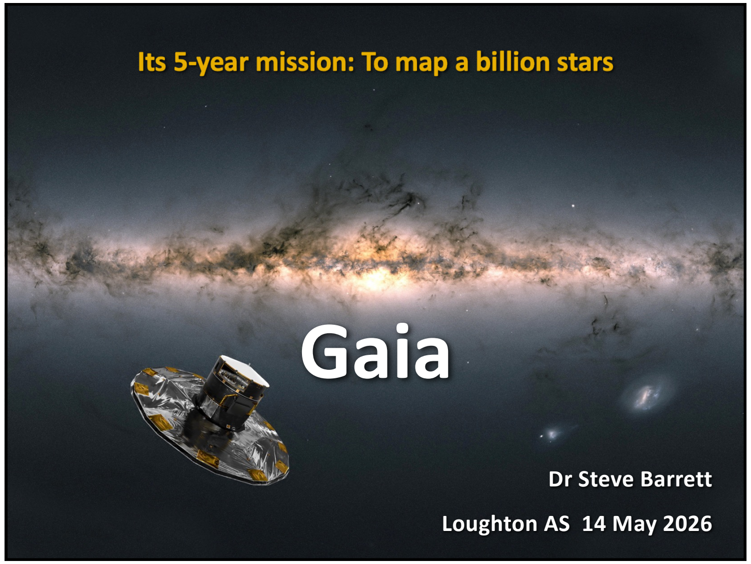


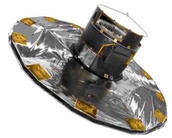
Contents

Why map the stars in the Milky Way?

How can they be mapped accurately?

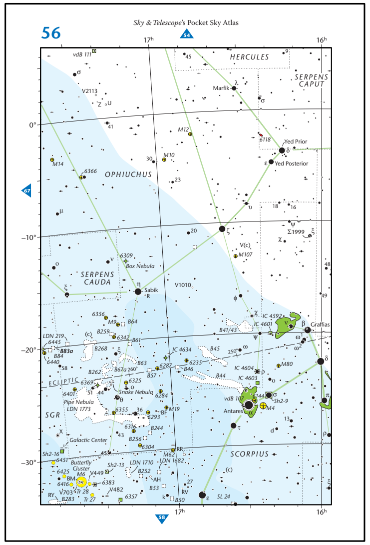
What type of data can be acquired?

What can we learn from the data?



UNIVERSITY OF LIVERPOOL

2



Mapping the Stars

It's a simple question …

Where are the stars?

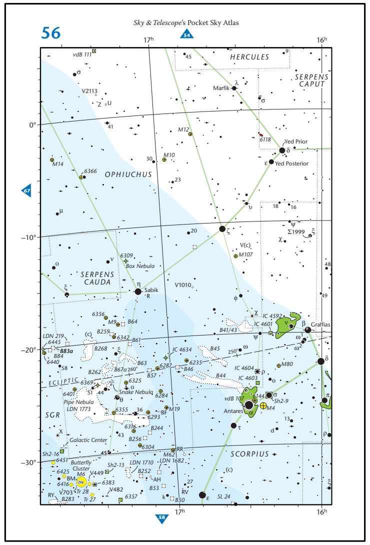
We want to be able to determine the position (on the sky) of any celestial object so that we can …

… 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.

4

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

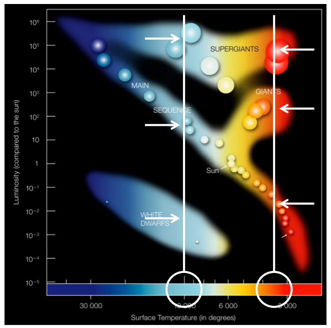
Knowing the positions of stars on the 2-dimensional sky is not enough to determine how they are arranged in 3-dimensions.

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.



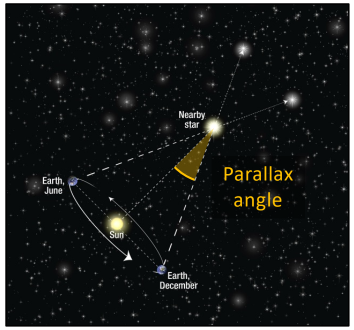
Without knowing the distance to a star we cannot determine its luminosity or its type.

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.

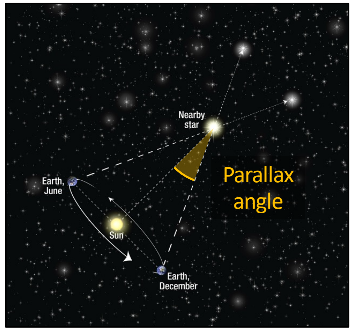
Diagrams like this always imply that a (nearby) star can be aligned with more distant (fixed) stars to determine the parallax angle.



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

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 "**par**allax **sec**ond".

1 parsec = 3.26 light-years

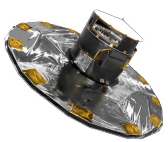
Measuring Parallax

So here is the crux of the problem.

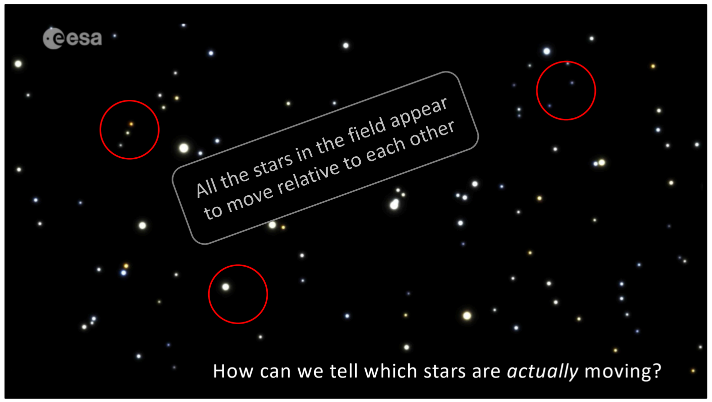
- To calculate distances we need parallax
- Parallax needs the stars' *actual* positions in the sky (not simply their position *relative* to other stars)
- The stars themselves are moving (proper motion)

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 1 AU to 1000 AU. 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 ~150 AU from Earth.]

UNIVERSITY OF LIVERPOOL 13

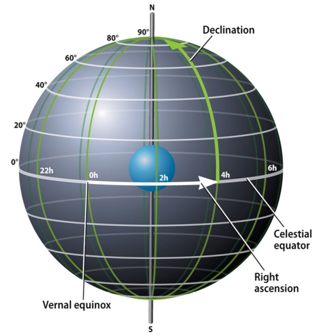
Coordinate Systems

What coordinate system should we use to map the stars?

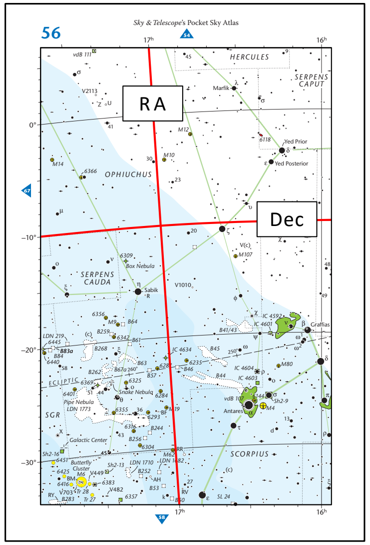
The equatorial coordinate system, comprising Right Ascension (RA) and Declination (Dec) coordinates, uses the celestial equator as a reference.

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

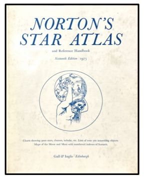
Why are they not good enough?



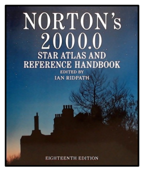
UNIVERSITY OF LIVERPOOL 14



Coordinate Systems



Epoch 1950.0

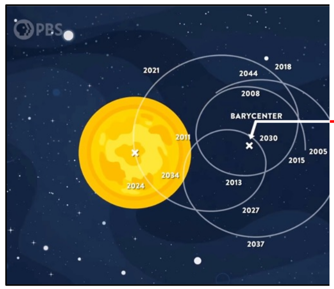


Epoch 2000.0

15

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.



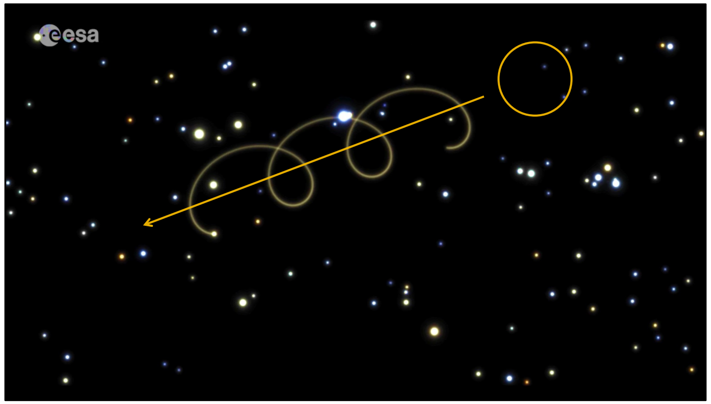
We think of planets orbiting the Sun, but actually they all orbit around a common *barycentre*

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

UNIVERSITY OF LIVERPOOL 16

Parallax Only

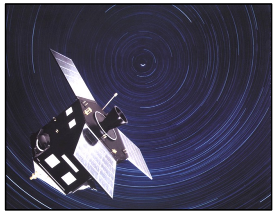
Parallax and Proper Motion



Hipparcos

HIgh **P**recision **PAR**allax **CO**llecting **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

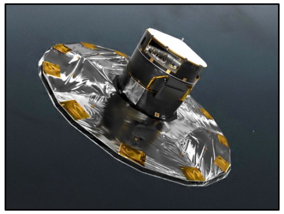
The Hipparcos catalogue was used by the Hubble Space Telescope.

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 ~10 μas. (1 μas = 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

Micro Arc Seconds

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

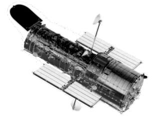
10 μas = 0.01 mas = 0.00001 arc seconds

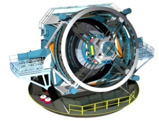
= the thickness of a human hair
seen from a distance of 1000 km

UNIVERSITY OF LIVERPOOL 21

Alternatives?

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

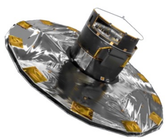




	Hubble Space Telescope	Simonyi (aka LSST) in Vera Rubin Obs
Precision	< 1 mas	100 mas
# stars	1000	> billion
Time to do all-sky survey	> 1000 y	10 y

UNIVERSITY OF LIVERPOOL 22

How does Gaia achieve this?



UNIVERSITY OF LIVERPOOL

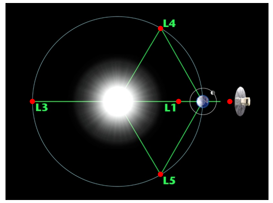
Gaia Hardware

esa ASTRIUM AIRBUS

Gaia was … constructed 2006 – 2012

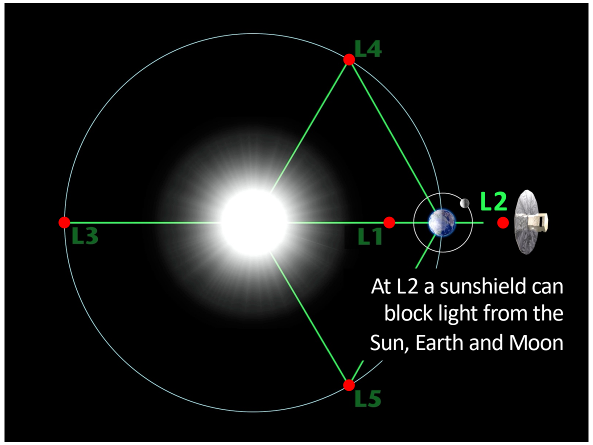
… launched in Dec 2013

… placed into a halo orbit around L2 in Jan 2014



UNIVERSITY OF LIVERPOOL 24

Why Park at L2?



UNIVERSITY OF LIVERPOOL

25

Sunshield Deployment

UNIVERSITY OF LIVERPOOL

26

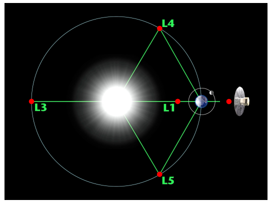
Gaia Hardware

esa ASTRIUM AIRBUS

Gaia was ... constructed 2006 – 2012

... launched in Dec 2013

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

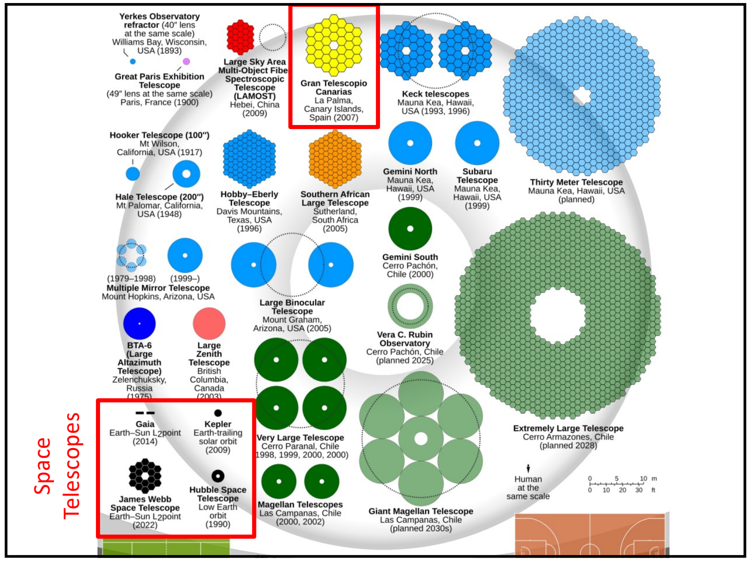


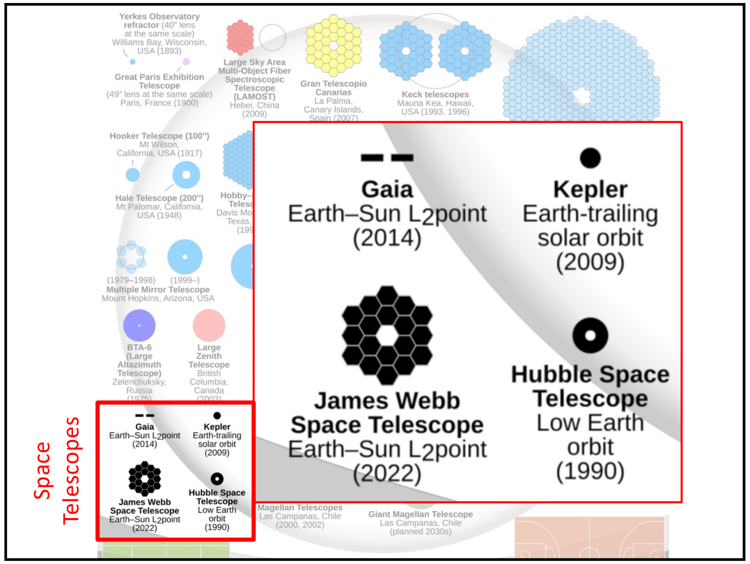
How was Gaia's micro arcsec (μas) precision achieved?

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

UNIVERSITY OF LIVERPOOL

27



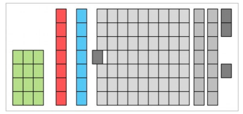


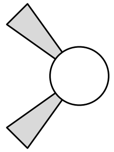
Gaia Hardware

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



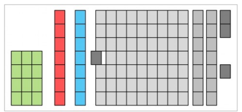


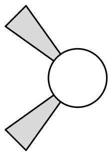
Gaia Operation

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

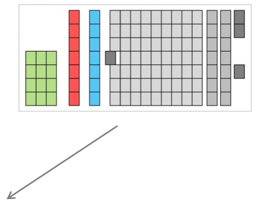




Gaia Operation

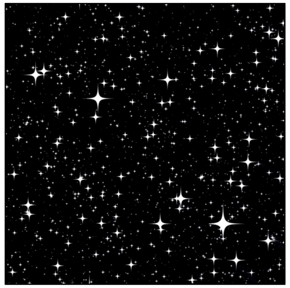
This makes Gaia very different to imaging space telescopes like the Hubble or James Webb Space Telescopes.

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
```

CCD Images

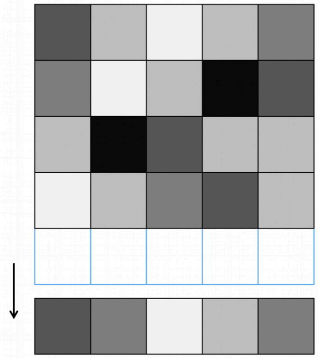


Imagine an image of a star field.

How is the image made?

Image data is just an array of numbers.

Reading a CCD In 'Stare' Mode



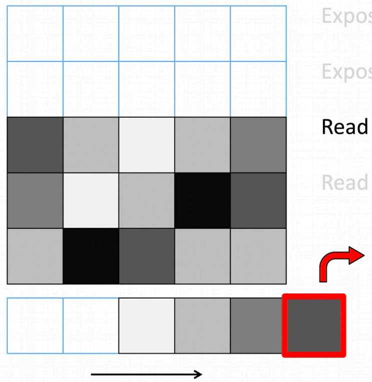
Expose CCD to light

Exposure complete

Read data from CCD

Read complete

Reading a CCD In 'Stare' Mode



Expose CCD to light

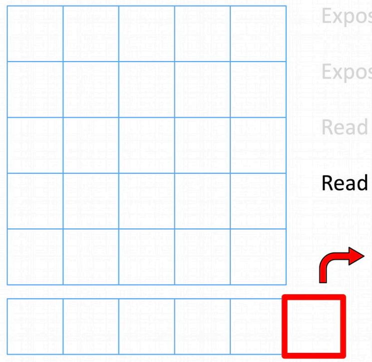
Exposure complete

Read data from CCD

Read complete

1001001011
0111

Reading a CCD In 'Stare' Mode



Expose CCD to light

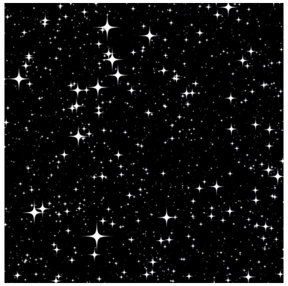
Exposure complete

Read data from CCD

Read complete

1001001011
0111100100
0101101110
1011100010
1001001011

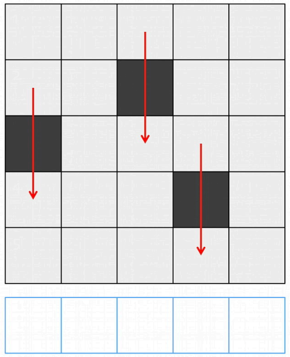
Reading a CCD In 'Drift' Mode



As Gaia spins, stars drift across the CCDs.

UNIVERSITY OF LIVERPOOL 37

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

UNIVERSITY OF LIVERPOOL 38

Reading a CCD In 'Drift' Mode

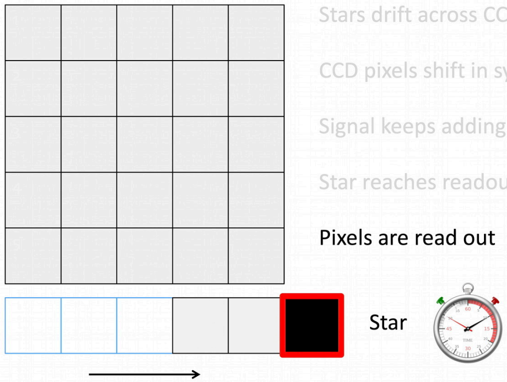
Stars drift across CCD

CCD pixels shift in synch

Signal keeps adding up

Star reaches readout

Pixels are read out

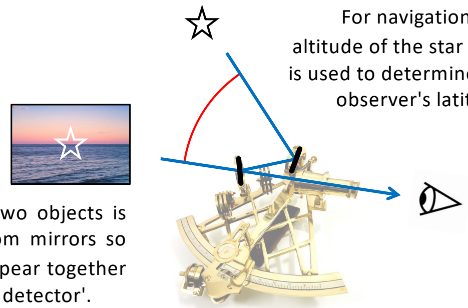


UNIVERSITY OF LIVERPOOL 39

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.

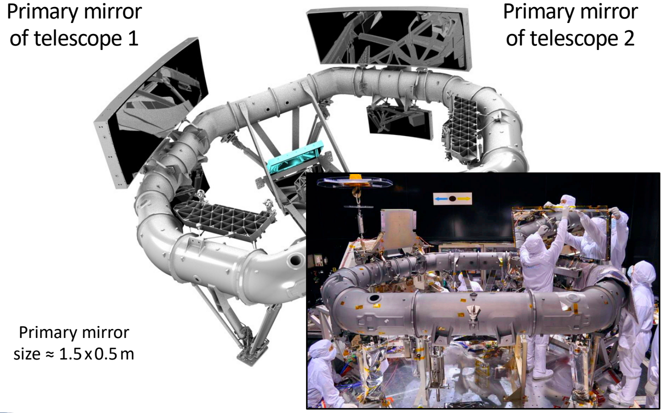


Light from two objects is reflected from mirrors so that they appear together in the 'same detector'.

UNIVERSITY OF LIVERPOOL 40

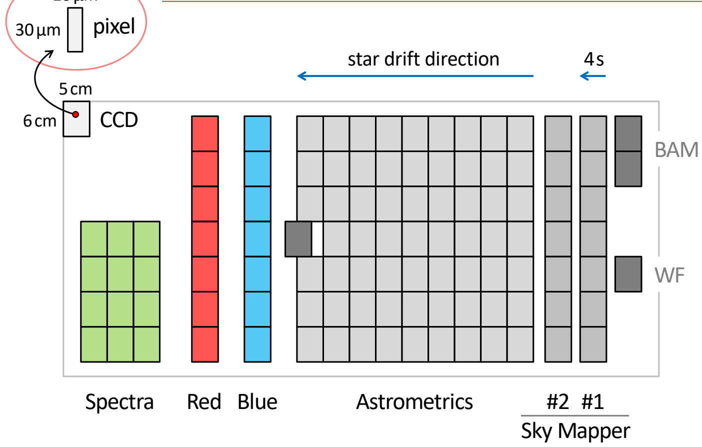
Gaia

Gaia Optical Bench



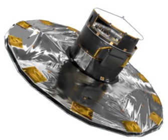
UNIVERSITY OF LIVERPOOL 41

Gigapixel CCD Array



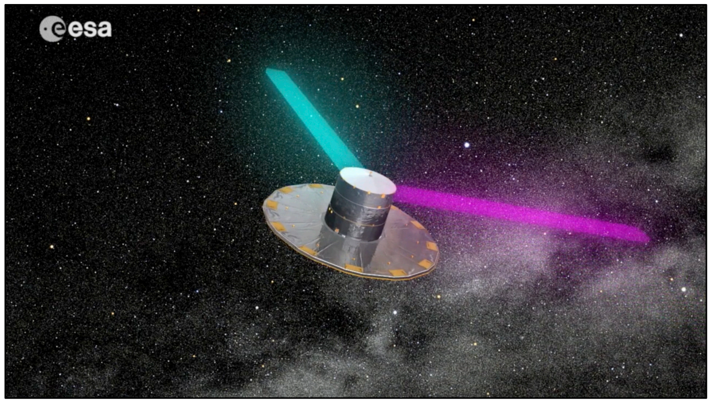
UNIVERSITY OF LIVERPOOL 42

Operation of Gaia



UNIVERSITY OF LIVERPOOL

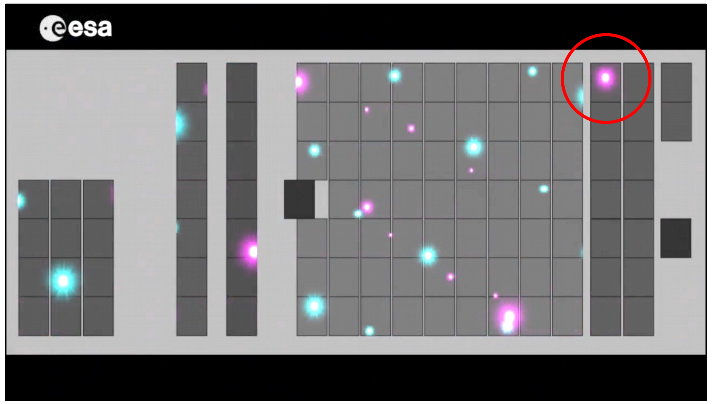
Gaia Operation



Two telescopes but one detector

UNIVERSITY OF LIVERPOOL 44

Stars Drift Across CCD

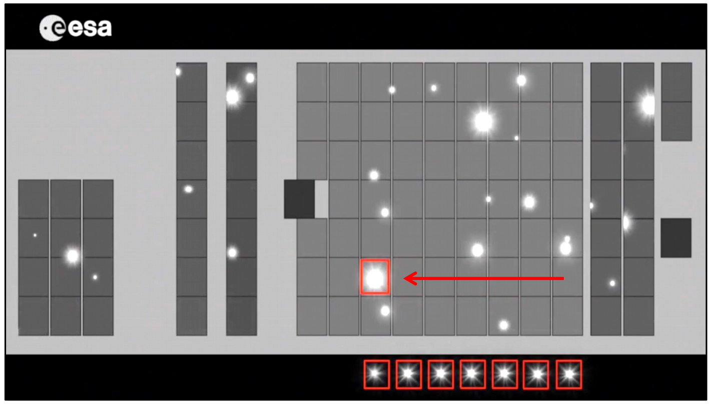


Star identified by sky mapper

UNIVERSITY OF LIVERPOOL

45

Stars Drift Across CCD

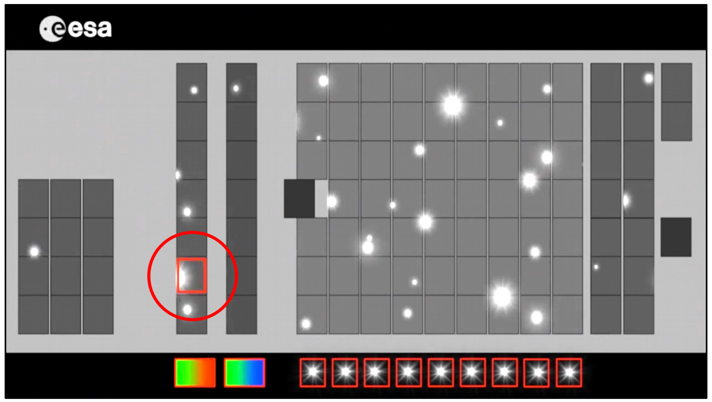


Star transits timed by astrometrics CCDs

UNIVERSITY OF LIVERPOOL

46

Stars Drift Across CCD

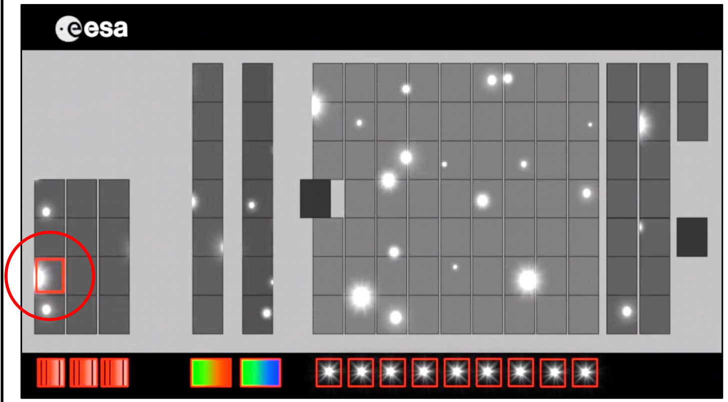


Star brightness measured in blue and red

UNIVERSITY OF LIVERPOOL

47

Stars Drift Across CCD

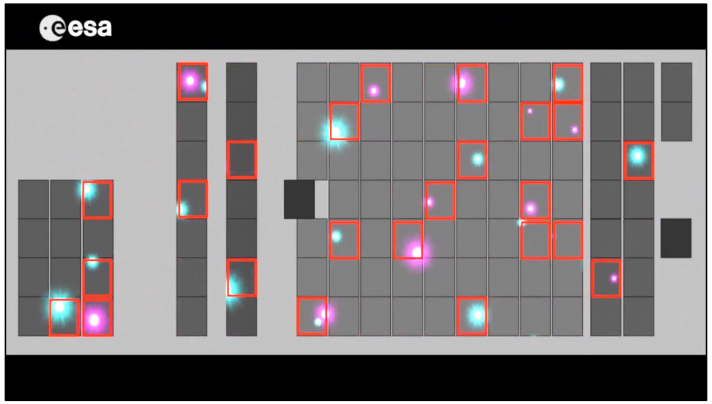


Star spectrum recorded

UNIVERSITY OF LIVERPOOL

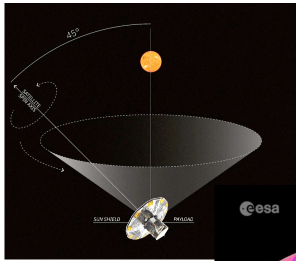
48

Stars Drift Across CCD



Thousands of stars measured per second

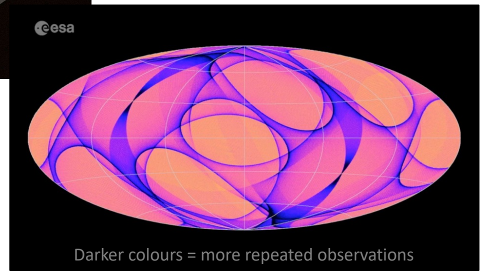
Gaia Operation



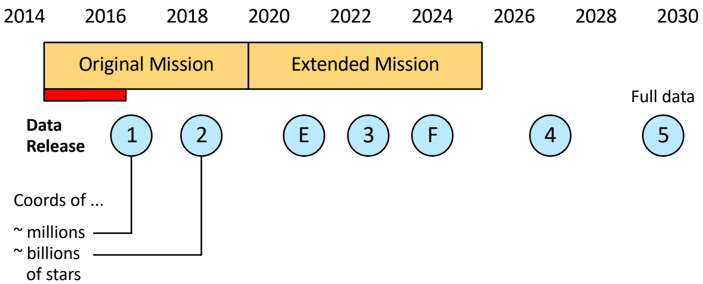
Gaia spins once every 6 hours

Its spin axis precesses around the Gaia-Sun axis every 63 days

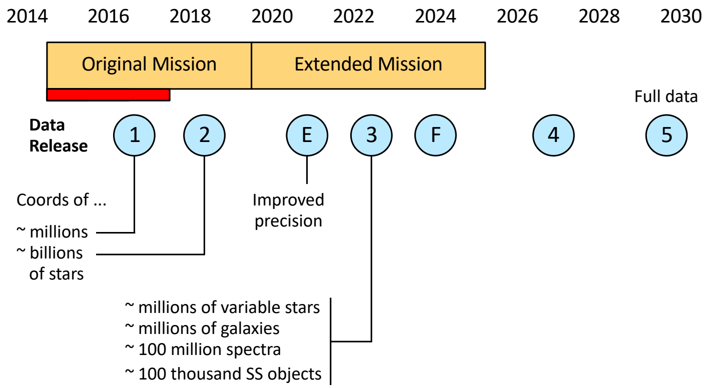
It covers the whole sky in under a year

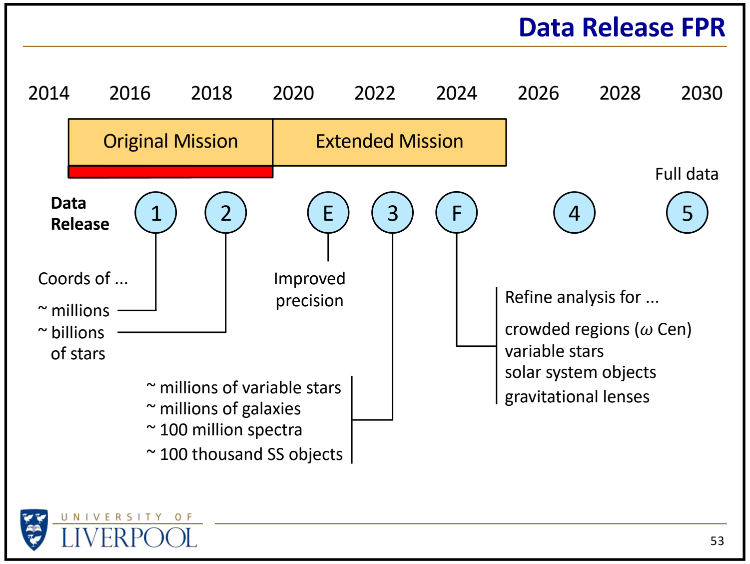


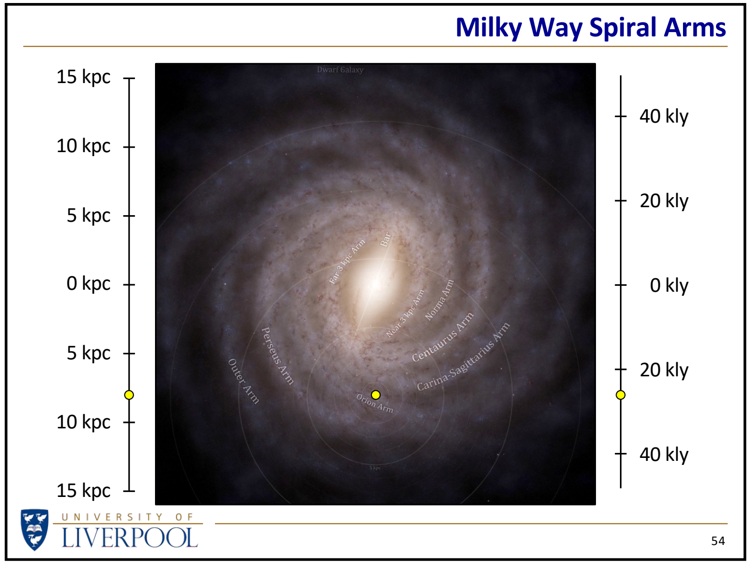
Data Releases DR1–2

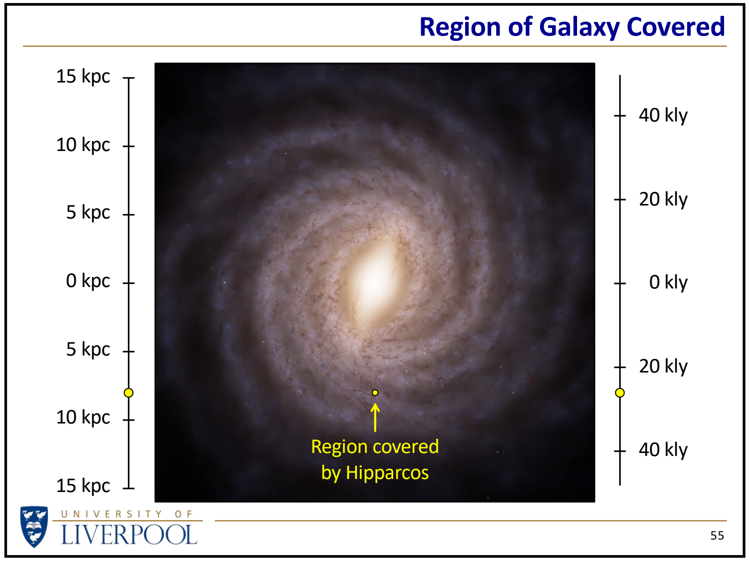


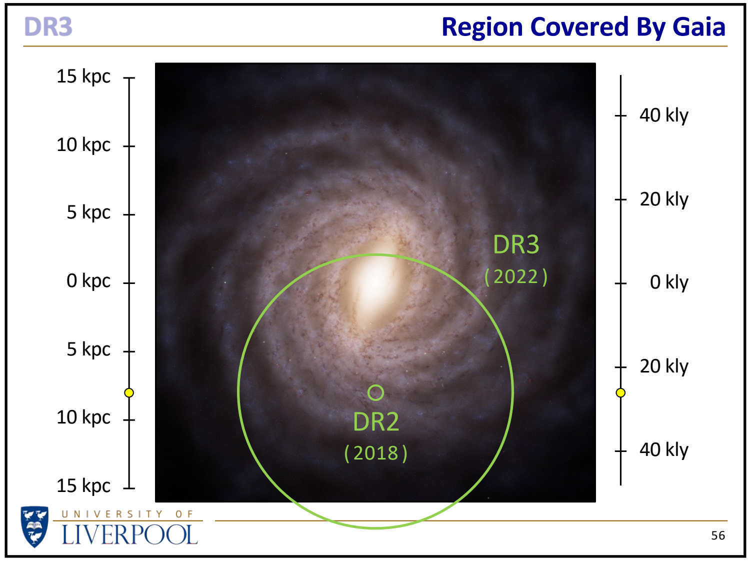
Data Release DR3



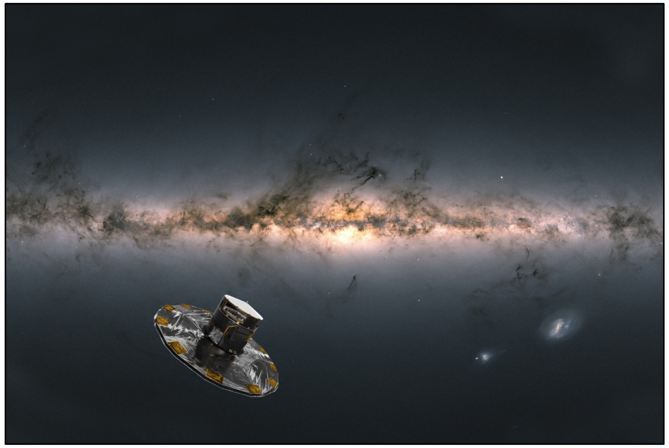

Data Release FPR
2014
2016
2018
2020
2022
2024
2026
2028
2030
Original Mission
Extended Mission
Full data
Data Release
1
2
E
3
F
4
5
Coords of ...
~ millions
~ billions
of stars
Improved precision
~ millions of variable stars
~ millions of galaxies
~ 100 million spectra
~ 100 thousand SS objects
Refine analysis for ...
crowded regions (ω Cen)
variable stars
solar system objects
gravitational lenses
UNIVERSITY OF LIVERPOOL
53


Milky Way Spiral Arms
15 kpc
10 kpc
5 kpc
0 kpc
5 kpc
10 kpc
15 kpc
40 kly
20 kly
0 kly
20 kly
40 kly
UNIVERSITY OF LIVERPOOL
54


Region of Galaxy Covered
15 kpc
10 kpc
5 kpc
0 kpc
5 kpc
10 kpc
15 kpc
40 kly
20 kly
0 kly
20 kly
40 kly
Region covered by Hipparcos
UNIVERSITY OF LIVERPOOL
55

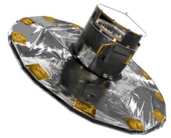

DR3
Region Covered By Gaia
15 kpc
10 kpc
5 kpc
0 kpc
5 kpc
10 kpc
15 kpc
40 kly
20 kly
0 kly
20 kly
40 kly
DR3
(2022)
DR2
(2018)
UNIVERSITY OF LIVERPOOL
56

DR2 **All-Sky Map**



UNIVERSITY OF LIVERPOOL 57

What can we learn from the data?

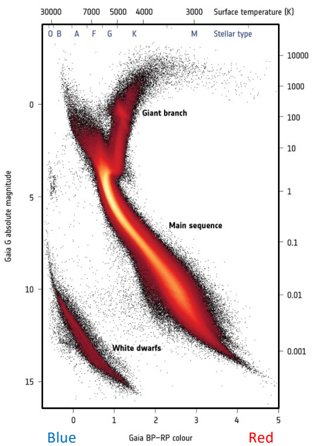


UNIVERSITY OF LIVERPOOL

DR2 **H-R Diagram**

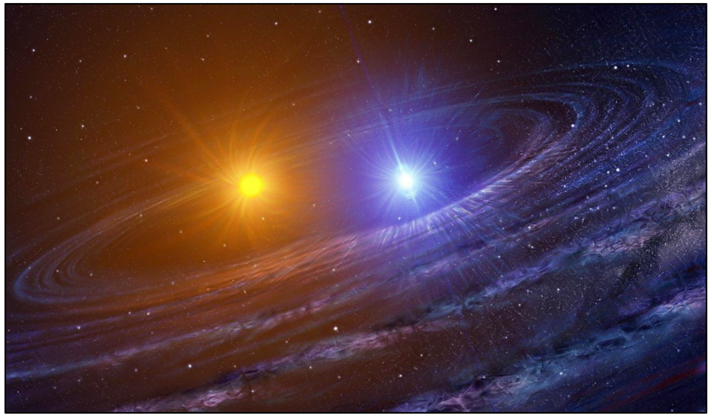
Hertzsprung–Russell diagrams plot the luminosity (vertical) against the colour (horizontal) for a population of stars.

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



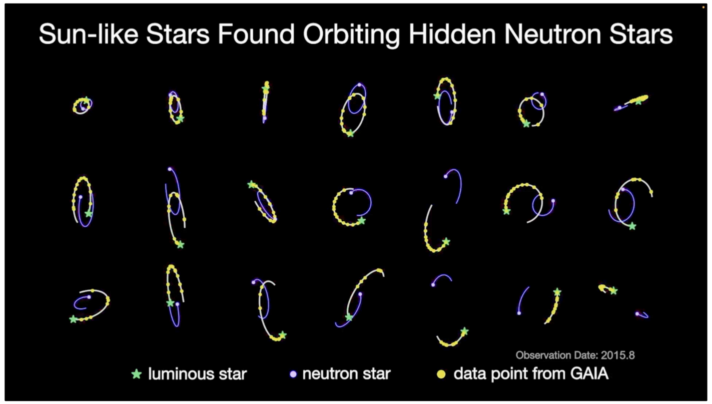
UNIVERSITY OF LIVERPOOL 59

DR3 **Sun-like Star and Neutron Star**



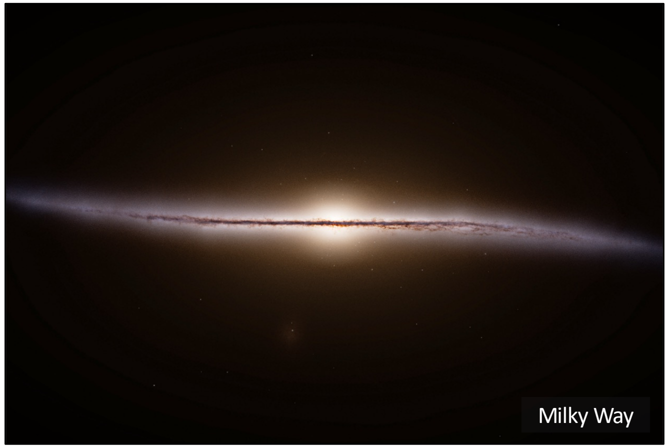
UNIVERSITY OF LIVERPOOL 60

DR3 **Hidden Neutron Stars**



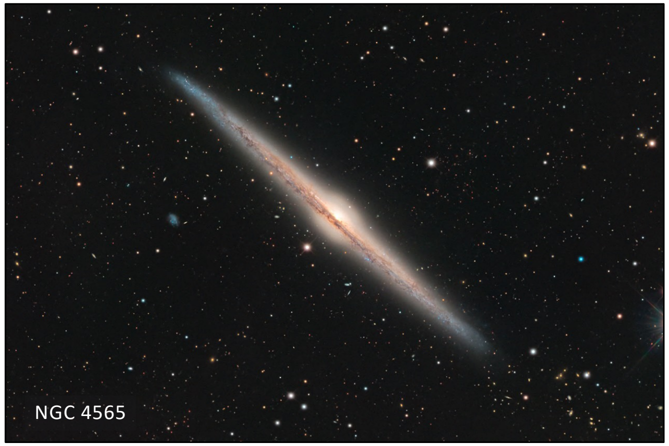
UNIVERSITY OF LIVERPOOL 61

DR2 **Warped Disc**



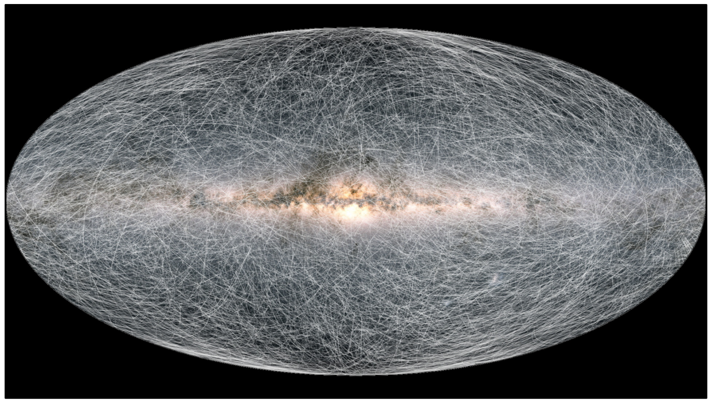
UNIVERSITY OF LIVERPOOL 62

Warped Disc



UNIVERSITY OF LIVERPOOL 63

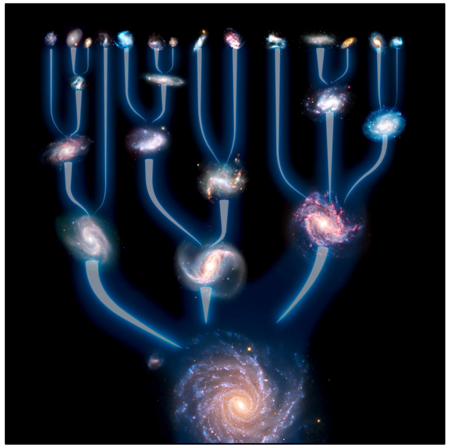
DR3 **Stellar Motion**



UNIVERSITY OF LIVERPOOL 64

Galaxy Mergers

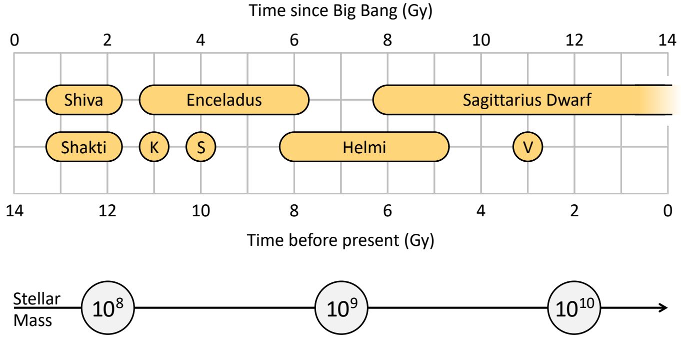
Hierarchical model
of galaxy formation



UNIVERSITY OF LIVERPOOL

65

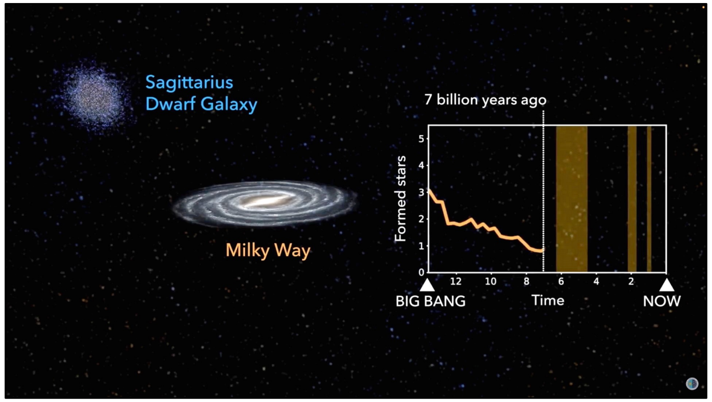
DR2 + DR3 Galaxy Merger History



UNIVERSITY OF LIVERPOOL

66

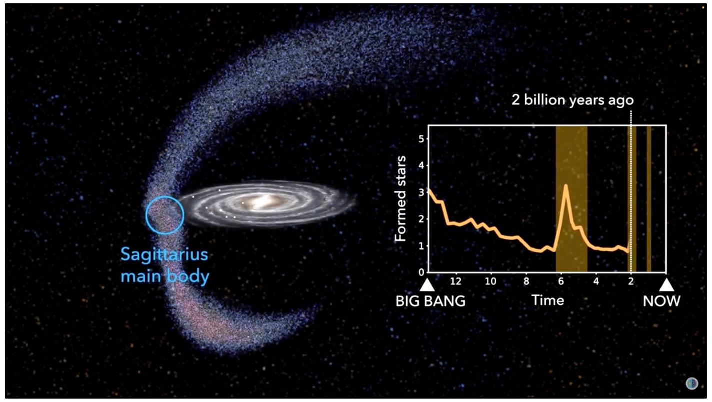
DR3 Sagittarius Dwarf Galaxy Mergers



UNIVERSITY OF LIVERPOOL

67

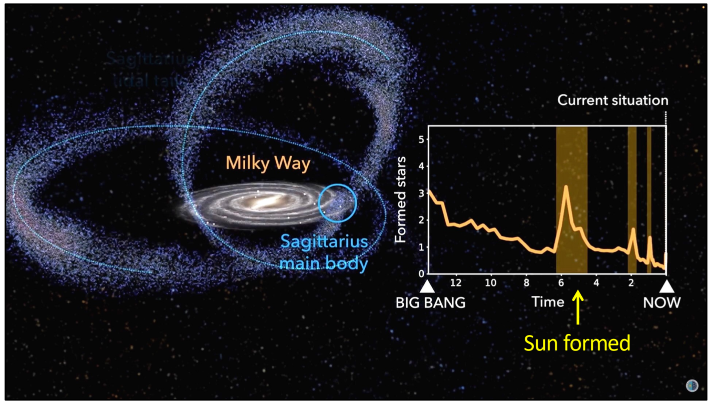
DR3 Sagittarius Dwarf Galaxy Mergers



UNIVERSITY OF LIVERPOOL

68

DR3 Sagittarius Dwarf Galaxy Mergers

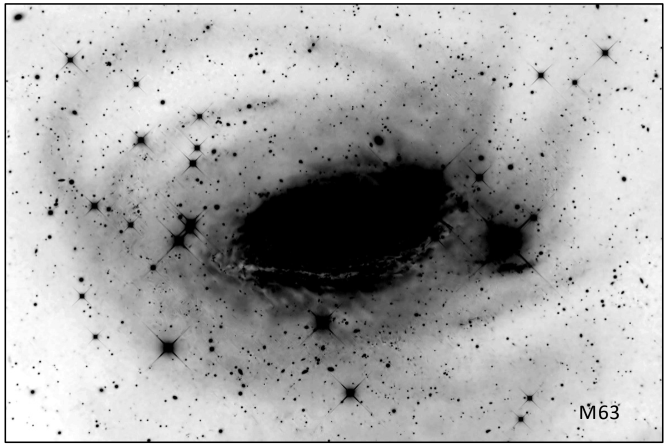


UNIVERSITY OF LIVERPOOL 69

Star Streams

UNIVERSITY OF LIVERPOOL 70

Star Streams

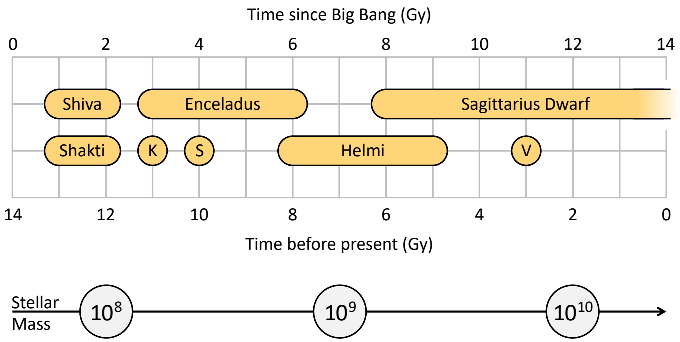


UNIVERSITY OF LIVERPOOL 71

Star Streams

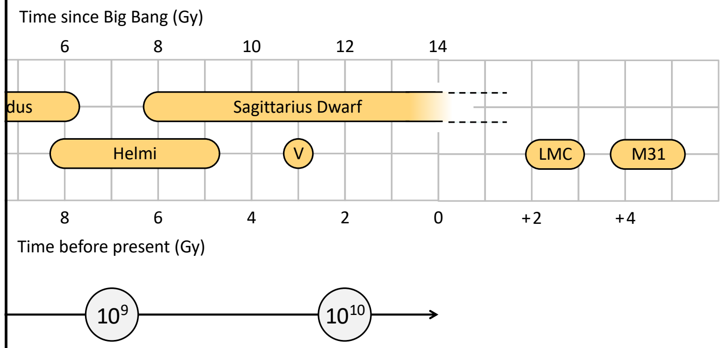
UNIVERSITY OF LIVERPOOL 72

DR2+DR3 **Galaxy Merger History**



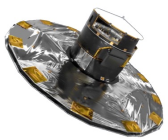
UNIVERSITY OF LIVERPOOL 73

DR2+DR3 **Galaxy Merger Future**



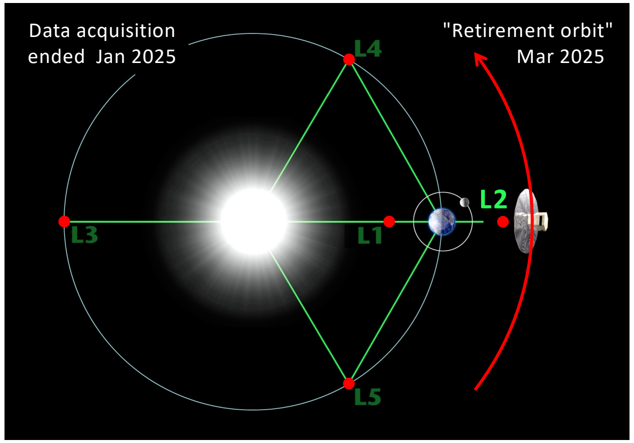
UNIVERSITY OF LIVERPOOL 74

Epilogue



UNIVERSITY OF LIVERPOOL

Gaia Epilogue

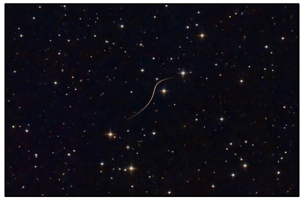


UNIVERSITY OF LIVERPOOL 76

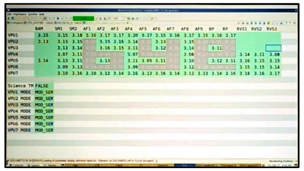
Gaia Epilogue

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.

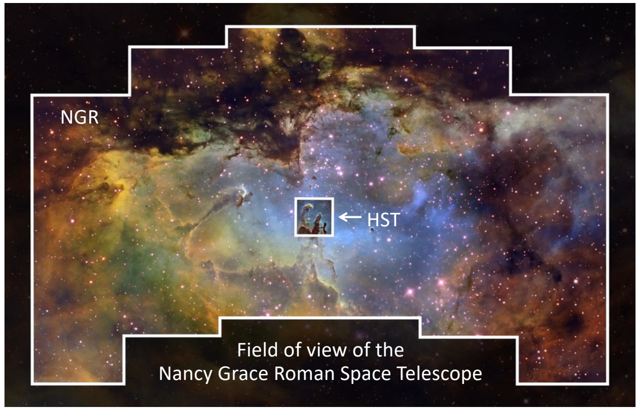


Before it was powered down Gaia sent a final status update.



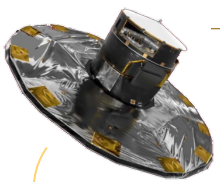
UNIVERSITY OF LIVERPOOL 77

Gaia Epilogue



UNIVERSITY OF LIVERPOOL 78

Gaia Epilogue



000001010
011100101
110111000
000001010
011100101
110111000

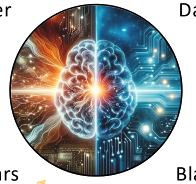
DR4 = 500 TB

Milky Way
Dynamics and Evolution

Dark Matter

Dark Energy

Solar System



Exoplanets

Neutron Stars

Black Holes

Stellar Evolution

UNIVERSITY OF LIVERPOOL 79