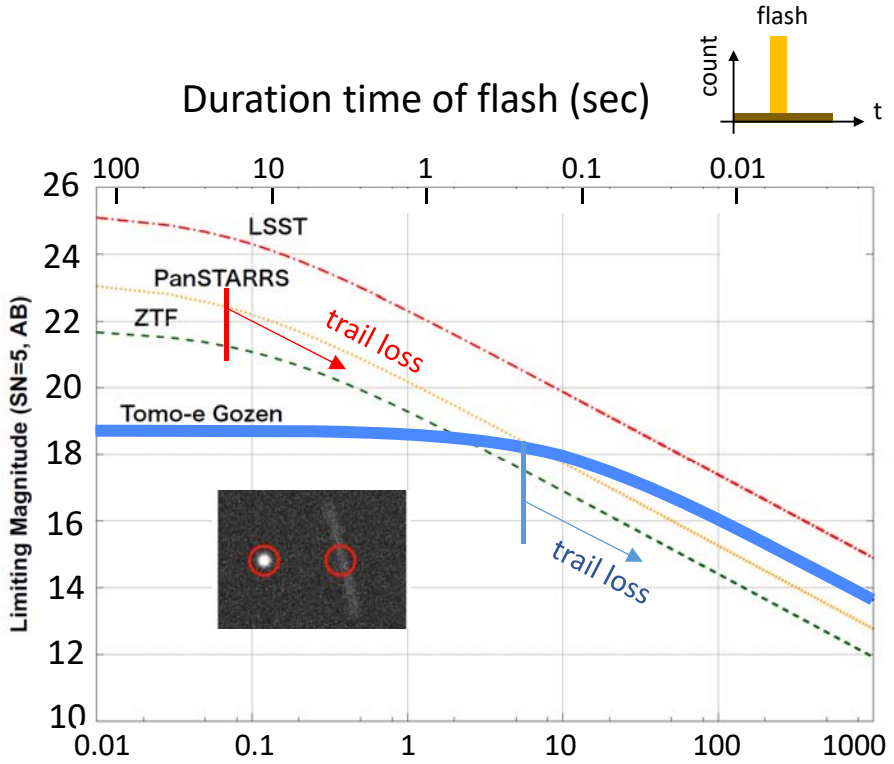
Limiting magnitude

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

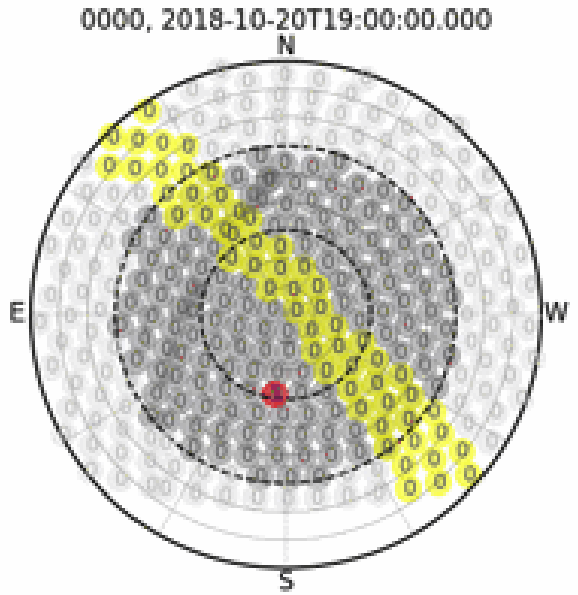
Tomo-e Gozen : 0.5 sec/frame, N_{read}=2 e-
PanSTARRS, ZTF : 30 sec/frame, N_{read}=5 e-
LSST : 60 sec/frame, N_{read}=10 e-

Kojima et al. 2018, SPIE

Intensive Science Programs

1. Northern sky 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 northern sky survey

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

2. Follow-up / Simultaneous

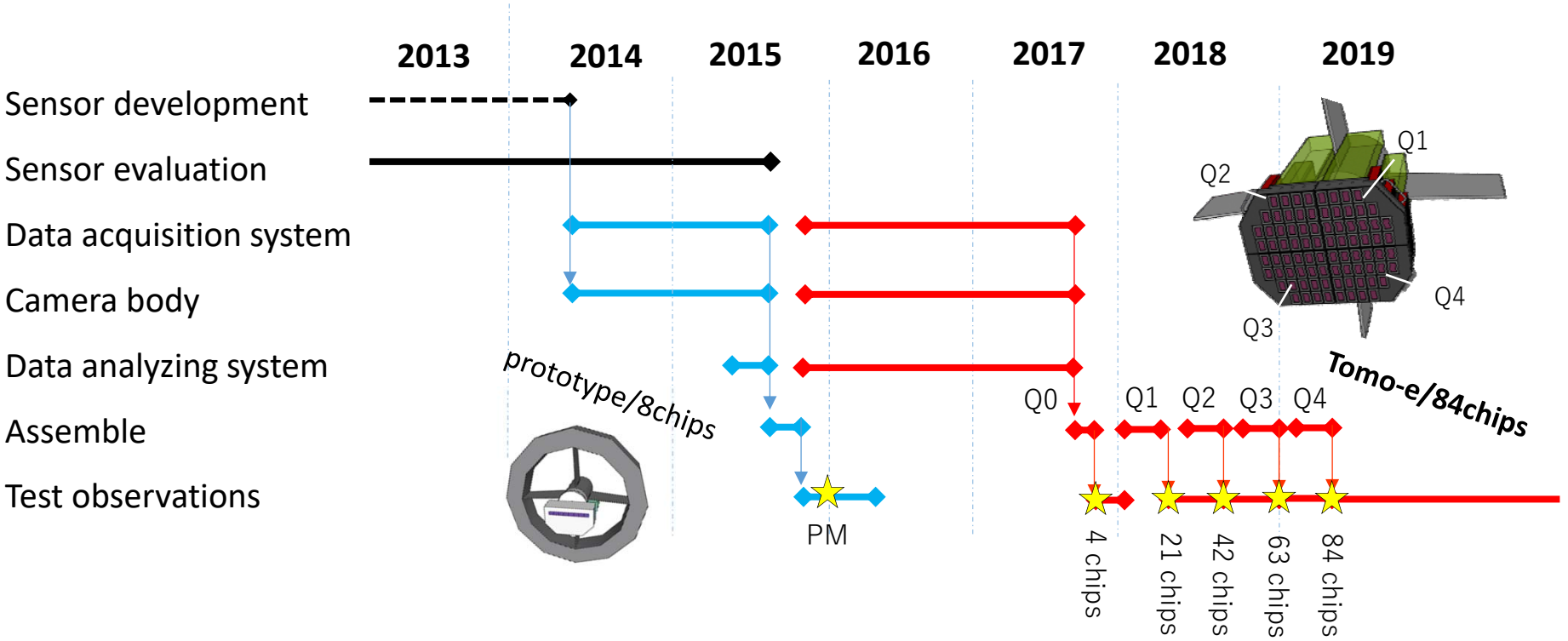
- GWs, neutrinos
- FRBs, NSs, BBHS, meteors, NEO,

3. Fixed FoV + high-speed

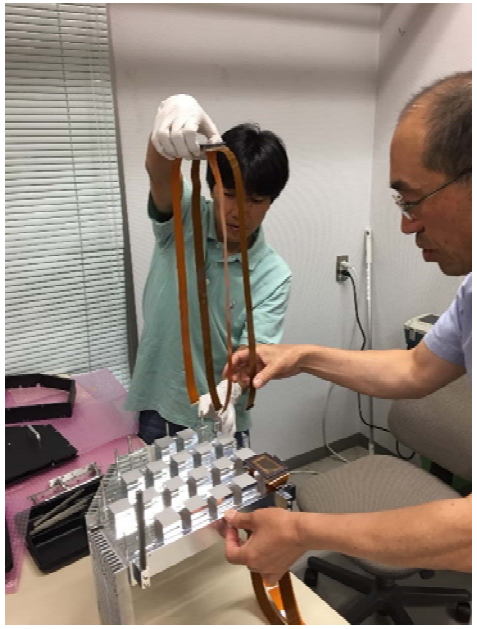
- 2-fps@ 20 deg^2 -- 200-fps@ 52” x 38”
- Occultation of TNOs, YSOs, flares, FRBs, NSs, BBHs, meteors, NEOs

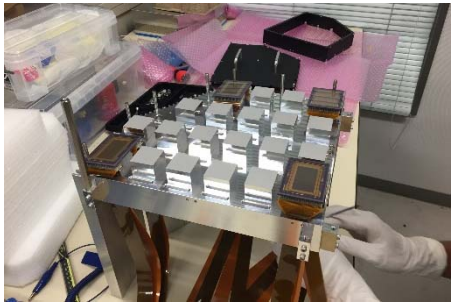
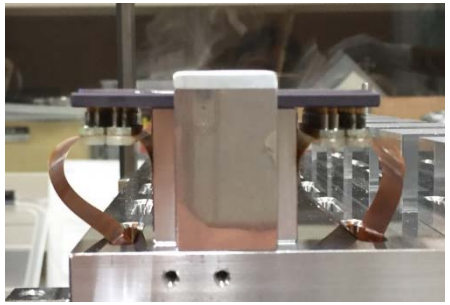
One year of Tomo-e Gozen

Timeline of Development

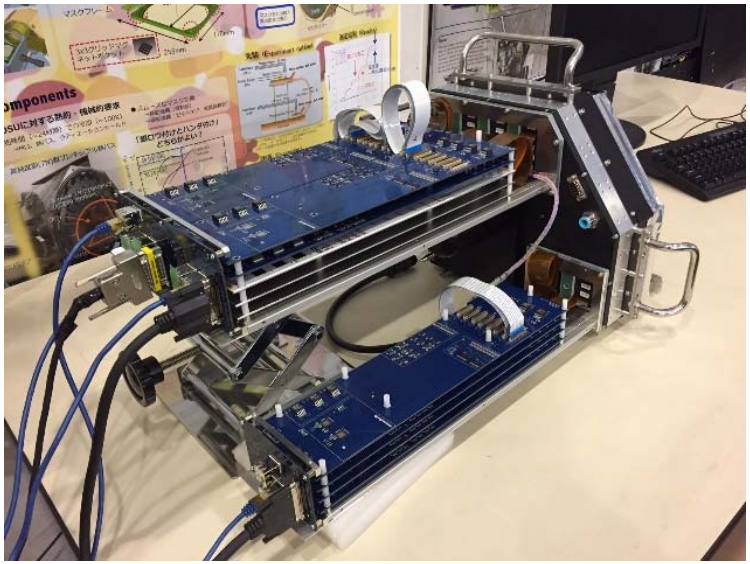


Tomo-e Q0 (4 chips) assembling

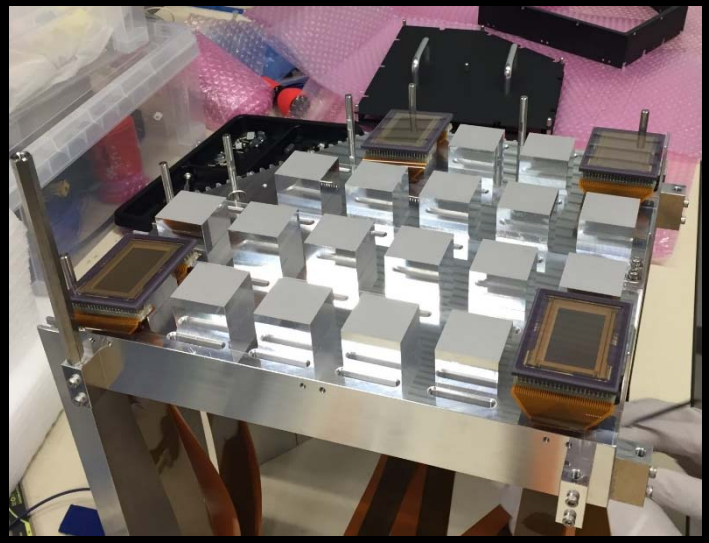


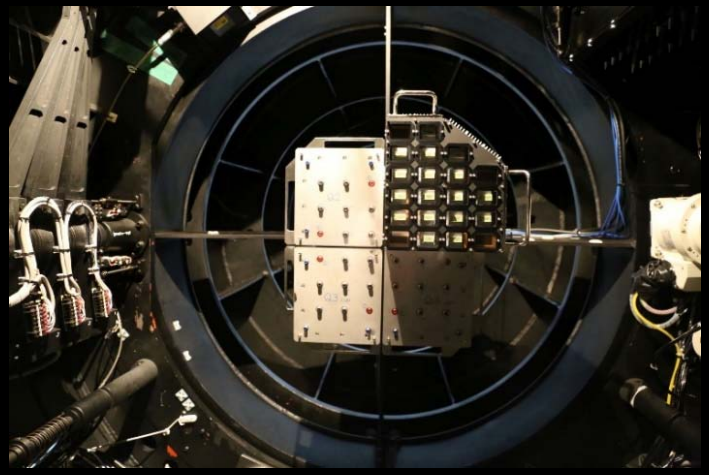



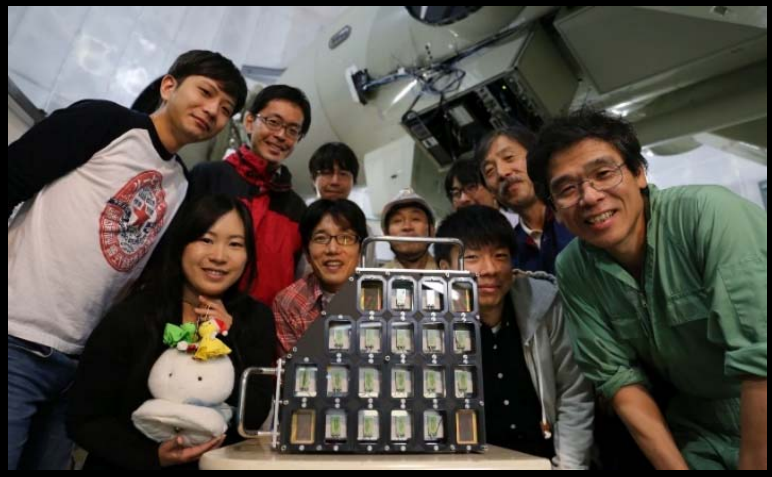




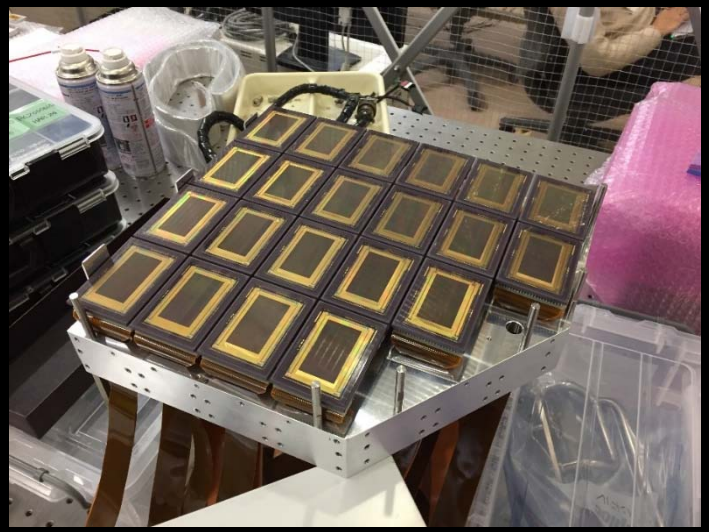
First light observations of Tomo-e Gozen Q0
2017/10/3

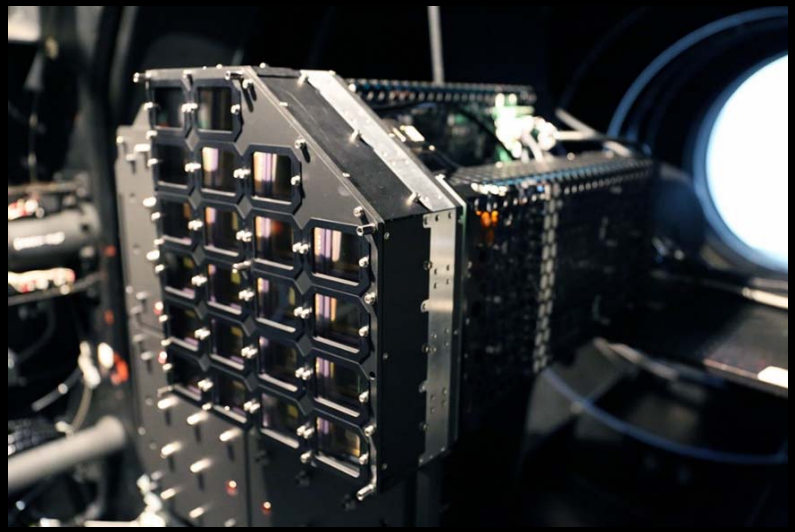


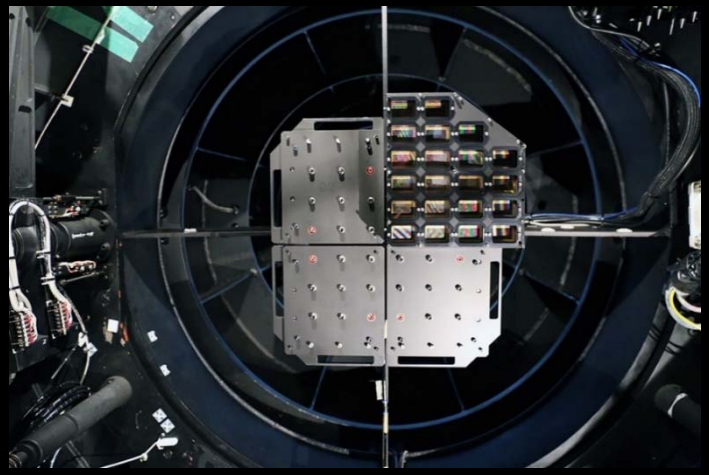


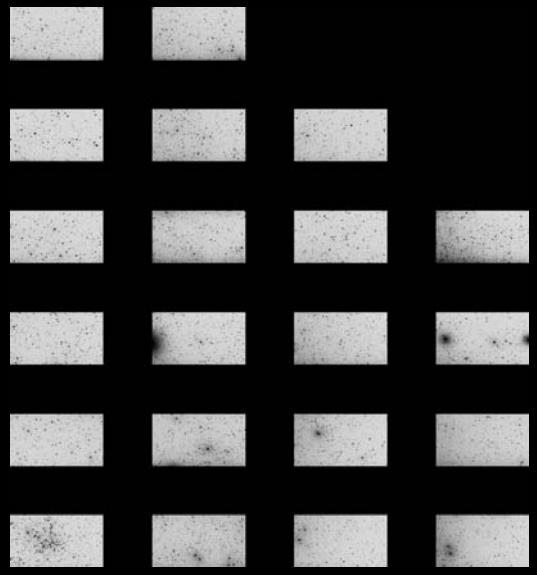


First light observations of Tomo-e Gozen Q1
2018/2/20



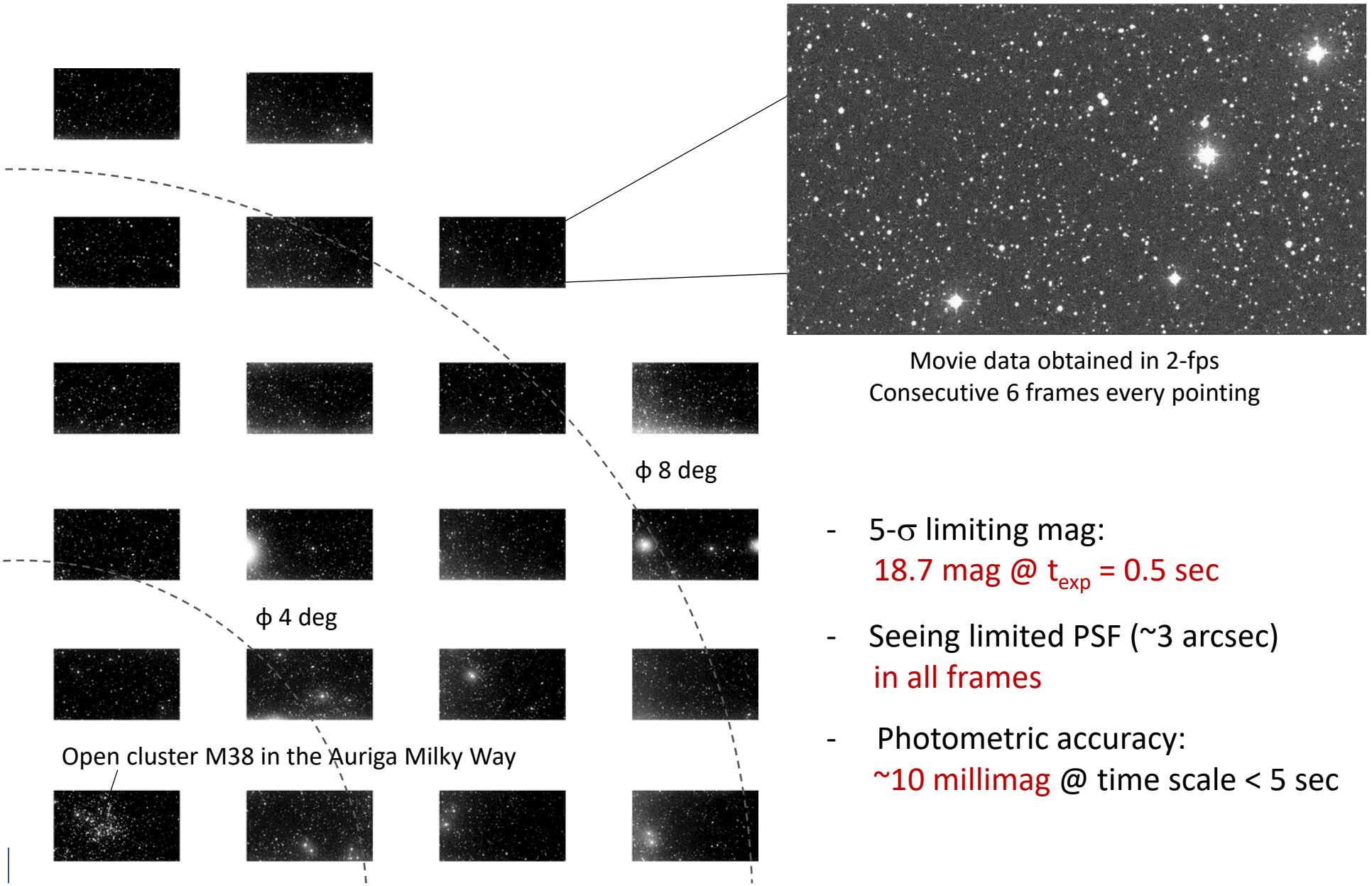






Images with 21 chips were successfully obtained

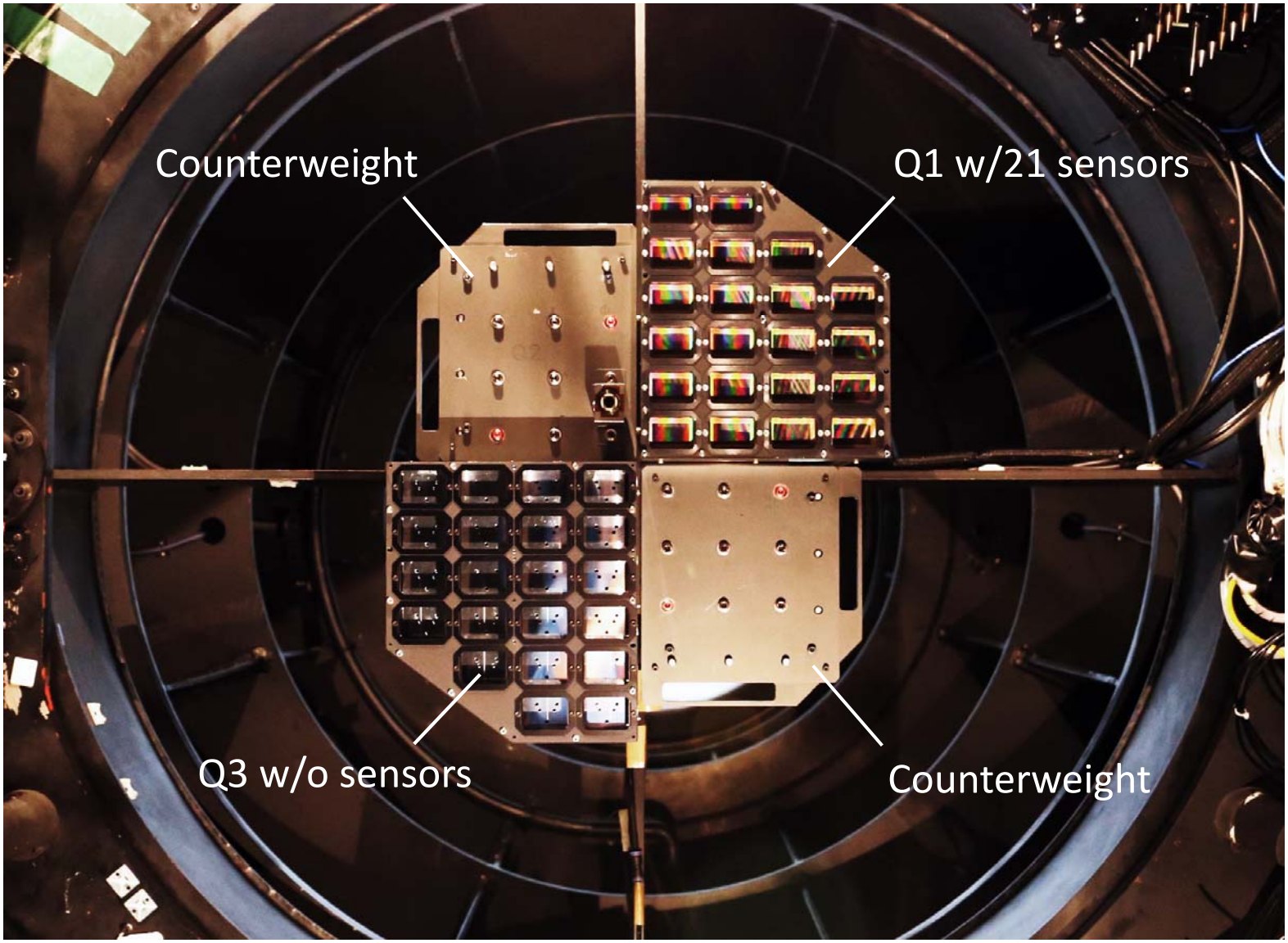
Commissioning run of Q1 in Feb. 2018



Movie data obtained in 2-fps
Consecutive 6 frames every pointing

- 5-σ limiting mag:
  18.7 mag @ t_{exp} = 0.5 sec
- Seeing limited PSF (~3 arcsec)
  in all frames
- Photometric accuracy:
  ~10 millimag @ time scale < 5 sec

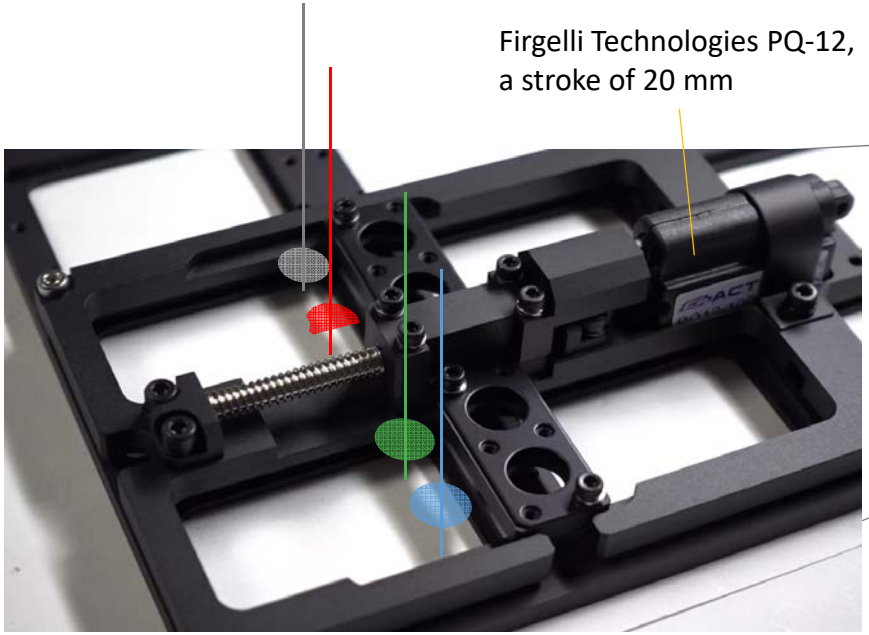
Picture taken on 2018/6/4



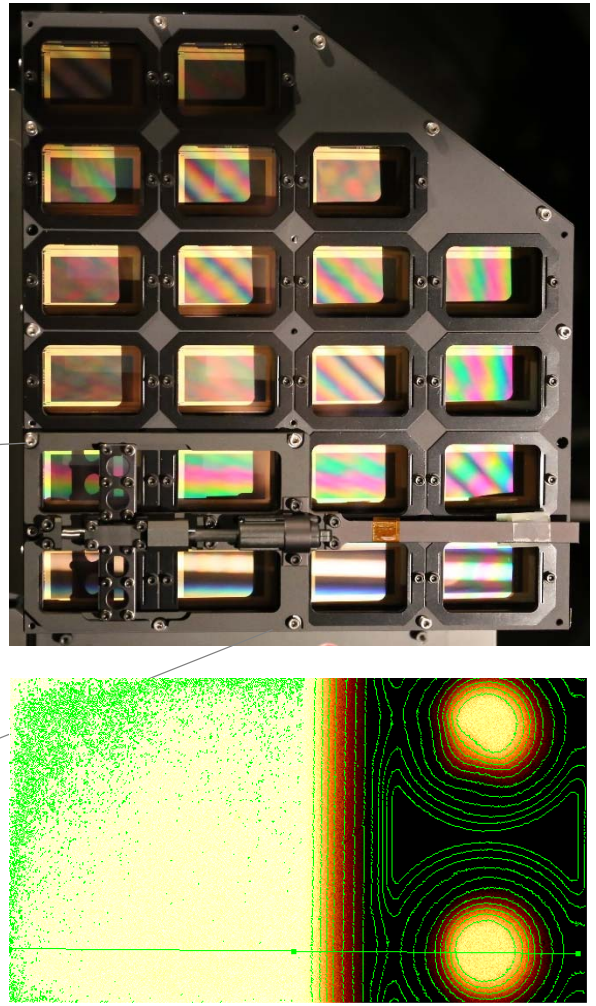
Q3 sensors has been installed on 2018/7/6

Filter exchange unit (optional)

- In GW observation case, self-follow-ups would be required.
- Gimmick to take color images quickly
- 4 colors of ϕ 2.5 arcmin
- Choose filters by telescope pointing



SDSS-g, r, i, and Hα filters (TBD)

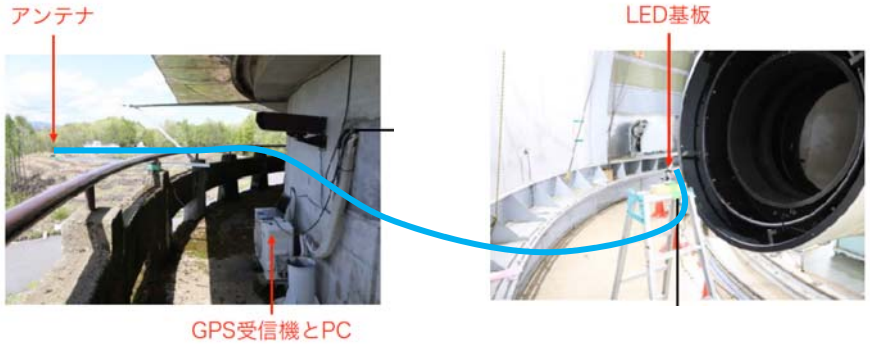


Flat image through filters

Time Accuracy

- Synchronized with GPS receiver
- Absolute time accuracy: ±0.2 msec
- Time stability: $\Delta f \sim 10^{5\text{-}6}$

Evaluation with LED synchronized by GPS

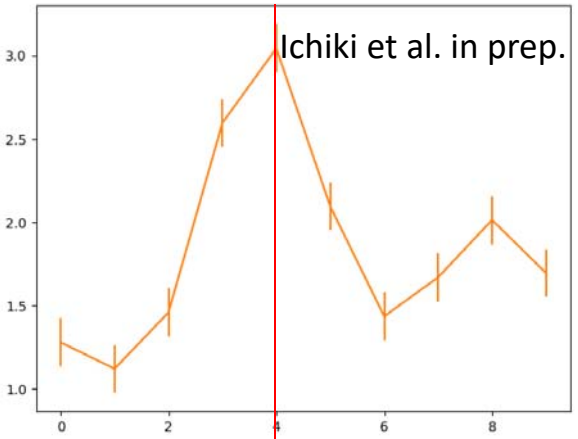


Kojima et al. 2018, SPIE

Optical pulses of Crab pulsar

電波での周期
P = 33.7464765718070ms

周期 33.746(2) [msec]



積分時間～5.5 msec

Main peak time (TDB) = 35229.416030 [s]
電波の時刻 - 0.3 msec

Main peak
Optical
35229.416~~030~~ [s] 電波の時刻 - 0.3 msec
35286.819~~329~~ [s] 電波の時刻 + 2 msec
35344.662~~472~~ [s] 電波の時刻＋1.8msec

Presentations

1. Symposium on "New development in astrophysics through multi-messenger observations of gravitational wave sources" (Panasonic Auditorium, Yukawa Hall, YITP , Kyoto University, 2017/8/24-26)
2. 2017年度岡山ユーザーズミーティング (第28回光赤外ユーザーズミーティング) (国立天文台, 2017/9/4-5)
3. 2017 年天文学会春季年会 (2017/9/11-13@北海道大学) , 4件
4. ワークショップ「データ駆動プラズマ物理研究の開拓」(キャンパスプラザ京都, 2017/9/14-15)
5. 第 7 回 可視赤外線観測装置技術ワークショップ 2017 (2017/11/16–17@京都大学) 、4件
6. 第 39 回 天文学に関する技術シンポジウム 2017 (2017/12/21-22–17@倉敷市芸文館)
7. 人工天体の地上観測の研究会 (JAXA相模原新 A 棟 2 階A会議室, 2018/2/5)
8. KOOLS-IFU 研究会 (2018/02/05–06 @京都大学) , 2件
9. PERC Int'l Symposium on Dust & Parent Bodies (2018/02/26–28 @千葉工大)
10. 2018 年天文学会春季年会 (2018/3/14-17@千葉大学)
11. 9th Workshop on Catastrophic Disruption in the Solar System (CD9)
12. 新学術領域「重力波物理学天文学・創世記」ワークショップ (Gravitational wave physics and astronomy: Genesis -- Area Workshop 2018 (Group B))
13. SPIE Astronomical Telescopes + Instrumentation (Austin Convention Center, 2018/06/10-15), 2件

SPIE2018

Publications

1. 平成29年度 東京大学天文学専攻修士論文発表会 (2018/02/08-09), 一木さん
2. 平成29年度東京大学天文学専攻修士論文発表会 (2018/02/08-09), 猪岡さん

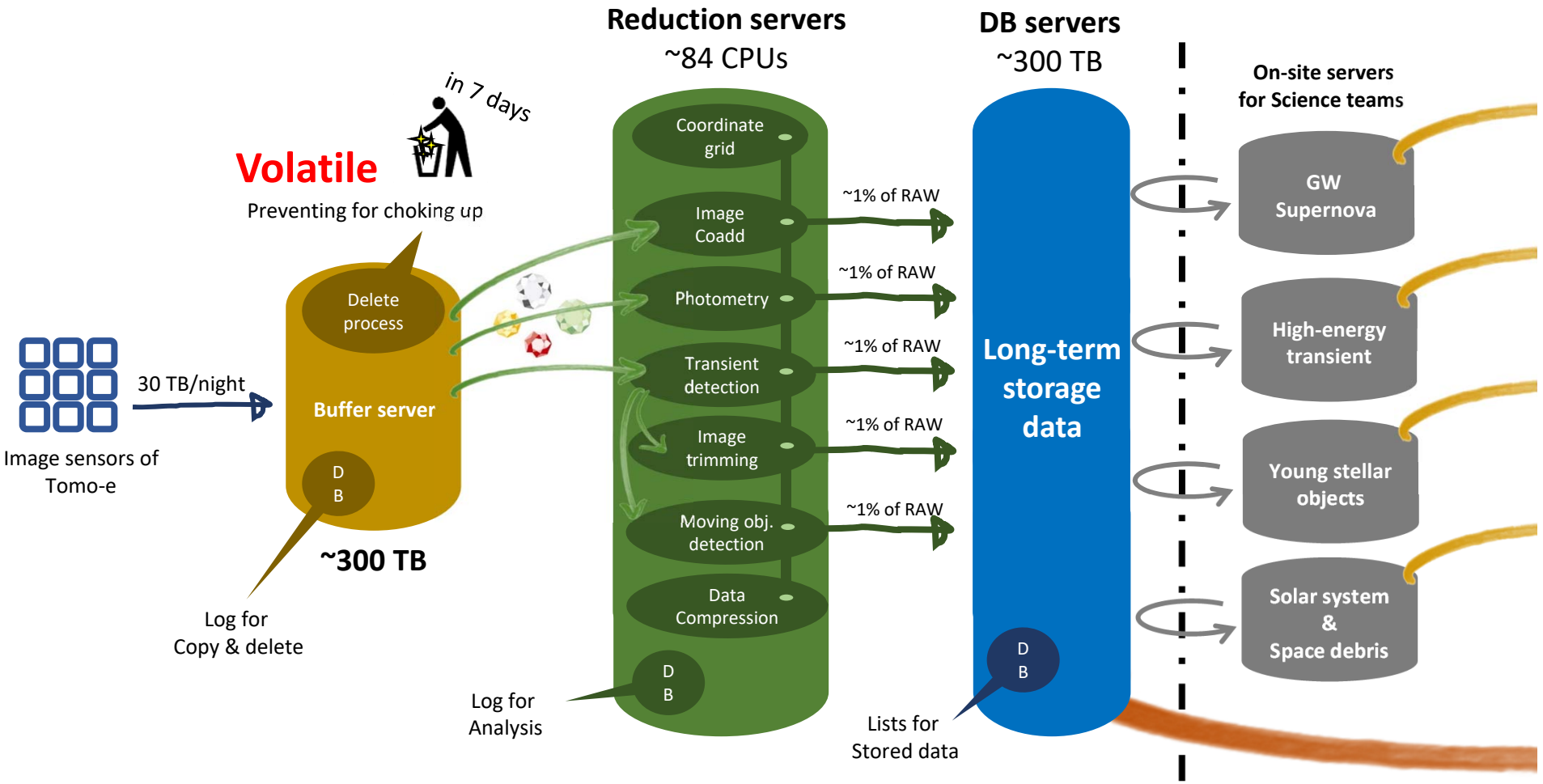
Outreach

1. 宇宙まるごと創生塾飛騨アカデミー (飛騨市神岡町公民館, 2017/12/3)
2. 日本オプトメカトロニクス協会 第1回光センシング技術部会（機械振興会館 別館 4 階, 2018/6/28）

Data of Tomo-e Gozen

Data Management System

On-site management (10 Gbps network)



Off-site

Every events (every 1min)

External sever

WWW server & DB

Transported every 1-month

Long term storage data

国立天文台 NAOJ National Astronomical Observatory of Japan

Astronomical data center

in National Astronomical Observatory (NAOJ)

at Mitaka, Tokyo

Data archive & web server

Data Analysis

30 TB/night

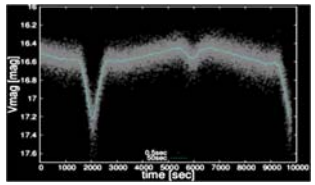
Raw frame data

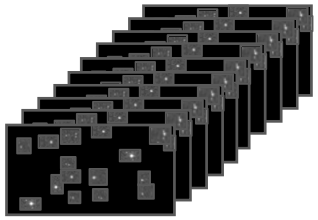
Buffer server

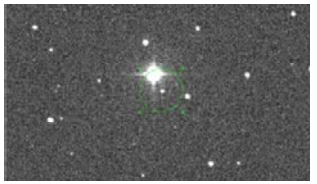
analized
in-real time

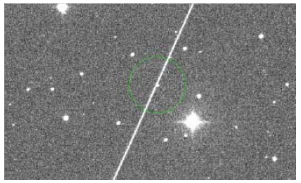
Informatics method

Machine learning, Sparse modeling, Movie recognition, Data compression







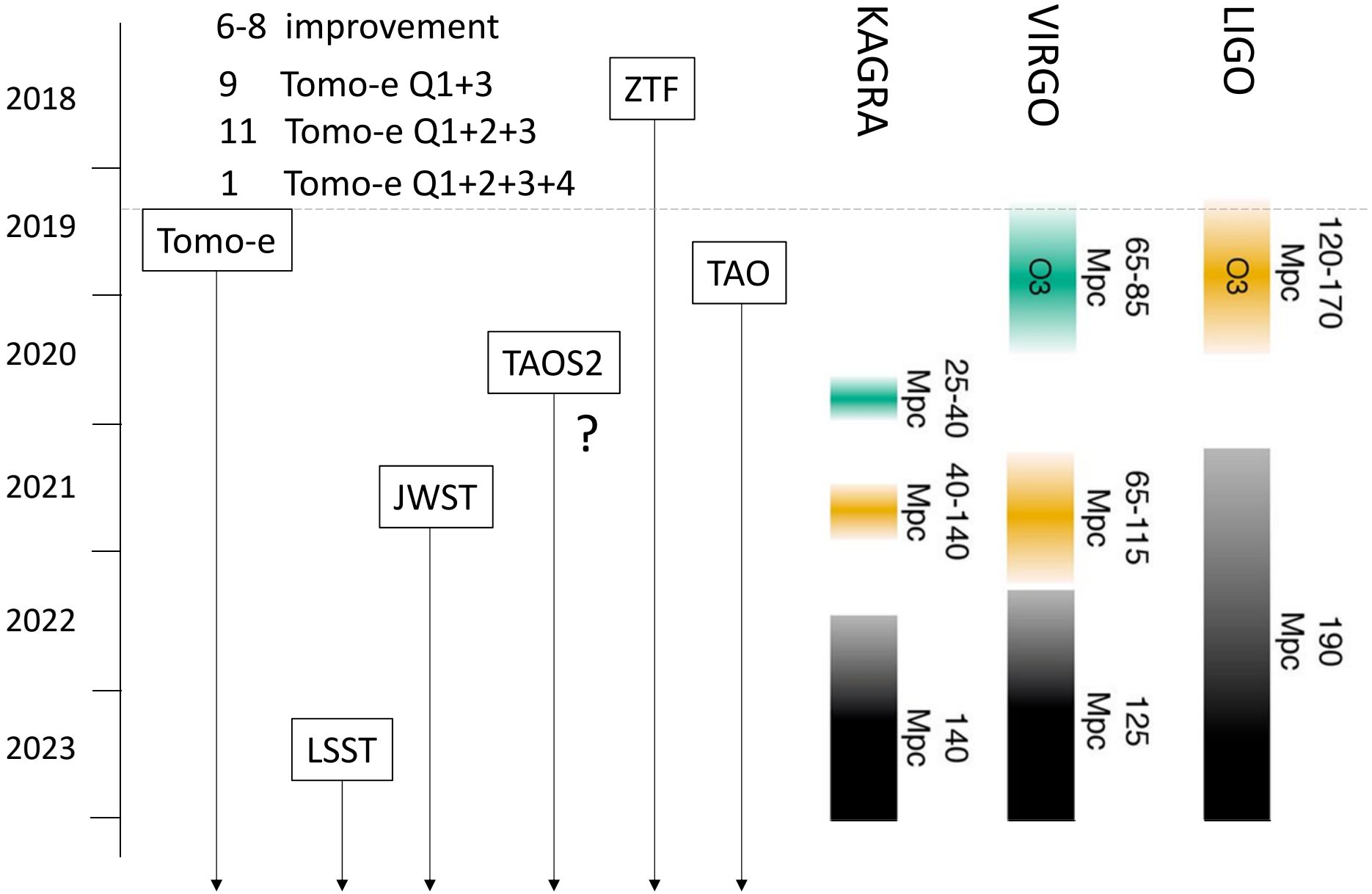


Photometry of sources detected in all frames	Detection of short timescale transient	Co-added consecutive frames	Detection of very-fast-moving objects
Text table	Masked 3D-FITS	2D-FITS	2D-FITS
Real-time	Real-time	Real-time	Day-time
Light curves of 10^5 objects	unknown	10^5 frames	10^5 frames

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

Schedule


6-8 improvement
9 Tomo-e Q1+3
11 Tomo-e Q1+2+3
1 Tomo-e Q1+2+3+4
2018
2019
2020
2021
2022
2023
Tomo-e
ZTF
TAO
TAOS2
?
JWST
LSST
KAGRA
VIRGO
LIGO
O3
65-85 Mpc
120-170 Mpc
25-40 Mpc
40-140 Mpc
140 Mpc
65-115 Mpc
125 Mpc
190 Mpc

APPENDIX

Fact sheet of the Tomo-e Gozen

Telescope	the Kiso 1.0-m f/3.1 Schmidt telescope, Kiso observatory, the University of Tokyo
Sensor	Canon 35MMFHDXM, 35-mm front-side-illuminated CMOS sensor with microlens array and AR coated cover glass
Sensor format	2,160 $\times$ 1,200 pix chip^{-1} (total), 2,000 $\times$ 1,128 pix chip^{-1} (photosensitive)
The Number of sensor chips	84 chips
Field of view	39.7' $\times$ 22.4' $\times$ 84 chips = 20.8 deg^2
Pixel size and scale	19 mm pix^{-1}, 1.189 " pix^{-1}
Sensitive wavelength	370 to 730 nm
Photoelectric conversion efficiency	0.68 at a peak of 500 nm
Photosensitive area / package area	0.35
Filters	Pre-set: transparent windows, optical filters, grisms (optional) Changeable: 4 pieces of f2.5' with the FEX unit
Max frame rate	2 fps in full-frame, maximum 500 fps in partial-frame
Read noise (2 fps)	2.0, 4.1, 9.2 e$^-$ in High-, Mid-, Low-gains
Well depth (linearity < 5%)	6,000, 25,000, 53,000 e$^-$ in High-, Mid-, Low-gains
Dark current	0.5 e$^-$ sec^{-1} pix^{-1} at 290 K, 6 e$^-$ sec^{-1} pix^{-1} at 305 K
Sky background (dark night)	50 e$^-$ sec^{-1} pix^{-1} (transparent windows)
Gain conversion factor	0.23 , 0.94, 2.4 e$^-$ ADU^{-1} in High-, Mid-, Low-gains
5σ limiting mag (High-gain)	16.7, 18.5, 19.9 mag at t_{exp} of 0.1, 1, 10 sec w/transparent windows
Photometric stability	4 to 30 milli-mag (time scale < 5 sec) 1 to 3 milli-mag (time scale > 100 sec)
Absolute time accuracy of time stamps	$\pm$0.2 millisecond
Stability of frame read time	10^{-5}
Output file (full-frame)	4.9 MByte frame^{-1}, 16-bit cube FITS
Data production rate (full-frame, 2 fps)	830 MByte s^{-1}, 30 TByte night^{-1}