

# A billion ways of using Gaia data

---

Tineke Roegiers

ESA ESTEC

31/08/2023



# Maybe not a billion... but a lot for sure!

## The billion ways of using the Gaia data

Tineke Roegiers <sup>1</sup>

### Solar System

Though Solar System science is not the primary goal for Gaia, a lot is achieved on this front since Gaia started releasing its data. When scanning, Gaia captures any object it scans across and thus observes many asteroids next to stars and galaxies.

Apart from Gaia's own data on Solar System objects, there are many indirect ways in which Gaia data influences our knowledge of the Solar System. The below list of topics can not be complete and

### Stars

The large, homogeneous all-sky Gaia catalogue of stars is a treasure chest for new discoveries, and brings substantial samples of special stars for detailed investigation. A taste of studies, discoveries and opportunities where Gaia helps out is given below. This is only a tiny selection of the many topics touched by the scientific community related to stars.

### 25pc sample

Early 2023 brought an update to the catalogue of nearby stars: CNS5. Within a sphere with 25pc radius around the Sun a total of 5931 objects are known now. This catalogue strives for completeness and was updated with the star information from Gaia's Early Data Release 3. The CNS5 is a great sample to study the Milky Way. This catalogue can be used to test a variety of theories and improve models of the Galactic Disk.

### Milky Way

Mapping the Milky Way is the core goal of Gaia and so it does, in full detail, in many dimensions. Stars and structures in the Milky Way are mapped, as well as dust and interstellar matter in between the stars. Gaia also maps the astrophysical information such as stellar ages, metallicity, and more. This variety of Milky Way mapping is highlighted in Gaia's [Multi-dimensional Milky Way](#), based on 10 Gaia sky maps. Full details explaining the

### Galaxies

Next to stars, asteroids, moons, comets, spacecraft, quasars, ... Gaia also observes galaxies. If observed as a whole, they show up as extended objects. First results from the processing of these extended objects were published with Gaia Data Release 3, leading to 4.8 million galaxy candidates (20% of which have redshift estimates). Gaia also observes individual stars inside galaxies, if these galaxies are close enough. This is the case for the Andromeda

### Earth orbit and L2

Some spacecraft orbiting Earth or located at L2 are powerful in studying a specific target with great detail. To make most efficient use of these telescopes, pointing them to the most promising sources is important. This is where Gaia helps out. Gaia, being an all-sky homogeneous survey, brings the perfect catalogue to make a first selection of interesting candidates for follow-up. In this way we can capture the best stars to follow the needles to

### Earth

On Earth, life has improved for astronomers following up on stellar occultations. With the star positions and motions of Gaia's first data release came improved predictions of the stellar occultation shadow paths on Earth. These shadow paths and their timing predictions are used to deploy the ground observations of these events. With each Gaia data release, the predictions improved and the chances of observing a stellar occultation increased! Through stellar

### Star groups

Some stars belong together. They travel together through space bound by a mutual gravitational attraction. In June 2022 Gaia published a catalogue of multi-star systems, containing stars with few companions. Gaia's full catalogue of over 1.8 billion stars is also heavily used to discover and improve our knowledge of stellar clusters, star groups composed of many stars.

### 100pc sample

As part of Gaia's Early Data Release 3, the Gaia Catalogue of Nearby Stars (GCNS) was published. With this catalogue, a unique census of stars within 100 pc of our Sun became available. At this distance, the coolest stars become too faint for Gaia's survey limit. Choosing 100pc hence allows to get a complete census of Gaia stars, including the coolest ones. Such a complete and homogeneous sample is important for studies of the Galaxy.

### Milky Way Halo

Following Gaia's first data release, an extended study was performed revealing rich structures of the nearby stellar halo. More studies followed soon, when more and better data became available with each Gaia data release. Below a small selection is given to demonstrate Gaia's impact on our knowledge of the Milky Way halo.

Stories published on this topic:

### Quasars

Gaia also observes distant quasars, many of them billions of lightyears away from the Sun and the Milky Way. The Gaia catalogue contains 1,614,173 quasars used to construct the Gaia Celestial Reference Frame. With the high quality of Gaia EDR3, Gaia was for the first time capable of observing the tiny effect of the acceleration of the solar system with respect to the distant universe. This effect was deduced from the aberration of light seen in these

### Sun

Though Gaia never looks at the Sun with its telescopes, it is capable of observing the Sun nonetheless. Close watch is kept on all temperature changes affecting the Gaia spacecraft as they have the potential of influencing the observations captured. The small drop in Solar irradiance caused by the transit of a cooler sun spot can be measured with Gaia's temperature monitors.

### Cavities in space

There is something to be learned from the absence of stars as well. A gigantic cavity in space was found by combining Gaia's 3D information with powerful new data science techniques in order to map molecular clouds in 3D gas density space. This led to the discovery of a gigantic cavity in space.

Stories published on this topic:

- The power of the third dimension - the

### Local Bubble

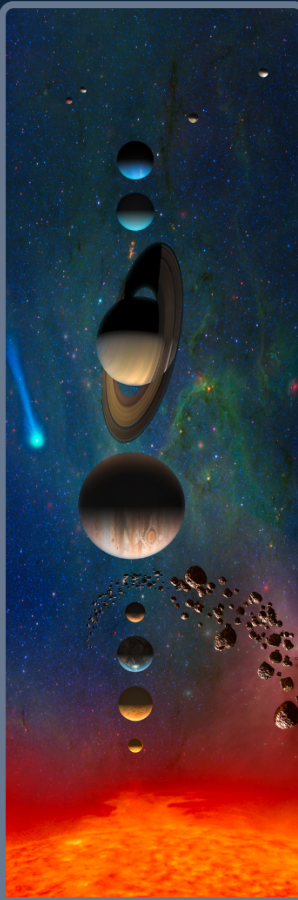
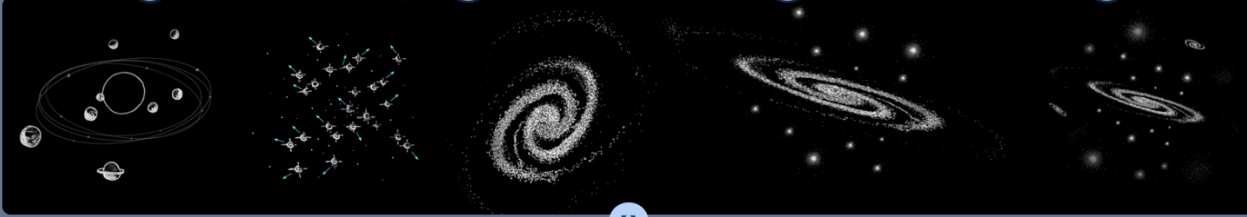
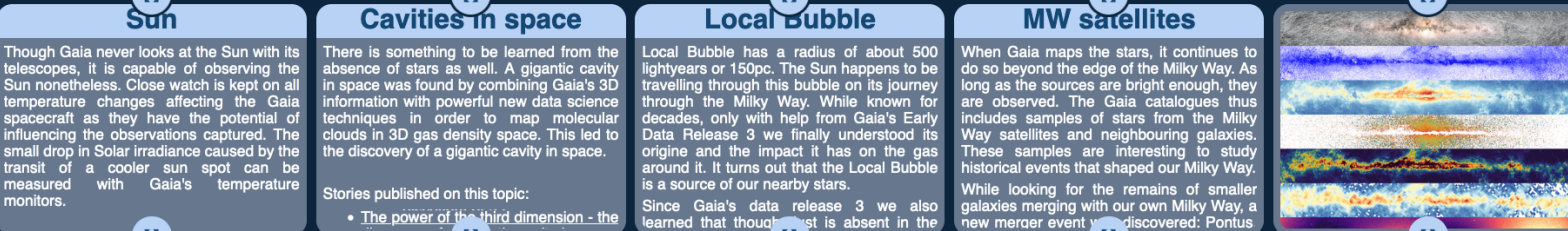
Local Bubble has a radius of about 500 lightyears or 150pc. The Sun happens to be travelling through this bubble on its journey through the Milky Way. While known for decades, only with help from Gaia's Early Data Release 3 we finally understood its origin and the impact it has on the gas around it. It turns out that the Local Bubble is a source of our nearby stars.

Since Gaia's data release 3 we also learned that though the Local Bubble is absent in the

### MW satellites

When Gaia maps the stars, it continues to do so beyond the edge of the Milky Way. As long as the sources are bright enough, they are observed. The Gaia catalogues thus includes samples of stars from the Milky Way satellites and neighbouring galaxies. These samples are interesting to study historical events that shaped our Milky Way.

While looking for the remains of smaller galaxies merging with our own Milky Way, a new merger event was discovered: Pontus

The Solar System. Credit: NASA-JPL Caltech Source

Credit: T. Roegiers. Source

# Solar observatory?

Gaia, a solar observatory?

How... Gaia never looks at the Sun!

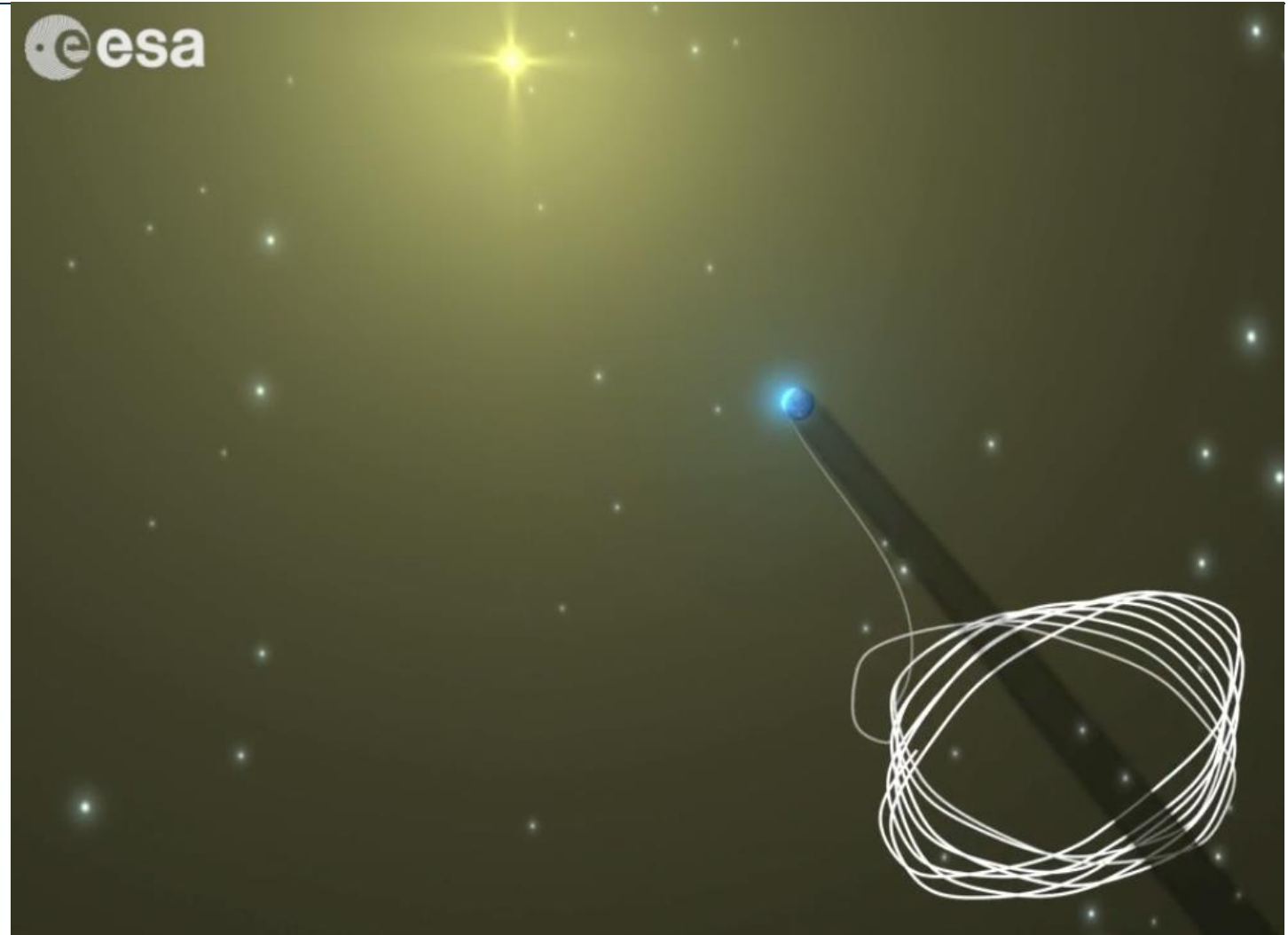
Well... it does “feel” the Sun

It feels tiny temperature drops from sun spots

It detects Solar energetic particles events

References:

- [Story: Solar System fingerprints found in memories of ESA flotilla](#)
- [Story: Gaia spots a sun spot](#)



*Credit: screenshot of video “[Gaia: launch to orbit](#)” / credit: ESA*

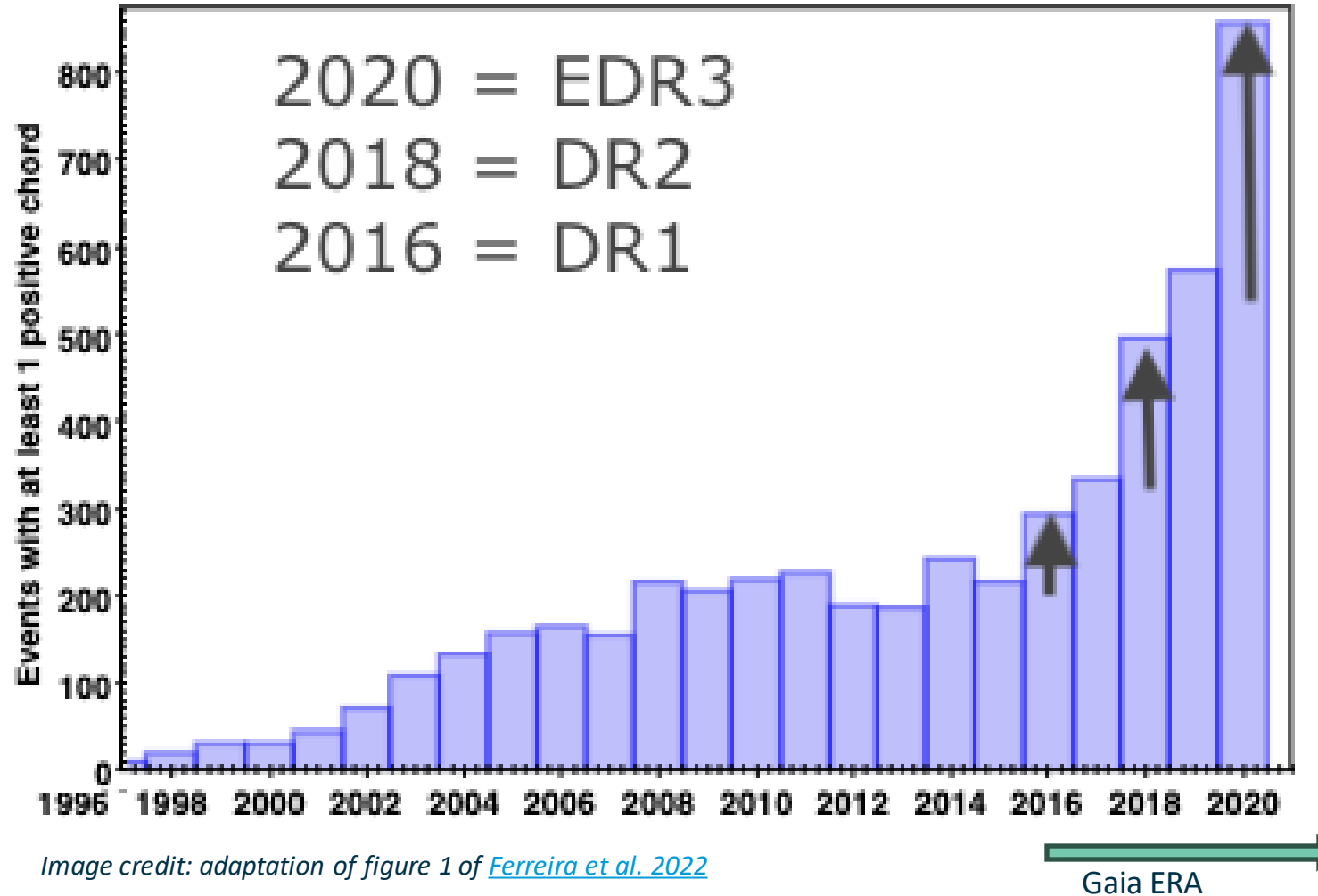


Image credit: adaptation of figure 1 of [Ferreira et al. 2022](#)

On Earth observing stellar occultations has become a lot easier.

Chances of actually capturing the occultation have increased!

What can we learn?

[Shape of asteroids](#) (e.g. Arrokoth)

[Rings of asteroids](#) (e.g. Chariklo)

[Atmosphere of moons](#) (e.g. Triton)

[Yarkovsky acceleration](#) (e.g. Apophis)

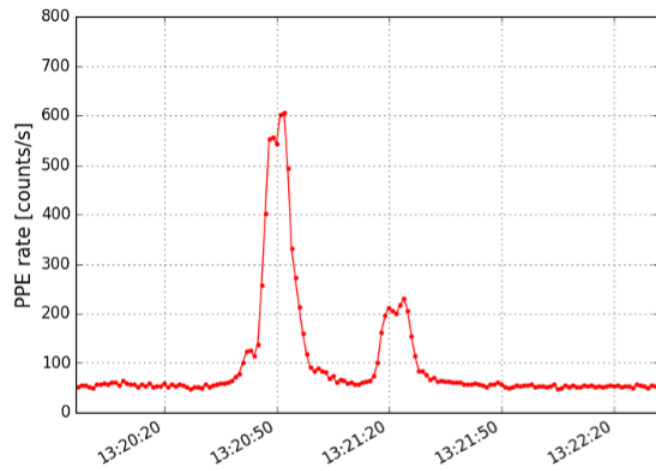
[Capturing NEO](#) (e.g. Didymos)

[Occultation astrometry](#)



# Gaia, the L2 observatory

- Measuring the impacts of micrometeoroids
- Measuring a gamma-ray burst
- [More details](#)



Credit: ESA/Gaia/DPAC, Ed Serpell



Credit: ESA/ATG medialab; background: ESO/S. Brunier



# The Solar System

Directly through Gaia observations

- [Mapping over 150,000 asteroids](#)
- [Follow-up on Gaia asteroid candidates](#)
- [Discovering new asteroids](#)
- [Spin state of 8600 asteroids](#)

Indirectly with Gaia stars

- [Improving asteroid orbits](#)  
(unseen by Gaia)
- Which allows to retrieve lost ones

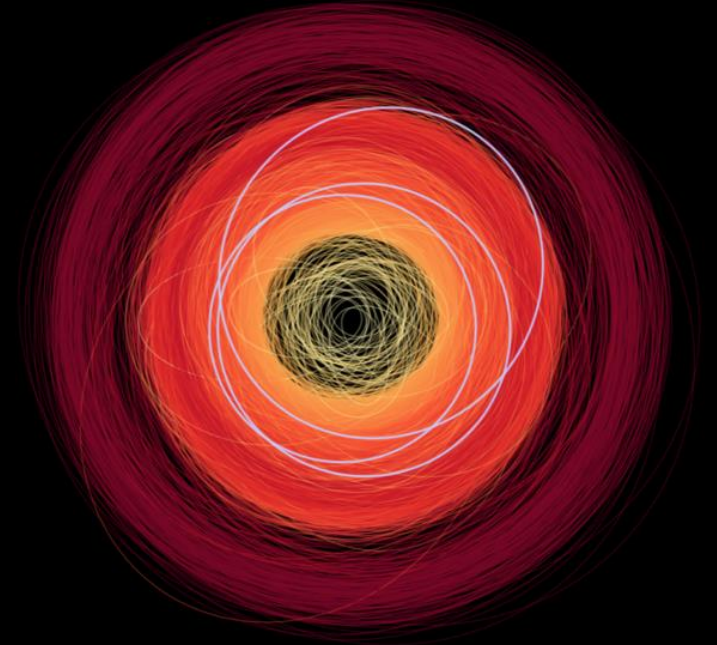
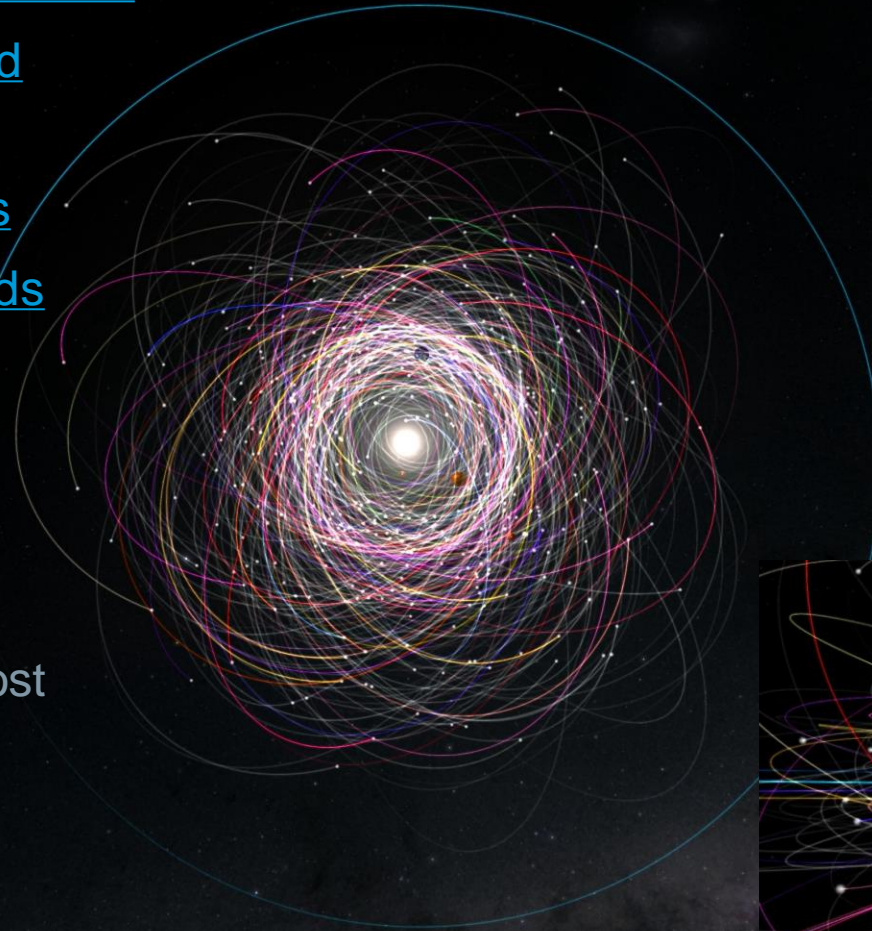
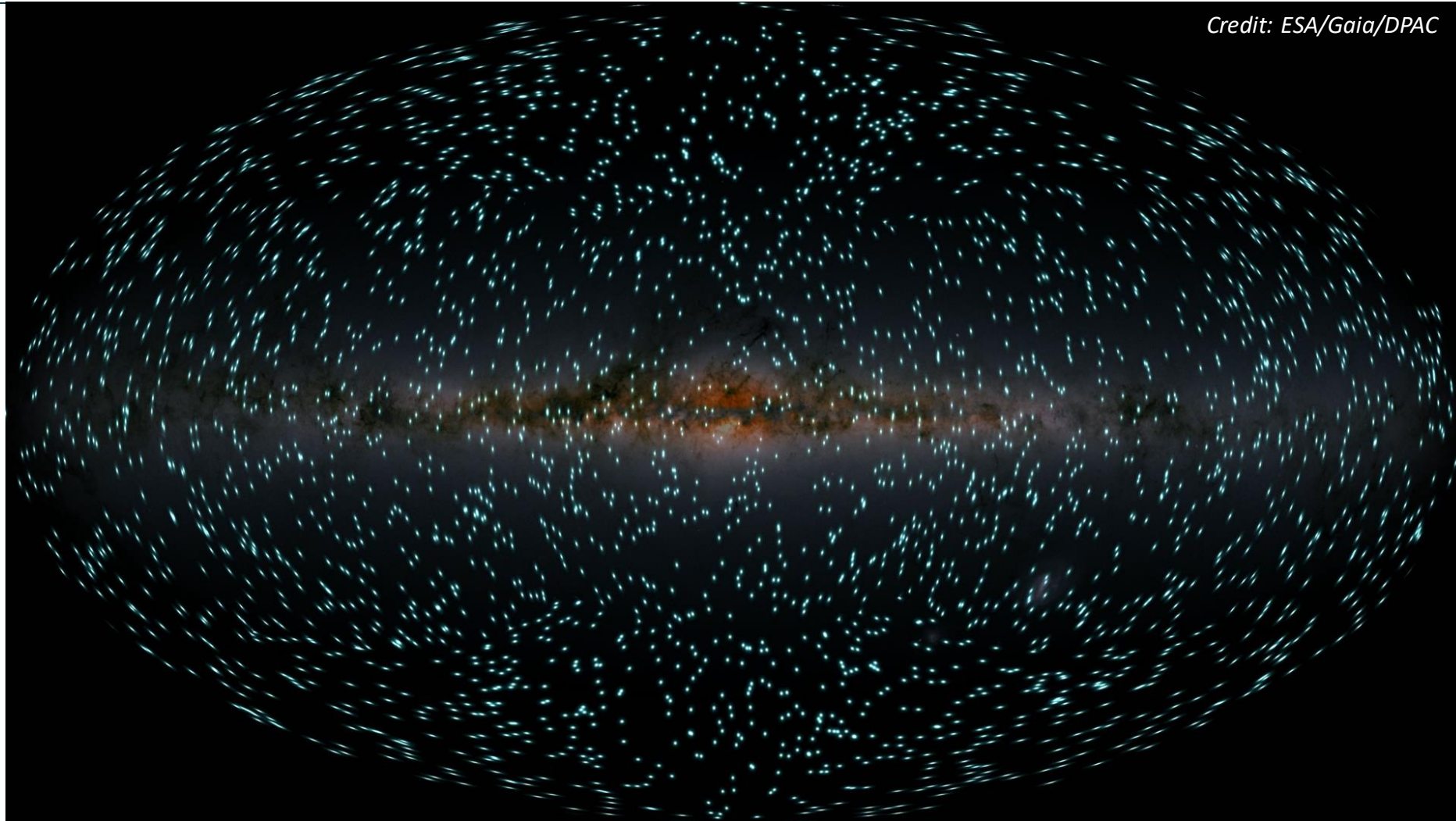


Image credits: ESA/Gaia/DPAC



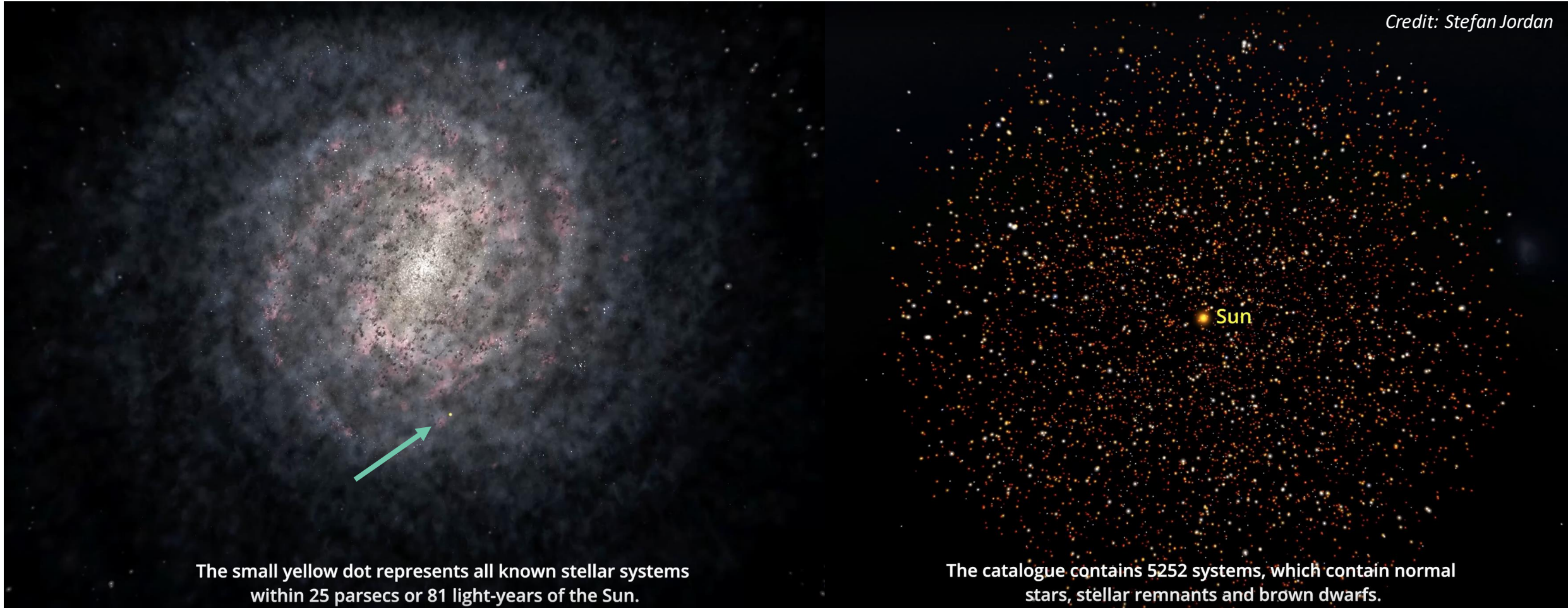
# The Solar System acceleration wrt the distant universe



[Gaia's measurement of the Solar System acceleration with respect to the distant universe](#)

# 10pc / 25pc / 100 pc - catalogues

Credit: Stefan Jordan



The small yellow dot represents all known stellar systems within 25 parsecs or 81 light-years of the Sun.

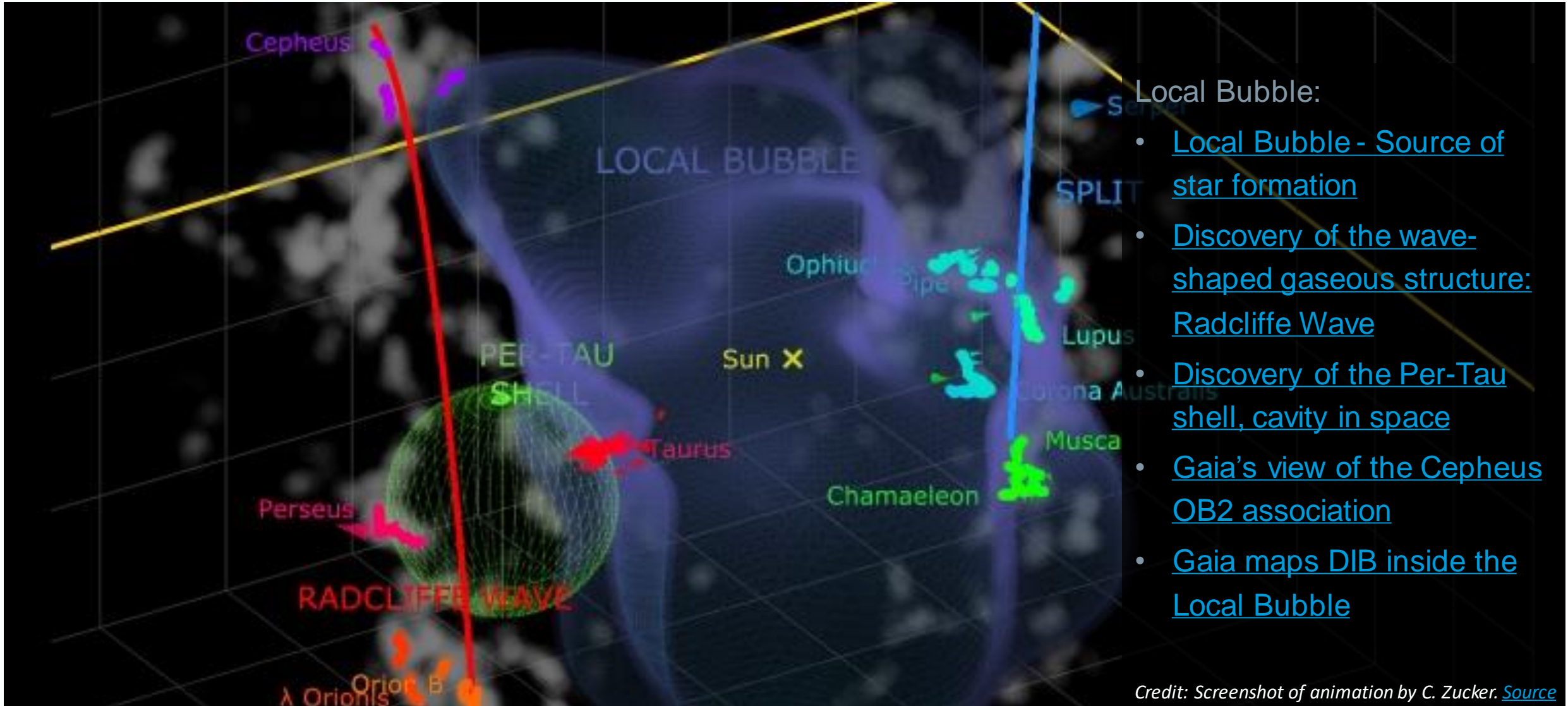
The catalogue contains 5252 systems, which contain normal stars, stellar remnants and brown dwarfs.

Composed of Gaia EDR3 + Hipparcos + ground-based IR parallax surveys (Best / Kirkpatrick)

[Meet your neighbours: CNS5 - the fifth catalogue of nearby stars \(within 25 pc\)](#)



# Local Bubble (stretches 300 pc / 1000 light-years)



- Local Bubble:
- [Local Bubble - Source of star formation](#)
  - [Discovery of the wave-shaped gaseous structure: Radcliffe Wave](#)
  - [Discovery of the Per-Tau shell, cavity in space](#)
  - [Gaia's view of the Cepheus OB2 association](#)
  - [Gaia maps DIB inside the Local Bubble](#)

Credit: Screenshot of animation by C. Zucker. [Source](#)

# Milky Way... structure

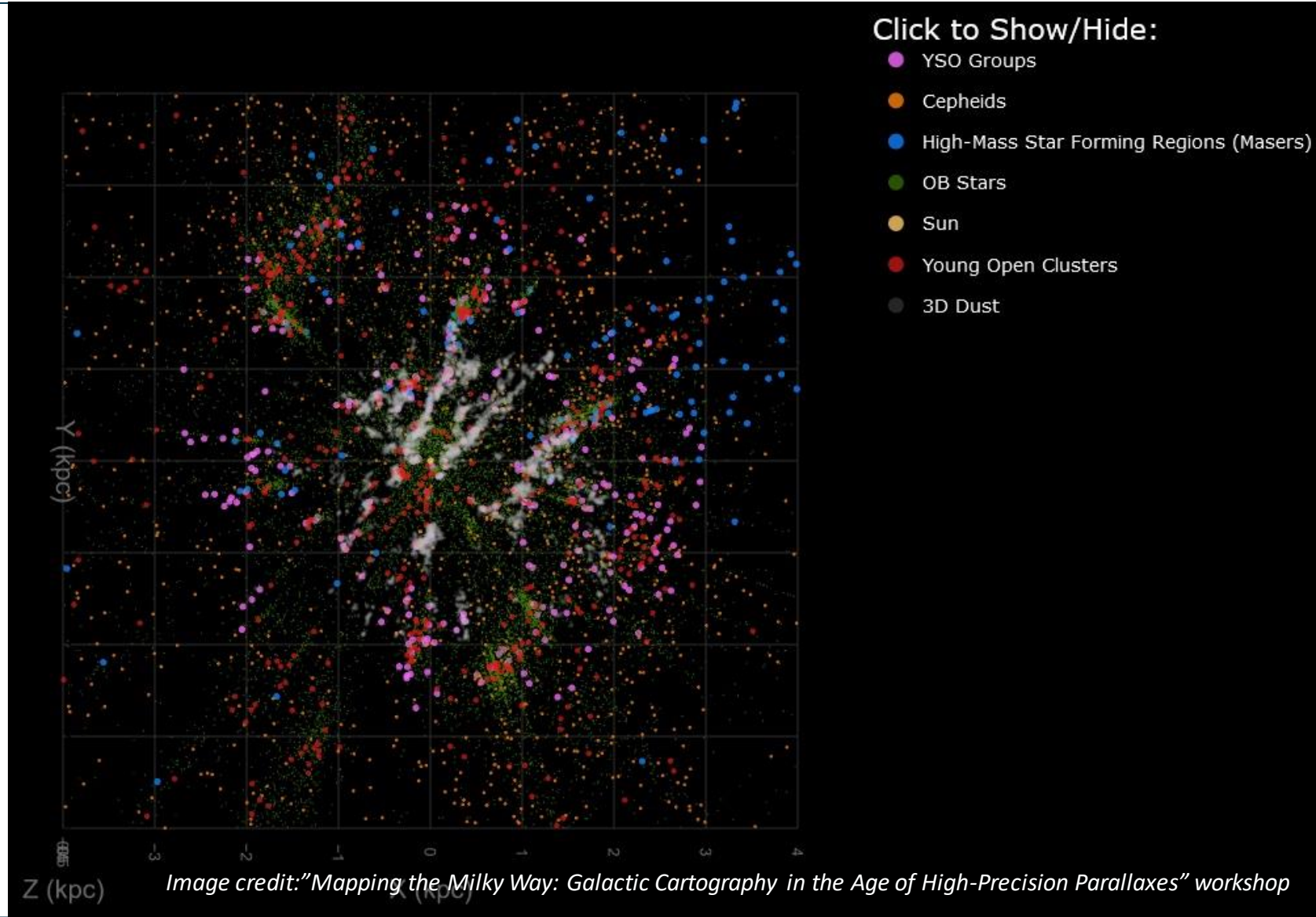
A renaissance in Galactic studies!

[Mapping the Milky Way](#) is one of Gaia's main goals!

An ever-evolving map.

With more data, more structures are seen.

[3D animation](#)





# The Milky Way... face-on



Image credit:ESA/Gaia/DPAC; CC BY-SA 3.0 IGO. Acknowledgements: Background image: Stefan Payne-Wardenaar. [Source](#)

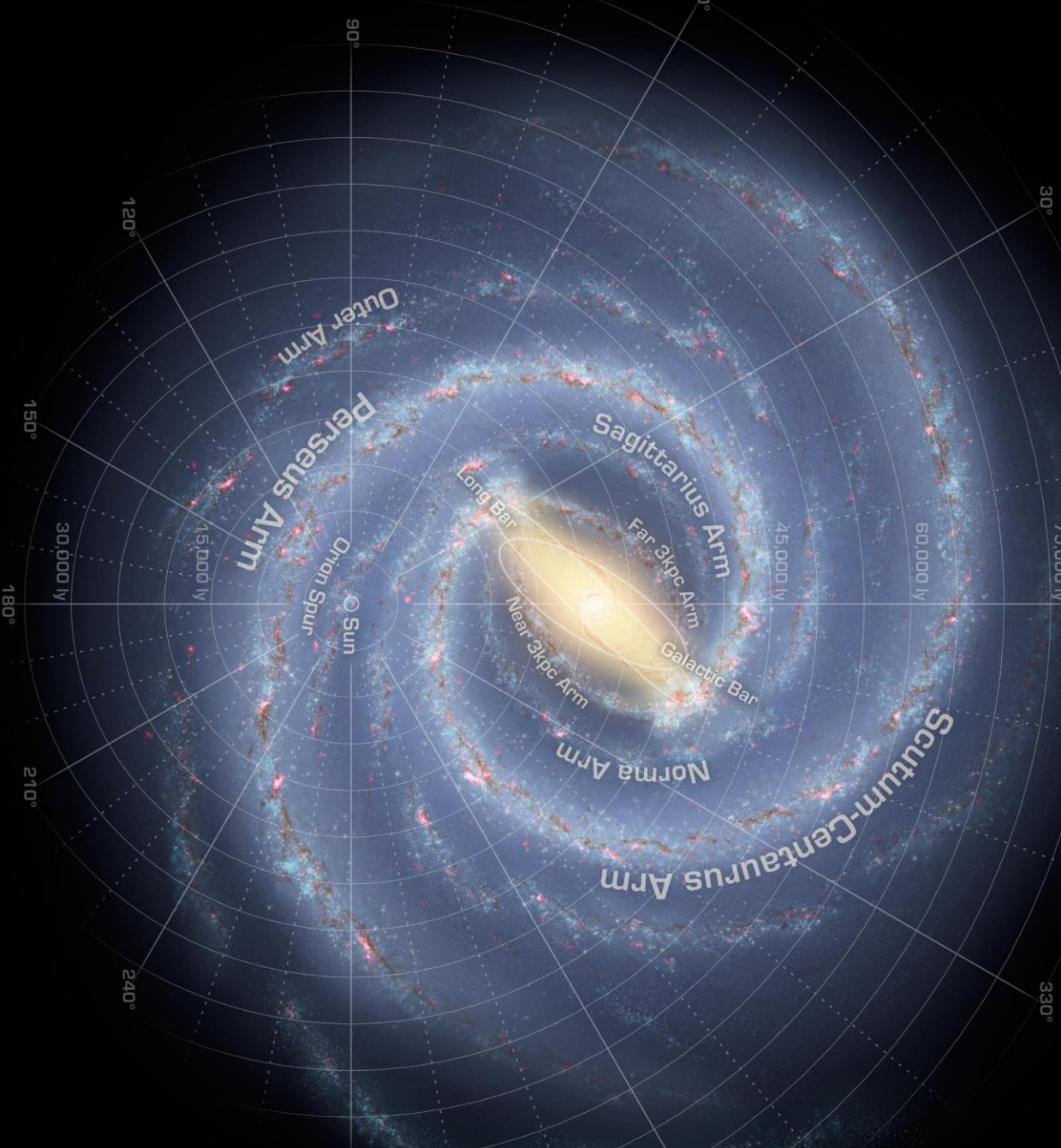
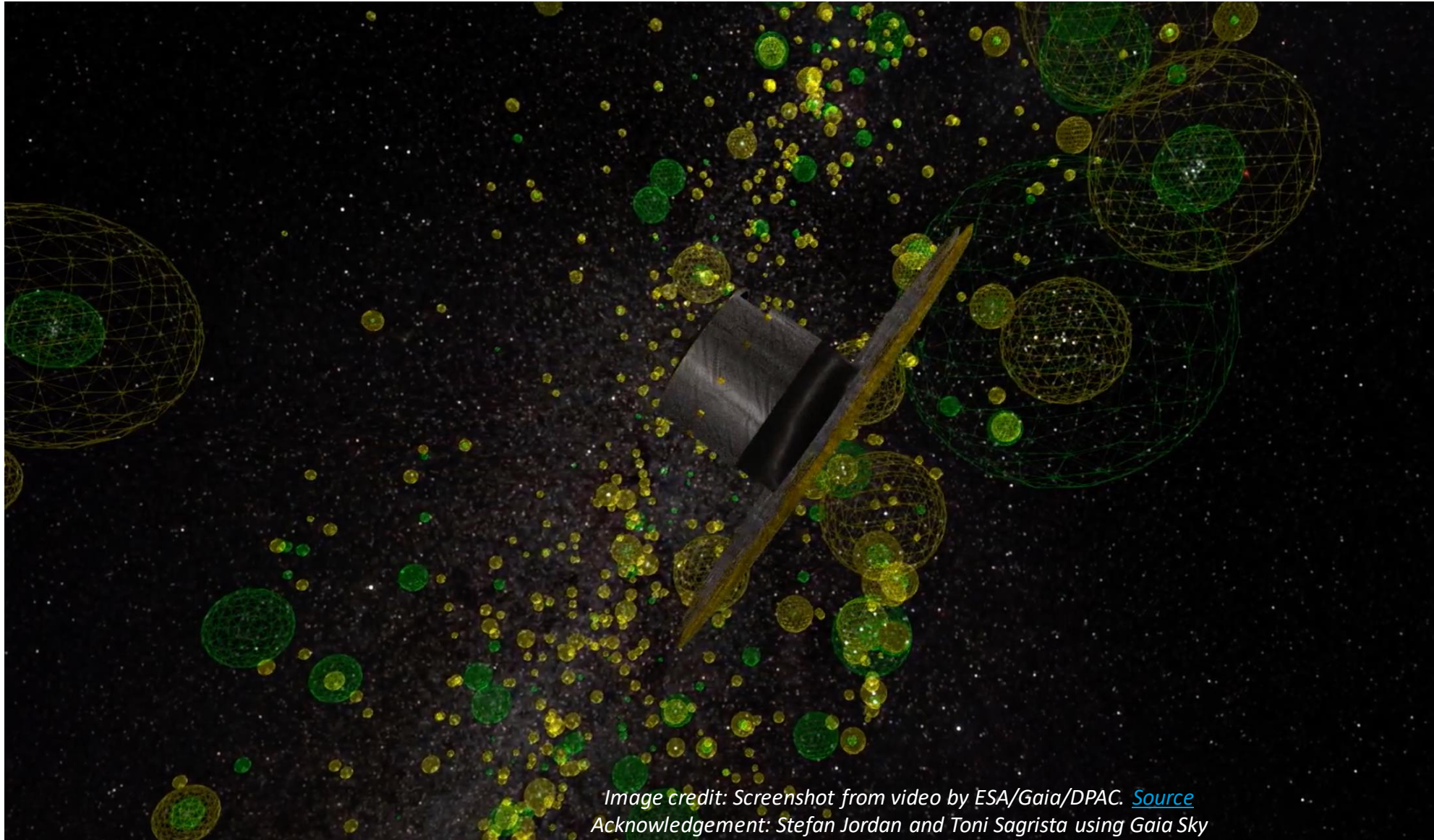


Image credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech) [Source](#)



# Milky Way... open clusters



To be or not to be

New open clusters found with each Gaia data release.

Gaia DR2: [several hundreds](#)

Gaia DR3: several thousands

Paper: [census of open clusters by Hunt & Reffert 2023](#)

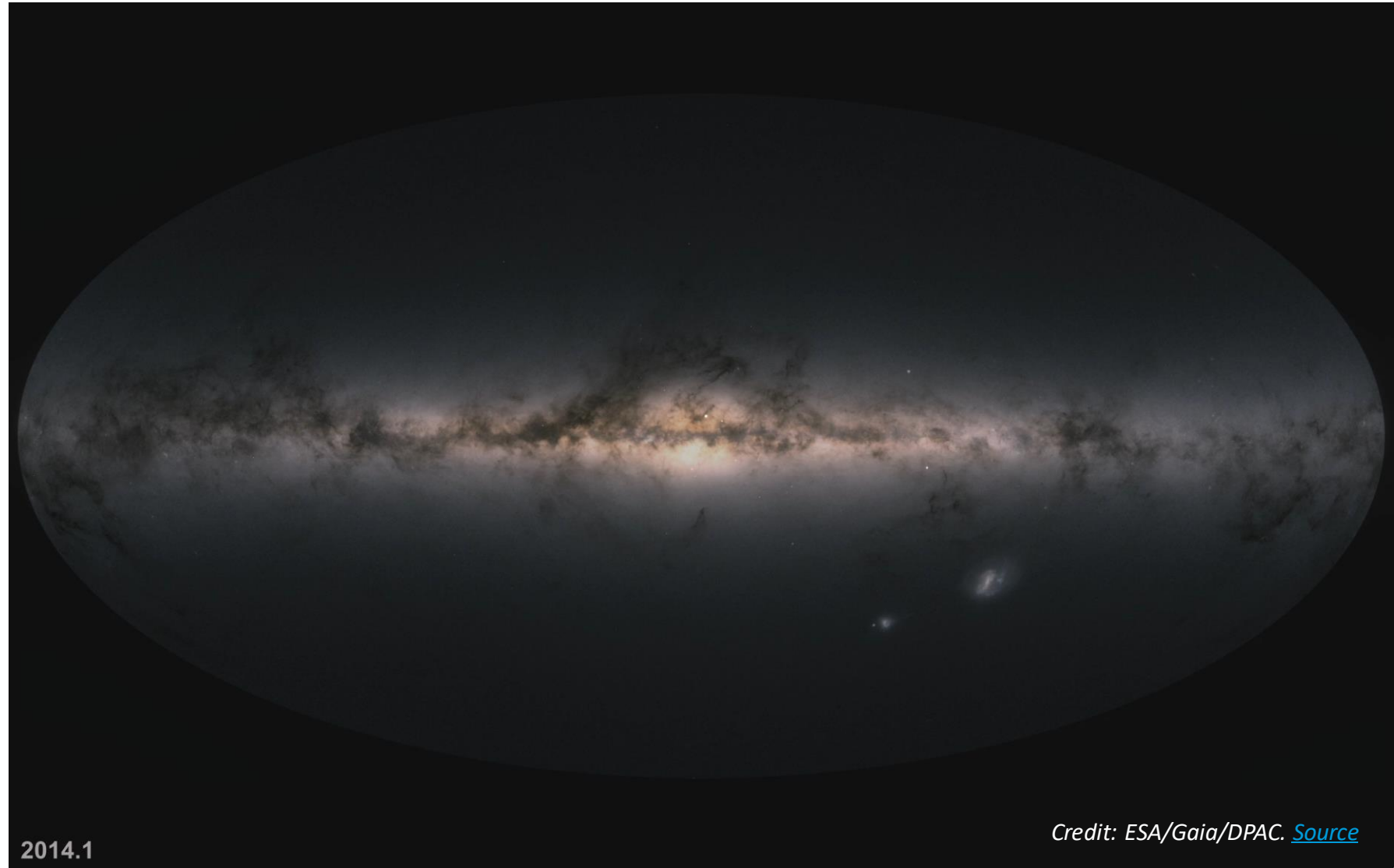




# The peculiar incident of the star in the night sky

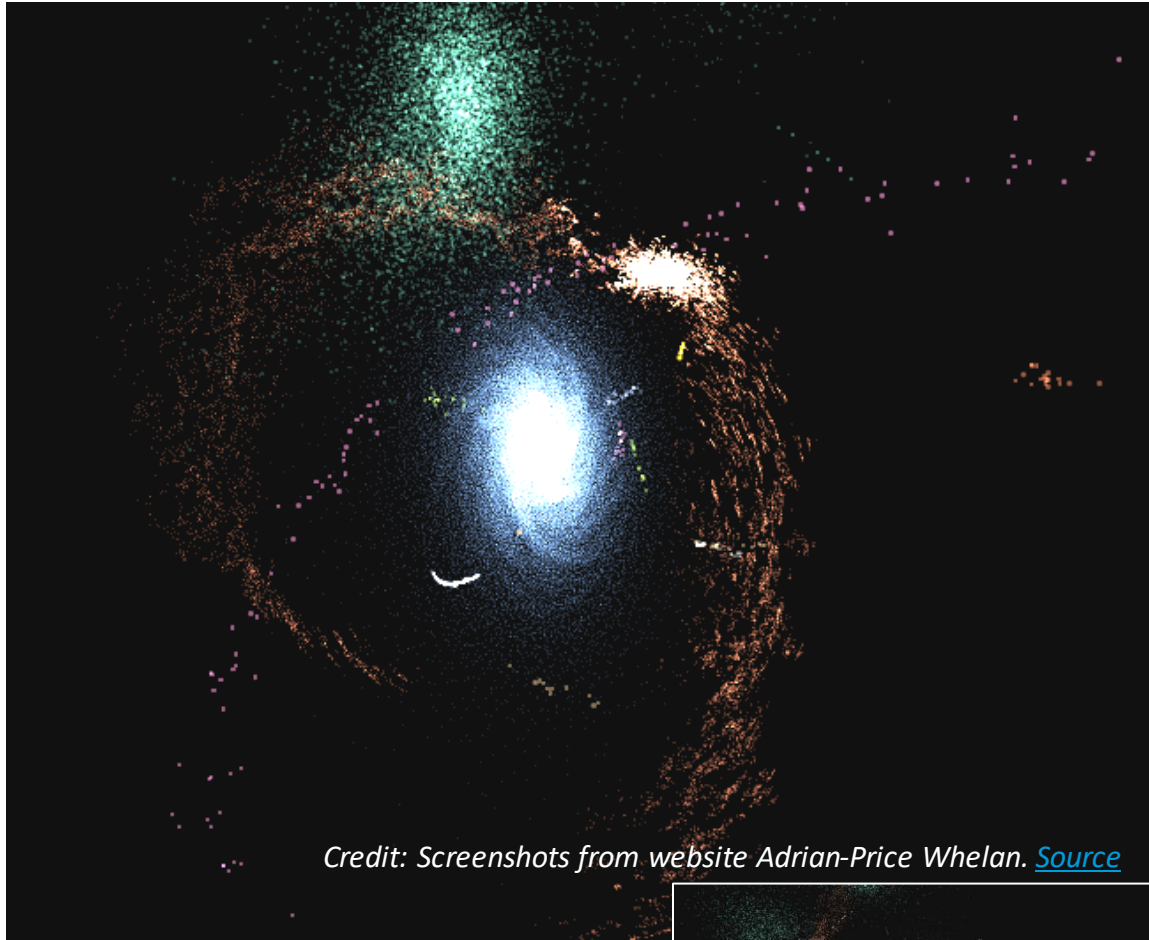
Peculiar incidents in  
the night sky:

- Microlensing events



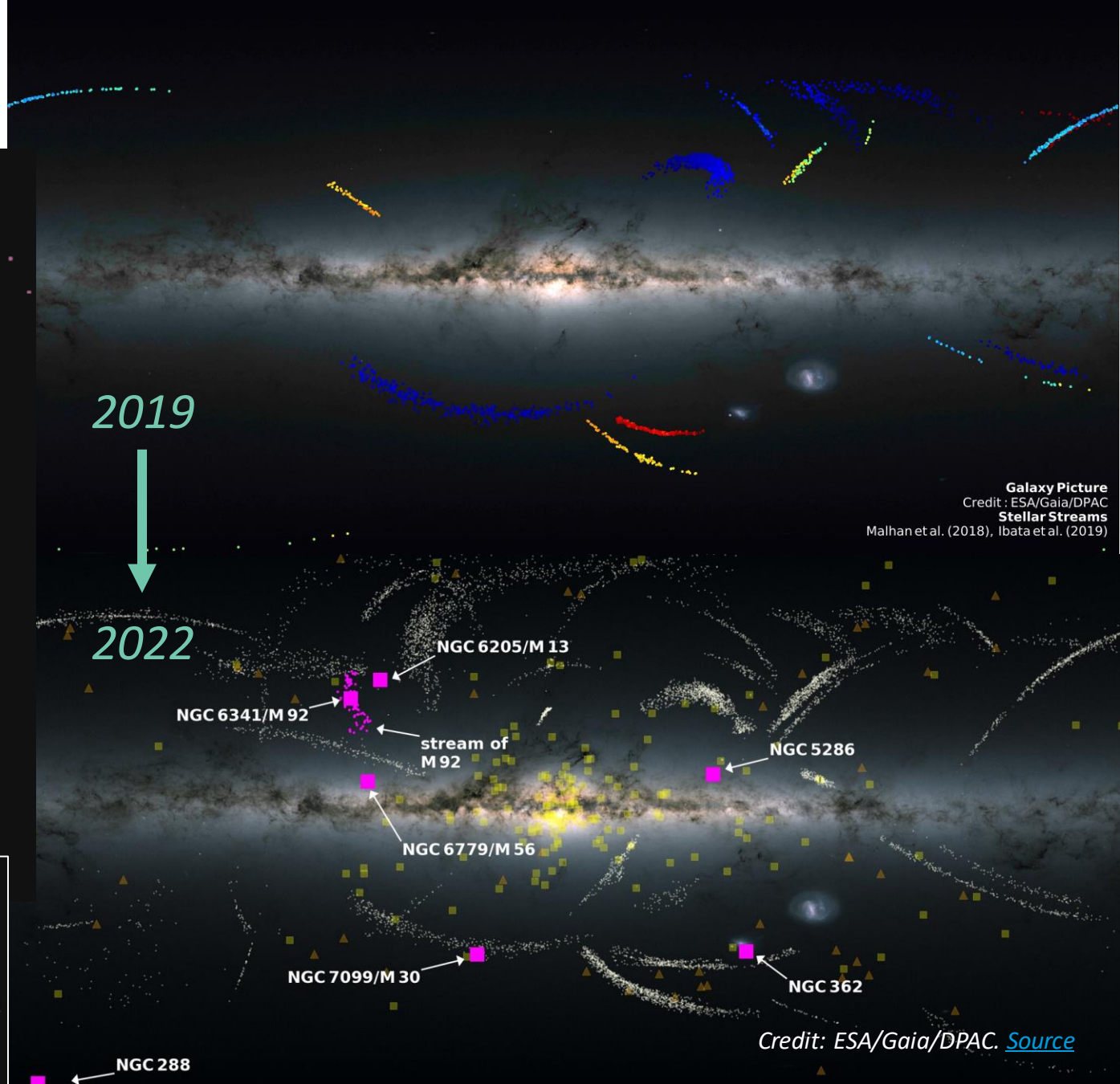
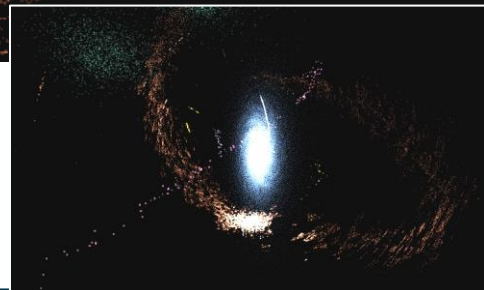


# Milky Way's stellar streams



Credit: Screenshots from website Adrian-Price Whelan. [Source](#)

[Explore in 3D](#)



Galaxy Picture  
Credit: ESA/Gaia/DPAC  
Stellar Streams  
Malhan et al. (2018), Ibata et al. (2019)

Credit: ESA/Gaia/DPAC. [Source](#)



# Globular clusters

Has Gaia found the link in black hole evolution?

Dark mass at the centre of M4

- Could be an ~800 mass black hole
- Could also be a dark population of stellar remnants

[More information](#)



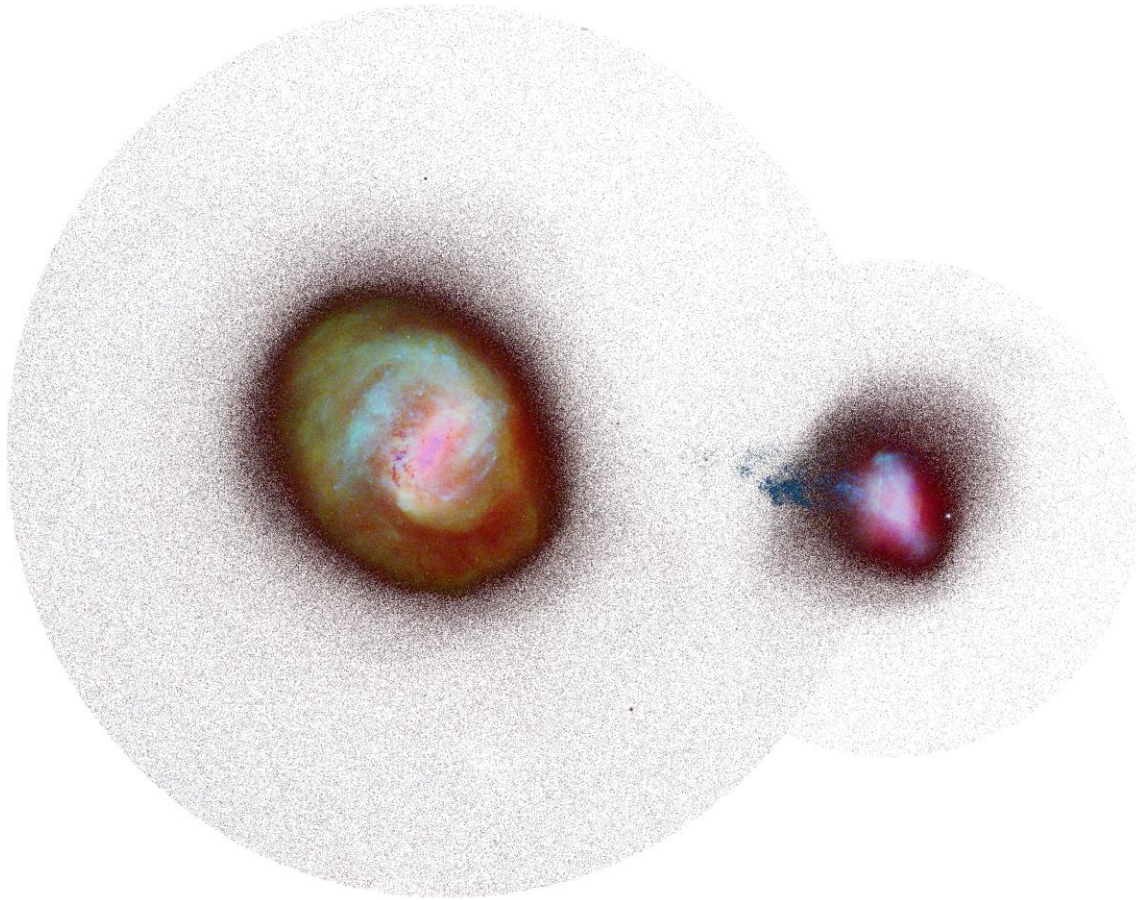


# Large and Small Magellanic Clouds

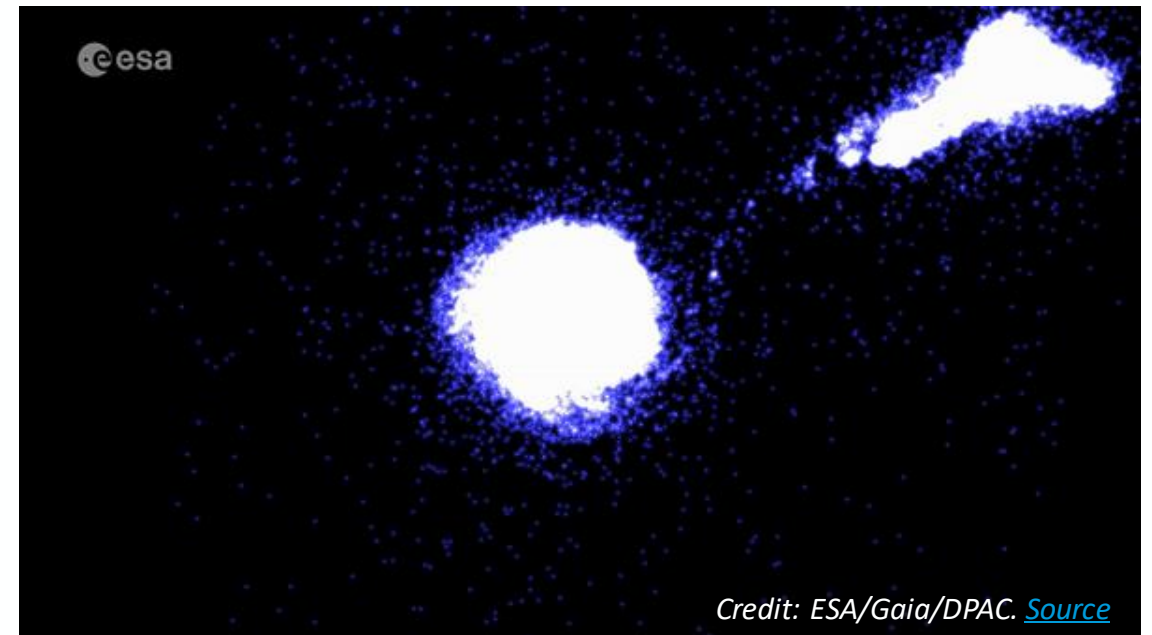
Mapped star by star

Mapped [kinematically](#)

Gaia shows the stars being pulled from the SMC

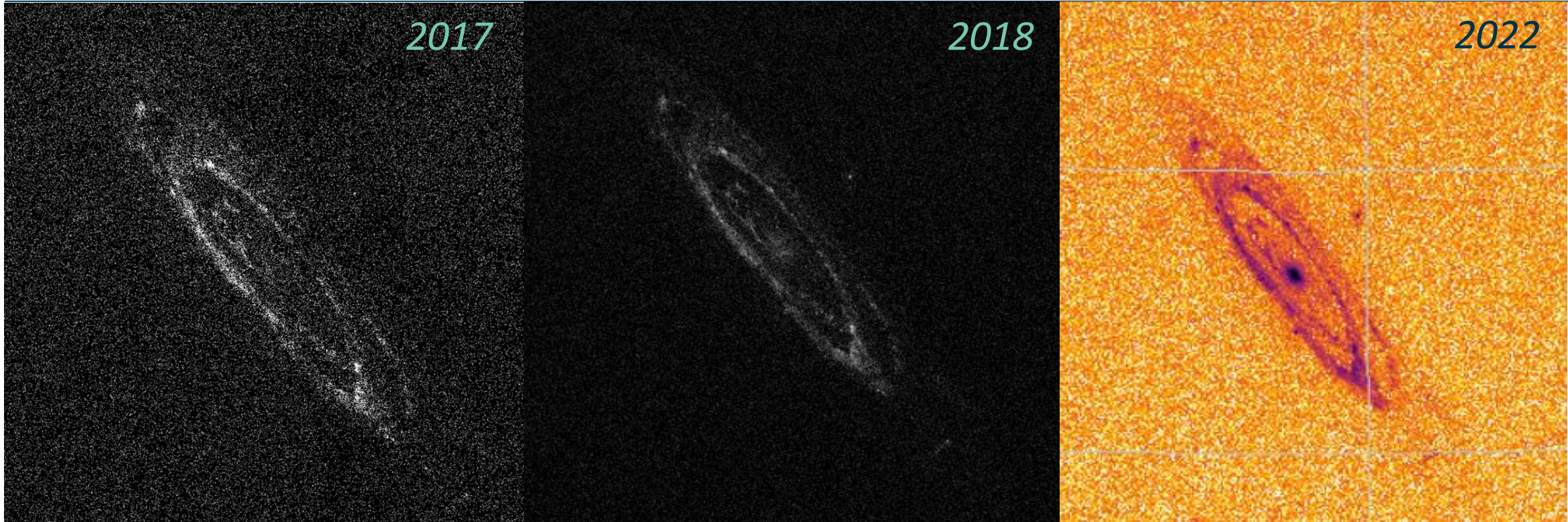


Credit: ESA/Gaia/DPAC. [Source](#)



Credit: ESA/Gaia/DPAC. [Source](#)





*Gaia's view on M31 with Gaia DR1  
Credit: ESA/Gaia/DPAC. [Source](#)*

*Gaia's view on M31 with Gaia DR2  
Credit: ESA/Gaia/DPAC. [Source](#)*

*Gaia's view on M31 with Gaia DR3  
Credit: ESA/Gaia/DPAC. [Source](#)*

Mapping some closeby galaxies star by star

[Mapping millions of galaxies](#) as extended objects



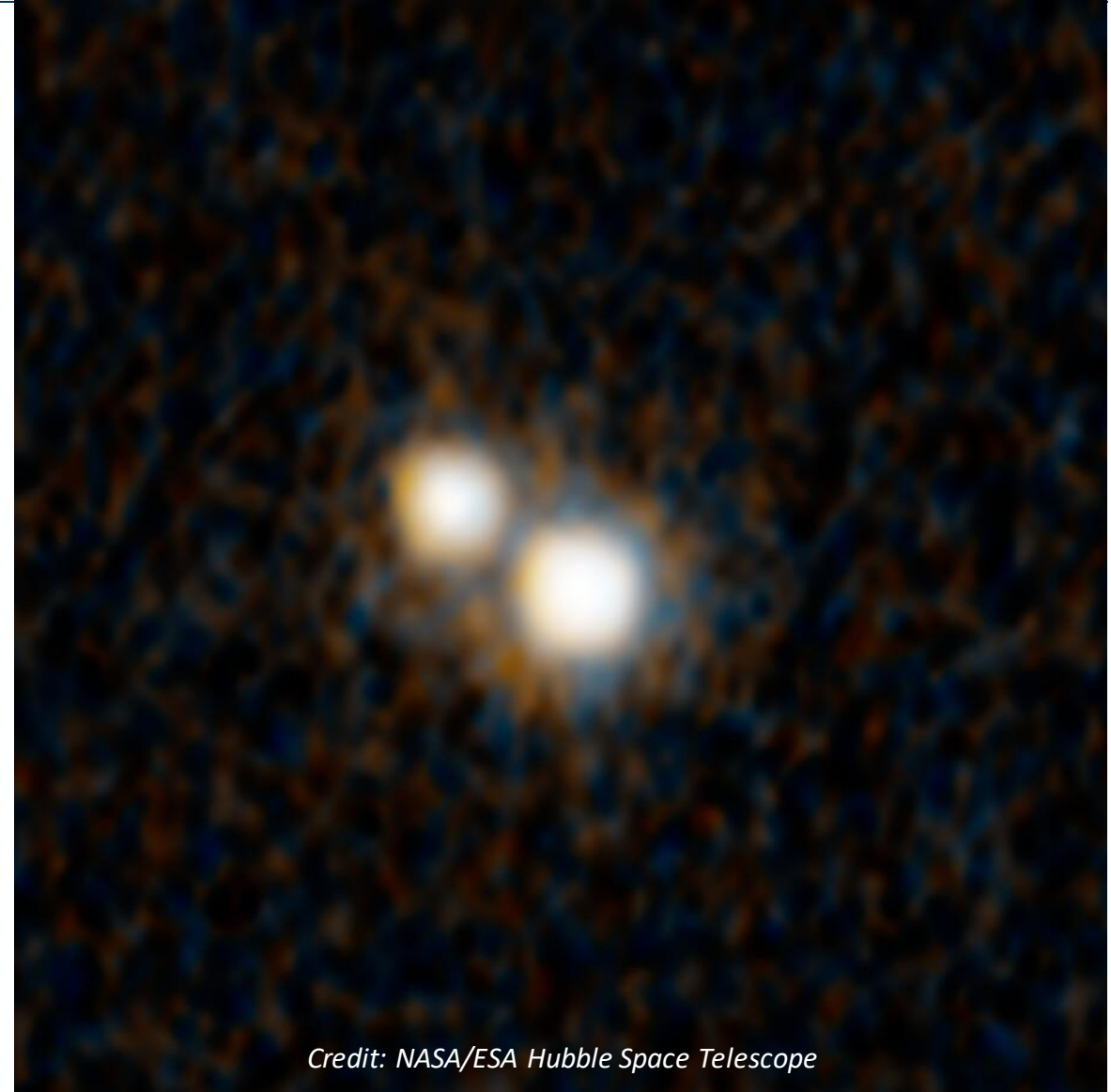
## [Quaia, an all-sky spectroscopic quasar sample](#)

-- With help from Gaia

Looking for [dual quasars](#)?

Then it's important to rule out gravitational lensing.

Coming up in October: [Gaia Focused Product Release](#), with gravitational lens candidates.



*Credit: NASA/ESA Hubble Space Telescope*



# The Universe... expansion



*Credit: ESA/ATG mediolab; background: ESO/S. Brunier*

A [0.9% calibration of the Galactic Cepheid Luminosity scale based on Gaia DR3 data of open clusters and Cepheids](#).

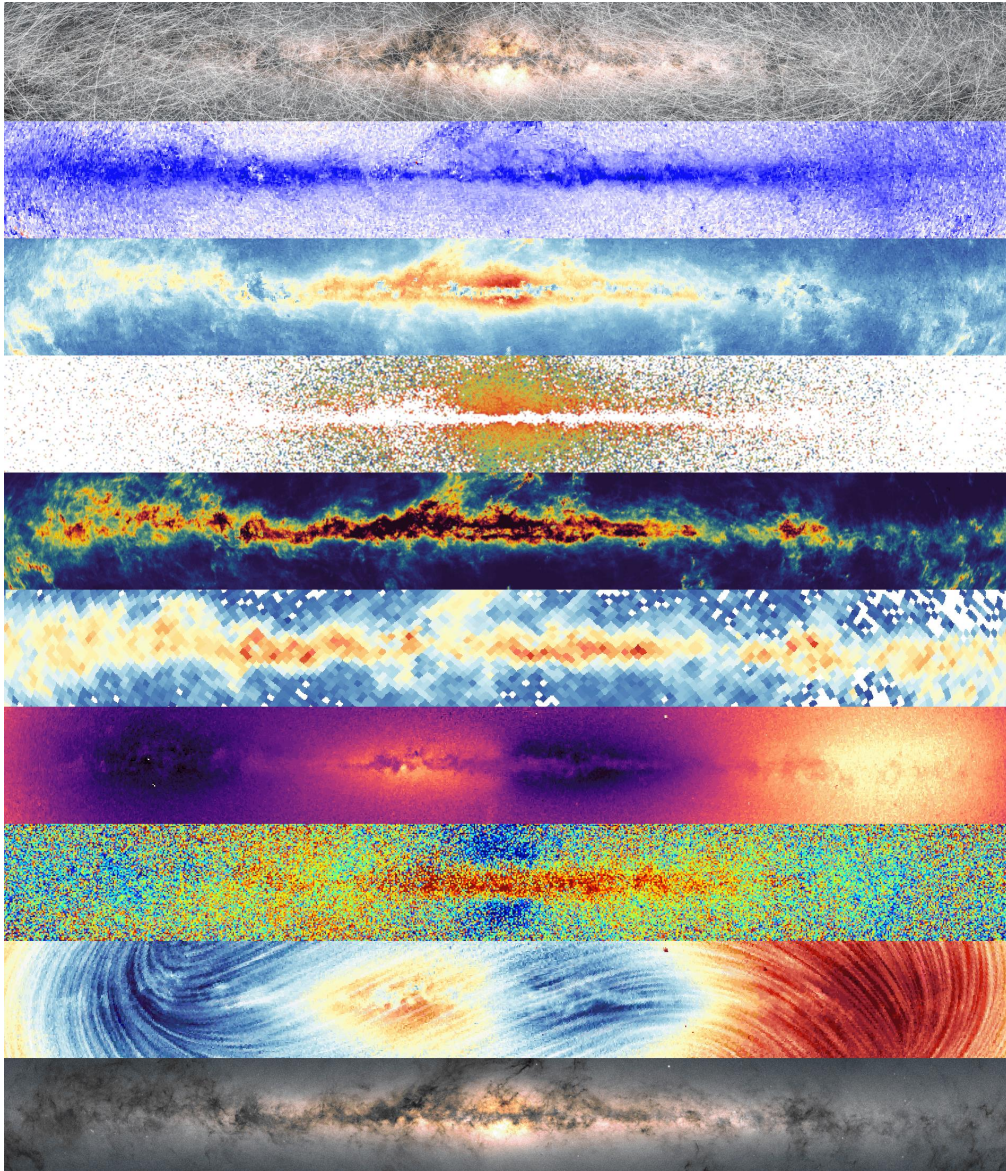
Using:

- Gaia's latest catalogue of Cepheids
- Open clusters

Confirms the 73 km/s/Mpc expansion rate



# Capturing the diversity



Proper motions on the sky

Stellar ages

Difference of G and G\_RVS brightnesses

Metallicity of Cepheids

Dust / Extinction

Interstellar medium

Line-of-sight velocities

Metallicities

3D motion of stars

The Milky Way in colour

Image credit: ESA/Gaia/DPAC. [Source](#) 21



# Maybe not a billion... but a lot for sure!

## The billion ways of using the Gaia data

Tineke Roegiers <sup>1</sup>

### Solar System

Though Solar System science is not the primary goal for Gaia, a lot is achieved on this front since Gaia started releasing its data. When scanning, Gaia captures any object it scans across and thus observes many asteroids next to stars and galaxies.

Apart from Gaia's own data on Solar System objects, there are many indirect ways in which Gaia data influences our knowledge of the Solar System. The below list of topics can not be complete and

### Stars

The large, homogeneous all-sky Gaia catalogue of stars is a treasure chest for new discoveries, and brings substantial samples of special stars for detailed investigation. A taste of studies, discoveries and opportunities where Gaia helps out is given below. This is only a tiny selection of the many topics touched by the scientific community related to stars.

### 25pc sample

Early 2023 brought an update to the catalogue of nearby stars: CNS5. Within a sphere with 25pc radius around the Sun a total of 5931 objects are known now. This catalogue strives for completeness and was updated with the star information from Gaia's Early Data Release 3. The CNS5 is a great sample to study the Milky Way. This catalogue can be used to test a variety of theories and improve models of the Galactic Disk.

### Milky Way

Mapping the Milky Way is the core goal of Gaia and so it does, in full detail, in many dimensions. Stars and structures in the Milky Way are mapped, as well as dust and interstellar matter in between the stars. Gaia also maps the astrophysical information such as stellar ages, metallicity, and more. This variety of Milky Way mapping is highlighted in Gaia's [Multi-dimensional Milky Way](#), based on 10 Gaia sky maps. Full details explaining the

### Galaxies

Next to stars, asteroids, moons, comets, spacecraft, quasars, ... Gaia also observes galaxies. If observed as a whole, they show up as extended objects. First results from the processing of these extended objects were published with Gaia Data Release 3, leading to 4.8 million galaxy candidates (20% of which have redshift estimates). Gaia also observes individual stars inside galaxies, if these galaxies are close enough. This is the case for the Andromeda

### Earth orbit and L2

Some spacecraft orbiting Earth or located at L2 are powerful in studying a specific target with great detail. To make most efficient use of these telescopes, pointing them to the most promising sources is important. This is where Gaia helps out. Gaia, being an all-sky homogeneous survey, brings the perfect catalogue to make a first selection of interesting candidates for follow-up. In this way we can capture the best stars to follow the needles to

### Earth

On Earth, life has improved for astronomers following up on stellar occultations. With the star positions and motions of Gaia's first data release came improved predictions of the stellar occultation shadow paths on Earth. These shadow paths and their timing predictions are used to deploy the ground observations of these events. With each Gaia data release, the predictions improved and the chances of observing a stellar occultation increased! Through stellar

### Star groups

Some stars belong together. They travel together through space bound by a mutual gravitational attraction. In June 2022 Gaia published a catalogue of multi-star systems, containing stars with few companions. Gaia's full catalogue of over 1.8 billion stars is also heavily used to discover and improve our knowledge of stellar clusters, star groups composed of many stars.

### 100pc sample

As part of Gaia's Early Data Release 3, the Gaia Catalogue of Nearby Stars (GCNS) was published. With this catalogue, a unique census of stars within 100 pc of our Sun became available. At this distance, the coolest stars become too faint for Gaia's survey limit. Choosing 100pc hence allows to get a complete census of Gaia stars, including the coolest ones. Such a complete and homogeneous sample is important for studies of the Galaxy.

### Milky Way Halo

Following Gaia's first data release, an extended study was performed revealing rich structures of the nearby stellar halo. More studies followed soon, when more and better data became available with each Gaia data release. Below a small selection is given to demonstrate Gaia's impact on our knowledge of the Milky Way halo.

Stories published on this topic:

### Quasars

Gaia also observes distant quasars, many of them billions of lightyears away from the Sun and the Milky Way. The Gaia catalogue contains 1,614,173 quasars used to construct the Gaia Celestial Reference Frame. With the high quality of Gaia EDR3, Gaia was for the first time capable of observing the tiny effect of the acceleration of the solar system with respect to the distant universe. This effect was deduced from the aberration of light seen in these

### Sun

Though Gaia never looks at the Sun with its telescopes, it is capable of observing the Sun nonetheless. Close watch is kept on all temperature changes affecting the Gaia spacecraft as they have the potential of influencing the observations captured. The small drop in Solar irradiance caused by the transit of a cooler sun spot can be measured with Gaia's temperature monitors.

### Cavities in space

There is something to be learned from the absence of stars as well. A gigantic cavity in space was found by combining Gaia's 3D information with powerful new data science techniques in order to map molecular clouds in 3D gas density space. This led to the discovery of a gigantic cavity in space.

Stories published on this topic:

- The power of the third dimension - the

### Local Bubble

Local Bubble has a radius of about 500 lightyears or 150pc. The Sun happens to be travelling through this bubble on its journey through the Milky Way. While known for decades, only with help from Gaia's Early Data Release 3 we finally understood its origin and the impact it has on the gas around it. It turns out that the Local Bubble is a source of our nearby stars.

Since Gaia's data release 3 we also learned that though the Local Bubble is absent in the

### MW satellites

When Gaia maps the stars, it continues to do so beyond the edge of the Milky Way. As long as the sources are bright enough, they are observed. The Gaia catalogues thus includes samples of stars from the Milky Way satellites and neighbouring galaxies. These samples are interesting to study historical events that shaped our Milky Way.

While looking for the remains of smaller galaxies merging with our own Milky Way, a new merger event was discovered: Pontus

Credit: T. Roegiers. [Source](#).

