Gaia

Stereoscopic Census of our Galaxy

http://gaia.ac.uk

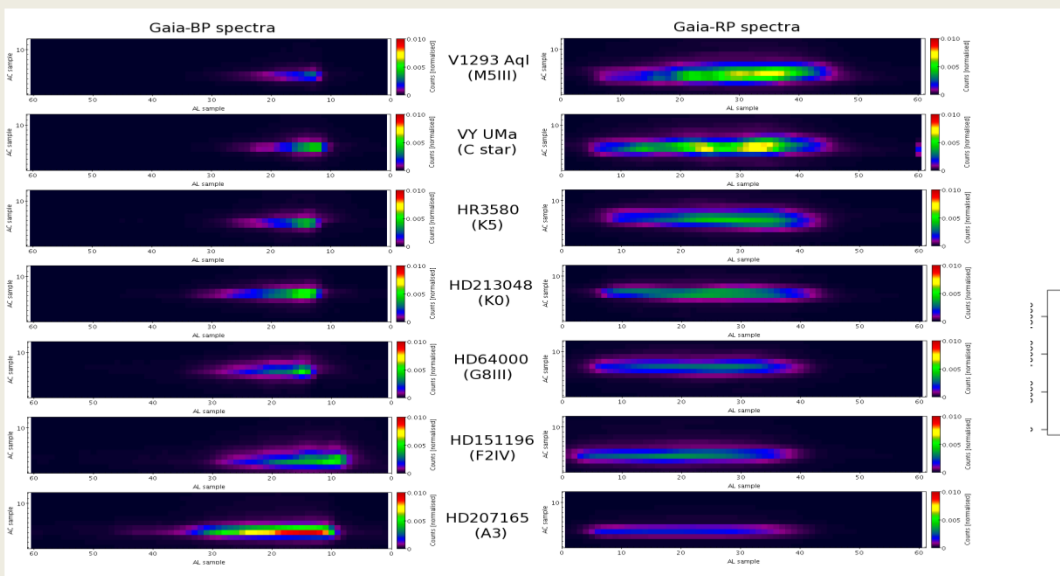
one billion pixels for one billion stars [& euro]

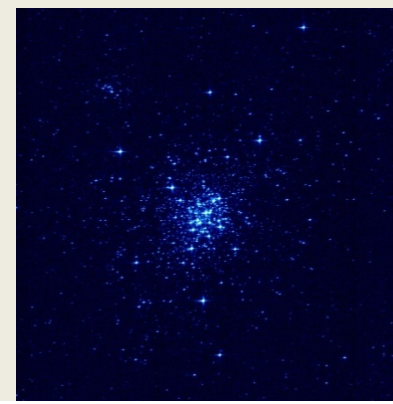
one percent of the visible Milky Way

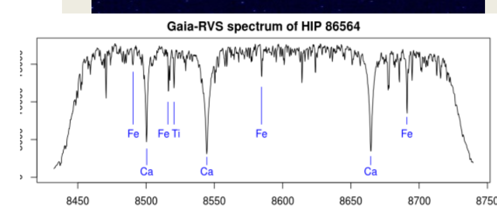
http://blogs.esa.int/gaia/

Gerry Gilmore

Institute of astronomy, Cambridge; UK Gaia PI

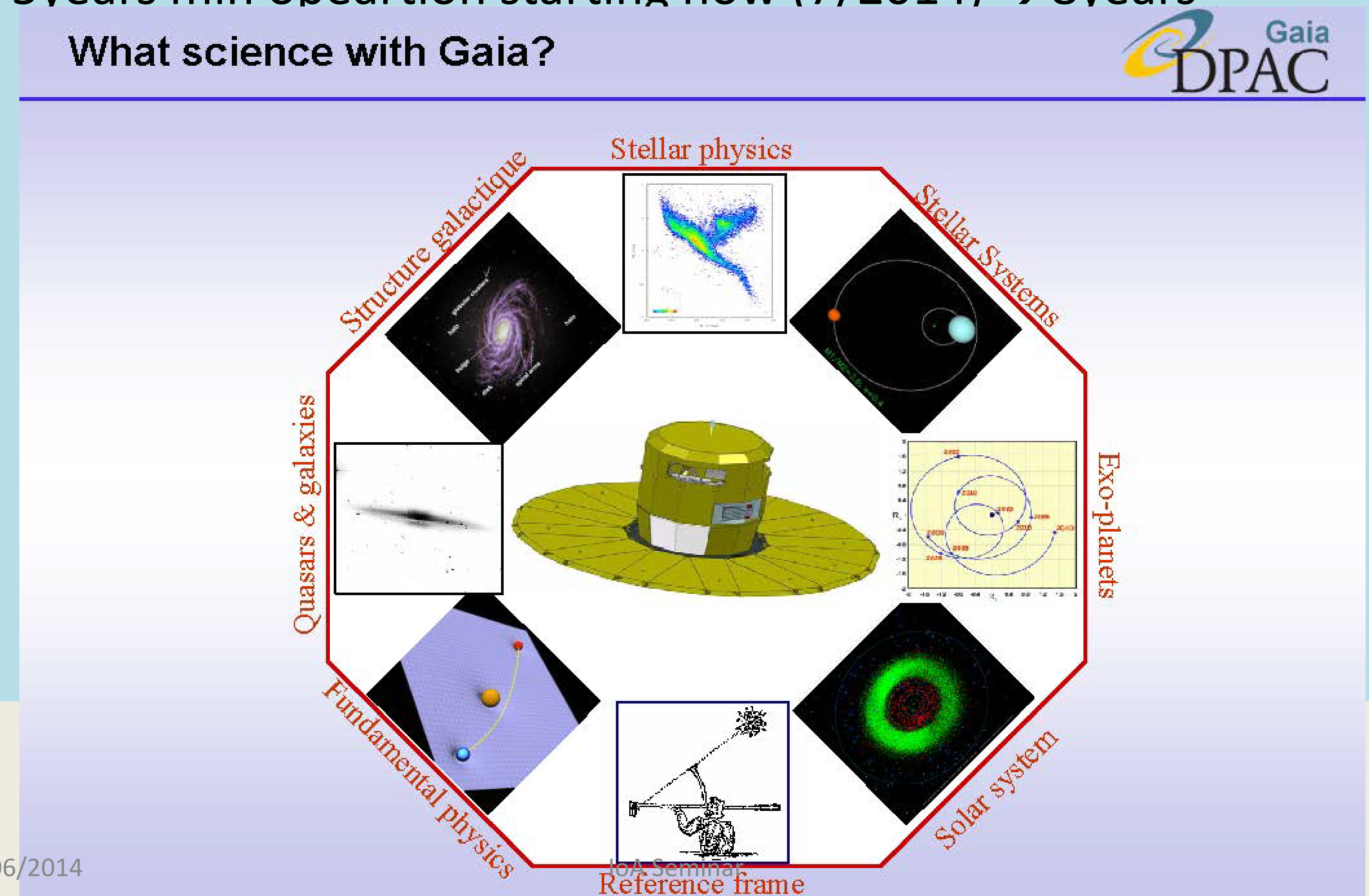






What is Gaia?

- A major ESA mission (cornerstone): the first all-sky, faint, precision, astrometry survey. Complete for 10^9 stars G<20, 5years min opeartion starting now (7/2014) →8years



GAIA: Key Science Objectives

⇒ Origin, Formation and Evolution of the Galaxy

Structure and kinematics of our Galaxy:

- shape and rotation of bulge, disk and halo
- internal motions of star forming regions, clusters, etc
- nature of spiral arms and the stellar warp
- space motions of all Galactic satellite systems

Stellar populations:

- physical characteristics of all Galactic components
- initial mass function, binaries, chemical evolution
- star formation histories

Tests of galaxy formation:

- **dynamical determination of dark matter distribution**
- reconstruction of merger and accretion history

Calibrate the distance scale using all types of tracers:

- cepheids, RR Lyrae, T-RGB, ….: test DF and zero points
- SN1a overlap regime with many 1000s of Cepheid distances possible

data support revolutionary science from solar system to cosmology, planets, fundamental physics…

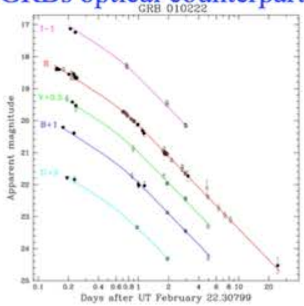
Gaia science: General Relativity/Metric/…

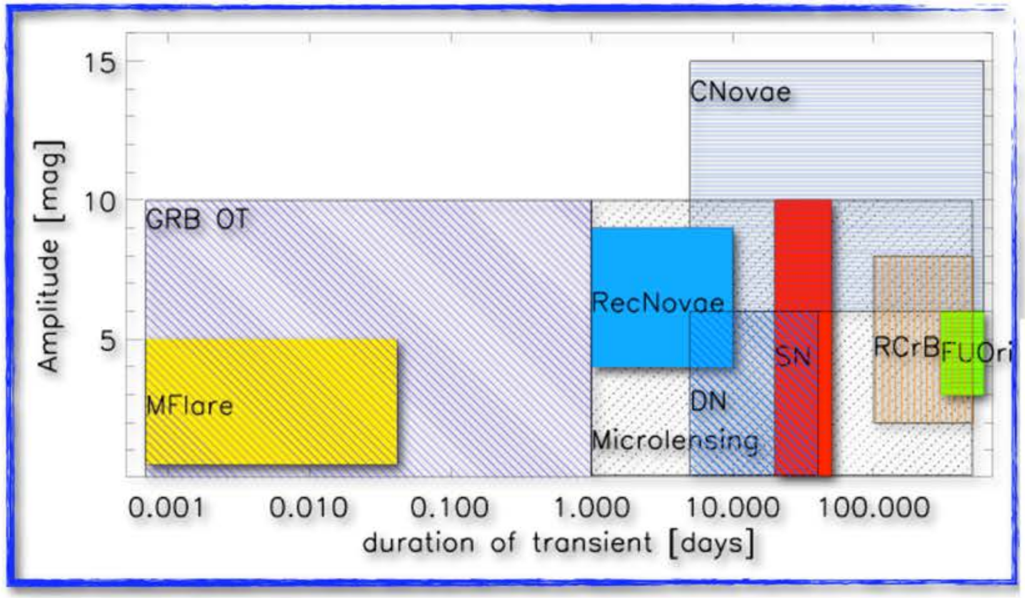
- From positional displacements:
  - γ to 5×10^{-7} (cf. 10^{-5} presently) $\Rightarrow$ scalar-tensor theories
  - effect of Sun: 4 mas at 90^{o}; Jovian limb: 17 mas; Earth: ~40 μas
- From perihelion precession of minor planets:
  - β to 3×10^{-4} - 3×10^{-5} ($\times$10-100 better than lunar laser 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)
- 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 (fewx100?)
- Galactocentric acceleration: 0.2 nm/s^2 $\Rightarrow$ Δ(aberration) = 4 μas/yr

Light-bending: 1."75 at solar rim, 1,750,000 microarcsec
Gaia will extend the Eddington test using Jupiter

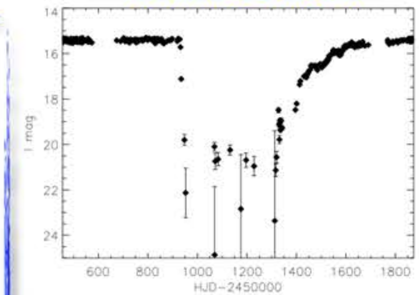
Gaia will also observe the transient sky

GRBs optical counterparts

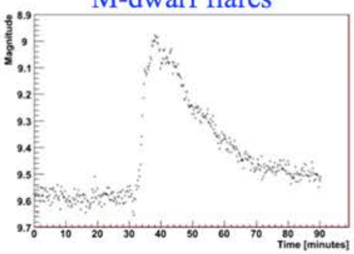




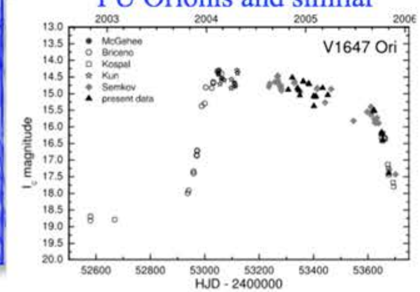
R Coronae Borealis



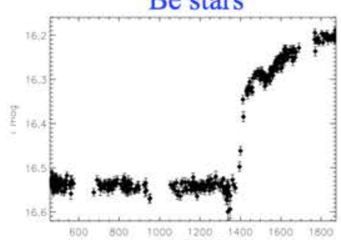
M-dwarf flares



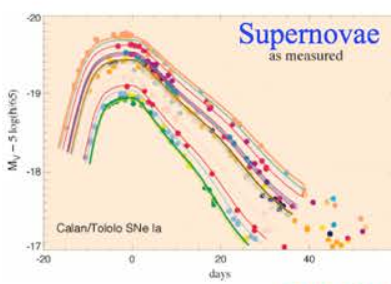
FU Orionis and similar

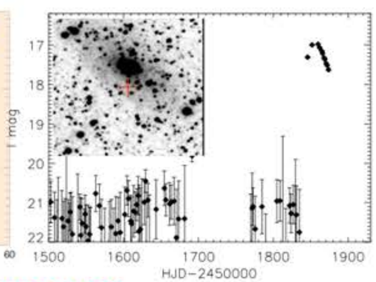


Be stars

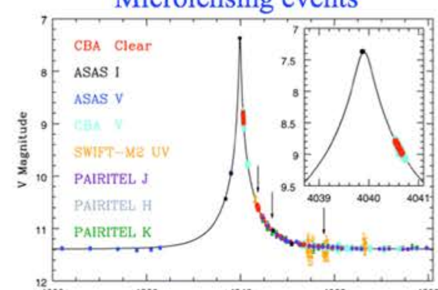


Supernovae
as measured

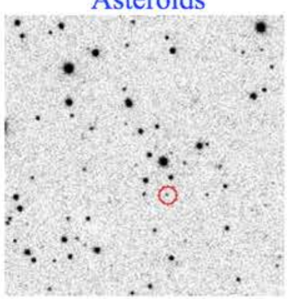




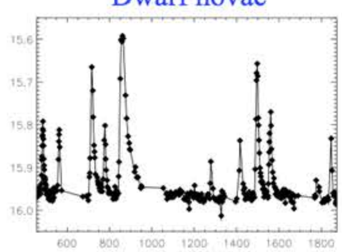
Microlensing events



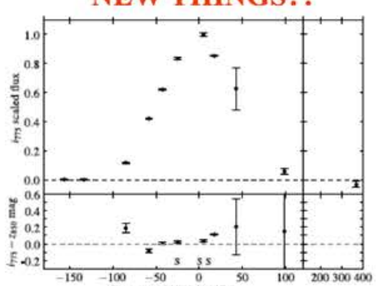
Asteroids



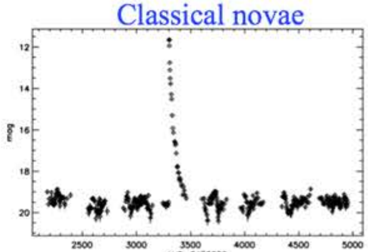
Dwarf novae



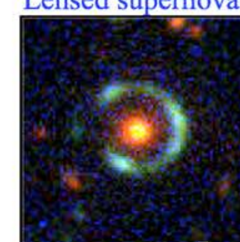
NEW THINGS??



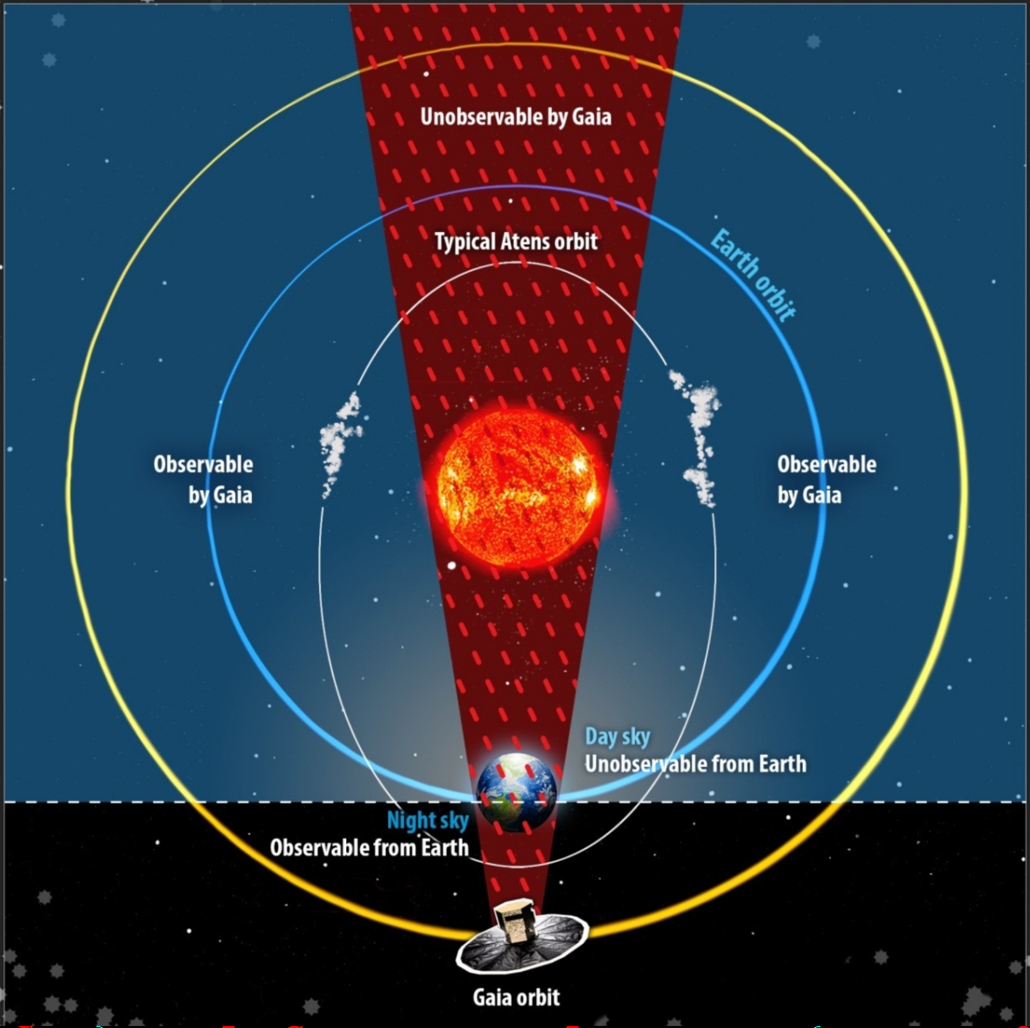
Classical novae



Lensed supernovae



GAIA is a Nemesis survey



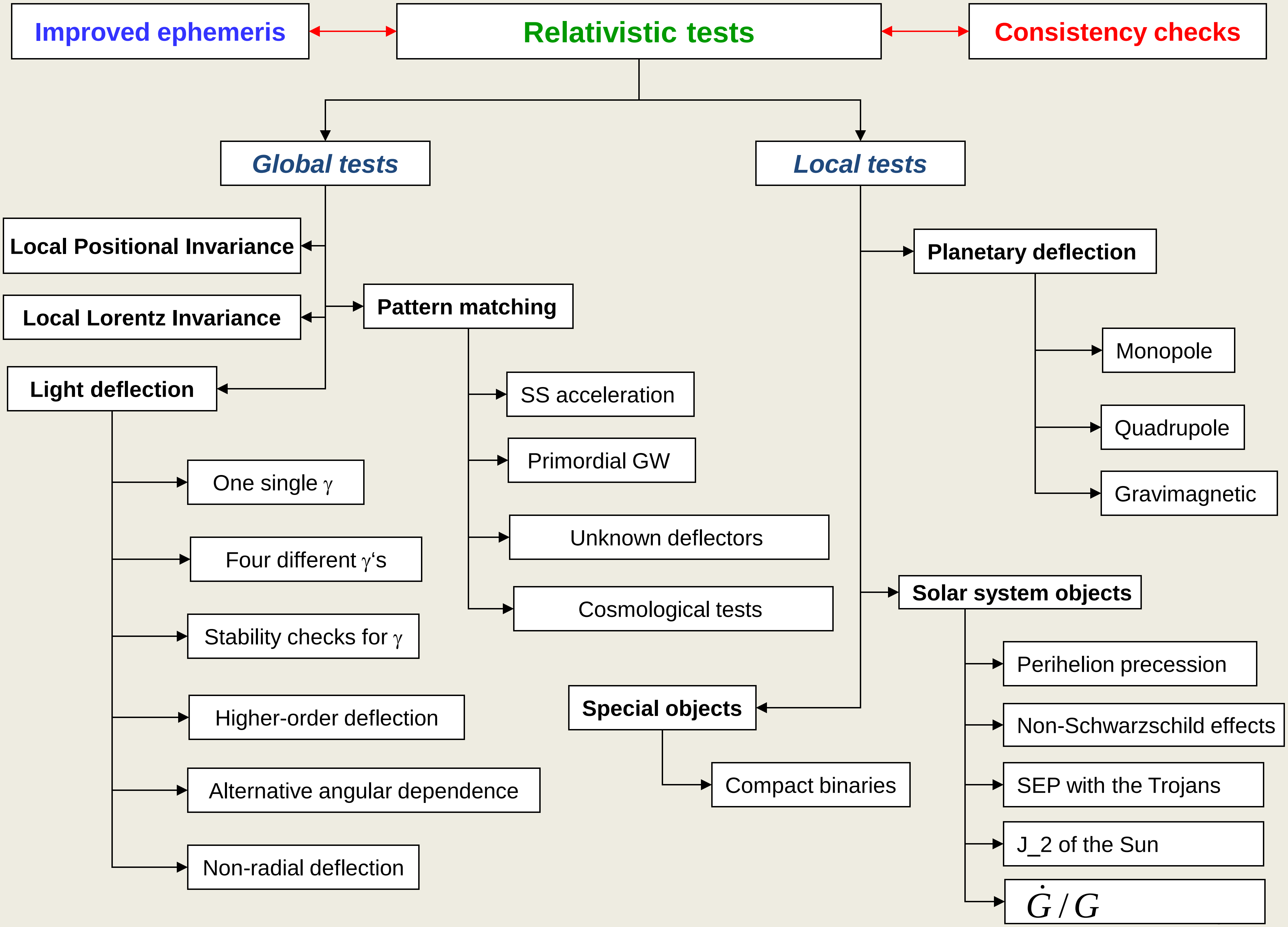
What’s the science? Part 1

- Proper motions of 20 muas/a: (V=15)

  - (M_V=+10) 20 muas/a = 10 m/s at 100 pc, i.e. planets can be found at half a million stars (Jupiter moves the sun by 15m/s)
  - (M_V=0) 20 muas/a = 1 km/s at 10 kpc, i.e. even the lowest-velocity stellar populations can be kinematically studied throughout the entire galaxy
  - (M_V=-3.5) 20 muas/a = 5 km/s at 50 kpc, i.e. the internal kinematics of the Magellanic clouds can be studied in as much detail as the solar neighbourhood can be now (5 km/s = 2.5 mas/a at 400 pc!)
  - (M_V=-10) 20 muas/a = 100 km/s at 1 Mpc, i.e. a handful of very luminous stars in M31 will show the galaxy’s rotation

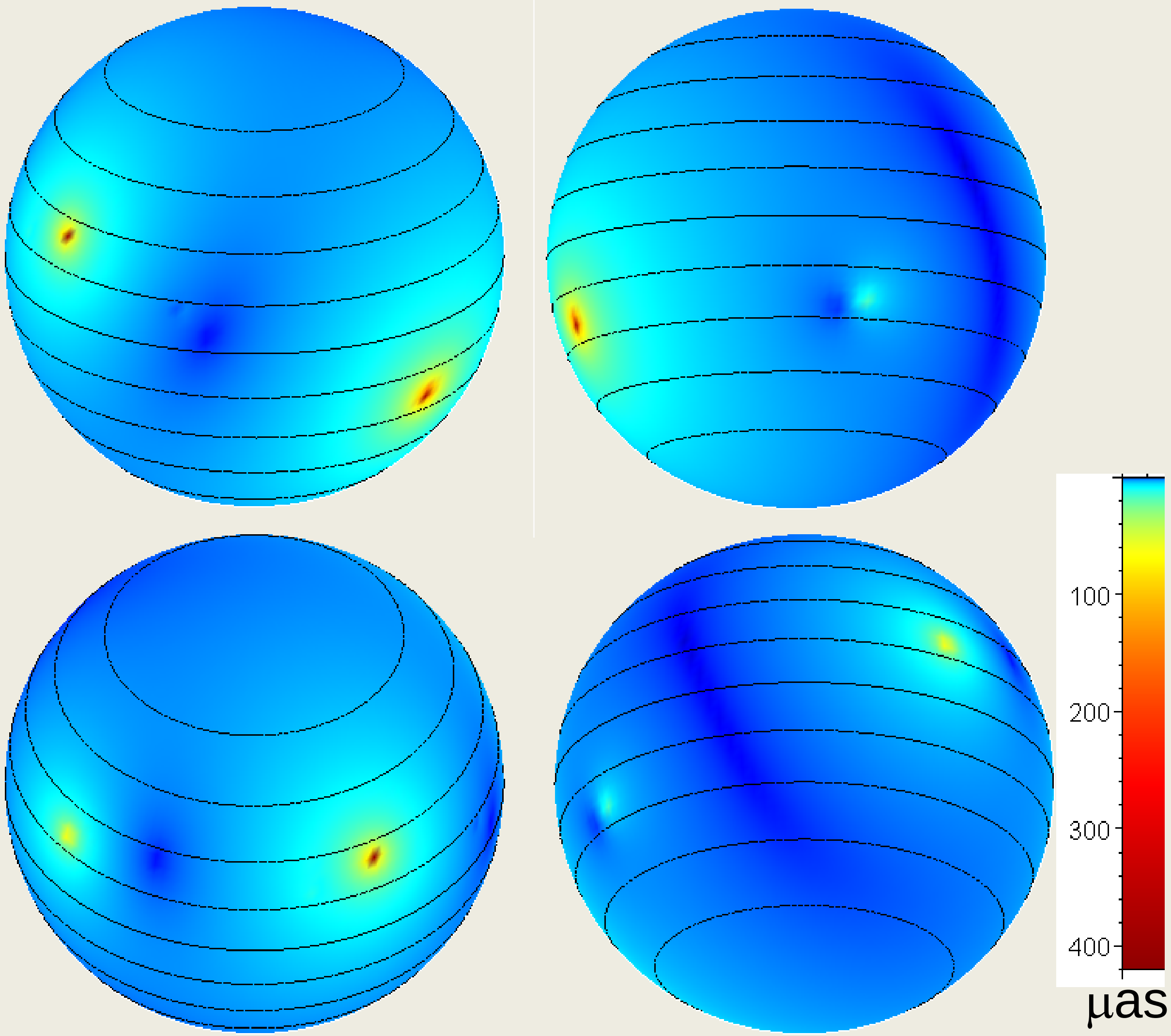
What's the science? Part 2

- Parallaxes of 20 muas: (V=15)
  - 20 muas = 1 percent at 0.5 kpc, i.e. 6-dimensional structure of the Orion complex at 2pc depth resolution
  - 20 muas = 10 percent at 5 kpc, i.e. direct high-precision distance determination of even very small stellar groups throughout most of the Galaxy
  - 20 muas = 100 percent at 50 kpc, i.e. a direct distance determination of the Magellanic clouds is at the edge
- Linear sizes of 20 muas: (V=15)
  - 20 muas = 1 solar diameter at 0.5 kpc, i.e. normal sunspots just do not disturb the measurements,
but Jupiters do!
  - 20 muas = 1 aU at 50 kpc, the limit of parallax measurements


Improved ephemeris
Relativistic tests
Consistency checks
Global tests
Local tests
Local Positional Invariance
Local Lorentz Invariance
Pattern matching
Light deflection
SS acceleration
Primordial GW
Unknown deflectors
Cosmological tests
One single γ
Four different γ's
Stability checks for γ
Higher-order deflection
Alternative angular dependence
Non-radial deflection
Planetary deflection
Monopole
Quadrupole
Gravimagnetic
Solar system objects
Perihelion precession
Non-Schwarzschild effects
SEP with the Trojans
J_2 of the Sun
$\dot{G}/G$
Special objects
Compact binaries

Monopole gravitational light deflection

- Monopole light deflection: distribution over the sky on 25.01.2006 at 16:45 equatorial coordinates

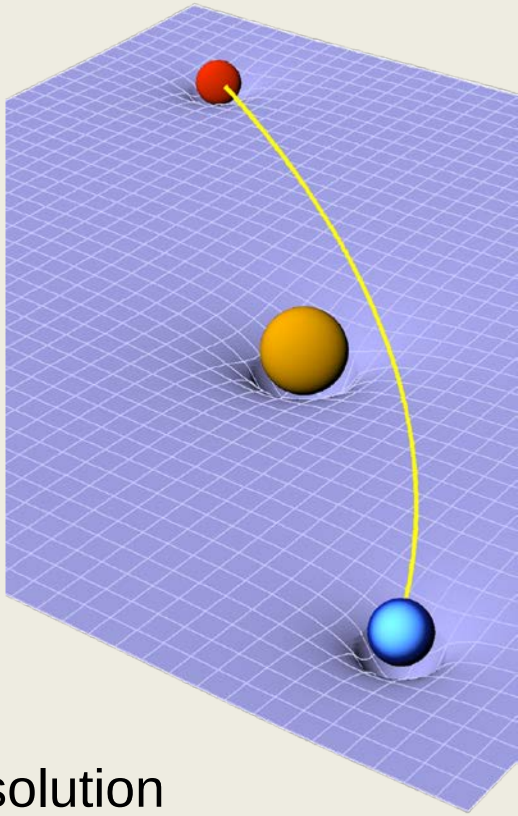


body	(µas)	>1µas
Sun	1.75″	180 °
Mercury	83	9 ′
Venus	493	4.5 °
Earth	574	125 °
Moon	26	5 °
Mars	116	25 ′
Jupiter	16270	90 °
Saturn	5780	17 °
Uranus	2080	71 ′
Neptune	2533	51 ′

PPN γ from light deflection

- Most precise test possible with Gaia

$$\sigma_\gamma > 10^{-6}$$



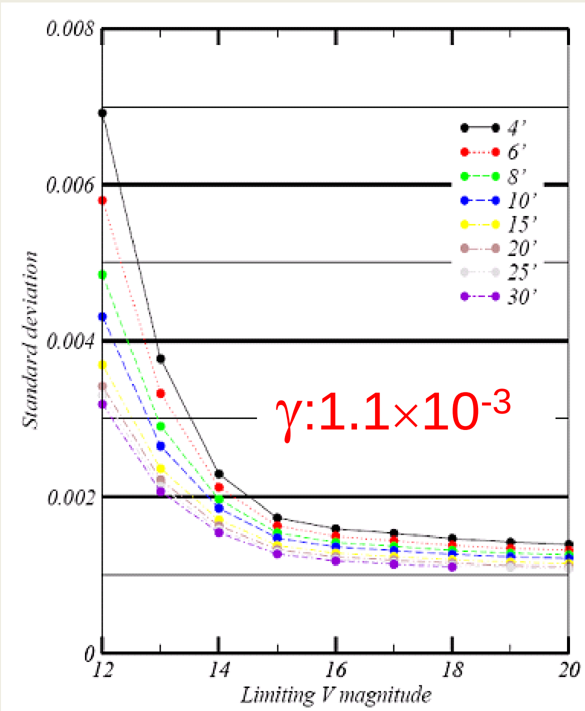
- Properties of the Gaia measurements
  - optical,
  - deflection (not Shapiro),
  - wide range of angular distances,
  - full-scale simulations of the experiments

- Problems with some of the „current best estimates“ of γ

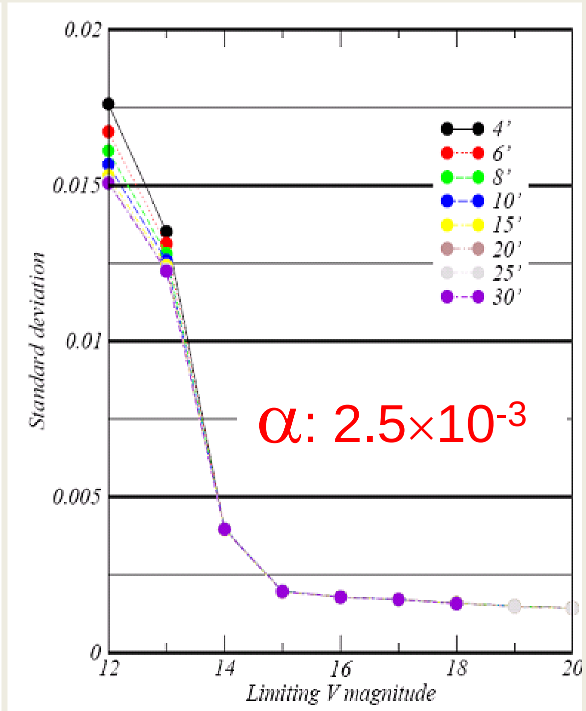
1. special fits of the post-fit residuals of a standard solution (e.g., missed correlations leads to wrong estimates of the uncertainty);
2. no special simulations with faked data to check what kind of effects we are really sensitive to

Light deflection from the planets

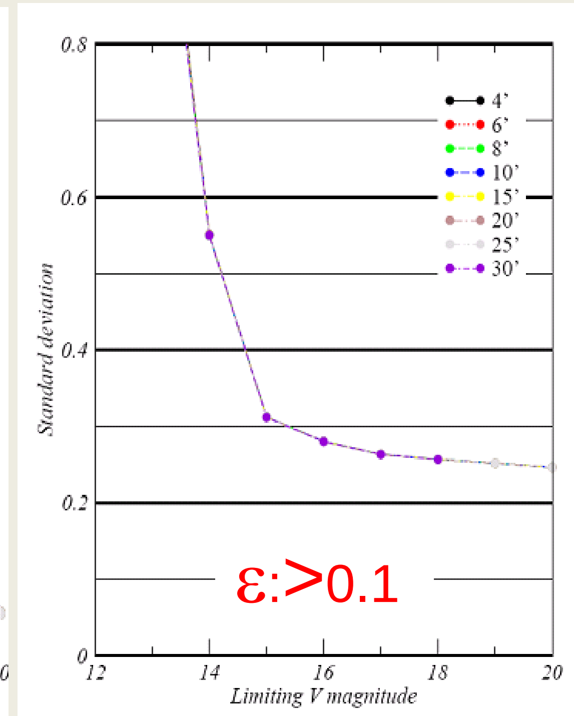
Jupiter: monopole



gradient-gravitomagnetic



quadrupole



Anglada-Escudé, Klioner, Torra, 2006
Crosta, Mignard, 2006

For other planets the results are worse: 0.1-0.007 for the monopole

Problem: rings, dust, gas, etc. in the vicinity of the giant planets

Relativistic effects with asteroids

Schwarzschild effects due to the Sun: perihelion precession
Preliminary results with limited number of sources and with perihelion only:

$$\sigma_\beta < 10^{-3}$$

$$\sigma_{J_2} < 10^{-7}$$

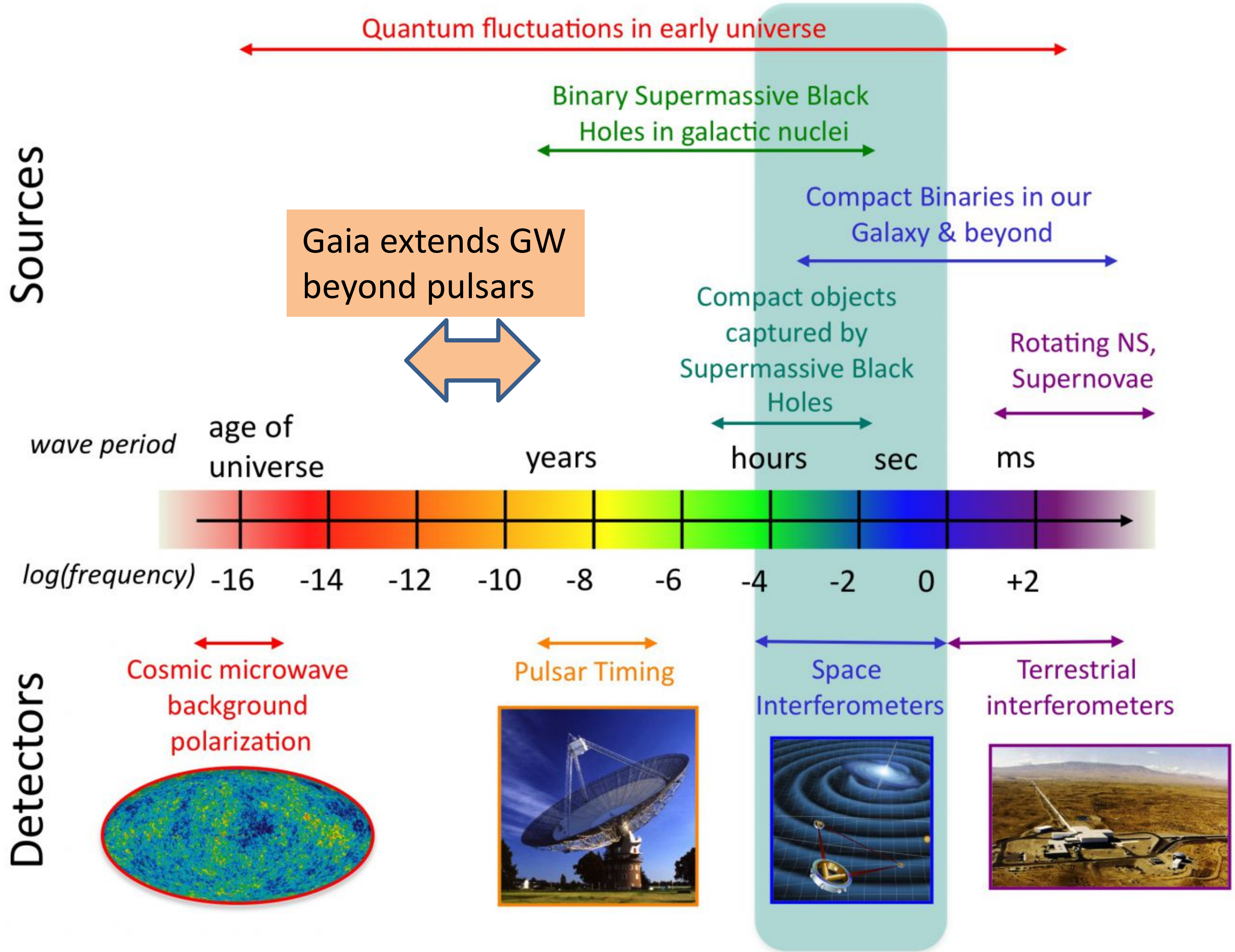
$$\sigma_{\dot{G}/G} < 5\times 10^{-13}\ \mathrm{yr}^{-1}$$

Non-Schwarzschild (3-body) effects: related to the tests of the Strong Equivalence Principle

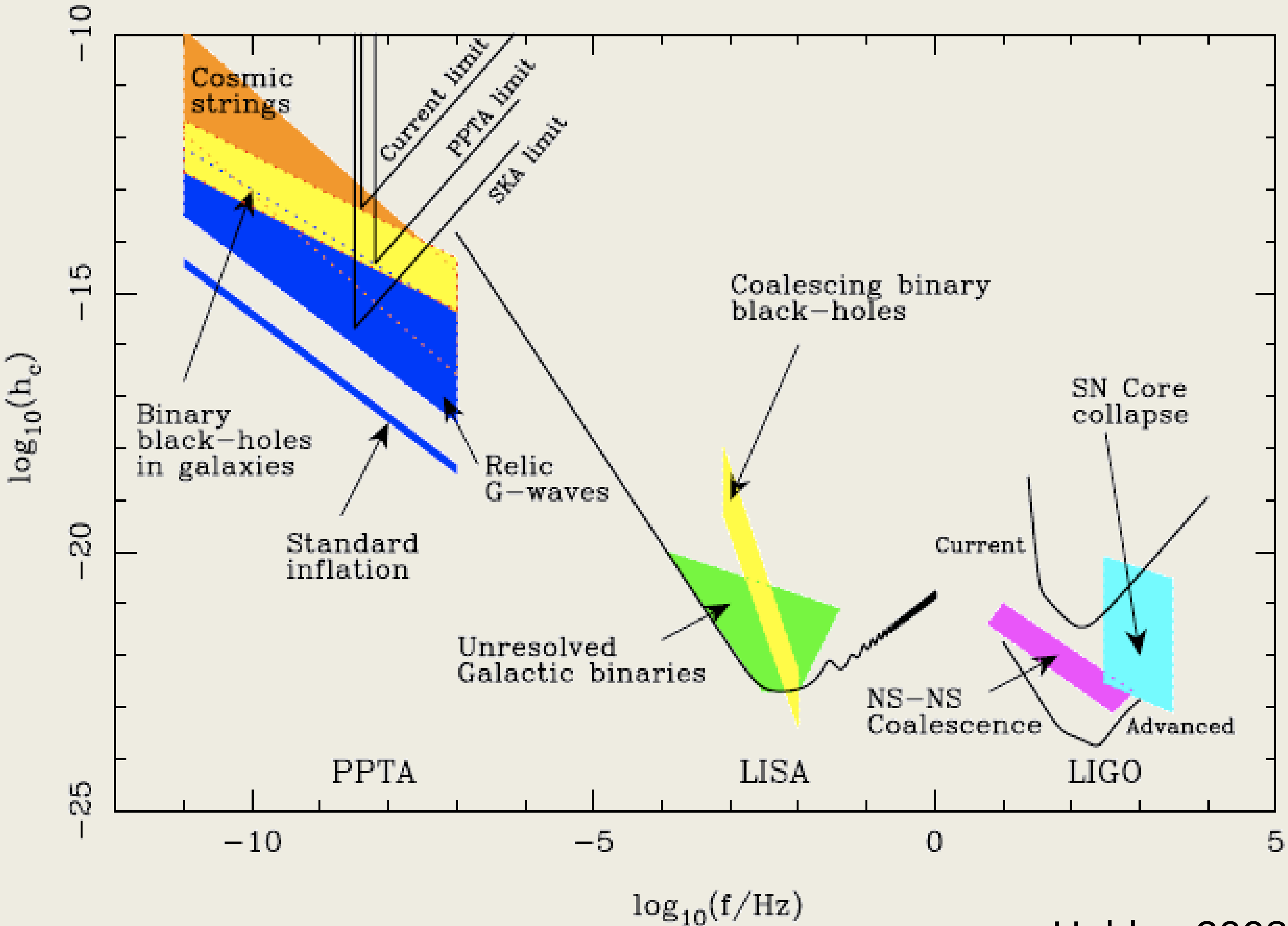
test non-standard combinations of the PPN β and γ

e.g. $\eta = 4\gamma - \beta - 3$

The Gravitational Wave Spectrum



Gravitational Wave Spectrum



Hobbs, 2008

Pattern matching in positions/proper motions

II. Constraint on very low frequency gravitational waves:

- constraint of stochastic GW flux with $\nu < 3 \times 10^{-9}$ Hz
  (similar study done for VLBI: Gwinn et al., ApJ, 1997)

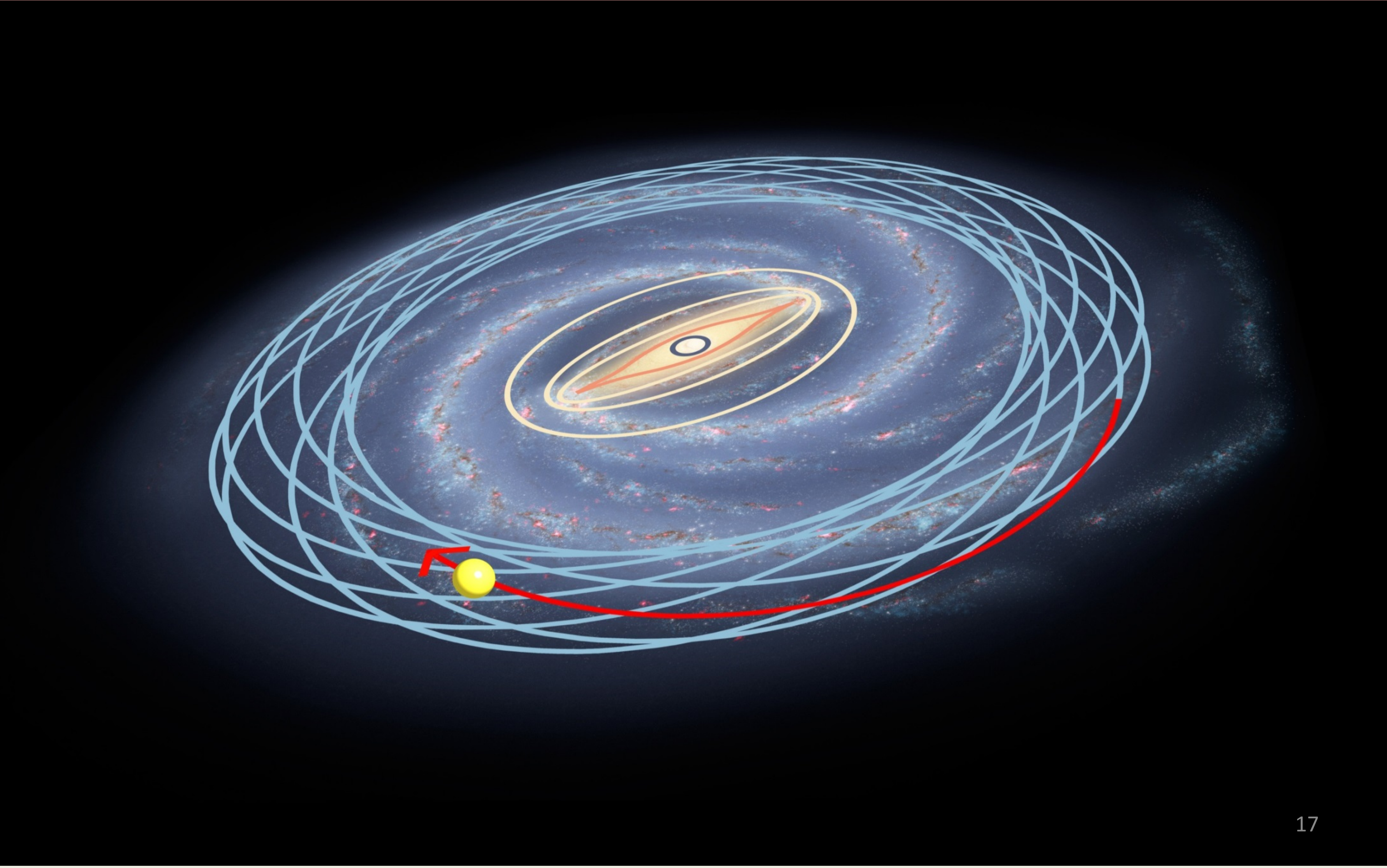
- attempts to fit a pattern of apparent motions induced by an individual GW with $\nu < 1.3 \times 10^{-7}$ Hz
  (matched filtering can be used, synergy with LISA & ground based)

The harmonic coefficients for n>1 give the GW-flux constraints

From Gaia for $\nu < 3 \times 10^{-9}$ Hz (95% confidence; preliminary analysis):

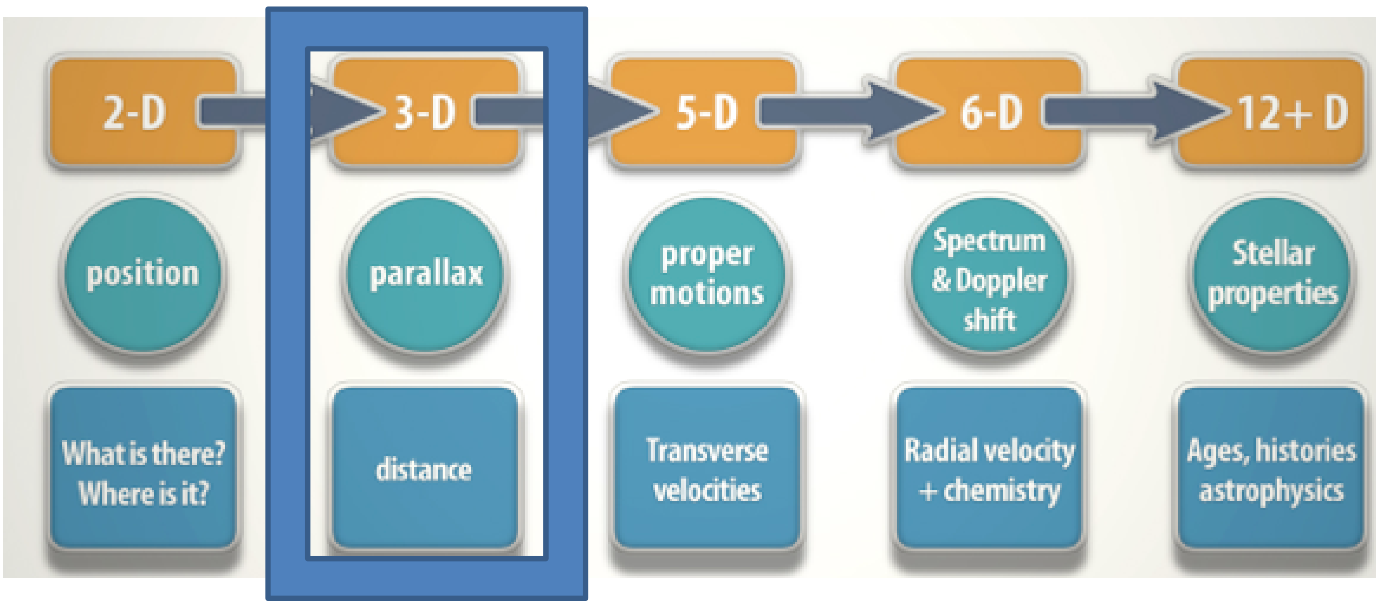
$$h^2 \Omega_{GW} < 0.001 \div 0.005$$

A galaxy is a gravitational potential which supports orbits. Stars occupy orbits, and are fossils, retaining memory of the history of chemical evolution prior to their formation. With astrometry, to provide orbits, chemistry to probe history, we deliver Galactic archaeology. And very much more: streams, accretion, dark matter potential, GR, killer asteroids, …



How does one study the Milky Way?

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

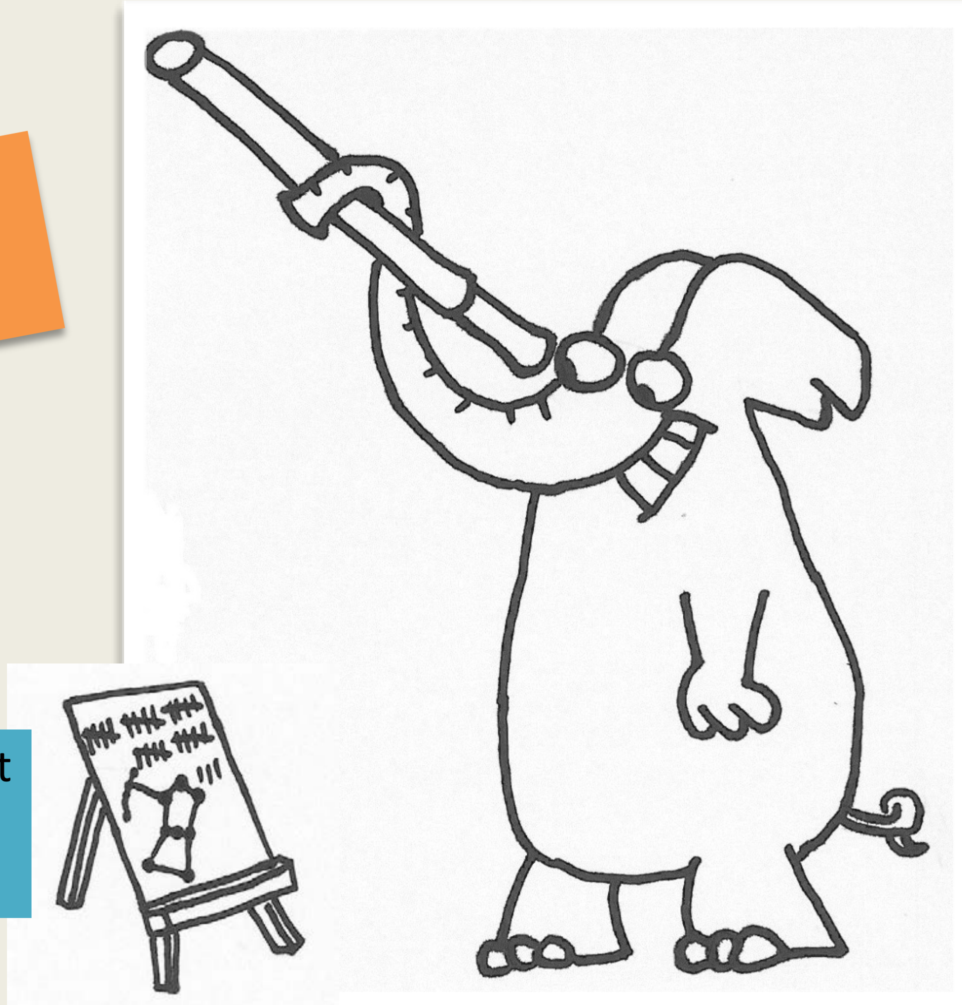


Stellar orbits, star formation history, origin of the elements, Galaxy assembly, dark matter, cosmological initial conditions, fundamental physics, solar system(s), …

There is an elephant in the astrophysics room:
all distances depend on too few, inaccurate, stellar parallaxes

The distance scale
is the weak link
in modern astrophysics

I gave my friend an elephant
He said: “thanks”
I said: “don’t mention it”

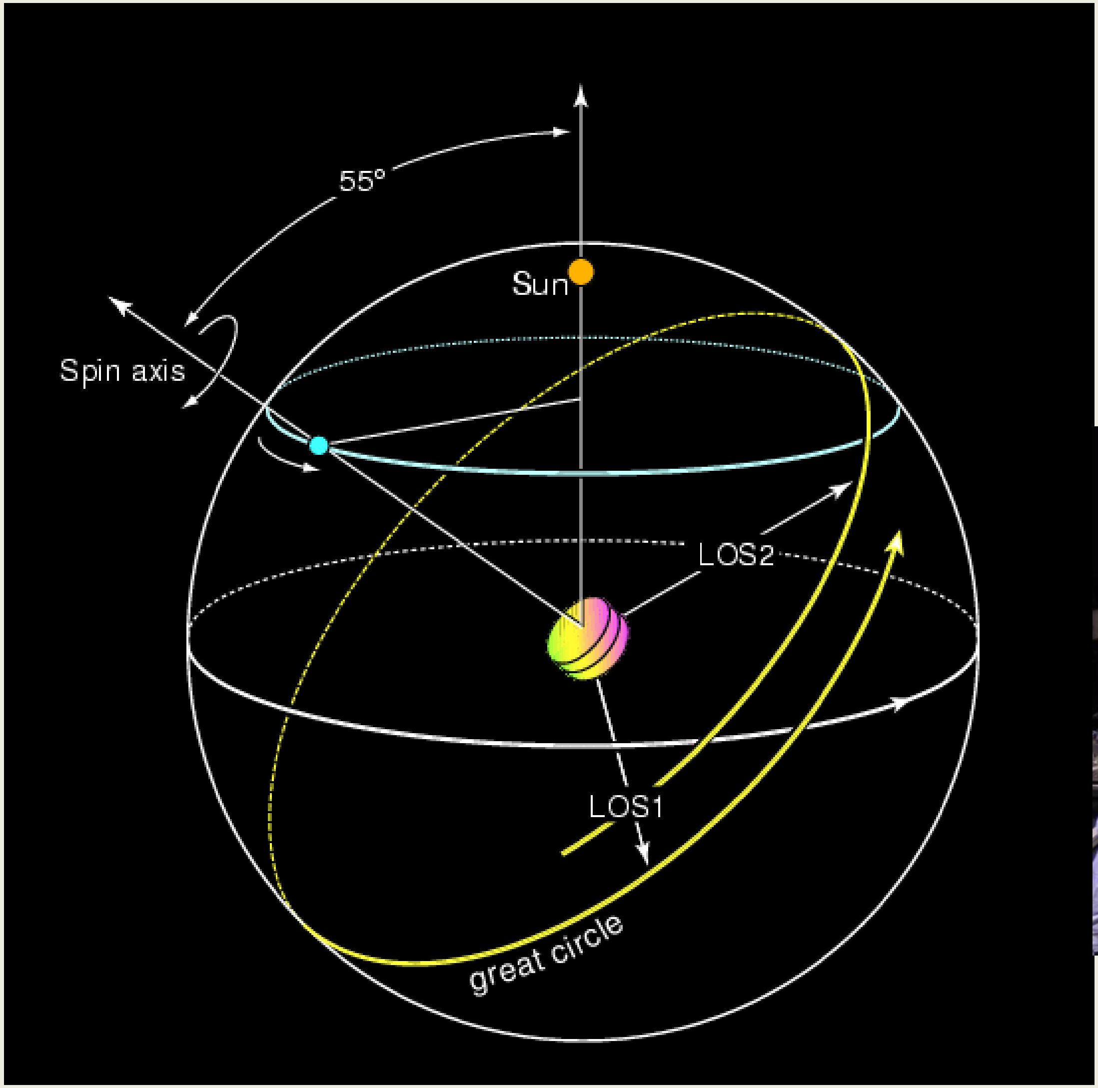


Thanks to Ian for the elephant

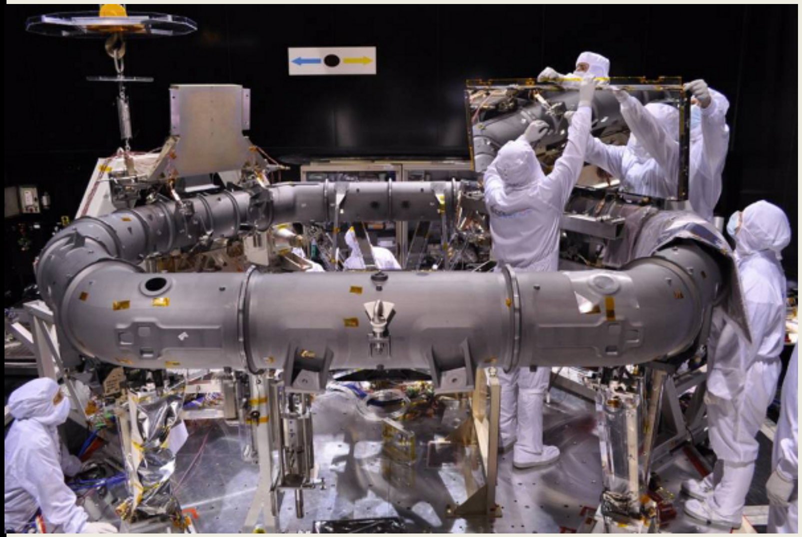
Luminosity calibrations with Hipparcos and Gaia

	Hipparcos	Hipparcos 2	Gaia
σ_π/π < 0.1 %	-	-	100 000 ★
σ_π/π < 1 %	442 ★	719 ★	~ 11 x 10^6 ★ up to 5-10 kpc (Mv<-5) up to 1-2 kpc (Mv<5)
σ_π/π < 10 %	22 396 ★	30 579 ★	~ 150 x 10^6 ★ up to 30-50 kpc (Mv<-5) 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

How does Gaia work?: Sky Scanning Principle

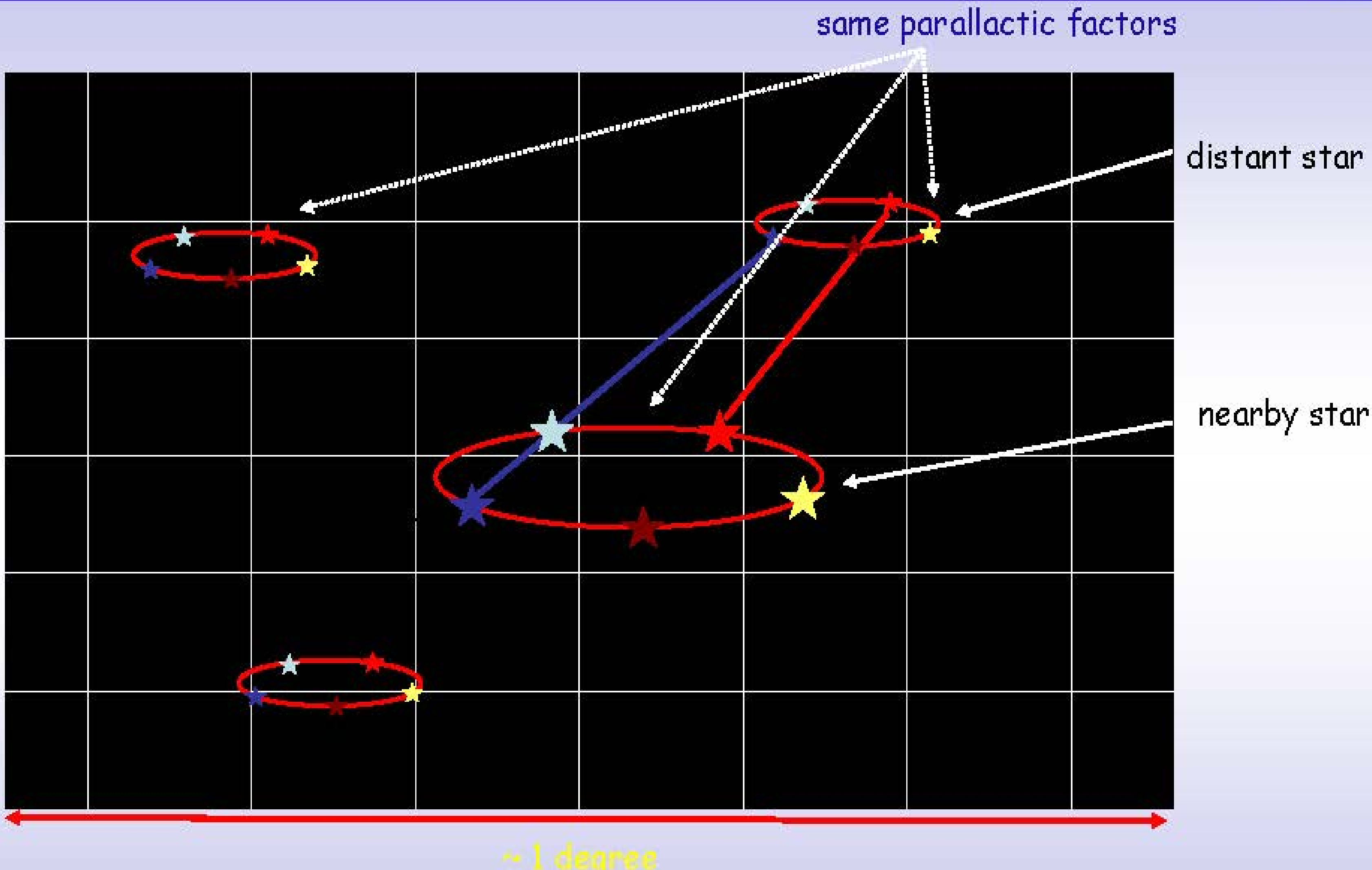


Observe sky with two telescopes
Measure relative positions of stars
Scan to measure every star
Solve to all-sky relative positions



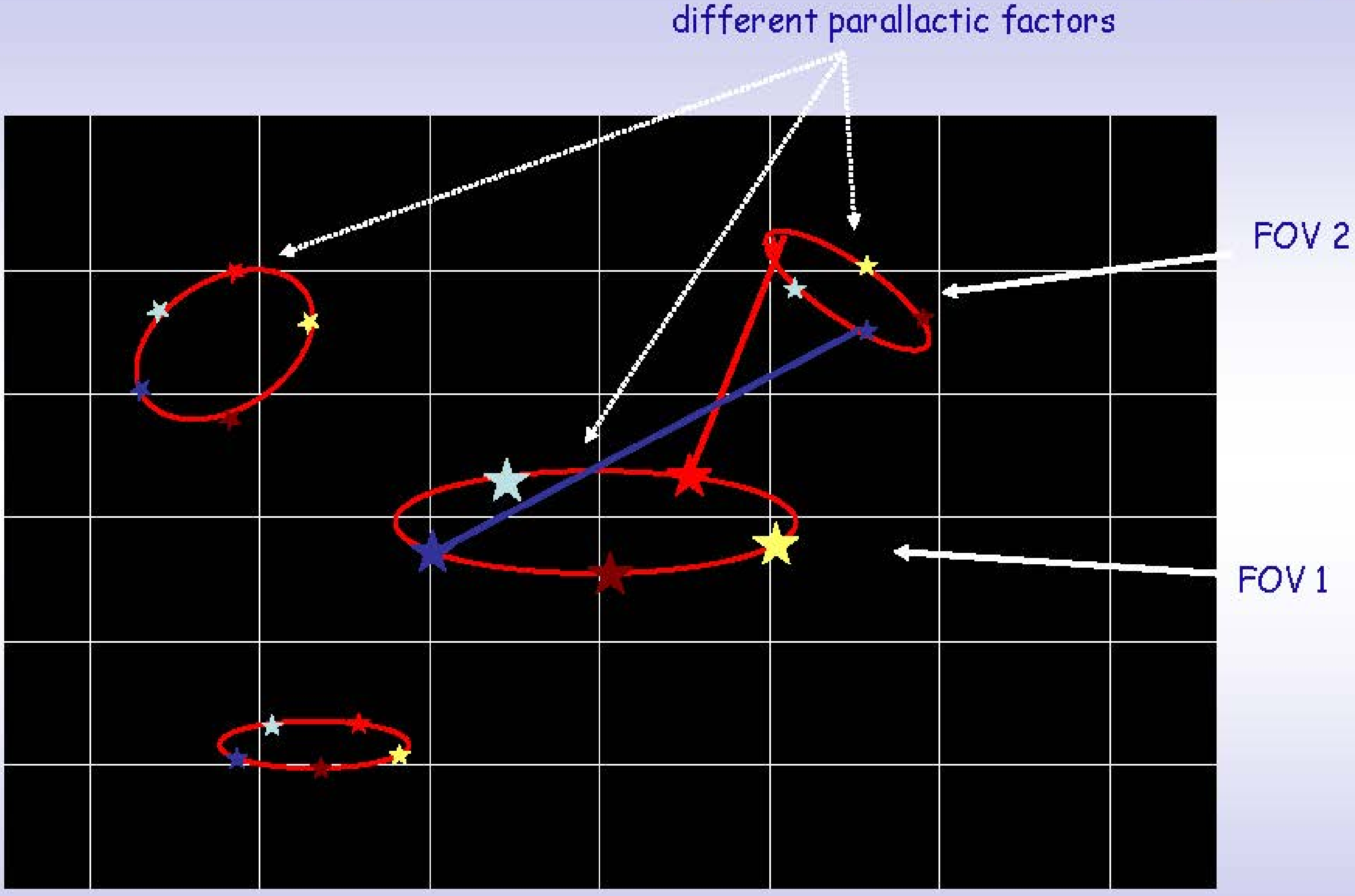
Precision: 50pico-rad, human hair at 1000km, 2cm on the moon...

Small field astrometry

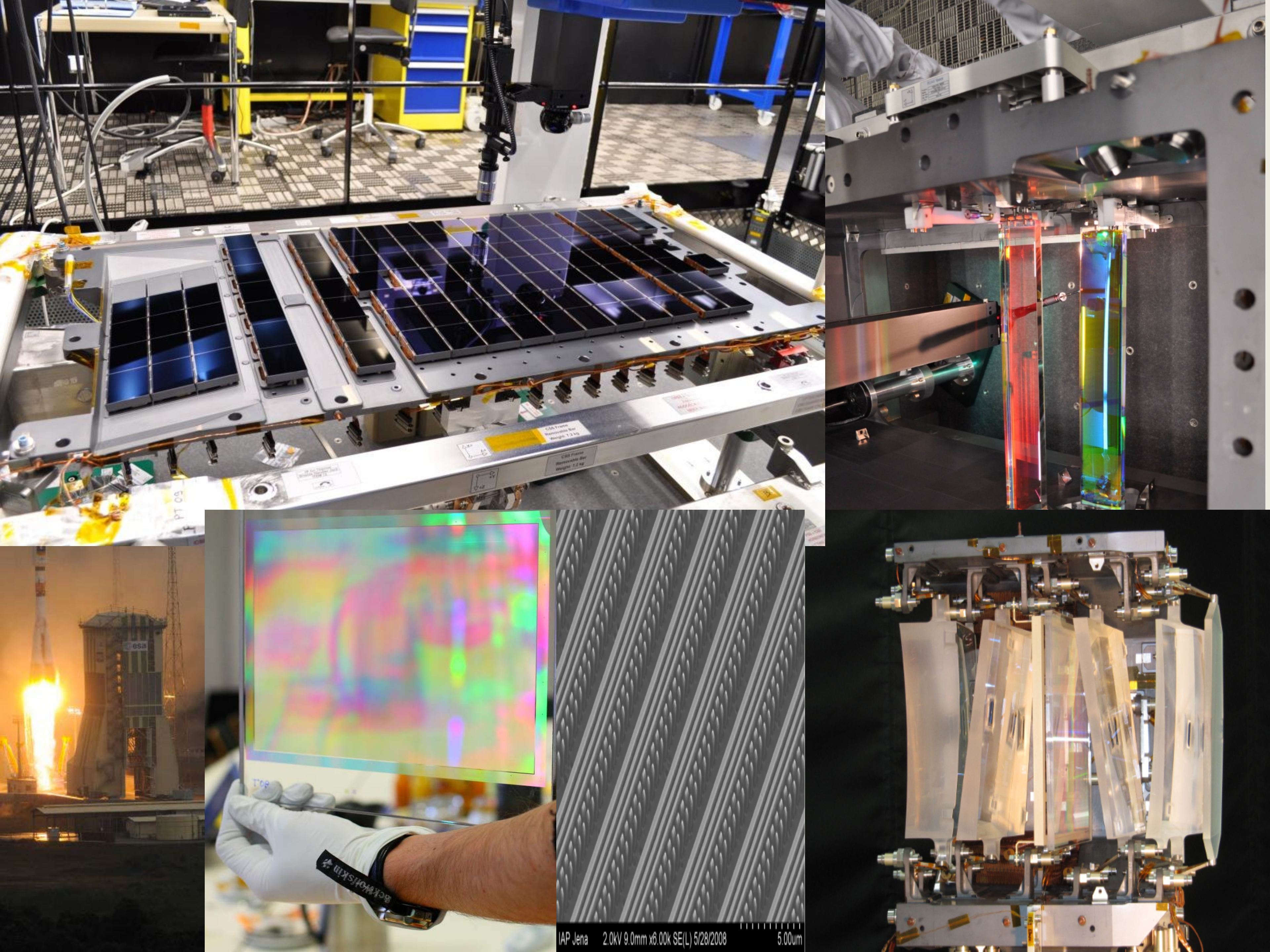


Measurable quantity : $f(t)*(\pi_2-\pi_1)$ ⟹ $\pi_2-\pi_1$

How parallaxes get absolute



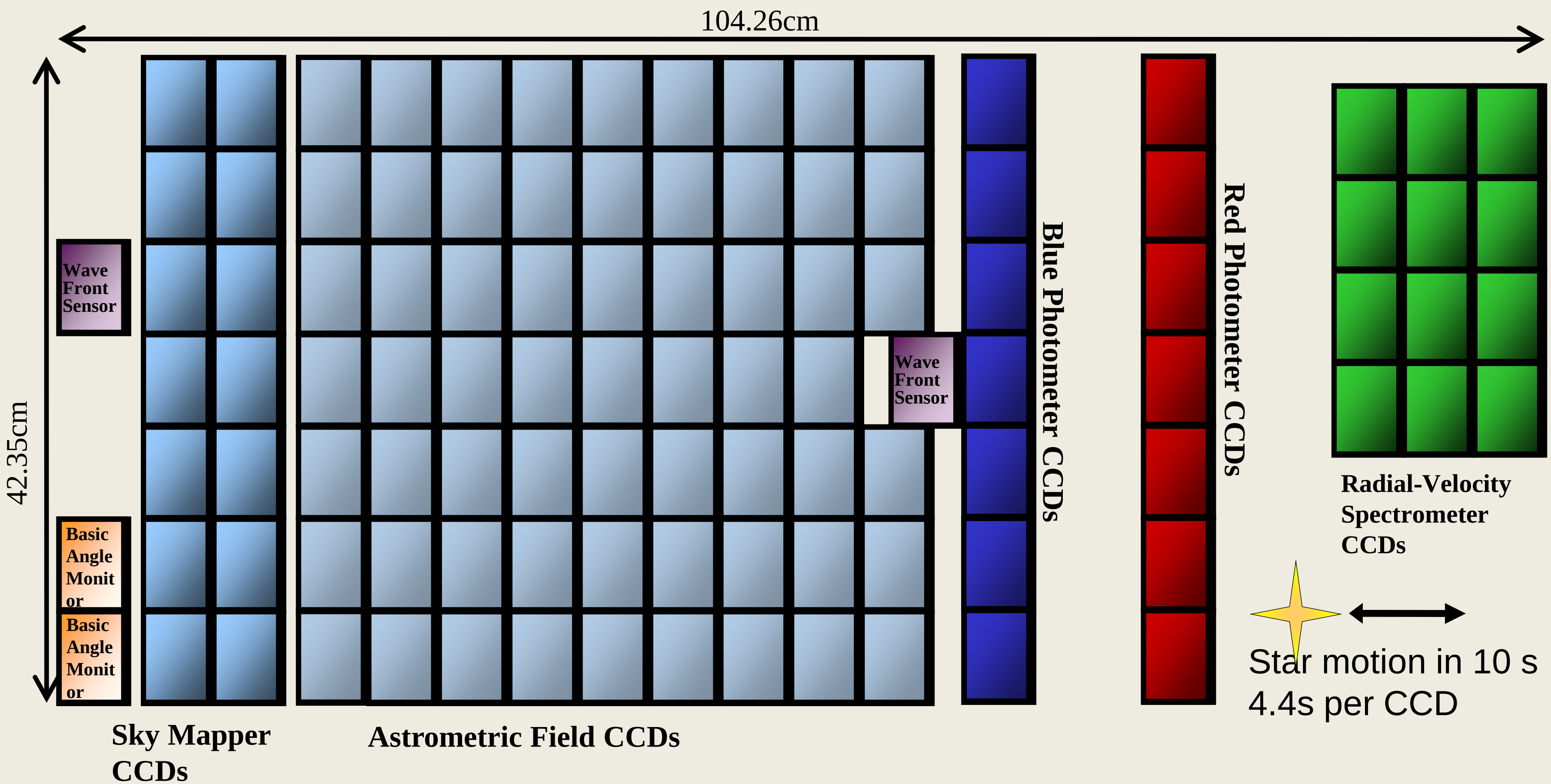
Measurable quantity : $f_2(t)*\pi_2 - f_1(t)*\pi_1$ ⇒ π_2 and π_1


IAP Jena 2.0kV 9.0mm x6.00k SE(L) 5/28/2008
5.00um

Data flow: 50Gb/day for 5-6 years; total processed data and archives ➔ 1PByte

Computational challenge : 1.5 x 10^{21} FLOP – and highly sophisticated algorithms

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

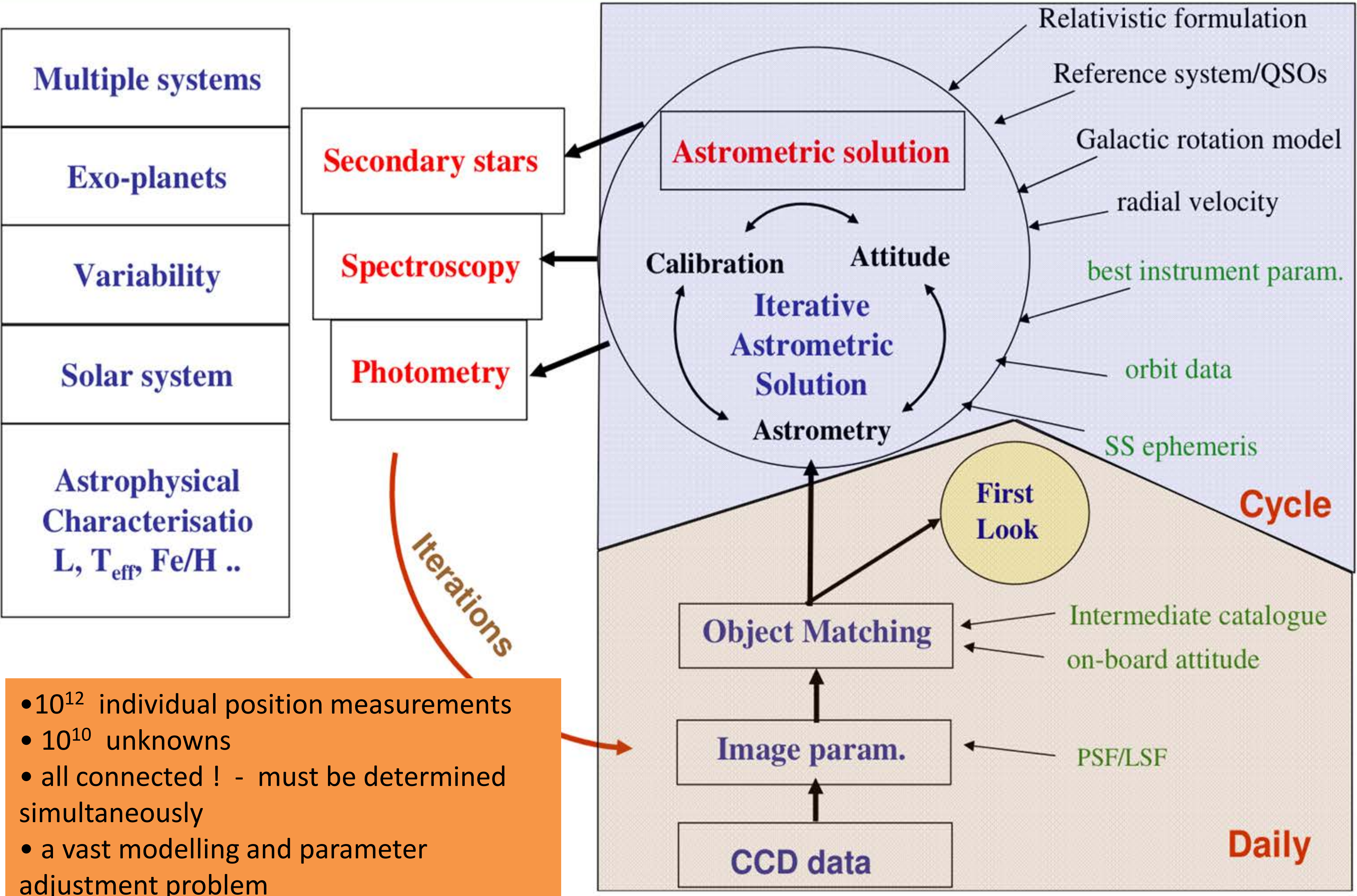
The fundamental Gaia measurement is an image and a time

- Micro-arcsec = 5×10^{-12} rad
  10^{-12} sec = required clock accuracy
  5×10^{-12} x c = 1.5mm/sec = satellite velocity accuracy

- 10^{13} individual time and flux measurements
- 10^{10} unknowns
- all connected ! - must be determined simultaneously
- a vast modelling and parameter adjustment problem

- 5000 million star unknowns (for simple stars)
- 150 million attitude unknowns
- 10 million calibration unknowns (maybe 50 million)
- a few dozen “global” unknowns

Overall chart of the data processing



- 10^{12} individual position measurements
- 10^{10} unknowns
- all connected ! - must be determined simultaneously
- a vast modelling and parameter adjustment problem

The DPAConsortium: the global view

Two main concepts:

1. Coordination Units
2. Data Processing Centres

CU1 Architecture / CU3 Astrometry — ESAC/BPC/OAOT

CU2 Simulation — BPC/CNES

CU4 Objects	CU5 Photometry	CU6 Spectroscopy	CU7 Variability	CU8 A.P.
CNES	Cambridge	CNES	ObsGE/ISDC	CNES

> 450 people

ALL distance indicators will have precision calibrations – consider one example

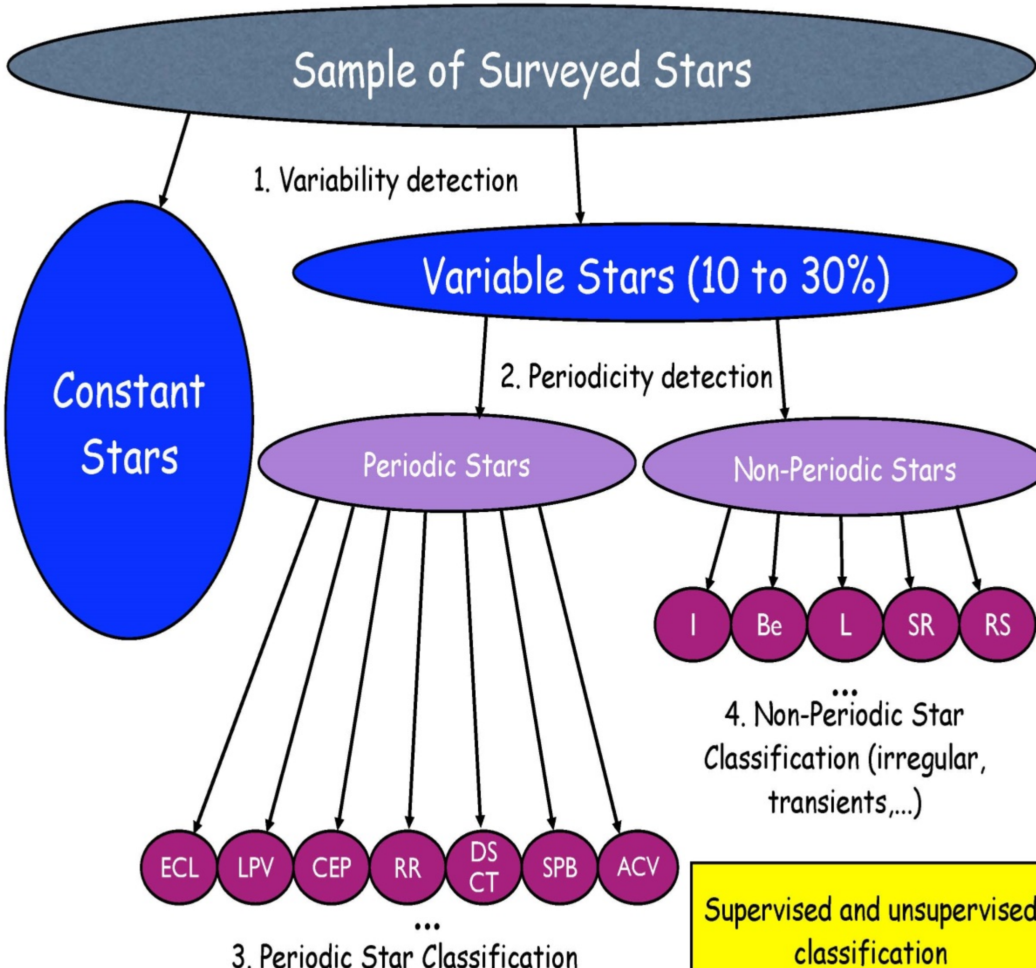
Pulsating variables from Hipparcos to Gaia

	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 $\sigma_\pi/\pi < 1\%$

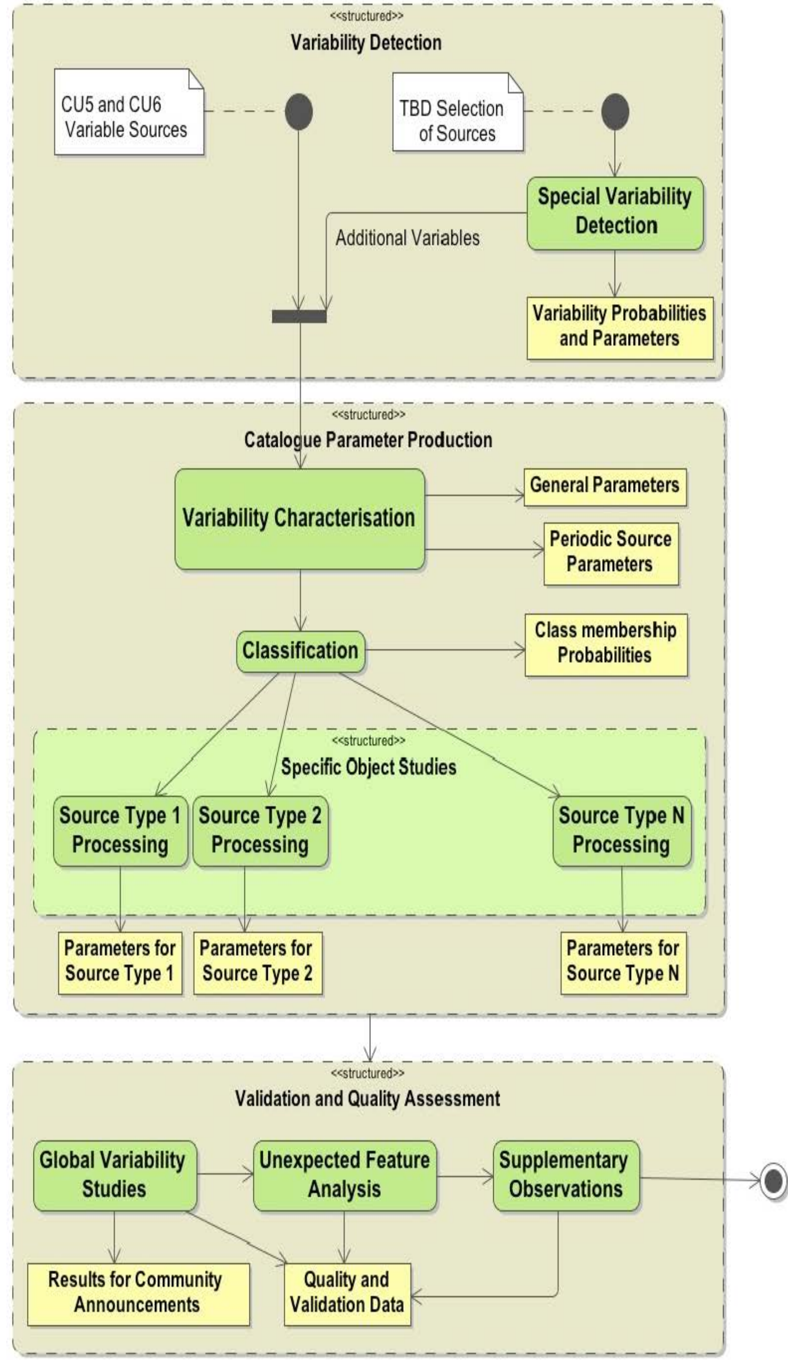
Windmark et al. 2011 (*) (**) Clementini 2010 (***) Eyer & Cuypers 2000

CU7
Variability Analysis

functional analysis

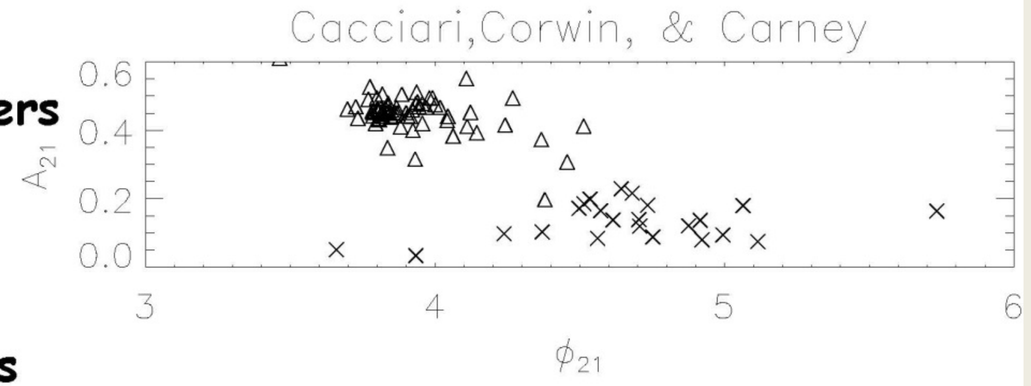


Supervised and unsupervised classification

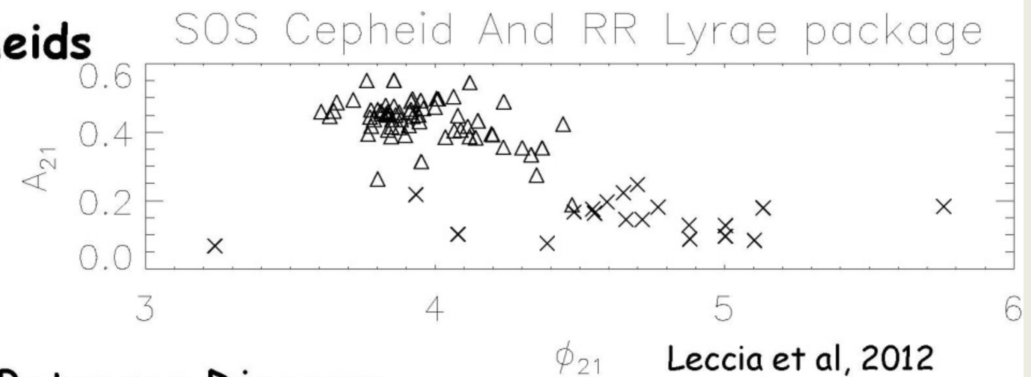


Example 1:Cepheid/RR Lyrae (Clementini, Bologna)

1. Determine the Fourier parameters



2. Identify Blazhko RR Lyrae stars and double mode RR Lyrae/Cepheids



Leccia et al, 2012

3. Identify pulsation mode

4. Determine stellar parameters

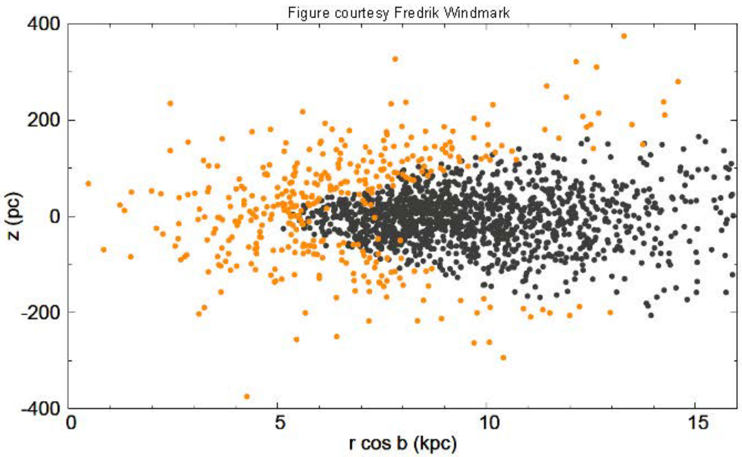
Petersen Diagram

Baade-Wesselink analysis

5. Identify binarity

6. Determine period changes

Galactic Cepheids



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

- Observable by Gaia
- Too faint for Gaia

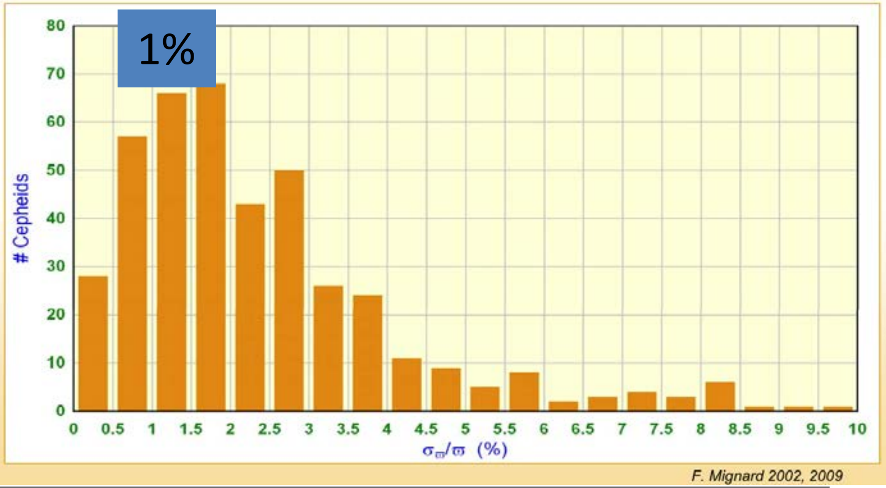
- Gaia will observe ~9,000 Galactic Cepheids (2011arXiv1104.2348W)
- Hundreds are visible near and behind the Galactic centre
- Beyond 5 kpc, all Cepheids are observed outside the plane

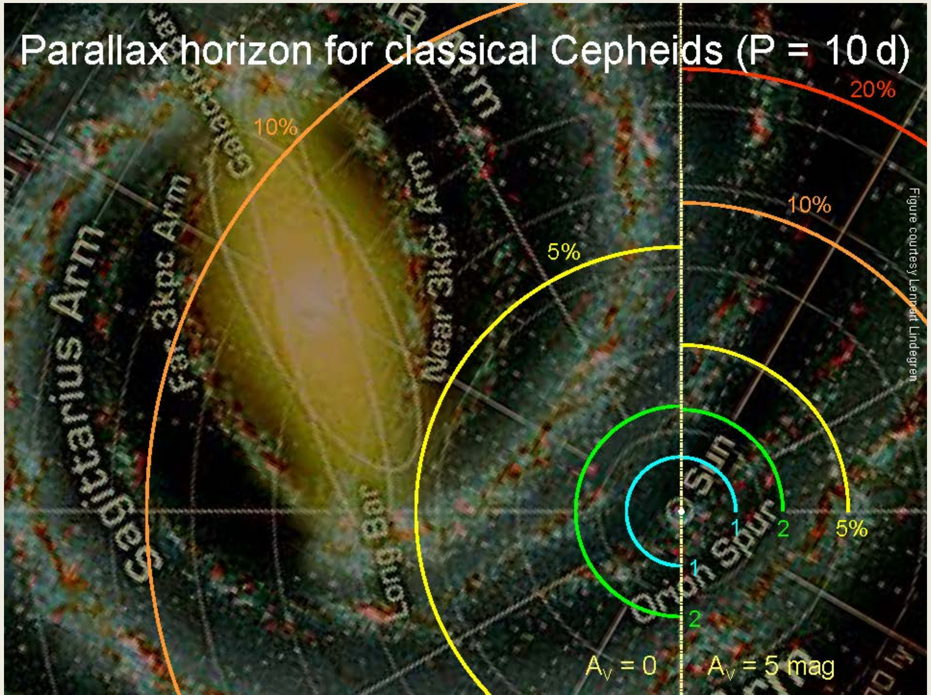
15 d < 0.5 kpc, 65 d< 1 kpc, 165 d < 2 kpc

- 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)**

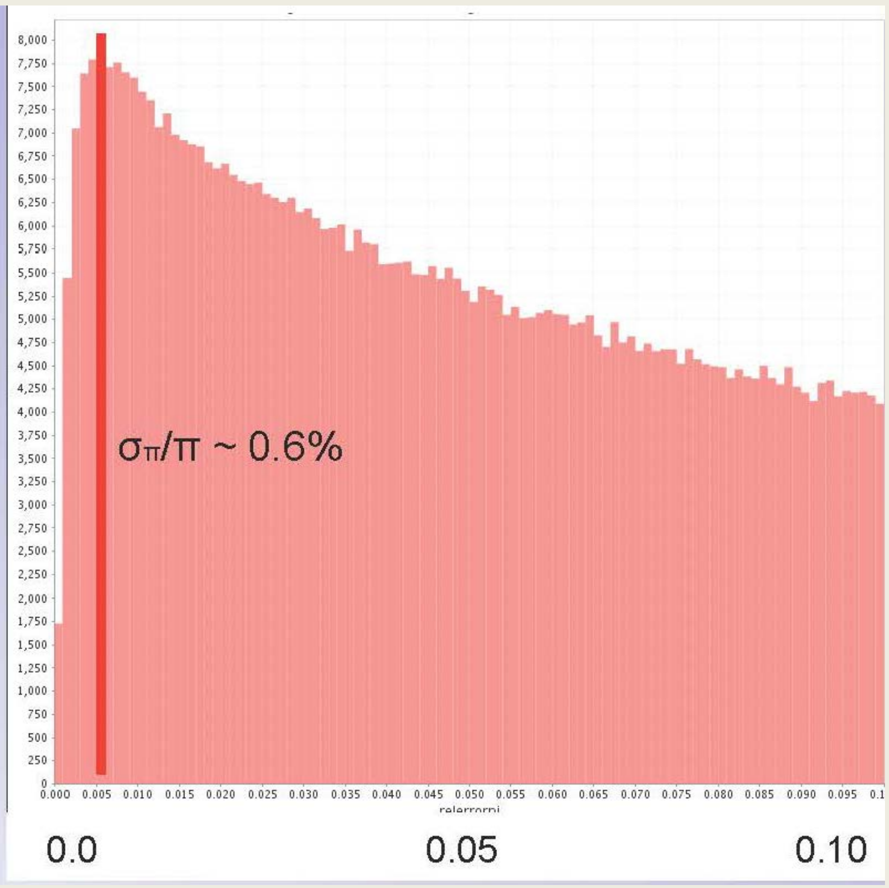
optimist: Gaia will multiply by 10 the Galactic Cepheid number

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

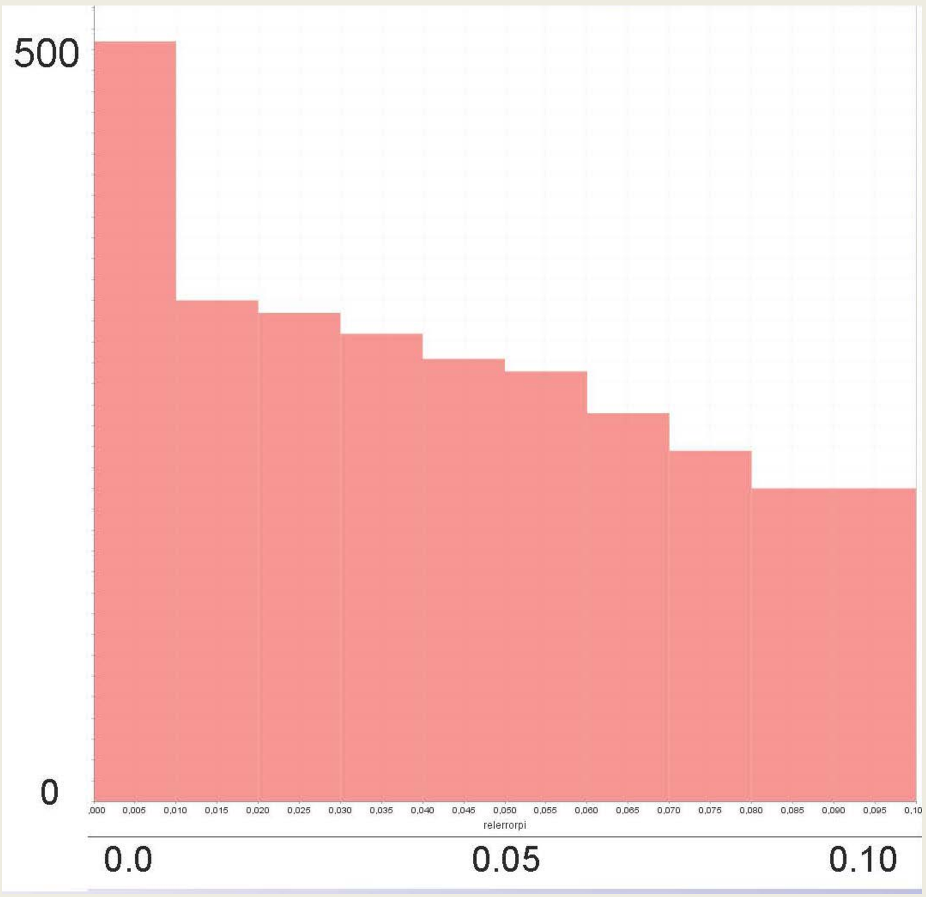
Astrometry distance accuracy DF simulated

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



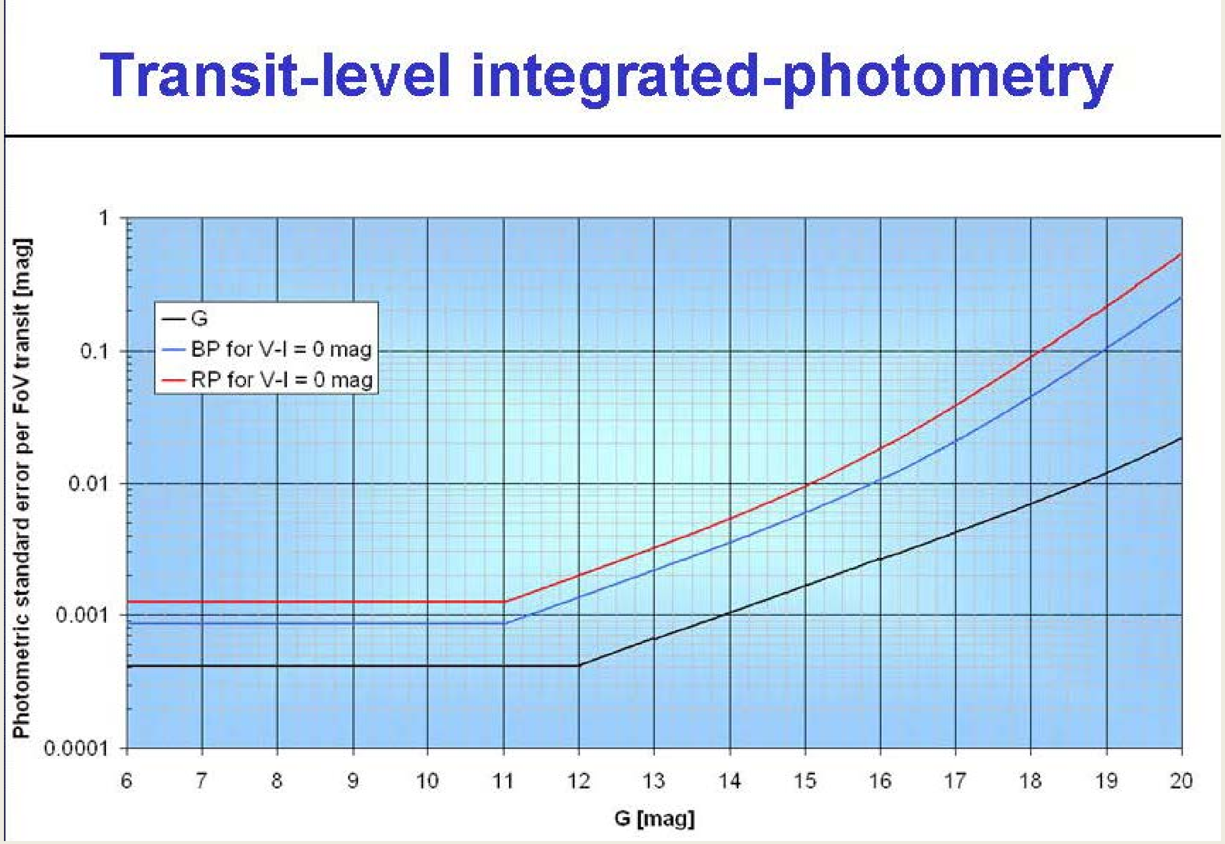
Cepheids



Science Alerts

all interesting sources released publically

will include ~6000SNIa
to z<0.08 in 5 years
these are the sample which can calibrate the SN1a DF overlap with the Cepheids and all other calibration methods



aims:

- detect unexpected and rapid changes in the flux, spectrum or position
- or appearance of new objects
- trigger ground-based follow-up
- provide targets to the community to be studied at peculiar states
- run in near-real-time: between couple of hours and 24h after observation
- use photometric, spectroscopic and astrometric Gaia data

Gaia science: when and to whom?
first supernovae: late 2014 (tbc)
first data release - 2016

Thanks to Sophie for the image

Formal ESA Gaia science data policy:
Free to all, no GTO, no priority science.

We did this deliberately – Gaia data is just so big and important there is enough for all

Will release all data, with as many as feasible derived parameters to allow science verification

gaia.ac.uk is a simple interface

- to all Gaia transient science:
  - material describing the discoveries
  - links to the robotic telescope for schools: Faulkes, Las Cumbres

All data are released to whole community – no GTO, no restrictions

Alerts – start as soon as we can, end- 2014, for 5+ years

mid 2016

The 90% sky-survey at 0.2arcsec spatial resolution:
Positions and magnitudes, proper motions for Hipparcos stars

early2017

5-parameter astrometric solutions; radial velocities, colours

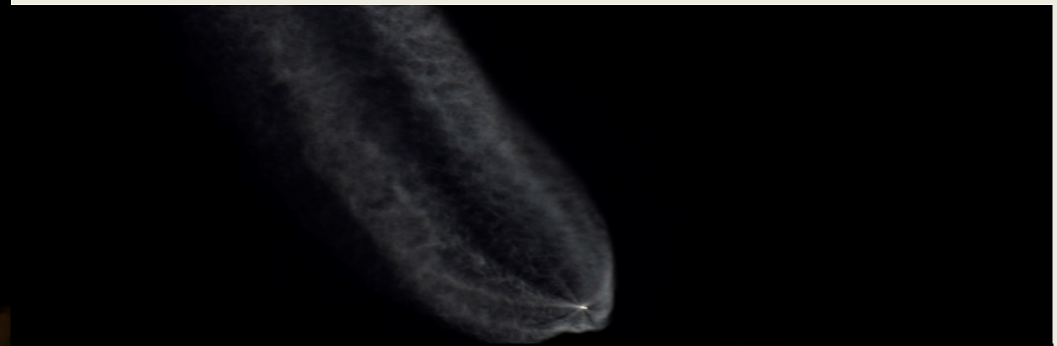
2017/18?

Astrometry for binaries, astrophysical parameters, more stars

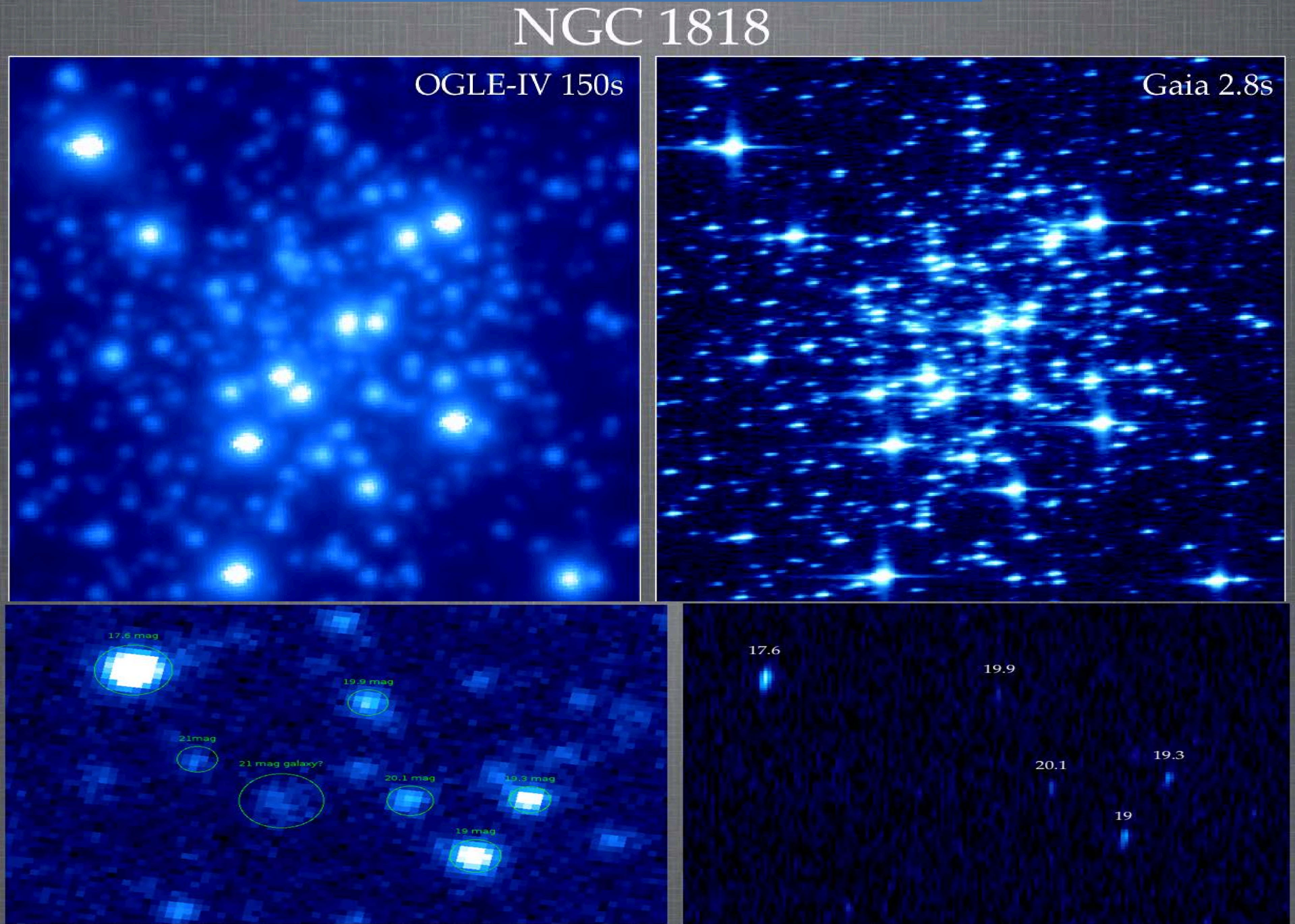
Data releases will continue through the mission as often as resources allow

Major public outreach program connecting Gaia Alerts to schools using LCOGT

Launch Dec 2013, at L2, commissioning



Gaia first light image – a glimpse of the future

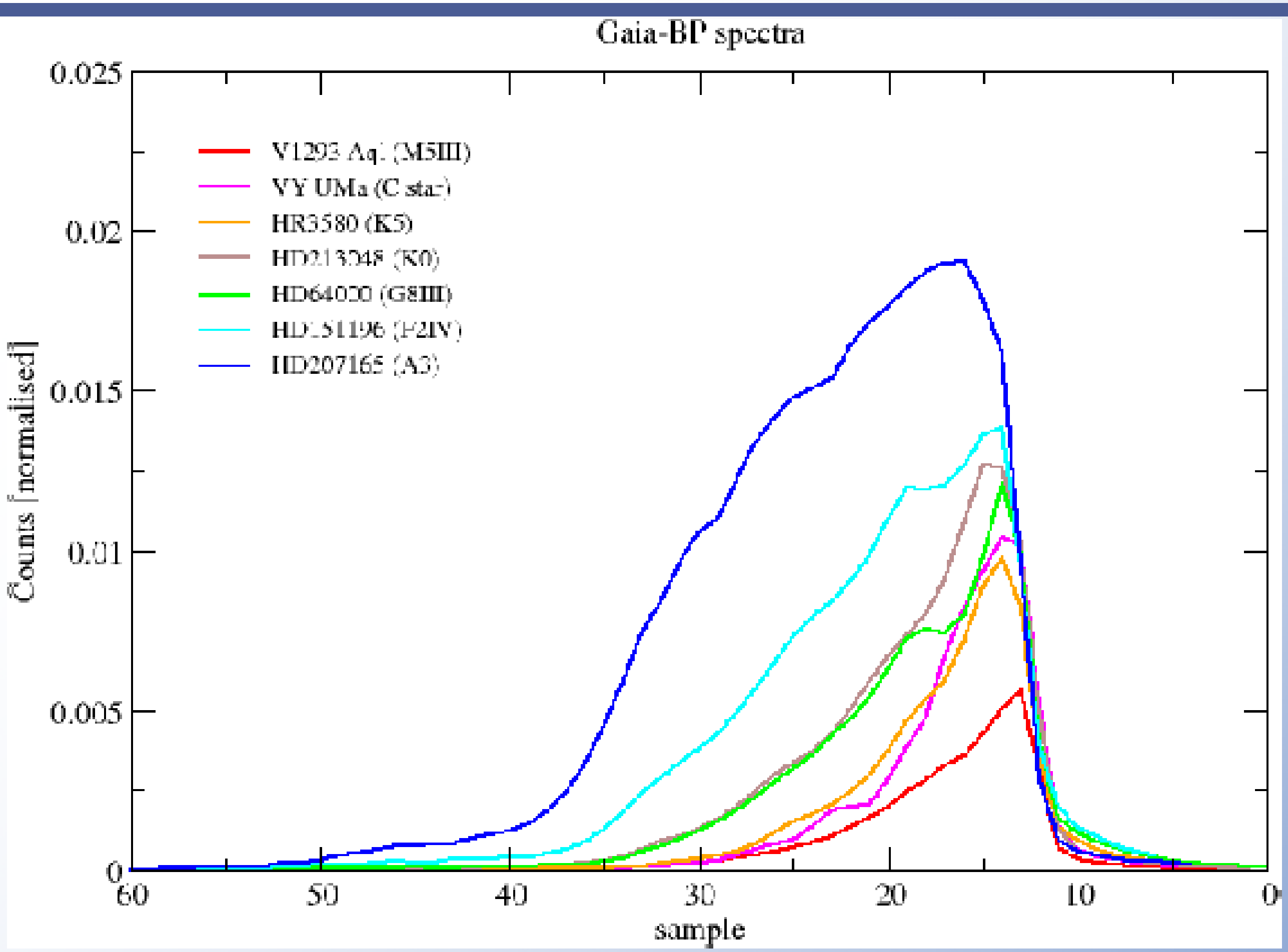


Gaia commissioning status

- The camera is working well – 106 CCDs+electronics
- The atomic clock is working
- The on-board computer systems are working
- The communications system is working
- The micro-propulsion system is working
- The telescope optics are better than expected
- The launch was perfect: saved fuel ➔ longer life
- Mission enhancements: going brighter; going fainter, going longer (5-year+1 plan, up to 8-years feasible)
- Science operations starts this week, routine from 26/10
- Overall: "parameters are nominal". Except for 3.

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

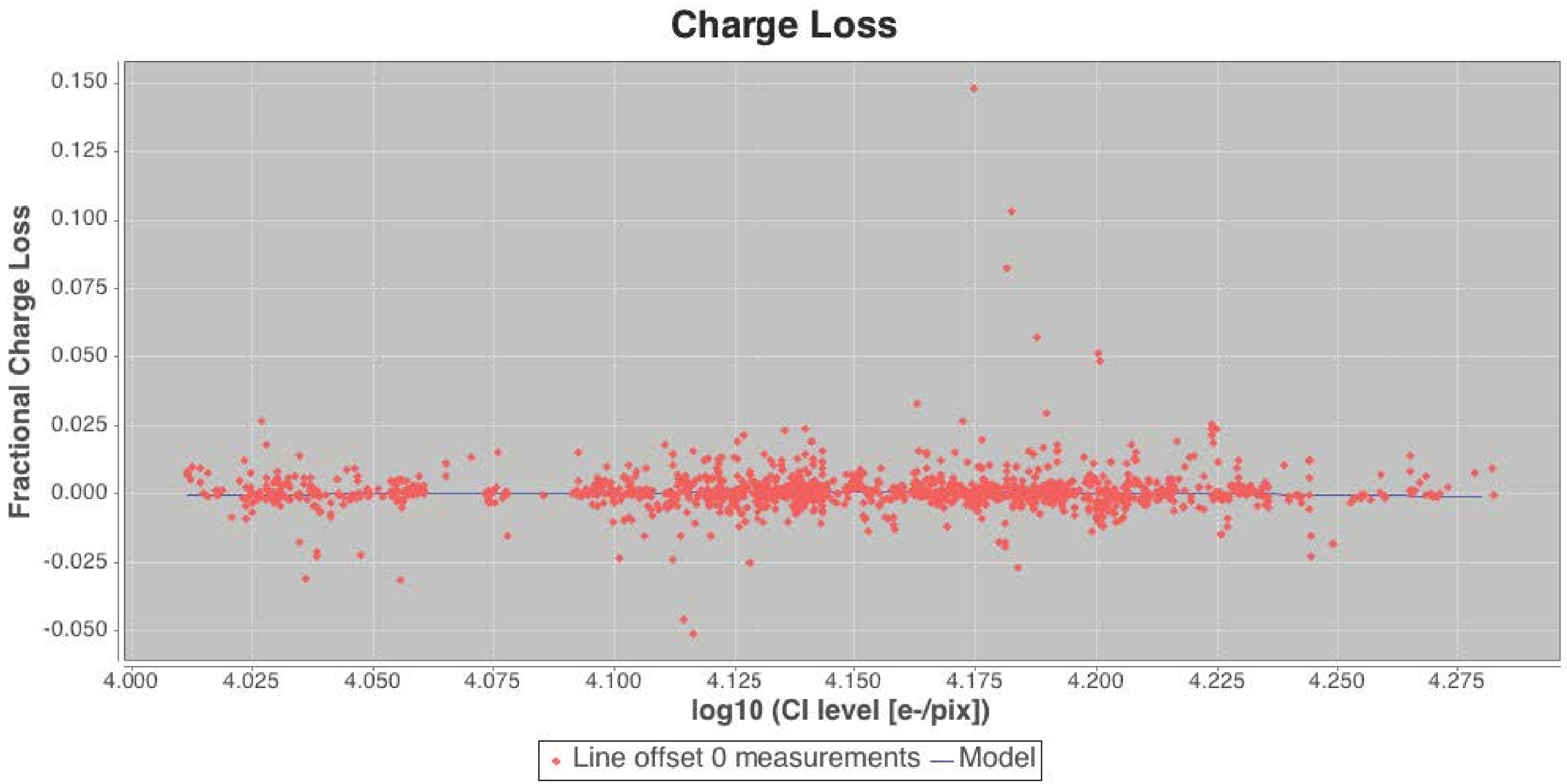
Photometry



Diagrams courtesy C. Jordi and J.-M. Carrasco

Initial radiation damage

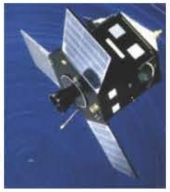
- Good news: initial radiation damage level appears low (now 6 months in-orbit), e.g. AF8 on row 2:



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
  - Rate diminished, but water source not yet exhausted
- Basic Angle variation larger than expected
  - Basic Angle Monitor providing very precise measurements of the changes

Precursor mission: Hipparcos



- ESA Hipparcos demonstrated the feasibility of space-borne scanning astrometry (final reductions by F. van Leeuwen, IoA)

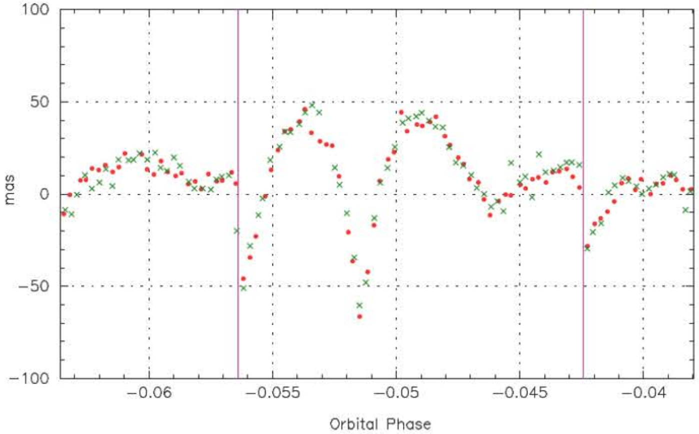


Fig. 5. A small external hit of the satellite as reflected in the abscissa residuals relative to the star-mapper based scan-phase reconstruction. The data are for orbit 715 (Oct.1990), for which the scan velocity at orbital phase -0.05148 changed abruptly by 4.7 mas s^{-1}. The crosses and circles represent data from the two fields of view. The data points are weighted averages over 10.6 s of observations. The vertical lines represent thruster firings.

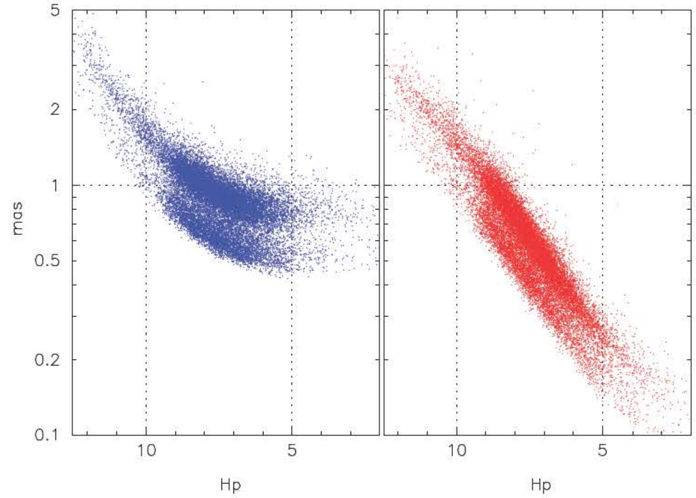


Fig. 18. The precisions (formal errors) of parallaxes in the published data (left) and the new solution (right) as a function of magnitude. The bimodal structure in the plots reflects the scanning strategy: around the ecliptic poles the number of observations and their distribution is far more favourable for accurate parallax measurements than around the ecliptic plane.

http://adsabs.harvard.edu/abs/2005A%26A...439..805V

http://adsabs.harvard.edu/abs/2005A%26A...439..791V

Scientific performance

For unreddened Solar type (G2V) star

V-magnitude	*Astrometry (parallax)*	*Photometry (BP/RP integrated)*	*Spectroscopy (radial velocity)*
6 to 12	***5-14*** **μas**	***4 mmag***	***1 km/s***
15	***25*** **μas**	***5 mmag***	***13 km/s***
20	***430*** **μas**	***60 (RP) – 80 (BP) mmag***	

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

Calculations by: D. Katz, C. Jordi, L. Lindegren, J. de Bruijne

Gaia has exciting outreach potential – as well as awesome science

Gaia will discover new transient sources in real-time, and we will distribute them freely.
We have a collaboration with Faulkes/Las Cumbres to work with schools and amateur astronomers to do original science analysing these, with data used in professional studies

--- to learn about science by doing science

Science verification starts today
Routine ops from Sept 26

Twinkle, twinkle, little star, how I wonder where you are...

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 1.5Mkm 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
- 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 225 tonnes 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

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, ...