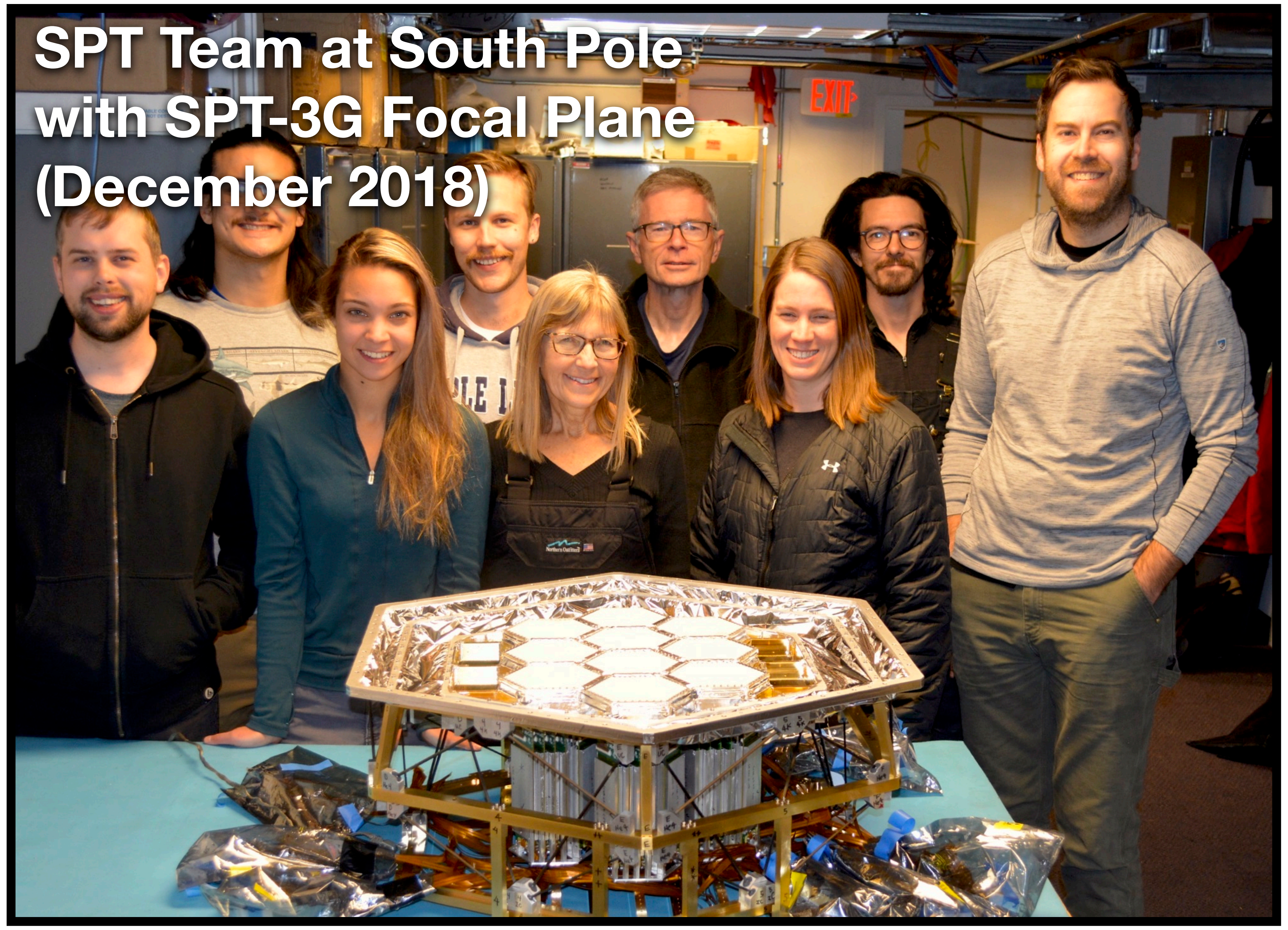
ASTR21200

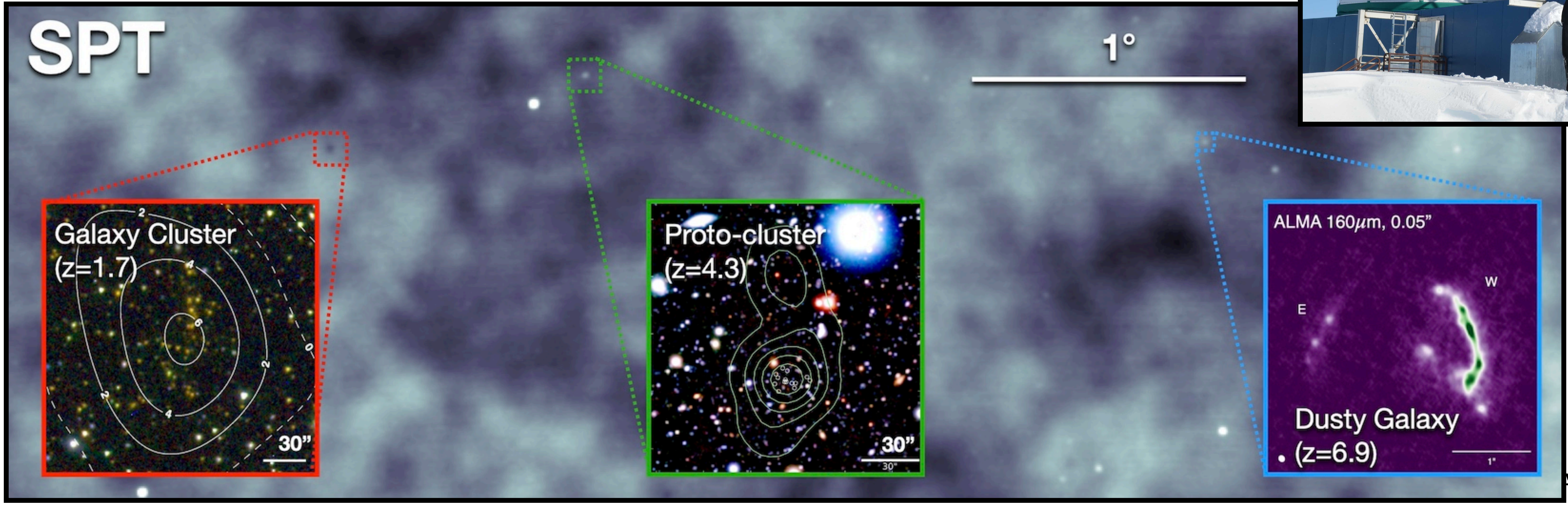
Observational Techniques in Astrophysics
Spring 2024

Bradford Benson

Hello!

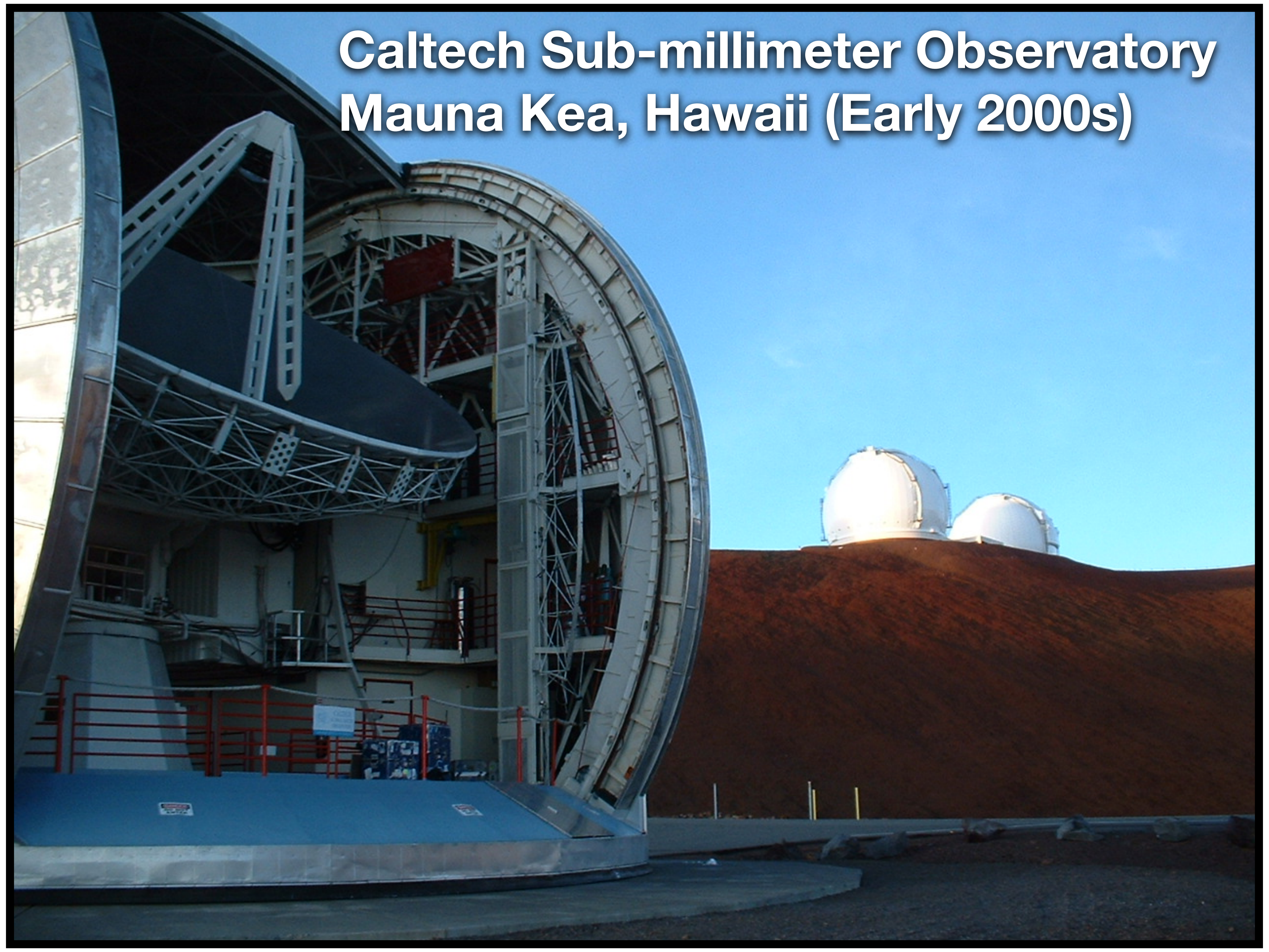
- Im an experimental cosmologist who builds instrumentation to study the cosmic microwave background (CMB), working primarily on the South Pole Telescope (SPT)





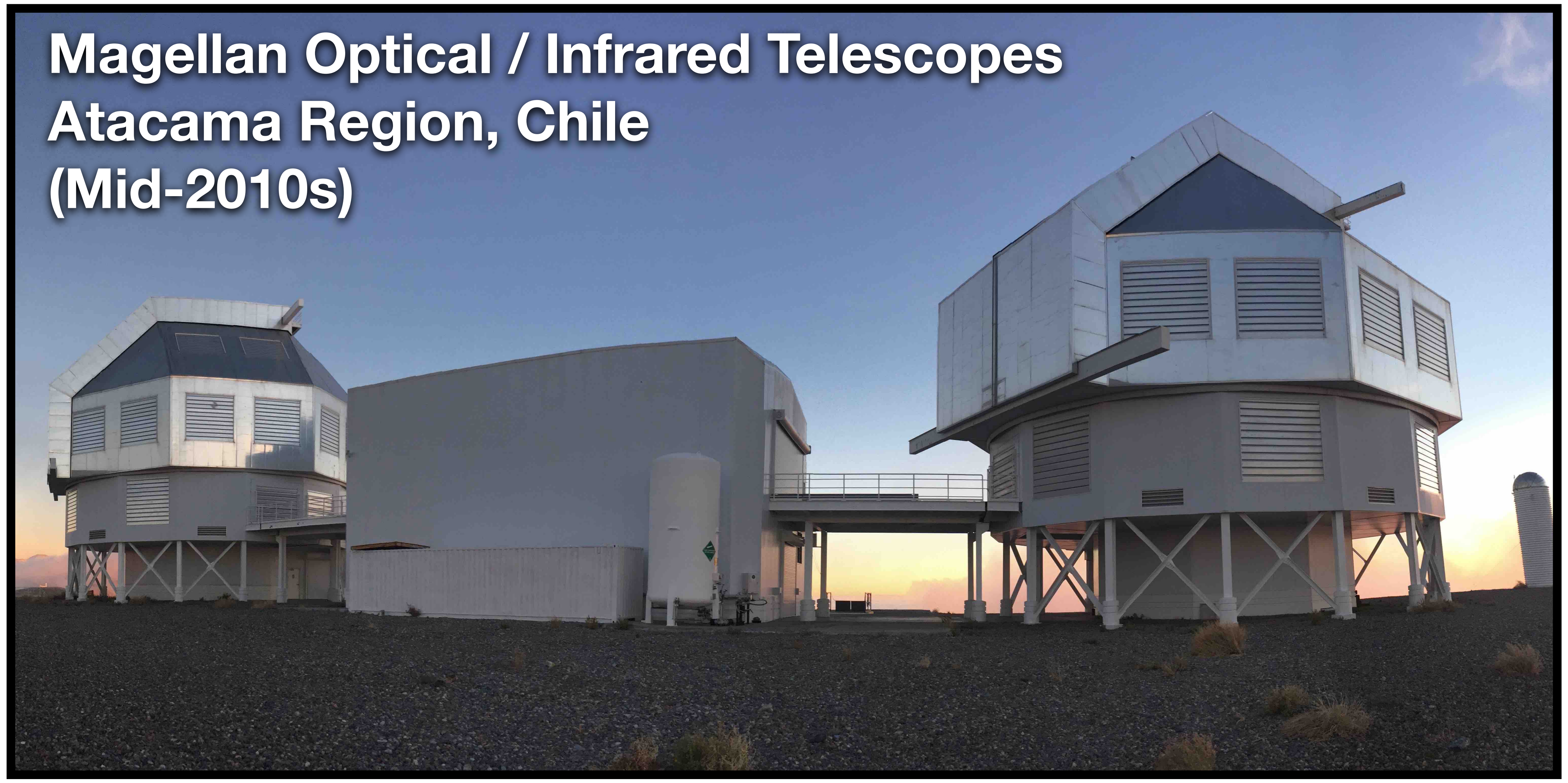
What do I do?

- Ive been observing in Hawaii, Chile, Antarctica
    - Spent nearly 2-years at South Pole over 12 trips
- Written proposals for Hubble, Chandra, XMM space telescopes
- Spanning radio, microwaves, X-ray, optical, infrared wavelengths



Caltech Sub-millimeter Observatory
Mauna Kea, Hawaii (Early 2000s)

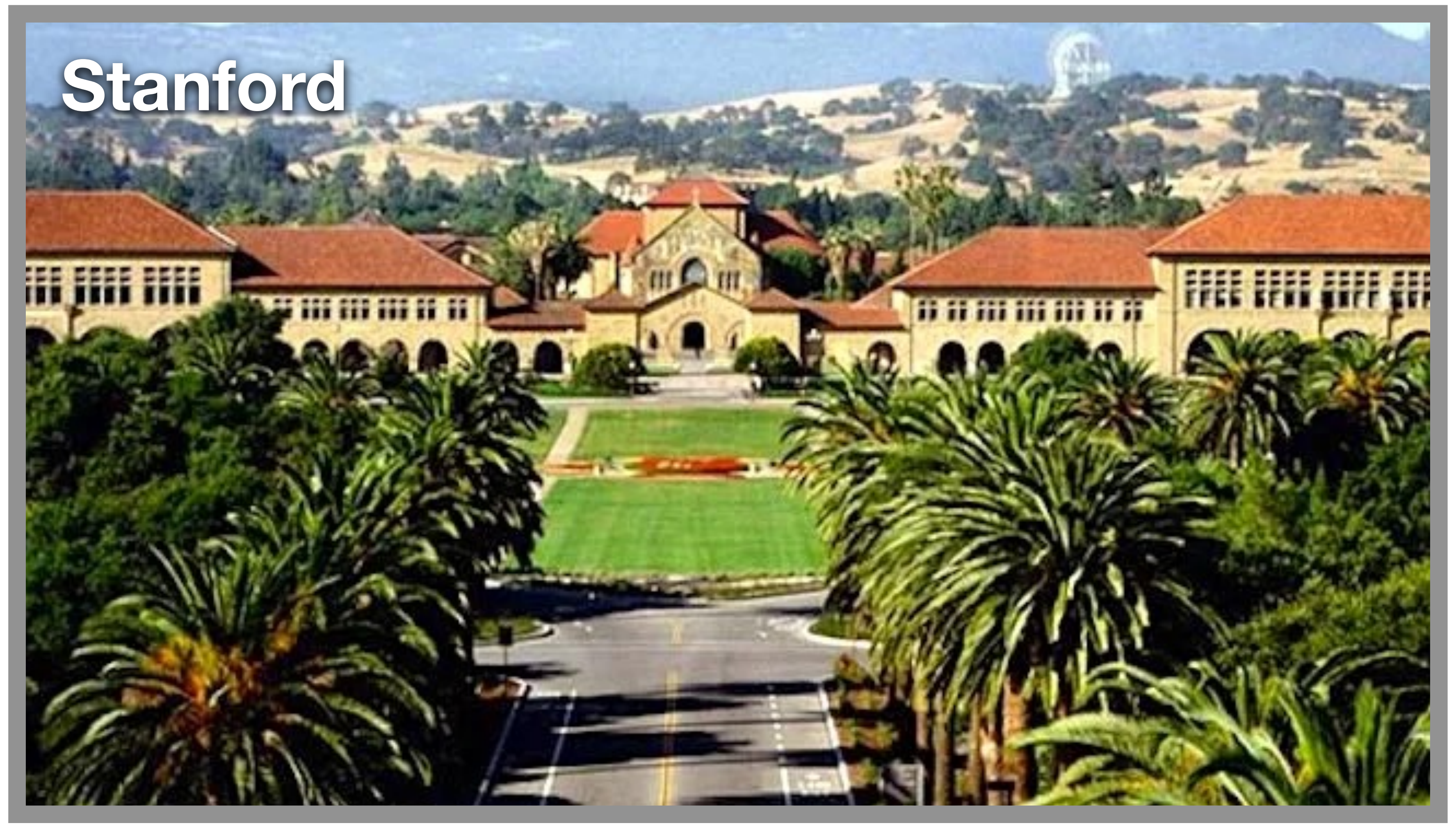
SPT at the South Pole
(December 2017)



Magellan Optical / Infrared Telescopes
Atacama Region, Chile
(Mid-2010s)

My Bio

- **Undergrad**: U. Wisconsin-Madison
- **PhD**: Stanford University
- **Post-docs**: U. California-Berkeley, U. Chicago
- **Since 2013:** Professor at U. Chicago, Scientist at Fermilab



Course LAs and Other Instructors:

Teaching Assistants (TAs/LAs):

- Dillon Bass (dillonjb 'at' uchicago.edu)
- Rohan Gupta (rohangupta 'at' uchicago.edu)

Knowledgeable People for Stone Edge Observatory (SEO) and this class:

- Dr. Al Harper (al 'at' oddjob.uchicago.edu) - Former instructor for this course
- Dr. Amanda Pagul (apagul 'at' uchicago.edu) - Support Astronomer for SEO
- Dr. Marc Berthoud (berthoud 'at' astro.uchicago.edu) - Research Engineer for SEO

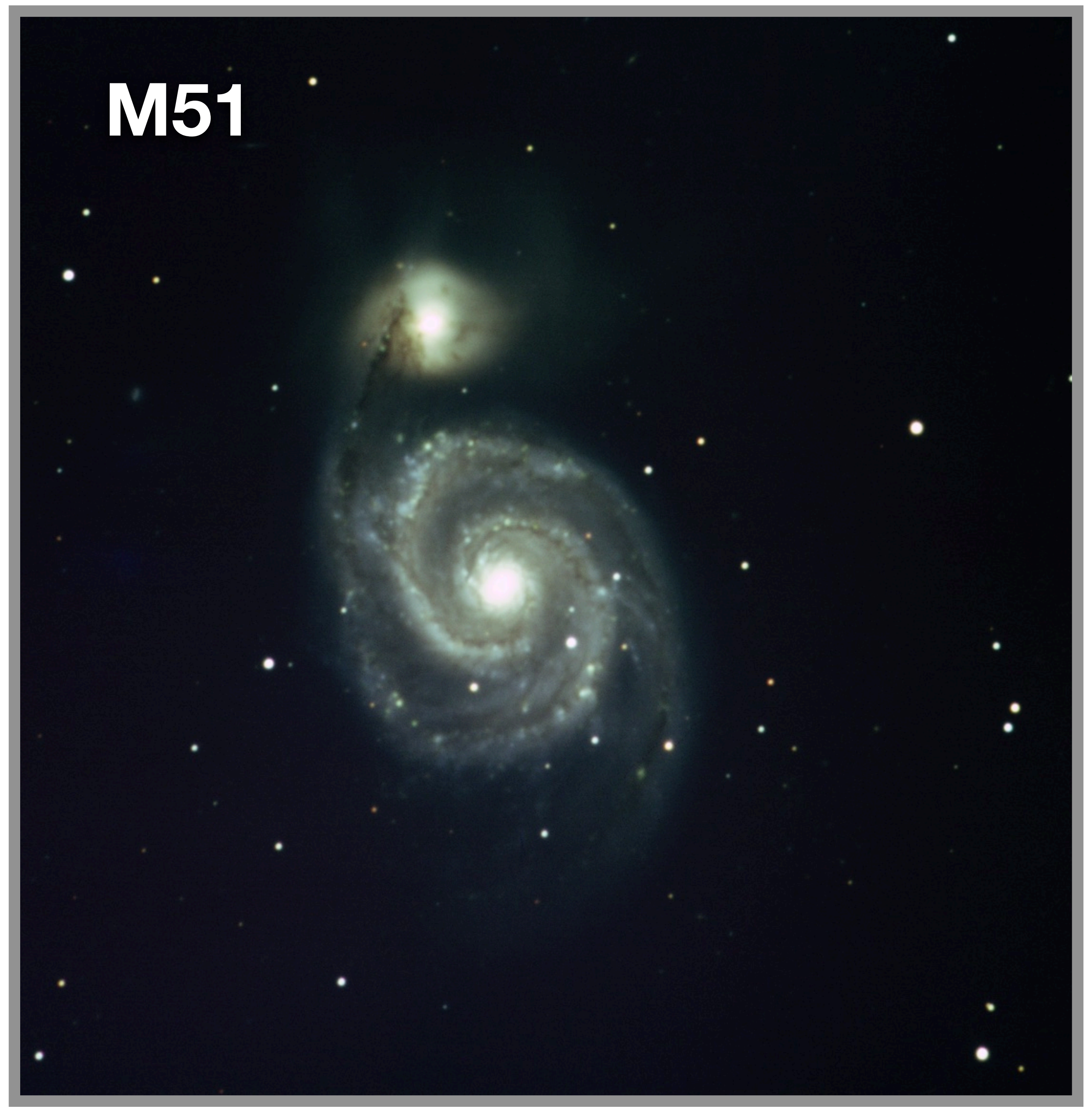
See more details on the class wiki at:
https://github.com/bradfordbenson/ASTR21200_2024/wiki

Course Purpose and Objectives

- Purpose: Teach you the basics of how to be an observational astronomer
  - Introduction to observational astronomy
  - Design, take, analyze and interpret astronomical observations
  - Report your work in lab reports and a scientific paper

Stone Edge Observatory (SEO)

- Located in Sonoma, CA, but operated by U. Chicago
- 0.5-m diameter aperture with a 26’ x 26’ field of view (FOV)
- Outfitted with a CCD with a set of standard broadband filters (g, r, i, z, …)
- More info at:
  - https://voices.uchicago.edu/stoneedgeobservatory/
  - https://sites.google.com/a/starsatyerkes.net/yerkesprojects/tools/telescope-upgrades/stone-edge-observatory?authuser=0
  - On the class wiki!



How to be become an observational astronomer

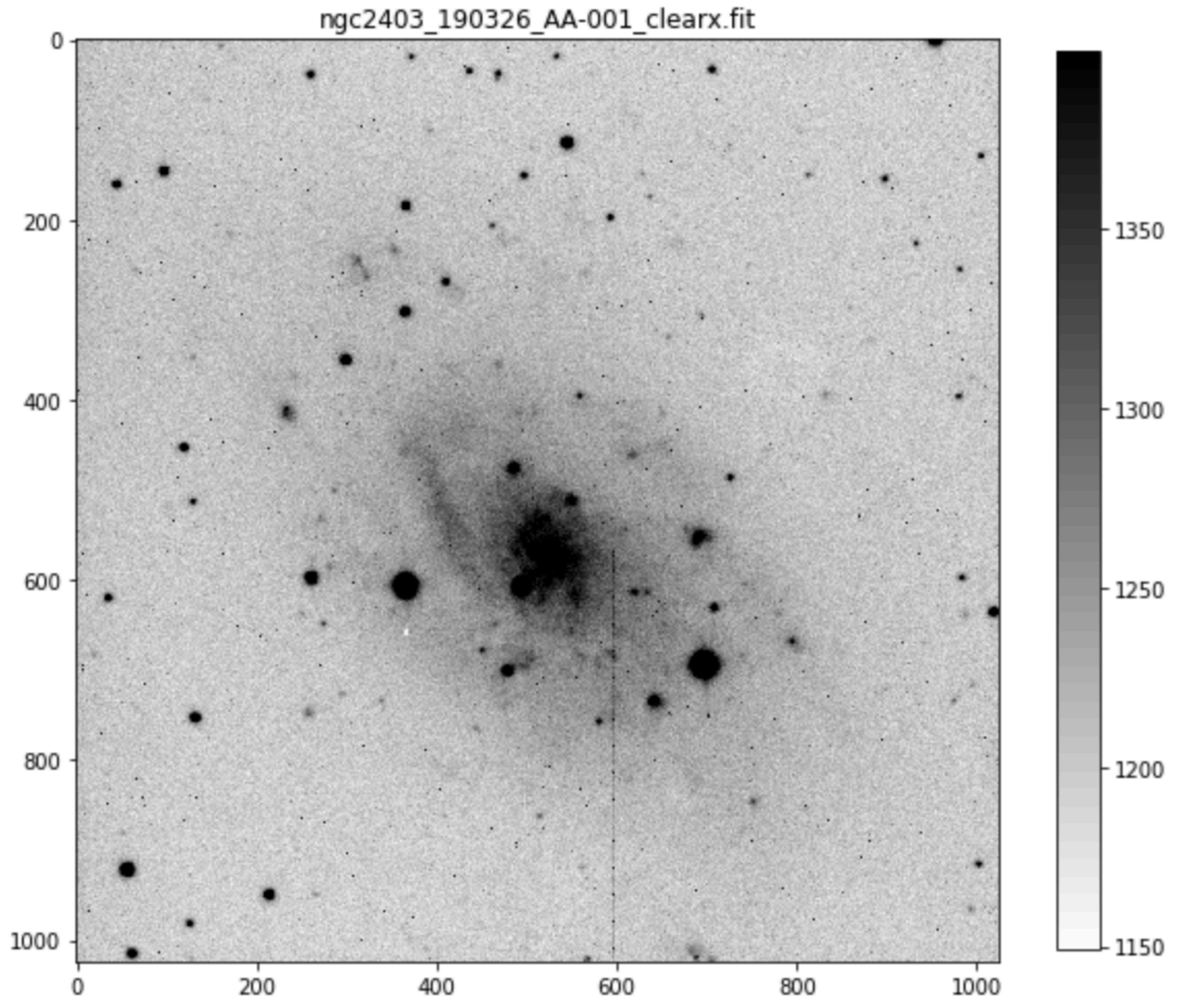
1. Come up with an interesting idea / hypothesis
2. Search for and analyze archival observations
3. Write a telescope proposal
4. Plan and execute your observations
5. Analyze your data
6. Write a journal paper
7. Present your work at conferences

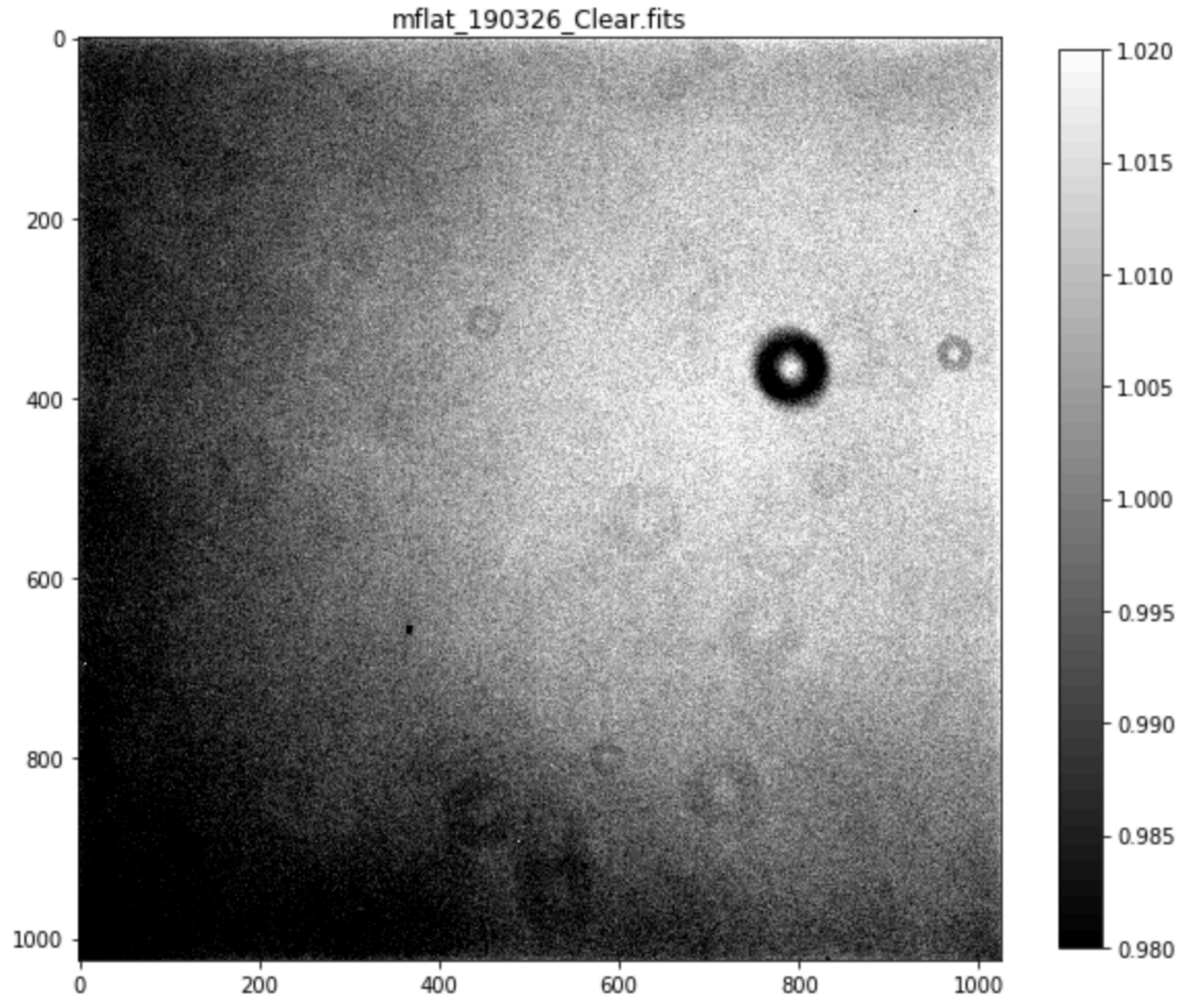
For this course, we’ll deviate a bit

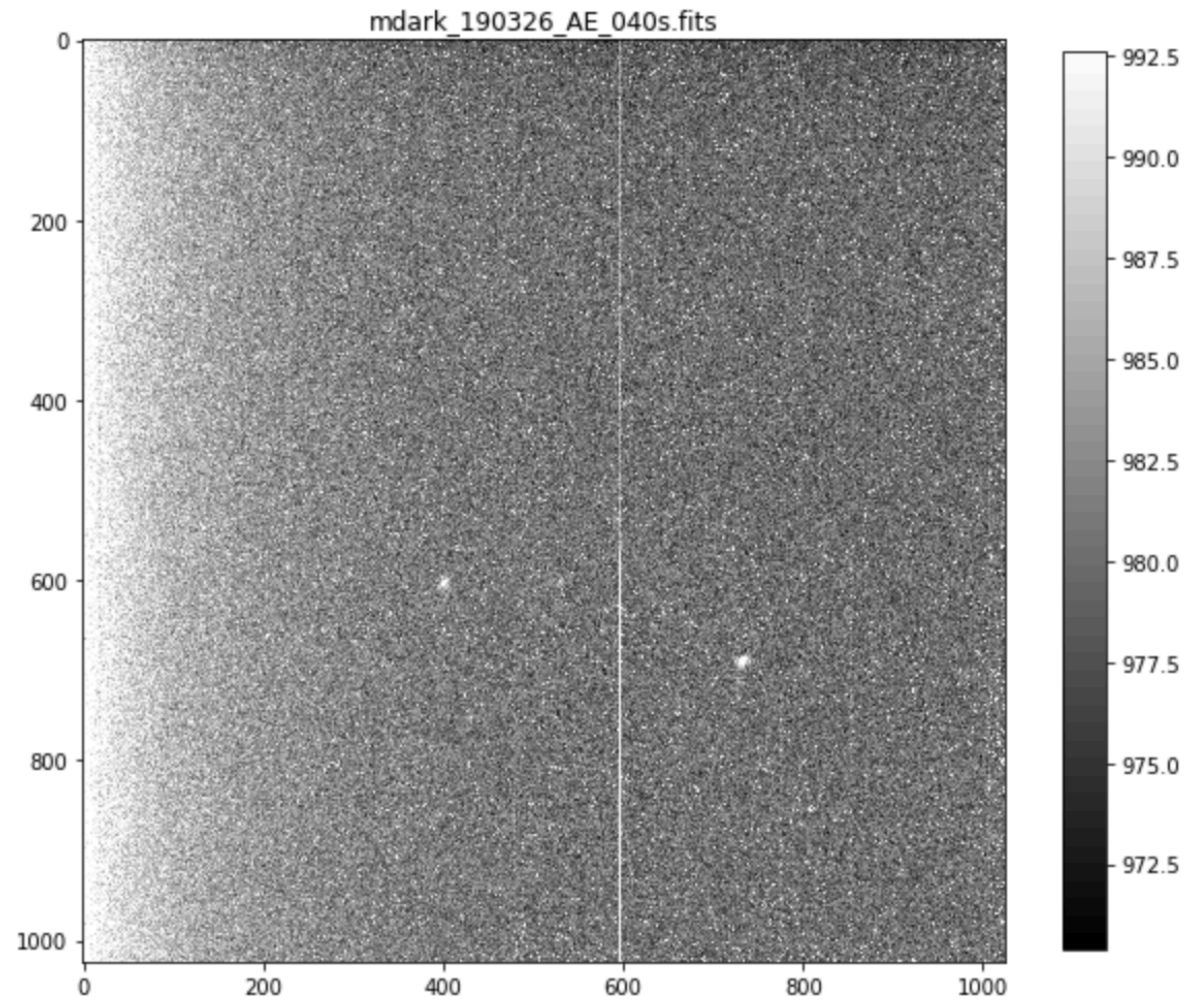
1. Come up with an interesting idea / hypothesis
2. Conduct and analyze observations
3. Journal paper -> Lab report
4. Present your work in class

Lab1 - CCDs

- Measure properties of CCD cameras
- Understand the role of calibration data
- Familiarize yourself with the equipment

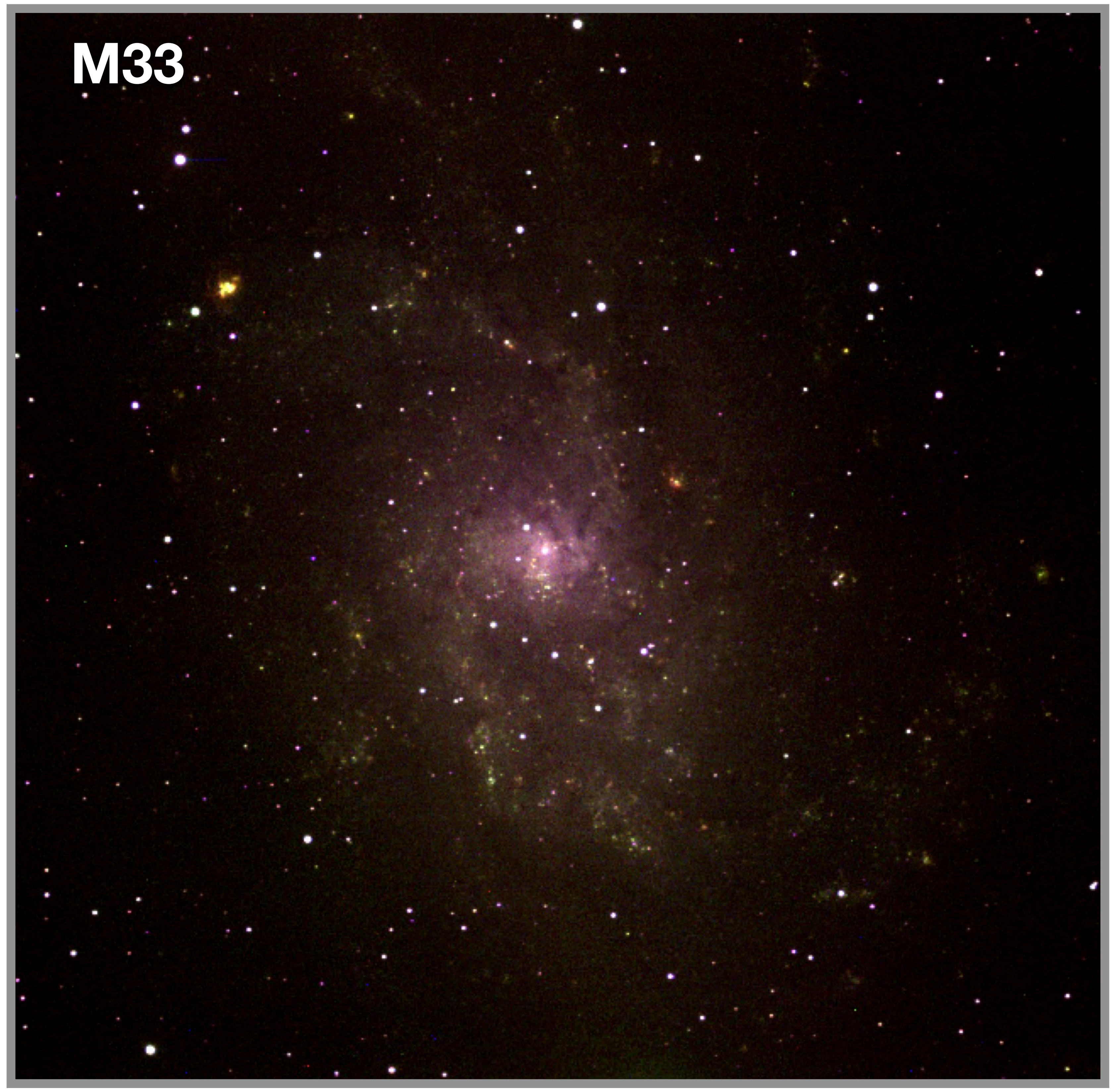


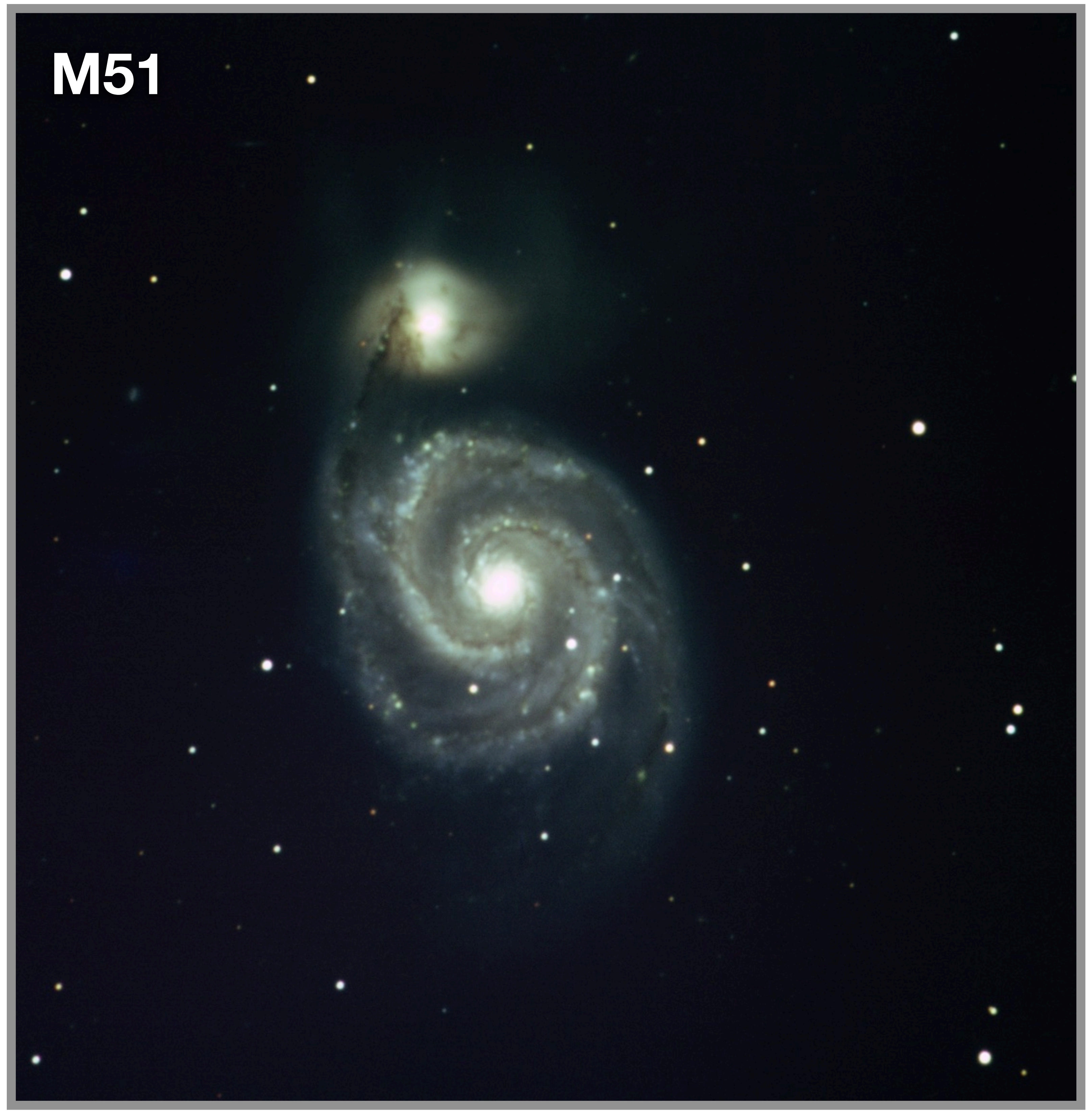




Lab2 - Optical Imaging

- Make RGB color images of nearby galaxies, to measure their size, and infer the expansion of the Universe (i.e., the Hubble constant)

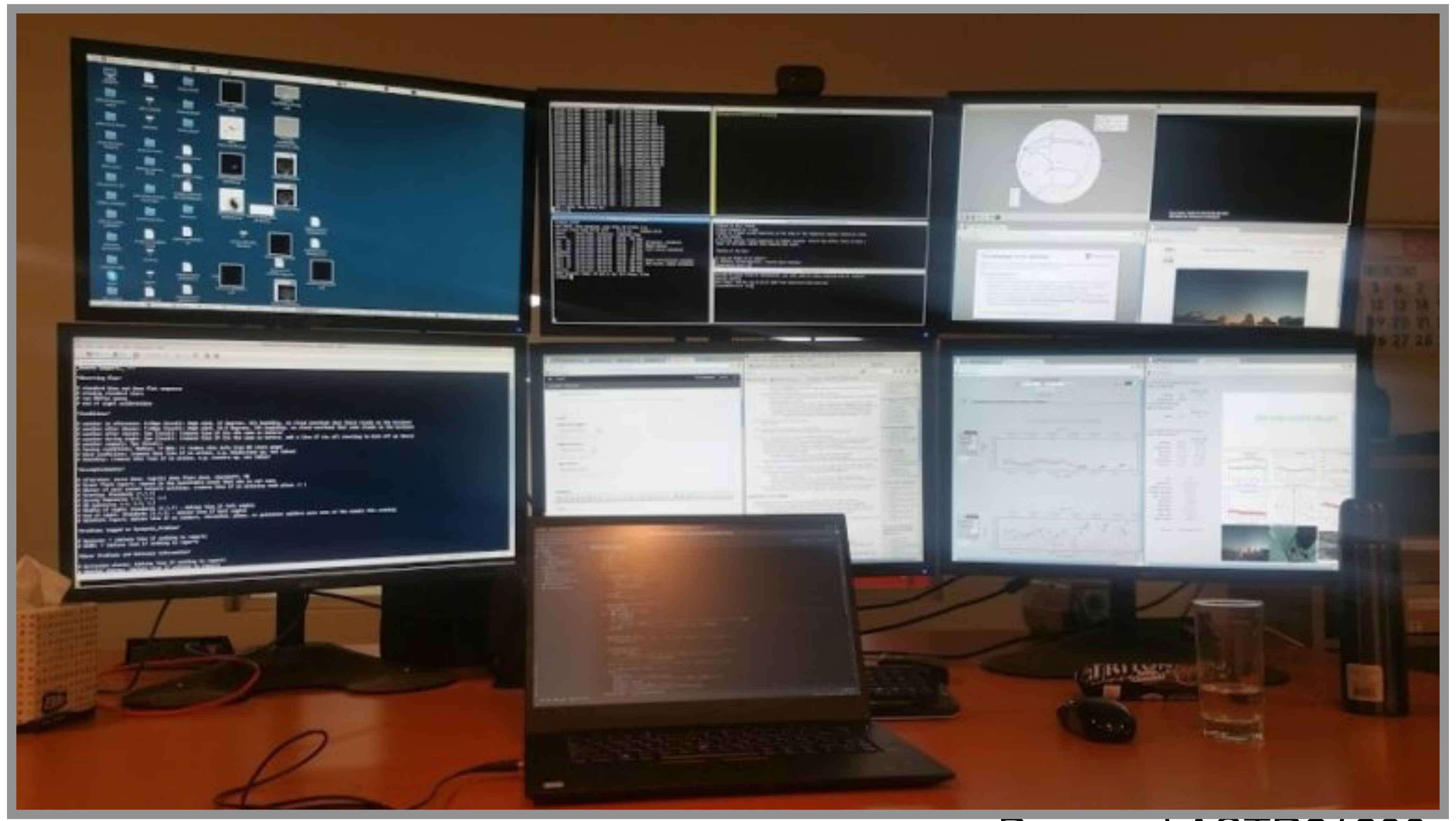




Lab 3 - Your own project idea

- Come up with your own project idea!
- Make observations
- Do analysis
- Do a class presentation

Observing



- https://astrobites.org/2016/02/04/living-the-magellan-life-observing-at-a-chilean-masterpiece/

Data Analysis

- CCD cameras and digital image processing were revolutionary for astronomy
  - ~1980: First CCD cameras used on telescopes
- The Sloan Digital Sky Survey (SDSS), designed in the 90s, was one of the first "Big Data" projects, followed by the Dark Energy Survey (DES)
  - U. Chicago had leading roles on both projects!
- Today we are preparing for the Vera Rubin Observatory's Legacy Survey of Space and Time (VRO/LSST), ~20 TB per night, every night for 10 years
- Research in astronomy requires programming, and statistical analysis of large datasets

Data Analysis

- Most astronomy research is done on Unix/Linux
    - "*bash*" is a Unix shell that provides an integrated scripting language
- *Python* is becoming ubiquitous in astronomy as a higher-level programming language, with astropy a widely used package with astronomy functions.
    - Other languages (e.g., *IDL*, *C*, *R, Fortran*) are sometimes used, depending on user-preference or the use case
- We will use several common astronomy software packages:
    - *Ds9*, *source extractor*, *astrometry.net*, etc.
    - See some common Astronomy-software tools on class wiki
- However, this is not a class on programming. We will provide basic instructions and help, but you will have to find many things out on your own (e.g., via google, online tutorials, other experts in your lab group, etc.)

Computing Resources

- SEO raw and reduced data will be on public webpage
- Run analysis on your laptop or using Google Collab
    - See more options on class wiki
- Back up your data, scripts, analyses, etc! (e.g., Google drive, Box, GitHub, etc.)

Class Structure

Class Times

- Tues & Thurs 500-620pm
    - 9 lectures in total over 9-week quarter
    - 9 “analysis help/hack” sessions to work on Labs with your group

Labs

- 3x Labs over the course of the quarter, starting in Week-3
- Will discuss more details as we get closer to Labs, but brief summary:
    - Work in groups of 3-5 students. Each student will need to submit their own report, either a Jupyter notebook or written report.
    - Schedule observing times with Stone Edge Observatory (SEO). Depending on weather, might need to schedule multiple nights.

Course Webpage

https://github.com/bradfordbenson/ASTR21200_2024
https://github.com/bradfordbenson/ASTR21200_2024/wiki

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Home

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Welcome to the ASTR21200 wiki!

Class time and place:

- Tuesday and Thursday, 5:00 - 6:20pm
- Hinds / HGS 101

Instructor:

- Bradford Benson
- Email: bbenson 'at' astro.uchicago.edu
- Office: Eckhardt Research Center (ERC) 589

TAs:

- Dillon Bass (dillonjb 'at' uchicago.edu)
- Rohan Gupta (rohangupta 'at' uchicago.edu)

Office hours:

- Brad: Thurs 12:00pm (ERC 589)

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- Measuring the Universe: A Multiwavelength Perspective, G. Rieke (Cambridge University Press, 2012)
- Data Reduction and Error Analysis for the Physical Sciences, P.R. Bevington & D. K. Robinson (McGraw-Hill Higher Education, 2003)
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Course Syllabus

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Class syllabus
Linked to the
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ASTR 21200: Observational Techniques in Astrophysics

Spring 2024, University of Chicago

Class Hours: T/Th 5.00-6.20pm
Class Room: Hinds/HGS 101

Instructor: Bradford Benson
E-mail: bbenson@astro.uchicago.edu
Office: Eckhardt Research Center (ERC) 589
Course Website: https://github.com/bradfordbenson/ASTR21200_2024
Course Wiki: https://github.com/bradfordbenson/ASTR21200_2024/wiki

Course Description

Astronomers explore the universe by detecting and analyzing light from all over the electromagnetic spectrum. This is an observational lab course, focused on obtaining and analyzing astronomical data with optical telescopes, namely the Stone Edge Observatory.

Students will work in groups of 3-5 students to conduct observational experiments via labs. For all the labs, the students will be responsible for scheduling the observations, analyzing the resultant data, and reporting their work in lab reports.

1. Lab 1: Students will measure properties of astronomical CCD cameras and develop a calibration scheme for optical imaging.
2. Lab 2: Students will acquire color images of galaxies, measure their angular size and radial profile, and infer the expansion rate of Universe (i.e., the Hubble constant)
3. Lab 3: Students will propose their own project and undertake observations.

The course will include a lecture component, that is intimately intertwined with the experimental aspects of the course. The students will learn the basics of practical observational astronomy, such as determining the observability of selected targets, telescope and detector technology, the use of photometric and spectroscopic techniques, and methods of error, statistical, and time-series analysis. A limited number of homework sets will be assigned to facilitate comprehension of the lecture material. Data analysis will be performed using standard astronomy software packages, as well as one general-purpose programming language such as python. In addition, students will need to familiarize themselves with standard Linux tools. Tutorials will be provided during class-time and/or as homework. Towards the end of the course, the students will prepare a final oral presentation on their final Lab Project.

1

Course Schedule

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Schedule Spring 2024

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	Mar-21	Practical Observing	Lect-2		
2	Mar-26	CCDs and Astronomical Images	Lect-3	[HW-2, Due Apr-2]	Python-2: CCD Images
	Mar-28	Intro to Stone Edge	Lect-4		Python-3: Astropy Fits
3	Apr-2	Intro to Labs and Lab1	Lect-5	Lab-1, Due Apr-16	Python-4: RGB Images
	Apr-4	(Analysis and Help/Hack Session)			
4	Apr-9	Statistics	Lect-6		
	Apr-11	(Analysis and Help/Hack Session)		[HW-3, Due Apr23]	
5	Apr-16	Intro to Lab2	Lect-7	[Lab-2, Due May-2]	SEO Cheat Sheet
	Apr-18	(Analysis and Help/Hack Session)			
6	Apr-23	(Analysis and Help/Hack Session)			
	Apr-25	(Analysis and Help/Hack Session)			
7	Apr-30	Intro to Lab 3, Project Ideas	Lect-8	[Lab-3, Due May-16]	
	May-2	(Analysis and Help/Hack Session)			

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Lecture notes
Homework
Labs
Tutorials

Will be linked to "Schedule"

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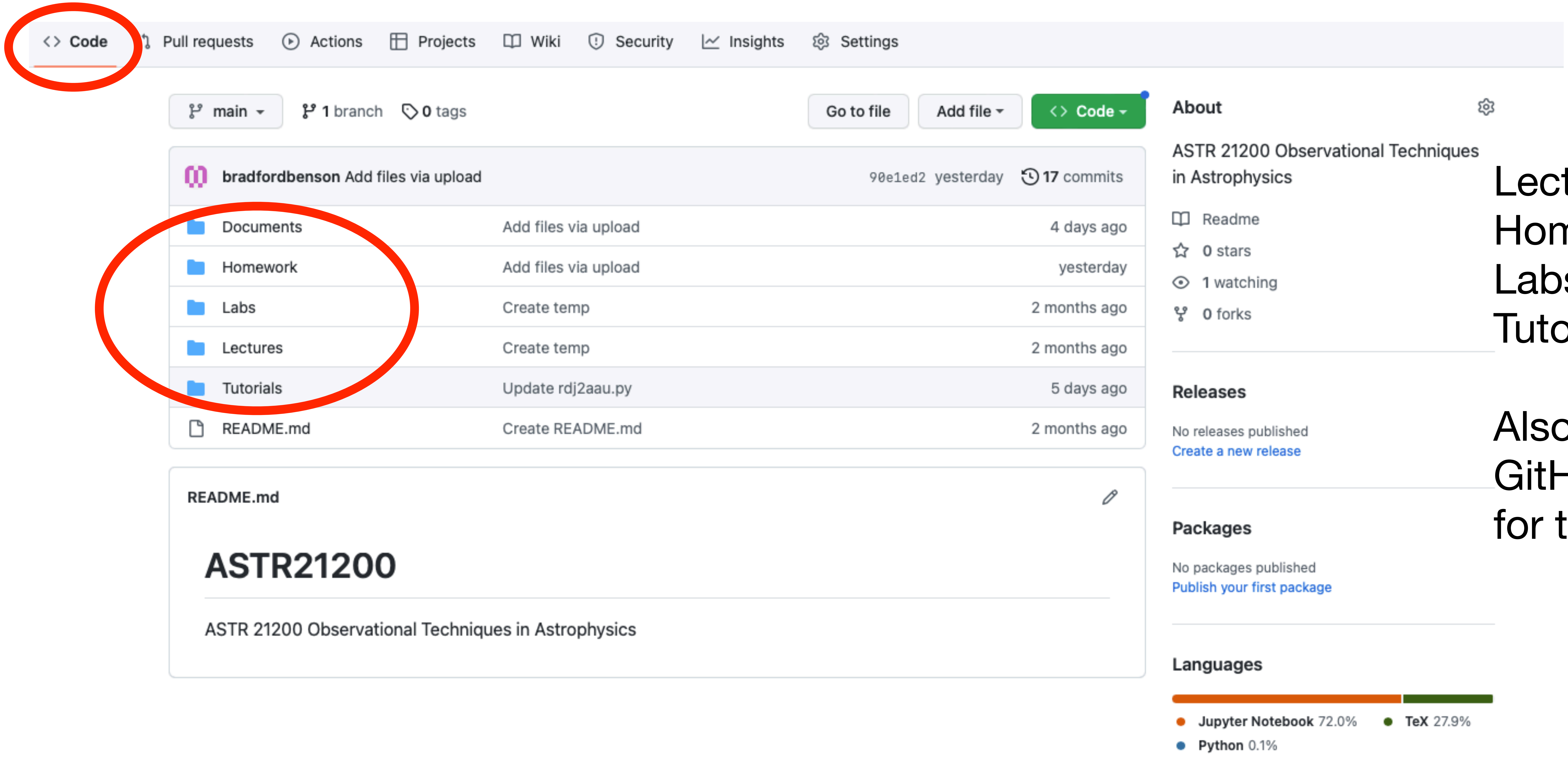

Lecture notes
Homework
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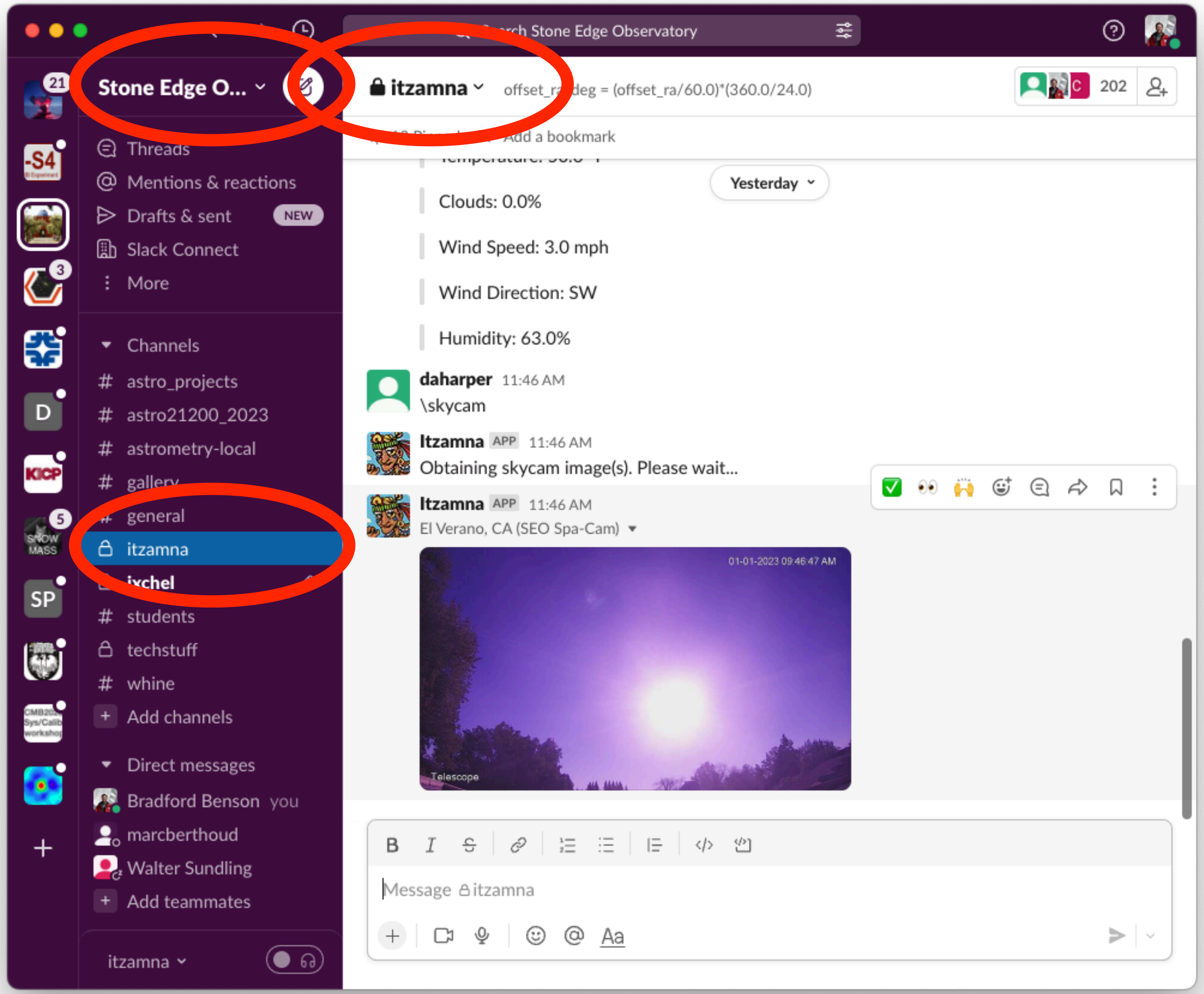
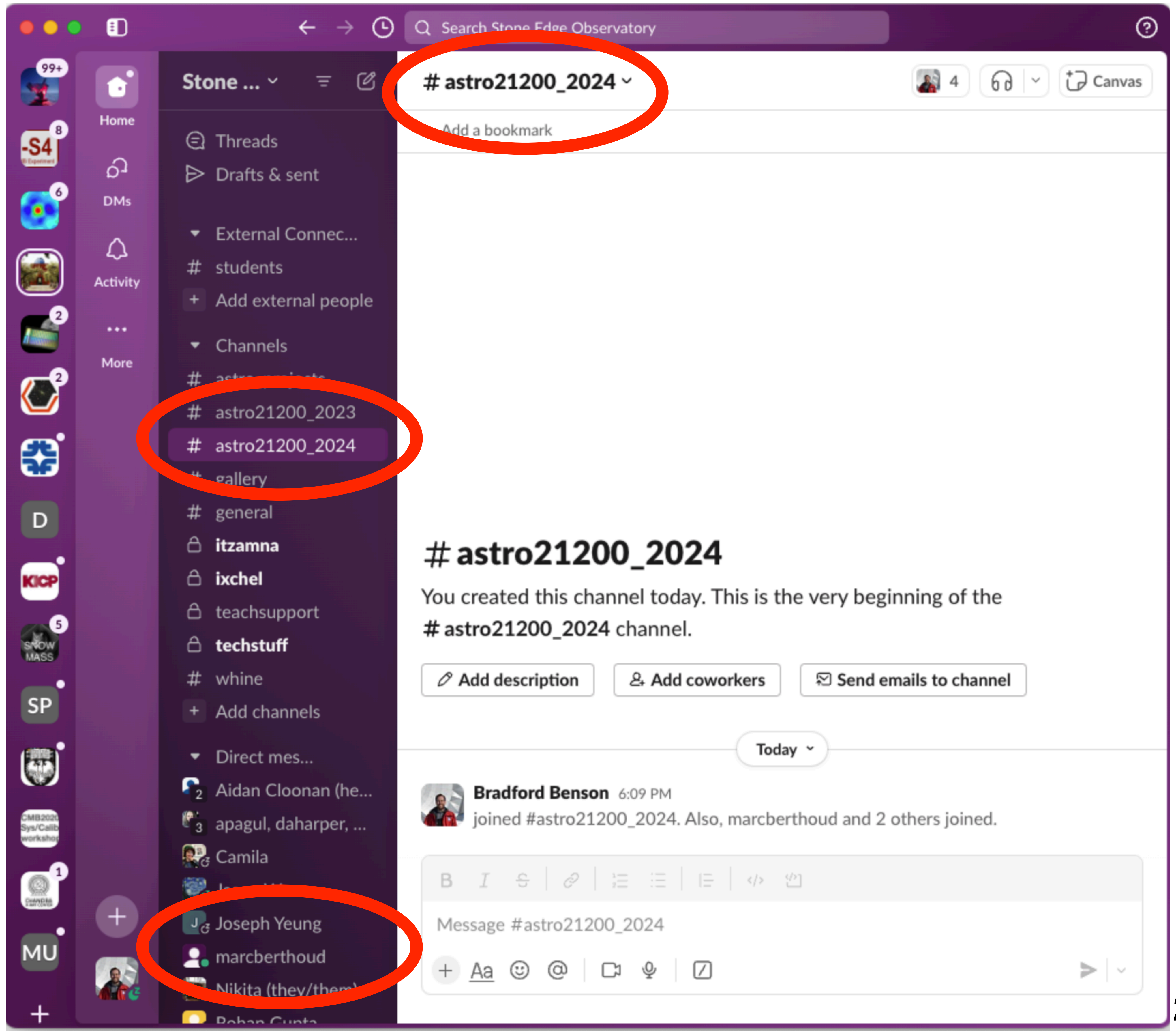
Tutorials

Also linked to the GitHub code repo for the class

Course Slack

- Install the Slack App on your computer (or use web interface)
  - Look for email invitation to "stoneedgeobservatory.slack.com" channel
- Observing through SEO will be done through "itzamna" channel
- General questions about lectures, computing, etc., can take place in the "astro21200_2024" channel
- Private messages to lab-mates, instructor, TAs, can happen through "Direct Messages"





Grading

See Homework and Lab Schedule on the wiki!

- Homeworks (30%)
  - 3x Homeworks (10% each)
  - First one is on canvas + wiki, and due next week Mar-26!
  - Submit HW and Lab reports via course webpage on **Canvas:**
    - https://canvas.uchicago.edu/courses/56896
- Labs (60%)
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- Final Presentation (10%)

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See Homework and Lab Schedule on the wiki!

Also on the wiki, you will find tutorials and readings that will help you with the homework and labs!

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Any questions?

Astronomical Coordinate Systems

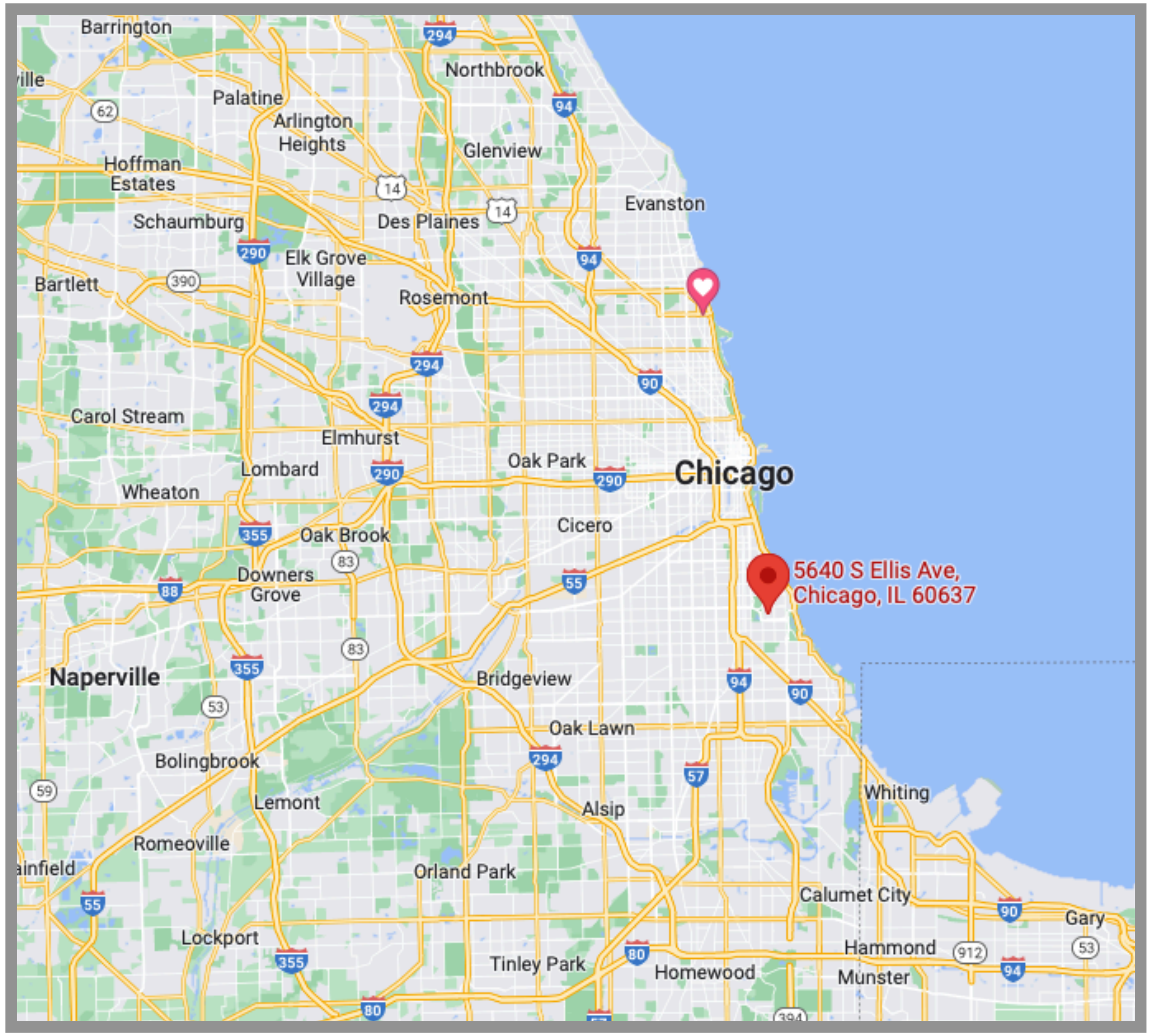
How do you find things on the sky?

Astronomical Coordinate Systems

How do you find things on the Earth? Maps!

We look for patterns:

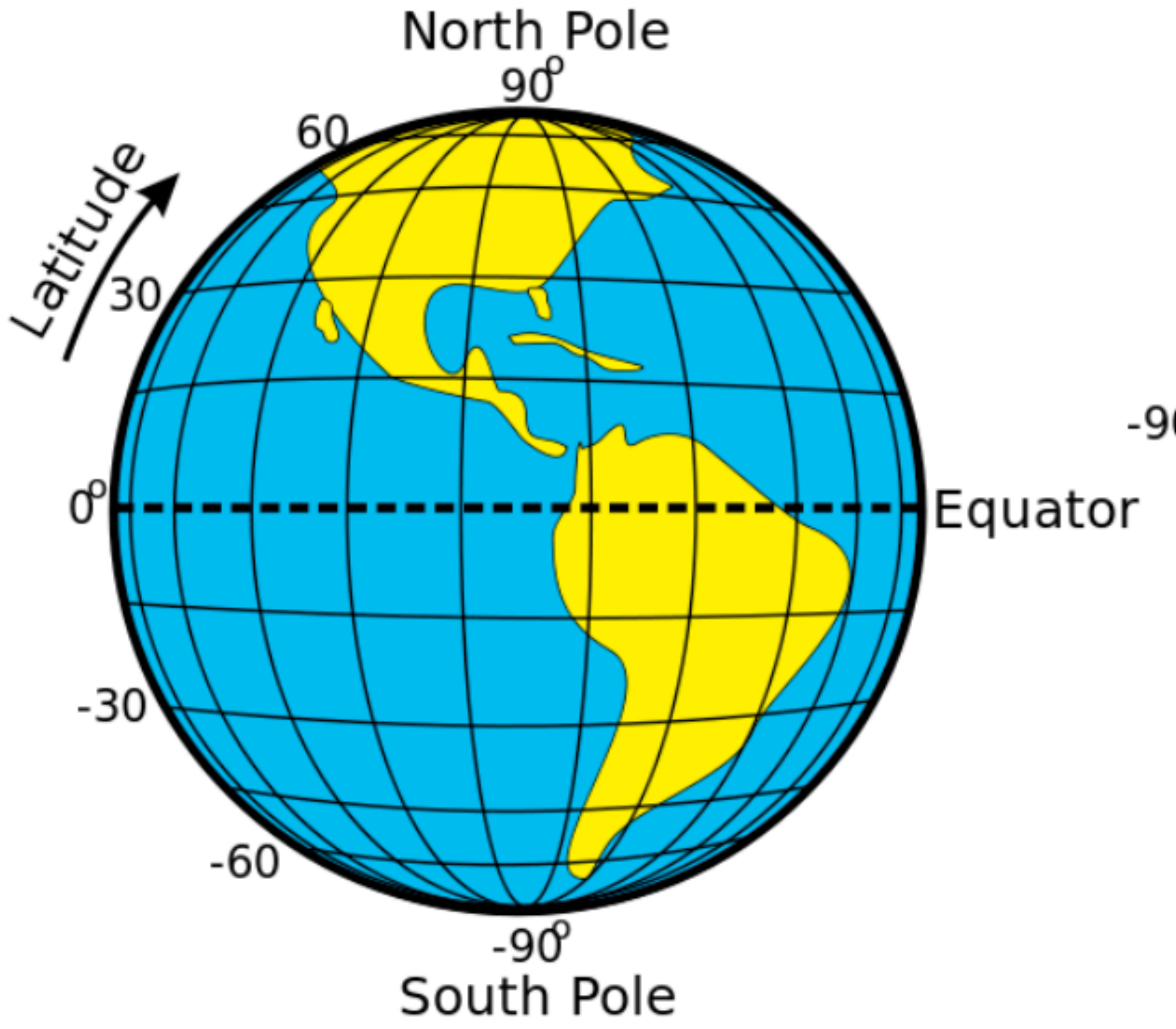
- U. Chicago is 7-miles South from downtown
- Eckhardt Research Center (ERC) is 1-block west of Reynolds Club

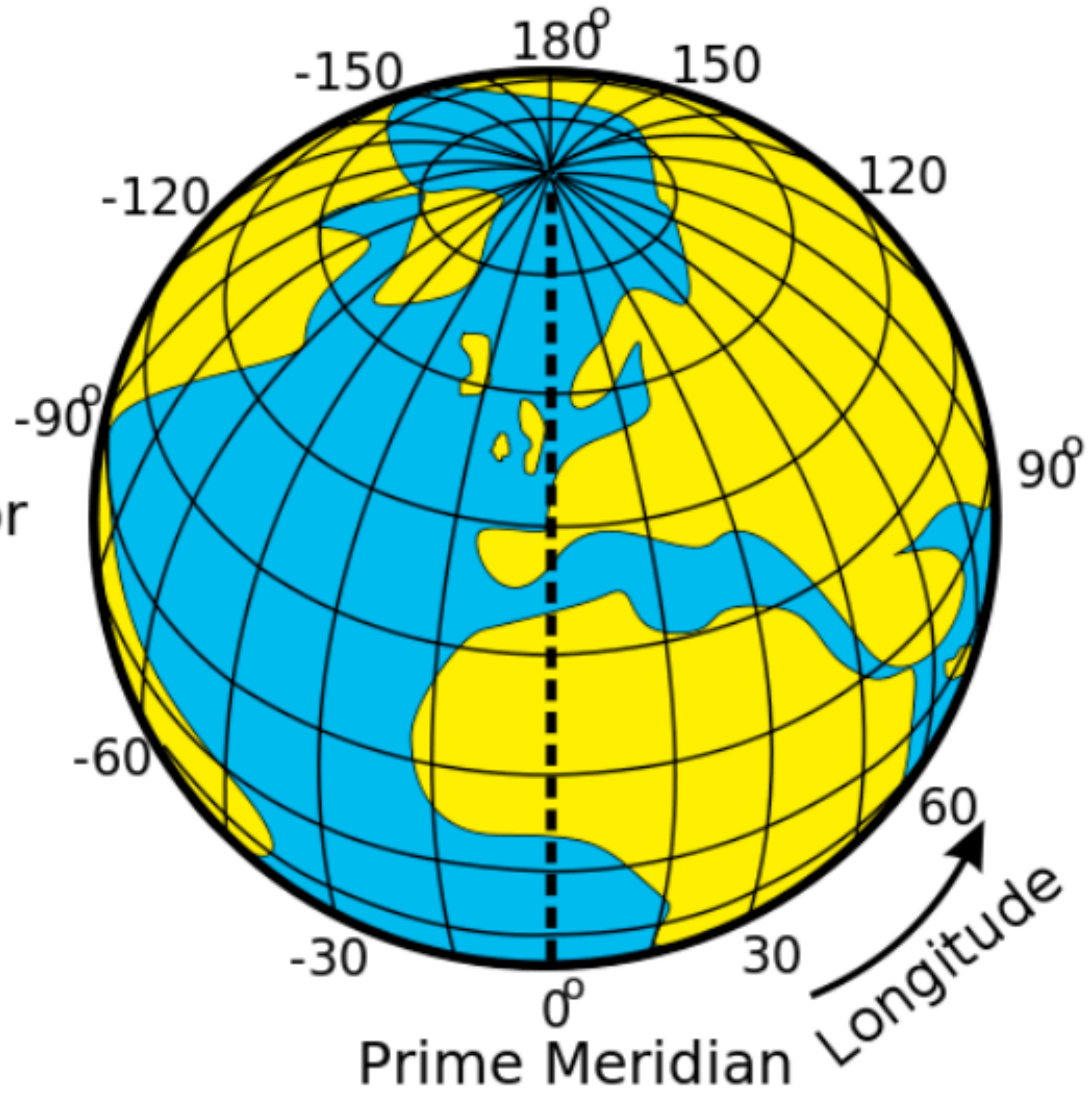


Astronomical Coordinate Systems

How do you find things on the Earth? Maps!

- Latitude and Longitude are angular coordinates related to Earth's rotation
    - Longitude goes from 0 to 360 deg, with Greenwich, England at 0 deg
    - Latitude goes from -90 to 90 deg, with Equator at 0 deg

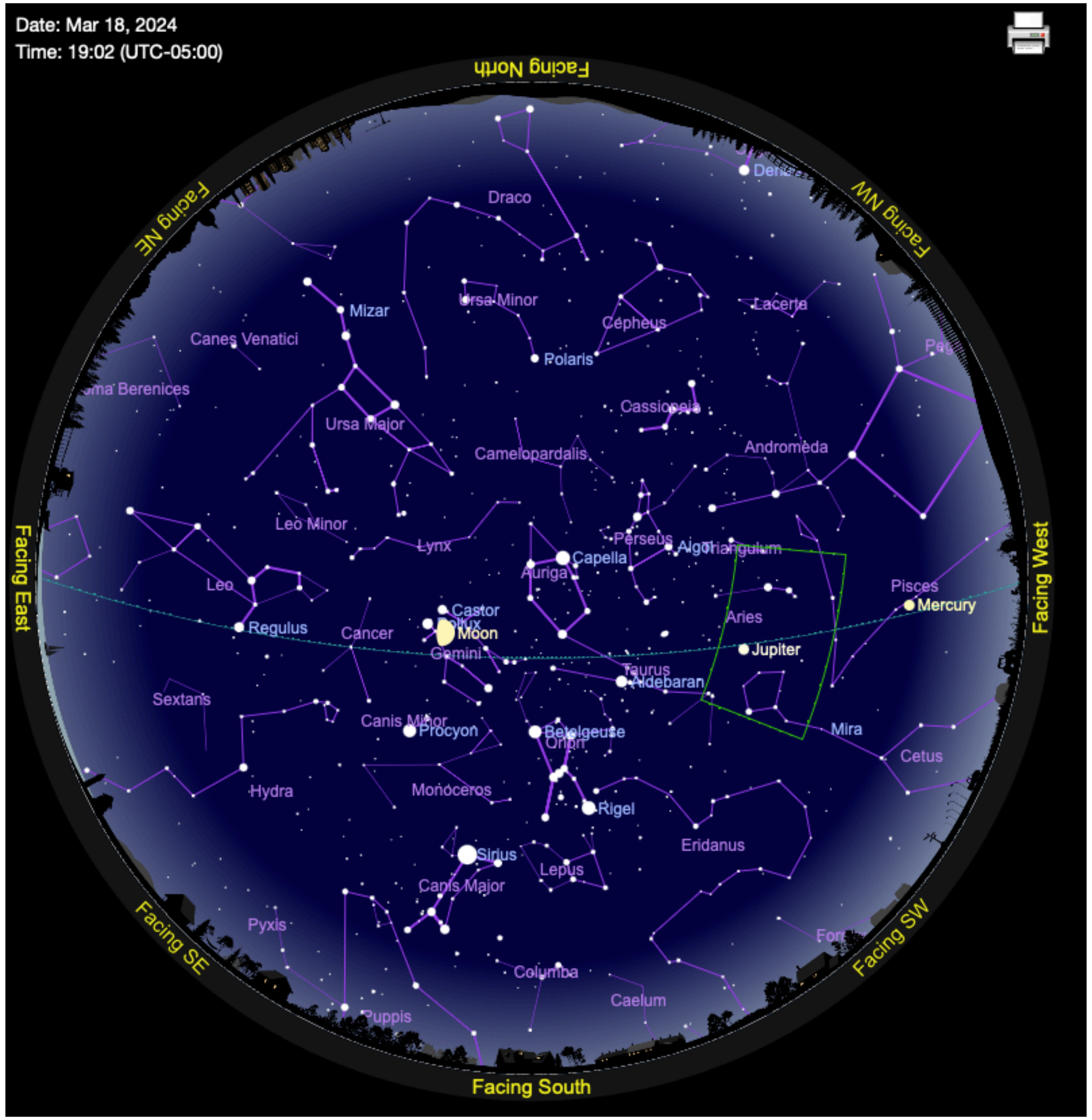




Astronomical Coordinate Systems

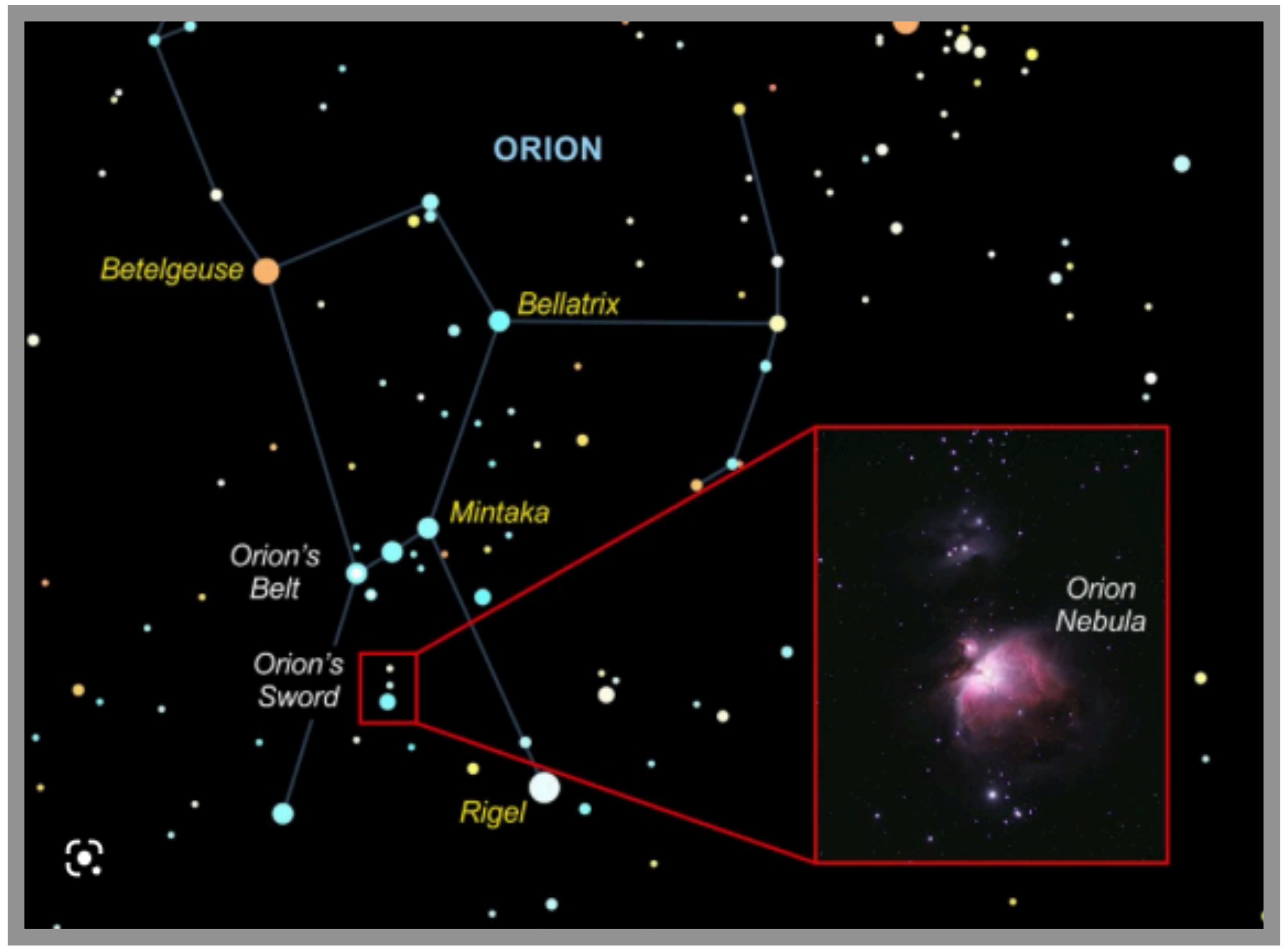
How do you find things on the Sky? Also Maps and Coordinates!

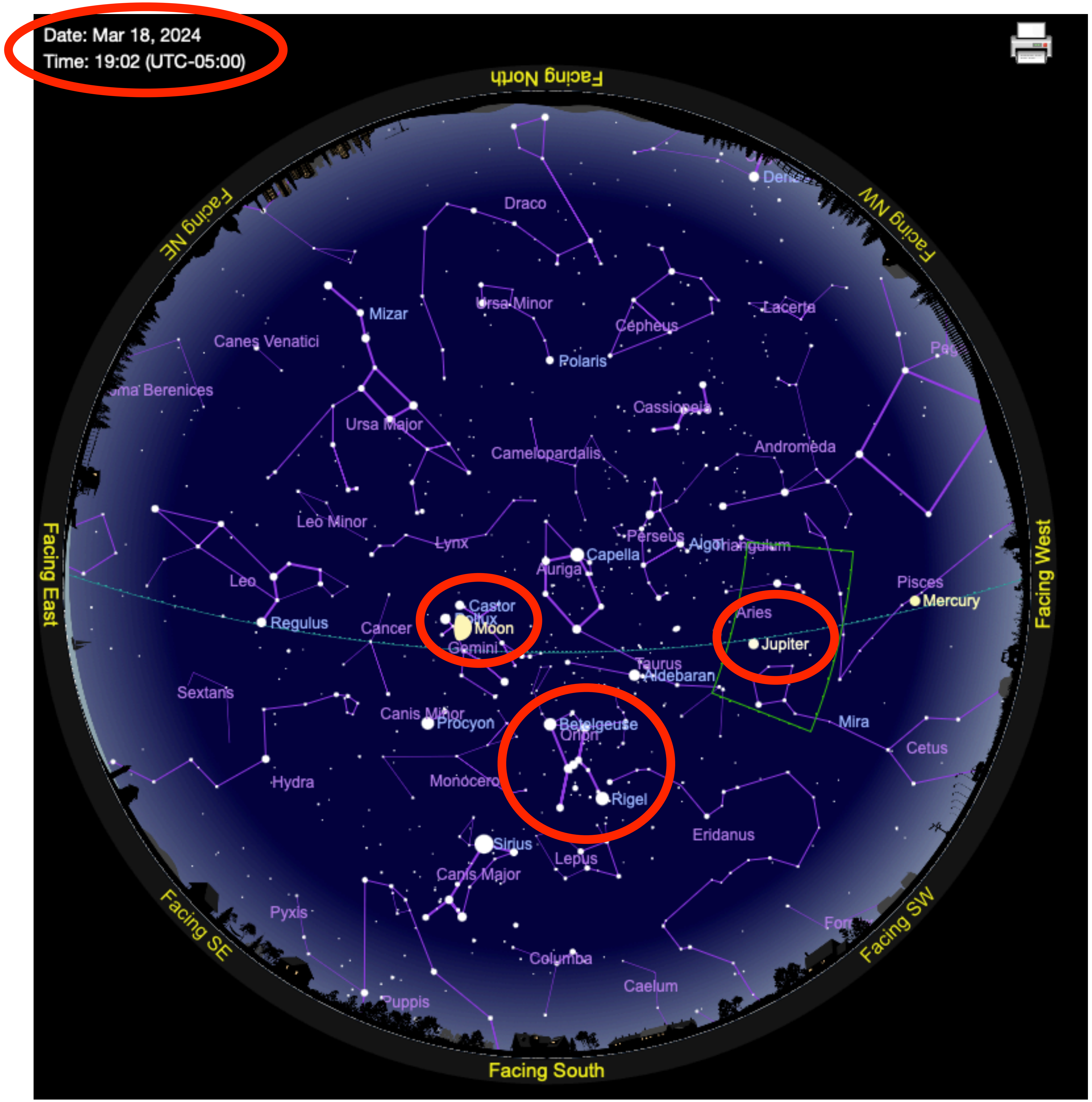
- Instead of looking “down” to the Earth, you are looking up at the Sky, so some things are flipped
  - Because of this “East” is “flipped” to the left because you are looking “up”
  - https://skyandtelescope.org/interactive-sky-chart/
- Also can use “pattern matching” to determine stars / objects relative to one another



How to find the Orion Constellation

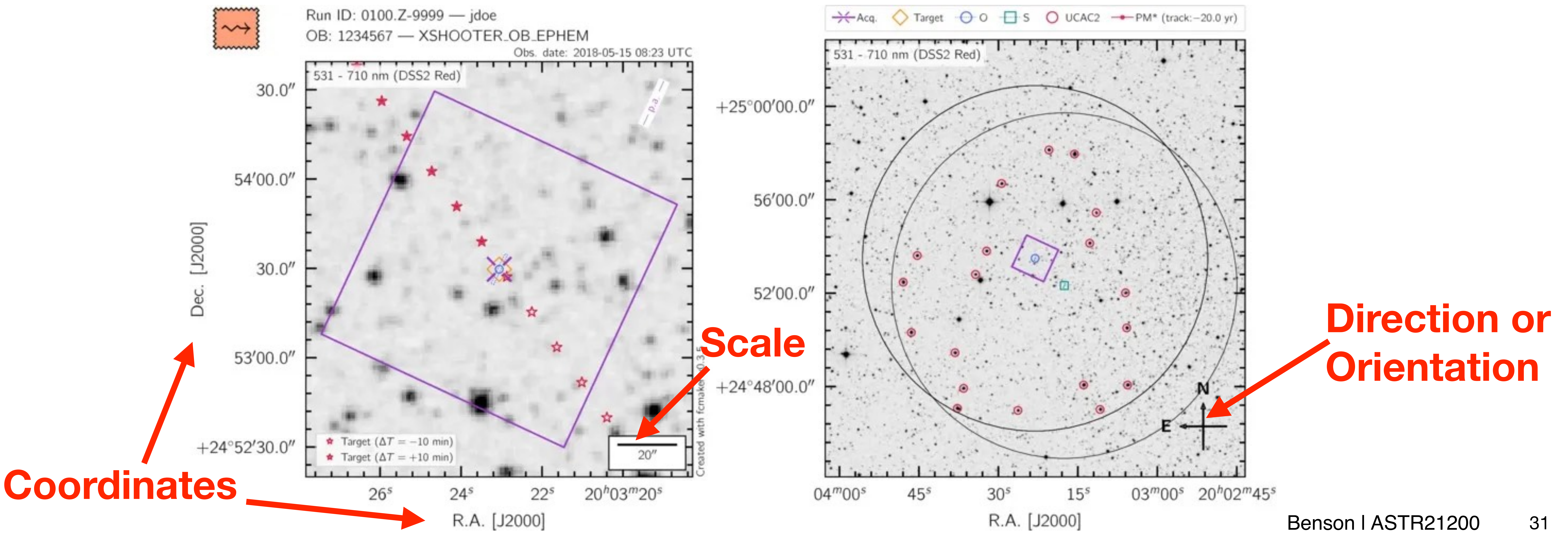
- Sunset about 7pm right now
- Jupiter is setting around 930pm, the Moon at about 4am
- Just after Sunset, find the Moon and Jupiter and look 1/3 in between both and South





Finding charts in professional astronomy

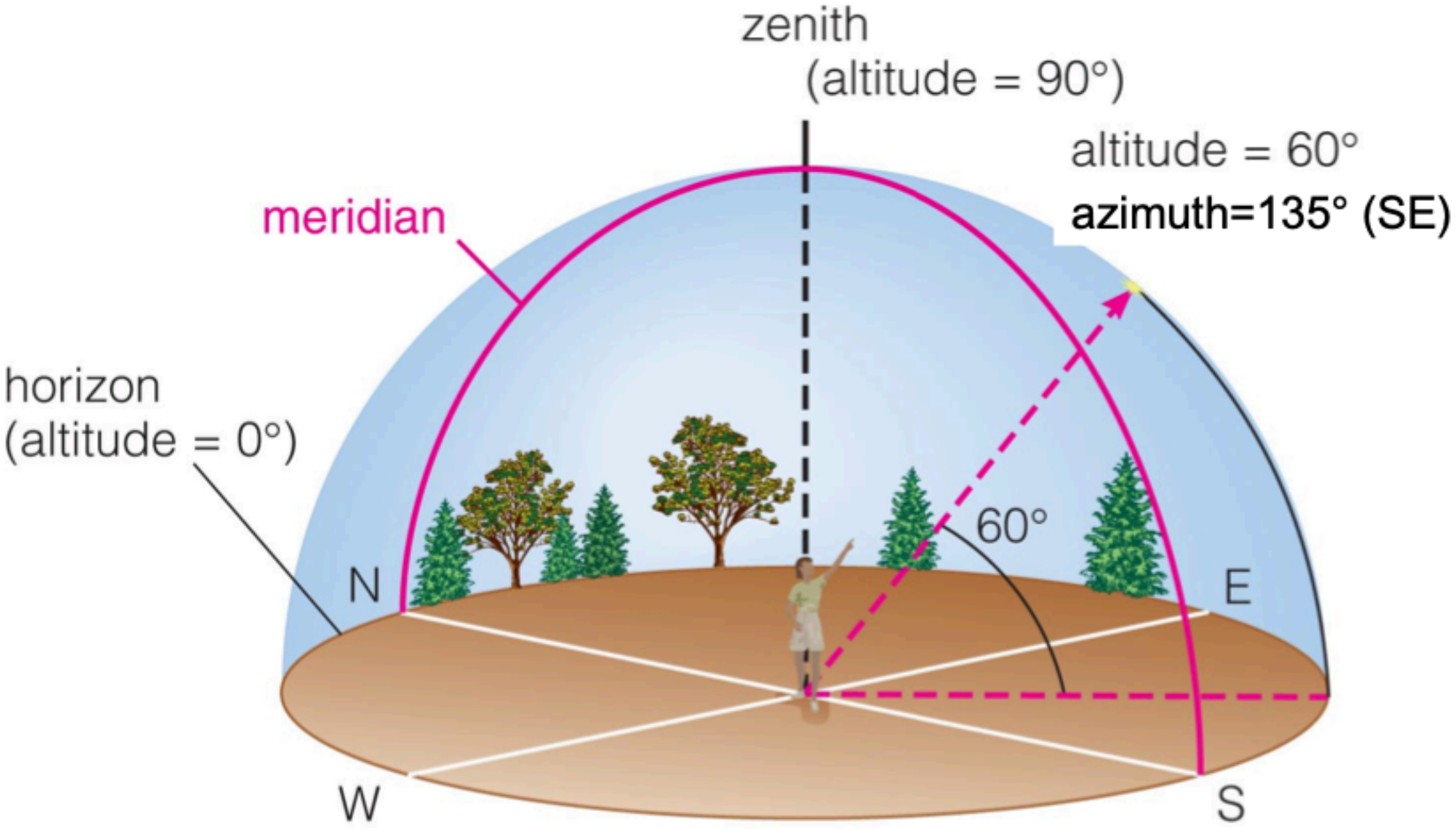
- Most "big telescopes" have relatively small (<0.5-deg) field of view (FOV)
  - e.g., Hubble "Wide Field Camera" only has a 2.7 x 2.7 arcmin FOV
- So need to make sure you are looking at the right object!



Alt/Az Coordinate System

The sky above a specific location at a specific time is a half sphere which can be described by 2 angular coordinates (Alt & Az)

- **Altitude (Alt):** angular distance to the horizon (sometimes called "elevation")
- **Azimuth (Az):** angular distance from North
- **Zenith:** Point overhead
- **Meridian:** North-South line



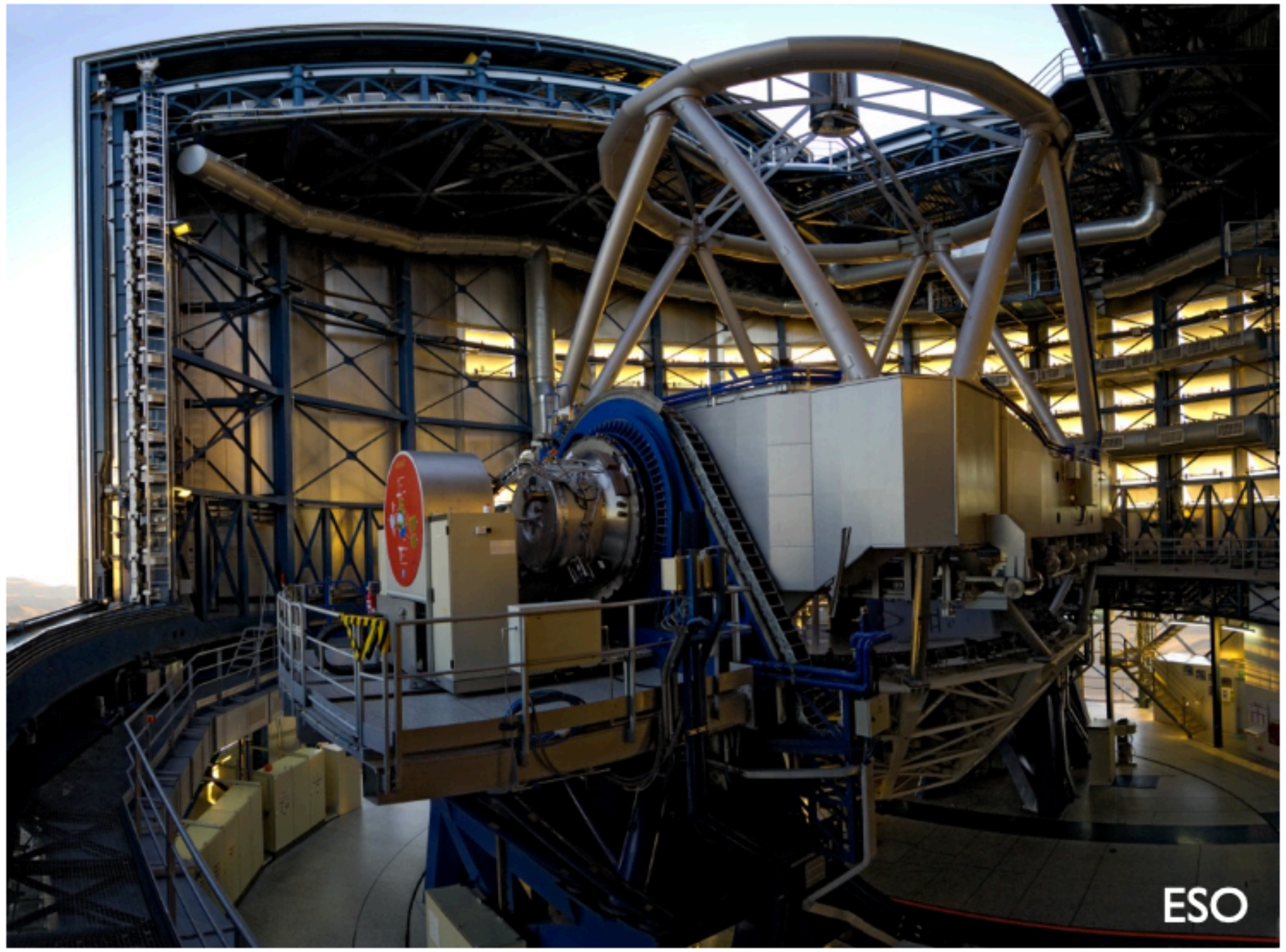
Pearson Education

Alt/Az Coordinate System

The sky above a specific location at a specific time is a half sphere which can be described by 2 angular coordinates (Alt & Az)

Alt-Az telescope mounts are very simple and stable

8-inch Dobsonian Telescope



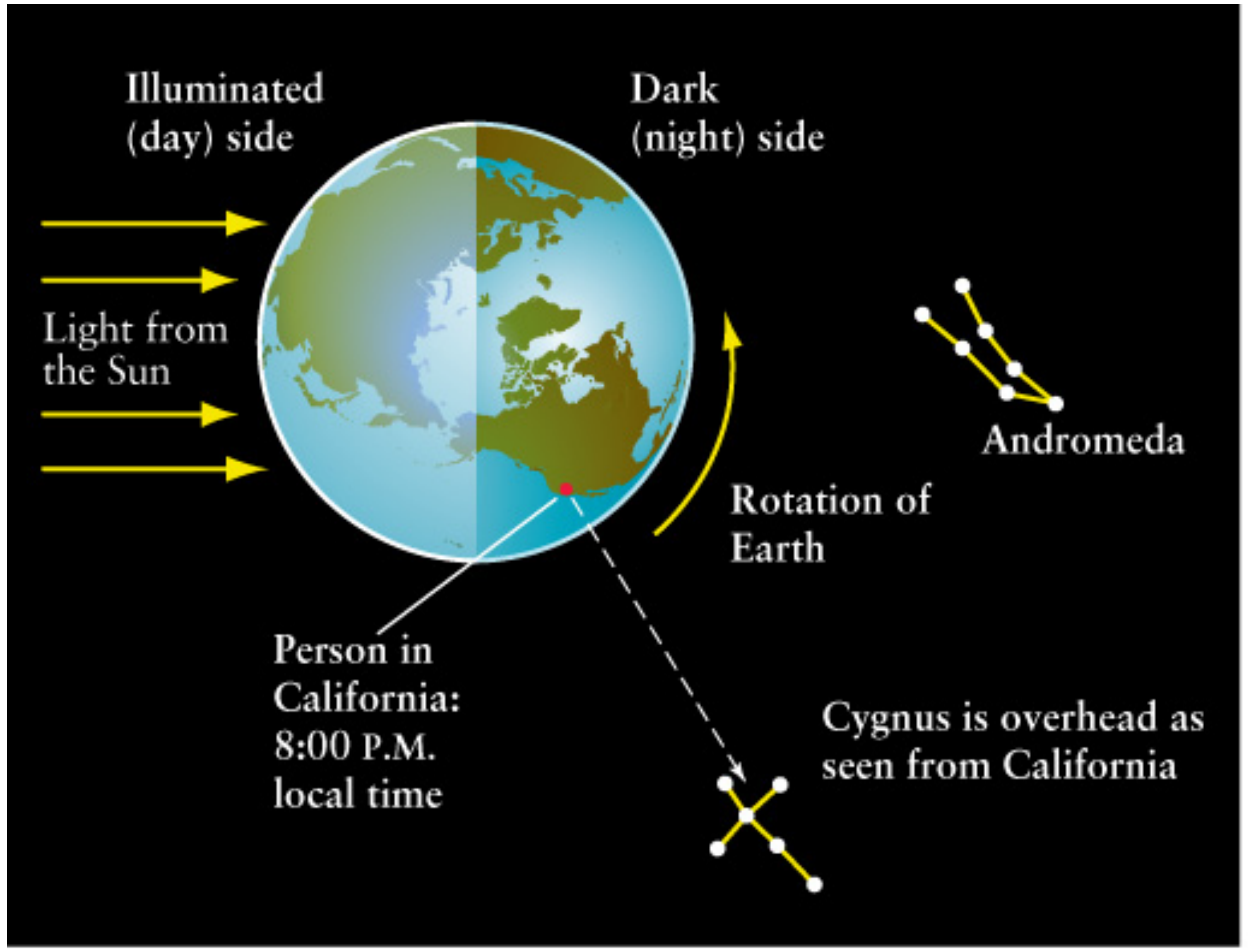
Very Large Telescope (8-meters)

Alt/Az Coordinate System

- Altitude and Azimuth of an object vary with time
    - -> because of the rotation of the Earth!
- In practice, we use “sky” coordinates to locate objects
- Still you will need to approximately know the Alt and Az of your target to plan your observing for the night, e.g.,
    - Is my target “up”? (i.e., Altitude > 0-degrees)
    - Is my target “observable”? (i.e., Altitude > ~40-degrees)

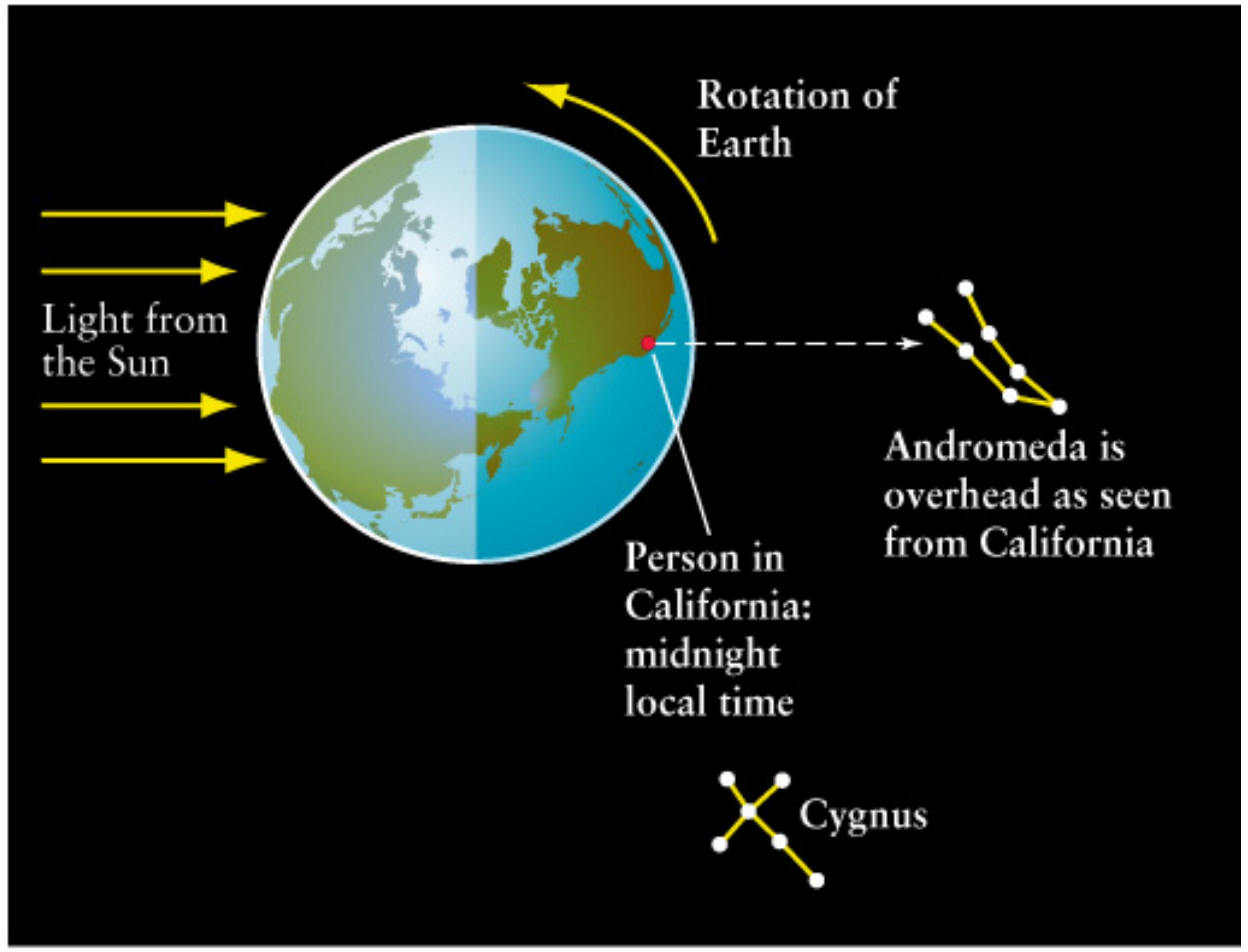
Rotation of the Earth

- Looking down on the North Pole, Earth rotates counter clockwise
- The Sky rotates from East to West
- Objects rise in the East, and set in the West
  - And “culminate” in the South when they cross the meridian



(a) Earth as seen from above the north pole

Andromeda is to the East; Cygnus is overhead

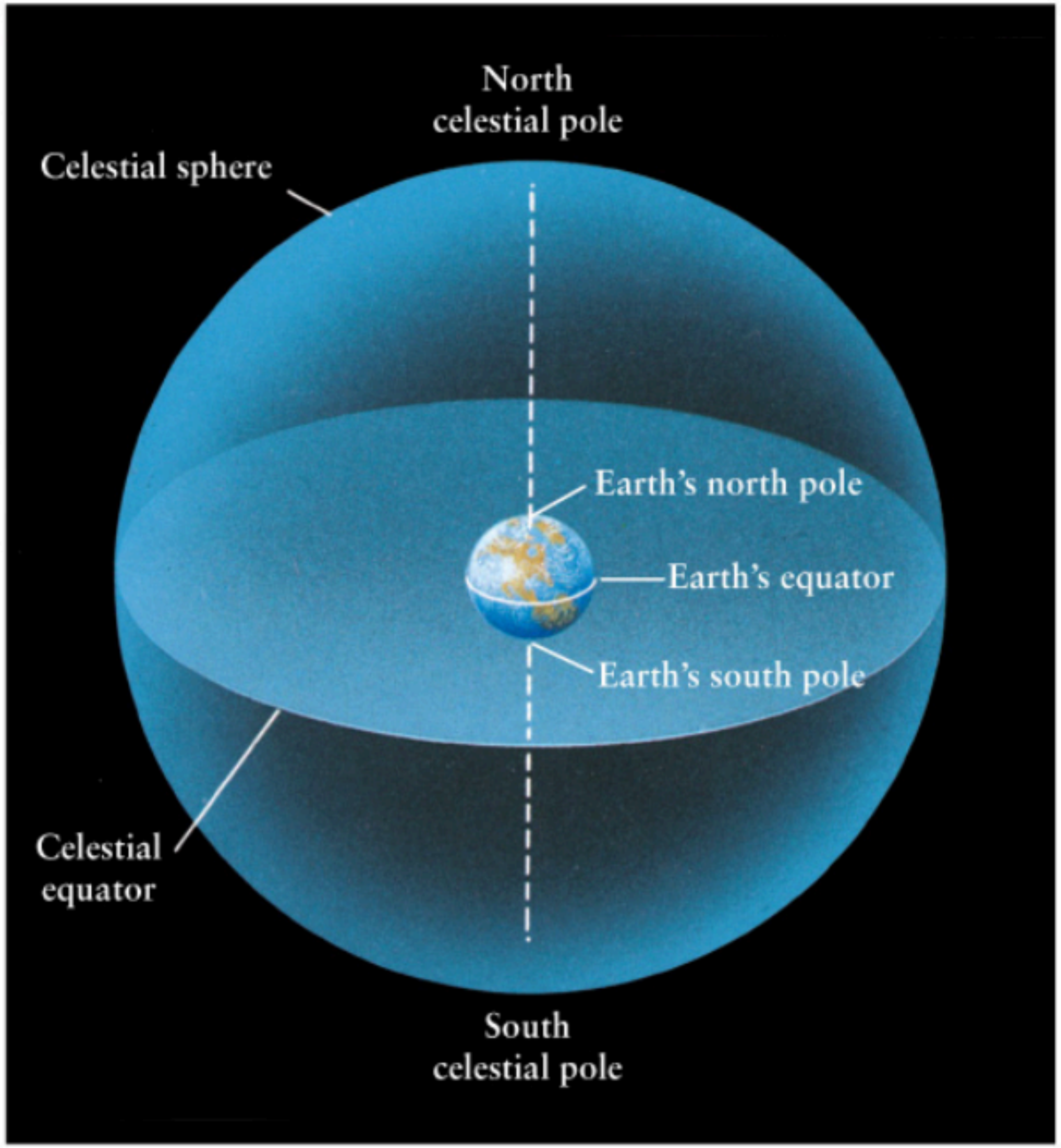


(b) 4 hours (one-sixth of a complete rotation) later

4 hrs later: Andromeda is overhead; Cygnus is to the West

Celestial Sphere

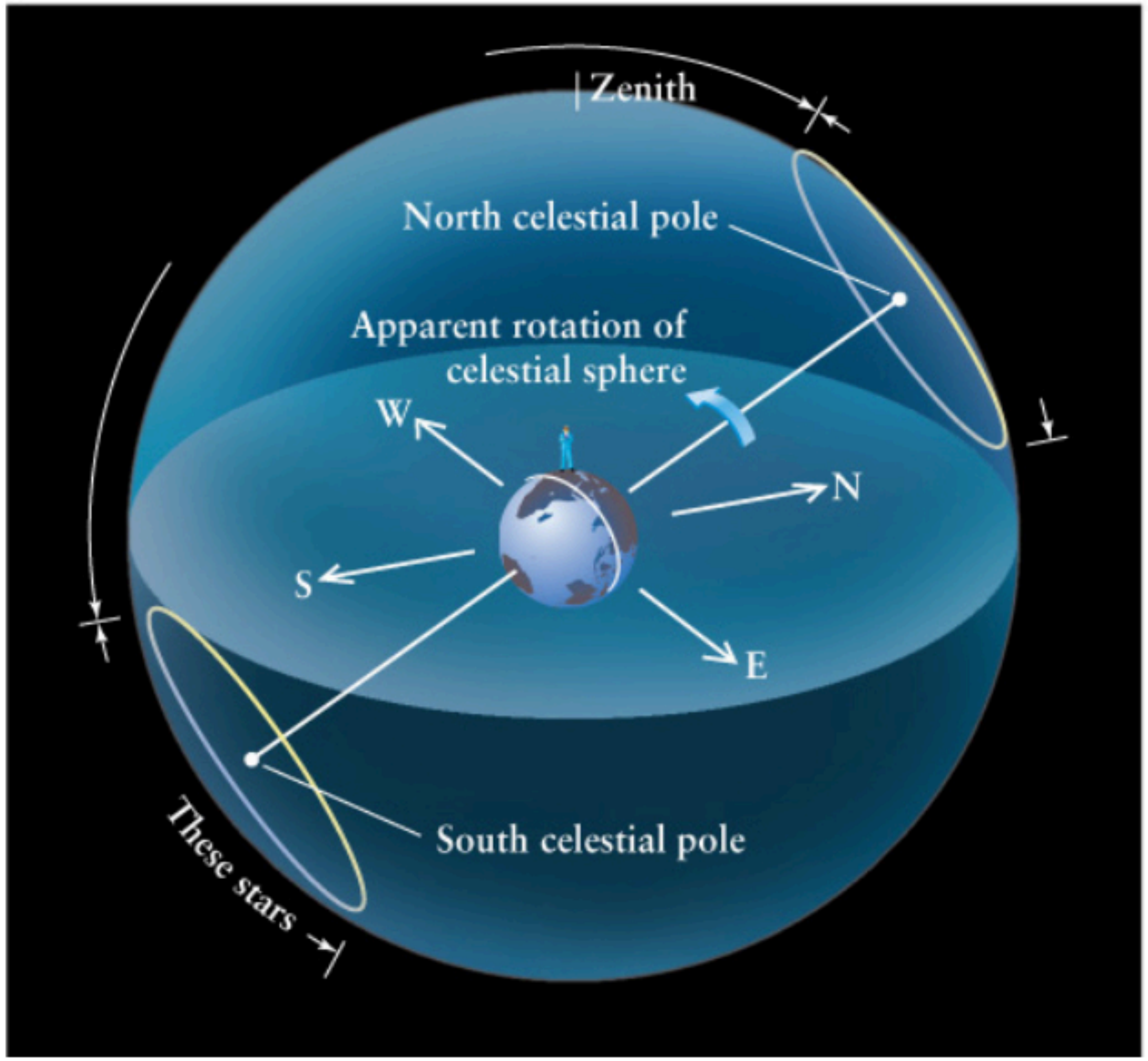
- **Celestial sphere:** Describe objects by their position on a sphere centered on the rotating Earth
- **Celestial North / South Pole:** projection of Earth's North / South Pole
- **Celestial Equator:** projection of Earth's equator



Bailey, Slater & Slater

Apparent Motion in the Sky

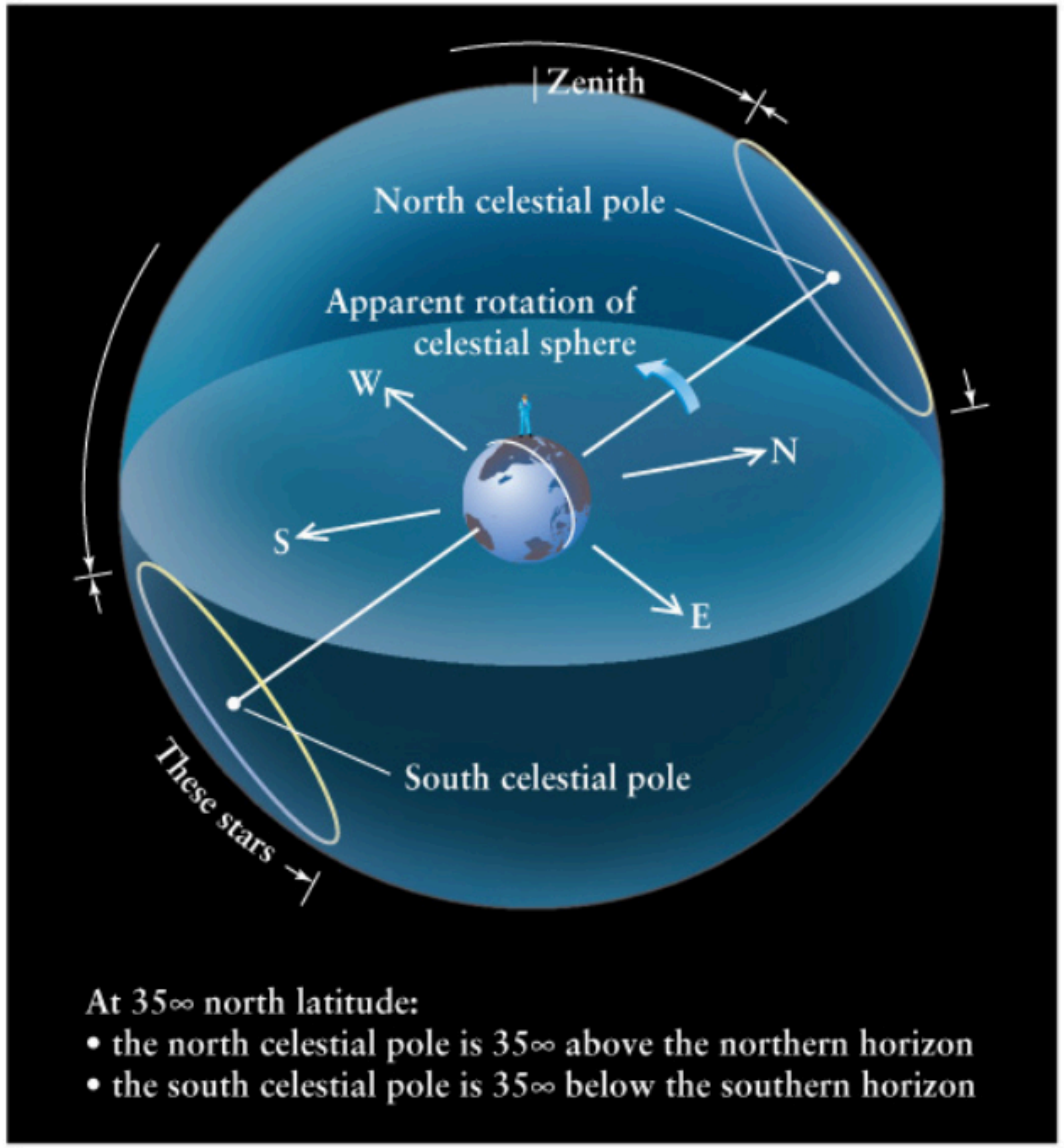
- Apparent sky motion depends on the latitude of the observer
- UChicago is at 41-deg North
- So North Pole is at what altitude?



Bailey, Slater & Slater

Apparent Motion in the Sky

- Apparent sky motion depends on the latitude of the observer
- UChicago is at 41-deg North
    - North Pole is at 41-deg altitude!
- Objects within 41-deg of NP are always “up” (i.e., “circumpolar”)
- We can never see objects within 41-deg of the South Pole
- All objects rise in the East, and set in the West

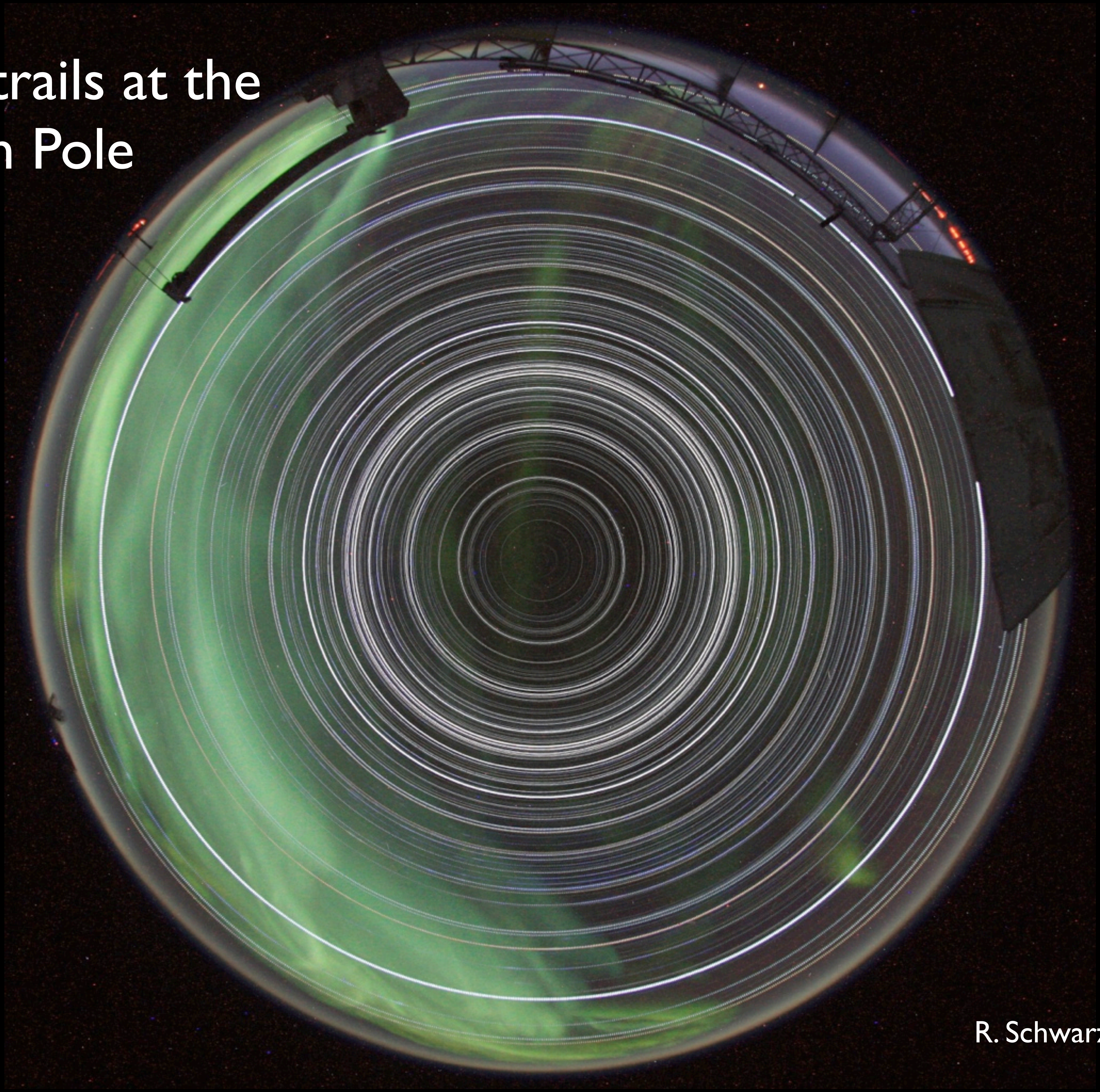


Bailey, Slater & Slater

Star trails over CTIO, (c) Jose Delgado

Star trails at the equator

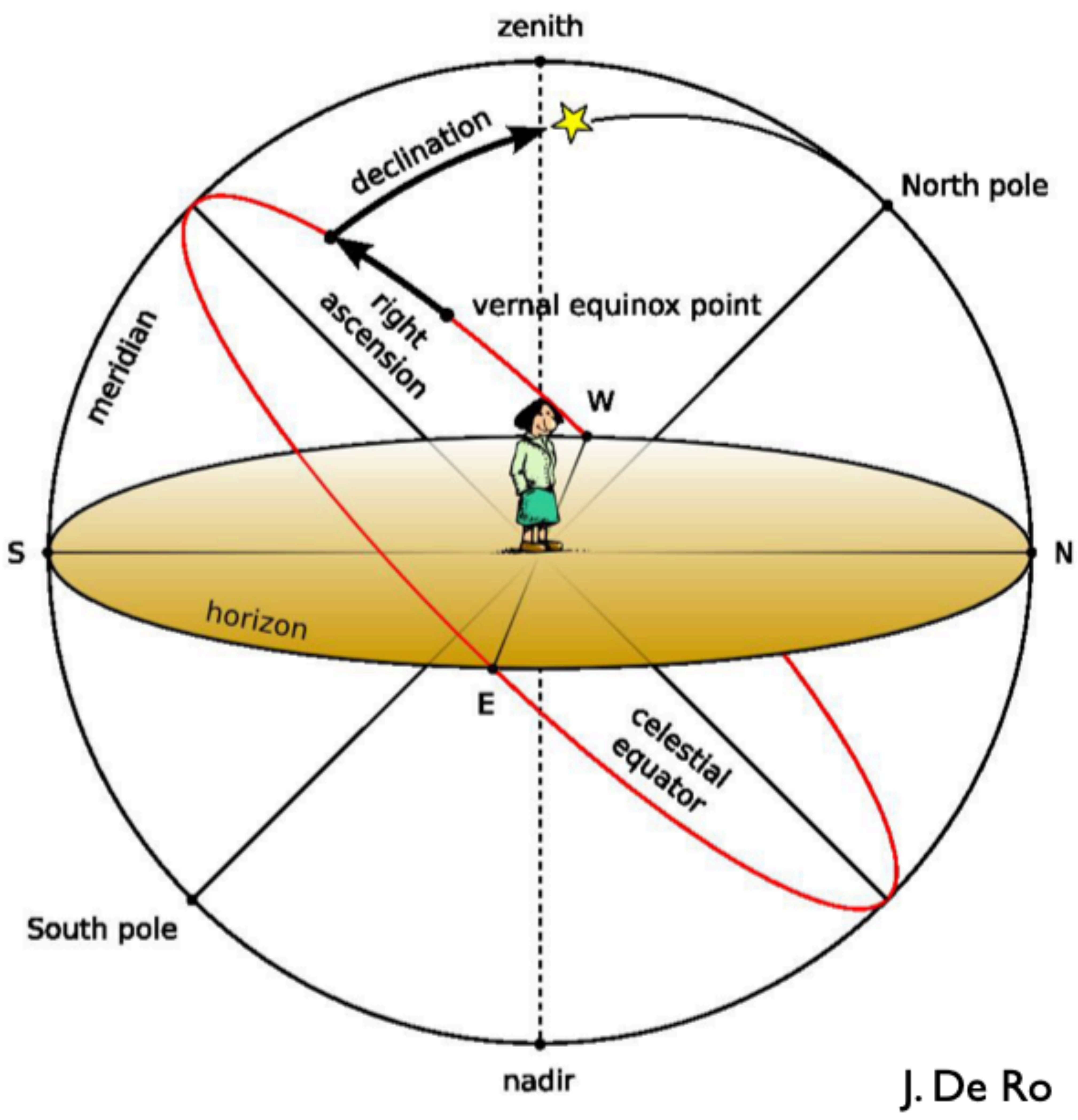
Star trails at the South Pole



R. Schwarz

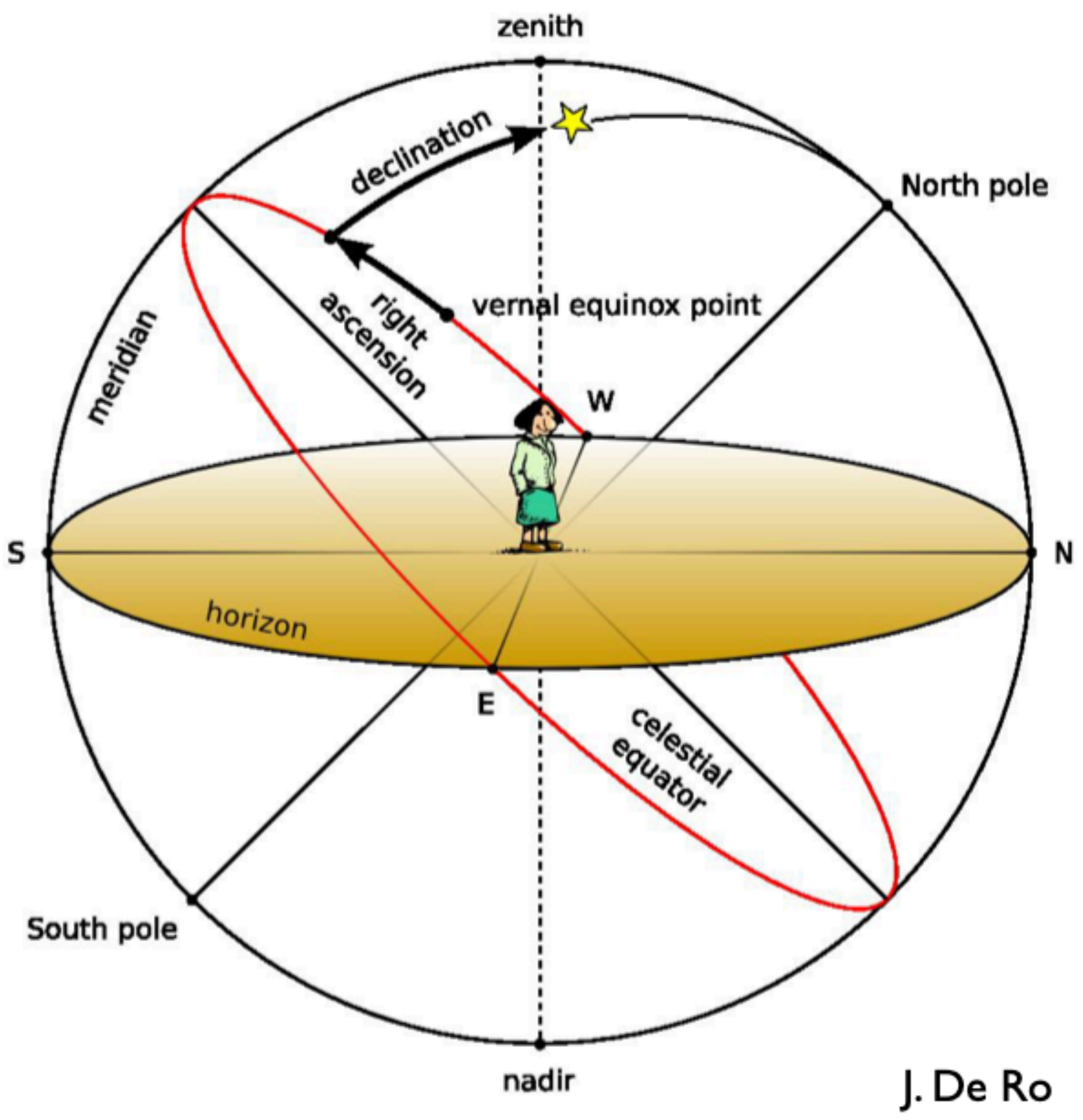
Equatorial (RA/Dec) Coordinate System

- Fixed to the celestial sphere, rotates with the sky
- **Declination (Dec, δ):** Angular distance from the celestial equator
- **Right Ascension (RA, α):** Angular distance from the vernal equinox (i.e., a special point on the equator)

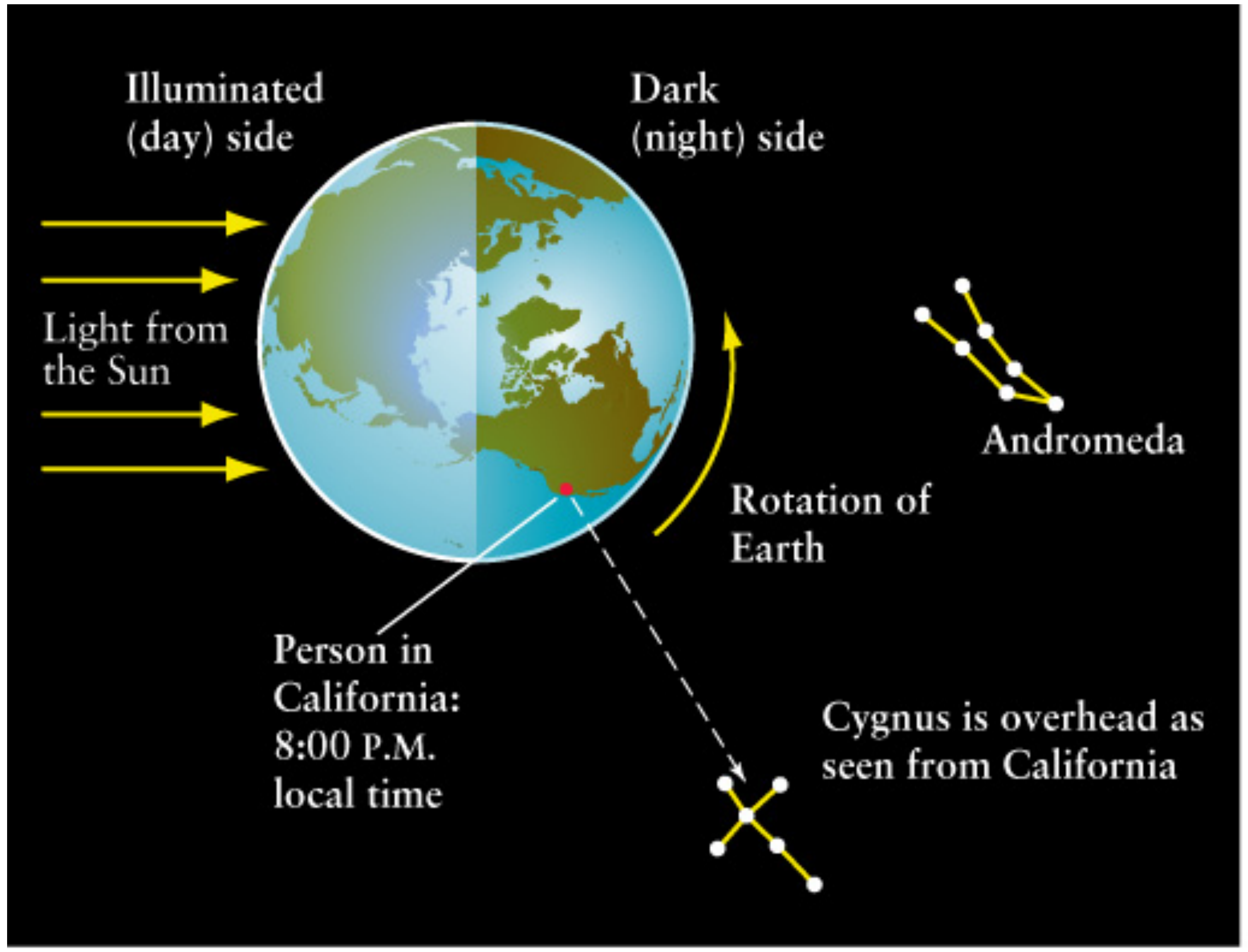


Equatorial (RA/Dec) Coordinate System

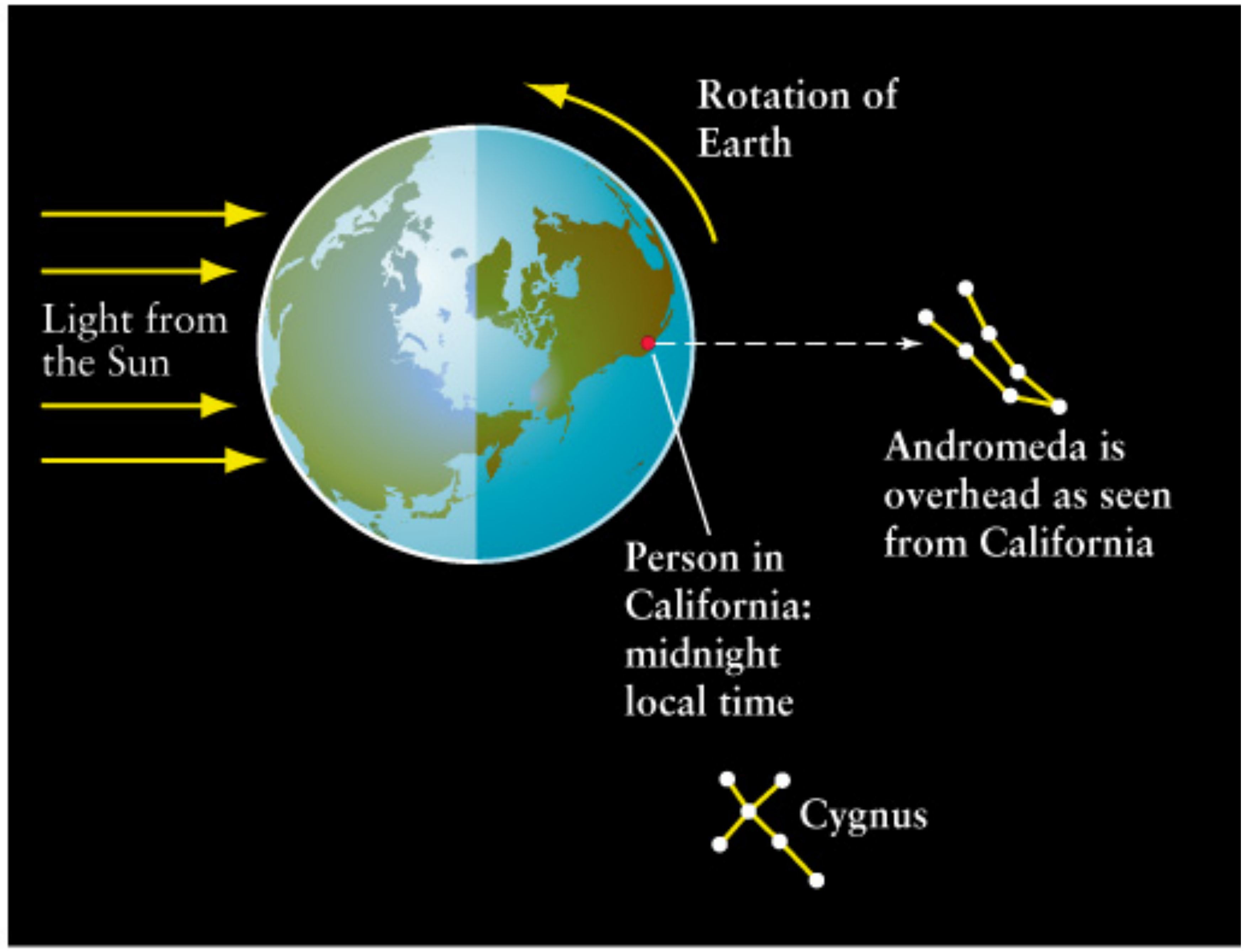
- **Declination (Dec, δ):** Measured in degrees, between -90d > **δ** > 90d
- **Right Ascension (RA, α):** Angular distance from the vernal equinox (i.e., a special point on the equator). Can also be measured in degrees between 0d < **α** < 360d



Right Ascension (RA)



(a) Earth as seen from above the north pole

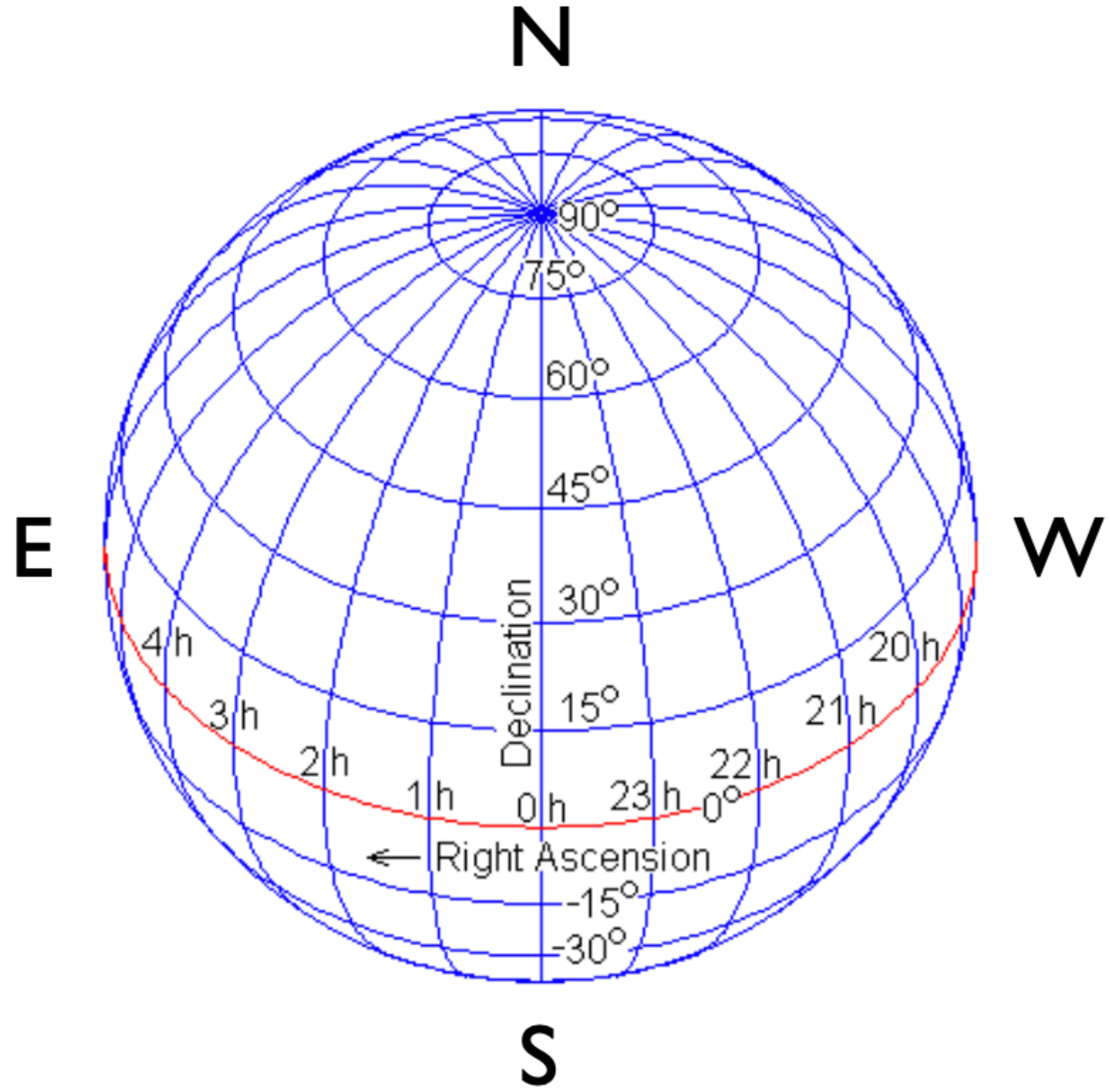


(b) 4 hours (one-sixth of a complete rotation) later

- A "natural" way to define RA is in units of time:
  - "Distance" between two points is given by the time interval between each of them passing the meridian
  - e.g., reference point (0h) culminates (passes meridian) at a certain time, all points that culminate 4-hrs later have **α = 4h**

Right Ascension (RA), Local Sidereal Time (LST)

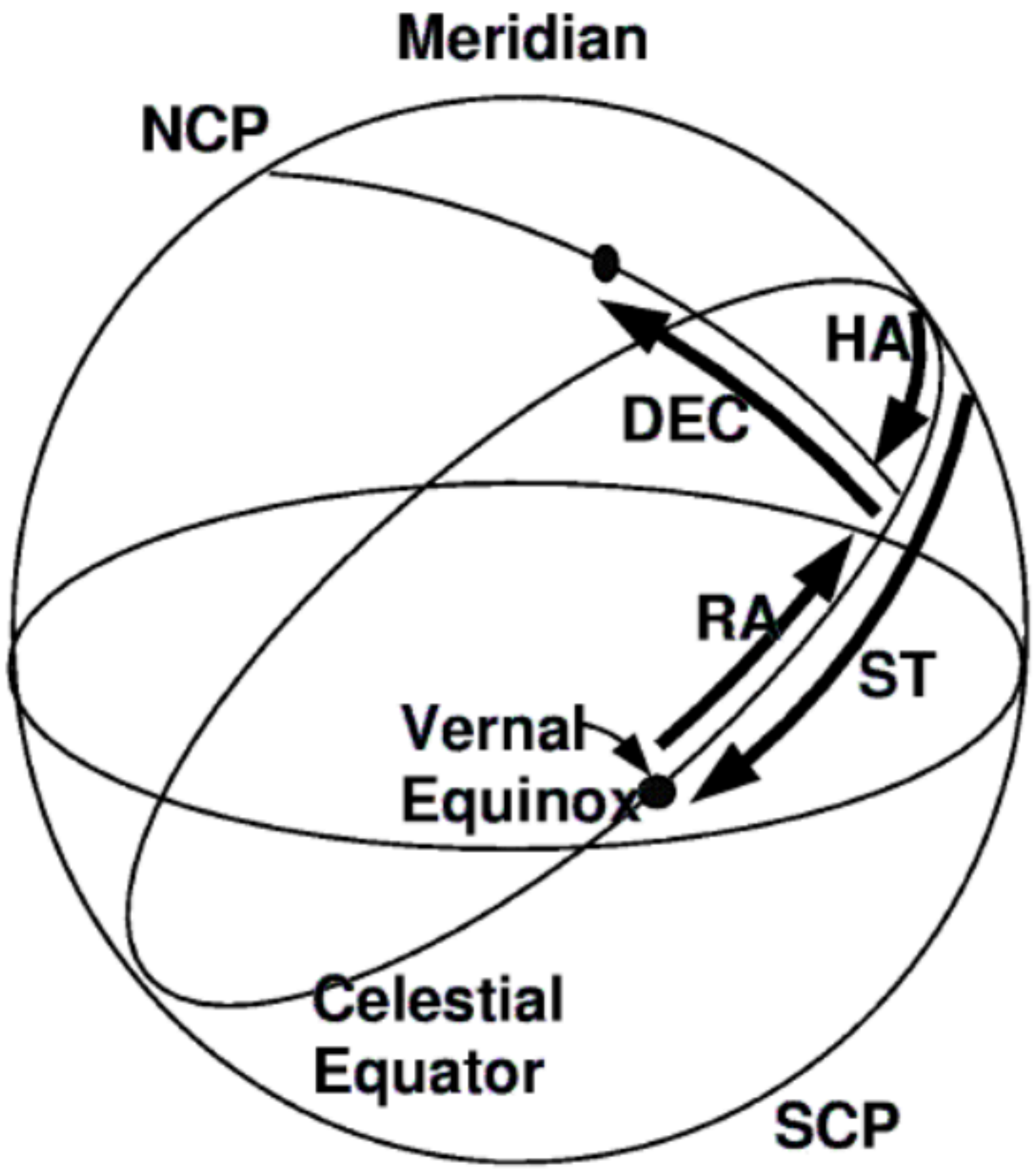
- Sky rotates East to West
  - East is “left"
- RA runs from right to left in astronomical maps
  - Larger RA values are on left of the image
- Local sidereal team (LST): RA of the objects currently culminating (on meridian)



S. Dutch

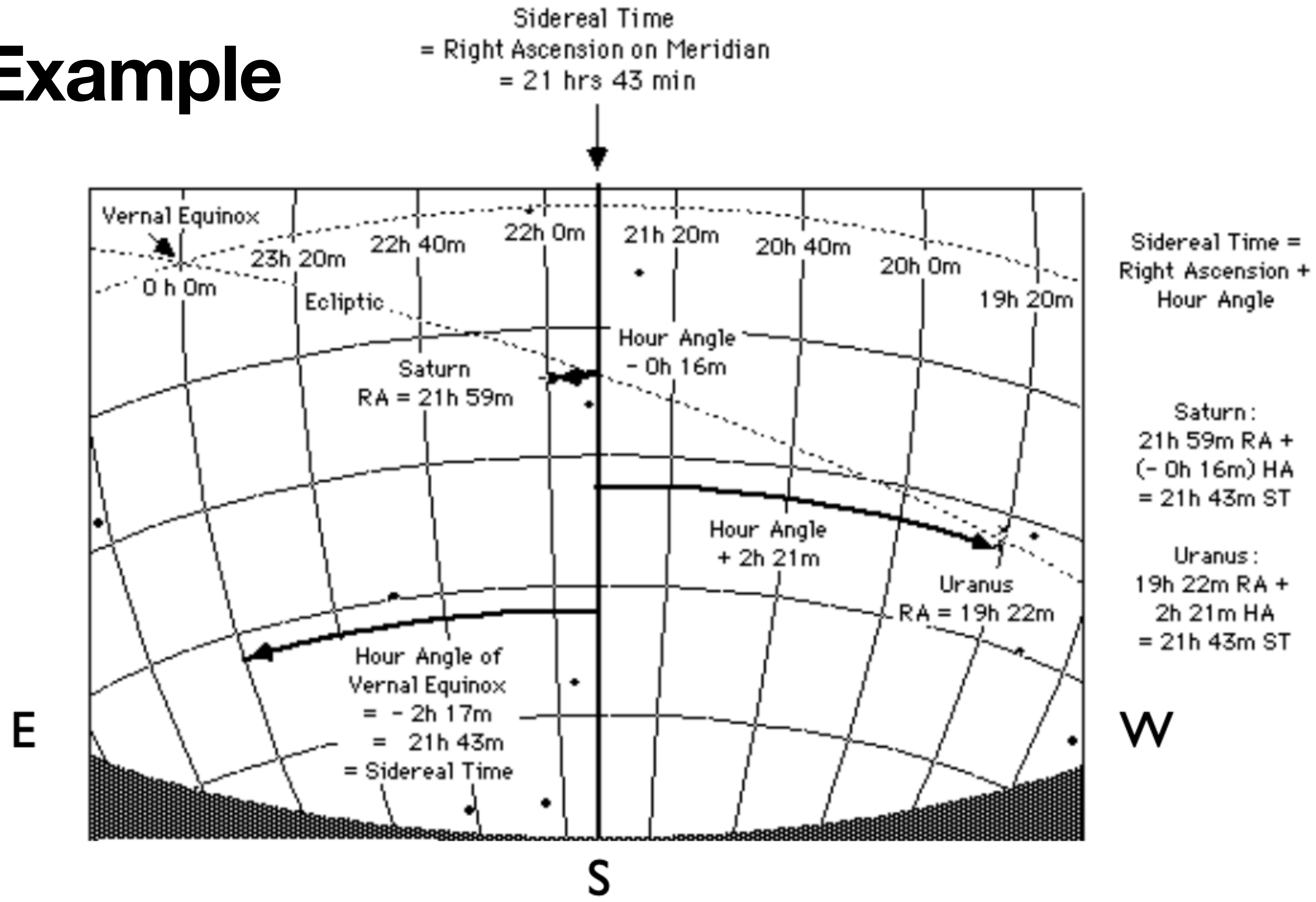
RA, LST, and Hour Angle

- Hour angle (HA): Time that has passed since object culminated
  - $HA = LST - \alpha_{object}$
- HA > 0h: Object has already culminated, it is "setting" and in the Western half of the sky
- HA < 0h: Object is rising, is in the Eastern half of the sky, will culminate in HA hours



R. O'Connell

HA Example



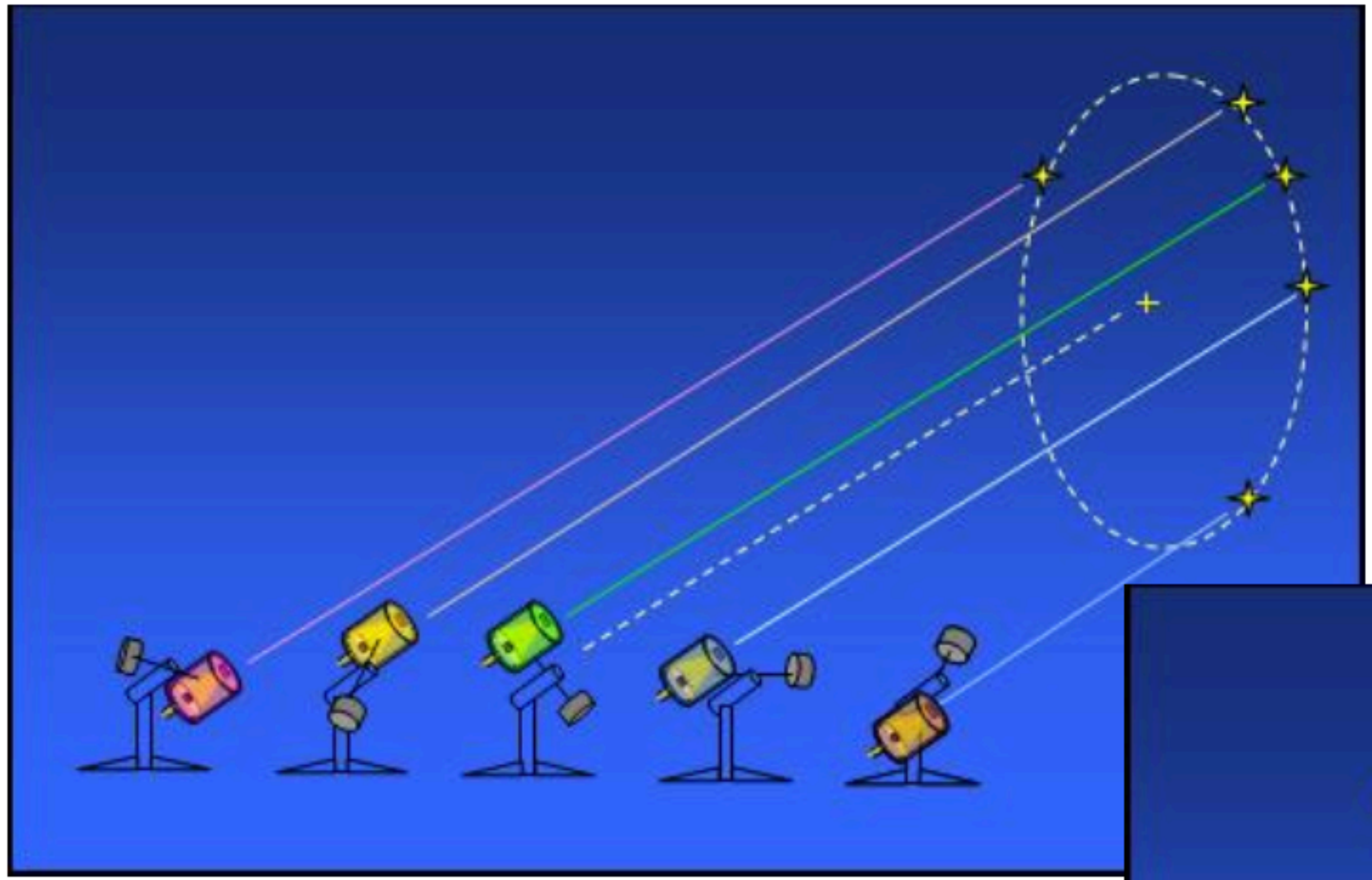
Sidereal Time
= Right Ascension on Meridian
= 21 hrs 43 min
Vernal Equinox
0 h 0m
23h 20m
22h 40m
22h 0m
21h 20m
20h 40m
20h 0m
19h 20m
Ecliptic
Hour Angle
- 0h 16m
Saturn
RA = 21h 59m
Hour Angle
+ 2h 21m
Uranus
RA = 19h 22m
Hour Angle of
Vernal Equinox
= - 2h 17m
= 21h 43m
= Sidereal Time
E
W
S
Sidereal Time =
Right Ascension +
Hour Angle
Saturn:
21h 59m RA +
(- 0h 16m) HA
= 21h 43m ST
Uranus:
19h 22m RA +
2h 21m HA
= 21h 43m ST

Equatorial Telescope Mounts

- **Alt/Az mounts:** need to track object in two axis, with variable speed
- **Equatorial mount:** One axis is parallel to Earth's rotation axis -> Need to track only in this axis with constant speed

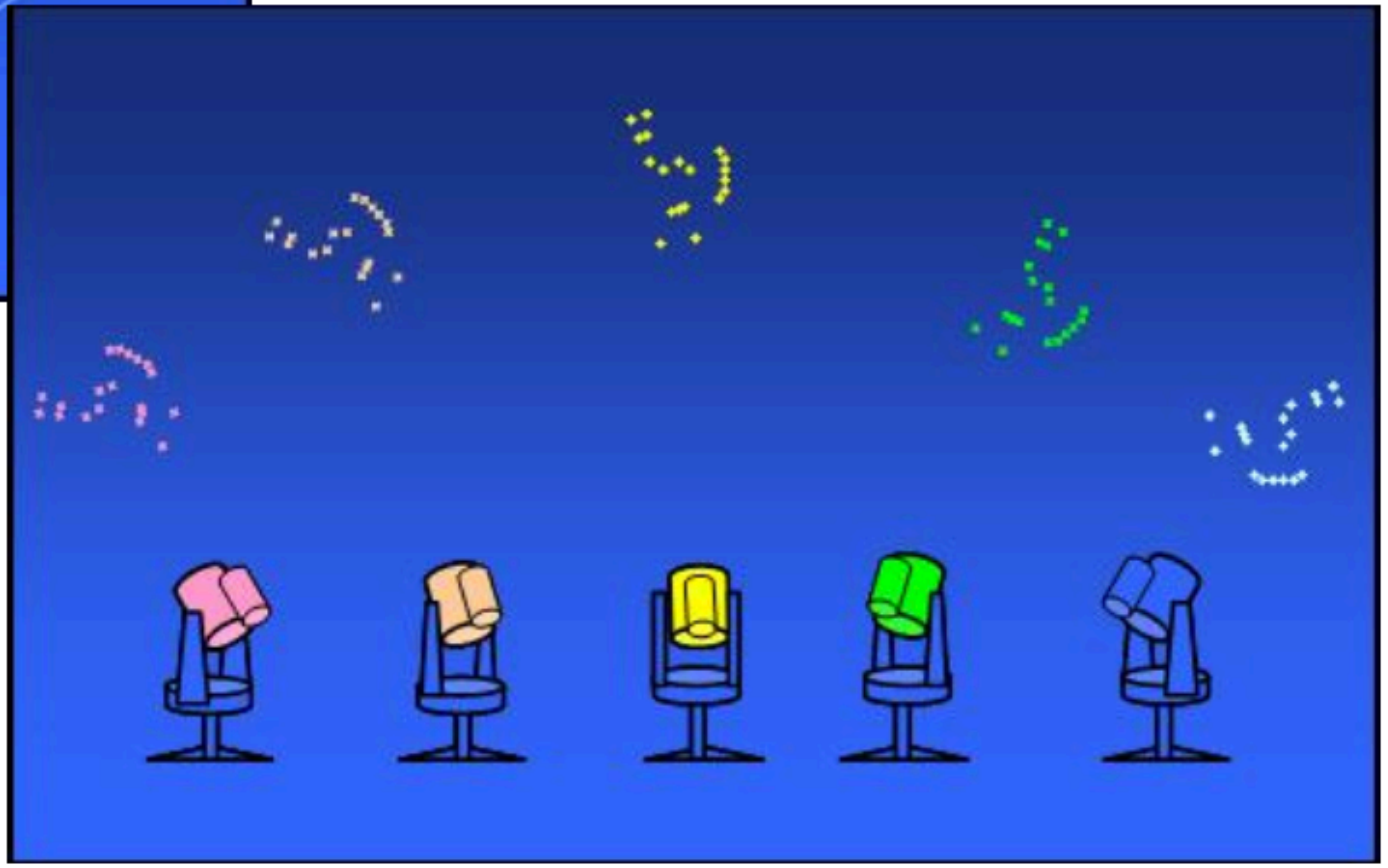
Equatorial Telescope Mounts

removes the need for a field de-rotator



equ. mount

alt/az mount



Astronomy Asylum

Equatorial Telescope Mounts

- Not feasible for the largest telescopes
- But found on some intermediate class telescopes, e.g., the 4-meter telescopes on Kitt Peak and Cerro Tololo

R.A. and Dec Format

both can be expressed as degrees:

$$0^\circ \leq \alpha < 360^\circ$$
$$-90^\circ \leq \delta \leq +90^\circ$$

e.g. M31: $10.6847^\circ, +41.26875^\circ$

often expressed in sexagesimal system:

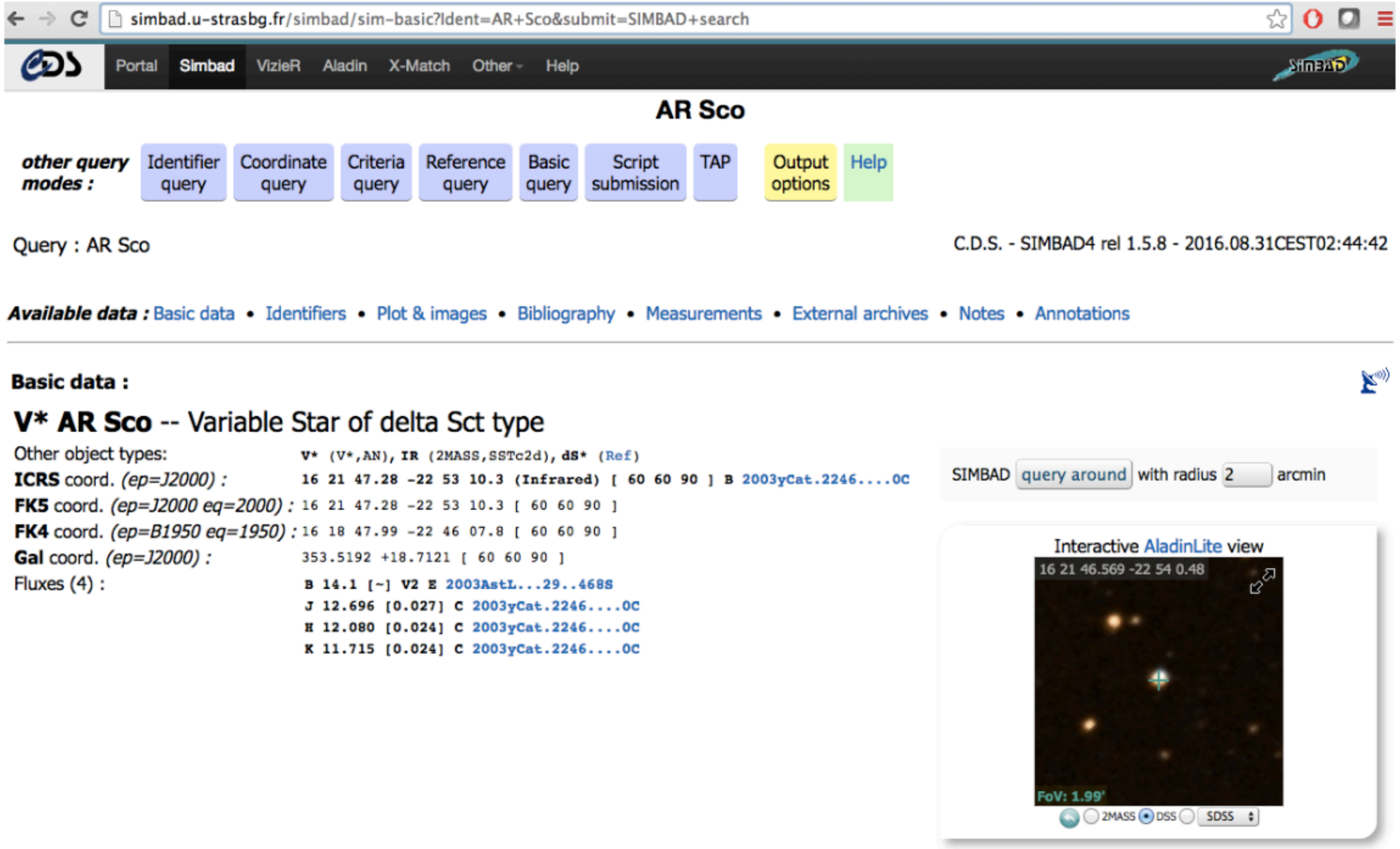
$$00^{\mathrm{h}}42^{\mathrm{m}}44.33^{\mathrm{s}}, +41^\circ 16'\, 07.5''$$
$$00\!:\!42\!:\!44.33, +41\!:\!16\!:\!07.5$$

note:

$$24^{\mathrm{h}} = 360^\circ$$
$$1^{\mathrm{h}} = 15^\circ$$
$$1^{\mathrm{m}} = 15^\circ/60 = 0.25^\circ = 15'$$
$$1^{\mathrm{s}} = 15^\circ/3600 = 0.25' = 15''$$

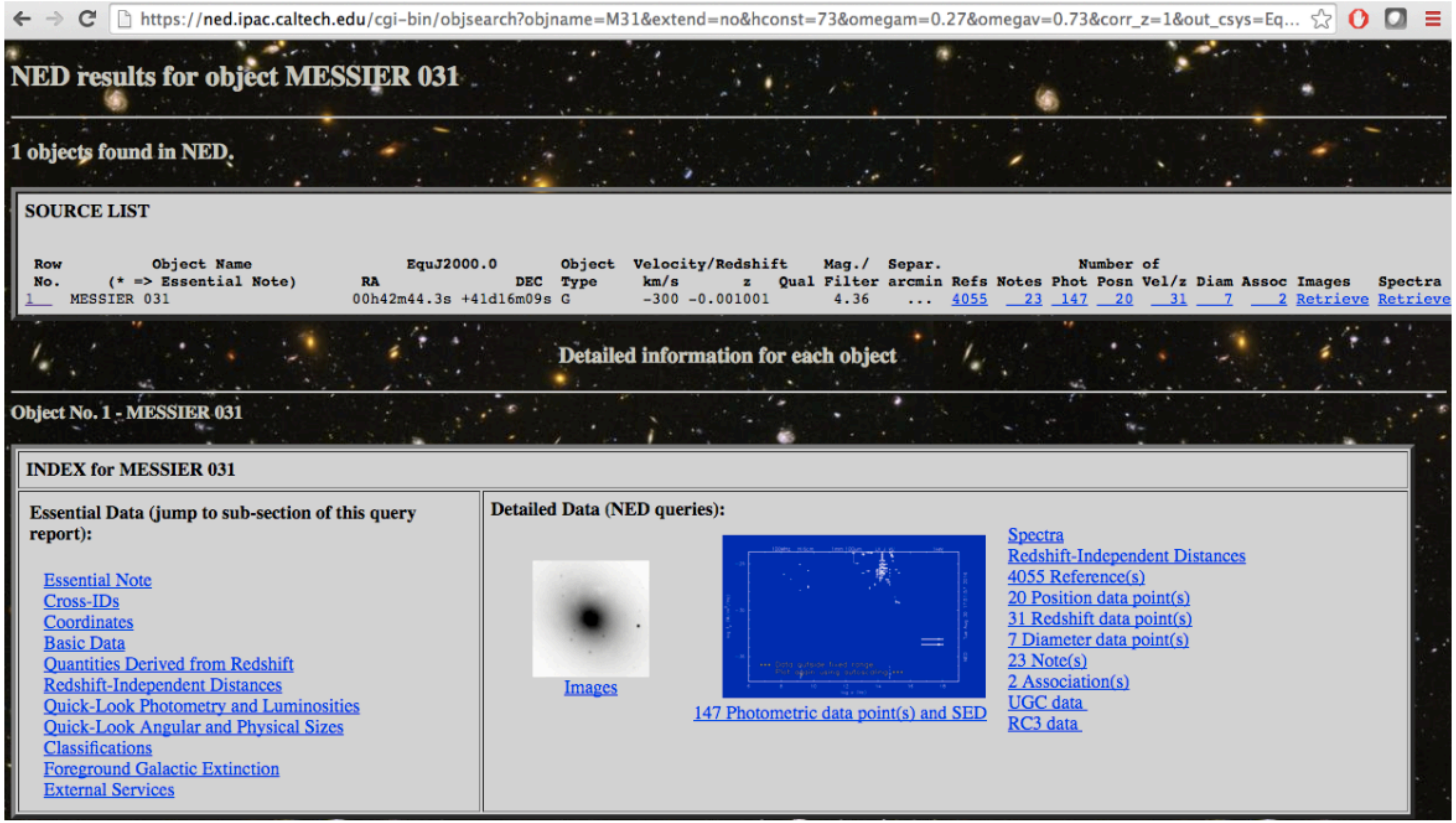
Looking up Coordinates and Information on an Object

- SIMBAD astronomical database: https://simbad.u-strasbg.fr/simbad/



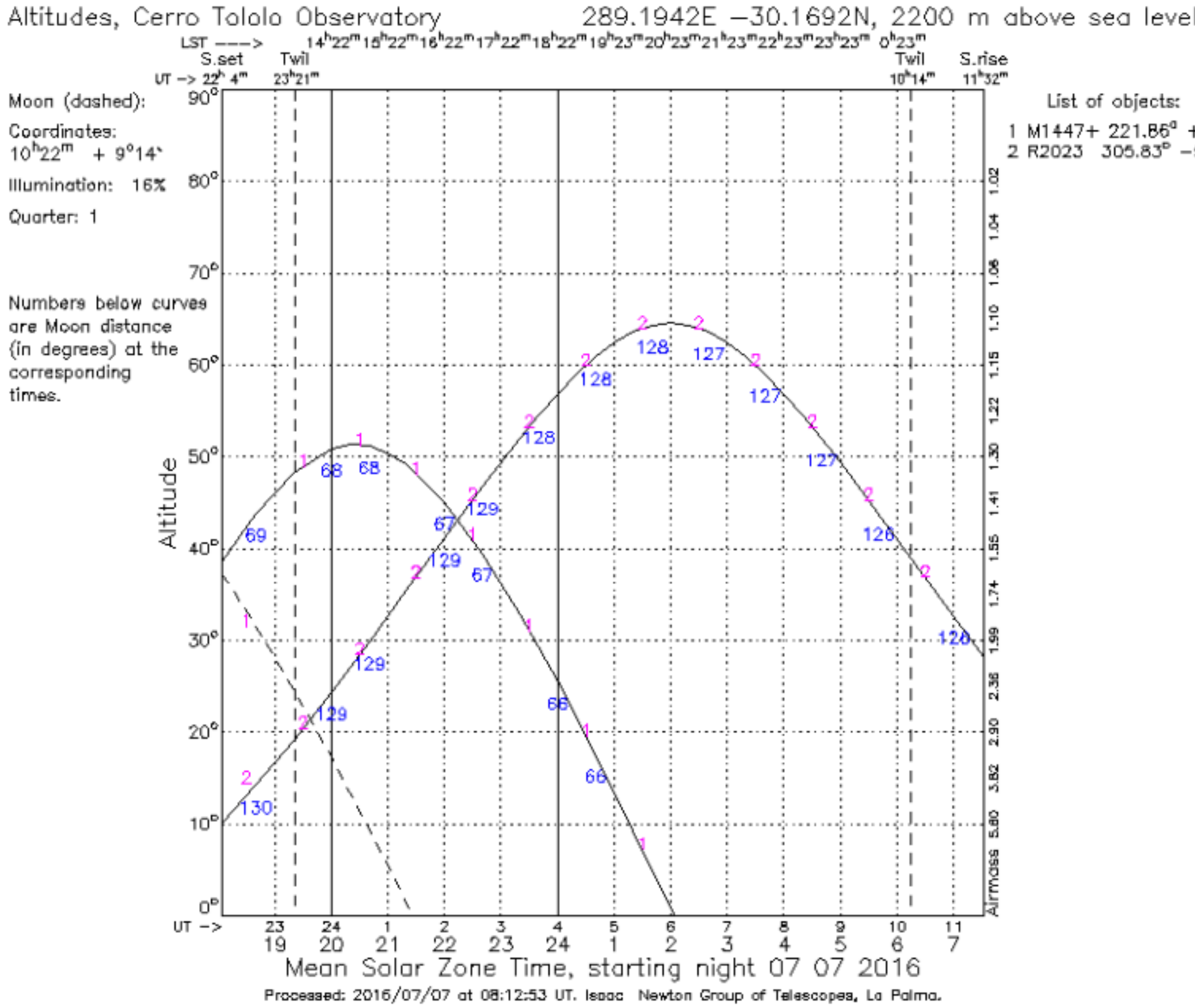
Looking up Coordinates and Information on an Object

- NASA/IPAC Extragalactic Database (NED): https://ned.ipac.caltech.edu/



Object Visibility Tool

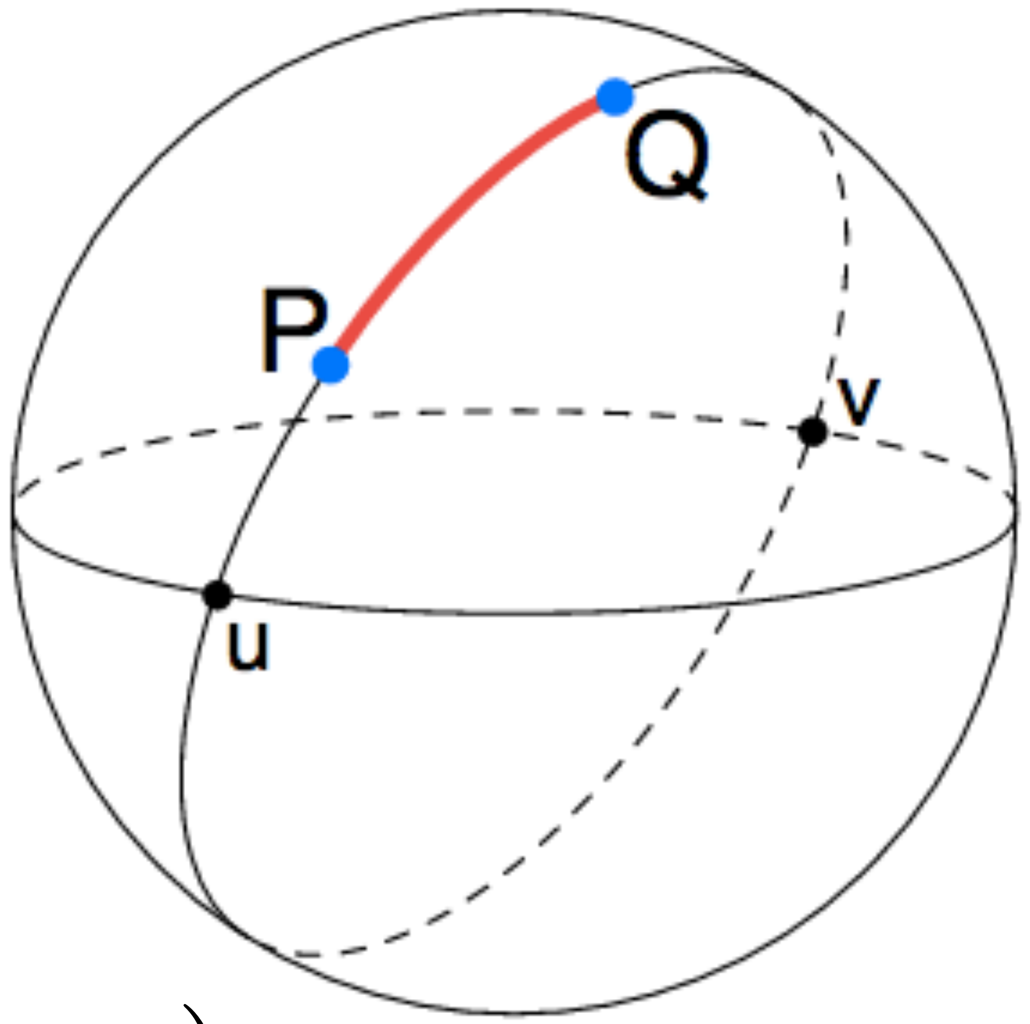
- “StarAlt”: http://catserver.ing.iac.es/staralt/
- Given catalog of object positions, StarAlt will plot their altitude vs time (and other features)
- Also see how to do this in python using week-1 tutorial linked on the wiki:
    - https://docs.astropy.org/en/stable/generated/examples/coordinates/plot_obs-planning.html



Distance between two objects

two objects at (α_1,δ_1) and (α_2,δ_2) - how far apart are they?

- surface of a sphere is non-Euclidian
- e.g. sum of angles in a triangle is >180°
- need to use spherical geometry



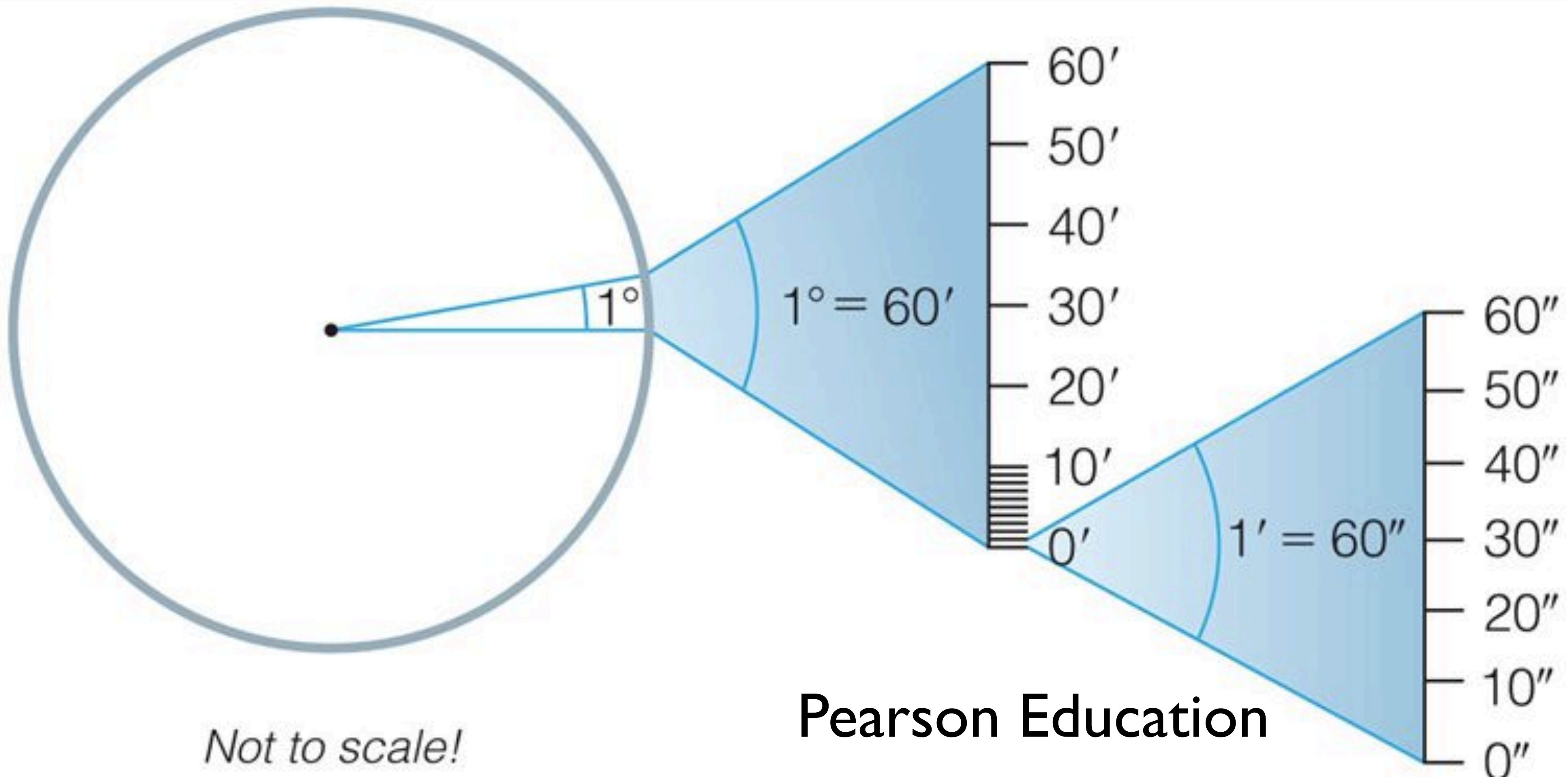
$$\cos(\gamma) = \cos(90^\circ - \delta_1)\cos(90^\circ - \delta_2) + \sin(90^\circ - \delta_1)\sin(90^\circ - \delta_2)\cos(\alpha_1 - \alpha_2)$$

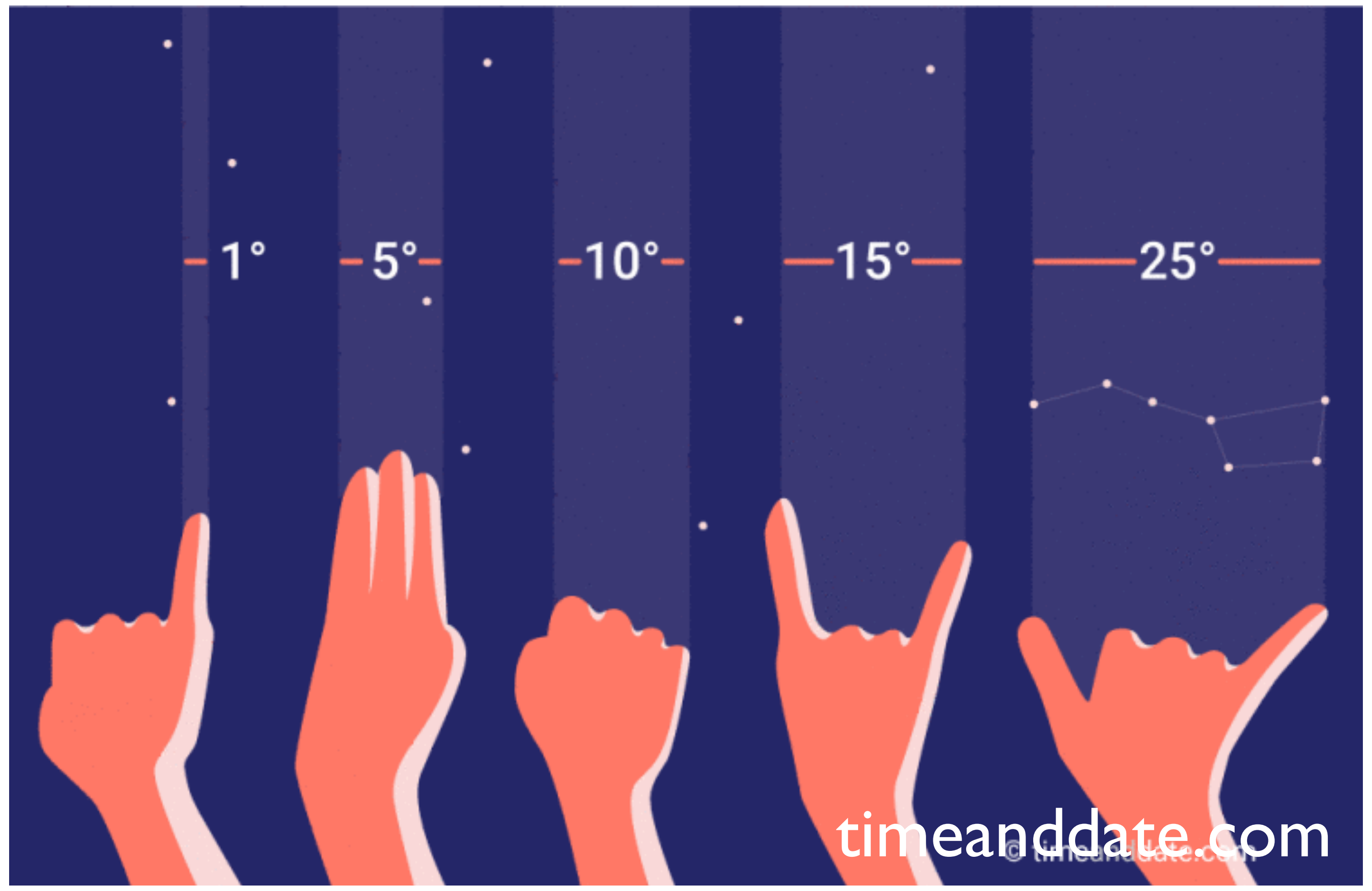
for small distances, can use Euclidian approximation;
HOWEVER, need to include $\cos(\delta)$

$$\gamma \simeq \sqrt{((\alpha_1 - \alpha_2)\cos(\delta_1))^2 + (\delta_1 - \delta_2)^2}$$

Lengths and Distances on the Sky

- Usually given in degrees (º), arc minutes (‘), and arcseconds(“)

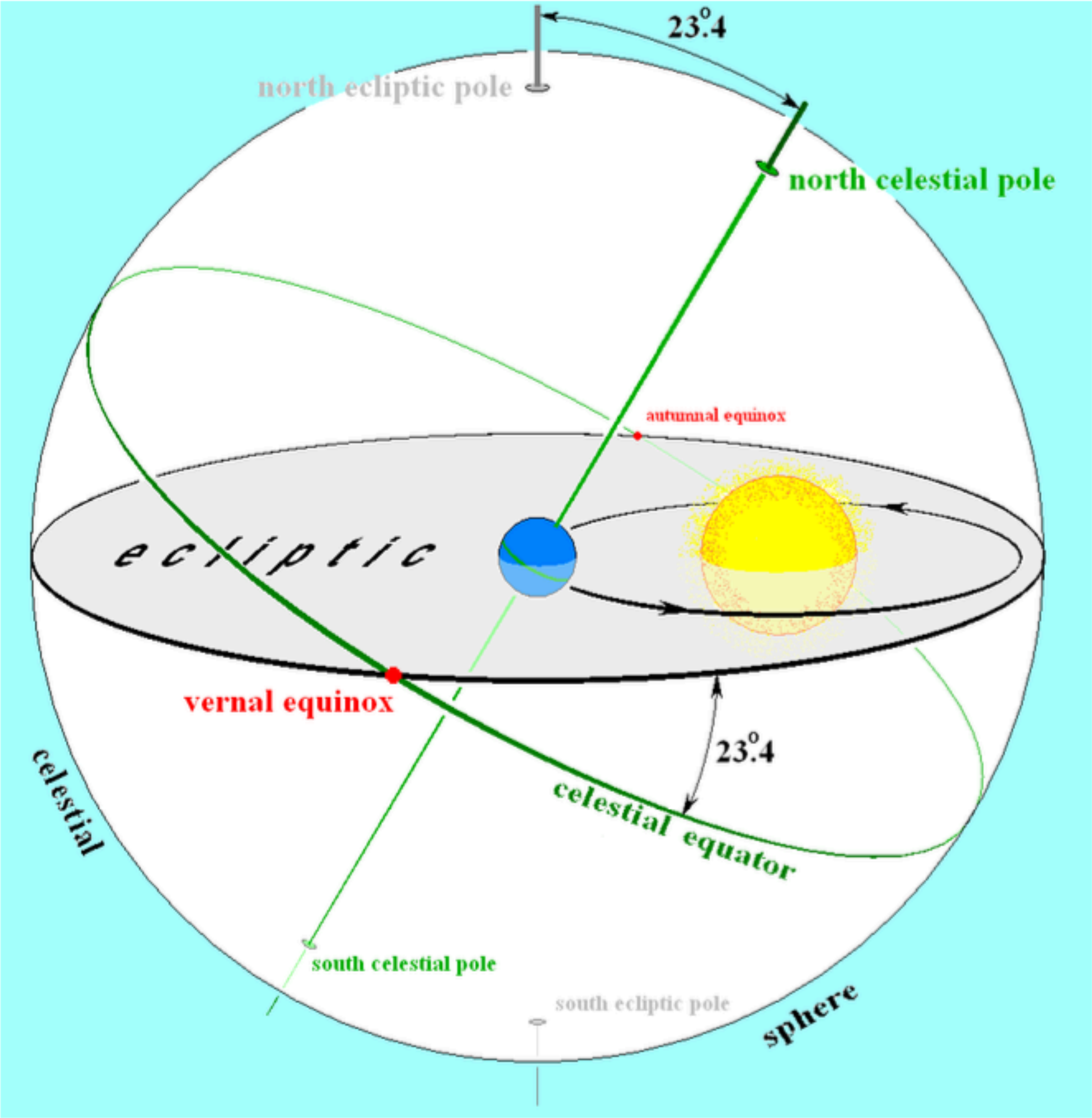




Moon: diameter is
~ 0.5˚ = 30’

Ecliptic Coordinates

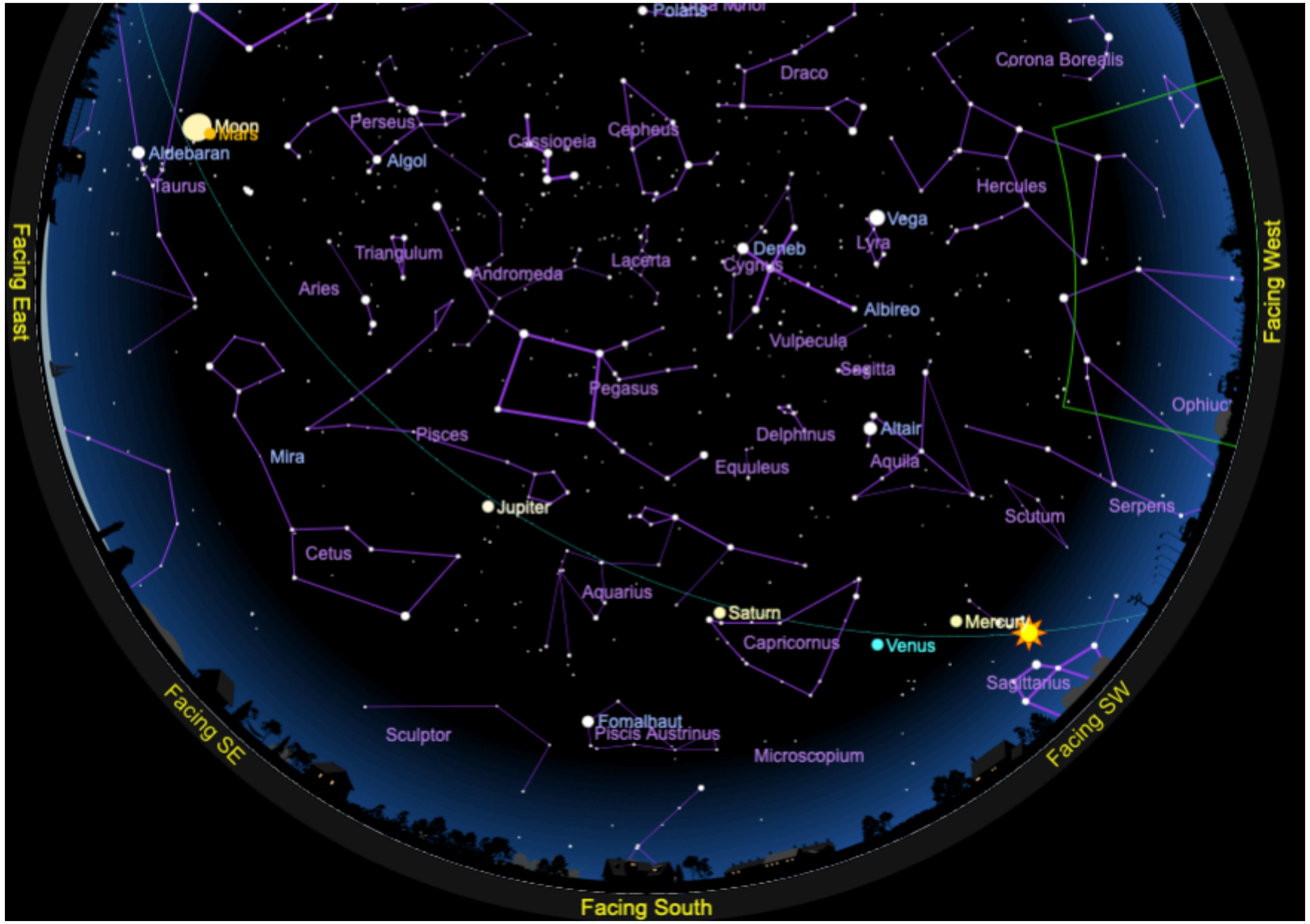
- Sun travels along the "Ecliptic"
- Equator and ecliptic intersect in two points: the equinoxes
- Why are they called equinoxes?
  - Vernal (spring) equinox marks RA=0h



wikipedia

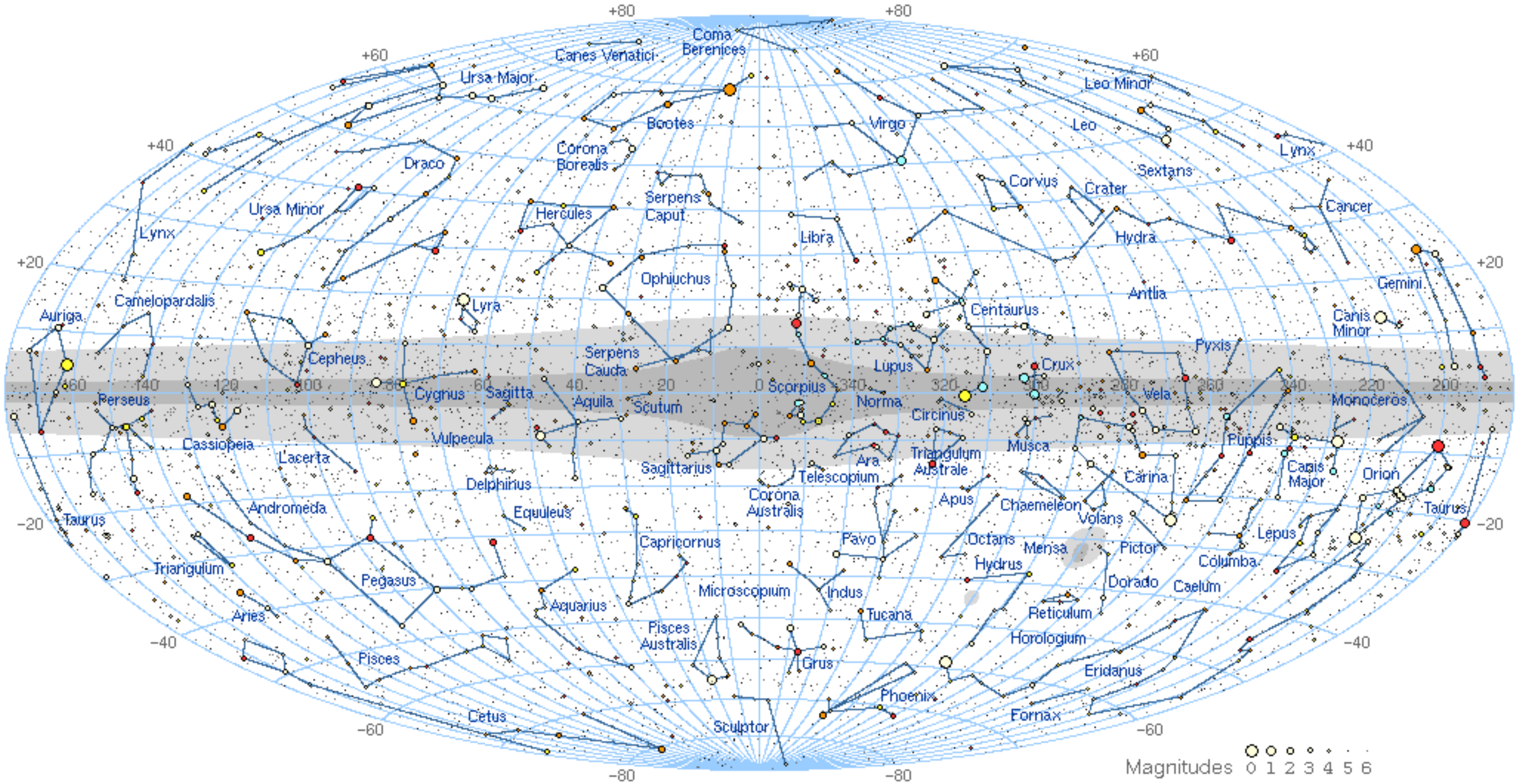
Solar System Objects

- Orbital planes of most planets and moons are similar to the Earth's orbital plane -> Moon and planets also approximately follow the ecliptic



Galactic Coordinates

- Can also use the plane of the Galaxy as the “equator”



Atlas of the Universe

Any final questions?