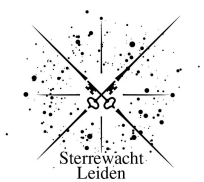
Gaia — Early data releases and thoughts on data access facilities

Anthony Brown

Sterrewacht Leiden, Leiden University
brown@strw.leidenuniv.nl

- Gaia status and survey overview
- Catalogue, archive, and data access facilities
- Data release scenario
- Extra material for weekend reading



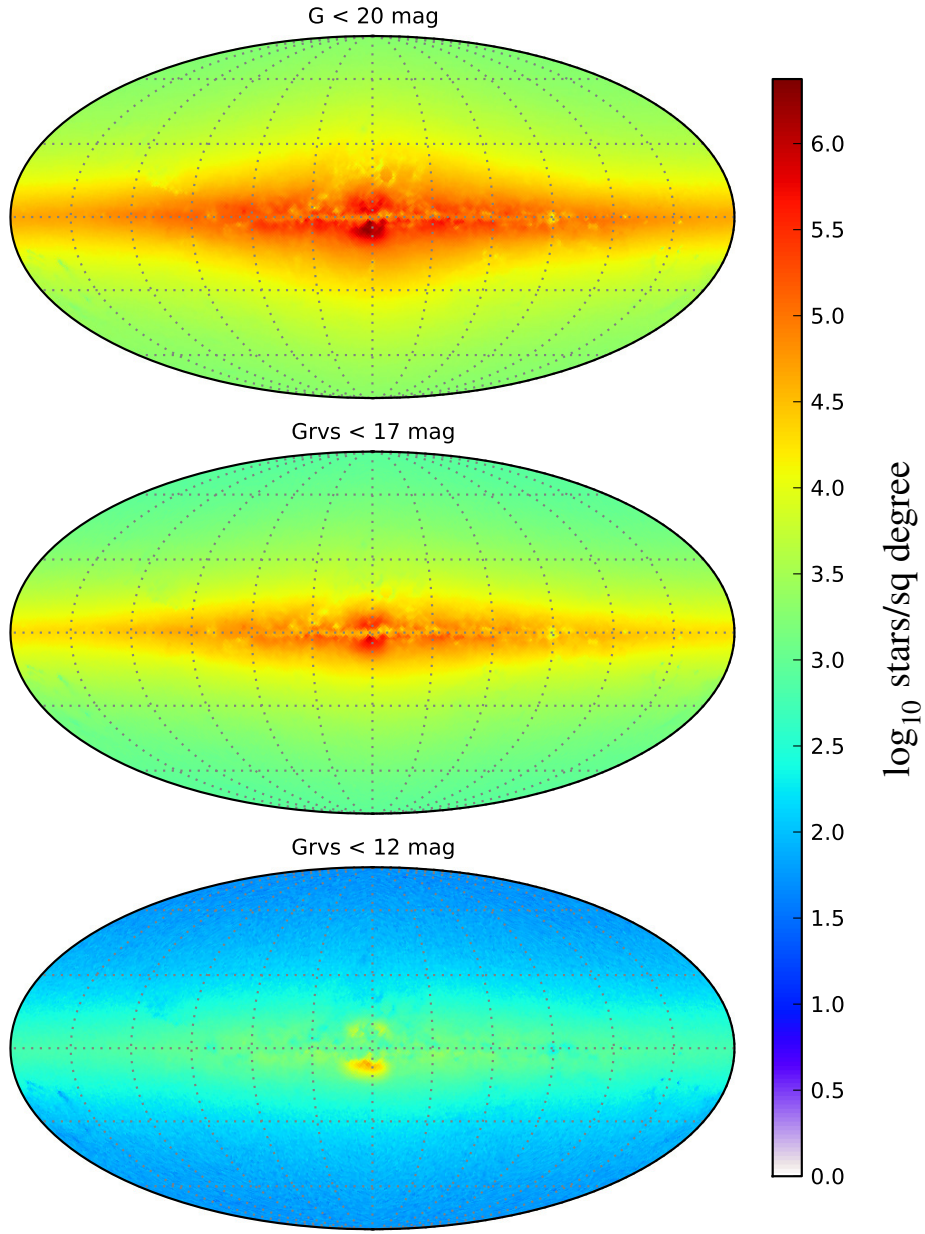
Survey capabilities

- Three simultaneous observing modes
- Complete to $G = 20$ ($V = 20$–22)
- Observing programme: autonomous on-board detection and unbiased
- Quasi-regular time-sampling over 5 years ($\sim$ 70 observations)
- Angular resolution comparable to HST

Number of objects

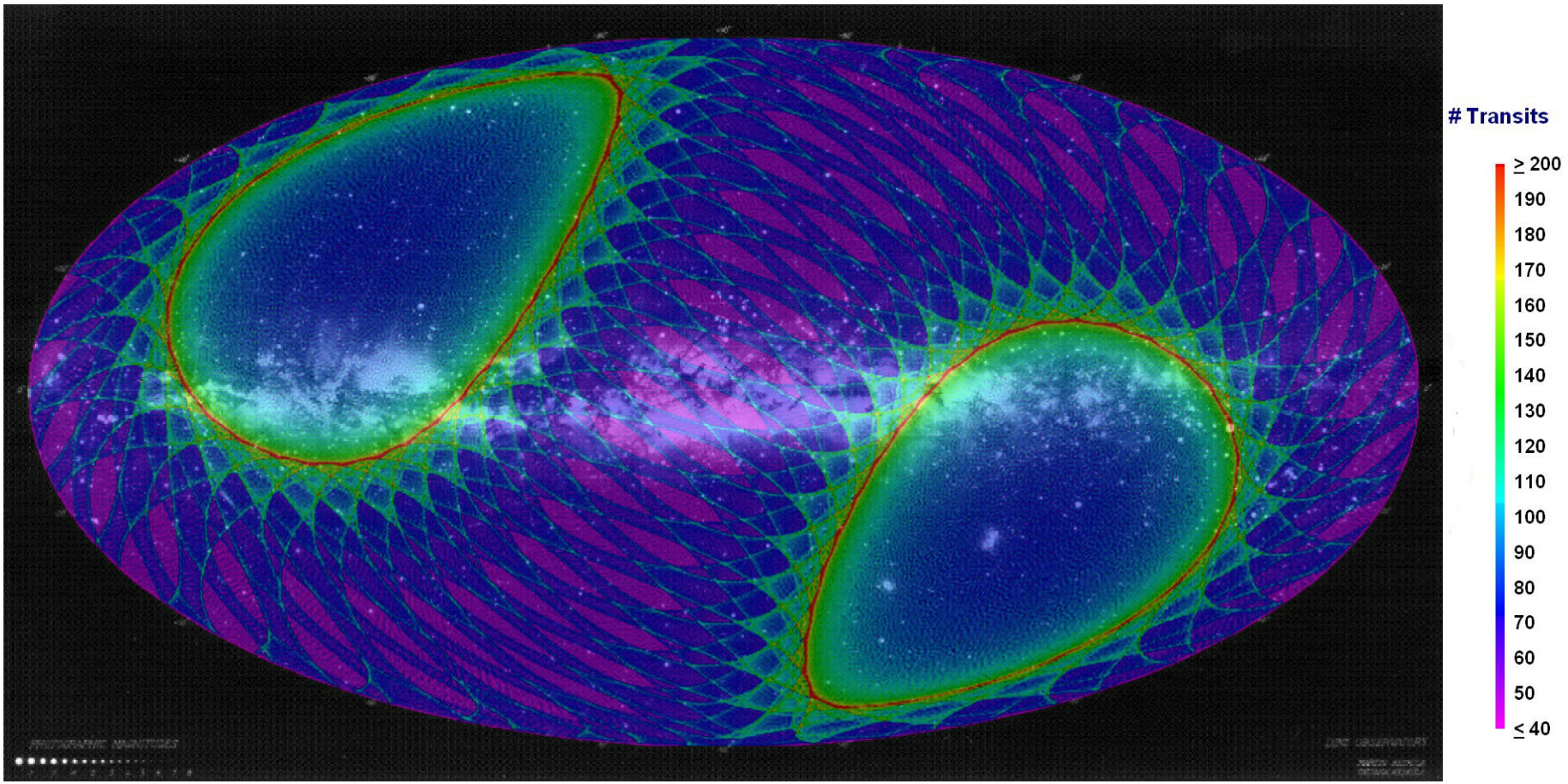
- 1 billion stars to $G = 20$
- 10^6–10^7 galaxies
- 500 000 quasars
- 3×10^5 solar system bodies
- tens of thousands of exoplanets

Simulated Gaia sky — Robin et al., arXiv:1202.0132

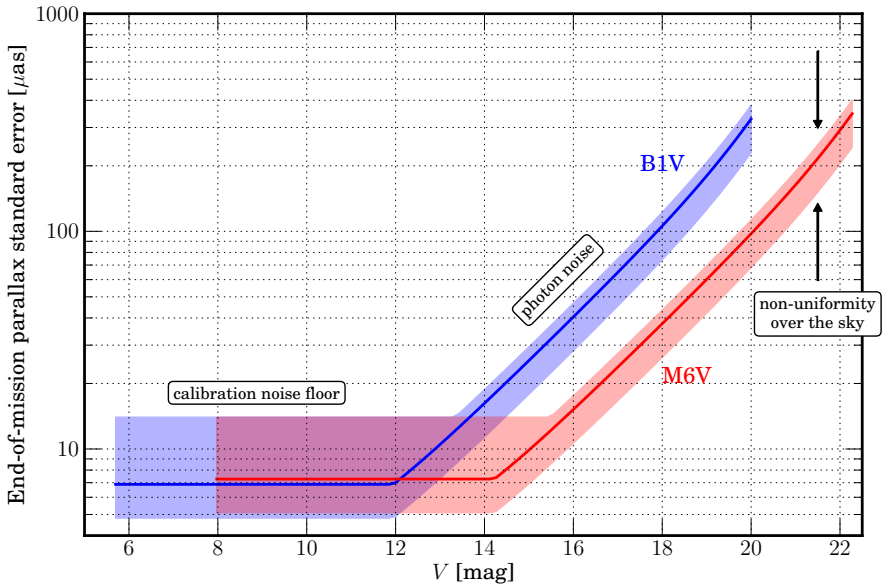


Survey capabilities

Number of field of view transits



Survey capabilities



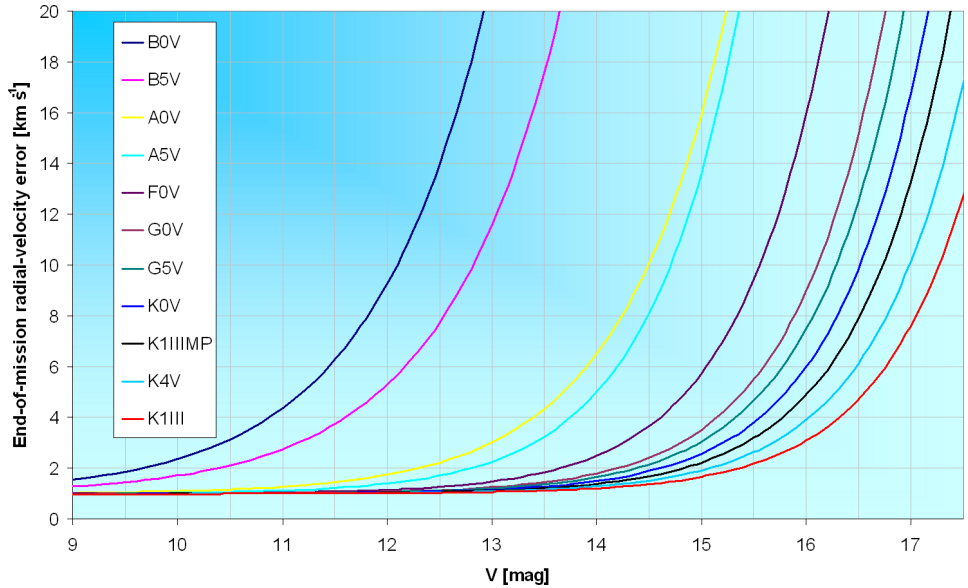
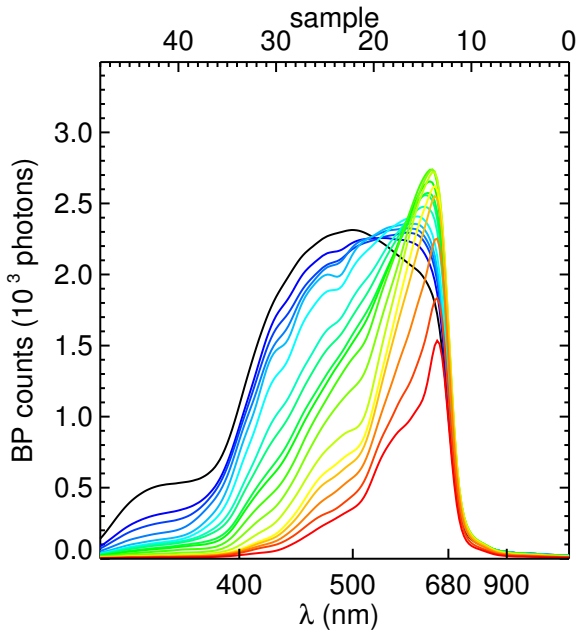
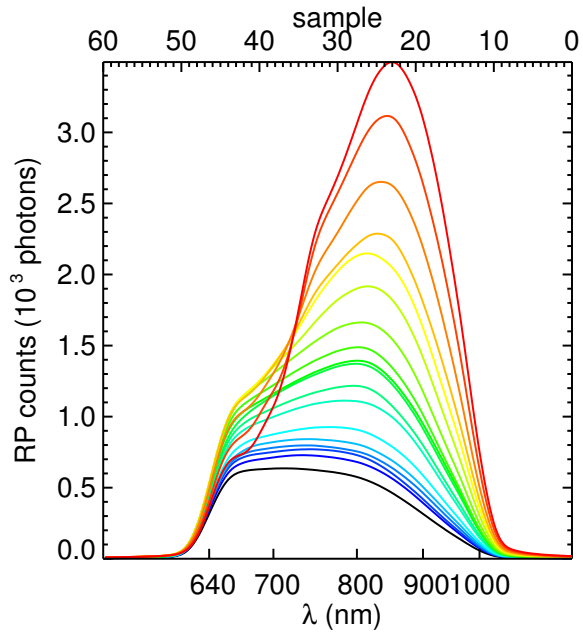


Figure by Jos de Bruijne

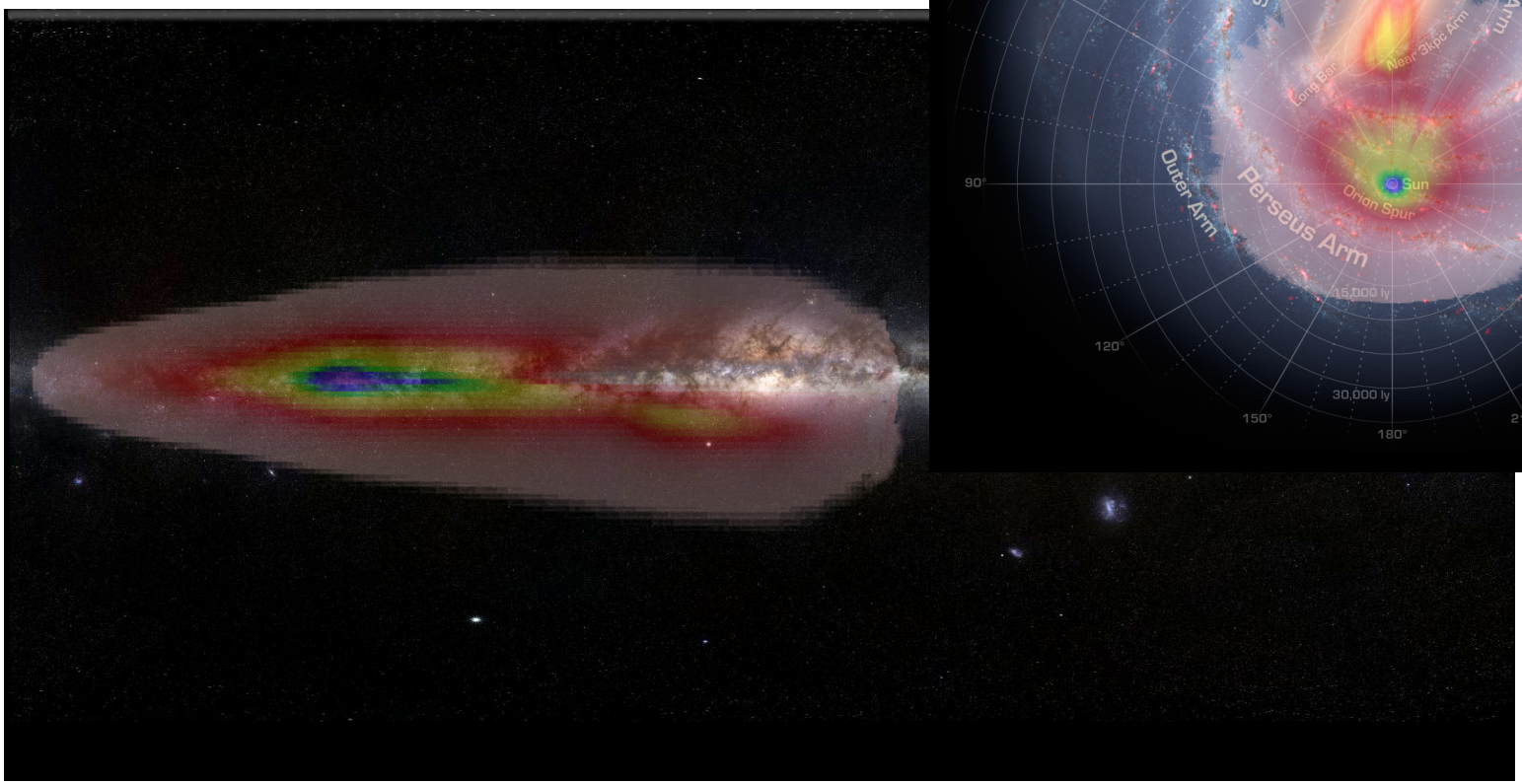
More info at www.rssd.esa.int/gaia ('Science Performance' button) and in arXiv:1201.3238

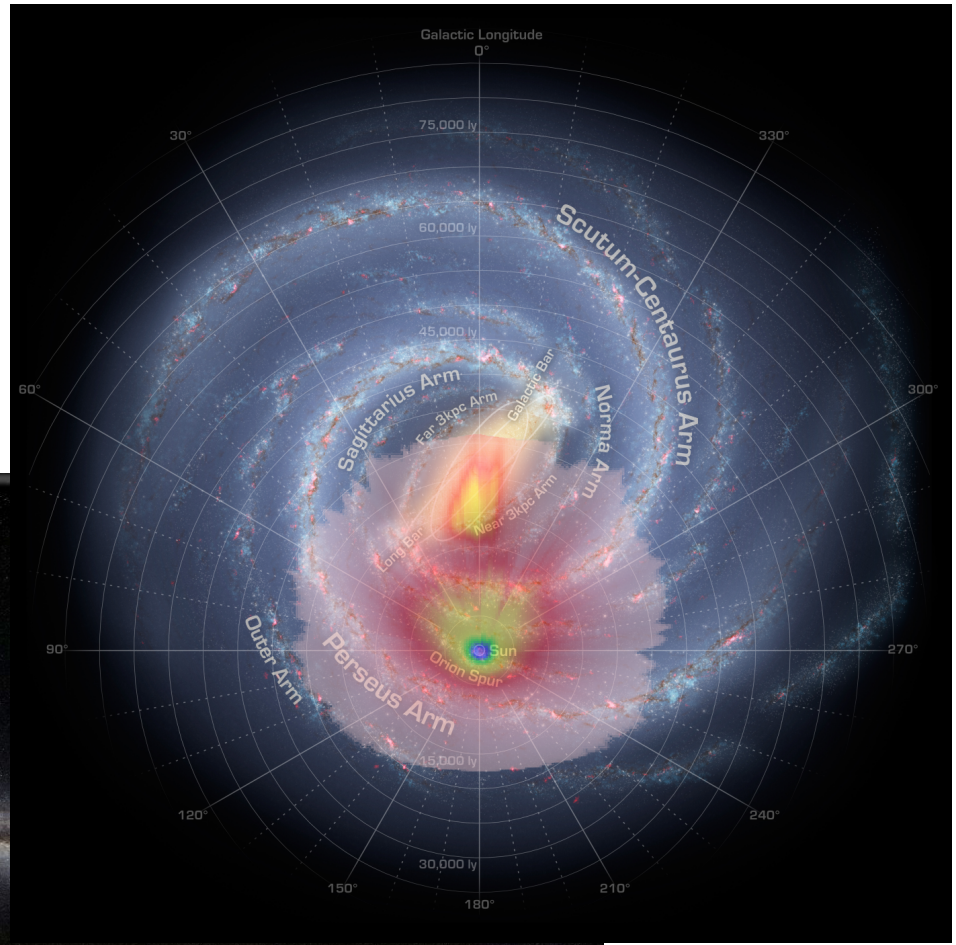




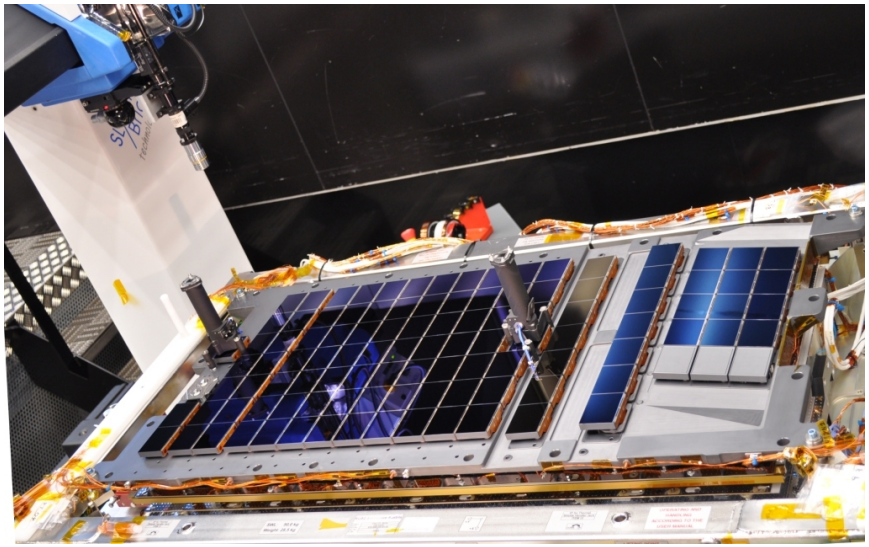
Survey capabilities

Figures courtesy Xavier Luri, DPAC-CU2 and NASA/JPL-Caltech/R. Hurt

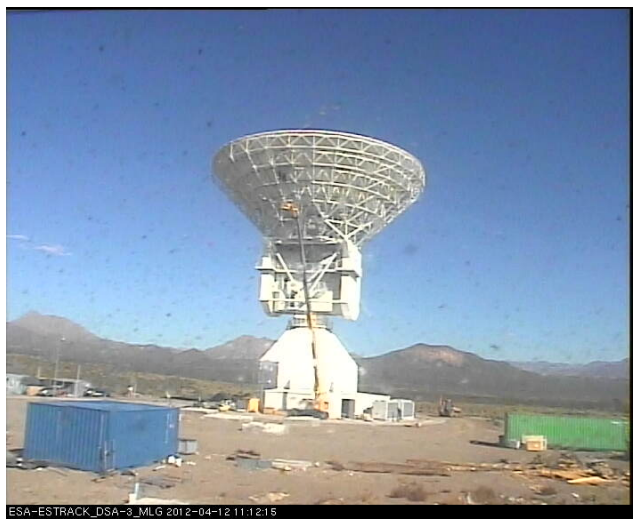




Launch August 2013



Images courtesy EADS-Astrium and ESA



Basic catalogue contents

Astrometry

- α, δ, ϖ, $\mu_{\alpha*}$, μ_δ for $\gtrsim$ 1 billion stars
- $\sim$ 60 million binaries, orbital solutions where possible
- ...

(Spectro)photometry

- Multi-epoch G, $G_{\rm BP}$, $G_{\rm RP}$, $G_{\rm RVS}$, blue and red photometer prism spectra
- A_V, $T_{\rm eff}$, $\log g$, [M/H], and [α/H] for brighter stars
- luminosity, mass, age for TBD subset of single stars
- ...

Spectroscopy

- Radial velocities to $V \sim 17$ ($\sim$ 150 million stars)
  - multi-epoch for $V < 13$
- Rotational velocities, atmospheric parameters, interstellar reddening ($V < 13$, 5 million)
- Abundances ($V < 12$, 2 million)
- ...

Ingredients for advanced data interpretation

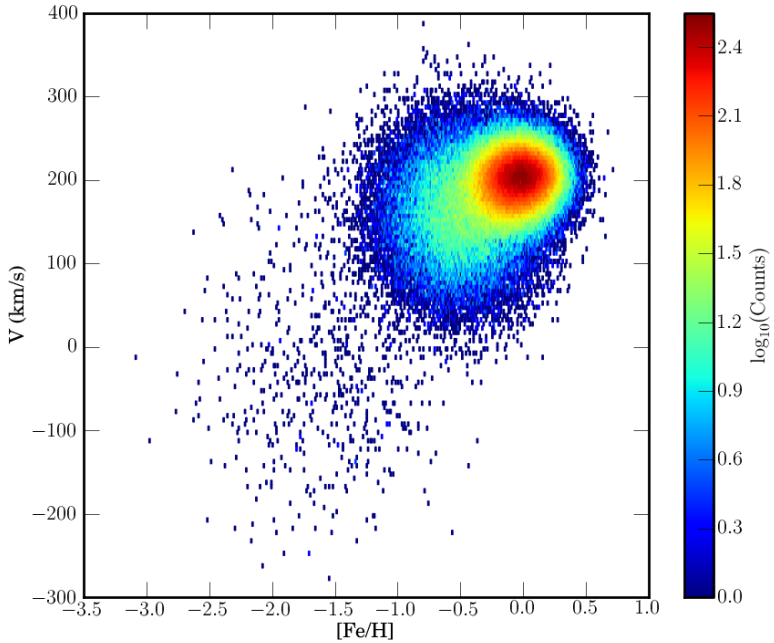
- Allow for precise hypothesis testing
  - Full covariance matrix of errors
  - Tools to calculate star-to-star covariance terms
- Intermediate data products, raw data, and processing software
  - re-processing of (parts of) the Gaia data based using better processing algorithms, new information, etc
- Detailed documentation on completeness function
  - important in, e.g., crowded regions
- Software to facilitate proper use of the data
  - For example, correctly incorporating parallaxes in distance or luminosity estimates
- 'Bring the processing to the data'
  - run your code on virtual machines near the data
- 'Living archive'
  - requires careful versioning
- Transparent inter-operation with other surveys
  - cross-matching not trivial

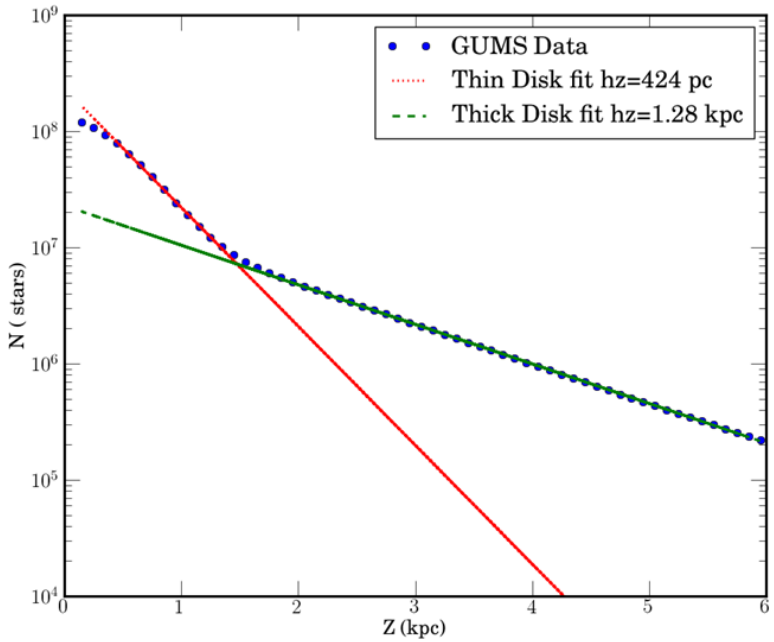
What the Gaia community can do for you

Go to: www.rssd.esa.int/gaia, look for ‘Science Performance’ button

- Background information on instruments and error modelling
- Interpolation tables and formulae
- Error variations on sky
- Transformations from Johnson, Sloan systems to Gaia photometric system
- Will be updated with more information on astrophysical parameter performances, other products from photometry and spectroscopy

What the Gaia community can do for you





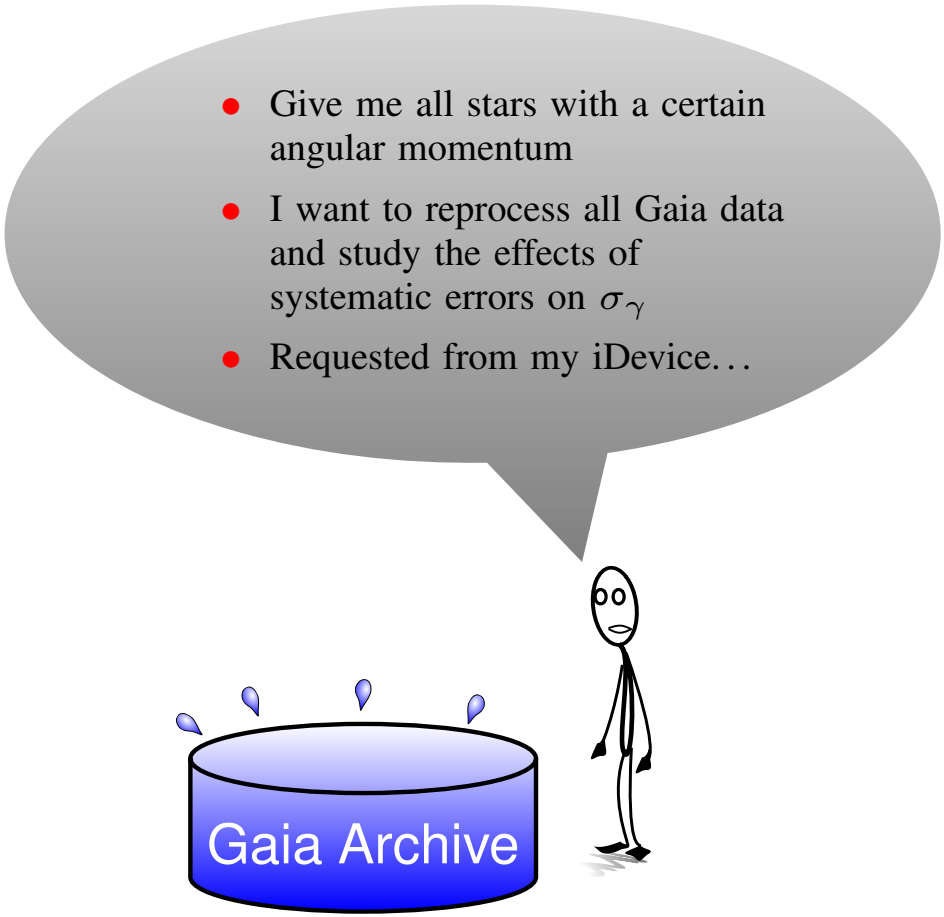
- Universe model is published (arXiv:1202.0132)
  - All sources that Gaia can observe within and outside the Galaxy
  - Available for use (on request for now)
- Simulated catalogue is done and will be made available
  - Gaia measurements and their errors
- Gaia simulator can also be used to process, e.g., *N*-body model outputs

More info at

`http://gaia.am.ub.es/GUMS-10/`

What you can do for the Gaia community

- Preparatory work for Gaia data publication and archiving has started
  - Will lead to new DPAC unit for data validation, publication, documentation (CU9)
- Maximizing science depends on archive that can deliver what you want
  - tell us how you want to use the Gaia data
  - feel free to go crazy...
  - think about possibilities in 2020!



Provide input through:
`http://great.ast.cam.ac.uk/Greatwiki/GaiaDataAccess`

Early data releases

- We're all impatient
- Science verification (dialogue 'modellers' $\leftrightarrow$ DPAC)
  - feedback to DPAC to improve data processing
- Target selection for complementary surveys
- Early familiarization with Gaia catalogue and archive
- Feedback on data access facilities

Earliest releases will concern transient sources ('Science Alerts') and Near Earth Objects. Not further discussed here

Constraints on early data releases

Time

- Launch date
- Anticipate $\sim$ 6 Months for cruise to L2, commissioning, DPAC systems initialization
- First full sky coverage after 6 months of nominal scanning
- Disentangling parallaxes and proper motions requires at least 18 Months of data collection
- Processing, calibration, validation take time
- Each data release requires time to go from DPAC internal database to public archive (3 Months)

Data processing and resources

- *Quality of the data*
- Inter-dependencies DPAC software systems
- Available staff effort (talk to your funding agencies!)

Data release scenario

Very tentative data releases — highly summarized:

- Assumes smooth operations!
- All values prior to final release *may* be truncated at some confidence level
- Each release updates the previous and contains significant new additions

August 2013 launch

L+22M Positions + G magnitude ($\sim$ all sky, single stars)
  - Includes more often scanned Ecliptic pole regions
  - Simultaneous two-colour photometry release still under study
  - Hundred Thousand Proper Motions (Hipparcos-Gaia, ~ 50 μas/yr)

L+28M *more tentative* radial velocities for bright stars and full astrometry (α, δ, ϖ, $\mu_{\alpha*}$, μ_δ) where available.

L+40M full astrometry, orbital solutions, $(G_{\rm BP} - G_{\rm RP})$, some BP/RP Spectrophotometry and astrophysical parameters , radial velocities, RVS spectra

L+65M Updates on previous release — including more sources, source classifications, multiple astrophysical parameters, variable star solutions and epoch photometry for them, solar system results

End+3yr Everything

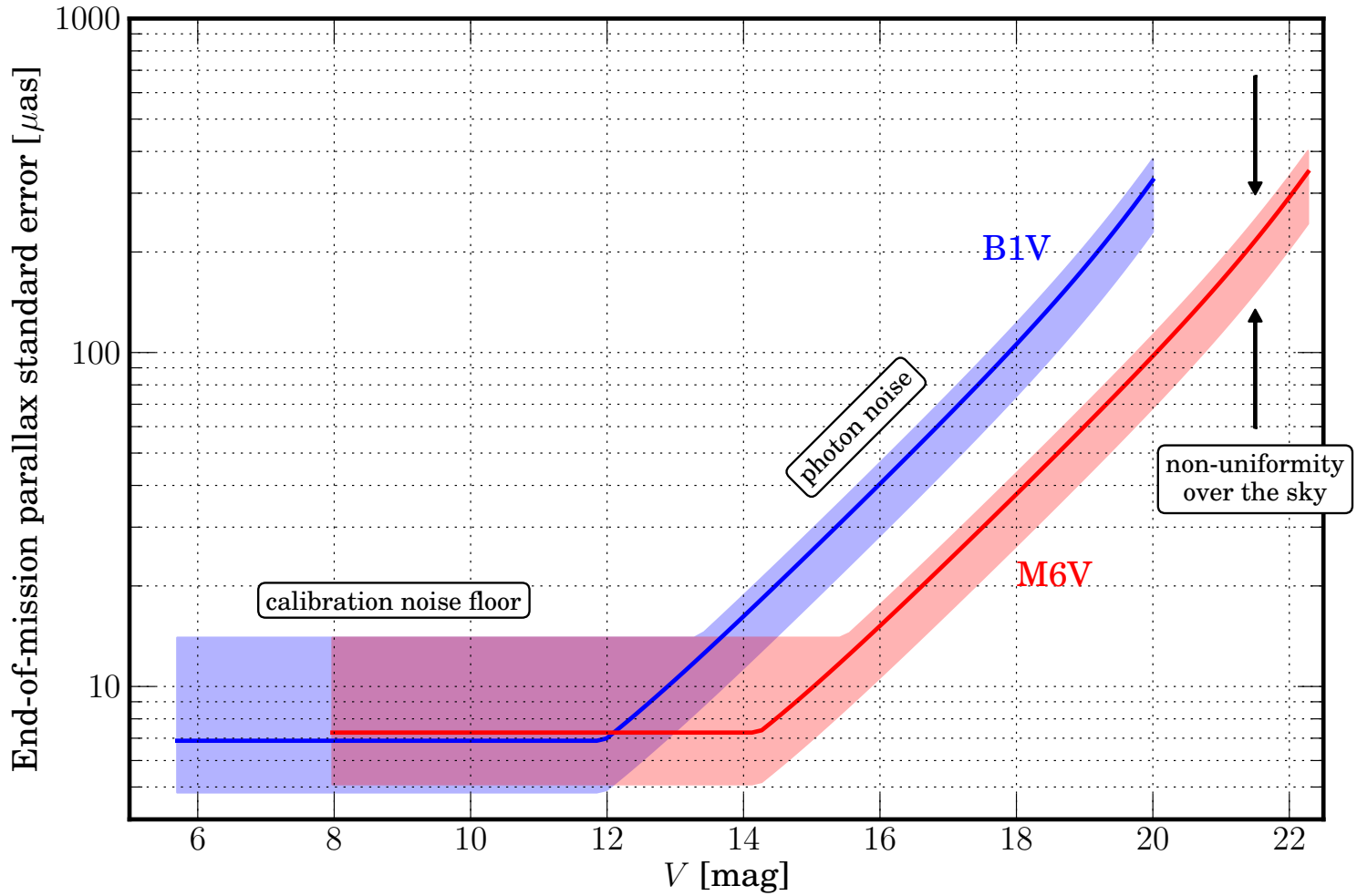
Extra material on expected Gaia performances

Sky averaged parallax accuracies (μas)

	B1V	G2V	M6V
Bright stars	($6 < V < 12$)	($6 < V < 12$)	($8 < V < 14$)
	5–14	5–14	5–14
$V = 15$	26	24	9
$V = 20$	330	290	100

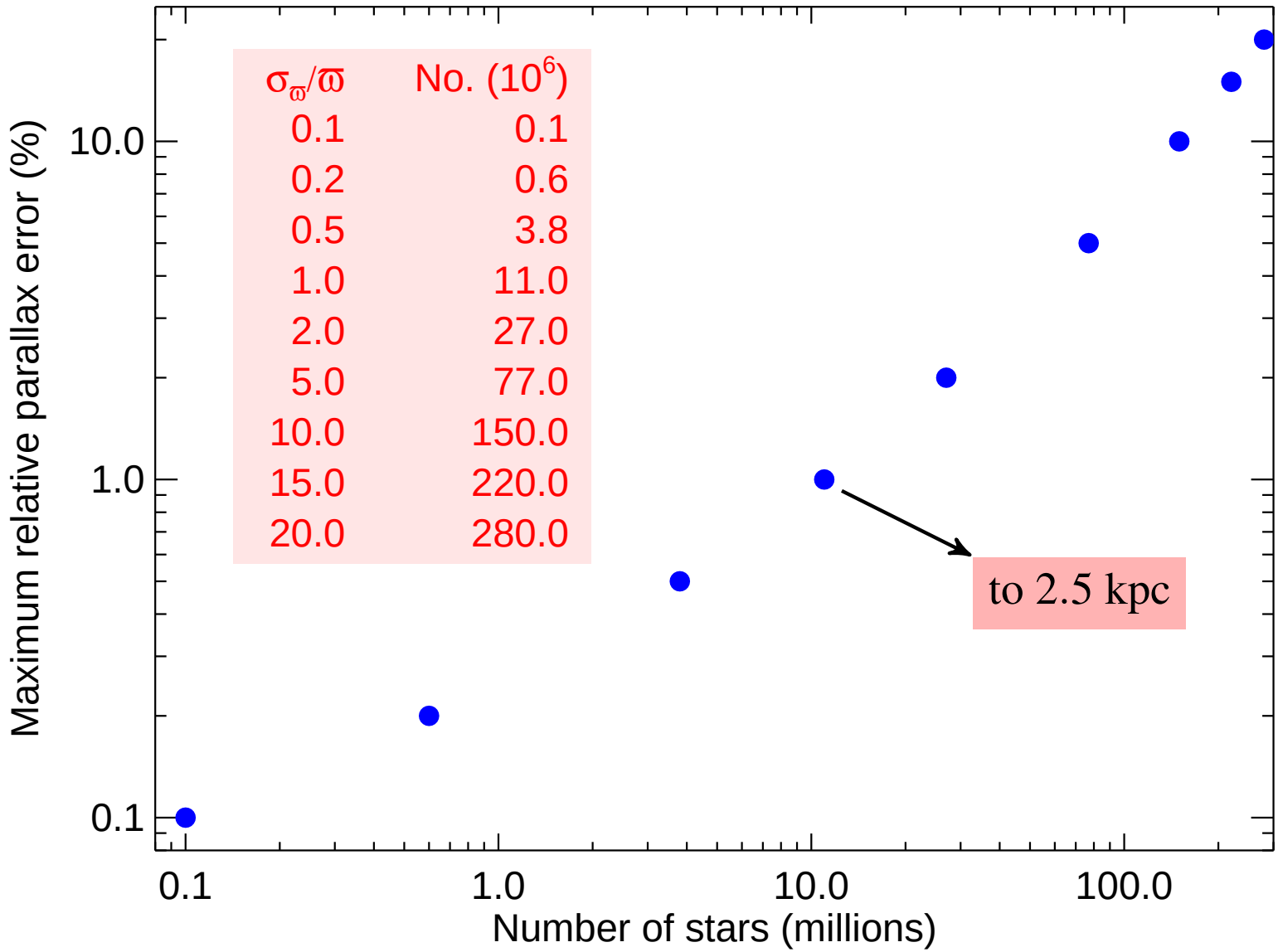
- Single stars, no extinction
- Apply factors ~ 0.5 and ~ 0.7 for positions and proper motions
- Radiation-damage effects on CCDs taken into account approximately
- Estimates include a 20% margin (factor 1.2) for unmodelled errors
- Astrometric instrument designed for up to 750 000 stars/degree^2

Gaia astrometry



1. $6 < G < 12$: bright star regime (calibration errors, CCD saturation)
2. $12 < G < 20$: photon-noise regime, sky-background and electronic noise setting in at $G \sim 20$

Statistics of relative parallax accuracies achieved by Gaia



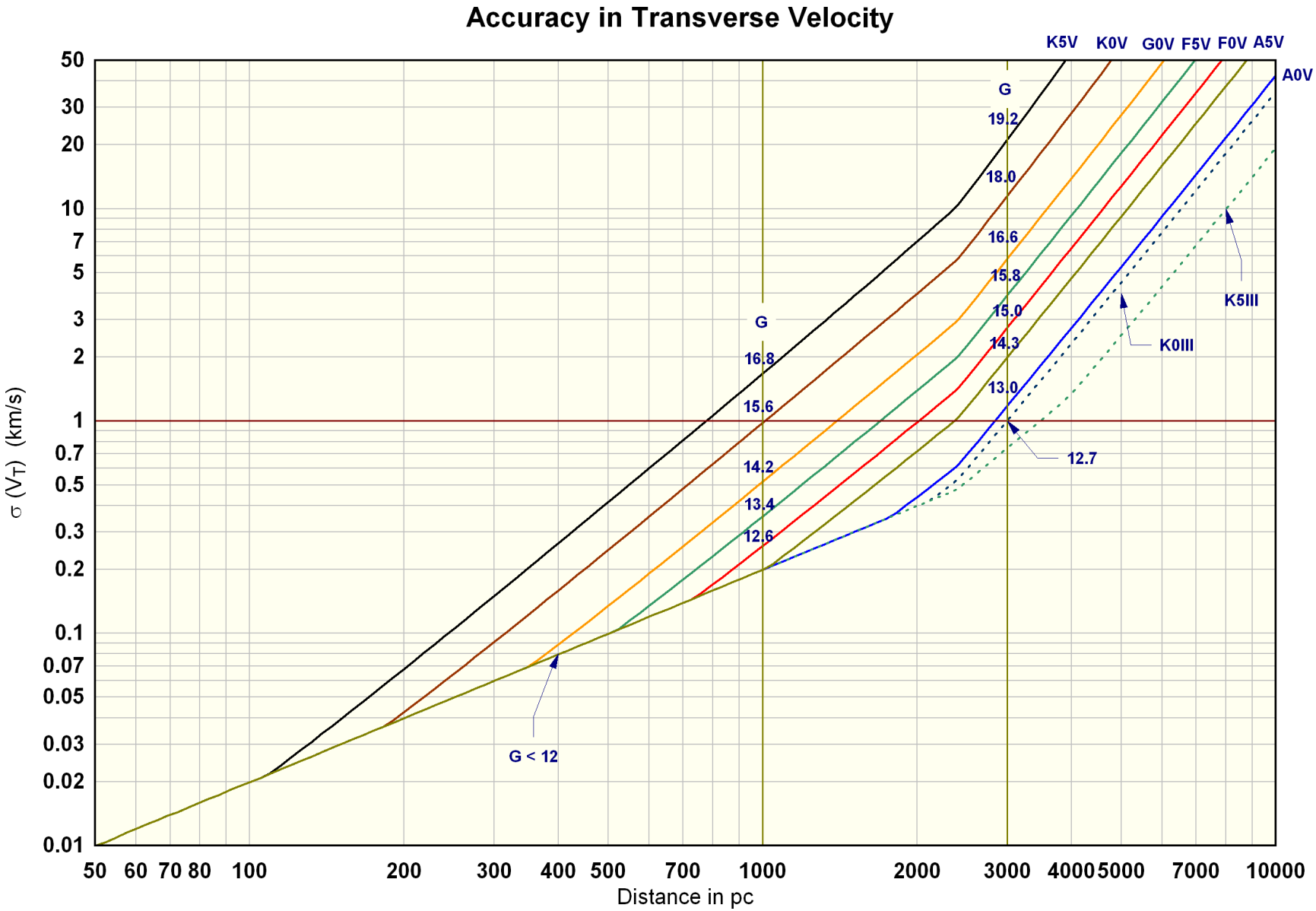


Figure courtesy François Mignard

Broad band photometry

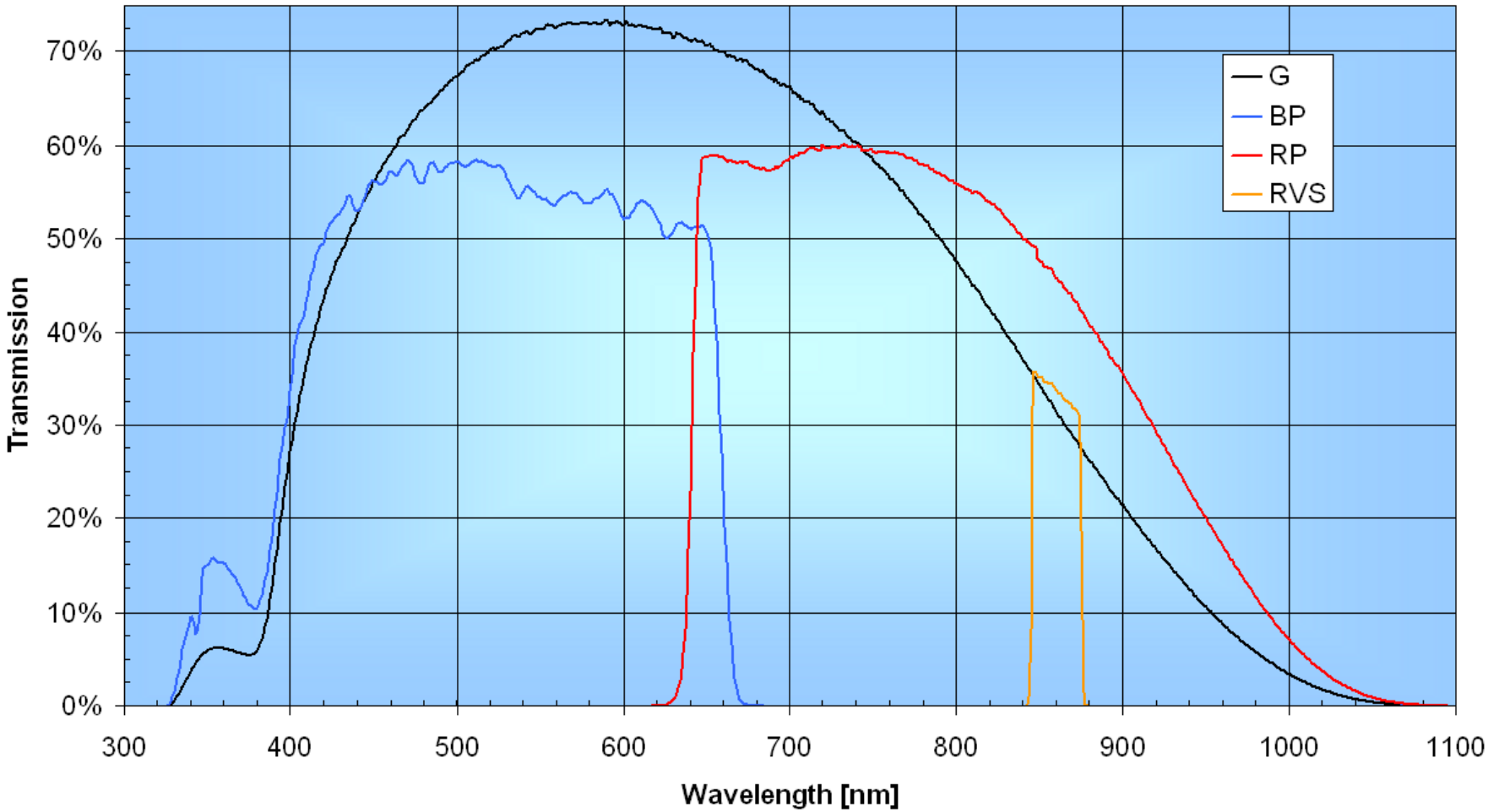


Figure courtesy Jos de Bruijne (ESA)

Broad band photometric accuracy per field of view transit

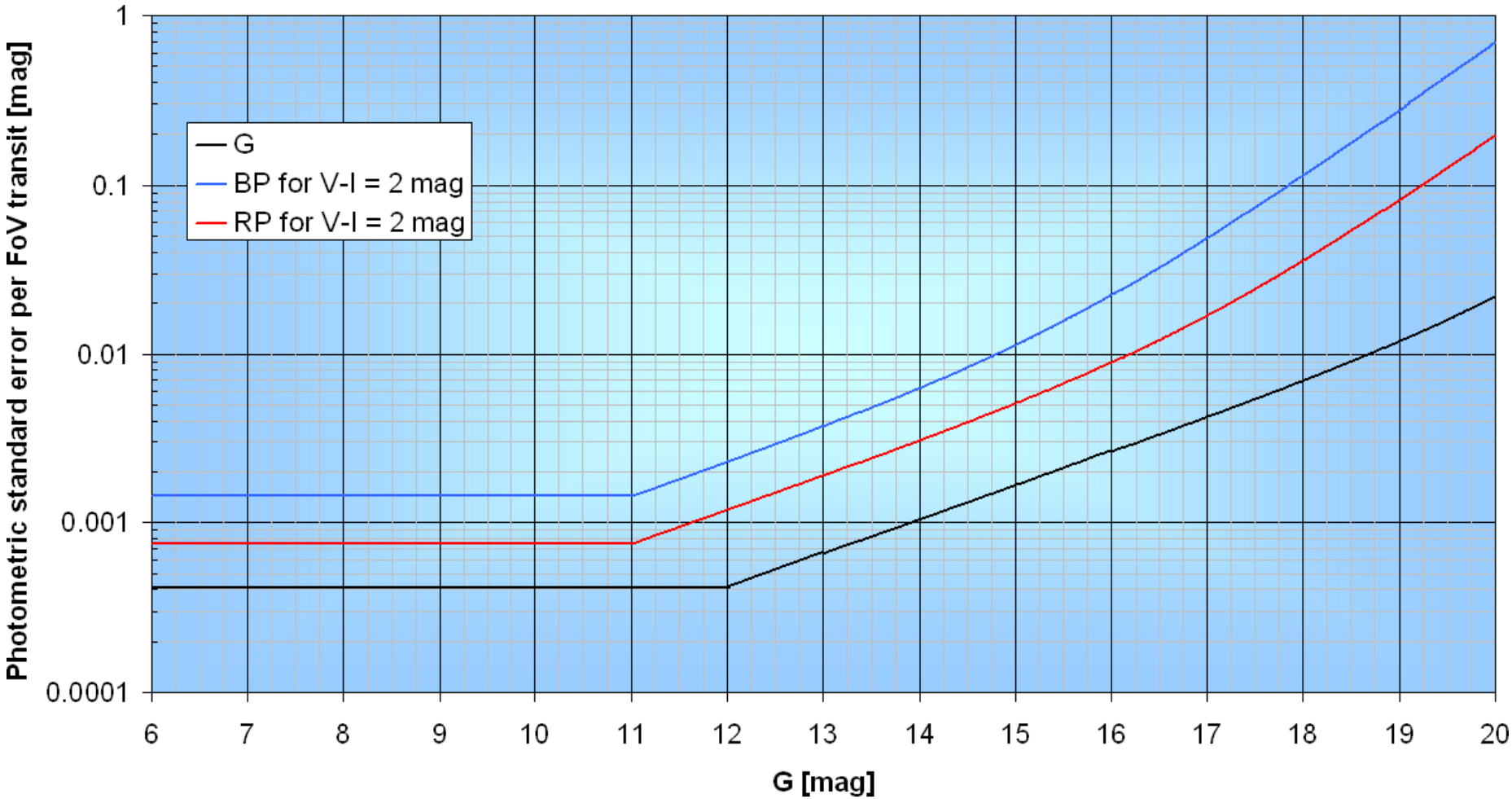
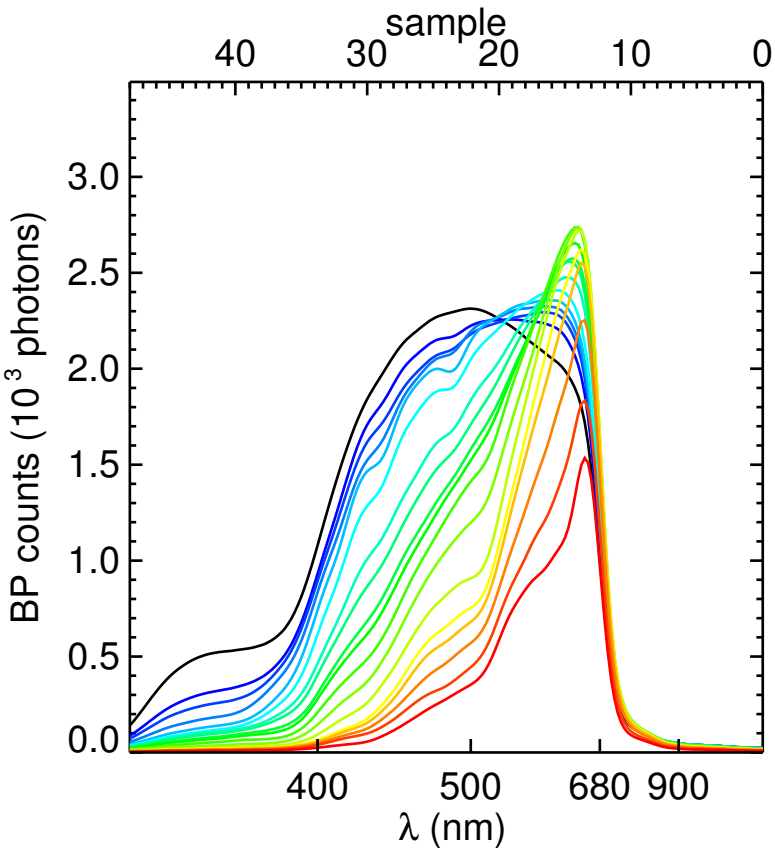
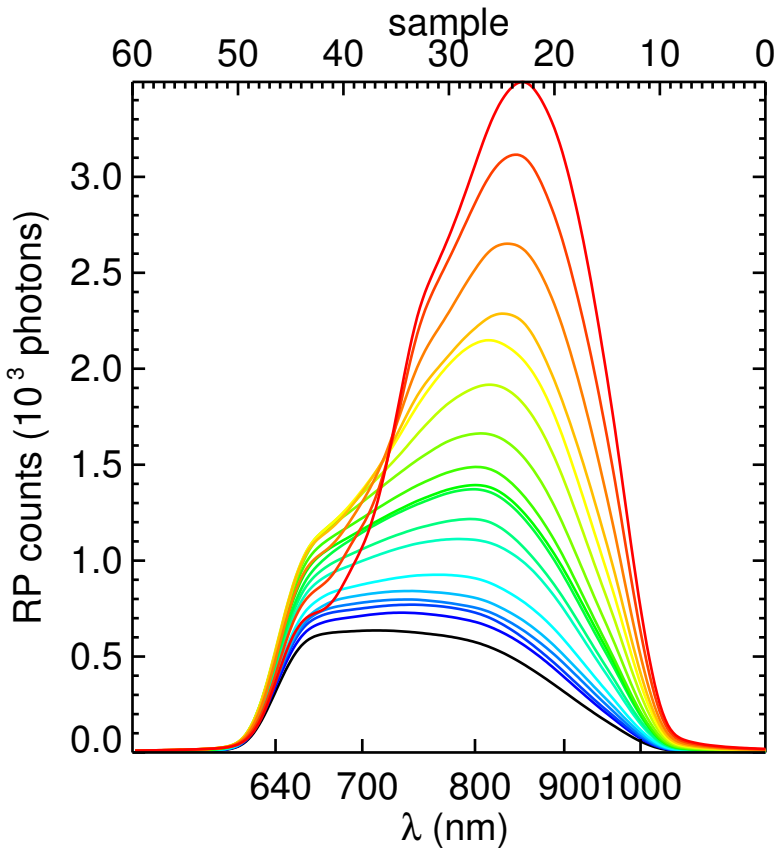


Figure courtesy Jos de Bruijne (ESA)

Spectrophotometer

- Two channels: 330–680 nm (BP), 640–1000 nm (RP)
- Low resolution ($\sim$ 3–30 nm/pixel) prism spectra
- Allows derivation of A_V, $T_{\rm eff}$, $\log g$, [M/H], and [α/H] for brighter stars





For preliminary estimates of the astrophysical parameter accuracies see Bailer-Jones, 2010, MNRAS 403, 96

- Slit-less spectroscopy in Ca triplet region (847–874 nm)
- $\lambda/\Delta\lambda \sim 11\,000$

Sky averaged radial velocity accuracies (km s^{-1})

	V	$\sigma_{v_{\rm rad}}$
B1V	7.0	1
	12.0	9
G2V	13.0	1
	16.5	13
K1IIIMP	13.5	1
	17.0	13

- Single stars, no extinction
- Radiation-damage effects on CCDs taken into account approximately
- Estimates include a 20% margin (factor 1.2) for unmodelled errors
- Spectroscopic instrument designed for up to 36 000 stars/degree^2

Gaia spectroscopy

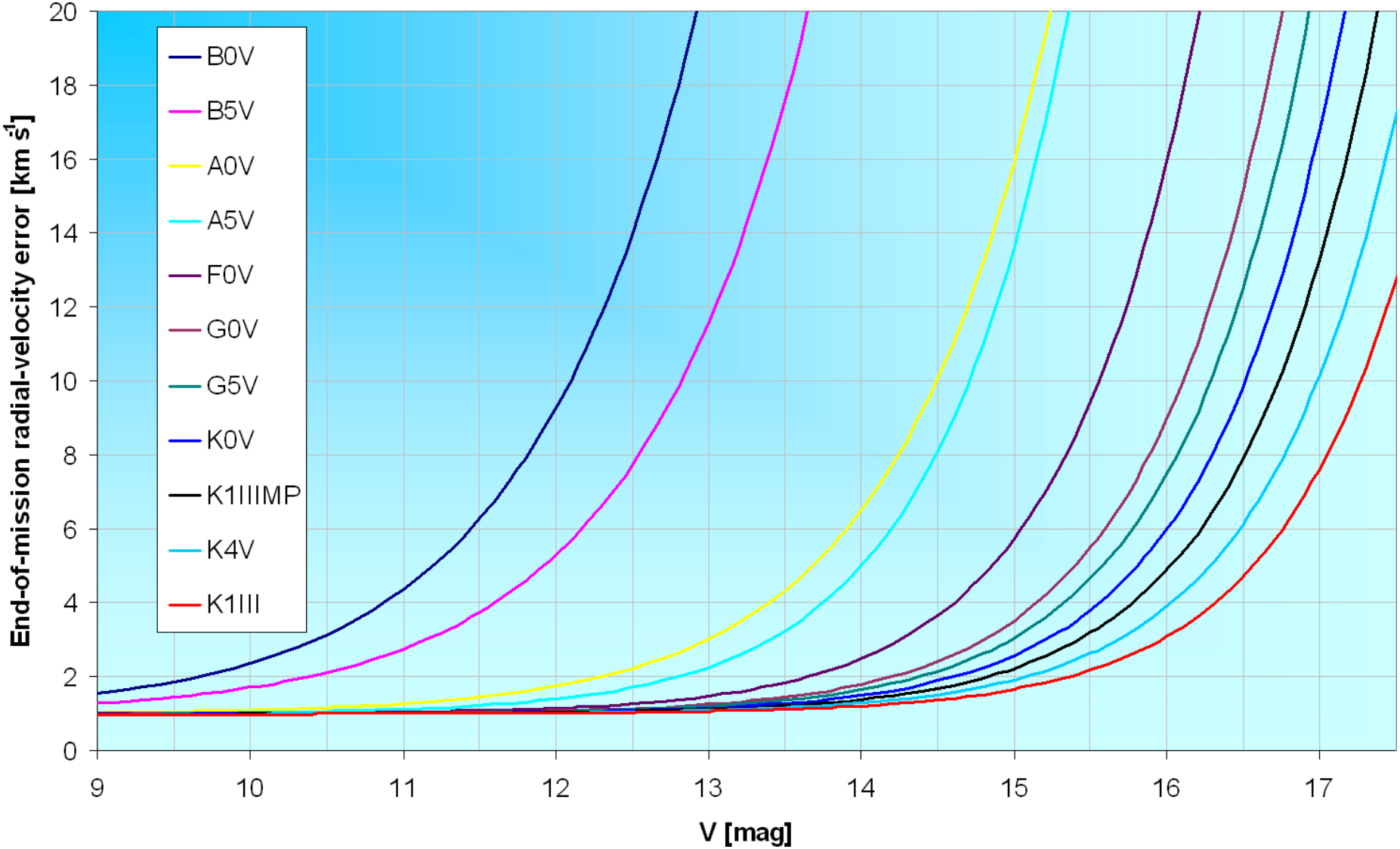


Figure courtesy Jos de Bruijne (ESA)

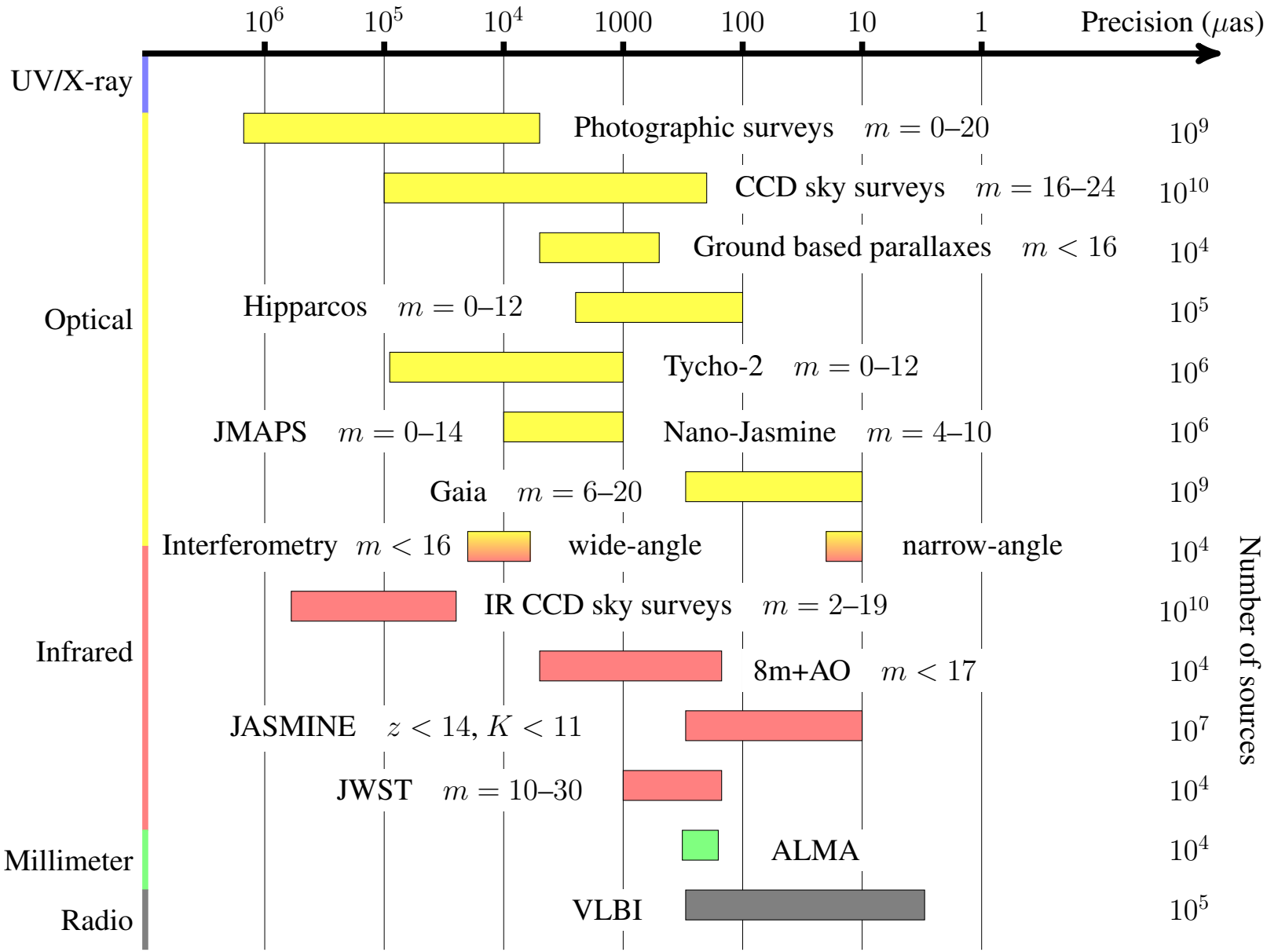
Stellar and interstellar parameters (conservative estimates)

◆ Radial velocities	$V \leq 17$	$\sim 150 \times 10^6$ stars
◆ Rotational velocities	$V \leq 13$	$\sim 5 \times 10^6$
◆ Atmospheric parameters	$V \leq 13$	$\sim 5 \times 10^6$
◆ Abundances	$V \leq 12$	$\sim 2 \times 10^6$
◆ Interstellar reddening	$V \leq 13$	$\sim 5 \times 10^6$

Diagnostics

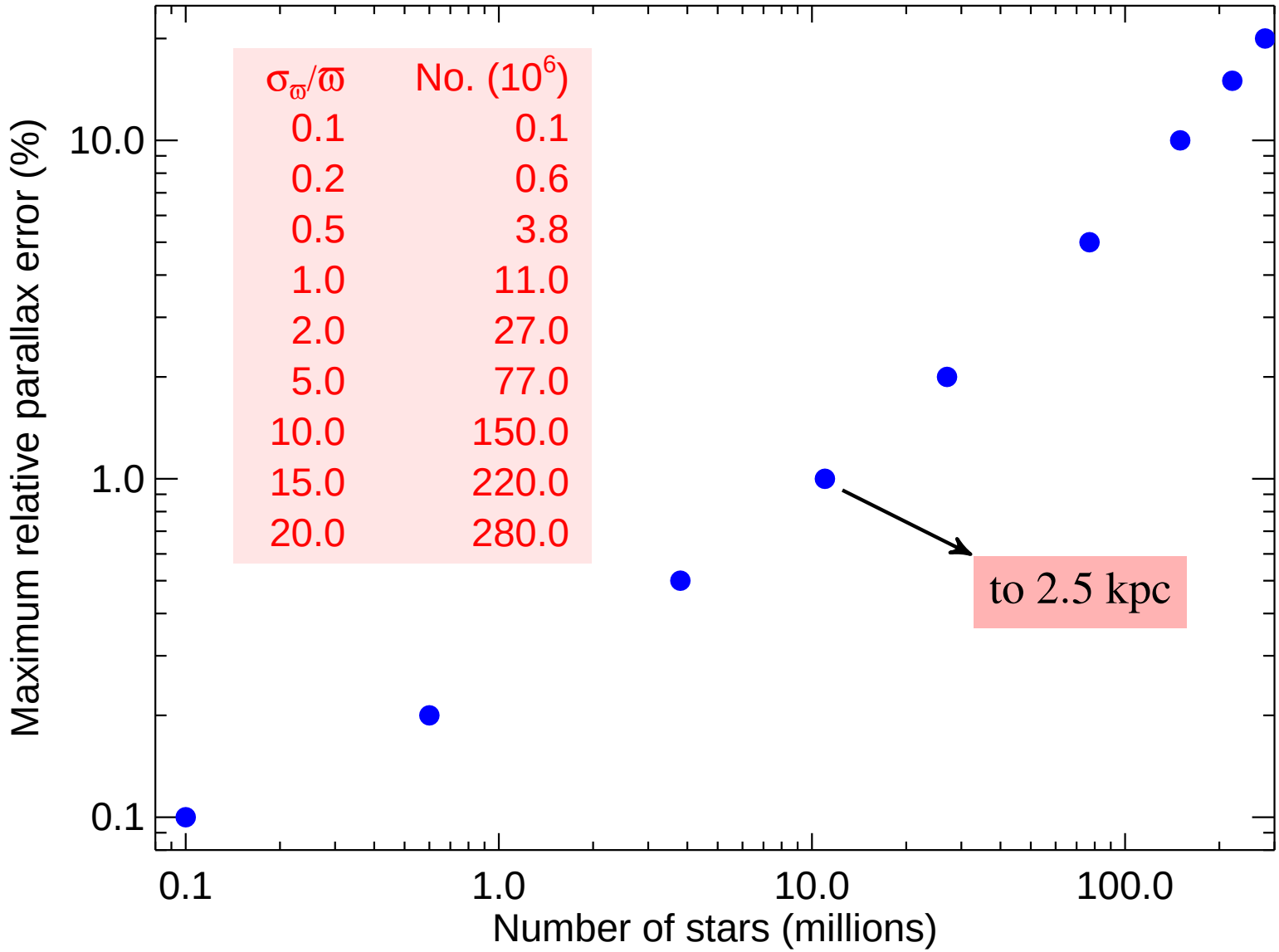
- Binarity/multiplicity, variability
- $\sim 10^6$ spectroscopic binaries
- $\sim 10^5$ eclipsing binaries ($\sim 25\%$ SB2 $\rightarrow$ masses)
- Long period classical Cepheids $\sigma_{v_r} < 7$ km/s $\rightarrow$ 20–30 kpc

Gaia in context of other astrometric surveys



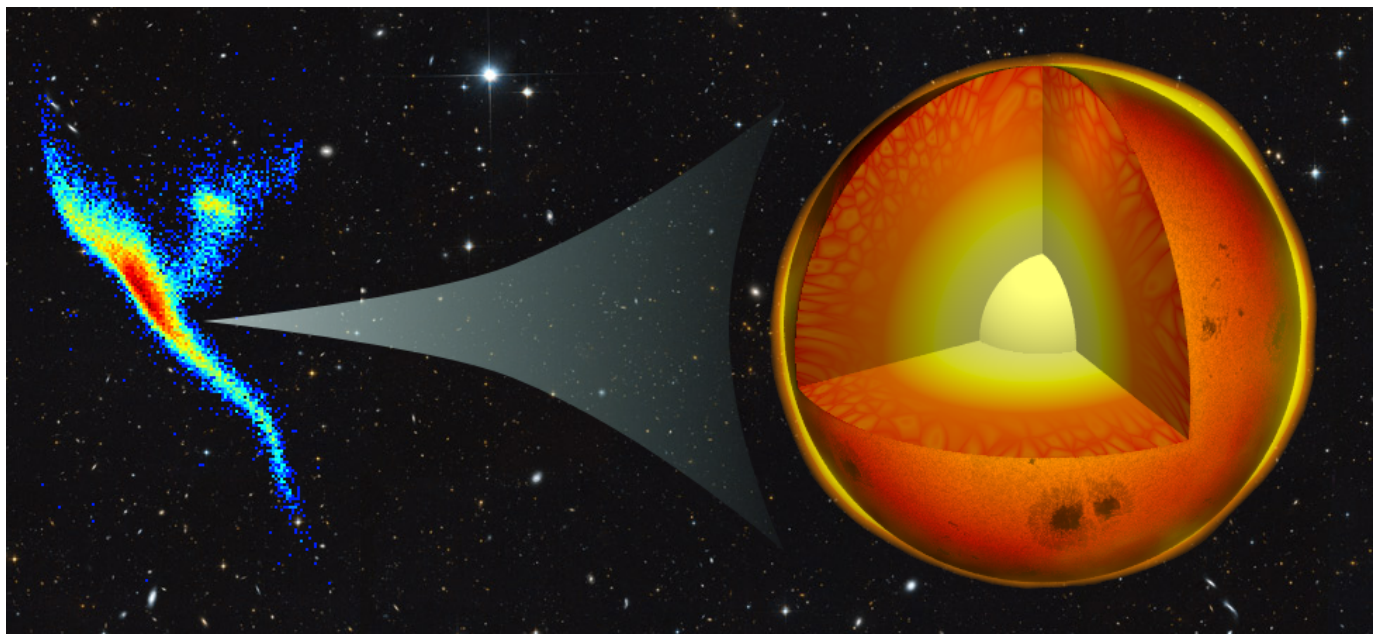
Examples of Gaia's impact on astronomy

Giant leap in parallax accuracy and reach



Accurate distances across the HR diagram

- luminosity calibration
  - calibration photometric and spectroscopic distance indicators
- astrometric detection of stellar, sub-stellar and planetary companions
  - 10 000 stars with masses to 1%
- fundamental parameters for rare stellar types
- precision tests of stellar interior models and stellar evolution



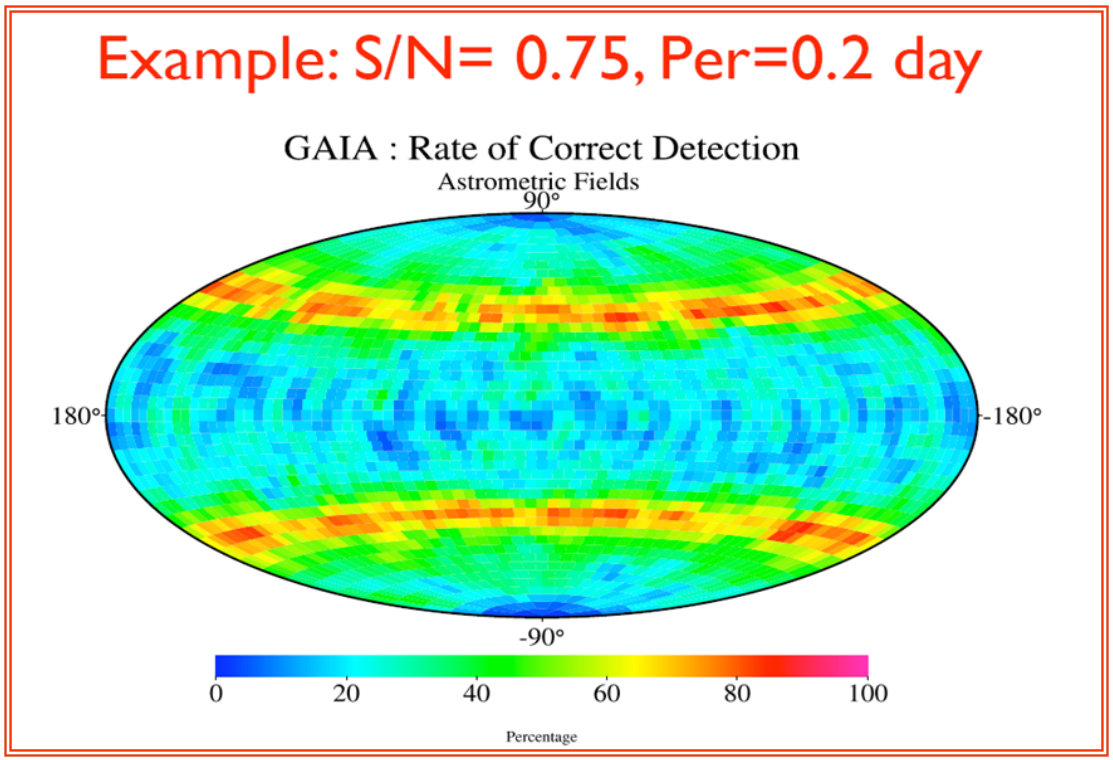
Stellar physics: variable stars

Gaia survey

- $\sim$ 70 epoch survey over 5 years
- mmag accuracy per single observation

Quantitative impact

- 20×10^6 classical variables
- 1–5 million eclipsing binaries
- $\sim$ 5000 Cepheids, 70 000 RR Lyr
  - RR Lyr visible out to $\sim$ 75 kpc



Eyer & Mignard 2005

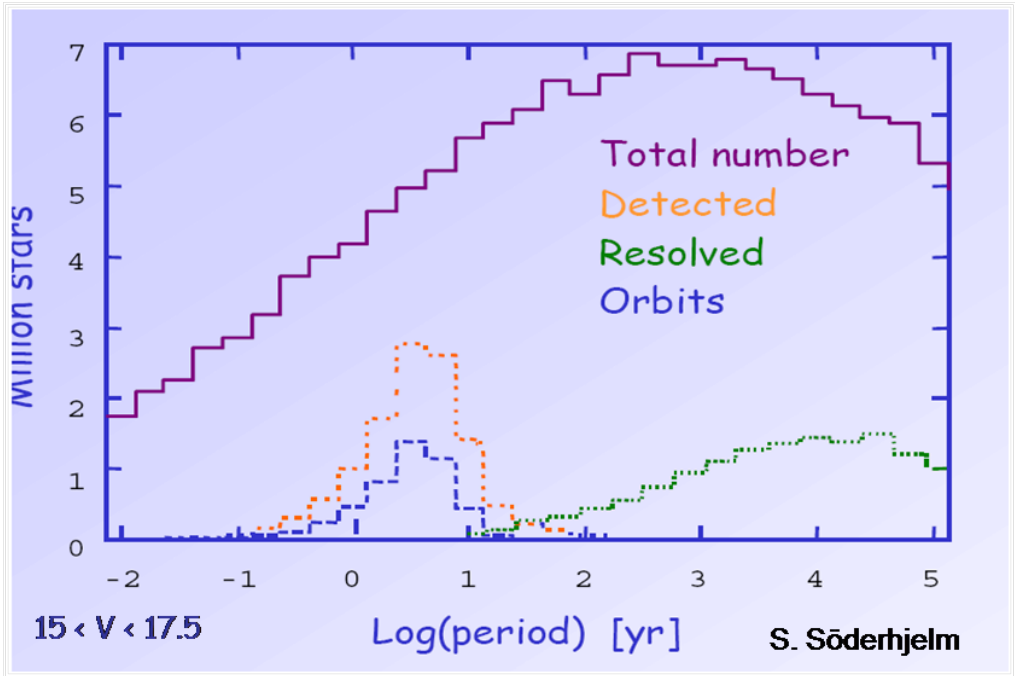
Stellar physics: small stellar systems

Power of Gaia

- Survey mode, sensitivity to non-linear motion
- quasi-regular time sampling over 5 yrs
- Large range of separations and Δm
- Spectroscopic measurements

Expected results

- various categories of binaries
  - 10^7 resolved within 250 pc (long period)
  - 10^7 astrometric binaries
  - 10^{6-7} eclipsing binaries, 10^6 spectroscopic
- 50% complete census to 250 pc
- masses to 1% for 10^4 stars
- constraints on evolutionary models



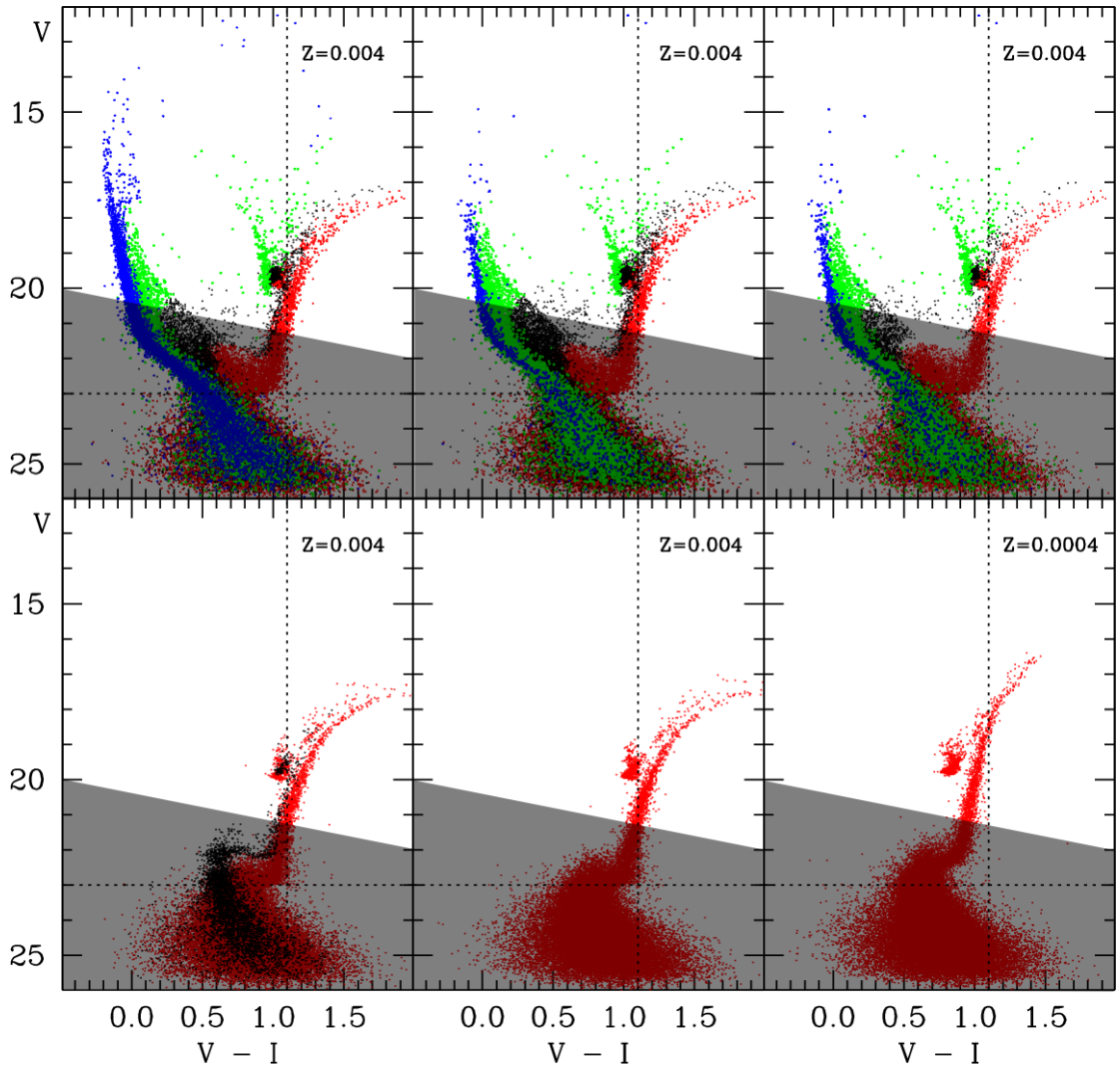
Söderhjelm 2005

Dissecting the Milky Way

- 6D phase $(\mathbf{r}, \mathbf{v})$ over full sky and large volume
- Mapping of stellar ages and compositions
  - in combination with complementary spectroscopic surveys
- Mapping of dynamical quantities (E, L_z, ...)
  - as a function of composition, age
- Study other 'solar neighbourhoods'
- Formation of inner halo
  - Gaia essential for detecting accretion signatures
- Mapping the ISM in 3D

Milky Way and Local Group

- Astrometry/photometry for *individual* stars in local group dwarf galaxies
- Survey limit $G = 20$ corresponds to $V = 20$–22

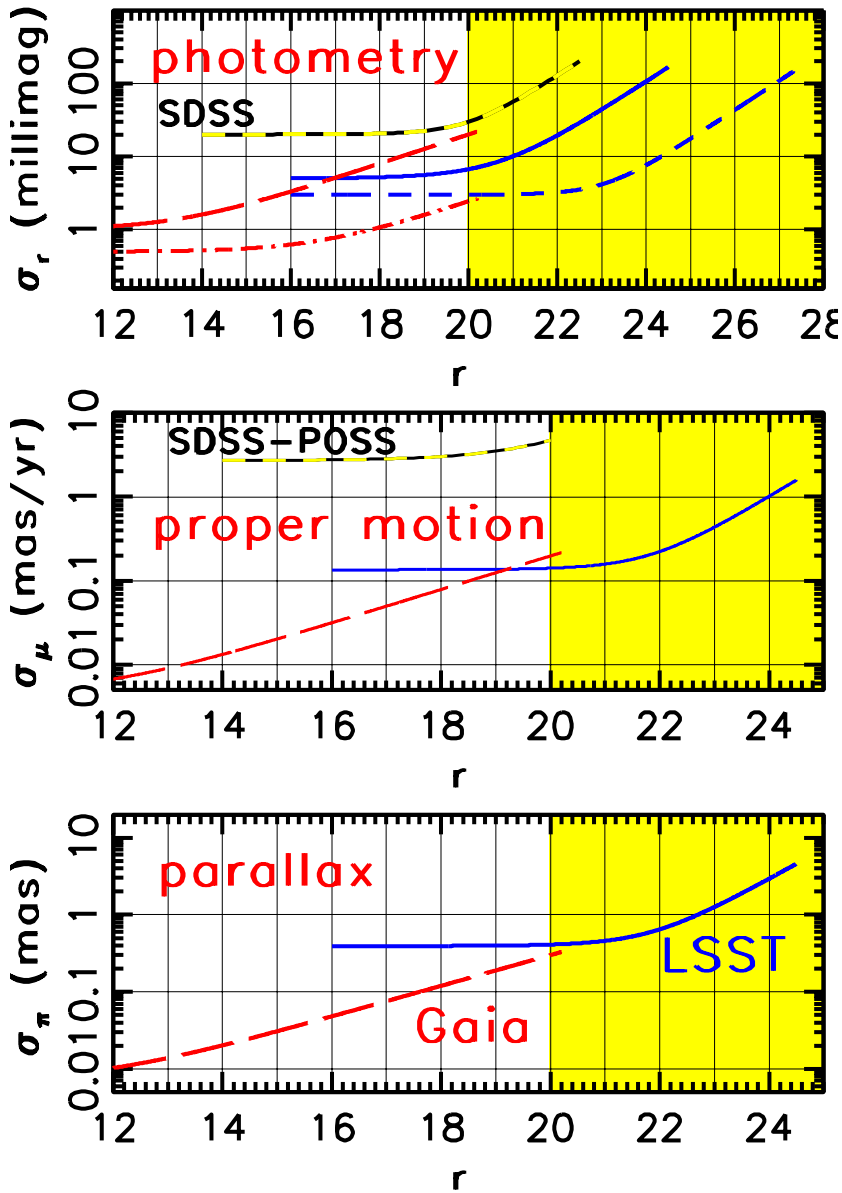


Tolstoy, Hill, Tosi 2009

Gaia and other surveys

What Gaia provides

- Excellent calibrations of standard candles that photometric surveys can see to 10× further distances
  - accurate distance moduli to main sequence stars of varying spectral types and abundances
  - same for brighter tracers including variables
- Reference frame for astrometry
- Target selection for spectroscopy (e.g., dwarf/giant separation with parallax)



LSST science book

Solar system science

- Accuracies: ground-based 0.1–1 arcsec, Gaia single measurement 0.1–1 mas
- Systematic survey down to 20 mag $\sim 3 \times 10^5$ objects
  - $\sim$ 50 000 new objects expected
  - Observations at high ecliptic latitudes and to within 45° from Sun $\rightarrow$ exotic orbits
- Orbits: for virtually all objects observed — $\times$30 better than now
- Masses from close encounters $\sim$ 100 masses expected
- Diameters for over 1000 asteroids: shape, density
- Photometric data in several bands: albedo, taxonomic classification
- Light curves over 5 years: rotation, pole, shape
- Space distribution vs. physical properties
- Perihelion precession for 300 planets: GR testing, solar J2

Exoplanets with Gaia

- Astrometric survey
  - monitoring of several 10^5 FGK stars to ~ 200 pc
  - detection limits $\sim 1\ M_{\rm J}$ and $P < 10$ yr
  - complete census of all stellar types over $P = 2$–9 yr
  - masses rather than lower limit ($m \sin i$)
  - multiple systems measurable
- Results expected
  - orbits for ~ 5000 systems
- Photometric transits
  - ~ 1000 to 10 000 with $a \lesssim 1$ AU

$d <$	stars	planets
100	60 000	1500–5000
200	500 000	5000–20 000

Fundamental physics

1. Light deflection
   - Monopole deflection from the Sun: $\sigma_\gamma \sim 10^{-6}$ (systematic errors remain a difficult challenge)
   - First detection of a number of subtle deflection effects from the planets: monopole, quadrupole, gravitomagnetic
2. Motion of the solar system: perihelion and node precessions, quadratic deviations in the mean longitudes

$$\sigma_\beta \sim 10^{-3}\,, \quad \sigma_{J_2^{\rm Sun}} \sim 10^{-7}\,, \quad \sigma_{\dot{G}/G} \sim 10^{-12}\ {\rm yr}^{-1}\,, \quad \sigma_\eta \sim 10^{-3}$$

3. Local Lorentz Invariance: Gaia is a kind of Michelson-Morley experiment
4. Pattern matching in proper motions and epoch astrometry:
   - Solar system acceleration $\sigma_a/a < 0.1$
   - Improved estimates of the stochastic background of primordial low frequency gravitational waves
5. Astrometric information for the optical components of some objects that are important for other relativistic tests