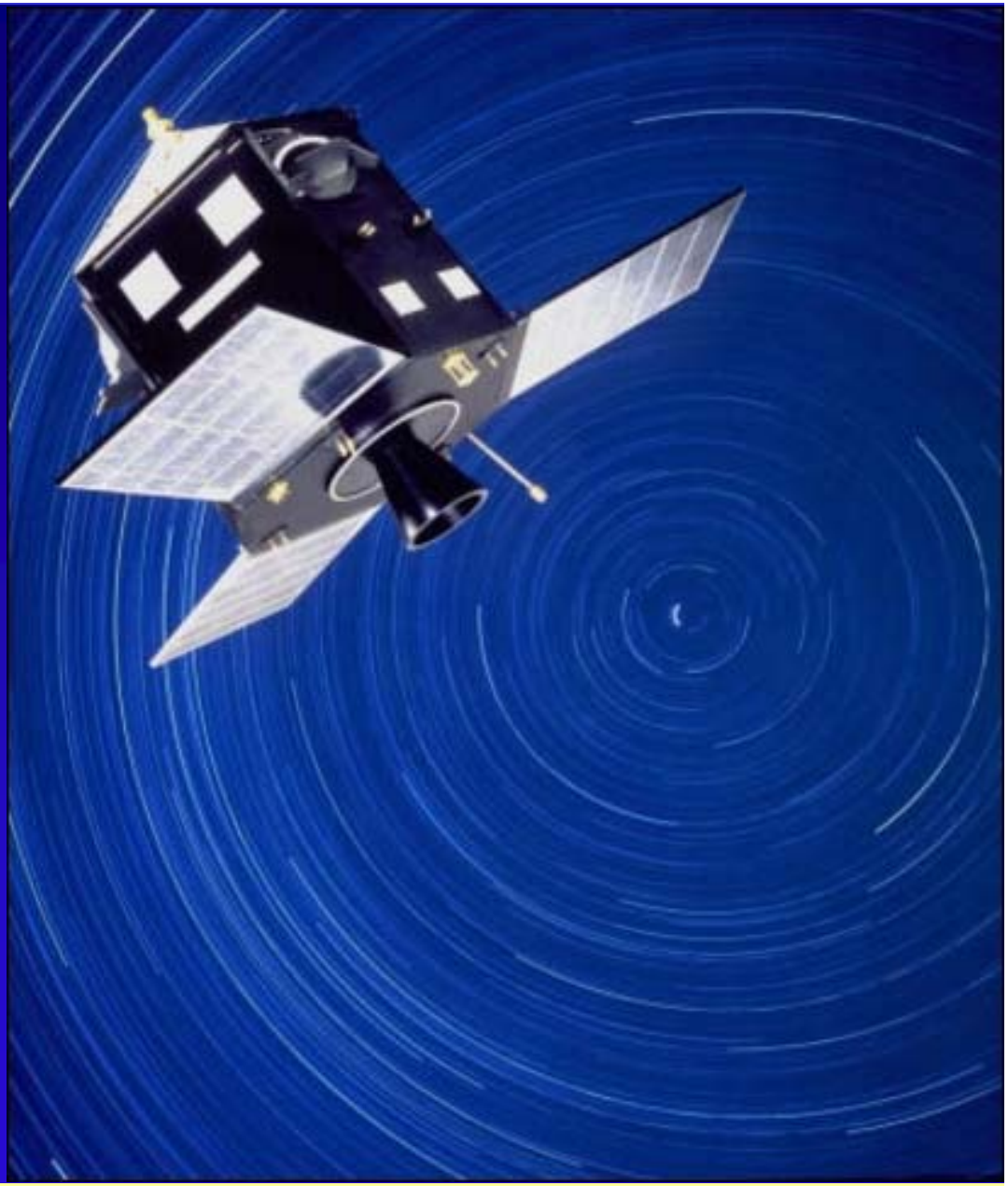
Space Astrometry

Principles, scientific objectives

I - Hipparcos

F. Mignard

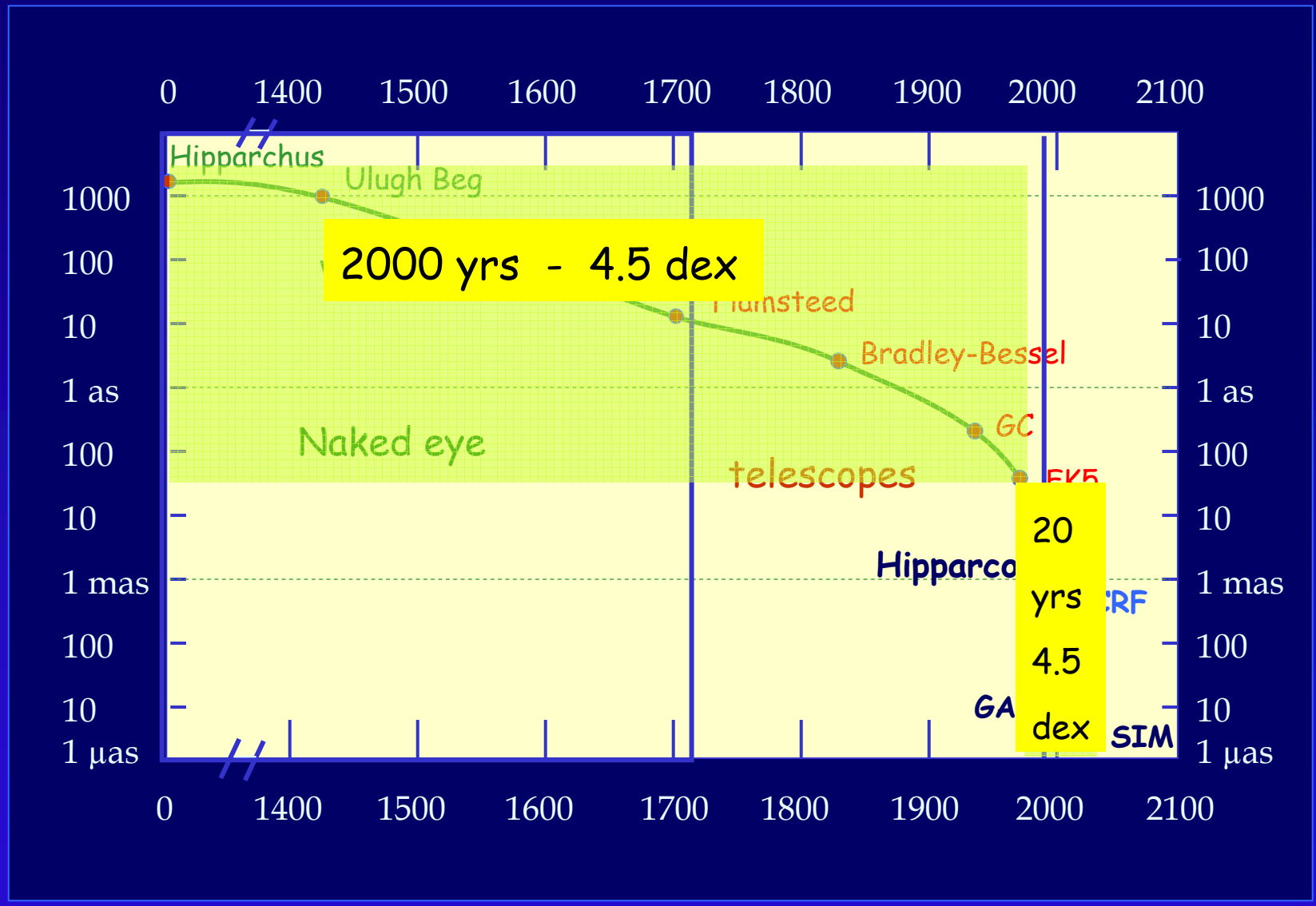
OCA/ Cassiopée



Summary

- Objectives of space astrometry
- Absolute and relative parallaxes
- The Hipparcos mission
- Summary of the main results
- Astrophysical exploitation
- Conclusion

the golden age of astrometry



Astrometry for Astrophysics

- Direct results

- Positions, parallaxes and proper motions of a very large number of stars
  - 1 mas (Hipparcos) to 1 μas (SIM)
- Photometry to the mmag, multi-epochs, ~ 10 bands
  - 50 to 400 observations per source
- Radial velocity to few km/s (GAIA, OBSS)
- Spectrophotometry in the visible, near IR ou UV
- Solar system objects (Hipparcos, DIVA, GAIA, OBSS)
- Detection and measures of visual and spectroscopic binaries

Final goals : Stellar and galactic physics

True Goals

- Mapping of the Milky-way
- Stellar physics (classification, L, log g, T_{eff}, [Fe/H])
- Galactic kinematics and dynamics
- Distance scale (geometric, HR diagrams, cepheids, RR Lyr)
- Age of the Universe (globular clusters, distance and luminosity)
- Dark matter (potential tracers)
- Reference frames (quasars)
- Extra-solar planets (astrometry, photometric transits)
- Fundamental physics (relativity experiments)
- Solar system objects (survey, taxonomy, masses)

What missions

- The ancestor : HIPPARCOS (ESA)
  - accuracy ~ 1 mas : 1 Dime at 1000 km

- Unsuccessful candidates:

  ROEMER, FAME_1, FAME_2, DIVA, LOMONOSSOV, AMEX

  ESA US US GER RU US

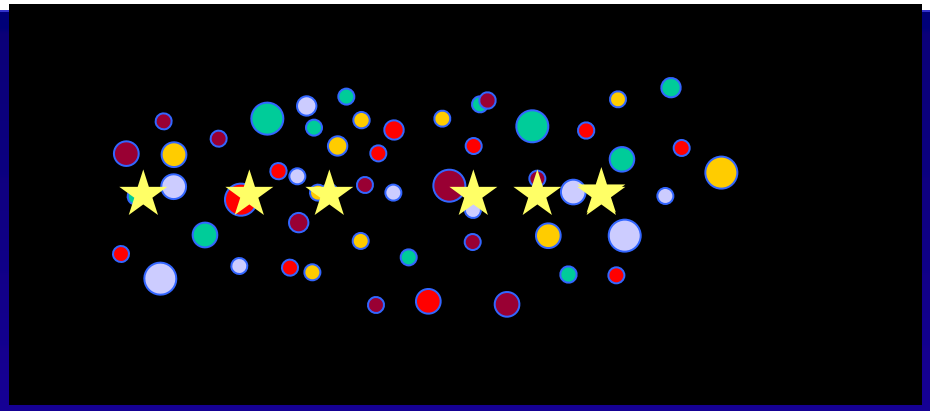
  - accuracy ~ 0.1 mas : 1 nail at 1000 km

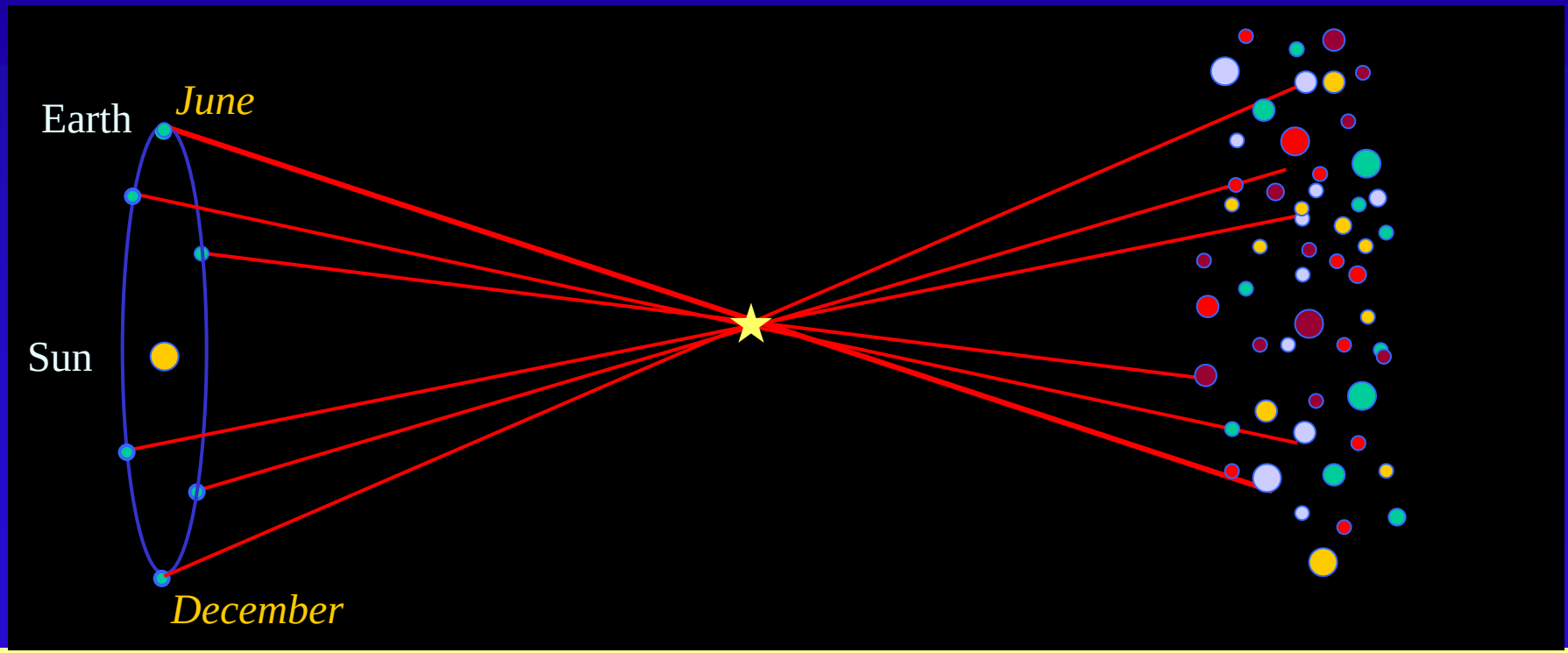
- Preliminary study : JASMINE (JAP), OBSS (US)

- Approved mission : GAIA (ESA) , SIM (US)
  - accuracy (Gaia) 20 μas : hair width at 1000 km

Stellar Parallaxes

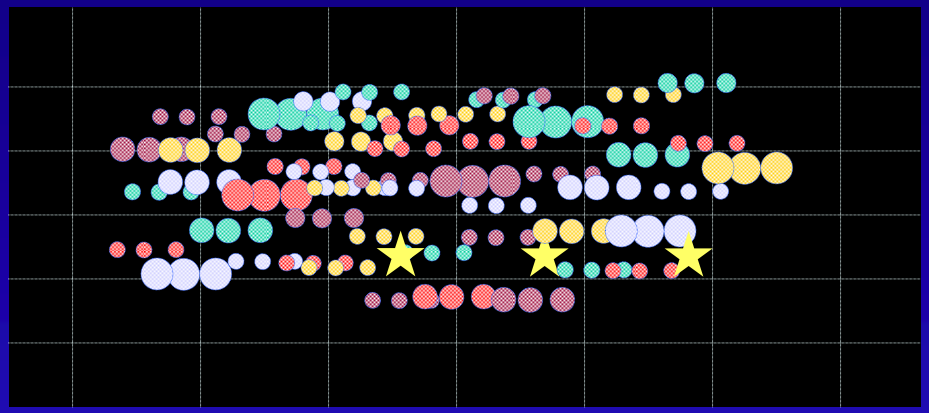
Stellar parallaxes





Relative parallaxes

Insight of the technique in the Dialogo of Galileo (Galileo, Dialogue 3rd day)



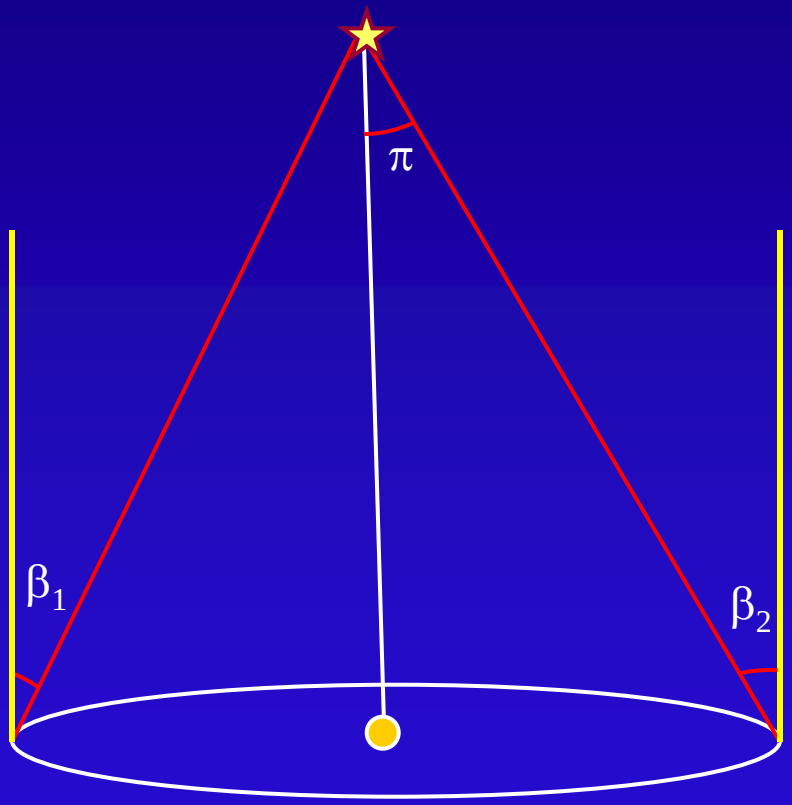
$\pi_* = \pi_{rel} + \langle\pi\rangle$

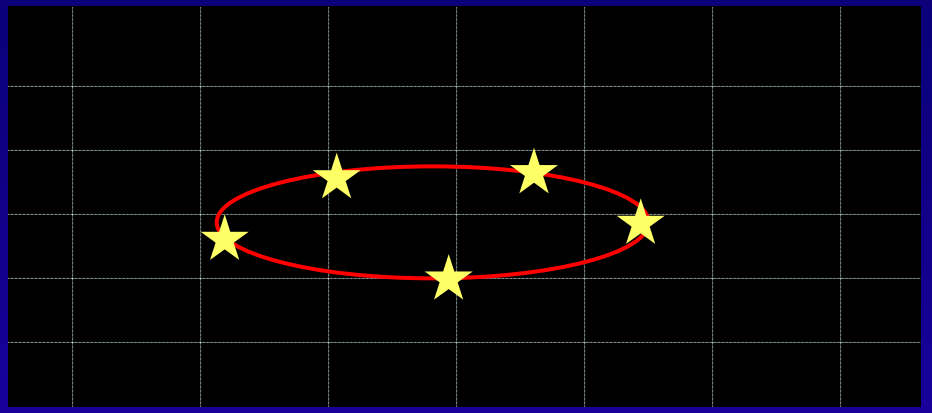
Relative measurements on a small field

assumption for the faint stars

- systematic errors as a result of a wrong $\langle\pi\rangle$
- not usable for distances > 100 pc

Absolute parallaxes



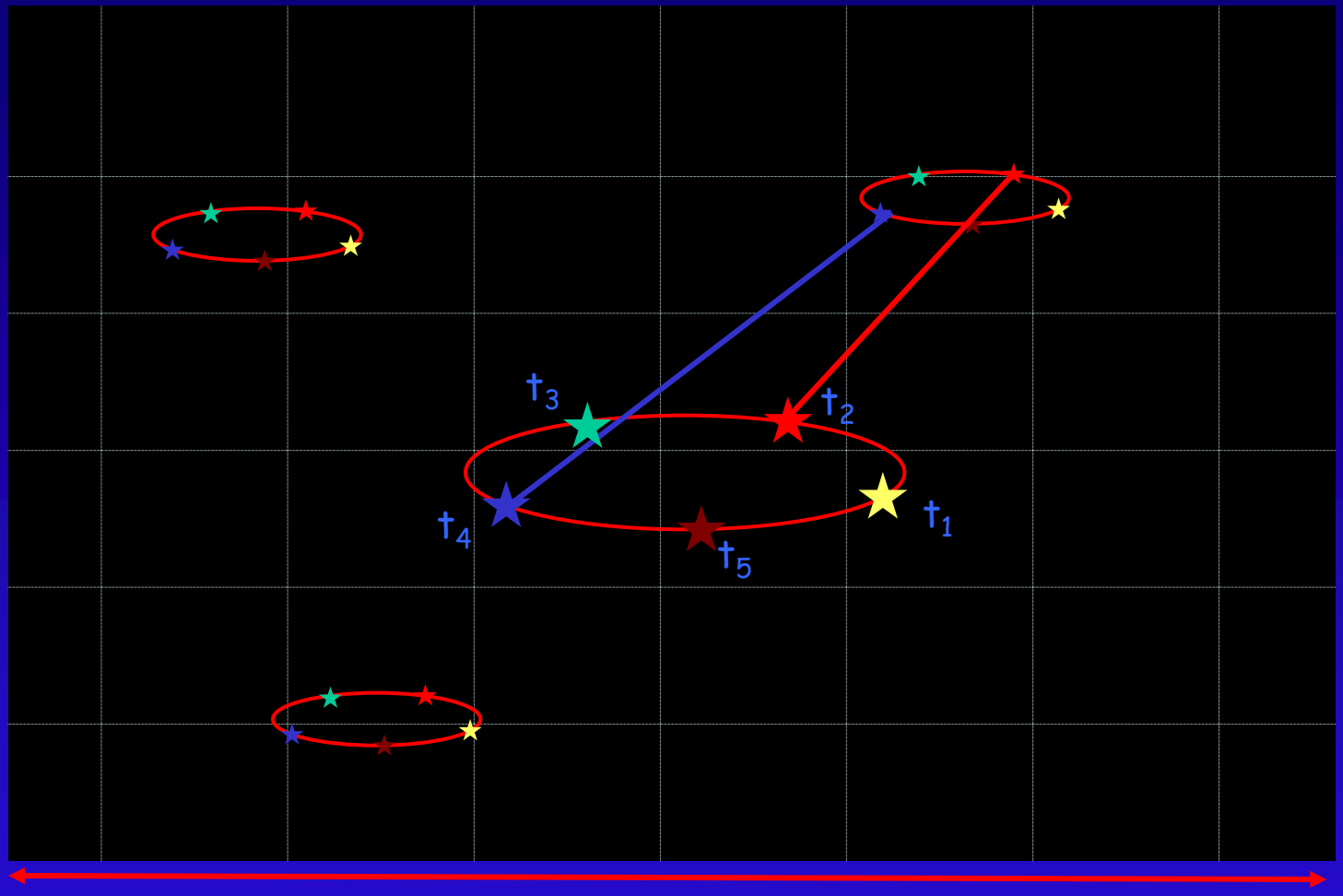


$$\pi = \frac{\beta_1 + \beta_2}{2}$$

Methods applied :

- measurements of declinations
- zenith distances

Small field astrometry



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

Evolution 1850 - 1980

- 1840 3 published parallaxes
- 1880 17 "
- 1900 50 "
- 1910 100 "
- 1930 2000 "
- 1965 7000 "
- 1980 10000 "

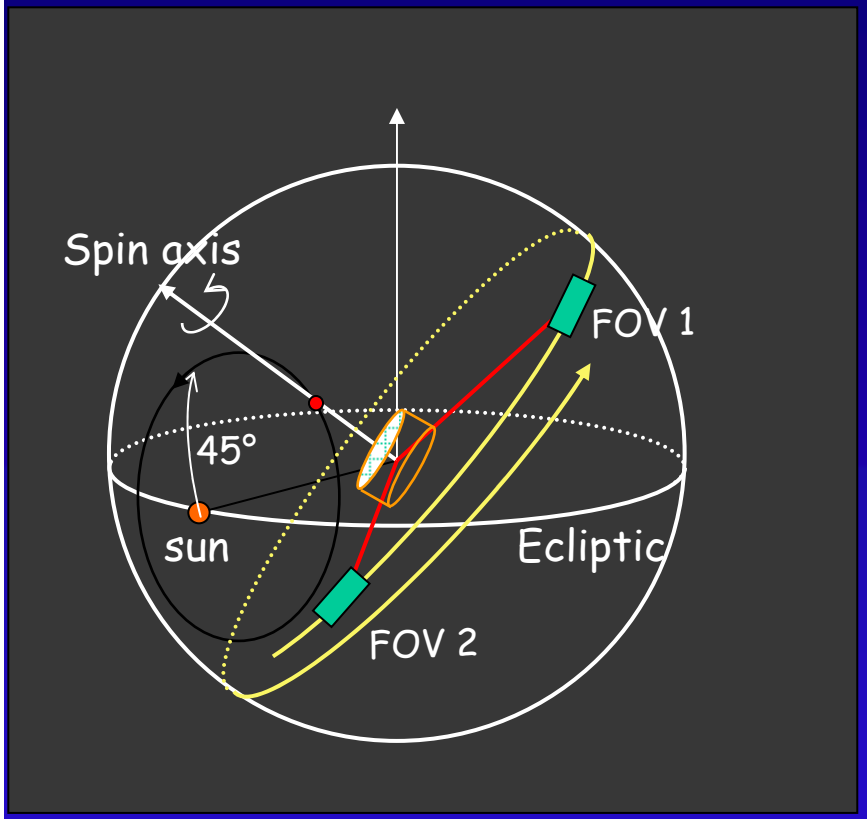
  - Estimated error : 0".016

    ==> $\sigma(\pi)/\pi$ = 50% at 30 pc !

  - Mean value of the parallaxes : 0".018

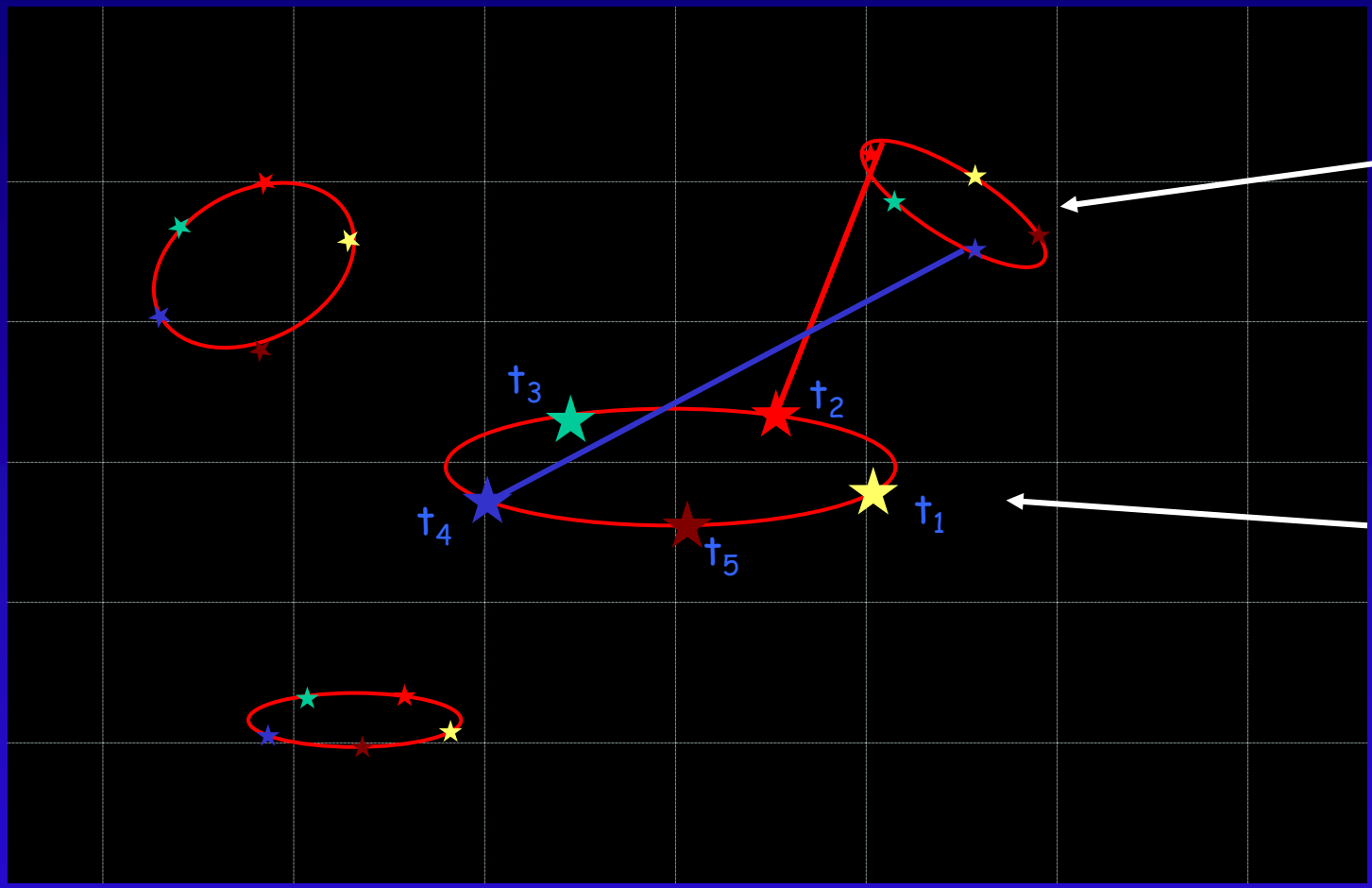
Most of these parallaxes have no individual meaning

A route to absolute parallaxes : Two fields of view



- Overall principles set forth by P. Lacroute in 1965.
- Optical combination of two viewing directions
- The two FOVs are mapped onto a common focal plane
- Stars are combined by pairs
- Wide angle measurements are carried out

How parallaxes get absolute



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

Space astrometry : two complementary concepts

- Survey of a large number of stars
  - Continuous scanning of the sky
  - Input catalogue or on-board detection
  - Complete up to a limiting magnitude or selection of stars
  - The scanning law determines the integration time
  - Frozen observing program

- Pointing at individual sources
  - Pre-selected sources
  - Variable and adapted integration time
  - Longer operation dead time
  - Flexible program, can react to external demand

The Hipparcos misssion and results

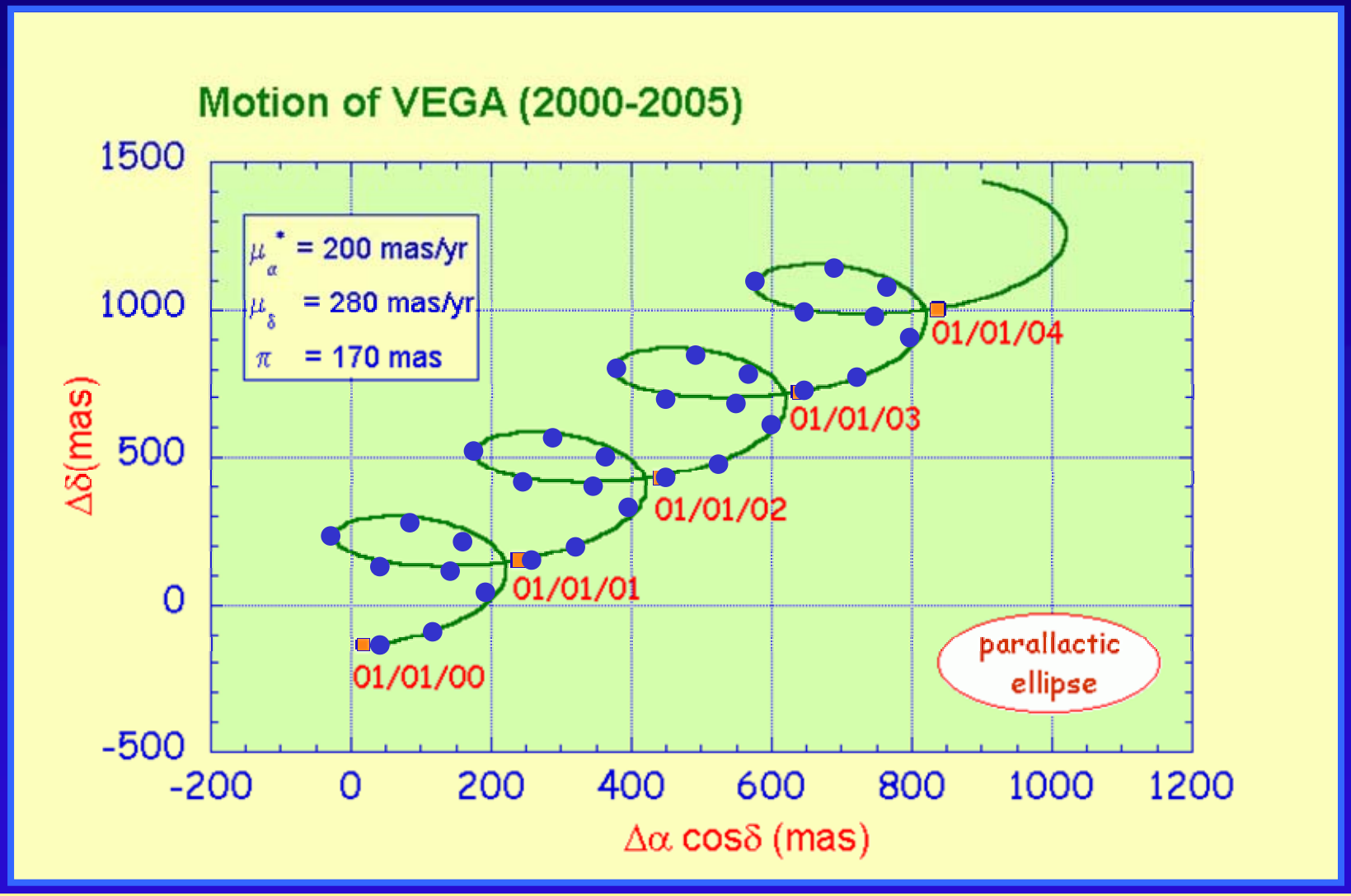
Main Features of Hipparcos

- ESA mission launched in August 1989
- Continuous sky scanning over 3.5 years
- Results published in 1996-7

- Two fields of view separated by 58°
- One single telescope of 29cm in diameter
- Detection with a photoelectric tube (r = 0.003)
- One source observed at a time

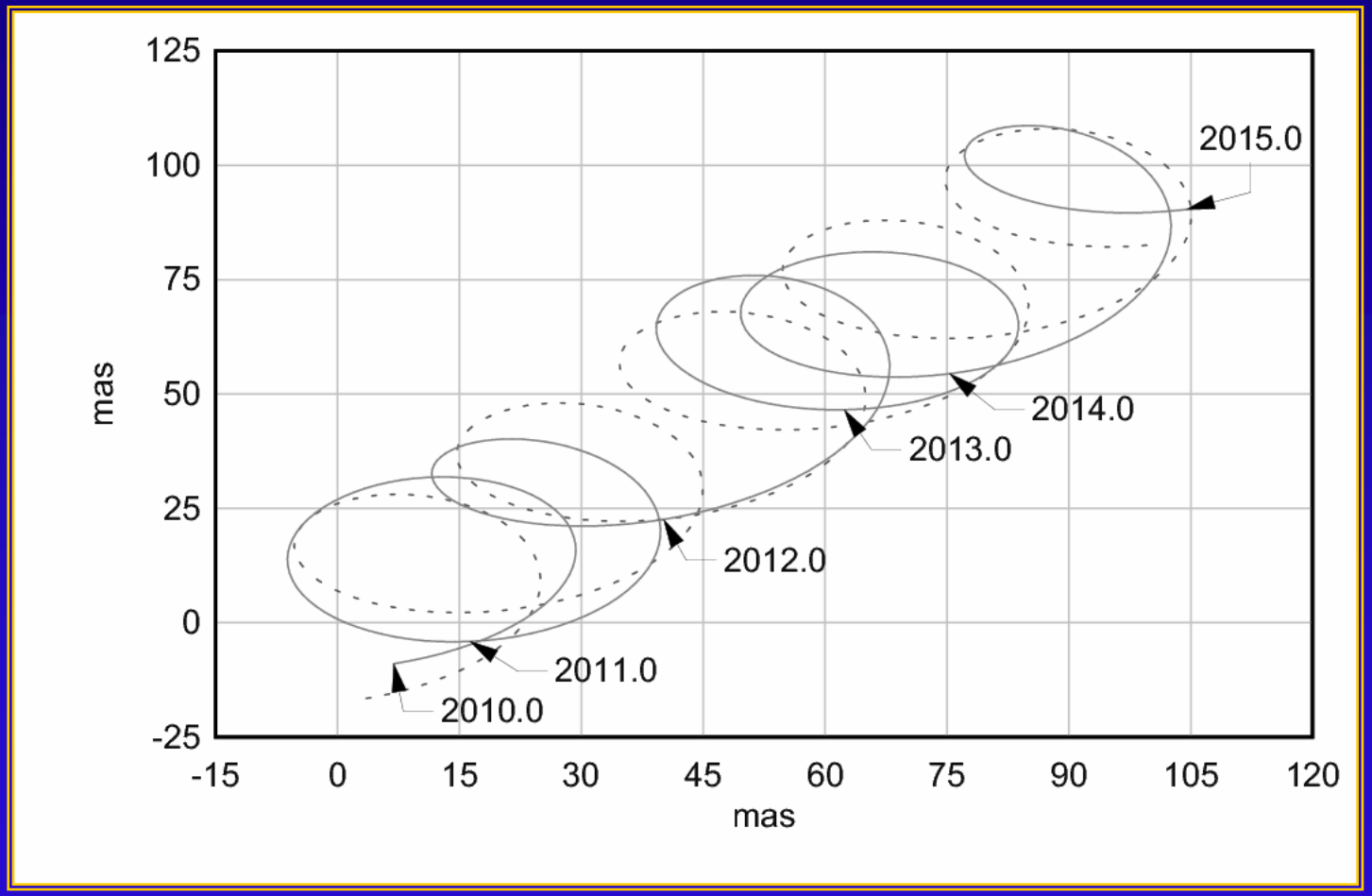
Basic astrometric model

- Absolute motion of Vega
  - non rotating reference frame



Model with an astrometric binary

- Sky path for the photocenter of a binary star :
  - μ = 20 mas/yr, π = 20 mas, P = 2.5 yrs



Main Results of Hipparcos

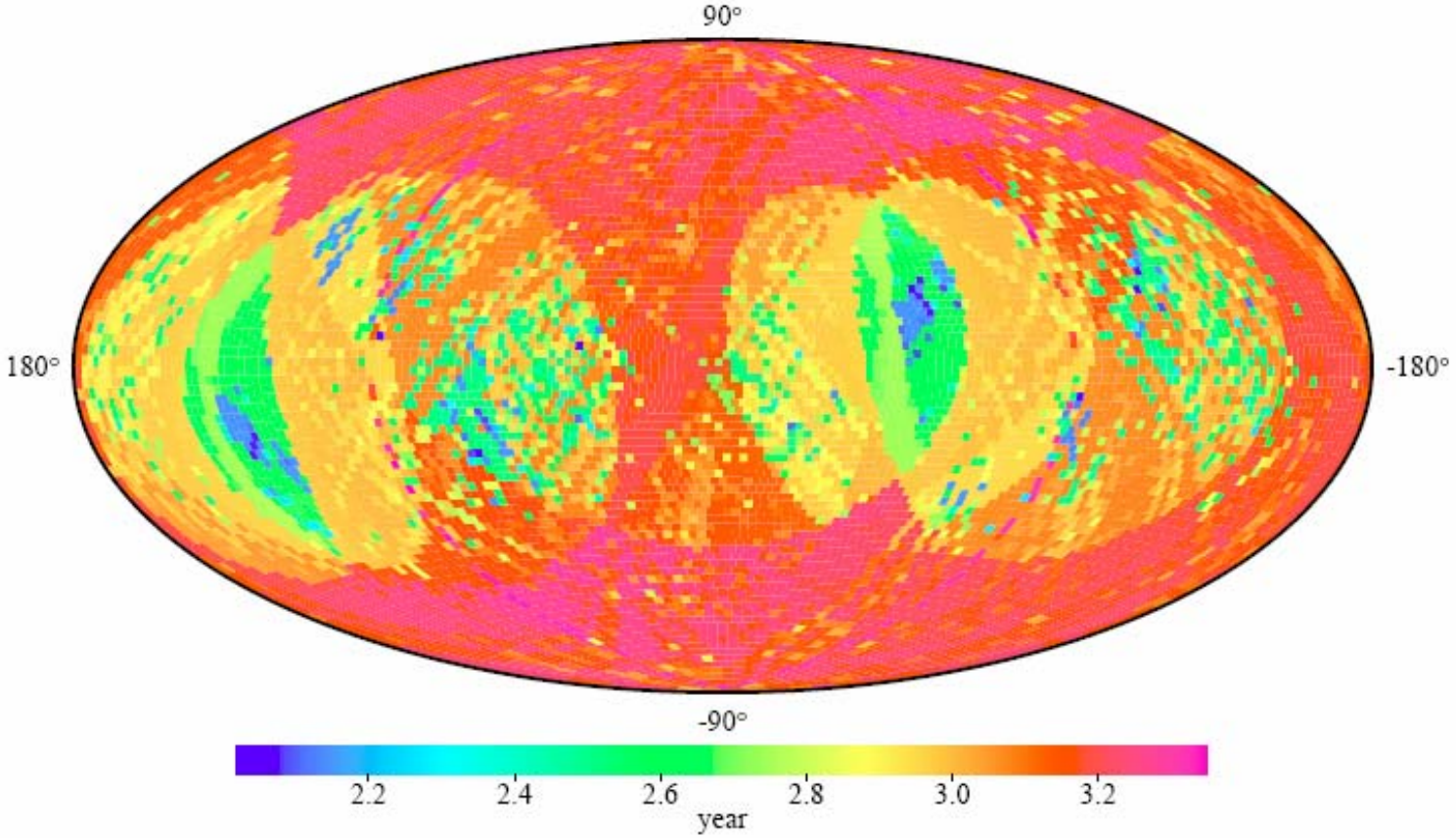
- An astrometric catalogue of 118 000 stars
  - Hipparcos is a fundamental catalogue
  - $\sigma(\alpha) \sim \sigma(\delta) \sim \sigma(\pi)$ ~ 1 mas at V = 9 at 1991.25
  - $\sigma(\mu_\alpha) \sim \sigma(\mu_\delta) \sim 1$ mas/yr at V = 9
- Complete to V = 7.3 - 9.2 (depending on galactic latitude)
- Limiting magnitude 12.4
- Distances better than 10% for 21 000 stars , D < 200 pc
- Density : 3.0 */ deg^2
- Linked to the ICRF with radio stars to within 0.6 mas and 0.25 mas/yr

Additional products

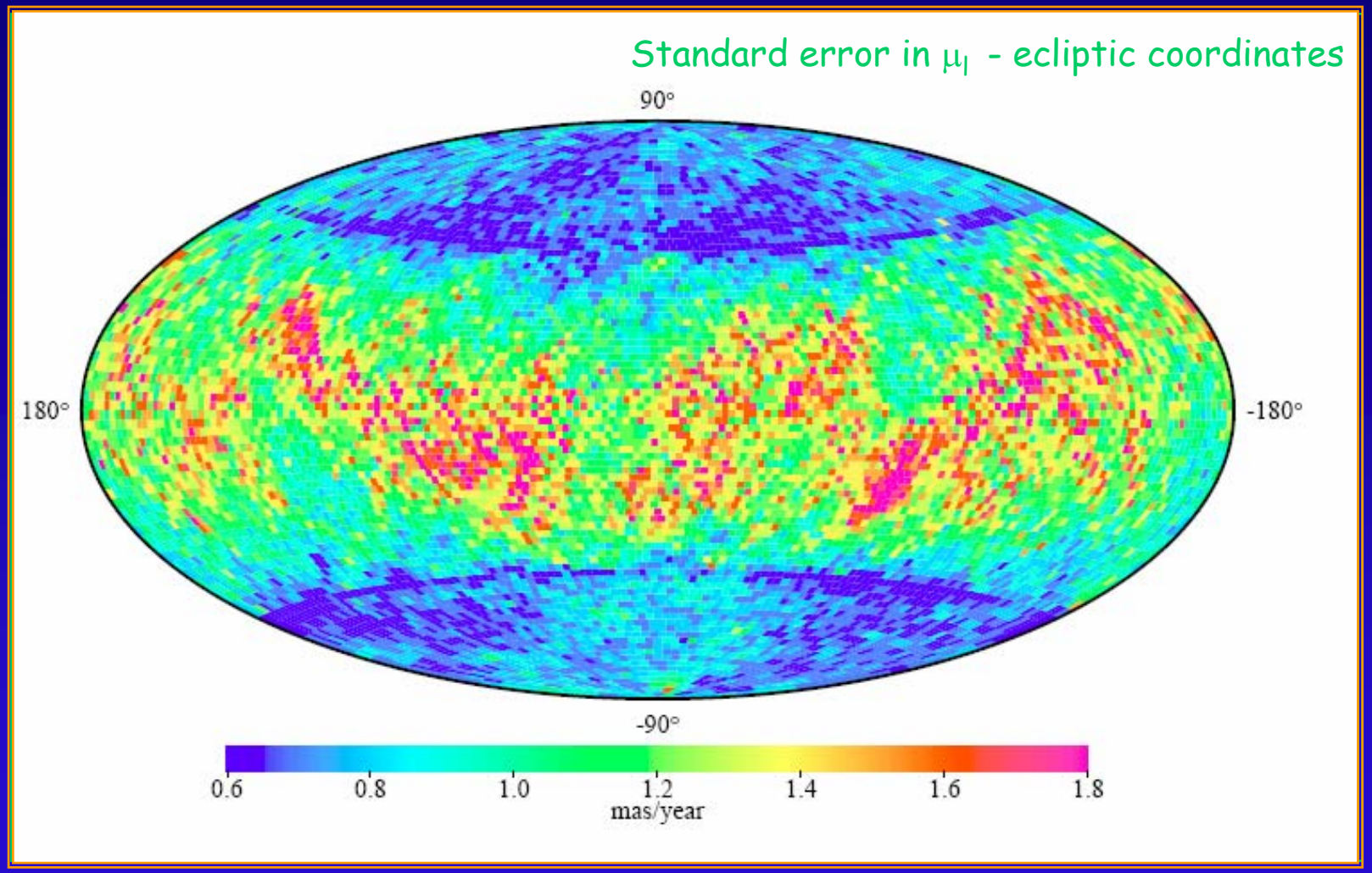
- A survey of binary stars
  - solution for 13000 systems
  - discovery of about 3000 new systems
  - astrometric detection of nearly 2000 pairs
  - masses for about 50 systems

- A photometric catalogue with 130 observations per star
  - $\sigma(H) \sim 0.001$ mag
  - 13×10^6 epoch observations
  - survey of variability for many types of stars to the mmag level
  - 2500 periodic variables with periods and folded light-curves

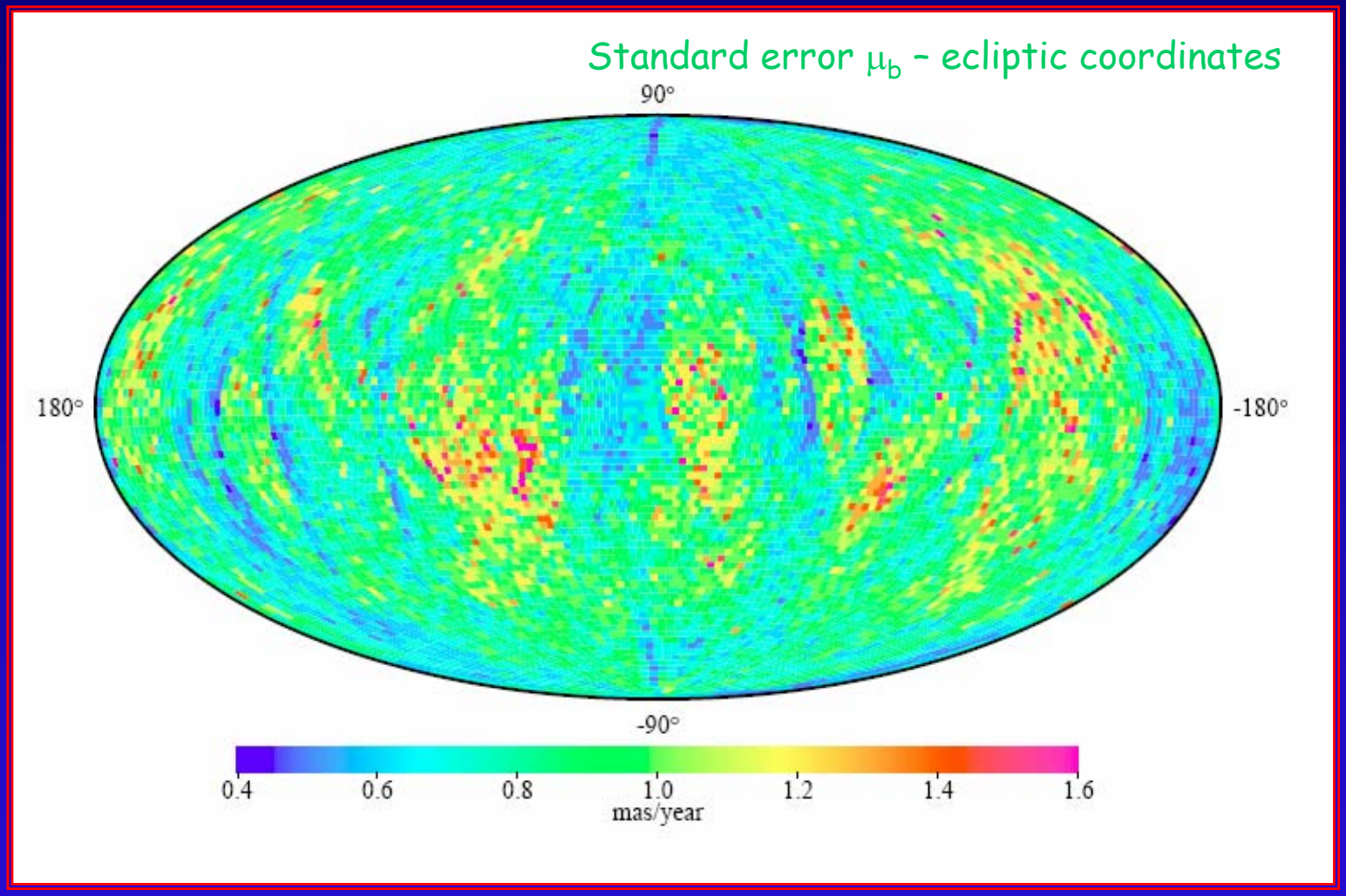
Duration between first and last observation



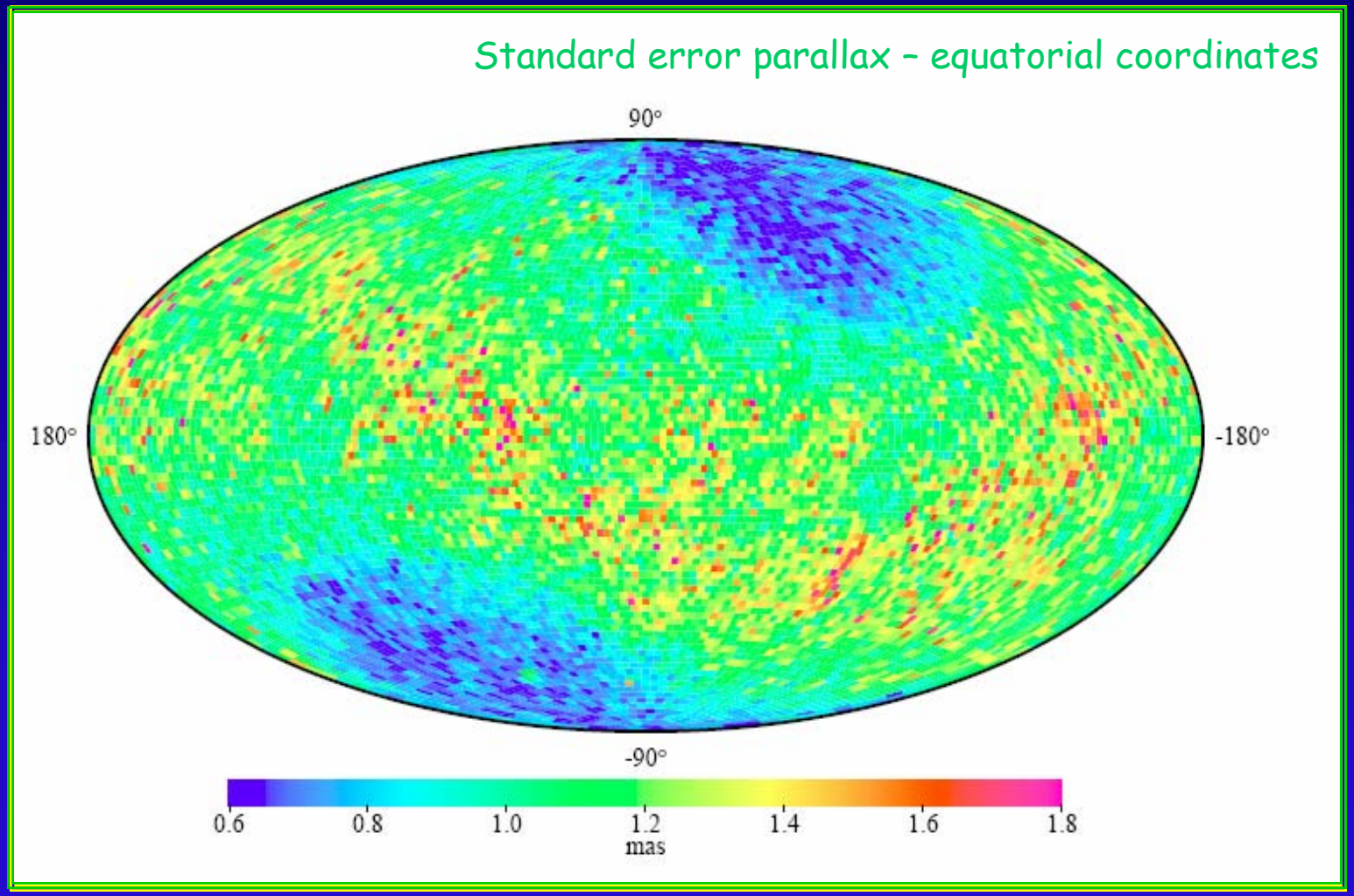
Ecliptic longitude



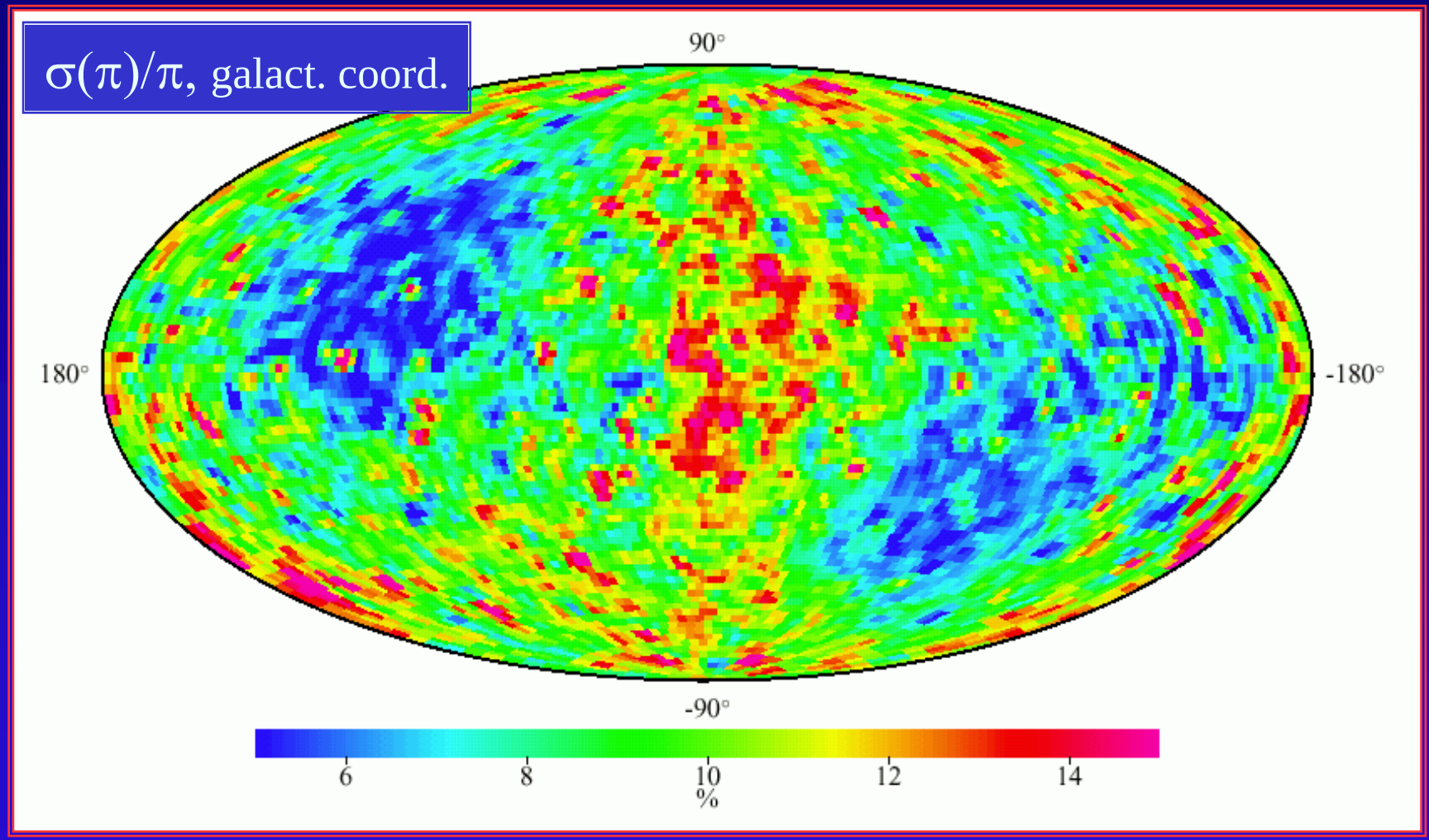
Ecliptic latitude



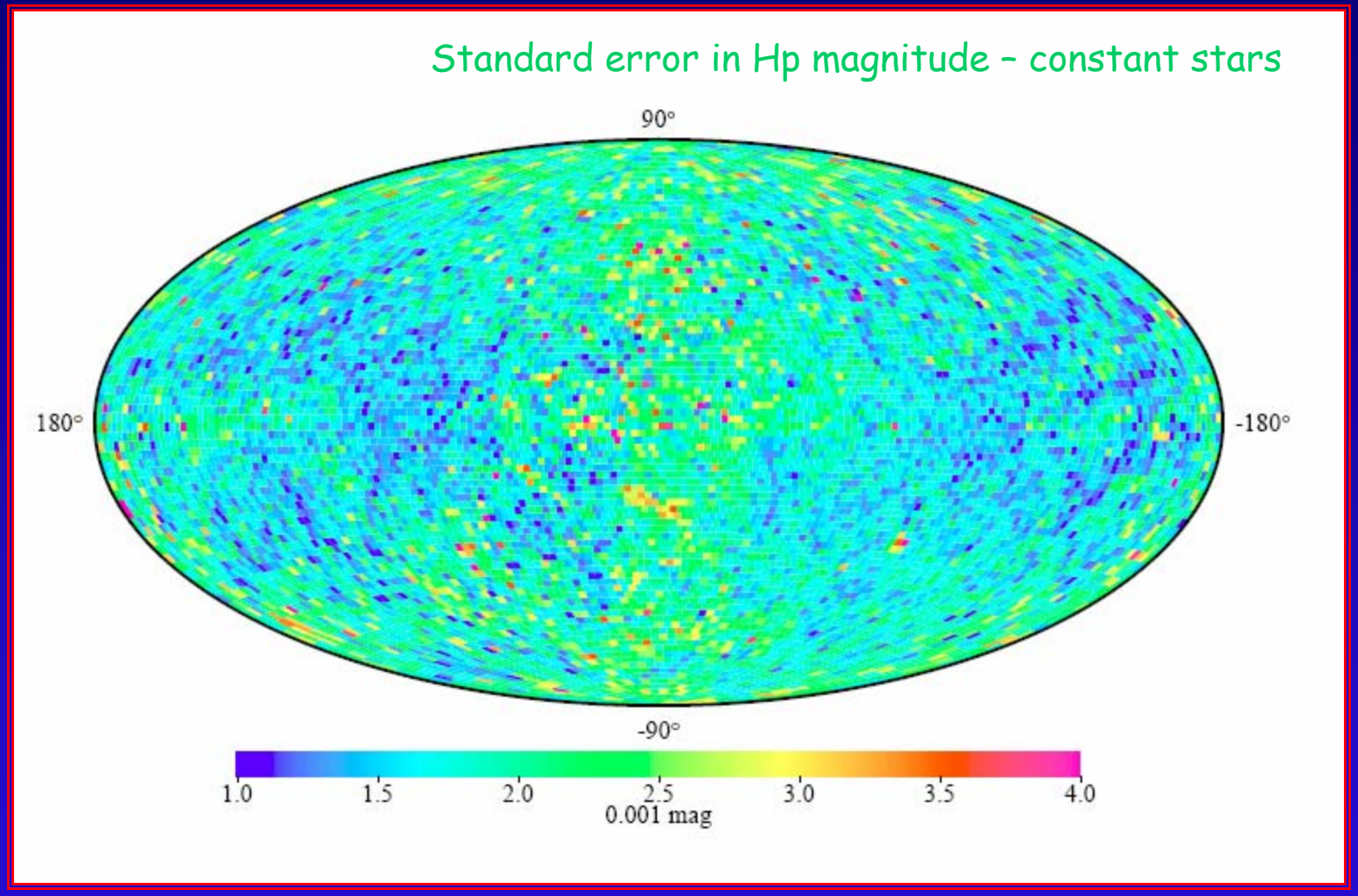
Parallaxes


Standard error parallax – equatorial coordinates
90°
180°
-180°
-90°
0.6
0.8
1.0
1.2
1.4
1.6
1.8
mas

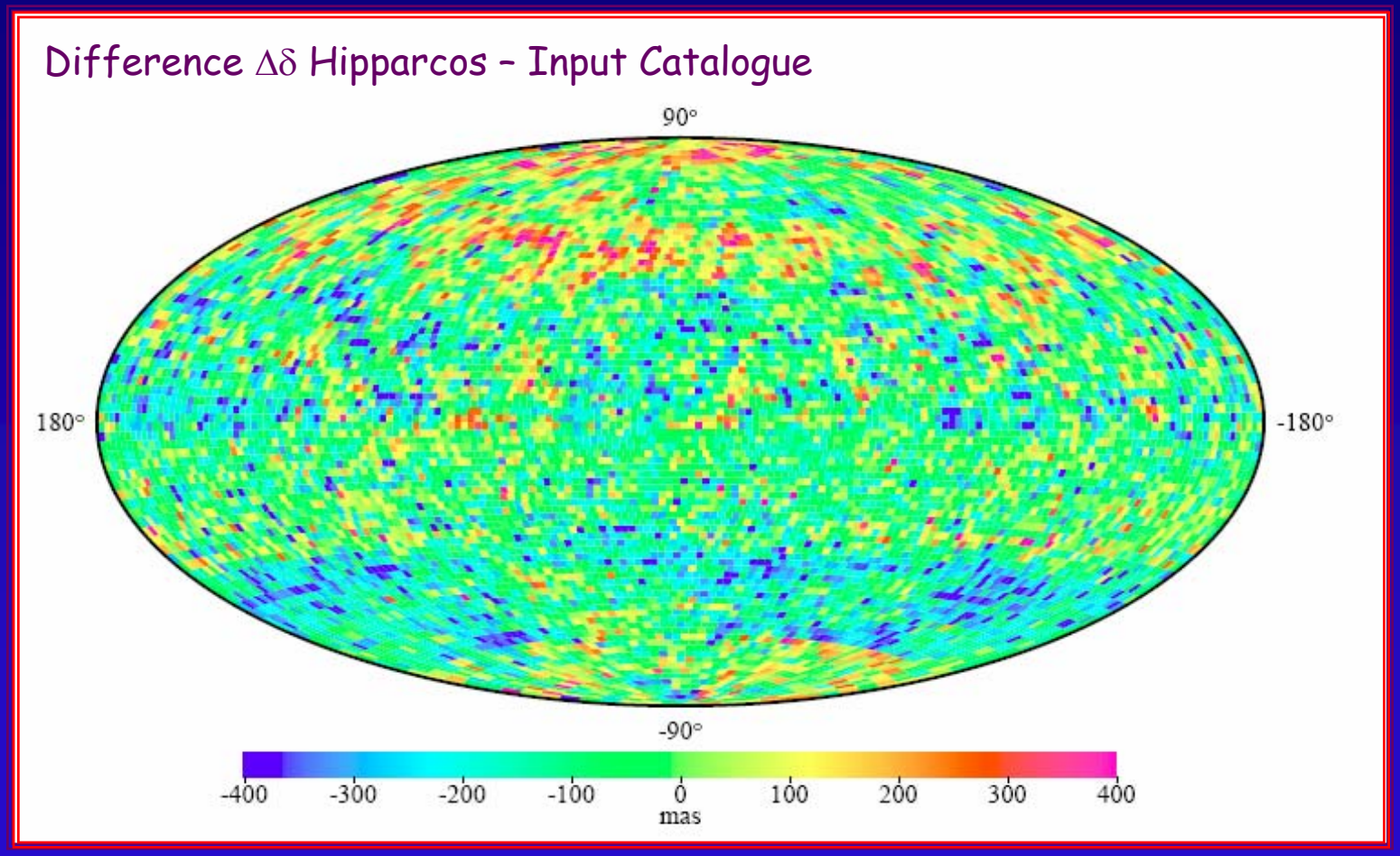
Relative accuracy of parallaxes



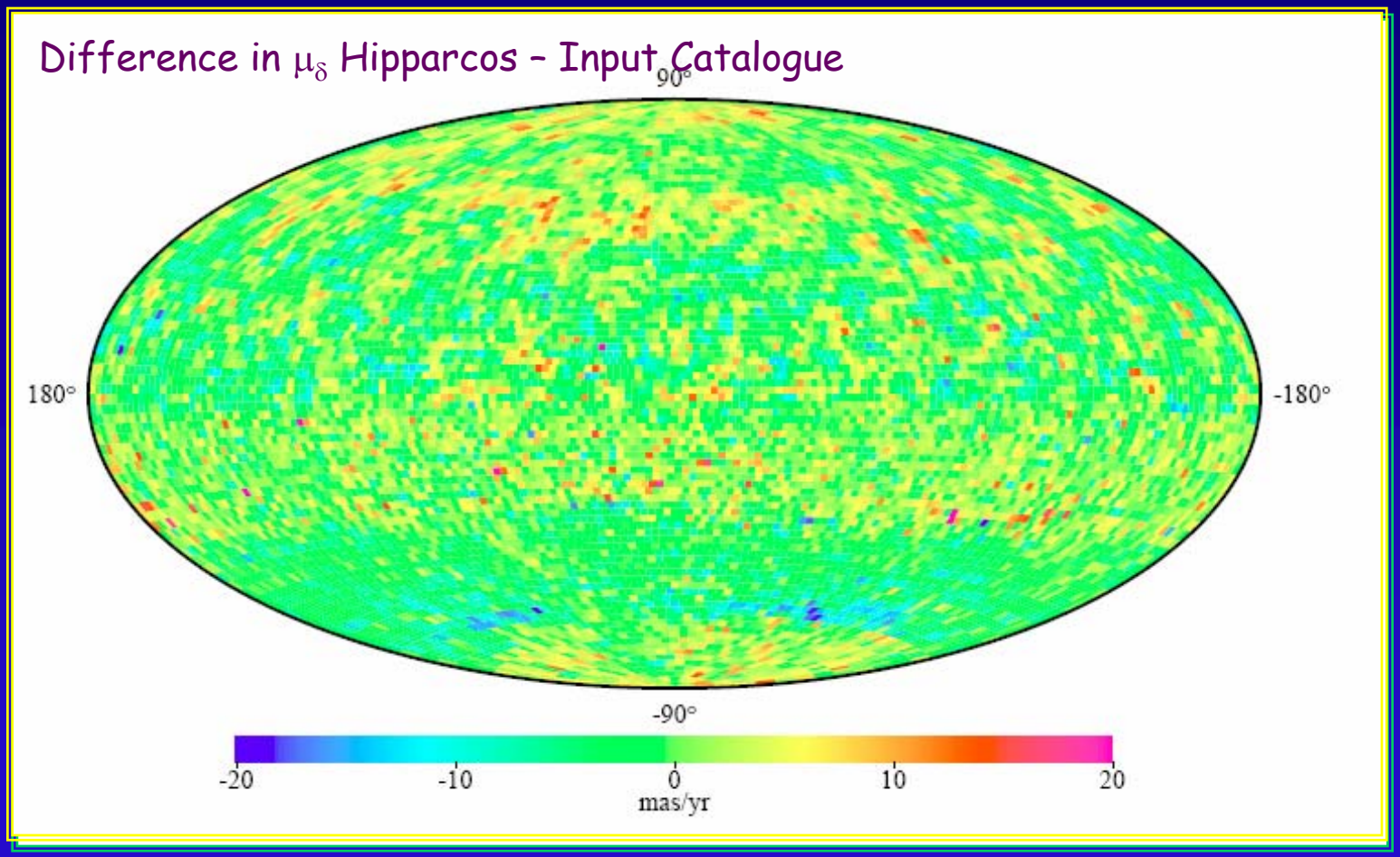
Magnitude


Standard error in Hp magnitude – constant stars
90°
180°
-180°
-90°
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.001 mag

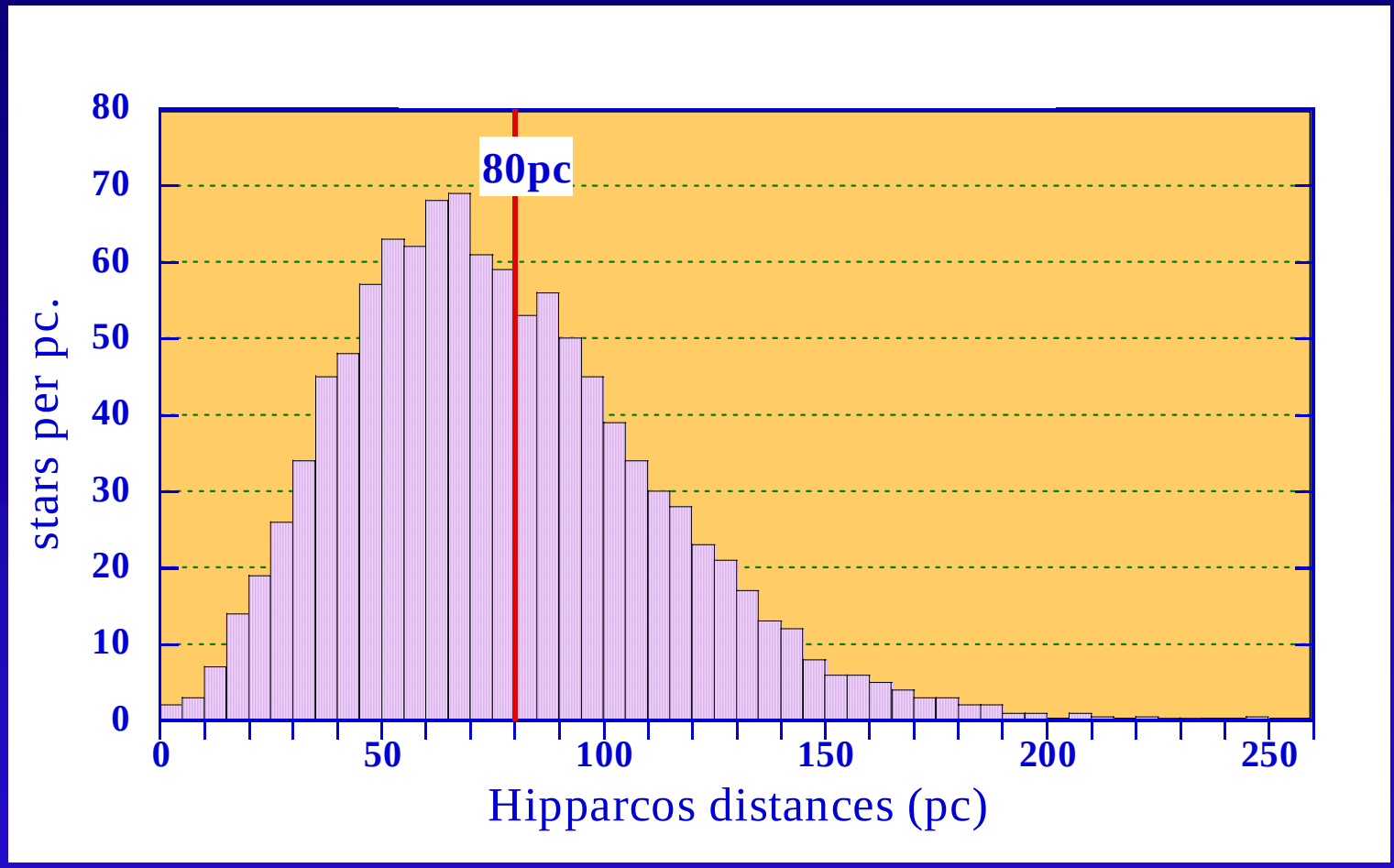
Hipparcos vs. Ground-based: Positions



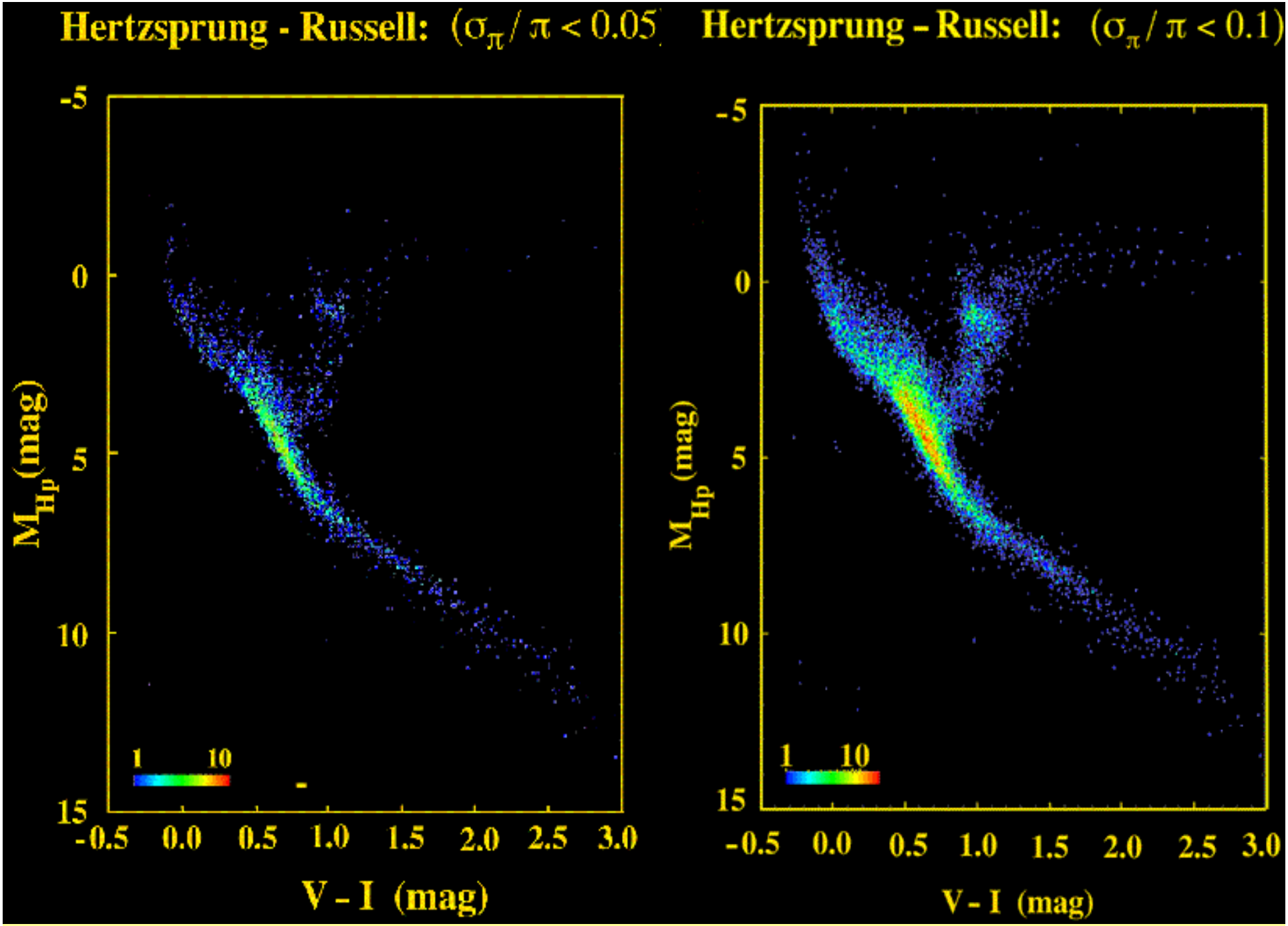
Hipparcos vs. Ground-based: Proper motions



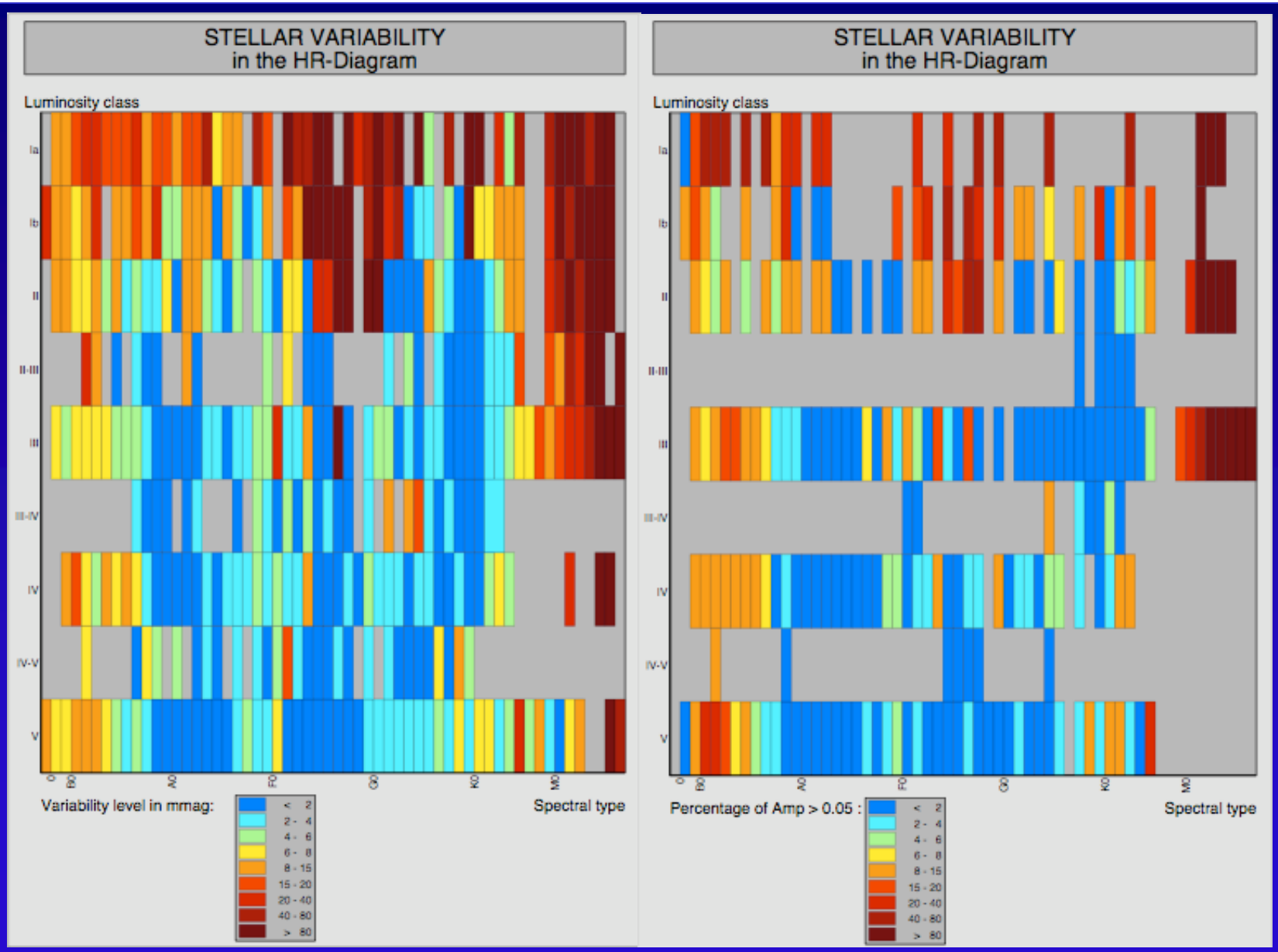
Ground vs. Space : Parallaxes



- Ground based ==> 5610 stars with distances d < 80 pc
- Hipparcos ==> 2384 > 80 pc

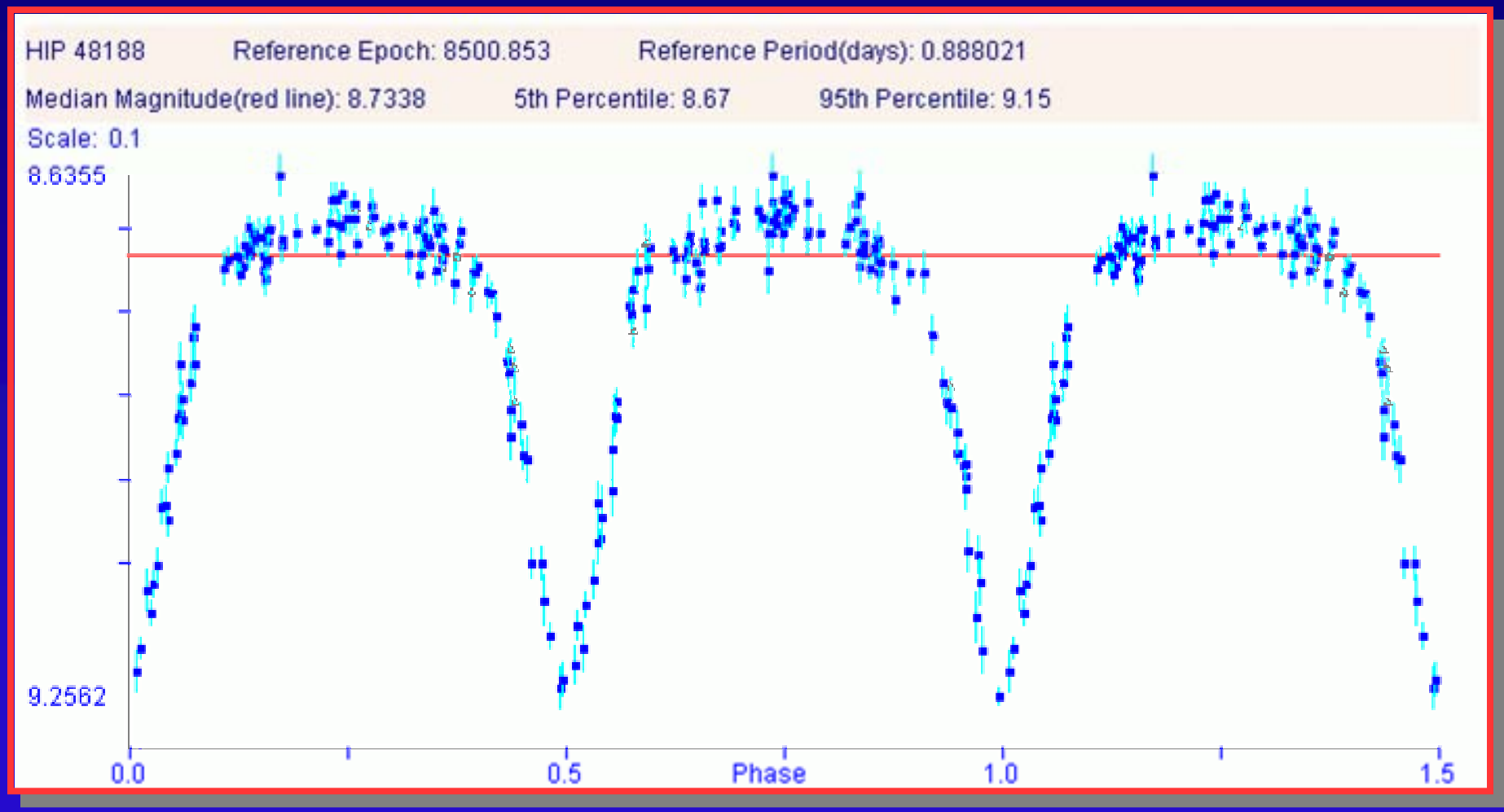

Hertzsprung - Russell: ($\sigma_\pi / \pi < 0.05$)
Hertzsprung – Russell: ($\sigma_\pi / \pi < 0.1$)
M_{Hp} (mag)
V - I (mag)
-5
0
5
10
15
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1
10

Variability analysis

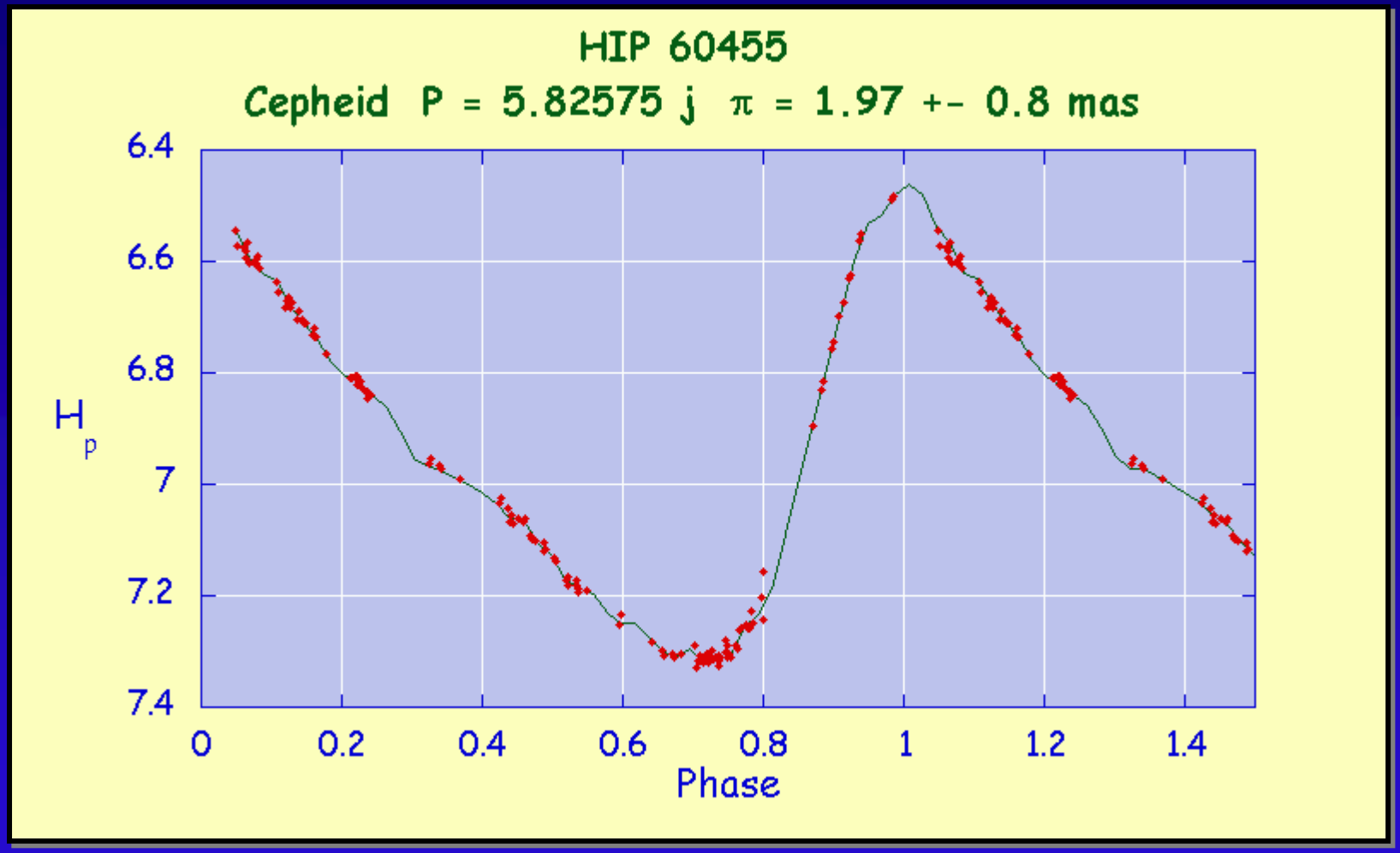


Eyer & Grenon, 2000

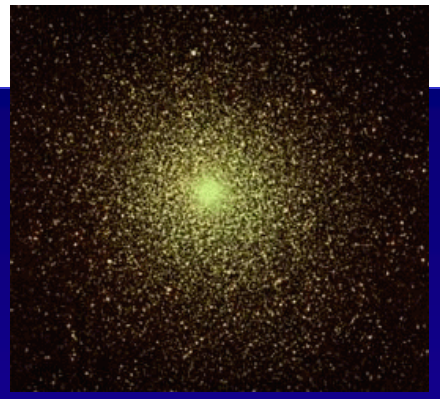
Variable stars : Eclipsing binary



Variable star : Cepheid

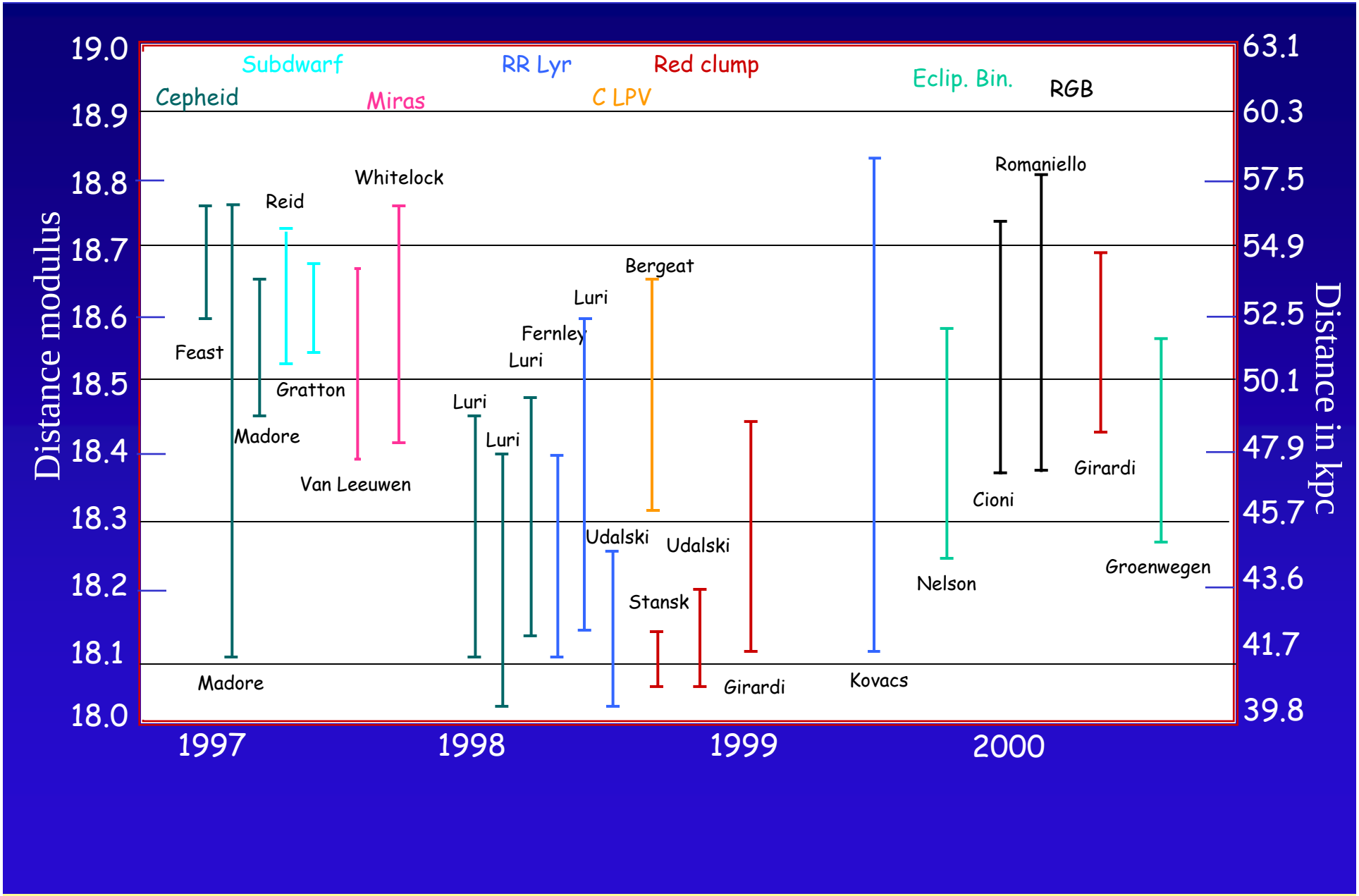


Age of the Universe



Subdwarfs MS fitting		Gyr	
Reid	1997	12.0 ± 1.0	(Hipparcos)
Gratton et al.	1998	12.3 ± 2.1	(Hipparcos)
Pont et al.	1998	14.0 ± 1.2	(Hipparcos)
Chaboyer et al.	1998	11.5 ± 1.3	(+ RR Lyr)
Cepheids			
Feast & Whitelock	1997	11	
Theoretical HB			
D'Antona et al.	1997	12.0 ± 1.0	
Salaris et al.	1997	12.2 ± 1.8	
Field subgiants			
Cayrel	1997	14.0 ± 2.0	(Hipparcos)

Distance to the LMC



Impact of Hipparcos : Publications

- Number of published papers using Hipparcos data

year	all	refereed
1996	57	24
1997	422	92
1998	411	220
1999	369	196
2000	392	193
2001	261	138
2002	245	142
2003	226	119
2004	167	92

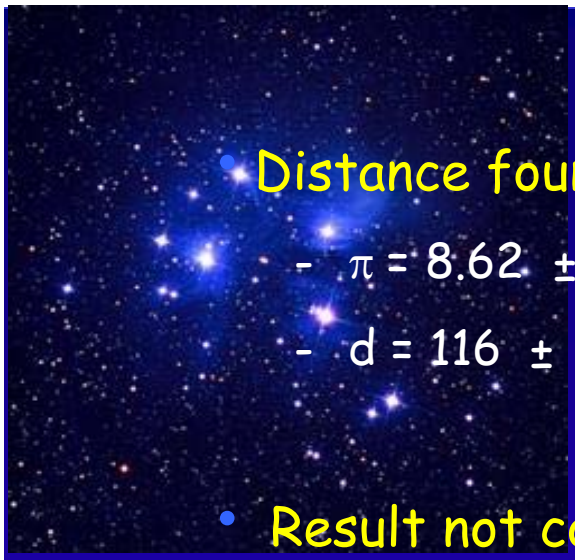
Impact of Hipparcos : Access

Access to the Catalogues at the CDS

% of retrieval

1997 to		➔ 2000	➔ 2005	
-	Hipparcos	10%	2MASS	10%
-	Tycho-2	5%	UNSO-B1	4.5%
-	USNO A2	3%	Hipparcos	3.5%
-	IRAS	1.5%	Tycho-2	3%
			GCS2	2.3%

The Pleiades issue I



- Distance found with Hipparcos by averaging over 54 clean stars
  - π = 8.62 ± 0.25 mas
  - d = 116 ± 3 pc
- Result not compatible with ground based determination
  - π = 7.7 mas ~ 10% more distant
  - d = 130 – 135 pc
  - all recent determinations support the large distance
- Result in conflict with theories of stellar evolution
  - stars 20% less luminous than expected
  - not compatible with reasonable change of the metallicity

The Pleiades issue II

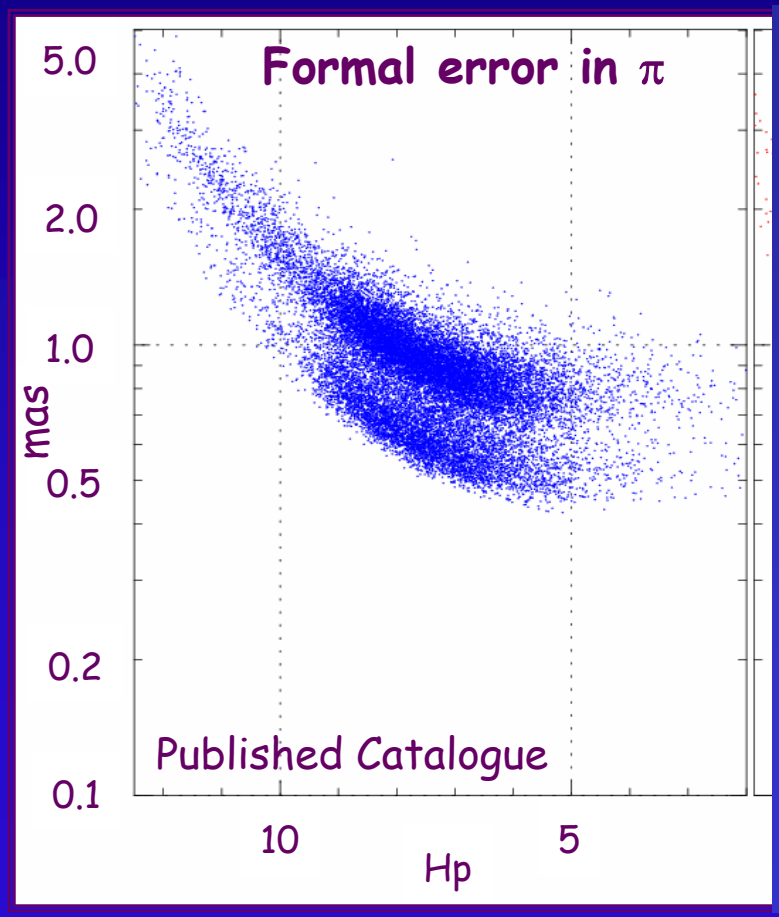
- No definite explanation found so far

- One approach seems reasonable
  - correlation between positions in small fields
  - during observation of the cluster, many bright stars in one field
  - overweight the attitude solution for this field
  - the individual errors quoted are good but globally in the same direction
  - no $n^{1/2}$ statistical improvement with the averaging over ~ 50 stars

- This does not invalidate at all the Hipparcos Catalogue
  - the error estimates have proved everywhere very realistic
  - no systematic or zonal effect found above the claimed value of 0.1 mas

Hipparcos reprocessing

- Single stars reprocessed by F. van Leeuwen (IoA, Cambridge)
  - full discussion of the field abscissa correlations
  - global fitting without using small timespan RGC



van Leeuwen, 2005

End of Lecture 1

The Pleiades issue : Hipparcos selection

- Hipparcos parallax data
  - 264 stars in Hipparcos Catalogue in the Pleiades area
  - ~ 200 easily discarded as non cluster member
  - 54 were kept as 'clean' solutions

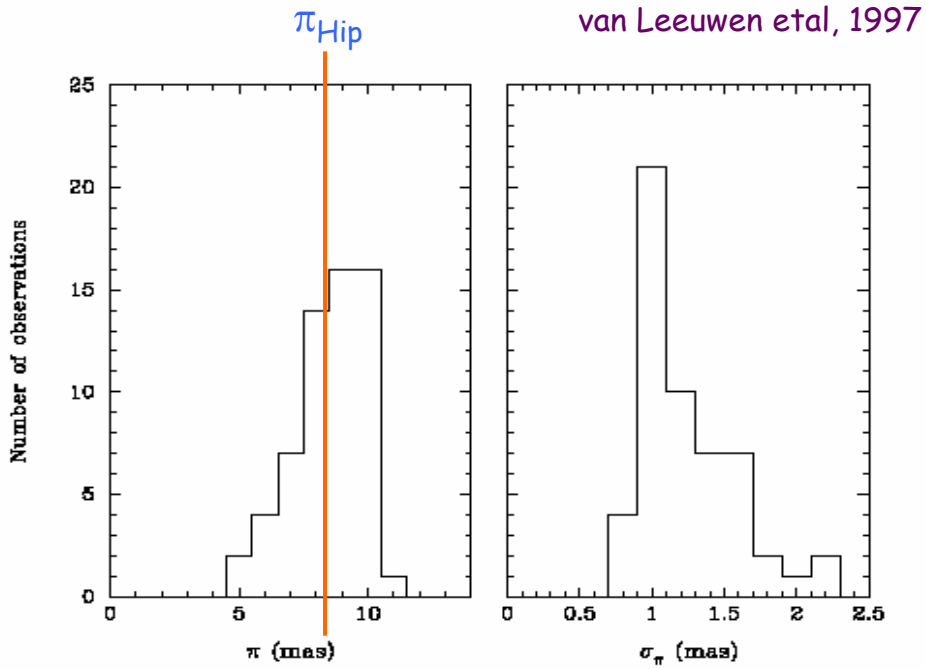
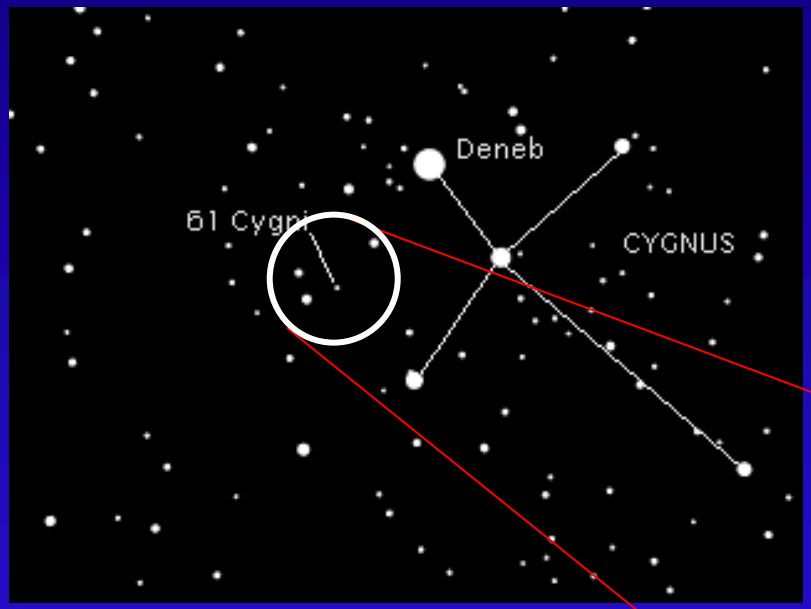


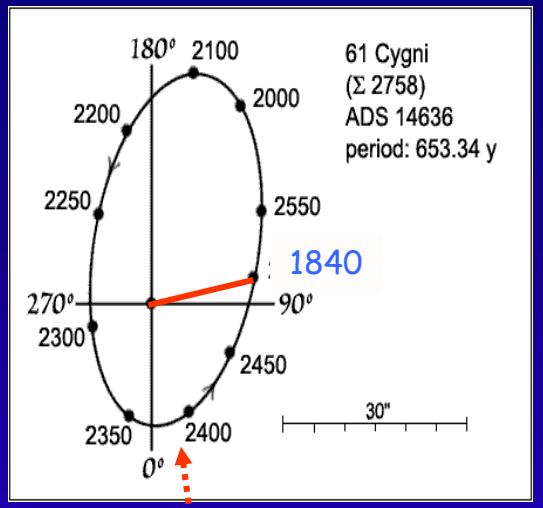
Figure 2. Distributions of the parallaxes and their accuracies for 54 Hipparcos Pleiades members.

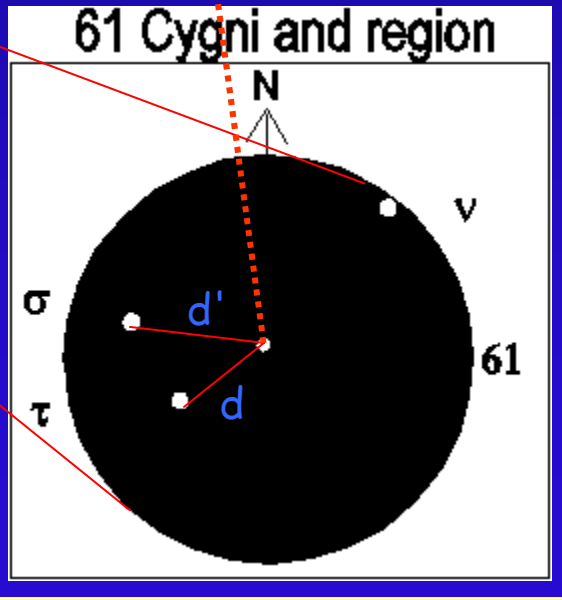
Work of Bessel

- Why 61 Cyg :
  - High proper motion star
  - well resolved binary (> 15")

F. Bessel (1784-1846)







Result of Bessel

- Solution by least square fitting

π = 0". 314 $\pm$ 0.02 (1839) , distance = 10.4 al

π = 0". 348 $\pm$ 0.01 (1841) , distance = 9.34 al

F. Bessel
Bestimmung der Entfernung des 61sten Sterns des Schwans
(Astr. Nachr. 365,366, 1838)