Extragalactic Distance Scale lect. IV

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Trigonometric Parallaxes

Diurnal parallax

Geocentric Parallax

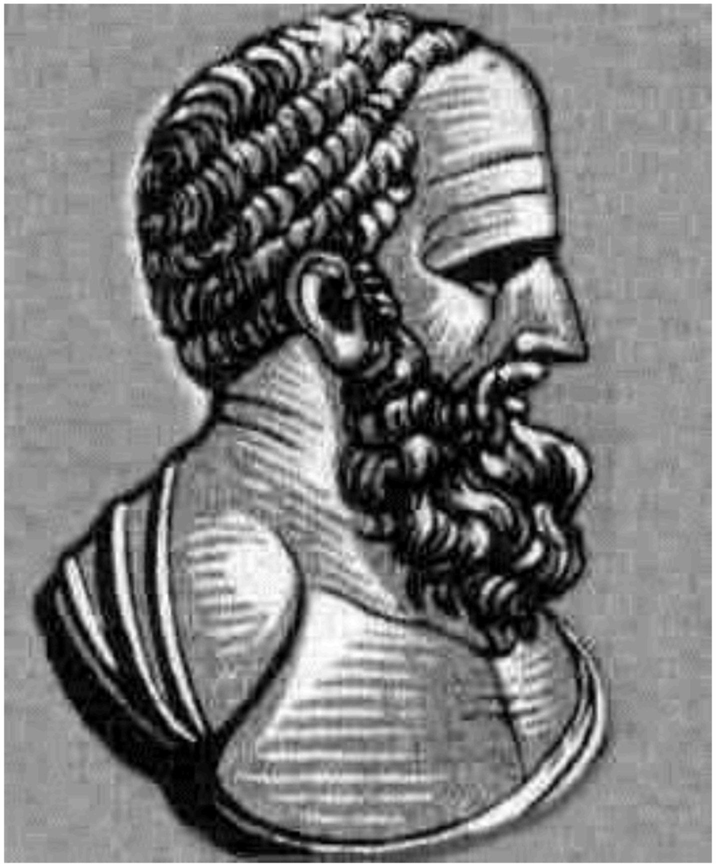
AU determinations

Historical parallax determinations

Hipparcos

Gaia mission

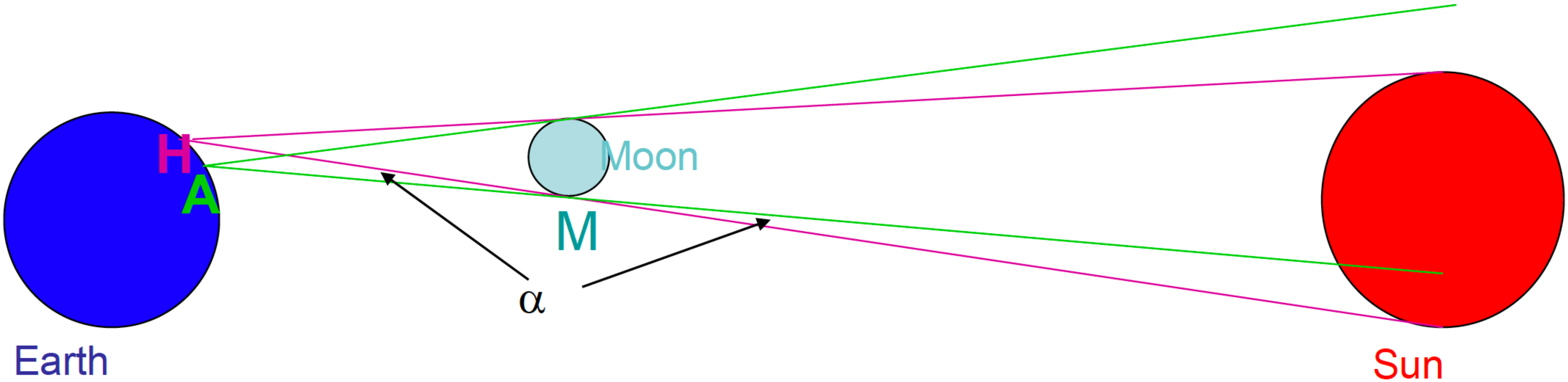
How high the Moon?

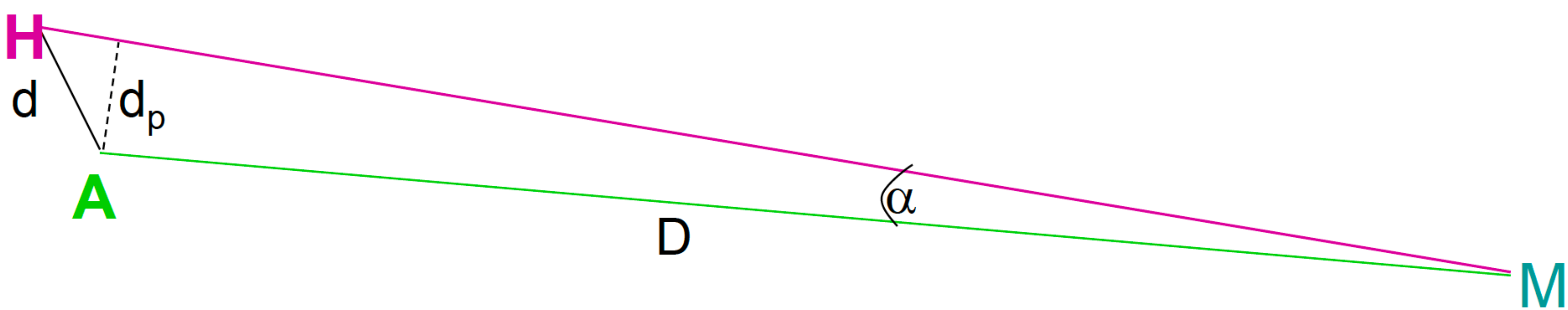


Hipparchus
(189 BC)

Total eclipse in Syene
Partial in Alexandria

How high the Moon?

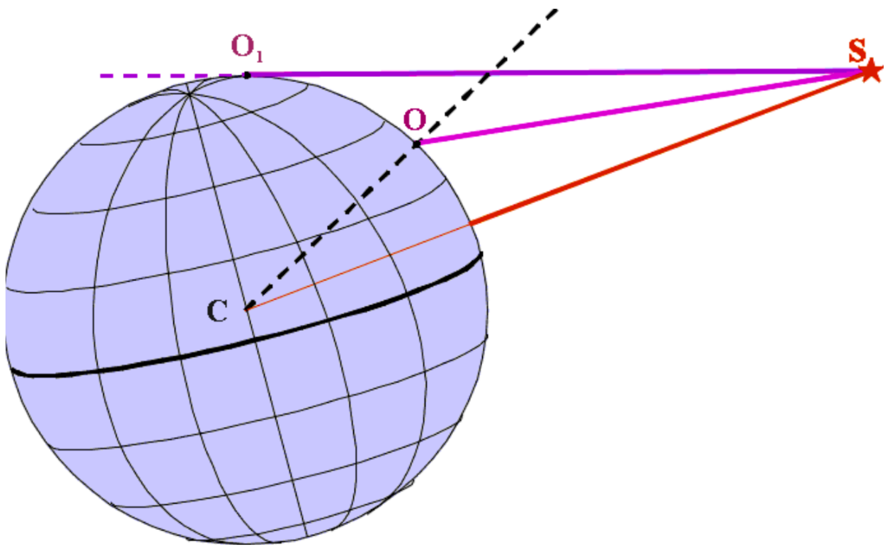




$$D = d_p / \alpha$$

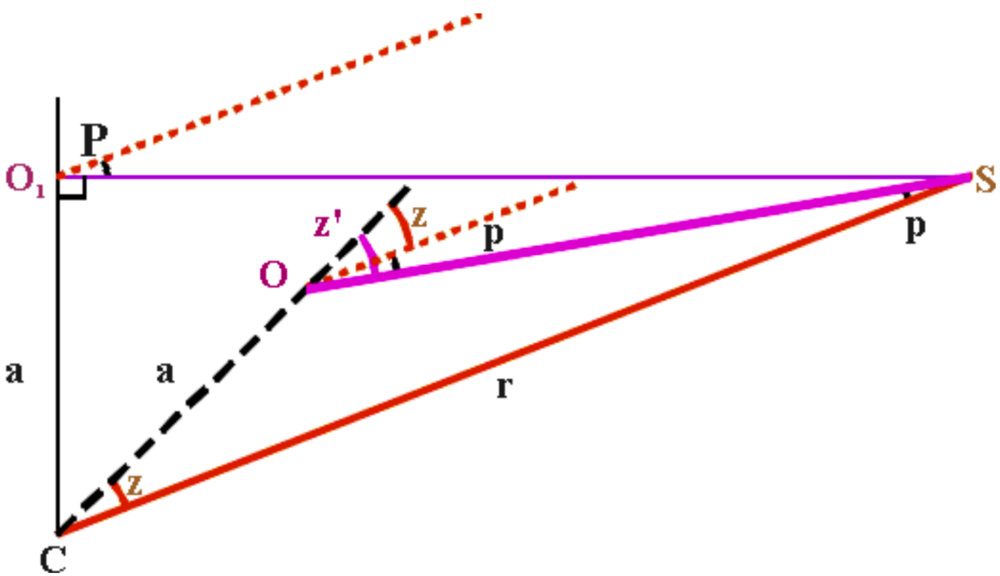
D(Moon) = 700 km / (0.1/57) = 400,000 km

True value is 384,000 km



Refraction affects the apparent altitude of a star.
But there are other phenomena that affect its apparent position, too. One of these is parallax. Refraction decreases the zenith angle, but parallax increases it.

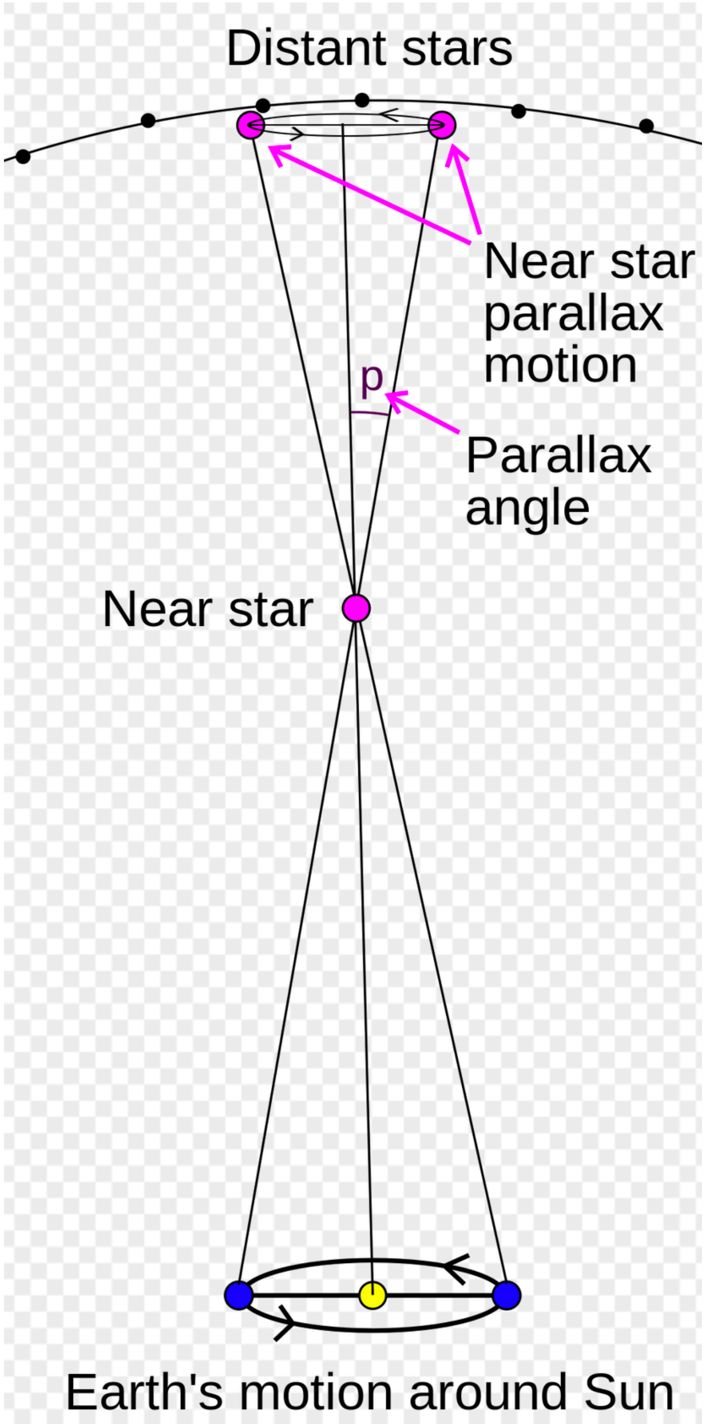
Our observations are made from the surface of the Earth, not its centre. This is irrelevant when observing distant objects such as stars. But for closer objects (*e.g.* within the Solar System), a correction must be made. This is **geocentric parallax**, or **diurnal** (daily) parallax (since it varies daily as the Earth spins around its axis)



To an observer at O, the zenith angle of object S appears to be z'. Its true zenith angle, as seen from the centre of the Earth C, is z, which is smaller.
Parallax is greatest for an observer at O_1,
where the object appears to be on the horizon.
We define the **angle of parallax** p by **p = z'-z**.

$\sin(p) = \sin(P) \sin(z')$

Agency	Description	Value (in meters)	Ref
IAU	nominal "zero tide" equatorial	6 378 100	[1]
IAU	nominal "zero tide" polar	6 356 800	[1]
IUGG	equatorial radius	6 378 137	[2]
IUGG	semiminor axis (b)	6 356 752.3141	[2]
IUGG	polar radius of curvature (c)	6 399 593.6259	[2]
IUGG	mean radius (R_1)	6 371 008.7714	[2]
IUGG	radius of sphere of same surface (R_2)	6 371 007.1810	[2]
IUGG	radius of sphere of same volume (R_3)	6 371 000.7900	[2]
IERS	WGS-84 ellipsoid, semi-major axis (a)	6 378 137.0	[6]
IERS	WGS-84 ellipsoid, semi-minor axis (b)	6 356 752.3142	[6]
IERS	WGS-84 first eccentricity squared (e^2)	0.006 694 379 990 14	[6]
IERS	WGS-84 ellipsoid, polar radius of curvature (c)	6 399 593.6258	[6]
IERS	WGS-84 ellipsoid, Mean radius of semi-axes (R_1)	6 371 008.7714	[6]
IERS	WGS-84 ellipsoid, Radius of Sphere of Equal Area (R_2)	6 371 007.1809	[6]
IERS	WGS-84 ellipsoid, Radius of Sphere of Equal Volume (R_3)	6 371 000.7900	[6]
	GRS 80 semi-major axis (a)	6 378 137.0	
	GRS 80 semi-minor axis (b)	≈6 356 752.314 140	
	Spherical Earth Approx. of Radius (R_E)	6 366 707.0195	[18]
	meridional radius of curvature at the equator	6 335 439	
	Maximum (the summit of Chimborazo)	6 384 400	[9]
	Minimum (the floor of the Arctic Ocean)	6 352 800	[9]
	Average distance from center to surface	6 371 230 ±10	[15]



Distance to the Sun was not intereting form a long time (just another distance) and the result from Arostarchus (too small by a factor of 20) was uncritically adopted.

Things changed completely with heliocentric system by Copernicus.

Why Tycho Brahe did not believe in the heliocentric model ?

Celestial Yardsticks: Measuring the Distance to the Sun

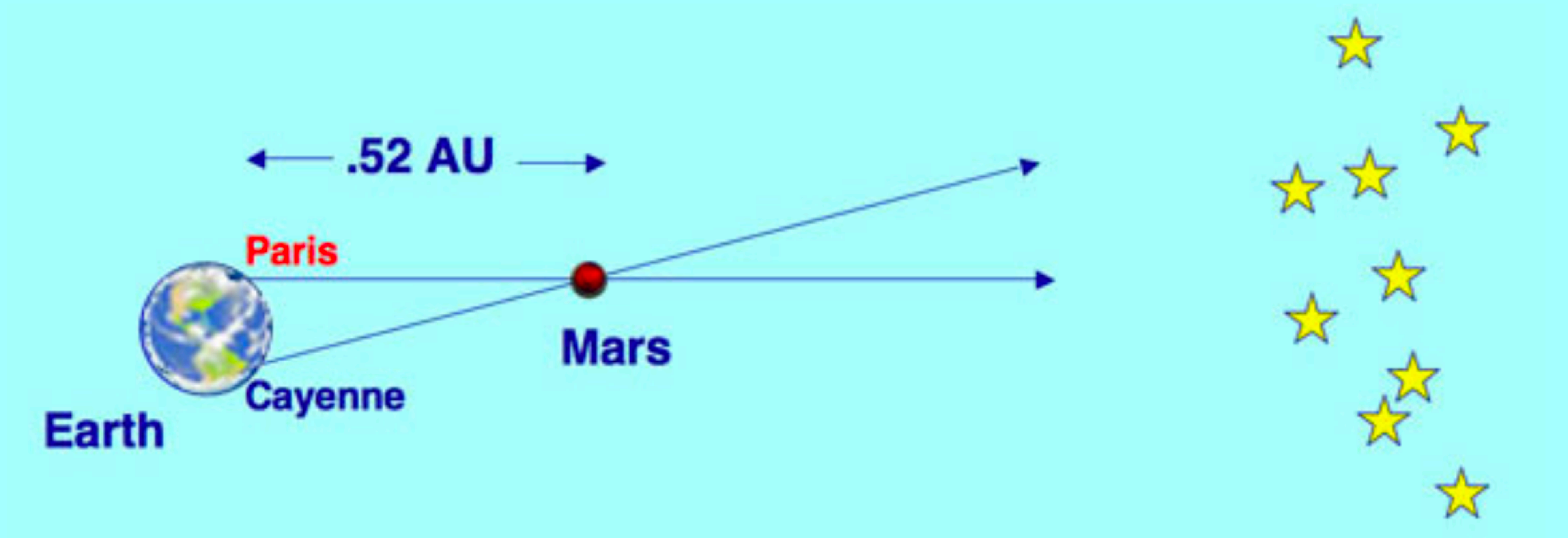
Distance to the Sun = 1 Astronomical Unit (AU)
Distance to the Moon = 60 Earth Radii (ER)

When	Who	How	1 AU =
3rd c BCE	Aristarchos	geometry	1,200 ER
2nd c CE	Ptolemy	" "	1,160 ER
1540	Copernicus	" "	1,142 ER
1600	Tycho	picked value halfway between Copernicus and Ptolemy	1,150 ER
1620	Kepler	chose value	1,800 ER
1672	Richer & Cassini	measured parallax of Mars	21,000 ER, or 140 million km
1761/1769		Transit of Venus	~124-154 million km
1771	Lalande	Transit of Venus	~153 million km
1874/1882		Transit of Venus	~149.1 million km
1877	Gill	parallax of Mars	~149.7 million km
1891	Newcomb	Transit of Venus	~149.6 million km

Triangulating the Distance to Mars

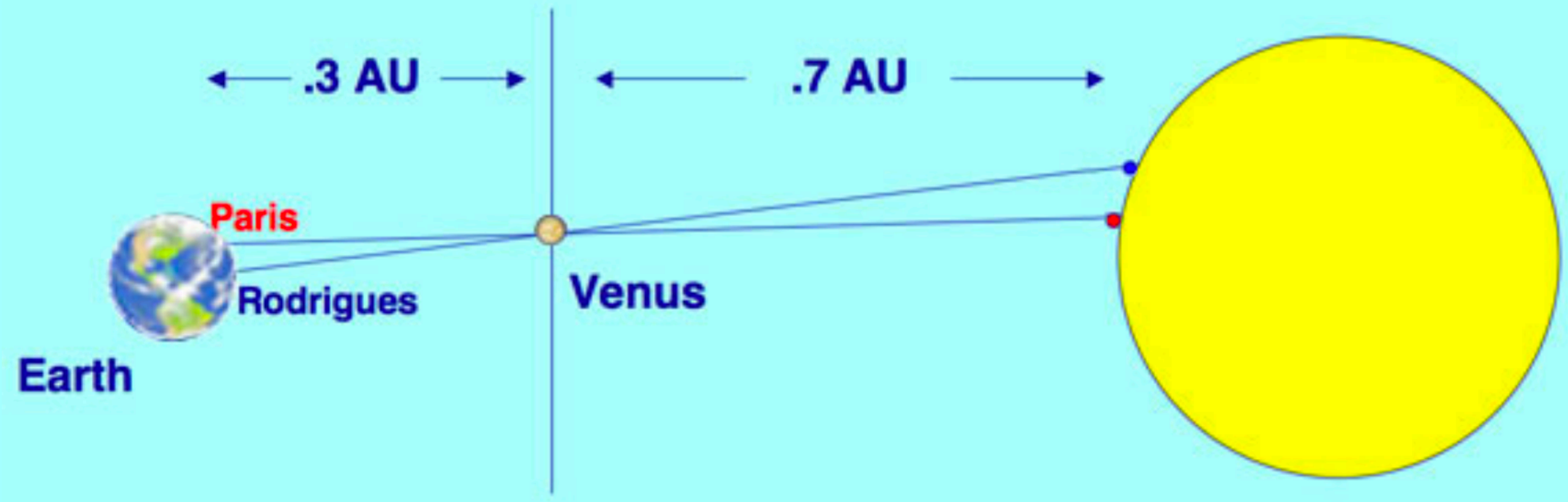
By the seventeeth century, improved instruments made it possible for astronomers to detect and measure very small differences in the positions of celestial bodies.

In 1672, when Mars was in opposition, **Giovanni Domenico Cassini (1625-1712)** and **Jean Richer (1630?-1696)** calculated a value for the distance to the Sun based on their observations of Mars from Paris and Cayenne in French Guiana.

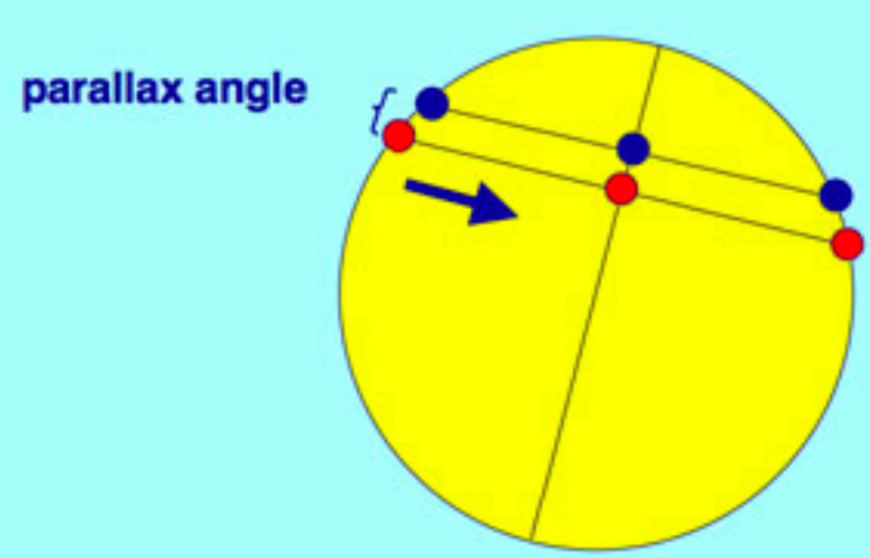


Triangulating the Distance to Venus

Edmond Halley (1656?-1743) didn't trust the accuracy of the results from the Mars observations. He suggested using a transit of the Sun by Venus as a superior method of determining the Earth's distance to the Sun.



In 1761, twenty years after Halley's death, groups of observers viewed a transit of Venus from widely separated locations (Paris and the island of Rodrigues, near Madagascar). Because of their very different vantage points, the two groups saw Venus appear to move across the Sun along different paths. The angular separation of these two paths gave astronomers a measure they could use to calculate the value of the astronomical unit.



Modern measurements

Direct radar measurements of the distances to Venus and Mars became available in the early 1960s

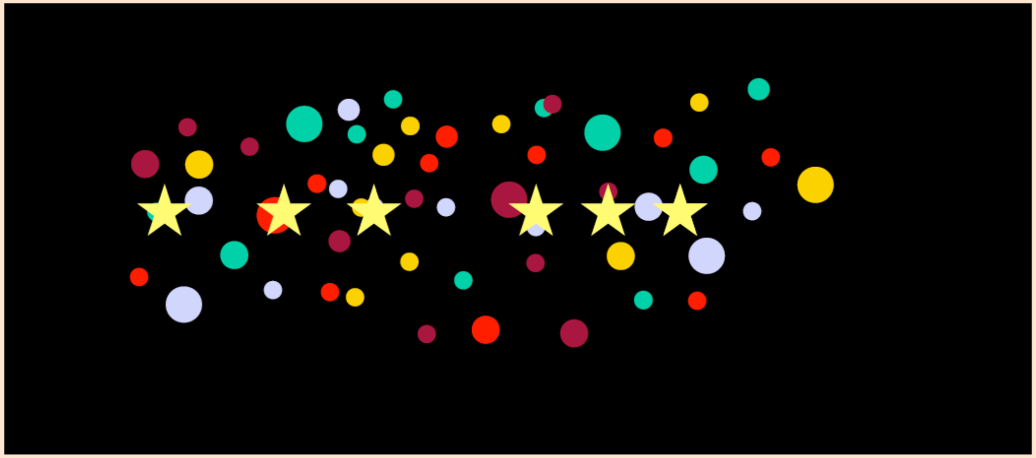
Telemetry (au)

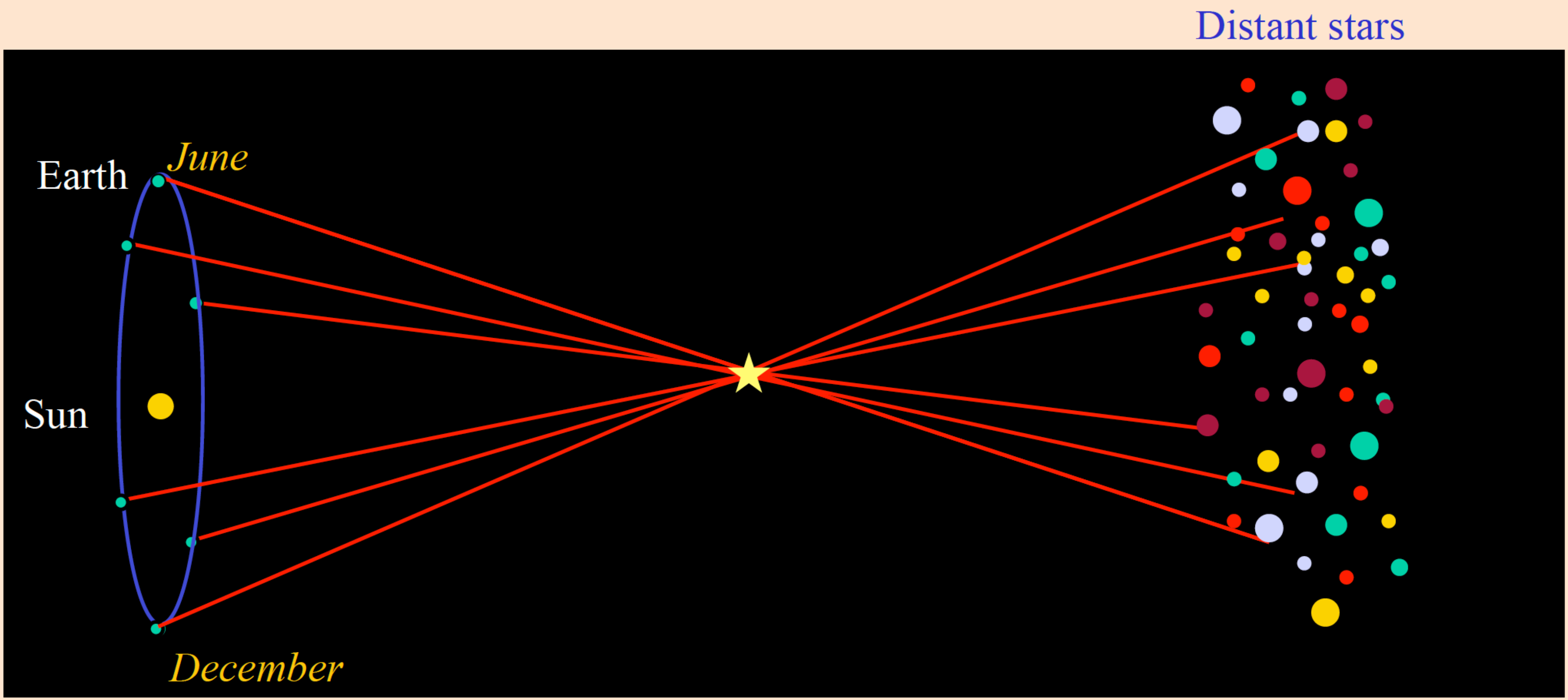
2009 $\pm$ 3 m

2012 - 149597870700 m

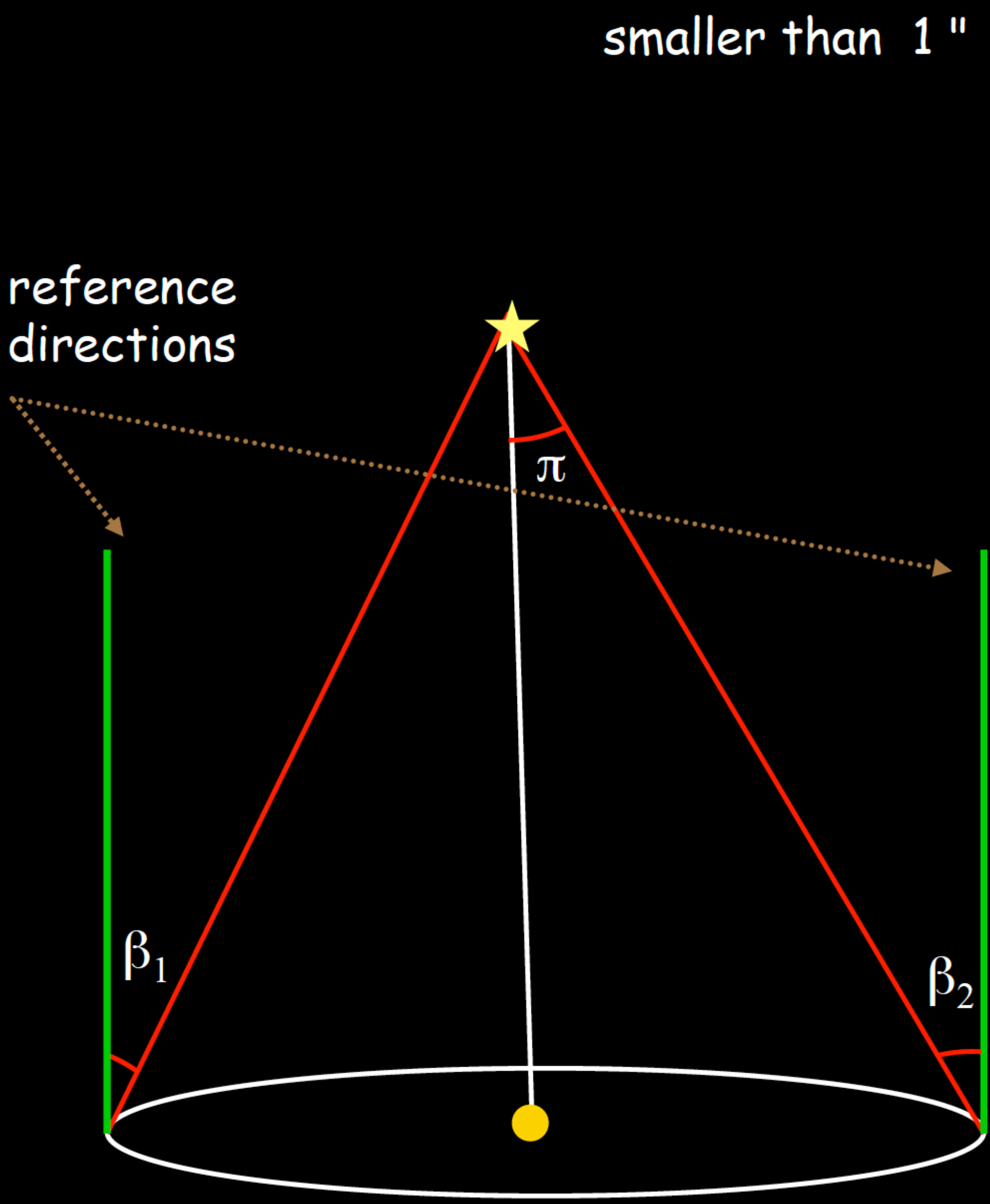
metric (SI) units	$1.495\,978\,707 \times 10^{11}$ m
imperial & US units	9.2956×10^{7} mi
astronomical units	4.8481×10^{-6} pc
	1.5813×10^{-5} ly

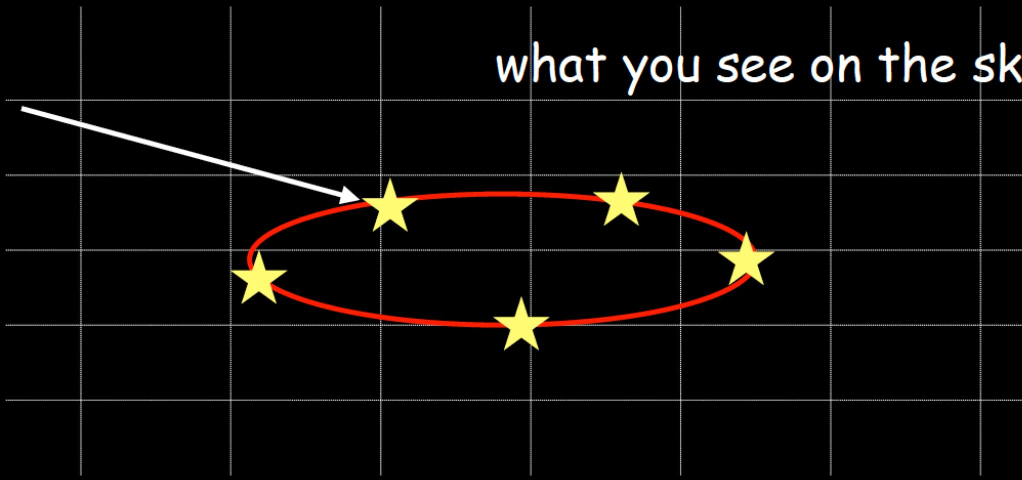
Stellar Parallax





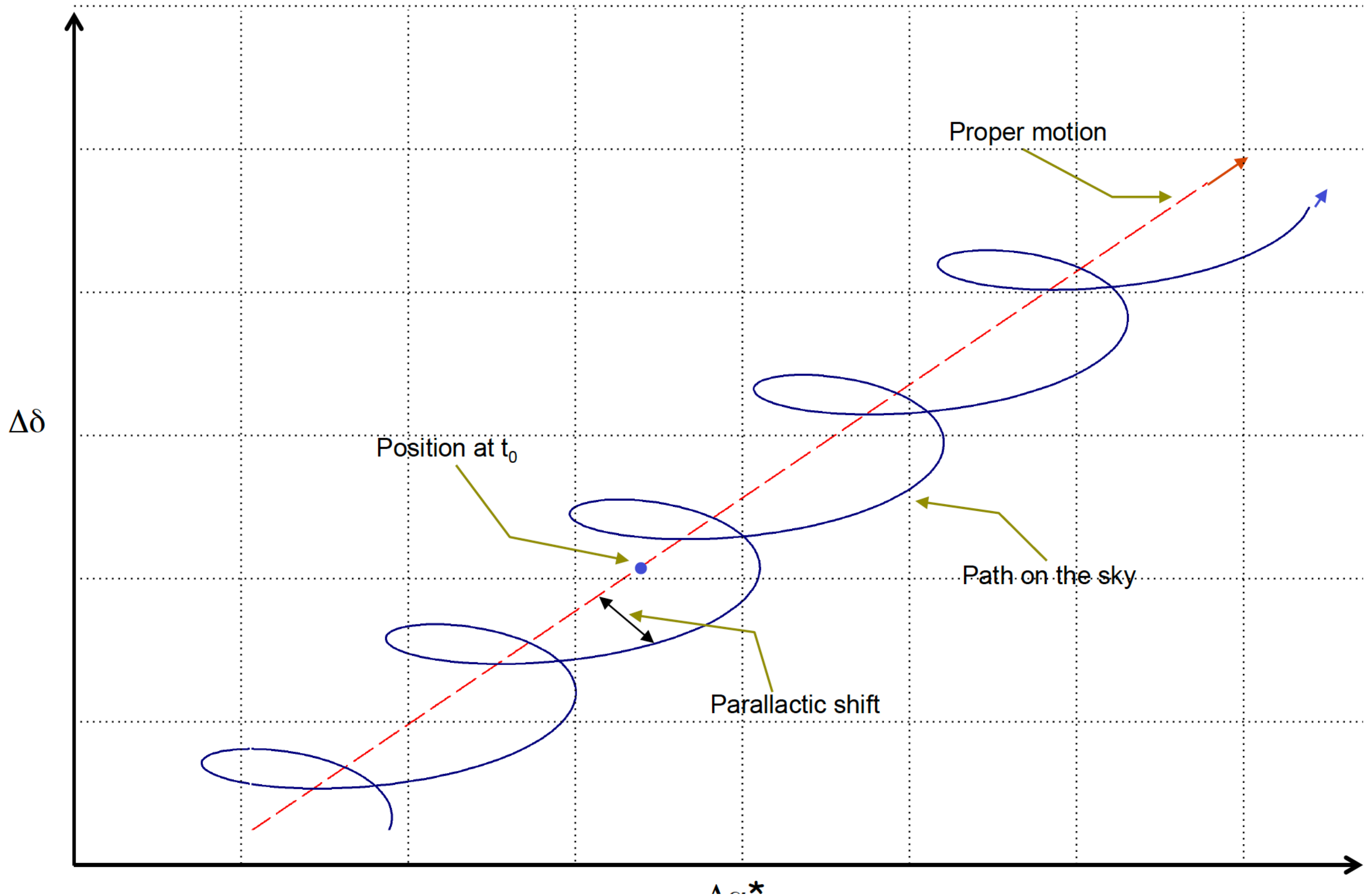
Parallactic effect





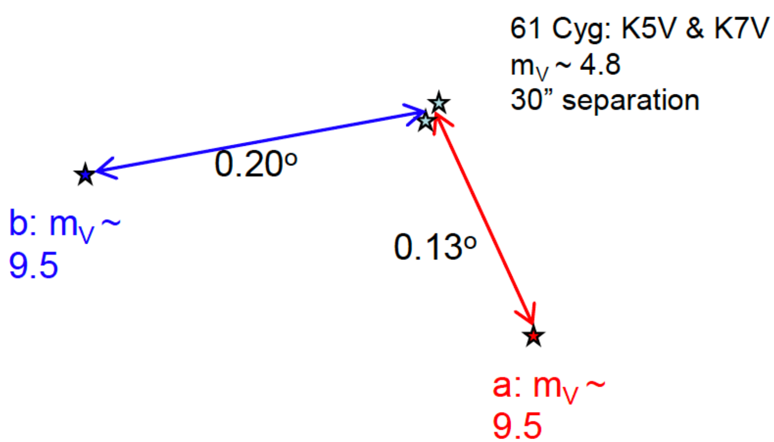
$$\pi = \frac{\beta_1 + \beta_2}{2}$$

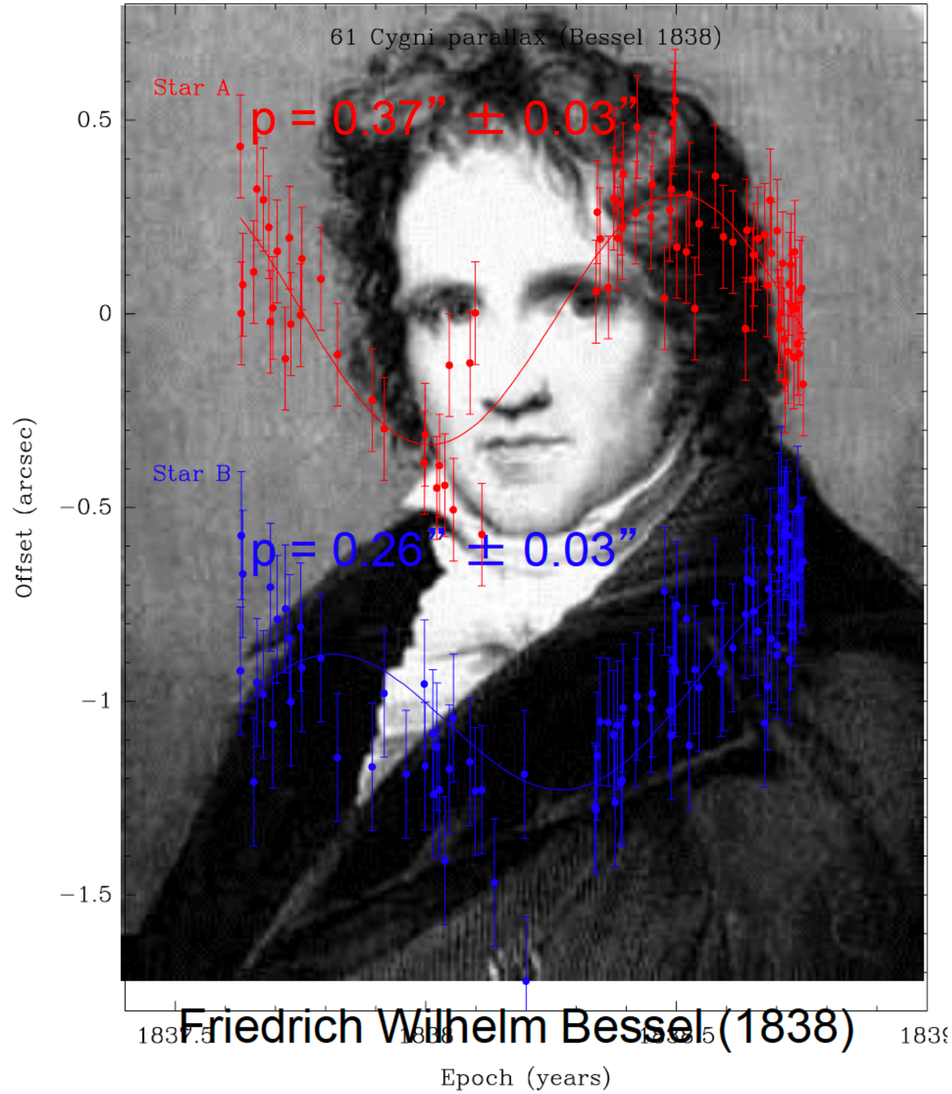
Apparent motion of a single star



Parallax: The Race to Measure the Cosmos

- Friedrich Wilhelm Bessel in 1838 using Fraunhofer's last telescope measured stellar parallax: 61 Cygni





Friedrich Wilhelm Bessel (1838)

- p = 0.314"   (p = 0.287")

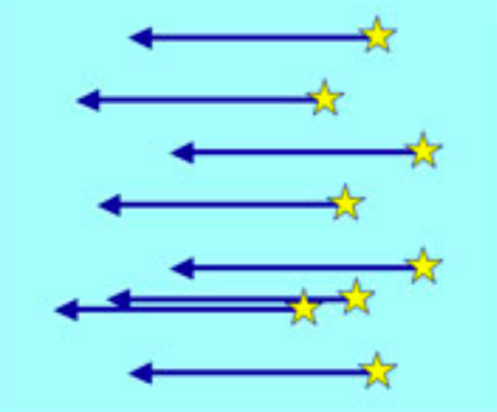
Published in MNRAS, communicated by John Herschel (William Herschel's son)

Statistical parallaxes ~ 500pc

By 1900, Dutch astronomer **Jacobus Kapteyn (1851-1922)** perfected a method of measuring the distance to stars that involved the collective motion of nearby clusters of stars -- groups of 100-200 stars that appear to be physically associated.

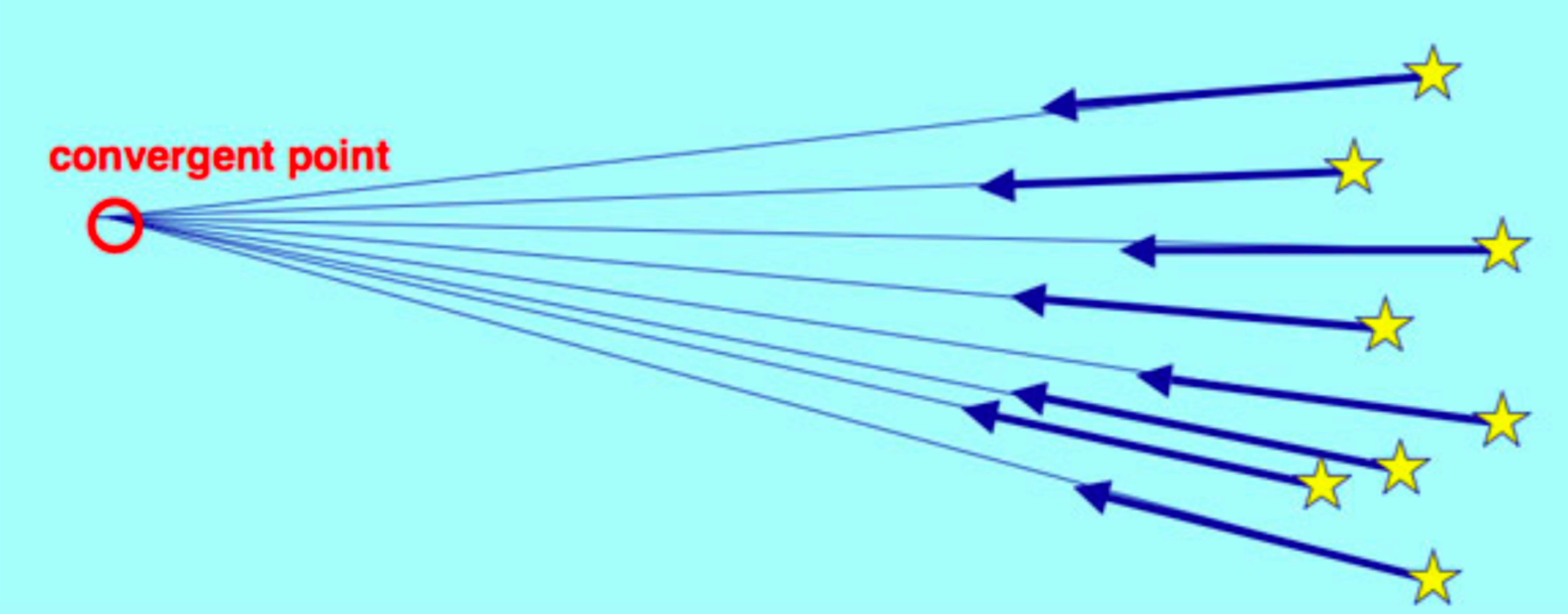
cluster	# of stars	distance
Ursa Major group	60	20 pc
Hyades (Taurus)	200	45 pc
M45 (Pleiades, Taurus)	600	125 pc
M44 (Beehive, Cancer)	50	160 pc
M7 (Scorpio)	80	240 pc

The stars in the nearby Hyades cluster move together as a group in space along roughly parallel paths.



Because of our vantage point, we see the Hyades stars appear to move toward a point of convergence. Identifying that point gives astronomers enough information to translate each star's apparent motion into a real space velocity.

The distance to a star in the cluster can be deduced by comparing its actual speed with how fast it appears to be moving towards the convergent point.



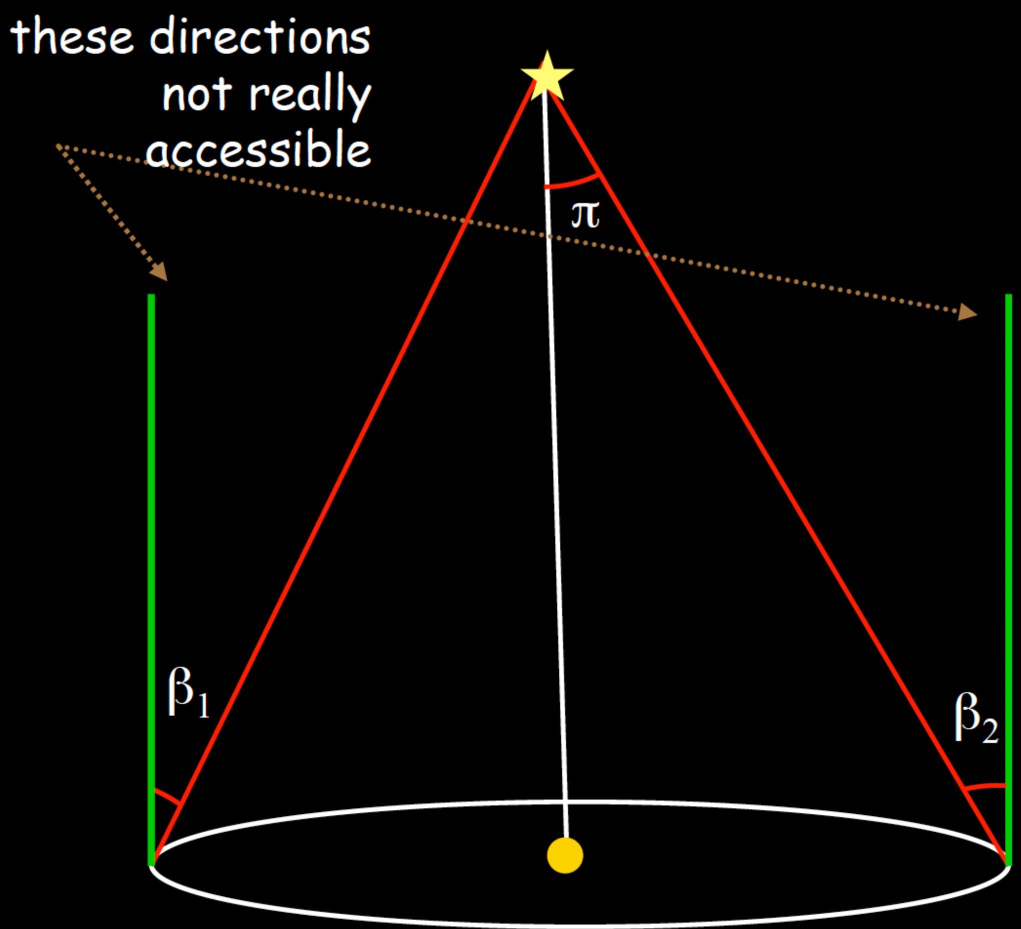
Stellar distances : 1850 -1980

- 1840 3 published distances
- 1850 20 "
- 1890 40 "
- 1910 100 "
- 1925 2000 " *photographic plates*
- 1965 7000 "
- 1980 10000 "
  - Relatively nearby stars
  - Arduous work, low yielding
  - large systematic errors
  - Very small sample compared to stellar surveys

Absolute parallaxes

Absolute positions

No reference to distant stars



$$\pi = \frac{\beta_1 + \beta_2}{2}$$

<u>Methods applied</u> :

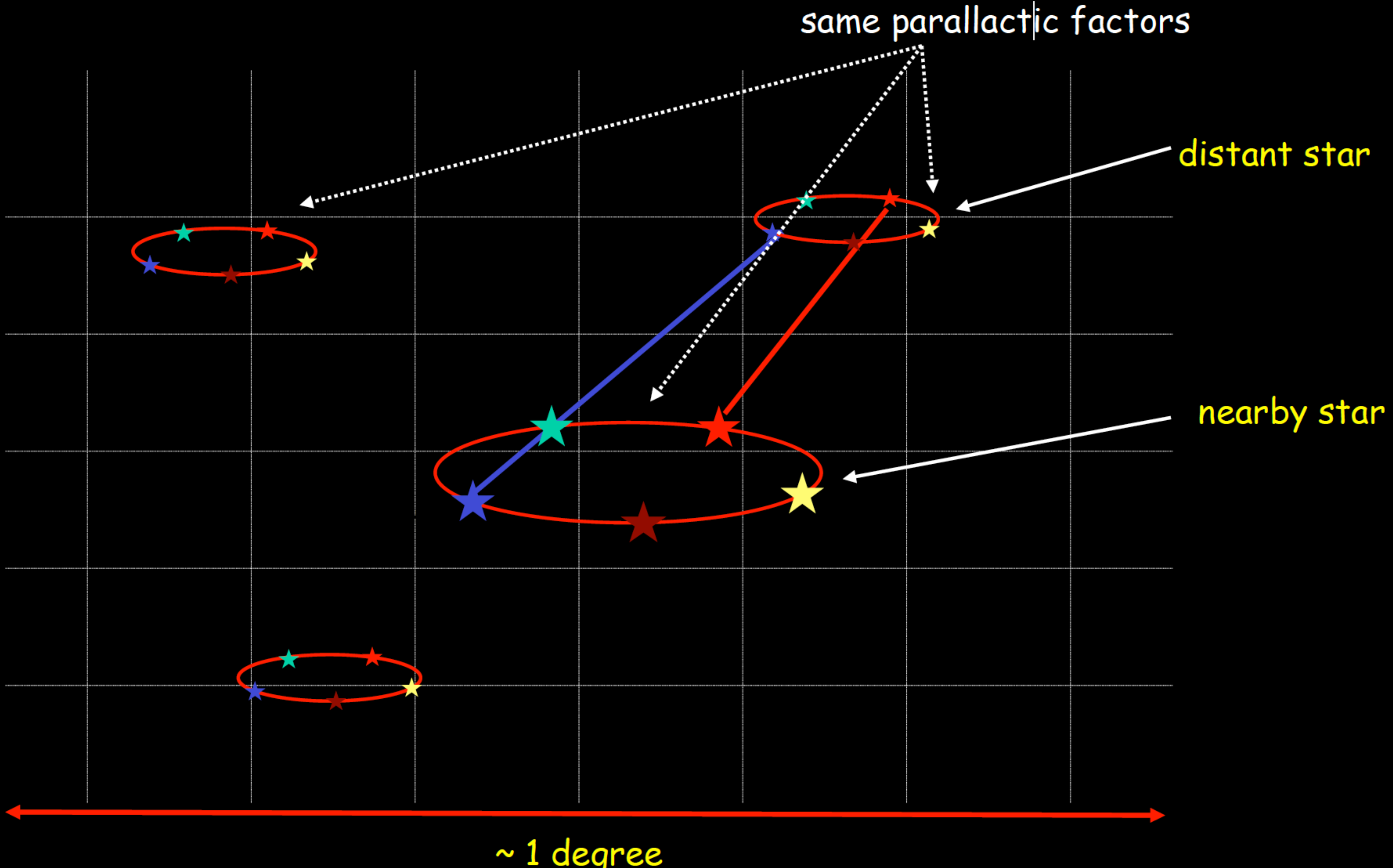
measurements of declinations

zenith distances

wide angle or global astrometry

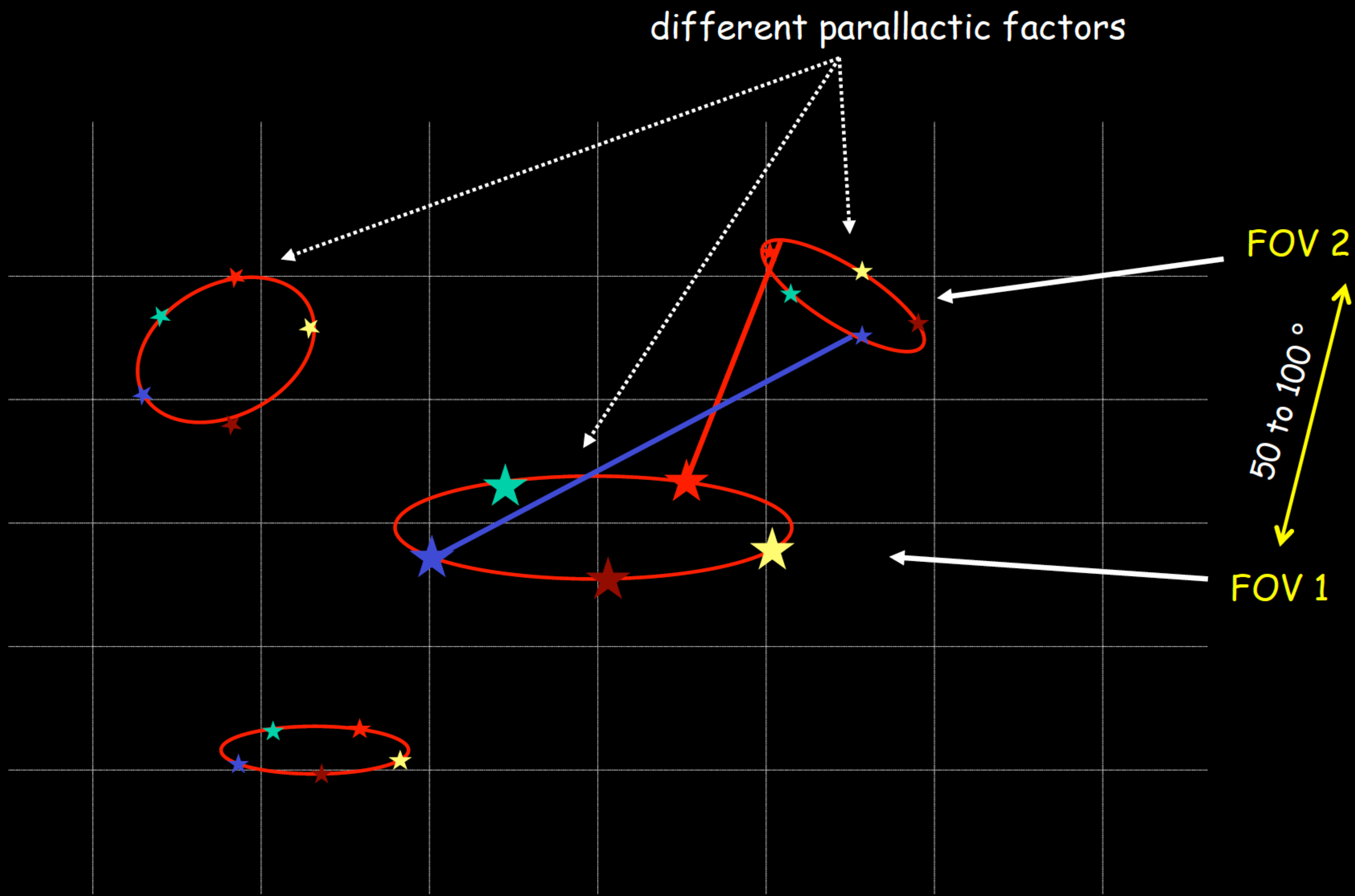
virtually impossible from the Earth to 0"001

Small field astrometry



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

How parallaxes get absolute with Gaia



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

HIPPARCOS

(HIgh Precision PARallax COllecting Satellite)

(Perryman et al 1997 A&A 323 49)

118,000 stellar parallaxes

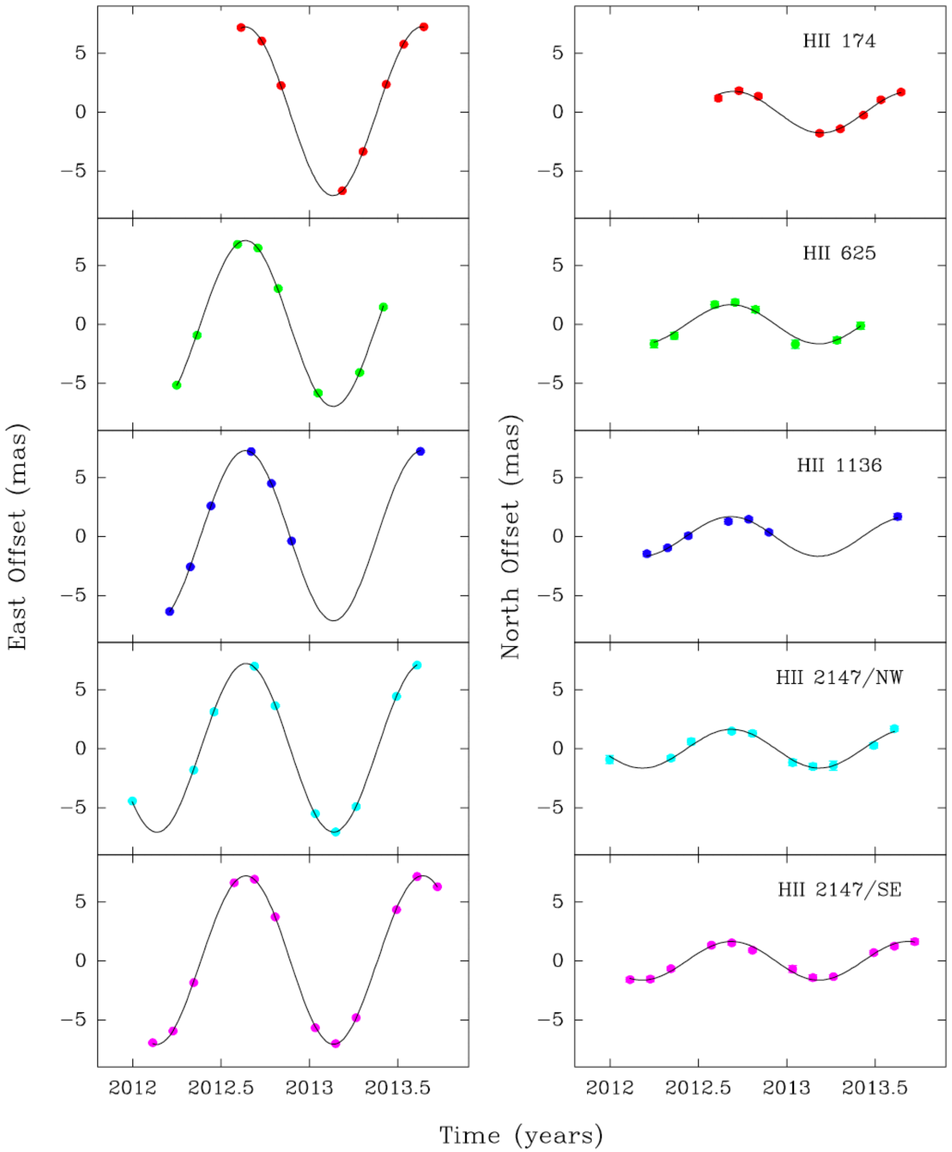
σ_π ~ 0.001 arcseconds (1 mas)

10% accuracy at 100 pc…

mapped solar neighborhood

Gaia hopes to do ~10^9 stars with accuracy ~0.02 mas

Pleiades Distance Problem



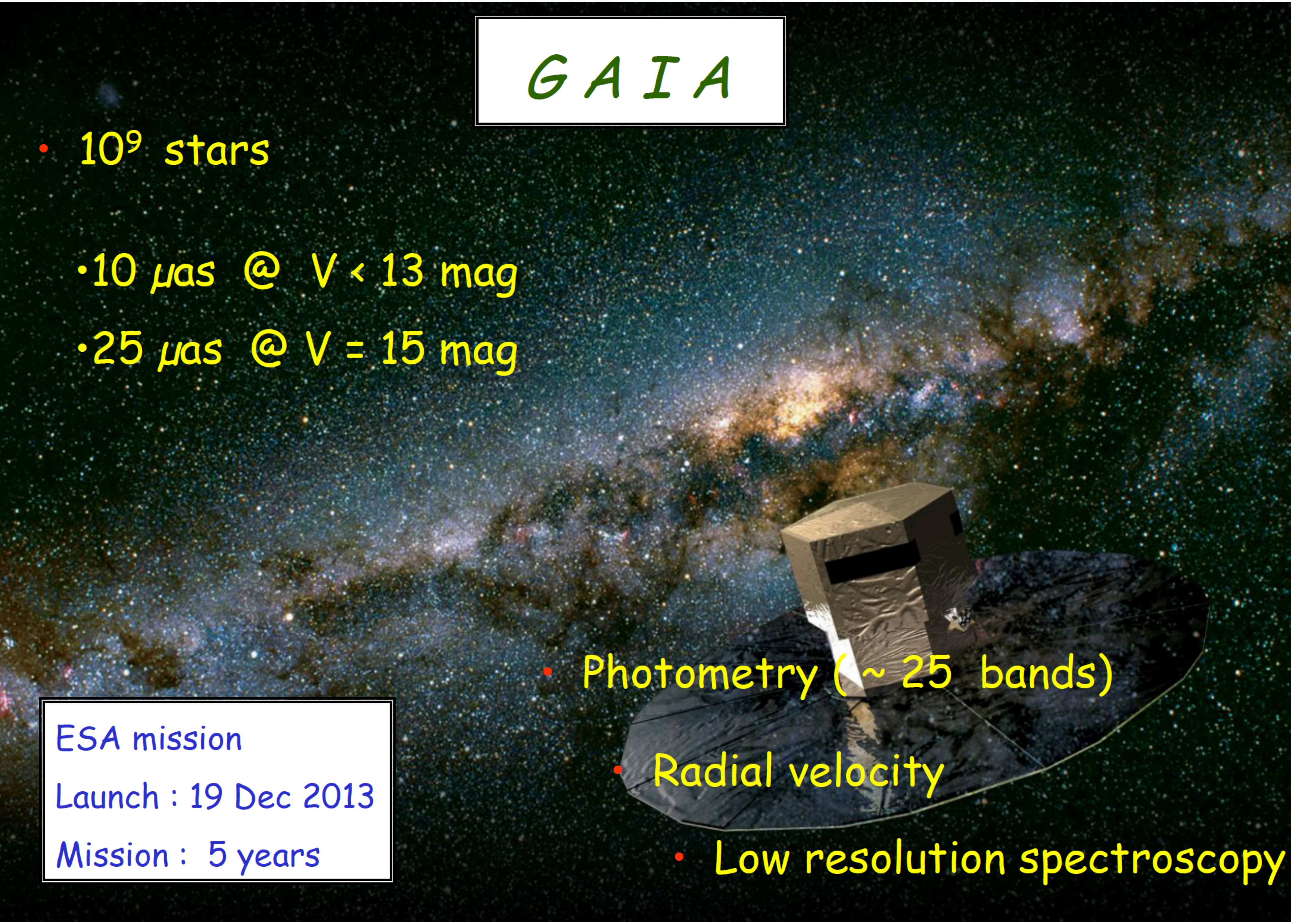
- Hipparcos: D = 120.2 ± 1.5 pc

- Ground based D = 131 → 135 pc
- HST (3 parallaxes): D = 134.6 ± 3.1 pc

- VLBA (4 parallaxes): D = 136.2 ± 1.2 pc

  Melis et al. (2014)

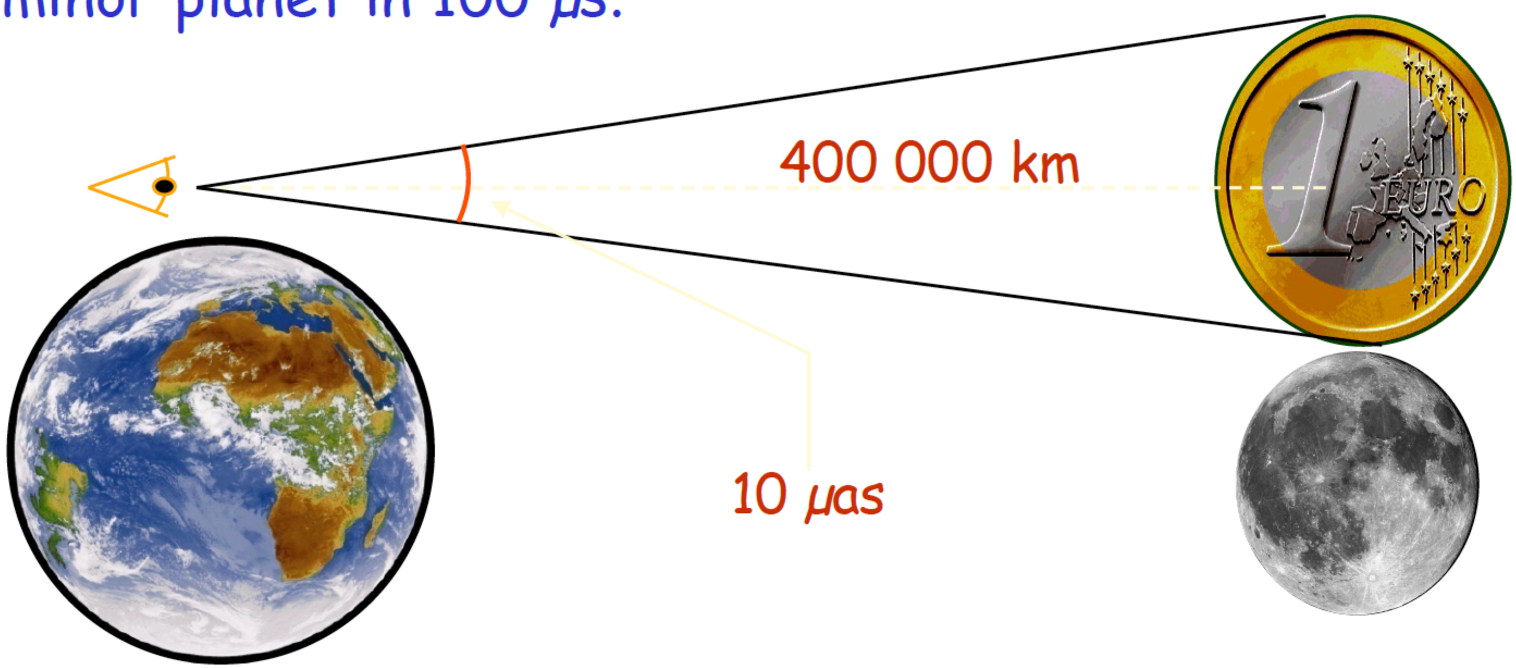
uncertainty dominated by cluster depth (2.3pc), not measurement accuracy


GAIA
• 10^9 stars
• 10 μas @ V < 13 mag
• 25 μas @ V = 15 mag
• Photometry (~ 25 bands)
• Radial velocity
• Low resolution spectroscopy
ESA mission
Launch : 19 Dec 2013
Mission : 5 years

10 μas: Incredibly small !

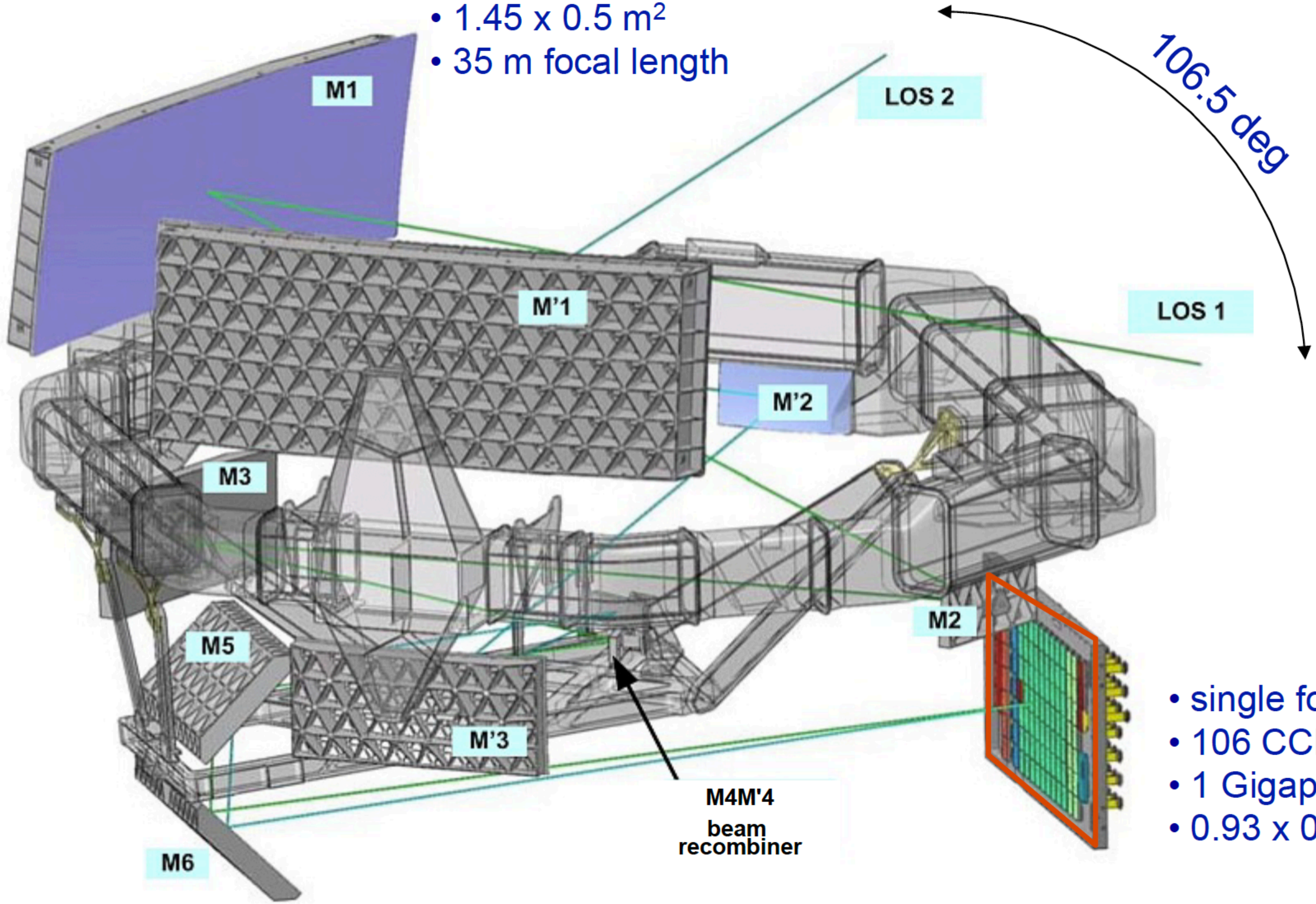
10 μas = 50 prad

- 0.3 mm displacement on the Earth
- edge-on sheet of paper @ 2000 km
- 1 hair @ 1000 km
- displacement of a 100 mas/yr star in one hour
- motion of a fast minor planet in 100 μs.



Gaia : telescopes and detector

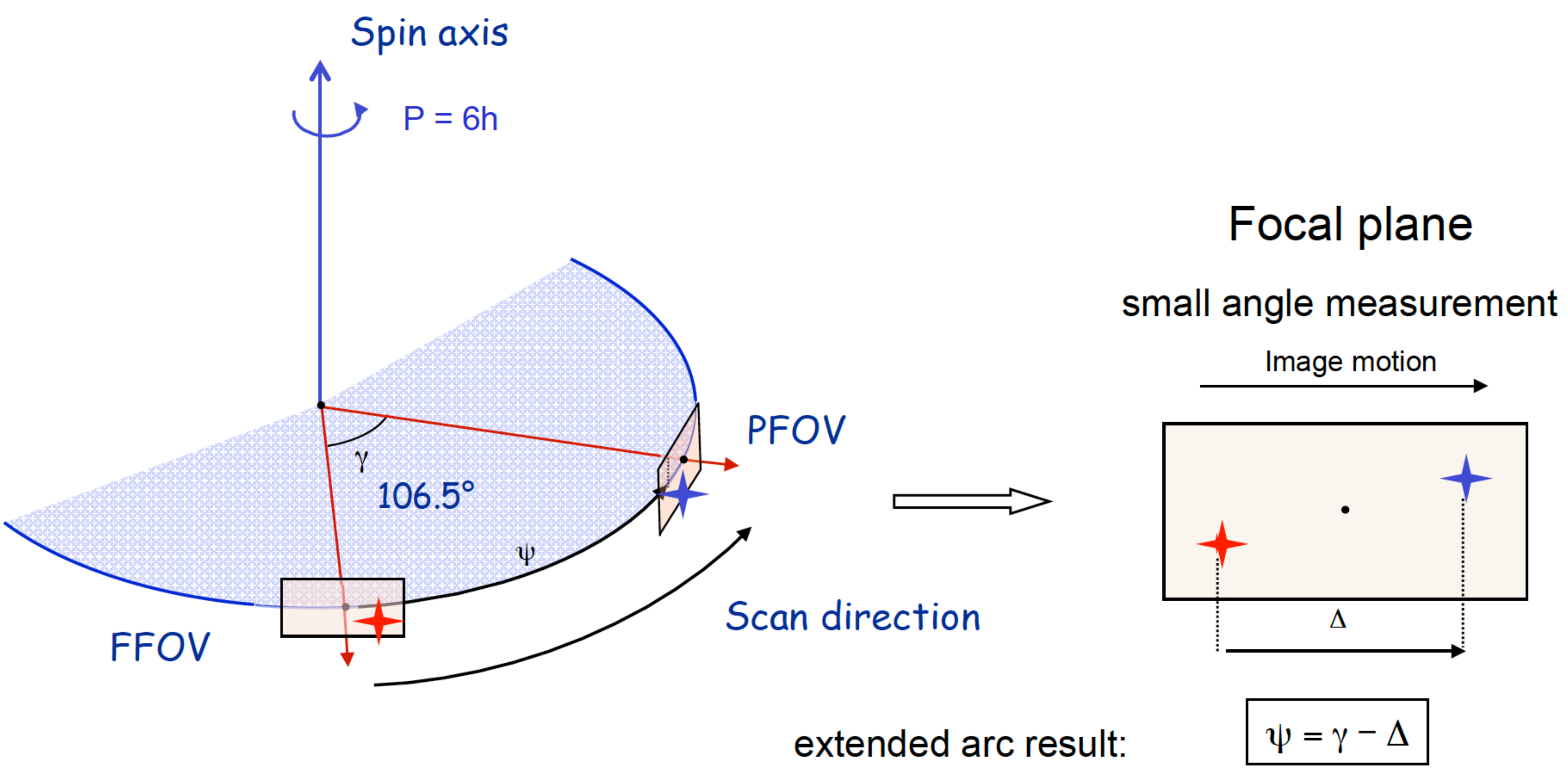
- 2 off-axis telescope
- 1.45 x 0.5 m^2
- 35 m focal length



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

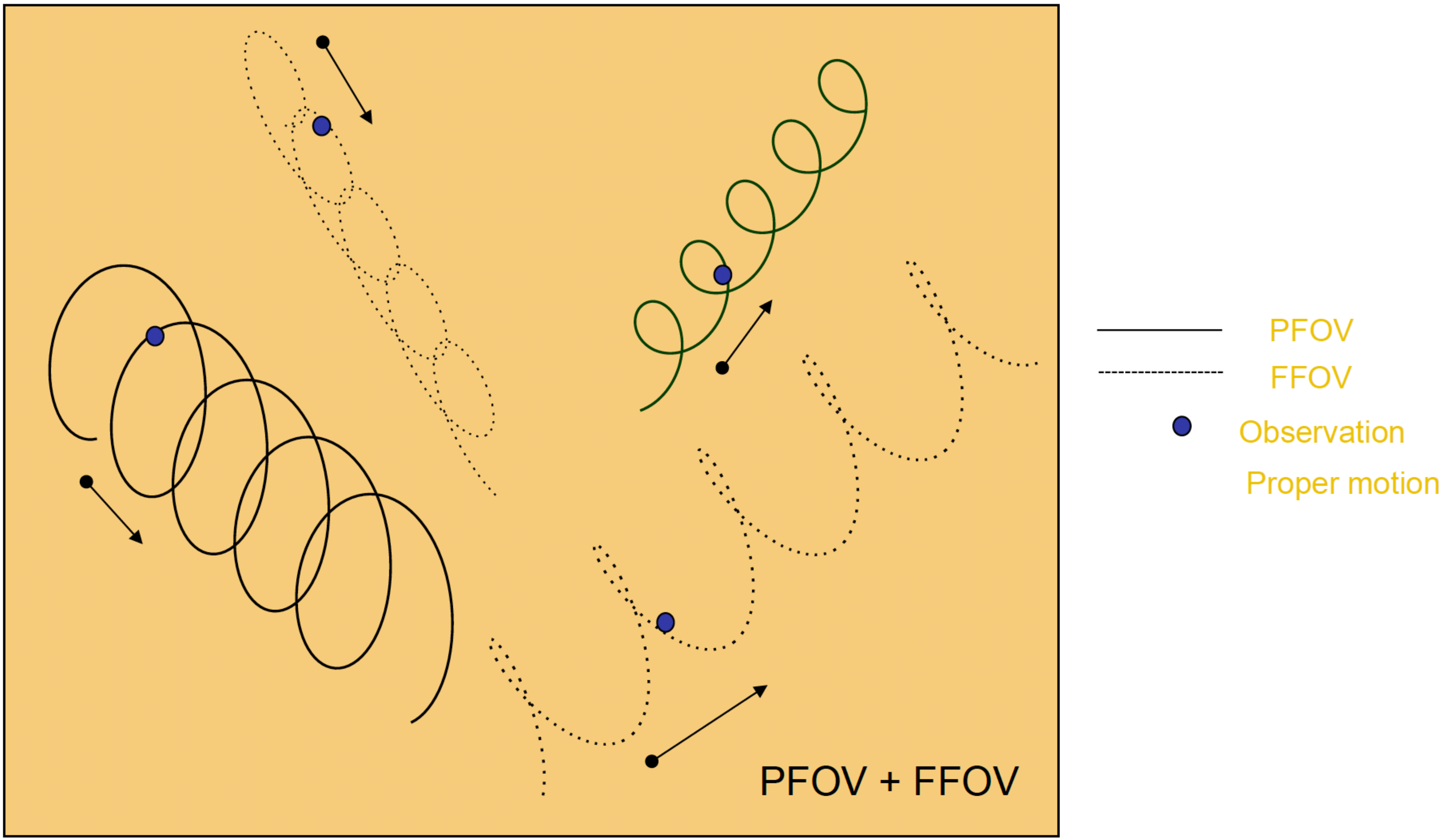
A simplified Gaia

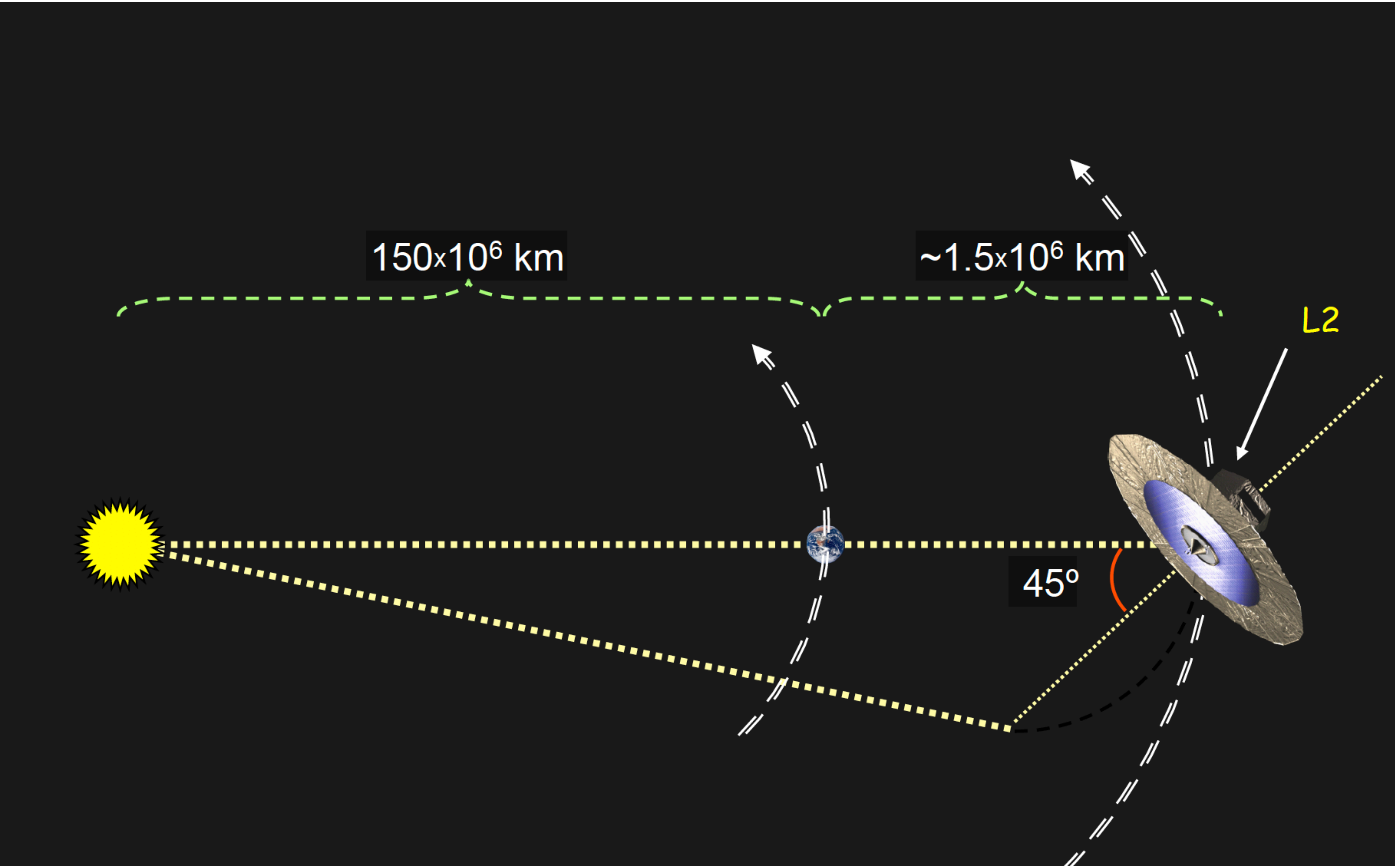
- Wide angle measurements between two FOVs
- One common focal plane where local measurements are done
- A stable angular standard is the heart of the metrology



Combining field of views

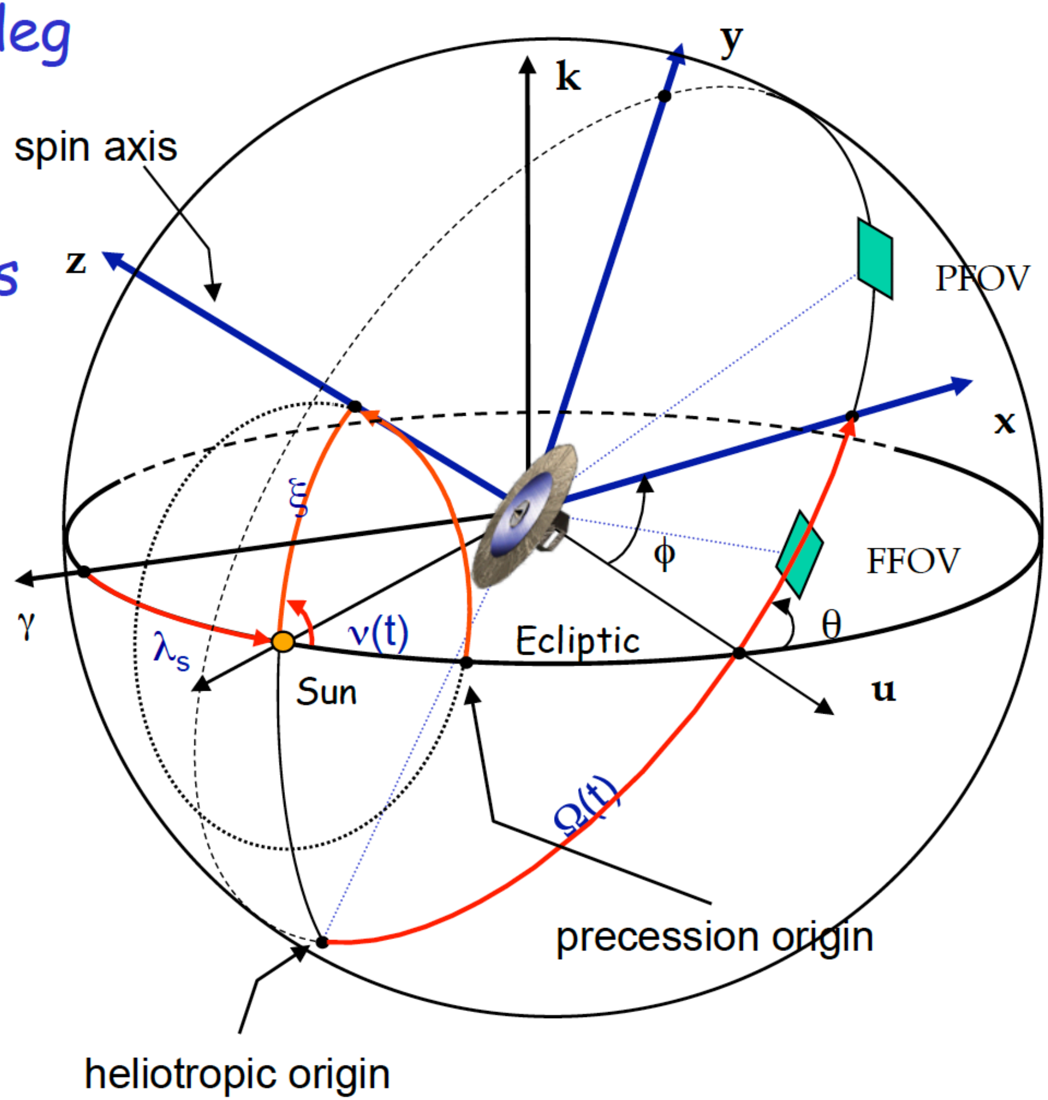
- Two regions of the sky are mapped at a particular time on the focal plane




150x10⁶ km
~1.5x10⁶ km
L2
45º

Gaia Scanning law parametrisation

- Sun aspect angle ξ 45 deg
- Basic angle Γ 106.5 deg
- Spin period $\Omega(t)$ 6h
- Precession period $\nu(t)$ 63 days
- Solar motion $\lambda(t)$ 1 yr

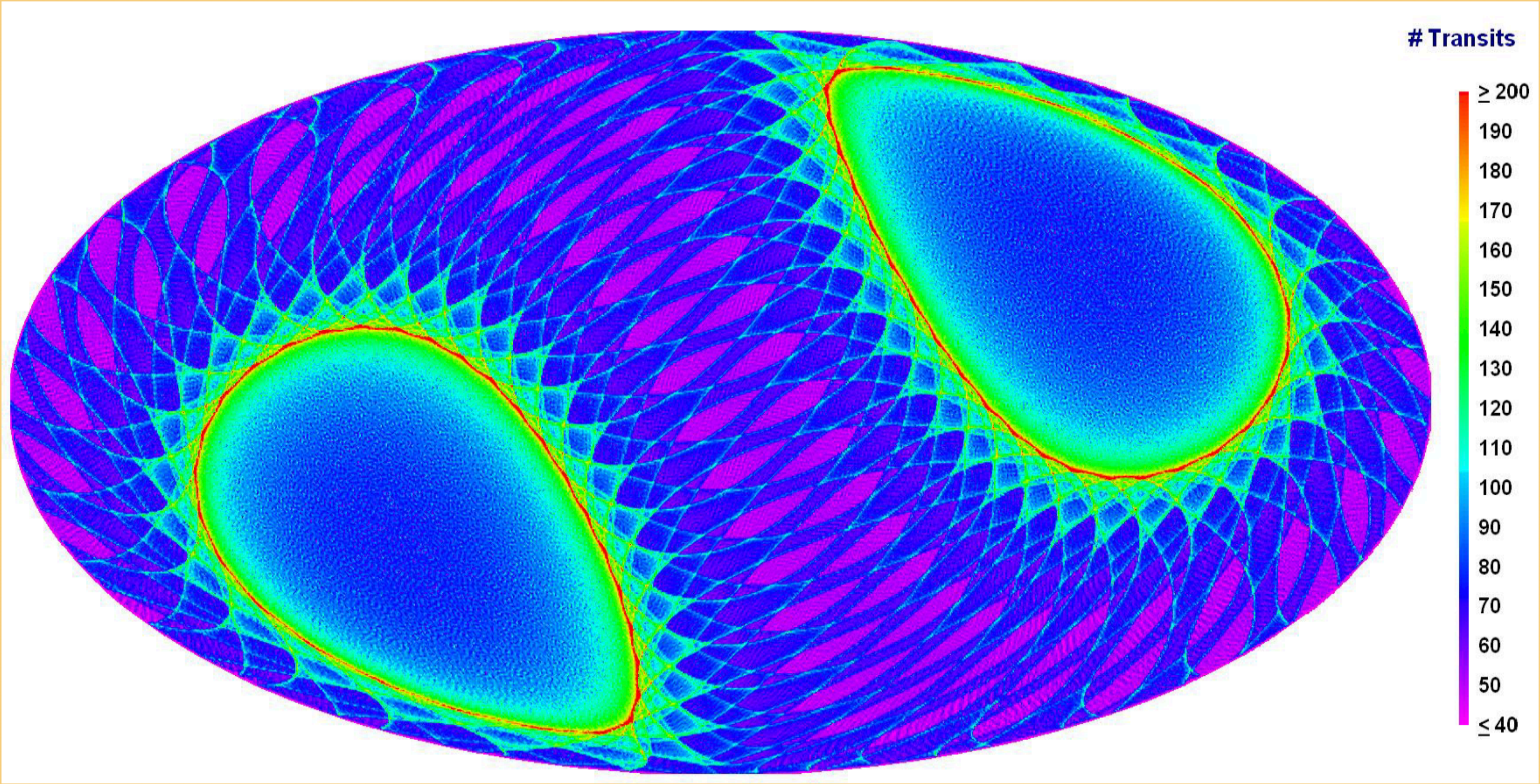


$\Omega(t)$ and $\nu(t)$

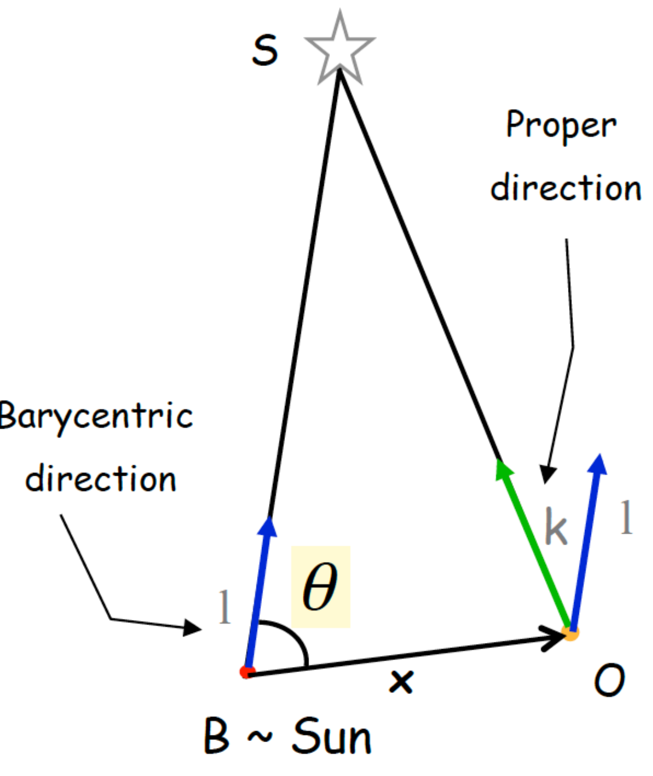
have complex analytical expressions

Scanning & Sky coverage

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



Observed direction vs. Barycentric direction



$$\mathbf{OS} = \mathbf{BS} - \mathbf{BO}$$

$\mathbf{BO} = a\mathbf{x}$ Barycentric position vector of GAIA

$$\mathbf{k} = \frac{\mathbf{OS}}{|\mathbf{OS}|} \qquad \mathbf{l} = \frac{\mathbf{BS}}{|\mathbf{BS}|} \qquad \pi = \frac{a}{|\mathbf{BS}|} \qquad a = 1\,\mathrm{au}$$

$$\mathbf{k} = \mathbf{l} + \pi(\mathbf{x}\times\mathbf{l})\times\mathbf{l} + \frac{\pi^2}{2}[3(\mathbf{x}.\mathbf{l})^2 - \mathbf{x}^2]\,\mathbf{l} + O(\pi^3)$$

$\pi < 1''$ ⟹ $\pi^2 < 5\ \mu as$

$$\mathbf{k} \approx \mathbf{l} + \pi\left[(\mathbf{x}\cdot\mathbf{l})\mathbf{l} - \mathbf{x}\right]$$

~1.01 au

$$|\mathbf{k}-\mathbf{l}| = \pi x \sin(\theta)$$

Parallactic shift: always towards the sun

Gaia DPAC

Gaia measures parallaxes, not distances !

- Basically one has for noiseless measurement

$$d = \frac{1}{\varpi} \quad \Rightarrow d \text{ in kpc with } \varpi \text{ in mas}$$

- But the measured quantity $\bar{\varpi}$ (or fitted parameter):
  - is the realisation of a random variable
  - is just a statistical estimate of an unknown quantity
  - it comes with an uncertainty
- The the best estimate of the distance is not $\bar{d} = \dfrac{1}{\bar{\varpi}}$

Parallaxes

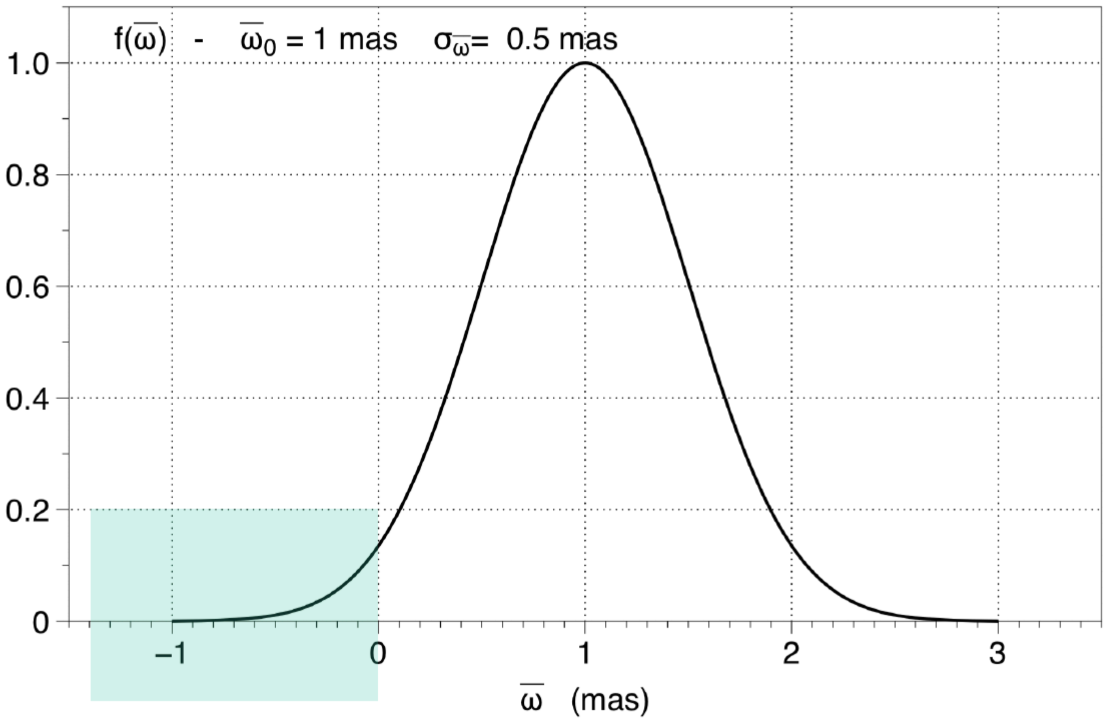
$$f(\varpi) = \frac{1}{\sqrt{2\pi}\sigma_\varpi} e^{-\frac{(\varpi-\varpi_0)^2}{2\sigma_\varpi^2}}$$

Distances

$$\Rightarrow \quad g(d) = \frac{1}{\sqrt{2\pi}\sigma_\varpi} \frac{1}{d^2} e^{-\frac{(1/d-\varpi_0)^2}{2\sigma_\varpi^2}}$$

Stellar distances and parallaxes II

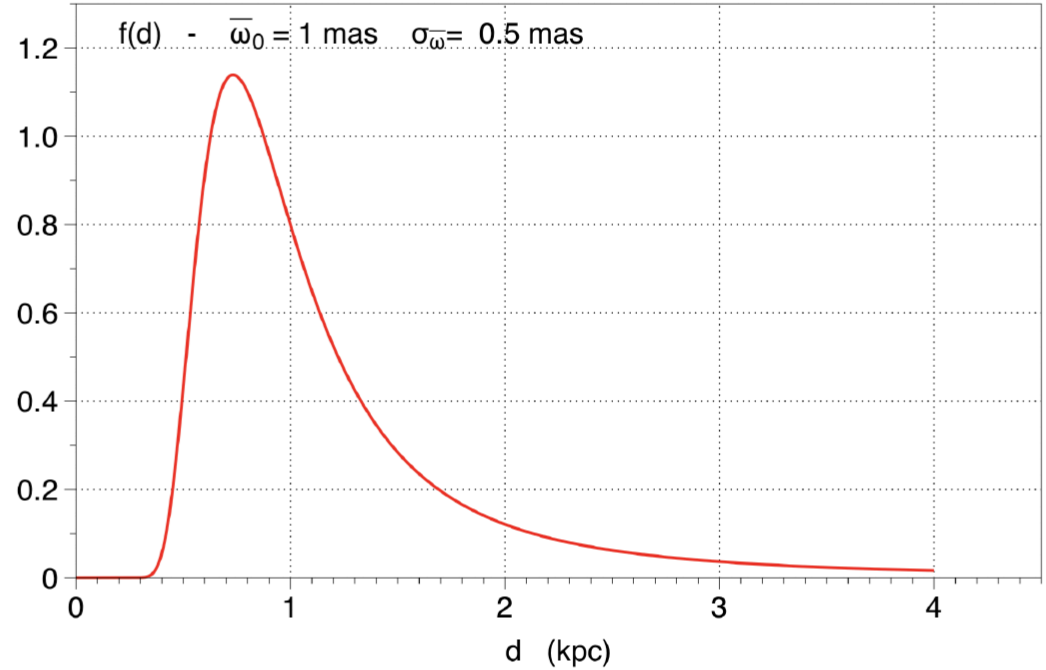
ϖ = 1 mas, d = 1 kpc, σ_ϖ = 0.5 mas



$\varpi < 0$

← PDF of the parallaxes

PDF of the distances →



Hipparcos parallaxes

Hipparcos mission was supposed to solve completely all problems related to the cosmic distance scale ☺☺☺

Parallax measurements at 10% for selected standard candles:

Cepheids 10 (all but one short period Cepheids)

Type II Cepheids 2 (one peculiar)

RR Lyrae 1 (RR Lyrae itself often discussed as peculiar)

Red clump stars 1000

Hipparcos parallaxes

Parallaxies improved significantly improved van der Leeuwen 2007

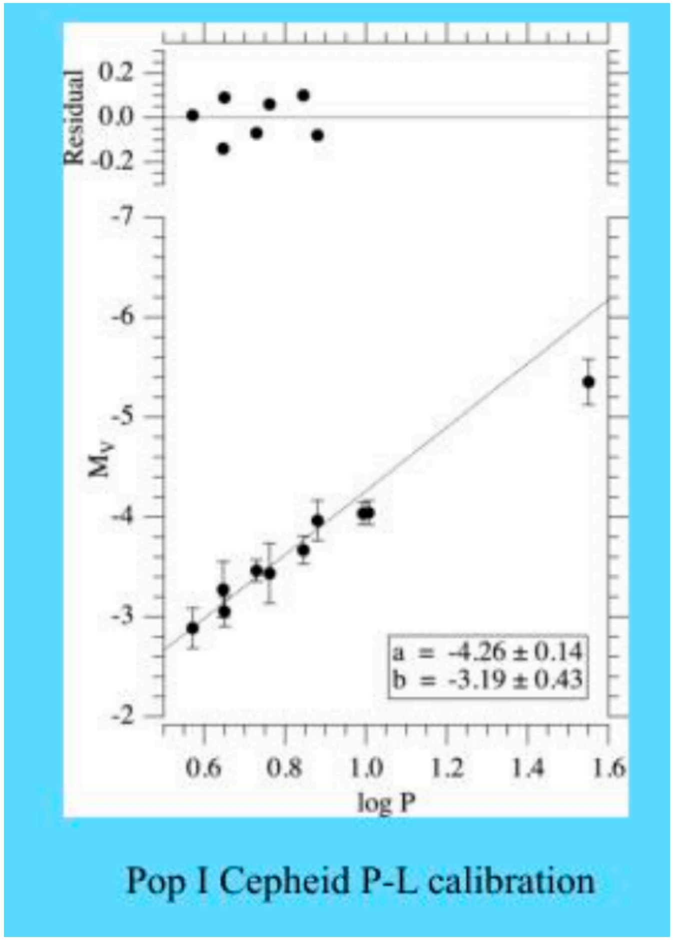
Pleiades problem never solved (5 and 7 parameter fit)

Lutz Kulker bias

At best 10% parallaxes. Estimated corrections at the level of

0.1-0.2 mag !

HST parallaxes



Benedict et al. 2009

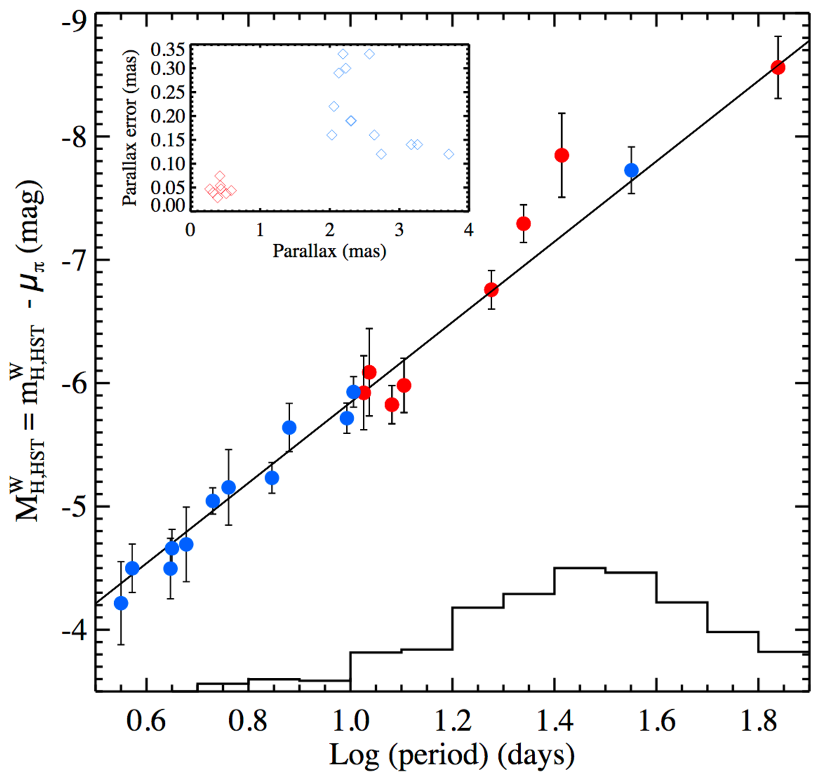


Figure 13. The *P–L* relation of Milky Way Cepheids based on trigonometric parallax measurements. The points in blue were measured with the *HST* FGS (Benedict et al. 2007) and *Hipparcos* (van Leeuwen et al. 2007) and are all within 0.5 kpc, and the points in red are presented here from spatial scanning of WFC3 and are in the range of $1.7 < D < 3.6$ kpc. The inset shows the uncertainties in the measured parallaxes.

Gaia parallaxes

1% at 1 kpc, so we should expect

several hundred of classical Cepheids, RR Lyrae stars, Type II Cepheids to be calibrated

And also many hundreds of eclipsing binaries, astrometric binaries to cross check the results

Gaia DR1, DR2

Spectacular data set for studying stellar motions, transients etc

BUT still not for measuring distances

First papers trying to calibrate:

Cepheids (Groenewegen et al. 2019, Riess et al. 2018)

RR Lyrae stars (Muraveve et al. 2018)

Systematic shift

Comparing to:

1) Quasars: shift of -0.03 mas and some internal correlations (Lindegren et al. 2018)

2) With other catalogs - 0.118±0.003 mas (Hipparcos) but mostly close -0.03 (especially catalogs in the MC) –0.0380 ± 0.0004 mas and–0.0268 ± 0.0006 mas

3) APOKASC-2 catalog and asteroseismic relations, Zinn et al. (2018) –0.053±2(stat)±1(syst) mas

4) Eclisping binaries Graczyk et al. 2018 –0.031 ± 0.011 mas

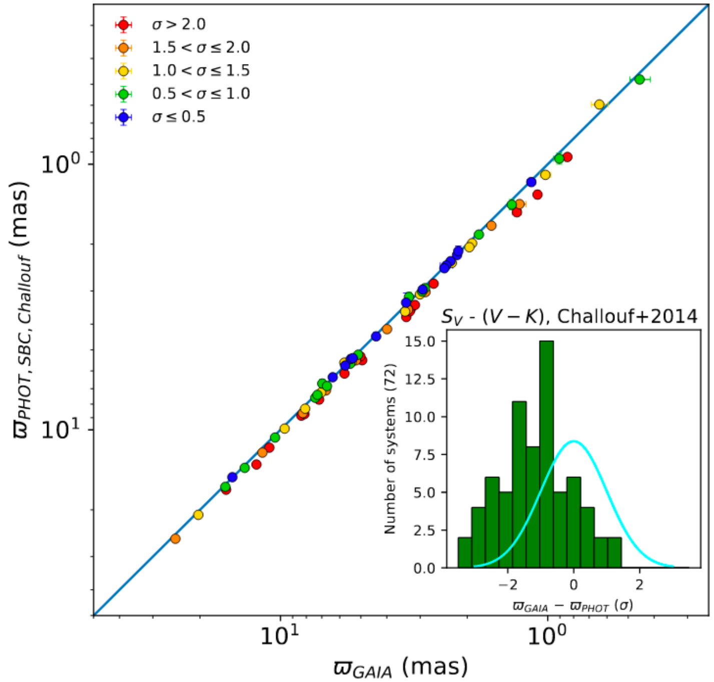


Table [illegible]

The zero point shifts $\varpi_{Gaia} - \varpi_{Phot}$ determined with eclipsing binaries for the different SBCRs

SBC relation	Band	Color	Range of color	$\log g$ (dex)	Number of systems	$(\varpi_{Gaia} - \varpi_{Phot})$ (mas) Unweighted	Weighted
Kervella et al. 2004	B	$B-K$	-0.25 - 2.36	>3.5	61	-0.046 ± 0.021	-0.025 ± 0.015
Kervella et al. 2004	B	$B-H$	-0.20 - 2.28	>3.5	60	-0.050 ± 0.028	-0.041 ± 0.018
Kervella et al. 2004	B	$B-J$	-0.17 - 2.08	>3.5	58	-0.092 ± 0.037	-0.067 ± 0.021
Kervella et al. 2004	V	$V-K$	-0.20 - 1.75	>3.5	62	-0.051 ± 0.021	-0.025 ± 0.015
Kervella et al. 2004	V	$V-H$	-0.15 - 1.66	>3.5	61	-0.051 ± 0.029	-0.040 ± 0.016
Kervella et al. 2004	V	$V-J$	-0.12 - 1.47	>3.5	60	-0.136 ± 0.040	-0.083 ± 0.020
di Benedetto 2005	V	$V-K$	-0.10 - 4.93	>2.0	62	-0.124 ± 0.025	-0.052 ± 0.020
Boyajian et al. 2014	V	$V-K$	-0.15 - 1.75	>3.5	62	-0.105 ± 0.024	-0.060 ± 0.019
Boyajian et al. 2014	V	$V-H$	-0.13 - 1.66	>3.5	61	-0.137 ± 0.031	-0.084 ± 0.021
Boyajian et al. 2014	V	$V-J$	-0.12 - 1.47	>3.5	60	-0.188 ± 0.044	-0.094 ± 0.019
Challouf et al. 2014	V	$V-K$	-0.60 - 4.93	>2.0	72	-0.196 ± 0.030	-0.092 ± 0.019
Bolometric	-	-	-	-	81	-0.103 ± 0.026	-0.067 ± 0.012