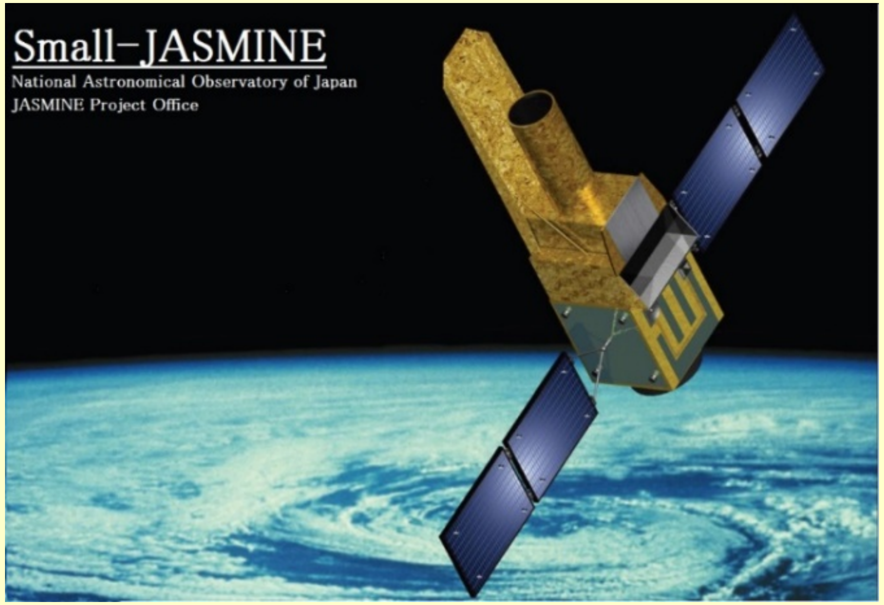
23th May, 2019

Small-JASMINE

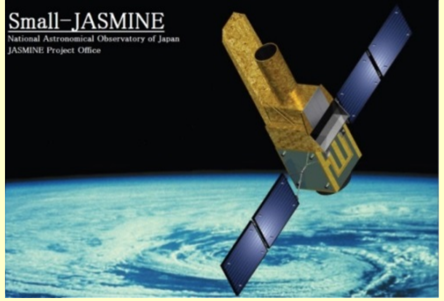
★JASMINE

ーJapan Astrometry Satellite Mission for INfrared Explorationー

JASMINE team



1. Outline of Mission



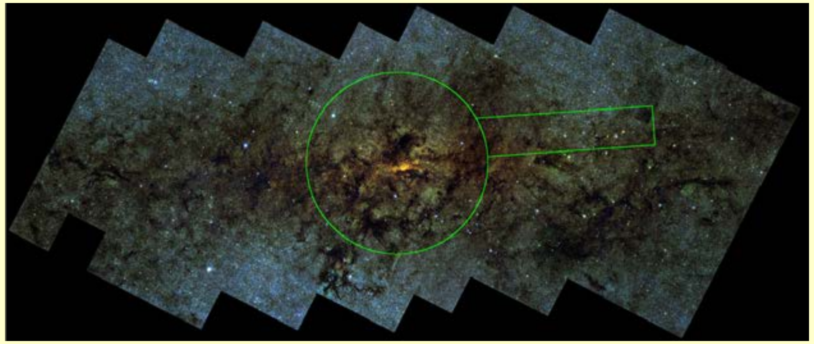
We have been aiming at the realization of the Small-JASMINE mission as a mission of the small science satellite program （M-class mission） executed by JAXA (Japanese Space Agency).

Astrometric Measurement in Hw-band(1.1μm~1.7μm) ***Hw~0.7J+0.3H**

Infrared astrometry missions have advantage in surveying the Galactic nuclear bulge, hidden by interstellar dust in optical bands!

Two survey modes

1. survey for **the key project** in **spring and autumn** → **Nuclear bulge around the Galactic center**



J, H, K tricolor composite image of the Galactic center area(imaged by SIRIUS on the Nagoya University IRSF 1.4m telescope: Nishiyama et al., 2004 Spring Astronomical Society Press Release).
The survey area of Small-JASMINE is written with the green line.

2. survey for **secondary objectives** in **summer and winter** → **some directions toward interesting target objects**

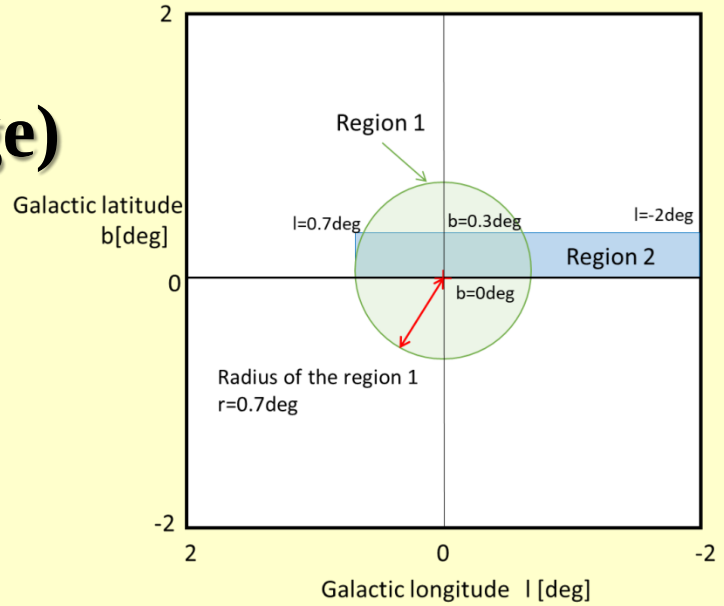
(e.g CygX-1, planetary systems of brown dwarfs, star-forming regions besides the area near the center)

Phenomena with short periods

Advantage of Small-JASMINE: every 100 minutes!
High frequent measurements of the same target

Good monitoring of photometric and astrometric time-variable phenomena!!

1.1The details of the survey mode
for the key project（toward the Galactic nuclear bulge)



★ Small-JASMINE will measure totally about 67,000 bulge stars＋31,000 disk stars for Hw<~15 mag.

Survey region 1:

the circle with **the radius of 0.7 degree** (～100pc) around the Galactic center

・the number of observable stars

bulge stars: ~**5000(Hw<12.5mag),** **<=precisions of parallax(<~25μas) and proper motion(<~25μas/yr)**

~**45000(12.5mag<Hw<15mag)** **<=precisions of proper motion(<~125μas/yr)**

(**disk stars:～4000(Hw<12.5) , ～21000(12.5mag<Hw<15) common with stars measured by Gaia**)

Survey region 2:

Survey region: Galactic longitude：**-2.0～0.7 degree** Galactic latitude： **0.0～0.3 degree**

・the number of observable stars

bulge stars: ~**3000 (Hw<12.5mag)** **<=precisions of parallax(<~25μas) and proper motion(<~25μas/yr)**

~**26000(12.5mag<Hw<15mag)** **<=precisions of proper motion(<~125μas/yr)**

(**disk stars: ～1500 (Hw<12.5), ～9500(12.5mag<Hw<15) common with stars measured by Gaia)**

Small-JASMINE will provide and open to science communities in the world the data of parallaxes, proper motions and time sequences of stellar positions on the celestial sphere in the survey region of the key project.

1.2 Science Goals and scientific objectives

Science Goal

Clarify galaxy formation and evolution through research of the Milky Way Galaxy as a testing ground

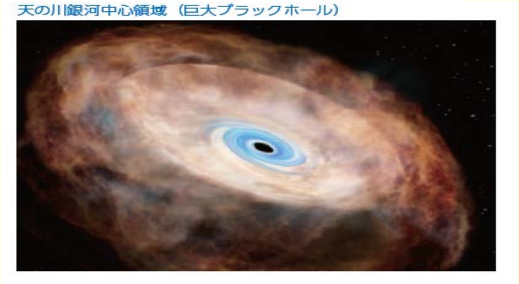
The Milky Way: very important target galaxy!!

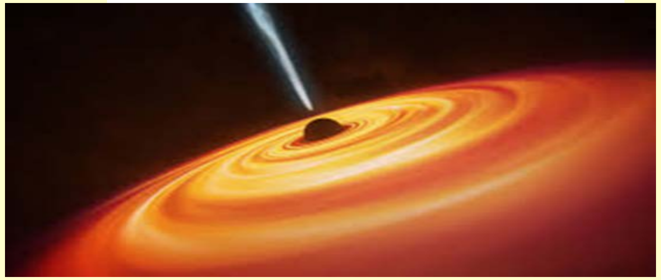
It is possible to observe in the Milky Way individual stars to obtain information on their 3-dimensional positions, 3-dimensional velocities (and metallicity) with good accuracies, which is,
in general, still not possible for galaxies outside the Milky Way.

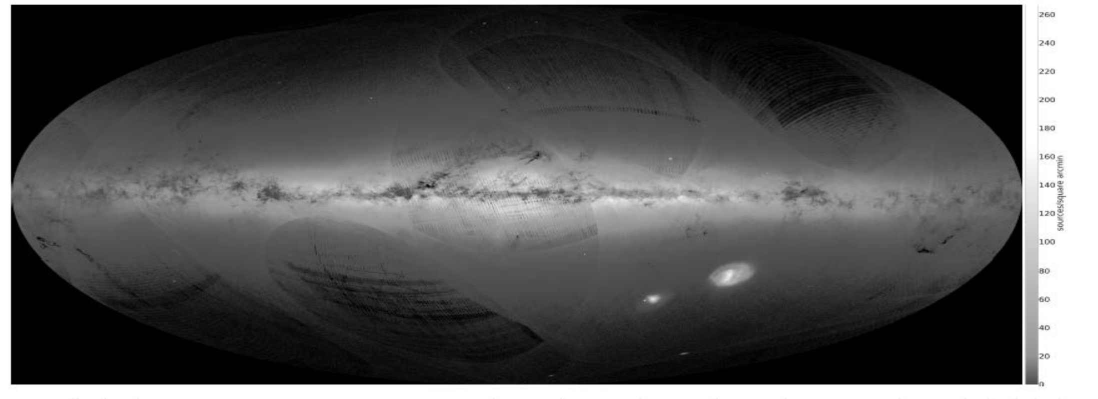
Small-JASMINE have a lot of concrete scientific objectives to achieve the above goal.

★Examples of scientific objectives of Small-JASMINE
are shown in the succeeding slides

Super massive black hole at the Milkyway Centre







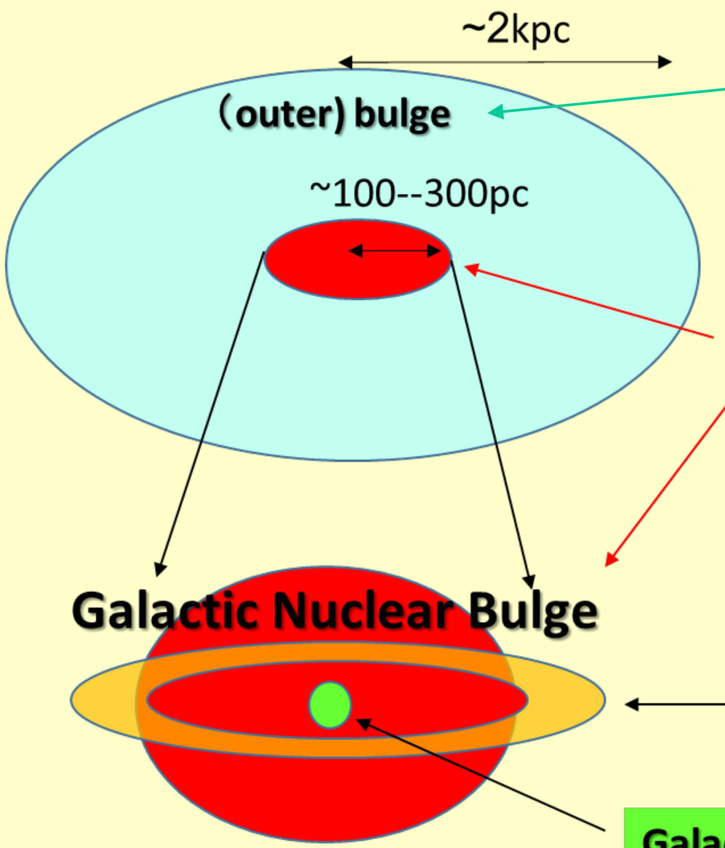
★Scientific Objectives

*: astrometry missions with high precisions (~ a few tens micro-arcseconds level)

Galactic Center Archaeology through the exploration of the Galactic nuclear bulge (in spring and autumn)

The Galactic nuclear bulge has strange unresolved astronomical phenomena and celestial objects

The Galactic nuclear bulge is very interesting and important target to clarify the outer bar, the bulge, and SMBH.



Gaia*(optical), (WFIRST*) BRAVA, etc (radial velocity, chemical components, type and age of stars)

Galactic nuclear bulge

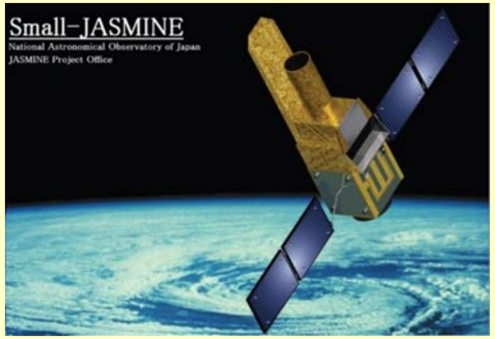
Small-JASMINE*←unique in the world!
APOGEE, VVV, MOONS GALACTICNUCLEUS,etc. (radial velocity, chemical components, type and age of stars)

Central Molecular Zone(CMZ)

Galactic central region (<10pc)

GRAVITY*(VLTI), TMT etc. (very narrow field of view) APOGEE, GALACTCNUCLEUS, etc.

★Complement to the Gaia mission in Small-JASMINE



＊ Gaia can measure only about ～70 bulge stars
with high precisions(<25μas precision of the parallax)
which are located in the same region as the whole
survey region of Small-JASMINE around
the Galactic center due to the effect of absorption
by the interstellar dust.
SJ (Small-JASMINE) => ～7000 bulge stars

＊ Gaia can measure the same target every 40 days.
So Gaia cannot resolve the astrophysical phenomena
with much shorter periods than around 40 days.
SJ=> every 100 minutes although the survey regions are restricted.

⇒ Small-JASMINE

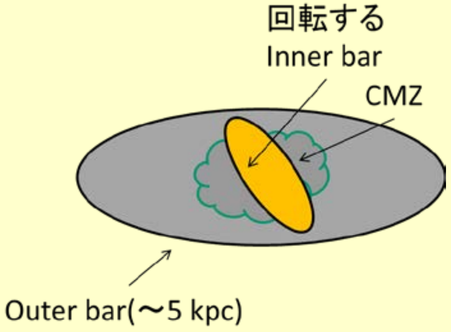
★Main scientific objective of Small-JASMINE

～Performance of the Galactic Center Archaeology through the exploration of the Galactic Nuclear Bulge which links the Galaxy to the Supermassive black hole by the use of 5-dimensional astronomical data in 6-dimensional phase distribution of stars. ～

Small-JASMINE aims to make a catalogue for time series data of stellar positions on the celestial sphere and also the annual parallaxes, proper motions and etc., which are led by the time-series data, and release the catalogue to the public in the world.

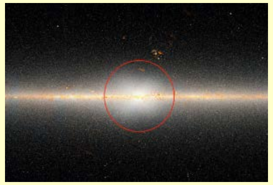
Detailed main objectives of Small-JASMINE

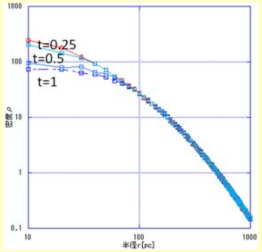
（SO-1）**Clarification of the Galactic Nuclear Disk, which leads to the classification of the Galactic bar and bulge structure by the use of Mira variables**

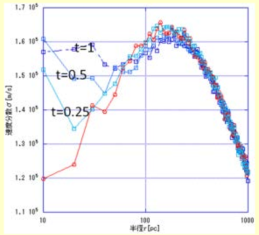


（SO-2）**Reconstruction of the Gravitational field which leads to the evolution of the Supermassive black hole and the activity of the Galactic central region**

（SO-3）**Characterization of the global dynamical structure around the Galactic nuclear disk and clarification its origin by the use of phase space distribution of stars**







Scientific objectives of Small-JASMINE

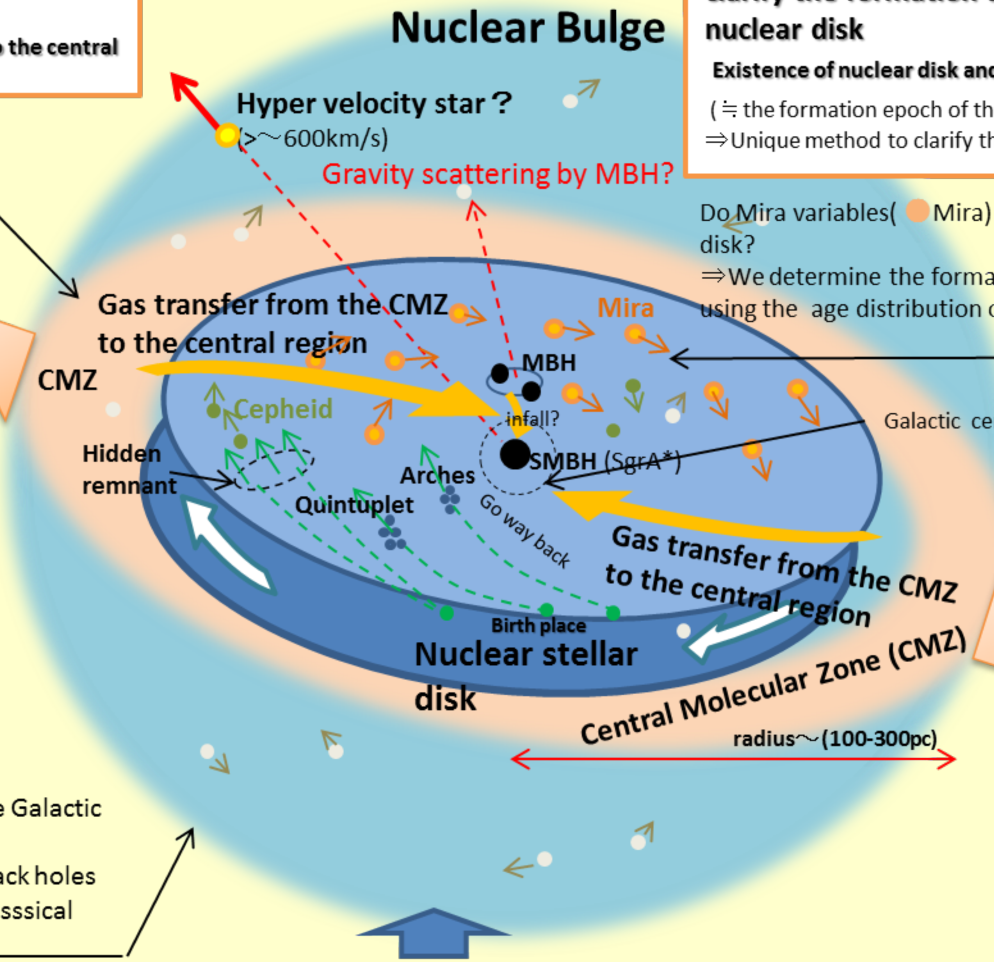
—Research Issues which Small-JASMINE can clarify for the Galactic nuclear bulge first in the world—

SO-2 Characterize the gravitational potential (of a bar structure)
What is the transport mechanism of gas from CMZ to the central region (radius of <~10pc)?

Collision of gas and shock-wave formation
⇒loss of angular momentum and energy of gas
⇒ inflow of the gas
Effect of the shock
⇒ it depends on the pattern speed of the nuclear stellar disk.
⇒ We investigate the pattern speed by using the phase space distribution of stars.

SO-1 Characterize the Galactic nuclear bulge to clarify the formation and evolution of the nuclear disk
Existence of nuclear disk and the formation epoch
(≒ the formation epoch of the outer bar) ?
⇒Unique method to clarify the formation epoch of the outer bar

Do Mira variables(Mira) attribute to the nuclear stellar disk?
⇒We determine the formation epoch of the nuclear disk using the age distribution of Mira variables in the disk.



SO-3 Characterize the global dynamical structure around the Galactic nuclear disk to clarify the origin of its structure by the use of phase space distribution

We verify whether or not some old stars in the Galactic nuclear are now in the equilibrium state due to the gravitational scattering by supermassive black holes
⇒Evolution of the SMBH or the remnant of classsical bulge?

***** Clarification of the formations of stars and stellar clusters in the nuclear bulge , and exploration of various kinds of celestial objects *****

Identify hidden remnants of stellar clusters
➔verification of Secular evolution

Clarifiy the birth places of stellar clusters, such as Arches, Quintuplet

Calrifiy whether Cepheids attribute the nuclear disk

What is the reason why hyper velocity stars (HVS)exit?

Exploration of various kinds of celestial objects
gravitational lens objects, compact objects, stellar physics, interstellar medium, etc.

The following slides show more details of the main scientific objectives for the key survey of the Galactic nuclear bulge (SO-1, SO-2, and SO-3).

Scientific objective SO-1

Existence of nuclear disk (or inner bar) and the formation epoch

* Identify the group members of Mira variables in the Galactic nuclear bulge which belong to the nuclear stellar disk (or inner bar) by the use of the proper motions of the Mira variables.
*Explore the orbital structures of the nuclear stellar disk by the use of the information of the velocity distribution of the Mira variables.
*Investigate the existence of old Mira variables which belong to the nuclear stellar disk by the use of the periods-age relation of the Mira variables and constrain the formation epoch of the nuclear stellar disk formation.

*Ref. Matsunaga, 2009 MNRAS.399. 1709.

Remark: the formation epoch of the nuclear stellar disk is similar to the formation epoch of the outer long bar which relates to the formation of the bulge, because numerical simulations suggest that the formation of the outer bar immediately caused the formation of the nuclear stellar bulge. On the other hand, the oldest age of stars founded in the outer bulge are not always the formation epoch of the bar, but the epoch of the disk structure. So the oldest age of stars in the bar is not always good indicator of the formation epoch of the outer bar.

Figure 1. An H-band image (or an RGB-composite image in the online journal) of the observed field. North in the equatorial system is up and east is to the left. Solid (or red) lines indicate $l = 0°$ and $b = 0°$, while a grid with a spacing of 0.1° is shown with dashed lines (or blue ones). The covered area is about 20×30 arcmin^2.

The Small-JASMINE satisfies the following mission

- Survey region :survey region (1)+ survey region (2)
- the proper motion precision is equal to or less than ~125μas/year(Hw<15mag) (<=~5km/s at 8kpc)
- the number of Miras measured in the survey region2 with the proper motion precisions shown just above and, with the periods of <250 days(the age is older than 10G years) is larger than about 100(<=Hw<15mag.).

<= enough range of the ages of Miras

The following success will be attainable

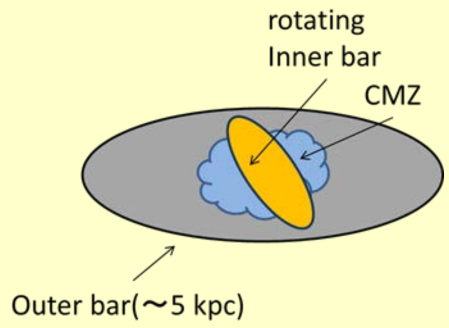
Identify the group members of Mira variables in the Galactic nuclear bulge which belong to the nuclear stellar disk by the use of the proper motions of the Mira variables. In this procedure, the measurement errors of the proper motions will be equal to or less than 10% of the value of the proper motion which corresponds to the prospected velocity dispersion of the nuclear bulge（~130km/s). Furthermore clarify the orbital structures of the nuclear stellar disk by the use of the information of the velocity distribution of the Mira variables. In this procedure, the measurement errors of the proper motions will be equal to or less than 10% of the value of the proper motion which corresponds to the prospected rotational velocity of the nuclear stellar disk(50-120km/s). Investigate the existence of old Mira variables which belong to the nuclear stellar disk by the use of the periods-age relation of the Mira variables and constrain the epoch of the nuclear stellar disk formation. In this procedure, measure enough number (>100)of Miras to get periods of <250 days which covers enough old ages(>10G years) of Miras.

Scientific objective SO-2

Gravitational potential at the Galactic nuclear bulge=>Gas infall into SgrA*?

Small-JASMINE's data will constrain models of the gravitational potential in the Galactic nuclear bulge region (within ~300pc or the Galactic center) with the phase-space density of stars

=>Clarify the gravitational potential field in the Galactic nuclear bulge, in particular, the physical characters of the bar potential which corresponds to the nuclear disk or the inner bar, such as the figure rotation, the flatness etc.



rotating bar=>Losing angular momentum and energy of gas

➡ candidate of key processes for transportation of gas

*need to clarify transport mechanism of gas to galactic centers

⬇

***Gas fueling is very important for the growth of SMBHs, activities of galactic nuclei, nuclear star bursts and the formation of super star clusters in the galactic central regions.**

The Small-JASMINE satisfies the following mission

･Survey region: Galactic longitude -2.0～0.7 degree
Galactic latitude 0.0～0.3 degree
･the proper motion precision is equal to or less than ~25μas/year(＜＝~1km/s at 8kpc) (Hw<12.5mag)
･the annual parallax precision is equal to or less than ~25μas (Hw<12.5mag)
<=refer to the Supplement for Parallax Error
･the number of bulge stars measured with the above is larger than about 3000.<=the criterion for the Poisson noise

The following success will be attainable

Clarify the gravitational potential field in the Galactic nuclear bulge, in particular, the velocity of the figure rotation (pattern speed) of the potential. In this procedure, measure the proper motions of stars with the precisions of the value which will be equal to or less than 10% of the value of the proper motion which corresponds to the prospected velocity of the figure rotation of the outer bar at 300pc (10-20km/s). The Poisson noise effect resulted from the finiteness of sample stars used for model fitting will be less than 10% or so to find a suitable model for the gravitational potential with a figure rotation velocity by the use of measured velocity distribution. Furthermore the errors of the annual parallaxes of the sample stars will be small enough to reduce the possibility that stars located at far disk structure are estimated in error to be located at the nuclear bulge by the bias effect caused by the parallax error.

Scientific objective SO-3

Infall of supermassive black holes into the Galactic center?

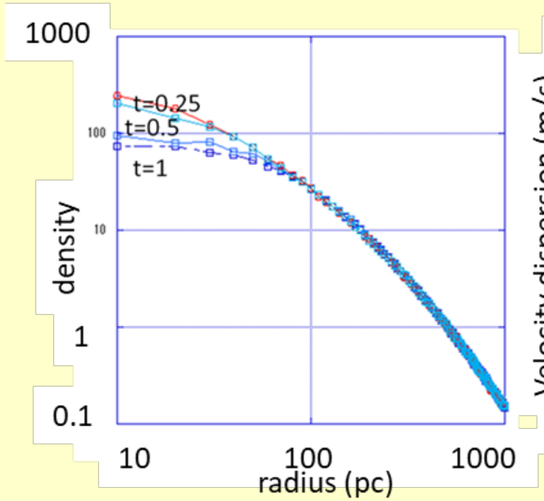
Verify whether or not some stars in the Galactic nuclear are now in the equilibrium state by the gravitational scattering by some celestial objects such as supermassive black holes.

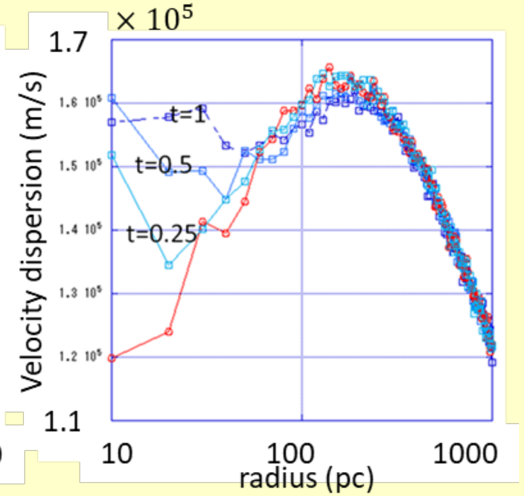
Equilibrium state: the effect of the dynamical friction and the release of the gravitational energy of binaries "heat up" the stars around the centre area (<100pc).

➔change of the density profile and the distribution of the velocity dispersion

*The stars within the radius of 100pc around the centre will be heated up

Change of the density profile and velocity dispersion profile of bulge stars within the radius of 100pc





density profile=>core structure

velocity dispersion profile=>flat profile

Important remark: these profiles do not depend on details of model (e.g. initial condition, mass distribution, etc)

The Small-JASMINE satisfies the following mission

･Survey region: the circle with the radius of 0.7 degree (～100pc)
･the annual parallax precision is equal to or less than ~25μas
<=refer to the Supplement for Parallax Error
･the proper motion precision is equal to or less than ~125μas/year(<=~5km/s at 8kpc)
･the number of bulge stars measured with the above precisions is larger than about 3000. <=the criterion for the Poisson noise

The following success will be attainable

Clarify the density profile and the velocity dispersion profile of stars in the Galactic nuclear stars. So measure annual parallaxes and the proper motions of bulge stars .
The precisions of the annual parallaxes and the proper motions will be enough to remove stars located on the disk structure in the sample. So the errors of the annual parallaxes of the sample stars will be small enough to reduce the possibility that stars located at far disk structure are estimated in error to be located at the nuclear bulge by the bias effect caused by the parallax error. Furthermore the measurement errors of the proper motions will be equal to or less than 10% of the value of the proper motion which corresponds to the prospected rotational velocity of the nuclear stellar disk(50-120km/s). The Poisson noise effect resulted from the finiteness of sample stars used for model fitting will be less than 10% or so to find suitable density profile and velocity dispersion profile.

1. **If the relaxation process will be suggested**, then we have high possibility that there happened the relaxation process by the gravitational scattering by some super massive black holes which moved around in the Galactic nuclear bulge.

➔We need large amount of energy to heat up stars which locate within 100pc.

➔ We can get such energy only if supermassive BHs (> 100,000 solar mass: it is assumed that the total mass of the supermassive BHs is 4 million solar mass which corresponds to that of Sgr A*) exist and they have fallen into the Galactic center (<100pc) by the dynamical friction within the cosmic age.

➔only the effect of the dynamical friction and the release of the gravitational energy of supermassive BH binaries can "heat up" the stars around the centre area (<100pc). ==>Origin of such a few supermassive BHs?

➔ relation of the evolution of Sgr A*

Difficult for { Globular clusters, Giant molecular clouds } to heat up the stars around the center area(<100pc) within the cosmic age.

2. **If the relaxation process will not be suggested**

=>we have possibility that we constrain the dynamical process which resulted in the present global dynamical structure of the spherical part of the nuclear bulge around the nuclear stellar disk, by using the observed density profile and the velocity dispersion (or velocity) profile provided by SJ.

➔We may constrain the formation model of the spherical part of the nuclear bulge (component of classical bulge?) .

Supplement for Parallax Error

Why do we need <~25μas?

Bias related to transformation

The distance, the astronomical quantity of interest, is the inverse of the parallax measured by the astrometry mission. While the parallax distribution is known to be Gaussian, the distribution function of the distance is not Gaussian. Neither is it symmetric because of the non-linear relation between distance and parallax (see the upper figure to the right). The deformation becomes larger for larger relative parallax errors, σ_π/π_{true}(see the lower figure of the right). The peak of the distribution will move to smaller values with a larger relative error. This means that the distances will be underestimated in the presence of large relative parallax errors.

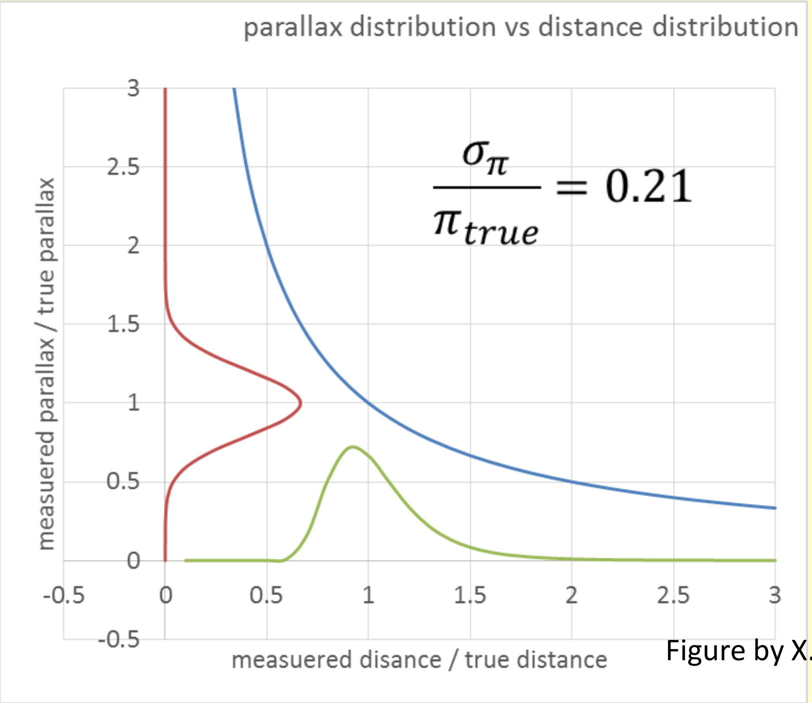
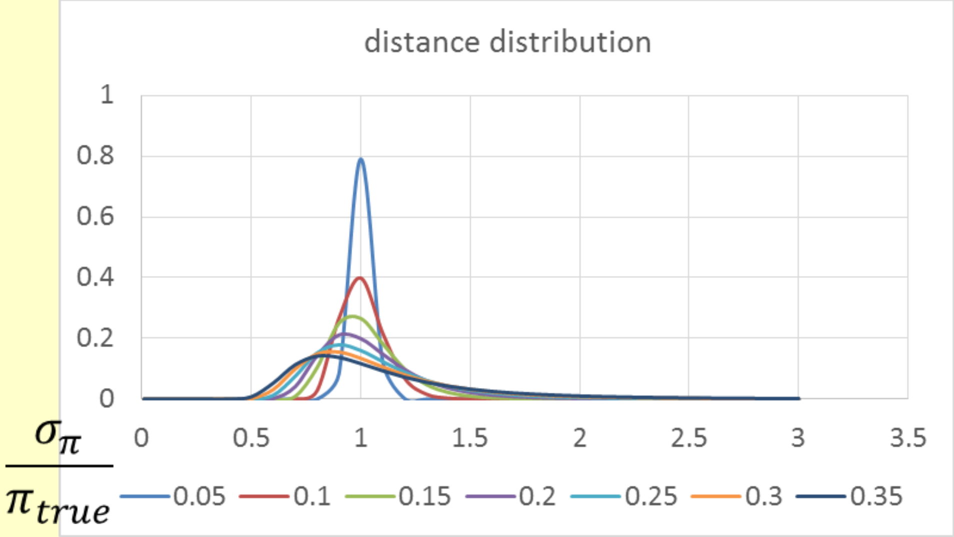


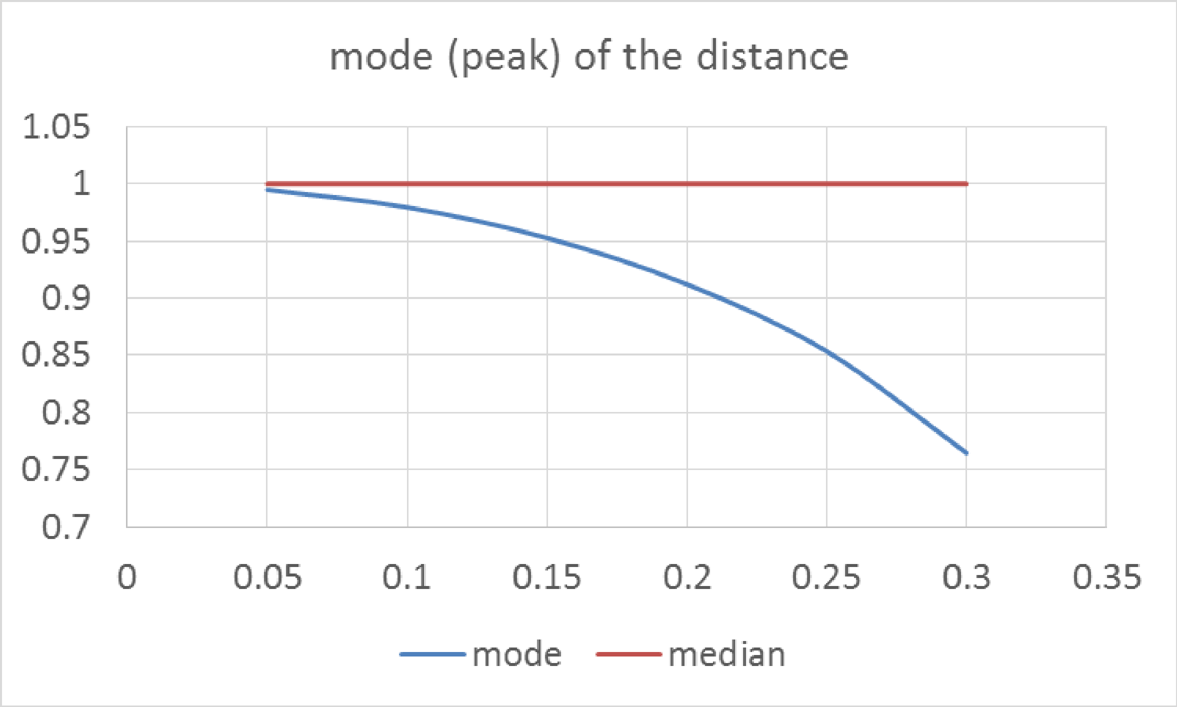
Figure by X. Luri



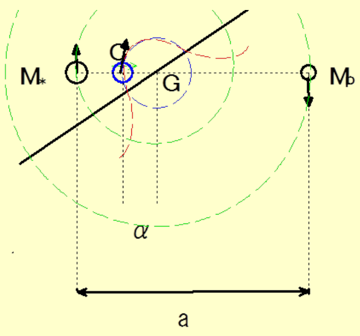
Why do we need <~25μas?

Bias related to transformation

The parallax corresponding to a distance of 10kpc from the Sun is 100μas. The right figure shows that estimated distance is 85% of the true distance due to the bias effect if the relative parallax error is 25%. Disk stars which are in truth at 10kpc may be estimated to be located at only 8.5kpc from the Sun, which puts them barely in the nuclear bulge region. Therefore the error must not exceed 25μas (0.25 × 100μas) as a requirement.



Other Scientific objectives in the key Projects



(a) Discovery of unknown BHs

(i) Residual from a helical motion ➔ discovery of BH-star binaries

➔ analysis of orbit element ➔ clarification of BH mass

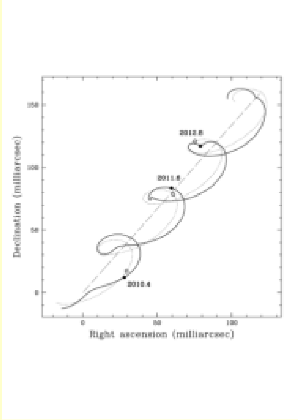
(ii) Astrometric microlensing

➔ discovery of BH, clarification of BH mass

****ref: the first detection of the astrometric microlensing effect***

***due to celestial objects outside the solar system* (HST: Sahu, et al., 2017)**

➔ Determination of the mass of the white drawf Stein2015B!



(b) Discovery of Hyper Velocity Stars(HVS) in the nuclear bulge

➔clarification of the origins of HVS and S-stars

*** Stellar binary+ SMBH or single star + IMBH-SgrA* binary**

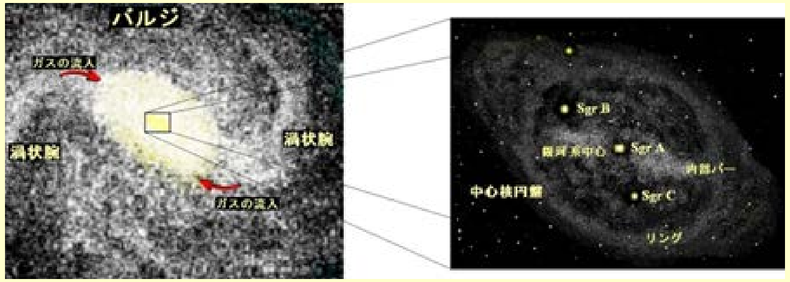
(c) Analysis of symbiotic X-ray binaries

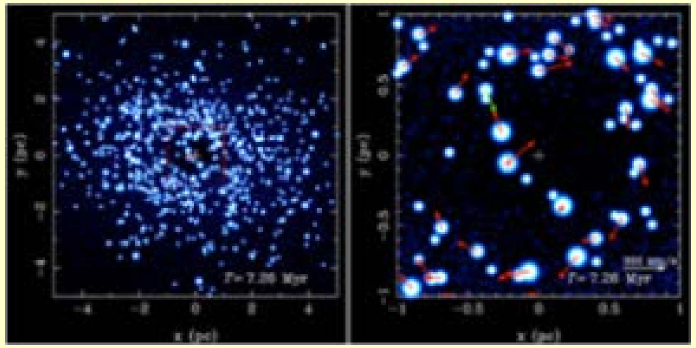
➔ the origin of X-ray emission spread along the galactic plane(!?).

Other Scientific objectives in the key project

(d) Motion of star clusters around the Galactic center

➔ the birth places of star clusters





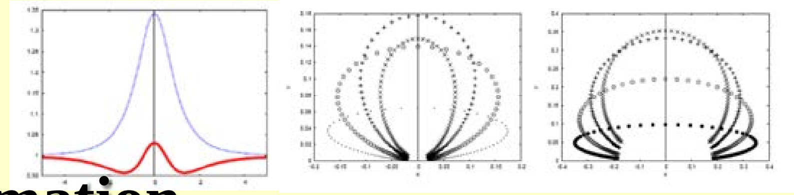
(e) Discovery of unknown stellar clusters in the nuclear bulge by detection of parallel movement of the stellar proper motions

➔ clarification of star formation rates

(f) Discovery of exoplanets by the use of astrometric method:

(g) Discovery of unknown objects

e.g. Wormholes?!

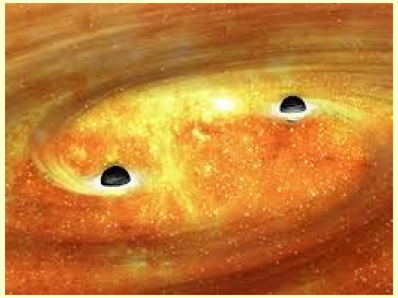


(h) Stellar physics, Star formation

* 3-Ddistribution of inter -stellar dust
* annual parallax and proper motions of Mira-type variable stars in the bulge

Supplement for Other Scientific Objectives

Scientific objective (a)(ii) & (g)

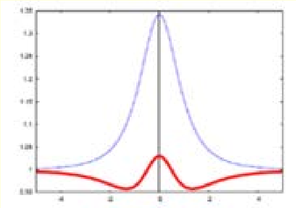


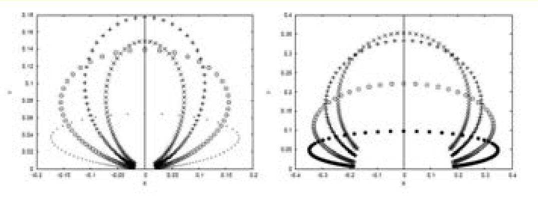
Detect the compacts objects by the astrometric microlensing effect to clarify physical characters of the compact objects

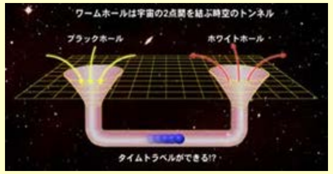
Search astrometric microlensing events and detect at least one event within the operation time with 3 σ confidence level. In particular, search massive BHs with 30 solar mass(#) (which may be a primordial black hole) by the use of astrometric microlensing effect.

 # a few massive BHs with ~ 30 solar mass were found by the gravitational wave (advanced LIGO)

 # whether the event rate of lens effect by massive BHs with 20 ~ 30 solar mass is lager than the expected mean rate or not ➔ the origin of such BHs







The Small-JASMINE satisfies the following mission(refer to p.3)

Survey region: the survey region (1)+the survey region(2)
*assumption: the number of bulge stars~ 9000
: effective operation time~1.5 years
: average mass of lens objects ~0.5 solar mass
:probability of observing a centroid shift within 1 year for a given observed star is given by Table 2 of Dominik and Sahu (ApJ, 2000)

Probability :1.0/9000/1.5 ~ 7.4×10^{-5} ➔ centroid shift>60μas
60μas/25μas=2.4 ➔2.4 σ detection

The following success will be attainable

Detect the compacts objects by the astrometric microlensing effect to clarify physical characters of the compact objects. So search astrometric microlensing events and detect at least one event within the operation time with 2.4 σ confidence level.
In particular, search massive BHs with 30 solar mass (which may be a primordial black hole) by the use of astrometric microlensing effect.

Cf. Gravitational Lens

The centroid of a background star moves with time variation of the brightness of the star because of the general relativistic effect when a compact object passes near the background star on the celestial sphere. In general, we can not predict when and how this gravitational effect will occur. However, we can estimate the possibility of the event.

The optical opacity of the gravitational effect is given as follows:

Dominik and Sahu (ApJ, 2000)

TABLE 2

PROBABILITY OF OBSERVING A SIGNIFICANT CENTROID-SHIFT VARIATION

THRESHOLD DIRECTION δ_T (μas)	PROBABILITY OF OBSERVING A CENTROID-SHIFT VARIATION LARGER THAN δ_T WITHIN $T_{obs} = 1$ yr FOR A GIVEN OBSERVED STAR	
	Bulge Stars toward Baade's Window[a]	Perpendicular to Galactic Plane[b]
	$\gamma_{var,0}$	$\gamma_{var,\infty}$
1	4.3×10^{-3}	3.0×10^{-4}
5	8.6×10^{-4}	6.0×10^{-5}
10	4.3×10^{-4}	3.0×10^{-5}
100	4.3×10^{-5}	3.0×10^{-6}

NOTE.—The probability of observing a variation in the centroid shift larger than the threshold δ_T, $\gamma_{var} \propto \rho_0 T_{obs} v \delta_T^{-1}$, is shown for sources (1) toward the Galactic bulge, eq. (65), and (2) perpendicular to the Galactic plane, eq. (90), with the reference values $T_{obs} = 1$ yr, $v = 100$ km s^{-1}, and $\rho_0 = 0.08\ M_\odot$ pc^{-3}.

[a] $\rho(x) = \rho_0$, and $D_S = 8.5$ kpc.

[b] $\rho(x) = \rho_0 \exp\{-xD_S/H\}$. and $D_S \gg H = 300$ pc.

Scientific objective (b)

Finding hyper velocity stars (HVSs) near the Galactic centre (GC) will be a key to understand the origin of HVSs and S-stars which are young stars orbiting very near Sgr A*.

Stellar binary + SMBH

or

single star + IMBH-SgrA* binary

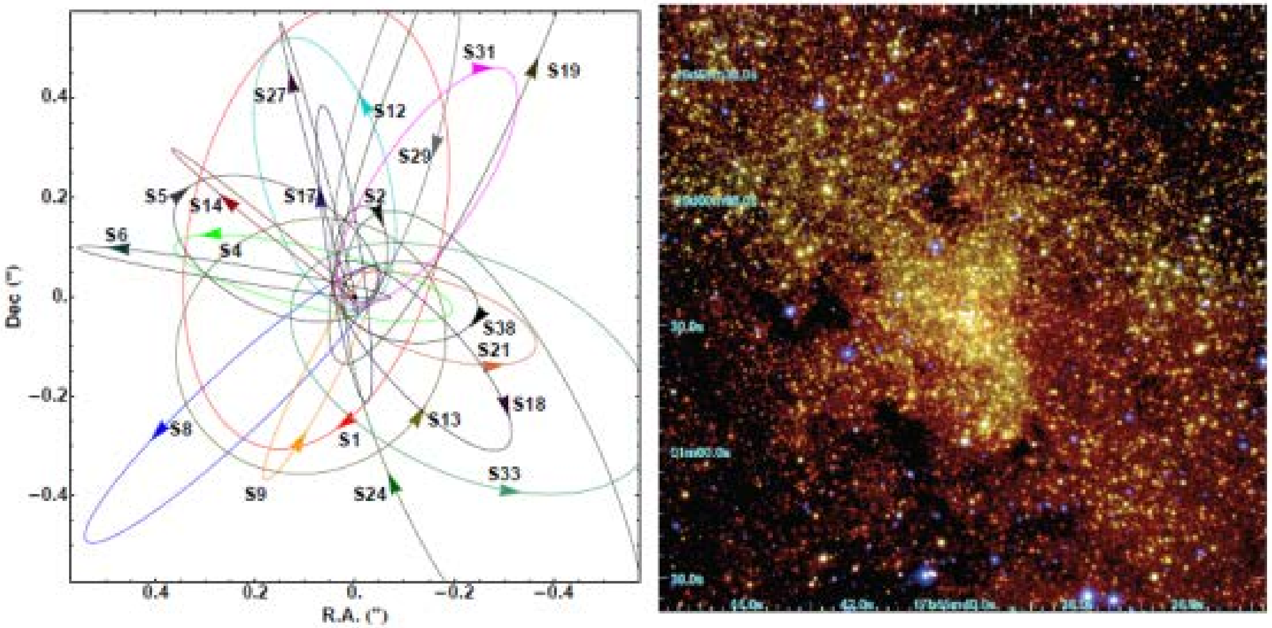


Figure 5.10: *Left*: Stellar orbits of S-stars in the central 1.″0 ~ 0.04 pc of our Galaxy. The coordinate system is chosen to such that Sgr A* is at rest (Fig. 16 in Gillessen et al., 2009). *Right*: Near-infrared three-color (1.19 μm, 1.71 μm, and 2.25 μm) composite image of the central ~ 150″ region of our Galaxy (Fig. 2 in Nishiyama & Schödel, 2013). The NSC in our Galaxy has a half-light radius of ≈ 100″ ~ 4 pc (Schödel et al., 2014).

The Small-JASMINE satisfies the following mission(refer to p.3)

*assumption: HVS is located 0.5 degree (1800") from the GC.
:the velocity of a HVS is 700 km/s ~ 18mas/yr (constant)
➔if the birth place is the GC, then the age is 1800"/(18 mas/yr) ~ 0.1 M years
*Proper motion error : 2.5"/0.1M yr ~ 25μas/yr
➔ the position error is within 0. 1pc(~ 2.5") , 0.1M years ago.
（very simple case: straight line)

The following success will be attainable

Finding hyper velocity stars (HVSs) near the Galactic centre (GC) will be a key to understand the origin of HVSs and S-stars which are young stars orbiting very near Sgr A*. So search the HVSs by the measurement of the proper motions of stars within the Galactic nuclear bulge and verify the hypothesis that the birth place is near the Galactic centre (within 0.1 pc ~ around the existence region S-stars' orbits).

Scientific objective（c）

Clarify physical characters of the compact objects in X-ray binary systems.

The Small-JASMINE satisfies the following mission(refer to p.3)

$$|\alpha| = 125[\mu\text{as}]\left(\frac{q}{0.2}\right)\left(\frac{a}{5\text{au}}\right)\left(\frac{D}{8\text{kpc}}\right)^{-1}$$

* Assumption : q ~ 0.2 (=Mp/ M_*, M_* ~10 solar mass, Mp~2 solar mass)
D ~ 8kpc
a~2.5 au(0.6 ~ 5 au) (period: T=1.1yr)

α ➔ ~61μas

61/25 ~2.4 ➔ 2.4σ detection

The following success will be attainable

Clarify physical characters of the compact objects in X-ray binary systems. In particular, detect X-ray binary systems with red giants (symbiotic X-ray binaries) with 2.4σ confidence level and measure the distances of the binaries

Scientific objective (d)

Clarify the formations of young massive star clusters found in the Galactic centre region, such as Quintuplet and Arches clusters.

The Small-JASMINE satisfies the following mission(refer to p.3)

*Survey region must include the above 2 star clusters.
cf. the survey region (1) include these star clusters.

*At least stars in the clusters can be confirmed within the bulge region by the estimate of the distance.
🡸 Parallax error : <~25μas
<=refer to the Supplement for Parallax error

*the age of the Quintuplet cluster is about 4M years.
When the star cluster goes back 4M years ago, the position error can be within 4pc ~100"(~the size of the star cluster).
🡸Proper motion error : 100"/4M year ~ 25μas/yr

(<=under the simple assumption in which the trace of the cluster was a strait line though the real orbit will be numerically analyzed under models of the gravitational potential.

The following success will be attainable

Clarify the young massive star clusters found in the Galactic centre region, such as Quintuplet and Arches clusters and so determine the birth places of Quintuplet and Arches clusters with the position error similar to the typical cluster size (〜2.0pc).

Scientific objective (e)

Galactic nuclear star clusters will be a key to understand the formation process of stars around the Galactic centre. There is possibility that the Galactic nuclear bulge have hidden remnants of star clusters. Hence it is interesting and important to find hidden remnants and enlarge the number of samples of the clusters.

If we get samples of star clusters with various ages (from a few Myrs to ~10Gyrs), this suggests verification of the secular evolution in the bulge.

Constrain the star formation history in the Galactic bulge

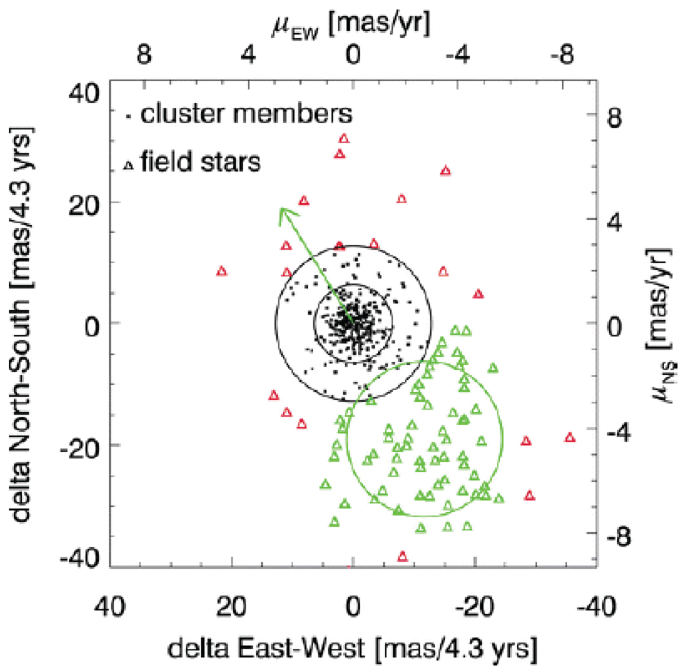


Figure 5.12: Spatial displacement of stars in the Arches cluster over 4.3 yr in the cluster reference frame. Arches candidate members (black dots) cluster around (0,0), while likely field stars (triangles) are mainly distributed to the lower right of the members. Adapted from Stolte et al. (2008), Fig. 3.

Remark (Nishiyama,2016)

It has been proposed that massive clusters formed at more than several parsec distance from Sgr A* are followed by an infall toward the central parsec via dynamical friction. The lifetime of the intermediate-age (~100Myr – 1Gyr) stars found in a few parsec region, more than ~100 Myr, is long enough for clusters to migrate from a few tens parsec distance to the central a few parsec region. A migration of stellar clusters to the center is a natural consequence if clusters are formed in this region, so at least some part of the Nuclear Stellar Cluster are expected to be formed as stellar clusters in the Galactic nuclear bulge.

➔

However, it is not easy to find such cluster in the Galactic center region. In projection on the sky toward the Galactic center, a density contrast between stellar clusters and inter-cluster fields is reduced because of accumulation of stars along the line of sight. In addition, the clusters expand as they age, and are disrupted mostly by tidal stripping and two-body relaxation.

➔

To identify such hidden cluster remnants, astrometric studies are necessary. In the GC region, the two-body relaxation time for a cluster with a mass of 10^4M is on the order of a few 10^9 yr. It means that a part of members of the clusters with an age of ~ 100 Myr still have a similar proper motion.

If stars with a common proper motion are clustered, they can be identified as a remnant of a cluster.

In addition, the cluster velocity carries the imprint of the motion of its native cloud, and studies of the cluster's 3D motion shed light on its origin.

The Small-JASMINE satisfies the following mission(refer to p.3)

Typical mass of the nuclear star cluster is about 10^4 Msun. Typical size is about 1pc. Hence typical velocity dispersion of internal motions of stars in a star cluster is about 200µas/yr and so the proper motion error of ~25µas/yr means that we can measure the velocity of the intrinsic motions of each star with the precision of 12% of
the dispersion. This makes it possible to identify the members of the cluster with an unprecedented precision*.

🡐Proper motion error: 0.12 × 200µas/yr=25µas/yr

○Stars in the clusters will be confirmed within the bulge region by the estimate of the distance and so at least the annual parallax precision should be equal to or less than ~25µas

<=refer to the Supplement for Parallax Error

The following success will be attainable

Galactic nuclear star clusters will be a key to understand the formation process of stars around the Galactic centre. Hence it is interesting and important to find hidden remnants and enlarge the number of samples of the clusters.
So discover cluster remnants by identifying the member of the cluster.

★Enlargement of scientific objectives of Small-JASMINE

Small-JASMINE=> proper motion of 70,000 bulge stars

＋spectroscopic measurements（radial velocities, type of stars, age of stars, etc.）, multi-photometric measurements（type and age of stars）

Enlargement of information of physical characters of stars

=>

Enlargement of scientific objectives of Small-JASMINE by scientific collaborations with other projects and collaborative research with other researchers in the world

＊Increase of great scientific outputs by the use of the Gaia data in many fields

➔Enlargement of scientific communities which use astrometric data.
Progress of analysis tools for the investigation of the Galactic dynamical structures and open use of these tools to the public.

＝＞Lead to great scientific outputs by the use of data provided by Small-JASMINE

Project Scientist: Prof.Kawata(UCL)➔Production of White Paper

1.3 Operation mode in summer and winter seasons

Option1: Transit observation of mid/late M-type stars (~3000K) to find terrestrial planets in the habitable zone

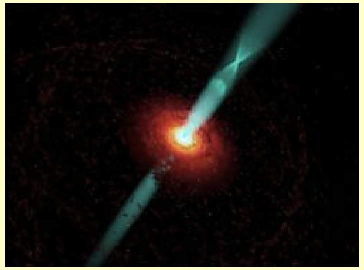
Establishment of science team independently of JASMINE team (exo JASMINE team)
PI.:Kawahara (Univ. of Tokyo),
Kotani(ABC), D.Suzuki, T.Yamada(ISAS), Masuda(Princeton Univ.), etc.

Option2: Clarification of very interesting and important target objective suggested by science communities.

Option3: Calibrations for the data analysis

Candidates of Other Scientific objectives in summer and winter seasons

Option2: Astrophysics besides the direction toward the Galactic nuclear bulge



Good candidates: phenomena with short periods, bright objects in infrared bands

B-1. Compact celestial objects

Determination of the orbit elements of X-ray binaries and γ-ray binaries

➔ Big revolution! ➔physics of accretion disk and jets, etc.

*a good candidate of X-ray binary：Cyg X-1:(l=71°, b=+3°)

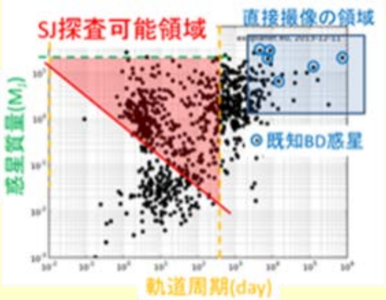
period:5.6 days(unmeasurable by Gaia) companion star: mv~9mag , change of the position:

40~50μas measurable by Small-JASMINE

➔identification of compact objects

*γCas: WD or NS=>1σ degree of confidence, HESS J0632: NS or BH (2σ)

B-2. Extra-planets



detection of planets by astrometric method

*determination of mass with precisions of <20% for stars measured by radial velocities

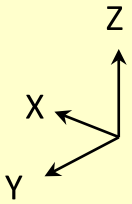
*primary star: low-mass star(late M-dwarf, brawn dwarf): H=10mag,V=16-18mag

B-3. Analysis of stellar hot spots

1. 3 Satellite

• Semi-custom-made bus module* which has been developed for JAXA small scientific satellite series is adopted. * the Standard Bus for Small Scientific Satellites by NEC

• Saving of both, development time and cost is expected.



Artist concept of
Small-JASMINE satellite

Bus module specification

Bus weight		200~250kg
Bus Size		1000x1000x1000 mm
Mission	weight	< 200kg
	power	< 300W
	size	1000x1000xheight
Attitude control		Three axis control
	Accuracy	< 1 arcmin
	Stability	< 0.1mas/10msec
	Maneuvering	180deg/10min
Propulsion system		Option → RCS*
Duration of life		> 1 year → 3 year*

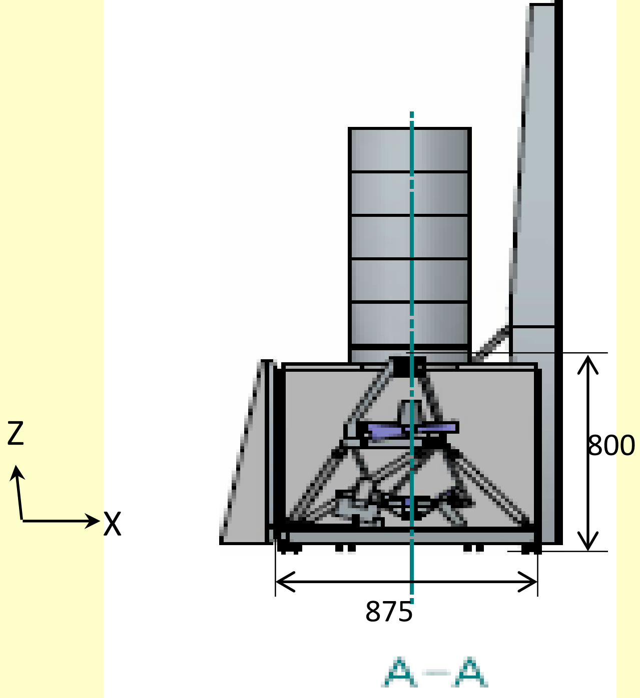
* Small-JASMINE adaption

(RCS = Reaction Control System)

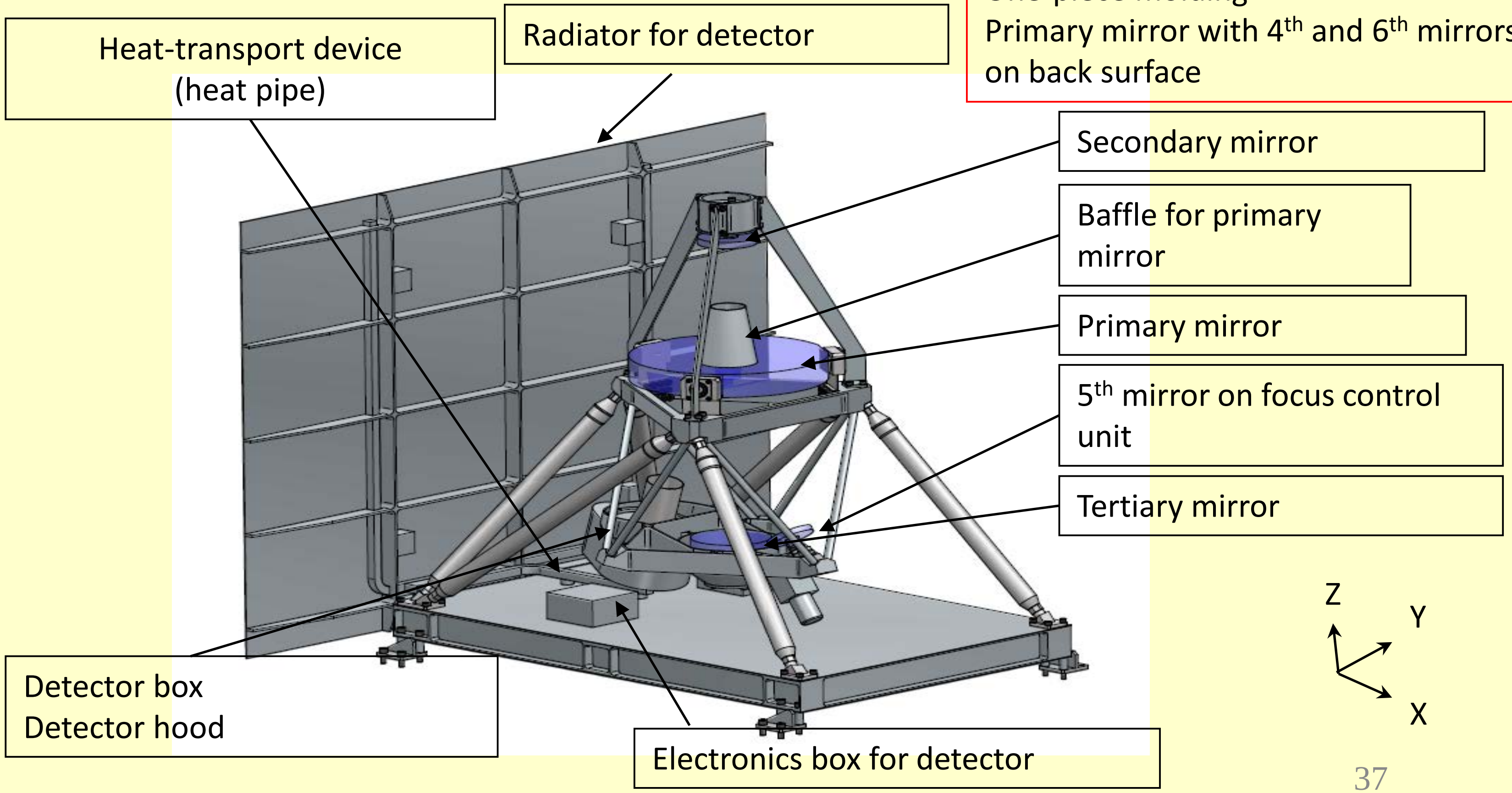
Telescope

- Athermal telescope structure is designed which is made of Super-Super Invar* of zero thermal expansion
  * Newly developed alloy, CTE (coefficient of thermal expansion): 0 ±5x10^{-8}/K,
    Martensite transformation temperature: below 180K
- Mirrors of CLEARCERAM® -Z EX, zero thermal expansion glass ceramic (CTE: 0 ±1x10^{-8}/K)
- Telescope temperature is controlled within 278±0.1K during observation of 50min.
- Detector is kept below 180K using Peltier module

Telescope is placed inside a telescope box with active temperature control



One-piece molding
Primary mirror with 4^{th} and 6^{th} mirrors on back surface



1.4. Satellite System Overview

- Optics design: Modified Korsch System (3mirrors)
- Material: CLEARCERAM (Ultra−Low Expansion Glass−Ceramics) T～278K
- Aperture size: 0.3m
- Focal length: 3.9m
- Field of view: 0.6 degree ×0.6 degree
- Detector: T<180K

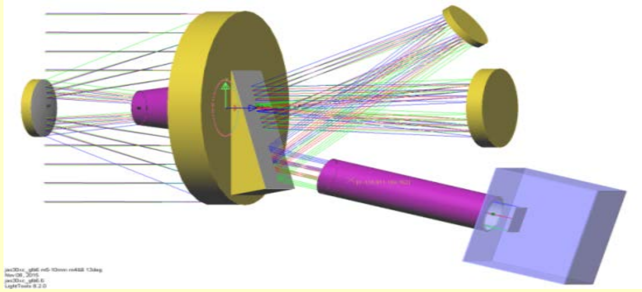
Hw-band: HgCdTe(H4RG), Number of detectors: 1
Band:1.1～1.7μm

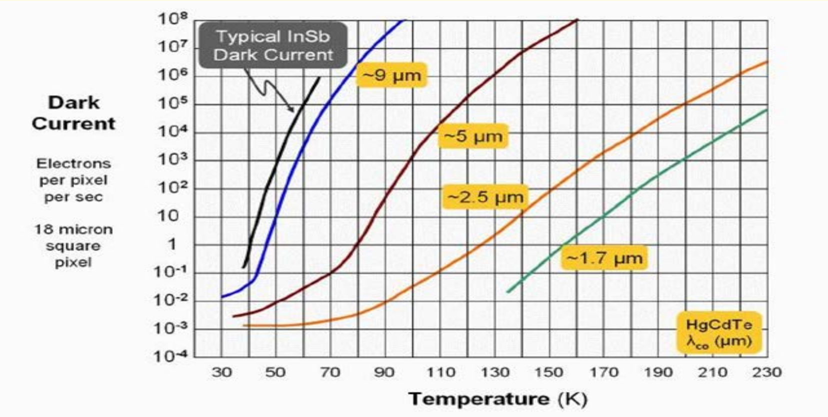
pixel size:10μm

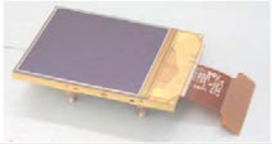
the number of pixels:4096×4096

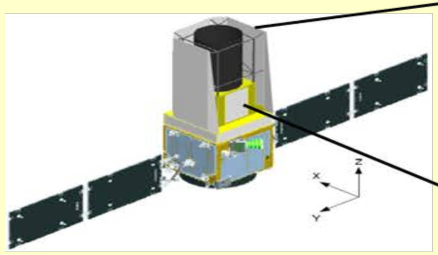
potential well:100,000

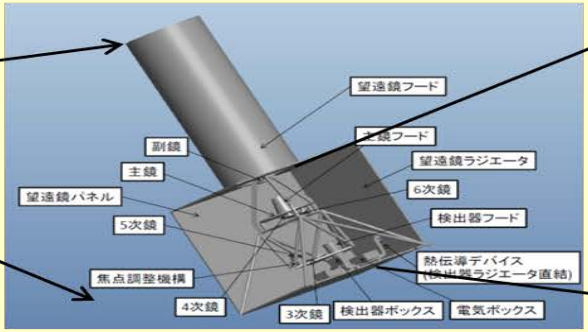
read-out noise :30e

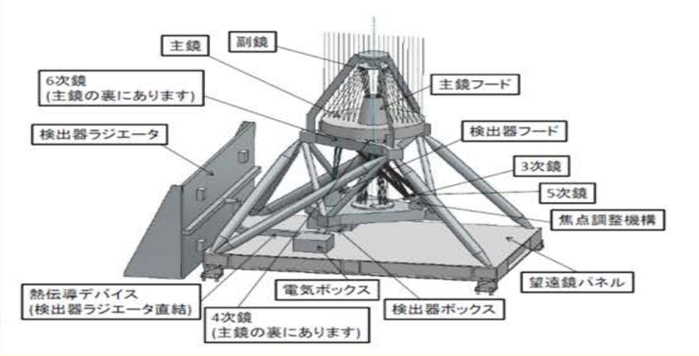












Structure model of the mission system

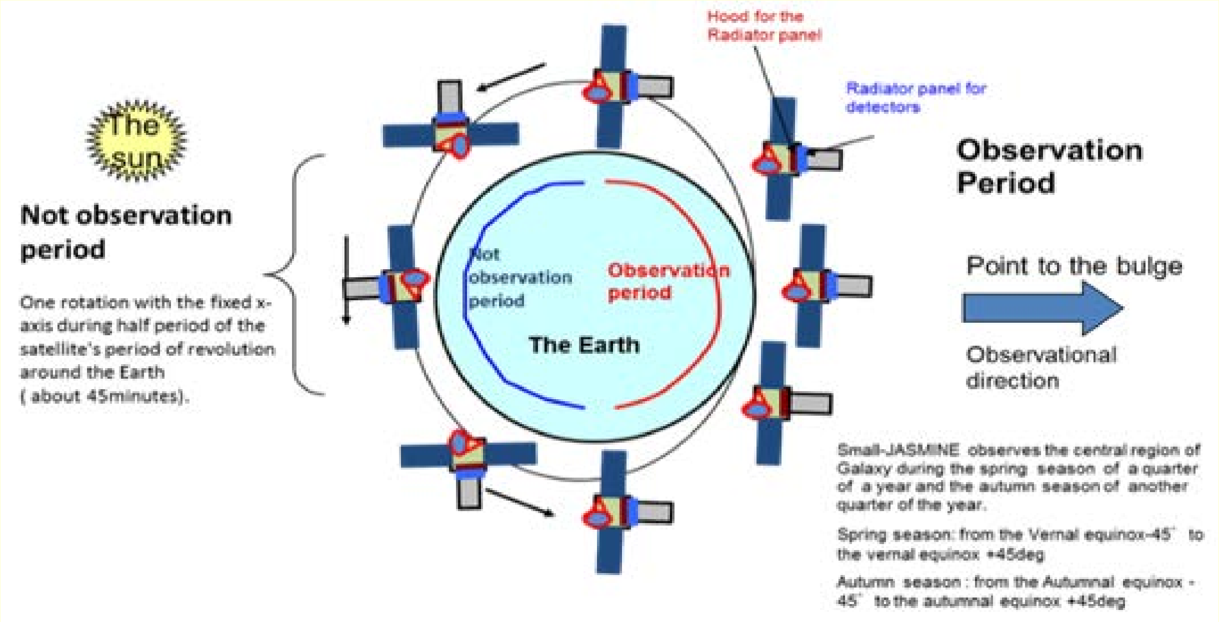
The target launch date is around ~2024

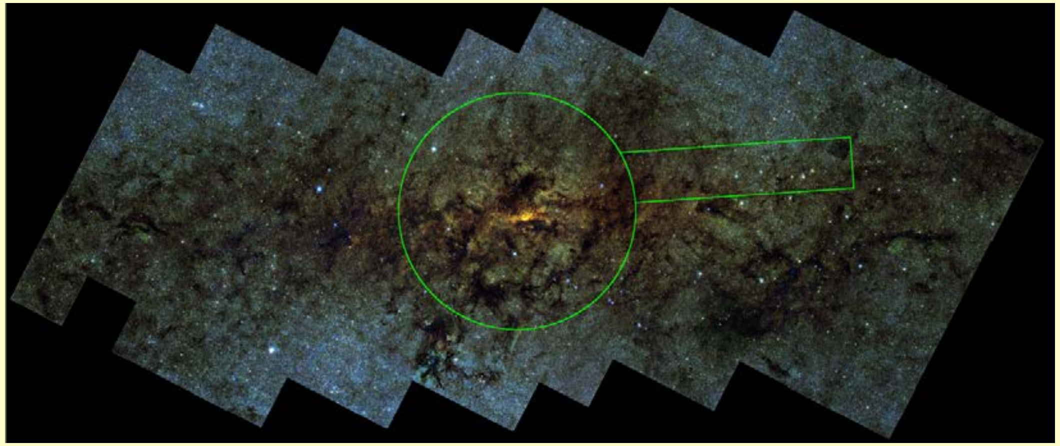
Mission life: ~3 years

Orbits: Sun synchronized orbit ~550km

Launcher: Epsilon launch vehicle(solid rocket) provided by JAXA

Sun Synchronous orbit with LTAN 6:00 or 18:00





J, H, K tricolor composite image of the Galactic center area(imaged by SIRIUS on the Nagoya University IRSF 1.4m telescope: Nishiyama et al., 2004 Spring Astronomical Society Press Release).
The survey area of Small-JASMINE is written with the green line.

Small JASMINE

Development effort of NAOJ with JAXA (Japan Aerospace eXploration Agency) and universities.

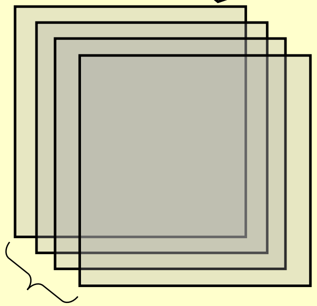
1.5 Observing strategy

We adopt “the point and stare” strategy and flames-link method(block-adjustment).

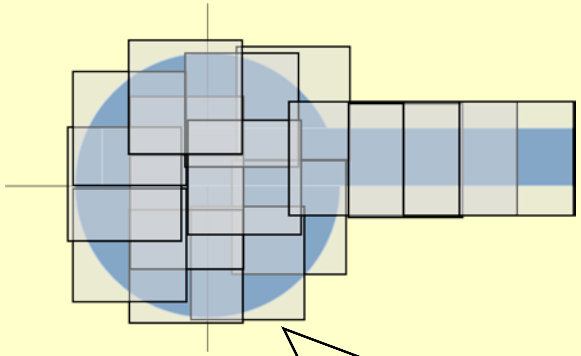
Frames-Link method

The whole survey region is composed by combining the small fields by using many stars in an overlap region between two consecutively observed adjacent small-fields. This method is suitable for surveys of the Galactic bulge because there is a sufficient number of stars to link small-fields with good accuracy.

Unit frame (image of FOV size taken in 7.1 seconds exposure):
(A) Estimate center of image position



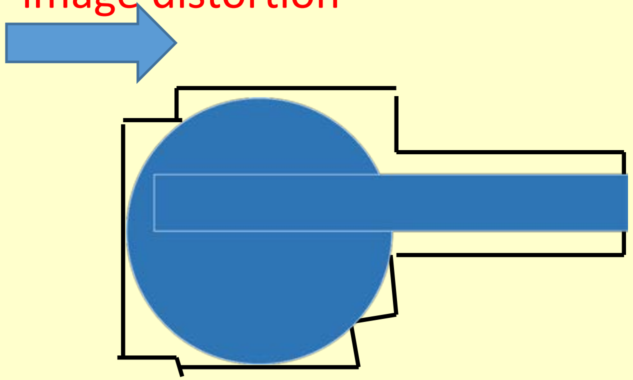
(almost same position) 20 unit frames
= small flame



Small frame (FOV size)

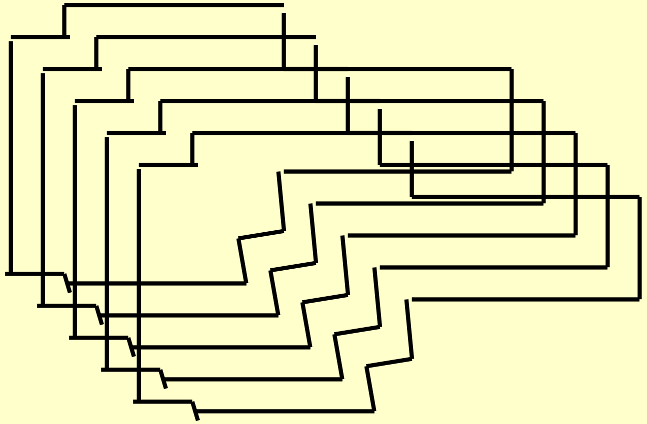
3 years operation
(3 months in autumn and 3 months in spring in every year)

(B):16 small frames ⇒ large frame
(50min ≈ half of orbital period)
Correct optical distortion and image distortion



Large frame
(whole observational area of bulge direction)

8000 large frames



(C):
Correct systematic error
Estimate parallax and proper motion

1.5 Data Analysis Overview

Multiple measurements of stellar positions on the trace of the star

0.15~0.6 million times!

★**Statistical error(random error)** **reduction according to 1/√N-law**

★**Systematic error** ⇨ **estimation, control , removal, calibration**

Estimation is important process for astrometry to reduce systematic errors

★**Self-Calibration**

○**Modelization of systematic errors by the use of stellar positions measured by SJ**

It is possible to model the systematic errors by the use of the fact that we can presume that relative stellar positions on the celestial sphere do not move in short periods and/or the trace of a single star with negligible effects of planets, gravitational lens and/or hot spots, has a definitive shape, that is, helical motion!

Then, in principle, systematic components of time variations of relative angular distances between stars are systematic errors.

***Even if we do not know in advance the physical causes of the systematic errors, we can model the errors by the use of fitting functions such as polynomial expression, Fourier series, Basian spline-type smoothing etc.**

***avoidance of overfitting problem=>the use of Akaike's Information Criterion**

***systematic errors with annual motions and/or linear motions have degeneracy with stellar motions**
➔**calibration by known annual parallaxes and proper motions of stars measured by other missions, such as Gaia.**

Cf. Data Analysis Overview

Modelling of systematic errors and estimation of the model

*****Systematic Error = Modelling Error + residual of estimation**, where

modelling error ≡ (best fitting function for the model of an error) – (true error)

Residual of estimation ≡ (estimated function by observations) – (best fitting function for the model)

○Important points

Residuals have no correlations ⇒ Errors decrease as 1/√N with large N (the number of observations)

Modelling error ⇒ Systematic error: Does not decrease even if many measurements are performed

⇒ Estimation: **Relative stellar positions can be "measured"**

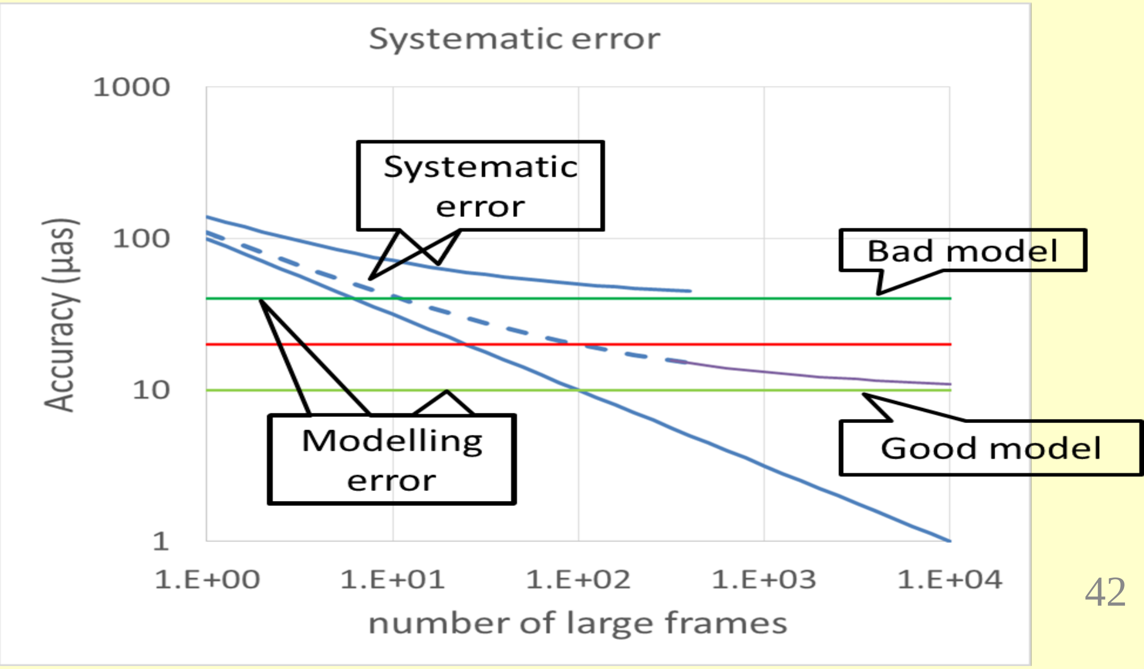
*****In short periods relative angular distances between stars should be constant.**

=> If time variations of relative angular distances exit

=>modelling of the systematic error

(*In long periods, helical motions for single stars can be measures)

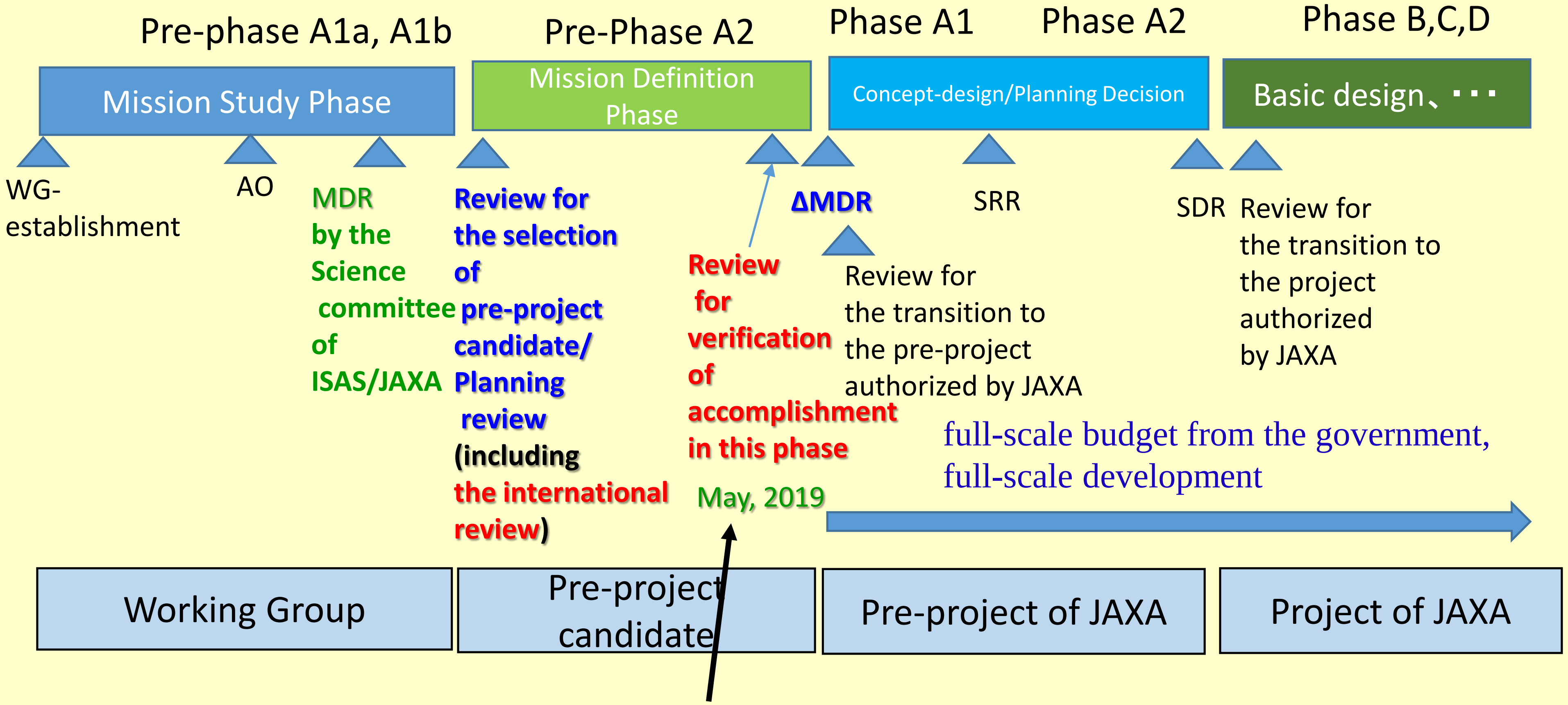
⇒ If a modelling error is larger than the required precision, we can find that error because the precision approaches a constant value with increasing number of observations. We modify the model, until the precision meets the required precision.



The knowledge of physical model is not necessary. The experimental confirmation is shown in session 3.

1.6 Present status of Small-JASMINE

～Multiple steps of reviews by JAXA～



Small-JASME successfully passed the review for verification of accomplishment of issues which should be solved in Pre-Phase A2 on 10th May 2019.

*ISAS: Institute of Space and Astronautical Institute (a branch of JAXA)

ISAS/JAXA has selected Small-JASMINE as the unique 3rd M-class science satellite mission whose official launch date is around FY2014!!

Ref. Small JASMINE international science review

Members of the review panel as appointed by the Director General of ISAS:

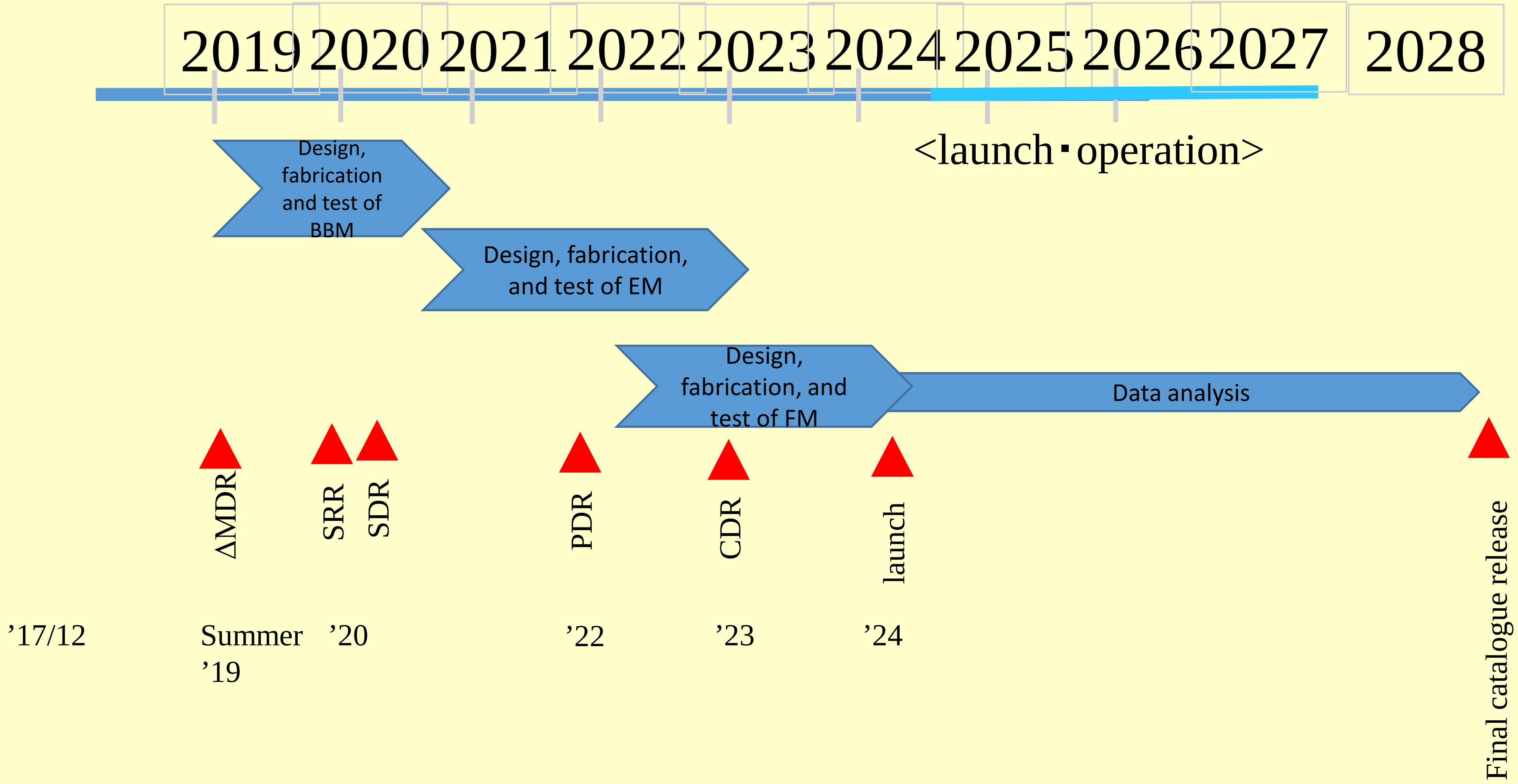
Andrea Bellini (Space Telescope Science Institute)=>HST/WFIRST, astrometry(GC)
Frank Eisenhauer (MPE)=>GRAVITY(VLTI), research of the Galactic center
Masaki Fujimoto (ISAS JAXA)
Lennart Lindegren (Lund Observatory)=>Gaia
Xavier Luri (Univ. Barcelona)＝＞Gaia
Michael Perryman (Princeton)＝＞PI of Hipparcos
Timo Prusti (ESA-ESTEC)＝＞PI of Gaia
Michael Rich (UCLA)＝＞PI of BRAVA, research of the Galactic bulge

(Observer)
Toru Yamada (ISAS JAXA)
Kazuhisa Mitsuda (ISAS JAXA: moderator)

Main conclusions and recommendations

The review committee is pleased to acknowledge that the SJ working group has performed great concept studies of a mission whose scientific objectives are potentially unique and compelling for the era of middle 2020's in the key science areas discussed below. The error budgets of the observation and the ground analysis methods are extensively studied and no technical showstopper was found at this phase.
However, the panel recommends further extensive studies both in the scientific objectives, and error budget analysis and experiments
in the next concept development phase.

1.7 Development Plan



1.8 International Collaboration

○IAU Commission A1 (astrometry) recommends Small-JASMINE for its unique infrared space astrometry mission!

○Close collaboration between Gaia and Small-JASMINE

＊Gaia DPAC members are supporting the development of data analysis for Nano-JASMINE and Small-JASMINE

＊We had the Gaia-JASMINE joint meeting in Mitaka, Tokyo in Dec. ,2016

In particular, the ZAH-ARI Gaia team and the astrometry group of Lohrmann Observatory, Technische Universität Dresden, has sent us the Letter of Interest for the data processing for Small-JASMINE

○Cooperation with APOGEE-2(S) and BRAVA is very strong synergy for studies of the Galactic bulge.

Information of radial velocities , chemical composition and photometry (in other bands) is complementary to Small-JASMINE for the scientific targets in the Galaxy.

In particular, MOU for powerful scientific collaboration between APOGEE-2(S), SDSS-IV collaboration and Small-JASMINE has been concluded.

○ Collaboration with Post-Gaia missions

Theia and GaiaNIR

JASMINE team is very happy to contribute to both missions in aspects of synergies for scientific outputs and the development of technologies which include the data analysis software.

***In particular, MOU for scientific and technical collaboration between Theia and Small-JASMINE has been concluded.**

***Small-JASMINE would like to play a role of a precursor to GaiaNIR as an infrared space astrometry mission.**

○ Collaboration with USNO

*USNO is now considering the support of development and tests
of the detector box unit including H4RG

We have regular TV conferences every week.

We plan to apply some grants such as MO of NASA.

○ Collaboration with ESA

***ESA is now considering the support of ground stations for the down link of scientific data provided by Small-JASMINE.**

ISAS/JAXA has started to negotiate with ESA.

ESA is very positive for the support due to Gaia teams' strong support of Small-JASMINE.

JASMINE

Thank you for your support!