The Astrometry Satellite Gaia

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Gaia's schedule

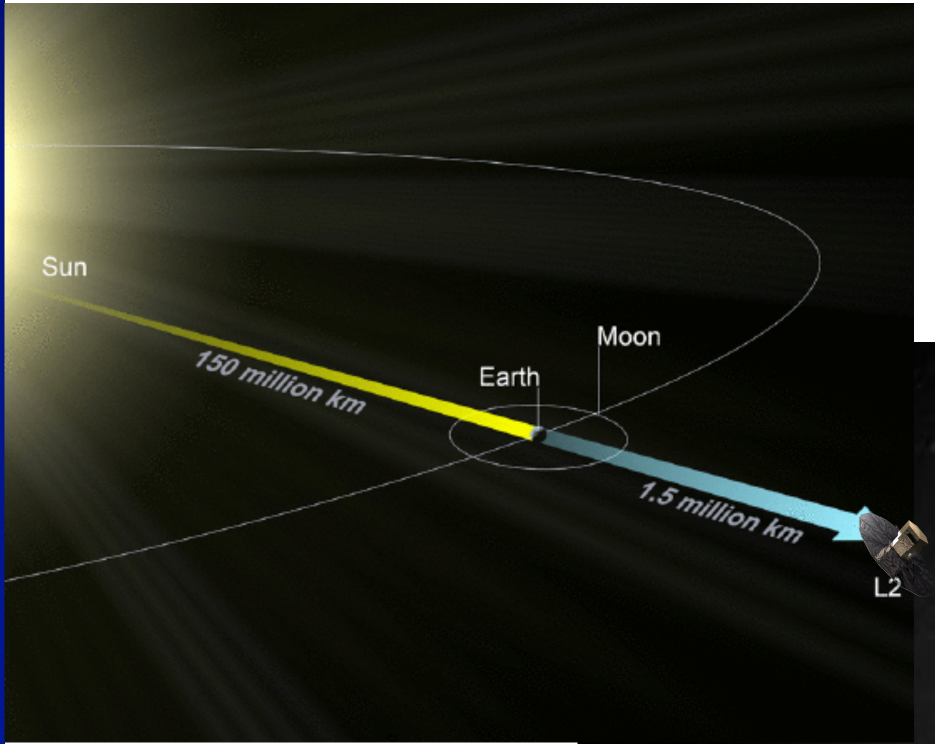
- **1993:** First proposal to ESA
- **2000:** accepted as „Cornerstone Mission“
- **Launch:** December 19, 2013
- **End of commissioning:** July 18, 2014
- **September 14, 2016, 12:30 CEST:** Gaia DR1
- **April 2018:** Gaia DR2
- **2019:** End of nominal measurements (5 years)
- **2022/2023:** Publication of final catalogue?

- Estimated end of mission due to cold gas exhaustion end-2023 ±1 year

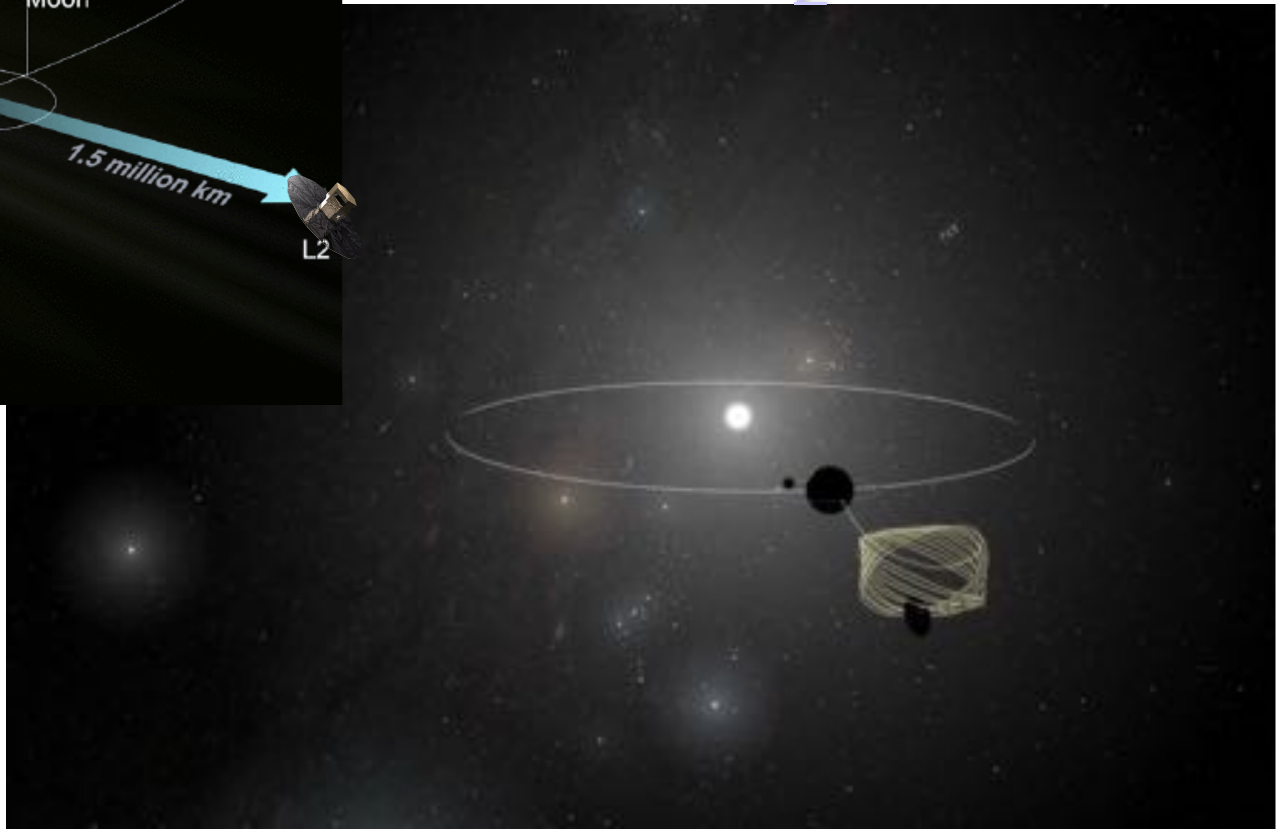
The Launch

- **Soyuz-Fregat**
- 47 m high
- Sinnamary in French Guyana
- Launch date: 19. Dezember 2013

Gaia at L2



Animation with Gaia Sky:
Toni Sagristà Sellés
(ARI/ZAH University of Heidelberg)
Software downloadable at
https://zah.uni-heidelberg.de/gaia/outreach/gaiasky/



Gaia's main goals

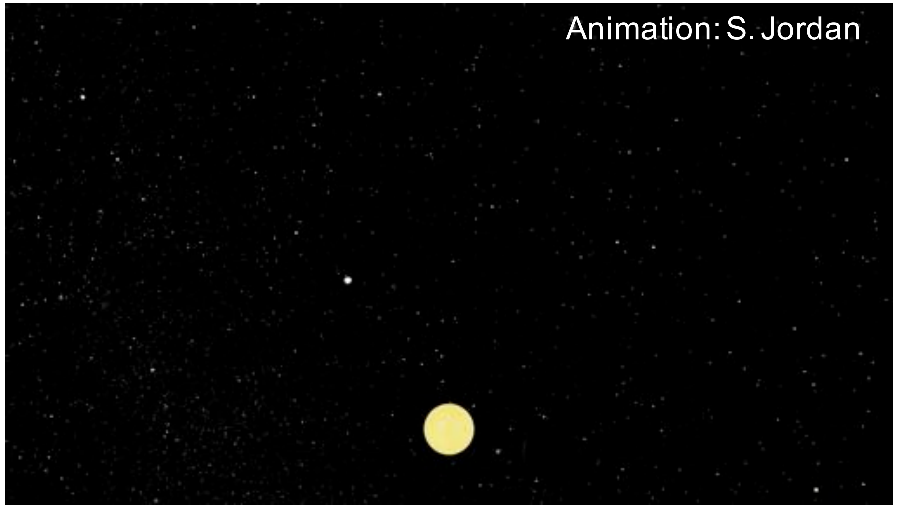
The determination of positions, movements and parallaxes (distances) of 1 billion stars

..

This means (practically) all stars down to magnitude 20.7 (equivalent to the brightness of a candle at 30000 km distance)

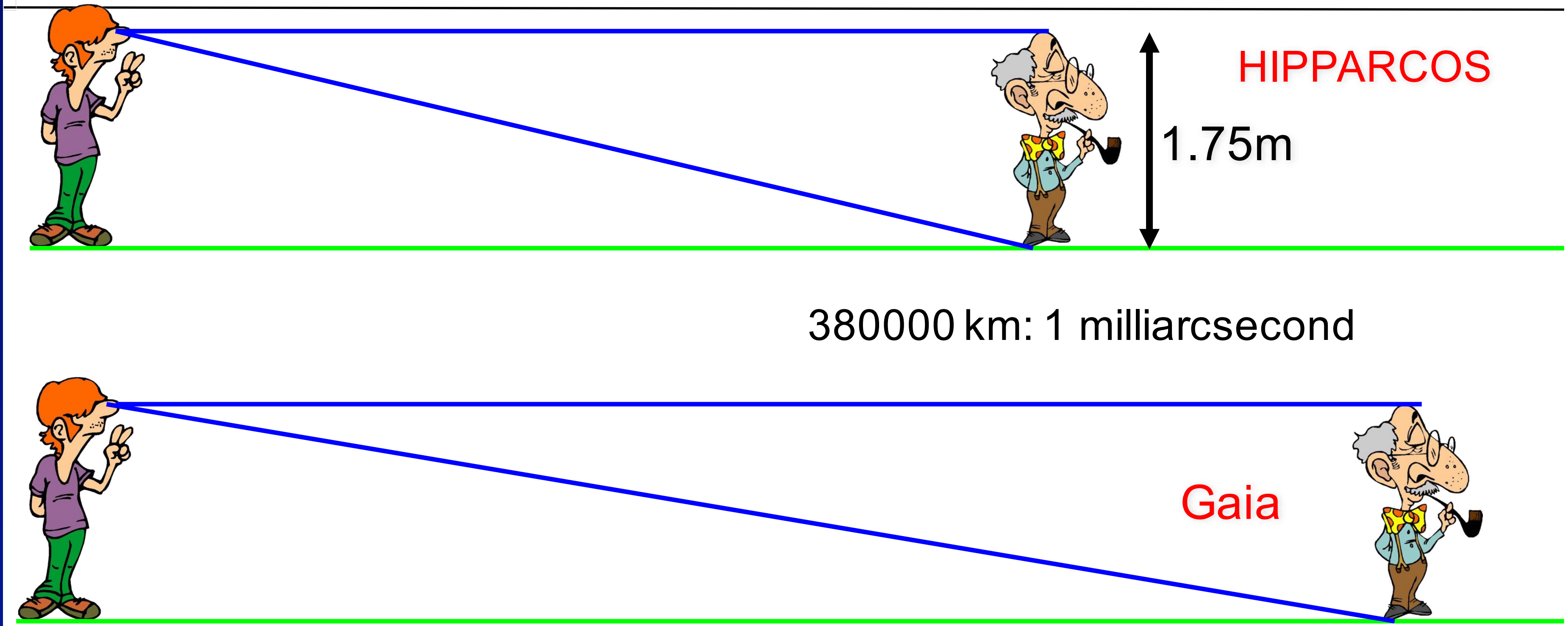
History of Parallax Measurements

Number of significant parallaxes:



- 1838 1
- 1900 100
- 1990 900
- 1997 50 000
- Since September 14, 2016: 600 000 von Gaia
- And many more to come in April 2018 and thereafter...

Parallaxes are small

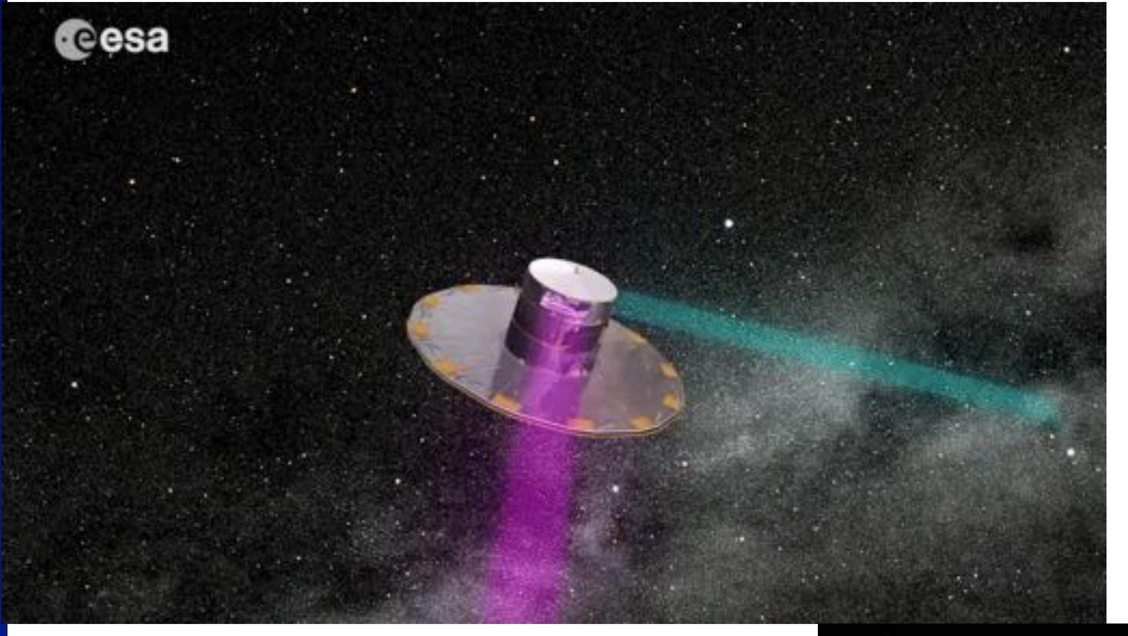


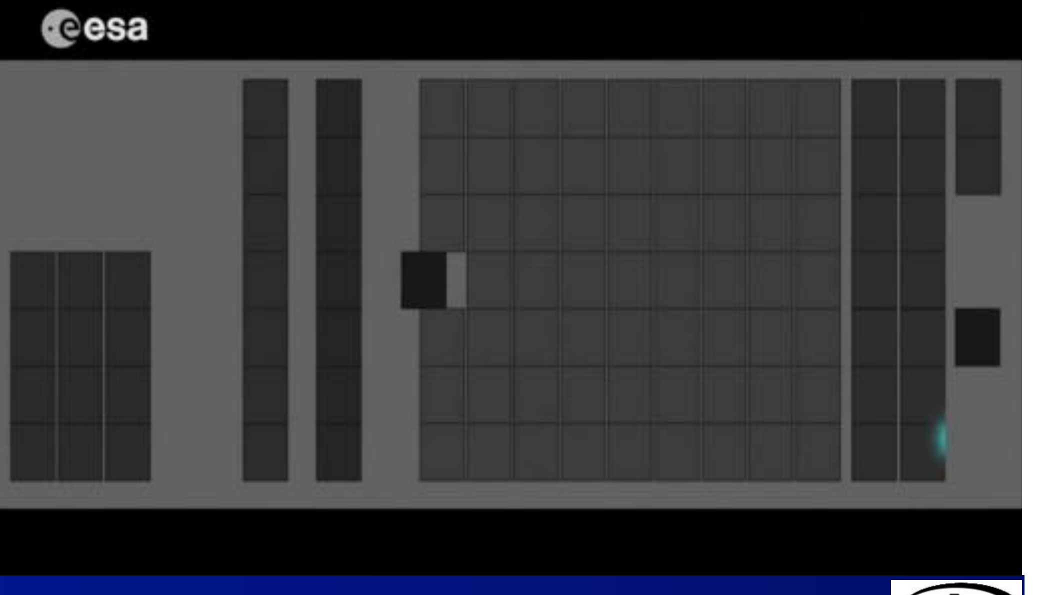
380000 km: 1 milliarcsecond

15 million km:
25 microarcsecond

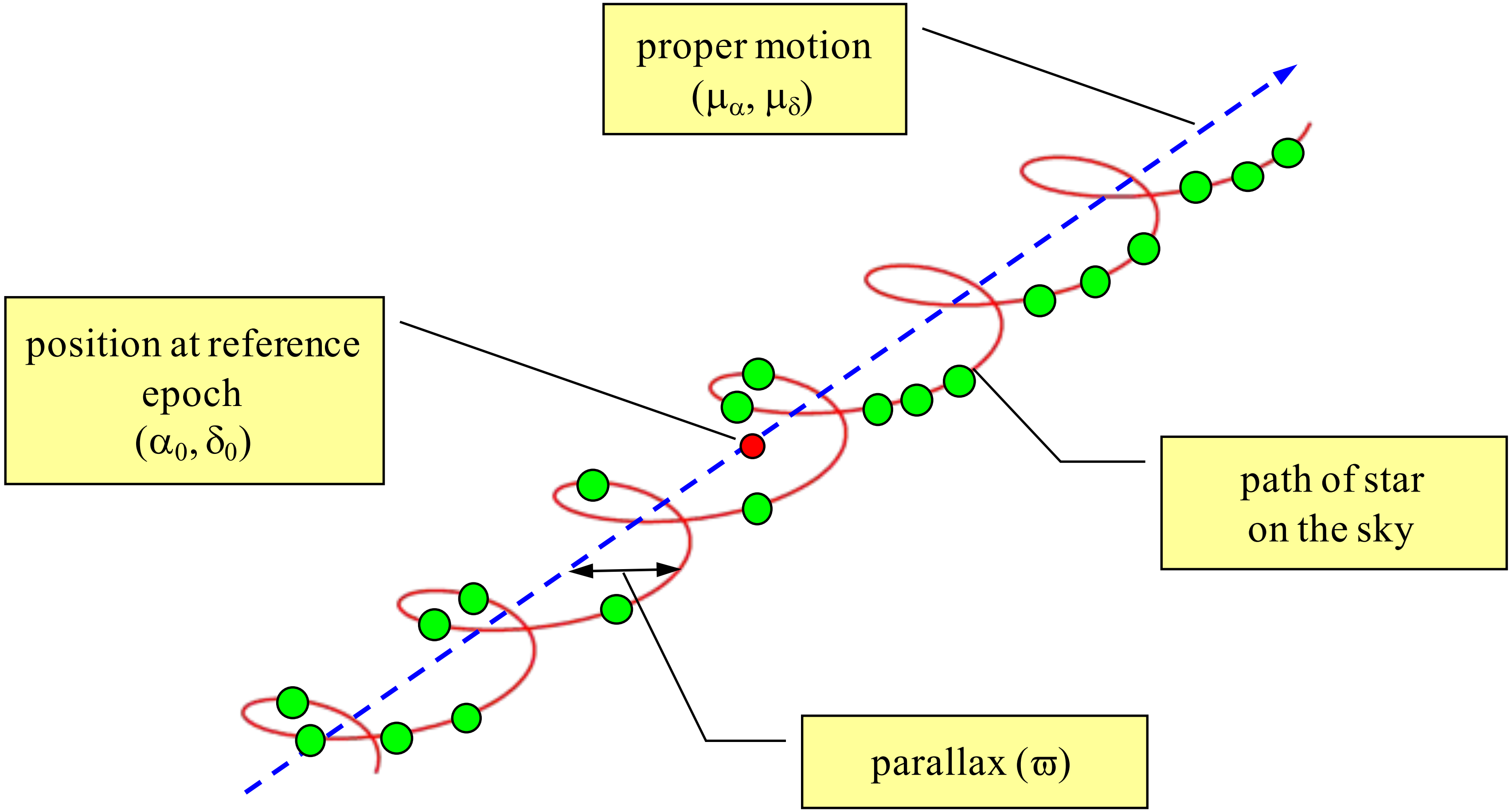
σ_π = 25μas	σ_π/π =	0.1%	d = 40 pc
at V = 15	σ_π/π =	1 %	d = 400 pc
	σ_π/π =	10%	d = 4 kpc

Scanning, Focal plane





How do stars move? 5 parameters



Gaia ‘s data reduction problem

With the same accuracy with which Gaia

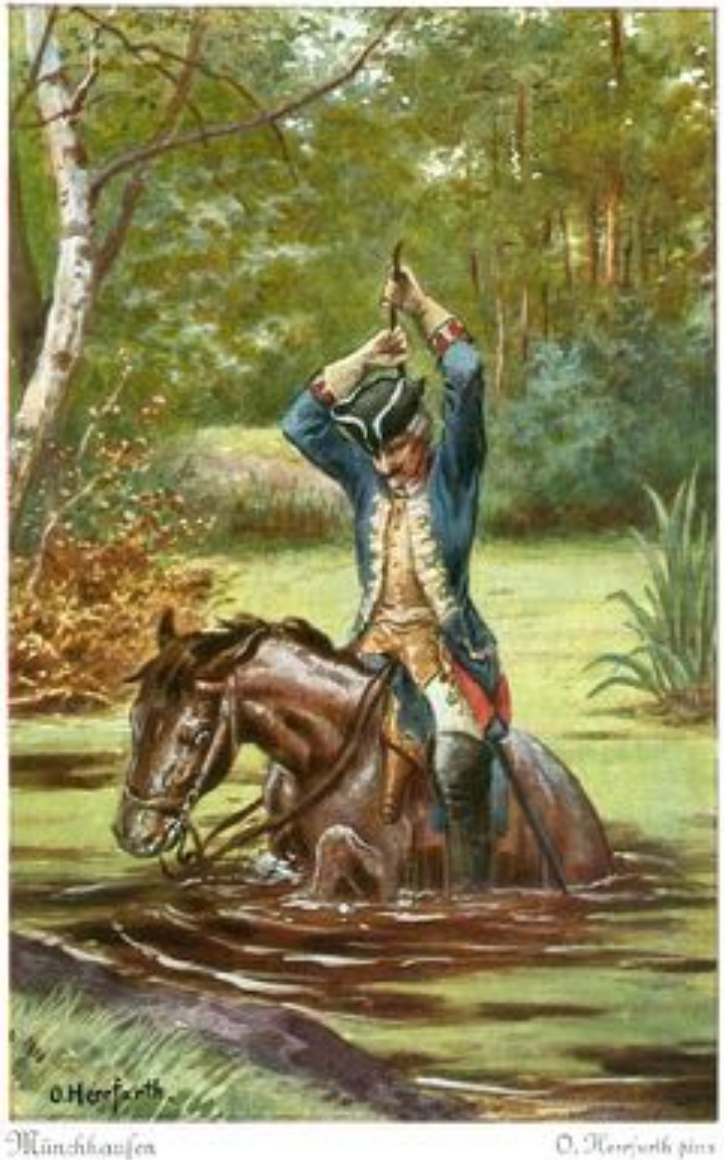
- measures position of stars,

it is necessary to know

- where Gaia is pointing at (attitude), where Gaia is, how fast it is,

how exactly

- the optic and detectors are aligned
- and, whether Einstein was fully right!!

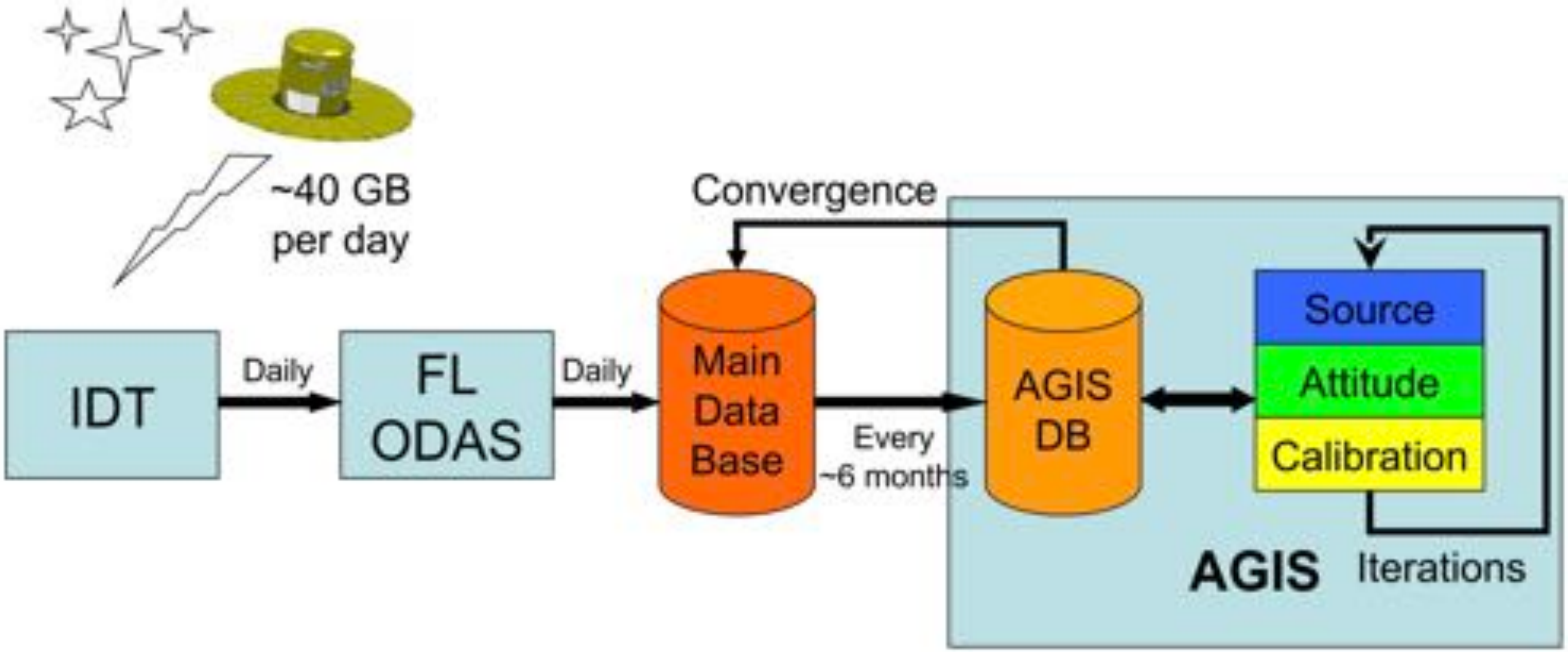


Astrometric data reduction

- 10^{12} individual measurements
- $<10^{10}$ unknowns
- The unknowns are strongly correlated with each other

- 5000 million astrometric parameters
- 150 million unknowns for the attitude
- 10-50 million other calibration parameters

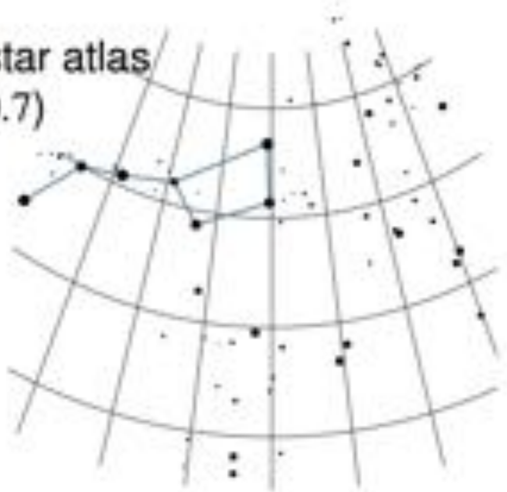
From raw data to catalogue



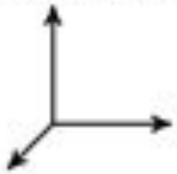
Credit: Uwe Lammers ESA Science Team,2010

Gaia DR1 content (Sep 14, 2016)

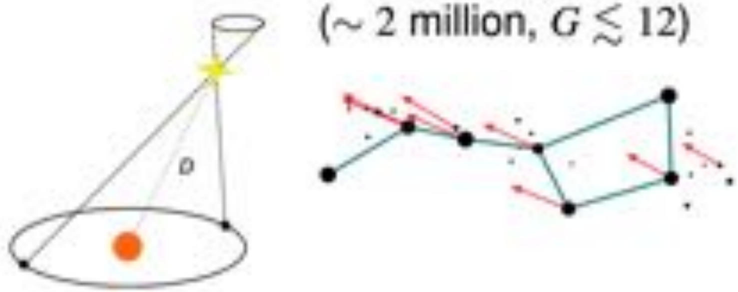
Billion star atlas
($G \lesssim 20.7$)

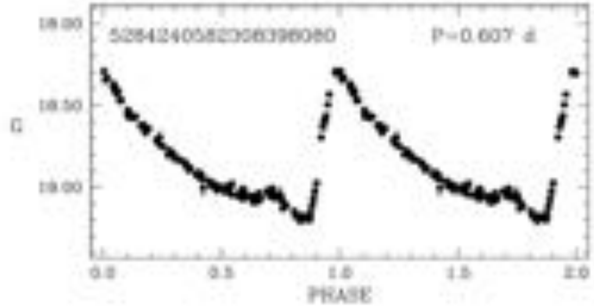


Positions and magnitudes
for $\sim$ 2000 ICRF quasars



Tycho-Gaia
Astrometric Solution
($\sim$ 2 million, $G \lesssim 12$)

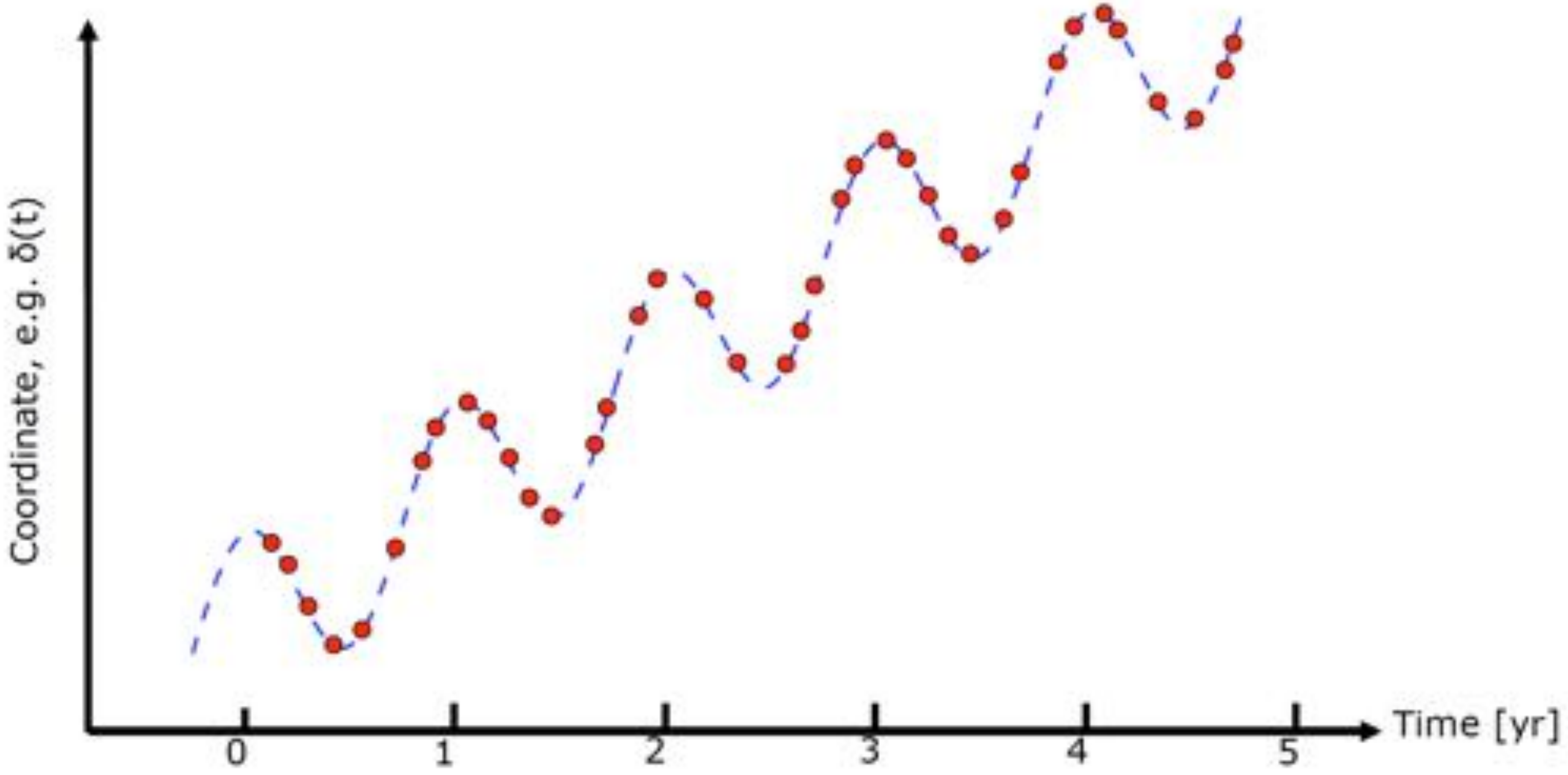




Variable stars near
south ecliptic pole
($\sim$ 600 Cepheids,
$\sim$ 2600 RR Lyrae)

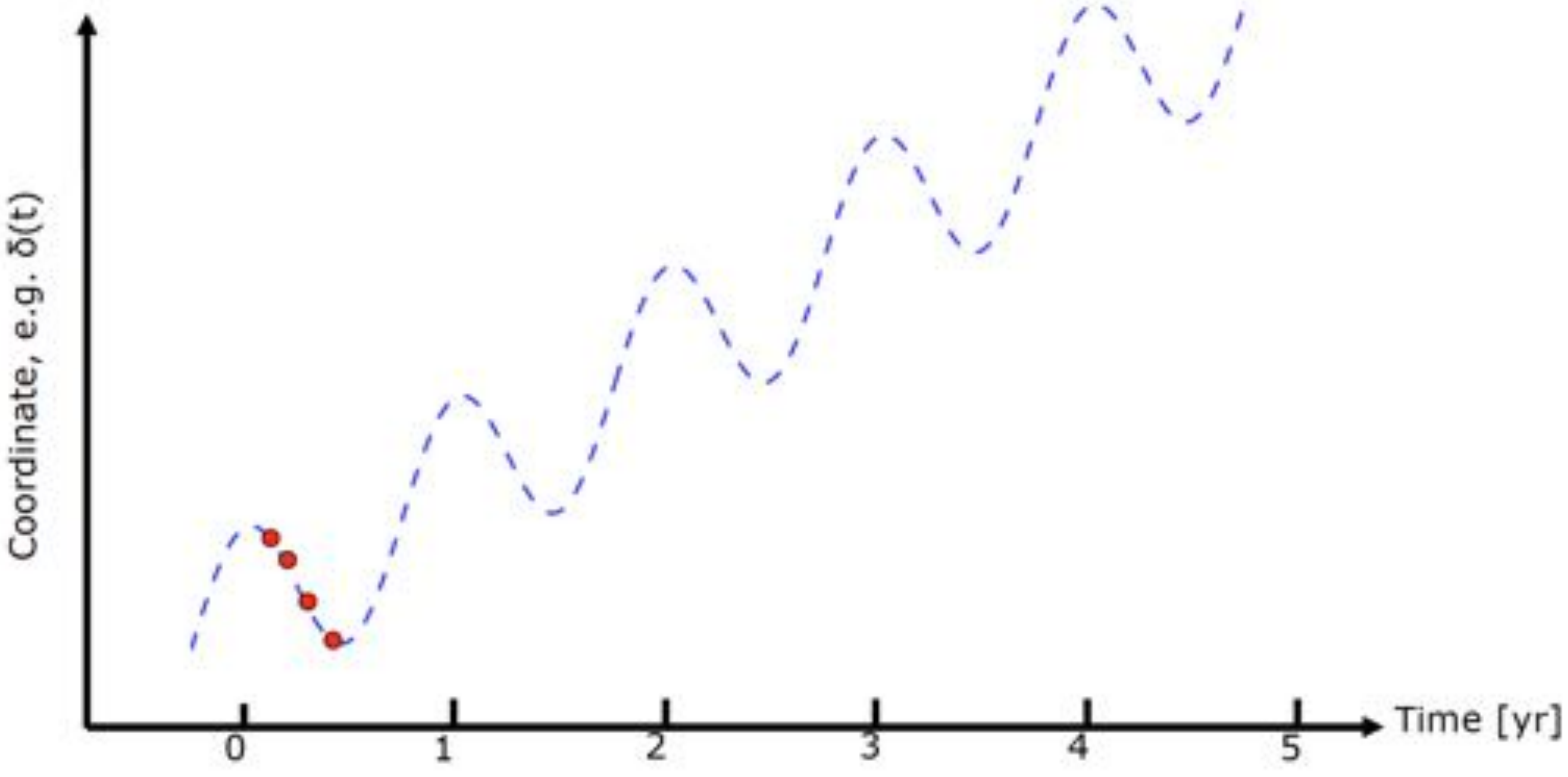
A. Brown

Observations over 5 yr ⇒ pos, par, p.m.



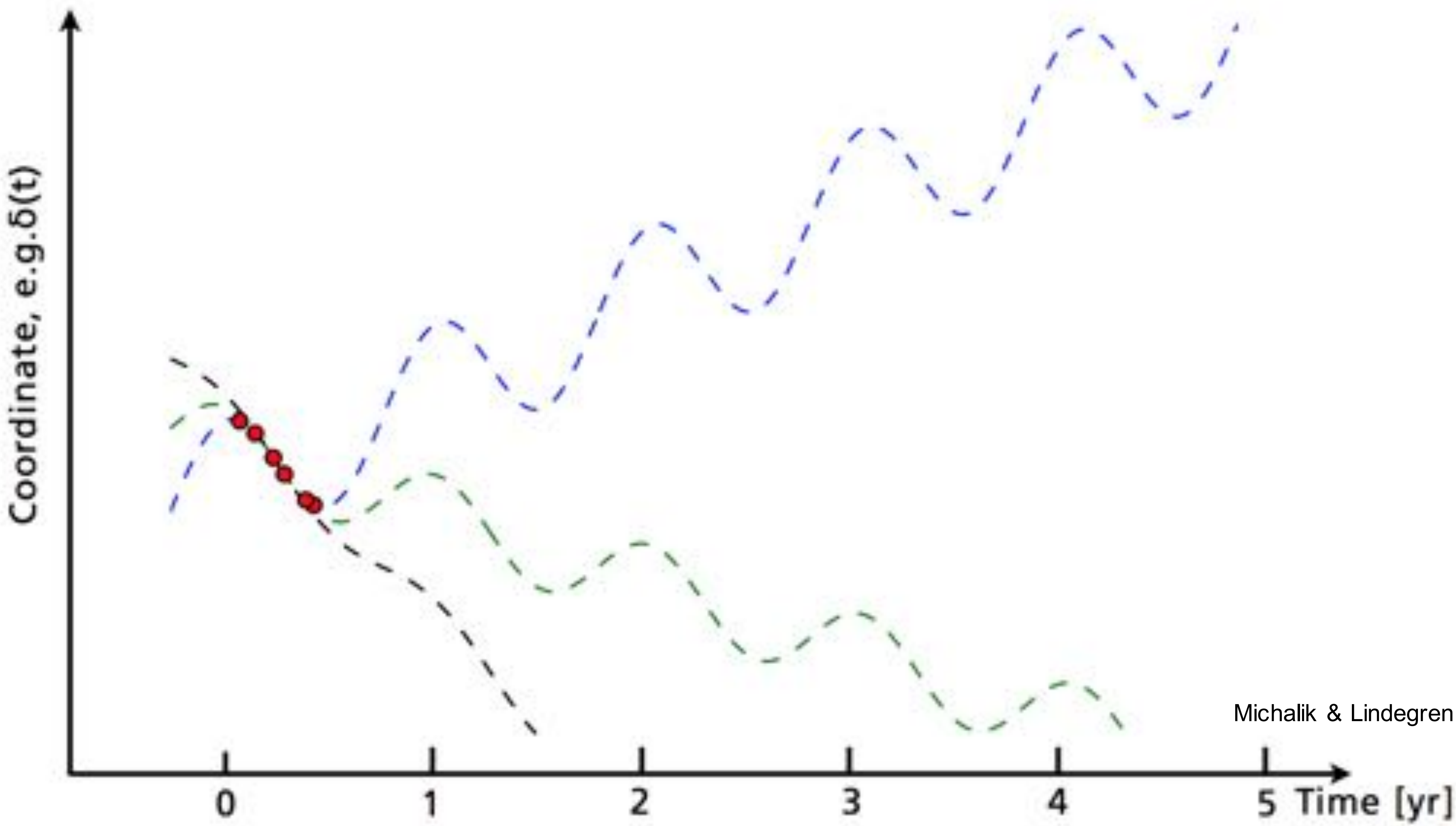
from Lammers et al.

Degeneracy for less than 1 year



from Lammers et al.

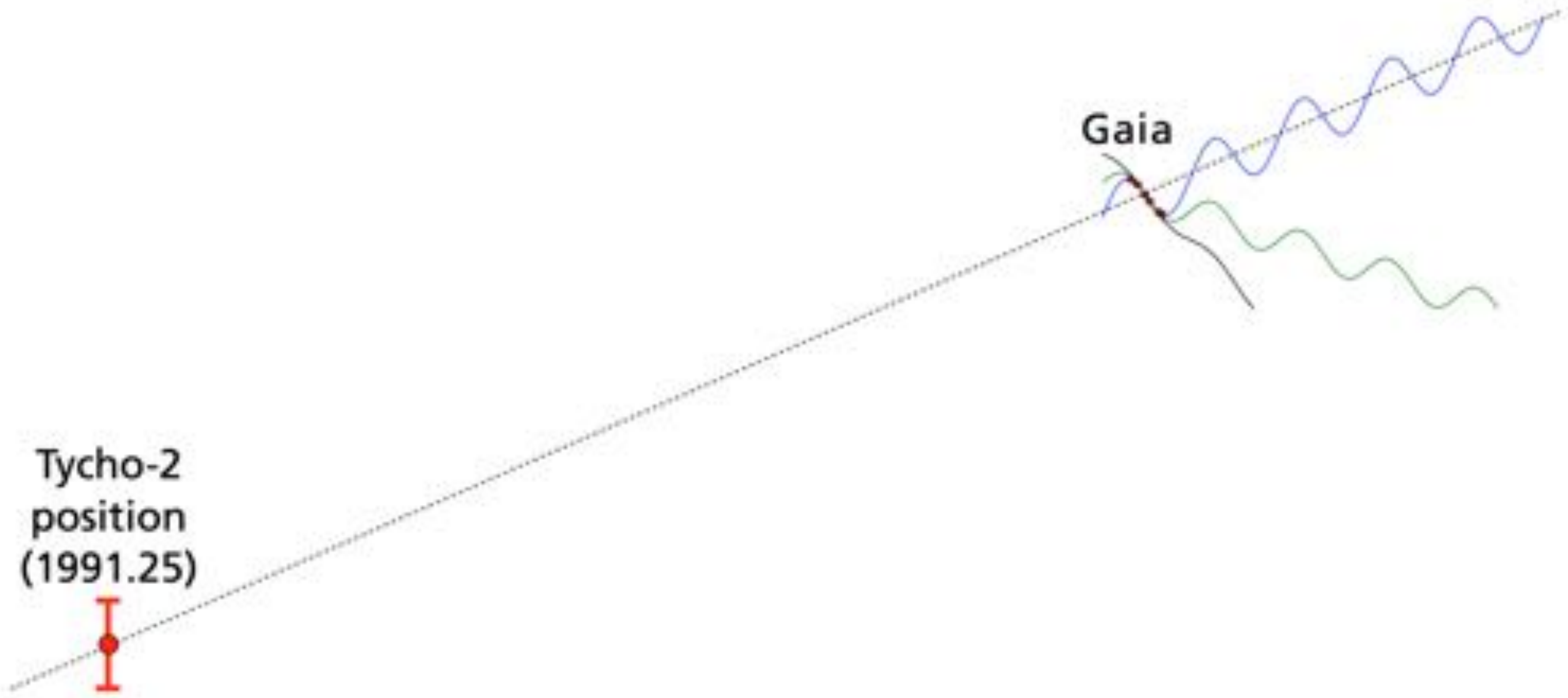
Degeneracy for less than 1 year



Michalik & Lindegren

Observation of less than one year plus one old position

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



Michalik & Lindegren

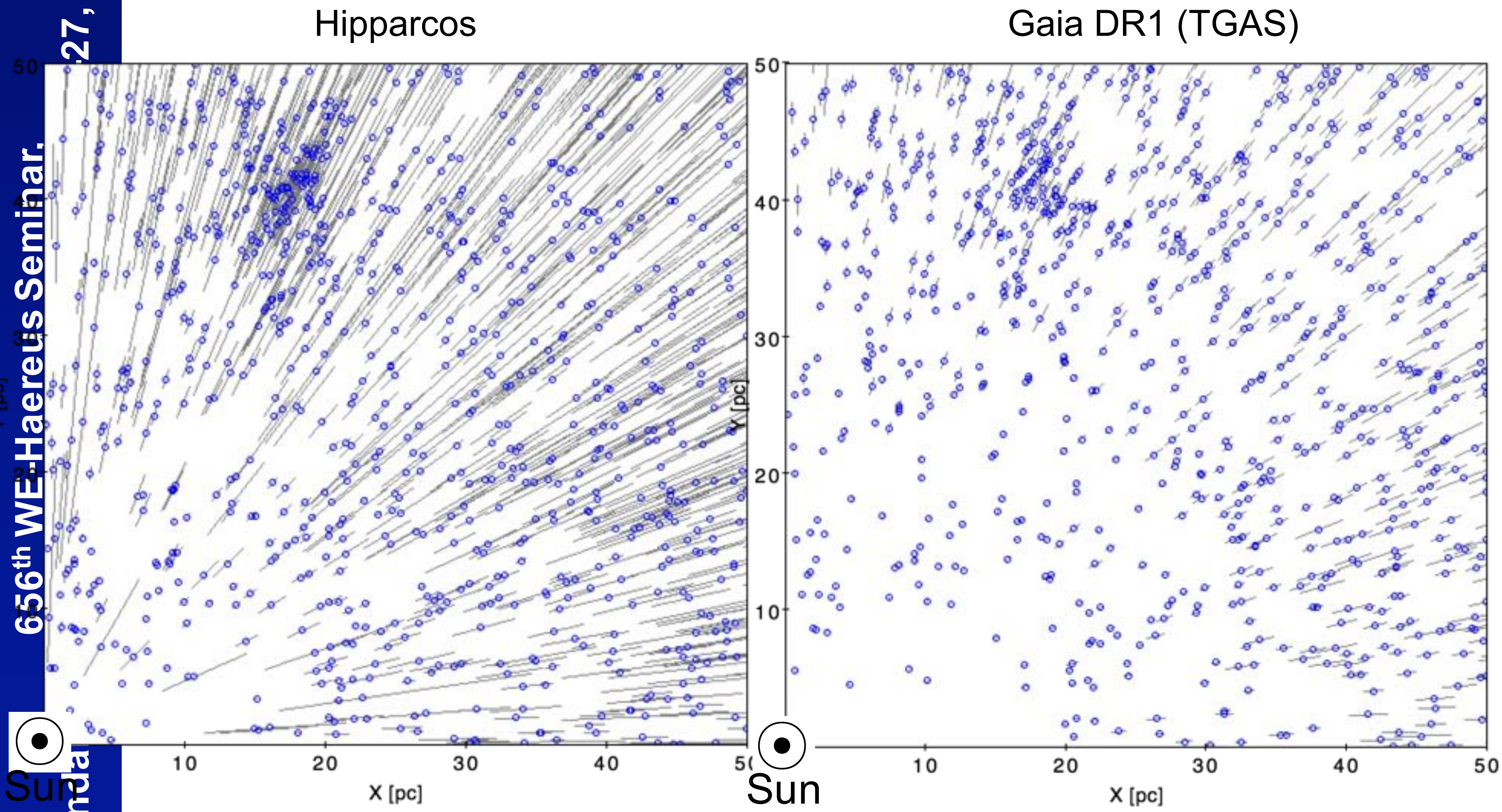
Number of sources and parameters in Gaia DR1

Solution	No. of sources	Param.	Prior used
Primary (TGAS) sources	2 057 050	5	positions at 1991.25
- of which Hipparcos	93 635	5	- Hipparcos positions
- of which Tycho-2 (excl Hipp)	1 963 415	5	- Tycho-2 positions
Secondary sources	1 140 622 719	2	ϖ, $\mu_{\alpha*}$, μ_δ = 0 ± few mas(/yr)
ICRF sources (*) = QSOs	2 191	2	$\mu_{\alpha*}$, μ_δ = 0 ± 0.01 mas/yr
All	**1 142 679 880**		$d(\mu_{\alpha*}, \mu_\delta)/dt = 0$, i.e. $v_r = 0$

(*) 2080 of the ICRF sources are also secondary sources (with slightly different positions)

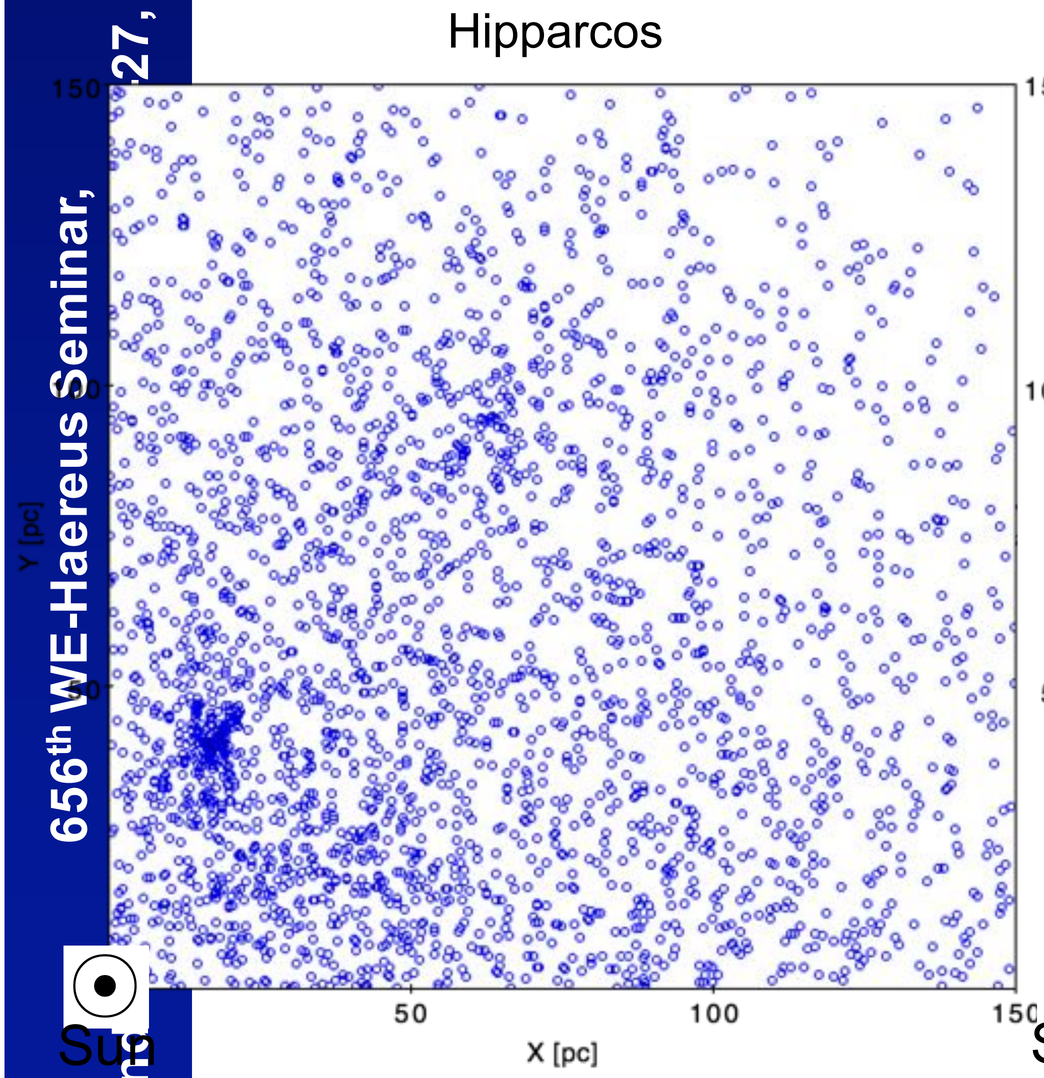
L. Lindegren

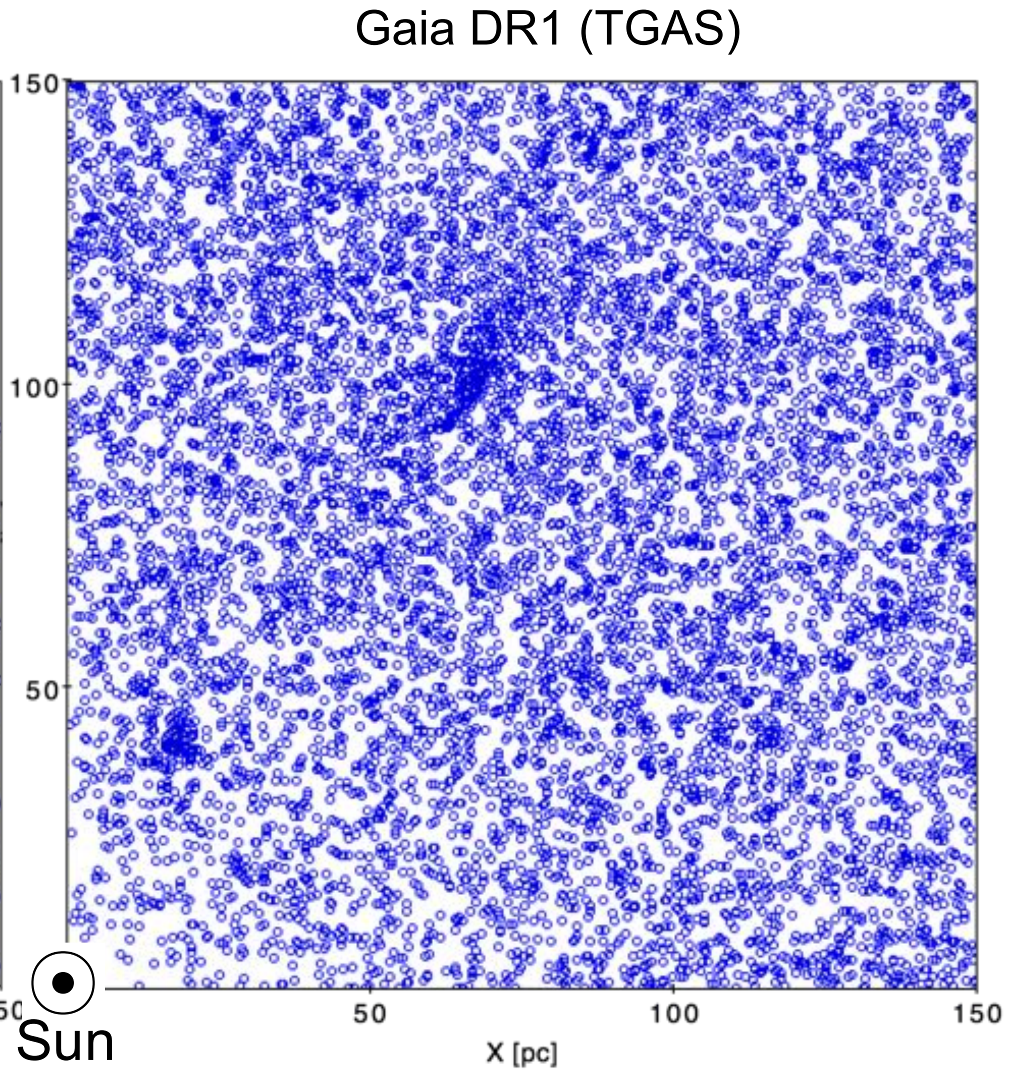
Improved distances to nearby stars



L. Lindegren

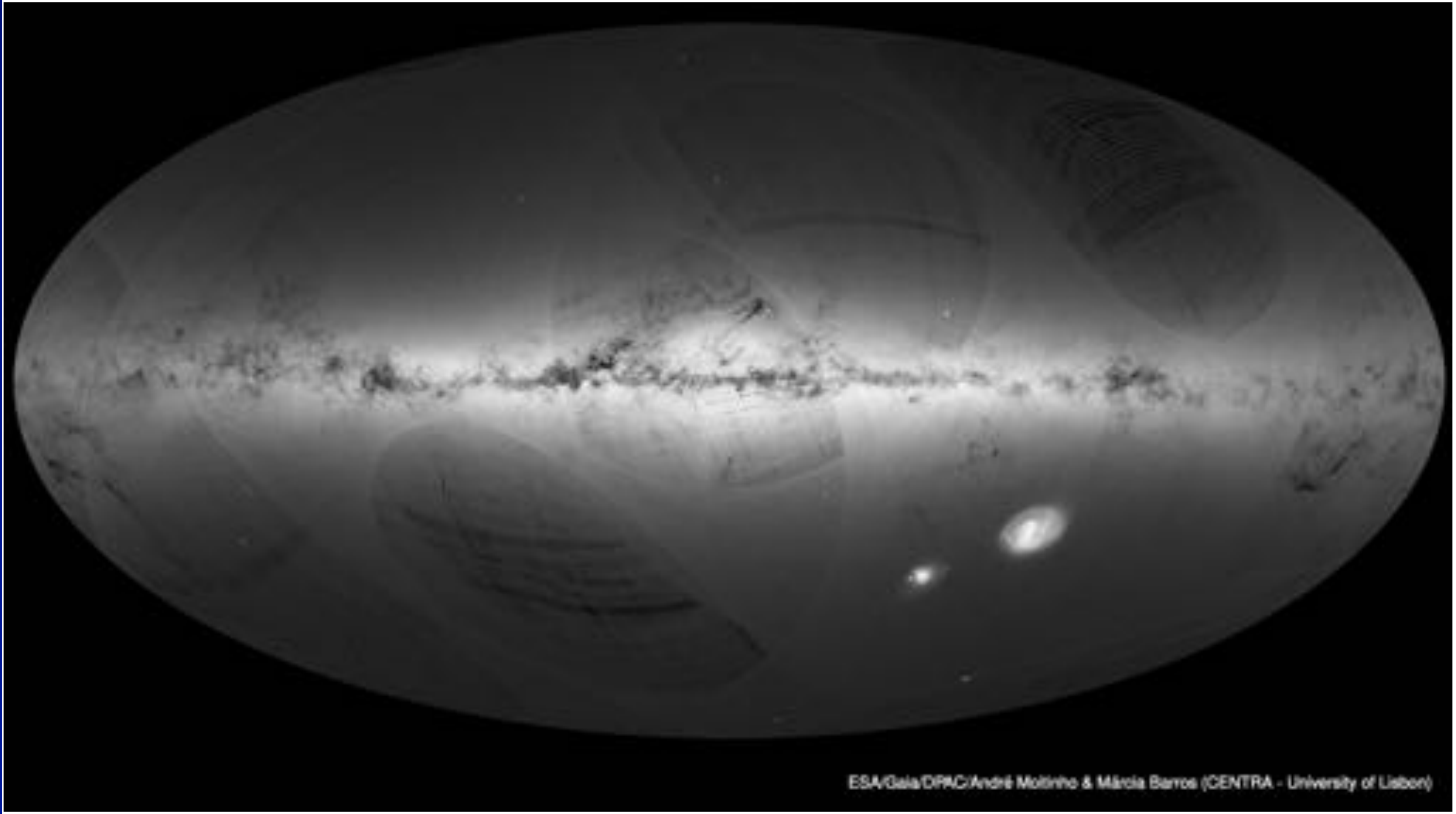
More stars within parallax horizon ($\varpi/\sigma_\varpi > 5$)





L. Lindegren

Source density map of Gaia DR1



Primary (TGAS) sources

2.06 M sources, mainly G < 11.5

- this is about 80% of the Hipparcos & Tycho-2 catalogues

Missing sources:

- brights stars (G < 6)
- high-proper motion stars (μ > 3.5 "/yr)
- some 20% of Hip + Tycho-2 with too few observations (quasi-random but with large variations over the sky)

"inflated" uncertainties; from Hipparcos comparison

Median position uncertainty: 0.23 mas at 2015.0

Median parallax uncertainty: 0.32 mas

Median proper motion uncertainty:

- 0.07 mas/yr (Hipparcos subset)
- 1.2 mas/yr (Tycho-2 subset)

Note difference!

L. Lindegren

Systematics in Gaia DR1 parallaxes

- Due to known limitations in the astrometric processing
  - - a global offset of ±0.1 mas may be present
  - - there are colour dependent, spatially correlated errors of ±0.2 mas
  - - over large spatial scales, parallax zero point errors reach ±0.3 mas
  - - in a few very small areas even ±1 mas (is indicated)

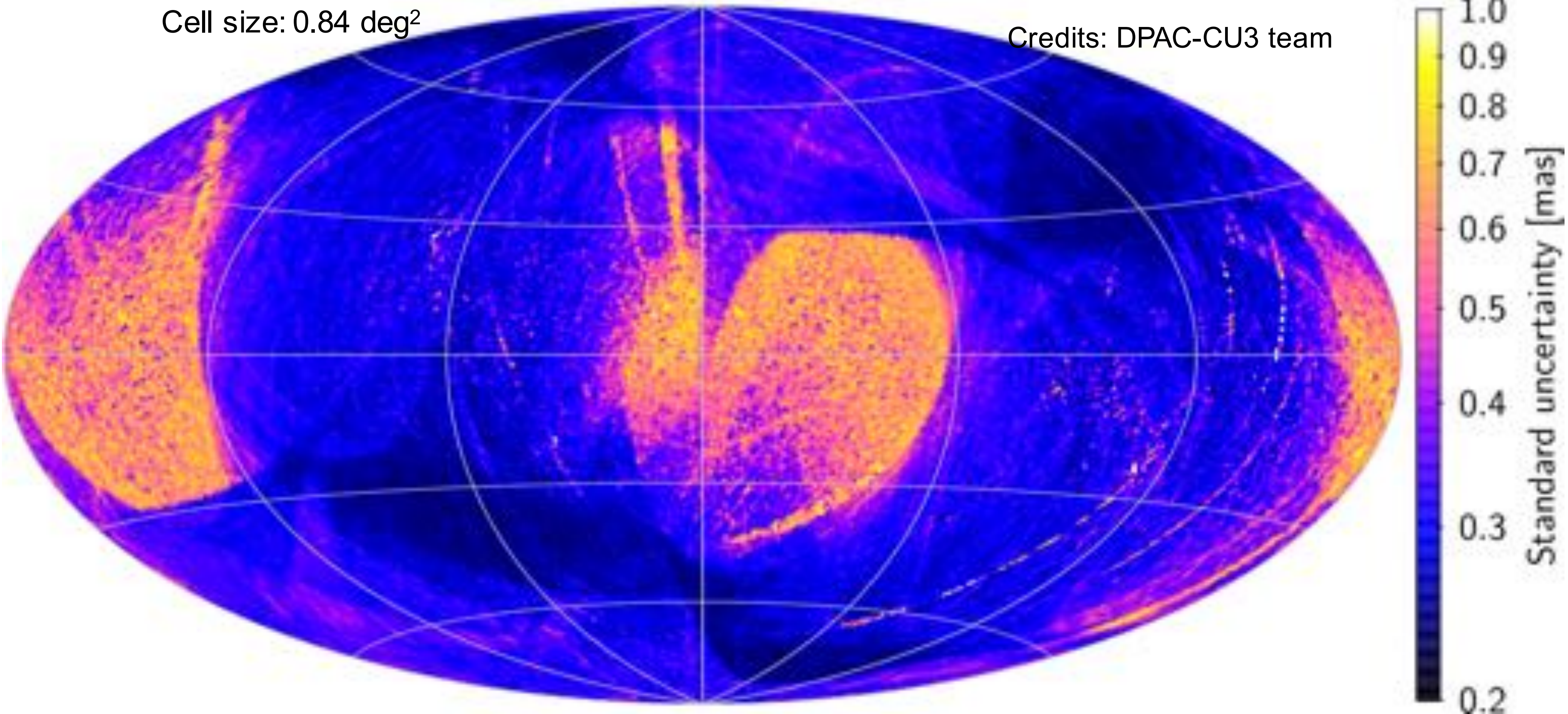
- Parallax uncertainties in restricted areas of the sky should be quoted as
- $\varpi \pm \sigma_\varpi$ (random) ± 0.3 mas (syst.)
- Averaging parallaxes e.g. in a cluster does not reduce the systematics!

L. Lindegren

DR1- Parallax uncertainty

Cell size: 0.84 deg^2

Credits: DPAC-CU3 team

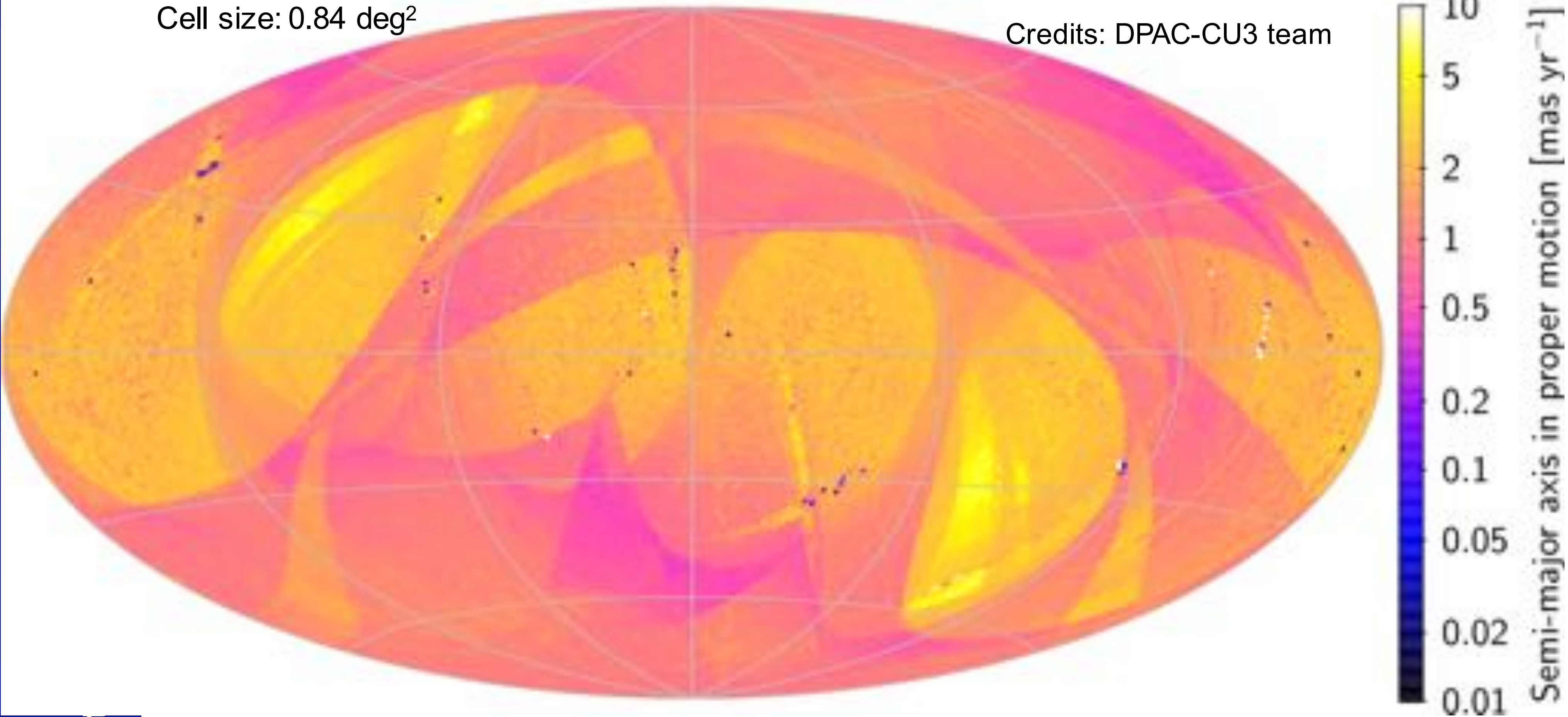


- Median parallax uncertainty ~ 0.3 mas
- Parallax systematics at 0.3 mas level
- Errors levels partly reflect early scanning law coverage and geometry

DR1- TGAS median proper motion uncertainty

Cell size: 0.84 deg²

Credits: DPAC-CU3 team

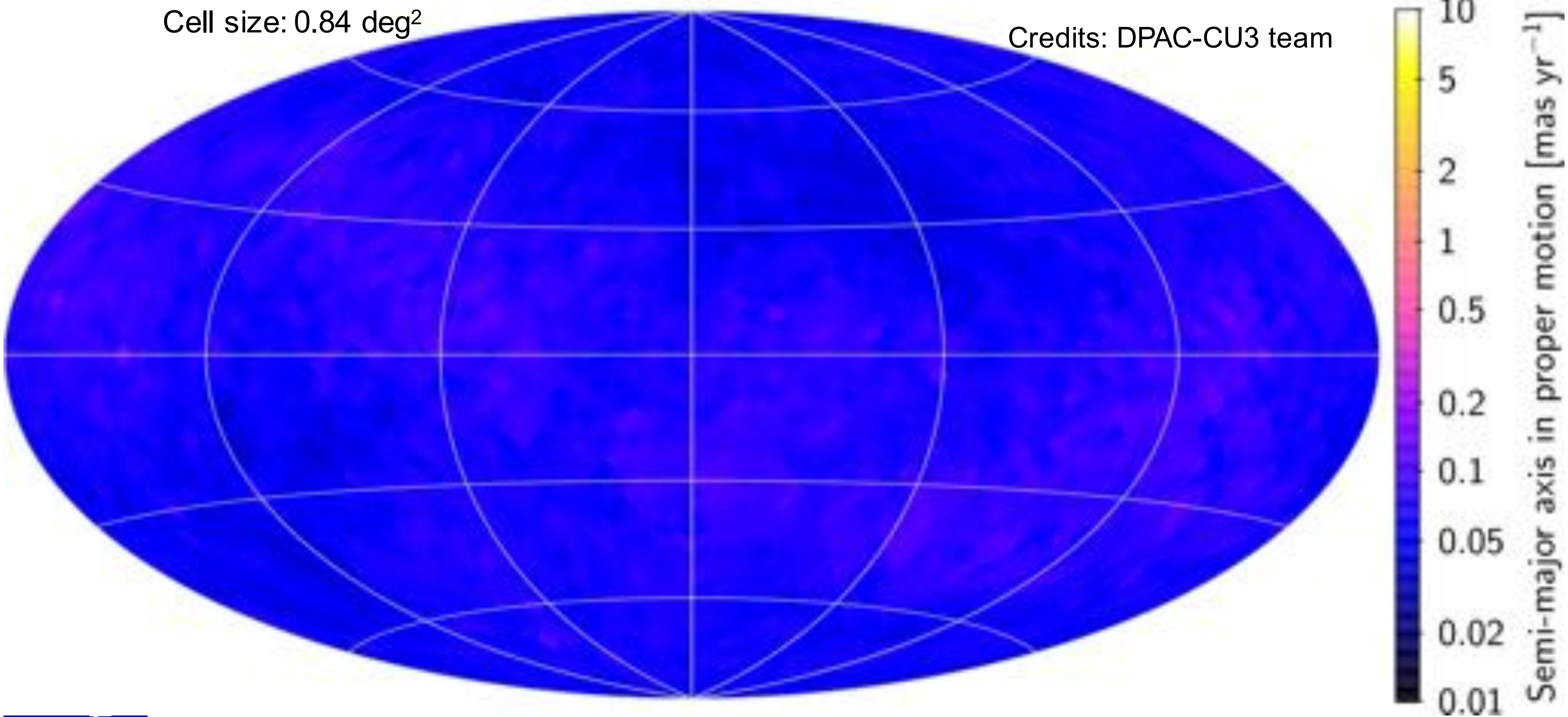


- Median proper motion uncertainty ≈ 1.3 mas yr^{-1}
- Also about 0.3 mas yr^{-1} systematic error!

DR1- TGAS (Hipparcos subset) median proper motion uncertainty

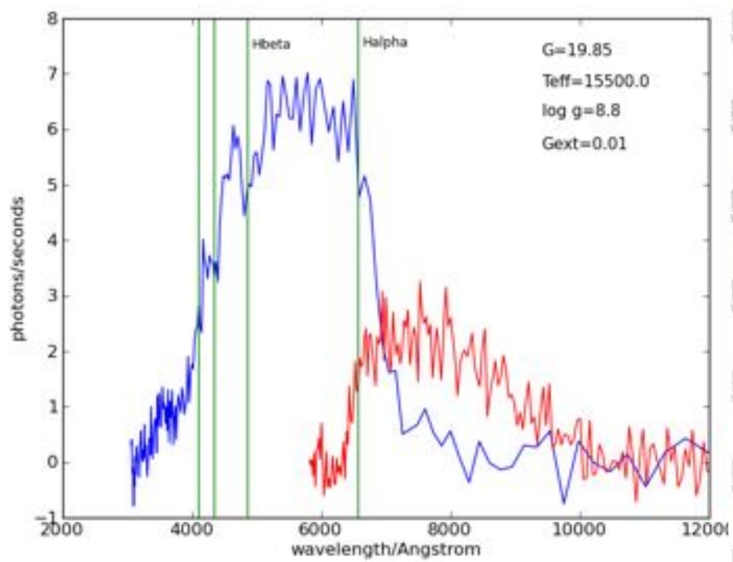
Cell size: 0.84 deg^2

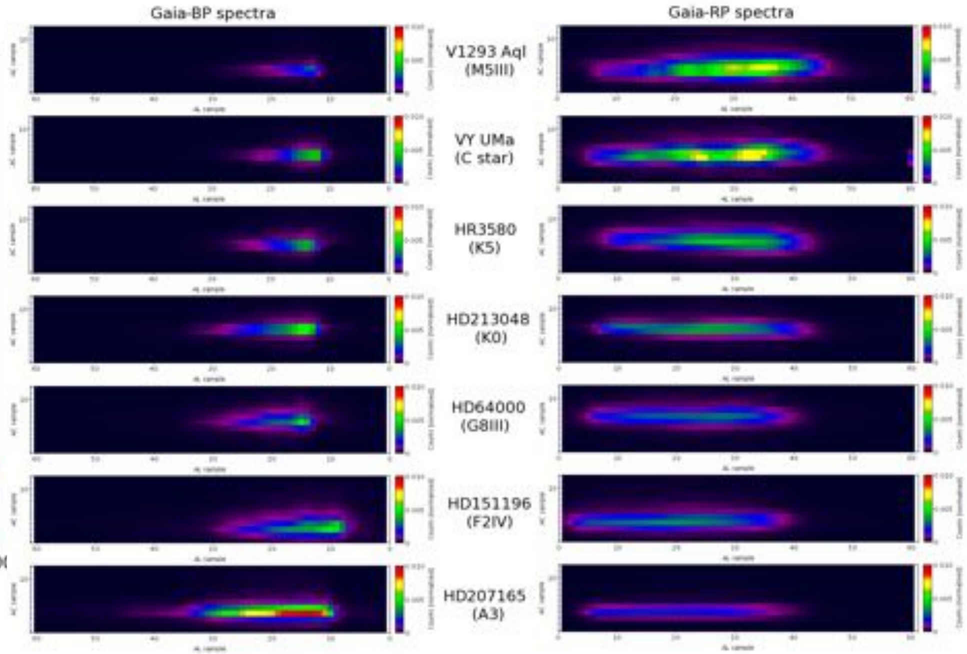
Credits: DPAC-CU3 team

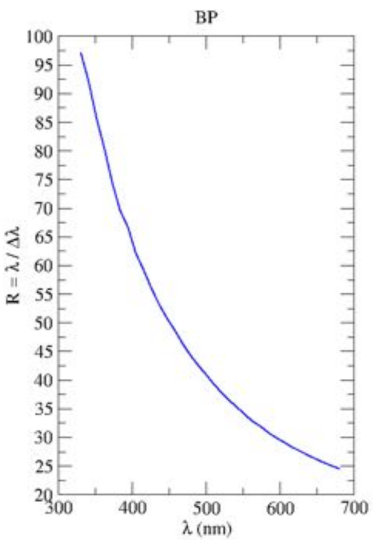


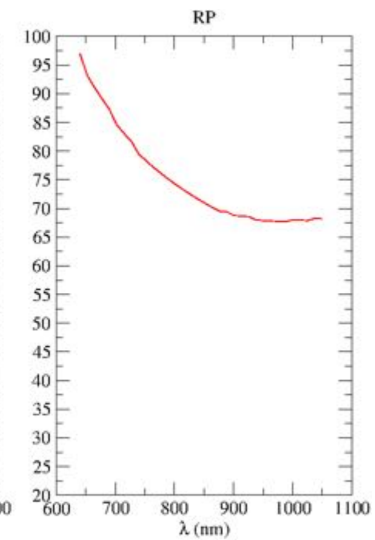
- Median proper motion uncertainty ≈ 0.07 mas yr^{-1}
- <0.1 mas yr^{-1} systematic error!

Blue and Red Photometer



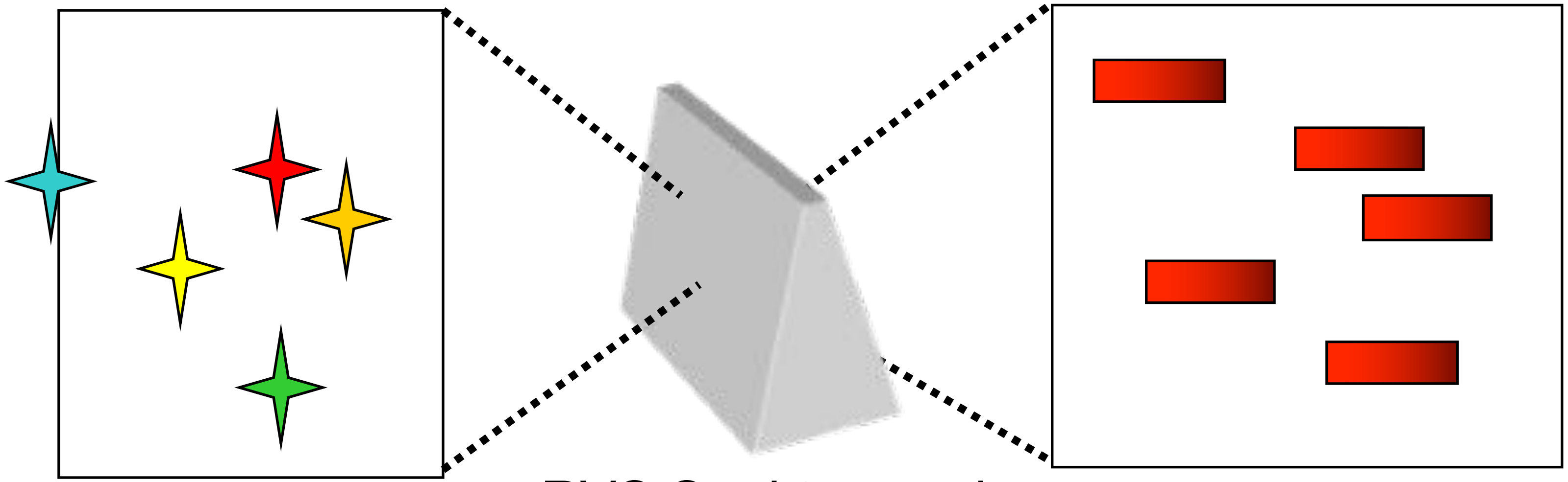


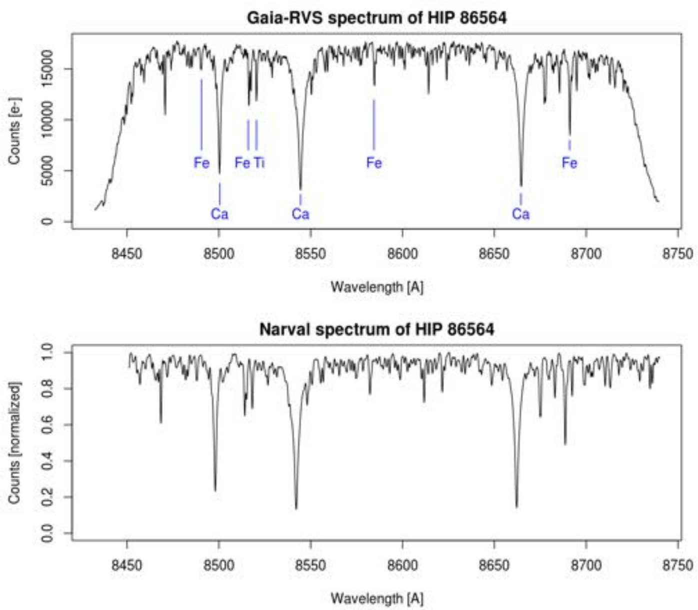




$\lambda/\Delta\lambda<100$

Radial-velocity Spectrograph



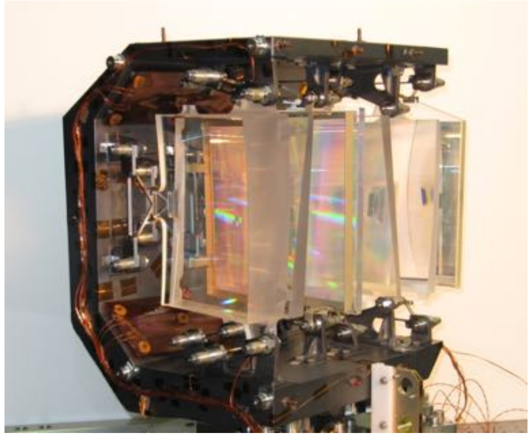


Single RVS spectrum of K5 star HIP 86563 (V=6.63) compared to a ground-based spectrum

$\Delta\lambda/\lambda$=11500

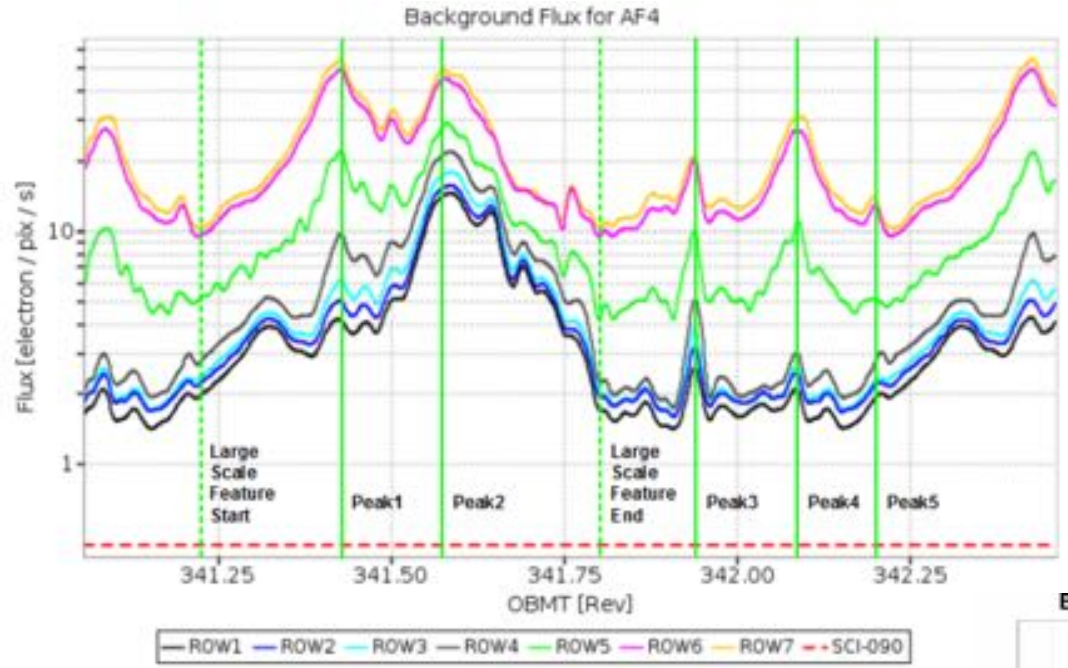
Status of measurements until Oct 24, 2017

- **Days in nominal mission:**1187
- **Astrometric measurements**: 858 billion
- G<20.7 mag
- Bright limit around G=2-3 mag
- All bright stars imaged (G<3 mag) (Gaia SM)
- **Photometric measurements**: 174 billion
  - 330-680 nm BP
  - 640-1050 nm RP
- Photometry in G-band on astrometric detectors
- **Spectroscopic measurements**: 16 billion
- G_{RVS}<16.2 mag
  - 845-872 nm with R about 11,000
- Radial Velocity Spectrometer for >100 million radial velocities
- Bright limit around G=2-3 mag



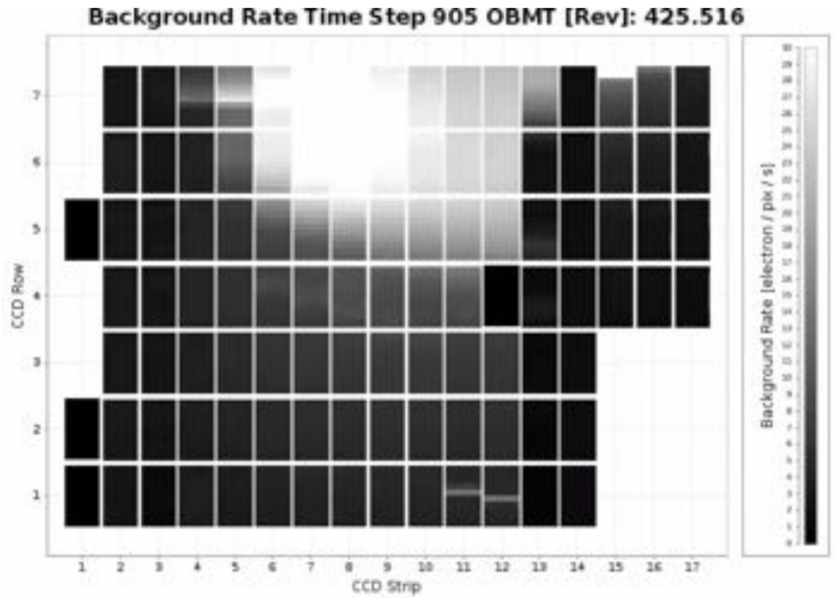
RVS spectrograph

Excessive Straylight

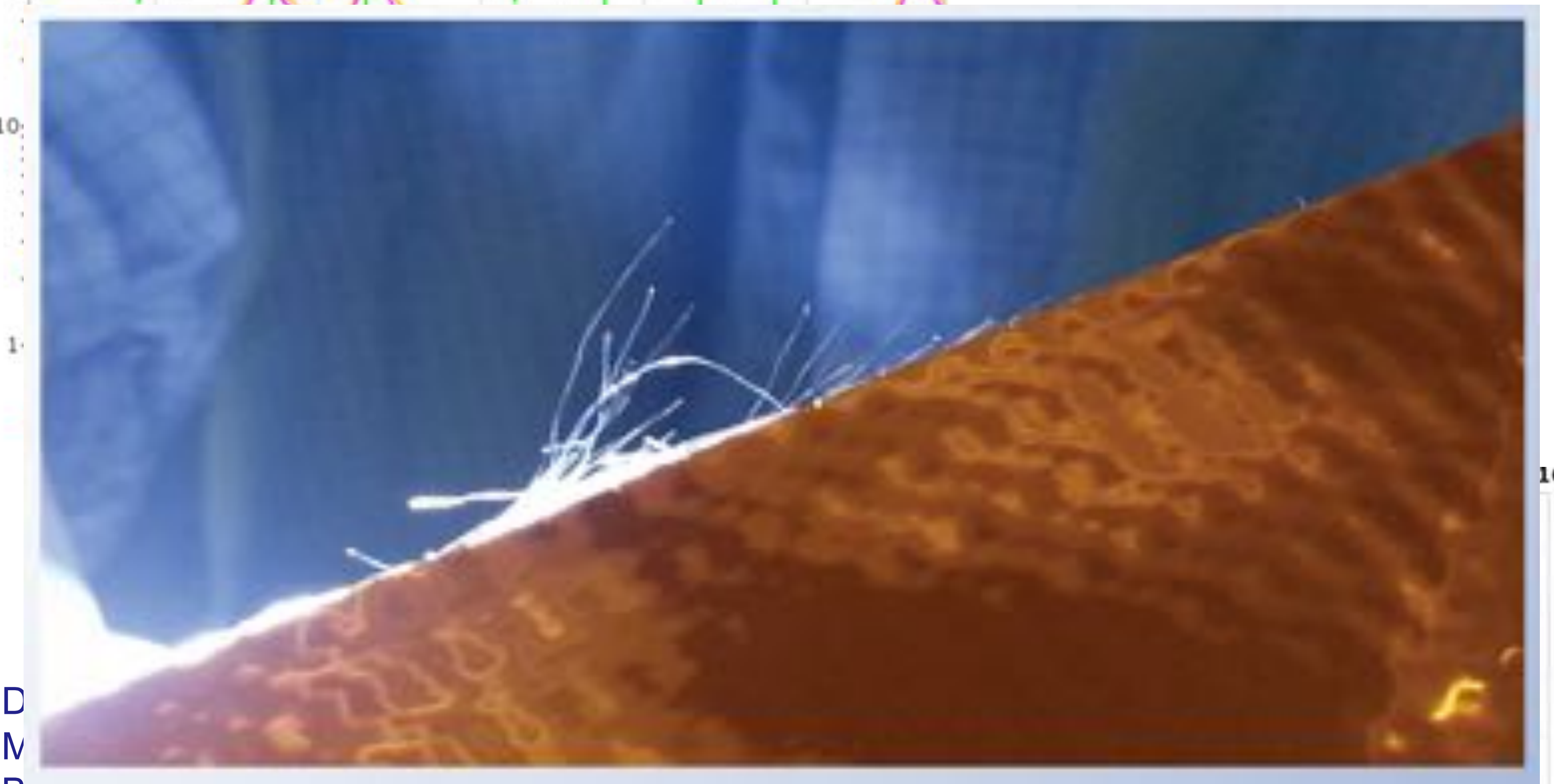


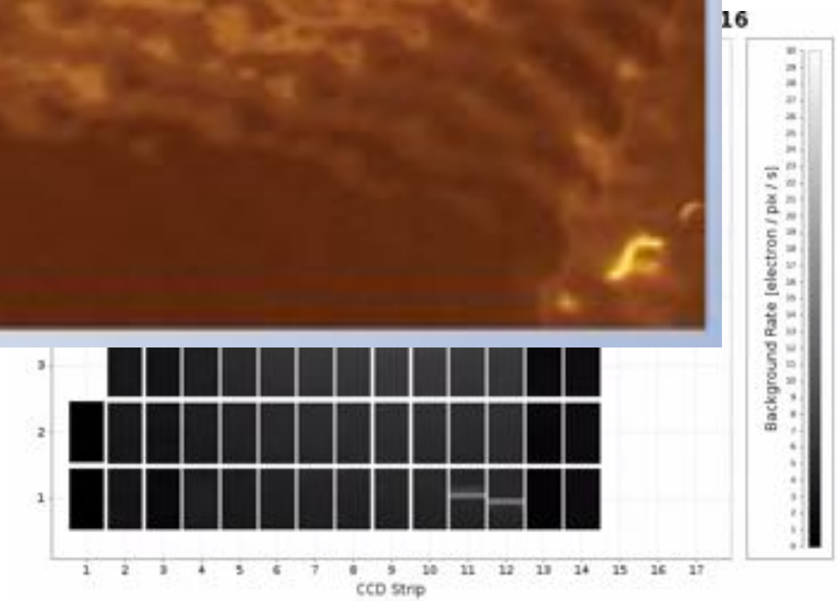
- Diffracted sunlight
- Milky Way
- Bright point objects

1. Sunshield
2. Insufficient baffling



Excessive Straylight

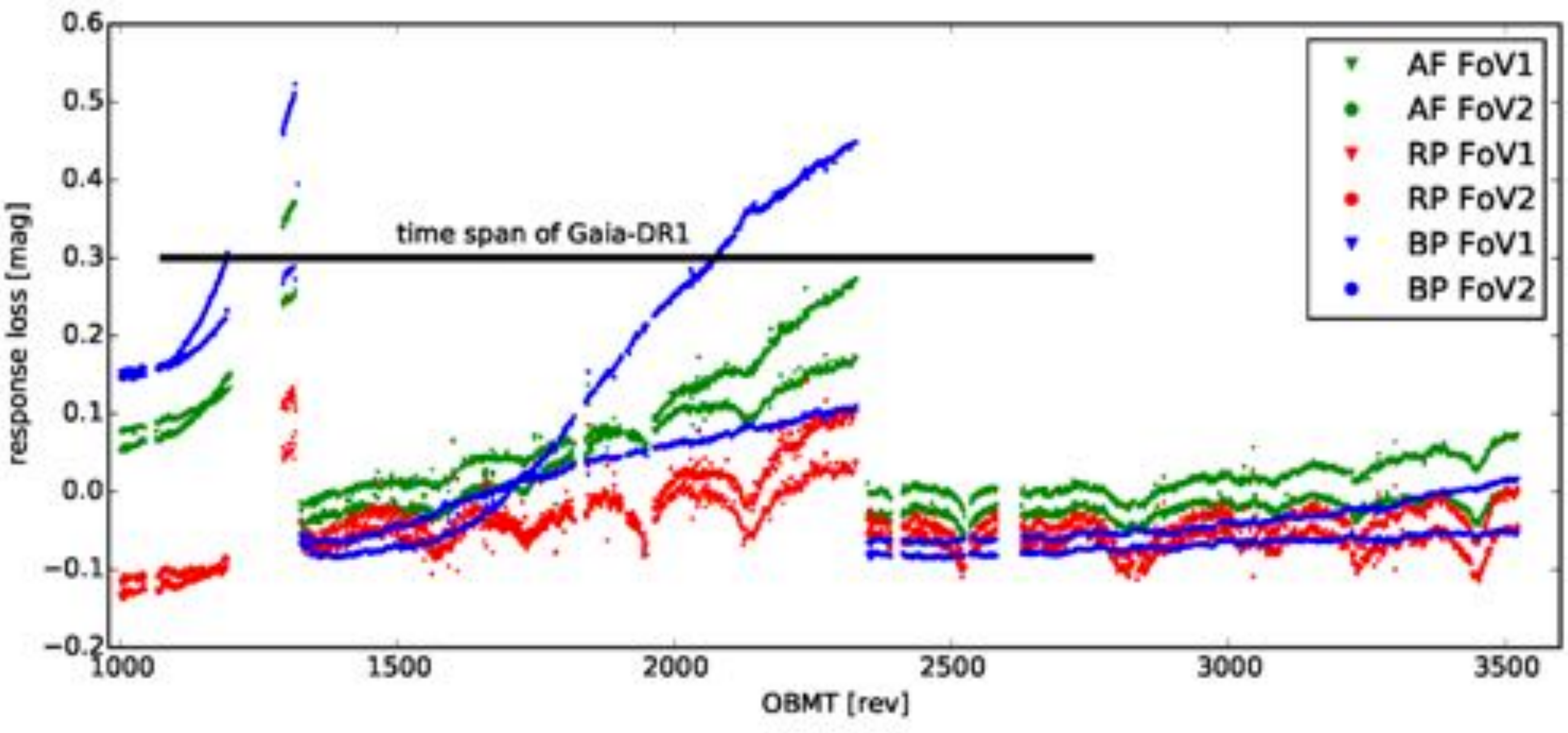




- D
- M
- Bright point objects

1. Sunshield
2. Insufficient baffling

Contamination



CU5/DPCI team

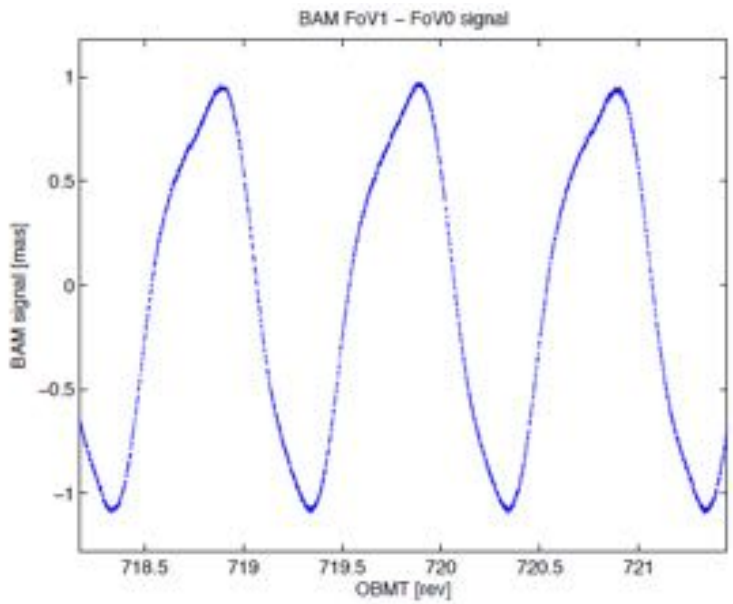
Cyclic Variation of the Basic Angle

- The basic angle varies with a period of 6 hours=rotation with respect to the Sun
- Amplitude: 1.1 milliarcseconds
- Specification: 4 microarcseconds
- Corresponds to a shift of only a few nanometers

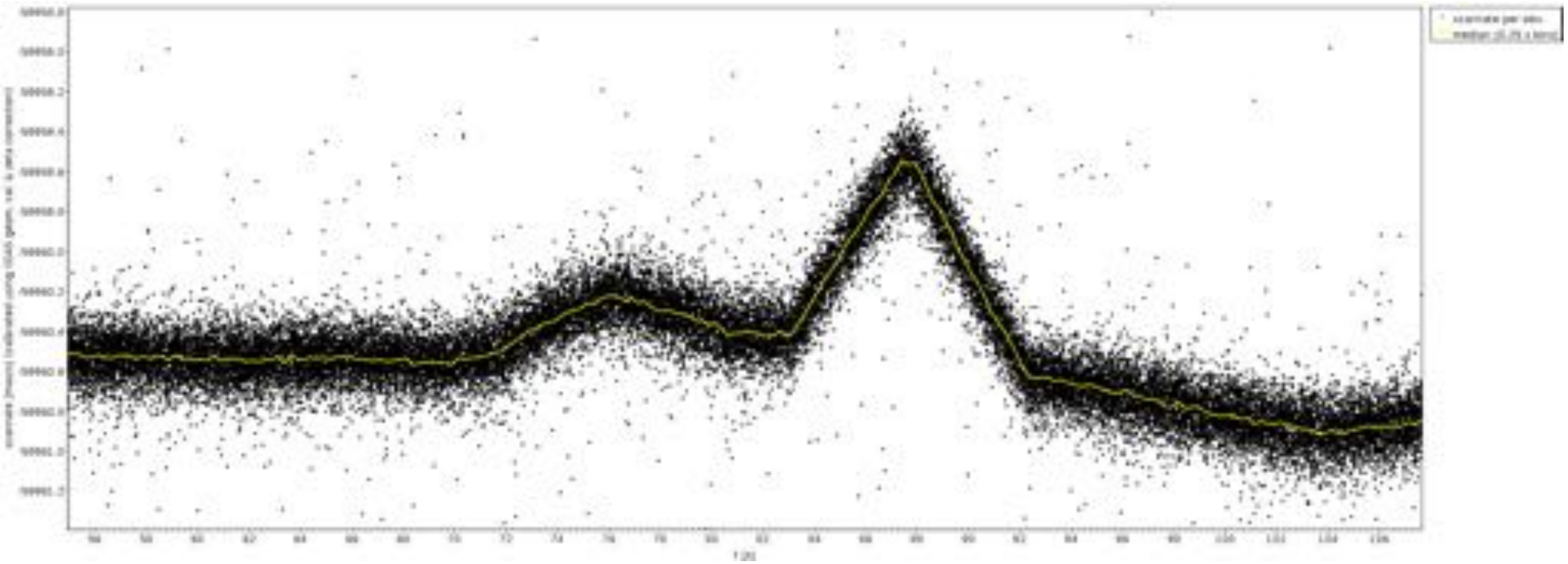
1 mas = 5•10^{-9} rad < 4 nm movement of the main-mirror edges ~ 10 Si atoms

(and even much less if it is a different mirror)

Noise: a dozen or so picometers!

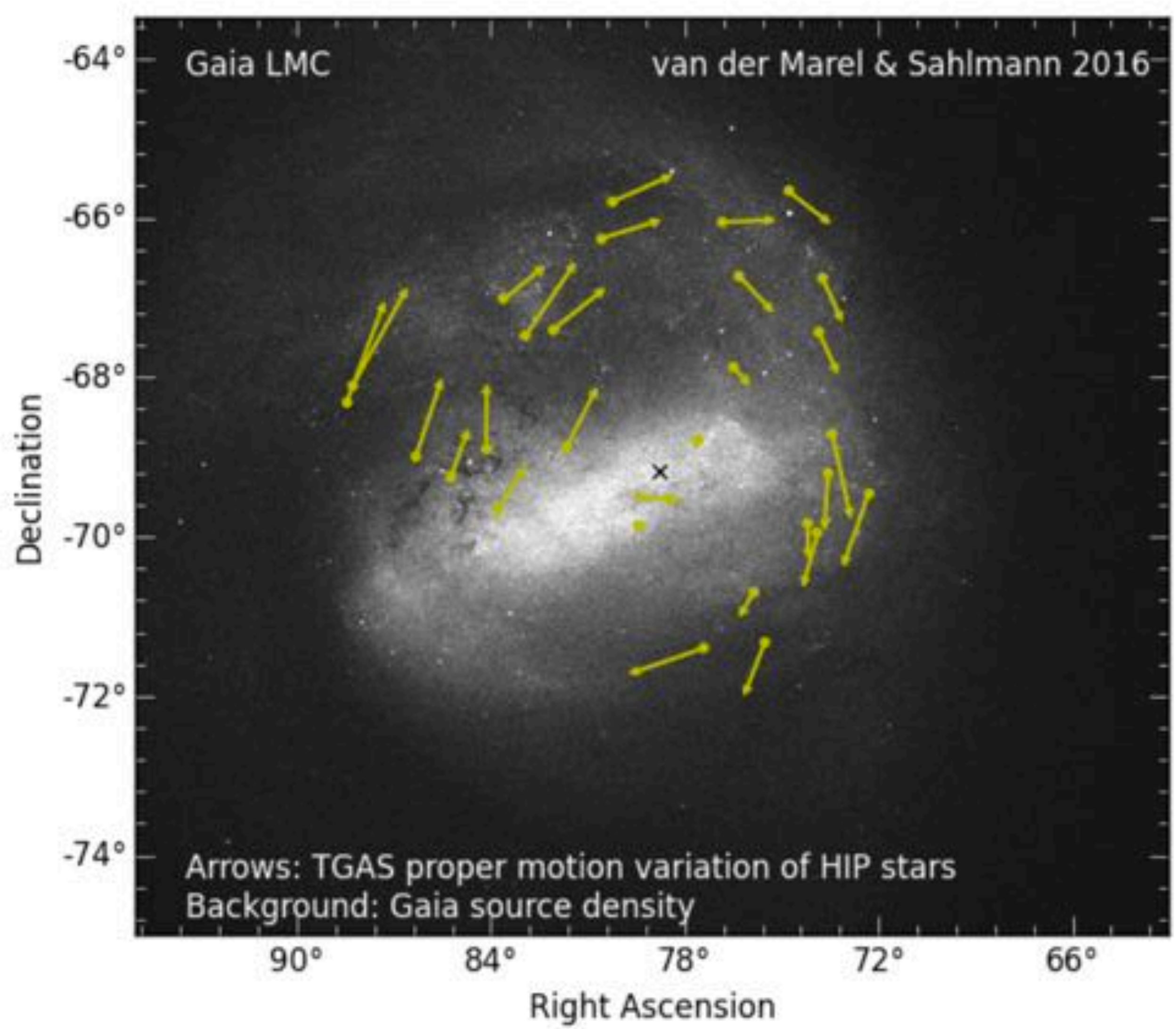


Apparent scan rate variations



Micro-clanks!

Very first science



A. Brown

190 Papers published on DR1

- http://adsabs.harvard.edu/cgi-bin/nph-abs_connect?library&libname=Gaia+DR1&libid=58e66b71f4

Fundamental Physics with Gaia

Stefan Jordan

ARI, Zentrum für Astronomie, Uni Heidelberg

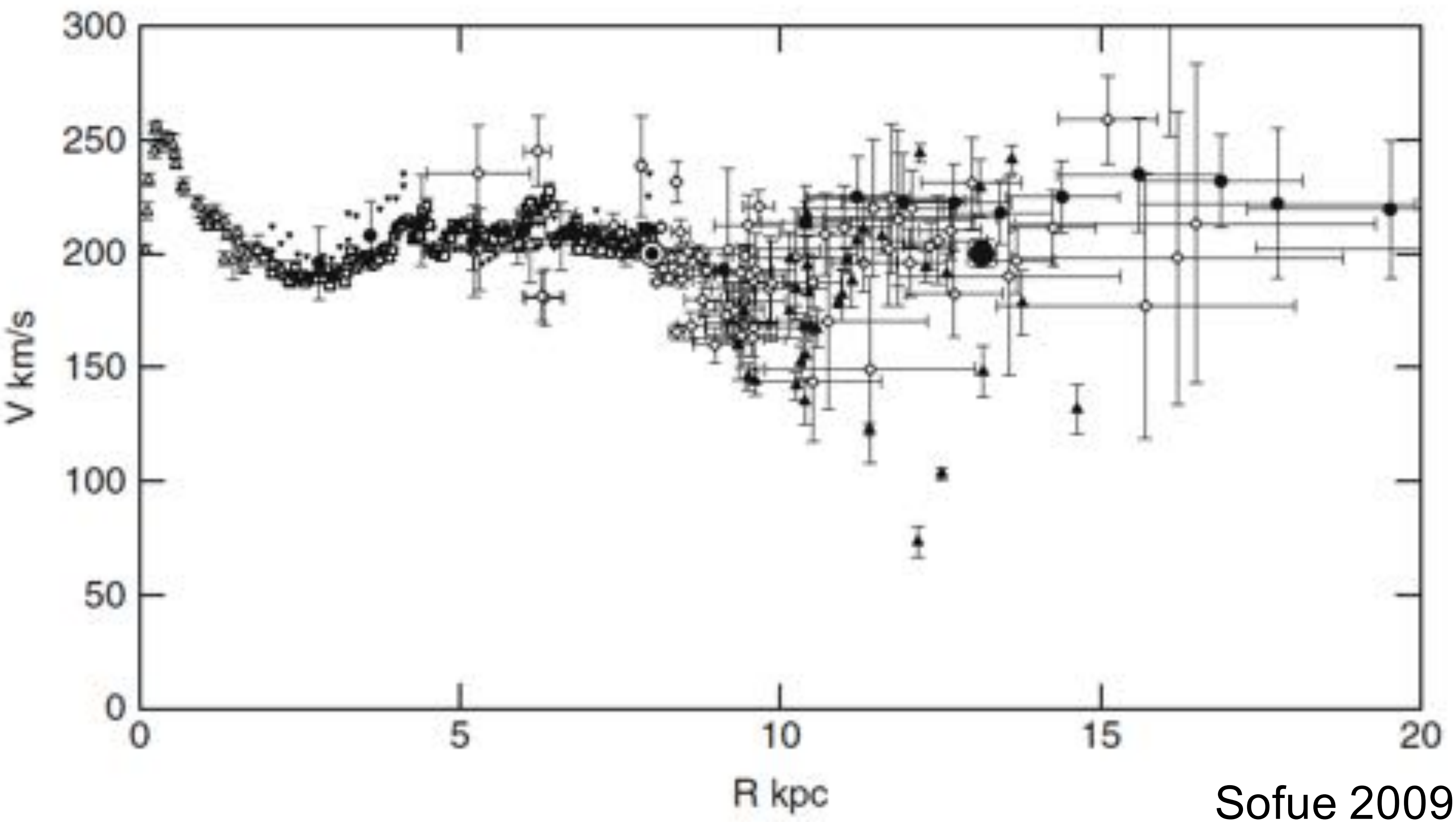
Gaia and Dark Matter

- The only way we've detected dark matter is through it's gravitational effects
- We can find the dark matter density by finding the gravitational potential (and subtracting off the baryonic contribution)

$$\nabla^2\Phi = 4\pi G(\rho_b + \rho_{DM})$$

Gaia and Dark Matter

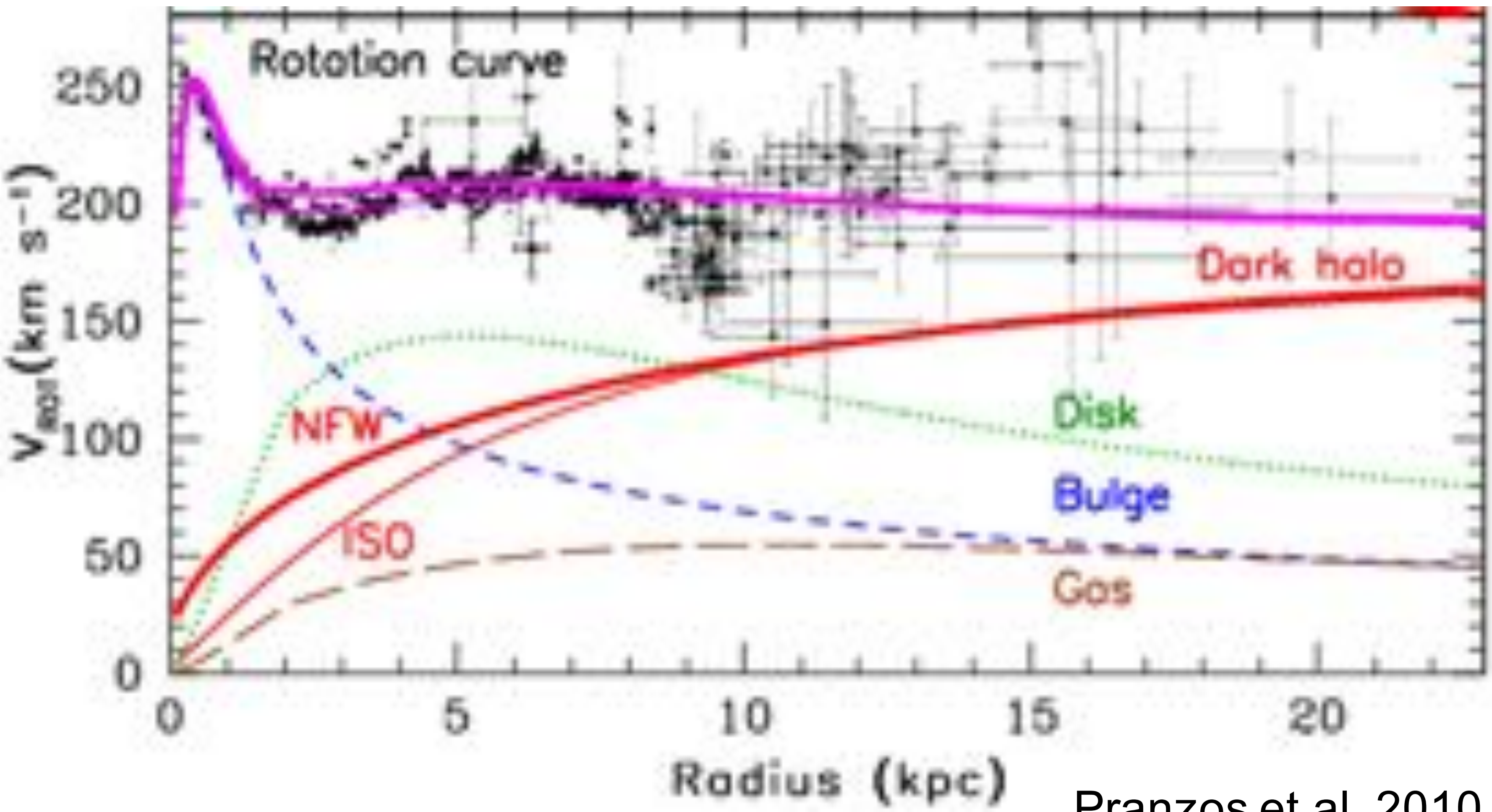
Rotation curve of our Milky Way



Sofue 2009

Gaia and Dark Matter

Fit with different components



Pranzos et al. 2010

Gaia and Dark Matter

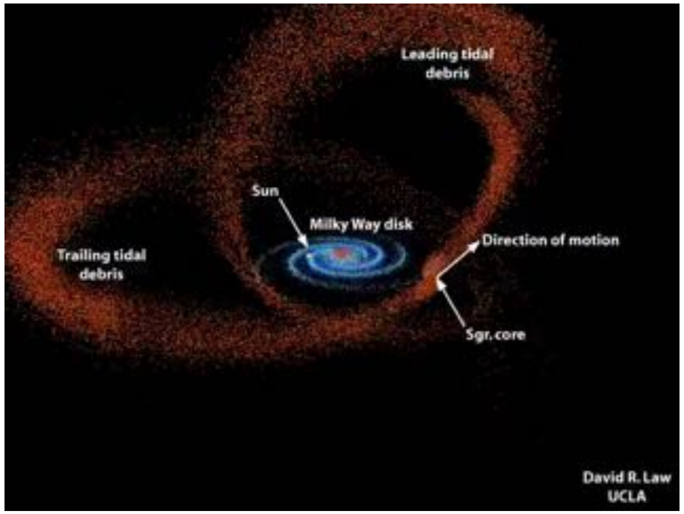
Where can Gaia help?

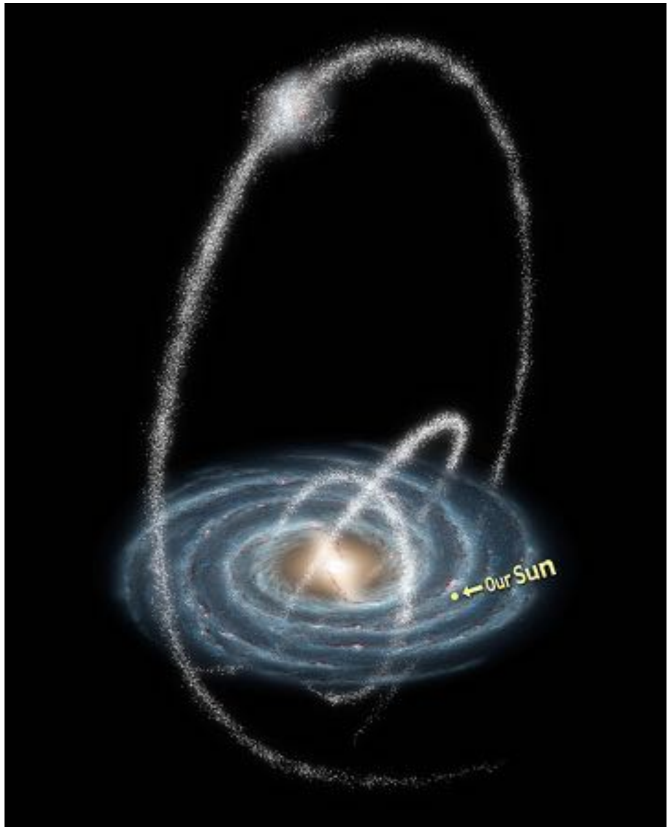
- Solar neighbourhood:
  - Precise rotation curves
  - Local volume density
    - DM contribution
    - Now: Baryonic contribution uncertain by 10% ➔DM uncertain by 100%
- Scale height
- Precise parallaxes not influenced by interstellar extinction ➔better scale length of Galaxy (mass determination)
- Stellar Streams

Gaia and Dark Matter

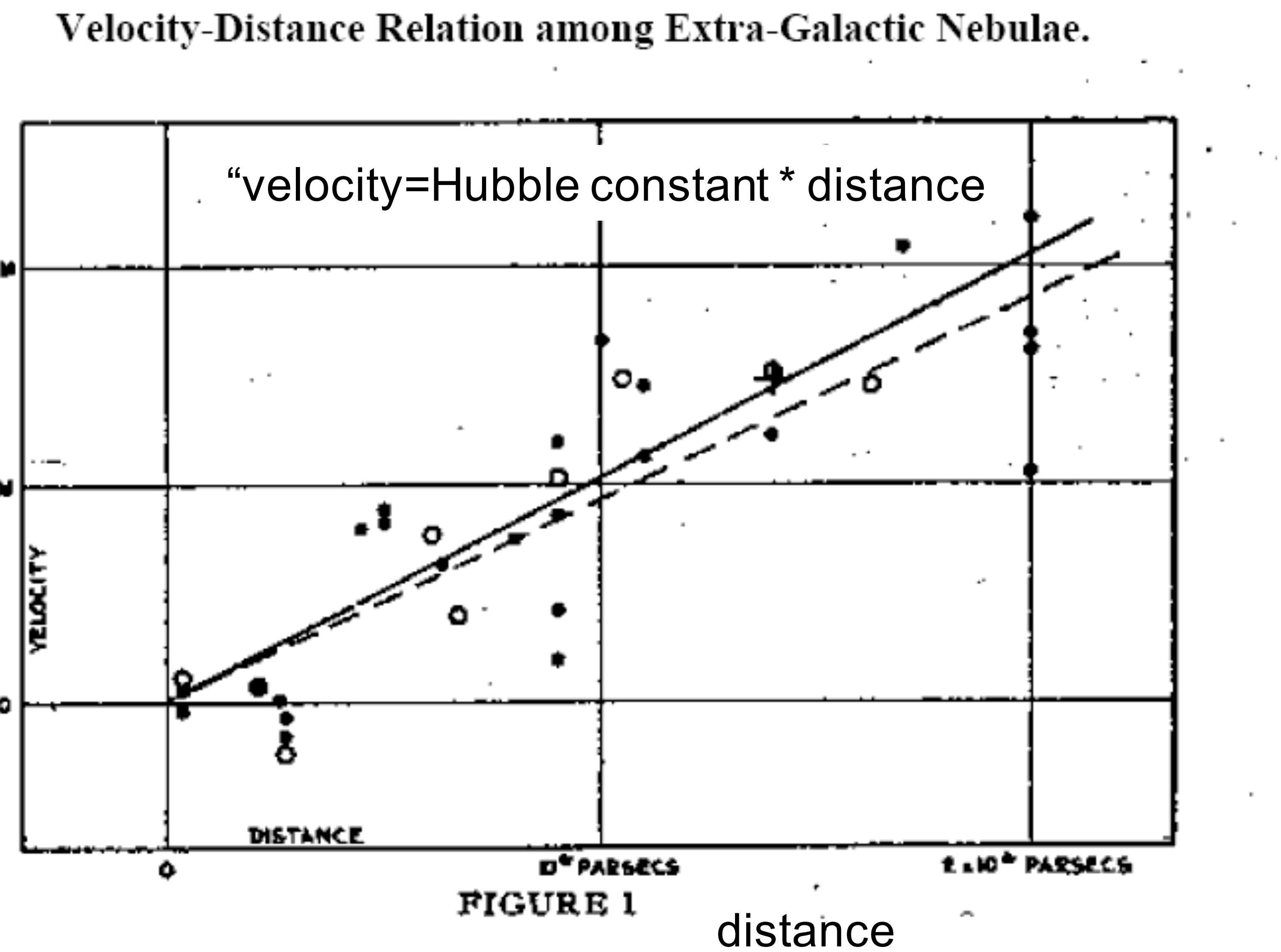
Stellar Streams probe the Galactic potential

- Precise parallaxes and proper motion
- Stellar streams probe the galactic potential also in the halo
- Oblateness of DM halo
- Clumpiness of DM halo

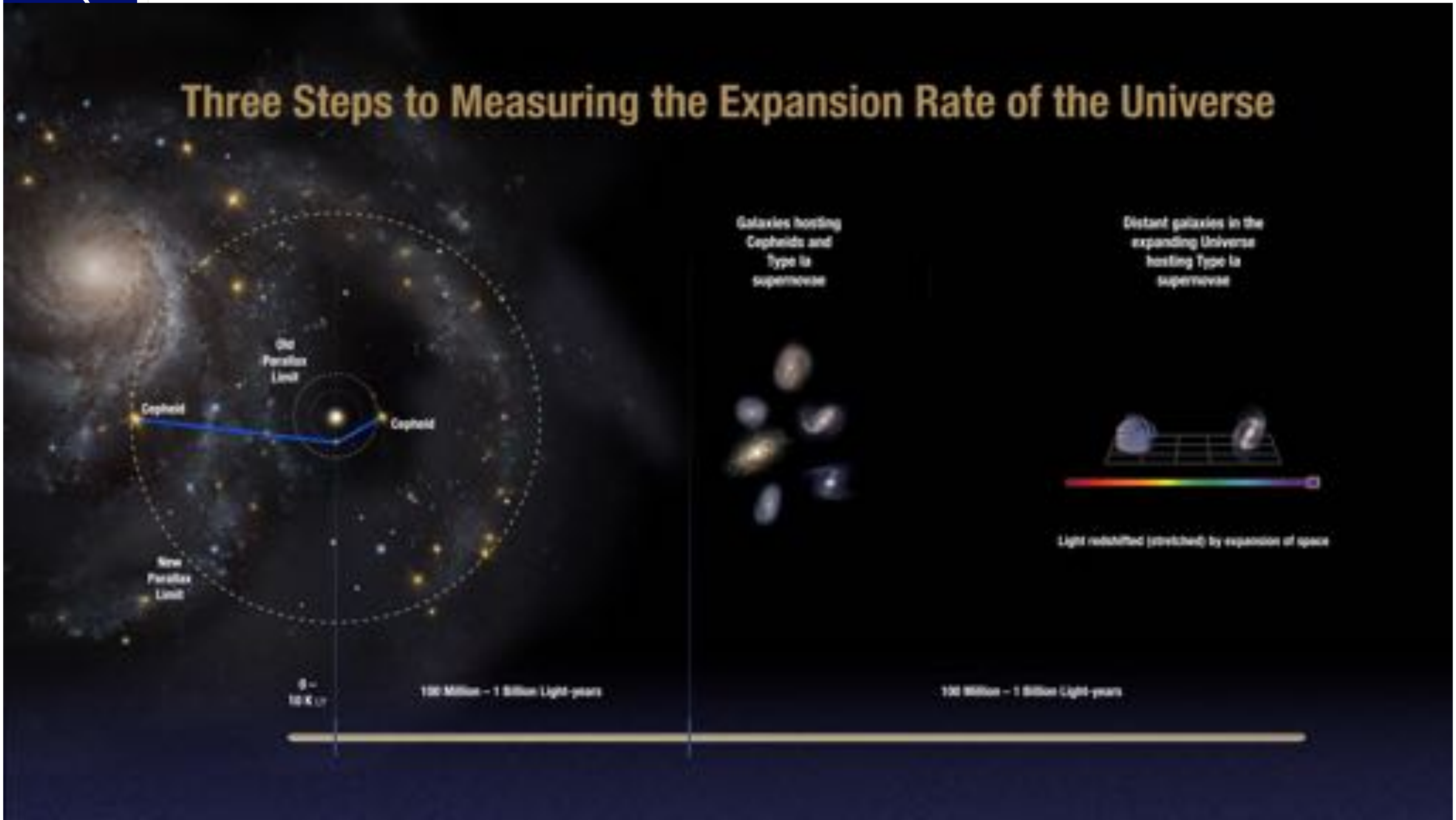




Improvement of Hubble constant with Gaia



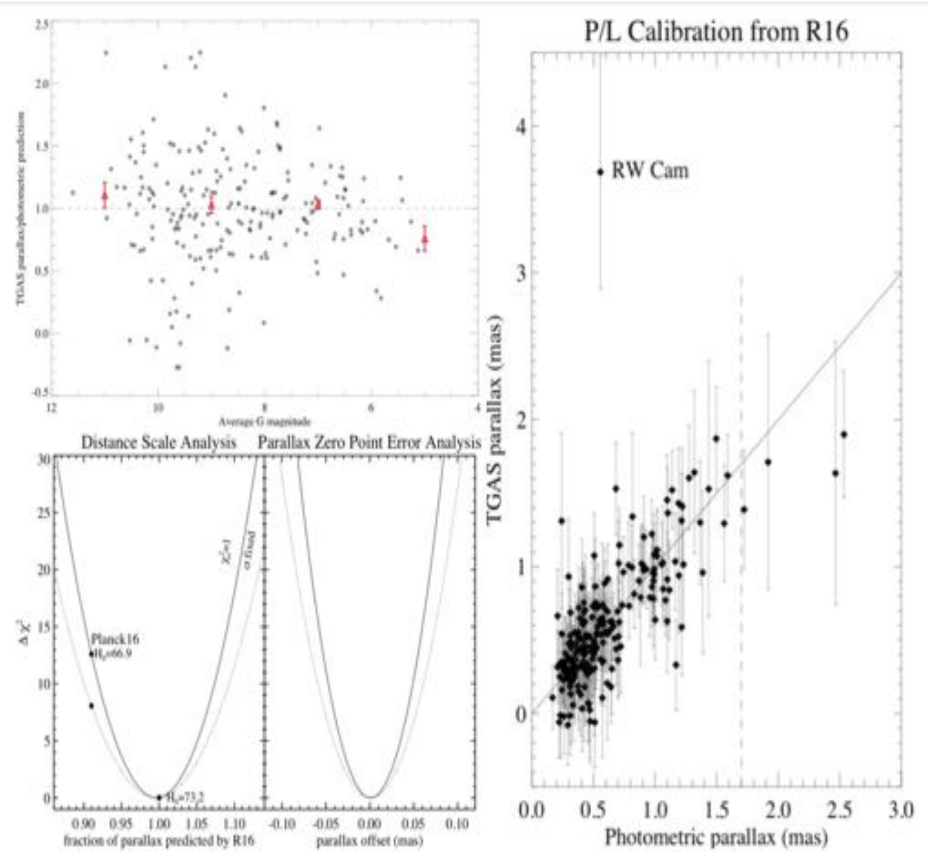
Improvement of Hubble constant with Gaia



Improvement of Hubble constant with Gaia

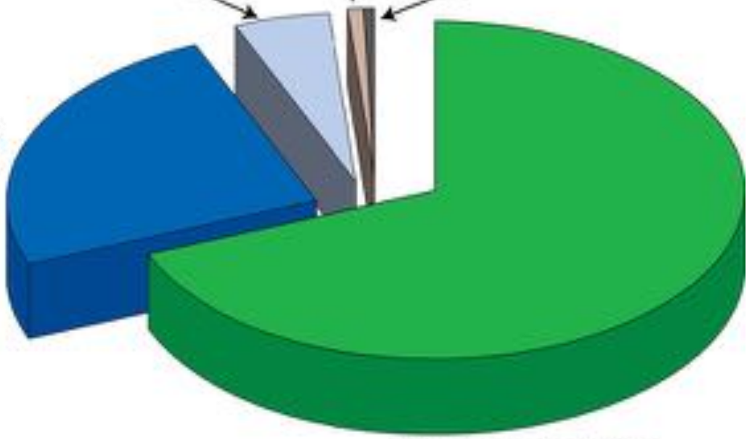
A test of Gaia Data Release 1 parallaxes: implications for the local distance scale

Stefano Casertano, Adam G. Riess, Beatrice Bucciarelli, Mario G. Lattanzi
Astronomy & Astrophysics, Volume 599, id.A67, 6 pp.



- Comparison of 212 Cepheide distances with current calibration with Gaia parallaxes
- DR1 parallaxes fit very well
- Gaia error overestimated by about 20%.
- If one trust the Gaia parallaxes fully: Hubble constant about 0.3% smaller than previously known.
- Gaia parallax zero point known better than ~20 µas.
- Full mission will allow measurement of better than 1%

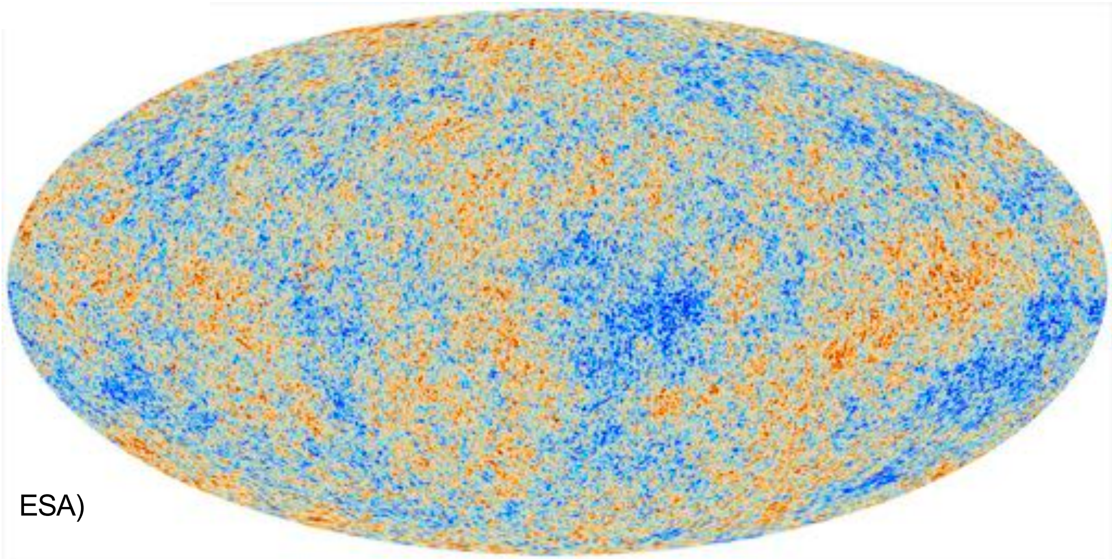
Improvement of Hubble constant with Gaia



H0 = 73.0 km s^{-1} Mpc^{-1}
(Gaia DR1)

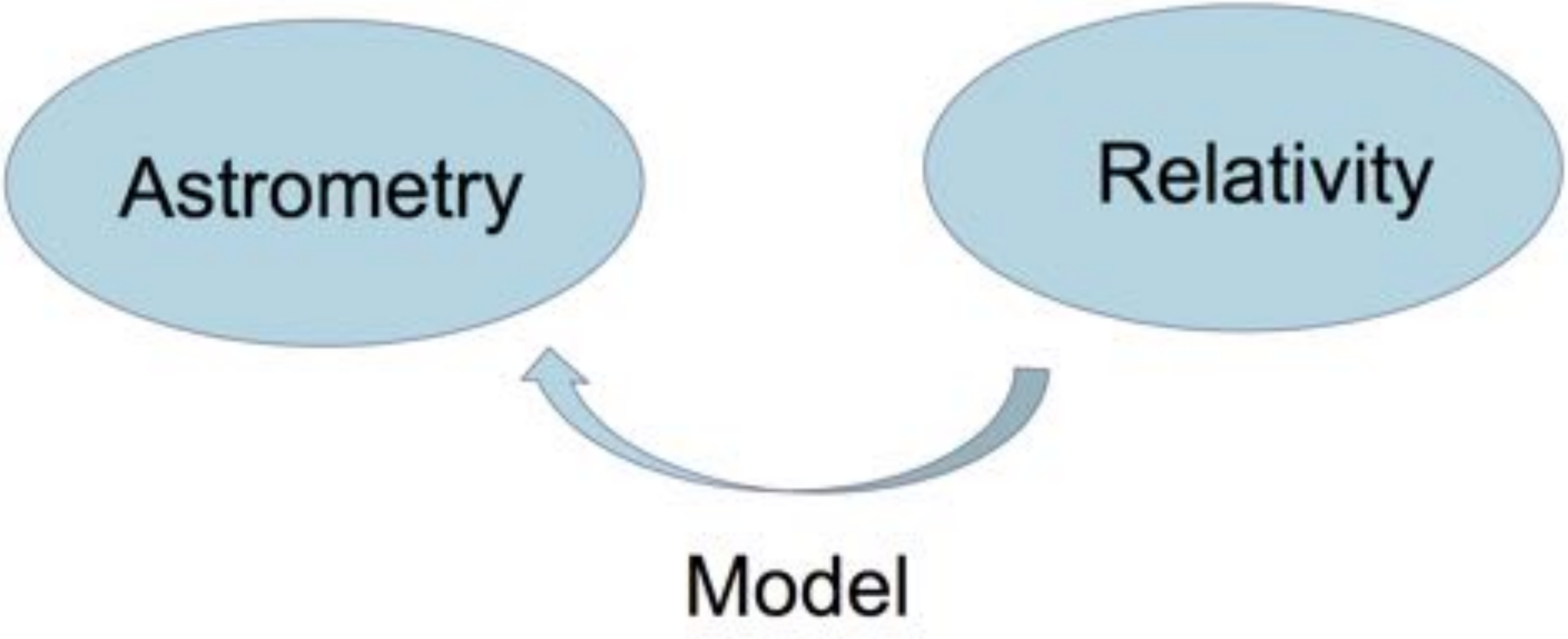
The Planck Collaboration (2016):
value of 66.9 km s^{-1} Mpc^{-1}

Difference of 2.5−3.5σ



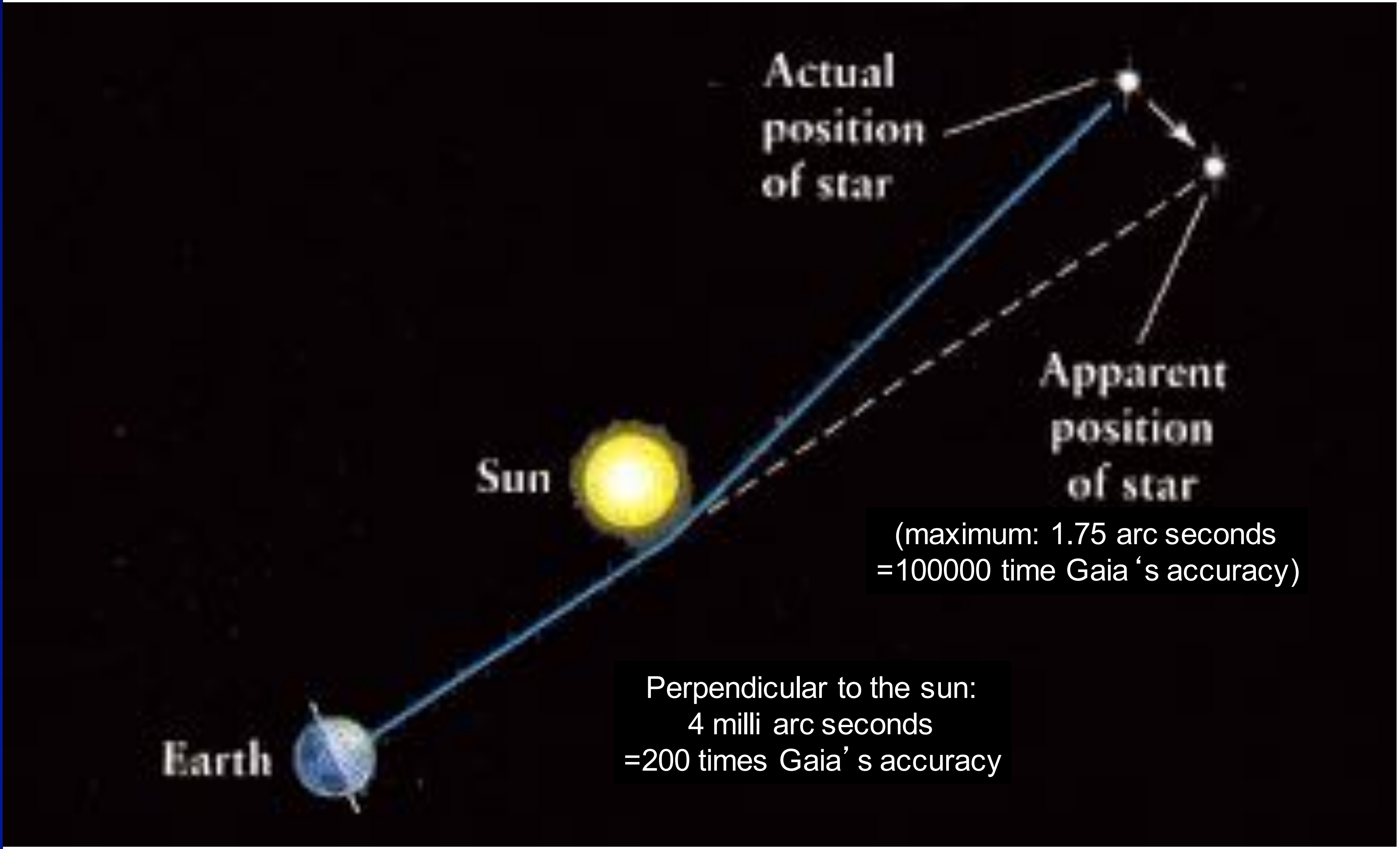
Credit: PLANCK-Kollaboration, ESA)

Gaia Relativity Model



Klioner

Light deflections at the sun



Gaia Relativity Model

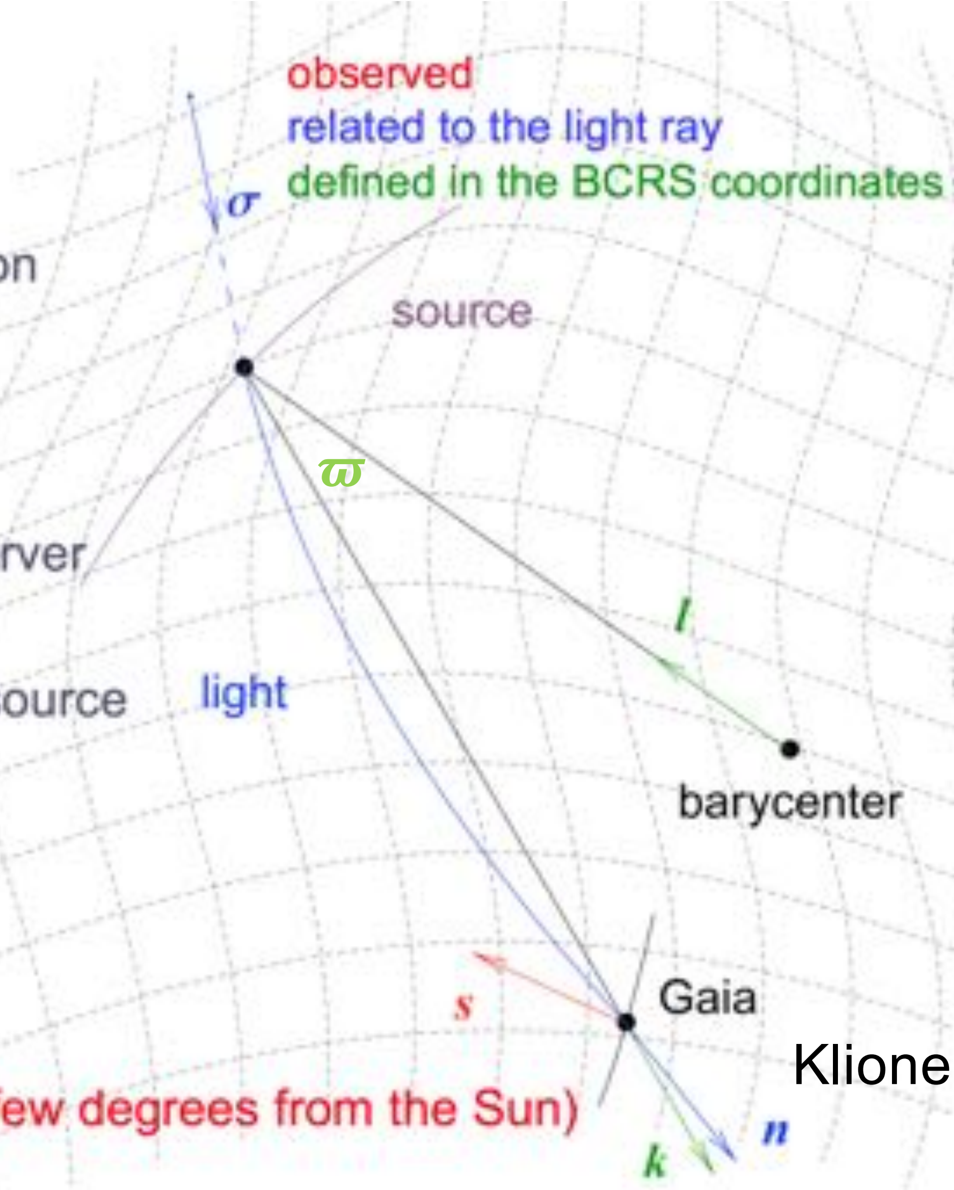
- Relativistic model for astrometric observations (Klioner 2003, 2004):
  - aberration via Lorentz transformations
- deflection of light: monopole (post- und post-post-Newtonian), quadrupole and gravitomagnetic terms
- up to 17 bodies routinely, more if needed
  - relativistic definitions of parallax, proper motion, etc.
  - relativistic definitions of observables and the attitude of the satellite
  - relativistic model for the synchronization of the Gaia atomic clock and ground-based time scale (Gaia proper time etc.)

- Accuracy: 0.1 µas (at a distance larger than a few degrees from the Sun). Gaia observes at distances > 45°

Klioner

Gaia Relativity Model

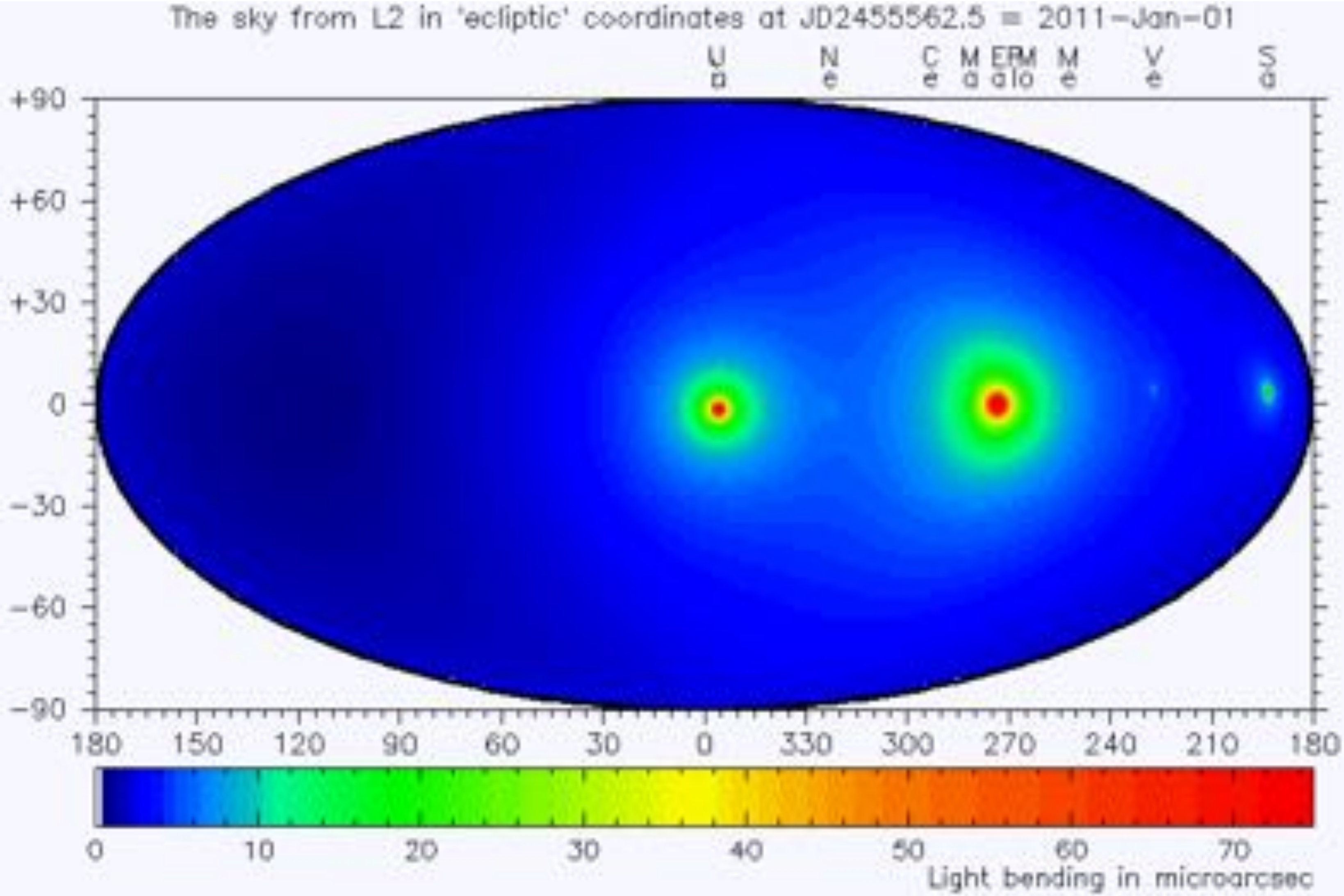
- s the observed direction
- n tangential to the light ray at the moment of observation
- σ tangential to the light ray at $t = -\infty$
- k the coordinate direction from the source to the observer
- l the coordinate direction from the barycentre to the source
- ϖ the parallax of the source in the BCRS



Accuracy limit: 0.1 µas
(at a distance larger than a few degrees from the Sun)

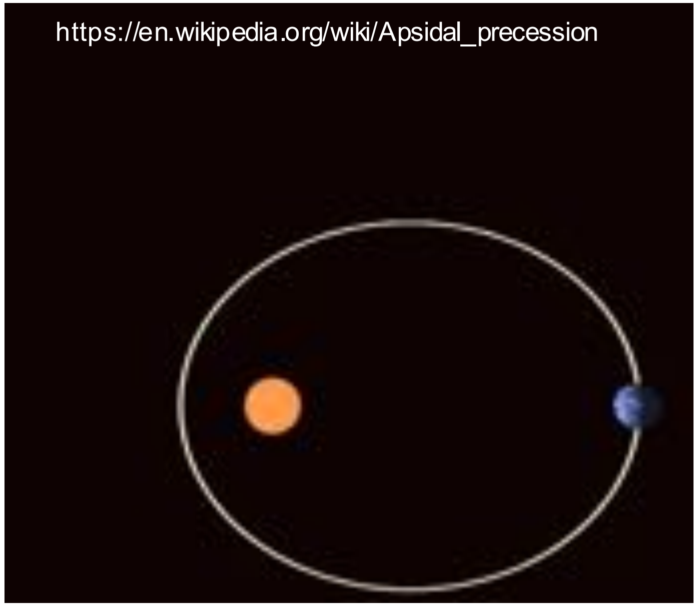
Klioner

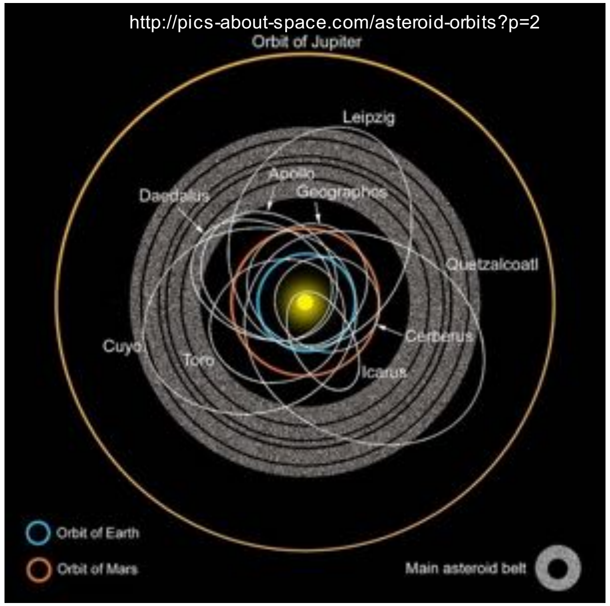
Light deflection by Planets



ESA/Jos de Bruijne

Perihelion precession



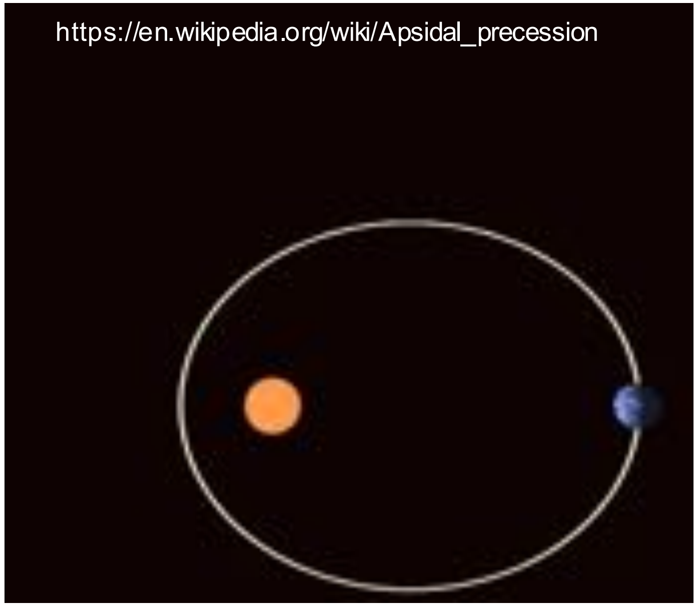


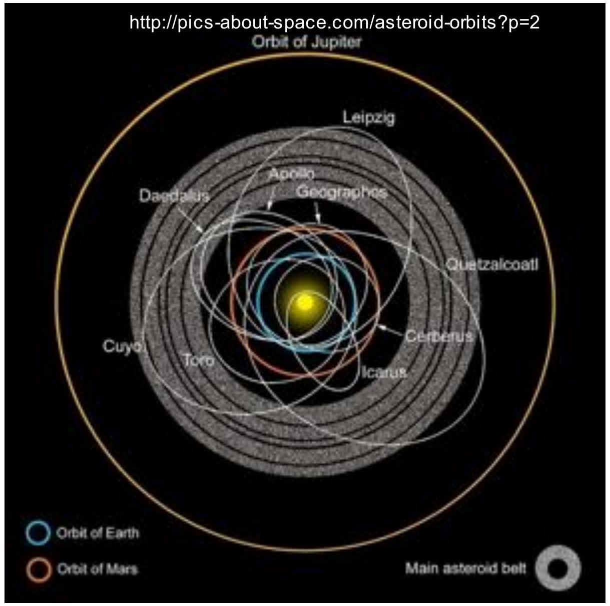
- 200-300,000 asteroids
- Several with large orbital eccentricities
- Disentangle solar quadrupole moment

$$\Delta\omega = \Delta\omega_{|PPN} + \Delta\omega_{|J2}$$
$$= \left[\frac{6\pi m_\odot}{a^{5/2}(1-e^2)} \Gamma + \frac{6\pi R_\odot^2}{4} \frac{5\cos^2 i - 1}{a^{7/2}(1-e^2)^2} J_2 \right] (t - t_0)$$
$$= \frac{3 m_\odot}{a(1-e^2)} \left[\Gamma + \frac{R_\odot^2}{4\, a\, m_\odot} \frac{(5\cos^2 i - 1)}{(1-e^2)} J_2 \right] n\,(t - t_0),$$

From Hestroffer et al. 2010

Perihelion precession



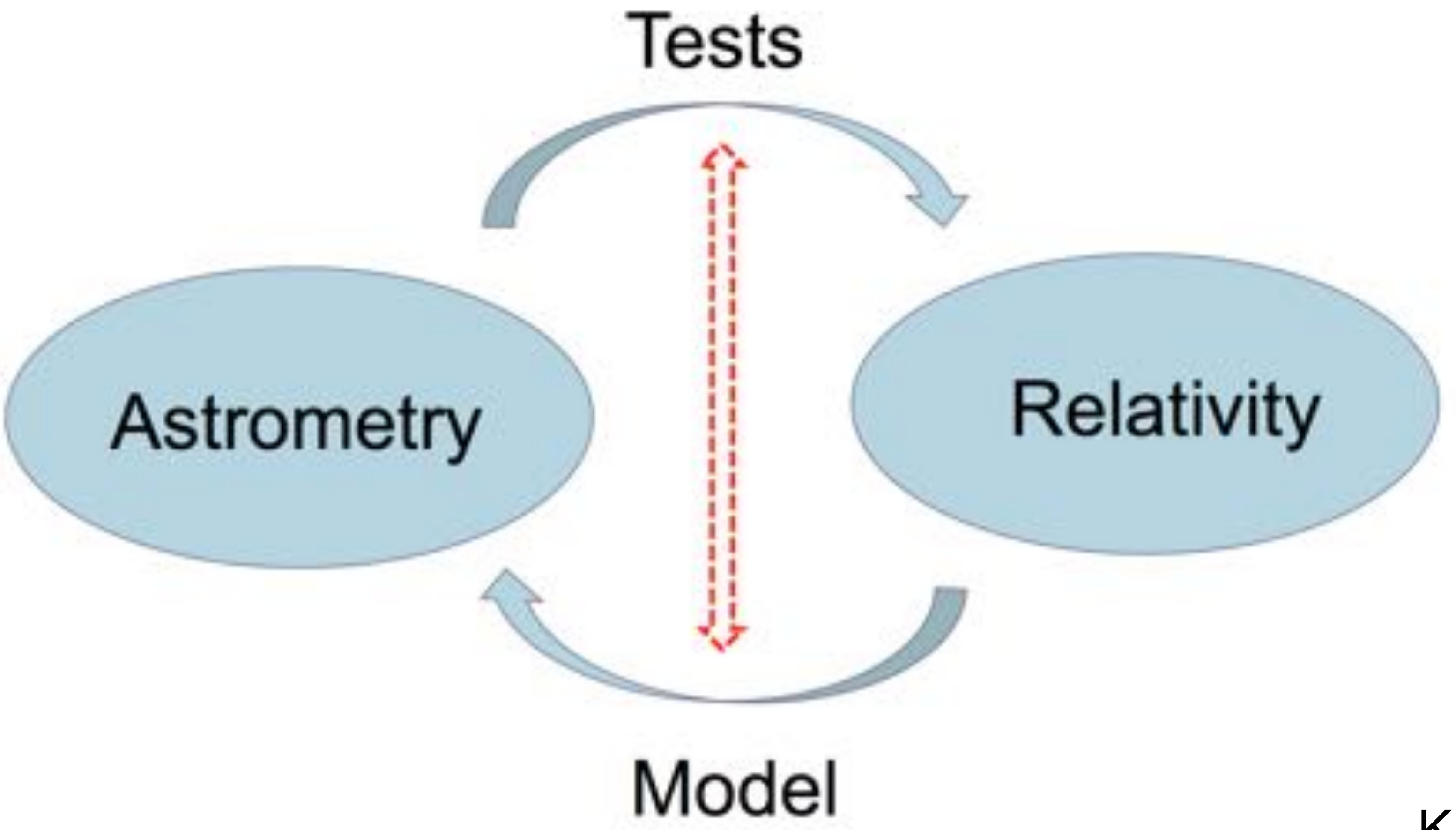


- 200-300,000 asteroids
- Several with large orbital eccentricities
- Disentangle solar quadrupole moment

			$\delta\varpi$: GR mas/yr	$J_2(=10^{-7})$ mas/yr
Mercury :			430	0.124
main belt :	a = 2.70 AU	e = 0.1	3.4	0.0001
3200 Phaeton	a = 1.27 AU	e = 0.83	102	0.040
1566 Icarus	a = 1.08 AU	e = 0.83	101	0.030
5786 Talos	a = 1.08 AU	e = 0.82	101	0.030

From ***M.T. Crosta and F.Mignard***

Gaia Relativity Model



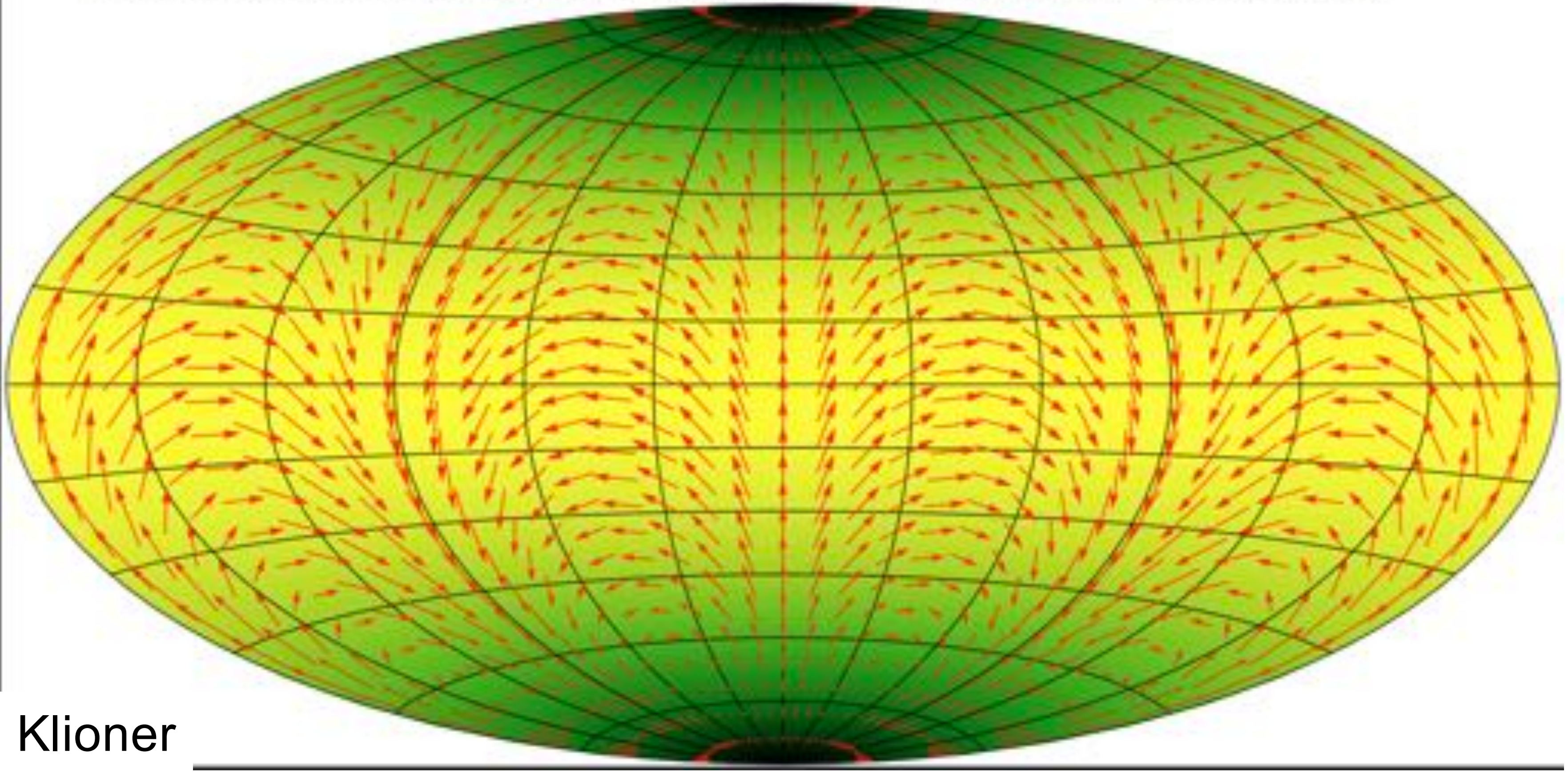
Klioner

Each relativistic effect used in the models can be used to test GR

Gravitational waves and astrometry

- At each moment of time a GW produces a deflection pattern on the sky: it is not a pure quadrupole, but rather close to it (Braginsky et al, 1991; Pyne et al, 2006; Gwinn et al, 2006; Book, Flanagan, 2011; Klioner, 2014-)

This is for a GW propagating in the direction δ=90° ("+" polarization)



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Low-frequency GWs

If the frequency of the GW is large enough, the time-dependence of the deflection does not allow the effect to be absorbed by proper motion.

This is now a time-dependent pattern in the residuals of the solution (at each moment of time only certain directions are observed):

2. Maximal theoretical sensitivity of Gaia to a constant parameter

$$\sigma_h \geq \left(W_{\mathrm{full}}\right)^{-1/2} = 5.4\times10^{-4}\ \mu\mathrm{as} = 2.6\times10^{-15}$$

The actual sensitivity is at least a factor 10-100 worse (Geyer, Klioner, 2014-)

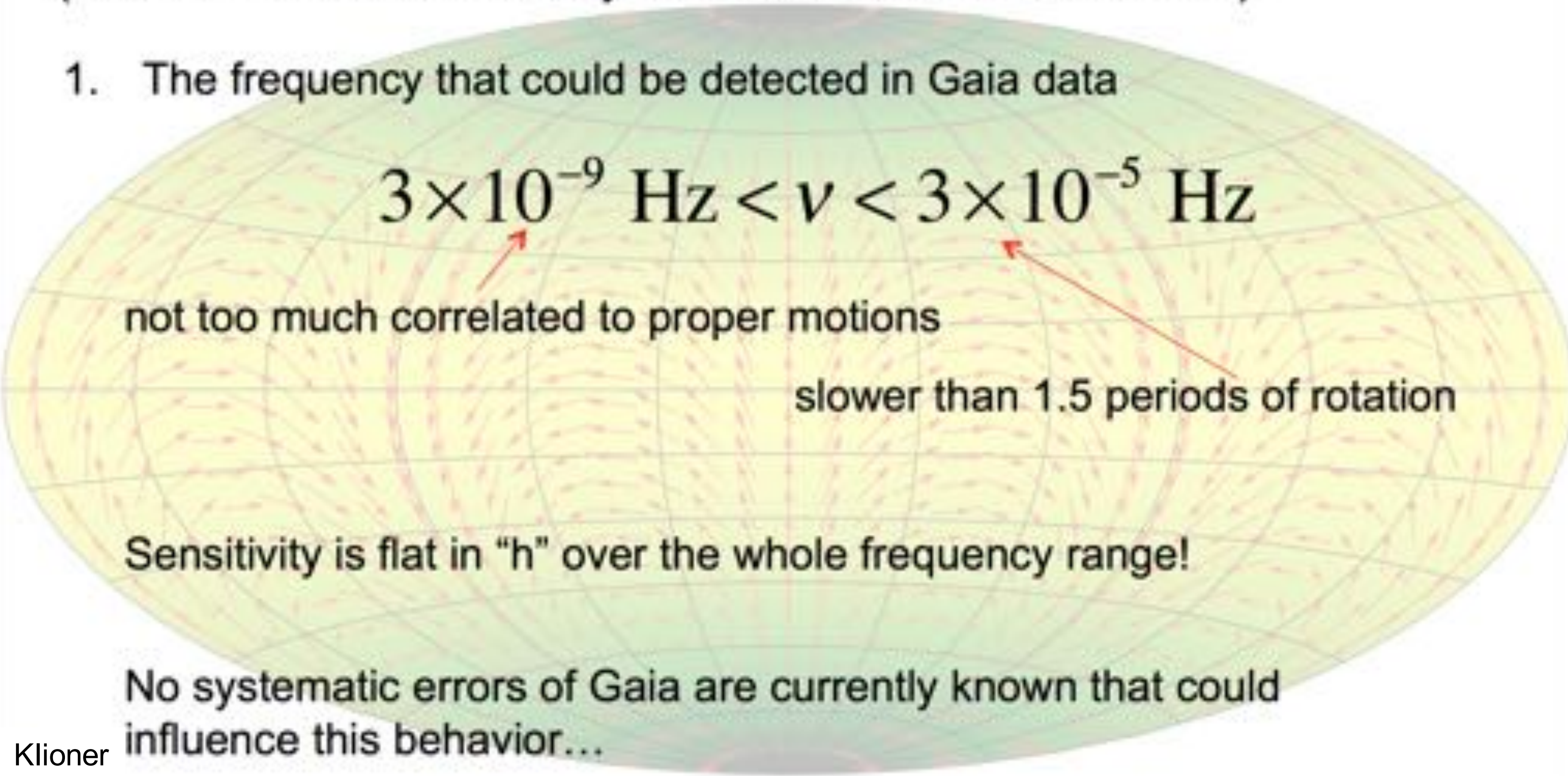
Systematic errors can significantly decrease the sensitivity (at all frequencies)

Klioner

Low-frequency GWs

If the frequency of the GW is large enough, the time-dependence of the deflection does not allow the effect to be absorbed by proper motion.

This is now a time-dependent pattern in the residuals of the solution (at each moment of time only certain directions are observed):



1. The frequency that could be detected in Gaia data

$$3\times10^{-9}\ \mathrm{Hz} < \nu < 3\times10^{-5}\ \mathrm{Hz}$$

not too much correlated to proper motions

slower than 1.5 periods of rotation

Sensitivity is flat in "h" over the whole frequency range!

No systematic errors of Gaia are currently known that could influence this behavior…

Klioner

Gaia extension

- Nominal Gaia mission ends mid-2019 after 5 years of measurements
- Hardware and operations designed for a 5-year survey for sky homogeneity
- Scientifically the best option is to start a new 5-year survey on top of the nominal 5-year survey

Notes on continued S/C operations

- All hardware in good shape
- Only limiting factor is micro-propulsion system fuel
- Estimated to run out by mid 2024

A. Brown

Improvement of scientific performance

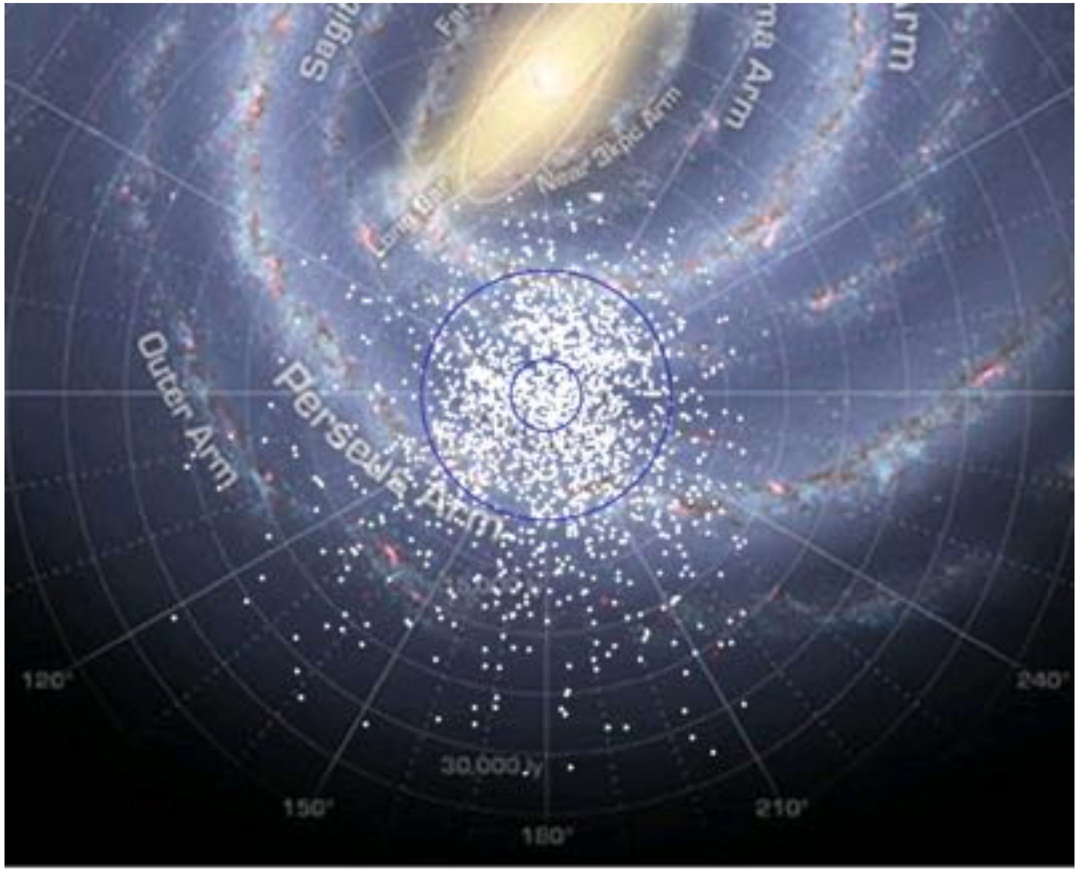
- Basic mission results improve with $t^{-0.5}$
  - Positions, parallaxes, photometry and radial velocities
- Rapidly increasing gain in kinematics and dynamics
  - Proper motion improvement scales as $t^{-1.5}$
  - More complex systems scale faster, e.g. improvement in unambiguous determination of orbital period,
  - mass and distance of a perturbing body scales as $t^{-4.5}$

Improvement factor for mission length increase from 5 to 10 years	Distance increase at the same accuracy	Volume increase at the same accuracy
Parallax	1.4	2.8
Proper motion	2.8	23

A. Brown

Improvement for stars and stellar clusters

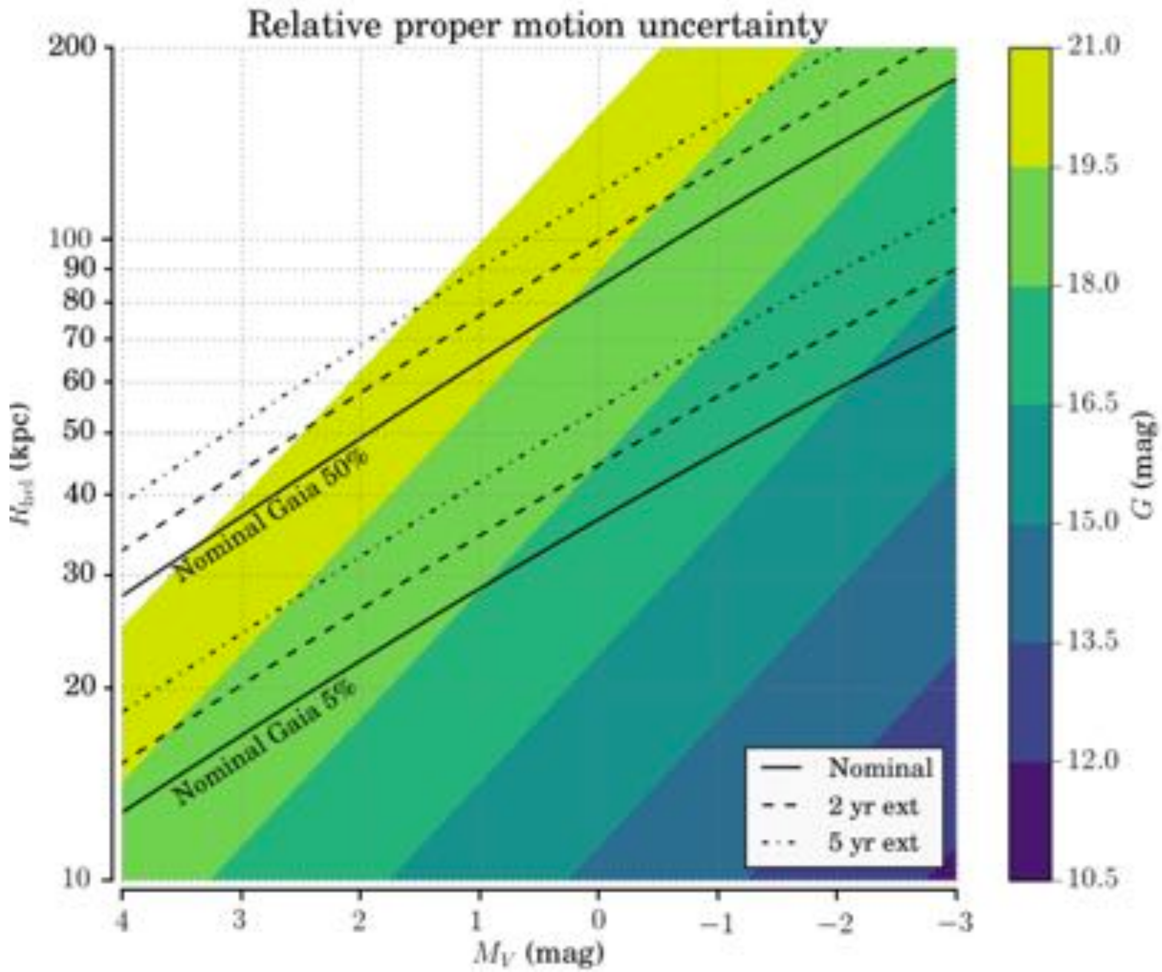
- Factor ~ 8 more clusters
- Reach inner and Perseus spiral arms
- Reach larger diversity of environments and cluster types
- Probe low stellar masses at larger distances



A. Brown

Improvement for MW and stellar populations

- Larger volume reached throughout the halo at given proper motion accuracy
- Tidal streams detection improvement
- Probe young and unmixed debris located beyond 20–30 kpc
- Calibration of photometric distance indicators on nearby samples ⇒ full gain in tangential motion performance



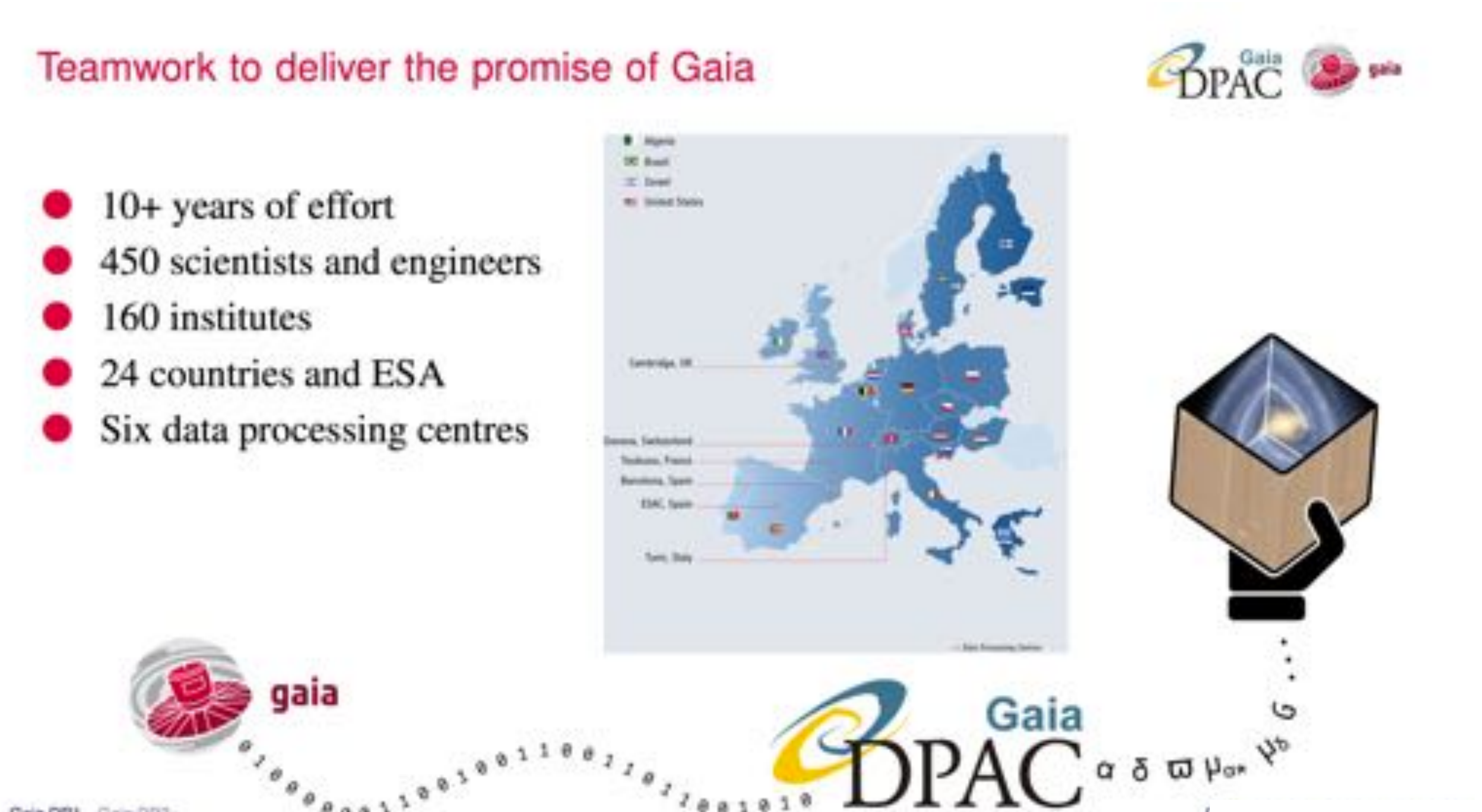
A. Brown

What can be expected from Gaia DR2?

- Will be completely independent of Hipparcos/Tycho-2
- Based on a longer stretch of data (22 versus 14 months)
- Improved attitude and instrument models will reduce the modelling errors and hence both random and systematic errors in results
- Parallax accuracies of about 50 µas can be reached for sources down to G ~ 15 mag, larger errors for fainter sources
- Proper motions of about 100 µas yr^{-1} (comparable to the Hipparcos subset of TGAS) down to G ~ 15 mag
- This will be obtained for many tens of millions of sources
- Improved and more photometry (G, BP, RP) will enhance the scientific usefulness enormously
- Gaia DR1 is a good training set to get prepared for the real thing!

L. Lindegren

Teamwork



A. Brown

Gaia Sky Flight
APOD: Here comes the Sun

Stamps to be published by German Post on December 7, 2017

Publication on December 7, 2017

Publication on December 7, 2017

54. Serie „Astrophysik"
„GAIA-Satellit"

55. Serie „Astrophysik"
„Gravitationswellen"

Publication on December 7, 2017

End of talk

- During this talk about 700,000 stars were measured by Gaia
- About 7 million astrometric measurements,
- 200,000 stellar spectra of 70,000 stars