The Tomo-e Gozen Camera
- The first wide-field CMOS imager -

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and Tomo-e Gozen team

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TOMO·E GOZEN

105-cm wide-field telescope

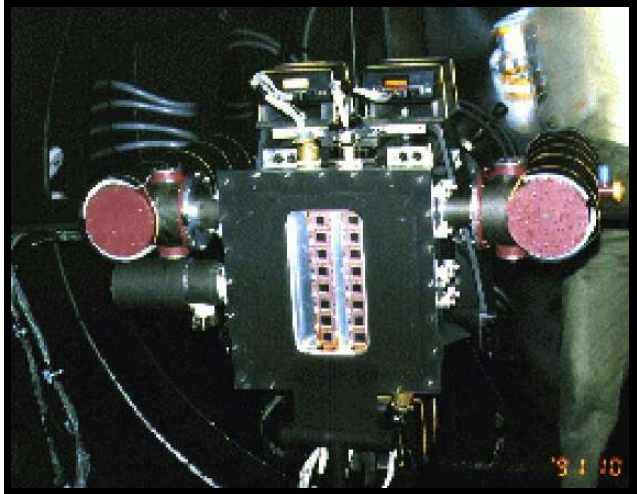
Kiso Schmidt telescope

- Kiso Observatory, IoA, School of Sci., UTokyo
- Kiso, Nagano, JAPAN
- since 1974
- Aperture diameter : 105cm
- Field of View : 9 degrees
- Focal length : 3,300 mm, f/3.1

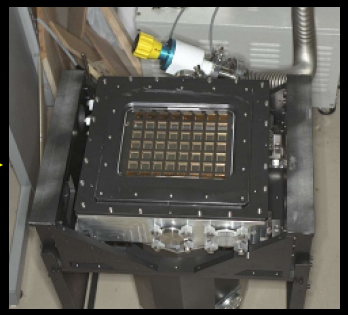
Image: KOJI OKUMURA (Forward Stroke)

History: wide-field cameras

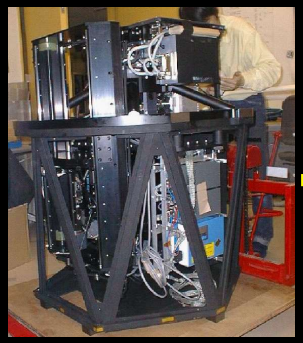
PI: Porf. Sadanori Okamura, Head Dr. Maki Sekiguchi



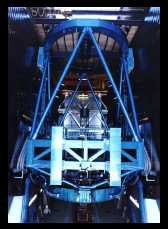
1991 1000x1000x16 pix
Mosaic CCD Camera I



1994 1000x1000x40
LCO Swope 1m
WHT 4.2m

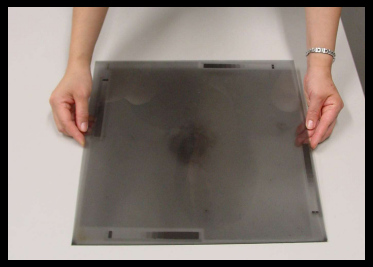


1999 4000x2000x10 Suprime-Cam
2012 4000x2000x116 Hyper SupC
8.2m Subaru



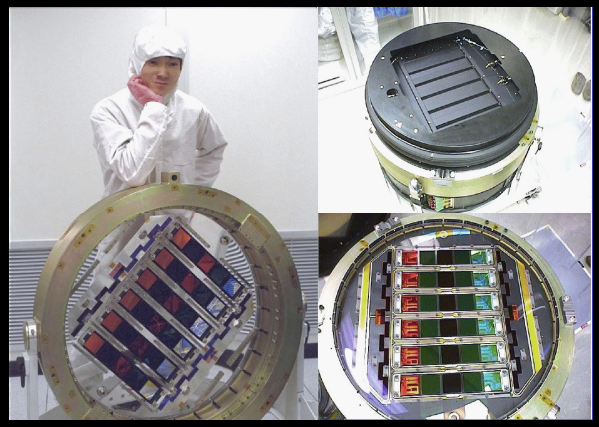
PI: Porf. Satoshi Miyazaki

Photographic Plate



by S. Okamura

Kiso 1.05m Schmidt
telescope



1998 2000x2000x30, 2000x400x24

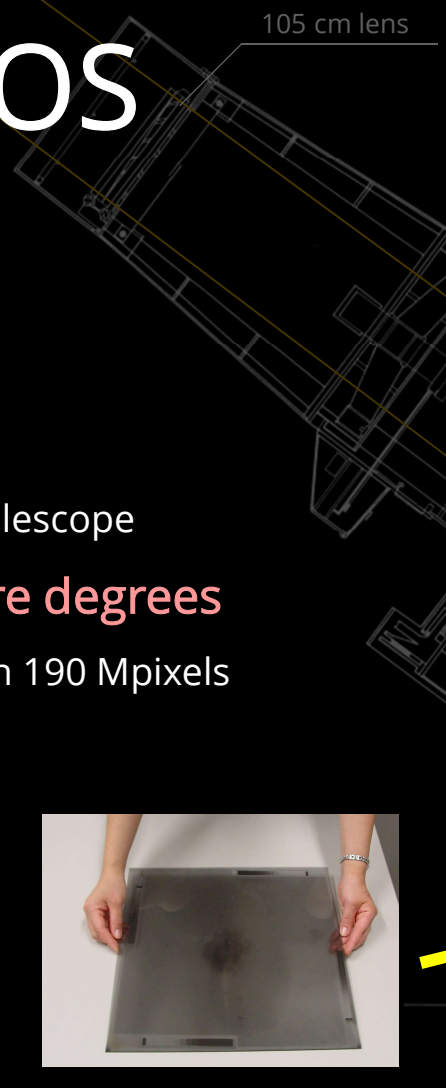
SDSS 2.5-m imager

First astronomical wide-field video camera

TOMO-E GOZEN

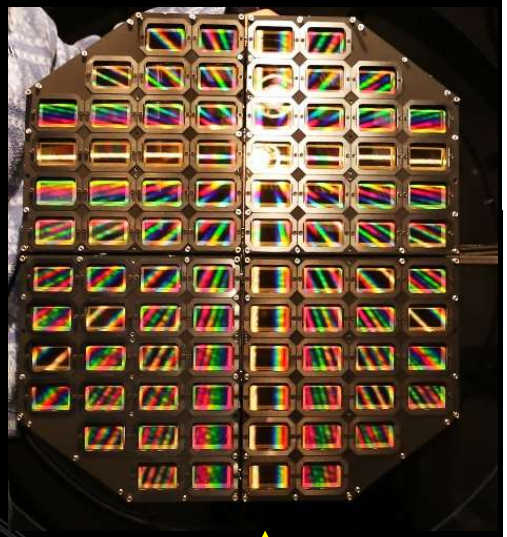
Mosaic CMOS camera

Sako et al. 2018, SPIE



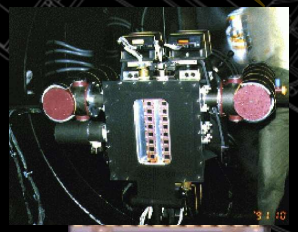
- On the Kiso 105cm Schmidt telescope
- Field-of-view : 20 square degrees
- 84 chips of CMOS sensors with 190 Mpixels
- Video in 2 frames/sec
- Big data of 30 TB/night
- Optical, single color
- Operation > 10 years

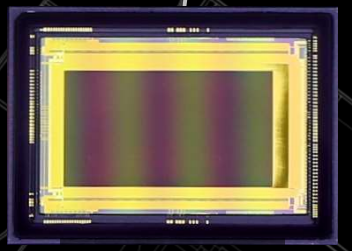
2019



2015

1991





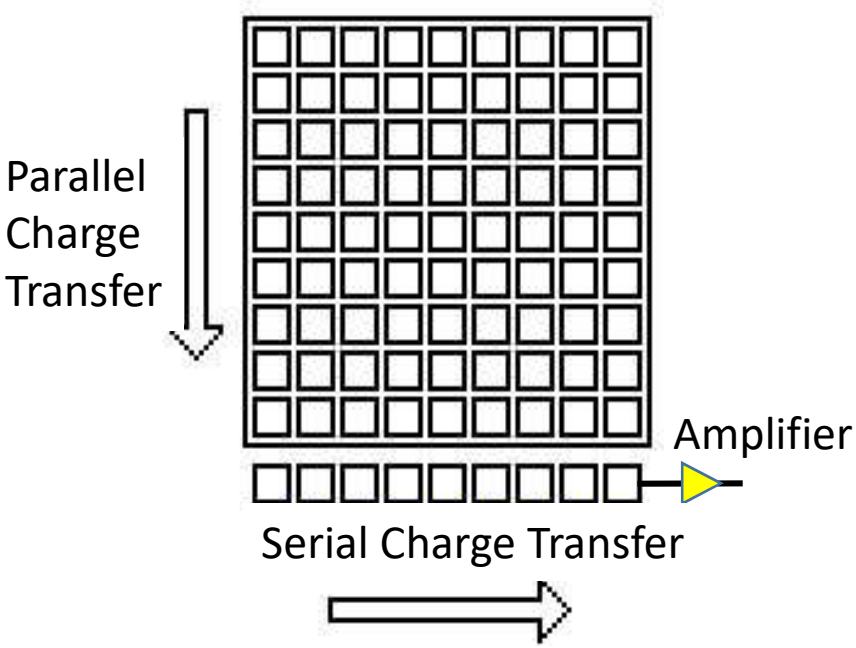
CMOS sensor

CCD

CCD and CMOS sensor

CCD

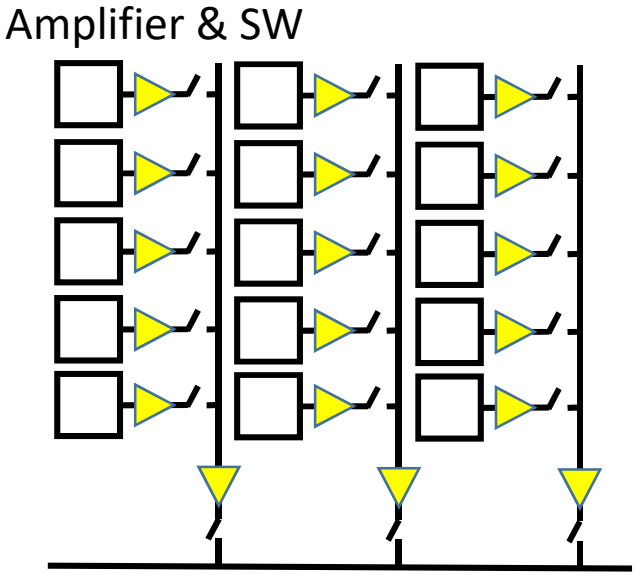
(Charge Coupled Device)



Transfer charges to the corner of the sensor
One frame time: ~10 second

⇒ take pictures

CMOS Sensor



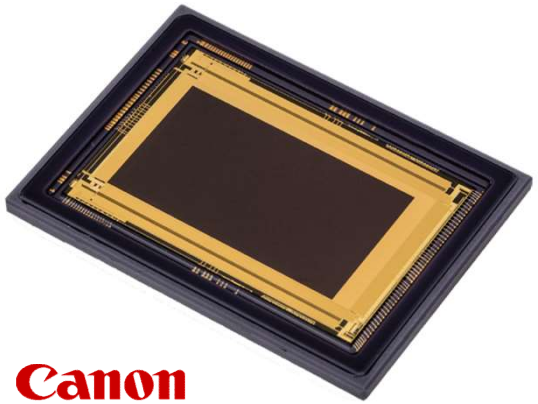
Read out each pixel with switching lines
Line read out time : ~1 msec

⇒ take videos

Large pixel CMOS sensor

Details are presented in Kojima et al. 2018, SPIE [10709-70]

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

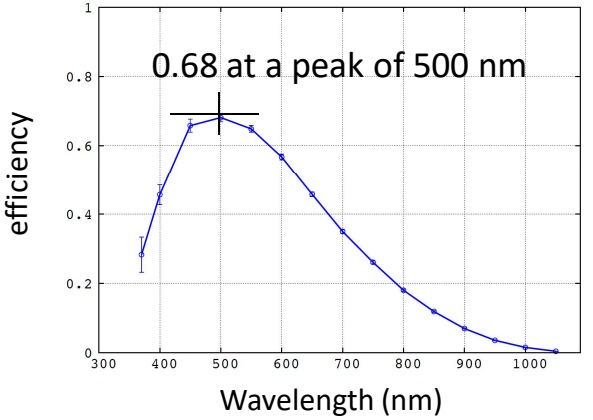


Canon

discussion started in 2010

- 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**

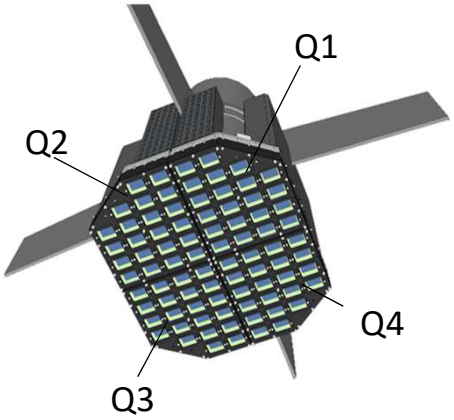
Photoelectric conversion efficiency



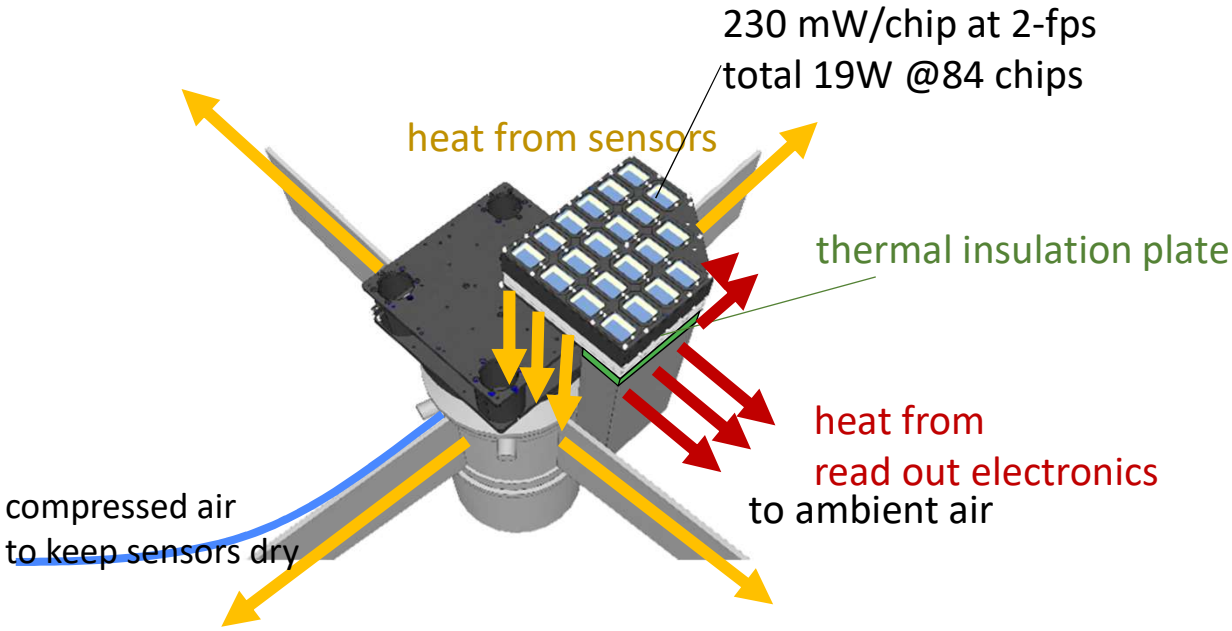
→ Less than sky background in dark night, 50 e$^-$ sec^{-1}, at room temperature

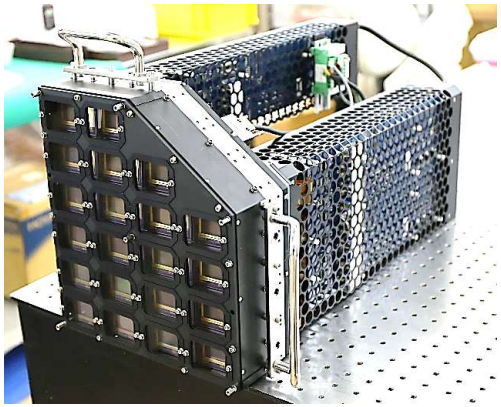
Design concept

- ✓ **Simple design**
  - w/o moving parts
  - ordinary temperature and pressure
    no cryogenic dewar
  - ⇒ wide field, easy maintenance

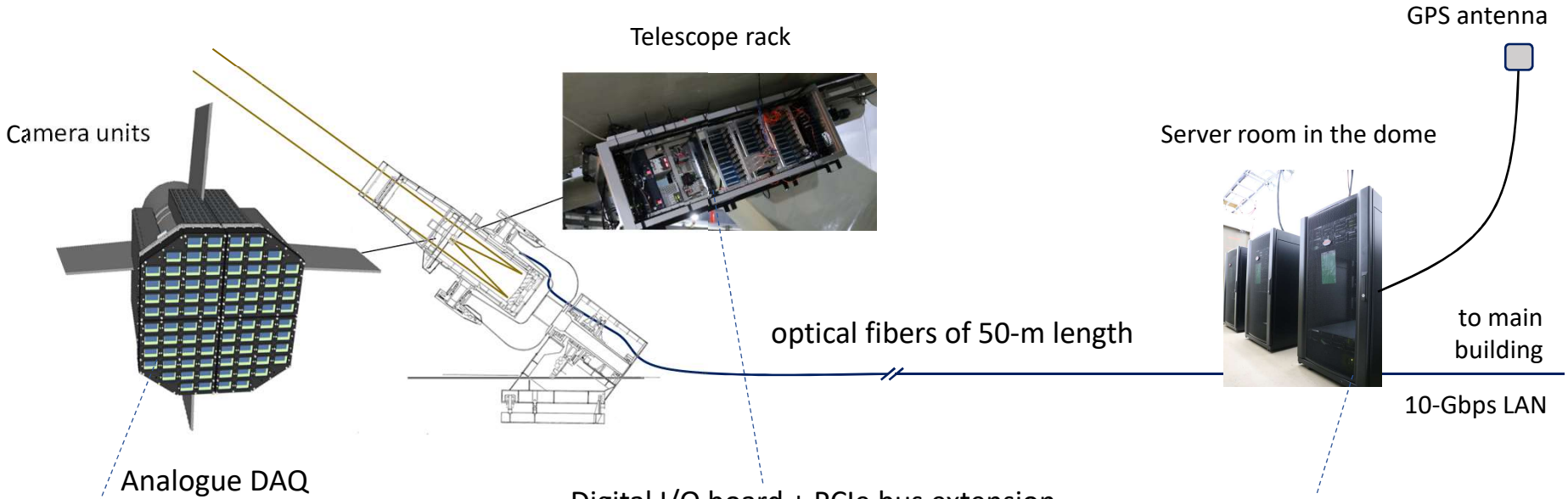


Front side view

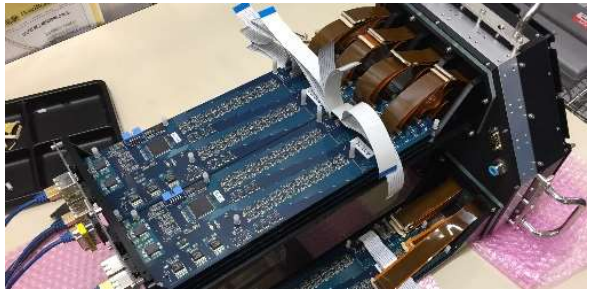



Tomo-e Gozen Q1
21 CMOS sensors

Data acquisition system



Analogue DAQ
(Dedicated)



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

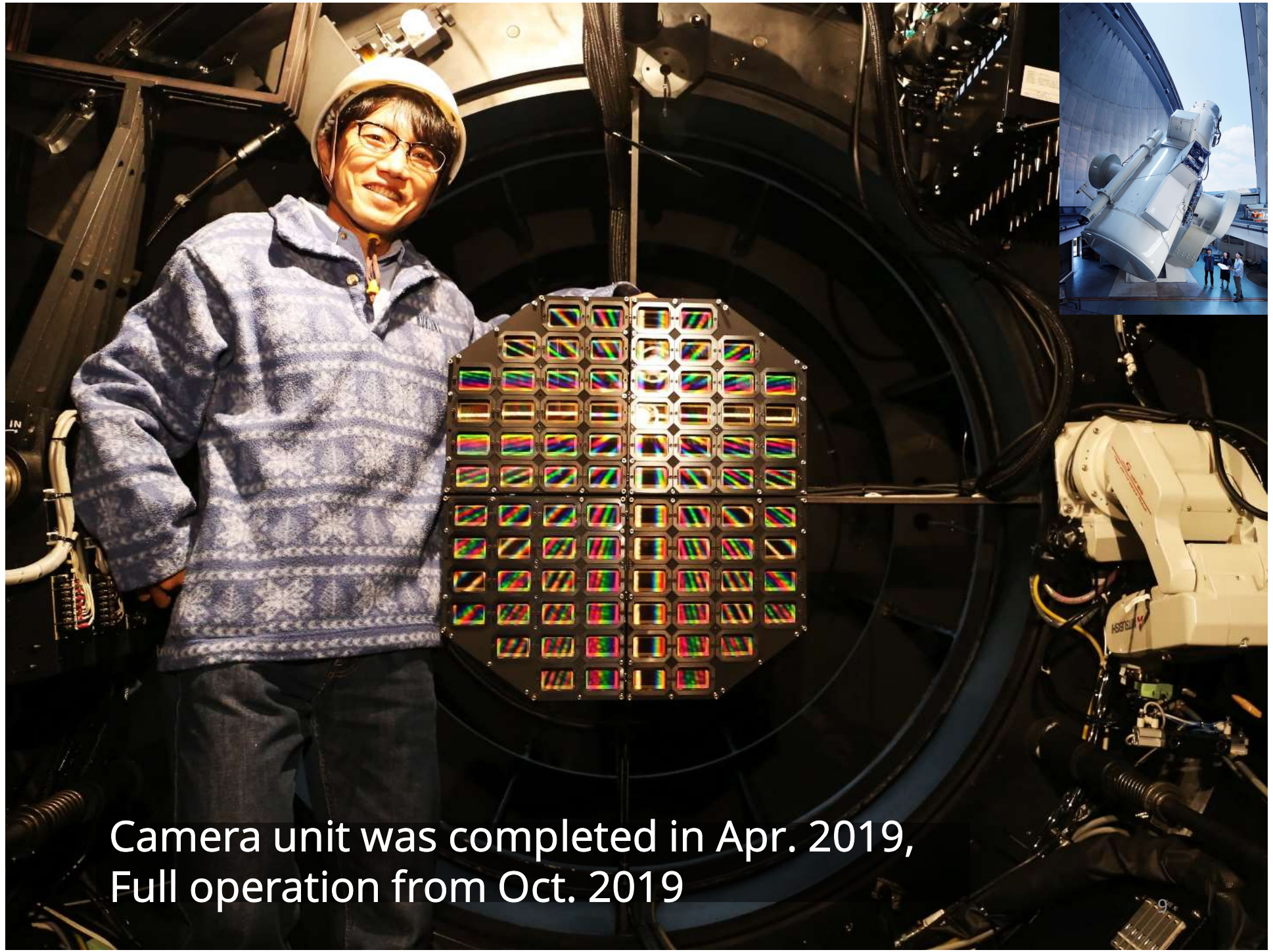
Digital I/O board + PCIe bus extension
(commercial)

- 24 boards, 32 bits, 10 MHz
- LVDS – optical convertor
- bus-mastering DMA

GPS receiver

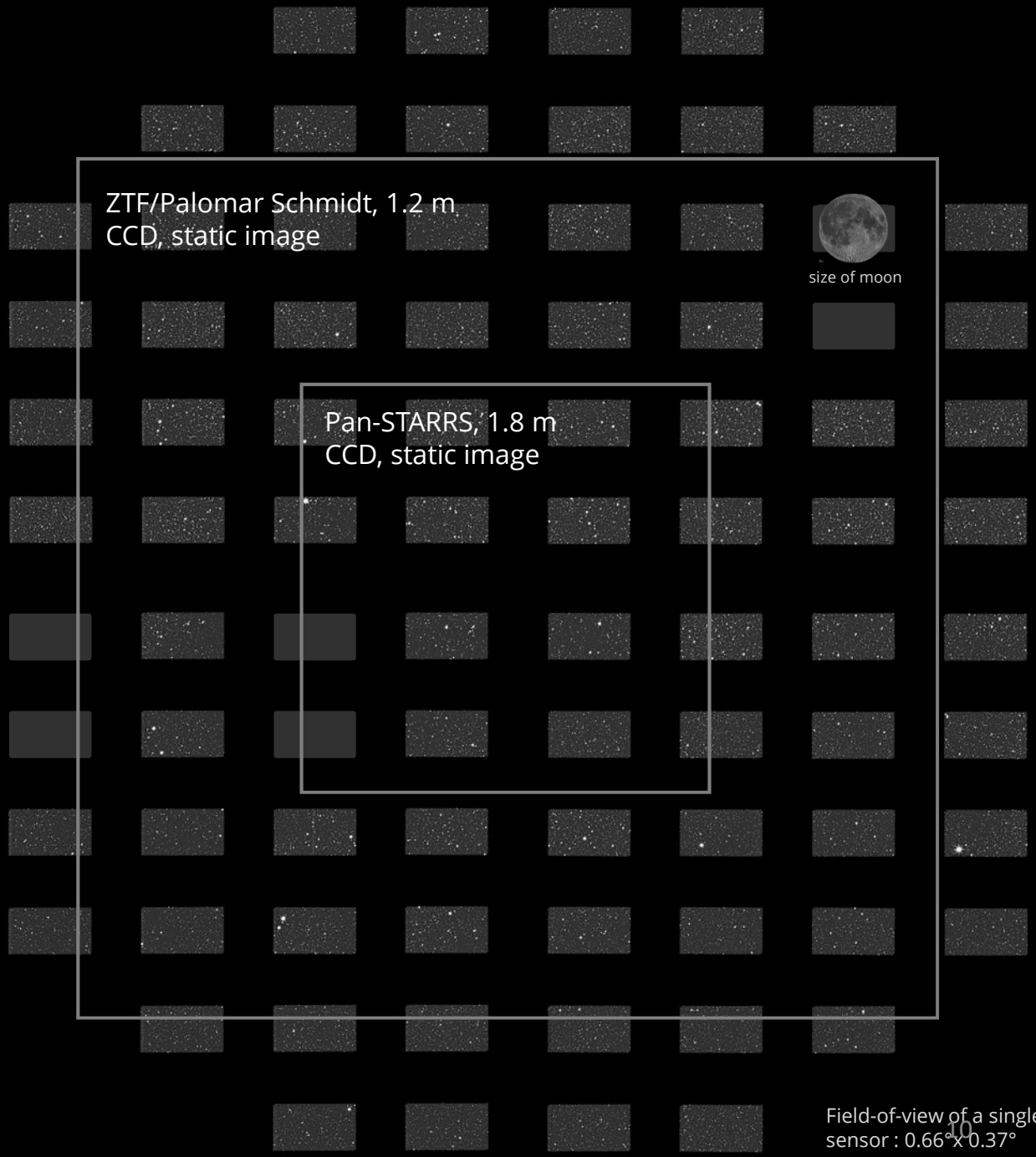
u-box EVK-M8N

- UTC time
- Absolute accuracy: ±0.2 msec
- Frequency stability: ~10^{-5}

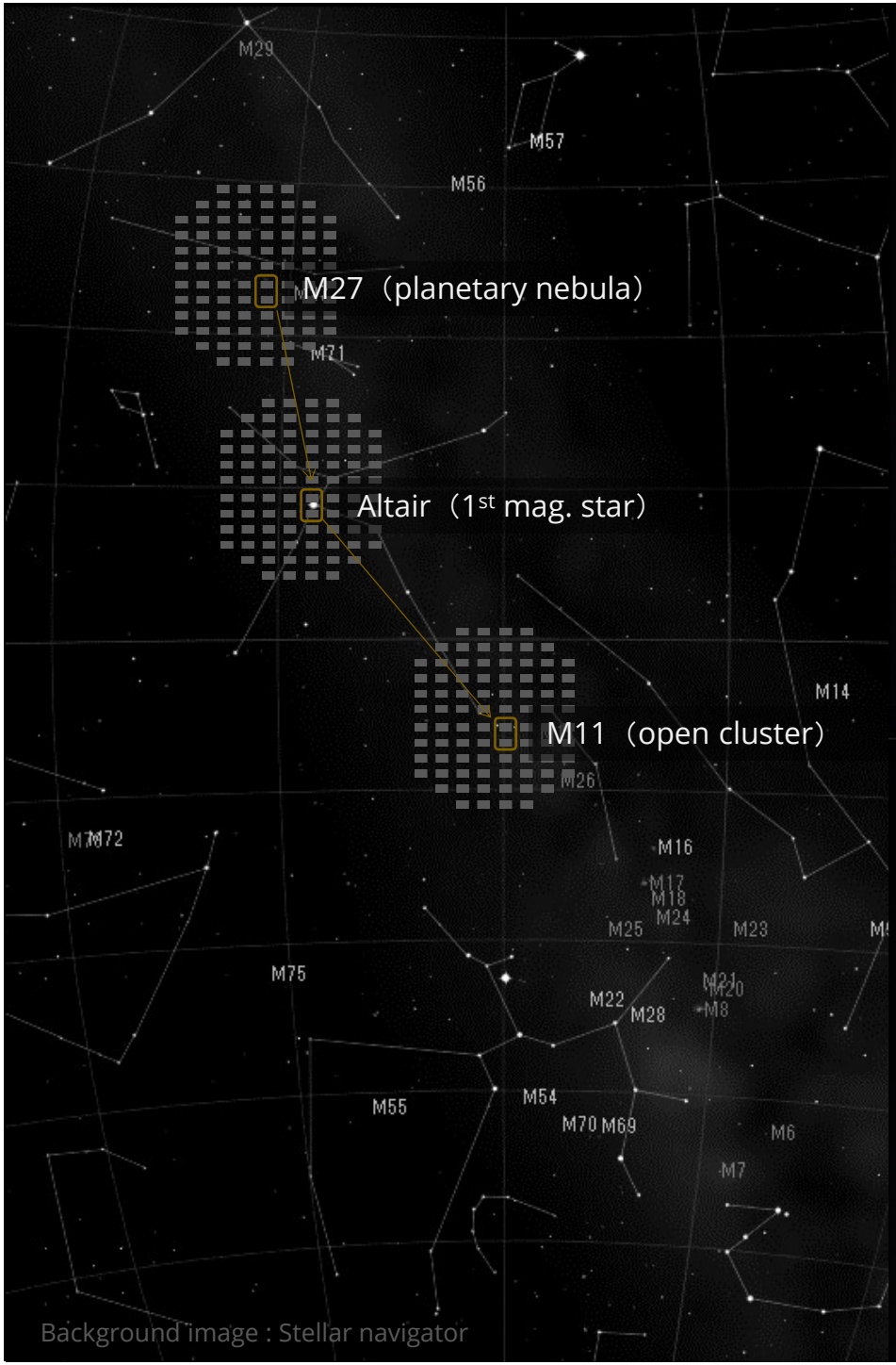


Camera unit was completed in Apr. 2019,
Full operation from Oct. 2019

Comparison of fields-of-view

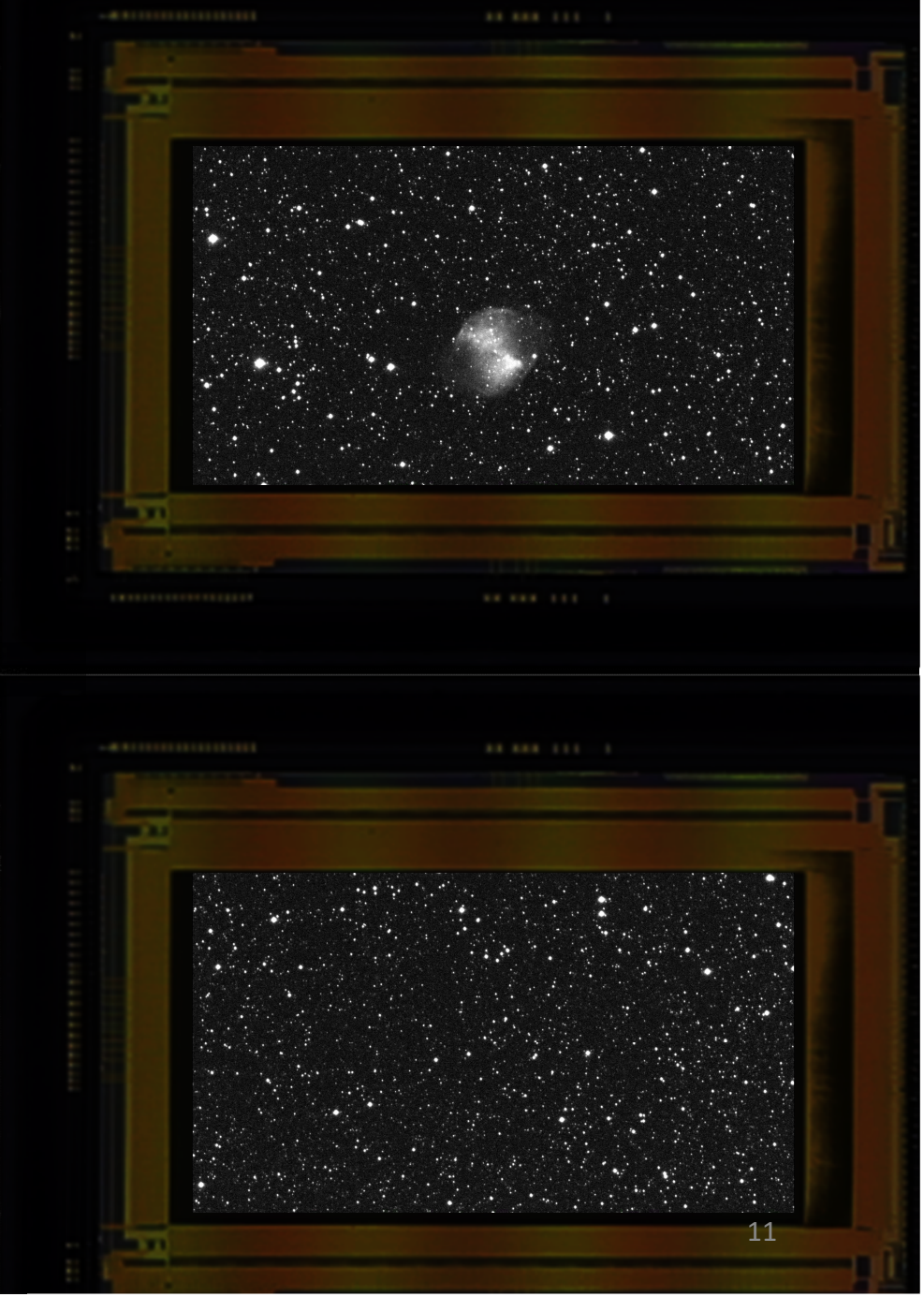


Tomo-e Gozen
Kiso Schmidt, 1.05 m,
CMOS, video



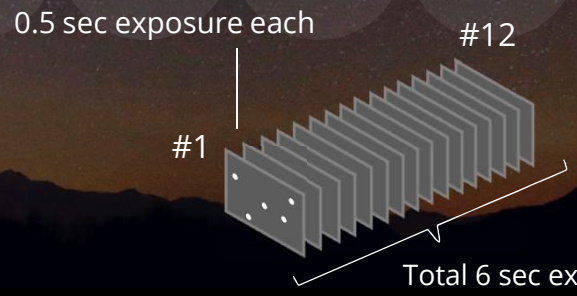
Background image : Stellar navigator

2-fps video taken by 2 sensors of Tomo-e Gozen



Wide sky areas are scanned in video to reveal rapidly changing universe

- Video observations of each sky area (2 frames/sec, for 6 sec)
- Scanning the sky of elevations > 35°(7,000 deg^2) in 2 hours
- Recording all events brighter than 18th mag



Northern Sky Transient Survey w/ Tomo-e Gozen

- no filter: effectively g+r bands
- 1 visit
  - 6 sec exposure: [0.5 sec exposure] x 12 ==> ~18-19 mag
  - ~60 deg2 w/ 2x2 (or 2x3) dithering to fill the gaps between sensors
- survey planning: Pedroso, Ikeda, Morokuma et al. in prep.

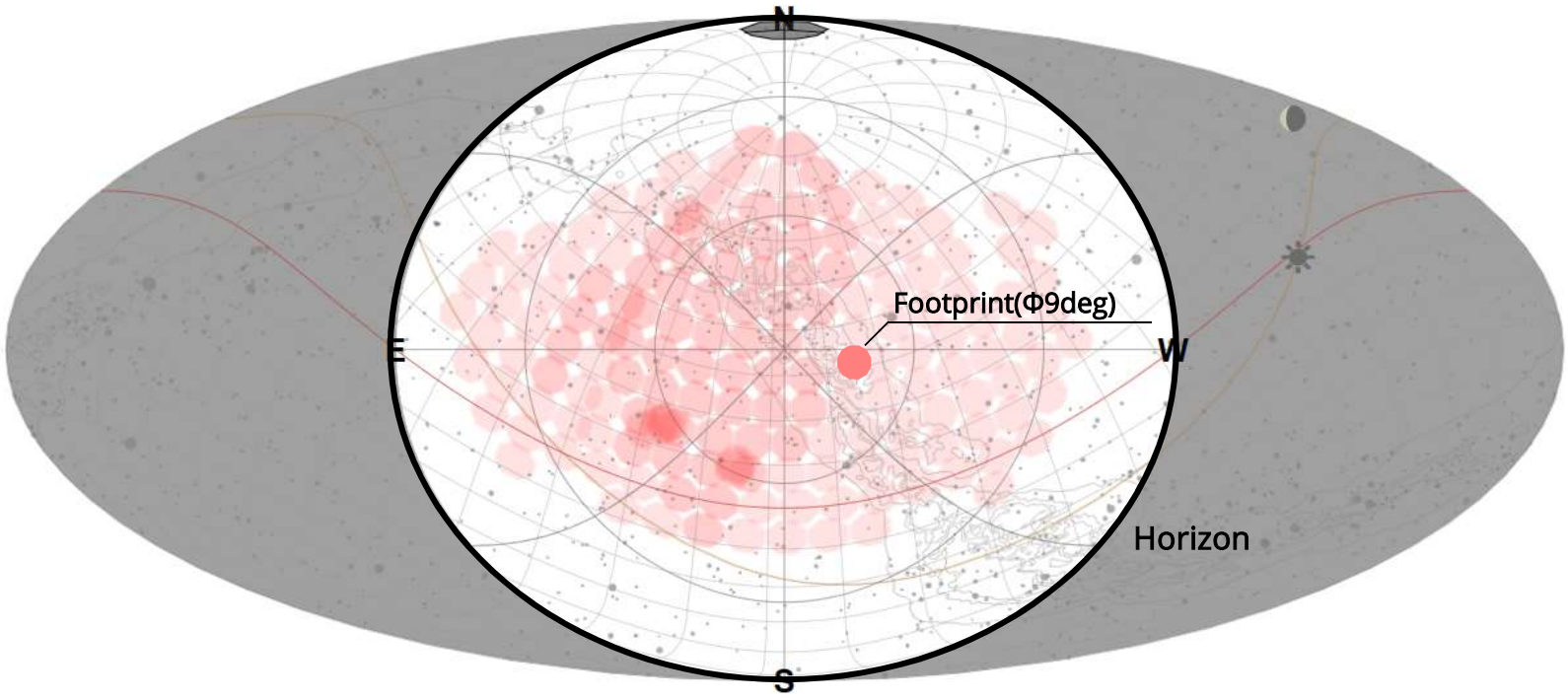
7,000 deg2 – 2 hr cadence – 18 mag depth 2019 (initial phase)

7,000 deg2 – one visit – 18 mag depth
==> 2,000 deg2 – 0.5 hr cadence – 18 mag depth 2020– (now)

- near-future changes:
  - 24 contiguous frames instead of 12?

Example of wide-field video survey

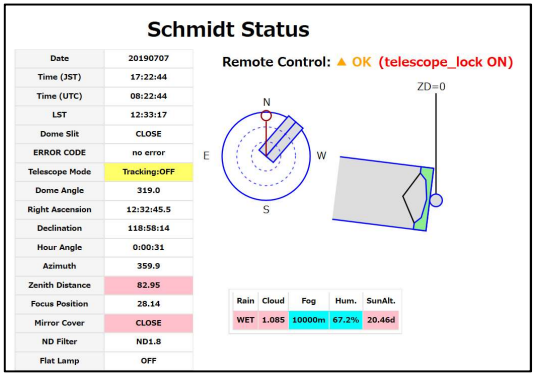
Footprints of Tomo-e Gozen on 25th Sep. 2019

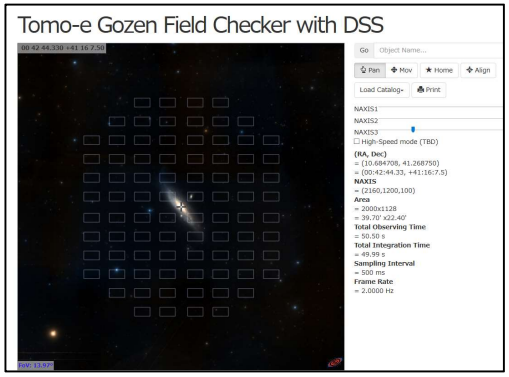


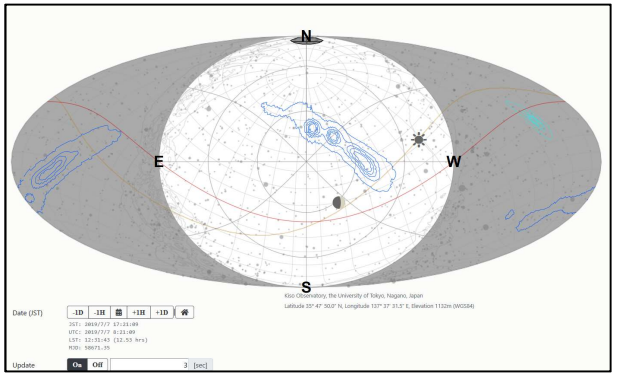
- Application of optimizations for traveling salesman problem
- Re-optimization according to changing situations (Pedroso in prep.)

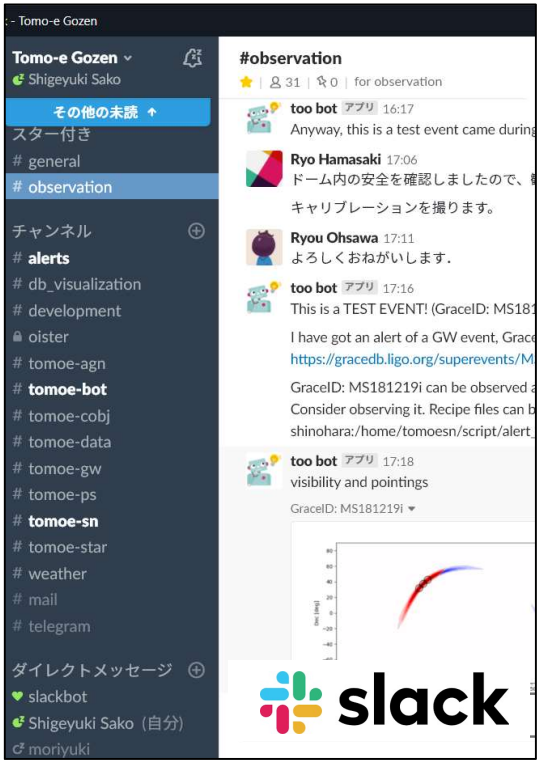
Operation

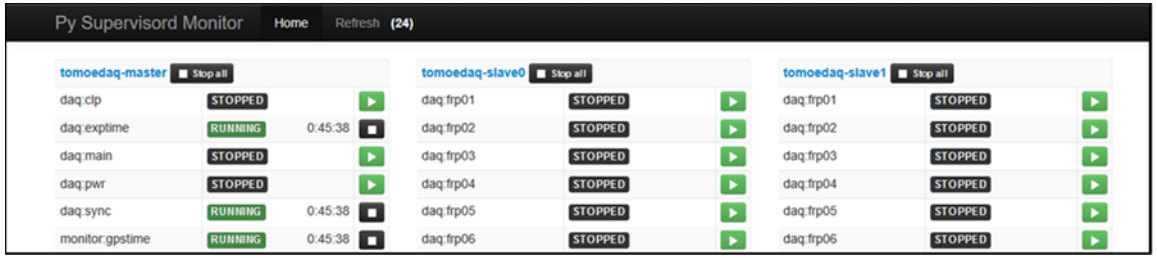
- Web browser base software
- Full-automatic observation by Queue system
- Quick information sharing by slack

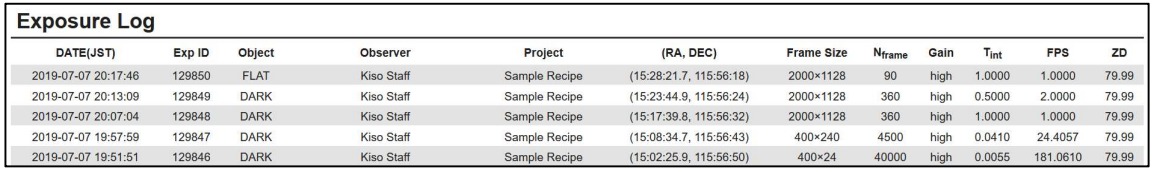












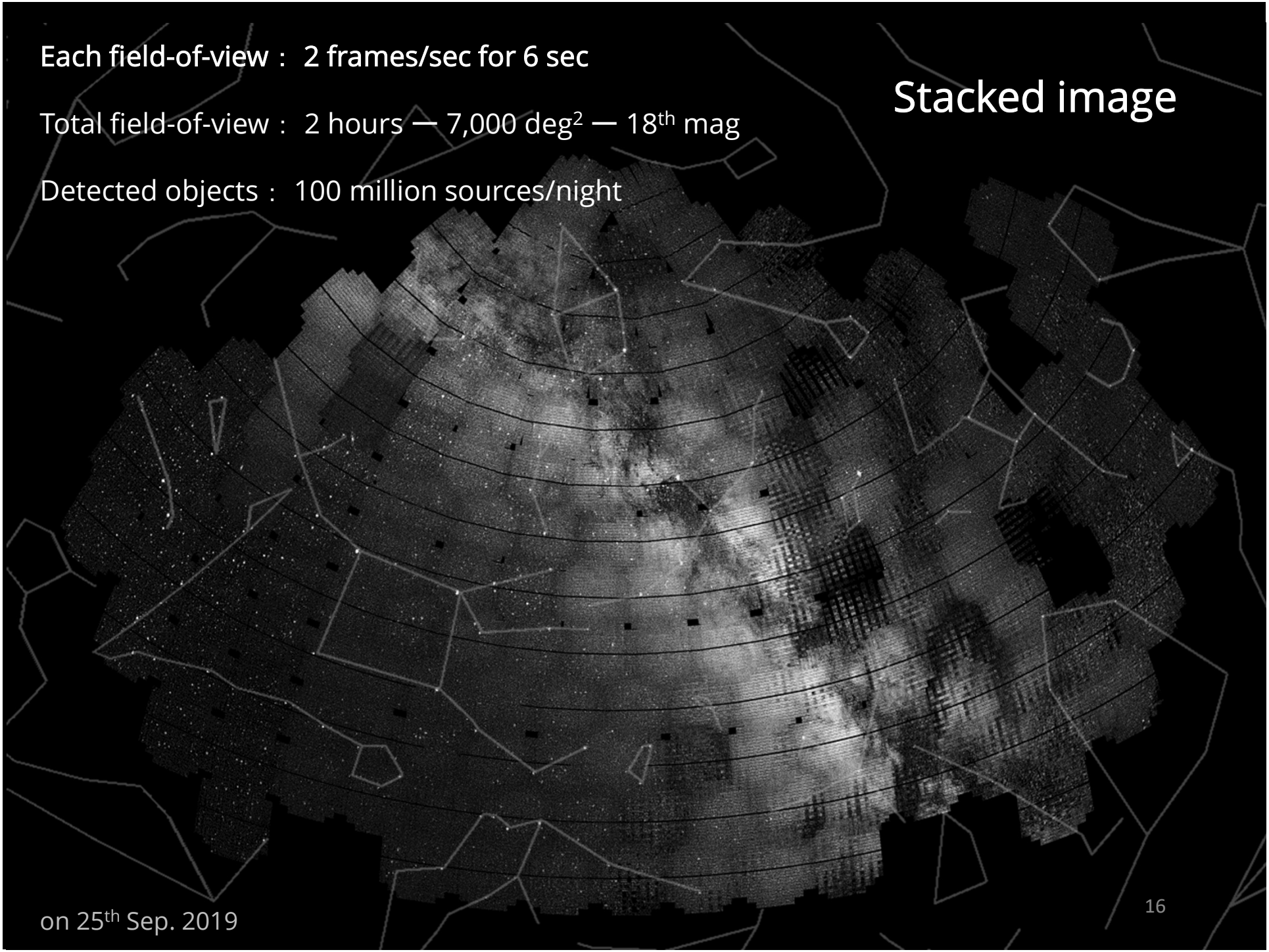
DATE(JST)	Exp ID	Object	Observer	Project	(RA, DEC)	Frame Size	N_{frame}	Gain	T_{int}	FPS	ZD
2019-07-07 20:17:46	129850	FLAT	Kiso Staff	Sample Recipe	(15:28:21.7, 115:56:18)	2000×1128	90	high	1.0000	1.0000	79.99
2019-07-07 20:13:09	129849	DARK	Kiso Staff	Sample Recipe	(15:23:44.9, 115:56:24)	2000×1128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

Each field-of-view： 2 frames/sec for 6 sec

Total field-of-view： 2 hours — 7,000 deg^2 — 18^{th} mag

Detected objects： 100 million sources/night

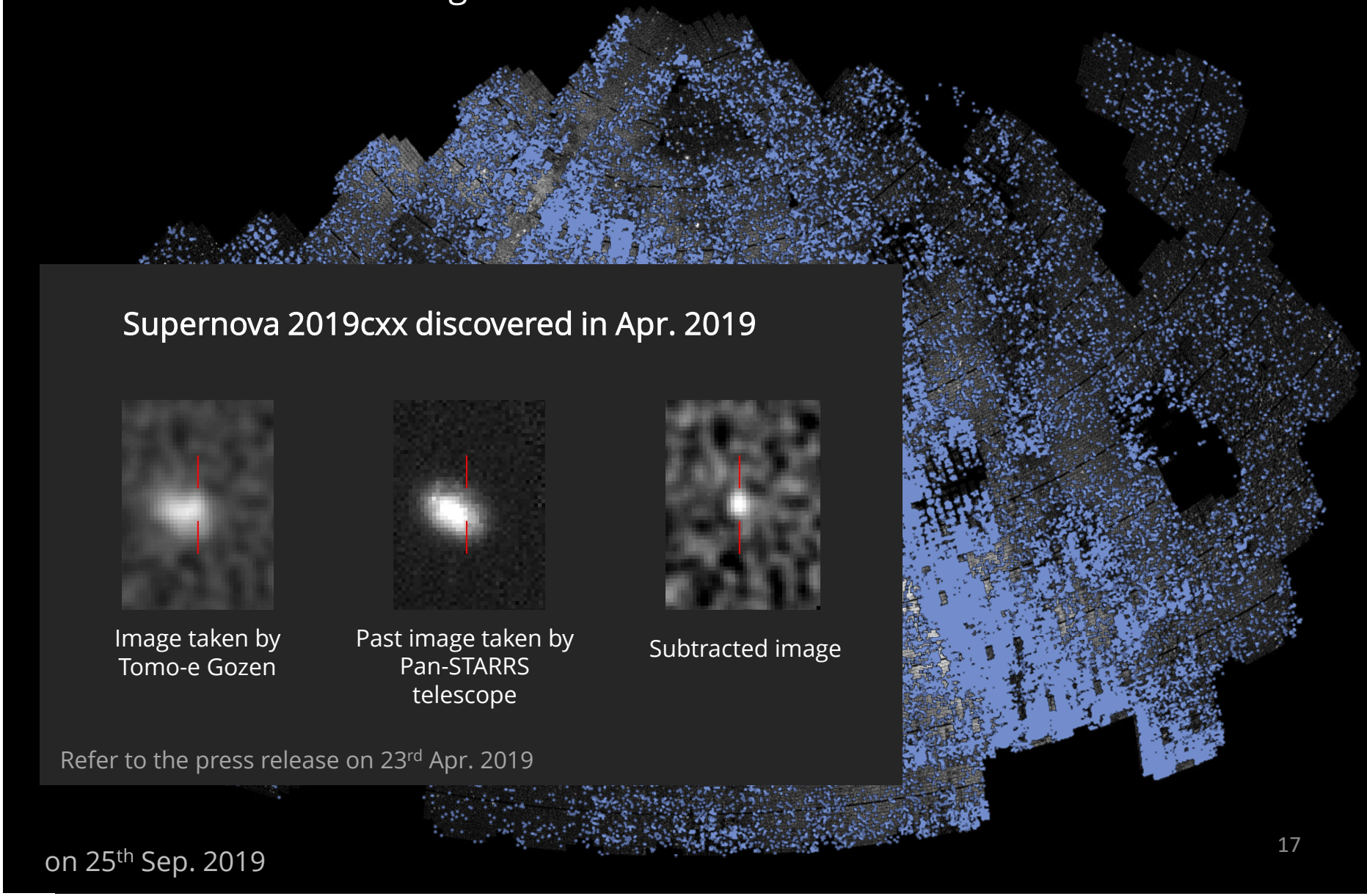
Stacked image



on 25^{th} Sep. 2019

- Transient candidates

130 thousand events/night



Supernova 2019cxx discovered in Apr. 2019

Image taken by Tomo-e Gozen

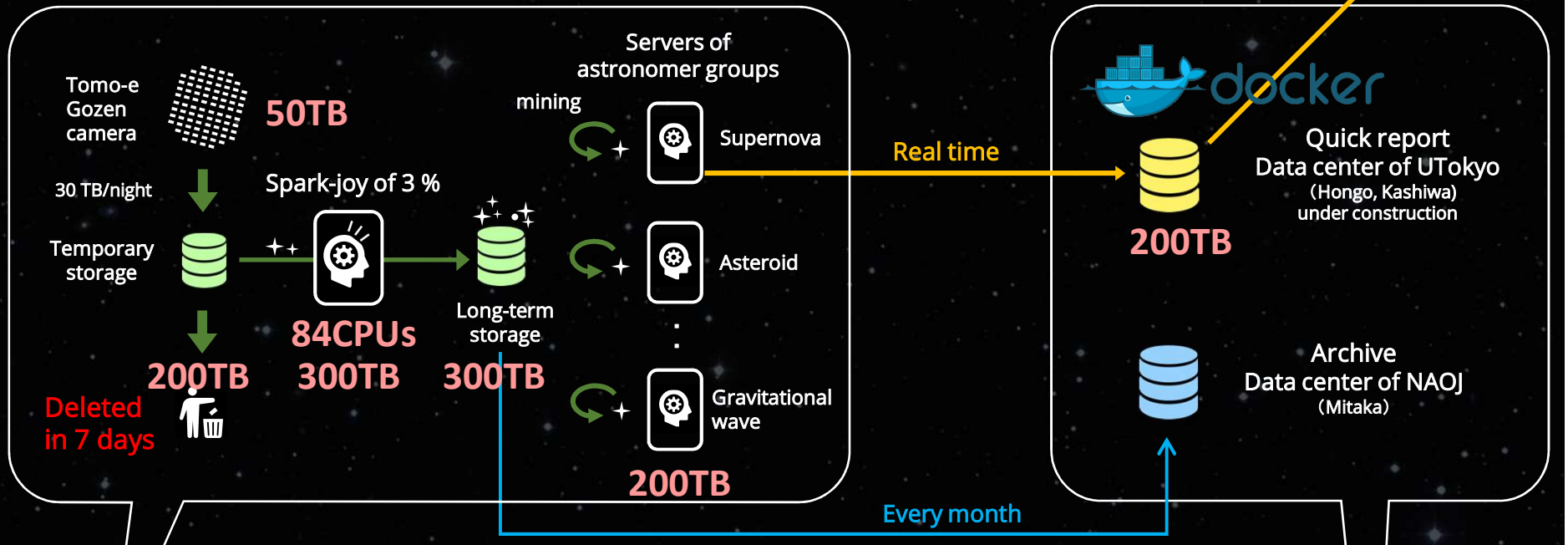
Past image taken by Pan-STARRS telescope

Subtracted image

Refer to the press release on 23rd Apr. 2019

on 25th Sep. 2019

Data flow



- Freshness is important
- Twitter-like

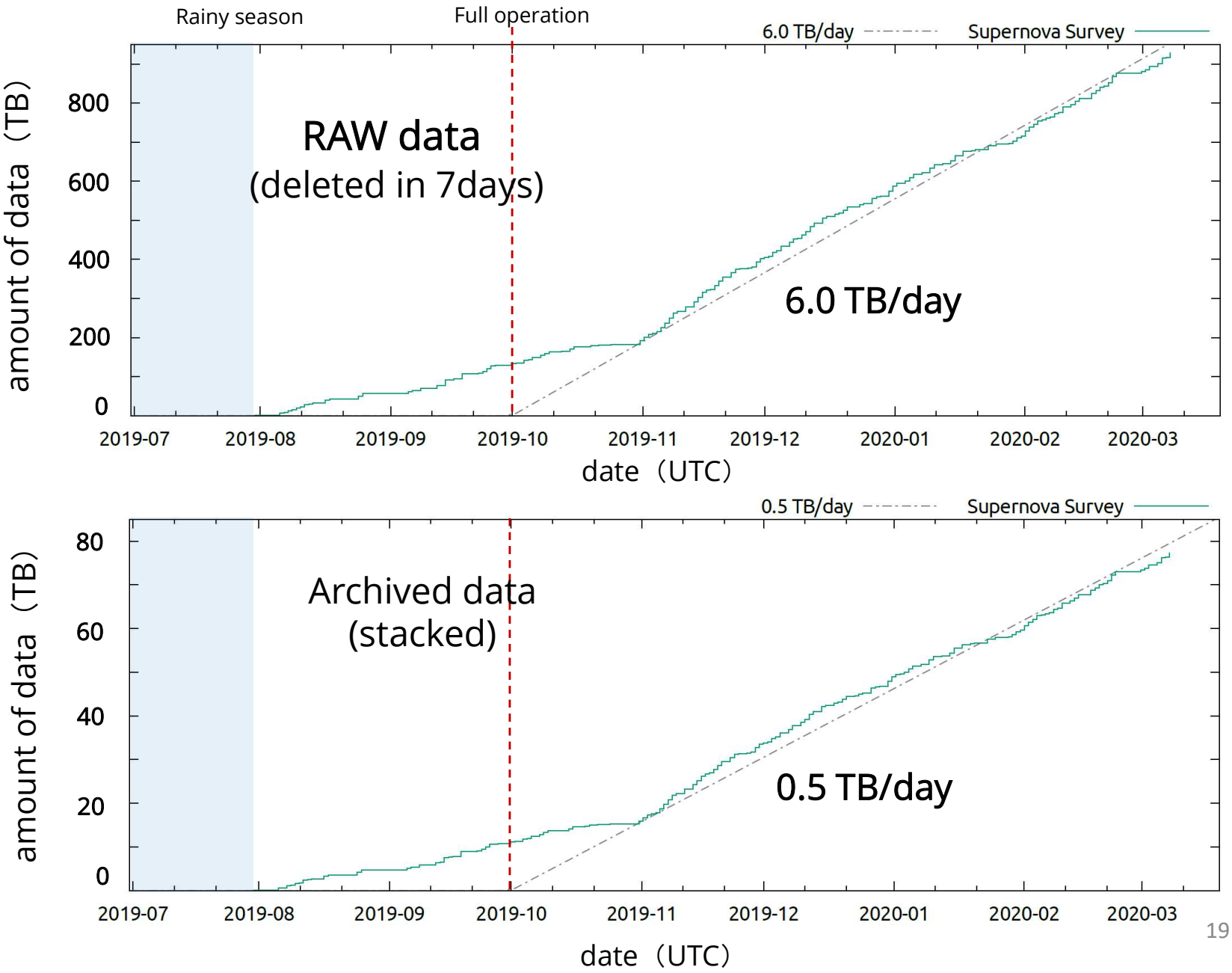
Kiso, Nagano

Mitaka, Hongo
Tokyo

Kashiwa,
Chiba

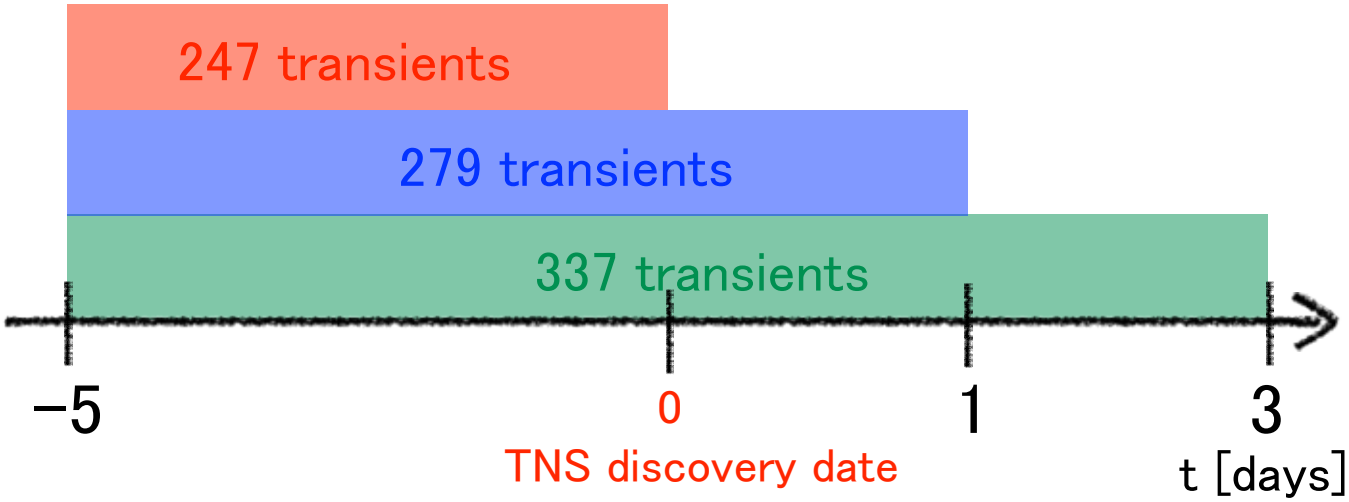
4-Gbps (shared line)
We hope that SINET will be connected to the KISO region.

Data taken in 2019（only from the survey）



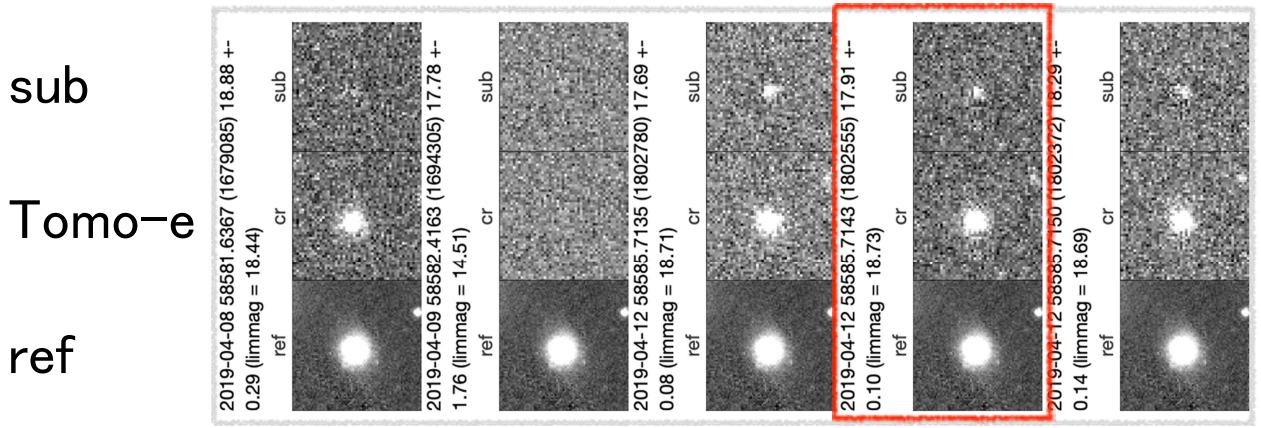
Transients in Transient Name Server (TNS)

- Dec > −3 deg & 2019/04/06 – 2019/12/31 (discovery date@TNS)
  ~1,600 transients reported to TNS
- #(Tomo-e Obs, deeper than discovery magnitude)



Example: SN 2019dwy (SN Ic)

Tomo-e discovery
(2nd detection), MJD=58585.71 (12 days before TNS discoery), ~18 mag



TNS discovery
MJD=58597.41
17.2 mag (ASAS-SN)

Progenitor of Type Ia supernova

white dwarf in close binary system

- steady accretion from normal star

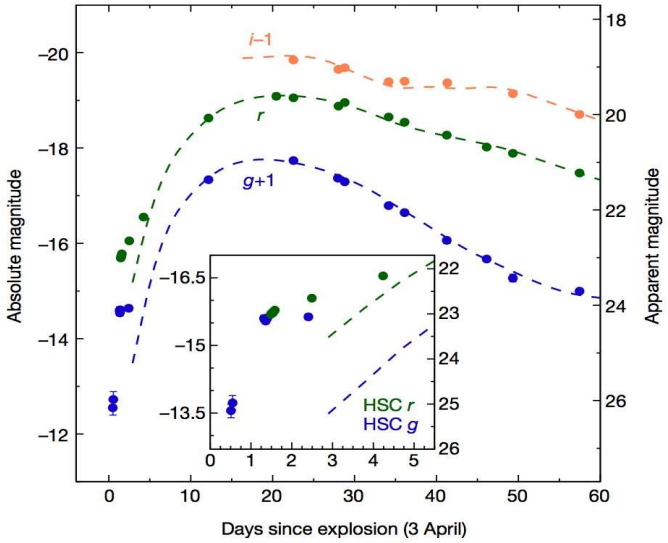
=> Single Degenerate (SD) scenario

- merging with another white dwarf

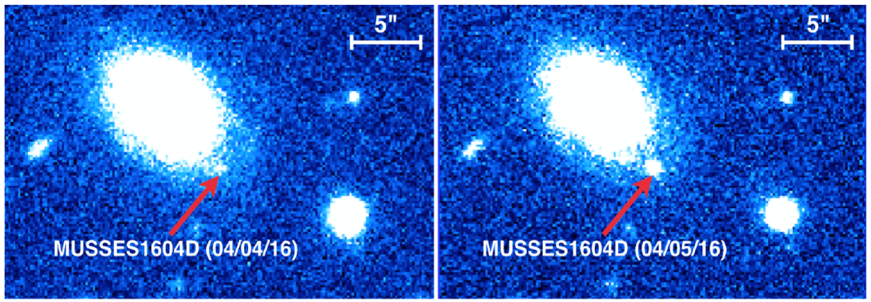
=> Double Degenerate (DD) scenario

Key to understand the progenitor system

Early phase interaction with companion/CSM



with Subaru HSC



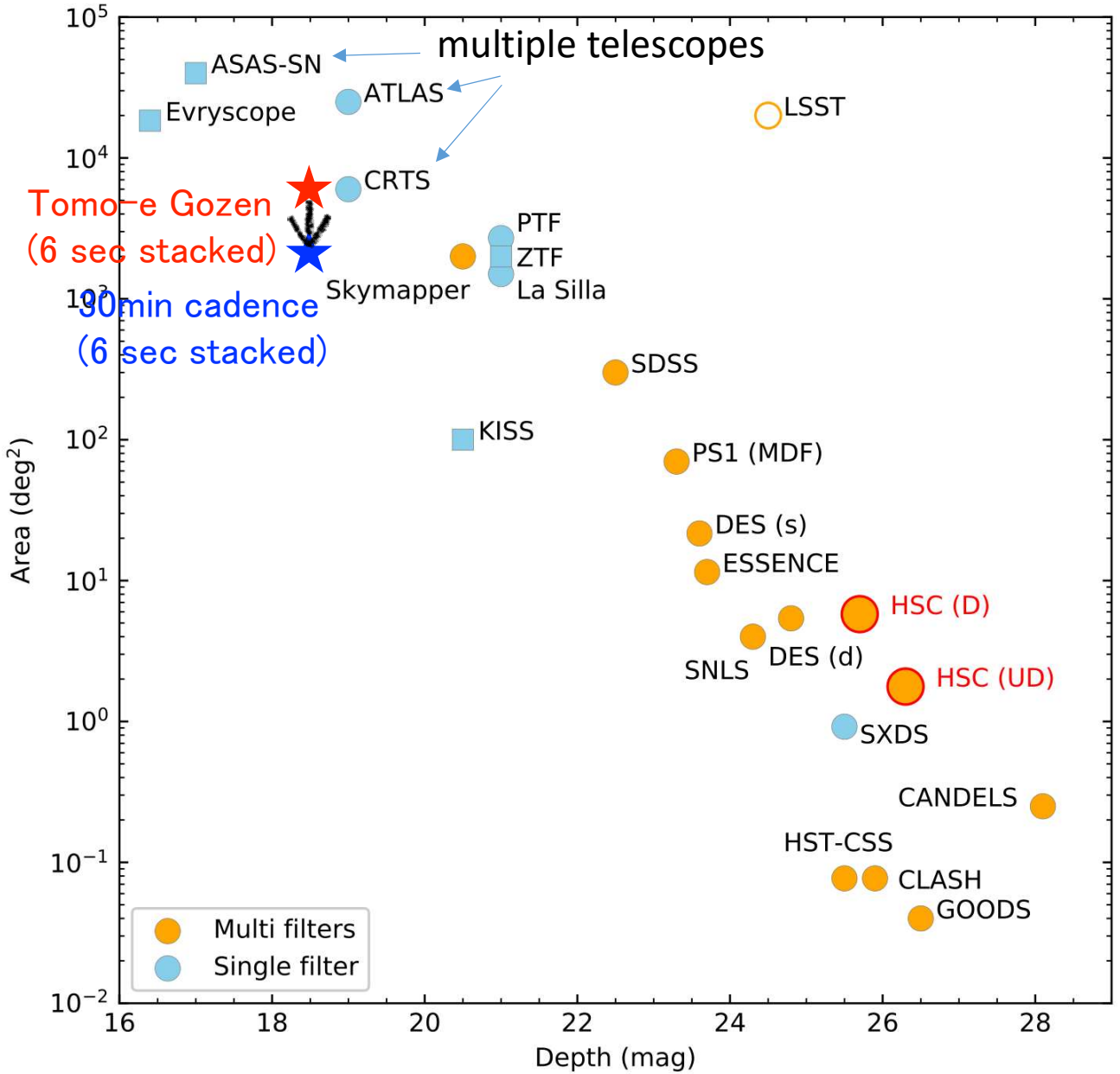
He detonation model

~Chandrasekar mass WD (~1.3-1.38M WD) ignited with a thin He shell detonation (0.01-0.03Mo)

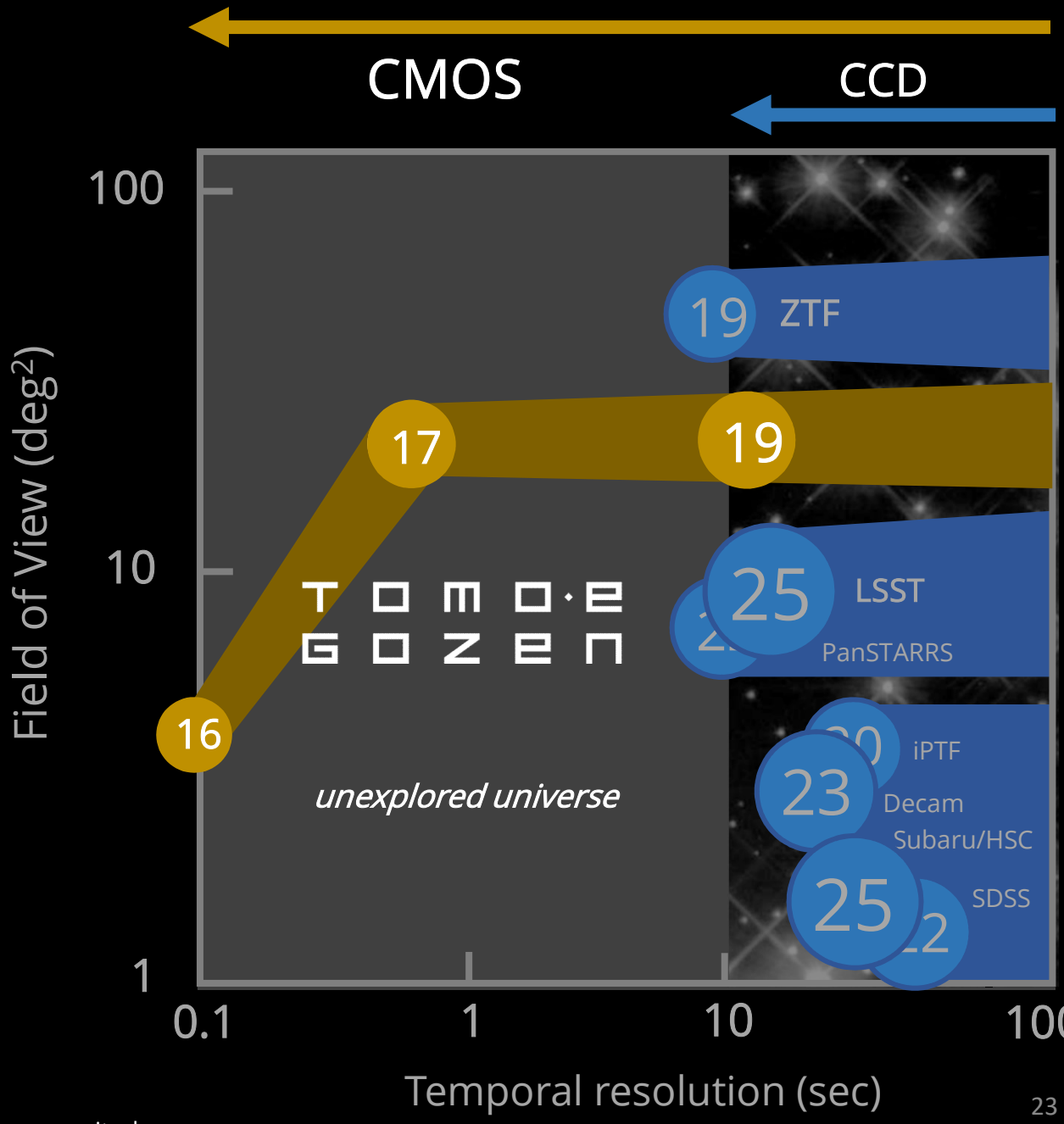
Jiang+2017, Nature

Transient Survey Power

Yasuda+2019



Survey power for transient events



The numbers in the circles show limiting magnitudes.

Expected Scientific Results

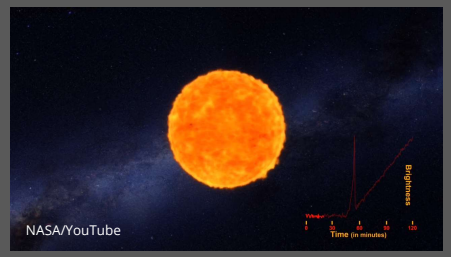
Discoveries of supernovae ・・・・・ 1,000 events/year

Supernovae just after explosions ・・ a few events/year

Near-earth asteroids ・・・・・・・・ 100 events/year

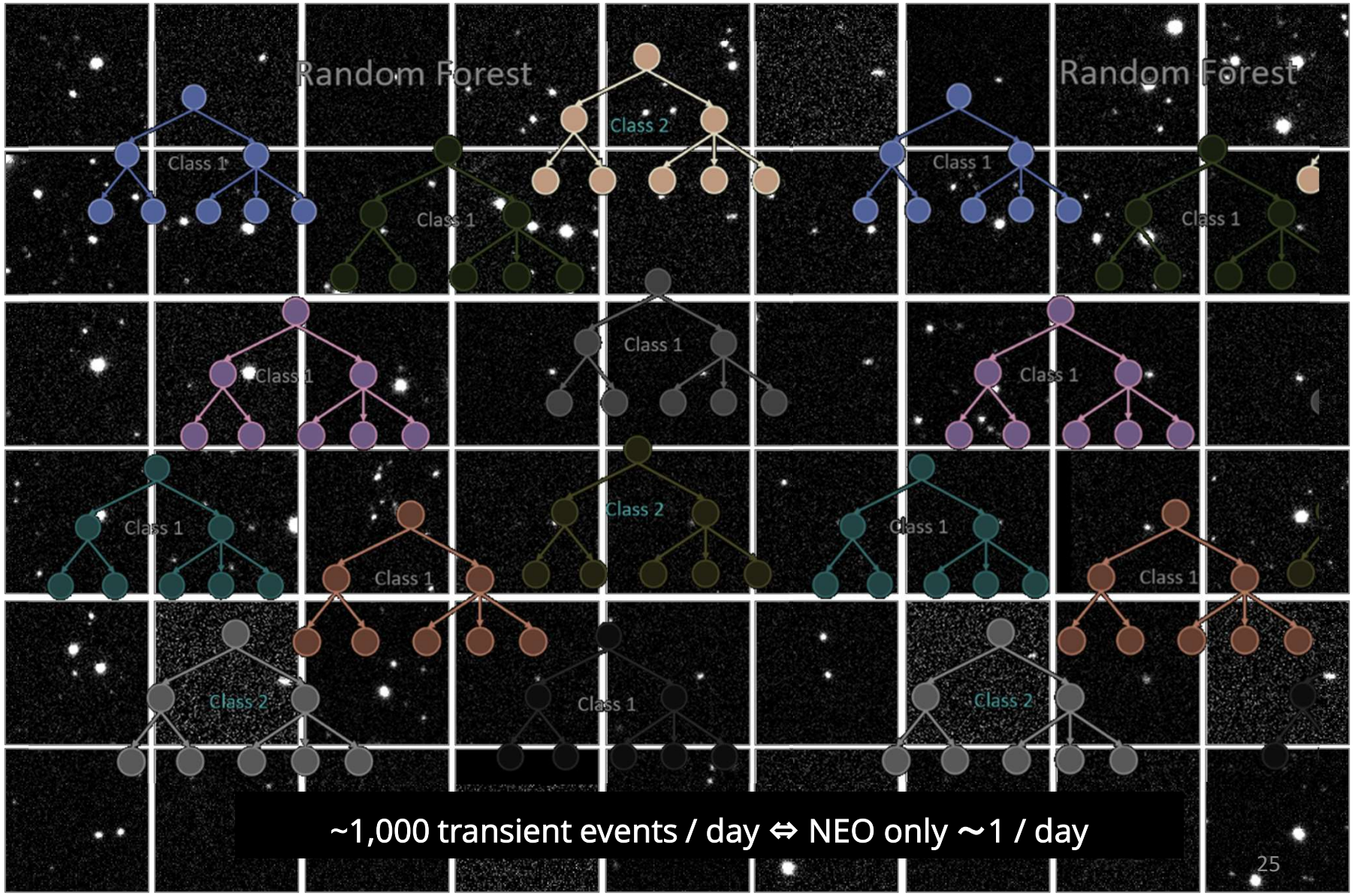
Variable stars, Novae, AGNs, ...

Shock breakouts of supernovae

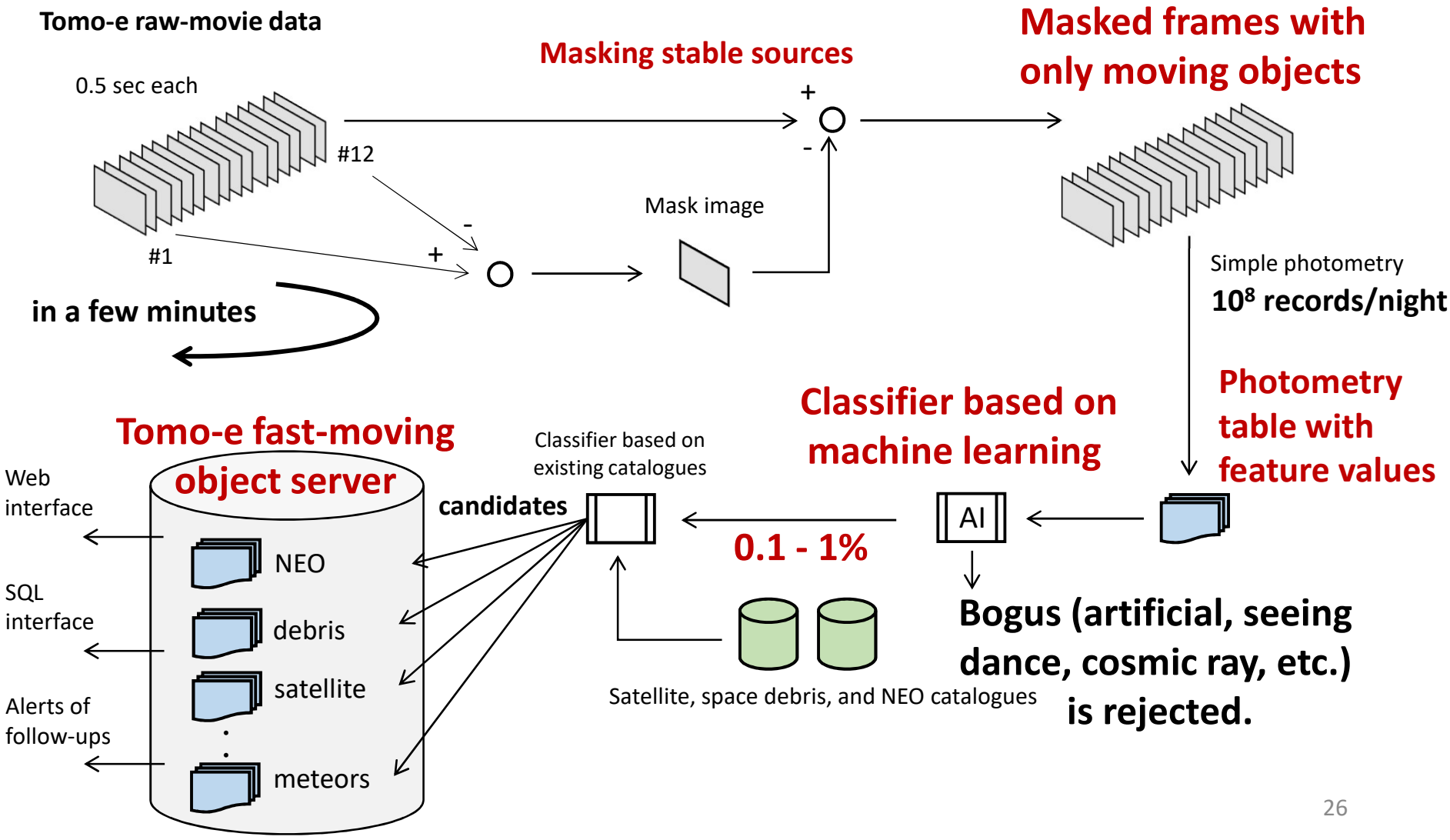


SNe just after explosions

Nar Earth Objects


Random Forest
Class 2
Class 1
Class 1
Class 1
Random Forest
Class 1
Class 1
Class 1
Class 1
Class 1
Class 1
Class 2
Class 1
Class 1
Class 1
Class 2
Class 1
Class 2
~1,000 transient events / day ⇔ NEO only ~1 / day

Detection for Fast Moving Objects with `v > 1 arcsec/sec'



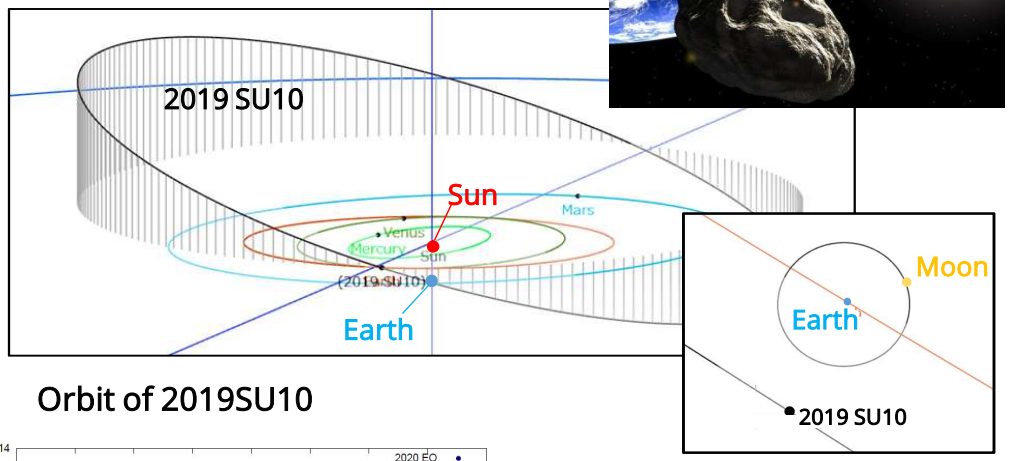
NO.	DATE(UTC),OBJECT,FITS	MATCHING	IMAGE	LIGHT CURVE	SCORE	RA, DEC	V_MEAN [°/sec]
13	2020-01-02T15:07:37.847 20amkwy_08011+20691 TMQ32020010200021826813.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.983	08h00m41.1176s +20d41m27.3921s	5.35
75	2020-01-02T12:08:03.495 20amkpz_02342+05475 TMQ32020010200021808713.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.982	02h20m29.7541s +05d28m20.9898s	15.18
101	2020-01-02T11:25:29.630 20amklu_04576-05758 TMQ12020010200021797841.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.981	04h34m33.9624s -05d45m30.1496s	7.65
95	2020-01-02T11:27:25.319 20amkma_04592-05750 TMQ12020010200021798431.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.979	04h35m32.1233s -05d45m02.3742s	7.54
4	2020-01-02T15:45:25.683 20amlaj_07983+19973 TMQ42020010200021835714.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.968	07h58m58.351s +19d58m26.8782s	6.44
110	2020-01-02T10:17:42.845 20amkei_04612-07426 TMQ32020010200021778411.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.964	04h36m44.5036s -07d25m26.4031s	10.36
116	2020-01-02T10:09:42.704 20amkdl_03428+04611 TMQ32020010200021776114.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.958	03h25m38.5353s +04d36m29.5043s	14.63
120	2020-01-02T10:05:14.537 20amkcy_04489-03946 TMQ42020010200021774816.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.956	04h29m19.8435s -03d56m45.5029s	12.36
1	2020-01-02T16:02:38.498 20amlcg_05309+12310 TMQ32020010200021840614.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.944	05h18m33.8163s +12d18m34.7262s	6.8

	20amknt_05285-04523 TMQ22020010200021802932.fits Tracklet Search Circle fit	Satellite NEO NEOCP	GIF		0.895	05h17m06.9861s -04d31m28.2281s	7.28
19	2020-01-02T15:00:34.544 20amkwf_05498-04235 TMQ12020010200021824944.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.892	05h29m52.3445s -04d14m16.6638s	5.73
8	2020-01-02T15:13:40.957 20amkxh_07252+31691 TMQ22020010200021827713.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.887	07h15m06.8848s +31d41m33.1599s	6.25
79	2020-01-02T12:02:47.375 20amkpk_02634+01881 TMQ12020010200021807232.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.887	02h38m00.6009s +01d52m41.7195s	14.86
64	2020-01-02T12:10:29.257 20amkqg_02473-05748 TMQ22020010200021809432.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.881	02h28m21.6532s -05d44m55.3739s	15.15
68	2020-01-02T12:09:37.519 20amkqe_02499+08385 TMQ22020010200021809242.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.881	02h29m54.2345s +08d23m05.277s	15.39
81	2020-01-02T12:02:11.739 20amkpi_02756+01494 TMQ12020010200021807022.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.881	02h45m23.1962s +01d29m46.7819s	10.92
102	2020-01-02T11:25:12.068 20amklt_04708-04014 TMQ12020010200021797723.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.881	04h42m28.2843s -04d00m57.0347s	7.13
111	2020-01-02T10:17:05.653 20amkeg_04622-05985 TMQ22020010200021778212.fits Tracklet Search Circle fit	Both Satellite NEO NEOCP	GIF		0.88	04h37m18.4347s -05d59m08.097s	7.18
115	2020-01-02T10:11:46.413 20amkdr_03181+02923 TMQ12020010200021776734.fits	Both Satellite NEO	GIF		0.879	03h10m51.2492s	15.84

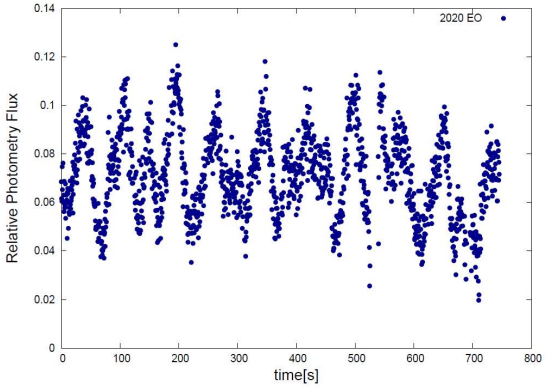
Able to find10-100 of Near Earth Object

8NEO registered by IAU by March 2020

#	name	Discovery date	Estimated diameter
8	2020 FA2	2020/3/18	~10m
7	2020 EO	2020/3/12	~24m
6	2019 XL3	2019/12/15	~13m
5	2019 XT2	2019/12/08	~17m
4	2019 XM2	2019/12/05	~18m
3	2019 VD3	2019/11/05	~21m
2	2019 SU10	2019/09/25	~12m
1	2019 FA	2019/03/16	~6m



Orbit of 2019SU10

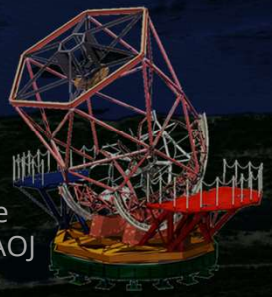


Light Curve of 2020EO (diameter ~10m)

Multi-messenger gravitational wave astronomy in the 2020s

Listen incoming of gravitational wave

Gravitational-wave observatory KAGRA



3.8m SEIMEI telescope
Okayama/Kyoto U, NAOJ

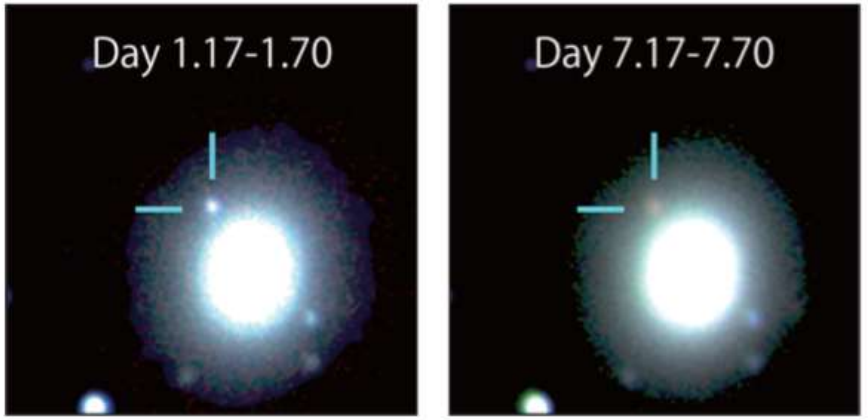
Tomo-e Gozen
Kiso, UTokyo

Aim the origin of the gravitational wave

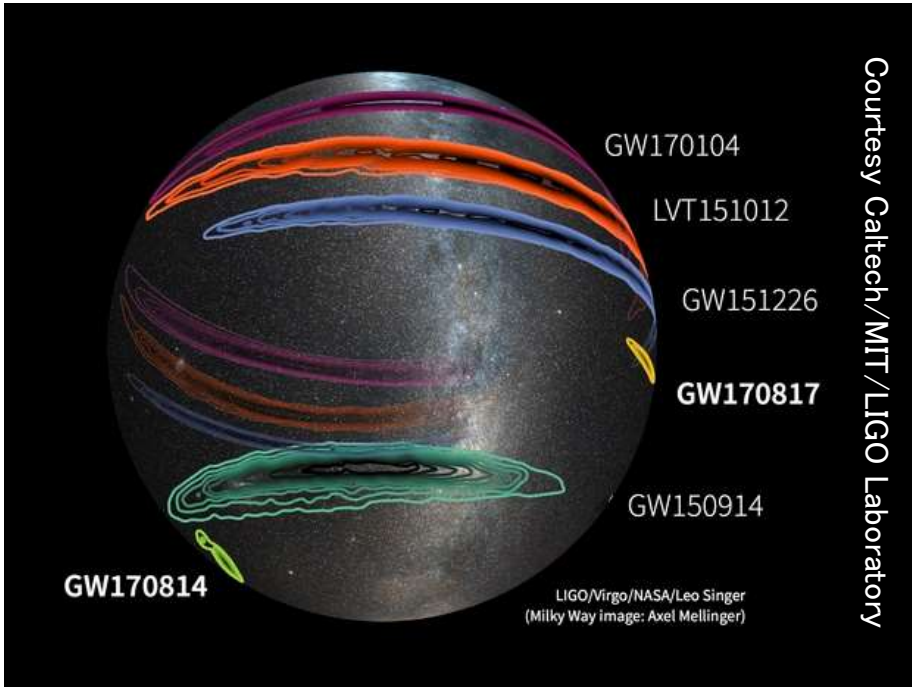
Find out an origin of the gravitational wave

Targeted observations
GW followup

- A kilonova associated with a GW event is found only in one case so far (GW170817/AT2017gfo).
  - Properties of kilonovae are still highly uncertain.
    - e.g., ejecta mass distribution, r-process abundance pattern
- typical localization of GW events ~ several × 100 deg^2
  - wide FoV and rapid readout speed of Tomo-e Gozen enable quick survey of a large area

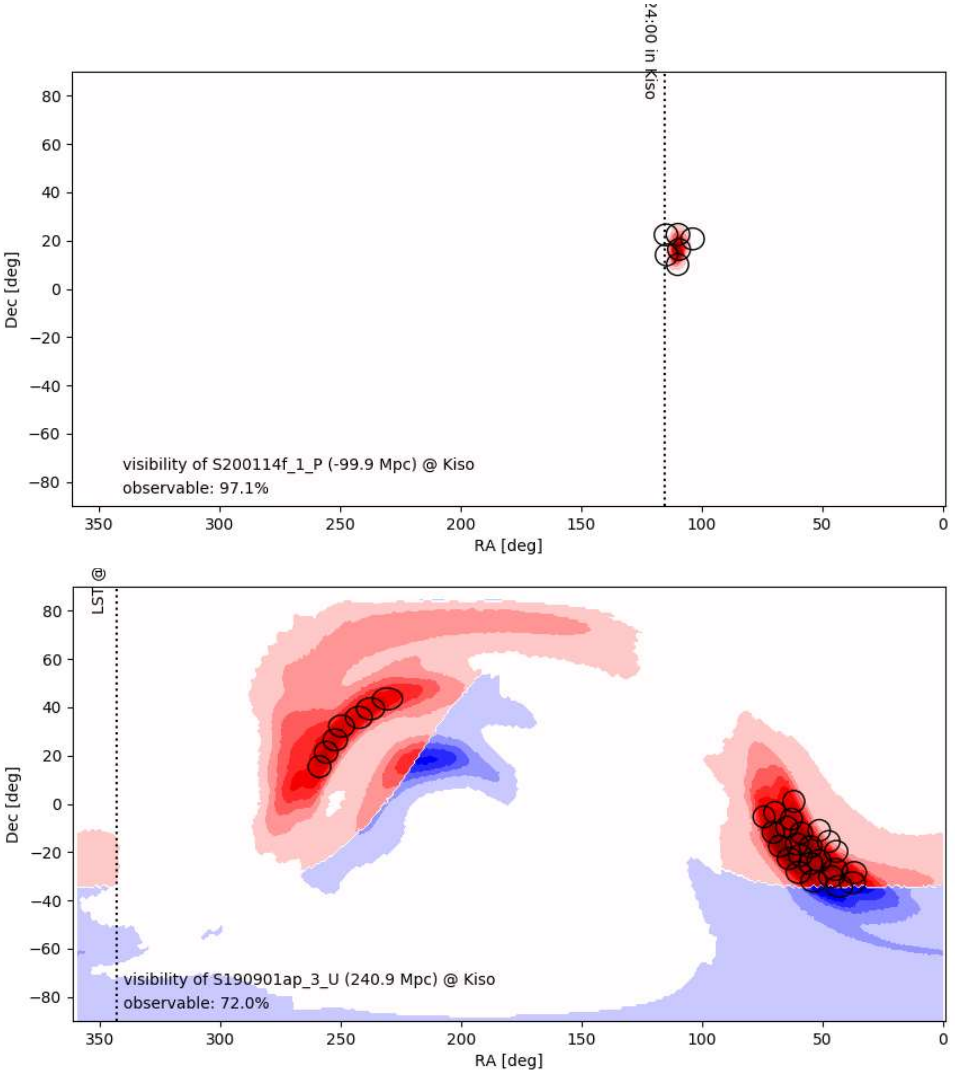


Utsumi et al. (2017, Subaru/HSC)



GW followup

- An automated system starts follow-up observation of GW events triggered by VOEvent alerts.
  - No observer needs to attend.
- During O3, Tomo-e Gozen followed 26 GW events and observed > 7,000 deg^2 in total.
  - No EM counterpart of a GW event is found during O3 neither by Tomo-e Gozen or by other telescopes.
  - GW events detected during O3 are more distant than GW170817.
- The automated observations are conducted as intended.



Probability skymaps of GW events with good and poor localization precision. Red colored region is visible from Kiso. Black circles represent telescope pointings computed by the automated system.

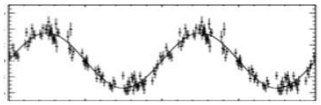
Tomo-e high-speed programs

Seconds or shorter timescale events

Fast spinning WDs

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

P = 1 – 100 sec

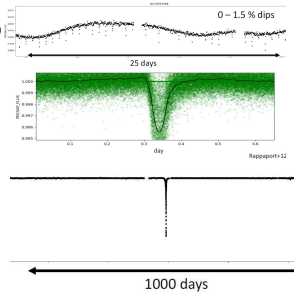


Kashiyama, Kawana+

Peculiar light curves of exoplanets

Evaporating rocky planet?
Alien's artificial planet?

Kawahara+ **t ~ 10 sec**



Keplar's light curve

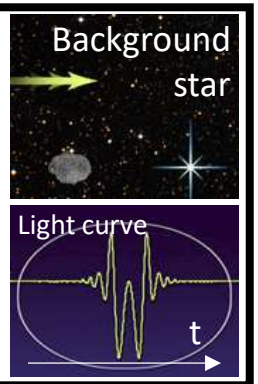
Occultations of small bodies

A few events per year

Km-size objects outer Neptune

Duration time ~ 0.3 sec

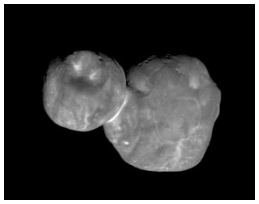
Watanabe+



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

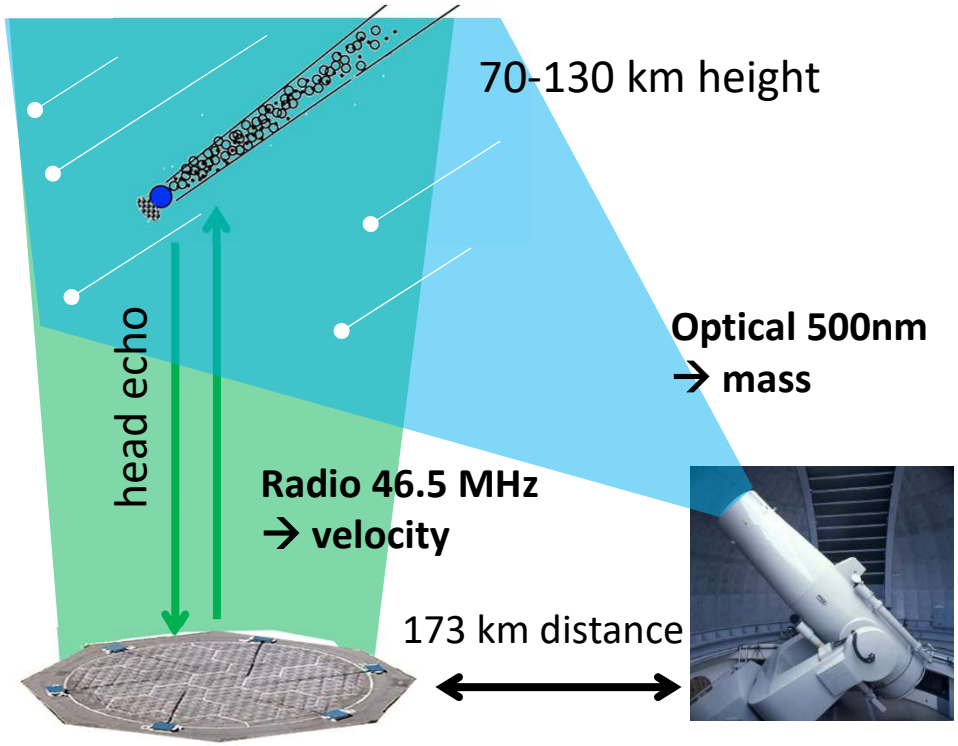
Optical counterparts of FRBs?
Unknown high-energy burst?
Unknown objects near earth?
Unknown physics? **t ≪ 1 sec**

Unknown unknown

Tomo-e high-speed programs

Ohsawa+2020

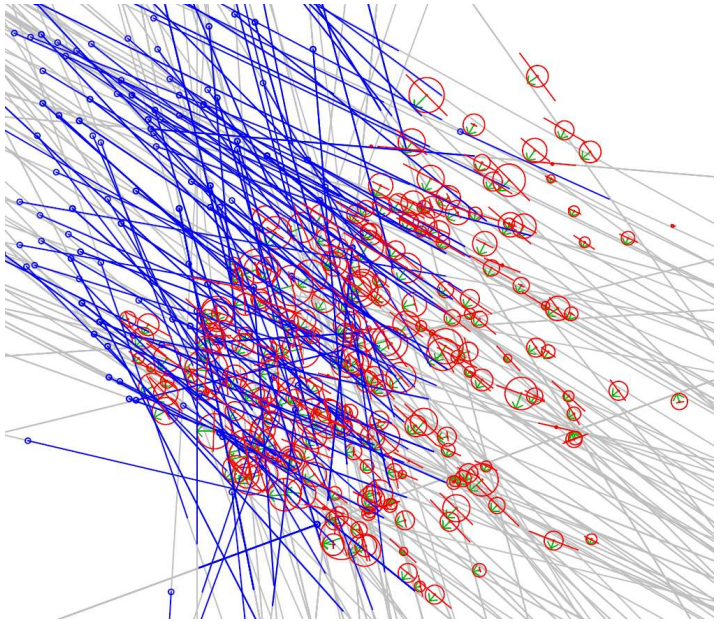
First simultaneous observations of faint meteors with optical and radio wavelengths



MU radar, Kyoto U @Shiga, Japan

Kiso Tomo-e @Kiso

331 simultaneous detections



Red: Tomo-e (optical)
Blue: MU radar (radio

5 deg

Successfully derived relationship between radar cross-section and optical brightness (= mass) for faint meteor.

Tomo-e high-speed programs

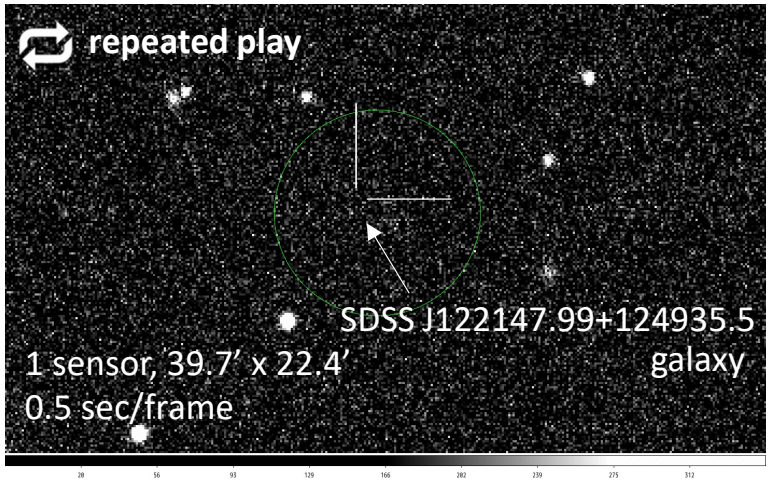
Test survey for single flash of t < 0.5 sec (= Tomo-e flash) with 8 sensors

- 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**

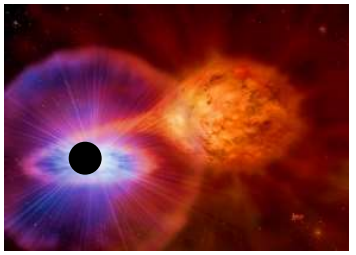


- Detected in only one frame, < 0.5 sec
- Single event (not repeated), 16-mag
- Same PSF as other sources, ~3"
- No color information obtained

Richmond+2020 search flash >=1.5sec

in partial read mode

Tomo-e very high-speed programs

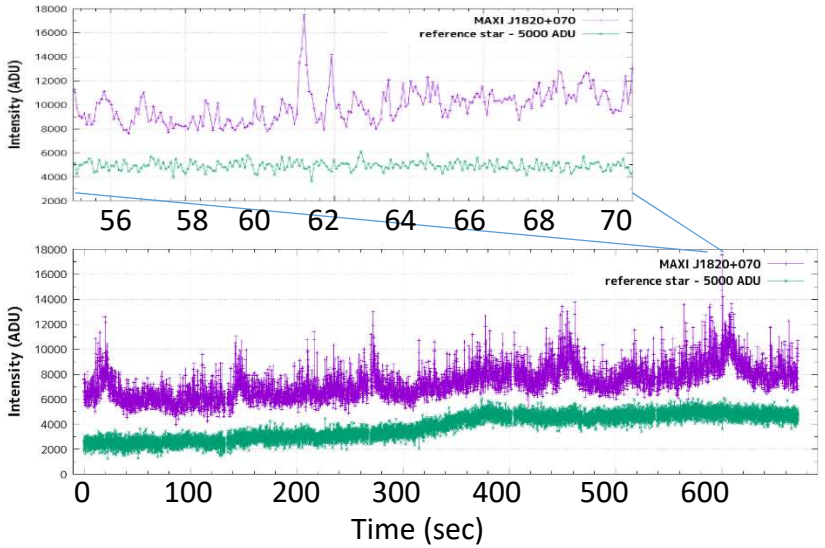


Detection of 10-msec scale flares in the black-hole binary MAXI J1820+070

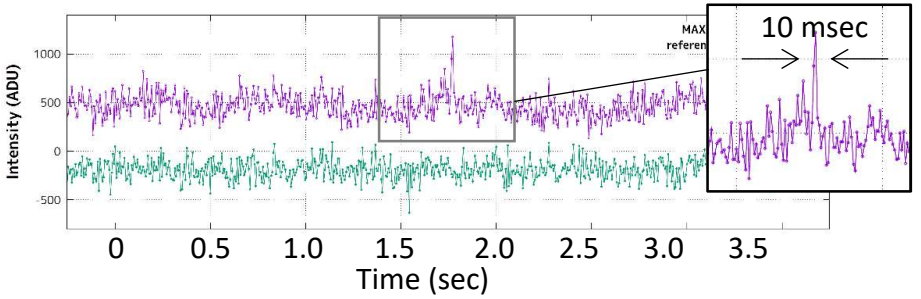
Sako et al. 2018, Atel #11426

Absolute time accuracy: ± 0.2 msec

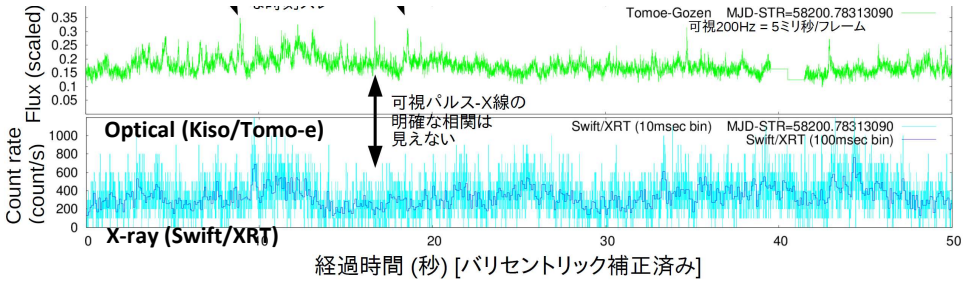
- **66.294 msec/frame,** 9.9' x 7.1‘,
  15 sets of consecutive 2,000 frames



- **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

in partial read mode

Tomo-e very high-speed programs

6.45-msec resolution observations of Crab pulsar

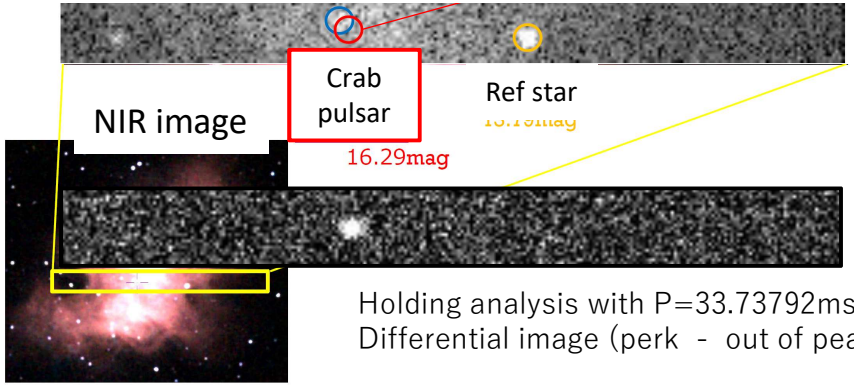
Periodic pulsations of 33.7 msec

Ichiki+2018, ASJ meeting

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

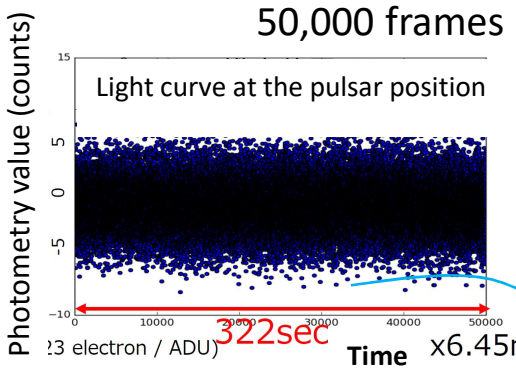
1 frame image (6.45msec exposure)

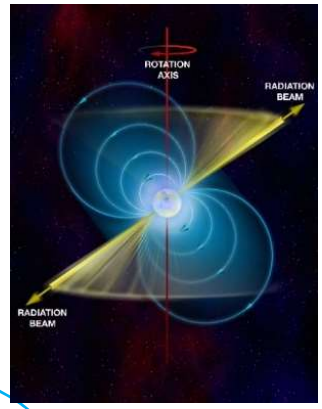
50,000 frame average image (total 322 sec exposure)

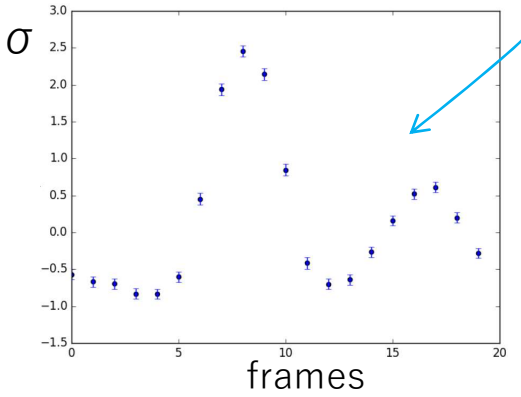


Holding analysis with P=33.73792msec
Differential image (perk - out of peak)

M1 Crab nebula (Supernova remnant)







Folding analysis
P=33.73792msec

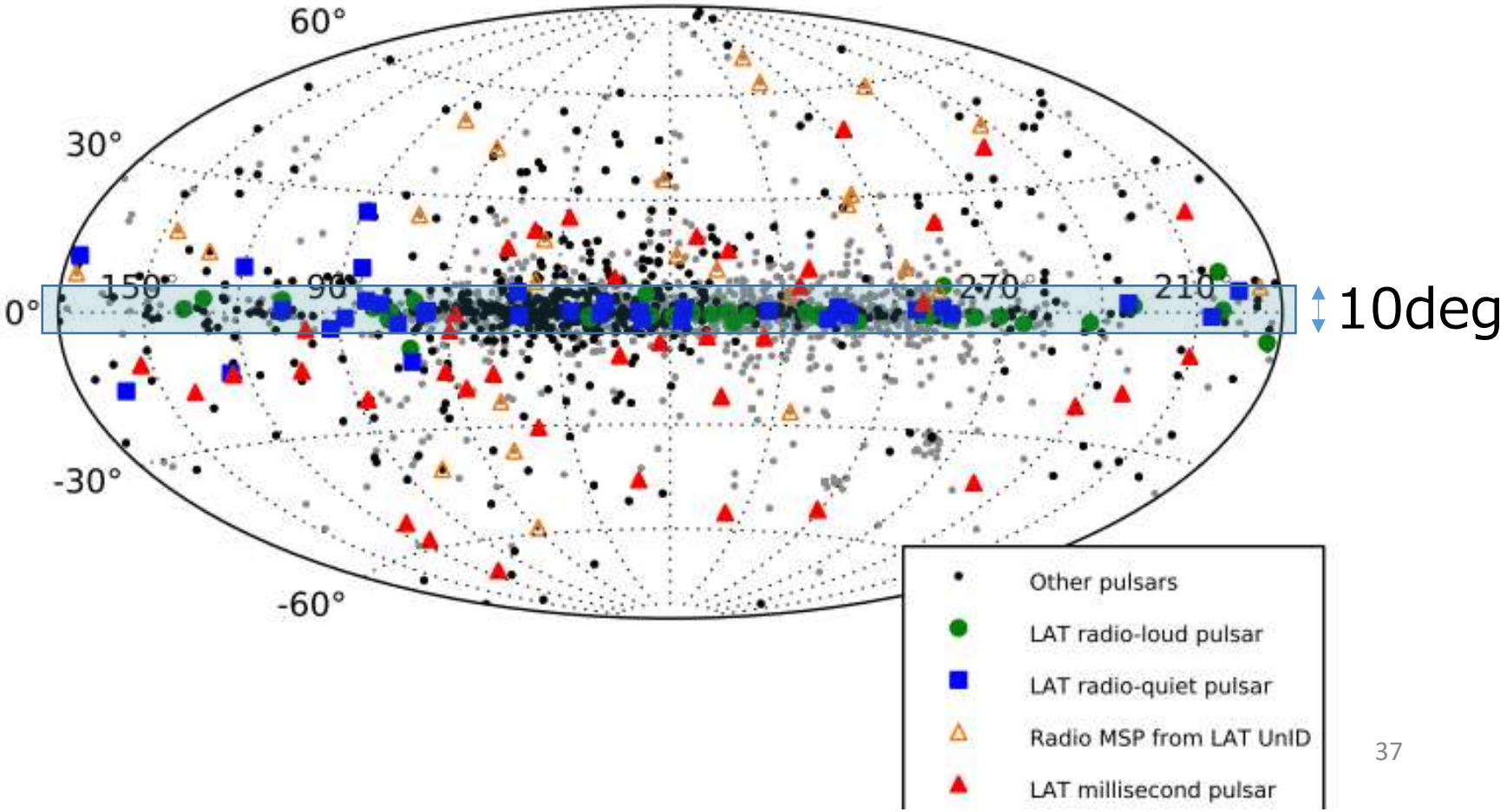
Pulsation clearly detected

Plans

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

First Optical Pulsar Survey with Tomo-e Gozen

Very high speed reading: 6.45msec/frame
0.053 deg^2 with 84 sensors
6 second observation per position : depth ~4kpc for L_{Crab}
$\Rightarrow$: 3800 deg^2 for ~40 clear nights



Summary

- Tomo-e Gozen Camera: First Wide-Field CMOS imager
- High time resolution optical imaging (area per shot)
  0.5sec/frame (20 deg^2) ~ 6msec/frame (0.053deg^2)
- Northern sky patrol (7000deg^2 1-2/night) and
  high cadence survey (2000 deg^2, every 30min)
- Various Scientific Targets
  GW/ν/FRB/GRB optical counter part, AGN, SN, Nova,
  compact binary, Pulsar, ..
- Observations automated, Data analysis Pipeline being developed

Very welcome for your joining Tomo-e collaboration!

TOMO·E GOZEN