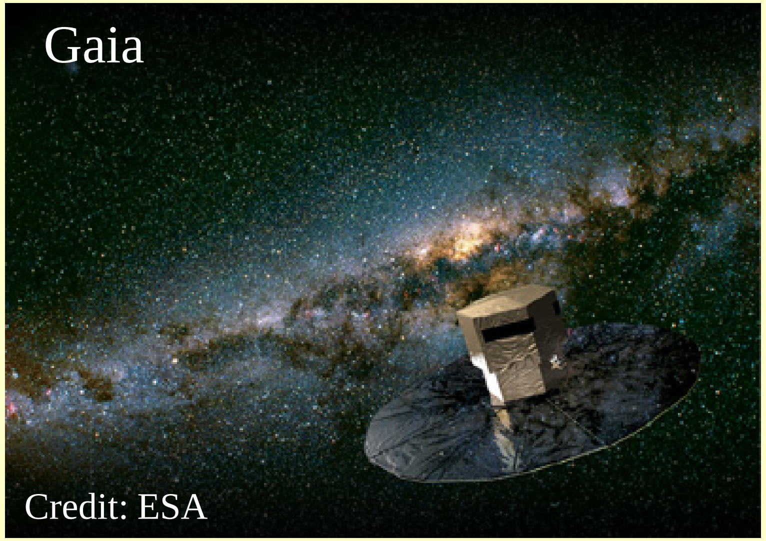
13th December 2019

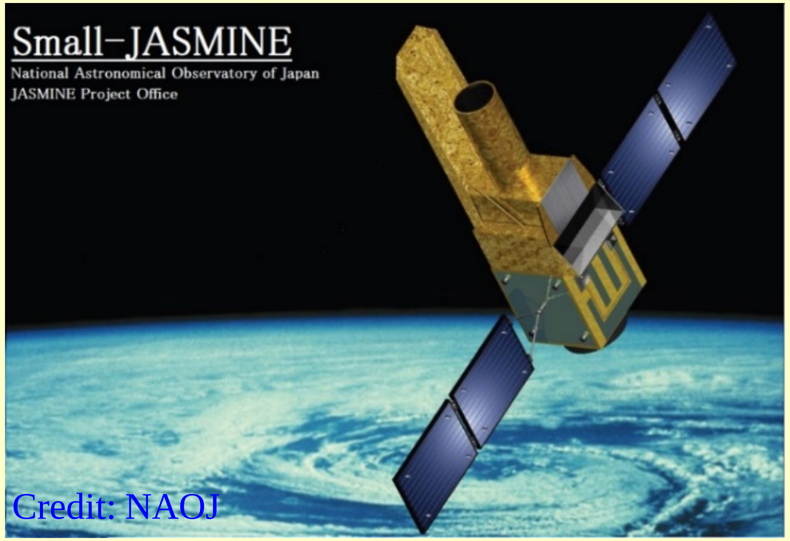
Achievement from Gaia and future prospects of JASMINE

★JASMINE

—Japan Astrometry Satellite Mission for INfrared Exploration—

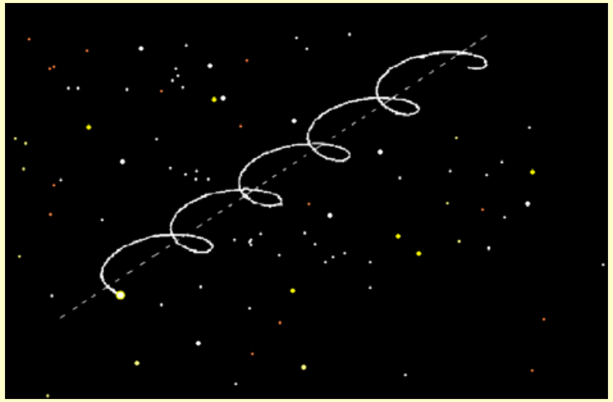
Naoteru Gouda(NAOJ)





1. Astrometry

Helical motion of a star on the celestial sphere

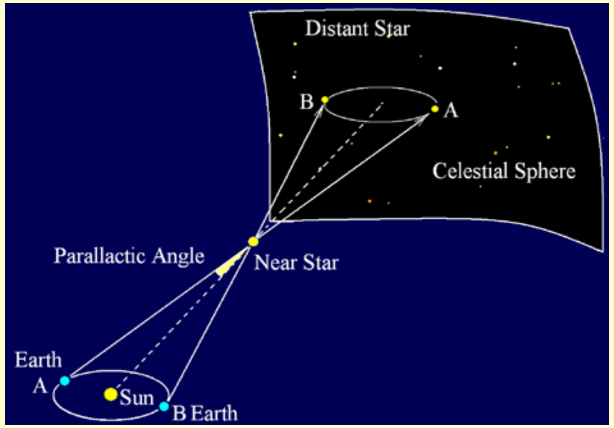


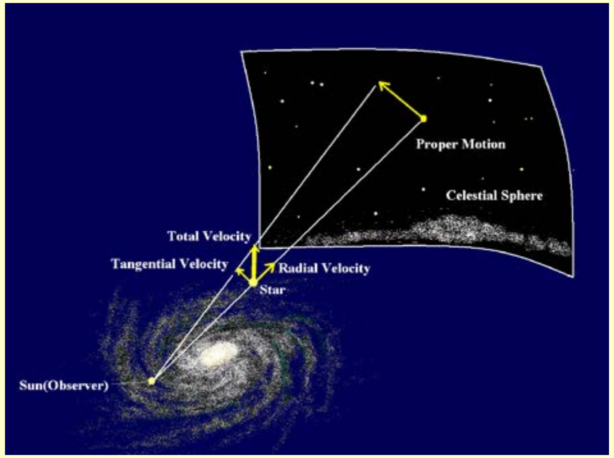
Apparent annual elliptical motion
➔annual parallax
➔ distance

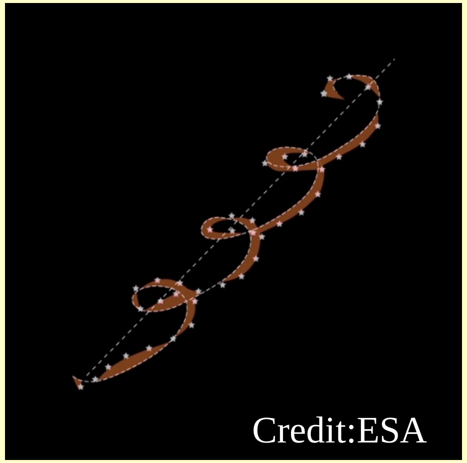
+

Motion of a straight line
➔proper motion
➔tangential velocity

+

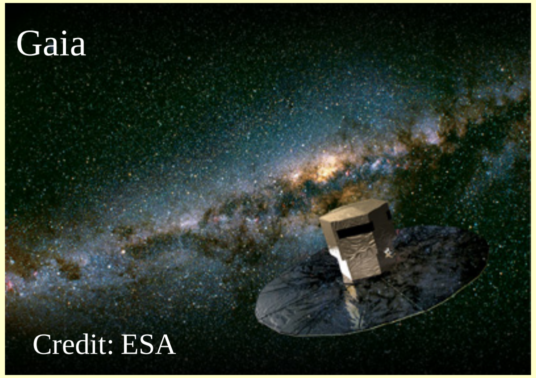






If any, residual motion from the helical motion
=>binary system, exo-planet systems, gravitational lens effect, hot spots

2. Outline of Gaia mission



Optical Space Astrometry Mission by ESA

＊launched on Dec.19th, 2013.

*mission extension :2019➔ end of 2020

indicative extension=>end of 2022

＊the final catalogue will be released(full release) after 2022 (TBD).

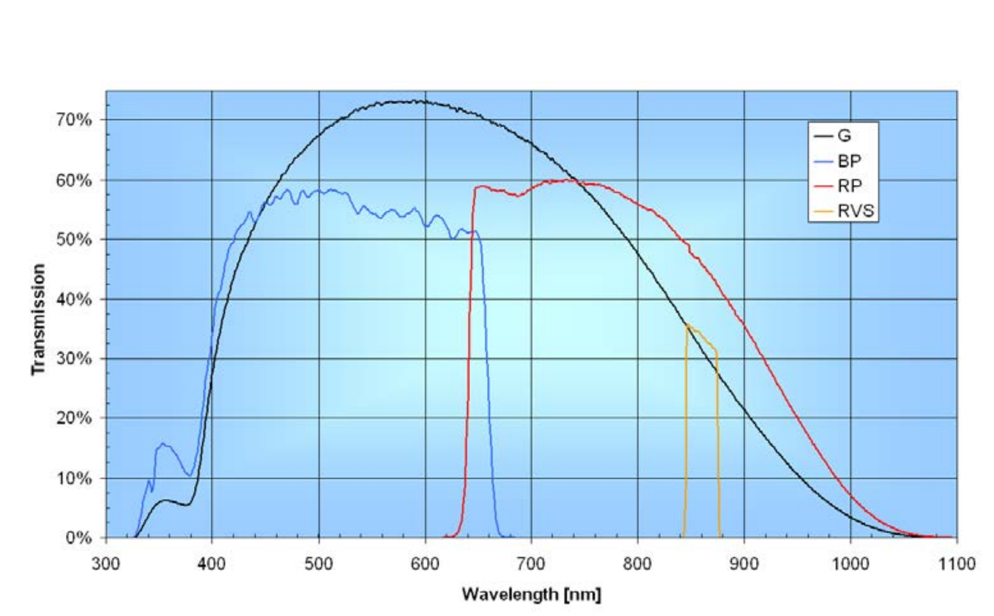
＊intermediate catalogues are released.（to be mentioned later)

the whole sky survey with an optical band（1.3(1.7) billion stars with <21 mag）

G-band（0.33-1.0μm）、 6（3）mag＜G<21mag

$G = V - 0.0257 - 0.0924 \cdot (V-I_C) - 0.1623 \cdot (V-I_C)^2 + 0.0090 \cdot (V-I_C)^3$ (fit error: 0.05mag)

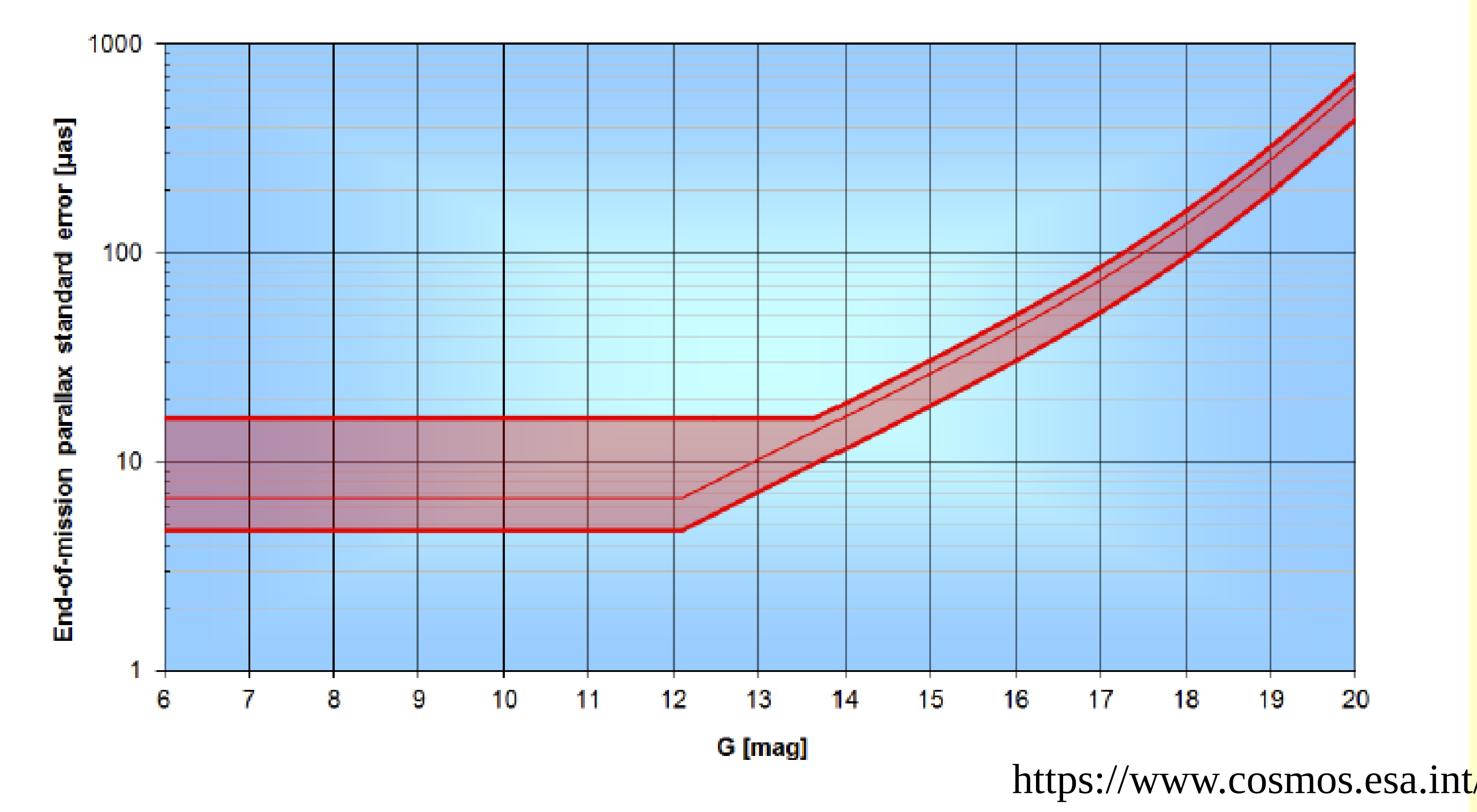
＊it is hard for Gaia to measure the centroids(星像中心）of bright stars(<3 mag)



https://www.cosmos.esa.int/web/gaia/transmissionwithoriginal

Gaia: expected astrometric accuracy

Precision of annual parallaxes predicted after the accomplishment of 5-years operation (nominal operation)



https://www.cosmos.esa.int/web/gaia/sp-figure1

$$G = V - 0.0257 - 0.0924\left(V - I_C\right) - 0.1623\left(V - I_C\right)^2 + 0.0090\left(V - I_C\right)^3$$

The predicted errors vary over the sky…（∵depends on the number of observations）

★ Gaia catalogue

1.First release(Gaia DR1): 14 September 2016

Astrometric data for 2 million stars

Precisions: parallax 0.3 mas, proper motion 1.3 mas/y (<15mag)

2.Second release(Gaia DR2): 15 April 2018

Astrometric data for 1.3 billion stars

Precisions: parallax 0.04 mas, proper motion 0.06 mas/y (<15mag)

3.Third release: EDR3 Q3 2020, DR3 H2 2021

parallax : a factor of 1.4 improvement with respect to DR2

proper motion : a factor of 1.9 improvement with respect to DR2

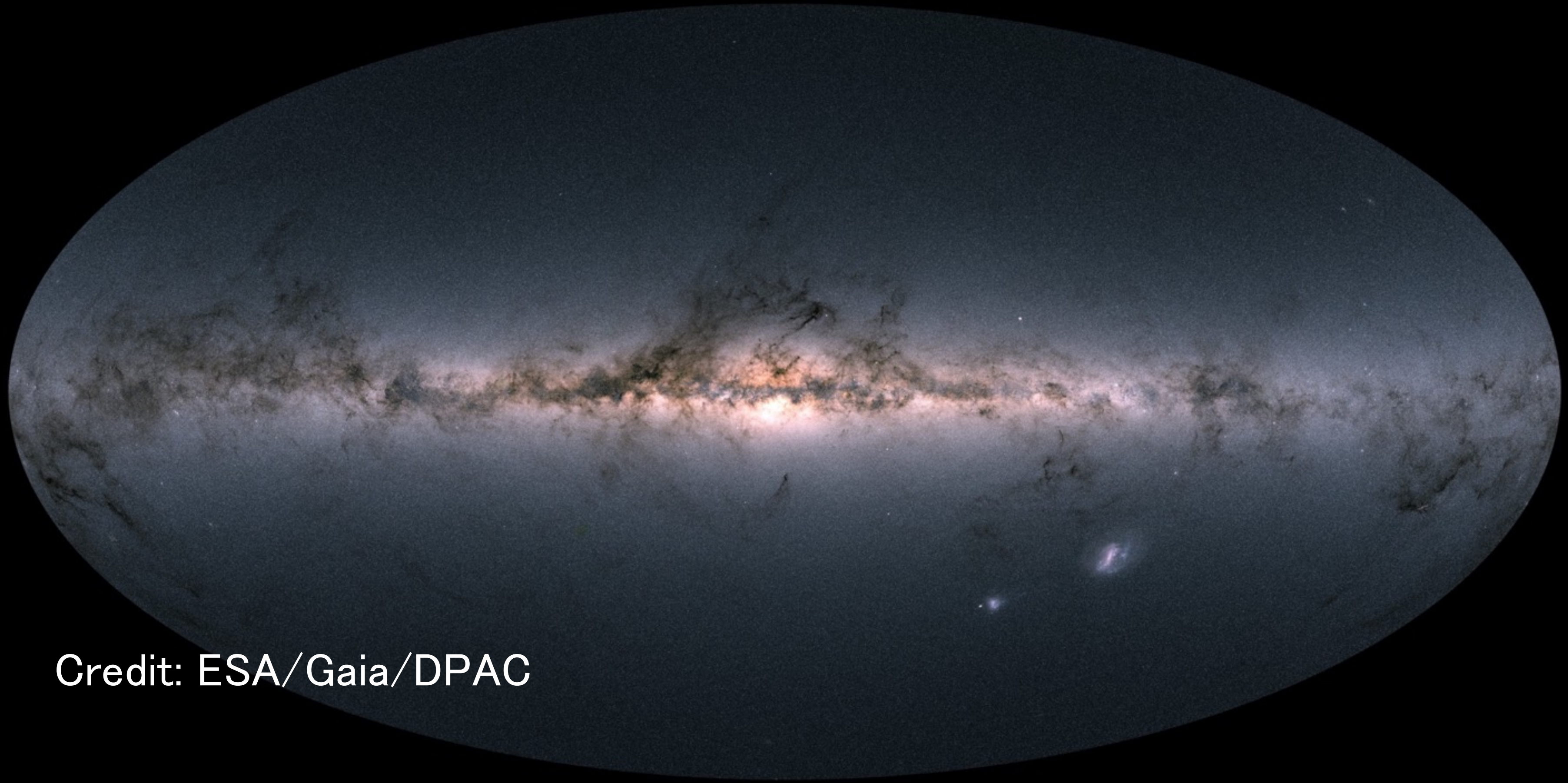
3.Forth release: DR4 ???

parallax : a factor of 1.7 improvement with respect to DR2

proper motion : a factor of 4.5 improvement with respect to DR2

Gaia DR2: 25 April 2018

First full astrometry catalogue of Gaia
parallax and proper motions for 1.3 B stars!
(DR1 was for 2 M bright stars)

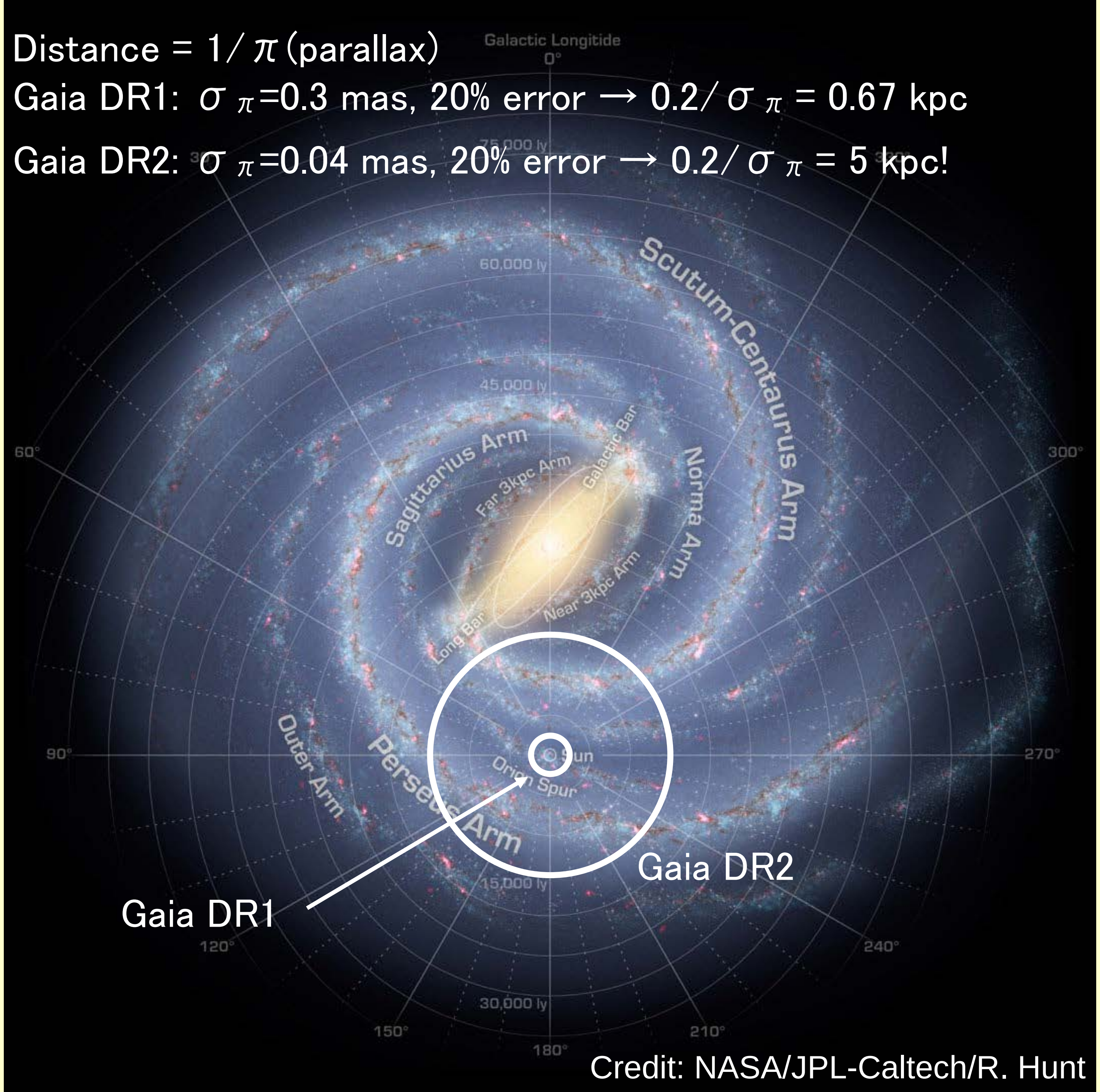


Slide by Kawata(UCL)

Distance = 1/ π (parallax)

Gaia DR1: σ_π=0.3 mas, 20% error → 0.2/ σ_π = 0.67 kpc

Gaia DR2: σ_π=0.04 mas, 20% error → 0.2/ σ_π = 5 kpc!



Credit: NASA/JPL-Caltech/R. Hunt

Slide by Kawata(UCL)

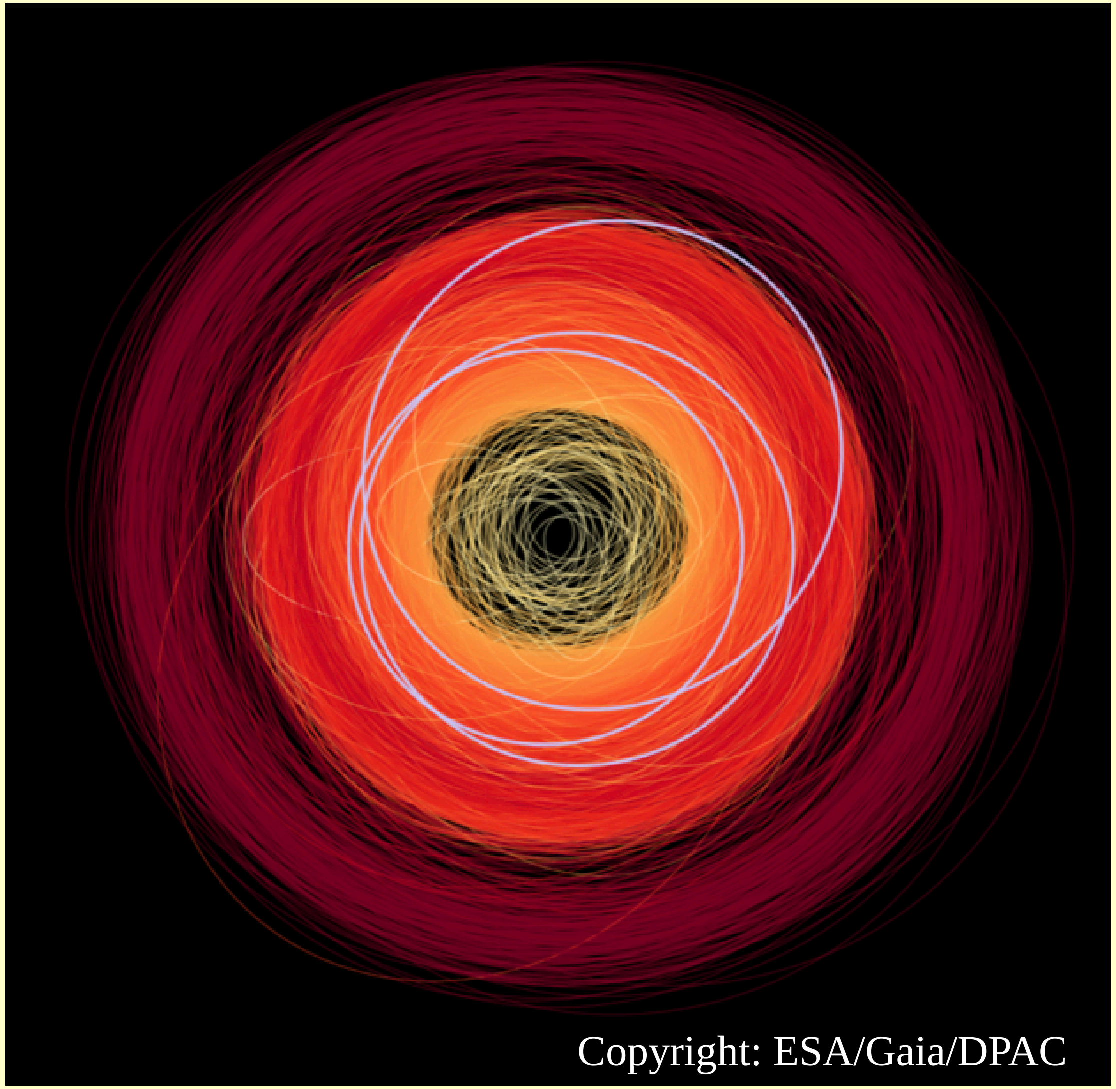
3. Examples of Scientific topics by Gaia DR2

About 2000 or more than 2000 papers were published

- Objects in the solar system
  interstellar "Oumuamua's home?
- Stellar evolution: H-R diagram
- Young exo-planet
- White dwarf cooling sequence,
  catalogue of WD
- Evolved carbon stars
- Hyper velocity stars
- Omega Centauri's lost stars
- Stellar cluster
- Star density
- Dust map
- Mass of the Milky Way Galaxy
- New speed for the MW-Andromeda collision

- merging of dwarf galaxies: Gaia-Enceladus stars
- stars flying between galaxies
- Sagittarius dwarf galaxy
- Bar structure
- Moving groups near the solar system
  ~ complicated velocity fields near the solar system ~
- Ripple of the Galactic Plane

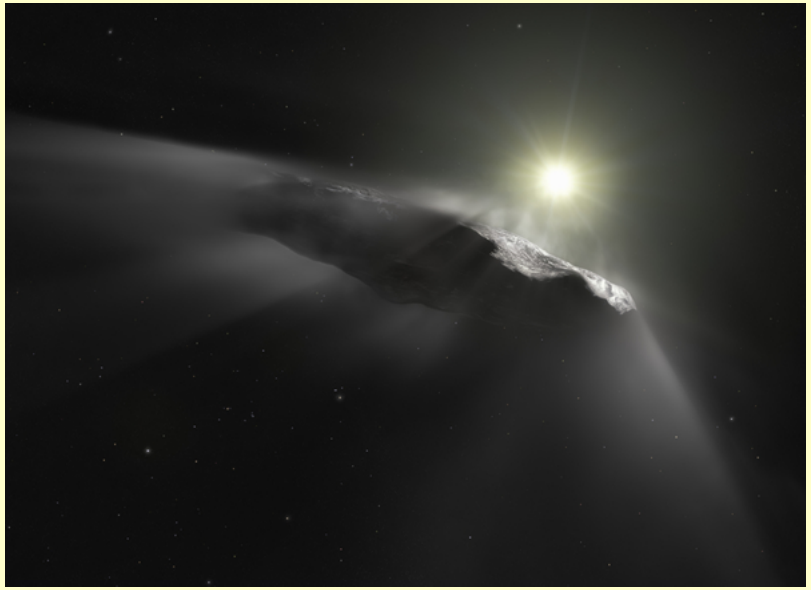
*Gaia's first asteroid discoveries



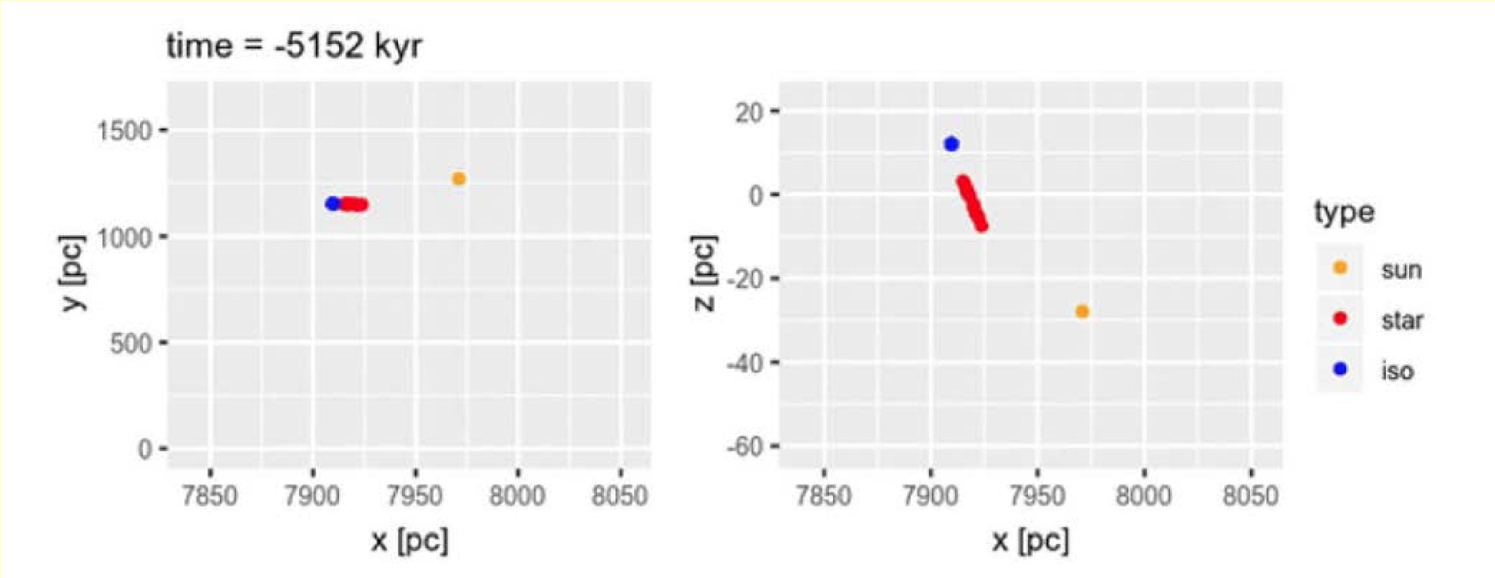
Gaia DR2➔more than 14 000 known asteroids (with the Sun at the centre of the image)

the three orbits shown in grey in this view: these are Gaia's first asteroid discoveries.

*Gaia finds candidates for interstellar 'Oumuamua's home

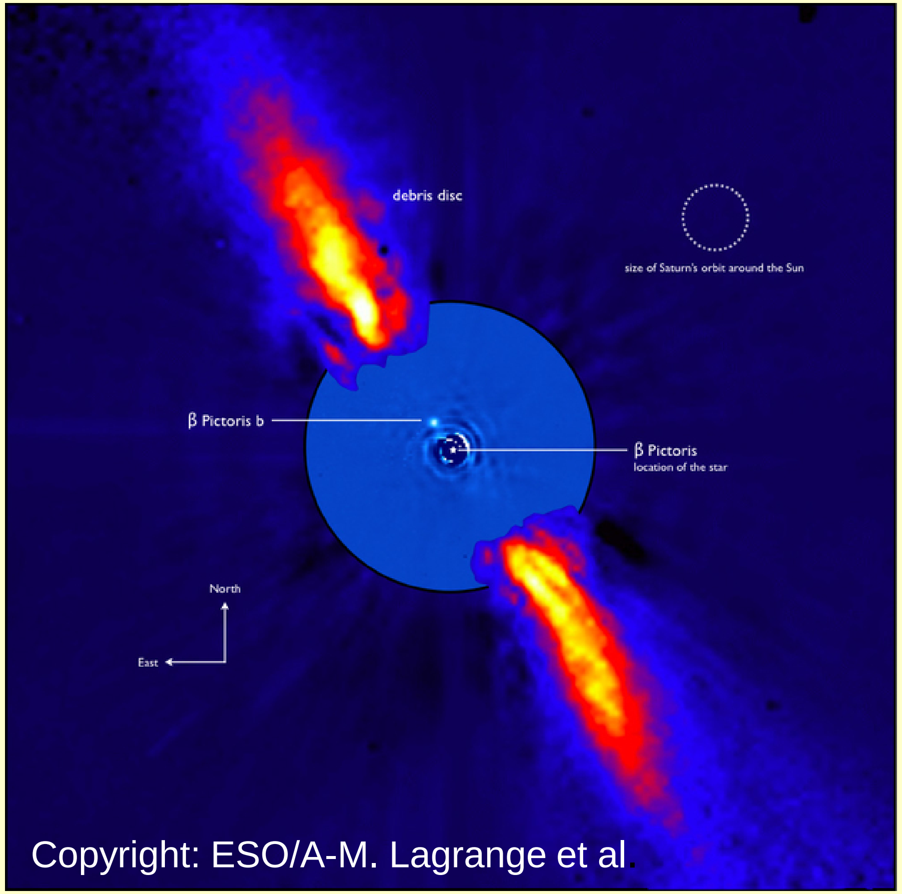


Artist's impression of 'Oumuamua.
Credit: ESA/Hubble, NASA, ESO, M. Kornmesser

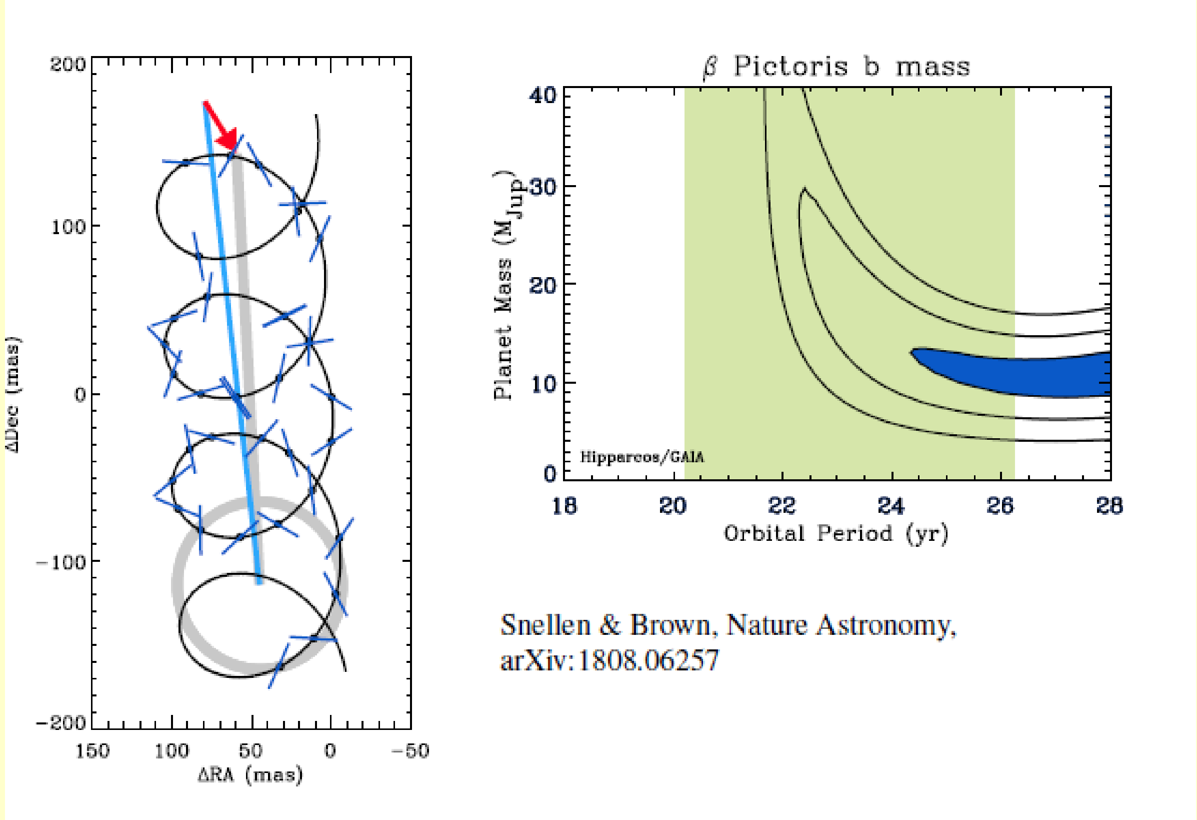


Relative trajectories of the Sun (yellow), 'Oumuamua (blue), and one of the stars that could be the interstellar comet's home (red, sampled many times).
Credit: C.A.L. Bailer-Jones et al. 2018

Infant exoplanet weighed by Hipparcos and Gaia



Planet Beta Pictoris b



Snellen & Brown, Nature Astronomy,
arXiv:1808.06257

The mass of a very young exoplanet has been revealed for the first time using data from ESA's star mapping spacecraft Gaia and its predecessor, the quarter-century retired Hipparcos satellite.

Difference Hipparcos and Hipparcos-Gaia proper motions reveals mass of planet (11±2M_{Jup})

Residuals of Hipparcos observations with respect to long term proper motion constrain orbital period

A river of stars

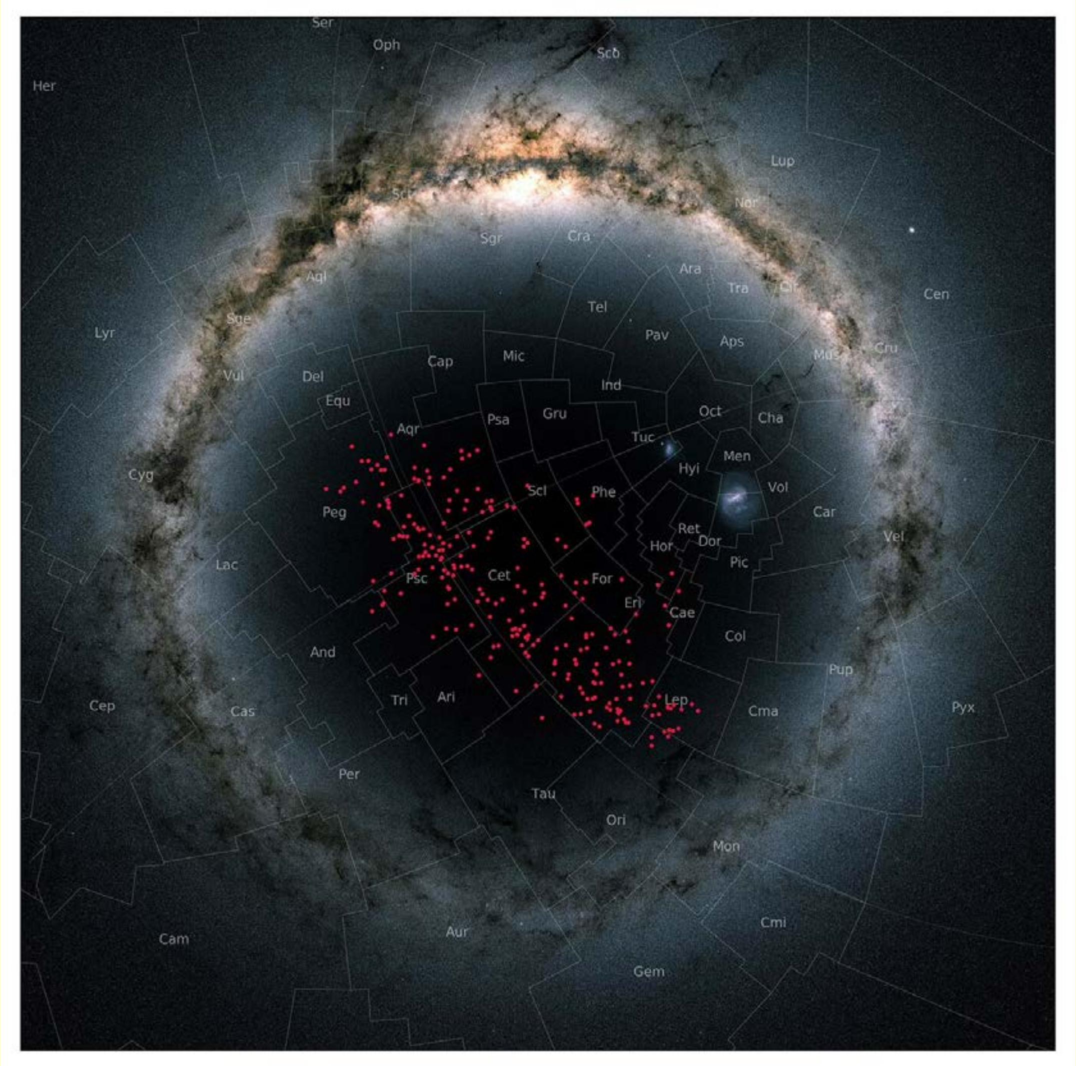
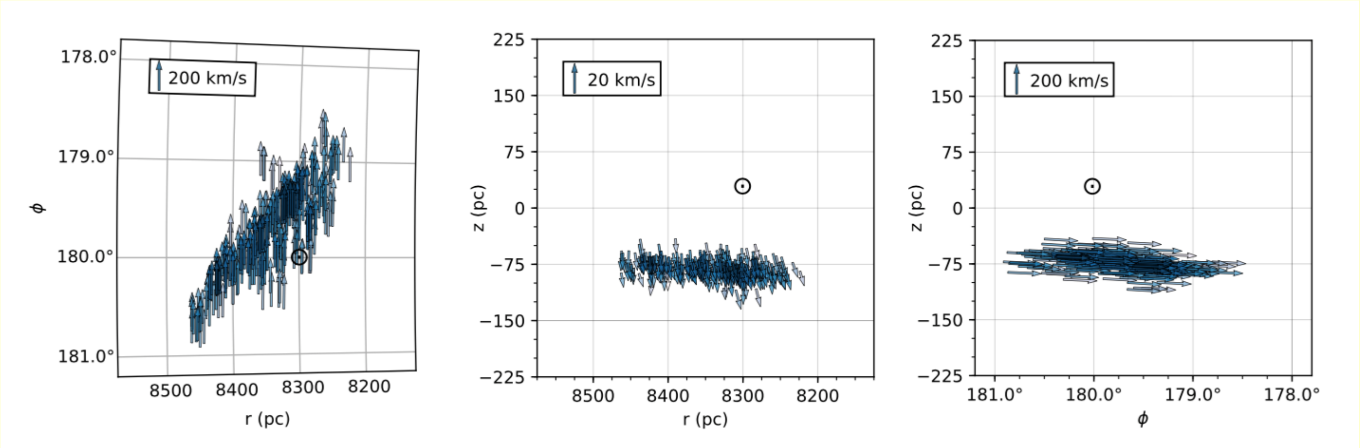


Image credits: Stefan Meingast, ESA/Gaia/DPAC



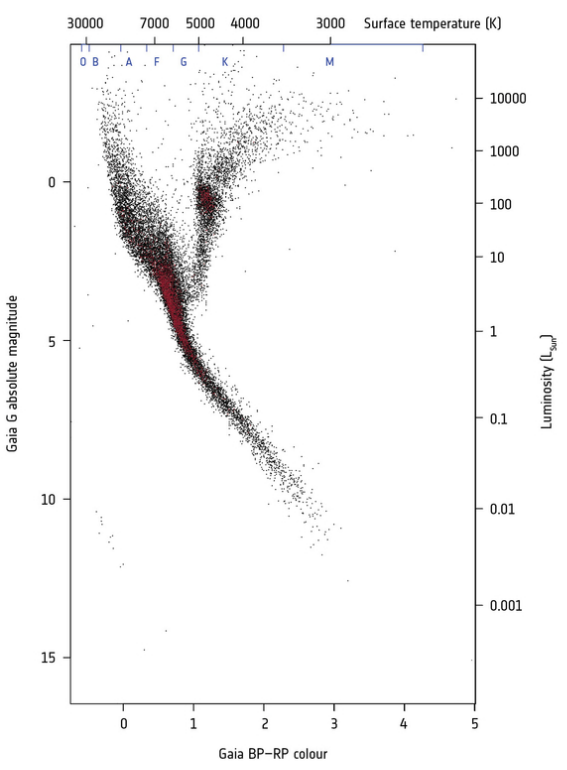
João Alves, Verena Fürnkranz - A&A 622, L13 (2019)

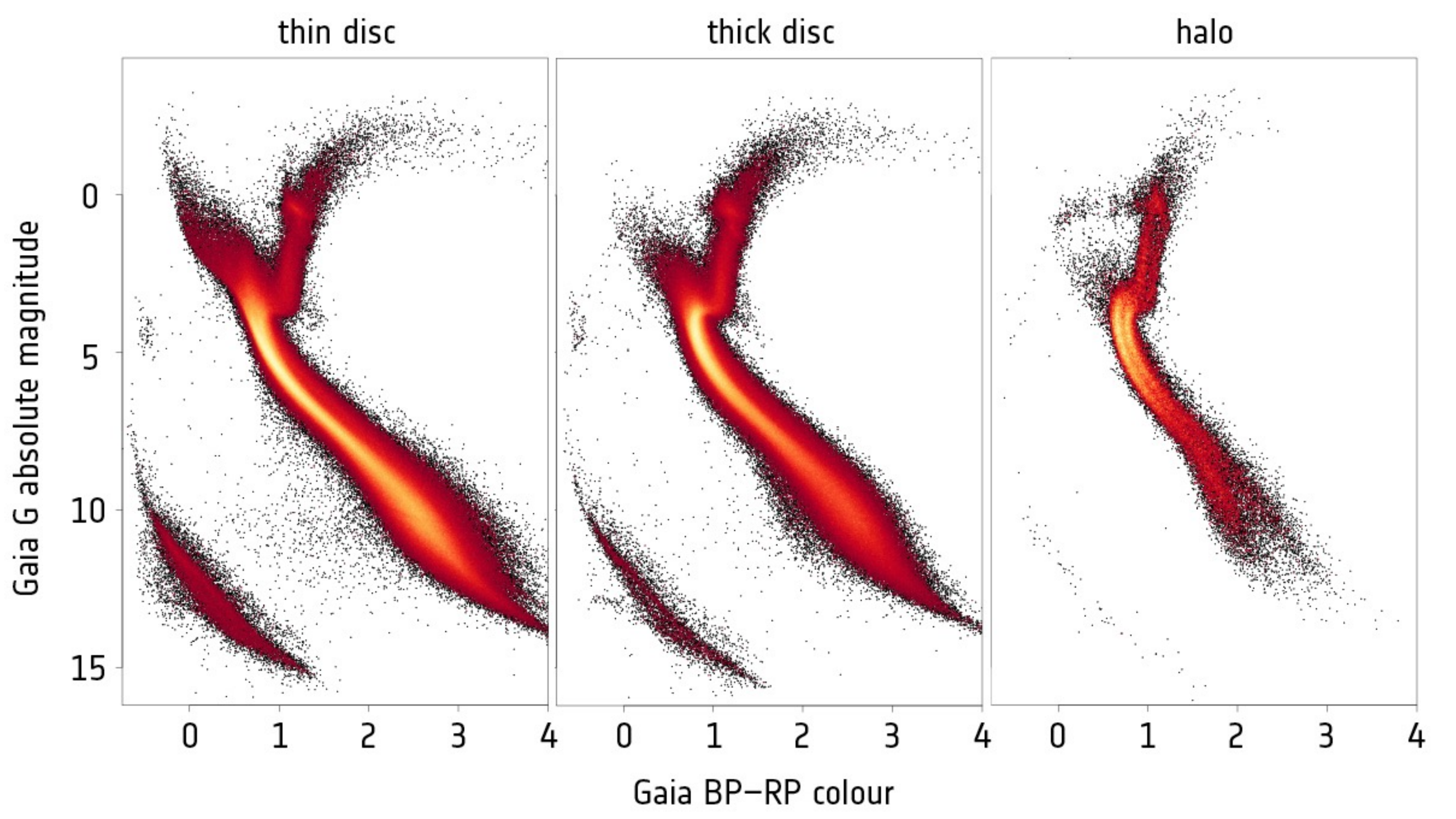
Existence of a stellar stream

*moving together near the solar system
*about 4000stars <=200 stars observed by DR2
*a length of about 400pc
*stream’s age: 1billion years

Hipparcos' H-R diagram

Gaia DR2' H-R diagram

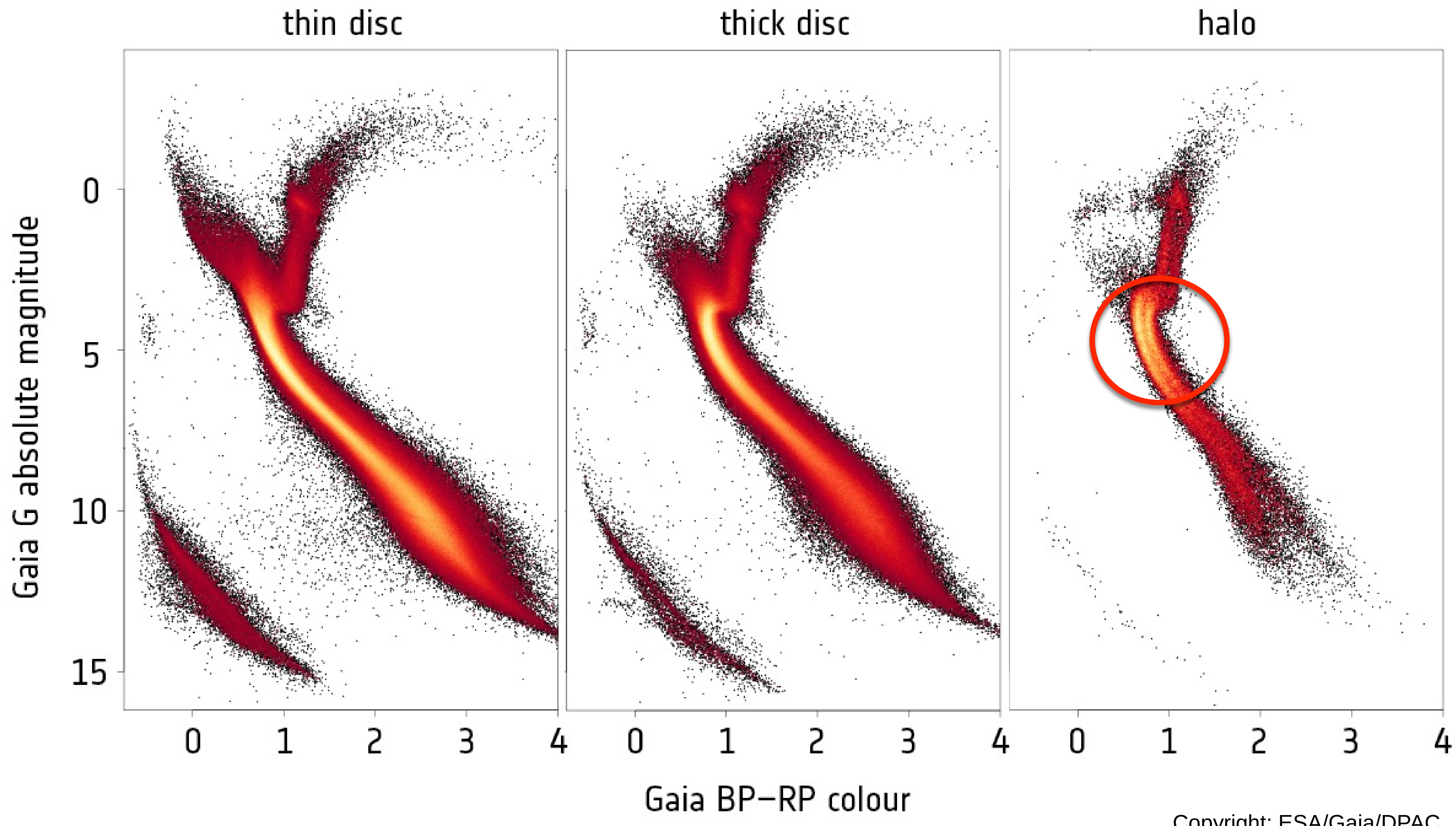




This diagram shows the absolute magnitude and colour of about 20 000 stars selected from the Hipparcos catalogue

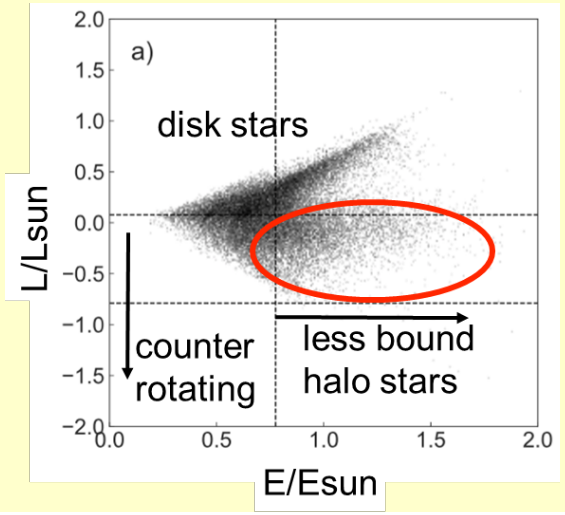
This image was created to provide a comparison with another Hertzsprung-Russell diagram, obtained using 4 million stars from Gaia DR2 , and to show the huge leap forward made in the past couple of decades.

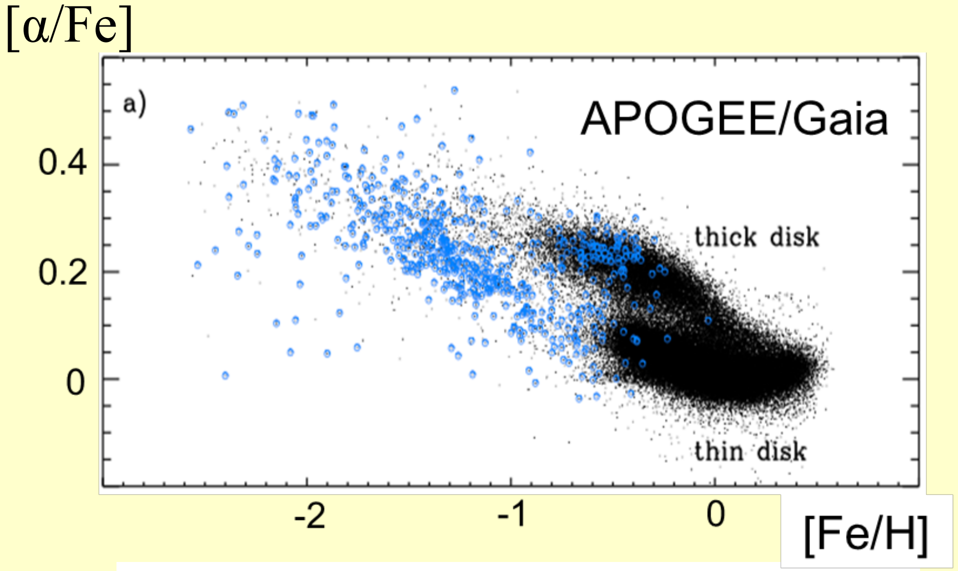
Gaia's HR diagram for different populations of stars

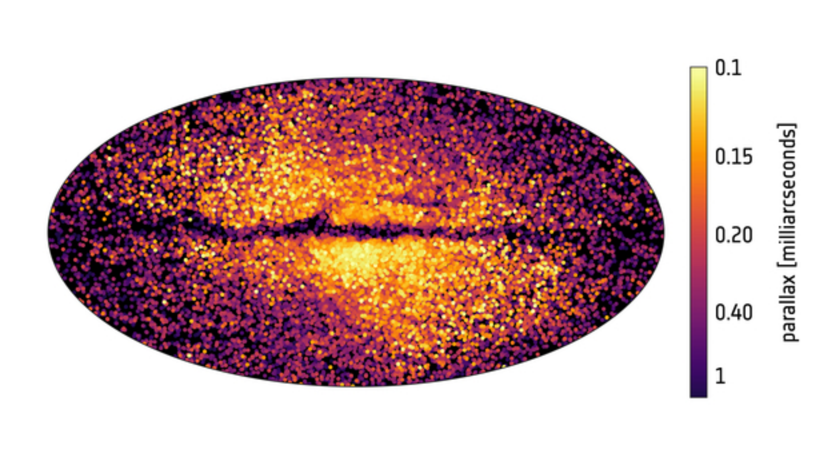


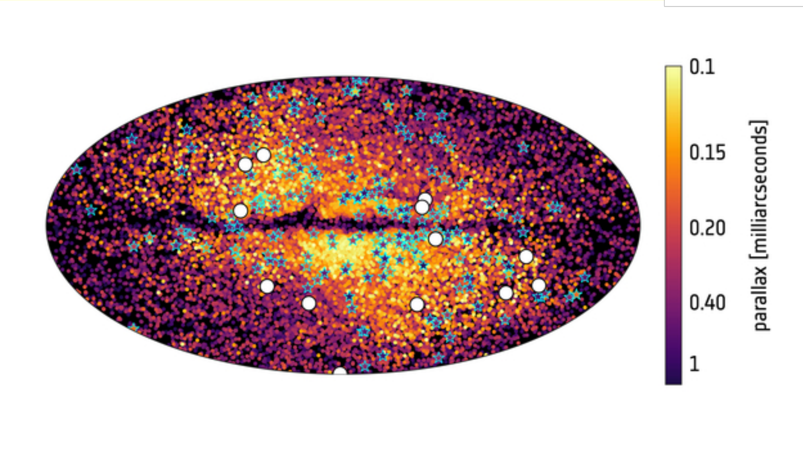
*Gaia-Enceladus stars across the sky

Counter-rotating, low [α/Fe] halo stars from a SMC-size galaxy, major merger at >10 Gyr ago!
=>Gaia Enceladus Sausage (GES)





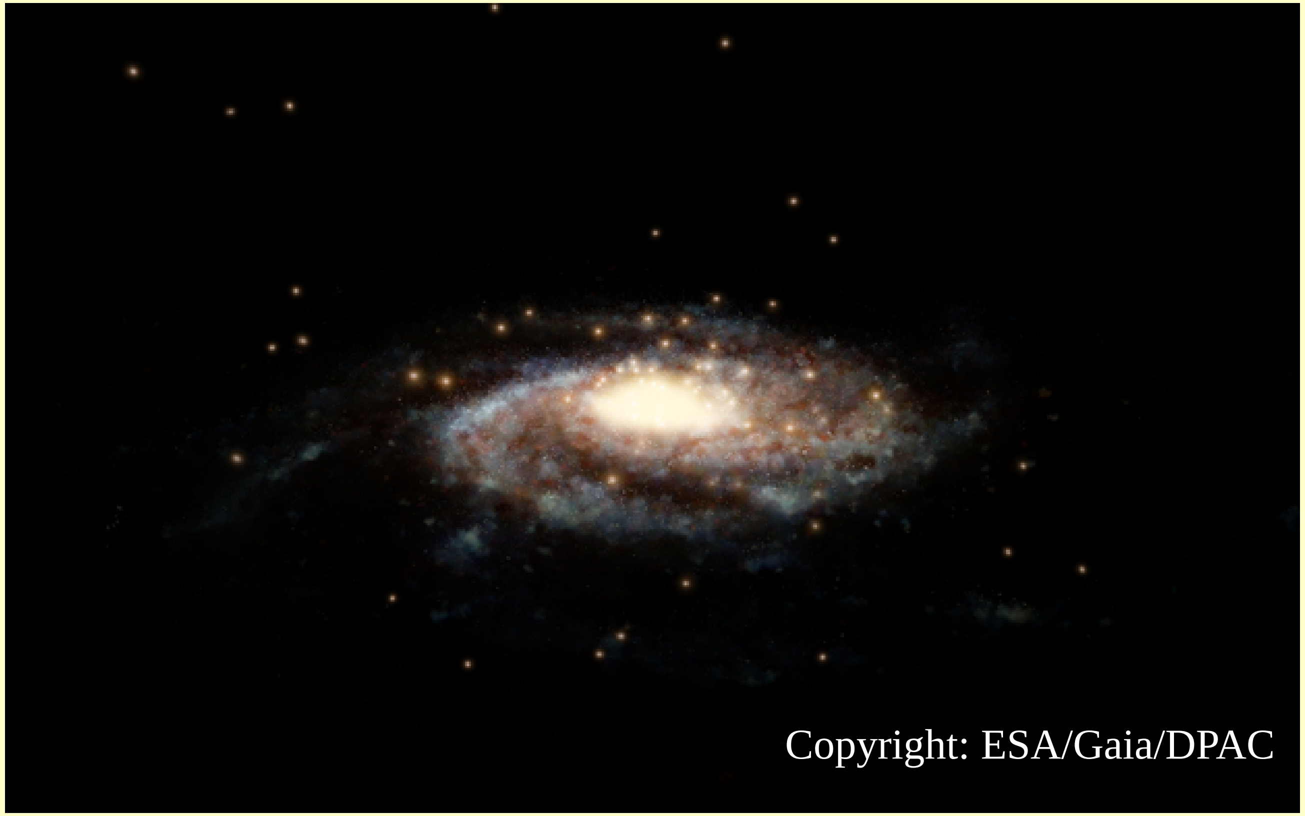




Helimi, et al. (2018)

All-sky image of Gaia-Enceladus galaxy merger debris

*Hubble & Gaia accurately weigh the Milky Way



In a striking example of multi-mission astronomy, measurements from the NASA/ESA Hubble Space Telescope and the ESA Gaia mission have been combined to improve the estimate of the mass of our home galaxy the Milky Way: 1.5 trillion solar masses.

from 500 billion to 3 trillion times the mass of the Sun.

This artist's impression shows a computer-generated model of the Milky Way and the accurate positions of the globular clusters used in this study surrounding it.

Gaia DR2: 34 globular clusters

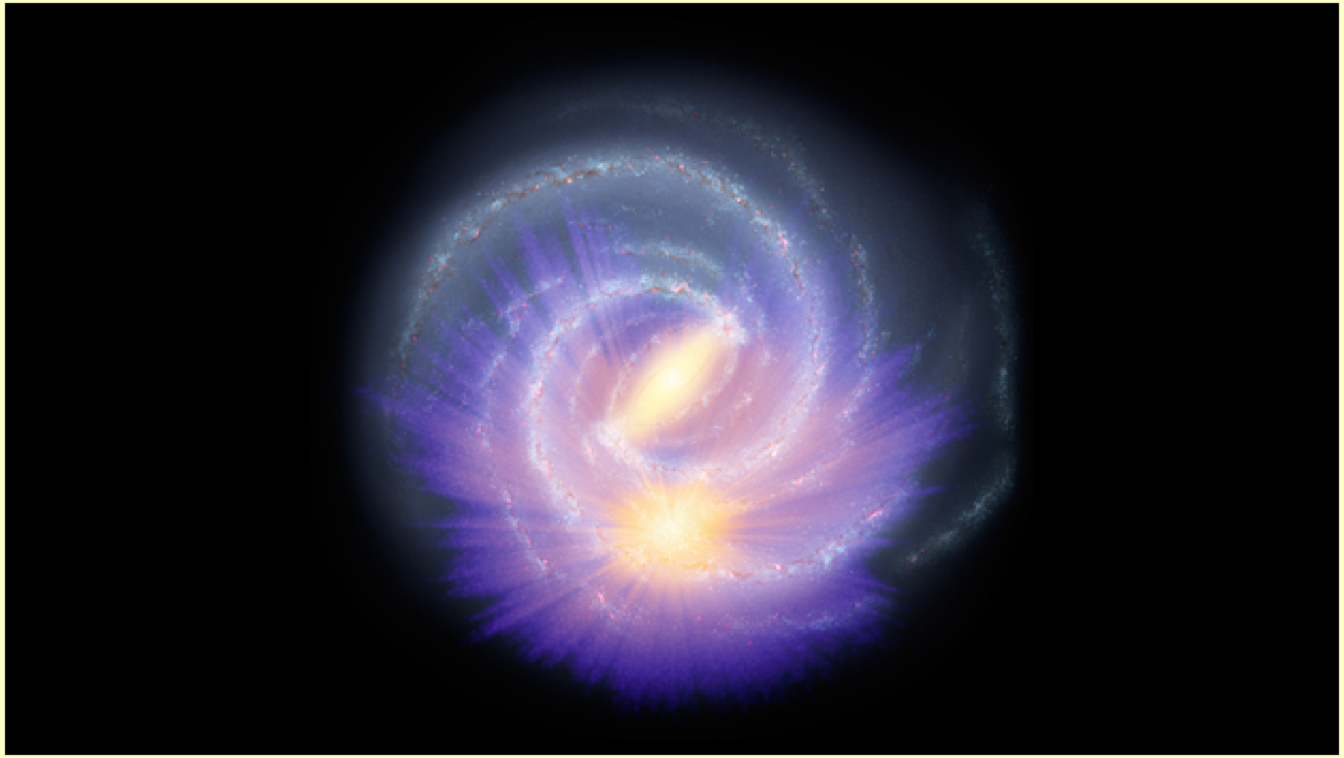
Hubble: 12 more distant globular clusters

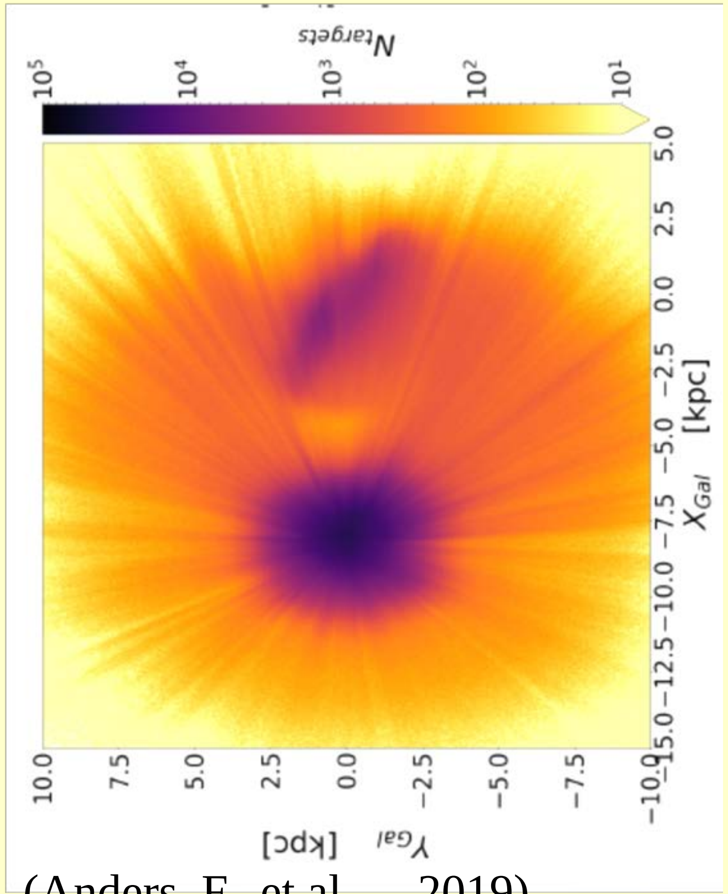
Galactic Dynamical Structures

⇩

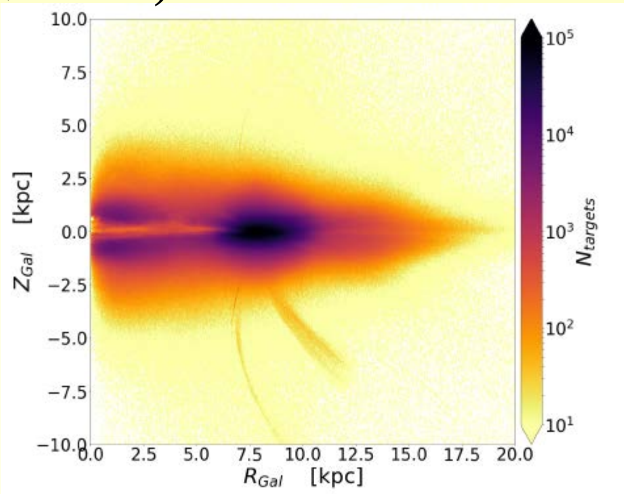
*complicated structures in velocity spaces of stars
*non-equilibrium state!!

Revealing the Galactic bar



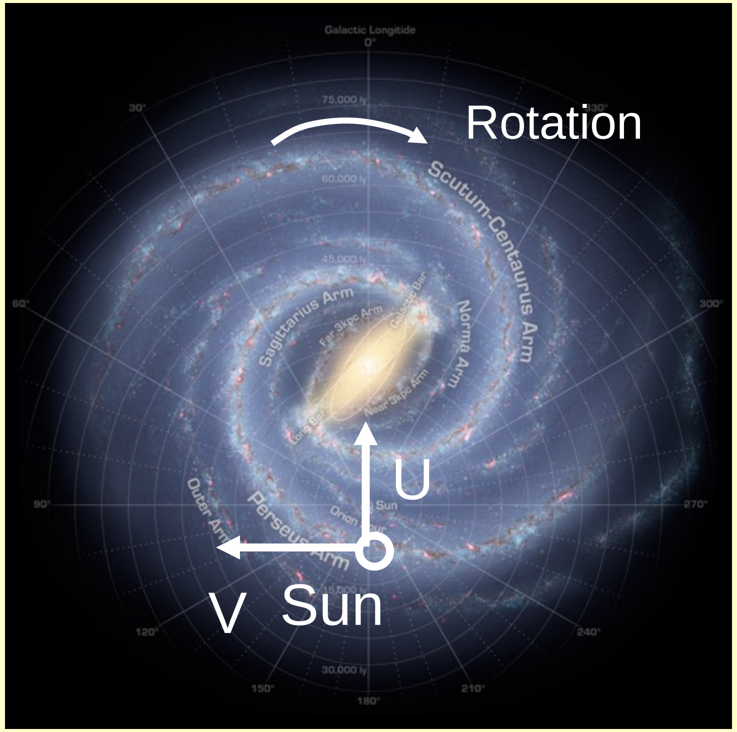


(Anders, F., et al.、 2019)

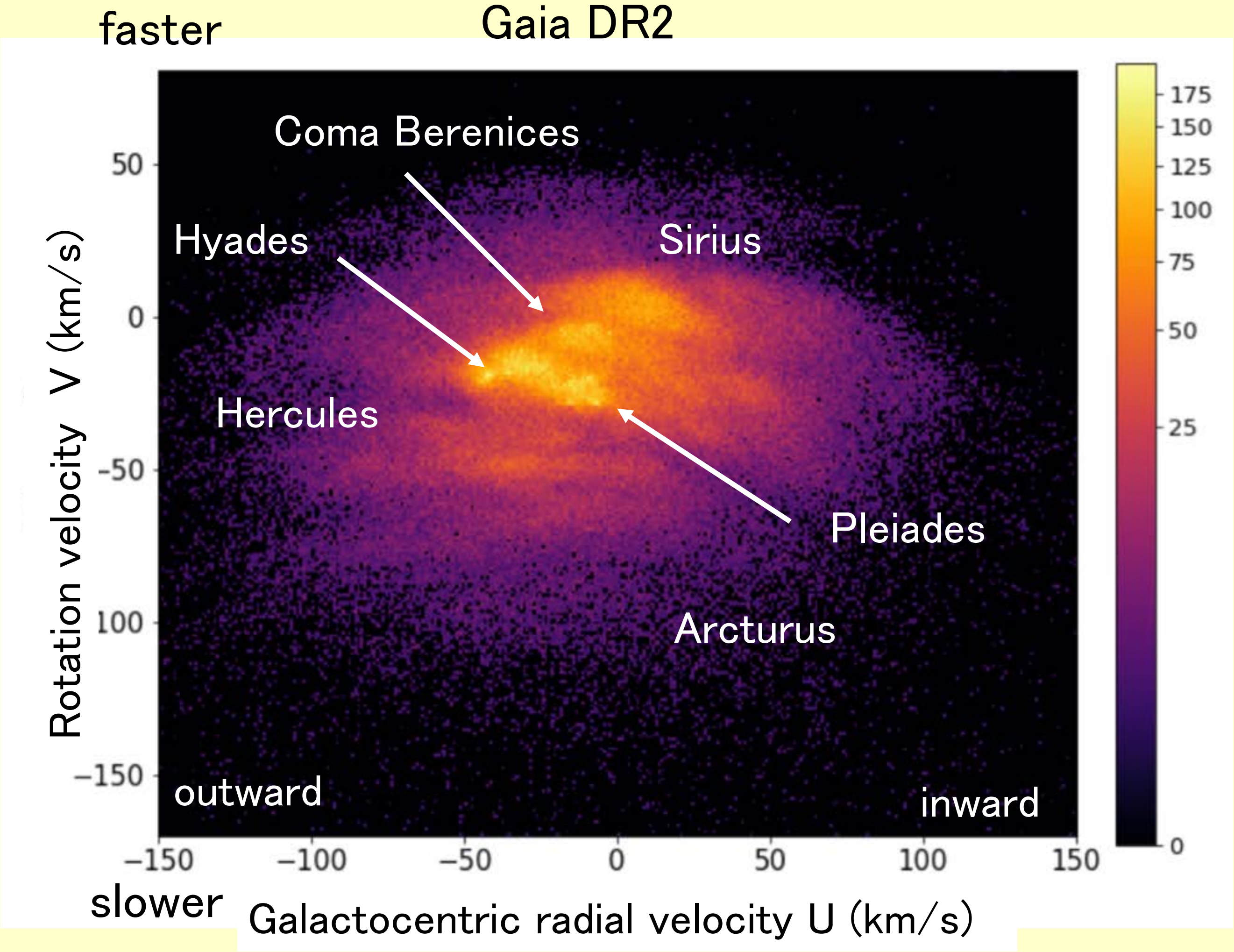


This colour chart shows the distribution of 150 million stars in the Milky Way probed using data from the second release of ESA's Gaia mission in combination with infrared and optical surveys, with orange/yellow hues indicating a greater density of stars. Most of these stars are red giants. The distribution is superimposed on an artistic top view of our galaxy

Stellar velocity distribution in the solar neighbourhood
Many velocity structures!



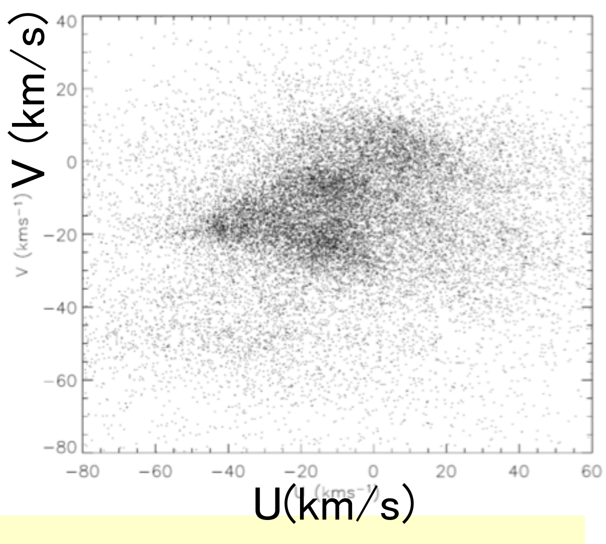
Gaia DR2



Gaia Collaboration, Katz et al. (2018)

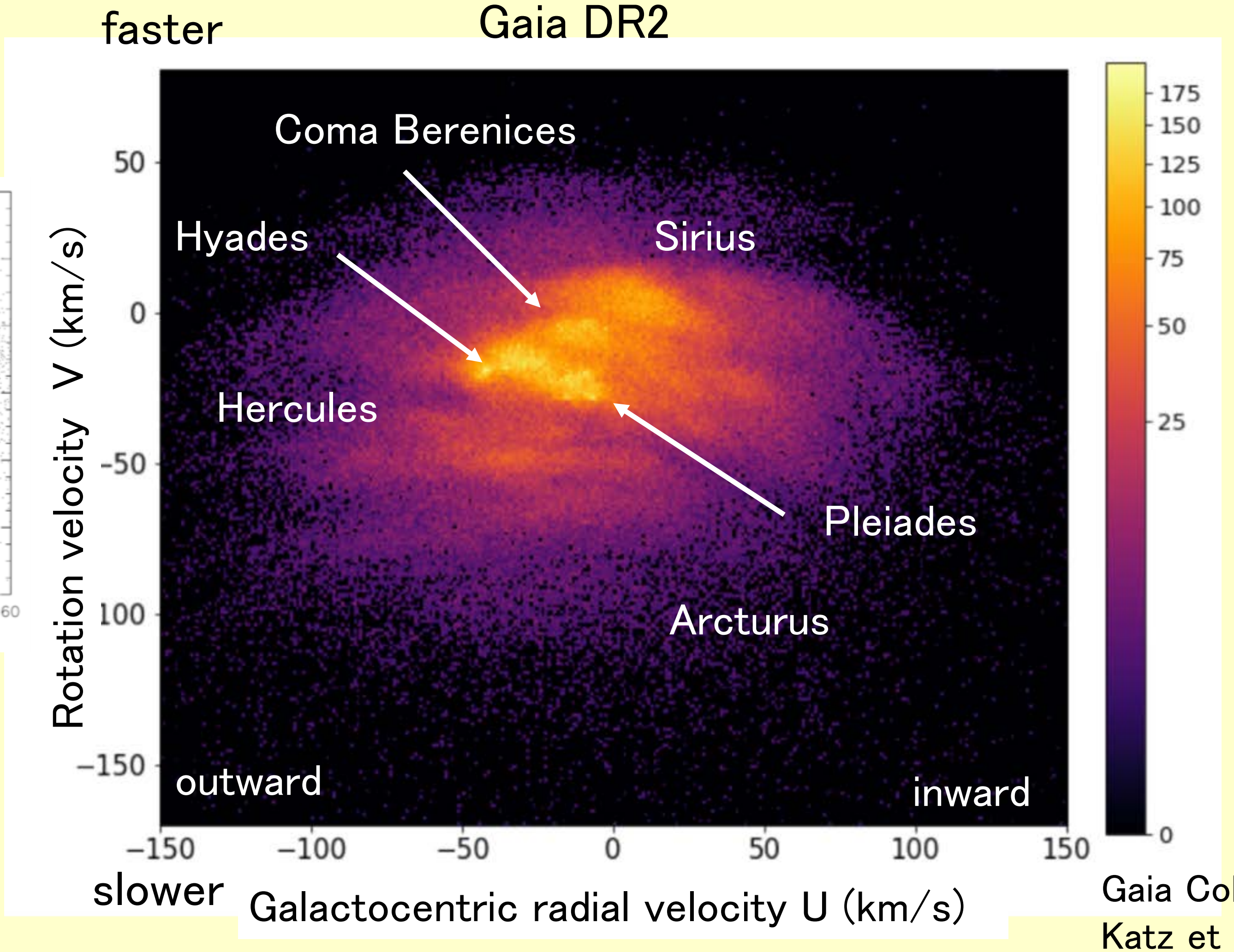
Stellar velocity distribution in the solar neighbourhood
Many velocity structures!

Hipparcos



Antoja et al. (2008)

Gaia DR2



Gaia Collaboration, Katz et al. (2018)

Origins? ＝＞resonant effects due to the bar and/or the spiral arm

infall of dwarf galaxies

Ex. *Resonances

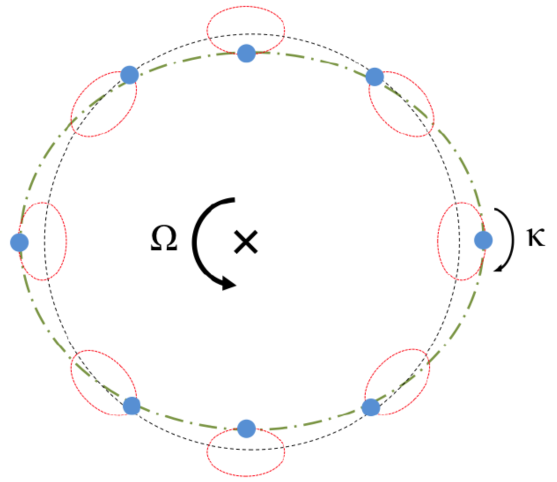


Figure 1.8: The orbital path of a star (blue dot) around the galactic centre with epicycle frequency of $\kappa = 2\Omega$. The epicycle, circular and resulting full orbital path are shown by the red, black and green lines.

https://astro3.sci.hokudai.ac.jp/~alex/Material/ARPettitt_chapter1.pdf

Resonances occur when the following relation holds:

$$\Omega - \Omega_p = \pm \frac{\kappa}{m}$$

Ω : rotation speed of a star

Ω_p : pattern speed of non-axisymmetric structure such as a bar and/or a spiral arm

κ : epicycle frequency, *m*: positive integer

＋ : Inner Lindblad resonances
－ : Outer Lindblad resonances

$\Omega = \Omega_p$: ➔Corotation resonance

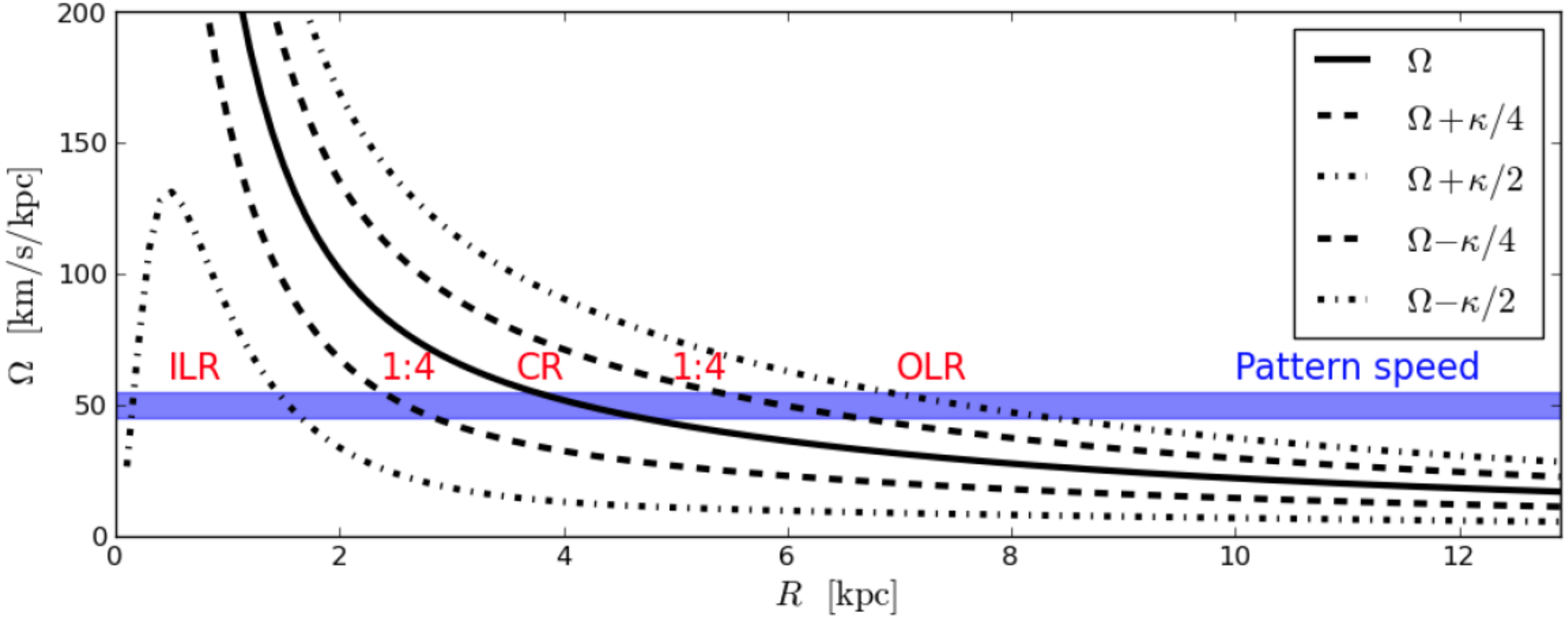
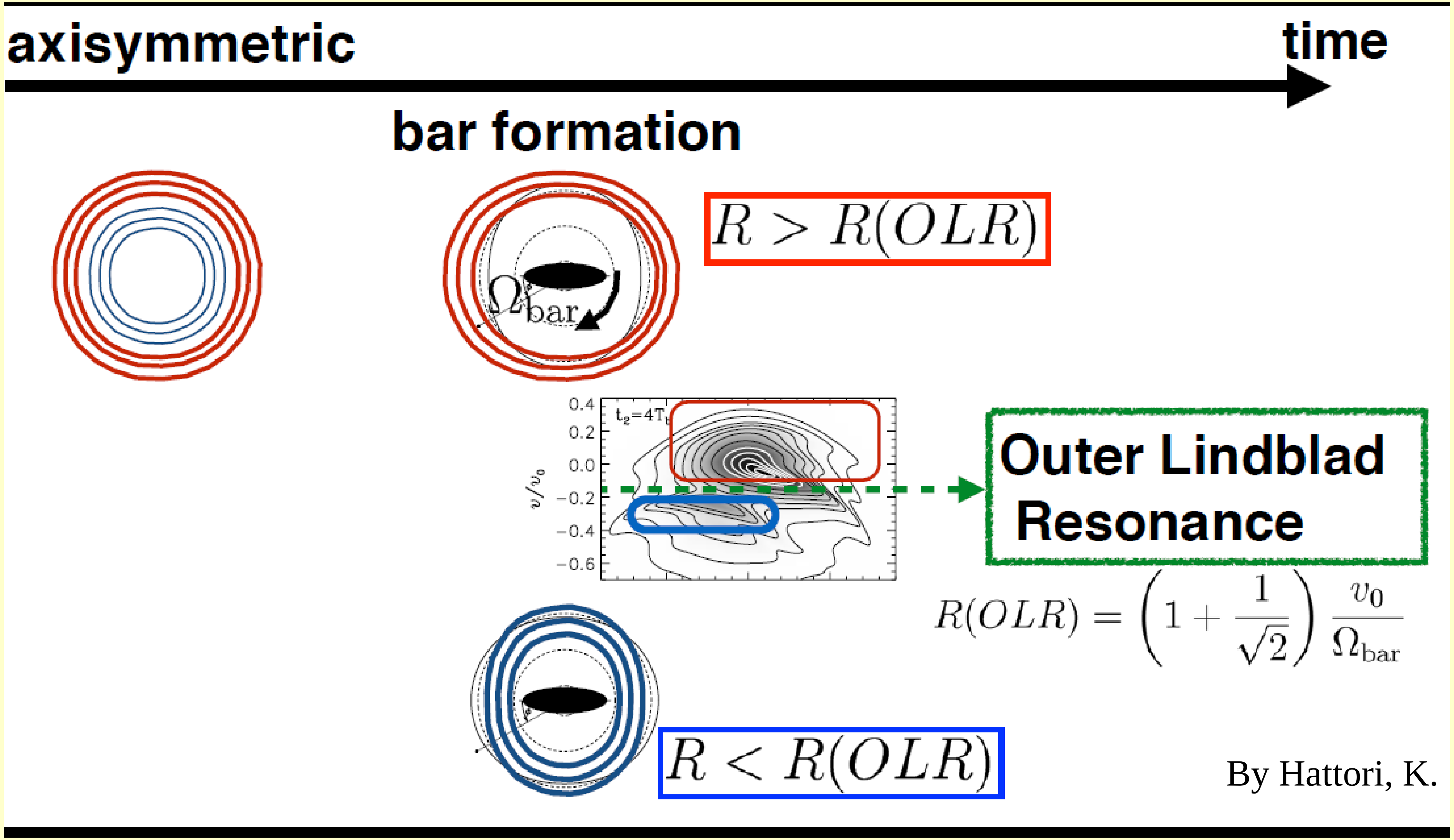


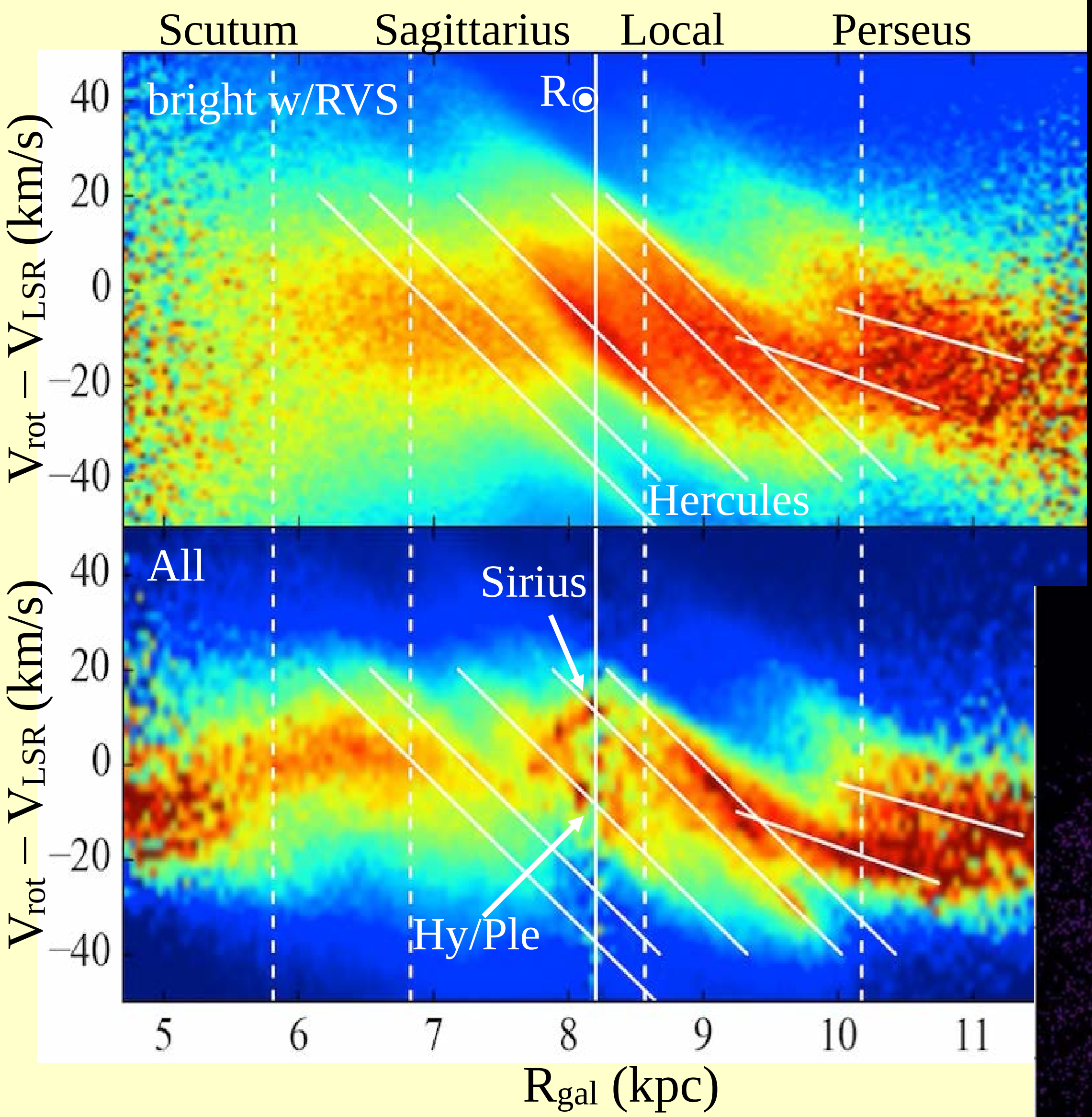
Figure 1.10: Rotation speeds for a Milky Way-like rotation curve. The dashed and dot-dashed lines show the 4:1 and 2:1 resonances calculated from the epicycle frequency, κ. The shaded region shows the the location of the pattern speed, which is in keeping with that of the Milky Way bar.

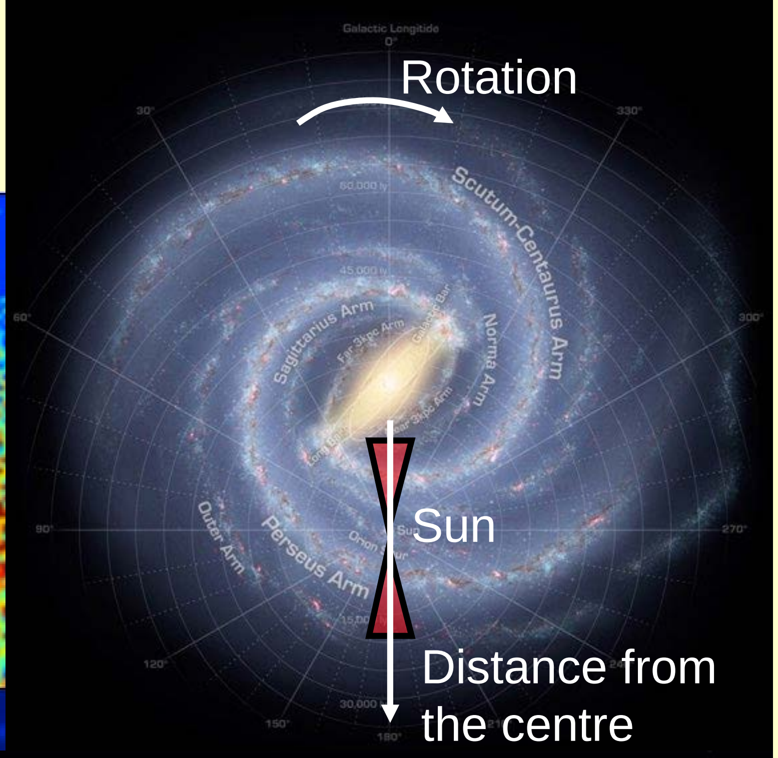
https://astro3.sci.hokudai.ac.jp/~alex/Material/ARPettitt_chapter1.pdf

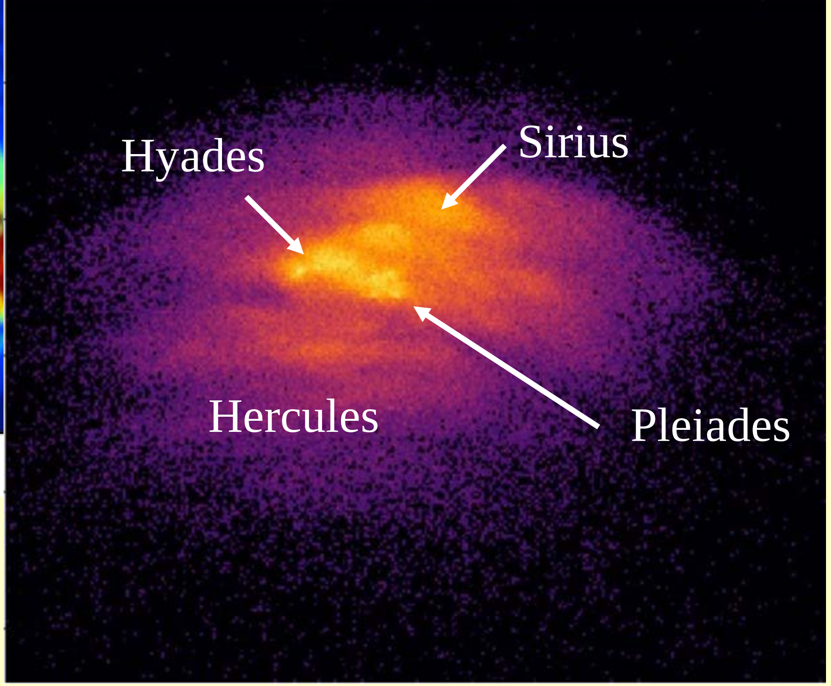


Bar structure, including its formation epoch is important key

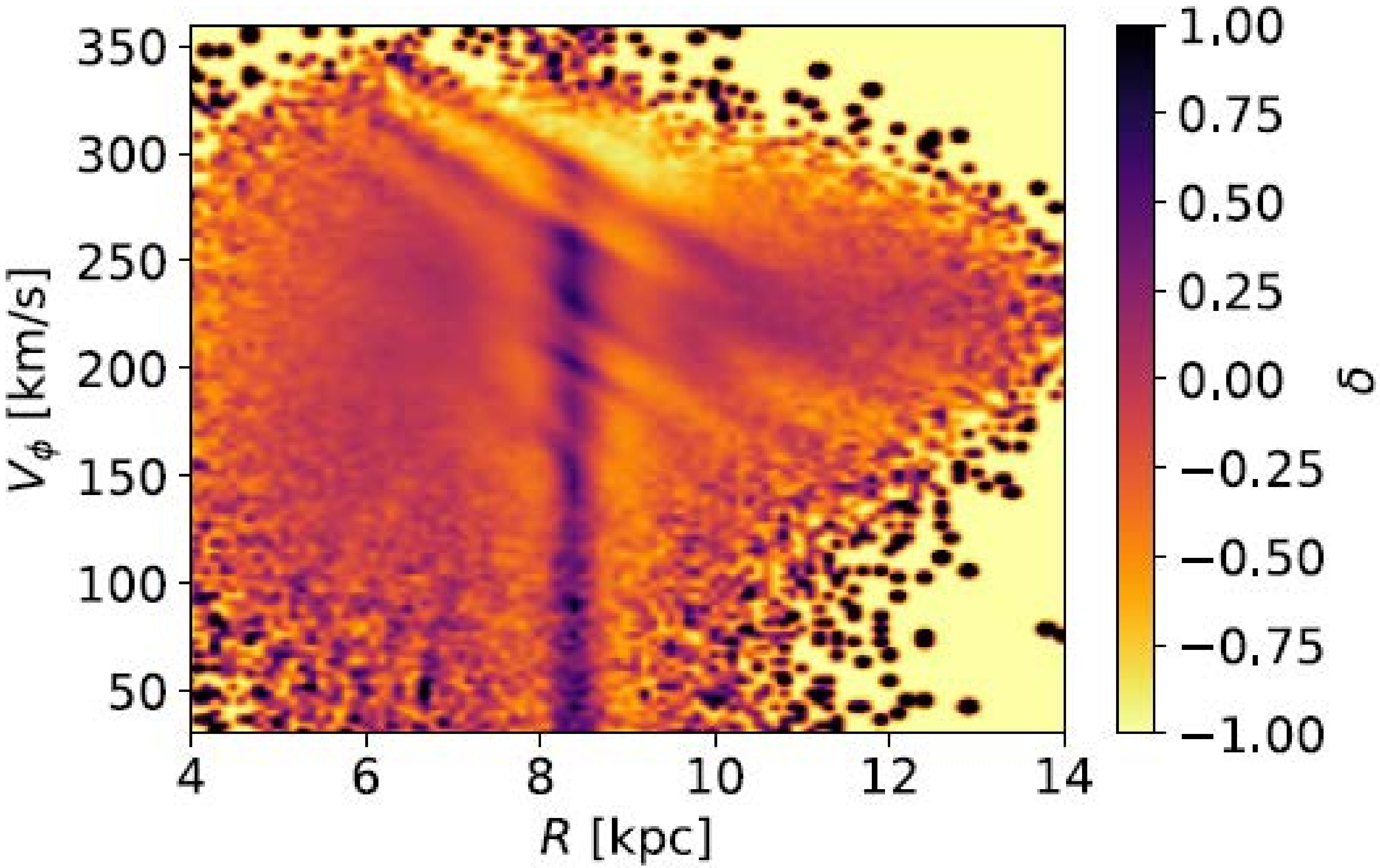
Many resonance-like features







Kawata et al. (2018, MNRAS, 479L, 108)



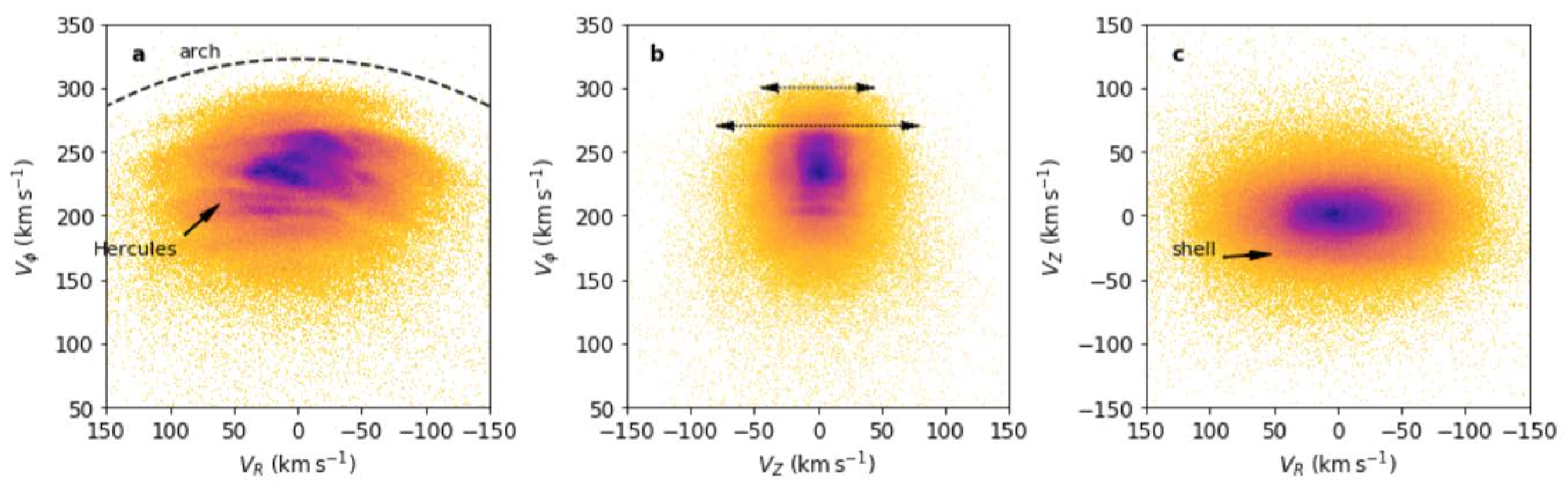
Laporte, et al., 2019

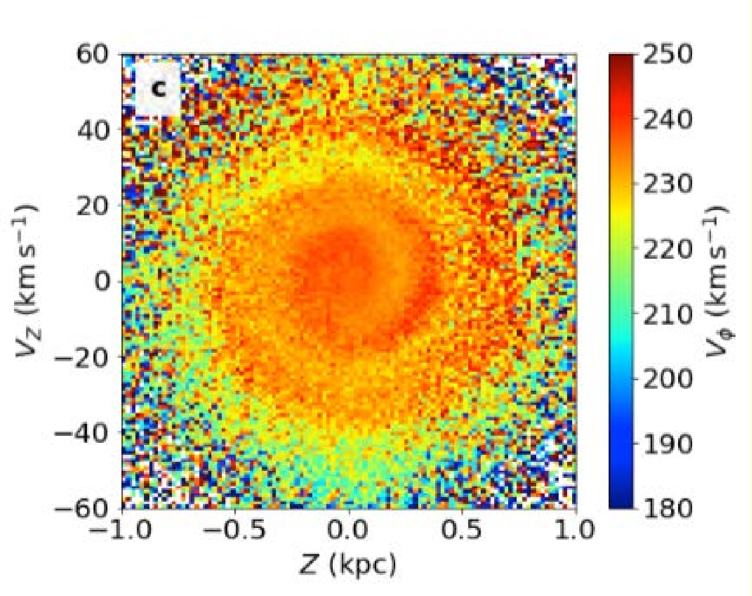
*Gaia hints at our Galaxy's turbulent life

like throwing a stone in a pond,
which displaces the water
as ripples and waves!!

Perturbations in the Milky Way. Credit: ESA

Galactic disk stars are not phase mixed, but perturbed recently?

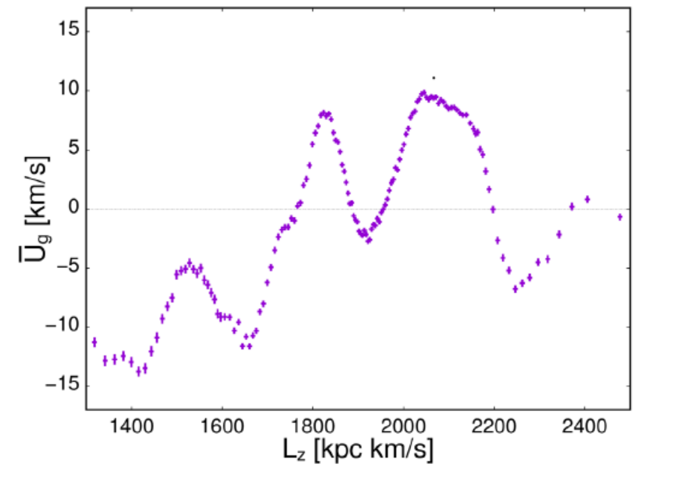




Antoja et al. (2018, Nature)

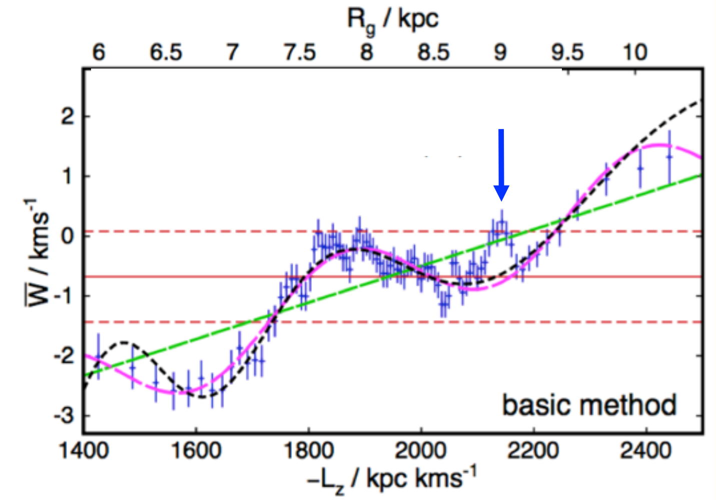
Vertical Oscillation

Consistent with what indicated in Gaia DR1



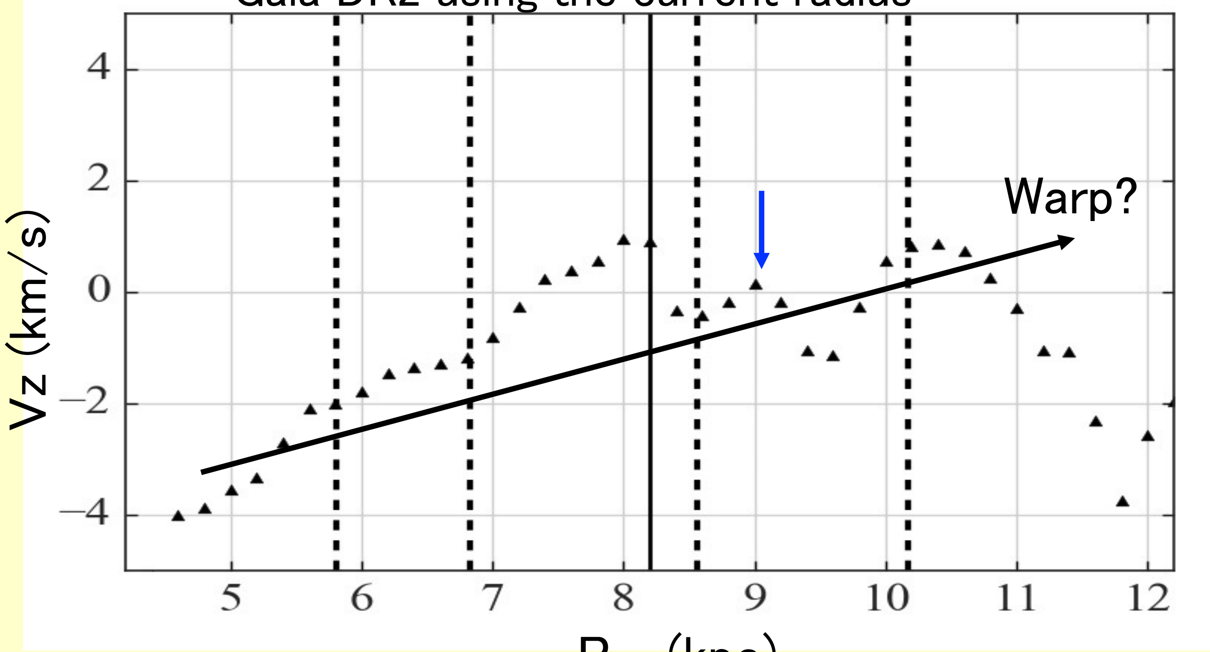
Friske & Schönrich (2019)

Gaia DR1 solar neighbourhood
Rg ← Lz



Schönrich & Dehnen (2018)

Gaia DR2 using the current radius



R_{gal} (kpc)

Kawata et al. (2018)

Gaia DR2 revealed the Milky Way disk is not a smoothly rotating disk, but heavily perturbed.

Galactoseismology

★What is the physical reason of the vertical oscillation?

Sagittarius dwarf?

Bar structure?

Spiral arms?

★Physical specifications of the oscillation

we need analysis for non-equilibrium state under the consideration of the vertical oscillation

⇩

*gravitational potential of the disk

*dark matter density in the disk

➔constraint on the kinds of dark matter

＊**Bar structure** plays very important roles in terms of the following phenomena.

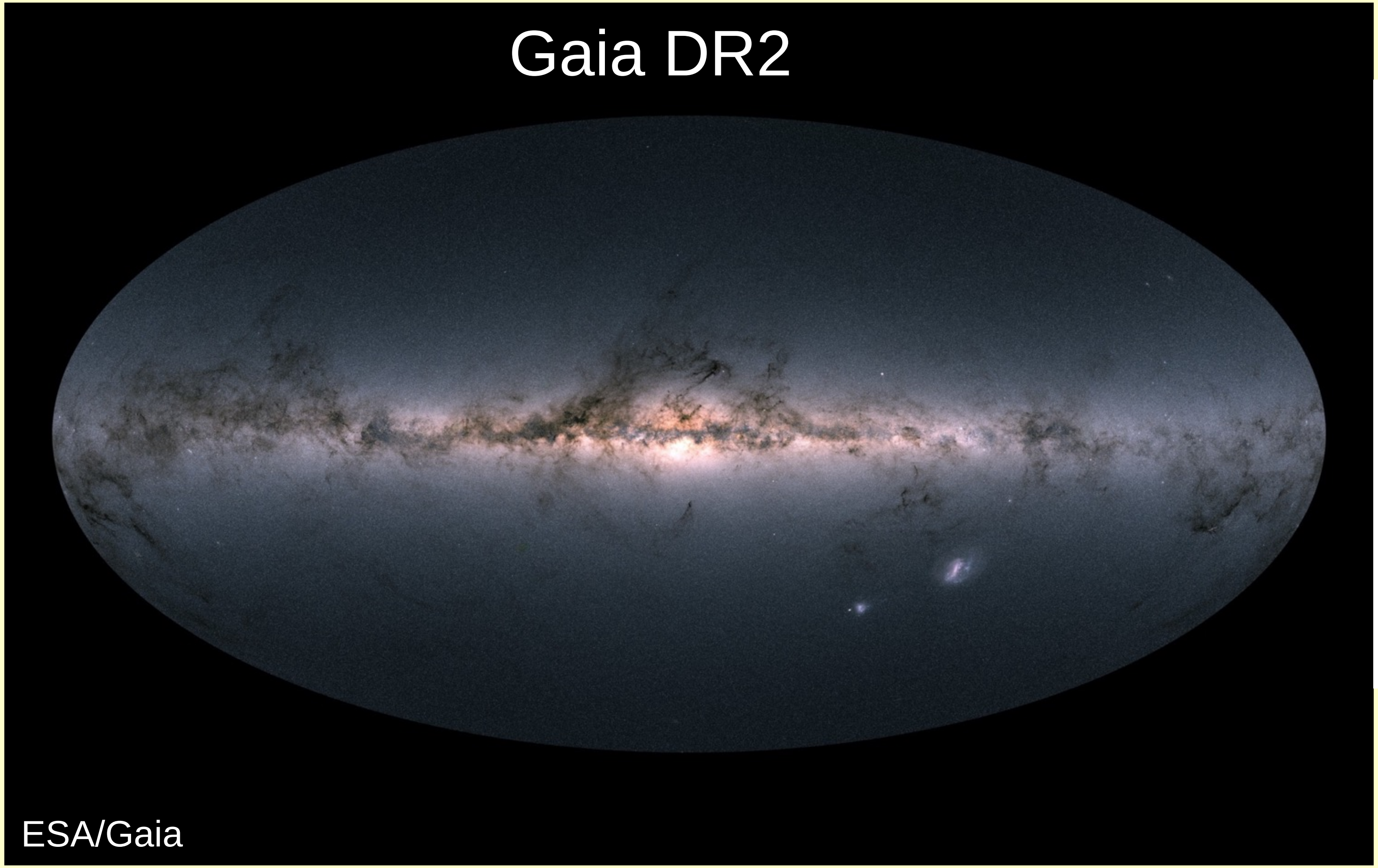
・Formation of the bulge and its evolution (buckling instability of orbits)
・Moving groups near the solar system
・ripple of the Galactic plane
・Gas supply from the disk to the central regions (~100pc away from the center)
・the trajectory of the sun in the MW
etc.

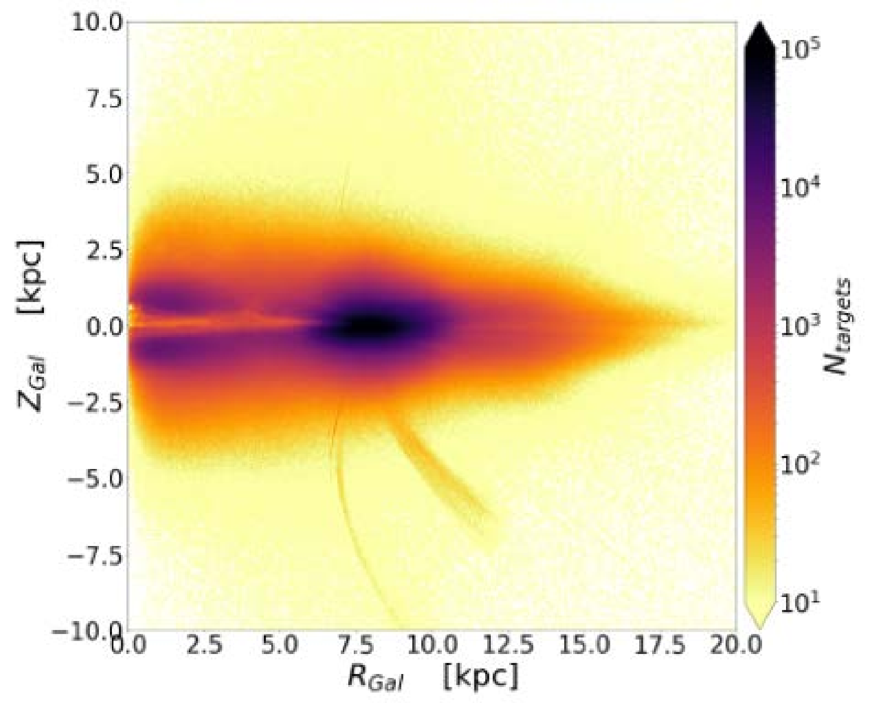
Gaia has already brought us many interesting and important scientific outputs

We can expect more revolutionary scientific outputs in near future.

However,･･･

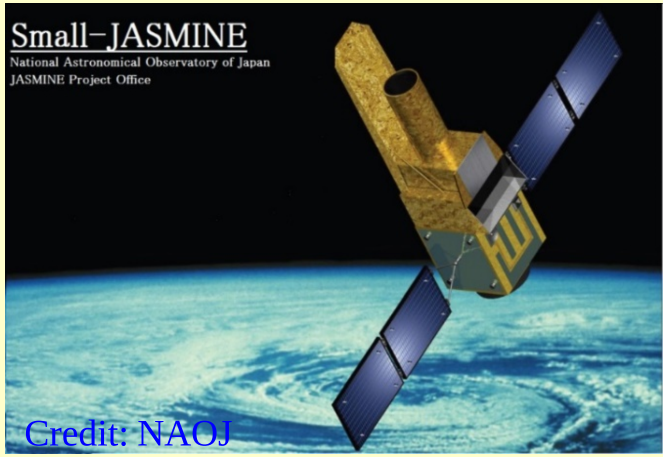
* **Gaia cannot see the central region and the Galactic plane farther than 3kpc away from us**





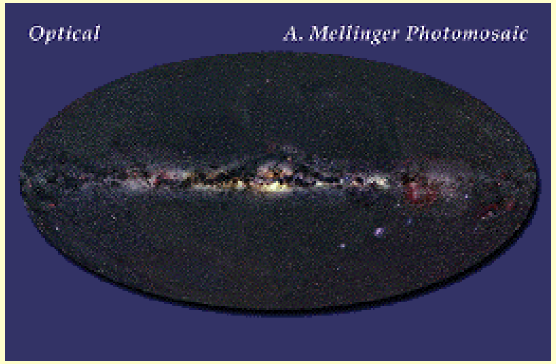
(Anders, F., et al.、 2019)

4. Small-JASMINE



Infrared Astrometry Space Mission

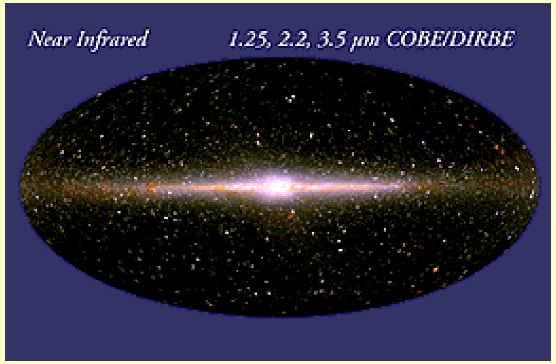
We have been aiming at the realization of the Small-JASMINE mission as a M-class mission of the science satellite program executed by JAXA.



ISAS/JAXA selected Small-JASMINE as the unique candidate for the 3rd M-class science satellite mission in May 2019!!

The target launch date is mid-2020s.

Credit: NASA



Launcher: epsilon rocket(JAXA)

1. Science Goal and science requirements

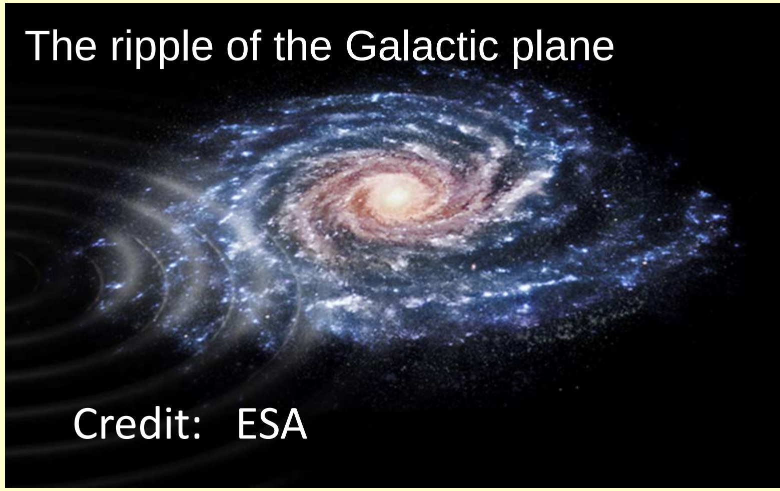
JASMINE science goal:

To understand the history of the Milky Way Galaxy that contains the Earth and habitable planets

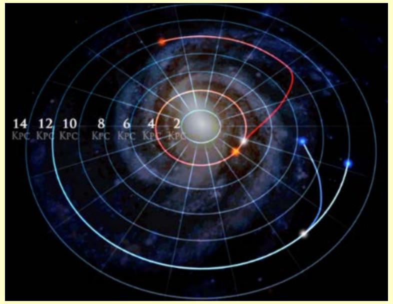
2 main science requirements:

(i) The ability to image the stellar kinematics in the central region of the Milky Way Galaxy at a distance of 8 kpc by the infrared astrometric observations

➔enabling the performance of Galactic Center Archeology +Galactoseismology

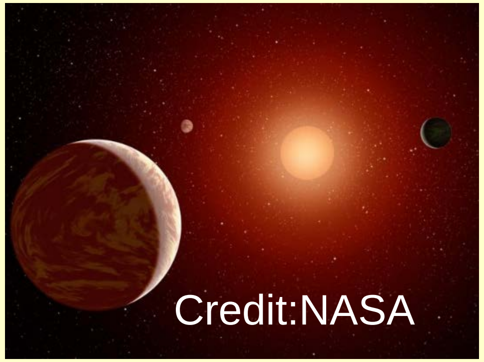


➔the birthplace of the sun and our way through the Milky Way



Credit: Dana Berry / SkyWorks Digital, Inc. / SDSS collaboration

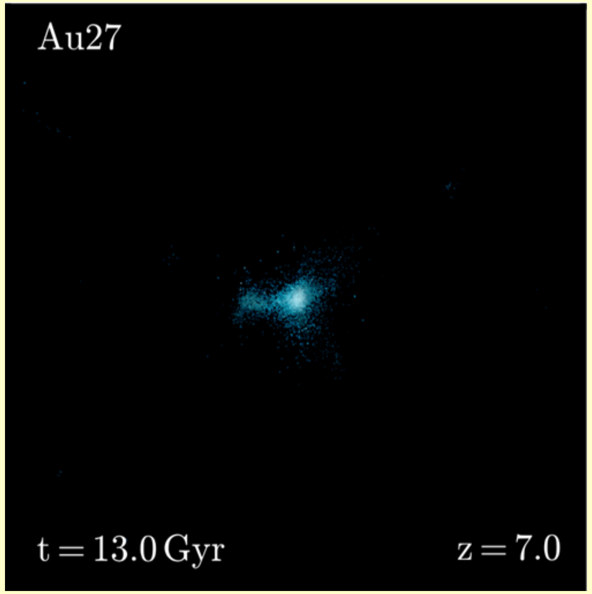
(ii) The ability to explore the potentially habitable exoplanets by the time-domain astronomical observations.

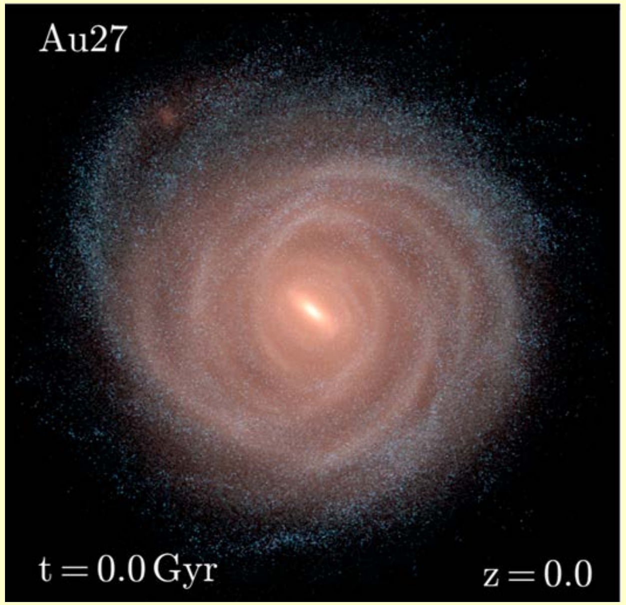


4.1 Galactic Center Archaeology

The Galactic nuclear bulge is very interesting and important target because of the treasure of the hidden history of the Galaxy and SMBH.

Galactic center contains the stellar population history from the first star formation to the present



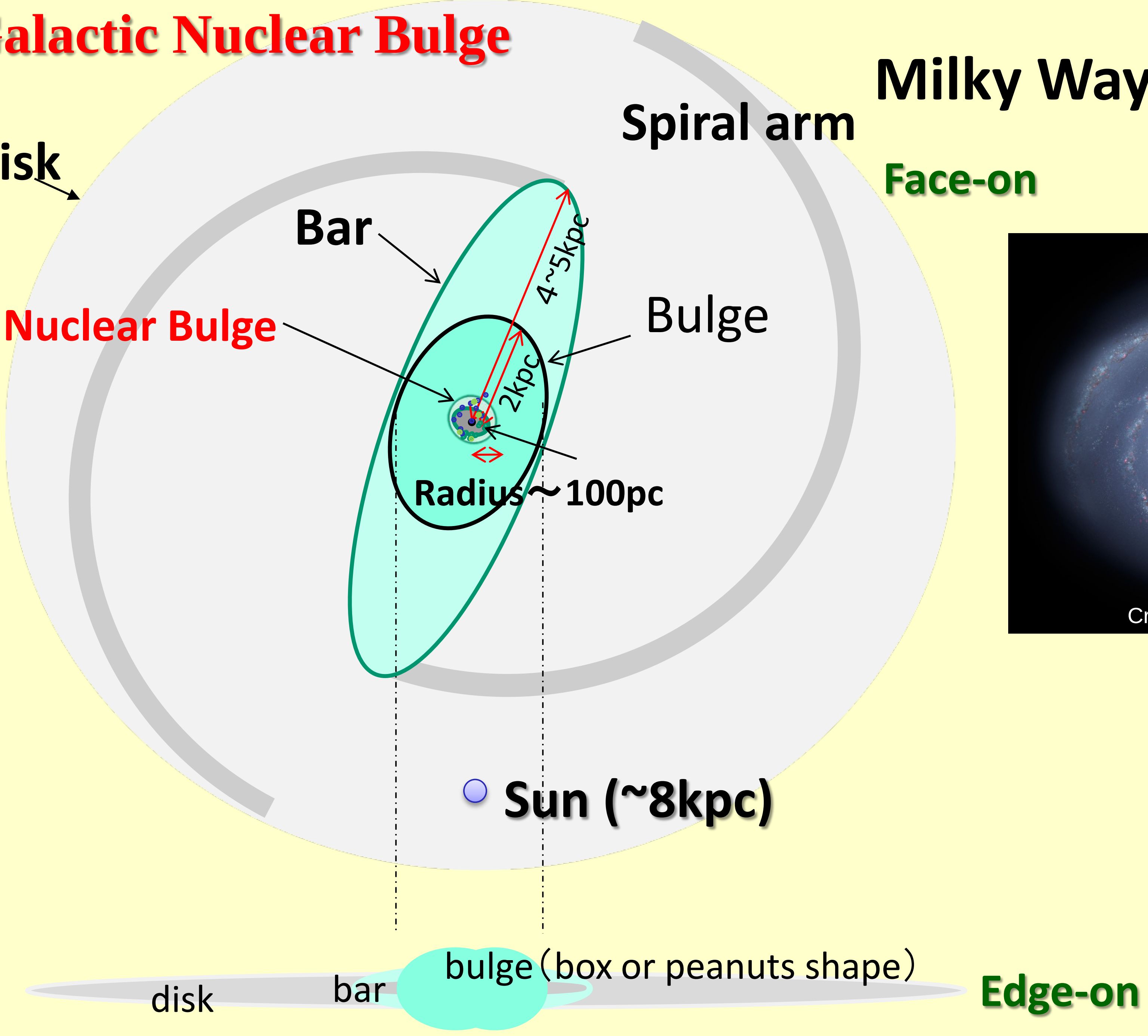


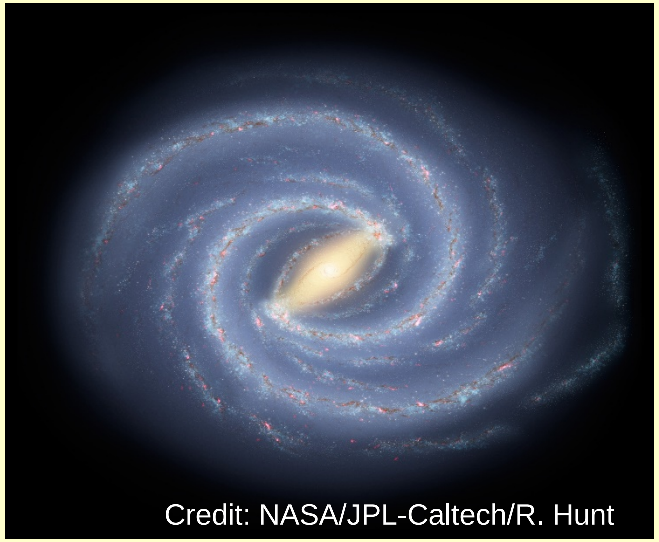
Auriga 27 (Grand et al. 2017)

Precise measurements of the motions of stars with different ages and metallicities will tell us the formation history of the Milky Way as well as the super massive BH formation process.

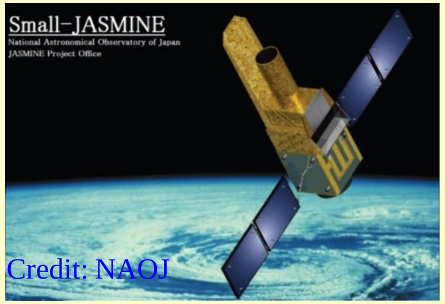
Galactic Nuclear Bulge

Milky Way Galaxy





4.2. Outline of Mission



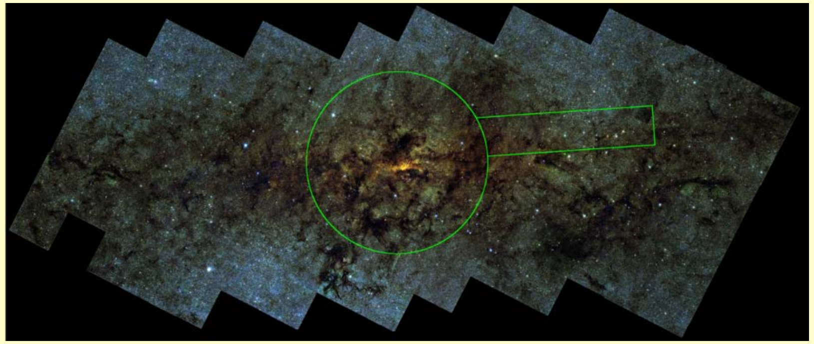
Astrometric Measurement in Hw-band(1.1μm~1.7μm)

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

***Hw~0.7J+0.3H**

Two survey modes

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



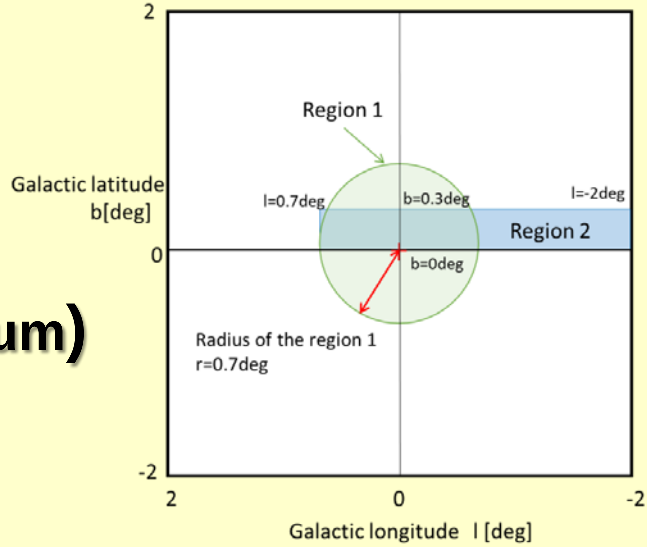
J, H, K tricolor composite image of the Galactic center area(imaged by SIRIUS on the Nagoya University IRSF 1.4m telescope: Nishiyama et al., 2004 Spring Astronomical Society Press Release).
The survey area of Small-JASMINE is written with the green line.

2. survey for **secondary objectives** in **non-bulge observations** → **some directions toward interesting target objects**

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

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

4.3The 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. (at minimum)

Survey region1:

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

➔ Galactic nuclear bulge

Survey region 2:

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

➔ Nuclear Stellar Disk(NSD) radius of 200 pc, height of 45 pc

Precisions:

Hw<12.5mag (7100 bulge stars, 4,900disk stars)

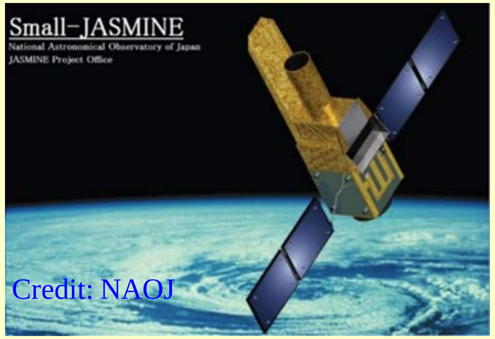
parallax：~25μas, proper motion: ~25μas/y ⇦ ~20% distance error and 1km/s tangential velocity error at 8kpc

12.5mag <Hw <15 mag

proper motion: 25μas/y~125μas/y ⇦ 1~5km/s tangential velocity error at 8kpc

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.

★Complement to the Gaia mission in Small-JASMINE



＊In the survey region of Small JASMINE
With high precision of parallax: < 25μas

Gaia can measure only about ～70 bulge stars
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

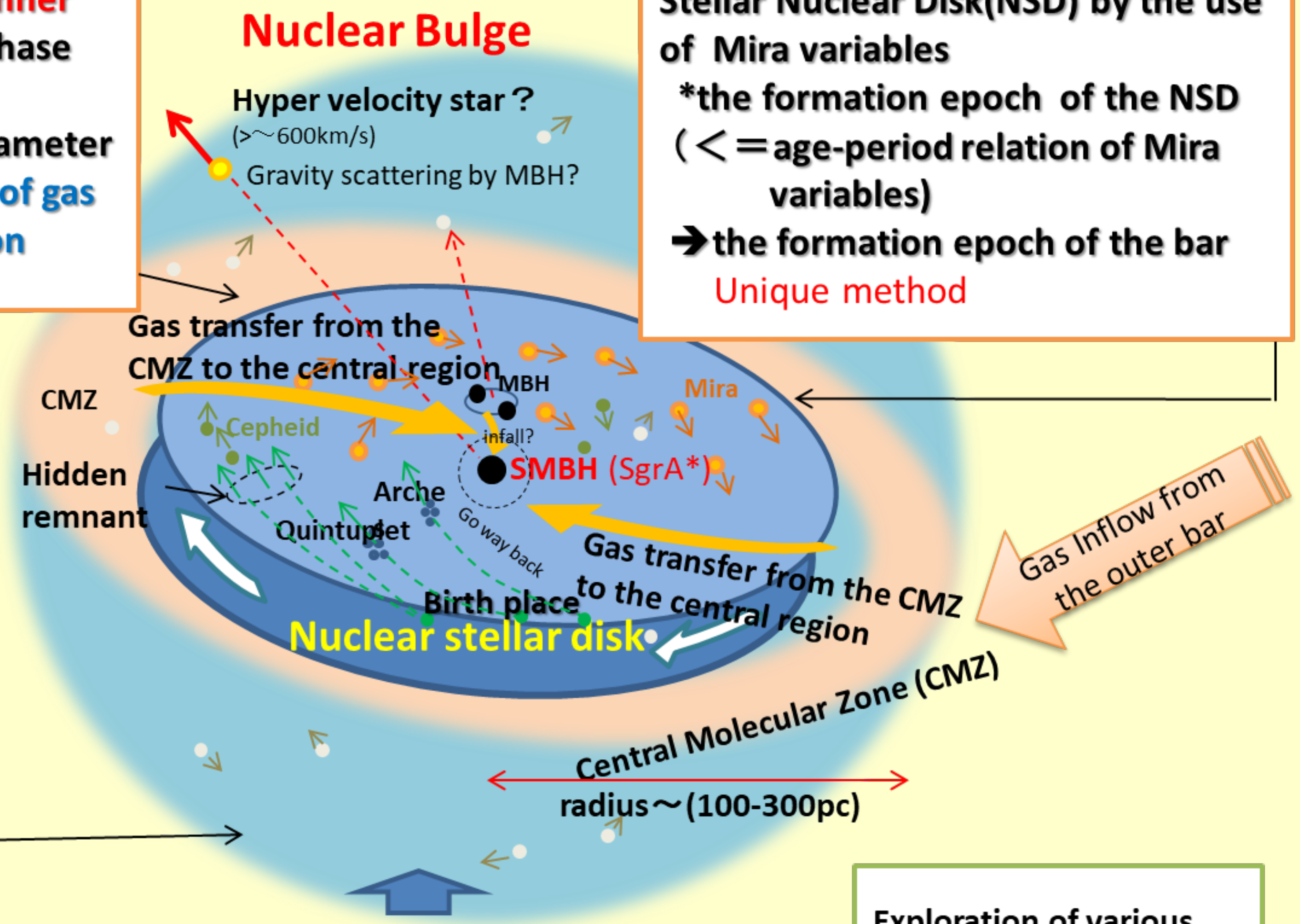
→ Small-JASMINE

Main Scientific Objectives of Small-JASMINE

SO-2 Characterization of the gravitational potential (of a inner bar structure) by the use of phase space distribution of stars
Patter speed=>Important parameter for the transport mechanism of gas from CMZ to the central region (<~10pc)

SO-1 Clarification of the Galactic Stellar Nuclear Disk(NSD) by the use of Mira variables
*the formation epoch of the NSD (＜＝age-period relation of Mira variables)
➔the formation epoch of the bar
Unique method

SO-3 Characterization of the global dynamical structure around the Galactic nuclear disk and clarification of its origin by the use of phase space distribution
➔Infall of intermediate massive BHs or Classical bulge?



Identify hidden remnants of stellar clusters
➔verification of Secular evolution

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

Clarify 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.

Scientific objective SO-1

The formation epoch and dynamical structure of NSD

The oldest stars in the NSD should correspond to the stars formed when the NSD formed

Baba & Kawata (2019)

Mira variables are good tracers for the investigation of age :
age distribution of Mira variables in NSD by the use of the age-period relation

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

It is very necessary and important to select Mira variables which belong to the NDS:

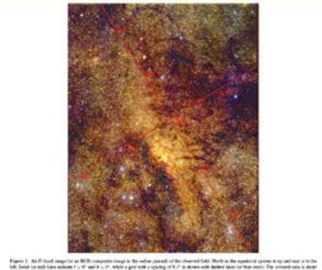
Reduction of contamination from the other stellar components, such as a classical bulge

*Proper motion => **Identification of the group members of Mira variables which belong to the nuclear stellar disk**

Proper motion: crucial information to distinguish the NSD from other stellar components, such as classical bulge

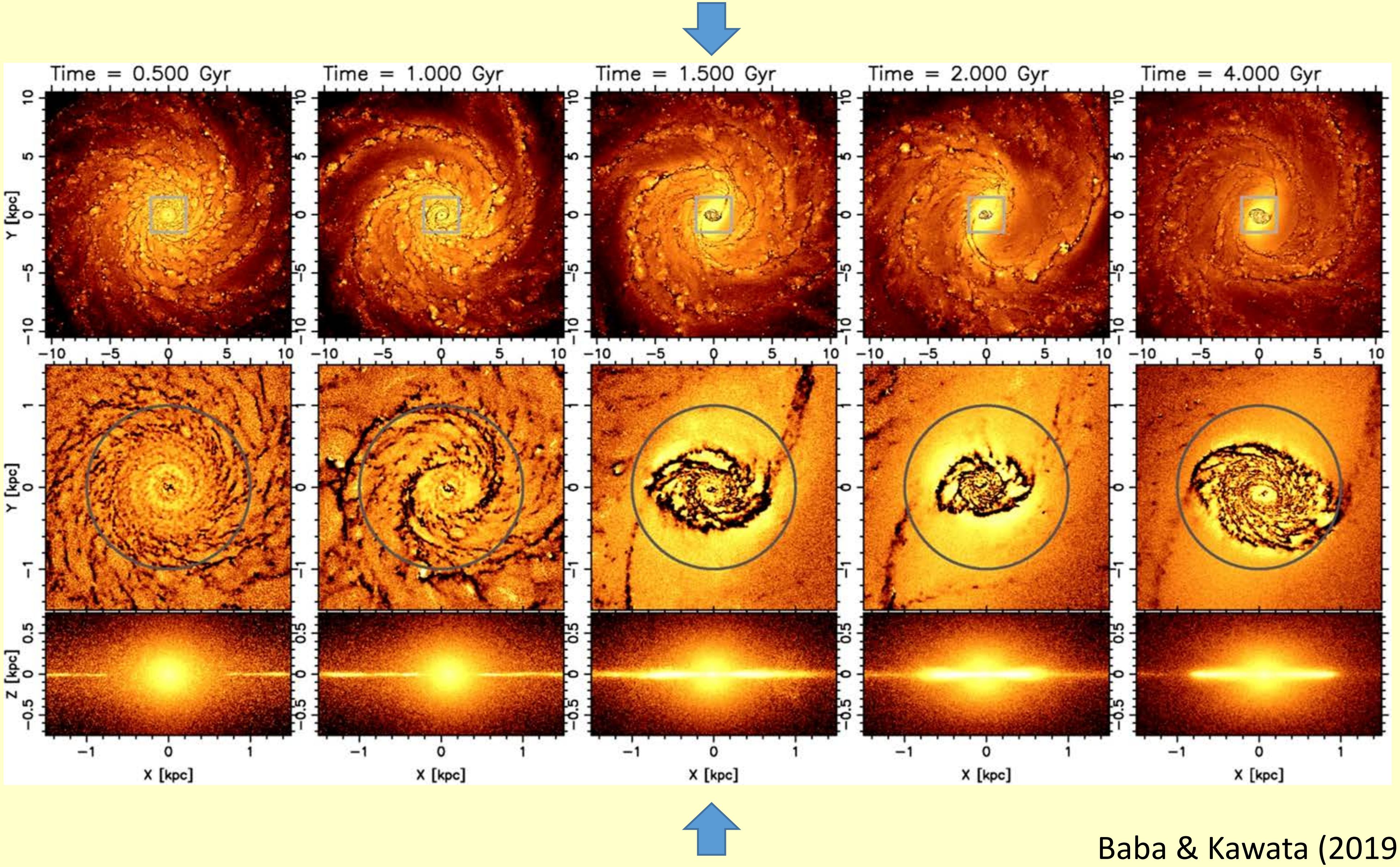
Baba & Kawata (2019)

the formation epoch of the NDS
～ the formation epoch of the outer long bar
which relates to the formation of the bulge
<= suggested by numerical simulations



Matsunaga et al.(2009, MNRAS)

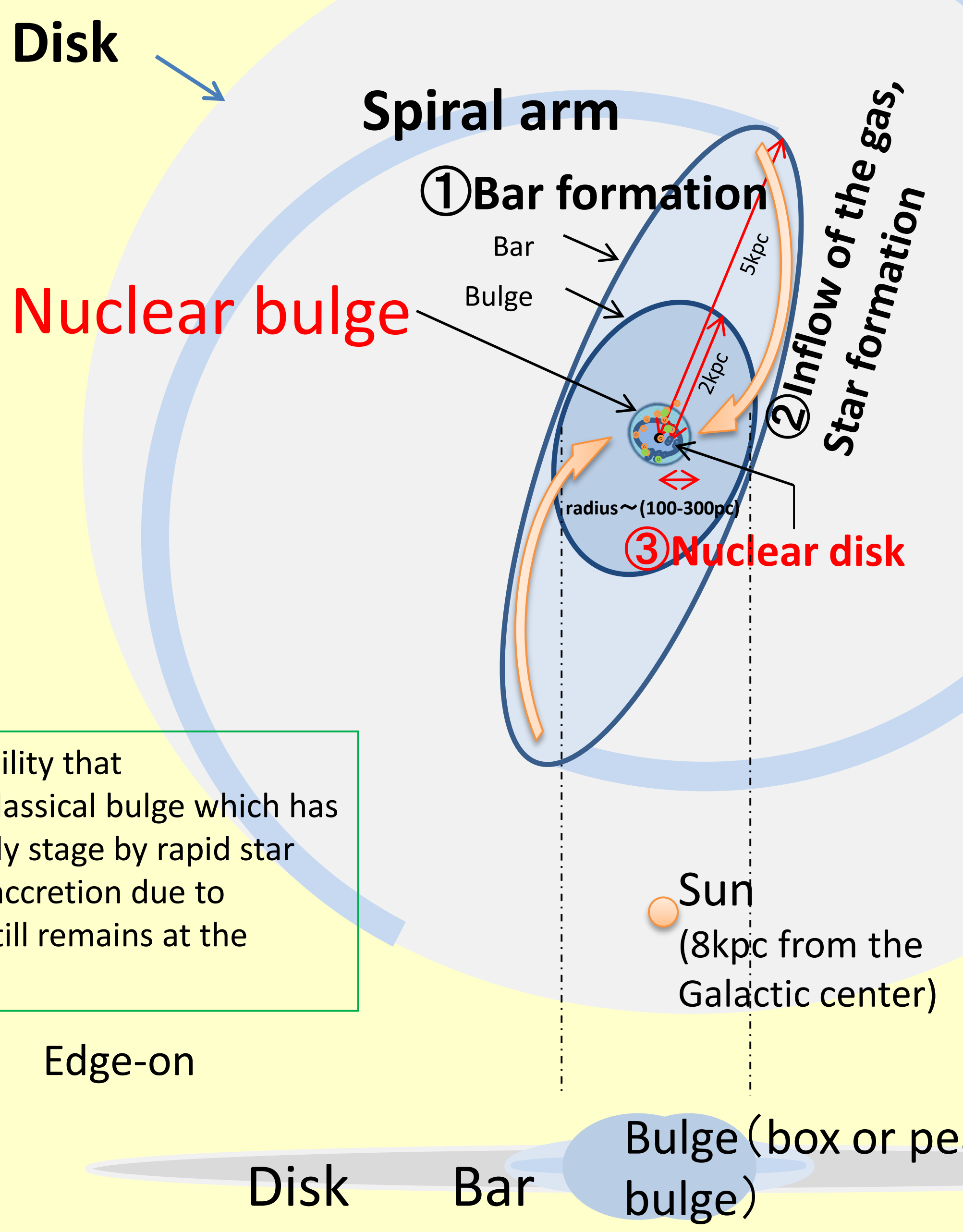
Formation of Bar



Formation of NSD

Baba & Kawata (2019)

★Standard scenario of bar, bulge, nuclear stellar disk



①Bar formation due to the bar instability in the disk → ②Bulge formation (buckling instability)

⬇

②Inflow of the gas to the central region.

⬇

③Formation of the nuclear stellar disk (radius of ~100pc--300pc)

Note: there is possibility that the component of classical bulge which has formed in a very early stage by rapid star formations and gas accretion due to merging of clumps still remains at the present time.

Soon after the process of ①, the process of ②and③ proceed.
⇒formation epoch of the bar ≒ formation epoch of the nuclear stellar disk（NSD)

Galactoseismology

★Wobble of stars

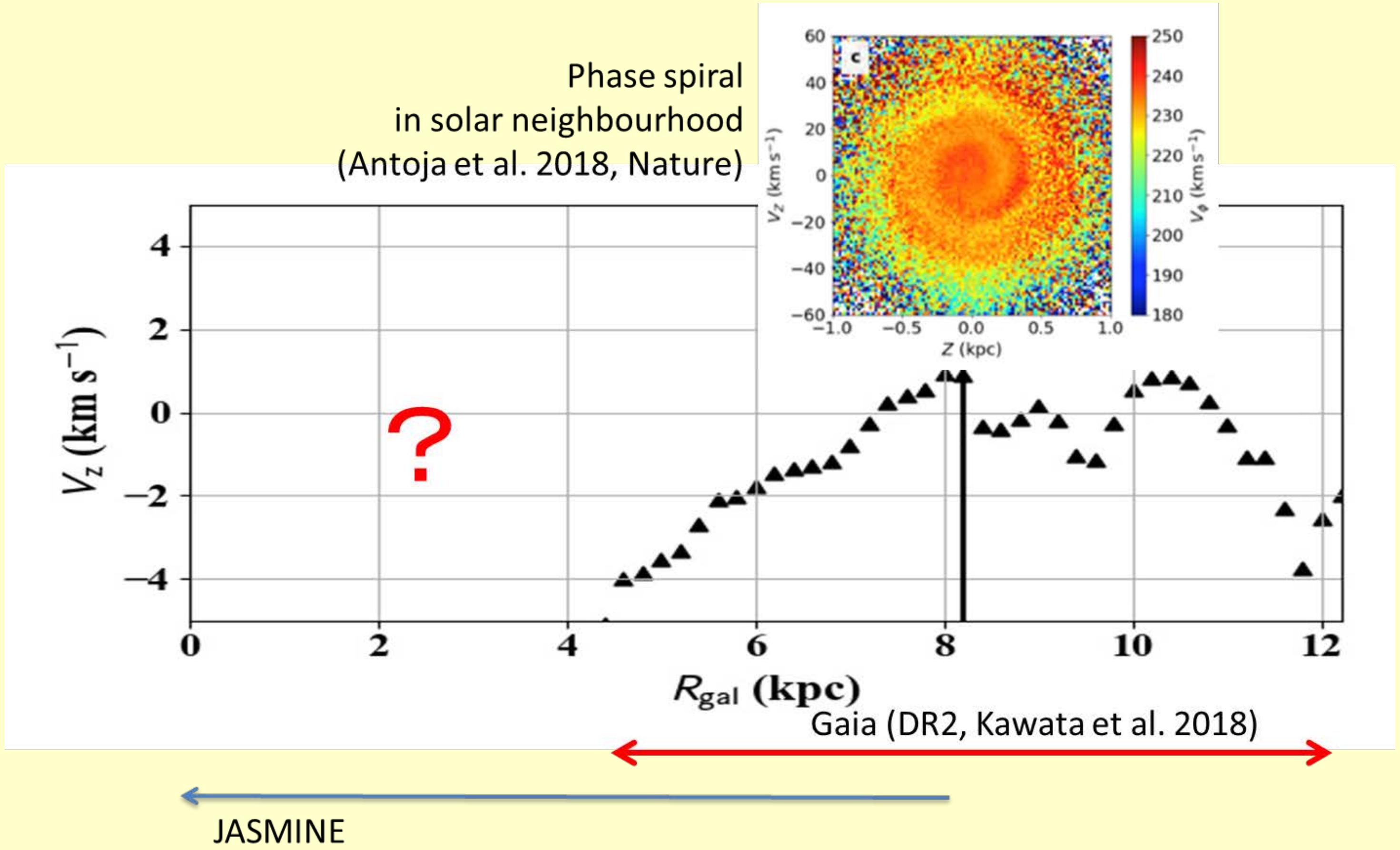
○physical origin of this oscillation?
Dwarf satellite? Bar?
Transient spiral arms?

○ gravitational potential and mass density of the disk

➔ dark matter distribution on the disk

➔constraint on types of dark matters

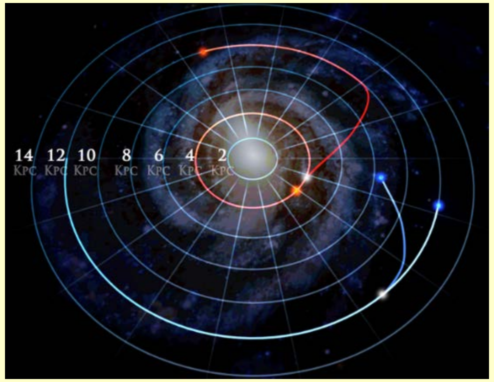
Phase spiral
in solar neighbourhood
(Antoja et al. 2018, Nature)



Gaia (DR2, Kawata et al. 2018)

JASMINE can see stellar velocity perpendicular to the Galactic mid-plane in inner disk.

Role of Small-JASINE for clarification of the bar and disk structure



Credit: Dana Berry / SkyWorks Digital, Inc. / SDSS collaboration

✱ The following phenomena and objects are more or less related to the bar and disk structures.

- ·Formation of the bulge and its evolution
- ·Moving groups near the solar system
- ·Ripple of the Galactic plane
- ·Gas supply form the disk to the central regions
- ·the birthplace and trajectory of the sun in the MW etc. (radial migration and wobble around the Galactic plane)

But the above problems have never been resolved

✱ Small-JASMINE:

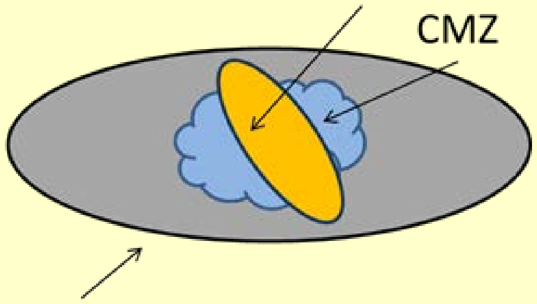
○Galactic Center Archeology

➔the formation time of the bar structure：very important key parameter

＋Galactoseismology in the inner disk

＝＞gravitational potential in the disk=>constrain to dark matter in disk

Other Scientific objectives in the key Projects



(a) Existence of a rotating inner bar?

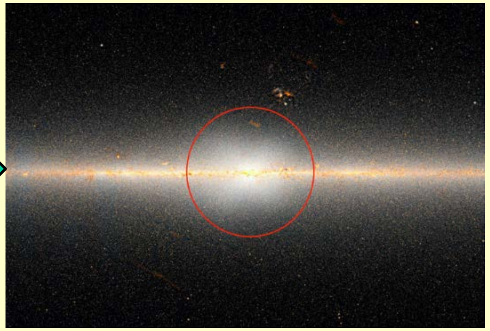
Pattern speed (figure rotation velocity) of the inner bar, if any

candidate of key processes for transportation of gas from CMZ to the central region(<~10pc) to feed the supermassive black hole and lead to activity of the Galactic center.

(b)Global dynamical structure around the NSD

*relic of classical bulge component？

Classical bulge in M81. *[Credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA).]*

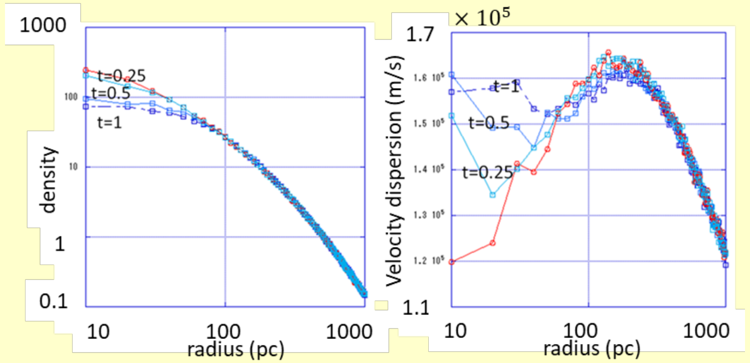


X-shaped distribution of stars in the bulge is visible.

Image credit: NASA/JPL-Caltech/D. Lang

* sub-structures in the Galactic nuclear bulge??

*if equilibrium state (core structure of the density profile and flat profile of the velocity distribution➔ high possibility of the past infall of a few supermassive black holes into the Galactic center



Other Scientific objectives in the key Projects

(c) Survey of the Galactic plane

*Galactoseismology
*Spiral arms

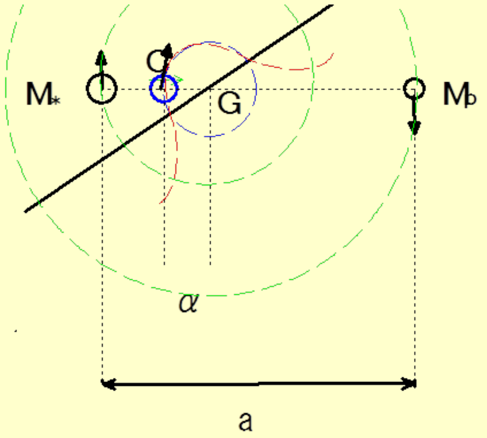
(d) Discovery of unknown BHs

(i) Residual motion 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!

(e) 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**

Other Scientific objectives in the key project

(f) Motion of star clusters around the Galactic center

➔ the birth places of star clusters

(g) Discovery of unknown stellar clusters in the nuclear bulge

by detection of parallel movement of the stellar proper motions

➔ clarification of star formation rates

(h) Analysis of symbiotic X-ray binaries

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

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

(j) Discovery of unknown objects

e.g. Wormholes?!

(k) Stellar physics, Star formation

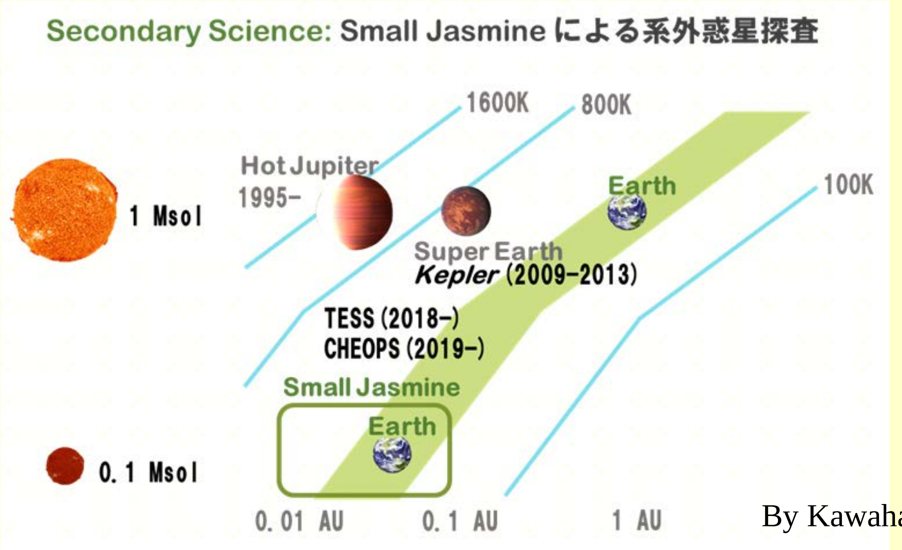
∗ 3-Ddistribution of inter -stellar dust

∗ annual parallax and proper motions of Mira-type variable stars in the bulge

4.4 Operation mode in non-bulge observations

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

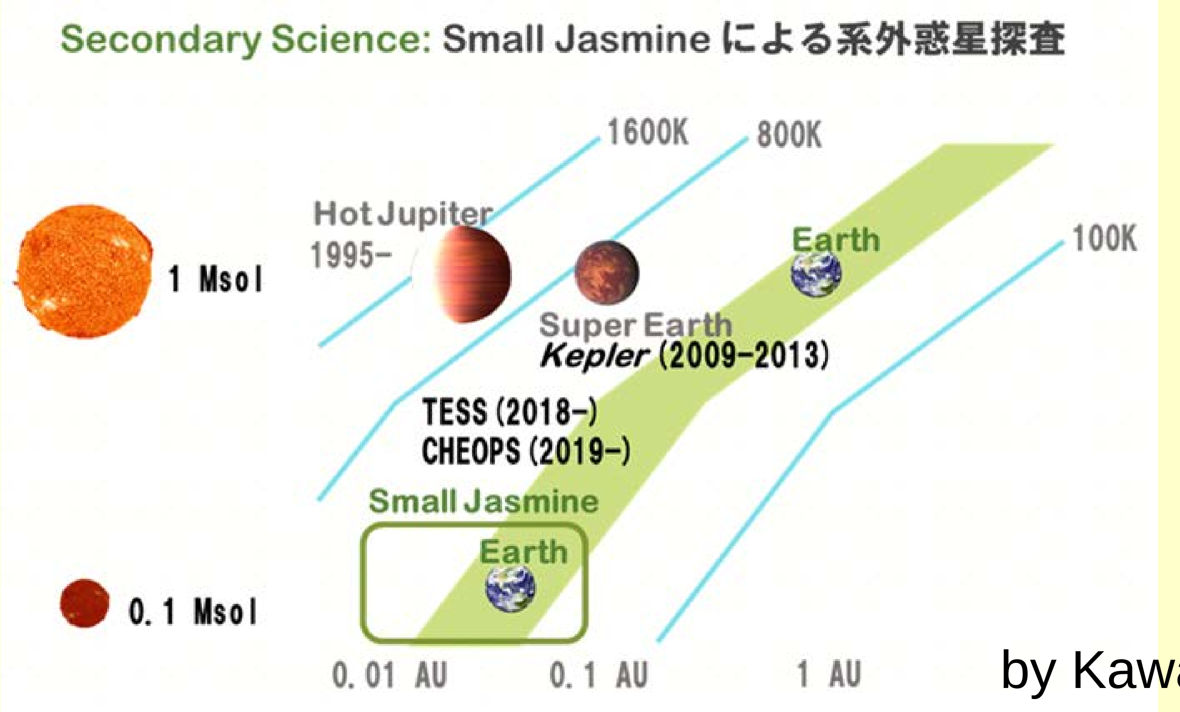
Establishment of science team independently of JASMINE team (exo JASMINE team)
PI.:Kawahara (Univ. of Tokyo),
Kotani(ABC), D.Suzuki, T.Yamada(ISAS), Masuda(Princeton Univ.), etc.



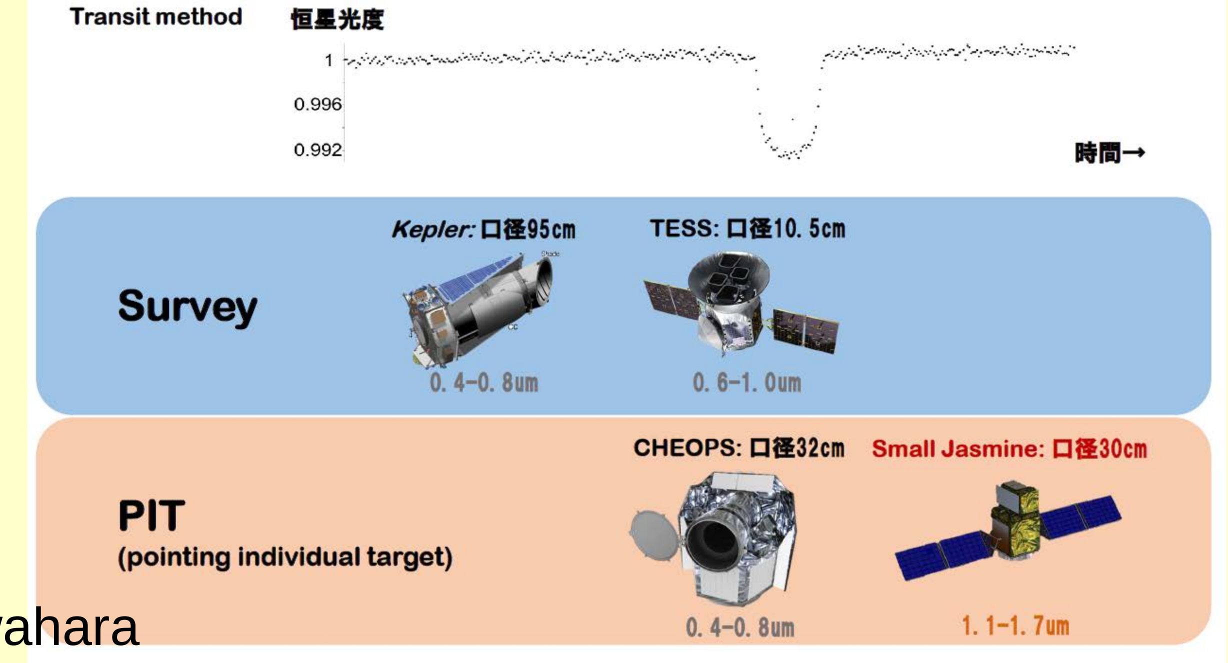
By Kawahara

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

Option3: Calibrations for the data analysis



by Kawahara



Target fixed star: 0.2 Rsol, 3000K, 16-25pc
Target planet: Earth-like planet at habitable zone
Period of revolution: 14 days – 30 days
The depth of the transit: 0.25%

Observation period: 20 – 30 days
Target : planetary systems whose inner planets and/or gas planets are found by TESS/RV survey (20 – 30 objects)

*Small-JASMINE has 20 times light-gathering power than that of TESS
*The targets of Small-JASMINE are below the detection limit of CHEOPS

4.5. 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 Small-JASMINE

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

e.g. APOGEE2, VVV, GALACTICNUCLEOUS, MWM, MOONS, PFS, ･･･

○ Collaboration with US team (USNO, SDL(Utah State Univ.), JPL, MIT, Virginia Univ. etc.)

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

We applied to Mission of Opportunity of NASA.

○ Collaboration with ESA

***ESA is now considering the support of ground stations for the down link of scientific data to be 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!