高速観測への備え

― 木曽トモエゴゼンの例 ―

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

第9回光赤外線天文学大学間連携ワークショップ, 2018/12/25, 埼玉大学

Outline

1. Kiso / Tomo-e Gozen
2. High-speed observation system of Tomo-e Gozen
3. Advantages of high-speed observations
4. New CMOS camera module

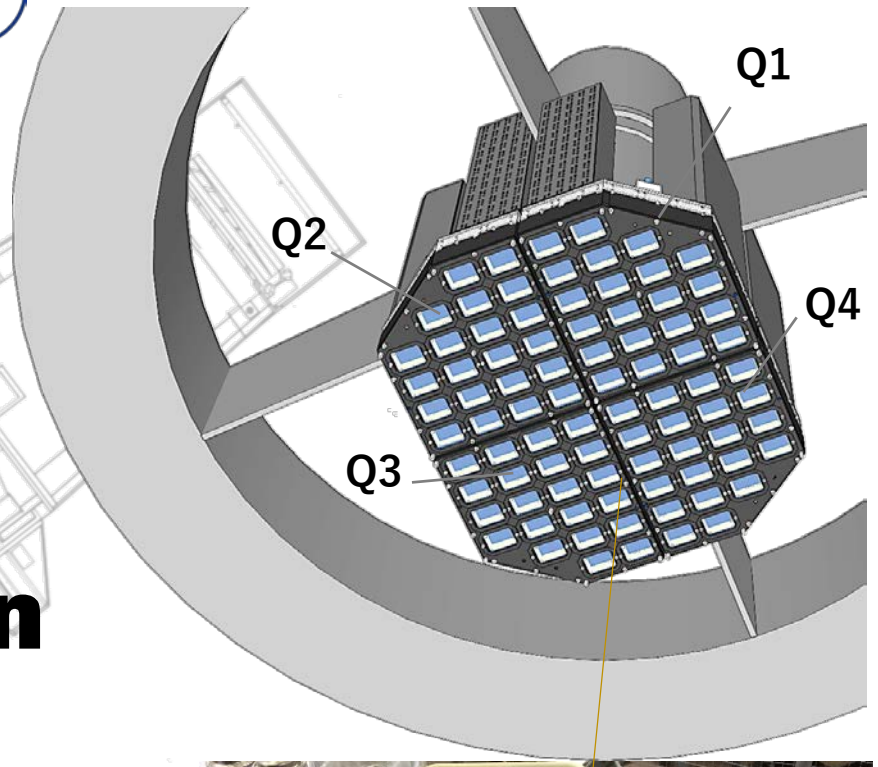
Kiso / Tomo-e Gozen

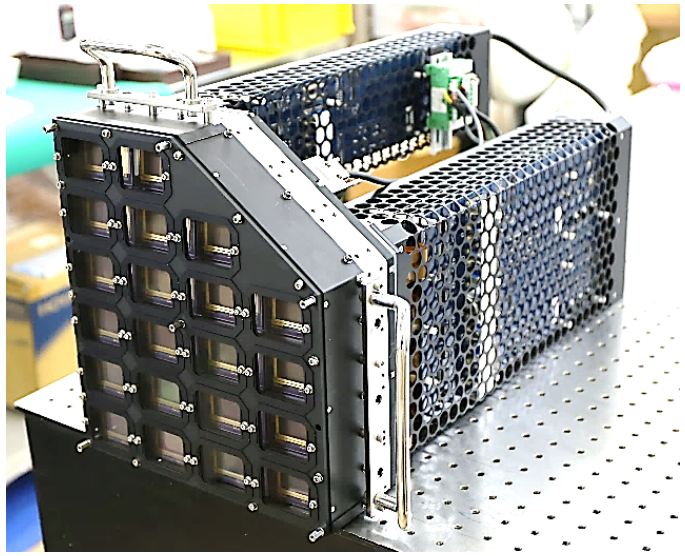
- Project P.I. Shigeyuki Sako
- Sako et al. 2018, SPIE

the first wide-field CMOS camera

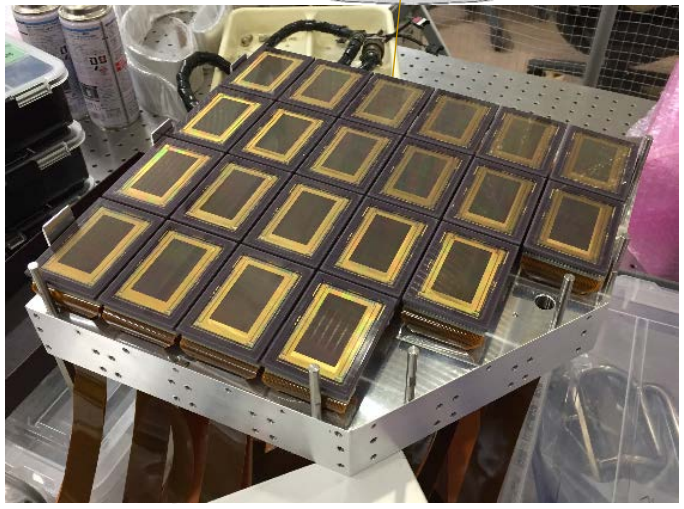
The Tomo-e Gozen

- 105-cm Kiso Schmidt telescope
- FoV of 20 deg^2 in ϕ 9 deg
- 84 chips of CMOS, 1k x 2k pixels
- **Consecutive frames in 2 fps (max)**
- **Movie big-data of 30 TB/night (max)**
- **Absolute time accuracy of 0.2 msec**
- Room temperature, Non-vacuum

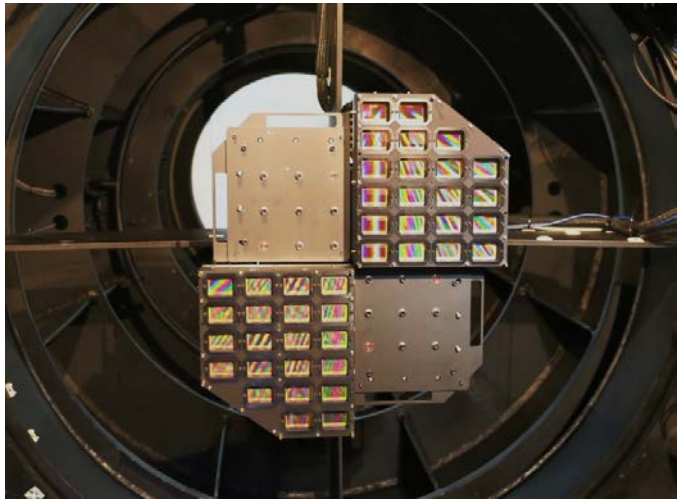




Camera body of the Tomo-e Gozen Q1

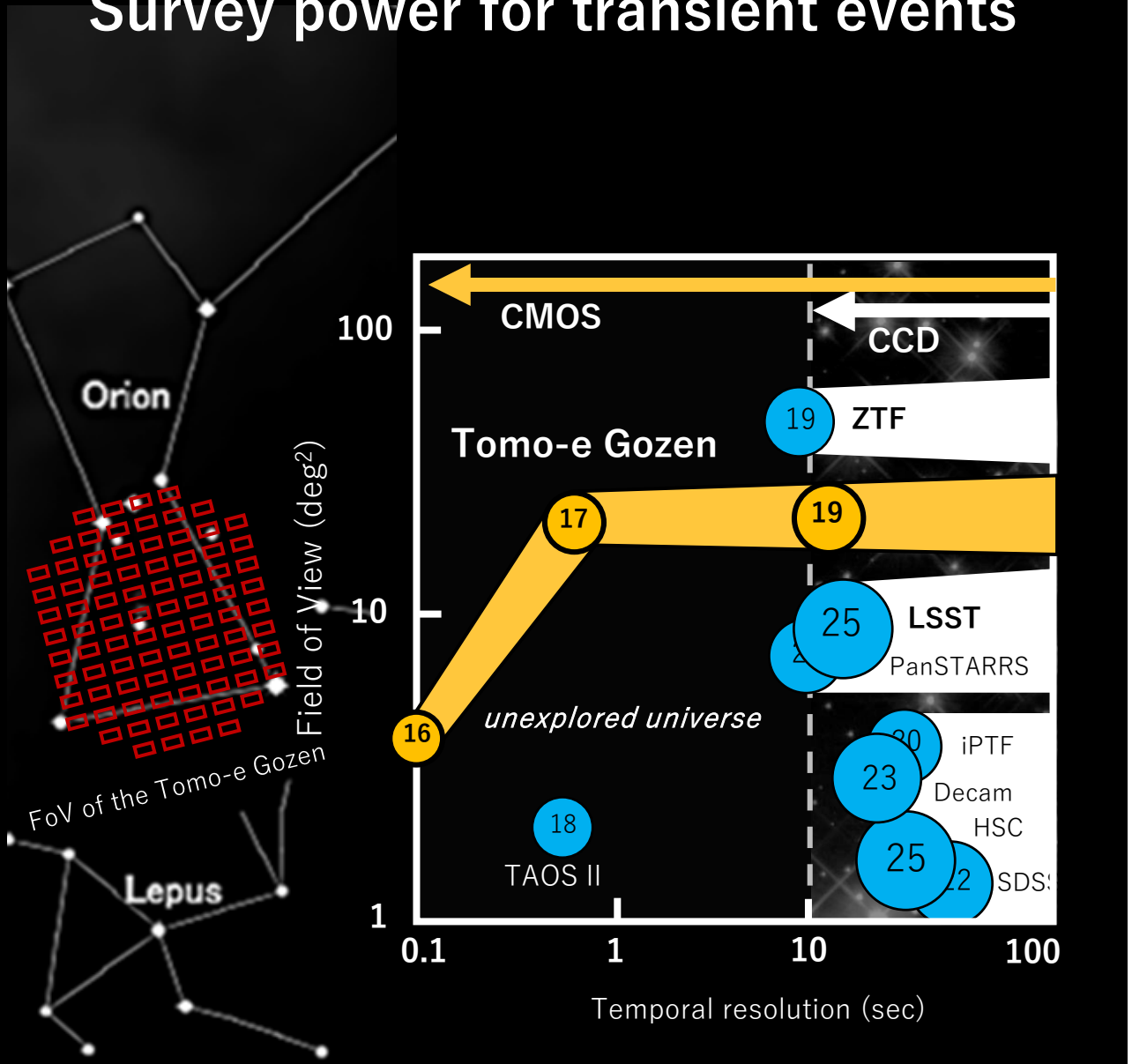


21 chips of CMOS sensors of Q1



Q1 and Q3 cameras on Schmidt telescope

Survey power for transient events

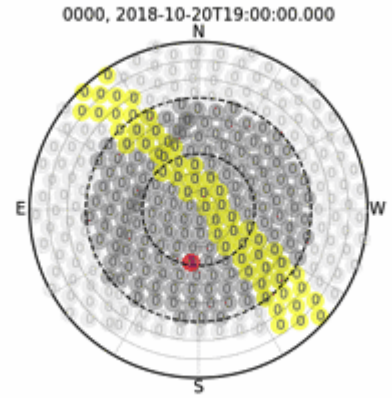


The numbers in the circles show limiting magnitudes.

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, NEOs



Simulation of northern sky survey
- Each circle: FoV with Φ9 deg
- Yellow: Milky way

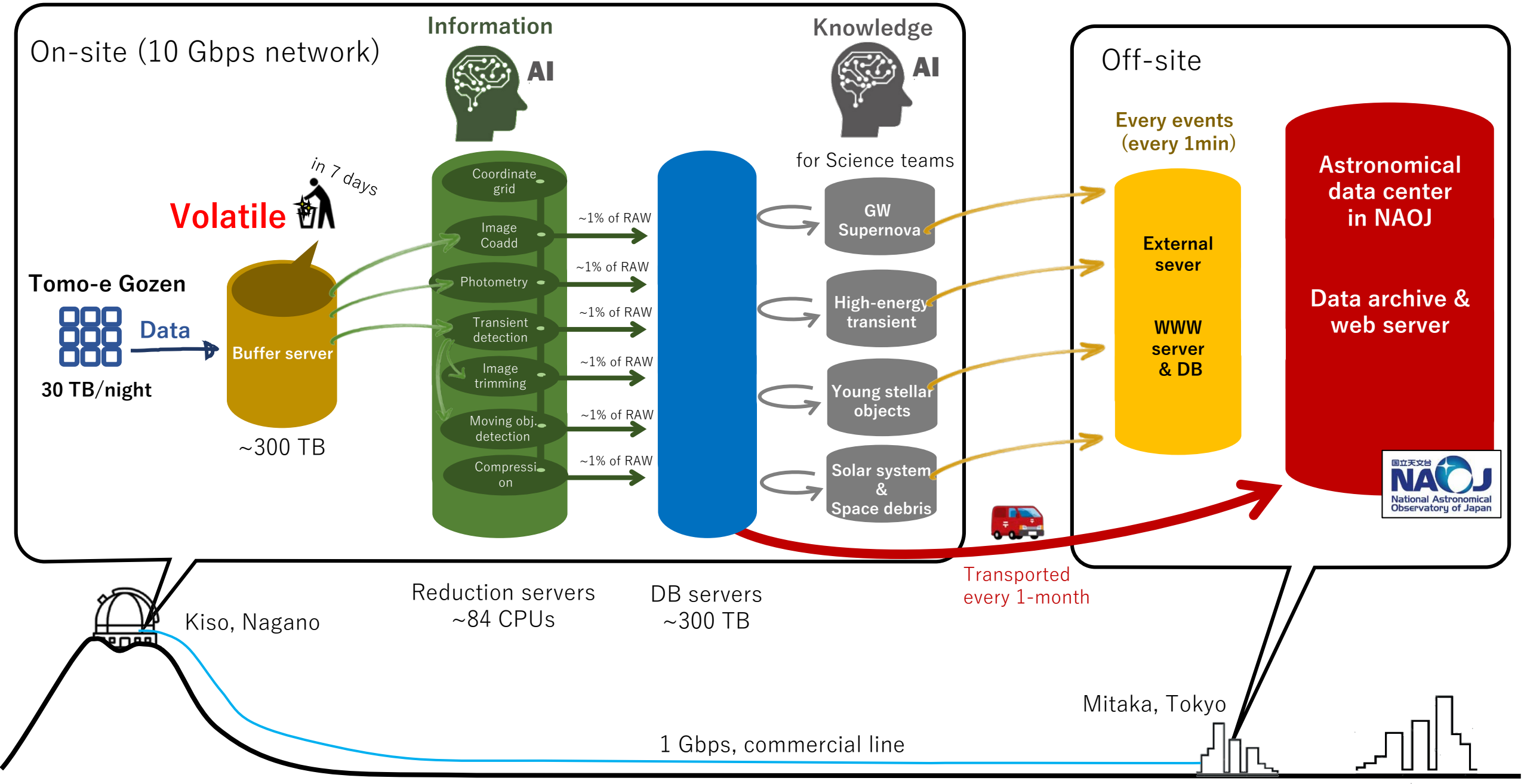
2. Follow-up / Simultaneous

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

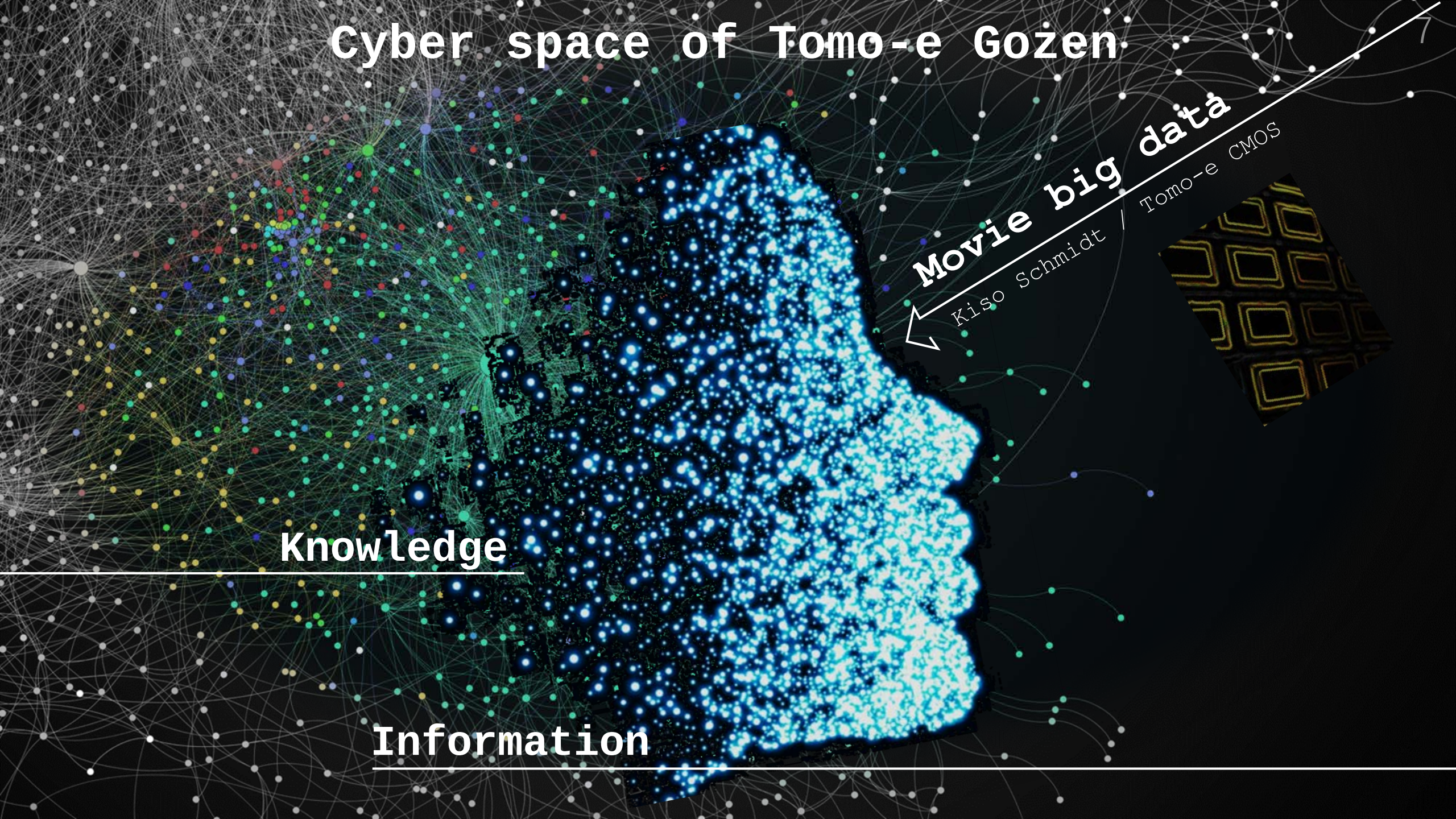
3. Fixed FoV + high-speed

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

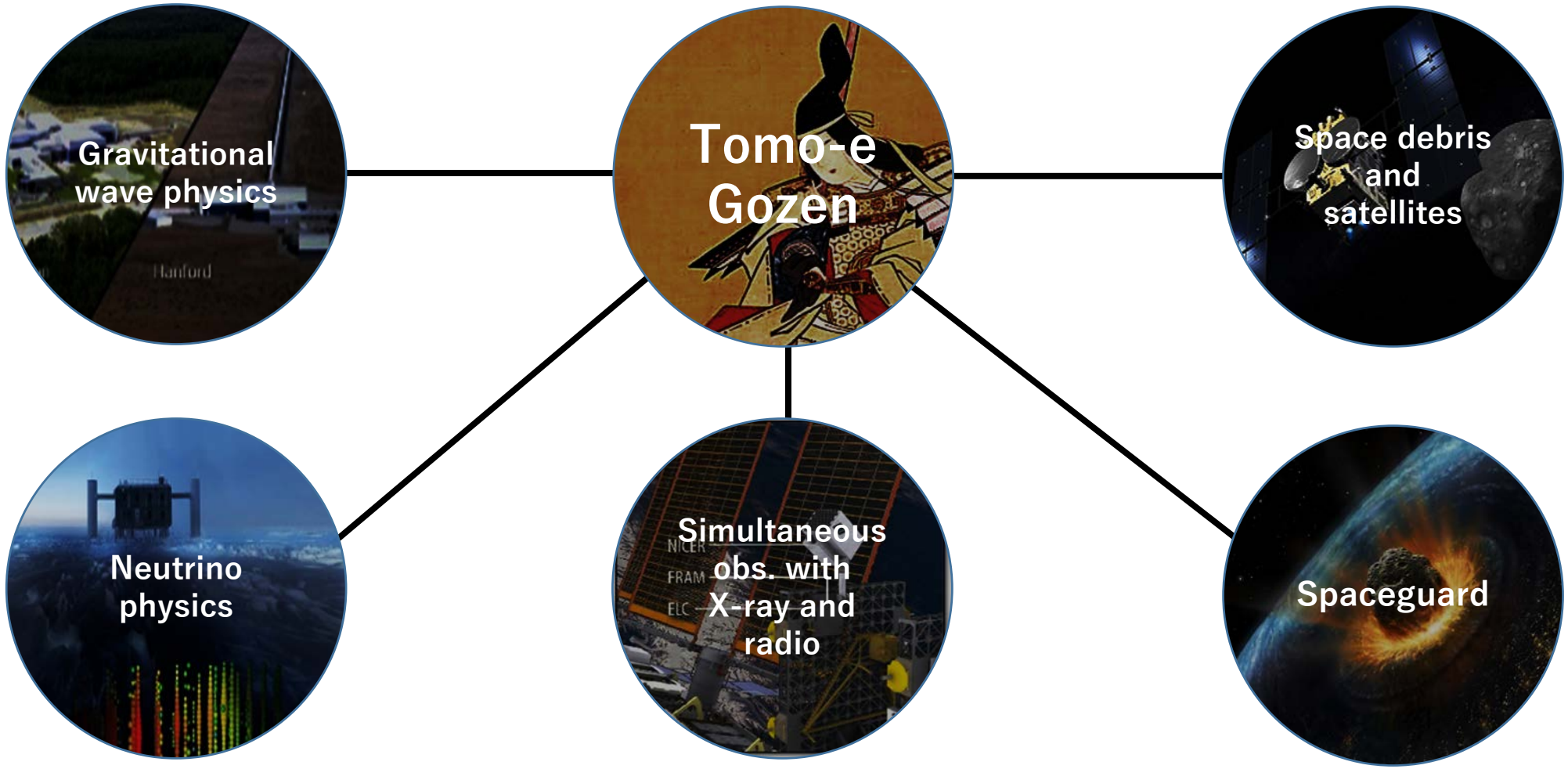
Volatile data management system



Cyber space of Tomo-e Gozen



Collaboration with various fields via movie big-data and AI



- Time-domain observations with HOURS to MSEC resolutions
- QUICK optical follow-ups with a few 10 DEG^2

High-speed observation system of Tomo-e Gozen

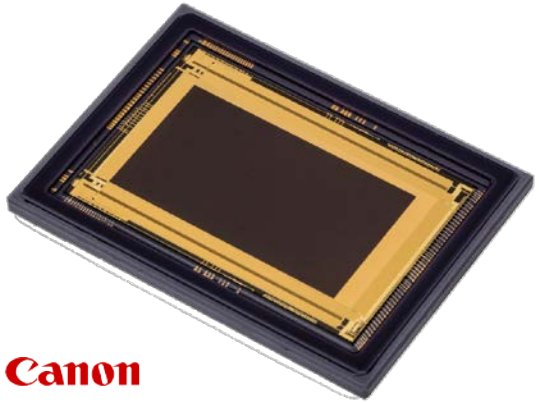
Performance necessary for high-speed optical observations

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

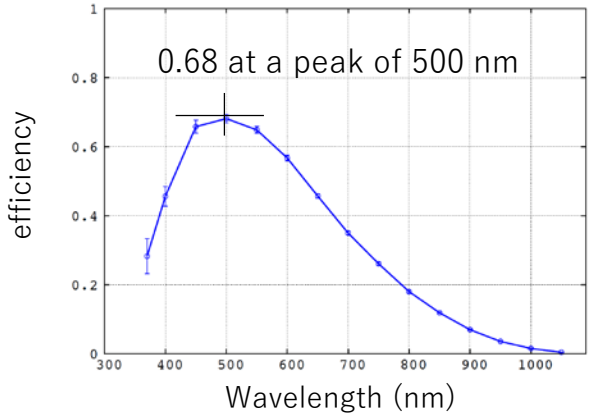
Large pixel CMOS sensor

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



Photoelectric conversion efficiency

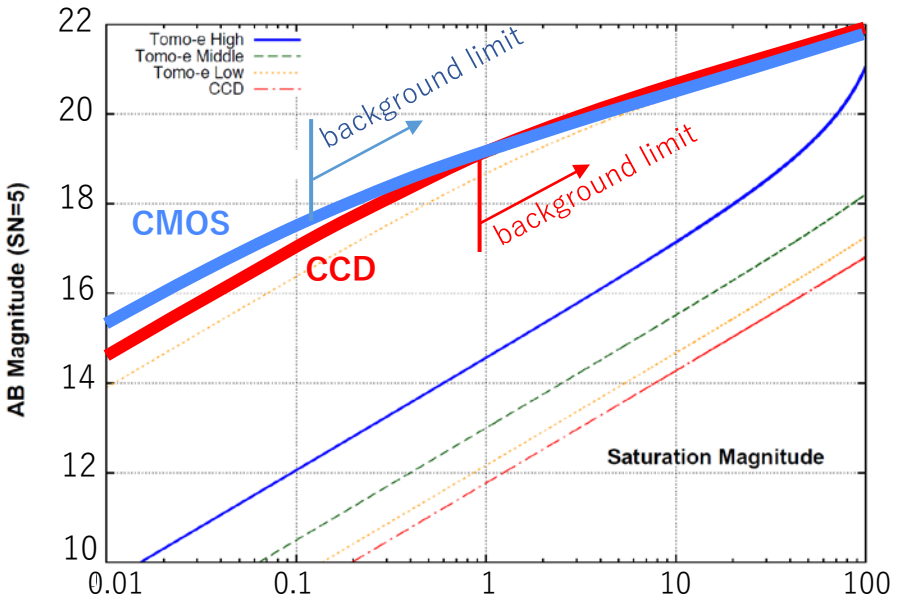


- Photon sensitive: 370 – 730 nm
- Well: 6,000 e$^-$, 53,000 e$^-$ @ G=x16, x1.7
- **Read noise: 2.0 e$^-$**, 9.2 e$^-$ @ G=x16, x1.7
- **Dark current: 6 e$^-$ sec^{-1} @305K**
- Power consumption: 230 mW chip^{-1} @2-fps

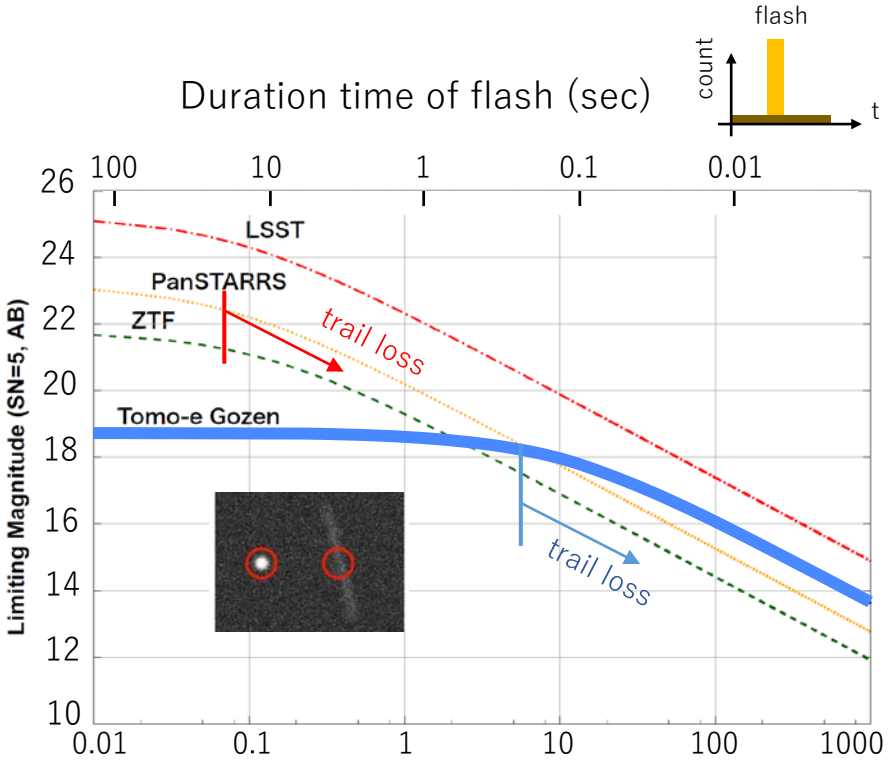
→ Less than sky background in dark night, 50 e$^-$ sec^{-1}, at room temperature

Limiting magnitude

5-σ limiting magnitude



Duration time of flash (sec)



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

assuming same filter-bandwidth and pixel size

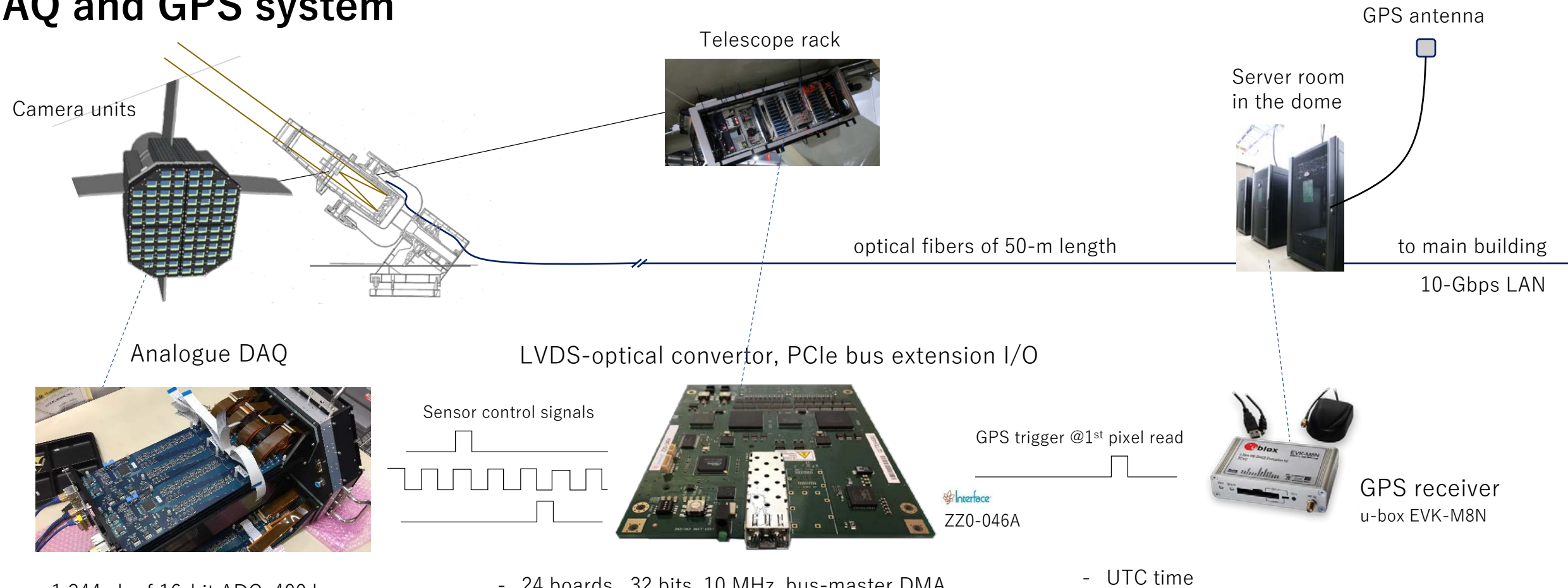
Tomo-e Gozen : 0.5 sec/frame, N_{read}=2 e-
PanSTARRS, ZTF : 30 sec/frame, N_{read}=5 e-
LSST : 60 sec/frame, N_{read}=10 e-

Kojima et al. 2018, SPIE

2. Data acquisition

- Consecutive data acquisition
- High absolute time accuracy
- High time stability

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**

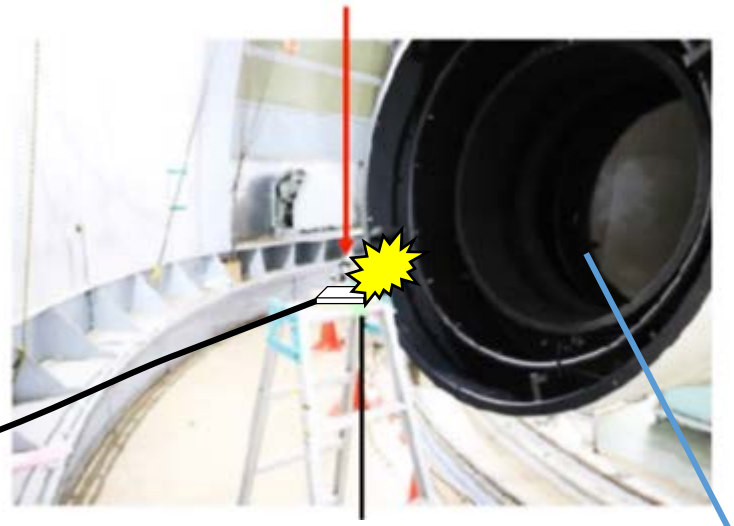
Measurement of absolute time accuracy of GPS system

GPS antenna

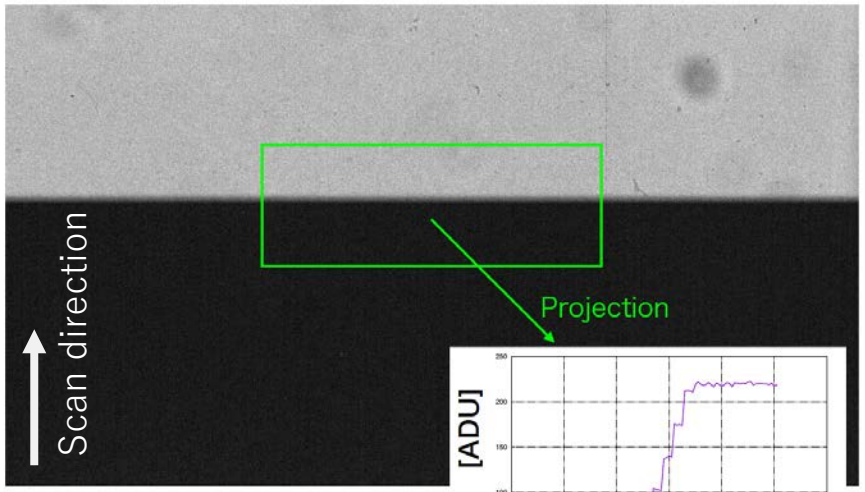
u-blox EVK-M8T

1PPS signals are generated.

LED circuit triggered by 1PPS signals



Correcting lens of Schmidt telescope



← Turning-on time

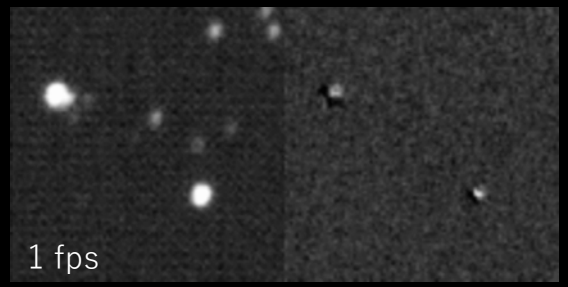
Obtained FITS frame

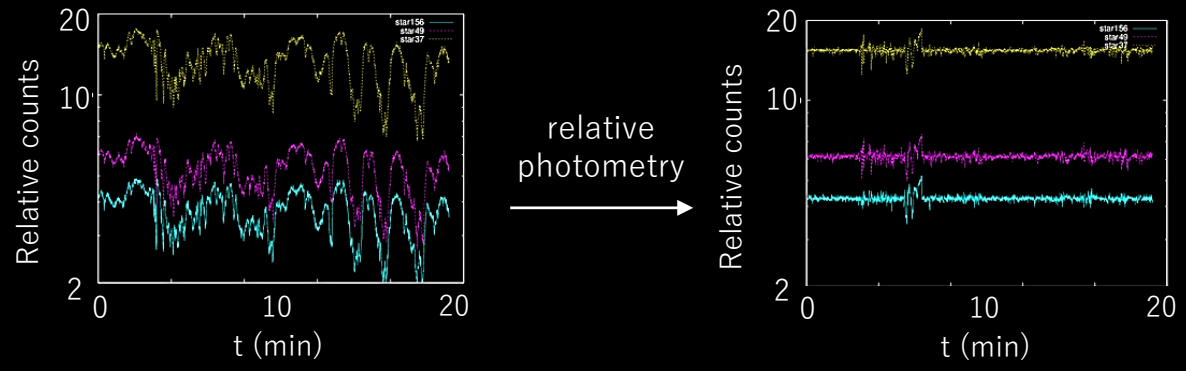
Absolute time accuracy of ±0.2 msec is confirmed.

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

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

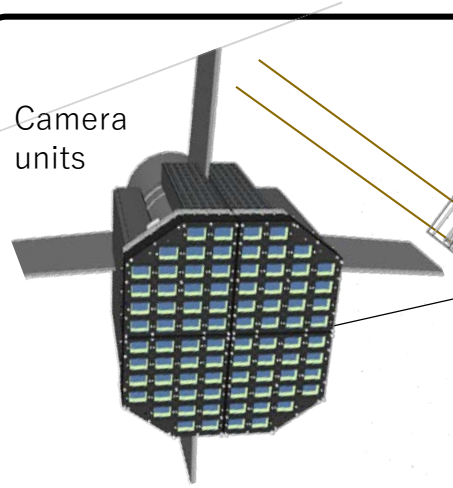
- 1 chip, FoV of 39.7’ x 22.4’
- 5-σ limiting mag: 18.7 mag
- Photometric accuracy: ~10 millimag @ time scale < 5 sec





Computing and data communication system implemented at Kiso observatory

Camera units



Telescope rack

digital I/O +
LVDS – opt convertor

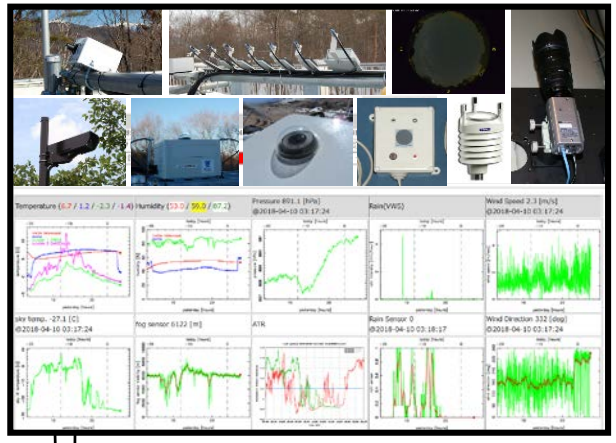
optical fibers of 50-m

Servers

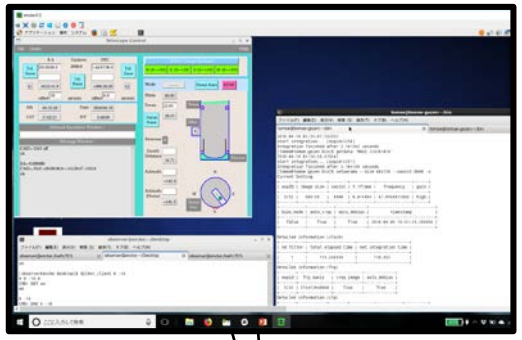
GPS antenna

- Abs. accuracy: ±0.2 msec
- Freq. stability: ~10^{-5}

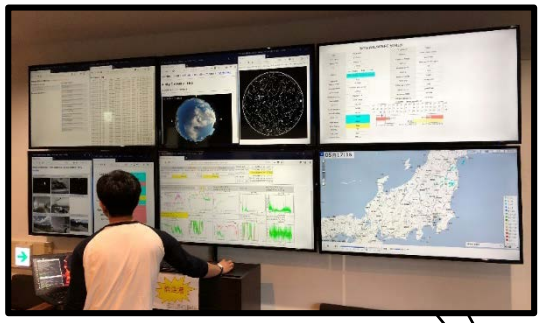
Weather monitoring system



Remote operation system via VPN + VNC



Status visualization system



Telescope dome

2F control room
- Telescope controller

1F server room

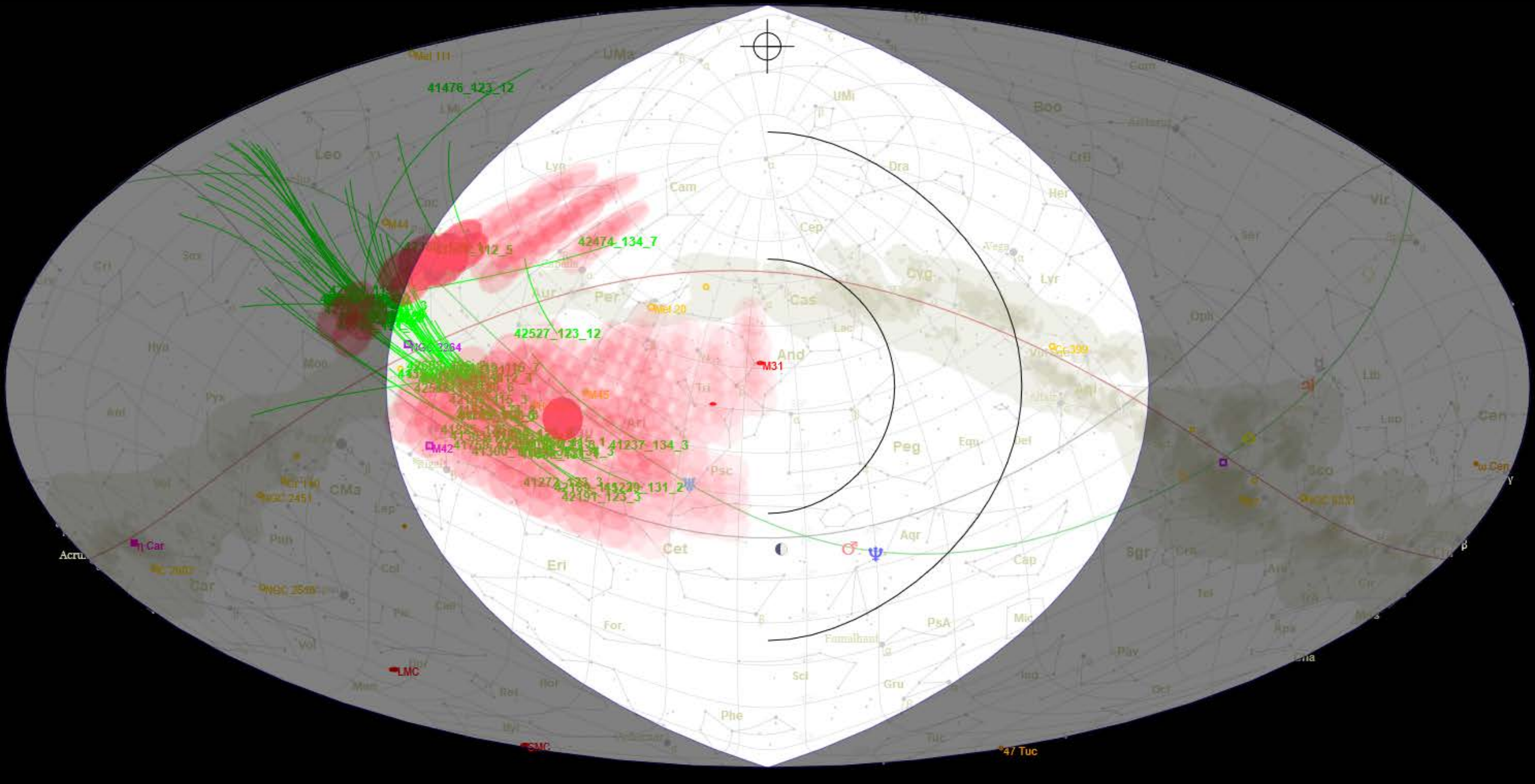
- Camera controllers — **CPU** 72 cores; Memory 640 GB; **HDD** 40 TB
- Buffer servers — **CPU** 24 cores; Memory 256 GB; **HDD** 384 TB
- Analysis servers — **CPU** 90 cores; Memory 1024 GB; **HDD** 96 TB
- Storage servers — **CPU** 12 cores; Memory 128 GB; **HDD** 384 TB

Main building

1 Gbps, FLETs, NTT

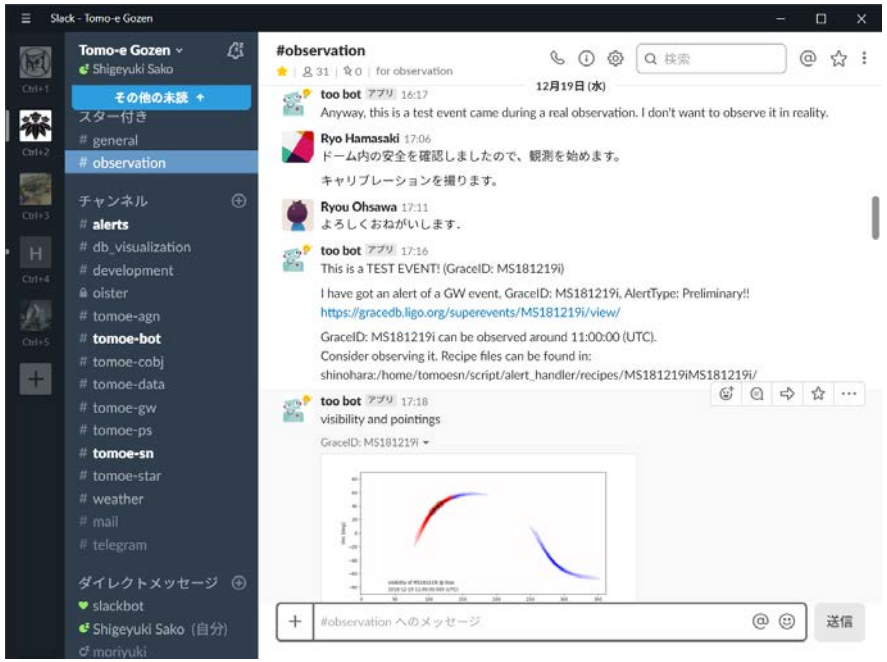
10 Gbps, fiber connection

Tomo-e Gozen Sky Map



• Quick information sharing

https://slack.com



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

Free plan is available, but standard plan:

¥960/user/month → Academic discount of 85% off!!

- Apps (unlimited)
- Searchable messages (unlimited)
- Group video call
- Screen sharing

• Project management

https://app.asana.com

- Status monitoring
- Free plan is available.

I recommend OISTER to use slack and asana-like services.

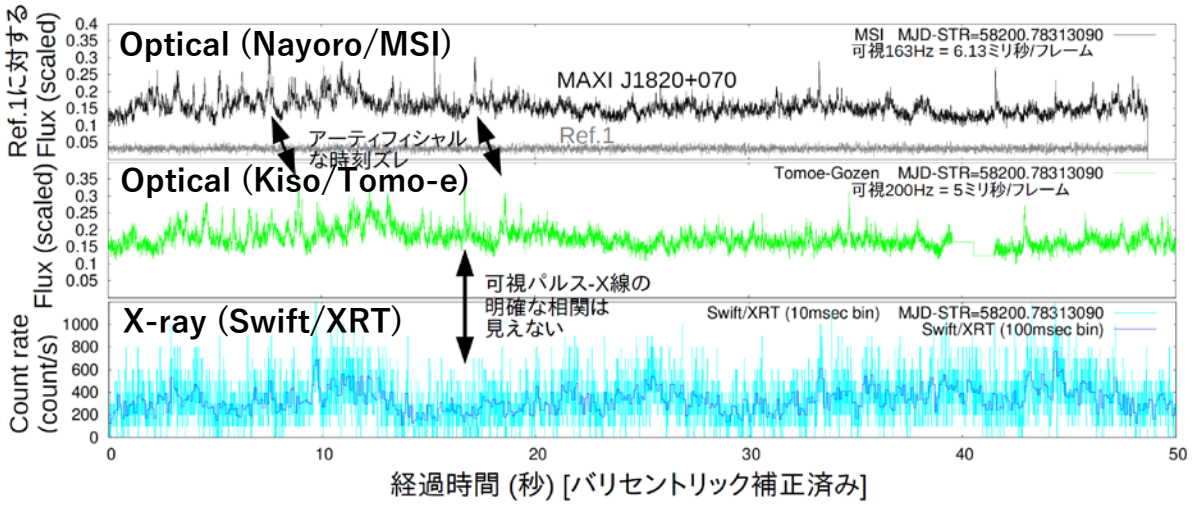
Advantages of high-speed observation

Advantages of movie data

1. Science objects	• Rapid variable objects • Fast-moving objects • Flash phenomena
2. Big-data approach	• Machine learning (random forest, SVM, neural network) • Sparse modeling • Data mining
3. Image processing	• Cosmic ray and spike noise removal • High dynamic range (HDR) processing
4. Statistic and frequency evaluation	• Noise spectrum • Periodic signal processing
5. Atmospheric variation	• Daily variation • Seeing variation

Rapid-variable objects: Binary black hole MAXI J1820+070

Simultaneous observations with Optical and X-ray

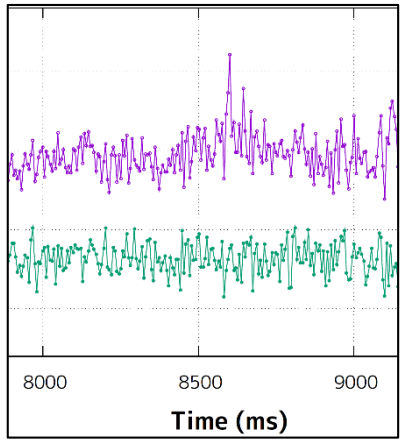


小久保ら 2018
天文学会春季年会

← absolute time accuracy of 0.2msec

← 100msec bin

6.149 msec/frame(150Hz, Kiso/Tomo-e)



Sako et al. 2018,
Astronomical telegram 11426

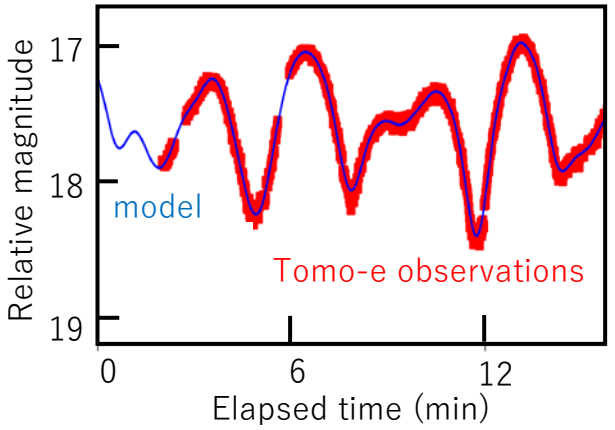
Fast –moving objects: Near earth object (NEO) 2012 TC4

Urakawa et al. 2018, JpGU2018

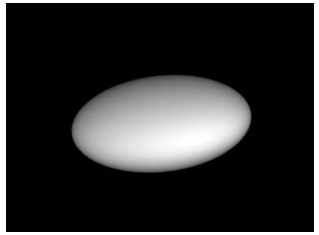
Movie data of 2012 TC4

- Kiso/Tomoe, 1 sensor, 39.7’ x 22.4’
- 2 sec/frame, reproduction speed x200

Light curve and Model fitted curve



Geometrical model



- Primary period is 12.3 min, with a Secondary period ~8.5 min.

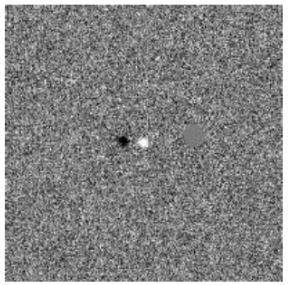
Machine learning

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

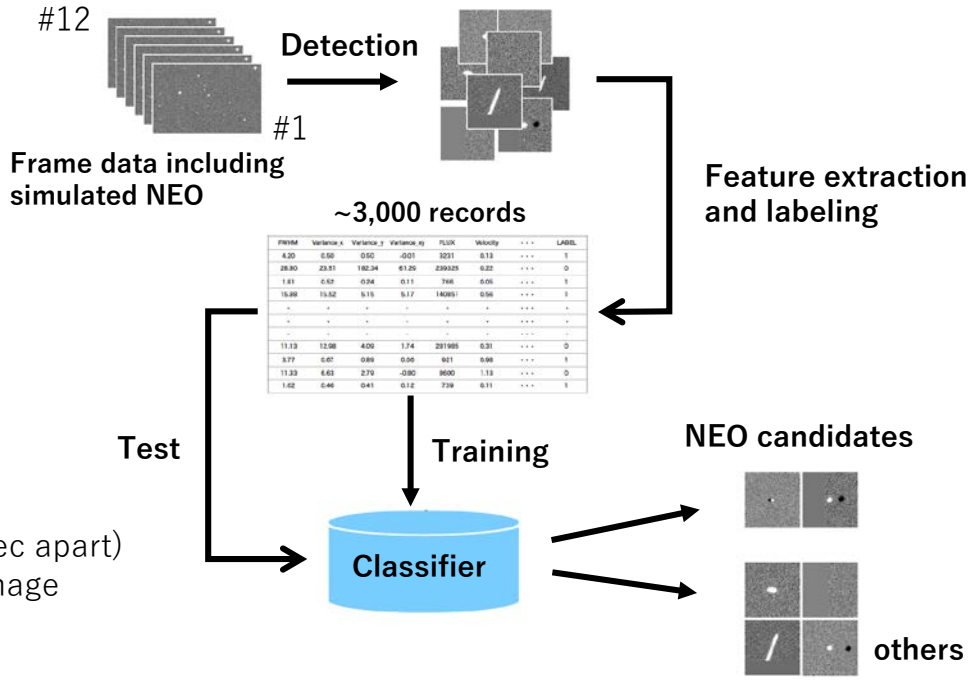
- False positive rate ~ 1%
- True positive rate ~ 99%

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

Kojima et al 2018, 天文学会秋季年会



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

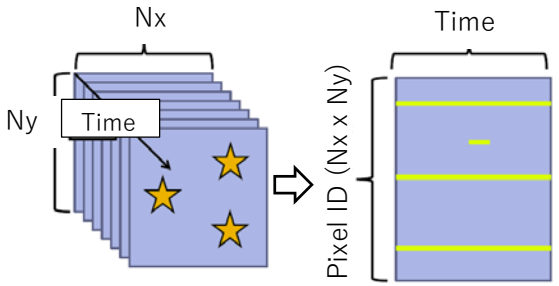


Sparse modeling

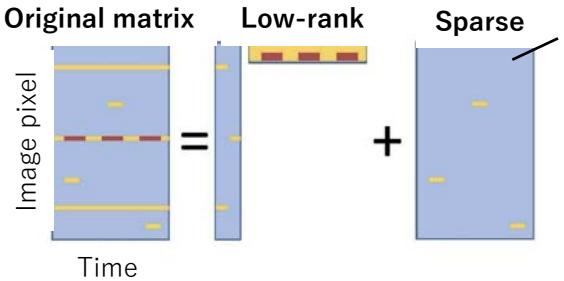
- Expressed movie frames as a matrix.

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

Morii et al 2017, AJ

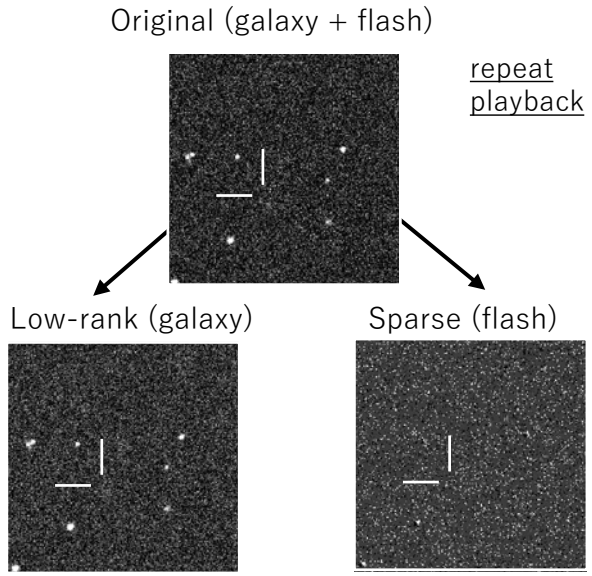


$$X = L + S + G$$
$$\min_{L,S} \|X - L - S\|_F^2 \quad s.t. \quad \mathrm{rank}\,(L) \le r, \quad \mathrm{card}\,(S) \le k.$$



Search for transient events in Sparse matrix.

Compressed to ~10% size



6.45-msec resolution observations of Crab pulsar

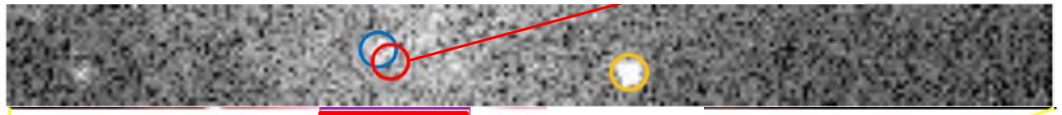
一木ら 2018, 天文学会春季年会

Periodic pulsations of 33.7 msec

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

1 frame image (6.45msec exposure)

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



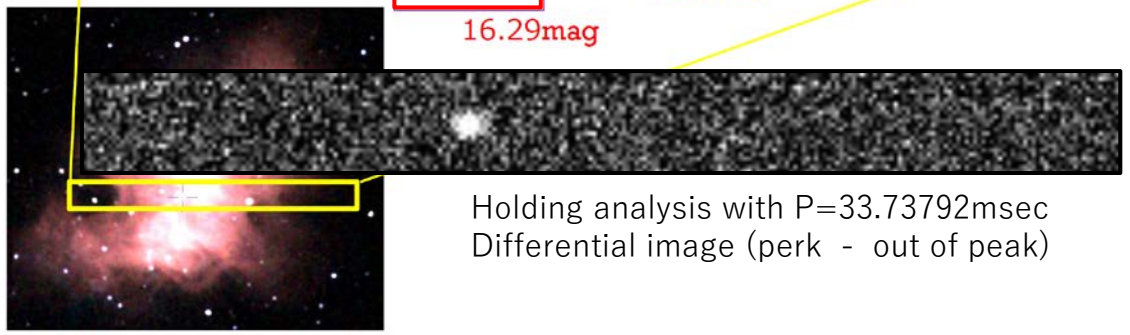
NIR image

Crab pulsar

16.29mag

Ref star

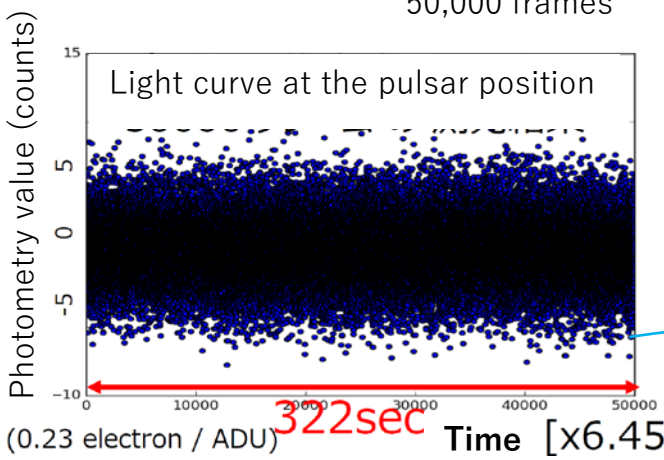
13.79mag

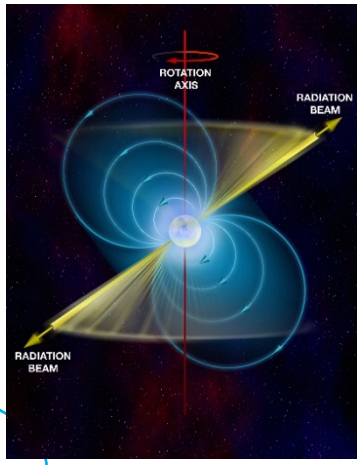


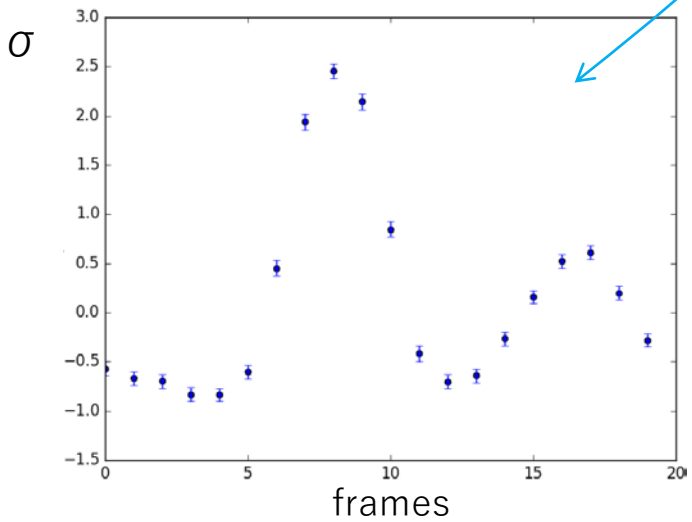
Holding analysis with P=33.73792msec
Differential image (perk - out of peak)

M1 Crab nebula (Supernova remnant)

50,000 frames







Folding analysis
P=33.73792msec

Pulsation clearly detected

- Daily variation 
- Seeing variation → Lucky imaging

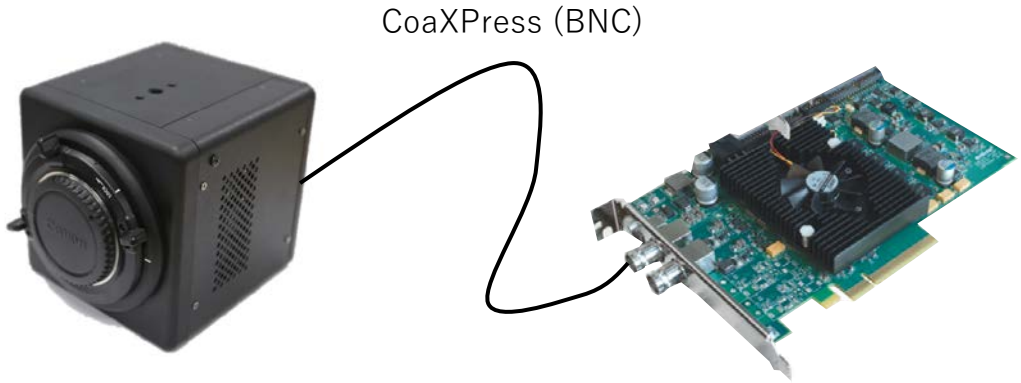
New CMOS camera module

Camera module with the Tomo-e CMOS sensor

- Front side illuminated CMOS with micro-lens array
- 2k x 1k pixels
- Read noise ~2 e-
- Rolling shutter

- max 100 fps (full-frame)
- Consecutive frame read
- 16-bit cube FITS
- GPS time stamp on image file
- CoaXPress interface

- Frame grabber board: Matrox Radient eV-CXP
- Development tool: MIL library



Now developing control software (Linux) with MIL library by IoA/UT team (Doi and Sako et al.).

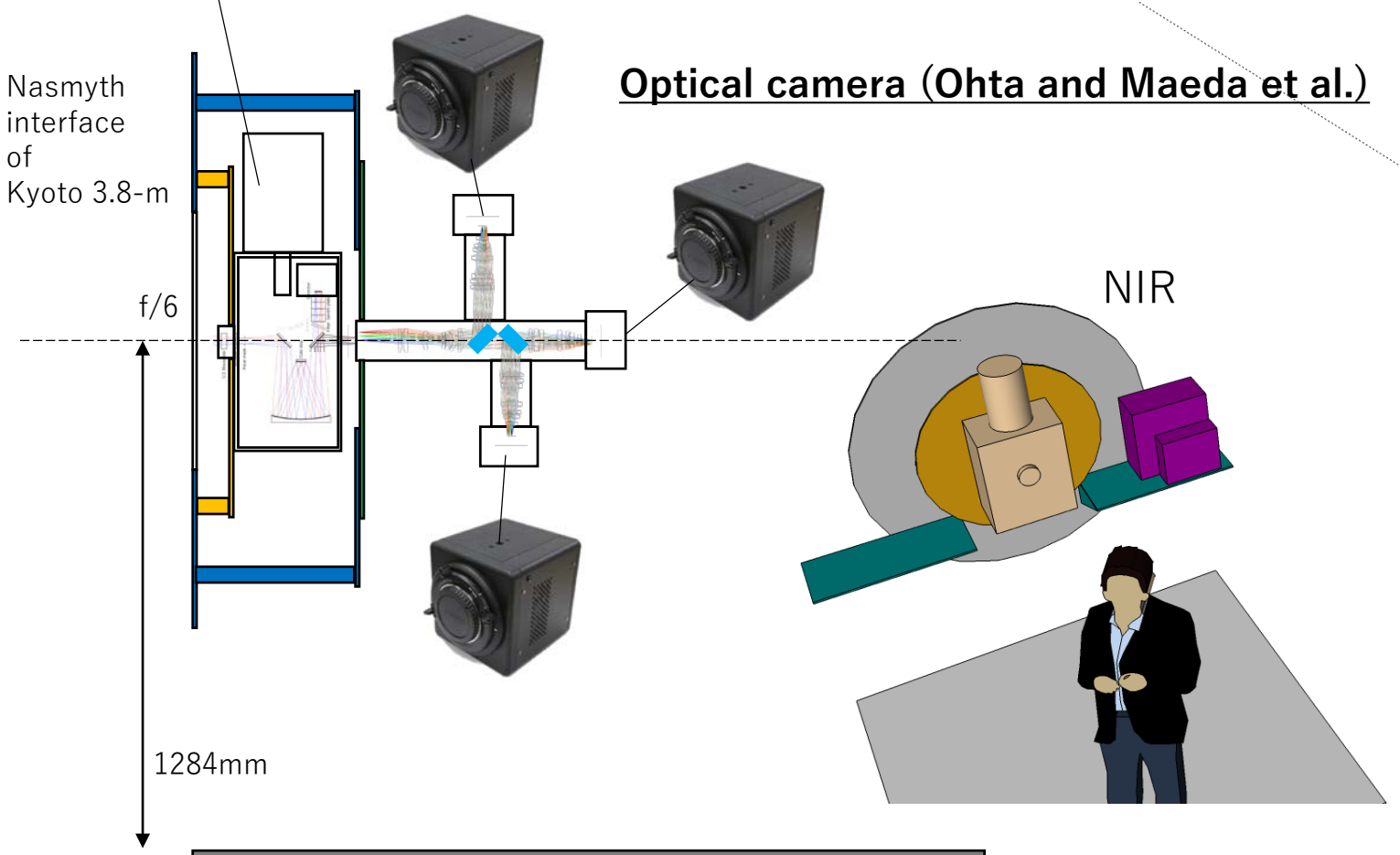
→ **This CMOS system will be available for astronomy community including OISTER in the near future.**

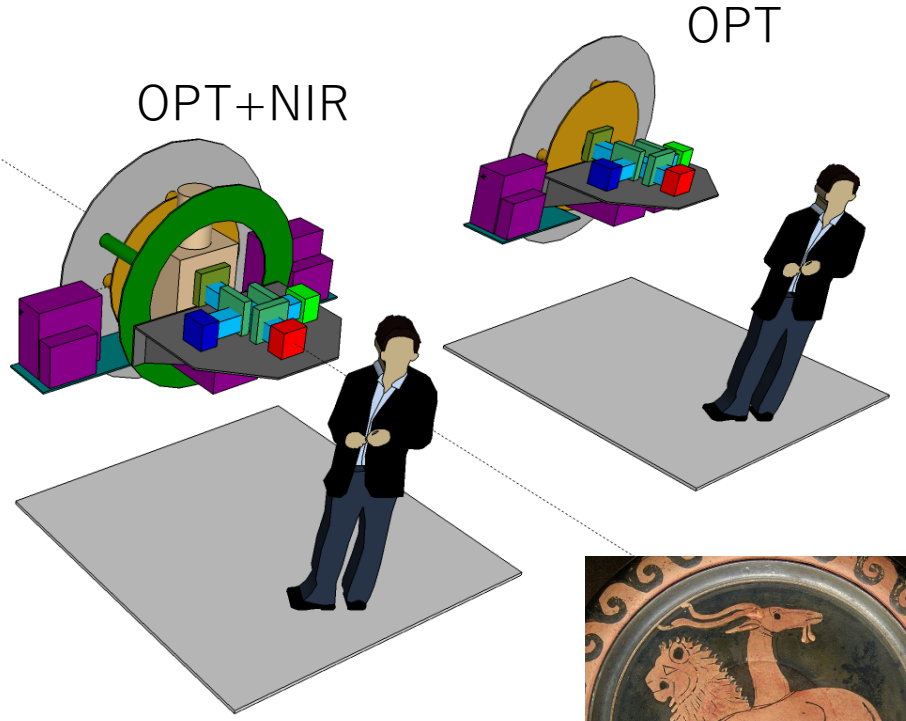
Optical triple-beam CMOS camera for Kyoto 3.8-m telescope

supported by KAKENHI Kiban-S, Supernova (P.I. Doi)

Near infrared camera (Nagata et al.)

Optical camera (Ohta and Maeda et al.)





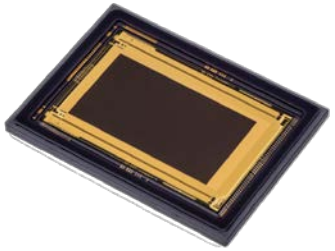
Chimera-like design

image: Wikipedia

Summary

- **1-m Kiso / Tomo-e Gozen**
  - CMOS x 84 chips, 20 deg^2, 2 fps
  - Movie big-data of 30 TB/night (max)
  - Absolute time accuracy of 0.2 msec
  - Collaboration with various research fields via Tomo-e cyber space

- **Performance necessary for high-speed optical observations**
  - High-speed frame read without dead time
  - Low noise, low power
  - Consecutive data acquisition
  - High time accuracy
  - Wide field
  - Large storage, high-speed processing & network, data visualization
  - Quick telescope and communication systems



- **Advantages of high-speed observation**
  - Science objects: rapid variable objects, fast-moving objects, flash phenomena
  - Big-data approach
  - Image processing
  - Statistic and frequency evaluation
  - Daily weather variation

- **Camera module with the Tomo-e CMOS sensor**
  - Control software is being developed
  - Optical triple-beam CMOS camera for Kyoto 3.8-m telescope

APPENDIX