

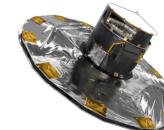
Contents

Why map the stars in the Milky Way?

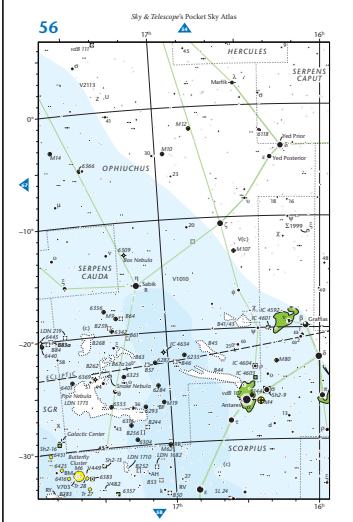
How can they be mapped accurately?

What type of data can be acquired?

What can we learn from the data?



2



Mapping the Stars

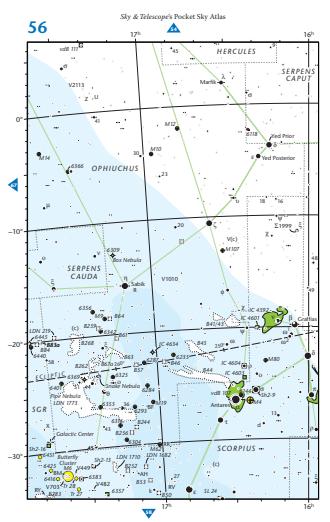
It's a simple question ...

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

3



Mapping the Stars

It's a simple question ...

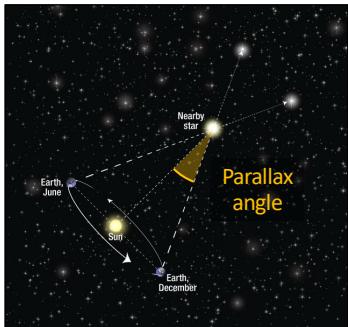
Where are the stars?

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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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.

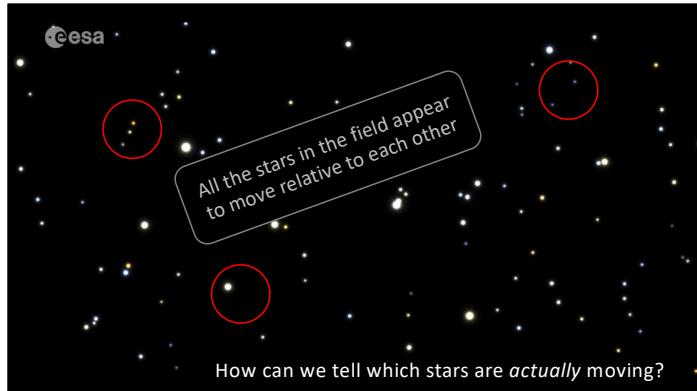
- To calculate distances we need parallax
- Parallax needs the stars' *actual* positions in the sky (not simply their position *relative* to other stars)
- The stars themselves are moving (proper motion)

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 \sim 150AU from Earth.]



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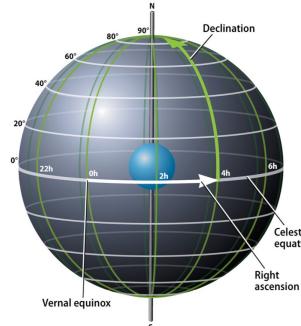
Coordinate Systems

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.

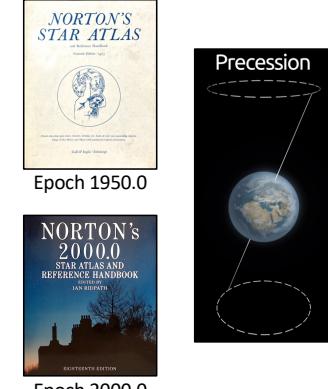
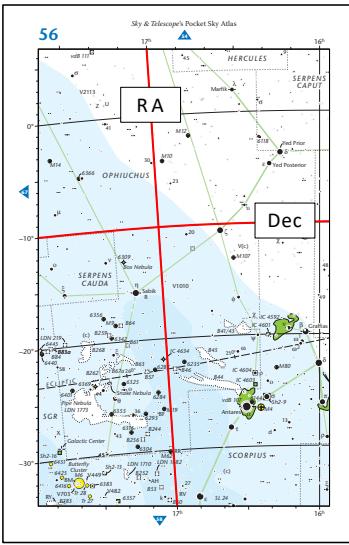
RA and Dec have been used in star atlases since the days of the first Astronomer Royal.

Why are they not good enough?



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Coordinate Systems



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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**

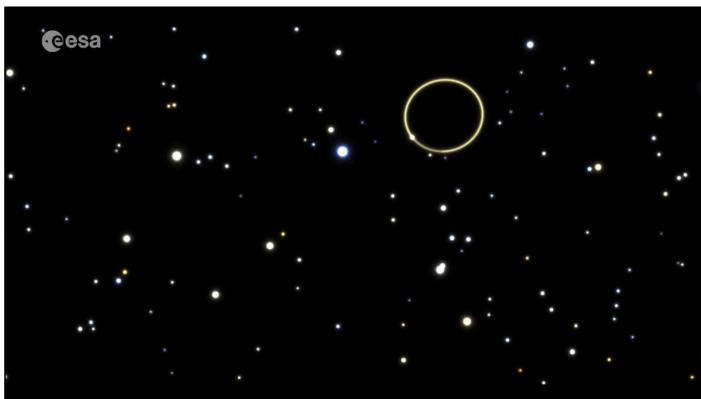
Hence the best coordinate system uses this barycentre as a fixed reference point.



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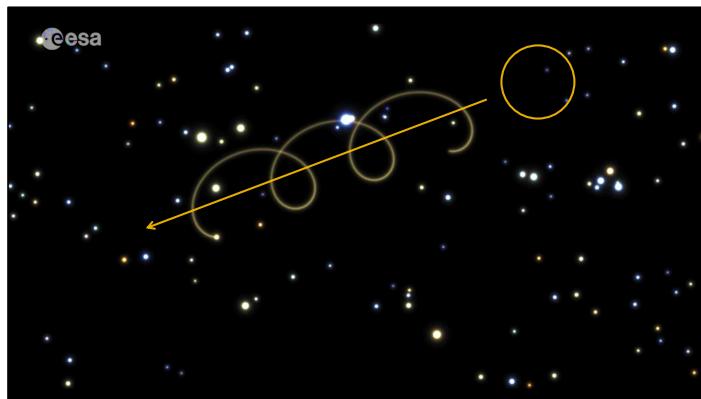
Gaia

Parallax Only



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Parallax and Proper Motion

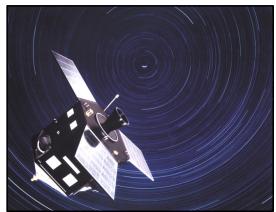


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Hipparcos

High **P**recision **P**ARallax **C**ollecting **S**atellite 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.



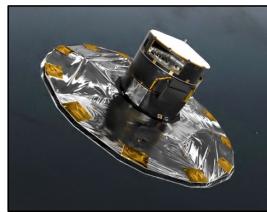
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Gaia

Global **A**strometric **I**nterferometer for **A**strophysics 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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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 1000km



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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?



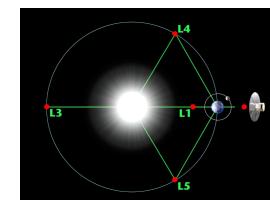
Gaia Hardware



Gaia was ... constructed 2006–2012

... launched in Dec 2013

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



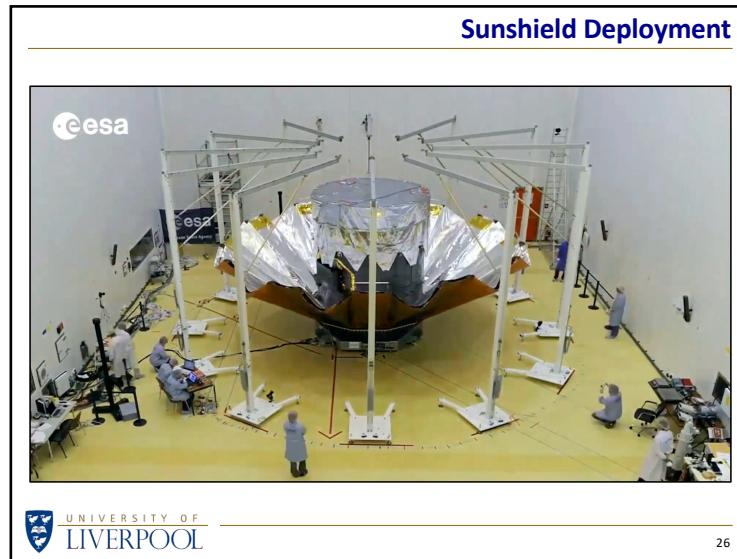
24

Why Park at L2?

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

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Gaia Hardware

esa ASTRUM AIRBUS

Gaia was ... constructed 2006–2012

... launched in Dec 2013

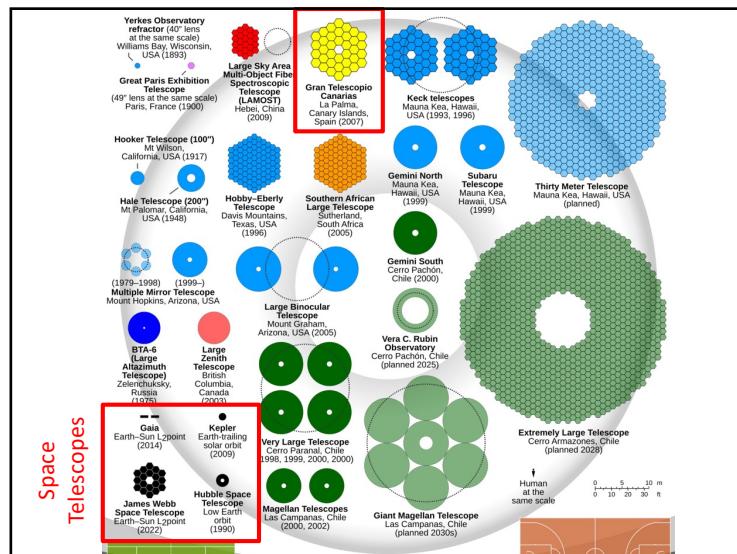
... placed into a halo orbit around L2 in Jan 2014

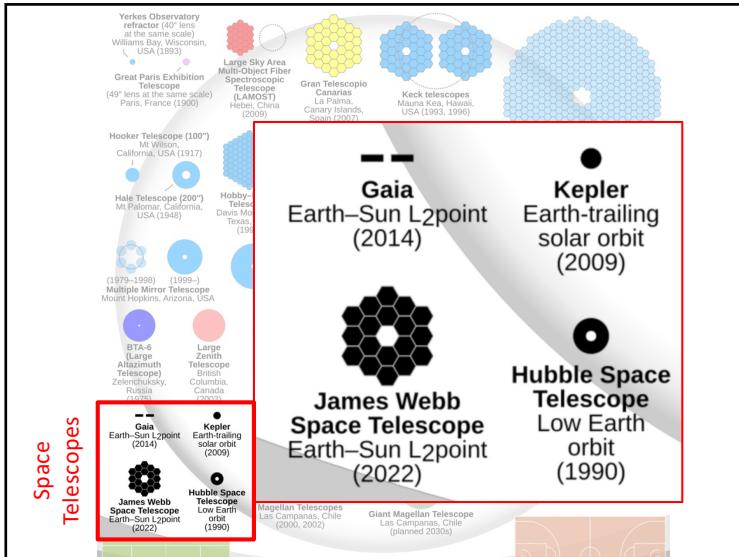
How was Gaia's micro arcsec (μ as) precision achieved?

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

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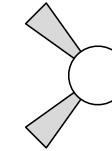
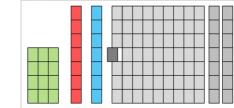


Gaia Hardware

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



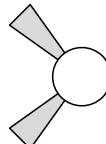
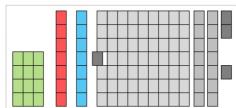
30

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

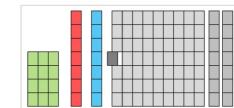


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Gaia Operation

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.

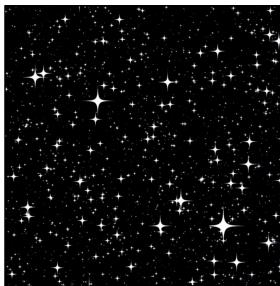


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000001010
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110111000
000001010
011100101
110111000
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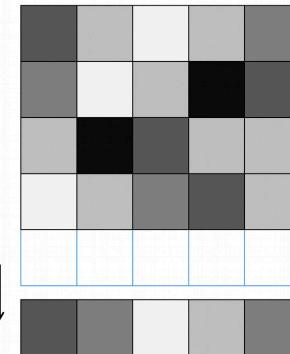
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CCD Images



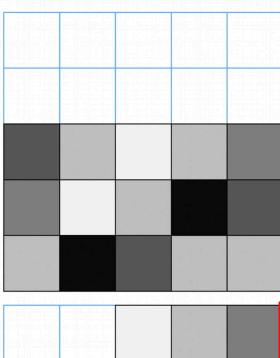
Imagine an image of a star field.
How is the image made?
Image data is just an array of numbers.

Reading a CCD In 'Stare' Mode



Expose CCD to light
Exposure complete
Read data from CCD
Read complete

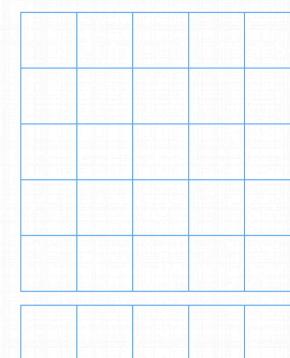
Reading a CCD In 'Stare' Mode



Expose CCD to light
Exposure complete
Read data from CCD
Read complete

1001001011
0111

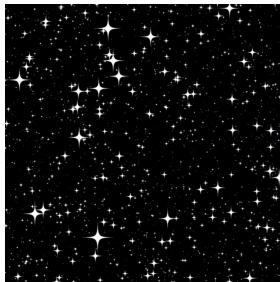
Reading a CCD In 'Stare' Mode



Expose CCD to light
Exposure complete
Read data from CCD
Read complete

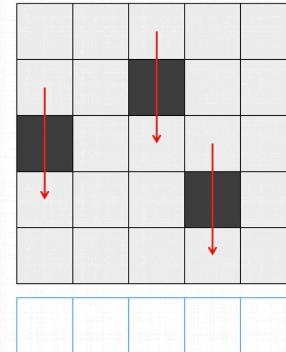
1001001011
0111100100
0101101110
1011100010
1001001011

Reading a CCD In 'Drift' Mode



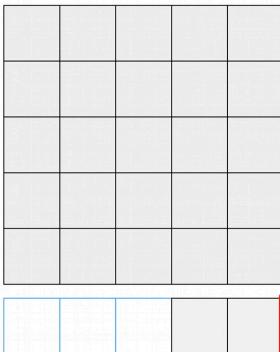
As Gaia spins, stars drift across the CCDs.

Reading a CCD In 'Drift' Mode



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

Reading a CCD In 'Drift' Mode



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

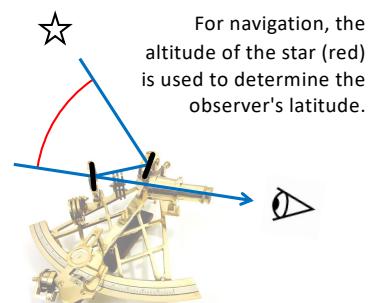


Two Telescopes, One Detector

A sextant works on a similar principle ...

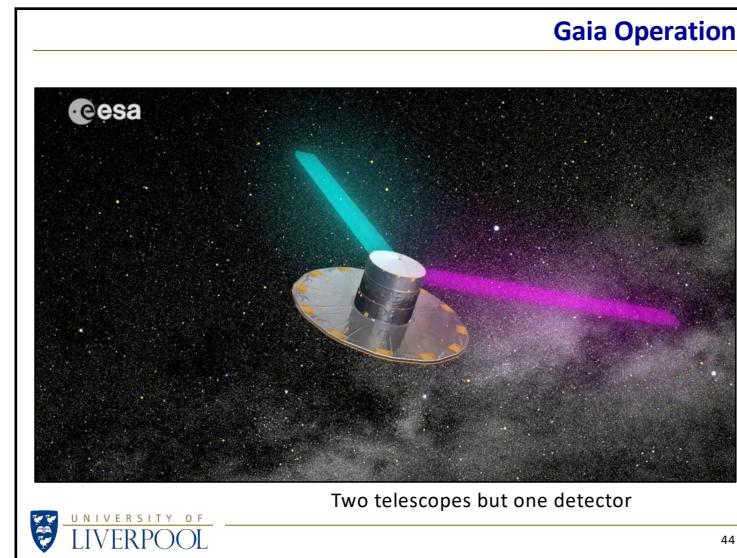
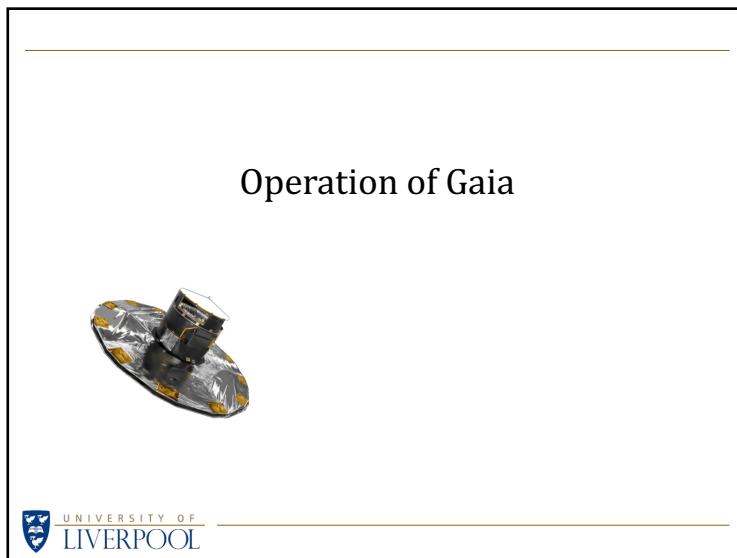
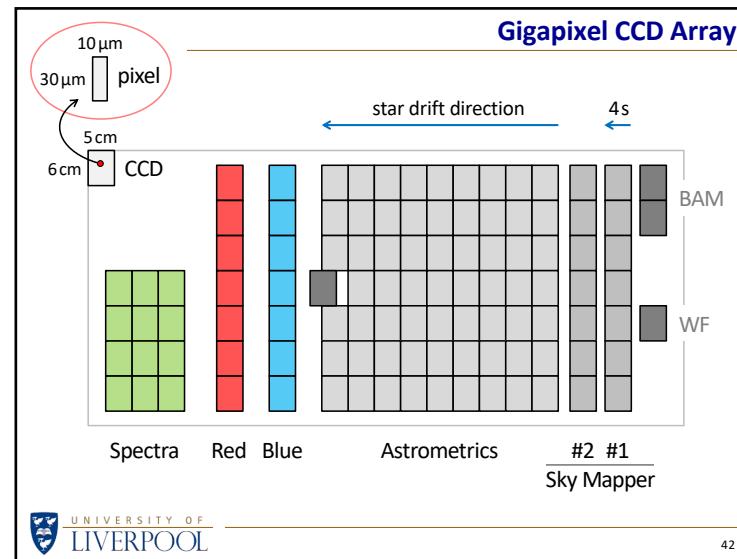
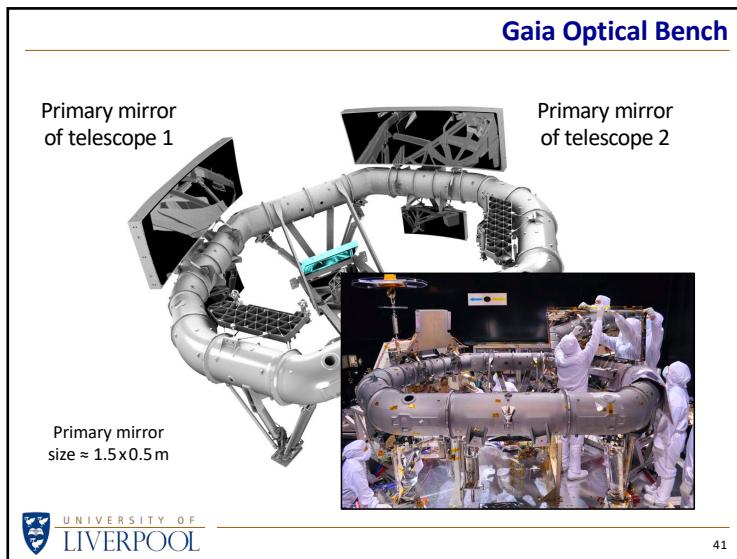


Light from two objects is reflected from mirrors so that they appear together in the 'same detector'.

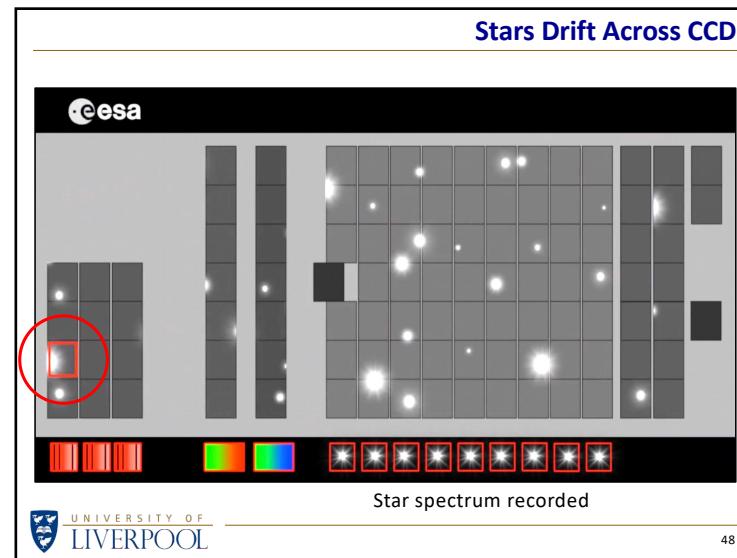
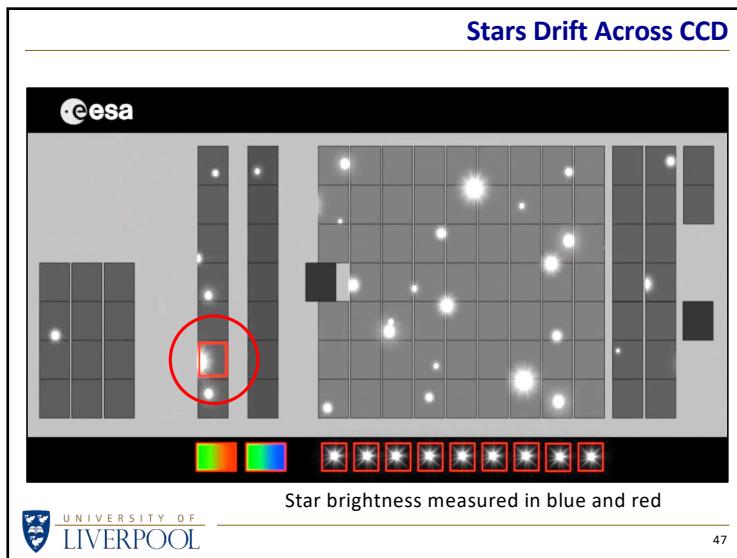
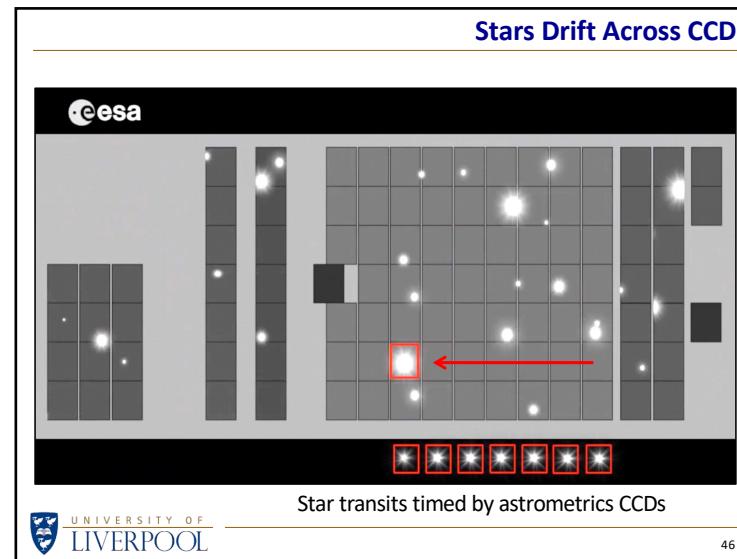
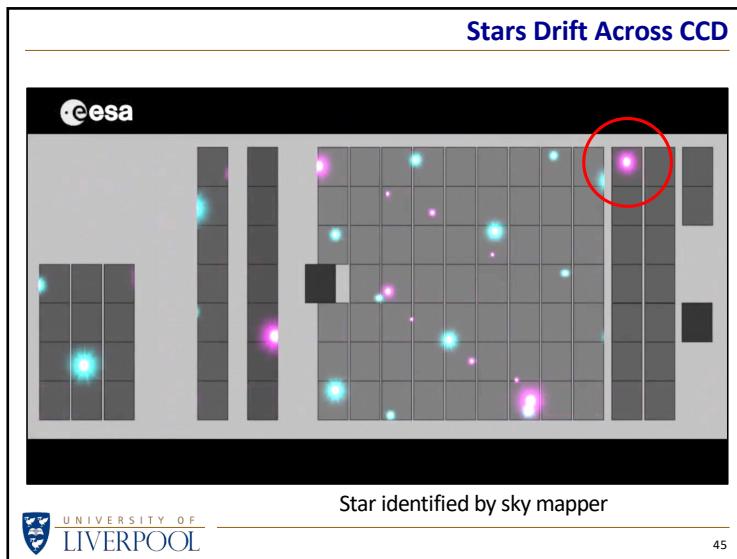


For navigation, the altitude of the star (red) is used to determine the observer's latitude.

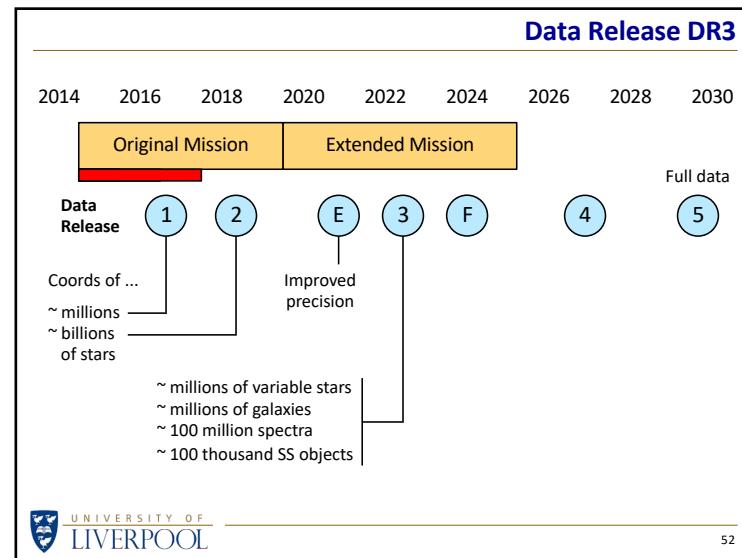
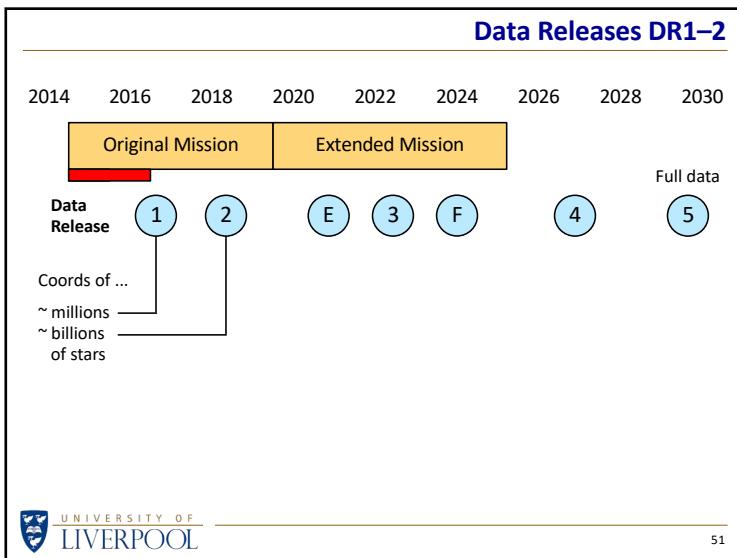
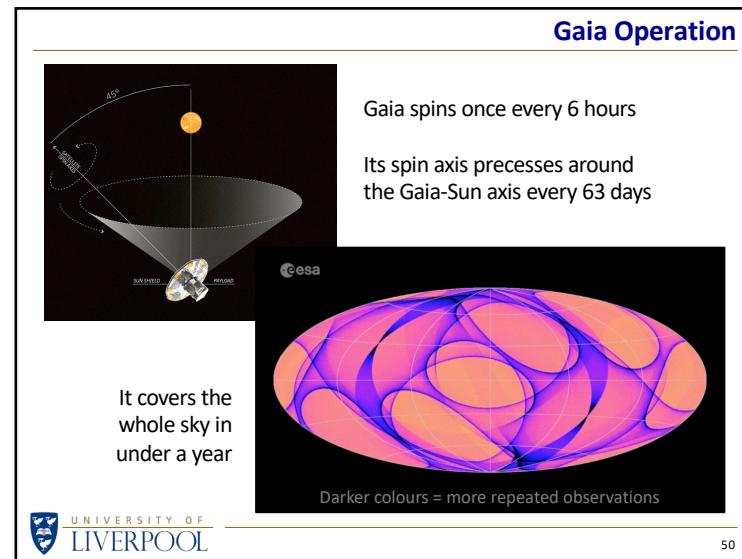
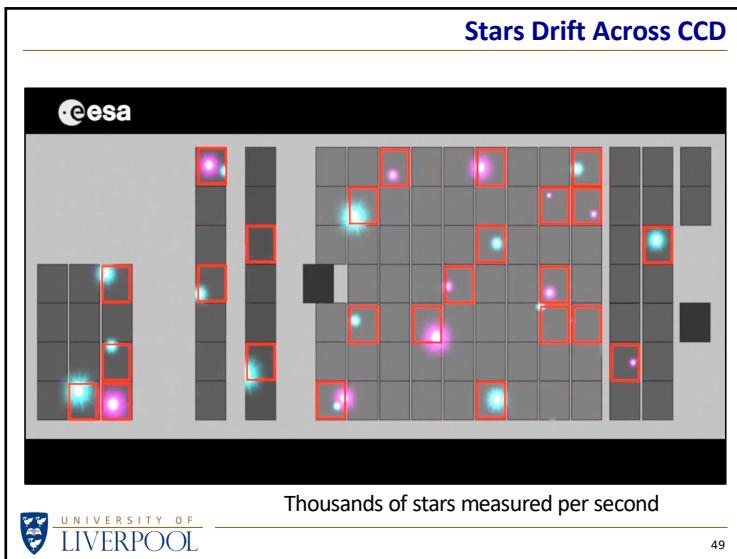
Gaia



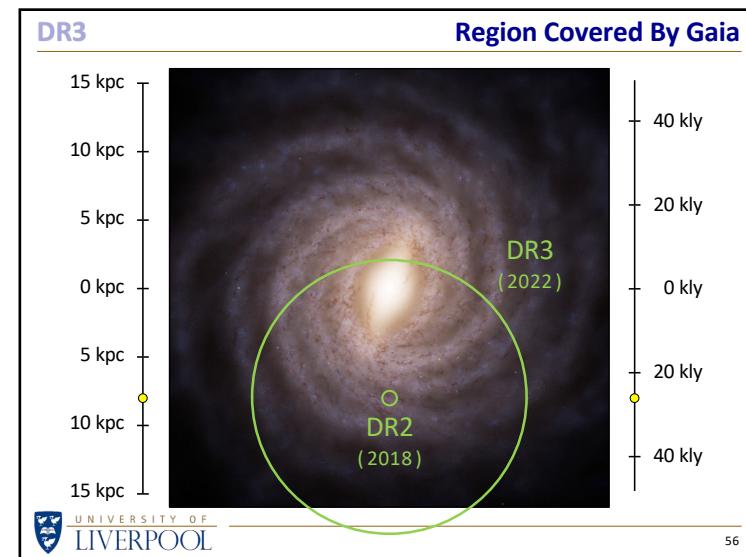
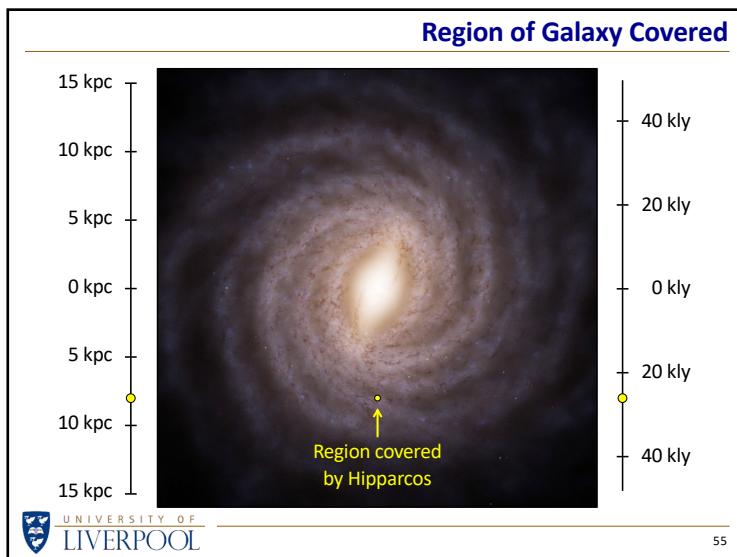
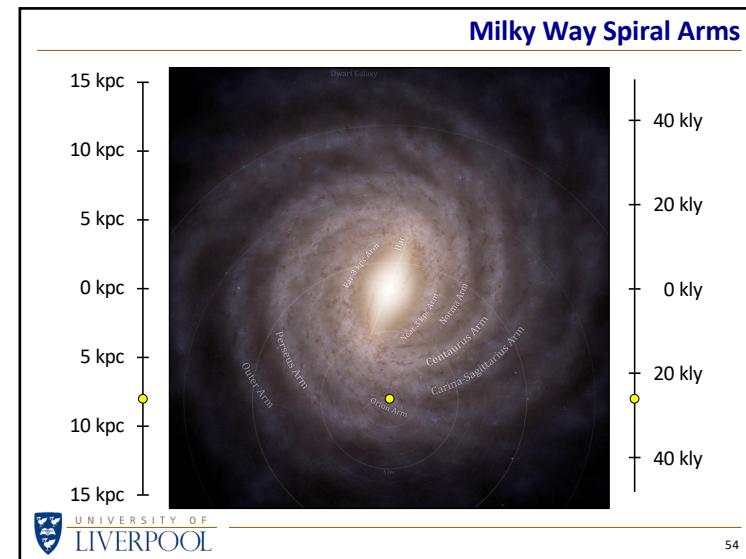
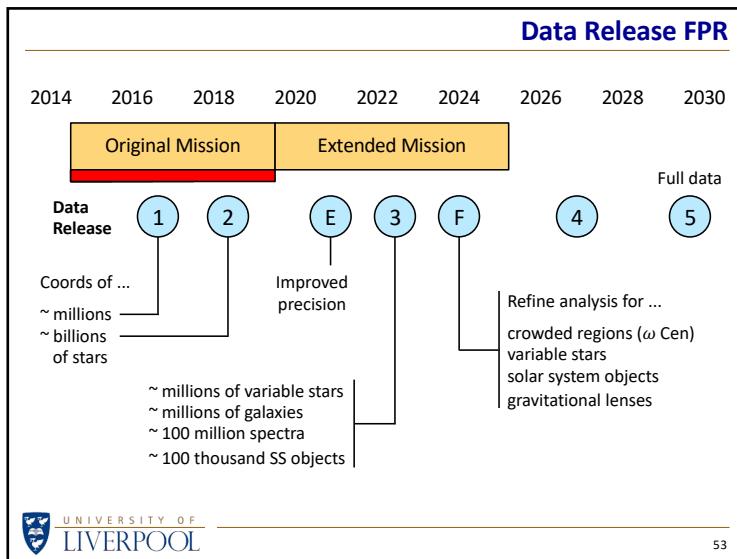
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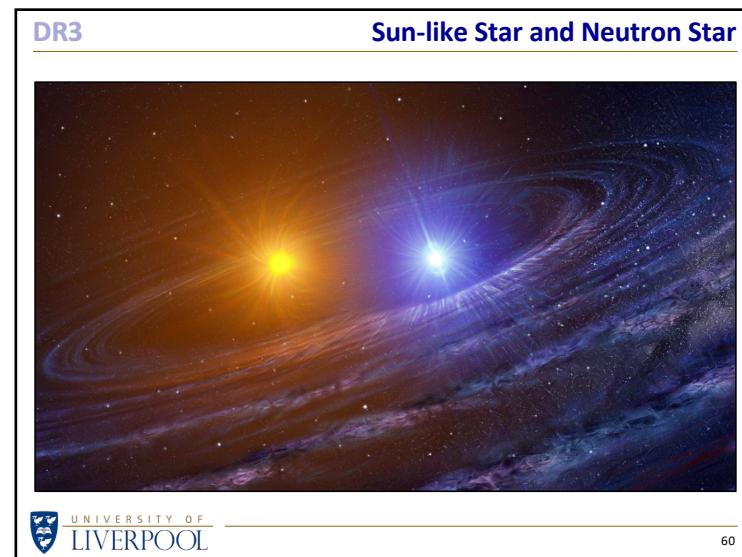
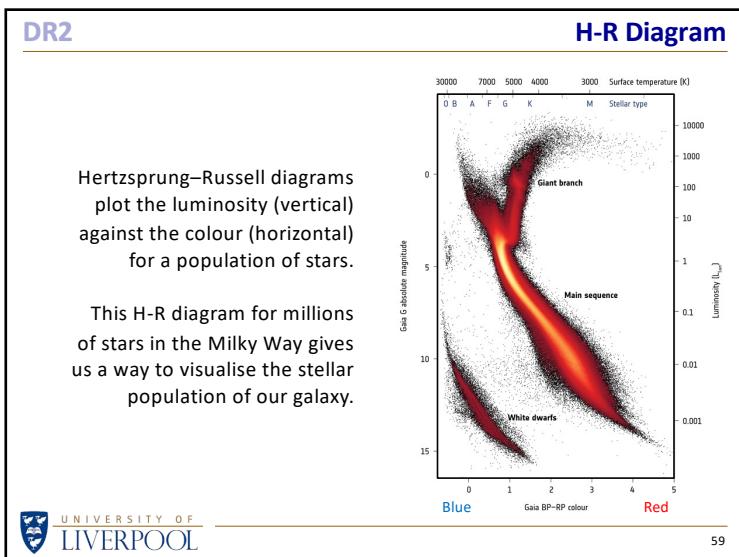
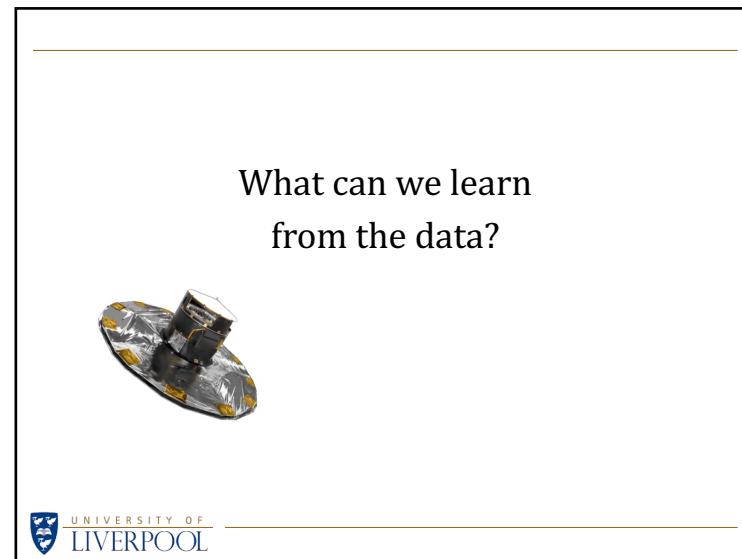
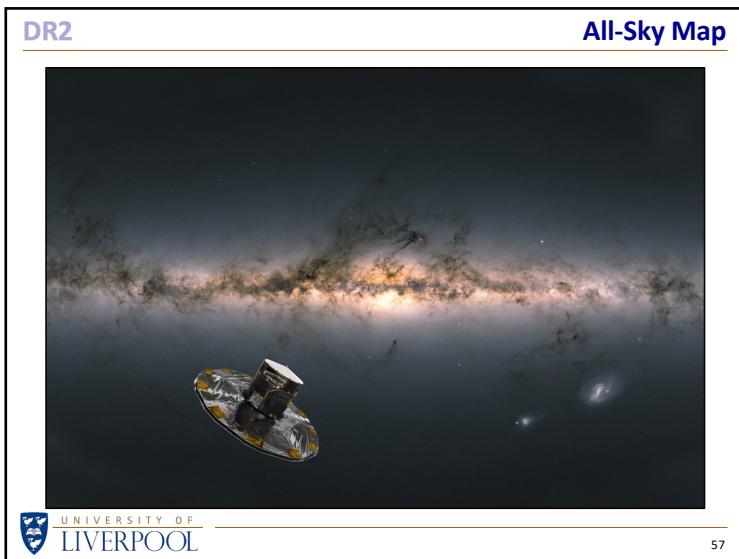


Gaia

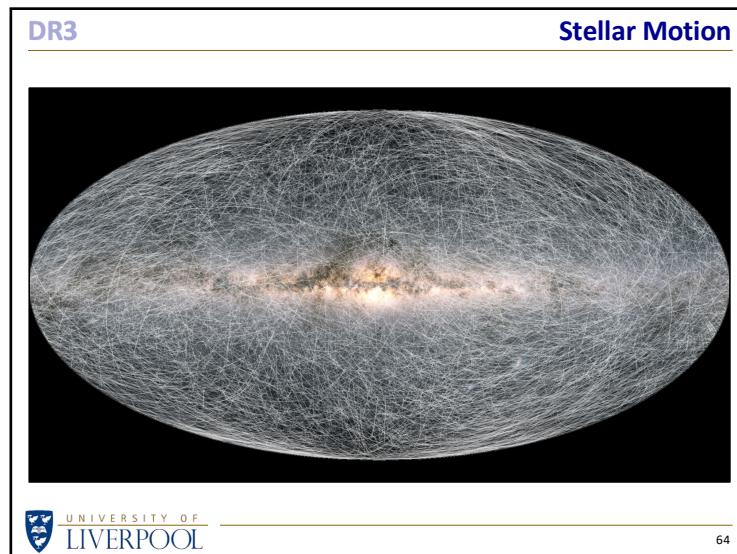
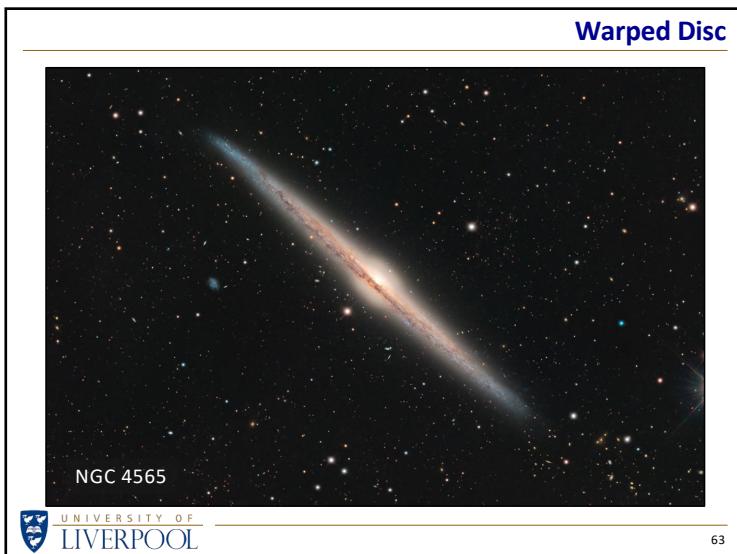
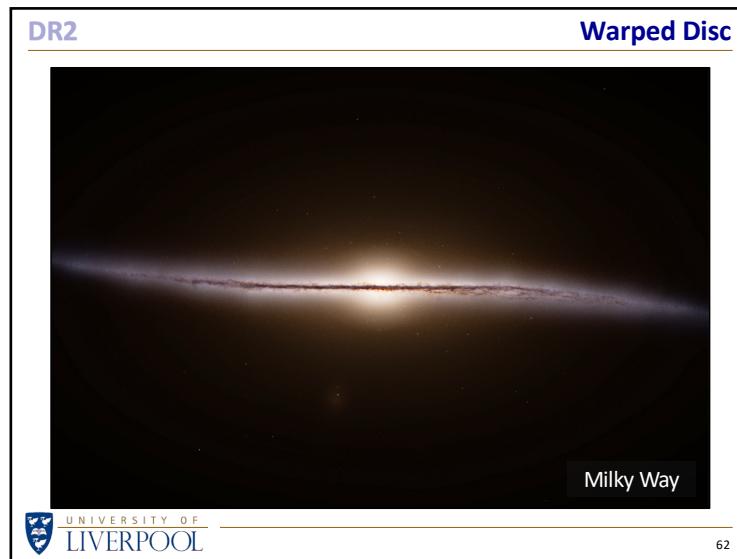
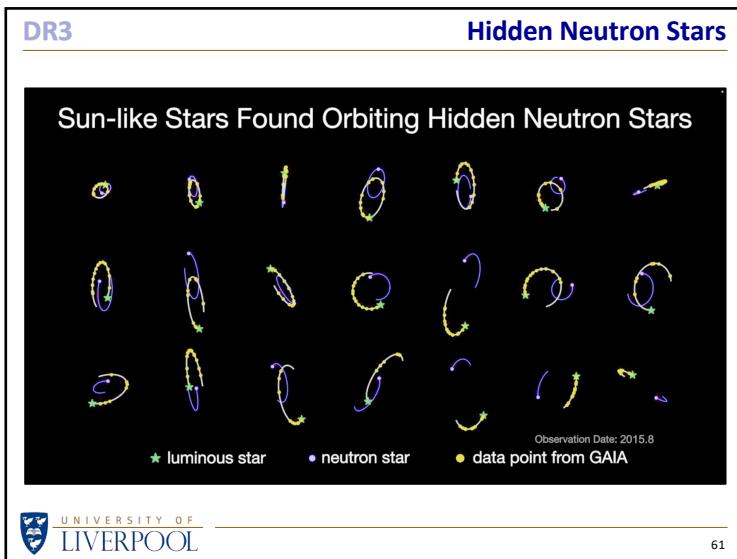


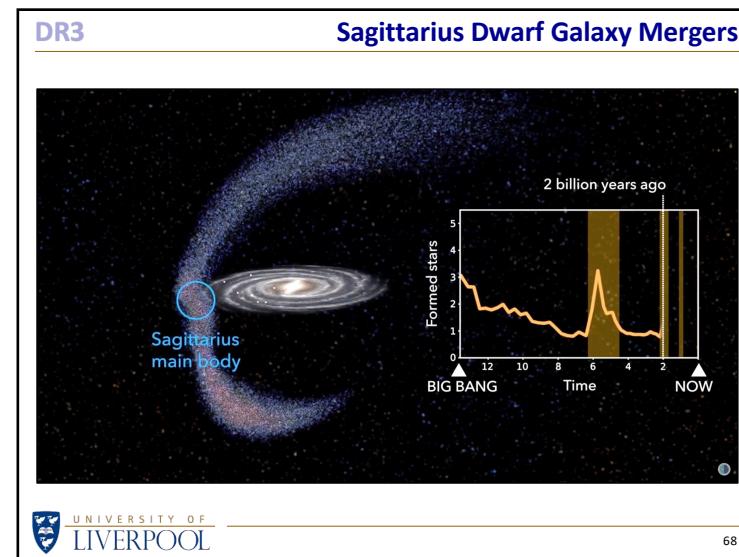
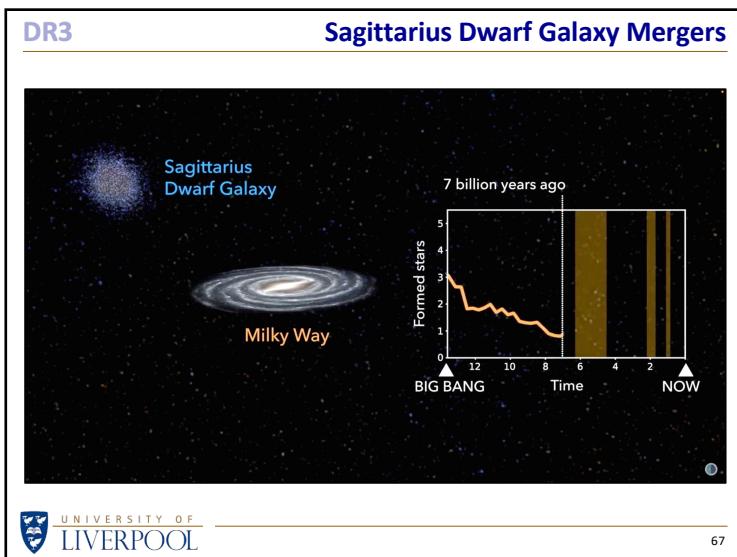
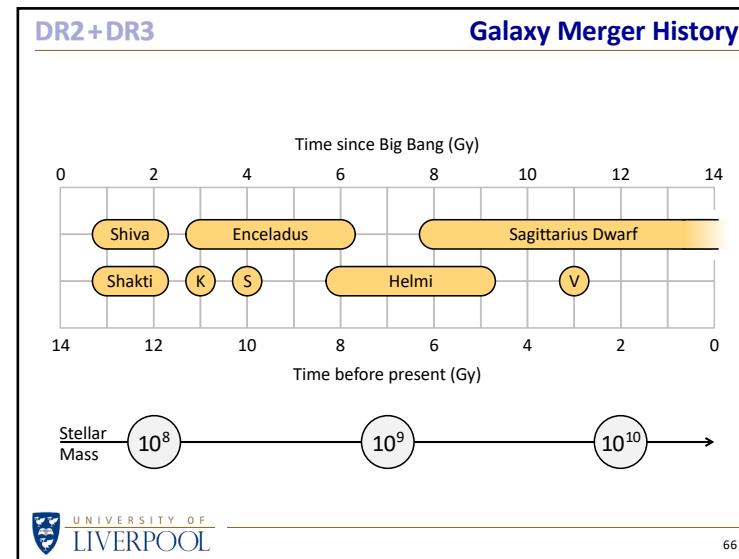
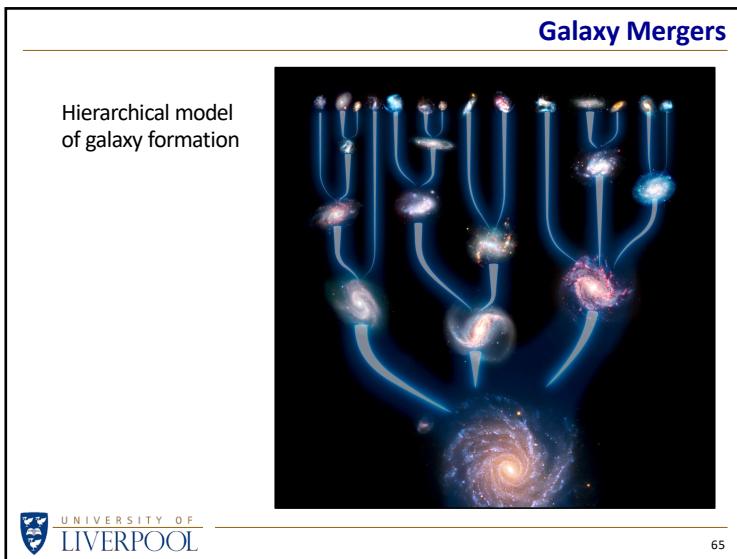
Gaia





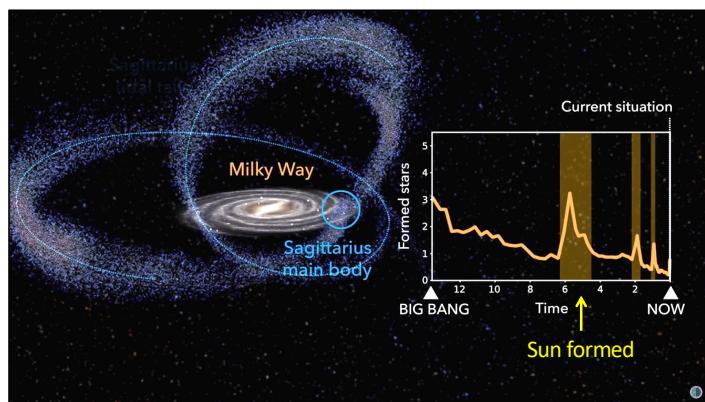
Gaia





DR3

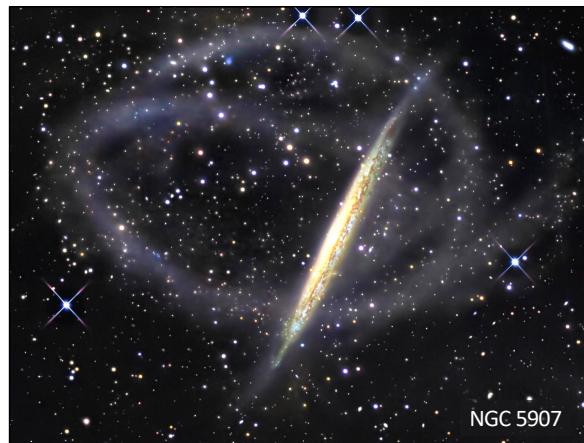
Sagittarius Dwarf Galaxy Mergers



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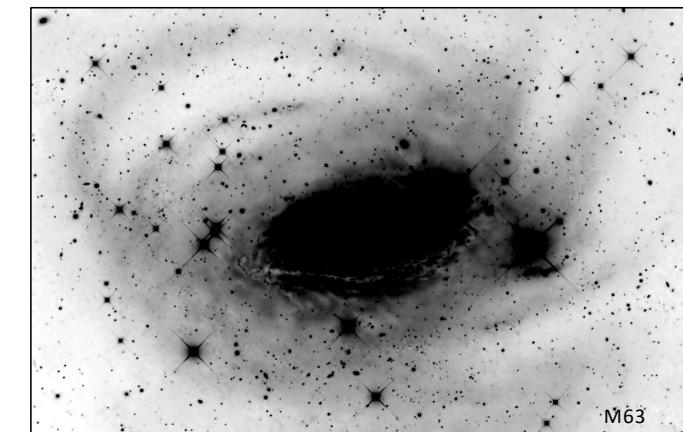
Star Streams



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Star Streams



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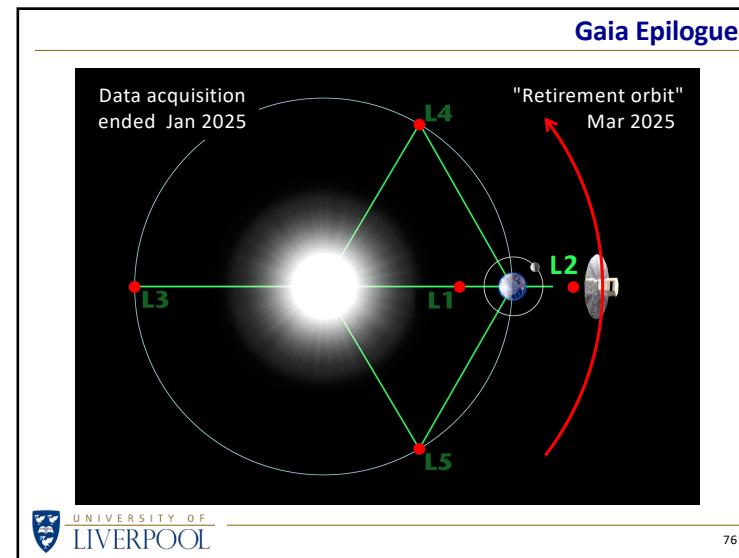
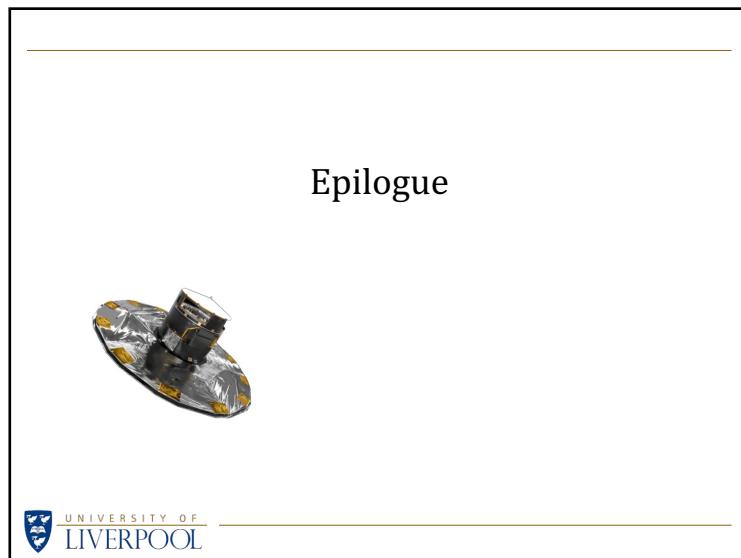
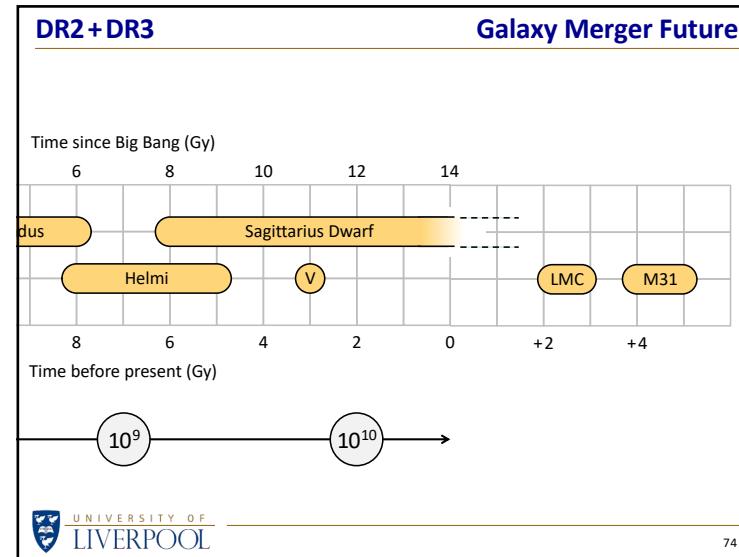
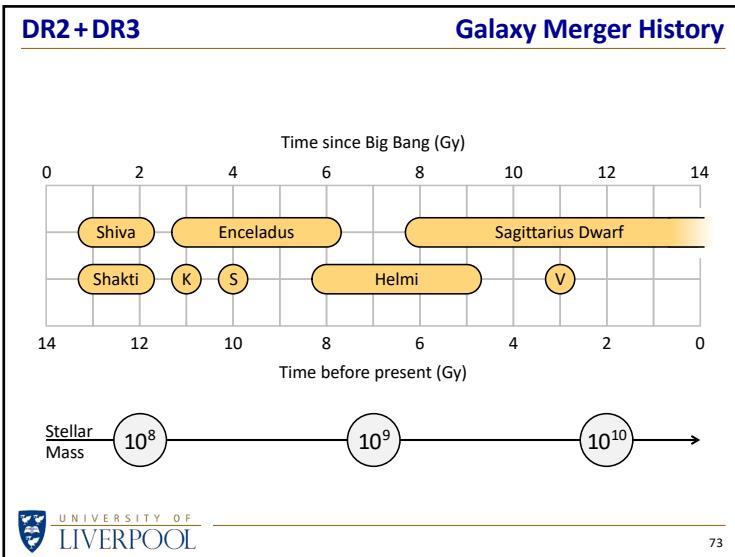
71

Star Streams



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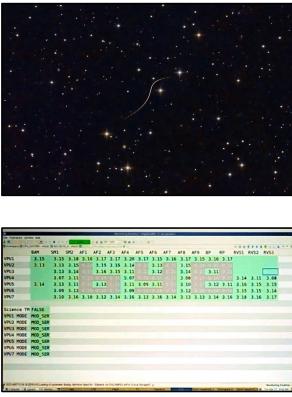


Gaia Epilogue

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.

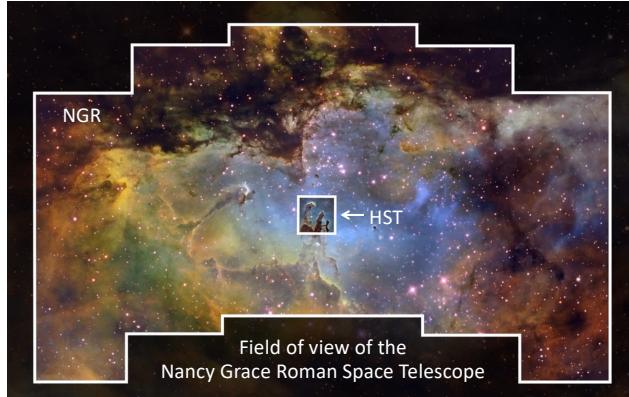
Before it was powered down Gaia sent a final status update.





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Gaia Epilogue





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Gaia Epilogue



000001010
011100101
110111000
000001010
011100101
110111000

DR4 = 500 TB

Milky Way Dynamics and Evolution

Dark Matter

Solar System

Neutron Stars

Stellar Evolution

Dark Energy

Exoplanets

Black Holes





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



Dr Steve Barrett

BASoc 16 Feb 2026