Observational Astronomy

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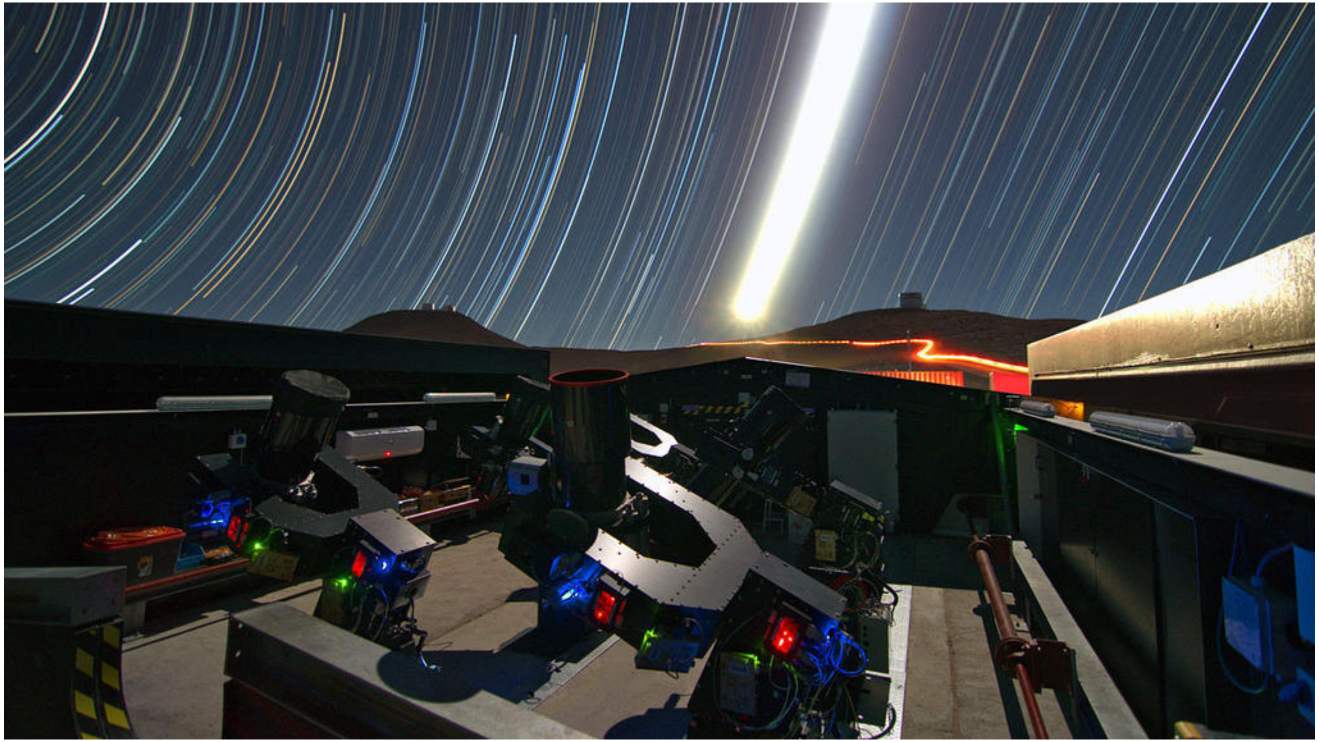

A brief history of observational astronomy

32,500 year old… star chart?

Astronomical alignments
e.g. Stonehenge c.5000 yr old

A brief history of observational astronomy

Armillary spheres and astrolabes

Independently invented in China and Greece c. 200bce

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Armillary spheres and astrolabes

Independently invented in China and Greece c. 200bce

Chaucer wrote a treatise on the astrolabe in 1391

A brief history of observational astronomy

The Antikythera Mechanism – a calendar and orrery from c.100bce

A brief history of observational astronomy

It took 1500 years to make similarly complex astronomical clocks – e.g. Samuel Watson of Coventry (1690)

Can show planetary orbits, dates, times, lunar and solar cycles, eclipses.

In the collection of Windsor castle (image reproduced from Royal Collections Trust)

The first telescopes

1608: Hans Lippershey/Jacob Metius
1608: Gallileo Gallilei
1611: Johannes Kepler

Refracting telescopes… may have been around decades before - or even longer

1668: Isaac Newton

Reflecting telescope – proposed earlier

1936: Karl Jansky

Radio telescopes

1963: Riccardo Giacconi

X-Ray telescopes

1968: Nancy Grace Roman

Space telescopes

Key Questions to consider:

Where is your target?
- coordinate systems
- precession of the equinoxes
- proper motion

When can you observe it?
- equatorial vs alt/az
- hour angles
- how do we measure time?

What effect will the atmosphere have?
- atmospheric refraction
- atmospheric extinction
- seeing and sky brightness
- adaptive optics

Angles

Observational astronomy is all about angles:

1 AU @ 1 pc subtends 1 arcsecond = 1”.

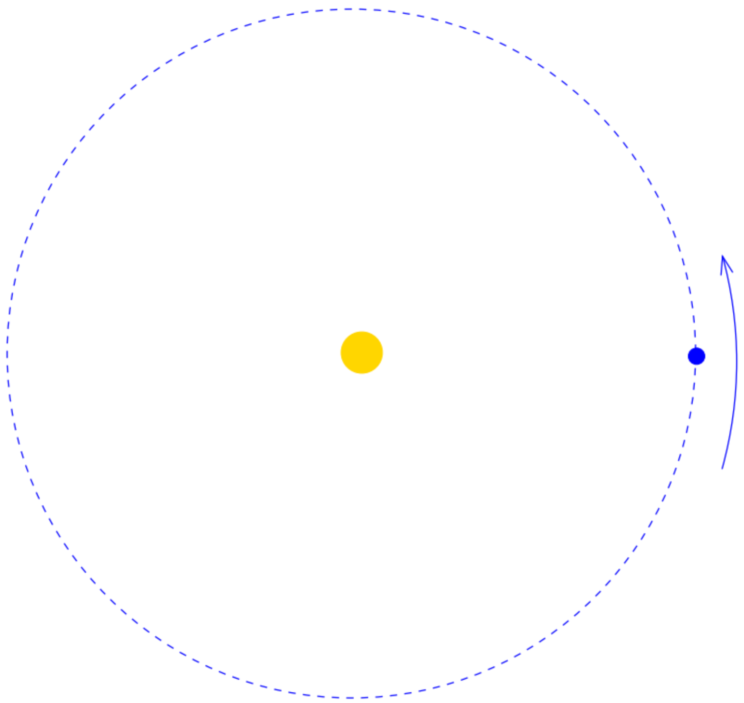
1” = 1/60’ = 1/3600° = 1/206264 radians.

Angles often written in the sexagesimal form inherited from the Babylonians, e.g.:

$$10° \, 24' \, 56.3'' = 10+24/60+56.3/3600 = 10.415639°$$

Sun & Earth

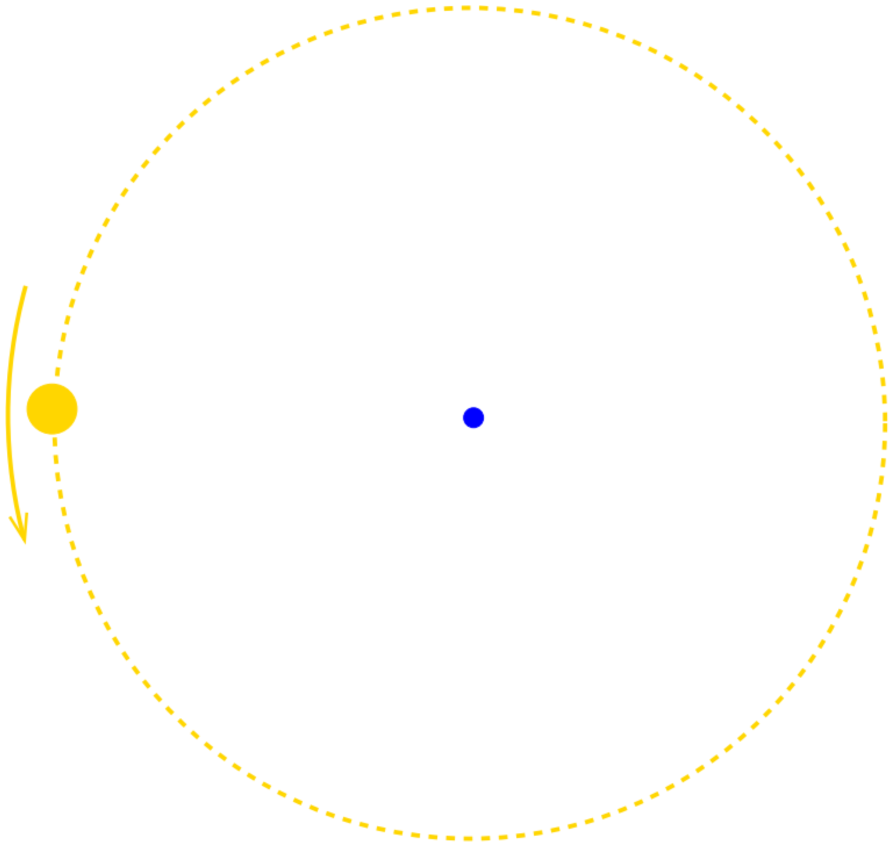
Earth goes round the Sun anti-clockwise when viewed from above the North Pole



Earth & Sun

For observing, it's sometimes convenient to adopt a Ptolemaic Earth-centred view (only aberration and parallax disturb this picture).

The Sun also goes anticlockwise.



Declination

Earth's rotation axis defines a natural polar axis ==> declination, equivalent to latitude on Earth

Declination runs from -90° to +90°, south to north pole.

Star trails from Tenerife, latitude +28°

Right Ascension

The equivalent of longitude is "Right Ascension" measured from the point where the Sun crosses the equator in spring (vernal equinox, also known as the "first point of Aries", but nowadays in Pisces due to precession).

Often measured in sexagesimal HH:MM:SS.SS

Sun at RA ~ 0, 6, 12, 18h at Mar 21, Jun 21, Sep 21 and Dec 21

Right Ascension in degrees

RA goes from 0 to 24 hours ==> 15° per hour.

So RA = 15:22:33.02 corresponds to:

15*(15+22/60+33.02/3600) = 230.63758°

Common to see / use both styles.

Right Ascension and Declination

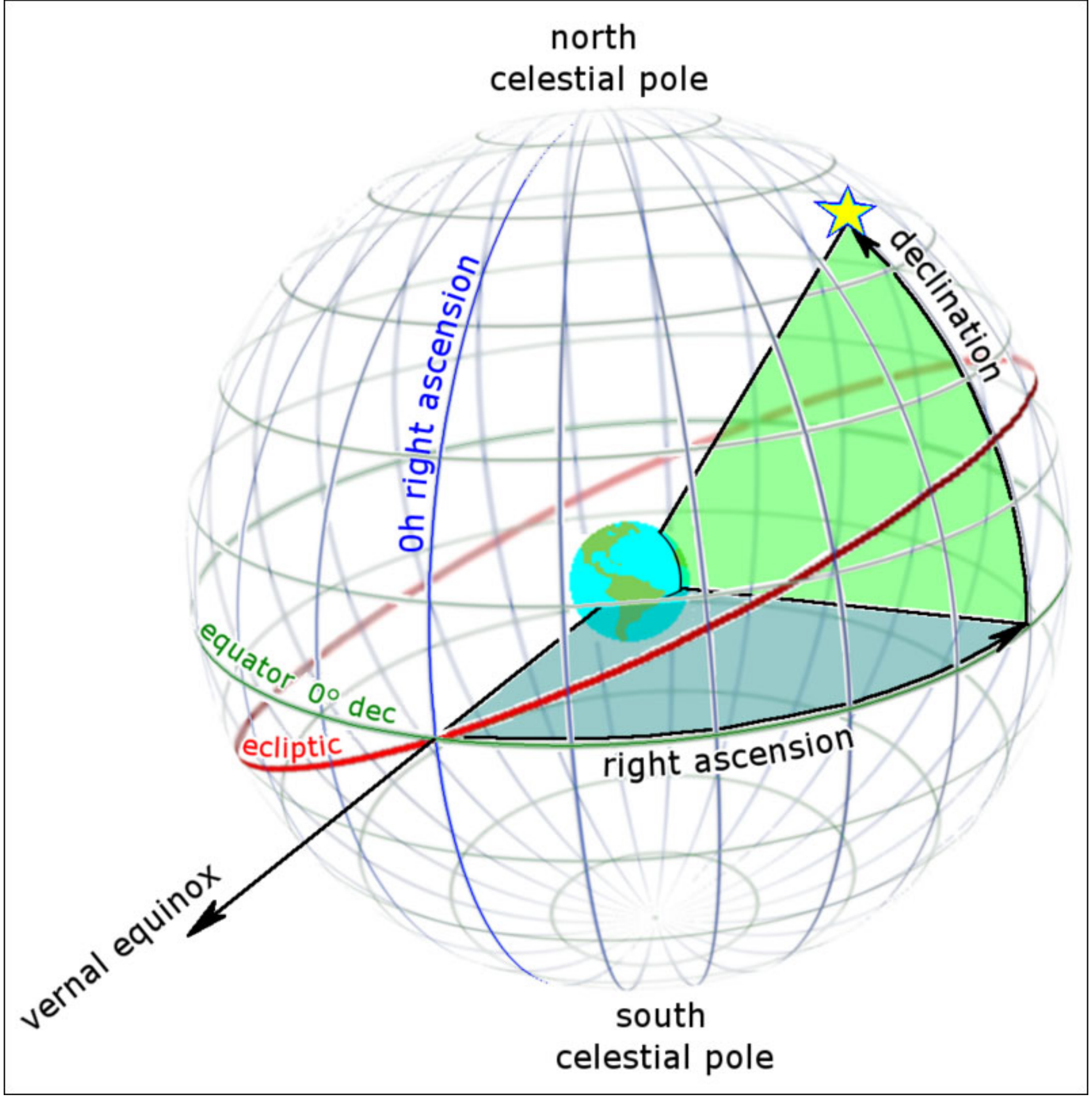


Image: https://skyandtelescope.org/astronomy-resources/right-ascension-declination-celestial-coordinates/

Ecliptic

Over the year the Sun traces out a great circle on the sky – the "ecliptic".

The ecliptic is tilted at 23.4° to the equator due to tilt of Earth's axis relative to it's orbital axis.

Thus the Sun is at (RA,Dec) = (α,δ) = (0^h,0°), (6^h,23°), (12^h,0°),(18^h,-23°) on the 21st of Mar, Jun, Sep and Dec.

Right Ascension and Declination

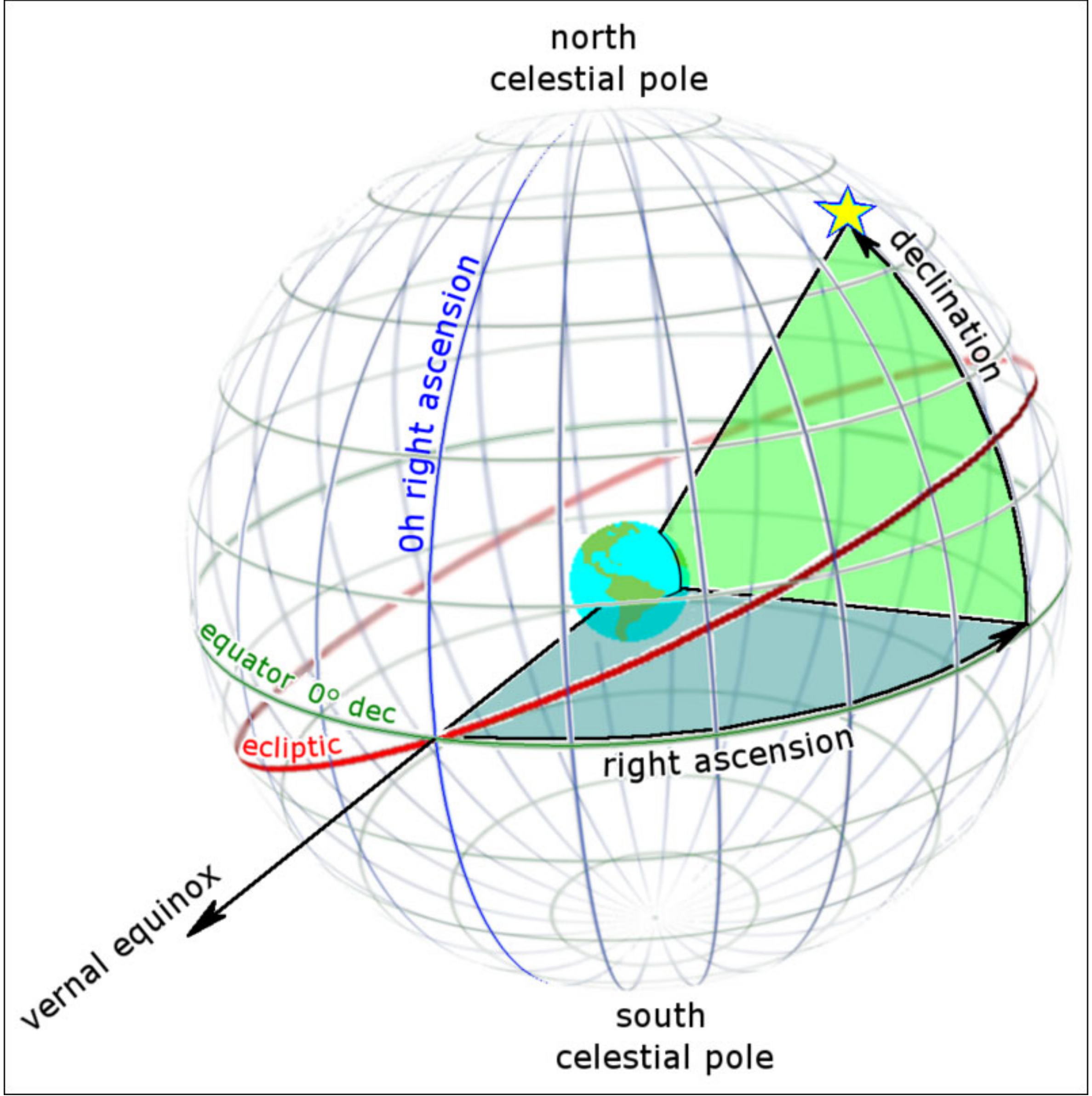
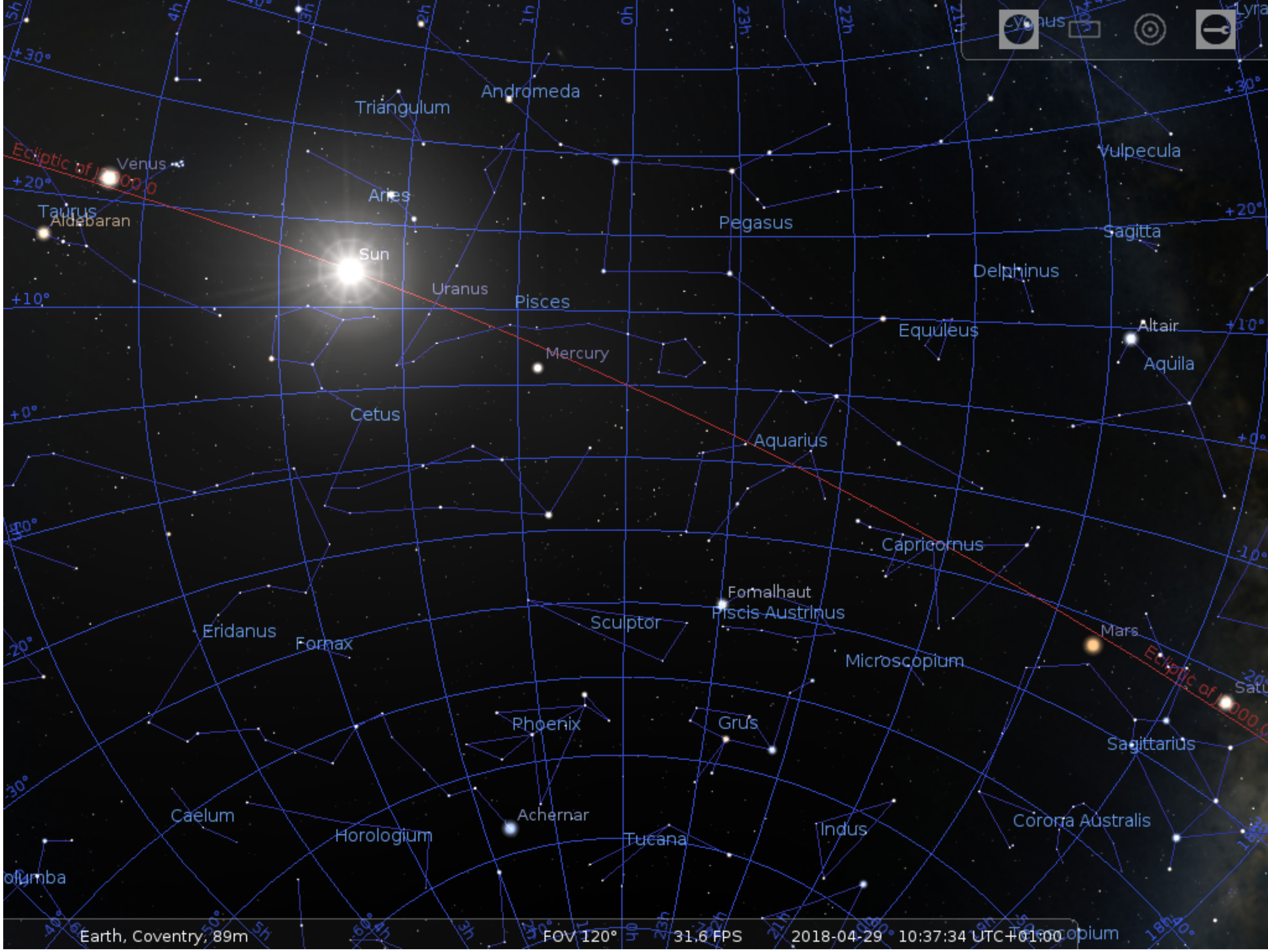


Image: https://skyandtelescope.org/astronomy-resources/right-ascension-declination-celestial-coordinates/

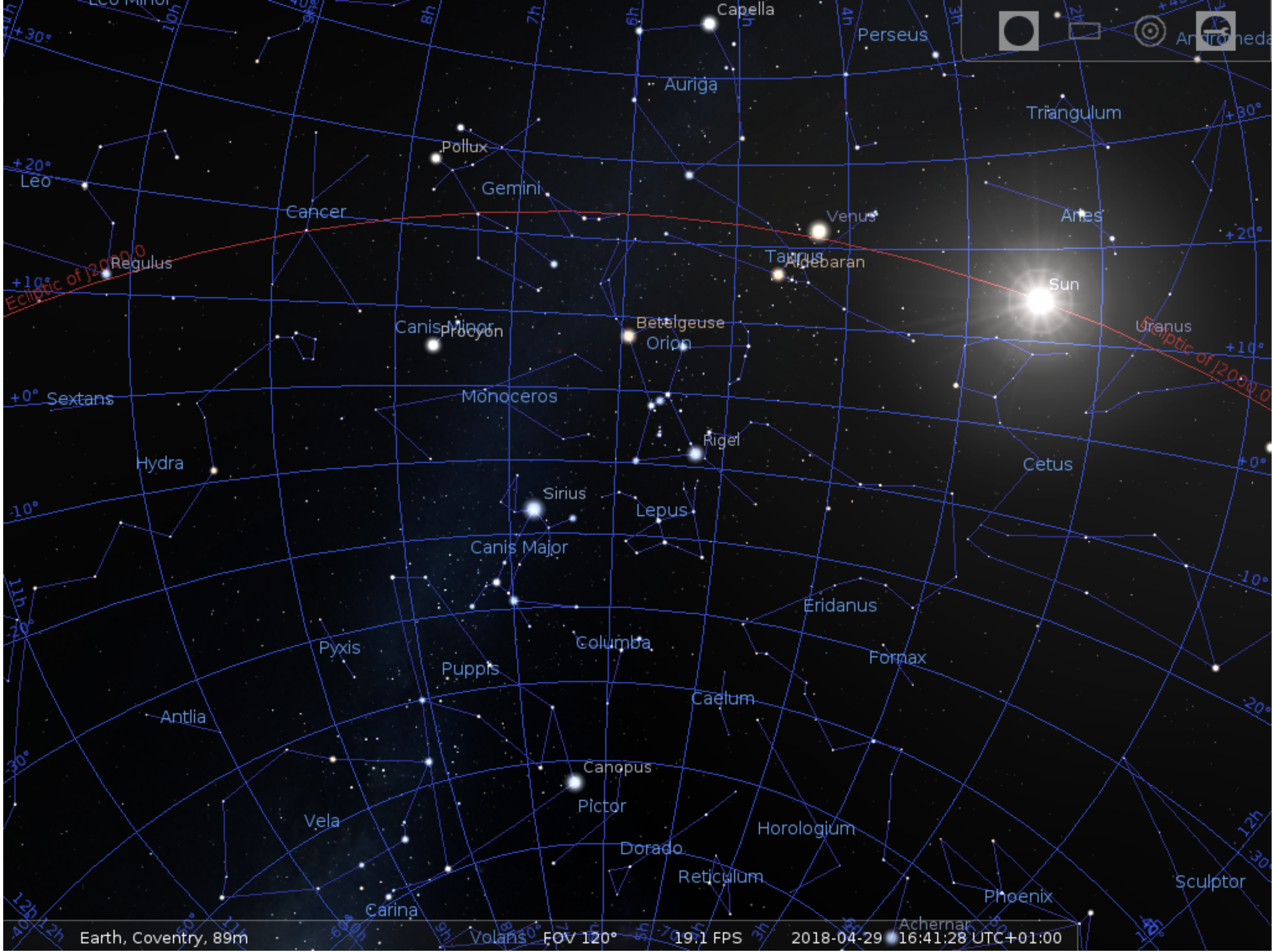
Sun on April 29, 2018, looking towards vernal equinox.

North is up; the Sun moves to the left and is moving North at the moment.



Same time, looking towards point of summer solstice (RA=6, Dec=+23)

Images made with *“stellarium” (free software)*



Moon & planets also near ecliptic

Atel 11448, 20 March 2018:

"Peter Dunsby (University of Cape Town) reports the detection of a very bright optical transient .... The object was … not seen when this field was observed previously …. The optical transient is at least first magnitude and is located at the following coordinates: RA (2000): 18h 04m 50s Declination (2000.0): -23d 29m 58s ….. Further observations are strongly encouraged to establish the nature of this very bright optical transient."

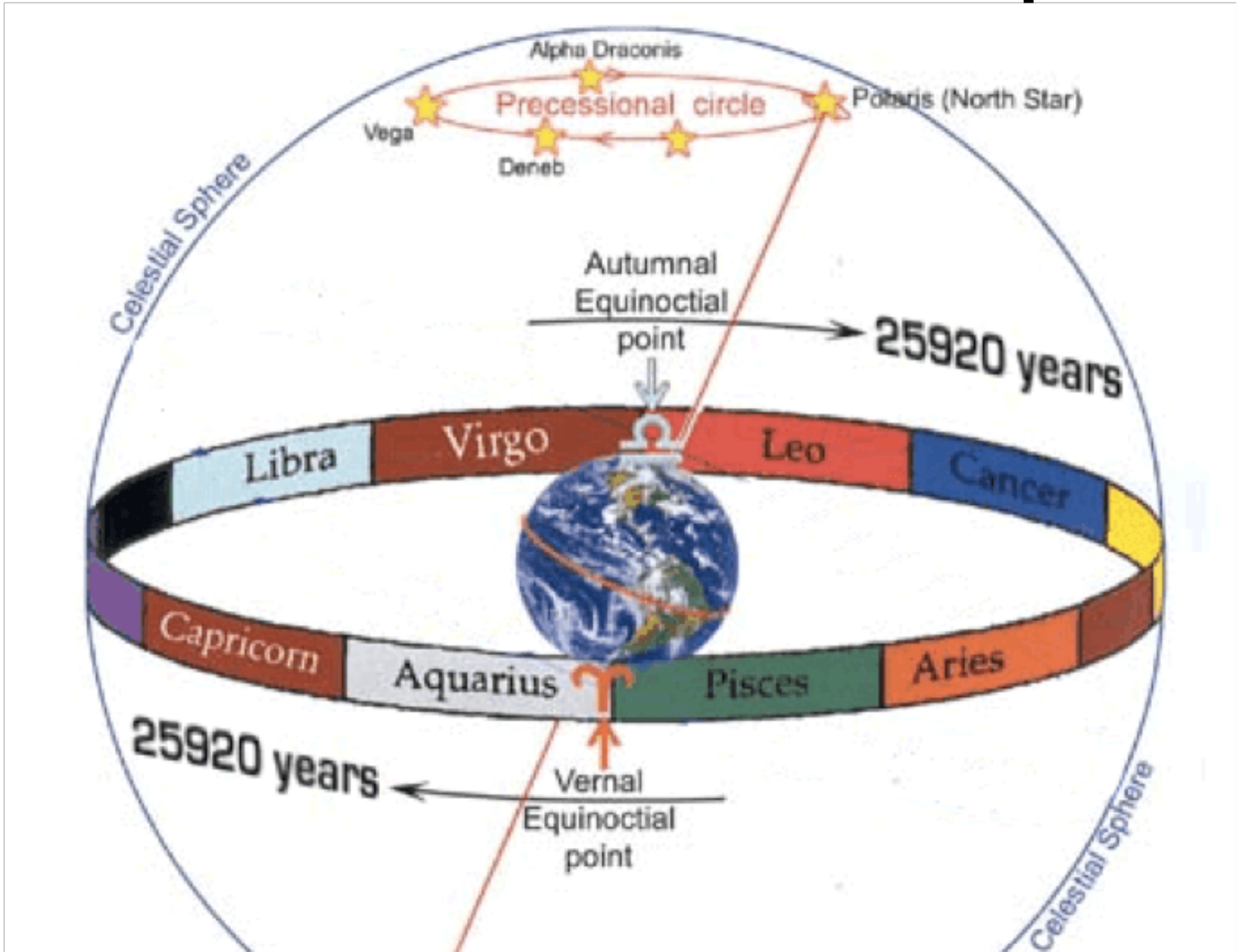
First Galactic SN since Kepler 1604?!? ….. or Mars ……

Precession of the Equinox

Earth's axis precesses around its orbital axis due to tides from Sun & Moon once per 26,000 years.

==> The north pole is constantly wobbling in a circle. Polaris is currently the "pole star" but for the Romans (~2000 years ago), other stars were closer to the pole.

Precession of the Equinox



Precession of the Equinox

Earth's axis precesses around its orbital axis due to tides from Sun & Moon once per 26,000 years.

==> RAs, Decs of celestial objects vary with time.

Need to specify date ("B1950.0", "J2000.0"). e.g. position of quasar 3C 273:

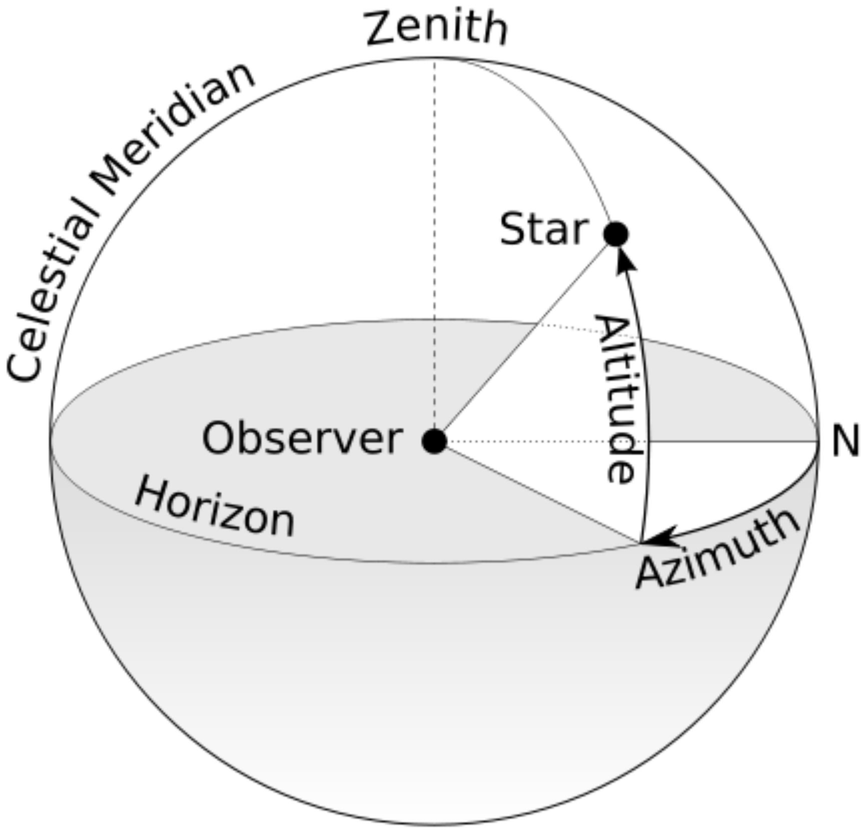
RA = 12 29 06.70, Dec = +02 03 08.7 (J2000)

RA = 12 26 33.28, Dec = +02 19 43.1 (B1950)

Azimuth & Elevation

RA & Dec are “equatorial coordinates”.

When observing, the position on the sky is measured by azimuth and elevation (aka altitude, hence “alt/az”)



Bluff your way in … *observing*

Meridian: imaginary line running North-South. Objects reach their maximum elevation on the meridian (“transit” or “culmination”)

Zenith: point directly above observer (elevation = 90°)

Zenith distance (z): angle measured from zenith (90-elevation)

Airmass (X): amount of atmosphere one is looking through relative to the zenith [~ sec(z)].

Hour angle (h): hours since object crossed the meridian.

Local Sidereal Time (LST): RA of object on meridian

RA, Dec to Alt, Az

RA, H.A. and LST are linked:

hour angle, $h = LST - RA$

h, the observer's latitude *l* and the declination δ are enough to determine the azimuth *a* and elevation *e.* There are some unmemorable formulae for this:

$$\cos(e)\cos(a) = \cos(l)\sin(\delta) - \sin(l)\cos(\delta)\cos(h)$$

$$\cos(e)\sin(a) = -\cos(\delta)\sin(h)$$

$$\sin(e) = \sin(l)\sin(\delta) + \cos(l)\cos(\delta)\cos(h)$$

but use astropy.coordinates (Python) or equivalent!!

Stellarium

Free software usually used by amateurs or for general interest.

Web version is simpler but easy to use without needing downloads

Automatically calculates precession, as well as RA and Dec and Alt/Az for a given time and observing location

Includes atmosphere etc.

Good for building intuition about how the sky moves.

https://stellarium.org/
https://stellarium-web.org/

Activity

We're going to look at Kepler's Supernova:

Location: 17h 30m 42s -21deg 29m

Date: 8th October 1604

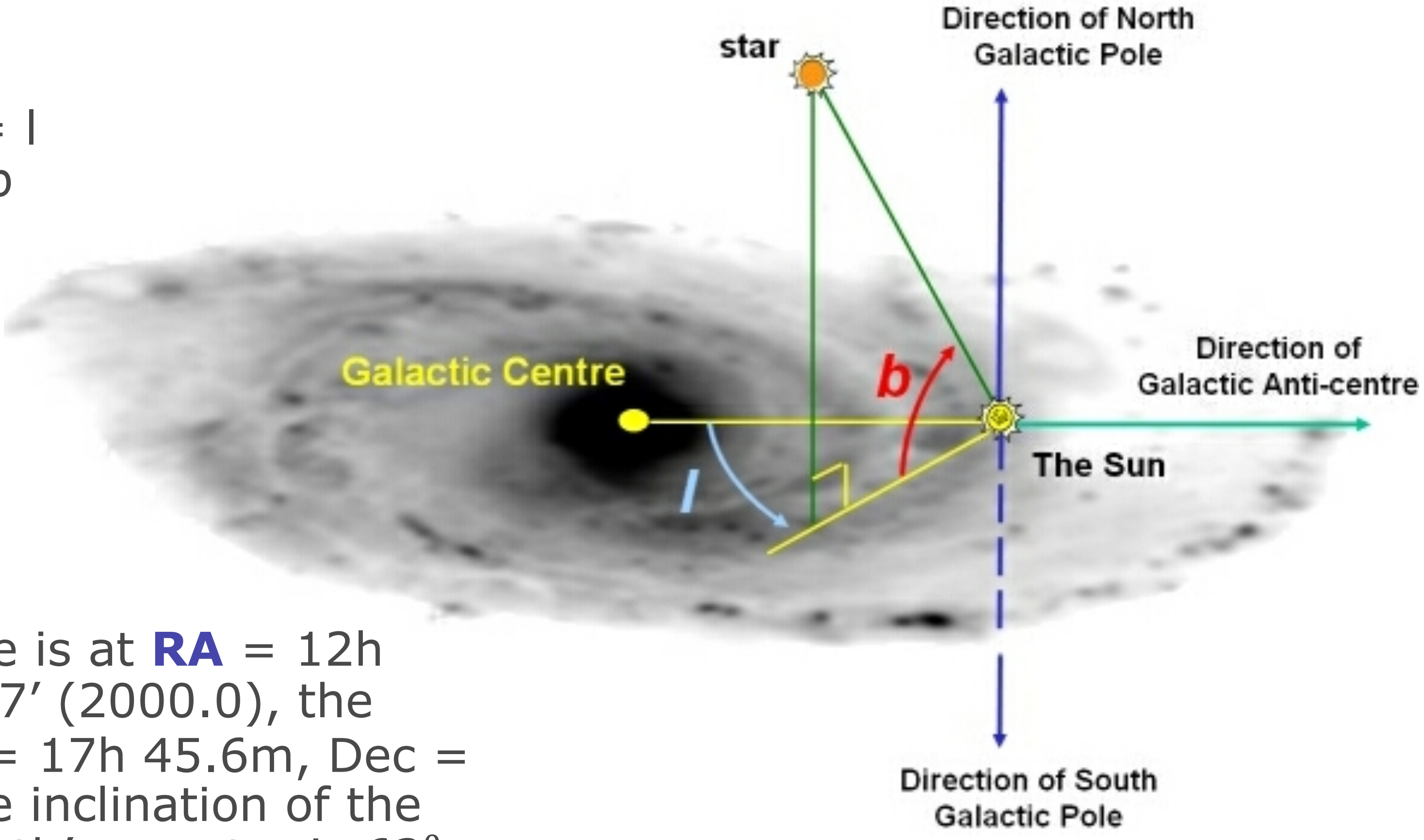
Observed from: Prague, visible for 18 months

Consider this event using Stellarium.

What direction was Kepler looking? At what time of night? What else was nearby in the sky? What challenges did he face? How did observability change over time?

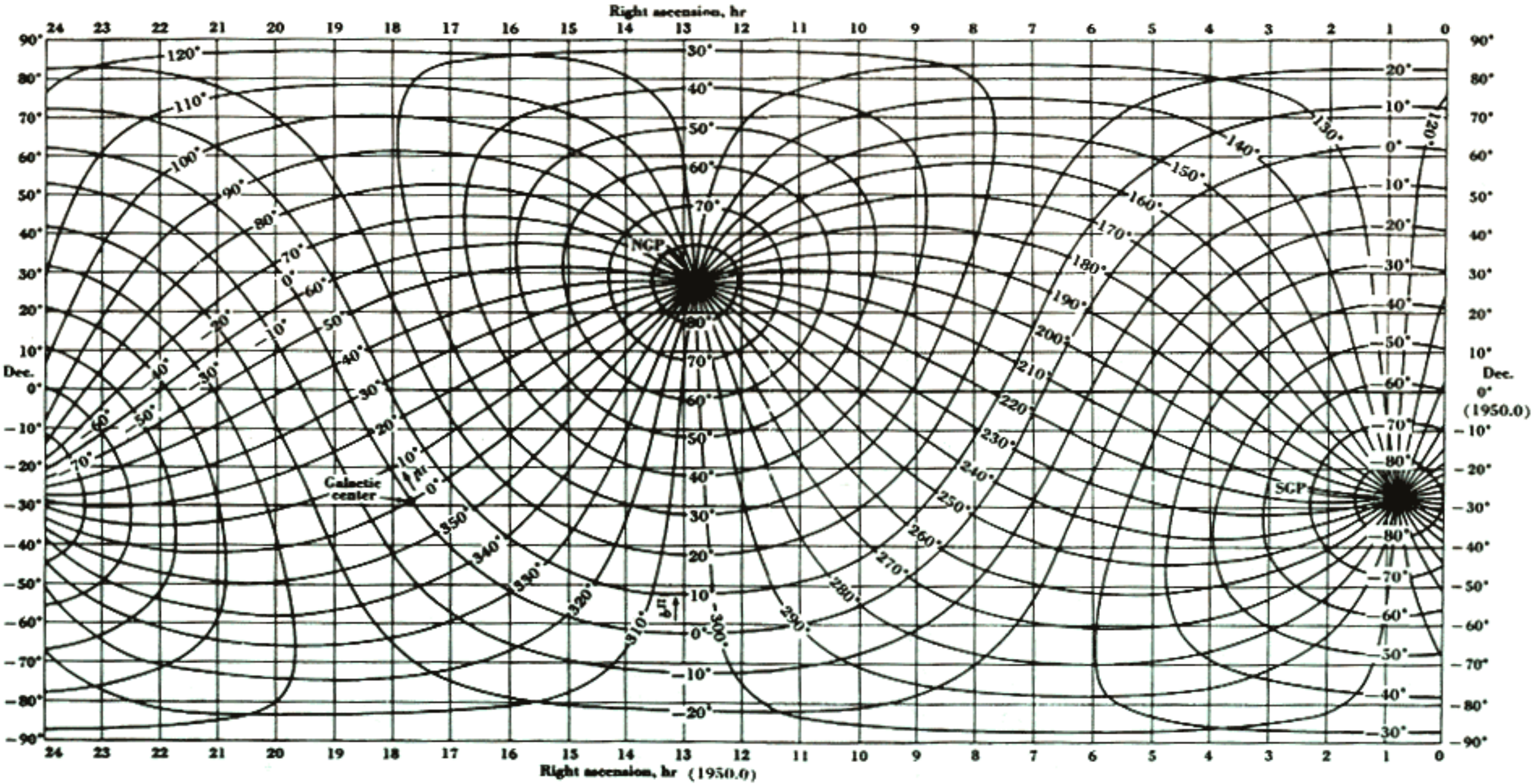
Galactic Coordinates

Galactic longitude = l
Galactic latitude = b



The galactic north pole is at **RA** = 12h 51.4m, **Dec** = +27^0 07′ (2000.0), the galactic centre at RA = 17h 45.6m, Dec = -28^0 56′ (2000.0). The inclination of the galactic equator to Earth's equator is 63^0.

https://astronomy.swin.edu.au/cosmos/G/Galactic+Coordinate+System



http://egg.astro.cornell.edu/alfalfa/grads/set5.htm

ICRS

International Celestial Reference System (ICRS): fixed reference frame defined by distance objects (QSOs).

Defined to be close to J2000 equinox coordinates.

(NB Precession is why the constellations of the "zodiac" beloved of astrologers are not quite right. e.g. you could be"a Scorpio" but the Sun was in Libra when you were born – oops.)

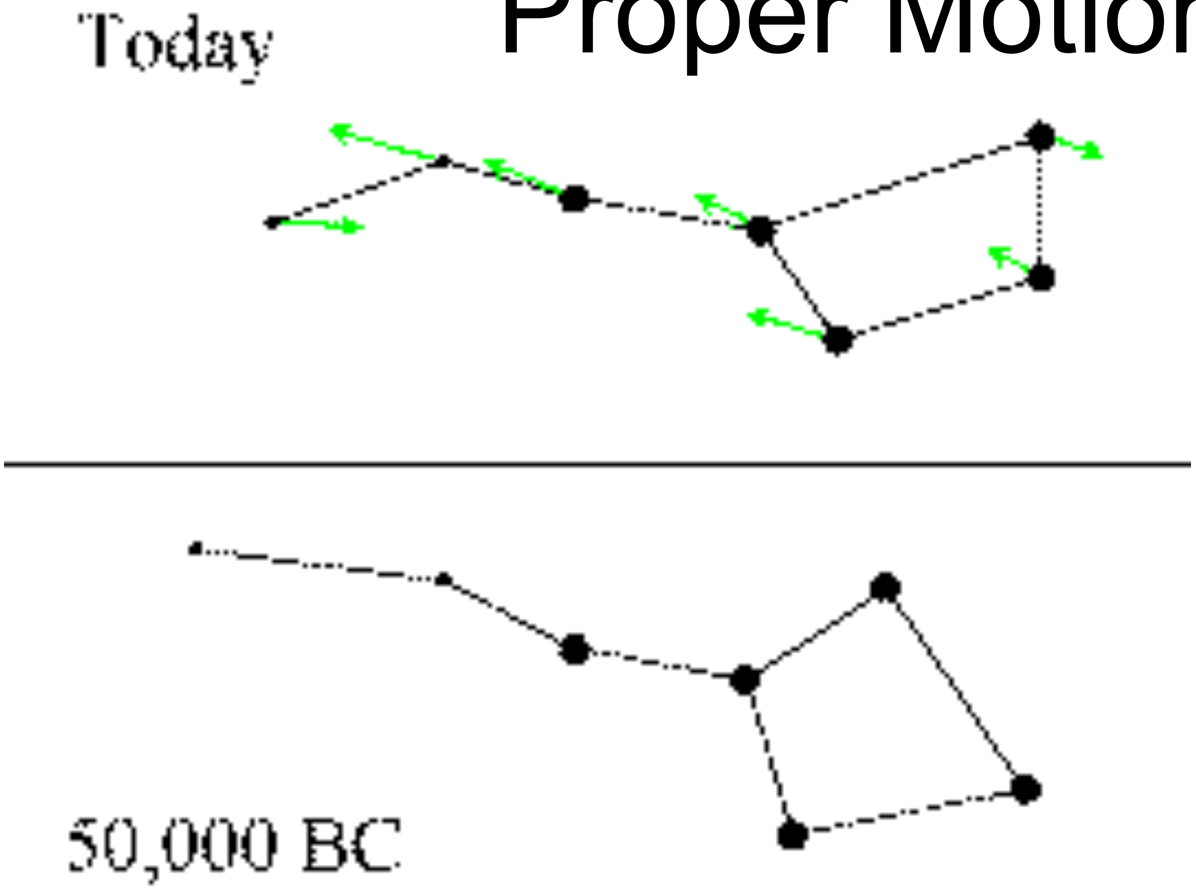
Proper Motion

Objects (especially if nearby) can genuinely change position. Called “proper motion”.

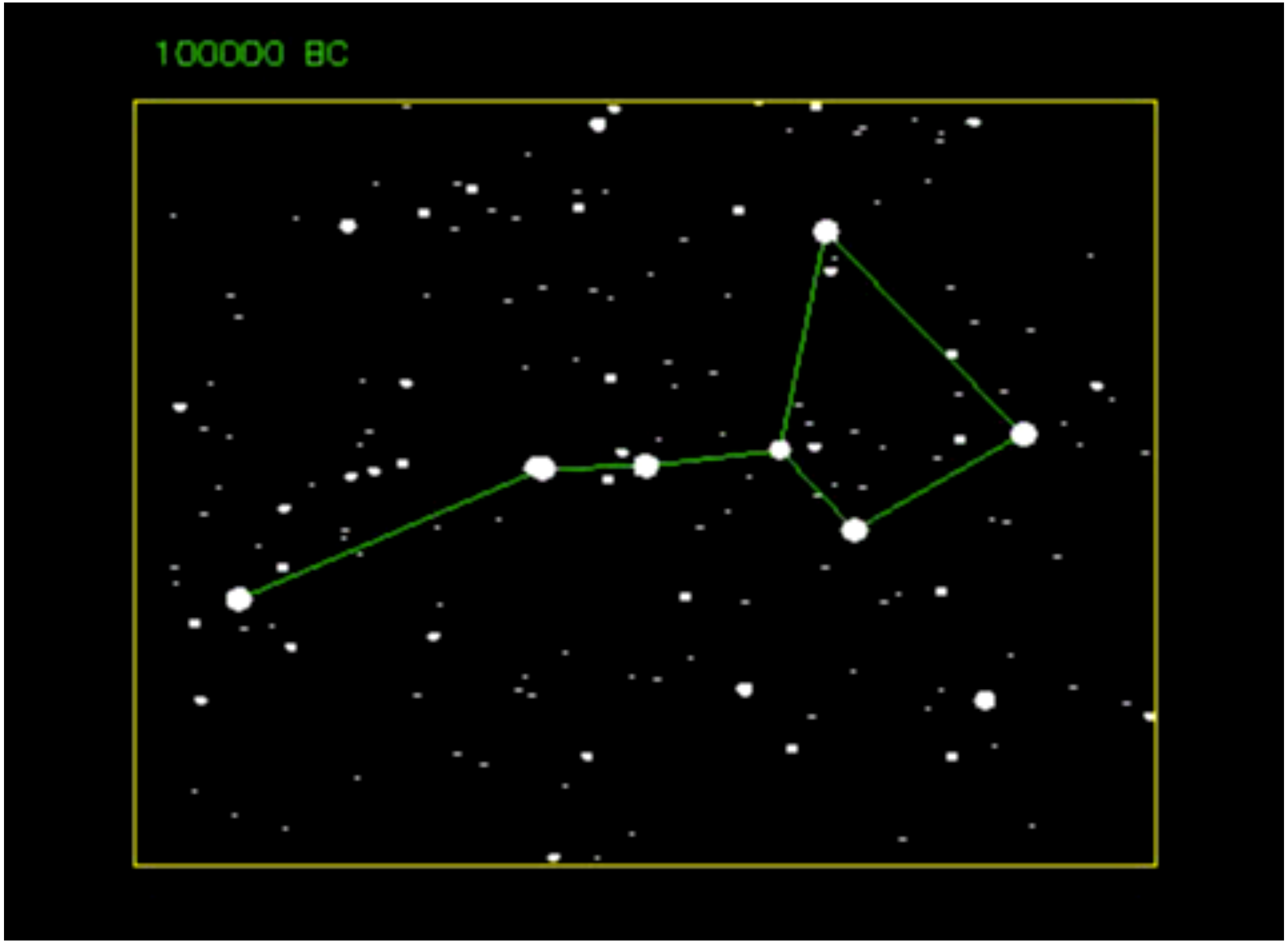
e.g. Gaia DR2 lists “pmra” and “pmdec” (and errors) in “mas/yr” (milliarcseconds per year).

Given proper motion, one needs to define the “epoch” of coordinates (e.g. 2015.5 for DR2).

Proper Motion



Proper Motion



http://www.astronomy.ohio-state.edu/~pogge/Ast162/Movies/proper.html

Proper motion: beware!

Some telescopes may need RA proper motions in “seconds of RA per year”.

>>>>>> 1 second of RA ≠ 15” <<<<<<

instead: 1 second of RA = 15” cos(δ)

Important to check for PM in targets *and* alignment or reference stars

Equatorial vs Alt-Az Telescopes

Equatorial telescopes are mounted with one axis parallel to Earth's axis ==> only need to rotate one axis to track stars

Alt-Az telescopes have a vertical & horizontal axis. Easier engineering-wise for large telescopes. Both axes needed to track stars. The field needs to be "de-rotated".

ESO 3.6m – equatorial

Is the telescope pointing North or South?

(ESO 3.6m is sited at La Silla, Chile)

4.2m WHT – alt-az

Alt-Az telescopes struggle to track near the zenith when azimuth changes rapidly.

De-rotation can hit end-stop in the middle of an observation (annoying).

All largest telescopes are alt-az.

Rule of thumb 1.

Can typically access targets with RAs opposite to the Sun, +/- 6 hours or so.

Which are [in principle] observable tonight from the UK and, if they are, are they best observed at the start, the middle or the end of the night?

1) RA = 11:30, Dec = +85:30

2) RA = 19:50, Dec = +20:20

3) RA = 06:20, Dec = -10:00

4) RA = 03:55, Dec = +55:00

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Sun is at 21h -16deg
At midnight, the LST will be 9h

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1) RA = 11:30, Dec = +85:30 — 2nd half of night

2) RA = 19:50, Dec = +20:20 — Daytime object

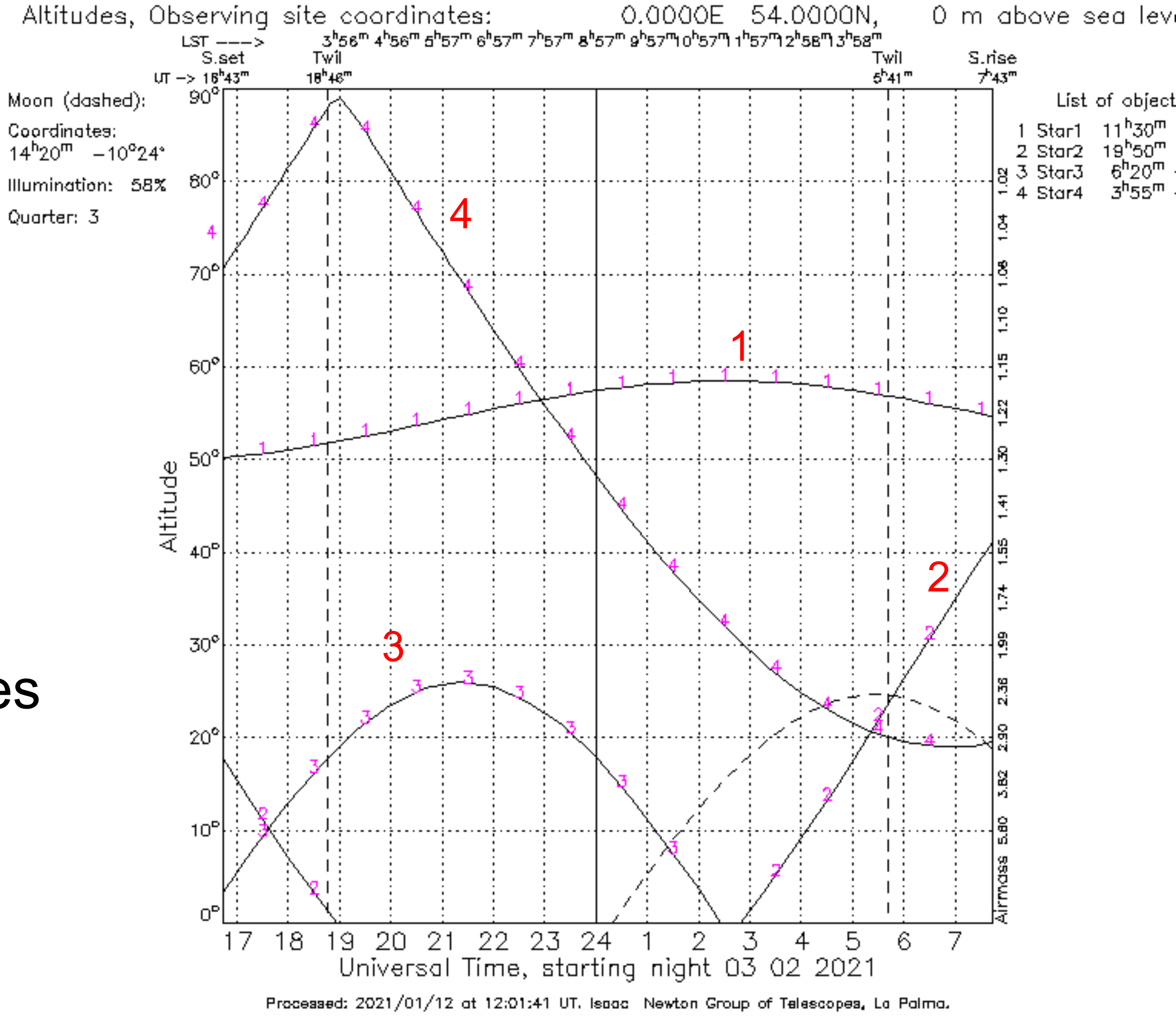
3) RA = 06:20, Dec = -10:00 — Near horizon

4) RA = 03:55, Dec = +55:00 — Start of night – but watch zenith

Sun is at 21h -16deg
At midnight, the LST will be 9h

Usually easiest to use online or software calculators for this

e.g. http://catserver.ing.iac.es/staralt/



Rule of thumb 2.

H.A. = h = LST – RA is useful at the telescope.

Objects are best observed with H.A. ~ 0, or RA ~ LST. Observatories often display the LST.

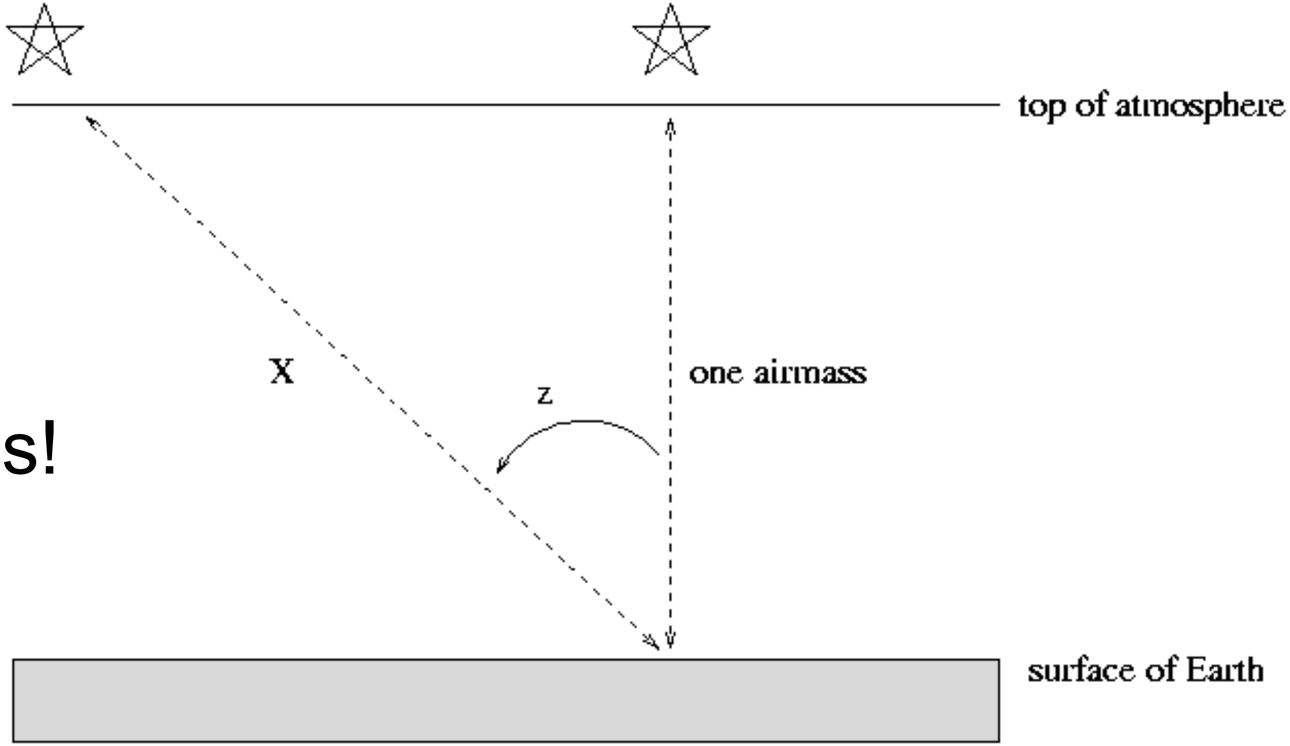
==> Objects of larger RA rise later

(N.B. 01 > 23 in RA-land)

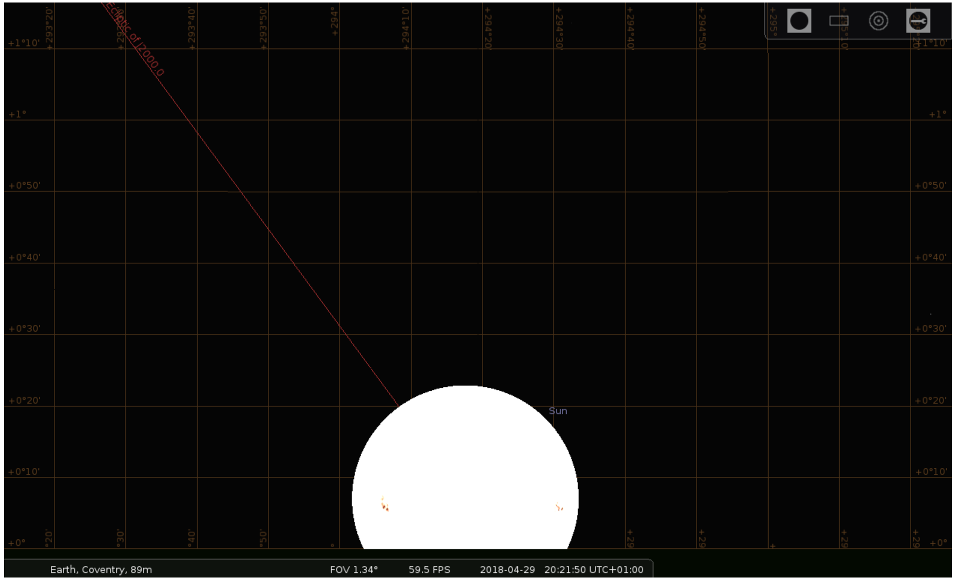
Rule of thumb 3

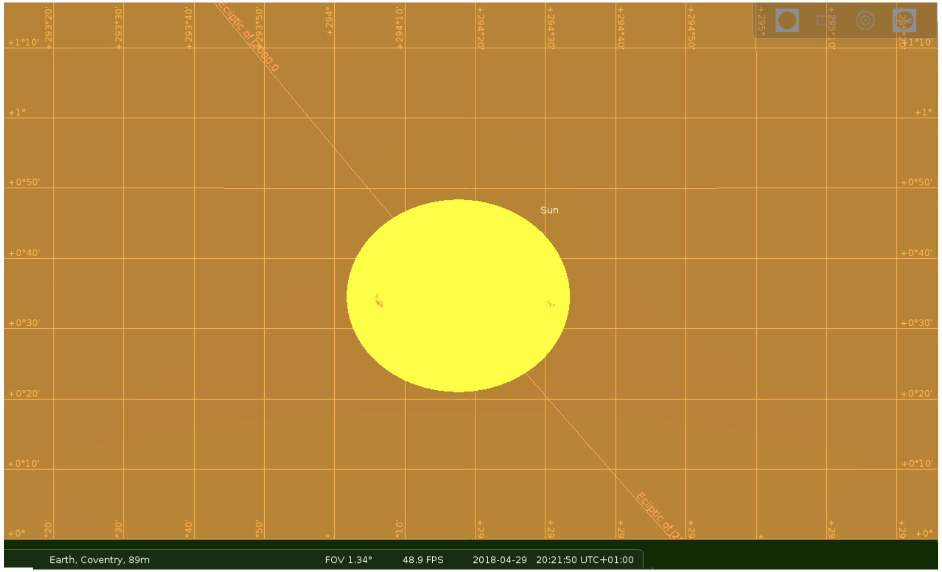
Don't, if you can avoid it, observe at zenith distances > 60° (which is airmass > 2)

Never observe at z > 70° ...
The light is struggling through 3 atmospheres!



Refraction





Same time near sunset, Coventry, April 29, without (left) & with (right) an atmosphere (according to “stellarium”)

Differential Refraction

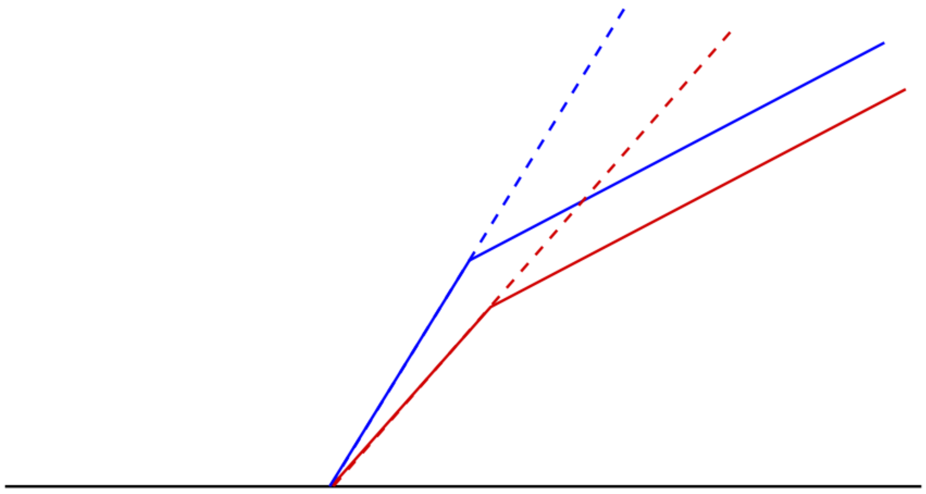
Refractive index increases towards bluer wavelengths ==> at large zenith distances, objects turn into mini, vertical rainbows.

Makes astrometry colour-dependent.

Leads to wavelength-dependent flux loss in spectroscopy

If no ADC (atmospheric dispersion corrector) observe near zenith and use a vertical slit.

Classic paper: Filippenko (1982, PASP)

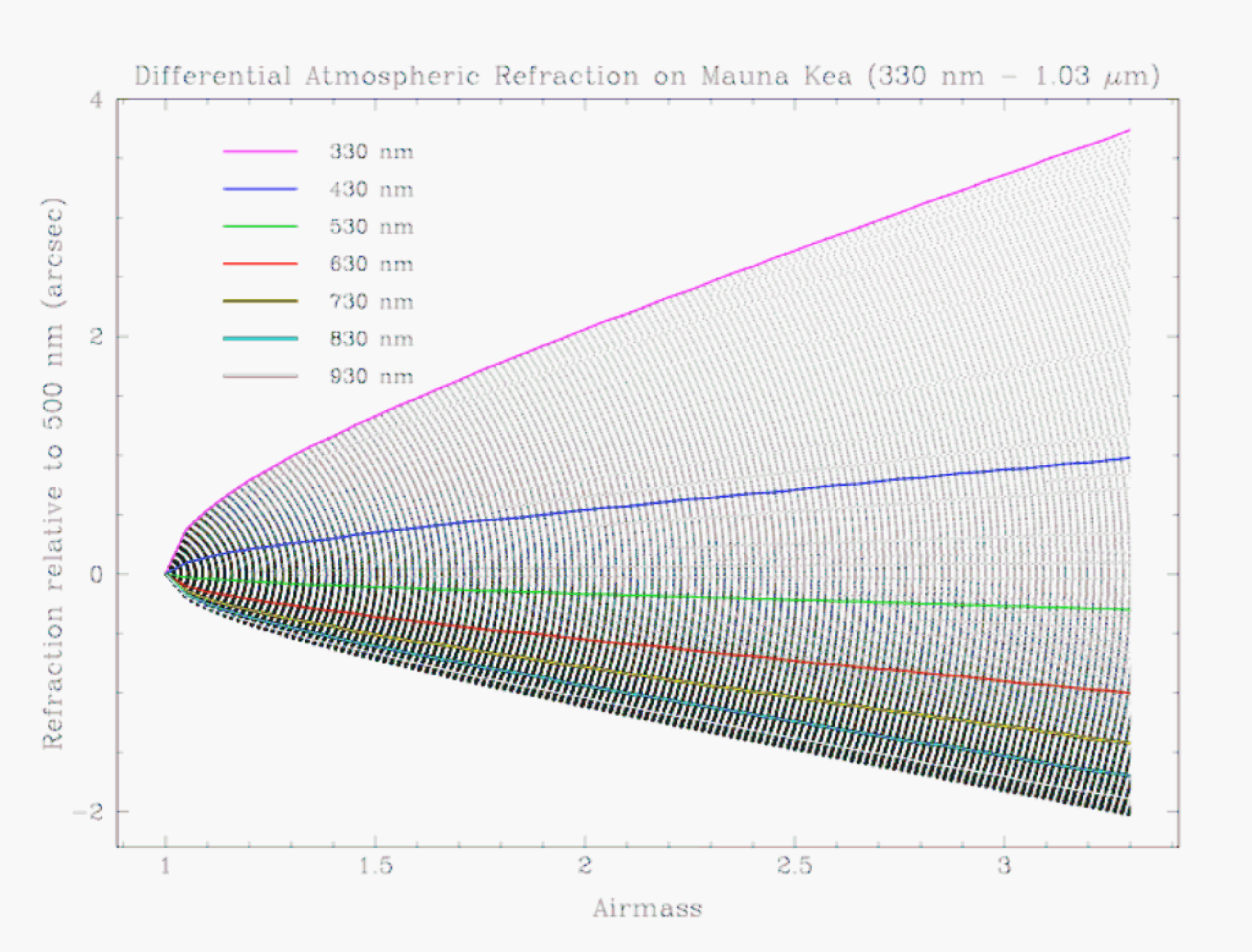


https://ui.adsabs.harvard.edu/abs/1982PASP...94..715F/abstract

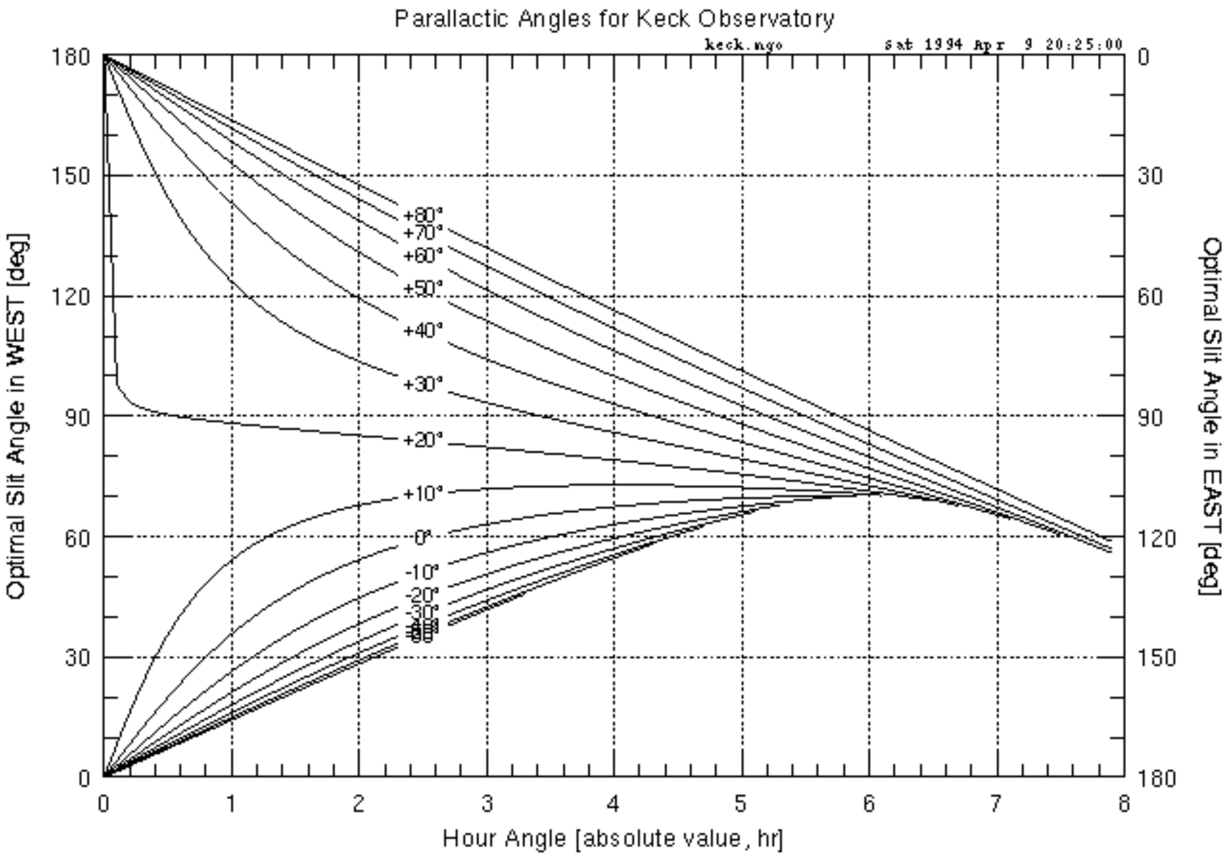
Typical slit widths are 0.7” to 1.2” on the sky (see later). Fibres tend to be 2” to 3”.

Differential refraction can be very significant, especially in the ultra-violet.

BE AWARE OF IT FOR OPTICAL SPECTROSCOPY!



The **parallactic angle** measures the direction from the target to the zenith.
Light is dispersed in this direction as a result of terrestrial atmospheric refraction. If the slit is not aligned to the parallactic angle then certain wavelengths of light will fall outside the slit and thus the resulting spectrum will not capture all of the light from the object.



https://www2.keck.hawaii.edu/inst/common/parallactic.html

Atmospheric Extinction 1

Earth's atmosphere absorbs and scatters light.

The effect is worst at short wavelengths (Rayleigh scattering)

Extinction makes stars fainter according to:

$$m(X) = m_0 + k\,X$$

where X is the airmass, m the magnitude.

k is the extinction coefficient, measured in mags/airmass

Atmospheric Extinction 2

Example coefficients:

La Palma: $k_r = 0.069$, $k_g = 0.161$, $k_u = 0.485$

Purple Mountain: $k_r = 0.55$, $k_g = 0.70$

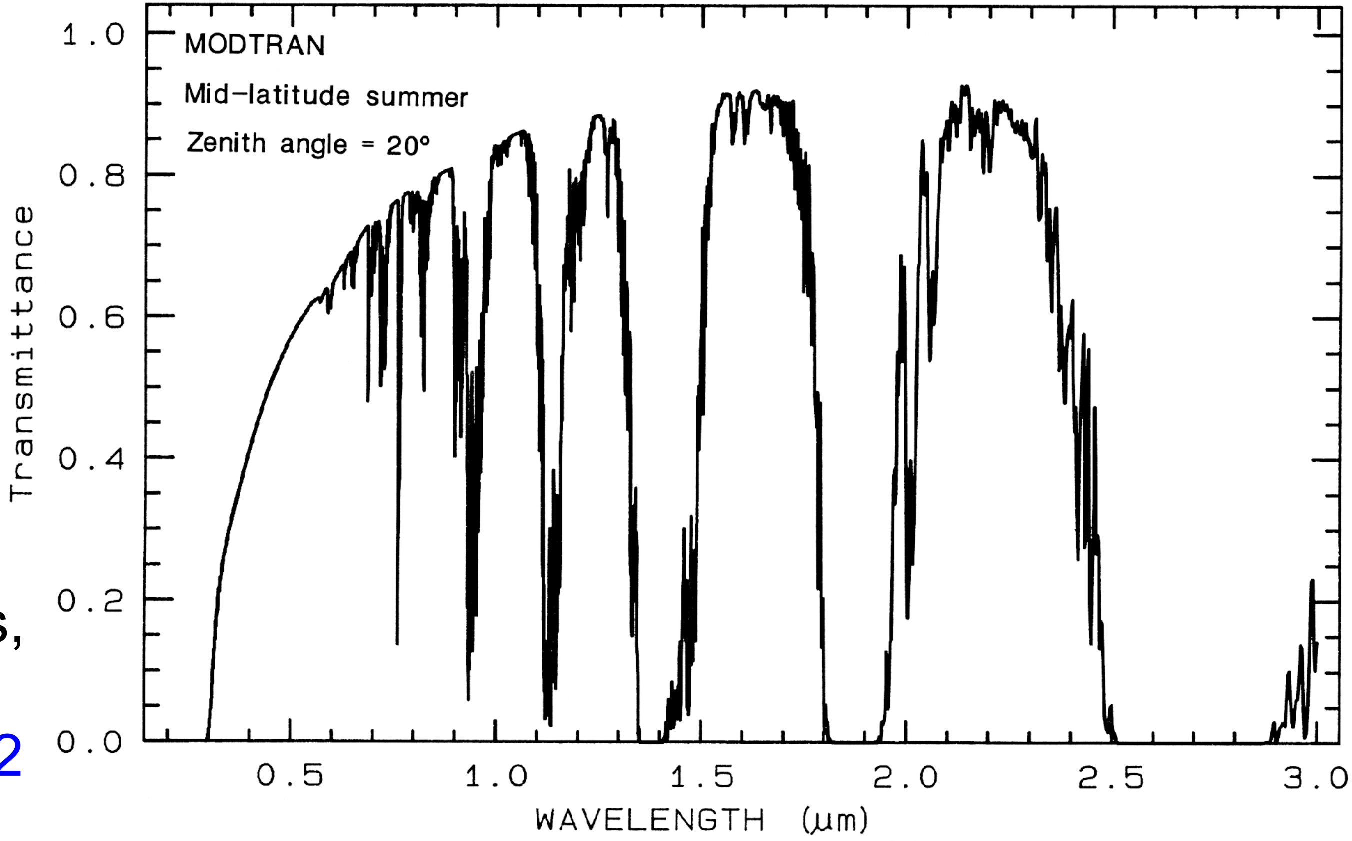
Extinction varies from site to site, and day to day. Measuring it requires observation over a wide range in airmass. Often easier to use measured mags for stars in the field than to try to derive from "standard stars" at other locations.

Atmospheric Extinction 3

Smooth Rayleigh scattering dominates the blue end of optical.

Molecular bands appear at longer wavelengths.

So strong that they define observing bands, e.g the near-infrared H & K bands at ~1.6 & 2.2 microns



Sky brightness

Sky background is a crucial component of observing.

Usually measured as an equivalent magnitude per square-arcsec.

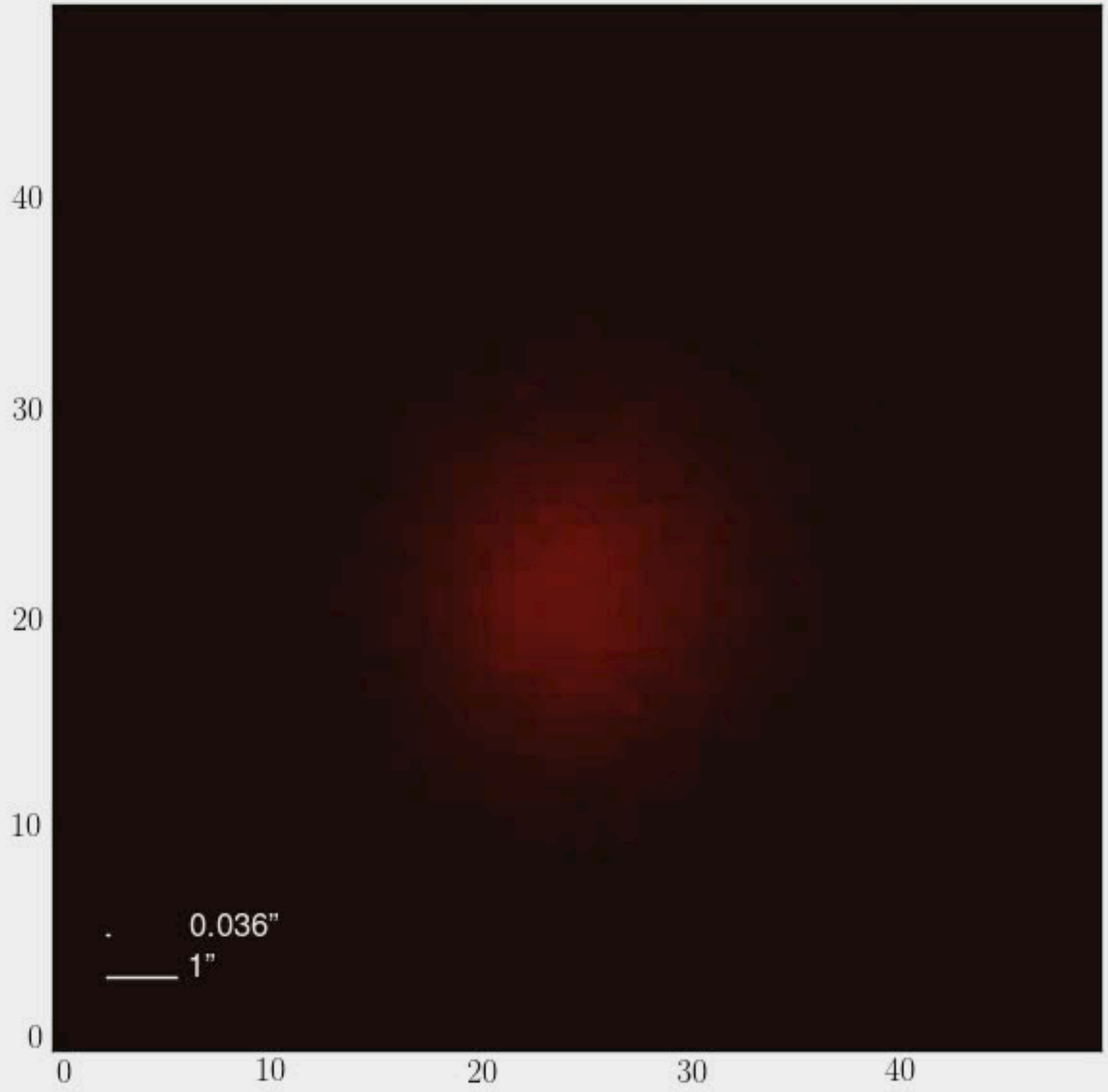
Typical dark site: V=21.9 (dark time, no Moon), rising to ~18 during Full Moon.

Brighter, but less affected by the Moon in the IR.

“Seeing”

A telescope of aperture 12 cm has a diffraction-limited angular resolution of $1.22\ \lambda/D = 1.04''$

Unfortunately a 12 m telescope is not necessarily any better because of “seeing”, the absolute bane of ground-based optical / IR astronomy.

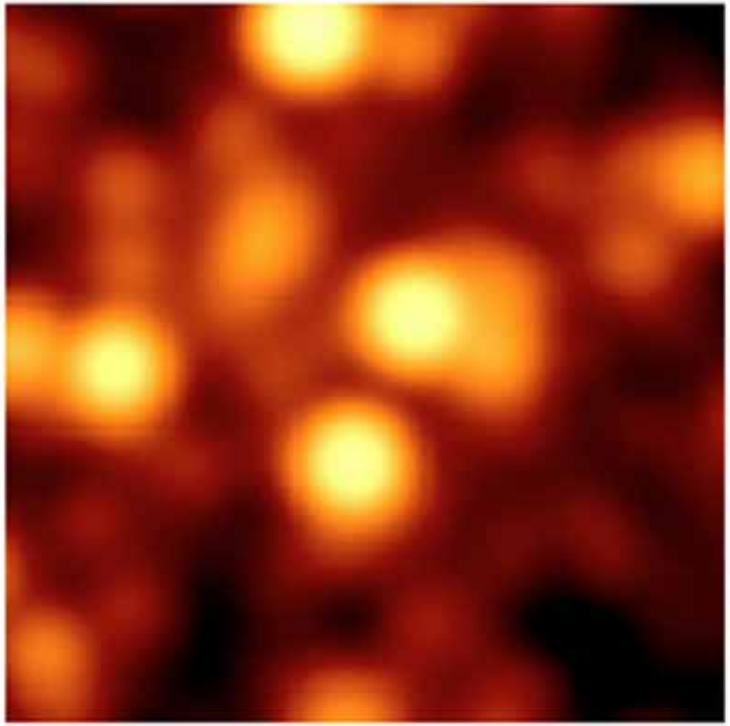


40
30
20
10
0
0
10
20
30
40
0.036"
1"

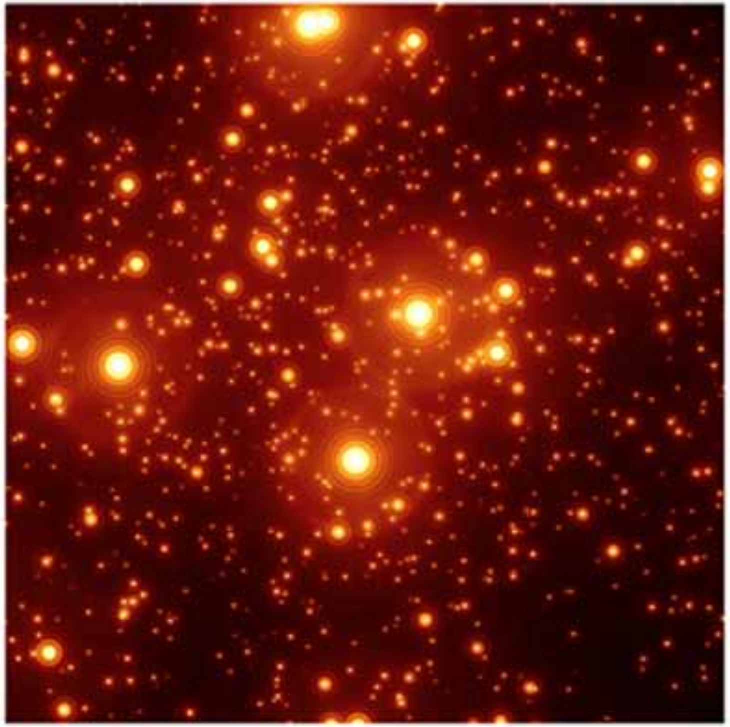
Seeing

Seeing is often worse than 1 or 2”.

The best sites sometimes have a “seeing” ~ 0.3”. Better than this requires adaptive optics or space to reach the diffusion limit.



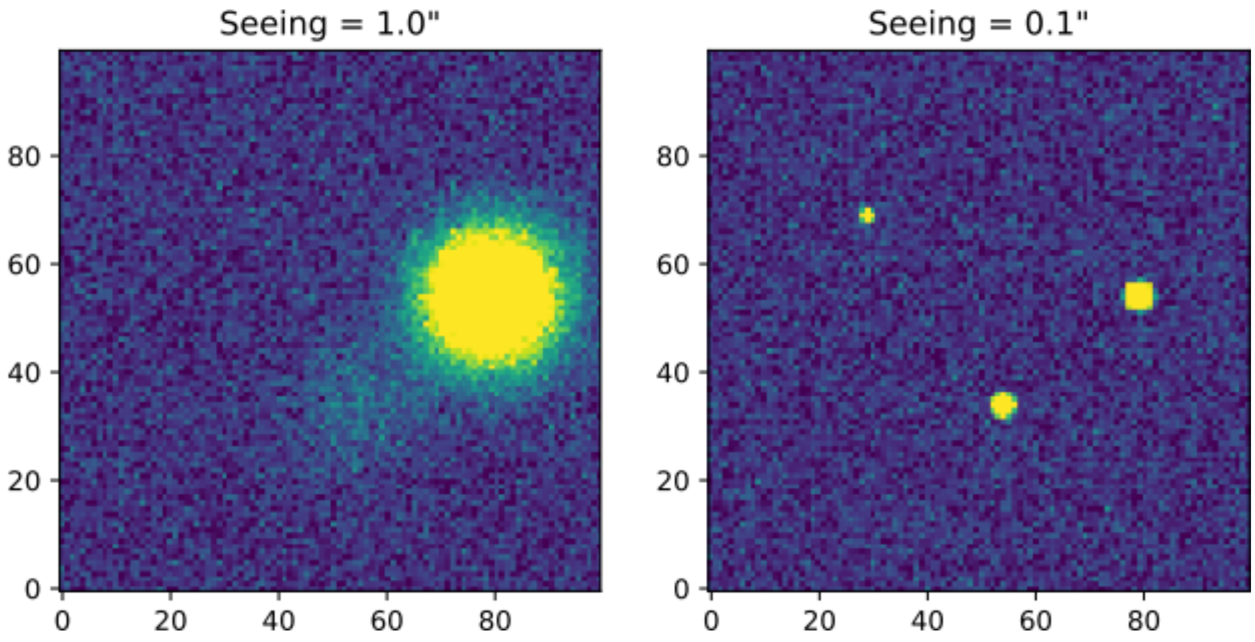
Atmospheric Seeing



Diffraction limited, 6m telescope

Faint Object Detection

Seeing is crucial for faint object detection and is the reason why the 2.4m HST can still beat much larger ground-based telescopes.



Faint Object Detection

In the previous slide, the faintest object has 1000 photons on top of a background of 100 photons per 0.05” pixel. Let’s estimate the signal-to-noise ratio in a circle of radius = 2*seeing:

N(pixels) = $\pi(2*\text{seeing}/0.05)^2$

Seeing ~ 1” ==> N(pixels) =~ 5000

Total sky counts = 5000*100 = 500,000

Faint Object Detection

So

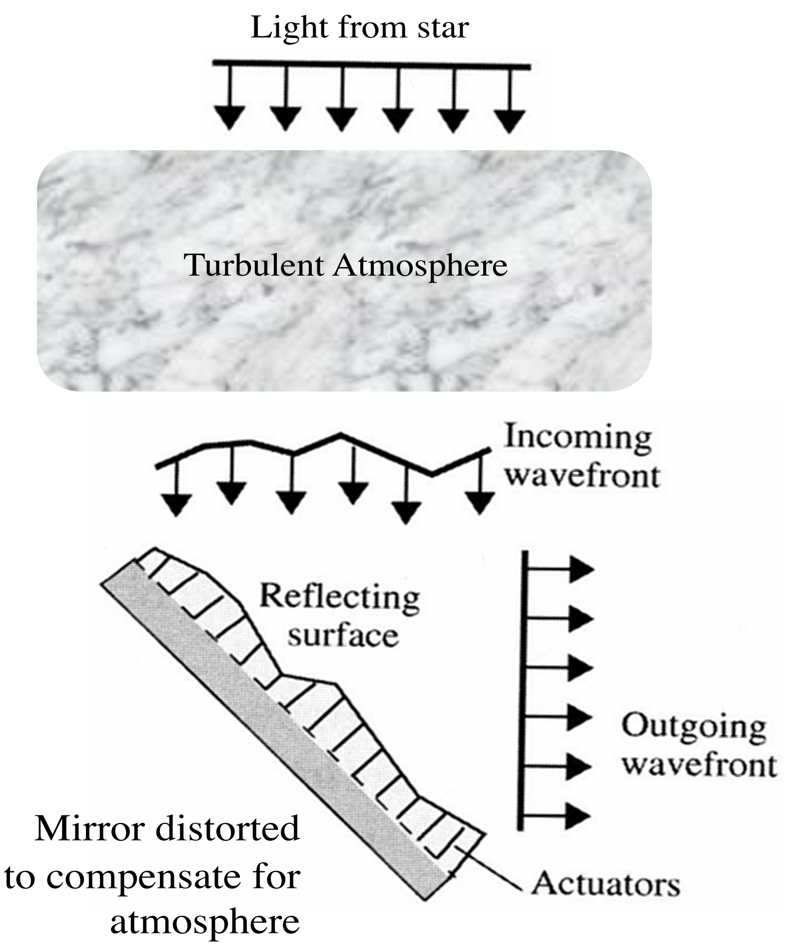
total counts = 501,000 which assuming Poisson stats ==> noise = sqrt(501,000) = 708

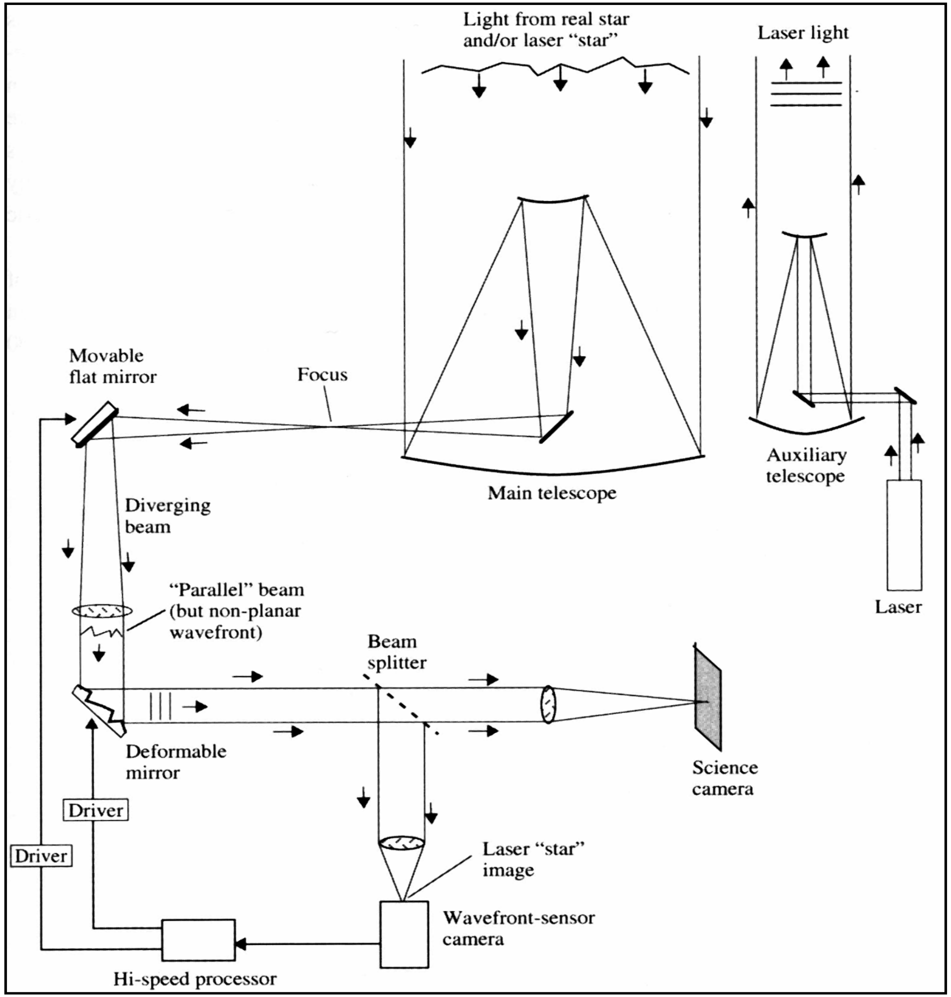
==> SNR = 1000/708 = 1.4 (no detection)

For seeing = 0.1”:

N(pixels) ↓ by 100x, so total counts = 6000, and SNR = 1000/sqrt(6000) = 12.9 (convincing detection).

Adaptive Optics (AO)





Adaptive Optics

Guide stars: must be bright (<12th mag) and close to target (within telescope field). Can be natural or a pocket of sodium atoms excited in the upper atmosphere by lasers.

Wavefront sensor: measures distortion of the guide star at kHz frequencies.

Deformable mirror: optical element distorted by actuators that respond to the wavefront censor to correct the wavefront.

Multi-Conjugate AO (MCAO): using several guide stars to correct a larger field.

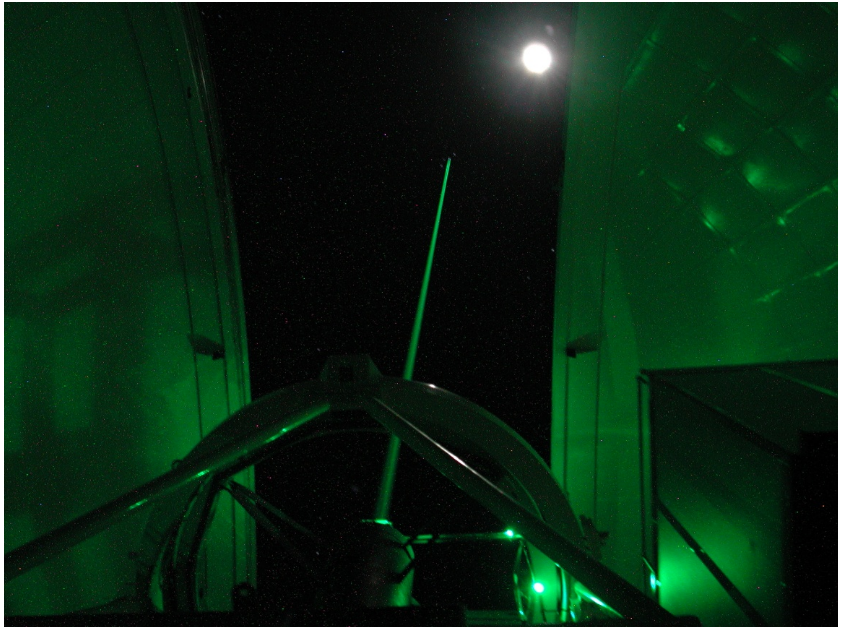
Strehl ratio: The degree of correction

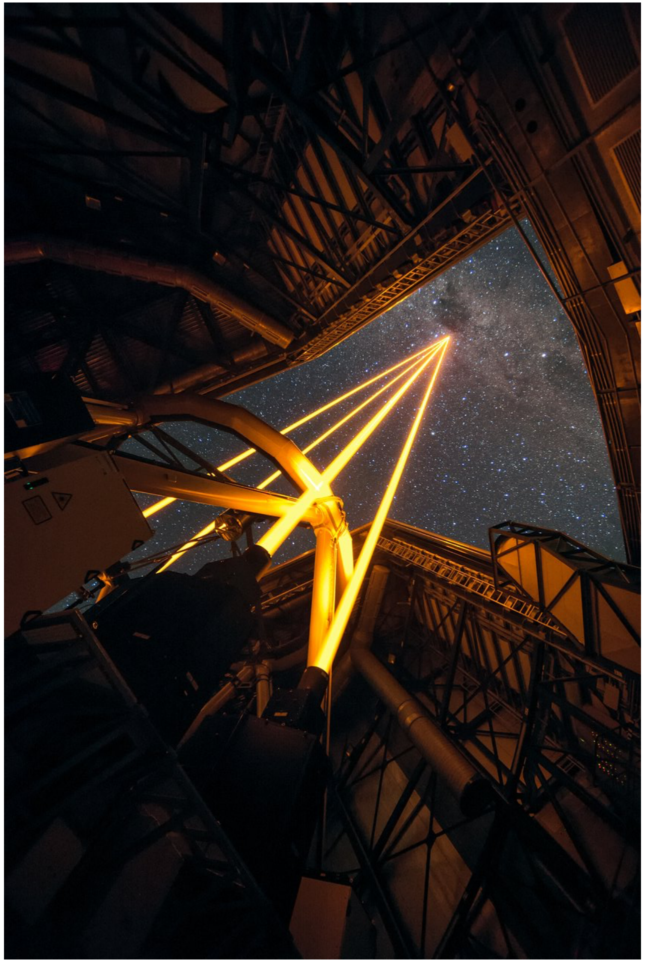
S = (observed peak intensity)/(diffraction limit theoretical peak intensity)

Laser AO in action

Very Large Telescope (VLT)

William Herschel Telescope

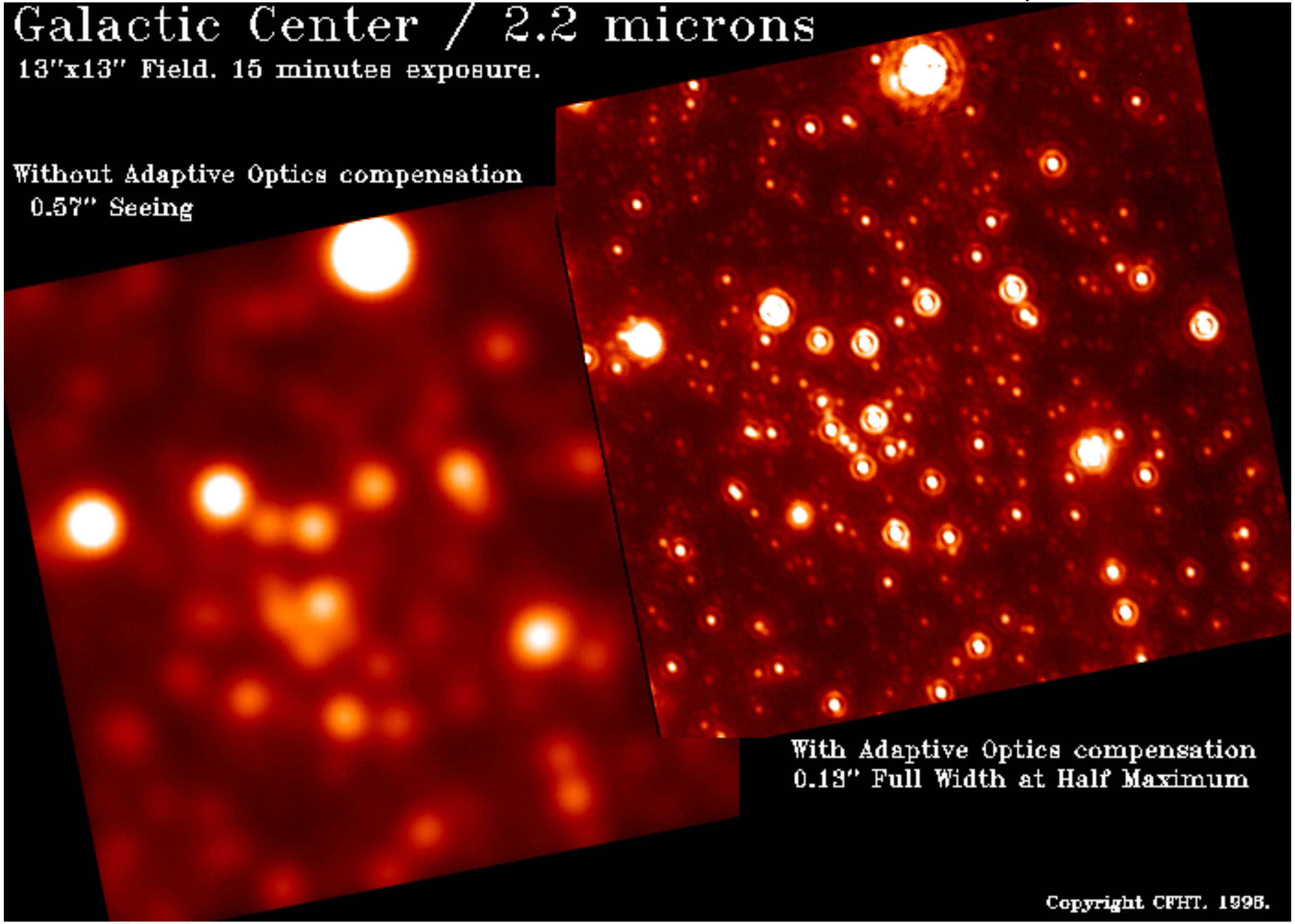




Credit: ESO https://cdn.eso.org/images/screen/eso1613a.jpg

AO results

Galactic centre observed with CFHT at 2.2μm



Correction easiest in the near-infrared

Corrected images often show the Airy disk around sources.

Astronomical Timescales

If you do any work on time-variable objects you will come across JD, MJD, HJD, UTC and perhaps BJD and TDB.

Many have been burned by one or more of these.

JD = Julian Date

Days since midday on Jan 1, 4713 BC

e.g May 1, 2018 at 15:00 was JD= 2458240.125

(4713 BC was chosen so that JDs would be > 0)

MJD, HJD, BJD

MJD = “Modified Julian Date” = JD – 2400000.5

(integer at midnight rather than midday)

HJD = “Heliocentric Julian Date” = JD of event as measured from the centre of the Sun (corrects for light-travel +/- 8 mins).

BJD = “Barycentric Julian Date” = JD of event measured from the barycentre of solar system (another +/- 2 secs relative to HJD)

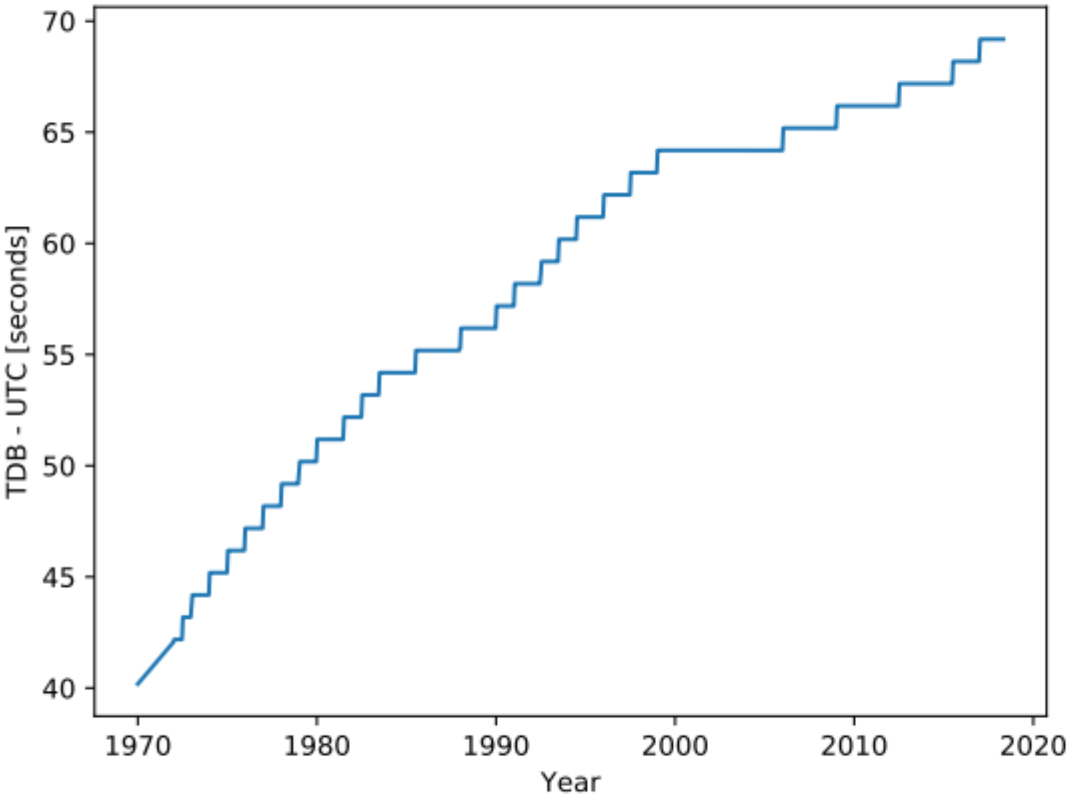
UTC

Most times in the literature (JDs, HJDs) are derived from UTC, an atomic time synchronised to Earth's slowing rotation with odd & unpredictable "leap seconds".

UTC is not suitable for precision times (better than a few seconds), especially over long timescales.

TDB

- For precision time, use TDB (Temps Dynamique Barycentrique).
- TDB is now > 1 minute ahead of UTC



Happy observing!

The assignment for this session includes a few examples of planning and taking observations.

If you are taking this module for credit please tackle these and e-mail me the answers (see the assignment for my address)

The assignment can be downloaded from: https://warwick.ac.uk/fac/sci/physics/research/astro/local_info/mpags