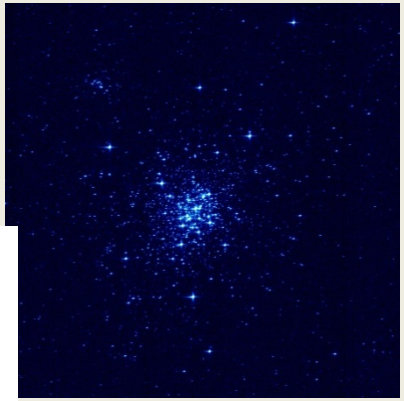
Gaia

Stereoscopic Census of our Galaxy

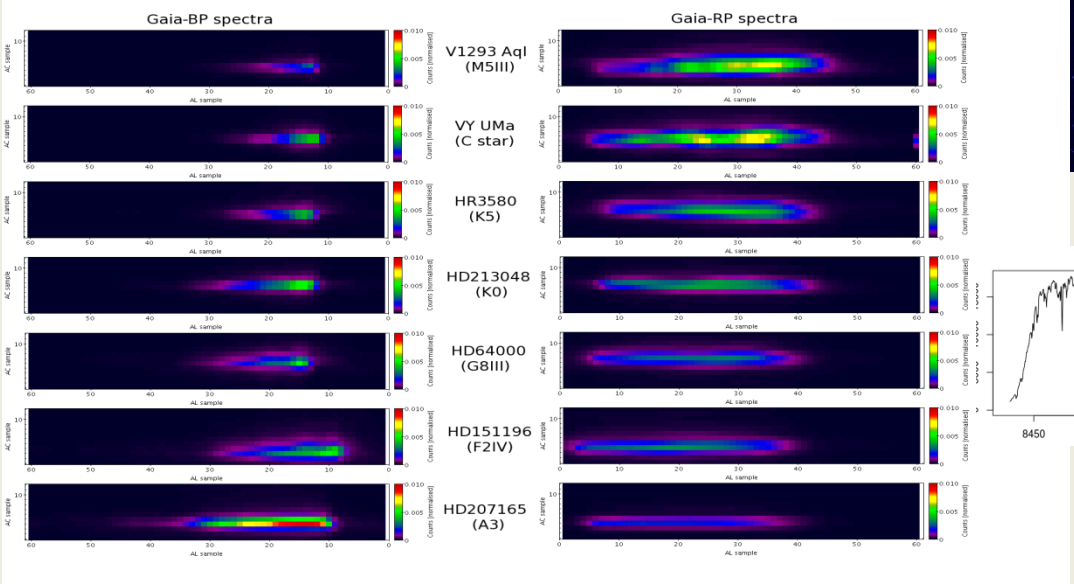
http://www.cosmos.esa.int/web/gaia http://gaia.ac.uk

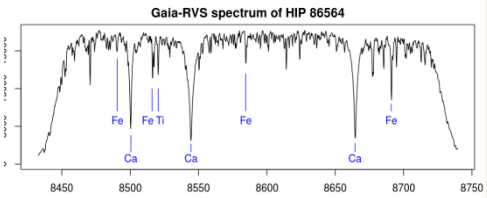
one billion pixels for one billion stars

one percent of the visible Milky Way



Gerry Gilmore FRS, UK Gaia PI, on behalf of DPAC





astrophysics cannot experiment – merely observe and deduce:

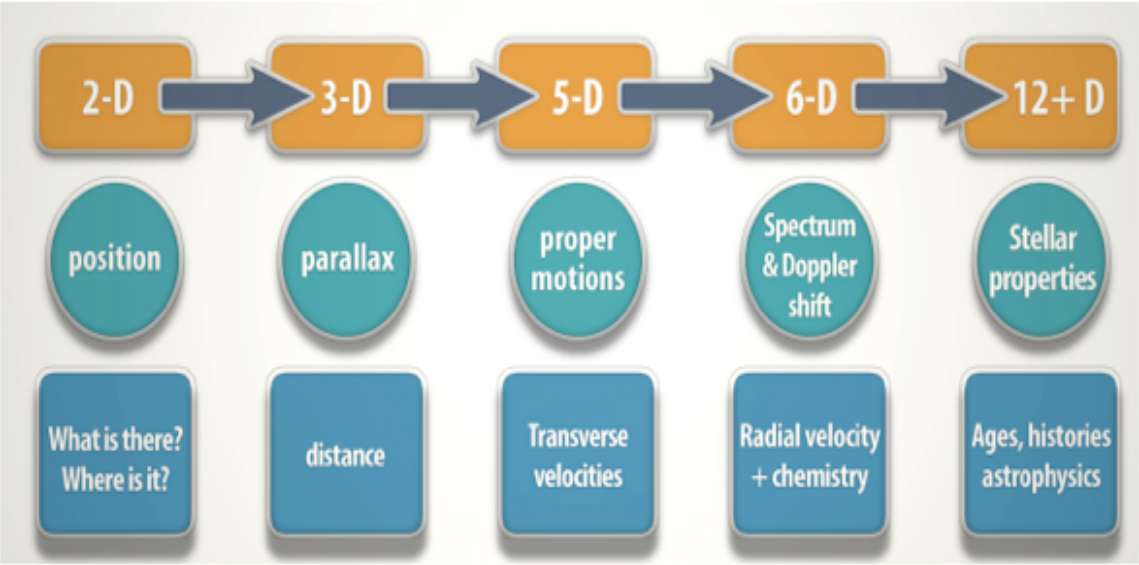
so how do we analyse the Milky Way?

- 2Dimensions: measure brightness *"star counts"*
- 3Dimensions: measure distances "*parallax*"
- 5Dimensions: watch the stars move "*proper motion*"
- 6Dimensions: measure doppler shift "*radial velocity*"
- Spectrum also measures *chemical elements*

- The future: Gaia: *taking the census of the Milky Way*

How does one study the Milky Way?

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

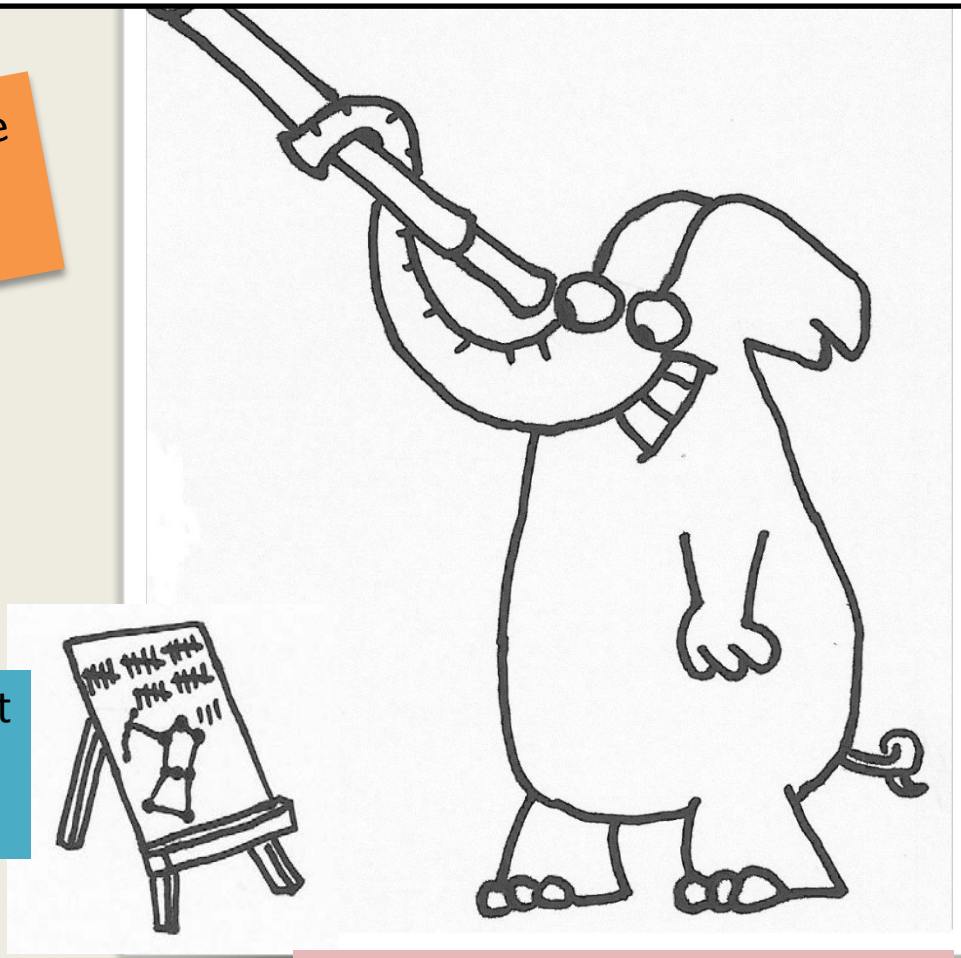


Stellar orbits, star formation history, origin of the elements, Galaxy assembly, dark matter, cosmological initial conditions, fundamental physics, solar system(s), ...

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

There is an elephant in the astrophysics room:
all distances depend on very few, inaccurate, stellar parallaxes
Good distances are known for only ~700 stars

The cosmological distance scale is the weak link in modern astrophysics



I gave my friend an elephant
He said: "thanks"
I said: "don't mention it"

Thanks to Ian for the elephant

Gaia: the goddess who created the universe and knowledge

Gaia is transformational – the first 3-D galaxy

precision distances and motions for 1 billion stars

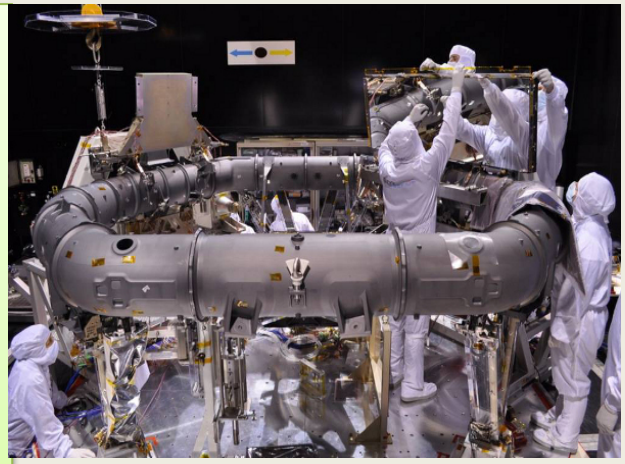
- Astrometry, photometry, spectroscopy, spectrophotometry,

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

Launch: 12/2013

Work started: ~1993
Project approved: 2000
Operations start 7/2014
5-7.5 years data
Project end: 2023+

Total cost: 960M€



The heart of Gaia is a large camera array, 1 giga-pixel, sending us a video of the sky for 5-8 years.

The imaging data is being processed in Cambridge.
6 billion transits processed so far

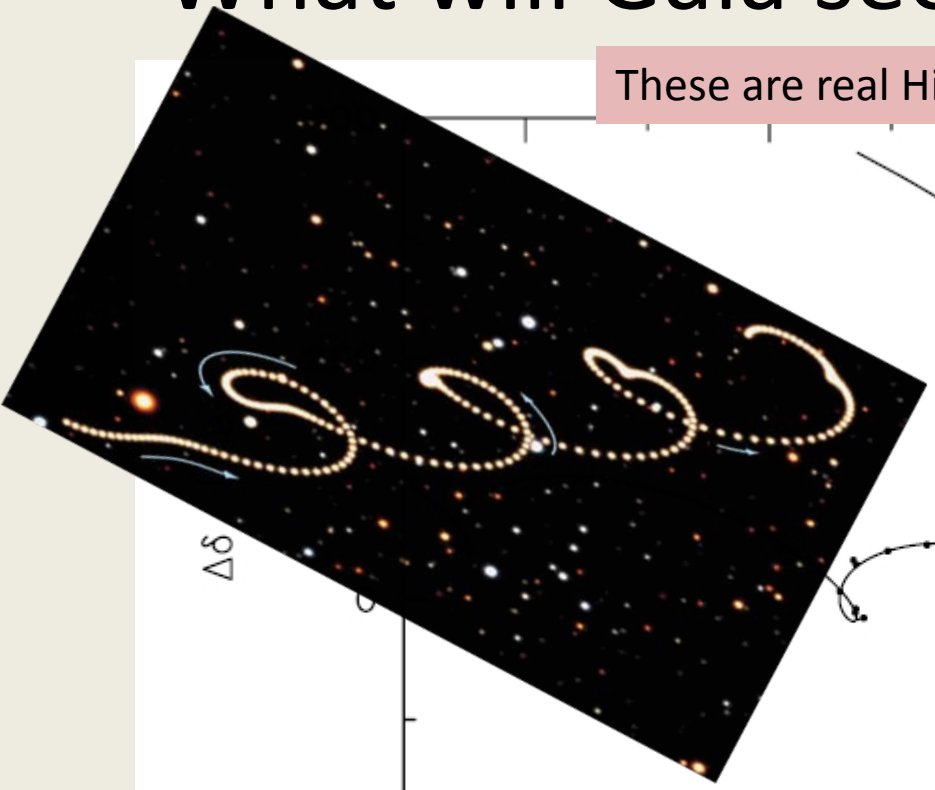
2 telescopes, 1.45 x 0.5 m primary, monolithic SiC optical bench, 0.06arcsec pixels

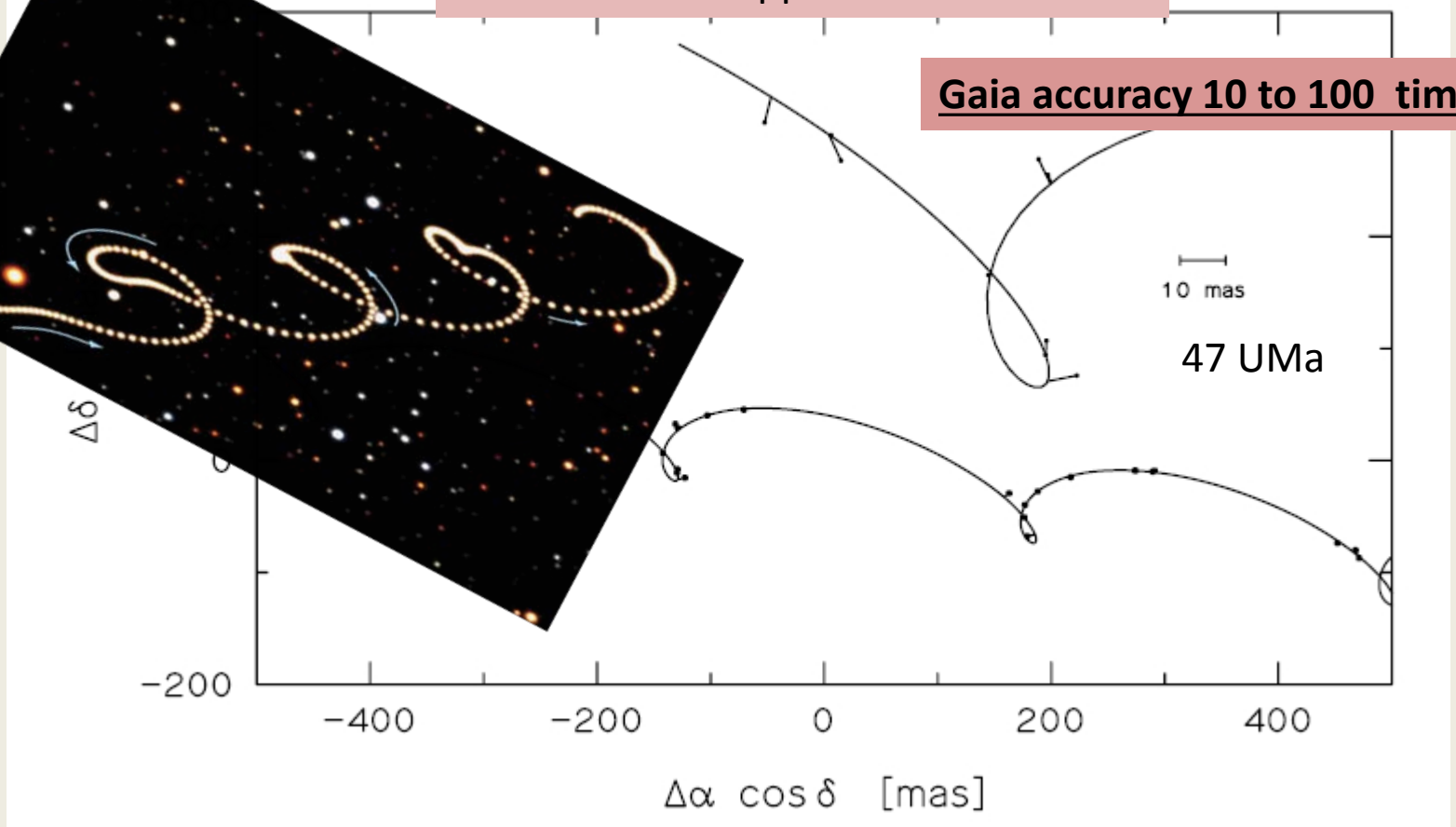
Data flow: 50Gb/day for 5-8 years; total processed data and archives ➔ 1PByte
Computational challenge : 1.5 x 10^{21} FLOP – and highly sophisticated algorithms

What will Gaia see as stars move?

These are real Hipparcos observations

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

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.

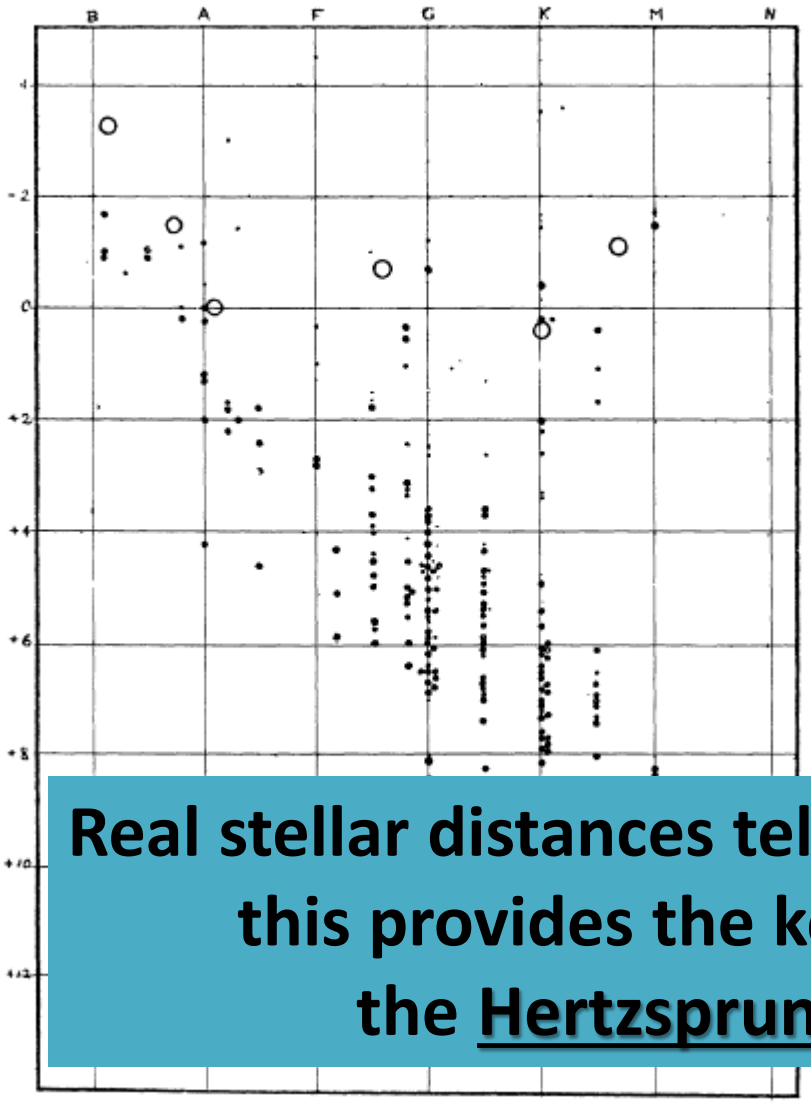
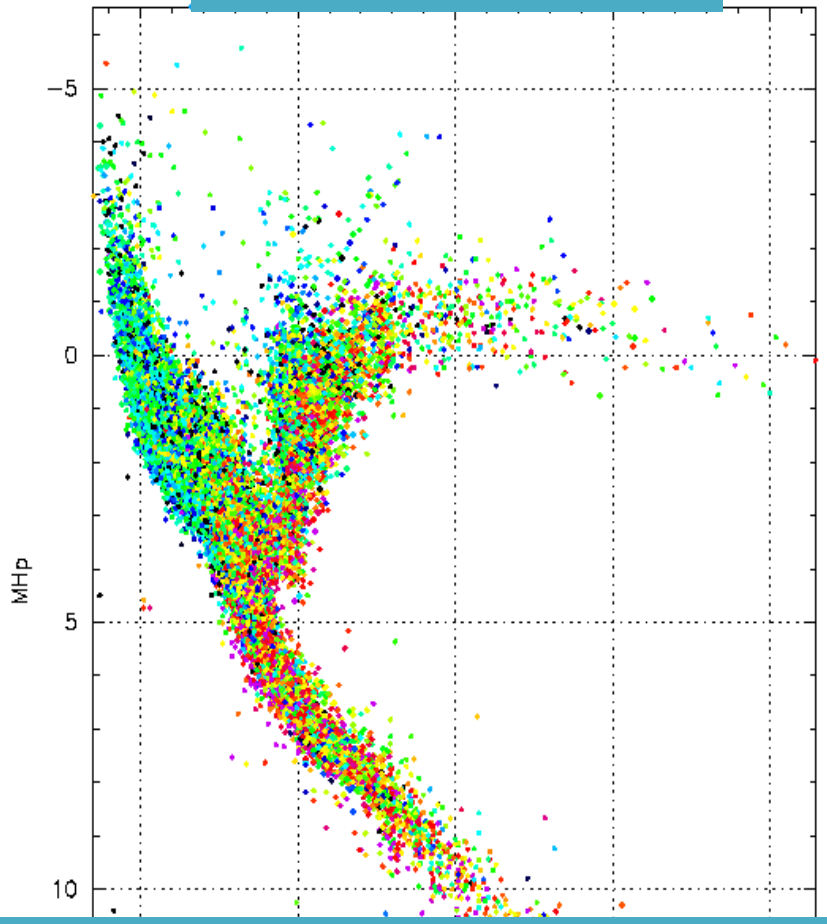


FIGURE 1.

HIPPARCOS mission 2005



V-I Colour

Real stellar distances tells us how bright stars really are
this provides the key to how stars evolve
the <u>Hertzsprung-Russell</u> diagram

Stellar distances: the Cambridge connection

A S T R O N (

FOUNDED BY B. A. GOULD.

Nos. 618-619.

VOL. XXVI. ALBANY, N.Y., 1910 OCTOBER 2

DETERMINATIONS OF STELLAR P

[From Photographs Taken at the Cambridge Observatory (England) by AR

By HENRY NORRIS RUSSELL.

The present communication co ates
of the first series of observations for stellar parallax made
at the *Cambridge Observatory*. The plans for the work*
were prepared by Mr. A. R. Hinks, Chief Assistant at the
Observatory, and d
a Research Assistant of the *Carnegie Institution* for the pur-
pose of this investigation. Mr. Hinks and the writer are
also jointly responsible for the photographic observations
in nearly equal shares. The former contributes 43%.
For the measurement and reduction of the plates, which
was begun at Cambridge and completed at Princeton, and
for the results and conclusions here detailed, the writer
is alone responsible.

The determinations of photometric magnitude and spec-
trum were made at the *Harvard College Observatory*, the lat-
ter by Mrs. Fleming, and the former by Prof. E. C. Pick-
ering, to whom the writer's most hearty thanks are due for
this extremely important addition to the value of the work.

I. Methods of Observation and Reduction.

A detailed account of the methods employed in the
present work, with the reasons for their adoption, is given
in the paper by Mr. Hinks and the writer, already referred

The photographs were taken with the Sheepshanks Equatorial of the Cambridge Observatory† — a *coudé* telescope of the polar siderostat type, of 12 inches effective aperture and 19.3 feet focal length. The stability of this instrument, and the performance of its driving clock and

were made to guide by hand.

The plates, coated on plate-glass, cover a field a little
less than $1\frac{1}{2}°$ square. Four exposures were usually made
on each, separated by $\frac{1}{2}$ mm. in declination. With the
standard exposure of five mi
eleventh (photographic) mag

* Hinks and Russell, *M.N.*, L
† Described by Sir Robert Ba

at once — because
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conditions of the wo
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systematic errors,
tude, which may a
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diminished the ph
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glass plate, placed
This worked very
until the gelatine p
of the glass. The
fourth magnitude w
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ons at two epoch
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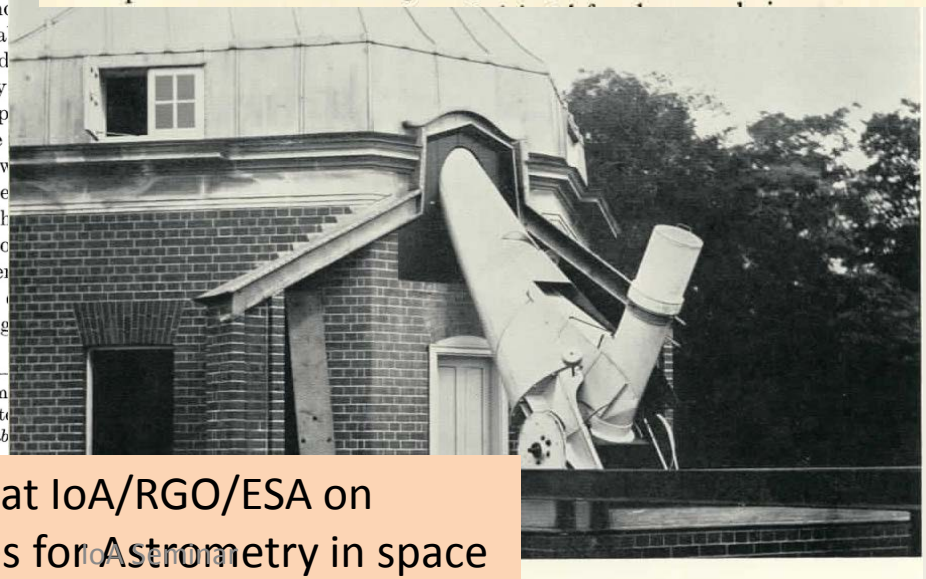
* The alternative m
circumstances to syst
See Kostinsky. *Pub*

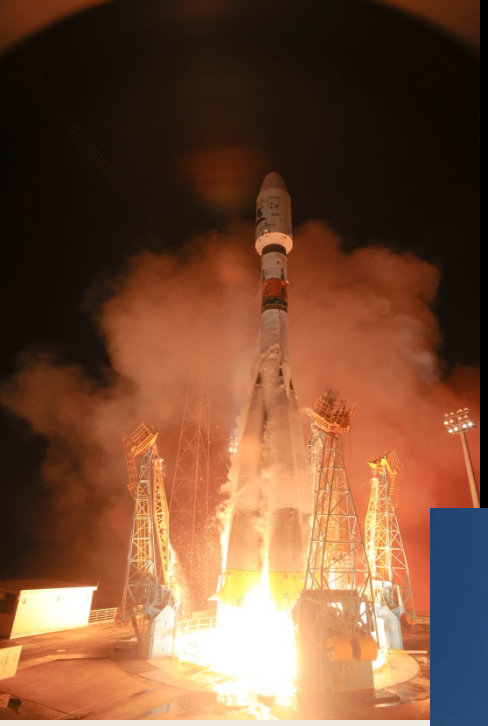
§8. *The Sheepshanks Telescope*. Professor Adams died in January 1892, leaving to the Observatory a portable equatoreal by Cooke and a valuable collection of books. He was succeeded as Lowndean Professor and Director of the Observatory by Sir Robert Ball. In a memorandum to the Syndicate in March 1893, the new Director pressed for the erection of a refracting telescope suitable for stellar photography, with a view to work on stellar parallax.

length that it should be carried on the same mounting as the Cumberland telescope which could be used as a guiding telescope. It was hoped to prov the greater part of the cost from the special Sheepshanks Fund and to appeal to the public for subscriptions to meet the balance. The appeal was not successful and it was decided to look to the Sheepshanks Fund for the whole sum. Professor Stokes, Mr Newall and the Director were appointed a committee to prepare plans and on their recommendatio a 12 ble apochromatic by Cooke was ordered in 1895. On the suggesti Dr Common and Pr it was agreed in March 18 modified form of equatoreal *coudé* mounting designed by Sir Howard Grubb of Dublin.



(*a*) SHEEPSHANKS TELESCOPE

1994 workshop at IoA/RGO/ESA on
Future Possibilities for Astrometry in space

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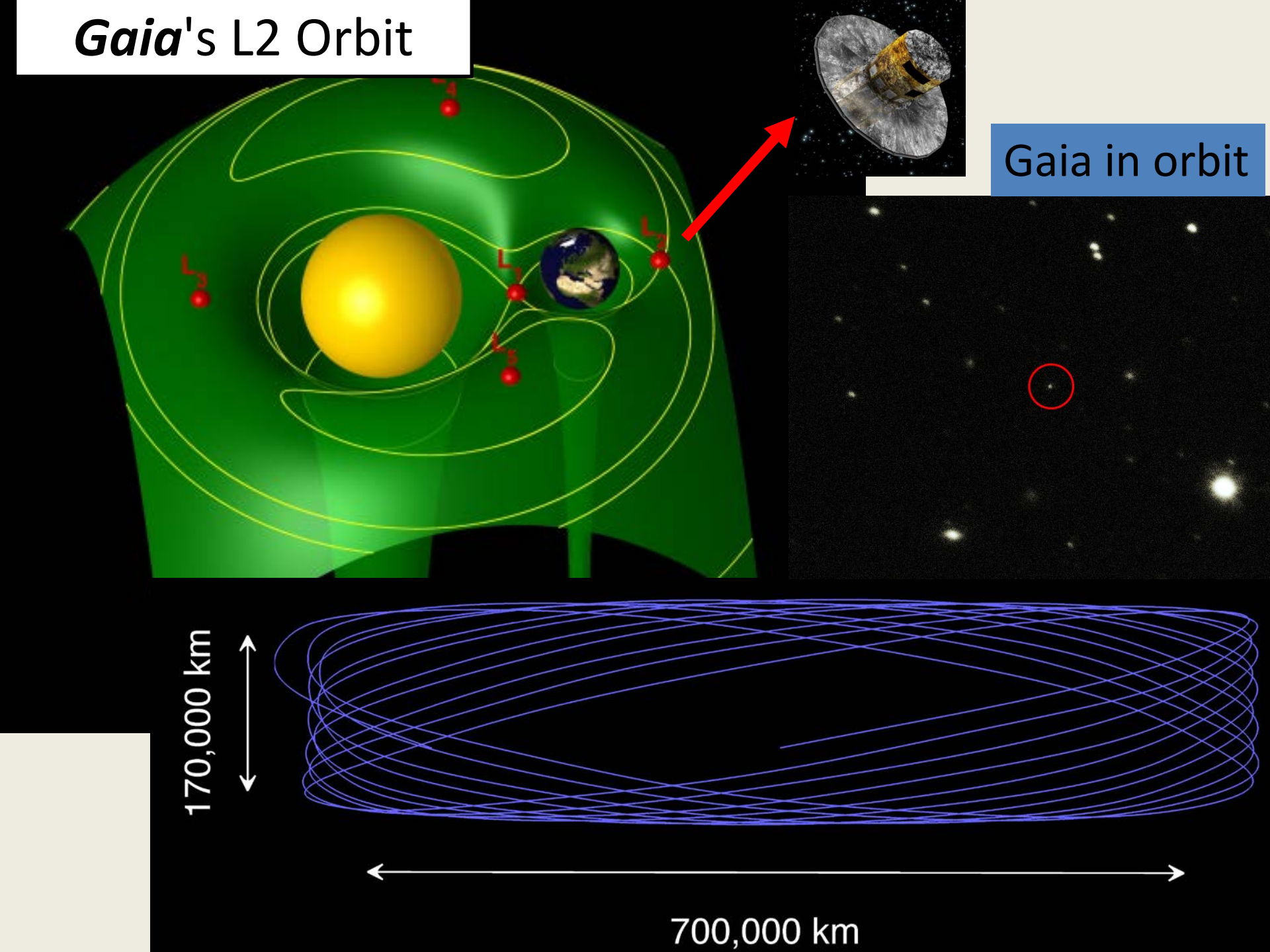
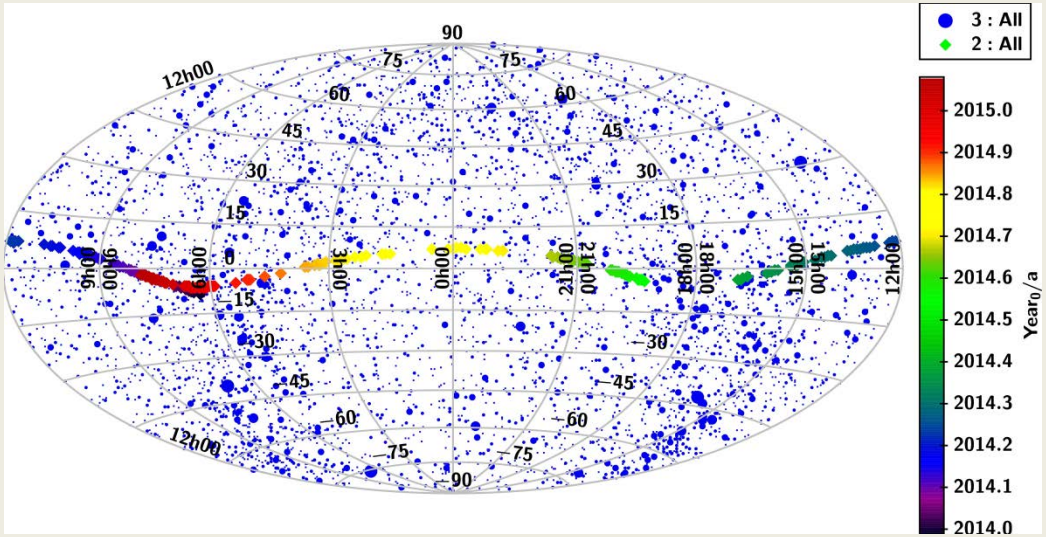
THE BILLION STAR SURVEYOR
The Gaia "Cuvée"
Gaia DPAC
gaia
cnes
Anne de Joyeuse

Gaia's L2 Orbit



Gaia the NEO…



MPC@CFA.HARVARD.EDU
URL
http://www.minorplanetcenter.net/
ISSN 1523-6714

DELETION OF 2015 HP116

The designation 2015 HP116, announced on MPEC 2015-H123, is being deleted.
The observations belong to the artifical object GAIA.

From a.fitzsimmons@qub.ac.uk Mon Apr 27 14:51:50 2015
Date: Mon, 27 Apr 2015 14:51:47 +0100
From: Alan Fitzsimmons <a.fitzsimmons@qub.ac.uk>
To: gil@ast.cam.ac.uk, sth@ast.cam.ac.uk
Subject: GAIA is not an asteroid

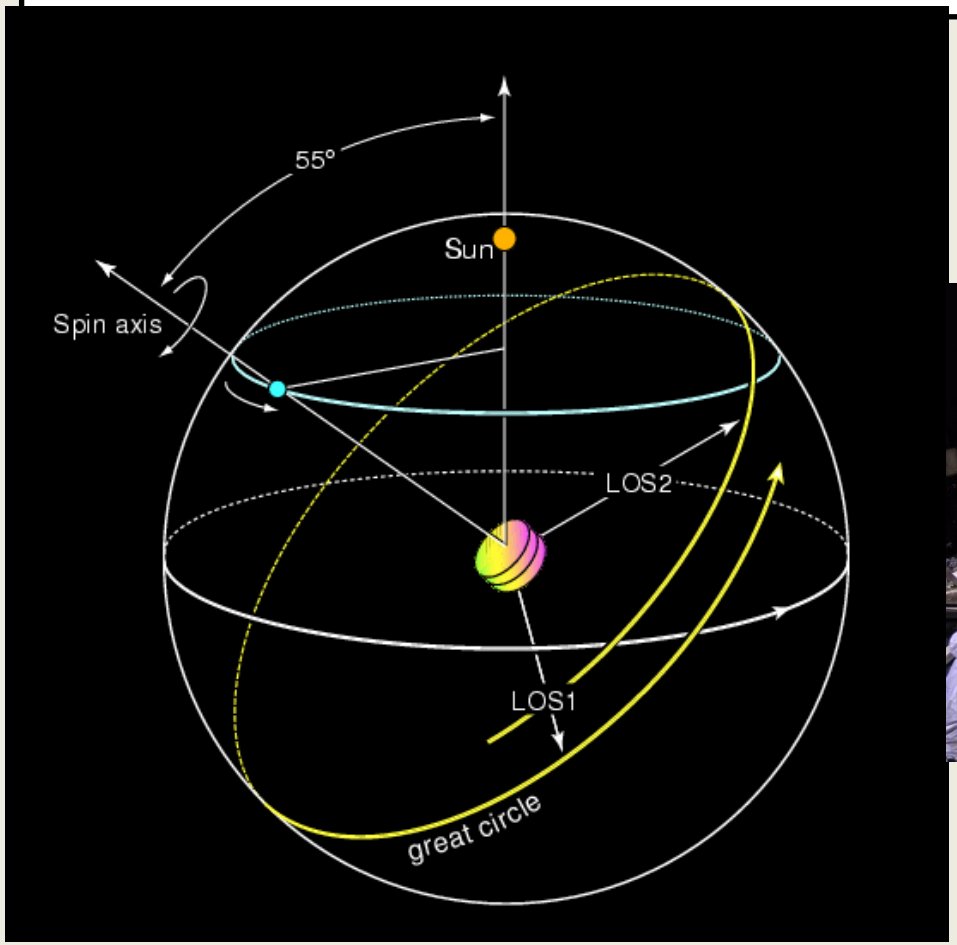
Hi Gerry, Simon

Just thought you might find it amusing that Gaia was listed a Near-Earth asteroid for 14 hours today until we realised what it was :-)

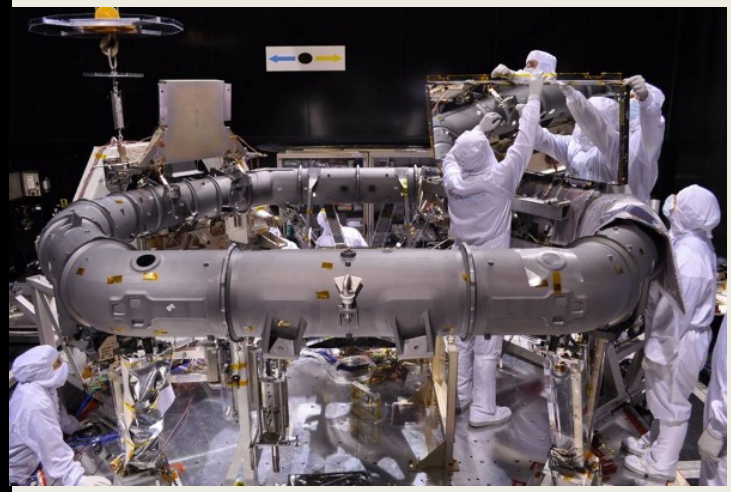
It was found 4 days ago by Pan-STARRS and it had a short life as confirmed asteroid 2015 HP116. (For some reason the automatic satellite identification routines at the Minor Planet Centre screwed up).

All the best
Alan

How does Gaia work?: Sky Scanning Principle

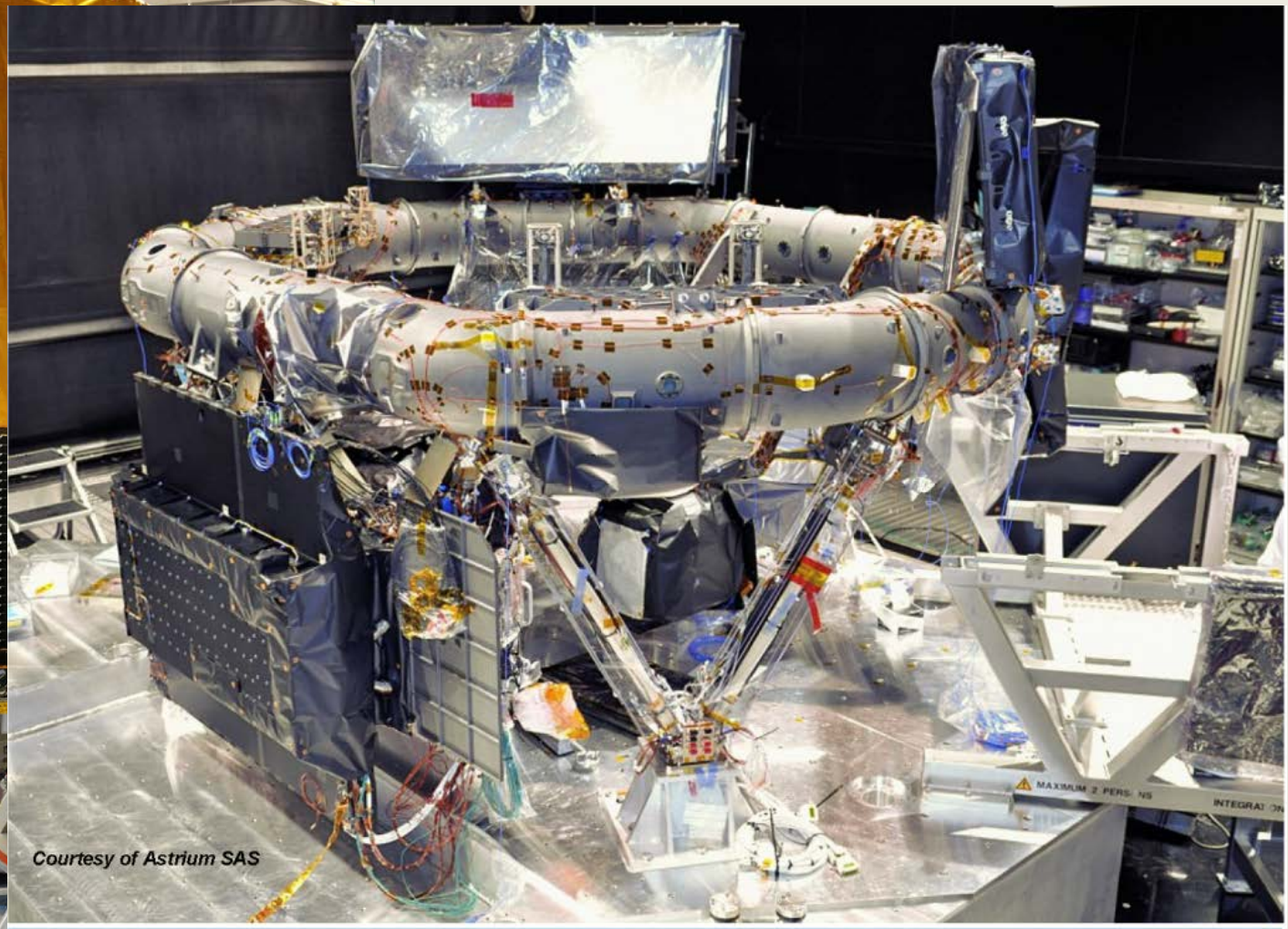


Observe sky with two telescopes



Precision: 50pico-rad, human hair at 1000km, 2cm on the moon...

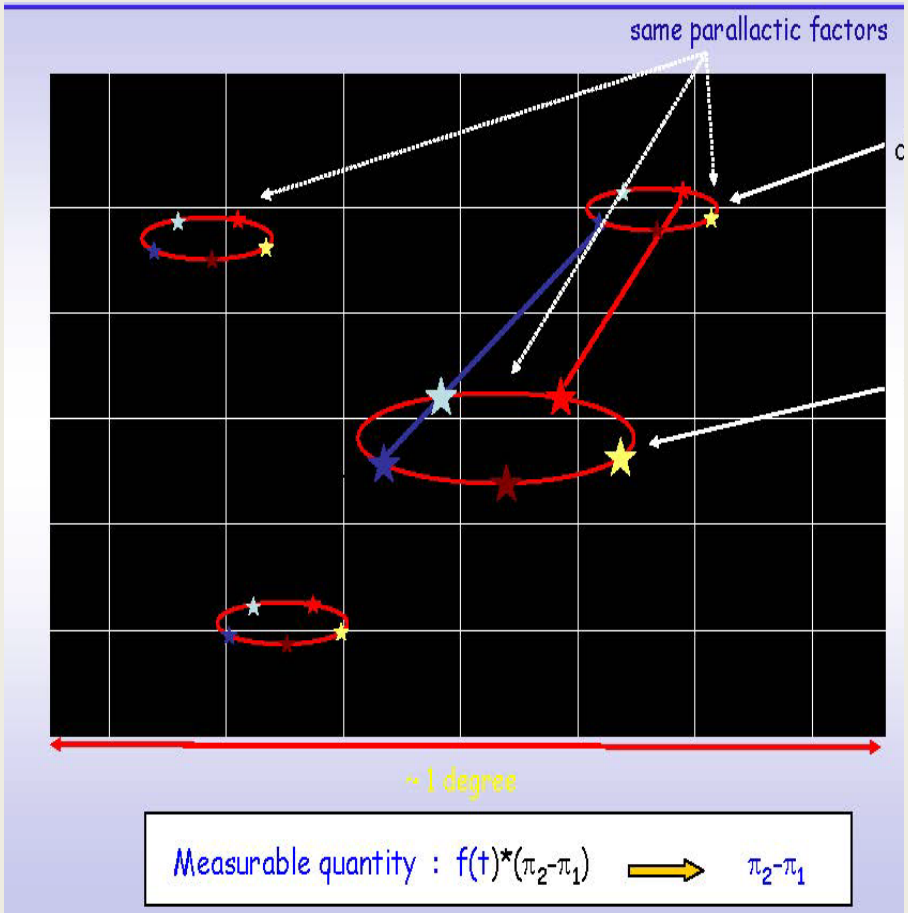
Gaia is a simple 2-telescope optical bench



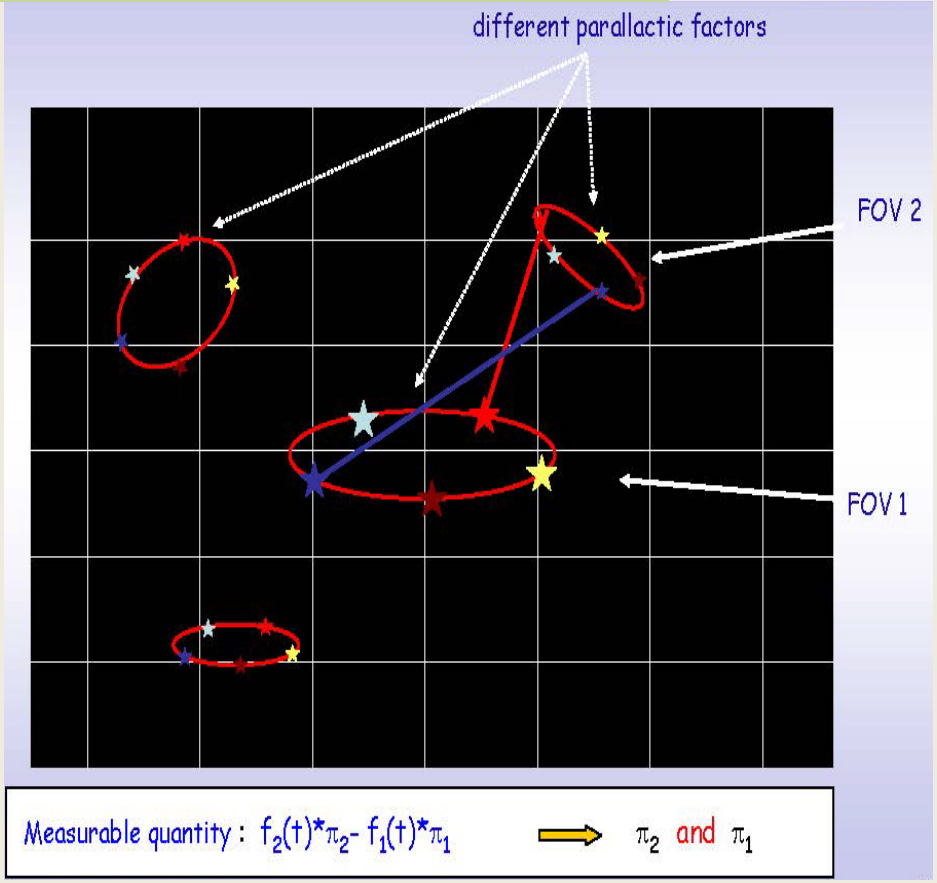
Gaia Payload Module fully assembled (except for external insulation *MLI*) ready to start the final environmental tests campaign.

Absolute astrometry

One field gives only relative measures ➔ model dependancy
Two fields break the degeneracy➔ allows absolute measurements.
Combining data at the limits of accuracy is not trivial!



Single field astrometry

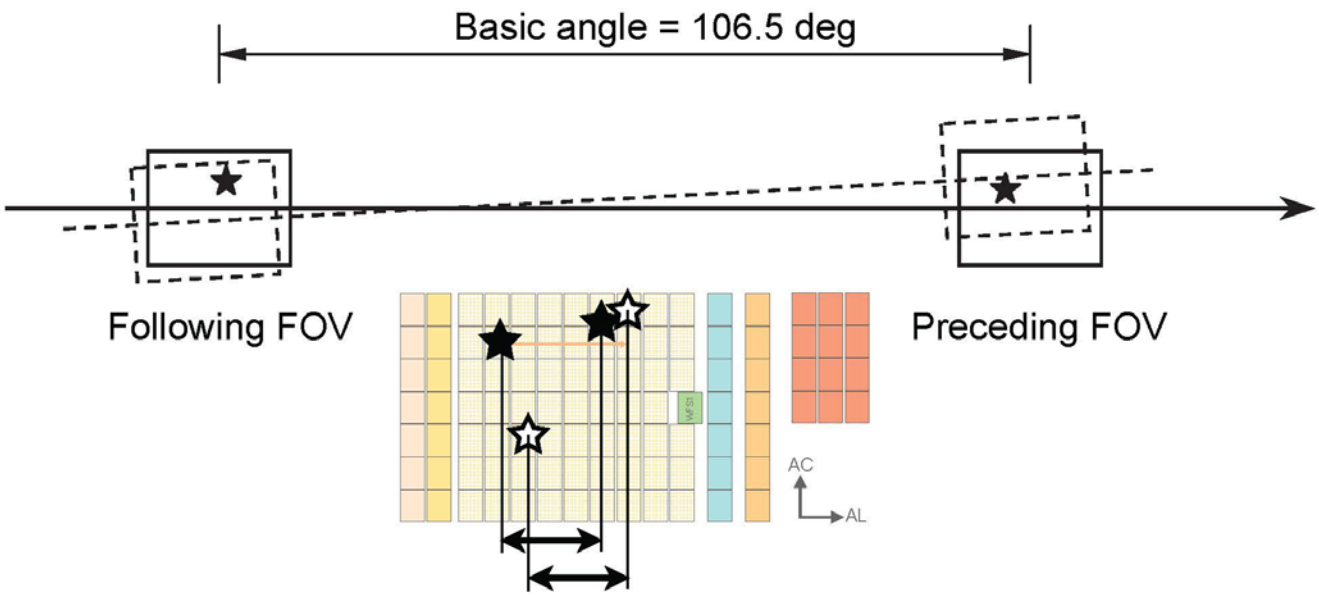


Two field astrometry

Observation principles

Why rectangular?

Why measurements are mainly 1 dimensional (along-scan):



Lindegren (2004), Fig 5.

Two stars observed simultaneously in different FOV:

- Along-scan projected **angle between stars is independent of instrument orientation** to first order (solid versus dashed lines).

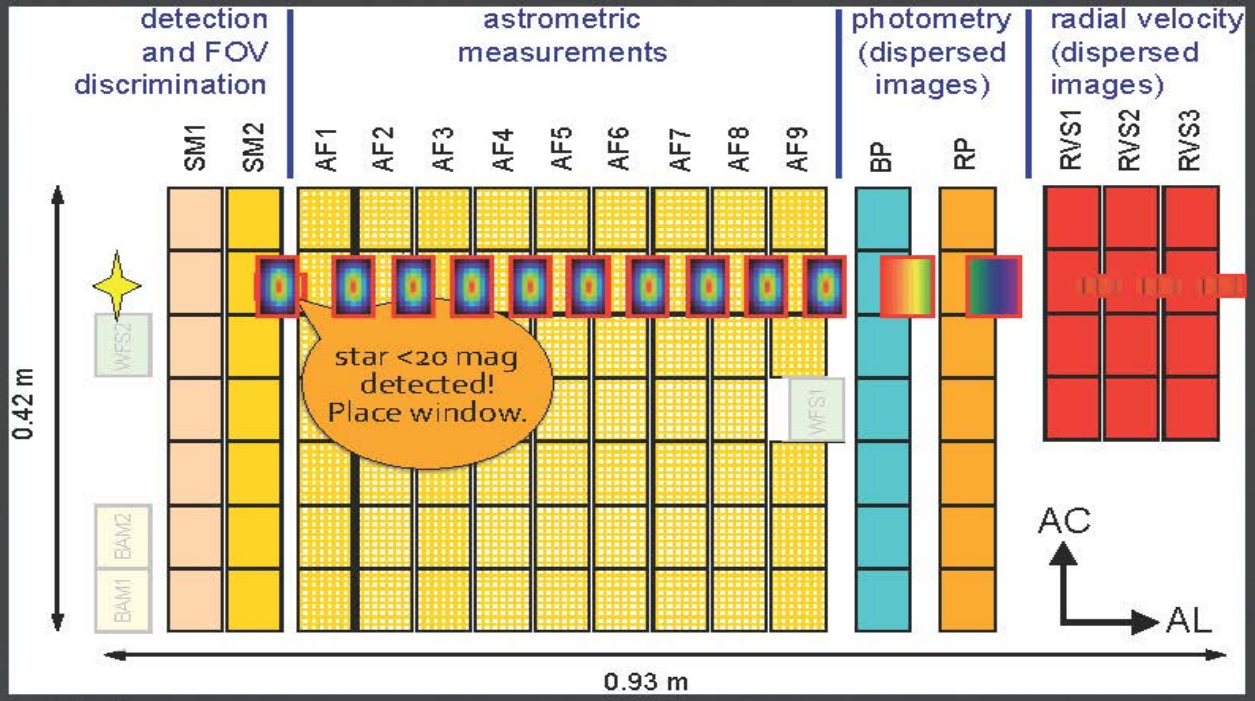
➔two-telescope scanning mission is optimal.
Since across-scan data is much less important, can save mass and use rectangular mirrors

SINGLE GAIA OBSERVATION = TRANSIT

Camera:

0.75 deg^2

pixel:
10x30 µm
(59x177 mas)

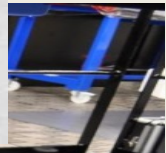


Animation by Berry Holl, Geneva

windows observed:

~4.4 sec

~45 sec



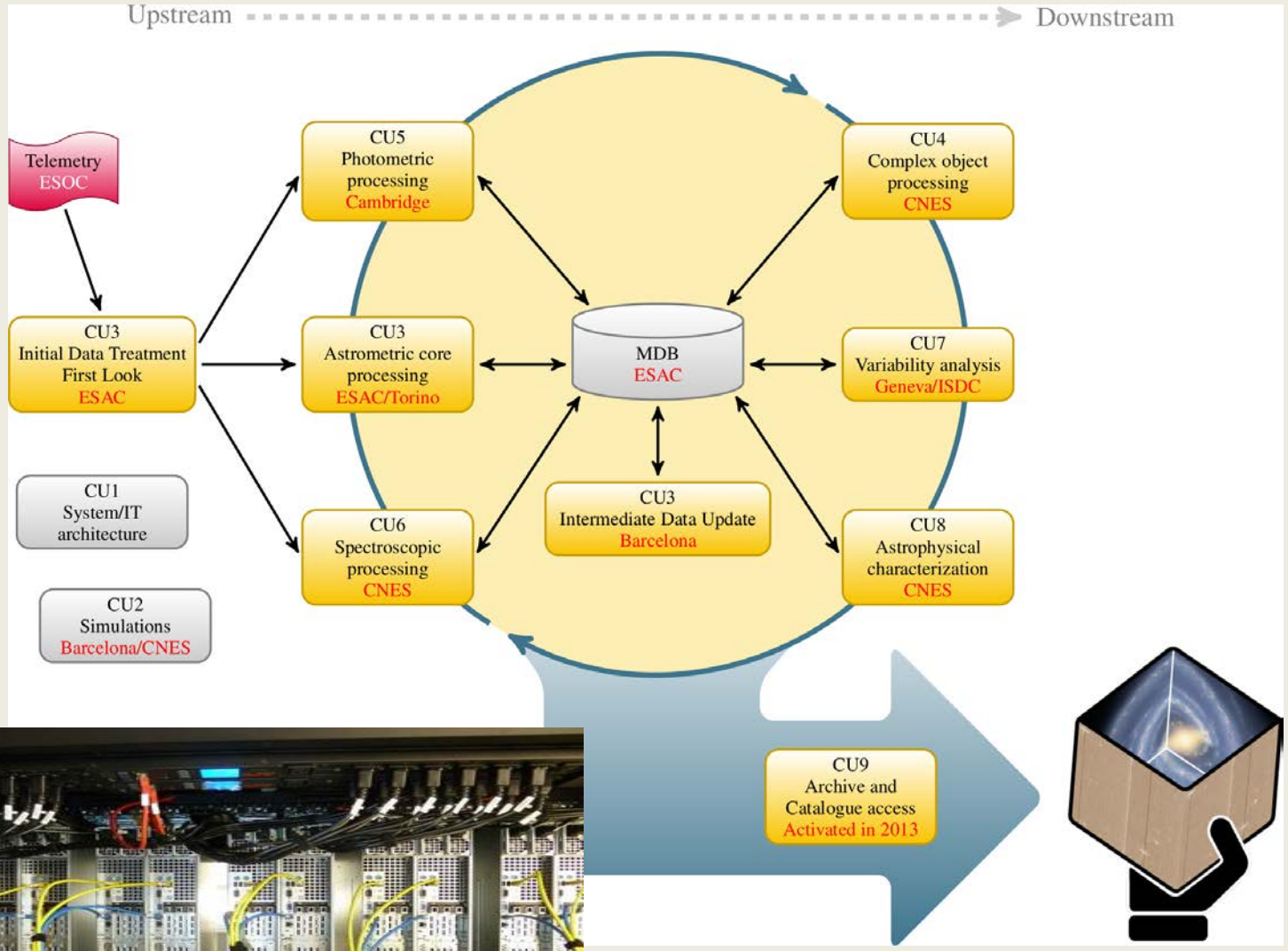
What does micro-arcsecond mean?

Precision: 50pico-rad, human hair at 1000km, earth-L2 dist to 1cm

- **Precision: 50pico-rad, human hair at 1000km, coin on the moon**
- **Astrometry needs more than signal to noise and image processing**
- **One must have a physical model and understanding of every contribution to the error budget at an appropriate level**
- **Einstein light bending at the Sun's edge is 1,750,000 microarcsec**
- **One mu-as is the limit to which we have tested GR…**
- **For Gaia the spin rate is controlled to 15 ppm**
- **The spacecraft distance is known to a few metre (at 1.5 Million km)**
- **The spacecraft speed is known to a few mm/s**
- **On-board interferometer measures mirror locations to picometre level every few seconds – a helium atom is 30picometre**
- **clocks, pixel substructure -- and very much more**

- **400 people are busy with the data processing and analysis**

Gaia science data flow: 5,000 stars/second on average



Cambridge Data Processing Centre

- The Cambridge team is responsible for the processing of the photometric data, about 50 GB per day for 5+ years.
- Both software and hardware! 2 proud parents

The astrometric data reduction

- 10^{13} individual position measurements
- 10^{10} unknowns – based on physical models
- all connected - must be determined simultaneously
- a vast modelling and parameter adjustment problem
- Iterative, self-calibrating, needs GR metric
- 5000 million star unknowns (for simple stars)
- 150 million attitude unknowns
- 50+ million calibration unknowns
- a few dozen "global" unknowns
- DPAC involves 400 people and 6 processing centres

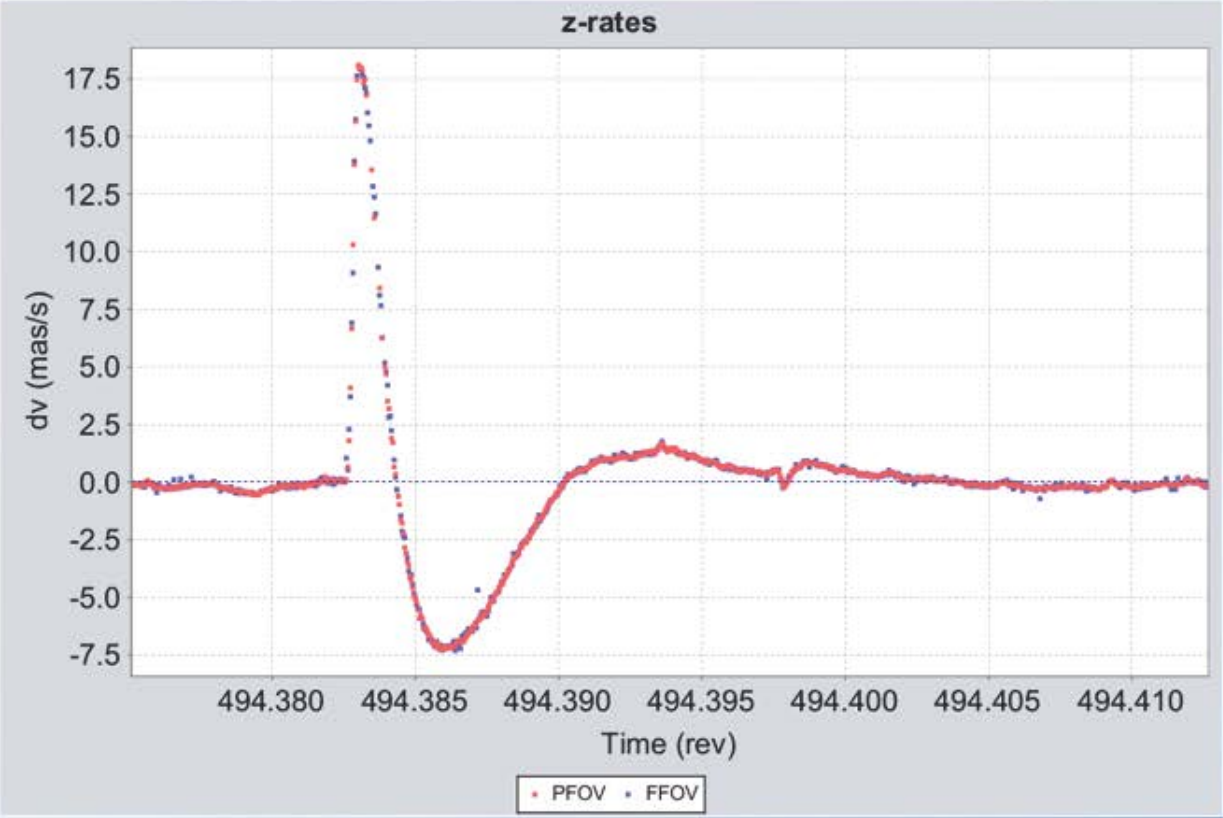
Eg, photometric ubercalibration:

- In total we use 200 million measurements with 6 million parameters and solve the system of linear equations to produce a calibration.
- The fit is done in 4 iterations where we reject measurements outlying by more than 1, 0.5, 0.2 magnitudes from the model fitted in the previous iteration.
- We achieve a precision of 0.02-0.025 magnitudes per ccd (i.e. <10 mmag for a transit)

Another order of magnitude to improve, but we are on the way

CCDs, electronics, clocks, communications, spacecraft control, … functioning nominally

- Micro propulsion system working well
- Attitude and Orbit Control System working well
- Phased Array Antenna operating with healthy link budget
- Clock working at required accuracy
- 106 CCDs, electronics, data acquisition and storage all f



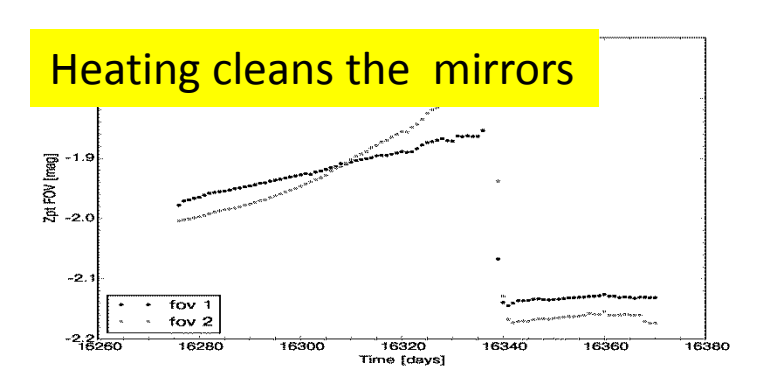
Micro-meteoroid hit example.
Figure by F. van Leeuwen

Complete sky survey from 0 < G > 20

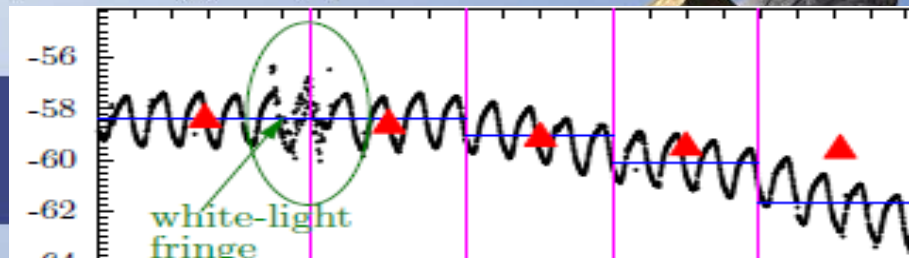
Mission extension from 5 years to 7.5 years under analysis

Unwanted surprises

- Stray light both from astronomical sources and the Sun
  - Sun stray light paths not yet identified
  - Impacts faint sources especially in spectroscopy
- Transmission loss due to continuing contamination of mirrors by frost
  - Water source not yet exhausted ar
    lost of the best transmission
  - Degradation of focus



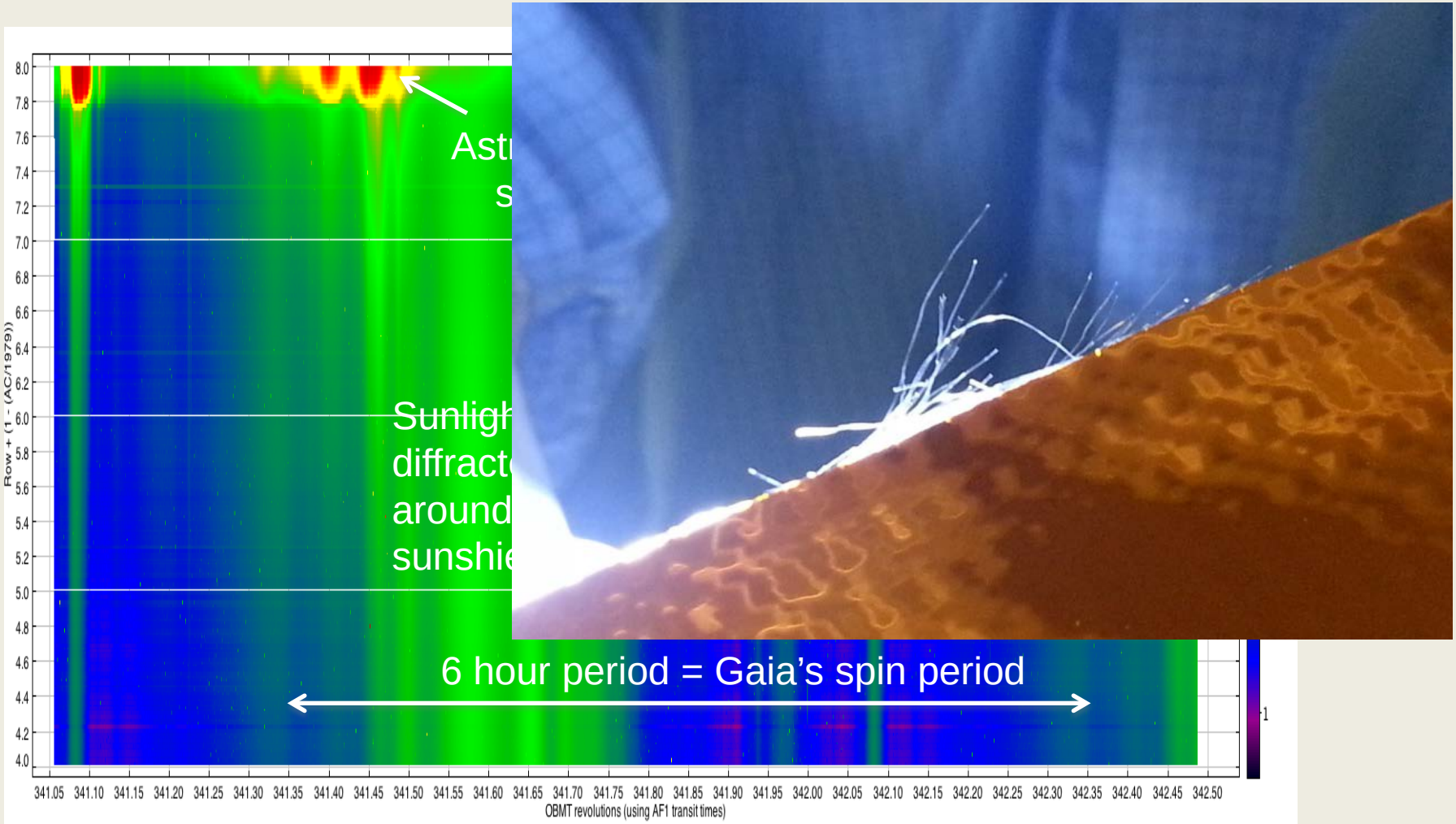
- Basic Angle variation larger than expected
  - However, Basic Angle Monitor providing very precise measurements of the changes



esa Gaia DPAC AIRBUS DEFENCE & SPACE

Scattered Light (RVS): mean level 30x expected

adds noise to faint sources – astrometry recovered by mission extension



RVS is delivering 60million spectra, R=11,000, complete to V<15.3

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,…

Best ground > mas accuracy

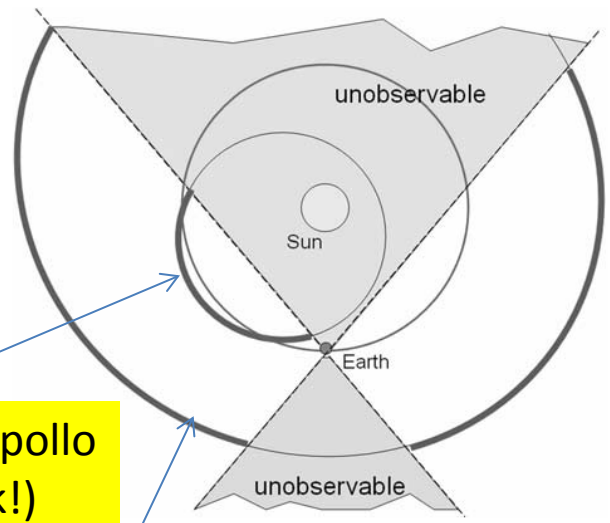


Fig. 6 The region not reached by Gaia, projected on the ecliptic, relative to Earth and Sun positions (shaded regions). The red arcs represent an example of observable orbit segments for a main-belt and a near-Earth asteroids. This picture is only meaningful at a particular time and as the Earth moves on its orbit the whole pattern is rotated and observations are performed on previously unseen parts of the asteroid orbit

NEO/Aten/Apollo (Chelyabinsk!)

Main belt asteroid

Orbital accuracy

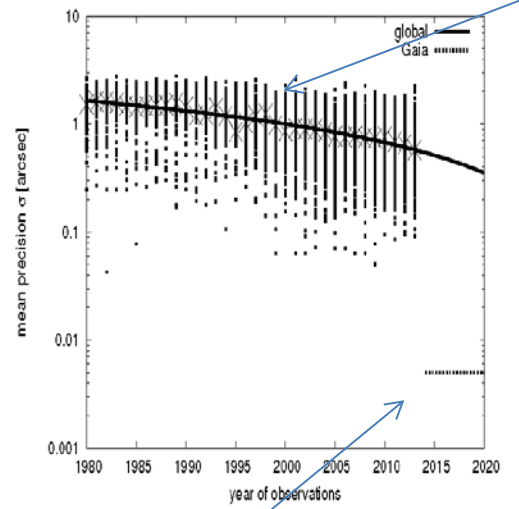


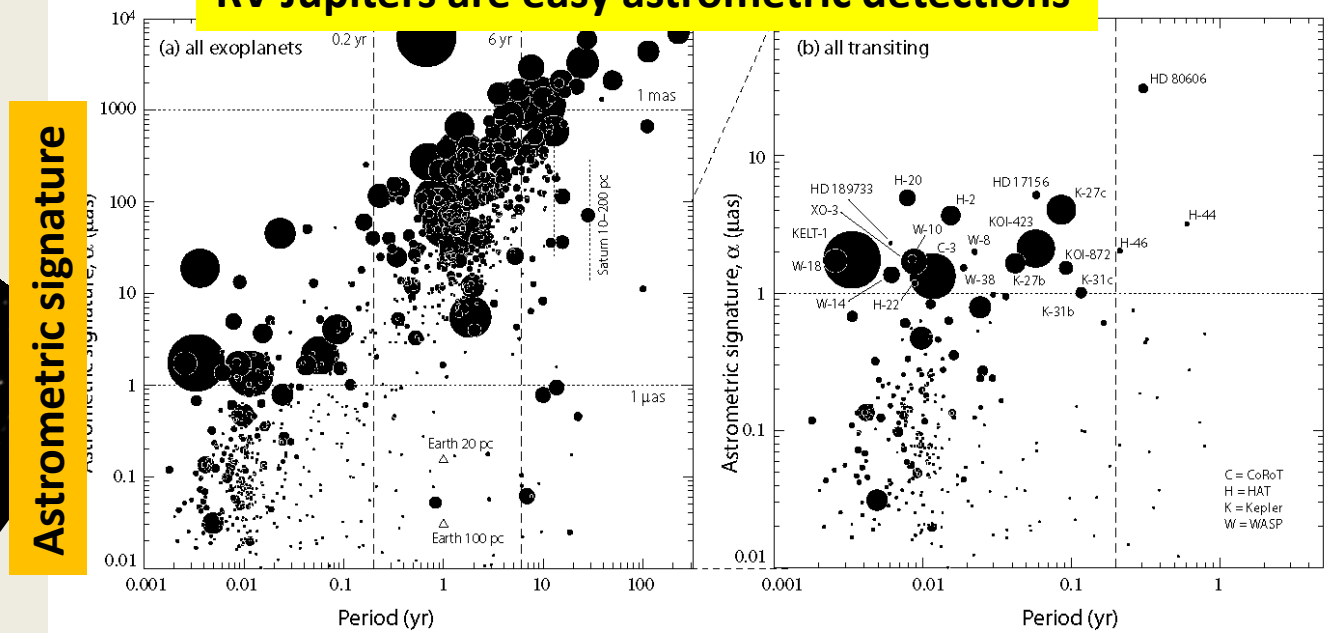
Fig. 2. The yearly astrometric mean precision ($\sigma = \sqrt{(\sigma_\alpha \cos\delta)^2 + (\sigma_\delta)^2}$) of each observatory with a Minor Planet Center designation and at least 10 submitted observations per year is plotted against time (dots). The crosses indicate global yearly averages, i.e. the weighted precision of all observations considered. The full line indicates the least squares trend of the global yearly averages, i.e. the mean quality of astrometric measurements. The dashed line represents pessimistic estimates for the performance of ESA's Gaia mission (Tanga & Mignard 2012).

Gaia

Planetary systems – Gaia will find some transiting systems, but the real value is definition of volume-complete stellar parent samples, plus direct astrometric discovery, and mass determinations, of nearby non-eclipsing jupiters.

<u>These will be ideal for follow-up direct coronographic imaging</u>

RV Jupiters are easy astrometric detections



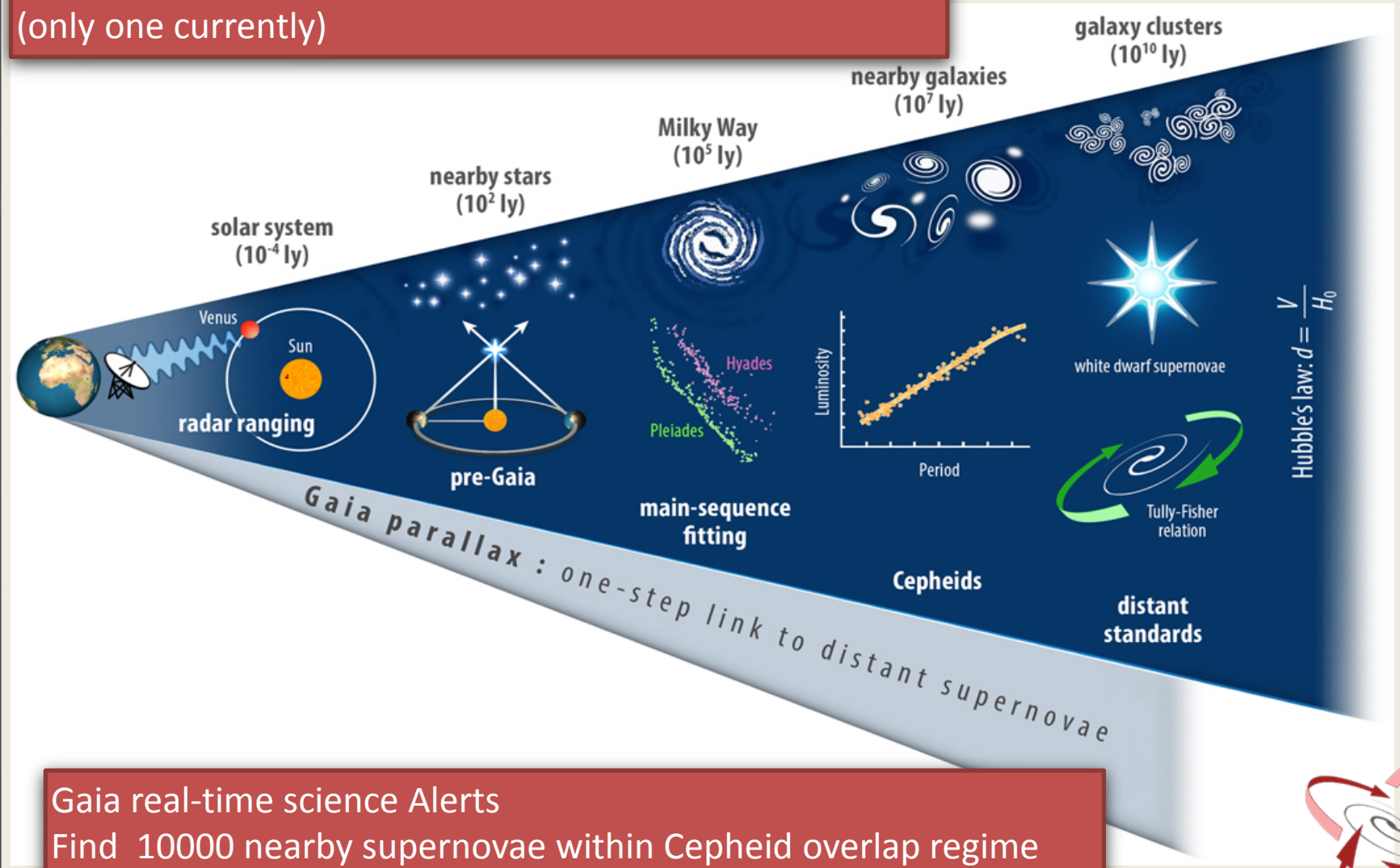
Period (yr)

Fig. 1.— Astrometric signature versus perio[illegible] objects listed in `exoplanet.eu` at 2014 September 1 for all 1821 confirmed planets (le[illegible] of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes are proportional to planet mass; the prominent object (left) at $P = 0.7$ yr, $\alpha = 6300\,\mu$as, is the $28.5 M_J$ astrometric detection DE0823–49 b. Unknown distances are set to $d = 1000$ pc. Transiting planets with $\alpha > 1\,\mu$as are labelled by (abbreviated) star name, indicating the discovery instrument, both ground (H = HAT, W = WASP) and space (C = CoRoT, K = Kepler). For the transiting planets above this threshold, the unknown distance affects only Kepler–27 b and c, and Kepler–31 b and c. Assuming $d = 500$ pc, α would increase by a factor 2, but their astrometric motion would remain undetectable by Gaia.

Perryman etal 2014 arXiv:1411.1173

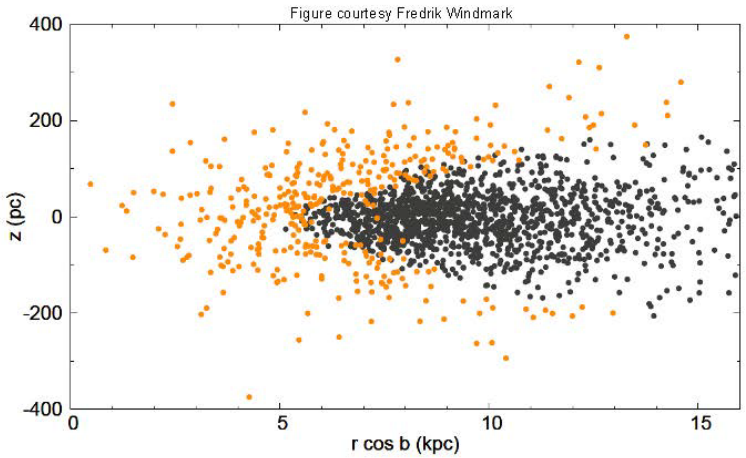
Taking the census of the Milky Way Galaxy

Precision Cosmology with Gaia
Precision calibration from parallaxes of 9000 Cepheids
(only one currently)



Gaia real-time science Alerts
Find 10000 nearby supernovae within Cepheid overlap regime

Galactic Cepheids



Cepheids in the inner Galaxy, with -5° < l < 5°

- Observable by Gaia
- Too faint for Gaia

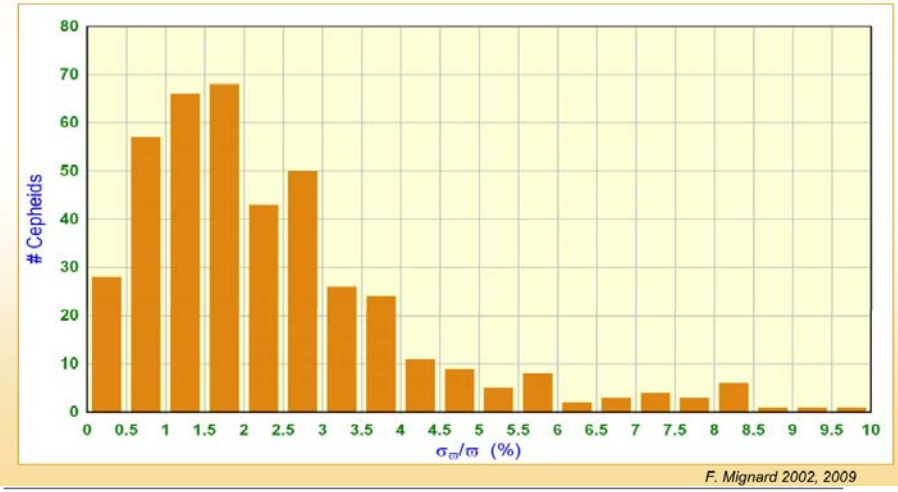
- Gaia will observe ~9,000 Galactic Cepheids (2011arXiv1104.2348W)
- Hundreds are visible near and behind the Galactic centre
- Beyond 5 kpc, all Cepheids are observed outside the plane

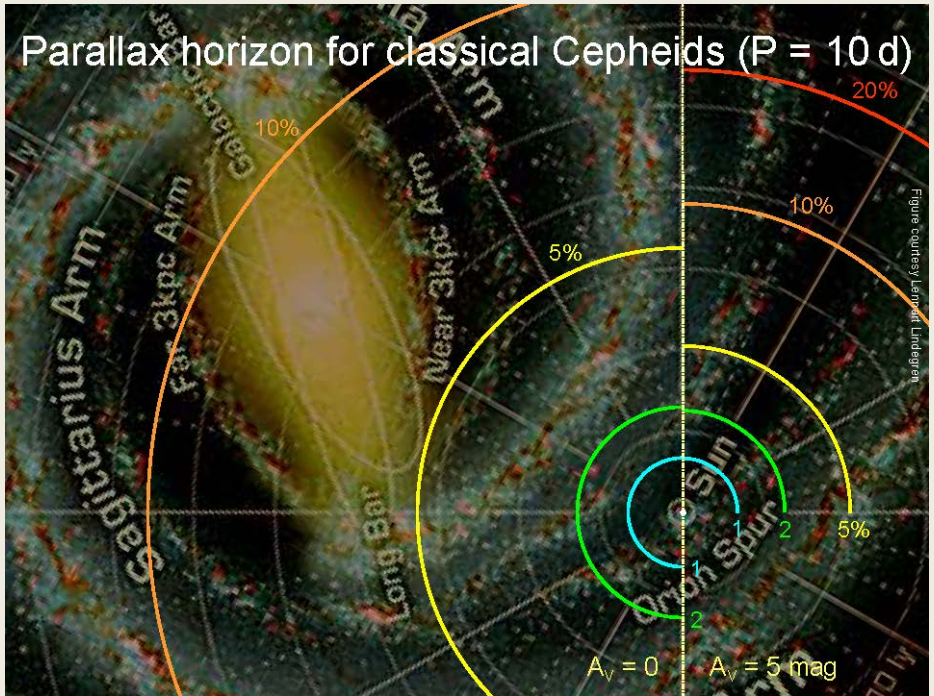
15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc

- bright enough (V < 14)

In the plot : 400 galactic cepheids from David Dunlap DB

- distance and magnitude ➔ Gaia predicted accuracy for parallax





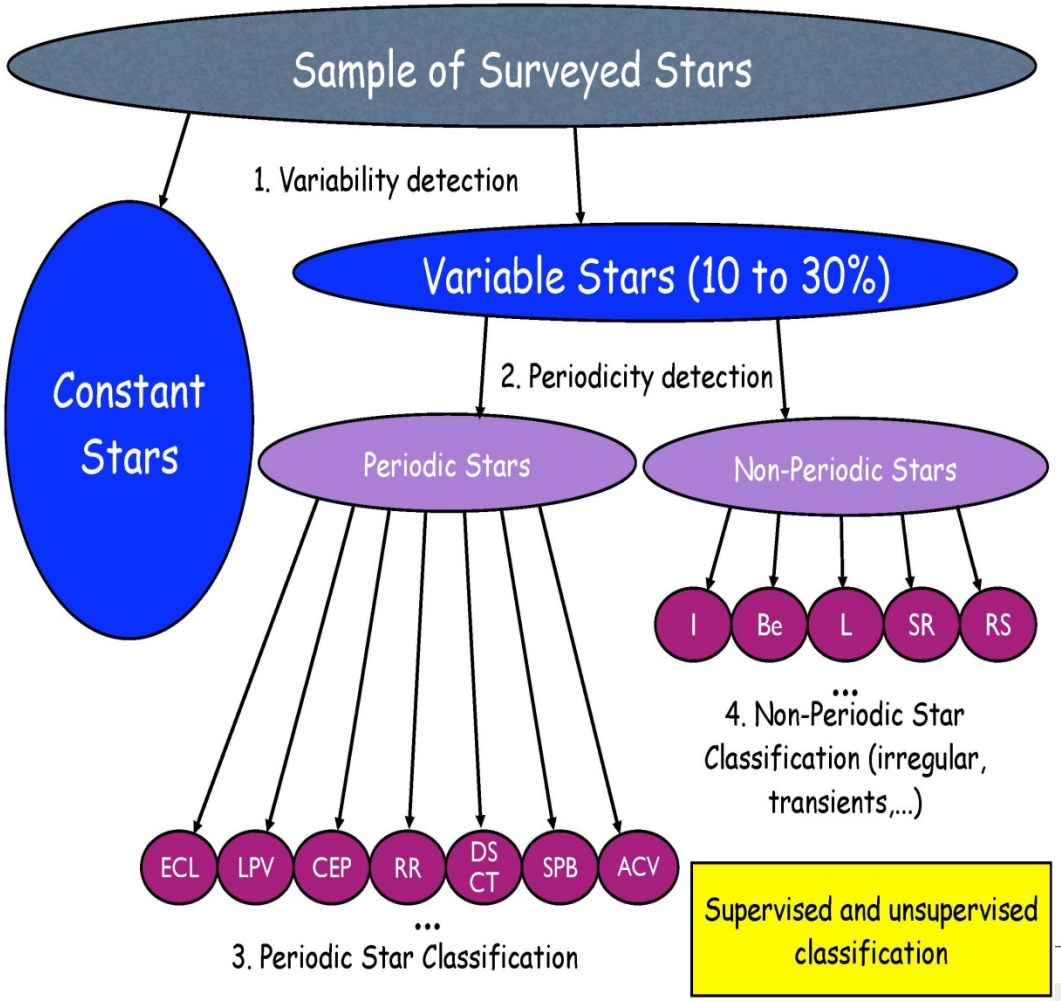
Galactic	Known	273	Hipparcos 1997
		509	Fernie et al. 1995
		455	Berdnikov et al 2000
		872	ASAS catalogue, as in 2011 Pojmanski
	Estimated for Gaia	**2,000-8,000**	**Eyer & Cuypers (2000)**
		9,000	**Windmark (2011)**

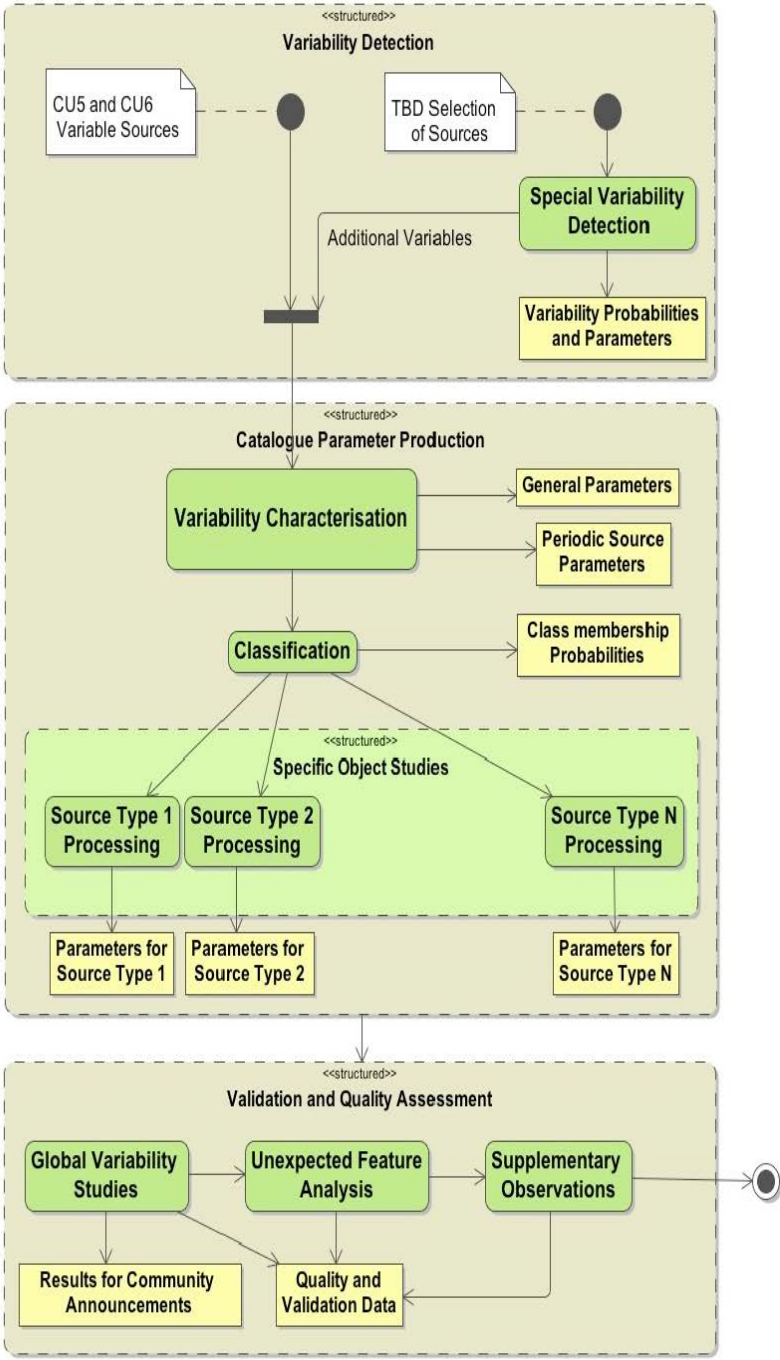
optimist: Gaia will multiply by 10 the Galactic Cepheid number

LMC	Known	3,361	OGLE-III, Soszynski et al 2008-2010
SMC		4,630	

CU7
Variability Analysis

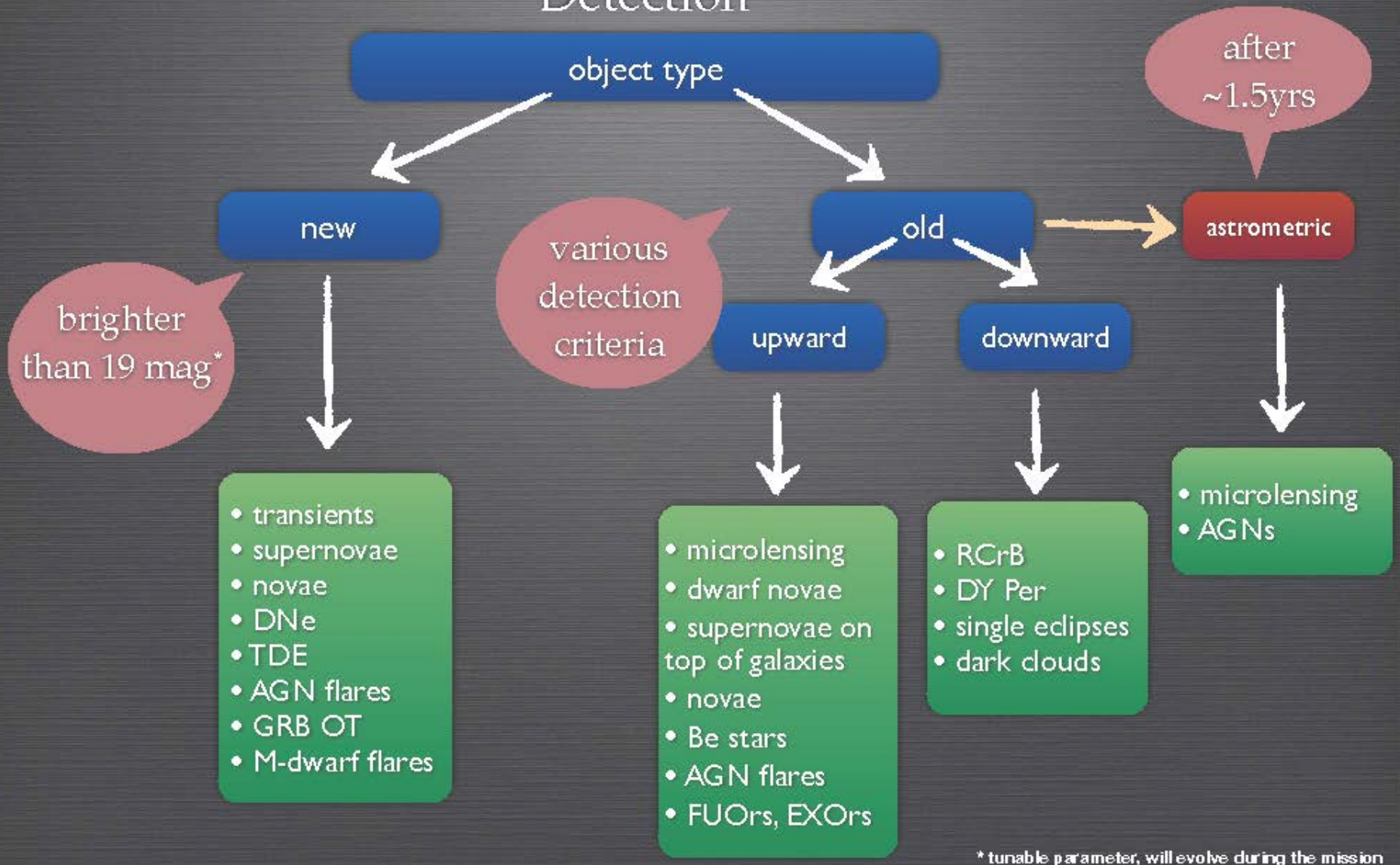
functional analysis



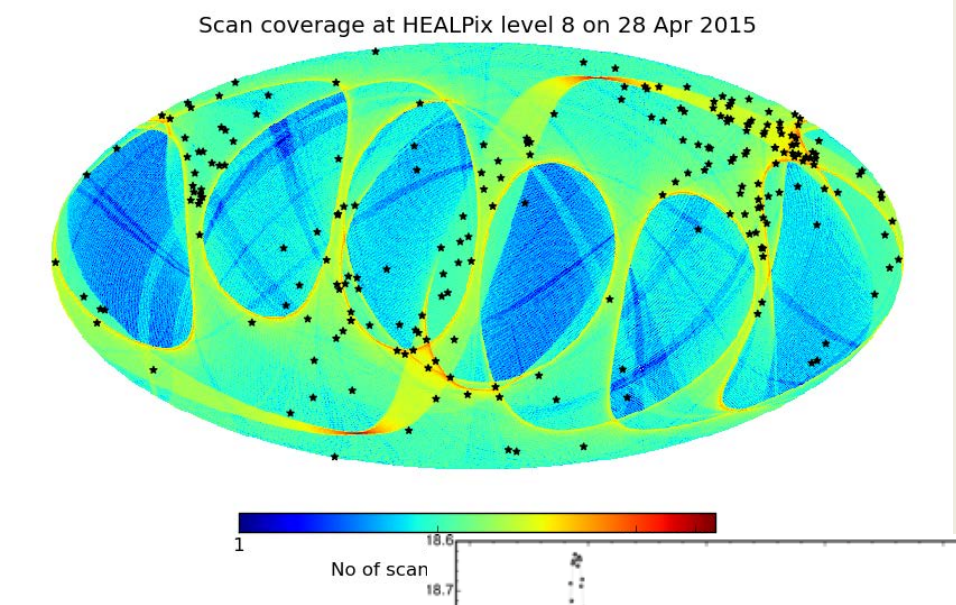


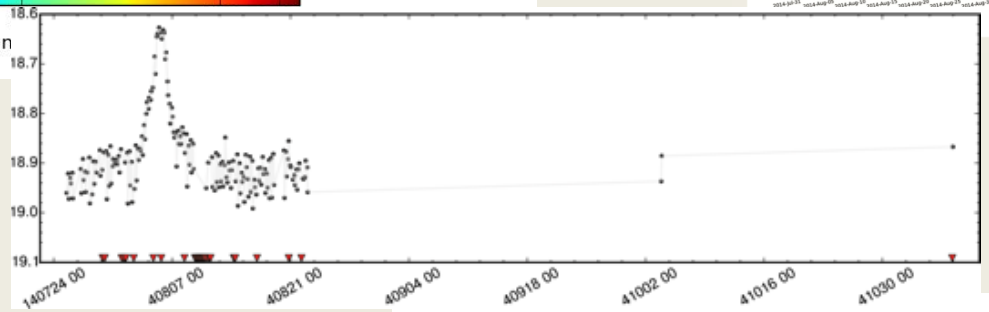
ANOMALY DETECTION SYSTEM

Detection

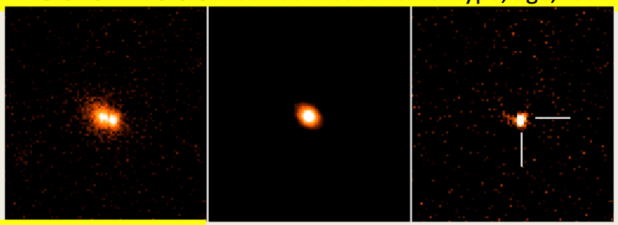


* tunable parameter, will evolve during the mission



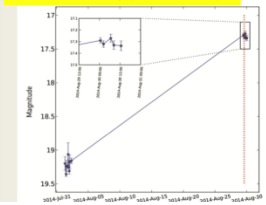


SN Gaia14aaa: correct deduction of type, age, redshift

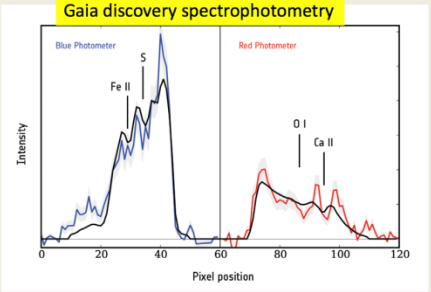


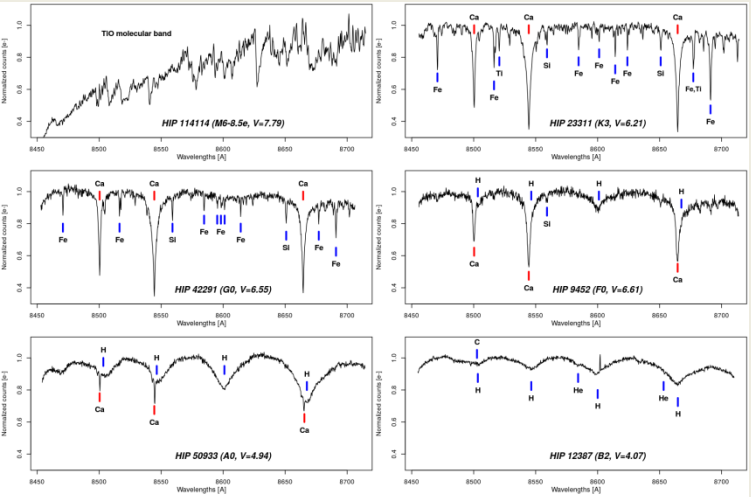
Images from Liverpool Telescope

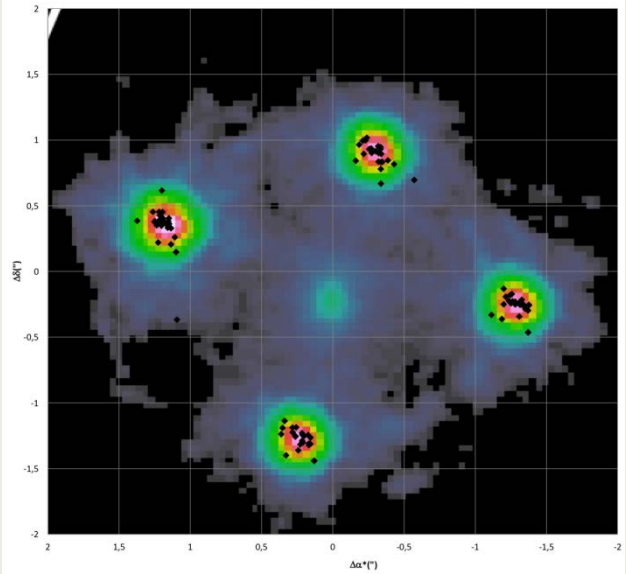
Gaia discovery photometry

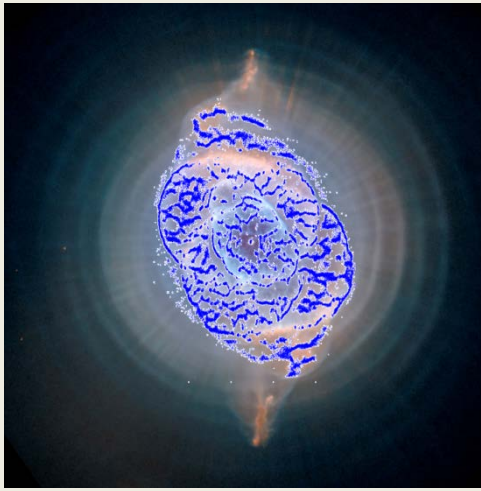


Gaia discovery spectrophotometry









Gaia science has started!
This will support a big outreach
& education programme w. Las Cumbres
few 1000 local SNe

Publishing Alerts

Gaia in the UK

Taking the Galactic Census

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You are here: Home » Gaia Photometric Science Alerts: Validation Phase

Gaia Photometric Science Alerts: Valida

Welcome! We have begun the experiment to validate our AlertPipe software.

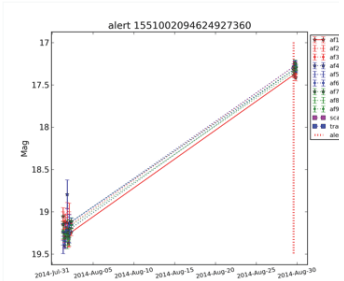
Name	UTC timestamp	RA	Dec	AlertMag	HistMag	HistStdDev	Class	Comment
Gaia14ada	2014-09-10 01:32:01	208.40506	34.82615	18.73	19.68	0.05	unknown	blue star, now faded, ROSAT source within error, CV?
	2014-11-01 23:47:20	211.56593	36.38459	18.96	Not known	Not known	unknown	blue in BP/RP; 5 arcsec from SDSS galaxy z=0.105
	2014-10-26 21:01:38	10.16959	-28.95650	18.41	19.63	0.06	unknown	Galaxy (2dFGRS TGS287Z263), small offset?
	2014-10-27 09:30:00	240.01542	33.18725	15.24	20.20	0.02	CV	Known Dwarf Nova: VW CrB (Blue SDSS star r=19.9, very blue in BP/RP)
	2014-10-24 03:35:31	37.28835	-32.96673	17.61	18.39	0.04	unknown	
	2014-10-25 07:06:23	182.44766	29.73023	18.40	18.97	0.03	unknown	very blue SDSS star at r=19.2
	2014-10-26 00:49:49	202.47026	31.90307	18.23	19.18	0.08	unknown	SDSS star at r=20
	2014-10-26 06:00:00	185.09378	28.41434	18.43	Not known	Not known	SN II	offset from SDSS galaxy;last non-det 2014-07-31;blue BPRP spectrum
	2014-10-06 18:34:25	57.51597	17.06699	19.22	19.95	0.10	unknown	
	2014-10-08 02:24:57	59.71412	14.18758	18.26	19.04	0.08	unknown	
	2014-10-08 00:38:02	59.52069	14.54791	17.70	18.34	0.06	unknown	

AM CVn: Gaia14aae 3

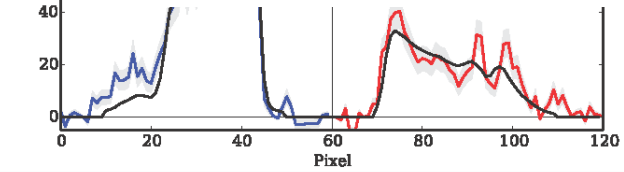
Table 1. Log of photometric observations of Gaia14aae used in this work.

Observatory	Obs. date (UT)	Filter	Exposures (s)
Gaia	2014 08 11	*G*	45
ASAS-SN	2012 - 2015	*V*	129×180
Loiano 1.5m Cassini	2014 10 24	*g*	3×300, 91×30
Telescope + BFOSC	2014 10 25	*g*	135×30
Bialkow 0.6m, Poland	2014 10 18	*BV*	30×120
	2014 10 19	*BV*	37×120
CIECEM 0.35m, Spain	2014 10 21 to	clear	40×180, 8×150
	2014 11 18		111×120, 399×90
pt5m, La Palma	2014 10 25	*V*	61×60
	2014 10 22	*V*	36×60, 21×120
0.6m ASV, Serbia	2014 10 21	*BVRI*	6×300
Belogradchik AO 0.6m, Bulgaria	2014 10 21	*BVR*	2× 300
Asiago 1.82m Copernico	2014 12 11	*r*	169×20
	2014 12 12	*g*	169×20
4.2m WHT+ACAM	2014 12 18	*V*	491×5
Mercator	2015 01 15	*g r+i*	232×30
Catalina *(historic)*	2005 - 2014	clear	107×30
Pan-STARRS1 *(historic)*	2010 - 2014	*grizy*	66×30

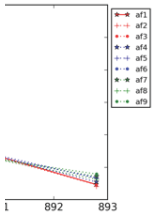
Highlights:



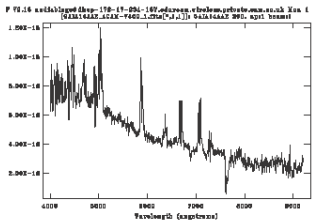
- Lightcurve showed significant brightening
- BP/RP spectrum best fit by model SN Ia



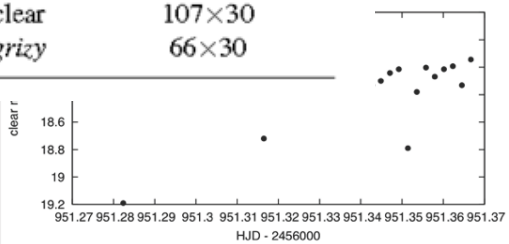
ne 3rd known eclipsing ndidate Ia progenitor)



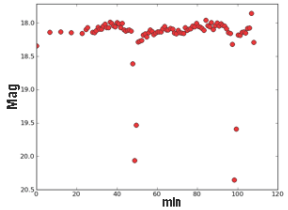
n in ASAS



WHT follow up sees strong Helium lines - AM CVn classification



Amateurs follow up and see eclipses!



Loiano Telescope follow-up confirms Period is ~50 mins

ALERTS VERIFICATION PHASE

Gaia Follow-Up Network for Transient Objects = Gaia-FUN-TO

- verification if the object exists
- verification of errors of the pipeline and data
- detailed classification and verification of Gaia classification
- network composed of robotic and manually operated telescopes
- reaction within 24h
- automatised reductions
- central data repositories (photometry and spectroscopy)

Photometry:

- Loiano (Italy)
- Rozen (Bulgaria)
- Warsaw, Wrocław (Poland)
- OHP (France)
- ASV (Serbia)
- RTT150, RTT100 (Turkey)

Spectroscopy:

- NTT (La Silla)
- WHT (La Palma)
- INT (La Palma)
- SAAO 1.9m
- Loiano (Italy)
- Asiago (Italy)

new members welcome!

OPTICON

The Gaia Data Release (GDR) Scenario

http://www.cosmos.esa.int/web/gaia/release

- GDR1 ~7/16: positions, G-magnitudes (~all sky, single stars)

  proper motions for Hipparcos stars (~50 μarcsec/yr) – the Hundred Thousand Proper Motions (HTPM) catalogue
- GDR2 ~2/17: + radial velocities for bright stars, two band photometry and full astrometry (α, δ, ϖ, μ_α, μ_δ) where available for intermediate brightness stars
- GDR3 ~1/18: + first all sky 5 parameter astrometric results (α, δ, ϖ, μ_α, μ_δ) BP/RP data, RVS radial velocities and spectra, astrophysical parameters, orbital solutions short period binaries
- GDR4 ~1/19: + variability, solar system objects, updates on previous releases, source classifications, astrophysical parameters, variable star solutions, epoch photometry
- GDR-Final: final data release (thus in 2022/23 or 2025)

Full dataset for more sophisticated modelling released at end of mission

a few Gaia numbers

- One billion stars = 1% of the Milky Way's stars
- One billion pixel camera
- Total project cost 960Meuro
- Project lifetime: 1993 – 2023+
- Accuracy – 10microarcsec = 10^{-10} rad: = thickness of a human hair at 1000km
- Einstein light bending at the Sun's edge is 1750000microarcsec
- Must know Gaia's location within 150m: it is about 1,500,000m away
- Gaia will travel about 16Mkm over 5 years
- Satellite global timing network extended to picosecs for Gaia
- In one picosec light travels 0.3mm
- Satellite communications link is 300W, total power use 1276W
- 100Tb raw compressed data – our database is 15Tb as of today
- 2 telescopes, 35m focal length, rectangular mirrors
- 3.5M hours of work to study, design & build = 300people x 7 years
- 400 scientists working on data processing
- Over 30,000 mission documents in archive
- Launch burned 225tonnes of kerosene+oxygen in 5 minutes
- In orbit micro-propulsion system ejects 1 microgram of nitrogen per thrust
- Gaia measures 40 million stars per day on average
- 60 million stars will have 6-D space motions
- Total number of measurements: 1,000,000,000,000

Find out more at http://gaia.ac.uk

PLUS: 1million galaxies; 500,000 QSOs; 10,000 Supernovae – in real-time; 250,000 asteroids; 15,000 extra-solar planets; 200,000 white dwarfs; 50,000 brown dwarfs, the new, ...

The videos shown before and during the talk are available at

http://gaia.ac.uk