GAIA: 3D Mapping of the Galaxy

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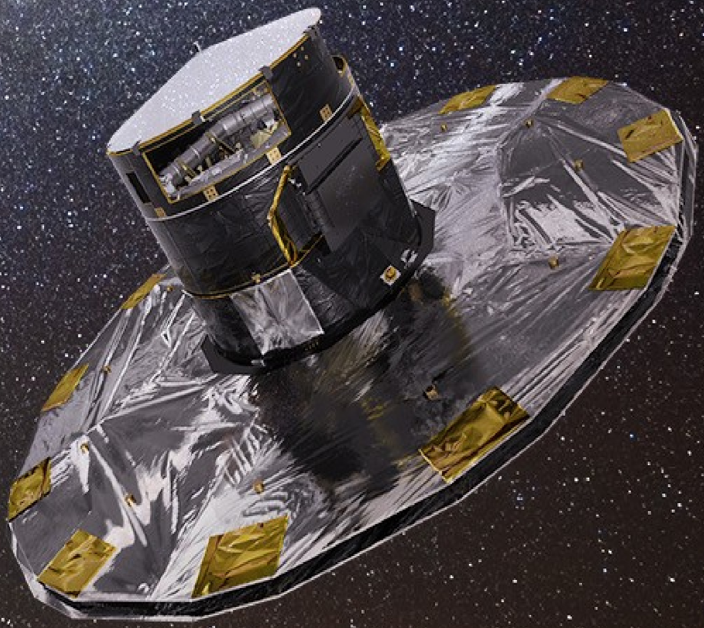
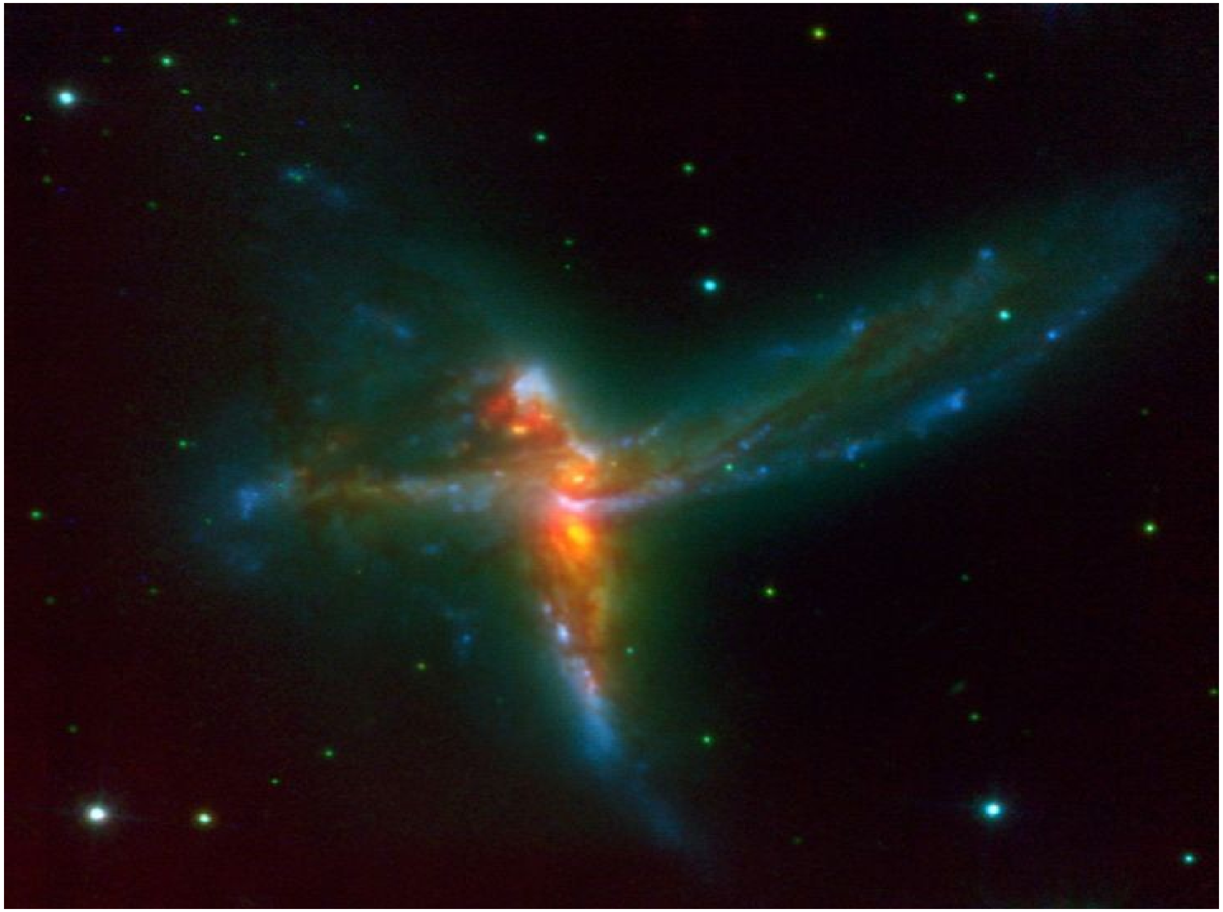


“*You understand something truly only when you can measure it precisely*.” Lord Kelvin

“With insufficient data it is easy to go wrong” Carl Sagan

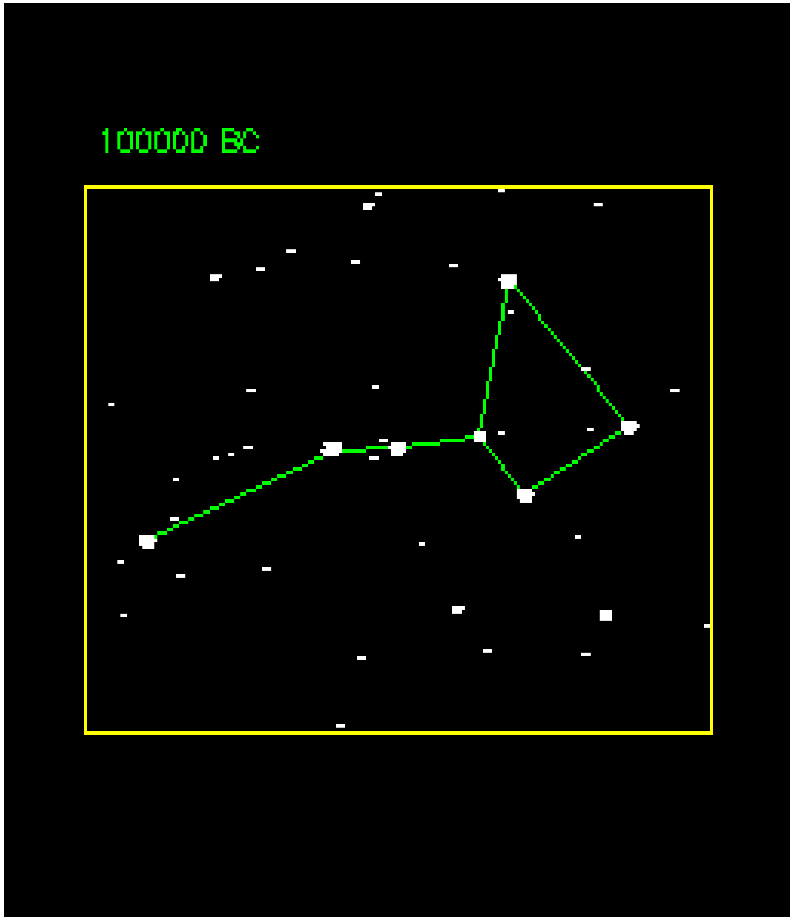
Dynamic universe



Dancing is creating a sculpture that is visible only for a moment."

— Erol Ozan

Astrometry:
The past, present & future



- Precise measurements of the positions and movements of stars and other celestial bodies.
- Provides information on the kinematics and physical origin of the Solar System and our galaxy, the Milky Way.

How small?

One second of arc: size of a Euro coin viewed from a distance of 5 km.

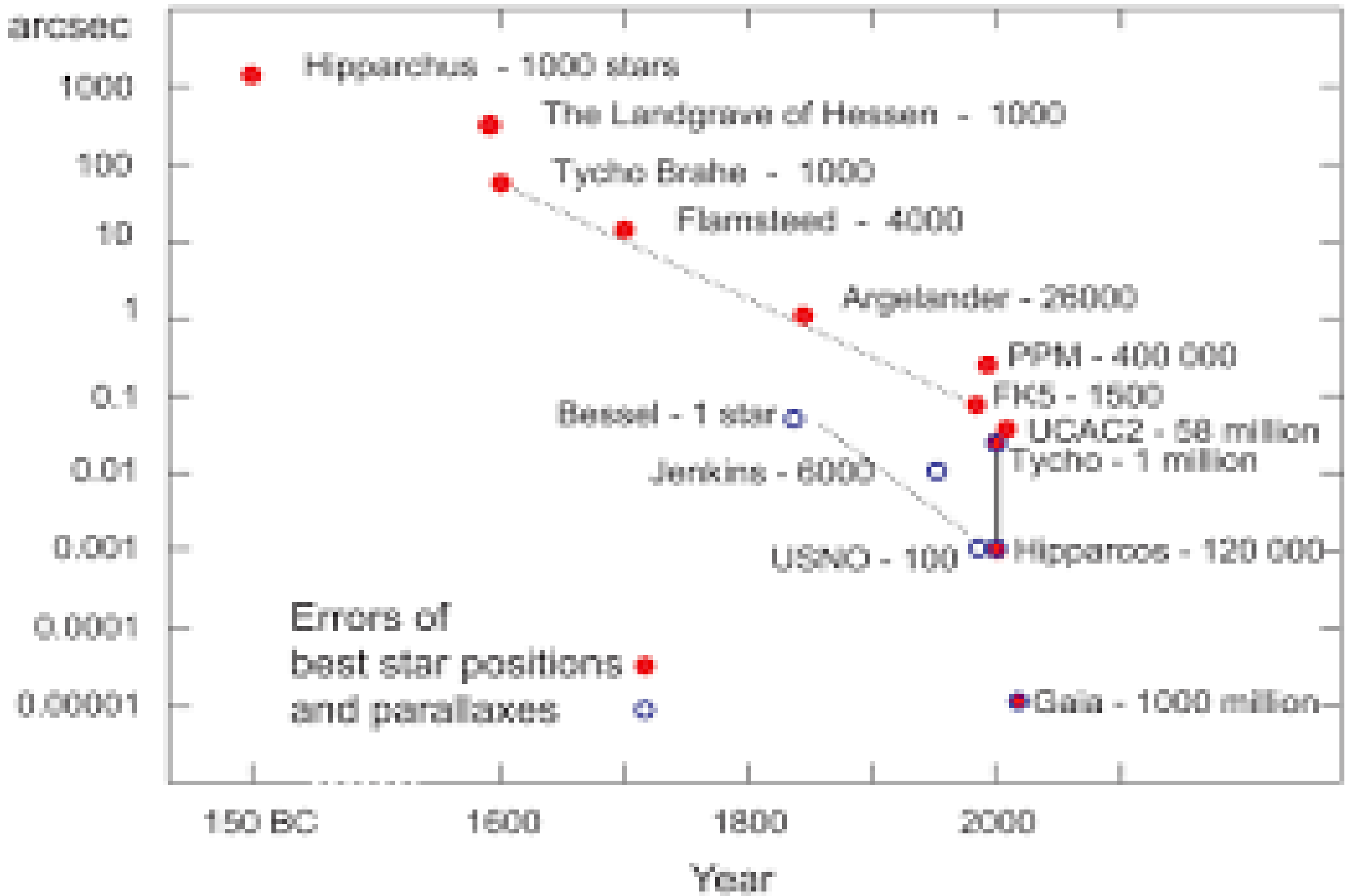
One thousandth of one second of arc: size of an astronaut on the Moon

viewed from Earth, a golf ball in New York viewed from Europe, the diameter of human hair seen from 10 km, or the (angular) growth rate of human hair in one second when viewed from a distance of 1 m.

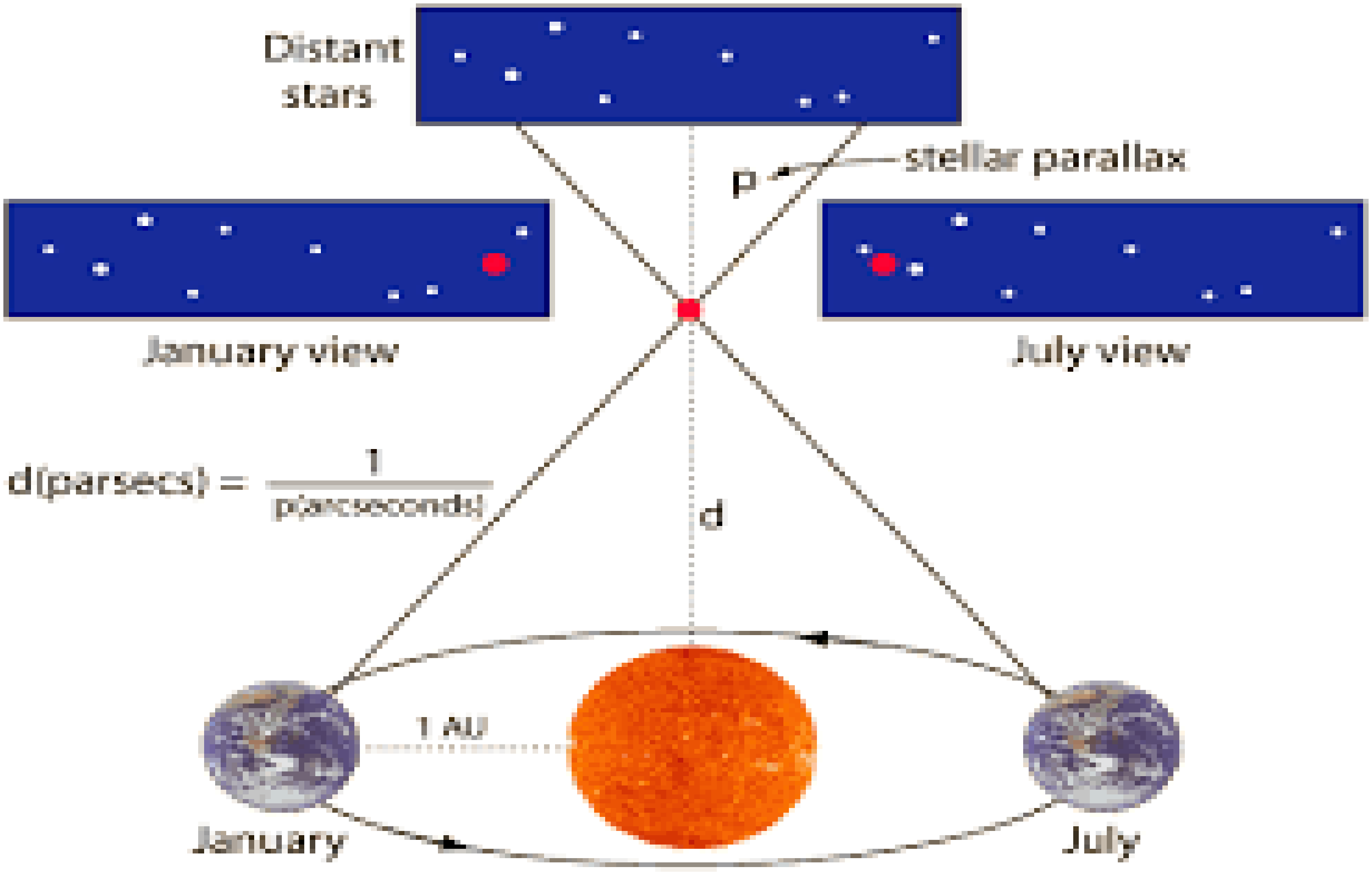
Gaia: few microseconds of arc: corresponding to one Bohr radius viewed from a distance of 1 m.

Such accuracies naturally pose extreme engineering challenges for optical quality, detector performance, and gravitational and thermal instrumental flexure.

Astrometry


arcsec
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
Hipparchus - 1000 stars
The Landgrave of Hessen - 1000
Tycho Brahe - 1000
Flamsteed - 4000
Argelander - 26000
PPM - 400 000
FK5 - 1500
Bessel - 1 star
UCAC2 - 58 million
Tycho - 1 million
Jenkins - 6000
USNO - 100
Hipparcos - 120 000
Errors of
best star positions
and parallaxes
Gaia - 1000 million
150 BC
1600
1800
2000
Year

Parallax



Distant stars
stellar parallax
p
January view
July view
d(parsecs) = 1 / p(arcseconds)
d
1 AU
January
July

Some Astrometric Catalogs

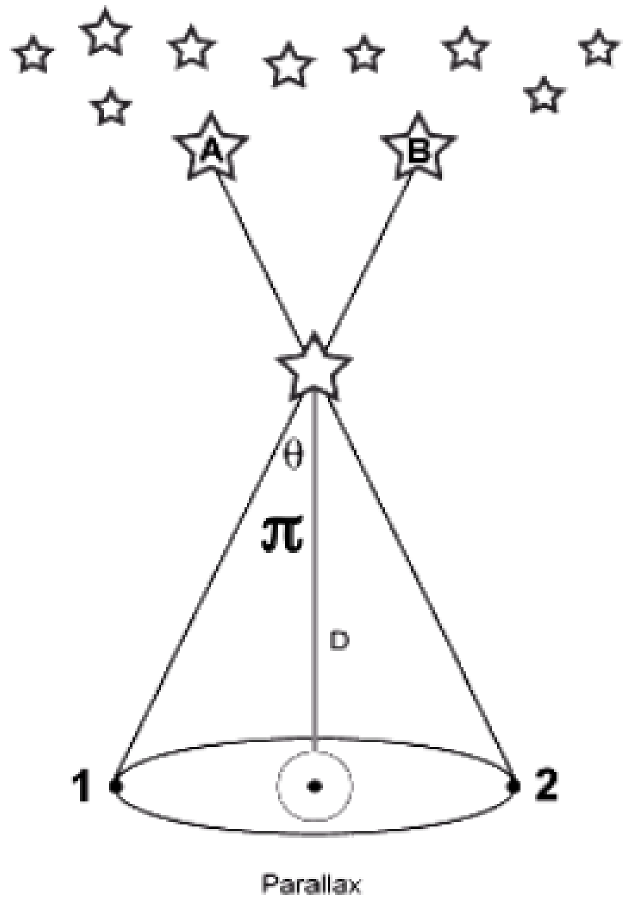
Name	*Date*	*Nstars*	*σ(p) (mas)*	*σ pm(mas/yr)*
SAO	1966	260 000	1000	10
ACRS	1991	320 000	200	5
PPM	1991	469 000	200	4
HIPPARCOS	1997	120 000	0.8	0.9
Tycho1	1997	1 060 000	40	40
ACT	1997	989 000	40	~ 2.5
TYCHO-2	1999	2 500 000	25	~ 2.5
UCAC-2	2003	48 330 000	22~70	1~6

Distances and Parallaxes

- Distances are necessary in order to convert apparent, measured quantities into absolute, physical ones (e.g., luminosity, size, mass…)
- Stellar parallax is the only direct way of measuring distances in astronomy! Nearly everything else provides relative distances and requires a basic calibration
- Small-angle formula applies:

  D [pc] **= 1 / π** [arcsec]

- Limited by the available astrometric accuracy (~ 1 mas, i.e., D < 1 kpc or so, now)



How Far Can We Measure Parallaxes?

Since nearest stars are > 1 pc away, and ground-based Telescopes have a resolution of ~1 arcsec, might seem impossible to measure π (and thus D) to any useful precision. Actually, it can be done :

1838: Bessel measured $\pi = 0.316$ arcsec for star 61 Cyg (modern value $\pi = 0.29$ arcsec)

Current ground-based: best errors of ~ 0.001 arcsec

Hipparcos satellite: measured ~10^5 bright stars with errors also of ~0.001 arcsec

GAIA satellite: will measure positions of ~10^9 stars with an accuracy of micro-arcsecs - this is a reasonable fraction of *all* the stars in the Milky Way!

Currently: measure D accurately to ~ a few $\times 100$ pc

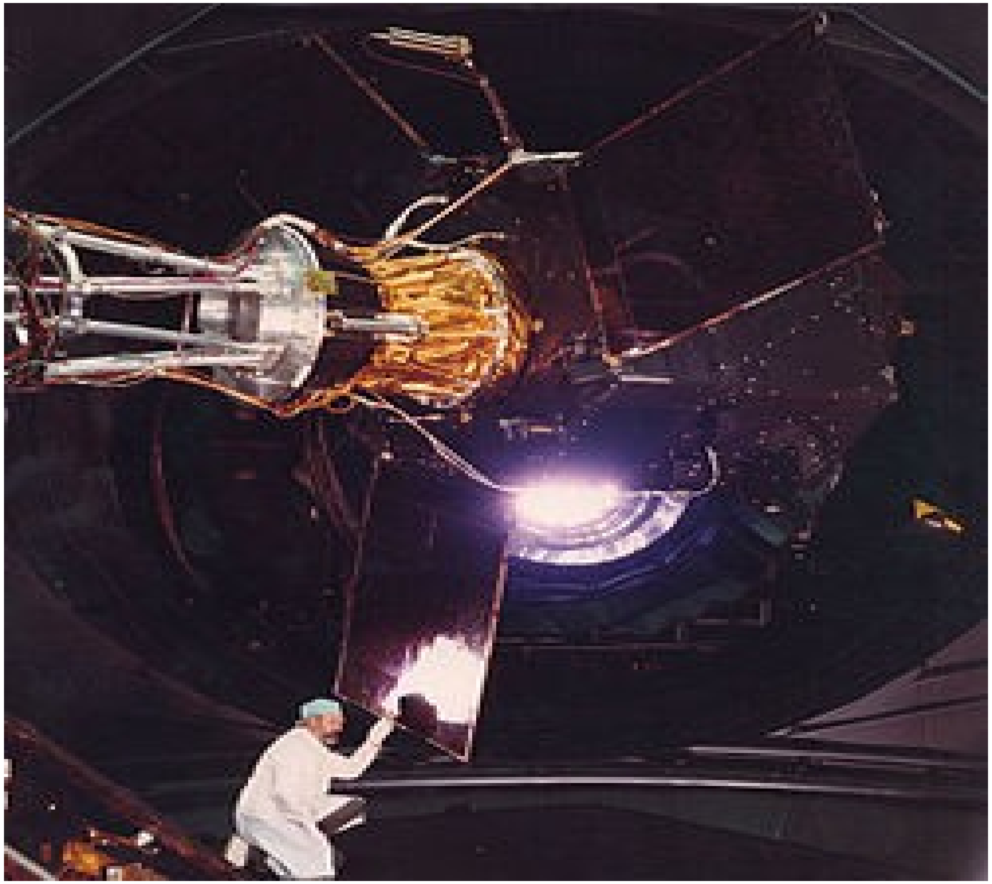
Astrometry in Practice

- Typically telescopes do not point better than to a few arcsec; so one points to a nearby star with precisely known coordinates, zeroes the telescope system, and does a small, "blind" offset to a target
- For imaging observations, one often uses positions of the stars in the frame, which have known positions (usually to a ~ 0.2 arcsec accuracy, e.g., from the ***USNO-B*** catalog), measures their XY positions in the image, and solves for the XY ⇆ RA,Dec transformation
- These transformation can be encoded in the image headers using the ***World Coordinate System (WCS)*** standard
- One-stop shop: http://www.usno.navy.mil/USNO
- Check out also http://Astrometry.net
- For the "real" astrometry, milli-arcsec is the relevant unit

Hipparcos (1989-1993)

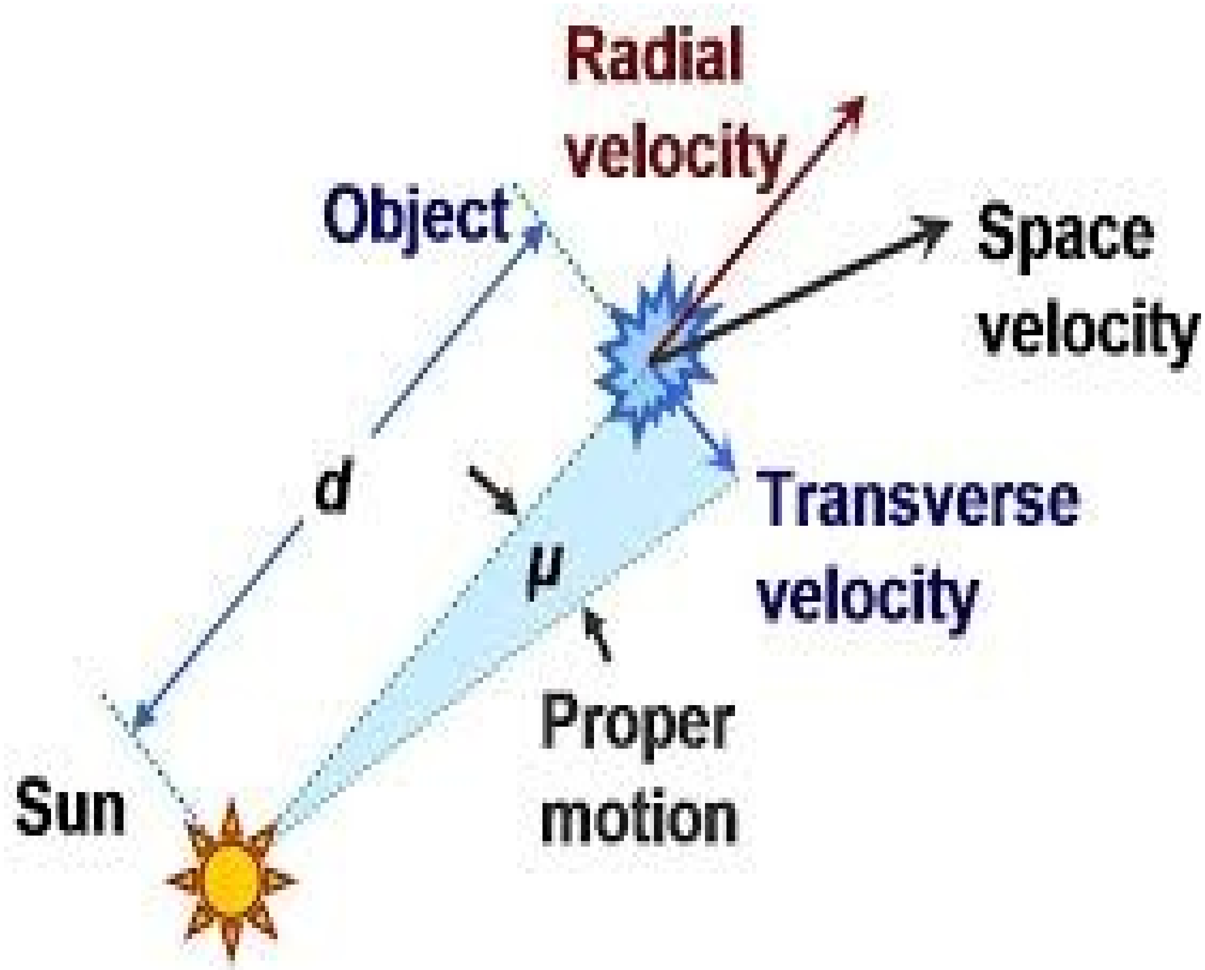
High precision parallax collecting satellite

- Accurate determination of proper motions and parallaxes of stars, radial velocity
- Hipparcos Catalogue, a high-precision catalogue of more than 118,200 stars, was published in 1997.
- The lower-precision Tycho Catalogue > million stars
- Tycho-2 Catalogue of 2.5 million stars was published in 2000.



Space Velocity

Radial velocity is determined from the Doppler effect in the spectra of the stars. ... Proper motion is the rate of angular drift across the sky (measured in arc seconds per year) and is found from the star's change of position on the sky



Astrometry

- Narrow angle Photometry
- Wide Angle Photometry

GAIA

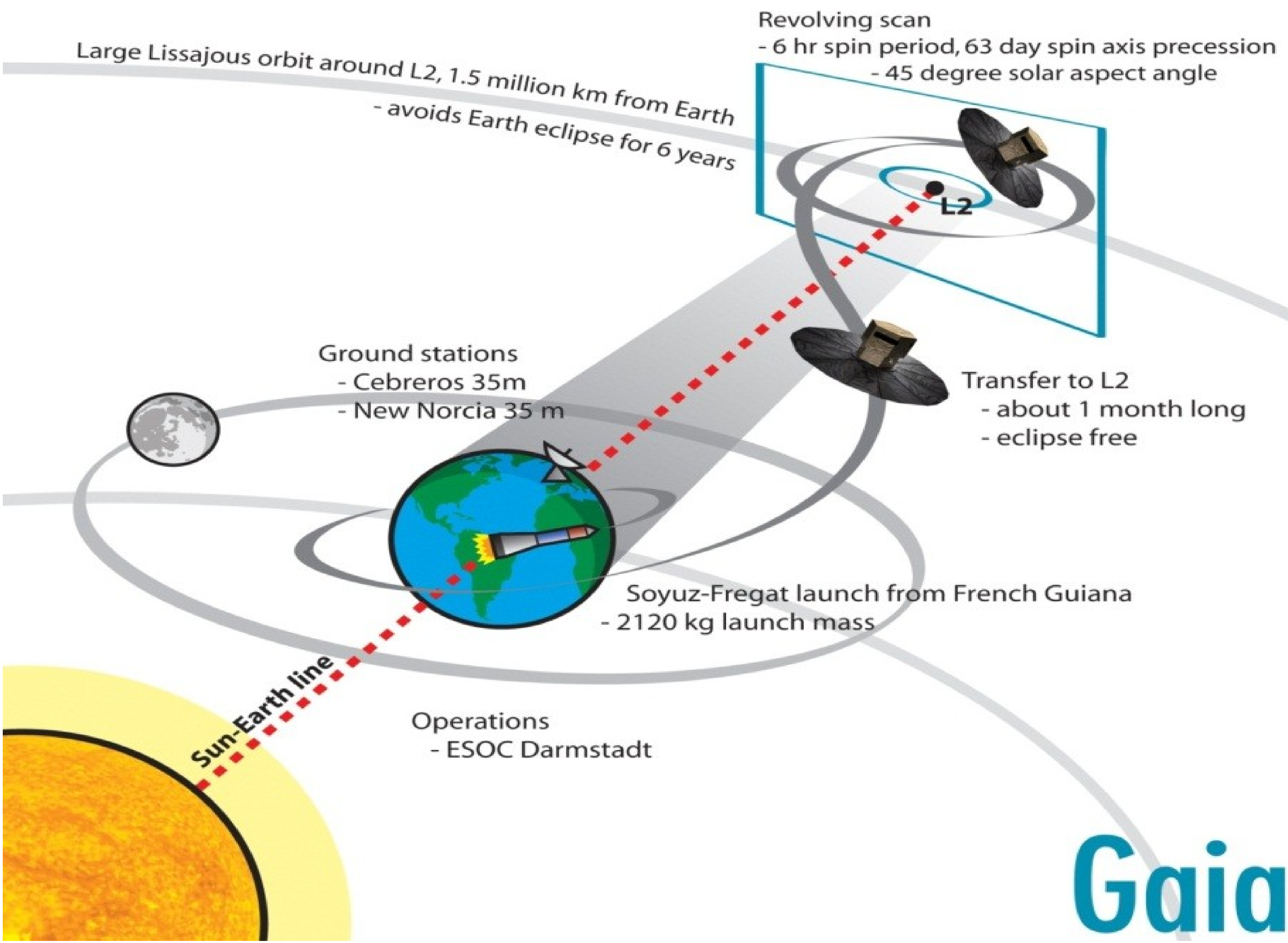
Why Space?

Bending and twinkling effects of the atmosphere,

Tiny variations in telescope alignment as the mountain-top observatories went through their endless day and night cycles of warming and cooling.

The variable flexing of telescopes under their own weight as the huge supporting structures were steered to observe different parts of the sky added other unpredictable distortions..

any telescope on Earth can observe only part of the sky at any one time:

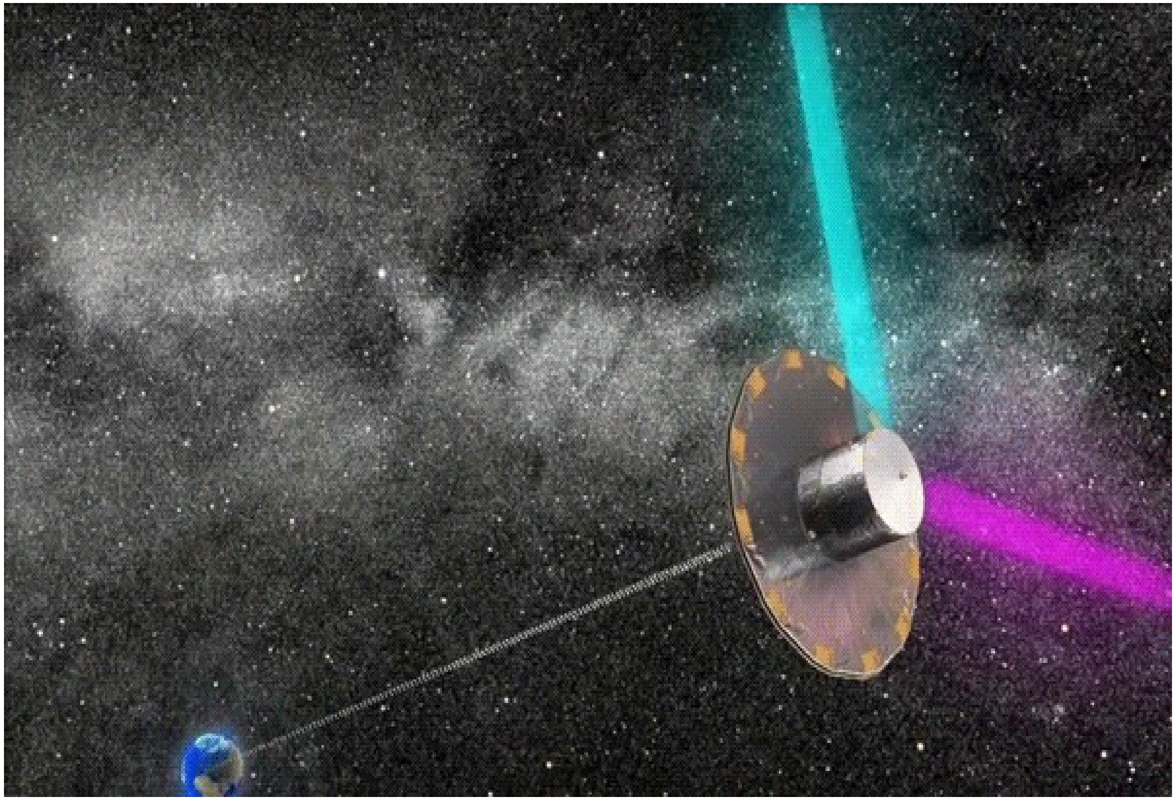


Revolving scan
- 6 hr spin period, 63 day spin axis precession
- 45 degree solar aspect angle
Large Lissajous orbit around L2, 1.5 million km from Earth
- avoids Earth eclipse for 6 years
L2
Ground stations
- Cebreros 35m
- New Norcia 35 m
Transfer to L2
- about 1 month long
- eclipse free
Soyuz-Fregat launch from French Guiana
- 2120 kg launch mass
Sun-Earth line
Operations
- ESOC Darmstadt
Gaia

GAIA: 6D revolution

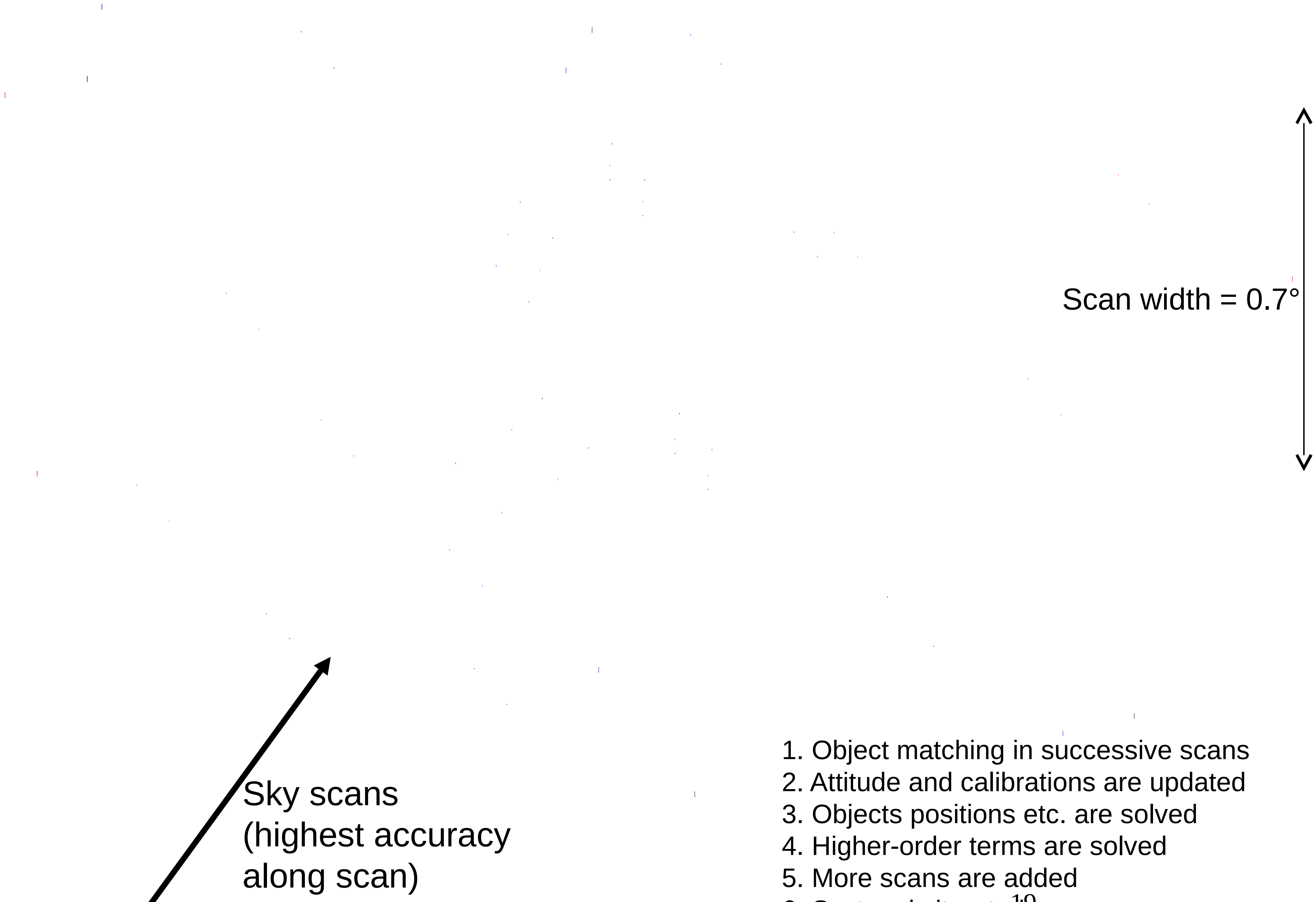
RA, Dec, parallax, RV, pmra, pmdec

Two identical, three-mirror anastigmatic (TMA) telescopes, with apertures of 1.45 m × 0.50 m pointing in directions separated by the basic angle ($\Gamma = 106^\circ.5$)
Accuracy of 24 microarcsec= 42 kpc,
0.06arcsec pixels



Galactic Archealogy!!! Imagine!!!

Data-Reduction Principles

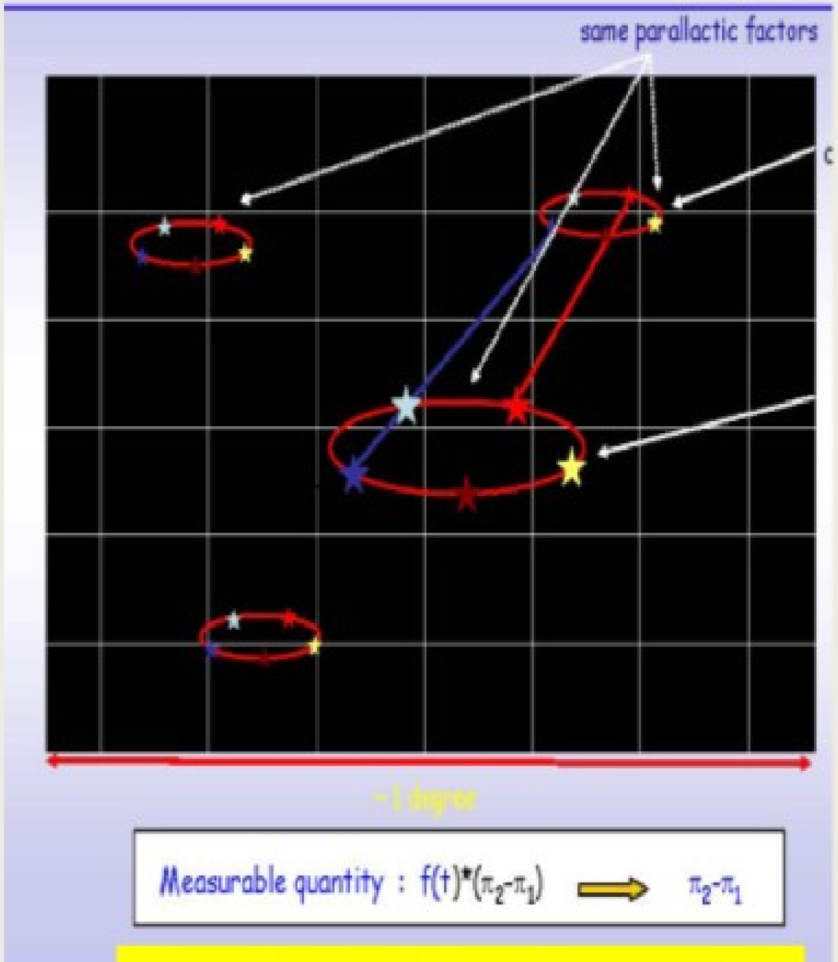


1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher-order terms are solved
5. More scans are added
6. System is iterated

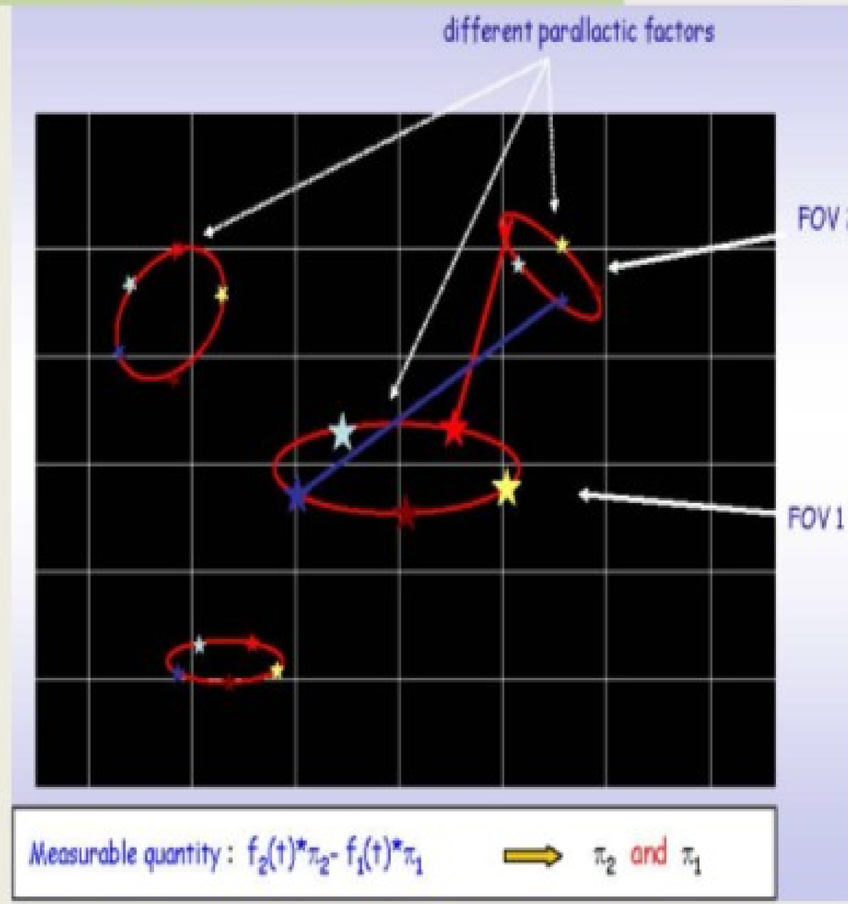
Figure courtesy Michael Perryman

Absolute astrometry

One field gives only relative measures ➔ model dependancy
Two fields break the degeneracy➔ allows absolute measurements.
Combining data at the limits of accuracy is not trivial!



Single field astrometry

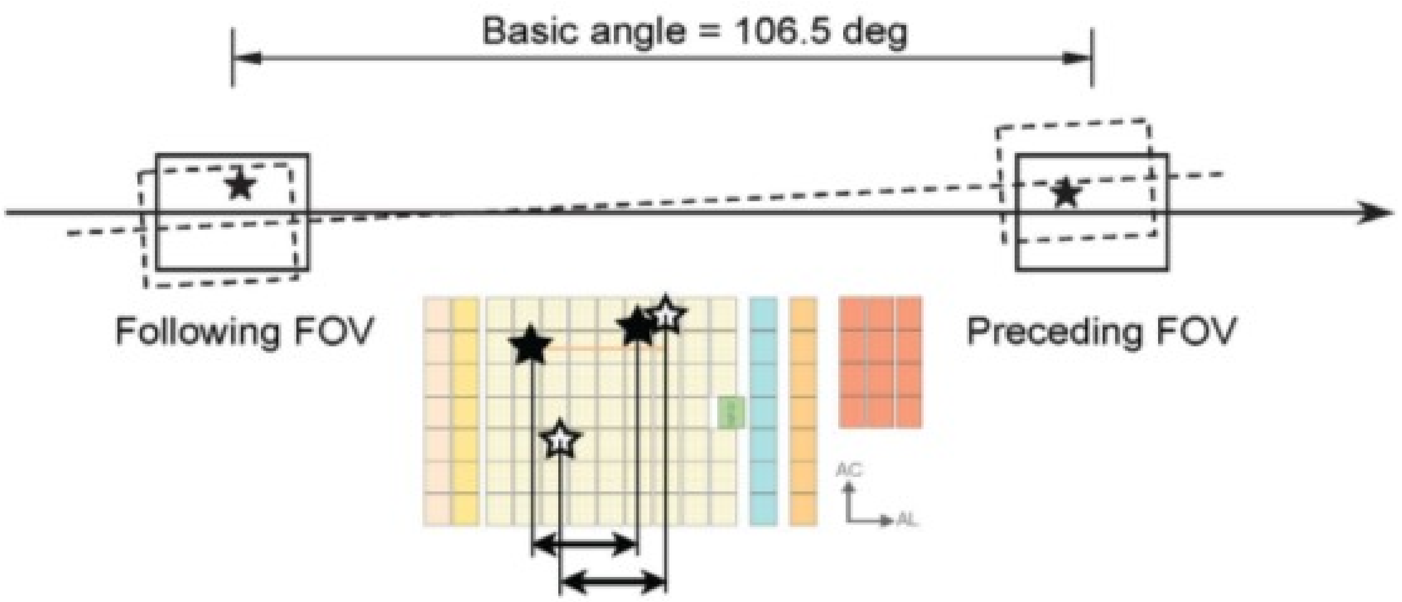


Two field astrometry

Observation principles

Why rectangular?

Why measurements are mainly 1 dimensional (along-scan):



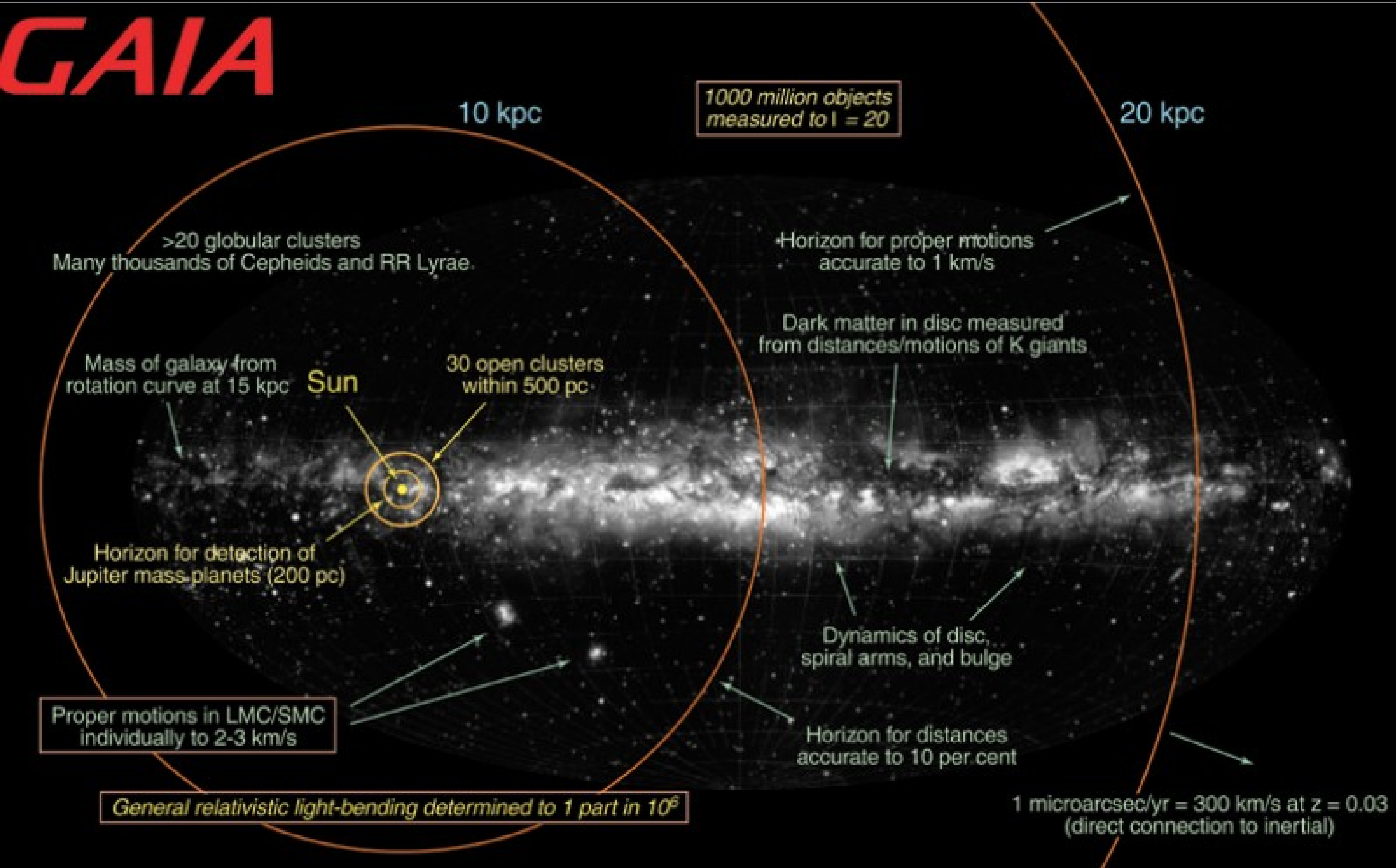
Lindegren (2004), Fig 5.

Two stars observed simultaneously in different FOV:

- Along-scan projected **angle between stars is independent of instrument orientation** to first order (solid versus dashed lines).

→two-telescope scanning mission is optimal.
Since across-scan data is much less important, can save mass and use rectangular mirrors

Scientific Goals of the GAIA Mission



Gaia: Design Considerations

- Astrometry ($G < 20$ mag):
  - completeness to 20 mag (on-board detection) $\Rightarrow 10^9$ stars
  - accuracy: 26 μarcsec at G=15 mag (Hipparcos: 1 milliarcsec at 9 mag)
  - scanning satellite, two viewing directions
    - $\Rightarrow$ global accuracy, with optimal use of observing time
  - principle: global astrometric reduction (as for Hipparcos)

- Photometry ($G < 20$ mag):
  - astrophysical diagnostics (low-dispersion photometry) + chromaticity
    - $\Rightarrow \Delta T_{eff} \sim 100$ K, log g, [Fe/H] to 0.2 dex, extinction (at G=15 mag)

- Radial velocity ($G_{RVS} < 16$ mag):
  - accuracy: 15 km s^{-1} at G_{RVS}=16 mag
  - application:
    - ∀ third component of space motion, perspective acceleration
    - ∀ dynamics, population studies, binaries
    - ∀ spectra for $G_{RVS} < 12$ mag: chemistry, rotation
  - principle: slitless spectroscopy in Ca triplet (845-872 nm) at R = ~10,800

Gaia: Complete, Faint, Accurate

	Hipparcos	Gaia
Magnitude limit	12 mag	20 mag
Completeness	7.3 – 9.0 mag	20 mag
Bright limit	0 mag	3 mag (assessment for brighter stars ongoing)
Number of objects	120,000	47 million to G = 15 mag
		360 million to G = 18 mag
		1192 million to G = 20 mag
Effective distance limit	1 kpc	50 kpc
Quasars	1 (3C 273)	500,000
Galaxies	None	1,000,000
Accuracy	1 milliarcsec	7 μarcsec at G = 10 mag
		26 μarcsec at G = 15 mag
		600 μarcsec at G = 20 mag
Photometry	2-colour (B and V)	Low-res. spectra to G = 20 mag
Radial velocity	None	15 km s^{-1} to G_{RVS} = 16 mag
Observing	Pre-selected	Complete and unbiased

Stellar Astrophysics

- Comprehensive luminosity calibration, for example:
  - distances to 1% for ~10 million stars to 2.5 kpc
  - distances to 10% for ~100 million stars to 25 kpc
  - rare stellar types and rapid evolutionary phases in large numbers
  - parallax calibration of all distance indicators

    e.g., Cepheids and RR Lyrae to LMC/SMC

- Physical properties, for example:
  - clean Hertzsprung–Russell diagrams throughout the Galaxy
  - Solar-neighbourhood mass and luminosity function

    e.g., white dwarfs (~400,000) and brown dwarfs (~500)
  - initial mass and luminosity functions in star-forming regions
  - luminosity function for pre-main-sequence stars
  - detection and dating of all spectral types and Galactic populations
  - detection and characterisation of variability for all spectral types

One Billion Stars in 3D will provide …

- in our Galaxy …
  - the distance and velocity distributions of all stellar populations
  - the spatial and dynamic structure of the disk and halo
  - its formation history
  - a detailed mapping of the Galactic dark-matter distribution
  - a rigorous framework for stellar-structure and evolution theories
  - a large-scale survey of extra-solar planets (~7,000)
  - a large-scale survey of Solar-system bodies (~250,000)

- … and beyond
  - definitive distance standards out to the LMC/SMC
  - rapid reaction alerts for supernovae and burst sources (~6,000)
  - quasar detection, redshifts, microlensing structure (~500,000)
  - fundamental quantities to unprecedented accuracy: γ to 2×10^{-6} (2×10^{-5} present)

Exo-Planets: Expected Discoveries

- Astrometric survey:
  - monitoring of ~150,000 FGK stars to ~200 pc
  - detection limits: ~1M_J and P < 10 years
  - complete census of all stellar types, P ~ 2-9 years
  - masses, rather than lower limits (m sin i)
  - multiple systems measurable, giving relative inclinations

- Results expected:
  - ~2000 exo-planets (single systems)
  - ~300 multi-planet systems
  - displacement for 47 UMa = 360 μas
  - orbits for ~1000 systems
  - masses down to 10 M_{Earth} to 10 pc

- Photometric transits: ~5000

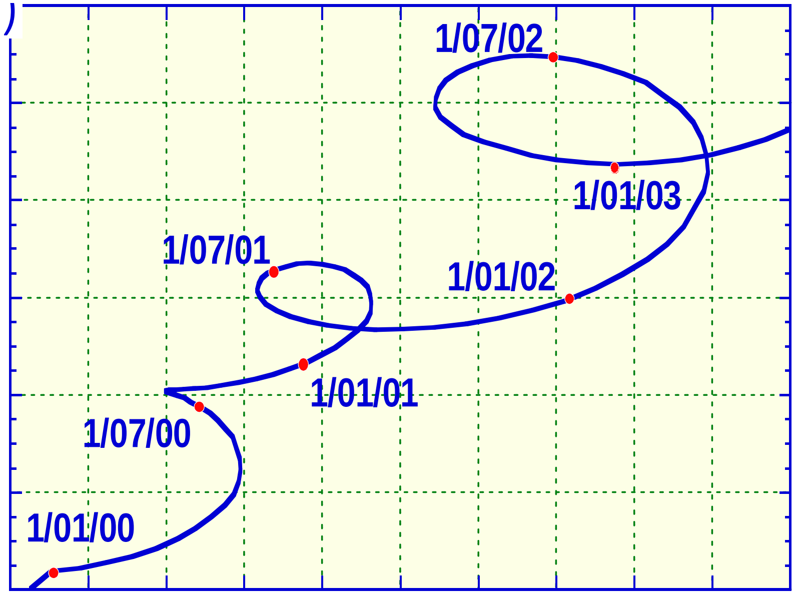


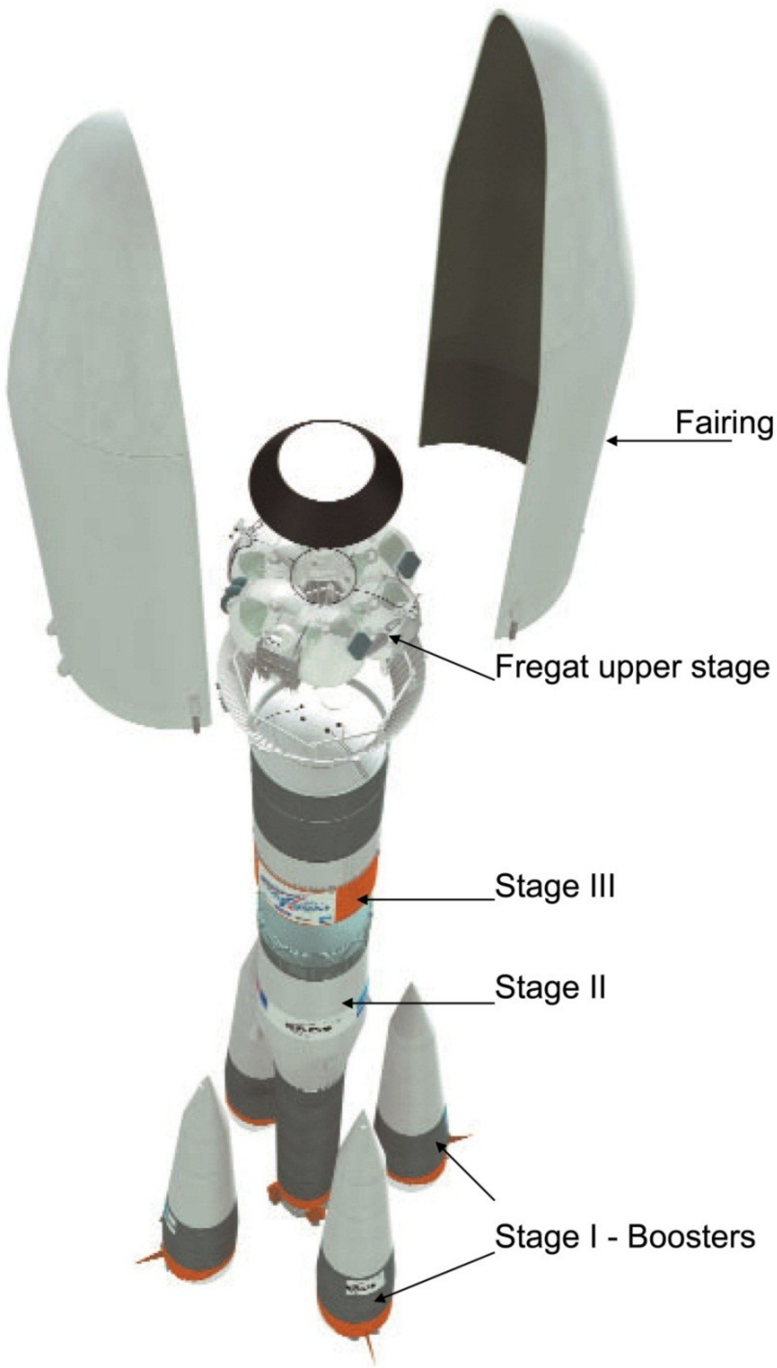
Figure courtesy François Mignard

Studies of the Solar System

- Asteroids etc.:
  - deep and uniform (G=20 mag) detection of all moving objects
  - ~250,000 objects observed, mainly main-belt asteroids
  - orbits: 30 times better than present, even after 100 years
  - spin-axis direction, rotation period, shape parameters for majority
  - taxonomy/mineralogical composition versus heliocentric distance
  - diameters for ~1000 to 20%, masses for ~150 to 10%
  - Trojan companions of Mars, Earth, and Venus
  - Kuiper-Belt objects: ~50 objects to G=20 mag (binarity, Plutinos)
  - Centaurs: ~50 objects

- Near-Earth Objects:
  - Amors, Apollos and Atens (4389, 5156, 811 known today)
  - ~1600 Potentially Hazardous Asteroids (PHA) >1 km predicted (1435 currently known)
  - detection limit: 260-590 m at 1 AU, depending on albedo

Satellite and System



- ESA-only mission
- Launch: 19 December 2013
- Launcher: Soyuz–Fregat from French Guiana
- Orbit: L2 Lissajous orbit
- Ground stations: Cebreros, New Norcia + Malargüe
- Lifetime: 5 years (1 year potential extension)
- Downlink rate: 4 - 8 Mbps

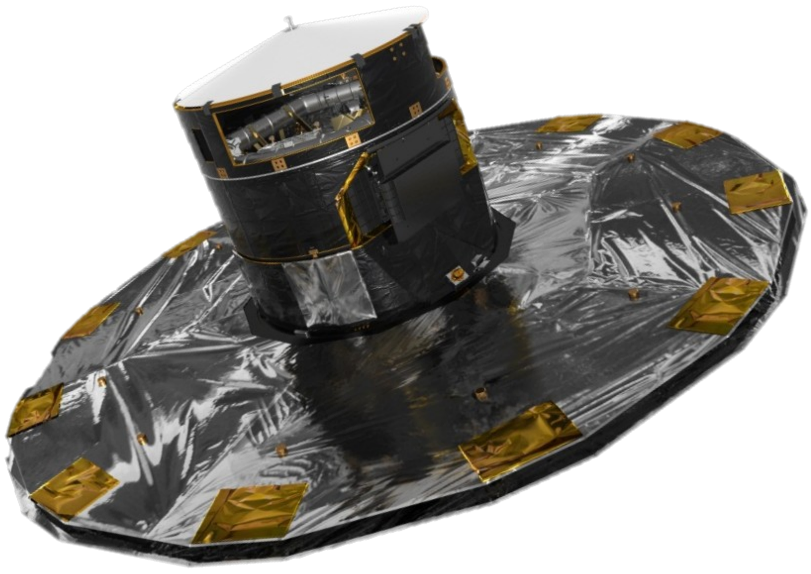


Figure Soyuz: Arianespace; figure Gaia: ESA - C. Carreau

Payload and Telescope

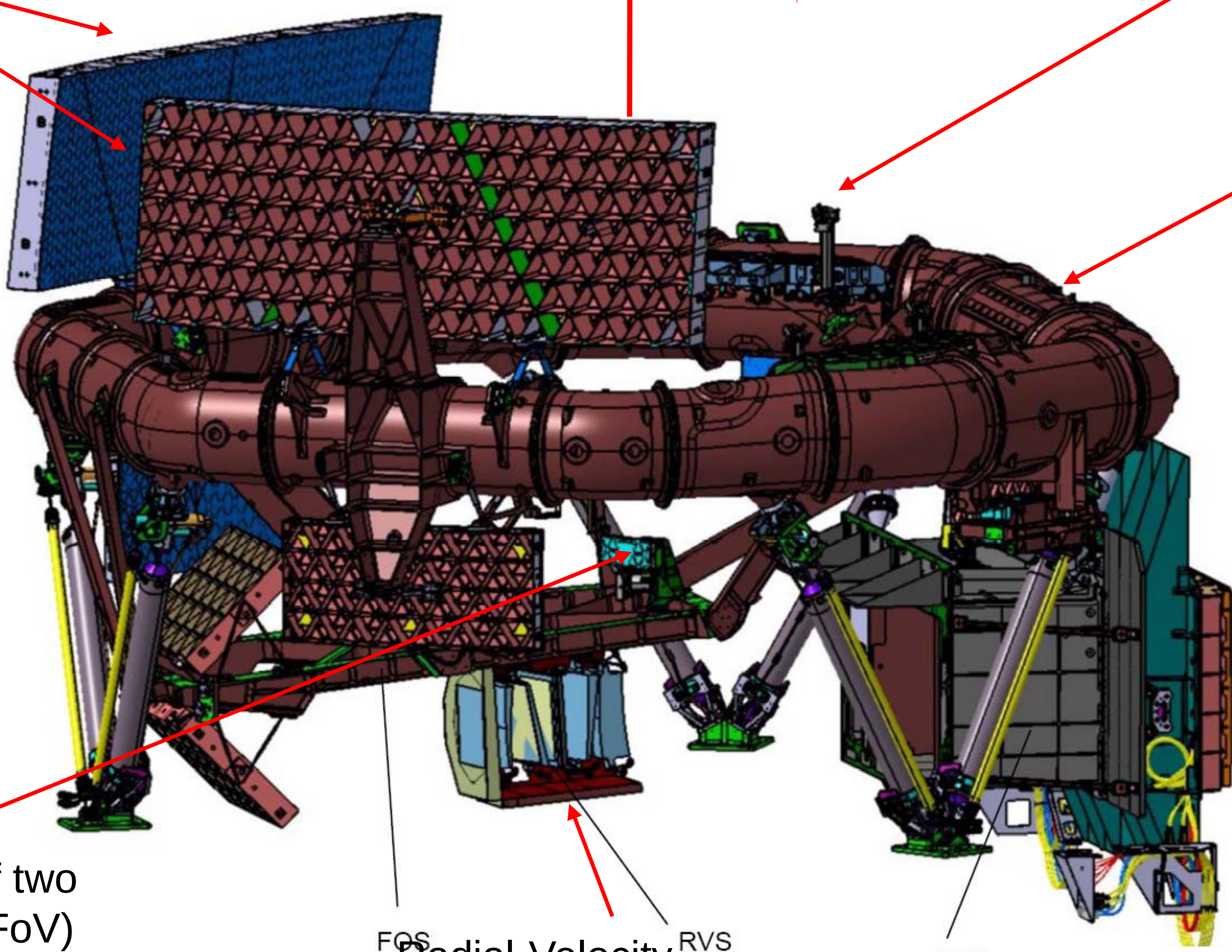
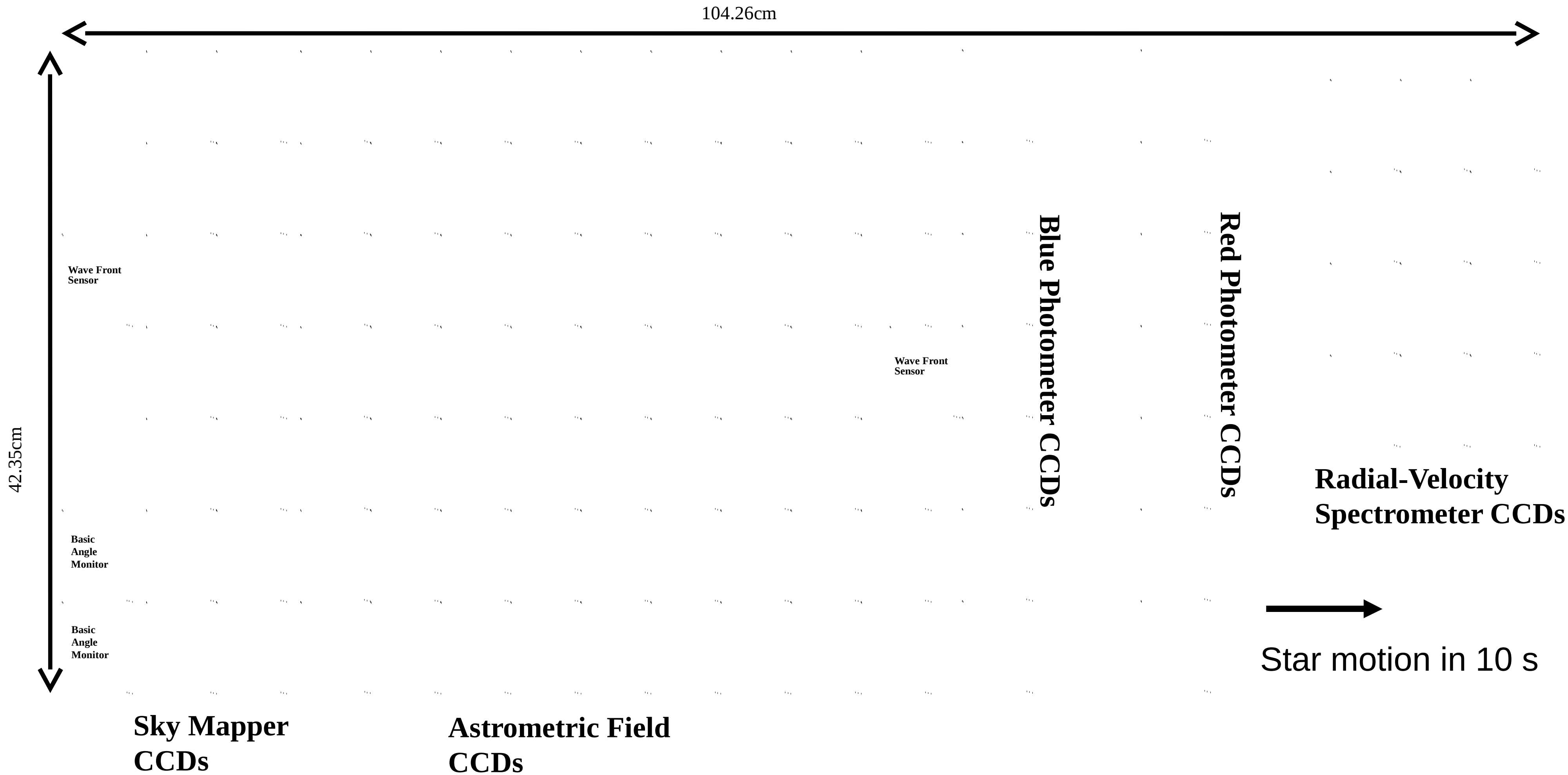


Figure courtesy EADS-Astrium

Figure courtesy Alex Short

Focal Plane



Total field:
- active area: 0.75 deg^2
- CCDs: 14 + 62 + 14 + 12 (+ 4)
- 4500 x 1966 pixels (TDI)
- pixel size = 10 µm x 30 µm
  = 59 mas x 177 mas

Sky mapper:
- detects all objects to G=20 mag
- rejects cosmic-ray events
- field-of-view discrimination

Astrometry:
- total detection noise ~ 4 e^-

Photometry:
- spectro-photometer
- blue and red CCDs

Spectroscopy:
- high-resolution spectra
- red CCDs

Sky-Scanning Principle

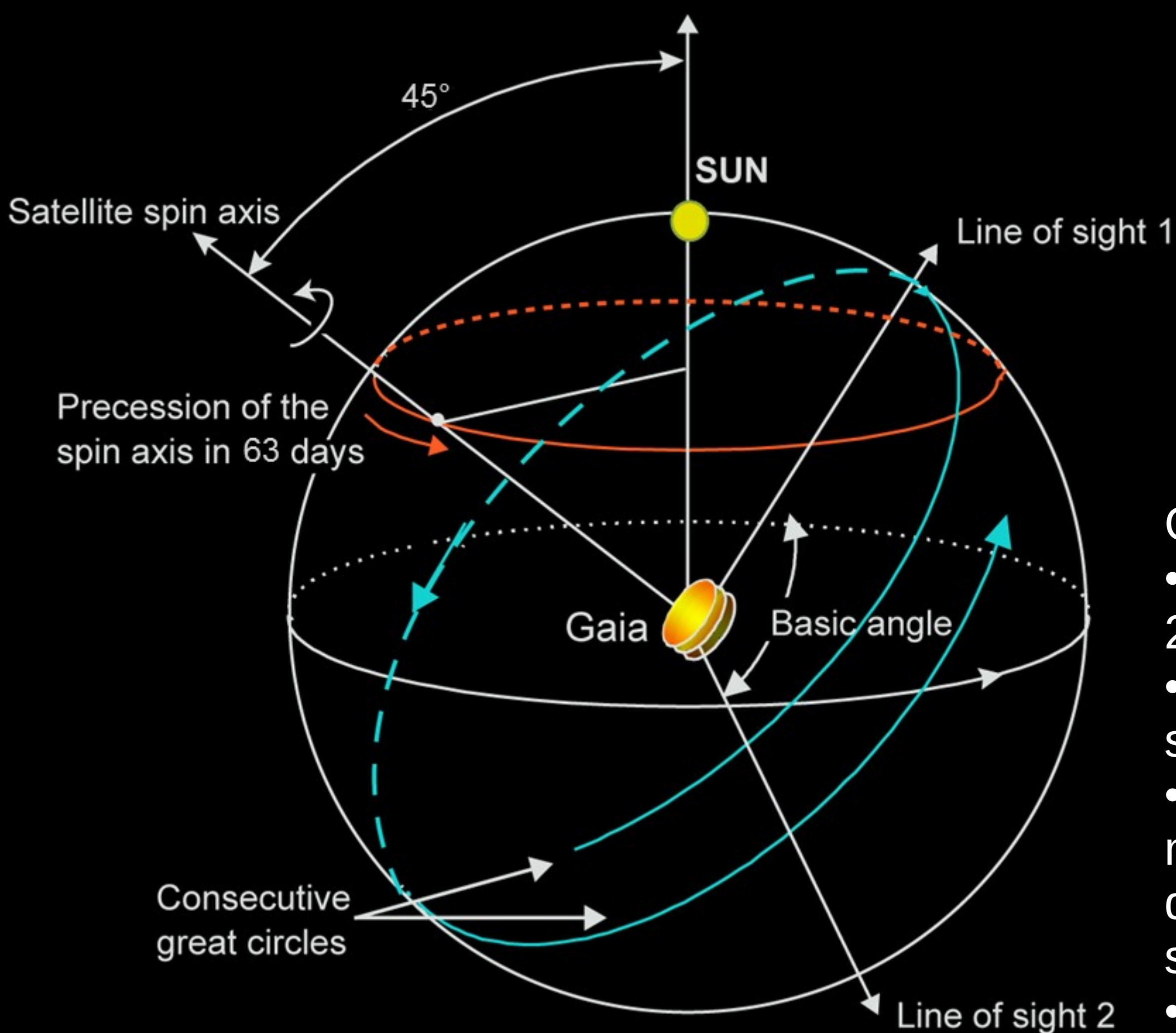


Figure ESA

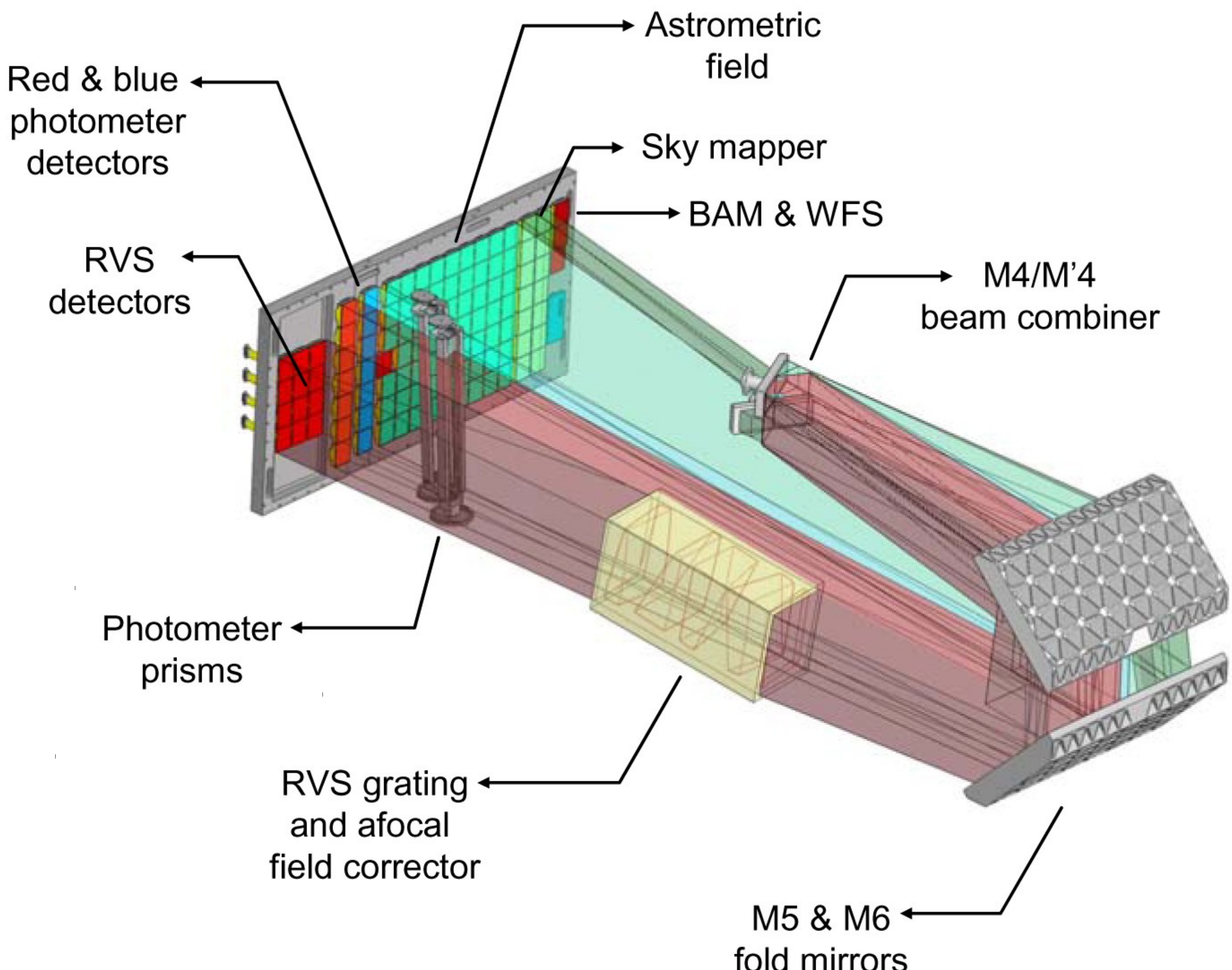
Spin axis 45° to Sun
Scan rate: 60 arcsec s^{-1}
Spin period: 6 hours

3 motions:
Spin
Precession: 63 days
Revolution: 365.25 days

Gaia operations

- Gaia in routine operations since July 2014
- Scanning operations with observing strategy of continuous measuring
- Dead-time: orbit maintenance, micrometeoroids, decontaminations, ground station weather
- Nominal 5-year mission ends mid-2019
- Estimated end of mission due to cold gas exhaustion end-2023 (±1year)

Photometry Measurement Concept



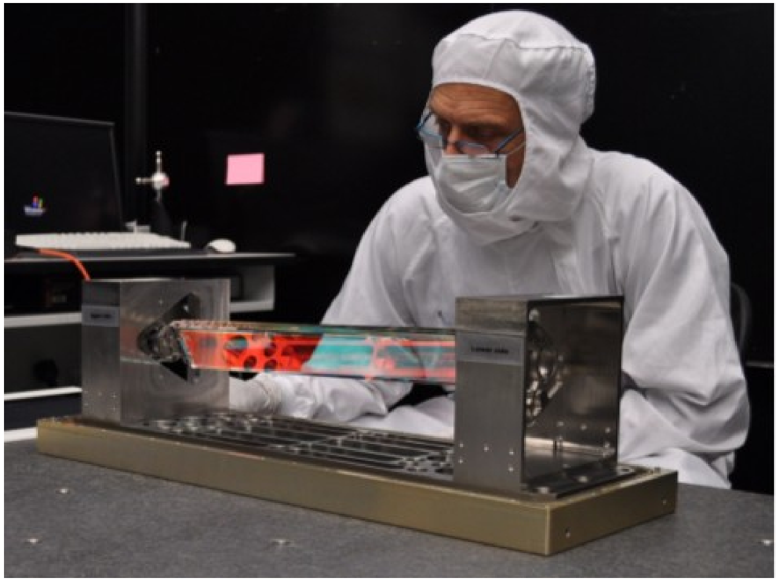
Blue photometer:
330 - 680 nm

Red photometer:
640 - 1050 nm

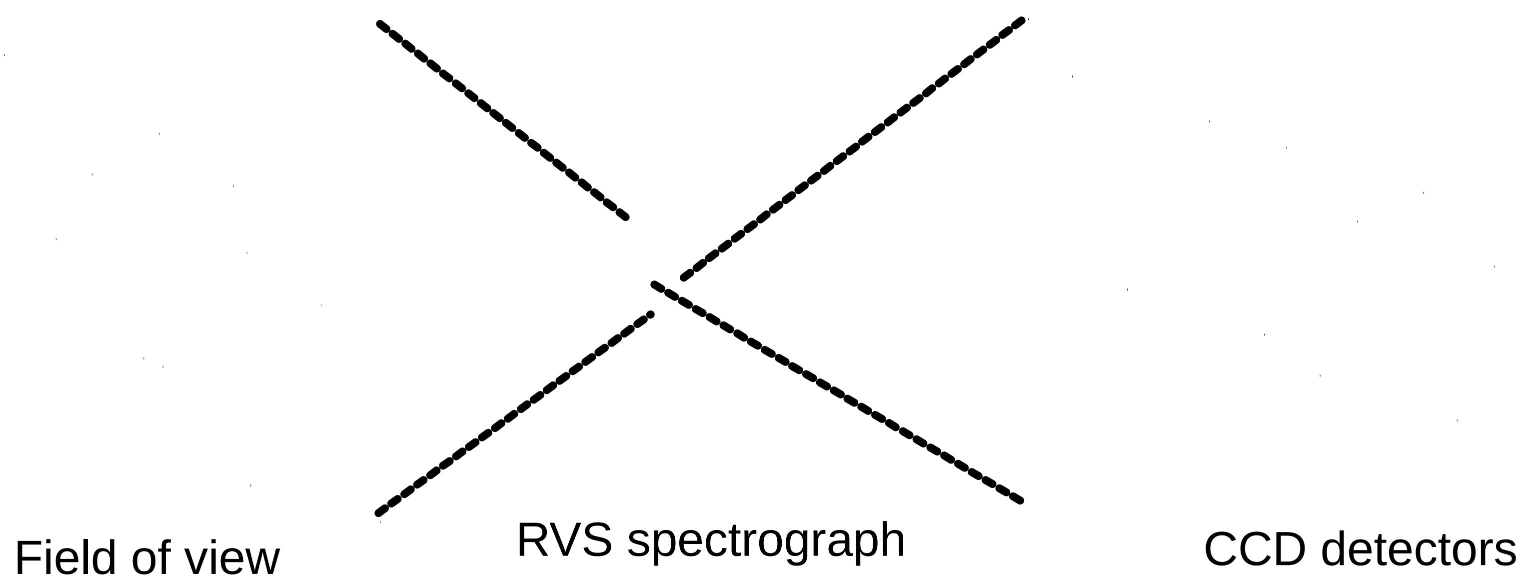
Figure courtesy EADS-Astrium

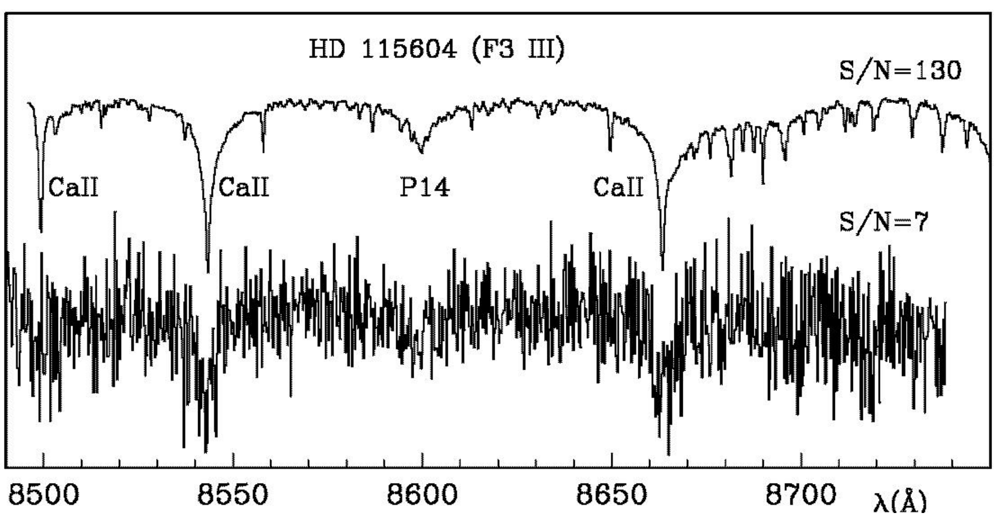
Gaia photometry

- Photometric measurements: 120 billion
- G<20.7 mag
- Spectrophotometry
- 330-680 nm BP
- 640-1050 nm RP
- Astrometric measurements also photometric in G-band
- In crowded regions on-board resource allocation exhausted
- Bright limit around G=2-3 mag
- Looking into more complete data collection for these stars



Radial-Velocity Measurement Concept (2/2)





RVS spectra of F3 giant (V = 16 mag)
S/N = 7 (single measurement)
S/N = 130 (summed over mission)

Figures courtesy David Katz

Gaia spectroscopy

- Spectroscopic measurements: 11 billion
- G RVS <16.2 mag
- 845-872 nm with R about 11,000
- Radial Velocity Spectrometer for >100 million radial velocities
- Spectroscopy till about G RVS =12 mag
- In crowded regions on-board resource allocation exhausted to some extent, but crowdedness sets in earlier
- Bright limit around G=2-3 mag

Some GAIA numbers

Once at the observation point, Gaia will start oscillating around L2 for 5 years, travelling for about 16 million kilometres. It is like going around the world each year 80 times for 5 years (instead of once in 80 days…).

Over its entire lifetime, Gaia will download around 100 TeraBytes of data (1 TeraByte = 1 000 000 000 000 bytes). If the data were copied onto CD-ROMs of 737 MB capacity, a total amount of 135 685 disks would be needed, enough to cover a surface of 7 basketball fields. Running out of CD-ROMs and using DVD writable discs instead, with a capacity of 4.7 GigaByte per DVD we would have 32 000 hours' worth of movies, that is, over 3 and half years of galactic entertainment.

And at the end, how much does a star cost? Gaia will measure an astounding 1 billion stars in its lifetime. If the overall cost of the Gaia mission is €950 000 000, (including the scientific consortium) that means that one star costs less than €1, overall a good deal!

Scientific Organisation

- Gaia Science Team (GST):
  7 members + ESA Project Scientist + DPAC Executive Chair

- Scientific community:
  - organised in Data Processing and Analysis Consortium (DPAC)
  - 450+ scientists in 20+ countries active at some level
  - GREAT network for post-mission science exploitation

- Community is active and productive:
  - regular Science Team / DPAC meetings
  - growing archive of scientific and processing-software reports
  - advance of algorithms, calibration models, accuracy models, etc.

- Data-distribution policy:
  - final catalogue ~2022
  - intermediate catalogues defined
    - intermediate releases starting 2016 with positions; parallaxes and proper motions will be added in 2017
  - science-alerts data released immediately
  - no proprietary data rights

How are stars formed?

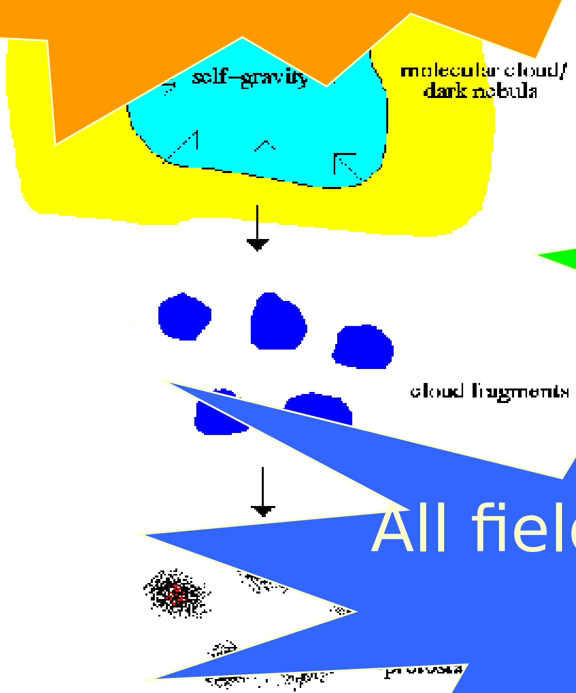
Stars are born in clouds as these:

- Giant Molecular clouds
- Very thin, **low-density** cloud
  (10,000 atoms per cm^3)
- Very **cold**, T~10-20 K, so molecules can form --> **molecular cloud**
- Made mostly of H (75%) and He (23-25%) gas and a bit of heavier atoms (<2%).

ation

Stars are not born in isolation!

vitational Vs Thermal energy

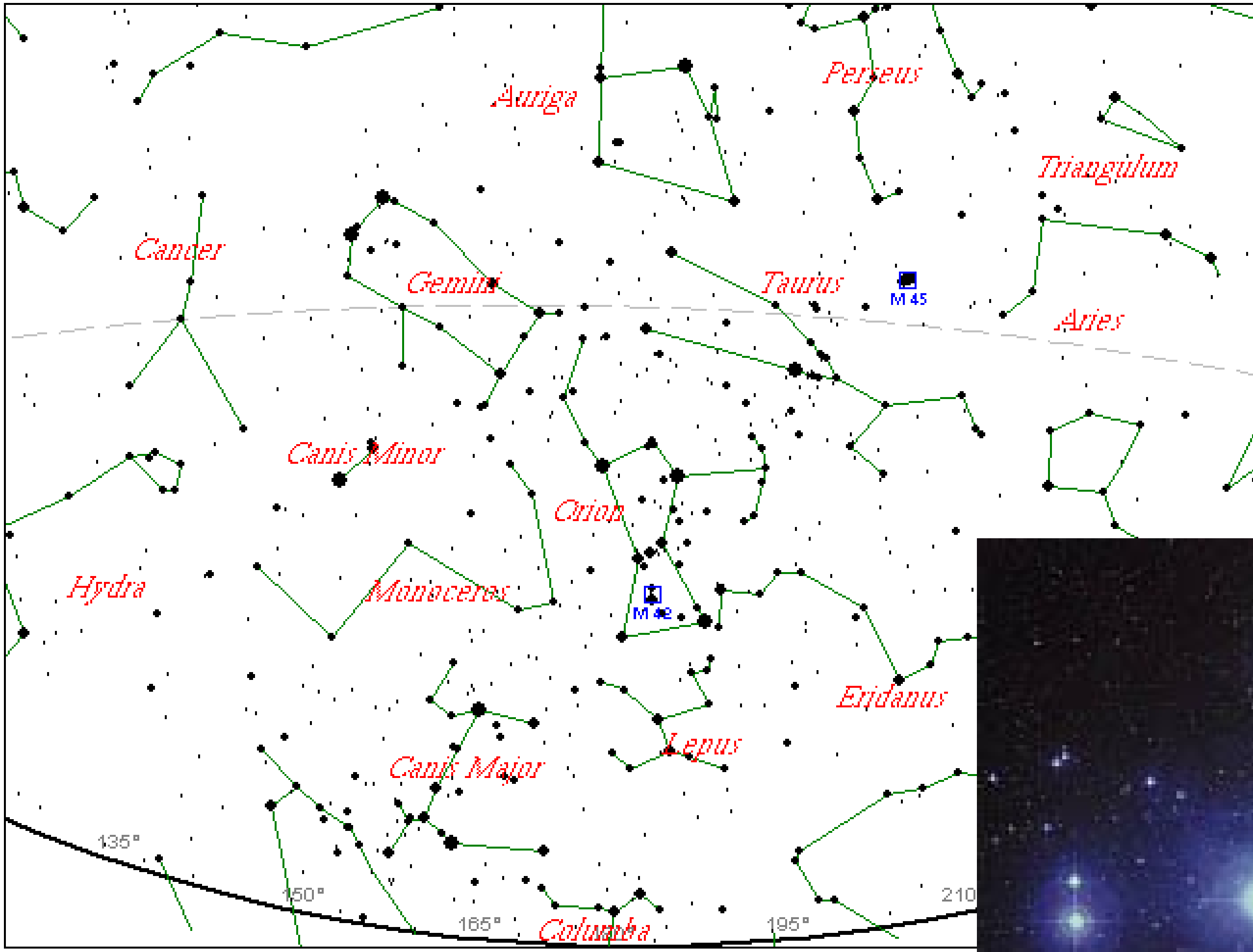


They are always born in groups

star cluster

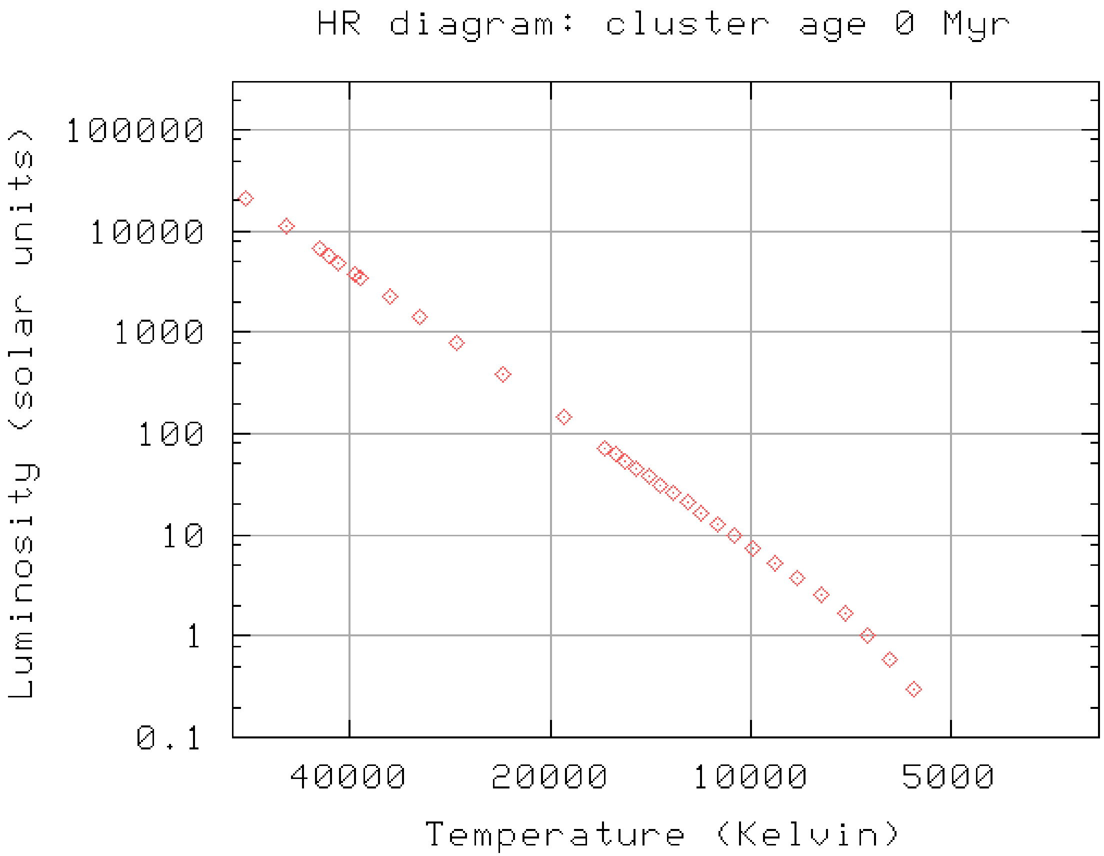
All field stars are from clusters

The Pleiades



27 April 2017

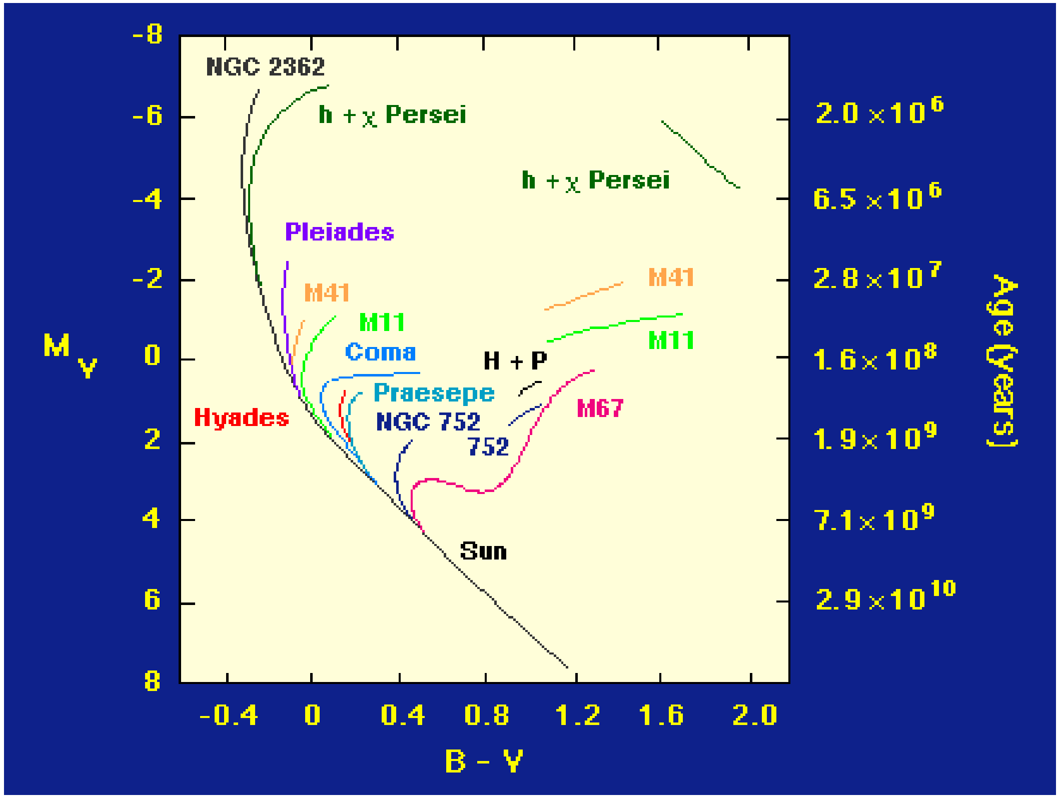
HR Diagram for star clusters



Zero-age main sequence (ZAMS)

Turn-off point

Open Cluster Parameters



Membership

Reddening

Distance

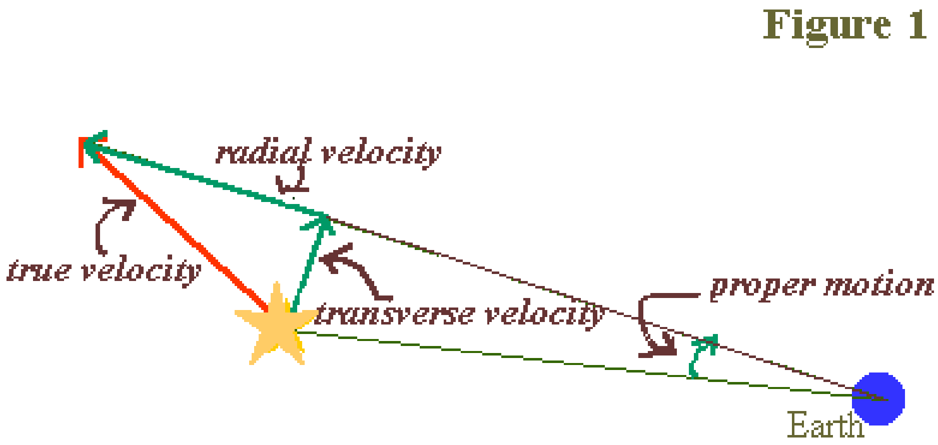
Age

Variable/Peculiar Stars

IMF, LF

Mass Segregation

Memb



Proper Motion

Hipparchos

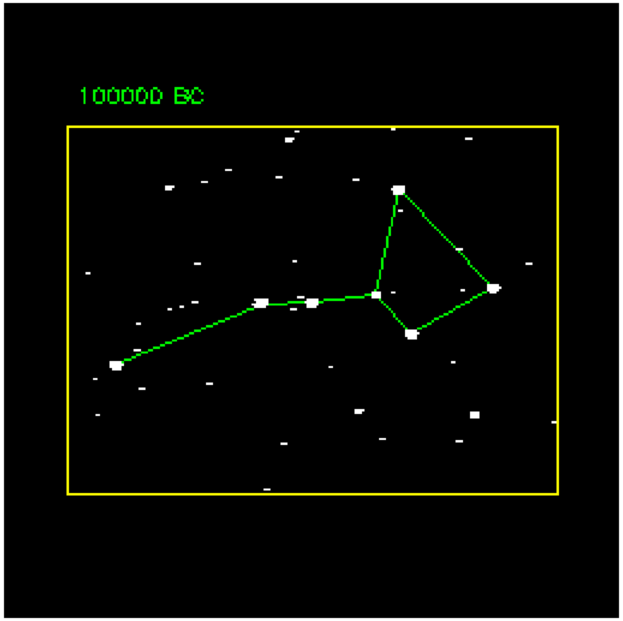
Tycho

Others

Spectroscopic

Photometric

Others

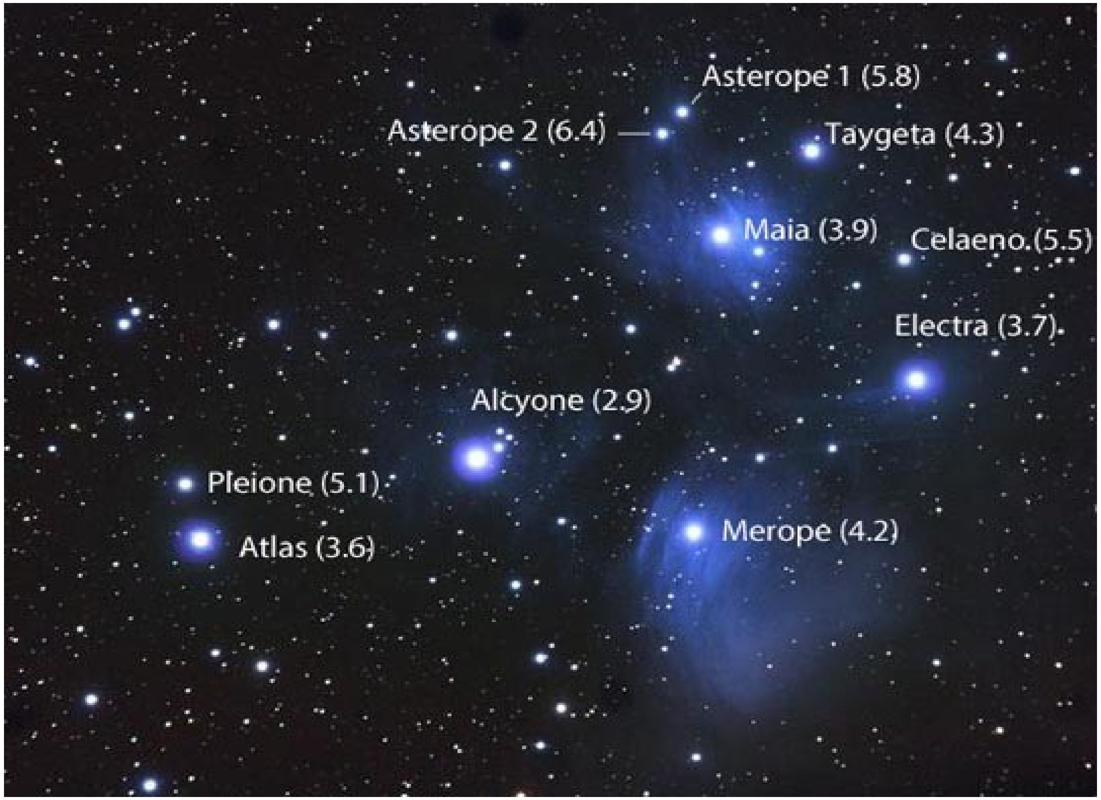


Back

Pleiades distance problem

Open star clusters like the Pleiades and Hyades are perfect proving grounds for models of stellar evolution because their stars all have the same age and composition yet exhibit a wide range of masses.

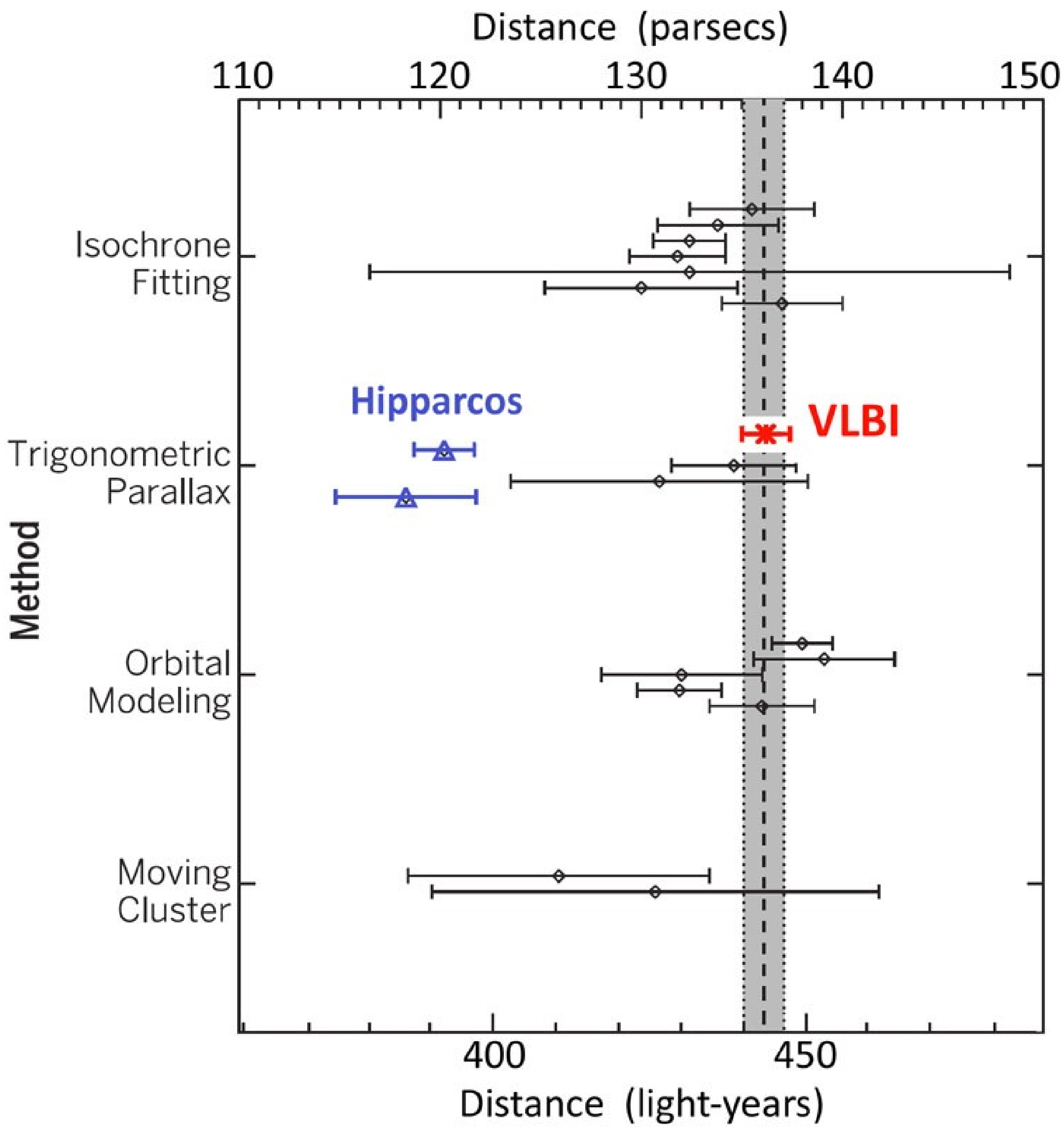
Hence it's critical that astronomers know the clusters' distances precisely.



Ground-based methods had consistently shown that the Pleiades lie about 435 light-years (133 parsecs) away.

According to Hipparcos, the cluster has a distance of just 392 light-years (120.2 parsecs), supposedly with an error of less than 1%.

Gaia Pleiades distance



Pleiades

- Determine parallax of Pleiades (following Gaia-DR1 paper)
- Cone search TGAS within 5° of Pleiades
- Plot pmra vs pmdec
- Identify comoving sources, create subset graphically
- Plot parallax histogram of comoving subset
- Restrict subset further to exclude parallax outliers
- Use Statistics window to determine cluster μ , σ
- Visualise cluster and non-cluster sources: in 3d space, showing proper motions

- ***Courtsey: Mark Taylor, TOPCAT and how to use it for Gaia, Gaia DR1 Workshop, ESAC, Madrid.***

TOPCAT

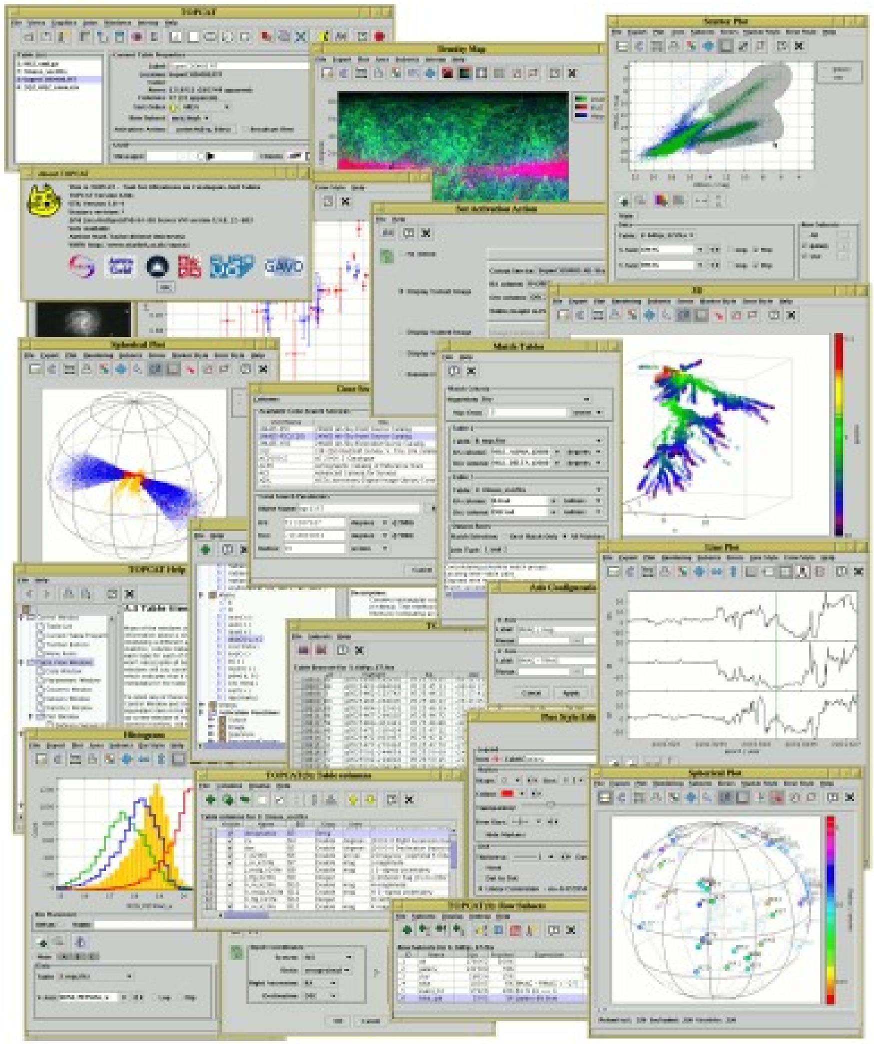
TOPCAT = Tool for OPerations on Catalogues And Tables

Capabilities:

- Does stuff with tables
- Talks to the *Virtual Observatory*

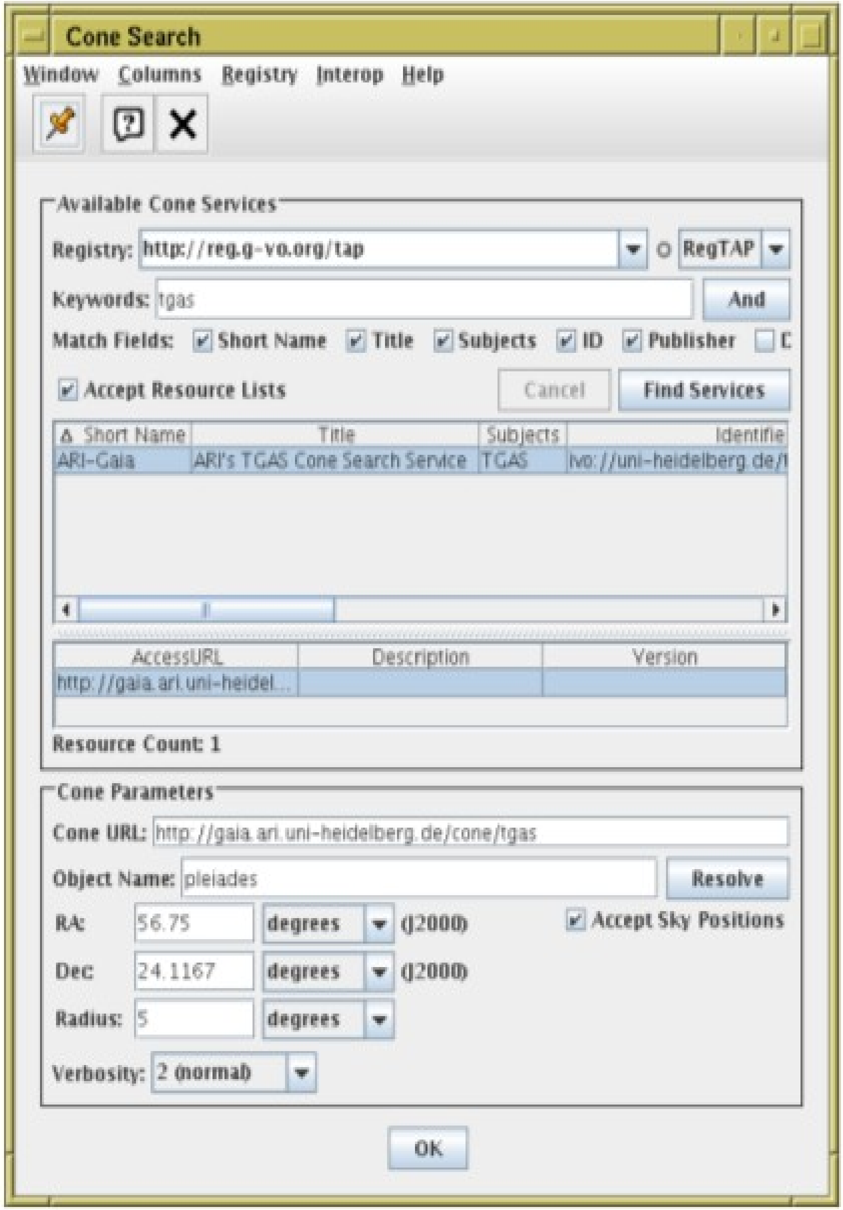
Help is available:

- Comprehensive HTML / PDF user manual
- **Help for Window** [?] button on every window
- Email support:
  - ▷ on list: topcat-user@bristol.ac.uk
  - ▷ in person: m.b.taylor@bristol.ac.uk
- Acknowledgement: 2005ASPC..347...29T



`http:/www.starlink.ac.uk/topcat/`

A.1: TGAS Cone Search

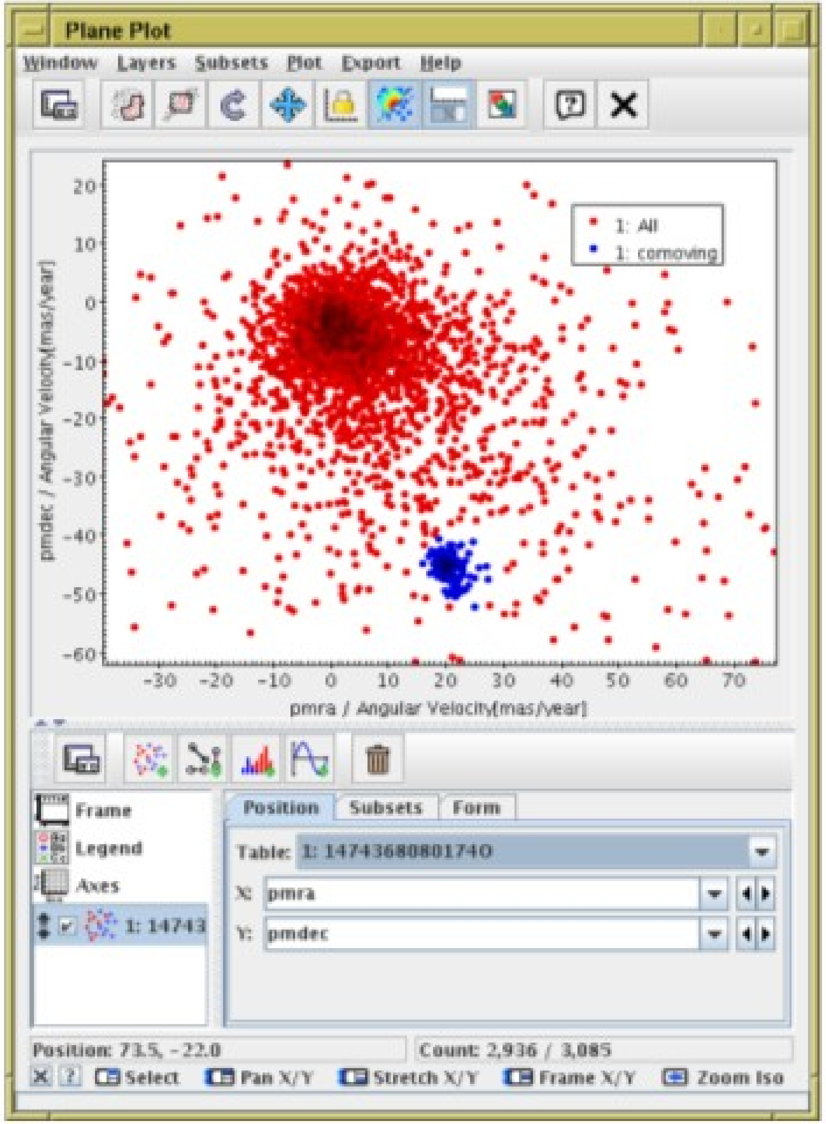


- Want to query TGAS sources within 5° of Pleiades

- Use TOPCAT Cone Search window:
  - ▷ **VO|Cone Search** menu item
  - ▷ **Keywords:** "`tgas`"
  - ▷ **Object Name:** "`pleiades`" + **Resolve**
  - ▷ **Radius:** "`5`"

- ... there are other ways to do it

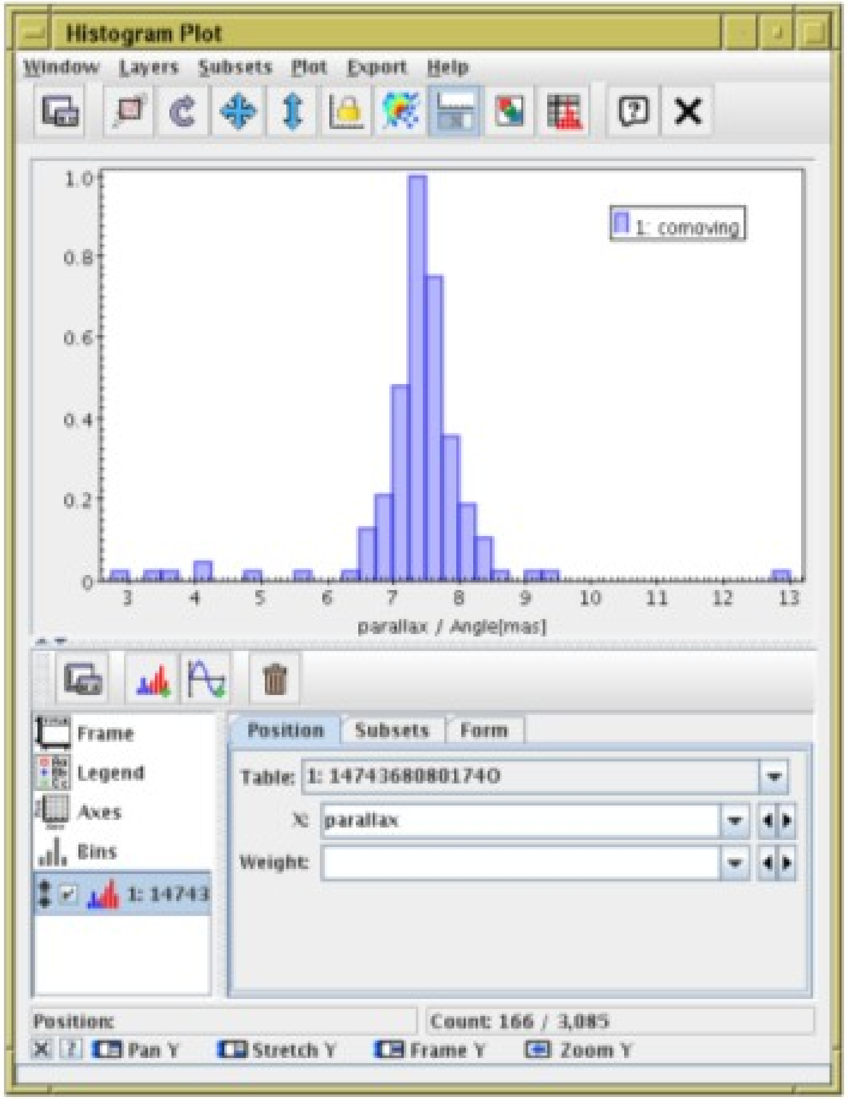
A.2: Proper motion plot



- Plot sources in proper motion space:
  - ▷ **Graphics|Plane Plot** menu item or toolbar button
  - ▷ **X:** "pmra"
  - ▷ **Y:** "pmdec"
  - ▷ Note overdensity far from (0,0)

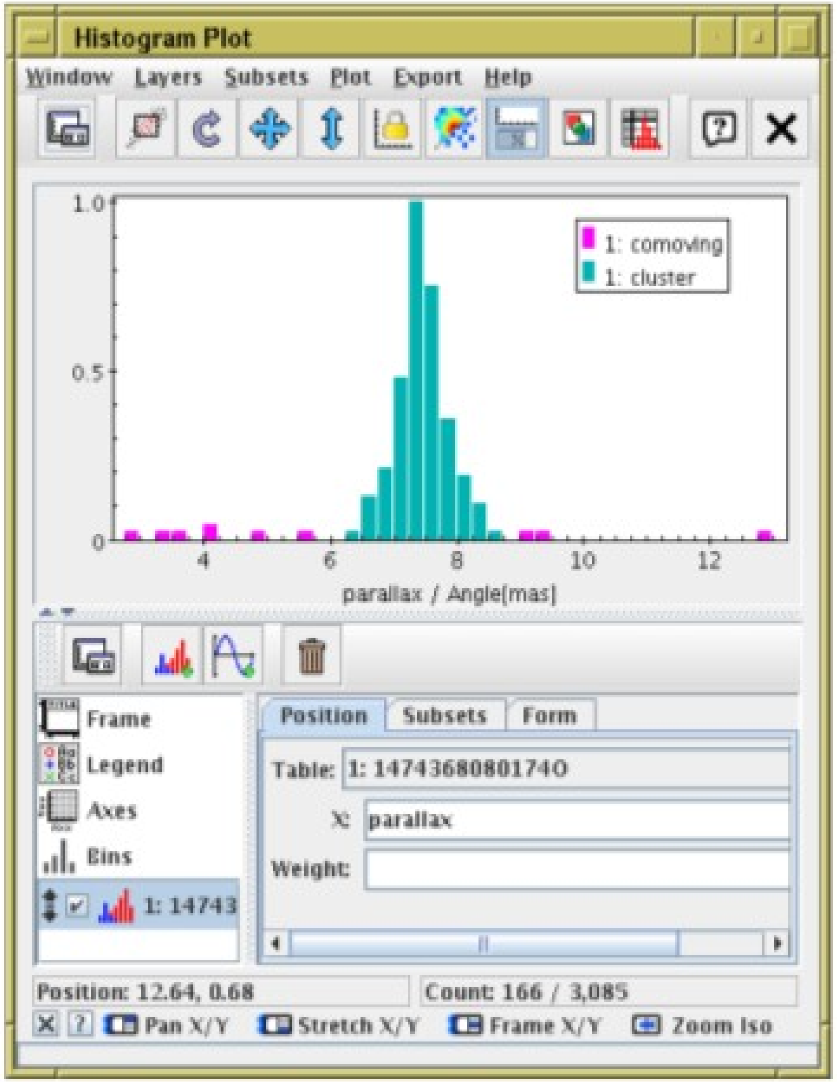
- Graphically select this comoving cluster as new Subset
  - ▷ button, drag mouse, again
  - ▷ **New Subset Name:** "comoving" + **Add Subset**

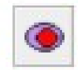
A.3: Parallax histogram



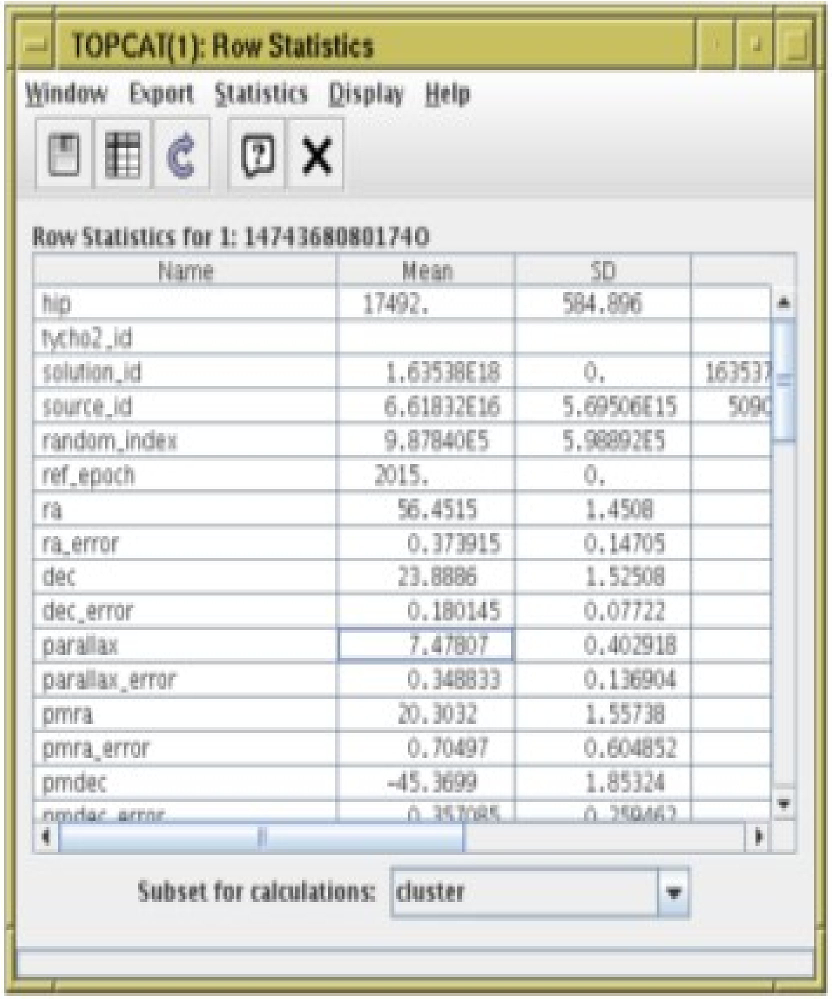
- Plot parallax histogram of comoving subset
  - ▷ **Graphics|Histogram plot** menu item or toolbar button
  - ▷ **X:** "parallax"

A.4: Exclude proper motion outliers



- Restrict comoving subset further to exclude parallax outliers
  - ▷  **Views|Row Subsets** menu item or toolbar button
  - ▷  toolbar button to create new algebraic subset
  - ▷ **Subset Name:** "cluster"
  - ▷ **Expression:** "`comoving && parallax>6 && parallax<9`"

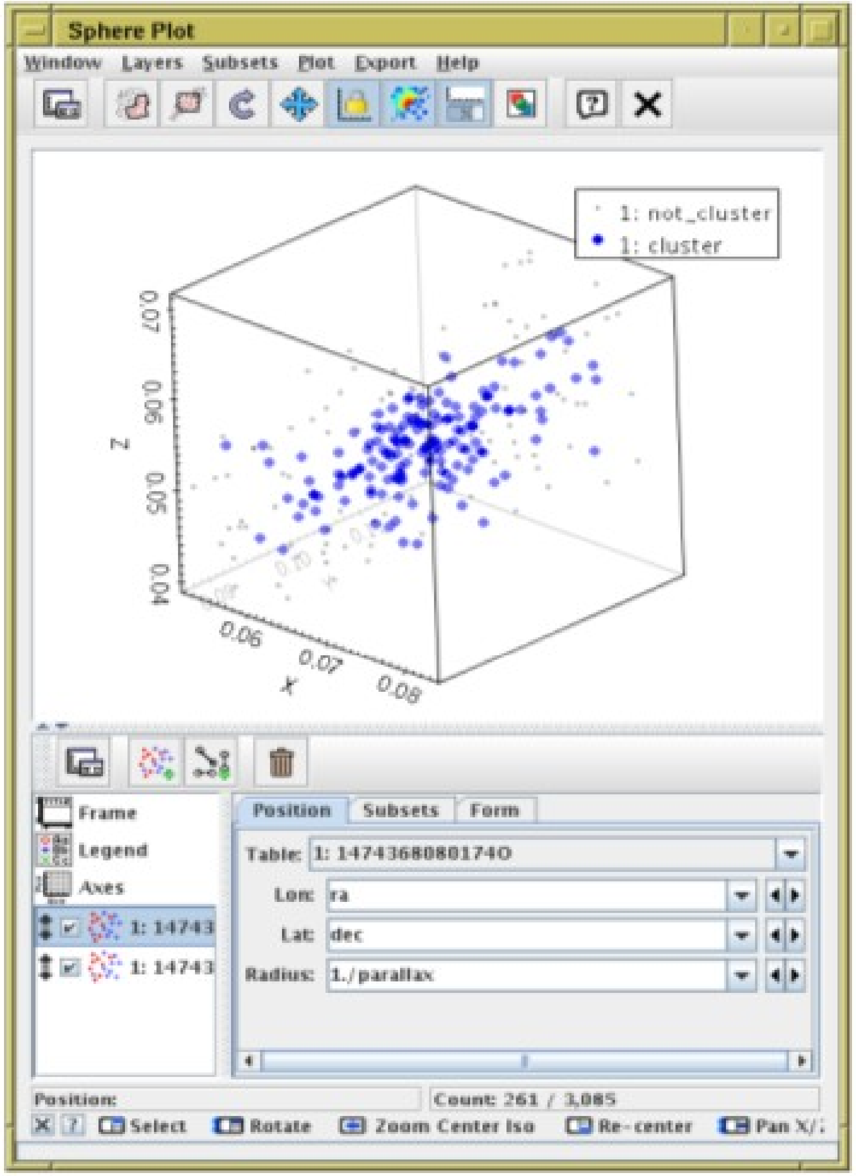
A.5: Cluster proper motion statistics



Name	Mean	SD	
hip	17492.	584.896	
tycho2_id			
solution_id	1.63538E18	0.	163537
source_id	6.61832E16	5.69506E15	5090
random_index	9.87840E5	5.98892E5	
ref_epoch	2015.	0.	
ra	56.4515	1.4508	
ra_error	0.373915	0.14705	
dec	23.8886	1.52508	
dec_error	0.180145	0.07722	
parallax	7.47807	0.402918	
parallax_error	0.348833	0.136904	
pmra	20.3032	1.55738	
pmra_error	0.70497	0.604852	
pmdec	-45.3699	1.85324	
pmdec_error	0.357085	0.259462	

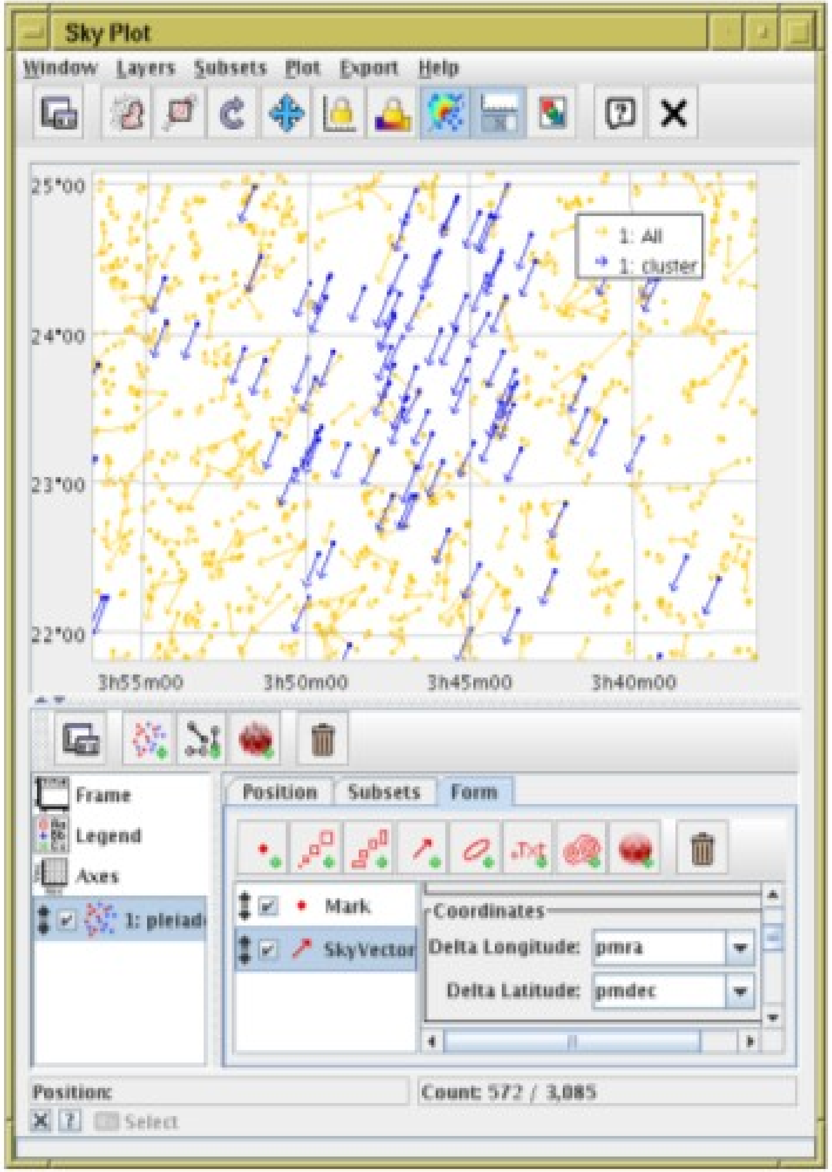
- Σ **Views|Column Statistics** menu item or toolbar button
- **Subset for Calculations:** "cluster"
- See **Mean** and **Stdev** columns
- → pleiades parallax ≈ 7.5 ± 0.4 mas
- careful with priors if converting to distance
- ... but parallax_error/parallax is quite high for all cluster members

A.6: 3d cluster positions



- **Graphics|Sphere Plot** menu item or toolbar button
- **Subsets** tab: select cluster subset only
- **Lon:** "ra"
- **Lat:** "dec"
- **Radius:** "1./parallax"
- Cluster positions are visible in 3d space
- You can turn on All/comoving subsets too

A.7: Visualise proper motions

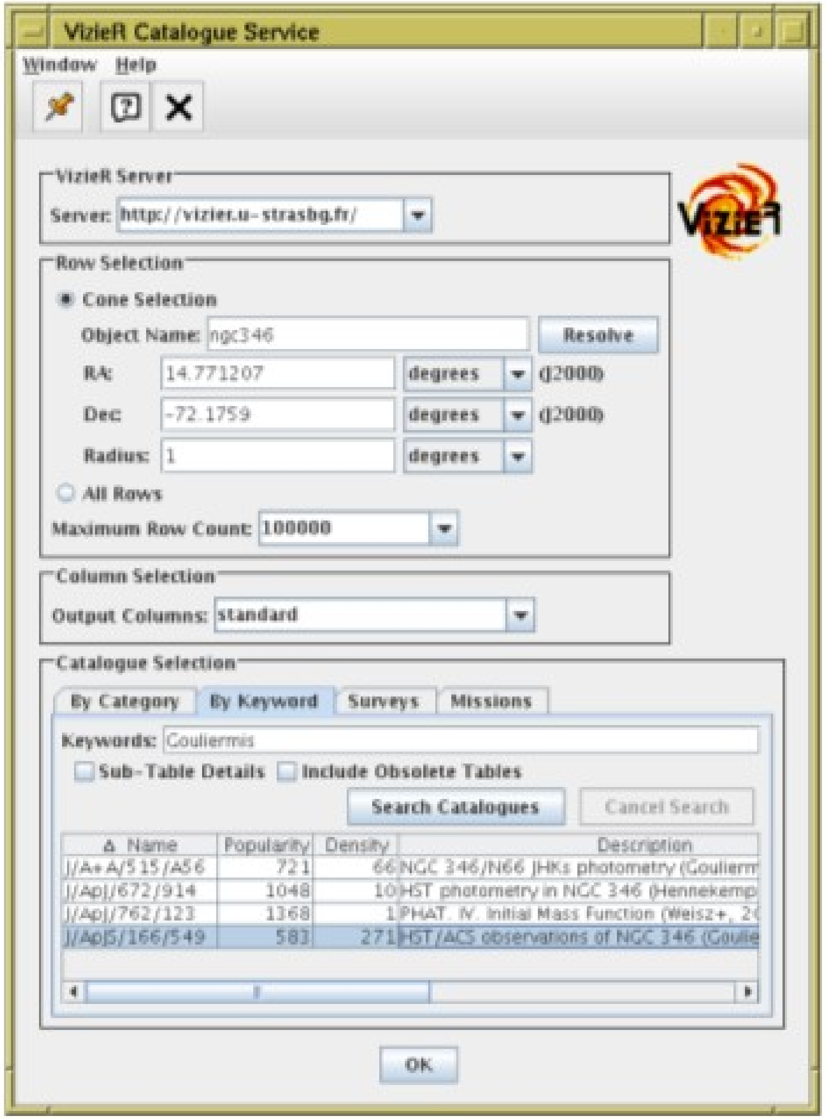


- **Graphics|Sky Plot** menu item or toolbar button
- Add new **SkyVector** form in **Form** tab
- **Delta Longitude:** "pmra"
- **Delta Latitude:** "pmdec"
- See the little arrows showing proper motion

- 7.4424 \pm 0.27

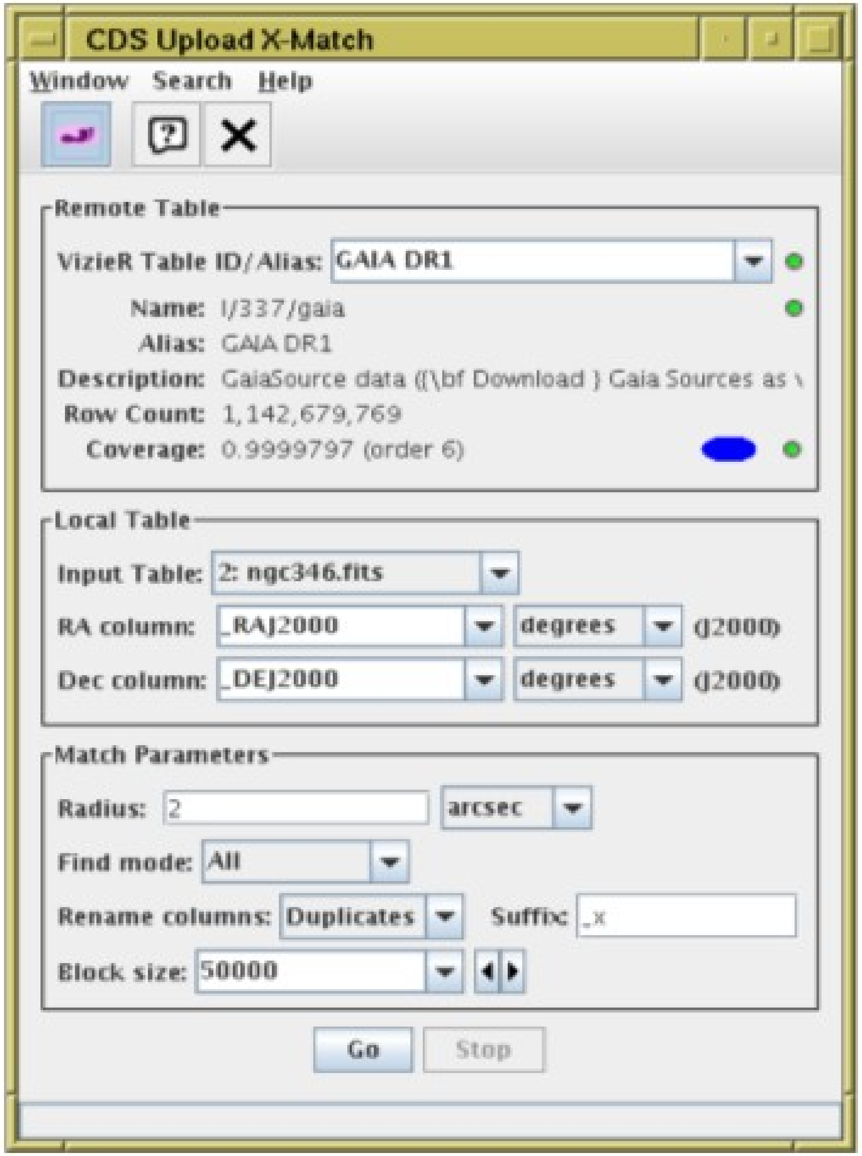
= 134.36 \pm

B.1: Acquire NGC 346 catalogue



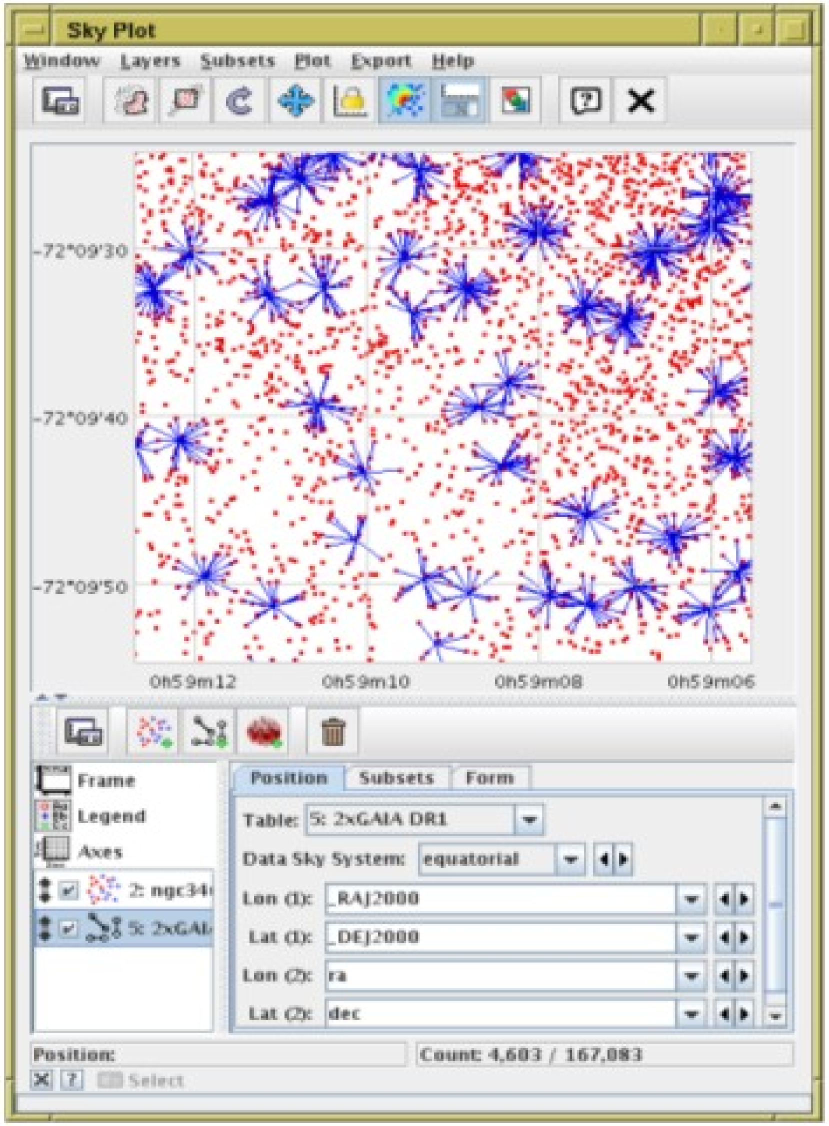
- Load catalogue from VizieR:
  - ▷ **VO|VizieR Catalogue Service** menu item
  - ▷ **All Rows** check box
  - ▷ **Maximum Row Count:** 100 000
  - ▷ Locate and load *Gouliermis et al. 2006* (J/ApJS/166/549)
- Or grab it from CDS VizieR web page

B.2: Crossmatch with Gaia



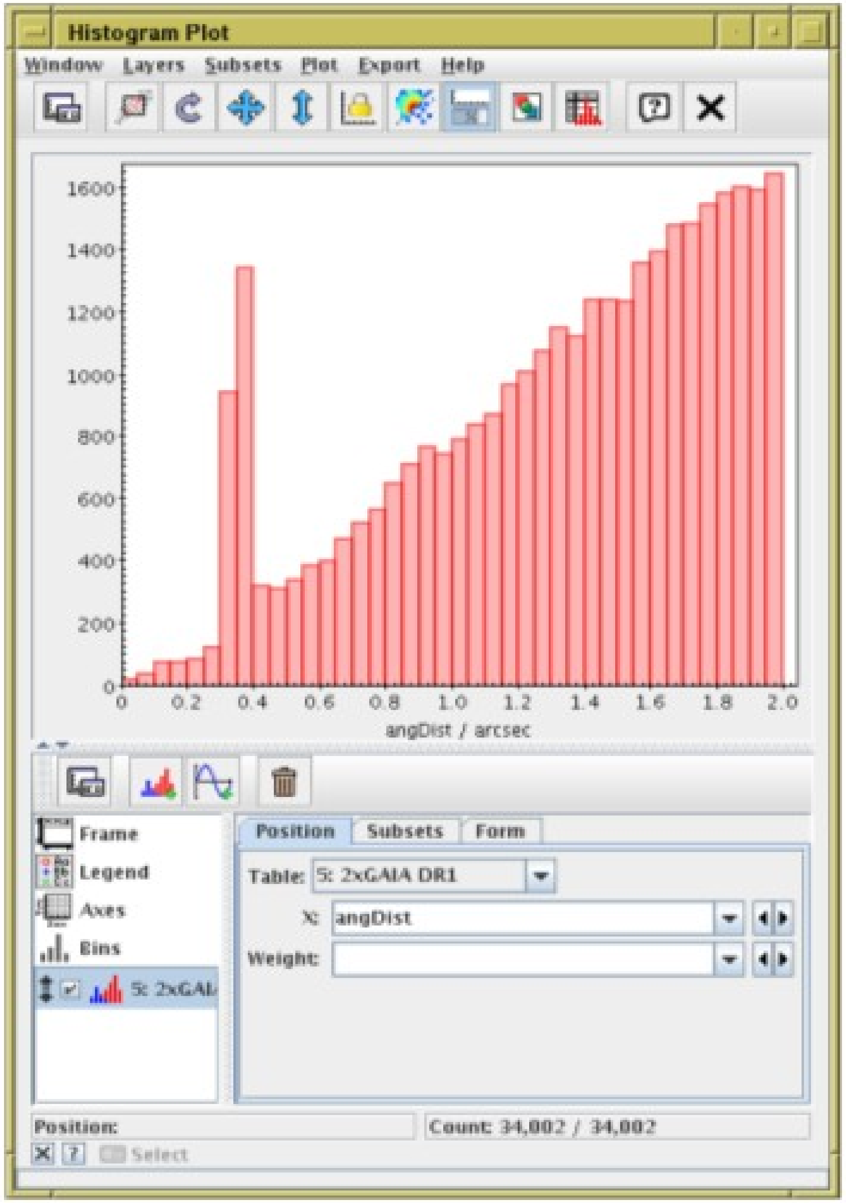
- **VO|CDS Upload X-Match** menu item or toolbar button
- **Vizier Table ID:** "GAIA DR1"
- **Radius:** "1" arcsec
- **Find mode:** All

B.3: Plot crossmatch results



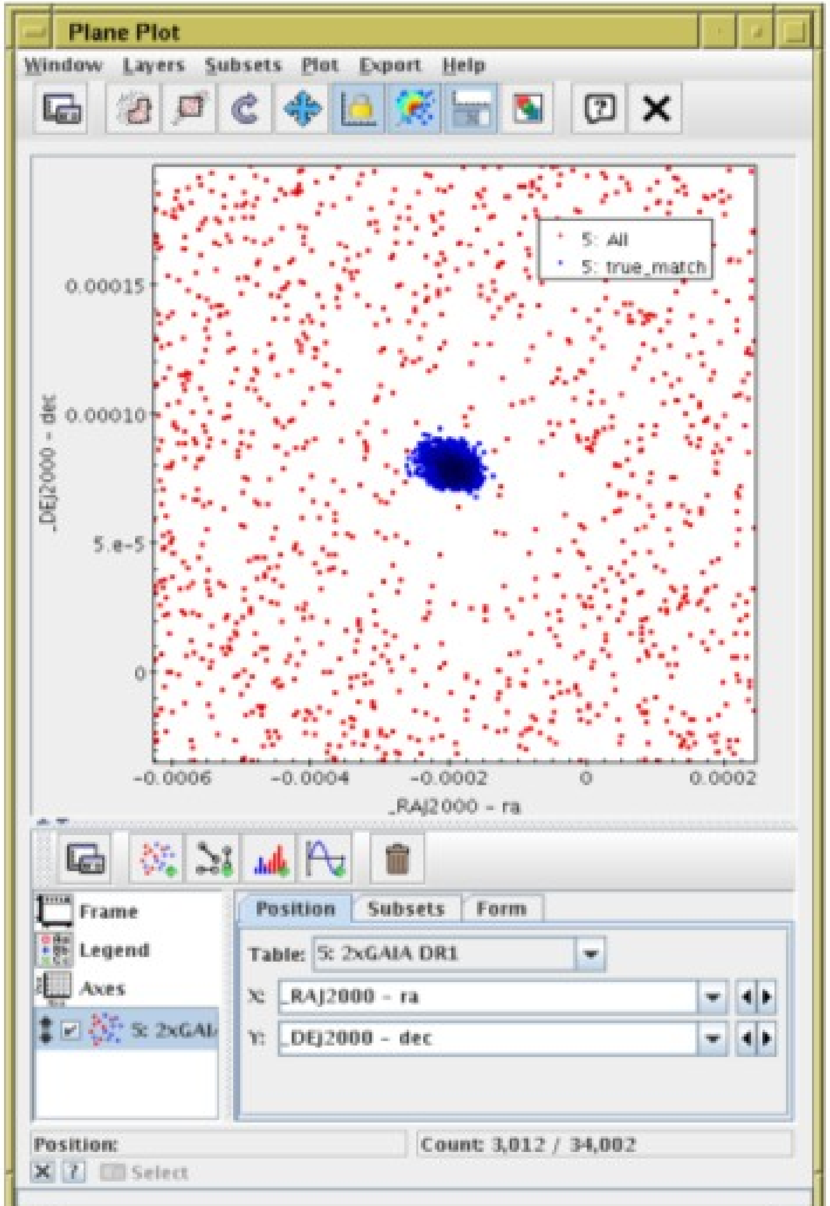
- **Graphics|Sky Plot** menu item or toolbar button
- Plot NGC 364 points
- Plot Gaia↔Gouliermis associations ([Goul] _RAJ2000, _DEJ2000, [Gaia] ra, dec)
- ... too many

B.4: Plot crossmatch offsets



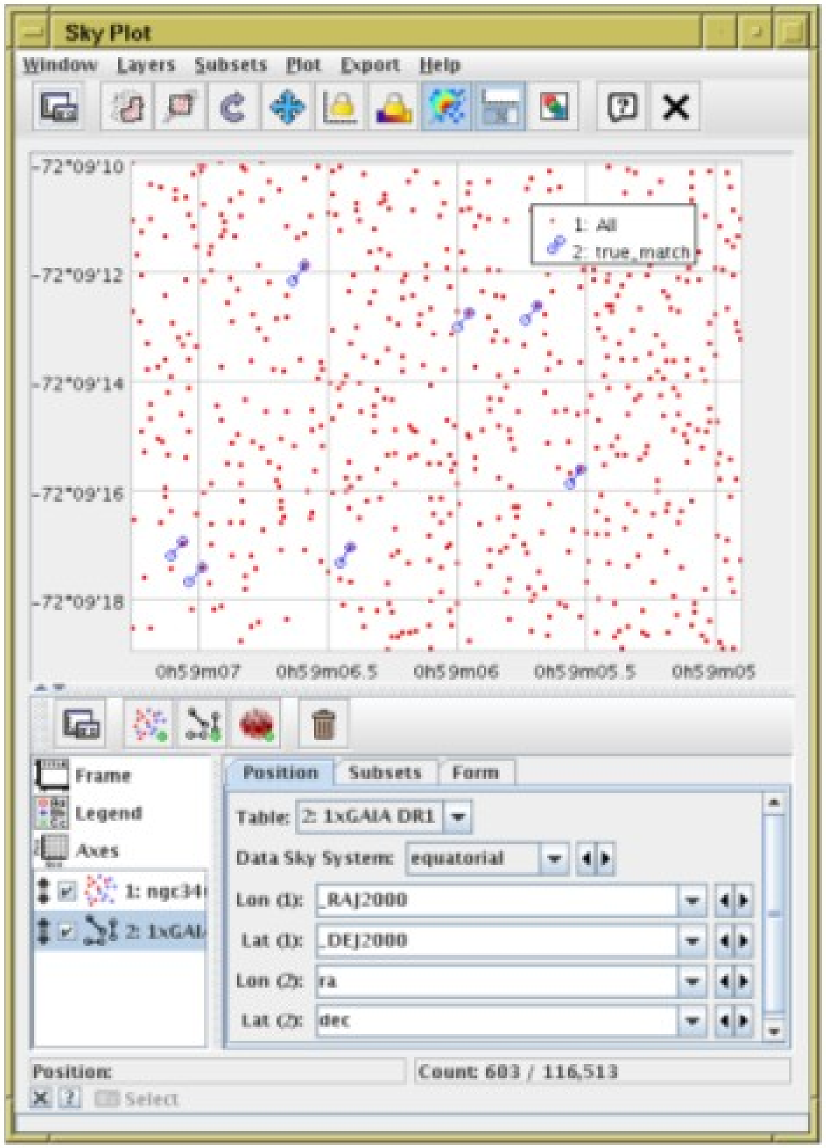
- Graphics|Histogram plot menu item or toolbar button
- **X:** "angDist" (Gaia—Gouliermis association distance)
- (some) true associations near 0.35 arcsec

B.5: Identify true matches



- Plot matches in xmatch offset space:
  - ▷ **Graphics|Plane Plot** menu item or toolbar button
  - ▷ **X:** "_RAJ2000 - ra"
  - ▷ **Y:** "_DEJ2000 - dec"
- Obvious overdensity — corresponds to true offset
- Select new subset true_match graphically

B.6: Visualise true matches



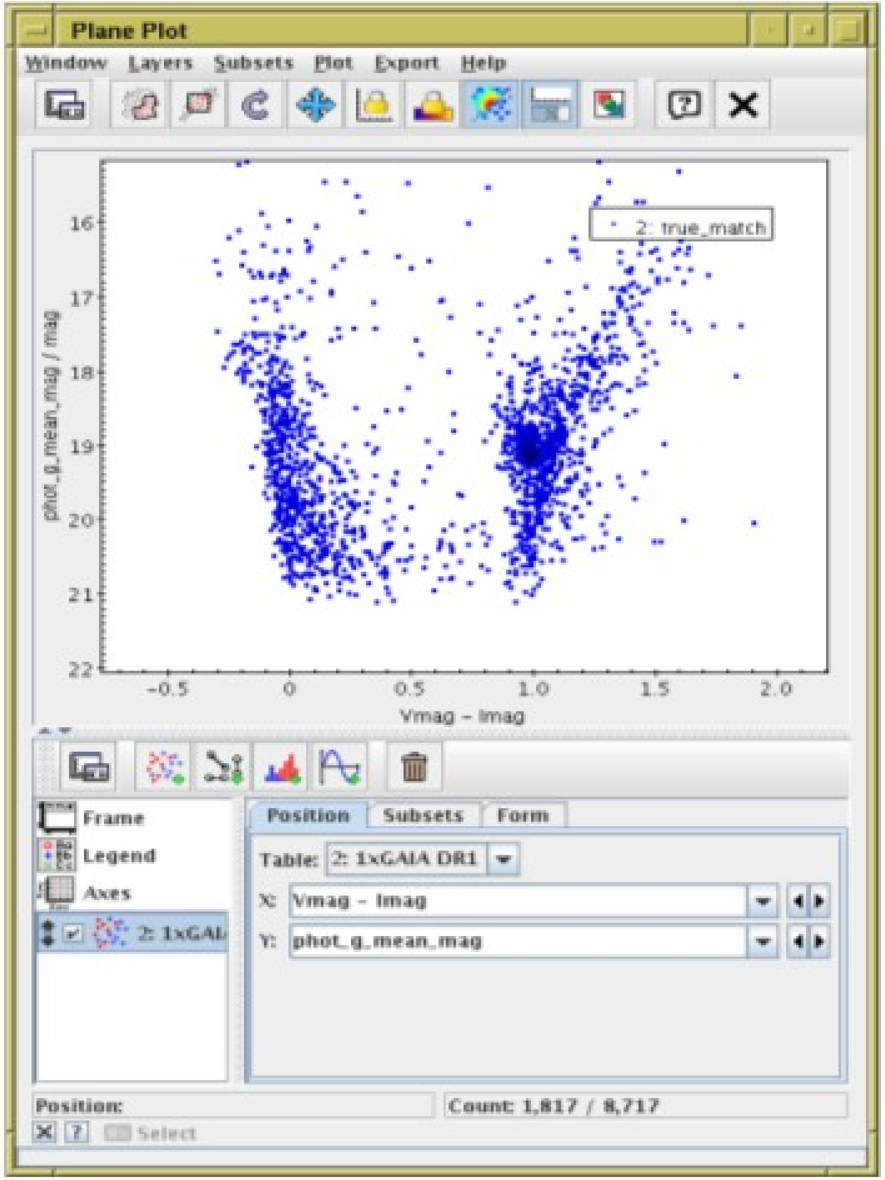
- Return to sky plot
- **Subsets** tab: select true_match only
- Common association vector, $= (\overline{\Delta\alpha}, \overline{\Delta\delta})$ in true_match subset, is displacement between Gouliermis & Gaia observations (1992?–2015.0):

$$\overline{\cos\delta\Delta\alpha} \approx +210 \pm 20 \text{ mas}$$
$$\overline{\Delta\delta} \approx -284 \pm 15 \text{ mas}$$

so proper motion:

$$\mu_{\alpha\star} \approx +9.1 \text{ mas.yr}^{-1}$$
$$\mu_{\delta} \approx -12 \text{ mas.yr}^{-1}$$

B.7: Combine HST and Gaia photometry



- Joined table now has Gaia G-band photometry alongside HST V/I-band photometry

STILTS

Most of TOPCAT's capabilities can be scripted

- STILTS: from command line (e.g. un*x shell)
- JyStilts: from Jython (python interface, but not CPython)

Details

- Not covered in this talk!
- But some examples available:

  See http://www.star.bristol.ac.uk/~mbt/gaia/tutorial.html

- Full documentation and examples in http://www.starlink.ac.uk/stilts/

Summary

- Lots of ways to get Gaia data into TOPCAT
  - Different ones most suitable for different situations
- Lots of things you can do with it once it's there
  - Play around with plots
  - Use documentation
  - Support on mailing list, email me, ...
- Scriptable access/manipulation available using STILTS or JyStilts
- Materials: http://www.star.bristol.ac.uk/~mbt/gaia/tutorial.html

The Gaia Data Release (GDR) Scenario

http://www.cosmos.esa.int/web/gaia/release

- GDR1 ~7/16: positions, G-magnitudes (~all sky, single stars)

  proper motions for Hipparcos stars (~50 μarcsec/yr) – the Hundred Thousand Proper Motions (HTPM) catalogue
- GDR2 ~2/17: + radial velocities for bright stars, two band photometry and full astrometry (α, δ, ϖ, μ_{α}, μ_{δ}) where available for intermediate brightness stars
- GDR3 ~1/18: + first all sky 5 parameter astrometric results (α, δ, ϖ, μ_{α}, μ_{δ}) BP/RP data, RVS radial velocities and spectra, astrophysical parameters, orbital solutions short period binaries
- GDR4 ~1/19: + variability, solar system objects, updates on previous releases, source classifications, astrophysical parameters, variable star solutions, epoch photometry
- GDR-Final: final data release (thus in 2022/23 or 2025)

Full dataset for more sophisticated modelling released at end of mission

Gaia Data Releases

Gaia DR1 contains:

The five-parameter astrometric solution - positions, parallaxes, and proper motions - for stars in common between the Tycho-2 Catalogue and Gaia is released.

Second release: April 2018

Five-parameter astrometric solutions for all sources with acceptable formal standard errors (>109 anticipated), and positions (α, δ) for sources for which parallaxes and proper motions cannot be derived.

G and integrated GBP and GRP photometric fluxes and magnitudes for all sources.

Median radial velocities for sources brighter than GRVS=12 mag.

For stars brighter than G=17 mag estimates of the effective temperature and, where possible, line-of-sight extinction will be provided, based on the above photometric data.

Photometric data for a sample of variable stars., Epoch astrometry for a pre-selected list of >10,000 asteroids

Third release: (TBC)

Orbital solutions, together with the system radial velocity and five-parameter astrometric solutions, for binaries having periods between 2 months and 75% of the observing time will be released., Object classification and astrophysical parameters, together with BP/RP spectra and/or RVS spectra they are based on, will be released for spectroscopically and (spectro-)photometrically well-behaved objects., mean radial velocities will be released for those stars not showing variability and with available atmospheric-parameter estimates.

Fourth release: (TBC)

Variable-star classifications will be released together with the epoch photometry used for the stars.

Solar-system results will be released with preliminary orbital solutions and individual epoch observations.

Non-single star catalogues will be released.

Final release: 2022

Full astrometric, photometric, and radial-velocity catalogues.

All available variable-star and non-single-star solutions.

Source classifications (probabilities) plus multiple astrophysical parameters (derived from BP/RP, RVS, and astrometry) for stars, unresolved binaries, galaxies, and quasars. Some parameters may not be available for faint(er) stars.

An exo-planet list.

All epoch and transit data for all sources.

All ground-based observations made for data-processing purposes.