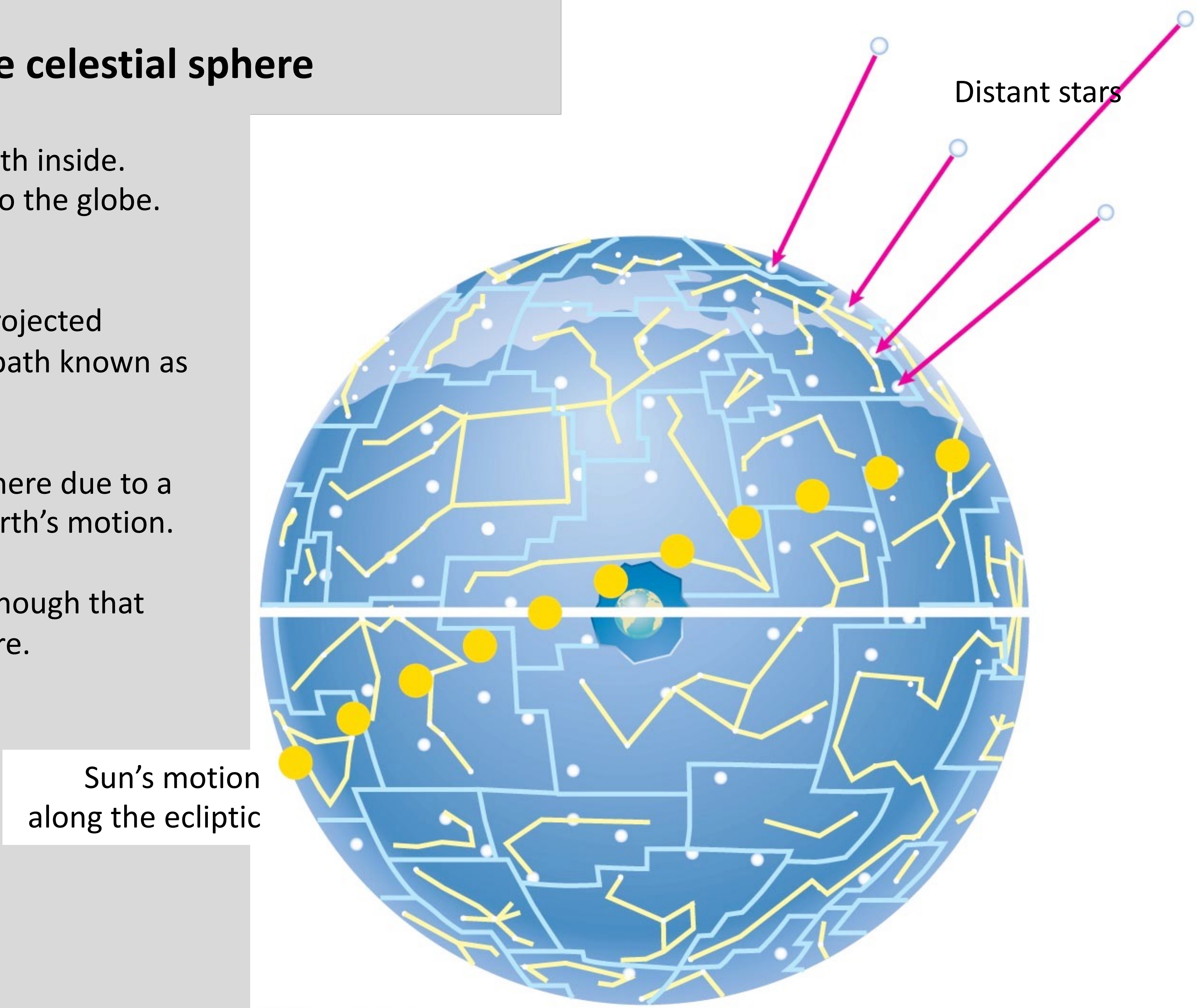
Astronomical Coordinates: The celestial sphere

Think of the sky as a globe, with the Earth inside. Objects in space are seen projected onto the globe.

As the Earth orbits the Sun, the Sun’s projected position on the sphere moves across a path known as **the ecliptic**.

Moon and planets also move on the sphere due to a combination of their motion and the Earth’s motion.

The motions of distant stars are small enough that they are essentially “fixed” on the sphere.



Local Sky Coordinates

You see half the celestial sphere at any given time.

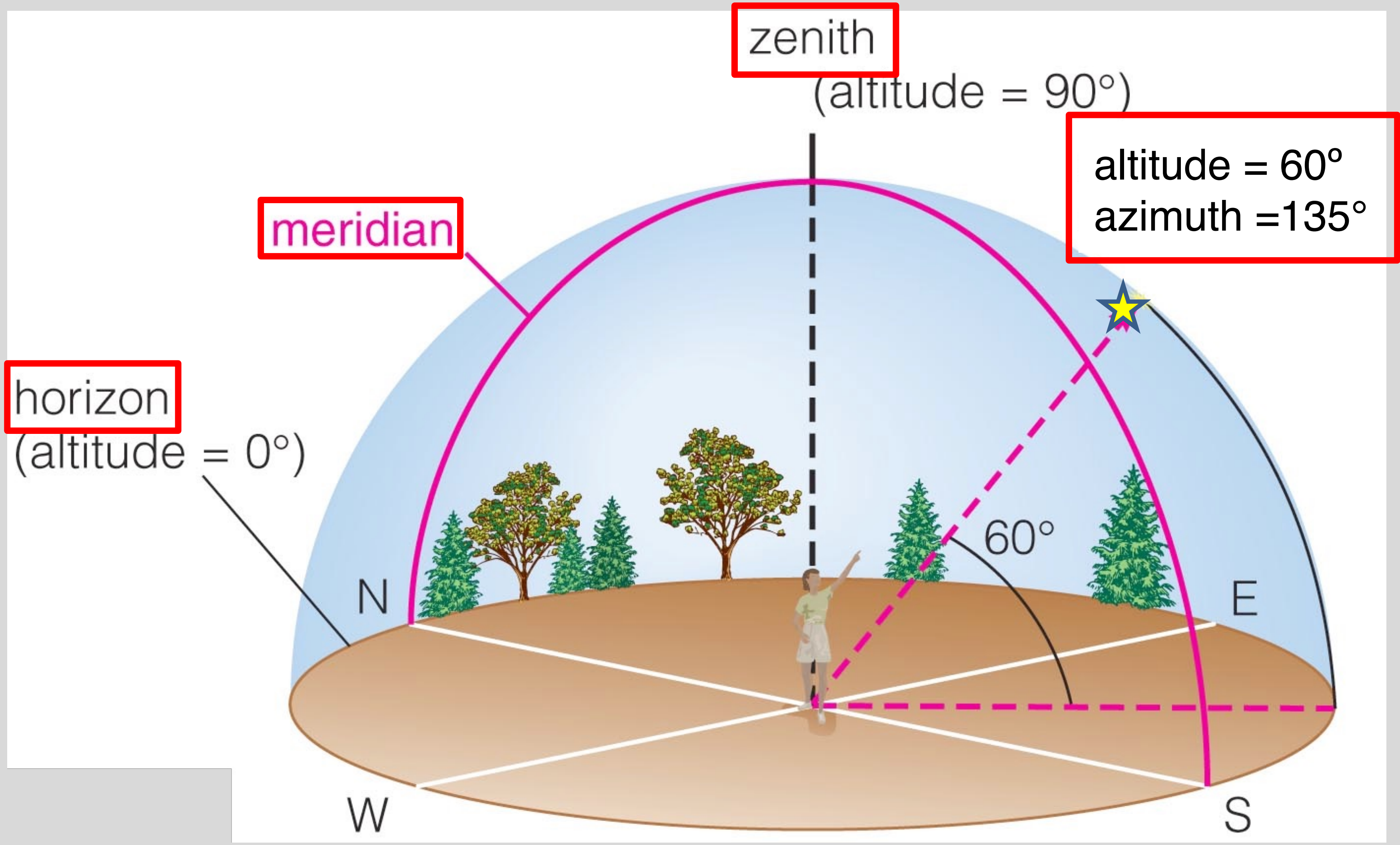
Zenith: directly above you

Horizon: where the sky “touches” the ground.

Meridian: imaginary line going north-south through the Zenith

Altitude and Azimuth: an object’s height ***above*** the horizon (in degrees), and position ***along*** the horizon, measured N through E.

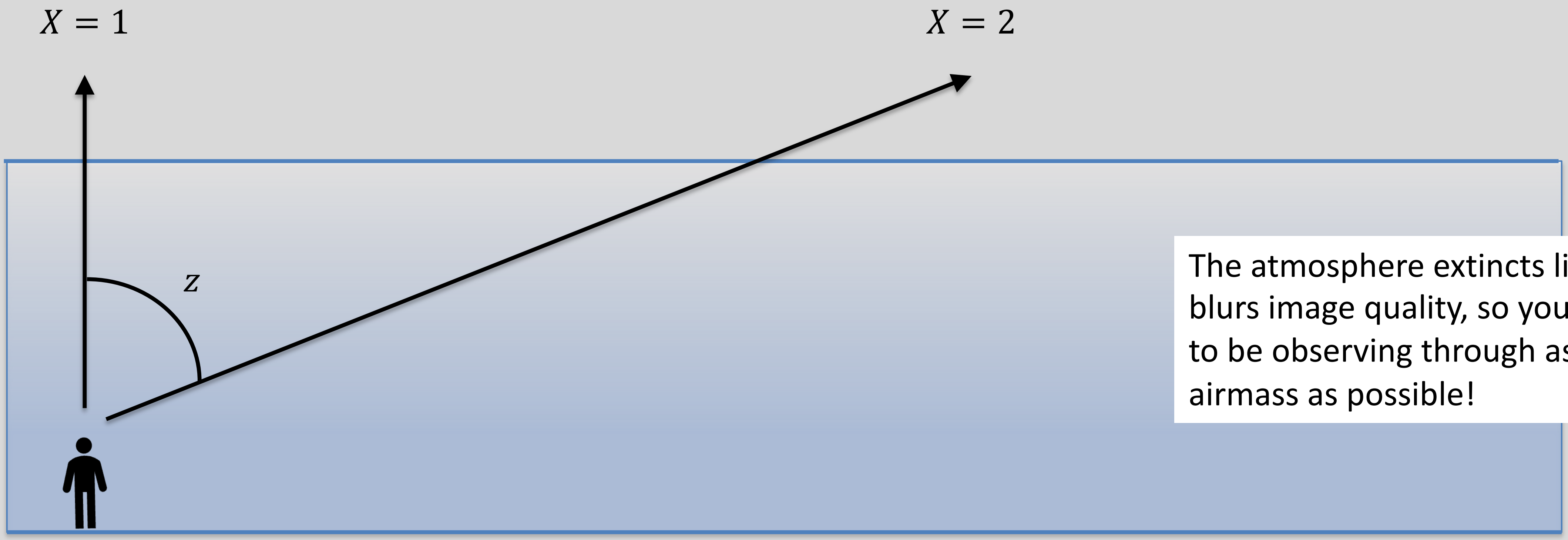
Zenith distance: $z = 90° - Altitude$



Airmass

Airmass ("X") measures of how much atmosphere you are looking through. Effectively another way of characterizing altitude of zenith distance.

- If you are looking straight up (zenith) you are looking through "one atmosphere", or an airmass of 1.
- If you are looking lower in the sky, you are looking through a larger path-length through the atmosphere, so a bigger airmass.
- A plane-parallel approximation is given by $X = \sec(z)$, where z is the zenith angle. Airmass is often also called "sec-z". And remember $\sec(z) = 1/\cos(z)$



The atmosphere extincts light and blurs image quality, so you want to be observing through as little airmass as possible!

Celestial Sphere Coordinates: Equatorial RA/Dec

Define coordinates by the projection of the Earth's pole and equator onto the celestial sphere.

Celestial poles: projection of Earth’s rotational axis

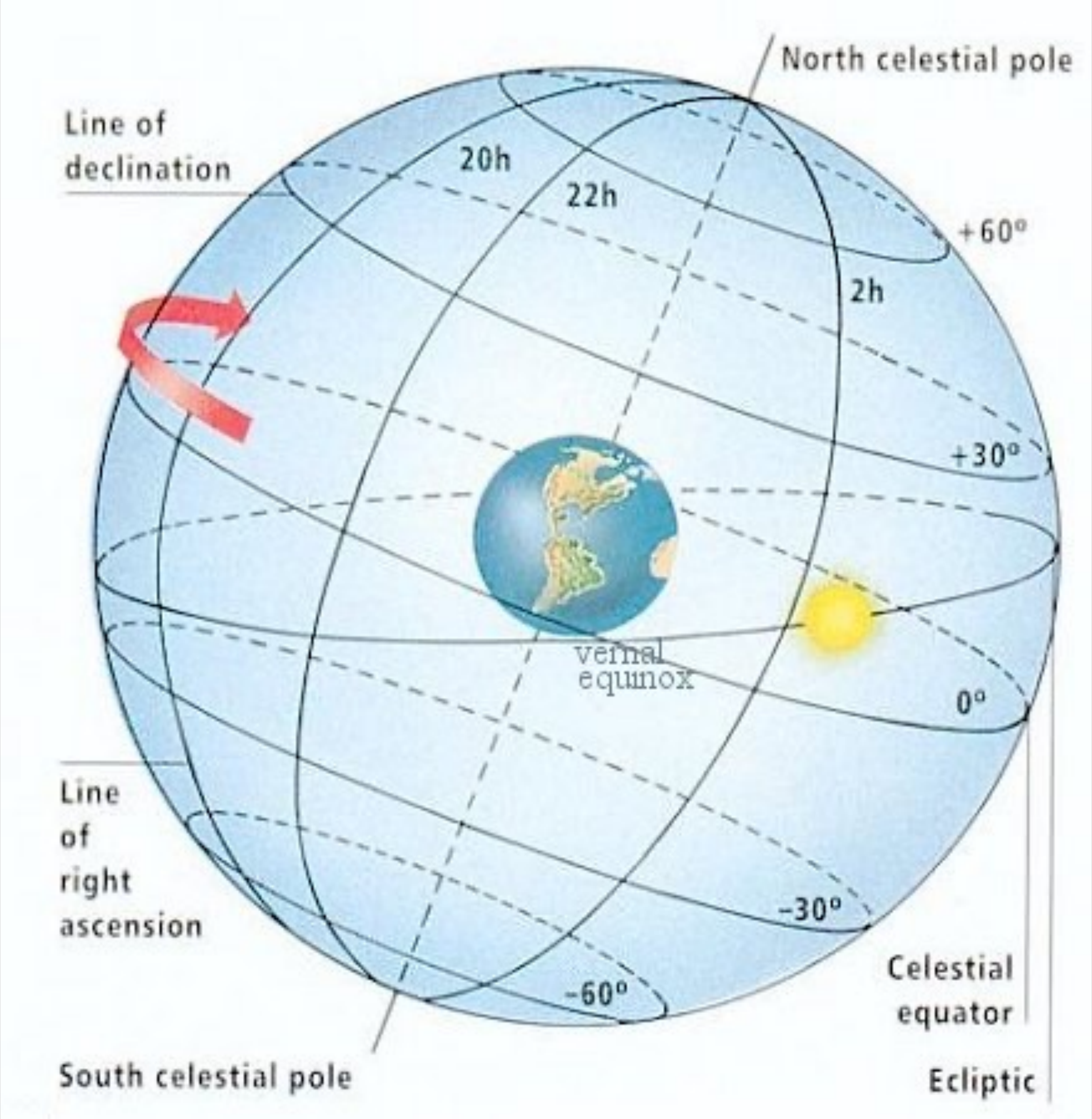
Celestial equator: projection of Earth's equator

Equatorial Coordinates:

Declination (δ): angular distance from the celestial equator (positive = north, negative = south)

Right Ascension (α): angular distance along circles parallel to the equator. Define $\alpha = 0$ to be the vernal equinox (first day of spring!), the point where the Sun's position in the sky crosses the celestial equator as it moves north. *Right ascension increases going eastward.*

RA and Dec are to the celestial sphere what longitude and latitude are to Earth coordinates.



Rotation of the Earth

As the Earth goes through daily rotation, the celestial sphere appears to rotate above us.

Stars rise in the East, cross the meridian, and then set in the West.

Transit: When a star crosses the meridian, it is at its highest elevation.

Hour angle: How many hours since an object transited. e.g., HA = −2 hrs means it is rising and will transit in 2 hours.

Coordinate Comparison:

- **RA, Dec**: an object's *fixed coordinates* on the celestial sphere, do not change as celestial sphere rotates.
- **Alt, Az (and HA)**: an object's *local sky coordinates*, change throughout the night.

Right Ascension and Declination coordinates

Declination (δ) is ***always*** measured in degrees (°), minutes (′), and seconds (″) **of arc**, or decimal degrees.

$$1° = 60' = 3600''$$

Right ascension (α) can be measured ***either*** in degrees ***or*** in sexagesimal time (hr, min, sec **of time**)

Important: Minutes and seconds of time are DIFFERENT from minutes and seconds of arc!
24 hrs = 360°, so 1 hr = 15°, so 1 minute of time = 1/60 of 15° = ¼ degree = 15′ of arc.

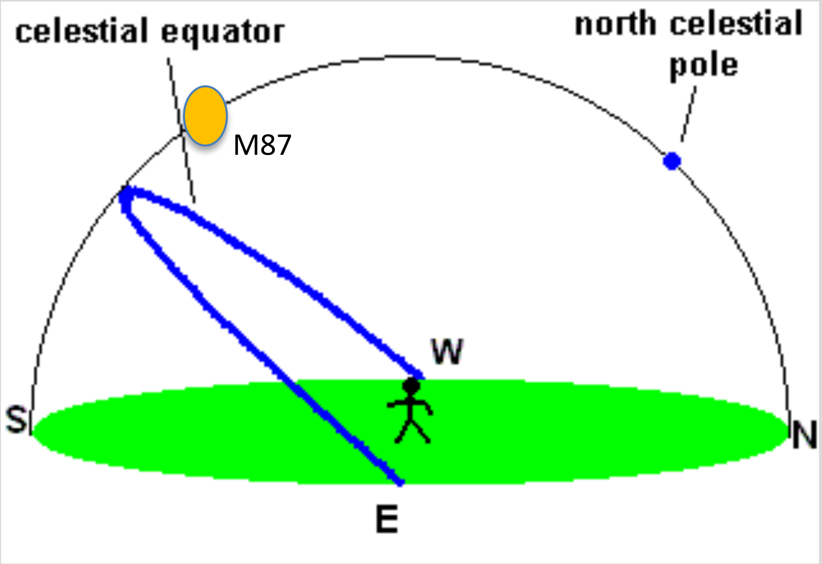
So, the coordinates for the galaxy M87 can be written as

(α,δ) = 12:30:49.0, +12:23:07 (or 12h30m49.0s, +12°23′07″)
or
(α,δ) = 12.51361h, +12.3962°
or
(α,δ) = 187.7042°, +12.3962°

How many digits of accuracy to use?

- 1″ is roughly ground-based resolution, generally no need for higher accuracy than this.
- 1″ = 1/3600° ≈ 0.0003° (so 4 decimal points of degree is ≈ 1″ accuracy)
- 1″ = 1/15 seconds of time ≈ 0.07s (use a decimal point for seconds of time but not for seconds of arc)

Connecting Equatorial Coordinates to Local Sky Coordinates



What is the declination of an object at zenith at the North Pole?

Zenith is straight up, and at the North Pole, straight up is the celestial pole, so $\delta = +90°$

What is the declination of an object at zenith at the Equator?

At the equator, straight up is the celestial equator, so $\delta = 0°$

What is the declination of an object at zenith in Cleveland? (Latitude: 41° N)

We've seen that zenith declination is your latitude, so $\delta = +41°$

The elliptical galaxy M87 has coordinates $(\alpha, \delta) = (187.7°, +12.4°)$. What is its altitude when it transits in Cleveland?, What time of year is it easily visible?

Solving Altitude: *Cleveland zenith declination is* $\delta = +41°$*, M87 declination is* $\delta = +12.4°$
So M87's zenith distance is $z = 41° - 12.4° = 28.6°$*, giving it an altitude of* $90 - z = 61.4°$
You are observing it through $sec(28.6°) = 1.14$ *airmasses*

Working out visibility: *Remember, right ascension is measured relative to the vernal equinox, so* $\alpha = 0°$ *is the position of the Sun on the first day of Spring.*
So $\alpha = 187.7°$ *is almost exactly halfway around the sky from that, so on the first day of spring, M87 is on the opposite side of the sky from the Sun. M87 will be high in the sky in the middle of the night in the Spring.*

Another Example: Circumpolar Stars

Observed from a some spot on the Earth, circumpolar stars are those stars close enough (in declination) to the celestial pole that they never set.

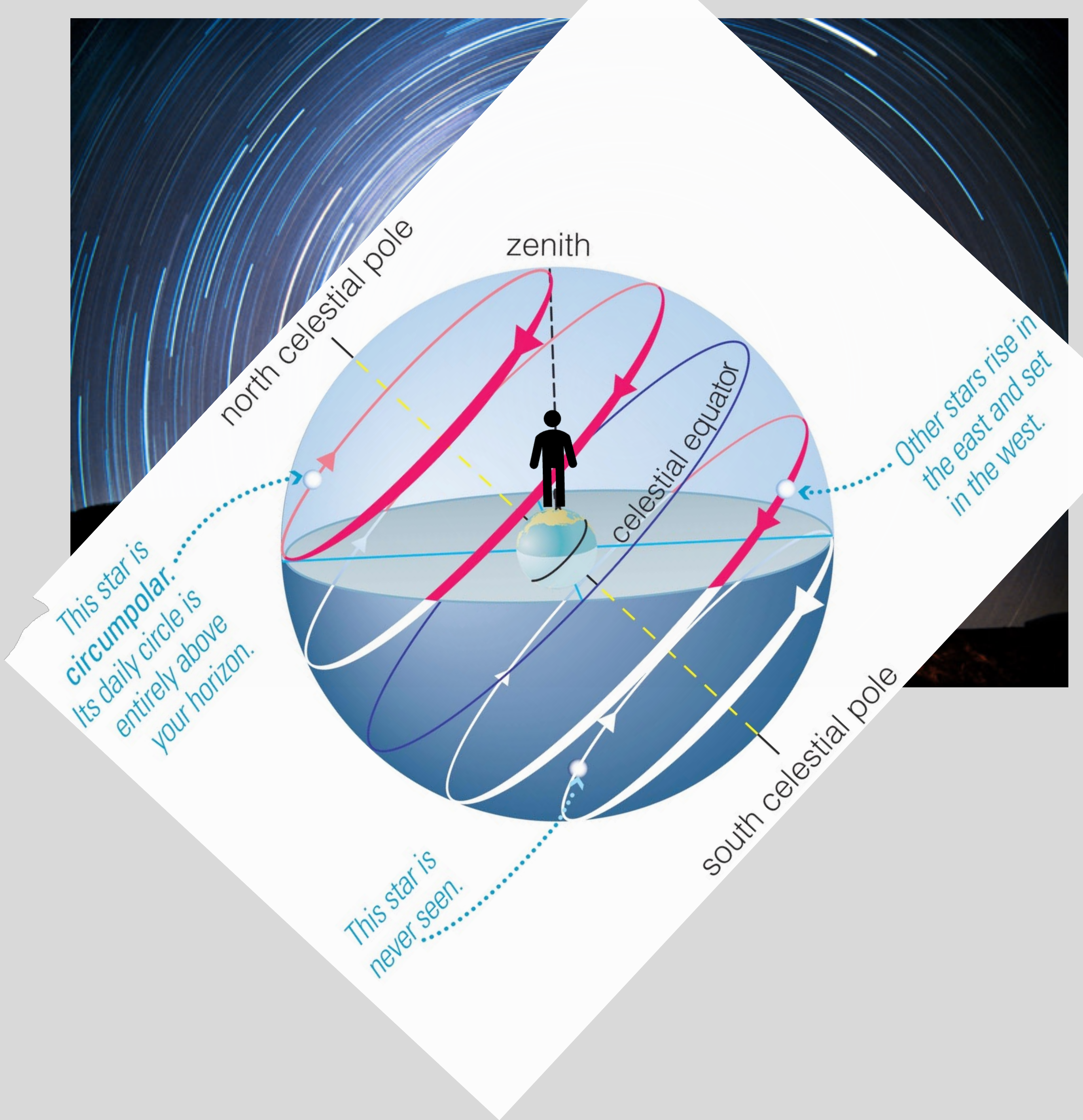
What is the declination criterion for circumpolar stars observed from Cleveland?

Working it out:

We've seen that the celestial pole has an altitude which is given by your latitude. So in Cleveland the north celestial pole has an altitude of 41°. Stars further away from the pole than 41° will go below the horizon at some point as the Earth rotates.

A star that is 41° away from the pole has a declination of $\delta > 90 - 41 = 49°$

So circumpolar stars from Cleveland: $\delta > 49°$



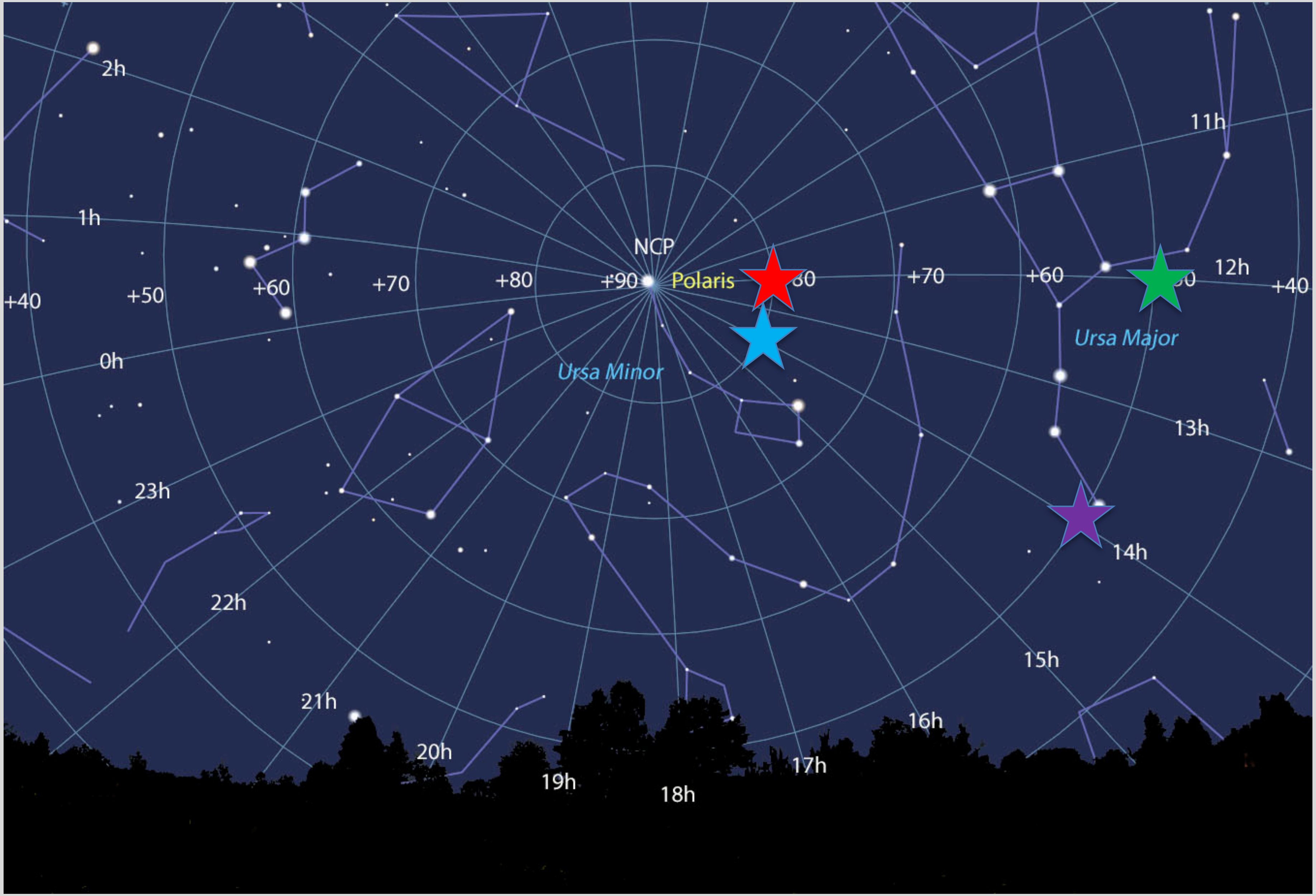
Coordinates and angular separations

Consider two pairs of stars:

Star 1: $(\alpha, \delta) = (12^h, +80)$
Star 2: $(\alpha, \delta) = (14^h, +80)$
they are pretty close together in the sky.

Star 3: $(\alpha, \delta) = (12^h, +50)$
Star 4: $(\alpha, \delta) = (14^h, +50)$
they are much further apart in the sky, even though they have the same coordinate distance.

Because lines of RA converge at the poles, coordinate distances are not the same as angular separations!



Coordinates and angular separations

For two objects with positions (α_1, δ_1) and (α_2, δ_2), what is their angular separation θ?

For small separations (where $\tan(\theta) \approx \theta$), we can do approximate Cartesian and say:

$$\theta \approx \sqrt{\Delta\alpha^2 + \Delta\delta^2}$$

where

$$\Delta\delta = (\delta_1 - \delta_2)$$
$$\Delta\alpha = (\alpha_1 - \alpha_2) \times \cos\bar{\delta}$$ ← the "cos-dec term"

(remember, if you have right ascension measured in hours, you need to multiply RA by 15 to get RA in degrees.)

As separations get large, this rapidly becomes a **bad** approximation. For a 1 degree field errors can be as large as 10 arcsec (depending on RA and dec). 1 degree = 3600 arcsec, so that's an error of 10/3600 ≈ 0.3%.

The error rapidly gets bigger for larger fields, though, so for accuracy you really should do the proper spherical trigonometry.

Computational notes on coordinates and angles

1. Remember that any time you see a "naked angle" (i.e., one outside of a trigonometric function) in an equation, that angle has units of ***radians*** unless explicitly stated otherwise. When using $\tan\theta \approx \theta$, theta must be in radians!

2. Remember that in most computer languages, the trig functions default to the assumption that angles are given in radians, not degrees. ALWAYS CHECK. In python, if angle is in degrees, you want to do:

```
np.cos(np.radians(theta))
```

3. Use astropy!

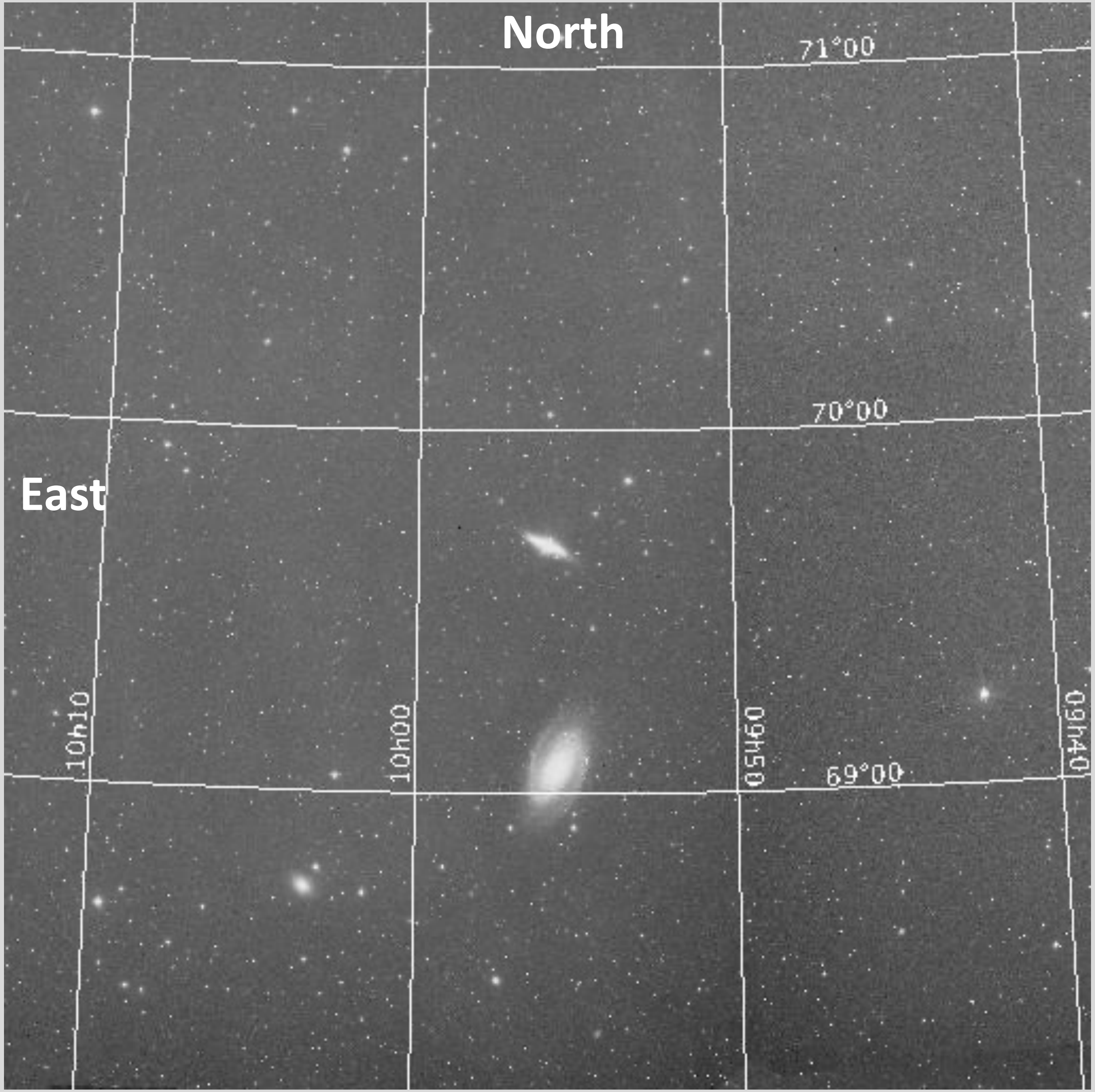
```
In [1]: from astropy.coordinates import SkyCoord

        # set up astropy coordinate objects for two galaxies
        # by giving the RA, dec coordinates in degrees
        M101coord = SkyCoord(210.80227,54.34895,unit='deg')
        N5477coord = SkyCoord(211.25671,53.66222,unit='deg')

        # calculate angular separation
        angsep = N5477coord.separation(M101coord)
        print('Angular seperation: {:.3f}'.format(angsep))
        print('Angular seperation: {:.3f}'.format(angsep.to('arcmin')))

        Angular seperation: 0.737 deg
        Angular seperation: 44.210 arcmin
```

Orientation and Directions

In astronomical images, East is always 90° counterclockwise from North.

Unless specified otherwise, standard orientation is North up and East to the left.

This is flipped from terrestrial maps, where East is usually on the right....



Note also that you can see the cos-dec term at work on this image – lines of RA are converging.

Solid Angle

Finally, **solid angle** is a measure of angular area on the sky. It relates to angle the way area relates to length and is measured in steradians.

Think of a patch of area on a sphere. If that patch has an area A, the solid angle Ω it corresponds to is defined by

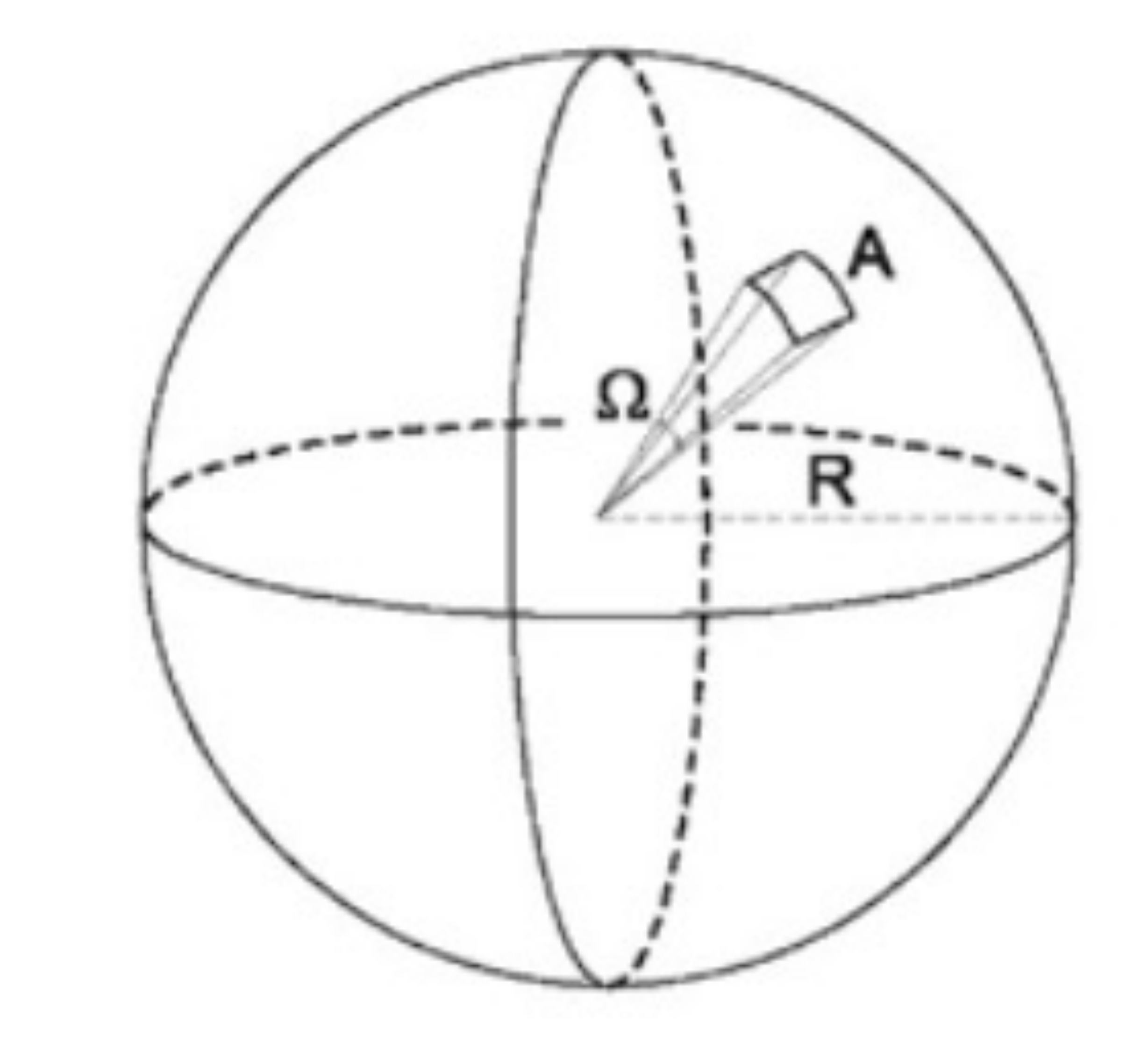
$$\Omega = \frac{A}{R^2}$$

For the entire sky, $A = 4\pi R^2$, so $\Omega = 4\pi$ steradians.

For smaller areas, we can talk about square degrees (41253 sq deg = whole sky) or square arcseconds.

Again, for small areas, cartesian approximation is ok: a 10”x10” box has an area of 100 square arcsec.

But for larger areas proper spherical trigonometry should be used...



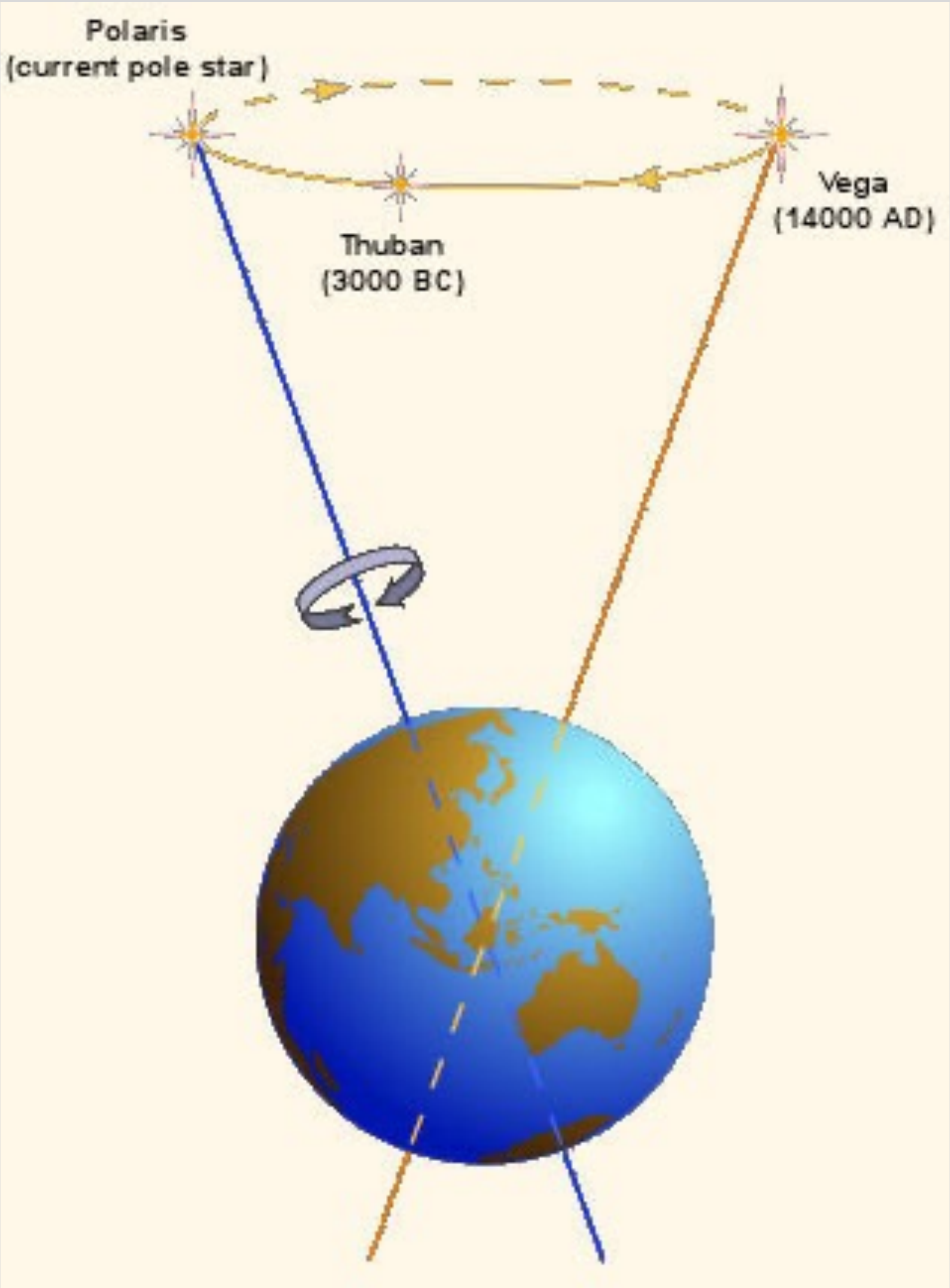
Coordinate Epochs

The equatorial coordinate system is tied to the Earth's rotational axis.

But the Earth's axis shifts with time, due to precession, over a periodic cycle of 25,800 years. This means the coordinate reference system is constantly sliding around!

So every coordinate must include an **epoch.** "B1950" refers to coordinates based on the 1950 pole position; "J2000" refers to coordinates based on the 2000 pole position.

Current standard is J2000, older papers use B1950. The coordinate differences can be as much as half a degree, so always check the epoch and convert (astropy has routines....)



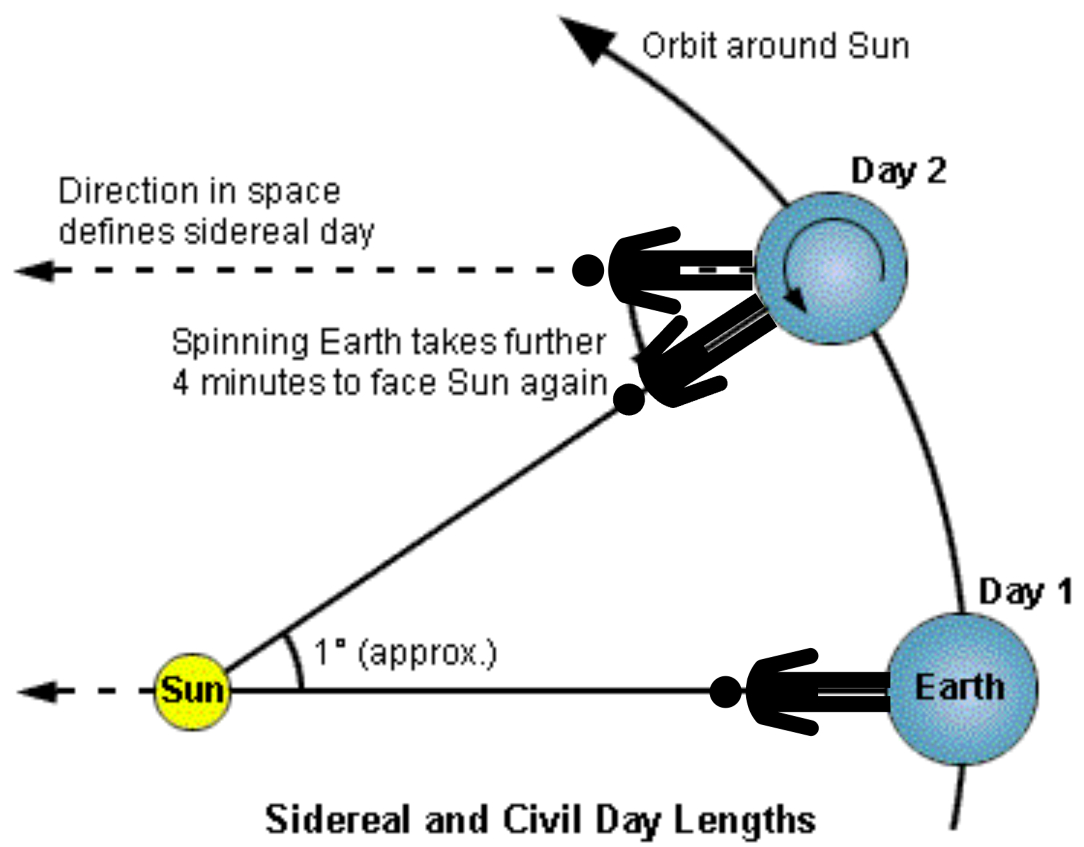
Time: Sidereal versus Solar

The Earth is spinning on its axis and orbiting the Sun. This means that a **solar day** (defined as noon-to-noon) is different from a **sidereal day** (defined as one Earth rotation).

Mean Solar day: 24hrs
Sidereal day: 23hrs, 56min

Rise/set times of an object are set by the Earth's rotation period, i.e., using sidereal time.

This means that a given star rises (or transits, or sets) 4 mins earlier each successive night, or two hours earlier each month. This is why the stars we see are different in different seasons!



Local Sidereal Time

We define the Local Sidereal Time to be the Right Ascension which is currently transiting. Depends on current time and your longitude on Earth (Cleveland longitude: 81.6944 degrees).

Now see how LST, RA, and Hour Angle fit together: **HA = LST - RA**

(Ground-based) Observing considerations:

- When is my object visible?
  - Depends on observing location, time of year.
  - Need to define "visible" – above the horizon? above a certain altitude?
- Is the moon up or down? How bright is the moon?
  - The moon makes the sky bright, hard to see faint objects.
  - "Dark time" (new moon) can be very competitive
- How many hours is my object visible for? How much observing time do I need?
  - If you need a quick observation (bright object) an hour may be enough
  - If you need very deep observations, you want the object visible for many hours.

Skycalc (http://www.briancasey.org/artifacts/astro/)

Moon Phase Page
Produces an image of the moon for a given date.

Astronomical Sky Calendar
The page generates a calendar for the given range of months which contains, for each day, the Julian Date, Sun rise & set times, Moon rise & set times and percent illumination, etc.

Daily Almanac
Lots of useful information, like sun rise and set, moon phase and position, etc. for a specific date.

Hourly Airmass Tables
Provides the airmass for a star (or other object) for each hour in a given night.

Object Seasonal Observability
Lists the rise,set, and transit times for an object on the full and new moons (i.e. bimonthly) over a period of time.

Planetary Positions
Lists the positions of the major planets for a given date.

Skycalc (http://www.briancasey.org/artifacts/astro/): **When is my object visible?**

Object Seasonal Observability

by Brian Casey , using Skycalc by John Thorstensen

Observatory Kitt Peak

If "Other" enter:

West Longitude (HOURS m s)

North Latitude (d m s)

Actual Elevation (meters)

Effective Elevation (for rise/set)

Site name

Standard Time zone, hours West

Time zone name

Time zone abbrev

Daylight-savings option: U.S. convention

Start Date Year: 2022 Month: January Day 13

End Date Year: 2023 Month: January Day 13

Stellar Parameters

Star Name M87

Right Ascension (hh mm ss) 12 30 00

Declination (dd mm ss) 12 00 00

Epoch (yyyy) 2000

Altitude of twilight sun (degrees) -18

Get Observability Table

Choose observatory (or enter location)

Important:
Skycalc wants coordinates without colons!
Be careful to verify you have entered coordinates properly….

Choose date ranges

Enter object information

Click "get observability table"

Skycalc (http://www.briancasey.org/artifacts/astro/)

- shows moon phase: F (full) / N (new)
- shows the object's Hour Angle (HA) and airmass (sec.z) at the end of evening twilight, center of the night, and start of morning twilight.
- shows how many hours during the night the object is above (i.e. higher in the sky) an airmass of 3, 2, and 1.5.

We see that M87 is above* 1.5 airmasses for 6+ hours each night in March and April. But we don't want the moon to interfere with our observations. So we might ask for observing time at the beginning or end of March, to avoid full moon.

* remember, "above 1.5 airmasses" means "higher in the sky than an airmass of 1.5, or in other words $\sec(z) < 1.5$.

*** Seasonal Observability of M87 ***

RA & dec: 12 30 00.0, 12 00 00, epoch 2000.0
Site long&lat: 7 26 28.0 (h.m.s) West, 31 57 12 North.

Shown: local eve. date, moon phase, hr ang and sec.z at (1) eve. twilight, (2) natural center of night, and (3) morning twilight; then comes number of nighttime hours during which object is at sec.z less than 3, 2, and 1.5. Night (and twilight) is defined by sun altitude < -18.0 degrees.

Date (eve)	moon	eve		cent		morn		night hrs@sec.z:		
		HA	sec.z	HA	sec.z	HA	sec.z	<3	<2	<1.5
2022 Jan 17	F	-9 55	down	-4 30	2.3	0 55	1.1	5.9	5.0	4.1
2022 Jan 31	N	-8 49	down	-3 32	1.6	1 45	1.2	6.7	5.9	4.9
2022 Feb 15	F	-7 38	down	-2 32	1.3	2 34	1.3	7.5	6.7	5.7
2022 Mar 1	N	-6 33	down	-1 39	1.2	3 15	1.5	8.2	7.4	6.4
2022 Mar 17	F	-5 18	3.8	-0 40	1.1	3 58	1.9	8.9	8.1	6.4
2022 Mar 31	N	-4 11	2.0	0 11	1.1	4 34	2.4	8.7	8.2	6.4
2022 Apr 15	F	-2 59	1.4	1 06	1.1	5 12	3.5	7.9	7.1	6.2
2022 Apr 30	N	-1 46	1.2	2 03	1.2	5 51	7.1	6.7	5.9	4.9
2022 May 15	F	-0 32	1.1	3 01	1.4	6 34	down	5.5	4.6	3.7
2022 May 29	N	0 36	1.1	3 58	1.9	7 18	down	4.3	3.5	2.6
2022 Jun 13	F	1 45	1.2	4 59	3.1	8 13	down	3.2	2.4	1.4
2022 Jun 28	N	2 48	1.4	6 02	9.8	9 16	down	2.2	1.3	0.4
2022 Jul 12	F	3 39	1.7	6 59	down	10 20	down	1.3	0.5	0.0
2022 Jul 27	N	4 26	2.3	7 59	down	11 33	down	0.5	0.0	0.0
2022 Aug 11	F	5 08	3.4	8 57	down	-11 14	down	0.0	0.0	0.0
2022 Aug 26	N	5 47	6.4	9 53	down	-10 01	down	0.0	0.0	0.0
2022 Sep 9	F	6 22	33.4	10 43	down	-8 55	down	0.0	0.0	0.0
2022 Sep 25	N	7 02	down	11 41	down	-7 41	down	0.0	0.0	0.0
2022 Oct 9	F	7 39	down	-11 29	down	-6 36	down	0.0	0.0	0.0
2022 Oct 24	N	8 22	down	-10 32	down	-5 27	4.4	0.0	0.0	0.0
2022 Nov 7	F	9 07	down	-9 38	down	-4 21	2.2	0.6	0.0	0.0
2022 Nov 23	N	10 03	down	-8 32	down	-3 06	1.5	1.8	1.0	0.1
2022 Dec 7	F	10 59	down	-7 31	down	-2 01	1.2	2.9	2.1	1.2
2022 Dec 22	N	-11 57	down	-6 25	52.8	-0 53	1.1	4.1	3.2	2.3
2023 Jan 6	F	-10 48	down	-5 19	3.9	0 11	1.1	5.1	4.3	3.4
2023 Jan 21	N	-9 38	down	-4 14	2.1	1 09	1.1	6.1	5.3	4.3

Skycalc (http://www.briancasey.org/artifacts/astro/): **What are the conditions on a particular night?**

Hourly Airmass Table

by Brian Casey , using Skycalc by John Thorstensen

Observatory Kitt Peak

Choose observatory (or enter location)

If "Other" enter:

West Longitude (HOURS m s)

North Latitude (d m s)

Actual Elevation (meters)

Effective Elevation (for rise/set)

Site name

Standard Time zone, hours West

Time zone name

Time zone abbrev

Daylight-savings option: U.S. convention

Date Year: 2022 Month: March Day 24

Choose date

Stellar Parameters

Star Name M87

Right Ascension (hh mm ss) 12 30 00

Declination (dd mm ss) 12 00 00

Enter object information

Epoch (yyyy) 2000

Altitude of twilight sun (degrees) -18

Get Airmass Table

Click “get airmass table”

Skycalc (http://www.briancasey.org/artifacts/astro/)

- Shows moon phase (half lit)
- Shows local time at observatory, universal time, local sidereal time
- Shows Hour Angle (HA) and airmass (secz) of the object over the course of the night.
- Show altitude of Sun and Moon

So on this night, if we wanted to observe with the object above and altitude of 1.5 airmasses and no moon:

- Start at about 9:30pm (above secz=1.5)
- End at about 3:00am (moonrise)

Hourly Airmass Table for M87 for Mar 24, 2022

```
*** Hourly airmass for M87 ***

Epoch 2000.00: RA  12 30 00.0, dec  12 00 00
Epoch 2022.23: RA  12 31 07.5, dec  11 52 38

At midnight: UT date 2022 Mar 25, Moon 0.49 illum,  95 degr from obj
```

Local	UT	LMST	HA	secz	par.angl.	SunAlt	MoonAlt
19 00	2 00	6 44	-5 47	6.485	-59.0	-4.9	...
20 00	3 00	7 44	-4 47	2.719	-60.1	-17.4	...
21 00	4 00	8 44	-3 47	1.774	-59.3	...	...
22 00	5 00	9 44	-2 47	1.373	-55.5	...	...
23 00	6 00	10 44	-1 47	1.176	-46.5	...	...
0 00	7 00	11 44	-0 47	1.085	-26.3	...	...
1 00	8 00	12 45	0 13	1.066	8.3	...	...
2 00	9 00	13 45	1 14	1.115	37.3	...	-0.5
3 00	10 00	14 45	2 14	1.247	51.5	...	9.3
4 00	11 00	15 45	3 14	1.517	57.7	...	17.8
5 00	12 00	16 45	4 14	2.088	59.9	...	24.6
6 00	13 00	17 45	5 14	3.658	59.8	-5.8	29.0