

# Gaia



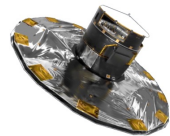
**Contents**

Why map the stars in the Milky Way?

How can they be mapped accurately?

What type of data can be acquired?

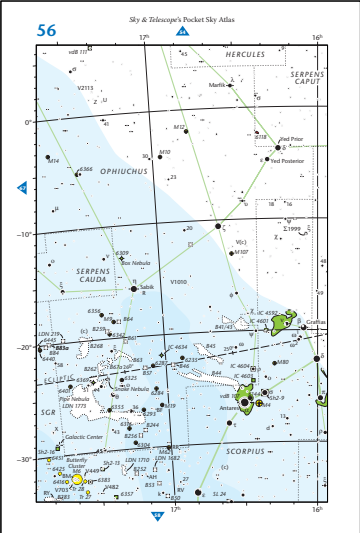
What can we learn from the data?



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**Mapping the Stars**



It's a simple question ...

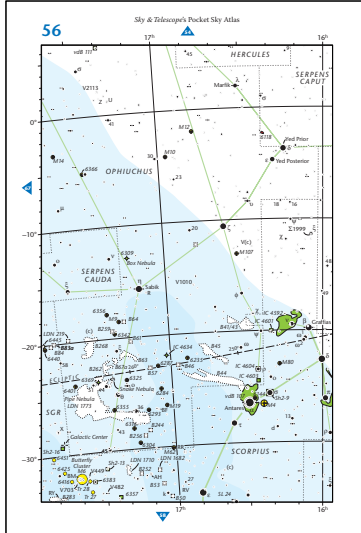
*Where are the stars?*

We want to be able to determine the position (on the sky) of any celestial object so that we can ...

- ... find it again at a later time
- ... tell if it has moved
- ... tell if any new objects appear

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**Mapping the Stars**



It's a simple question ...

*Where are the stars?*

Also, if we can determine the positions of stars in our galaxy with high precision, then we can gain a better understanding of the structure and the history of the Milky Way.

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# Gaia

## Mapping the Stars

So how do we map the sky? Can we just take lots of photos of the night sky and stitch them together?

That approach seems to work fine for mapping the surface of the Earth from space, so what's the problem?

### Problem #1 – Stars move

( nothing in the galaxy is static )

## Mapping the Stars

### Problem #2 – Stars are at different distances

Knowing the positions of stars on the 2-dimensional sky is not enough to determine how they are arranged in 3-dimensions.



We also need to know their distances.

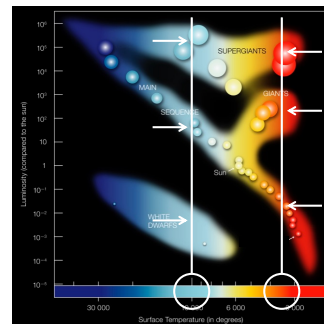
## Mapping the Stars

Being able to determine the distances to stars is important not only for understanding the structure of the Milky Way ...

... but also for understanding the stars themselves.

Without knowing the distance to a star we cannot determine its luminosity or its type.

Without its type, we cannot determine the properties of any of its exoplanets.

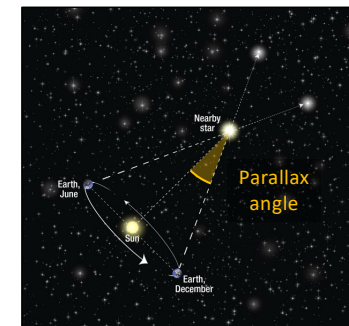


## Parallax

Parallax is the apparent change in the position of a celestial object due to the motion of the Earth around the Sun.

Diagrams like this always imply that a (nearby) star can be aligned with more distant (fixed) stars to determine the parallax angle.

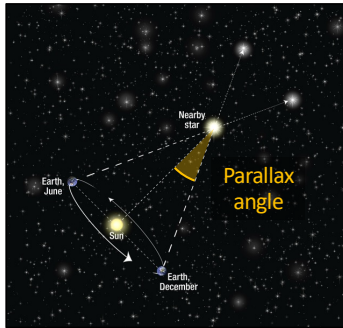
However, in practice, *all* stars appear to move as the Earth orbits the Sun.



# Gaia

## Parallax

Parallax is the apparent change in the position of a celestial object due to the motion of the Earth around the Sun.



A star  $\sim 3$  ly distant would show a parallax angle of  $\sim 1$  arc second.

This distance is defined as one "parallax second".

1 parsec = 3.26 light-years

## Measuring Parallax

So here is the crux of the problem.

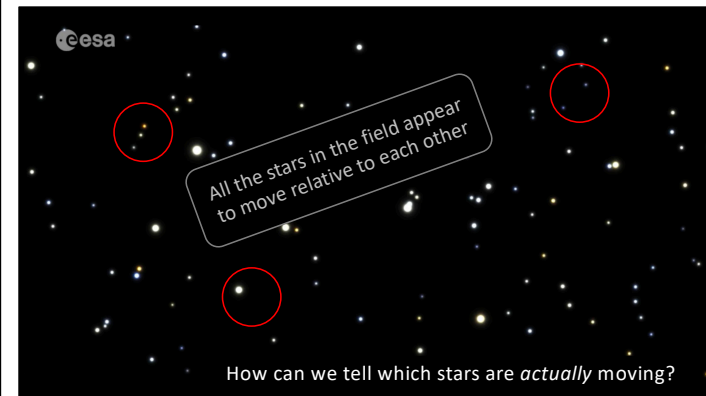
- To calculate distances we need parallax
- Parallax needs the stars' *actual* positions in the sky (not simply their position *relative* to other stars)
- The stars themselves are moving (proper motion)

This is why mapping the stars in the Milky Way is not a trivial task.

How can they be mapped accurately?



## Mapping the Stars




# Gaia

## Measuring Parallax

To untangle the apparent motion of a star due to parallax from its proper motion as it moves within the Milky Way we need

- High precision measurements <<< **parallax angles are very small**
- A fixed coordinate system <<< **Earth *and* stars are in motion**

[ Aside – There were plans in the 1980s to make the parallax angles larger (and so easier to measure) by increasing the baseline from 1AU to 1000AU. Flying a spacecraft with an ion drive that far out into the solar system would take 50 years. For a sense of scale, the Voyager spacecraft are currently ~ 150AU from Earth. ]

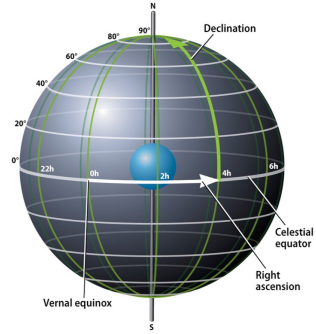


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## Coordinate Systems


What coordinate system should we use to map the stars?

The equatorial coordinate system, comprising Right Ascension (RA) and Declination (Dec) coordinates, uses the celestial equator as a reference.



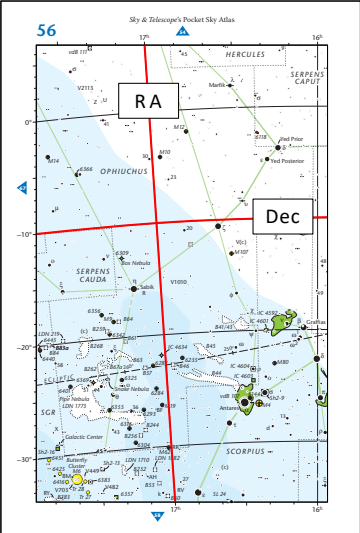
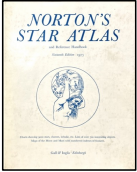
RA and Dec have been used in star atlases since the days of the first Astronomer Royal.

Why are they not good enough?

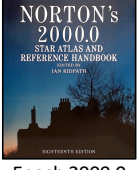


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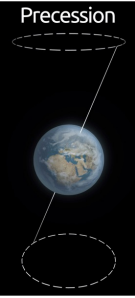
## Coordinate Systems

Epoch 1950.0



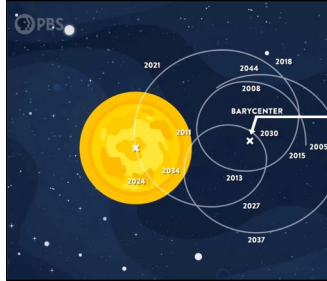
Epoch 2000.0



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## Coordinates Relative to the Sun

So if an Earth-based coordinate system is not suitable, what about using the Sun as a reference? That would also lead to small errors because the Sun orbits around the solar system's centre of mass.



We think of planets orbiting the Sun, but actually they all orbit around a common **barycentre**

Hence the best coordinate system uses this barycentre as a fixed reference point.

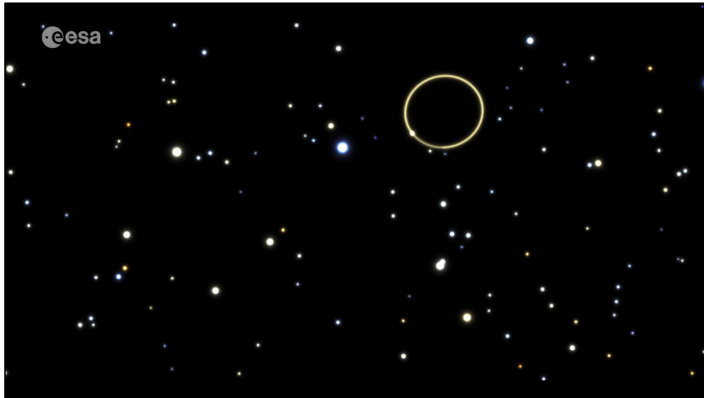


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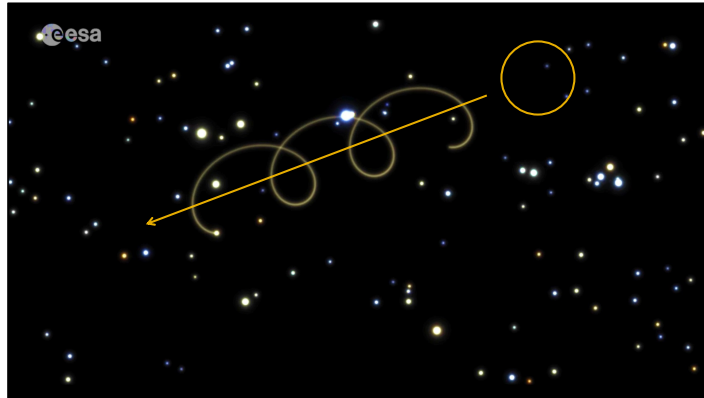
**Parallax Only**



The image shows a field of stars against a black background. A single star is circled in yellow, illustrating the concept of parallax measurement.

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**Parallax and Proper Motion**



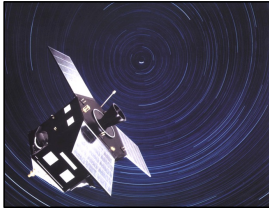
The image shows a field of stars. A star is circled in yellow, and a yellow arrow points from it towards the left, indicating its proper motion. The path of the star is shown as a series of overlapping yellow circles, illustrating the combination of parallax and proper motion.

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**Hipparcos**

**High Precision PARallax COLlecting Satellite** 1989–1993

Hipparcos was the first space telescope dedicated to high-precision measurements of star positions. Its name was also a homage to the Greek astronomer Hipparchus, the founder of trigonometry.



Hipparcos catalogued 100,000 stars with a precision of  $\sim 0.001$  arcsec.  
(  $0.001$  arcsec = milli arcsec = mas )

Faintest stars = mag 12

The Hipparcos catalogue was used by the Hubble Space Telescope.

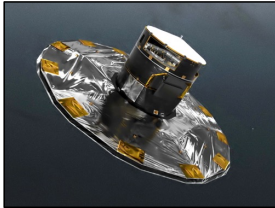
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**Gaia**

**Global Astrometric Interferometer for Astrophysics** 2013–2025

( Note that the acronym is no longer relevant as its design changed )

Gaia's mission was to improve on Hipparcos by mapping a billion stars with a precision of  $\sim 10 \mu\text{as}$ .  
(  $1 \mu\text{as} = 0.001$  mas )



Higher precision meant that stars at greater distances could have their parallax measured, and so Gaia could 'reach' further into the Milky Way.

Faintest stars = mag 20

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# Gaia


### Micro Arc Seconds

An analogy for Gaia's ability to measure tiny angles precisely ...

$10 \mu\text{as} = 0.01 \text{ mas} = 0.00001 \text{ arc seconds}$


= the thickness of a human hair  
seen from a distance of 1000 km



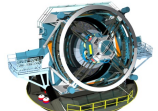
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### Alternatives?

Why build a new telescope to achieve this? Why not use ...




Hubble  
Space Telescope



Simonyi (aka LSST)  
in Vera Rubin Obs

Precision	< 1 mas	100 mas
# stars	1000	> billion
Time to do all-sky survey	> 1000 y	10 y



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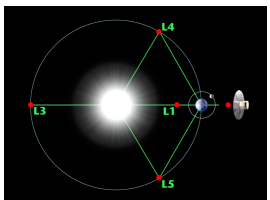
## How does Gaia achieve this?





### Gaia Hardware







Gaia was ... constructed 2006–2012

... launched in Dec 2013

... placed into a halo orbit  
around L2 in Jan 2014

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# Gaia

### Why Park at L2?

At L2 a sunshield can block light from the Sun, Earth and Moon

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### Sunshield Deployment

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### Gaia Hardware

Gaia was ... constructed 2006–2012

... launched in Dec 2013

... placed into a halo orbit around L2 in Jan 2014

How was Gaia's micro arcsec ( $\mu\text{s}$ ) precision achieved?

Would it need a big mirror, a few km in diameter? Obviously not.

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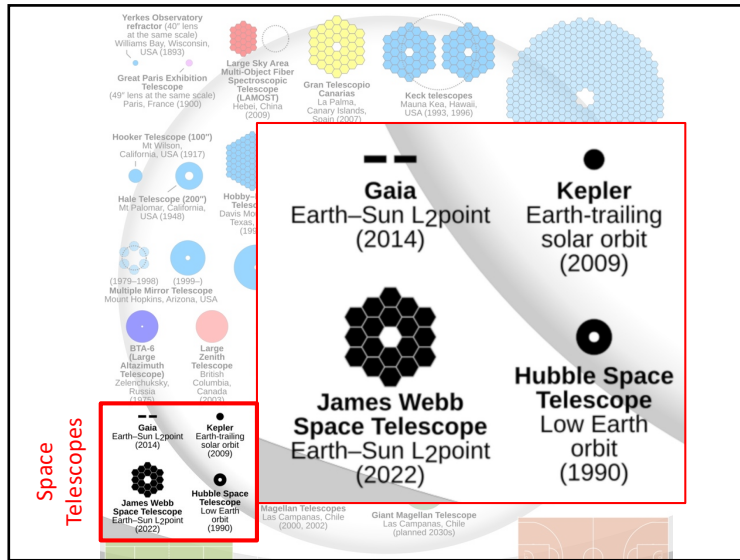
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**Space Telescopes**

- Yerkes Observatory refractor (40" lens at the same scale) Williams Bay, Wisconsin, USA (1893)
- Great Paris Exhibition Telescope (49" lens at the same scale) Paris, France (1900)
- Hooker Telescope (100") Mt Wilson, California, USA (1917)
- Hale Telescope (200") Mt Palomar, California, USA (1949)
- (1979–1998) Multiple Mirror Telescope Mount Hopkins, Arizona, USA
- ST-4 Large Altazimuth Telescope (British Columbia, Russia (1976))
- Gaia Earth-Sun L2 point (2014)
- James Webb Space Telescope Earth-Sun L2 point (2022)
- Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) Hebei, China (2009)
- Gran Telescopio Canarias La Palma, Canary Islands, Spain (2007)
- Keck telescopes Mauna Kea, Hawaii, USA (1993, 1996)
- Gemini North Mauna Kea, Hawaii, USA (1999)
- Subaru Telescope Mauna Kea, Hawaii, USA (1999)
- Thirty Meter Telescope Mauna Kea, Hawaii, USA (planned)
- Gemini South Cerro Pachon, Chile (2000)
- Large Binocular Telescope Mount Graham, Arizona, USA (2005)
- Vera C. Rubin Observatory Cerro Pachon, Chile (planned 2025)
- Very Large Telescope Cerro Paranal, Chile (1998, 1999, 2000, 2000)
- Extremely Large Telescope Cerro Armazones, Chile (planned 2028)
- Kepler Earth-trailing solar orbit (2009)
- Magellan Telescopes Las Campanas, Chile (2000, 2002)
- Giant Magellan Telescope Las Campanas, Chile (planned 2030s)
- Human at the same scale

0 5 10 m

# Gaia

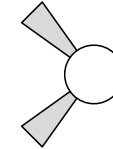
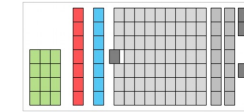


## Gaia Hardware

Gaia achieves its high precision through an ingenious combination of instrumental hardware and a novel mode of operating:

### Hardware

- A large (Gigapixel) detector array comprising 106 CCD sensors
- Two telescopes that simultaneously image different patches of the sky

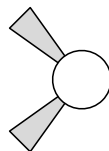
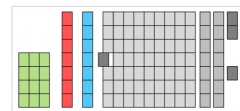


## Gaia Operation

Gaia achieves its high precision through an ingenious combination of instrumental hardware and a novel mode of operating:

### Operation

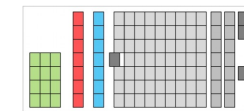
- Both telescopes create star images on the **same** detector array
- Gaia spins and so the star images **drift** across the detector CCDs
- Gaia does **not** take images



## Gaia Operation

This makes Gaia very different to imaging space telescopes like the Hubble or James Webb Space Telescopes.

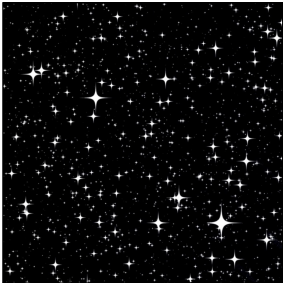
Reading data from the CCDs is a crucial element of the operation and so it is worth taking a closer look at how this is done.



```
000001010
011100101
110111000
000001010
011100101
110111000
```

# Gaia

**CCD Images**



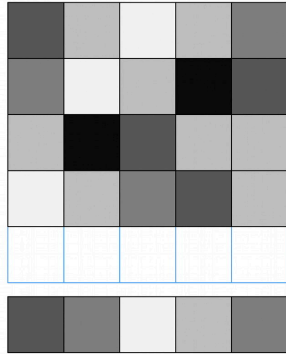
Imagine an image of a star field.

How is the image made?

Image data is just an array of numbers.

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**Reading a CCD In 'Stare' Mode**



Expose CCD to light

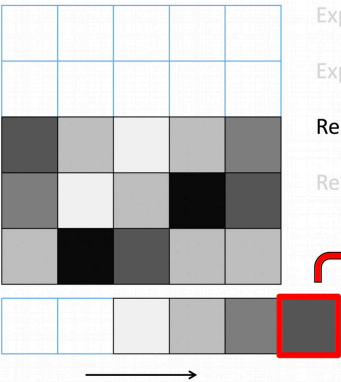
Exposure complete

Read data from CCD

Read complete

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**Reading a CCD In 'Stare' Mode**



Expose CCD to light

Exposure complete

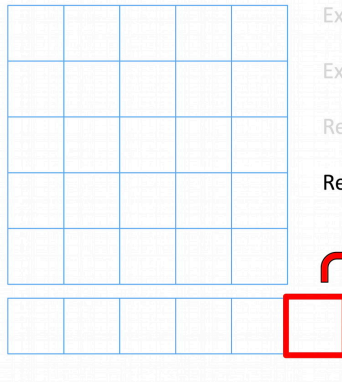
Read data from CCD

Read complete

1001001011  
0111

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**Reading a CCD In 'Stare' Mode**



Expose CCD to light

Exposure complete

Read data from CCD

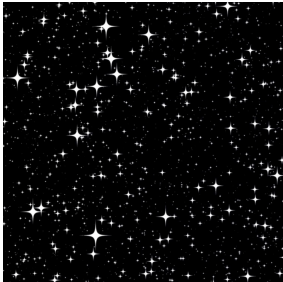
Read complete

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# Gaia

### Reading a CCD In 'Drift' Mode

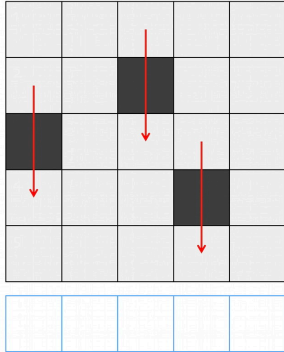


As Gaia spins, stars drift across the CCDs.




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### Reading a CCD In 'Drift' Mode

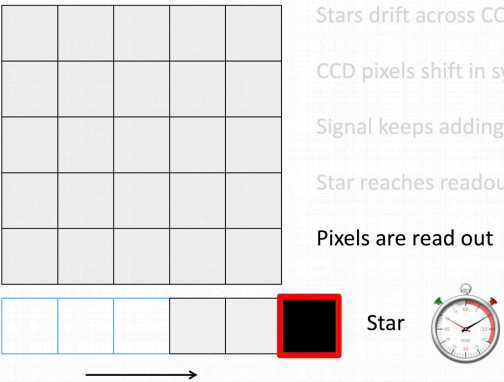


- Stars drift across CCD
- CCD pixels shift in synch
- Signal keeps adding up
- Star reaches readout
- Pixels are read out




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### Reading a CCD In 'Drift' Mode



- Stars drift across CCD
- CCD pixels shift in synch
- Signal keeps adding up
- Star reaches readout
- Pixels are read out


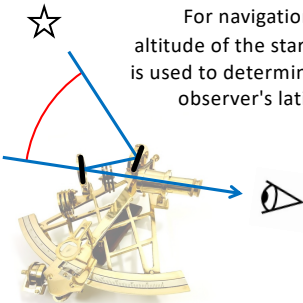
Star



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### Two Telescopes, One Detector

A sextant works on a similar principle ...

For navigation, the altitude of the star (red) is used to determine the observer's latitude.

Light from two objects is reflected from mirrors so that they appear together in the 'same detector'.



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# Gaia

### Gaia Optical Bench

Primary mirror of telescope 1

Primary mirror of telescope 2

Primary mirror size  $\approx 1.5 \times 0.5$  m

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### Gigapixel CCD Array

10  $\mu\text{m}$   
30  $\mu\text{m}$  pixel

5 cm  
6 cm CCD

star drift direction

4 s

Spectra Red Blue Astrometrics #2 #1 Sky Mapper

BAM

WF

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### Operation of Gaia

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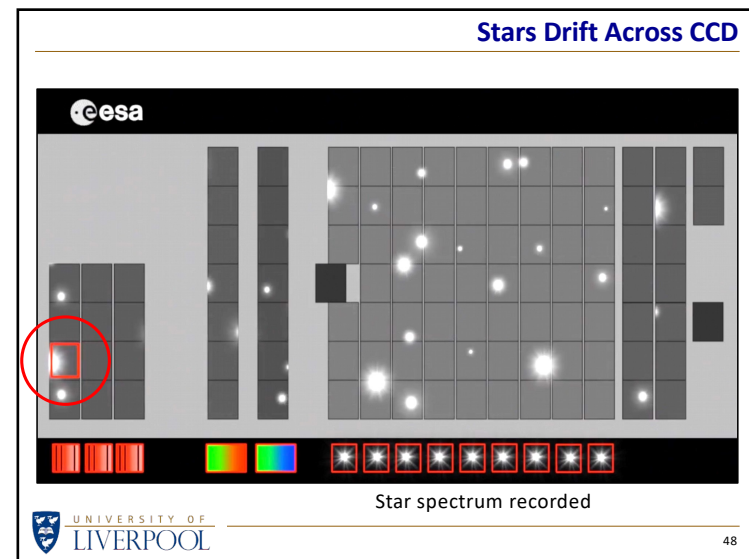
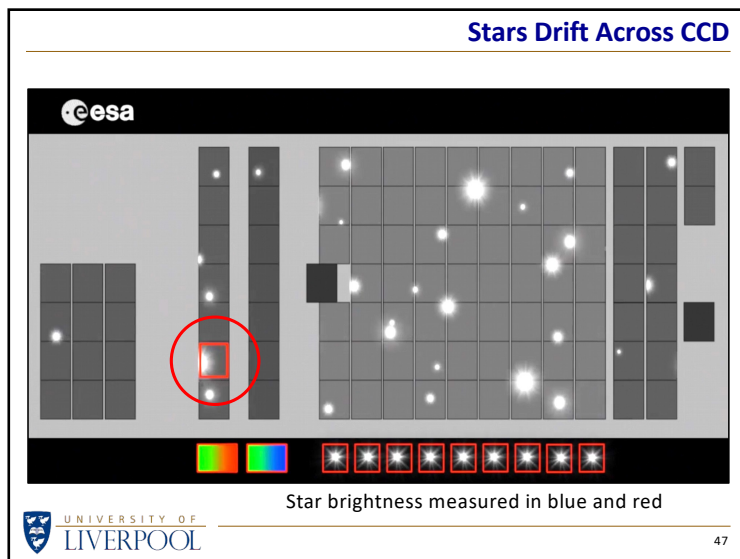
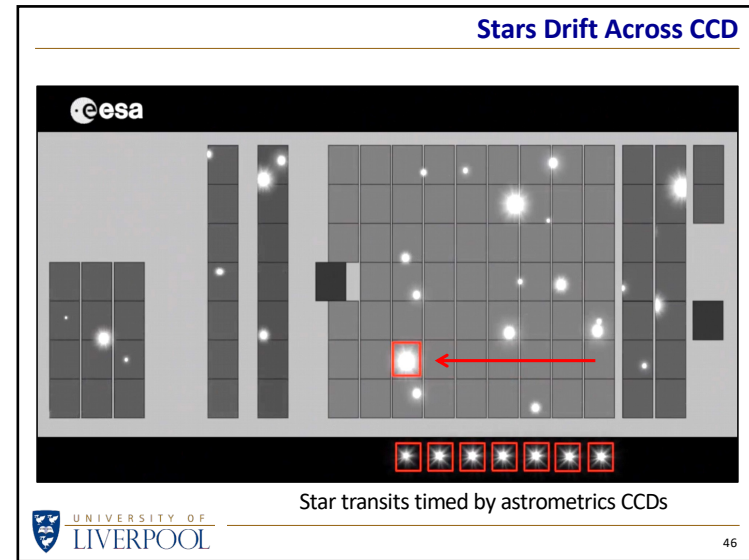
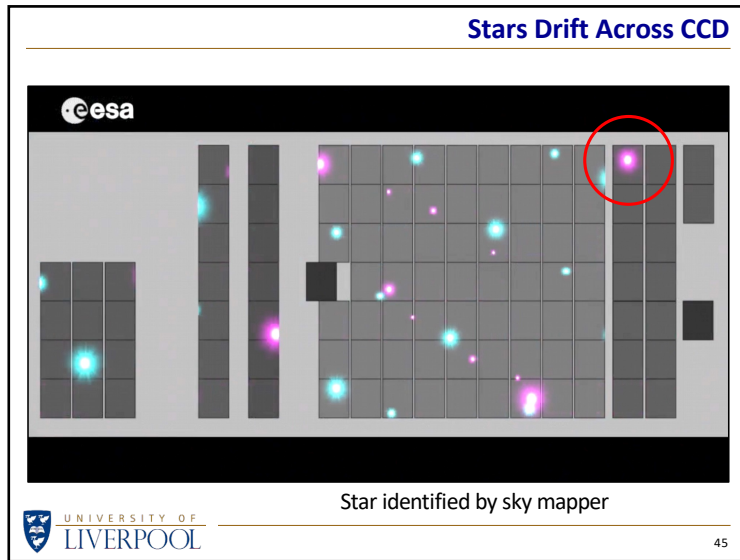
### Gaia Operation

Two telescopes but one detector

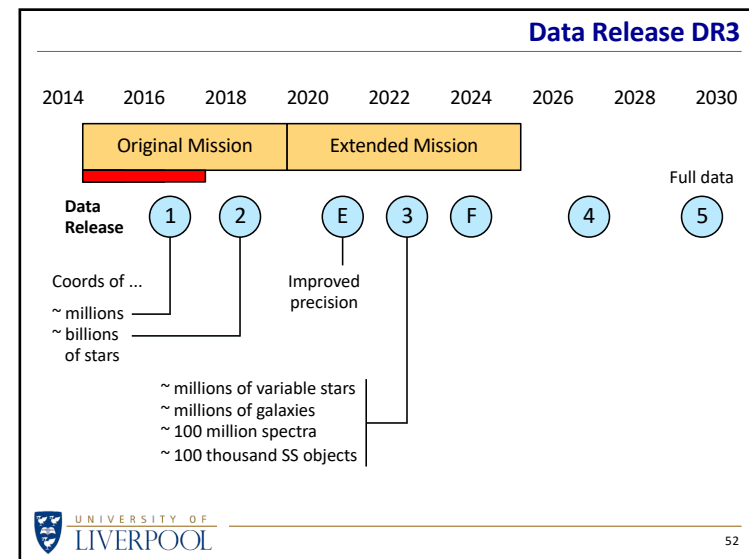
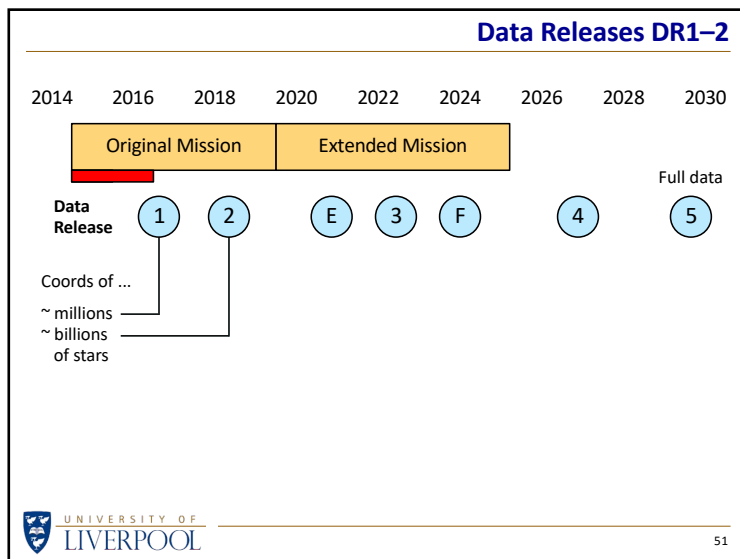
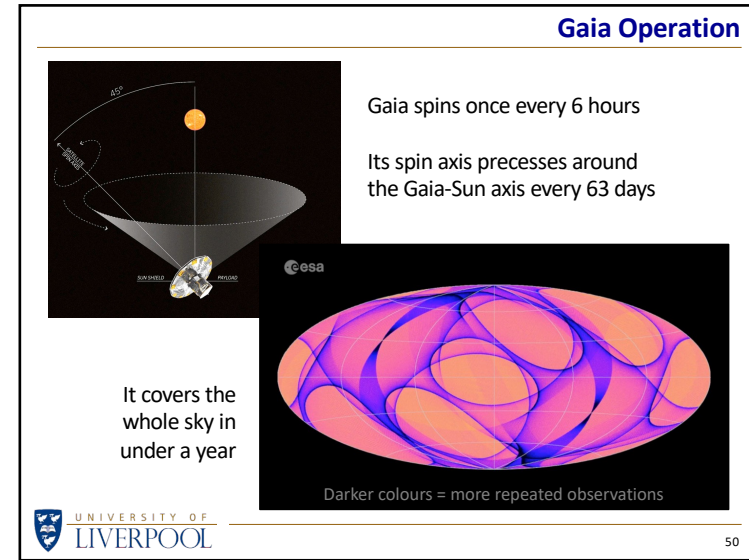
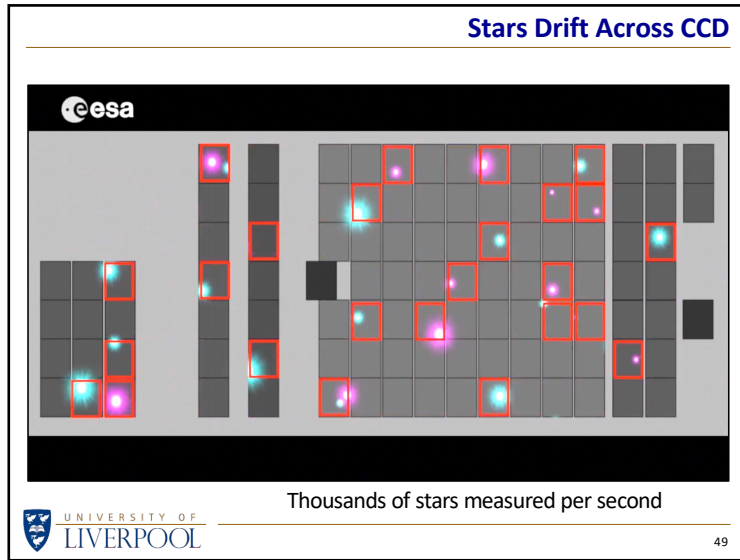
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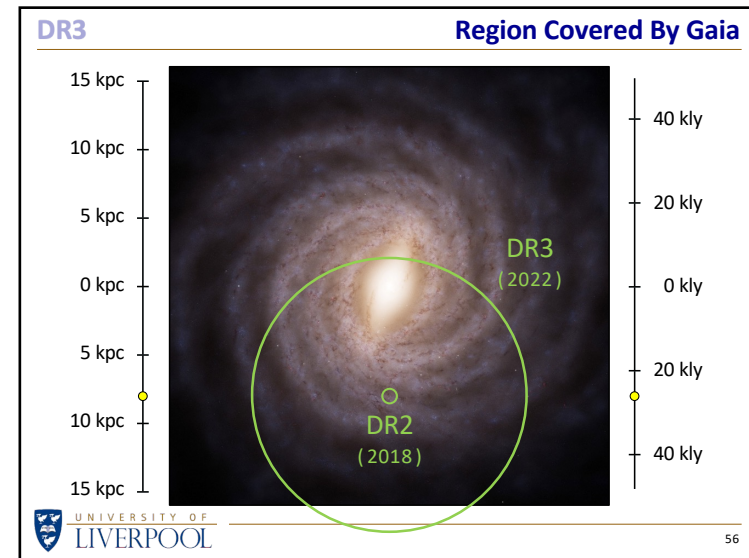
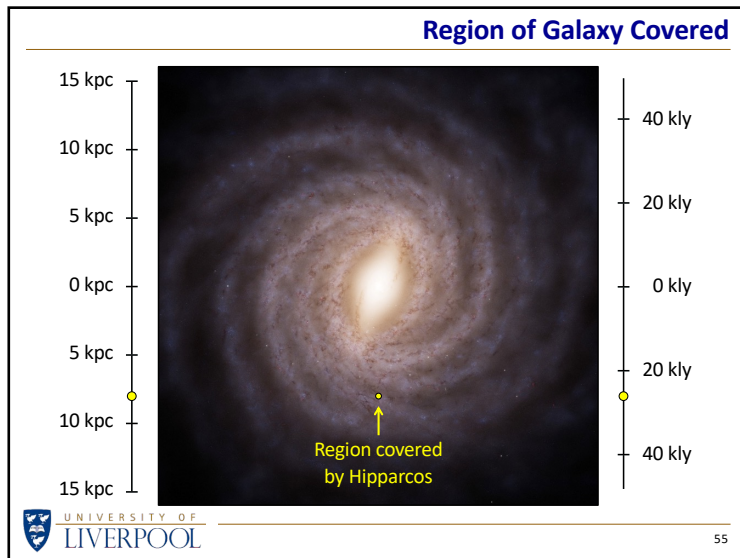
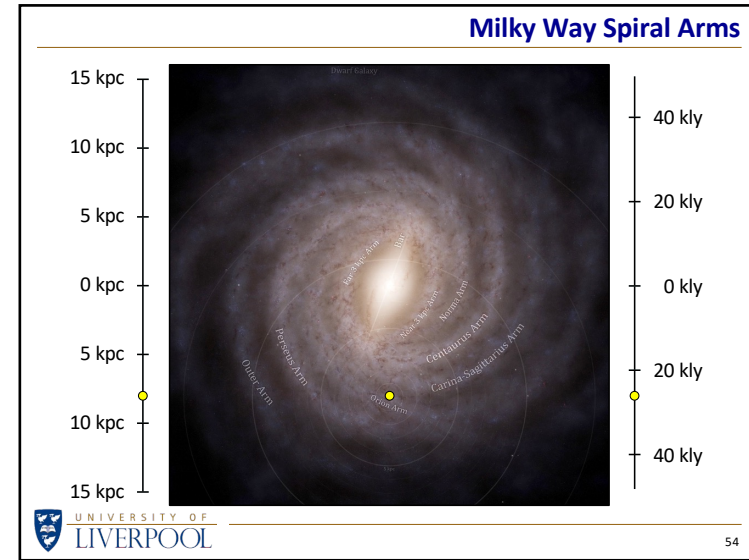
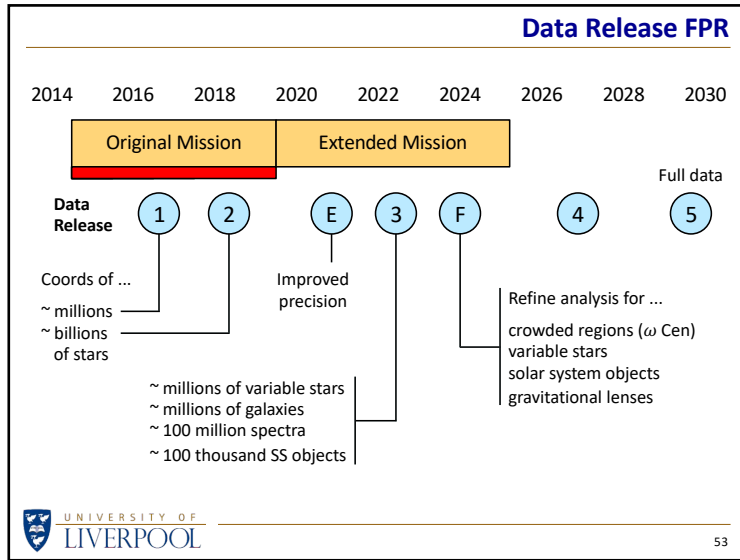
# Gaia



# Gaia



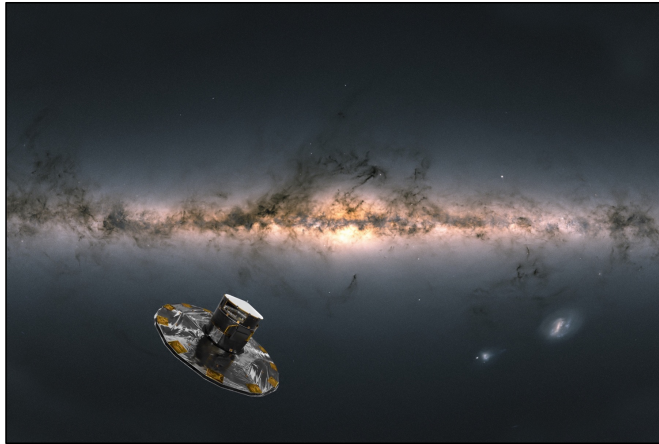
# Gaia



# Gaia

DR2

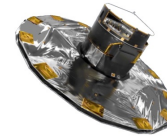
All-Sky Map



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What can we learn  
from the data?



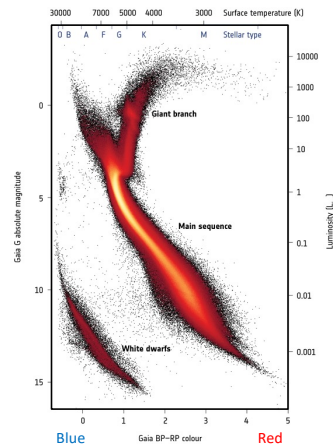
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DR2

H-R Diagram

Hertzsprung–Russell diagrams plot the luminosity (vertical) against the colour (horizontal) for a population of stars.

This H-R diagram for millions of stars in the Milky Way gives us a way to visualise the stellar population of our galaxy.



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DR3

Sun-like Star and Neutron Star

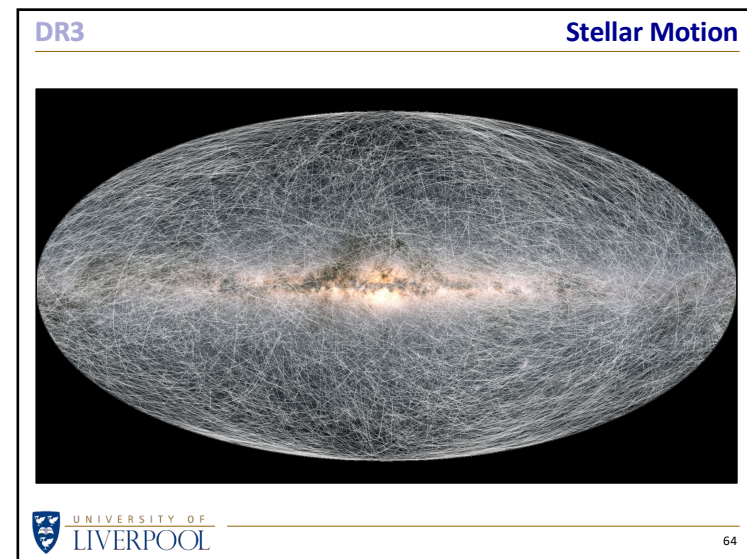
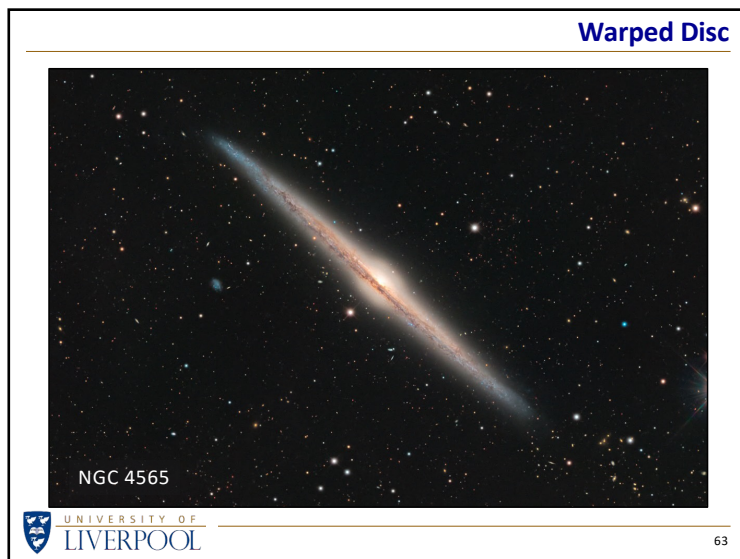
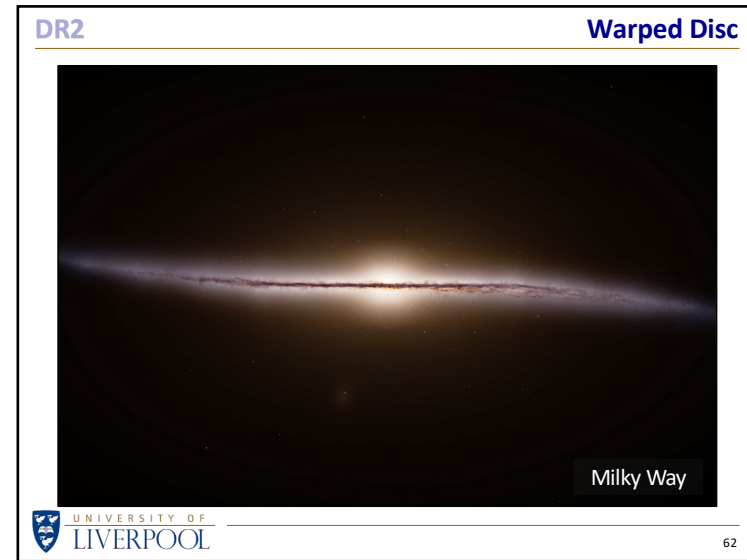
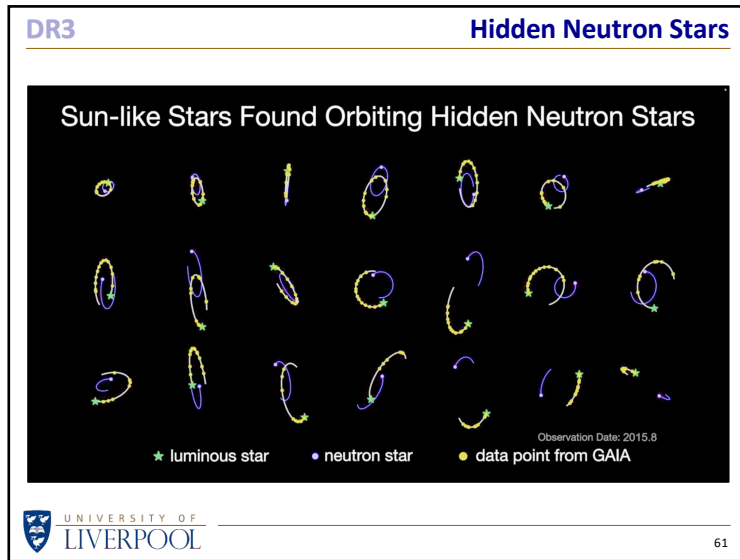


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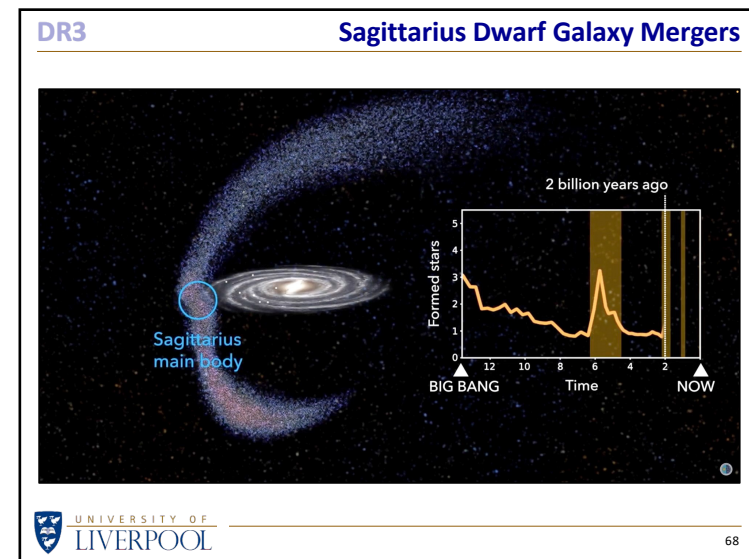
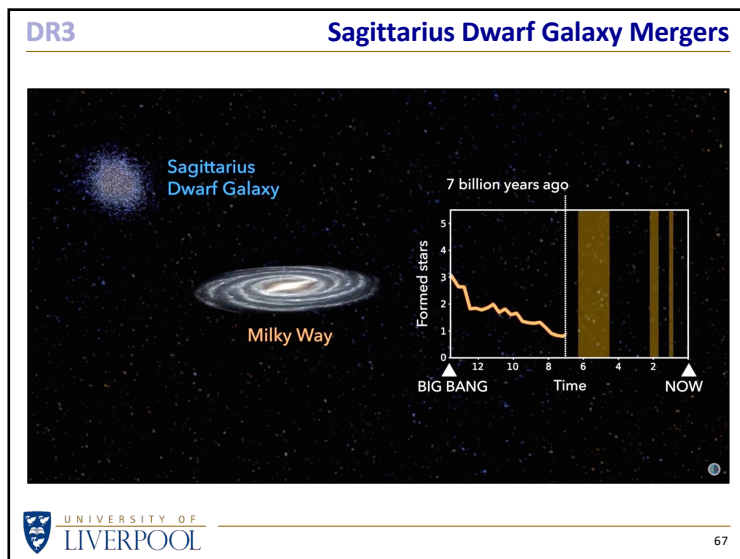
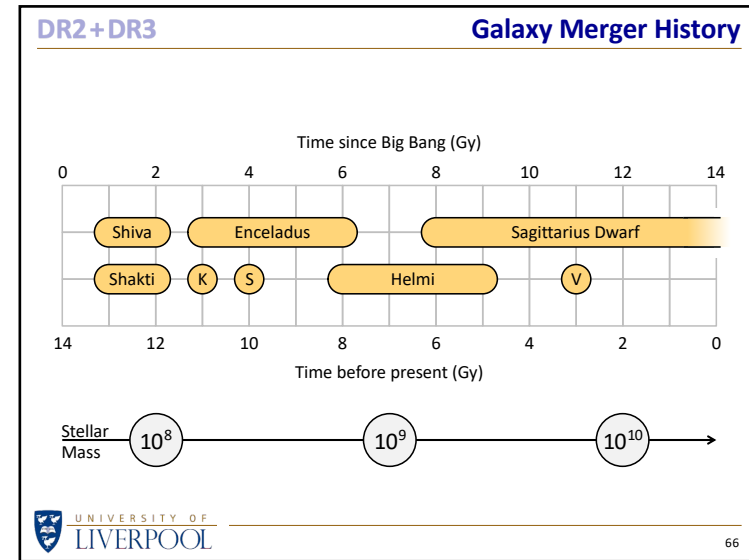
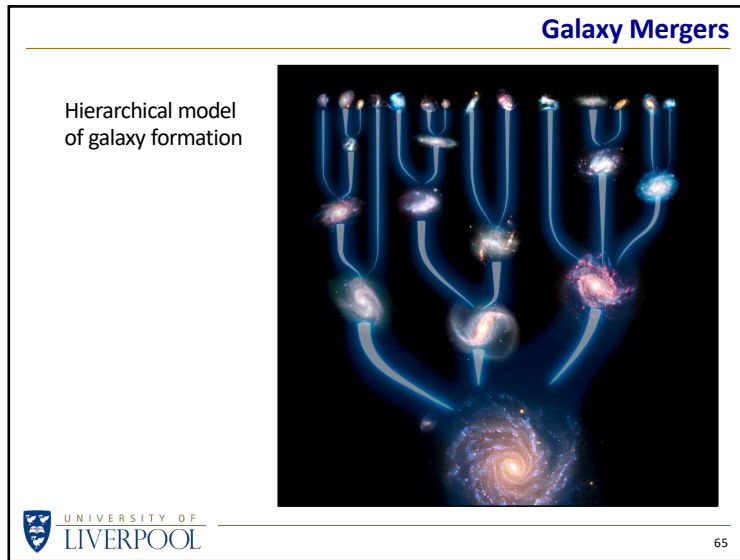
60

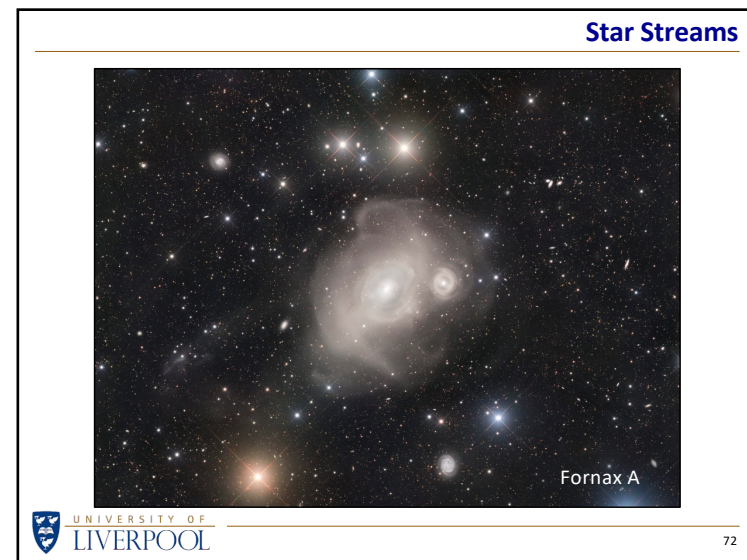
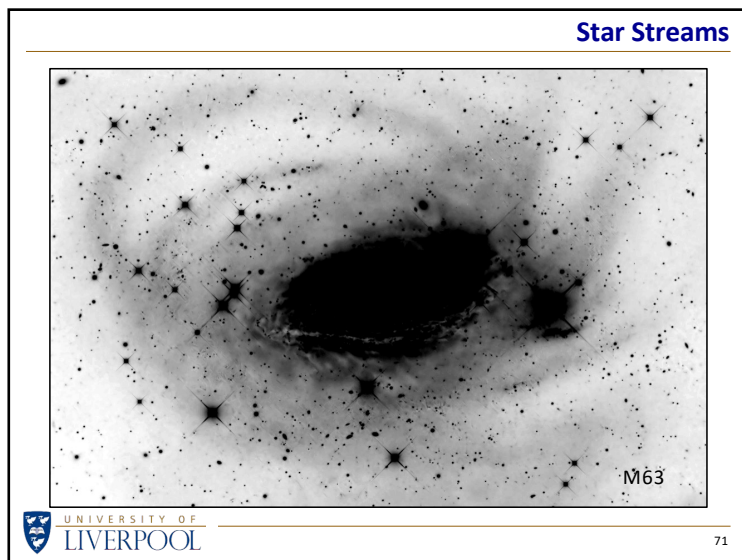
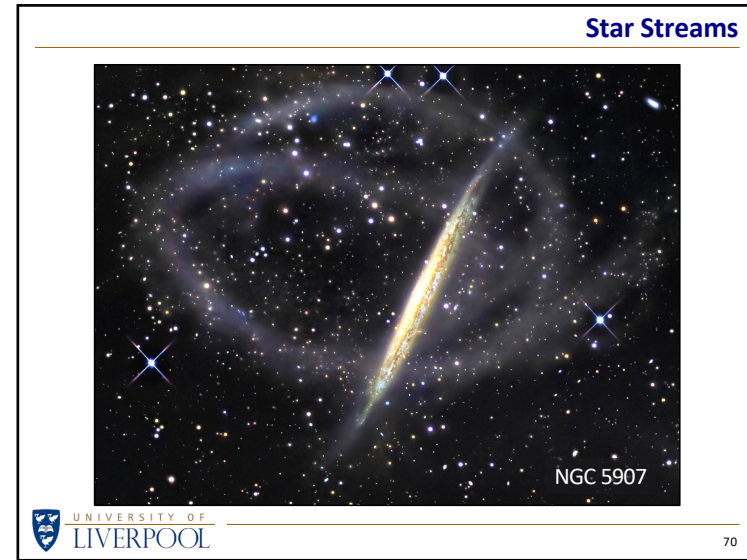
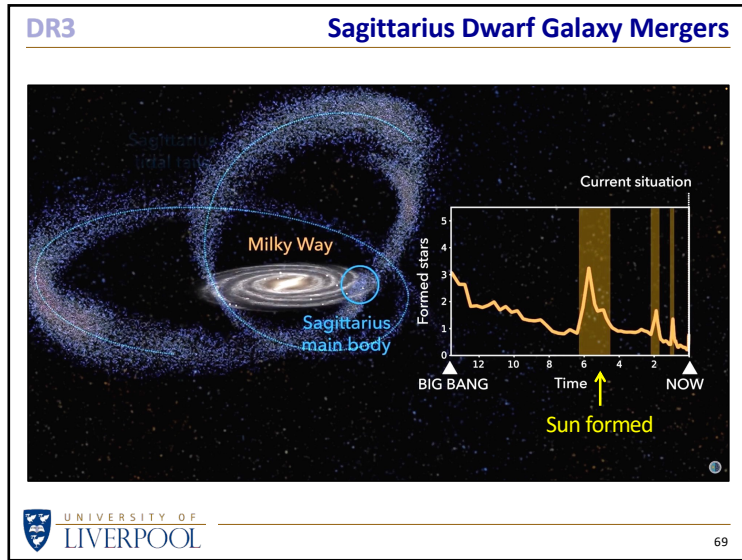


# Gaia

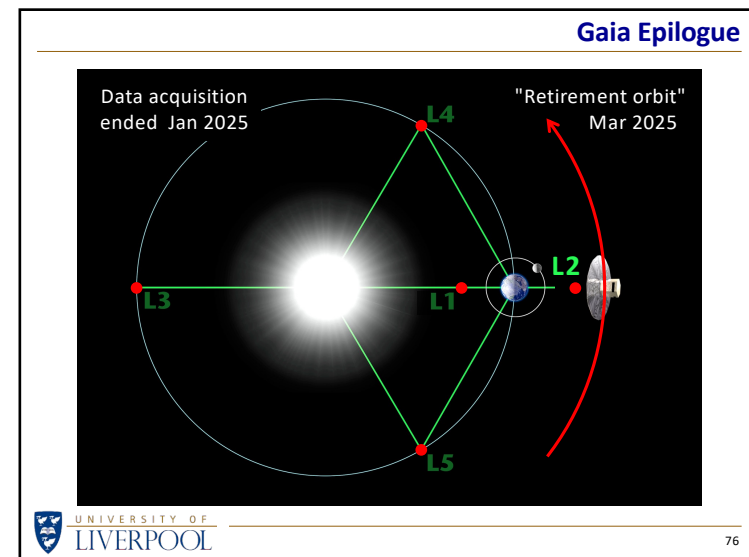
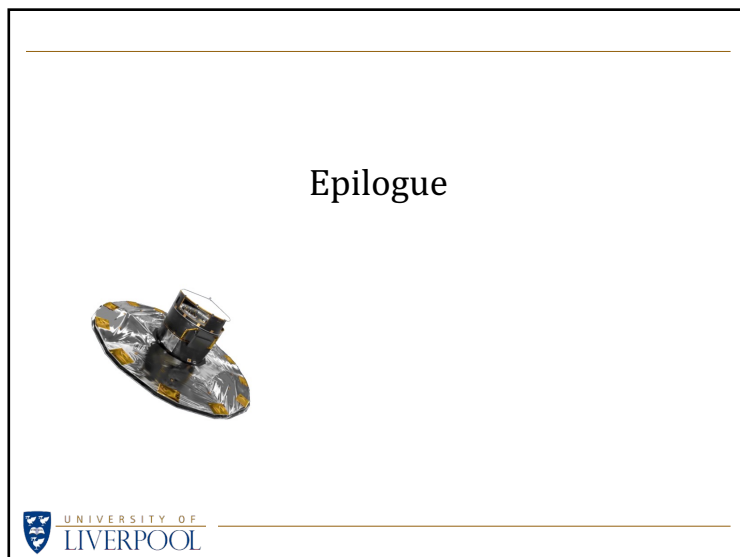
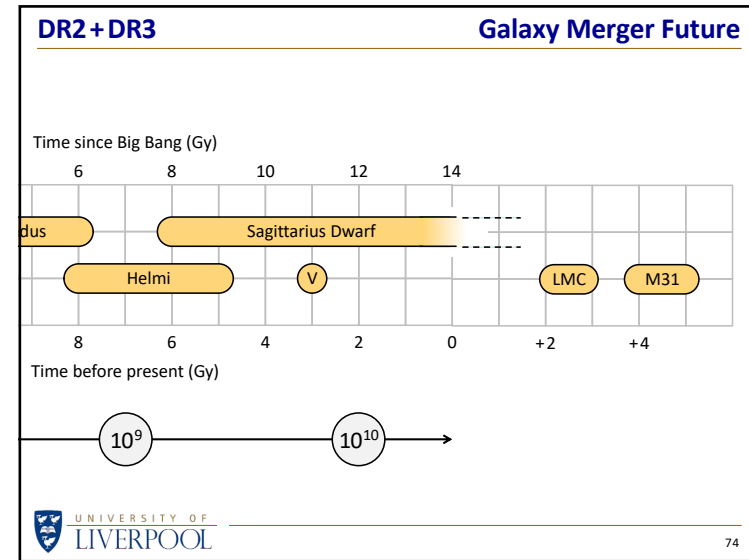
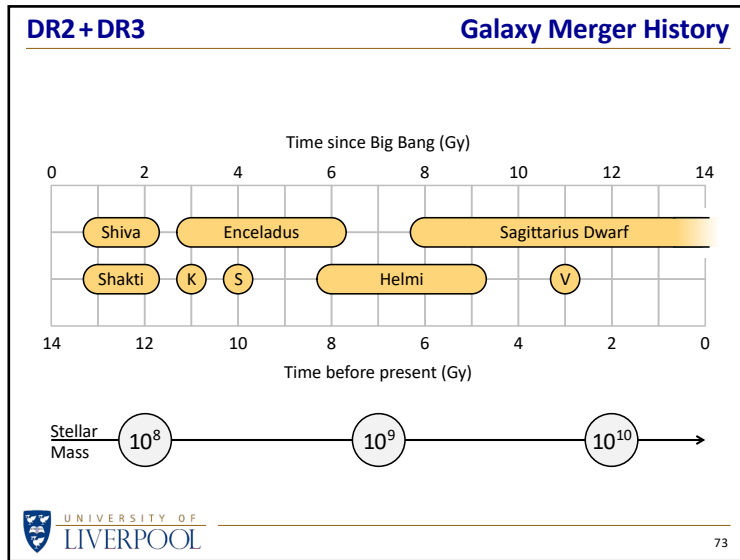








# Gaia



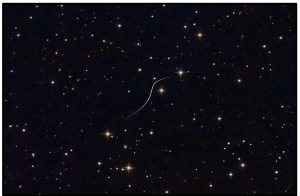
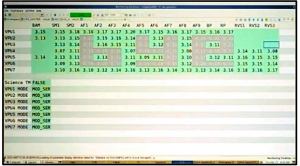
# Gaia

### Gaia Epilogue

As it drifted away from L2 it was bright enough to be imaged by amateur astrophotographers.

Its heliocentric orbit will bring it close to Earth every 14 years.

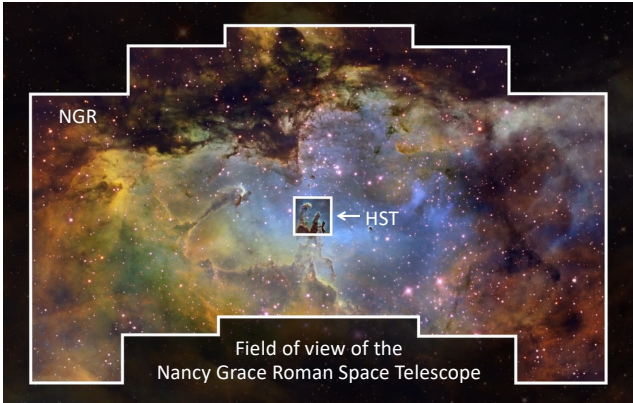
Before it was powered down Gaia sent a final status update.

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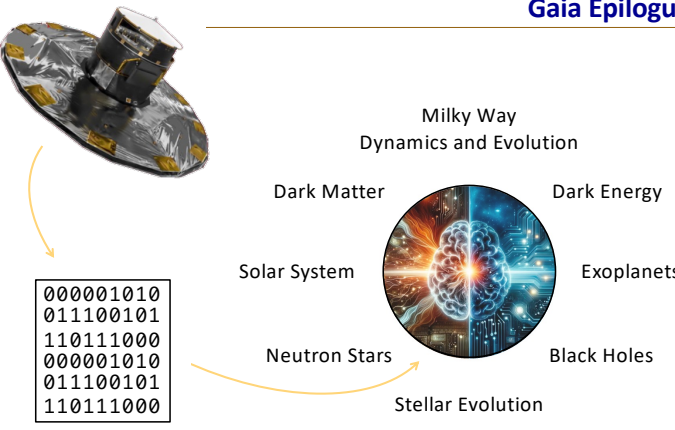
### Gaia Epilogue



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### Gaia Epilogue



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000001010
011100101
110111000
000001010
011100101
110111000
    
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DR4 = 500 TB

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[www.liverpool.ac.uk/~sdb/Talks](http://www.liverpool.ac.uk/~sdb/Talks)



# Gaia

Dr Steve Barrett  
BASoc 16 Feb 2026