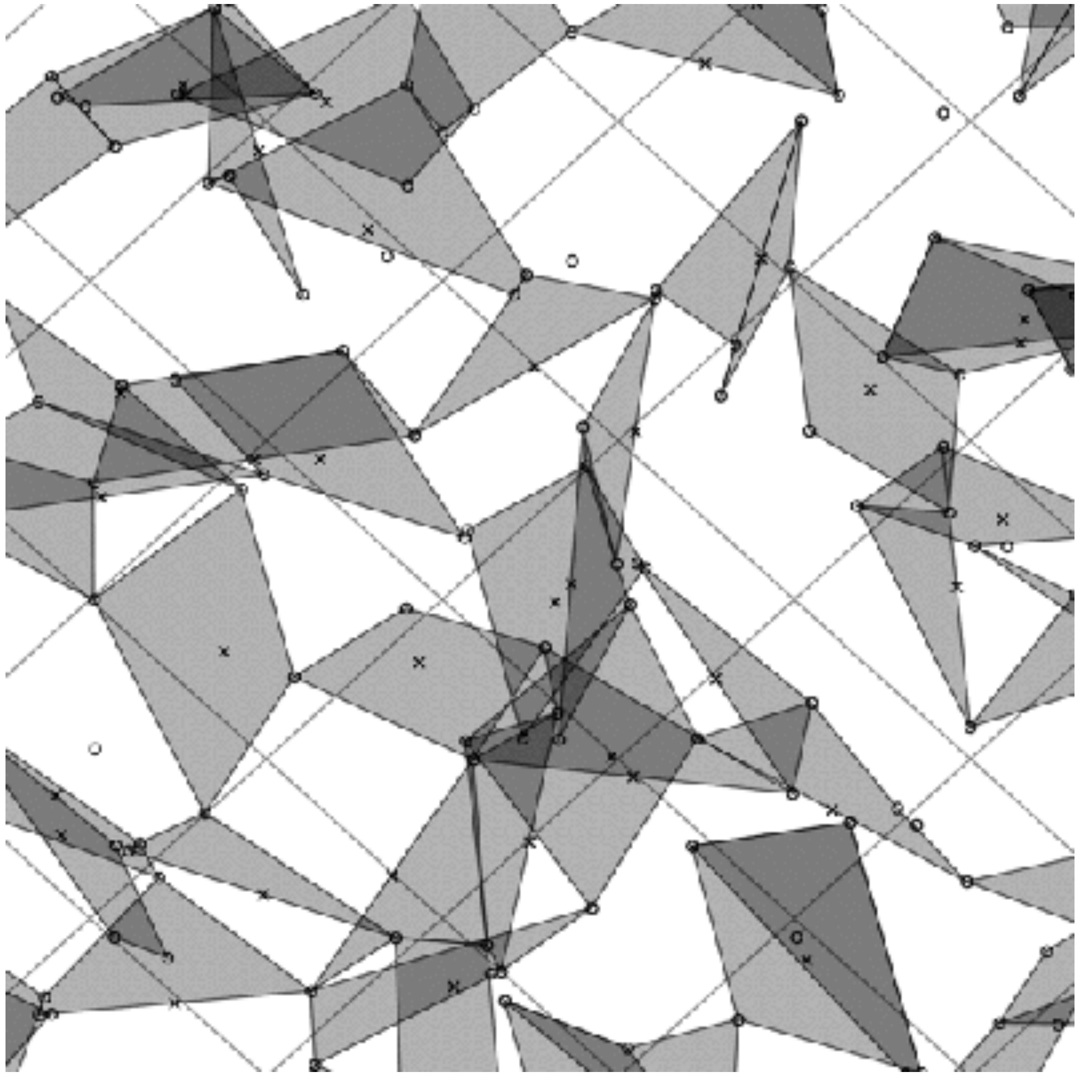
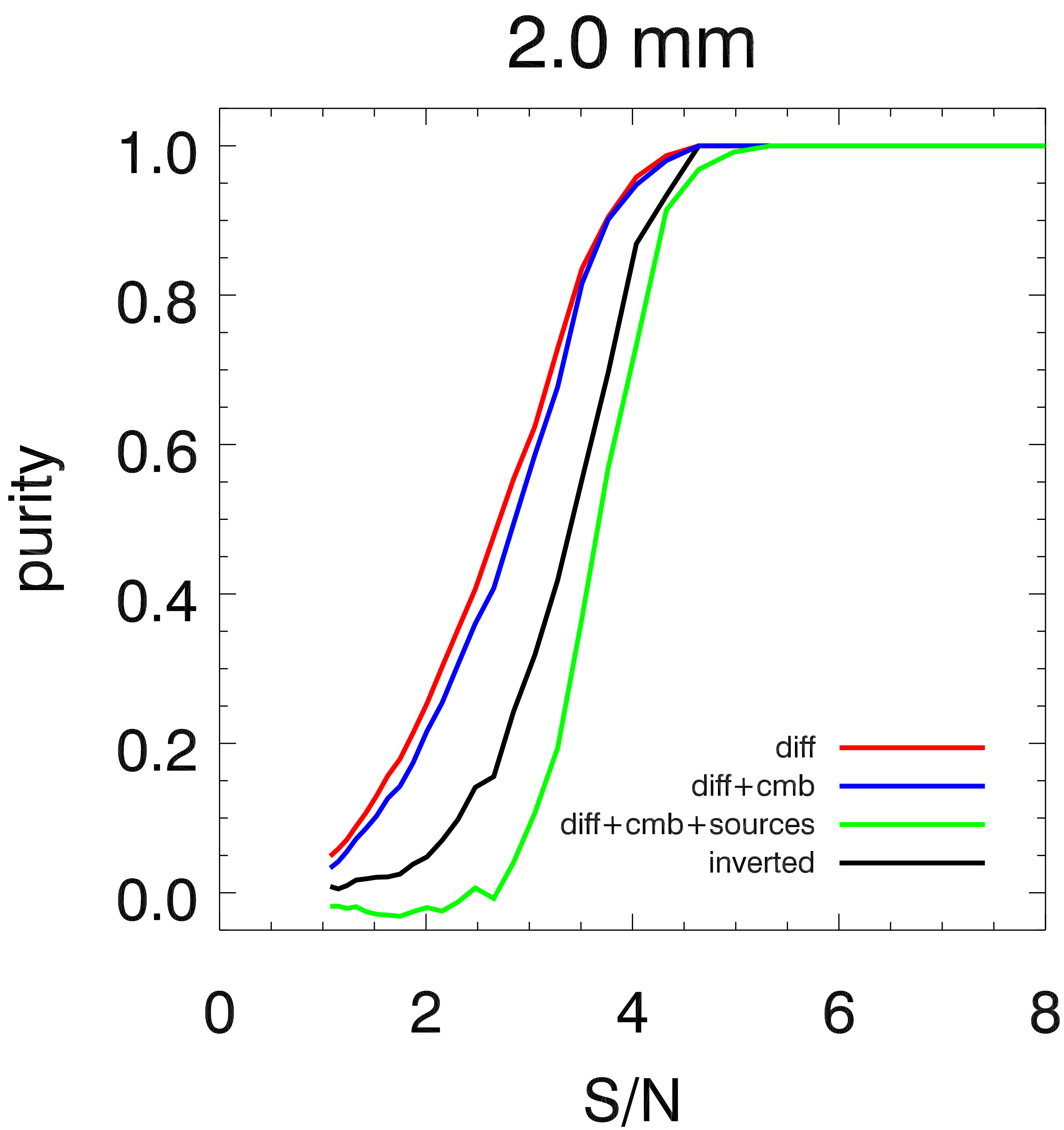
Astronomy 503
Observational Astronomy



Prof. Gautham Narayan

Lecture 06: Catalogs

Catalog Purity

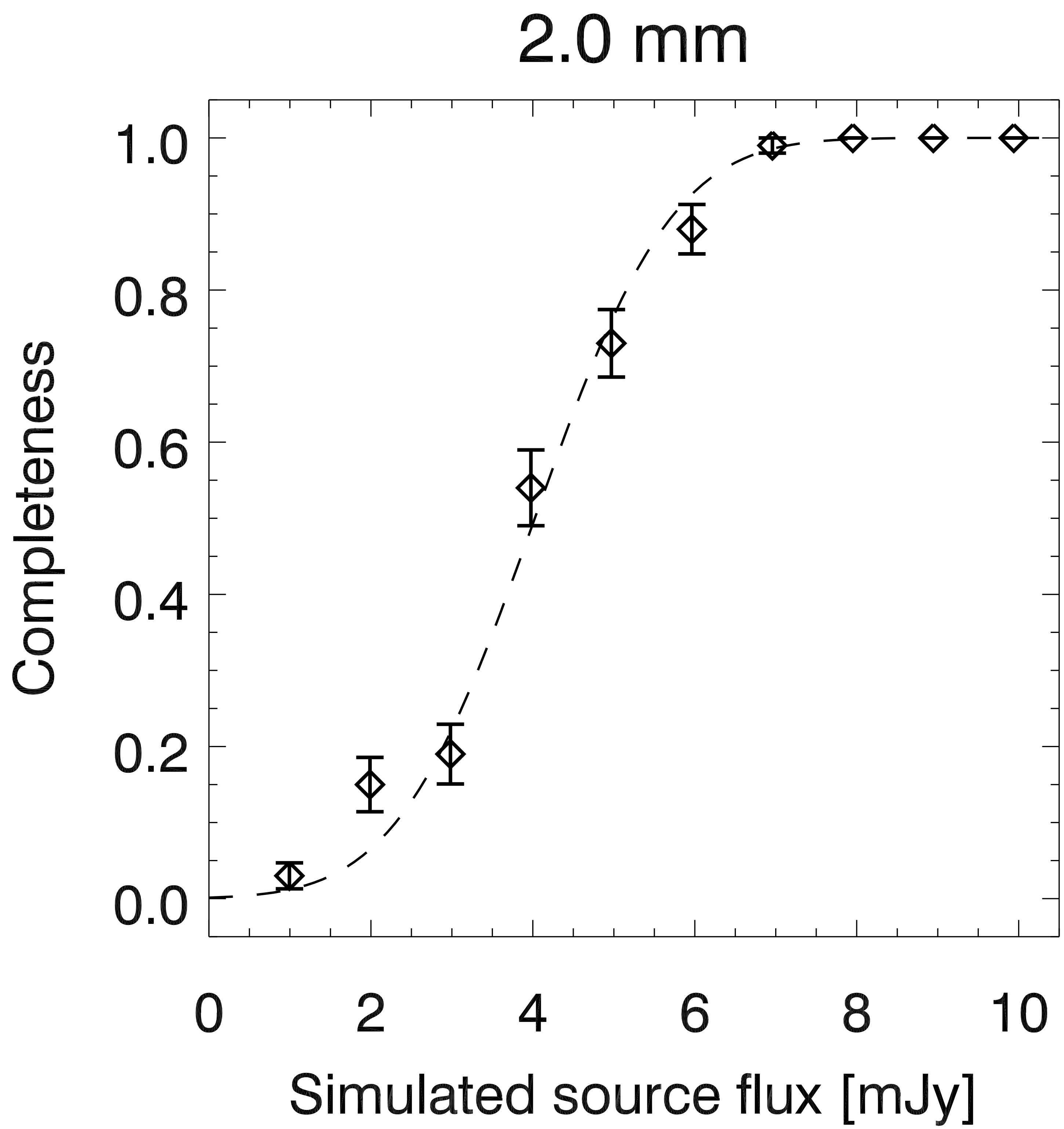


At a given S/N, what fraction of sources are real?

multiple ways of testing this.

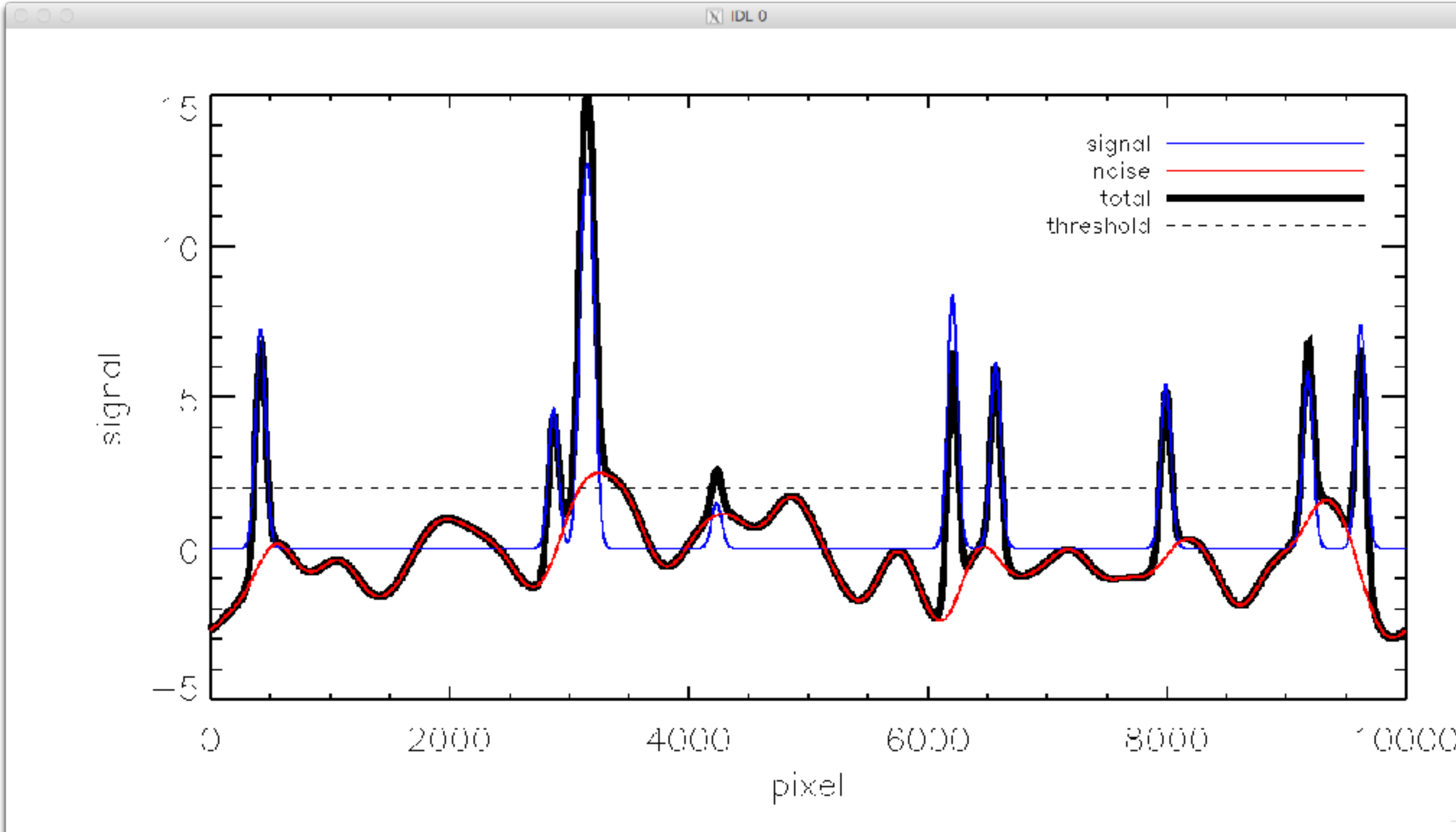
Which is best?

Catalog Completeness



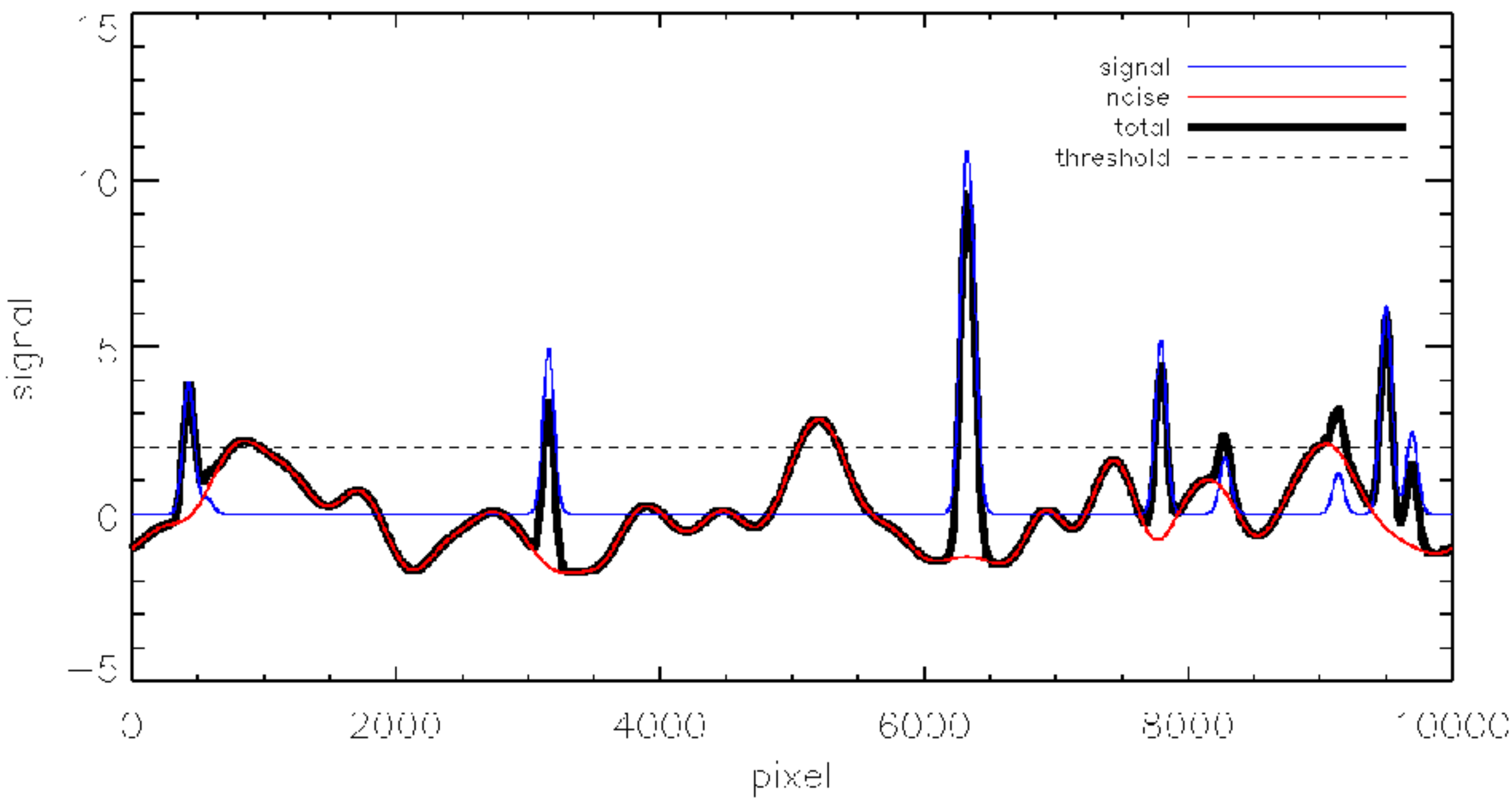
How many true sources do you expect to recover at a given flux level?

erf with 50% at the detection threshold and width the noise


IDL 0
signal
noise
total
threshold
15
10
5
0
−5
0
2000
4000
6000
8000
10000
pixel

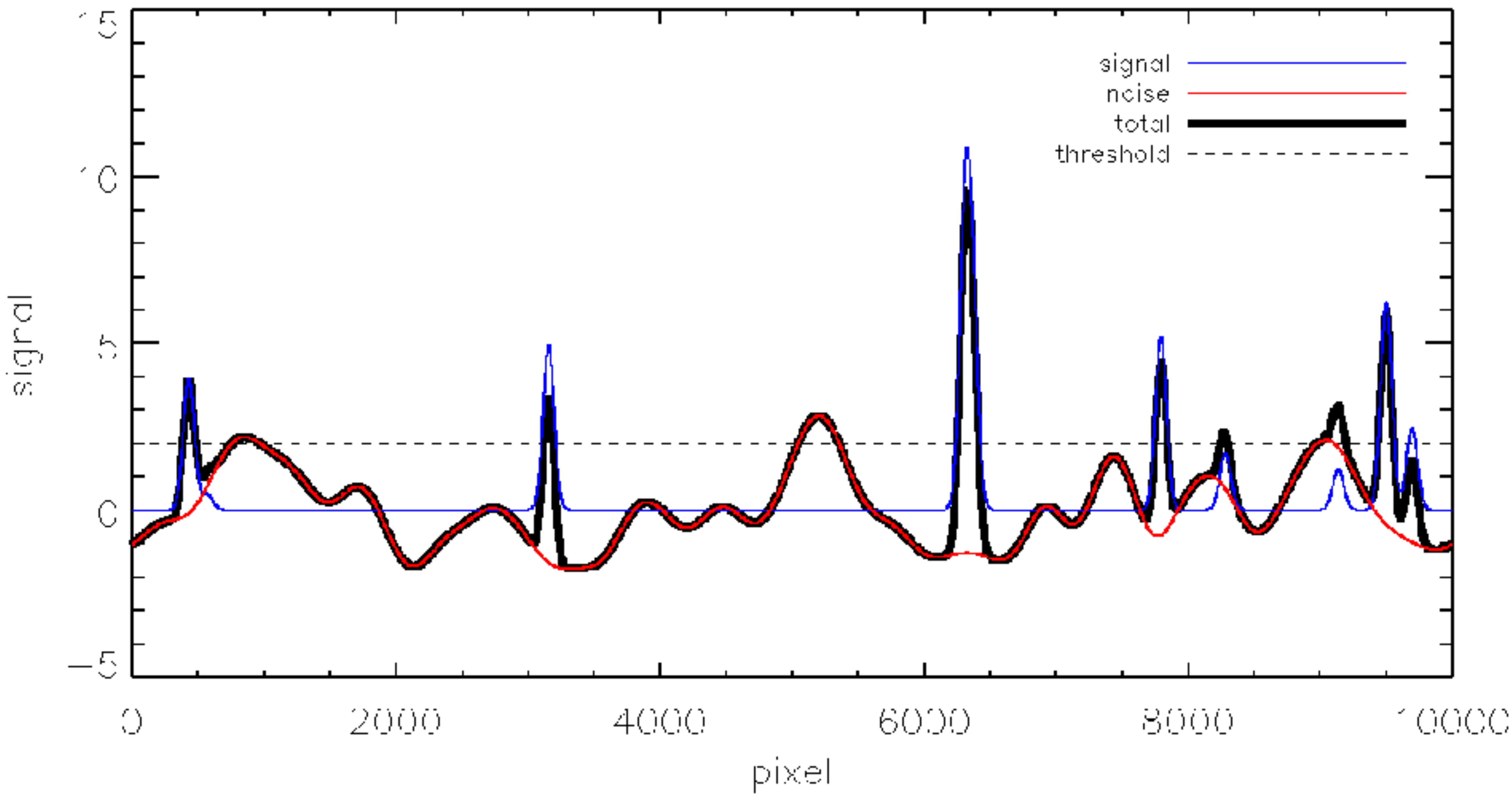
How many sources detected?

A. 6
B. 7
C. 9
D. 18



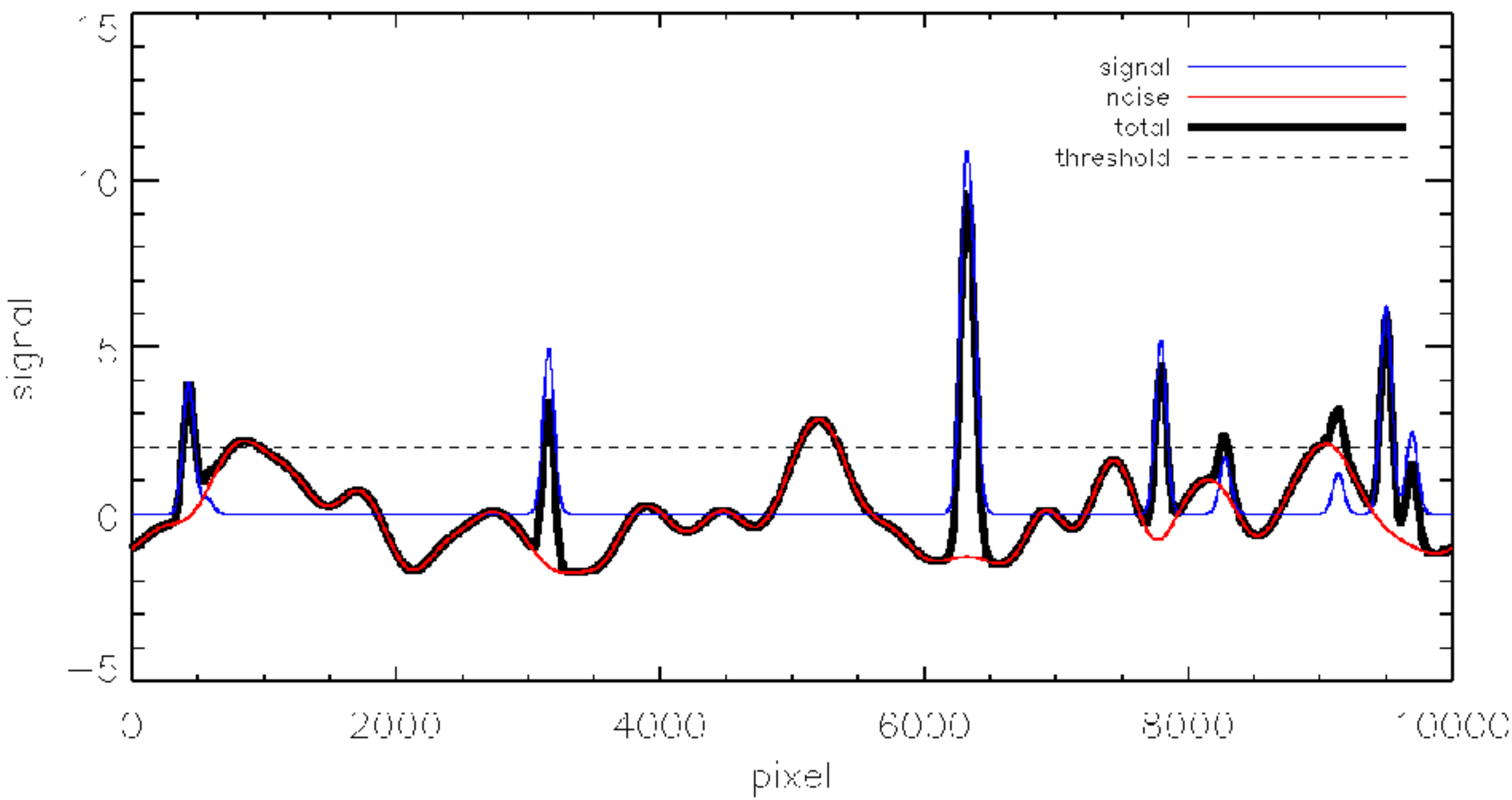
How many real sources that should have been detected are missed?

A. 0
B. 1
C. 3
D. 6



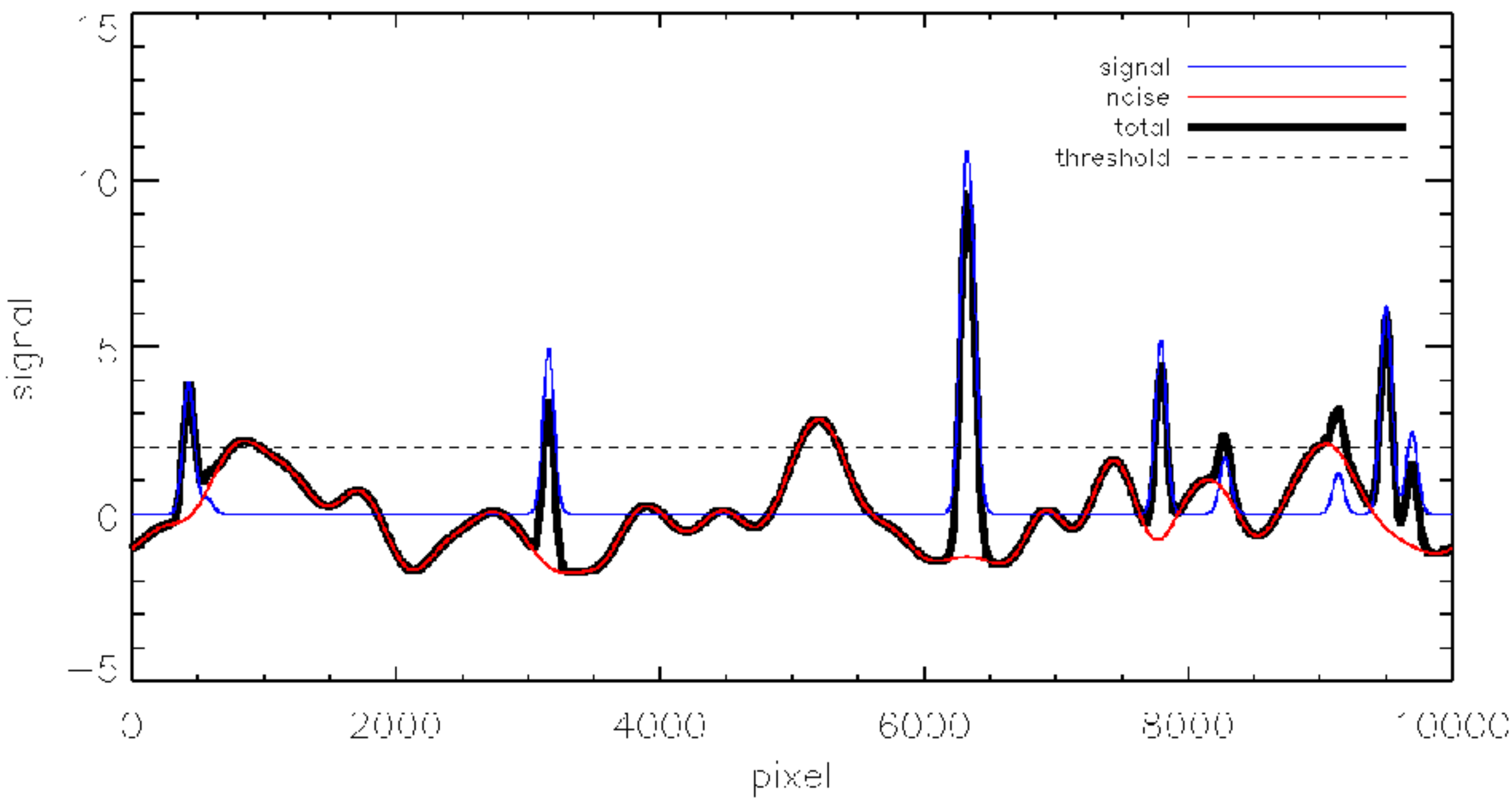
Completeness

n real sources detected / n real sources above threshold = 5/6 = 83%



Purity

n real sources above threshold / n sources detected = 5/9 = >50%



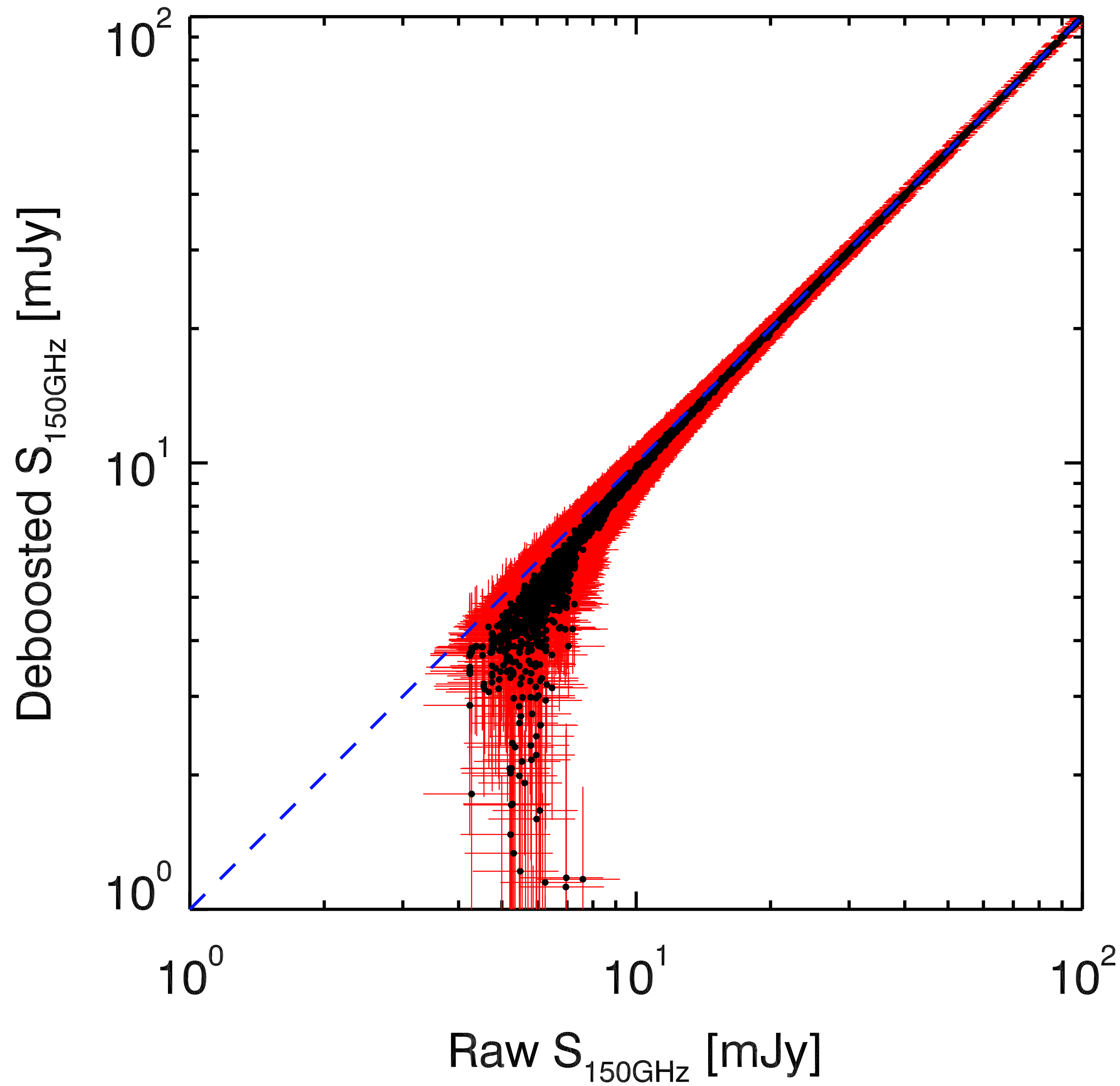
Flux boosting bias

"Blind" detection algorithms uses S/N as a threshold parameter

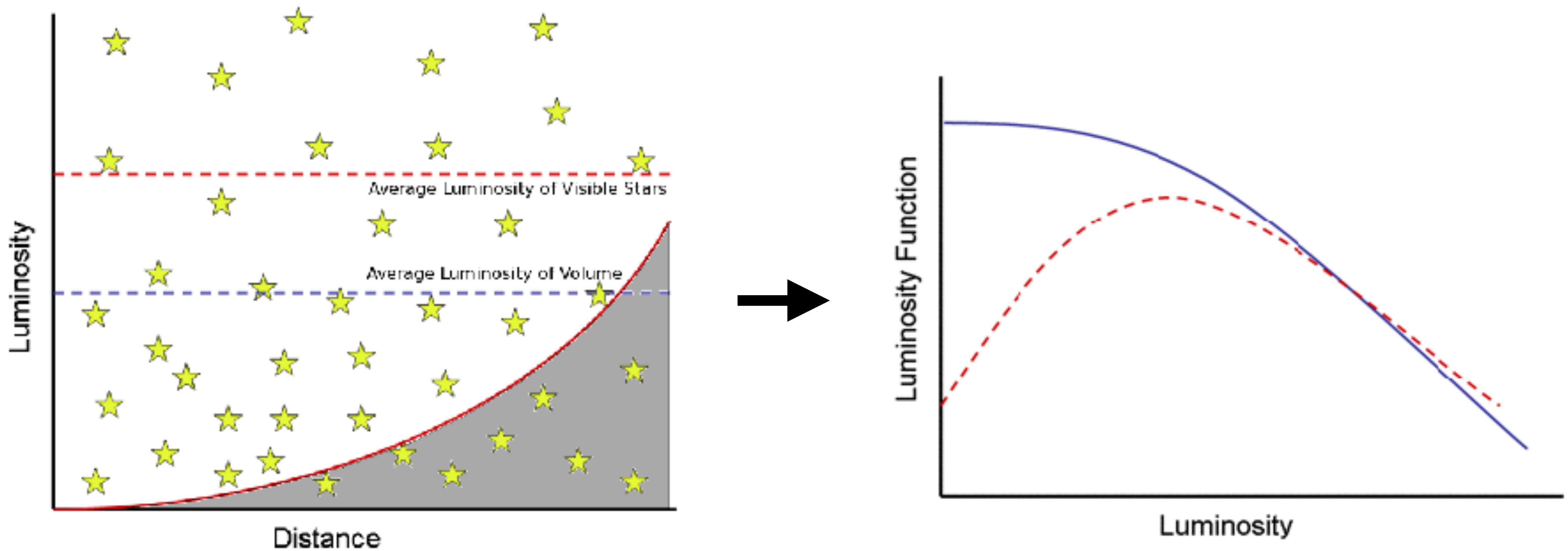
Real data has noise

Naturally, detections are biased toward sources that coincide with noise peaks

This "boosts" faint source flux above the threshold and leads to <u>systematically overestimated</u> fluxes for these objects



Malmquist bias



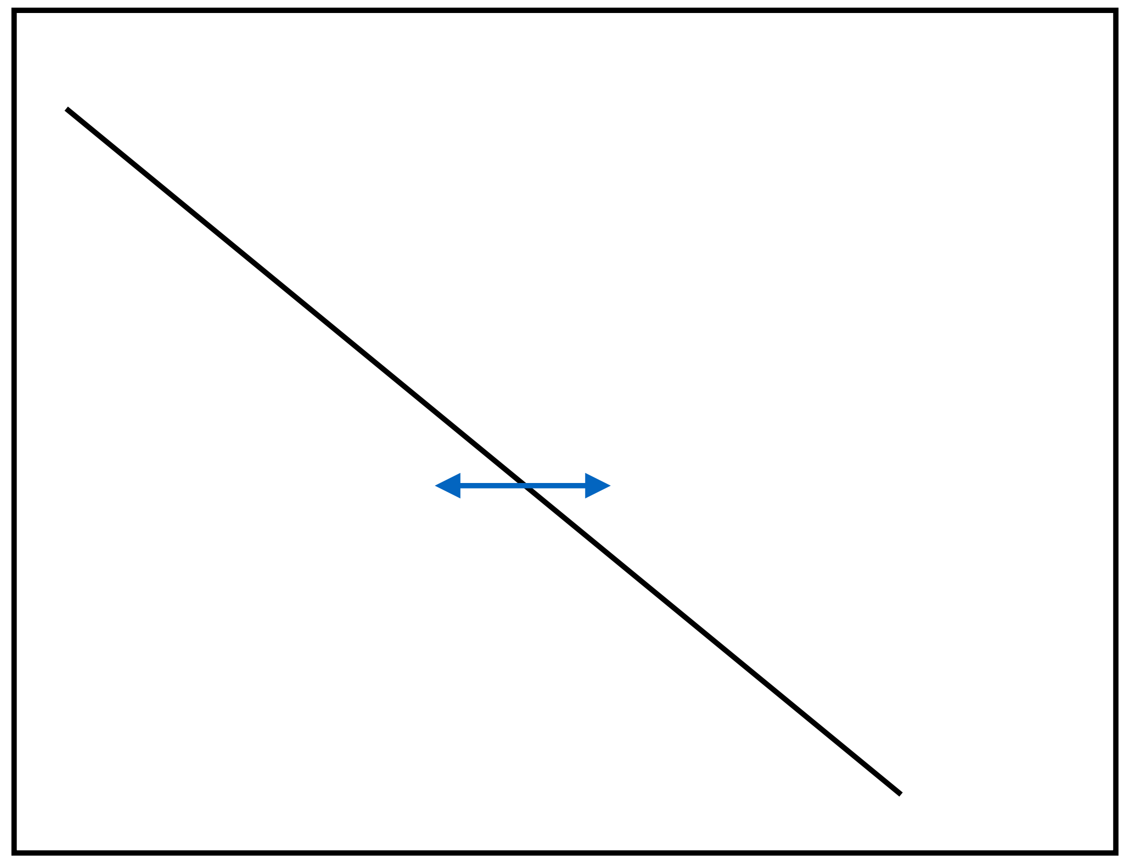
Given a fixed detection threshold, things farther away tend to be more intrinsically luminous - i.e. a biased population.

Not accounting for this can bias your luminosity function:

https://www.astroml.org/book_figures_1ed/chapter5/fig_malmquist_bias.html

Eddington Bias

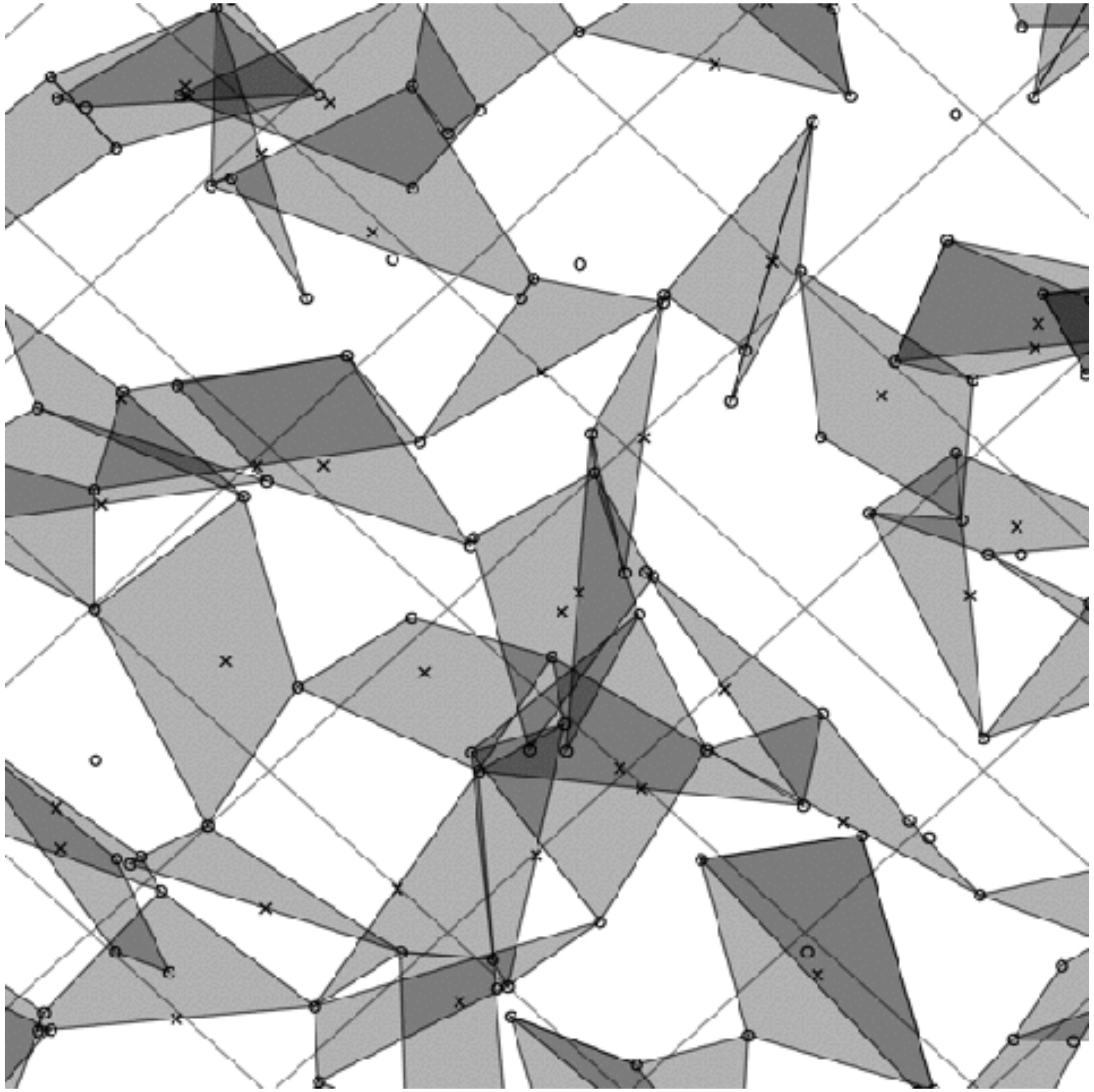
dn/dlnM

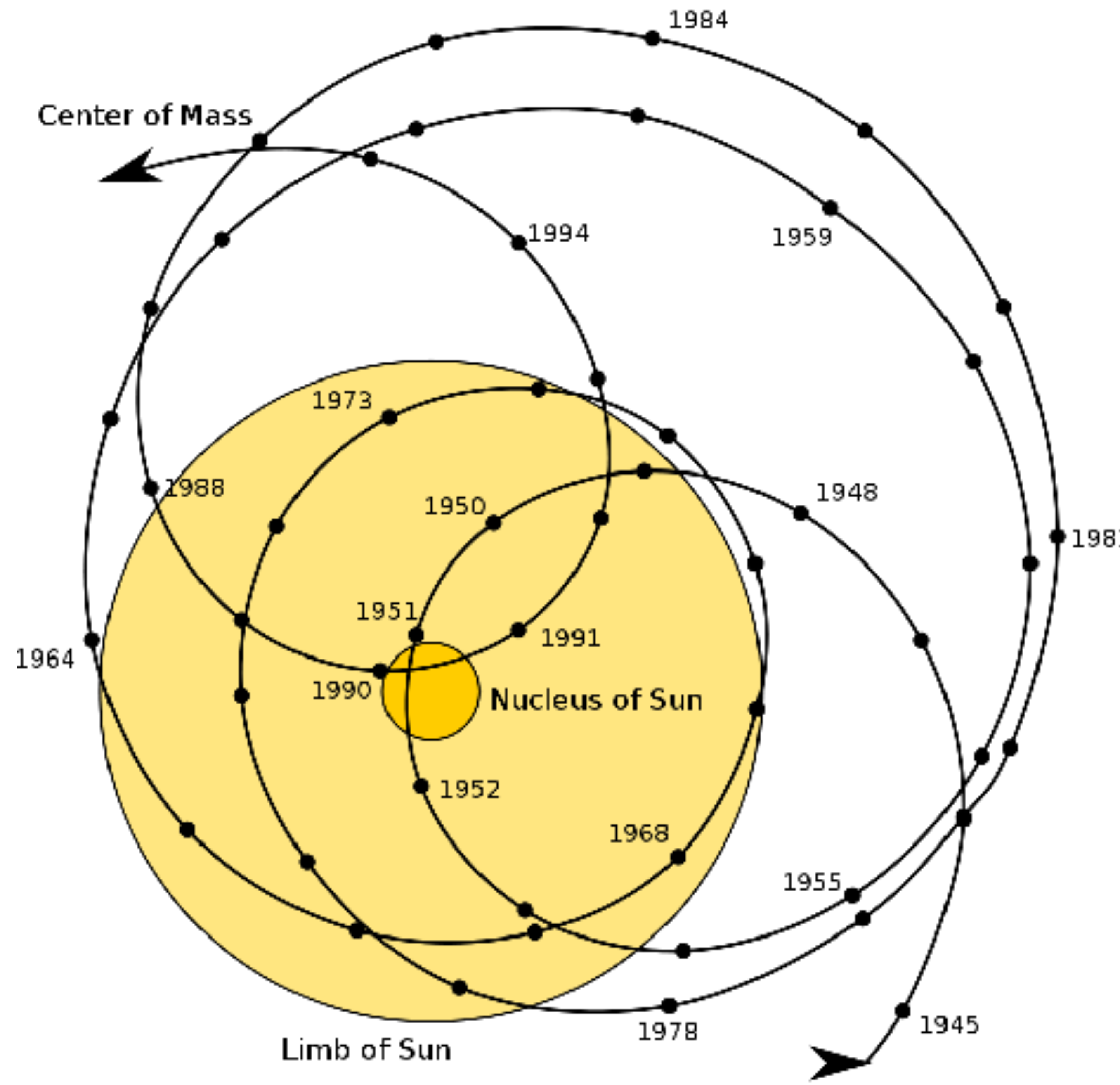


dlnM

There tend to be more faint sources than bright sources

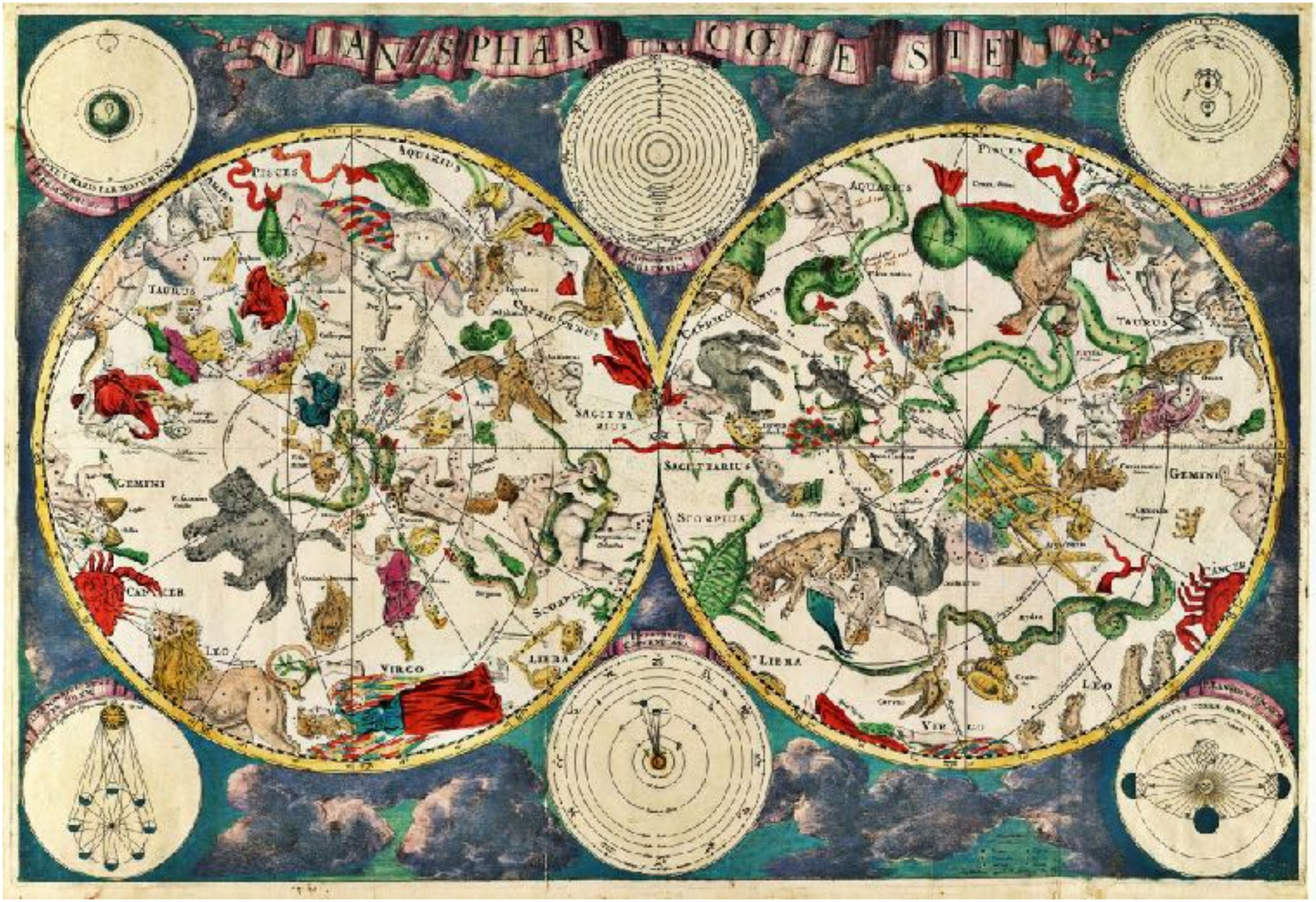
Flux boosting will make more faint things brighter than bright things fainter





Astrometry

The branch of astronomy that
involves precise measurements
of the positions and movements
of stars and other celestial bodies.



Motions of the Heavens

Motions in the sky

- Watching the night sky could lead you to some profound insights into the Universe.
- Sun, Moon, planets, stars all travel with different rhythms.
- Clues to Copernican Universe.
- Look even closer and there is parallax.

Time

- Time is intricately linked to motion.
- Astronomy, Astrometry, and horology share an intimate connection and even a historical rivalry.
- The three are intimately linked to understanding our place in the cosmos, as well as navigation.

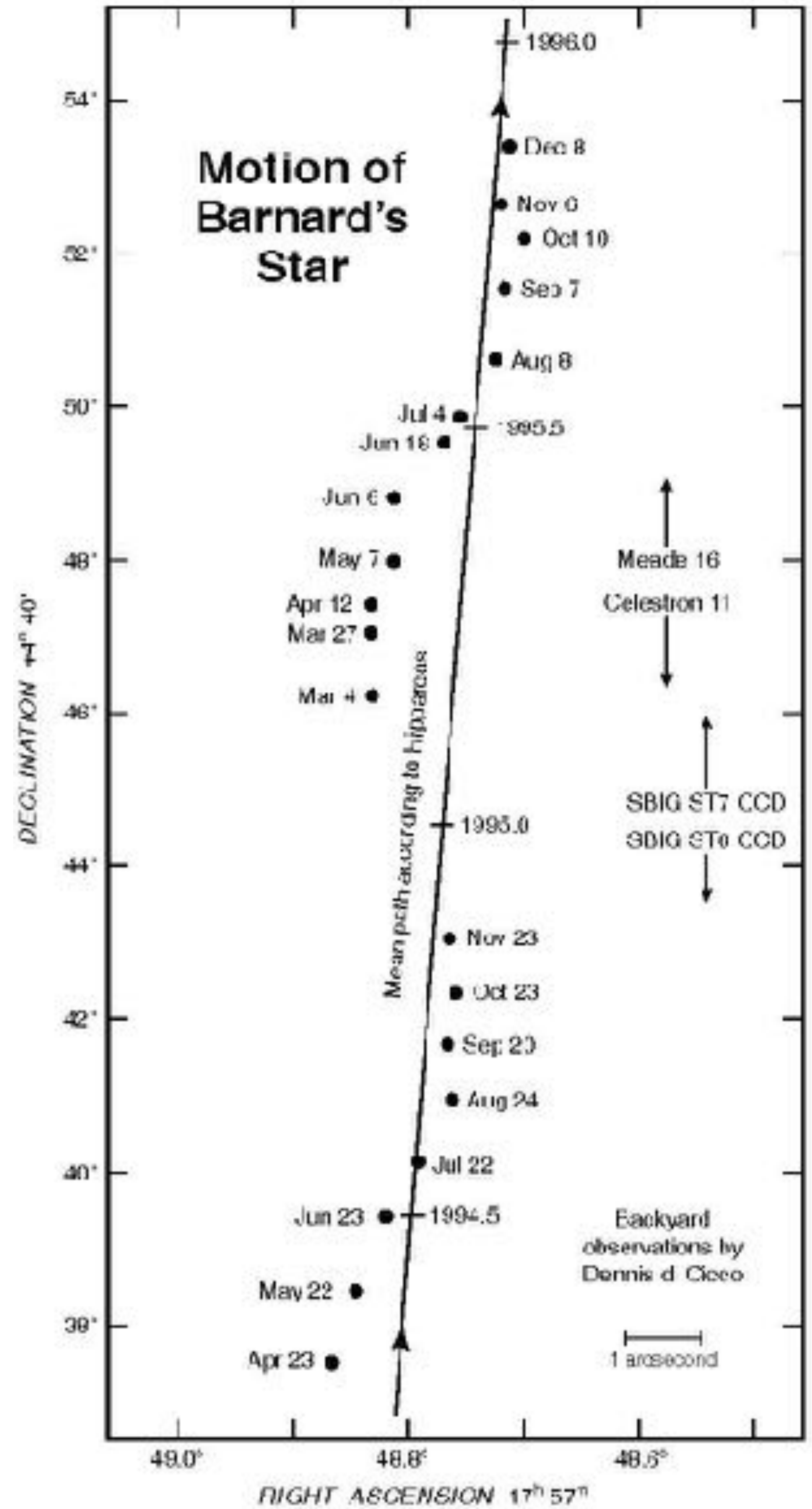
Velocities of celestial bodies

- The ability to measure velocities (spectroscopy and redshifts) and distances (variable stars and cepheids) led to the discovery of the expansion of the Universe and the field of modern cosmology.

Astrometric quantities

- Time: t
- Position: (α, δ)
- Distance: d
- Proper motion: $V_T = (\mu_\alpha, \mu_\delta)$
- Parallax: π
- Radial velocity: V_R
- 3-D space velocity:

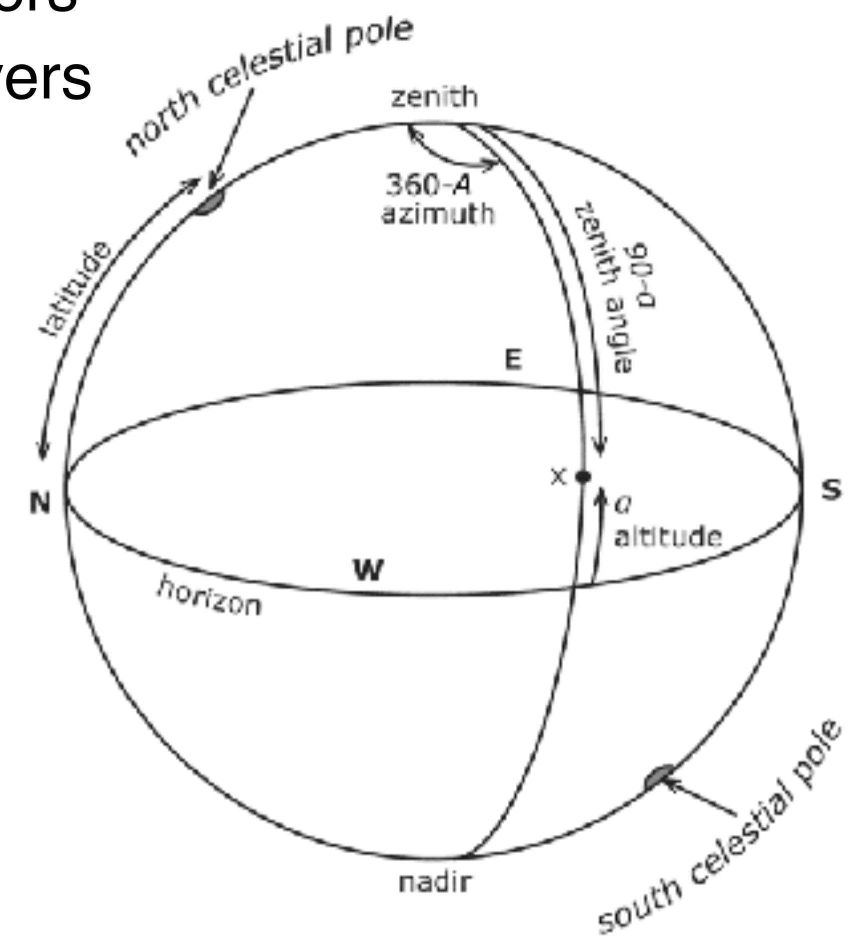
$$V_S = \sqrt{V_R^2 + V_T^2}$$



Coordinate Systems

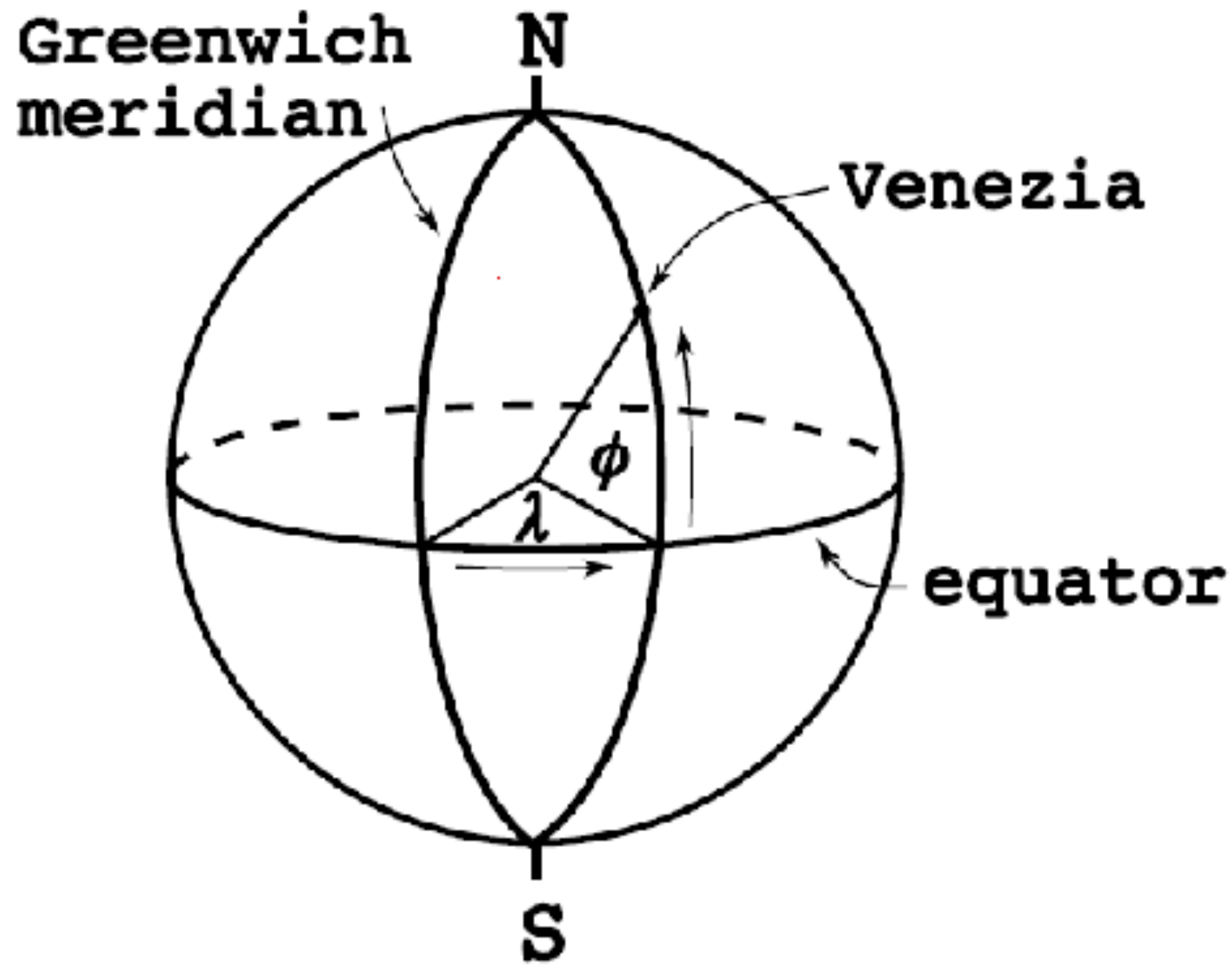
- There are different kinds of coordinate systems used in astronomy.
- The common ones use a coordinate grid projected onto the celestial sphere.
- These coordinate systems are characterized by a fundamental circle, a secondary great circle, a zero point on the secondary circle, and one of the poles of this circle.

- Common Coordinate Systems Used in Astronomy
  - Horizon (Alt,Az) or (El,Az) useful for observers
  - Equatorial (α,δ) (RA,DEC) useful for observers
  - Ecliptic (λ,β) for solar system
  - Galactic (l,b) for galactic astronomers
  - supergalactic (SGL, SGB)



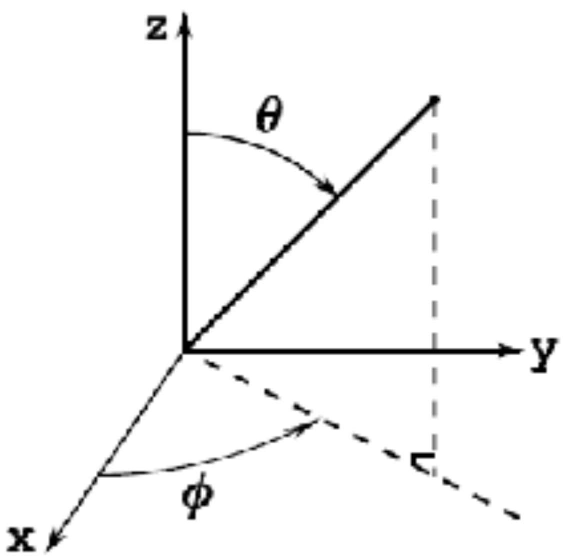
Latitude and longitude

- ***Latitude*** measured N (+d) or S (-d) from the equator. Ranges from 90° north (positive) to 90 ° south (negative)
- ***Longitude*** measured east (+hr) from the Greenwich meridian:
  - ***West*** longitude qualifier may be used.



Spherical coordinate systems

Spherical coordinates



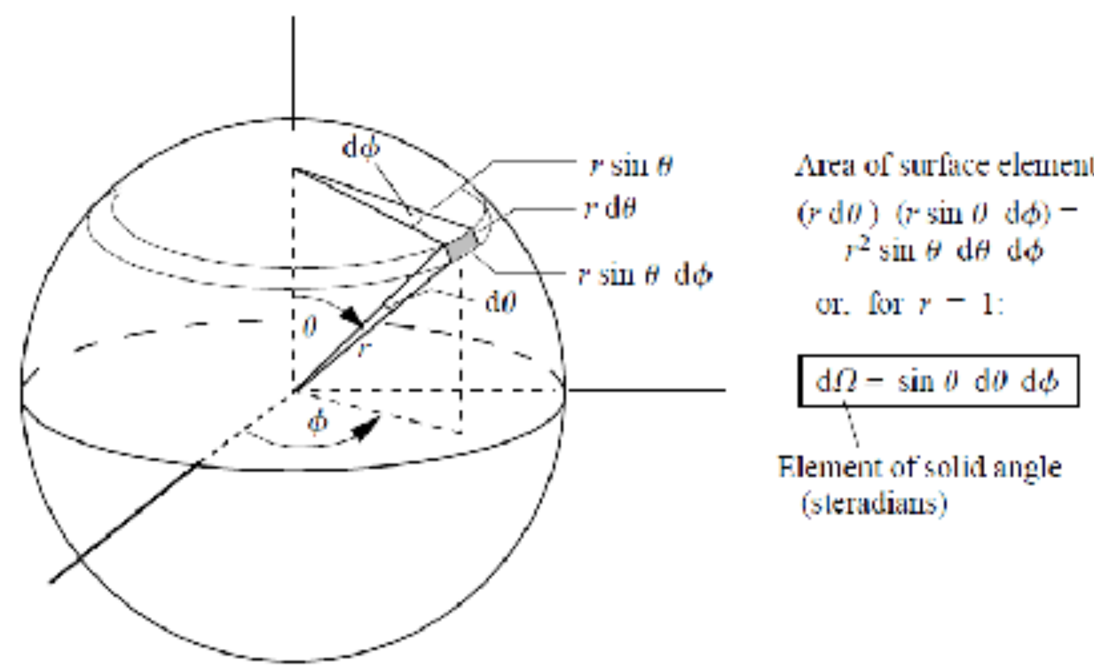
$$z = r \cos\theta$$

$$x = r \sin\theta \cos\phi$$

$$x = r \sin\theta \sin\phi$$

Solid angle

Fig. 3.7. : Solid angle



Spherical trigonometry: triangles on a sphere

Sine rule:

$$\frac{\sin A}{\sin a} = \frac{\sin B}{\sin b} = \frac{\sin C}{\sin c}$$

Cosine rule:

$$\cos a = \cos b \cos c + \sin b \sin c \cos A$$

$$\cos b = \cos c \cos a + \sin c \sin a \cos B$$

$$\cos c = \cos a \cos b + \sin a \sin b \cos C$$

Example derived relations:

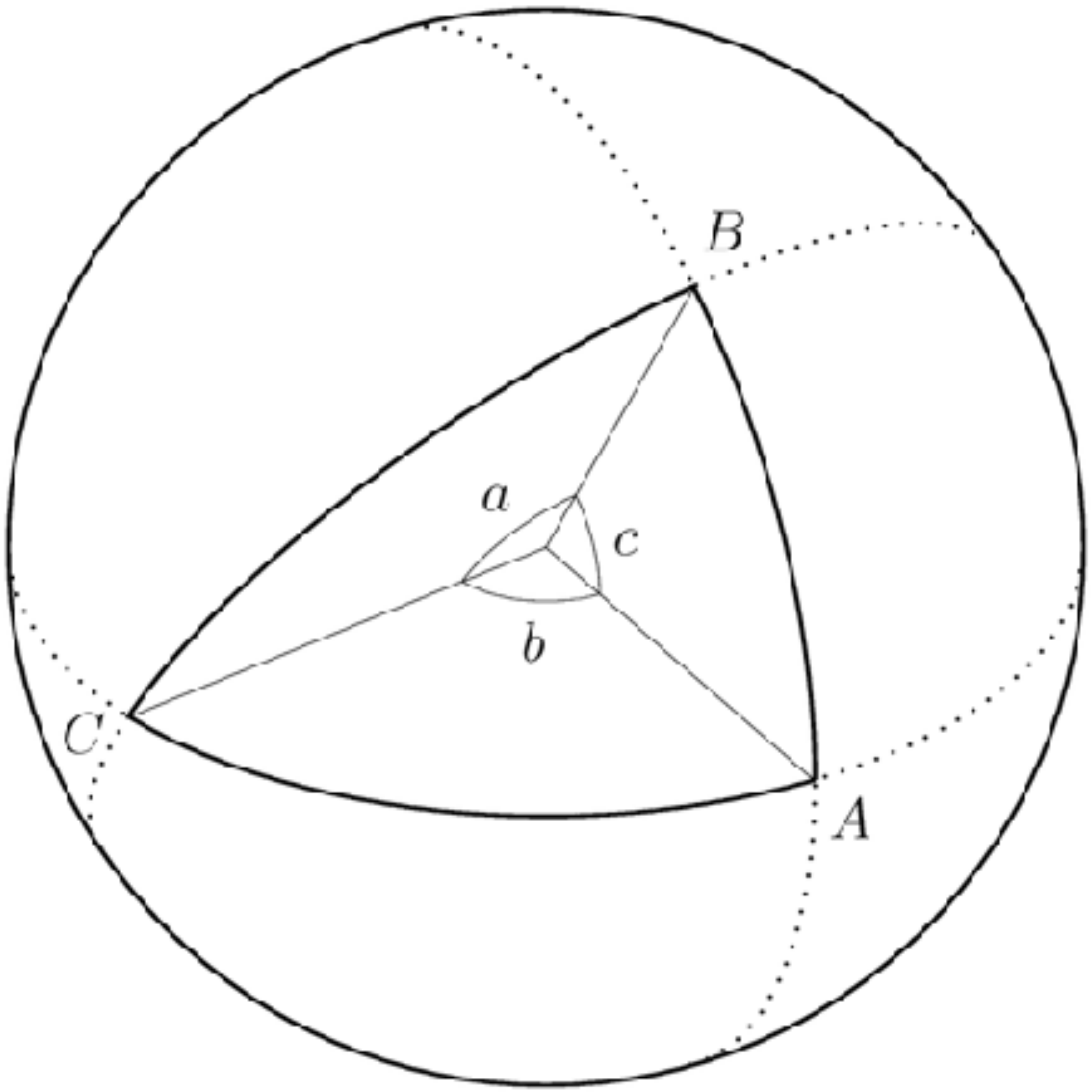
$$\sin a \sin B = \sin b \sin A$$

$$\sin a \cos B = \cos b \sin c - \sin b \cos c \cos A$$

$$\sin a \sin C = \sin c \sin A$$

$$\sin a \cos C = \sin b \cos c - \cos b \sin c \cos A$$

and others.



Rotation matrices

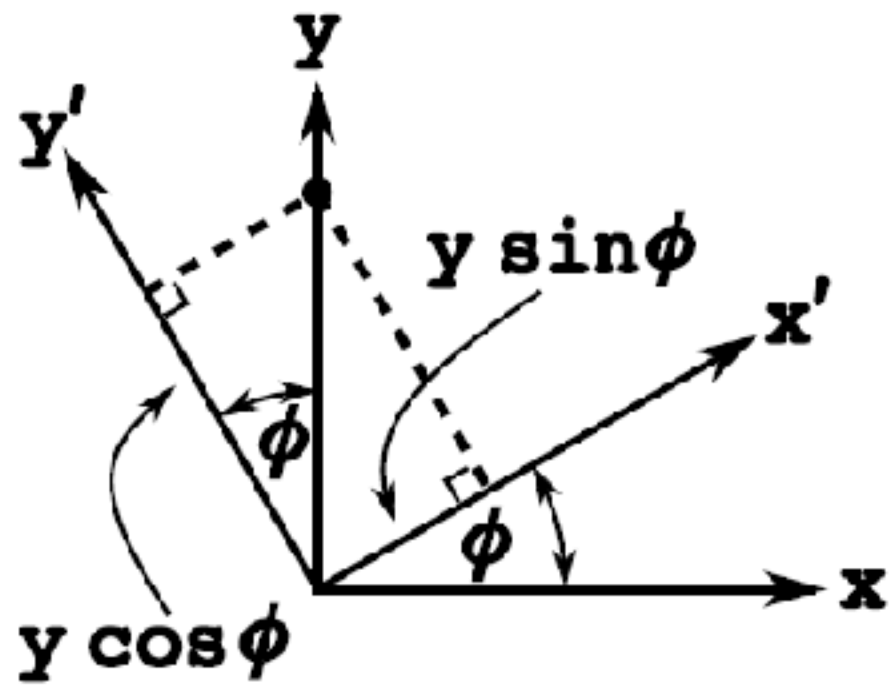
- Can also use rectangular coordinates for spherical geometry, e.g. rotation about z axis has rotation matrix,

$$\left|\begin{matrix} x' \\ y' \end{matrix}\right| = \left|\begin{matrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{matrix}\right| \left|\begin{matrix} x \\ y \end{matrix}\right|,$$

- In 3-D:

$$R_z(\phi) = \left|\begin{matrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{matrix}\right|$$

- Arbitrary rotation can be achieved as product of rotation matrices about cardinal axes.



Tangent plane coordinates

- Recall line element on surface of sphere in polar coordinates:

$$d\vec{s} = d\theta\,\hat{\theta} + \sin\theta\, d\phi\,\hat{\phi}$$

- For equatorial right ascension and declination on the celestial sphere:

$$d\vec{s} = d\delta\,\hat{\delta} + \cos\delta\, d\alpha\,\widehat{\alpha}$$

- The cosine(dec) factor reflects the convergence of right ascension meridians towards the poles.
- Right ascension units:
  - 24h = 360 deg
  - 1 second of time = 15 seconds of arc (arcsec)

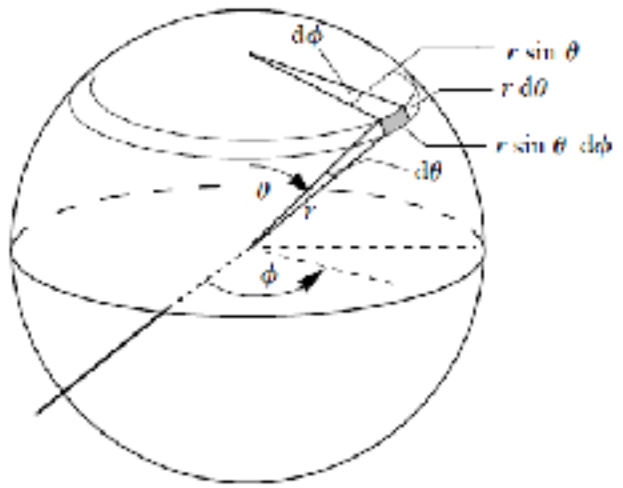
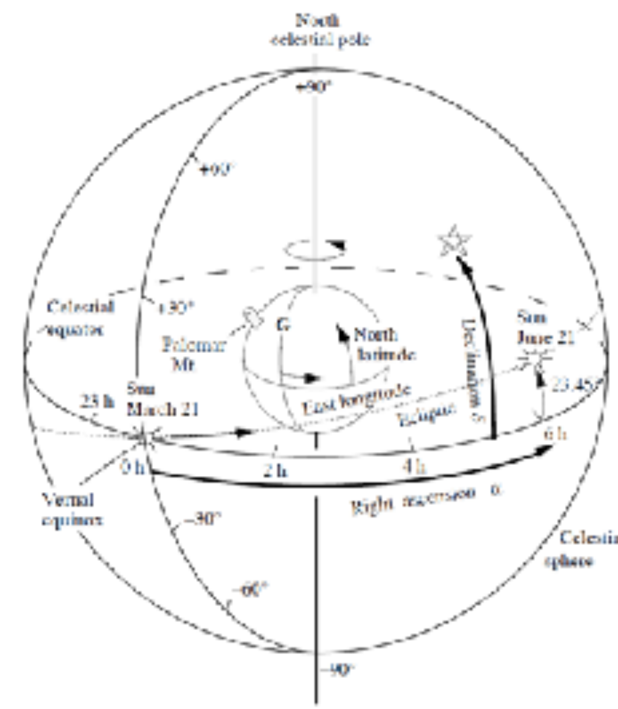


Fig. 3.1. : Celestial Coordinates



(Bradt 2004)

Observer perspective on ground-based positional astronomy

Scientific coordinates on the celestial sphere

- Coordinates on the celestial sphere, referred to a specific epoch, equinox, and center:
  - Longitude and latitude: e.g. RA-DEC (α,δ)
  - Proper motion:
    $$V_T = (\mu_\alpha, \mu_\delta)$$
  - Parallax: π
  - Radial velocity: V_R

Celestial motions

Local horizon coordinates

- In topocentric frame at date of observation:
  - Angular coordinates: e.g.
    - Altitude and azimuth, or
    - Hour Angle and elevation.
    - (and their time derivatives).
  - Dopper-shifted frequency.

Instrument

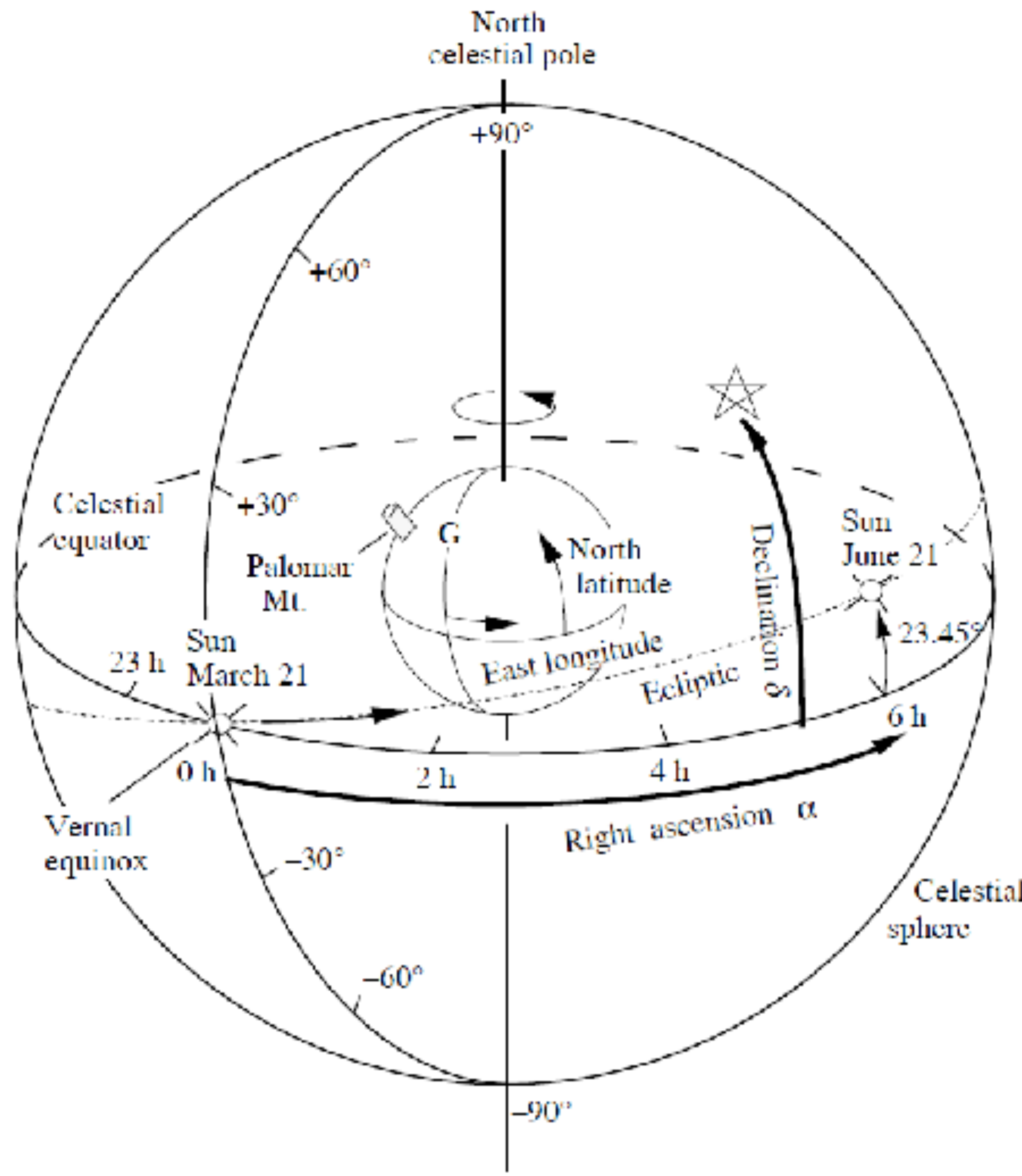
Instrument coordinates

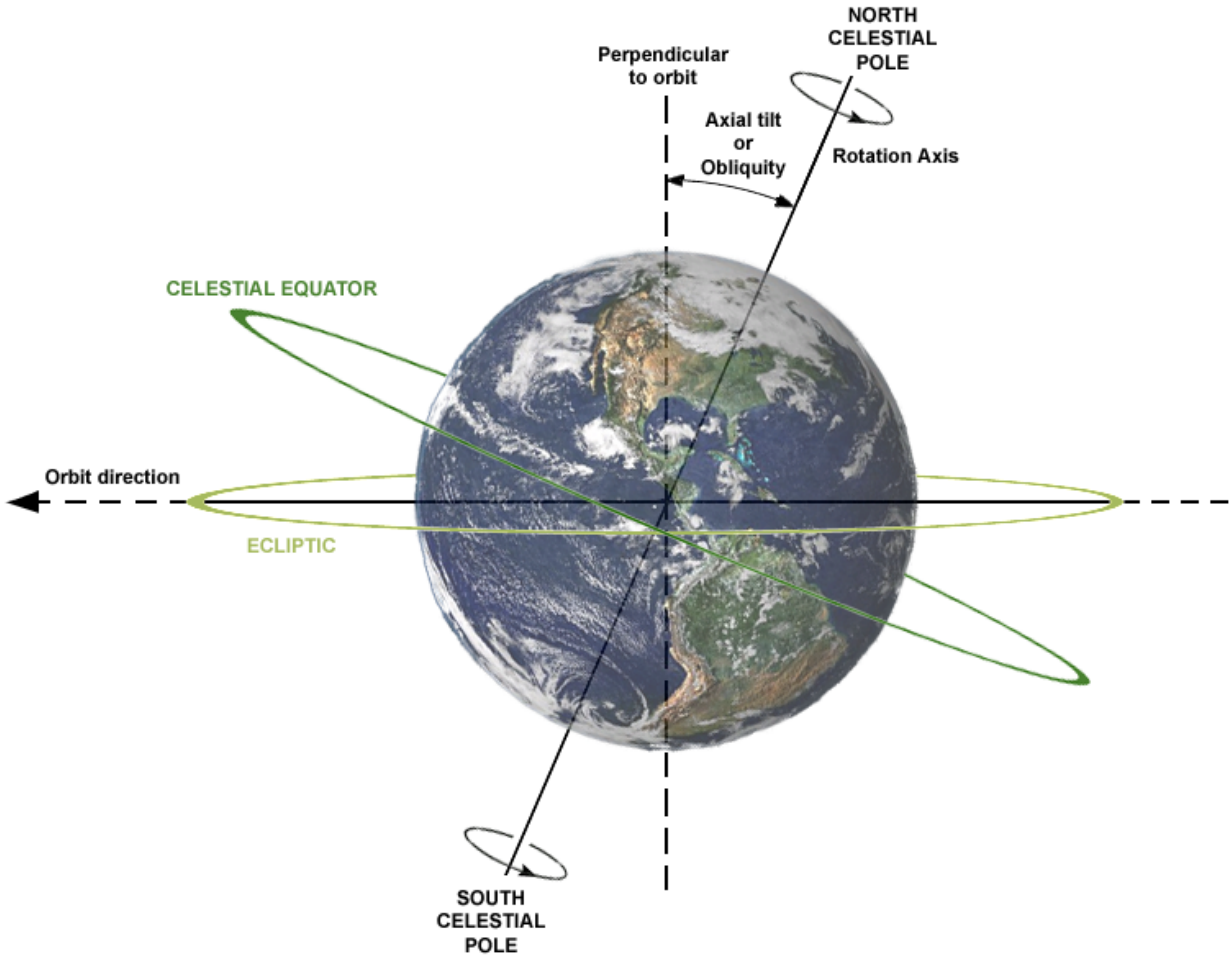
- Axis drive positions and rates, including instrumental offsets.
- Electronic or data acquisition settings.

The celestial sphere

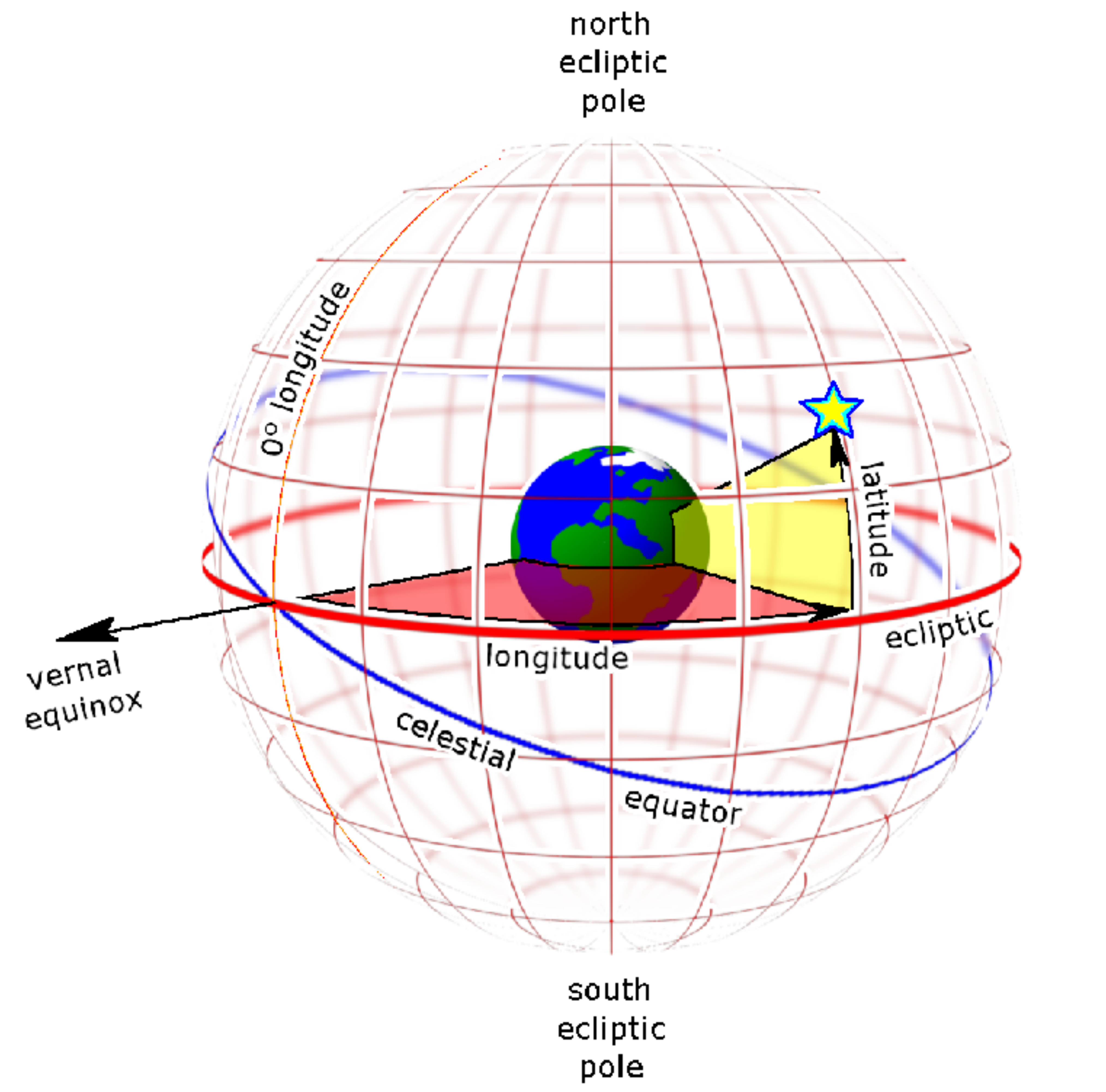
- A sphere at infinity, against which astrometric positions are projected.
- ***Great circle*** – any circle whose plane passes through the center of the sphere.
- Astrometric positions defined by ***two angular coordinates*** (longitude and latitude) on the sphere in a celestial coordinate system, comprising:
  - Equator – great circle of zero latitude.
  - Zero point must be defined for longitude.
- ***Meridian*** – line of constant longitude.
- ***Equatorial coordinates*** – right ascension and declination.

Fig. 3.1. : Celestial Coordinates





NORTH CELESTIAL POLE
Perpendicular to orbit
Axial tilt or Obliquity
Rotation Axis
CELESTIAL EQUATOR
Orbit direction
ECLIPTIC
SOUTH CELESTIAL POLE


north
ecliptic
pole
0° longitude
latitude
vernal
equinox
longitude
ecliptic
celestial
equator
south
ecliptic
pole

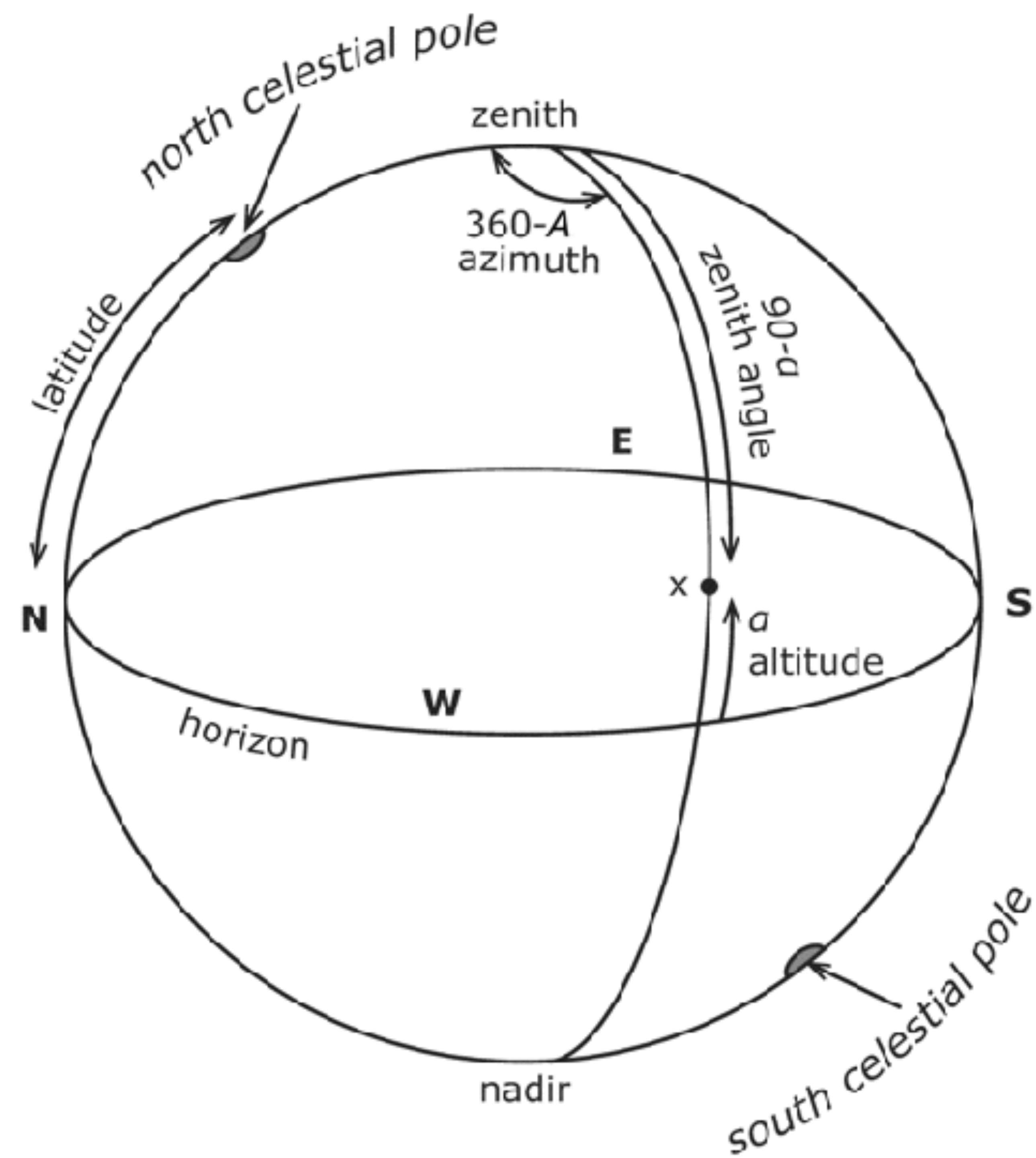
Horizon Coordinate system (Alt-Az)

Zenith: The point on the celestial sphere that lies vertically above an observer and is 90° from all points on the horizon

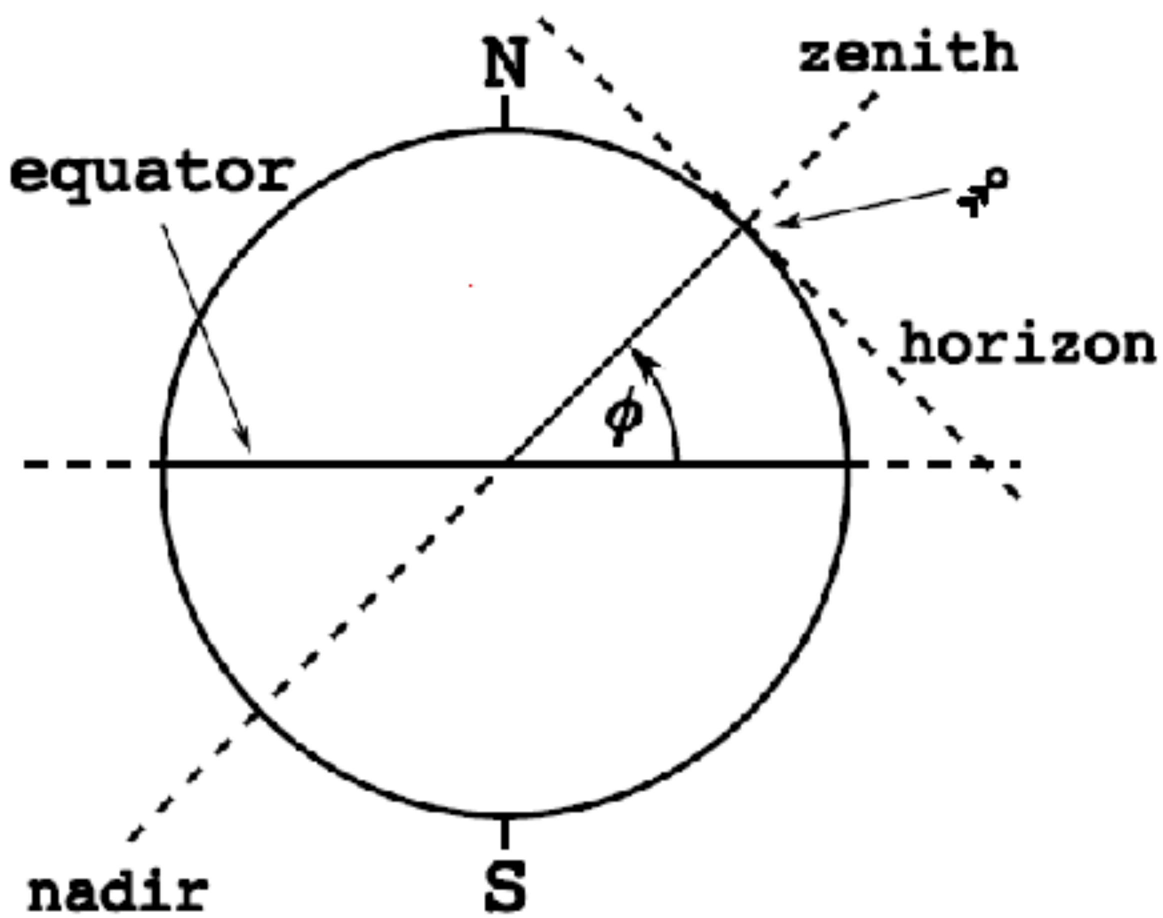
Nadir: The point on the celestial sphere that lies directly beneath an observer. It is diametrically opposite the zenith..

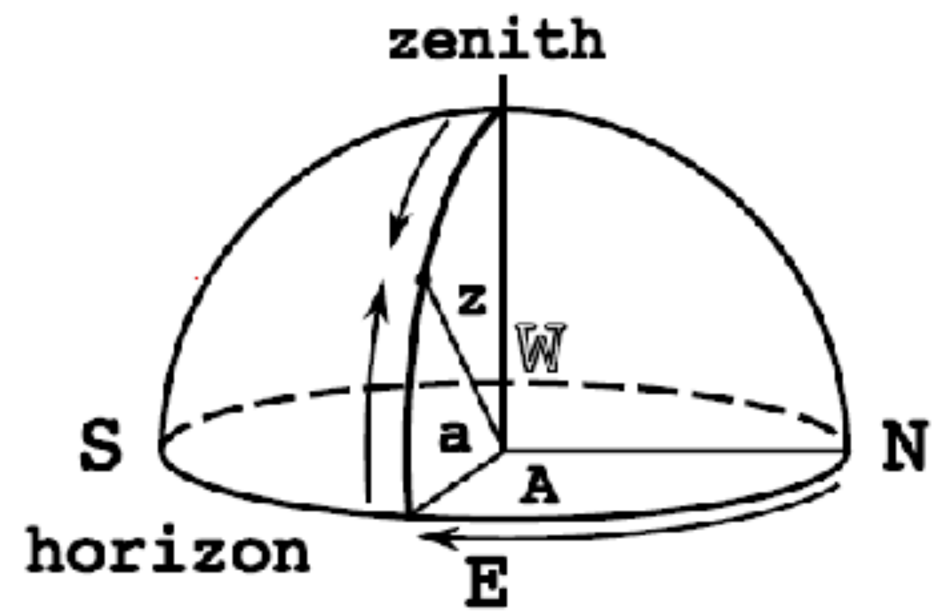
The celestial meridian is great circle that intersects the zenith, the nadir, and the celestial poles.

The astronomical horizon is a great circle on the celestial sphere which is perpendicular to the zenith-nadir axis.



Horizon coordinates





- Coordinates relative to an equator defined by the observer's horizon.
- The horizon is the great circle defined by the intersection of the plane tangent to the Earth's surface at the observer's location with the celestial sphere.
- ***Azimuth*** – longitude measured along horizon from North through East.
- ***Altitude*** – latitude relative to horizon.

Hour Angle and Time

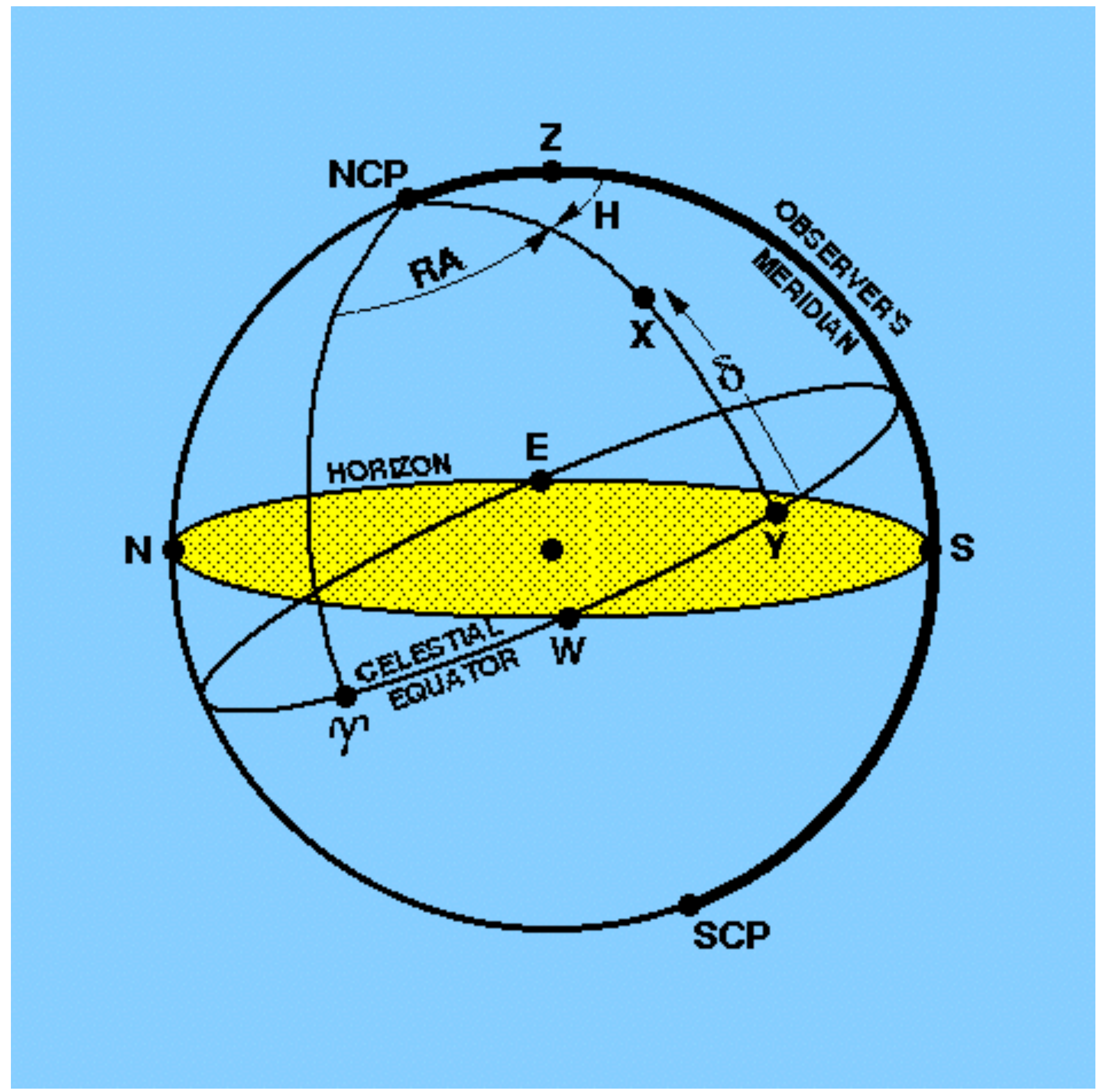
Hour angle : is the angle measured westwards along the celestial equator from the observer's meridian to the hour circle of the celestial body.

Another way to think about it is: the *hour angle* of a celestial body: is the time elapsed since the celestial body's last transit of the observer's meridian.

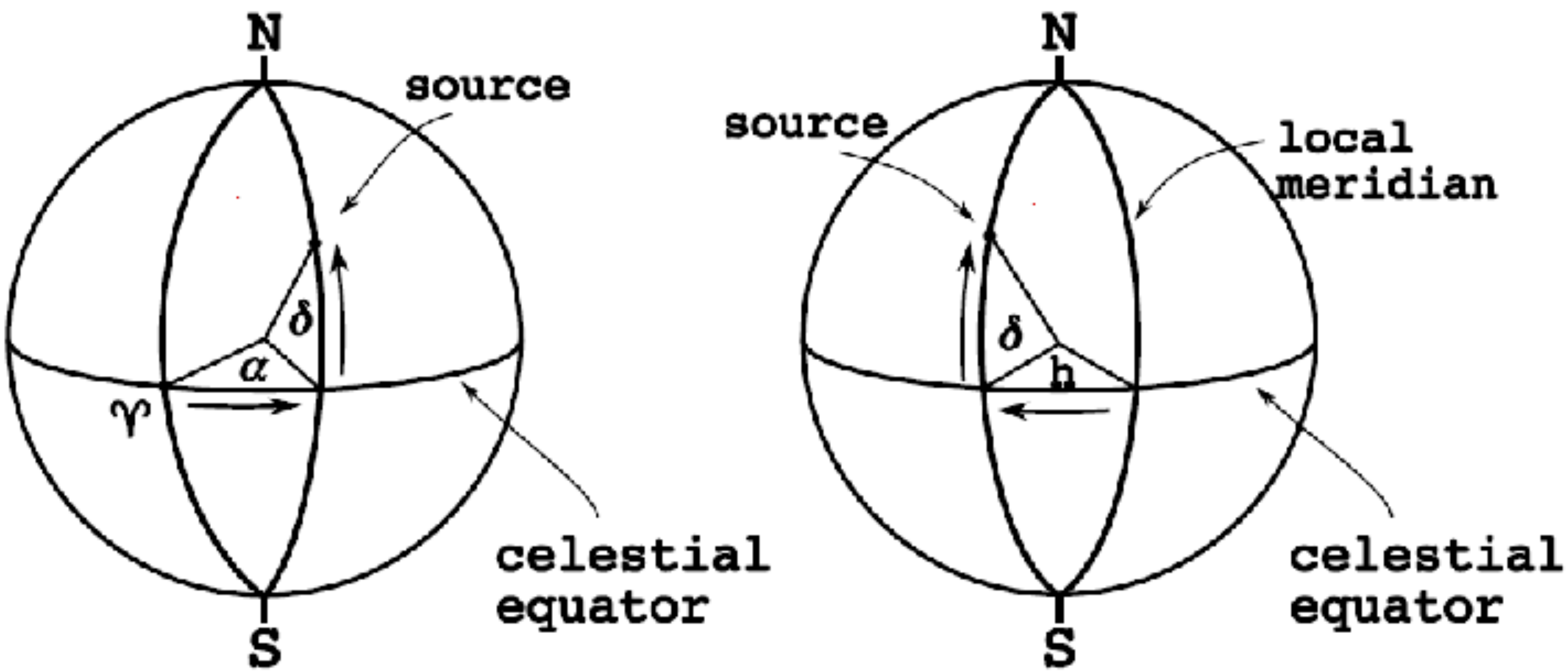
If HA = -1 (it will be 1 hour before the object is on the meridian. This is the same as HA = 23.

If HA = 0 (it is on the meridian)

If HA = 2 (it has been 2 hours since the object was on the meridian.



Horizon coordinates (hour angle, declination)



- ***Hour angle*** – angle measured on the equator west from the local meridian to the hour angle circle of the source.
- ***Declination*** – latitude δ relative to the celestial equator.

Horizon Coordinate System

- Advantage: Easy to use system. It is often useful to know how high a star is above the horizon and in what direction it can be found.

  Many telescopes use the alt-az mounts because of lower cost and greater stability.

- Disadvantage: because any coordinates depend on:

  **place* of observation

  (because the sky appears different from different points on Earth)

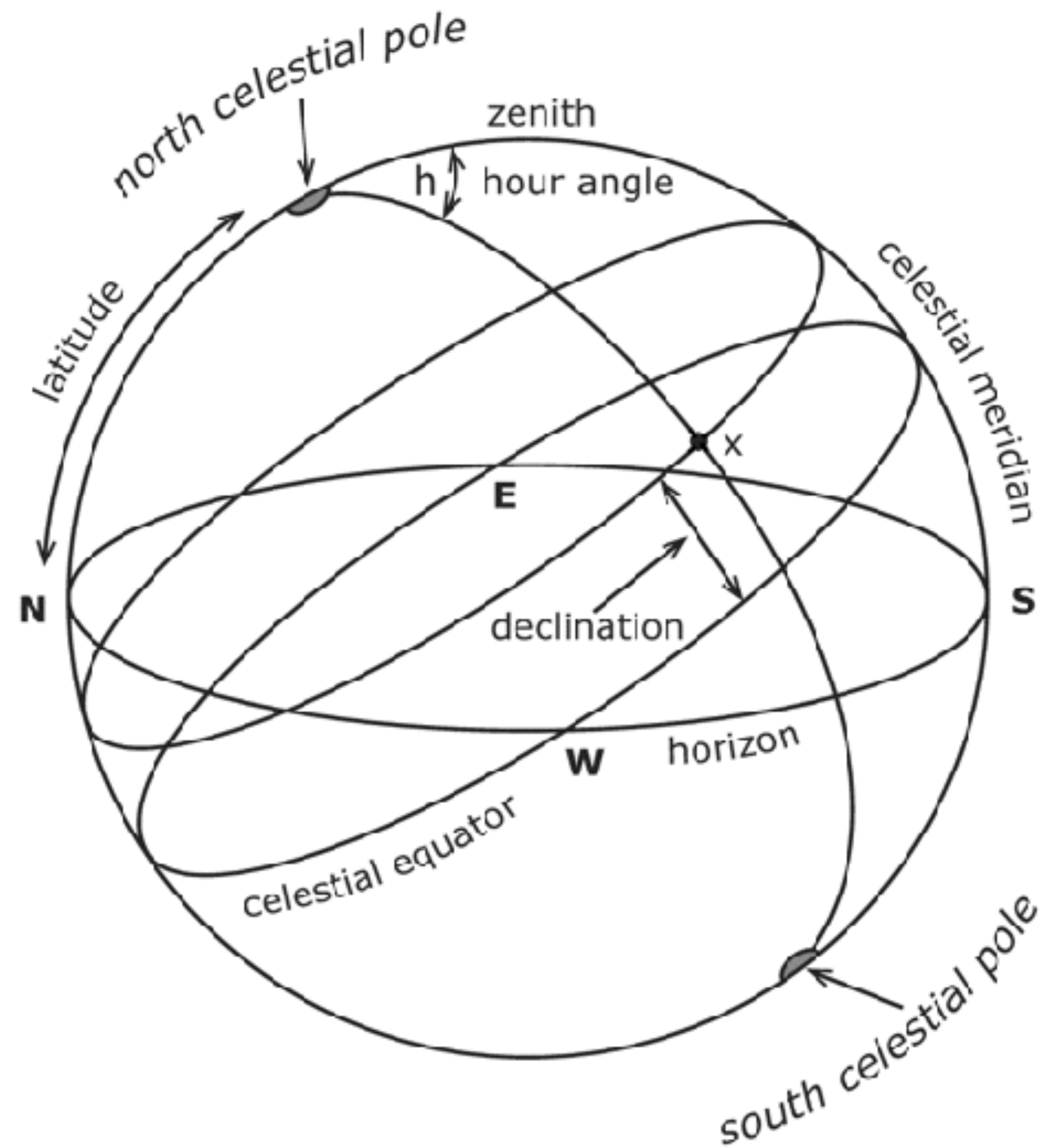
  *on the *time* of observation

  (because the Earth rotates, the zenith is always moving relative to the stars)

- We need a system of celestial coordinates that is fixed on the sky, independent of the observer's time and place. For this, we change the *fundamental circle* from the horizon to the *celestial equator*.

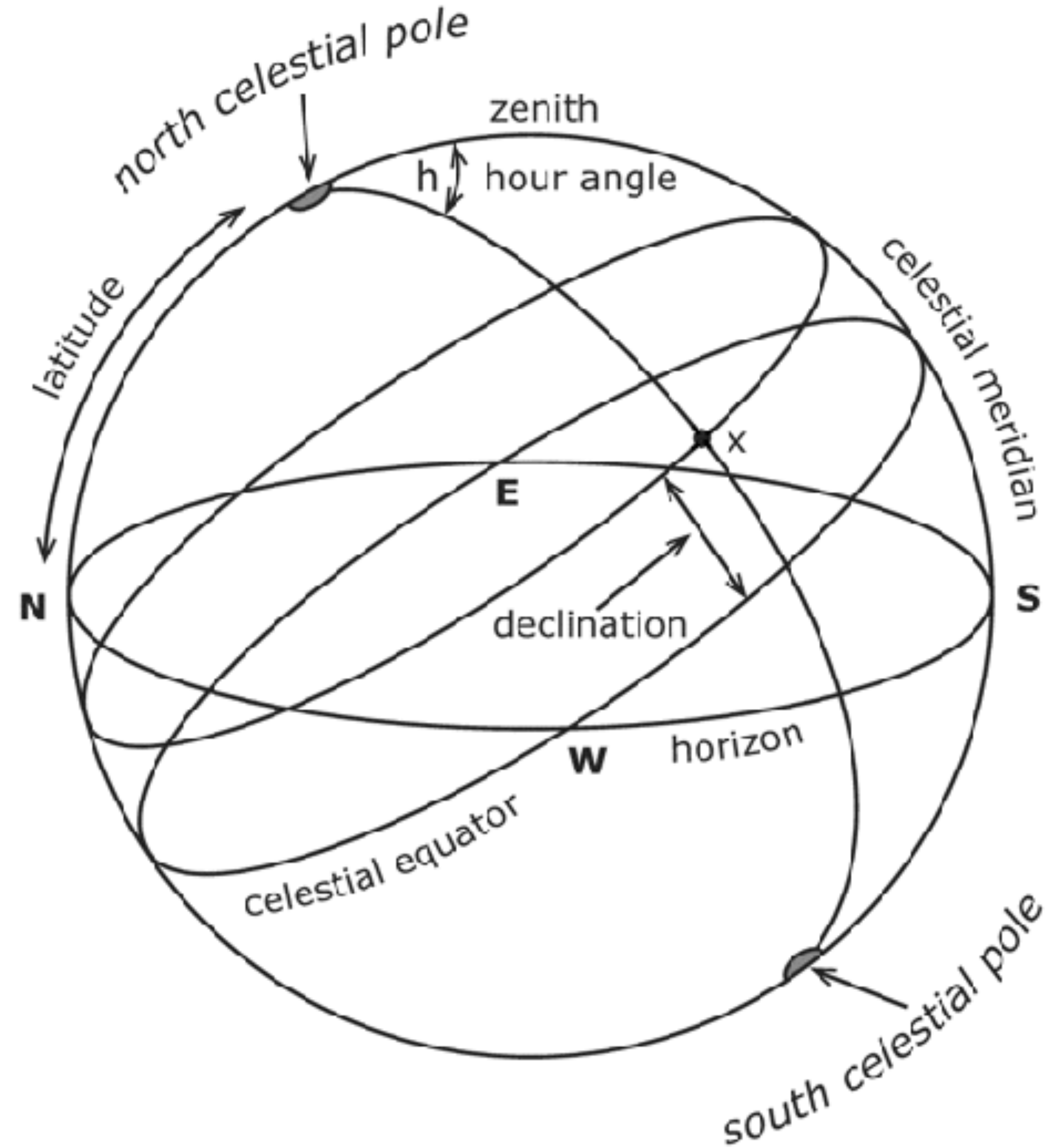
1st Equatorial System (Hour angle, Declination)

- The celestial meridian (observer's meridian) is great circle which intersects the zenith, the nadir, and the celestial poles.
- The declination (δ) of X is the angular distance from the celestial equator to X, measured from -90° at the SCP to +90° at the NCP.
- The Hour Angle or HA (H) of object X is the angular distance between the meridian of X and celestial meridian.
  It is measured westwards in hours, 0h-24h.
- This system is still dependent on the time of observation, but an object's declination generally doesn't change rapidly, and its Hour Angle can be determined quite simply, given the time and the location.



2^{nd} Equatorial System (Right Ascension and Declination)

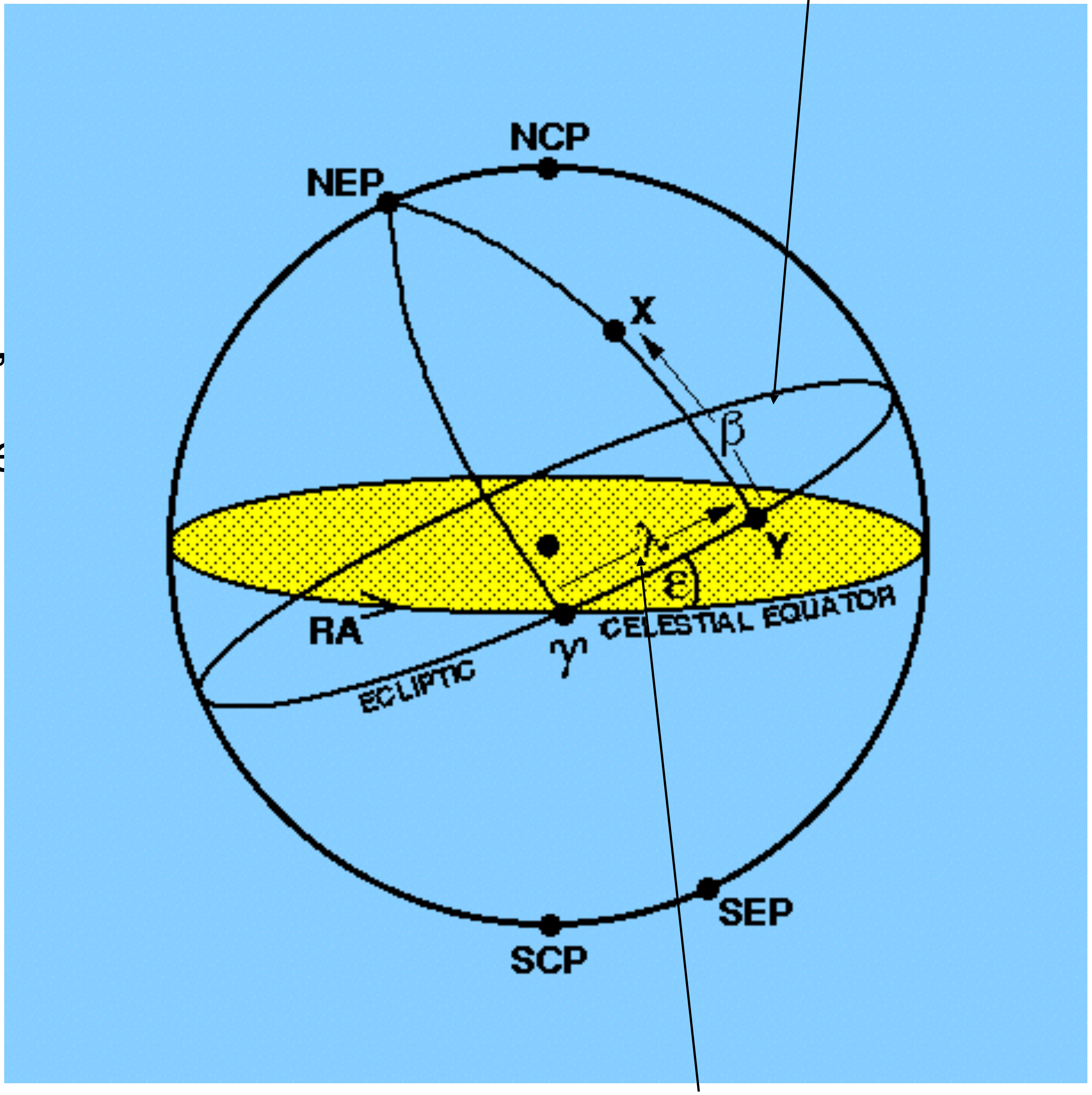
- Most widely used coordinate system (for objects outside the solar system).
- Fundamental circle: celestial equator
- Zero point: vernal equinox.
- The right ascension of a point it is the angular distance measured eastward along the celestial equator between vernal equinox and the hour circle intersecting the point. It is measured in hours, minutes, and seconds from 0 to 24 hours.
- The declination of a point is the angular distance above or below the celestial equator. It is measured in degrees, minutes, and seconds from –90° to +90° with 0° being on the celestial equator. Negative degrees indicate that the point is south of the celestial equator, while positive degrees indicate that it is north of the celestial equator.



Ecliptic Coordinate System

- When dealing with the positions and motions of solar system objects, it is often more convenient to refer positions to the mean orbital plane of the solar system using ecliptic coordinates.
- Fundamental circle is the ecliptic.
- Zero point: vernal equinox.
- Ecliptic latitude, β, is analogous to declination, but measures distance north or south of the ecliptic, attaining +90° at the *north ecliptic pole (NEP)* and -90° at the *south ecliptic pole (SEP)*.
  Ecliptic longitude, λ , is analogous to right ascension and is measured from the vernal equinox , in the same direction as right ascension but along the ecliptic rather than the celestial equator.

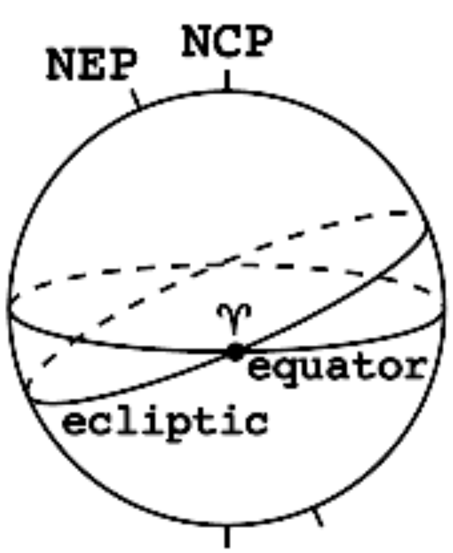
Ecliptic Latitude



Ecliptic Longitude

Ecliptic coordinate system

- Equator is the ecliptic (23.4 deg from celestial equator)
- Ecliptic pole perpendicular to ecliptic plane
- Zero of ecliptic longitude is the vernal equinox.



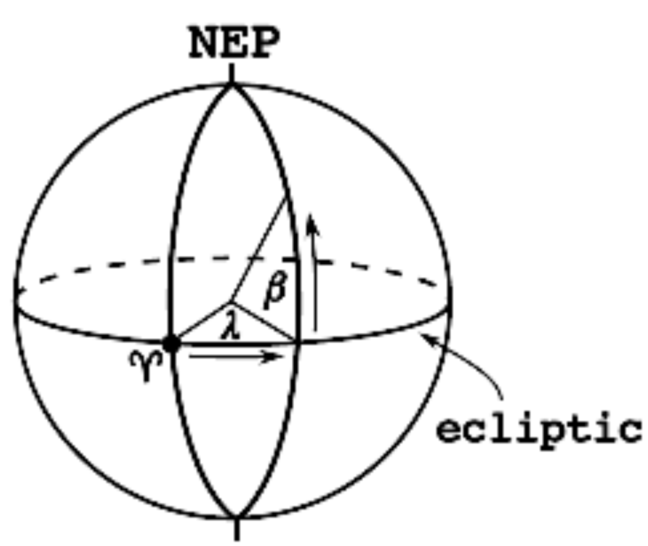
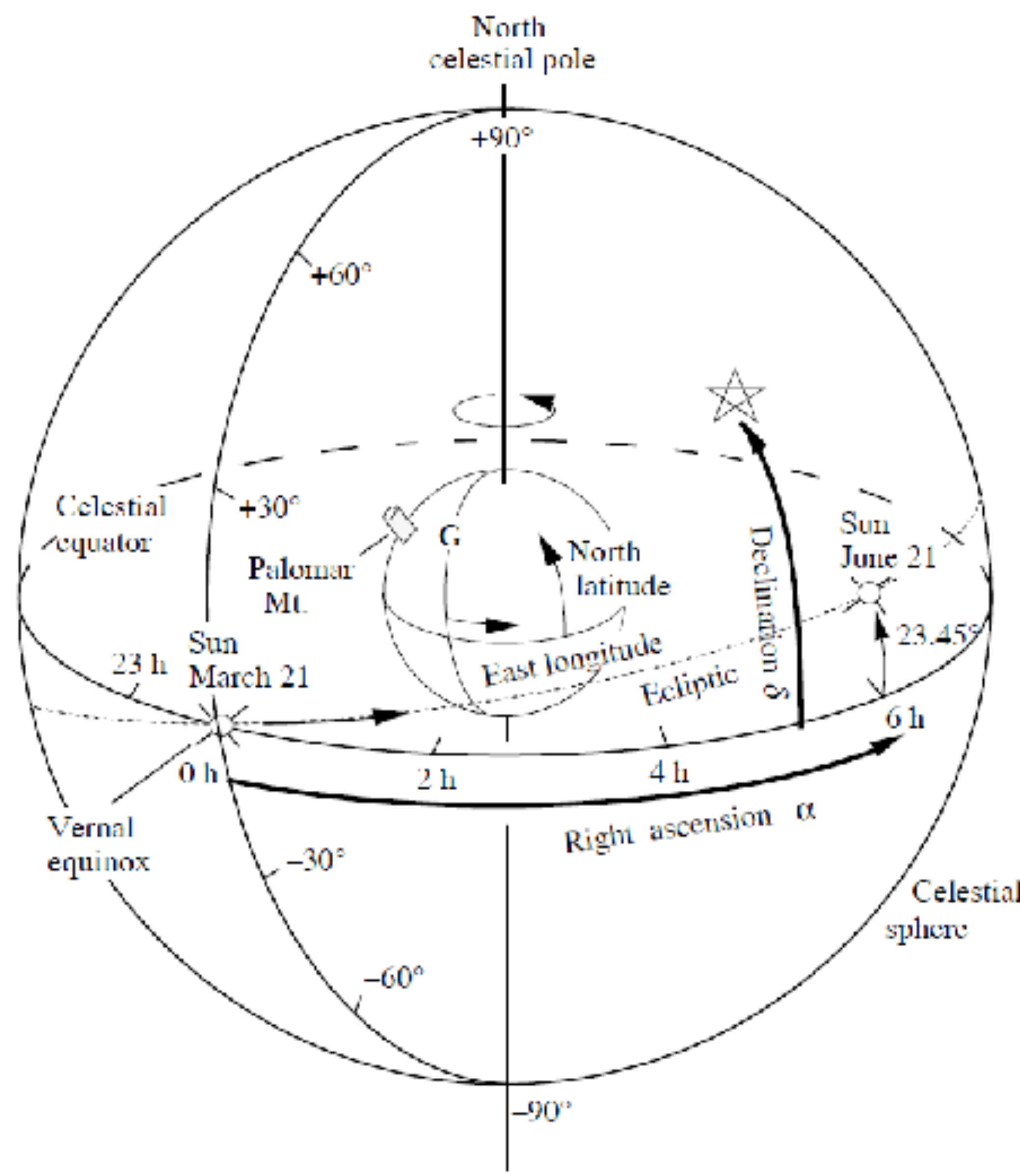


Fig. 3.1. : Celestial Coordinates

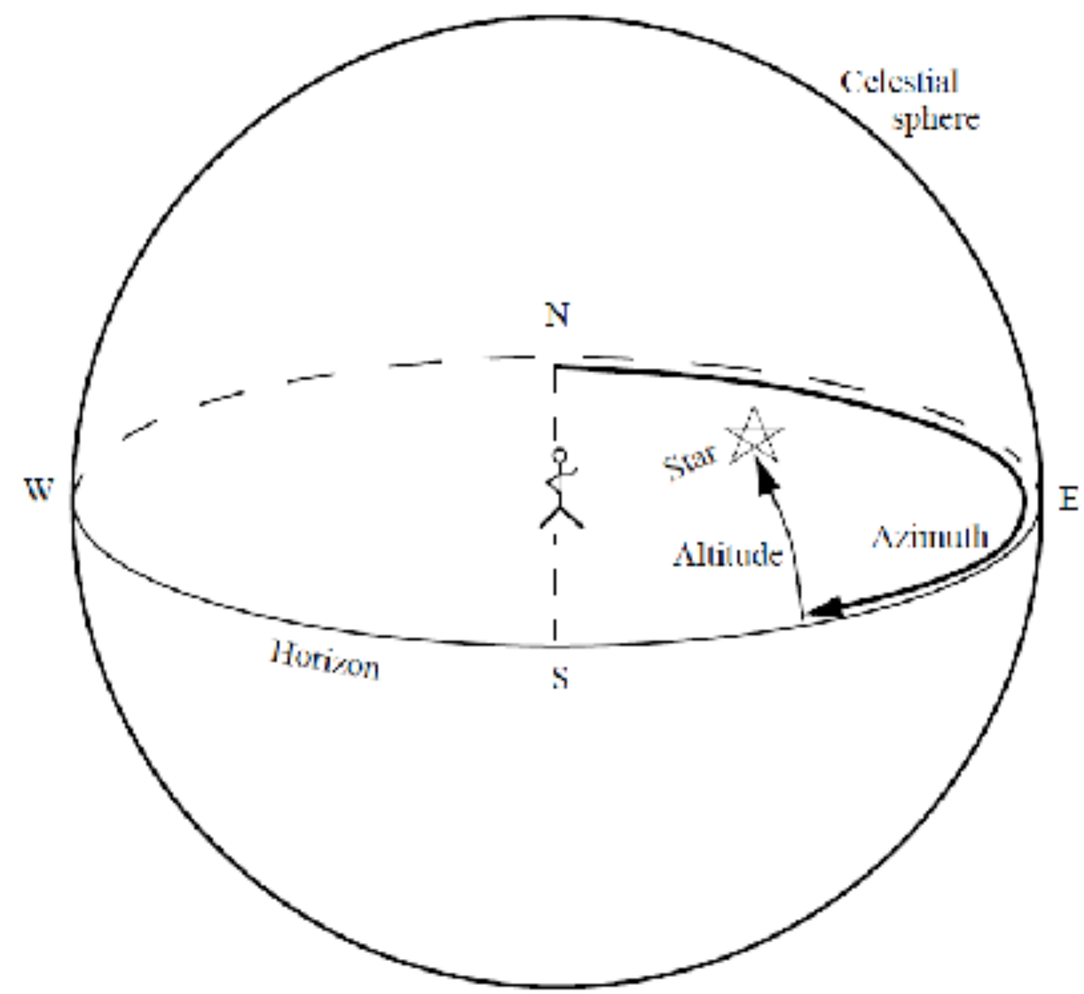


Relationship between horizon and equatorial coordinates

- Define:
  - ***(A,a)*** **–** azimuth and altitude
  - ***(α,δ)*** – right ascension and declination
  - ***(H)*** **–** hour angle
  - θ_{lat} - observer latitude
- Using spherical trigonometry, we can derive relationships between these coordinates.

$$\sin\delta = \sin a \sin\theta_{lat} + \cos a \cos\theta_{lat} \cos A$$
$$\sin a = \sin\delta \sin\theta_{lat} + \cos\delta \cos\theta_{lat} \cos H$$

Fig. 3.2 Horizon Coordinates



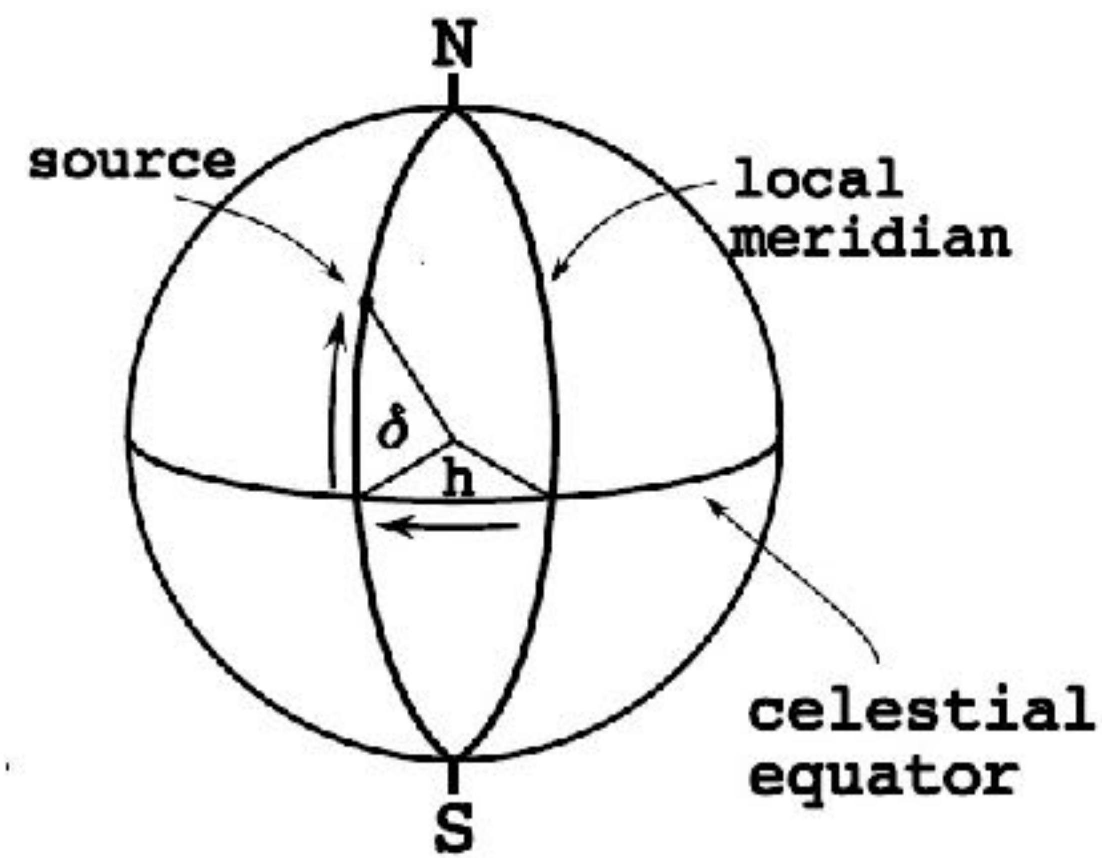
(Bradt 2004)

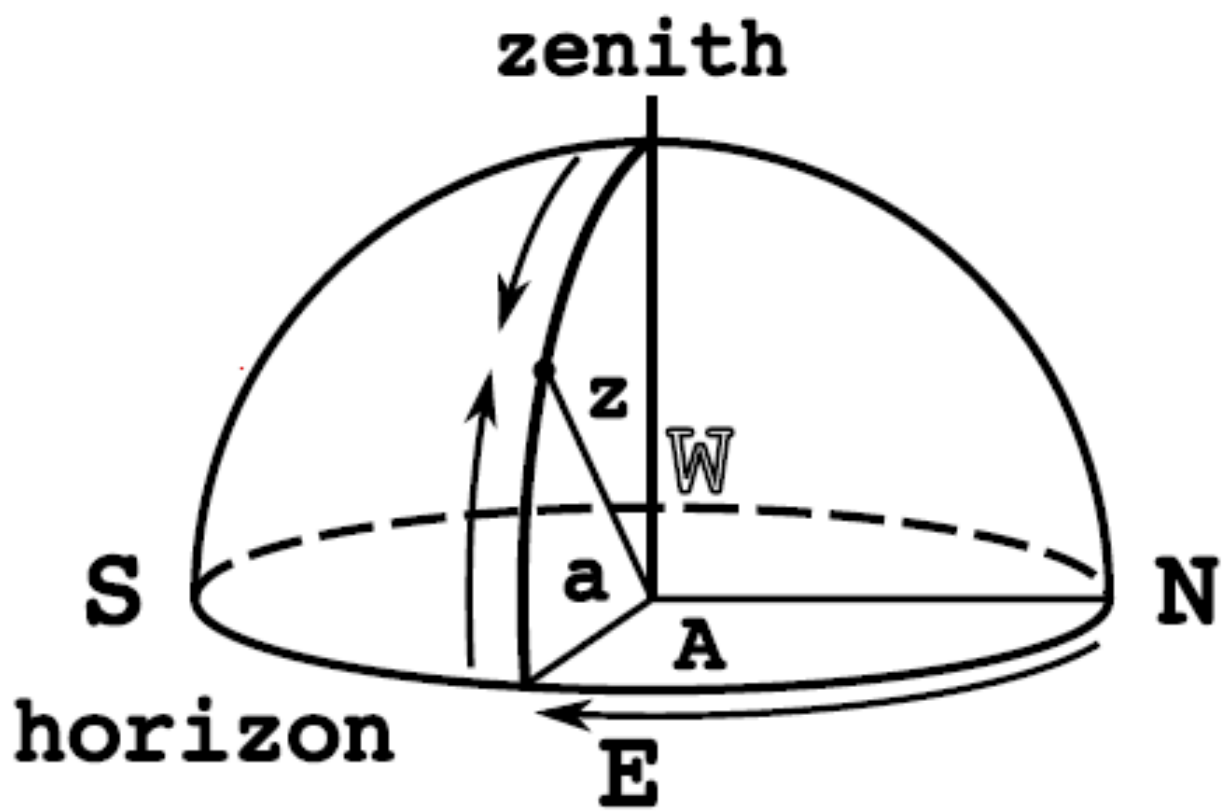
Local Sidereal Time and Right Ascension

The Local Sidereal Time (LST) = Hour Angle of the vernal equinox.
LST is 0 hours when the vernal equinox is on the observer's local meridian.

- Lets suppose that LST = 1h.
  This means that the vernal equinox has moved 15° (1h) west of the meridian, and now some other star X is on the meridian.
  But the Right Ascension of star X is the angular distance from the vernal equinox to X = 1h = LST.
  So at any instant, Local Sidereal Time = Right Ascension of whichever stars are on the meridian.
- And in general, the $\text{Hour Angle}_{\text{Object}} = \text{LST} - \text{RA}_{\text{Object}}$

Conversion between HA/dec and Alt/Az





$$\cos a \; \sin A = - \; \cos\delta \sin h$$

$$\cos a \; \cos A = \sin\delta \; \cos\phi - \cos\delta \; \cos h \; \sin\phi$$

$$\sin a = \sin\delta \; \sin\phi + \cos\delta \; \cos h \; \cos\phi$$

$$\cos\delta \; \cos h = \sin a \; \cos\phi - \cos a \; \cos A \; \sin\phi$$

$$\sin\delta = \sin a \; \sin\phi + \cos a \; \cos A \; \cos\phi$$

Galactic coordinates (*l*,*b*)

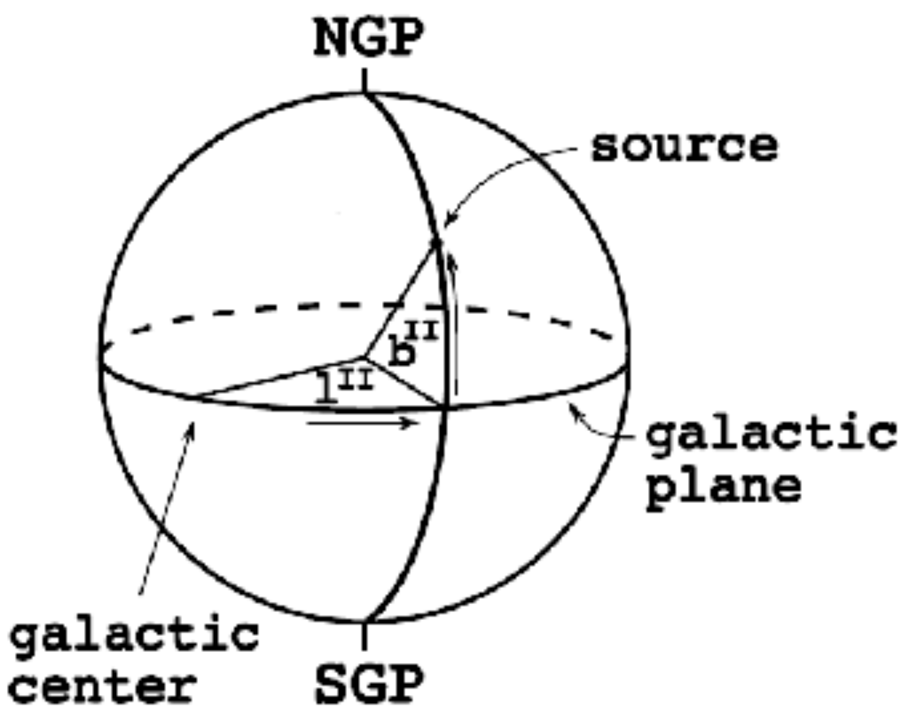
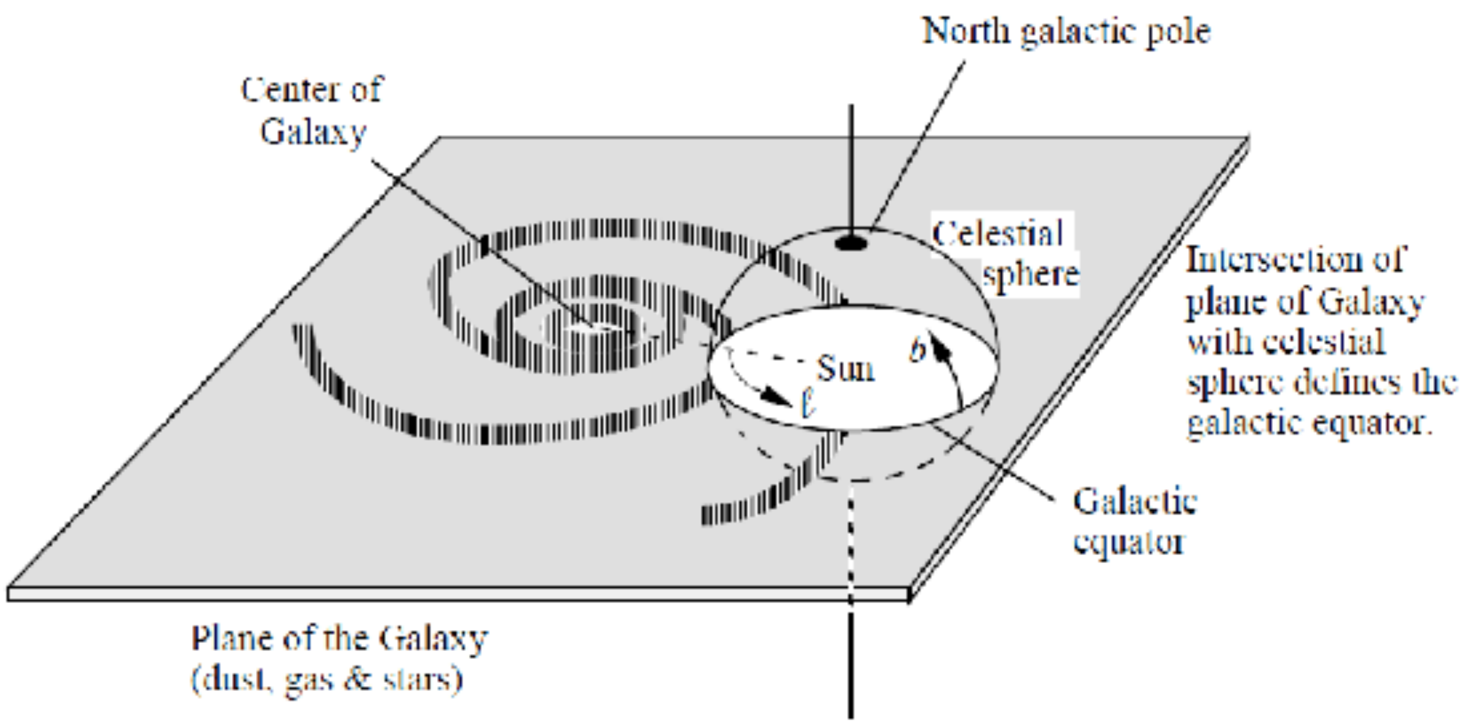


Fig. 3.4. Galactic coordinates

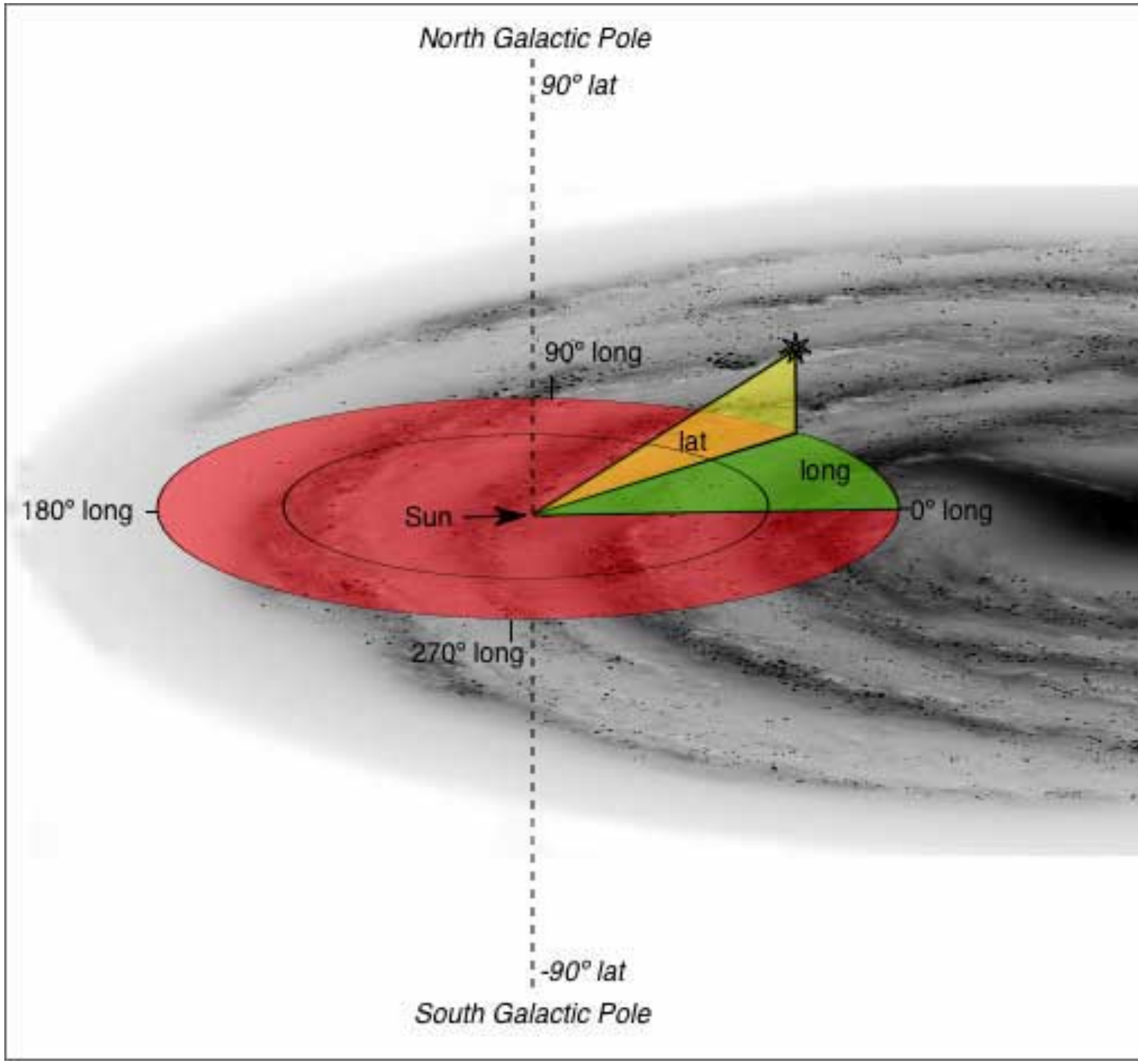


(Bradt 2004)

Galactic Coordinate System

The equatorial system is geocentric and thus provides an inappropriate viewpoint for problems of Galactic structure and dynamics.

- •The fundamental circle is galactic equator which is coincident with the plane of the Milky Way Galaxy (shown in red). The plane is inclined at an angle of 62.87 degrees to celestial equator.)
- •Zero point lies in the direction of the galactic center as seen from Earth
- •Galactic latitude (b) of a celestial body is its angular distance north (+) or south (-) of the galactic equator (it ranges from 0 to 90°)
- •Galactic Longitude (l) of a celestial body is its angular distance (from 0 to 360°) from the nominal galactic center measured eastwards along the galactic equator to the intersection of the great circle passing through the body.



Galactic coordinates

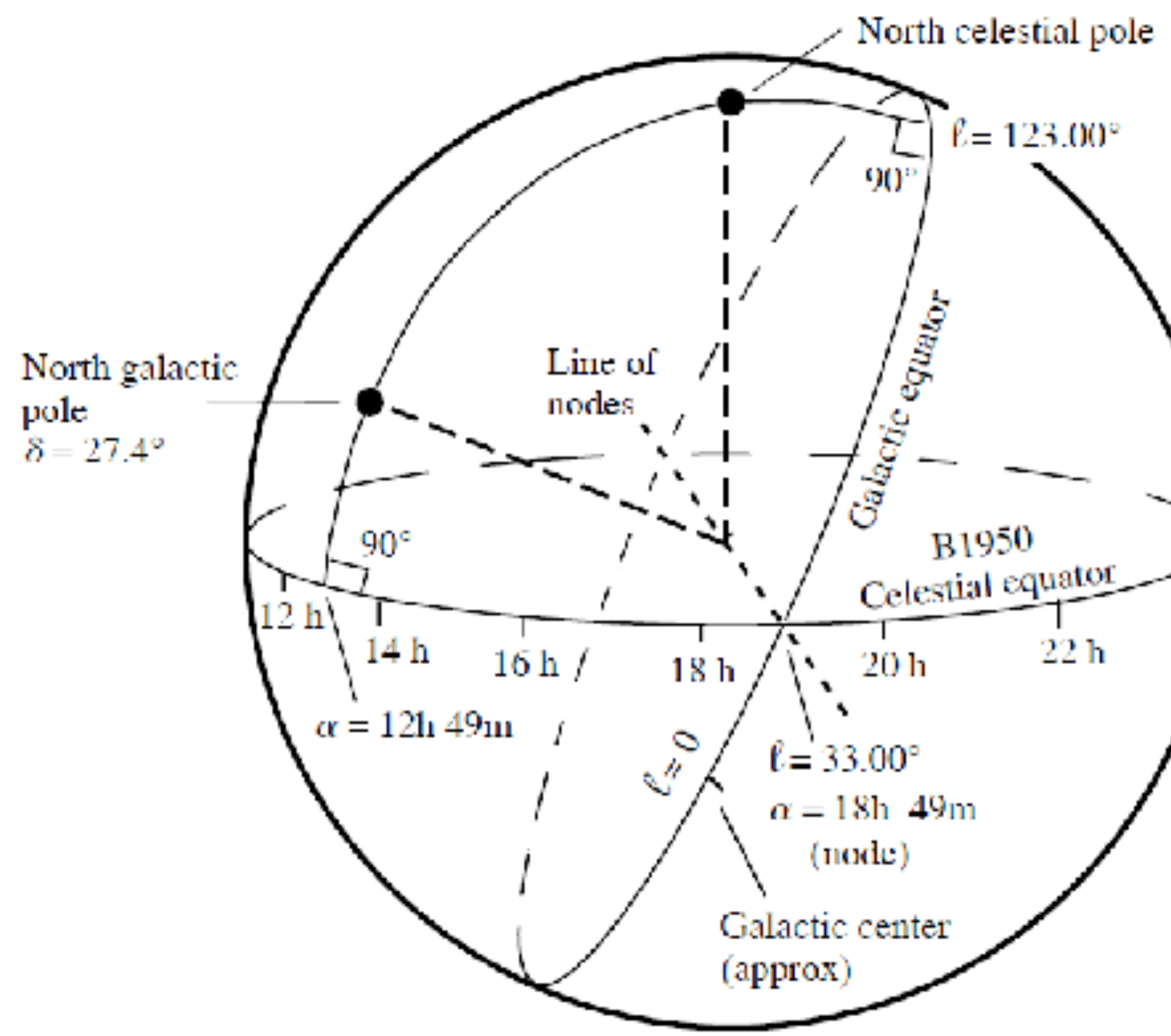
- International Astronomical Union (IAU) adopted the following (exact) equatorial coordinates for the North Galactic Pole (NGP):

$$\alpha_{NGP}(\mathrm{B1950}) = 12\,\mathrm{h}\,49\,\mathrm{m} = 192.25^\circ$$

$$\delta_{NGP}(\mathrm{B1950}) = +27^\circ 24' = +27.4^\circ$$

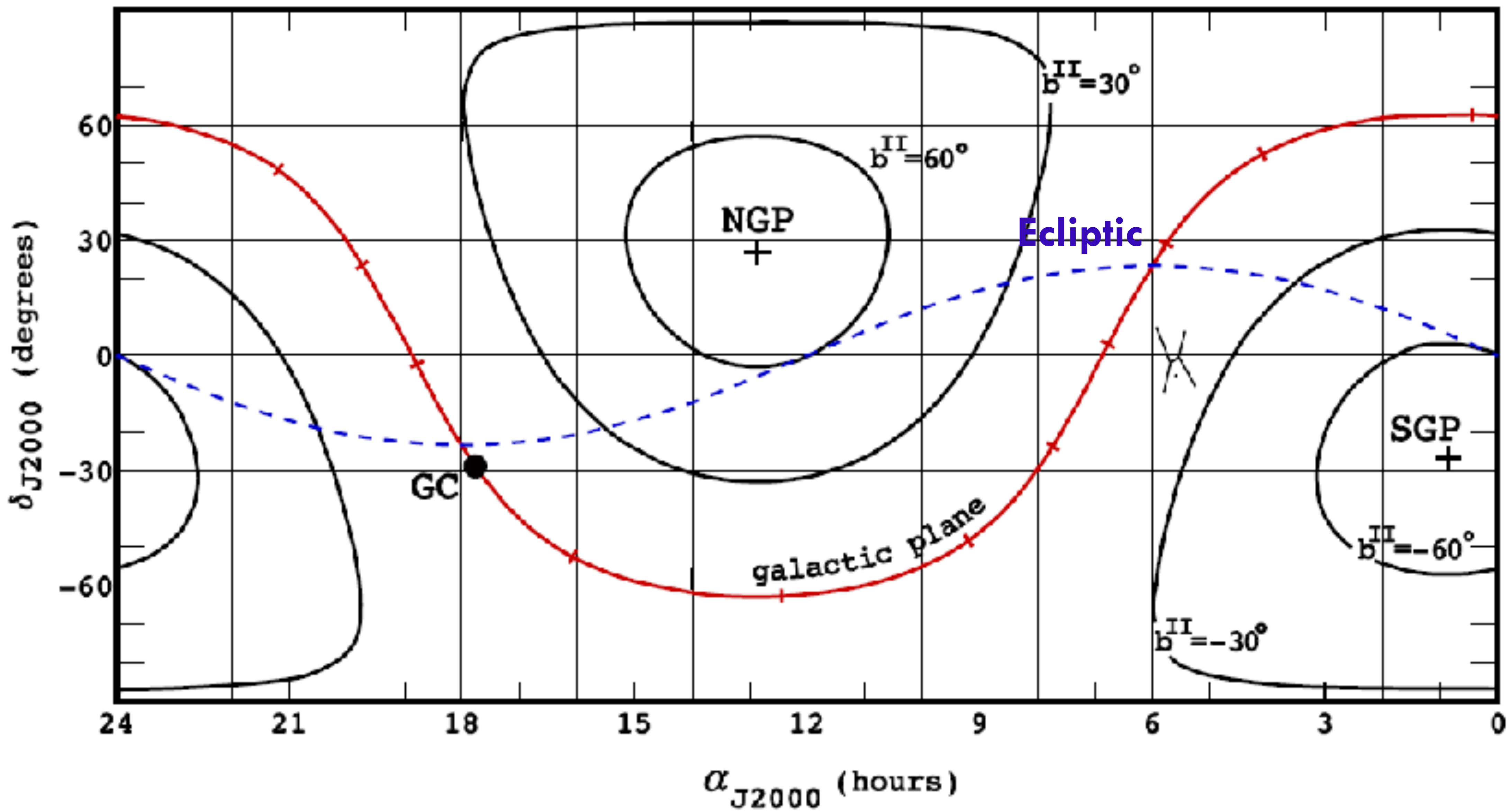
- Galactic equator and celestial equator intersect along lind of nodes
- Zero of galactic longitude near galactic center:

$$l_{NCP} = 123^\circ$$

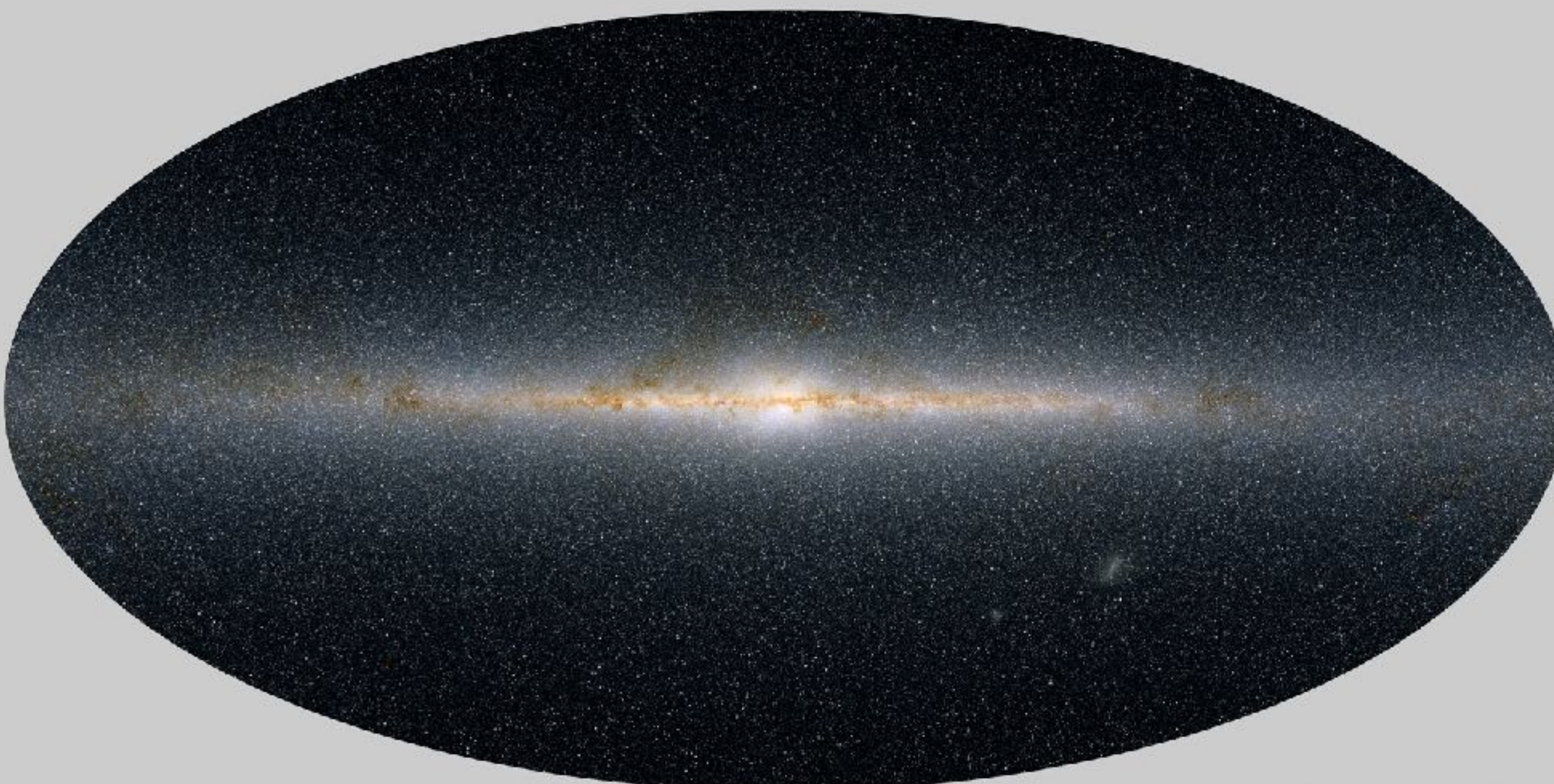


(Bradt 2004)

Galactic plane in equatorial coordinates

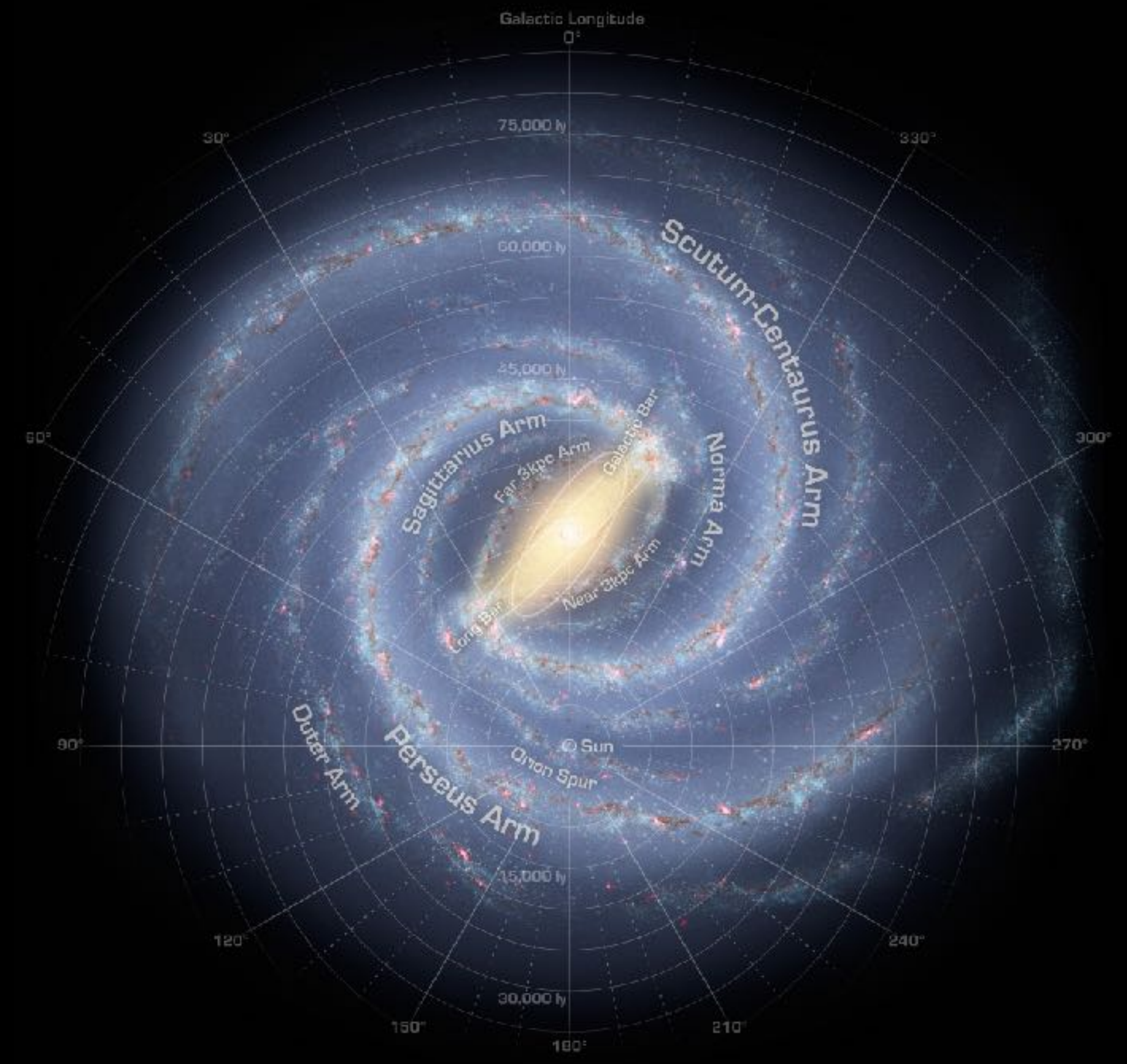


Galactic Coordinates

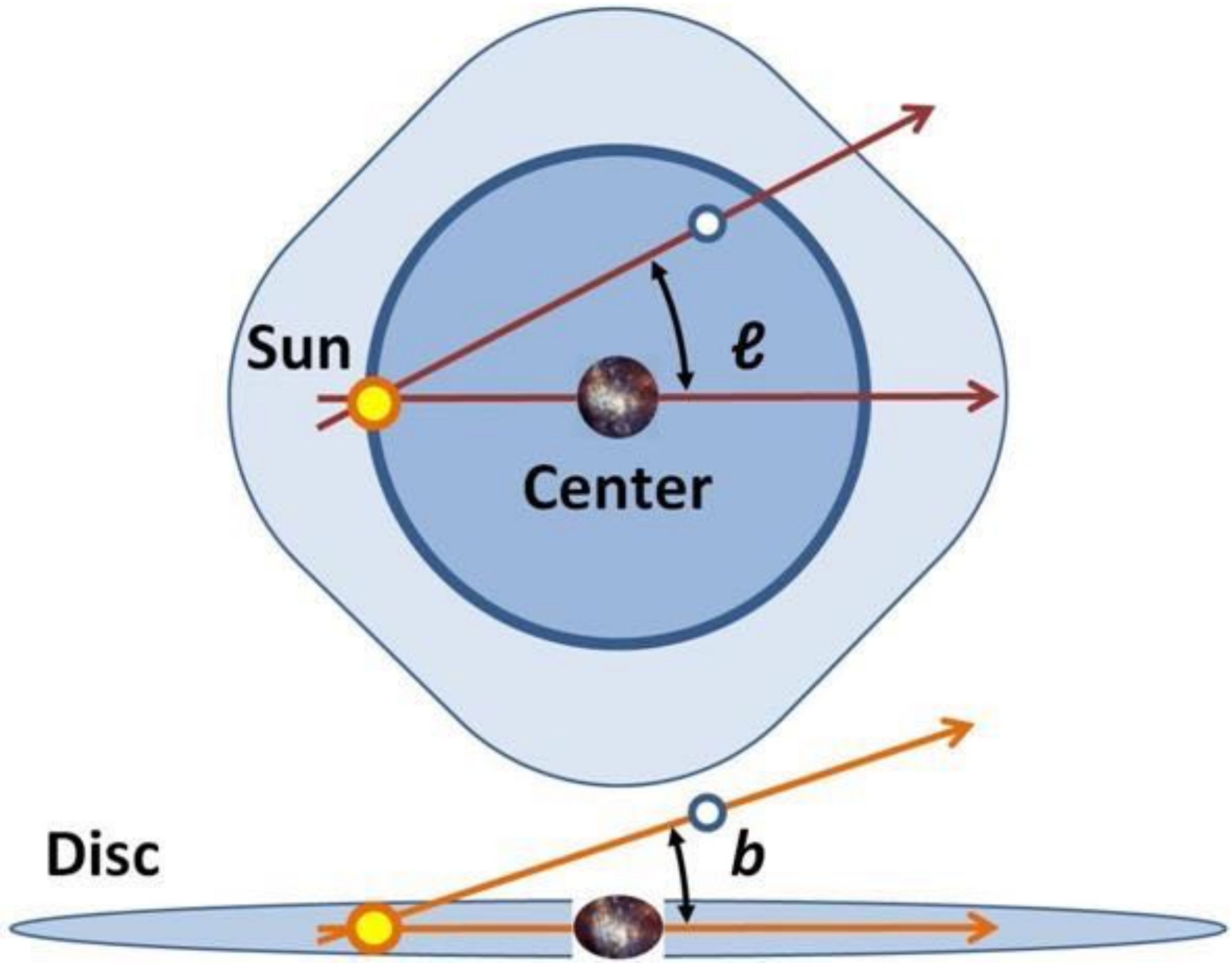


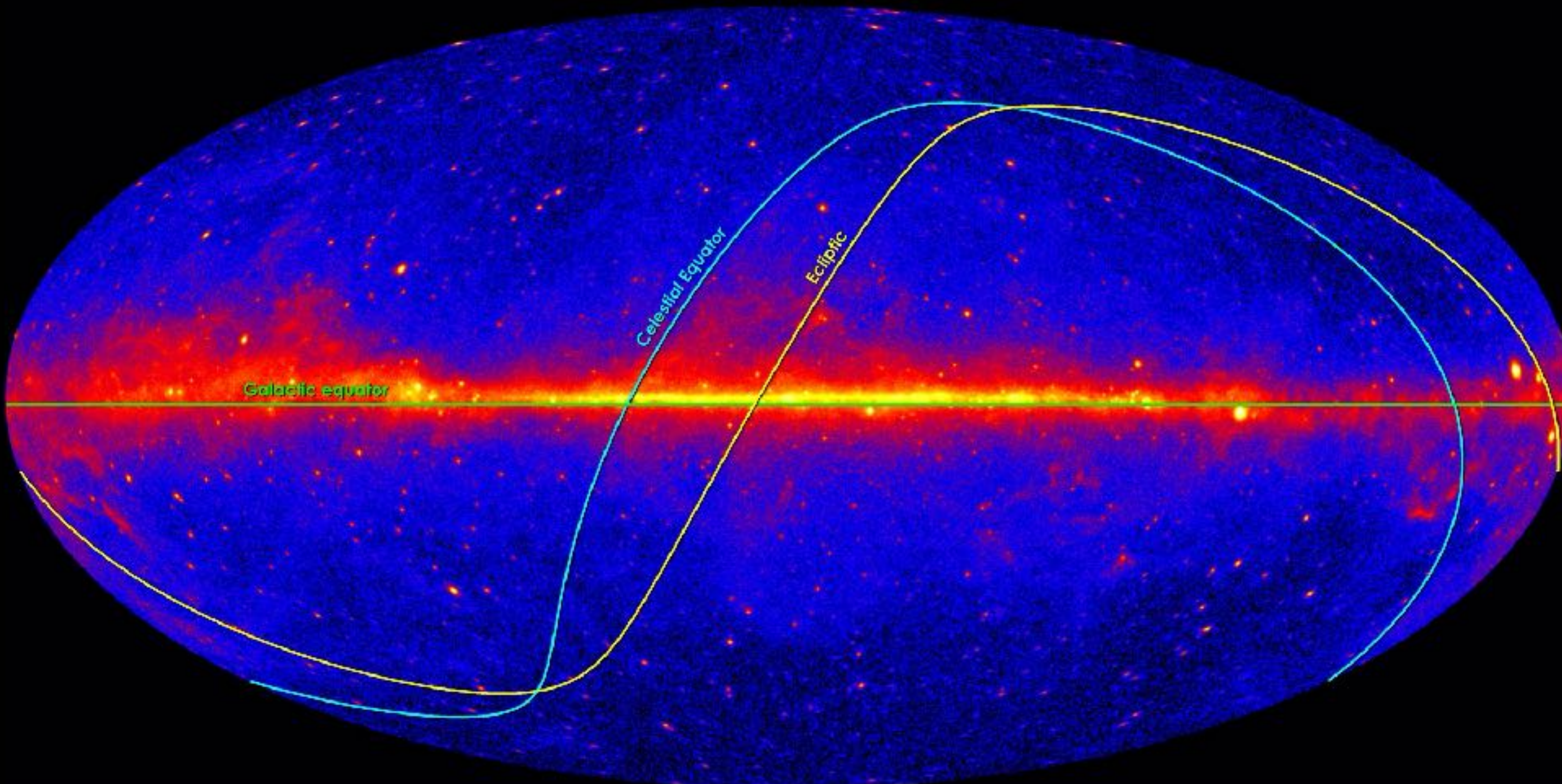
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

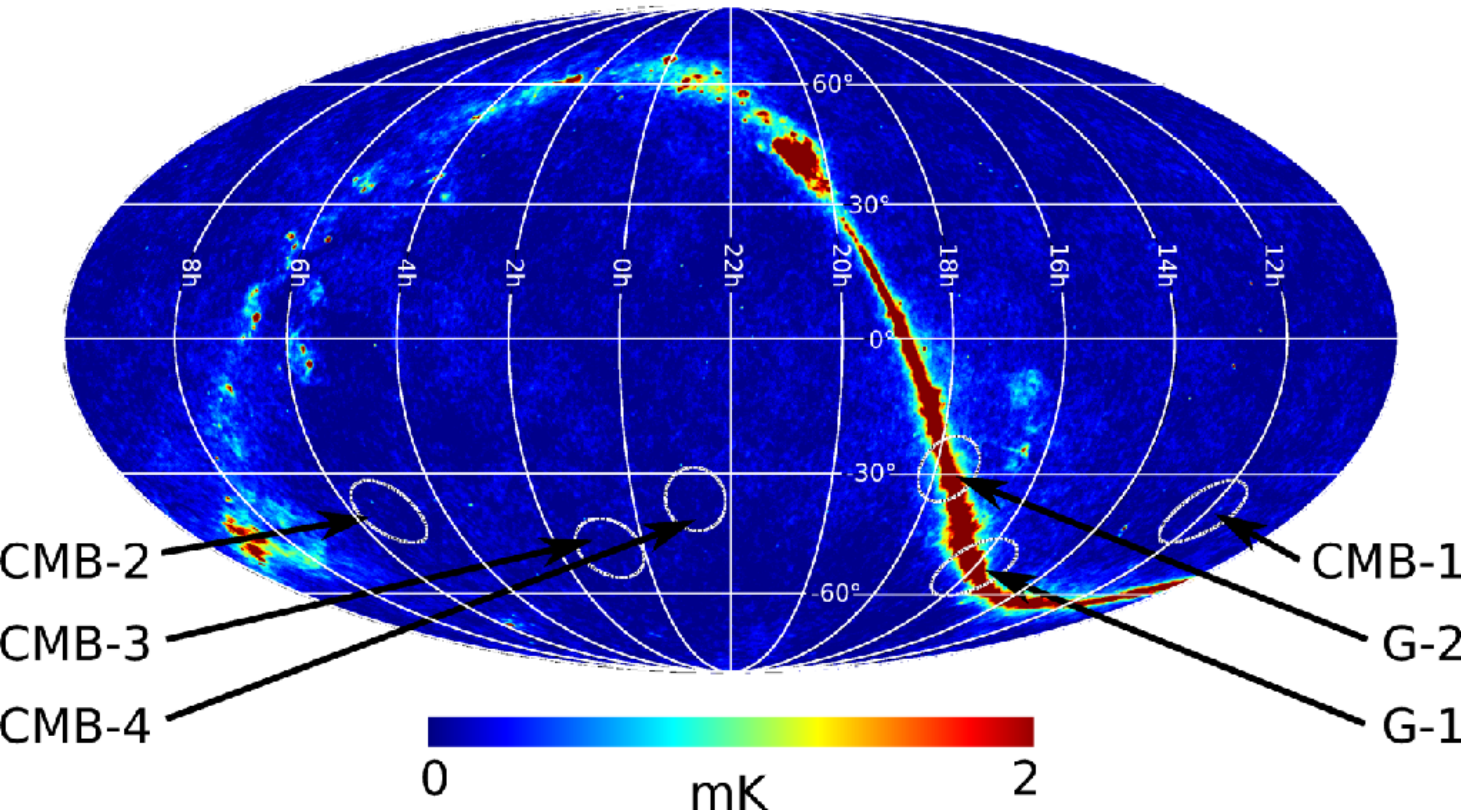
Galactic Coordinates



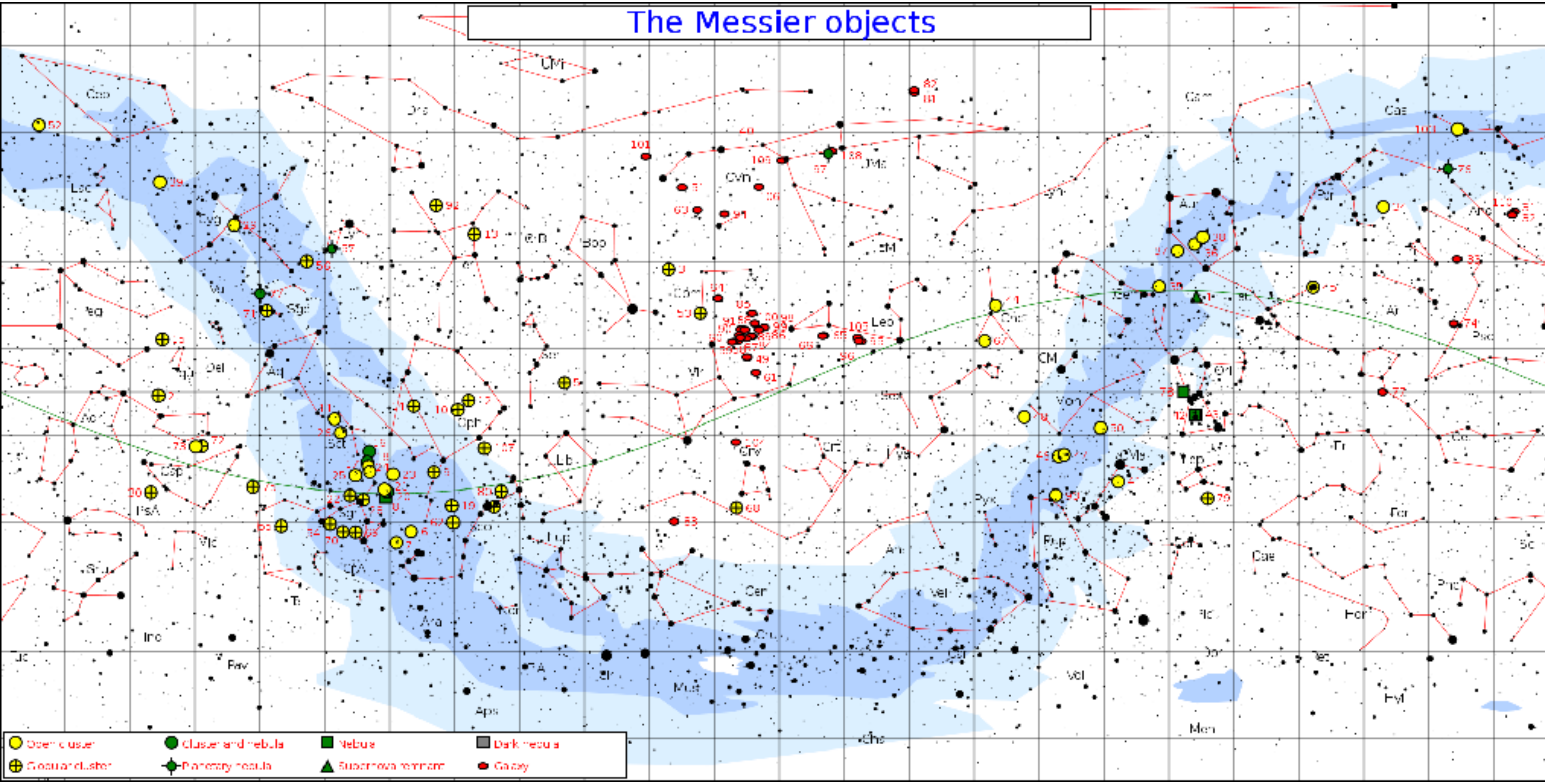
Galactic Coordinates

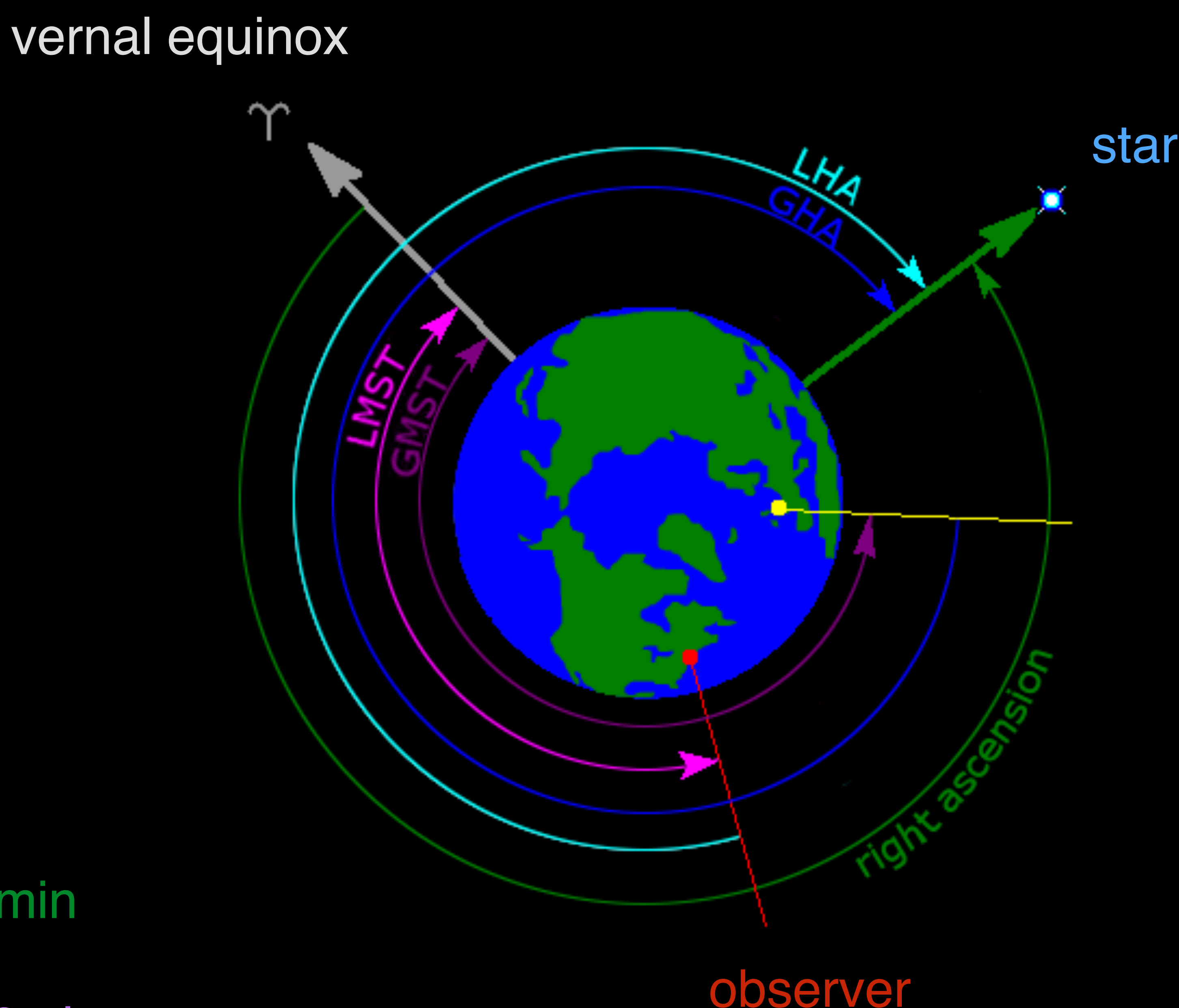



Galactic equator
Celestial Equator
Ecliptic



60°
30°
0°
-30°
-60°
8h
6h
4h
2h
0h
22h
20h
18h
16h
14h
12h
CMB-1
CMB-2
CMB-3
CMB-4
G-1
G-2
0
2
mK


The Messier objects
Open cluster
Cluster and nebula
Nebula
Dark nebula
Globular cluster
Planetary nebula
Supernova remnant
Galaxy



RA ~ 17hr20min
HA ~ 7hr
LST ~ 10hr40min

Computing approximate rise and set times

- Define:
  - ***(A,a)*** **–** azimuth and altitude
  - ***(α,δ)*** – right ascension and declination
  - ***(H)*** **–** hour angle
  - θ_{lat} - observer latitude
  - L_E **–** observer East longitude.

Compute hour angle of source at zero elevatio

$\sin a = \sin\delta \sin\theta_{lat} + \cos\delta \cos\theta_{lat} \cos H$

Set $a = 0$

$H = \frac{1}{15}\cos^{-1}\left(-\tan\theta_{lat} \tan\delta\right)$

↓

Compute local sidereal time at rise and se t

$LST_{rise} = 24 + \alpha - H$

$LST_{set} = \alpha + H$

↓

Convert local sidereal time to GS

$GST = LST - L_E$

↓

Convert Greenwich sidereal time to U

GMST at 0hUT1 = 6h41m50.54841s +

(8,640,184.812866 T + 0.093104 T^2 – 6.2x10$^{-6}T^3$) s

↓

Convert UT to local civil tin

UT + time zone correction.

Notation

α = right ascension

δ = declination

ϕ = latitude

a = altitude

Rise and Set times

- The standard formula for the altitude of an object is:
  $\sin(a) = \sin(\delta)\sin(\phi) + \cos(\delta)\cos(\phi)\cos(H)$
- If $a = 0°$ (the object is on horizon, either rising or setting),
  then this equation becomes:
  $\cos(H) = -\tan(\phi)\tan(\delta)$
- This gives the **semi-diurnal arc** H:
  the time between the object crossing the horizon, and crossing the meridian.
- Knowing the Right Ascension of the object, and its semi-diurnal arc,
  we can find the Local Sidereal Time of meridian transit,
  and hence calculate its rising and setting times.
- One should put in a correction for atmospheric refraction, but we will neglect it for the moment

Illinois Observatory ϕ = +40.1105

At this time of year, when does Arcturus rise?
Arcturus α = 14h15m39.7s +19d10m56s

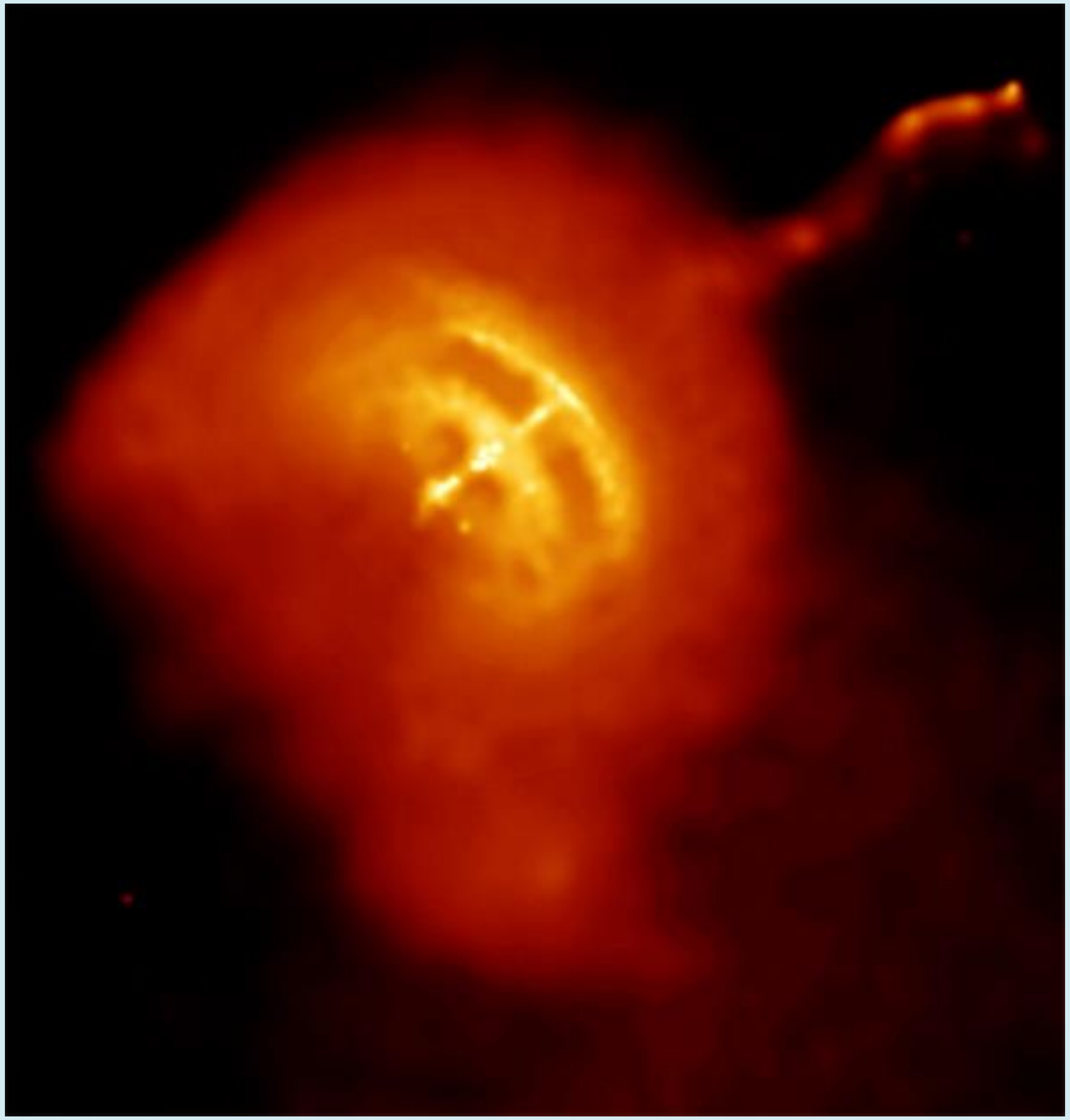
$\cos(H) = -\tan(\phi)\tan(\delta) = -(0.842)(0.348) = -0.293$

H = 1.86 radians = 107 degrees

In time units H = 107/15 = 7.1 hours. Arcturus will rise 7.1 hours before it reaches the meridian and set 7.1 hours after it passes the meridian.

Precise time measurement in observational astronomy

- Accurate time measurement is critical to observational astronomy:
  - It's an implicit ***dynamical variable*** in describing celestial motions and calculating astronomical coordinates.
  - Needed to label observed astronomical data uniformly and to allow long-term preservation.
  - Some astronomical phenomena are very time-critical (e.g. pulsar timing)

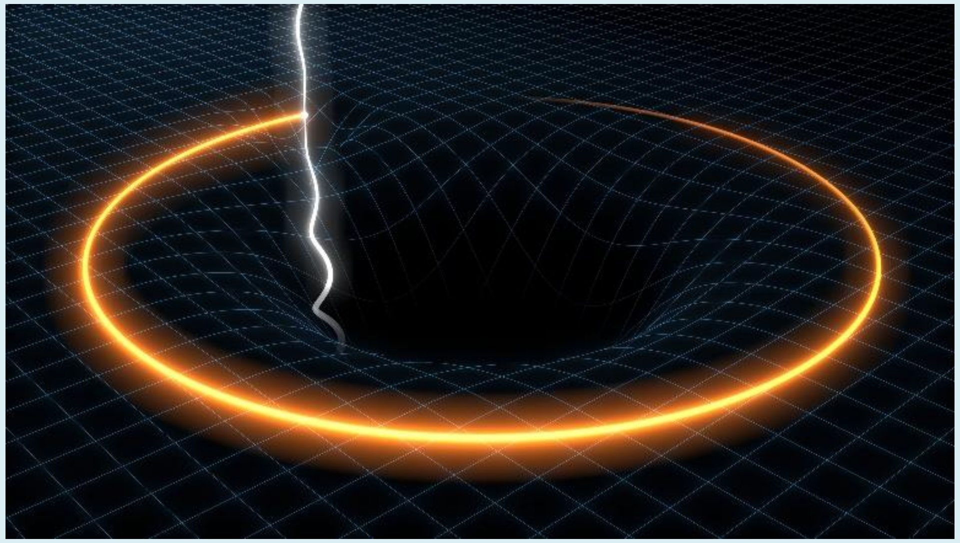


(NASA/CXC/PSU/G.Pavlov et al.)

Testing general relativity

Testing strong-field gravity

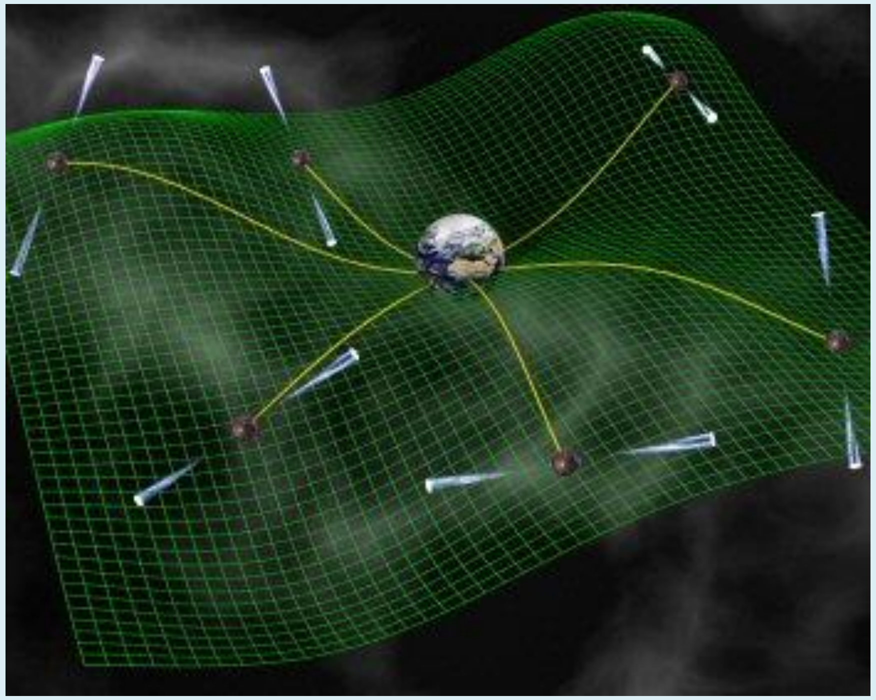
- *Galactic census of pulsars O(10^4)*
- *Locate and time black hole – pulsar binary systems*



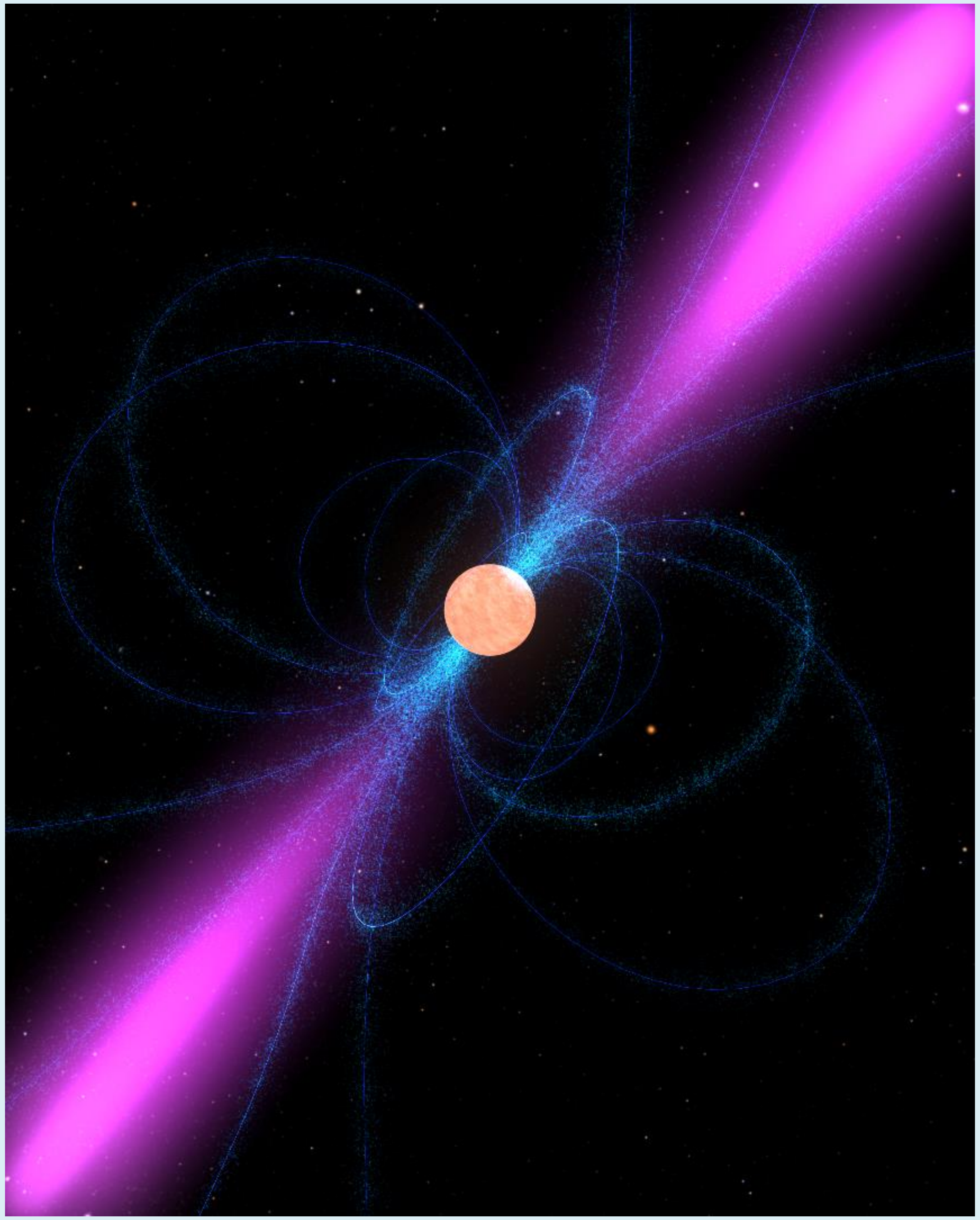
(Credit: SKA Organisation / Swinburne Astronomy Productions)

Detecting gravitational waves

- *Monitor timing from an ensemble of ms pulsars*



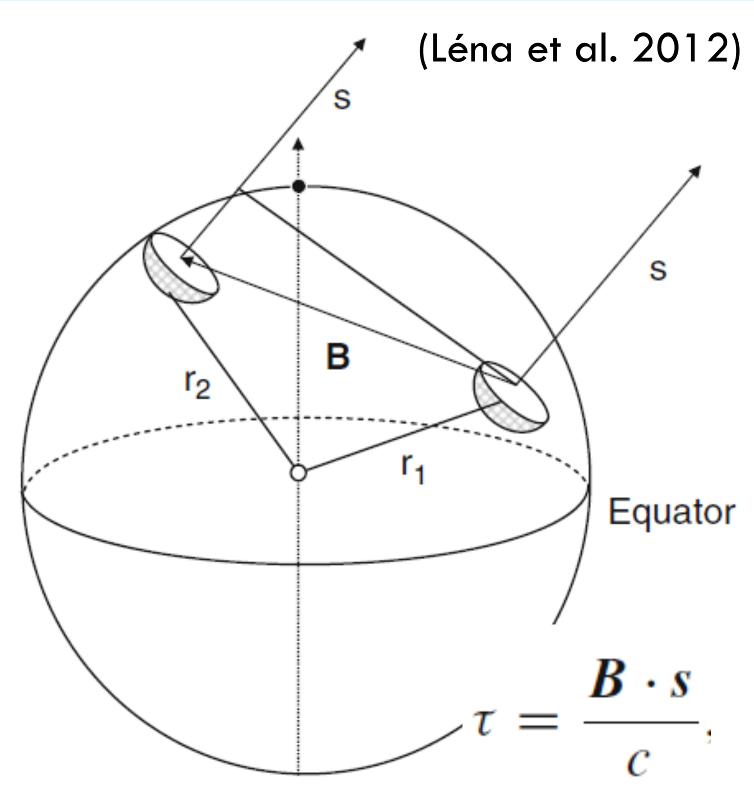
(Credit: www.jb.man.ac.uk)

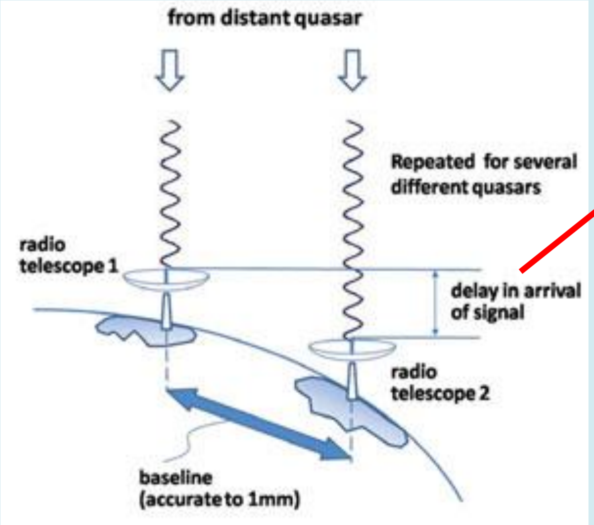


(Credit: NASA/Fermi)

The International Celestial Reference Frame (ICRF)

- ***ICRF*** adopted by IAU in 1991, defining an inertial frame in terms of ***distant radio sources relative to the barycenter.***
  - At cosmological distances, quasars are unaffected by local galactic proper motions and have low intrinsic proper motions.
- Accurate clocks are essential in maintaining Earth orientation and astrometric measurements central to these frames.





(Survey Quartely 2009)

$$\Delta\tau = \frac{R_{Earth}}{c}\cos(\Delta\theta_{lat}) = 21.2\cos(\Delta\theta_{lat})\ \text{ms}$$

(NRAO)

TIME SCALES

Temporal reference systems.

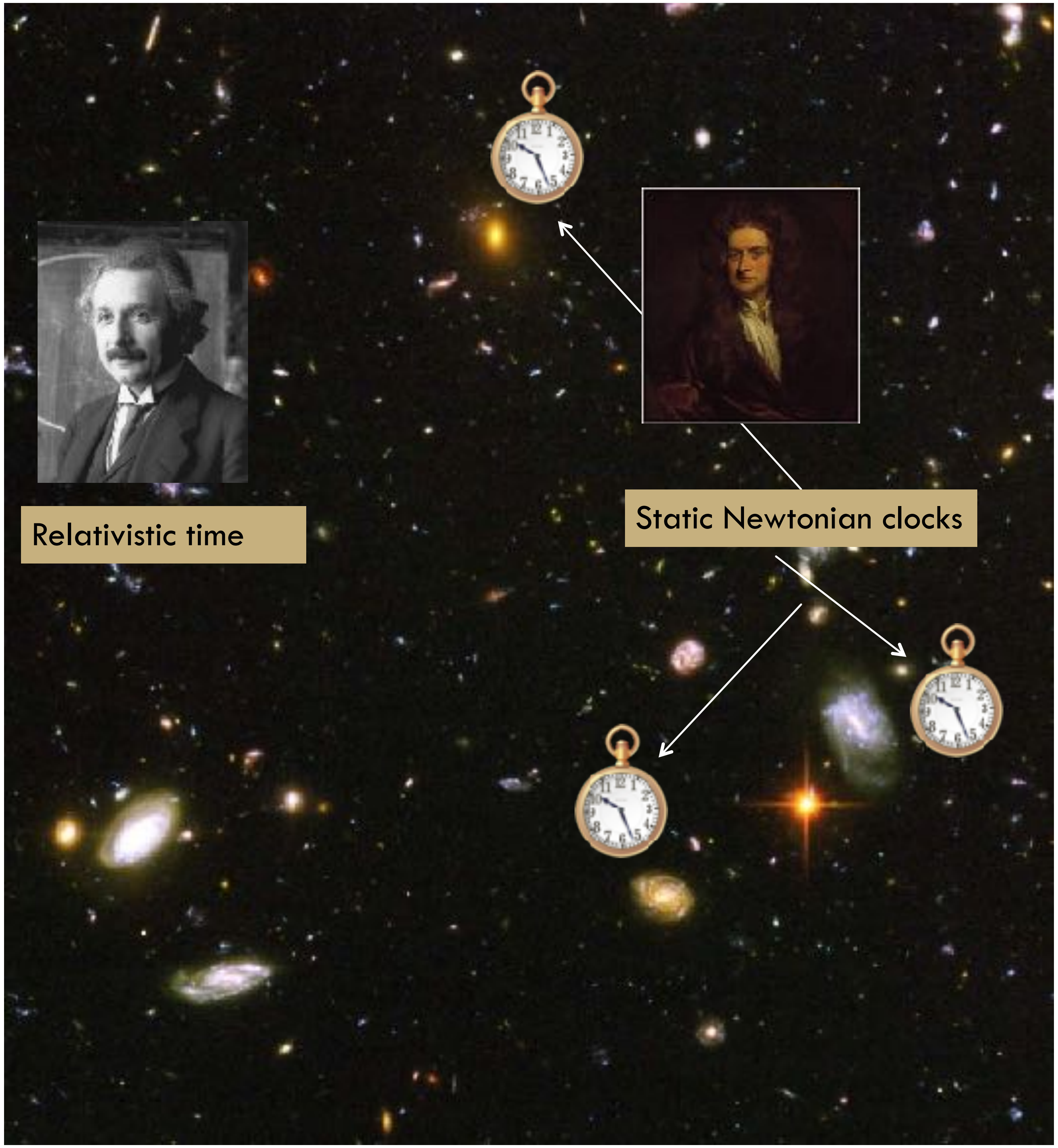
Temporal reference systems

- A ***temporal reference system*** requires:

- There are analogies with the establishment of ***spatial reference frames*** in astronomy.

Models of time: General Relativity

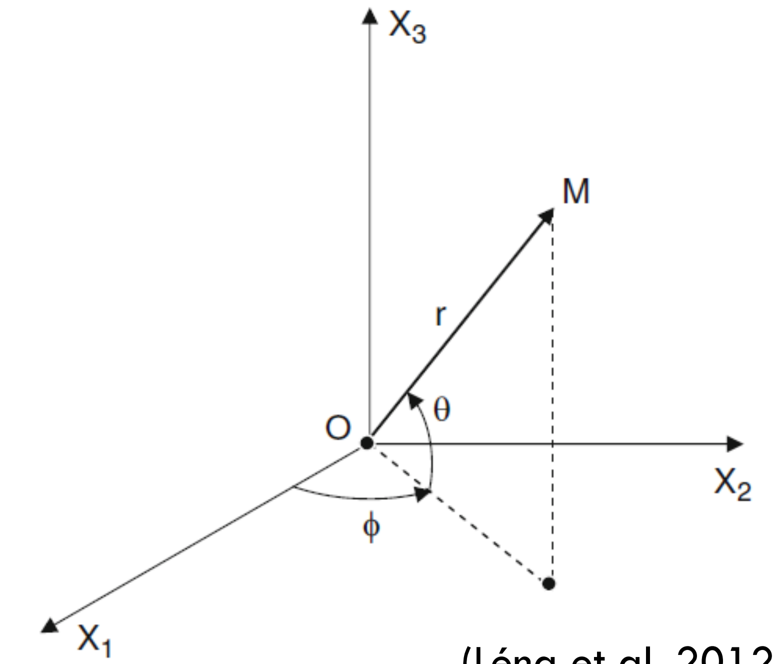
- ***Time in General Relativity:***
  - Time is not a static, uniformly-flowing stream.
  - It's measurement across the Universe depends on each observer's motion (worldline) and the curvature of spacetime in their location (gravitational fields).
    - ***Proper time*** measured by each observer depends on their worldline through curved spacetime.
    - Differs from ***coordinate time.***
  - Clocks run slower both in higher gravitational fields and for observers moving at higher relative speeds.
  - At the highest precision, we need to account for gravity and motion in time measurement.



Historical evolution of time scales

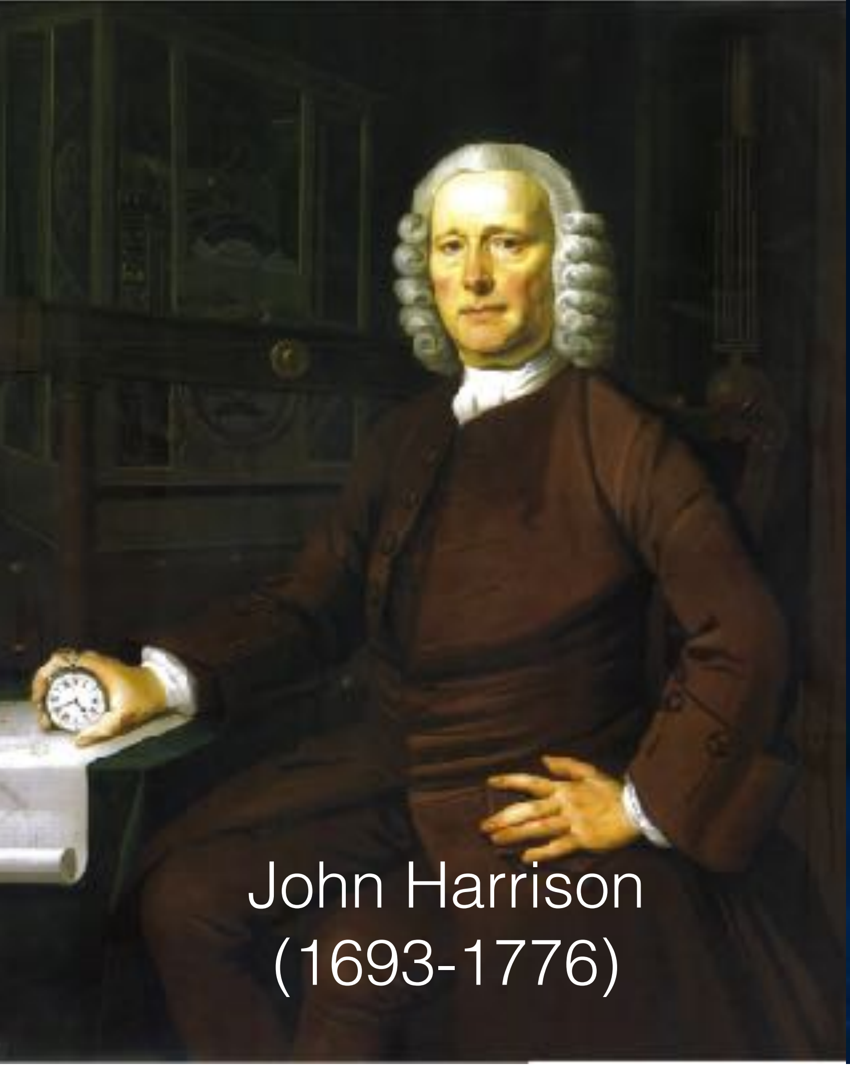
- Astronomical time scales and units have a long history of association with ***celestial motions*** or ***dynamics***.
  - An ephemeris predicts a position vector $\boldsymbol{r}(t)$ for **OM** as defined in spatial reference systems. Observation yields position **OM**, ***dynamical time*** is obtained as solution of $\boldsymbol{OM} = \boldsymbol{r}(t)$.
    - E.g. Fixed Earth rotation $\phi = \omega t, \omega\ const.$ used until ~1960.
  - ***Ephemeris time*** based on Earth orbit until ~1960-1967.

- ***Atomic standards independent of celestial motions*** (SI second and TAI) adopted after 1967.

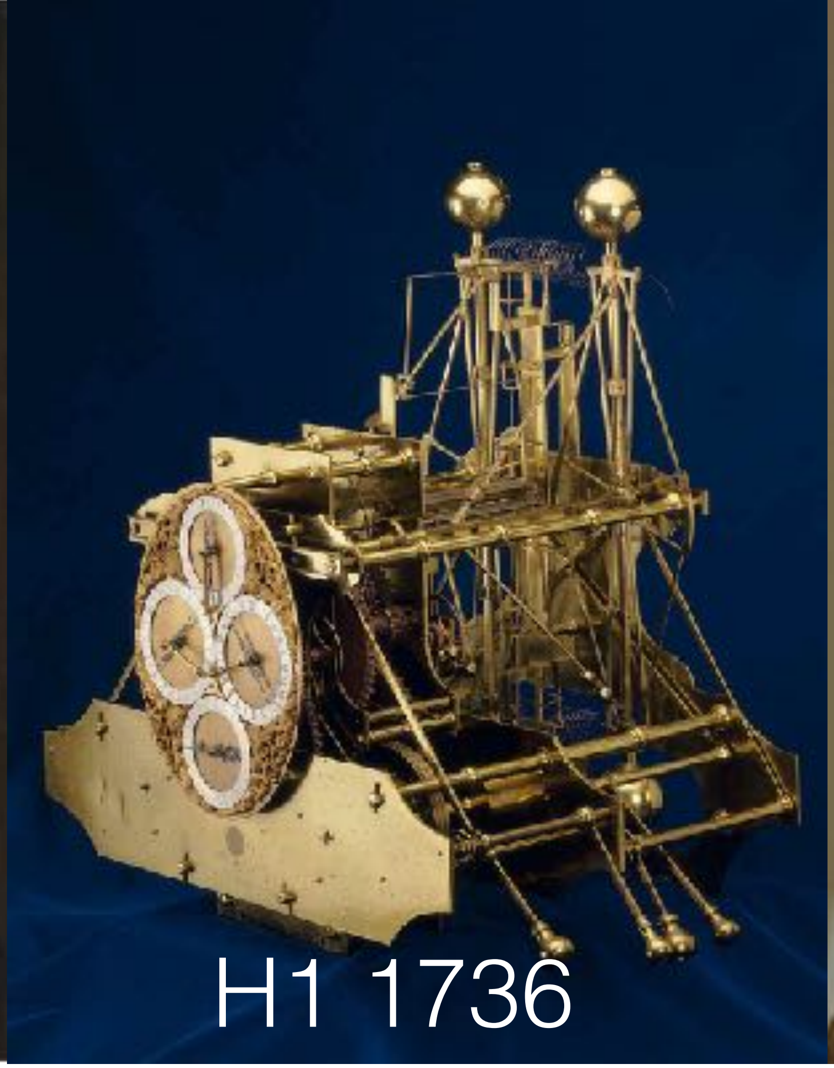


(Léna et al. 2012


(NASA/Goddard — Space Flight Center Scientific Visualization Studio)



John Harrison (1693-1776)



H1 1736

H5 1772

- Harrison was a cabinet maker. Made his first clock at age 20 out of wood.
- Longitude Act of 1714 promised £10,000 for one degree of longitude (60 knots, 110 km) and £20,000 (~$4M today) for a method that could place longitude to within 30 minutes (30 nautical miles or 35 miles)
- The chronometers kept time to within a few a few seconds per day, which was about 10km for a trip across the Atlantic.
- Issues were thermal stability, winding, friction, humidity, etc.
- The main competition was from Astronomers using the Moon.
- The cost of these initial chronometers was about 30% the cost of a ship, but cost dropped and they never broke.

Historical evolution of time scales

ASTRONOMY

PHYSICS

Table 4.5 The evolution of time scales

Epoch	Physical phenomenon	Definition of the second	Scale of time
Before 1960	Rotation of the Earth	1/86 400 of the mean solar day	Universal Time (UT)
1960–1967	Orbital motion of the Earth	1/31 556 925.974 7 of the 1900.0 tropical year	Ephemeris Time (ET)
1967	Transition between two atomic levels	9 192 631 770 transition periods of Cs 133	Atomic time scale
1971			Atomic time scale of BIH (then BIPM) becomes International Atomic Time (TAI)

(Léna et al. 2012

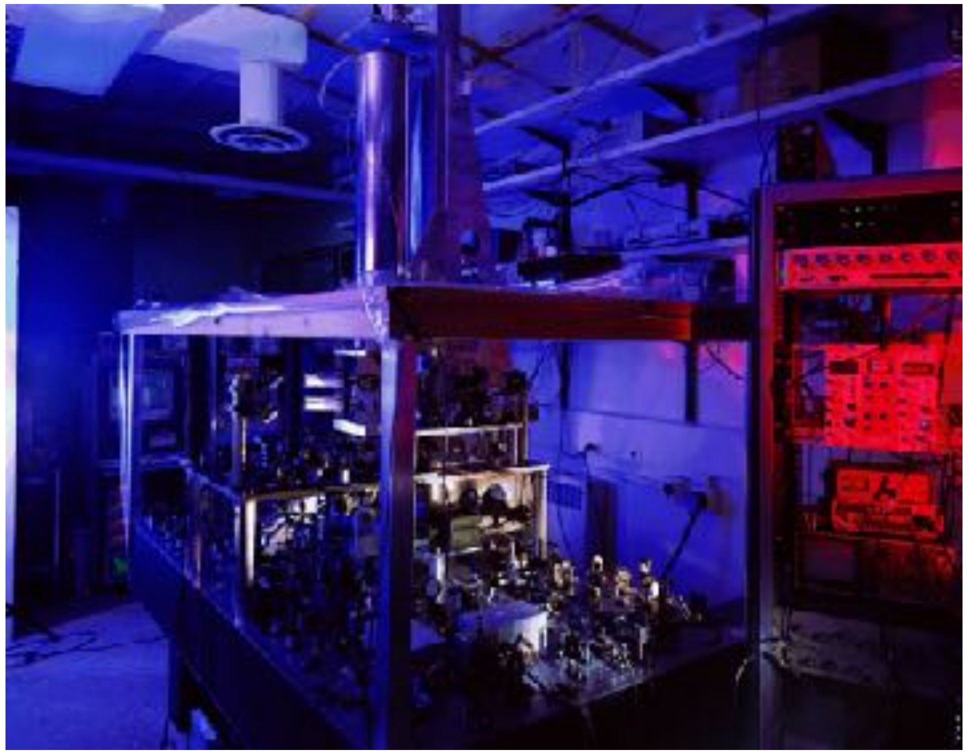
Atomic time

- The most accurate natural clocks are atomic clocks:
  - These are electronic oscillators tuned precisely to atomic transitions under controlled conditions.
- In 1967 the ***atomic second*** or ***SI second*** was defined as:
  - 1.0 atomic second = 9,192,631,770 cycles of the hyperfine transition F=4→3 of the $^2S_{1/2}$ ground state of Cs^{133}
- ***International Atomic Time*** or TAI (Temps Atomique International):
  - Combines an average of 150-200 worldwide frequency standards to set an accurate common atomic time.

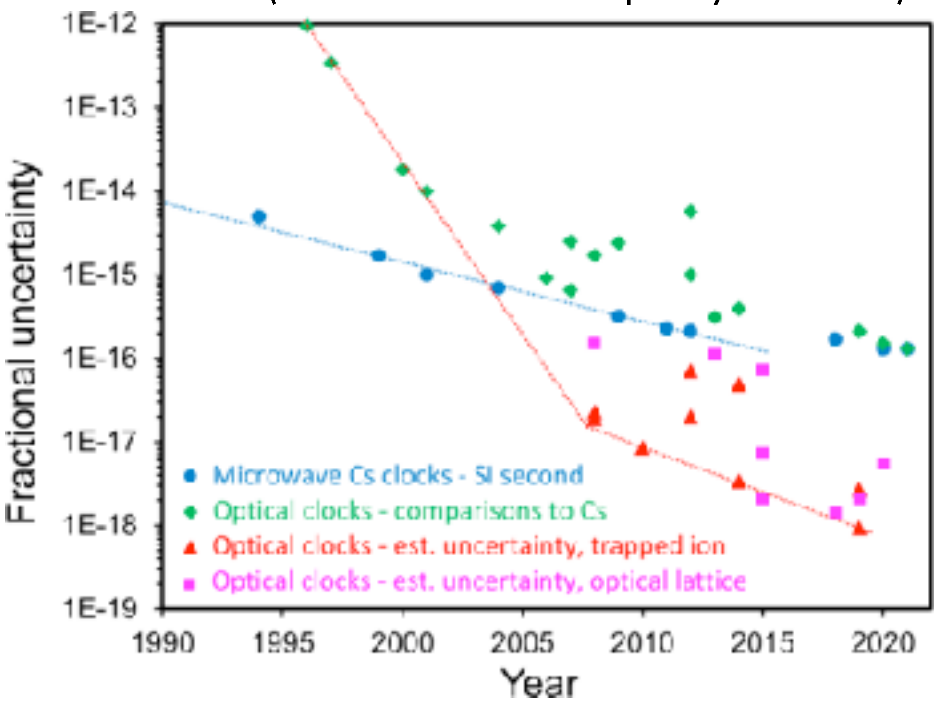
$$\frac{dP}{dt} \sim 1.5 - 3 \times 10^{-14}$$

  - Duration interval conforms as closely as possible to standard of SI second.
  - Referred gravitationally to an observer at Earth's geoid (mean sea level).
  - Compare an early precision chronometer:

$$\dot{P} \sim 7 \times 10^{-7}$$



(NIST-F1: Cesium frequency standard)



(Atomic frequency standard stability: NIST)

Remember that technology and science co-evolve

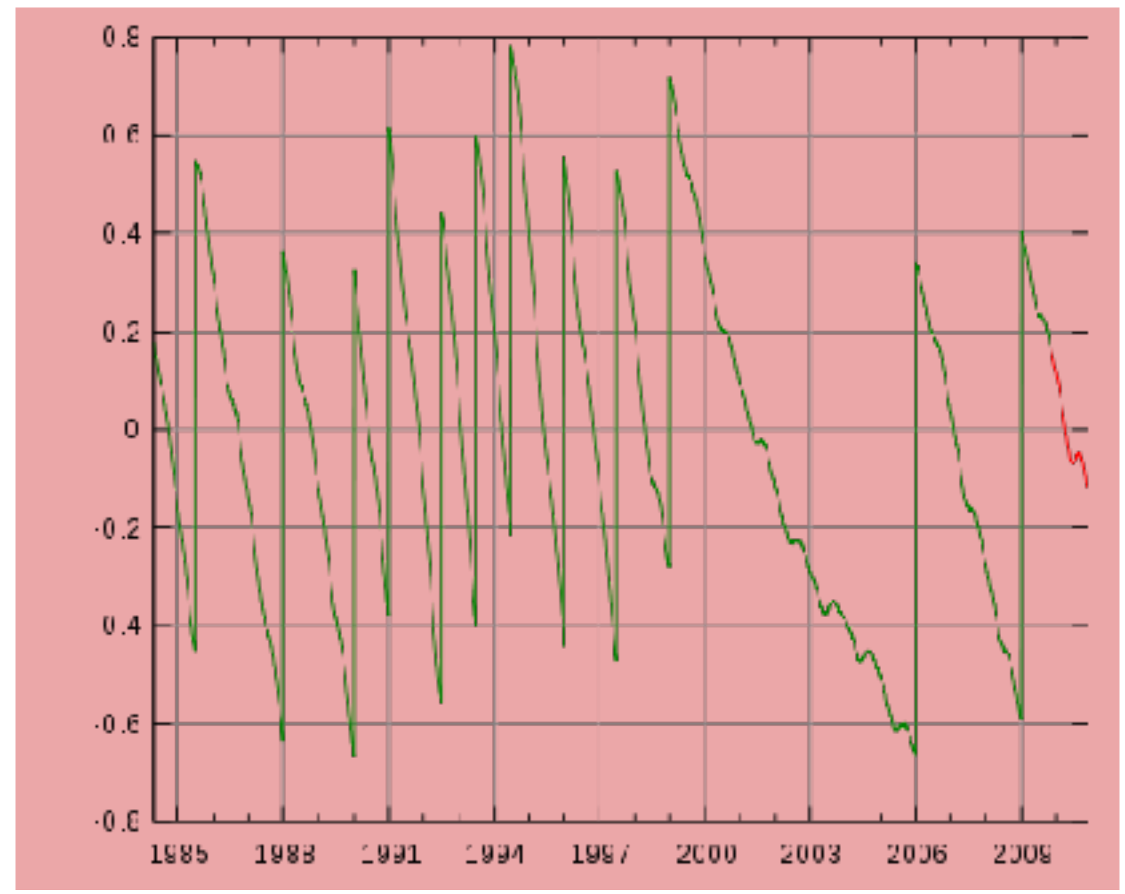
https://www.researchgate.net/publication/365611896_Cold_atoms_in_space_community_workshop_summary_and_proposed_road-map

Coordinated Universal Time: UTC

- TAI is, by definition, ***not*** tied to astronomical motions.
- ***Universal Coordinated Time (UTC):***
  - Time systems decoupled from astronomical motions (e.g. TAI) are less useful.
  - UTC is based on the atomic (SI) second, but occasionally adjusted by a ***leap second*** to maintain it within 0.9 s of UT1.
- ***Universal Time (UT1):***
  - ***Duration interval:***
    - Uses Earth's spin as the clock, i.e. second is variable. [Earth rotation]
  - ***Zero:***
    - Adjusted to track mean solar time at Greenwich so that the mean sun* is on average on the meridian at noon at Greenwich.
    - *Ephemeris for the fictitious mean sun was defined by Newcomb (1898):
      - RA(mean sun) = f(t), plus later innovations

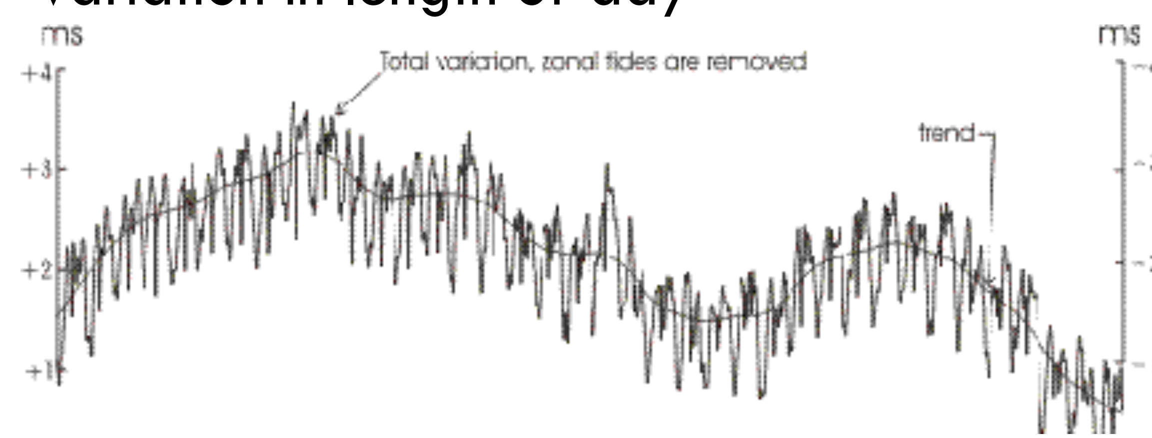
Time systems have an ***interval duration*** (e.g. day or second) and the ***epoch or zero point*** of the time system.

UT1-UTC



(CC)

Variation in length of day



(www.iers.org)

Distributing UTC

- Quartz oscillators are common secondary time standards.
- UTC distribution:

Method	Accuracy
Radio (WWV, WWVB) kHz-MHz	*1 ms*
Global Positioning Satellite	*10 ns*
Internet: Network Time Protocol	*1-50 ms*
Cell phone: CDMA	*1 ms*

(GPS; CC)

Julian date

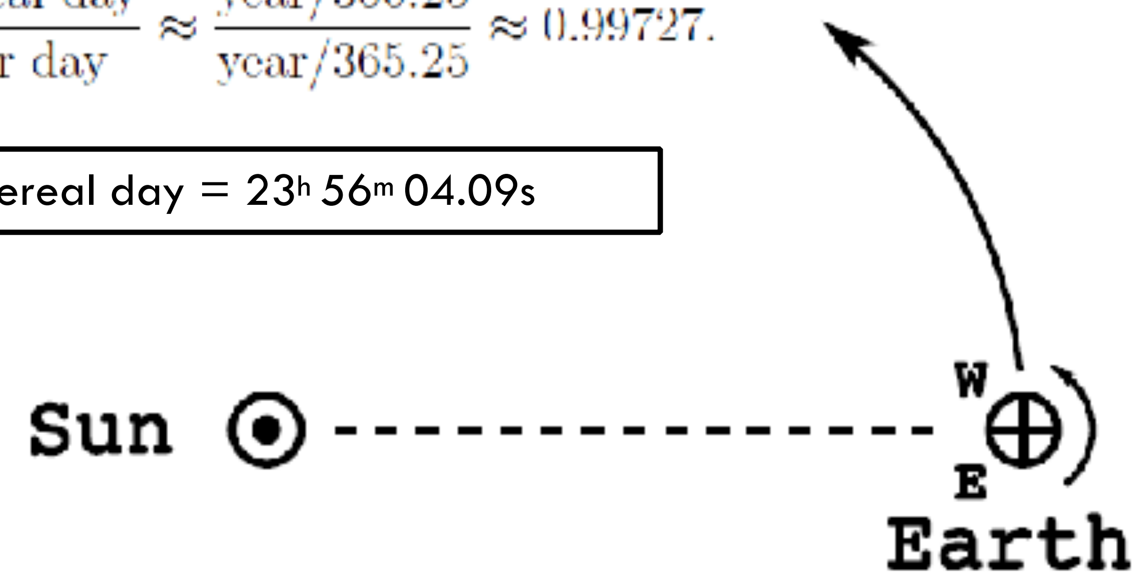
- ***Julian date:***
  - Defined in 1582 by Justus Scaliger
  - JD = 0.0 on Jan 1, 4713 BC
  - Beginning of each Julian date is noon at Greenwich, 12h UTC or 12h TT.
  - Julian day at noon on 2000 Jan 1: JD= 2,451,545.
  - Julian century is exactly 36,525 d
    - Gregorian century depends on number of leap years
  - Modified Julian day number:
    - MJD = JD – 2,400,000.5
  - Need to specify JD and MJD time system:
    - i.e. TT, TDB, and UTC.

Rotational time systems: sidereal time

- Sidereal and solar times differ by about 1 part in 365 (i.e. 4 min per day)
- An astronomical source will cross the local meridian ~4 min earlier (in local solar time) each day.

$$\frac{\text{sidereal day}}{\text{solar day}} \approx \frac{\text{year}/366.25}{\text{year}/365.25} \approx 0.99727.$$

1 sidereal day = $23^h\,56^m\,04.09s$

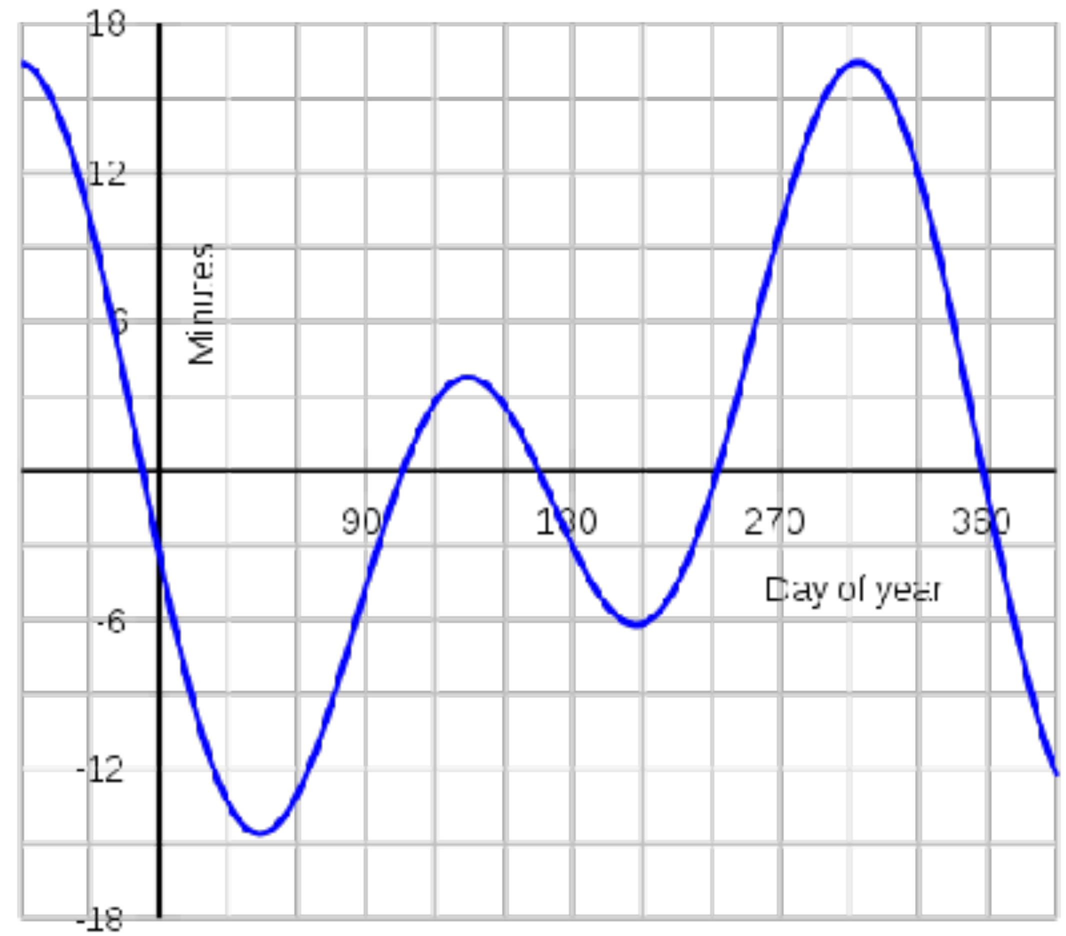


Changes of Celestial Coordinates

- The are several effects that cause the coordinates of a star to deviate from those given in star catalogs.
  - Precession
  - Nutation
  - Proper Motion
  - Parallax
  - Refraction
  - Aberration of light

Rotational time systems: solar time

- ***Solar time*** at a given time and place is:
  - The location of the observer's meridian with respect to the Sun.
- Solar time progresses at variable speed, due to the:
  - Earth's elliptical orbit around the Sun.
  - Earth's obliquity.
- ***Mean solar time*** averages out these differences by defining a fictitious ***mean sun***:
  - Difference between solar time and mean solar time is the ***equation of time.***
  - Can reach a peak of ~16 min.



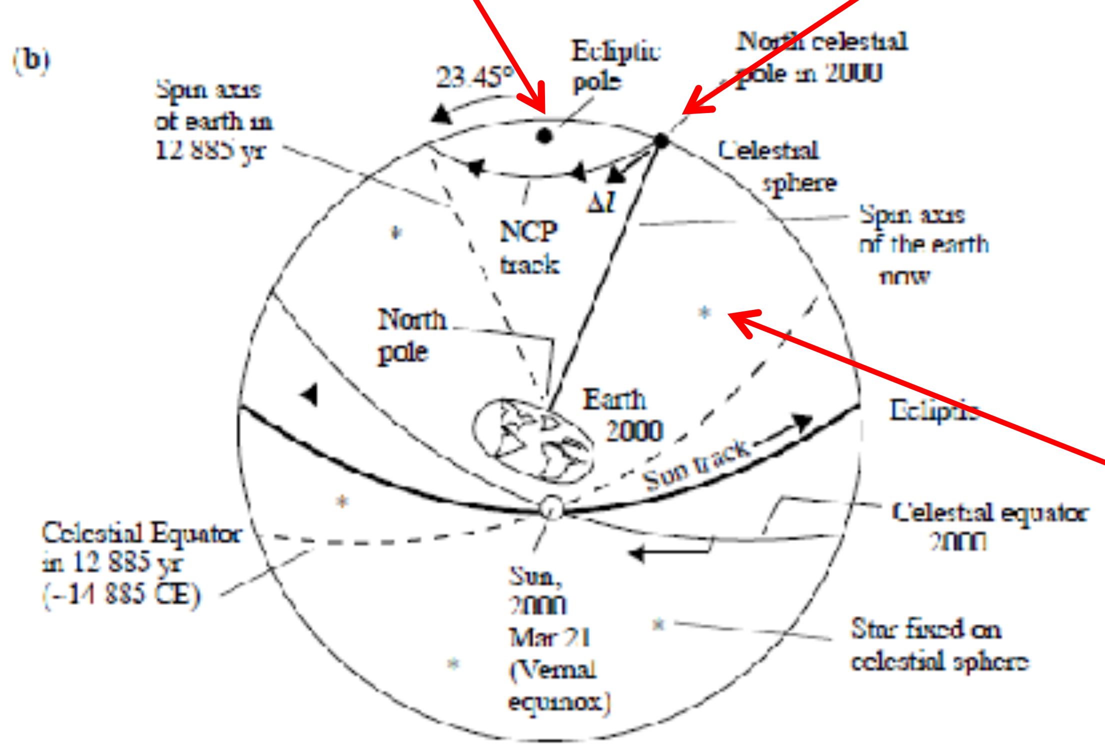
Residual motions of the celestial sphere

- ***Luni-solar precession:***
  - Long-term average or secular precession motion.
- ***Nutation:***
  - Short-term periodic oscillations about the mean secular motion.

Ecliptic pole rotates due to ***planetary precession.***

NCP rotates due to ***luni-solar precession*** and ***nutation.***

Star may move due to ***proper motion.***

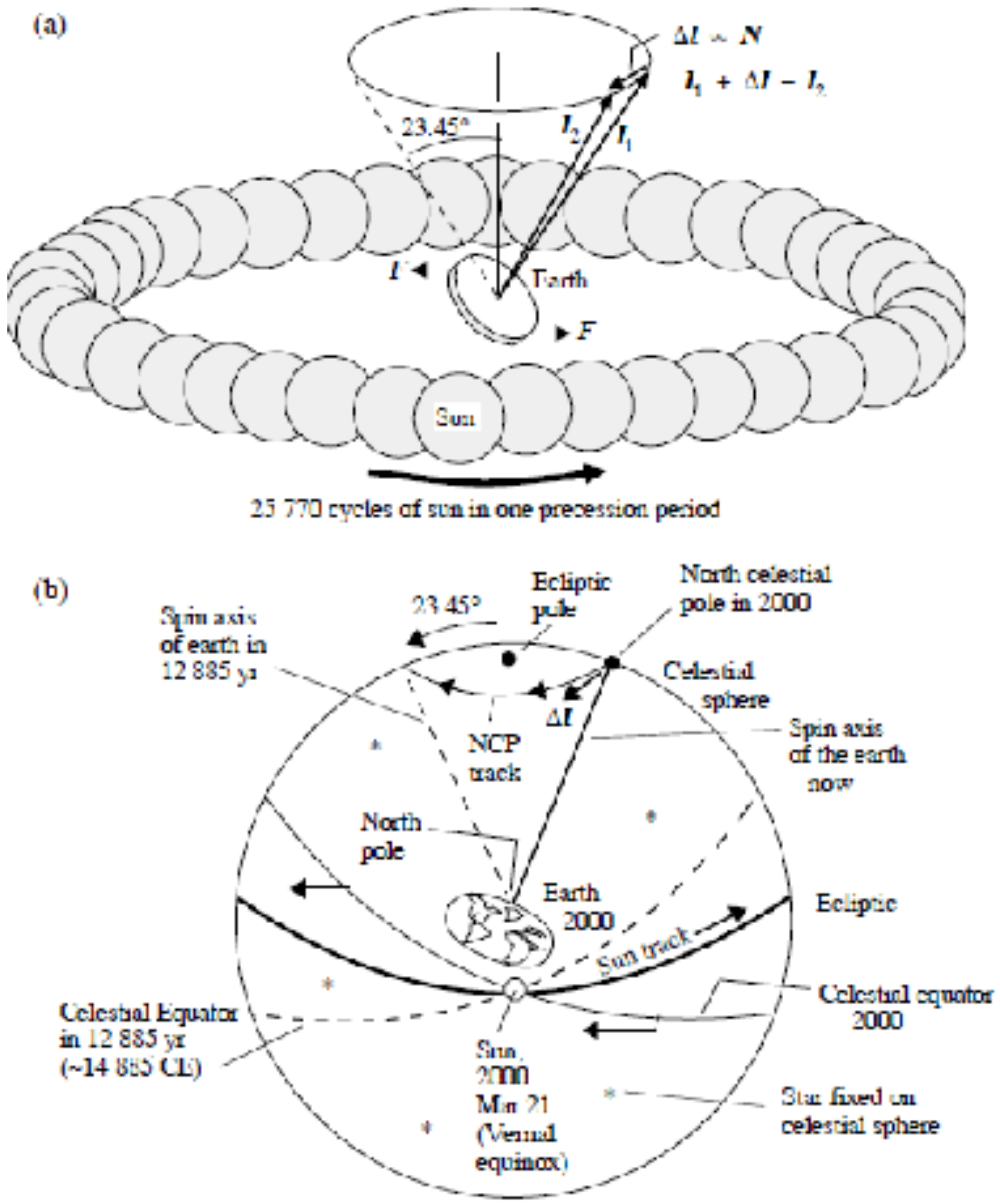


(Bradt 2004)

Equinox and epoch

- Equatorial coordinate system drifts over time due to precession of Earth's axis of rotation.
- Must specify an equinox/ epoch to define coordinate system orientation.
- **B1950.0** – Earth's orientation at 22h09 Universal Time on 31 Dec 1949, based on Besselian year.
- **J2000.0** – Earth's orientation near noon GMT on 1 Jan 2000, based on Julian year.

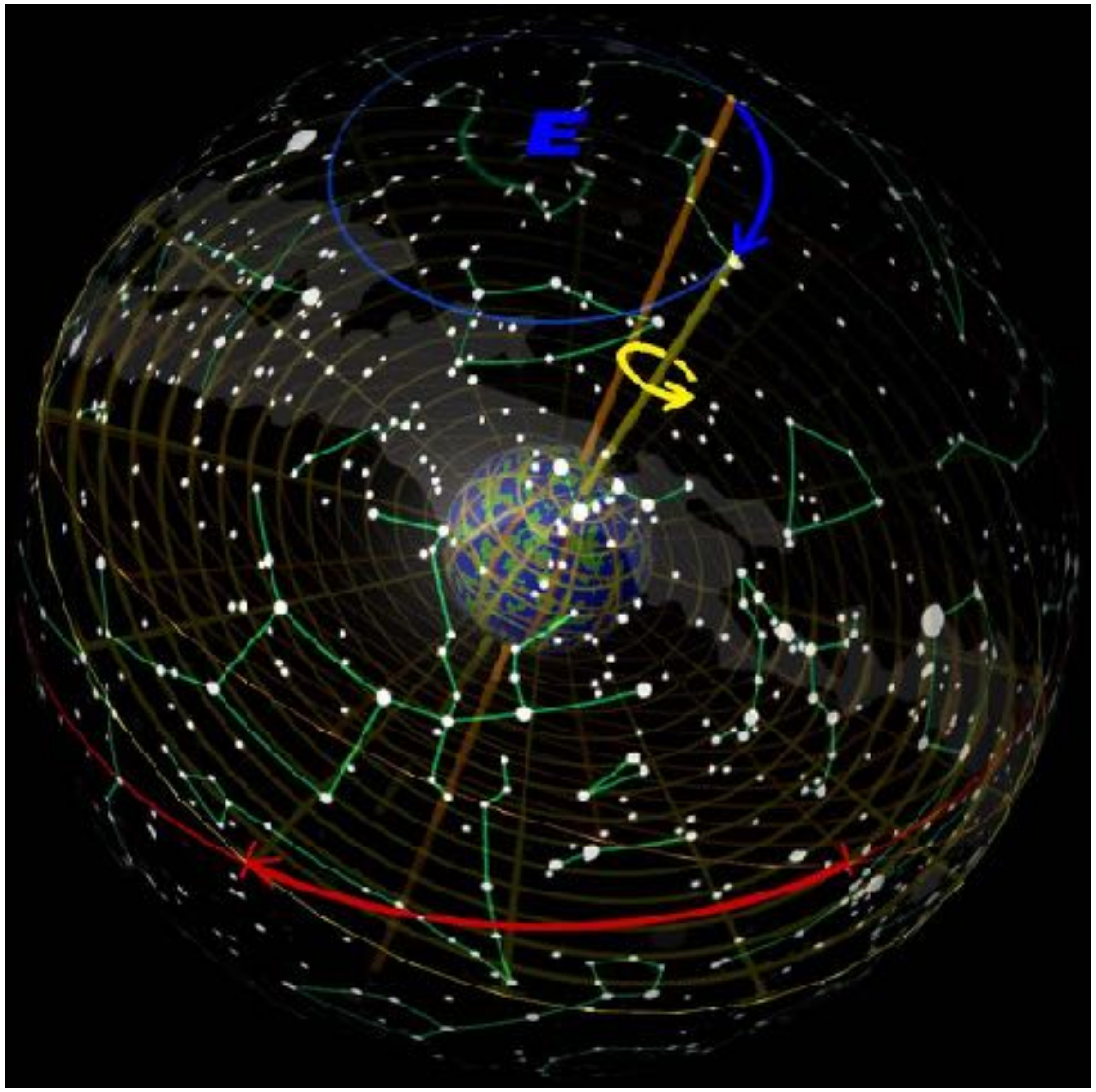
Fig. 4.4 Precession of the Earth



(Bradt 2004)

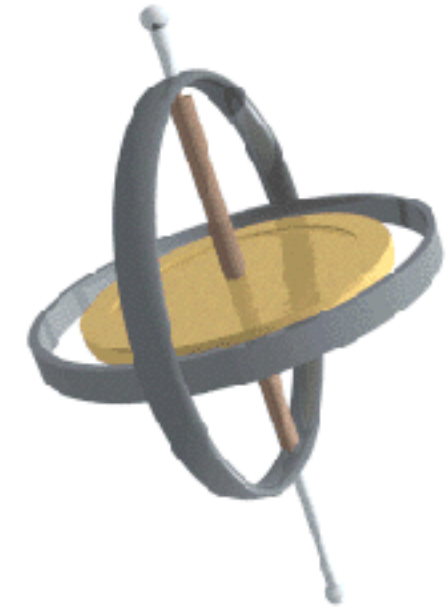
Precession

- Earth is oblate.
- Sun, Moon, and planets exert a torque ***N*** on the Earth.
- Resulting precession of spin axis of Earth around ecliptic pole.
- Period ~ 25,770 yr



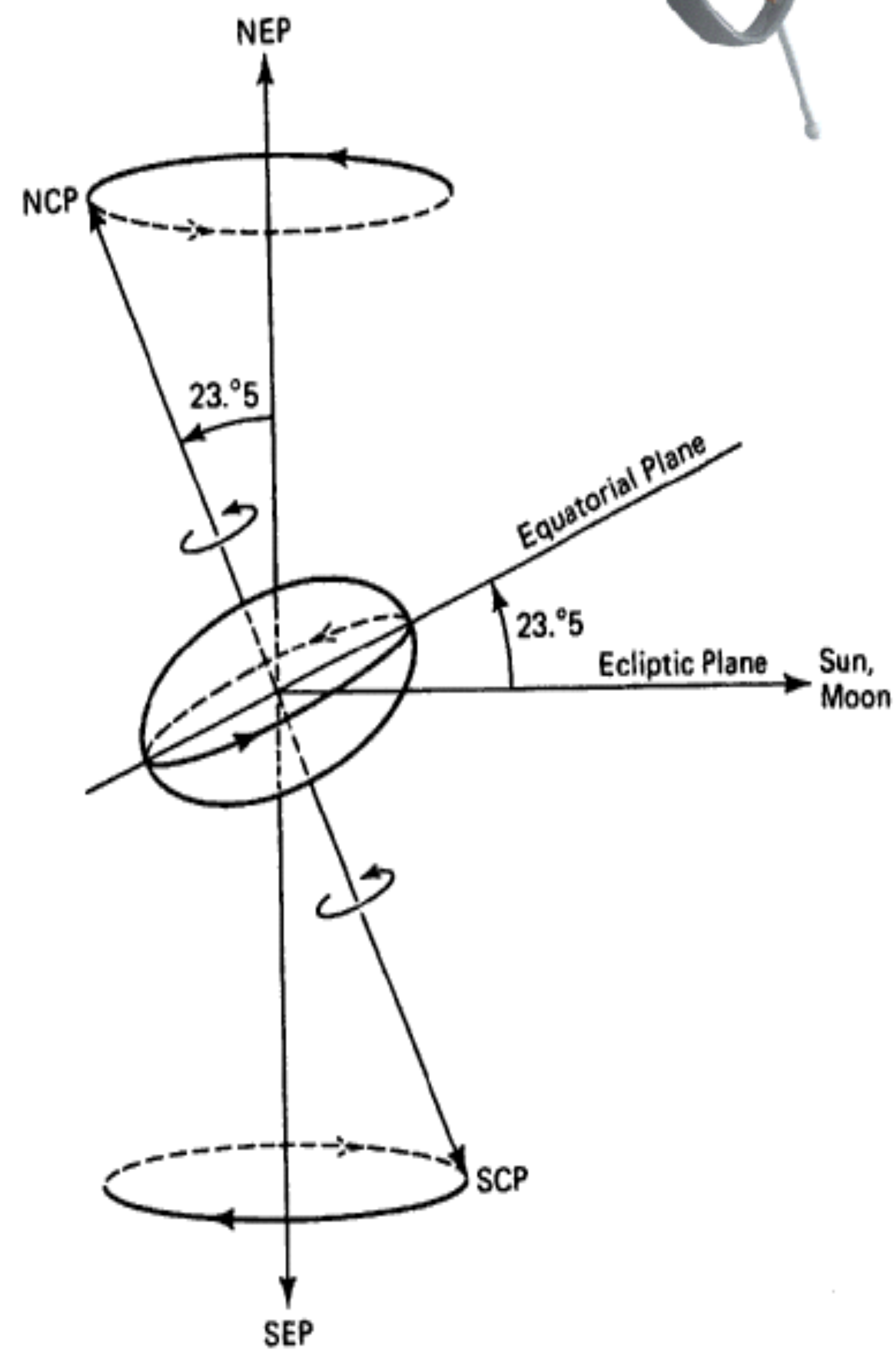
(CC: Tau'olunga)

Earth's Axial Precession



The Earth's axis is not fixed in space, but like a spinning top, the direction of the rotation axis executes a slow precession with a period of 26,000 years.

Cause: the Moon and the Sun exert tidal forces on the equatorial bulge of the Earth, and there are small effects from the rest of the planets in the solar system. This complex set of forces causes the rotational axis to gyrate, or precess, about the orbital axis. -> North and South Celestial Poles to circle around the Ecliptic Poles.



Carte du Ciel data acquisition

data reduction

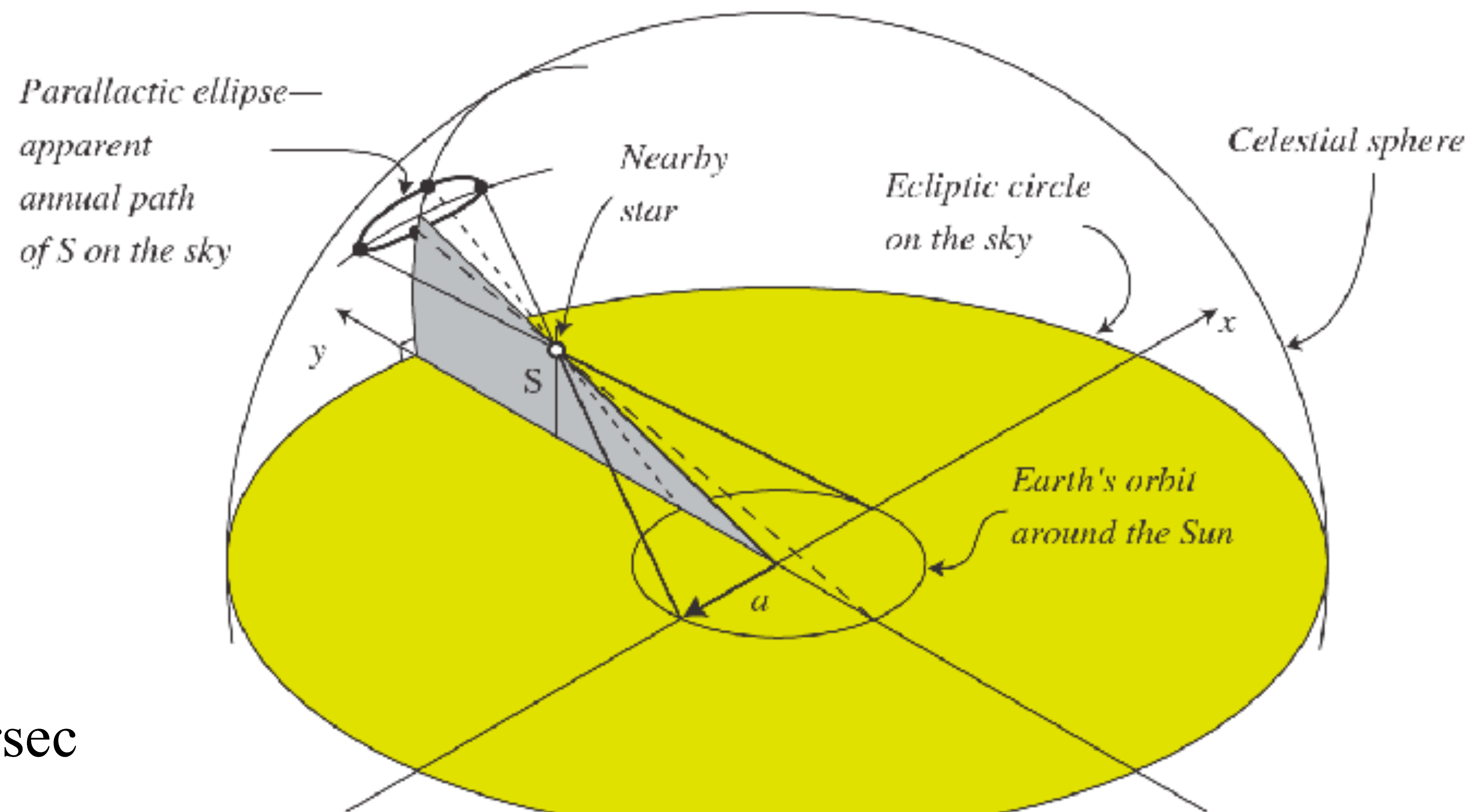
Annual parallax

Distance: d

Radius of Earth's orbit: a

$a = 1.496 \times 10^{11}$ m (1 AU)

Parallax angle: θ_{par}



$$\tan\theta_{par} = \frac{a}{d}$$

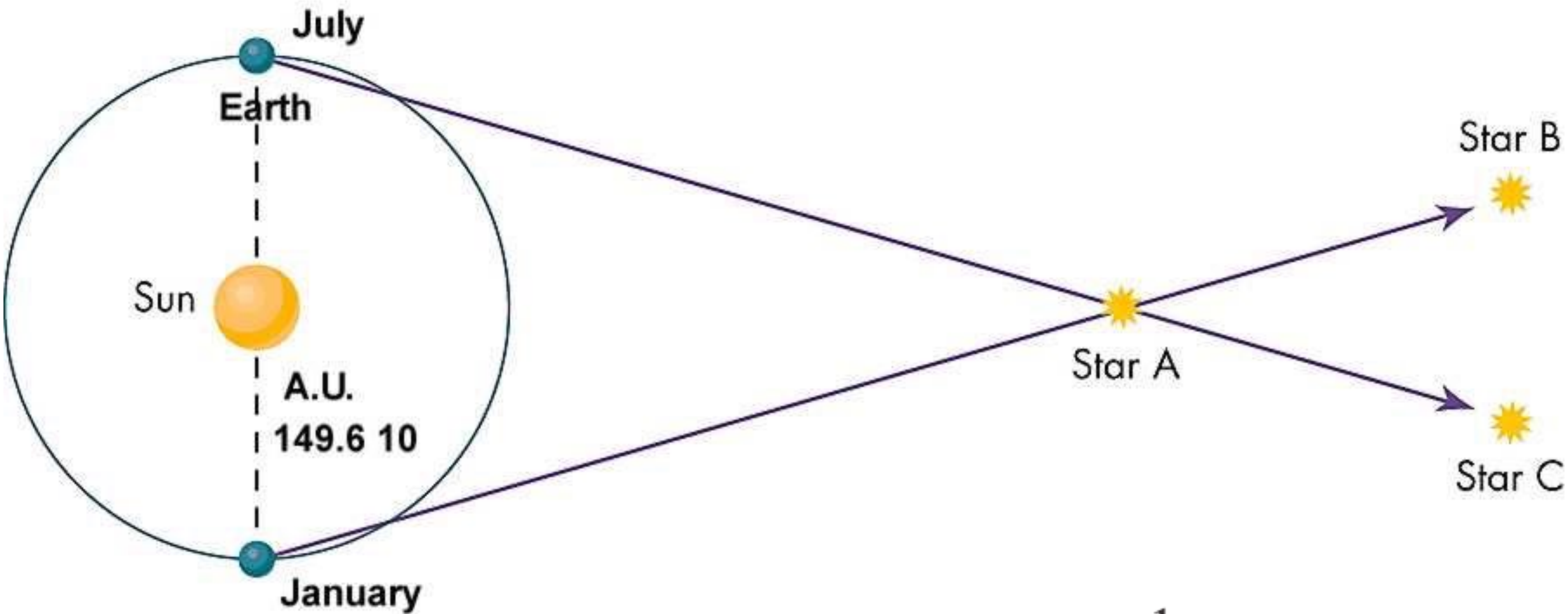
$$\theta_{par} \approx \frac{a}{d}, \text{ for } \theta_{par} \ll 1 \text{ rad}$$

For θ_{par} in arcsec, d in parsec

(1pc = 206,265 AU)

$$p[\text{arcsec}] = \frac{a[\text{au}]}{r[\text{pc}]} \qquad p[\text{arcsec}] = \frac{1}{r[\text{pc}]}$$

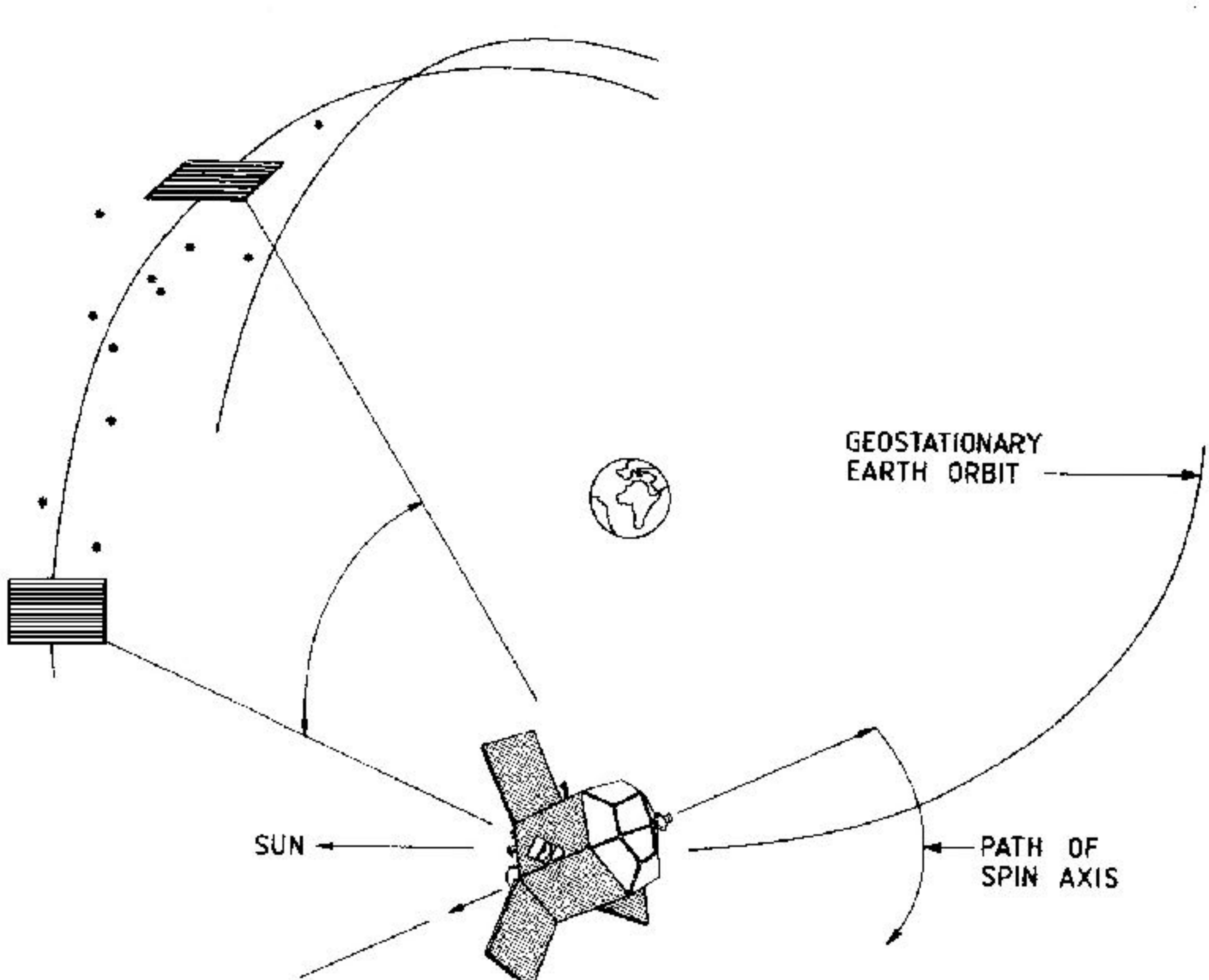
Annual parallax



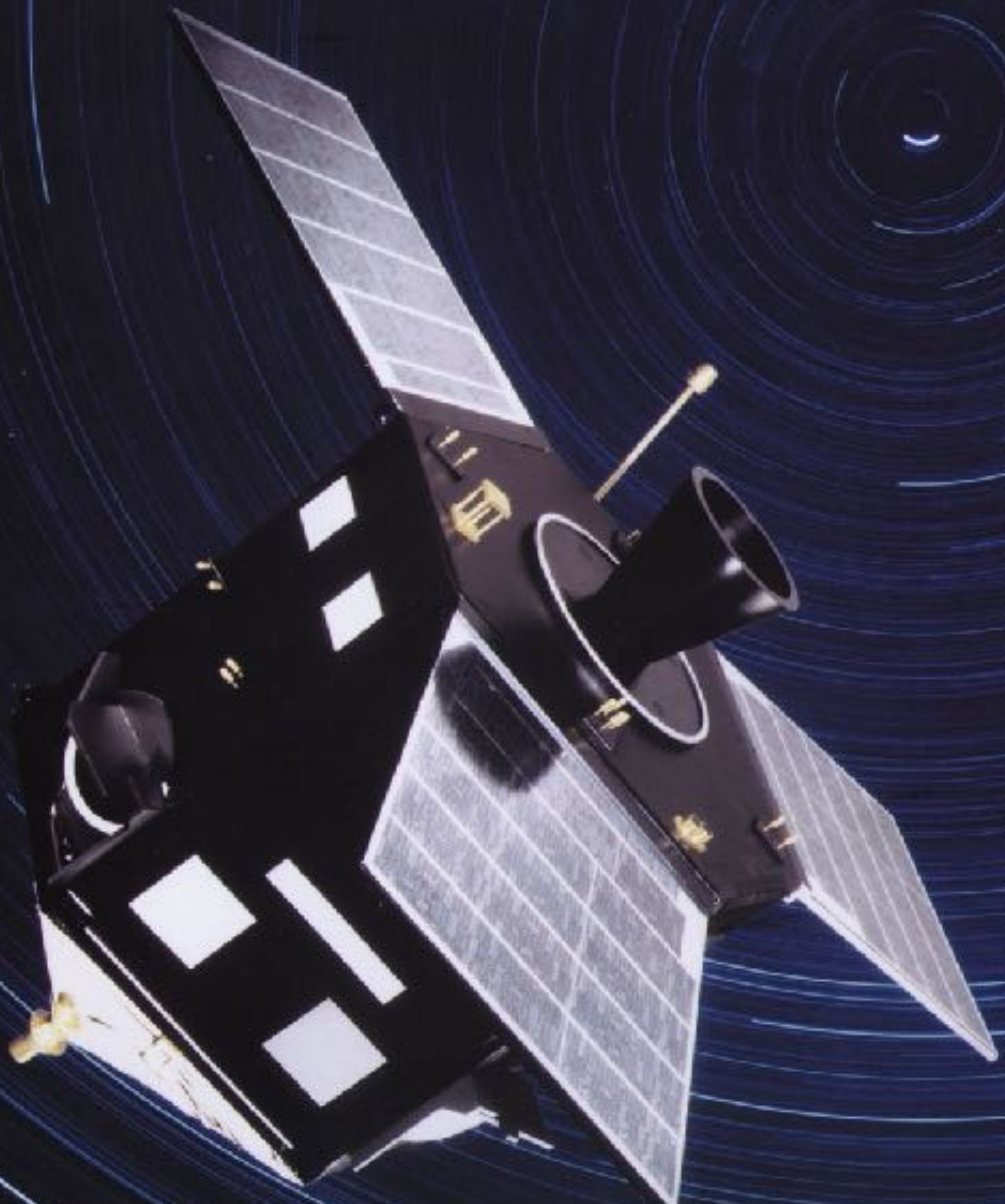
$$p[\mathrm{arcsec}] = \frac{1}{r[\mathrm{pc}]}$$

1 pc = 3.26 ly

A big advance required a new approach - Hipparcos. The satellite spun (2 hours for the entire sky) and its telescope compared two directions separated by about 50 degrees.



HiPParCoS
ESA
1989–1993

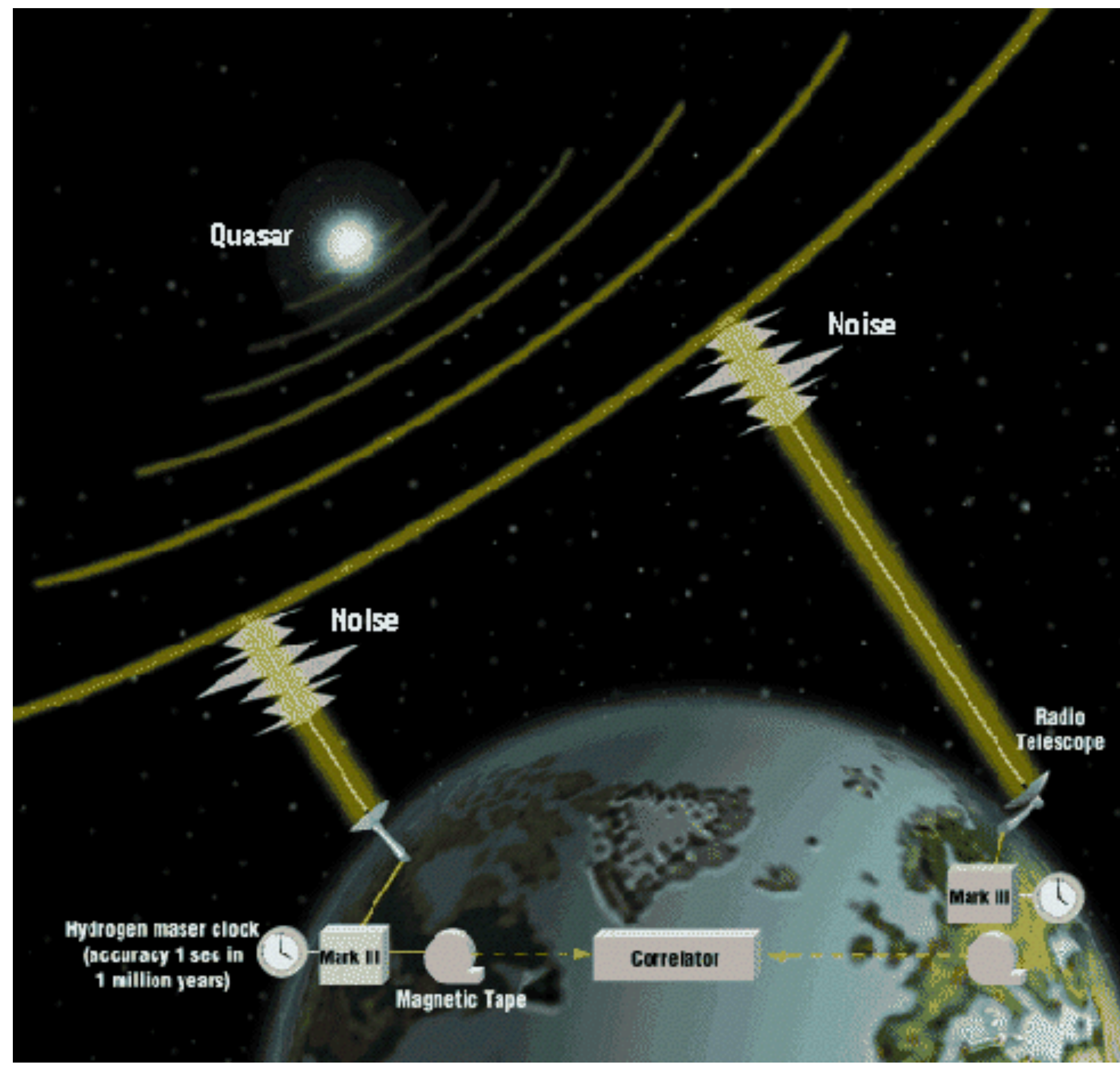


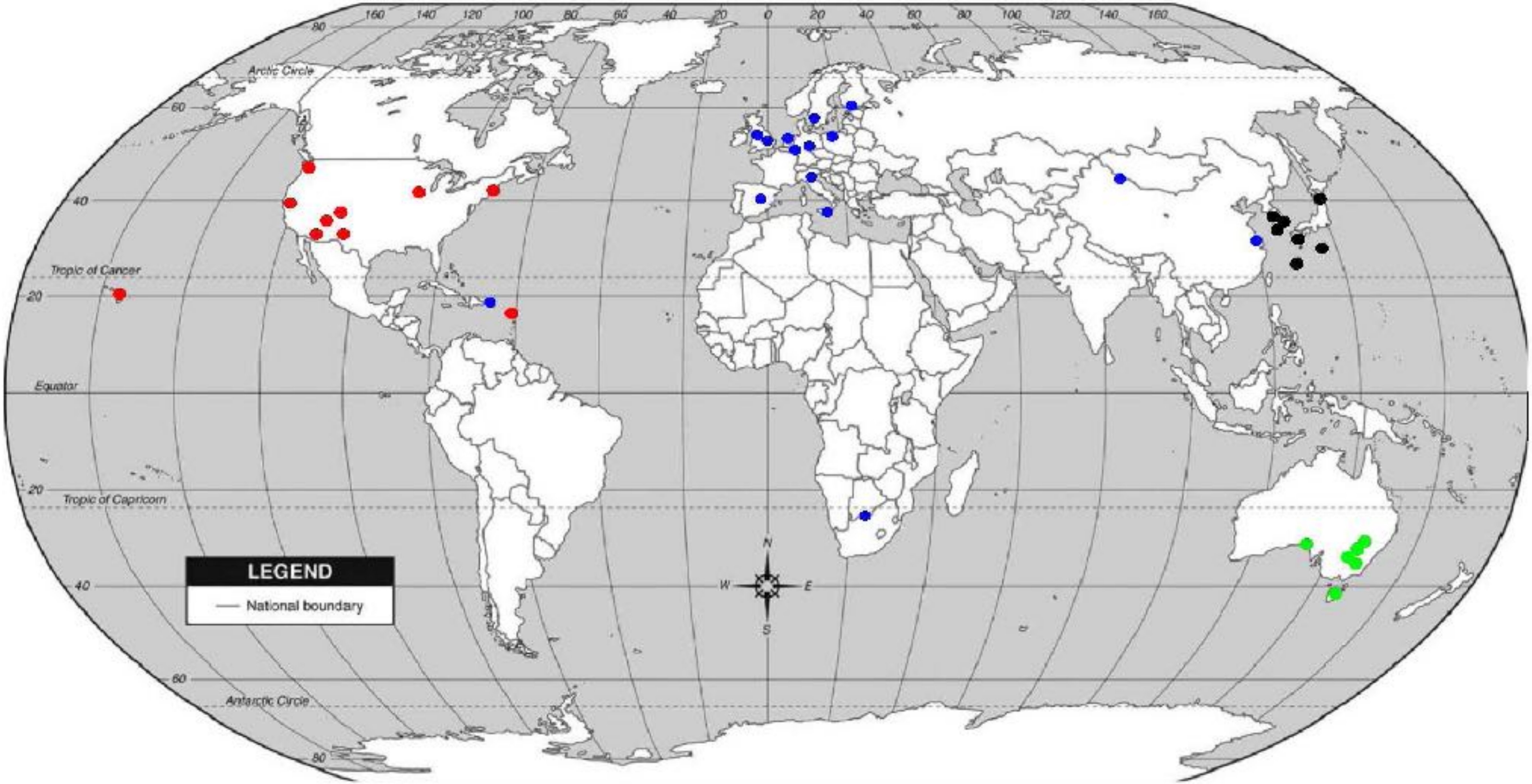
- **Hi**gh **P**recision **Par**allax **Co**llecting **S**atellite
- First space mission devoted to astrometry
- improved astrometric and parallax measurements by x10
- ~3 mas accuracy
- Could only measure parallax up to 1,600 light years away, or only ~ 1% of the diameter of the Milky Way.
- Measured astrometry for ~100,000 stars.

VLBI is a geometric astrometrical technique

VLBI measures the time difference between the arrival at two Earth-based antennas of a radio wave-front emitted by a distant quasar (or other source). Using large numbers of time difference measurements from many quasars observed with a global network of antennas, VLBI determines the inertial reference frame defined by the quasars and simultaneously the precise positions of the antennas.

Because the time difference measurements are precise to a few picoseconds, VLBI determines the relative positions of the antennas to a few millimeters and the quasar positions to fractions of a milliarcsecond.

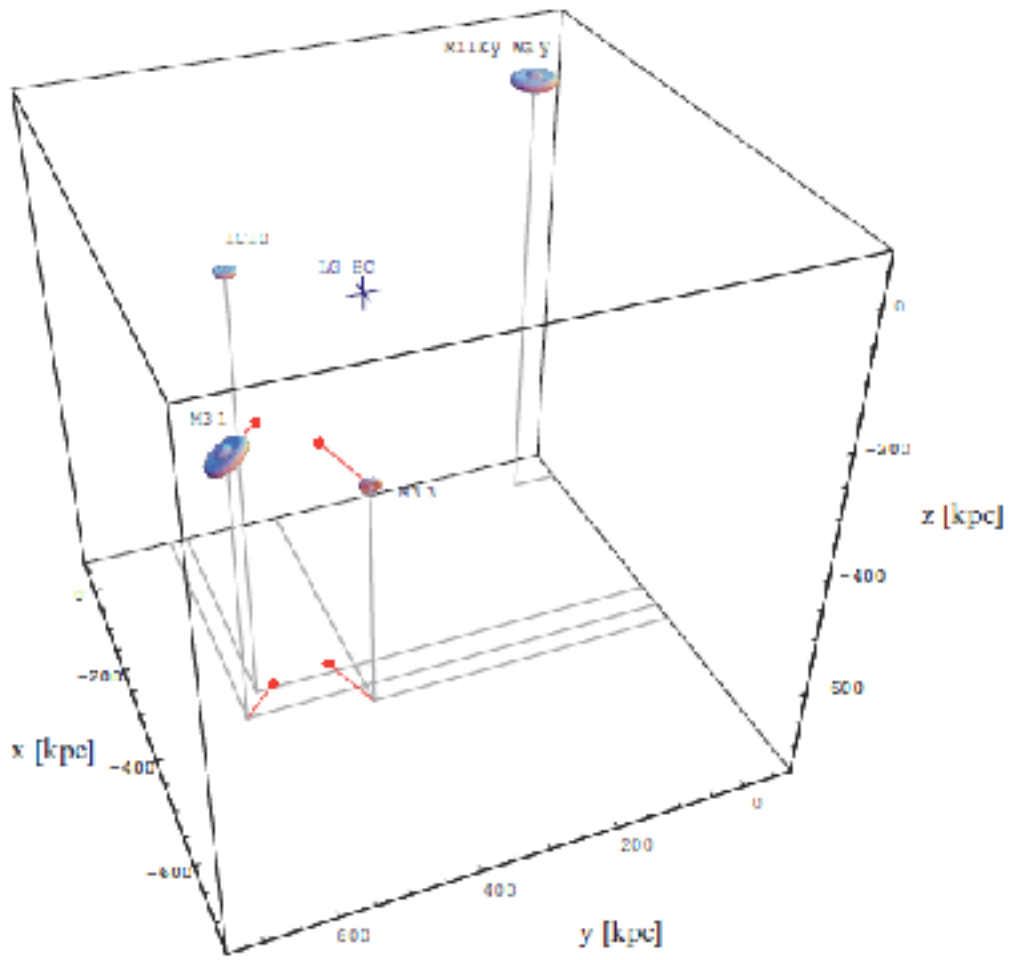




160
140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
160
80
Arctic Circle
60
40
Tropic of Cancer
20
Equator
20
Tropic of Capricorn
40
60
Antarctic Circle
80
LEGEND
National boundary
N
S
W
E

State of the art astrometry

- Leading-edge science: microarcsecond astronometry of the local group of galaxies using VLBI.

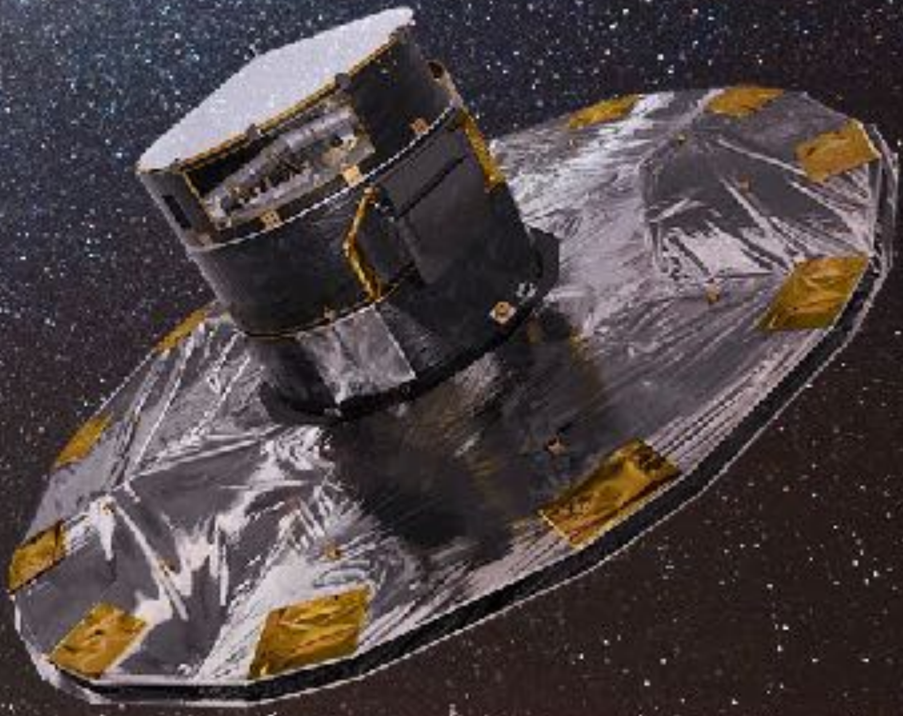


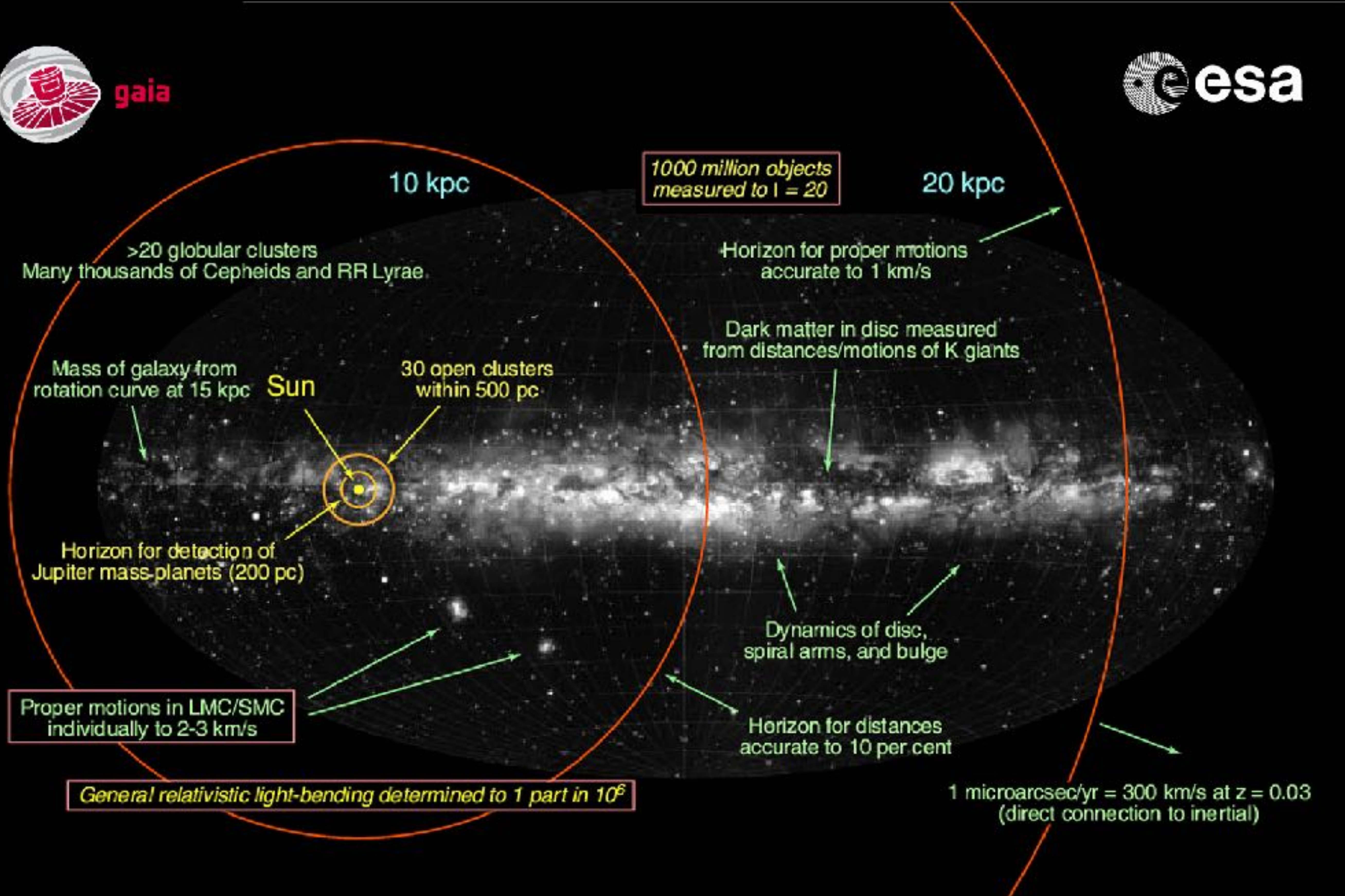
Brunthaler et al. (2005)

(NRAO)

Gaia

- ESA GAIA Satellite Launched in 2013
- Successor to HiPParCoS
- Astrometric precision of 20—200 μas (~x100 better than HiPParCoS)
- Covers the full sky 70 times over 5 years
- Will measure parallaxes for 1 billion stars — ~1% of the stars in our Milky Way Galaxy
- 1B pixel CCD observing at 400-1000 nm — largest ever in space
- Will detect 500,000 quasars (x5 of SDSS)
- Will find thousands of massive exoplanets




gaia
esa
1000 million objects measured to I = 20
10 kpc
20 kpc
>20 globular clusters
Many thousands of Cepheids and RR Lyrae
Horizon for proper motions accurate to 1 km/s
Dark matter in disc measured from distances/motions of K giants
Mass of galaxy from rotation curve at 15 kpc
Sun
30 open clusters within 500 pc
Horizon for detection of Jupiter mass planets (200 pc)
Dynamics of disc, spiral arms, and bulge
Proper motions in LMC/SMC individually to 2-3 km/s
Horizon for distances accurate to 10 per cent
General relativistic light-bending determined to 1 part in 10^6
1 microarcsec/yr = 300 km/s at z = 0.03 (direct connection to inertial)

Gaia's payload consists of a single integrated instrument that comprises 3 major functions:

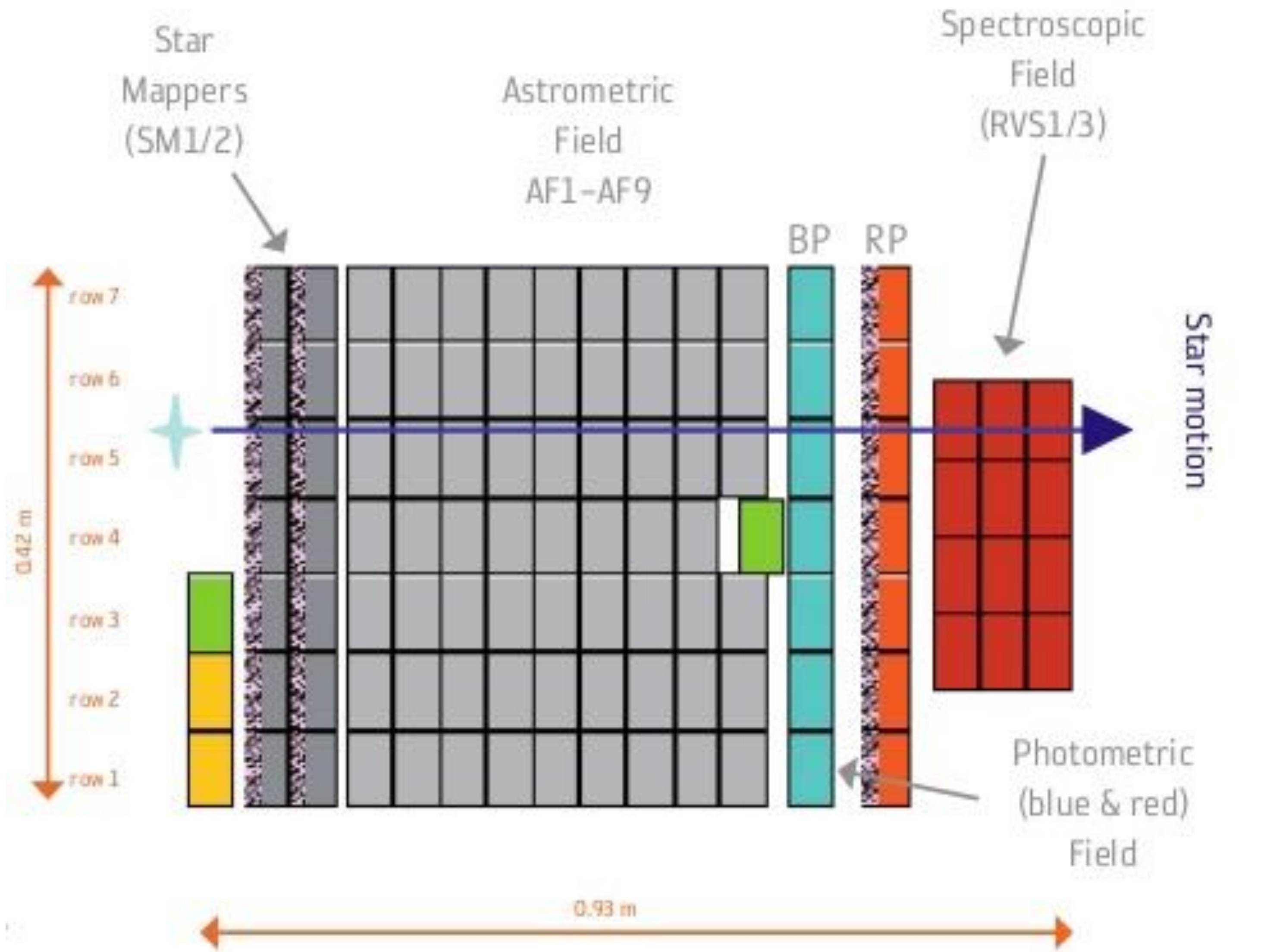
1.The Astrometric instrument is devoted to star angular position measurements, providing

Star position
Proper motion
Parallax (distance)

2. The Photometric instrument provides continuous star spectra in the band 320-1000 nm

3. The Radial Velocity Spectrometer (RVS) provides radial velocity and high resolution spectral data in the narrow band 847-874 nm

CCD Focal Plane: 106 CCDS



•4 CCDs: Metrology & Alignment (Green: wave front sensors, Yellow: basic angle monitoring)

•14 CCDs: Initial Star Detection (Strips SM1 & SM2)

•62 CCDs: Astrometric Field (AF1-AF9) used for precise position measurements

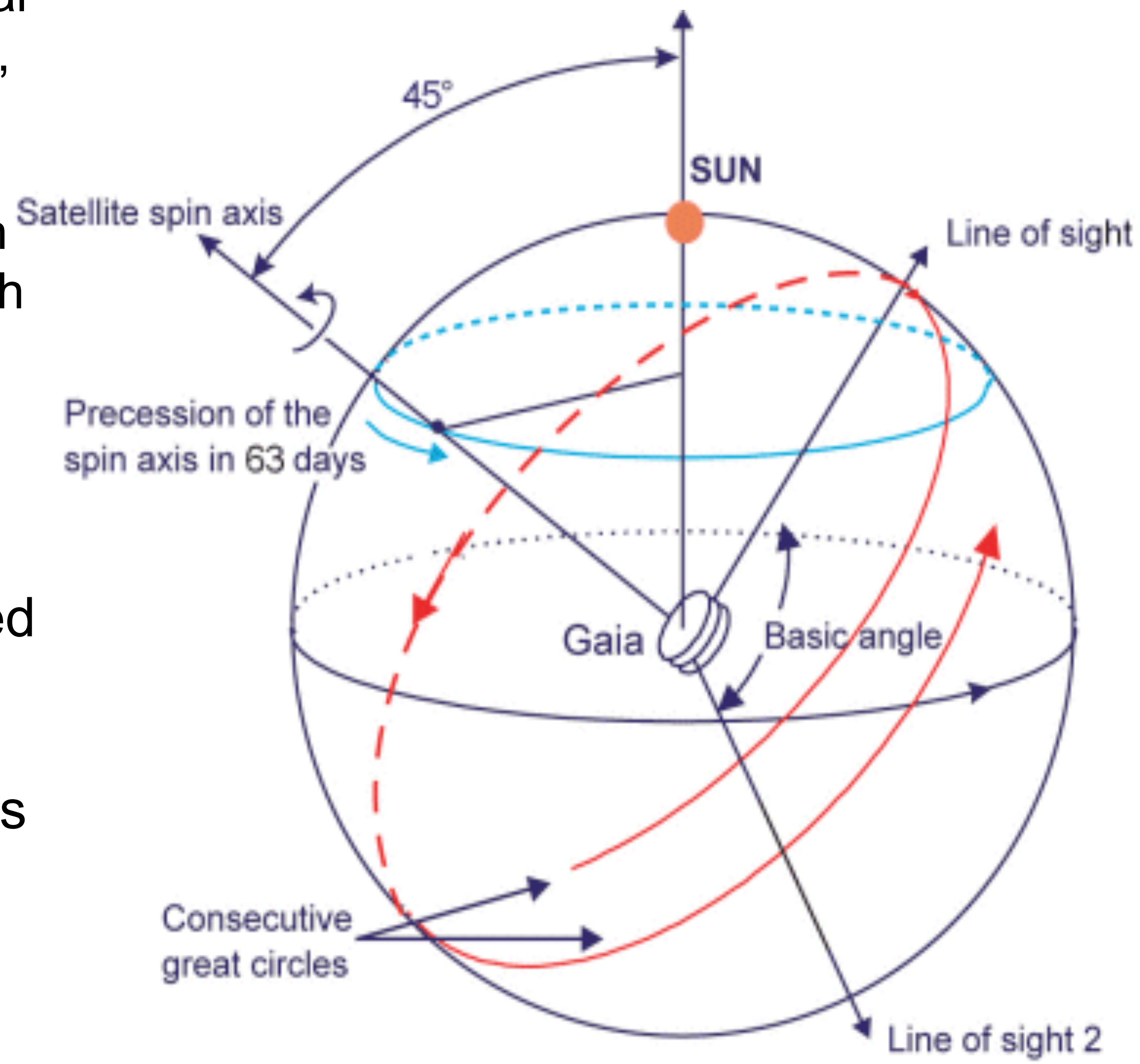
•14 CCDs: Photometry, 7 Blue CCDs (BP) spectral measurements in 330- 680 nm & 7 Red CCDs (RP) spectral measurements in 640-1000 nm.

•12 CCDs: Spectroscopy (RVS1-RVS3) 847-874 nm

GAIA's Observing strategy

Gaia's measurement principle relies on the systematic and repeating observation of the star positions in two fields of view. For this purpose, the spacecraft is slowly rotating at a constant angular rate of 1° per minute around an axis perpendicular to those two fields of view, which thus describe a circle in the sky in 6 hours. With a basic angle of 106.5° separating the astrometric fields of view, objects transit in the second field of view 106.5 minutes after crossing the first one.

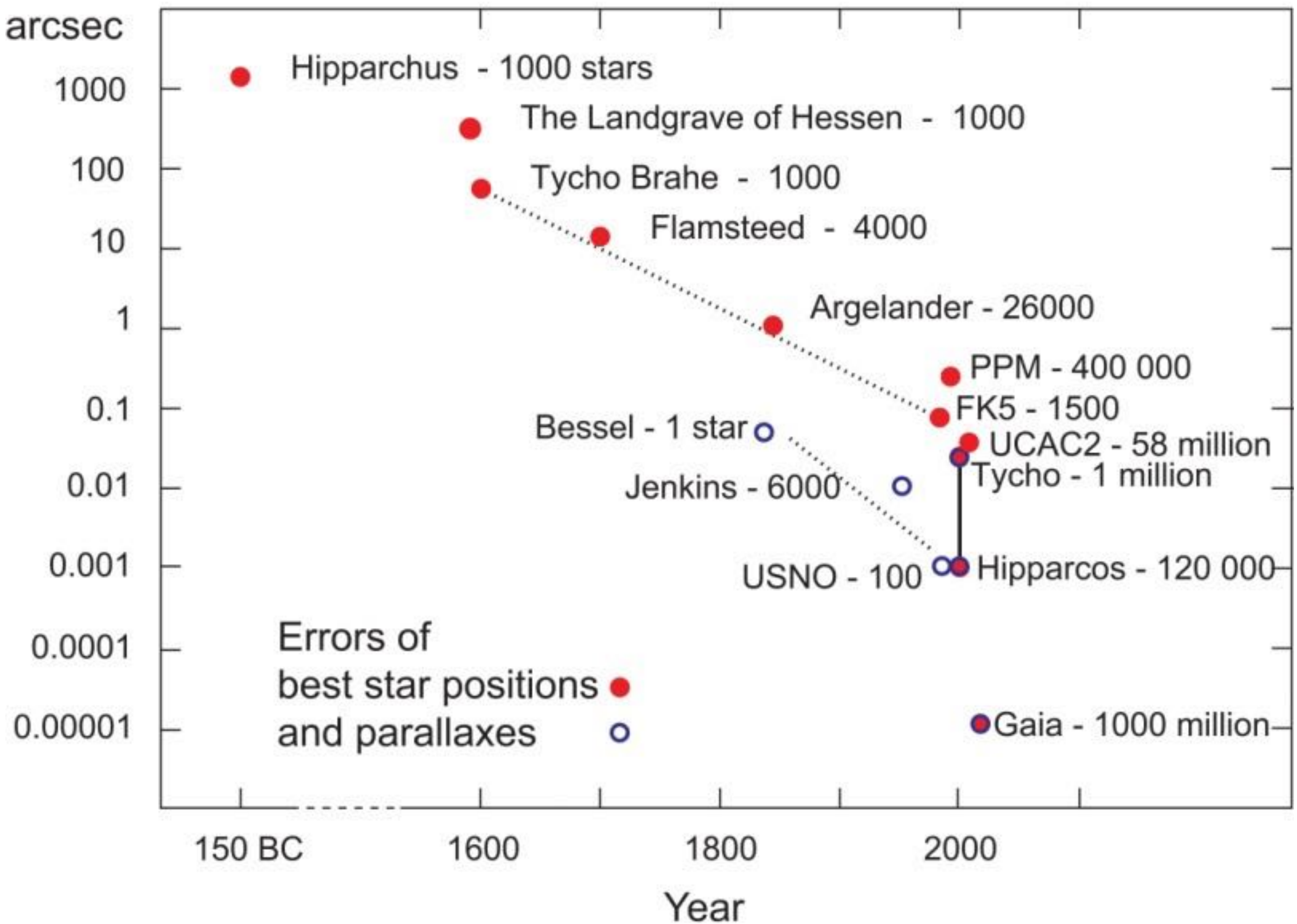
The orientation of the spin axis is modulated by a slow precession around the Sun-to-Earth line with a period of 63.12 days than enables the observation of about 70 transits of the 1 billion stars.



Gaia: Complete, Faint, Accurate

	Hipparcos	Gaia
Magnitude limit	12	20 mag
Completeness	7.3 – 9.0	20 mag
Bright limit	0	6 mag
Number of objects	120 000	26 million to V = 15 250 million to V = 18 1000 million to V = 20
Effective distance	1 kpc	50 kpc
Quasars	1 (3C 273)	500,000
Galaxies	None	1,000,000
Accuracy	1 milliarcsec	7 μarcsec at V = 10 10 – 25 μarcsec at V = 15 300 μarcsec at V = 20
Photometry	2-colour (B and V)	Low-res. spectra to V = 20
Radial velocity	None	15 km/s to V = 16-17
Observing	Pre-selected	Complete and unbiased

Astrometry over time



Reference Frames

The establishment of celestial reference frames is coordinated by the International Astronomical Union (IAU).

- Fifth Fundamental Catalog (FK5), J2000 (1988) (FK4 B1950, 1963)
  - A catalog of 1535 bright stars (to magnitude 7.5), supplemented by a fainter extension of 3117 additional stars (to magnitude 9.5)
  - Complied from meridian observations taken in the visual band
  - The catalogs list mostly nearby stars so any definition of coordinates tied to these catalogs is subject to errors due to motions of stars on the sky.
- Success of precise wide-angle astrometry with radio observations, using the techniques of Very Long Baseline Interferometry (VLBI) -> new system
  - Uncertainties in radio source positions listed in all-sky VLBI catalogs are typically less than 1 milliarcsecond (and often a factor to 10 better)
  - These radio sources are very distant extragalactic objects (mostly quasars) that are not expected to show measurable intrinsic motion.
  - VLBI observations revealed that models of the Earth's precession and nutation (that were part of the FK5 system) were inadequate for modern astrometric precision. (The "constant of precession" has been over-estimated by about 0.3 arc seconds per century)
  - Success of Hipparcos astrometric satellite (launch 1989) lead to a new set of very accurate star coordinates in the optical regime.

International Reference System (ICRS)

The ICRS is the fundamental celestial reference system adopted by the IAU in 1997.

•Axes are fixed with respect to a set extragalactic objects which are assumed to have no measurable proper motion.

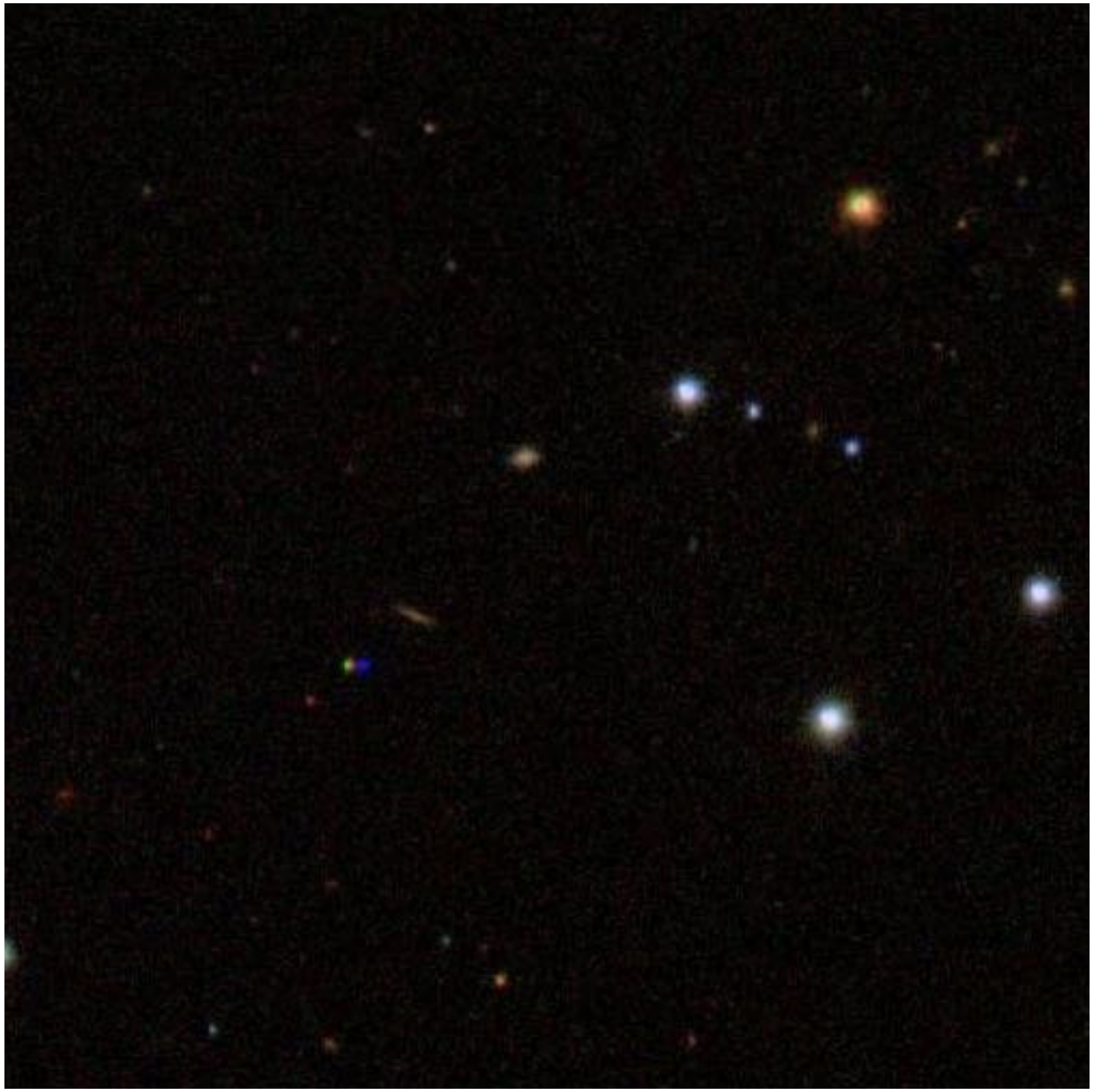
•The International Reference Frame (ICRF) is the realization of the ICRS

Based on radio positions of 608 extragalactic sources observed with the VLBI distributed over the entire sky.

- 212 of the 608 sources are defining sources that establish the orientation of the IRCS axes, with the origin at the solar system barycenter.
- The positional uncertainty of the defining sources are on the order of 0.5 milliarcsecond.
- The axes correspond closely to the “equator and equinox” of J2000.0
- The ICRS is realized at optical wavelengths by stars in the Hipparcos Catalog (118,218 stars, some as faint as 12). Only stars with well-determined proper motions are used for the ICRS realization (85%)

Finding charts

- Finding chart - an enlarged image of the sky region with the star of interest indicated.
  - Can generate from current digital surveys, e.g. SDSS
- Relative astrometry requires a dense distribution of cataloged astrometric reference objects.



(http://cas.sdss.org/astro/en/tools/chart/chart.asp)

Astrometric software: libraries

SuperNOVAS

SuperNOVAS C/C++ astrometry library

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

SuperNOVAS is a C/C++ astronomy software library, providing high-precision astrometry such as one might need for running an observatory or a precise planetarium program. It is a fork of the Naval Observatory Vector Astrometry Software (NOVAS) C version 3.1, providing bug fixes and making it safer and easier to use overall.

SuperNOVAS is entirely free to use without licensing restrictions. Its source code is compatible with the C90 standard, and hence should be suitable for old and new platforms alike. It is light-weight and easy to use, with full support for the IAU 2000/2006 standards for sub-microarcsecond position calculations.

SuperNOVAS is maintained by Attila Kovacs at the Center for Astrophysics | Harvard & Smithsonian, and it available via the Smithsonian/SuperNOVAS repository on GitHub.

Modern source naming conventions

- Syntax:

  <*catalog*> <*equinox*> <*ra*><*dec*>
- Examples:
  - XTE J1748-288
  - QSO B0957+561
- Note:
  - Declination is in fractional degrees if 3-digit format: 28.8

Name	Equinox	Right ascension	Declination	Catalog
0137+331	*J2000*	*01h37m41.299431s*	*33d09'35.132990"*	*3C48*
0134+329	*B1950*	*01h34m49.826400s*	*32d54'20.259000"*	
SDSS J123456.89-012345.6	*J2000*	*12h34m56.89s*	*-01d23'45.6"*	

Survey catalogs

Survey	Survey prefix
Messier (1781)	M
New General Catalog of Nebulae and Clusters of Stars (1888)	NGC
Index Catalog (1895,1908)	IC
Third and Fourth Cambridge Surveys (1959,1965)	3C, 4C
Parkes Observatory (1969)	PKS
Palomar Observatory Sky Survey (POSS) and Digitized Sky Survey (DSS) (1956, 1994)	
Two Micron All Sky Survey (1997-2001)	2MASS
Sloan Digital Sky Survey (2001-2011)	SDSS
+ many others …	

Reference Star Catalogs

http://tdc-www.harvard.edu/catalogs/

Star catalog contain a list of stars according to position and magnitude and in some cases other properties (e.g. proper motion, spectral type, and parallax).

- Hipparcos contains positions, proper motions, parallaxes, and B and V magnitudes for 118,218 stars. Complete to V = 7.3 Positional accuracy, 1-3 mas at epoch 1991.25. Proper motion accuracy around 1 to 2 mas/yr.
- UCAC2: (Preliminary catalog, 86% of sky, 48 million stars in the R = 8.0 to 16.0 magnitude range. Contains positions (20 to 70 mas) and proper motion (1 to 7 mas/yr)
- TYCHO-2 contains position, proper motions and two-color photometric data for 2,539,913 stars. The catalog is 99% complete to V = 11.0. Positional accuracies 10 to 100 mas and proper motions accuracies from 1 to 3 mas.
- USNO B 1.0 a catalog of over 1 billion objects. The Tycho-2 catalog is the astrometric reference. All-sky coverage down to V = 21, 200 mas accuracy at J2000, 0.3 magnitude photometric accuracy in up to five colors, and 85% accuracy for distinguishing stars from non-stellar objects.
- 2MASS- Two Micron All Sky Survey. Point source catalog contain 470 million objects, mostly stars. The extended source catalog contains data on 1.6 million objects. Observations on three photometric bands (JHK). The positions accuracy is about 70 mas. No proper motions.
- Sloan Digital Sky Survey (SDSS) – mapped one-quarter of the sky in 5 optical bandpasses, and obtained spectra of galaxies and quasars. The 6^{th} data release contains 287 million objects. (SDSS-I 2000-2005, SDSS-II 2005-2008) SDSS—III 2008-2014

https://www.stsci.edu/hst/instrumentation/reference-data-for-calibration-and-tools/astronomical-catalogs/calspec

Astrometry and your images

Few people want to deal with the details of positional astronomy, but many people want to know the precise position of objects they have observed.

There are many software tools to aid you in determining an astrometric solution for your data (IRAF, WCS tools, tools inPython).

But first we need discuss the world coordinate system and FITS images.

World Coordinate System and FITS

In the late 1970's astronomers developed, the Flexible Image Transport System, FITS, as an archive and interchange format for astronomical data files.

In the past decade FITS has also become the standard formats for on-line data that can be directly read and written by data analysis software.

FITS is much more than just an image format (such as JPG or GIF) and is primary designed to store scientific data sets consisting of multidimensional arrays and 2-dimensional tables containing rows and columns of data.

A FITS File

A FITS file consists of one or more Header + Data Units (HDUs), where the first HDU is called the "Primary Array".

- The primary array contains an N-dimensional array of pixels. This array can be a 1-D spectrum, a 2-D image or a 3-D data cube.
- Any number of additional HDUs, called "extensions", may follow the primary array.
- Every HDU consists of a ASCII formatted "Header Unit" followed by an optional "Data Unit". Each header unit consists of any number of 80-character records which have the general form :
  KEYNAME = value / comment string

The keyword names may be up to 8 characters long and can only contain upper-case letters, the digits 0-9, the hyphen, and the underscore character. The value of the keyword my be an integer, a floating point number, a character string, or a Boolean value (the letter T or F). There are many rules governing the exact format of keyword records so it usually best to rely on a standard interface software like CFITSIO, IRAF or the IDL astro library to correctly construct or parse the keyword records rather than directly reading or writing the raw FITS file.

World Coordinate System

There are a set of FITS conventions that have been defined to specify the physical, or world, coordinates to be attached to each pixel of an N-dimensional image. By world coordinates, one means coordinates that serve to locate a measurement in some multi-dimensional parameter space.

One common example is to link each pixel in an astronomical image to a specific equatorial coordinate (right ascension and declination).

In general the FITS world coordinate system (WCS) of an image is defined by keywords in the FITS header. The basic idea is that each axis of the image has the following keywords associated with it:

- CTYPE*i* Type of coordinate on Axis *i*, 8 characters(The FITS WCS standard defined 25 different projections which are specified by the CTYPE keyword.)
- CRPIX*i* Reference pixel on Axis *i*
- CRVAL*i* Value of World Coordinate at Axis *i* at reference point (CRPIX*i*)
- *Cd*i_j A Matrix of partial derivatives of the World Coordinates with respect to the pixel coordinates.

Old style:

- CDELT*i* coordinate increment on Axis i
- CROTA*i* rotation parameter for each Axis *i*

cd1_1 = crpix1 cos(crota2)
cd1_2 = crpix2 cos(crota2)
cd2_1 = -crpix1 cos(crota2)
cd2_2 = crpix2 cos(crota2)

FITS Header WCS Example for IRAC Mosaicked image

```
SIMPLE  =                    T / Fits standard
BITPIX  =                  -64 / Bits per pixel
NAXIS   =                    2 / Number of axes
NAXIS1  =                13600 / Axis length
NAXIS2  =                16700 / Axis length
EXTEND  =                    T / File may contain extensions
ORIGIN  = 'NOAO-IRAF FITS Image Kernel July 2003' / FITS file originator
DATE    = '2008-10-20T16:11:11' / Date FITS file was generated
IRAF-TLM= '13:21:02 (22/10/2008)' / Time of last modification
COMMENT   FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT   and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
CTYPE1  = 'RA---TAN'
CTYPE2  = 'DEC--TAN'
CRVAL1  =        217.812837962
CRVAL2  =         34.051007516
CDELT1  =         -0.000239631
CDELT2  =          0.000239631
CRPIX1  =                7105.
CRPIX2  =               8073.5
CROTA2  =                  0.0
PROGID  =                40839
BUNIT   = 'MJy/sr  '
ZEROPT  =               17.997
HISTORY = 'BCD 16.1.0,17.0.4'
HISTORY = 'IRACproc-4.1.2; Schuster et al 2006, SPIE, 6270, 65'
HISTORY = 'Montage-v3.0'
HISTORY = 'Processed for the Spitzer Deep-Wide Field Survey team'
HISTORY = 'SDWFS, at the Harvard-Smithsonian Center for Astrophysics'
HISTORY = 'by MLN Ashby, 2008 October 22.  Version 3.2'
END
```

Xi = cdelt1* (x-crpix1) * cos(crota2) – cdelt2 * (y-crpix2) * sin(crota2)
Eta = cdelt1*(x-crpix1) * sin(crota2) + cdelt2 * (y-crpix2) * cos(crota2)

Or

Xi = cd1_1*(x-crpix1) + cd1_2*(y-crpix2)
Eta = cd2_1*(x-crpix1) + cd2_2*(y-crpix2)

Then:

α = tan projection (xi,eta)
δ = tan projection (xi,eta)

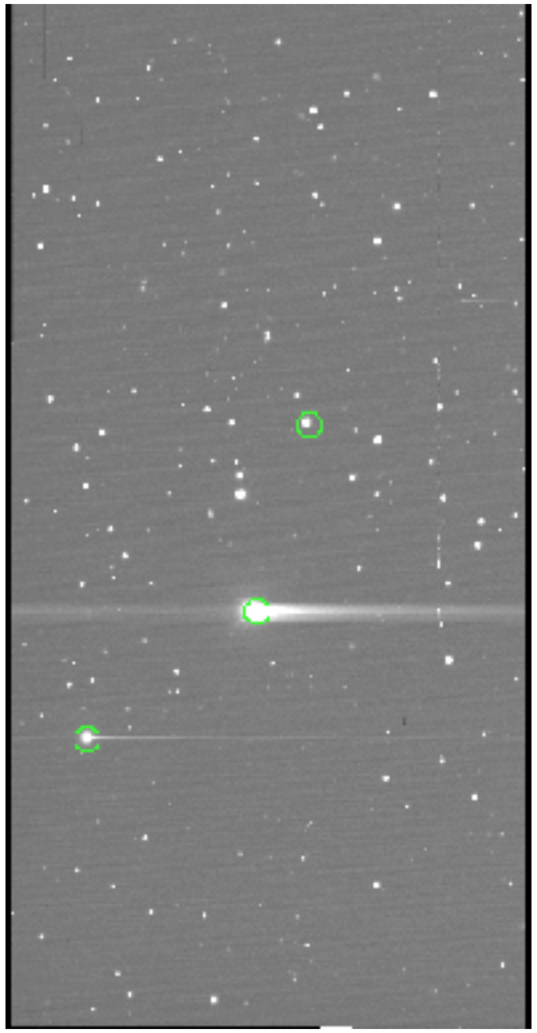
Practical Usage of the FITS/WCS- matching your data to a reference catalog

There are a number of software packages that aid the astronomer in reading, using, or modifying the astrometric information found WCS parameters of the image header. A few of the most commonly used packages are IRAF, WCStools, WCSLIB, and packages in the astronomy IDL library.

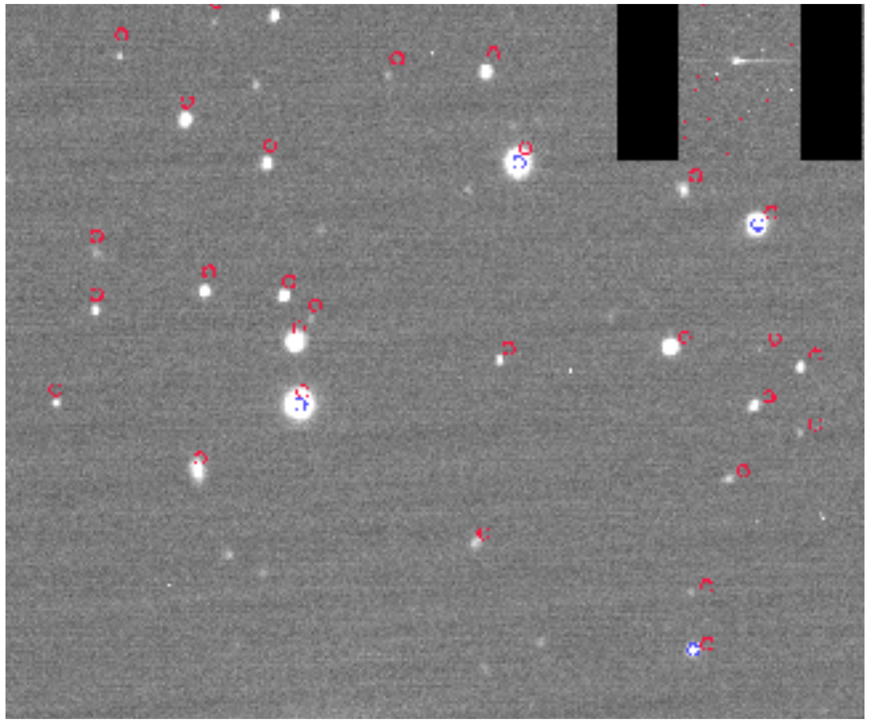
If an adequate WCS does not exist for an image the basic steps are:

1. Read in the FITS image and its header
2. Read in a reference catalog (selecting appropriate parameters)
3. Match the reference stars to the image stars – producing a matched reference catalog, pixel values, α, δ
4. Using one of the above WCS software packages perform a fit between the matched star's pixel and α, δ . (The fit can account for various types of distortions on the image, coma, differential astronomical refraction, and telescope flexure). Write the resulting WCS information to the header.
5. Check the result and perform steps 3 and 4 until satisfied

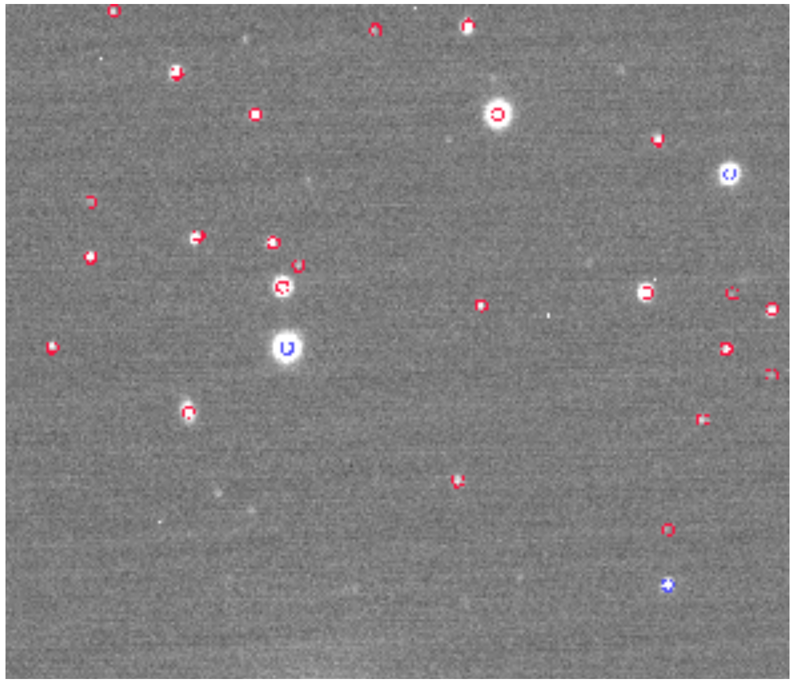
Example of Creating a WCS



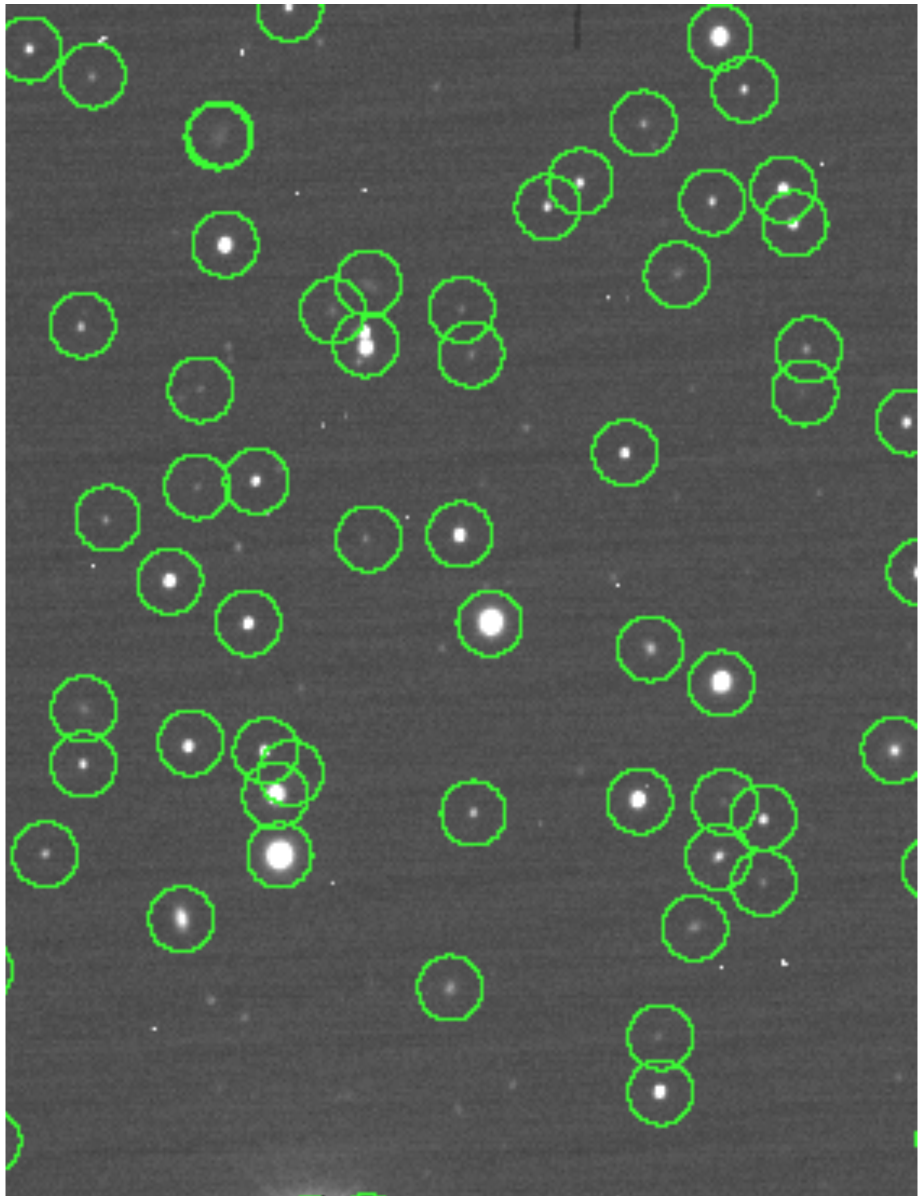
To get an initial WCS you must have at least 3 coordinate pairs (pixel position & coordinates of object)



Improvement – blue using more reference stars (min ~ 12)

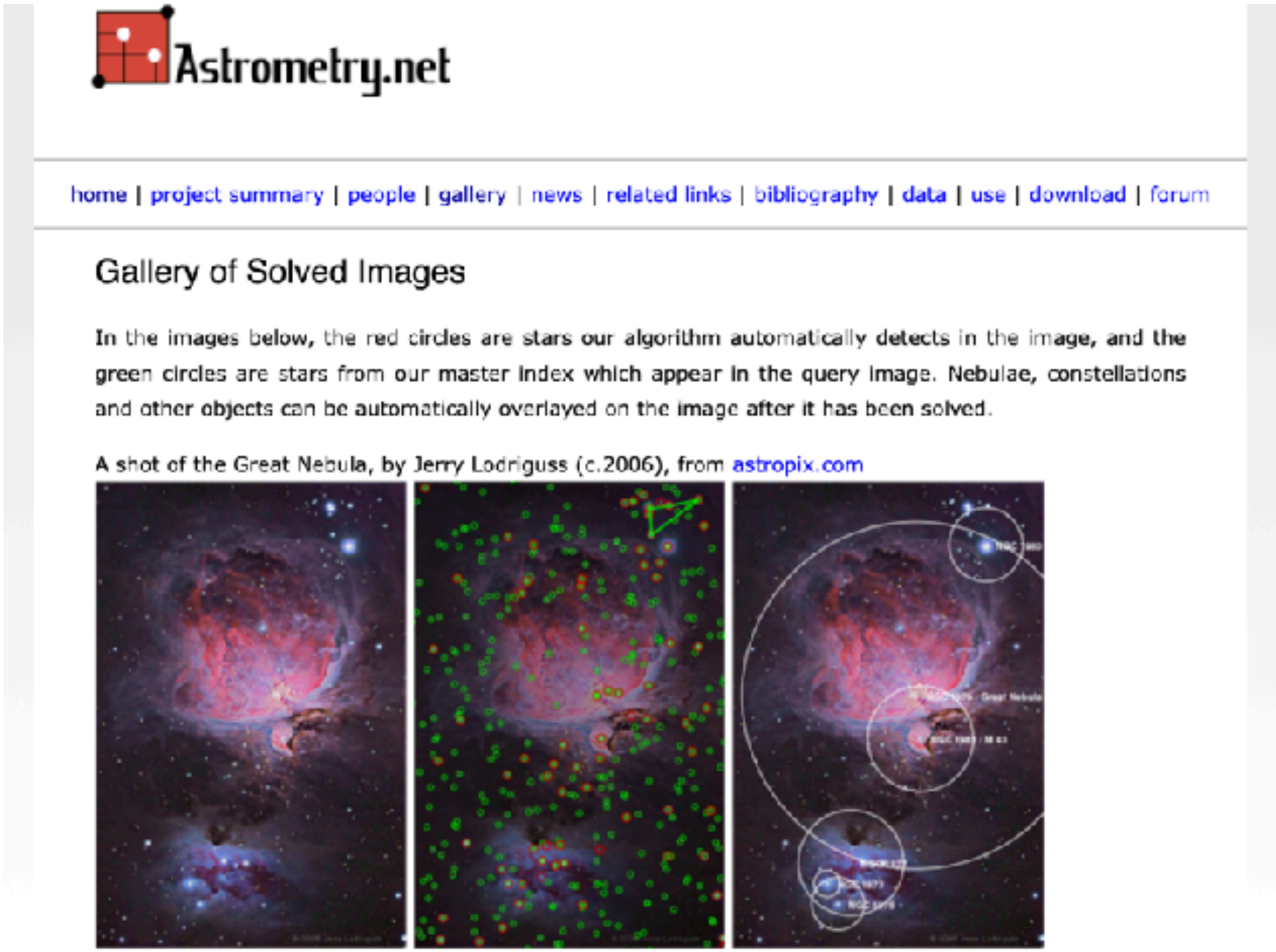


Improvement



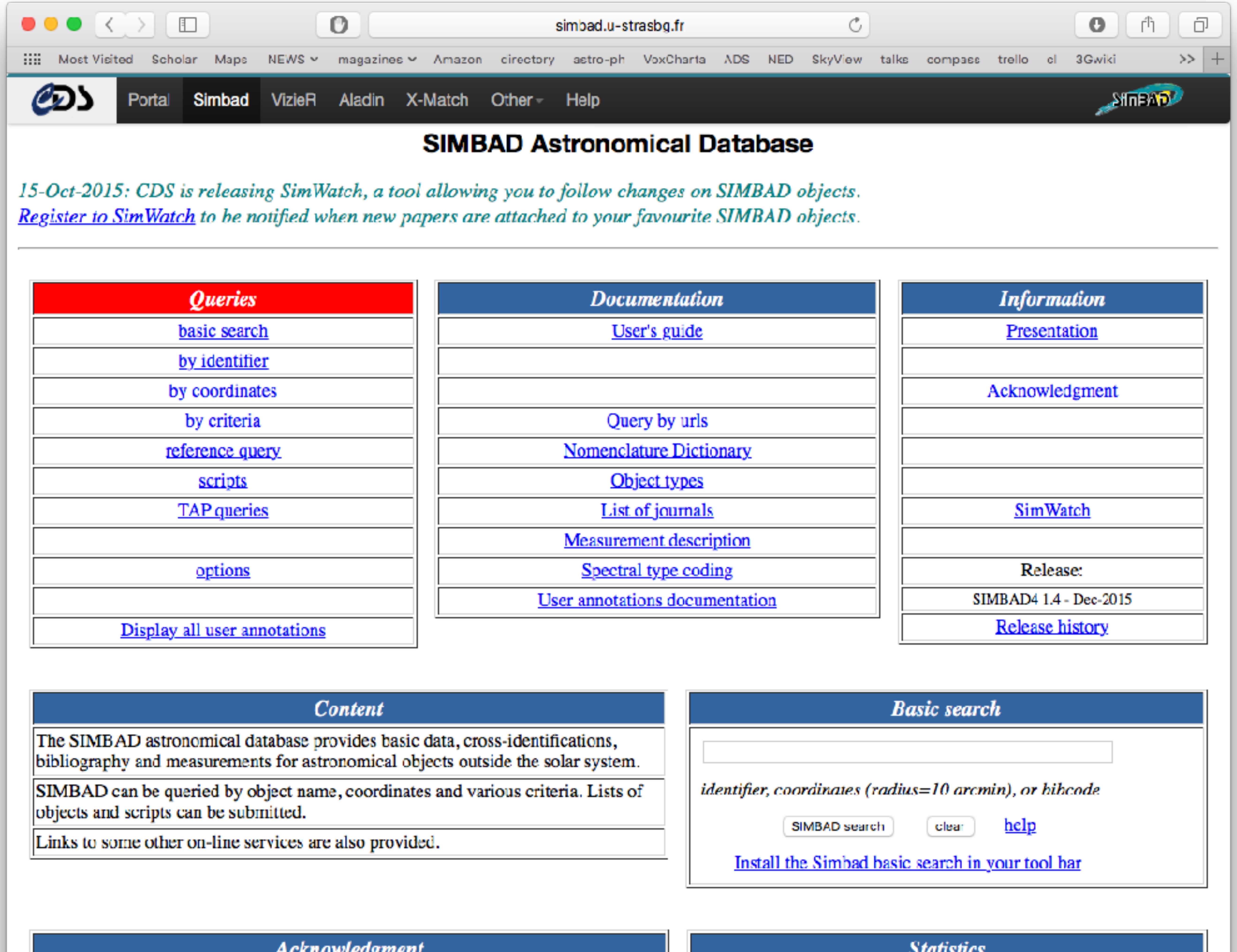
Verify - Finished

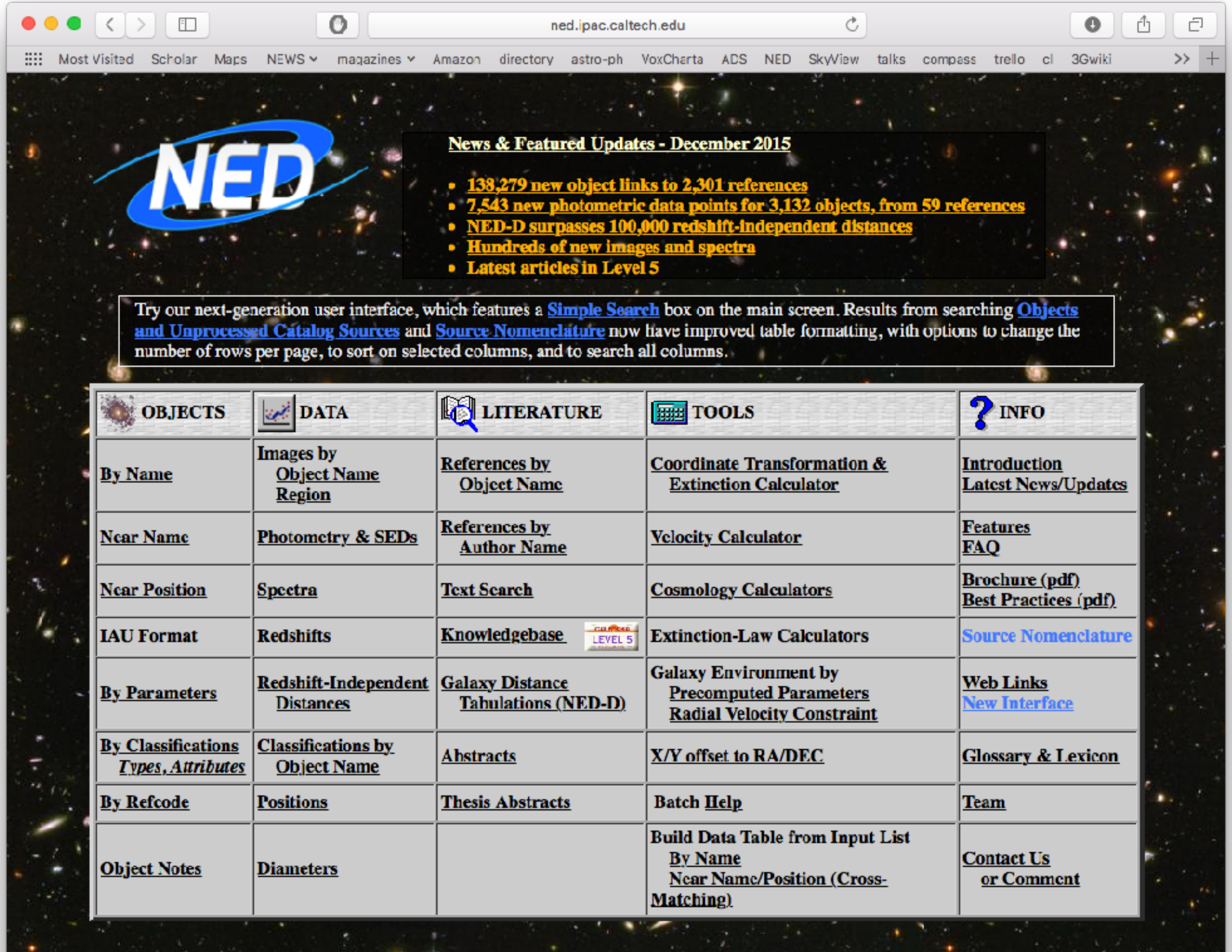
Astrometric software: libraries



https://pypi.org/project/astrometry/

Getting/Using Catalogs


simbad.u-strasbg.fr
Most Visited Scholar Maps NEWS magazines Amazon directory astro-ph VoxCharta ADS NED SkyView talks compass trello cl 3Gwiki
Portal Simbad VizieR Aladin X-Match Other Help
SIMBAD Astronomical Database
15-Oct-2015: CDS is releasing SimWatch, a tool allowing you to follow changes on SIMBAD objects.
Register to SimWatch to be notified when new papers are attached to your favourite SIMBAD objects.
Queries
basic search
by identifier
by coordinates
by criteria
reference query
scripts
TAP queries
options
Display all user annotations
Documentation
User's guide
Query by urls
Nomenclature Dictionary
Object types
List of journals
Measurement description
Spectral type coding
User annotations documentation
Information
Presentation
Acknowledgment
SimWatch
Release:
SIMBAD4 1.4 - Dec-2015
Release history
Content
The SIMBAD astronomical database provides basic data, cross-identifications, bibliography and measurements for astronomical objects outside the solar system.
SIMBAD can be queried by object name, coordinates and various criteria. Lists of objects and scripts can be submitted.
Links to some other on-line services are also provided.
Basic search
identifier, coordinates (radius=10 arcmin), or bibcode
SIMBAD search
clear
help
Install the Simbad basic search in your tool bar
Acknowledgment
Statistics



News & Featured Updates - December 2015

- 138,279 new object links to 2,301 references
- 7,543 new photometric data points for 3,132 objects, from 59 references
- NED-D surpasses 100,000 redshift-independent distances
- Hundreds of new images and spectra
- Latest articles in Level 5

Try our next-generation user interface, which features a Simple Search box on the main screen. Results from searching Objects and Unprocessed Catalog Sources and Source Nomenclature now have improved table formatting, with options to change the number of rows per page, to sort on selected columns, and to search all columns.

OBJECTS	DATA	LITERATURE	TOOLS	INFO
By Name	Images by Object Name Region	References by Object Name	Coordinate Transformation & Extinction Calculator	Introduction Latest News/Updates
Near Name	Photometry & SEDs	References by Author Name	Velocity Calculator	Features FAQ
Near Position	Spectra	Text Search	Cosmology Calculators	Brochure (pdf) Best Practices (pdf)
IAU Format	Redshifts	Knowledgebase LEVEL 5	Extinction-Law Calculators	Source Nomenclature
By Parameters	Redshift-Independent Distances	Galaxy Distance Tabulations (NED-D)	Galaxy Environment by Precomputed Parameters Radial Velocity Constraint	Web Links New Interface
By Classifications *Types, Attributes*	Classifications by Object Name	Abstracts	X/Y offset to RA/DEC	Glossary & Lexicon
By Refcode	Positions	Thesis Abstracts	Batch Help	Team
Object Notes	Diameters		Build Data Table from Input List By Name Near Name/Position (Cross-Matching)	Contact Us or Comment

https://astroquery.readthedocs.io/en/latest/