Observational Techniques

Pat Roche

About me

- I moved to Oxford 30 years ago and have been involved with many observatories, telescopes, and instruments, e.g.
  - Chair of ESO Council and Scientific & Technical committee
  - Chair of ALMA, UKIRT and AAT Boards
  - Chair of NOVA instrument Steering Committee (Netherlands)
  - Member of ESO and ALMA visiting committees
  - Review panel chair or member for numerous instruments and telescopes
  - UK Gemini Project Scientist
  - PI for UFTI and WHIRCAM instruments for UKIRT & WHT
- Research interests in interstellar matter, star formation, cosmic dust

Synopsis

- Introduction to astronomical facilities
- Coordinates, catalogues, time, observability
- Earth's Atmosphere and advantages of Space
  - Atmospheric Transmission and Emission
  - Refraction and Seeing
- High Resolution : Corrections for atmospheric phase
  - Adaptive Optics,
  - Interferometry
- Telescopes
- Detectors
- Photometry
- Spectroscopy
- Proposals,

Radio Astronomy

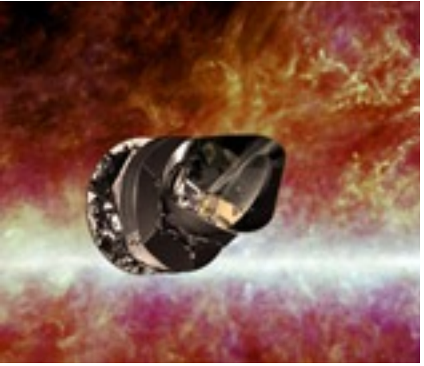
- VLA - ATCA - MeerKAT - e-Merlin
- GMRT

- Large Radio Dishes :
  - GBT, Effelsberg, Bonn, Parkes, Westerbork, Jodrell, Medicina, Jingdong 120m
  - FAST, (Arecibo)
- VLBA, EVN/JIVE VLBI
- LOFAR : sub-mJy sensitivity over the northern sky
- SKA & Pathfinders

Revolutionary Capabilities at low-frequencies

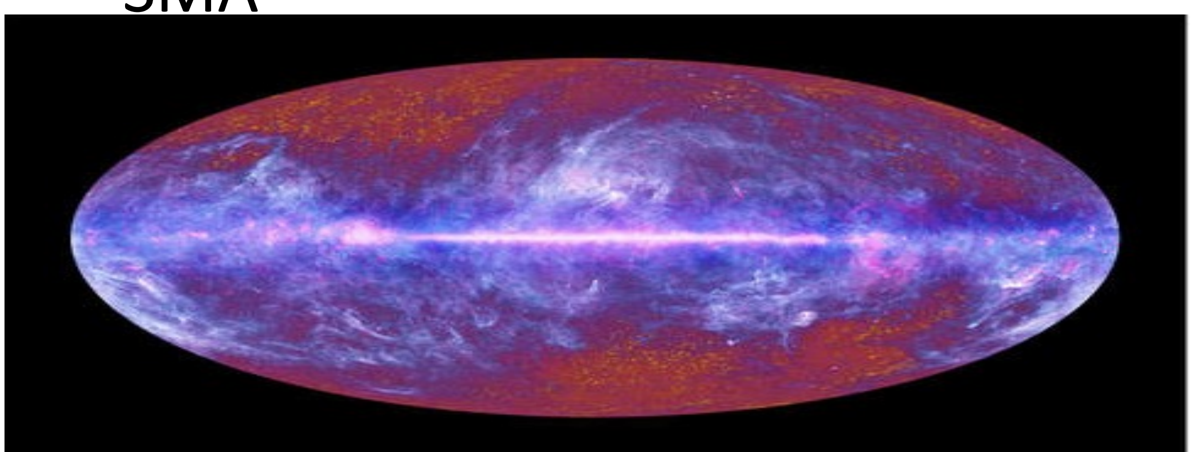
- EVLA 1 – 50GHz 27 x 25-m antennas 2-6μJy sensitivity
- LOFAR 30-250MHz NL/European Array Phased arrays baseline 100m -1500km
- SKA Pathfinders and Phase I:
  Phased array feeds
  - ASKAP 36 x 12-m dishes in WA
  - MeerKat 64 x 13.5-m dishes 1-15GHz
- Africa Telescope
  - Plans to connect surplus communication dishes across Africa

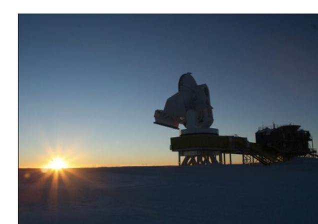


Microwave Astronomy

- WMAP and Planck Legacy,
- CMB intensity and polarization maps, Galactic foregrounds and point sources :
  - ACTPOL, PolarBear, QUIJOTE, SPT, GEM, CBASS ….
- APEX and JCMT : Scuba-2, LaBoca
- SMA



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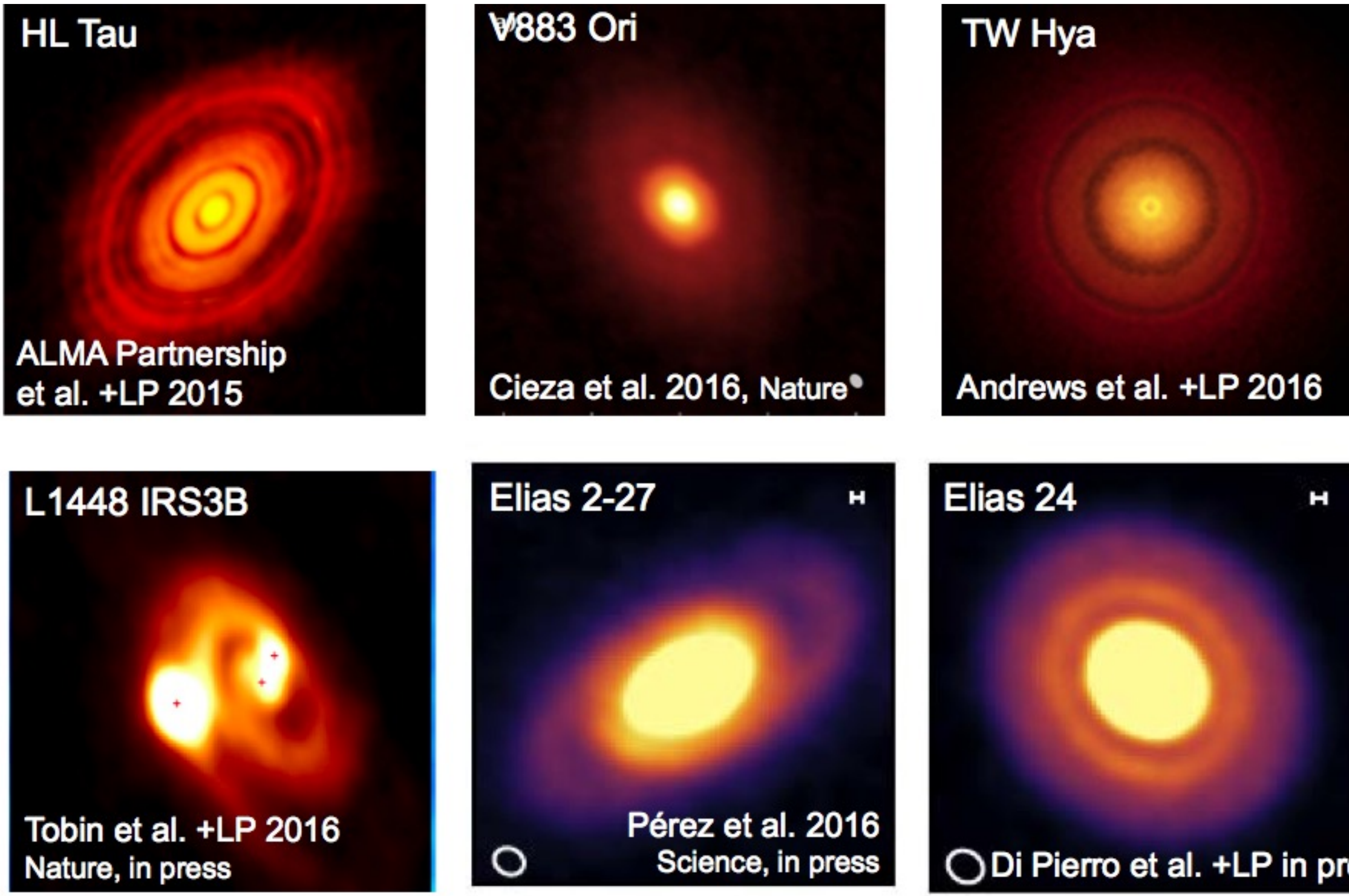
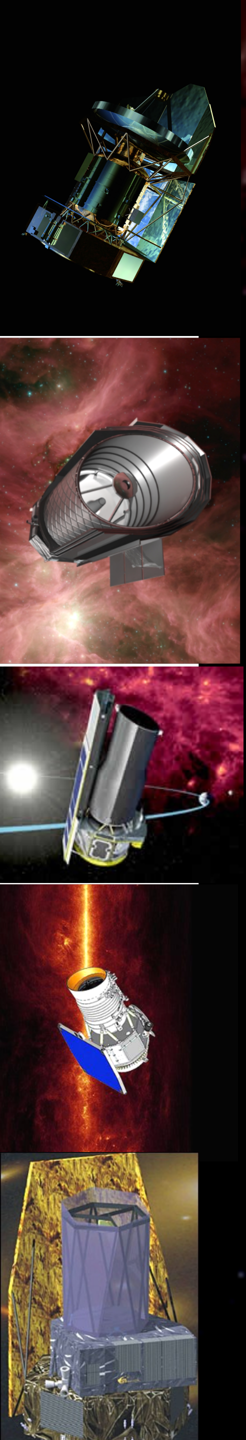

HL Tau
ALMA Partnership
et al. +LP 2015
V883 Ori
Cieza et al. 2016, Nature
TW Hya
Andrews et al. +LP 2016
L1448 IRS3B
Tobin et al. +LP 2016
Nature, in press
Elias 2-27
Pérez et al. 2016
Science, in press
Elias 24
Di Pierro et al. +LP in pre

Infrared Surveys

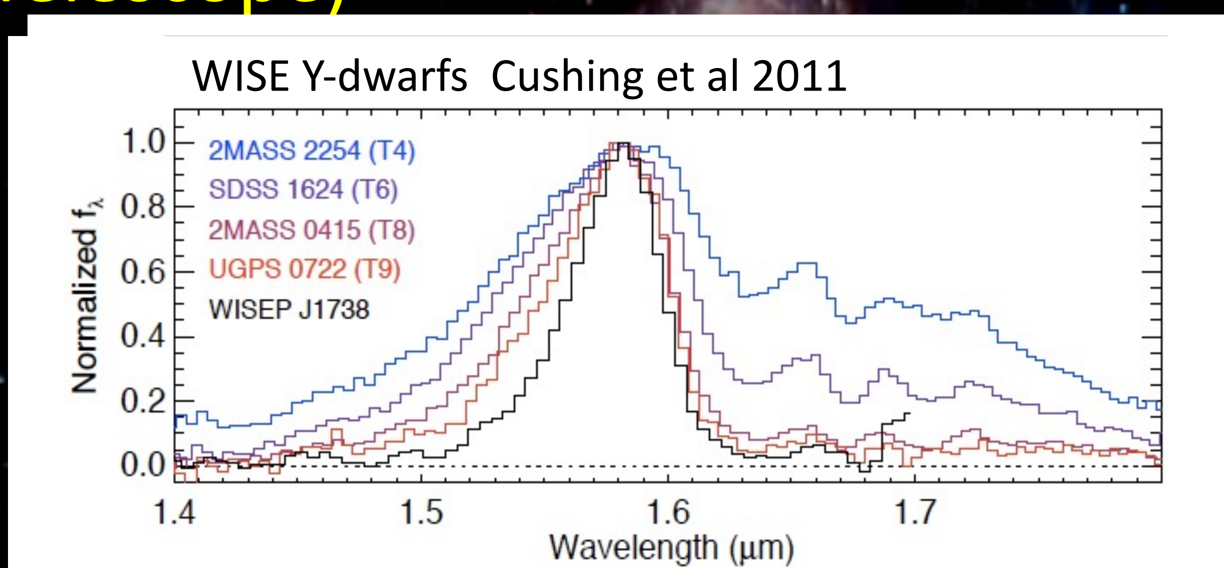


Herschel – (SPICA)

Spitzer – Akari - JWST

2MASS - UKIRT – VISTA – (SASIR)

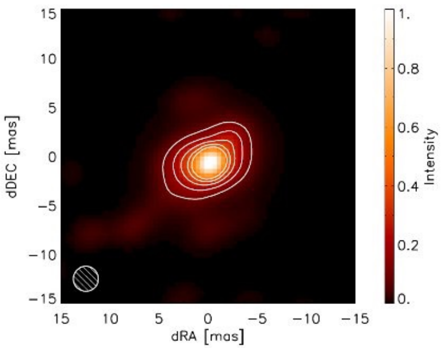
WISE – EUCLID - WFIRST (Roman Space Telescope)



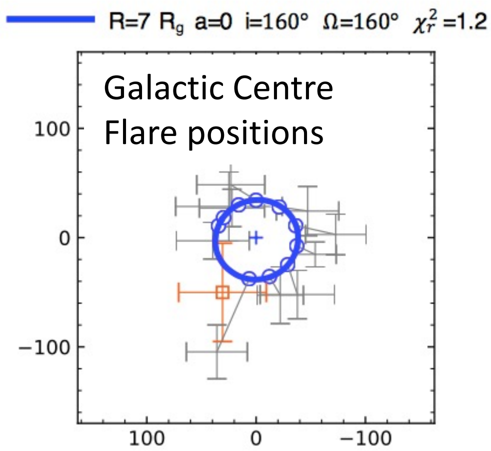
Infrared Interferometry

- Lower sensitivity but higher resolution than the ELTs by factors of 5+
  - Phase-referencing to allow longer integrations
  - Astrometric and Imaging programmes with ~10 microarcsecond precision and milli-arcsec resolution
- Near- and mid-IR images and Spectroscopy
- Chara, Keck, LBT, Magdalena Ridge, VLTI

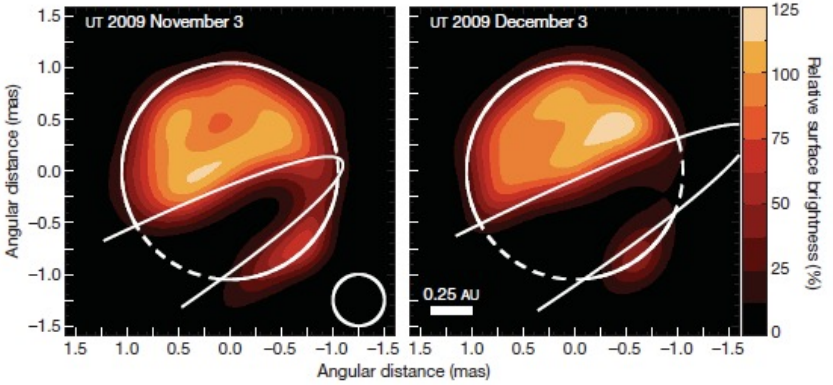
VLTI/AMBER image of the disk in IRAS 13481-6124



R Abuter et al 2018

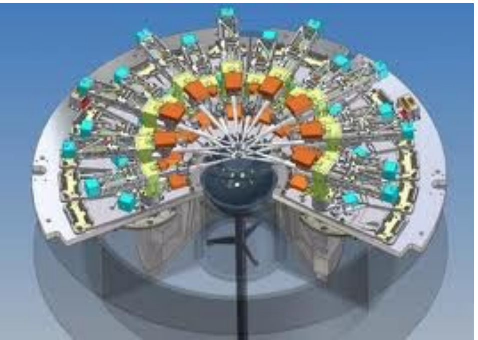


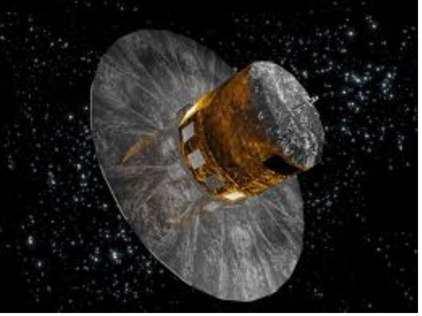
Chara image of ε Aur in Eclipse



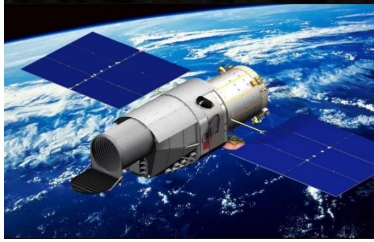
New IR Facilities

- SOFIA
- Ground- based MOS and multi-IFU instruments
- Wider field and higher order AO
- JWST
  - Synergies in the near-IR
  - Complementarity in the mid-IR
  - Resolution from the ground for the brightest objects
  - Sensitivity from Space. - launch in December 2021?

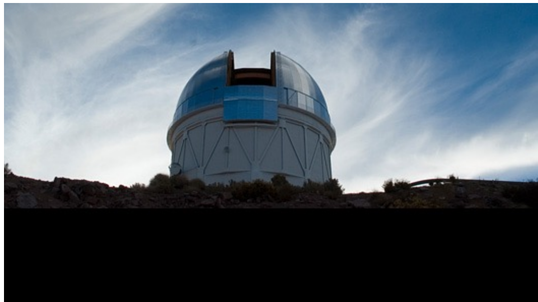




Optical Surveys

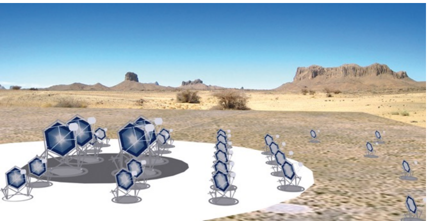


- HST, Galex Legacy, Xuntian (CSST)
- Imaging Surveys
  - PanStarrs, Skymapper, VST, DES, HSC
- LSST/ Vera Rubin Observatory 8.4-m aperture
  - Large Synoptic Survey Telescope, operations start 2023
  - Multifilter, deep maps of the southern sky every 3 days
- Large Spectroscopic Surveys
  - 2DF – SDSS – BOSS - LAMOST – HETDEX- DESI
- GAIA



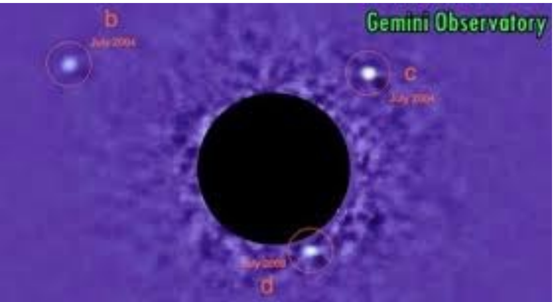
High Energy Facilities

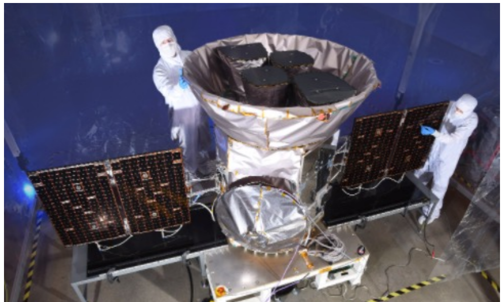
- Chandra - XMM-Newton – SWIFT – FERMI
- NuStar - (Hitomi) – XRISM – IXPE - Athena
- Cosmic ray telescopes
  - Auger + Enhancements
- Cerenkov Telescope Arrays
  - Hess, Magic, CTA

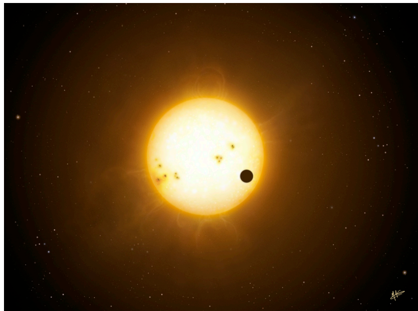


Exoplanet detection and characterization

- RV Spectrographs :
  - Keck, Lick, AAT, HARPS-S and -N, Carmenes, Spirou, Espresso….
- Transit Searches and spectroscopy
  - Corot, Kepler, TESS, CHEOPS, Plato (2026), Ariel (2029) …. coordination with ground-based facilities
  - Superwasp, TrES, NGTS……
  - Hubble, Spitzer, JWST + ground-based telescopes
- High contrast AO Planet Imagers
  - VLT/Sphere, Gemini/GPI, Subaru /HiCiao EPICS
- Astrometric Searches
  - Gaia, Gravity
  - magnetopheric radio emission : LOFAR and SKA
- microLensing detections

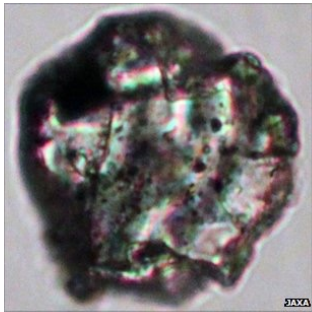






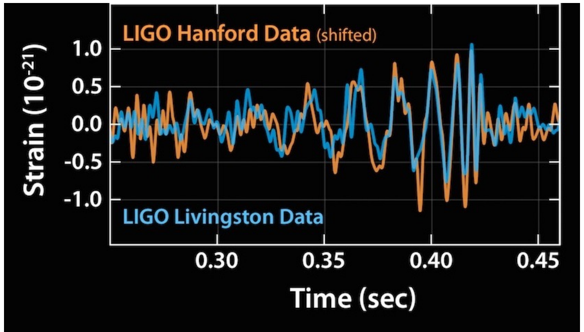
+ a host of other facilities

- General purpose ground-based telescopes
  - Workhorses for most programmes
  - Next generation 8 and 10-m telescope instruments aimed at ambitious programmes with large time allocations
- ELTs : 39m ESO ELT, 30m TMT, GMT
- Solar system exploration and exoplanet synergies
- Meteoritics and Interplanetary /interstellar dust particles
- Laboratory studies – molecular and atomic physics and chemistry
- Theory and simulations



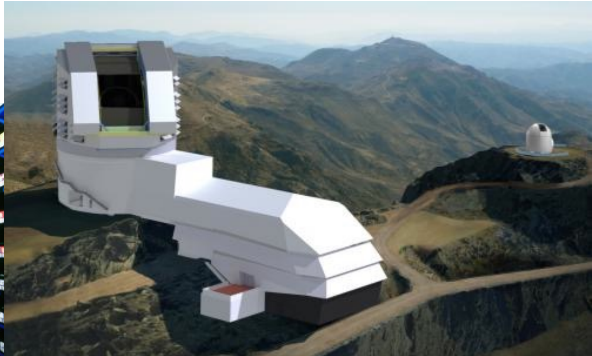
Beyond the Electromagnetic Spectrum

- aLIGO - VIRGO – GEO600 – LISA-Pathfinder
  - Gravitational wave detectors have opened up a new window.
  - Astronomical target identification and follow-up
    - Merging Black Holes, Coalescing neutron stars
- Direct Dark Matter detection
- Neutrinos and other Particle Physics



Opportunities in the Time Domain

- Quasi-continuous monitoring of large areas of sky provides new opportunities for discovery with SKA and LSST from 2023 onwards
  - Poorly sampled variability parameter space may yield surprises
  - Rapid follow-up required via automated systems
- Data digestion or indigestion
- Serious collaboration with computer science and engineering departments

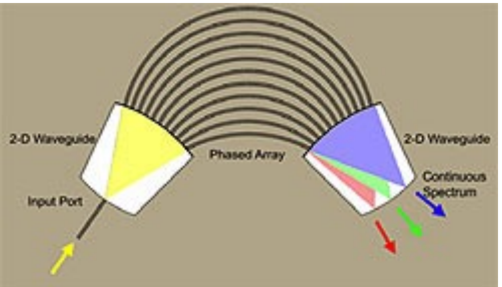


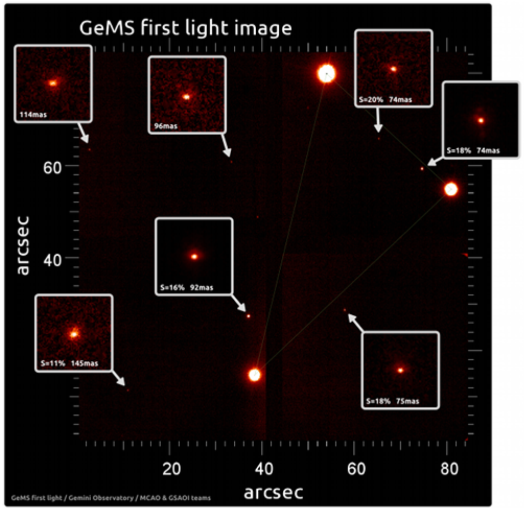
And Threats

- Mega Constellations
  - Optical reflected light produces bright streaks
  - Radio communications and interference.
- Light Pollution and dust
- Politics

Technology Developments

- Resolution, Sensitivity and multiplex gains
  - Mass-production : VLT/MUSE HET/VIRUS SKA
- Detectors
  - larger format IR detectors, fast, low noise sensors for WFS
  - multi-pixel heterodyne receivers, phased arrays
- Adaptive Optics,
  - more actuators, more lasers
  - faster reconstructors/electromechanics,
  - higher reliability/availability More conjugation
- Photonic instruments
  - Integrated optics
  - Background suppression via notch filters
- Energy-resolving detectors? KIDS





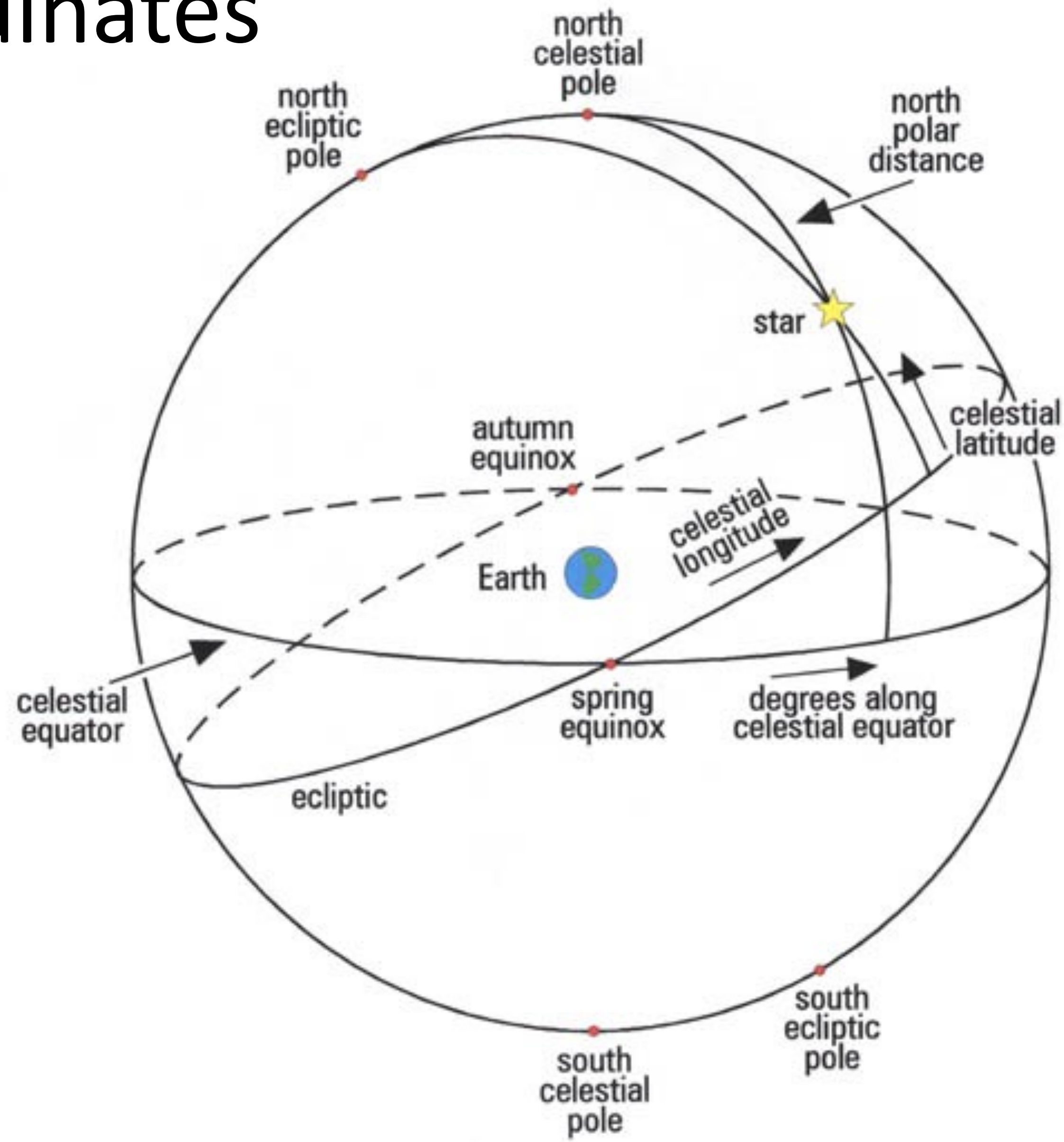
Astronomical objects

- Positions on the celestial sphere
- Constellations for bright objects, but more usually catalogue numbers
- Astronomical seasons : Optimum Observing Periods
  - Orion in December,
  - summer triangle (Vega, Altair, Deneb) or Galactic Centre in June
  - Or perhaps more relevantly Virgo ~Easter,
  - HDF–N 12 36 49.4, +62° 12′ 58″
  - HDF -S 22 32 56.2, −60° 33′ 03″

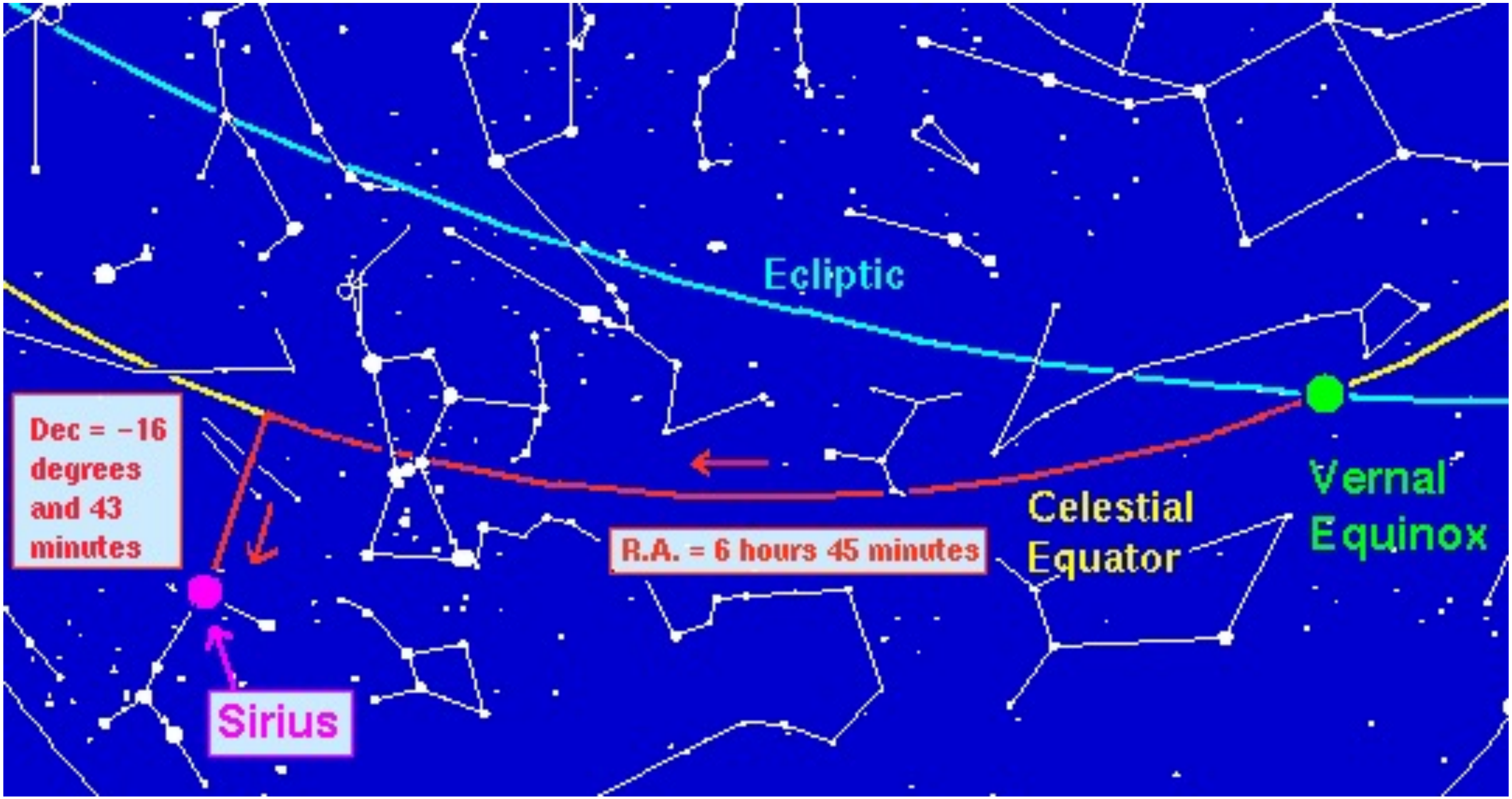
Celestial Coordinates

Coordinates measured from a rotating and orbiting platform which is subject to orbital such as precession and atmospheric refraction that have to be taken into account.

Requirements for coordinate precision depend on the application, but can be at milli- or micro- arcsec levels ($\sim 10^{-9}$ radians)



Celestial Coordinates



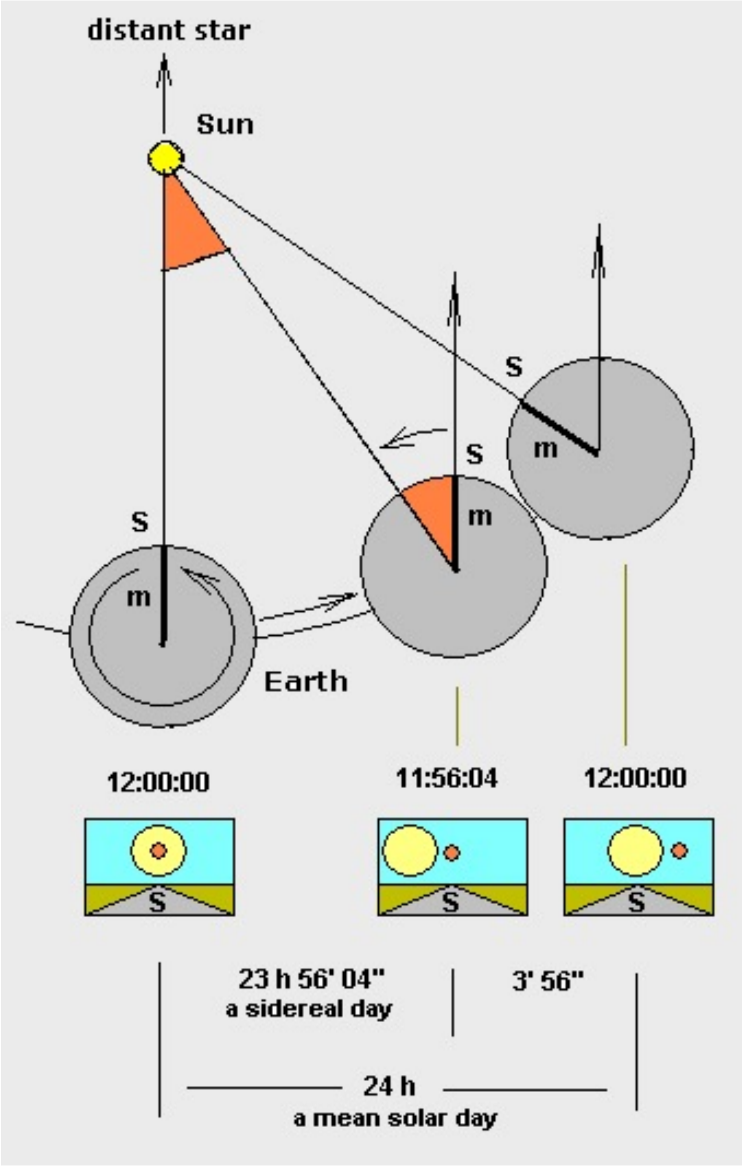
Coordinates

- Star and galaxy catalogues normally employ Equatorial coordinates with a rest frame tied to quasars.
- Recent data use ICRS equatorial J2000 (Epoch 2000), though older catalogues may be wrt to epoch 1950 (B1950). But note that the HD catalogue has epoch 1900!
  - J2000 Epoch 1 Jan 2000 at 12:00 UT = JD2455200.5
  - May need to take precession (and perhaps proper motion) into account for any other epoch.

- Expressed in Right Ascension (α in HMS) and Declination (δ in DMS) where RA is in the plane of the Earth's equator and Declination (latitude) is normal to it, reaching +/-90deg at the equatorial poles.
- Note that the RA coordinate may need to be compensated for cosine(δ) if true angles on the celestial sphere are required. 1 hour of RA = 15 degrees at the equator (δ=0)

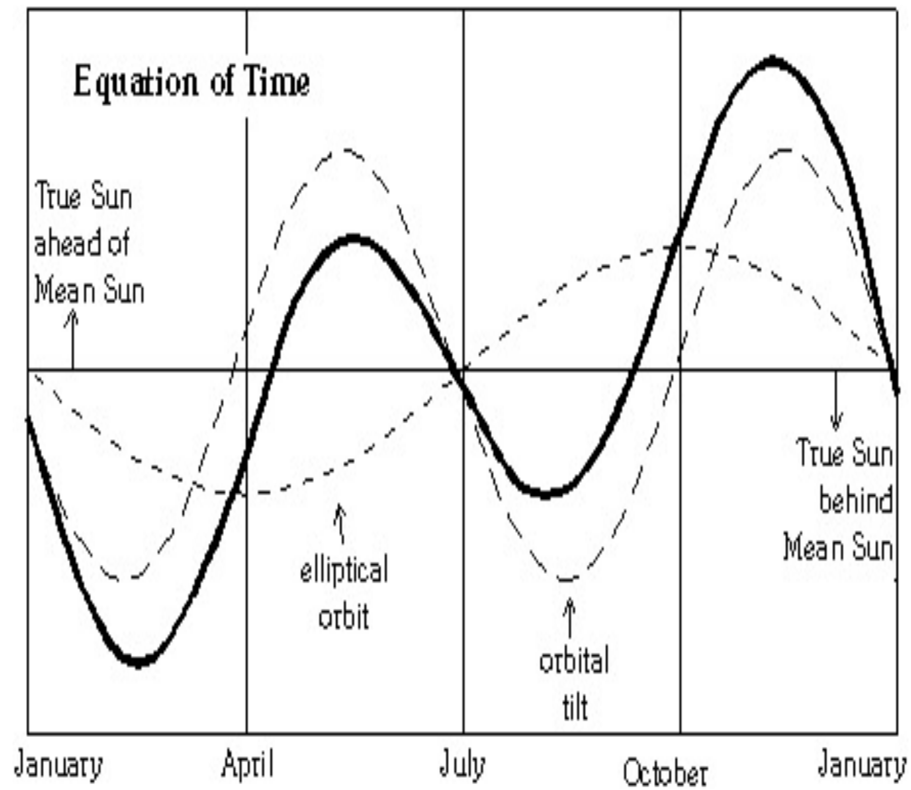
Equatorial Coordinates

- The zero point of the equatorial coordinate system is defined to be the intersection of the ecliptic and equatorial planes. (earth's orbital and rotational planes). This is not a fixed point, but changes because of precession and nutation. The annual vernal equinox precession is westward and northwards by :
  - $3.073 + 1.336 \sin\alpha \tan\delta$ seconds of time
  - $20.043 \cos\alpha$ arcsec
- Civil Time (e.g UTC) is based on the Earth's mean rotation around the sun, (the sun is at maximum elevation at mid-day) but it is more convenient in astronomy to use Sidereal Time, based on the Earth's rotation with respect to the fixed pattern of the star.
- The solar day is ~4 min longer than the sidereal day.
- Local Sidereal Time is used for astronomical observatories and equals the Hour Angle of the vernal equinox, where HA = ST-α
- A star is on the meridian when the ST equals the star's RA



Time Systems

- Universal Time
  - mean solar time
  - ignores variations over the year
- Sidereal time
  - reference to the ‘fixed pattern of the stars
  - runs 1 day/year (~4min/day) faster than solar time
  - http://www.jgiesen.de/astro/astroJS/siderealClock/
- Julian Date
  - counted from Jan 1 4713BC
  - Changes at mid-day
  - Modified JD -2400000.5



The Observer's location, celestial coordinates (α, δ) and the sidereal time of observation give:
Hour Angle of observation Mm, where H.A. = (ST-α)
And the latitude of the observer, ϕ, is the arc ZM

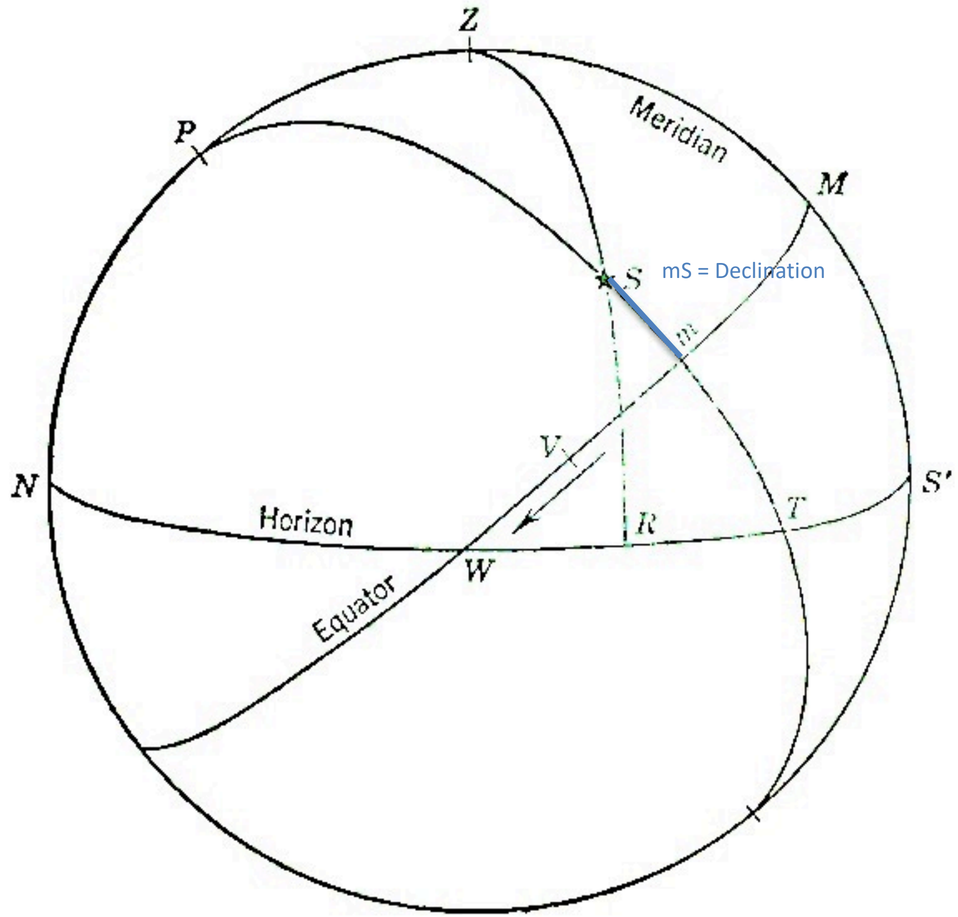


FIG. 20. The Sphere Seen from the Outside

The altitude, is given by :

$\sin(h) = \cos(\phi-\delta) - 2\cos\phi \cos\delta \sin^2(HA/2)$

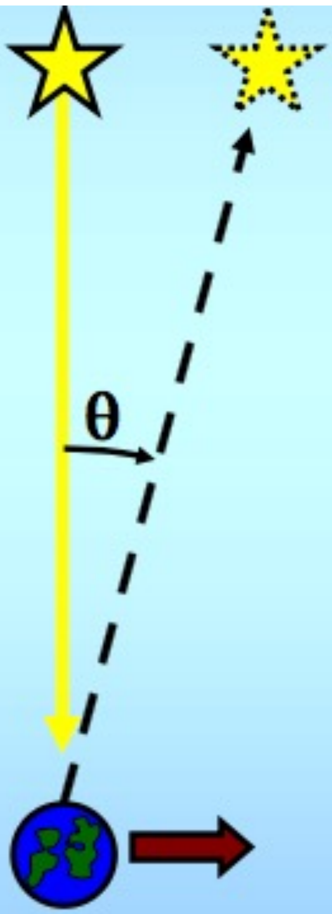
And the Zenith Distance, ZS = (90 – h) deg

Equatorial Coordinates

- Local Siderial Time calculator : http://www.jgiesen.de/astro/astroJS/siderealClock/
- Star catalogues may use barycentric equatorial (J2000)
  - Helio-centric equatorial coordinates may be used for planetary bodies
  - Apparent equatorial coordinates are referred to the location of the observer.
  - For distant objects, the differences become small, but for nearby, and particularly solar system objects they become very large due to parallax.
- Note that RA becomes undefined at the celestial pole

Other Effects

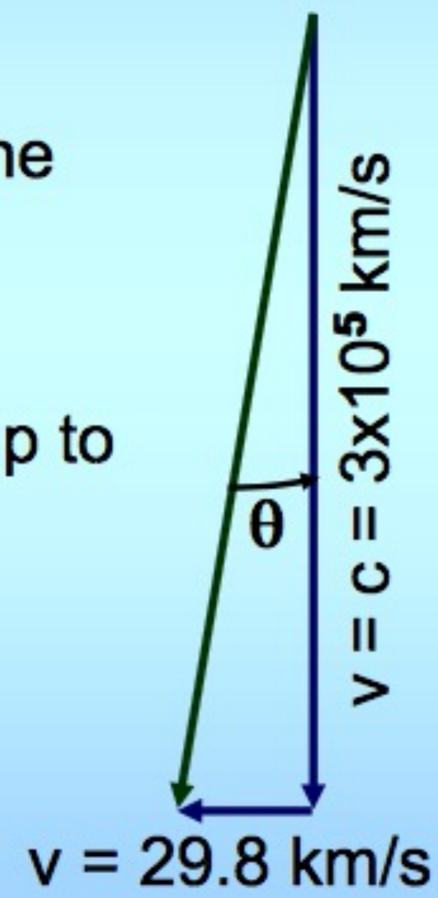
Stellar aberration – discovered by Bradley in 1727 when searching for stellar parallax



1. Light has a finite velocity
2. The Earth moves relative to the star
3. The combination of velocities "moves" the star position by up to 20".49.

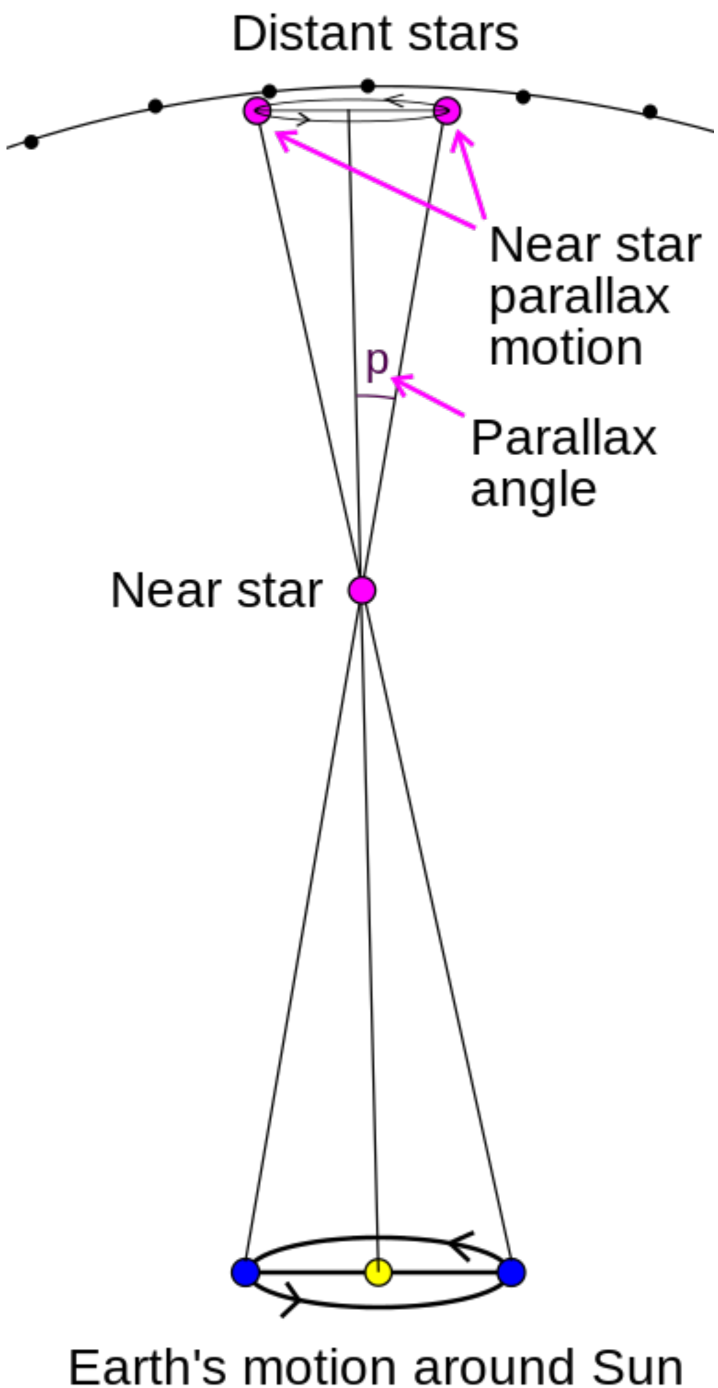
$$\tan\theta = \frac{29.8}{3\times10^5}$$

$$\Rightarrow \theta = 20''.49$$



Parallax

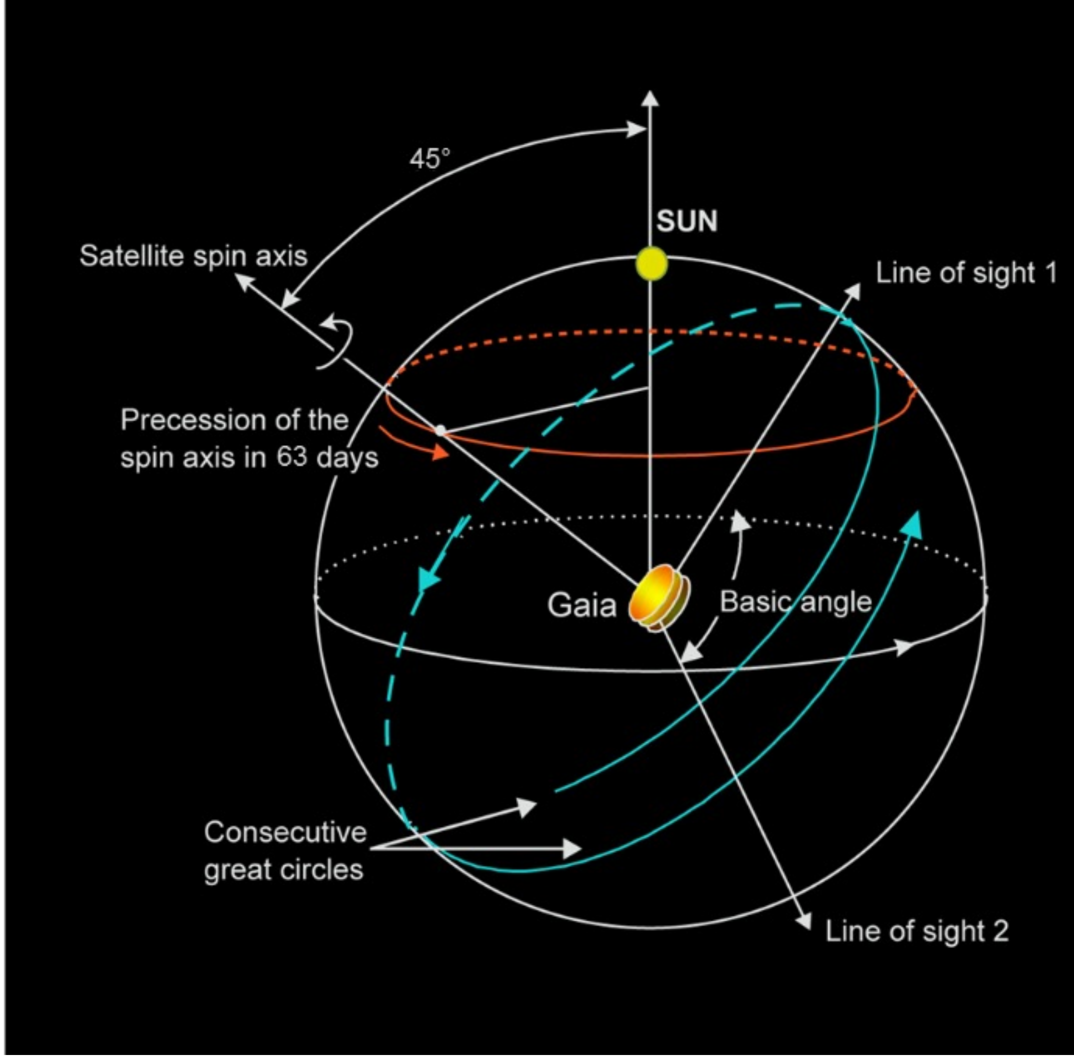
- As the Earth orbits the sun, the angle at which stars are observed alters relative to the barycentre
- For nearby (solar system) objects, the effects of parallax are large and need to be taken into account
- The nearest star, Proxima Cen has a parallax of 0.76”   (d=1.3pc), and for most objects, the effect is small.
- But this is the basis of the Hipparcos and Gaia astrometric satellites which have and are providing accurate distances to large numbers of stars



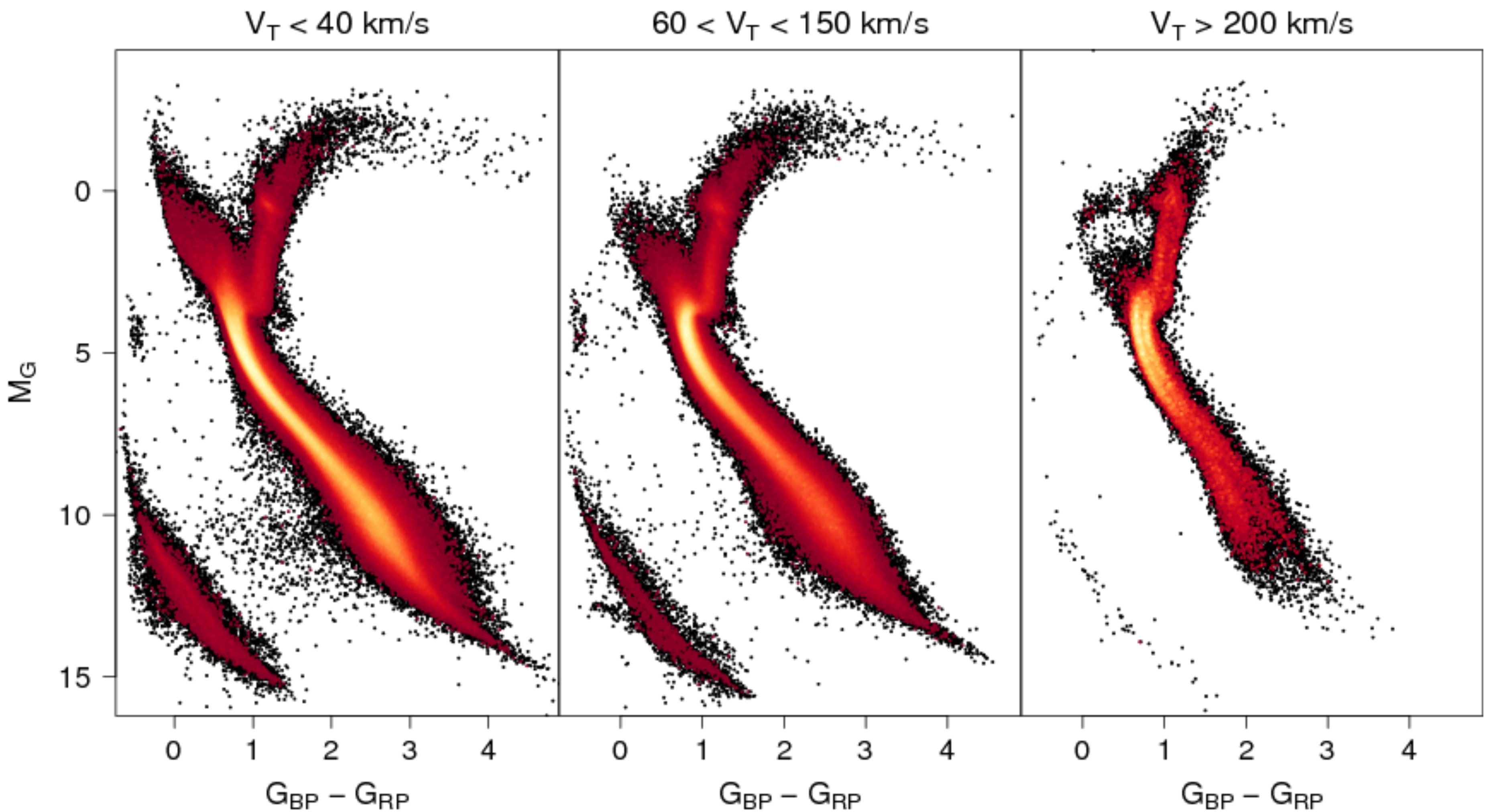
Gaia operations

- 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)

Mission extended by 2 years in 2018



ESA Gaia mission underway,
2nd data release occurred in April 2018 with > 1 billion stars; Early 3rd data release is planned for 03/12/20, with full release in 2022.
Precisions will increase as more data are collected, but on-track to reach parallax measurements ranging from <10 μ-arcsec at V= 6 mag to 500 μ-arcsec at V~20, together with photometric accuracies of 4m-mag on bright (V<15) stars



Gaia H-R Diagrams for thin disk (low v_T), thick disk (mid v_T) and Halo populations

Gaia is on track to deliver the mission goals, revolutionising distance estimates and Galactic structure – as well as abundance estimates, Galactic archaeology etc…

Data Release 2 provides astrometric information on more than 1.3 billion stars :

RA, Dec, Parallax, Proper motions + Radial velocities for several million

SIMBAD
http://simbad.u-strasbg.fr/simbad/

V* V645 Cen -- Flare Star

Other object types:	* (*,CSI,...), X (1E,2E,...), PM* (Ci,LFT,...), UV (2EUVE,EUVE,...), ** (CCDM,WDS), Fl* (Ref,[GKL99]), V* (V*,CSV), IR (IRAS,2MASS)
ICRS coord. *(ep=J2000) :*	14 29 42.94853 -62 40 46.1631 (Optical) [17.66 14.33 90] A 2007A&A...474..653V
FK5 coord. *(ep=J2000 eq=2000) :*	14 29 42.949 -62 40 46.16 [17.66 14.33 90]
FK4 coord. *(ep=B1950 eq=1950) :*	14 26 18.98 -62 28 04.2 [102.04 82.75 90]
Gal coord. *(ep=J2000) :*	313.9399 -01.9271 [17.66 14.33 90]
Proper motions *mas/yr* :	-3775.75 765.54 [1.63 2.01 0] A 2007A&A...474..653V
Radial velocity / Redshift / cz :	V(km/s) -22.40 [0.5] / z(~) -0.000075 [0.000002] / cz -22.40 [0.50] A 2006A&A...460..695T
Parallaxes *(mas)*:	768.13 [1.04] ~ 2014AJ....148...91L
Spectral type:	M5.5Ve C 1991AJ....101..662B
Fluxes (8) :	U 14.21 [~] D 2014AJ....147...21J B 12.95 [~] D 2014AJ....147...21J V 11.13 [~] D 2014AJ....147...21J R 9.45 [~] D 2014AJ....147...21J I 7.41 [~] D 2014AJ....147...21J

NAME Sgr A* -- X-ray source

Other object types:	Rad (), gam (), X (AX,CXOGC,...)
ICRS coord. *(ep=J2000) :*	17 45 40.03599 -29 00 28.1699 (Radio) [2.65 1.42 0]
FK5 coord. *(ep=J2000 eq=2000) :*	17 45 40.036 -29 00 28.17 [2.65 1.42 0]
FK4 coord. *(ep=B1950 eq=1950) :*	17 42 29.30 -28 59 18.6 [2.65 1.42 0]
Gal coord. *(ep=J2000) :*	359.9442 -00.0462 [2.65 1.42 0]

Ecliptic Coordinates

- Instead of using the earth's rotation as the plane of longitude, ecliptic co-ordinates use the plane of the Earth's orbit around the sun, which is inclined by 23.5deg

Ecliptic coordinates are normally only used for solar system objects and can be obtained by spherical trigonometry transforms from α, δ to λ, β

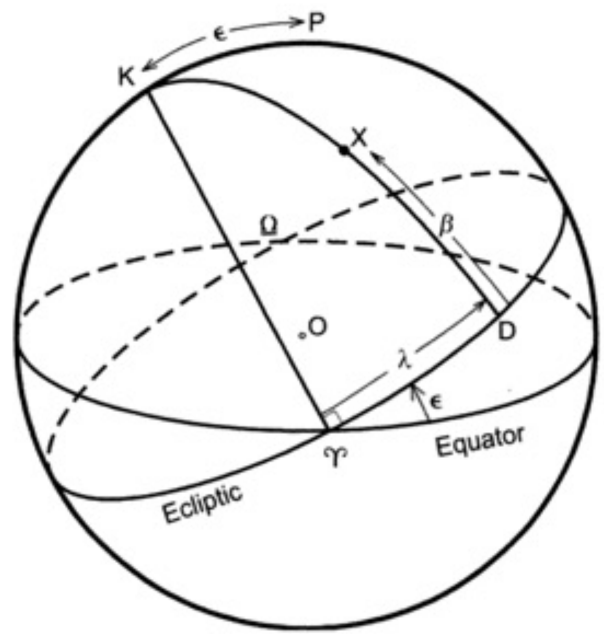
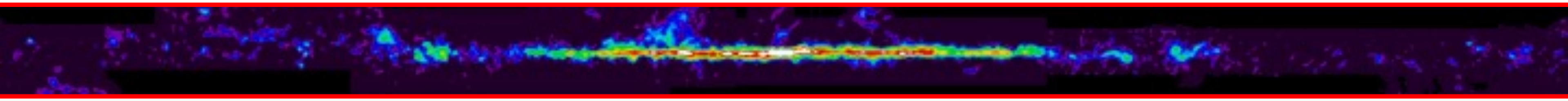


Figure 2.5

of Aries ♈ and Libra Ω) at an angle of 23° 26′, usually denoted by ϵ and referred to as the obliquity of the ecliptic. The pole K of the ecliptic makes the same angle ϵ with the north celestial pole.

Galactic Coordinates

- Studies in the Milky Way may benefit from using Galactic coordinates, where longitude is measured along the Galactic plane with the origin at the Galactic Centre, and latitude normal to it. The north Galactic Pole is at α= 12h 51.4, δ= +27^{o} 07. The coordinates use *l, b for longitude and latitude* and may be in J2000, B1950 etc.



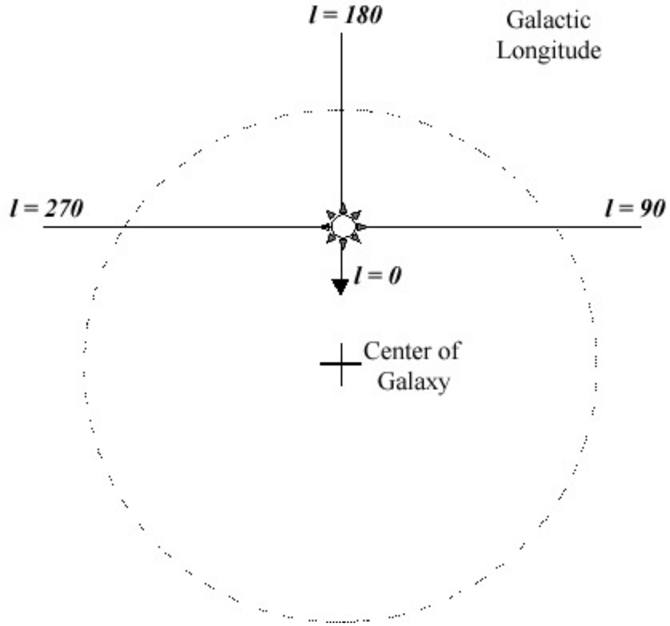
- There are many routines available to convert between Coordinate systems
  - e.g. coco in the Starlink collection -Converts between equatorial, ecliptic, Galactic with choice of epochs
  - Or a more user friendly site: http://ned.ipac.caltech.edu/forms/calculator.html

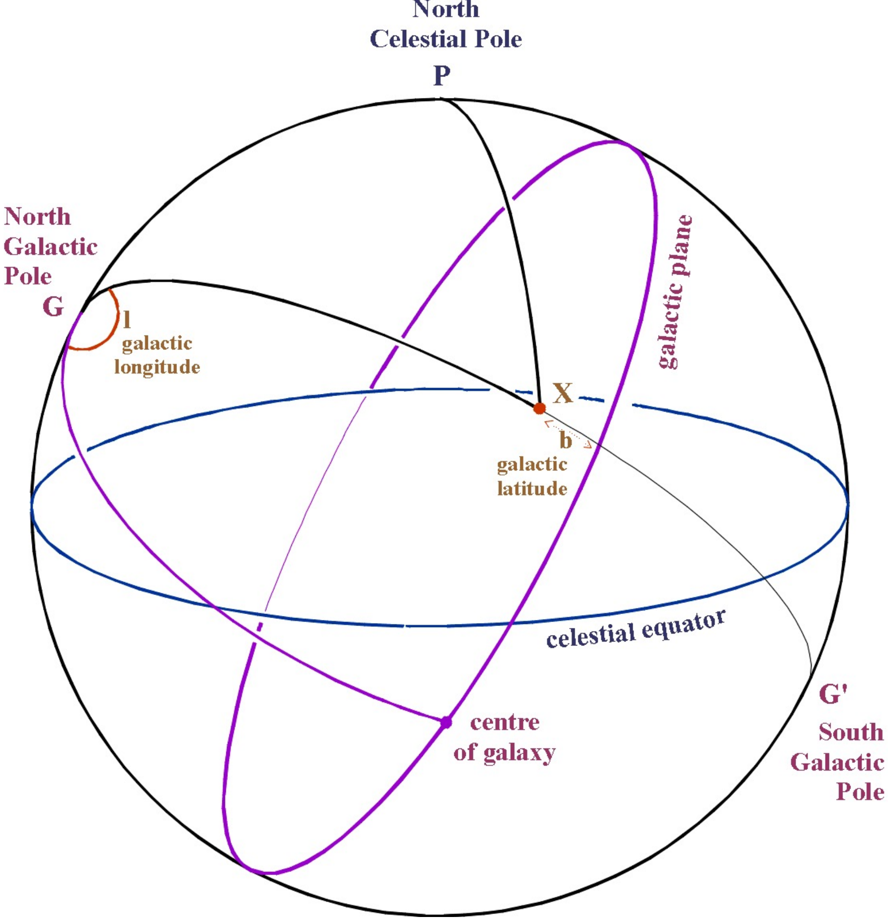
COCO

```
% coco
 *  Celestial Coordinate Conversions
 <- ?
    Input format:
        RA     Dec       PM       Px    RV
      h m s  d ' "  [s/y  "/y    ["  [km/s]]]
 <-   I 5
    Conversion is from:
      FK5, equinox J2000.0, epoch J2000.00 (barycentric)
 <- O G 2000
    Conversion is to:   Galactic, epoch J2000.00 (barycentric)

 <- 17 45 40.036 -29 00 28.17

  = 17 45 40.036 -29 00 28.17  J2000.00  J2000.00  FK5  0.000    0.0
 -> 359.94423   -0.04616  J2000.00  galactic (II)
```

A good reference for postional astronomy & coordinates is http://star-www.rl.ac.uk/docs/sun67.htx/sun67se4.html

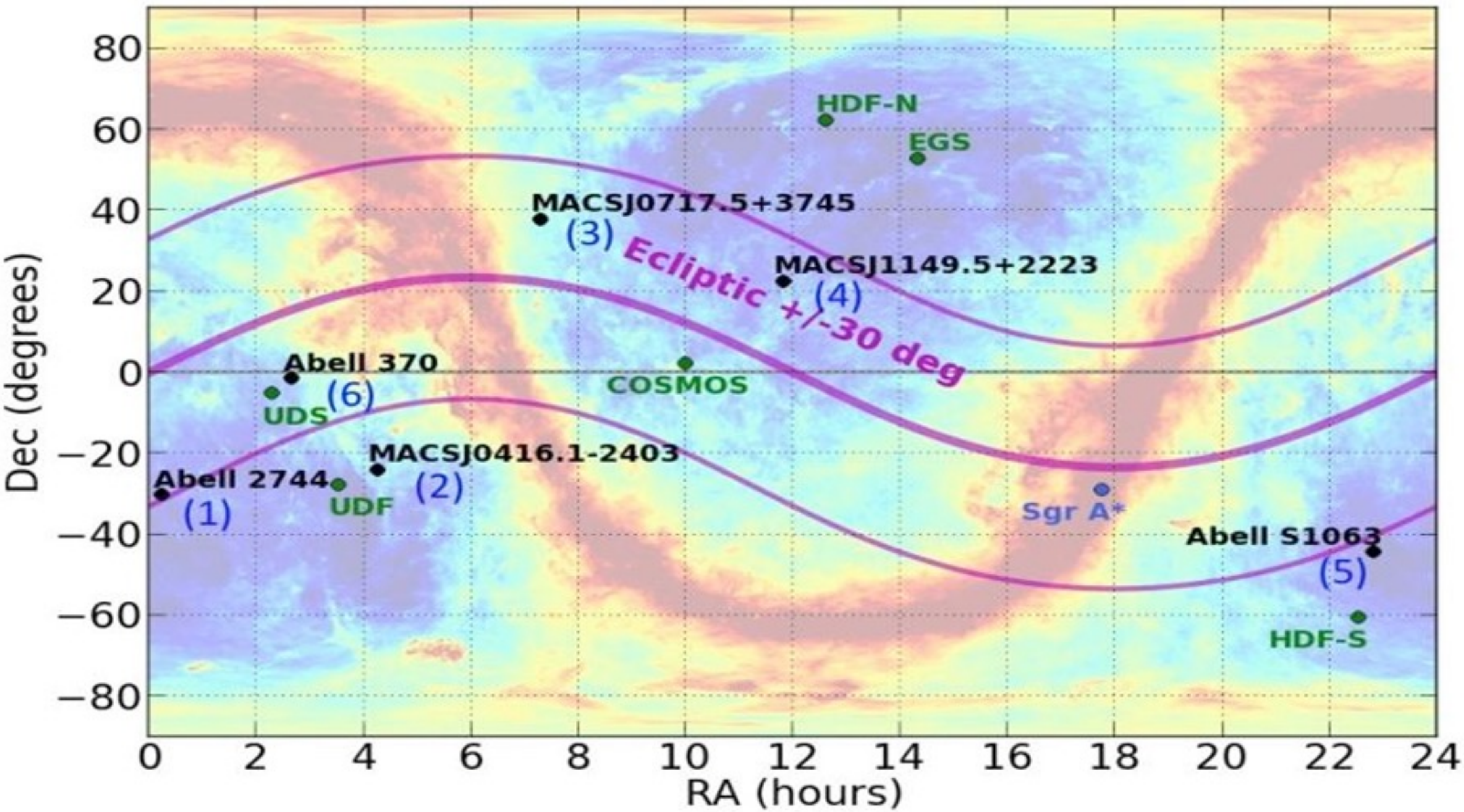
Galactic Coordinates



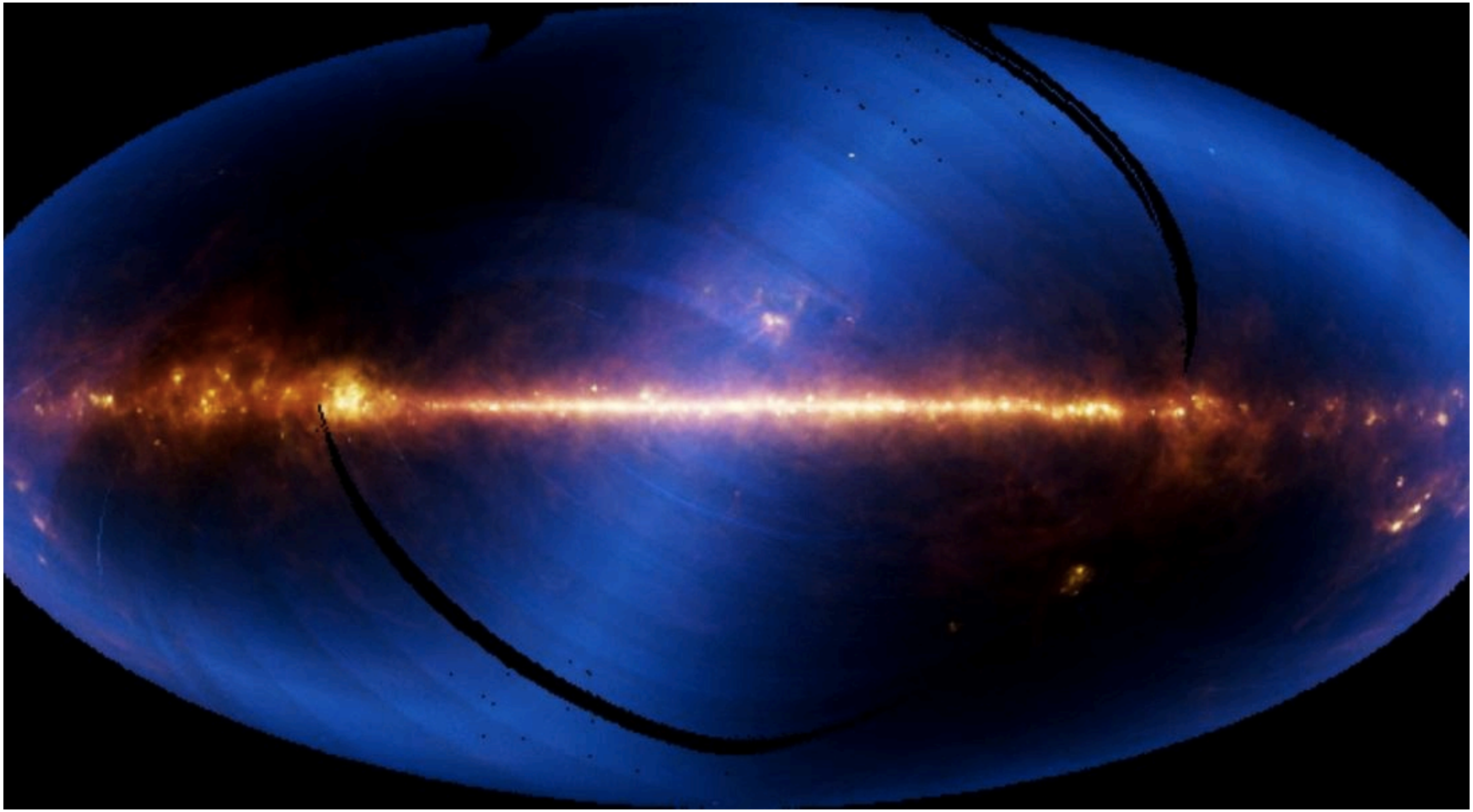


- Galactic coordinates (l^{II},b^{II}) with latitude b^{II} = 0 in the galactic plane, and l^{II}=0 toward the Galactic Center.
- Local Standard of Rest (LSR) moves with circular velocity about GC at Sun's radius.

Equatorial Coordinates



IRAS Survey



The Galactic Plane is the bright horizontal band, with Orion towards the right edge. The North and South celestial poles appear dark, as there is less dust emission while the faint blue haze represents warm dust emission from zodiacal light, tracing out the plane of the ecliptic