Gaia

Stereoscopic Census of our Galaxy

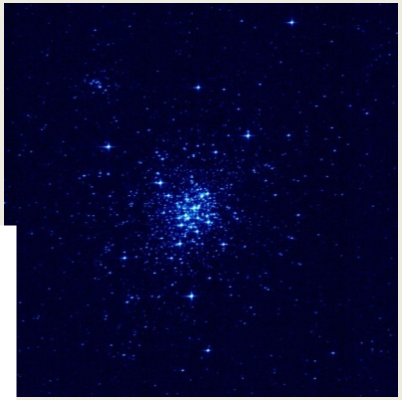
http://www.cosmos.esa.int/web/gaia http://gaia.ac.uk

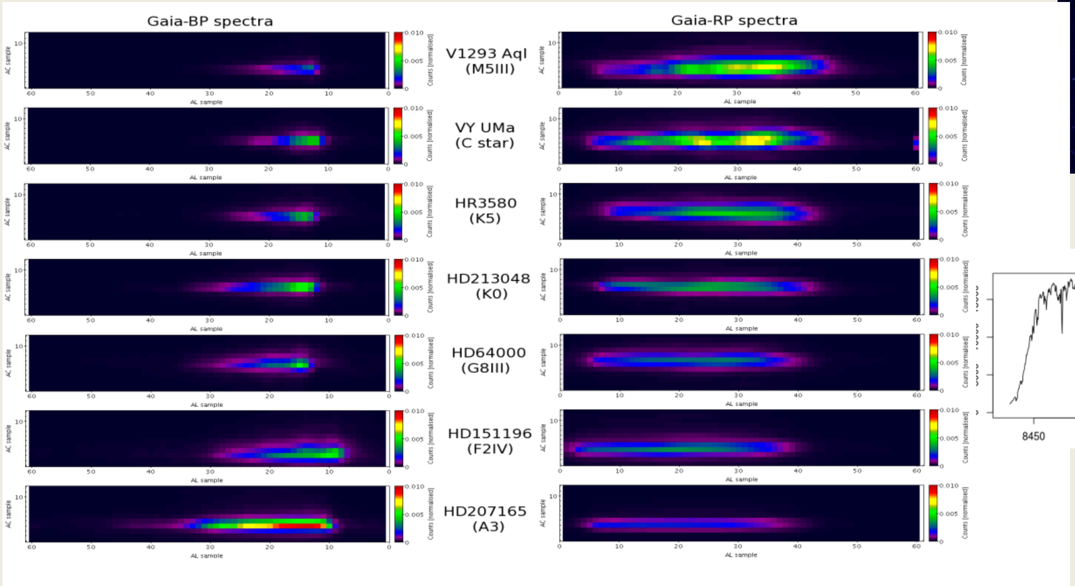
one billion pixels for one billion stars

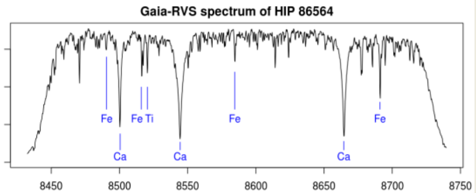
one percent of the visible Milky Way

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

Gaia Data release 1 – Sept 14 2016







Gaia: the goddess who created the universe and knowledge

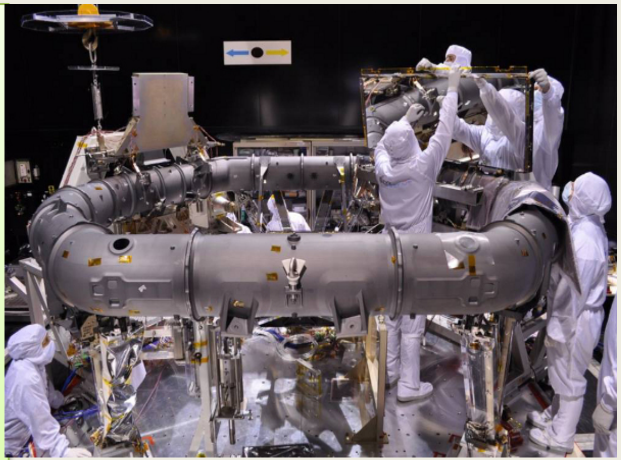
Gaia is transformational – the first 3-D galaxy
precision distances and motions for 1 billion stars

- 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€



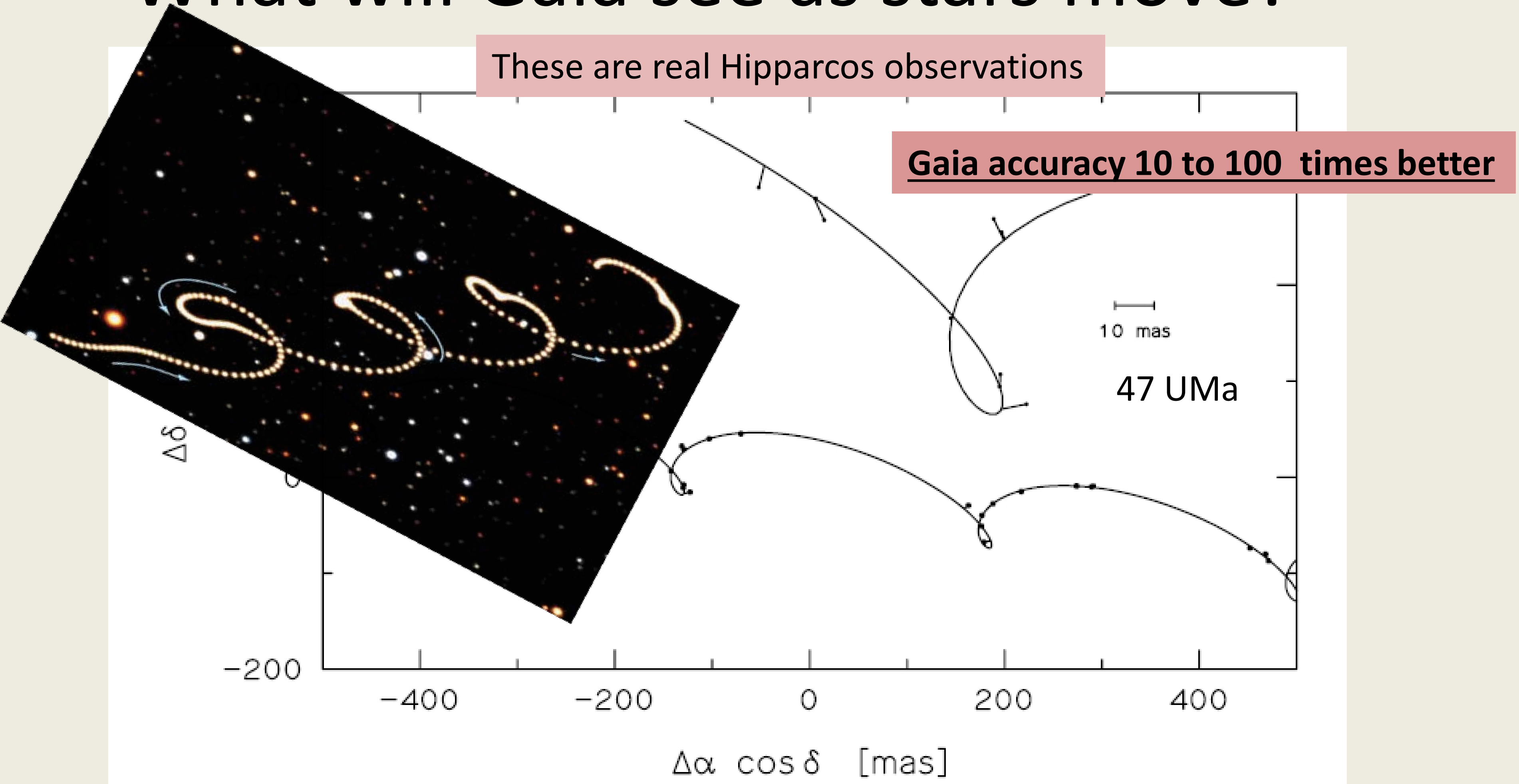
The heart of Gaia is a large camera array, 1 giga-pixel, sending us a video of the sky for 5-8 years.

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

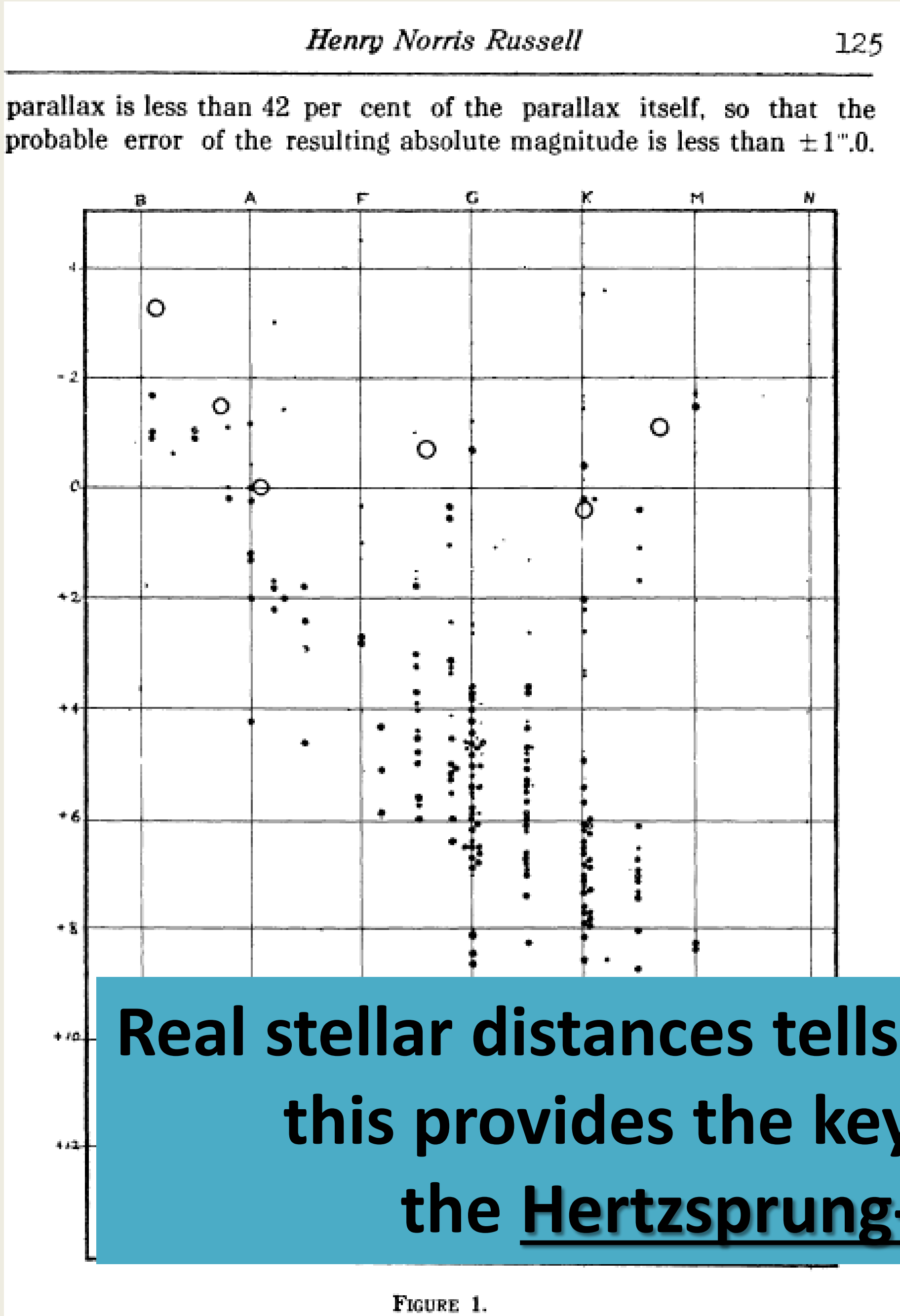
2 telescopes, 1.45 x 0.5 m primary, monolithic SiC optical bench, 0.06arcsec pixels

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

What will Gaia see as stars move?



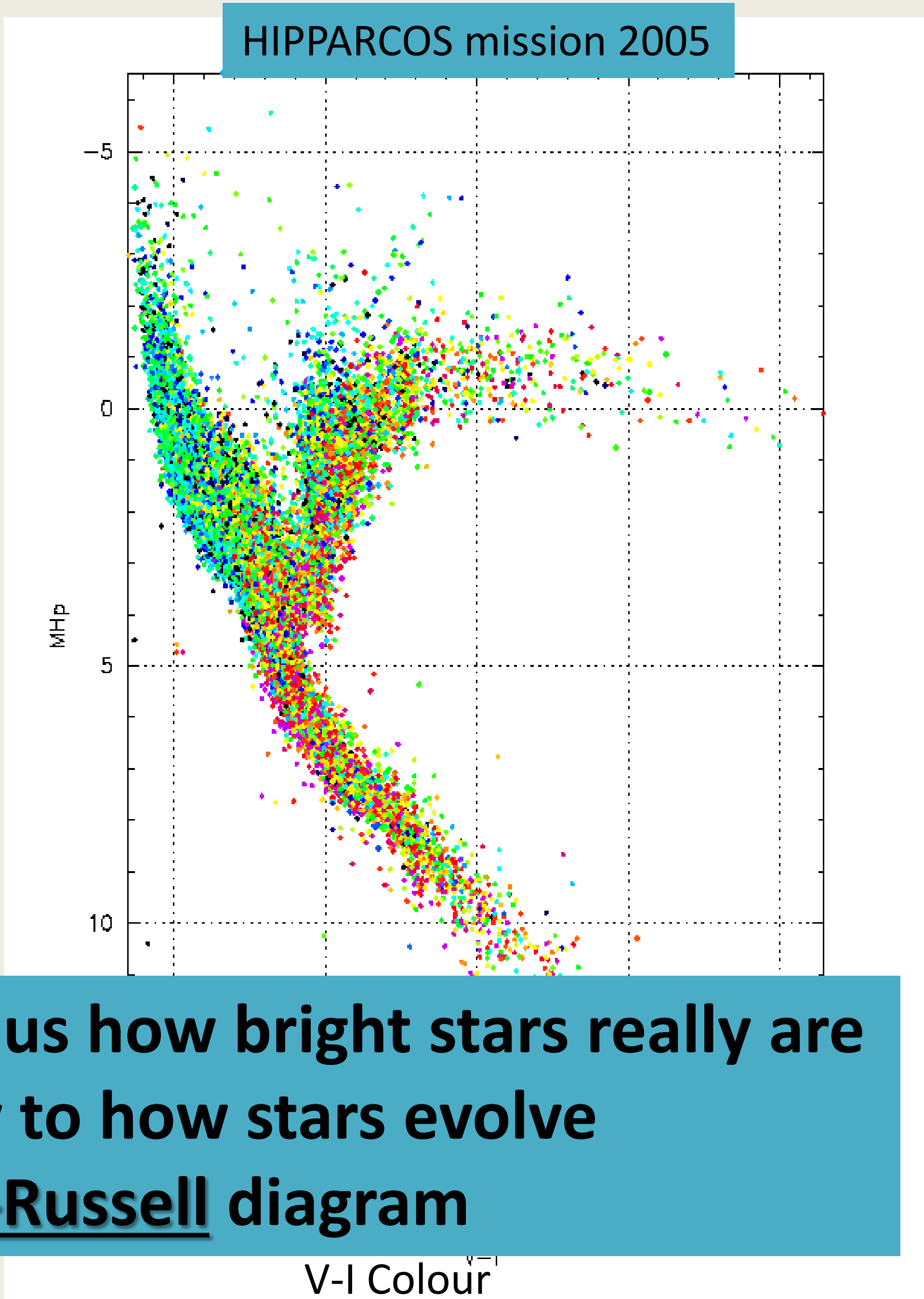
Trend: stellar orbit ➔ Galactic dynamics, dark matter, assembly history, ...
Cycloid: parallax = 1/distance ➔ Galactic structure, star formation history
Loops: high frequency motion ➔ massive planetary systems



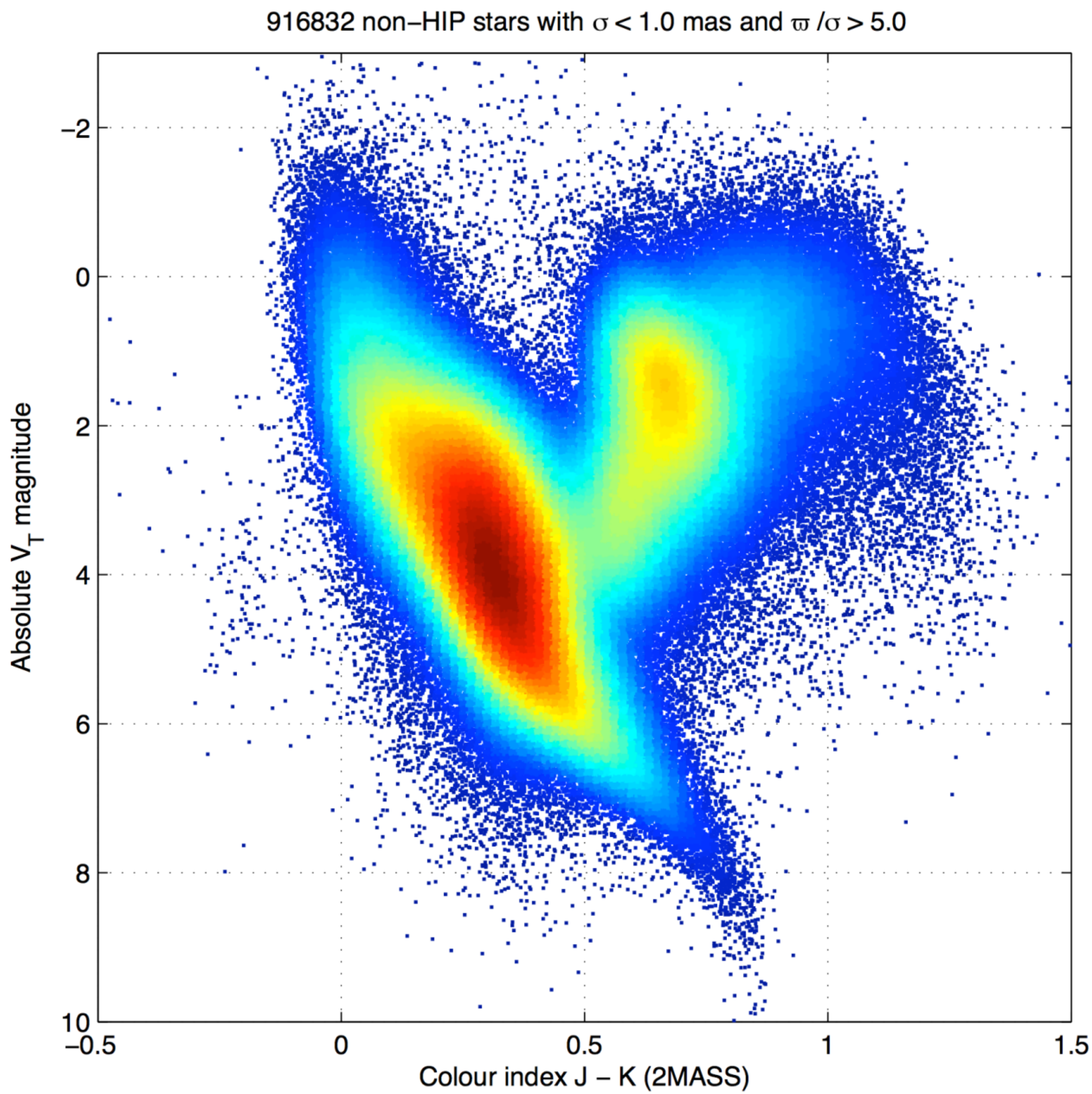
Henry Norris Russell 125

parallax is less than 42 per cent of the parallax itself, so that the probable error of the resulting absolute magnitude is less than $\pm 1^{m}.0$.

FIGURE 1.

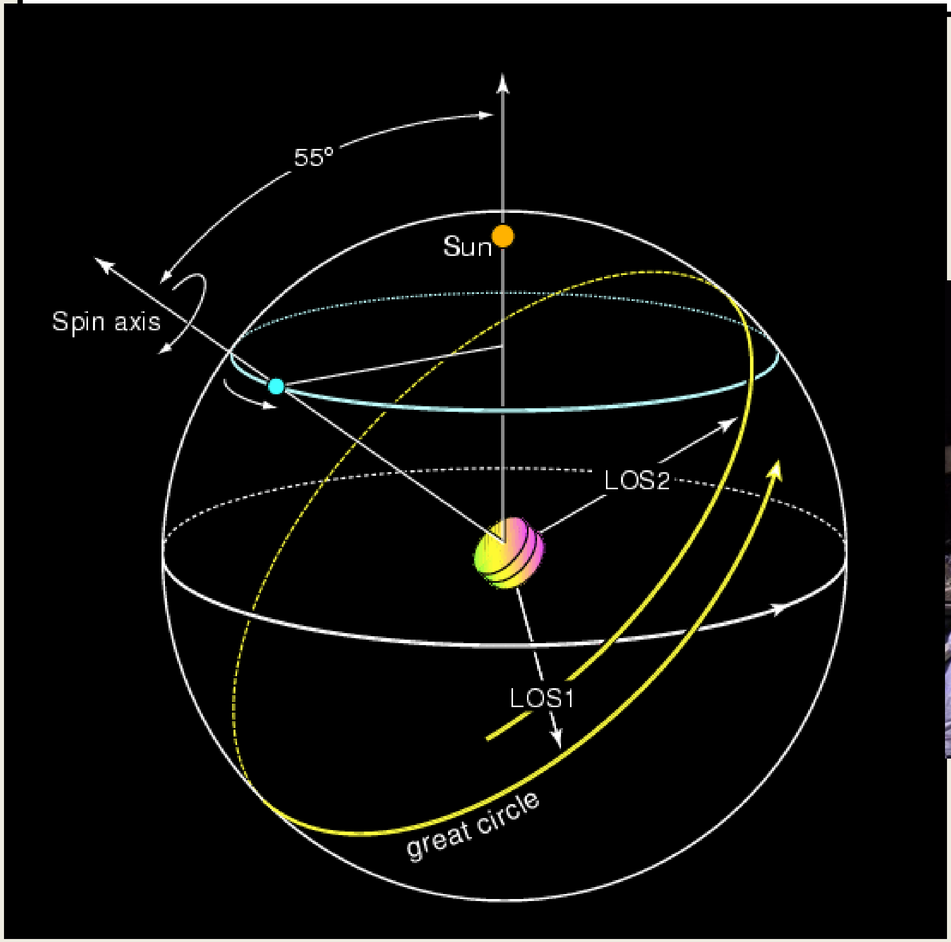


Real stellar distances tells us how bright stars really are this provides the key to how stars evolve the <u>Hertzsprung-Russell</u> diagram

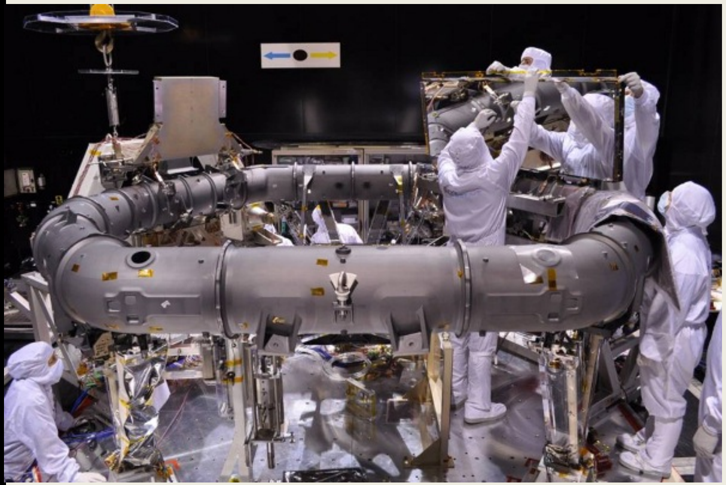


916832 non–HIP stars with σ < 1.0 mas and ϖ /σ > 5.0
Absolute V_T magnitude
Colour index J – K (2MASS)
−2
0
2
4
6
8
10
−0.5
0
0.5
1
1.5

How does Gaia work?: Sky Scanning Principle

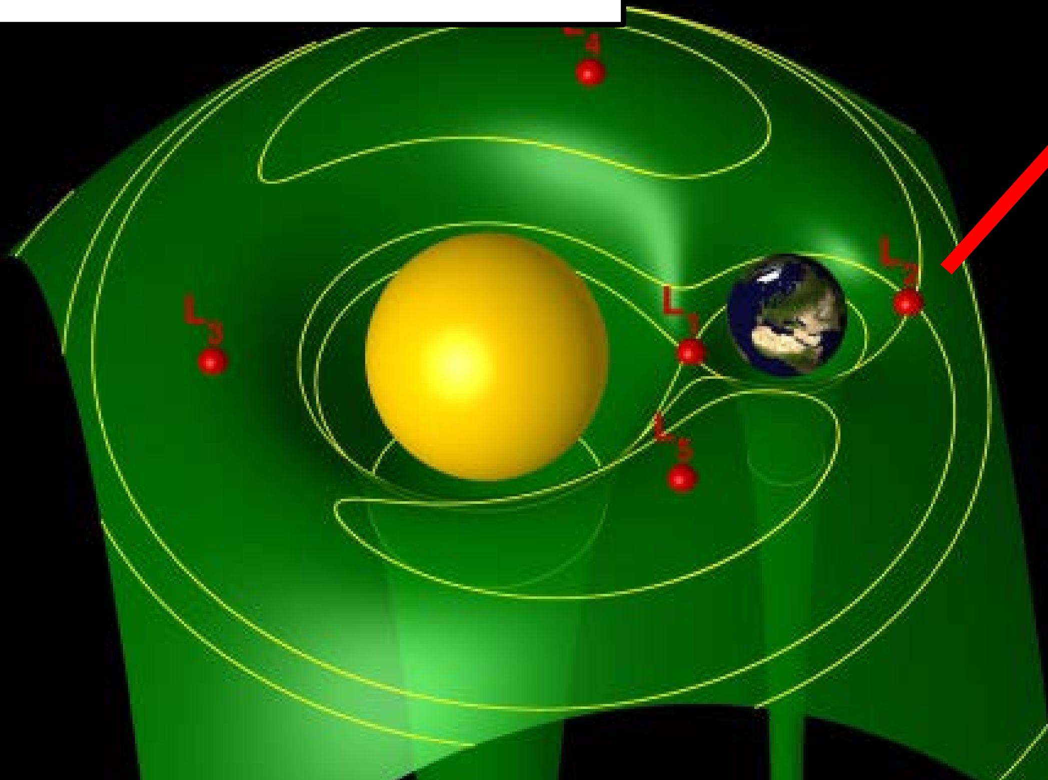


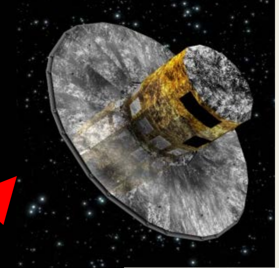
Observe sky with two telescopes



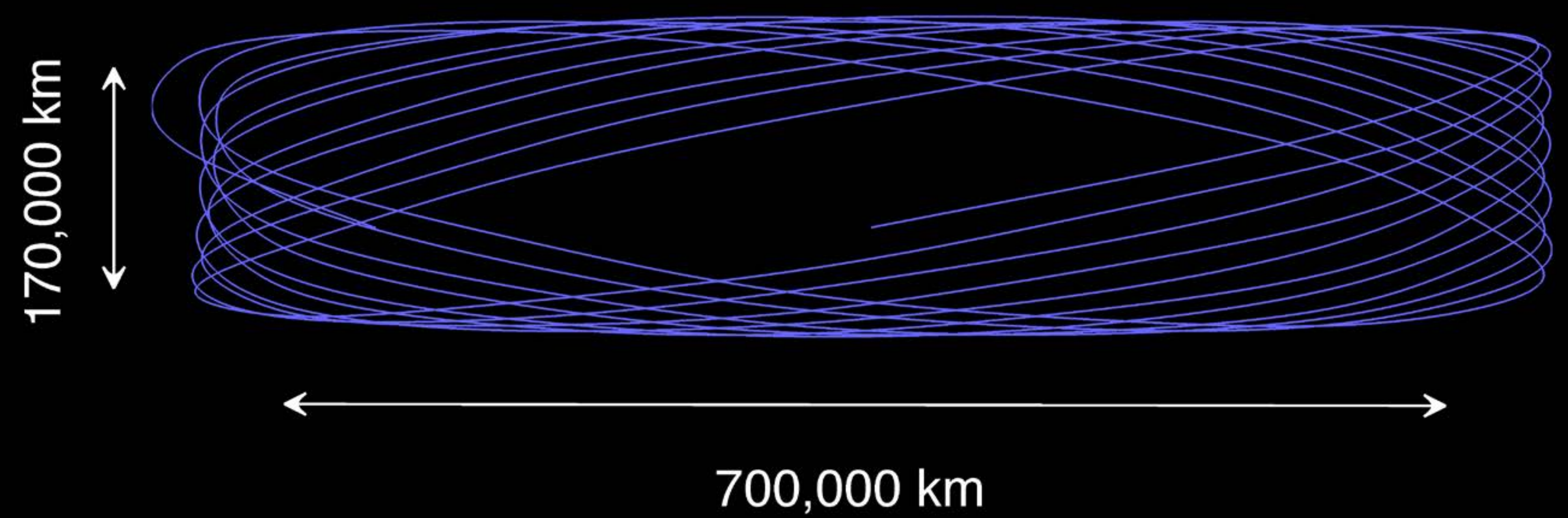
Precision: 50pico-rad, human hair at 1000km, 2cm on the moon...

Gaia's L2 Orbit



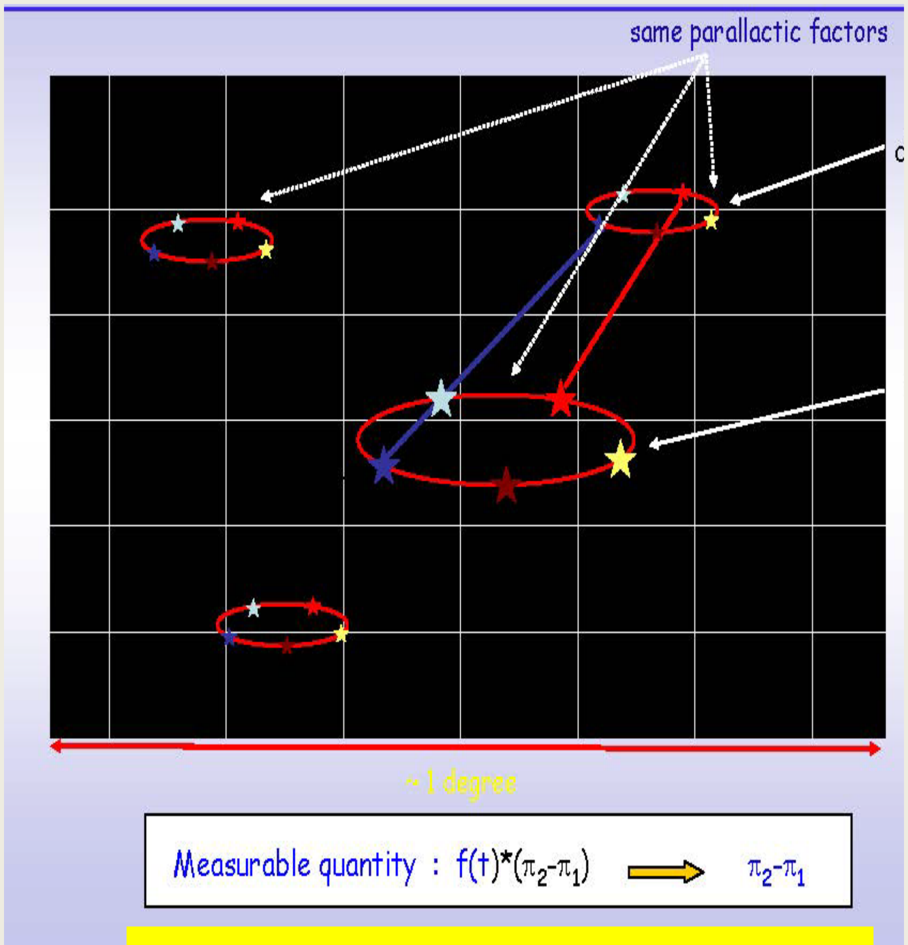


Gaia in orbit

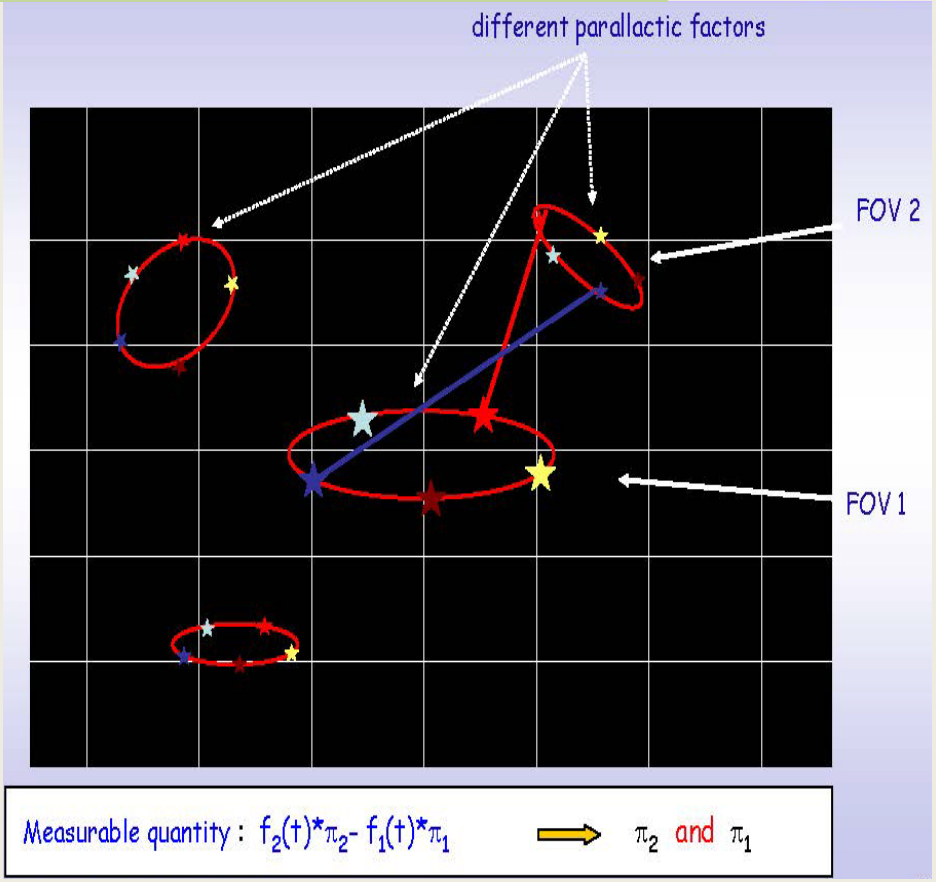


Absolute astrometry

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



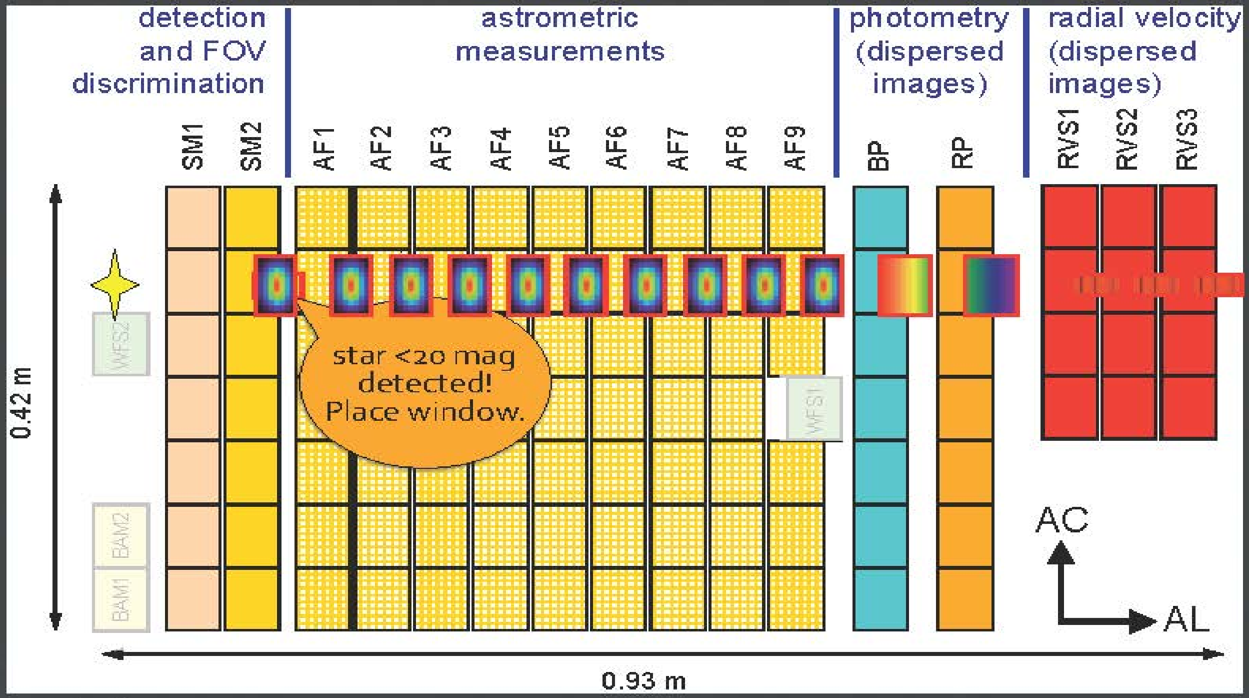
Two field astrometry

SINGLE GAIA OBSERVATION = TRANSIT

Camera:

0.75 deg^2

pixel:
10x30 μm
(59x177 mas)



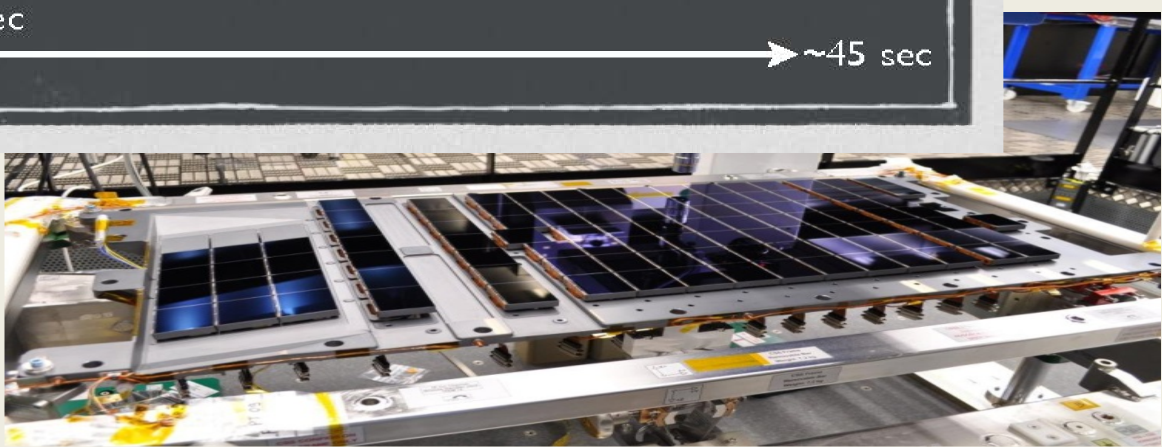
Animation by Berry Holl, Geneva

windows observed:

→ ~4.4 sec

→ ~45 sec

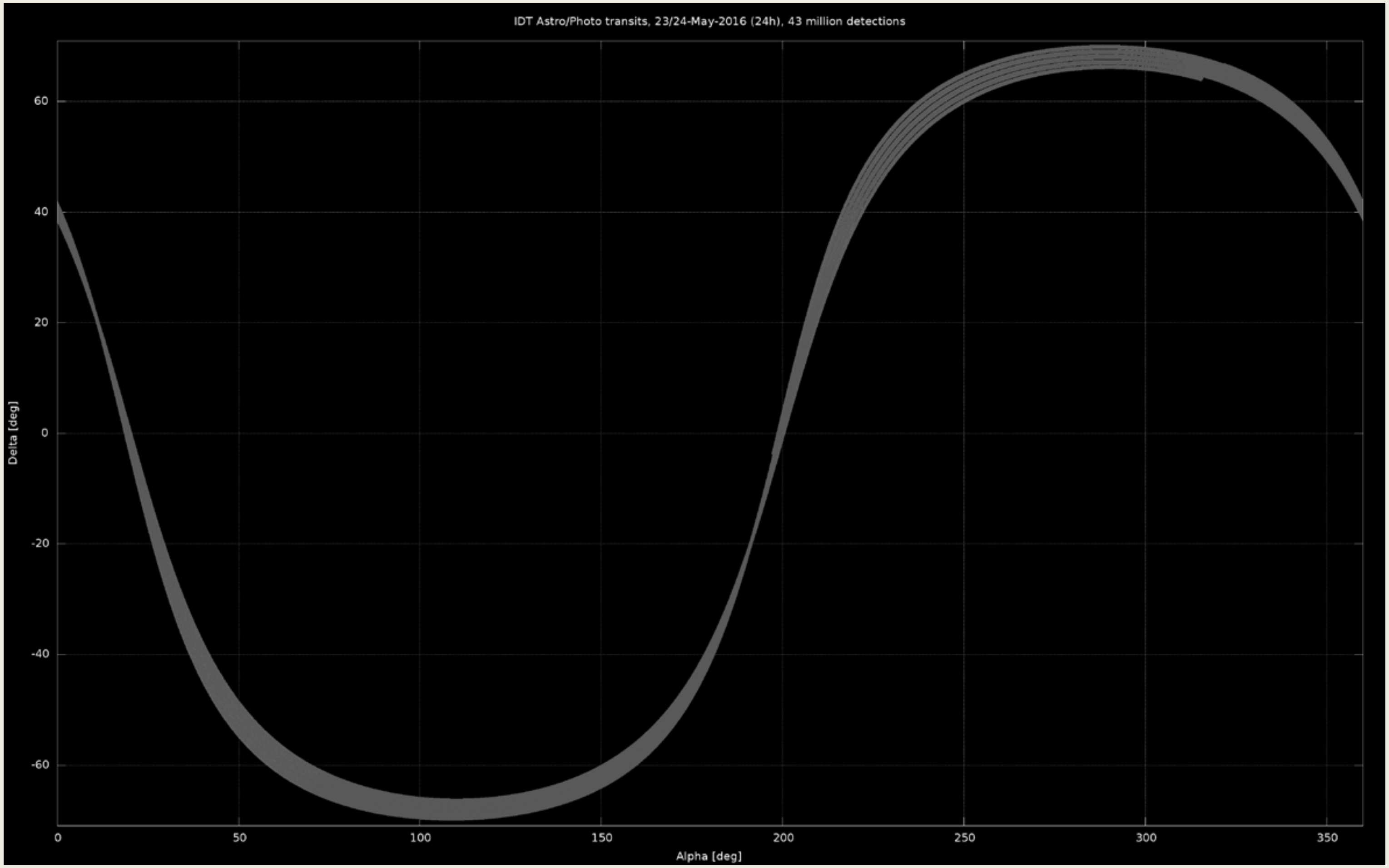
e2v

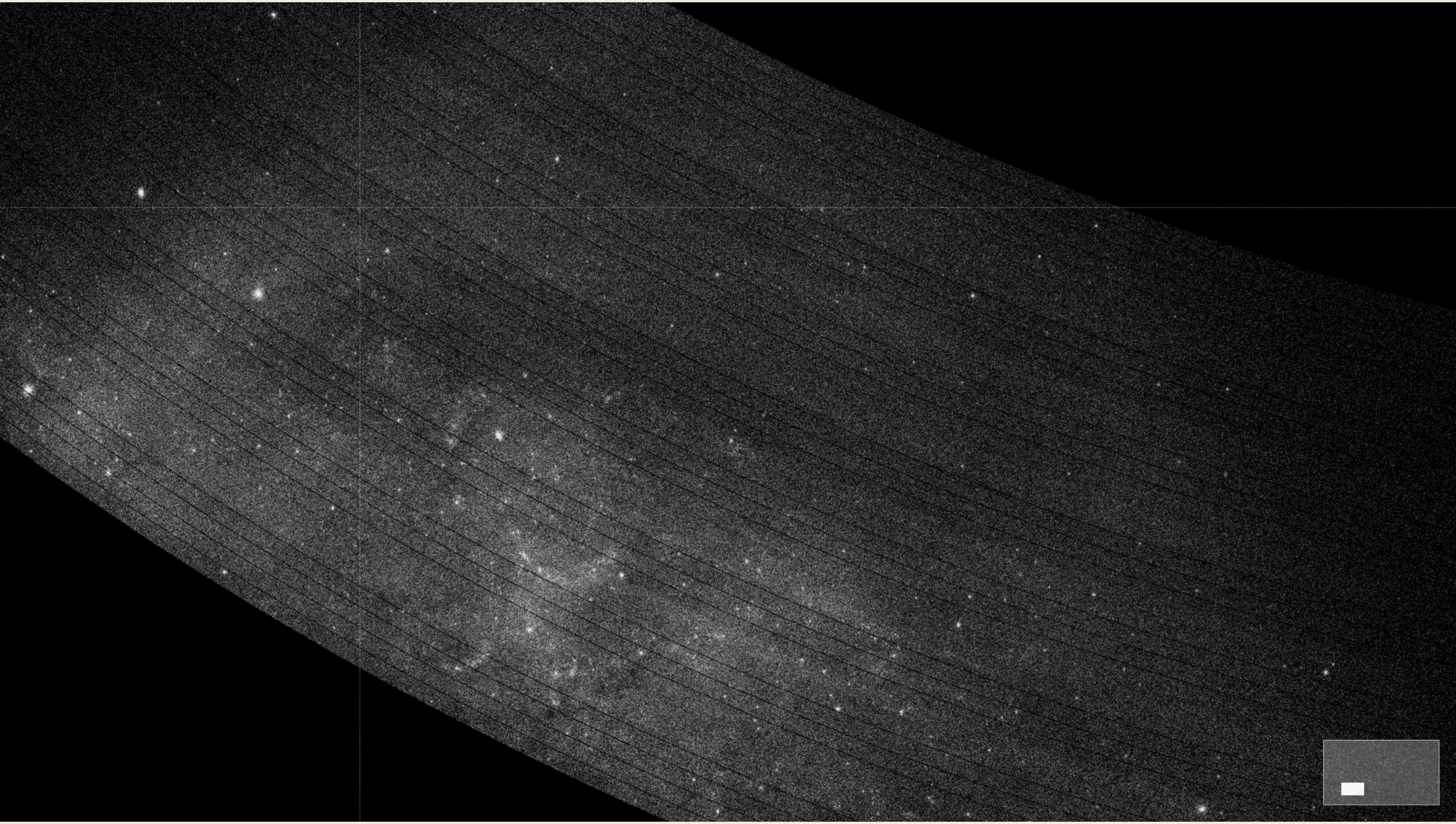


What does micro-arcsecond mean?

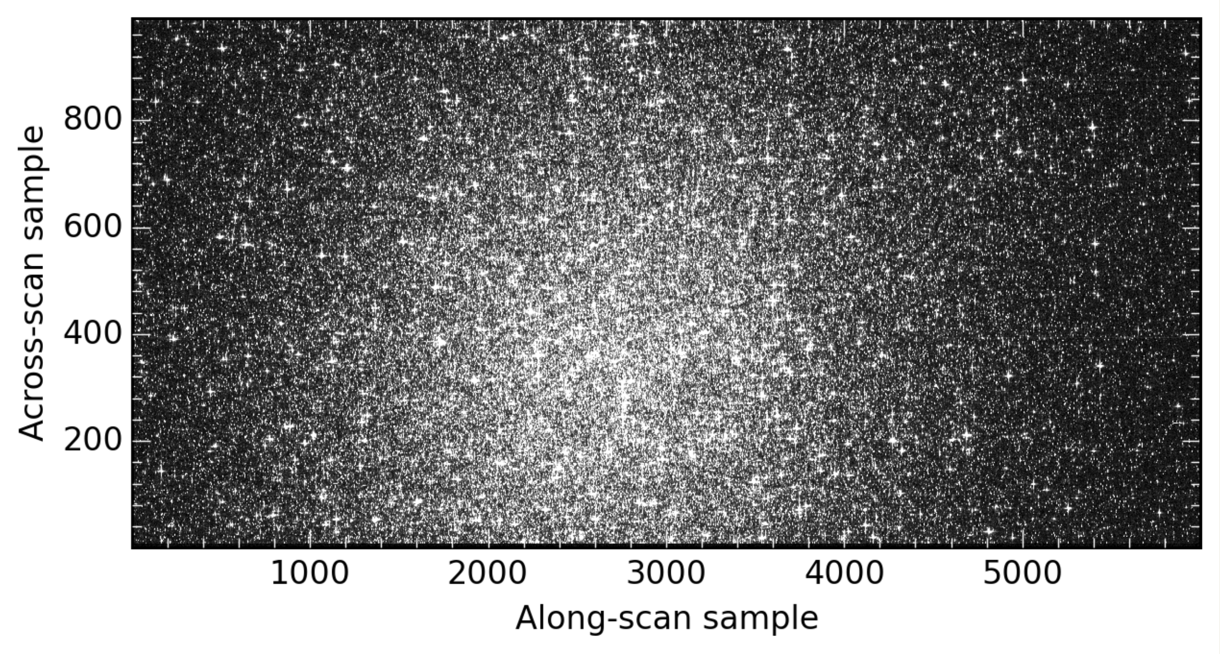
Precision: 50pico-rad, human hair at 1000km, earth-L2 dist to 1cm

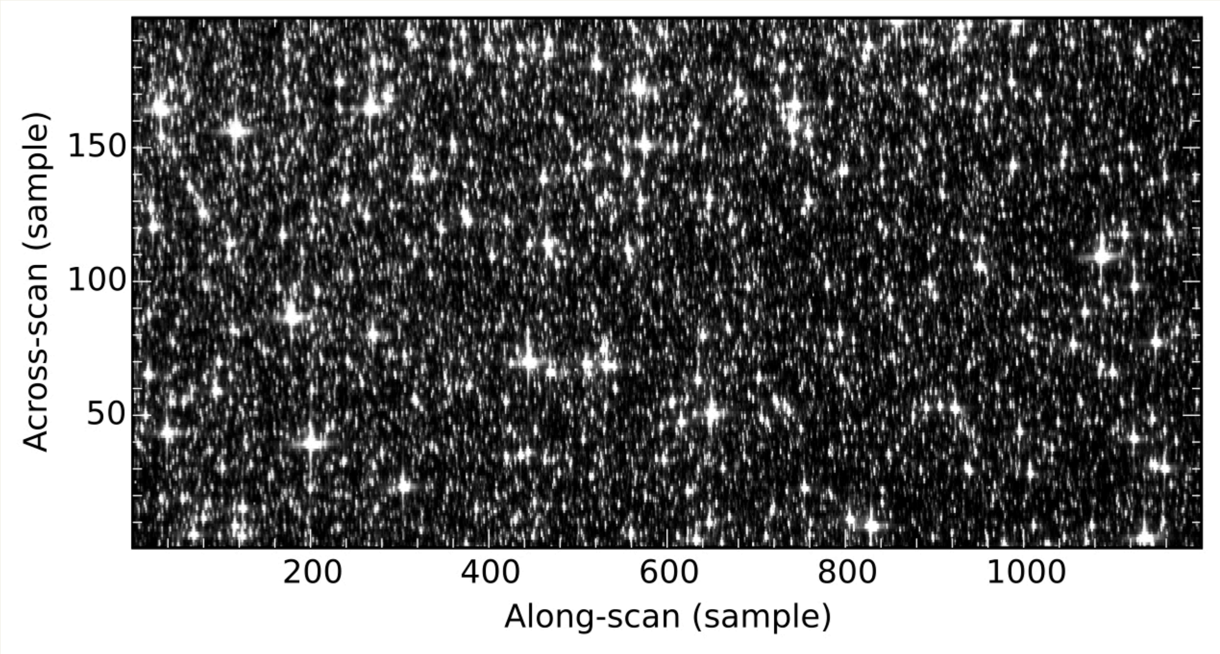
- **Precision: 50pico-rad, human hair at 1000km, coin on the moon**
- **Astrometry needs more than signal to noise and image processing**
- **One must have a physical model and understanding of every contribution to the error budget at an appropriate level**
- **Einstein light bending at the Sun's edge 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 < 1kmetre (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**


IDT Astro/Photo transits, 23/24-May-2016 (24h), 43 million detections
Delta [deg]
60
40
20
0
-20
-40
-60
0
50
100
150
200
250
300
350
Alpha [deg]




IDT Astro/Photo transits, 23/24-May-2016 (24h)
Delta [deg]
Alpha [deg]
-64.7
-64.8
-64.9
-65
-65.1
-65.2
-65.3
-65.4
-65.5
-65.6
76.5
77
77.5
78
78.5


Across-scan sample
800
600
400
200
1000
2000
3000
4000
5000
Along-scan sample

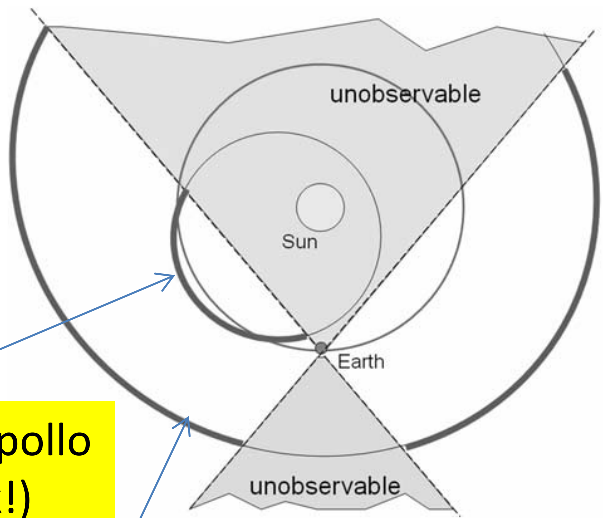

Across-scan (sample)
150
100
50
200
400
600
800
1000
Along-scan (sample)

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

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



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

Orbital accuracy

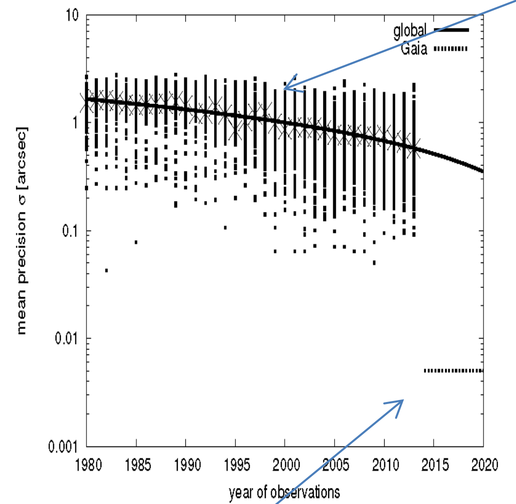
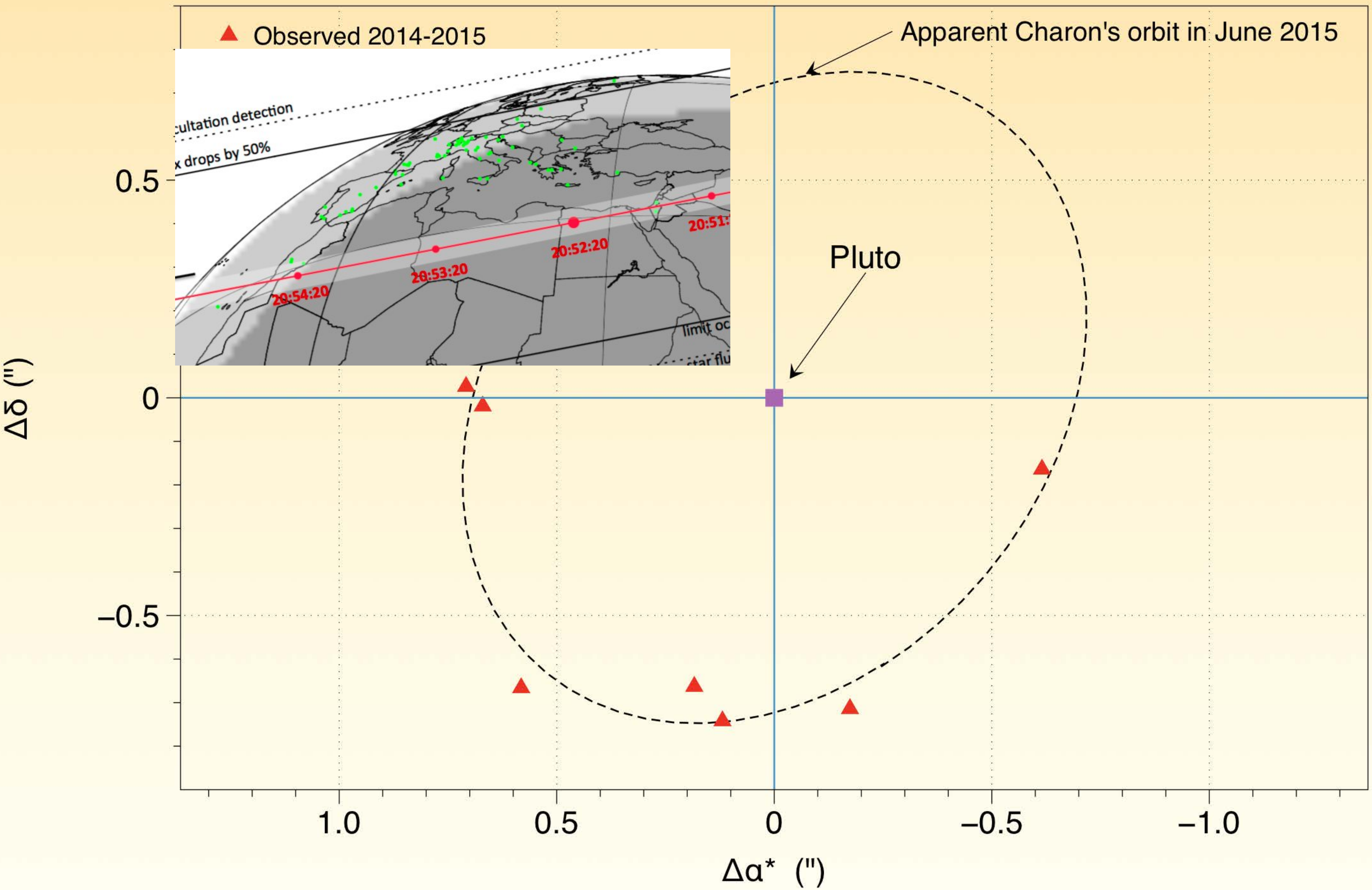


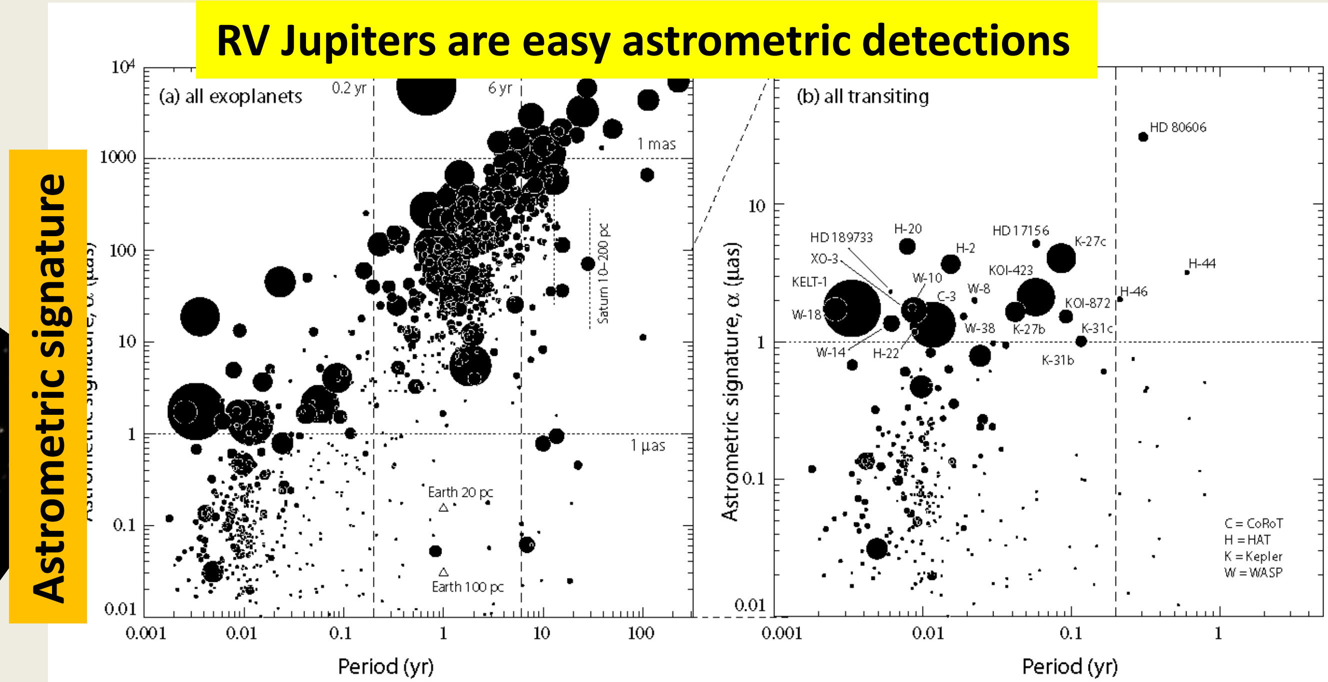
Fig. 2. The yearly astrometric mean precision ($\sigma = \sqrt{(\sigma_\alpha \cos\delta)^2 + (\sigma_\delta)^2}$) of each observatory with a Minor Planet Center designation and at least 10 submitted observations per year is plotted against time (dots). The crosses indicate global yearly averages, i.e.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


Observed 2014-2015
Apparent Charon's orbit in June 2015
Pluto
20:54:20
20:53:20
20:52:20
0.5
0
−0.5
1.0
0.5
0
−0.5
−1.0
Δδ (")
Δα* (")

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.

These will be ideal for follow-up direct coronographic imaging



Period (yr)

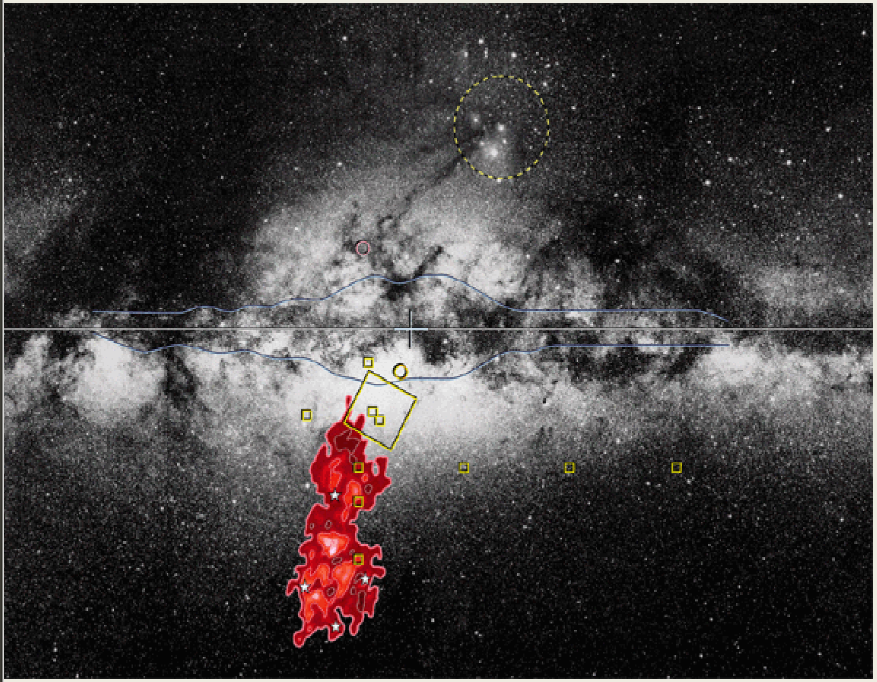
Fig. 1.— Astrometric signature versus perio[...]objects listed in exoplanet.eu at 2014 September 1 for all 1821 confirmed planets (le[...]t of 1129 transiting planets with appropriately known data (right). Note the different scales in abscissa and ordinate. Circle sizes are proportional to planet mass; 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, α would increase by a factor 2, but their astrometric motion would remain undetectable by Gaia.

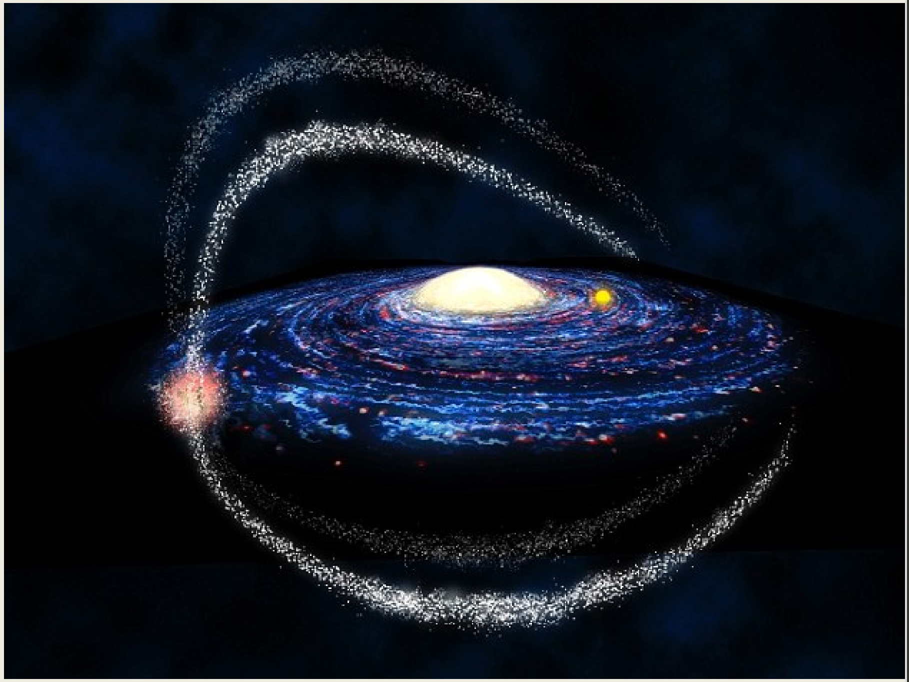
Perryman etal 2014 arXiv:1411.1173

Star counts build a rough model of the Milky Way

Sagittarius dwarf galaxy.
Our nearest neighbour. Discovered 1994.

Sagittarius is the prototype of the many small galaxies which merge to assemble large galaxies





We have now found 25+ new satellites of the Milky Way, and several debris streams: counting stars discovers the continuing assembly of the outer Galaxy

Local dark matter cold thin disk (Randall) or cored?

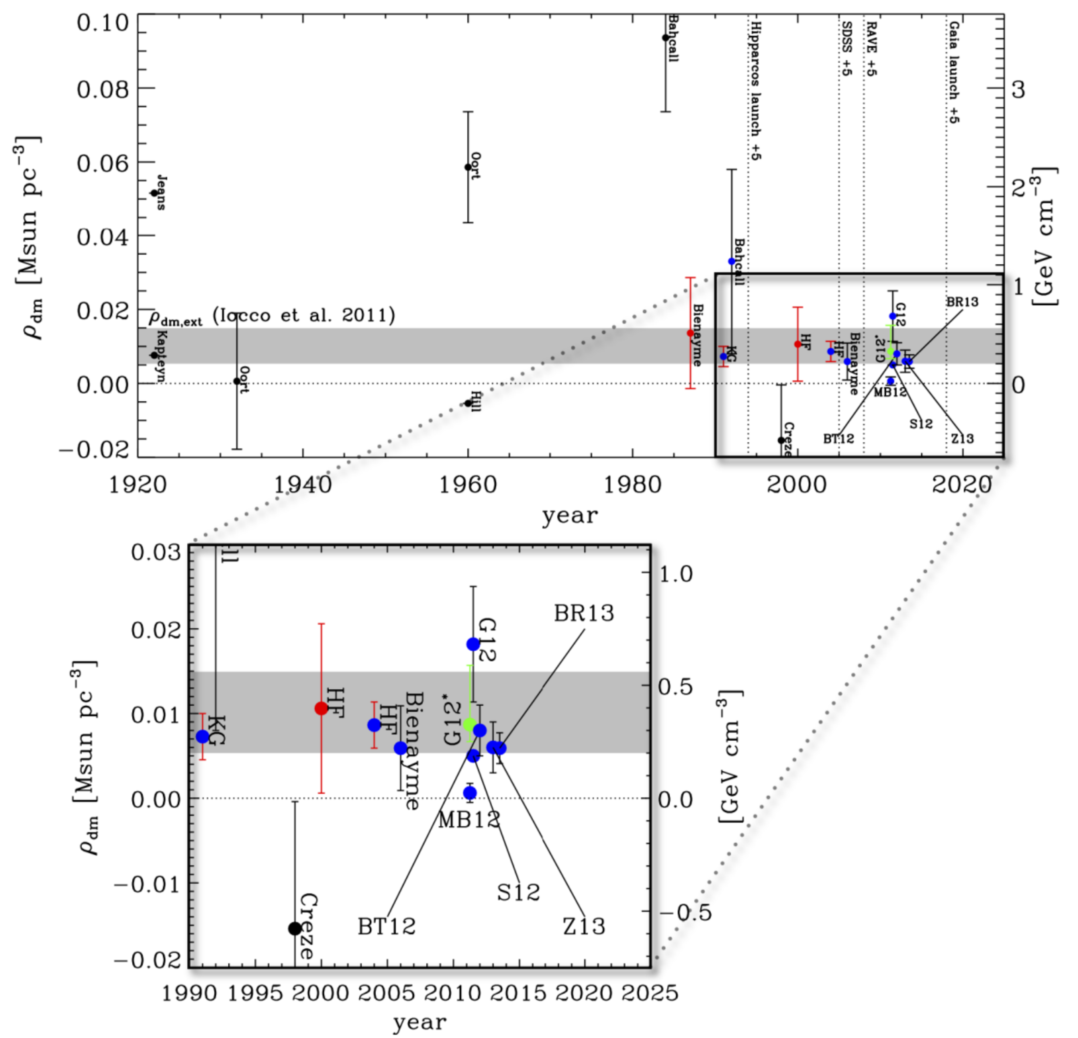
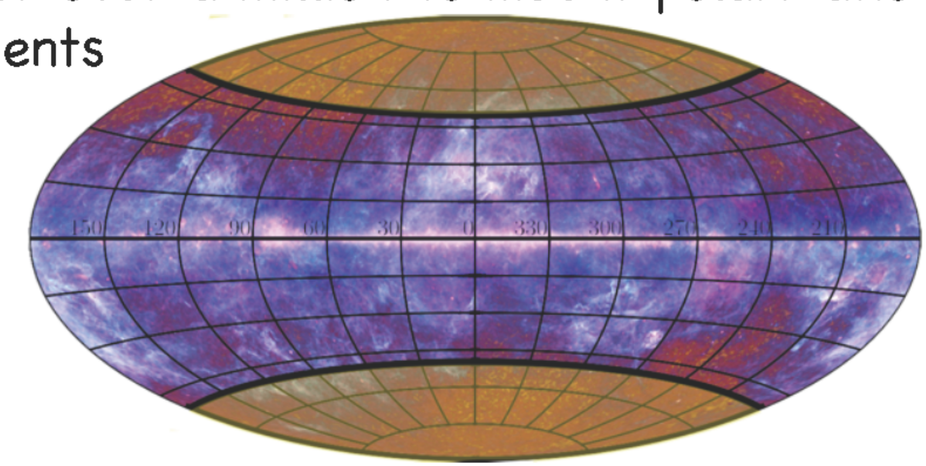


Figure 2: A century of measurements of ρ_{dm}. In all cases, I assume the same matter density and surface density of $\rho_b = 0.0914\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$ and $\Sigma_b = 55\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}$ (Flynn et al., 2006). Values derived from a surface density rather than a volume density have a blue filled circle; red data points indicate the use of a 'rotation curve' prior (see §3.5.1). The green data point is derived from Garbari et al. (2012) assuming a stronger prior on $\Sigma_b = 55 \pm 1\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}$ (see §5). All error bars represent either 1σ uncertainties or 68% confidence intervals. Overlaid are: $\rho_{\mathrm{dm,ext}}$ extrapolated from the rotation curve assuming spherical symmetry (grey band); the launch dates plus 5 years for the Hipparcos and Gaia astrometric satellite missions; and the start date plus 5 years of the SDSS and RAVE surveys. Where no error bar was calculated for a given measurement, there is simply a horizontal line through that data point. All data and references

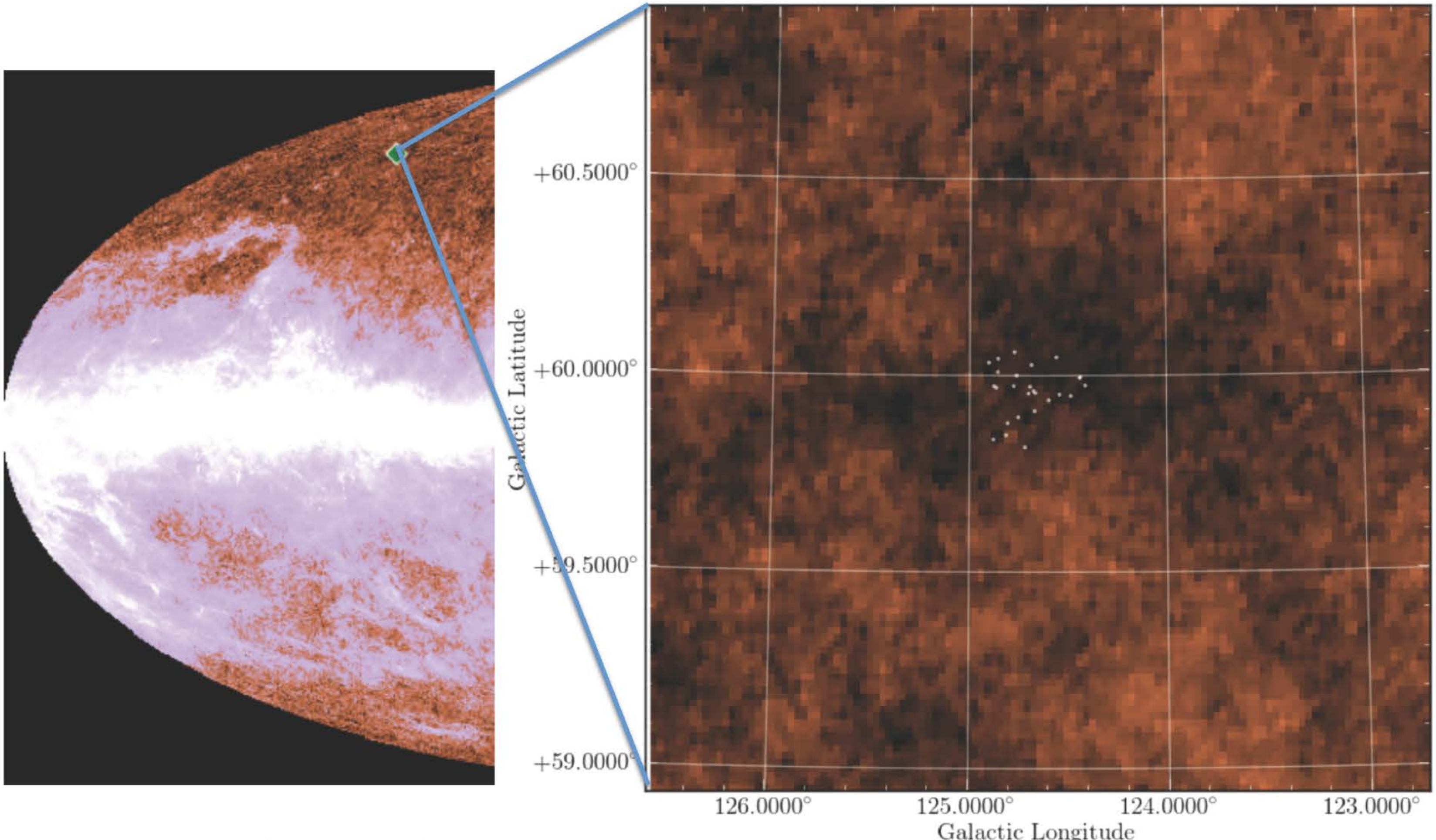
PASIPHAE

Polar-Area Stellar Imaging in Polarization High-Accuracy Experiment

- Will measure polarization down to 0.3% at 3σ for all stars with Rmag $\leq$ 16.5
- Survey will run concurrently in north (Skinakas 1.3m telescope) and south (South African Astronomical Observatory 1m telescope) over 4 years (2018-2021)
- Will cover the sky at $|b| \geq 50°$ over 9,000 sqdeg
- Will deliver over a million confident polarization measurements



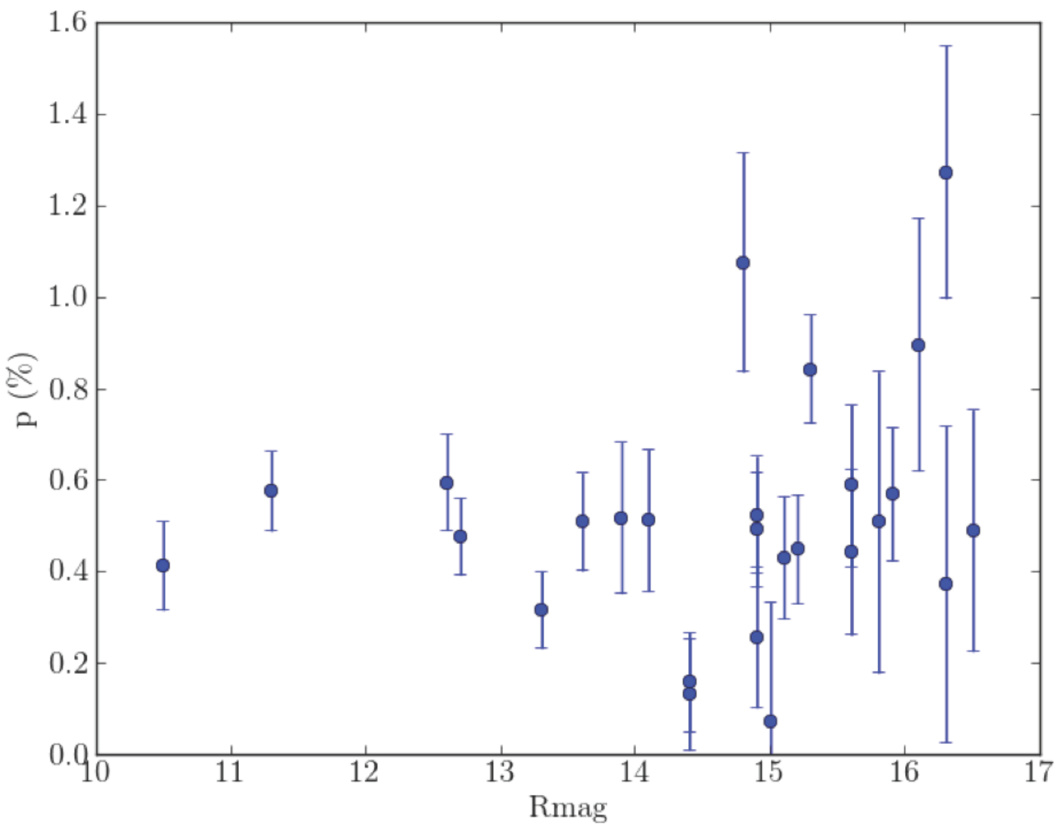
Is Star Light significantly Polarized?



Go to the "darkest" spot - in dust emission according to Planck - of the northern sky and measure starlight polarization with RoboPol

Is Star Light significantly Polarized?

Yes!



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:
  - γ to 5×10^{-7} (cf. 10^{-5} presently) $\Rightarrow$ scalar-tensor theories
  - effect of Sun: 4 mas at 90°; Jovian limb: 17 mas; Earth: ~40 μas
- From perihelion precession of minor planets:
  - β to 3×10^{-4} - 3×10^{-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)

Galaxies, Quasars, and the Reference Frame

- Parallax distances, orbits, and internal dynamics of nearby galaxies
- Galaxy survey, including large-scale structure
- ~500,000 quasars: kinematic and photometric detection
- ~10,000 supernovae [few/day ➔ real-time alerts]
- Ω_M, Ω_Λ from multiple quasar images (3500 to 21 mag)
- Galactocentric acceleration: 0.2 nm/s^2 $\Rightarrow$ Δ(aberration) = 4 μas/yr
- Globally accurate reference frame to ~0.4 μas/yr

- Will Gaia contribute to cosmology and fundamental physics?

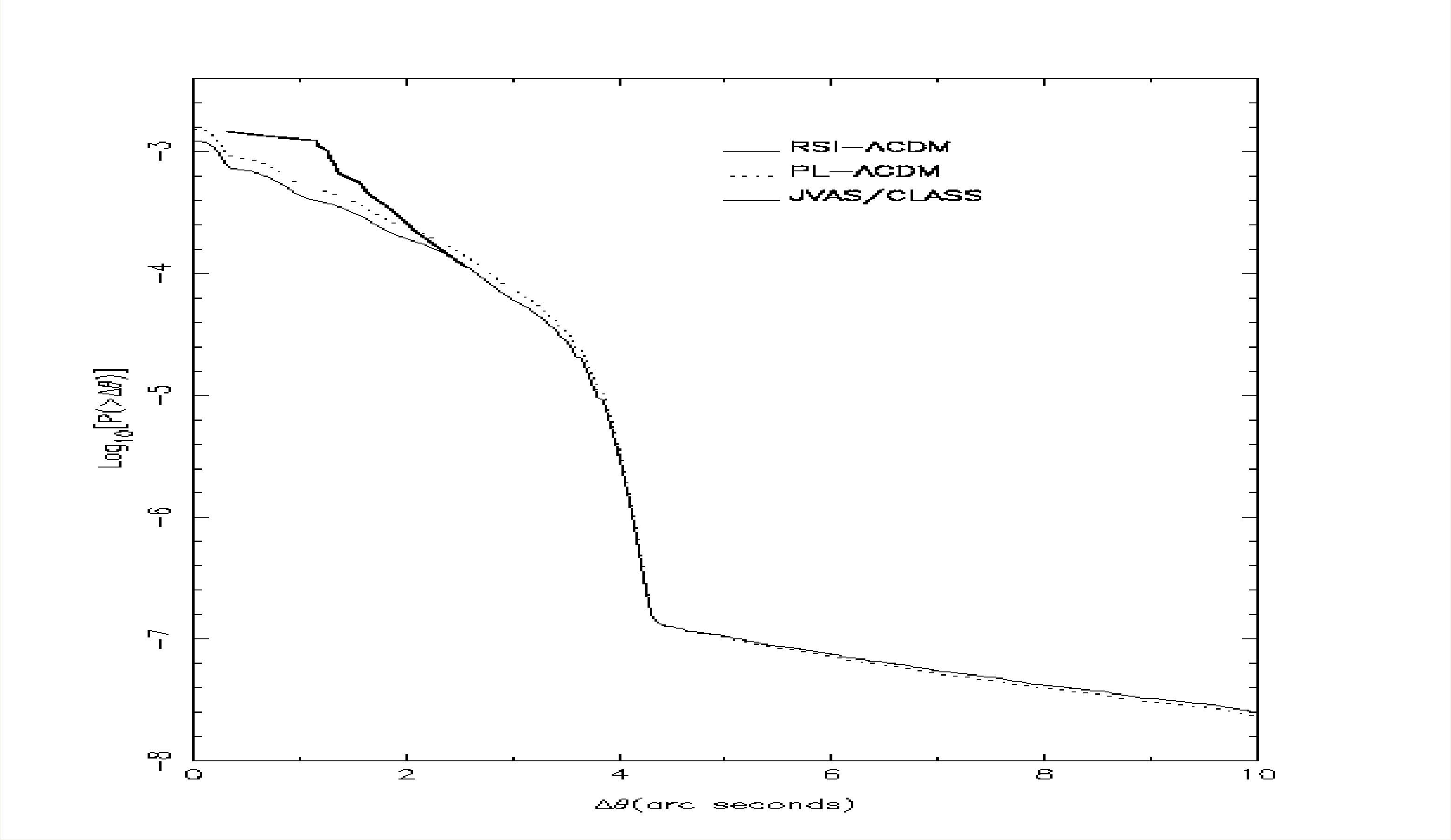
Gaia will discover 500,000 quasars, all with high-resolution imaging to quantify strong-lensing structure (11 qso lenses known in DR3…),

[discovery: spectrophotometry, emission lines, astrometry]

2000 new strong-lensed QSO expected, under standard CDM

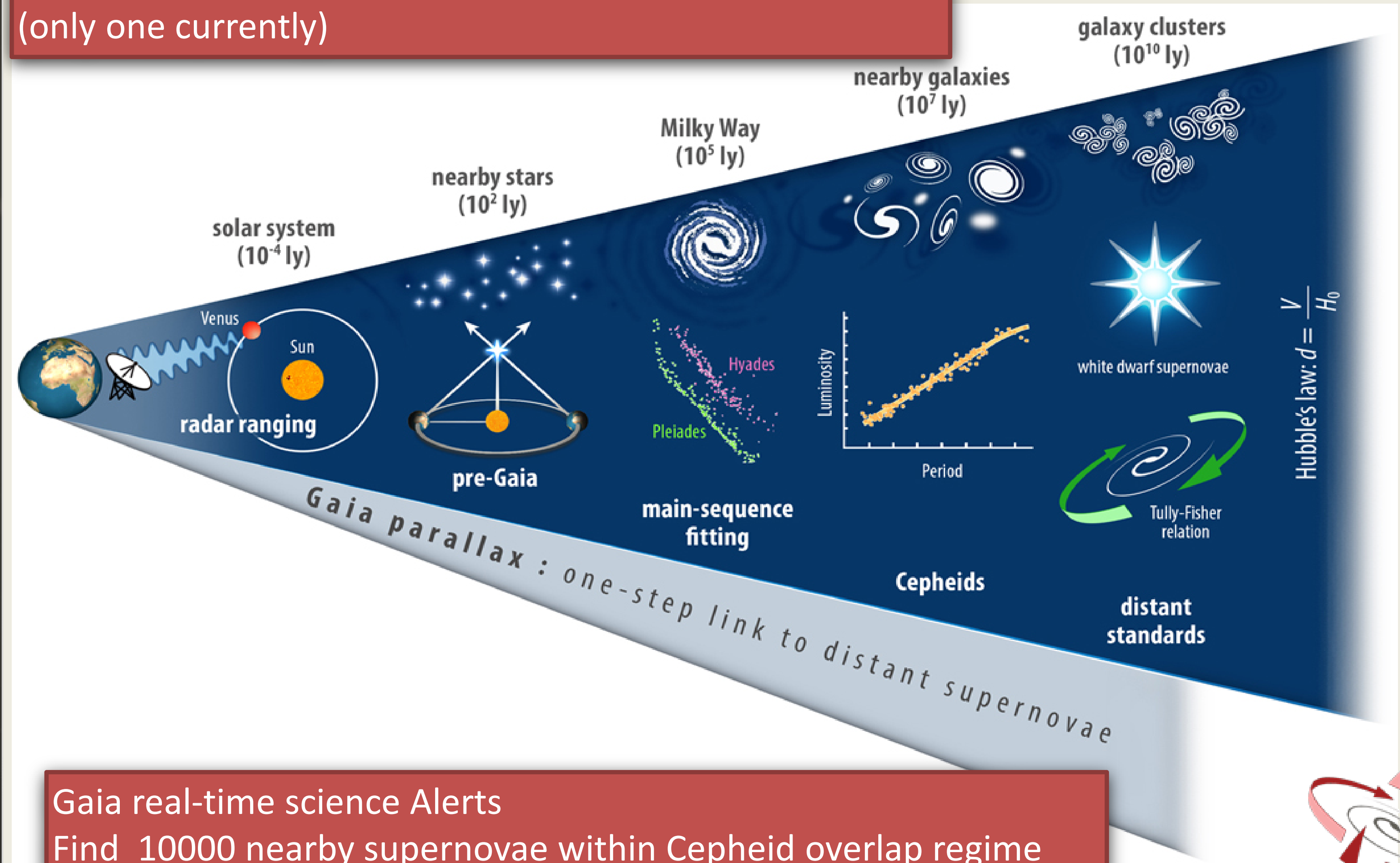
Ω_M, Ω_Λ from multiple quasar images

The separation DF is also a measure of the small-scale perturbation spectrum



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

Pulsating variables from Hipparcos to Gaia

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

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

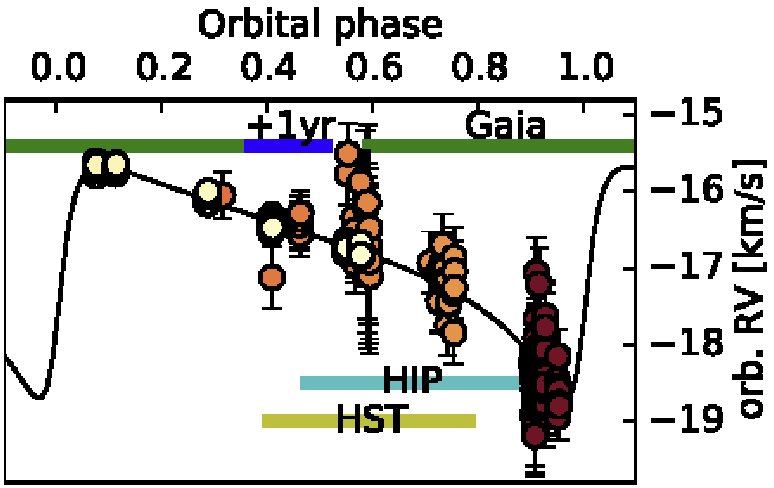
CEPHEIDS

There are ~12 Cepheids with *G* < 6 → distances relevant for cosmic distance scale (e.g. Benedict et al. 2007)

Talk by Breitfelder (Wednesday)

Example: δ Cep (HIP 110991) *G* = 3.9

Discovered to be spectroscopic binary with precision radial velocities (P = 2200 d, ecc = 0.67, a_rel = 5.8 AU, $M_1 \sim 5\ M_{Sun}$ $M_2 \sim 0.2\ M_{Sun}$)



Anderson, Sahlmann, Holl, et al. 2015, ApJ, 804

Minimum astrometric orbit size: a_1 sin i = 0.84 mas

Gaia will observe δ Cep about 90 times over 5 years

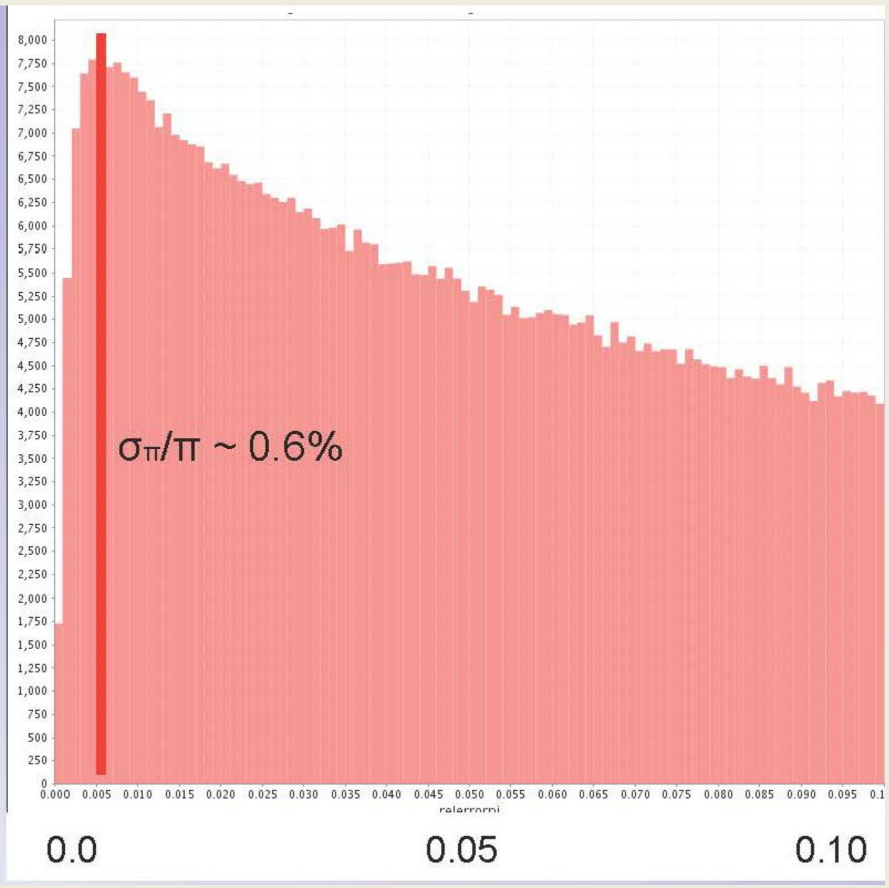
→ Gaia will detect the the astrometric orbit detection with high signal-to-noise

→ accurate parallax determination

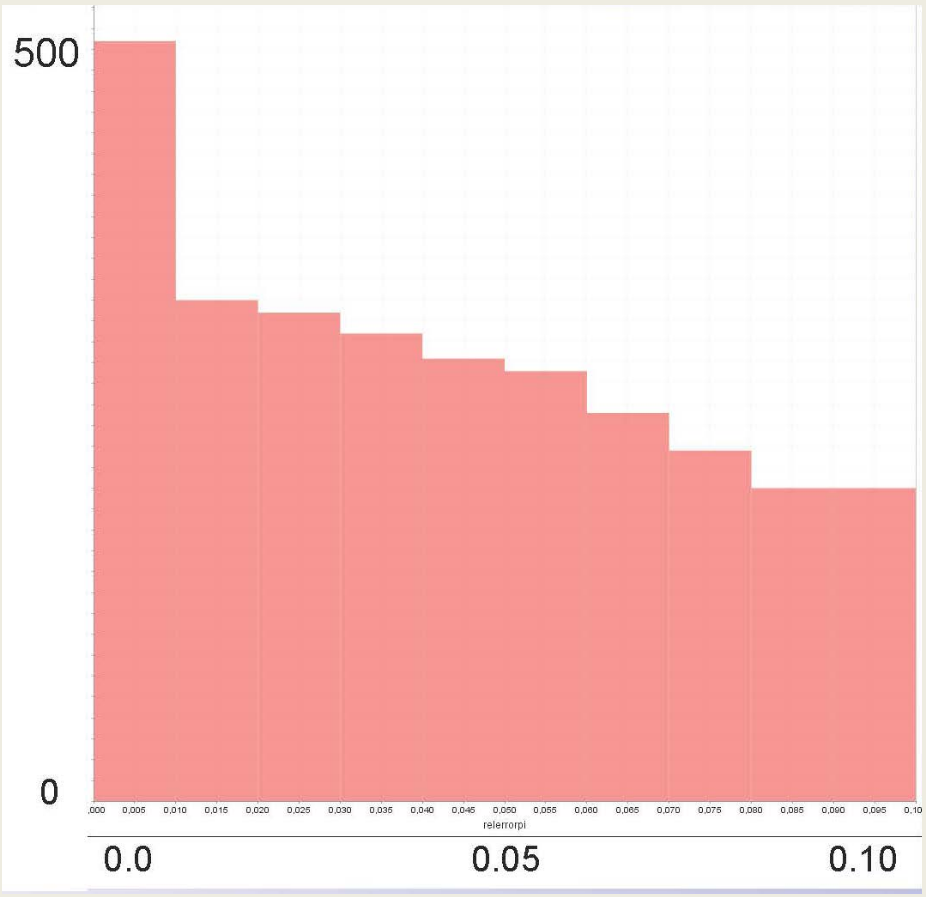
Astrometry distance accuracy DF simulated

P-L relation will be known to an accuracy < 0.01mag.
Gaia's Cepheid calibration will be limited by extinction uncertainties
 - and the astrophysical variance we haven't noticed yet

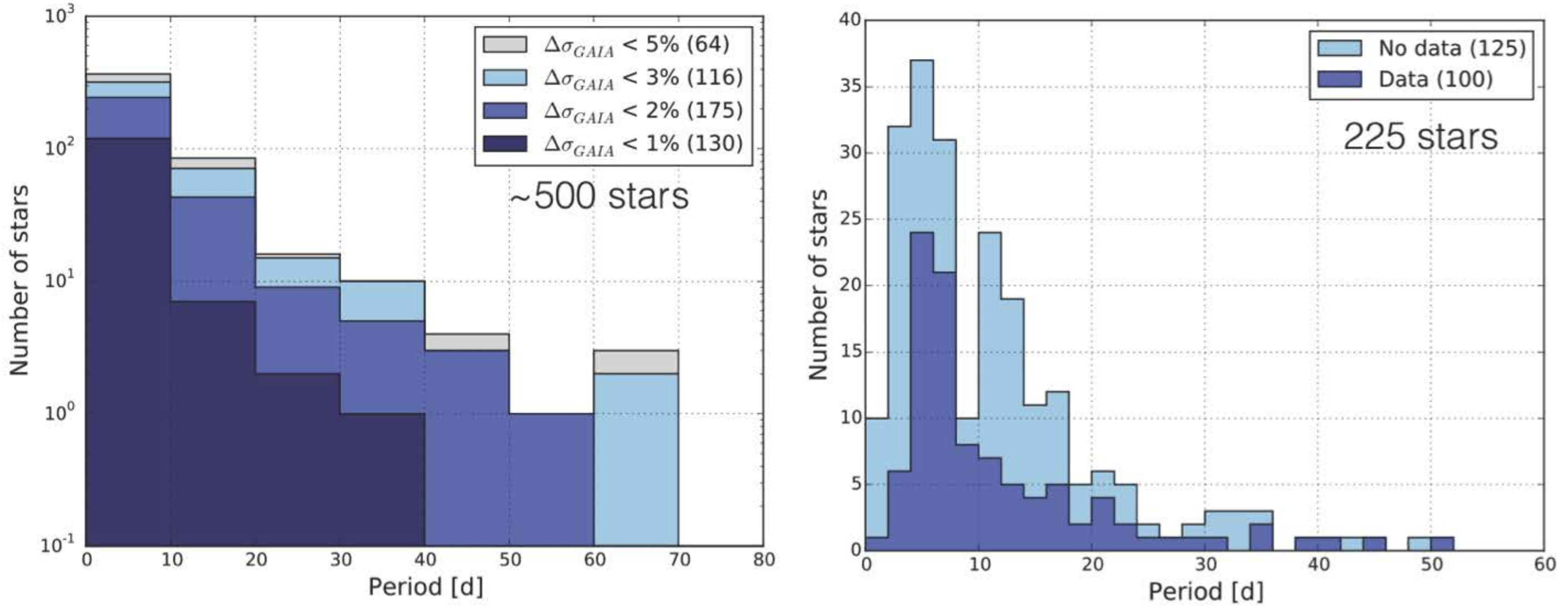
All stars



Cepheids



Gaia parallaxes predicted for known Cepheids



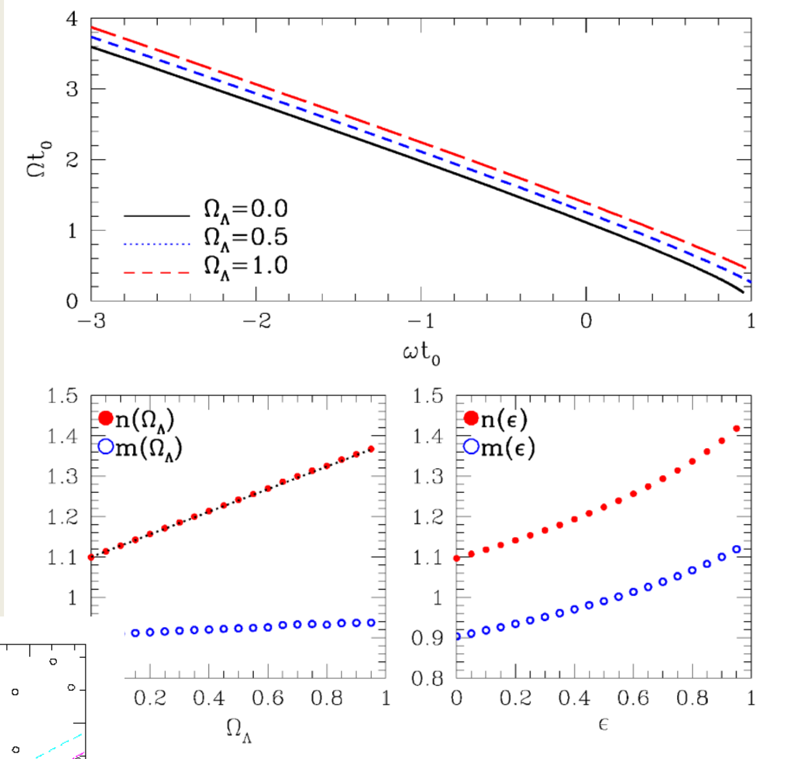
Figures : Anthony Soulain

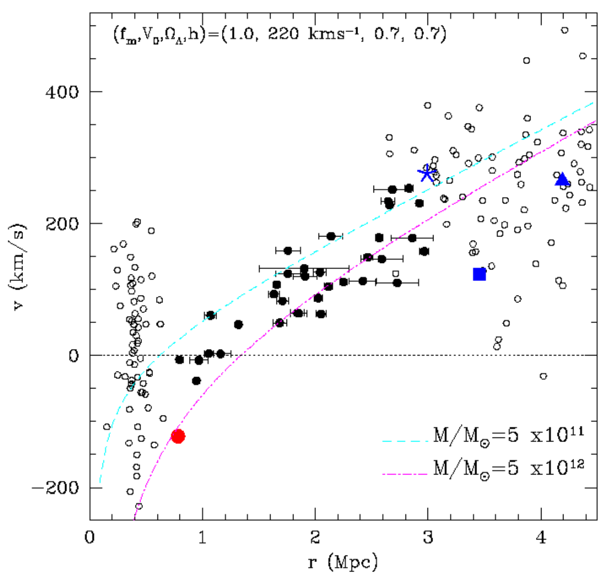
In the **225 "best" Cepheids** :

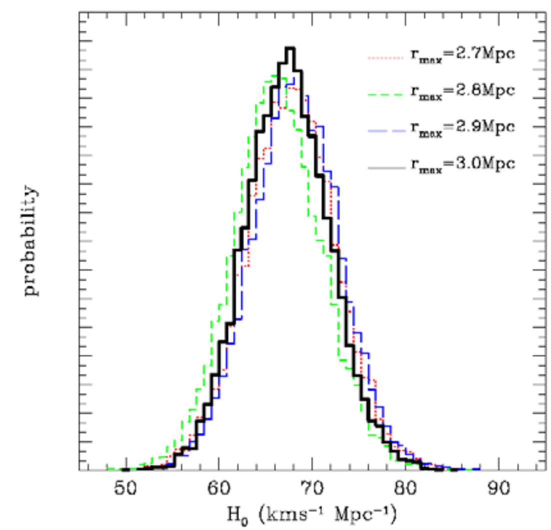
- 30 with numerous data + interferometry → "complete" **SPI**PS method
- 70 with numerous data → **SP**IPS method
- 125 with no data → SPIPS method with Gaia data + new observations

A dynamical model of the local cosmic expansion

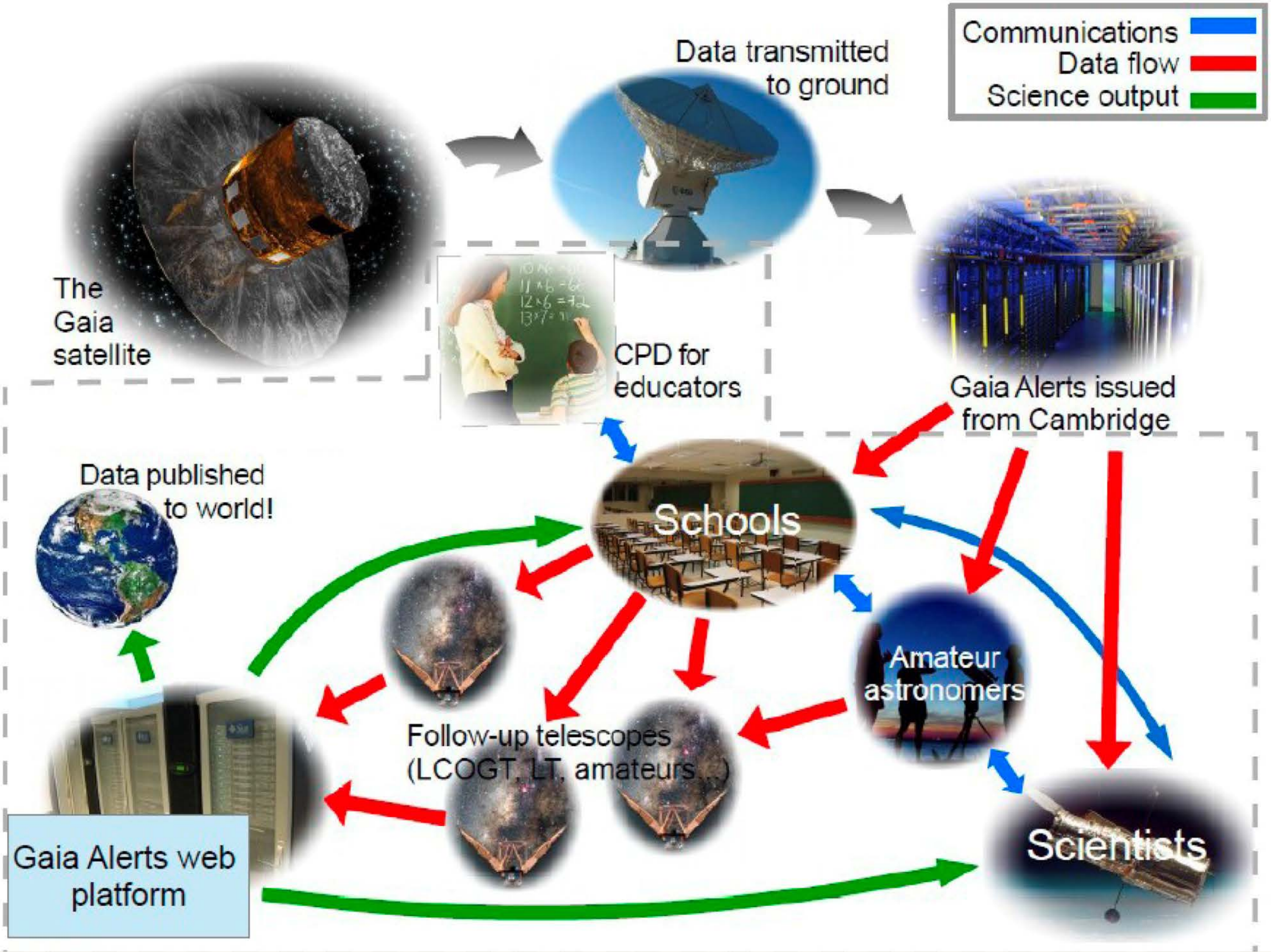
Jorge Peñarrubia[1,2,3⋆], Yin-Zhe Ma[4,5], Matthew G. Walker[6], Alan McConnachie[7]

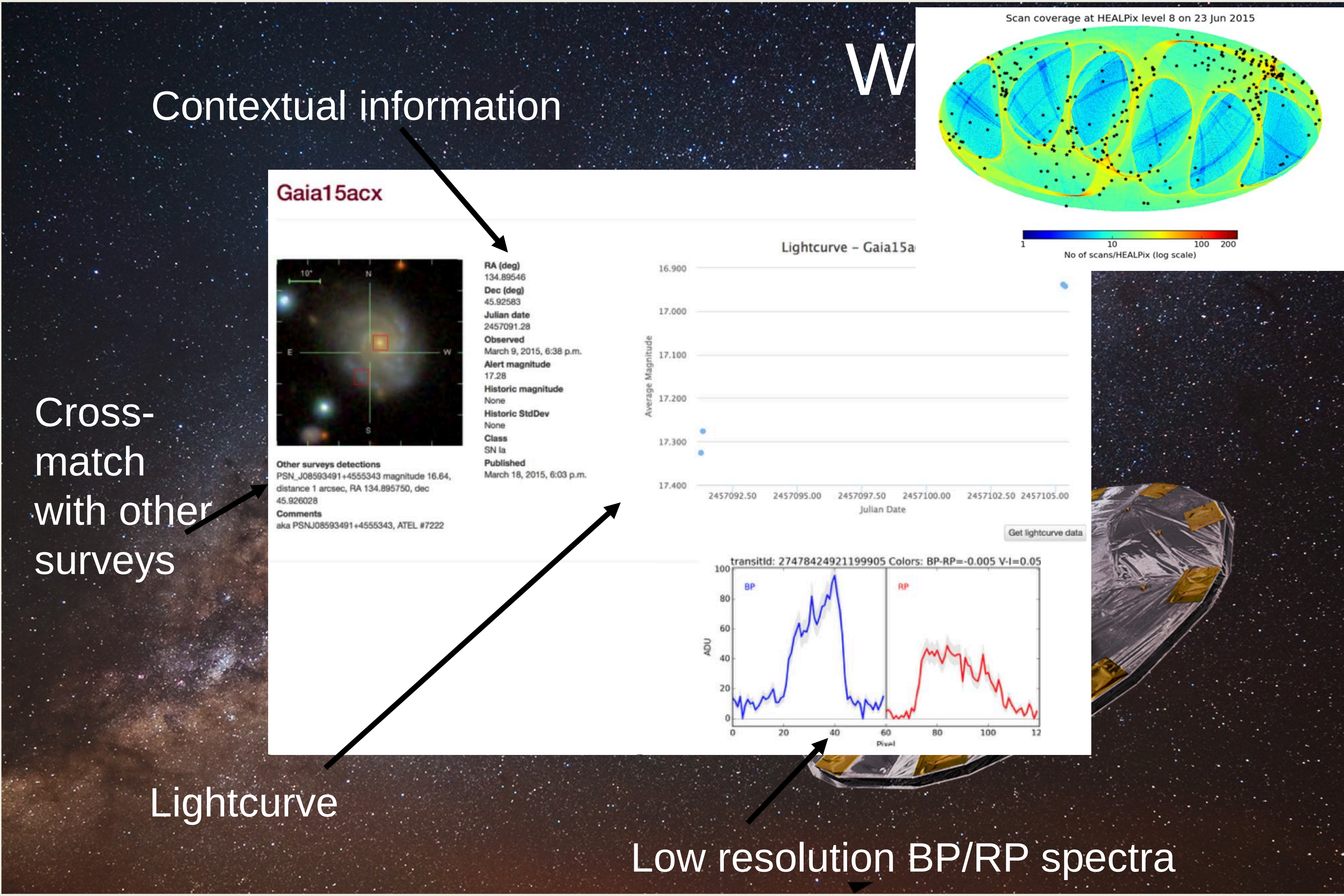






Alerts publication flow




W
Scan coverage at HEALPix level 8 on 23 Jun 2015
1
10
100
200
No of scans/HEALPix (log scale)
Contextual information
Gaia15acx
10"
N
E
W
S
RA (deg)
134.89546
Dec (deg)
45.92583
Julian date
2457091.28
Observed
March 9, 2015, 6:38 p.m.
Alert magnitude
17.28
Historic magnitude
None
Historic StdDev
None
Class
SN Ia
Published
March 18, 2015, 6:03 p.m.
Other surveys detections
PSN_J08593491+4555343 magnitude 16.64, distance 1 arcsec, RA 134.895750, dec 45.926028
Comments
aka PSNJ08593491+4555343, ATEL #7222
Lightcurve – Gaia15a
Average Magnitude
16.900
17.000
17.100
17.200
17.300
17.400
2457092.50
2457095.00
2457097.50
2457100.00
2457102.50
2457105.00
Julian Date
Get lightcurve data
transitId: 27478424921199905 Colors: BP-RP=-0.005 V-I=0.05
BP
RP
ADU
100
80
60
40
20
0
0
20
40
60
80
100
12
Pixel
Cross-match with other surveys
Lightcurve
Low resolution BP/RP spectra

Gaia science: teaching 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

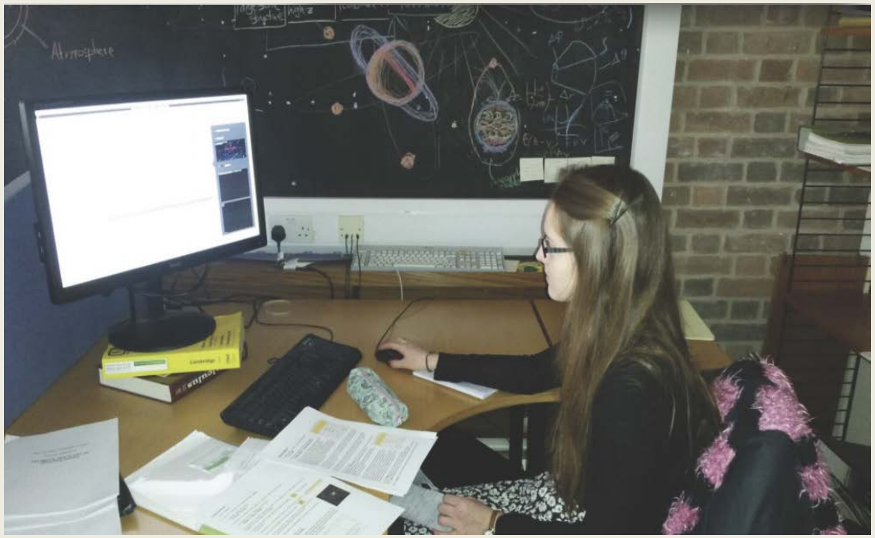
We are working with global robotic telescopes available for school educational use to follow-up Gaia discoveries.

School classes can learn science by doing original science. “Adopt a Supernova”

<u>Teaching children to follow Copernicus:</u>

<u>Learn from data, not preconceptions.</u>

Move Alerts to mobile devices if we find funds

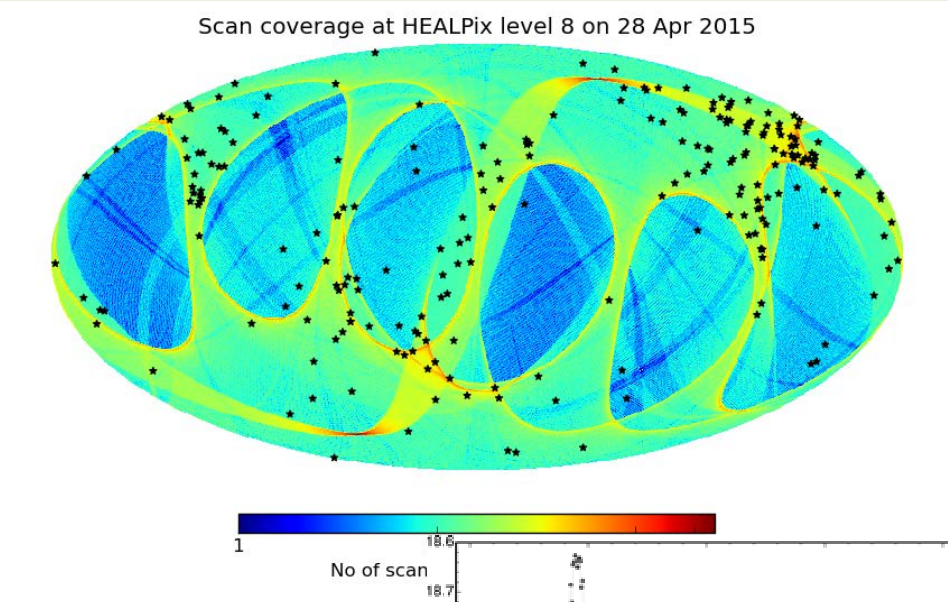


The Gaia Data Release (GDR) Scenario

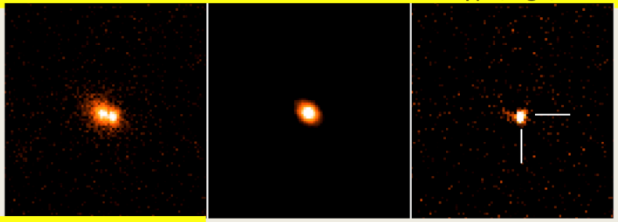
http://www.cosmos.esa.int/web/gaia/release

- GDR1 9/16: positions, G-magnitudes (~all sky, single stars)
  proper motions for 2 million Tycho stars (~50 μarcsec/yr)
  GDR2 late/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 /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 /19: + variability, solar system objects, updates on previous releases, source classifications, astrophysical parameters, variable star solutions, epoch photometry
- GDR-X: 5-year data release (thus in 2022/23 or 2025)
- 5 year extension under analysis

Full dataset for more sophisticated modelling released later in mission

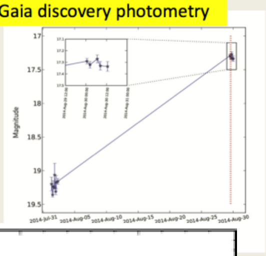


SN Gaia14aaa: correct deduction of type, age, redshift

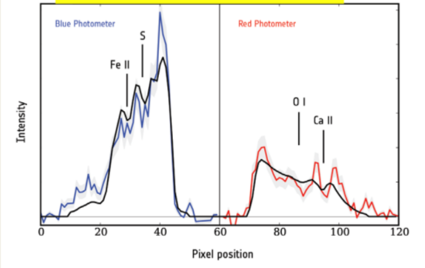


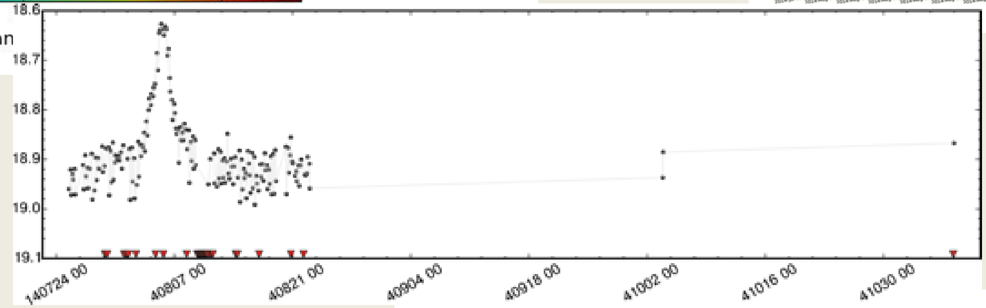
Images from Liverpool Telescope

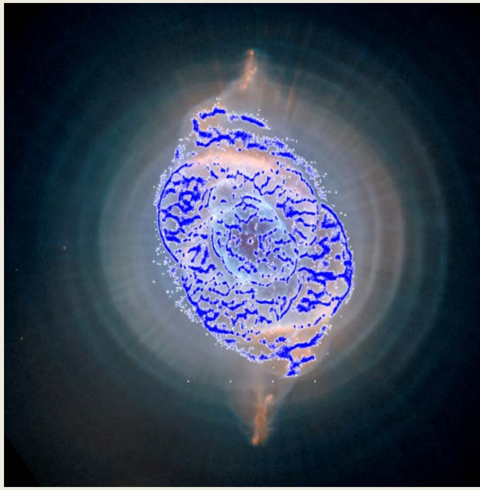
Gaia discovery photometry

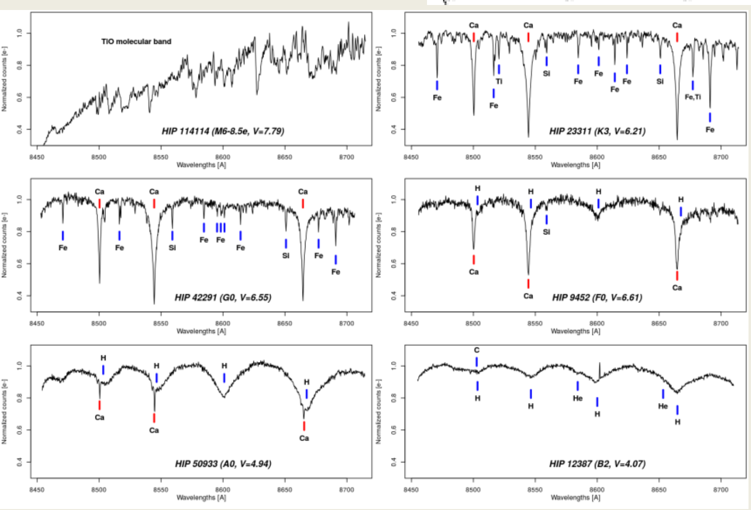


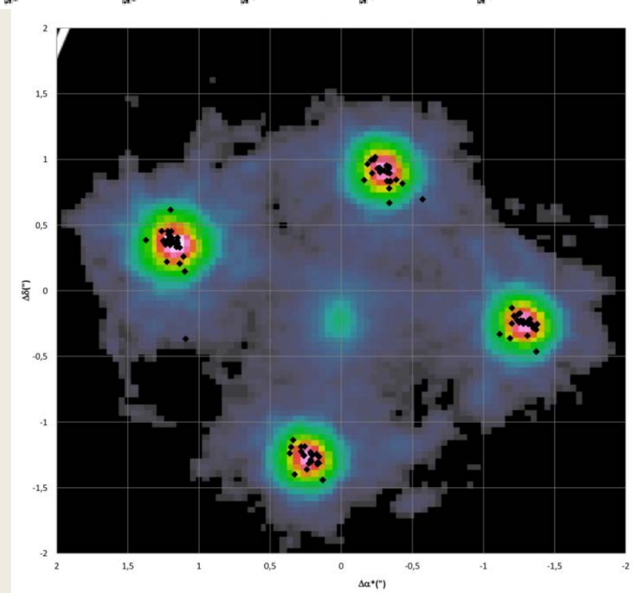
Gaia discovery spectrophotometry



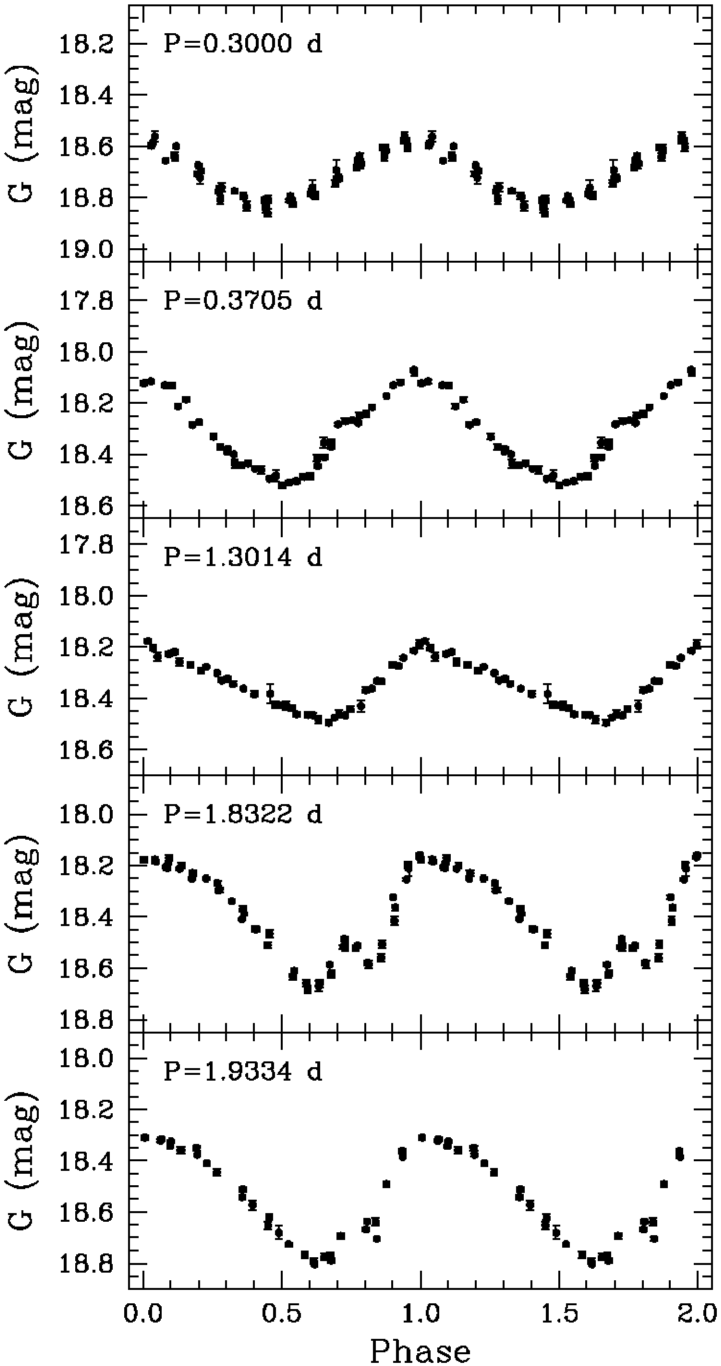


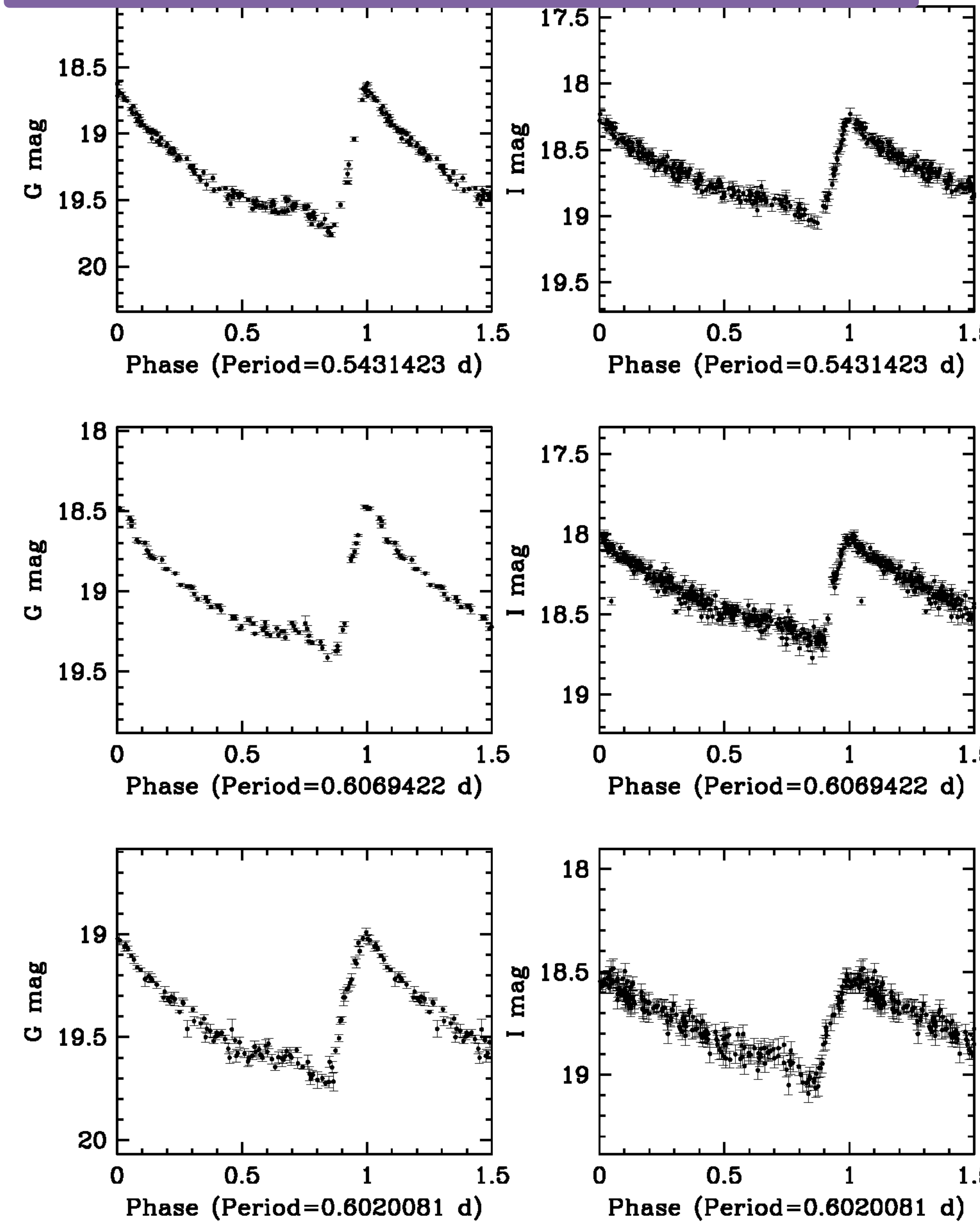






Gaia light curves of LMC Cepheids and RRLyrae





The 1 billion positions

- Probably ~1.5 billion
- Mostly G=12-20
- On average on the ICRS/ICRF system to sub-mas precision.
- But:
  - too few Gaia observations for 5-parameter solutions
  - Bayesian prior that parallax and motions are „small", implying a Galaxy model,
    see Michalik et al 2015, A&A, 583, A68, ArXiV 1507.02963
  - effectively a „reasonable" 2-parameter solution; no pm and parallaxes published

- Thus:
  - typically uncertain by 1-3 mas due to unknown parallax and proper motion
  - perhaps 10 percent with formal uncertainties >15 mas
  - a few unrecognized high proper motions and parallaxes -> outliers
    and of course the usual outliers due to disturbed measurements

- No problem for all applications that I could think of.
  - giant advance over all existing large reference catalogues
  - precision and accuracy quickly deteriorating (few years, both future and past)
  - for the future: to be replaced by Gaia DR2 before this problem can take effect in the future
  - for the past: the time of applicability can be extended by combination with known pm,
    or by direct combination with older known positions

Gaia DR1 Sept 2016

Position alone sufficient to lift the degeneracy

⇒ **Independent** long-baseline proper motions, parallaxes

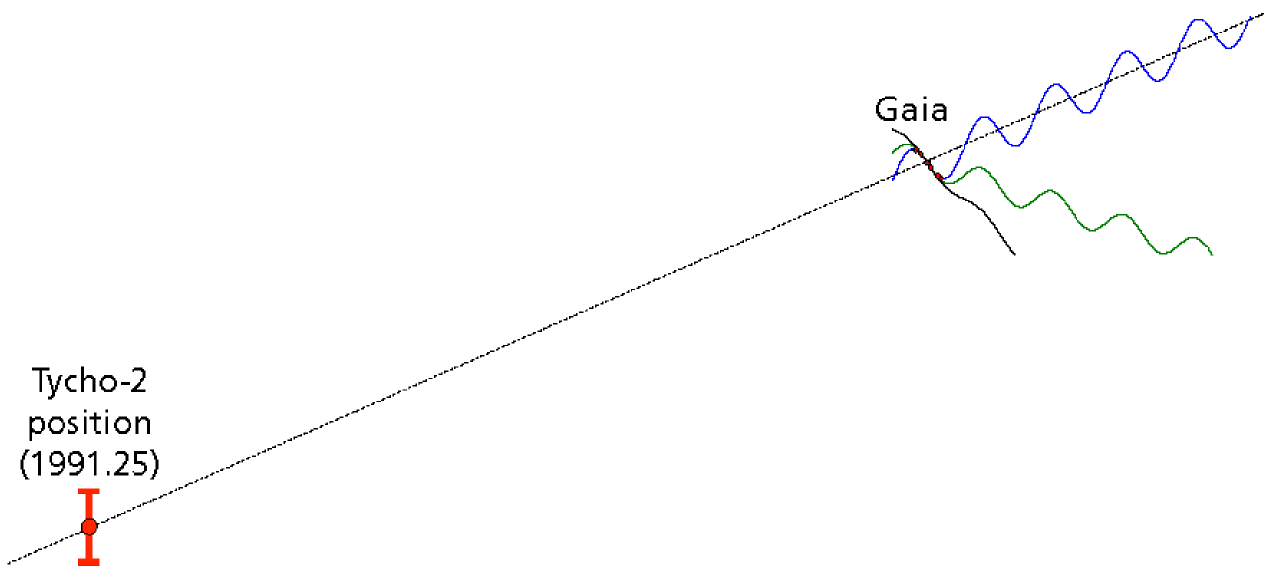


Figure: L. Lindegren & D. Michalik

The 2 million parallaxes and motions

- Too few Gaia observations for 5-parameter solutions

- Solved by combination with Tycho-2 positions
  - genuine 5-parameter solutions
  - valid proper motions and parallaxes
  - but: depending on Tycho-2 (incl. HIP) positions,
    not on Tycho-2 and HIP motions and parallaxes, however.

- Comparisons:
  - Number of objects: 20 times better than HIP
  - Parallaxes typically below 0.5 mas, i.e. better than HIP
  - Motions typically 2 mas/yr, i.e. worse than HIP (but 0.1 mas for HIP stars)
  - Systematic errors: worse than HIP; a number will be given with the release
  - Not yet comparable with expected Gaia performances !
    DR2 will be the first proper Gaia Catalogue
  - Beware of the systematics !

Systematic errors

- Size in DR1 is similar to the individual uncertainties
  - causes:
    - colour terms, PSF time variations, basic-angle oscillations
    - clanks
    - dependence on Tycho-2
    - ...
- Averages over many stars will not be (much) better than the numbers for a single star
- Clusters, absolute brightness of standard candles, ...
- Recipe:
  - quadratically add a systematic uncertainty after averaging
  better:
  - give separate random and systematic uncertainties
- **ACCURACY FLOOR in DR1 = 0.3mas**

The inverse of a parallax ...

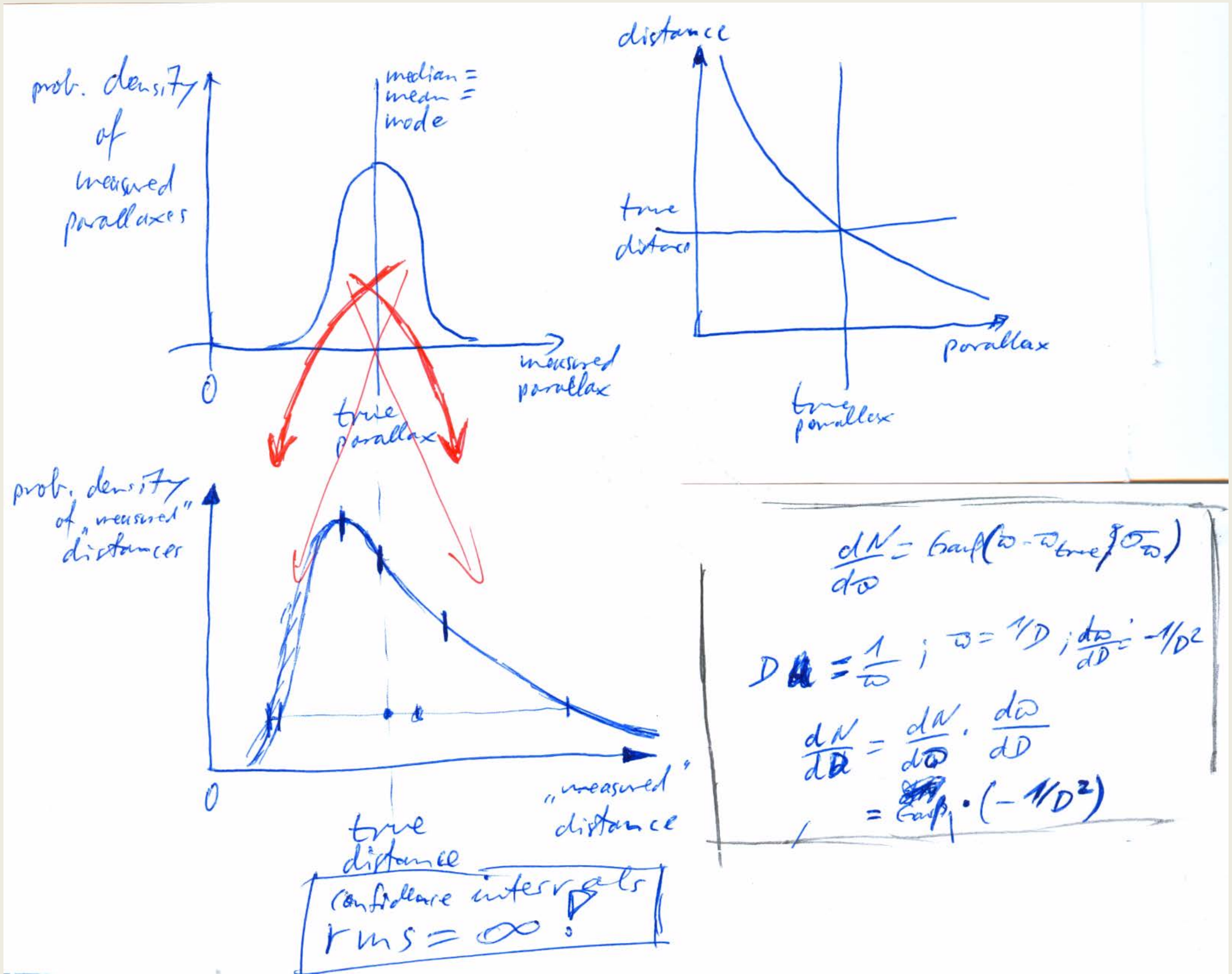
- Mean, median, mode, rms of a trigonometric distance
  - Consider a given true parallax p
  - Distance D=1/p (see next page)
- Recipe to avoid scientific trouble:
  - Always use forward modelling to measured parallaxes to fit higher-level unknown quantities
  - In other words: Do not use derived quantities like individual distances or absolute magnitudes to fit higher-level unknown quantities

The inverse of a parallax ...

- „Estimating distance from parallax“,
  C. Bailer-Jones, EWASS 2016 & PASP, Oct 2015

- Various Bayesian priors giving realistic means and variances - for various circumstances

The inverse of a parallax ...



During this presentation

- about 1 million stars were measured by Gaia,

- roughly 10 million astrometric measurements were taken,

- about 300,000 spectra were made of 100,000 stars

DR1 – September14 2016

Verification of TGAS parallaxes through quasars

Are BAM measurements real? (Michalik & Lindegren 2016)

But: Independent quasar solution in TGAS not possible

1. Add prior for quasars: Assuming zero proper motion
2. Compare resulting parallaxes to zero (BAM expectation: 871.9 μas)

Demonstrated in simulations

Subset	Median [μas]
with spurious proper motions	
Stars	872.0 ± 0.2
Quasars	877.7 ± 3.4
with 5% contamination	
Stars	872.0 ± 0.2
Quasars	872.0 ± 2.4

Table: excerpt from Michalik & Lindegren 2016, Table 1

Tycho-Gaia and beyond // D. Michalik (Lund University) // 4 Apr 2016 23/24