Gaia

A Stereoscopic Census of our Galaxy

Based on slides from http://www.cosmos.esa.int/web/gaia/presentations
and http://online.kitp.ucsb.edu/online/galarcheo-c15/brown

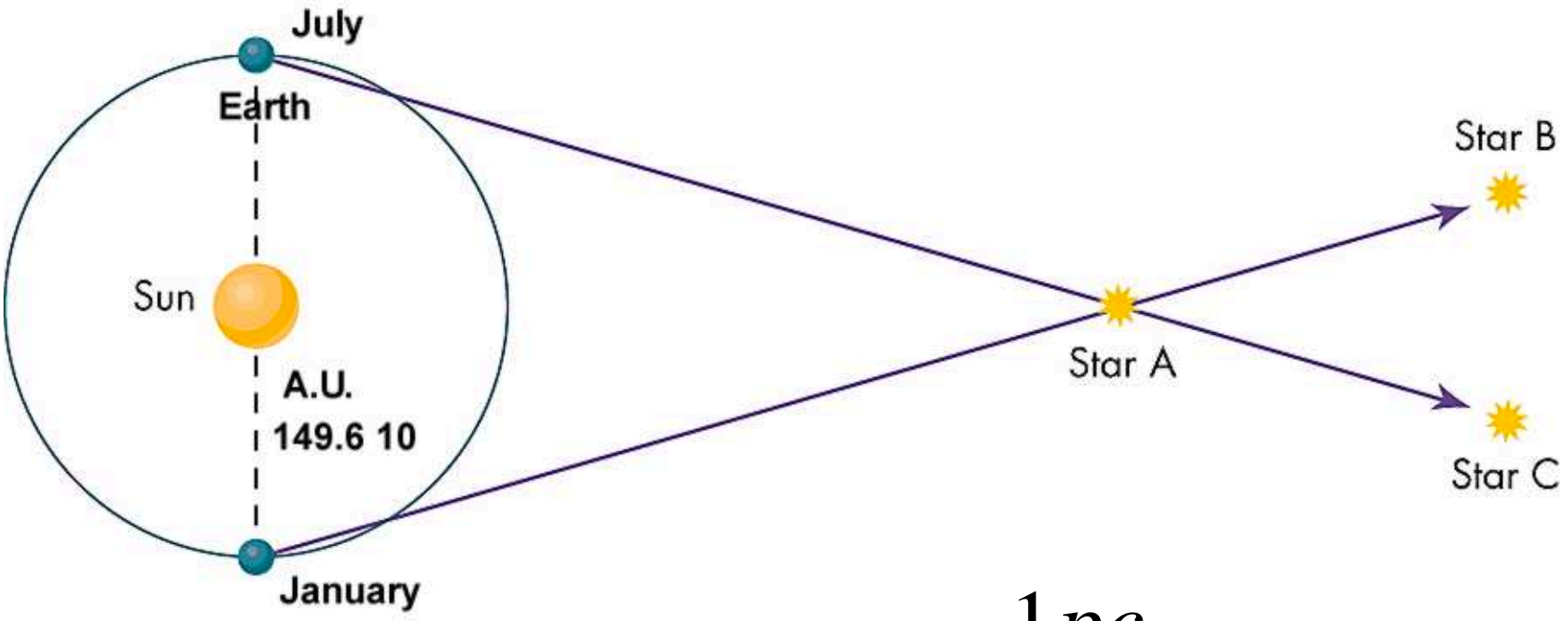
Gaia: An Astrometric* Survey Mission

- **Astrometry (G < 20 mag):**
  - completeness to 20 mag (on-board detection) $\Rightarrow 10^9$ stars
  - accuracy: 26 μarcsec at G=15 mag (Hipparcos: 1 milliarcsec at 9 mag)
  - scanning satellite, two viewing directions
    $\Rightarrow$ global accuracy, with optimal use of observing time
  - principle: global astrometric reduction (as for Hipparcos)

- **Photometry (G < 20 mag):**
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
    $\Rightarrow \Delta T_{eff} \sim 100$ K, log g, [Fe/H] to 0.2 dex, extinction (at G=15 mag)

- **Radial velocity (G_{RVS} < 16 mag):**
  - accuracy: 15 km s^{-1} at G_{RVS}=16 mag
  - application:
    - third component of space motion, perspective acceleration
    - dynamics, population studies, binaries
    - spectra for G_{RVS} < 12 mag: chemistry, rotation
  - principle: slitless spectroscopy in Ca triplet (845-872 nm) at R = ~10,800

From Precision Astrometry to Distance Measurement



$$d = \frac{1pc}{parallax"}$$

Gaia Catalog: Complete, Faint, Accurate

	Hipparcos	**Gaia**
Magnitude limit	12 mag	20 mag
Completeness	7.3 – 9.0 mag	20 mag
Bright limit	0 mag	3 mag (assessment for brighter stars ongoing)
Number of objects	120,000	47 million to G = 15 mag 360 million to G = 18 mag 1192 million to G = 20 mag
Effective distance limit	1 kpc	50 kpc
Quasars	1 (3C 273)	500,000
Galaxies	None	1,000,000
Accuracy	1 milliarcsec	7 μarcsec at G = 10 mag 26 μarcsec at G = 15 mag 600 μarcsec at G = 20 mag
Photometry	2-colour (B and V)	Low-res. spectra to G = 20 mag
Radial velocity	None	15 km s^{-1} to G_{RVS} = 16 mag
Observing	Pre-selected	Complete and unbiased

Stellar Astrophysics

- **Comprehensive luminosity calibration, for example:**
  - distances to 1% for ~11 million stars to 2.5 kpc
  - distances to 10% for ~150 million stars to 25 kpc
  - rare stellar types and rapid evolutionary phases in large numbers
  - parallax calibration of all distance indicators
    e.g., Cepheids and RR Lyrae to LMC/SMC

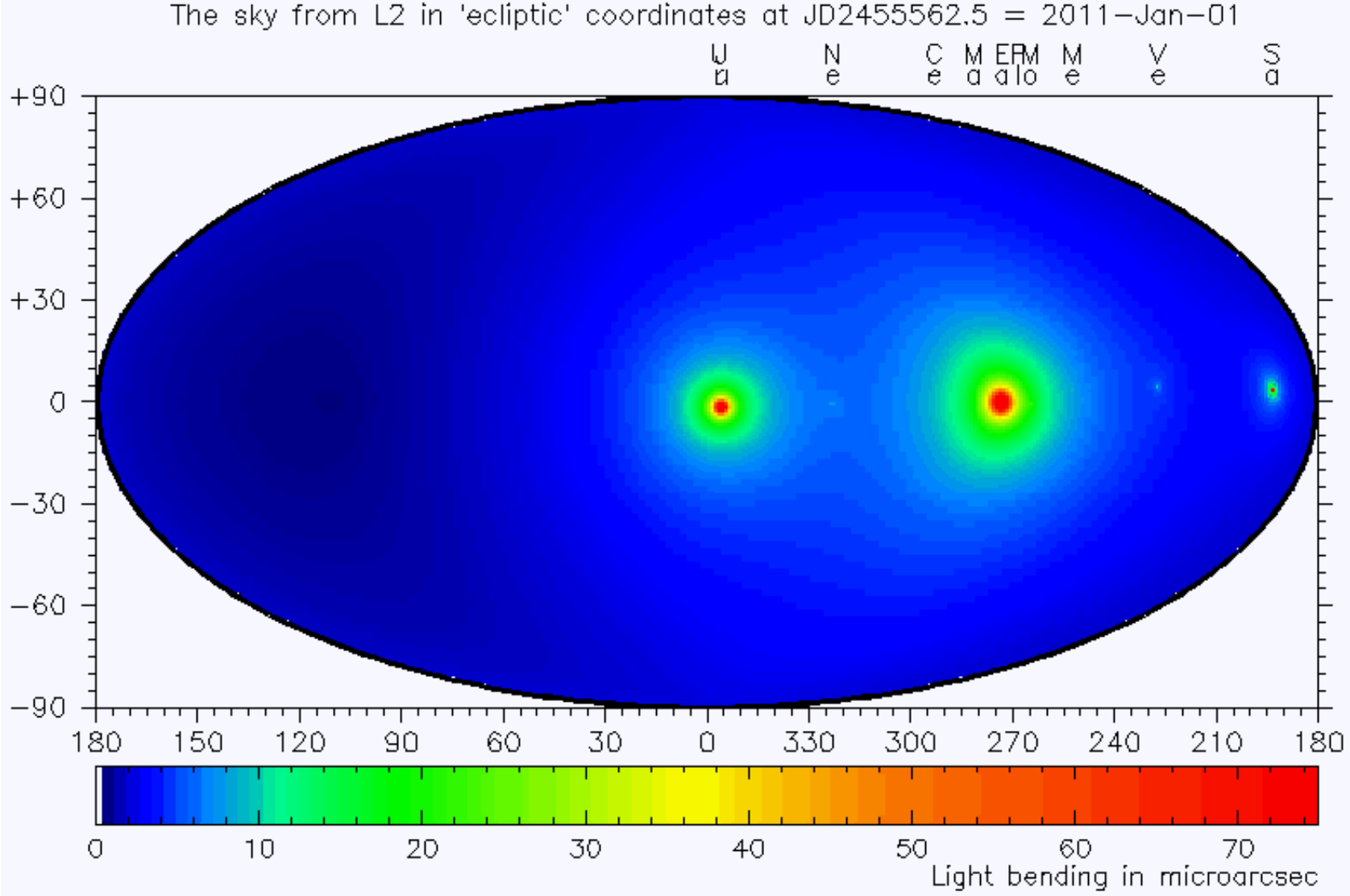
- **Physical properties, for example:**
  - Solar-neighbourhood mass and luminosity function
    e.g., white dwarfs (~400,000) and brown dwarfs (~500)
  - initial mass and luminosity functions in star-forming regions
  - luminosity function for pre-main-sequence stars
  - detection and dating of all spectral types and Galactic populations
  - detection and characterisation of variability for all spectral types

One Billion Stars in 3D will provide …

- 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 (~7,000)
  - a large-scale survey of Solar-system bodies (~250,000)

- … and beyond
  - definitive distance standards out to the LMC/SMC
  - rapid reaction alerts for supernovae and burst sources (~6,000)
  - quasar detection, redshifts, microlensing structure (~500,000)
  - fundamental quantities to unprecedented accuracy: PPN γ to 2×10^{-6} (2×10^{-5} present)

Light Bending in Solar System



Light bending in microarcsec, after subtraction of the much larger effect by the Sun

Movie courtesy Jos de Bruijne

Exo-Planets: Expected Discoveries

- Astrometric survey:
  - monitoring of ~150,000 FGK stars to ~200 pc
  - detection limits: ~1M_J and P < 10 years
  - complete census of all stellar types, P ~ 2-9 years
  - masses, rather than lower limits (m sin i)
  - multiple systems measurable, giving relative inclinations

- Results expected:
  - ~2000 exo-planets (single systems)
  - ~300 multi-planet systems
  - displacement for 47 UMa = 360 μas
  - orbits for ~1000 systems
  - masses down to 10 M_{Earth} to 10 pc

- Photometric transits: ~5000

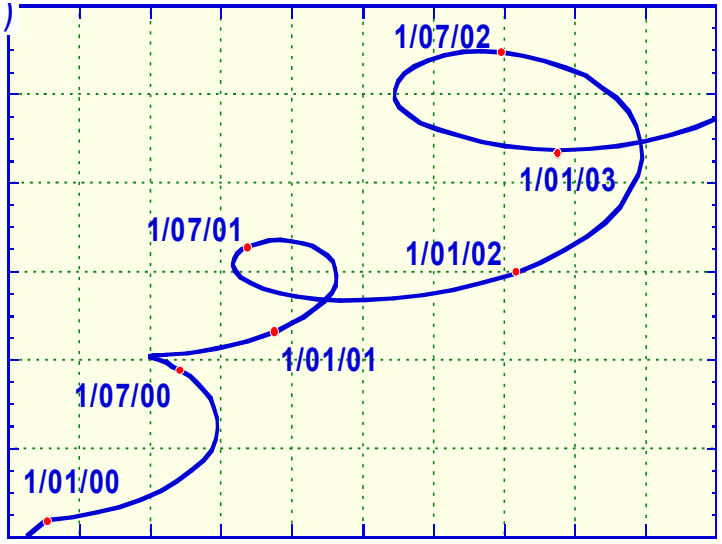


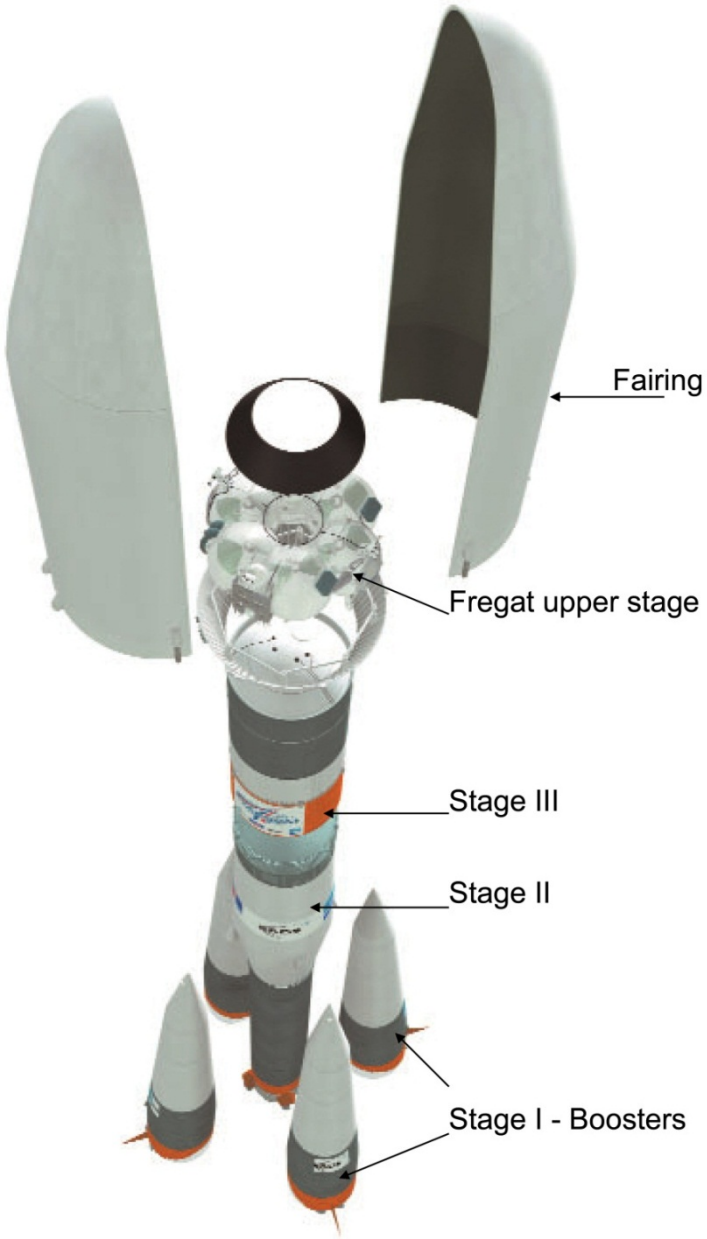
Figure courtesy François Mignard

Studies of the Solar System

- Asteroids etc.:
  - deep and uniform (G=20 mag) detection of all moving objects
  - ~250,000 objects observed, mainly main-belt asteroids
  - orbits: 30 times better than present, even after 100 years
  - spin-axis direction, rotation period, shape parameters for majority
  - taxonomy/mineralogical composition versus heliocentric distance
  - diameters for ~1000 to 20%, masses for ~150 to 10%
  - Trojan companions of Mars, Earth, and Venus
  - Kuiper-Belt objects: ~50 objects to G=20 mag (binarity, Plutinos)
  - Centaurs: ~50 objects

- Near-Earth Objects:
  - Amors, Apollos and Atens (4389, 5156, 811 known today)
  - ~1600 Potentially Hazardous Asteroids (PHA) >1 km predicted (1435 currently known)
  - detection limit: 260-590 m at 1 AU, depending on albedo

Satellite and System



- ESA-only mission
- Launch: 19 December 2013
- Launcher: Soyuz–Fregat from French Guiana
- Orbit: L2 Lissajous orbit
- Ground stations: Cebreros, New Norcia + Malargüe
- Lifetime: 5 years (1 year potential extension)
- Downlink rate: 4 - 8 Mbps

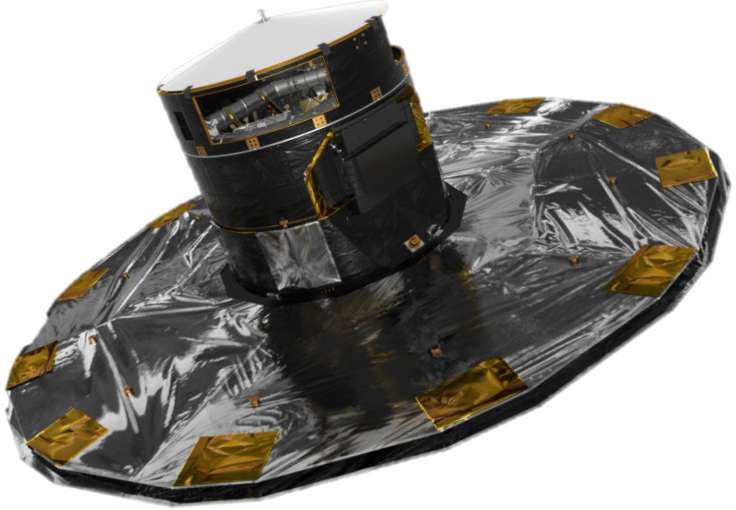


Figure Soyuz: Arianespace; figure Gaia: ESA - C. Carreau

Payload and Telescope

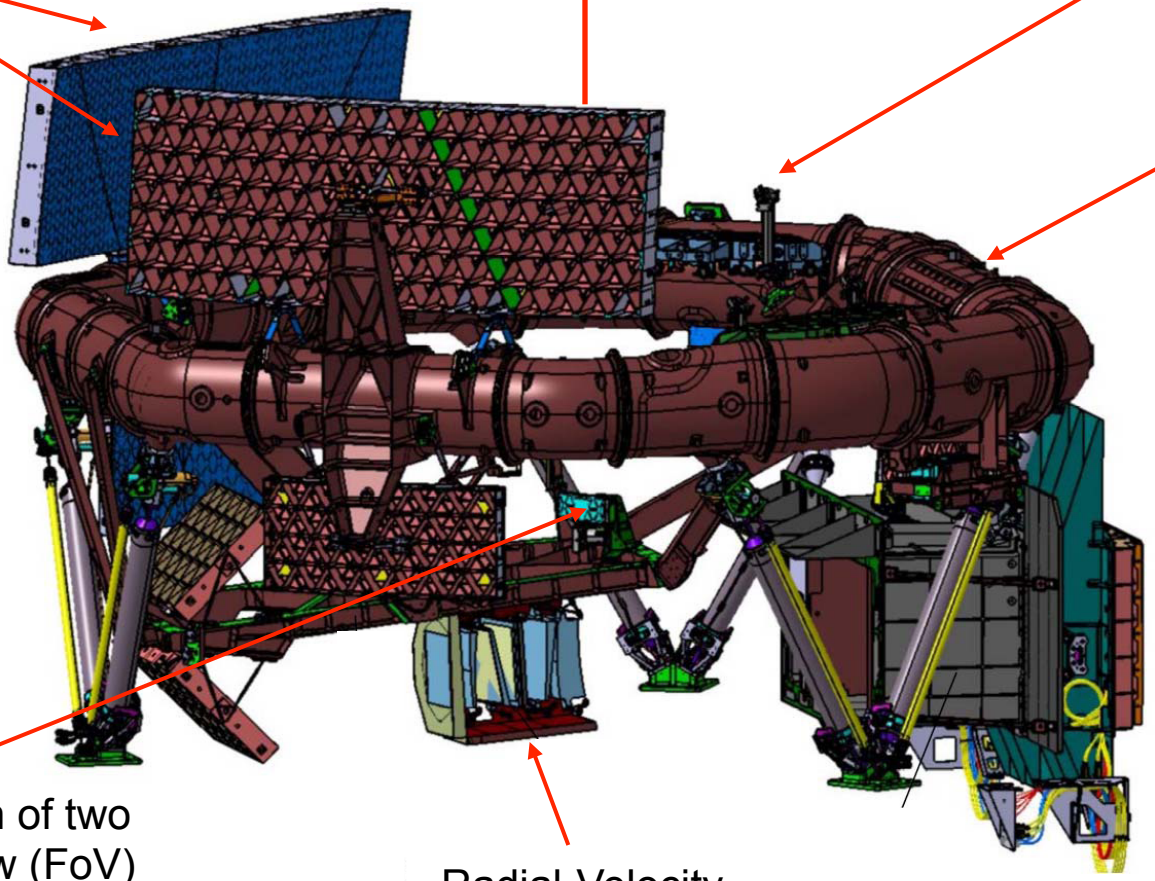
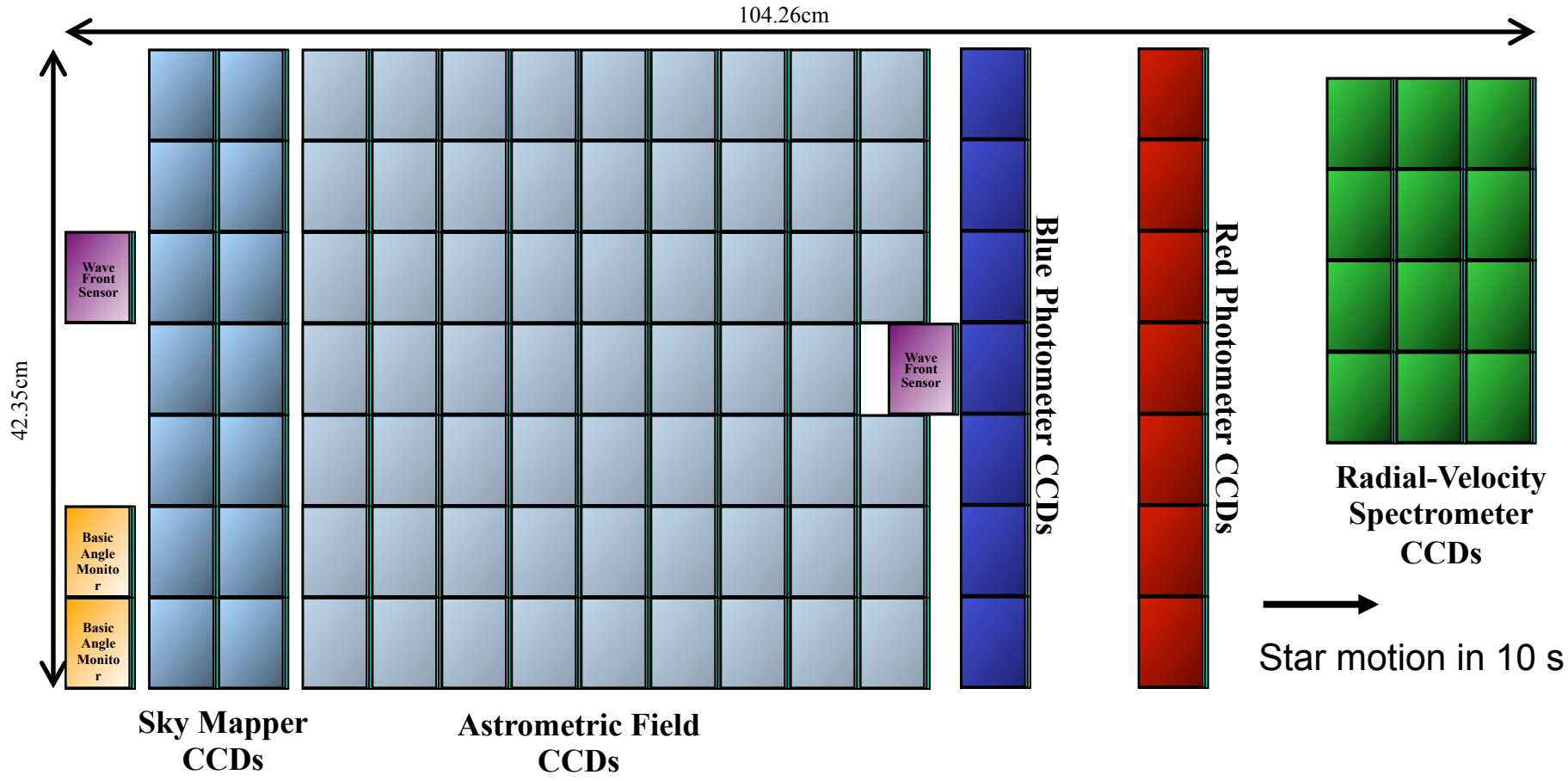


Figure courtesy EADS-Astrium

Figure courtesy Alex Short

Focal Plane



Total field:
- active area: 0.75 deg^2
- CCDs: 14 + 62 + 14 + 12 (+ 4)
- 4500 x 1966 pixels (TDI)
- pixel size = 10 μm x 30 μm
  = 59 mas x 177 mas

Sky mapper:
- detects all objects to G=20 mag
- rejects cosmic-ray events
- field-of-view discrimination

Astrometry:
- total detection noise ~ 4 e$^-$

Photometry:
- spectro-photometer
- blue and red CCDs

Spectroscopy:
- high-resolution spectra
- red CCDs

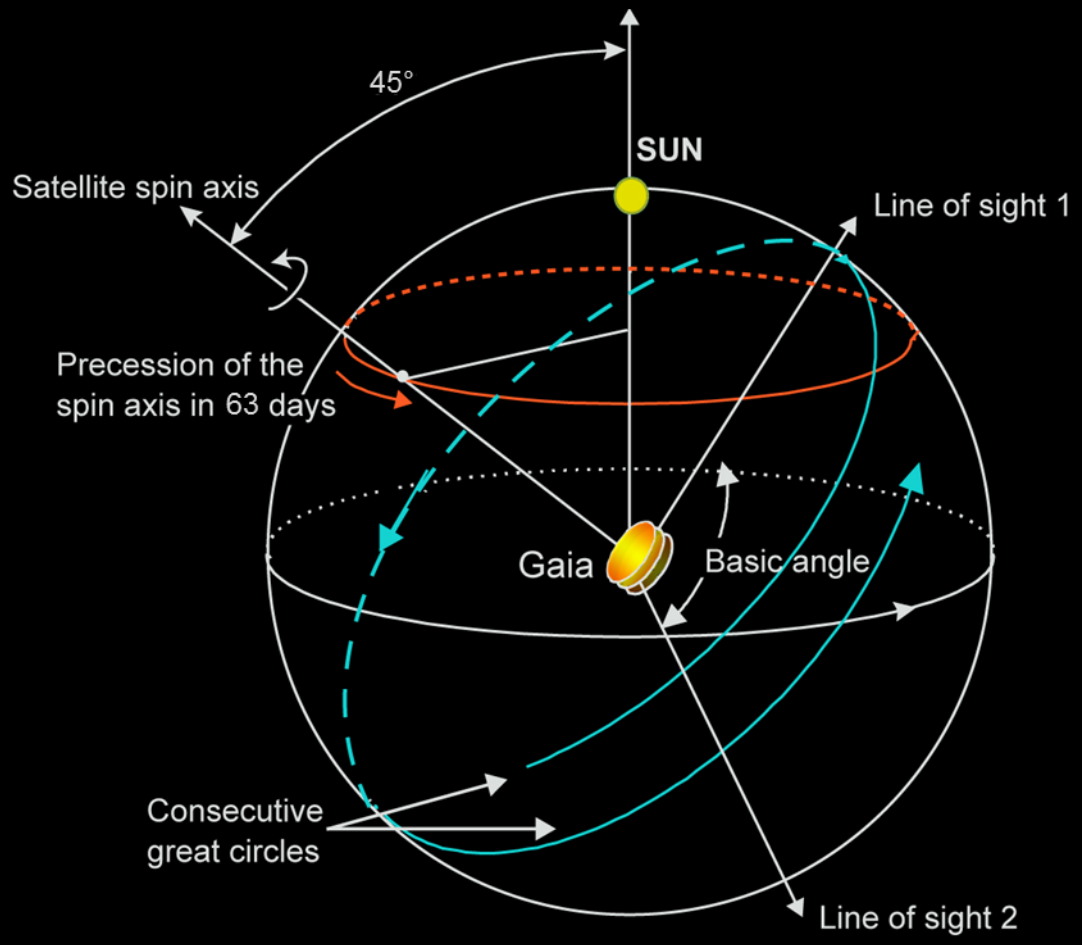
On-Board Object Detection

- Requirements:
  - unbiased sky sampling (magnitude, colour, resolution)
  - all-sky catalogue at Gaia resolution (0.1 arcsec) to G~20 mag does not exist

- Solution is on-board detection:
  - no input catalogue or observing programme
  - good detection efficiency to G~21 mag
  - low false-detection rate, even at high star densities

- Gaia will therefore detect:
  - variable stars (eclipsing binaries, Cepheids, etc.)
  - supernovae: ~6,000
  - gravitational-lensing events: ~1000 photometric and ~100 astrometric
  - Solar-system objects, including near-Earth asteroids and Kuiper-Belt objects

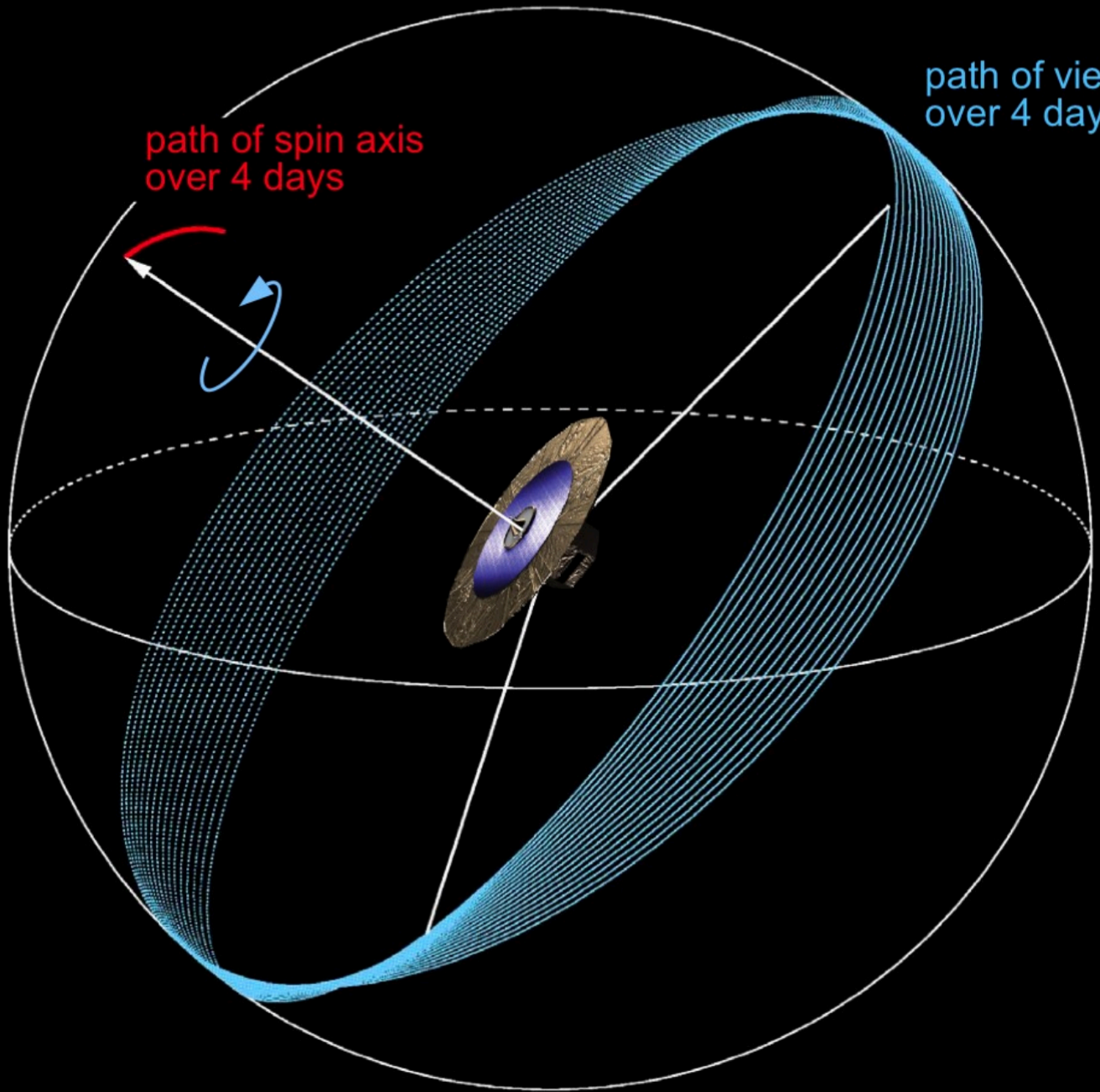
Sky-Scanning Principle



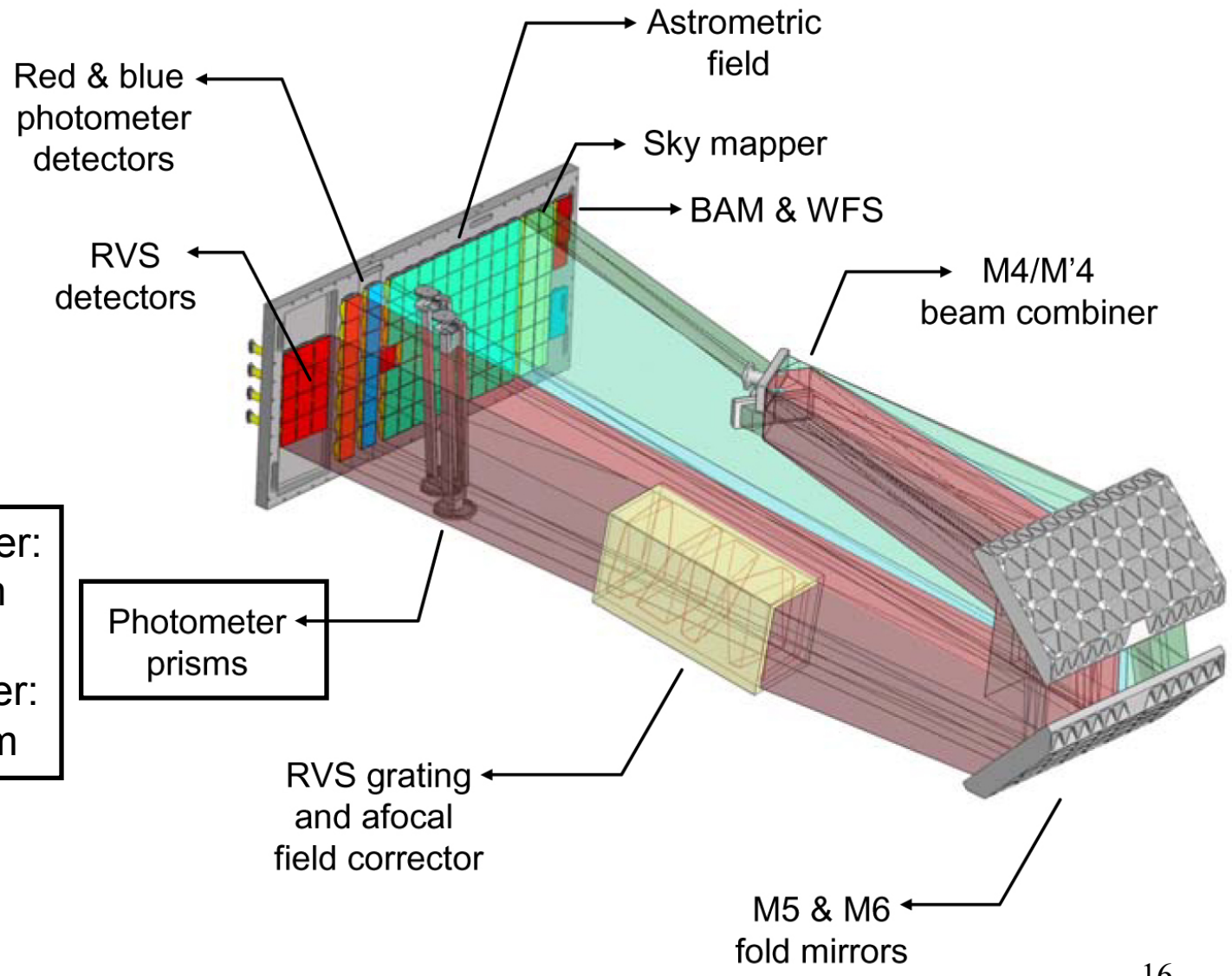
Spin axis	45° to Sun
Scan rate:	60 arcsec s^{-1}
Spin period:	6 hours

Figure ESA

Gaia scanning (2): Fast sky coverage through revolving motion + spin



Photometry Measurement Concept (1/2)

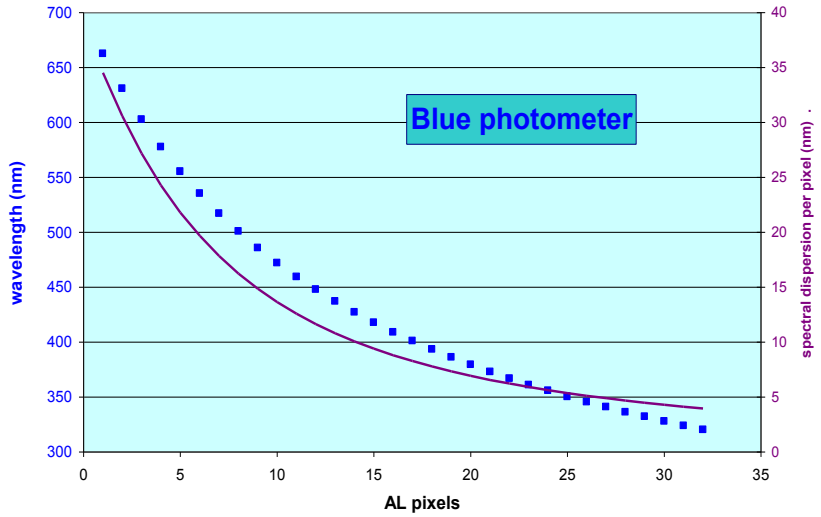


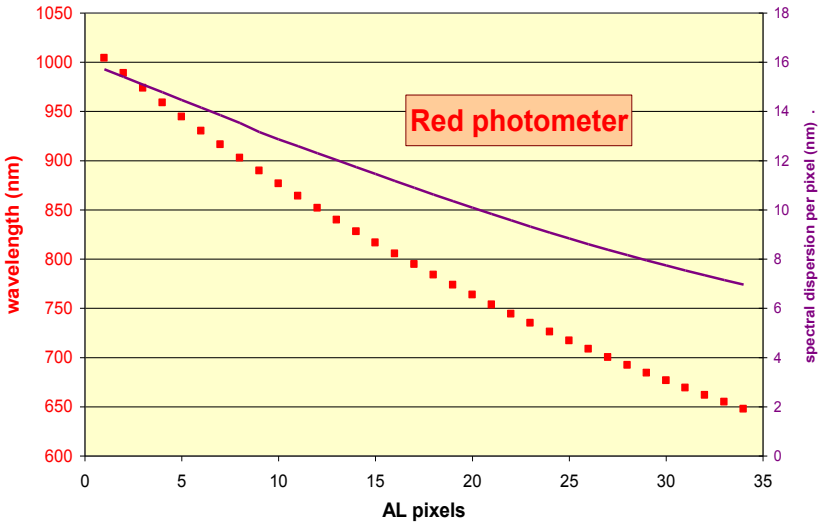
Blue photometer:
330 - 680 nm

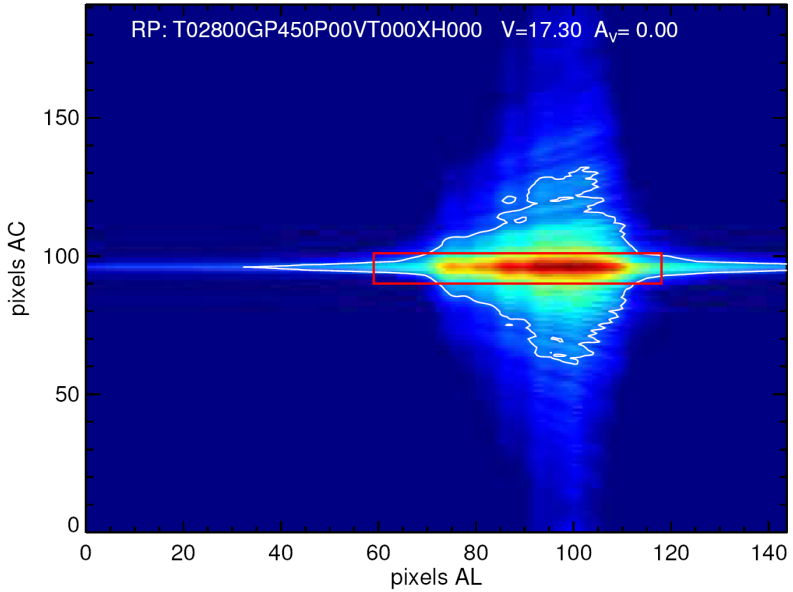
Red photometer:
640 - 1050 nm

Figure courtesy EADS-Astrium

Photometry Measurement Concept (2/2)







RP spectrum of M dwarf (V = 17.3 mag)
Red box: data sent to ground
White contour: sky-background level
Colour coding: signal intensity

Figures courtesy Anthony Brown

Radial-Velocity Measurement Concept (1/2)

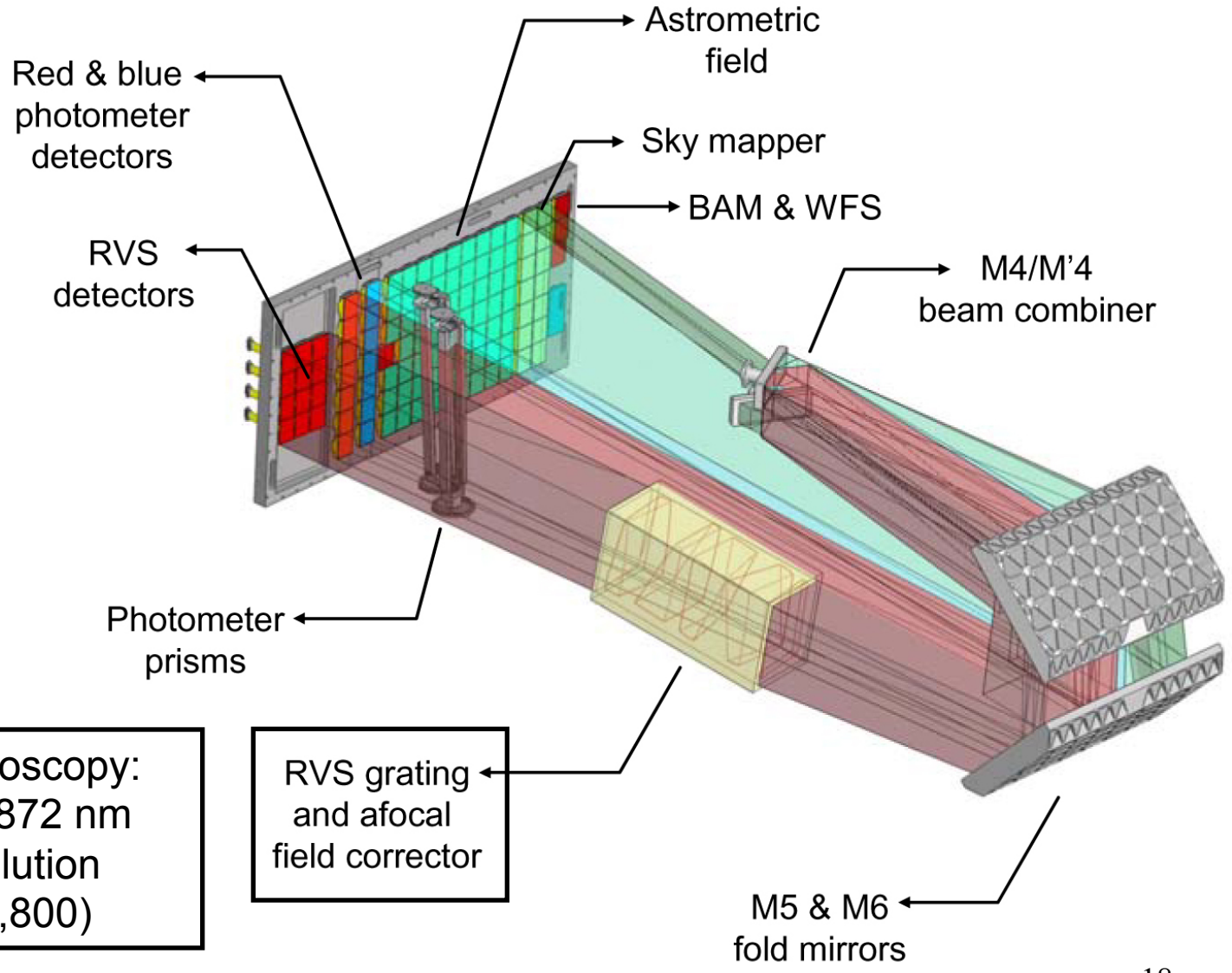
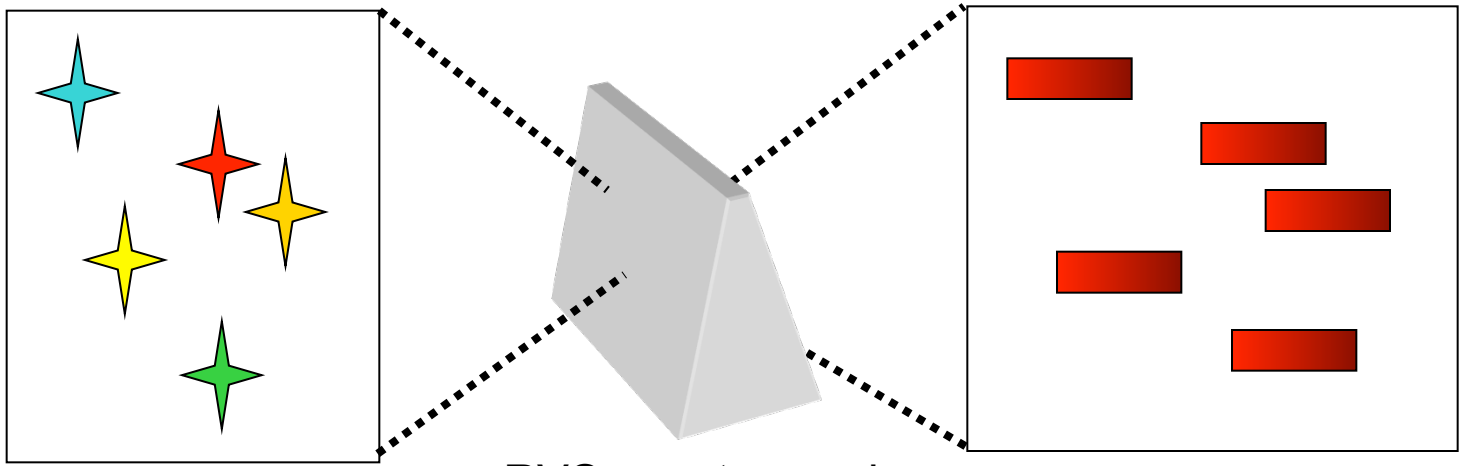
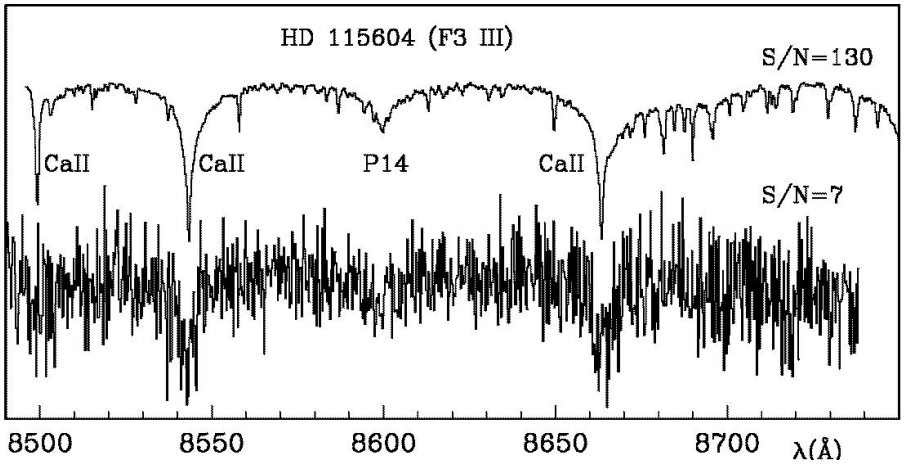


Figure courtesy EADS-Astrium

Radial-Velocity Measurement Concept (2/2)





RVS spectra of F3 giant (V = 16 mag)
S/N = 7 (single measurement)
S/N = 130 (summed over mission)

Figures courtesy David Katz

Data Reduction Principles

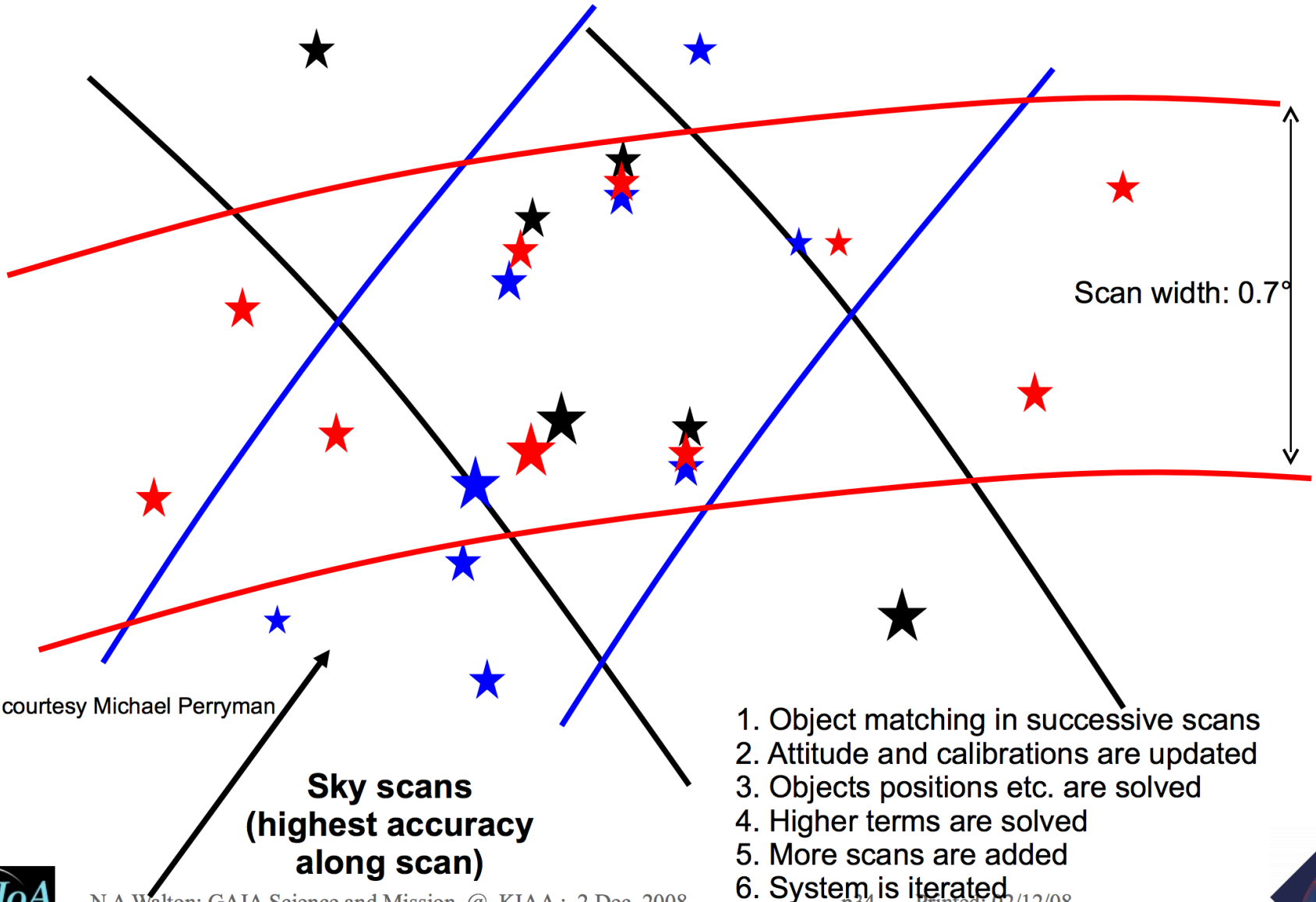


Figure courtesy Michael Perryman

1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher terms are solved
5. More scans are added
6. System is iterated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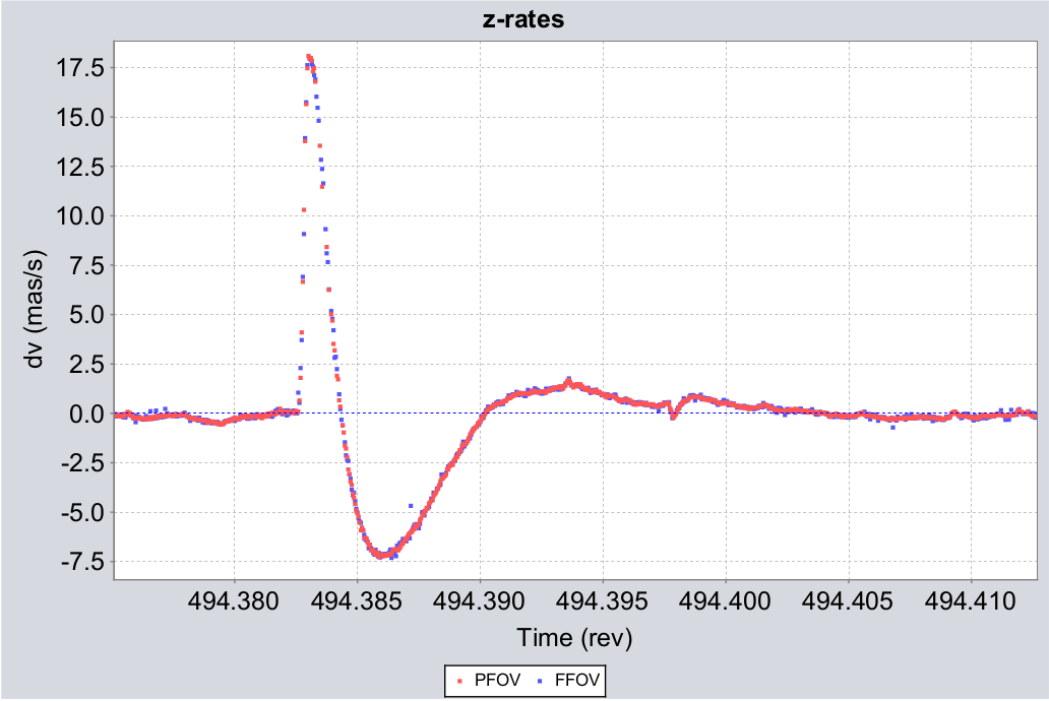
Commissioning results

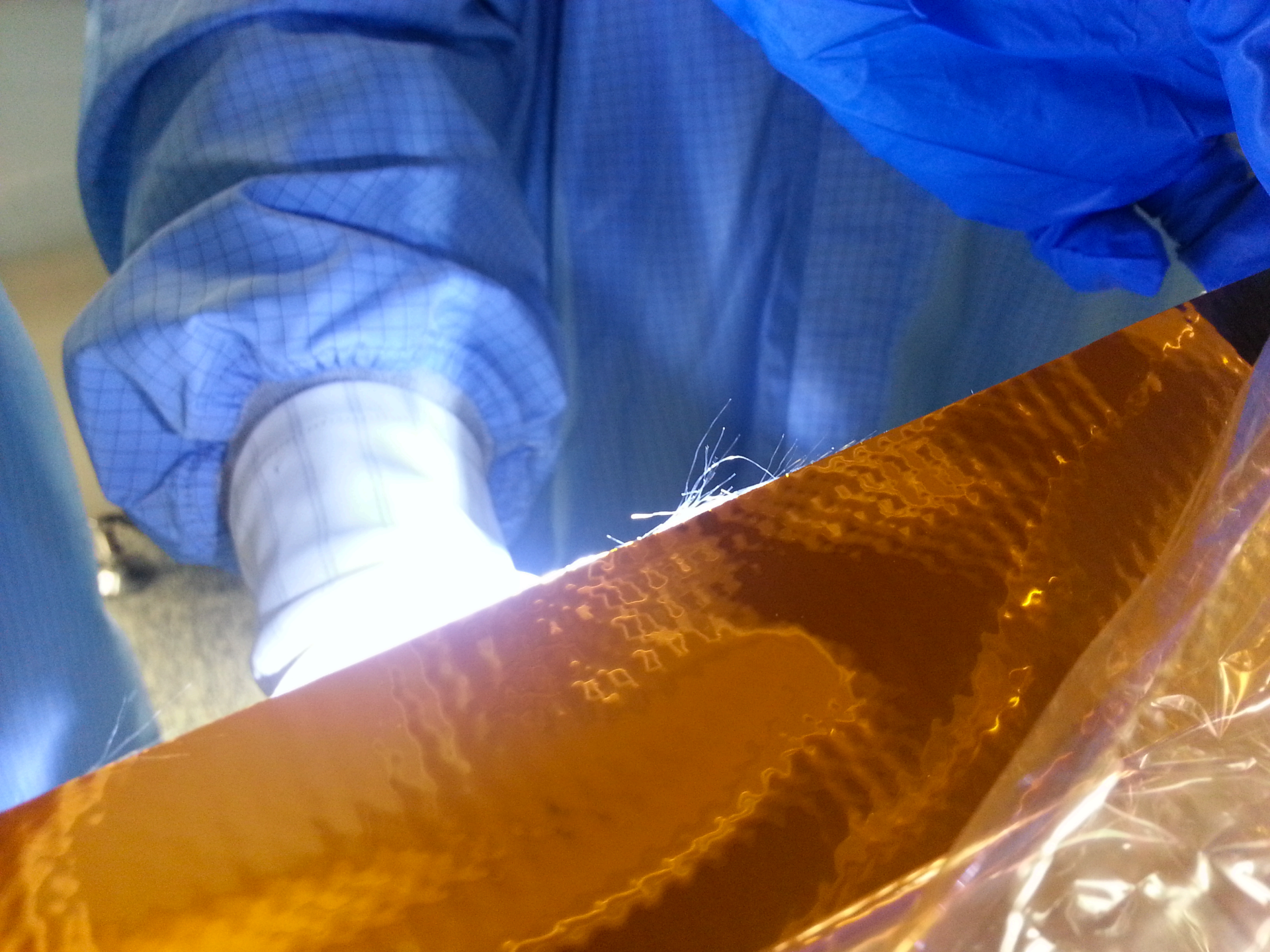
- Micro propulsion system working well
- Attitude and orbit control system functioning well
- Phased array antenna operating with healthy link budget
- Clock working at required accuracy
- 106 CCDs, electronics, data acquisition and storage all functioning



Micro-meteoroid hit example,
figure courtesy F. van Leeuwen

Unwanted surprises

- Stray light both from astronomical sources and the Sun
  - Sun stray light due to scattering by fibres at sunshield edges
  - Impacts faint sources, especially in spectroscopy
- Transmission loss due to continuing contamination of mirrors by water
  - Water source not yet exhausted, maximum contamination rate now at 3 mmag/day
  - Currently primarily blue light is affected
- Basic Angle variation larger than expected
- Video Processing Unit (VPU) resets observed around high density regions



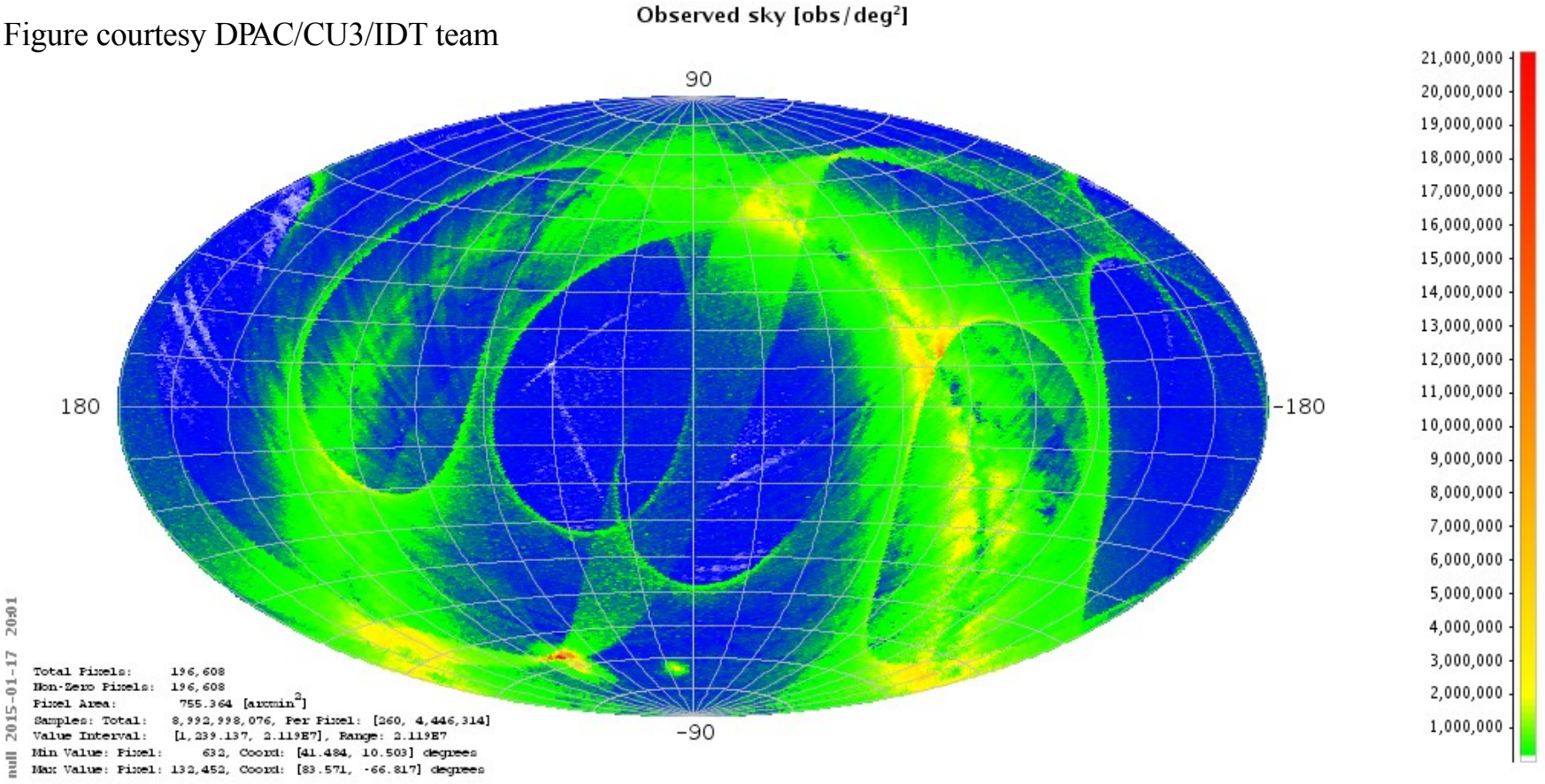
Next steps

- Stray light
  - Root cause understood
  - Data processing software adapted to model background fluctuations
  - On-board S/W modification being implemented for the spectroscopy
- Contamination
  - A new decontamination procedure has been executed involving a short heating of mirrors (executed 22–23 September) → full transmission recovery and re-focus 24 October with continued monitoring
- Basic Angle variation larger than expected
  - Analysis of dedicated measurements have verified reality of Basic Angle variation
  - Working group established to chase the root cause of the variations
- VPU software patch with more diagnostics was uplinked

Data collection stats

Number of astrometric observations per square degree up to end of January

Figure courtesy DPAC/CU3/IDT team



Whole sky seen by Gaia! — Up to 21 million per square degree

As of End Jan 2015: 16 billion astrometric/photometric transits, 1.6 billion spectroscopic

Early astrometric performance assessment

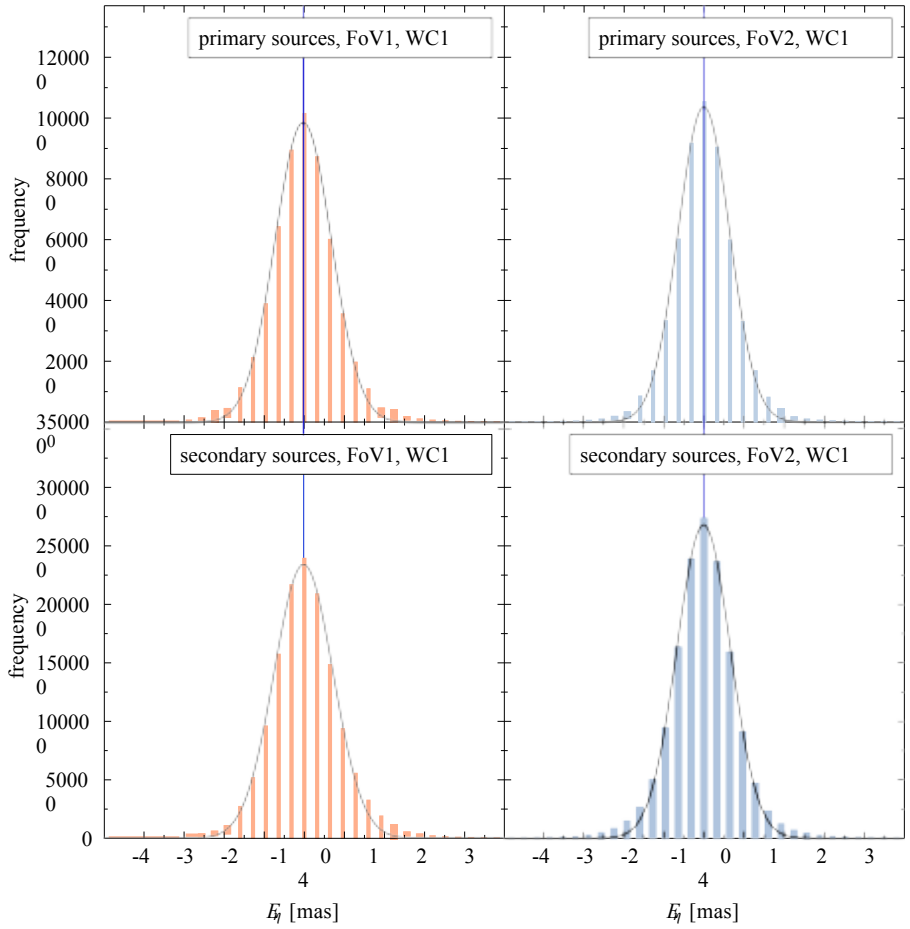
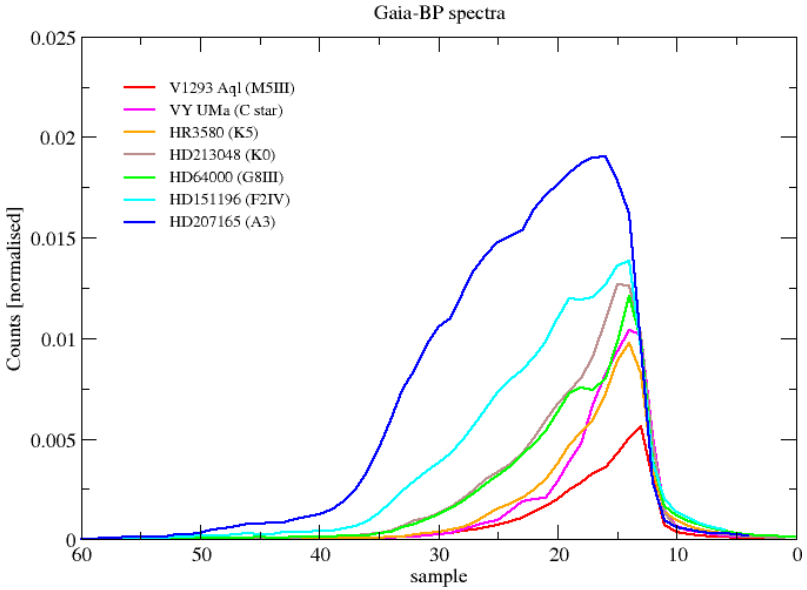
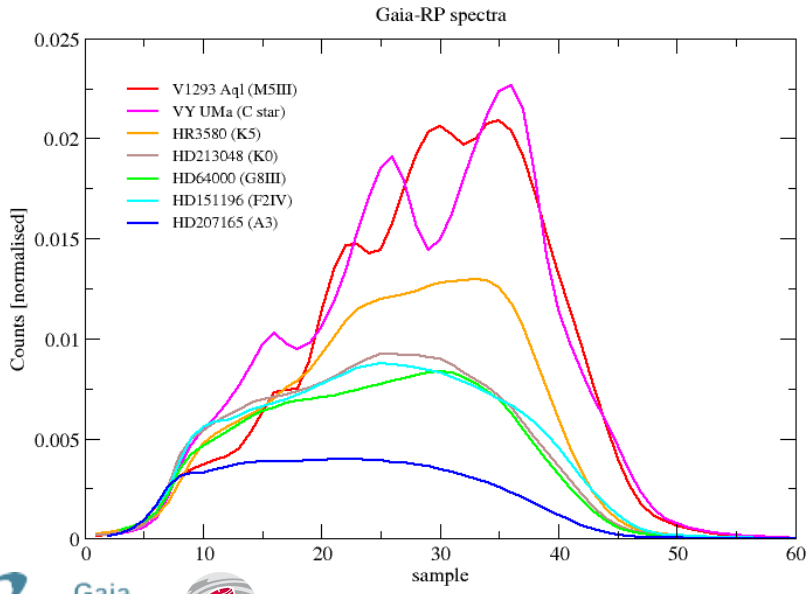


Figure courtesy First Look team

- ODAS Residuals 0.6 mas at G = 15 in June/July
  - target is 0.3 mas
- Caveats at this stage
  - coarse attitude model
  - poor PSF calibrations, no source colours
  - imperfect stray light corrections
  - throughput loss
- For clean telescopes throughput is as expected
- Read noise within requirements
- Corrections for bias non-uniformity under control
- High accuracy timing works nominally (detailed verification pending)

Early photometric performance assessment

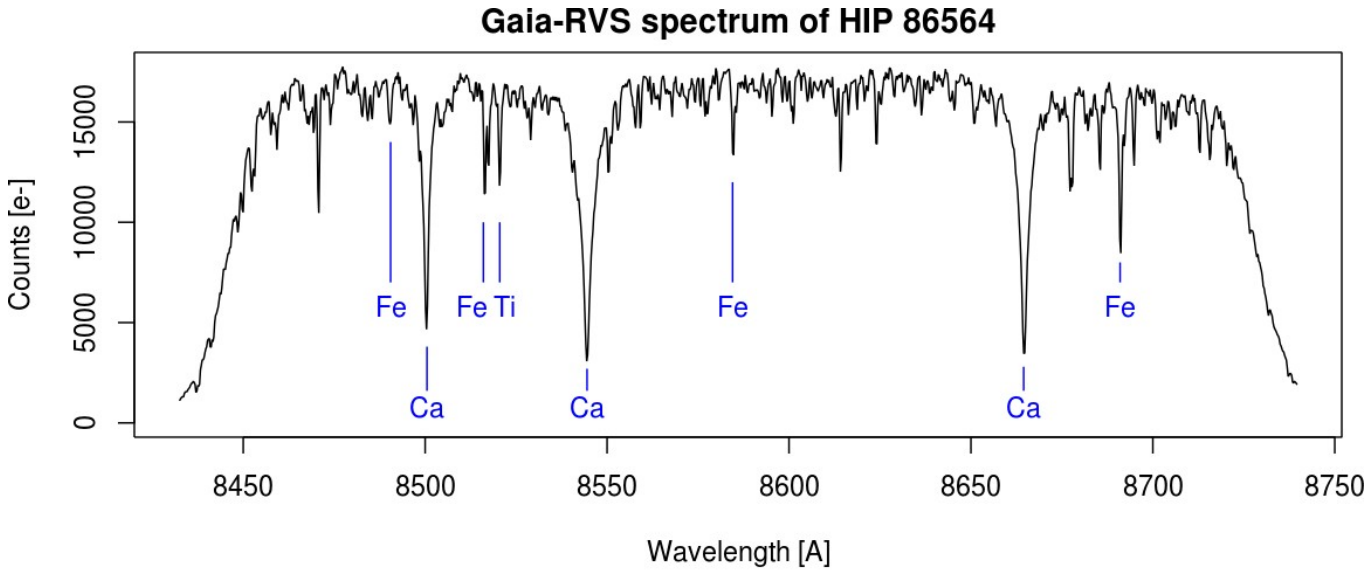




- Spectra appear as expected: classification and parametrization possible
- For clean telescopes throughput is as expected
- Read noise within requirements
- Corrections for bias non-uniformity under control

Figure courtesy C. Jordi & J.-M. Carrasco

Preliminary RVS performance at bright end



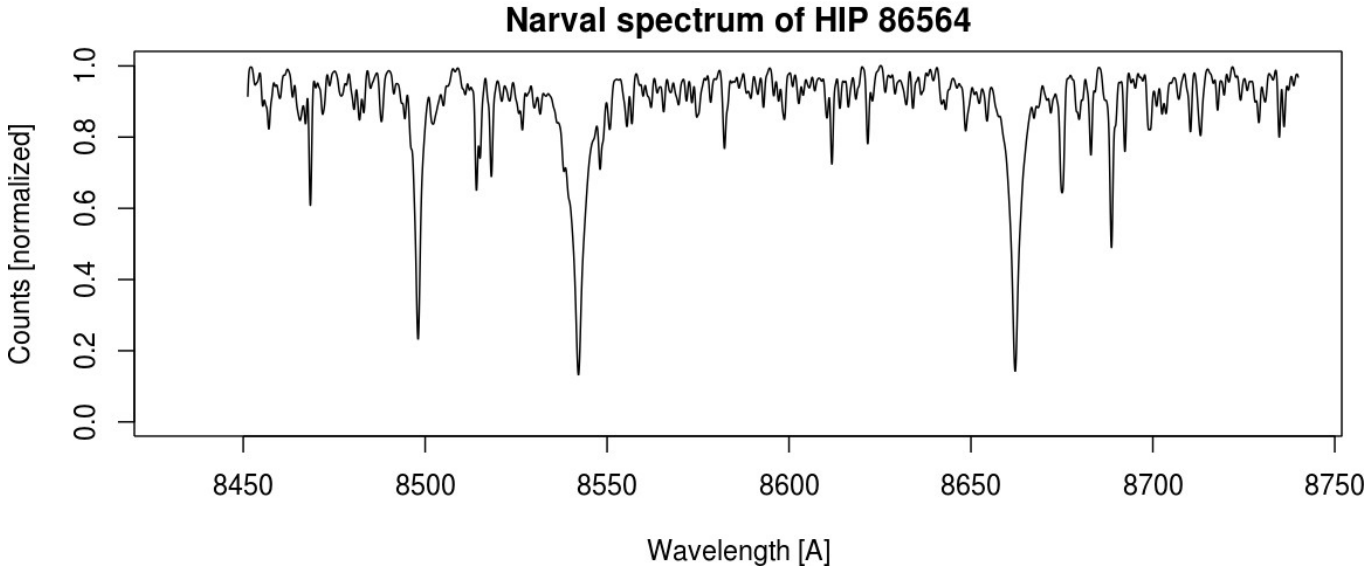
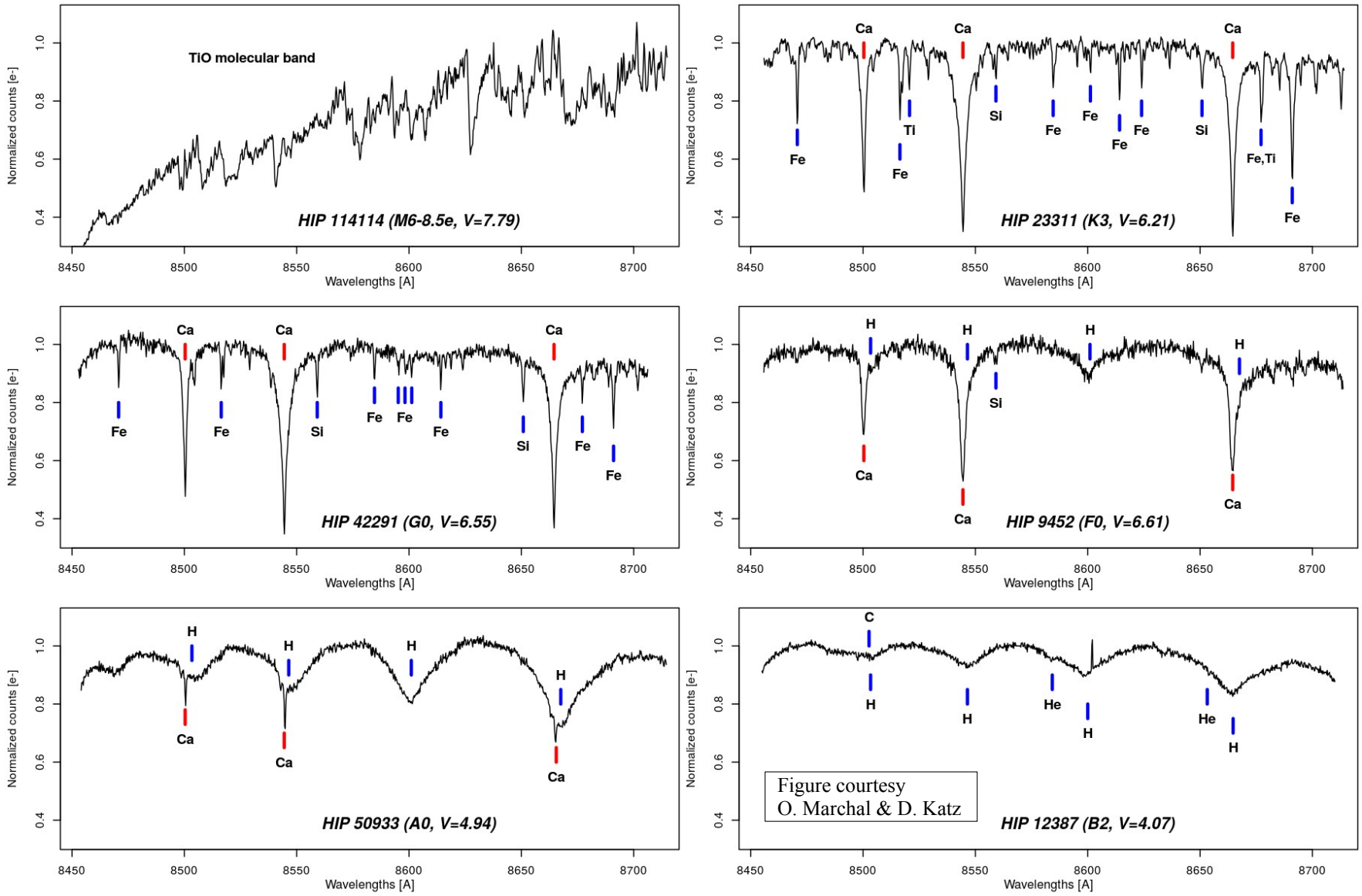


Figure courtesy D. Katz, O. Marchal, C. Soubiran

Preliminary RVS performance at bright end



Preliminary RVS performance at bright end

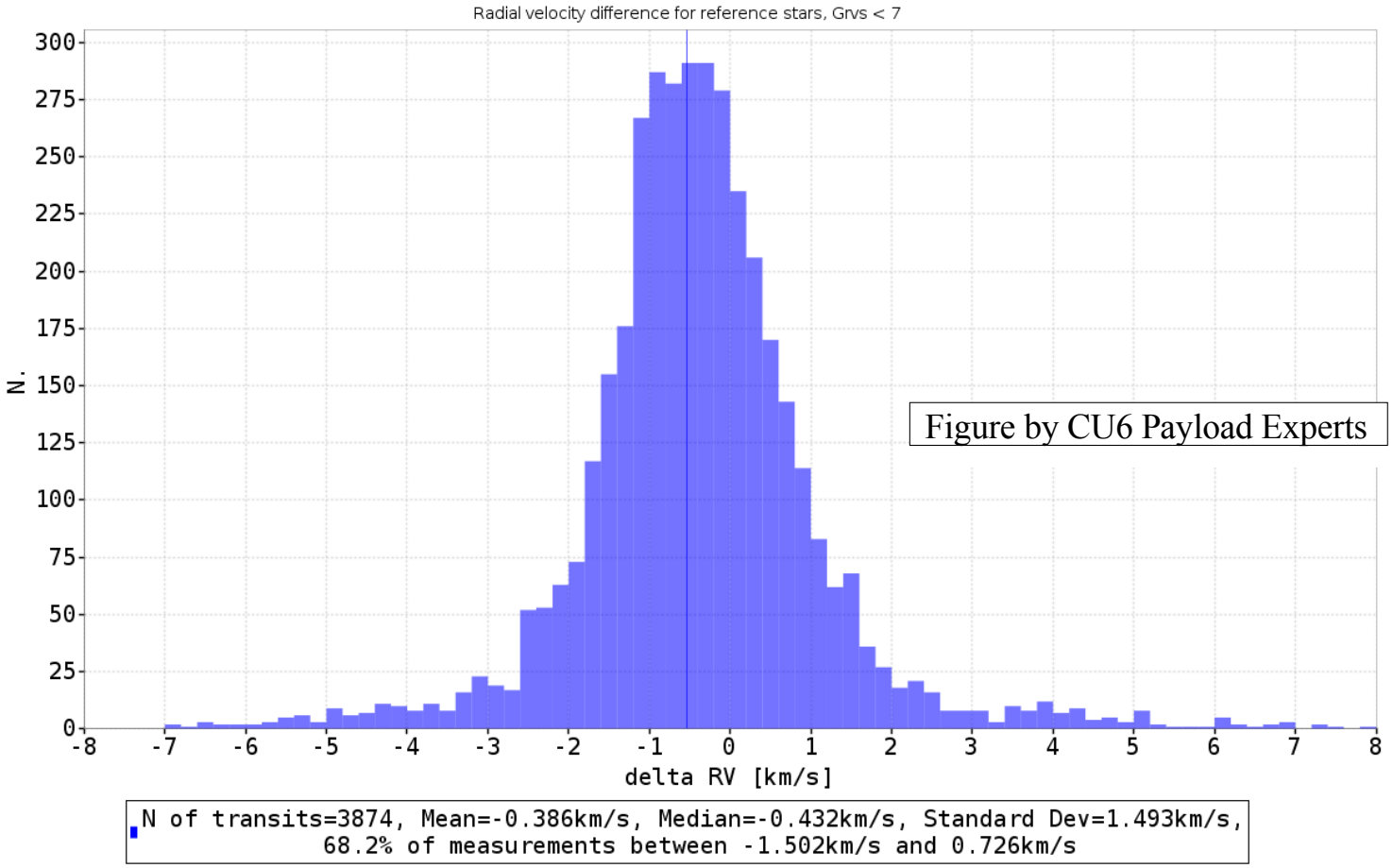
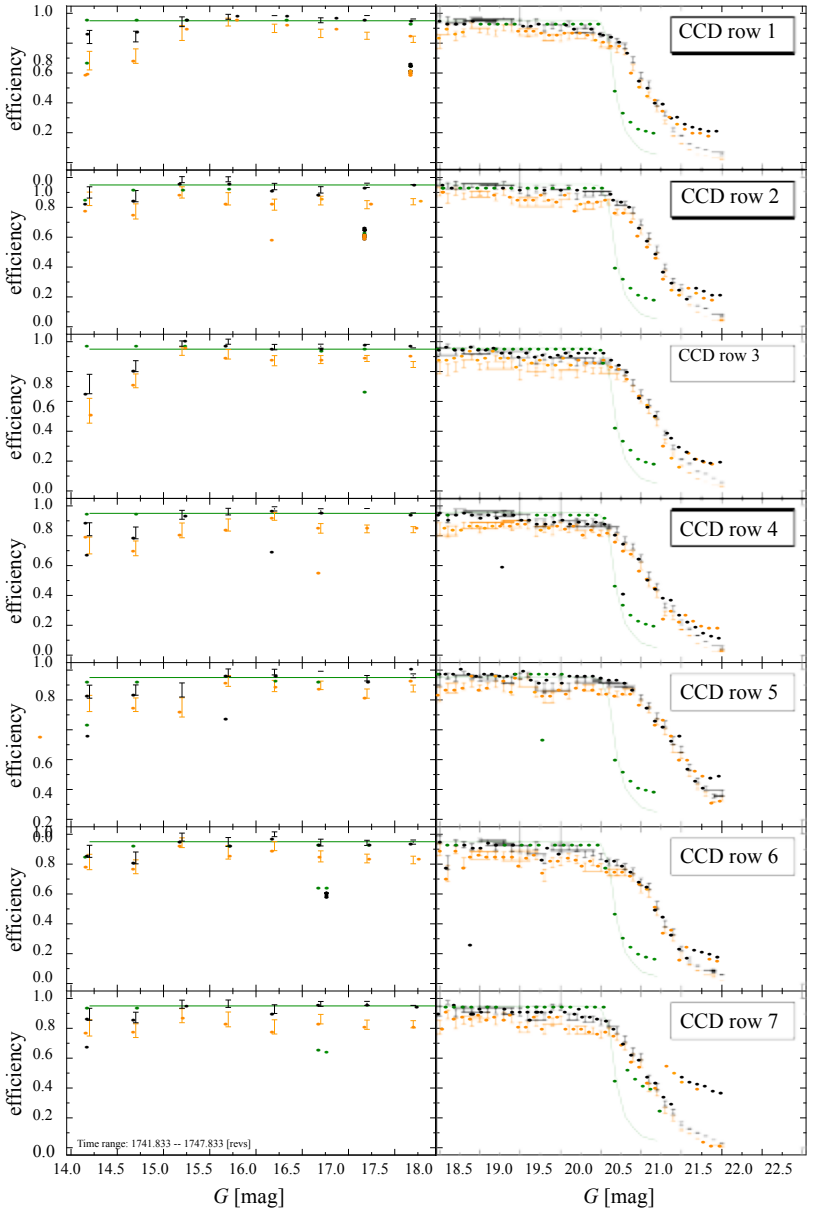
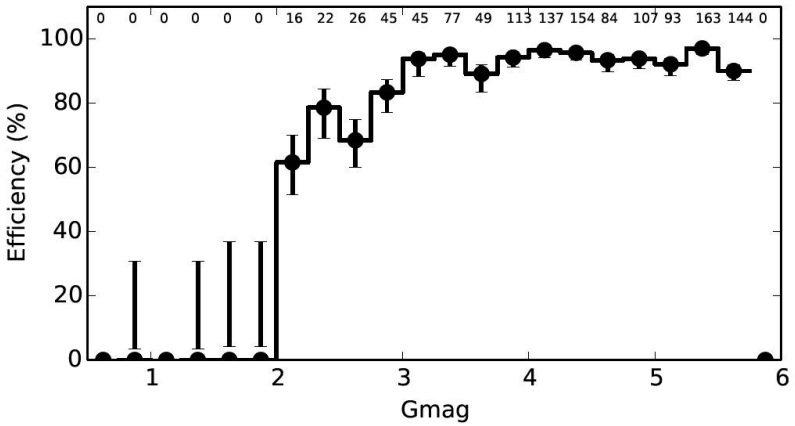


Figure by CU6 Payload Experts

- Differences between measured and expected v_{rad} for bright ($G_{RVS} < 7$) ground based radial velocity standards
- 68% of measurements are within 1.1 km s^{-1} from the median

Detection efficiencies





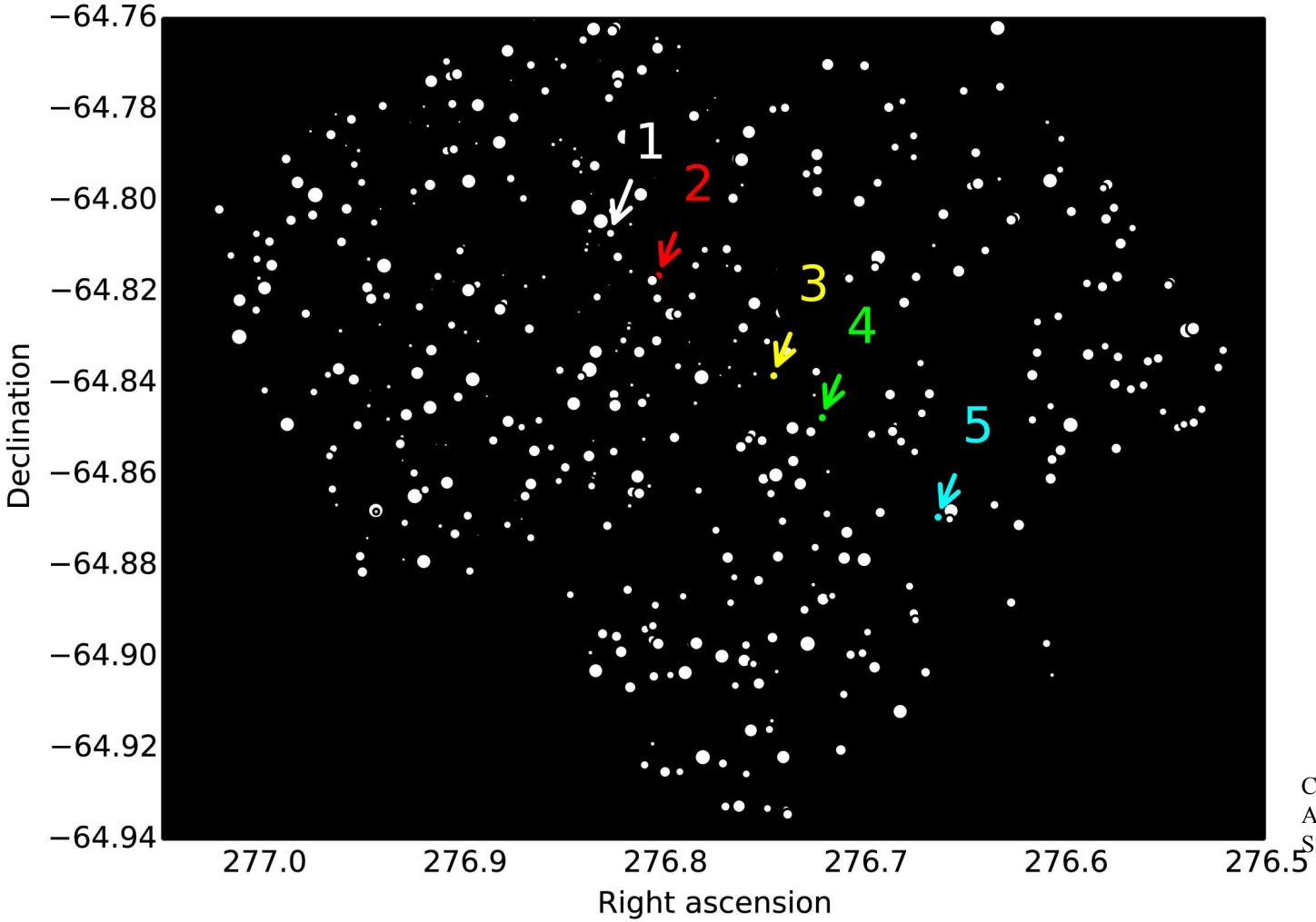
- Faint end efficiencies measured against dedicated Ecliptic Pole survey
- Bright end extended to $G \approx 0$ through detection algorithm improvements and employment of special observing mode

Figures courtesy DPAC-FL team and SOC Calibration Team

Solar system objects

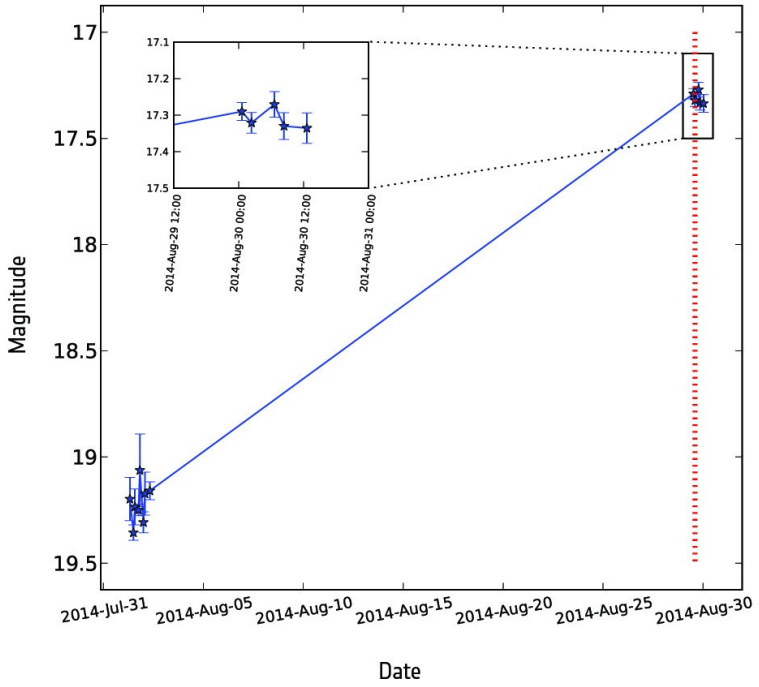
Credits: ESA/Gaia/DPAC/Airbus DS, UB-IDT, OCA-SSO

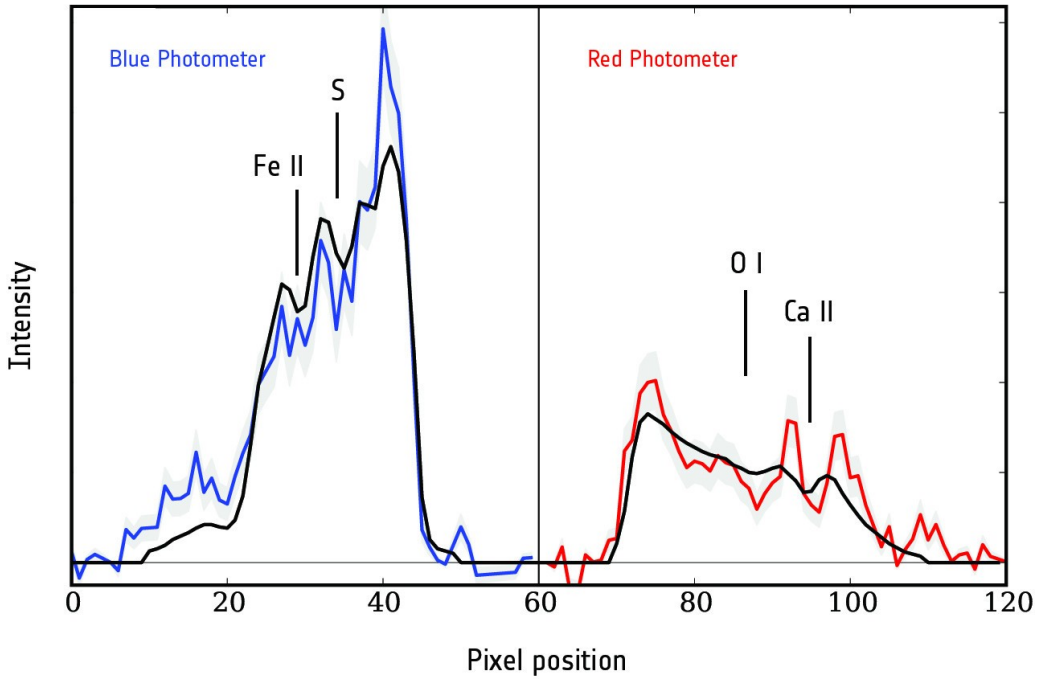
Solar system objects

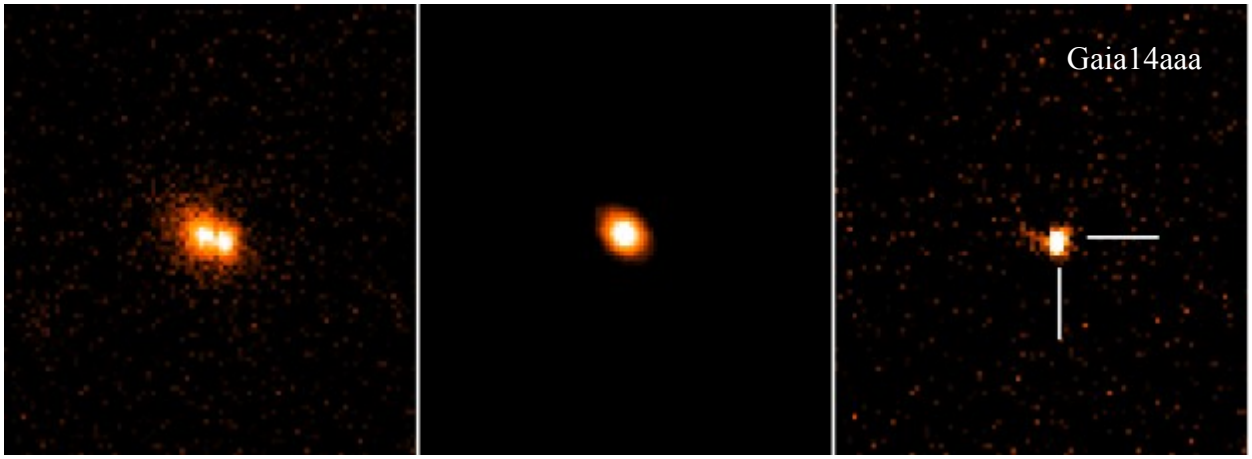


Credits: ESA/ Gaia/ DPAC/ Airbus DS, UB-IDT, OCA-SSO

First supernova discovery

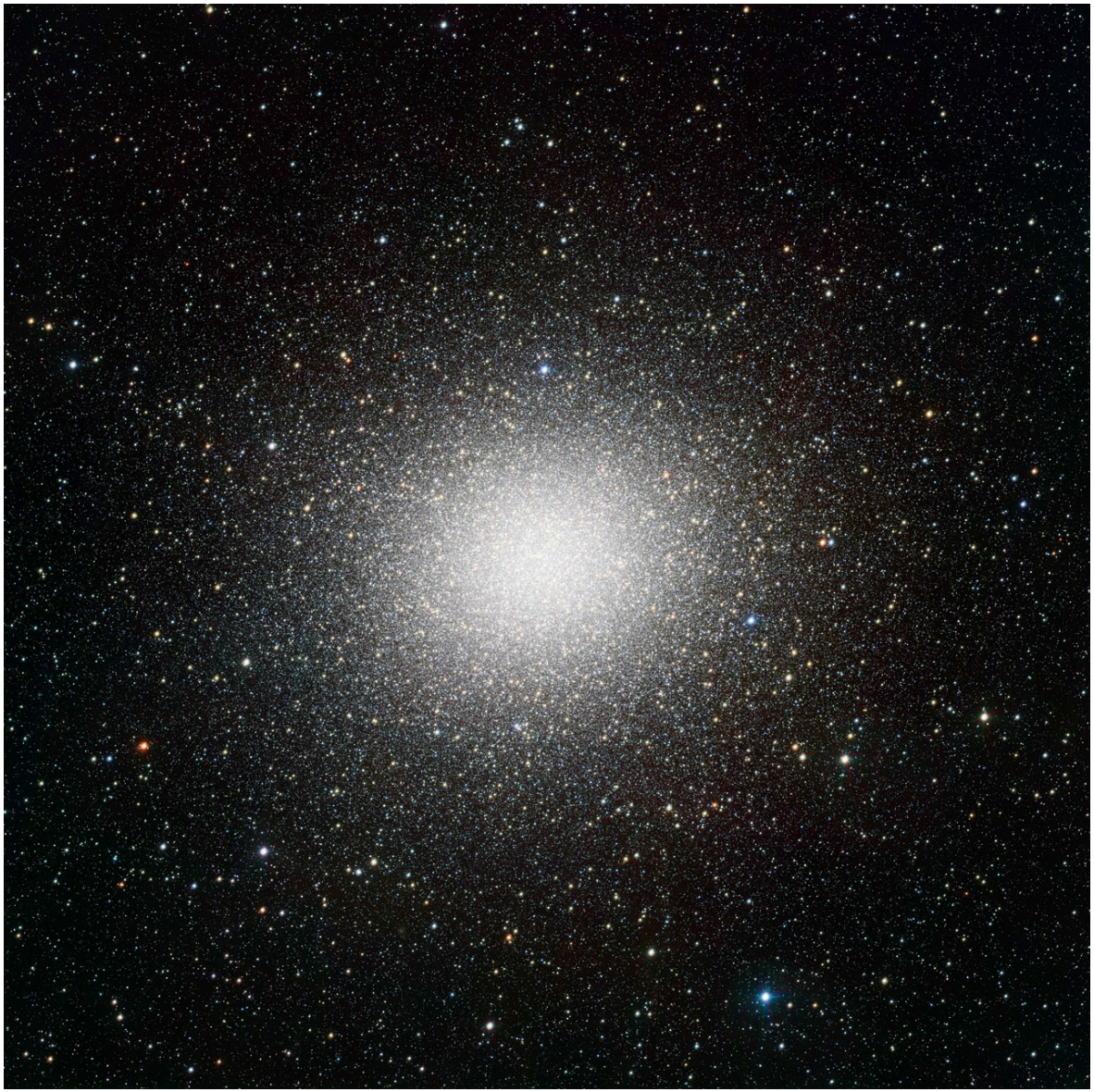




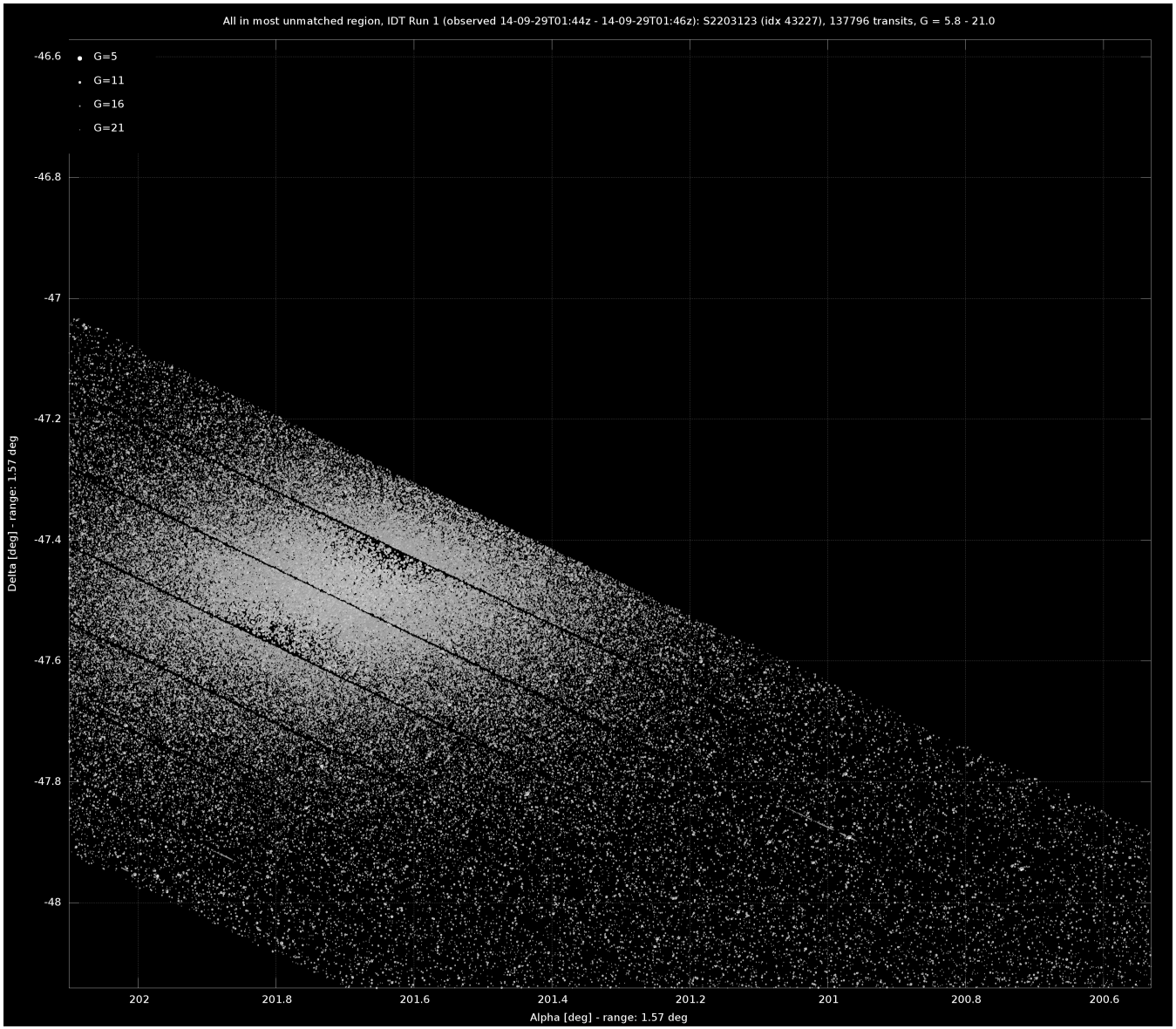


Credits: M. Fraser/ S. Hodgkin/ Ł. Wyrzykowski/ H. Campbell/ N. Blagorodnova/ Z. Kostrzewa-Rutkowska/ Liverpool Telescope/ SDSS/ ESA/ Gaia/ DPAC

Omega Centauri



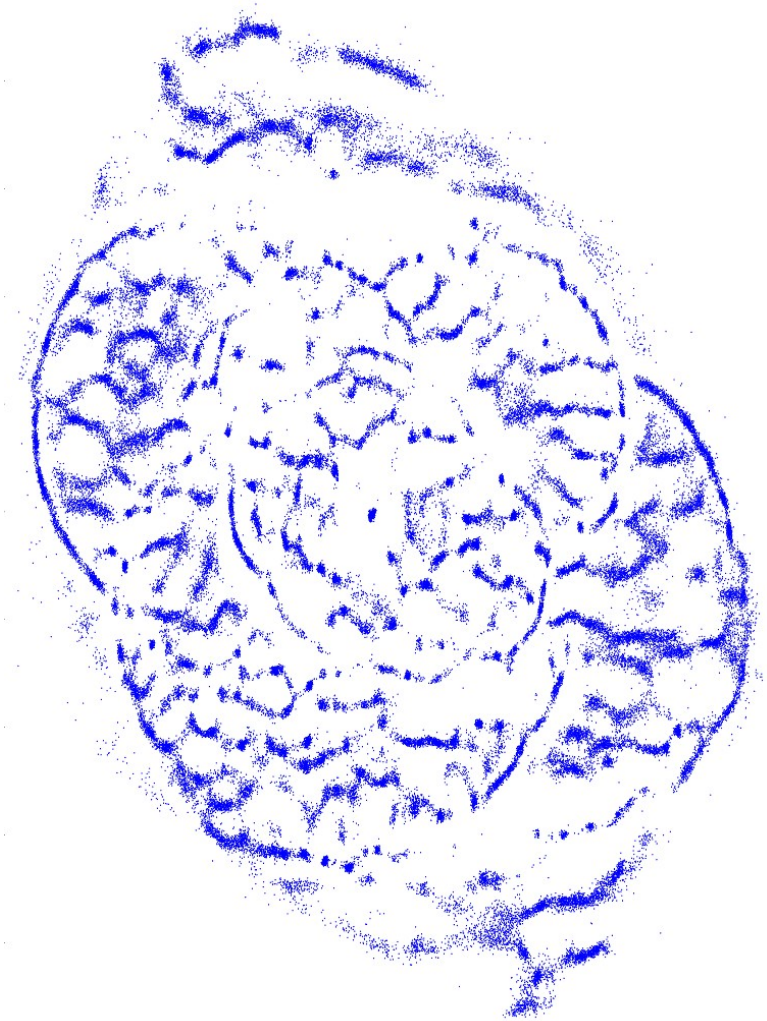
Credits: ESO/ INAF-VST/ OmegaCAM



The Gaia view

Credits: ESA/ Gaia/ DPAC/ UB/ IEEC

The Cat's Eye

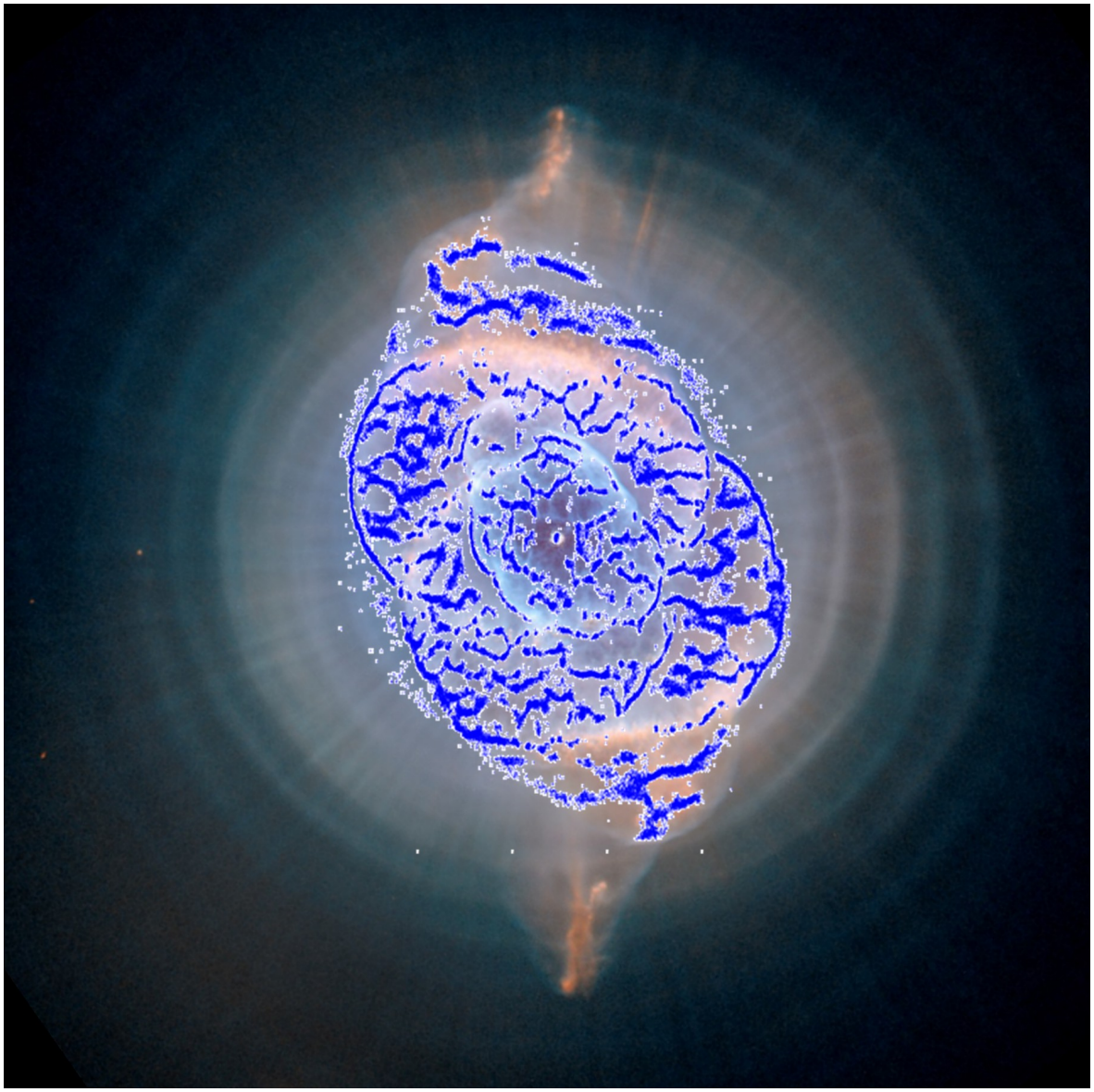


Credits: ESA/ Gaia/ DPAC/ UB/ IEEC

The Cat's Eye

Credits: NASA, ESA, HEIC, and The Hubble Heritage Team (STScI/AURA)

The Cat's Eye



Credits: NASA, ESA, HEIC, and The Hubble Heritage Team (STScI/AURA)

Credits: ESA/ Gaia/ DPAC/ UB/ IEEC

Expected Performance Based on Commissioning Data

	B1V	G2V	M6V
V-I_C [mag]	-0.22	0.75	3.85
Bright stars	5-16 μas (3 mag < V < 12 mag)	5-16 μas (3 mag < V < 12 mag)	5-16 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

	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 (millimag)

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

Radial velocity performance

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

Data Release Scenarios

- **First release: summer 2016**
  - Positions and G-band magnitudes for ~all stars (90% of the sky will have been covered)
  - Ecliptic pole data (region of high overlap)
  - Stars common with the Hipparcos Catalog
- **Second release: early 2017**
  - Five-parameter astrometric solutions of objects with single-star behavior
  - Integrated BP/RP photometry
  - Mean radial velocities will be released for objects showing no radial-velocity variation
- **Third release: 2017 or 2018**
- **Fourth release: 2018 or 2019**

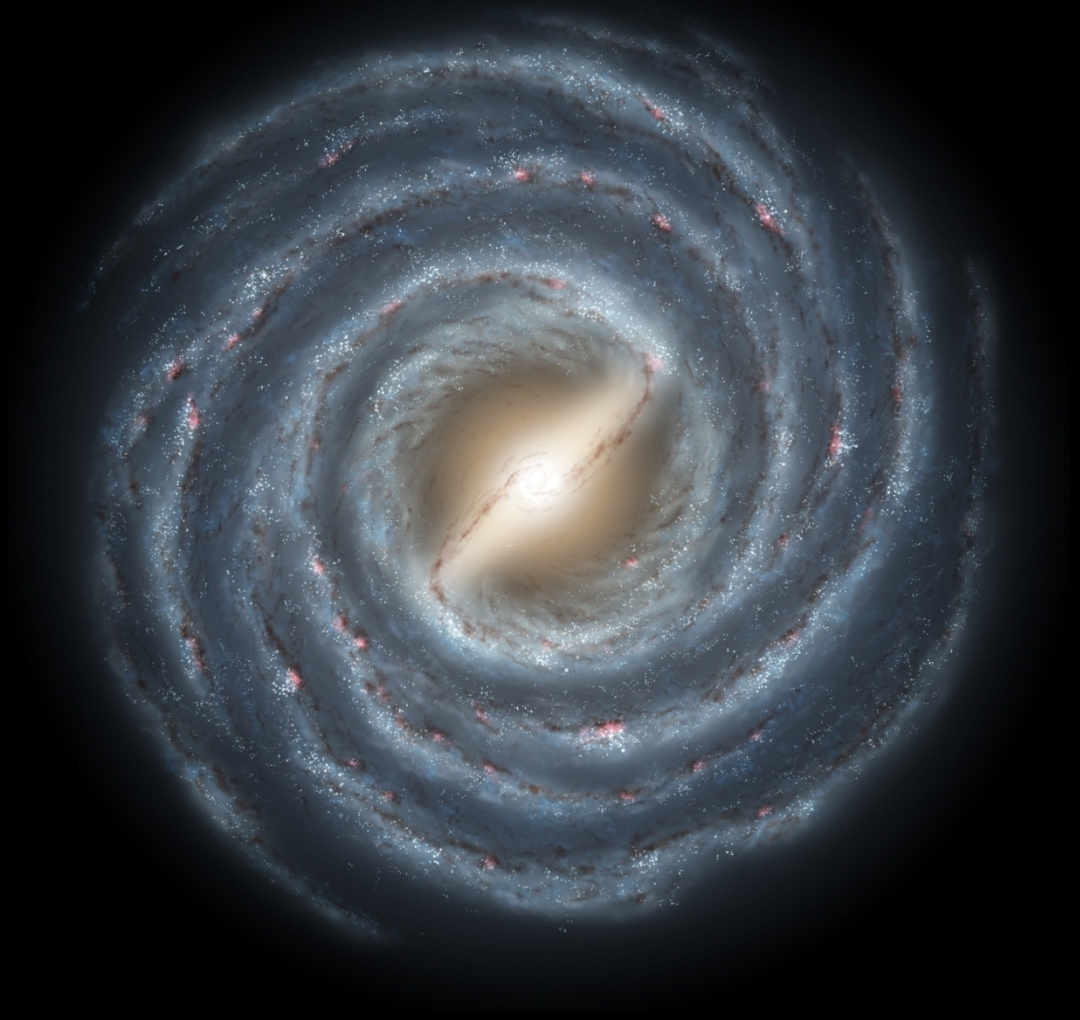
http://www.cosmos.esa.int/web/gaia/release

Data Release Scenarios

- **Final release: 2022**
  - Full astrometric, photometric, and radial-velocity catalogues.
  - All available variable-star and non-single-star solutions.
  - Source classifications (probabilities) plus multiple astrophysical parameters (derived from BP/RP, RVS, and astrometry) for stars, unresolved binaries, galaxies, and quasars. Some parameters may not be available for faint(er) stars.
  - An exo-planet list.
  - All epoch and transit data for all sources.
  - All ground-based observations made for data-processing purposes.

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

Gaia



Time line

- Routine phase started with 28 days of Ecliptic Pole Scanning
- Now operating in optimised Nominal Scanning Law
  - catch bright stars near Jupiter in 2017 to detect quadrupole light bending
- No bright magnitude limit
  - Stars G = 3–20.7 observed in nominal mode (and G = 2–3 with 75% probability)
  - Stars brighter than 3 mag with Sky Mapper imaging
- Activities to be finished:
  - Magnitude limit for astrometry and photometry (now 20.7)
  - Magnitude limit for spectroscopy (now 16.2)
  - Upgrade of on-board SW to optimize spectroscopy
  - Decontamination as needed followed by focus check
  - Completion of BA and stray light WG tasks and possible follow-up
  - Sort out ground station time for larger amounts of telemetry
  - Consolidate intermediate release schedule for summer 2016 and early 2017

Schedule

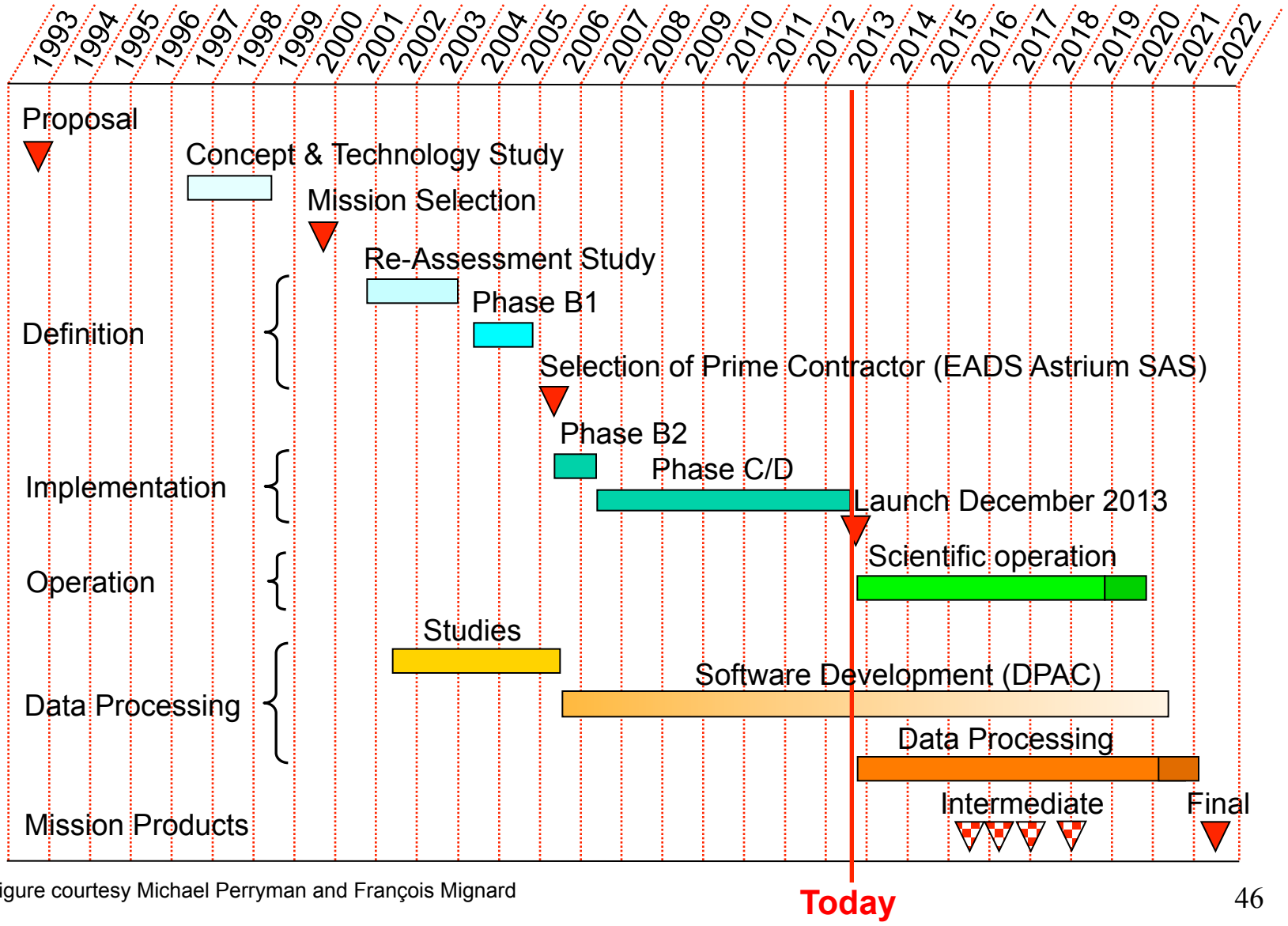
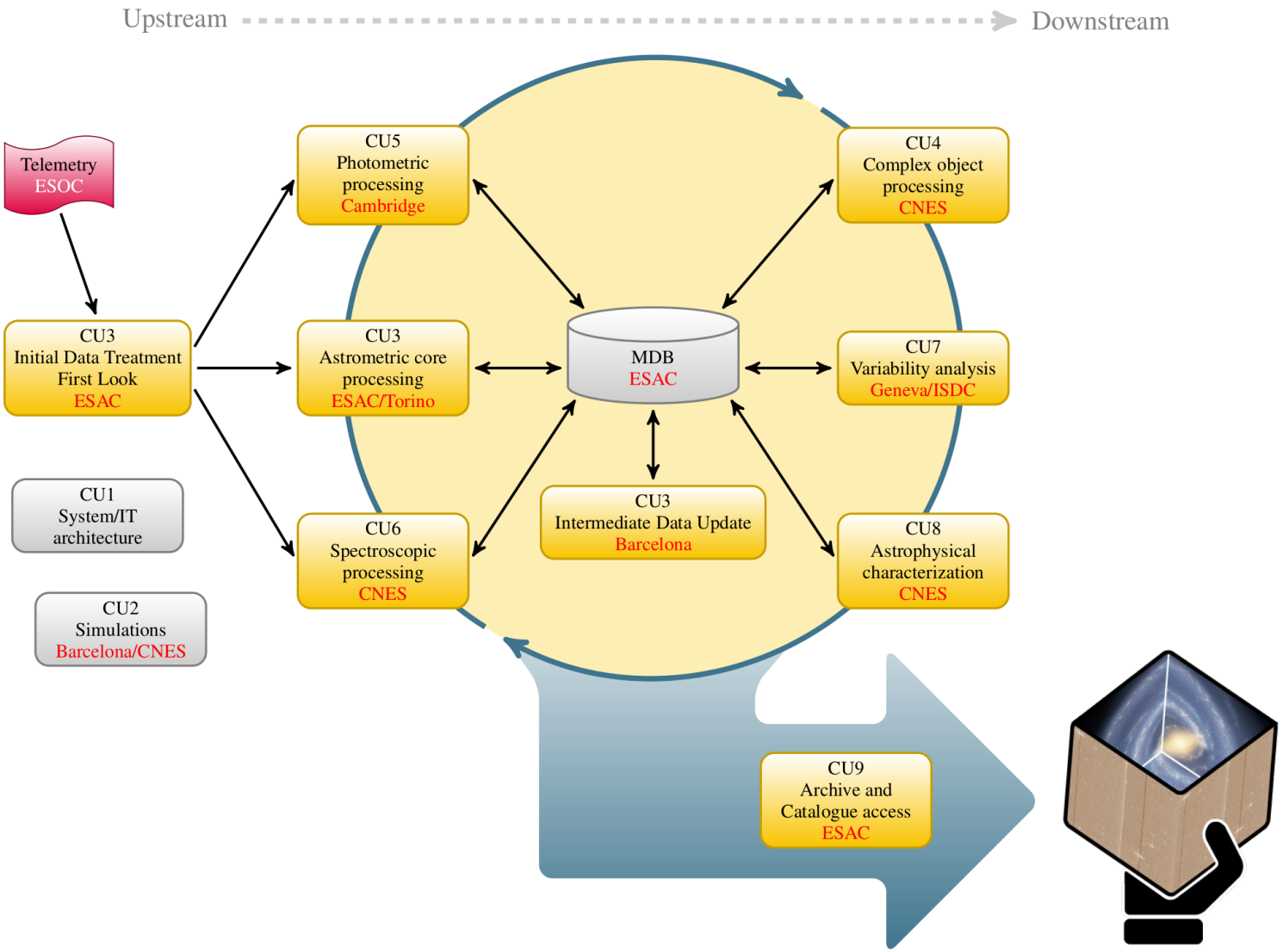
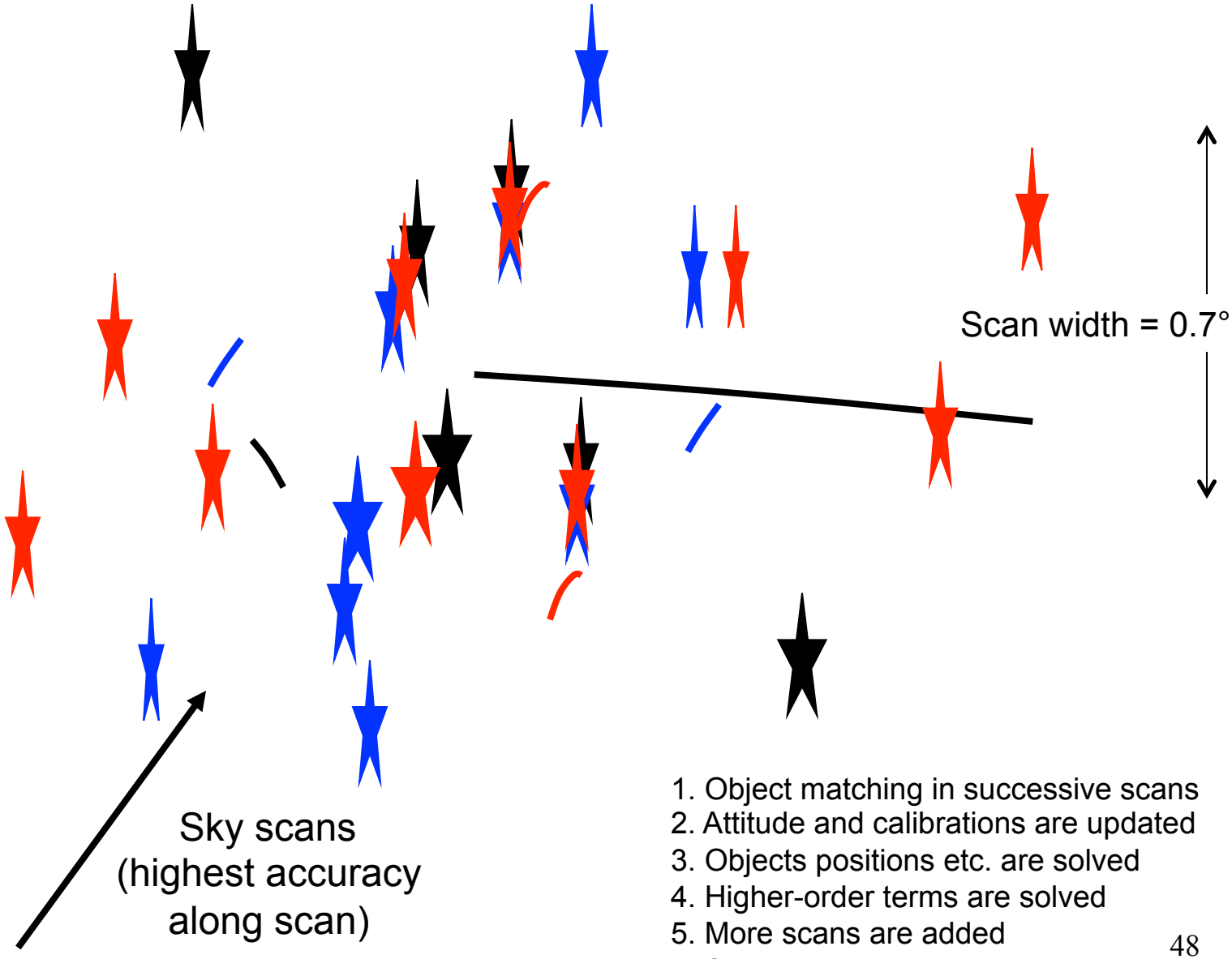


Figure courtesy Michael Perryman and François Mignard

Data Processing Concept



Data-Reduction Principles



1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher-order terms are solved
5. More scans are added
6. System is iterated

Figure courtesy Michael Perryman