

Gaia



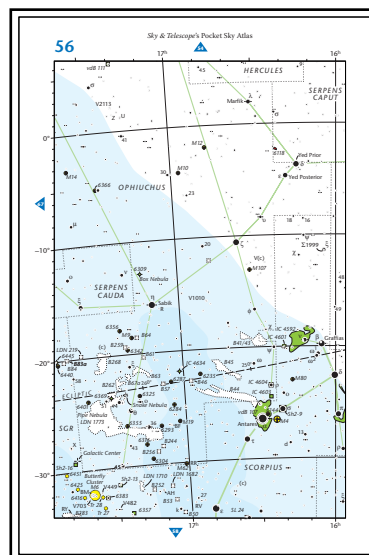
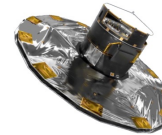
Contents

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?



Mapping the Stars

It's a simple question ...

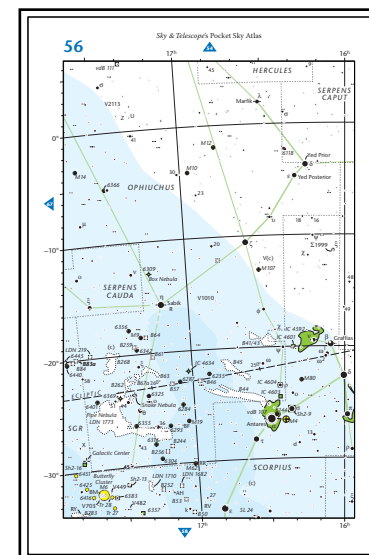
Where are the stars?

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



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.

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.

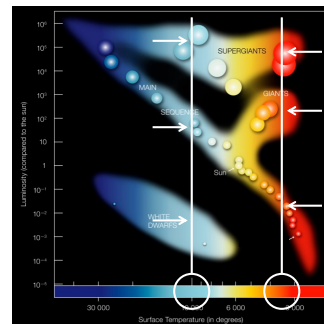
Mapping the Stars

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.

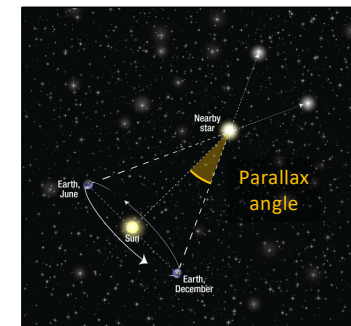


Parallax

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.

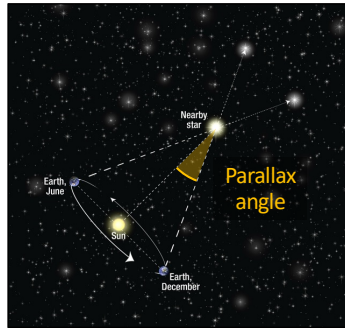
However, in practice, *all* stars appear to move as the Earth orbits the Sun.



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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 ~3 ly distant would show a parallax angle of ~1 arc second.

This distance is defined as one "parallax second".

1 parsec = 3.26 light-years

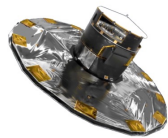
Measuring Parallax

So here is the crux of the problem.

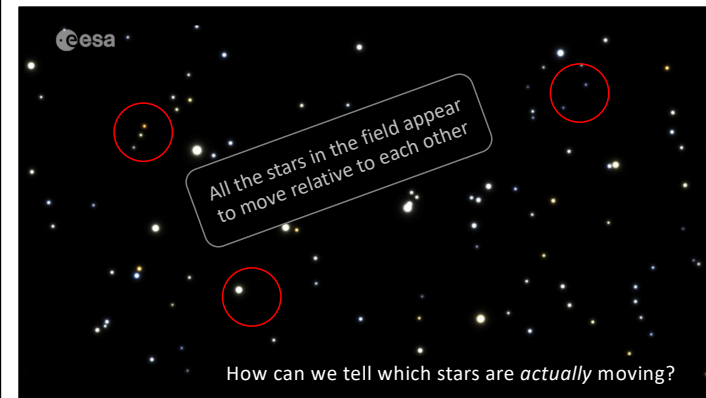
- To calculate distances we need parallax
- Parallax needs the stars' *actual* positions in the sky (not simply their position *relative* to other stars)
- The stars themselves are moving (proper motion)

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

How can they be mapped accurately?



Mapping the Stars



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.]

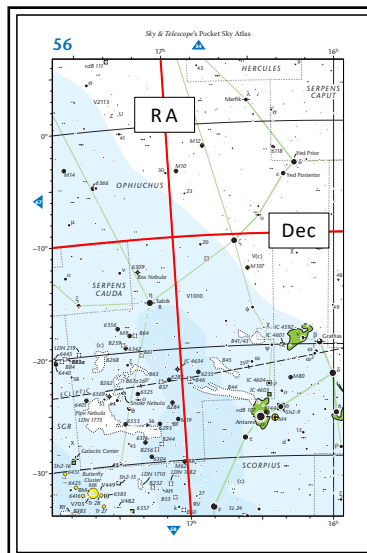
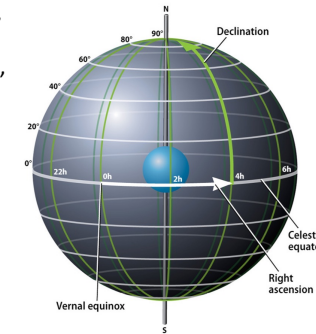
Coordinate Systems

What coordinate system should we use to map the stars?

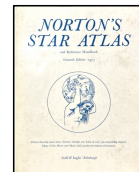
The equatorial coordinate system, comprising Right Ascension (RA) and Declination (Dec) coordinates, uses the celestial equator as a reference.

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

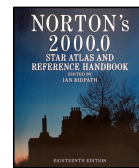
Why are they not good enough?



Coordinate Systems



Epoch 1950.0

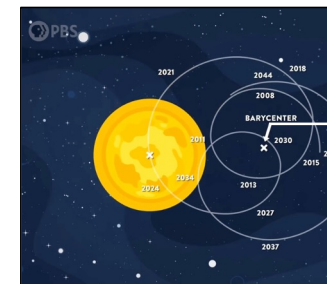


Epoch 2000.0



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.

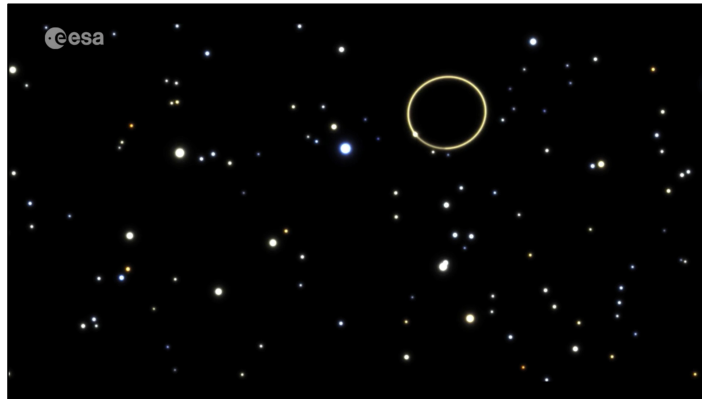


We think of planets orbiting the Sun, but actually they all orbit around a common **barycentre**

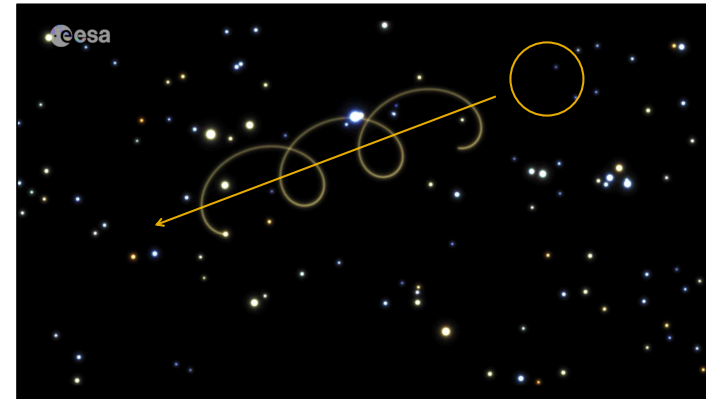
Hence the best coordinate system uses this barycentre as a fixed reference point.

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Parallax Only



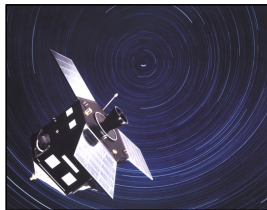
Parallax and Proper Motion



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 ~ 0.001 arcsec.

(0.001 arcsec = milli arcsec = mas)

Faintest stars = mag 12

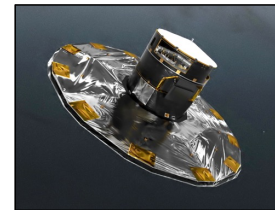
The Hipparcos catalogue was used by the Hubble Space Telescope.

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

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

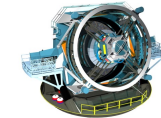


Alternatives?

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



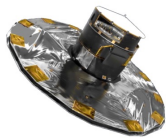
Hubble
Space Telescope



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

How does Gaia
achieve this?



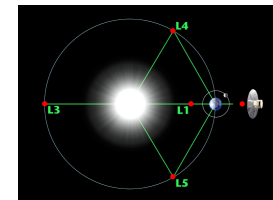
Gaia Hardware



Gaia was ... constructed 2006–2012

... launched in Dec 2013

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



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 (μas) precision achieved?

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

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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 (1948)

(1979–1998) Multiple Mirror Telescope Mount Hopkins, Arizona, USA

ST-6 Large Aperture Telescope (1999–) Zelenchuksky, Russia (2003)

Large Zenith Telescope British Columbia, Canada (2003)

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)

Hobby-Eberly Telescope Davis Mountains, Texas, USA (1996)

Southern African Large Telescope Sutherland, South Africa (2005)

Large Binocular Telescope Mount Graham, Arizona, USA (2005)

Very Large Telescope Cerro Paranal, Chile 1998, 1999, 2000, 2000

Magellan Telescopes Las Campanas, Chile (2000, 2002)

Keck telescopes Mauna Kea, Hawaii, USA (1993, 1996)

Gemini North Mauna Kea, Hawaii, USA (1999)

Gemini South Cerro Pachón, Chile (2000)

Vera C. Rubin Observatory Cerro Pachón, Chile (planned 2025)

Subaru Telescope Mauna Kea, Hawaii, USA (1999)

Thirty Meter Telescope Mauna Kea, Hawaii, USA (planned)

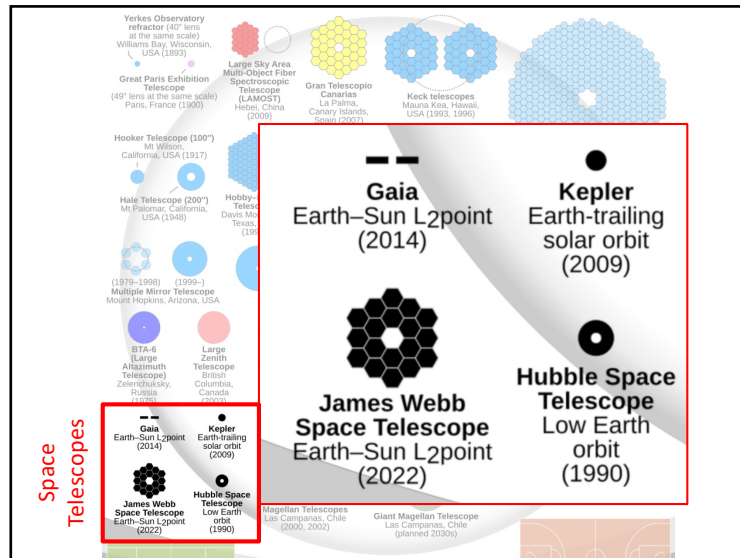
Extremely Large Telescope Cerro Armazones, Chile (planned 2028)

Giant Magellan Telescope Las Campanas, Chile (planned 2030s)

Human at the same scale

0 5 10 20 30 m

Gaia

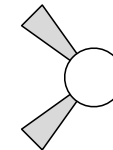
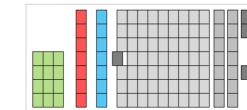


Gaia Hardware

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

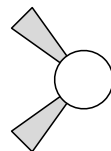
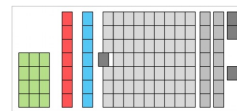


Gaia Operation

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

Operation

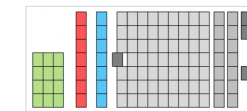
- Both telescopes create star images on the **same** detector array
- Gaia spins and so the star images **drift** across the detector CCDs
- Gaia does **not** take images



Gaia Operation

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

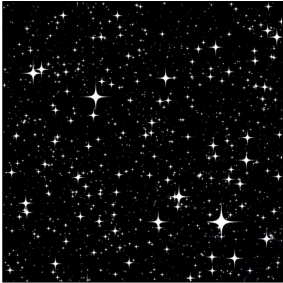
Reading data from the CCDs is a crucial element of the operation and so it is worth taking a closer look at how this is done.



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000001010
011100101
110111000
000001010
011100101
110111000
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Gaia

CCD Images



Imagine an image of a star field.

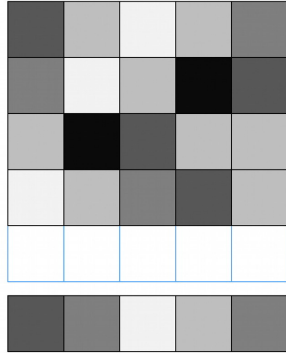
How is the image made?

Image data is just an array of numbers.

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Reading a CCD In 'Stare' Mode



Expose CCD to light

Exposure complete

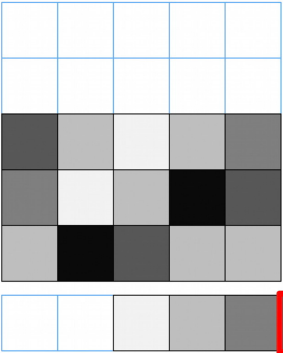
Read data from CCD

Read complete

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Reading a CCD In 'Stare' Mode



Expose CCD to light

Exposure complete

Read data from CCD

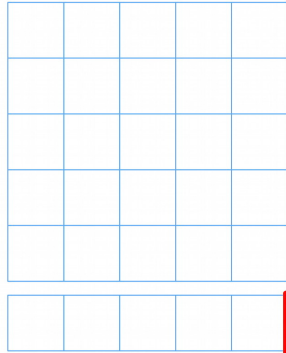
Read complete

1001001011
0111

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Reading a CCD In 'Stare' Mode



Expose CCD to light

Exposure complete

Read data from CCD

Read complete

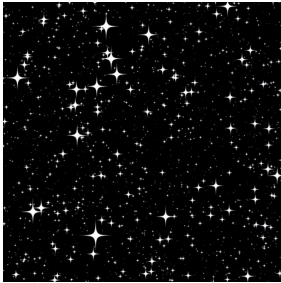
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Gaia

Reading a CCD In 'Drift' Mode

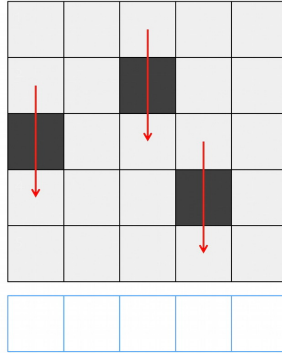


As Gaia spins, stars drift across the CCDs.

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Reading a CCD In 'Drift' Mode

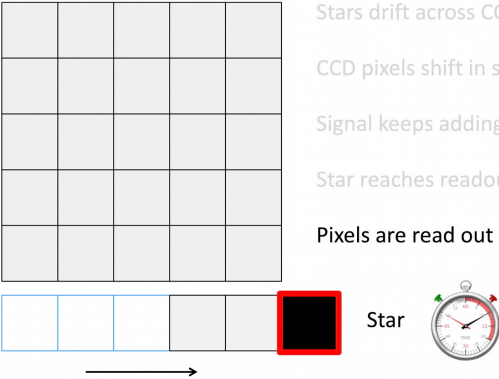


- Stars drift across CCD
- CCD pixels shift in synch
- Signal keeps adding up
- Star reaches readout
- Pixels are read out

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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

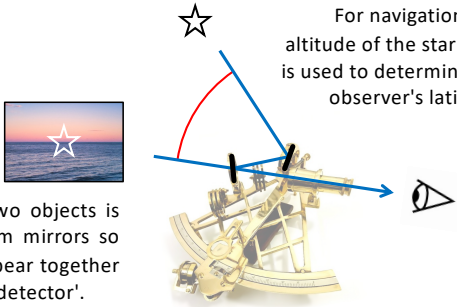
Star

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Two Telescopes, One Detector

A sextant works on a similar principle ...



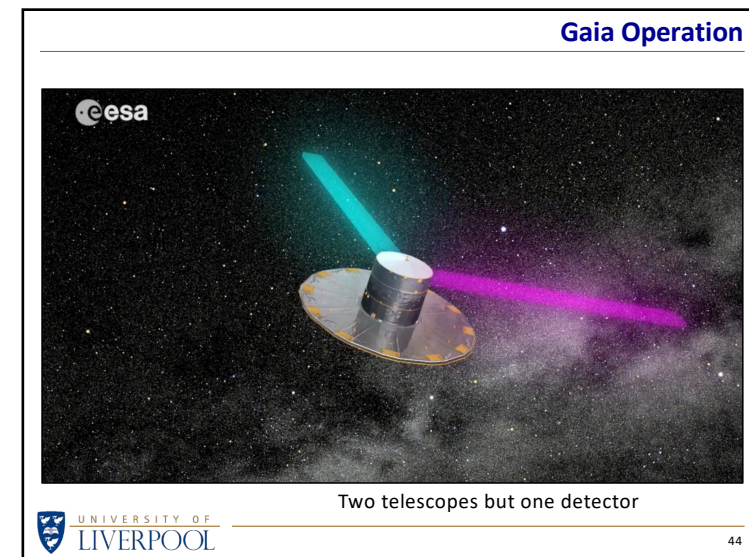
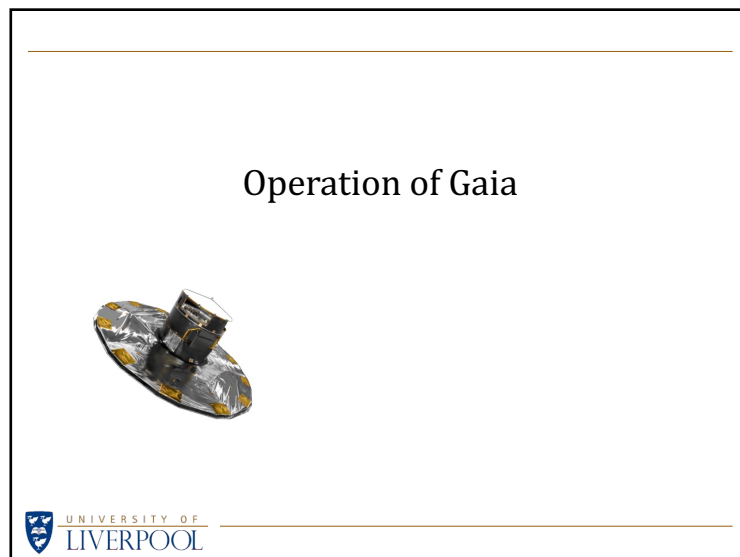
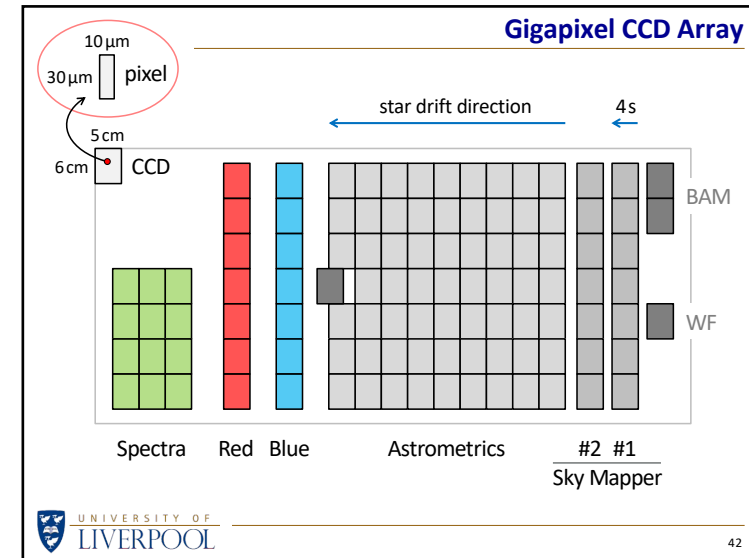
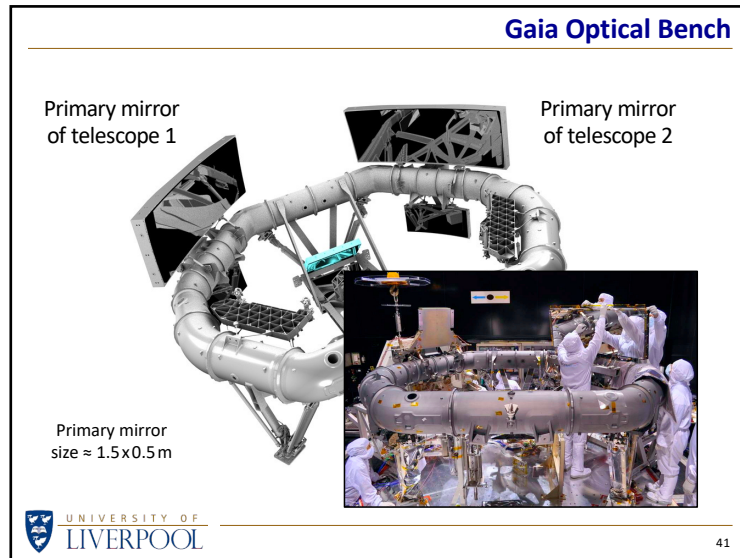
For navigation, the altitude of the star (red) is used to determine the observer's latitude.

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

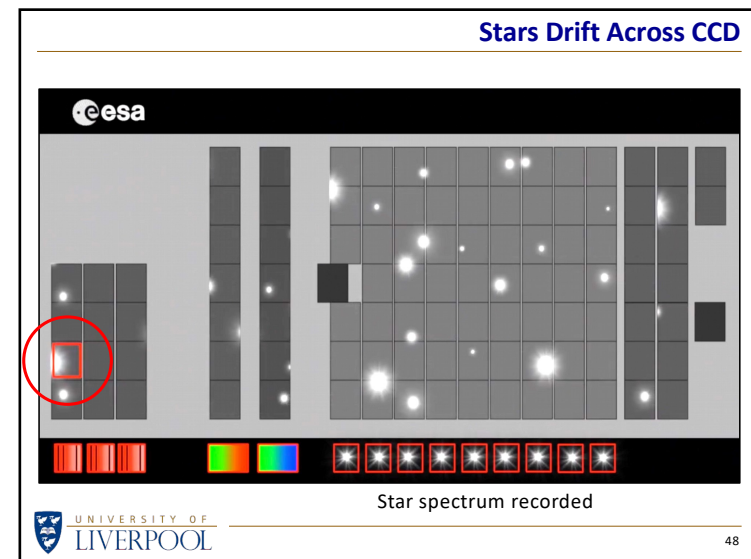
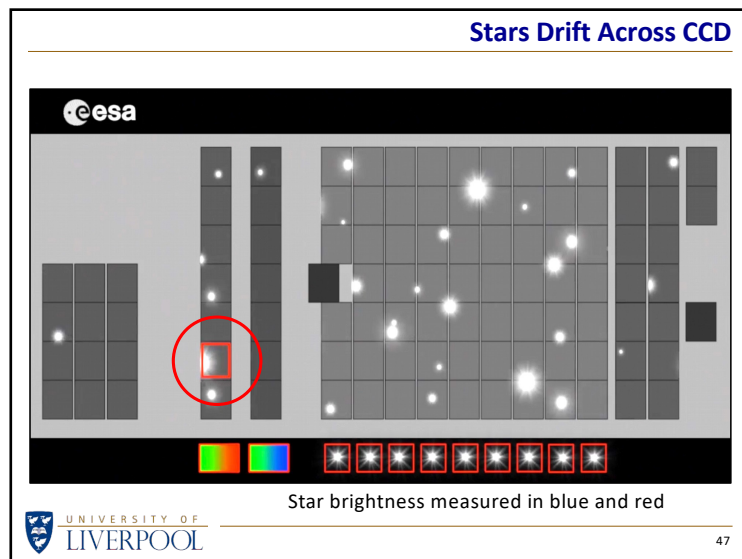
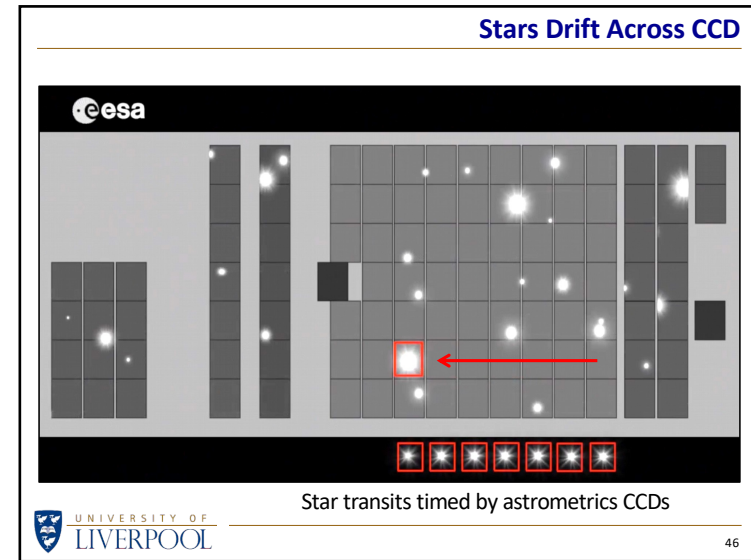
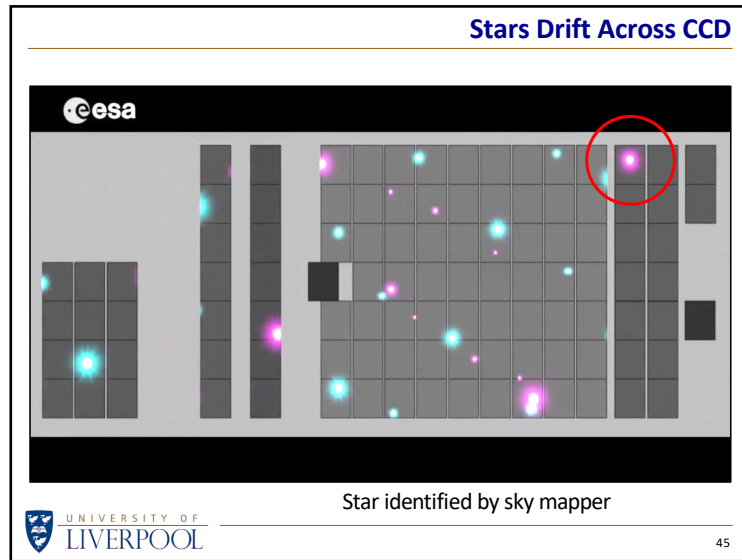
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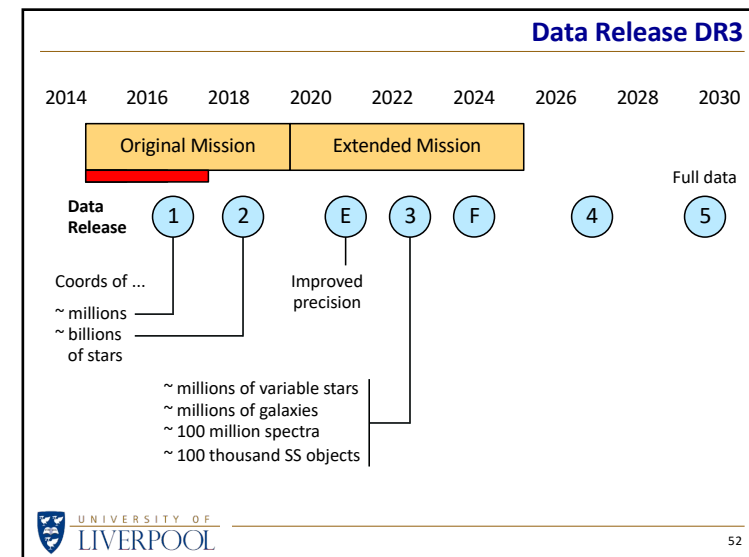
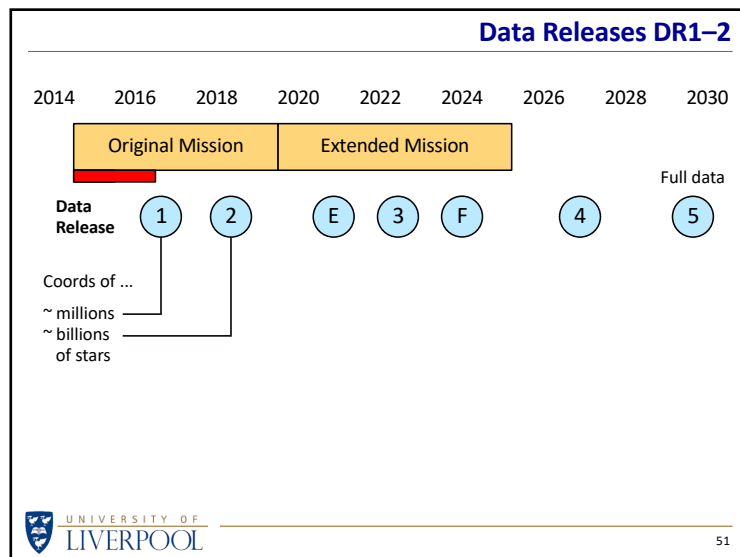
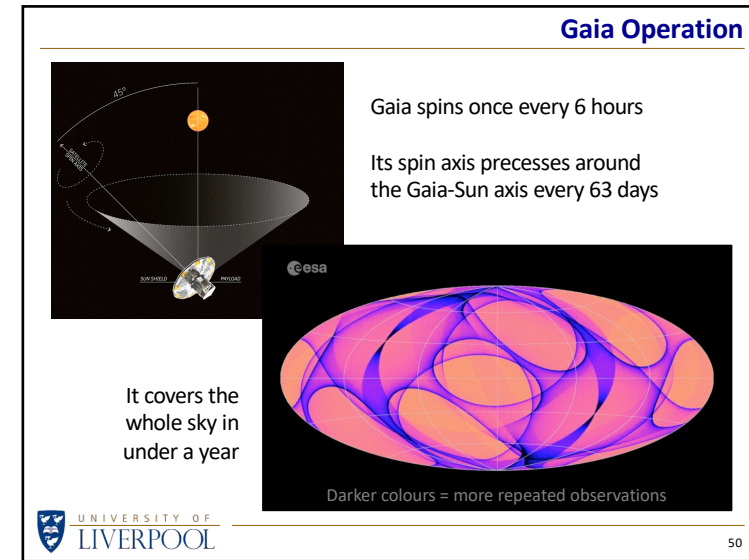
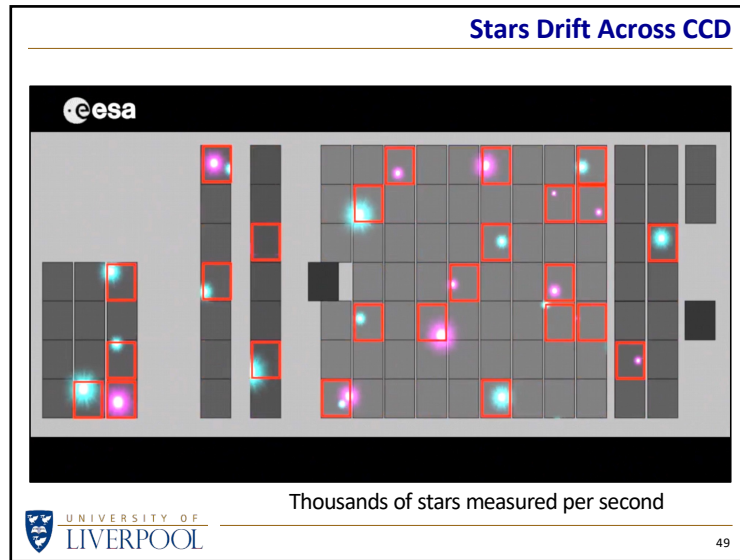
Gaia



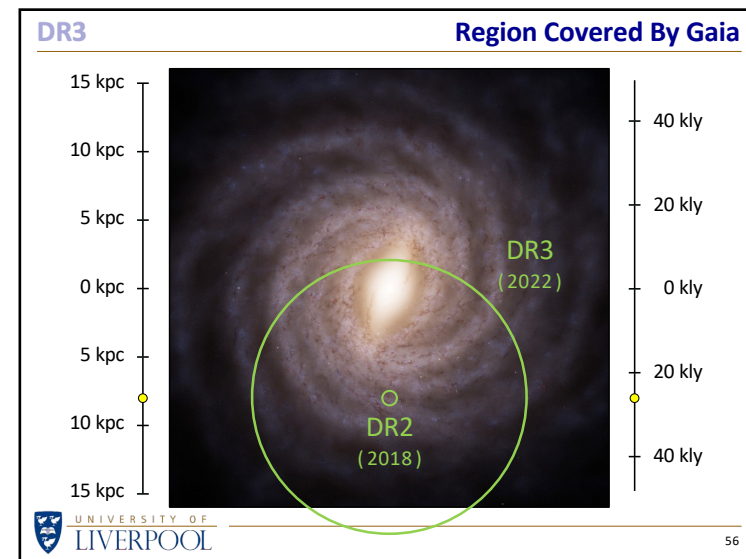
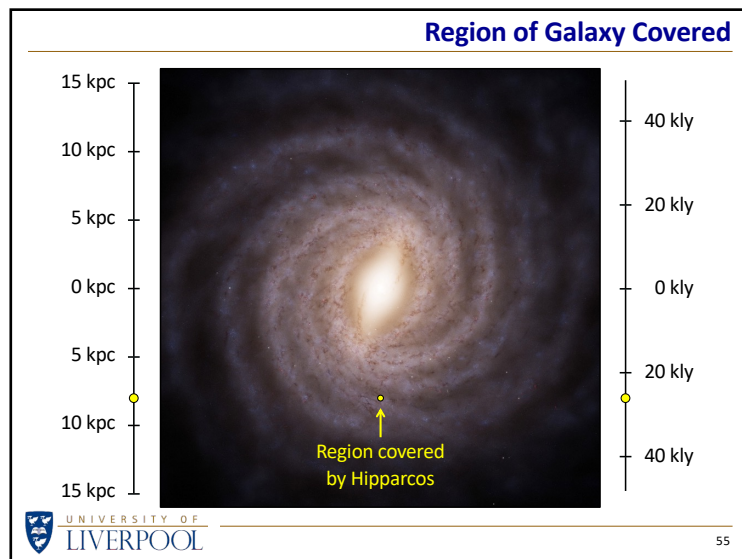
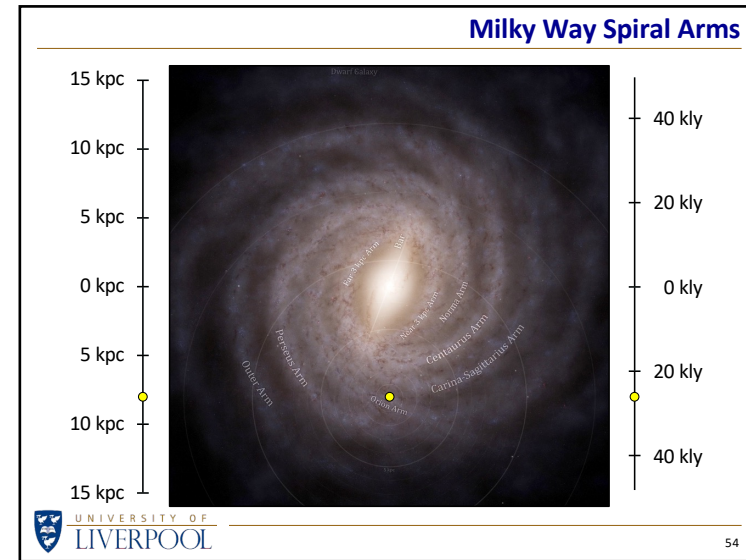
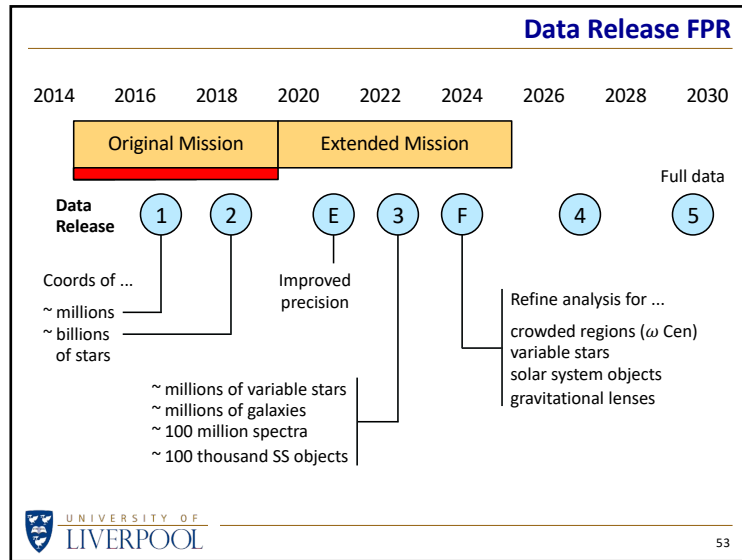
Gaia



Gaia



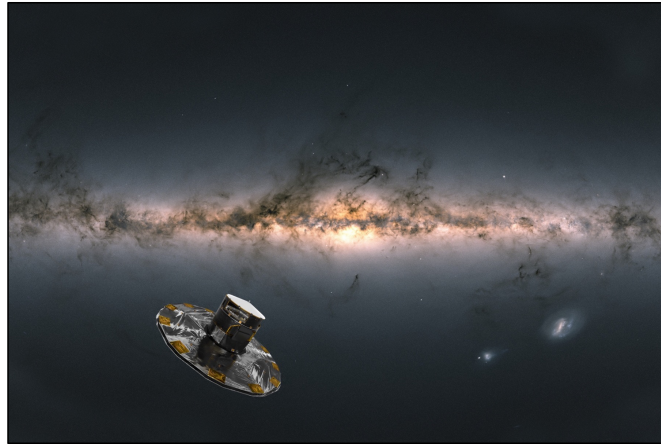
Gaia



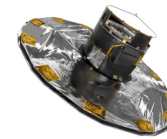
Gaia

DR2

All-Sky Map



What can we learn
from the data?

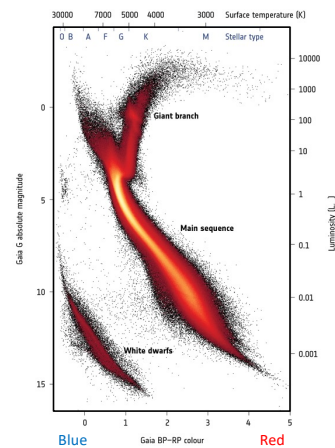


DR2

H-R Diagram

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

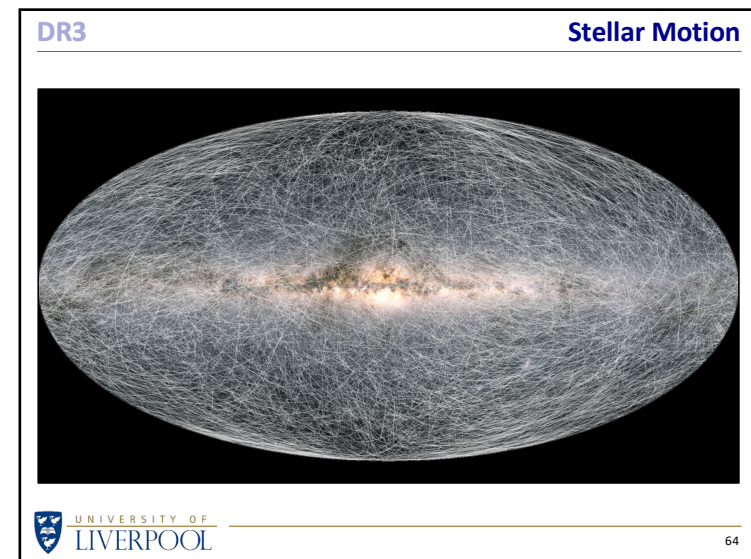
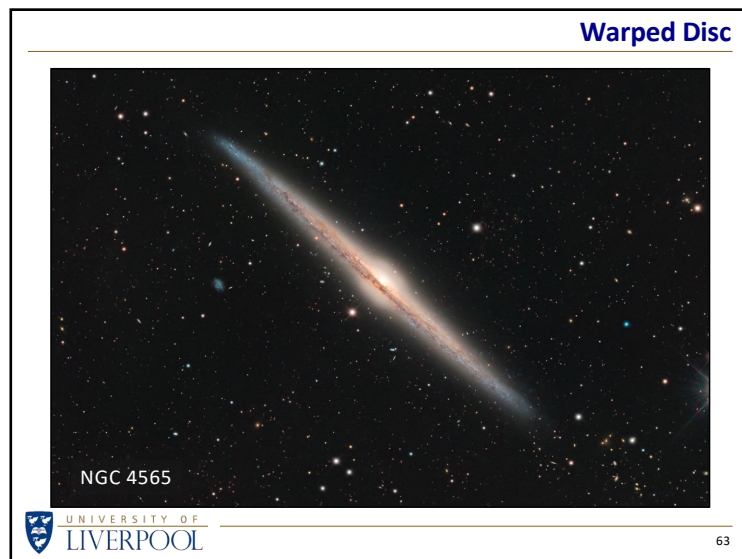
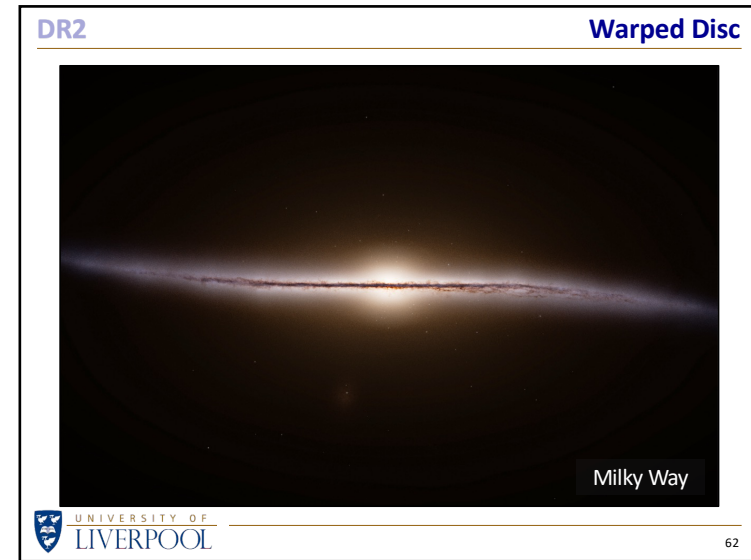
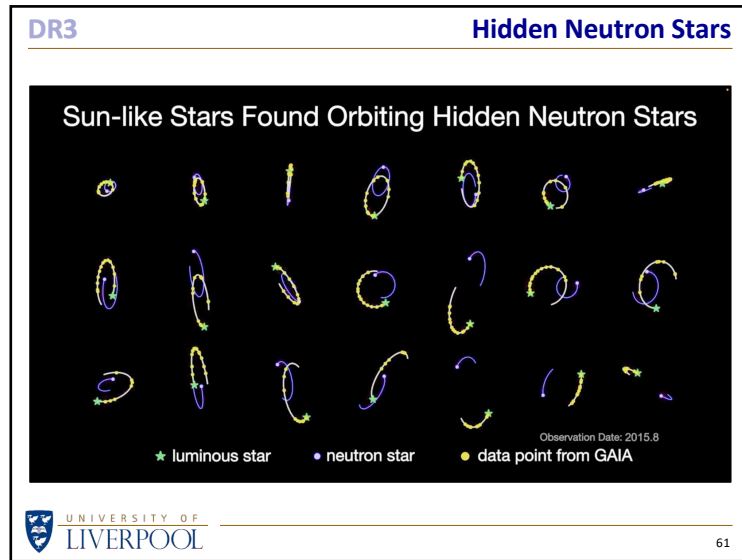
This H-R diagram for millions
of stars in the Milky Way gives
us a way to visualise the stellar
population of our galaxy.

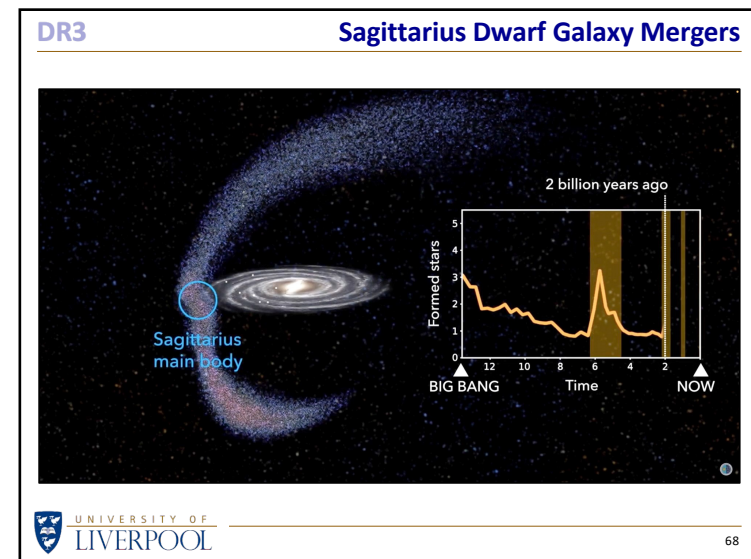
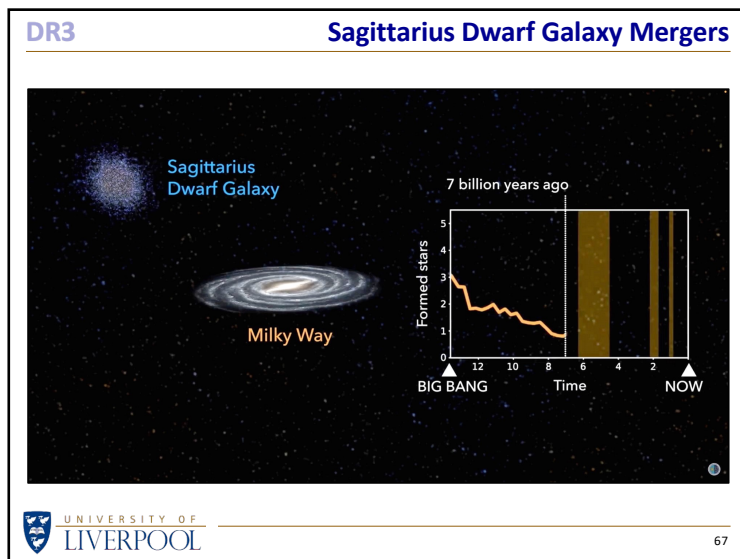
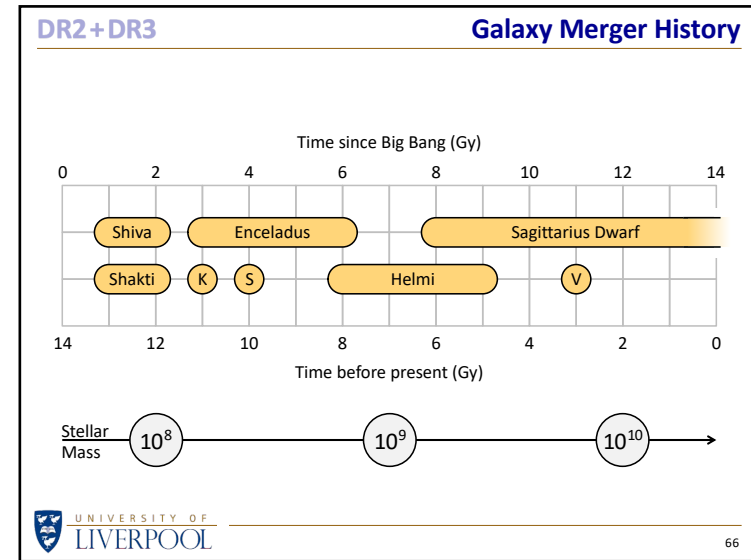
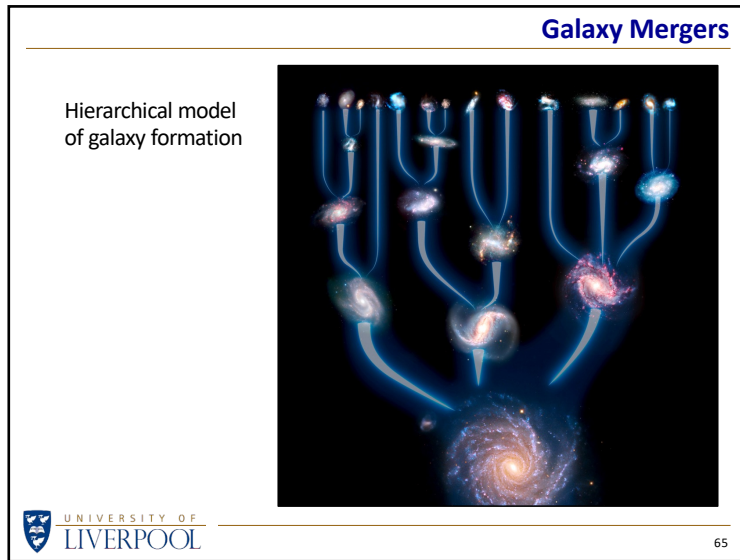


DR3

Sun-like Star and Neutron Star

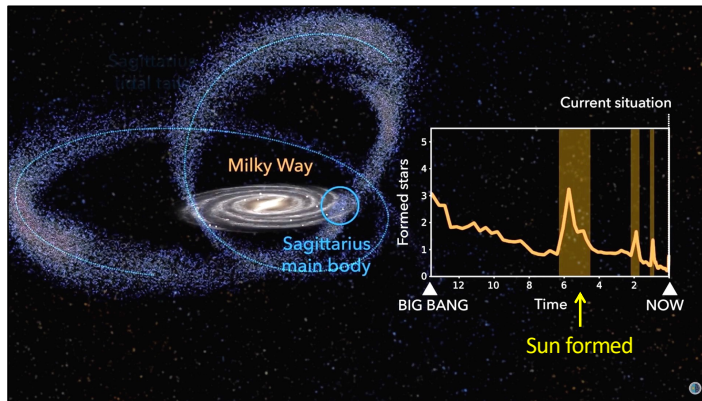




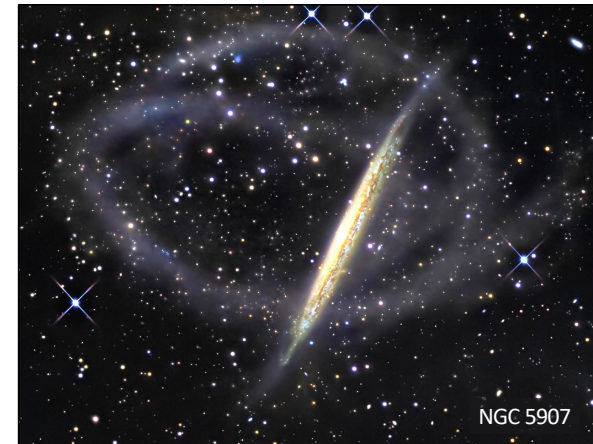


DR3

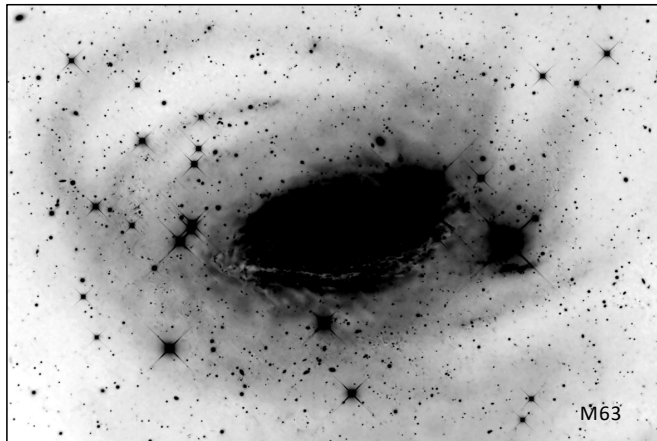
Sagittarius Dwarf Galaxy Mergers



Star Streams



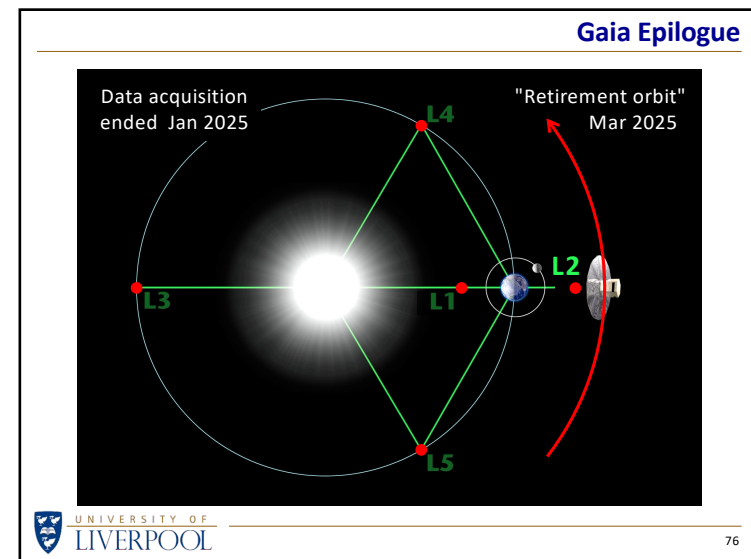
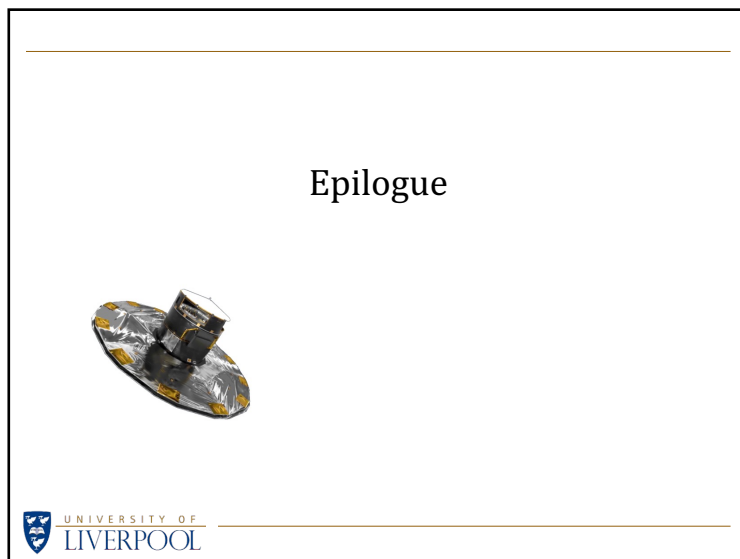
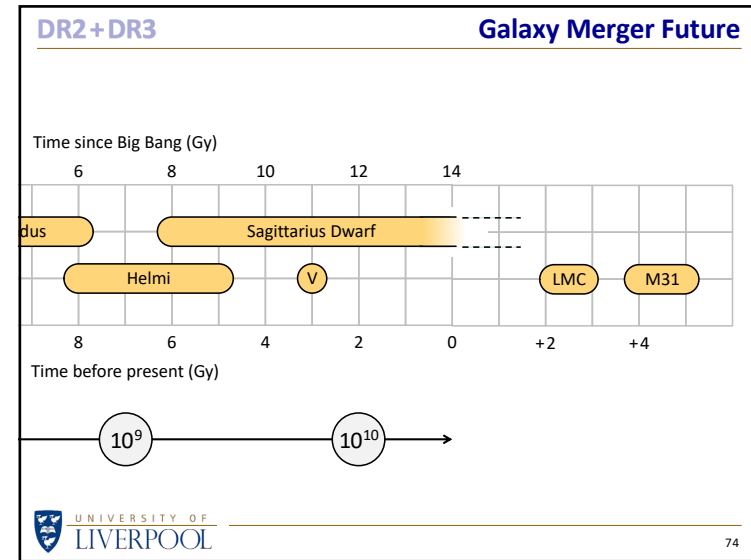
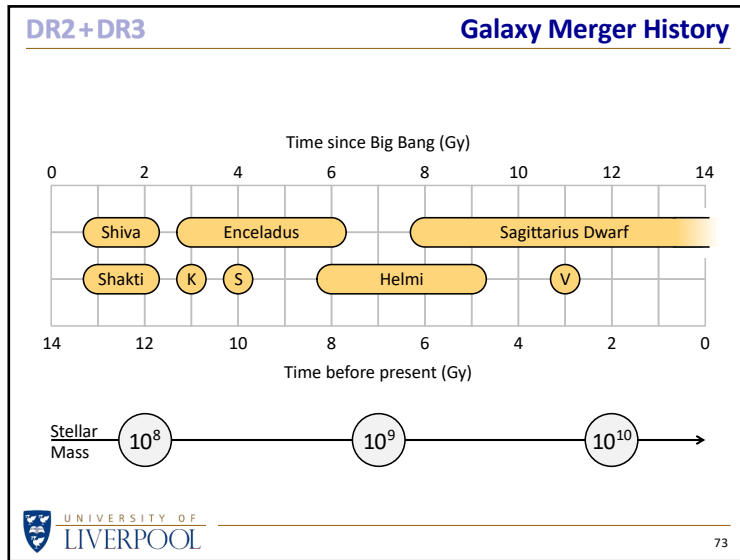
Star Streams



Star Streams



Gaia



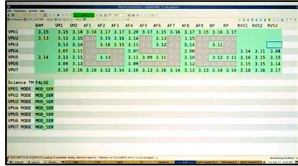
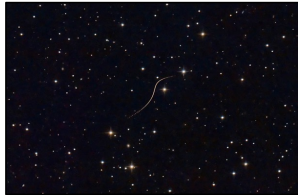
Gaia

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.

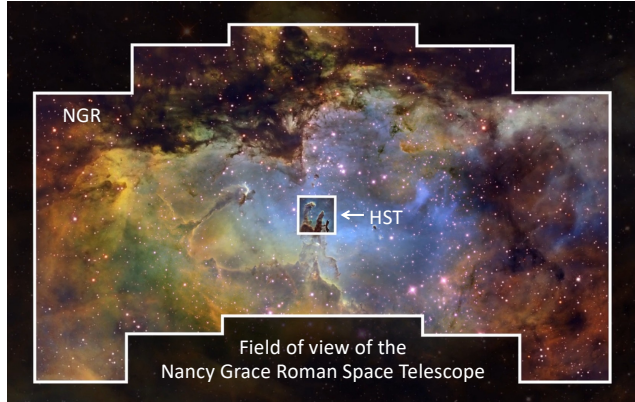
Before it was powered down Gaia sent a final status update.

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Gaia Epilogue



NGR

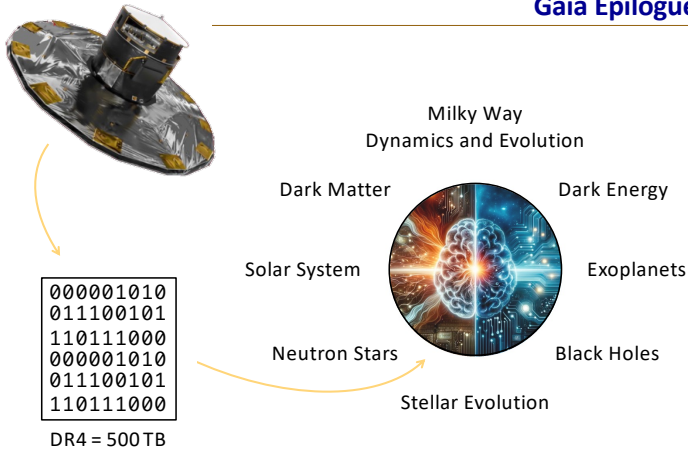
HST

Field of view of the Nancy Grace Roman Space Telescope

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Gaia Epilogue



Milky Way Dynamics and Evolution

Dark Matter

Dark Energy

Solar System

Exoplanets

Neutron Stars

Black Holes

Stellar Evolution

DR4 = 500 TB

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www.liverpool.ac.uk/~sdb/Talks

Gaia

Dr Steve Barrett

SAS 19 Sep 2026