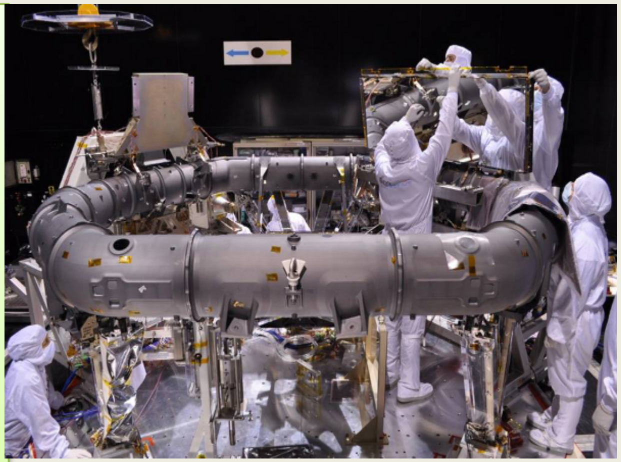
# Gaia: ESA's premier astrophysics mission of the decade

***Gaia is transformational*** – the first 3-D galaxy **precision distances and motions for 1 billion stars**

Gerry Gilmore, IoA Cambridge, UK Gaia PI

| | |
|---|---|
| Launch: | 12/2013 |
| Work started: | 1990 |
| 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.

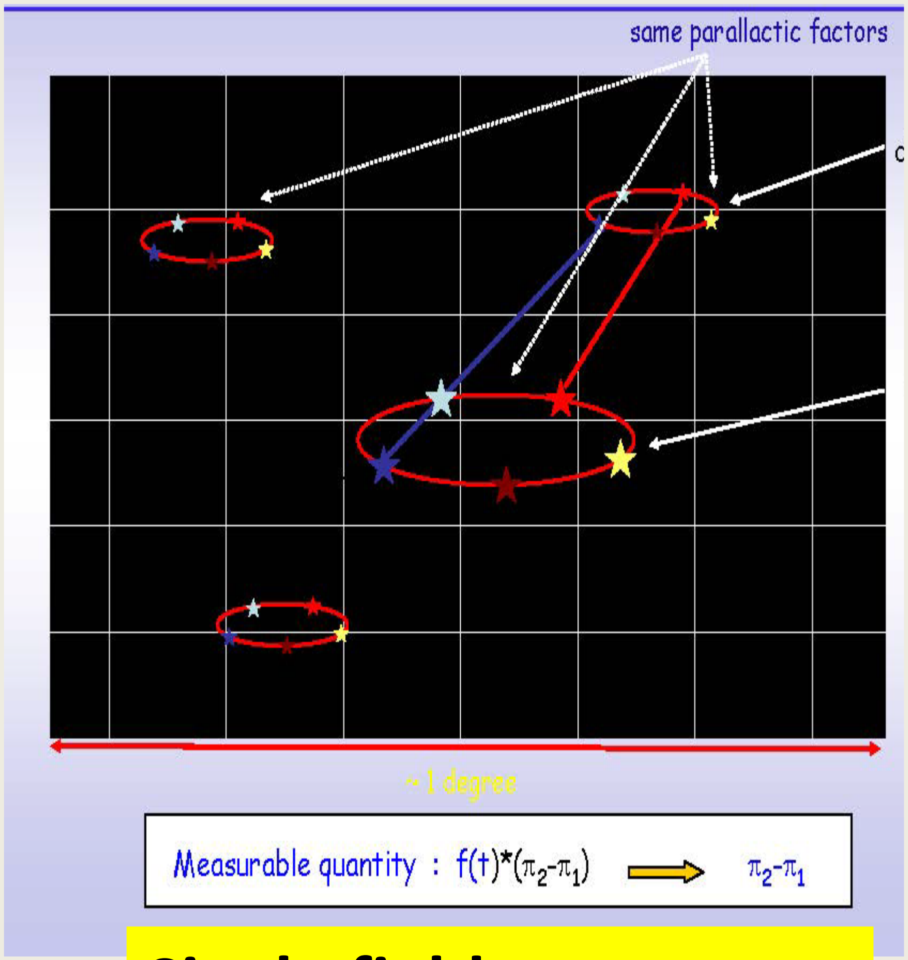
The imaging data is being processed in Cambridge.
4 billion transits processed so far

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

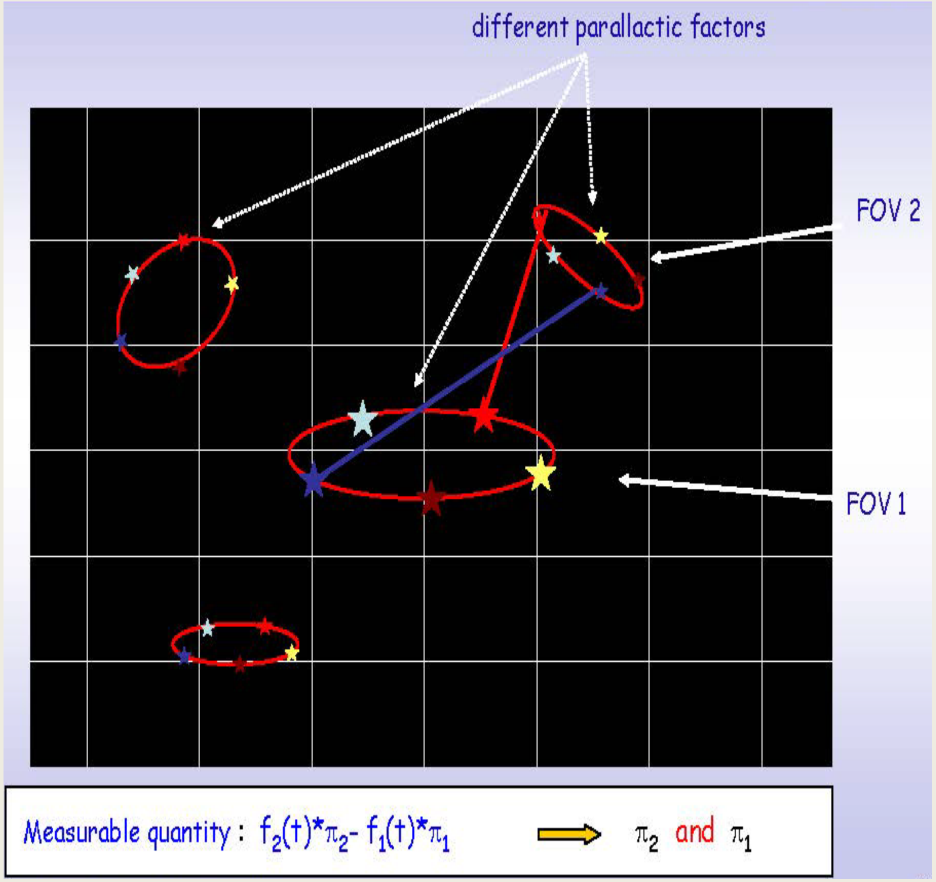
Data flow: 50Gb/day for 5-8 years; total processed data and archives → 1PByte
Computational challenge : 1.5 x $10^{21}$ FLOP – and highly sophisticated algorithms

# Why two telescopes?

**One field gives only relative measures ➔ model dependancy**
**Two fields break the degeneracy➔ allows absolute measurements.**




**Single field astrometry**

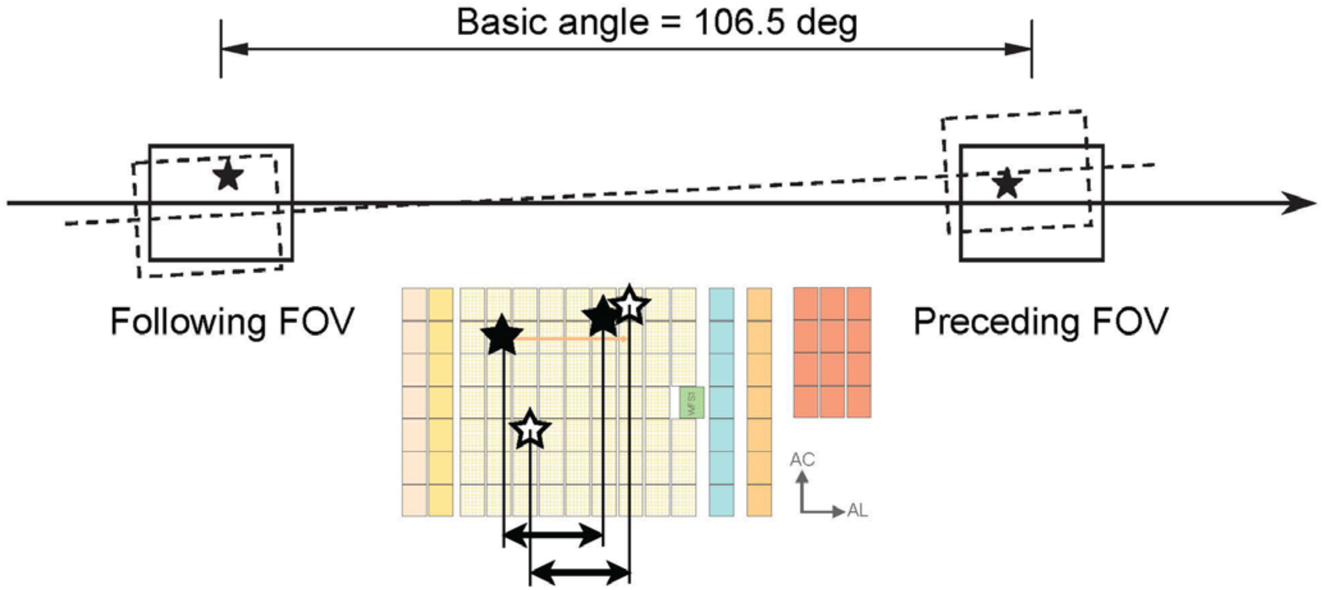



**Two field astrometry**

# 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**

Gaia is precision: **complete survey 0<G<20.6**

Light-bending: 1."75 at solar rim, 1,750,000 microarcsec

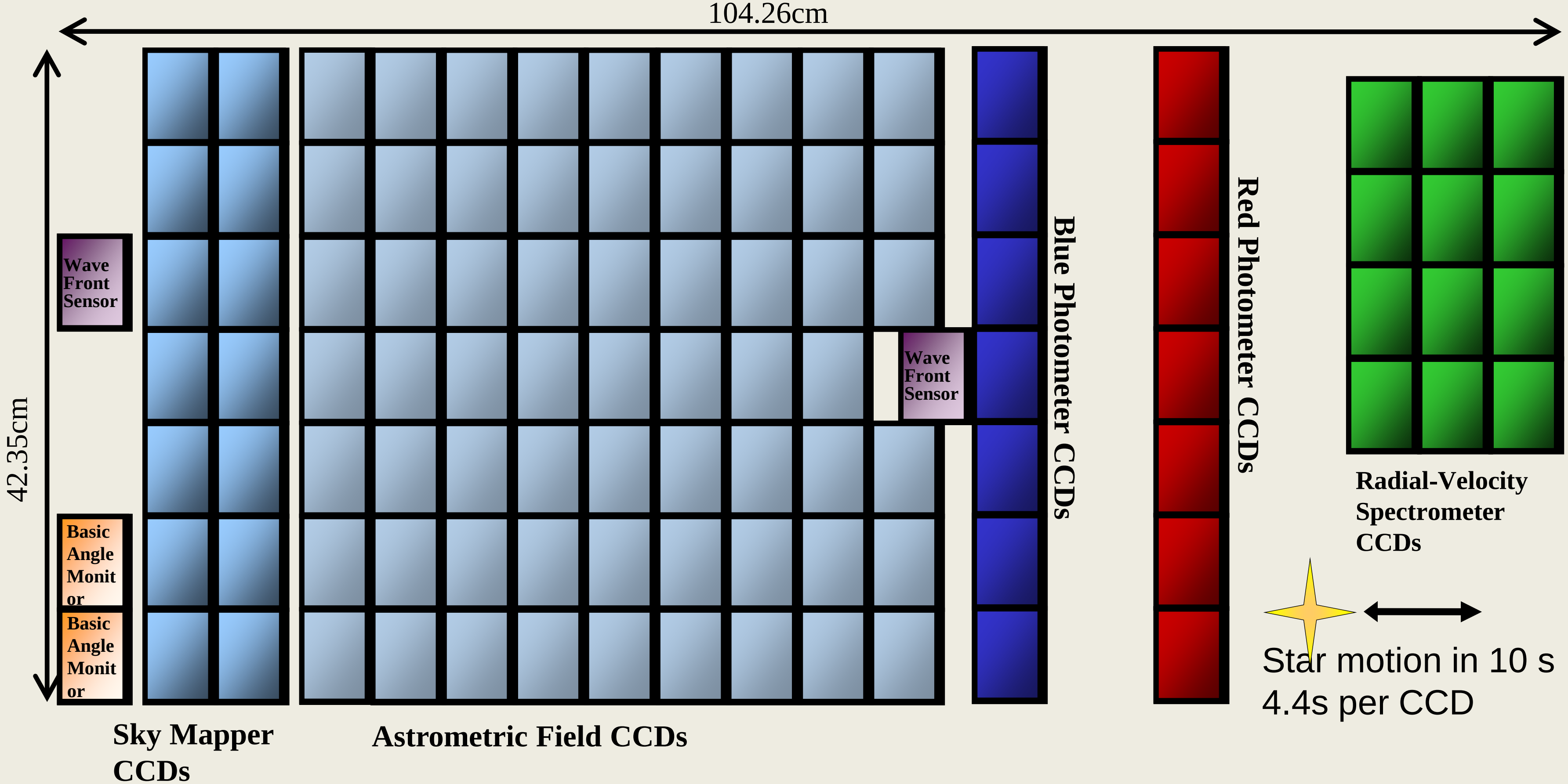
**Precision: 50pico-rad, human hair at 1000km, earth-L2 dist to 1cm**

- **in our Galaxy …**
  - the distance and velocity distributions of all stellar populations
  - the spatial and dynamic structure of the disk and halo
  - its formation history
  - a detailed mapping of the Galactic dark-matter distribution
  - a rigorous framework for stellar-structure and evolution theories
  - a large-scale survey of extra-solar planets (~20,000)
  - a large-scale survey of inner Solar-system bodies (~250,000)
- **… and beyond**
  - definitive distance standards out to the LMC/SMC
  - rapid reaction alerts for supernovae and burst sources (~20,000)
  - quasar detection, redshifts, lensing structures (~500,000)
  - fundamental quantities to unprecedented accuracy: e.g. relativistic light bending due to gravity: PPN $\sigma_\gamma \sim 2\times10^{-6}$ ($\sim 2\times10^{-5}$ present)

$$\sigma_\gamma \approx 1\times10^{-6} \text{ to } 3\times10^{-7}$$

# Gaia Focal Plane

Figure courtesy Alex Short




**Total field:**

- active area: 0.75 $deg^2$
- CCDs: 14 + 62 + 14 + 12
- 4500 x 1966 pixels (TDI)
- pixel size = 10 µm x 30 µm

  = 59 mas x 177 mas

**Sky mapper:**

- detects all objects to 20 mag
- rejects cosmic-ray events
- FoV discrimination

**Astrometry:**

- total detection noise: ~6 $e^-$

**Photometry:**

- spectro-photometer
- blue and red CCDs

**Spectroscopy:**

- high-resolution spectra
- red CCDs

# 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

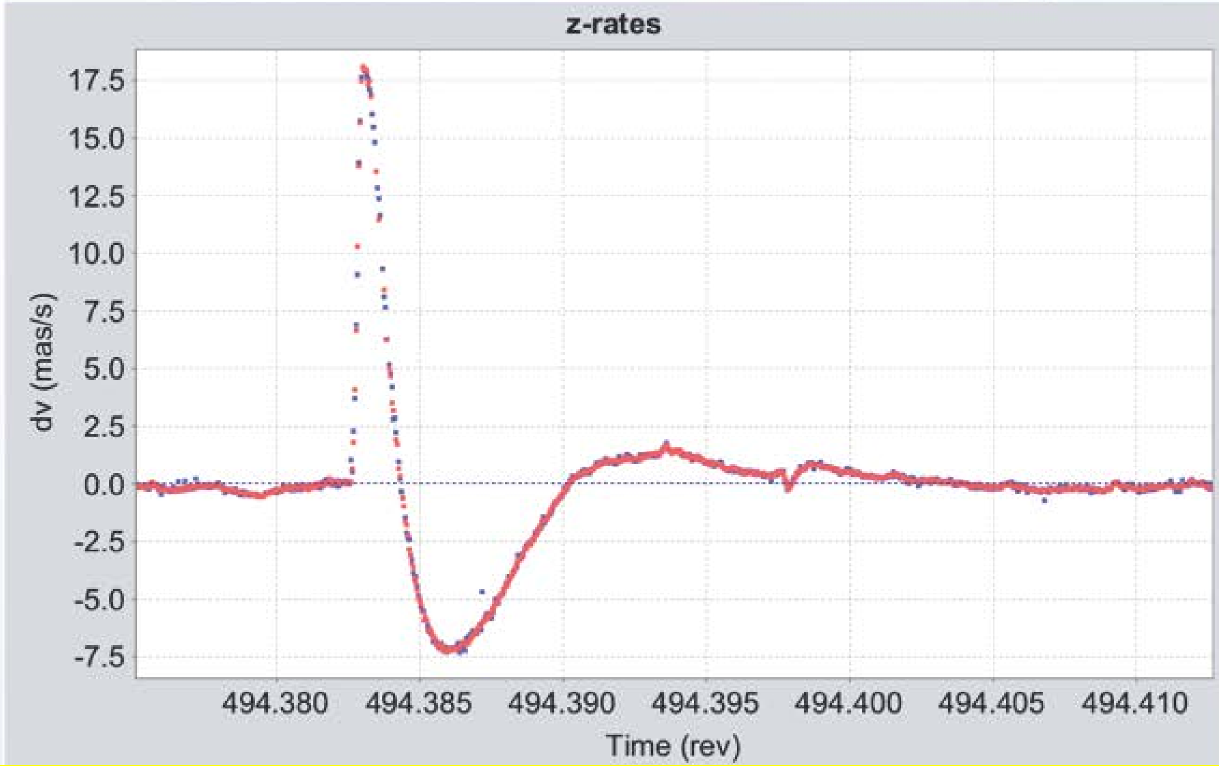
Eg, photometric ubercalibration:

- 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 storag




Higher L2 dust environs will gently sand-blast JWST's mirror….

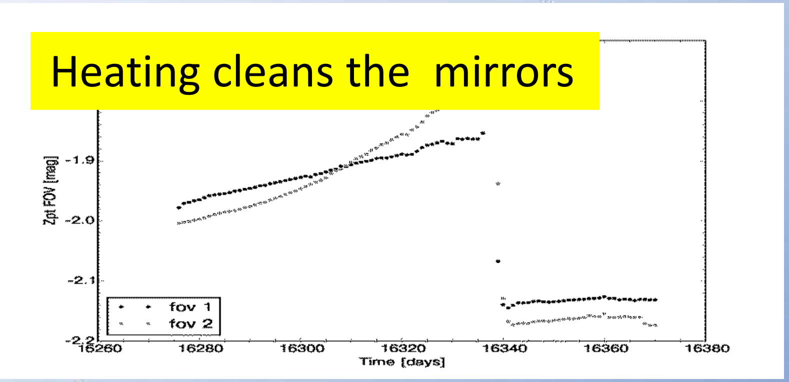
Micro-meteoroid hit example.

uwen

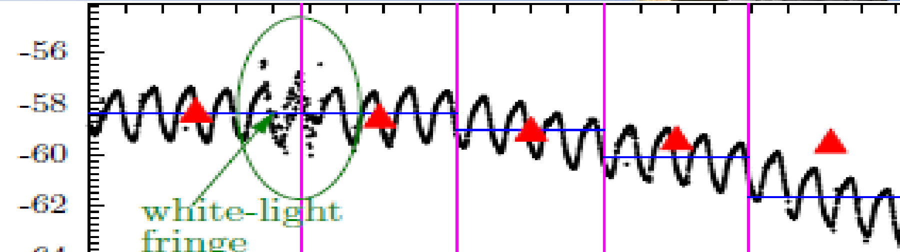
Complete sky survey from 0 < G < 20
Extension to G=20.5 under test (1.6 billion stars)
Mission extension from 5 years to 7.5 years under analysis

# 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

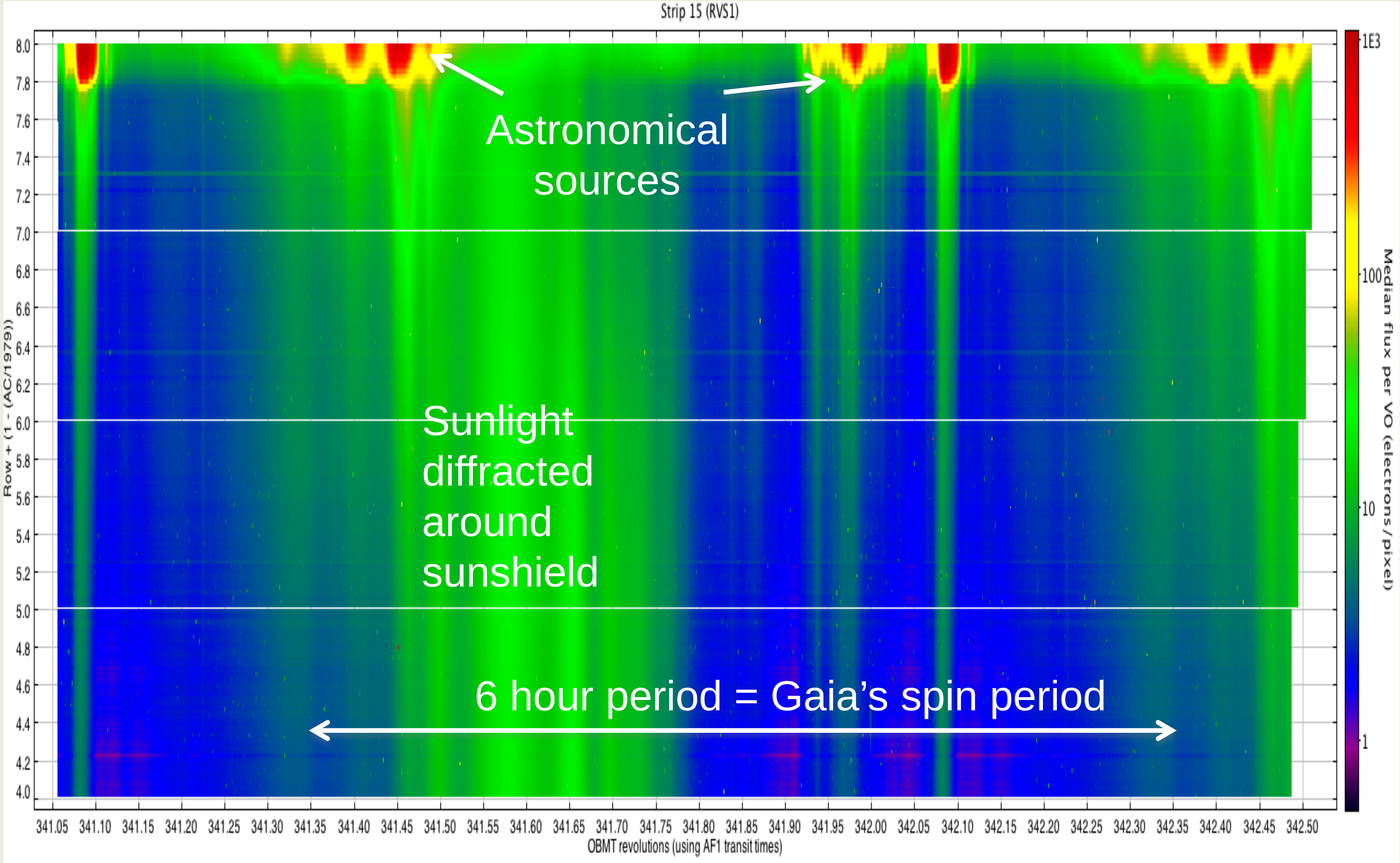



- Basic Angle variation larger than expected
  - However, Basic Angle Monitor providing very precise measurements of the changes



# Scattered Light (RVS): mean level 30x expected

adds noise to faint sources – astrometry recovered by mission extension




RVS is delivering 60million spectra, R=110000, complete to V<15.3

# Gaia Performance

## (at In Orbit Commissioning Review)

http://www.cosmos.esa.int/web/gaia/science-performance

| | B1V | G2V | M6V |
|---|---|---|---|
| $V-I_C$ [mag] | -0.22 | 0.75 | 3.85 |
| Bright stars | 5-14 µas (3 mag < V < 12 mag) | 5-14 µas (3 mag < V < 12 mag) | 5-14 µas (5 mag < V < 14 mag) |
| V = 15 mag | 26 µas | 24 µas | 9 µas |
| V = 20 mag | 600 µas | 540 µas | 130 µas |

Astrometric Performance

Complete sky survey 0 < G < 20

| | B1V | | | G2V | | | M6V | | |
|---|---|---|---|---|---|---|---|---|---|
| G [mag] | G | BP | RP | G | BP | RP | G | BP | RP |
| 15 | 1 | 4 | 4 | 1 | 4 | 4 | 1 | 7 | 4 |
| 18 | 2 | 8 | 19 | 2 | 13 | 11 | 2 | 89 | 6 |
| 20 | 6 | 51 | 110 | 6 | 80 | 59 | 6 | 490 | 24 |

Photometric Performance: units=mmag

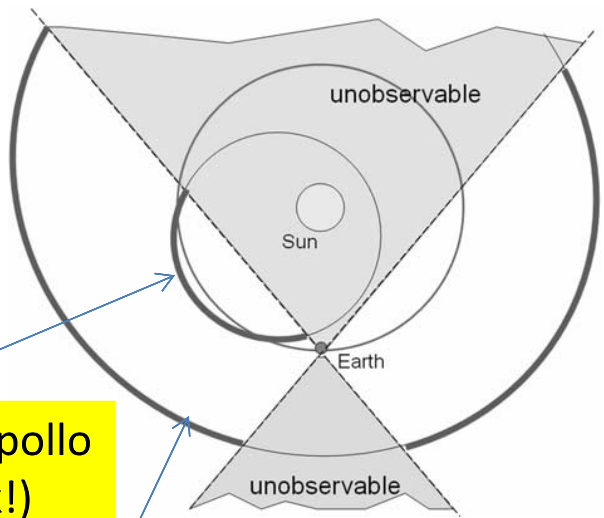
| Spectral type | V [mag] | Radial-velocity error [km $s^{-1}$] |
|---|---|---|
| B1V | 7.5 | 1 |
| | 11.3 | 15 |
| G2V | 12.3 | 1 |
| | 15.2 | 15 |
| K1III-MP (metal-poor) | 12.8 | 1 |
| | 15.7 | 15 |

Spectroscopic Performance: 60 million RVs

Plus Spectro-Photometry, astrophysical parameters , light curves, … for all 1+ billion sources

# 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,…

The Gaia Mission 105



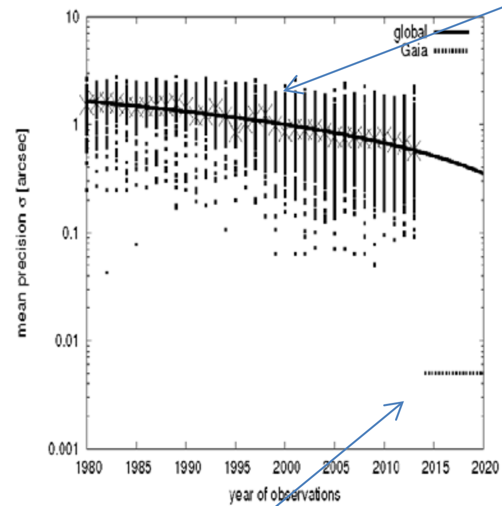

NEO/Aten/Apollo (Chelyabinsk!)

Main belt asteroid

**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

Best ground > mas accuracy

Orbital accuracy




Gaia

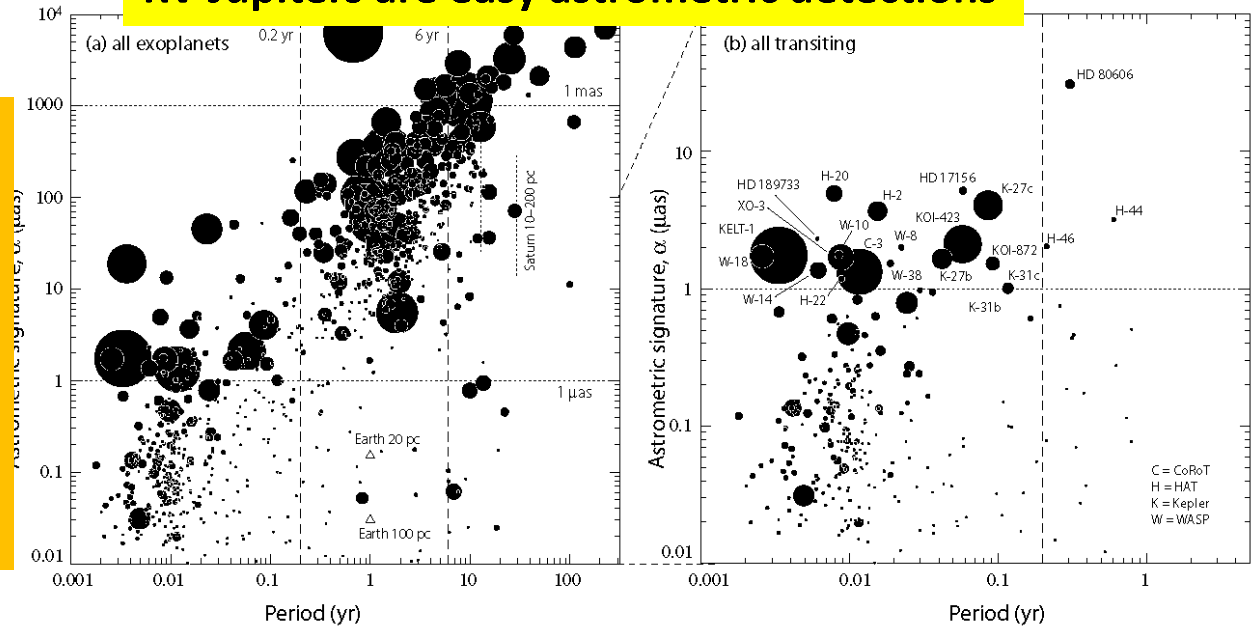
**Fig. 2.** The yearly astrometric mean precision ($\sigma = \sqrt{(\sigma_\alpha \cos\delta)^2 + (\sigma_\delta)^2}$) of each observatory with a Minor Planet Center designation and at least 10 submitted observations per year is plotted against time (dots). The crosses indicate global yearly averages, 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).

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>**

cf Avi Shporer talk

**RV Jupiters are easy astrometric detections**




Astrometric signature

Period (yr)

Fig. 1.— Astrometric signature versus perio[...] objects listed in exoplanet.eu at 2014 September 1 for all 1821 confirmed planets (le[...]t 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, $\alpha$ would increase by a factor 2, but their astrometric motion would remain undetectable by Gaia.

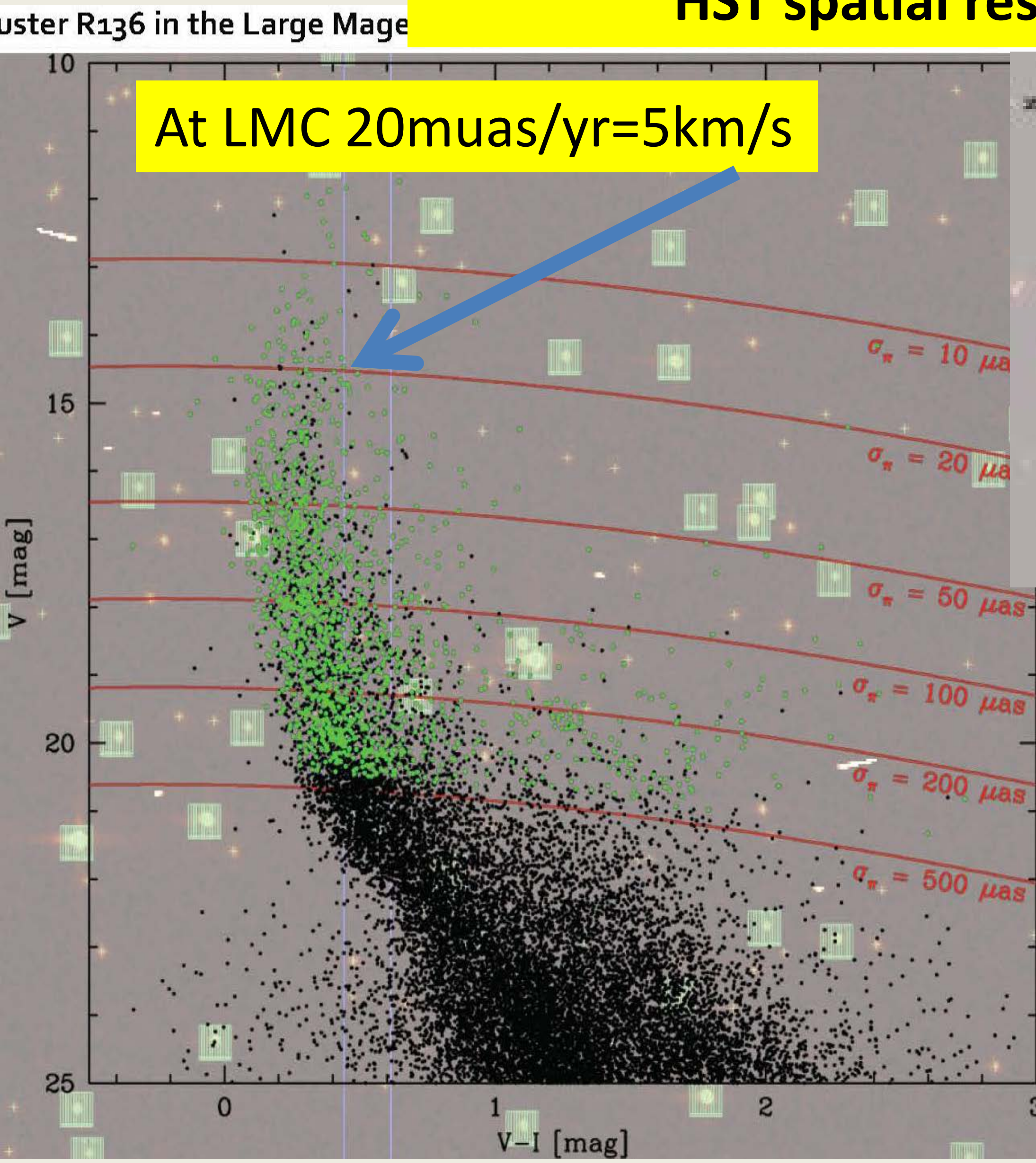
Perryman etal 2014 arXiv:1411.1173

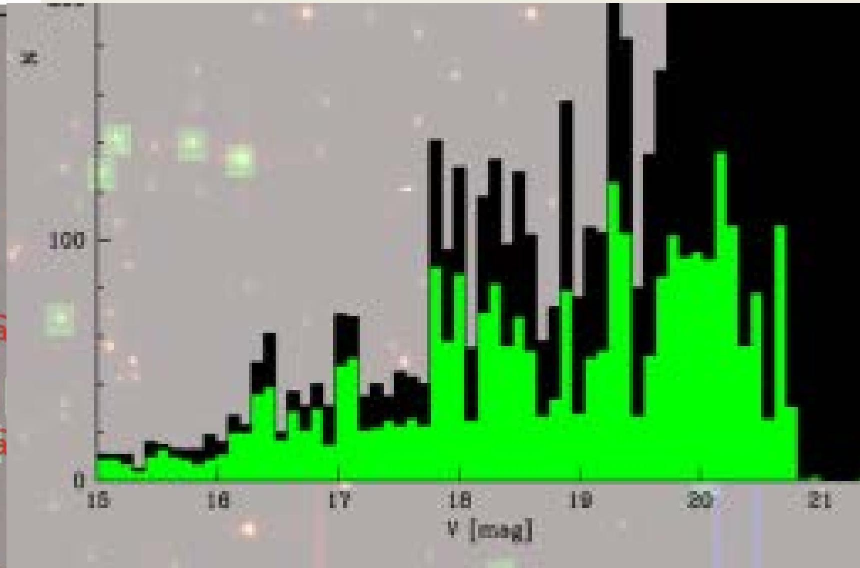
**Stellar evolution, young stars, rare objects, Galactic structure, SFR(t)**

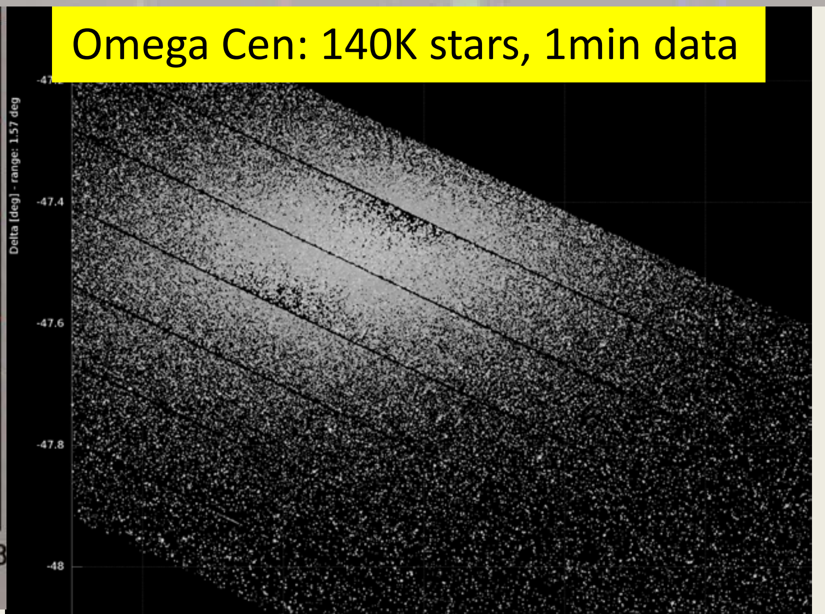
# Luminosity calibrations with Hipparcos and Gaia

| | Hipparcos | Hipparcos 2 | Gaia |
|---|---|---|---|
| $\sigma_\pi/\pi < 0.1$ % | - | 3 | 100000 ★ |
| $\sigma_\pi/\pi < 1$ % | 442 ★ | 719 ★ | ~ 11 x $10^6$ ★<br>up to 5-10 kpc (Mv<-5)<br>up to 1-2 kpc (Mv<5) |
| $\sigma_\pi/\pi < 10$ % | 22 396 ★ | 30 579 ★ | ~ 150 x $10^6$ ★<br>up to 30-50 kpc (Mv<-5)<br>up to 2-5 kpc (Mv<5) |
| Error on Mv | 0.3 mag at 100 pc | | 0.1 mag at 10 kpc |
| Stellar pop. | mainly disk | | all populations, even the rarest |
| HR diagram < 10 % | -4 to 13, -0.2 to 1.7 | | all mag and colours |

# Stellar populations
# Gaia manages most of the sky uncrowded
# ~HST spatial resolution



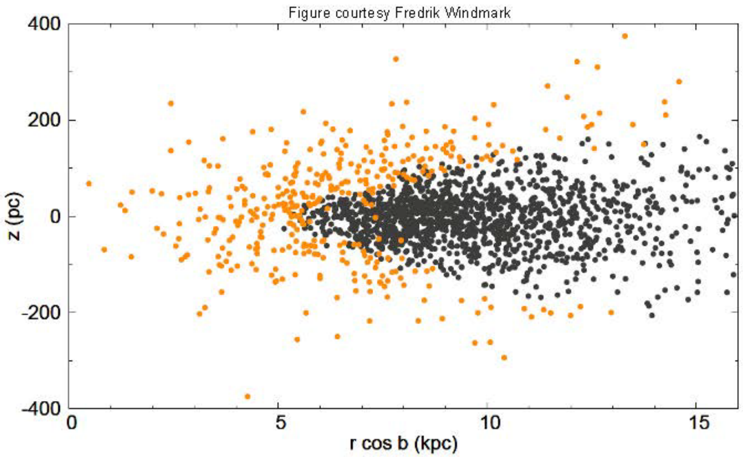
# Cosmological distance scale calibration at mmag level

## Pulsating variables from Hipparcos to Gaia

| | Hipparcos | Gaia |
|---|---|---|
| Cepheids | 273 (2 new)<br>~ 100 with $\sigma_\pi < 1$ mas<br>P : 2 to 36 days | Census of galactic Cepheids with G ≤ 20<br>~ 9000 Cepheids (*)<br>All periods, colours and metallicity<br>Up to 5-8 kpc with $\sigma_\pi/\pi < 1\%$<br>All galactic with $\sigma_\pi/\pi < 10\%$ |
| Pop II Cepheids | ~ 30 | ~ 2000 |
| in LMC | none | 1000-2000 Cepheids with $\sigma_\pi/\pi$ ~ 80-100 %<br>Mean distance expected to 7-8 % (**) |
| RR Lyrae | 186 (9 new)<br>only RR Lyr with good $\pi$ | All galactic RR Lyrae: 70000 (***)<br>All metallicity<br>Up to 1.5 kpc with $\sigma_\pi/\pi < 1\%$, $\sigma_\pi/\pi < 10\%$<br>In globular clusters: mean $\sigma_\pi/\pi < 1\%$ |

Windmark et al. 2011 (*) (**) Clementini 2010 (***) Eyer & Cuypers 2000

# Galactic Cepheids




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

- Observable by Gaia
- Too faint for Gaia

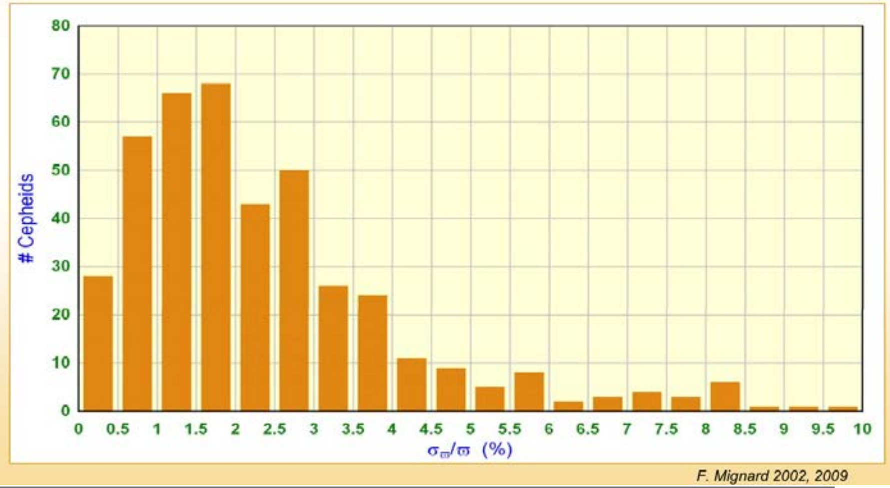
- Gaia will observe ~9,000 Galactic Cepheids (2011arXiv1104.2348W)
- Hundreds are visible near and behind the Galactic centre
- Beyond 5 kpc, all Cepheids are observed outside the plane

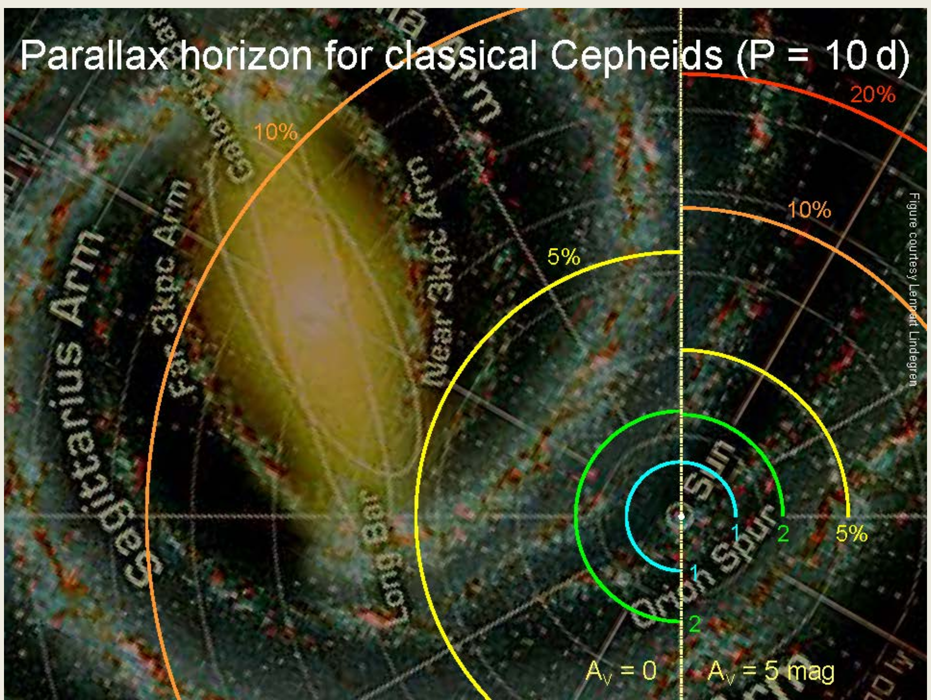
15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc

- bright enough ( V < 14)

In the plot : 400 galactic cepheids from David Dunlap DB

- distance and magnitude ➔ Gaia predicted accuracy for parallax




| | | | |
|---|---|---|---|
| Galactic | | 273 | Hipparcos 1997 |
| | Known | 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**

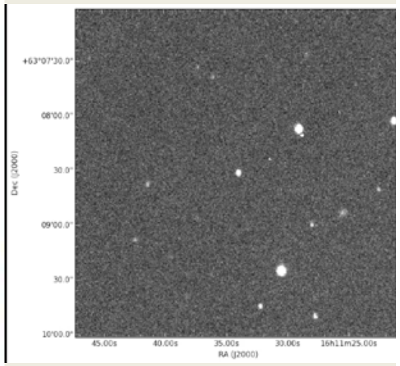
| | | | |
|---|---|---|---|
| LMC | Known | 3,361 | OGLE-III, Soszynski et al 2008-2010 |
| SMC | | 4,630 | |

## Gaia will repeat the Eddington 1919 light-bending test 100 years later, with 100,000 times higher precision

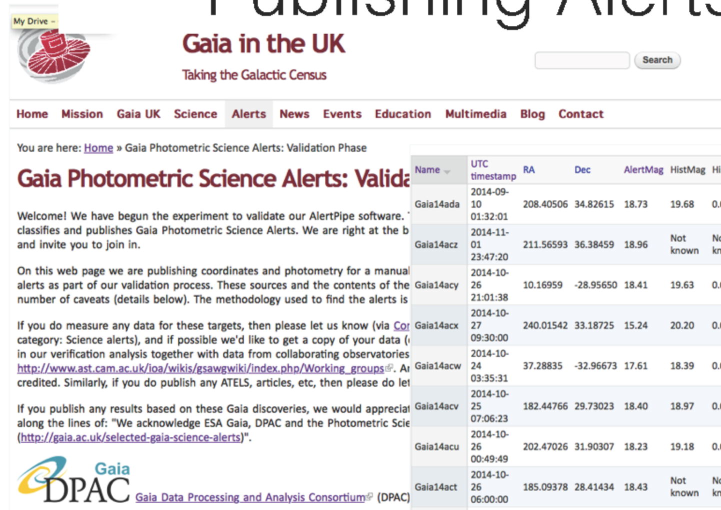
Gaia will measure light bending by Jupiter to test GR

- From positional displacements:
  - $\gamma$ to $5\times10^{-7}$ (cf. $10^{-5}$ presently) $\Rightarrow$ scalar-tensor theories
  - effect of Sun: 4 mas at $90^{o}$; Jovian limb: 17 mas; Earth: ~40 $\mu$as
- From perihelion precession of minor planets:
  - $\beta$ to $3\times10^{-4}$ - $3\times10^{-5}$ ($\times$10-100 better than lunar laser ranging)
  - Solar $J_2$ to $10^{-7}$ - $10^{-8}$ (cf. lunar libration and planetary motion)
- From white dwarf cooling curves:
  - dG/dT to $10^{-12}$ - $10^{-13}$ per year (cf. PSR 1913+16 and solar structure)
- Gravitational wave energy: $10^{-12} < f < 10^{-9}$ Hz
- Microlensing: photometric (~1000) and astrometric (few) events
- Cosmological shear and rotation (cf. VLBI)

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

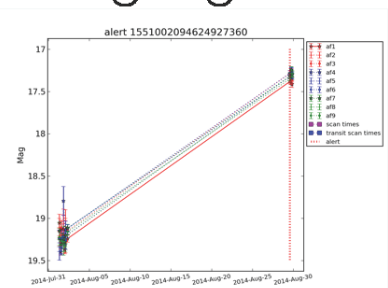
# Publishing Alerts

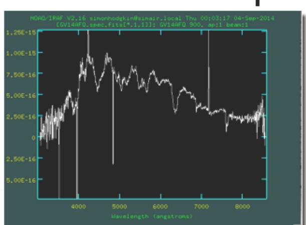



| Name | UTC timestamp | RA | Dec | AlertMag | HistMag | HistStdDev | Class | Comment |
|---|---|---|---|---|---|---|---|---|
| Gaia14ada | 2014-09-10 01:32:01 | 208.40506 | 34.82615 | 18.73 | 19.68 | 0.05 | unknown | blue star, now faded, ROSAT source within error, CV? |
| Gaia14acz | 2014-11-01 23:47:20 | 211.56593 | 36.38459 | 18.96 | Not known | Not known | unknown | blue in BP/RP; 5 arcsec from SDSS galaxy z=0.105 |
| Gaia14acy | 2014-10-26 21:01:38 | 10.16959 | -28.95650 | 18.41 | 19.63 | 0.06 | unknown | Galaxy (2dFGRS TGS287Z263), small offset? |
| Gaia14acx | 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) |
| Gaia14acw | 2014-10-24 03:35:31 | 37.28835 | -32.96673 | 17.61 | 18.39 | 0.04 | unknown | |
| Gaia14acv | 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 |
| Gaia14acu | 2014-10-26 00:49:49 | 202.47026 | 31.90307 | 18.23 | 19.18 | 0.08 | unknown | SDSS star at r=20 |
| Gaia14act | 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 |
| Gaia14acs | 2014-10-06 18:34:25 | 57.51597 | 17.06699 | 19.22 | 19.95 | 0.10 | unknown | |
| Gaia14acr | 2014-10-08 02:24:57 | 59.71412 | 14.18758 | 18.26 | 19.04 | 0.08 | unknown | |
| Gaia14acq | 2014-10-08 00:38:02 | 59.52069 | 14.54791 | 17.70 | 18.34 | 0.06 | unknown | |

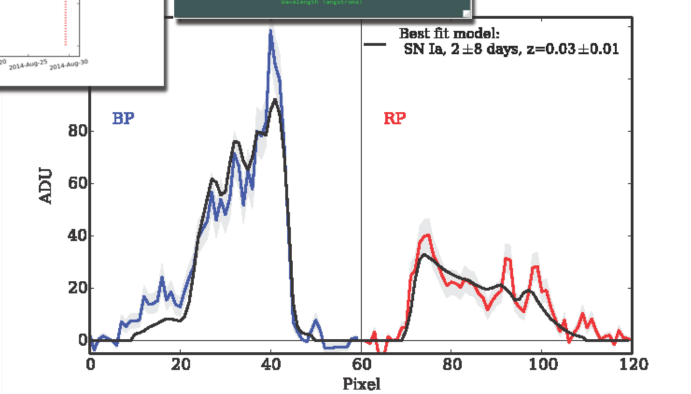
Initial simple table. Web pages per object and automatically generated CSV lists are coming soon (weeks)

# Highlights: Our first Supernova



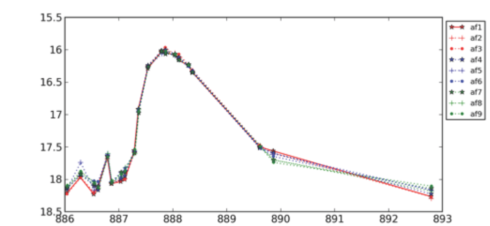



Spectrum confirmed from ground with Isaac Newton Telescope

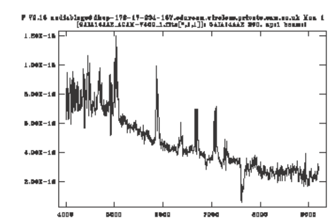



- Lightcurve showed significant brightening
- BP/RP spectrum best fit by model SN Ia

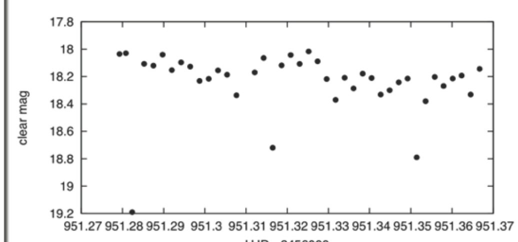
# Discovery of the 3rd known eclipsing AM CVn (candidate Ia progenitor)



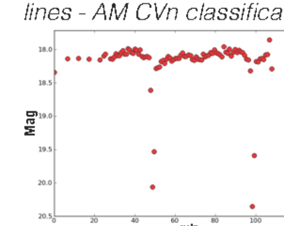
*Outburst in Gaia, also seen in ASAS*



*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*

# 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 ($\alpha$, $\delta$, $\varpi$, $\mu_\alpha$, $\mu_\delta$ ) where available for intermediate brightness stars
- GDR3 ~1/18: + first all sky 5 parameter astrometric results ($\alpha$, $\delta$, $\varpi$, $\mu_\alpha$, $\mu_\delta$ ) 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)

There is an interesting tension between early data release, quality control, and over-ambition

# Gaia Catalogue

Main Data Base
Archive Architecture Design
Hardware & Operations
User Support

Hosted at Partner Data Centres

And Affiliated Data Centres

# summary

- Gaia is operating and will deliver precision data across many astrophysical fields – reference system…
- Incl potential coronograph planetary targets
- WFIRST-AFTA* (Euclid, LSST, …) is an exciting mission which will benefit from and go beyond Gaia.
- Astrometry delivers fundamental advances in many topical fields (& serendipity) – it is a technically sophisticated subject, very difficult at precision limits. It needs precision clocks, orbit location, GR metric…. must be designed into the mission hardware and operations – cannot retrofit at nano-radian level

* Not the best possible name…