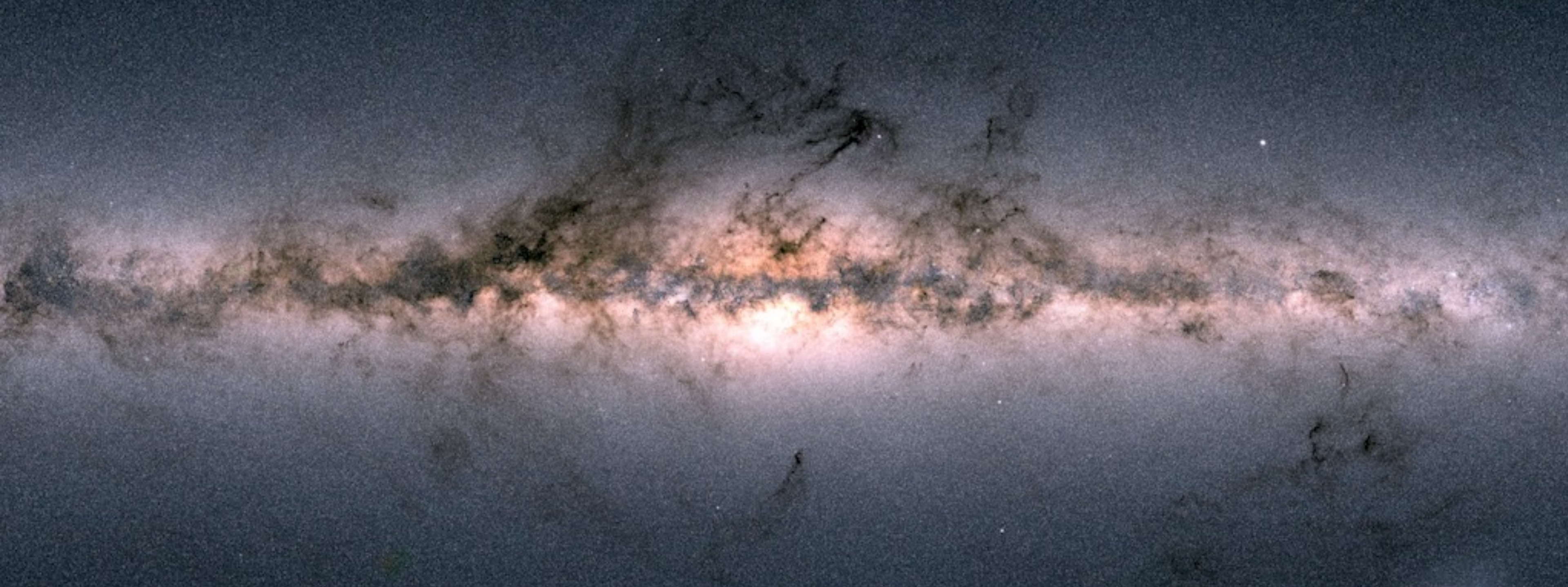
Astronomy 1: The Evolving Universe

Spring 2021

Prof. S. George Djorgovski



https://sites.astro.caltech.edu/ay1

Milky Way as seen by *Gaia*

Some Class Logistics

- Class website: https://sites.astro.caltech.edu/ay1
  for the lectures (videos, slides), announcements, links.
  Canvas website for the assignments (homework, exams)
- A weekly summary lecture: Mondays 2-3 pm, on Zoom
  - Videos of the lectures from the previous years are linked on the class website, along with the pdfs of the slides. Along with posted readings and links, ***that is your "textbook"***
  - You can supplement them with ***any*** intro astronomy textbook you like, and our Library has a plenty of them, some of them available on line (see the website)
- Sections (mandatory!): Friday 2-3 pm on Zoom
- Weekly homework, except for the midterm and final weeks
- **Ask questions!**

Ay 1 - The Evolving Universe

Spring 2021

- Home
- About the class
- Class times+location
- The Evolving Syllabus
- Homeworks + exams
- Recitation
- Useful links
- Videos (YouTube)
- Facebook group
- **Lectures**

Welcome to the Ay 1 - The Evolving Universe!

Please explore the links on the left.

Announcements:

- March 29: Welcome to the class! Please explore the links to the left. All lectures, slides, etc., will be posted here. All homeworks, solutions, and exams will be handled through the Canvas site. The first, introductory/summary lecture will be today, 2-3 pm; see the "times + location" tab.

https://sites.astro.caltech.edu/ay1

Ay 1 - The Evolving Universe

Spring 2021

- Home
- About the class
- Class times+location
- The Evolving Syllabus
- Homeworks + exams
- Recitation
- Useful links
- Videos (YouTube)
- Facebook group
- **Lectures**

Lectures:

Lecture transcripts, in compressed folders: (pdf) * (txt). These are imperfect, but you may find them useful.

Lecture 1: Astronomy as a science

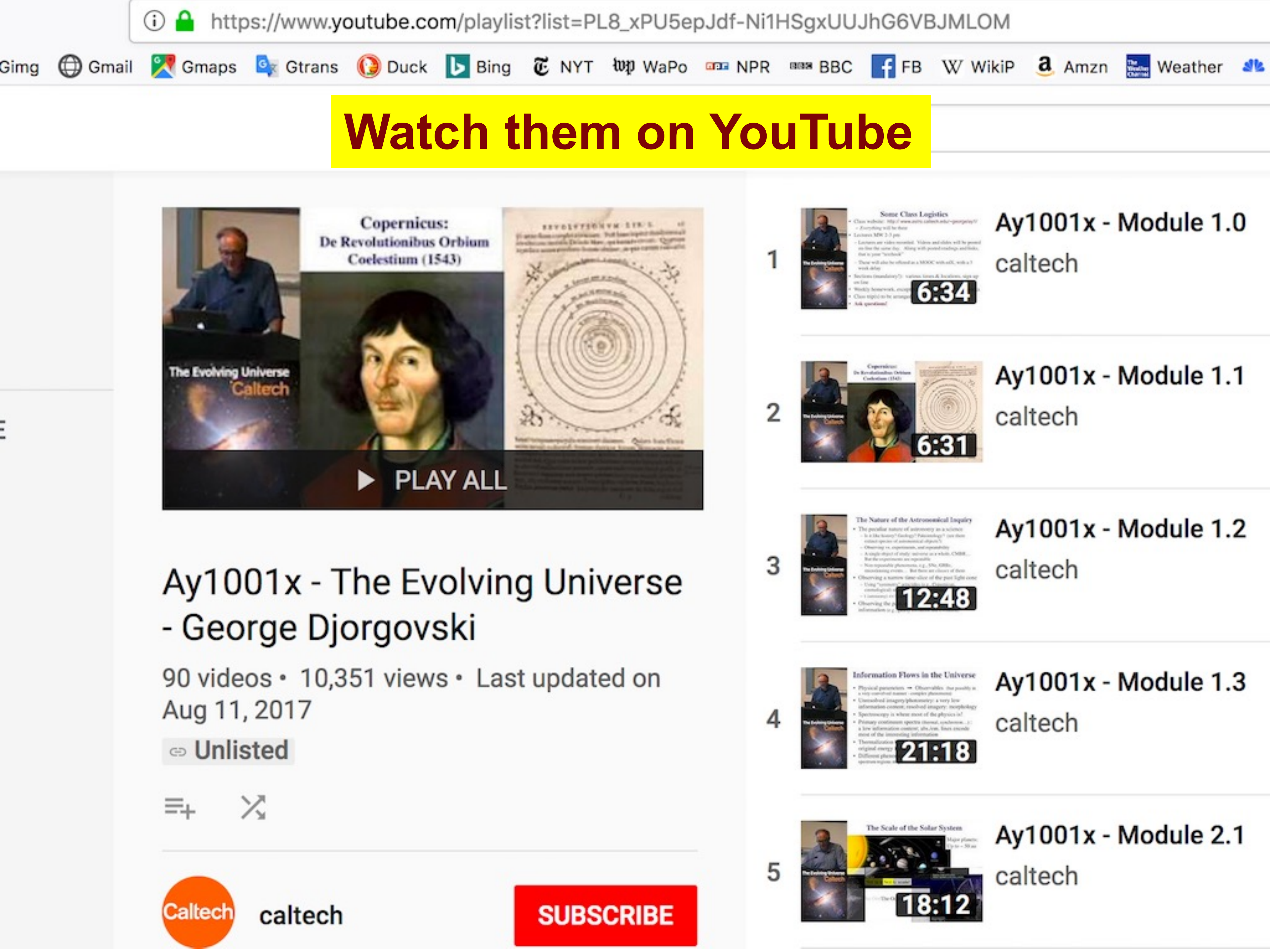
Some early history. Astronomy as a quantitative science, and as a branch of physics. Types of observations and their intrinsic limitations.

- Slides (pdf)
- Lecture videos:
  - Module 1.0: Introduction and Logistics
  - Module 1.1: The Oldest Science
  - Module 1.2: Astronomy as a Science
  - Module 1.3: Messengers from the Universe

Lecture 2: Starting the Exploration

Some common units. Distances and parallaxes. An overview of scales and

Watch them on YouTube



Ay 1 - The Evolving Universe

Spring 2018

- Home
- About the class
- Class times+location
- The Evolving Syllabus
- Your teaching team
- Homeworks + exams
- Recitation
- Useful links
- Videos (Echo360)
- Videos (YouTube)
- Facebook group

Lectures

Some useful links:

More will be added, and suggestions are always welcome.

On-line education/outreach resources:

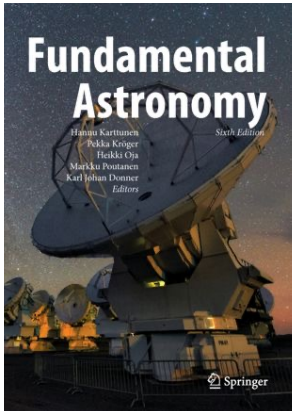
- Caltech astronomy outreach
- JPL (many popular astronomy links)
- The Library of Congress Astronomy Resources on the Internet
- Sky & Telescope Online Astronomy Links
- AstronomyOnline
- Imagine the Universe from the NASA GSFC
- CDS AstroWeb
- Griffith Observatory
- ispySpace.com
- StarDate
- PBS Astronomy Programs
- Popular astronomy links from UH/IfA
- Cornell astronomy links
- APOD educational links

Pretty pictures:

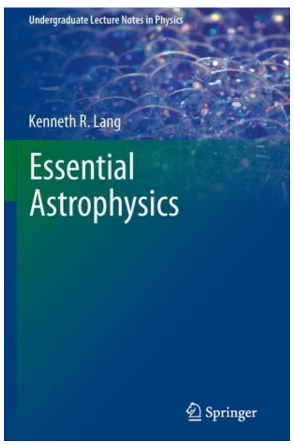
On-line Textbooks

Accessible from the caltech.edu domain

These can be used to ***supplement*** the classroom lectures (videos, ppts, links)



Karttunen, H., et al., "Fundamental Astronomy"



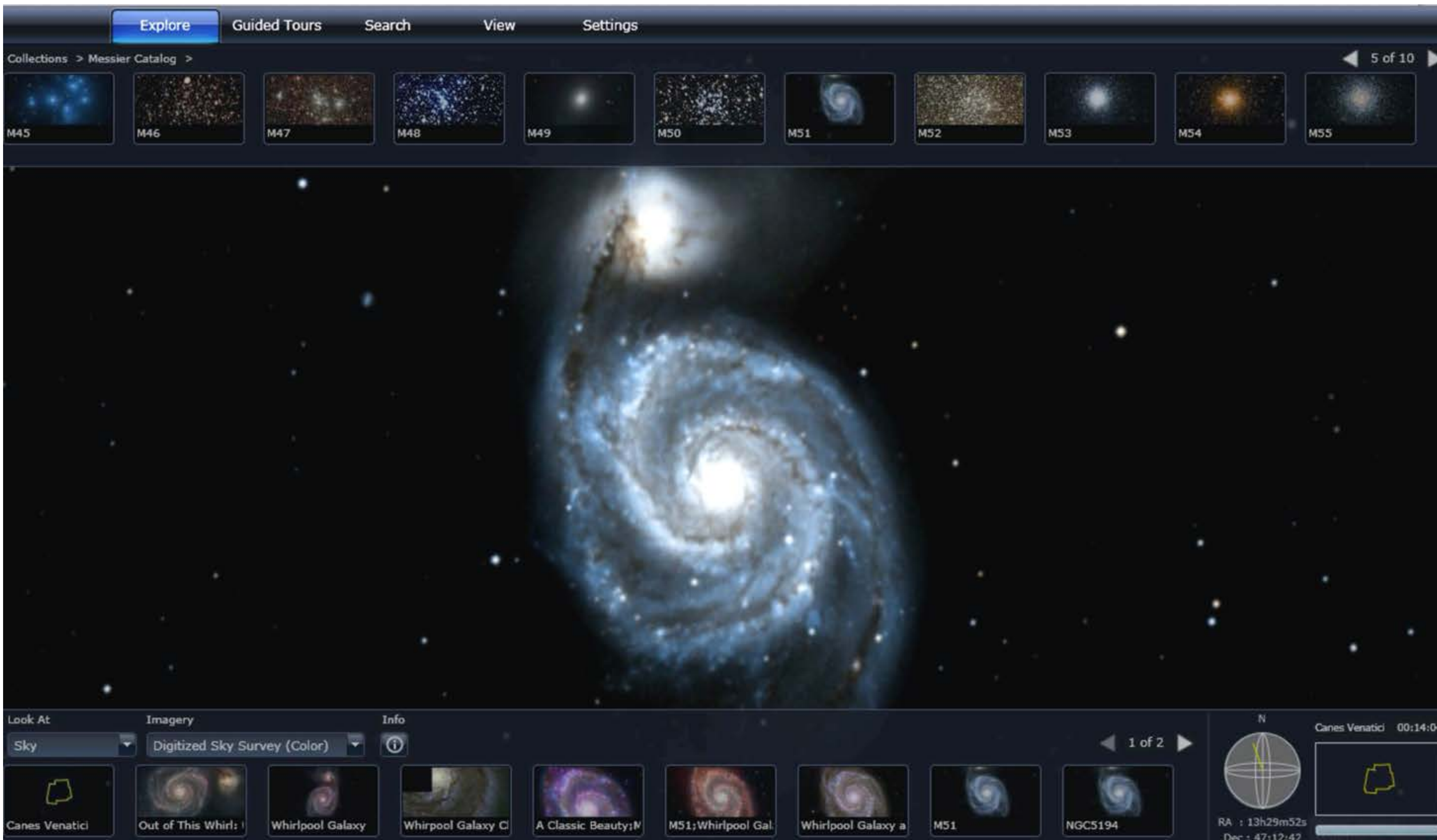
Lang, K., "Essential Astrophysics"

Fraknoi, A., Morrison, D., & Wolff, S., "Astronomy", [may be too elementary for this class]

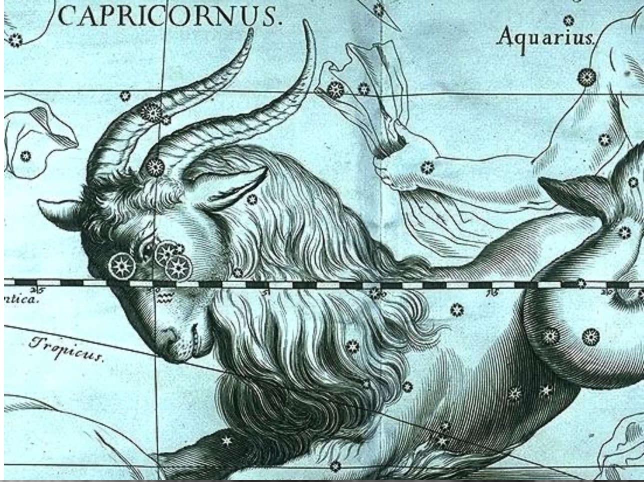
Use the *WorldWide Telescope*

http://www.worldwidetelescope.org/webclient/

A great sky browser – try it!



The Evolution of Astronomy



- From astrology to classical astronomy (~ positional astronomy and cellestial mechanics) to astrophysics

- A strong and growing connection with physics, starting with Newton … Today astronomy is one of the most exciting branches of physics

- Many important developments happened in Pasadena (Hale, Hubble, Zwicky, Baade, Minkowski, Sandage, …)

How is Astronomy Possible?

The universe is really, really big, and we cannot experiment in the lab with any of the objects in it

But we can use…

Data

+

Logic (~ math)

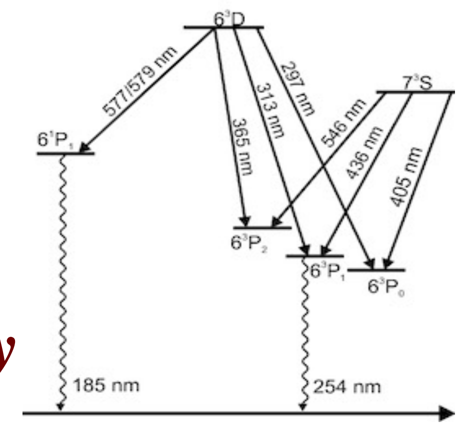
= Scientific method

… and use physics as an interpretative framework

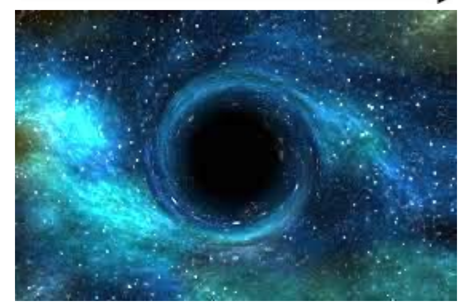
The Nature of the Astronomical Inquiry

- The peculiar nature of astronomy as a science
  - Is it like history? Geology? Paleontology? (are there extinct species of astronomical objects?)
  - Observing vs. experiments, and repeatability
  - A single object of study: universe as a whole, CMB…. But the experiments are repeatable
  - Non-repeatable phenomena, e.g., SNe, GRBs, microlensing events… But there are *classes* of them
- Observing a narrow time-slice of the past light cone
  - Using symmetry principles (Copernican, cosmological) as a substitute for unobtainable information
  - t (astronomy) << t (universe) ➙ inevitable biases
- Deducing the past it from the "fossil" information (e.g., galaxy formation and evolution)

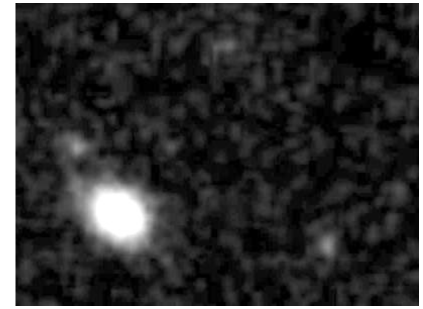
Astronomy as a Branch of Physics

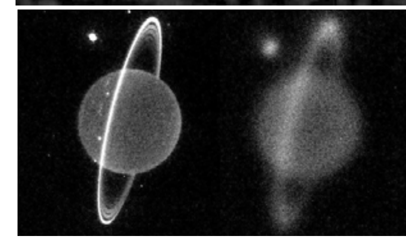


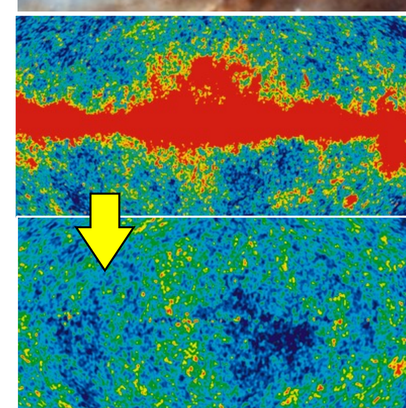
- ***Using the apparatus of physics*** to gather and interpret the data: assume that our physics is universal (and we can test that!)
- Astronomical phenomena as a ***cosmic laboratory***
  - Relativistic physics (black holes, gravitational waves, jets, gravitational lensing …)
  - Cosmic accelerators (high energy cosmic rays, neutrinos) and the early universe
  - Matter in extreme conditions (e.g., neutron stars, GRBs, high & low density plasmas …)
- ***Astronomical discoveries as a gateway to the new physics*** (e.g., dark matter and dark energy; neutrino mixing; inflation; etc.)
- ***Progress is driven by the technology*** (optics, detectors, spacecraft, computing…)



Fundamental Limits to Measurements and Selection Effects



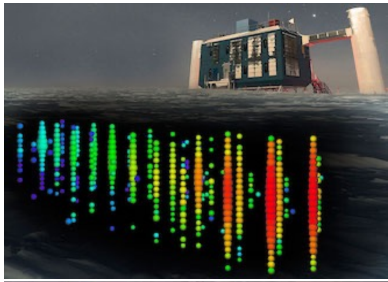




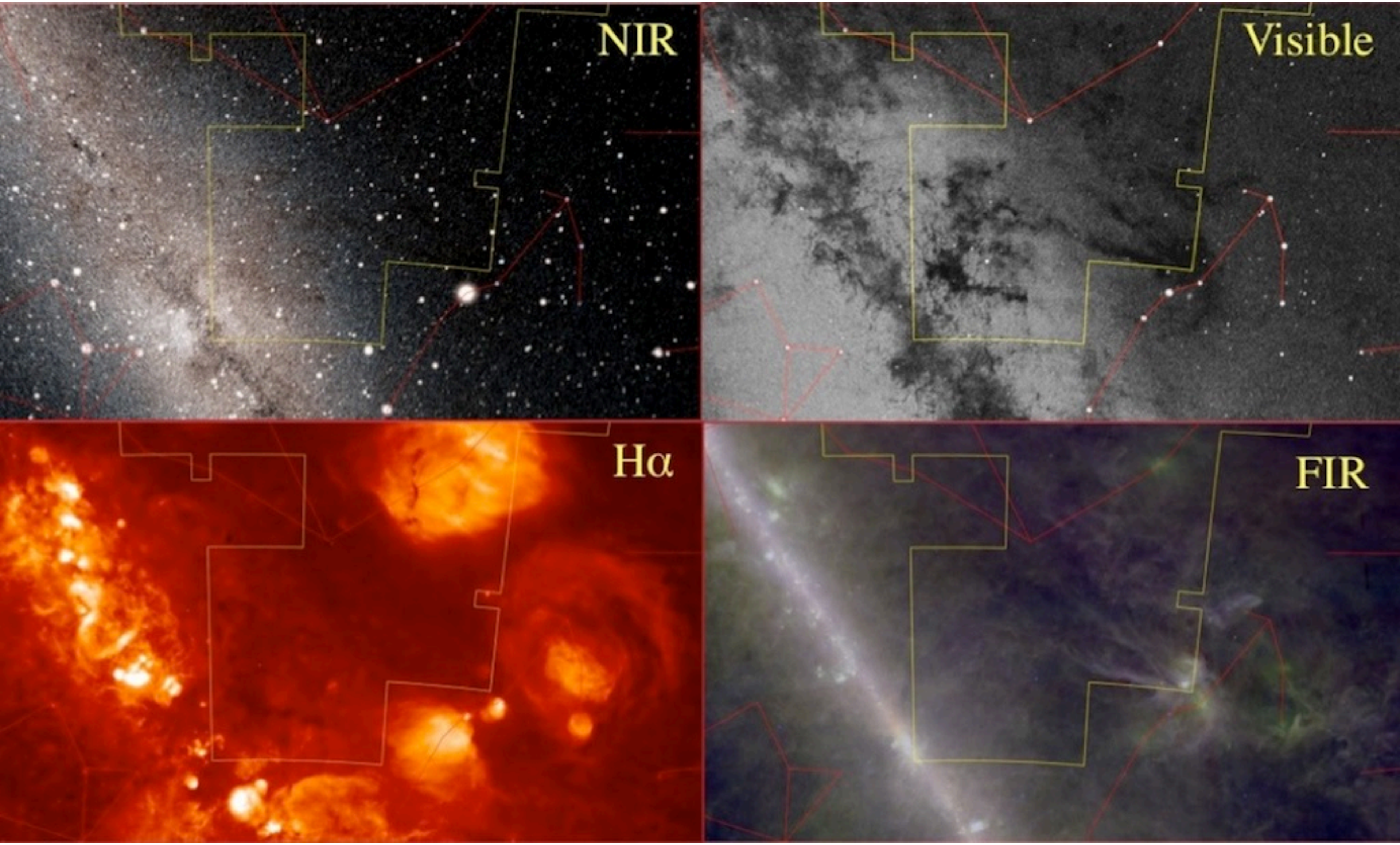
- S/N Poissonian and quantum limits of detection
- Geometrical optics limits of angular resolution
- Turbulence of the atmosphere/ISM: erasing the spatial information
- Opacity of the Earth's atmosphere and the Galactic interstellar medium
- Obscuration by dust in galaxies
- Convolved backgrounds and foregrounds (example: Cosmic Microwave Background)
- And the "un-natural" limits: politics, funding, social psychology …

Information Channels in Astronomy

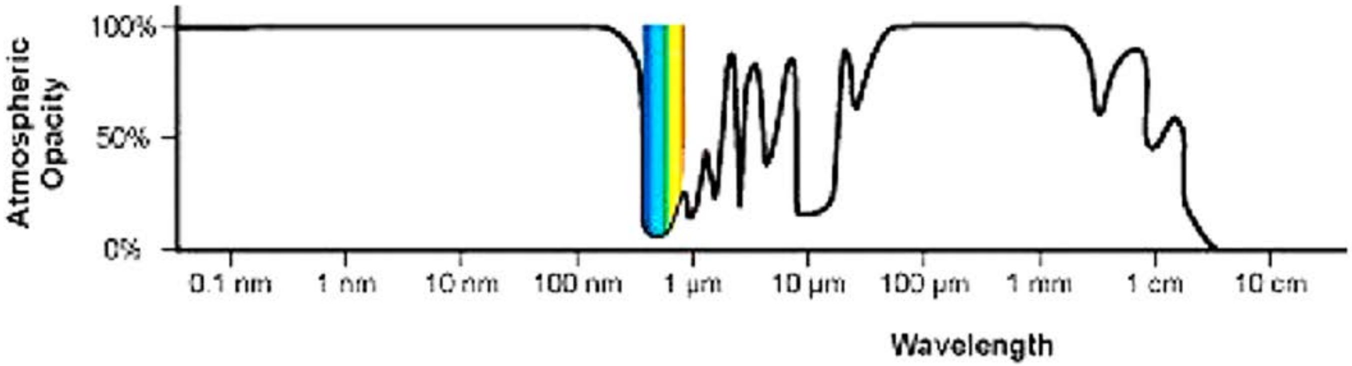
- Mostly electromagnetic! Methodologies:
  - Single-channel photometry
  - 2D imaging (photometry, morphology, positions/motions)
  - 1D spectroscopy
  - 2D (long-slit) spectroscopy
  - 3D data cubes (2 spatial + 1 spectro)
  - All can include polarimetry
  - All can be time-resolved (synoptic)
  - Can be single-dish, or interferometric
- Particles:
  - Cosmic rays: Cherenkov, particle detectors …
  - Neutrinos: big tanks of something, IceCube …
- Gravitational Waves: LIGO/LISA interferometers
- Dark Matter: lab detectors, gravitational lensing



The Panchromatic Universe



Atmospheric Transmission Windows



Ionospheric cutoff

And that is why we need space observatories!

But there as an even more profound limitation:

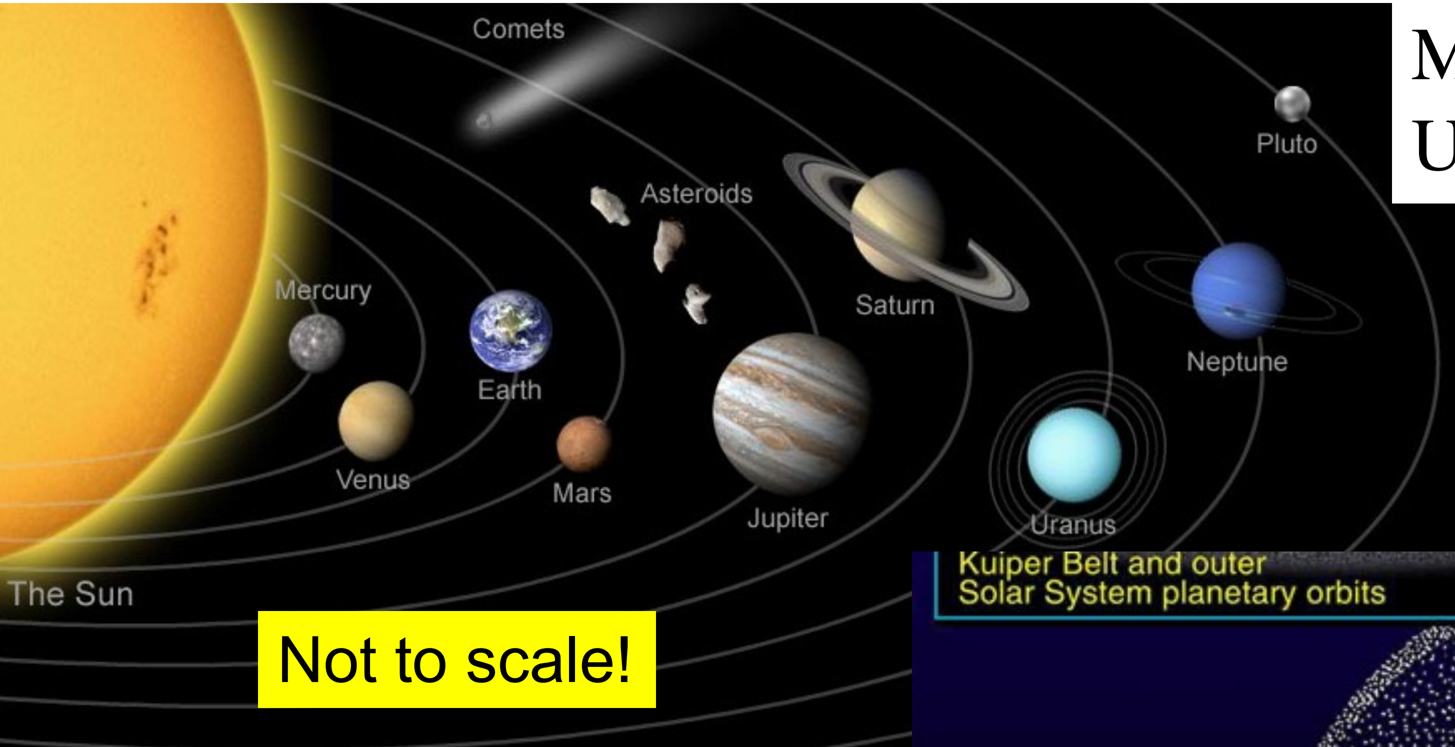
The Galactic "atmosphere" - the interstellar medium - also absorbs very long wavelengths, and hard UV / soft X-rays (the interstellar fog); and of course the dust absorbs the blue/UV light (the interstellar smog).

This may be very important: perhaps 90% of the baryons in the universe are in the form of a "warm" ($T \sim 10^5$ K) gas, which emits mostly soft X-rays

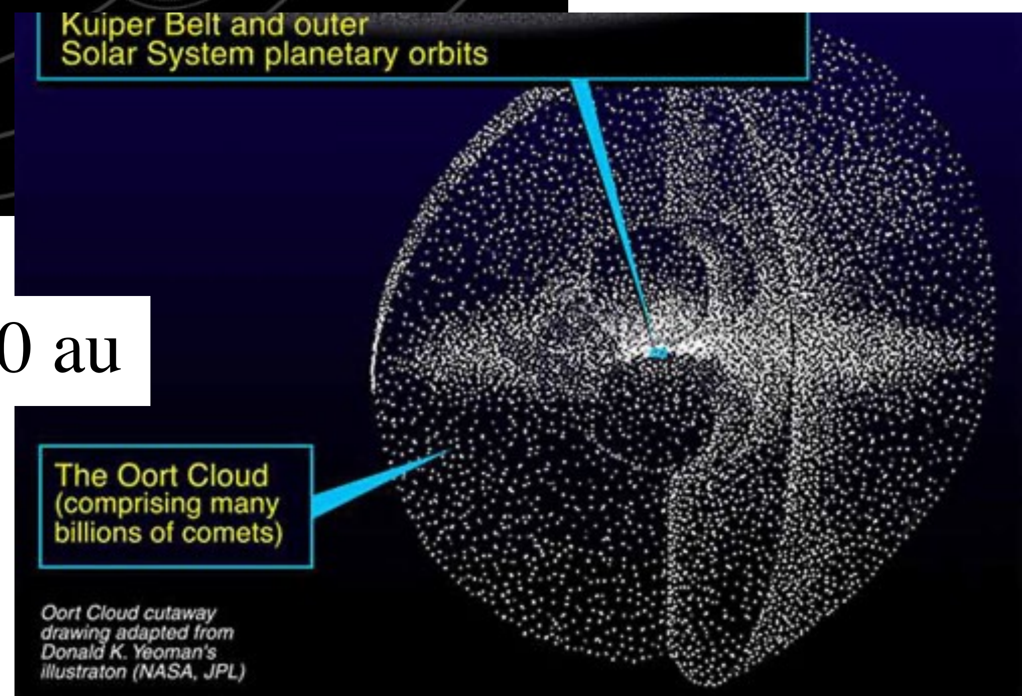
Some Commonly Used Units

- **Distance:**
  - Astronomical unit: the distance from the Earth to the Sun, 1 au = 1.496×10^{13} cm ~ 1.5×10^{13} cm
  - Light year: c $\times$1 yr, 1 ly = 9.463×10^{17} cm ~ 10^{18} cm
  - Parsec: the distance from which 1 au subtends an angle of 1 arcsec,
    1 pc = 3.086×10^{18} cm ~ 3×10^{18} cm
    1 pc = 3.26 ly ~ 3 ly
    1 pc = 206,264.8 au ~ 2×10^{5} au
- **Mass and Luminosity:**
  - Solar mass: 1 $M_{\odot}$ = 1.989×10^{33} g ~ 2×10^{33} g
  - Solar luminosity: 1 $L_{\odot}$ = 3.826×10^{33} erg/s ~ 4×10^{33} erg/s

The Scale of the Solar System



Major planets:
Up to ~ 50 au

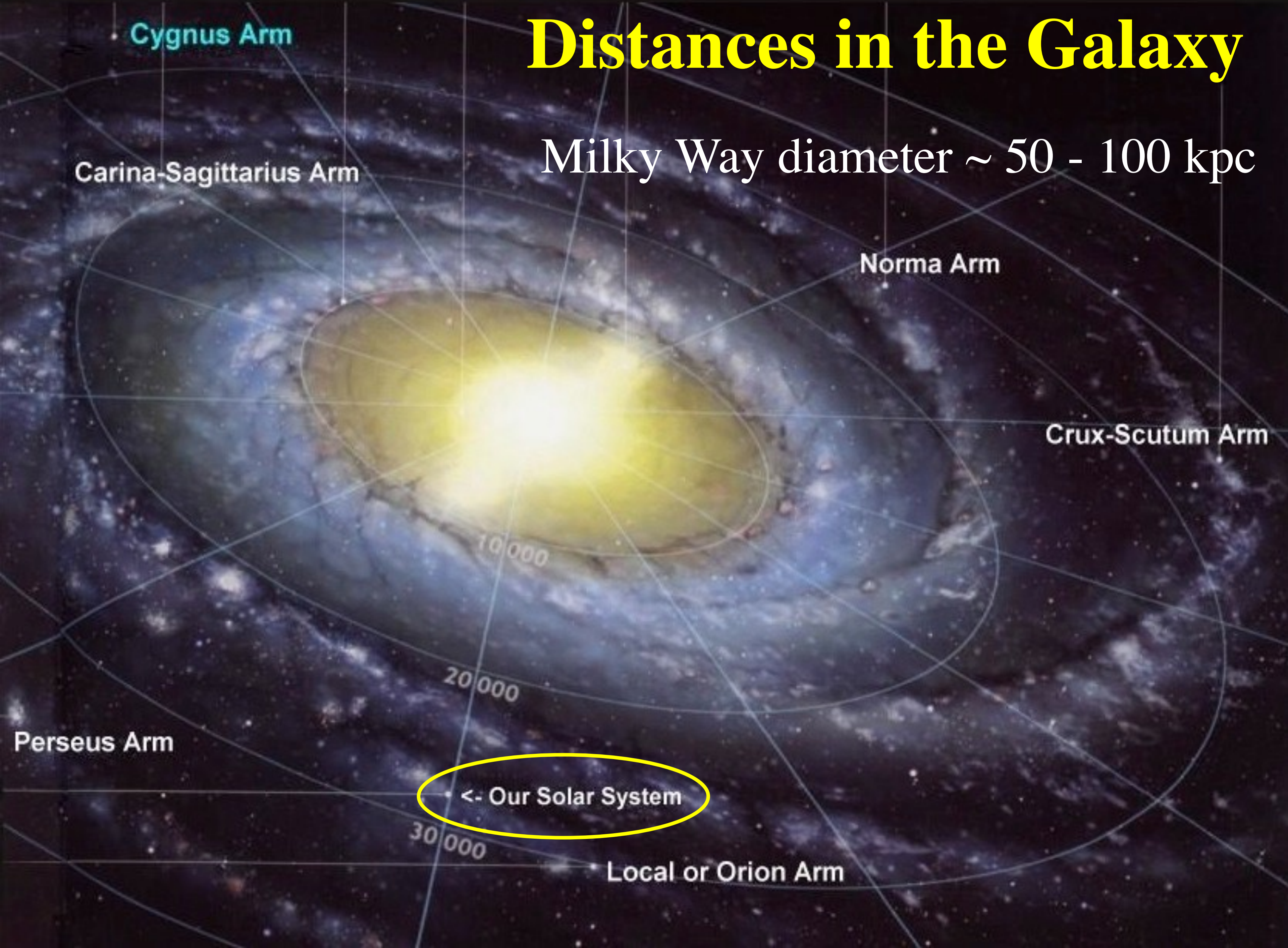


The Oort cloud: ~ 1000 au

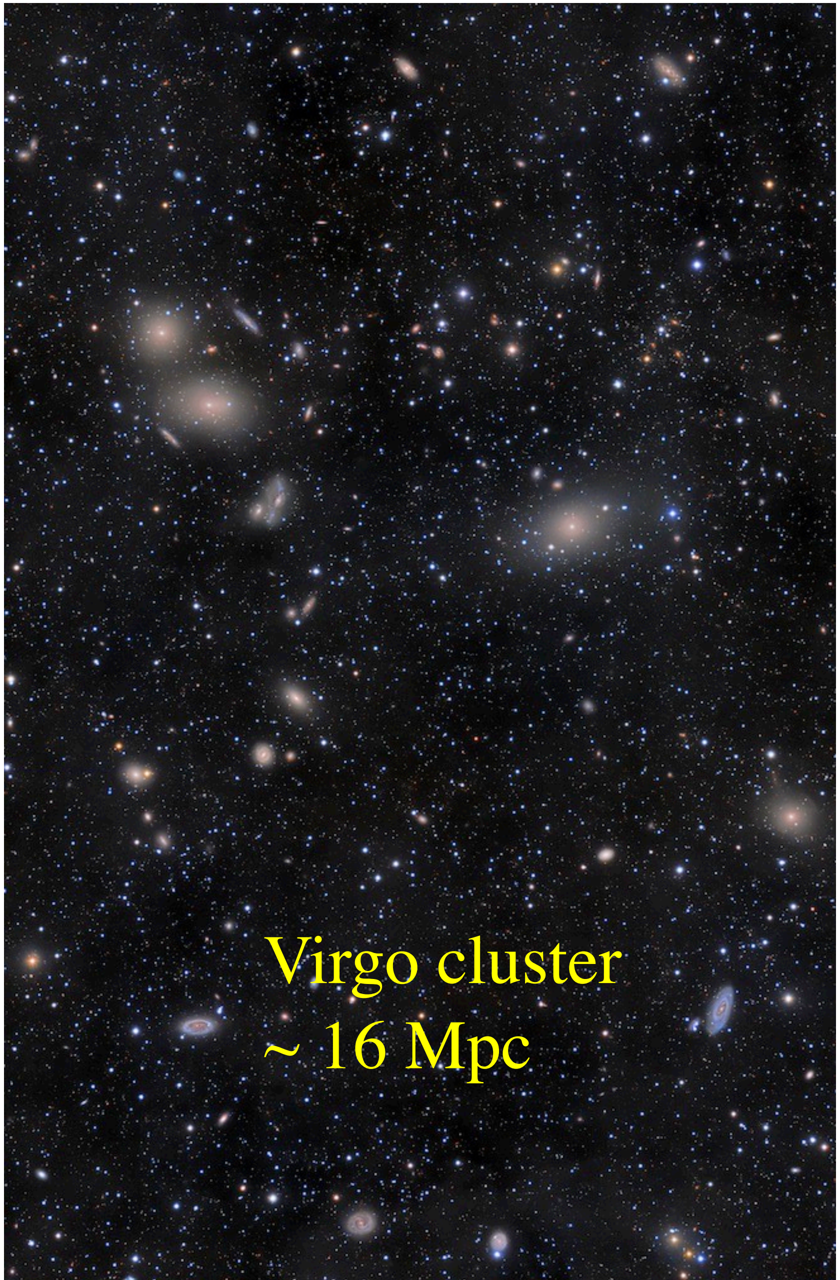
Stellar Distances

Distances in the Galaxy

Milky Way diameter ~ 50 - 100 kpc



Our Extragalactic Neighborhood



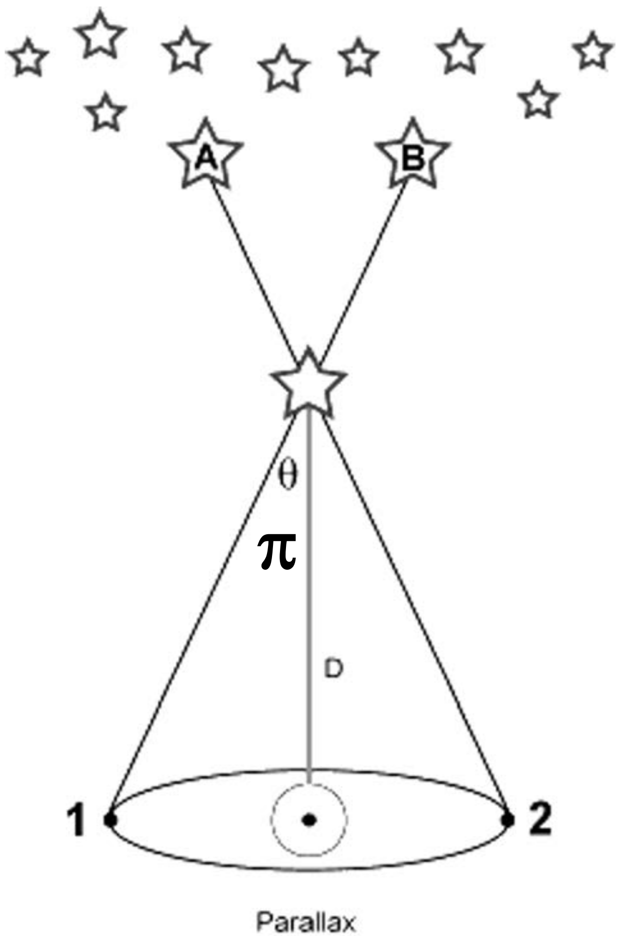
The Deep Universe: ~ 1 – 10 Gpc

Distances and Parallaxes

- Distances are necessary in order to convert apparent, measured quantities into absolute, physical ones (e.g., luminosity, size, mass…)
- Stellar parallax is ***the only*** direct way of measuring distances in astronomy! Nearly everything else provides relative distances and requires a basic calibration
- Small-angle formula applies:

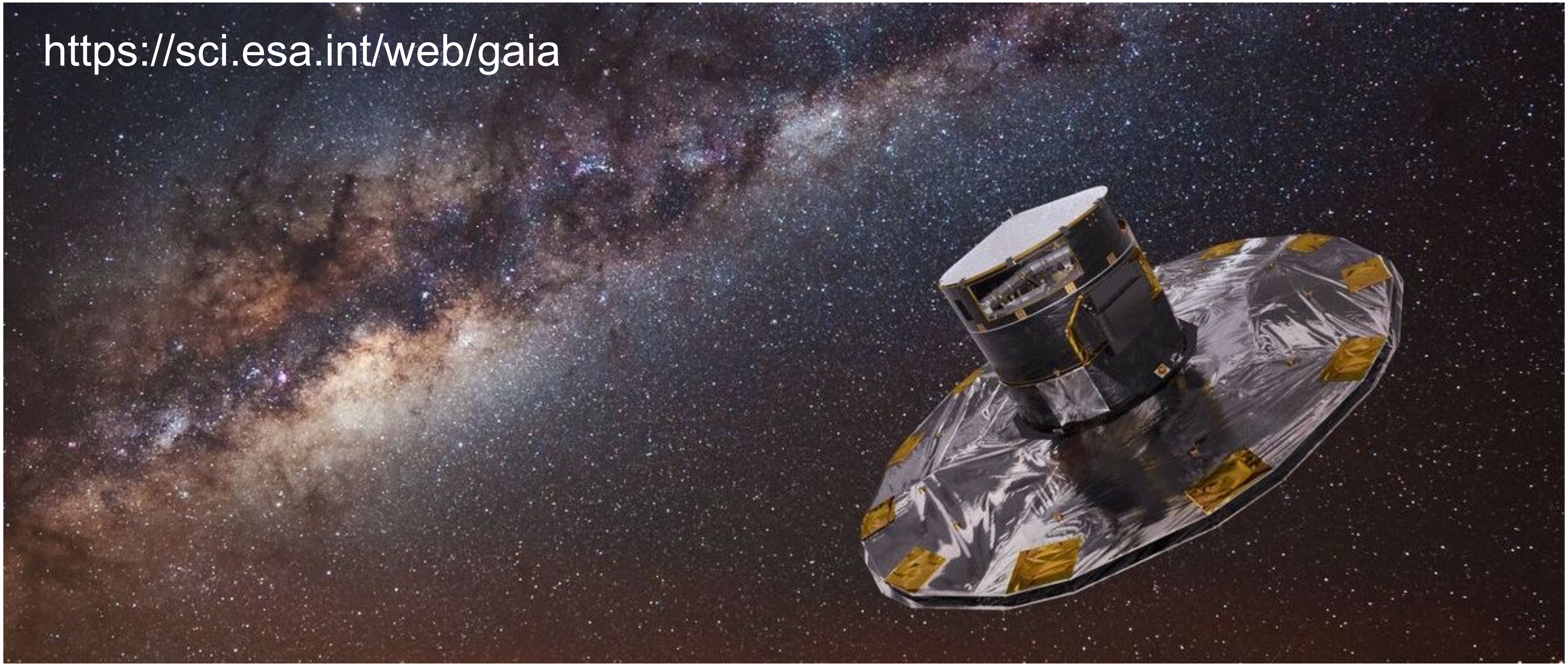
  $$\mathbf{D}\ [\mathrm{pc}] = \mathbf{1} / \pi\ [\mathrm{arcsec}]$$

- Limited by the available astrometric accuracy (~ 1 mas, i.e., D < 1 kpc or so, now)



How Far Can We Measure Parallaxes?

Gaia **satellite** (launched 2013) is measuring the positions and proper motions of ~ 2×10^9 stars over the entire sky with an accuracy < 0.1 milliarcsec (distances ~ 10 kpc, i.e., most of the Milky Way!) + a lot of other data. It is revolutionizing the stellar and Galactic astronomy.



Kepler's Laws:

1. The orbits of planets are elliptical, with the Sun at a focus
2. Radius vectors of planets sweep out equal areas per unit time
3. Squares of orbital periods are proportional to cubes of semimajor axes:

$$P^2\,[\mathrm{yr}] = a_{pl}^3\,[\mathrm{au}]$$

- Derived empirically from Tycho de Brahe's data
- Explained by the Newton's theory of gravity

Newton's Laws

1. Inertia…
2. Force: $F = m\,a$
3. $F_{action} = F_{reaction}$

(Laws 1 and 2 → Conservation laws (E, $\boldsymbol{p}$, $\boldsymbol{L}$))

e.g., for a circular motion in grav. field:

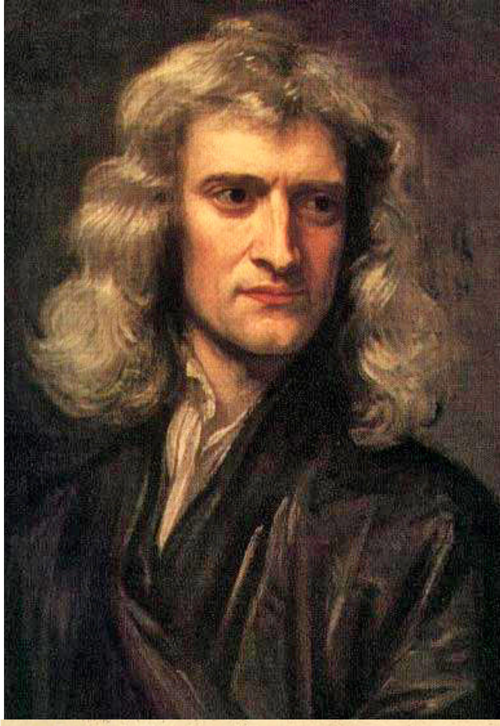
centifugal force = centripetal force

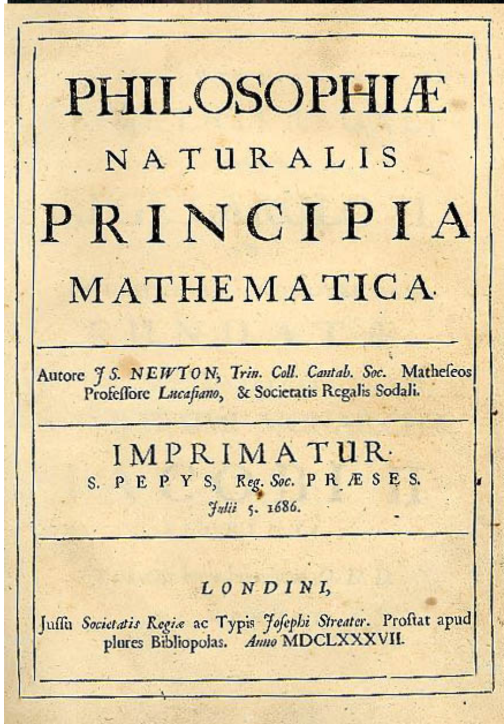
$$\frac{m\,V^2}{R} = G\,\frac{m\,M}{R^2}$$

- The law of gravity: $F = G\,\dfrac{m_1\,m_2}{r^2}$
- Energy: $E_{total} = E_{kinetic} + E_{potential}$

$$\frac{m\,V^2}{2} \qquad \frac{G\,m\,M}{R} \quad \text{(gravitational)}$$

- Angular momentum: $L = m\,V\,R$ (point mass)





PHILOSOPHIÆ NATURALIS PRINCIPIA MATHEMATICA

Autore JS. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR. S. PEPYS, Reg. Soc. PRÆSES. Julii 5. 1686.

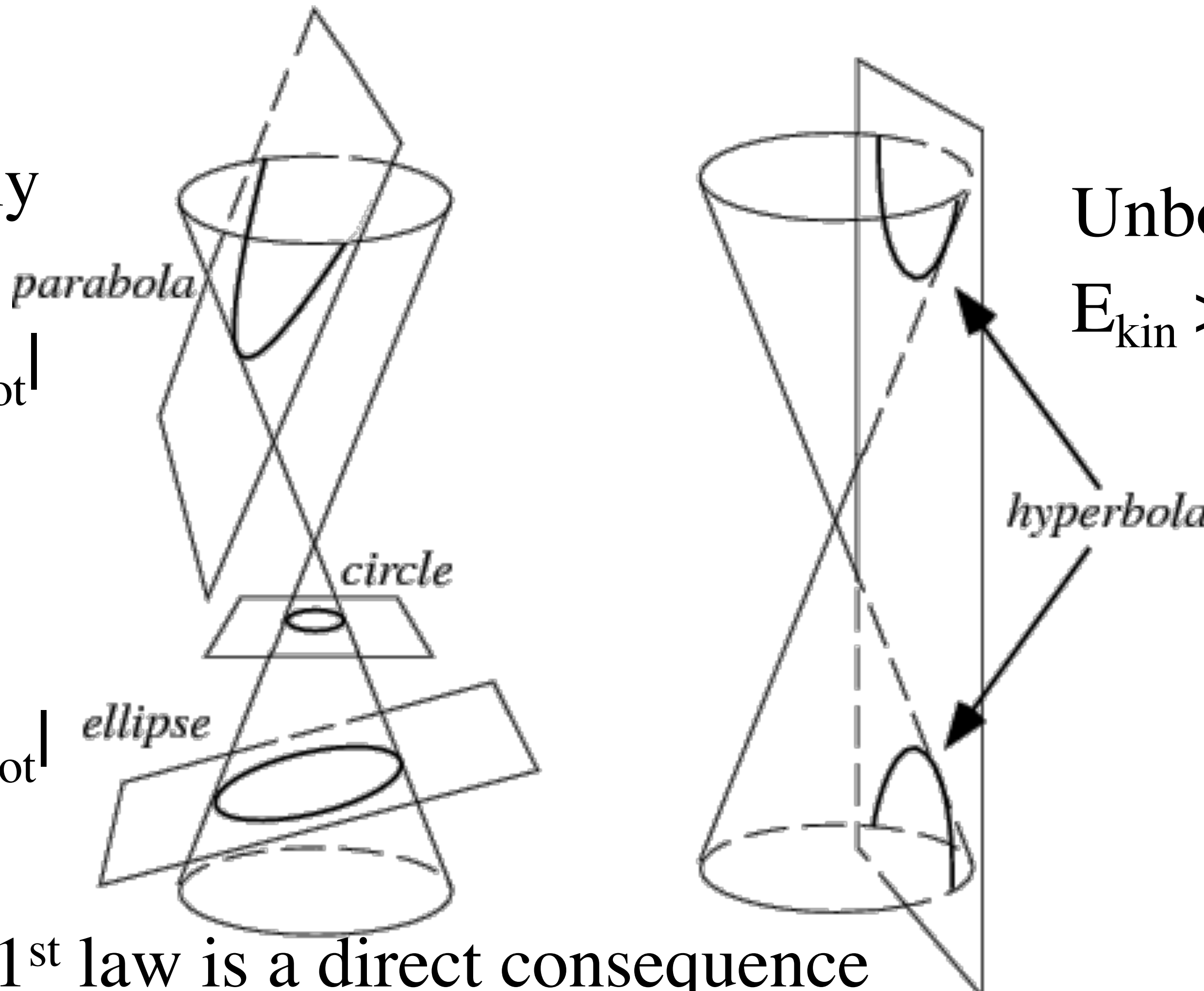
LONDINI, Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Motions in a Gravitational Field

- Motions of two particles interacting according to the inverse square law are conic sections:

Marginally bound:
$E_{kin} = |E_{pot}|$

Bound:
$E_{kin} < |E_{pot}|$



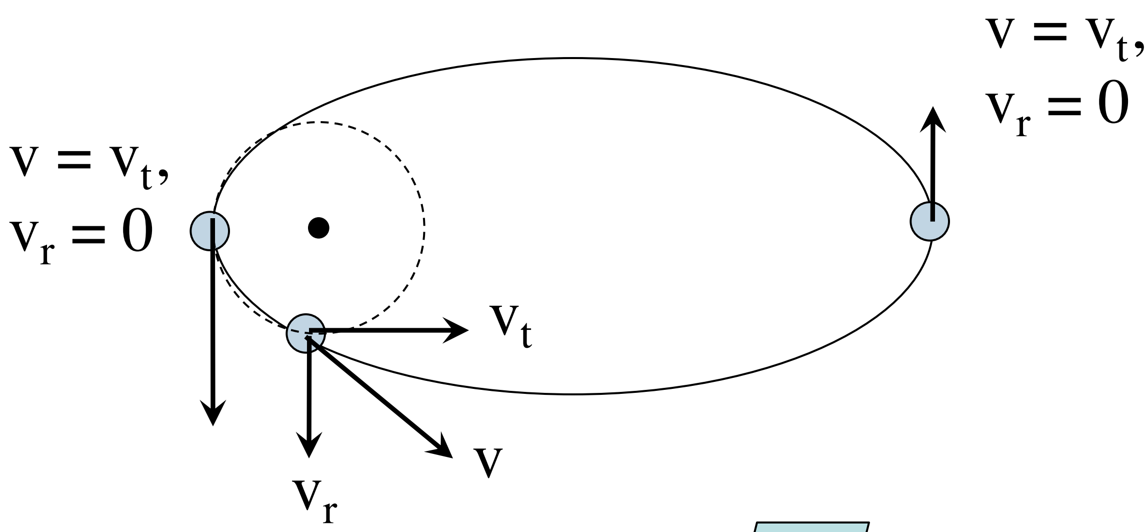
Unbound:
$E_{kin} > |E_{pot}|$

- Kepler's 1st law is a direct consequence

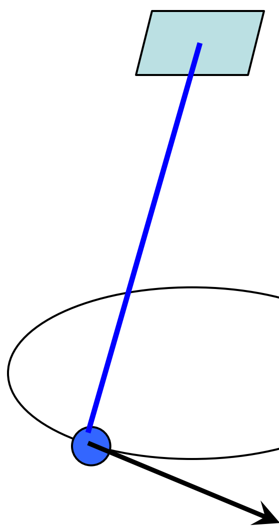
Why Ellipses?

A rigorous derivation (in polar coordinates) is a bit tedious, but we can have a simple intuitive hint:

Decompose the total velocity v into the radial (v_r) and tangential (v_t) components

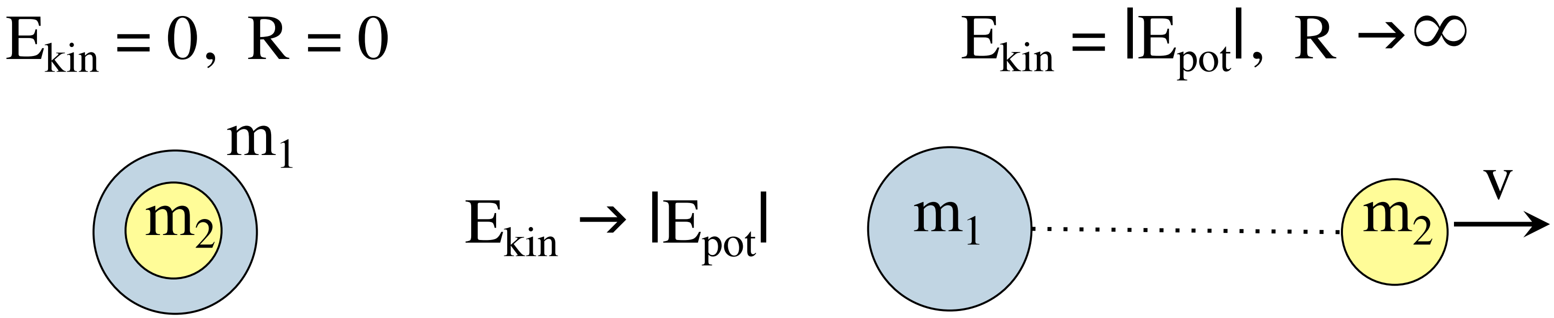


Consider the total motion as a synchronous combination of a radial and circular harmonic oscillator (recall that the period does not depend on the amplitude)



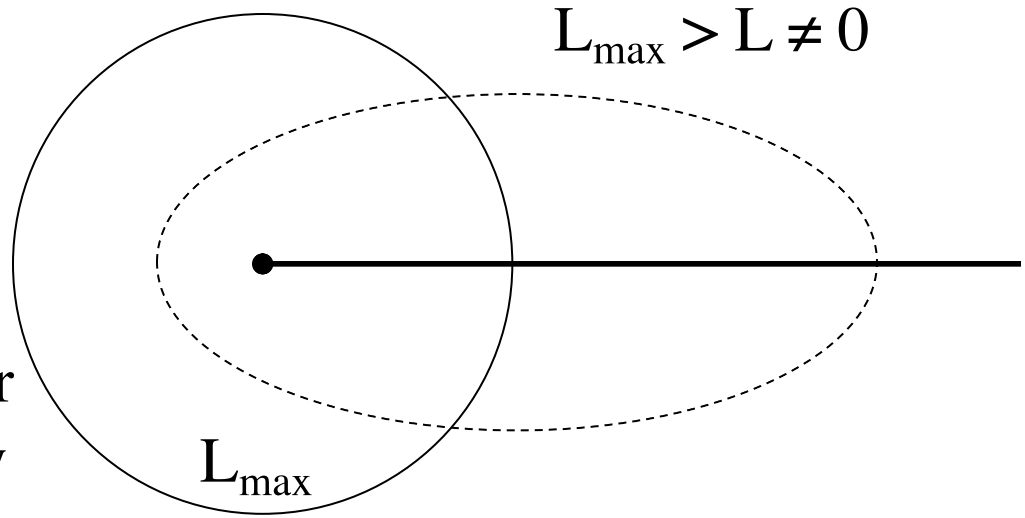
Orbit Sizes and Shapes

- For bound (elliptical) orbits, the *size* (semimajor axis) depends on the total energy:



- The *shape* (eccentricity) of the orbit depends on the angular momentum:

Circular orbit: maximum angular momentum for a given energy



Radial orbit: zero angular momentum

$L = 0$

Kepler's 2nd Law: A quick and simple derivation

Angular momentum, at any time: $L = M_{pl}\, V\, r = const.$

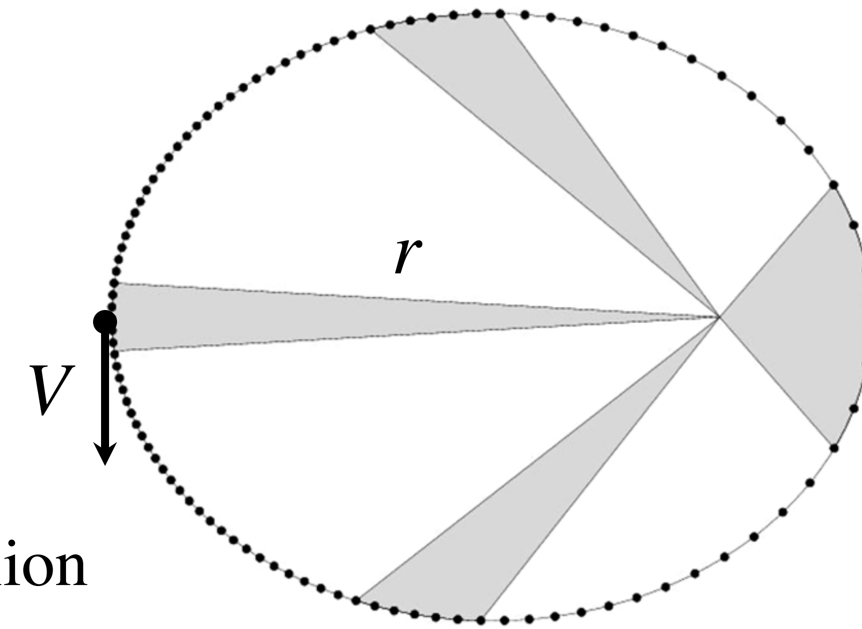
Thus: $V\, r = const.$ (this is also an "adiabatic invariant")

Element of area swept: $dA = V\, r\, dt$

Sectorial velocity: $dA/dt = V\, r = const.$

Independent of M_{pl} !

It is ***a consequence of the conservation of angular momentum.***



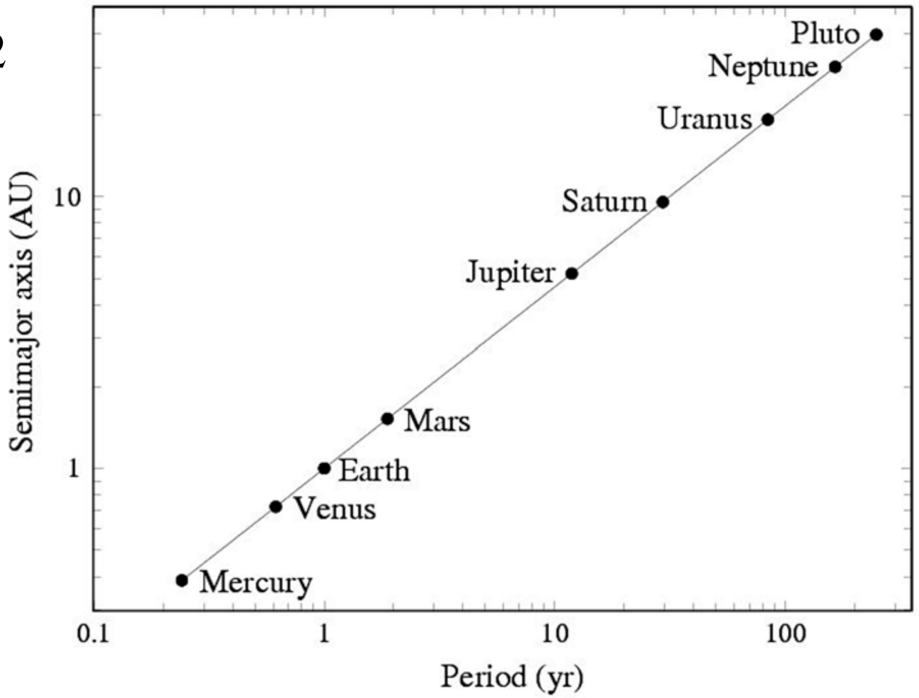
Planets move slower at the aphelion and faster at the perihelion

Kepler's 3rd Law: A quick and simple derivation

$F_{cp} = G\, M_{pl}\, M_{\odot} / (a_{pl} + a_{\odot})^2$

$\approx G\, M_{pl}\, M_{\odot} / a_{pl}^{\,2}$

(since $M_{pl} << M_{\odot}$, $a_{pl} >> a_{\odot}$)



$F_{cf} = M_{pl}\, V_{pl}^{\,2} / a_{pl}$

$= 4\, \pi^2\, M_{pl}\, a_{pl} / P^2$

(since $V_{pl} = 2\, \pi\, a_{pl} / P$)

$F_{cp} = F_{cf}$ ➞ $4\, \pi^2\, a_{pl}^{\,3} = G\, M_{\odot}\, P^2$ (independent of M_{pl} !)

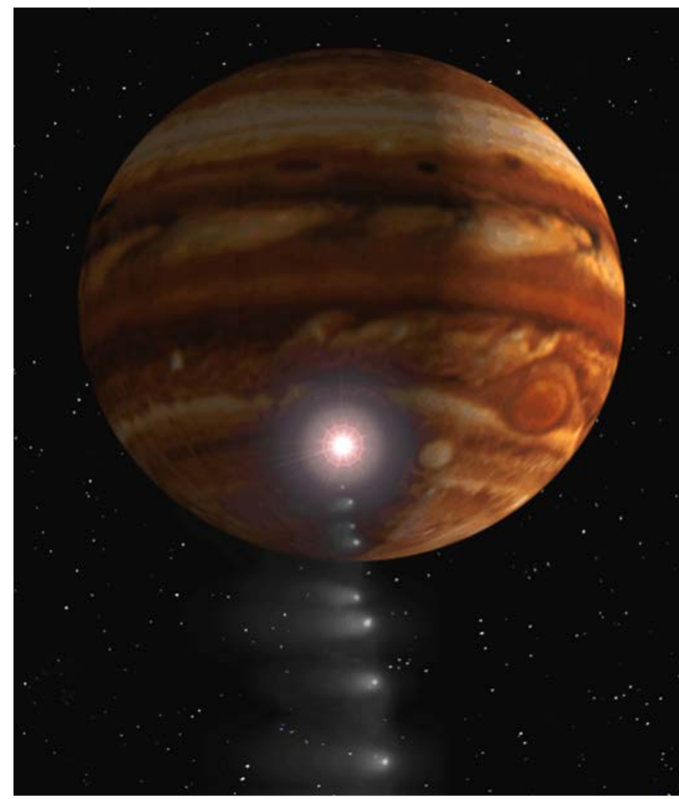
Another way: $E_{kin} = M_{pl} V_{pl}^{\,2} / 2 = E_{pot} \approx G\, M_{pl} M_{\odot} / a_{pl}$

Substitute for V_{pl}: $4\, \pi^2\, a_{pl}^{\,3} = G\, M_{\odot}\, P^2$

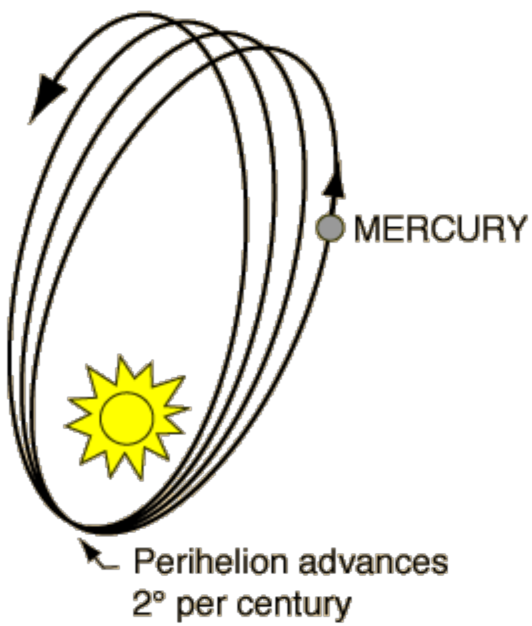
➞ It is ***a consequence of the conservation of energy***

It Is Actually A Bit More Complex …

- Kepler's laws are just an approximation: we are treating the whole system as a collection of isolated 2-body problems
- There are *no analytical solutions* for a general problem with > 2 bodies! But there is a good ***perturbation theory,*** which can produce very precise, but always approximate solutions
  - Discovery of Neptune (1846)
  - Comet impacts on Jupiter

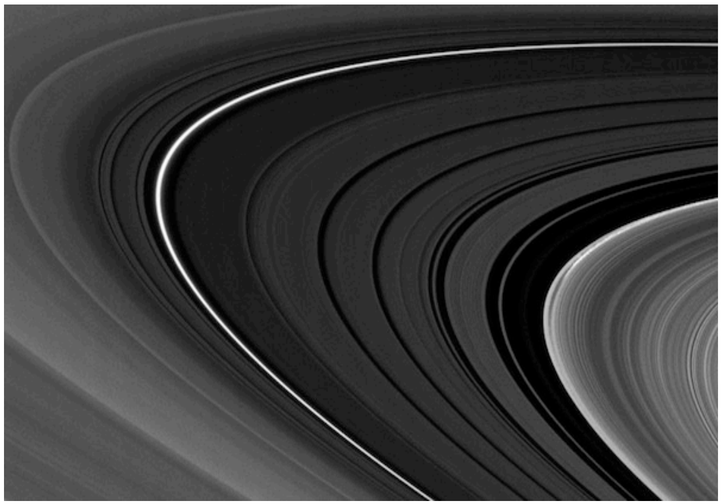


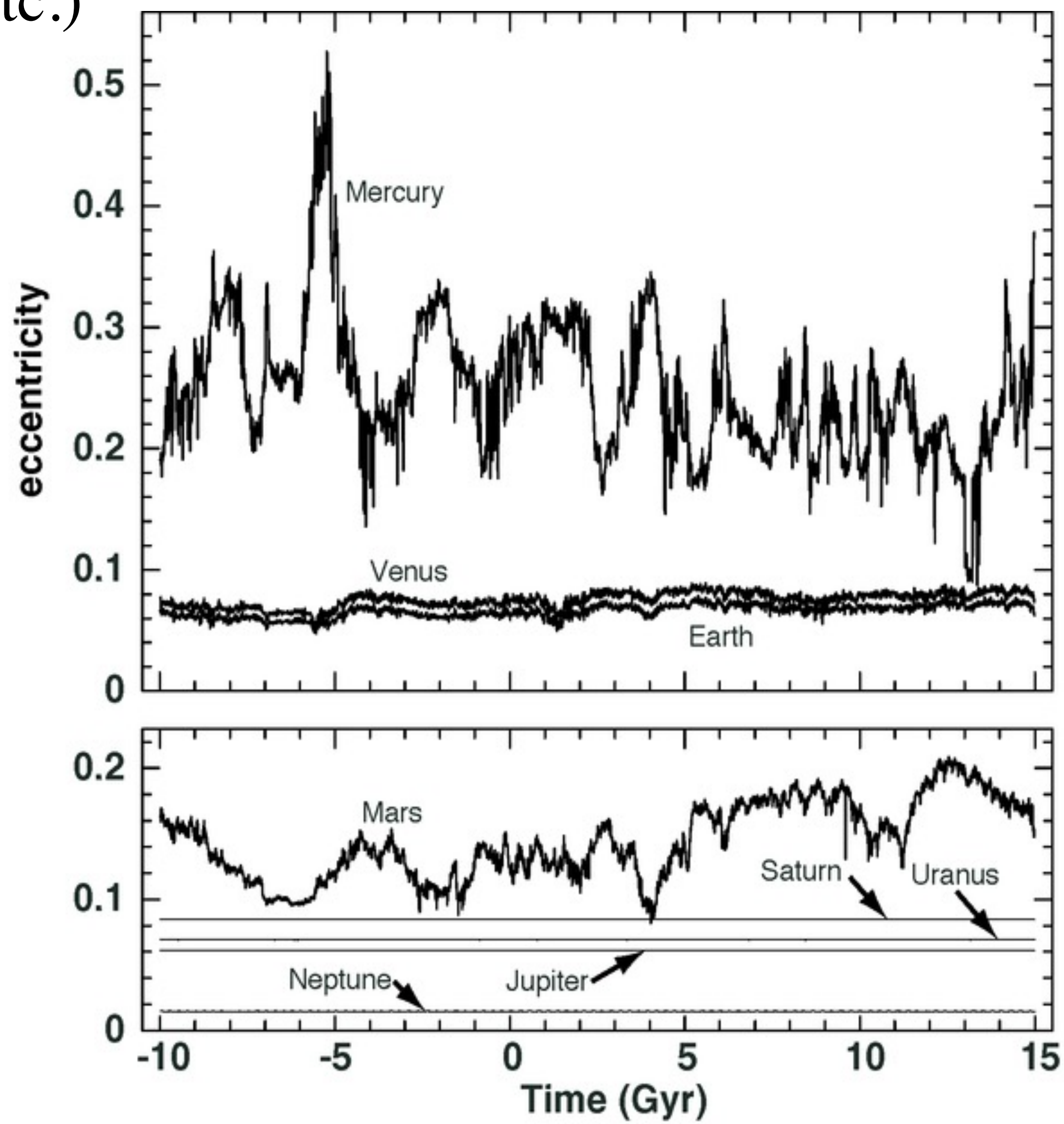
- Relativistic effects can be used to test theory of relativity (e.g., precession of Mercury's orbit



It Is Actually A *Lot* More Complex …

- Dynamical resonances can develop (rotation/revolution periods, asteroids; Kirkwood gaps; etc.)

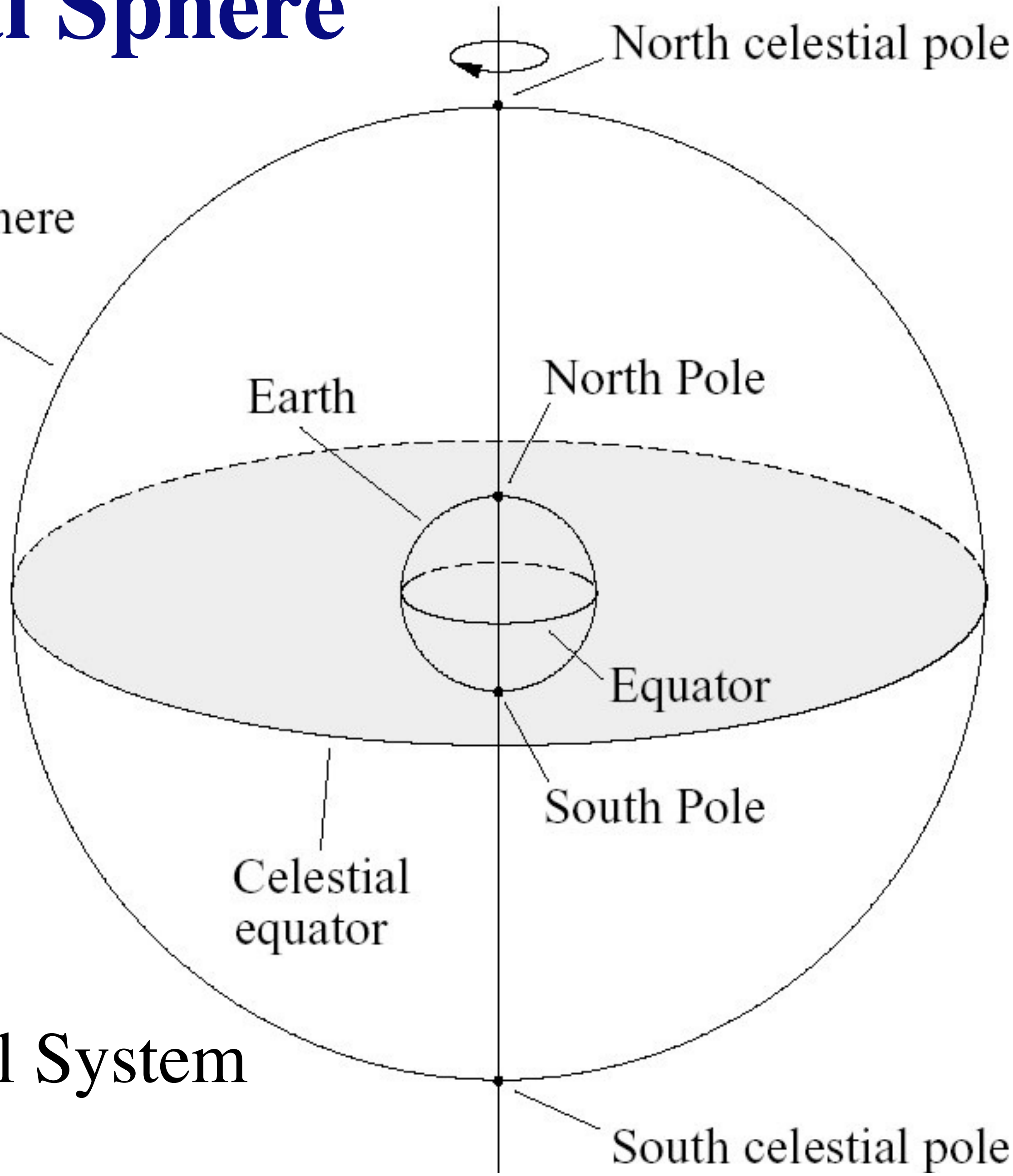




- If you wait long enough, more complex dynamics can occur, including dynamical chaos

(Is Solar System stable?)

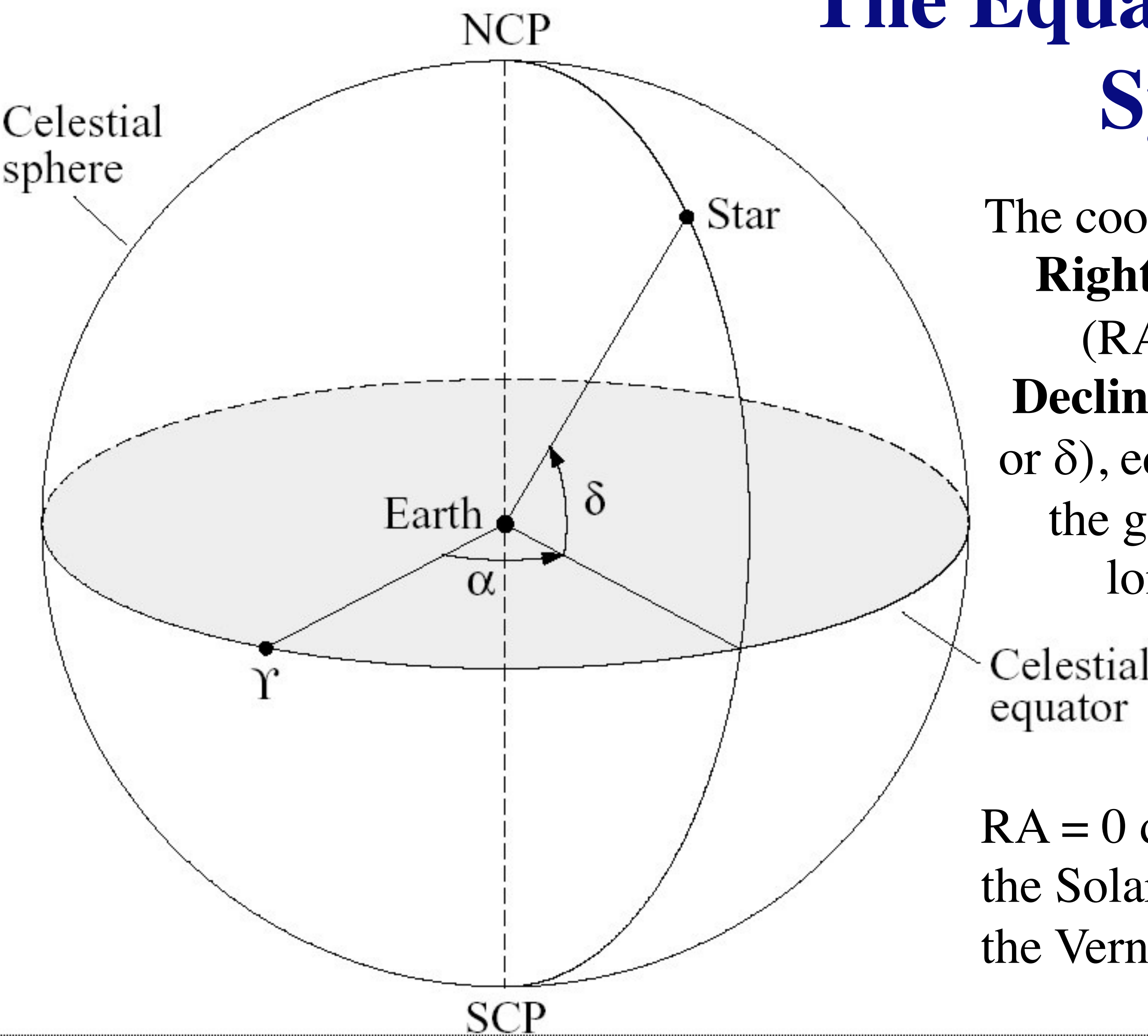
The Celestial Sphere



Think of it as an outward projection of the terrestrial long-lat coordinate system onto the sky

➙ the Equatorial System

The Equatorial System



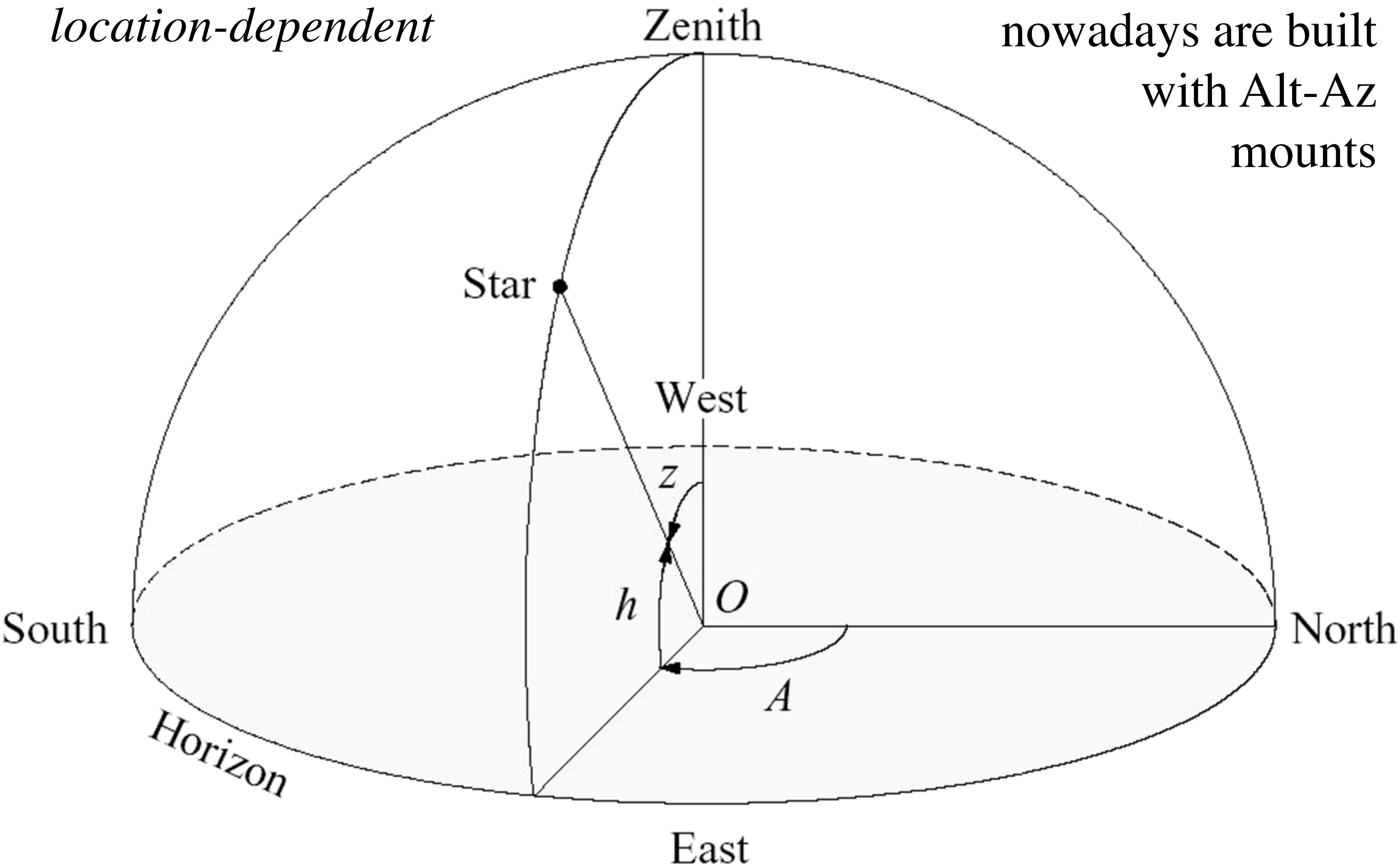
The coordinates are **Right Ascension** (RA, or α) and **Declination** (Dec, or δ), equivalent to the georgaphical longitude and latitude

RA = 0 defined by the Solar position at the Vernal Equinox

The Alt-Az Coordinate System

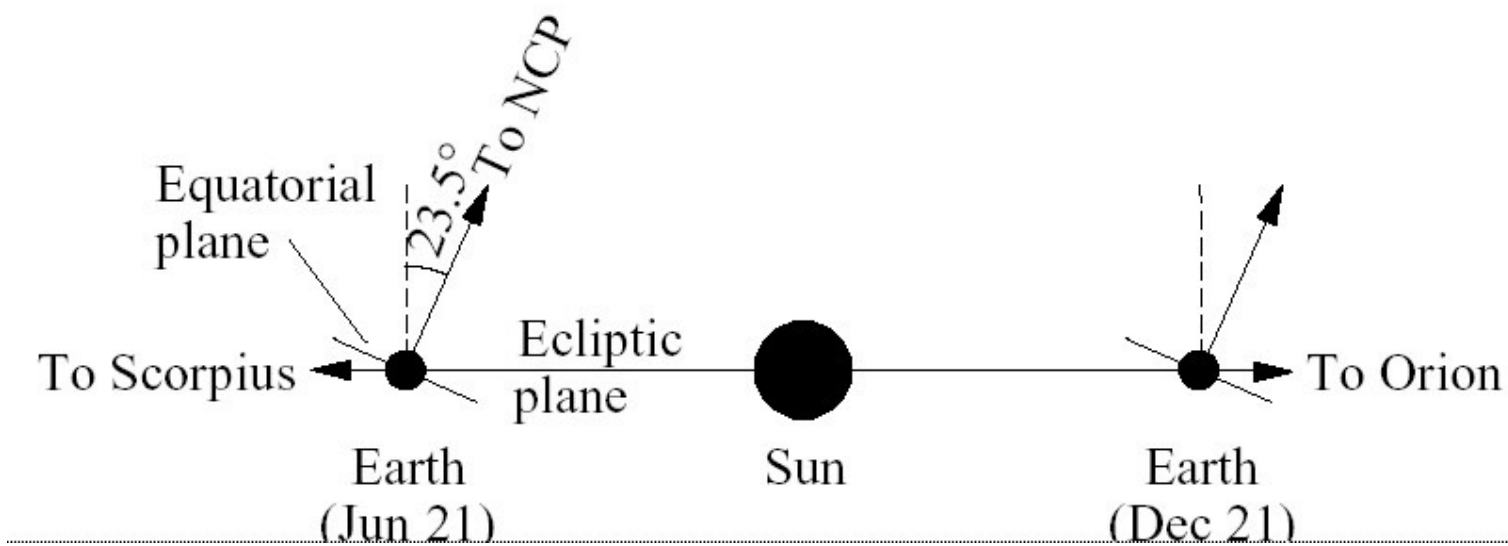
It is obviously *location-dependent*

Most telescopes nowadays are built with Alt-Az mounts



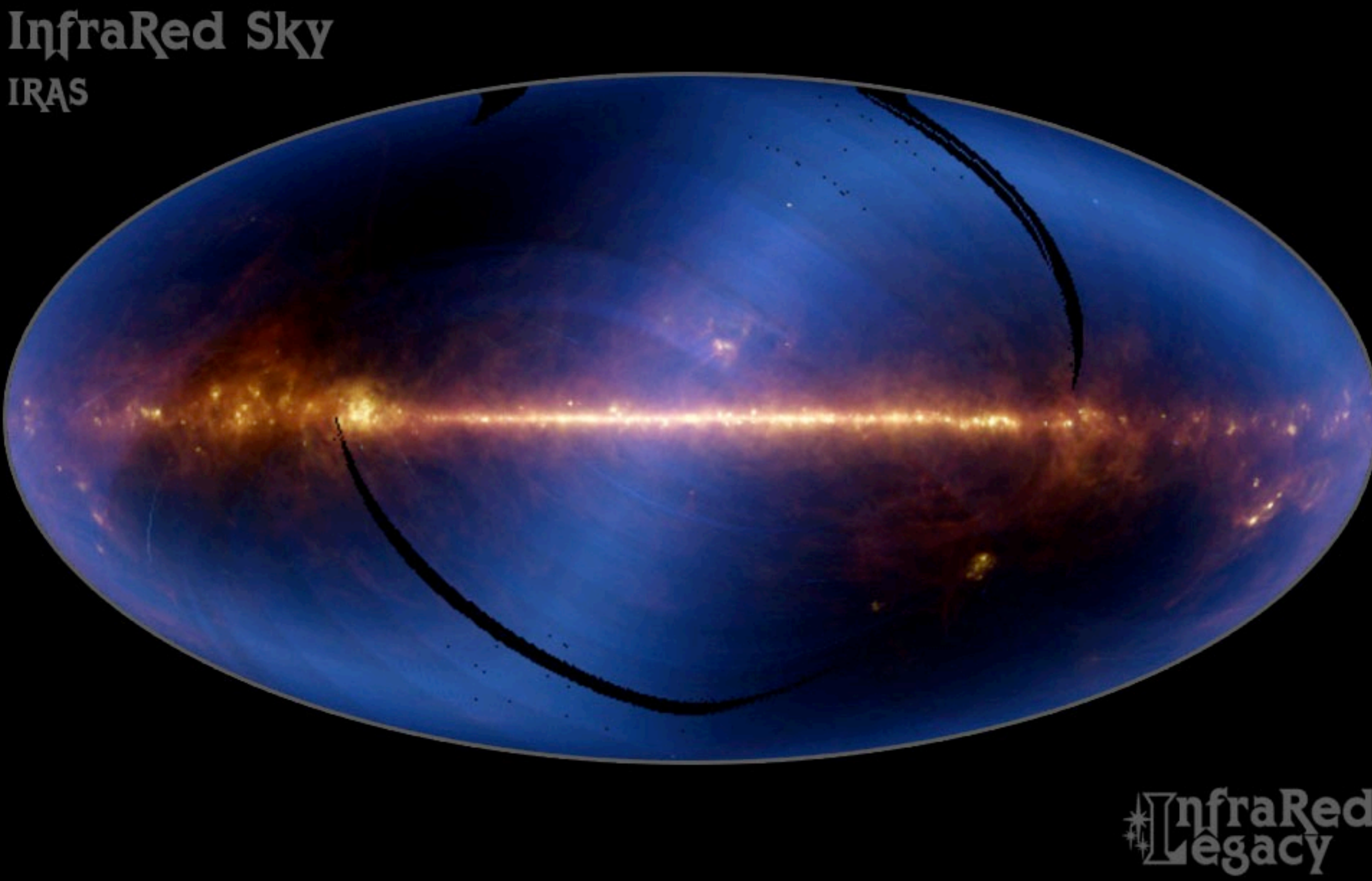
Other Common Cellestial Coordinate Systems

Ecliptic: projection of the Earth's orbit plane defines the Ecliptic Equator. Sun defines the longitude = 0.

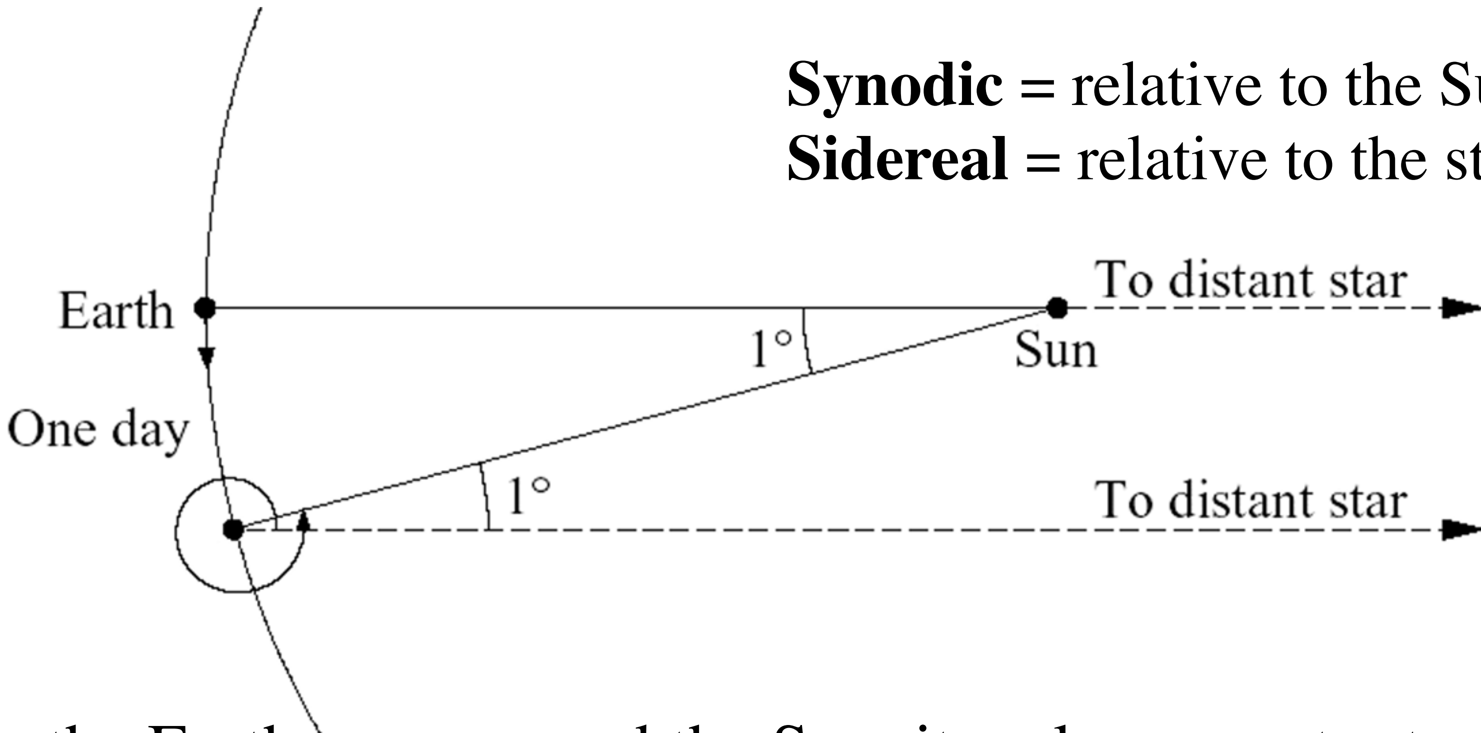


Galactic: projection of the mean Galactic plane is close to the agreed-upon Galactic Equator; longitude = 0 close, but not quite at the Galactic center. $(\alpha,\delta) \rightarrow (l,b)$

Ecliptic (Blue) and Galactic Plane (Red)



Synodic and Sidereal Times



Synodic = relative to the Sun
Sidereal = relative to the stars

As the Earth goes around the Sun, it makes an extra turn. Thus:

Synodic/tropical year = 365.25 (solar) days

Sidereal year = 366.25 sidereal days = 365.25 solar days

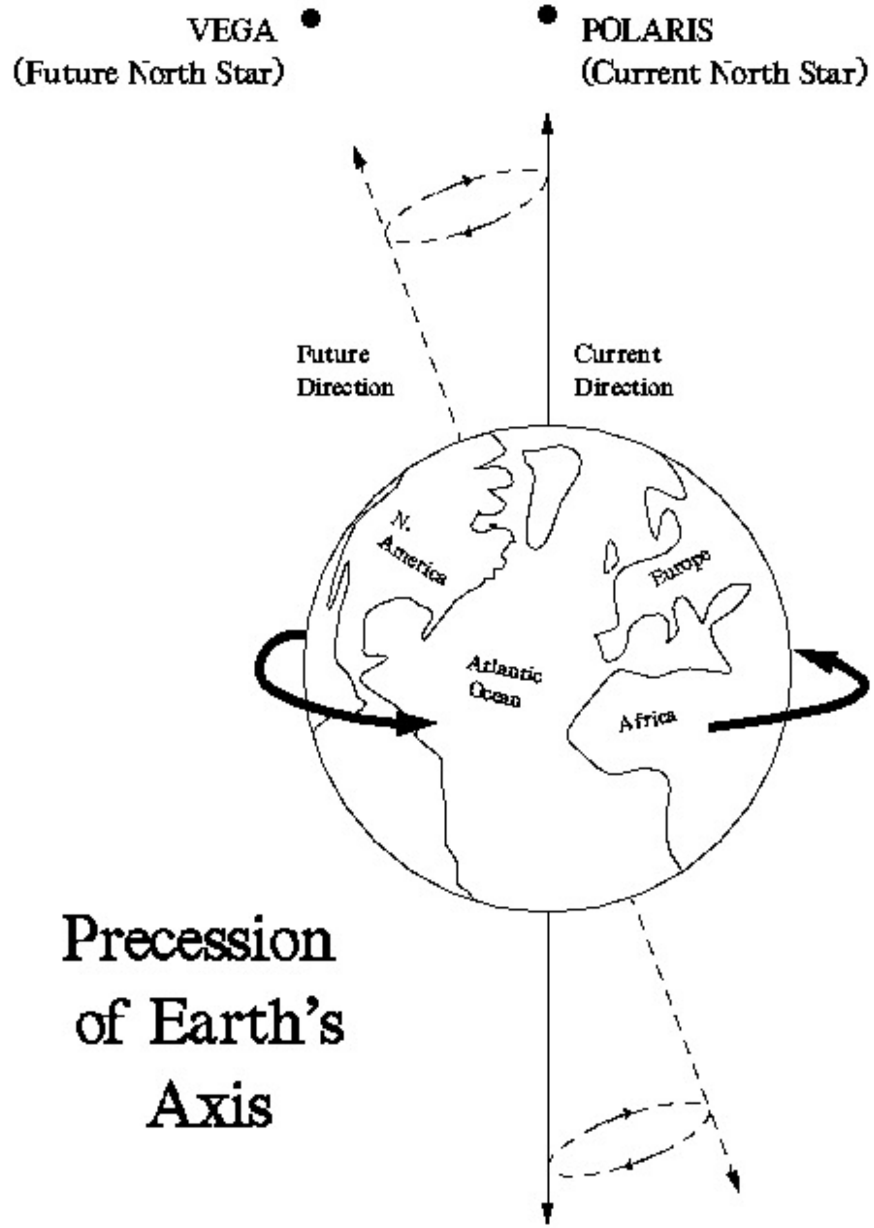
Universal time, UT = relative to the Sun, at Grenwich

Local Sidereal Time (LST) = relative to the celestial sphere

= RA now crossing the local meridian (to the South)

The Precession of the Equinoxes

- The Earth's rotation axis precesses with a period of ~ 26,000 yrs, caused by the tidal attraction of the Moon and Sun on the the Earth's equatorial bulge
- There is also *nutation* (wobbling of the Earth's rotation axis), with a period of ~ 19 yrs
- Coordinates are specified for a given **equinox** (e.g., B1950, J2000) and sometimes **epoch**

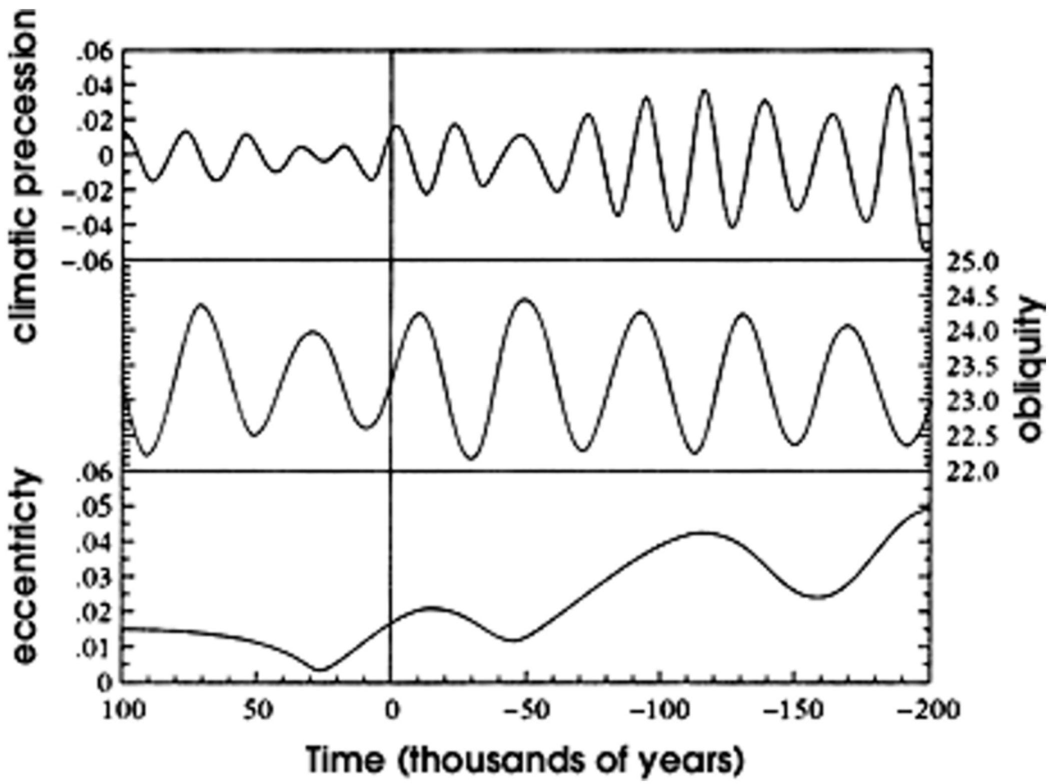


Earth’s Orbit, Rotation, and the Ice Ages

Milankovich Theory: cyclical variations in Earth-Sun geometry combine to produce variations in the amount of solar energy that reaches Earth, in particular the ice-forming regions:

1. Changes in obliquity (rotation axis tilt)
2. Orbit eccentricity
3. Precession

These variations correlate well with the ice ages!



Questions, please!

Theory

Reality?