Leslie Bedford Lecture 2017

Gaia Mapping a Billion Stars

Gerry Gilmore FRS

The universe in which we live…

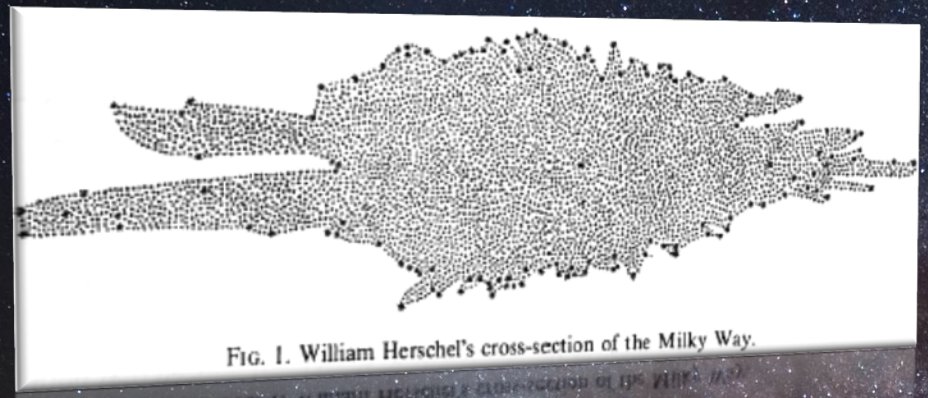
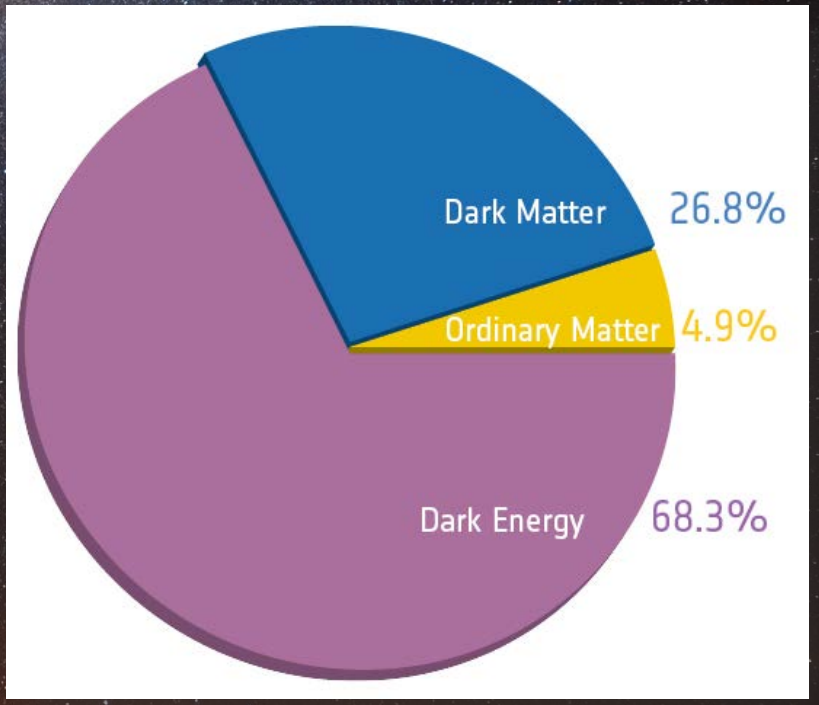
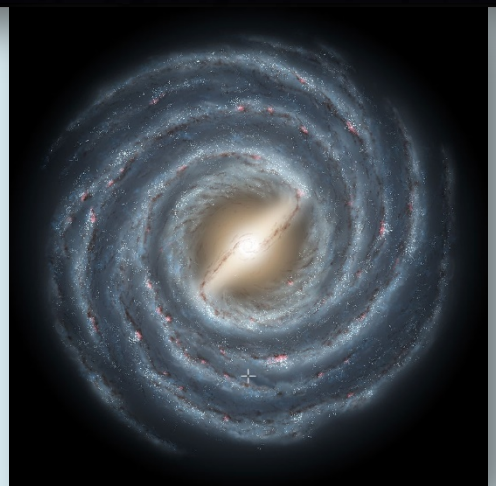


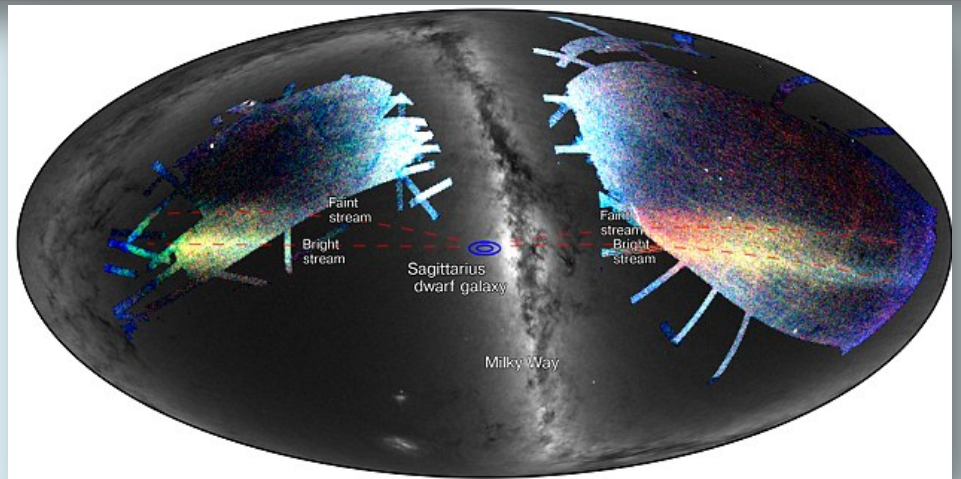
FIG. 1. William Herschel's cross-section of the Milky Way.



Gaia will make our Milky Way a Rosetta Stone

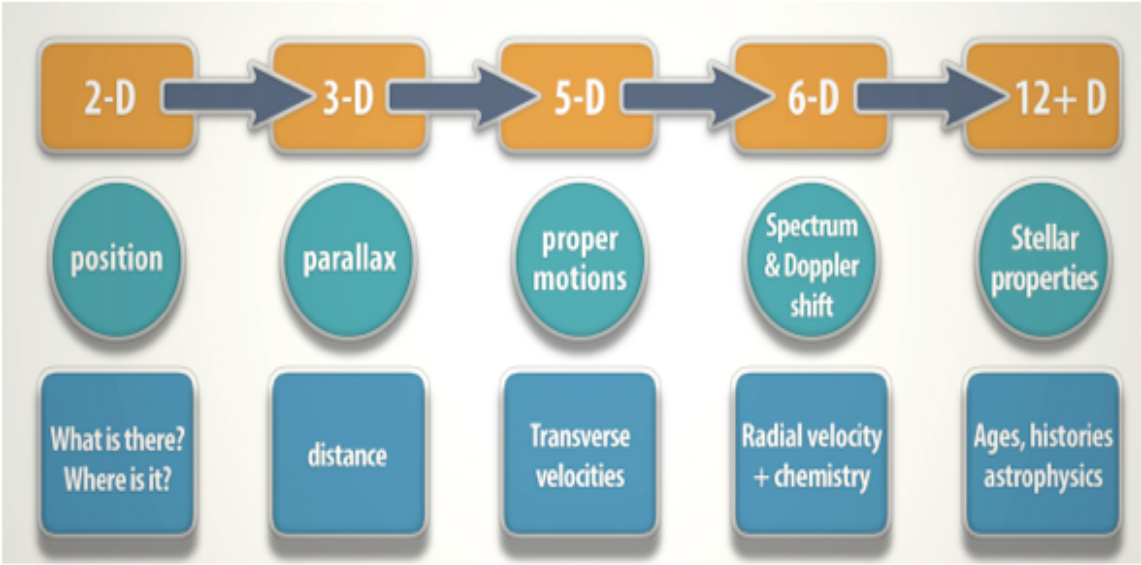
- When and how do galaxies form?
- What is the Dark Matter which dominates over visible matter?
- When and where do stars and planets form?
- Where are chemical elements created?
- What do we look like? Why? What does the future hold?





How does one study the Milky Way?

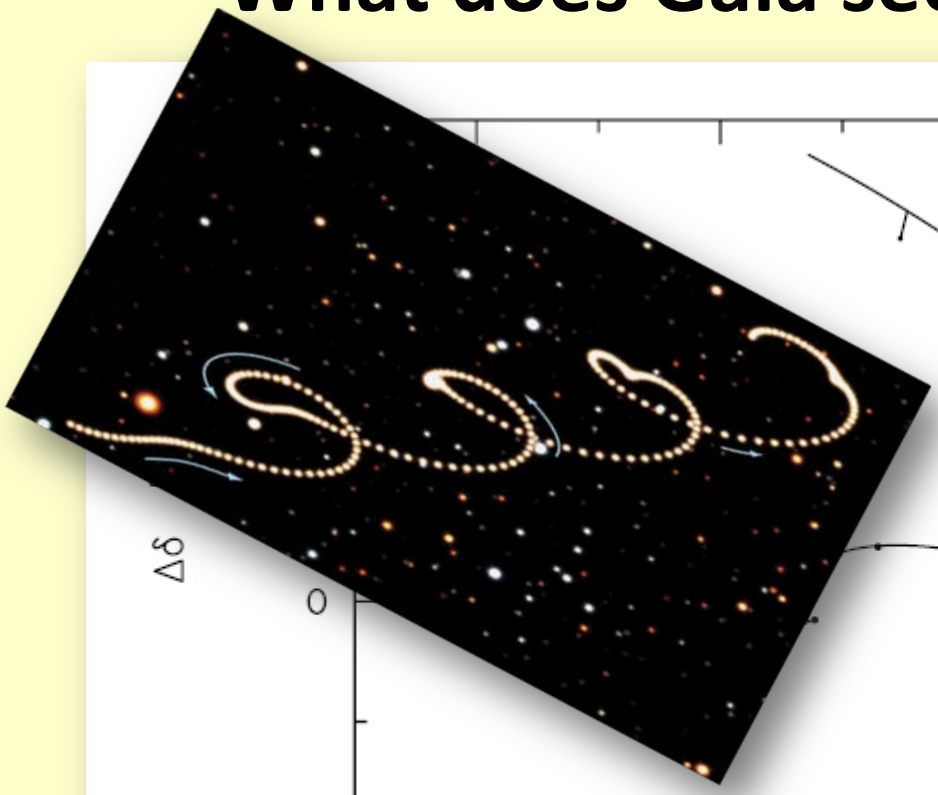
scientific discovery involves knowing an object exists, how it moves, its composition



Stellar orbits, star formation history, origin of the elements, Galaxy assembly, dark matter, cosmological initial conditions, fundamental physics, solar system(s), ...

Position
Distance
Size
Colour
Motion
Rotation
Shape
Texture
Brightness
Changes
...
Taste
Sound
Touch
Smell...

What does Gaia see as stars move?



Gaia accuracy 10 to 100 times better

Trend: stellar orbit ➔ Galactic dynamics, dark matter, assembly history, ...
Cycloid: parallax = 1/distance ➔ Galactic structure, star formation history
Loops: high frequency motion ➔ massive planetary systems

Star counting has a distinguished history

Success!

XII. *On the Conſtruction of the Heavens.*
By William Herſchel, *Eſq. F. R. S.*

Phil Trans
75 213-266

Read February 3, 1785.

THE ſubject of the Conſtruction of the Heavens, on which I have ſo lately ventured to deliver my thoughts to this Society, is of ſo extenſive and important a nature, that we cannot exert too much attention in our endeavours to throw all poſſible light upon it; I ſhall, therefore, now attempt to purſue the delineations of which a faint outline was begun in my former paper.

Challenges: Newton's "stellae fixae" notes for Principia 2nd ed. 1686 CU Library

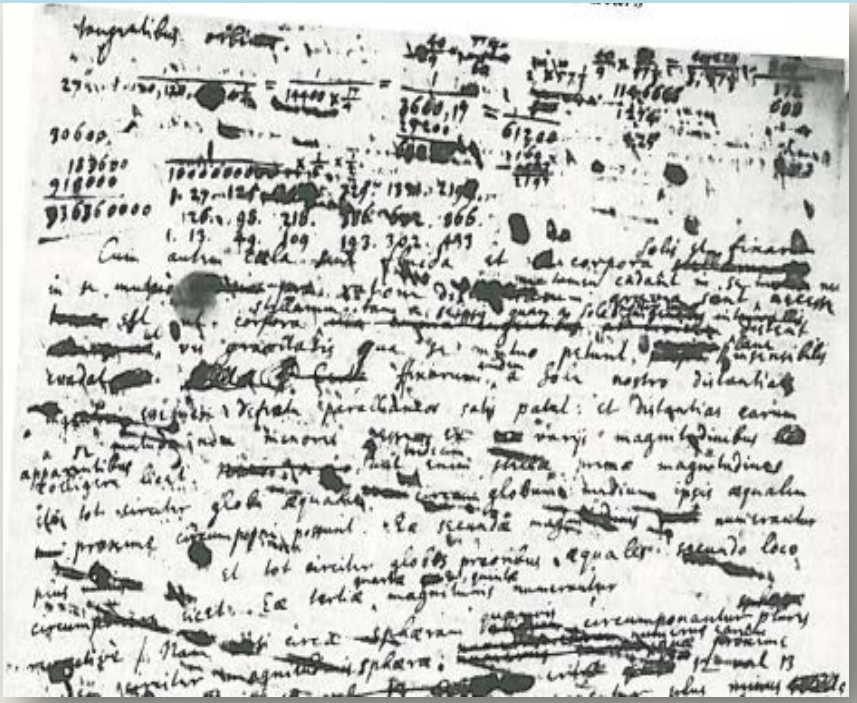


FIG. 1. William Herschel's cross-section of the Milky Way.

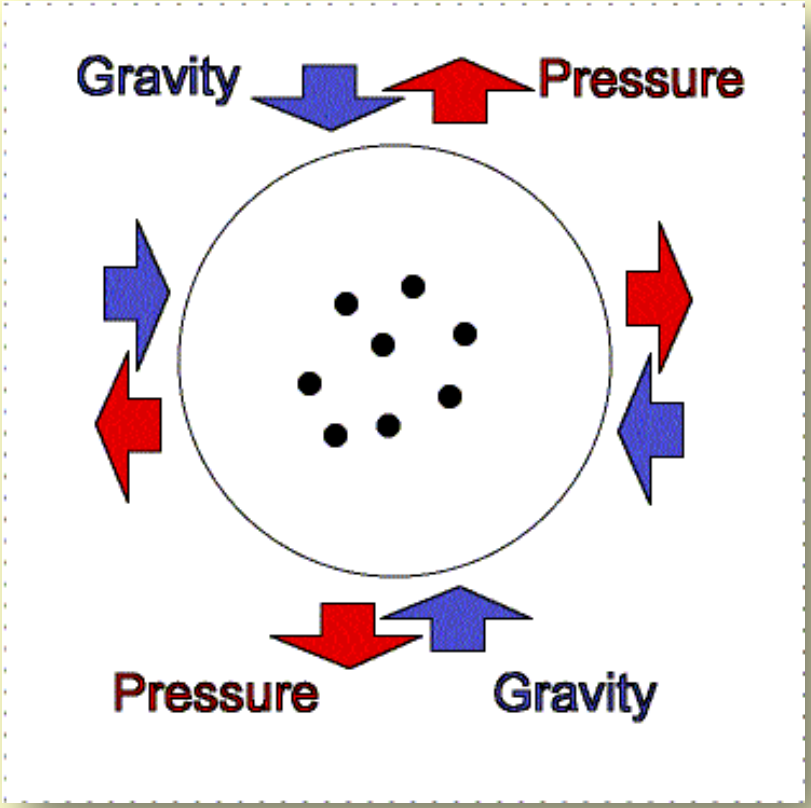
Another dimension: adding kinematics

- Stellar velocities are the information to weigh the Galaxy. The stellar velocities provide a pressure which balances gravity. We can deduce the gravitational field and mass.
- This leads to an anomaly: there is more mass locally than is visible

➔ dark matter

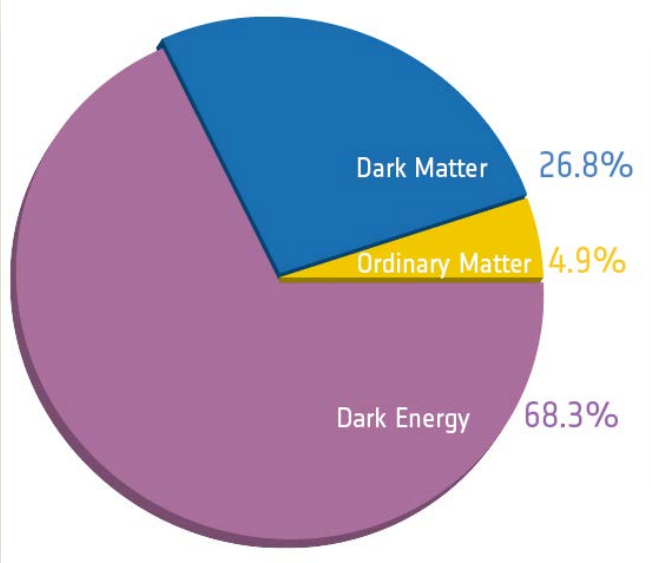
dark matter is none of the things we know...

The Copernican principle has gone extreme
not only do we not matter,
our matter doesn't matter



4-D data: The nature of reality

- The matter of which we are made, the matter we study, is insignificant in the Universe – reality is “Dark Matter”. Discovered only in astrophysics, moving beyond the particle physics Standard Model.
- What is it? This is the biggest question in physics.
- We measure it by kinematics/dynamics/weighing – structure on all scales
- Challenge – extend the precision of kinematics in distance



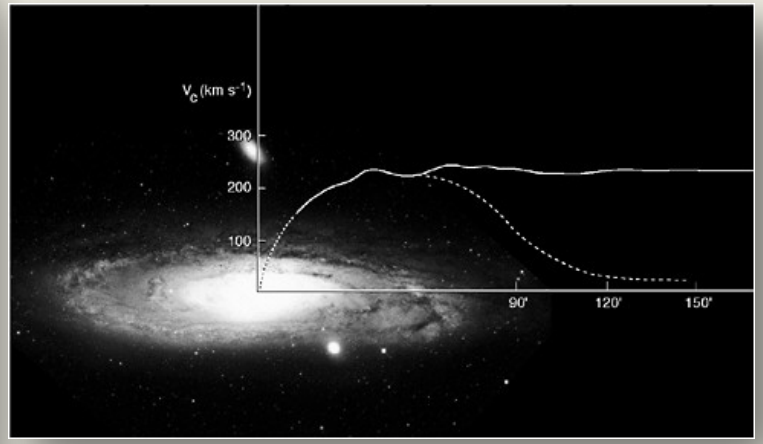
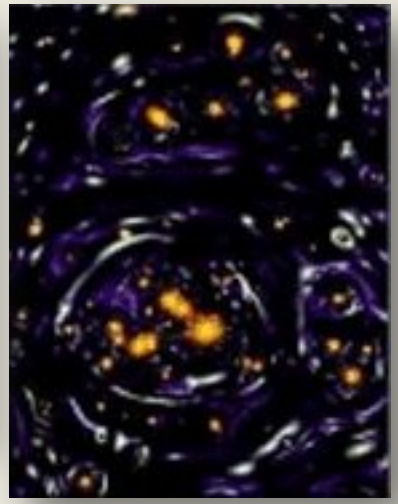


Image courtesy M Roberts



Gaia

Γαῖα δέ τοι πρῶτον μὲν ἐγείνατο ἶσον ἑωυτῇ
Οὐρανὸν ἀστερόεντ', ἵνα μιν περὶ πάντα καλύπτοι,

The goddess who came into being after Chaos and generated the starry sky

(Hesiod, Theogony 116/117 and 126/127)

a contrast to the unintelligible and generator of the explorable

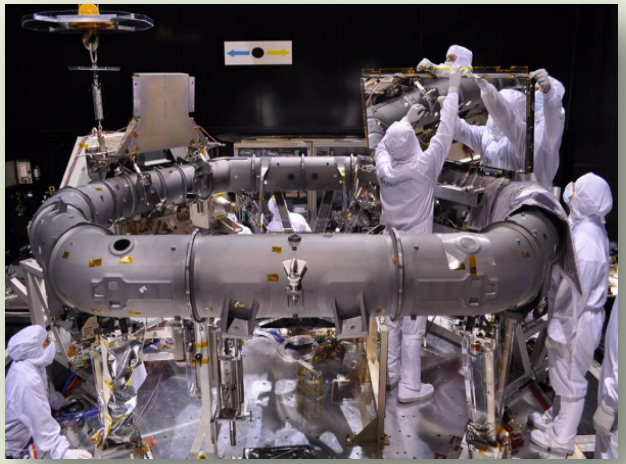
Gaia is transformational – the first 3-D galaxy

precision distances and motions for 1 billion stars

- Astrometry, photometry, spectroscopy, spectrophotometry,

Teff, log g, Av, [Fe/H], binarity, planets, periods for variables,…

Launch	12/2013
Work started	~1993
Project approved	2000
Operations start	7/2014
	5-9.5 years data
Project end	2026+
Total cost	960M€



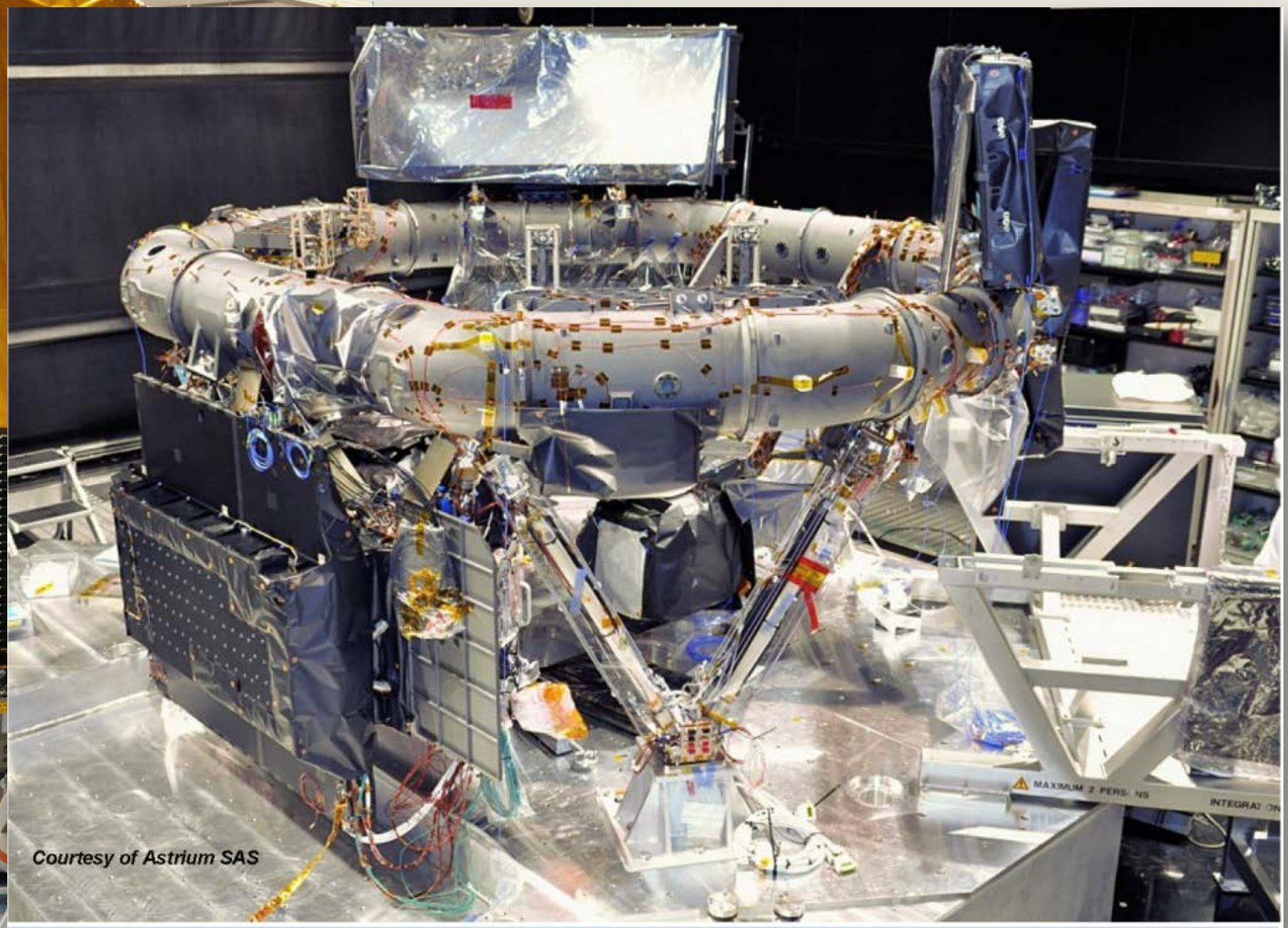
The heart of Gaia is a large camera array, 1 giga-pixel, sending us a video of the sky for 5-9 years.

The imaging data is being processed in Cambridge.

2 telescopes, 1.45 x 0.5 m primary, monolithic SiC optical bench, 0.06arcsec pixels

Gaia is a 2-telescope optical bench

AIRBUS DEFENCE & SPACE



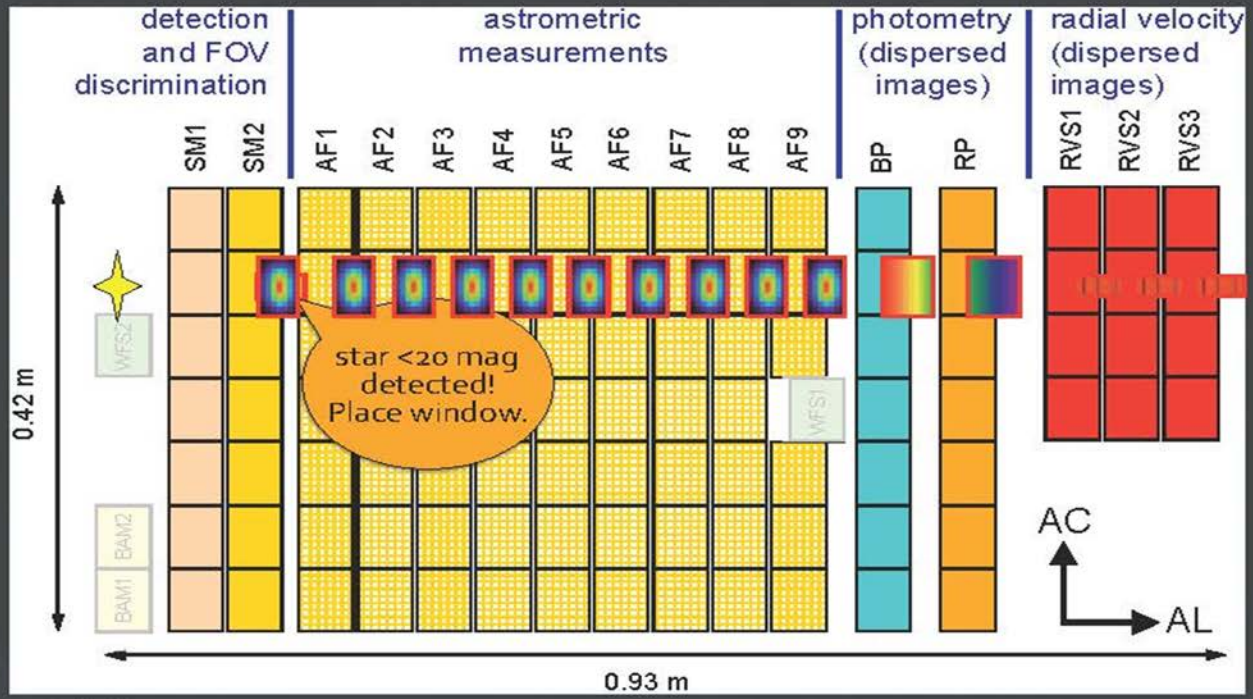
Gaia Payload Module fully assembled (except for external insulation *MLI*) ready to start the final environmental tests campaign.

SINGLE GAIA OBSERVATION = TRANSIT

Camera:

0.75 deg^2

pixel:
10x30 µm
(59x177 mas)



Animation by Berry Holl, Geneva

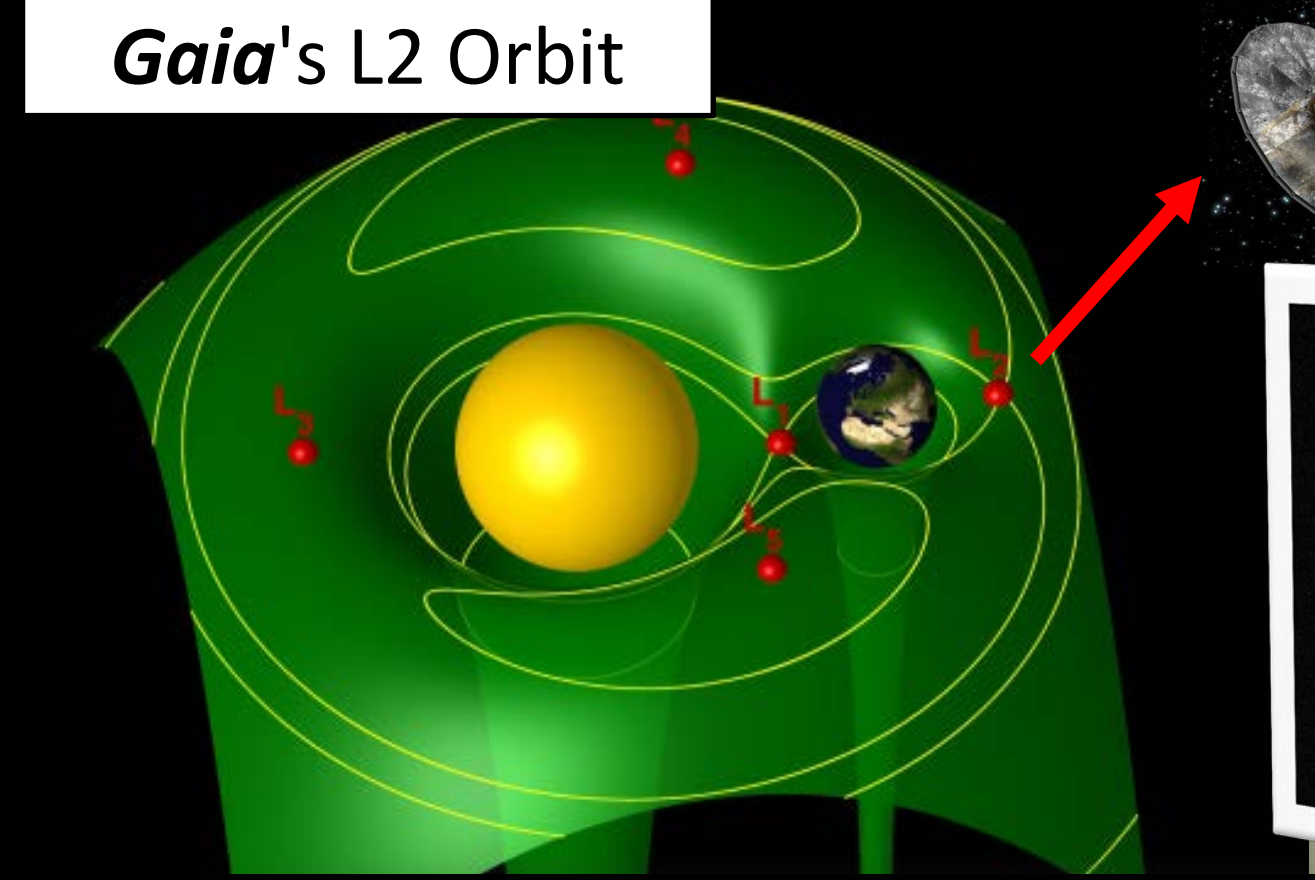
windows observed:

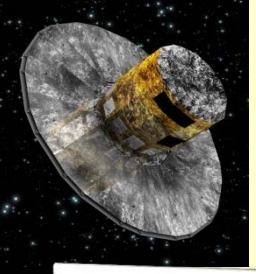
→ ~4.4 sec

→ ~45 sec

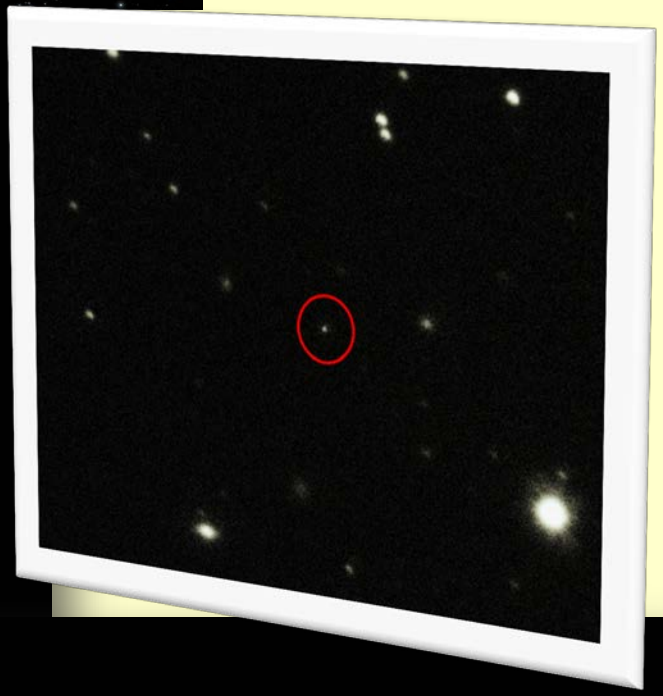
e2v

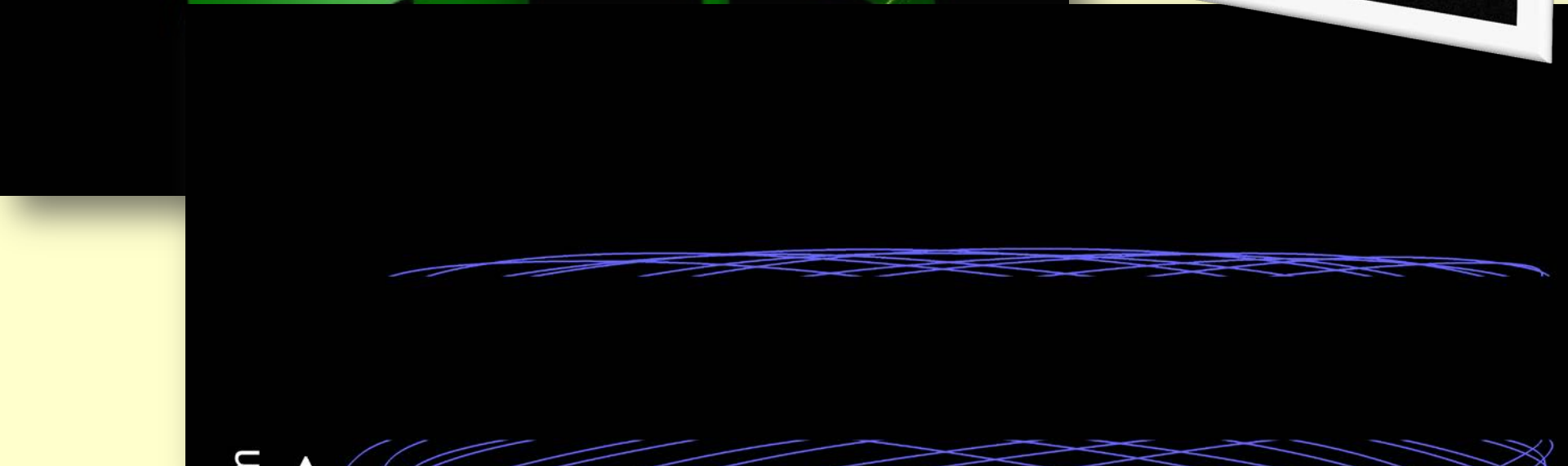
Gaia's L2 Orbit





Gaia in orbit



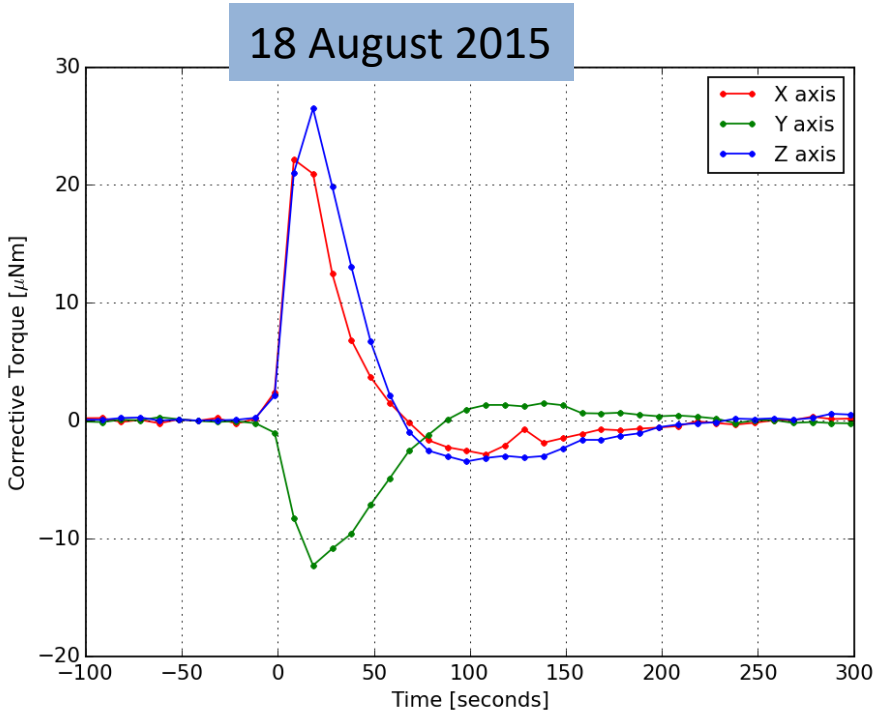


Gaia is a pico-radian machine

- We measure pixel-flux at a measured time
- Need spacecraft position, attitude, velocity, structure … to convert time to sky coordinate
- pico-radian = one part in 10^{12},
- ➔ Special, General Relativity are dominant terms
- ➔ velocity to mm/sec [c= 3.10^{11}mm/s]
- ➔ position at L2 to ~km
- ➔ instantaneous spin rate
- Solar light bending at 90deg from Sun = milli-as
- The wonderful engineers who built Gaia kindly left some operational complexity to retain our interest

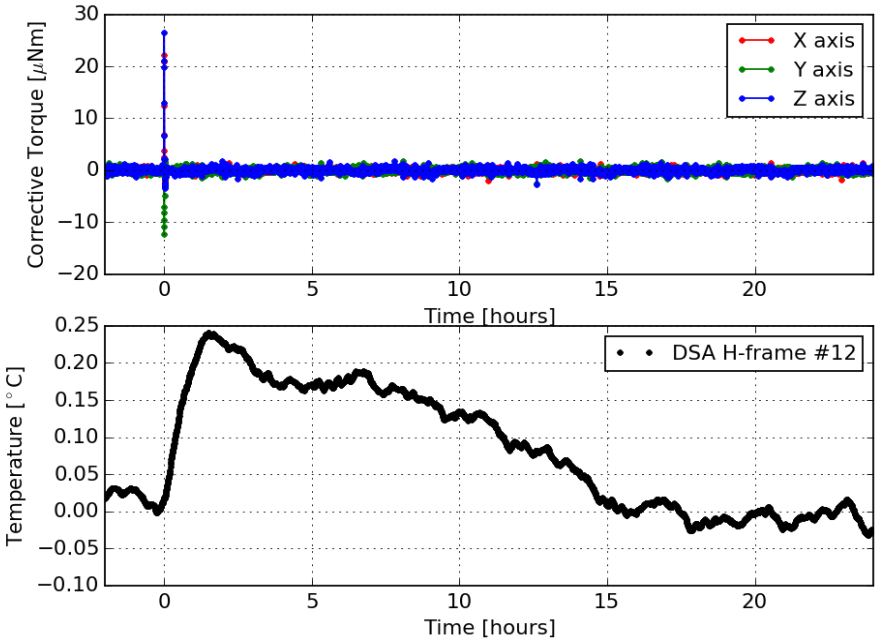
Wikipedia Fact:

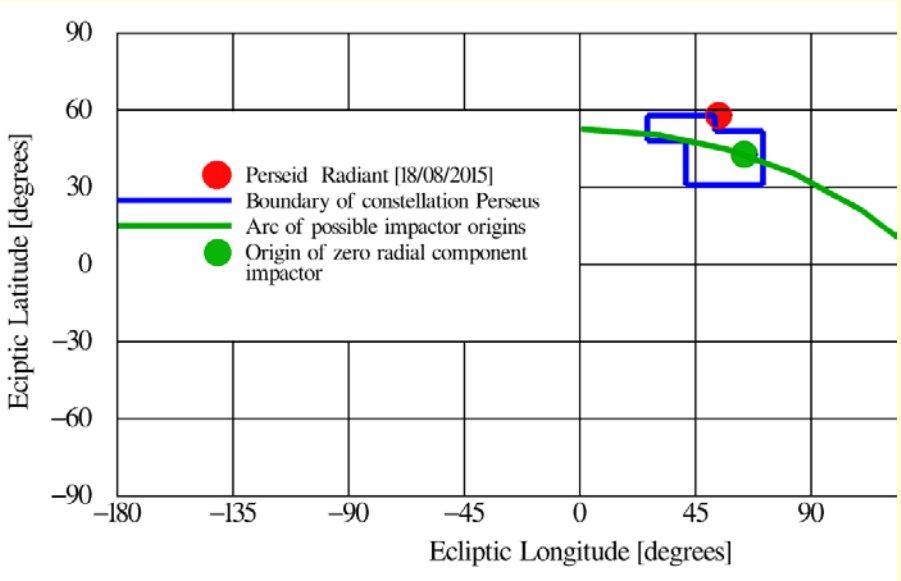
*A microarcsecond is about the size of a period at the end of a sentence in the Apollo mission manuals left on the Moon as seen from Earth.



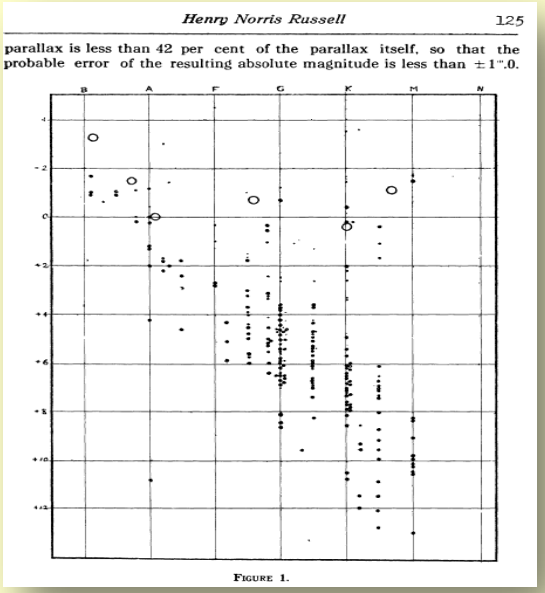
Gaia meets a Perseid meteorite

Gaia's spin rate is corrected after a hit.
The hit was near a temperature sensor, so location and momentum known.
This deposited 84J.
A Perseid travels at 59km/s, so this weighed 48 micro-gram.
84J is half the muzzle momentum of a .22 rifle bullet.





Two million stellar distances
eye➔ telescope ➔ photograph ➔ CCD



Henry Norris Russell 125

parallax is less than 42 per cent of the parallax itself, so that the probable error of the resulting absolute magnitude is less than ±1ᵐ.0.

B A F G K M N

FIGURE 1.

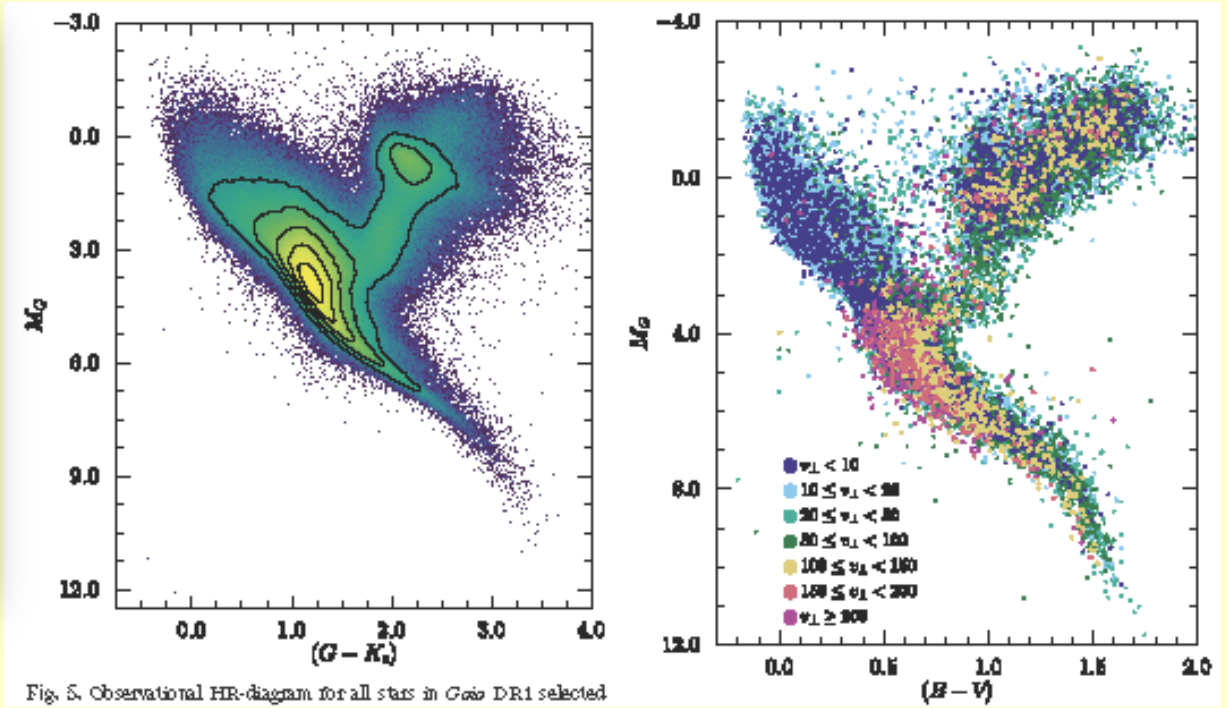
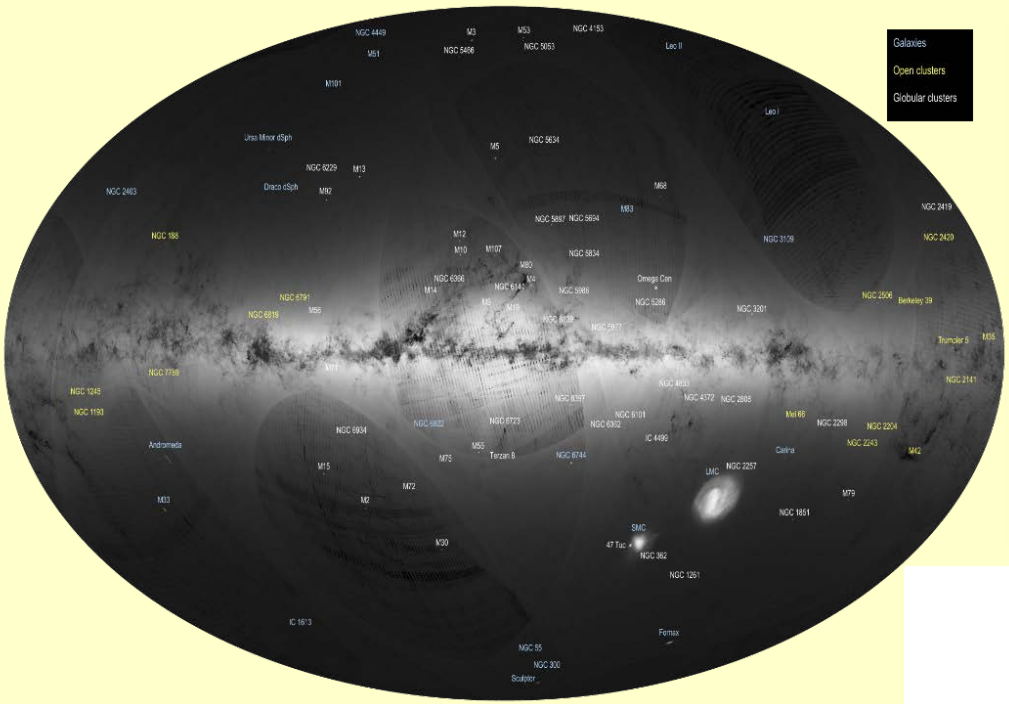


Fig. 5. Observational HR-diagram for all stars in *Gaia* DR1 selected

Colour-magnitude relation
Accurate distances define the way stars evolve

Science applications: stellar evolution, structure of the Milky Way, spiral arm dynamics, Dark Matter distribution, stellar mass function, planet host properties, history of the chemical elements, solar siblings, star cluster evolution and dissolution……

Gaia's first all-sky-map



Testing stellar evolution

Combine distance and apparent brightness to determine intrinsic properties of the stars in a single-age cluster:

Observe the effects of mass on otherwise similar stars

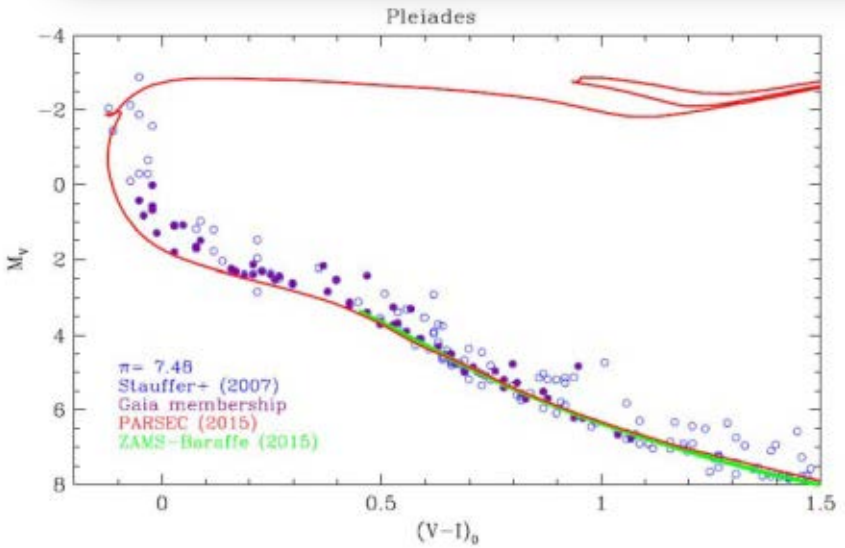
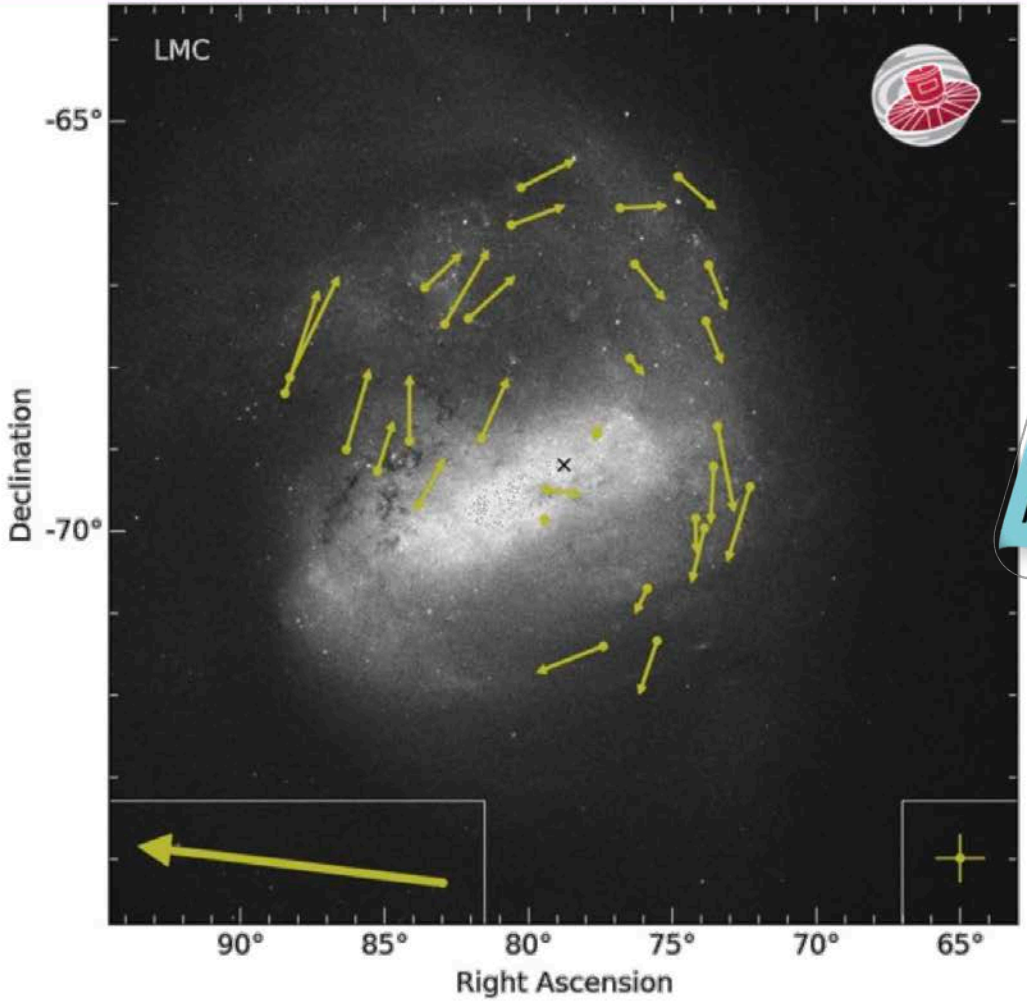


Fig. 25. M_V, $(B-V)_0$ HR diagram of the Pleiades, with several sets of commonly used isochrones (top). Bottom panel is the analogous in the M_V, $(V-I)_0$. We assume an age of 130 Myr, solar metallicity, A_V=0.1

Rotation of the LMC seen with TGAS



van der Marel & Sahlmann, 2016, ApJL (arXiv:1609.04395)

Seeing another galaxy rotate
The Large Magellanic Cloud

Rotation period = 10^8 years

The scale of the Universe: calibrating the calibrators
The Henrietta Leavitt law for Cepheid variable stars

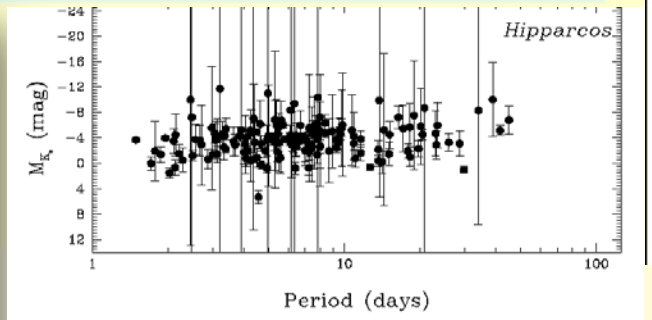
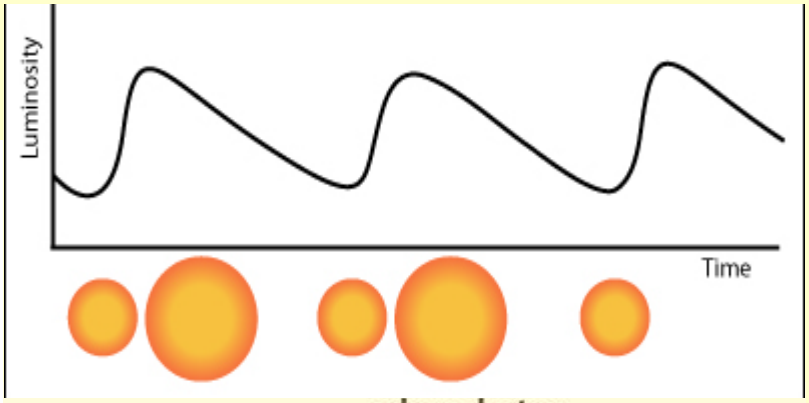
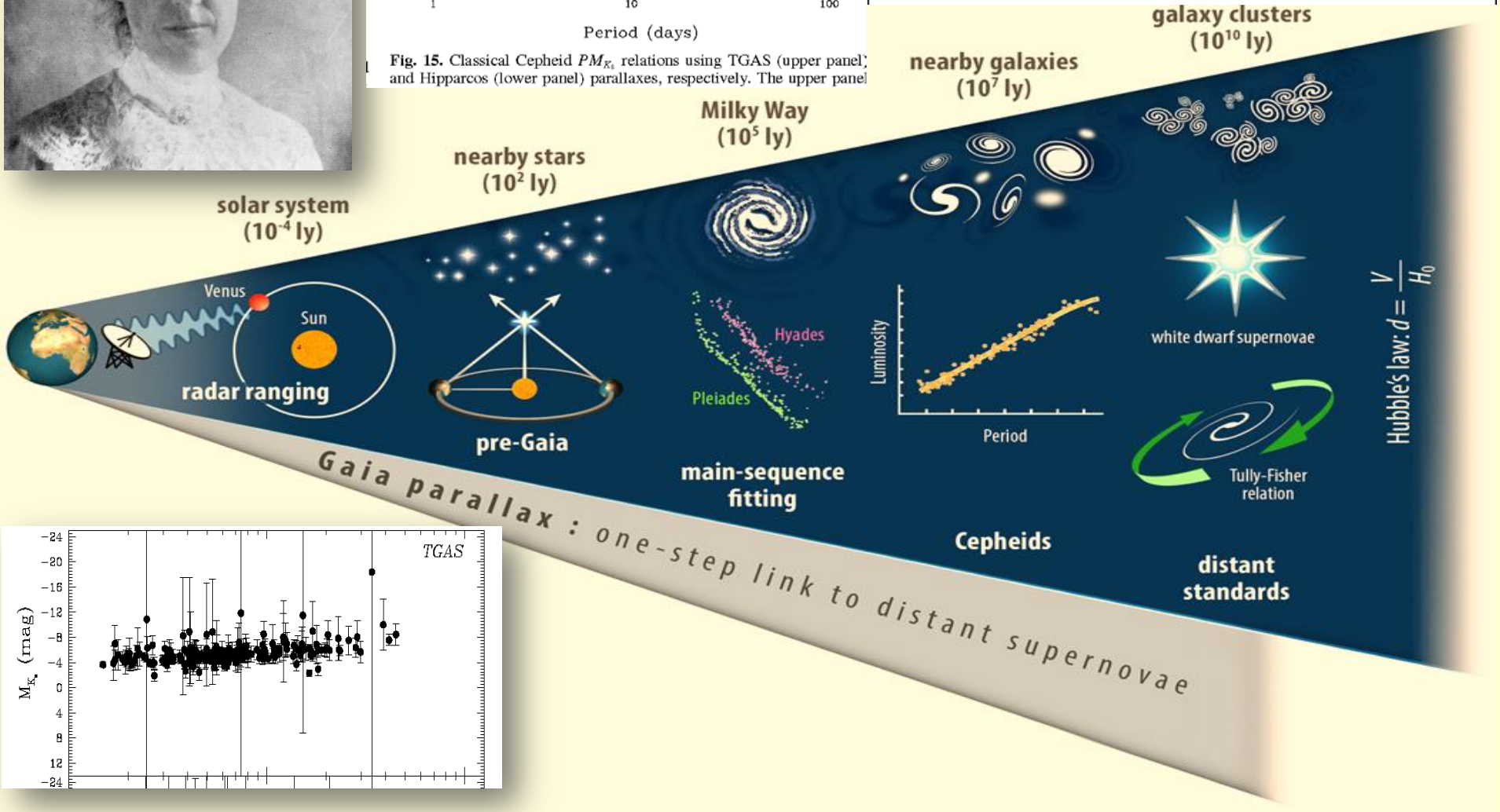
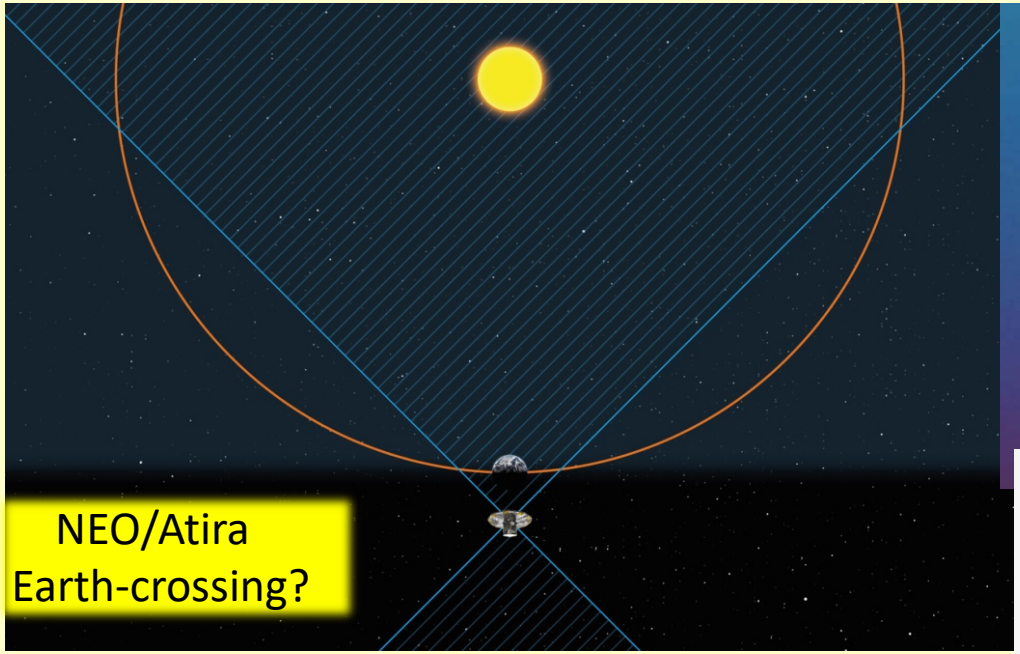


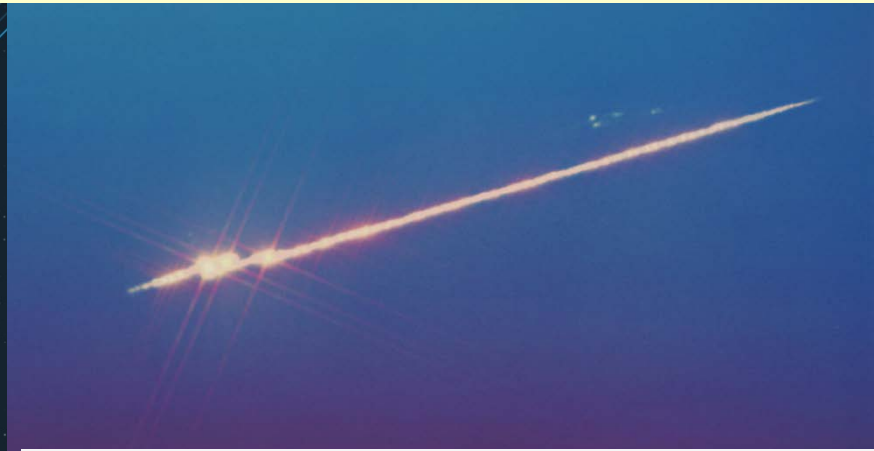
Fig. 15. Classical Cepheid PM_{K_s} relations using TGAS (upper panel) and Hipparcos (lower panel) parallaxes, respectively. The upper panel

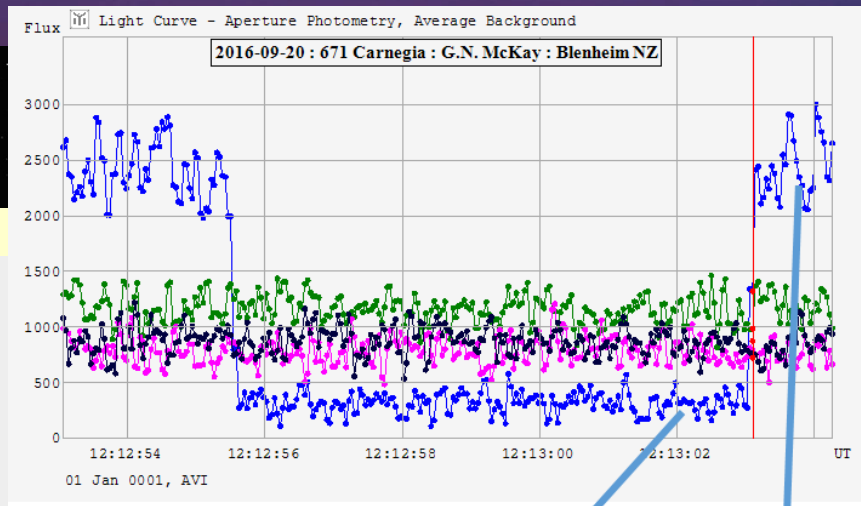


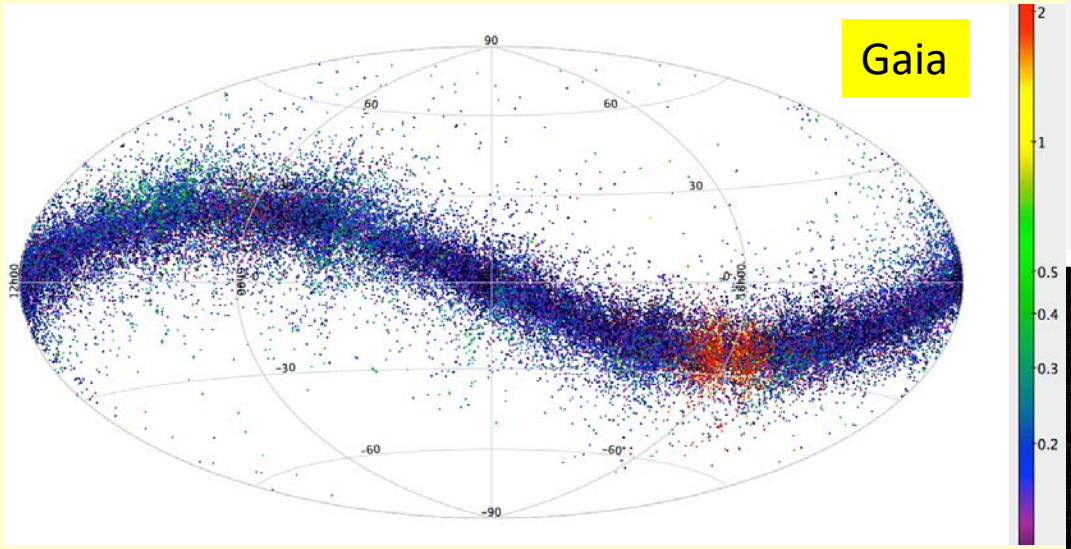


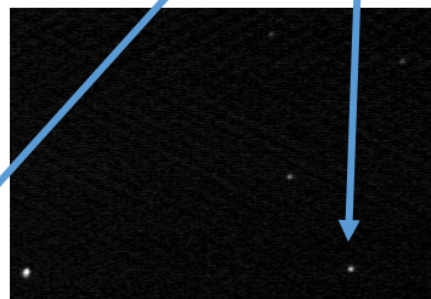
Gaia is providing a survey of NEO-threat asteroids with orbits interior to Earth and improved orbits for many MB asteroids, with many masses, radii,…

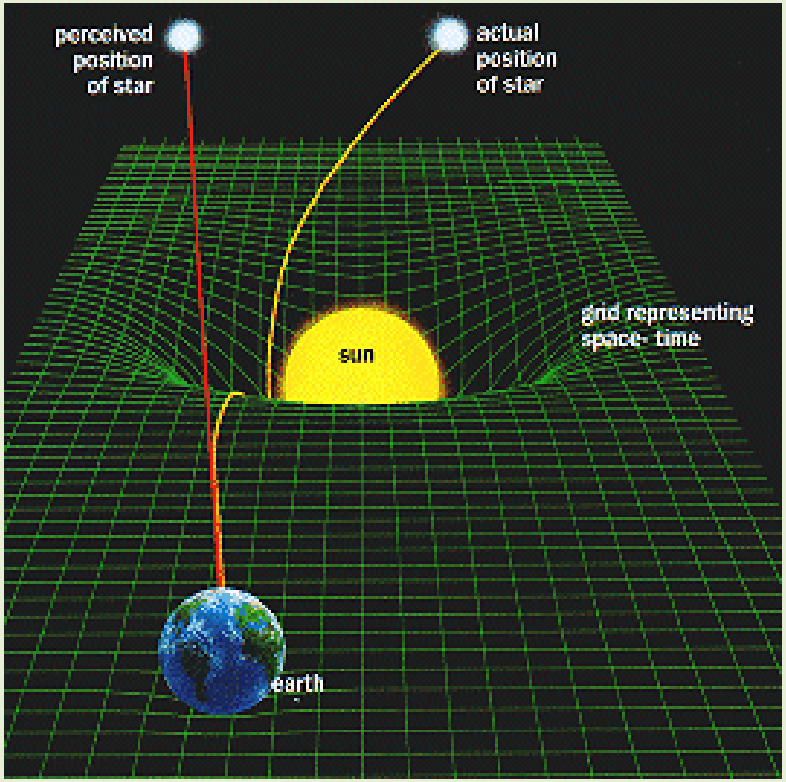


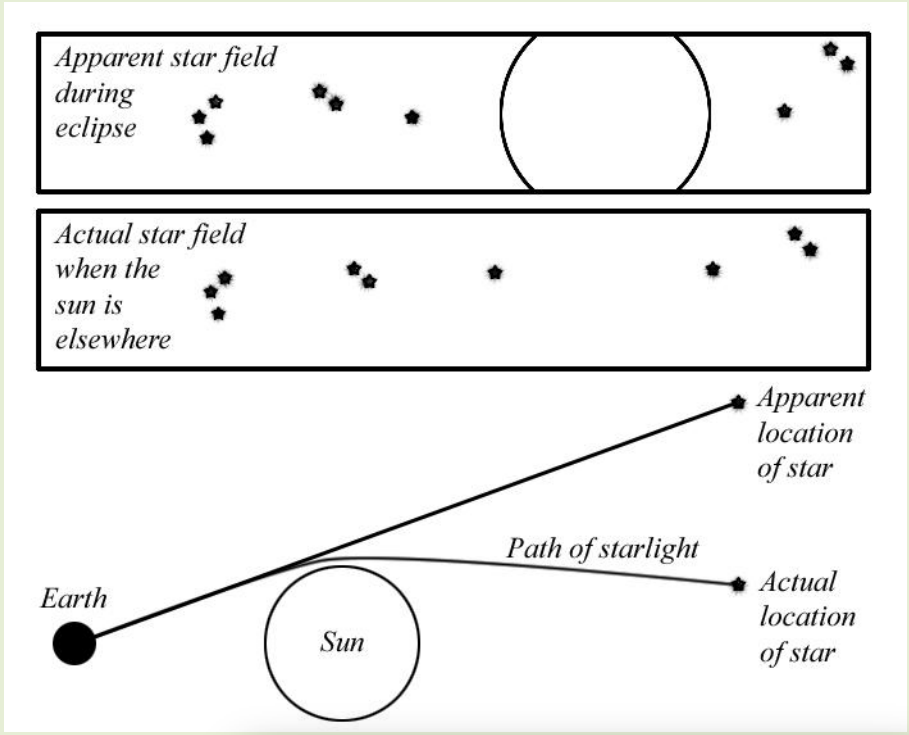








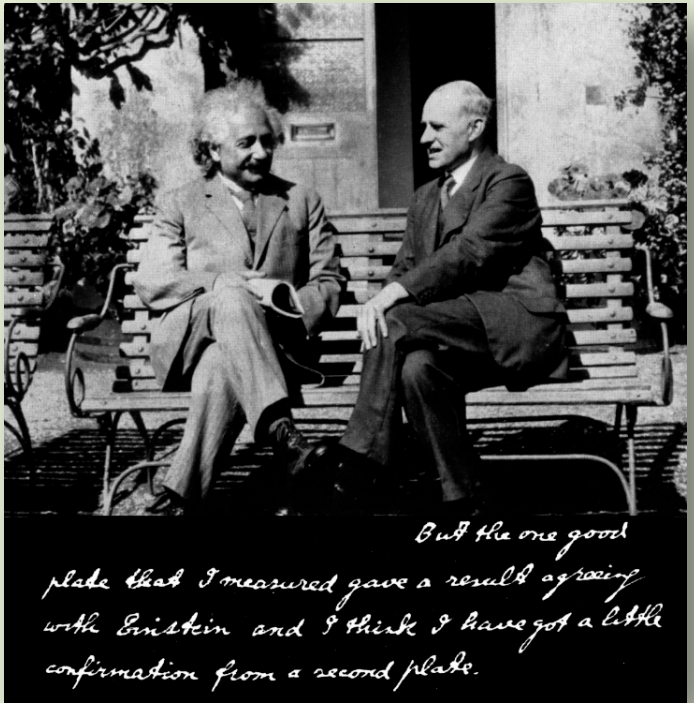




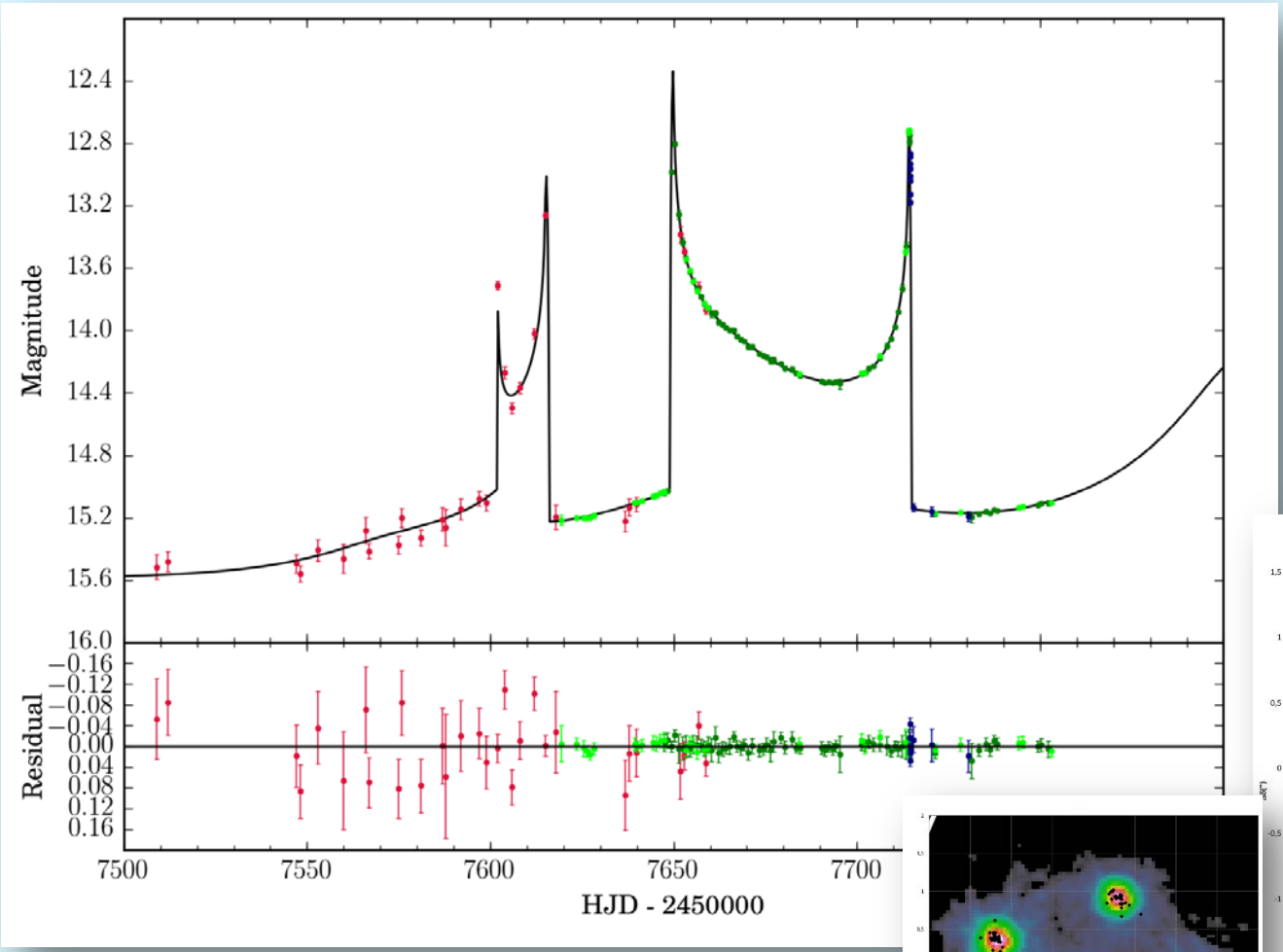
Eddington's 1919 measurements

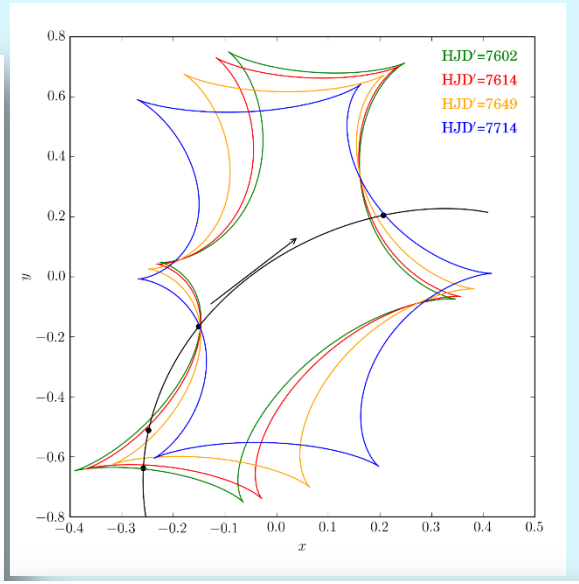
The Sun and stars distort space-time and the path of light. This deflection was first measured by Eddington in 1919, establishing General Relativity.

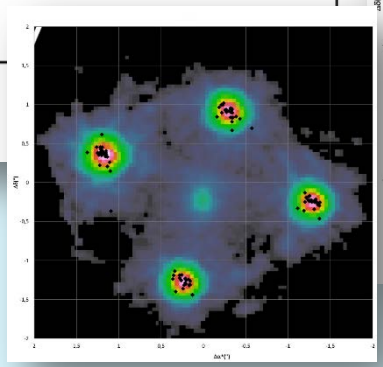
Gaia sees that in every measurement it makes so we can test Relativity to much improved accuracy

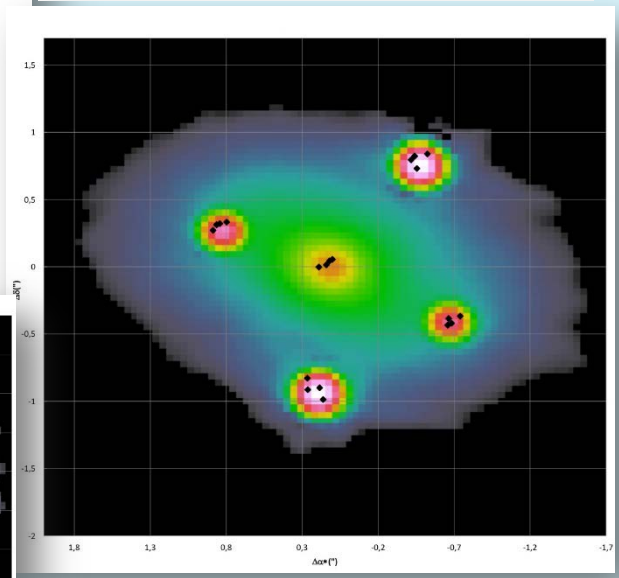


Gaia16aye – a background star whose light is lensed by the space-time distortion of a binary – two stars exactly lined up between us the star.
The changing star brightness and positions are mapping the space-time distortion caused by the foreground binary star

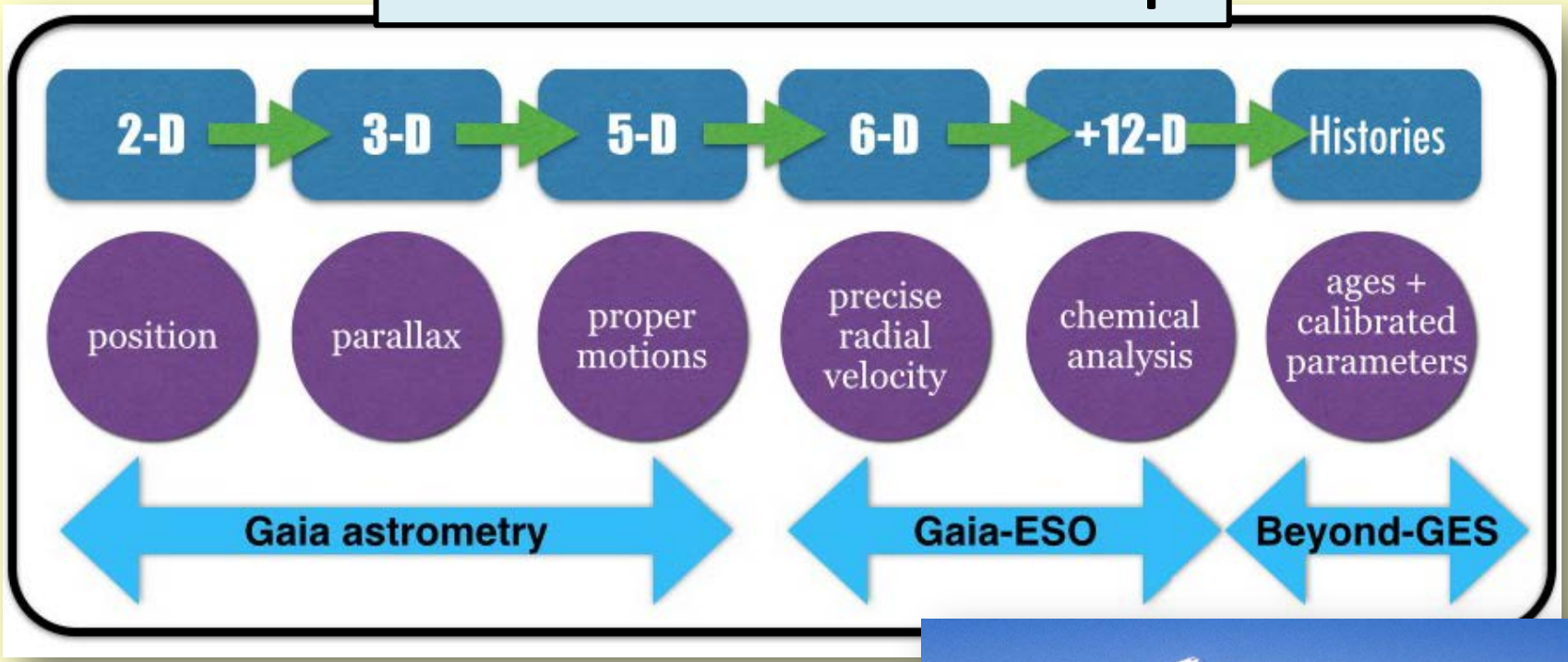






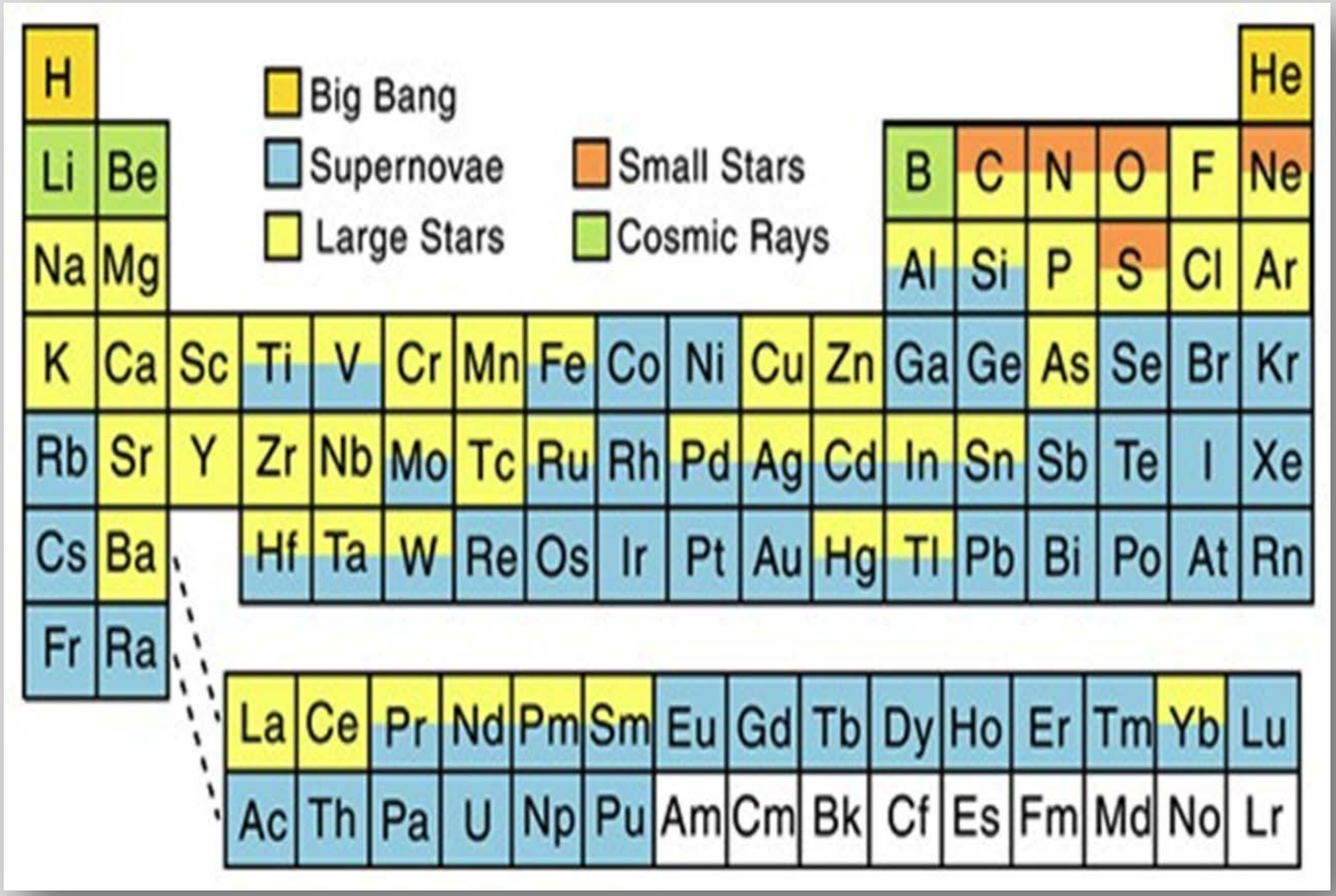


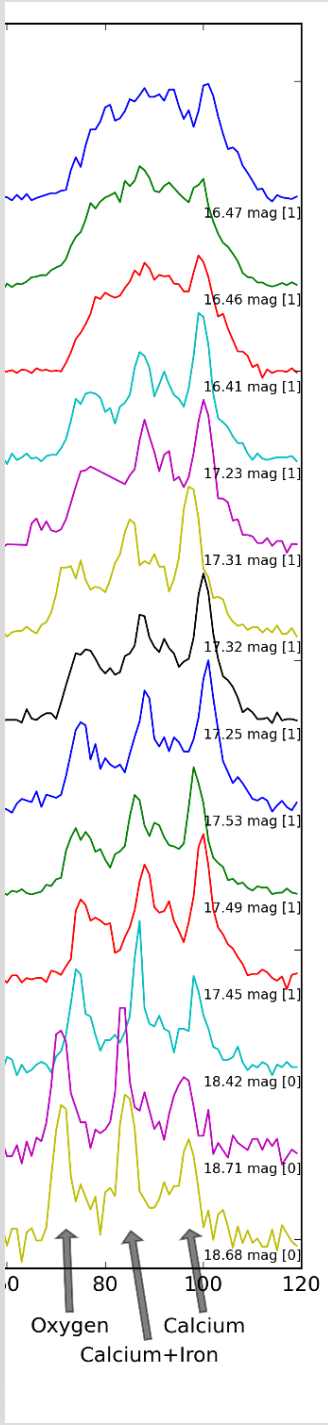
Ambitions for the next steps



Tracking stardust: origins of the chemical elements

- H, He & Li are ashes from the Big Bang. All other elements are created in (or by) stars, becoming available to form new stars, planets, and people.
- the elements form a cosmic clock, which allows us to decode the sequence of events which began 13Gyr ago, and which continues today





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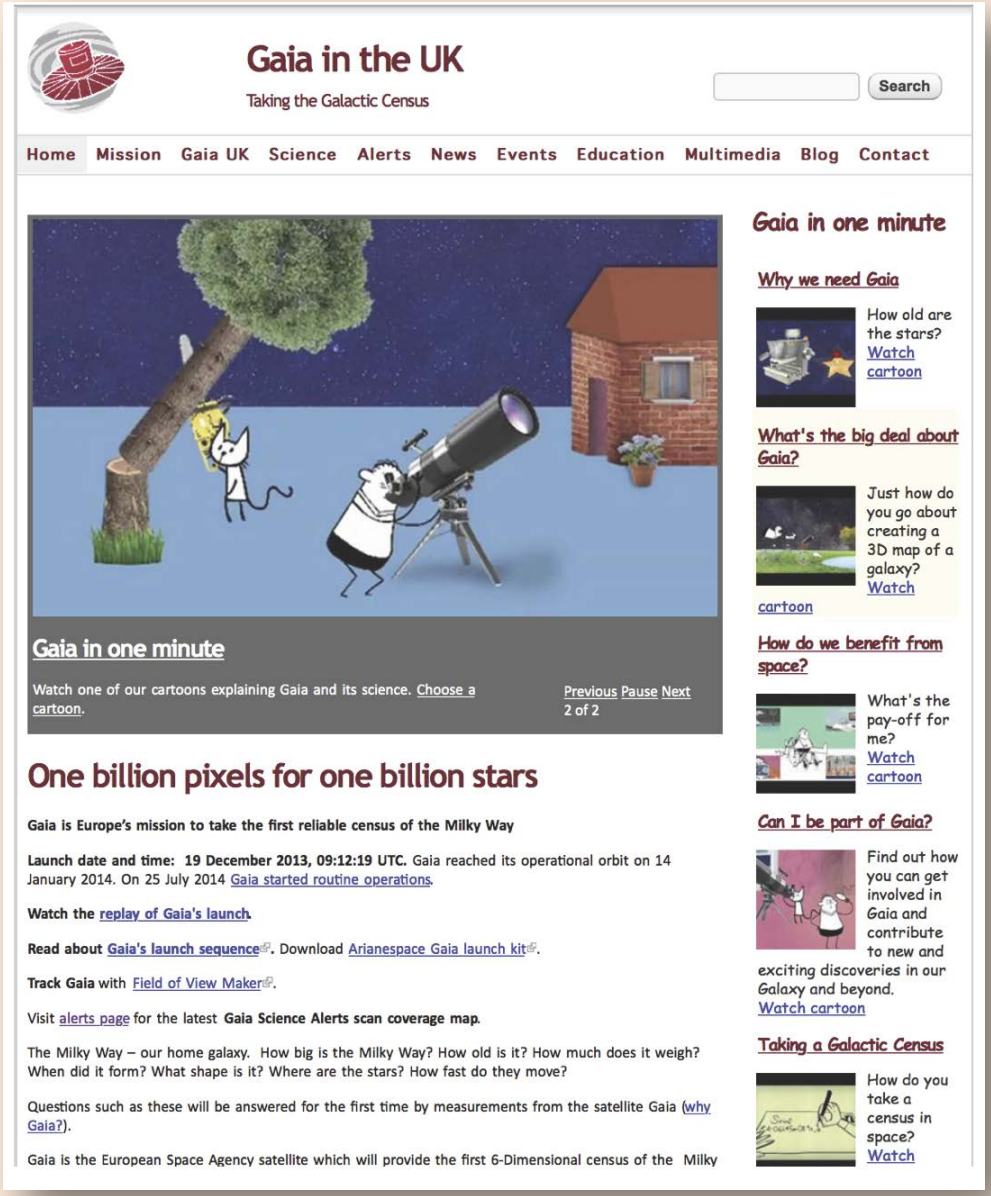
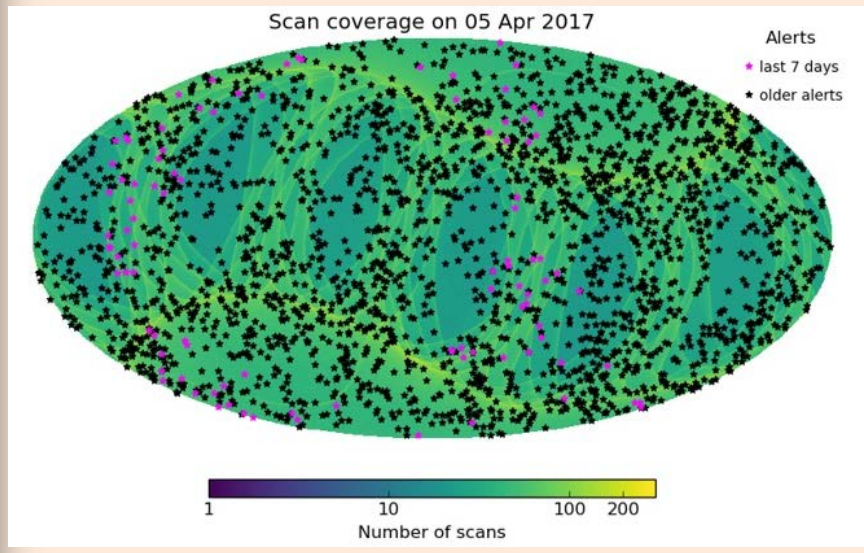


This is home for the Gaia Science Alerts outreach effort

- Gaia Alerts
- Educational Materials
- Background and Context
- Activities
- Download our app!

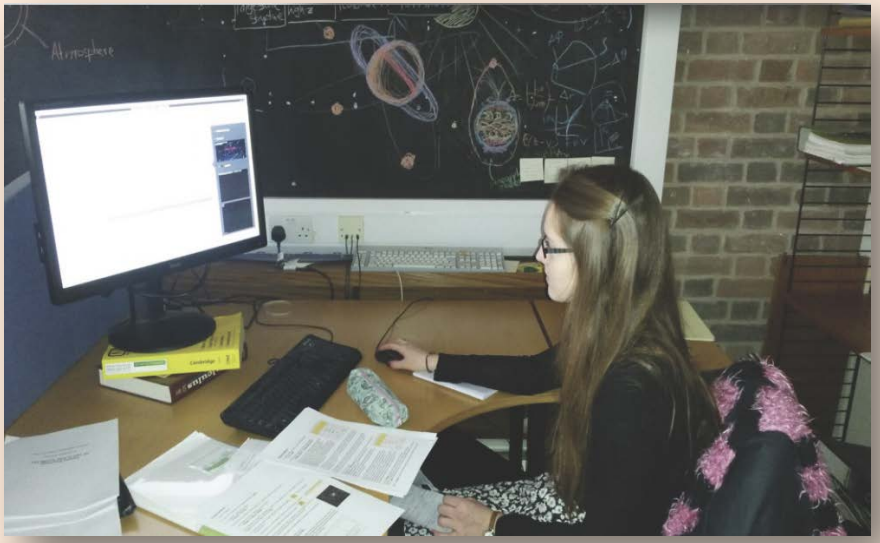


Gaia science: learning how to learn

Science results – new sources, supernovae directly to the public.

For schools, amateurs, anyone….

- gaia.ac.uk is a simple interface to all Gaia science



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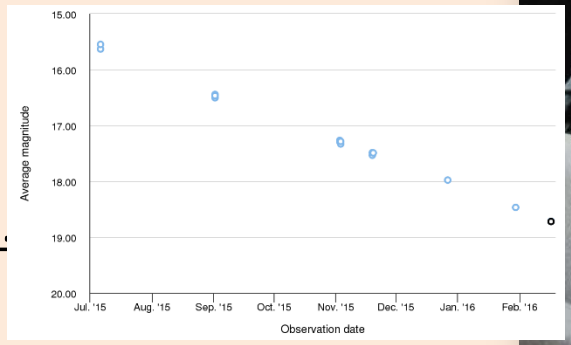
<u>follow Copernicus:</u>

<u>learn from data,</u>

<u>not preconceptions.</u>



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epour[59], and S. Zschocke[11]

The *Gaia* mission

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ratory Global Telescope Network. In addition
ce those employed in the design, manufacturing
ed yet spent countless hours, occasionally during
cifically name, in alphabetical order, from Airbus
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ns in the text.

UK industrial partners

- **Airbus D&S**: Electrical Service Module
- **Selex Systems**: Spacecraft documentation, configuration, schedule support
- **e2v Technologies**: CCD detectors
- **Airbus D&S**: Payload module & focal plane assembly structural pieces
- **Airbus D&S**: Video processing unit
- **MSSL**: Focal plane assembly: CCD/Proximity electronics module coupling
- **Airbus D&S**: Chemical propulsion system
- **ABSL**: Battery
- **Aerostanrew Ltd**: Avionics model bench structure
- **SIRA**: CCD radiation testing.

What technology does science need next?

- How complex is the Dark Sector? Physics beyond the standard model motivates CERN/LHC, many ground and space experiments.
- Quantifying gravitating structure in galaxy cores and halos is the information to quantify the physical properties of dark matter particles
- Challenge – precision kinematics beyond Gaia. An optimal system!!
- To do better needs baseline – nano-astrometry ➔ 100+m baselines

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
Strength relative to electromag for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

The light sector is complex: is the dark sector?

Does this lumpy model match reality?

Gaia Statistics @ 6-Apr-2017 11:50 UT

CURRENT DATE AND TIME	2017-04-06T11:52:39 (TCB)
MISSION STATUS	
Satellite distance from Earth (in km)	1,457,124
Number of days having passed since 25 July 2014	986
OPERATIONS DATA (collected since 2014/07/25)	
Volume of science data collected (in GB)	35,510
Number of object transits through the focal plane	68,966,272,156
Number of astrometric CCD measurements	679,810,396,966
Number of photometric CCD measurements	145,372,218,146
Number of spectroscopic CCD measurements	13,539,370,137
Number of object transits through the RVS instrument	4,271,580,366

during this talk Gaia measured ≈3,000,000 objects

(…including 0.5M spectra, 6M photometry, 25M astrometry points)

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