Gaia Performances & Observations Principles

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&

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Outline

- Overall Goals of the Mission
- Working Principles
- Performances
- Observing with Windows
- Sky Coverage

Goals of Space Astrometry

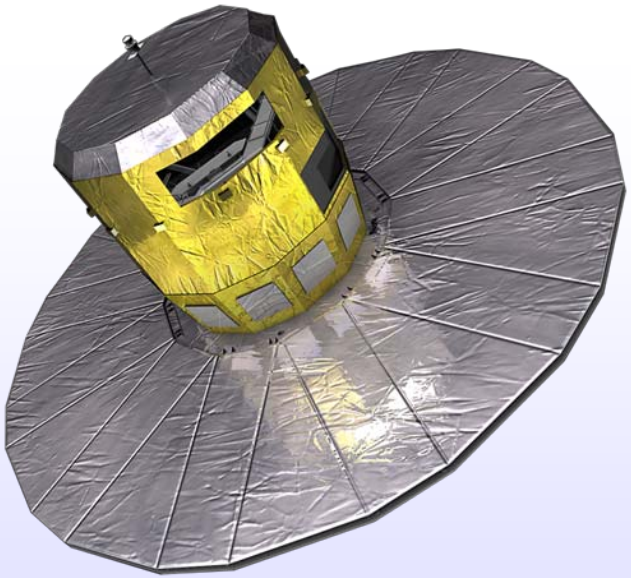
- Primary Objectives not achievable from Earth
  - Ascertain the distances of the stars
    - **absolute** stellar parallaxes for astronomers
  - Define and materialise the inertial frame
    - now based on extragalactic sources
- Secondary objectives
  - Astrophysics with astrometry, photometry, spectroscopy
    - stellar and galactic physics
    - detection of extrasolar planets
    - solar system dynamics
  - Tests of fundamental physics in space
    - based on light path geometry

Mission requirements summary

- A Stereoscopic Census of Our Galaxy
- Astrometry (V < 20):
  - completeness to 20 mag (on-board detection) 10^9 stars
  - parallax accuracy: 7 μas at <10 mag; 12–25 μas at 15 mag 100–300 μas at 20 mag
- Photometry (V < 20):
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
  - 8–20 mmag at 15 mag: Teff ~ 200 K, log g, [Fe/H] to 0.2 dex, extinction
- Radial velocity (V < 16.5–17):
  - Third component of space motion, perspective acceleration
  - <1 km/s at 13-13.5 mag and <15 km/s at 16.5-17 mag

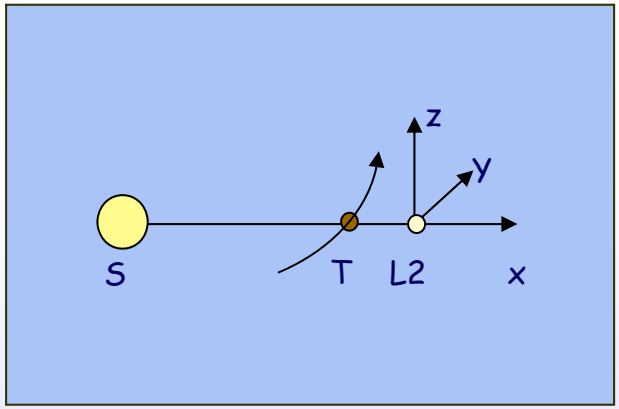
Gaia quick fact sheet

- Main goal : astrometry and photometric survey to V = 20
  - ~ 10^9 sources
    - stars, QSOs, Solar system, galaxies
- Accuracy in astrometry : 25 μas @ V = 15 for parallax
  - 10 μas V < 13 - 300 μas V = 20
- Regular scan of sky over 5 yrs
  - each source observed about ~80 times
  - internal autonomous detection system
- Launch fall 2013 from Kourou
- Current integration of P/L and S/M advancing smoothly

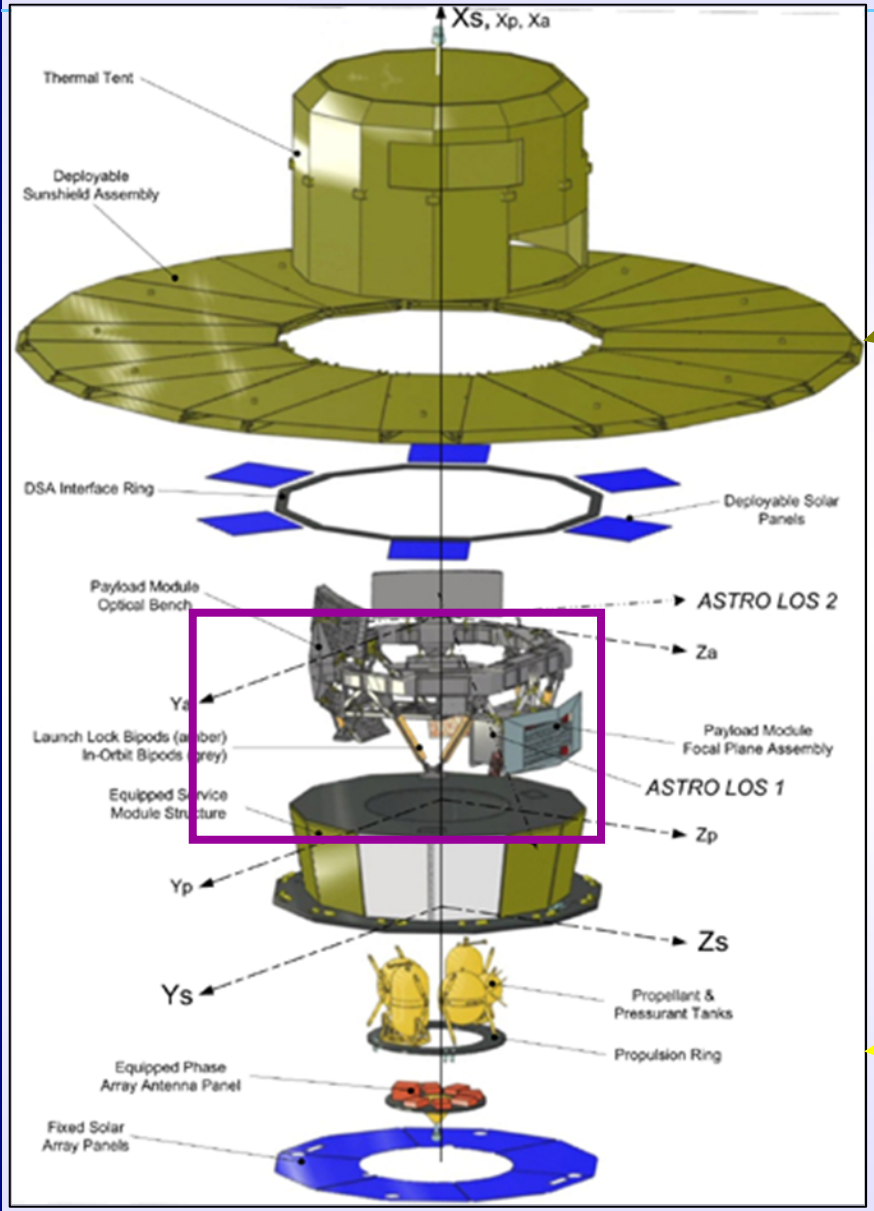


Timeline of the mission

- Selection by ESA in 2000 (and confirmed in 2002)
- Prime contractor selected in February 2006
- Data analysis consortium formed in June 2006
  - selected by ESA SPC in March 2007
- Launch : fall 2013
  - from Kourou with a Soyuz + Fregat
- Orbit around L2
- Continuous observation to 2019
- End of data processing to 2020
- Results and data available in 2021
  - intermediate releases planned during the mission



Gaia: The Spacecraft



Thermal shielding

Ø ~ 10 m

Solar panels

Telescopes

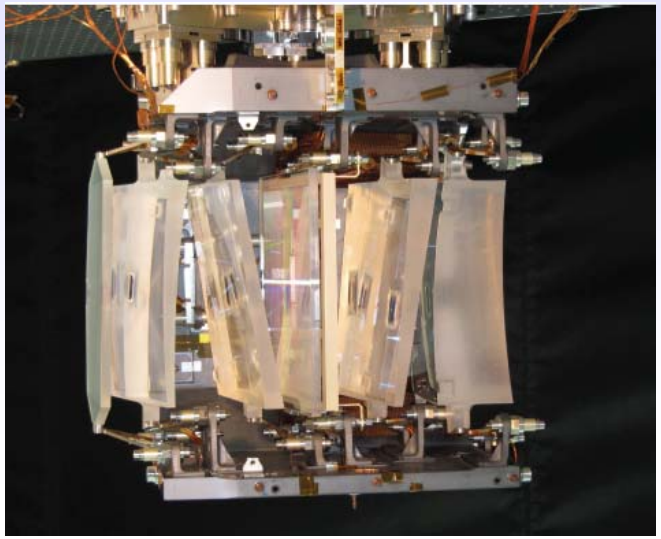
focal plane

Propulsion module

Antenna (2-4 Mbit/s)

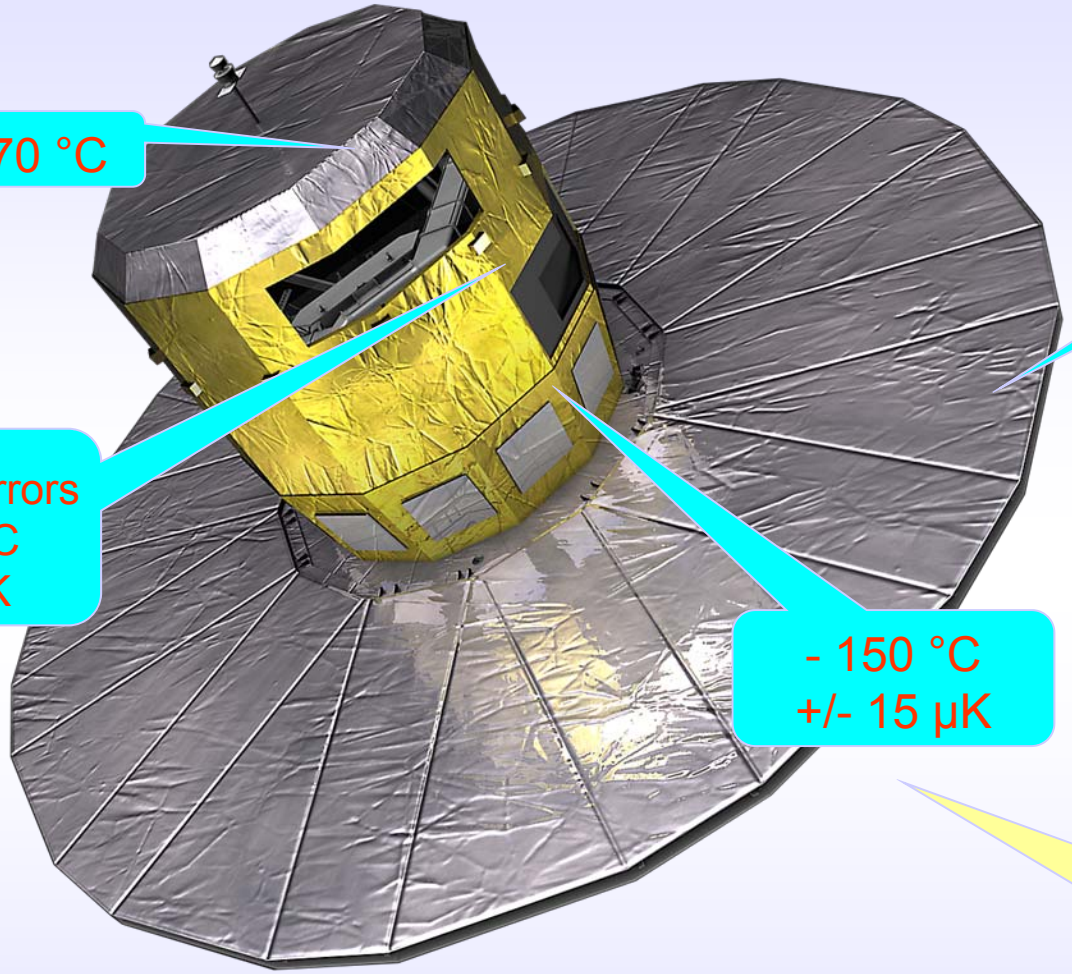
Main Activities on the P/L

- Assembly, Integration and Testing of the payload
- Telescope alignment completed with final checks underway
- Focal Plane Assembly completed
- On-going final thermo-mechanical tests



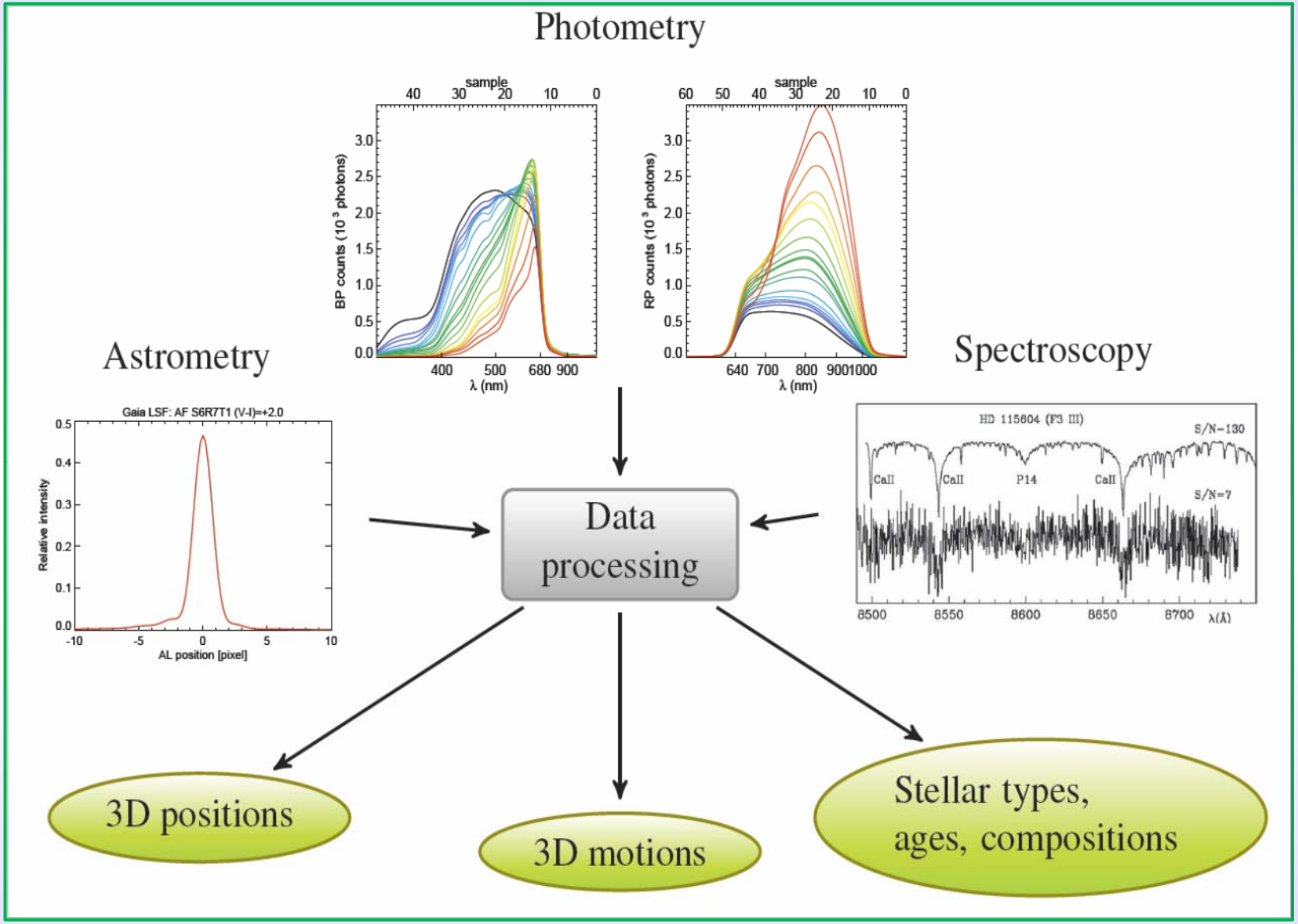


Thermal Insulation

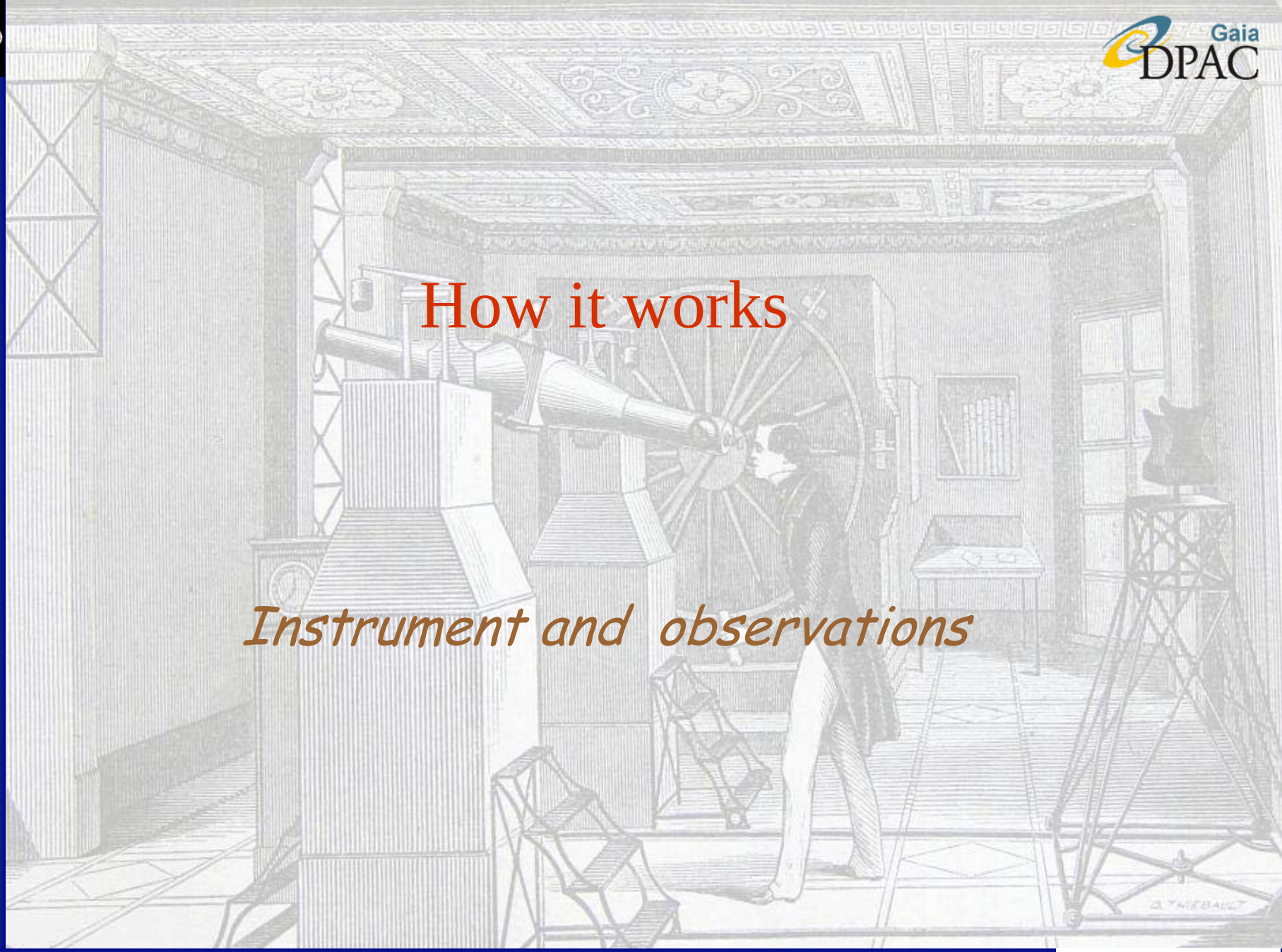


Credit: F. Chassat, Astrium

What Gaia will deliver: wide variety



cartoon: A. Brown

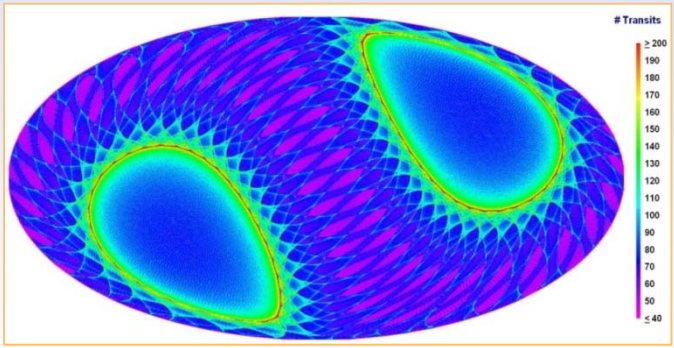


How it works

Instrument and observations

Observation principles

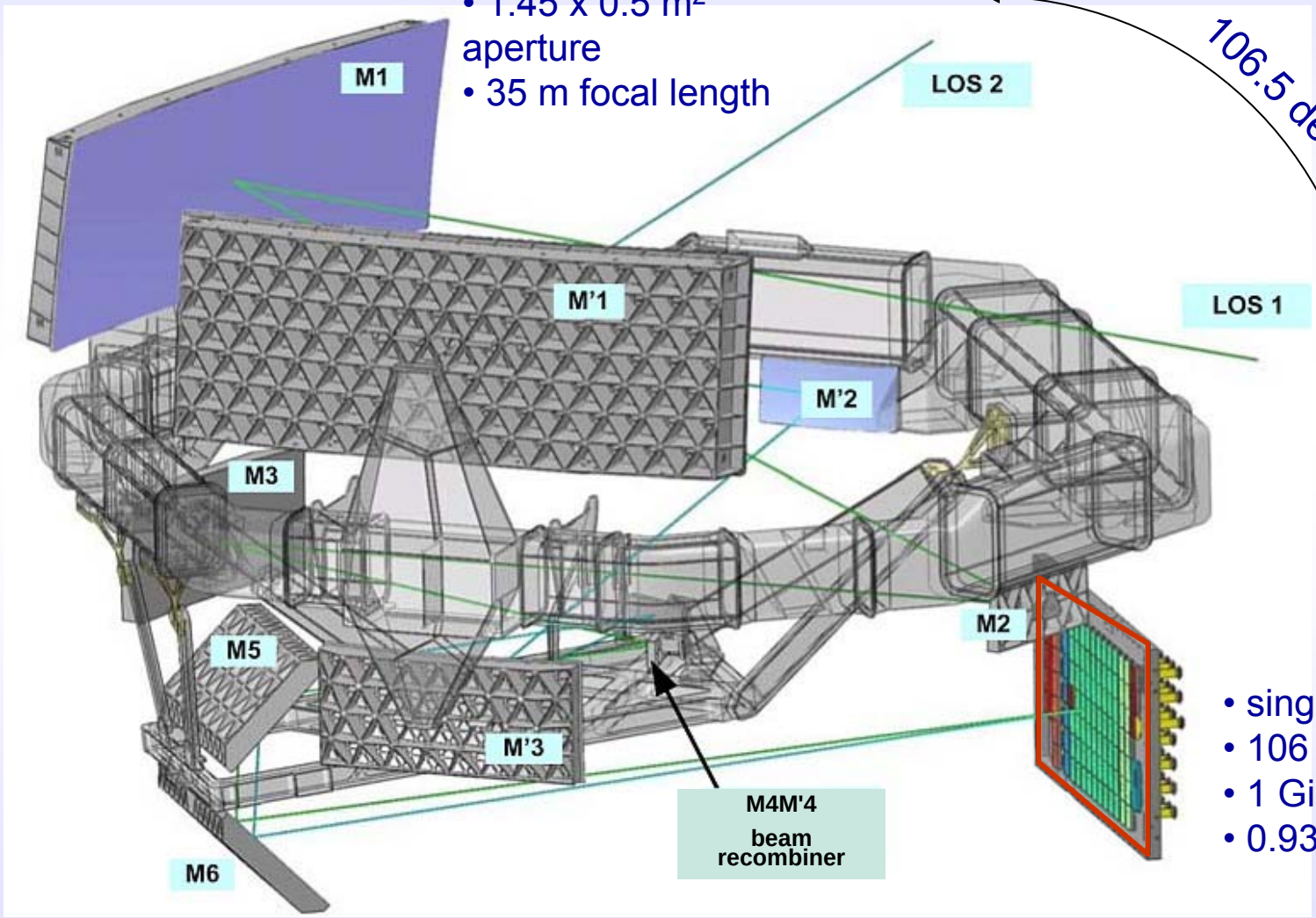
- Gaia is a scanning mission
  - no pointing, no change in the schedule



- Gaia gathers astrometric, photometric and spectroscopic data
  - each source is observed ~ 75 times in astrometry & photom. , 50 in spectroscopy
- Gaia has an internal system of detection
  - sensitivity limited detection at G ~ R = 20
- Objects are reasonably regularly measured during the mission
  - orbit reconstruction
  - light curves

Gaia : telescopes and detector

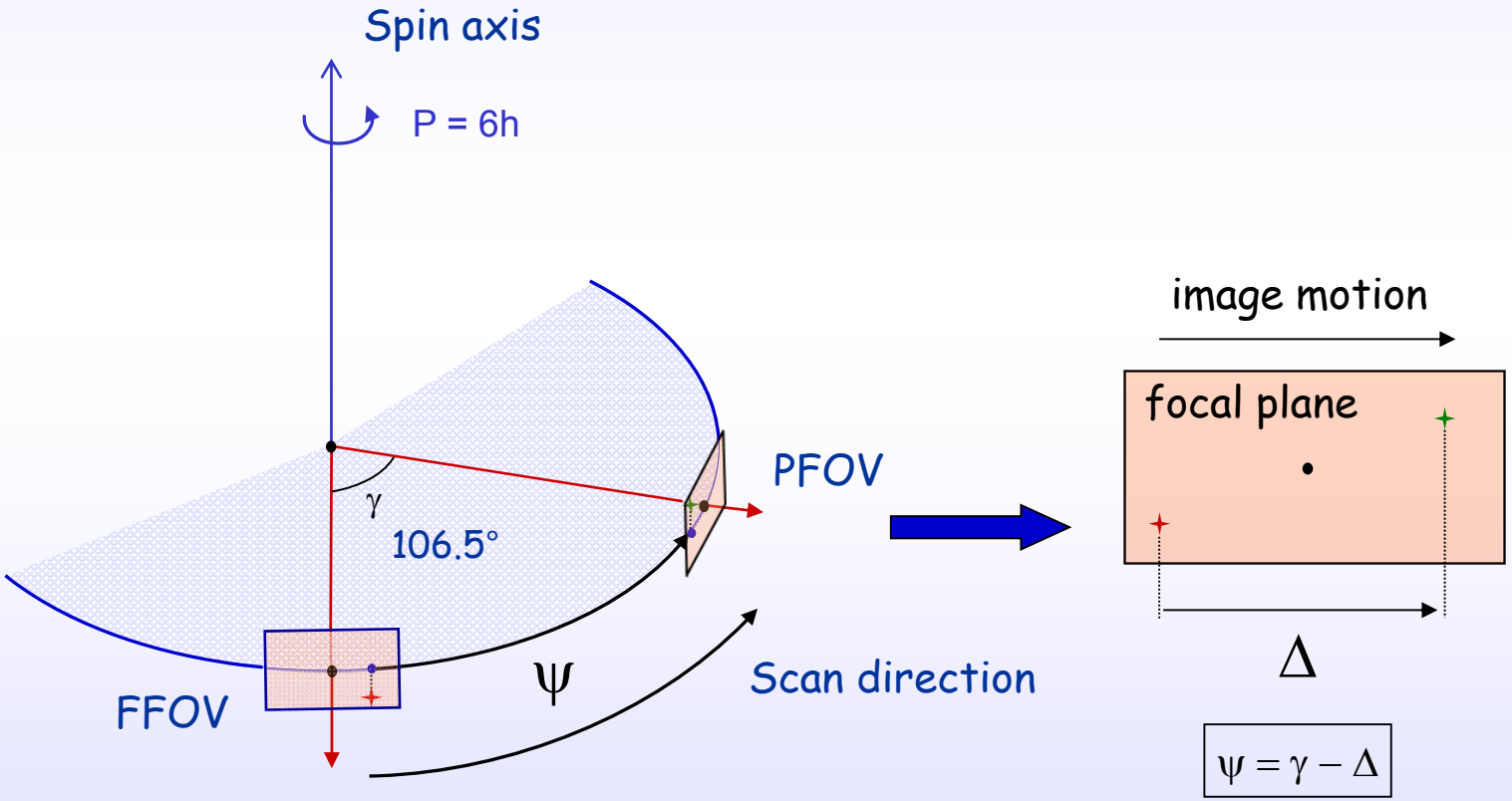
- 2 off-axis telescope
- 1.45 x 0.5 m^2 aperture
- 35 m focal length



- single focal plane
- 106 CCDs
- 1 Gigapixel
- 0.93 x 0.42 m^2

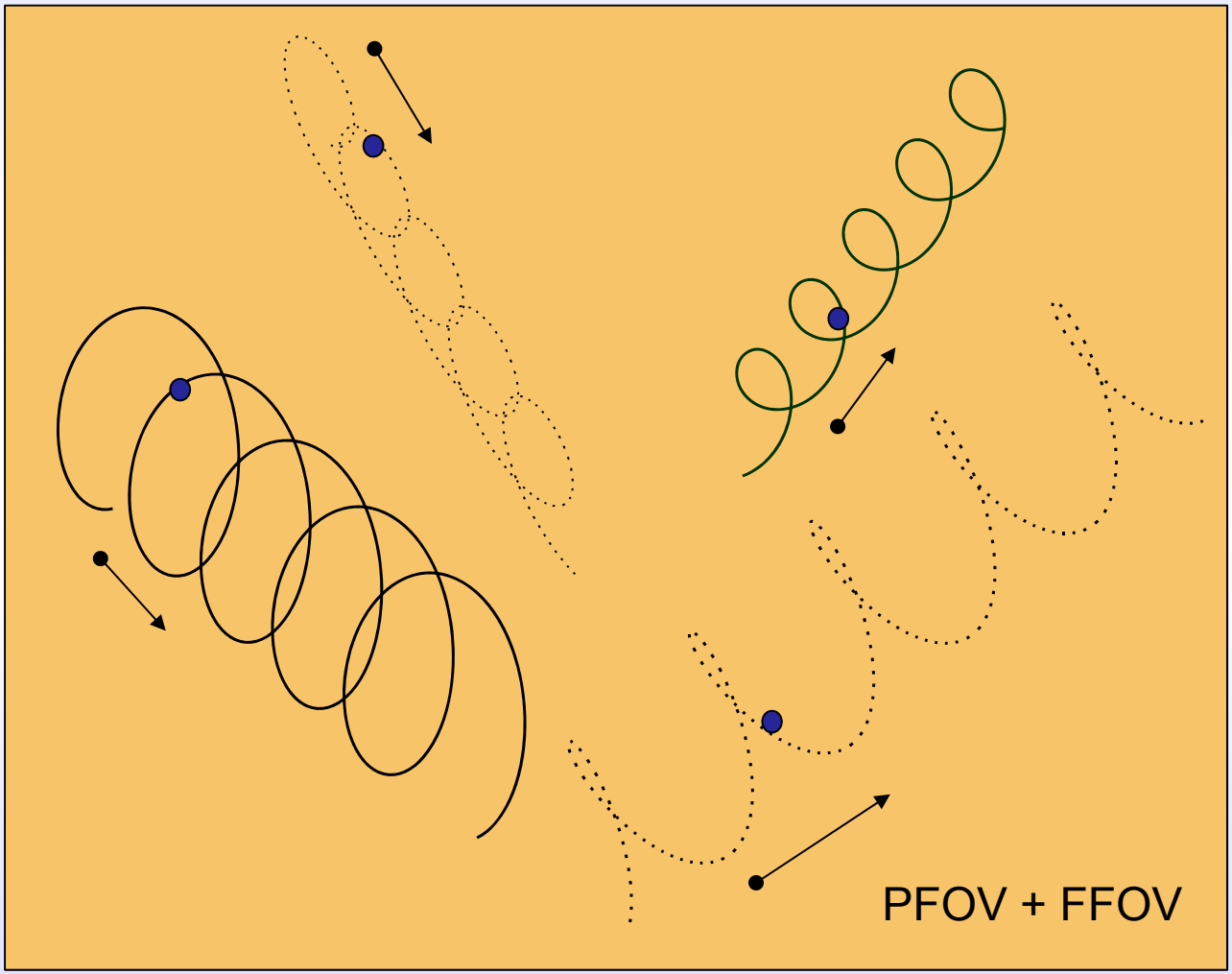
Global astrometry in space

- Wide angle measurements with overlapping fields



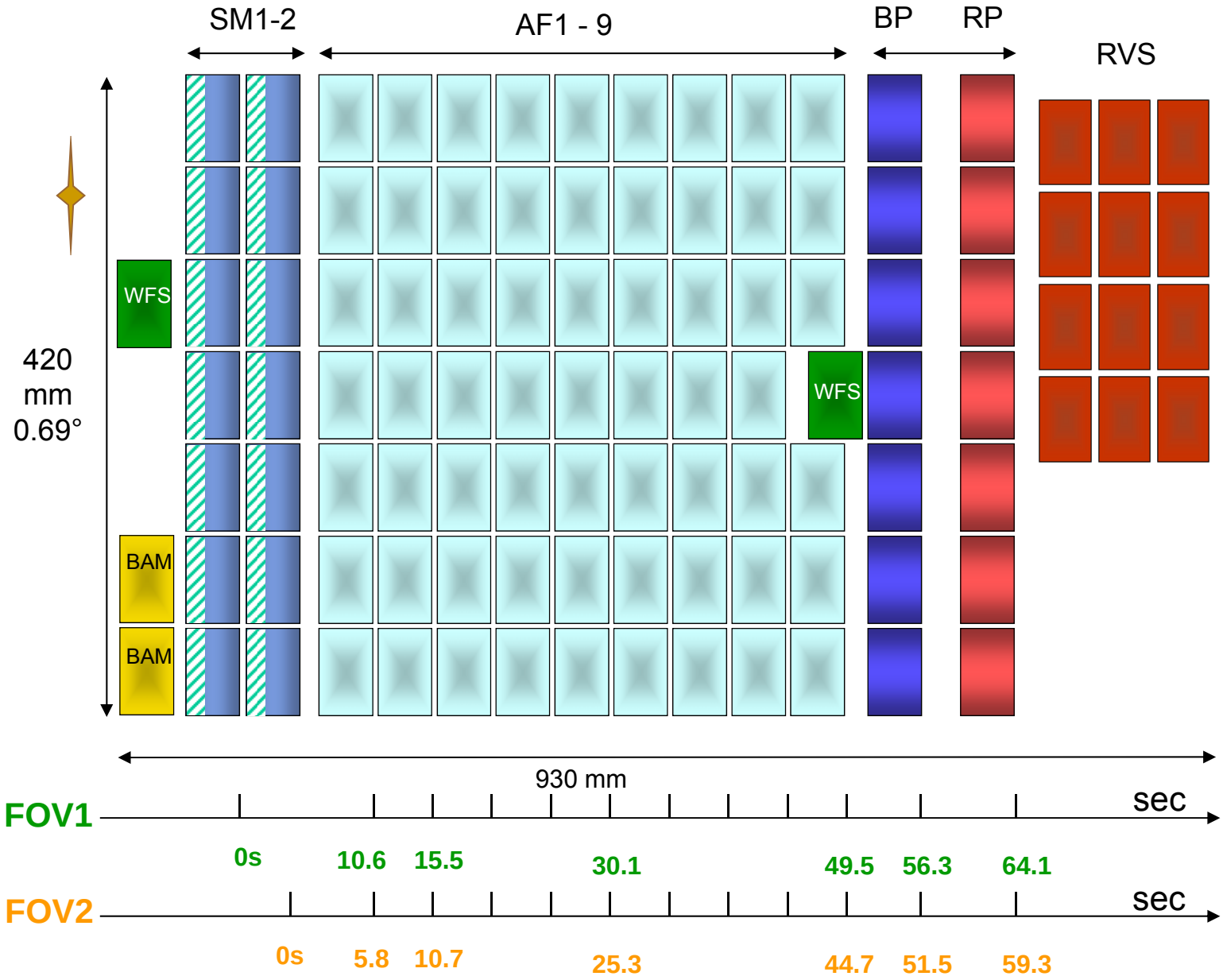
Combining field of views

- Two regions of the sky are mapped at a particular time on the focal plane



PFOV
FFOV
Observation
Proper motion

Focal Plane Assembly

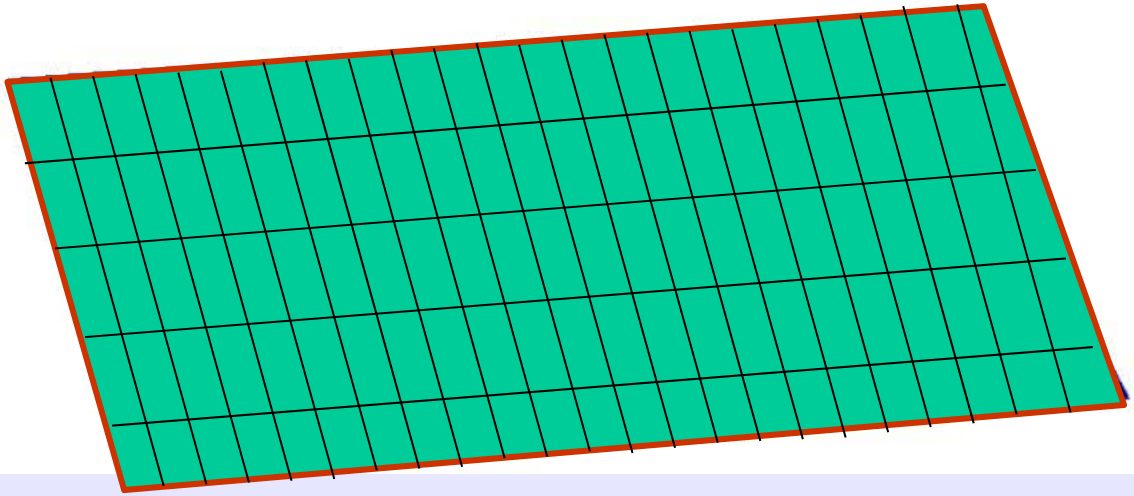


106 CCDs , 938 million pixels, 2800 cm2

How does the TDI work ?

- Charges are displaced from one pixel to the next in the same column
- Transfer speed is synchronised to the satellite spin rate
- Number of stars entering in the focal plane per second 1000 to 50,000





CCD

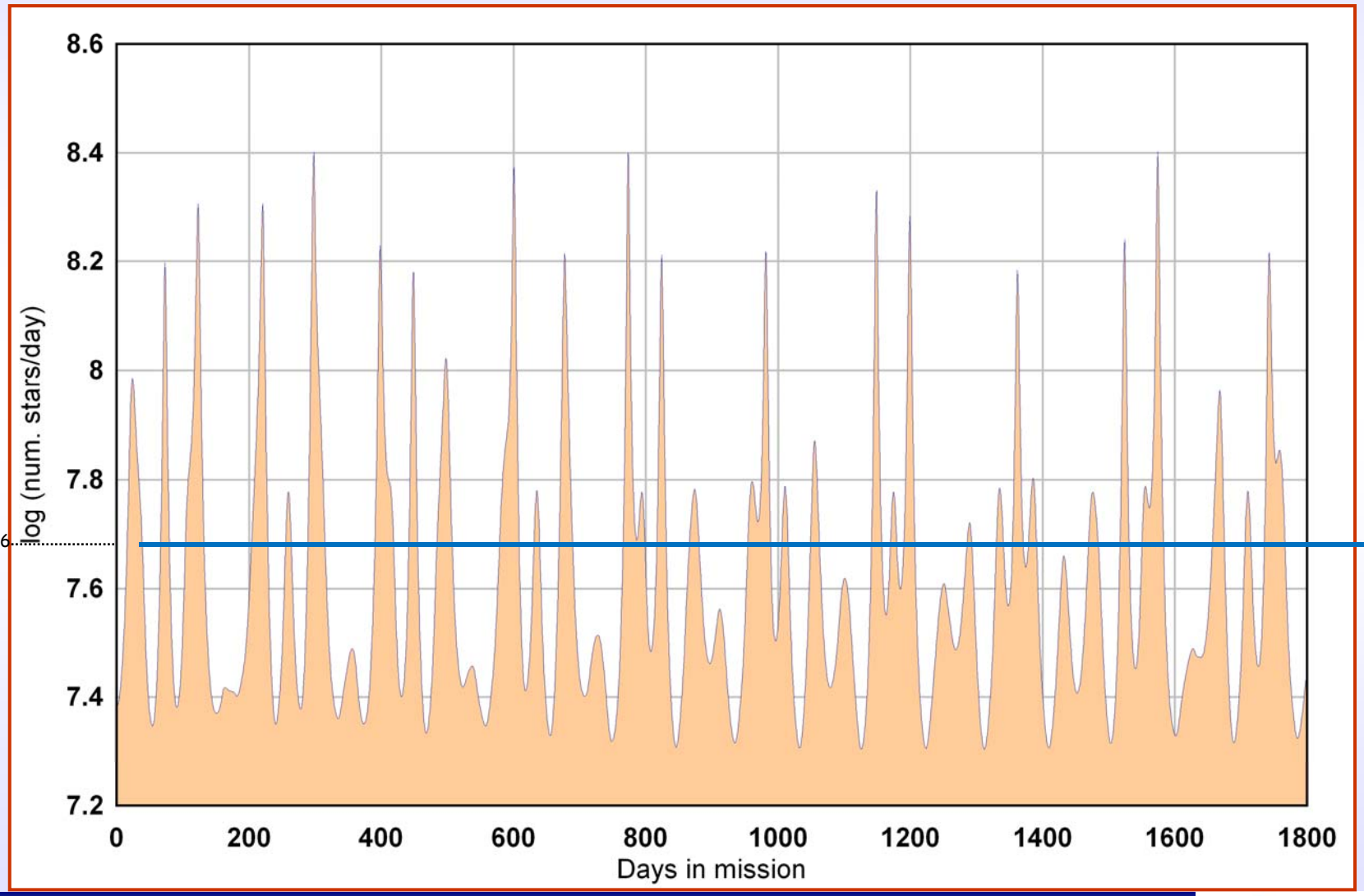
Animation : J. Portell

Number of sources per day

- How many sources per day to be processed on board ?
  - number of sources brighter than 20 mag — ~ 10^9
  - duration of the nominal mission — 1800 days
  - average number of field transits per source — ~ 80 *(no dead time)*
  - average number per day — ~ 10^9*80/1800 = ~ 45 x10^6
- But large scatter with the orientation of the scan wrt the Galactic plane.
- Detailed study done with a simulation using the nominal scanning law and a galactic model

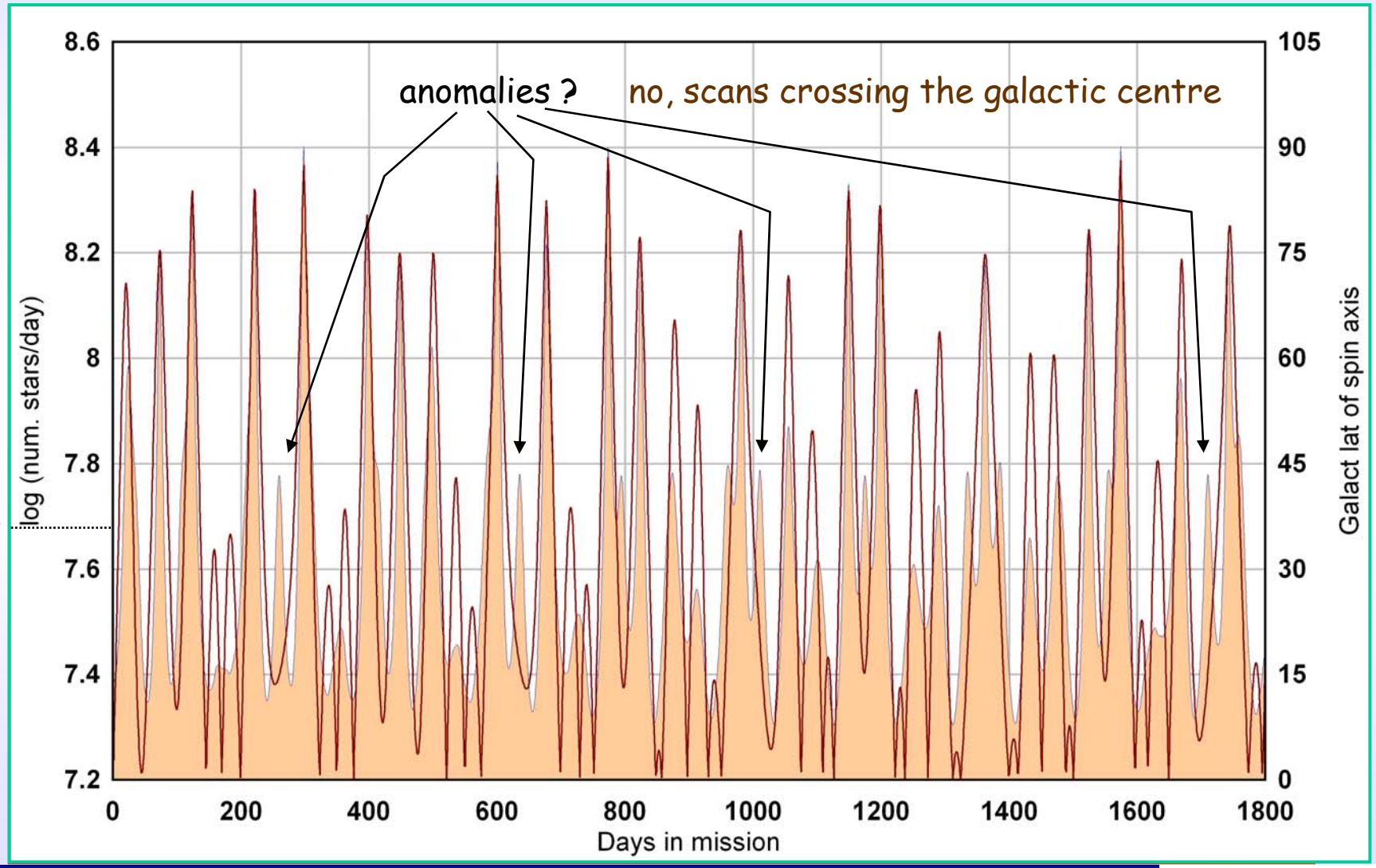
Number of sources per day

- Number of sources detected per day (log scale) during the mission



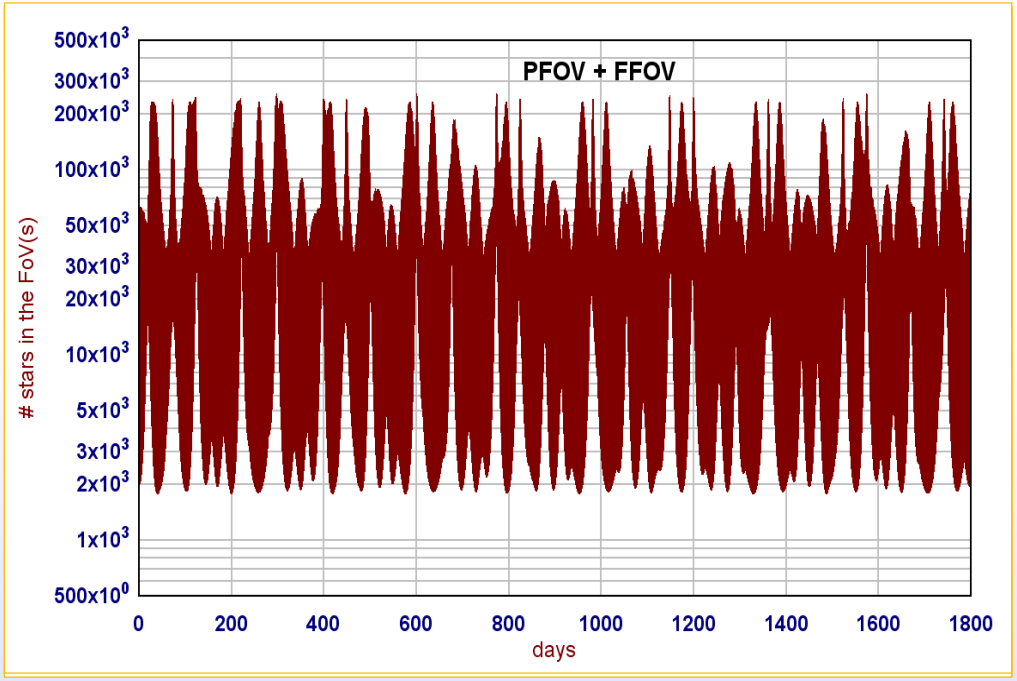
Number of sources per day

- Superimpose the direction of the spin axis wrt the galactic plane



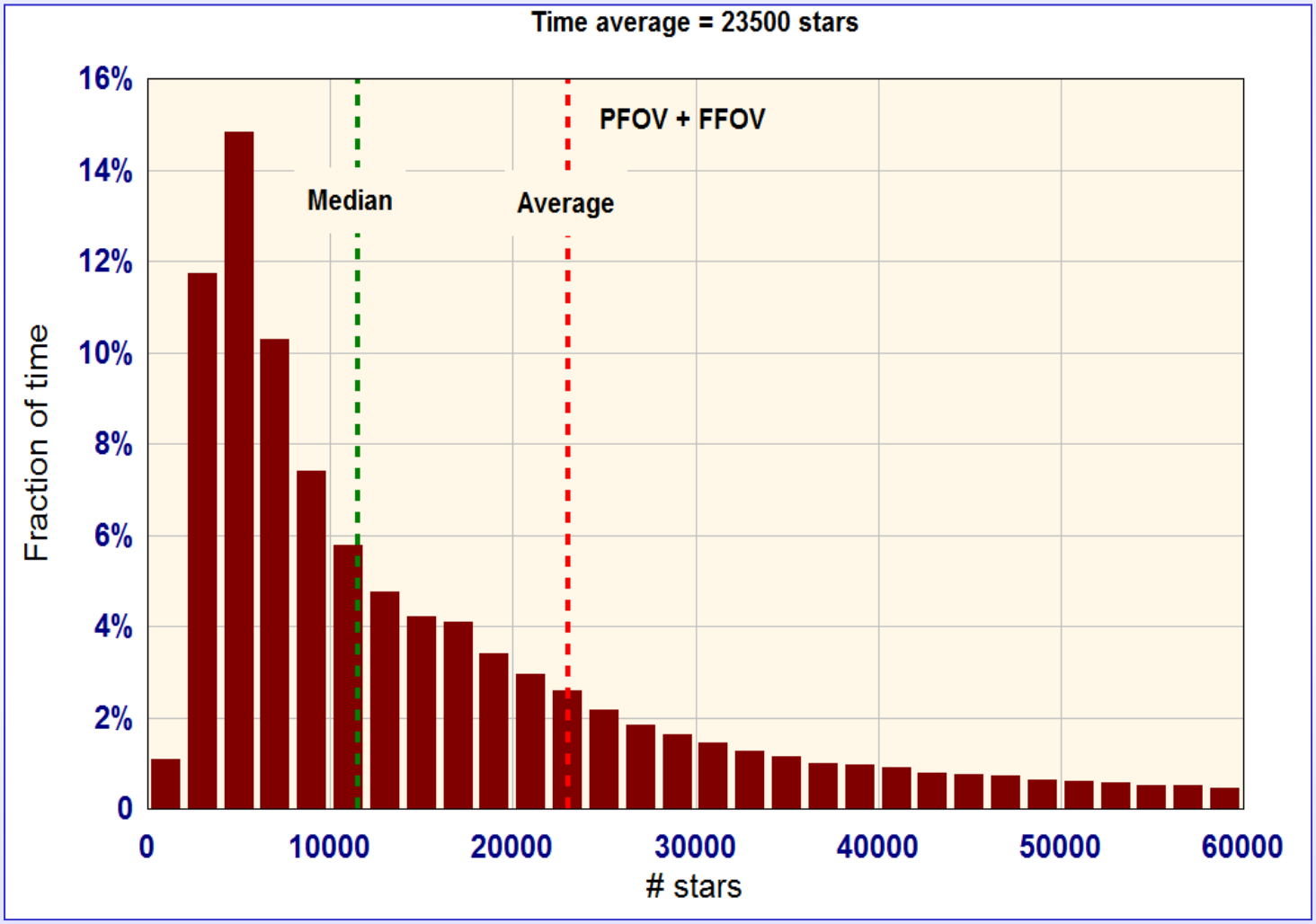
How many stars in the FoVs ?

- Computation with the Nominal scanning law
  - time sampling = 7.5 mn over 5 years
- Pointing directions of each FoV in galactic coordinates
- Galaxy model for the stellar density
- The two FoVs are mapped on the same detector and densities added



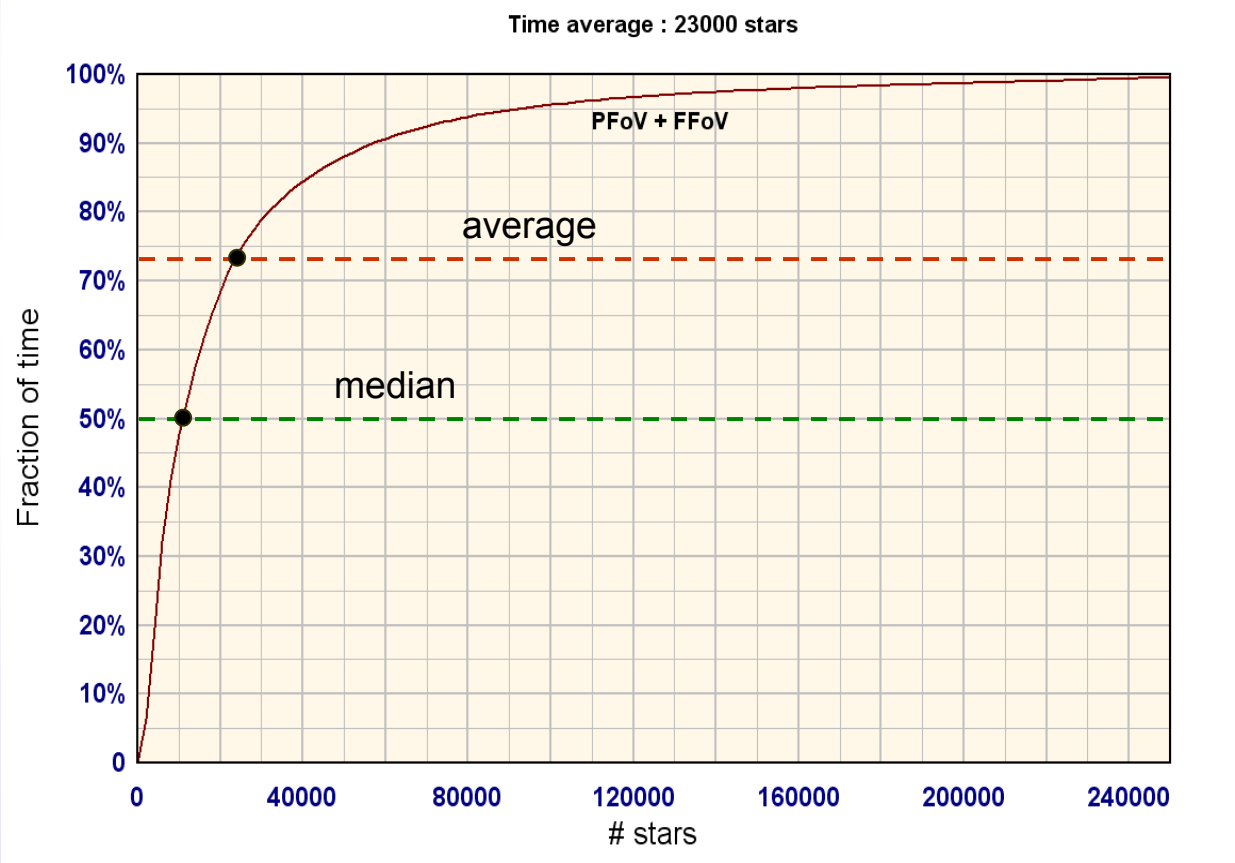
Number of stars in the FOVs

- # stars measured at any time in the combined FOVs



Time distribution

- Time distribution of the stellar density on the focal plane
  - > 50% of time with combined area < 12000 stars in the Astro CCDs



The sky mapped onto the focal plane

- Sky average density to V = 20 : 25000 */deg^2
  - But with large concentration near the galactic plane
- However Gaia spends more time in low-density areas
  - Time average is smaller ➔ sky is "empty" outside the galactic plane
- But the two FoVs are not superimposed as independent samplings

On the average on the sky one has:

350 stars

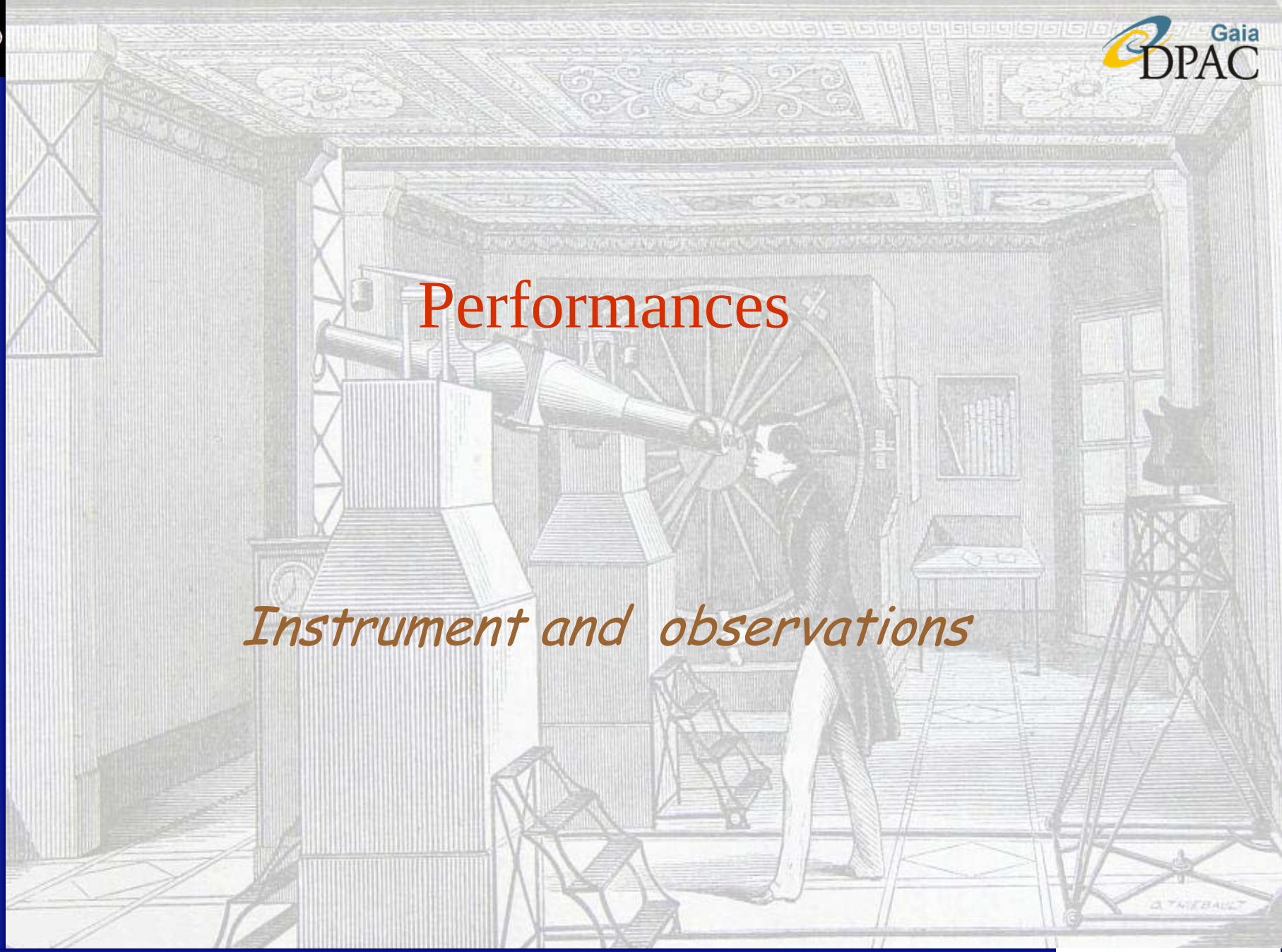
in

one CCD



Elementary data on ground

- One billion sources to be observed
  - Stars, galaxies, QSOs, SSOs
- Average of 80 transits per sources during the mission
  - min ~ 50 max ~ 200
- Every source transits over 9 AF CCDs
  - 700 individual measurements per source
- 0.7 x 10^{12} CCD images produced by the mission
  - ~ one trillion elementary data
- Most images are 1D with have 6 samples
  - But some have 12 or 18
  - Bright sources are 2D
  - BP/RP have window 60-pixel wide

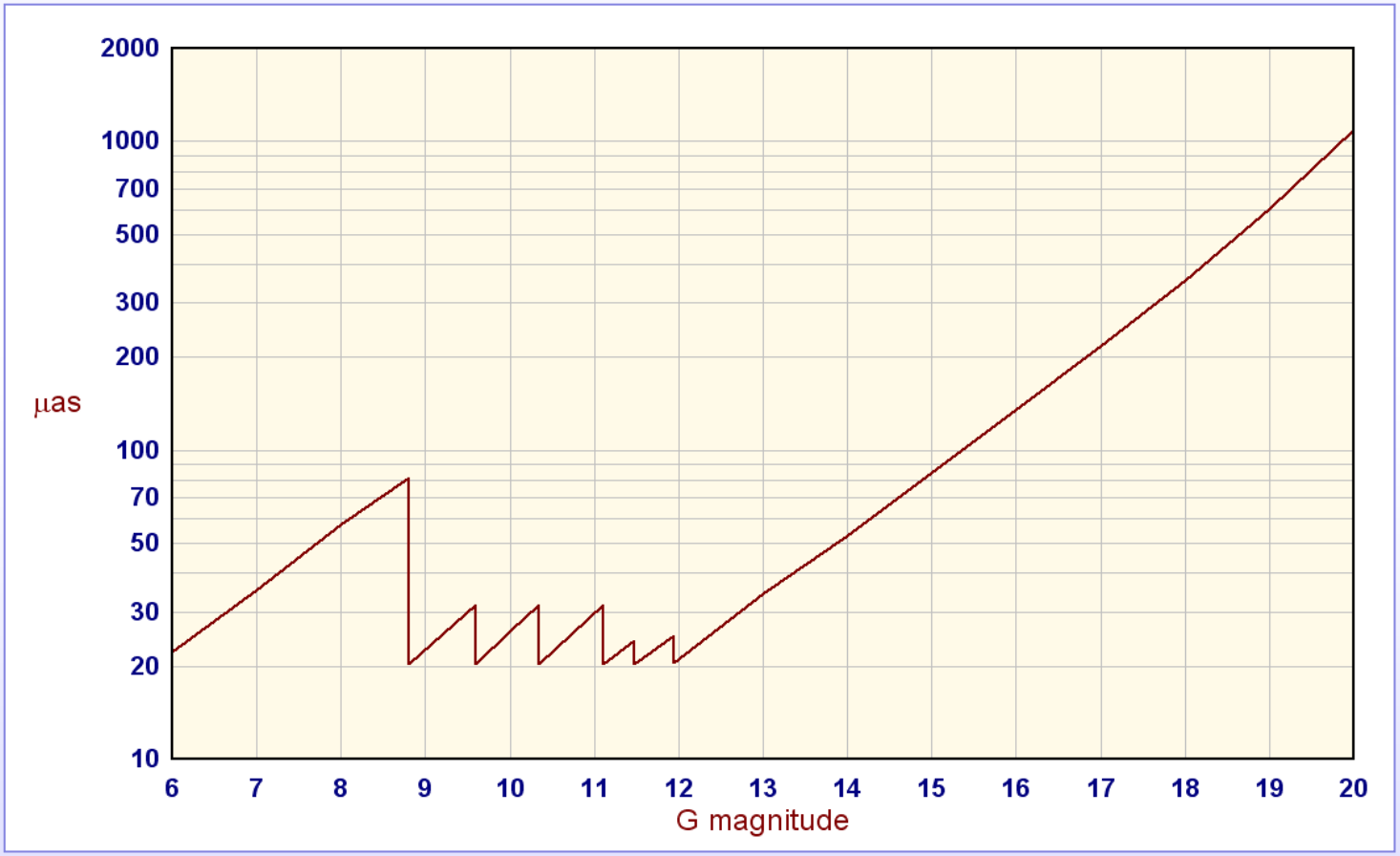


Performances

Instrument and observations

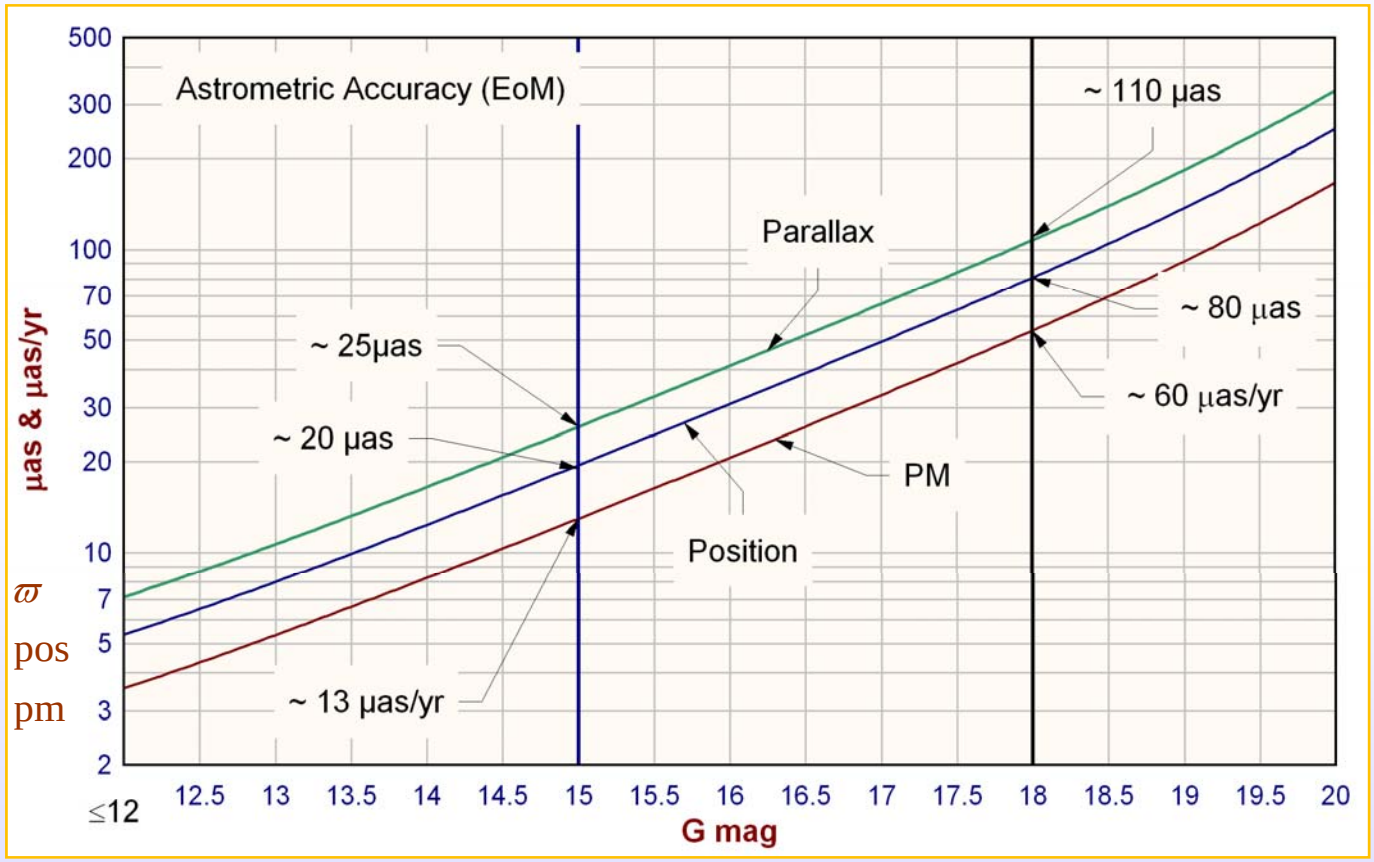
Astrometric accuracy: single transit

- Single observation accuracy ➔ orbit, solar system
  - one field transit: integration over 9 AF CCDs
  - point source



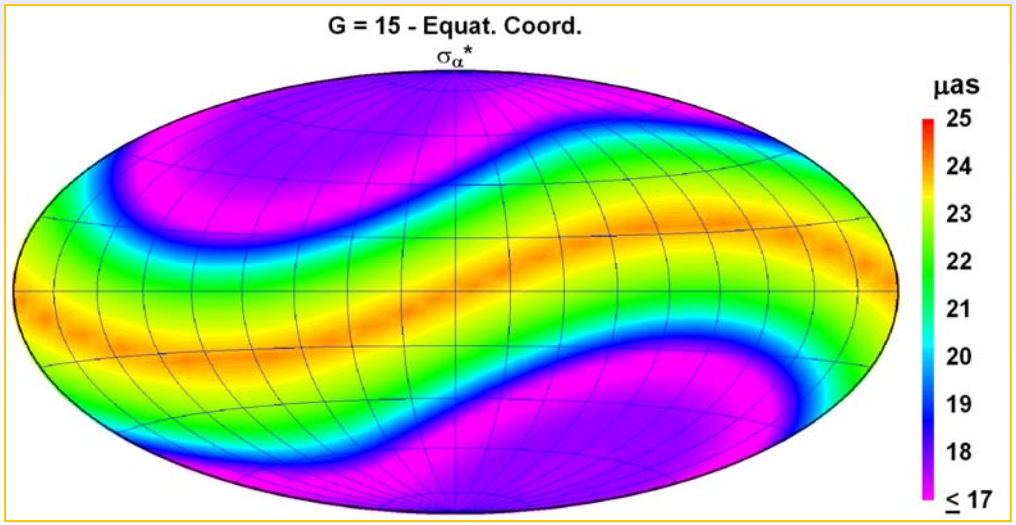
Gaia Accuracy at mean epoch

- Five year mission, sky -averaged
  - reference value: σ_ω = 25 μas @ G = 15
  - based on data from J. De Bruijne (ESA)



Sky distribution – Positions (~ 2016.5)

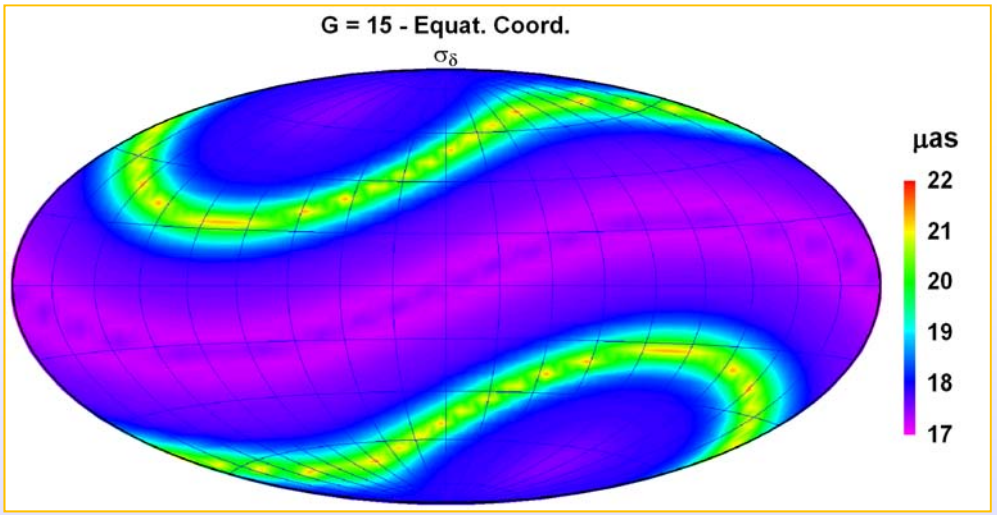
- Plots for *G* =15, but scalable to other magnitudes



$$< \sigma_\alpha^* > = 21 \mu\text{as}$$

$$\sigma_\alpha^* - \mu\text{as}$$

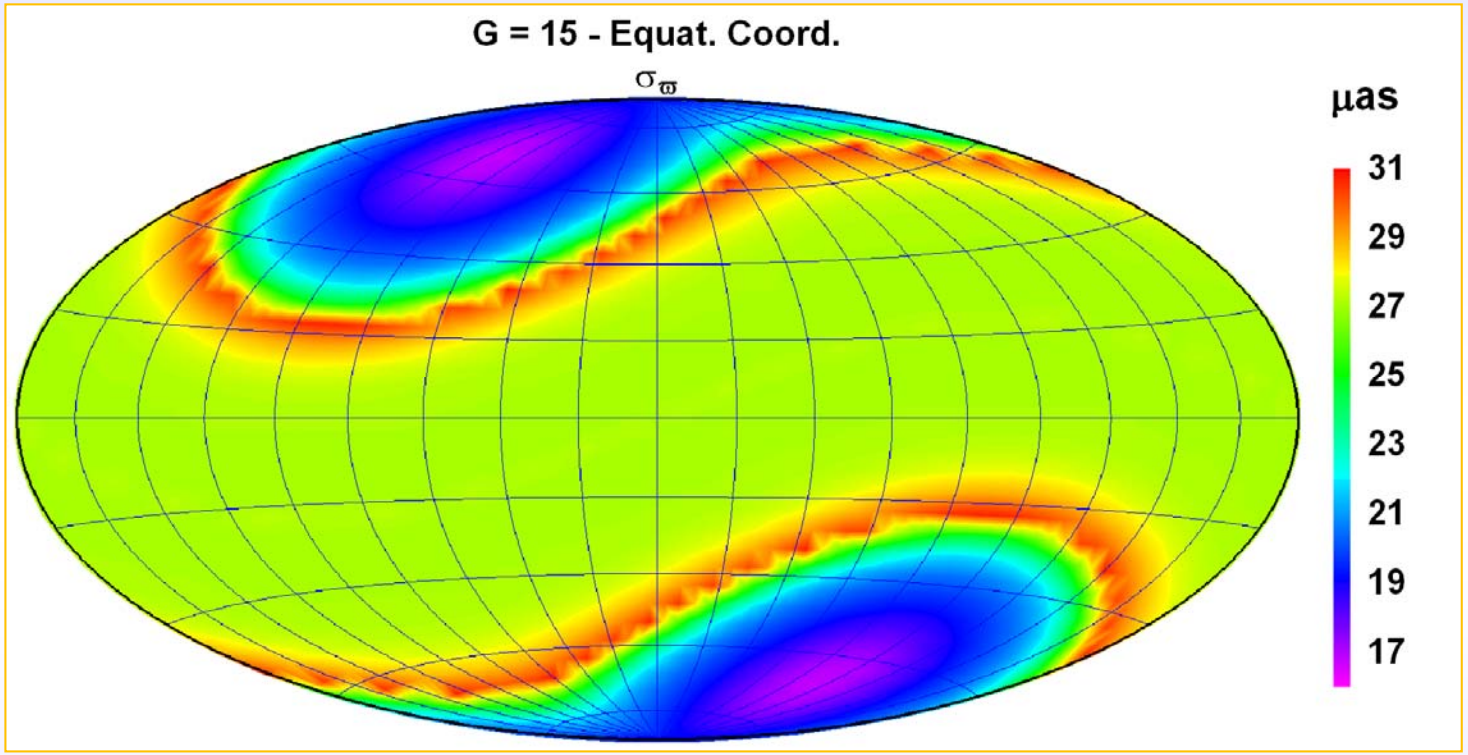
$$< \sigma_\delta > = 18 \mu\text{as}$$



$$\sigma_\delta - \mu\text{as}$$

Sky distribution – Parallaxes

- Plot for *G* =15, but scalable to other magnitudes

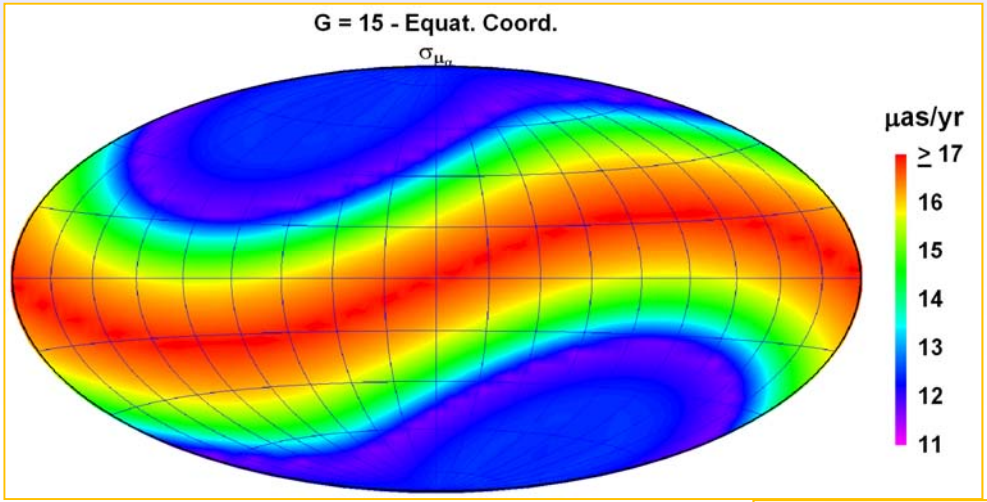


σ_{ϖ} – μas

$$< \sigma_{\varpi} > = 25\ \mu\text{as}$$

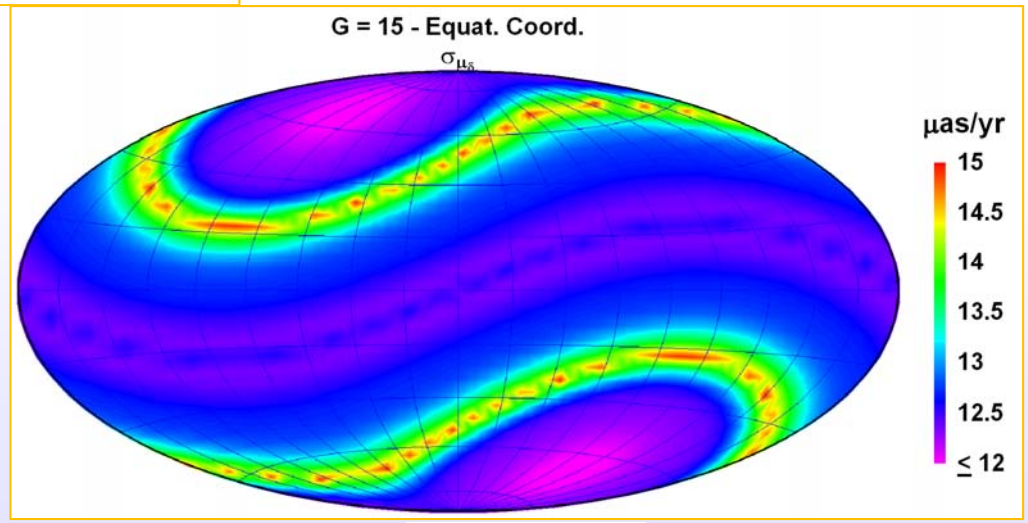
Sky distribution – Proper motions

- Plots for G =15, but scalable to other magnitudes



$$\sigma^*_{\mu_\alpha} - \mu\text{as yr}^{-1}$$

$$< \sigma^*_{\mu_\alpha} > = 15\,\mu\text{as yr}^{-1}$$



$$\sigma_{\mu_\delta} - \mu\text{as yr}^{-1}$$

$$< \sigma_{\mu_\delta} > = 13\,\mu\text{as yr}^{-1}$$

Transverse Velocity

- Combination of proper motion and distance

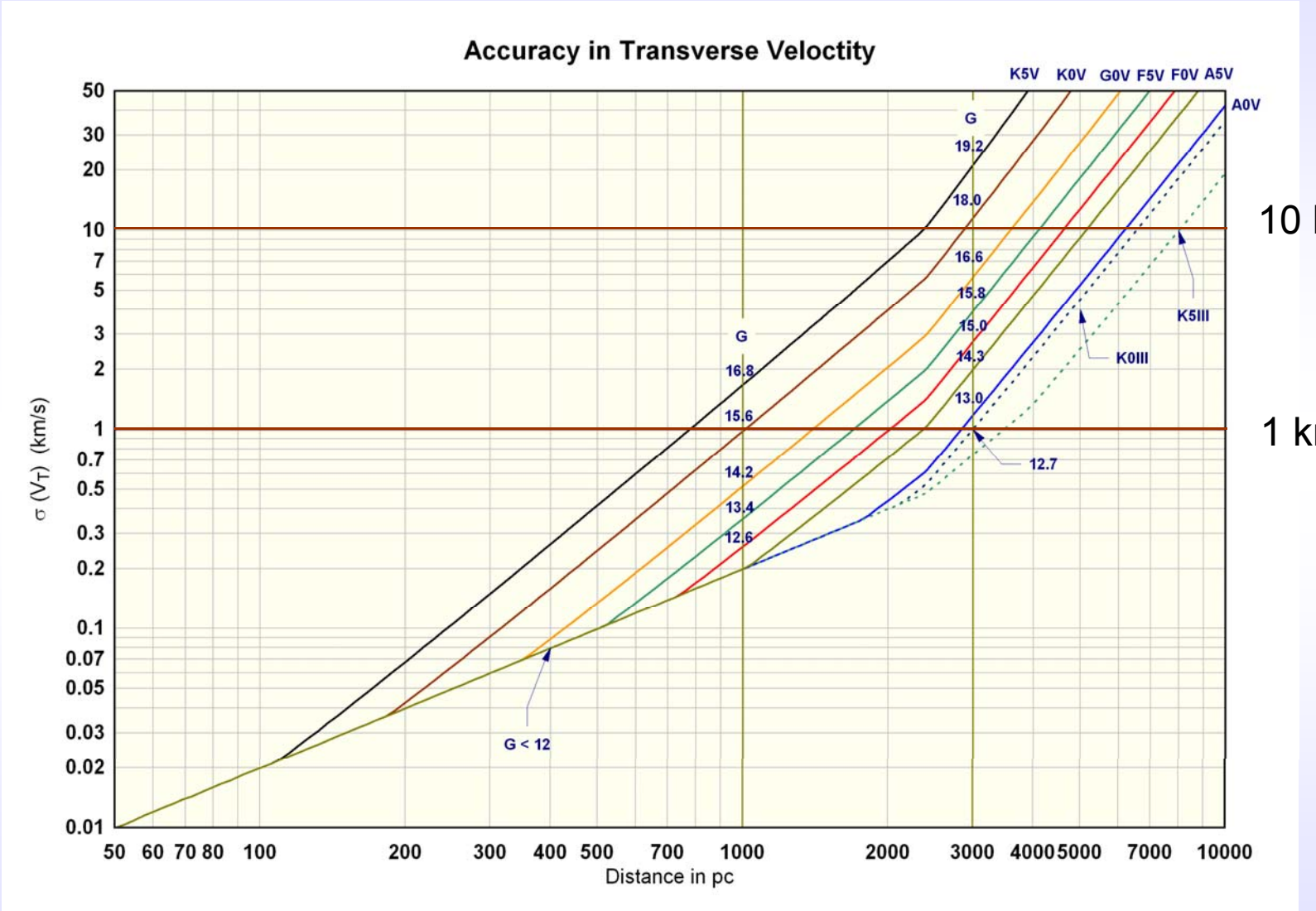
$$V_T = 4.74 \frac{\mu}{\varpi} \qquad \text{km/s, mas/yr, mas}$$

$$\sigma_{V_t} \sim V_T \left(\frac{\sigma_\mu}{\mu} + \frac{\sigma_\varpi}{\varpi} \right)$$

ϖ factor ~ 10 x μ ➔

- Must be compared to V_r for different types of stars

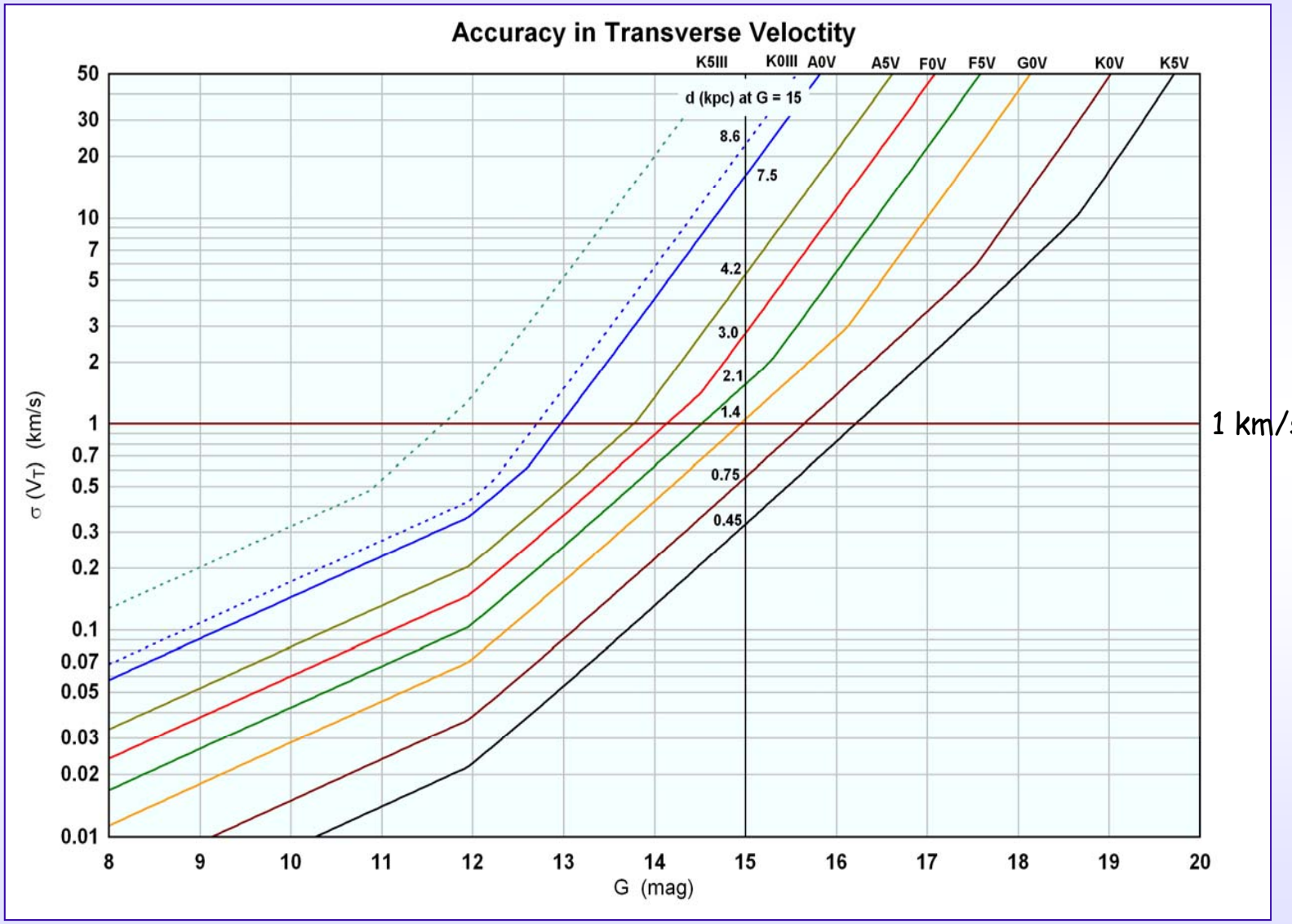
Transverse velocity estimate with Gaia



10 km/s

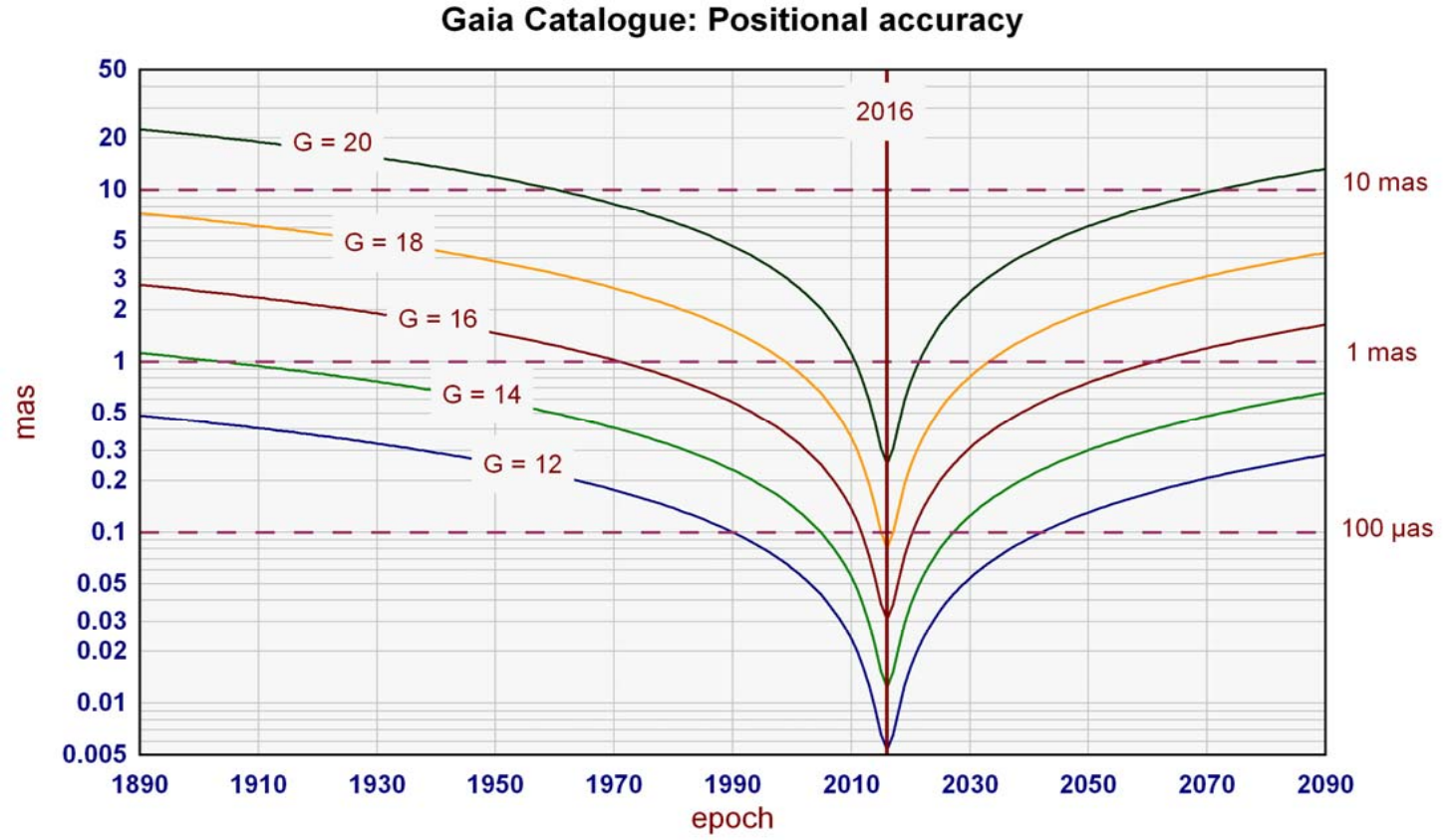
1 km/s

Transverse velocity estimate with Gaia

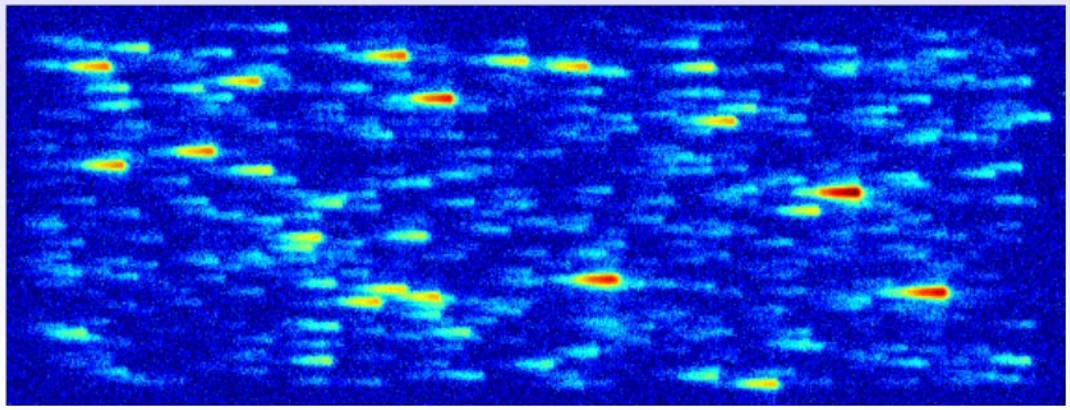


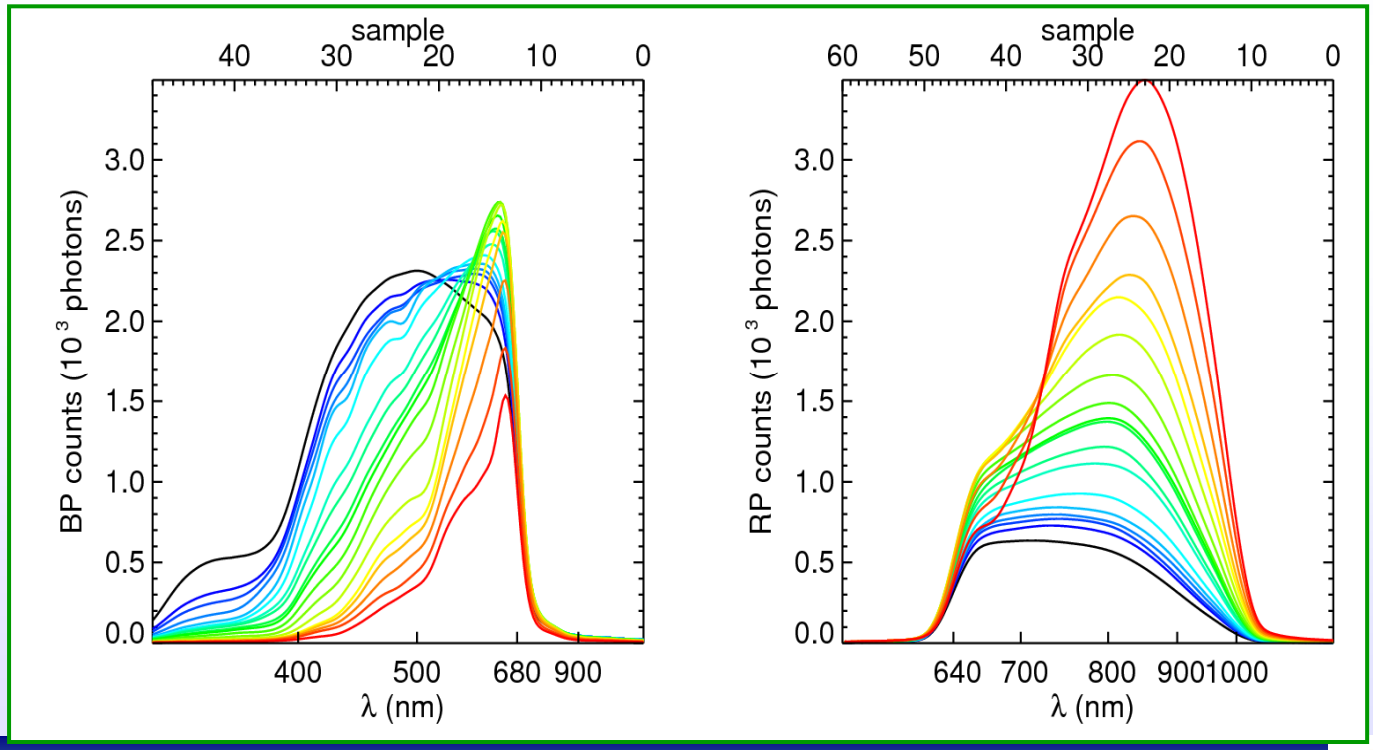
Gaia Accuracy in the past and future

- Covariance matrix fully propagated at t = 1890..2090 step 1 yr
  - sky averaged accuracy
  - mean accuracy between α and δ



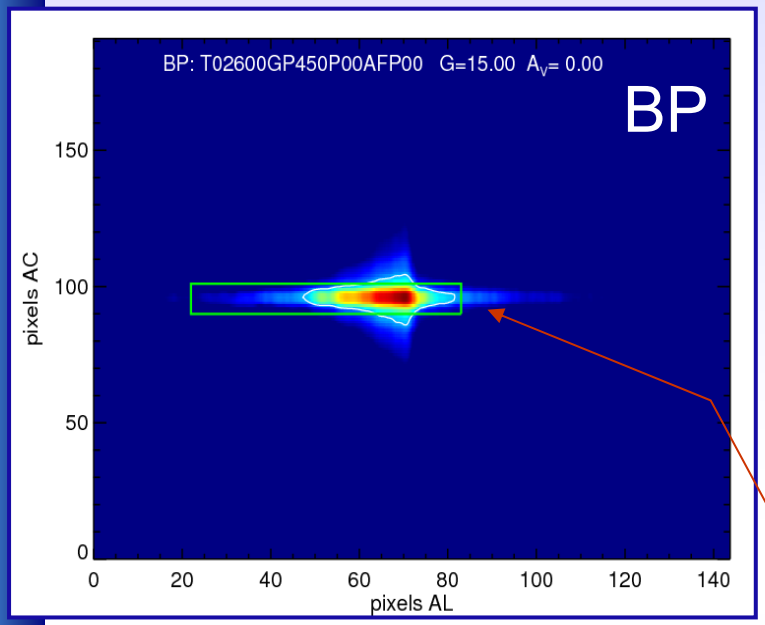
BP/RP fields



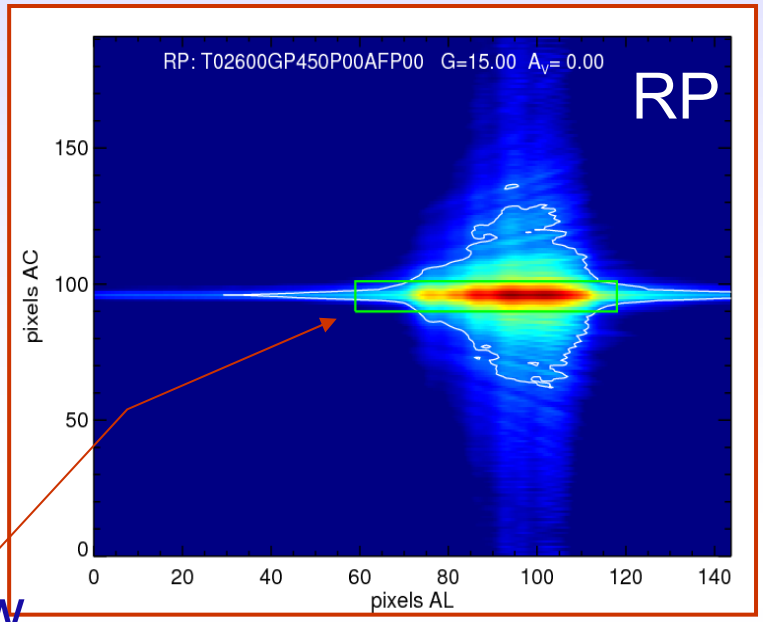


Plots: A. Brown

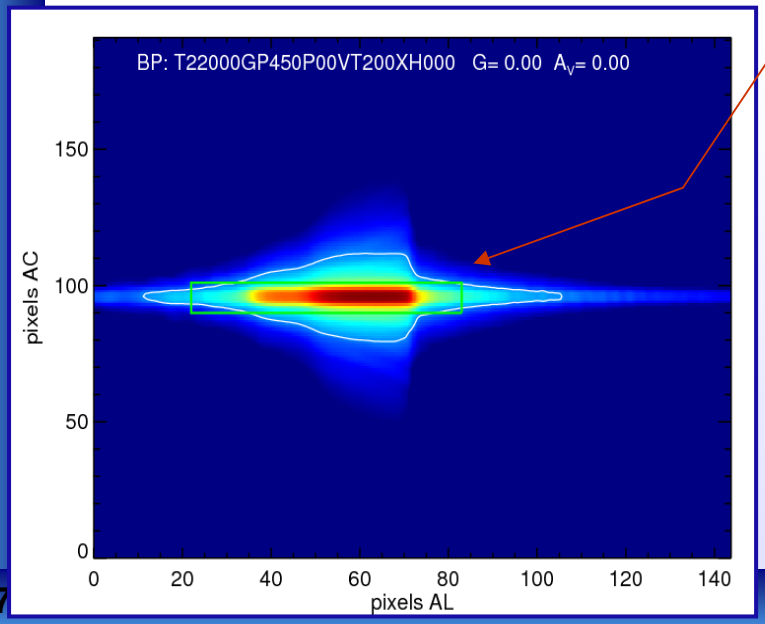
Dispersed images BP - RP



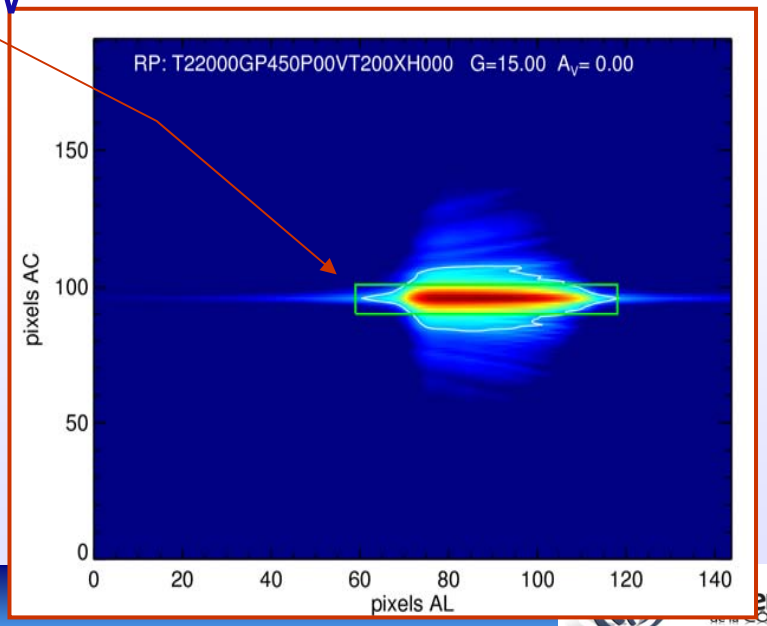
T = 2600



window

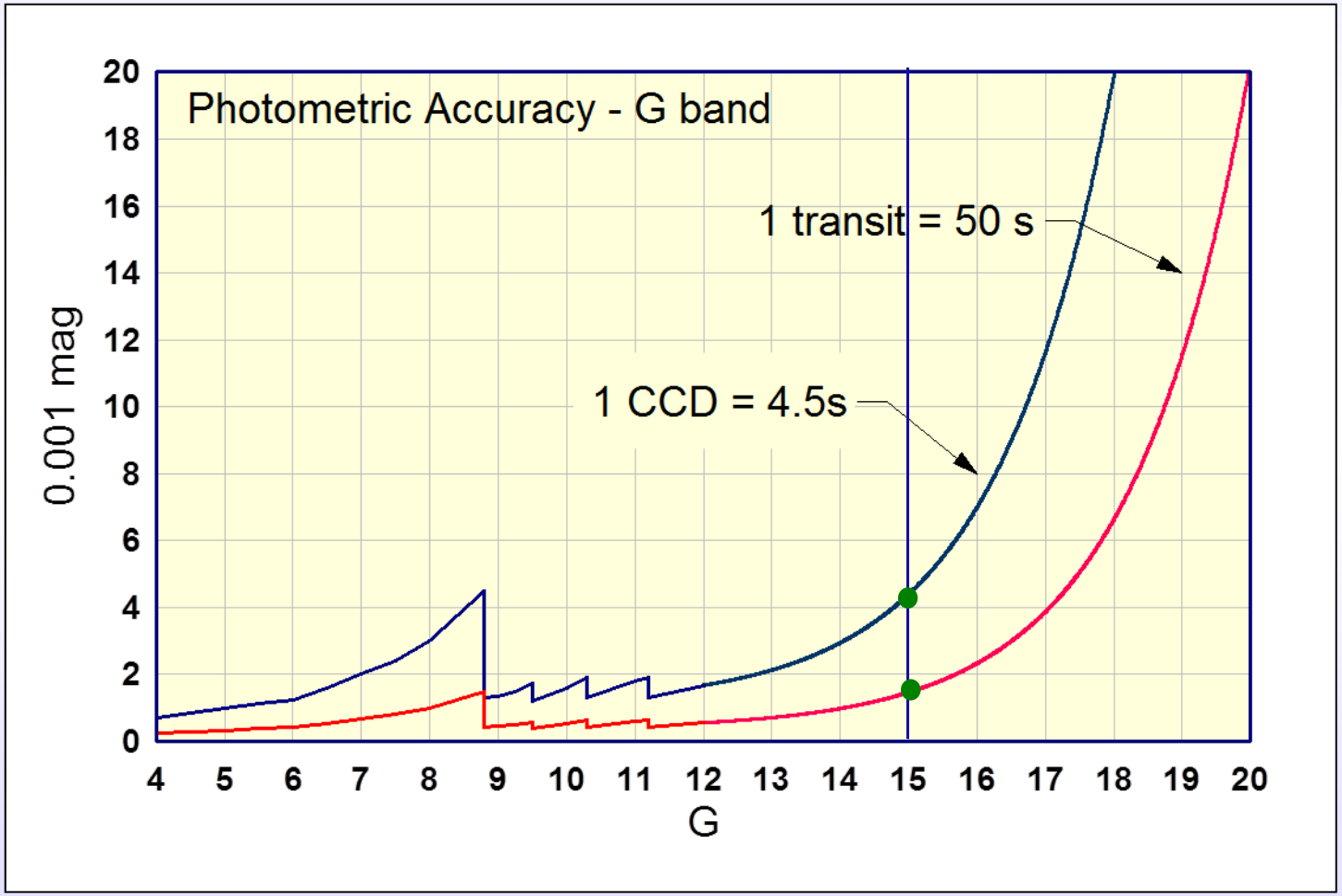


T = 22000



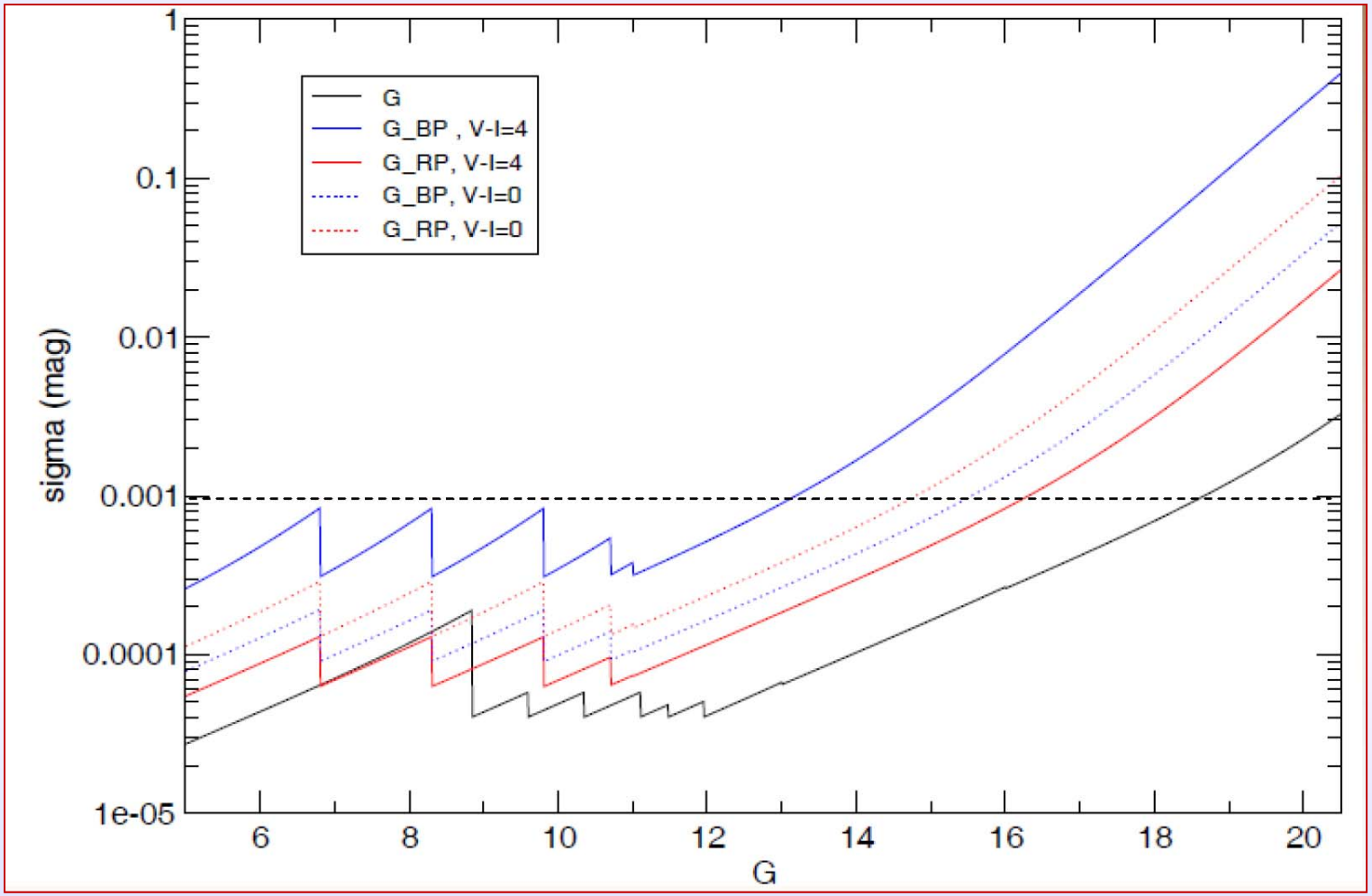
Photometric performance II

- Highest time resolution
- Illustration with the full light band (*G*-band)



Photometric Performance - I

- End of Mission, constant source



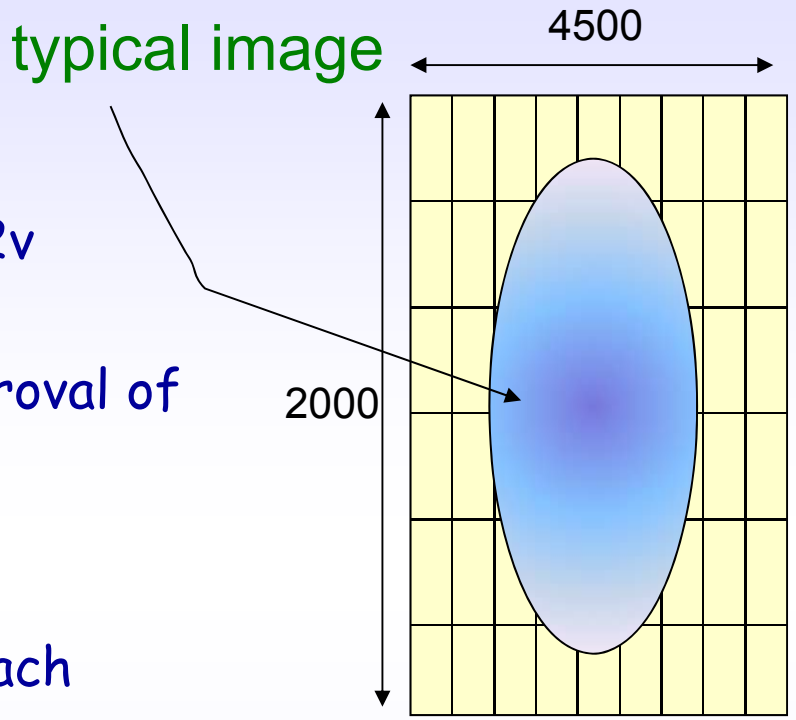
Credit: D.W. Evans

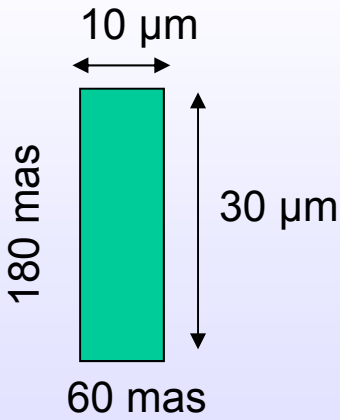
On-board acquisition

Windows & Gates

Gaia : CCD

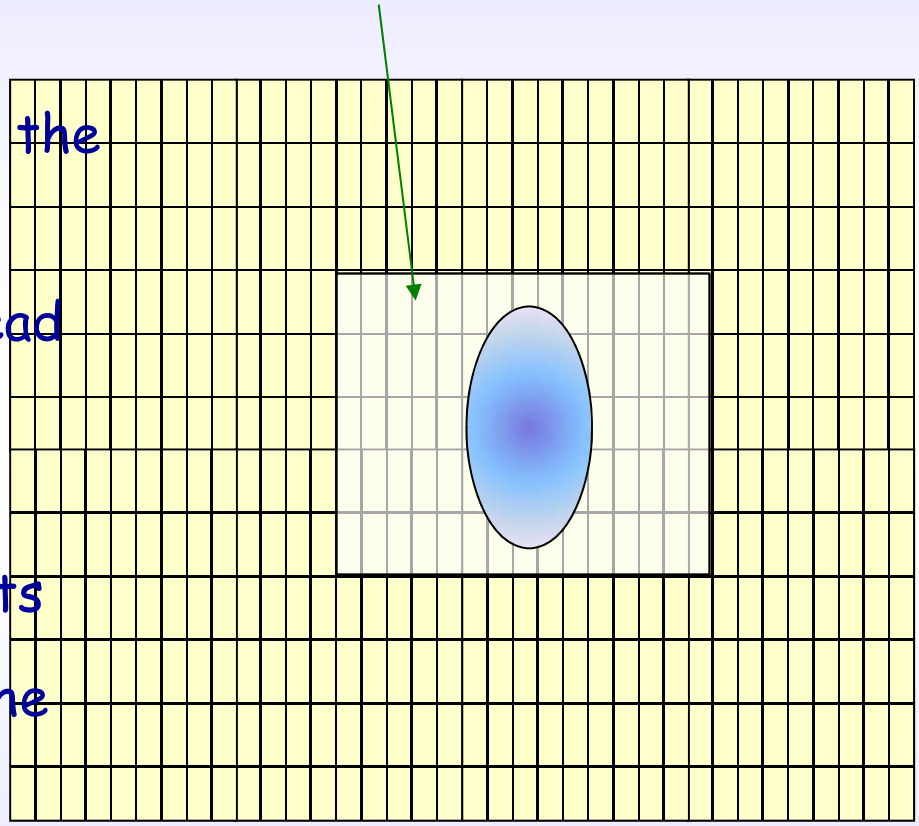
- Identical structure for every CCD
- Manufactured by the UK company e2v
- Contract granted before formal approval of Gaia
- 106 CCDs in total, 4.5 x 6.0 cm^2 each
- Works in TDI mode
- all delivered, certified and integrated in the FPA



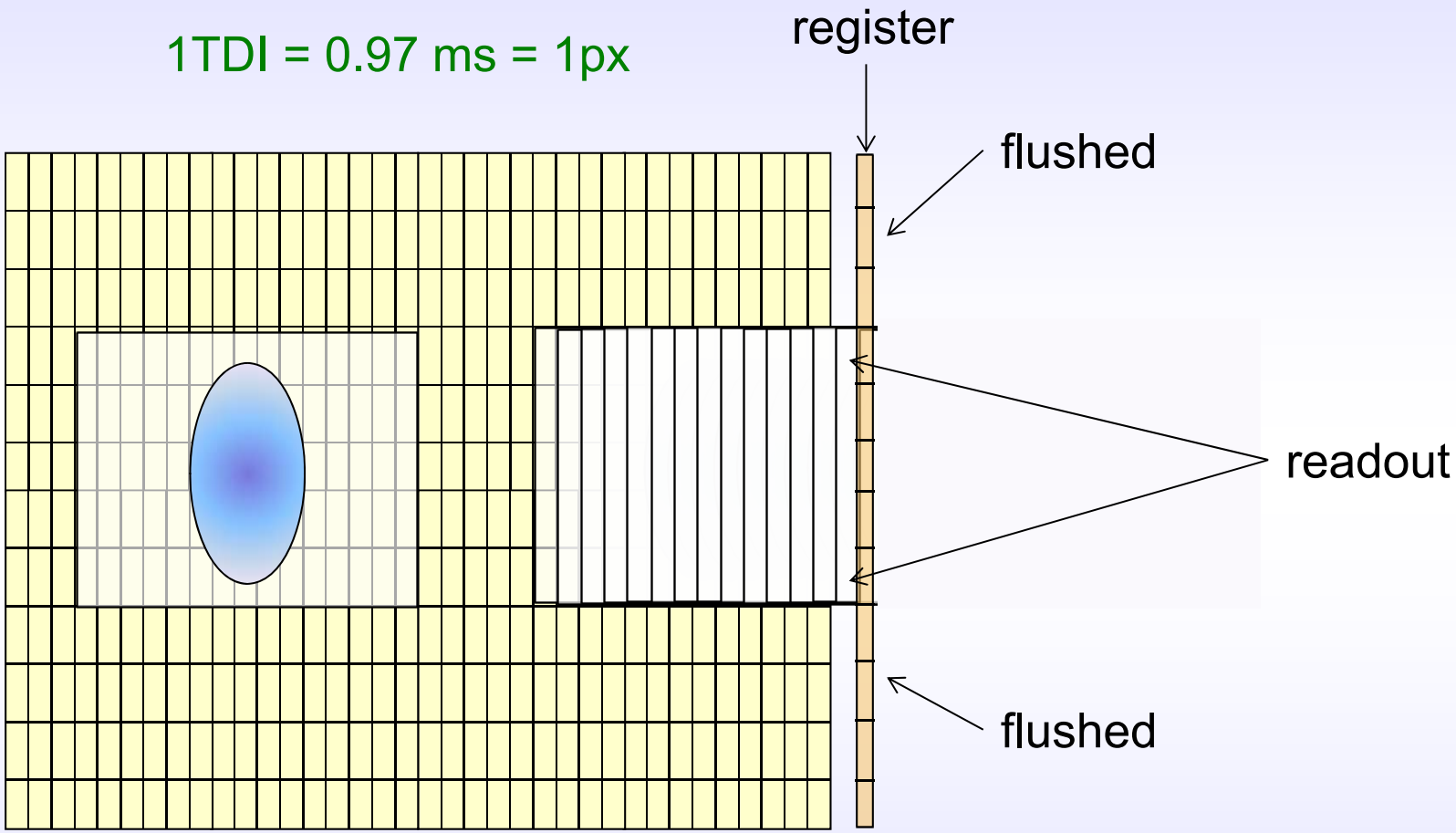


Windows

- Most of the sky (outside the Galactic plane) is empty
- Sending the full CCD read-out to the ground would mean a few Gbit/s
- Reading out the full CCD would lead to excessive read-out noise
- Gaia astrometry only requires accurate along-scan measurements
- Only pixels in windows around the images are read-out
  - **priority to useful pixels**



Operating Windows

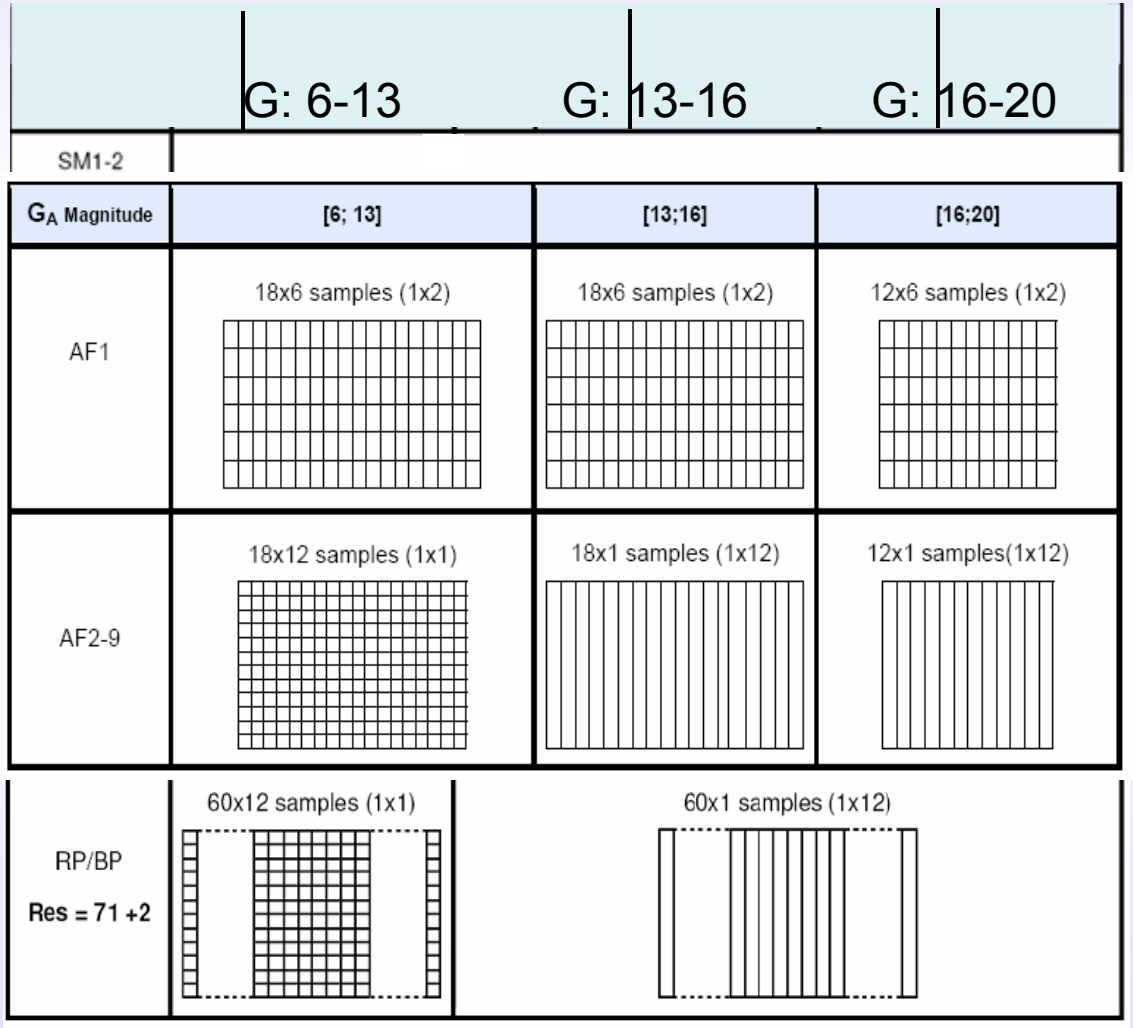


Observing with windows

- On-board windows
  - on-chip binning performed across scan
  - must be compatible with the CCD saturation
- No effect during TDI
  - windows exist only at the readout register
- One has lines of 2000 pixels to be read out or flushed in 0.9 ms
  - window pixels are read out more slowly than flushed pixels
- There is a complex strategy in the selection of the window size
  - optimise the downlink data volume and rate
  - collect most of the light at the right place
  - sample background for calibration

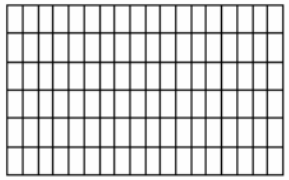
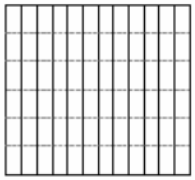
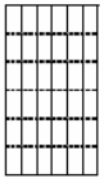
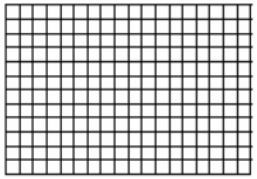
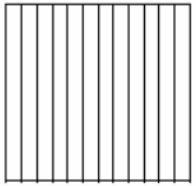
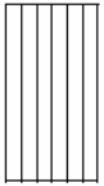
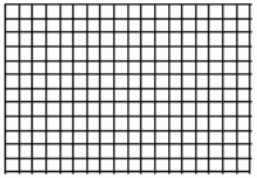
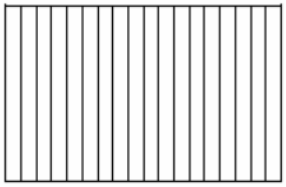
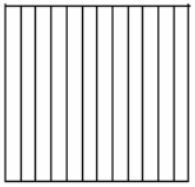
Observing with windows

- Windows are used to read-out useful pixels
- On-board windows



Processing observations with windows

- Transmitted windows
  - they are usually binned in the transverse direction

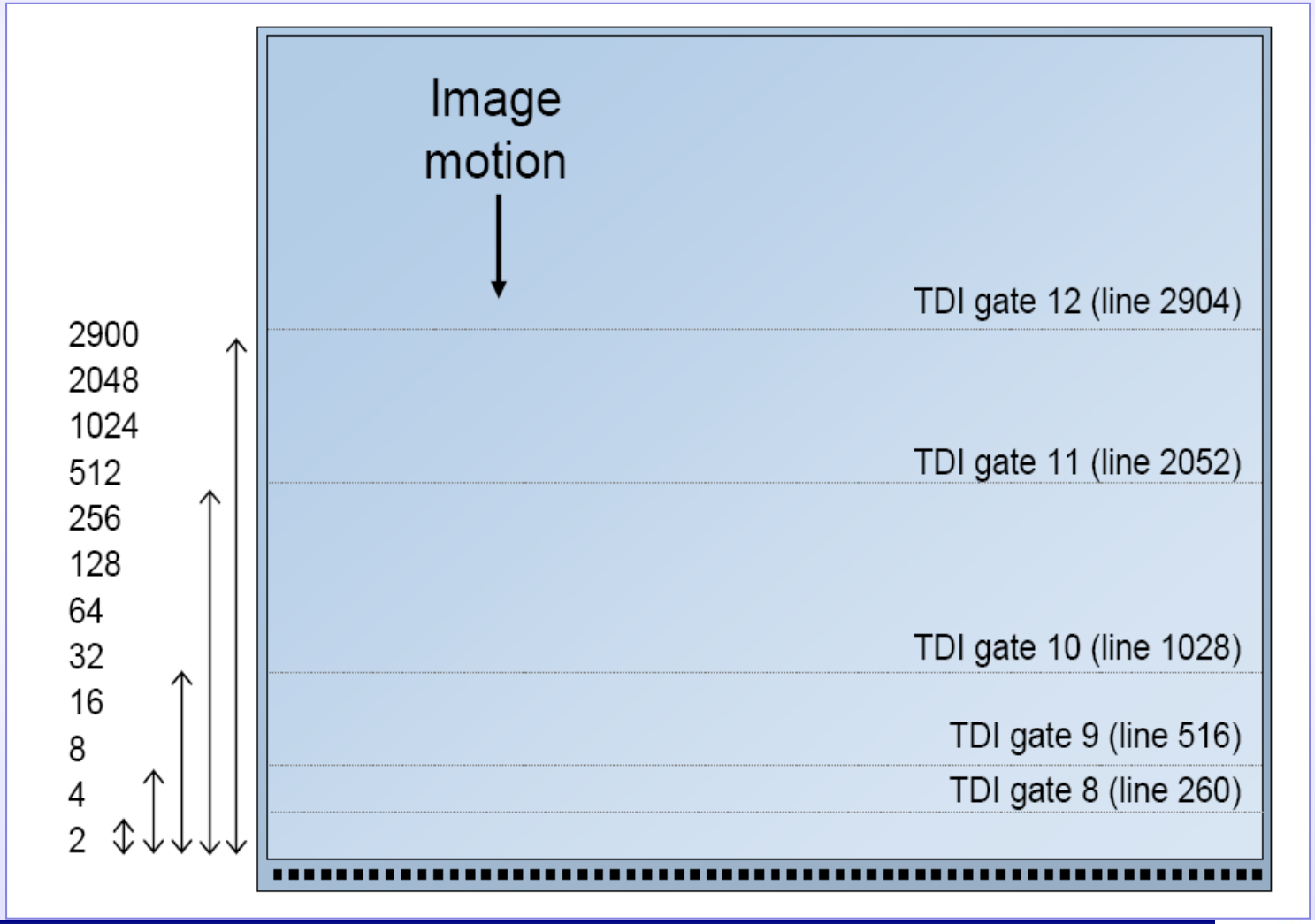
G_A Magnitude	[6; 13]	[13;16]	[16;20]
AF1	18x6 samples (1x2) 	12x1 samples (1x12) 	6x1 samples (1x12) 
AF 3, 4, 6, 7, 9	18x12 samples (1x1) 	12x1 samples (1x12) 	6x1 samples (1x12) 
AF 2, 5, 8	18x12 samples (1x1) 	18x1 samples (1x12) 	12x1 samples (1x12) 

Gates

- CCDs saturate at ~ 2x 10^5 e-
  - def: full well capacity at 1% non linearity
  - this corresponds to a star of magnitude ~ 12
- Gate length in pixel
  - 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, 2900
  - 4500 → no gate
  - SM always with gate 12 (2900)
- Gates are activated or de-activated by the on-board S/W

Gates

- Sensitive area with gates activated



Gates: how is works

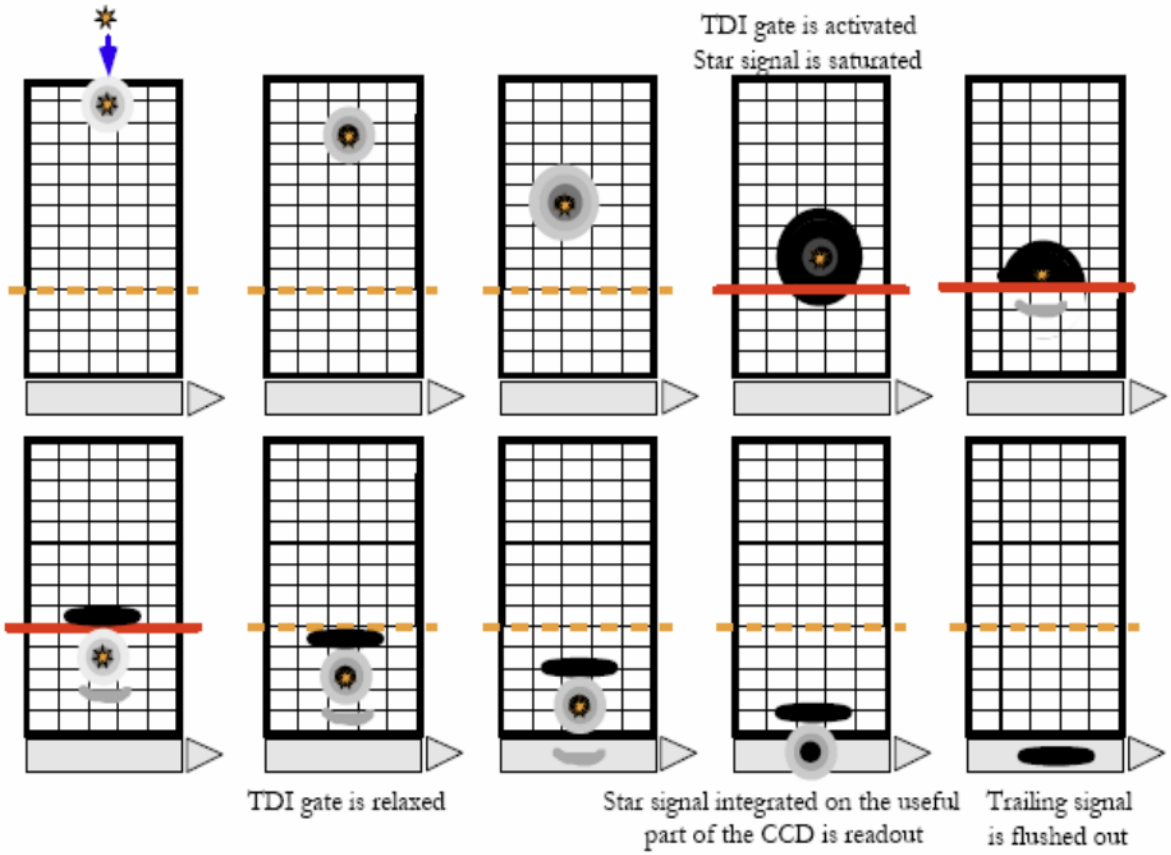


Figure 7-13: the TDI gates operation

Gates and magnitude of activation

- Table gives the range of magnitude of each gate level
  - **this is one possible scheme**
  - **possibilities limited by the lack of calibration bright stars**
  - **the scheme has consequences on the astrometric and photometric accuracy**

G_{min} [mag]	G_{max} [mag]	Gate identification	Gate length ("TDI") [TDI stages]
5.70	8.84	4	16
8.84	9.59	8	256
9.59	10.34	9	512
10.34	11.10	10	1024
11.10	11.47	11	2048
11.47	11.95	12	2900

Raw Gaia data

- Data transmitted are electron counts recorded at the serial register
- Initial astrometric and photometric parameters are derived from these counts
  - **transit time in TDI, flux**

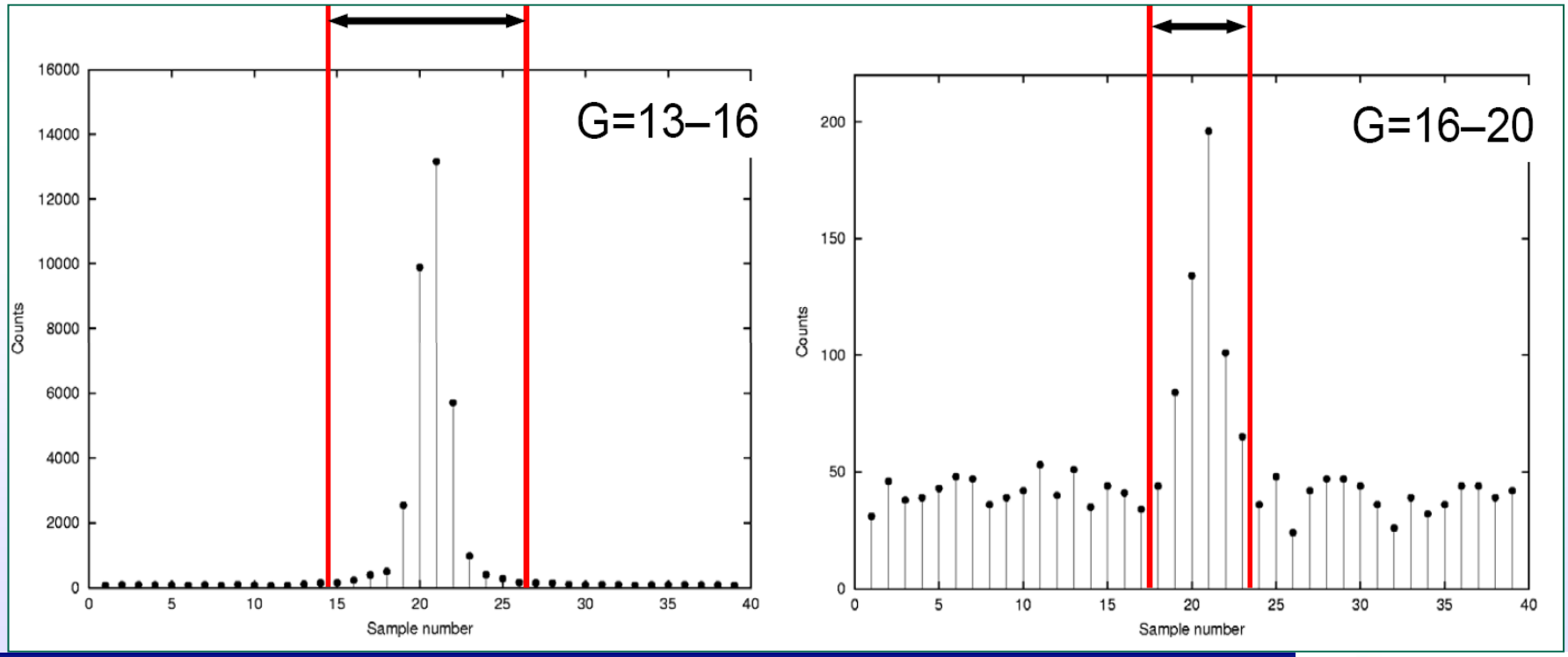
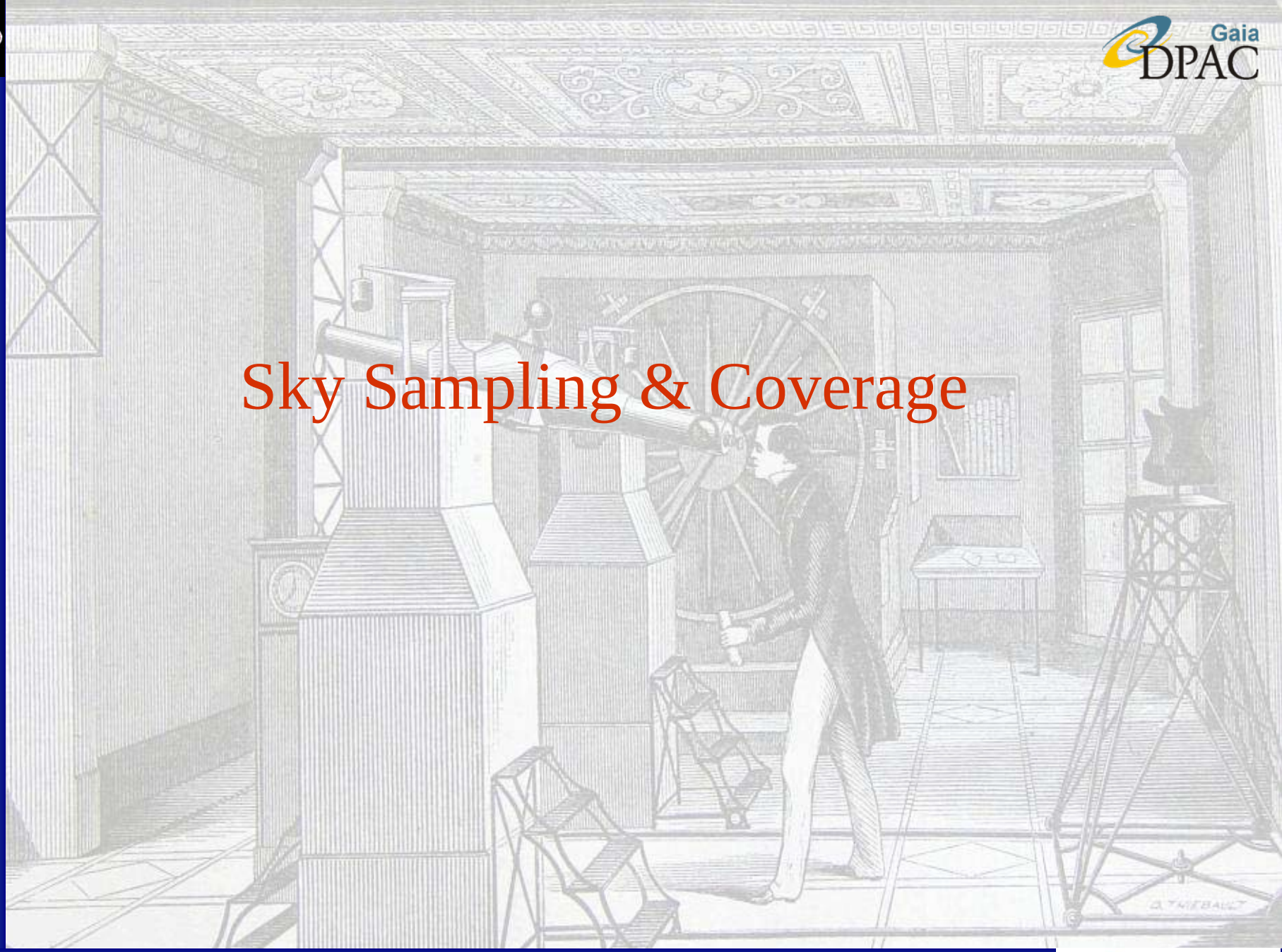


diagram: J. de Bruijne



Sky Sampling & Coverage

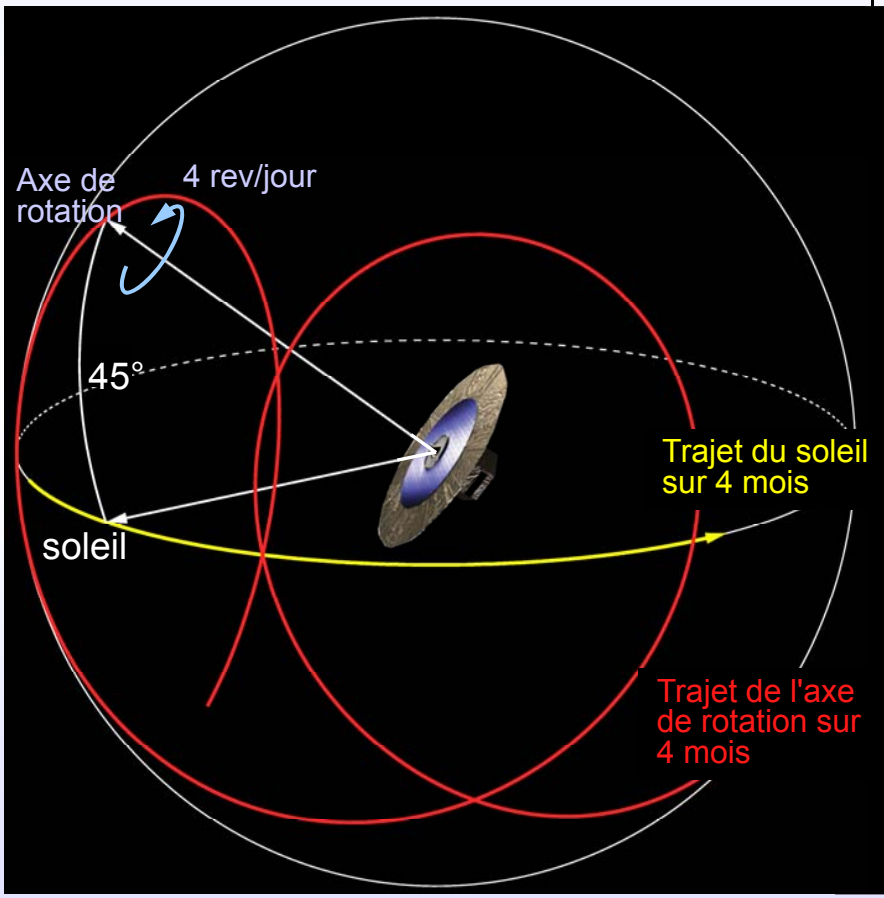
Sky coverage

- The Scanning law is optimized to explore the same area at more or less regular intervals:
  - **parallax, proper motion, variability, orbits**
- The scan direction must allow alpha and dec measurements
- The along-scan speed must be constant
- Mathematically: a set of two differential equations
  - **Three independent rotational motions**

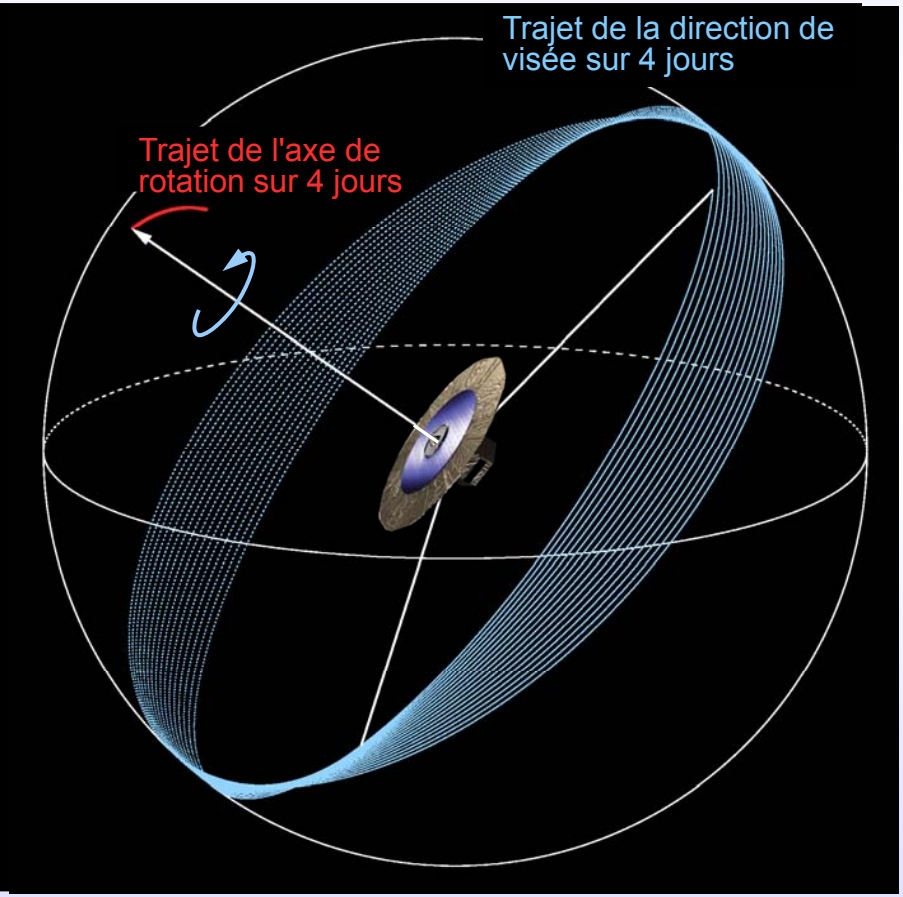
Gaia : Scanning

(diagrams L. Lindegren)

Motion of the spin axis

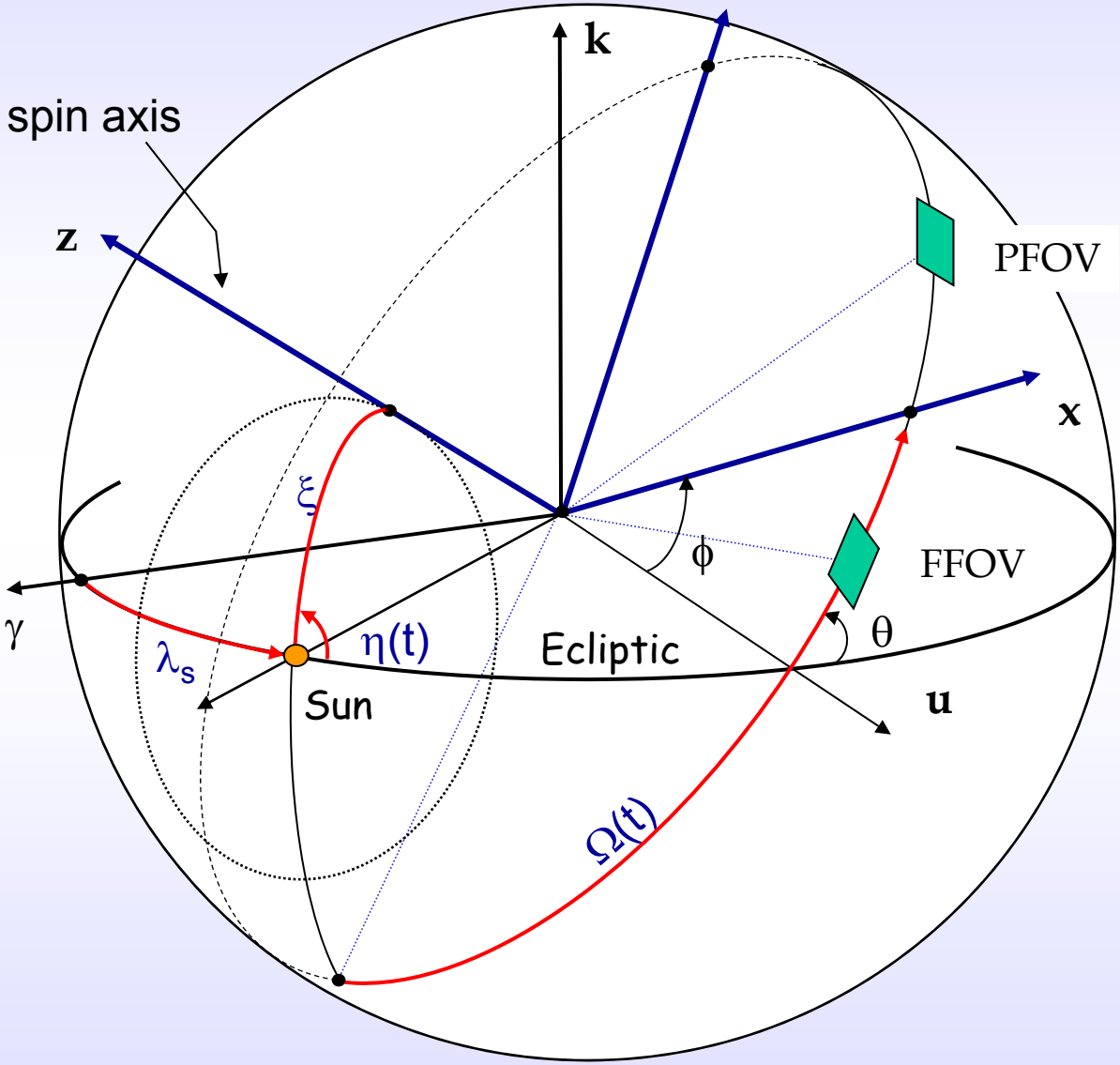


Sky covered over 4 days



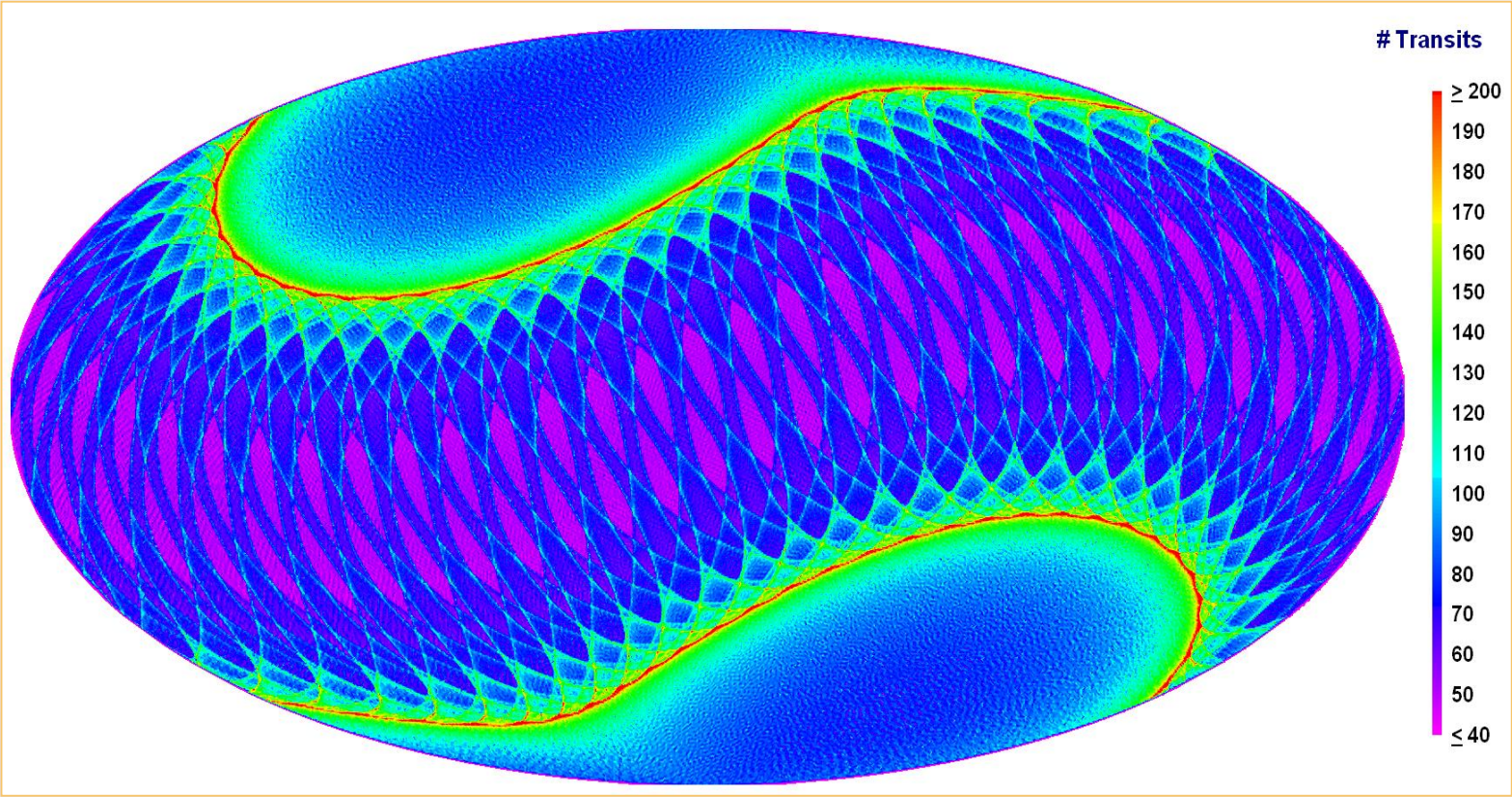
Gaia scanning in 3D: two free parameters

- Used to optimise the relativity experiments



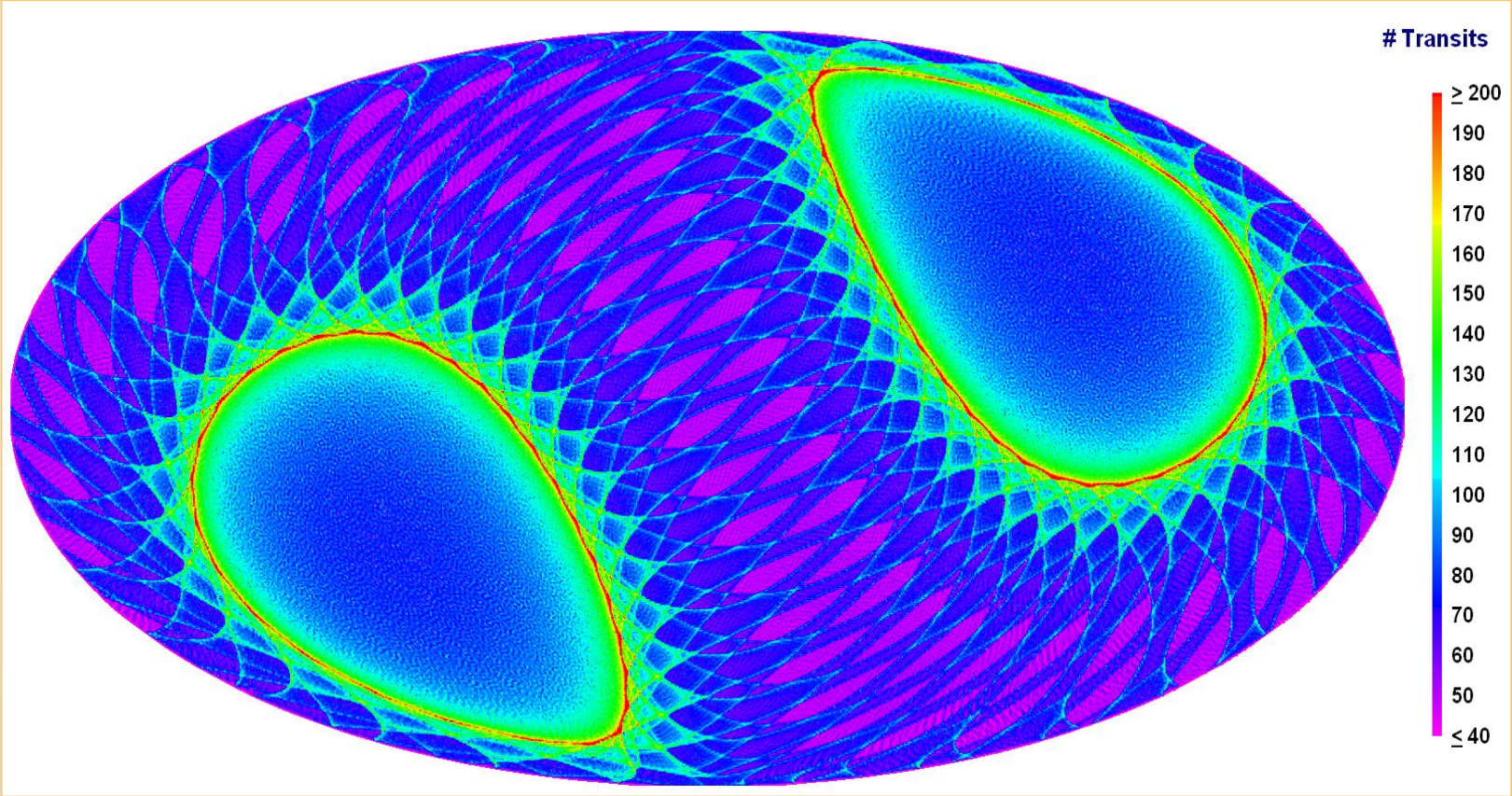
Sky coverage: Equatorial coordinates

Transits during the mission



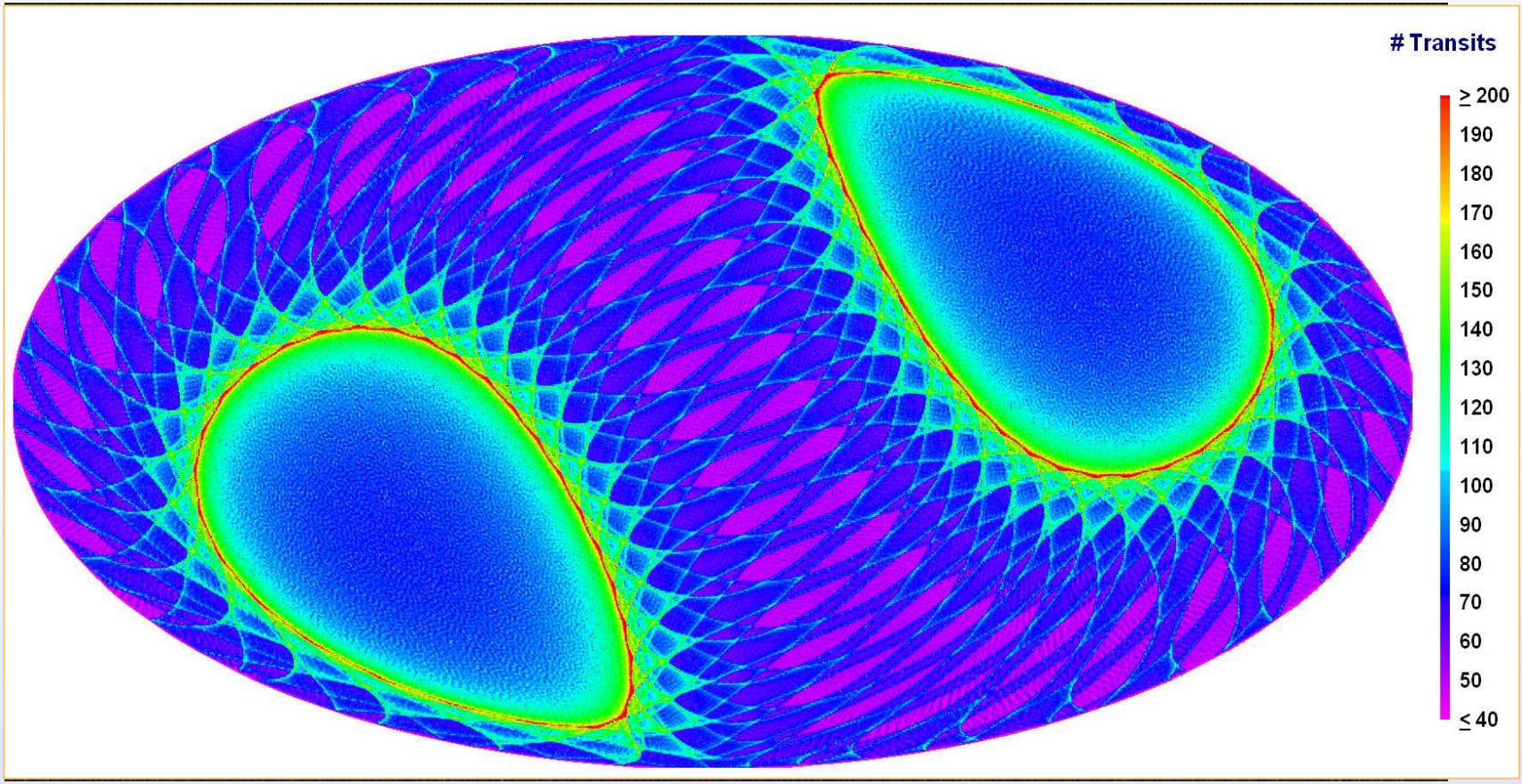
Sky coverage: Galactic coordinates

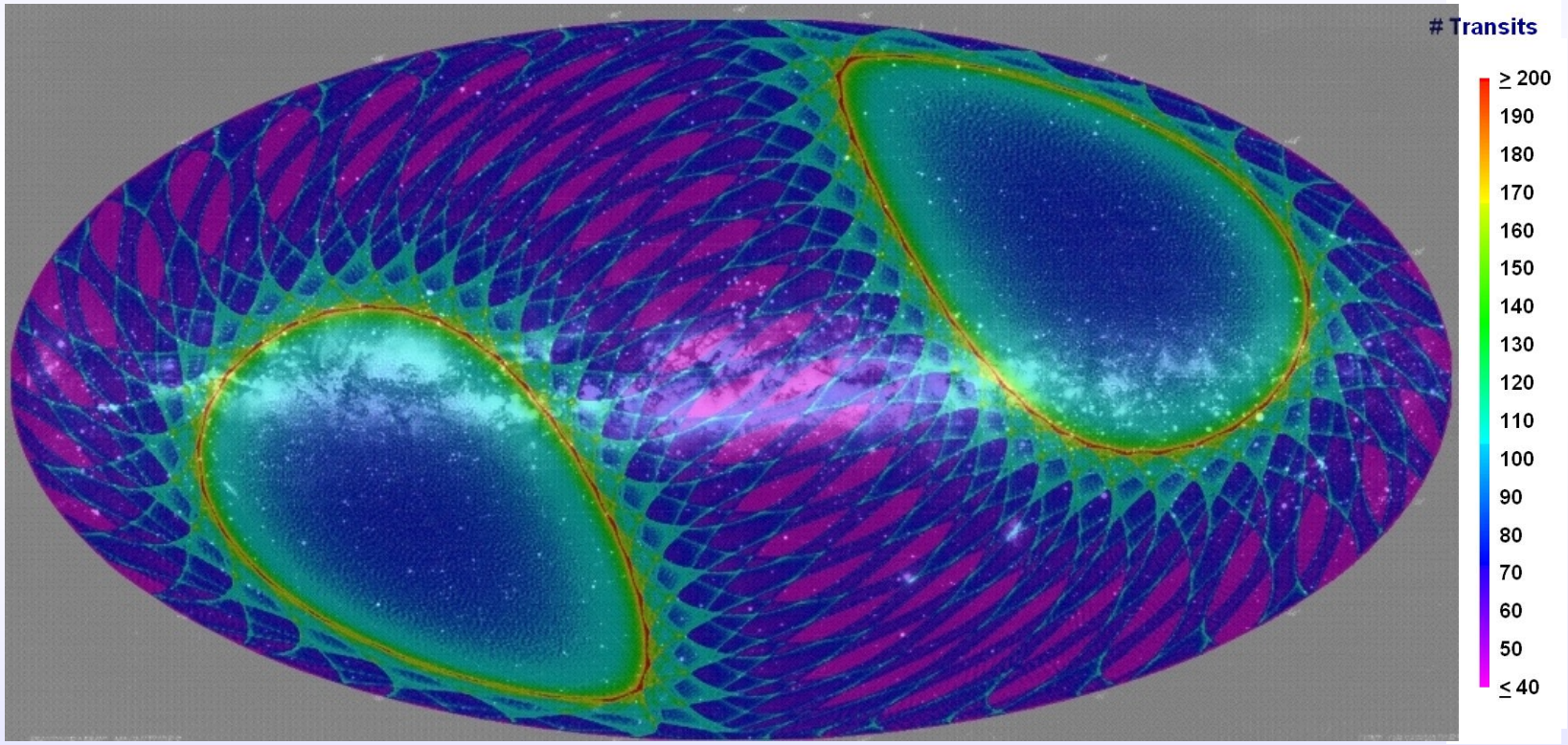
Transits during the mission



Sky coverage

- Time average is a combination of the sky distribution and the scanning law
  - two different symmetries: galactic plane and eclitpic plane




Transits
≥ 200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
≤ 40

Interval between observations

- Typical Sequences
  - **Successive observations :**
    - PFOV, FVOV, PFOV ….
    - FFOV, PFOV ….
  - **a short sequence of successive observations is *a bundle***
    - it corresponds to an epoch for astrometry
    - it is very important for solar system object identification
  - **Return of a short sequence after few weeks**
    - Typical gaps of 30 days, but smallest gap < 10 days
- Dependence with ecliptic latitude
- over the mission: about 85 observations and 30 epochs

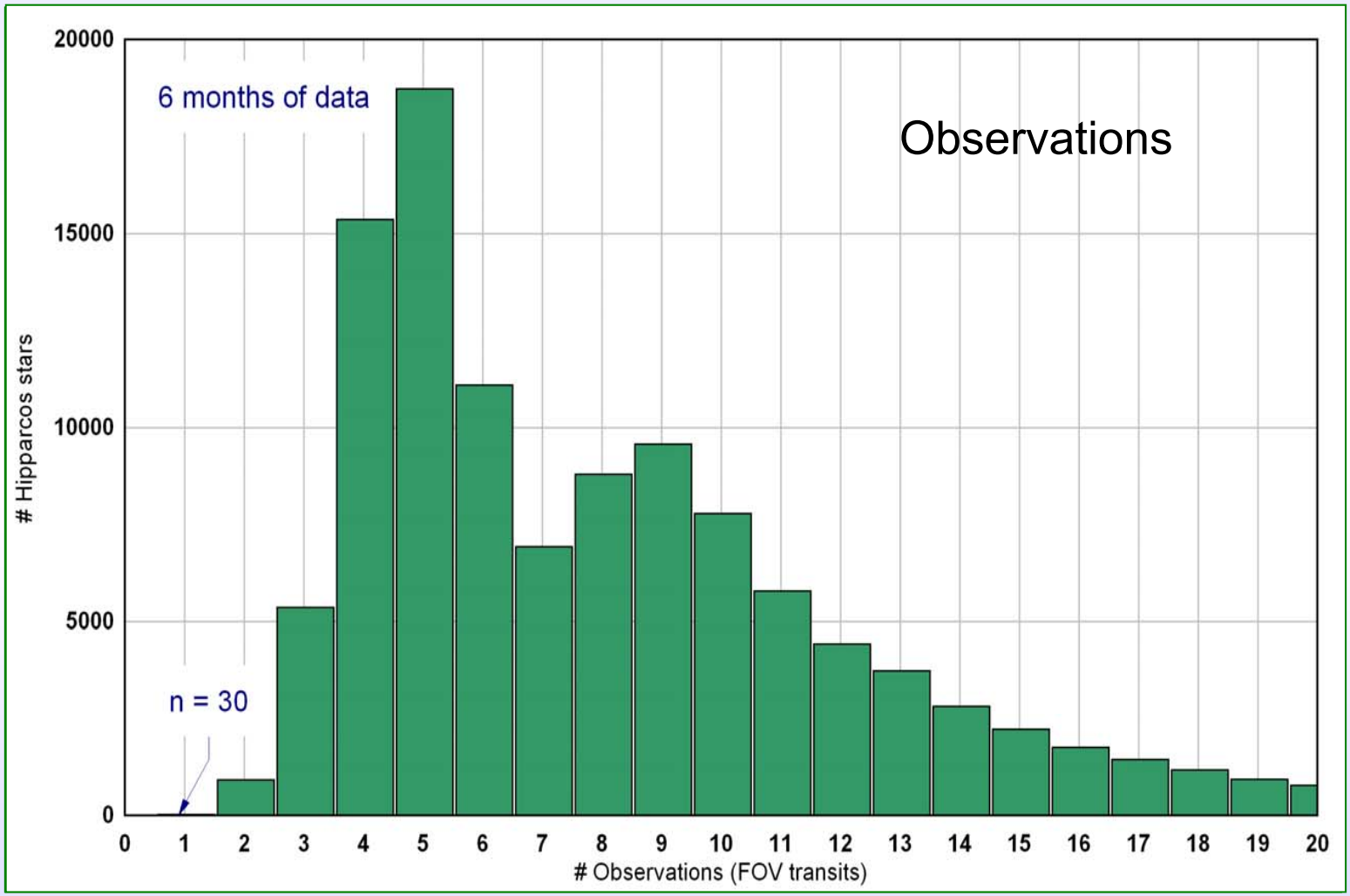
Distribution of short sequences

P… (70%)	Freq		F… (30%)	Freq
	%			%
P	24		F	56
PF	60		FP	23
PFP	6		FPF	14
PFPF	6		FPFP	2
PFPFP	1		FPFPF	2
PFPFP…	3		FPFPF…	3

- Statistics from solar system objects

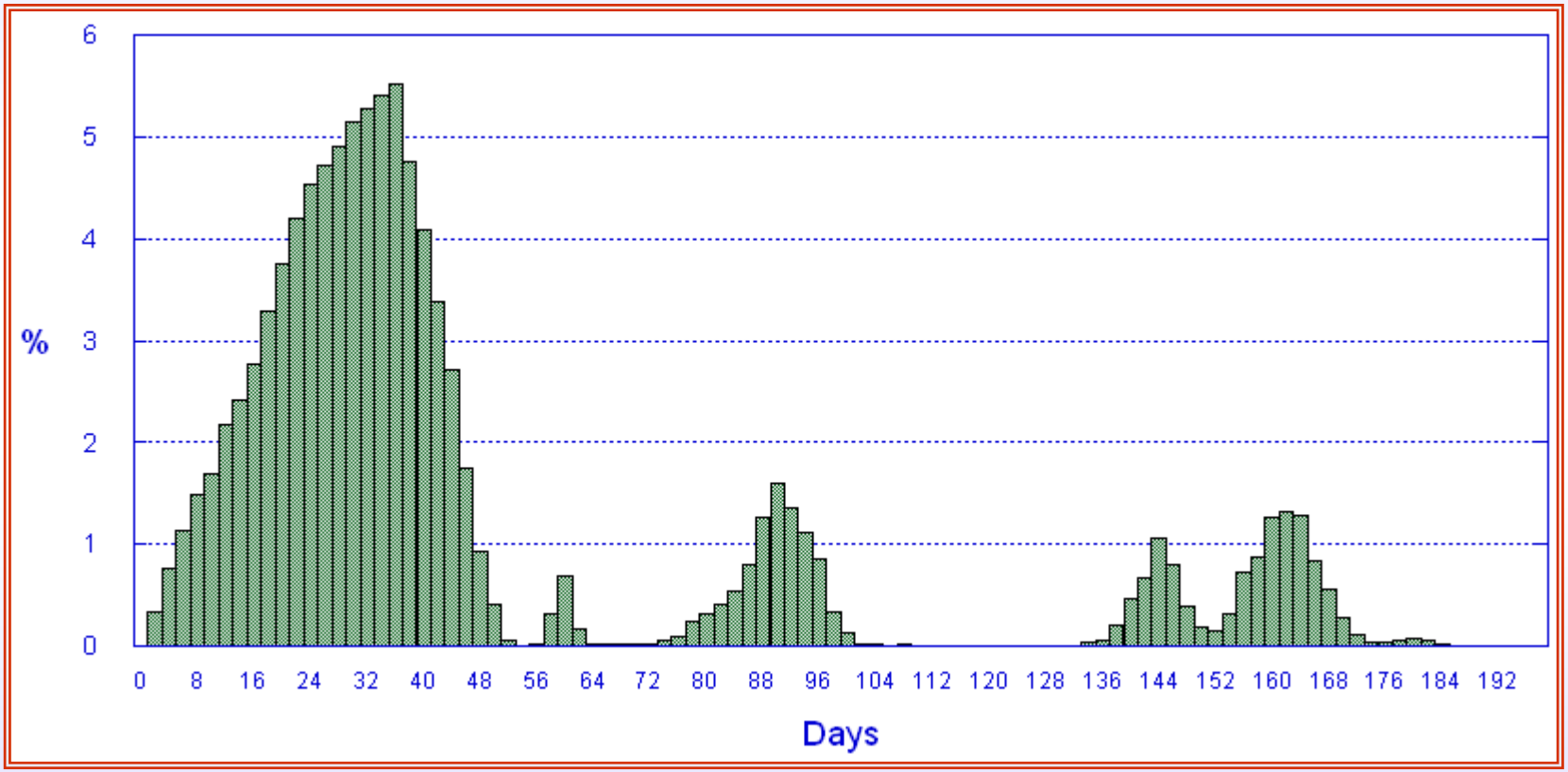
Sky coverage after six months

- Statistics for the ~ 120,000 Hipparcos stars



Distribution of long gaps

- Histogram of the gaplengths between two short sequences




Thanks for your attention
esa