JASMINE

near-infrared space astrometry mission for explorations of the Galactic nuclear region

―Japan Astrometry Satellite Mission for INfrared Exploration―

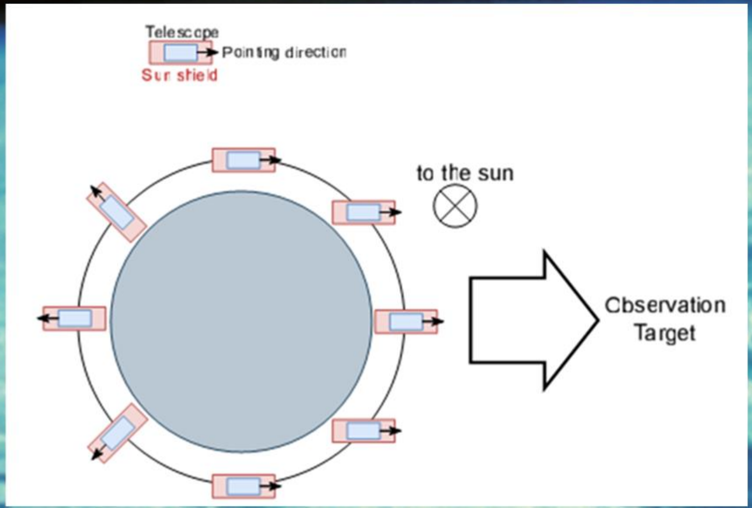
Naoteru Gouda(JASMINE Project Office/NAOJ) and JASMINE team

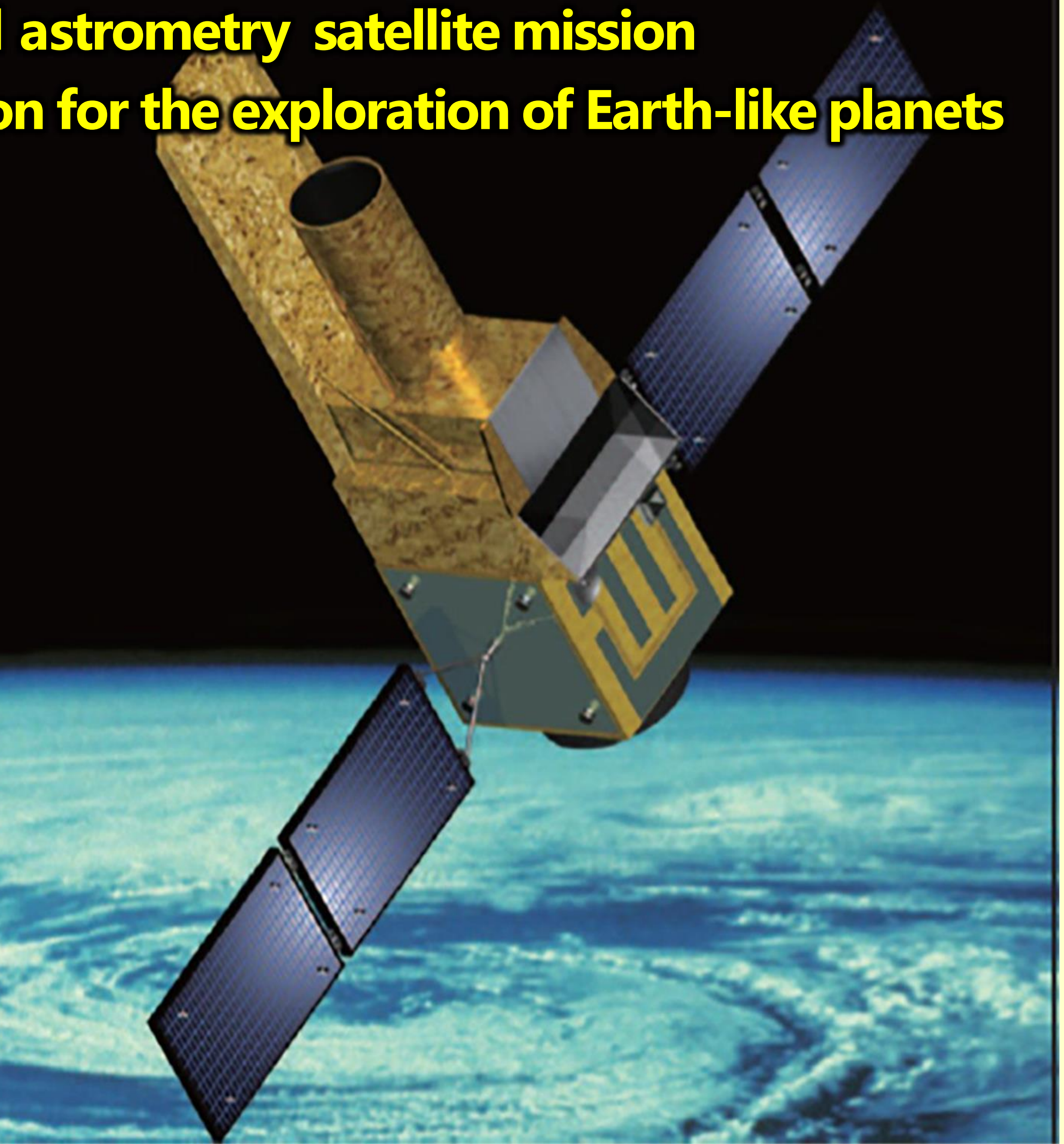
***It used to be called Small-JASMINE, but it was officially renamed JASMINE.**

1. Mission concept of JASMINE

JASMINE：High-precision infrared astrometry satellite mission
Transit observation mission for the exploration of Earth-like planets

- highly thermal stable telescope
- Diameter of the primary mirror ～36cm
- Infrared sensor (InGaAs): 2k×2k×4
  - wavelength1.0-1.6μm
- Satellite weight ～600kg (wet)
- Launch by epsilon-s rocket (JAXA)
- science operation for 3 years (nominal)
- Sun-synchronized orbit・altitude ～600km





1. Mission concept of JASMINE（continued)

★Output data of astrometry to be provided by JASMINE

We will create a catalog of the time-series data of the stellar positions on the celestial sphere observed in the direction of the Galactic nuclear region and the annual parallaxes and proper motions of stars derived from the data, and we will make the catalog available to researchers around the world.

Spring and Autumn：

Astrometric survey in the direction of the Galactic nuclear region

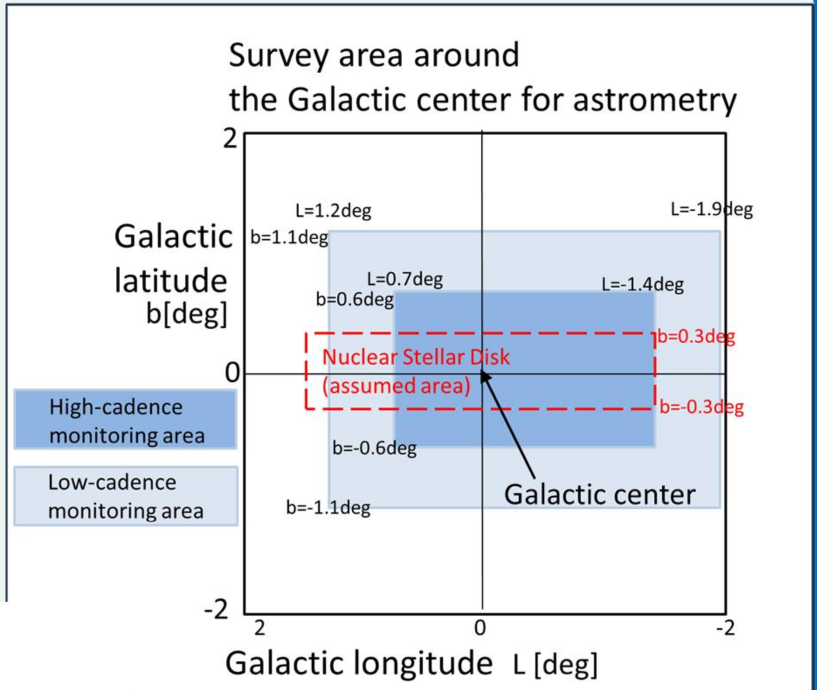
Stellar images are taken continuously every about 12.5 seconds(exposure time)

Hw-band: 1.0μm～1.6μm **$*Hw \sim 0.9J+0.1H-0.06(J-H)^2$**

The magnitude range for the stars to be downloaded to the ground every exposure time➔
～10.0 mag< Hw <～14.5mag

➔ About 120,000 stars in the high-cadence monitoring area.

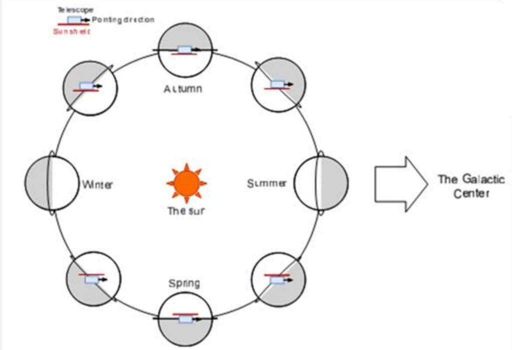
Full-frame of 1 field of view is planned to be downloaded every a few dozen exposure times.
Full-frame downloads will become possible more frequently if the amount of communication data sent to the ground increases with the support of some stations besides JAXA.



Precisions:

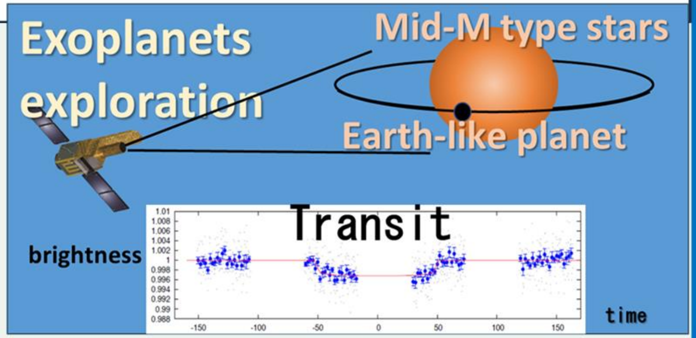
position, parallax：＜25μas～125μas
proper motion: ＜25μas/y～125μas/y
1~5km/s tangential velocity error at 8kpc

about 35μas（μas/y) ～180μas（μas/y) for low-cadence area



Ref. Summer and Winter：

Transit observations of mid-M type stars to find Earth-like planets in the habitable zone
Time-series photometric data with photometric accuracy to detect 0.3% transit depth for 17 or more target objects (observation period of 2-5 weeks or more for one target)



2. JASMINE Current status

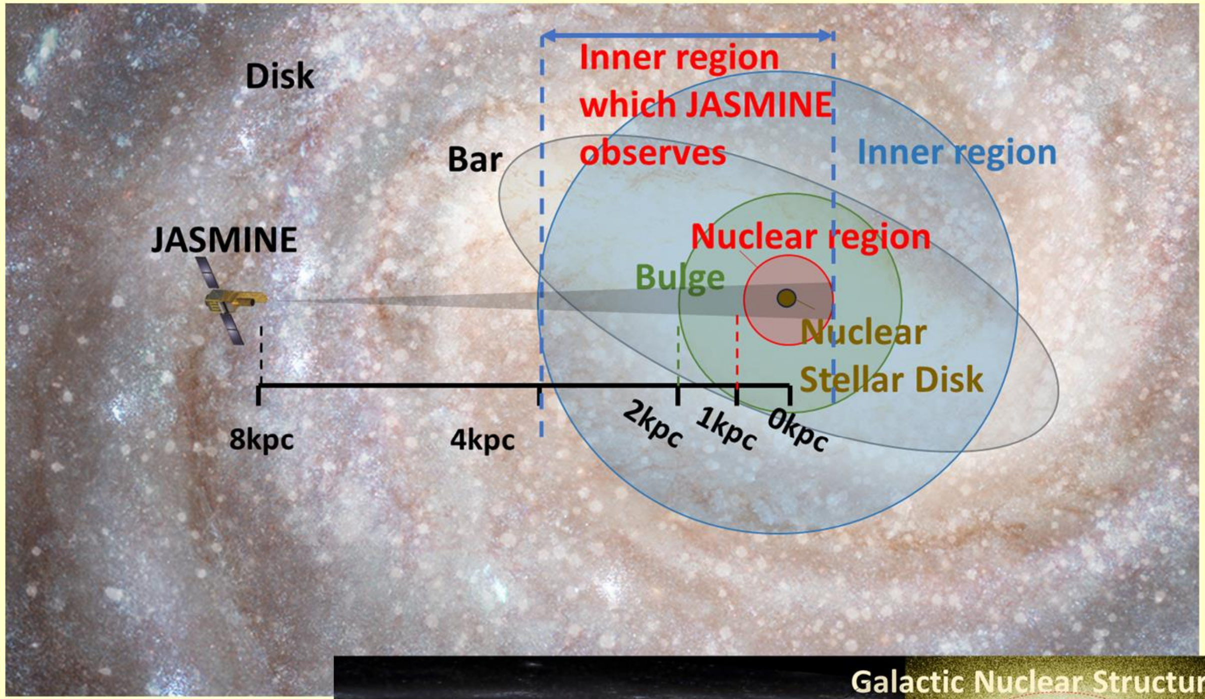
- ISAS(Institute of Space and Astronautical Science)/JAXA (the Japan Aerospace Exploration Agency) selected JASMINE for the 3rd Competitive Medium-class science satellite mission in May 2019, and the launch of JASMINE is scheduled tentatively for 2028 in Space Basic Plan, Cabinet Office, the Japanese government.

  ＊Some delay in the launch year is anticipated due to external factors such as schedule adjustment of satellite manufacturing companies.

- We are promoting JASMINE with the aim of gradually improving the development stage at JAXA.

- JASMINE passed ISAS's MDR(Mission Definition Review) in July of this year and is going to Phase A study.

3. Science Objectives of Astrometry in JASMINE



The target is the Galactic inner region along the Galactic plane around the center

★Inner region: Inside the radius of～4kpc from the center along the Galactic plane

This region is hard for astrometric measurements in optical bands

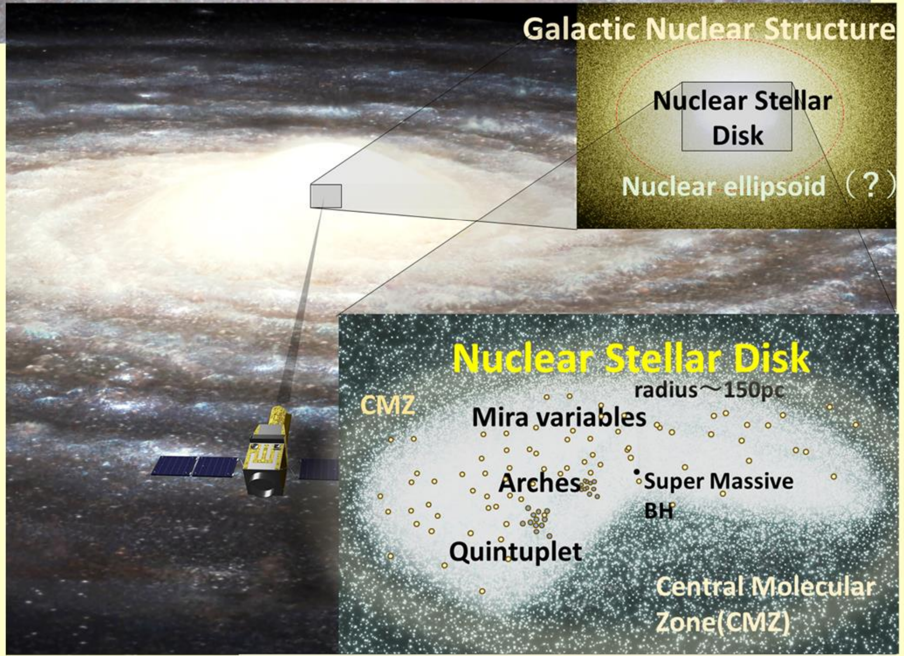
1 Nuclear Region inside the radius of ＜～1kpc from the center

- Nuclear stellar disk
- Nuclear ellipsoid (classical bulge)(?)
- Nuclear star cluster

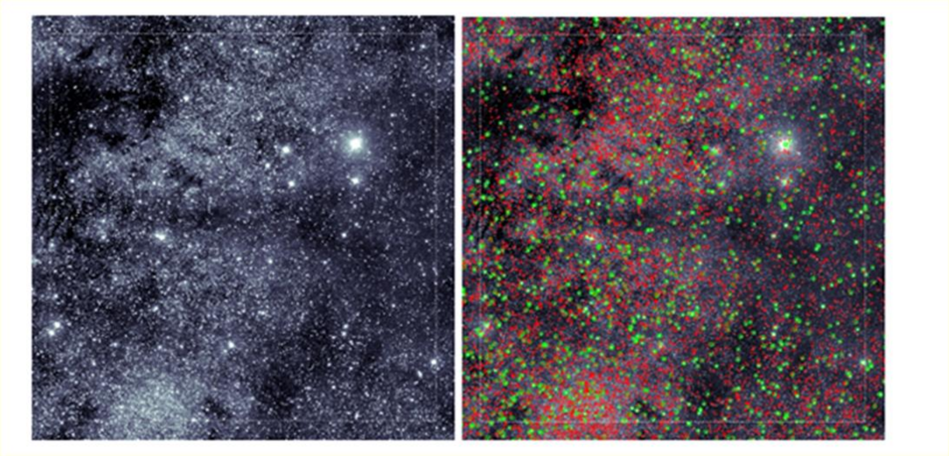
2 bulge/bar +long bar+ inner disk along the Galactic plane

The range of the radius of ～1kpc＜r＜～4kpc from the center

There are many unknowns in the inner region, and it is an important region where a lot of important information is hidden for astronomy and astrophysics.



Our main science objectives:



A. Galactic center archeology

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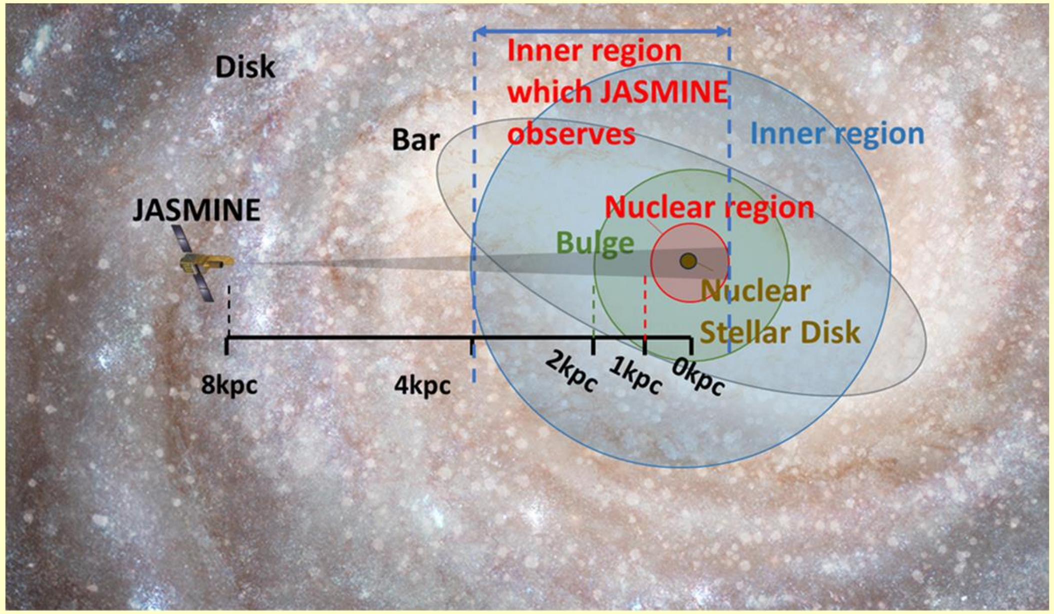
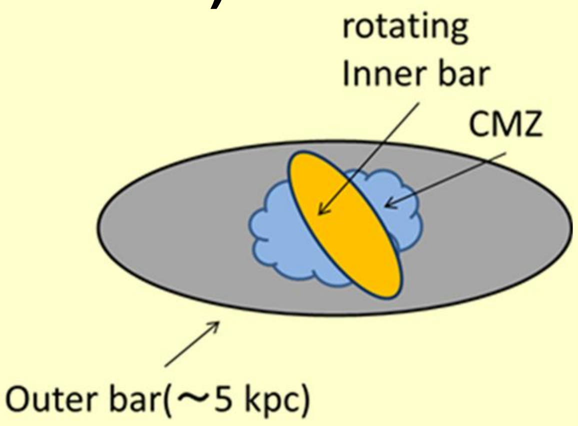
Galactic inner structures

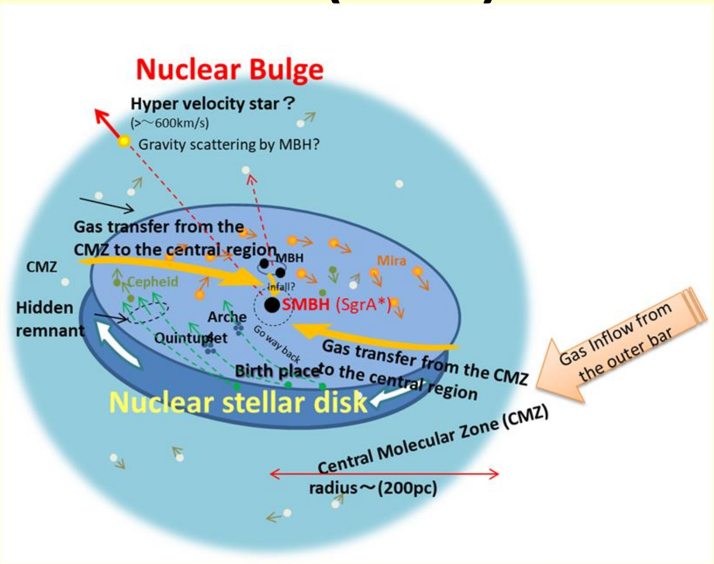
*Dynamical structures along the Galactic plane in the region of ~1kpc<r<~4kpc



★ Details of Galactic Center Archeology

（1）Clarification of orbits structure of the Galactic Nuclear Stellar Disk(NSD) and the existence of non-axisymmetric structure (inner bar structure)





Pattern speed of the inner bar structure

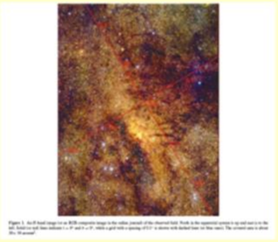
➔ **transport mechanism of gas into the Galactic center:**

the torque from the bar structure causes the gas to lose angular momentum and energy, allowing it to fall toward the center.

➔ **evolution of SgrA*, activity of the Galactic center**

（2）Formation epoch of the Galactic Nuclear Stellar Disk(NSD) by the use of Mira variables ← selection by JASMINE

Matsunaga et al .(2009, MNRAS)



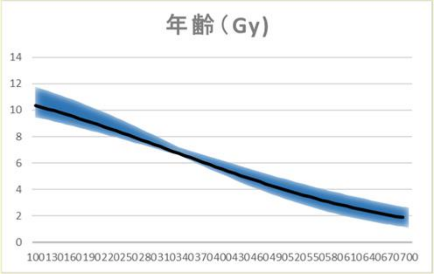
Age-period relation of Mira variable

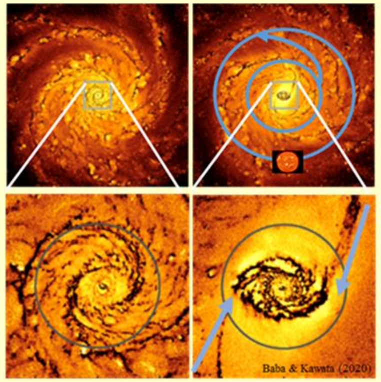
➔ **age-distribution of the Mira in NSD**

➔ **formation epoch of the NSD(+age distribution within NSD)**

➔ **formation epoch of the outer bar**

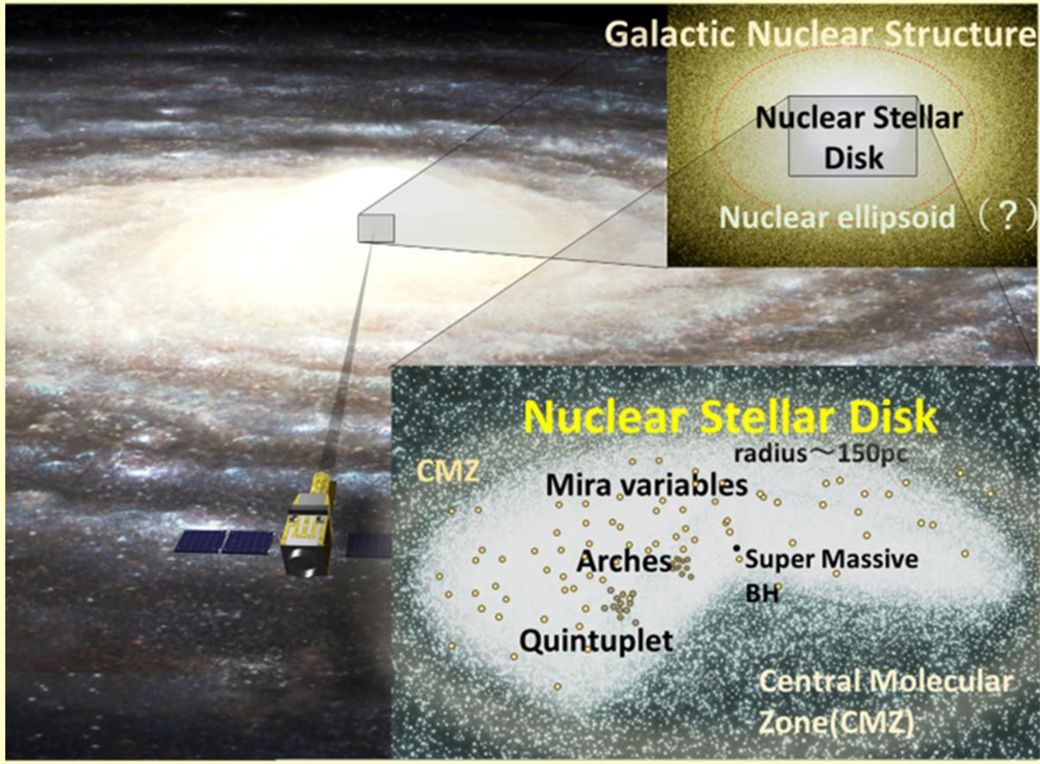
The formation epoch of the outer bar is much related to the clarification of the birthplace and trajectory of the Sun in the MW etc. (radial migration and wobble around the Galactic plane)





(Baba&Kawata 2020)

（2）Characterization of the global dynamical structure （Nuclear ellipsoid) around the NSD in the Galactic nuclear region



*relic of classical bulge formed at the early stage of the Galaxy evolution ?

The classical bulge is a different dynamical structure from the structures of the box/peanut bulge and the nuclear stellar disk. JASMINE may be able to provide the clue information to confirm the existence of the classical bulge.

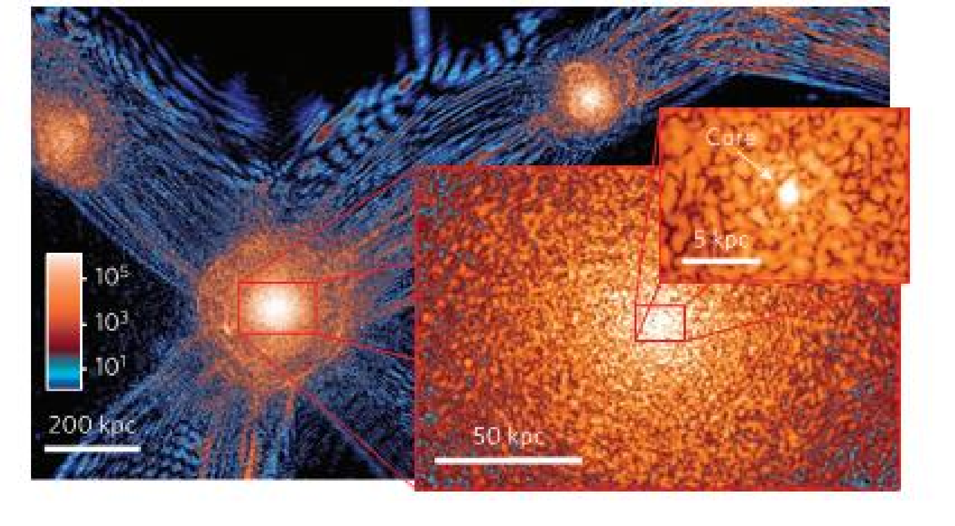
*kinematical relic of infall of supermassive BHs?

infall of some supermassive BHs➔ they provide dynamical heating to stars in the nuclear region. The stars in the nuclear region have specific features of density distribution and also velocity-dispersion distribution. JASMINE may suggest such specific features of stars in the nuclear region.

(3) Discovery of unknown star clusters in the inner region by the detection of parallel movement of the stellar proper motion

This result will lead to clarification of star formation history in the NSD.

B. Physics hidden in the inner region
Hunt of:



Schive, et al. Nature Physics 2014

(1) dark matters DM on the inner disk/long bar ←**kinematic information**

(2) Black Holes

- **＊Black Hole-star binaries** ←**orbital analysis of stars**
- **＊Intermediate Massive Black Holes** ←**gravitational lens effects**

(3) Orbital analysis of X-ray binaries ➔ **compact objects**

(4) Stellar physics, star formation, 3-dimensional distribution of inter-stellar dust

⋮

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arXiv:2307.05666v1 [astro-ph.IM] 11 Jul 2023

JASMINE: Near-Infrared Astrometry and Time Series Photometry Science

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Please refer to JASMINE White Paper
(Kawata, D. et al.,
Publications of the Astronomical Society of Japan, Advance Access Pub Date: April 2024)

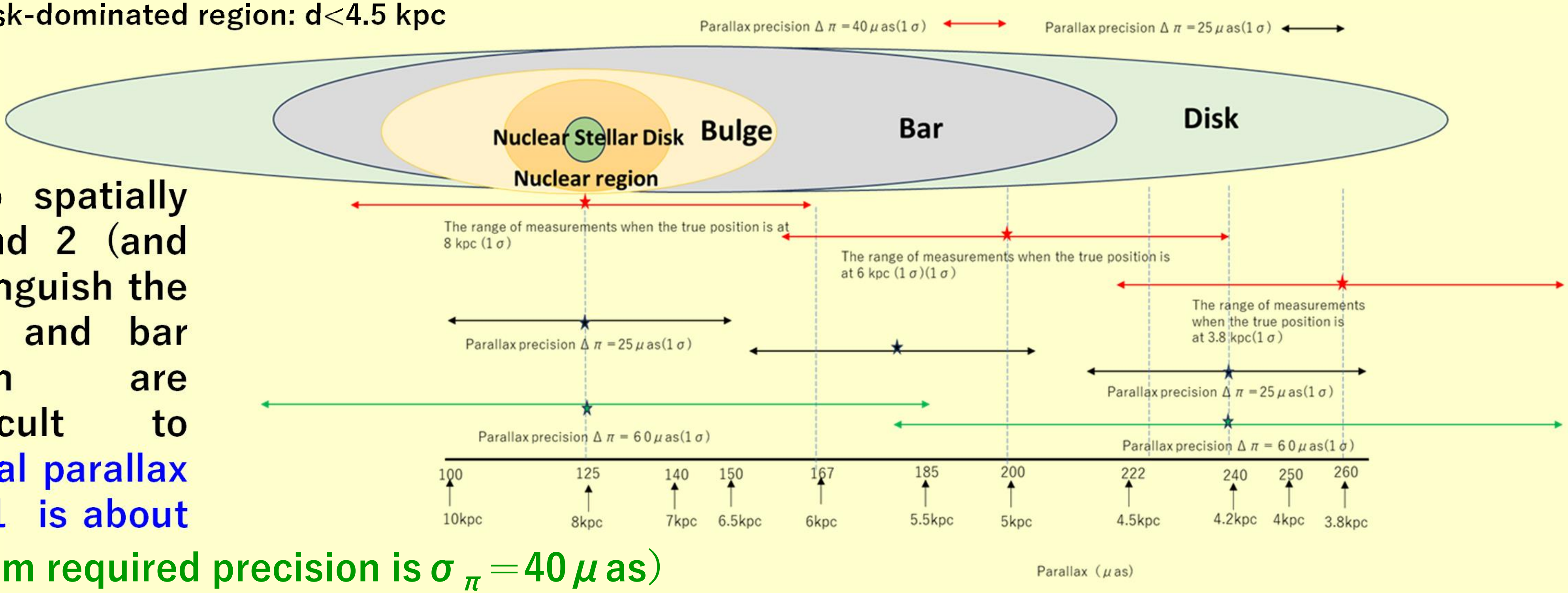
*Target parallax precision

JASMINE will provide 25μas as the best precisions of the annual parallax for brighter stars than 12.5 mag.

Region 1: The nuclear region including the nuclear stellar disk and the bulge: Annual parallax spread of about 40 μas

Region 2: Region dominated by bar structures (long rod-like structures): Annual parallax spread of about 80 μas

Region 3: Disk-dominated region: d<4.5 kpc



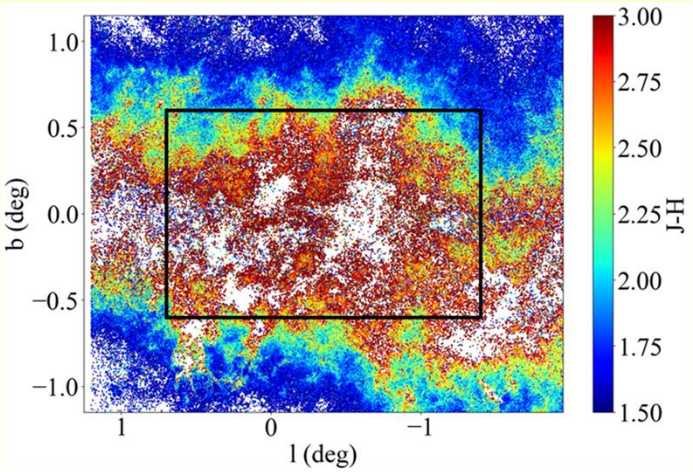
This is sufficient to spatially resolve regions 1 and 2 (and also region 3) to distinguish the nuclear stellar disk and bar structures, which are kinematically difficult to distinguish. The annual parallax spread of the region 1 is about 40 μas. (the minimum required precision is $\sigma_\pi = 40\mu$as)

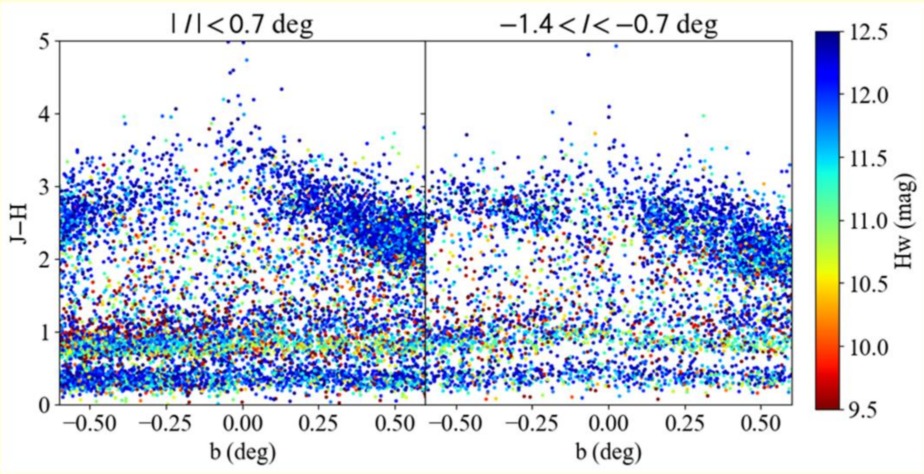
***There are several different structures (NSD, nuclear ellipsoid, or box/peanut bulge) within Region 1, and we use the motion of stars to determine which structure a star in Region 1 belongs to.**

This is also sufficient to verify the validity of the reddening condition (based on the spread of spatial distribution (standard deviation)) that serve as a criterion for selecting stars in the nuclear region based on their color.

Reference

Reddening Condition

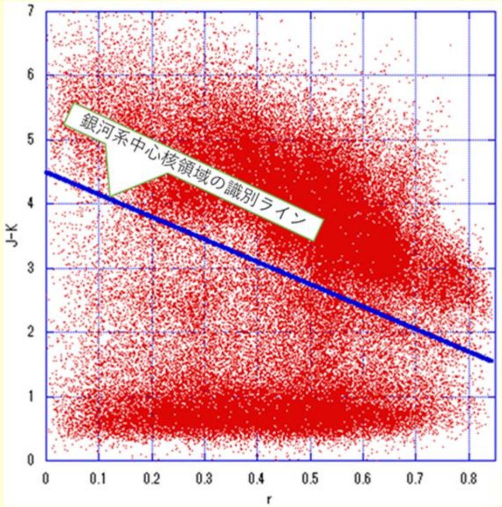




Some observations resulted in that the standard value of the color (J-H or J-K) of stars expected to be in the nuclear region within the observation field, that is, the reddening condition, has been obtained from existing observational data.

Basically, it depends mainly on the galactic latitude, and the lower the galactic latitude, the redder the color tends to be.

Red Condition formula $J - K > 4.5 - 3.5r$ $r = \sqrt{(b + 0.05)^2 + \frac{(l + 0.05)^2}{2.5^2}}$

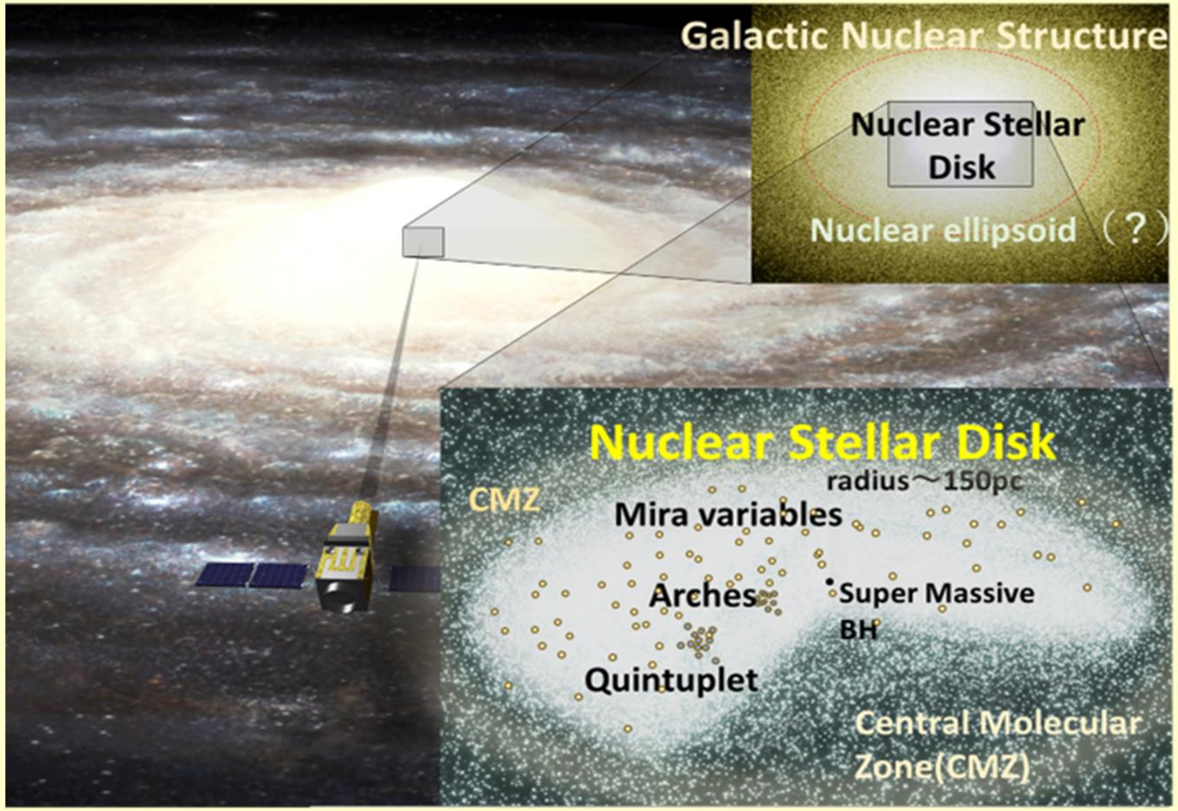


However, verification by annual parallax is required.

To show that the stars selected under these conditions are within Region 1 and do not extend into Region 2, a precision of the annual parallax of 25 μas（＜40μas） is sufficient.

*There are several different structures（NSD, nuclear ellipsoid, and box/peanut bulge) within Region 1, and we use the motion of stars to determine which structure a star in Region 1 belongs to.

If possible, we would like to know more precisely which structures in the region 1 stars belong to by measuring the annual parallaxes. Furthermore, if possible, it would be a major breakthrough if we could determine the spatial distribution of stars within the nuclear disk.



The radius of the nuclear stellar disk(NSD) corresponds to about 3μas in the annual parallax.

↓

If it becomes possible in the future to carry out infrared astrometric observations that can achieve an annual parallax precision of about 1 μas , it is expected to bring about a major impact and breakthrough also in the Galactic center archeology.

★Cooperation with other observation projects for the Galactic nuclear region

*Photometry+Astrometry: VVV, GALACTICNUCLEUS, Ultimate-Subaru, ROMAN,JWST, GREX+,GaiaNIR ,…
(for faint stars)

*Catalogue of Mira variables: PRIME

*Techniques: HiZ-GUNDUM

*Spectroscopy: Subaru-PFS, APOGEE-2,MOONS, Milky Way Mapper, …

*Observations with other wavelengths: JEDI, ALMA, SKA, ngVLA, …

Subaru-PFS (spectral observation) can measure the radial velocity (+metals) of all stars targeted by JASMINE before JASMINE's launch.

The stars targeted by JASMINE can have six-dimensional phase space information. They will be very unique and valuable information in the Galactic nuclear region.

Telescope/Instrument	Aperture of the primary mirror	Field of view [square degrees]	Number of the fibers	Observation wavelength range	Wavelength resolution (λ/Δλ)
Subaru/PFS	8.2 m	1.25	2,400	0.38-1.26	4300@<1.26μm

★Mission instruments

Optical design: Modified Korsch System with 3mirrors and two folding flats to fit the focal length

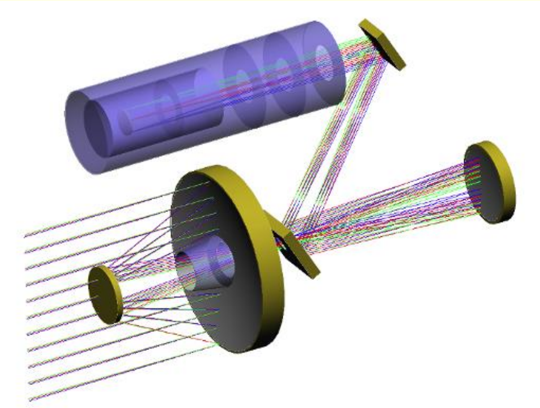
- Aperture size: 0.36m
- Focal length: 4.37m
- Field of view: 0.55°× 0.55 °
- Detector: 4× domestic CMOS sensors

T～278K

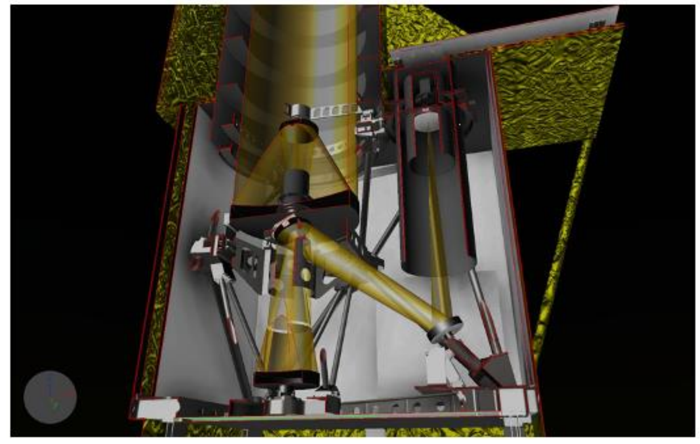
InGaAs (2k×2k)

Hw-band:1.0～1.6μm

operating temperature: <~173K



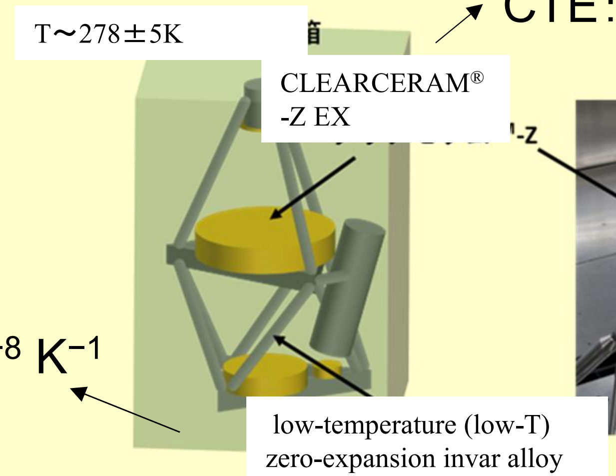
Preliminary optical design



An example of schematic view of the payload layout

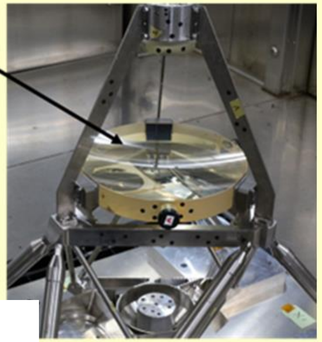
（Kawata et al.2024）

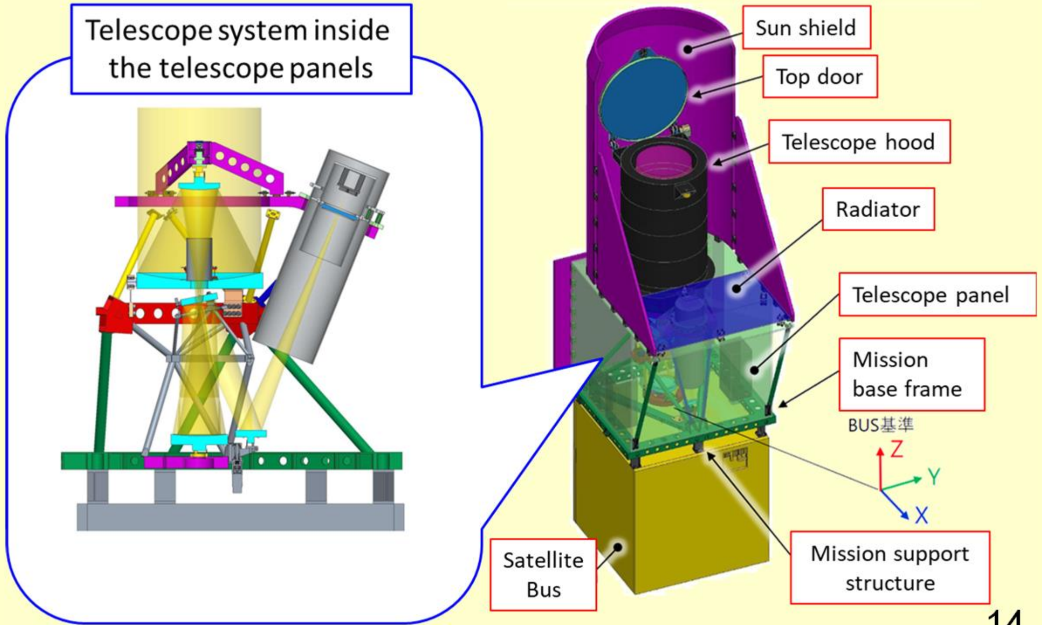
Telescope structure with little thermal structure time-variation



CTE: $0 \pm 1\times10^{-8}\ K^{-1}$

CTE: $0 \pm 5\times10^{-8}\ K^{-1}$



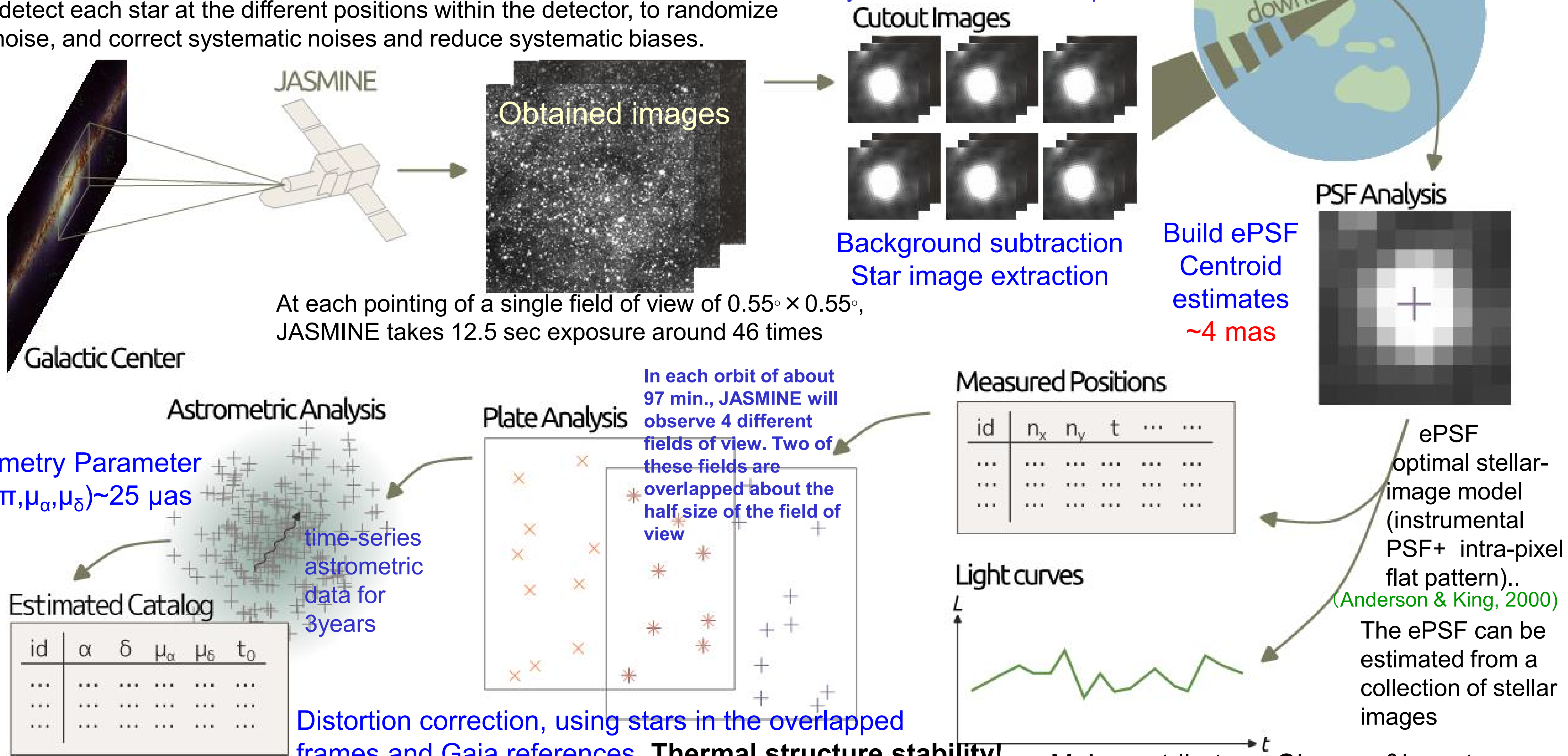


Dataflow of JASMINE mission

Because of the limited downlink capacity, only the data of 9 ×9 pixels around every target star（120k）are planned to be downlinked to the ground station every exposure time.

In addition, downlink of one full-frame every about a few dozen exposure times.

“The point and stare” strategy: The whole survey region will be mapped to observe all the stars in this region for a similar number of times for three years and detect each star at the different positions within the detector, to randomize the noise, and correct systematic noises and reduce systematic biases.



Main contributors: Ohsawa &kawata

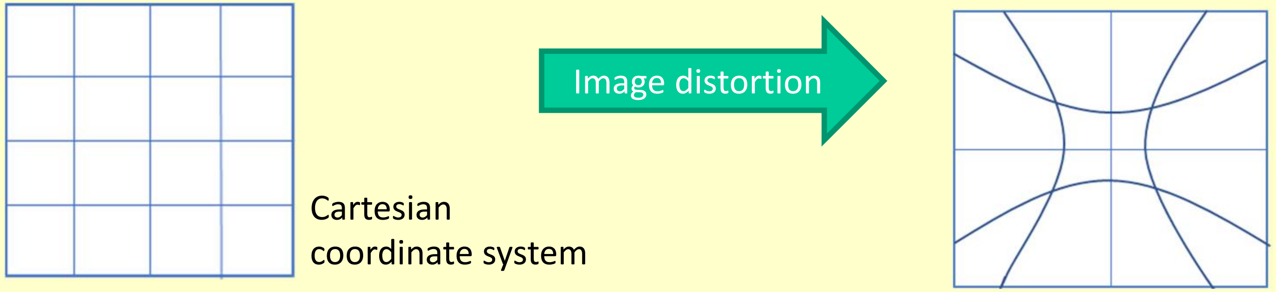
Plate Analysis

The relative positions of stars in the overlapping regions of different images are maintained over a short period. However, in fact, the measured relative positions will change according to the image distortions due to the telescope and the detectors. So the image distortions patterns can be resolved under the constraints that the real relative positions of stars do not vary.

Solving a complicated optimization problem with more than 10^6 parameters which includes the true stellar positions and also image distortion patterns occurred by the telescope and the detector.

Image distortion correction

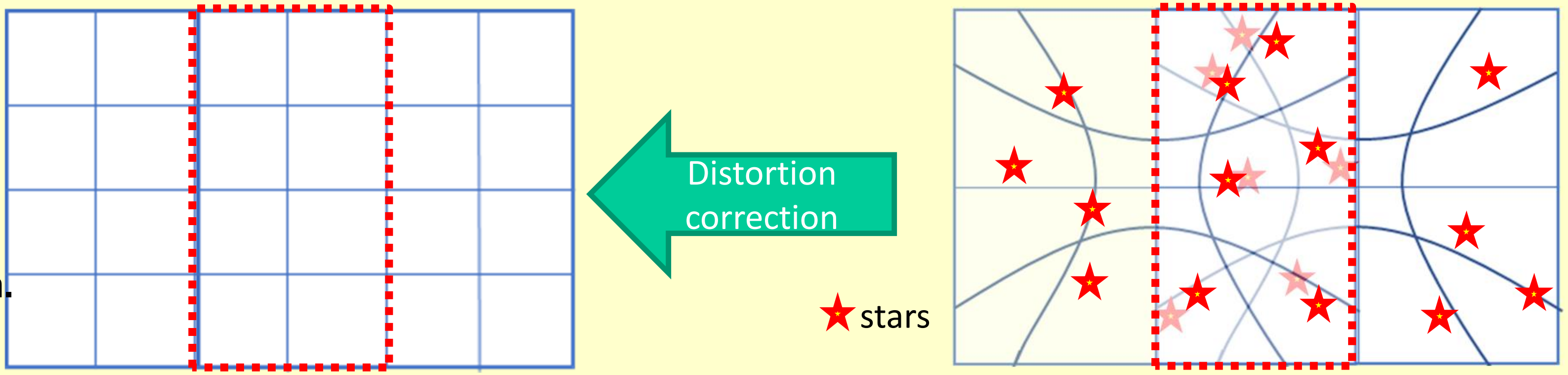
- On the sky image
- On the focal plane/detector image



Cartesian coordinate system

Not observed as a Cartesian coordinate system

Same stars on the different FoV positions



The telescope should be stable enough for the period of one revolution around the Earth to allow us to ignore the time variation of the coefficients of the terms higher than the first order of the polynomial functions for the distortion correction. This is because we have to solve mathematically the above problem with high precisions even though we have the limited number of information of the observed stars.

The time variation of the first order of the distortion, expansion and contraction, will be modelled with the stars whose parallaxes and proper motions are accurately measured with Gaia.

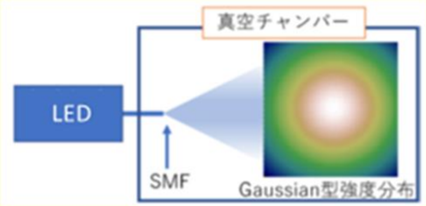
highly stable mission instrument system

★Key requirements for the system to achieve the target precisions in data analysis

It is essential to obtain a good Point Spread Function (PSF) in JASMINE to estimate the precise centroids of stellar images. The PSF is estimated using multiple images within a single exposure in the step-stare method.

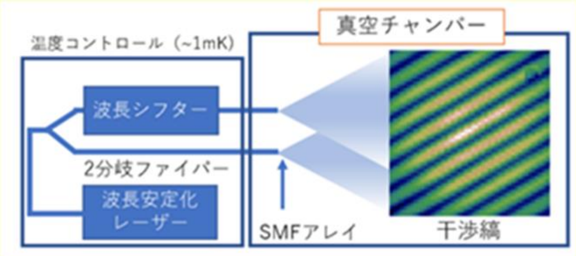
*sharp and uniform stellar images across the entire field of view.

*high-precision calibration for interpixel flat (inhomogeneous sensitivity on different pixels)



Development of high-precision calibration system

・a light source with a stable luminance distribution using a single-mode fiber (SMF) that can be mounted on the satellite



・Preparing a measurement system for pixel misalignment, size unevenness, and intra-pixel sensitivity unevenness due to interference fringes from two SMFs.

*the uniformity of pixel size and arrangement of the detectors

highly stable mission instrument system

*the time scales over which image distortions change is long.

JASMINE observation simulation software for feasibility evaluation of our data analysis method

End-to-End simulation (E2E)

Mock Catalogue, which compiles the near Infrared sources inside the JASMINE survey area (+α) already observed by other point source catalogues(VVV,SIRUS, 2MASS) in the literature. In addition, we add proper motions and distances from Gaia and a Galactic model.

. This software takes into account various factors such as the optical PSF, telescope jitter caused by the satellite's attitude control error, detector flat patterns, exposure timing differences between detector pixels, and various noise factors.

Mock Catalog

id	α	δ	μ_α	μ_δ	t_0
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

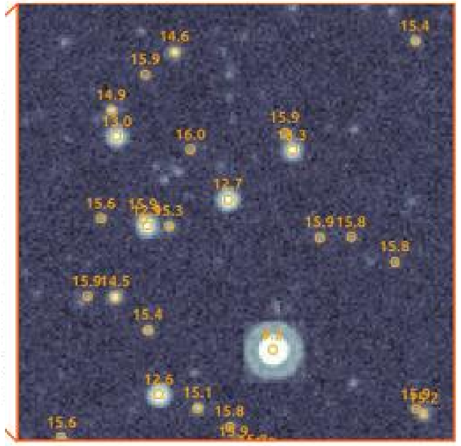
Observation Schedule

id	α	δ	θ	t	...
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

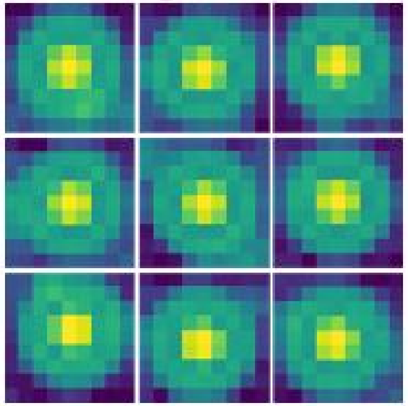
Imagesim

We develop an image simulation software which produces realistic observation images.

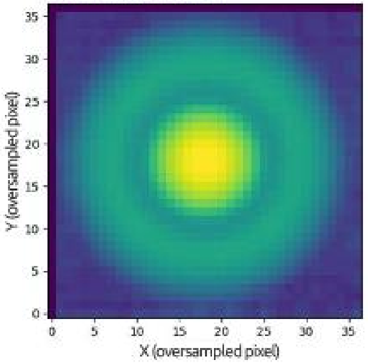
Simulated Images



stellar images



estimated ePSF



We confirmed that the center position can be estimated with high precision by applying one of the star image models, the ePSF method.

Measured Positions

id	n_x	n_y	t	...	...
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

Light curves

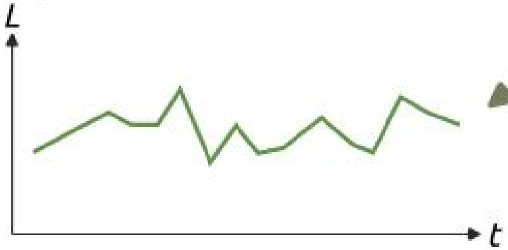
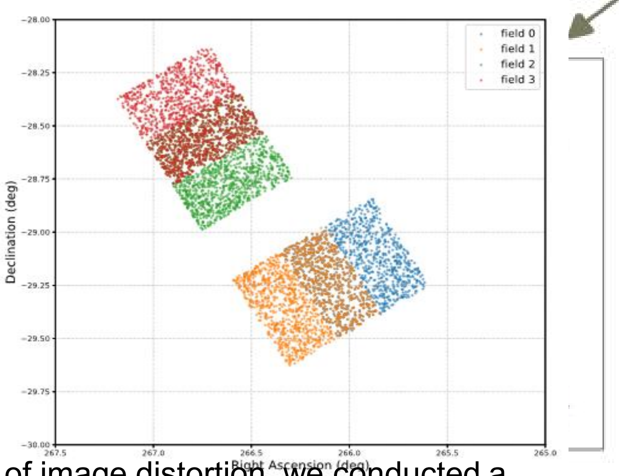
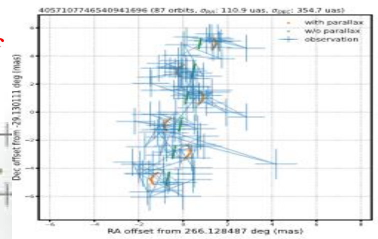


Plate Analysis



To verify analysis of image distortion, we conducted a mini-survey simulating observation data for 100 orbits.

Astrometric Analysis



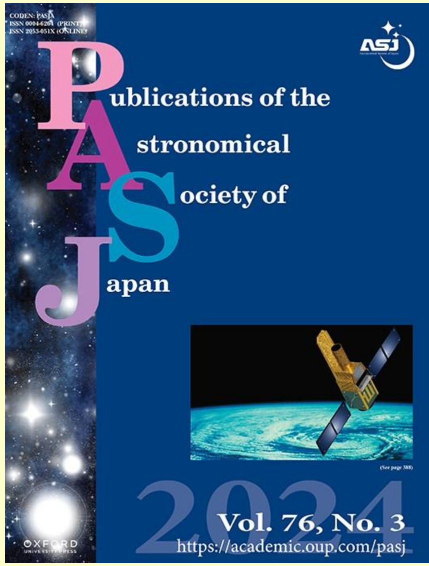
By using an appropriate reference star catalog, image distortion analysis could be performed self-consistently. The time series transition of the estimated coordinates reproduced the proper motions and annual parallaxes in the mini mock survey of JASMINE.

Estimated Catalog

id	α	δ	μ_α	μ_δ	t_0
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...

Main contributors: Ohsawa, kawata, Kamizuka, Kawahara, Ramos

5. International Collaboration



○ **Investigations of science cases**

***MOU between Theia collaboration and JASMINE Project Office/NAOJ （2017）**

***We published the White Paper in PASJ by international collaboration**

○ **an ARI (Astronomisches Rechen-Institut) group at the Heidelberg University in Germany has already started on the collaboration of the data analysis of JASMINE. We have regular joint meetings. Furthermore, a group at Technische Universität Dresden is considering the collaboration on the data analysis.**

○**Scientific cooperation with other observations for measurements of radial velocities, chemical compositions and photometry is very strong synergy for studies of the Galactic nuclear region.**

e.g. APOGEE2, VVV, GALACTICNUCLEOUS, MWM, MOONS, Roman, JWST, GaiaNIR, ･･･

○ **Collaboration in the downlink of scientific data**

***ESA is now considering the support of ground stations for the down link of scientific data to be provided by JASMINE. ISAS/JAXA has started to negotiate with ESA.**

JASMINE project is seeking for more bandwidth in foreign ground stations for download of scientific data.

This is required for improving overall scientific productivity of the mission for more frequent downloads of full-frames.

Jasmine

Thank you for your support!