Observing Techniques & Instrumentation

Niranjan Thatte

About me

- I moved to Oxford 22 years ago and have been involved with many observatories, telescopes, and instruments, e.g.
  – Ph.D work with Hat Creek Radio Interferometer (later BIMA)
  – Visitor Instrument MPE-3D at AAT, WHT, La Silla 2.2m, Calar Alto
  – PI of tip-tilt AO corrector (ROGUE) for MPE-3D
  – Lead of AIM: interface between MPE-3D and ALFA
  – PI of SPIFFI (spectrometer in SINFONI) at ESO-VLT
  – Board member of LBT, Mt. Graham
  – Observer at Keck telescopes, Kitt Peak, VLA
  – PI of SWIFT IFS (with PALM3K AO) at Palomar 200 inch
  – Review panel chair or member for numerous instruments and telescope time allocation panels
  – PI of HARMONI – first light IFS for ELT
- Research interests in AGN/black holes, exoplanets, galaxy evolution, star formation, dynamics & kinematics.

Synopsis

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

Radio Astronomy

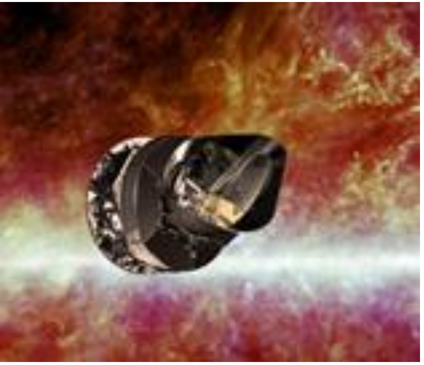
- VLA - ATCA - MeerKAT - e-Merlin
- GMRT

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

Revolutionary Capabilities at low-frequencies

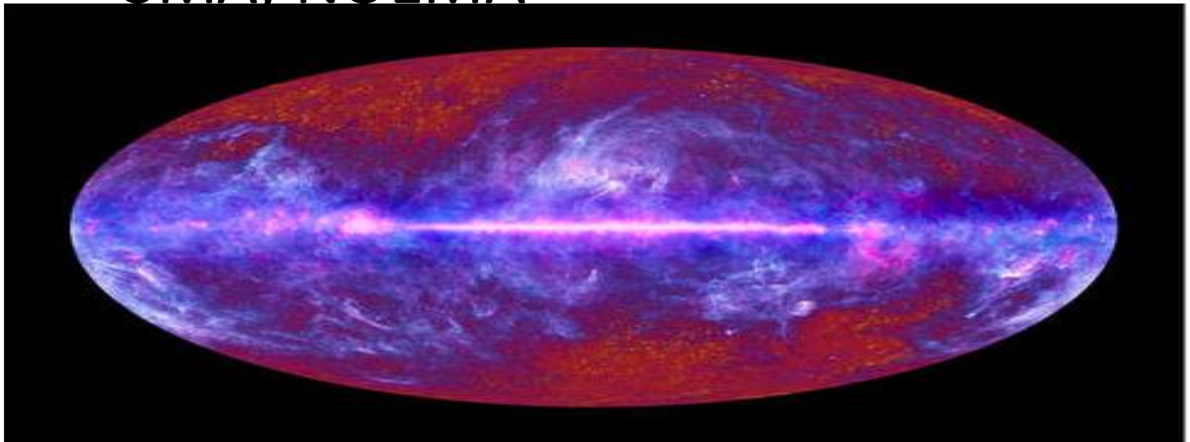
- EVLA 1 – 50GHz 27 × 25-m antennas 2-6μJy sensitivity
- LOFAR 30-250MHz NL/European Array Phased arrays baseline 100m -1500km
- SKA Pathfinders and Phase I:
  Phased array feeds
  - ASKAP 36 × 12-m dishes in WA
  - MeerKat 64 × 13.5-m dishes 1-15GHz
- Africa Telescope
  - Plans to connect surplus communication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



Microwave Astronomy

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

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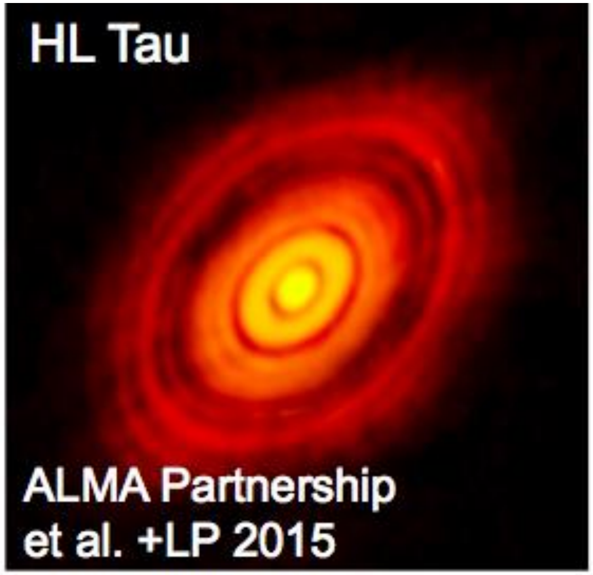
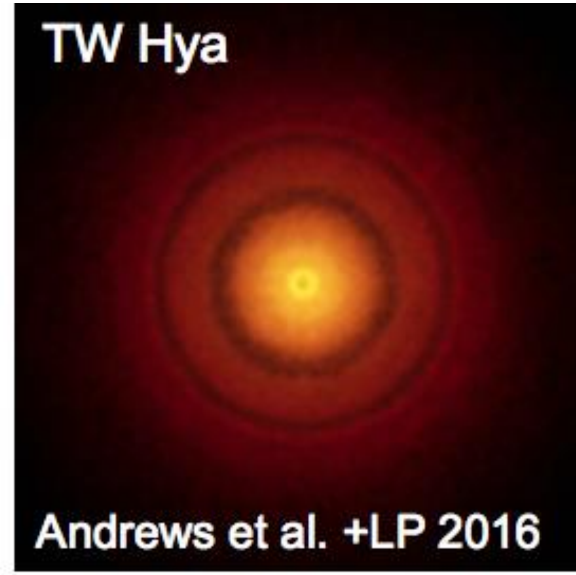
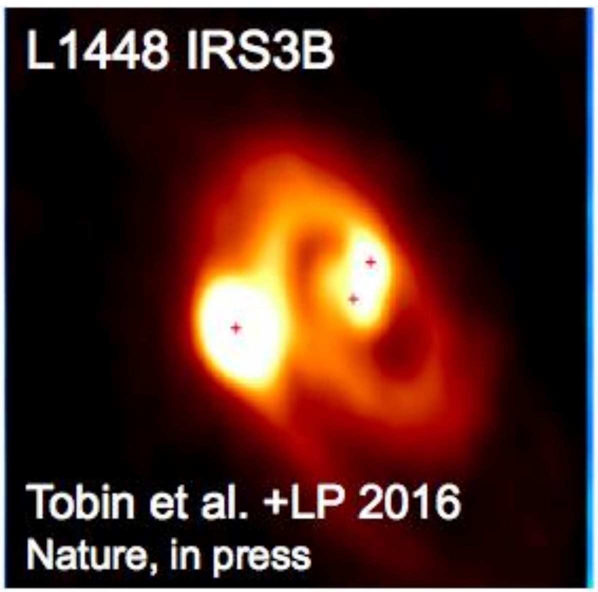
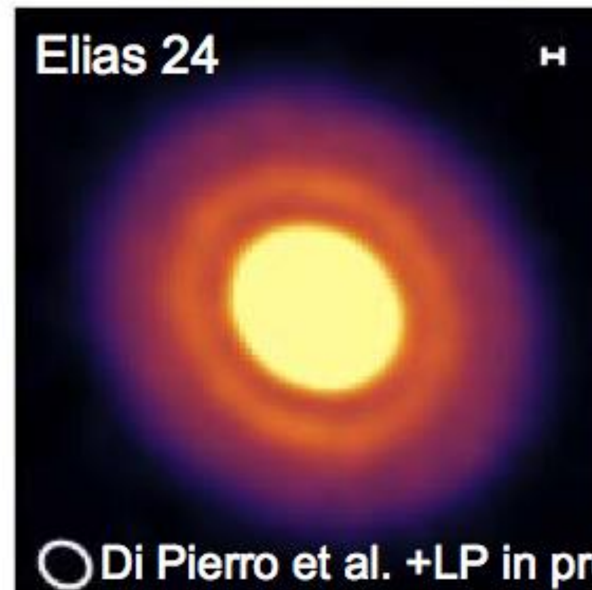

HL Tau
ALMA Partnership
et al. +LP 2015


V883 Ori
Cieza et al. 2016, Nature

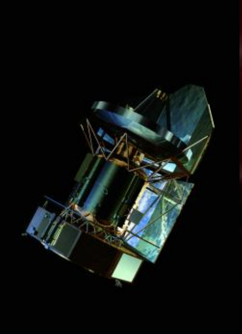

TW Hya
Andrews et al. +LP 2016

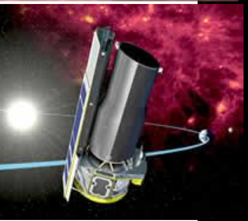

L1448 IRS3B
Tobin et al. +LP 2016
Nature, in press

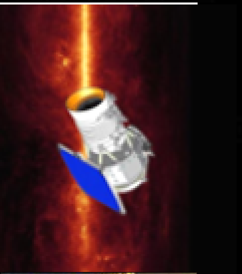

Elias 2-27
Pérez et al. 2016
Science, in press

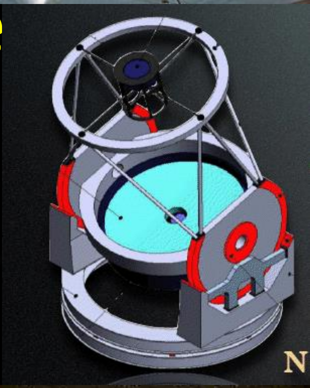

Elias 24
Di Pierro et al. +LP in pre

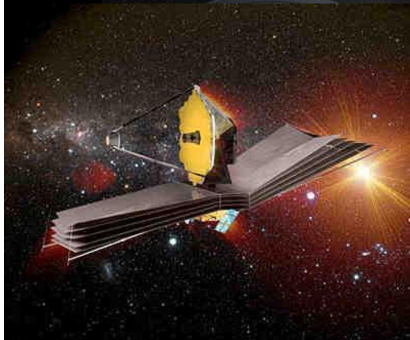
Infrared Surveys









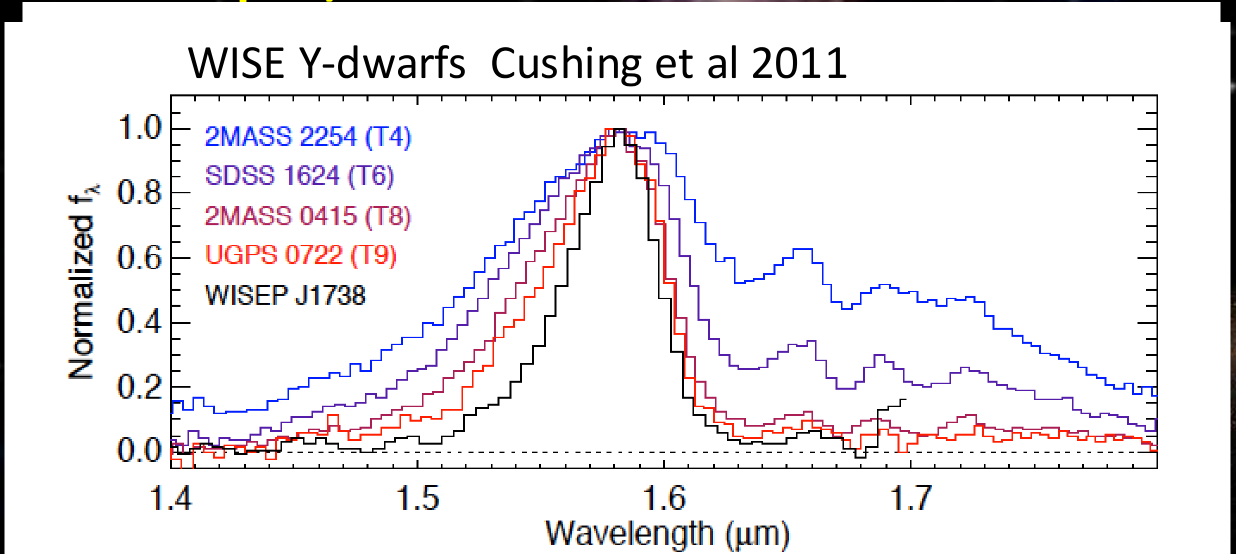


Herschel – ISO

IRAS - Spitzer – Akari - JWST

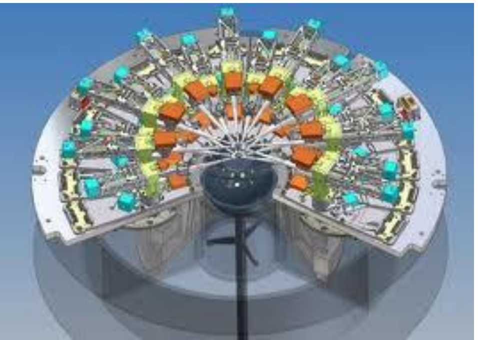
2MASS - UKIRT – VISTA – (SASIR)

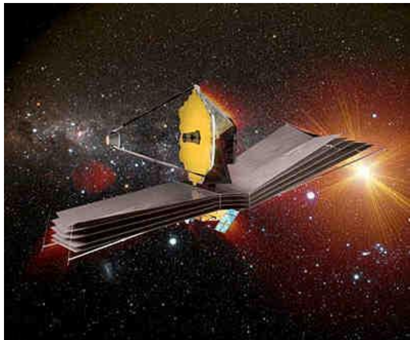
WISE – EUCLID - WFIRST (Roman Space Telescope)



New IR Facilities

- SOFIA (Boeing 747 borne 3.5m telescope) - retired
- Ground- based MOS and multi-IFU instruments
- Wider field and higher order Adaptive Optics
- Extremely Large Telescopes
- JWST
  - Synergies in the near-IR
  - Complementarity in the mid-IR
  - Resolution from the ground for the brightest objects
  - Sensitivity from Space. - launched in December 2021

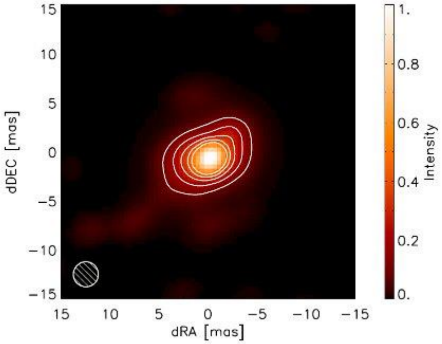




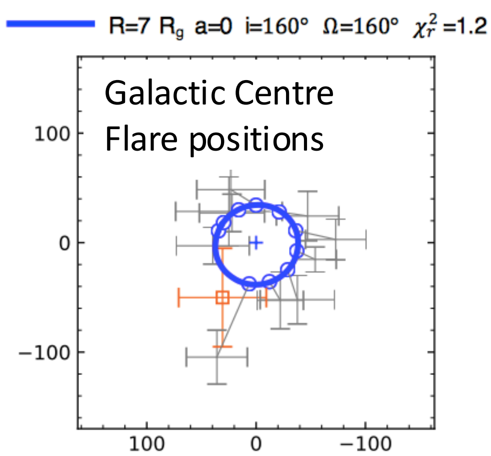
Infrared Interferometry

- Coherently combining beams from separated telescopes: 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, Gravity (+)

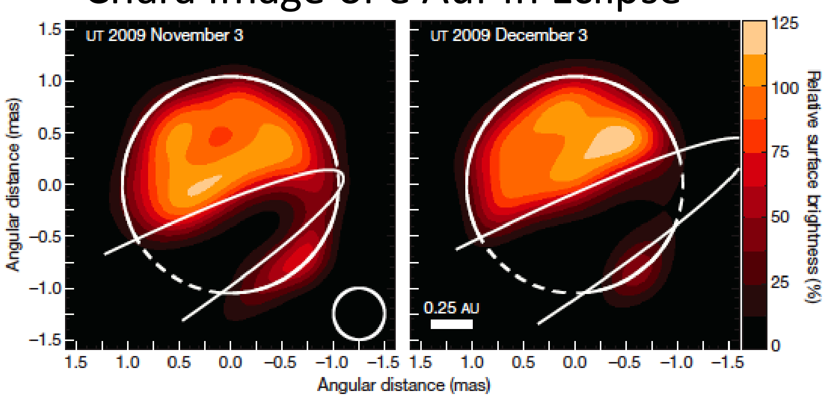
VLTI/AMBER image of the disk in IRAS 13481-6124

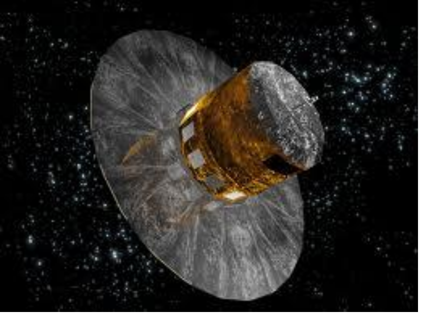


R Abuter et al 2018

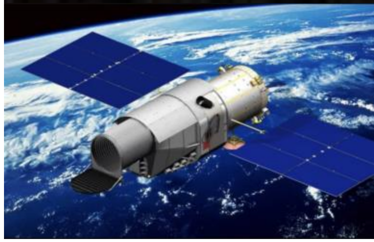


Chara image of ε Aur in Eclipse






Optical Surveys

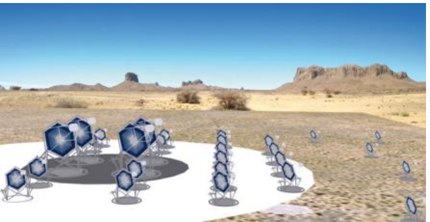


- HST, Galex Legacy, Xuntian (CSST)
- Imaging Surveys
  - PanStarrs, Skymapper, VST, DES, HSC
- LSST / Vera Rubin Observatory 8.4-m aperture
  - Legacy Survey of Space & Time, operations start 2025
  - Multifilter, deep maps of the southern sky every 3 days
- Large Spectroscopic Surveys
  - 2DF – SDSS – BOSS - LAMOST – HETDEX- DESI
- GAIA



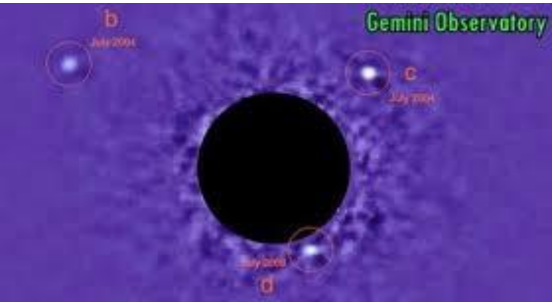
High Energy Facilities

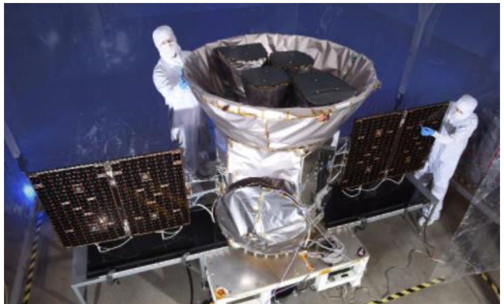
- Chandra - XMM-Newton – SWIFT – FERMI
- NuStar - (Hitomi) – XRISM – IXPE - Athena
- Cosmic ray telescopes
  - Auger + Enhancements
- Cerenkov Telescope Arrays
  - Hess, Magic, CTA

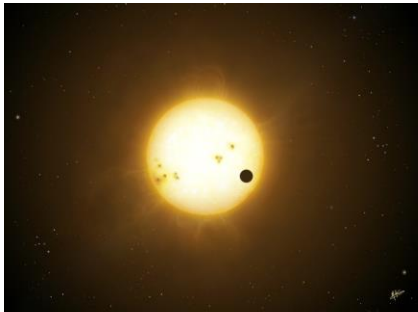


Exoplanet detection and characterization

- 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 ELT-PCS
- Astrometric Searches
  - Gaia, Gravity
  - magnetospheric radio emission : LOFAR and SKA
- microLensing detections

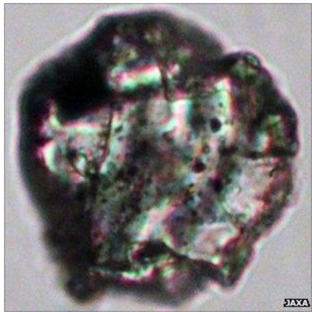






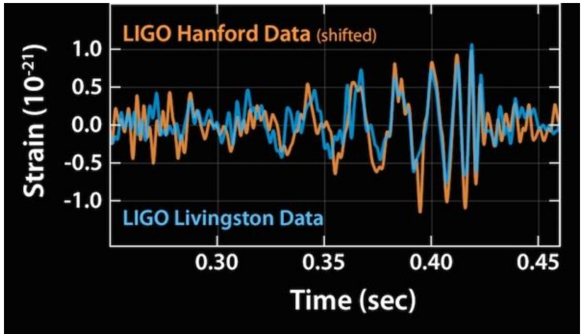
+ a host of other facilities

- 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



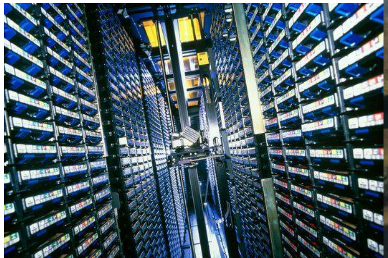
Beyond the Electromagnetic Spectrum

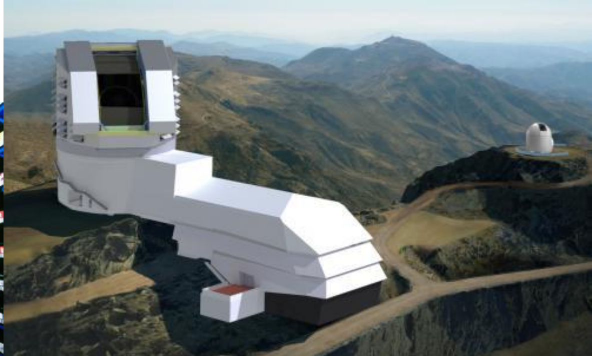
- aLIGO - VIRGO – GEO600 – LISA-Pathfinder
  - Gravitational wave detectors have opened up a new window.
  - Astronomical target identification and follow-up
    - Merging Black Holes, Coalescing neutron stars
- Direct Dark Matter detection
- Neutrinos and other Particle Physics



Opportunities in the Time Domain

- Quasi-continuous monitoring of large areas of sky provides new opportunities for discovery with SKA and LSST from 2025 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

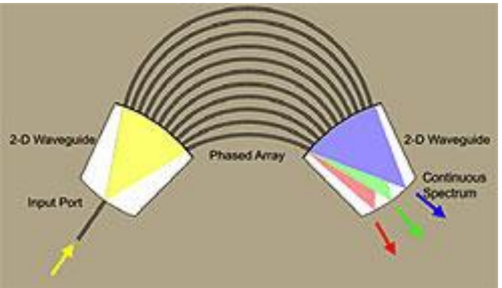
- Mega Constellations
  - Optical reflected light produces bright streaks
  - Radio communications and interference.

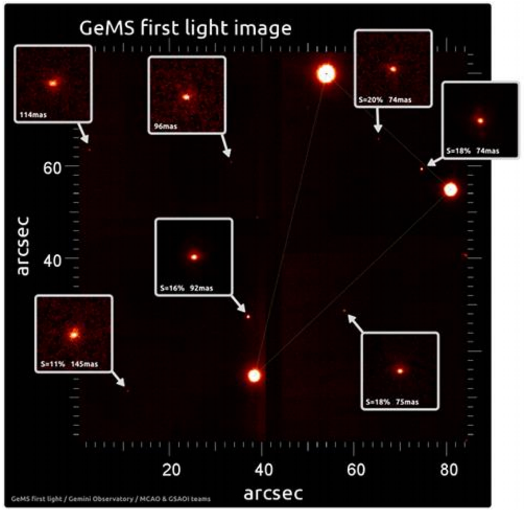
- Light Pollution and dust

- 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
  - Zero noise detectors (APD 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





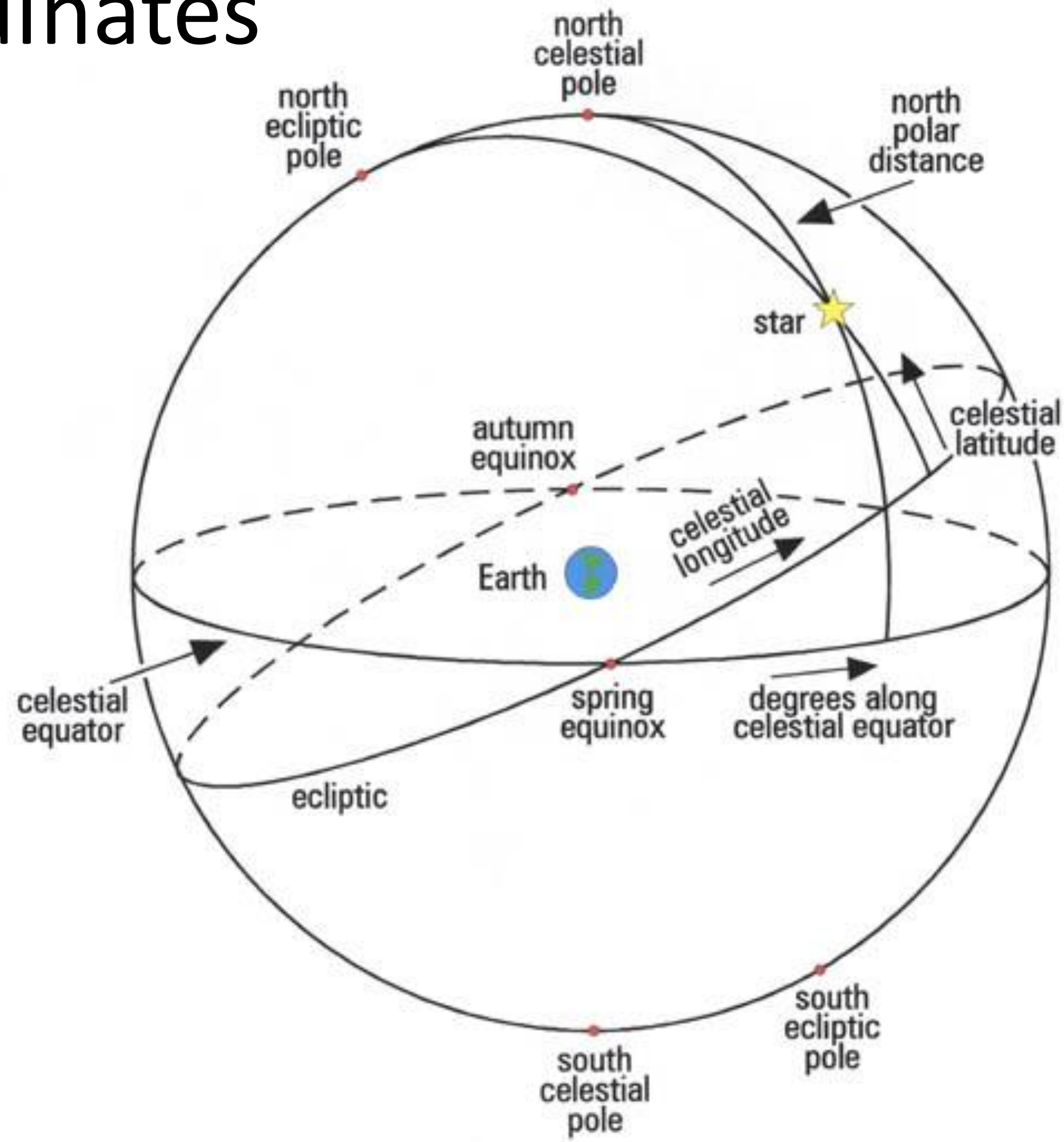
Astronomical objects

- 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″

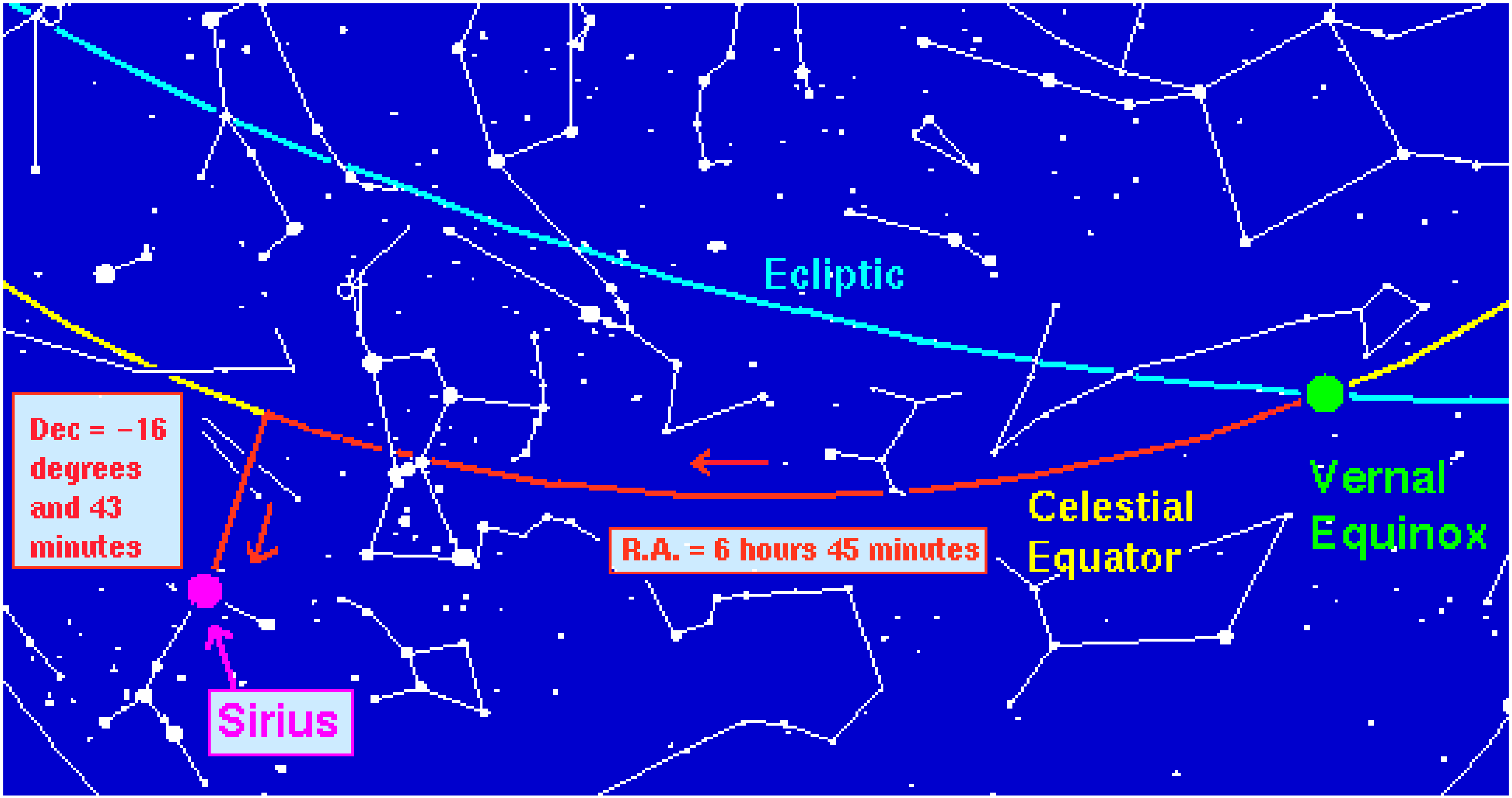
Celestial Coordinates

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 (~10^{-9} radians)



Celestial Coordinates



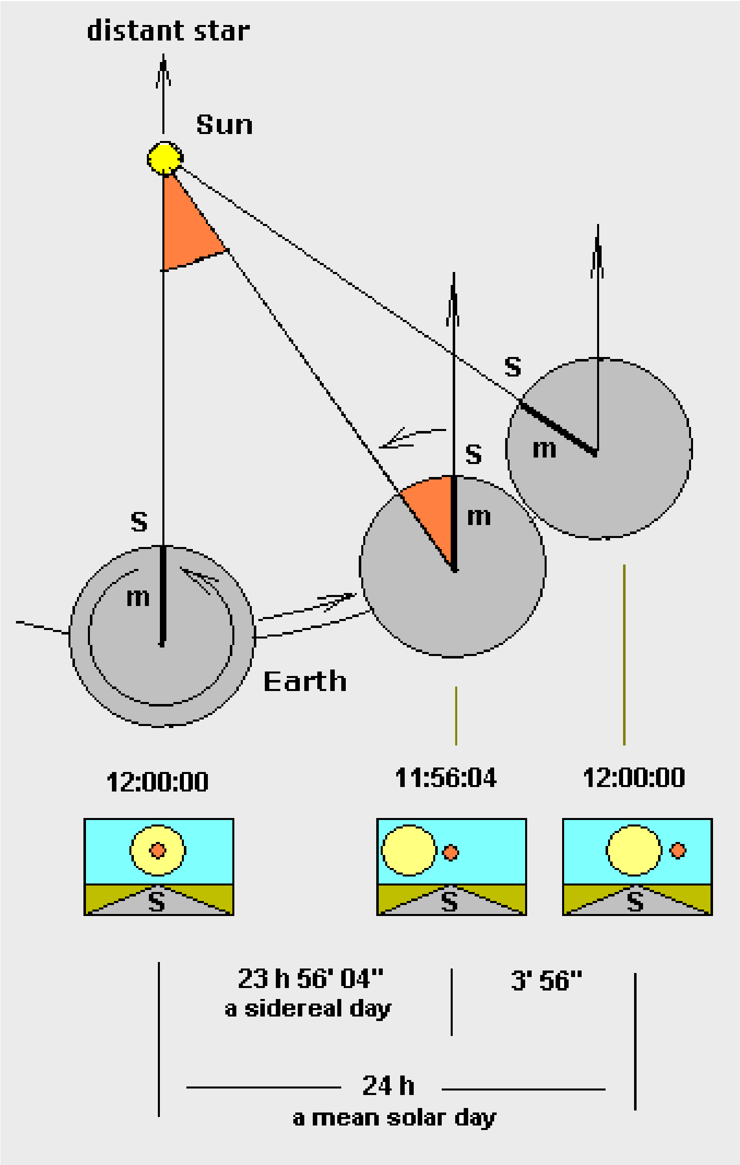
Coordinates

- 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 w.r.t 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)

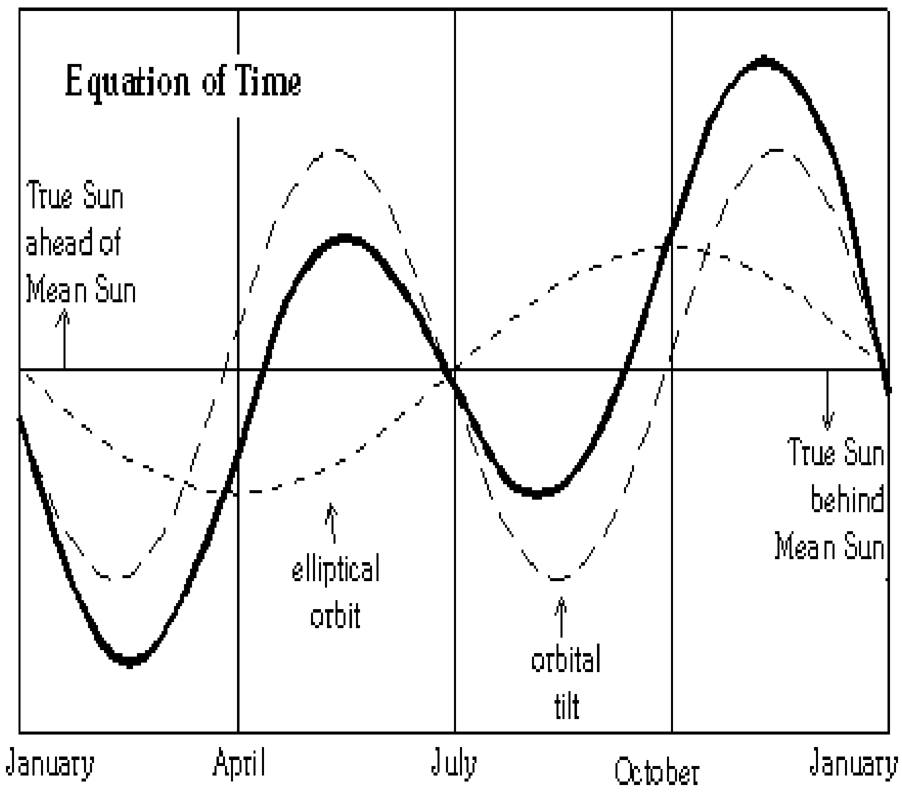
Equatorial Coordinates

- 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 stars.
- 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
  - ignore 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

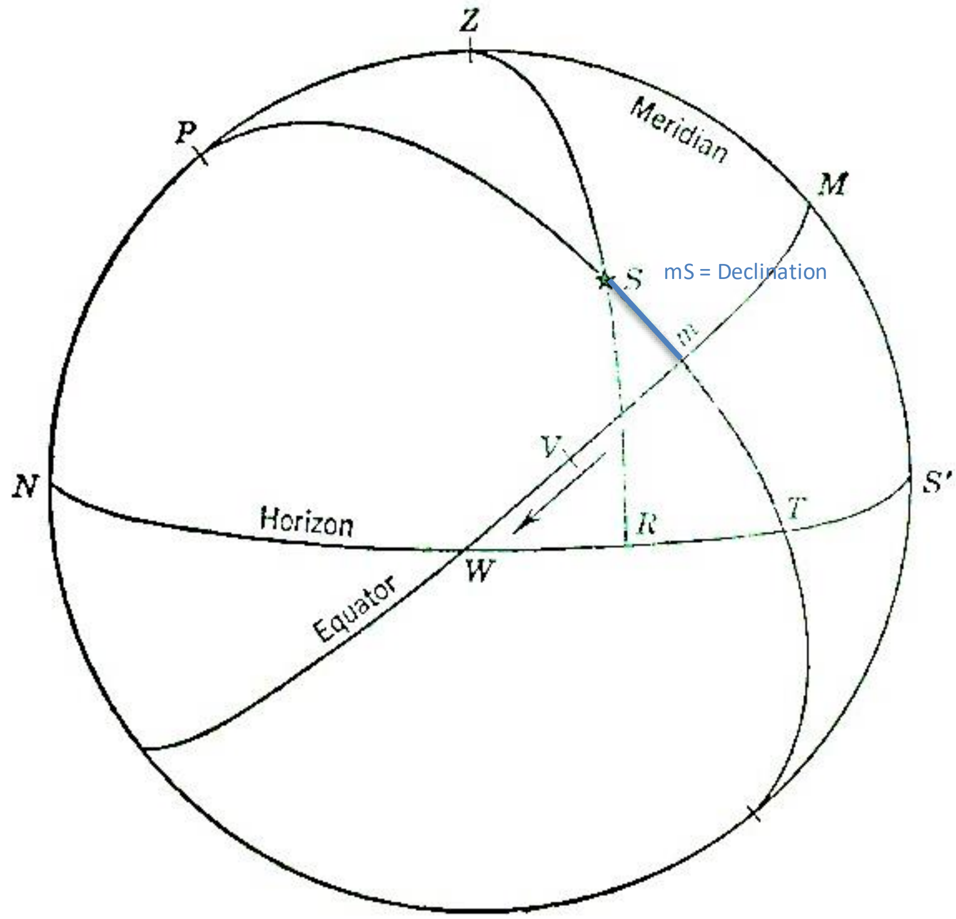


FIG. 20. The Sphere Seen from the Outside

The altitude (SR), is given by :

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

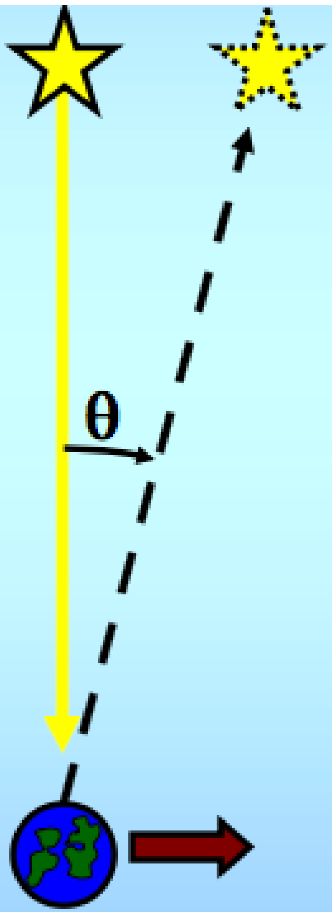
And the Zenith Distance, ZS = (90 – h) deg

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

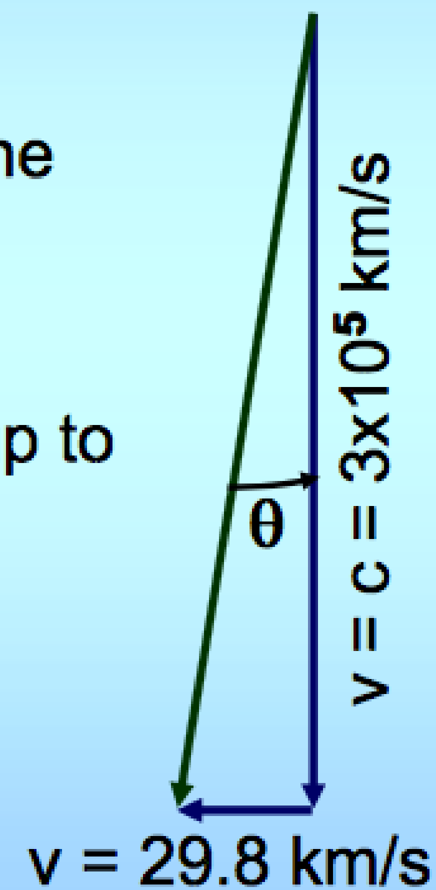
Stellar aberration – discovered by Bradley in 1727 when searching for stellar parallax



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.

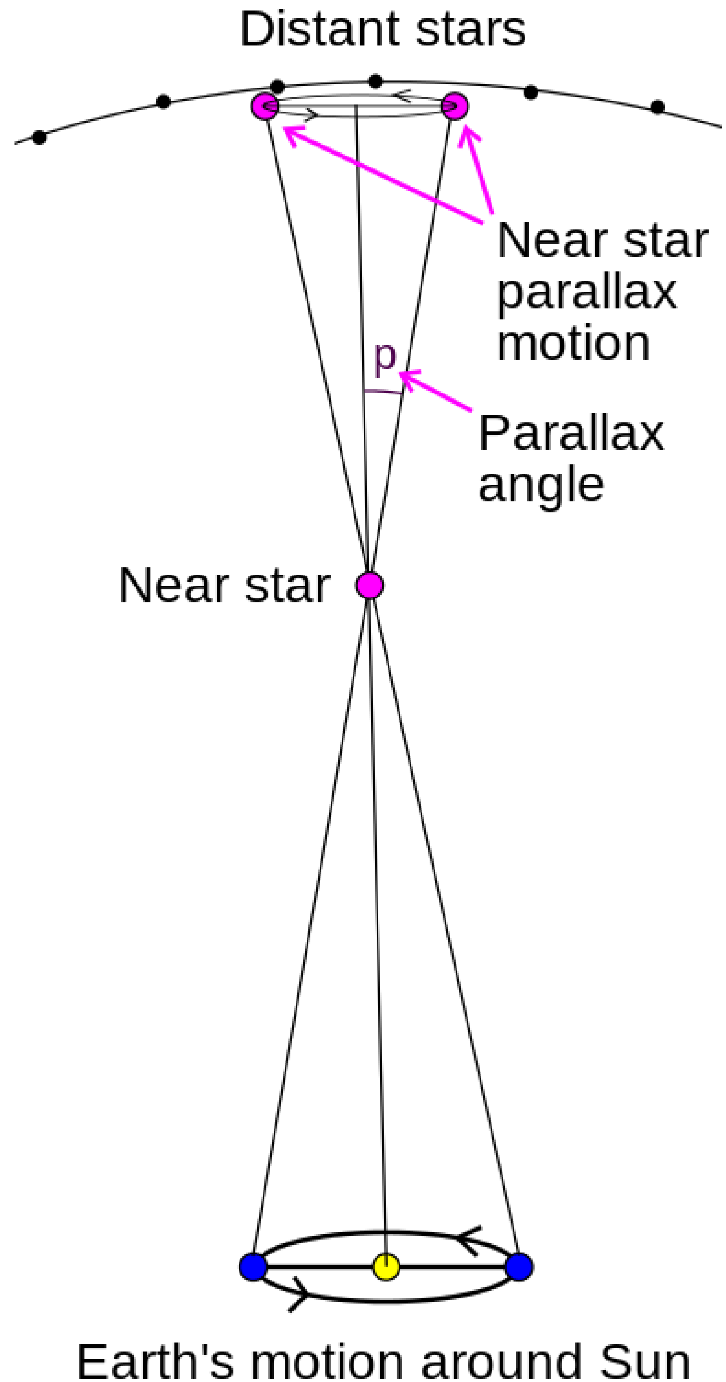
$$\tan\theta = \frac{29.8}{3\times10^5}$$

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



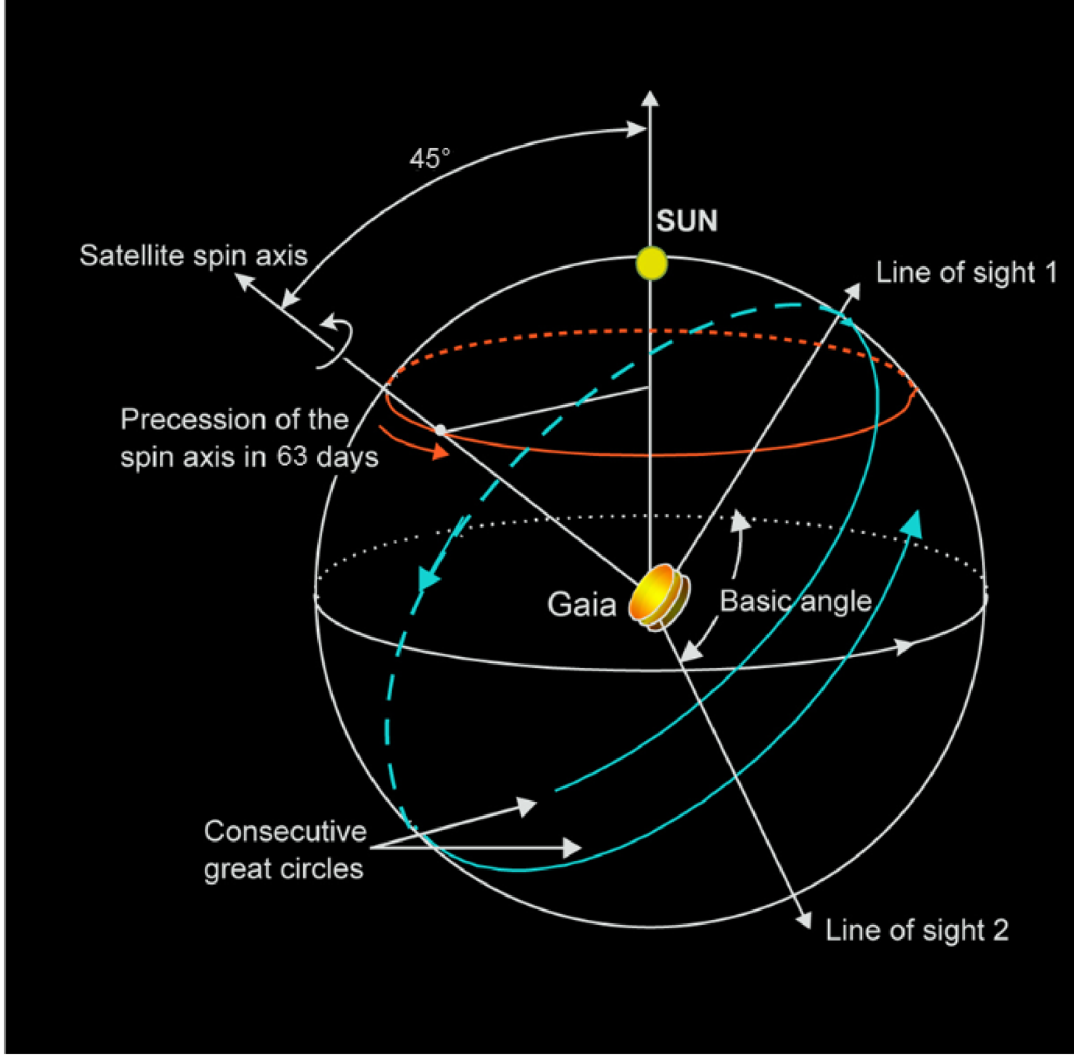
Parallax

- 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

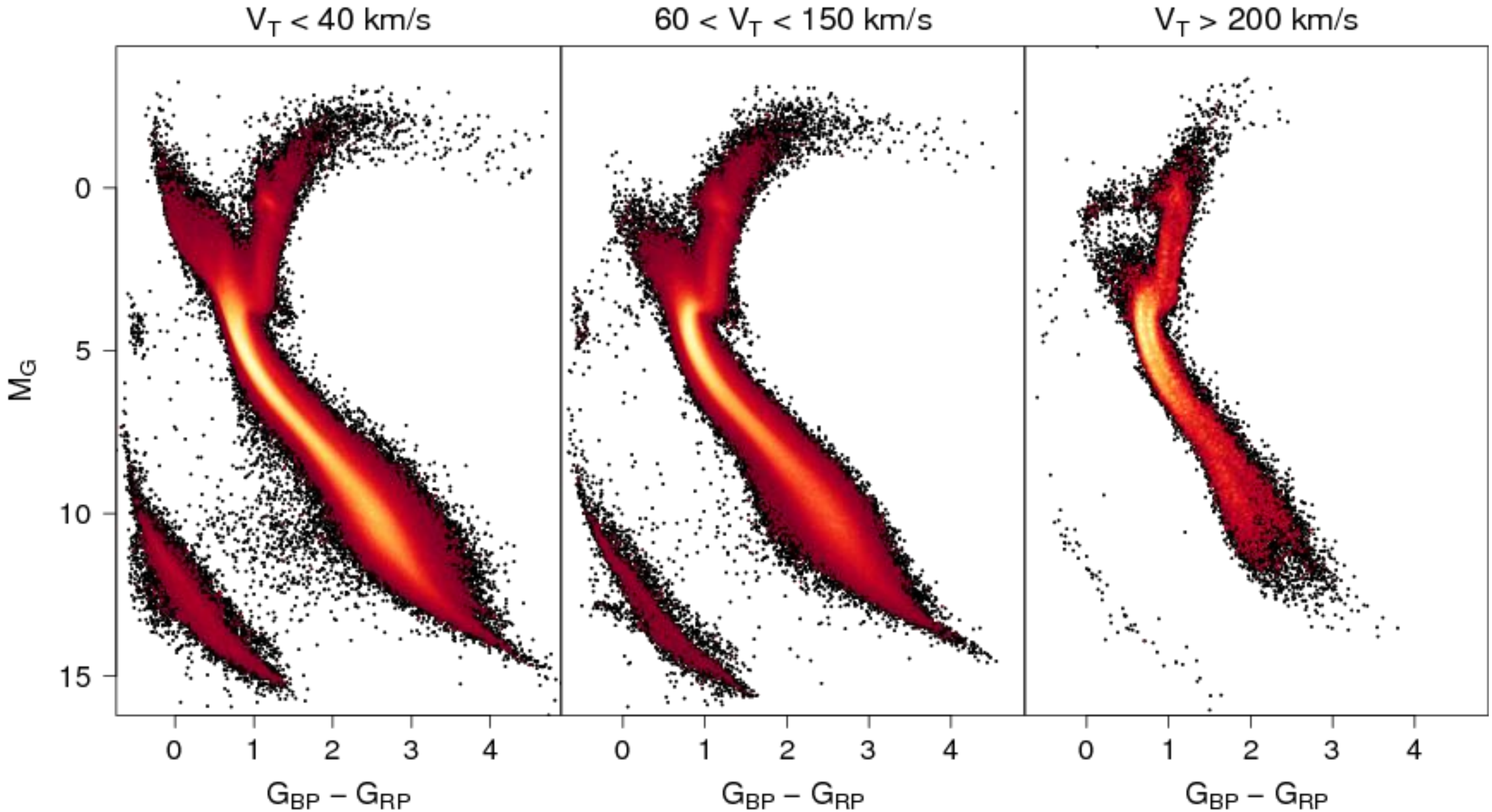


Gaia operations

- 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 in 2025



3rd data release occurred in June 2022 with 1.8 billion stars
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
Latest release includes 800,000 binary star system orbits and 33,000,000 radial velocities



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…
https://www.gaia.ac.uk/data/gaia-data-release-3