The Milky Way (revealed) in the Gaia Era

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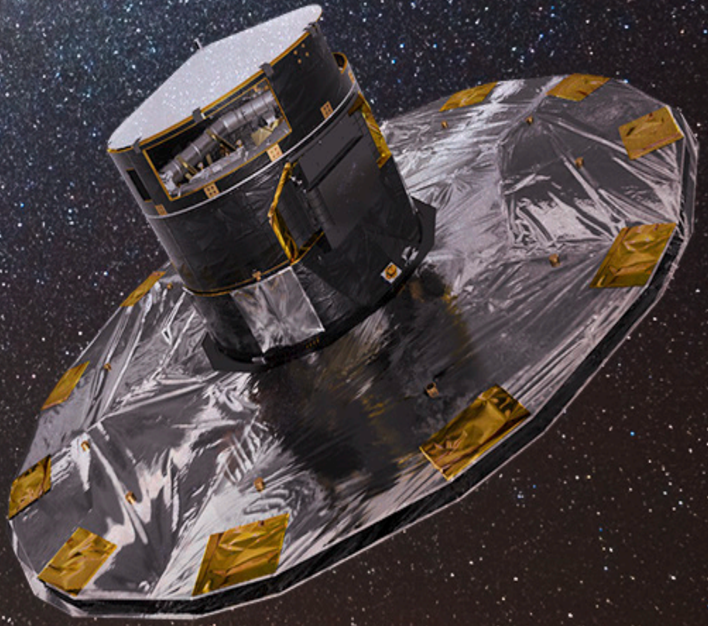
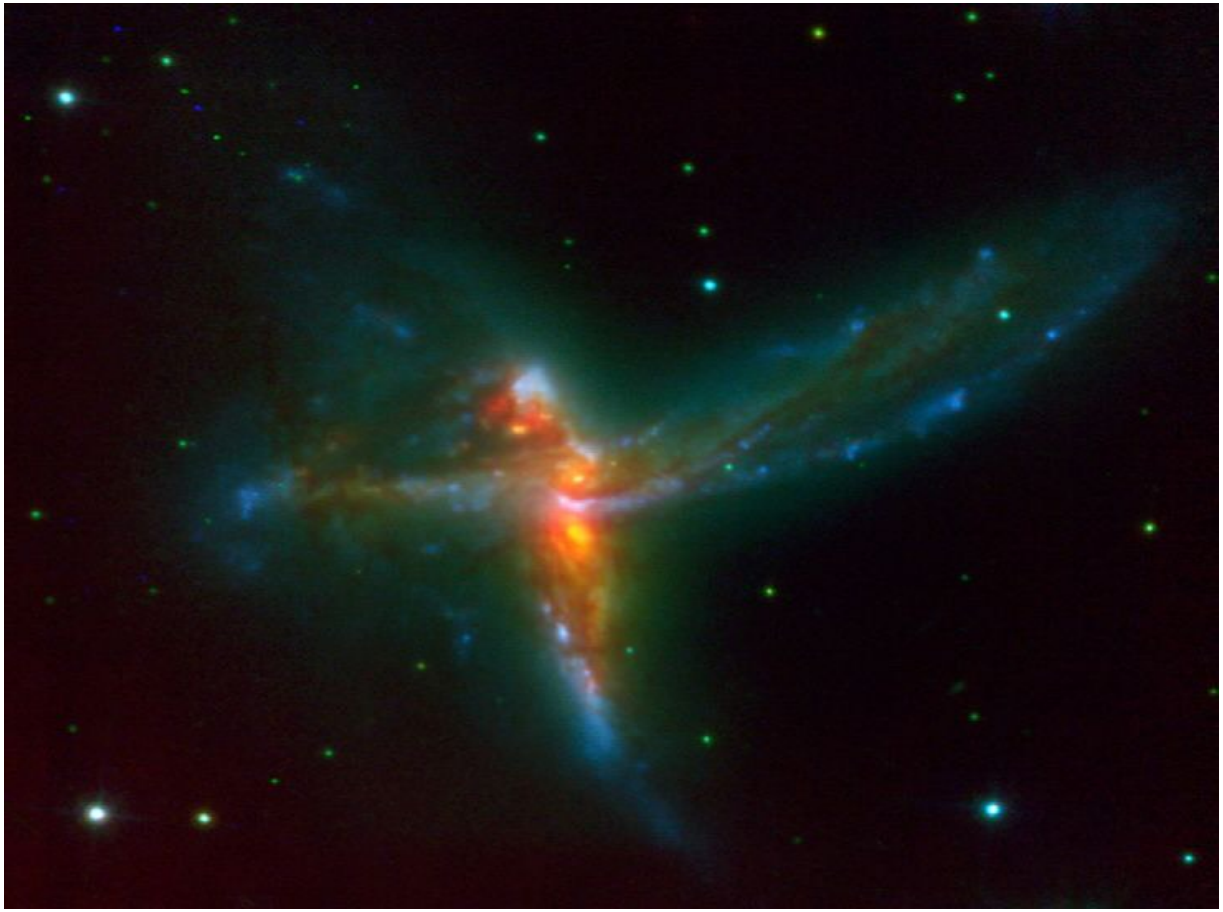


Dynamic universe

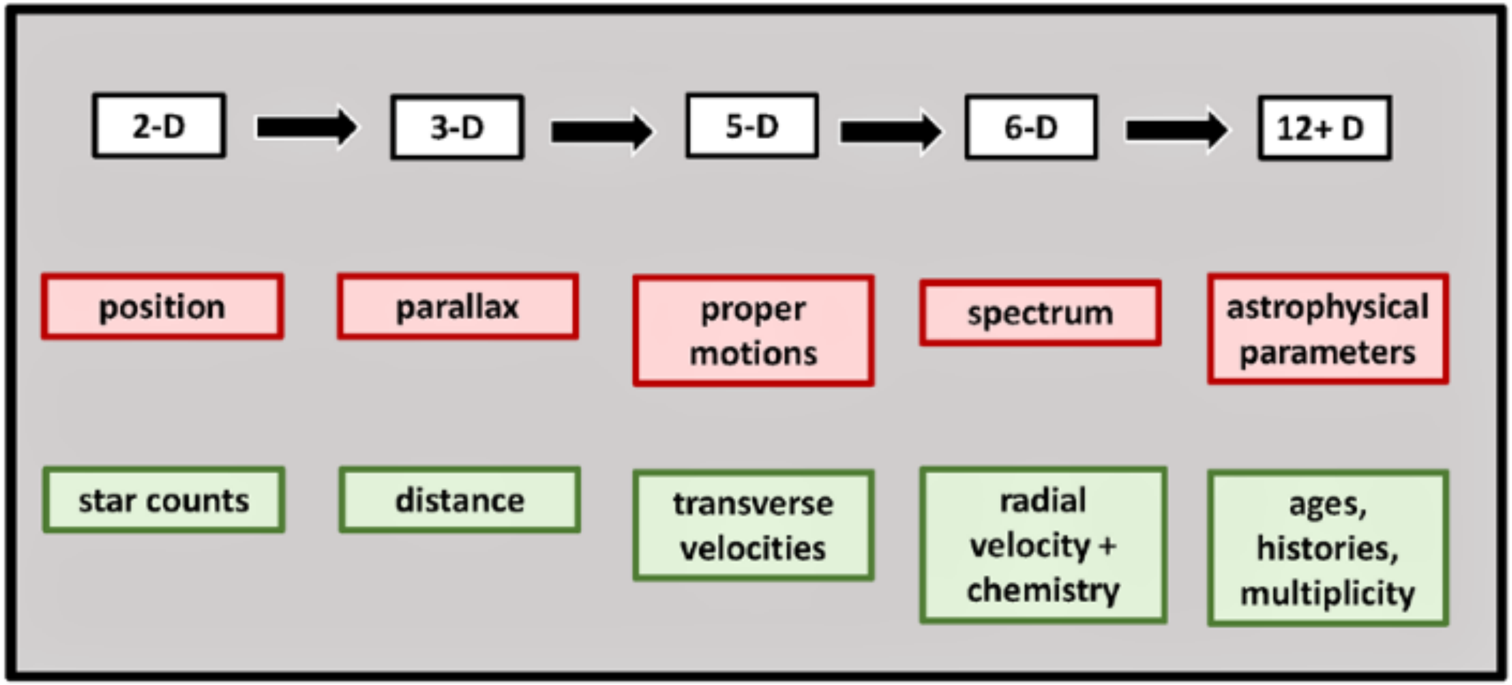


***Dancing** is creating a sculpture that is visible only for a moment."*

-Erol Ozan

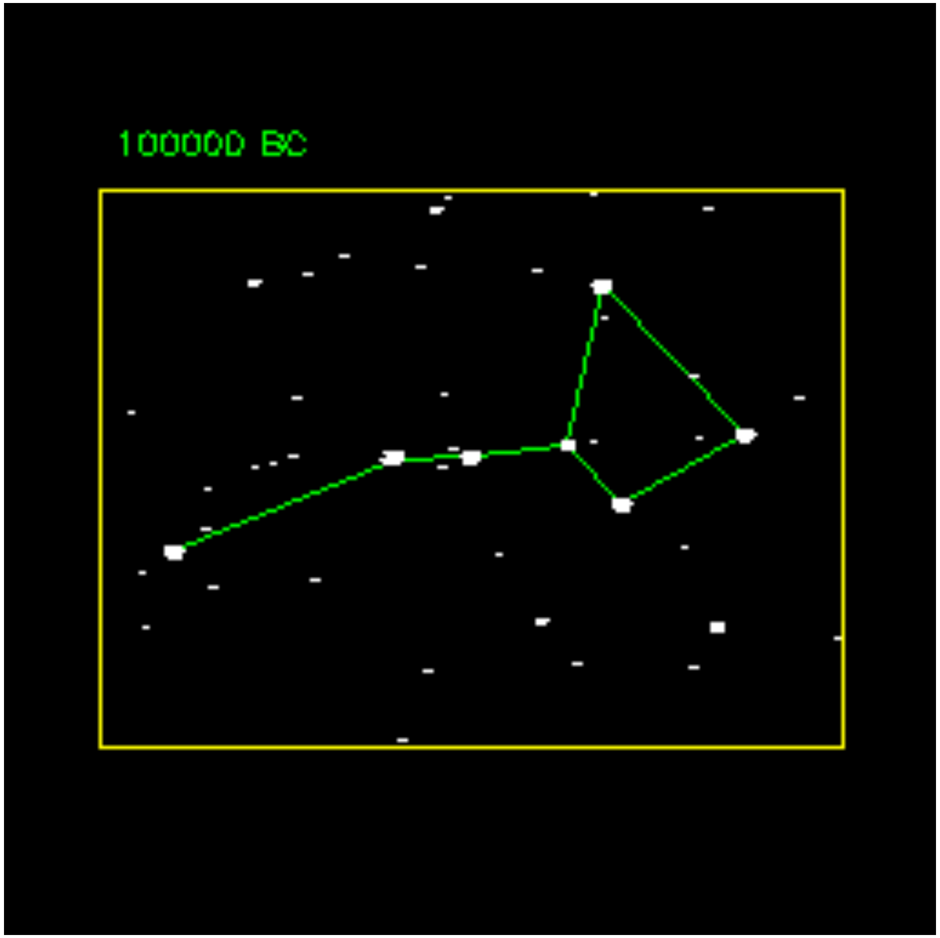
Growth of Knowledge

Gilmore, 2018



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.



What are small angles?

One second of arc: size of a rupee/euro coin viewed from a distance of 5 km.

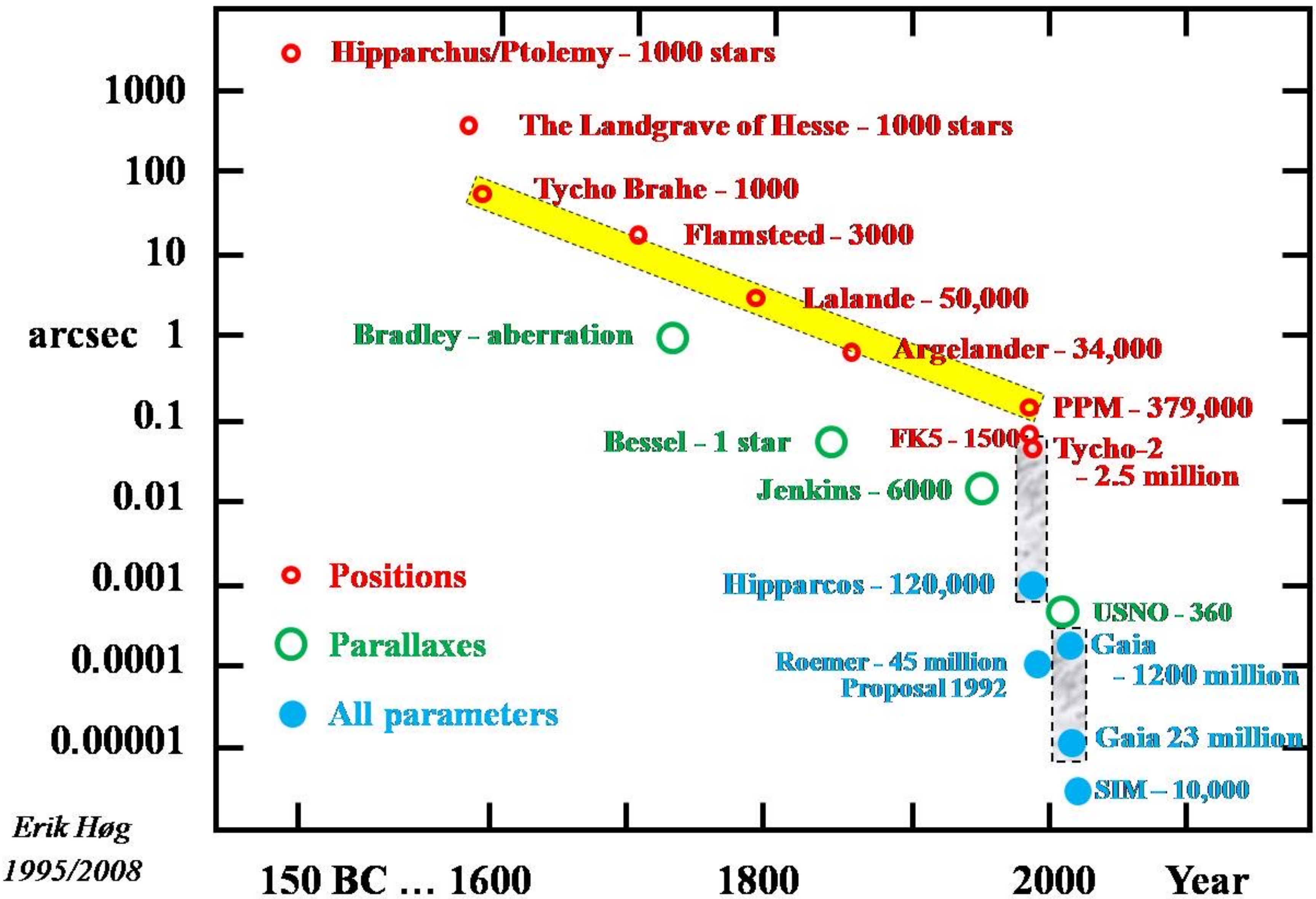
One thousandth of one second of arc (1mas):

size of an astronaut on the Moon, viewed from Earth, a golf ball in New York viewed from Europe (~6400 km), 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.

Astrometric Accuracy versus Time



Hogg, 2011, Perryman, 2012

Some Astrometric Catalogs

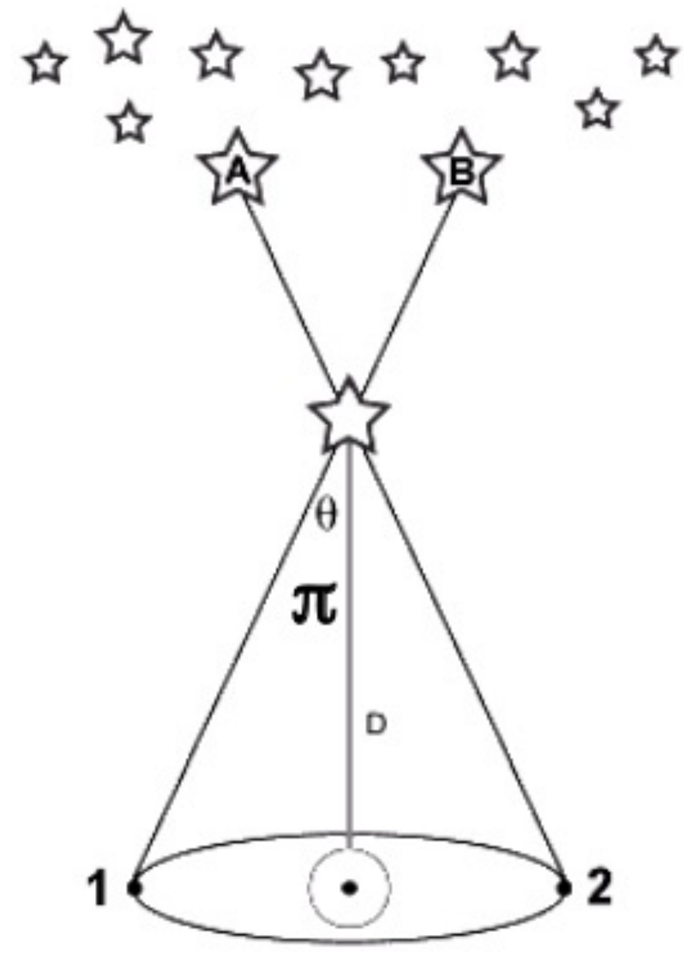
Name	Date	Nstars	σ(p) (mas)	σ pm(mas/yr)
SAO	1966	260 000	1000	10
ACRS	1991	320 000	200	5
PPM	1991	469 000	200	4
HIPPARCOS	1997	120 000	0.8	0.9
Tycho1	1997	1 060 000	40	40
ACT	1997	989 000	40	~ 2.5
TYCHO-2	1999	2 500 000	25	~ 2.5
UCAC-2	2003	48 330 000	22~70	1~6

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:

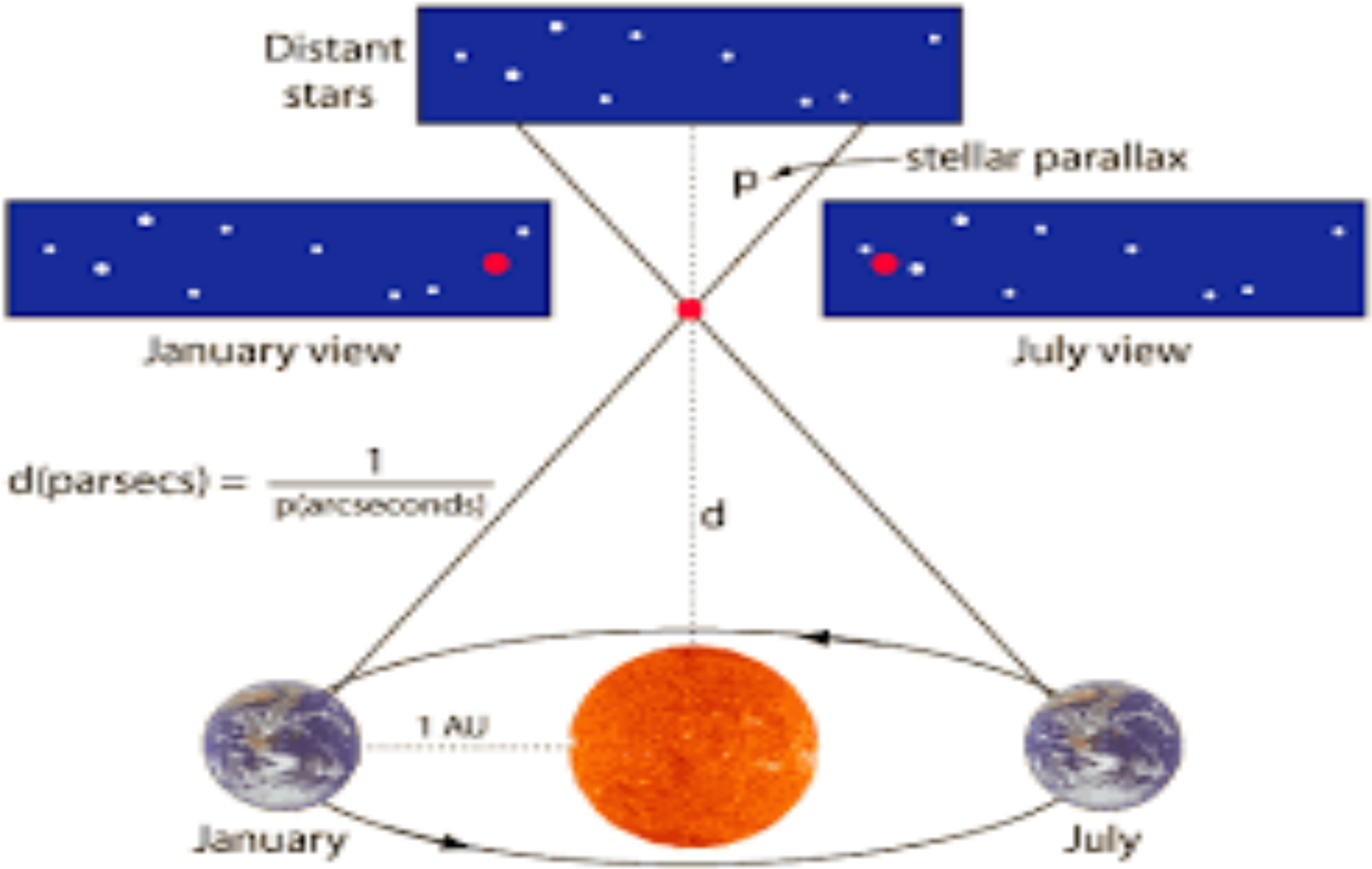
  $$\mathbf{D}\ [\mathrm{pc}] = \mathbf{1} / \boldsymbol{\pi}\ [\mathrm{arcsec}]$$

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



Parallax

Parallax



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

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 $\sim 10^5$ bright stars with
errors also of ~0.001 arcsec
GAIA satellite: will measure positions of $\sim 10^9$ 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

Space Astrometry

All-sky coverage

Relatively stable

Temperature and gravity invariant

Precision, accuracy and sample volume several orders of magnitude greater than ground-based results.

Absolute astrometry!

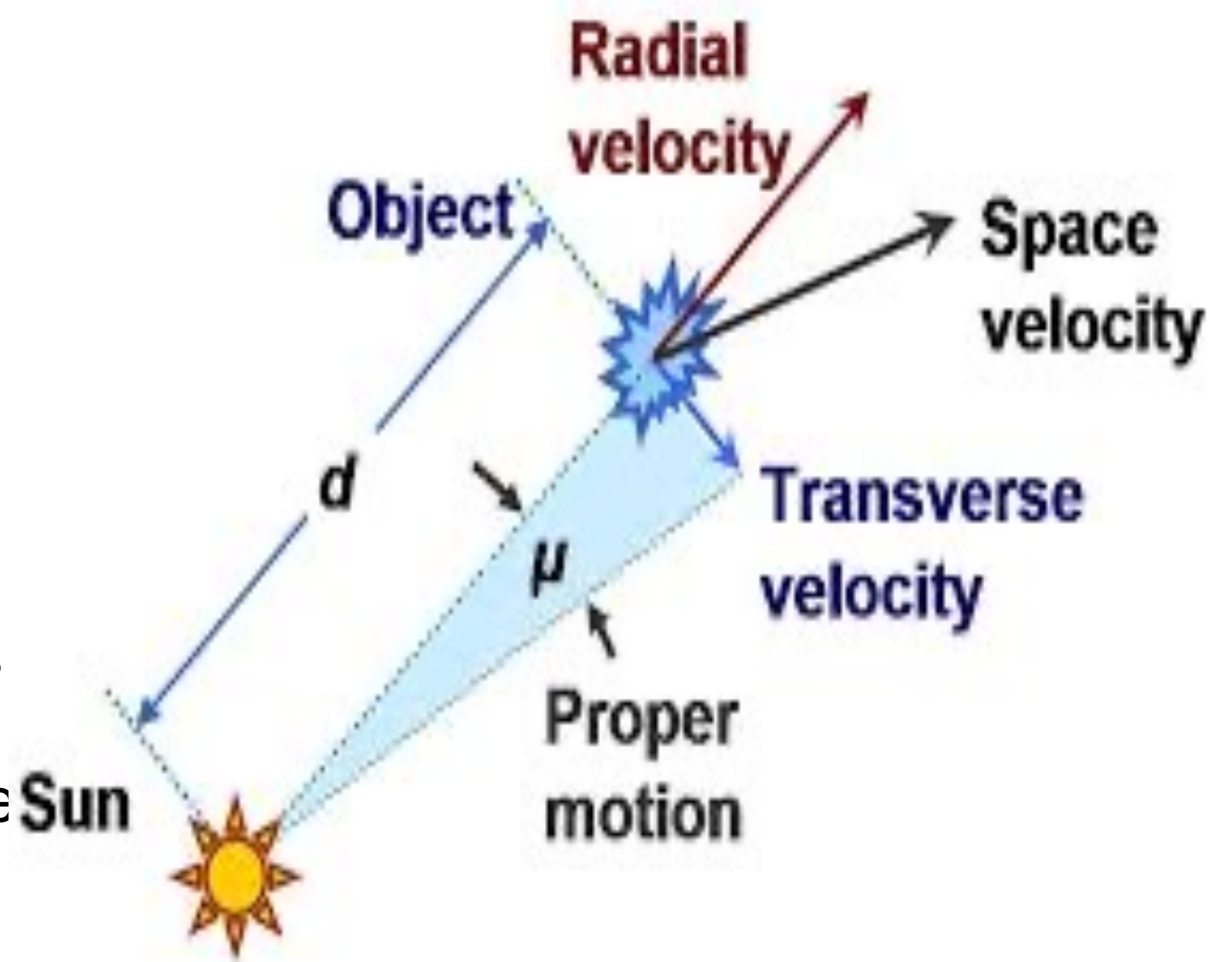
Hipparcos (1989-1993) High precision parallax collecting satellite

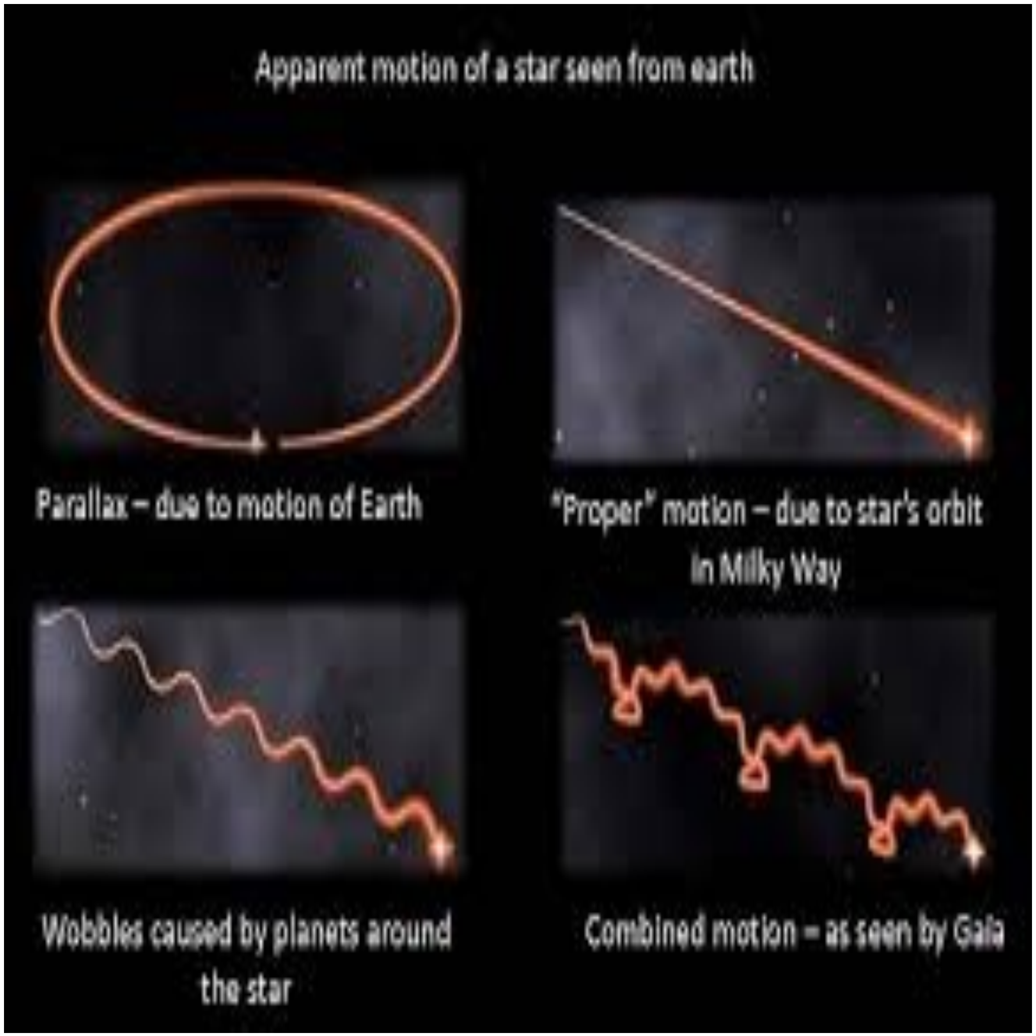
- Accurate determination of proper motions and parallaxes of stars, radial velocity
- Hipparcos Catalogue, a high-precision catalogue of more than 118,200 stars, was published in 1997.
- The lower-precision Tycho Catalogue > million stars
- Tycho-2 Catalogue of 2.5 million stars was published in 2000.

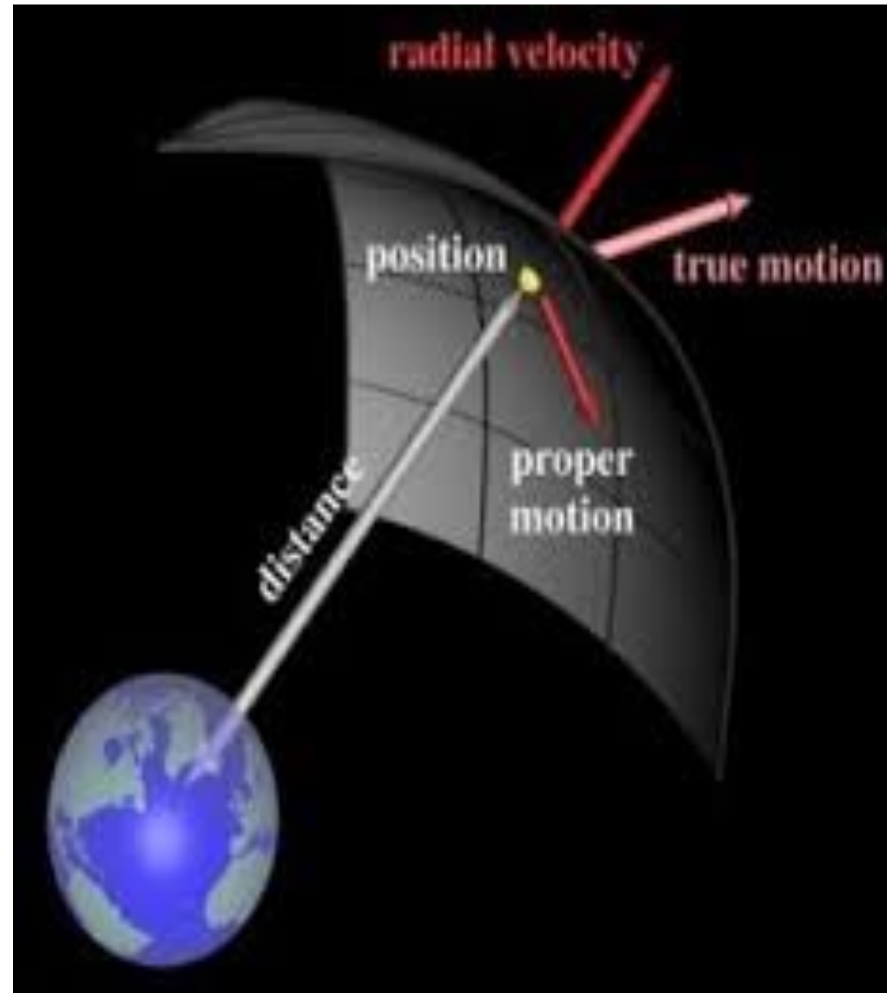
Stellar Motions

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




Apparent motion of a star seen from earth
Parallax – due to motion of Earth
"Proper" motion – due to star's orbit in Milky Way
Wobbles caused by planets around the star
Combined motion – as seen by Gaia


radial velocity
position
true motion
proper motion
distance

GAIA

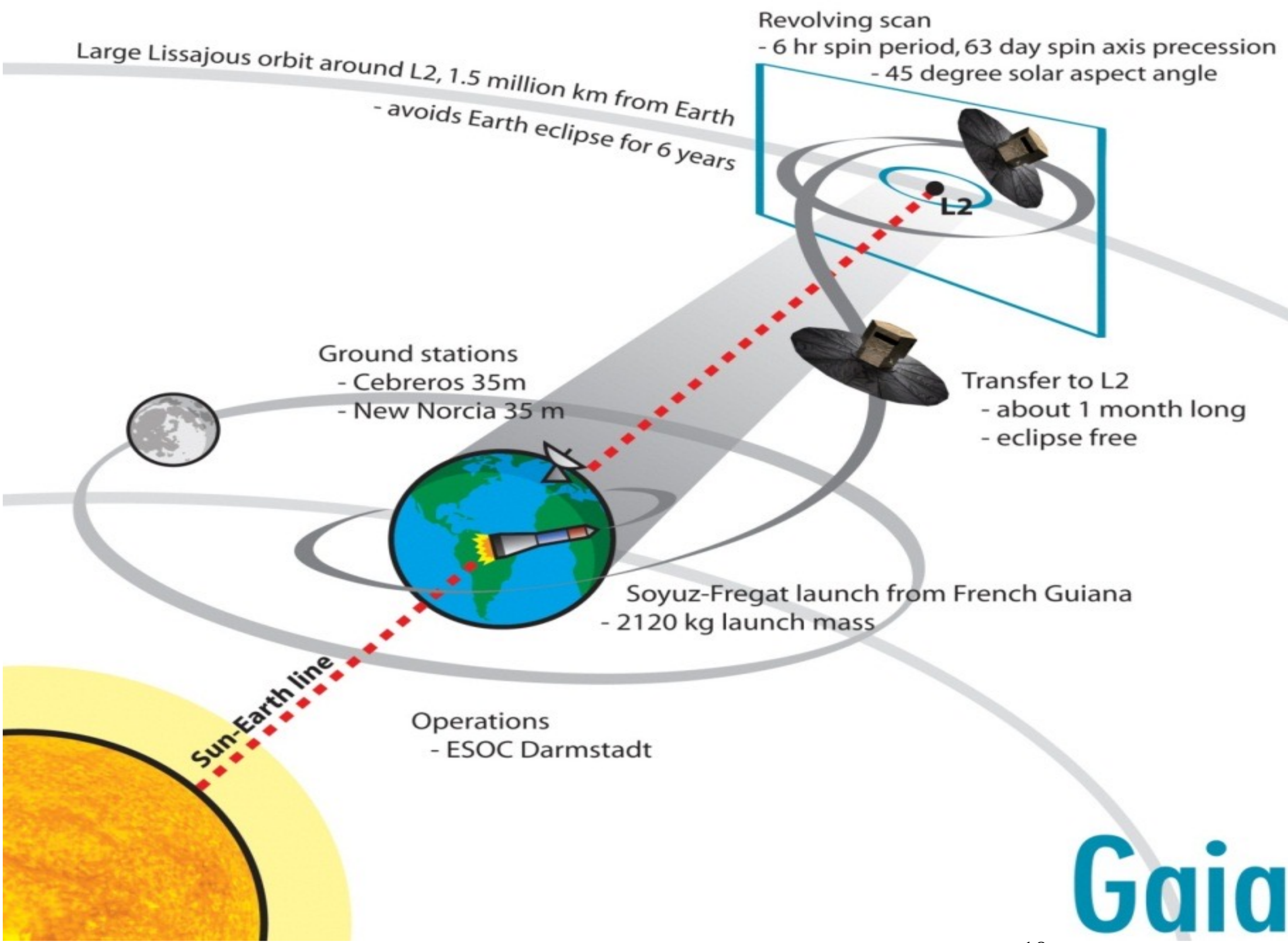
Why Space?

Bending and twinkling effects of the atmosphere,

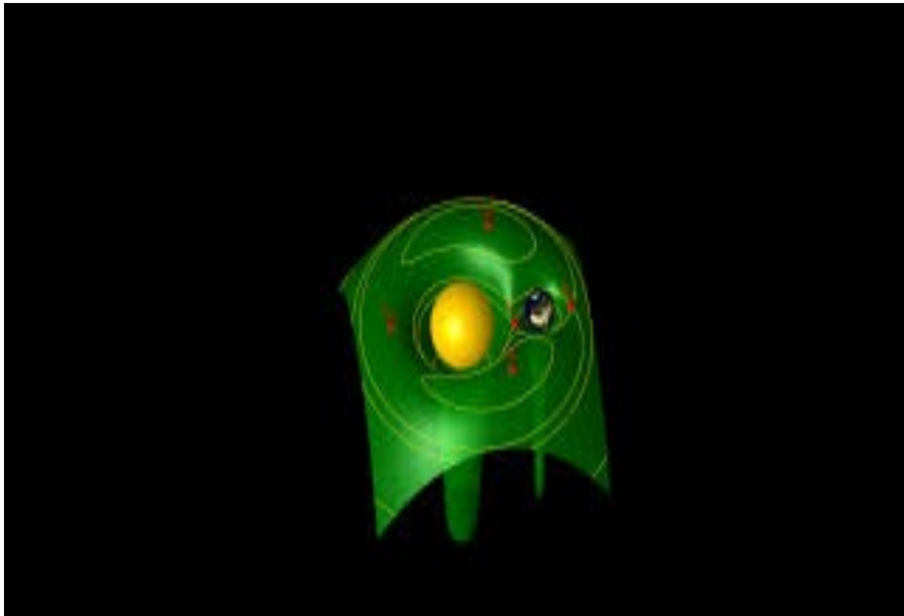
Tiny variations in telescope alignment as the mountain-top observatories went through their endless day and night cycles of warming and cooling.

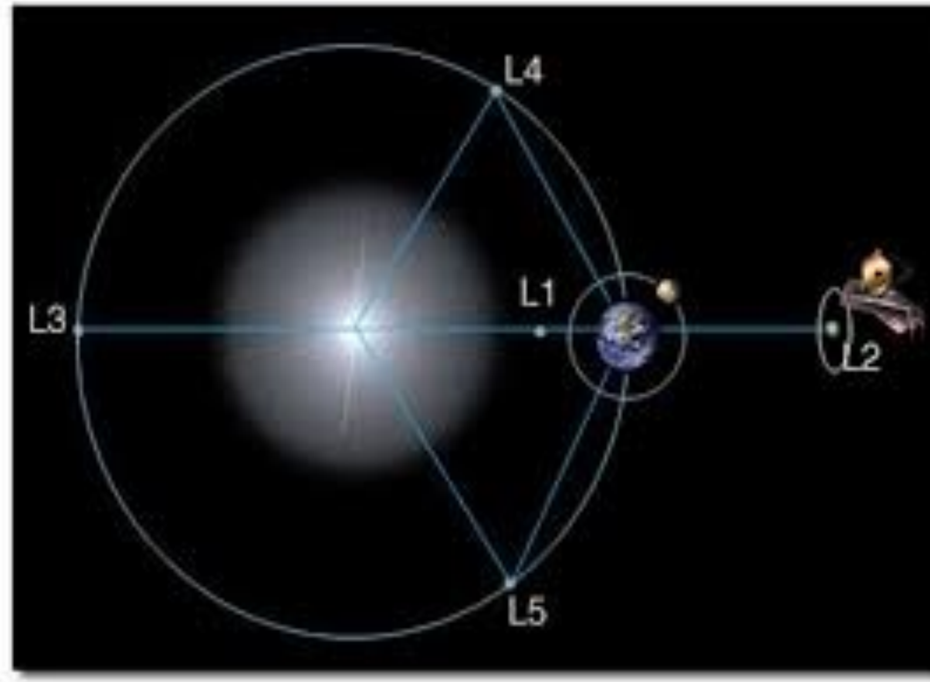
The variable flexing of telescopes under their own weight as the huge supporting structures were steered to observe different parts of the sky added other unpredictable distortions..

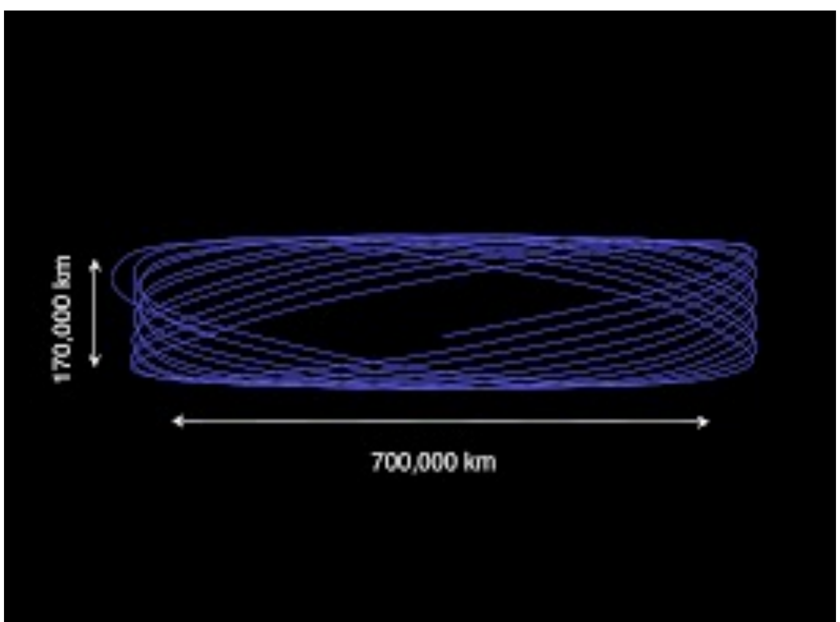
Any telescope on Earth can observe only part of the sky at any one time:

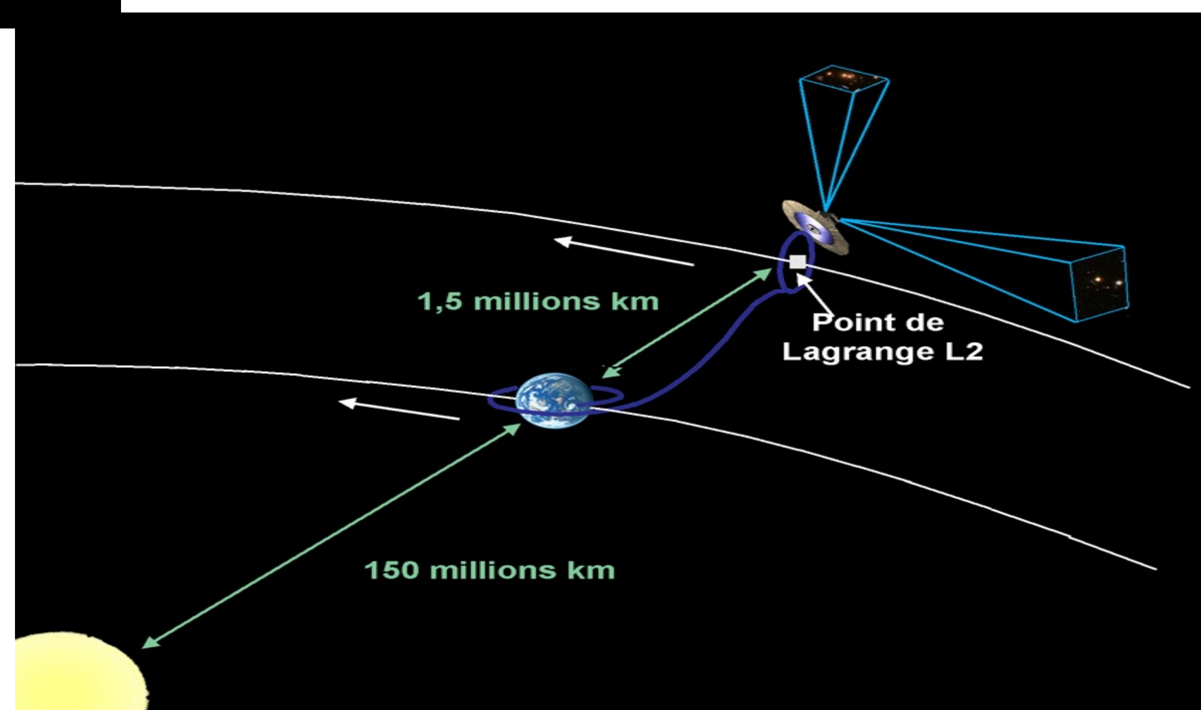


Revolving scan
- 6 hr spin period, 63 day spin axis precession
- 45 degree solar aspect angle
Large Lissajous orbit around L2, 1.5 million km from Earth
- avoids Earth eclipse for 6 years
L2
Ground stations
- Cebreros 35m
- New Norcia 35 m
Transfer to L2
- about 1 month long
- eclipse free
Soyuz-Fregat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




L4
L1
L3
L2
L5

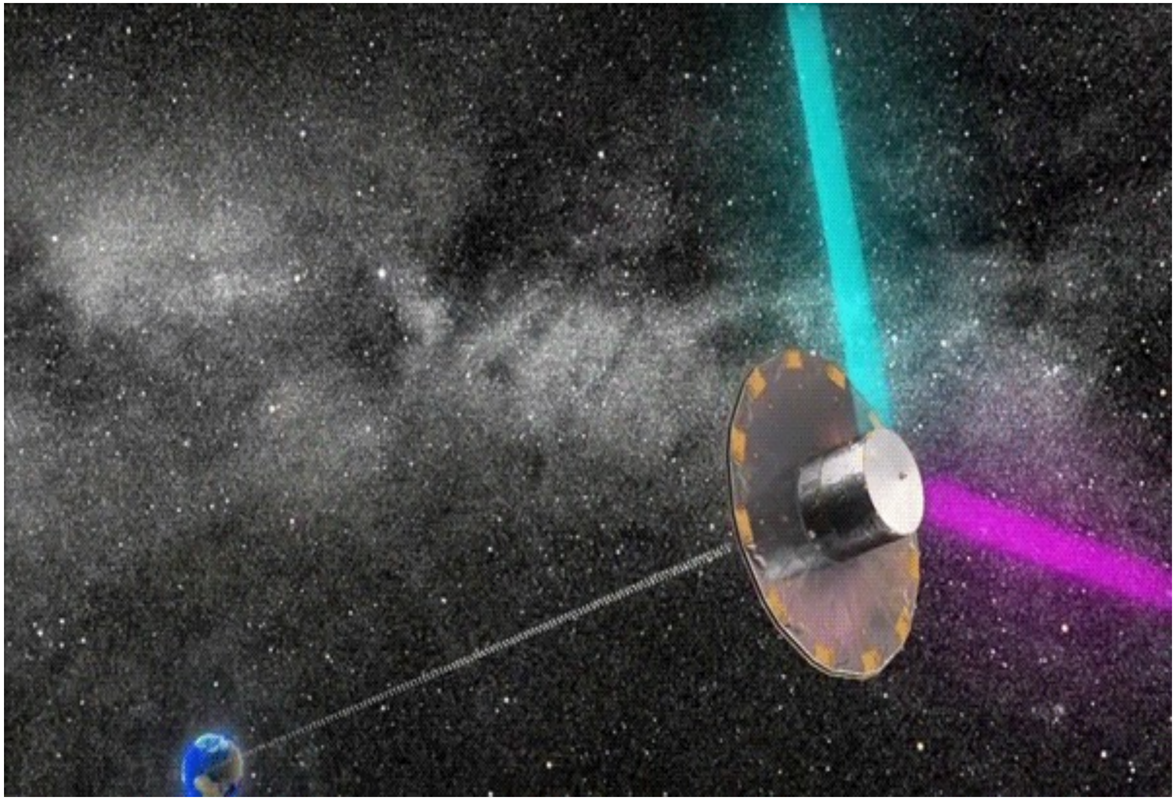

170,000 km
700,000 km


1,5 millions km
Point de
Lagrange L2
150 millions km

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!!!

Gaia Data Releases
Launch 2013, Science Operation 2014

DR1, 2016, 1X 10^9 positions and magnitudes

TGAS: 2 X 10^6 parallaxes and proper motions

DR2: 2018, 1.6 X 10^9 positions and magnitudes

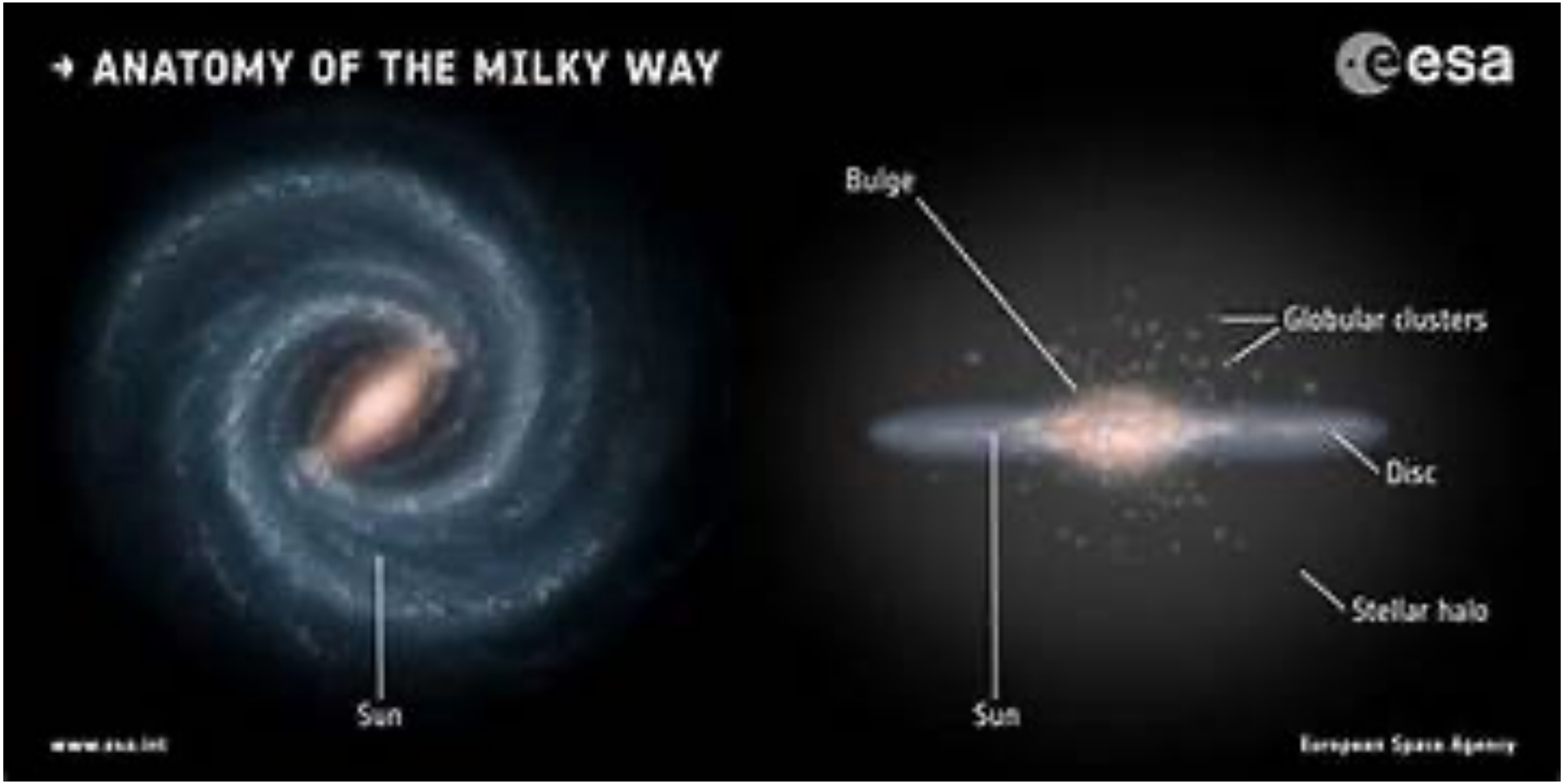
1.3 X 10^9, parallaxes and proper motions

EDR3: 2020, similar to DR2 but better precision (30% parallax, factor of 2 for pm)

DR3: 2022, 33 X 10^6 radial velocities

DR4

DR5



ANATOMY OF THE MILKY WAY
esa
Bulge
Globular clusters
Disc
Stellar halo
Sun
Sun
www.esa.int
European Space Agency

Part 2: TopCat Tutorial

Plotting HR Diagrams with Gaia

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Some important questions?

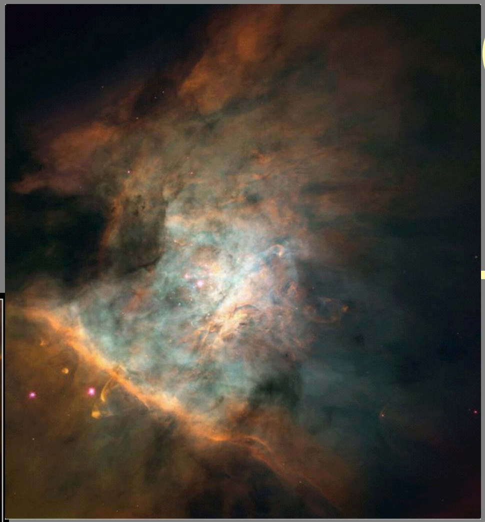
- Are stars born?
- Do stars evolve?
- Do stars die?

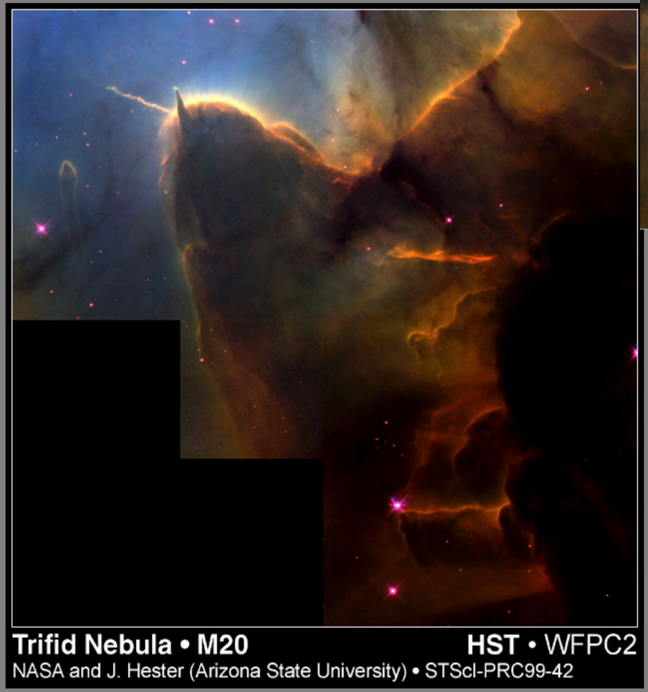
Short answer:

Yes stars are born, since they are radiating, hence they should evolve and they end-up (die) in different forms depending their initial mass and chemical composition.

Stars are born in clouds as these:

Orion nebula





Giant Molecular clouds

- **Low-density cloud (10,000 atoms per cm^3)**

Very cold: T~10-20 K

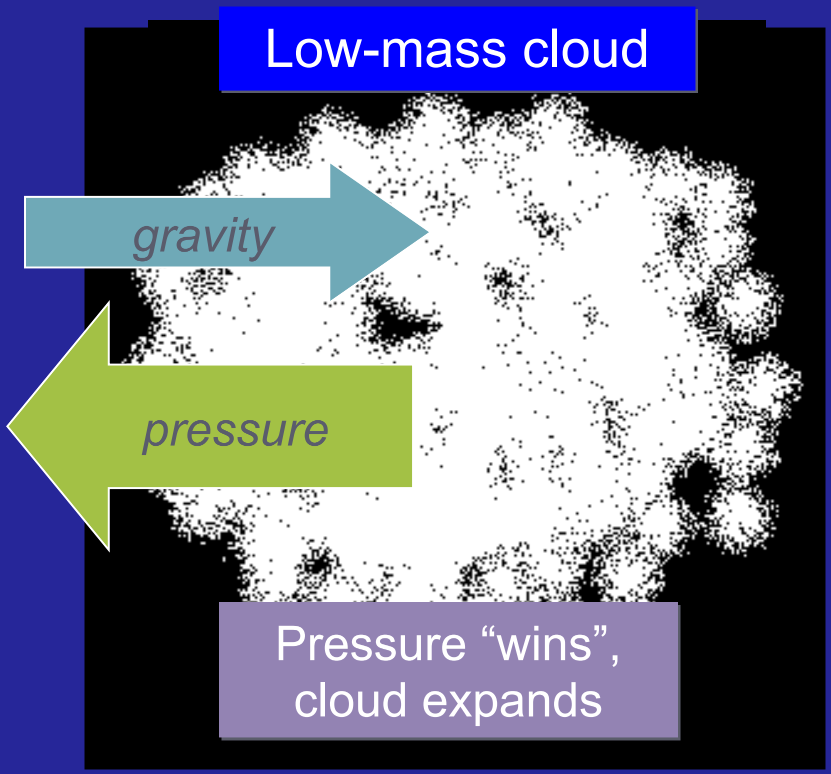
Made mostly of: H (75%) and He (23-25%) and a bit of heavier elements (<2%).

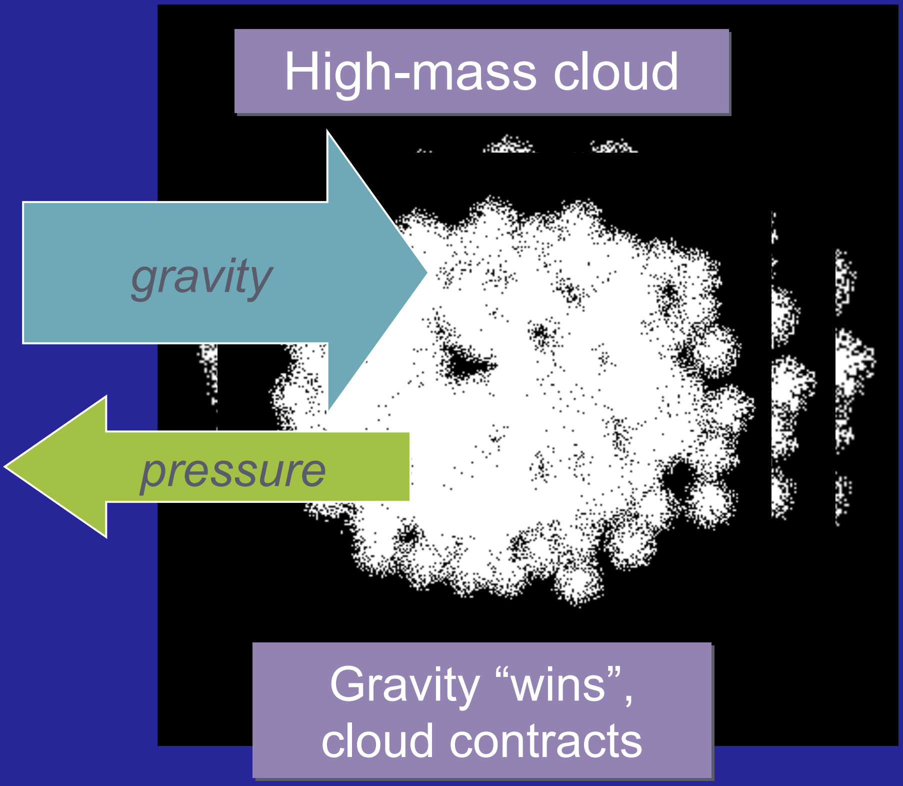
If the molecular cloud has sufficient mass and low temperature it collapses under its own gravity.

Two forces act on the system:

(1) Gravity which tries to collapse the cloud

(2) Pressure (thermal) which tries to expand the cloud

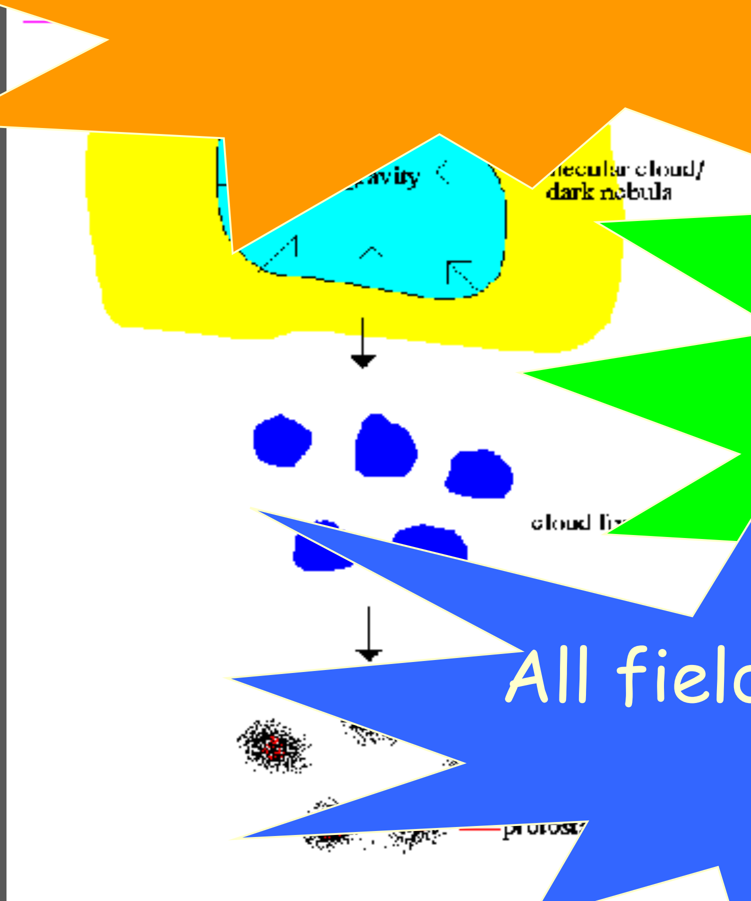




Stars are not born in isolation!

They are always born in groups

All field stars are from clusters



tational Vs Thermal

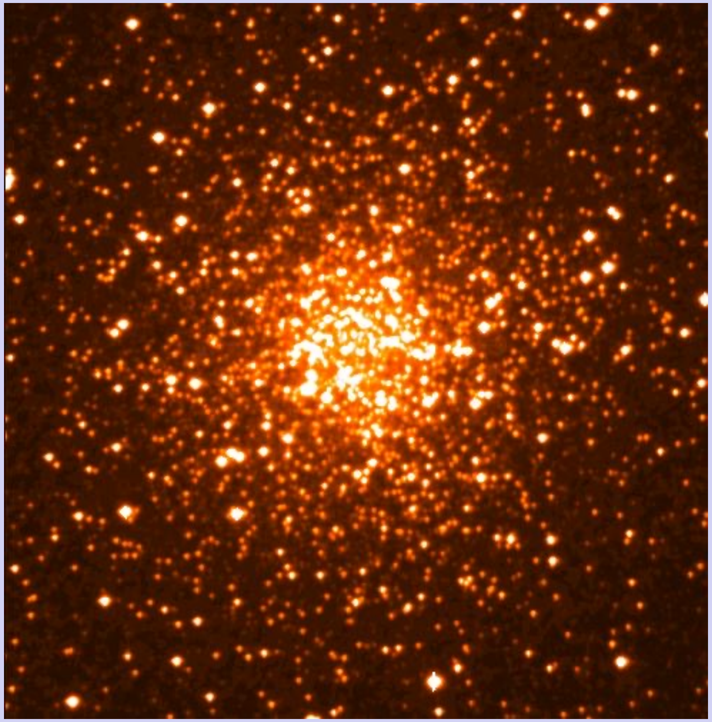
of a star cluster

Star clusters

A star cluster is a sample of stars formed from the same molecular cloud, where all the stars have the same age, chemical composition and are at the same distance, differ only in ***mass****!!*

Types of Clusters

- Open Clusters
- Globular clusters
- Associations



Stars formed at the same time,distance, chemical composition…..differ only in mass.

Globular Clusters

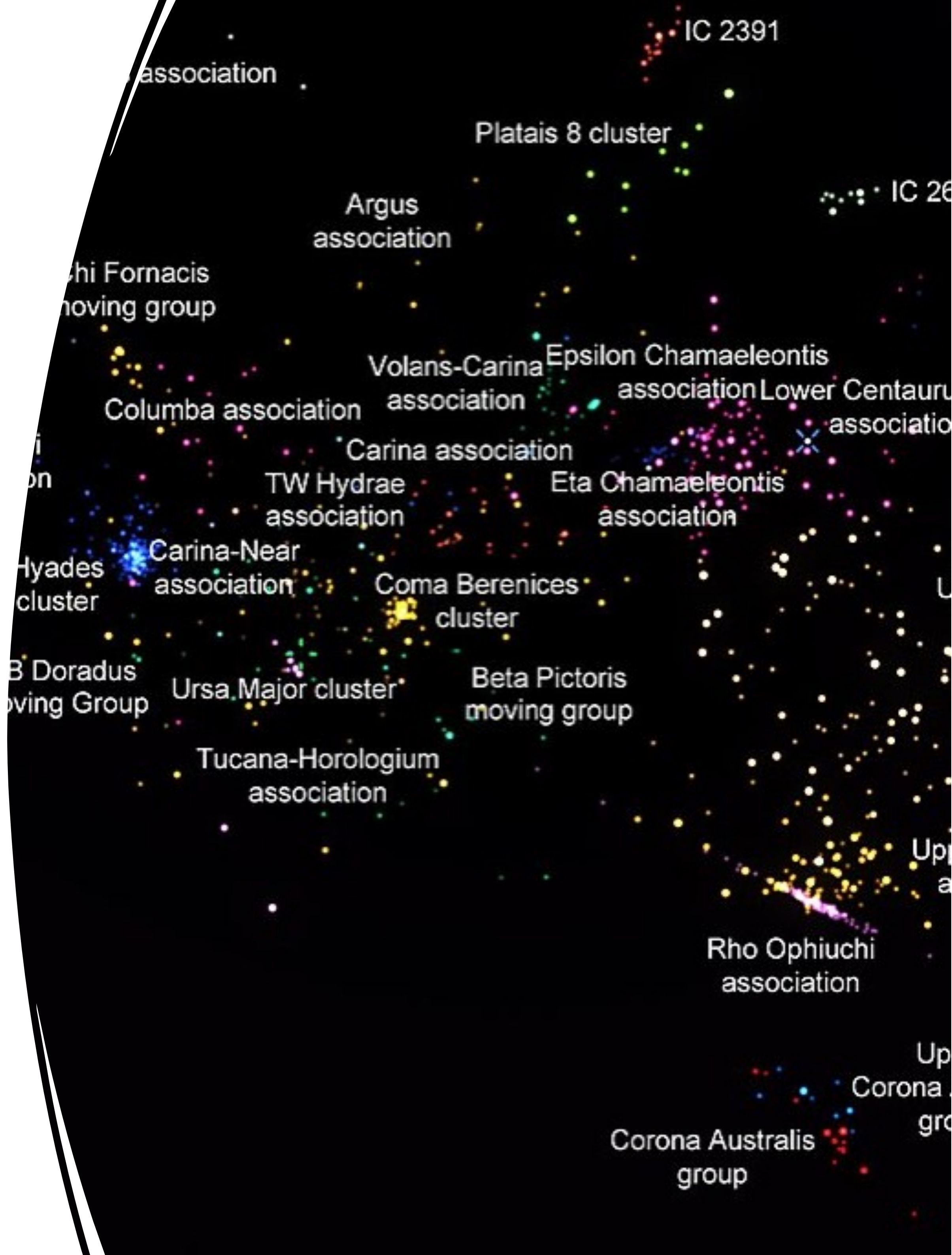
- **appearance** compact
- **number of stars** 50,000 – 1,000,000
- **Mass** 10^5 M_{sun}
- **colors** mostly red
- **age** very old, $\sim 10^{10}$ yrs
- **distribution** more broadly distributed, are gravitationally bound, are spherical in shape
- **population** Pop II
- **orbits** highly eccentric, elliptical

Open Clusters

- **appearance** Loose
- **number of stars** 20 – 1000
- **Mass** 10^5 M_{sun}
- **colors** mostly blue
- **age** young ~10^6-10^8 yrs
- **distribution** close to the plane of the Milky Way, may not be bound by their own gravity, spiral arm tracers
- **population** Pop I
- **orbits** Regular, planar

Star Associations

- OB associations: 10–100 massive stars of spectral class O and B
- T associations R associations



Known associations

- The Hipparcos satellite: ~10 OB associations within 650 parsecs of the Sun
- The nearest OB association:Scorpius–Centaurus Association ~ 120 pc
- The Ursa Major Moving Group (Except for α Ursae Majoris and η Ursae Majoris, all the stars in the Plough/Big Dipper are part of that group.)
- Other young moving groups include:
- Local Association (Pleiades moving group), Hyades Stream, IC 2391 supercluster, Beta Pictoris moving group, Castor moving group, AB Doradus moving group, Zeta Herculis moving group, Alpha Persei moving cluster

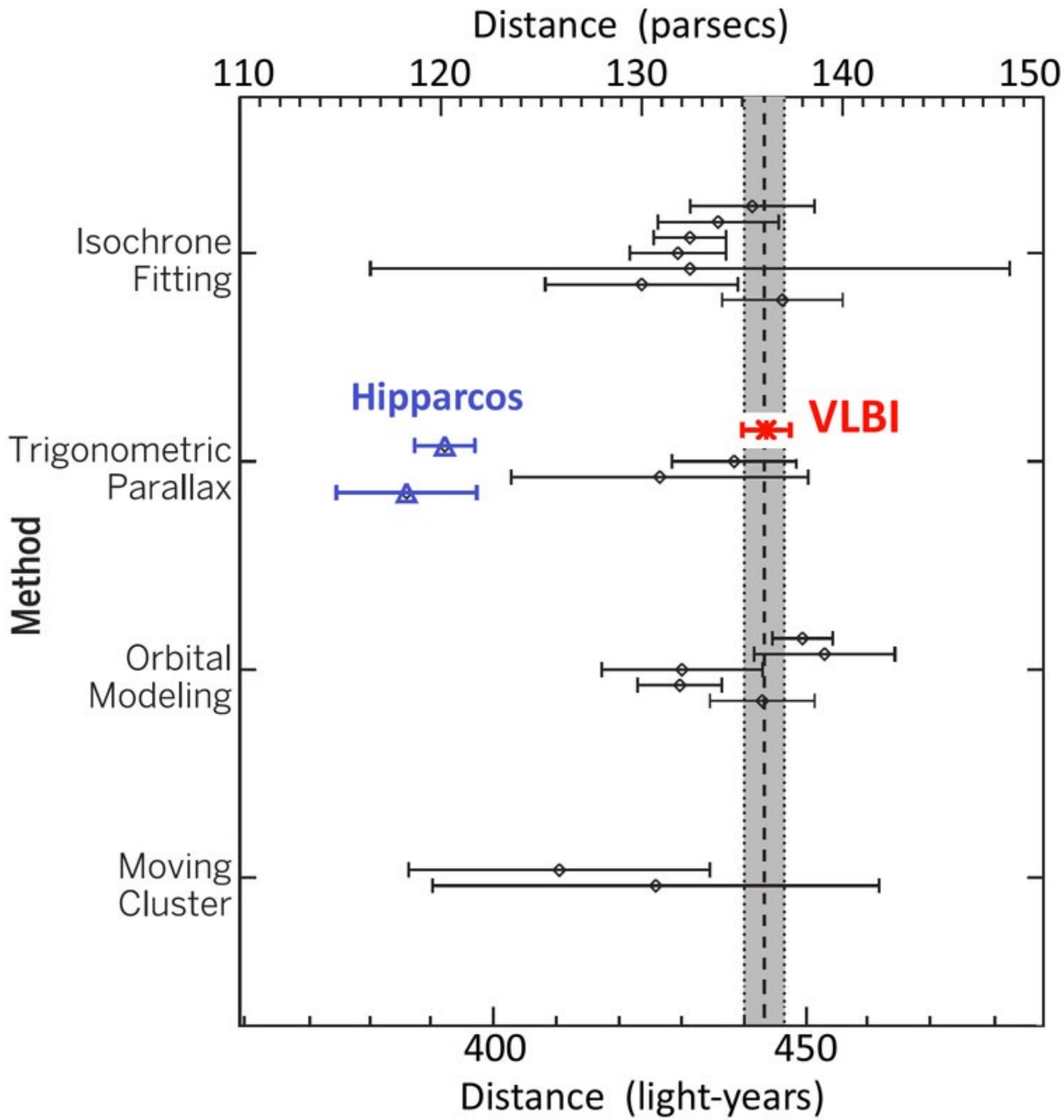
Pleiades distance problem (M45)

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%

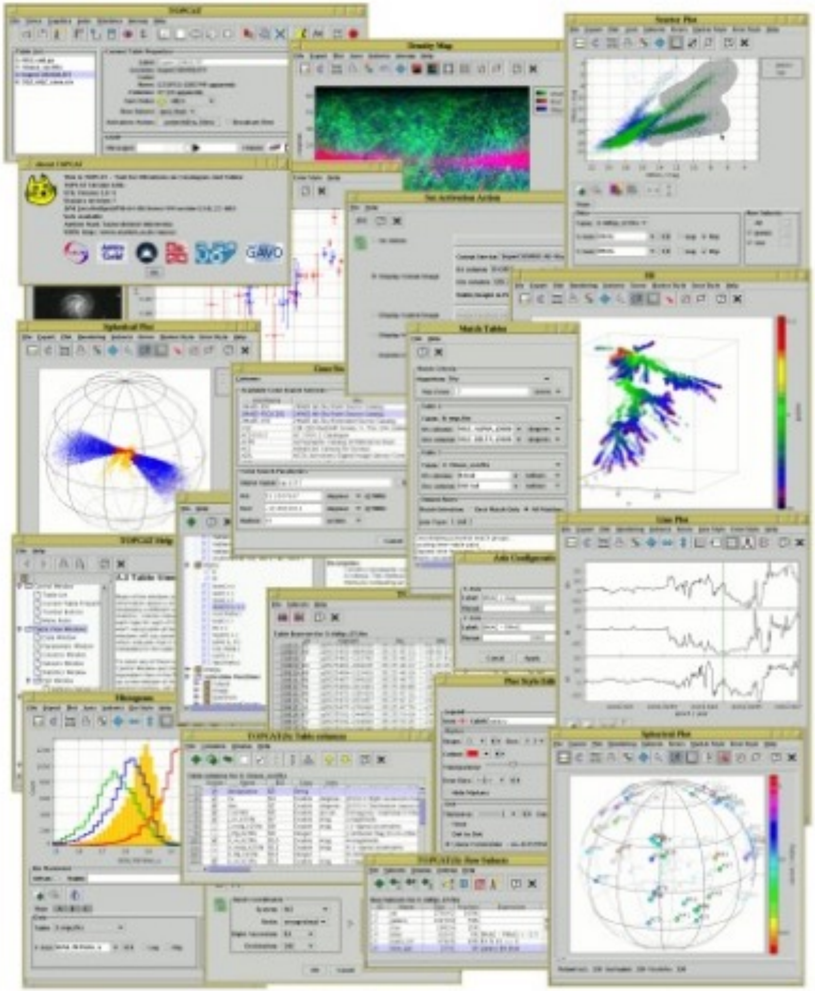
Courtsey: Mark Taylor, TOPCAT and how to use it for Gaia, Gaia DR1 Workshop, ESAC, Madrid.

Pleadis Distance



TOPCAT

TOPCAT = Tool for OPerations on Catalogues And Tables



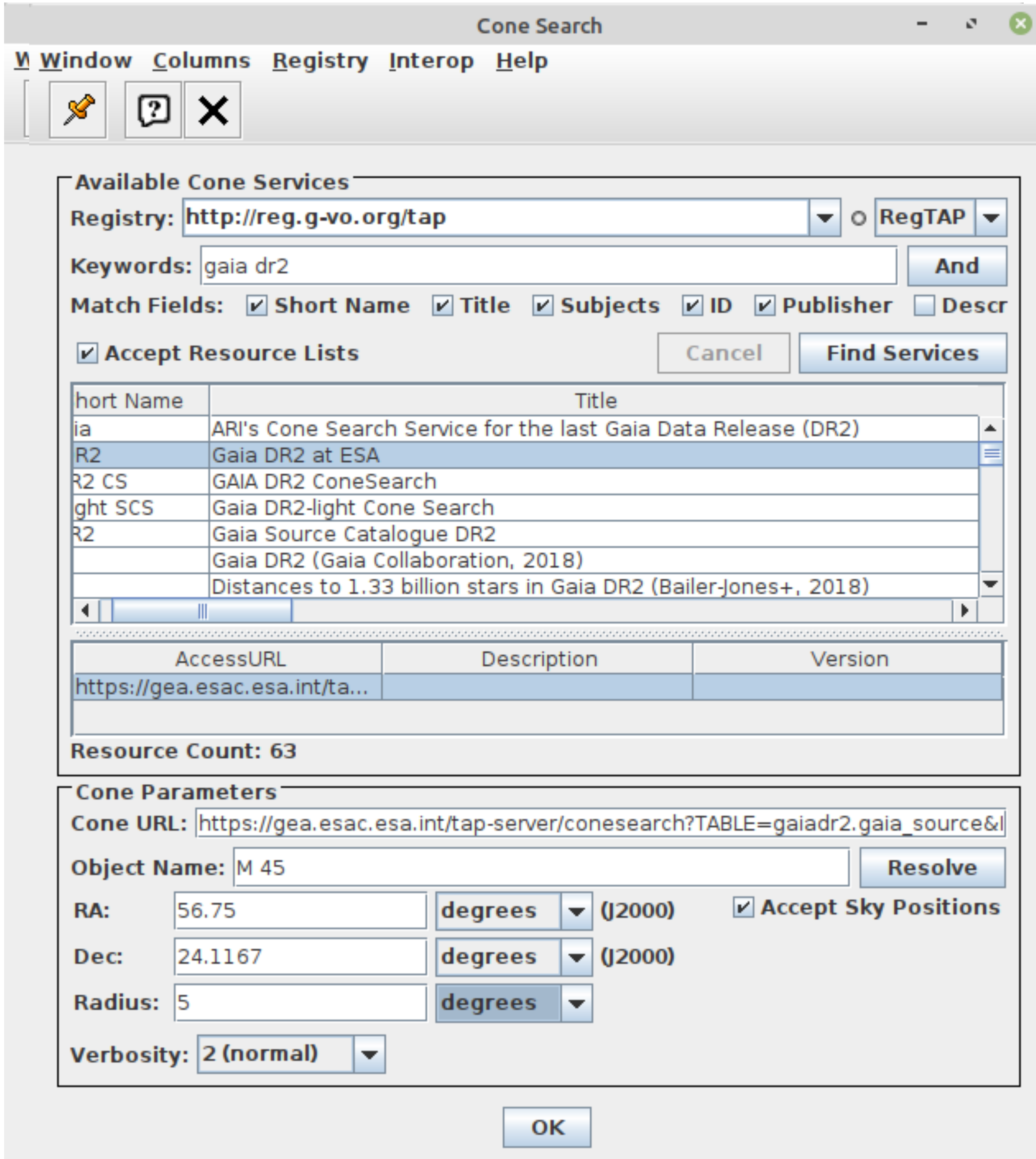
Capabilities:

- 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/`


Cone Search
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Available Cone Services
Registry: http://reg.g-vo.org/tap
RegTAP
Keywords: gaia dr2
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Match Fields: Short Name Title Subjects ID Publisher Descr
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ARI's Cone Search Service for the last Gaia Data Release (DR2)
R2
Gaia DR2 at ESA
R2 CS
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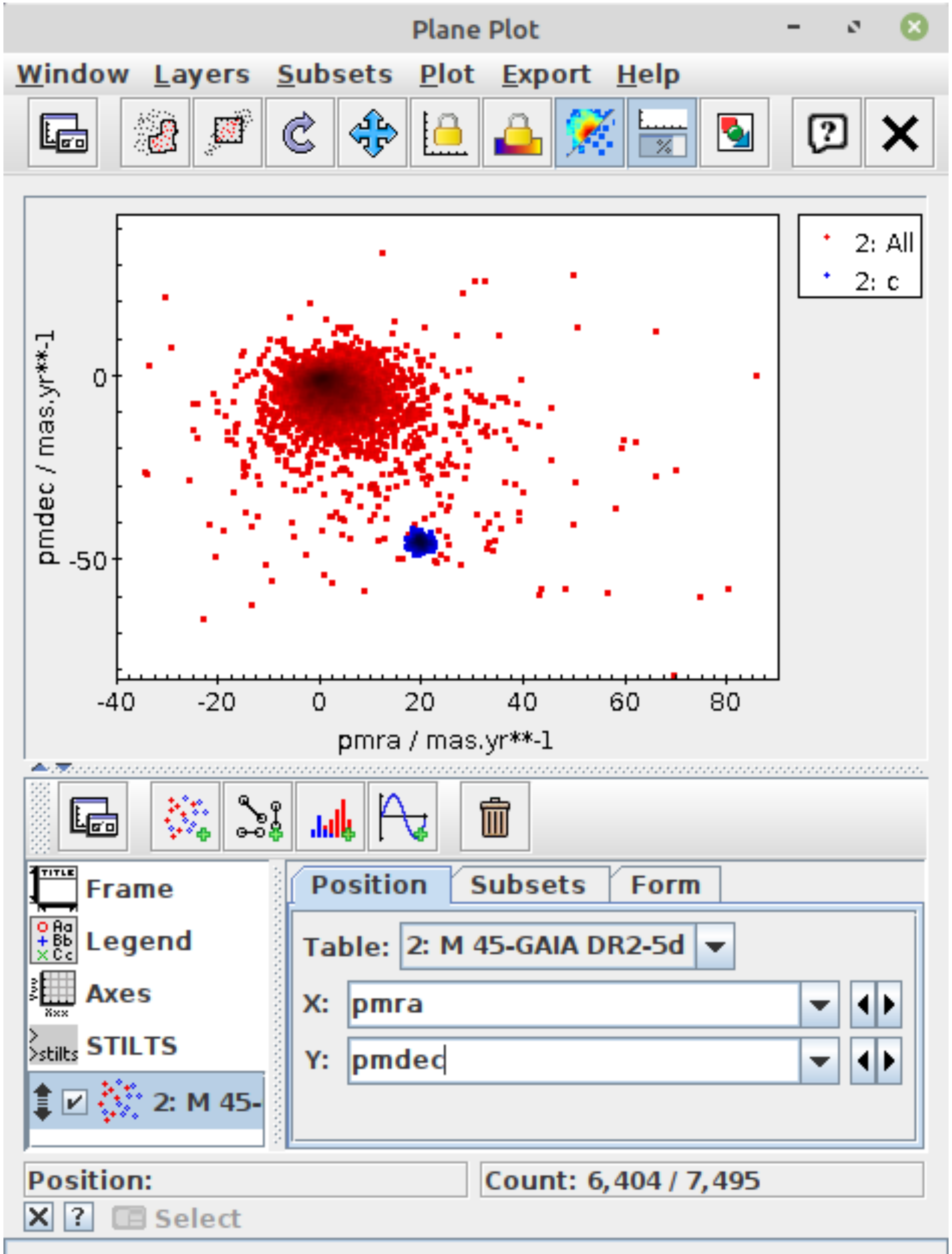
R2
Gaia Source Catalogue DR2
Gaia DR2 (Gaia Collaboration, 2018)
Distances to 1.33 billion stars in Gaia DR2 (Bailer-Jones+, 2018)
AccessURL
Description
Version
https://gea.esac.esa.int/ta...
Resource Count: 63
Cone Parameters
Cone URL: https://gea.esac.esa.int/tap-server/conesearch?TABLE=gaiadr2.gaia_source&
Object Name: M 45
Resolve
RA: 56.75 degrees (J2000)
Accept Sky Positions
Dec: 24.1167 degrees (J2000)
Radius: 5 degrees
Verbosity: 2 (normal)
OK



Plane Plot
Window Layers Subsets Plot Export Help
2: All
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pmdec / mas.yr**-1
0
-50
-40 -20 0 20 40 60 80
pmra / mas.yr**-1
Frame
Legend
Axes
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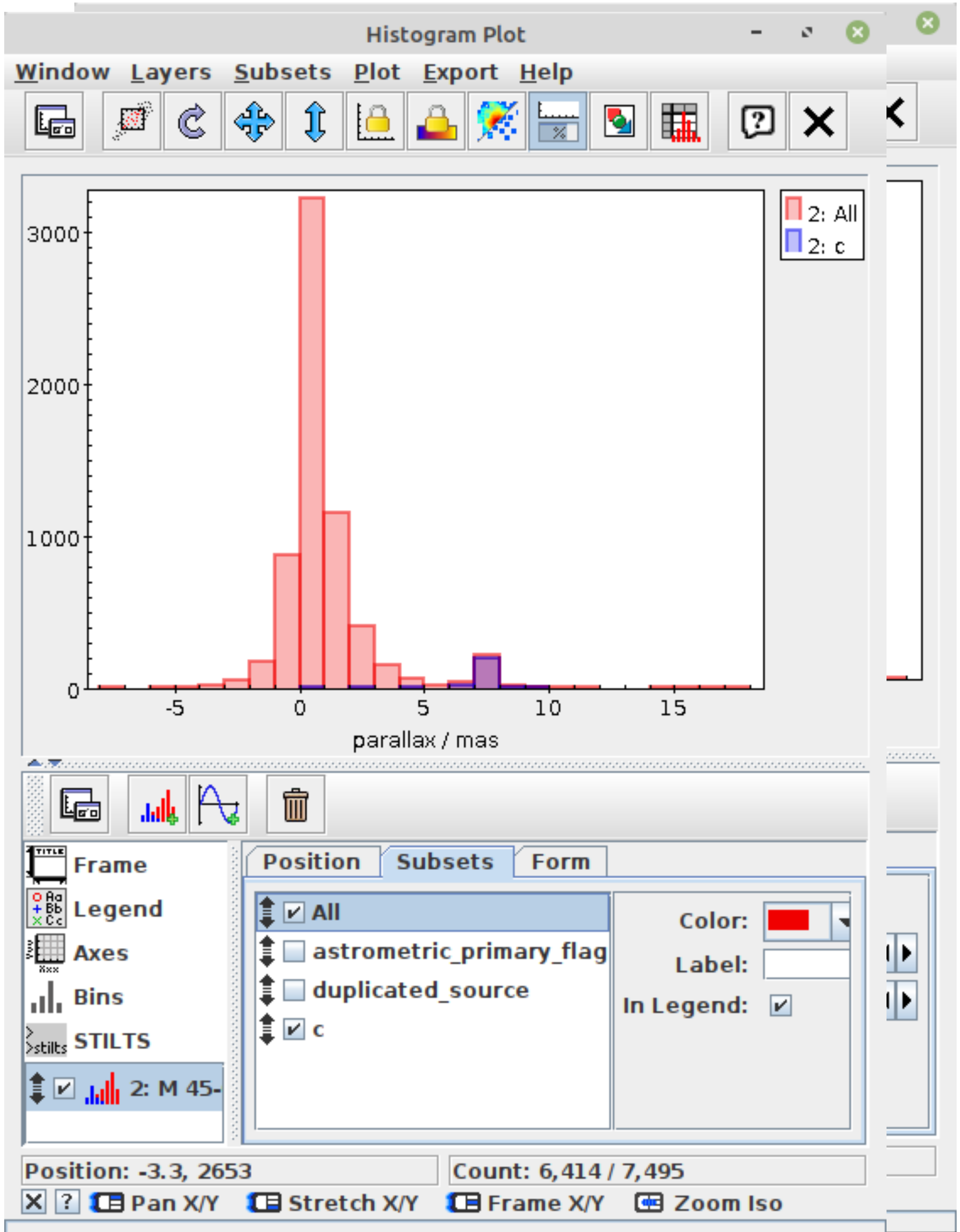
2: M 45-
Position Subsets Form
Table: 2: M 45-GAIA DR2-5d
X: pmra
Y: pmdec
Position:
Count: 6,404 / 7,495
Select



Histogram Plot
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Pan X/Y
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Frame X/Y
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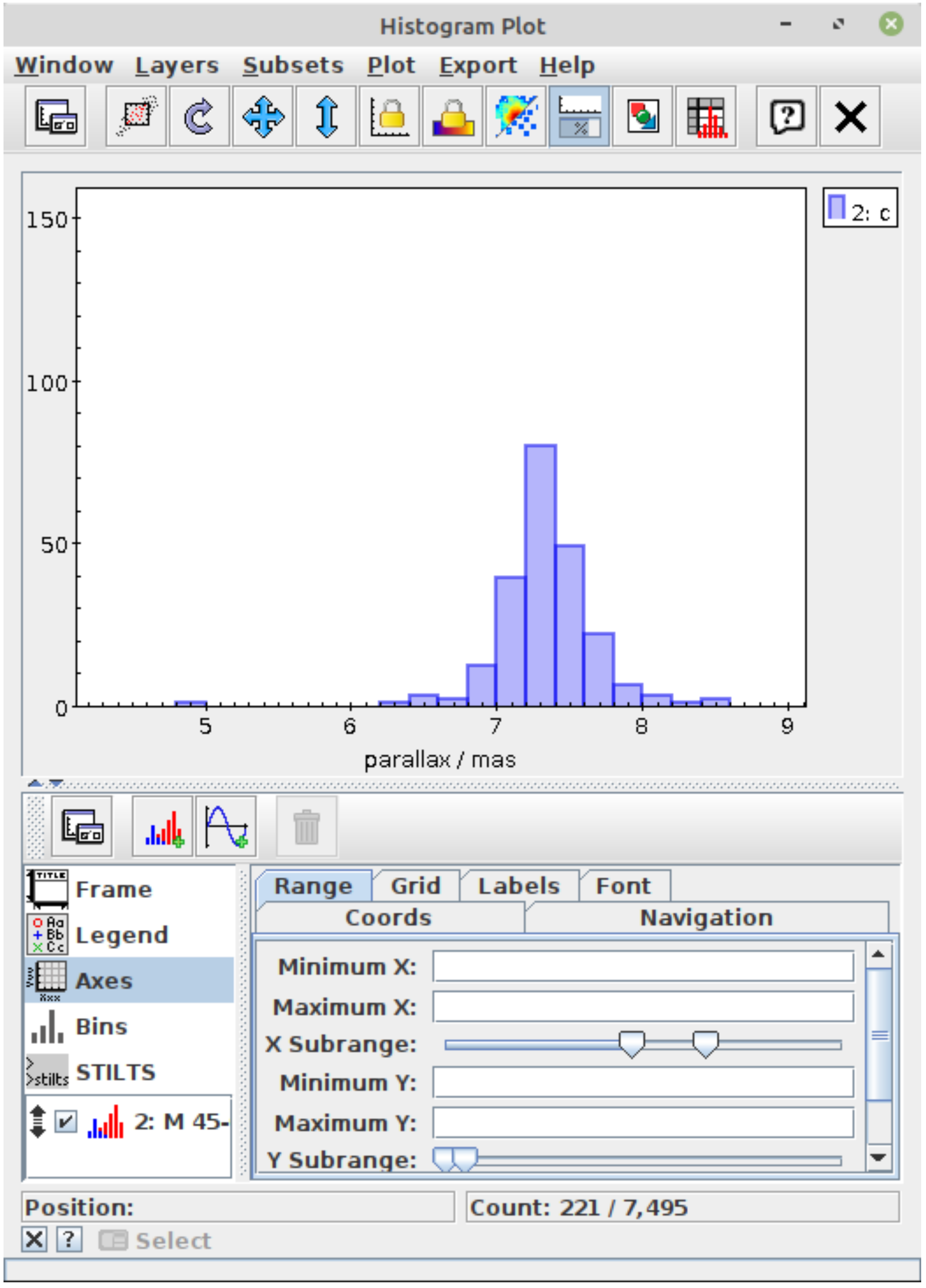
Histogram Plot
Window Layers Subsets Plot Export Help
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parallax / mas
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Range
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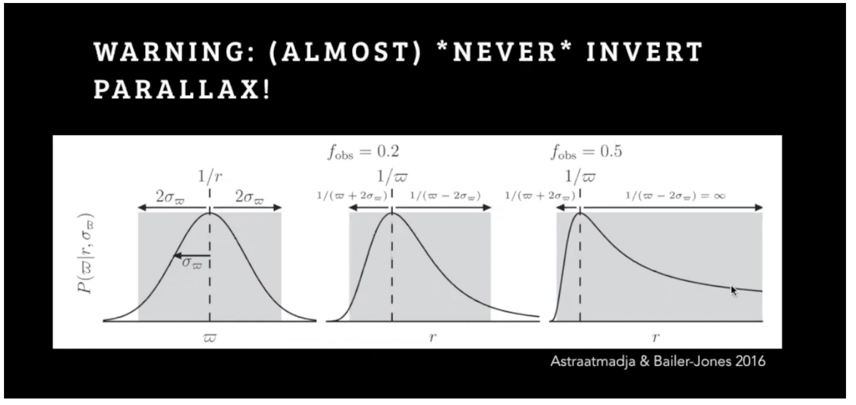
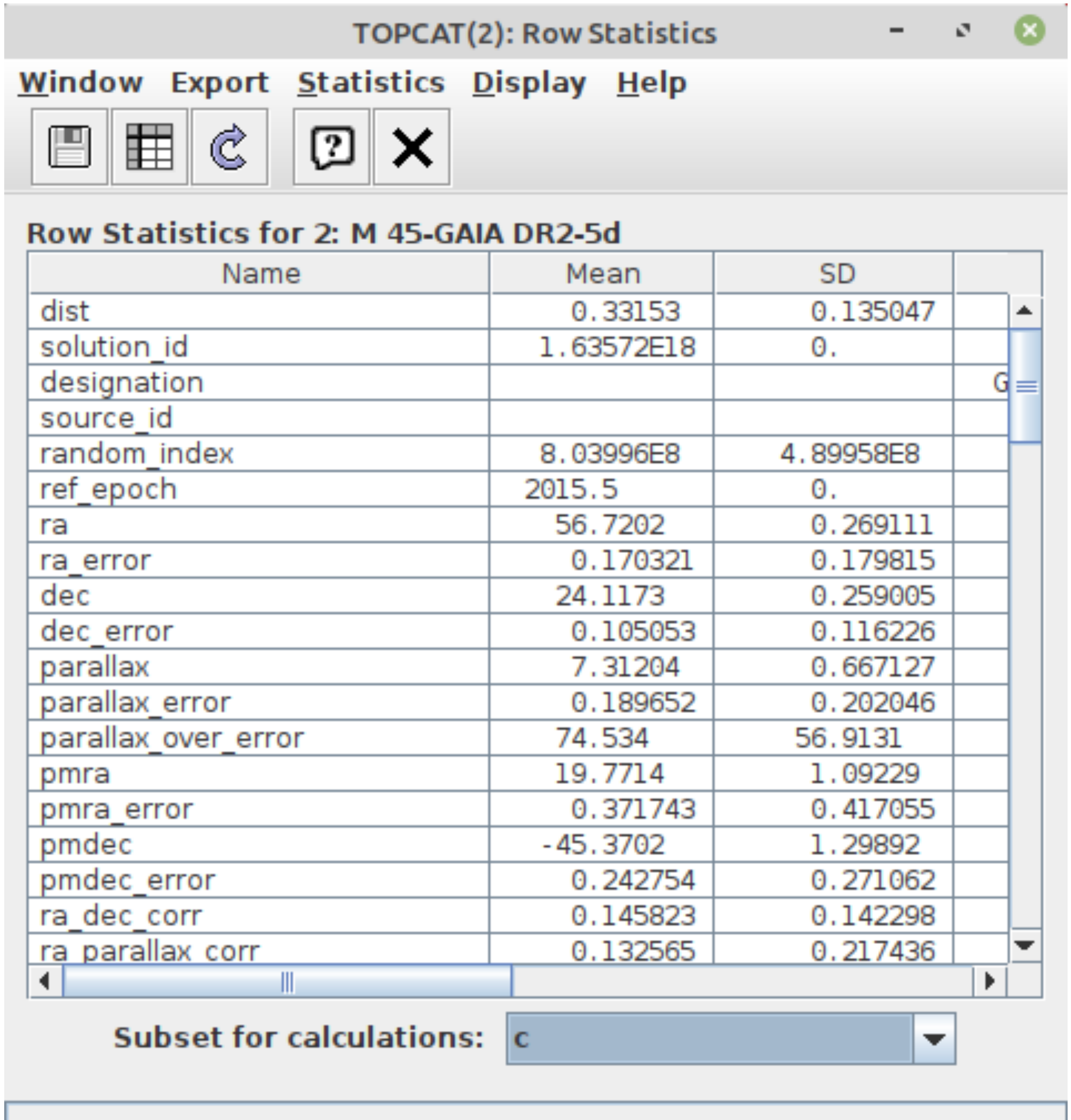
Maximum X:
X Subrange:
Minimum Y:
Maximum Y:
Y Subrange:
Position:
Count: 221 / 7,495
Select


WARNING: (ALMOST) *NEVER* INVERT PARALLAX!
$f_{obs} = 0.2$
$f_{obs} = 0.5$
$1/r$
$1/\varpi$
$2\sigma_\varpi$
$P(\varpi|r, \sigma_\varpi)$
ϖ
r
Astraatmadja & Bailer-Jones 2016



Name	Mean	SD	
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designation			G
source_id			
random_index	8.03996E8	4.89958E8	
ref_epoch	2015.5	0.	
ra	56.7202	0.269111	
ra_error	0.170321	0.179815	
dec	24.1173	0.259005	
dec_error	0.105053	0.116226	
parallax	7.31204	0.667127	
parallax_error	0.189652	0.202046	
parallax_over_error	74.534	56.9131	
pmra	19.7714	1.09229	
pmra_error	0.371743	0.417055	
pmdec	-45.3702	1.29892	
pmdec_error	0.242754	0.271062	
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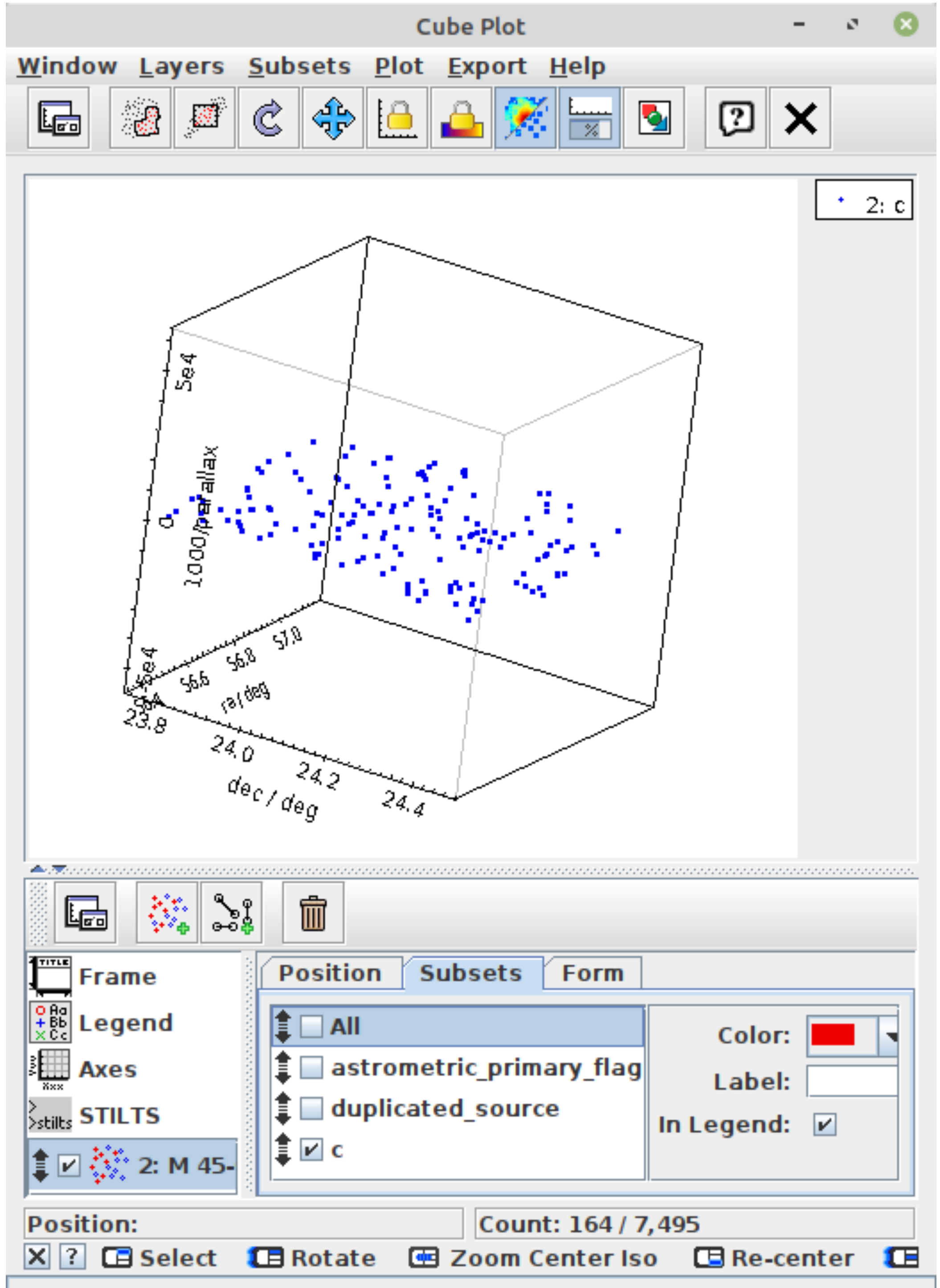
Cube Plot
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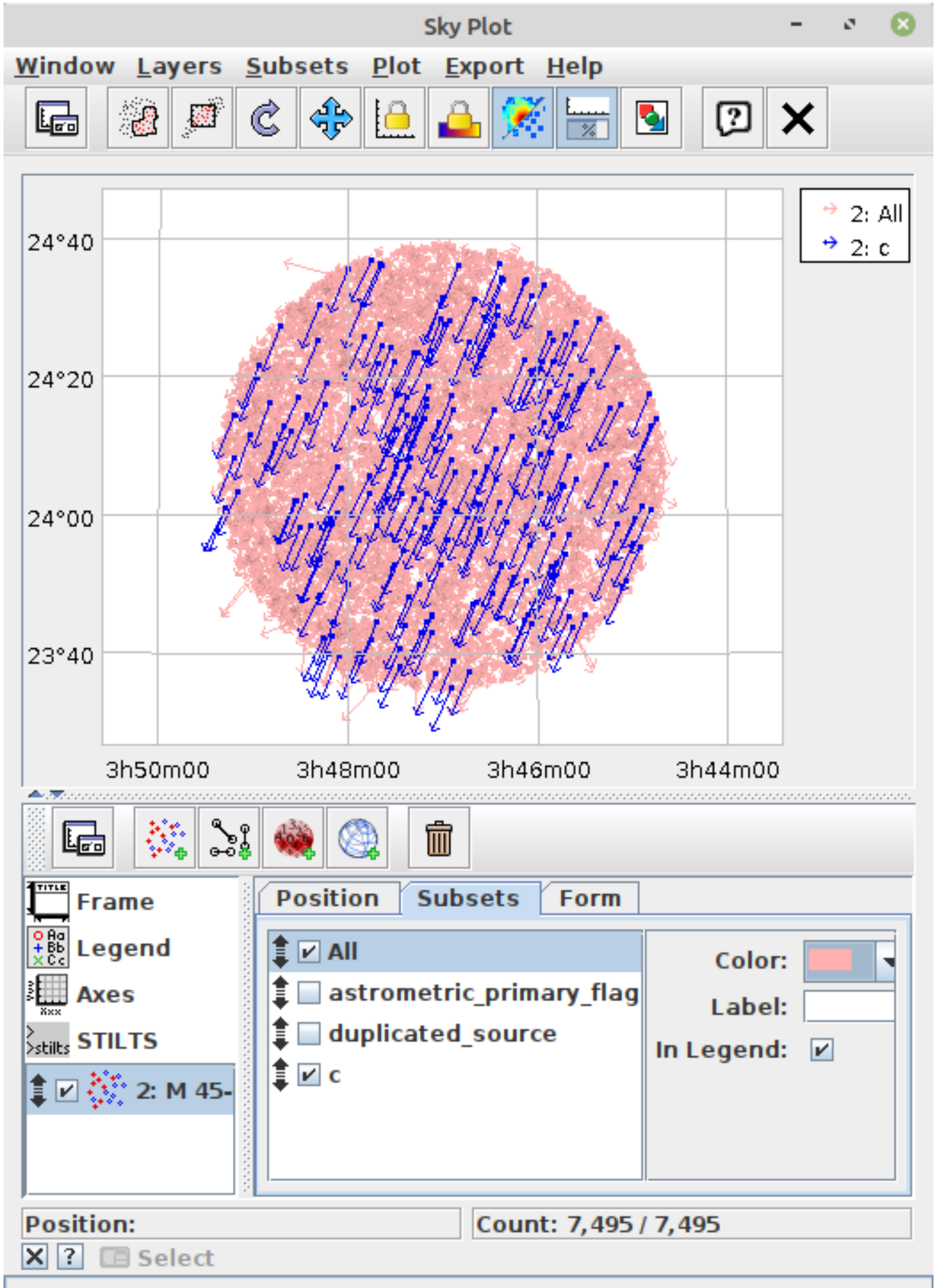

Sky Plot
Window Layers Subsets Plot Export Help
24°40
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astrometric_primary_flag
duplicated_source
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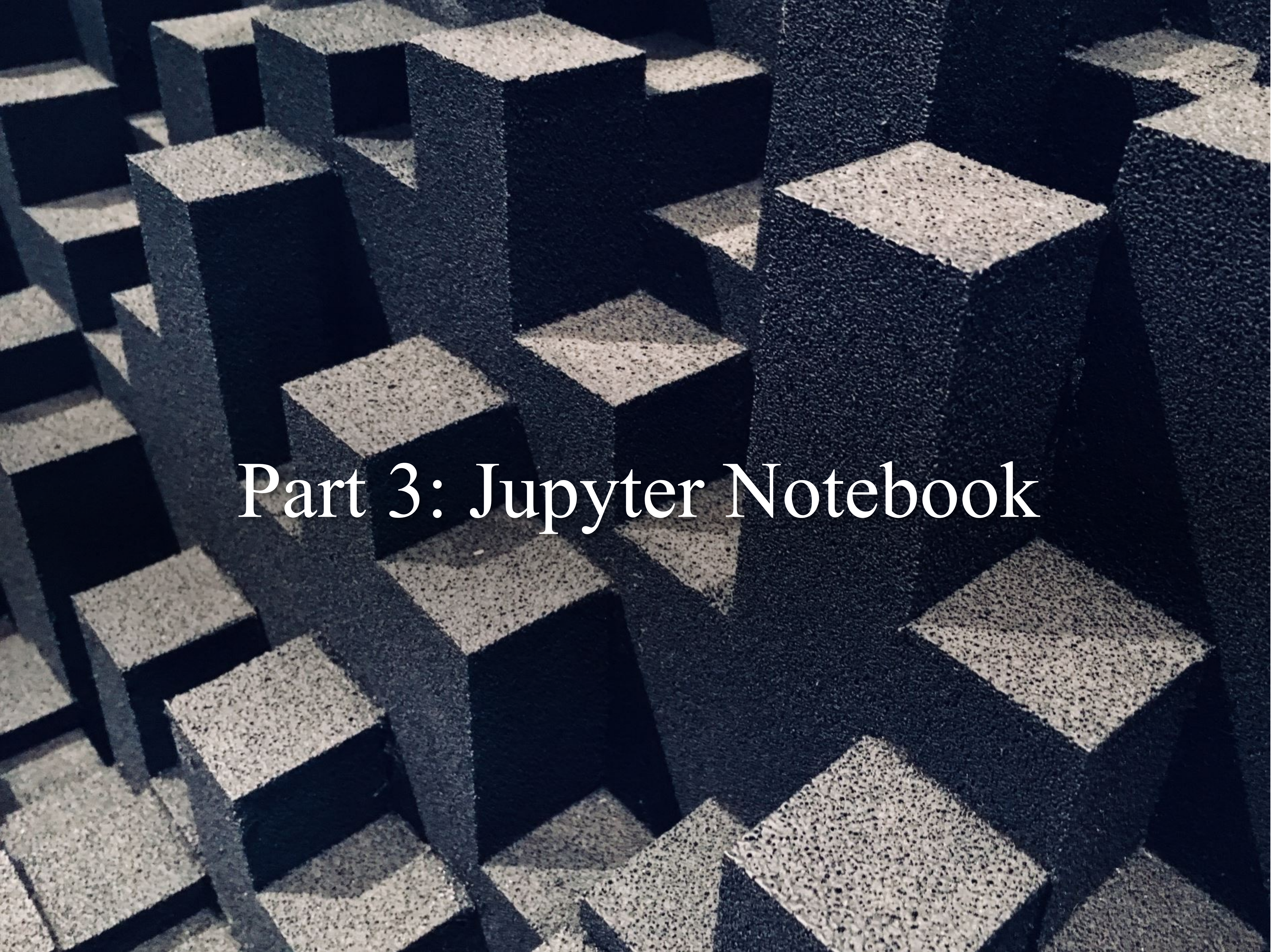
Color:
Label:
In Legend:
Position:
Count: 7,495 / 7,495
Select


So now we can find a cluster...


Part 3: Jupyter Notebook