第4回可視赤外線観測装置技術ワークショップ
2014. 12. 3, 国立天文台三鷹すばる棟大セミナー室

東京大学木曽観測所超広視野高速CMOSカメラ Tomo-eの開発

酒向 重行
(Institute of Astronomy, the University of Tokyo)
and
the Tomo-e Gozen project team:
M. Doi, K. Motohara, T. Miyata, N. Kobayashi, T. Morokuma, H. Takahashi, R. Osawa, T. Aoki, T. Soyano, K. Tarusawa, H. Maehara, H. Mito, Y. Nakada, S. Todo, Y. Kikuchi, (IoA, U Tokyo), F. Usui, N. Matsunaga (DoA, U Tokyo), M. Tanaka, J. Watanabe (NAOJ), N. Tominaga (Konan U), Y. Sarugaku, K. Arimatsu (ISAS/JAXA), Y. Ita, H. Onozato, T. Hanaue, H. Iwasaki (Tohoku U), S. Urakawa (Japan Spaceguard Association), H. Kawakita, S. Kondo (Kyoto Sangyo University)

次の時代、

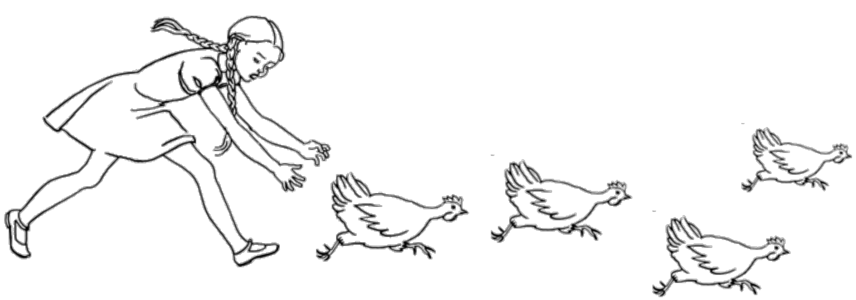
国内、可視光、口径１ｍ、

シーイング４秒角、

で、何ができると言うのか？

間違いなく言えること、

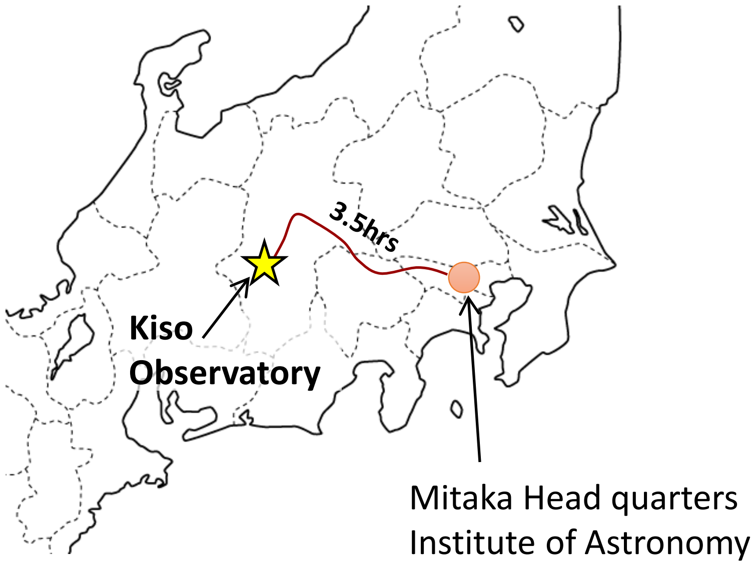
後追いでは、勝てない。



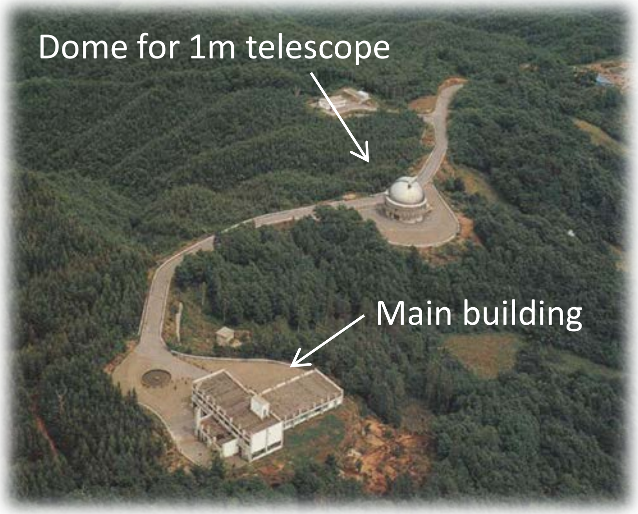
Outline

- ☑ **Overview of Kiso wide-field CMOS camera, Tomo-e**
- ☐ Development of Tomo-e
- ☐ New science capability with Tomo-e

Kiso Observatory



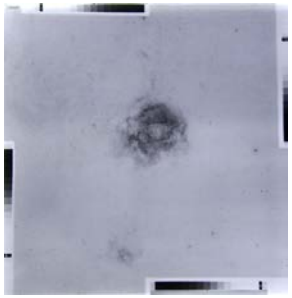
- Established in 1974
- Open use operation
- Dark sky, 1,120m altitude
- Accommodation, Cafeteria



Kiso 105 cm Schmidt Telescope

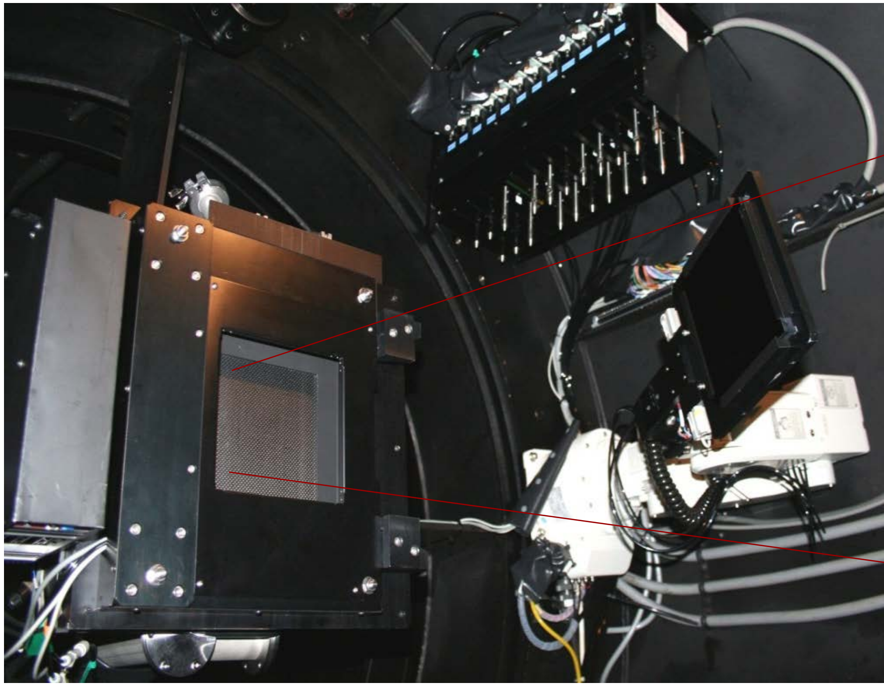
Extremely wide field telescope

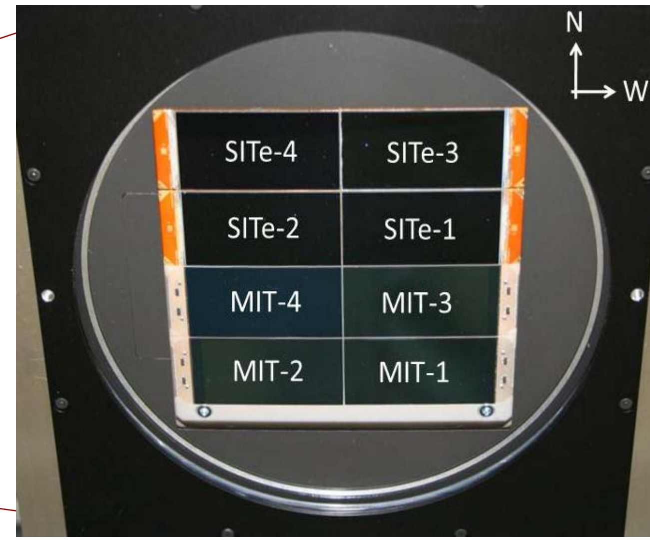
- Field of view : ϕ 9 degrees
- Primary : 150 cm spherical mirror
- Corrector : 105 cm aperture
- Focal ratio : 3.1



Photographic plate
(36 cm x 36 cm)
used until the 1990s

KWFC: Kiso Wide Field Camera

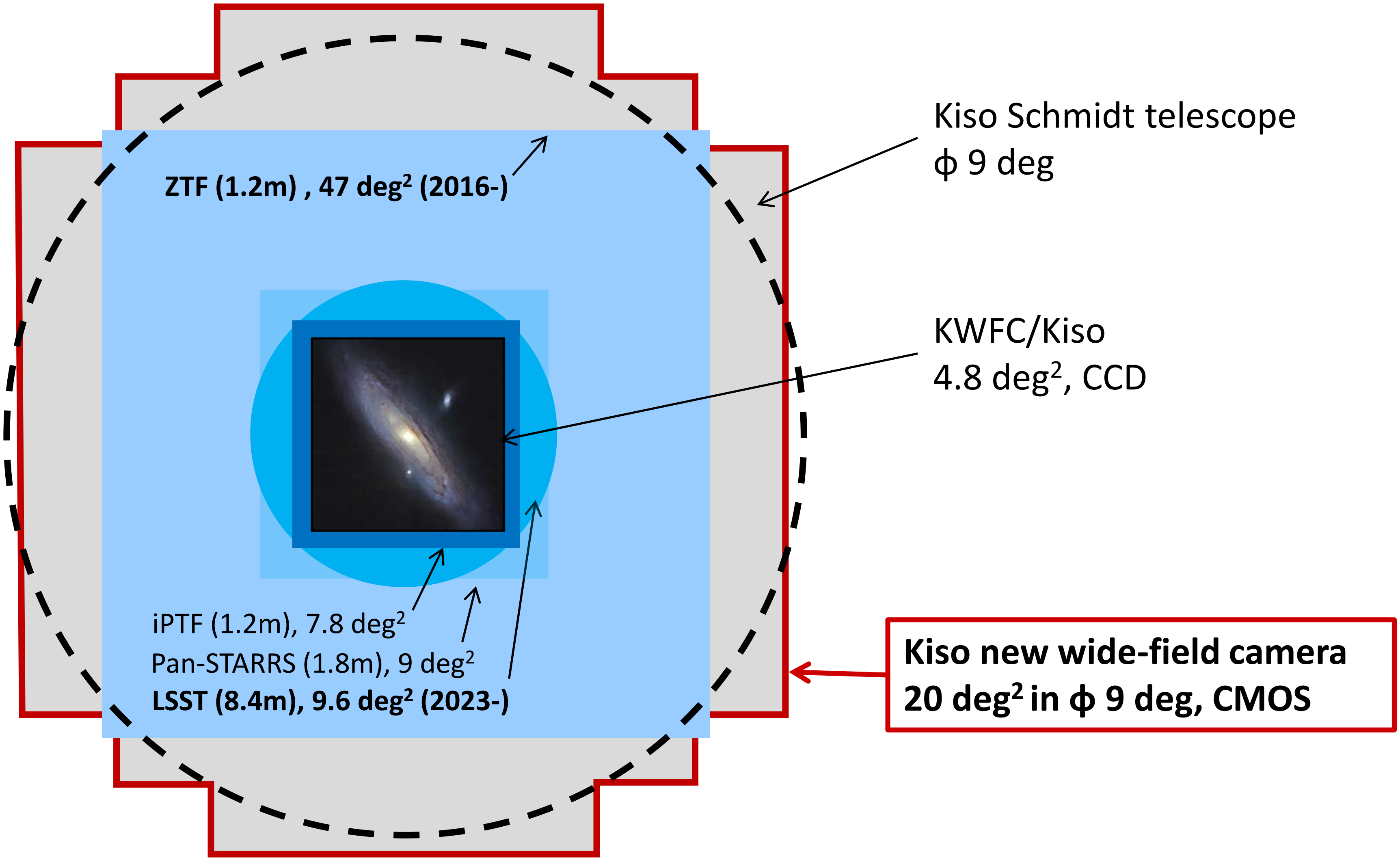




- 8 CCD chips with 8k x 8k pixels
- F.O.V of 4.8 deg^2 (2.2 deg. x 2.2 deg).
- Open use operation started in April 2012
- **Fully automatic observation system using queue lists**

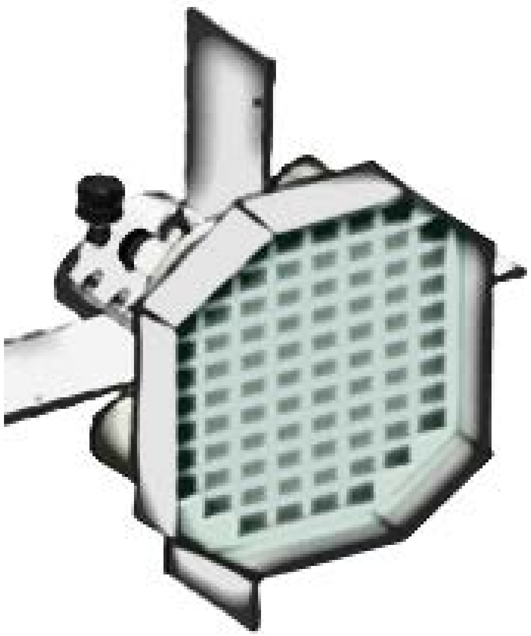
Pixel scale	0.946 arcsec/pix
CCDs	2k x 4k MIT x 4
	2k x 4k SITe x 4
Read noise	5 – 10 e^- (MIT),
	20 e^- (SITe)
Dark current	< 5e^- / hour @-100 deg

Field of View



the Tomo-e Gozen Camera; Tomo-e

- Telescope: Kiso 105 cm Schmidt
- Field of view : 20 deg^2 in ϕ 9 deg
- Sensor: 1k x 2k CMOS sensor†
- Chips: 84
- Pixel scale : 1.2 arcsec/pix
- Frame rate : 2 frames/sec (max)
- Filter : SDSS-g+r, SDSS-g, SDSS-r ‡



† Driven at ordinary temperature and pressure
‡ Manually exchange between filters in the daytime

Extremely Wide-field CMOS Camera

the Tomo-e Gozen Camera

- Telescope: Kiso 105 cm Schmidt
- Field of view : 20 deg^2 in ϕ 9 deg
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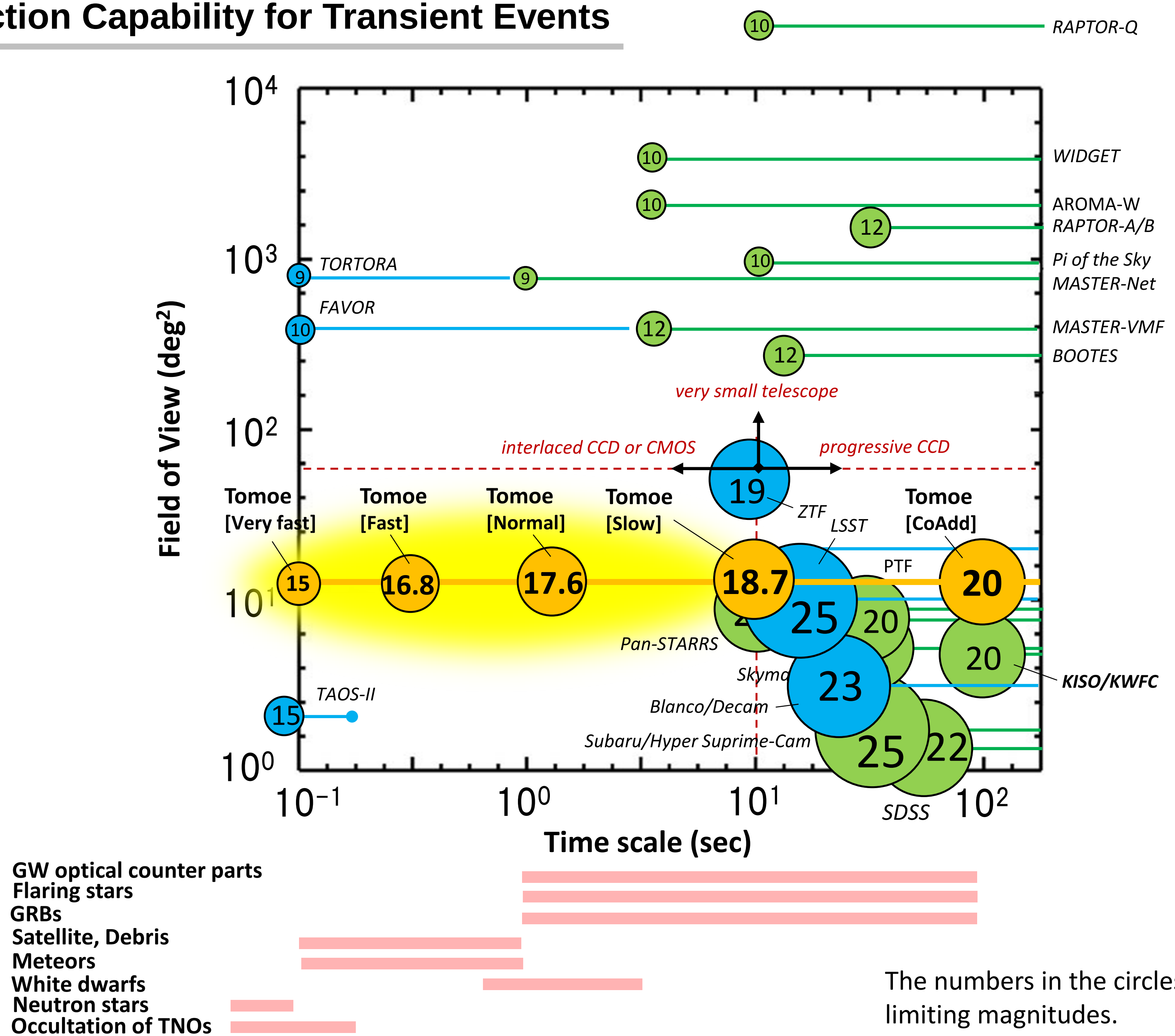
Tomo-e Gozen (Lady Tomo-e, 巴御前)
born in the Kiso region in the 12th century and known with beauty and bravery.

Detection Capability for Transient Events

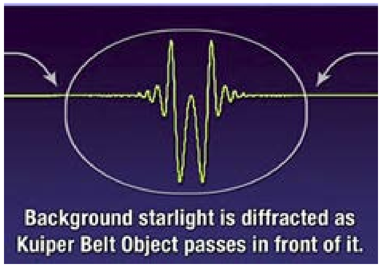


The numbers in the circles indicate limiting magnitudes.

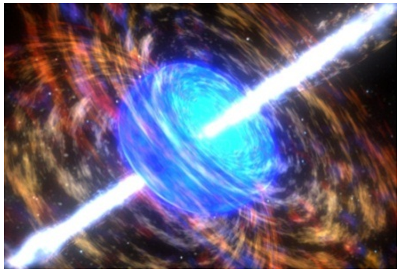
Targets of Tomo-e

Rare and Transient Phenomena

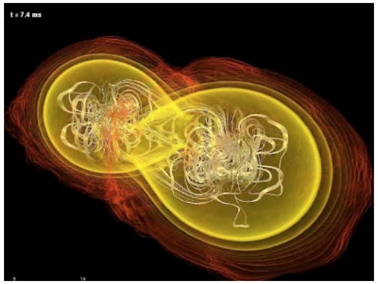
- Shock Breakout of core-collapse SN
- Explosion of Nova
- Optical follow up of Gravitational wave
- Afterglow of Gamma-ray burst
- Optical candidate of fast radio burst
- X-ray time variable objects
- Transit of Exoplanet
- Occultation by Trans-Neptune object
- Potentially Hazardous Asteroid
- Faint meteor



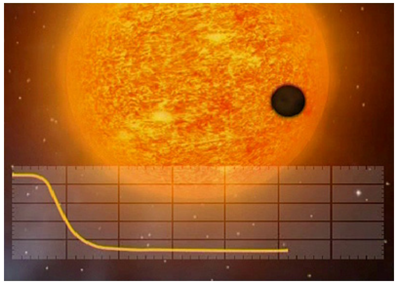
Occultation by TNO



Gamma ray burst



Neutron star marger → GW



Planet transit

Outline

- ☐ Overview of Kiso wide-field CMOS camera, Tomo-e
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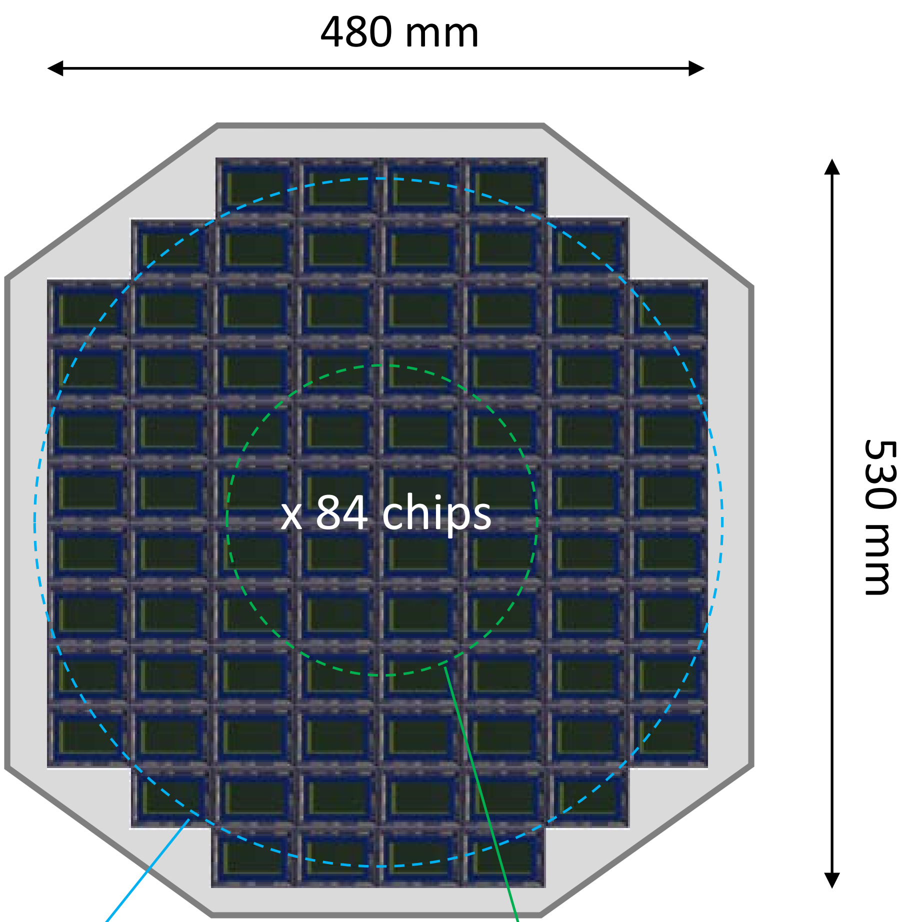
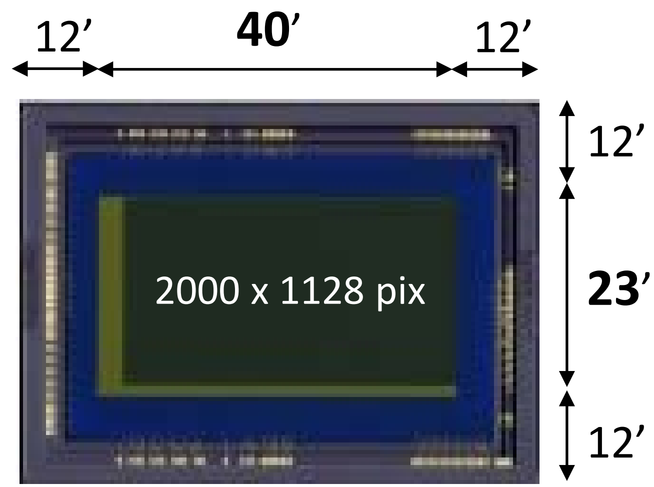
- ☐ New science capability with Tomo-e

Focal Plane



ϕ 9 degree
vignetting 0.44mag

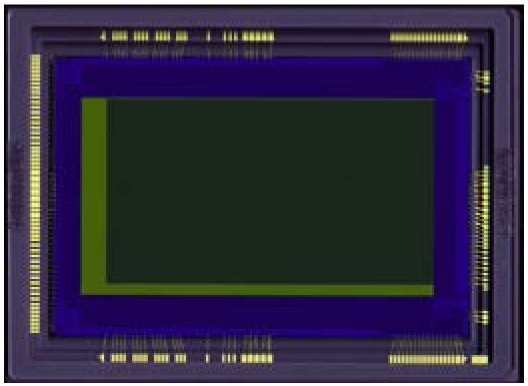
ϕ 4 degree
vignetting free area



35mm Full HD CMOS sensor
sensor / package area = 0.3

- Total sky coverage 20 deg^2
- Total 190 Mpixels
- 760 MB/exposure

CMOS Imaging Sensor



Canon

35 mm full HD CMOS sensor
developed by Canon and U-Tokyo based on products for commercial use.

- Low dark current at Room temperature
- Low readout noise in Fast frame rate

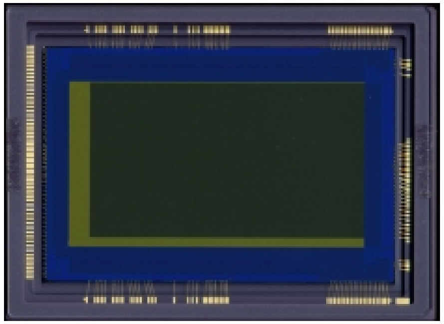
Specification

Pixels	2000 x 1128
Pixel size	19 μm
Architecture	Front side illuminated + micro lens array
Surface protection	Cover glass with AR coating
Output	16 ch differential analog out
Internal amplifier	G = x1, x4, x16, x64, x256
Frame rate	30 fps (max)
Read out mode	Rolling read out
Power dissipation	1.8 W @30 fps
QE (Aη)	0.45 @λ_{peak}=500nm, 0.25 @λ=380, 700nm
Read out noise	2.3 e^- rms @30 fps @G = x16
Dark current	0.05 e^-/pix/sec @273 K
Saturation	55,000 e^-/pix @G = x1
	5,700 e^-/pix @G = x16
Filling factor	Sensor area/Package area = 0.3
Package size	60.9 mm x 44.6 mm

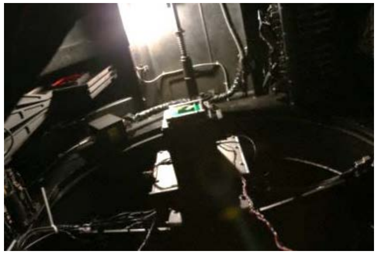
Evaluations of Front-side CMOS Sensor

Laboratory test and Test observations in U-Tokyo (2012-2013)

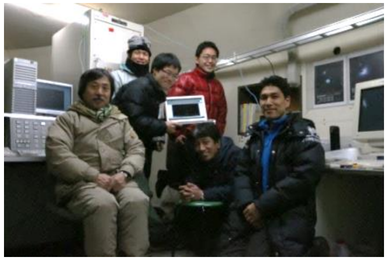
- Readout noise
- Cross talk, Hysteresis
- Linearity, Dynamic range, Flatness
- Photometric accuracy
- Quantum efficiency, Sensitivity
- Aperture ratio, Efficiency of micro lens
- Dark current
- Temperature dependence (20 – 60 degrees)



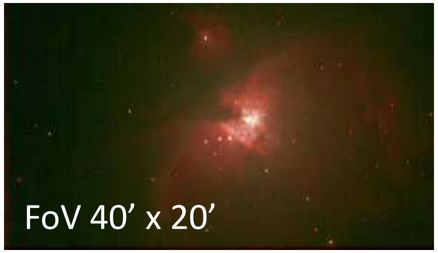
35mm Full HD CMOS sensor



CMOS sensor mounted on Kiso Schmidt telescope



First light observations 2012/12/16-17



High dynamic range image
M42 Orion star-forming region
1/30 sec x1,000 frame x 2 bands

Long integration time image
NGC891 nearby edge-on galaxy
2 sec x100 frame x 5 dithers, V band

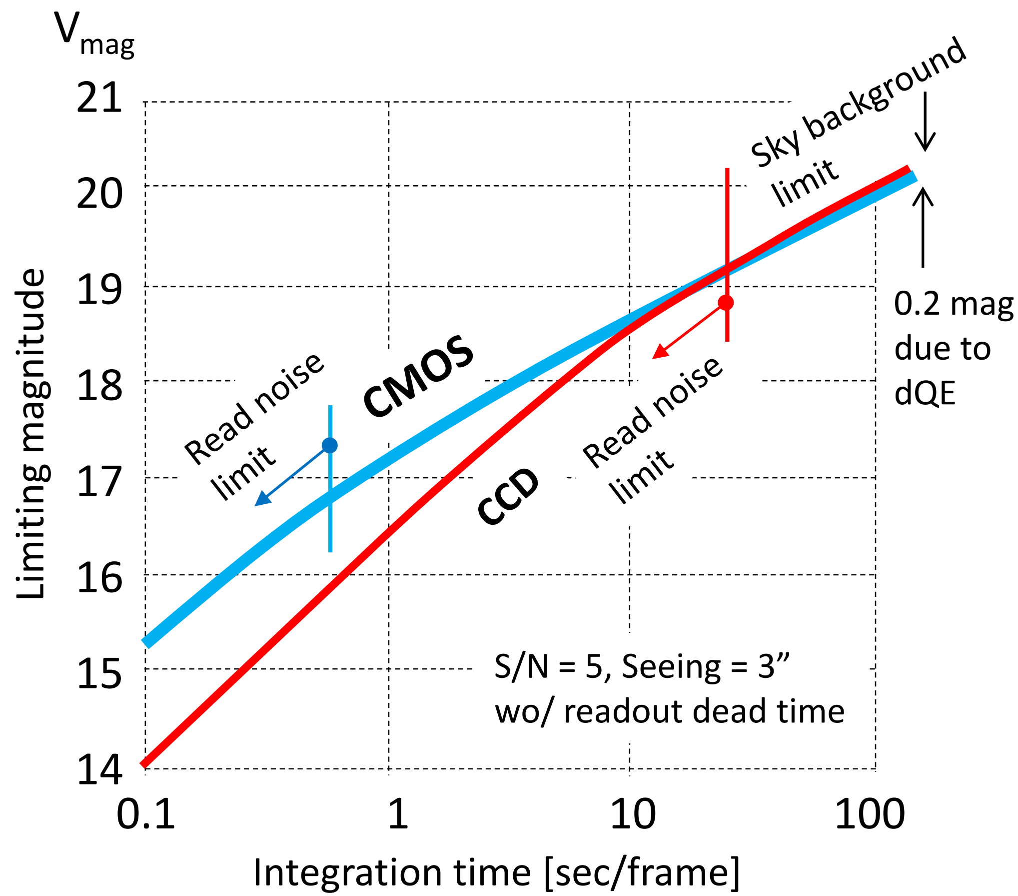
Limiting Magnitude of Tomo-e

Background photons:	13	$e^-/s/pix$
Readout noise:	2.5	e^-
Dark current at 273 K:	0.05	$e^-/s/pix$

w/ broad band on Kiso Schmidt in dark sky (20 mag/arcsec^2)

Limiting magnitude of Tomo-e

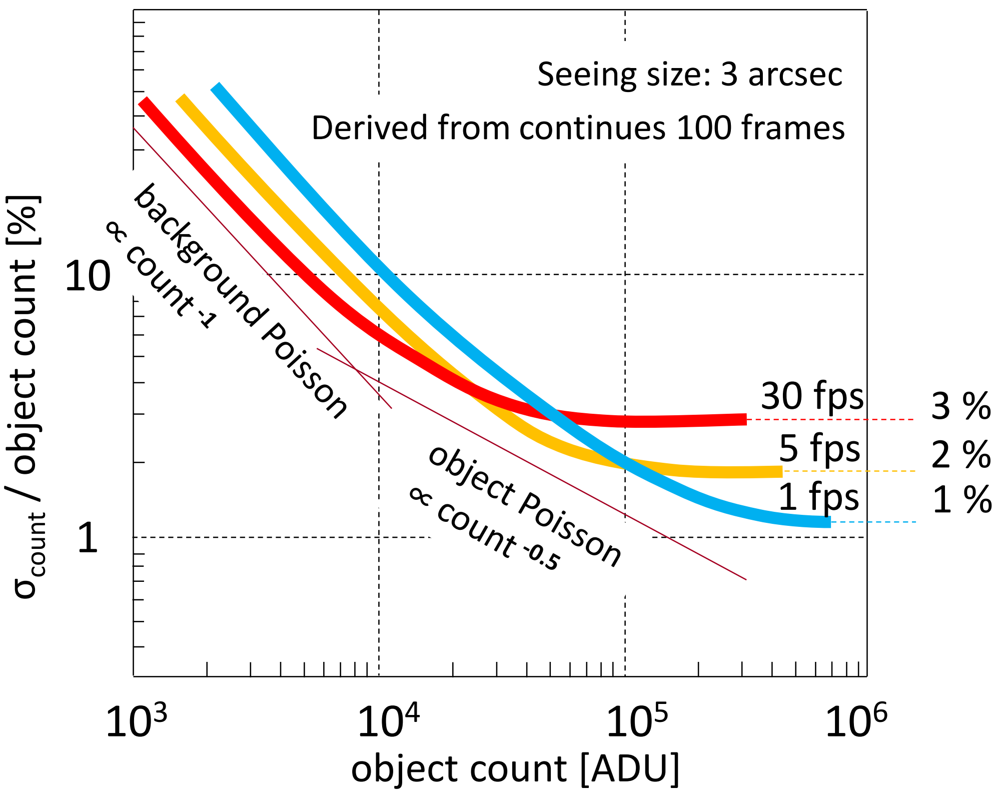
Integration time (sec)	V_{mag}
1/10	15.3
1	17.2
10	18.7
100	19.9

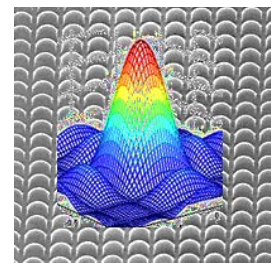


- Higher sensitivity than CCD in t_{integ} < 10 sec.
- Higher exposure efficiency expected in continues observations because of zero readout time.

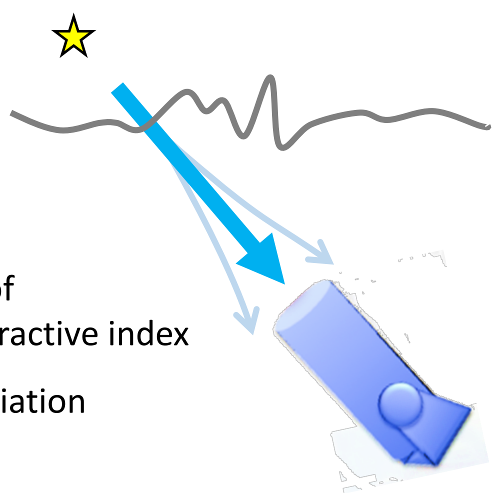
Photometric Accuracy

Measured photometric error





- PSF on microlens array
- 1.2 arcsec/pix
- Sufficient over-sampling



Time variation of atmospheric refractive index

→ Flux time-variation

- Photometric degradation originated from microlens array not confirmed.
- Photometric accuracy depends on a frame rate.

Cross talk and Hysteresis

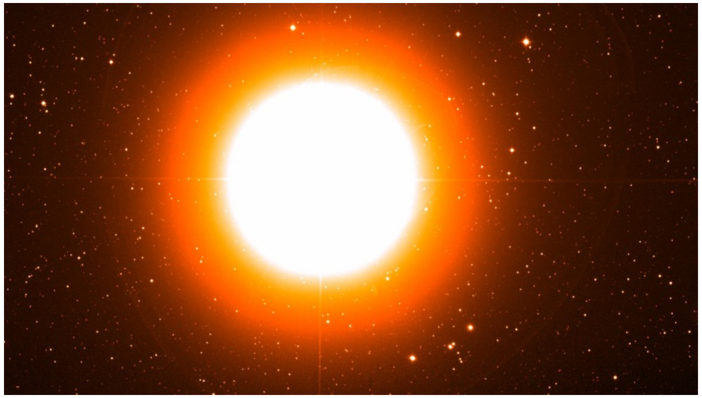


Image of α Aur (V_{mag} = 0.08)

- Cross talk in the same frame

  - Between separated pixels: < $\mathbf{10^{-8}}$

  - Between neighbor pixels: *not measured*

- Hysteresis between frames

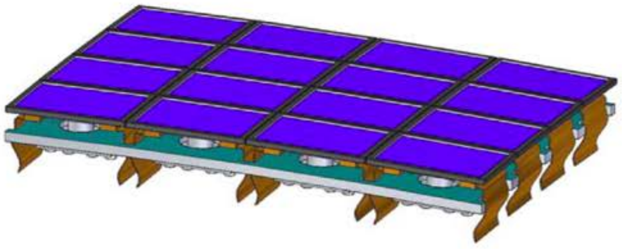
  - A few second time scale: < $\mathbf{10^{-6}}$

  - Sub-second time scale: *not measured*

Good performance on cross talk and hysteresis confirmed

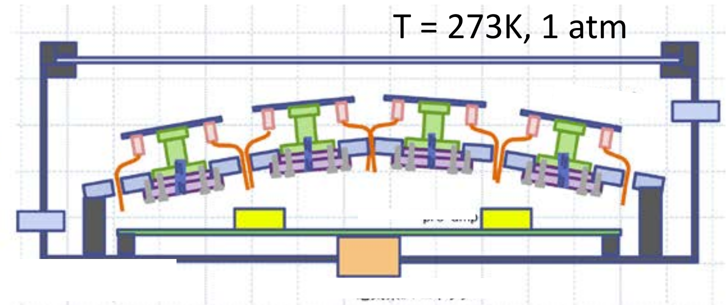
Conceptual Design of Camera System

✓ Mosaic mount of CMOS sensors



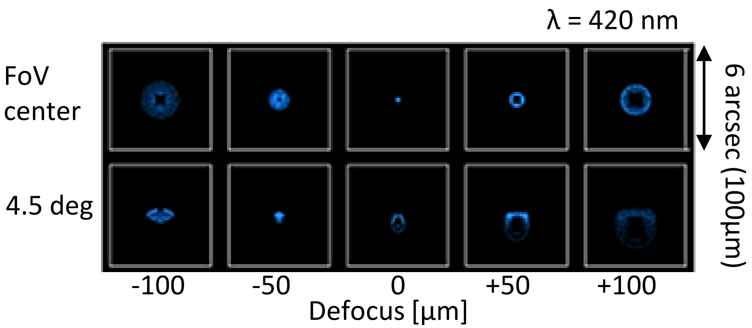
On a spherical surface of R = 3,300 mm

✓ Thermal and structural design



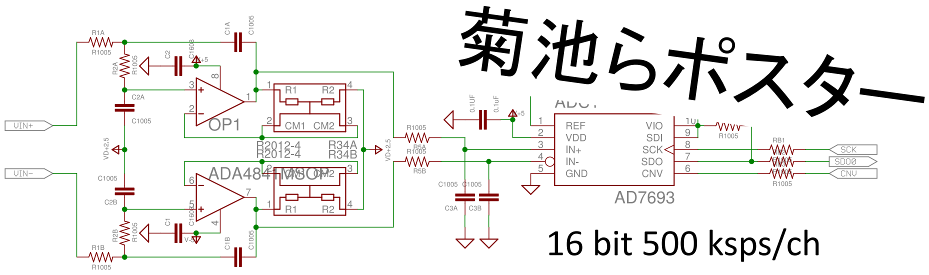
Ordinal pressure and Room temperature inside the chassis

✓ Optical alignment accuracy



Alignment accuracy of ± 100 μm required

✓ Video readout circuit



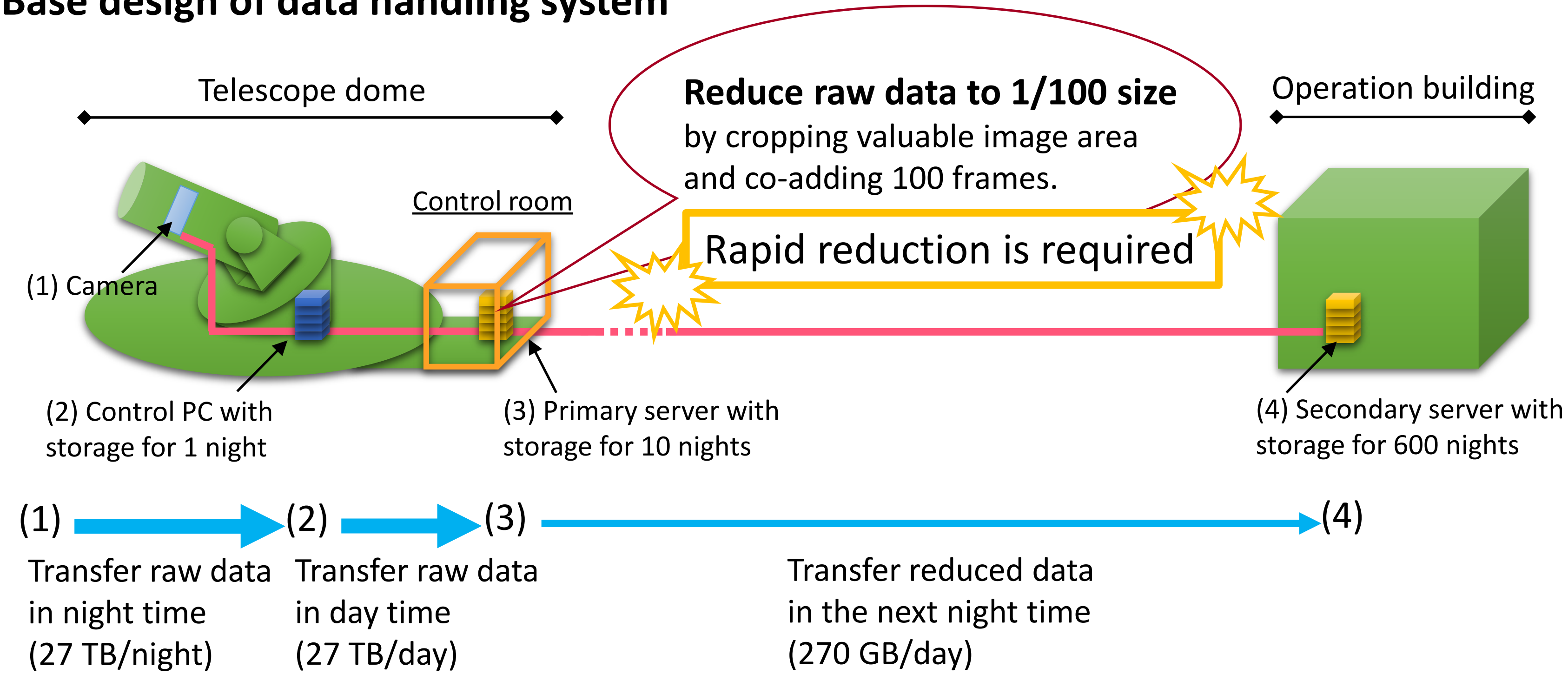
- Differential amplifiers and A/D convertors
- Total power dissipation is 30 W.

Data Handling and Storage

Large amount of data (760 MB/sec, 27 TB/night) is produced in 2 fps observation.

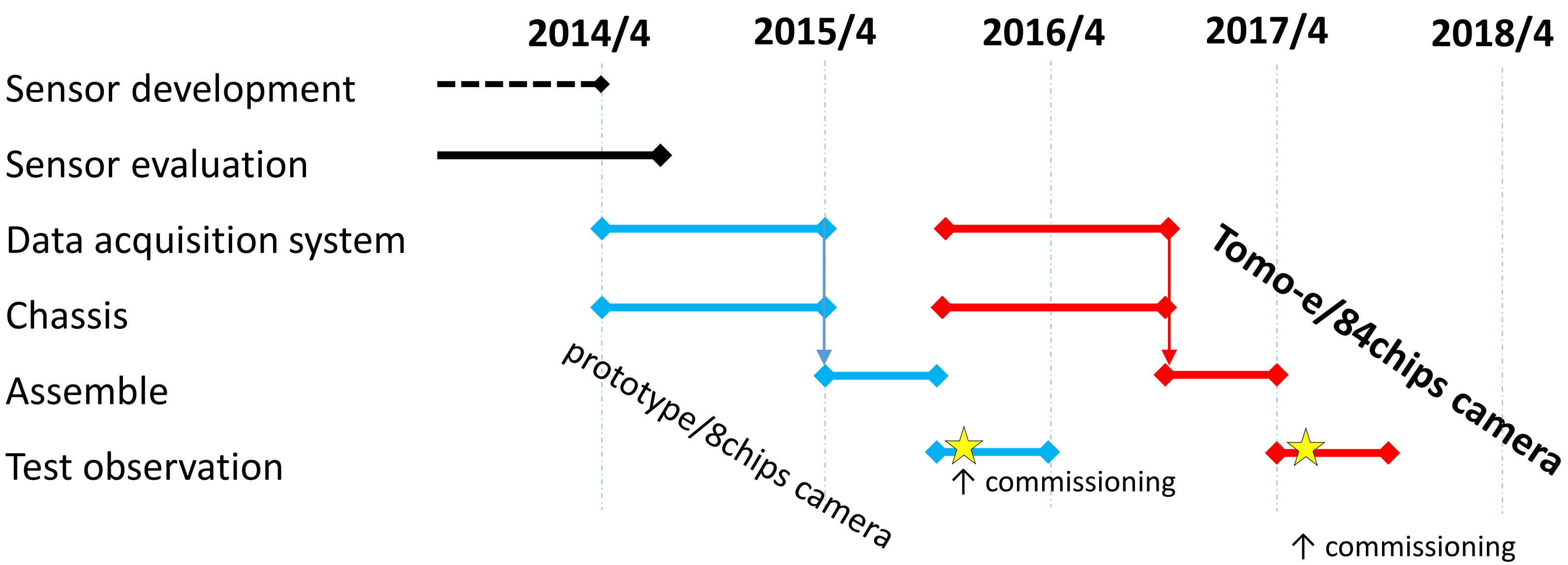
→ Drastic reduction of raw data is required to record in storage.

✓ **Base design of data handling system**



Time Table for Development of Tomo-e

Tomo-e will be commissioning in 2017



Outline

- ☐ Overview of Kiso wide-field CMOS camera, Tomo-e
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- ☑ **New science capability with Tomo-e**

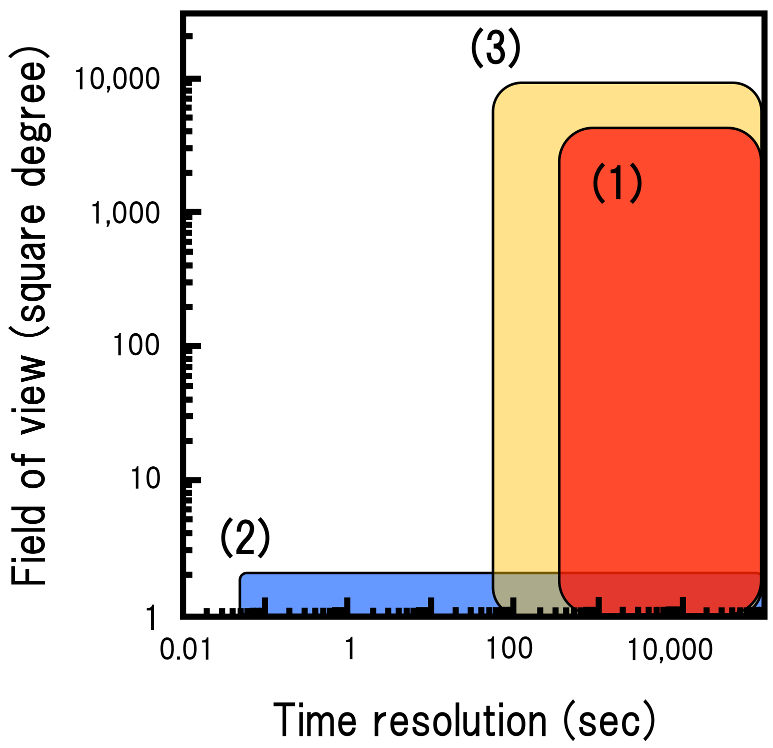
Observation Strategy of Tomo-e

(1) 1-hour-cadence all-sky monitoring
(high-cadence + very-wide-field)

(2) 20-fps wide-field monitoring
(very-high-cadence + wide-field)

(3) Synergy with high-energy astronomy
(very-wide-field + quick follow-up)

(4) Near and interior Earth objects
(wide-field monitoring for fast moving objects)

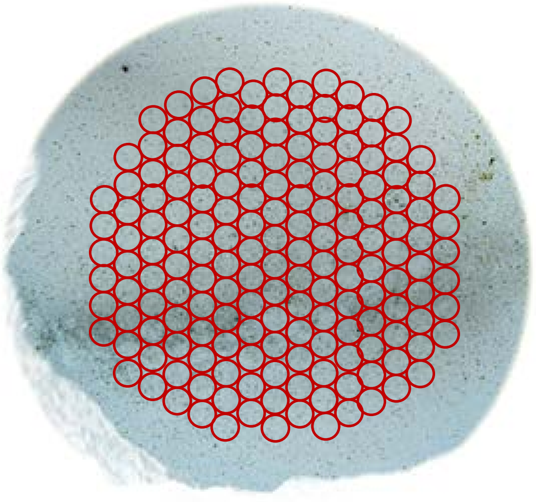


☑ 1-hour-cadence All-sky Monitoring

Observation plan

- All sky (10,000 deg^2), 1 hour cadence
- Recording period: 3 years
- Observation sequence:
  - 4 dithers x 170 pointing
  - short exposure (3 sec) → readout (0 sec) → dithering (2 sec)
- Limiting magnitude: V_{mag} ~ 18 (1 hour cadence)

  V_{mag} ~ 19 (1 day cadence)



ϕ 9 deg x 170 pointing,
1 hour cadence, 18 mag

Expected results

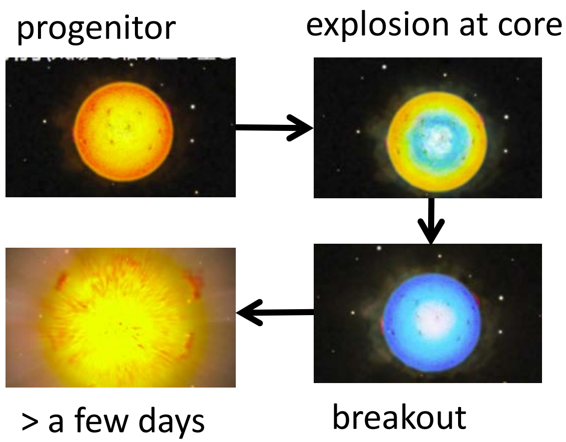
Bright, but **Rare** and **Fast time-variable** events

- Supernovae, Neutron star mergers, AGNs, Gravity lensing
- Novae, Stellar flares, Eclipsing binaries, Late type star, Exosolar planets
- Bursts of comets and asteroids
- Unknown transient phenomena

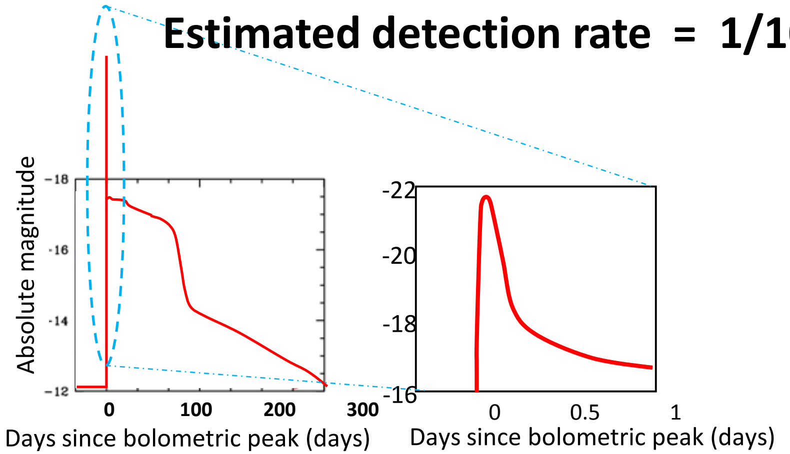
High-cadence All-sky SNe survey

the Tomoe Gozen
Kiso Observatory
東京大学
THE UNIVERSITY OF TOKYO

- Early phase light curve to constrain SN Ia progenitor
- Shock breakout of core-collapse supernovae



Estimated detection rate = 1/100 SNe



- Tomo-e has 5 times higher capability than KWFC/Kiss SN survey (P.I. T. Morokuma) to detect SN shock breakouts.
- Spectroscopic data of All objects discovered by this survey can be obtained by 1 – 2 m class telescopes.

Expected detection rates of Novae and SNe

N. Tominaga+ 2014/10

- **1 hour cadence, all-sky, 18 mag**

Event	Detection rate (events/year)	
Early phase of Nova	2	including M31
Shock breakout of C-C SN	5	

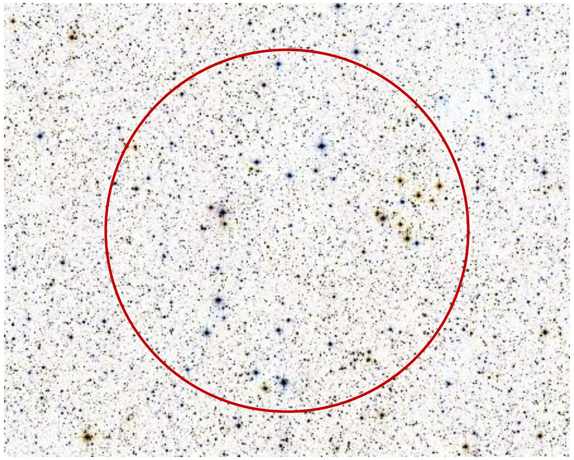
- **1 day cadence, all-sky, 19 mag**

Event	Detection rate (events/year)	
Discovery of Nova	10	including M31
Early phase of Ia SN	1,600	M_V ~ -18 mag, 260 Mpc
Early phase of C-C SN	300	M_V ~ -16 mag, 100 Mpc
Superluminous SN	30	M_V ~ -21 mag, 1,000 Mpc
SN in Near-by Galaxy	0.5	M_V ~ -11 mag, 10 Mpc
Discovery of Faint SN	unknown	

☑ 20-fps Wide-field Monitoring

Observation plan

- 2 deg^2 (partially readout) in ϕ 9 deg
- 20 frame/sec
- Continuous monitoring of 10,000 stars
- Recording period: 1 year
- Limiting magnitude: V_{mag} ~ 14



2 deg^2 in ϕ 9 deg,
20-fps, 10,000 stars

Expected results

Very bright, but **Rare** and **Very Fast time-variable** events

- Stellar occultations by Solar system objects
  - Duration time: a few 100 msec,   Rate: a few dozen events/year
- Optical counterparts of Fast Radio Bursts
  - Duration time: ~10 msec, Rate: 0.5 events/day (when brightest case)
- X-ray variable objects: AGNs, YSOs, stellar flares

by Totani-san (private communication). Note, this flux estimation contains an inaccuracy of 7 orders.

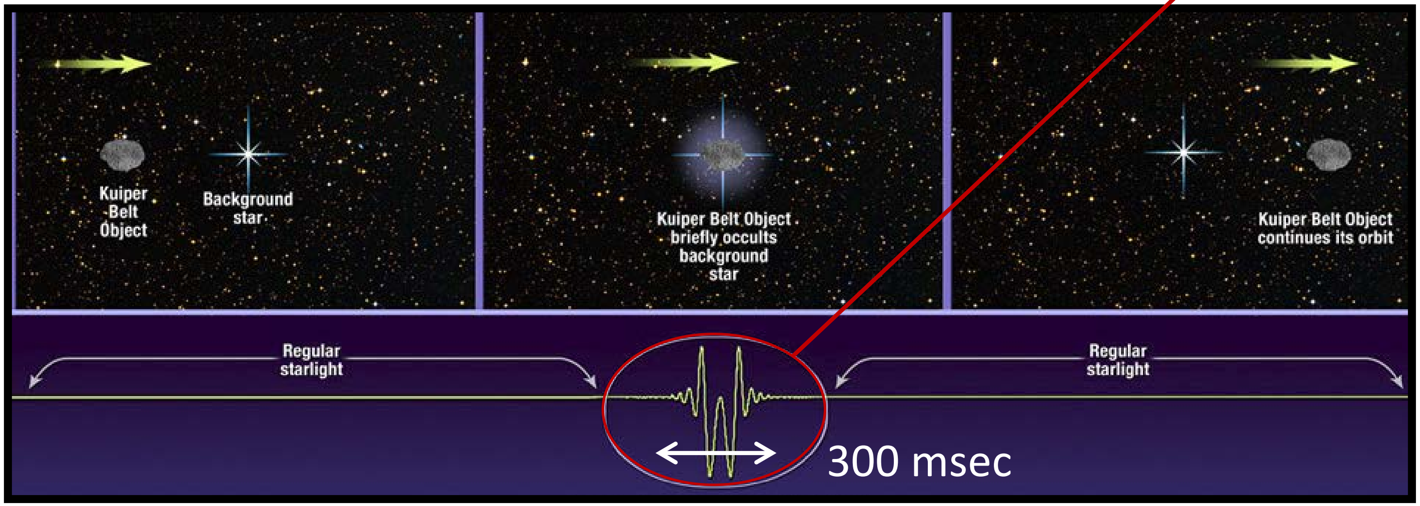
Stellar occultations by TNOs

- TNOs (Trans Neptune Objects) keep composition in pre-solar age.
- Bodies with km-size are important.
- It is too small to detect them even with large telescopes.

→ **Stellar occultations**

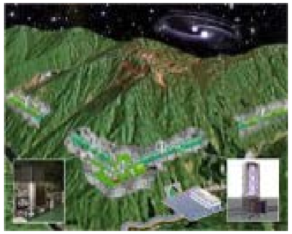
→ **Fast (20 fps) wide-field monitoring by Tomo-e**
A few events/year

Size and distance of TNOs

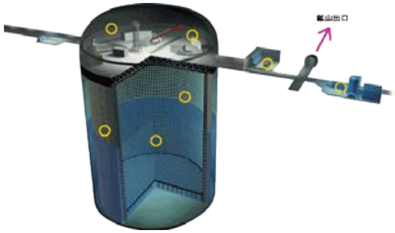


http://hubblesite.org/newscenter/archive/releases/2009/33/image/c/format/web_print/

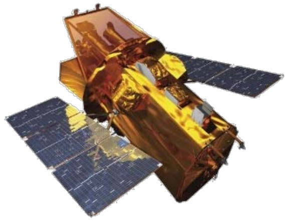
☑ Synergy with High-energy Astronomy



Gravitational wave detector
KAGRA



Neutrino detector
Super-Kamiokannde



Gamma-ray telescope
SWIFT, Fermi, MAXI

N-N merger?
N-B merger?
Core collapse SN?
Magnetar?

Nearby Supernova

Gamma-ray burst

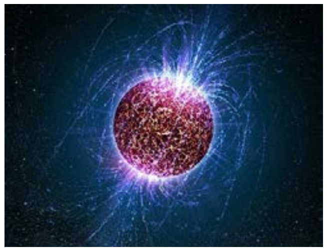
External trigger

w/ error of arrival direction: a few degrees

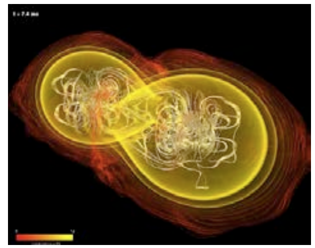
Optical wide-field follow-up by Tomo-e

Gravitational Wave Counterpart

Collapsar, Long GRB
NS/BH formation
< 10 Mpc for GW

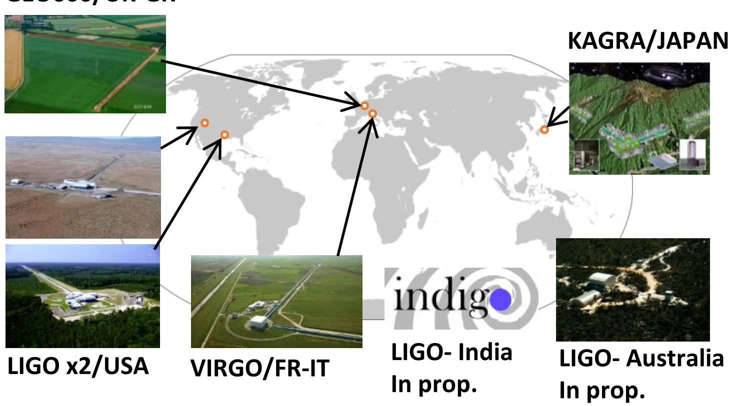


Magnetar Flare, Short GRB
NS oscillation
< 10kpc for GW

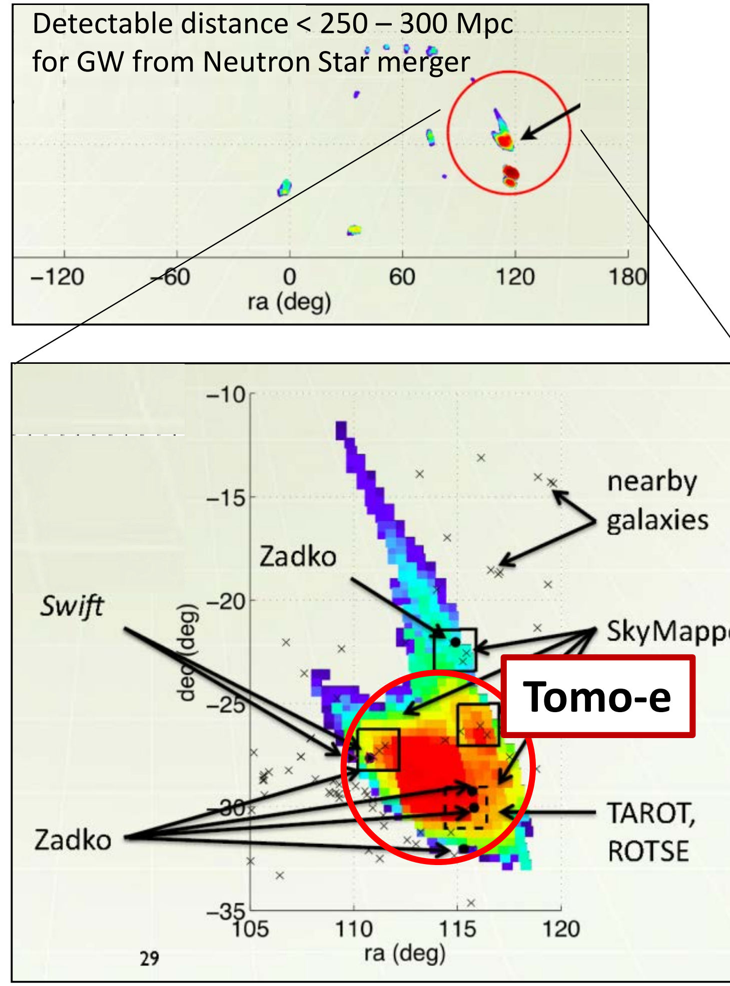


Neutron Star Merger, Short GRB?
NS-NS/NS-BH
< 200 Mpc for GW

KI 01, Kashiyama & KI 11



- ✓ Error circle of arrival direction of GW **~ϕ 5 deg**
- ✓ Tomo-e can follow-up GW events with **ϕ 9 deg**



Estimation of arrival direction of gravitational wave.
Hayama (NAOJ) 2012

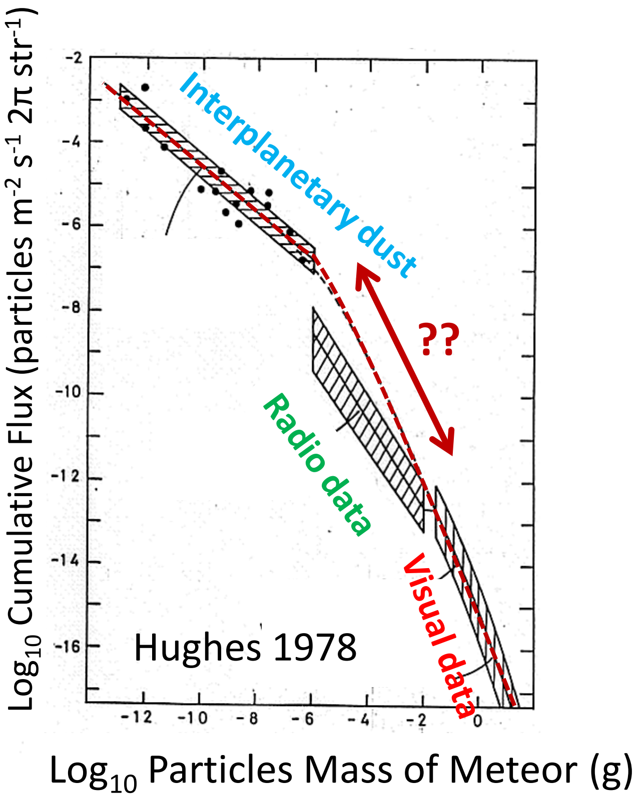
☑ Near and Interior Earth Objects

Observation plan

- Phenomena in background
- During other surveys

Expected results

- Faint meteor (sporadic and meteor shower)
  - Rate: a few dozen events/min
  - Brightness distribution of meteors.
  - Is the power law extended to faint meteors?



- Fast moving NEOs including PHA (Potentially Hazardous Asteroid)
  - Moving speed: 10-100 arcmin/sec
  - Such fast moving asteroids are not detected by CCDs with an ordinal FoV and exposure time.

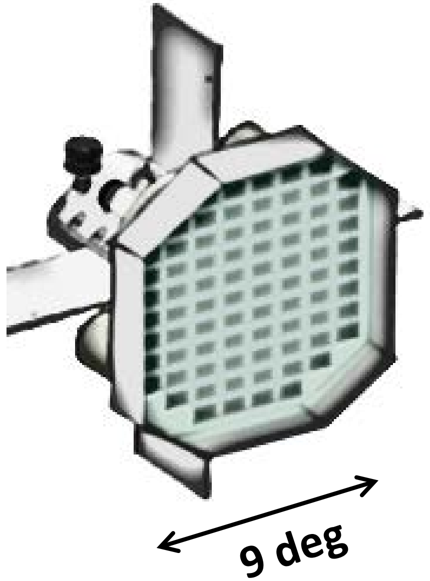
Summary

the Tomoe Gozen Kiso Observatory

東京大学 THE UNIVERSITY OF TOKYO

Kiso Wide-field CMOS camera : Tomo-e

- ☐ Telescope: Kiso 105 cm Schmidt
- ☐ Field of view : 20 deg^2 in ϕ 9 deg
- ☐ Sensor: 84 CMOS chips
- ☐ Frame rate : 2 frames/sec (max)
- ☐ Commissioning : 2017
- ☐ Outstanding issue: Data handling and storage



Scientific strategies

- ☐ 1-hour-cadence all-sky monitoring
- ☐ 20-fps wide-field monitoring
- ☐ Synergy with high-energy astronomy
- ☐ Near and interior Earth objects

⇦

Rare and Transient Phenomena

Sub-second Time-domain