Optical Observations of Faint Meteors with the Extremely Wide Field Mosaic CMOS Camera: Tomo-e Gozen

Ryou Ohsawa (Univ. of Tokyo)

S. Sako, A. Hirota, K. Morita, S. Abe, J. Kero, D. Kastinen, T. Nakamura, F. Usui, Y. Sarugaku, M. Sato, Y. Fujiwara, T. Ootsubo, K. Arimatsu, T. Kasuga, J. Watanabe, and the Tomo-e Gozen project

2019.03.06

Outline

1. Brief introduction of optical meteor observations
2. Kiso Observatory and Tomo-e Gozen
3. Faint meteors captured by Tomo-e Gozen
   - Observations with a prototype camera in 2016
   - MU radar & Tomo-e Gozen observations in 2018
4. Other science topics with Tomo-e Gozen

Summary

About 1,000 meteors can be detected in a night with the Tomo-e Gozen camera.
A small-end size distribution is provided with optical-radar simultaneous observations.
Tomo-e Gozen has a high performance in detecting faint transient events.

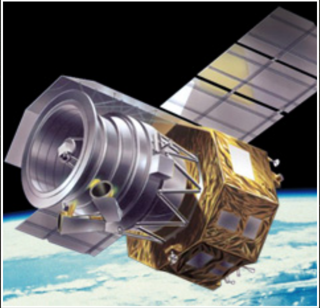
Self Introduction

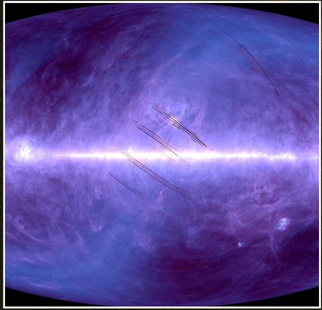
Name: Ryou Ohsawa

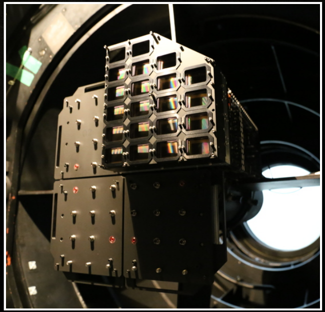
Affilication: The Institute of Astronomy, The University of Tokyo

Science: Optical/Infrared Observatoinal Astronomy

Formation and Evolution of dust grains in the Universe
Development of Cameras (MIMIZUKU, Tomo-e Gozen)







Dust grains

Solid-state material in the Universe

Obscure objects, absorbing light

Carriers of heavy elements (e.g., Mg, Fe, Si)

- important role in galactic chemical evolution
- ingredients for planets, satellites, and lifes

Spitzer/IRAC image of M81 (nasa.gov)
(B,G,Y,R) = (3.6 μm, 4.5 μm, 5.8 μm, 8.0 μm)

Ubiquitously observed

- evolved stars, star-forming regions, and distant galaxies

Important sites for chemical reactions

- formation of H_2 and other molecules

Draine (2011), Princeton Univ. Press; Field (1974), AJ, 187, 453; Jenkins (2009) ApJ, 700, 1299

Size Distribution of Dust Grains

Important characteristics of dust grains

⇆ not easy to measure the size of dust particles

Grains around evolved stars like AGB-stars

- large (~μm) grains formed around evolved stars — e.g., Ohnaka et al. 2016 A&A...589A..91
- dust size distribution ~ single population?

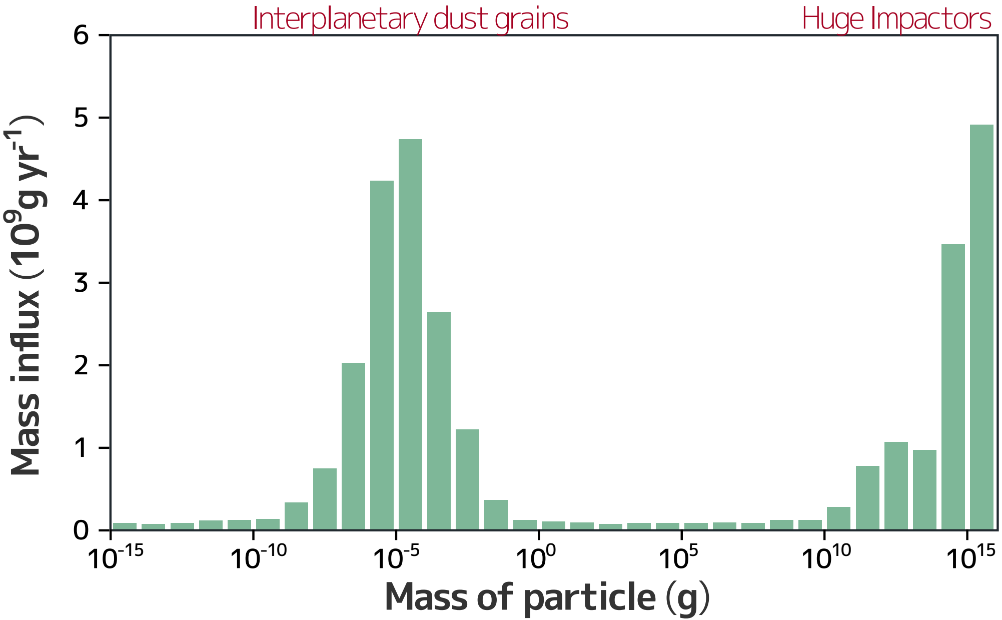
Grains in the interstellar space

- size distribution ~ a single power-law function — e.g., Mathis et al. 1977ApJ...217..425
- shattering in diffuse interstellar space — e.g., Jones et al. 1996ApJ...469..740

Grains in the Solar System $dN(D) \propto D^{-q} dD$

- 4P/Faye: 3 μm — 5 mm, power law (q ~ 3.5) — Sarugaku et al. 2007 PASJ...59L..25
- 2P/Encke: 30 μm — 110 mm, power law (q ~ 3.4) — Sarugaku et al. 2015 ApJ...804..127

Mass influx onto the Earth



from Cosmic dust in the earth's atmosphere, Plane (2012)

Single Grain Experiment

1. Using instruments onboard spacecrafts

    Ulysses, Galileo, Cassini, Rosetta, DESTINY+, ...

    direct measurements of mass and chemical compositions

2. Sample return missions

    cometary dust (Stardust), asteroids (Hayabusa, Hayabusa-2, OSIRIS-REx), ...

3. Meteor observations

    using the atmosphere/surface of the Earth (other planets) as a detector

    the magnitude of the event corresponds to the mass (energy)

Grün et al. (1992), A&AS, 92, 411; Srama et al. (2004), SSR, 114, 465; Sandford et al. (2006), Science, 314, 1720

Observations of Meteors

Optical observations

- direct and passive measurement
- optical brightness ∝ kinetic energy ∝ mass
- trajectory from multi-site observations

Radar echo observations

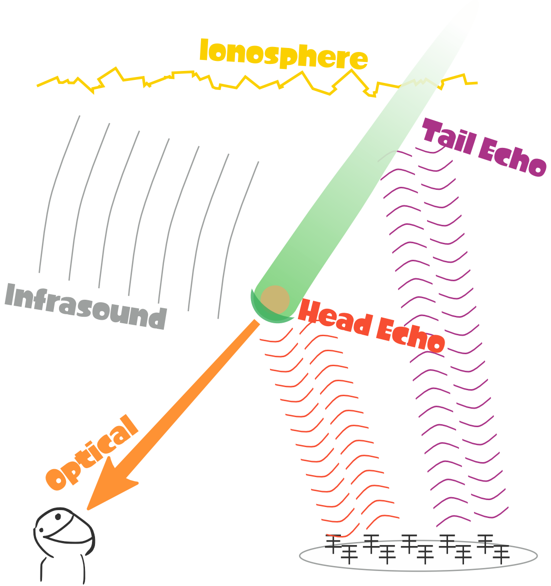
- direct and active measurement
- volume of ionized region ∝ energy ∝ mass
- trajectory from a single-site observation (head echo)

Infrasound obsrevations

- indirect and passive measurement
- only available for large bolides

Ionosphere disturbance observations

- indirect and passive measurement
- only available for large bolides



Jenniskens (2006), Cambrige Univ. Press; Mathews et al. (1997), Icarus, 126, 157
Brown et al. (2007), JASTP, 69, 600; Yang et al. (2014), Radio Sci., 49, 341

Meteor Observation Networks

- Major Networks
  - Cameras for Allsky Meteor Surveillance (CAMS)
  - SonotaCo Network
  - European viDeo Meteor Observation Network (EDMONd)
- Mostly supported by amateur astronomers
- About 1,000,000 meteor orbits have been identified
- Observing down to +4 mag. (~1 cm, ~1 g)

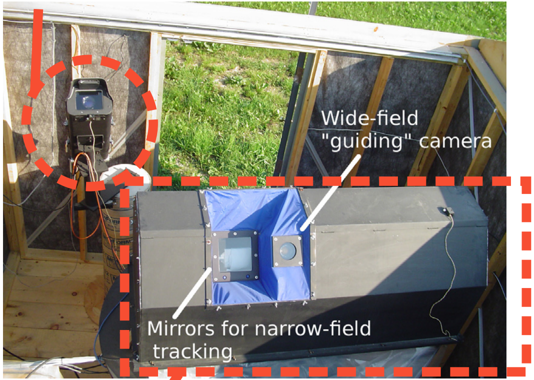
Canadian Automated Meteor Observatory (CAMO)

Automated observing system operated by the University of Western Ontario

Consists of two stations with two camera systems

High Resolution Wide-field Camera / High Resolution Narrow-field Camera

Wide-field Camera



Narrow-field Camera

Weryk et al. (2013), Icarus, 225, 614-622

Canadian Automated Meteor Observatory (CAMO)

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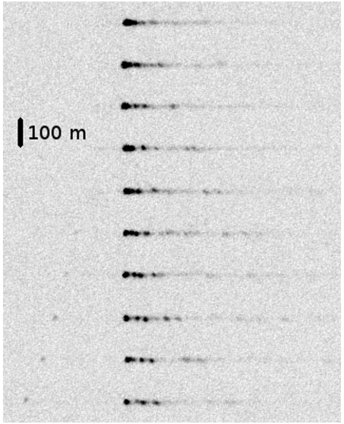
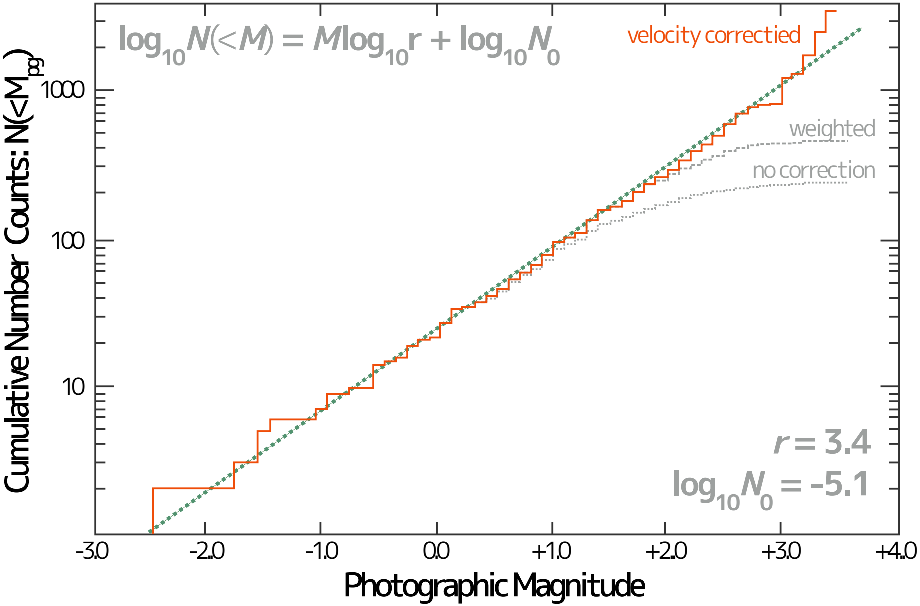


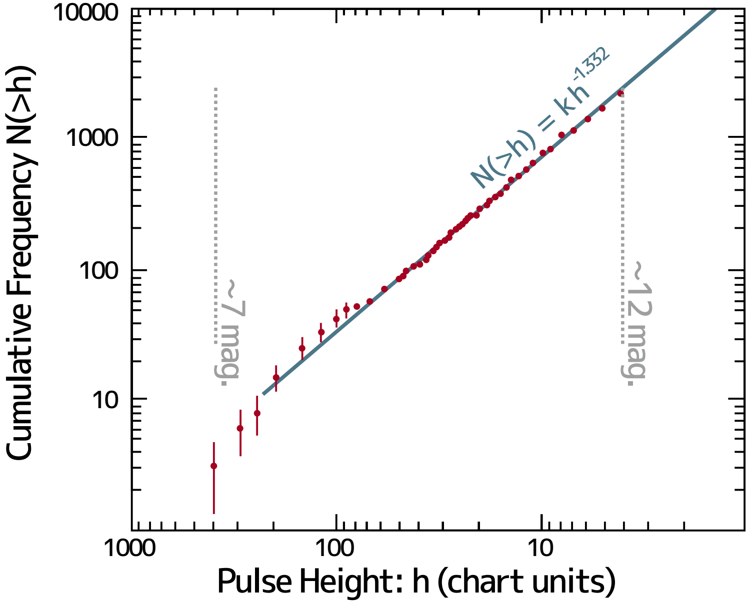
Weryk et al. (2013), Icarus, 225, 614-622

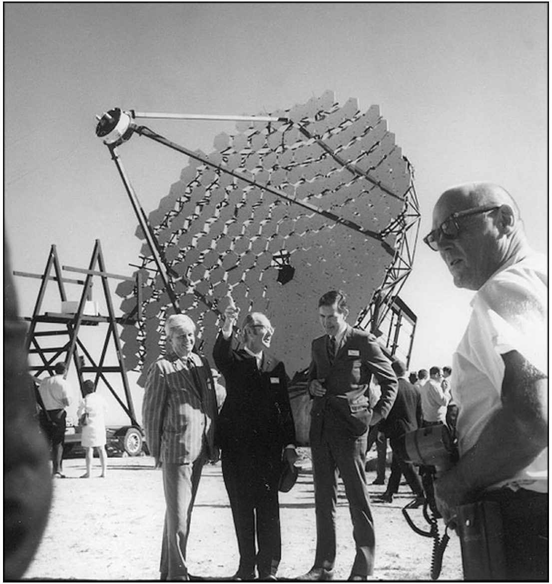
Luminosity Function of Sporadic Meteors



Luminosity function with SuperSchmidt camera, adapted from Hawkins & Upton (1958)

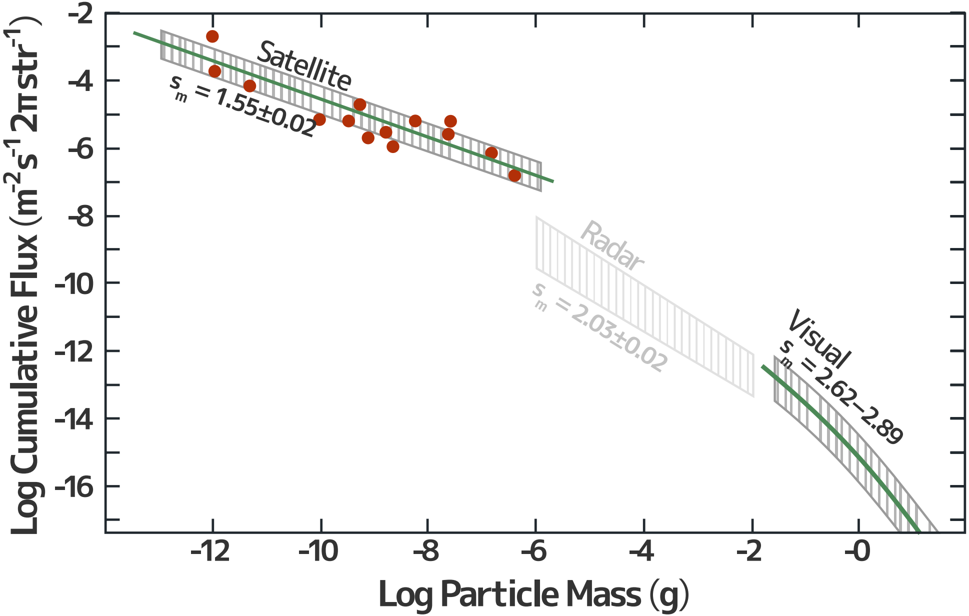
Luminosity Function of Faint Sporadic Meteors





Luminosity function with a 10-m reflector and a Phototube, adapted from Cook, et al. (1980)

Cumulative Mass Distribution



Cumulative flux of particles to the Earth's surface, adapted from Hughes (1987)

How to detect fainter meteors

Preferred Specifications

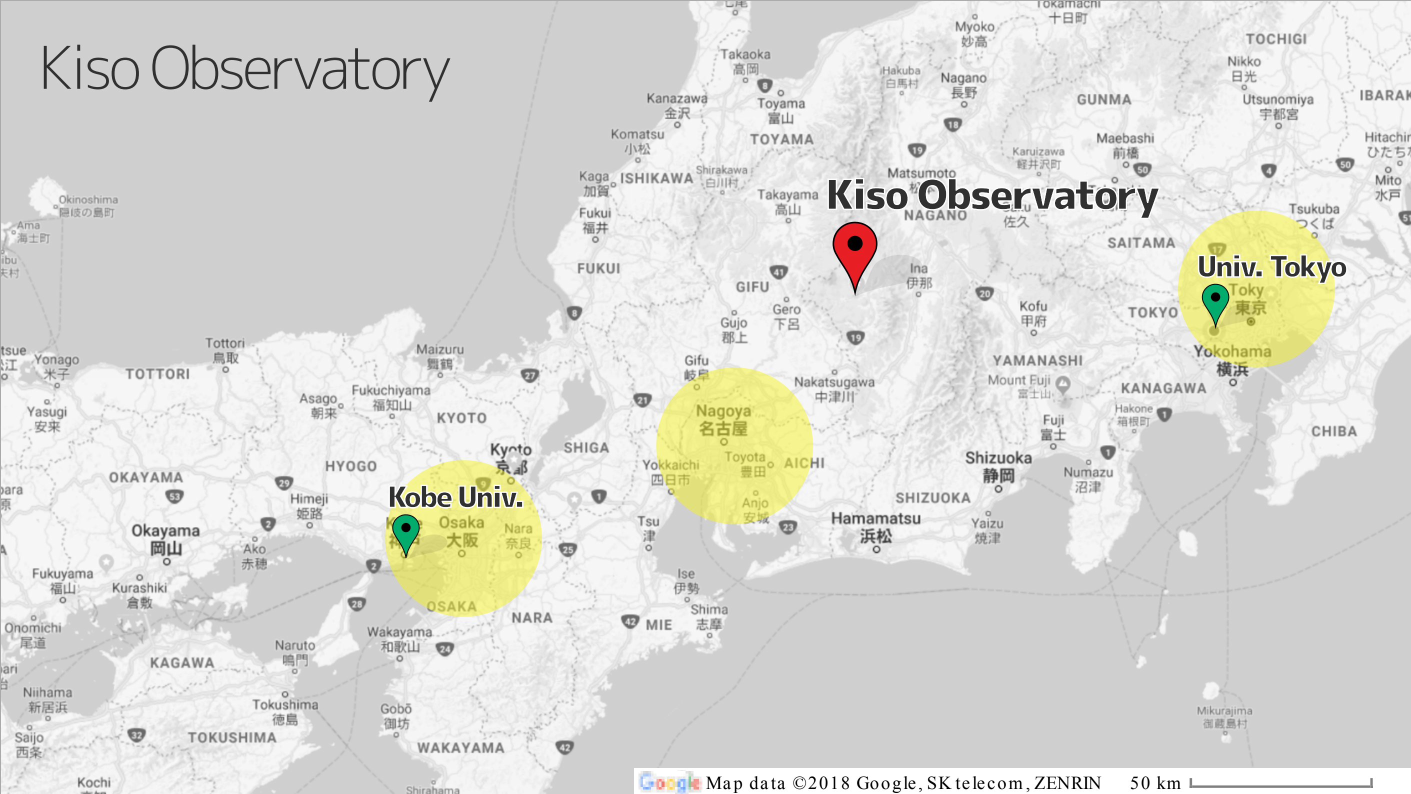
1. **Larger aperture** to collect more photons
2. **Larger field-of-view** not to miss meteor events
3. **Higher frame rate** to avoid/decrease the trail loss

Possible Solution

A high-sensitive video camera + A wide-field large telescope

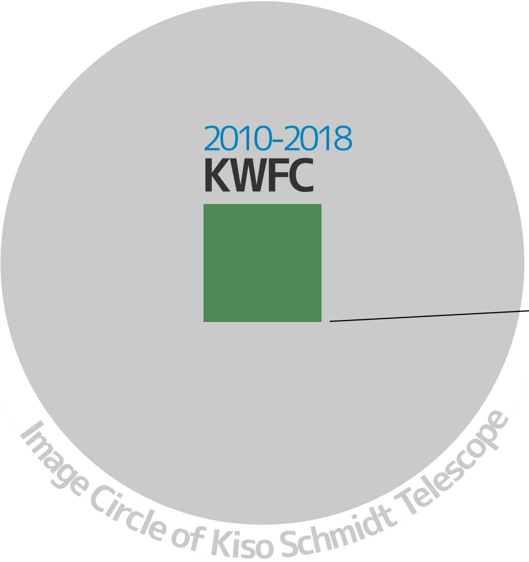

Kiso Observatory & Tomo-e Gozen

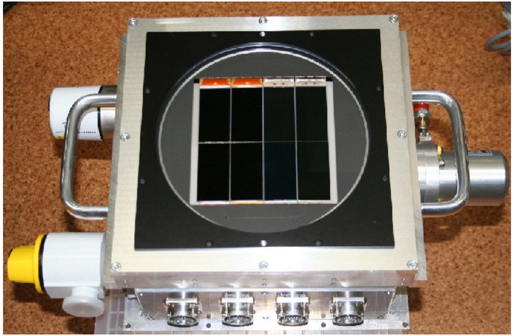
Kiso Observatory



Kiso Observatory

Previous Instrument: Kiso Wide Field Camera

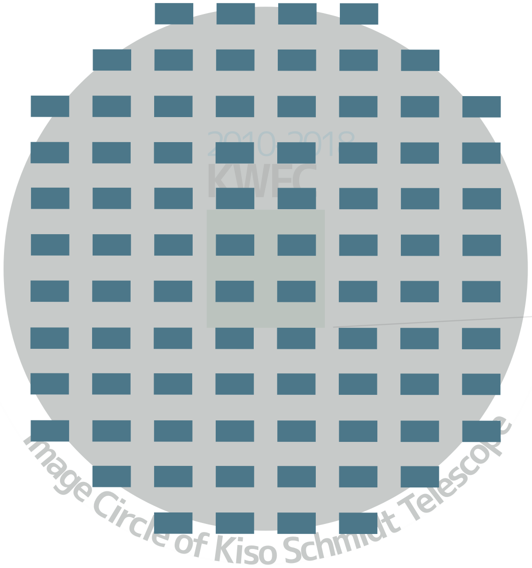




Kiso Wide Field Camera (KWFC)
2° × 2° FOV (8 CCD sensors)

Image of KWFC from the website of Kiso Observatory

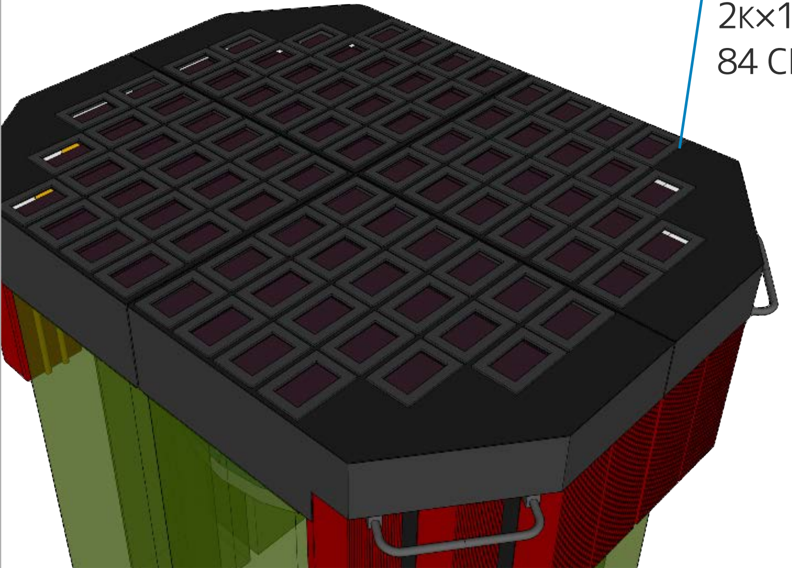
New Wide-Field CMOS Camera: Tomo-e Gozen

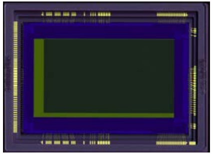


Kiso Wide Field Camera (KWFC)
2° × 2° FOV (8 CCD sensors)

Tomo-e Gozen

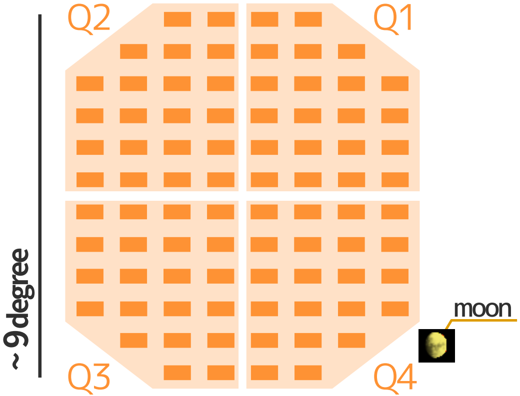
An overview of the camera modules





2K×1K CMOS image sensor by **Canon**

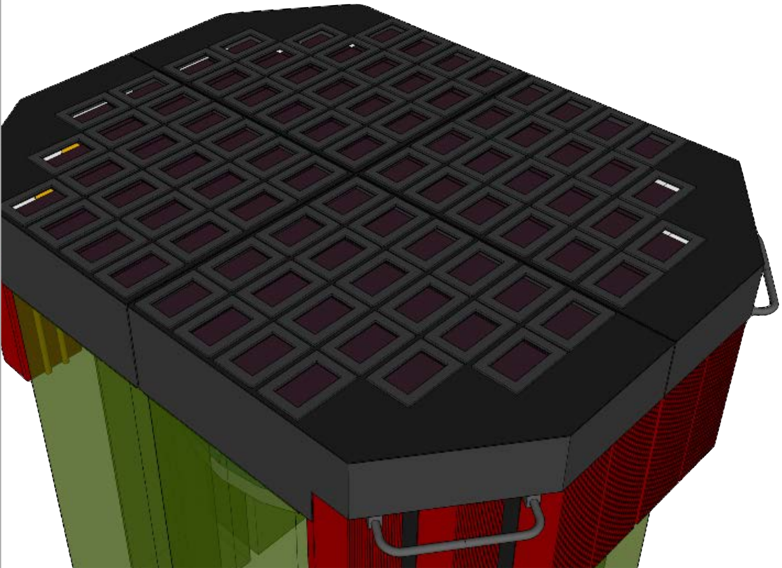
84 CMOS sensors are tiled to cover ~20□°



Composed of four camera modules

Tomo-e Gozen

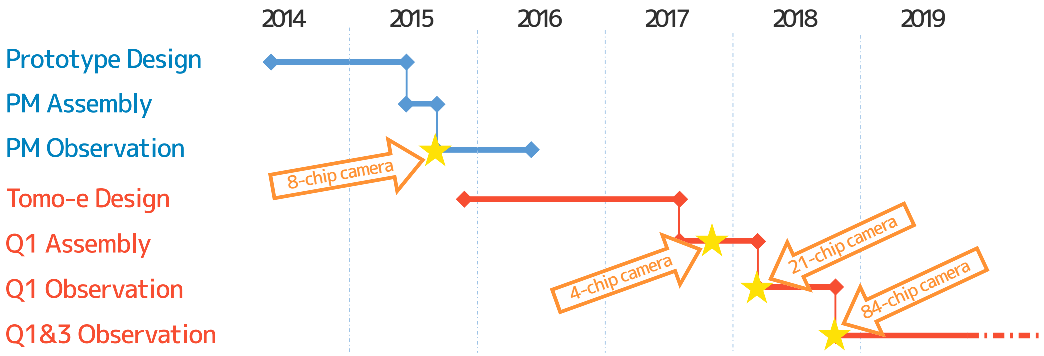
An overview of the camera modules

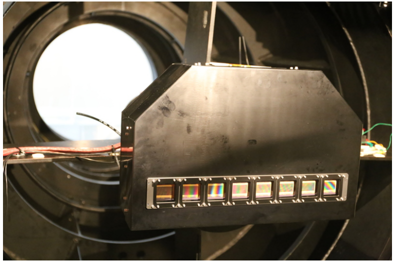


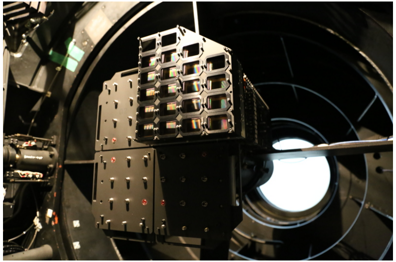
Specifications (Sako et al. Proc. SPIE, 2018)

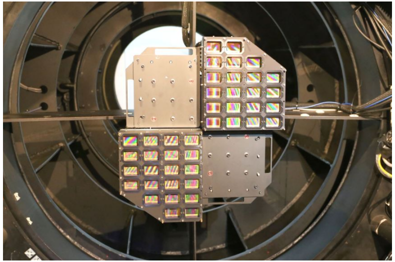
Observatory	Kiso Observatory
Telescope	1.0-m f/3.1 Schmidt telescope
Sensor format	2160×1200 pix chip^{-1}
Field of view	**39′.7×22′.4 × 84 chips (~20 deg^2)**
Pixel scale	19 µm, 1″.189 pix^{-1}
Wavelength	350–700 nm (peak at 500 nm)
Filters	optical broadband (transparent)
Frame rate	**2 Hz (max, continuous, full frame)**
Read noise	~1.9 e^- at 2 Hz
Dark current	~0.1 e^- sec^{-1} pix^{-1} at 277 K
Well depth	~6,400 e^-
5σ lim. mag.	**~18.5 mag. in 0.5 sec exposure**

Development of Tomo-e Gozen



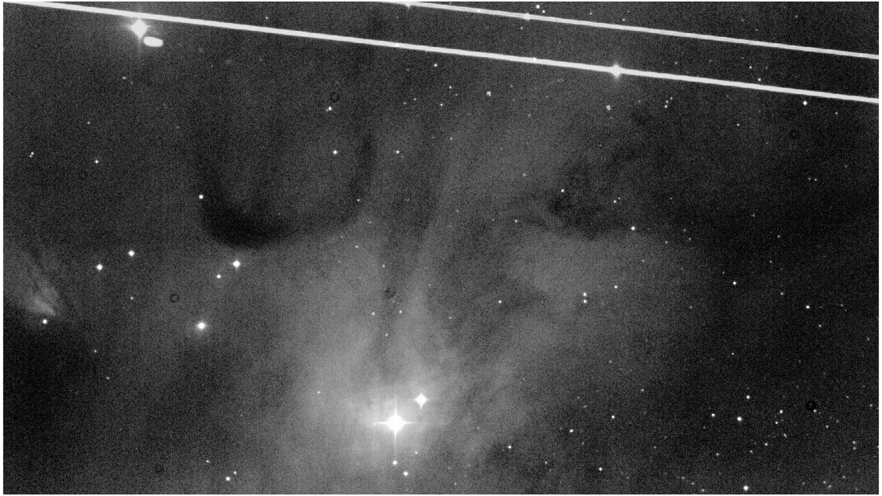


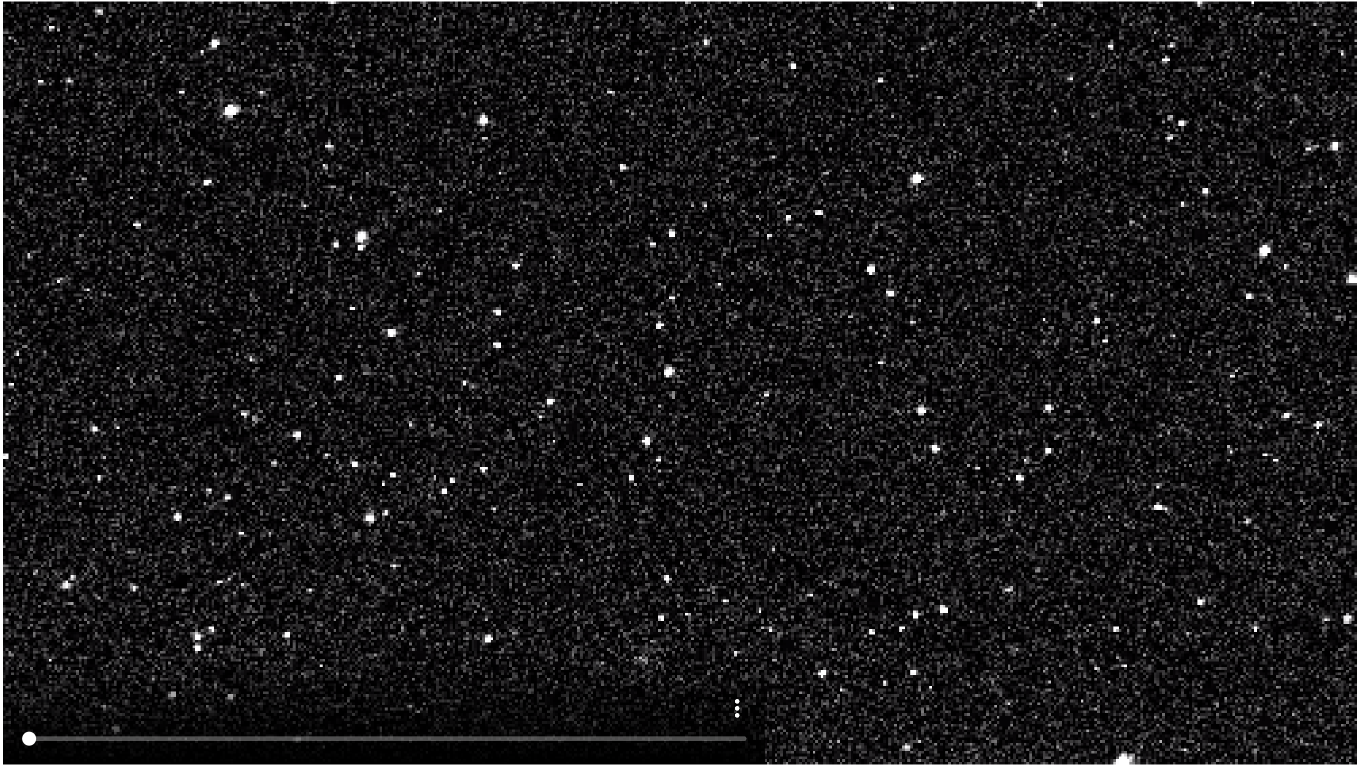




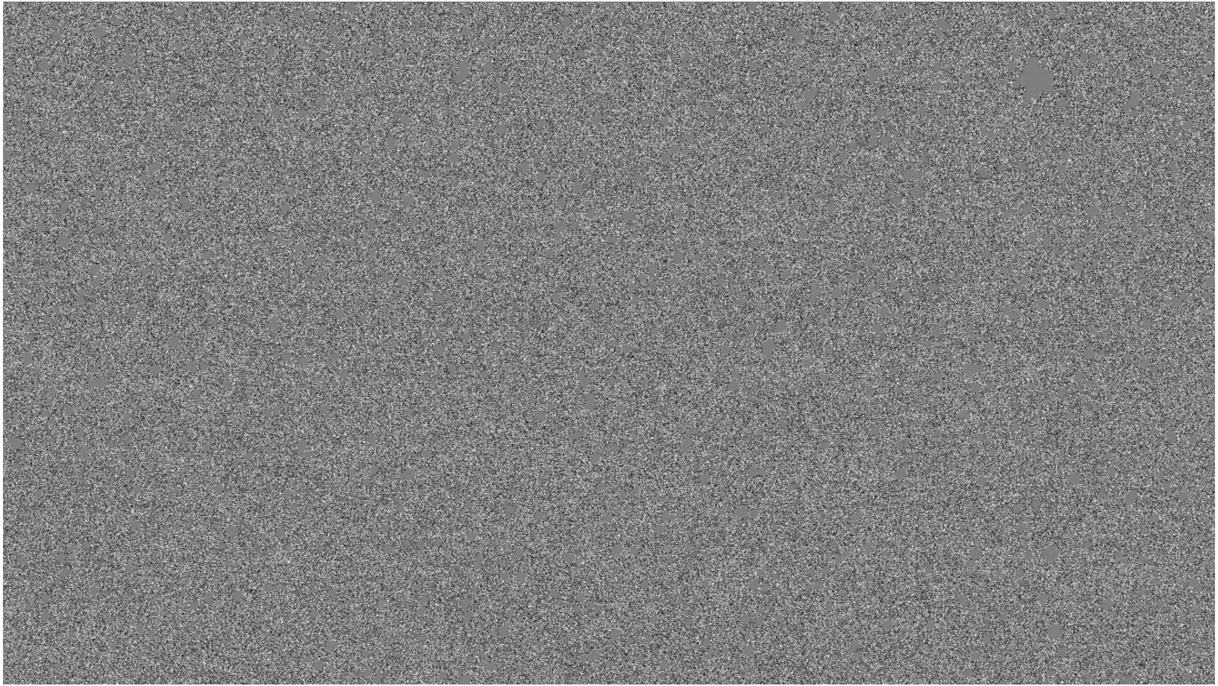
Meteors with Tomo-e Gozen

2 Hz observation ➪ meteors are captured as streaks and sometimes truncated.
Typical distance ~ 80–120 km ➪ meteors are defocused.
Expected limiting magnitude is ~12 mag at the *V*-band (taking the trail loss into account).

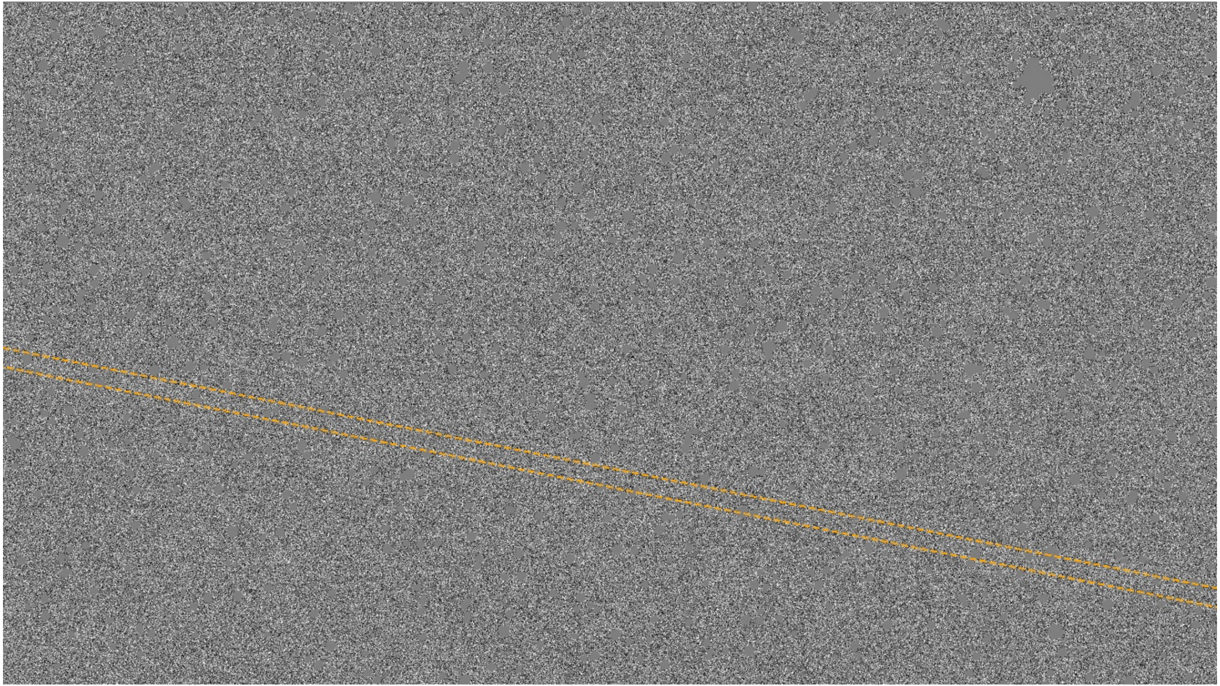




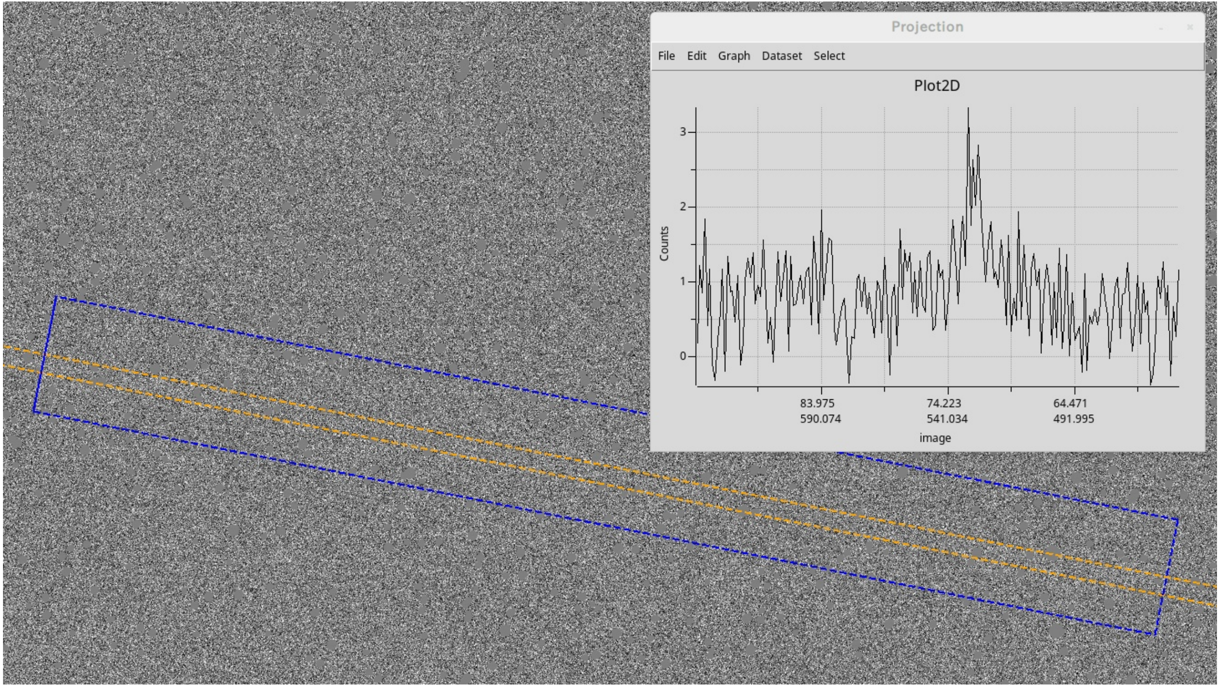
An image contains **a faint meteor** (stellar sources are masked)



An image contains **a faint meteor** (stellar sources are masked)

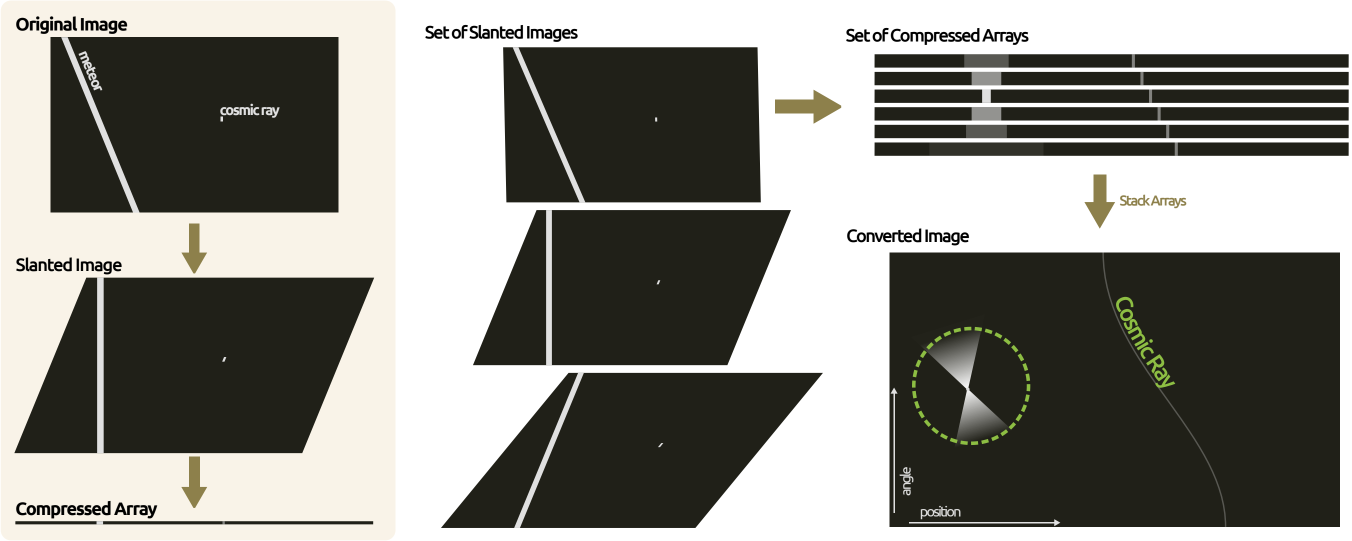


An image contains **a faint meteor** (stellar sources are masked)



Automated detection of lines

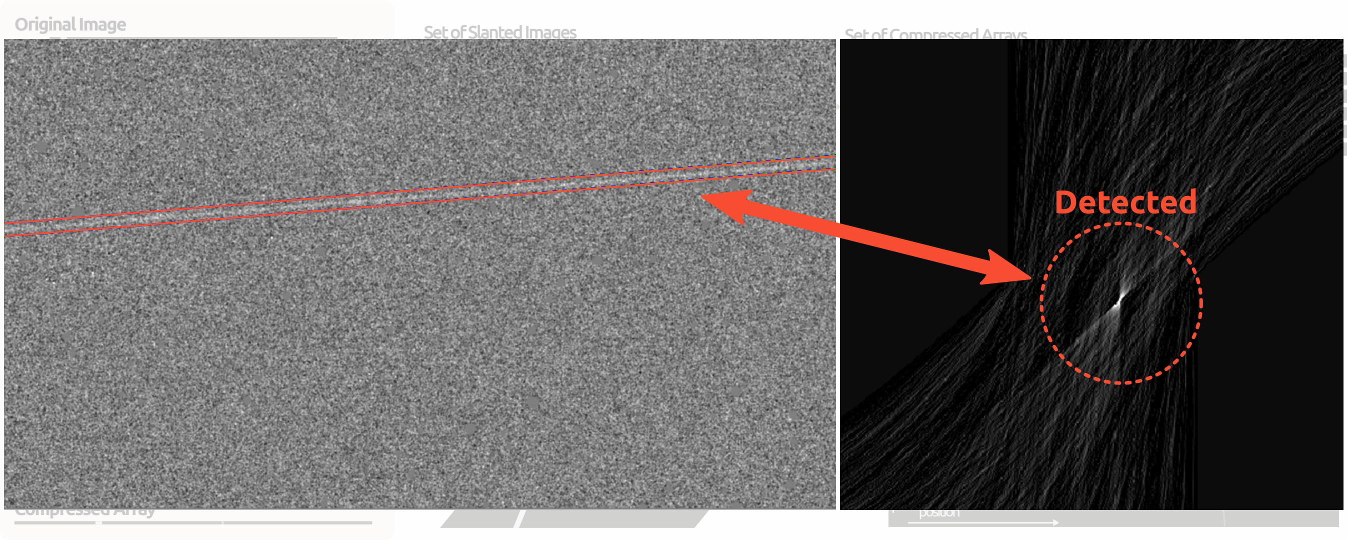
An algorithm based on the Hough transformation



Ohsawa et al. (2016), Proc. SPIE, 9913, 39

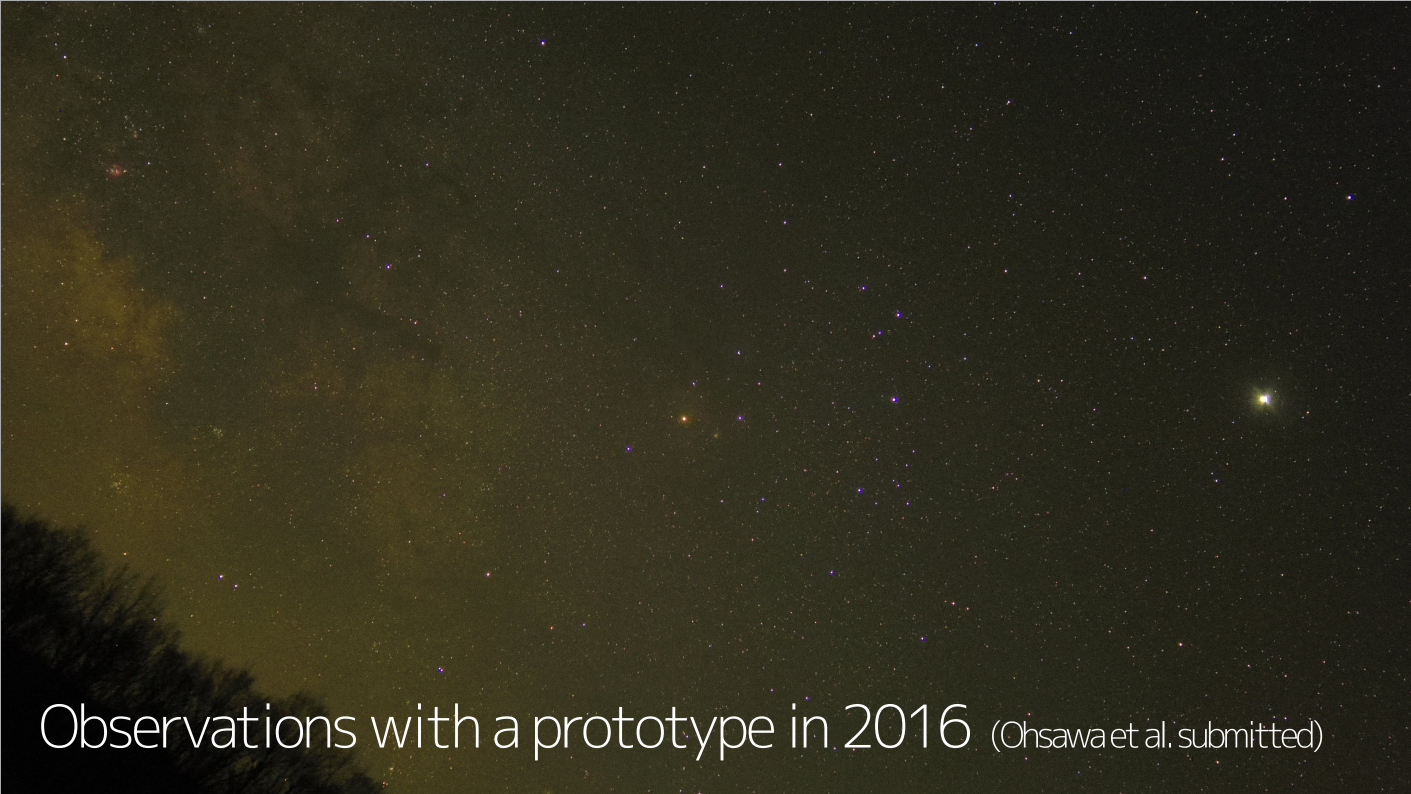
Automated detection of lines

An algorithm based on the Hough transformation



Ohsawa et al. (2016), Proc. SPIE, 9913, 39

Observations with a prototype in 2016 (Ohsawa et al. submitted)



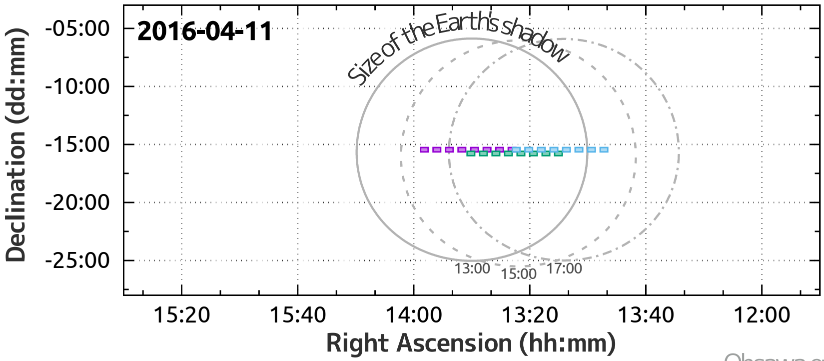
Overview of observations

Tomo-e Gozen (prototype) with 8 CMOS sensors.

2 Hz monitoring observations on 11 and 14 April, 2016.

Sidereal tracking, pointing the inside of the Earth's shadow every 2 hours.

Measure the video-rate magnitude assuming the velocity = $10°s^{-1}$ (Iye et al., 2004).



Ohsawa et al. (2019), P&SS, 165, 281

Details of Obeservations

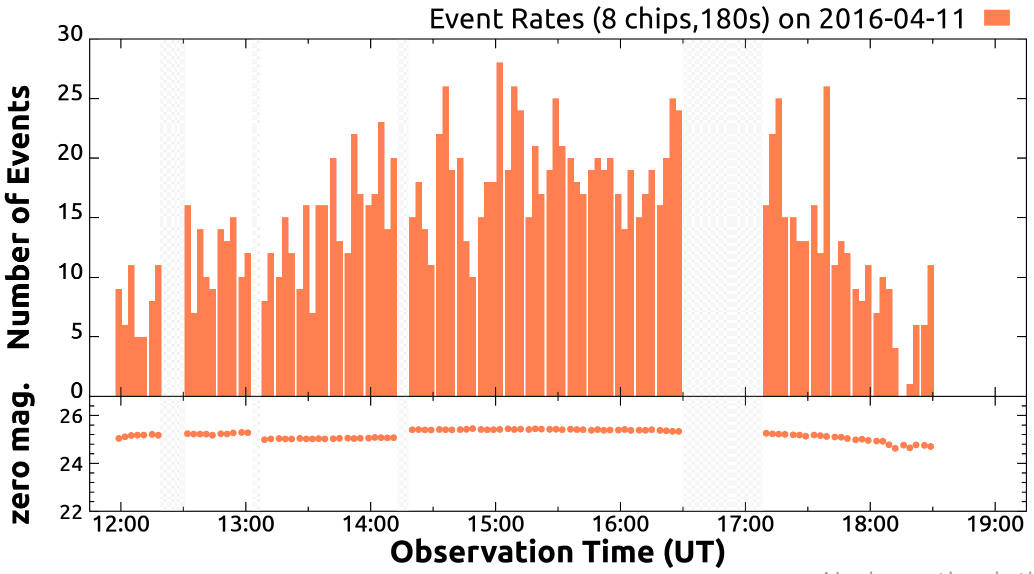
Obs. Date	2016.04.11	2016.04.14
Obs. Field	Inside the Earth's shadow	Inside the Earth's shadow
Exposures	1 set = 0.5 s × 360 frame	1 set = 0.5 s × 360 frame
Obs. Time	~5.1 hours	~5.5 hours
Filter	Blank	Blank
# Frames	290880 frm.	316800 frm.
Unique Meteors	1514 events	706 events
Mean Rates	~15 events/180s	~6.4 events/180s
Magnitudes*	4.5–12.5 mag.	4.5–11.5 mag.

*Apparent Video rate magnitude (Iye+ 2007)

Ohsawa et al. (2019), P&SS, 165, 281

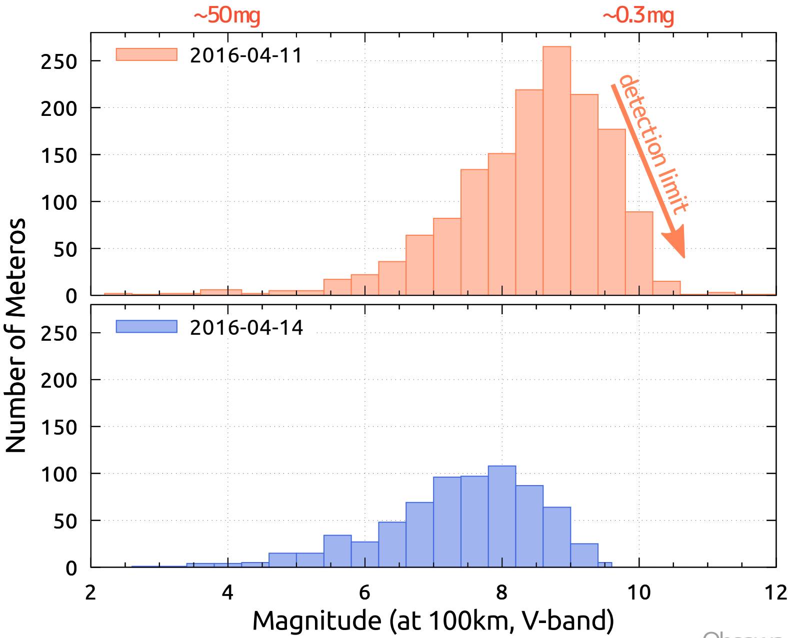
Unique Meteor Events

Event rates per 3 minutes on the first day



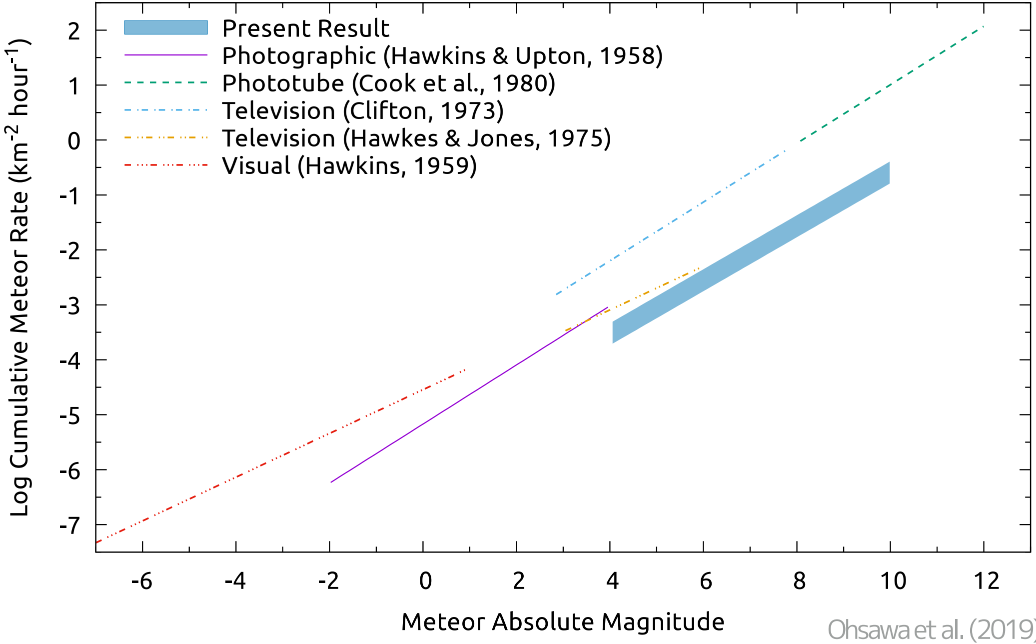
No observations in the shaded regions.

Meteor Magnitude Distributions



Ohsawa et al. (2019), P&SS, 165, 281

Luminosity Function



Ohsawa et al. (2019), P&SS, 165, 281

Short Summary

Kiso Observatory + Tomo-e Gozen

- 20 deg^2 CMOS mosaic camera mounted on a 1-m Schmidt type telescope
- detection limits in 2 Hz monitoring: ~18 mag (star) & ~12 mag (meteor)

Meteor Observation with Tomo-e Gozen (8 sensors)

- more than 1,000 unique meteor events in a night
- meteor limiting magnitude ~12 mag. was confirmed in real observations
- providing a practical tool to investigate ~0.1–10 mg interplanetary grains

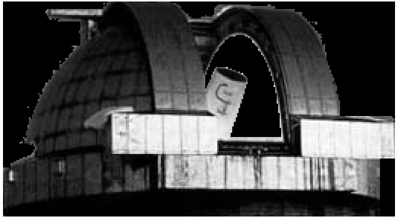
Limitation of Tomo-e Gozen

Kiso Observatory + Tomo-e Gozen is unique

no counterpart for simultaneous optical observations

⇨ no information on the trajectory or the apparent velocity

⇨ large uncertaninty of the meteor brightness

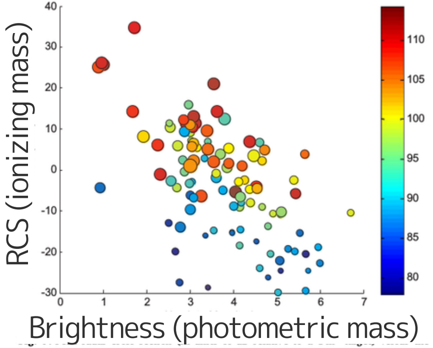


Kiso Schmidt + Tomo-e Gozen

Non-existent counterpart


MU Radar & Tomo-e Gozen observations in 2018

Previous Works



observed magnitude at the same height as the RCS measurement for the head echo with symbol size proportional to speed and color coding by height (in km). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

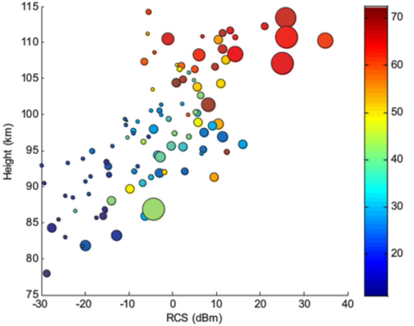
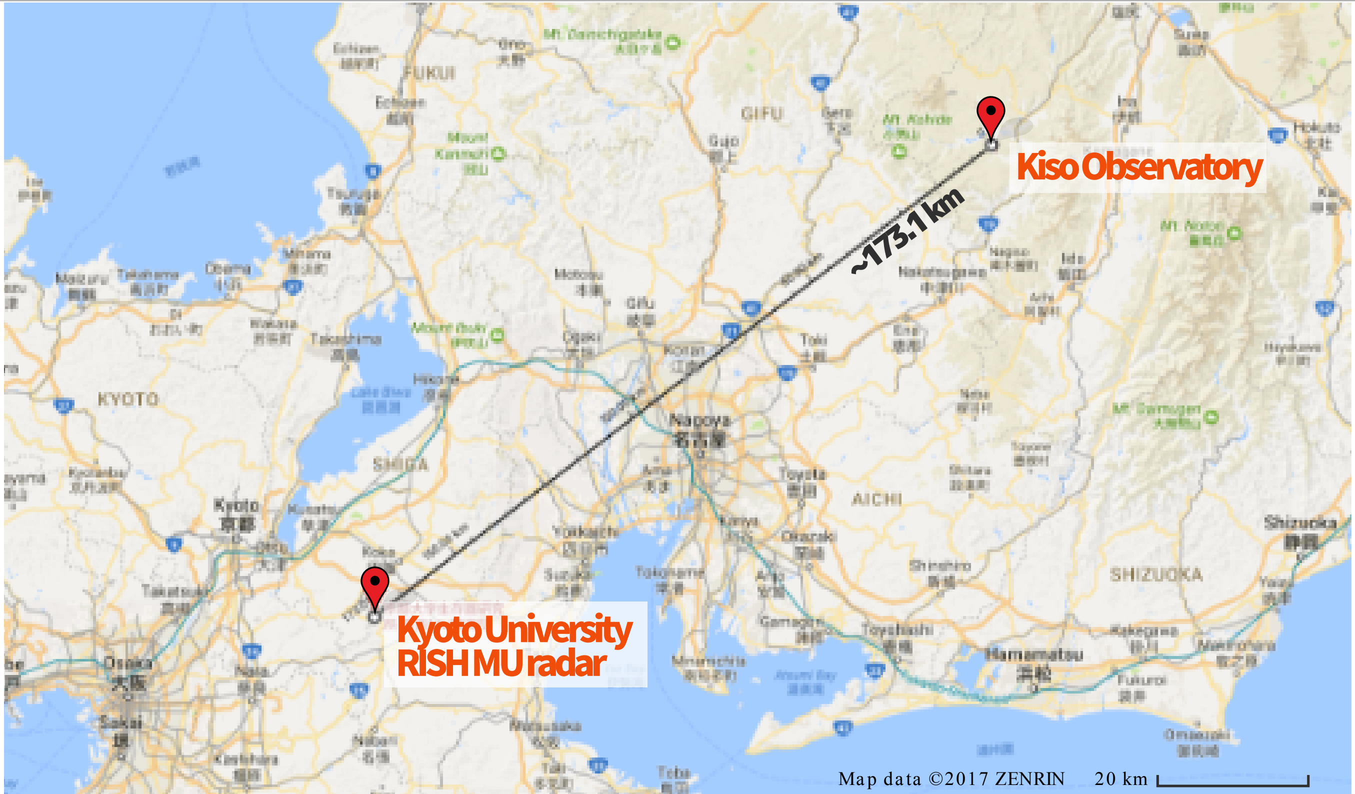


Fig. 10. Height versus peak radar cross section (in units of dB relative to a 1 m^2 target) as a function of speed (color coding in km/s) with symbol sizes representing peak meteor absolute brightness in watts. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Brown et al. (2017), P&SS, **142**, 25

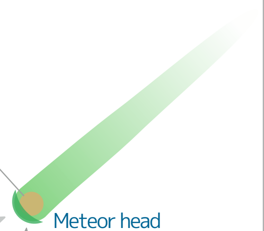
Nishimura et al. (2001)	MU radar & optical camera	35 meteors / 2 nights
Michell (2010)	PFISR & optical camera	7 meteors / 1 night
Campbell-Brown et al. (2012)	EISCAT & two optical cameras	4 meteors / 11 hours
Michell et al. (2015)	SAAMR & optical camera	6 meteors / 1 night
Brown et al. (2017)	MAARSY & two optical cameras	105 meteors / 242 hours


Kiso Observatory
~173.1 km
Kyoto University
RISH MU radar
Map data ©2017 ZENRIN
20 km

Collaboration with MU radar

- determine ~1,000 meteor orbits and sizes per night
- investigate ~100 meteor spectra per night
- connect radar and optical observations

The first collaboration successfully conducted in April, 2018.

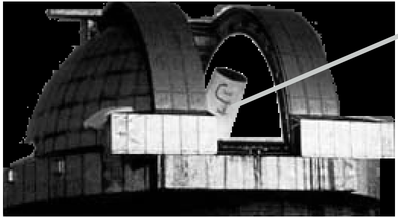


Optical Observation:

brightness (size) distribution
elemental abundance by spectroscopy (optional)

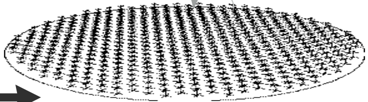
Radar Observation:

direct measurements of meteor motion
accurate time stamps



Kiso Schmidt telescope

Distance ~ 173 km



Kyoto Univ. MU Radar

Observations

	Time (JST)	comment
Day 1	2018-04-18 20:00 — 2018-04-19 05:00	partly cloudy
Day 2	2018-04-19 20:00 — 2018-04-20 05:00	clear sky
Day 3	2018-04-20 20:00 — 2018-04-21 05:00	clear sky
Day 4	2018-04-21 20:00 — 2018-04-22 05:00	clear sky

MU radar (J. Kero & S. Abe)

configuration optimized for meteor head echo observations
radar beam pointed at the zenith

Akira Hirota & Kohei Morita
(Nihon Univ.)

Tomo-e Gozen (R. Ohsawa)

2 Hz monitoring with 20 image sensors (one was severely affected by electric noise)

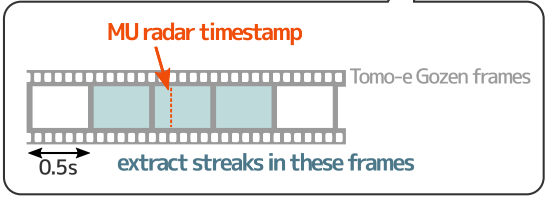

Type: star
Magnitude: 15.60 (extincted to: 15.88)
Color Index (B-V): 0.07
RA/Dec (J2000.0): 11h08m54.22s/-10°21'39.6"
RA/Dec (on date): 11h09m50.45s/-10°27'44.3"
HA/Dec: 3h01m01.59s/-10°26'15.5" (apparent)
Az./Alt.: +231°41'24.8"/+27°06'05.8" (apparent)
Gal. long./lat.: -94°04'52.7"/+45°00'57.1"
Supergal. long./lat.: +119°58'21.9"/-28°08'26.7"
Ecl. long./lat. (J2000.0): +172°23'57.9"/-14°34'04.2"
Ecl. long./lat. (on date): +172°39'30.4"/-14°34'03.8"
Ecliptic obliquity (on date): +23°26'07.0"
Mean Sidereal Time: 14h10m58.0s
Apparent Sidereal Time: 14h10m57.1s
Rise: 15h31m
Transit: 21h04m
Set: 2h37m
IAU Constellation: Crt
RA/Dec (J2000.0): 9h21m14.62s/-28°35'31.0"
Virgo
Leo Minor
Leo
(1) Ceres
Corvus
Crater
Sextans
Cancer
Beehive Cluster
Hydra
ω Cen Cluster
Centaurus
SW
W
Direction to MU radar
Image by Stellarium
Earth, Kiso, Nagano, 1130 m
FOV 61.9°
24.7 FPS
2018-04-21 00:05:50 UTC+09:00

Type: star
Magnitude: 15.60 (extincted to: 15.88)
Color Index (B-V): 0.07
RA/Dec (J2000.0): 11h08m54.22s/-10°21'39.6"
RA/Dec (on date): 11h09m50.45s/-10°27'44.3"
HA/Dec: 3h01m01.59s/-10°26'15.5" (apparent)
Az./Alt.: +231°41'24.8"/+27°06'05.8" (apparent)
Gal. long./lat.: -94°04'52.7"/+45°00'57.1"
Supergal. long./lat.: +119°58'21.9"/-28°08'26.7"
Ecl. long./lat. (J2000.0): +172°23'57.9"/-14°34'04.2"
Ecl. long./lat. (on date): +172°39'30.4"/-14°34'03.8"
Ecliptic obliquity (on date): +23°26'07.0"
Mean Sidereal Time: 14h10m58.0s
Apparent Sidereal Time: 14h10m57.1s
Rise: 15h31m
Transit: 21h04m
Set: 2h37m
IAU Constellation: Crt
RA/Dec (J2000.0): 9h23m37.80s/-29°13'22.6"
Virgo
Leo Minor
Leo
Corvus
Crater
Sextans
Hydra
Cancer
Beehive Cluster
(1) Ceres
ω Cen Cluster
Centaurus
SW
W
Direction to MU radar
Image by Stellarium
Earth, Kiso, Nagano, 1130 m
FOV 61.9°
18.7 FPS
2018-04-21 00:05:50 UTC+09:00

Simultaneous Events

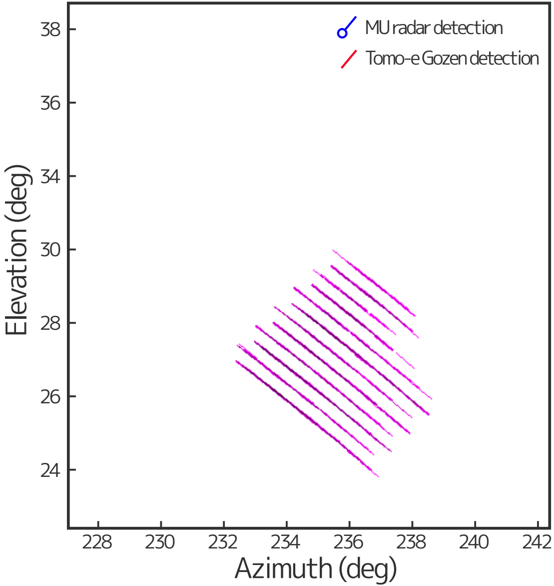
Selection by the time windows

	#events (MU)	#events (Tomo-e)†
Day 1	1041	197
Day 2	942	265
Day 3	1031	285
Day 4	1004	207
Total	**4018**	**954**

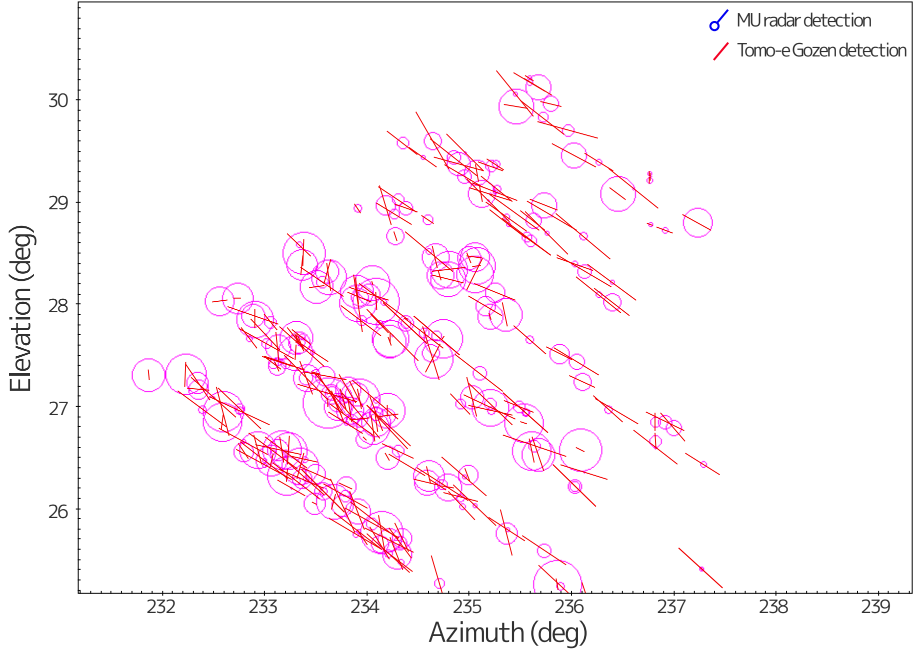


† these include non-meteor events (debris and LEO satellites)

Selection on the projected sky



Simultaneous Events



954 candidates

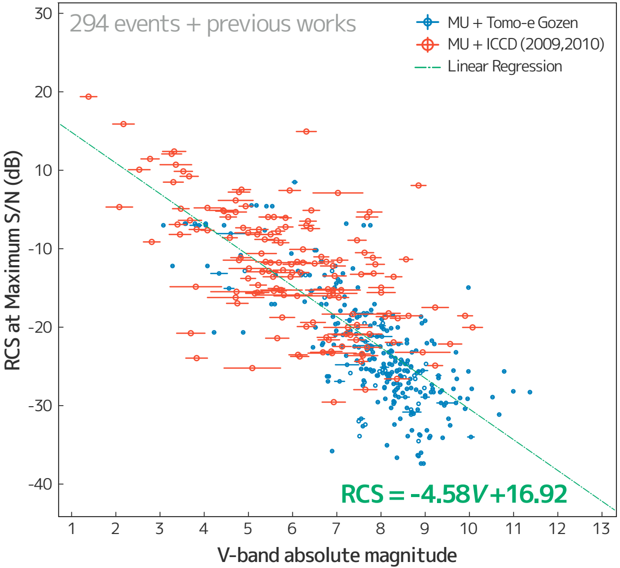
eye inspection

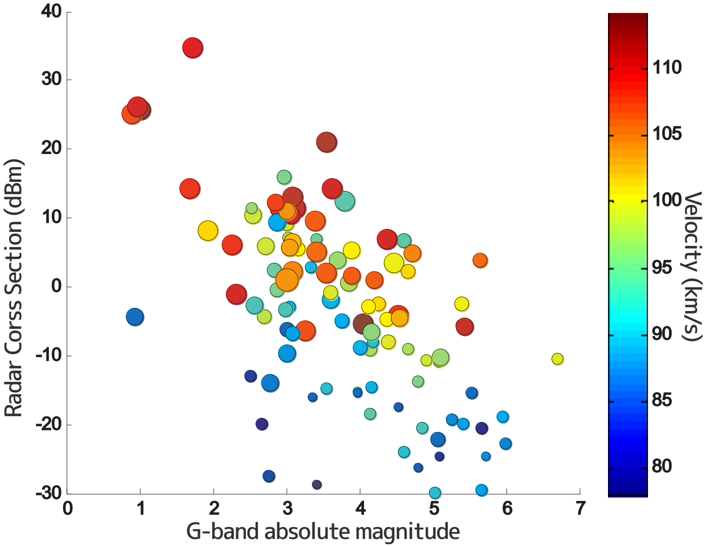
894 confirmed simultaneous events

check overwrap

294 fully-overlapped simultaneous events

Meteor RCS and Magnitude conversion

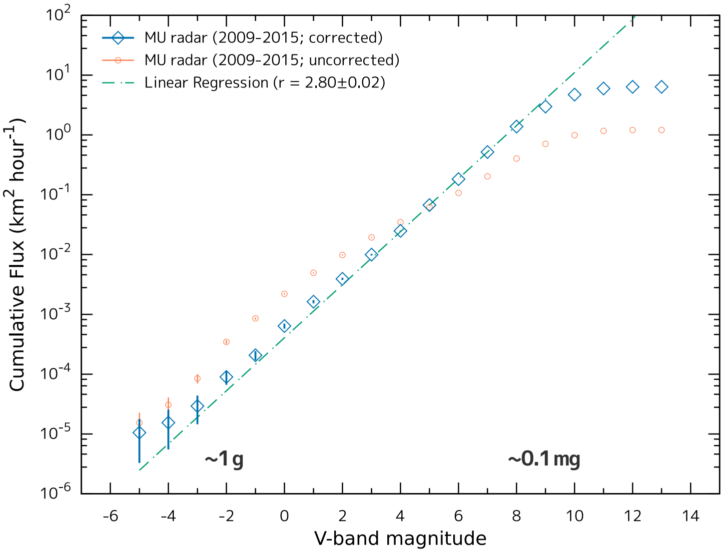




(Right) Brown et al. (2017), P&SS, 141, 25-34

Brightness of MU-detected meteors

Applying the derived conversion law to the meteors detected by MU in 2009-2015

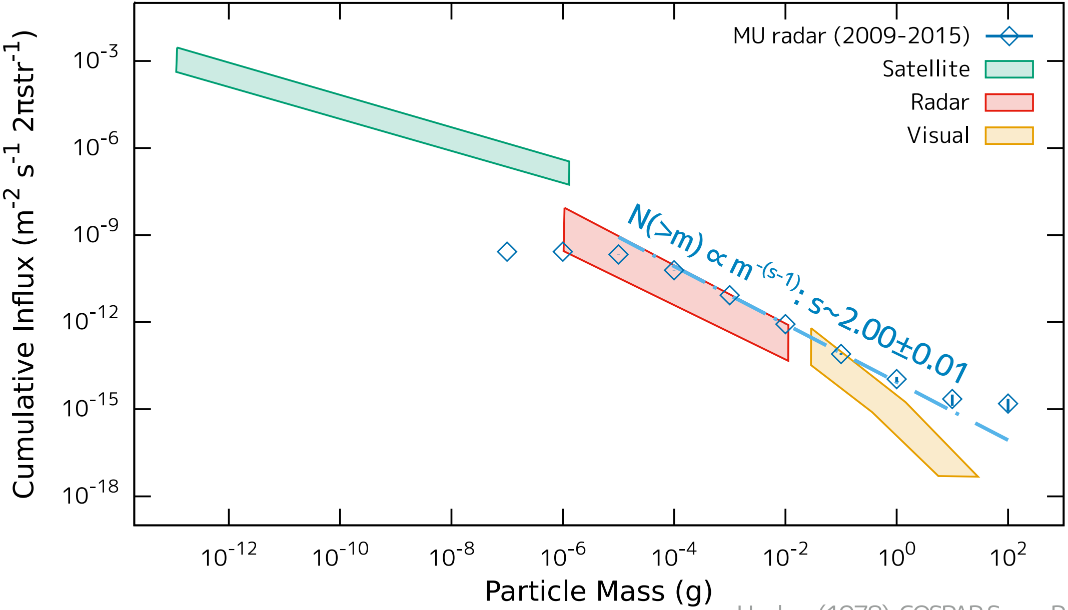


Present result: **r = 2.80±0.02**

Hawkins & Upton (1958)	**3.4±0.2**
Hawkins (1959)	**~2.5**
Clifton (1973)	**~3.4**
Hawkes & Jones (1975)	**~2.5**
Cook et al. (1980)	**3.41**
Rendtel (2004)	**2.95±0.06**
Ohsawa et al. (2019)	**3.10±0.4**

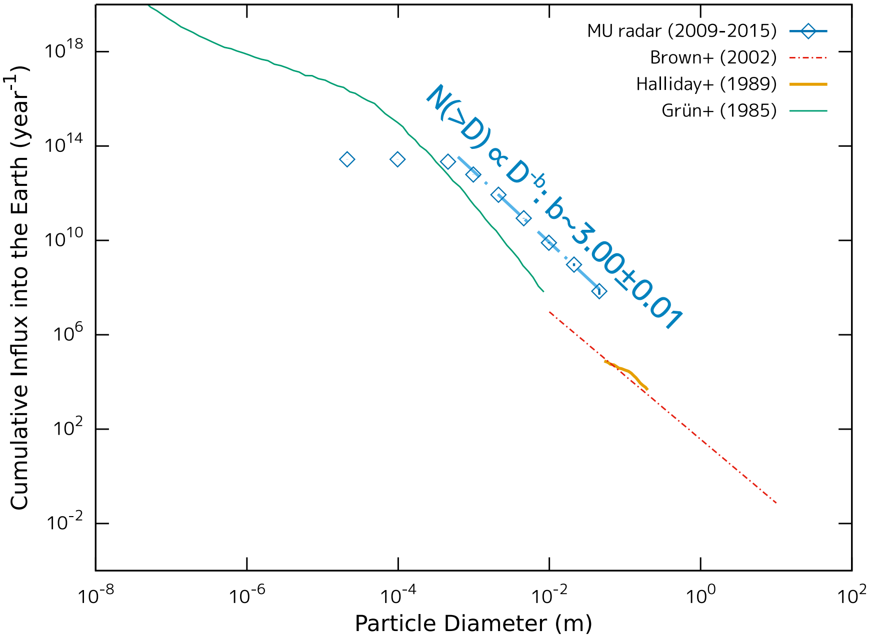
Kero et al. (2011), MNRAS, 416, 2550; Kero et al. (2012), 425, 135

Mass Distribution



Hughes (1978), COSPAR Space Research XVIII, 427

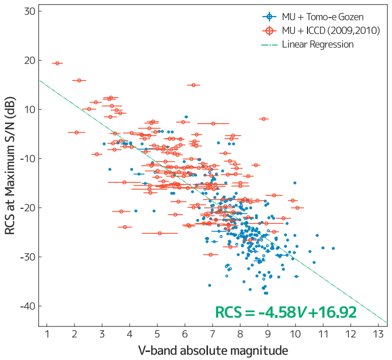
Size Distribution

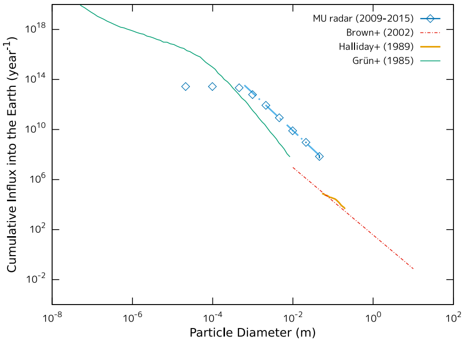


Short Summary

Tomo-e Gozen & MU radar simultaneous observation

- More than 800 simultaneous meteor events detected only in 4 nights.
- We derived a RCS-magnitude relationship with confidence.
- MU radar detects meteors down to ~100 μm in size or ~0.1mg in mass





Tomo-e Gozen and meteors

A CMOS mosaic camera with an extremely wide field-of-view (~20 sq-deg).
Limiting magnitude for stars: ~18 mag. / for meteors: ~12 mag.
More than 1,000 meteor events per night will be captured by Tomo-e Gozen.

We demonstrated early results of a Tomo-e Gozen and MU radar collaboration.
More than 800 simultaneous events were detected only in 4 nights.
Further collaborations (e.g., spectroscopy, meteor showers) are planned.

Tomo-e Gozen and the Solar System

Objects in the Solar System are major science targets (meteor, NEO, comet, etc...).

Ohsawa et al. (2019), P&SS; Urakawa et al. (2019), AJ; Kojima (2019), MThesis

We are always welcome for collaborations!