Introduction to Cosmology

ASTR 434

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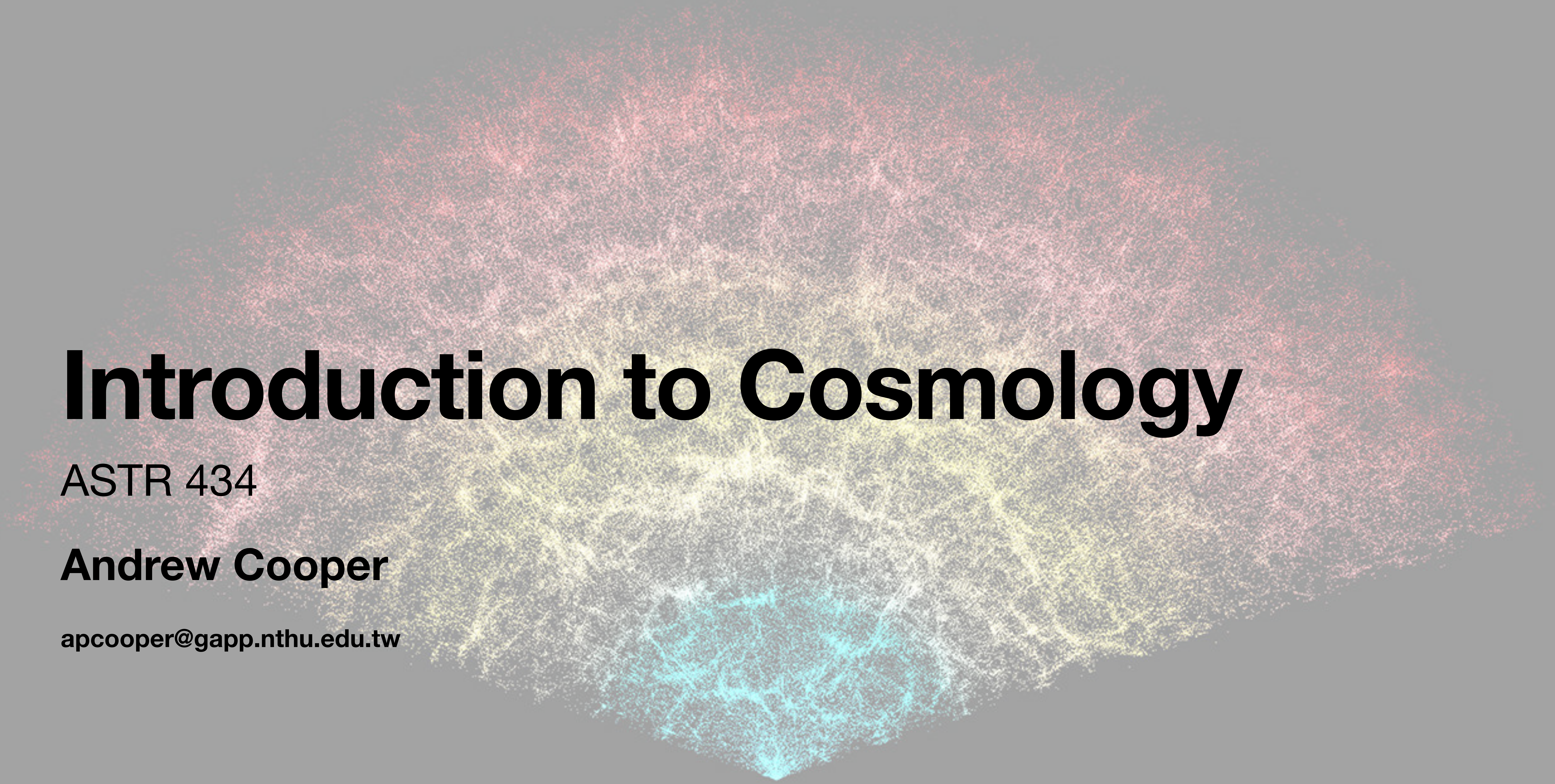
Lecture 1 / September 3rd 2024



DESI Collaboration/NOIRLab/NSF/AURA/R. Proctor

The aim of the course

By the end of the course, you should be able to tell a coherent, complete and accurate story about what kind of stuff there is in the Universe and what happened over the last 14 billion years.

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Credit: ESO


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Astrophysics and Cosmology

“Astrophysical Cosmology” deals with:

- The story of the origin, evolution and ultimate fate of the Universe;
- The application of fundamental physics to the Universe as a whole;
- The initial and boundary conditions for galaxy formation.

The basic idea

By comparing **observations** to **predictions** from **models** of the Universe, we have deduced (for example):

- The Universe has (effectively) infinite extent in space.
- The Universe has finite age (~14 billion years) and has changed over time.
    - *The Universe has 'expanded', in the sense that regions that used to be closer together are now further apart;*
    - *In the beginning, matter was distributed very smoothly; now it is much more 'lumpy';*
    - *In those lumps, galaxies form.*

Models of the Universe

In this course, we we will introduce the ideas behind cosmological models, what they predict, the data we have to test them, and what we have learned about the Universe over the last century.

Cosmological models are based on a very fundamental principle: the ‘laws of physics’ that we test with experiments in the lab are true everywhere and at all times.

Models of the Universe

When we're trying to model the whole Universe, we have to go back to basics.

What do we really want to predict?

What do we really mean by observables like "distance", "time", "mass" and "energy"?

The theory of General Relativity links these things together. It allow us to build models that describe how the universe changes based on assumptions about (or observations of) its contents.

Although GR is fundamental to the philosophy of modern cosmology, we will only use its *principles* in this course. The quantitative, mathematical machinery of GR is not required.

The story of modern cosmology is shockingly simple!

The ΛCDM Model

The current "best" (or "benchmark" or "consensus") model of cosmology is called ΛCDM, where Λ stands for "dark energy" and CDM stands for "cold dark matter".

ΛCDM has ~ 10 parameters (not many!), most of which have been measured to precision better than $10\,\%$. It has been extremely successful in explaining many different types of observations.

In this course, we will study the ingredients of the ΛCDM model.

ΛCDM is an "empirical" model: the ingredients are determined by what best explains what we observe, rather than starting from the Standard Model of particle physics and trying to work up to cosmic scales. We will think about what this means later.


THE EAGLE PROJECT

The goal

By the end of the course, you should be able to tell a coherent, complete and accurate story about what kind of stuff there is in the Universe and what happened over the last 14 billion years.

Another way to say this: you should be able to answer the question “where do galaxies come from?”

Course requirements

Basic astronomy knowledge: for example, “star”, “galaxy”. We’ll review some of the most important ideas in this lecture.

1st/2nd year physics:

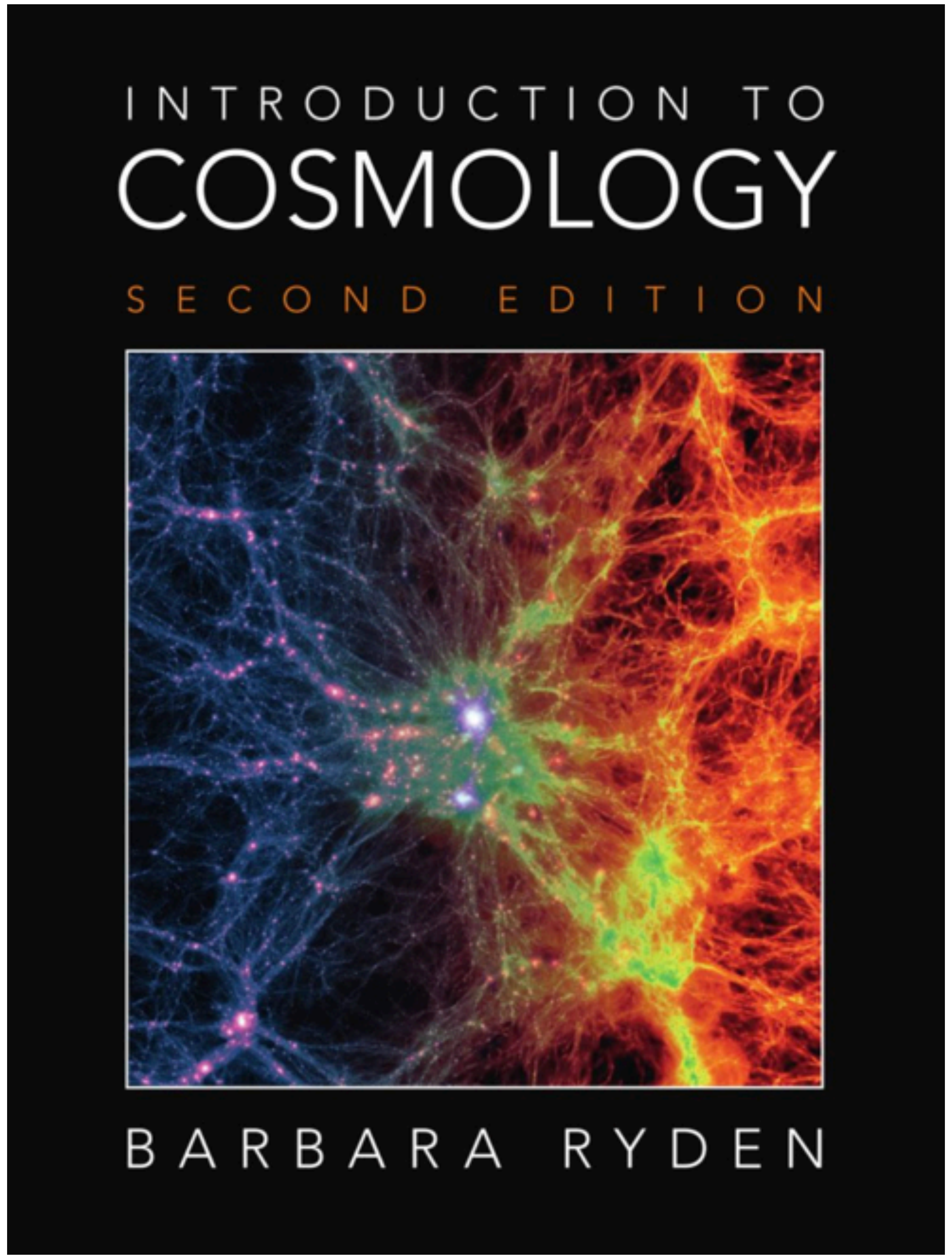
> *Newtonian mechanics; Newtonian gravity; concept of temperature; basic idea of the propagation of light signals; concept of special relativity (no detailed calculations); $E = mc^2$; basic idea of quantisation of energy in understanding the physics of interactions between atoms and photons; the Hydrogen atom.*

Fundamental mathematics for physicists:

> *Derivatives and integrals of simple functions, trigonometry, logarithms.*

Please ask me or the TA as soon as possible if you feel lost…

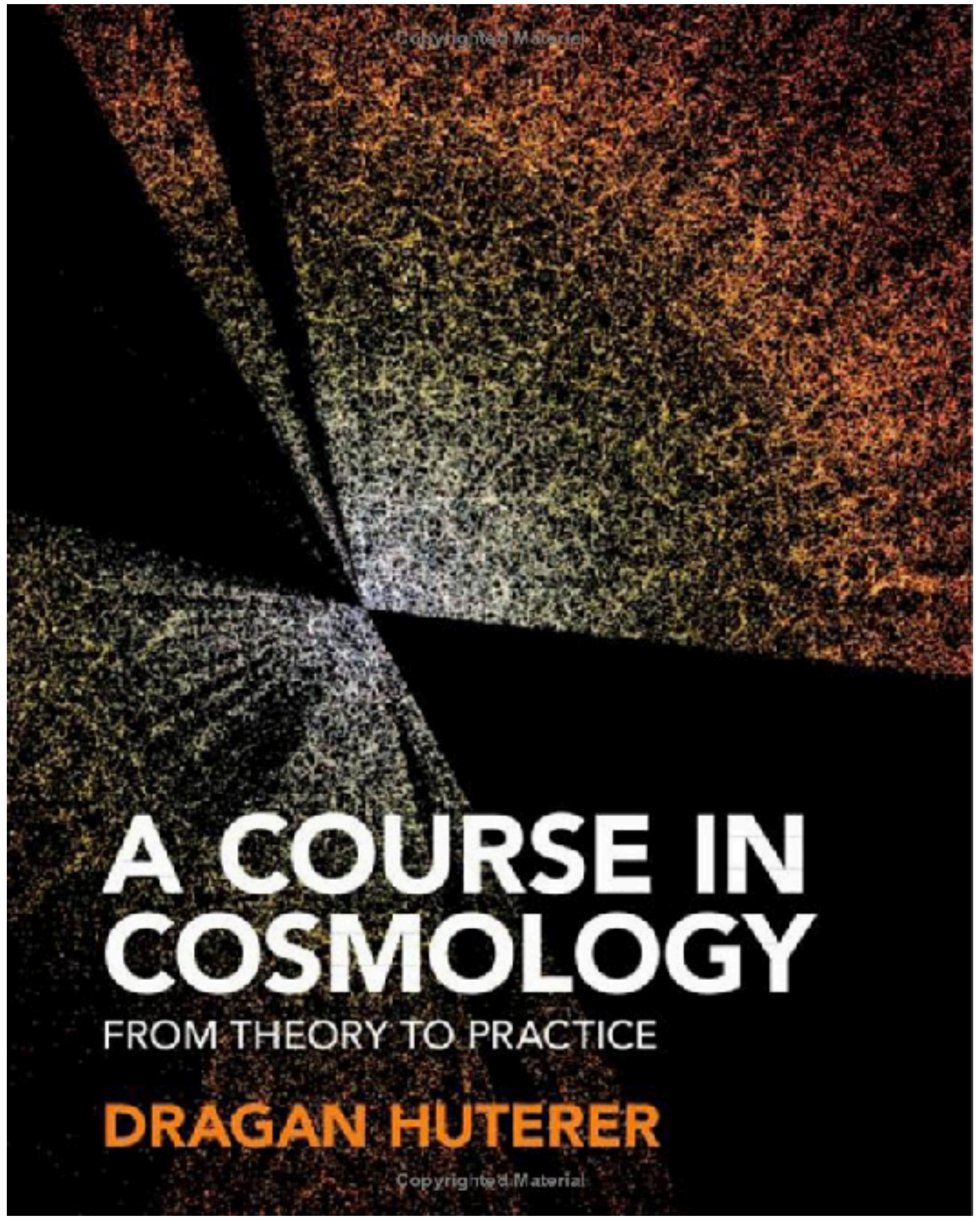
Textbooks



Ryden

Basic, classic.

US-style language and cultural references.



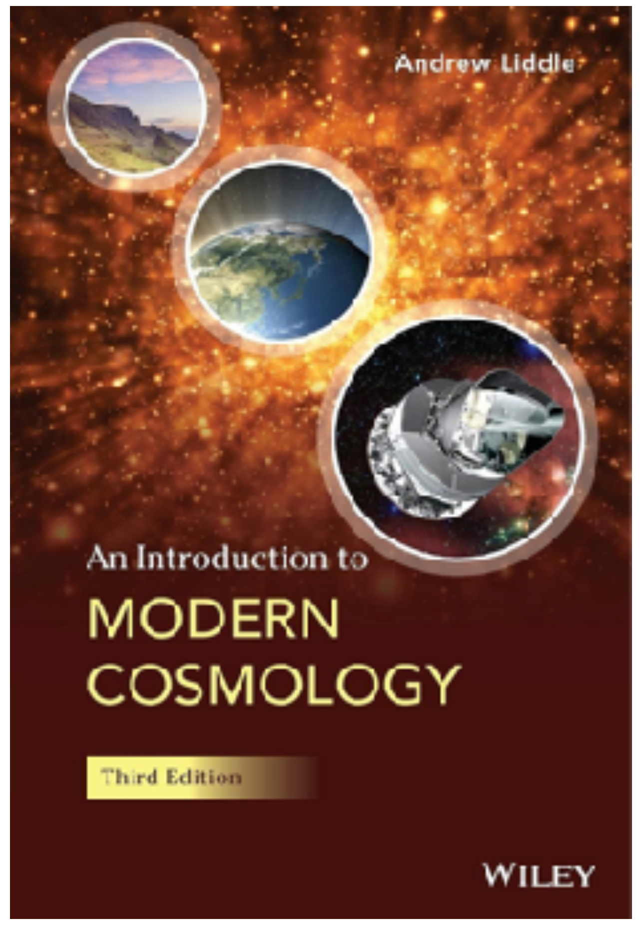
Huterer

More up-to-date; more in-depth material.

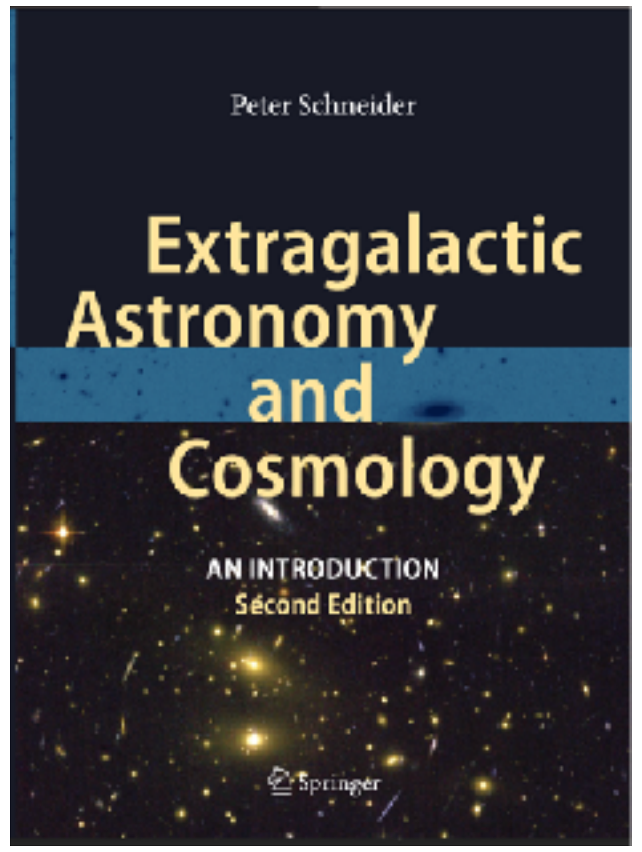
Computational problems!

Other books

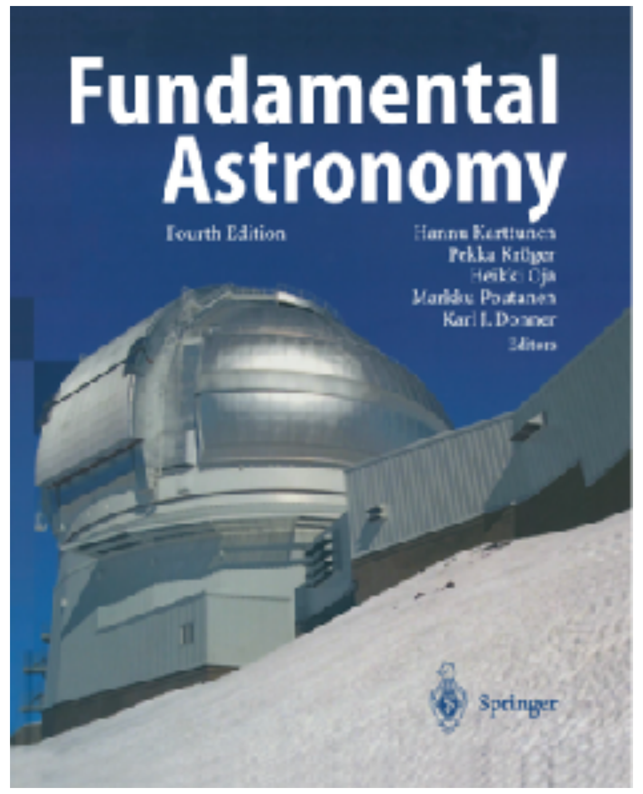
Andrew Liddle, *An Introduction to Modern Cosmology*, 3rd Edition (ISBN: 9781118502143)



Peter Schneider, *Extragalactic Astronomy and Cosmology*, 2nd Edition (ISBN: 9783642069710)



H. Karttunen et al., *Fundamental Astronomy*, 6th Edition (ISBN: 3662530449)



Graduate textbooks (not needed for this course):

John Peacock, *Cosmology* (https://doi.org/10.1017/CBO9780511804533)

James Peebles, *Principles of Physical Cosmology* (ISBN: 9780691209814)

Course plan

70% Homework, 30% Final

No midterm.

No lectures for the next two weeks!

An extra lecture or workshop class will be scheduled in October to make up for this.

Week	Class	Date	Day	Topic	Homework
1	1	03/09/2024	Tue	Introduction / measuring the universe	
2		10/09/2024	Tue	**NO CLASS (Andrew Away)**	
3		17/09/2024	Tue	**NO CLASS (Mid-Autumn)**	
4	2	24/09/2024	Tue	The expanding universe	**SET**
5	3	01/10/2024	Tue	Friedmann equations	**DUE**
6	4	08/10/2024	Tue	Friedmann models	
7	5	15/10/2024	Tue	Dark energy and dark matter	**SET**
8	6	22/10/2024	Tue	CMB	**DUE**
9	7	29/10/2024	Tue	CMB	
10	8	05/11/2024	Tue	Primordial nucleosynthesis	**SET**
11	9	12/11/2024	Tue	Cosmic inflation	**DUE**
12	10	19/11/2024	Tue	Structure formation	
13	11	26/11/2024	Tue	Structure formation	**SET**
14	12	03/12/2024	Tue	The galaxy-halo connection	**DUE**
15	13	10/12/2024	Tue	(Topic to be decided)	
16	14	17/12/2024	Tue	**Final Exam**	

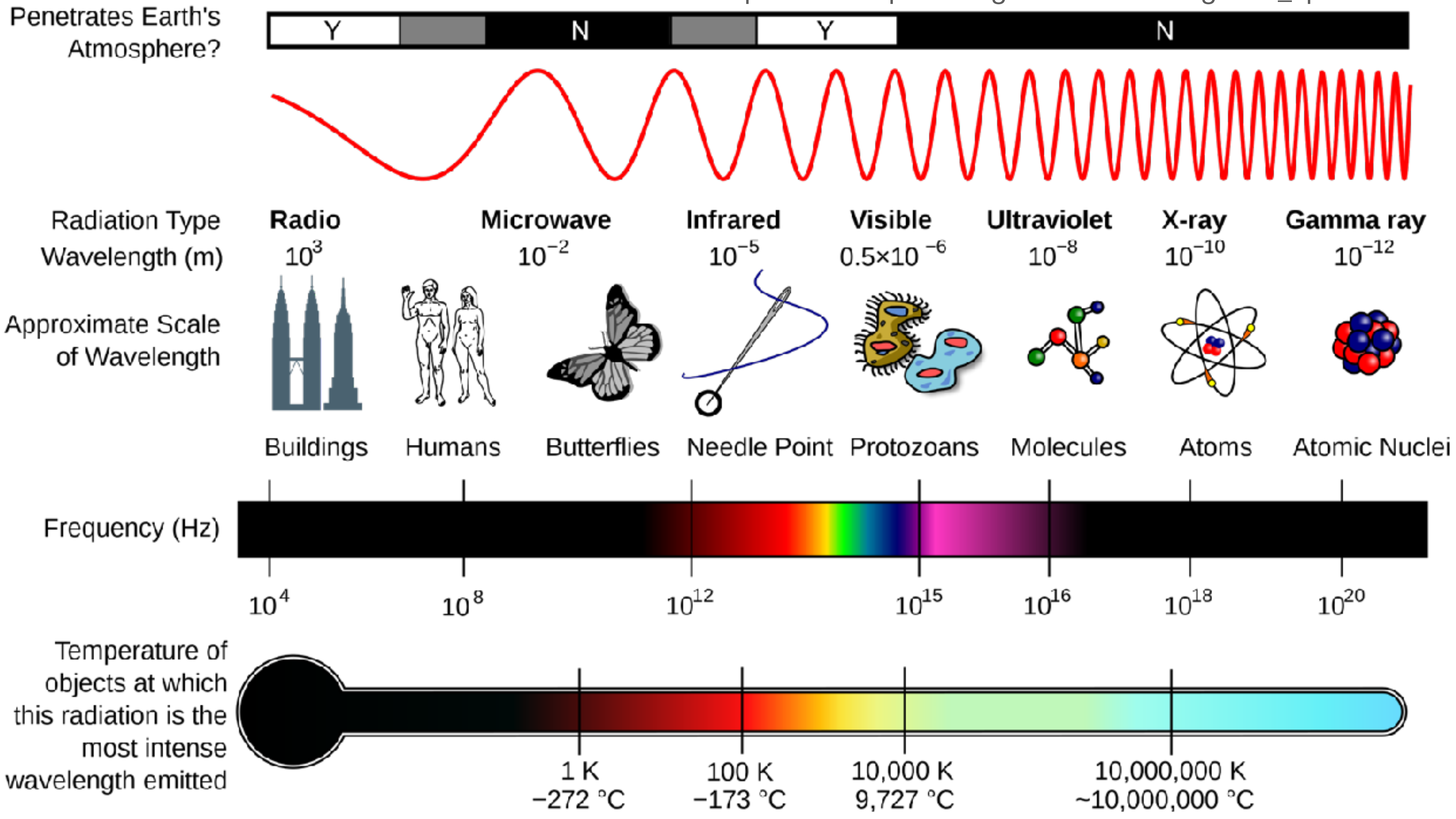
Measuring the Universe

As distance increases, a **ruler** appears smaller and a **lightbulb** appears dimmer.

Electromagnetic waves

Most of our information about the universe comes from electromagnetic waves, i.e. **light signals** of various wavelengths:

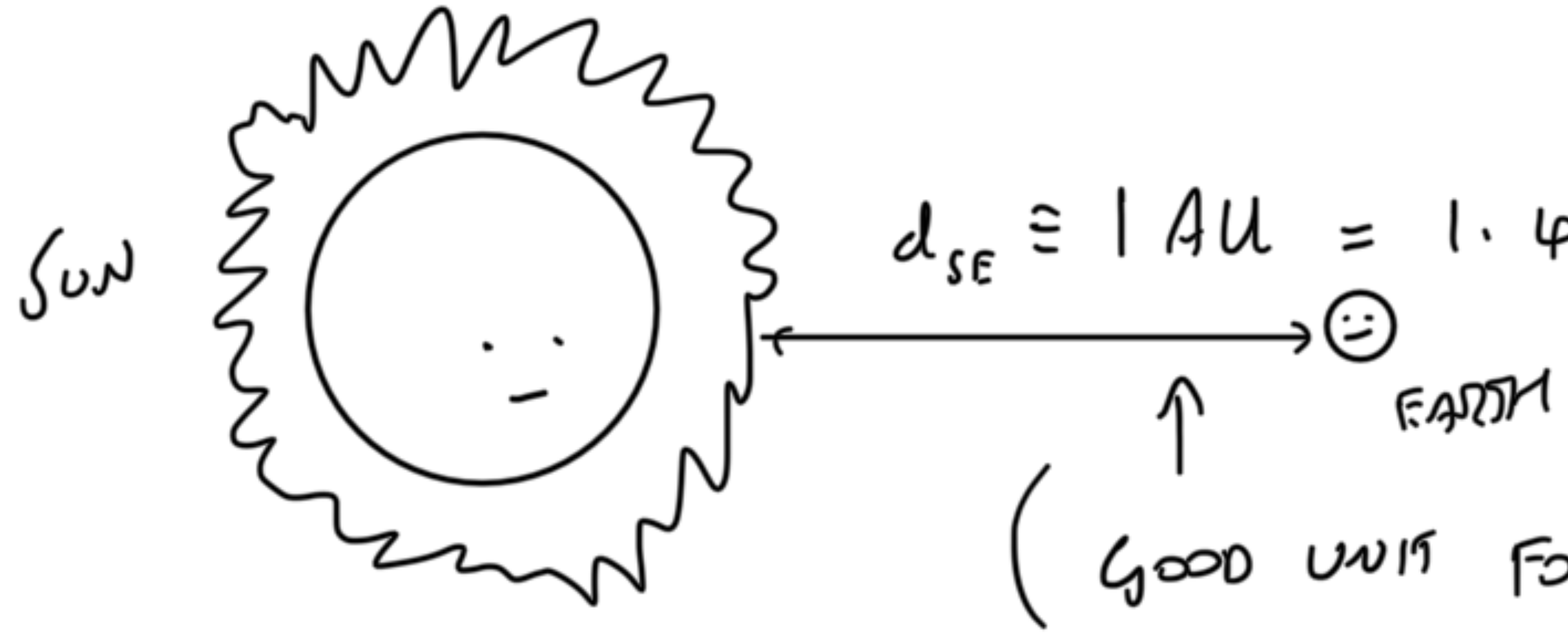
https://en.wikipedia.org/wiki/Electromagnetic_spectrum



Finite speed of light

LIGHT PROPAGATES AT SPEED $c \simeq 3 \times 10^{8}\ \mathrm{m\,s^{-1}}$

Note the "scientific" ("exponential") notation for big numbers…



$d_{SE} \cong 1\,\mathrm{AU} = 1.496 \times 10^{8}\ \mathrm{km}$

(GOOD UNIT FOR SOLAR SYSTEM DISTANCES!)

SO THE TIME FOR LIGHT TO GET FROM S. TO E. IS

$$t = \frac{\text{DISTANCE}}{\text{SPEED}} = \frac{(1.496 \times 10^{8})(10^{3}\ \mathrm{m/km})}{3 \times 10^{8}} \sim \frac{1.5}{3} \times 10^{3}\ \mathrm{s}$$

$$\simeq 5 \times 10^{2}\ \mathrm{s} \simeq 500\ \mathrm{s} \simeq \underline{8\ \text{MINUTES}}$$

Light travel time

The light we collect from the Sun tells us what the Sun looked like **8 minutes in the past**.

In the solar system, we can measure distances with **radar**: $d = ct$ (where t in this case is the time for the light to return from the source — half the time we have to wait after sending the radar signal out!).

No physical signal can travel faster than the speed of light.

Light arriving at our detector "now" after travelling a distance d from the source tells us about the time $t = d/c$ in the past.

We can write distances in terms of the light travel time, i.e. $d_{SE} = (c \times t) \sim 500$ "light seconds".

(where $c = 1$ "light second per second")

Light Years — not a good unit!

$$1 \text{ LIGHT YEAR} = 3 \times 10^8 \, ms^{-1} \times 31,557,600 \, s \simeq 9.461 \times 10^{15} \, m$$
$$\simeq 63\,241 \text{ AU}$$

THE DISTANCE TO THE NEXT NEAREST STAR IS ~ 4 LY.
(~ AVERAGE DISTANCE BETWEEN STARS IN GALAXY)

<u>ASTRONOMERS</u> <u>NEVER</u> <u>USE</u> <u>LIGHT</u> <u>YEARS</u> TO REPORT DISTANCES.

Parsecs

The preferred unit of distance in astronomy is the **parsec**, short for *parallax second of arc.*

"A transverse distance of 1 AU subtends an angle of 1 arcsecond at a distance of 1 pc"

1 degree = 3600 arcseconds.

n.b. there is no such word as "parsecond".

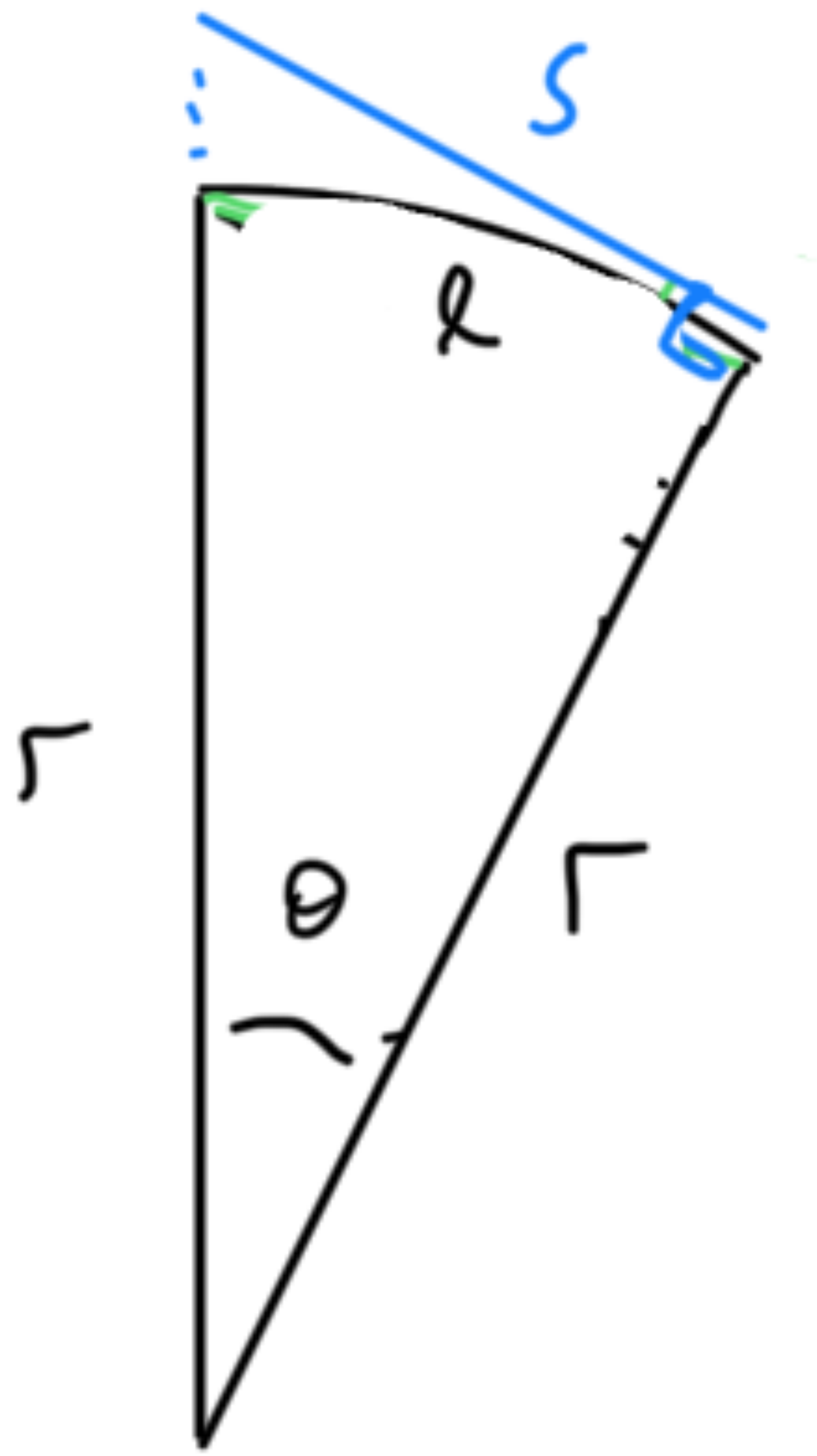
Angles on the sky

The sky looks like a dome — the *celestial sphere*. (A lot of ancient cosmologies were based on the idea that it really was some sort of spherical surface.)

Optically, it is the "surface" of all points that are at a distance of "infinity".

We measure distances (**separations**) on this imaginary sphere as *angles* (or if you like, *arc lengths*).

Angles on the sky



Arc length $l = r\theta$ (for θ in radians)

Small angle approximation: $\tan\theta \approx \sin\theta \approx \theta$

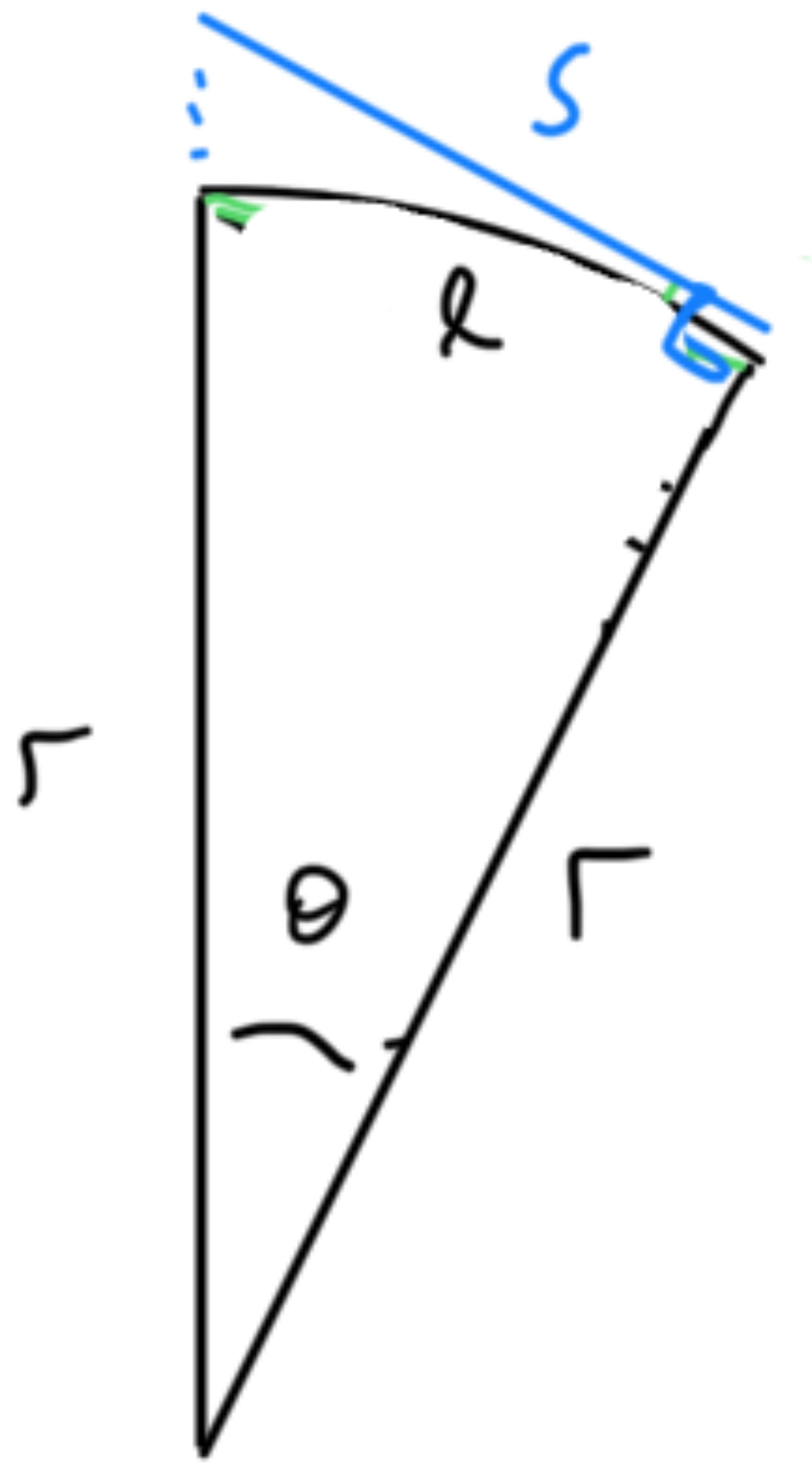
So $\theta \approx \dfrac{s}{r}$ and $l \to s$ as $\theta \to 0$.

In astronomy, most angles of interest are "small".

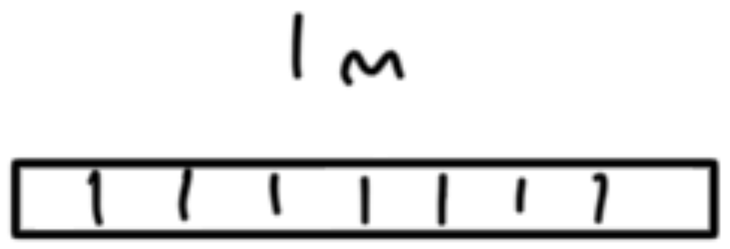
For some sense of scale, the angular diameter of the Moon is ~ 0.5 degrees.

We say "l **subtends** an angle θ" e.g. "the Moon ***subtends*** an angle of 0.5 degrees".

Angles on the sky



STANDARD RULER:



AT 100 m, SUBTENDS

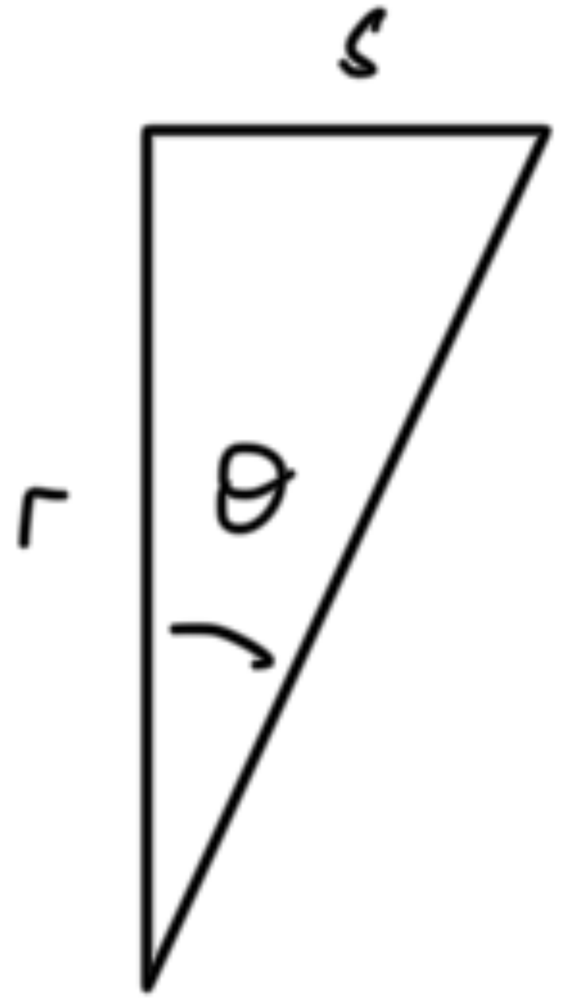
$\theta \sim \frac{1m}{100m} \sim 0.01$ rad

IN DEGREES: $0.573°$

AT 1000 m: $\theta \sim 0.001$ rad $\sim 5.73 \times 10^{-2}$ deg

AT 1 million m: $\theta \sim 1 \times 10^{-6}$ rad $\sim 5.73 \times 10^{-5}$ deg

Distances from angles



Know $\theta, r \Rightarrow s$
Know $\theta, s \Rightarrow r$

Distance can be determined from the angle subtended by a known length

(angular size of “standard ruler”)

As distance d increases, a fixed transverse length s appears smaller as $1/d$.

Area $\propto s^2$, so the area of an object appears smaller as $1/d^2$.

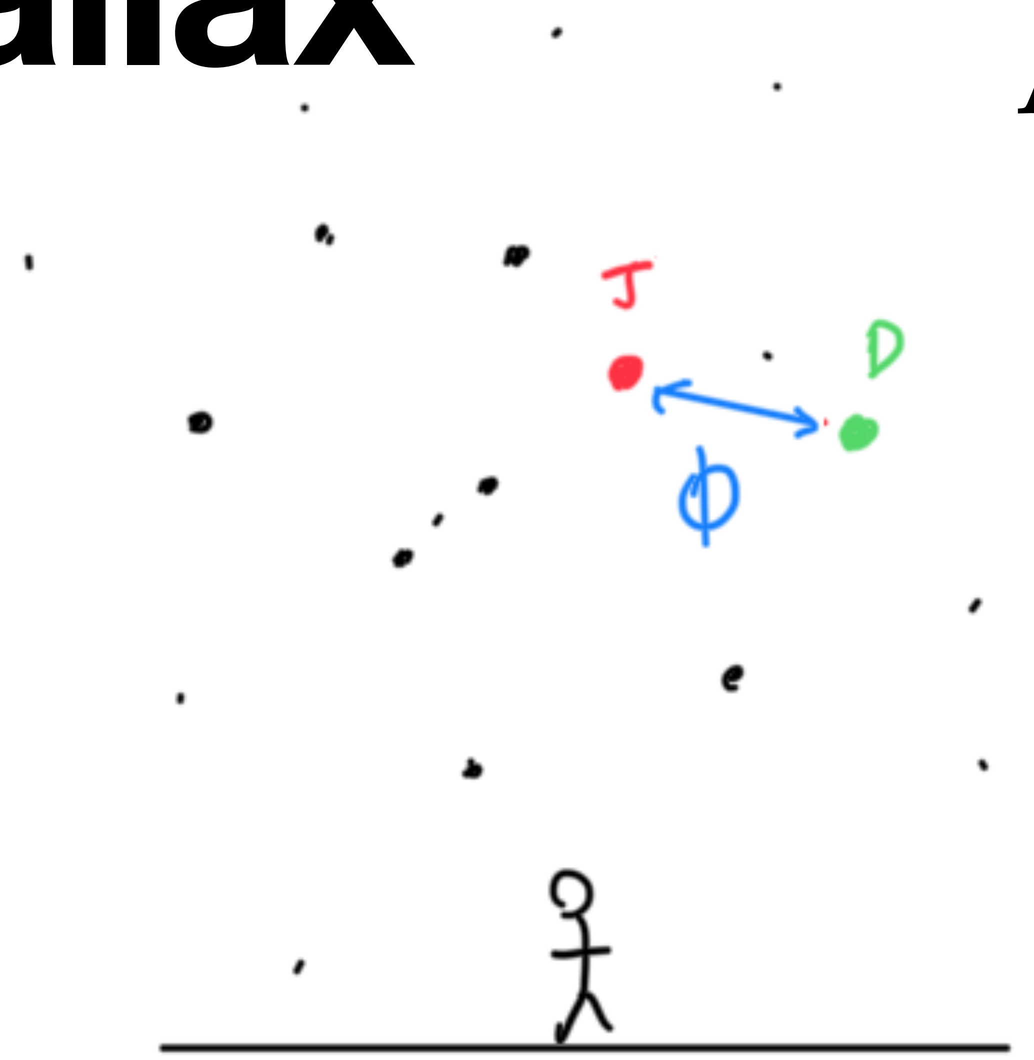
Parallax

Using this principle, we can measure distances even if we don’t know the true size of the object we’re looking at, provided it is **close enough**.

This is the method of **parallax**.

The trick is to observe the distant object from two different point on a **baseline** of known length.

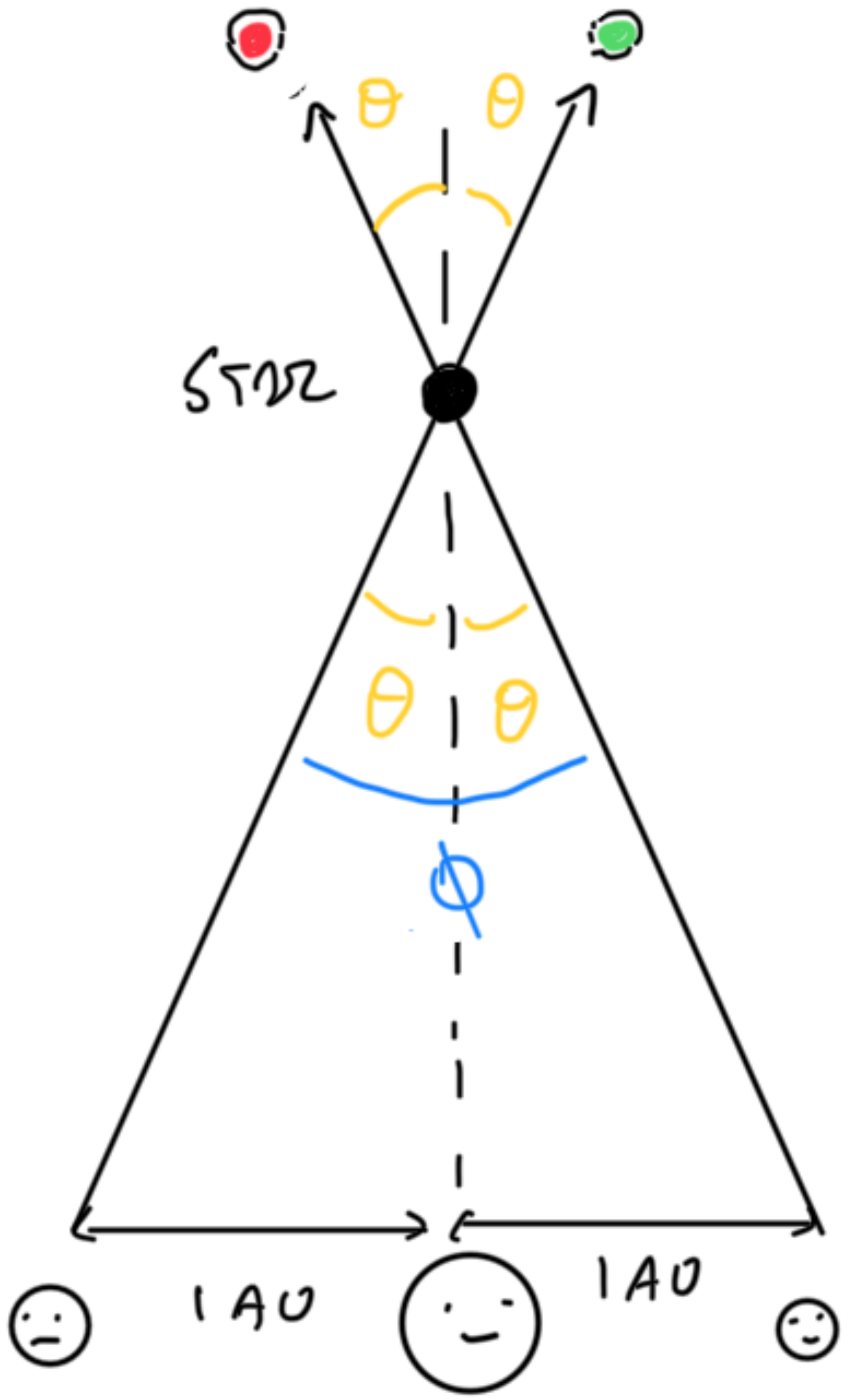
Parallax



(*Real parallaxes are very small!*)

Apparent position of star…

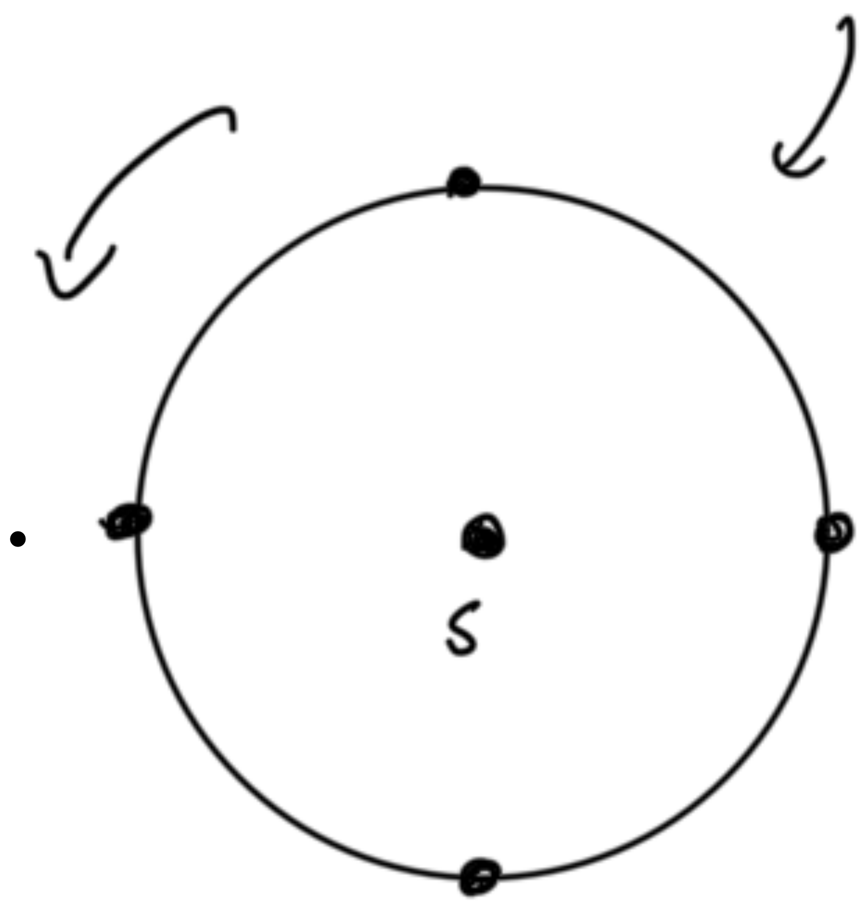
in June | in Dec.



December | *Sun* | June

Earth orbits the Sun…

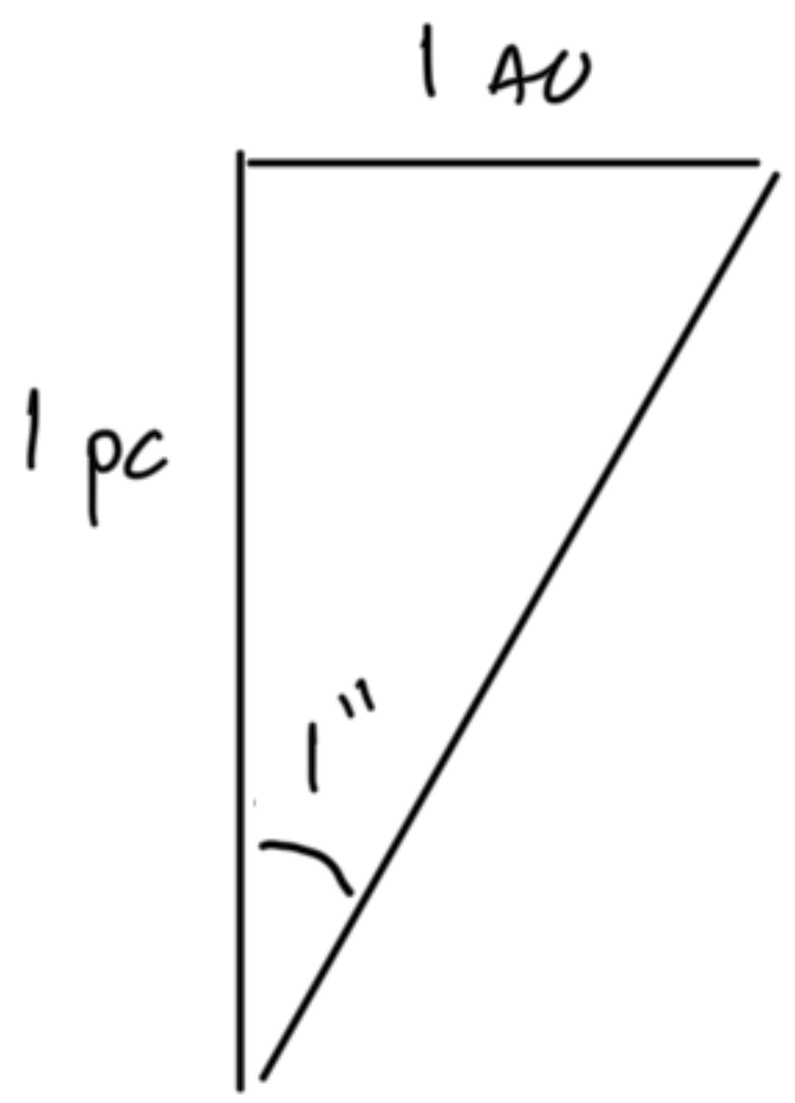
Dec. | June



Observe change in position of star (relative to others) over 6 months.

Parallax

MORE DISTANT STARS $\Rightarrow$ SMALLER PLX. <u>DEFINE</u> A UNIT OF DISTANCE CORRESPONDING TO $\theta = 1$ ARCSECOND (AS MEASURED ON OPPOSITE SIDES OF A CIRCLE, RADIUS 1 AU):



$$\Rightarrow \frac{1\ \mathrm{AU}}{1\ \mathrm{pc}} = \tan(1'') \sim \mathrm{rad}(1'')$$

$$\Rightarrow 1\ \mathrm{AU} \simeq 1.848 \times 10^{-6}\ \mathrm{pc}$$

$$\Rightarrow 1\ \mathrm{pc} \simeq 206{,}265\ \mathrm{AU}.$$

Cosmic distance scale

DISTANCE TO NEAREST STAR ~ 1.3 pc

" " CENTRE OF MILKY WAY: ~ 8000 pc = 8 Kpc

DIAMETER OF MILKY WAY ~ 20 Kpc

DISTANCE TO ANDROMEDA GALAXY ~ 800 Kpc (~ 1 Mpc)

DISTANCE TO VIRGO CLUSTER ~ 12 Mpc

DIAMETER OF "LOCAL GROUP" ~ 1.5 Mpc

TYPICAL SEPARATION BETWEEN GALAXIES ~ 1 Mpc

⇑

1 MEGAPARSEC IS A GOOD CHOICE OF DISTANCE UNIT FOR COSMOLOGISTS, BECAUSE THE BASIC "UNIT" OF COSMOLOGICAL OBSERVATION IS A GALAXY.

Cosmic distance scale

There are technical limits to how accurately we can measure differences between angular positions on the sky (and some fundamental limits, e.g. diffraction)

$\Longrightarrow$ Can't measure parallax distances for very far-away stars (or galaxies, even further away!)

If we have a long enough "standard ruler", we can measure distances from its angular size → see later.

Standard candles

WE CAN ALSO MEASURE DISTANCES USING <u>STANDARD</u> <u>CANDLES</u>:

LIGHT BULB EMITS ENERGY (E.M. RADIATION)
AT A RATE OF SO MANY $J\,s^{-1} \equiv W$.
$\Rightarrow$ <u>LUMINOSITY</u>

SUN EMITS $1\,L_{\odot} \simeq 3.83 \times 10^{26}\,W$

Flux and luminosity

IMAGINE A DISTANT STAR (POINT SOURCE, SIZE << DISTANCE)

THE STAR EMITS LIGHT IN ALL DIRECTIONS

$\Rightarrow$ AT DISTANCE d, ENERGY (i.e. LUMINOSITY) IS SPREAD OUT A SPHERE OF AREA $4\pi d^2$.

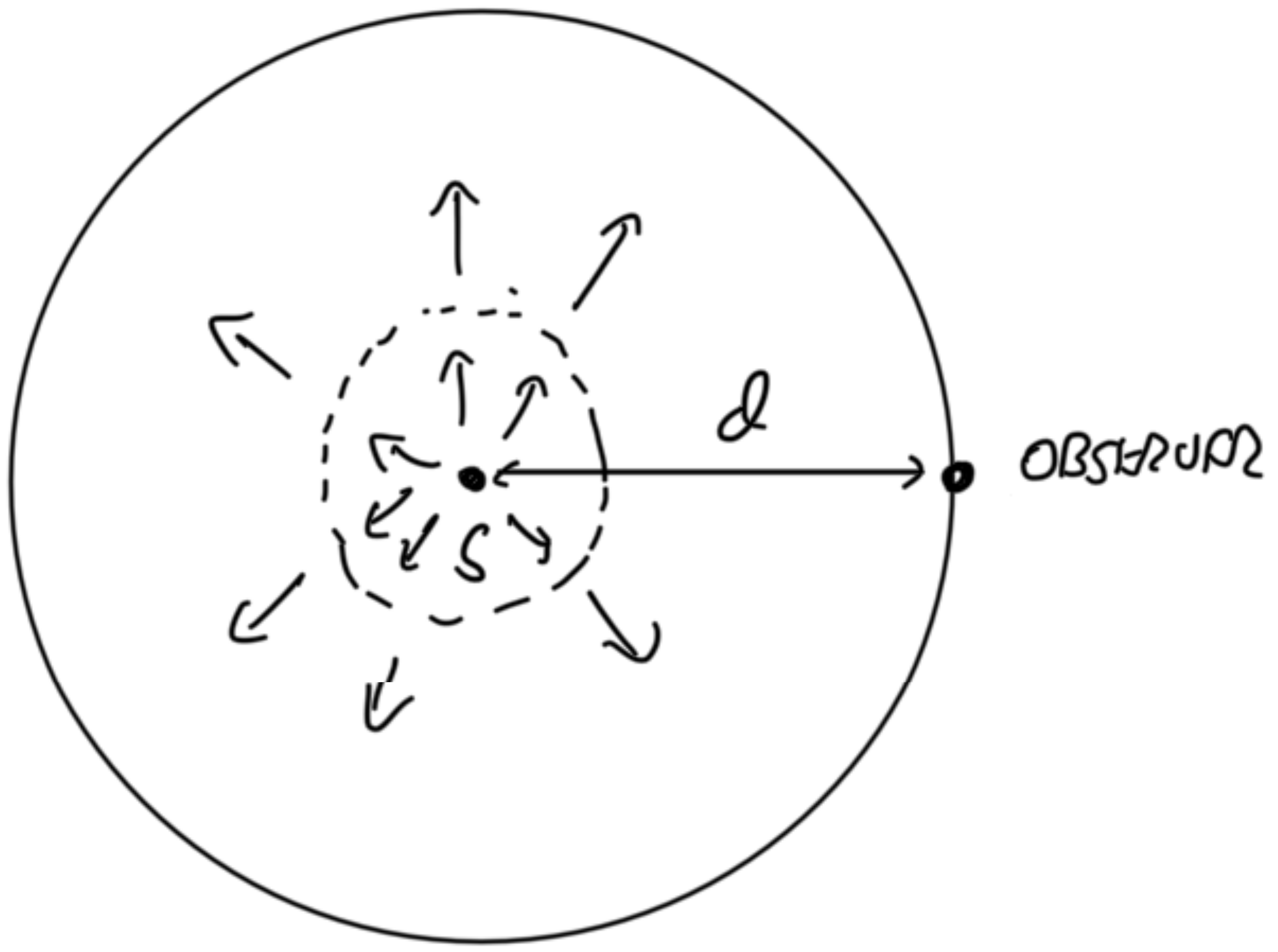
$\therefore$ LUMINOSITY RECEIVED PER UNIT AREA IS

$$f = \frac{\text{TOTAL LUMINOSITY}}{\text{SURFACE AREA}} = \frac{L}{4\pi d^2}$$

OUTPUT LUMINOSITY

FLUX ($W m^{-2}$)

DISTANCE TO SOURCE



Standard candles

$$F = \frac{L}{4\pi d^2}$$

Important point: lightbulbs look **fainter** when they're further away because the energy they emitted is then spread over a larger area.

Distant light sources appear fainter as $1/d^2$.

If we **know** the total luminosity of an object, we can **infer** its distance from its apparent brightness (i.e. from its flux, F):

$$d_L = \left(\frac{L}{4\pi F}\right)^{\frac{1}{2}}$$

Standard candles

$$F = \frac{L}{4\pi d^2}$$

It ***seems*** obvious that we should infer the same distance using the brightness of a standard candle and the length of a standard ruler, if they really are at the same **proper distance** from us. However, there is a deeper assumption behind that, which we will explore later.

Examples of standard candles in astronomy:

- *Brightest red giant stars in a galaxy;*
- *Maximum brightness of a Type 1a supernova*;*
- *Cepheid variable stars*;*

** These are not standard candles, rather **standardisable** candles. The don't all have the same luminosity, be we can use other measurements to deduce their true luminosity.*

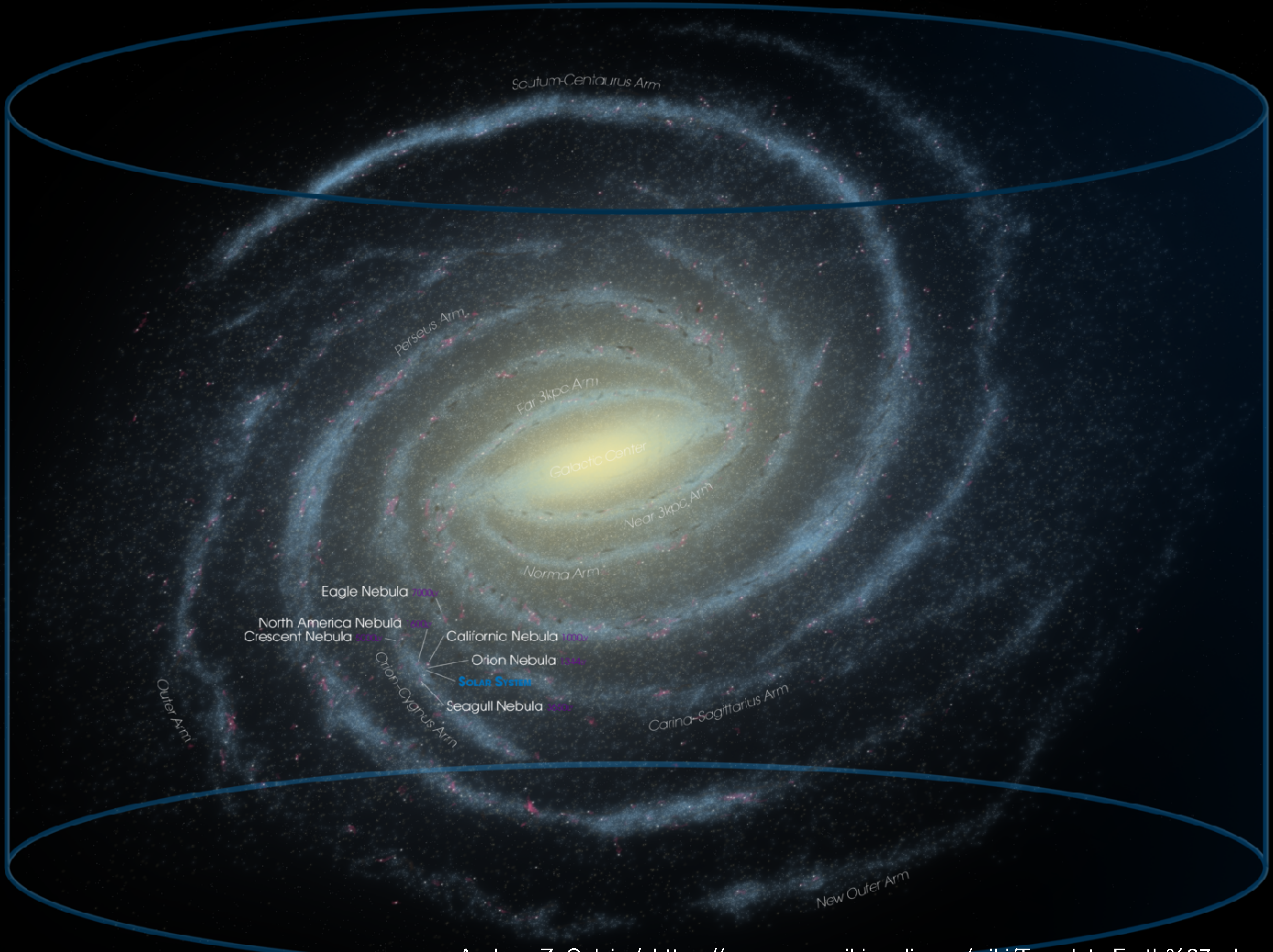
The distance ladder

- Solar system (e.g. the AU)…
  - Parallax distances to nearby stars…
    - Standard candle variables…
      - Supernovae (precise) and galaxy properties (imprecise)

With these measurements, we can start to tackle one of the big questions in cosmology: **how far away is everything?**

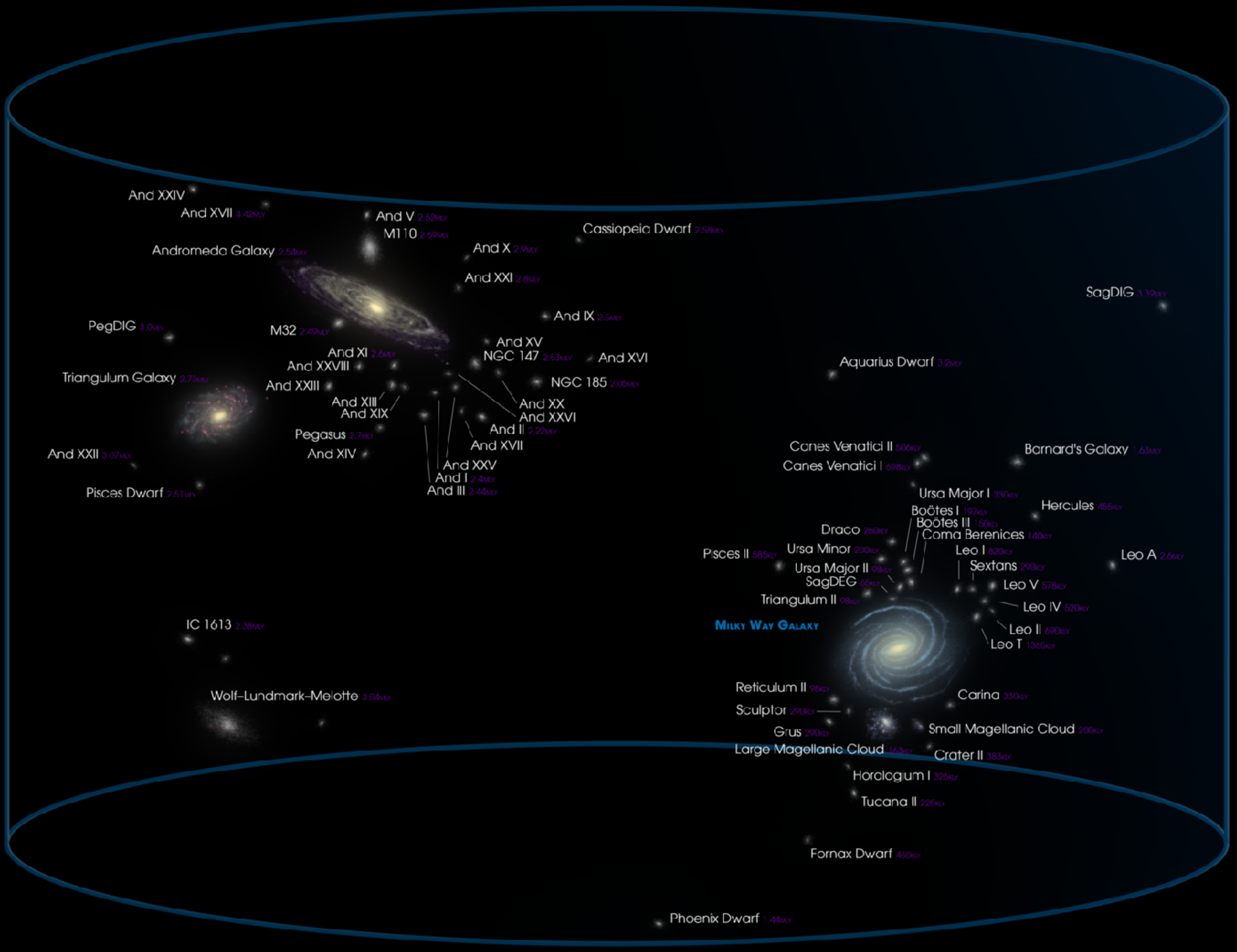
We can map out, in 3 dimensions, how **visible matter** (stars and gas) is distributed on megaparsec scales.

MILKY WAY GALAXY



Andrew Z. Colvin / https://commons.wikimedia.org/wiki/Template:Earth%27s_Location_in_The_Universe

LOCAL GROUP



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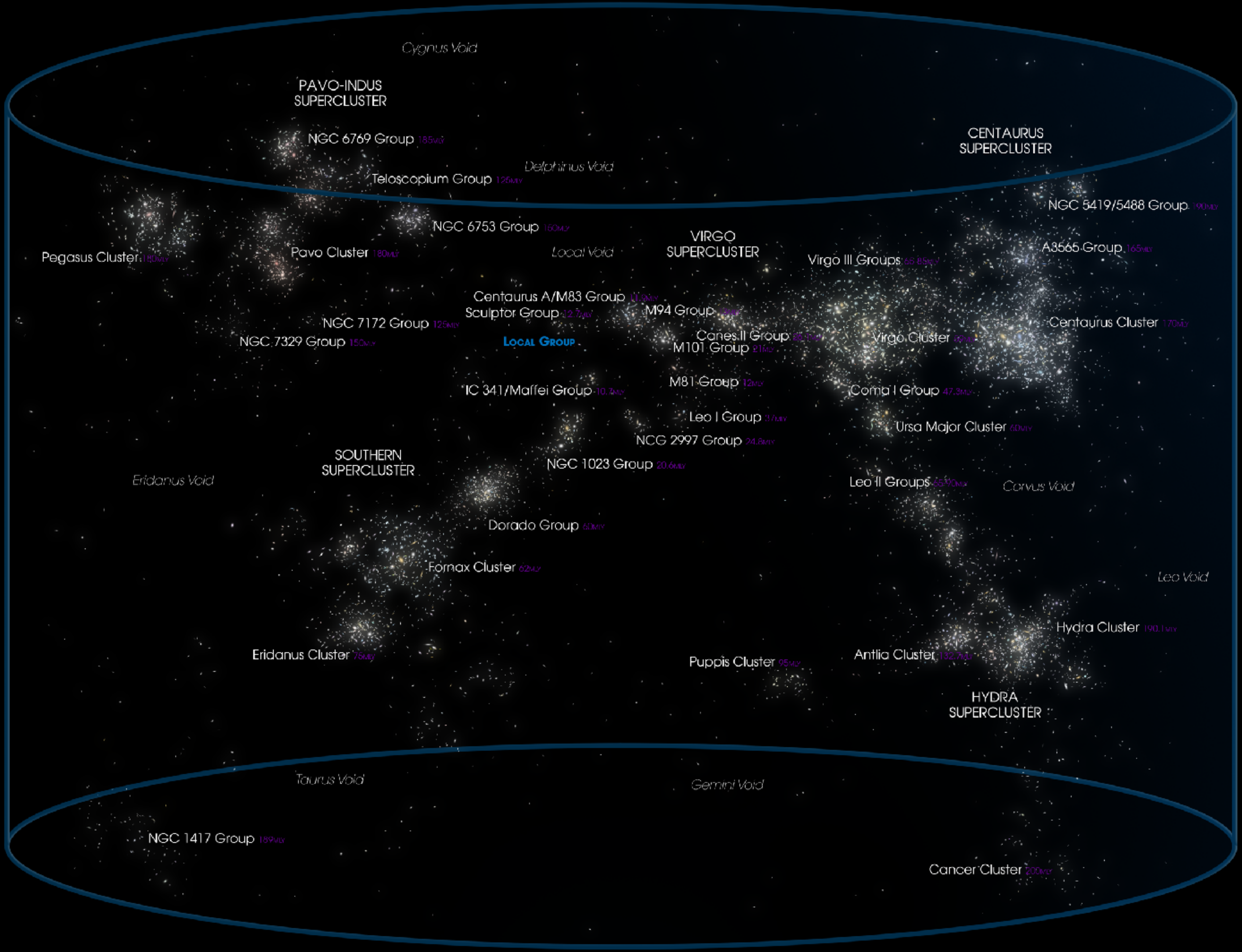
LANIAKEA



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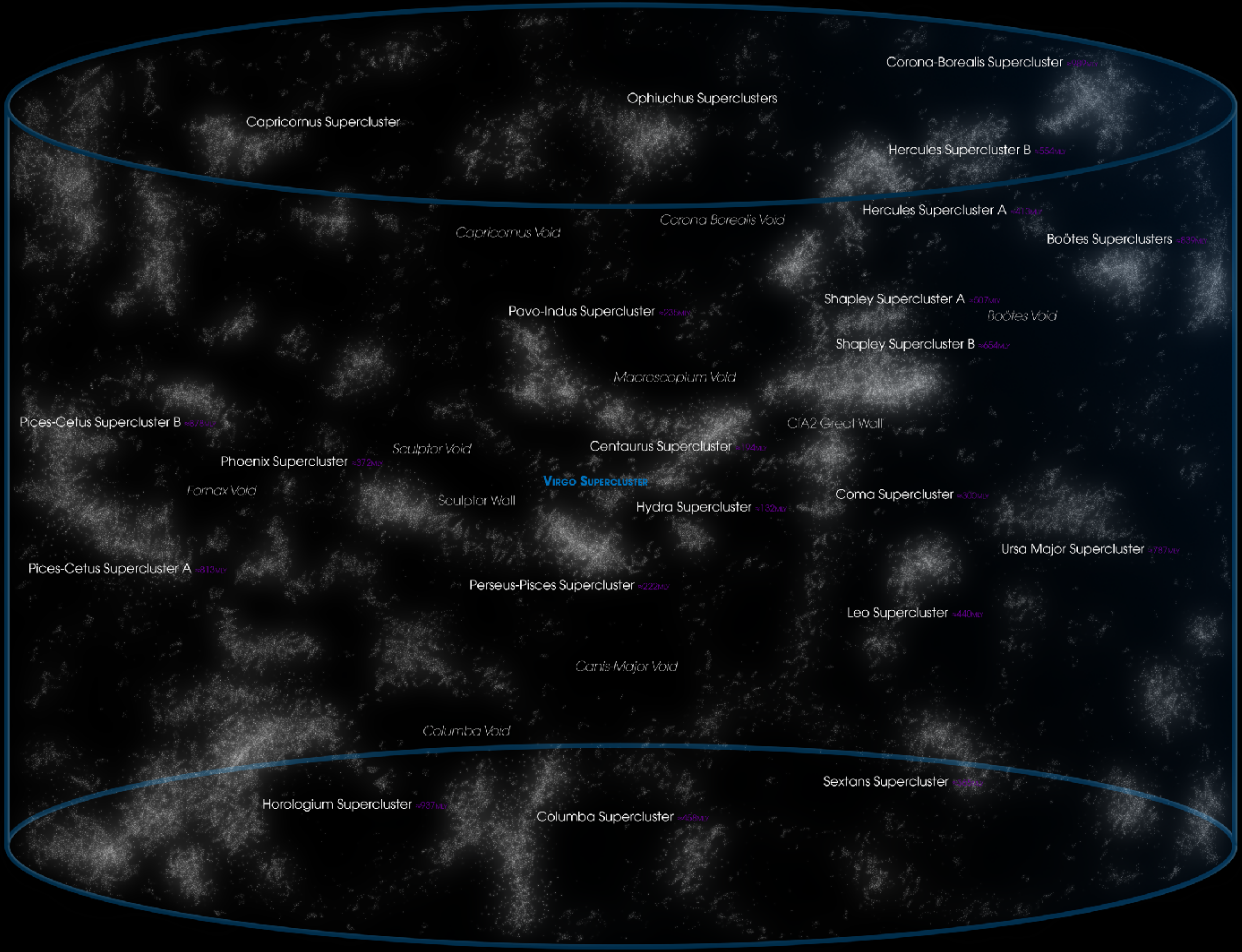
LOCAL SUPERCLUSTERS



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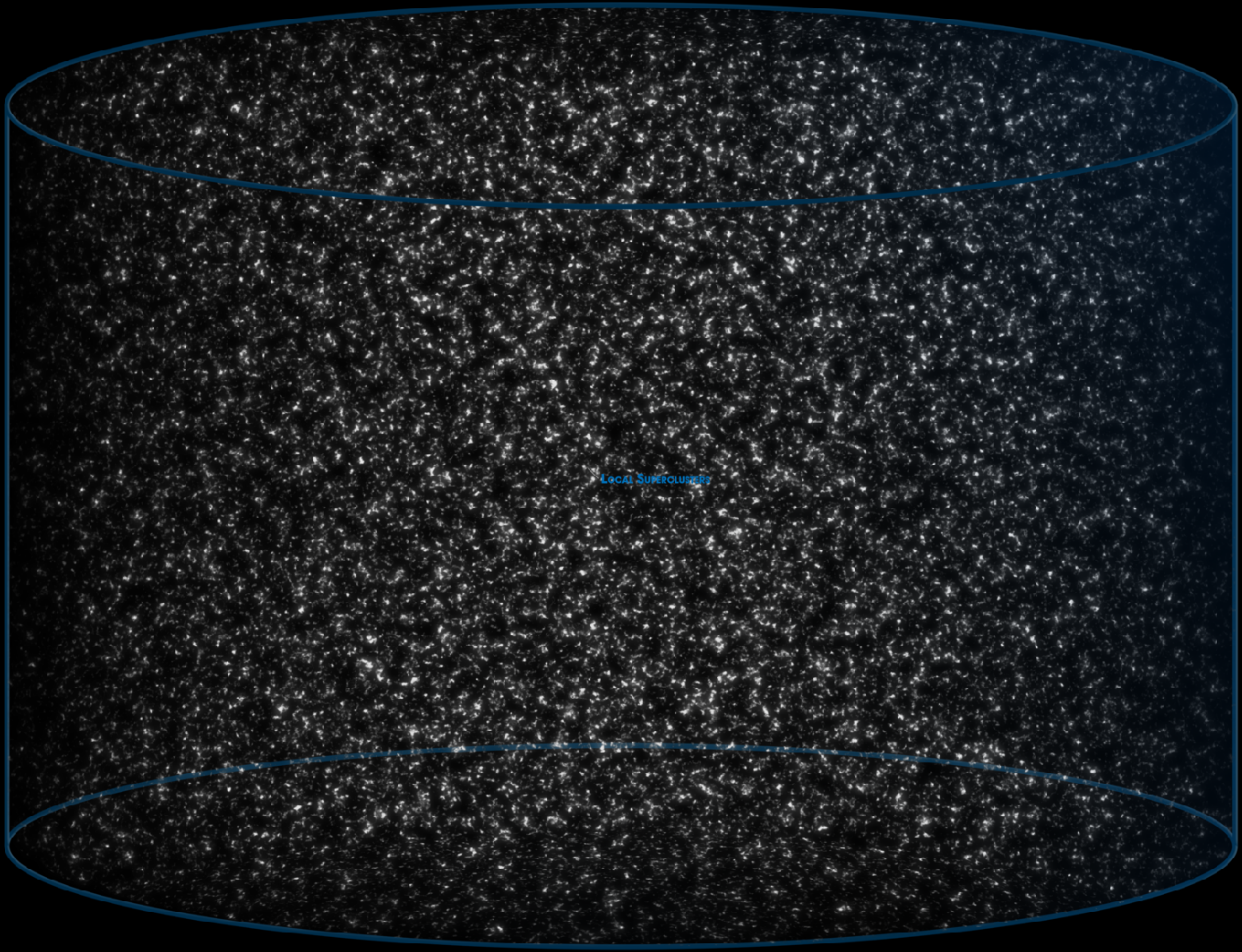
OBSERVABLE UNIVERSE



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Timescales

The age of the Sun is ~ 4.6 billion years (Gigayears), based on comparison to models of stellar evolution and nuclear dating of Solar system material.

Stellar evolution theory can also be used to estimate the ages of star clusters statistically; the oldest known **globular clusters** are ~ 13 — 14 Gyr old.

This is a lower limit to the age of the Universe.

The Gigayear (Gyr) is a good time unit in cosmology.

Velocity

Gravity is the only long-range force that we know about that acts on a cosmological scale (i.e. that affects the motions of stars and galaxies).

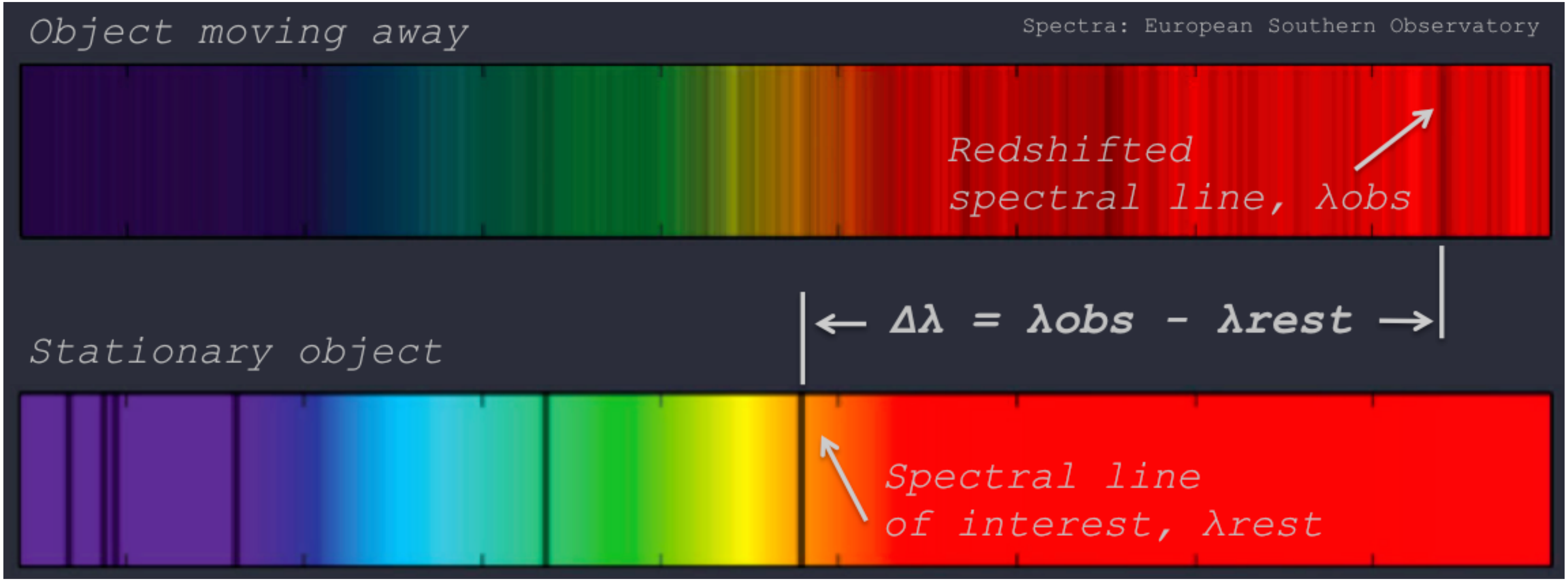
In principle, the velocities of stars in the galaxy, and galaxies in groups of galaxies, allows us to infer the strength of the **gravitational potential** that binds those objects together.

*(For reasons we will see later, these velocities due to local gravitational accelerations are called **peculiar** velocities.)*

The component of velocity **perpendicular** to the line of sight can only be measured as a **change in position over time** (proper motion). This is hard; even nearby stars have proper motions of only $\sim 1/1000$ arcsecond/year.

The component of velocity **parallel to (i.e. along)** the line of sight is easier to measure via the **shift of spectral features** due to relative motion (**blue- or red-shifting)**.

Shifted spectra



https://itu.physics.uiowa.edu/labs/advanced/astronomical-redshift

Definition of redshift

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$$

Redshift can be **interpreted** as a Doppler shift due to relative motion of the source and observer in a fixed frame of reference. As we will see later, this is not the correct interpretation of **cosmological** redshift.

Neverthless**, if** redshift is interpreted as a Doppler shift, then for $z \ll 1$, it can be associated with a velocity using the non-relativistic expression, $v = cz$. This is the low-speed limit of the full special-relativistic formula.

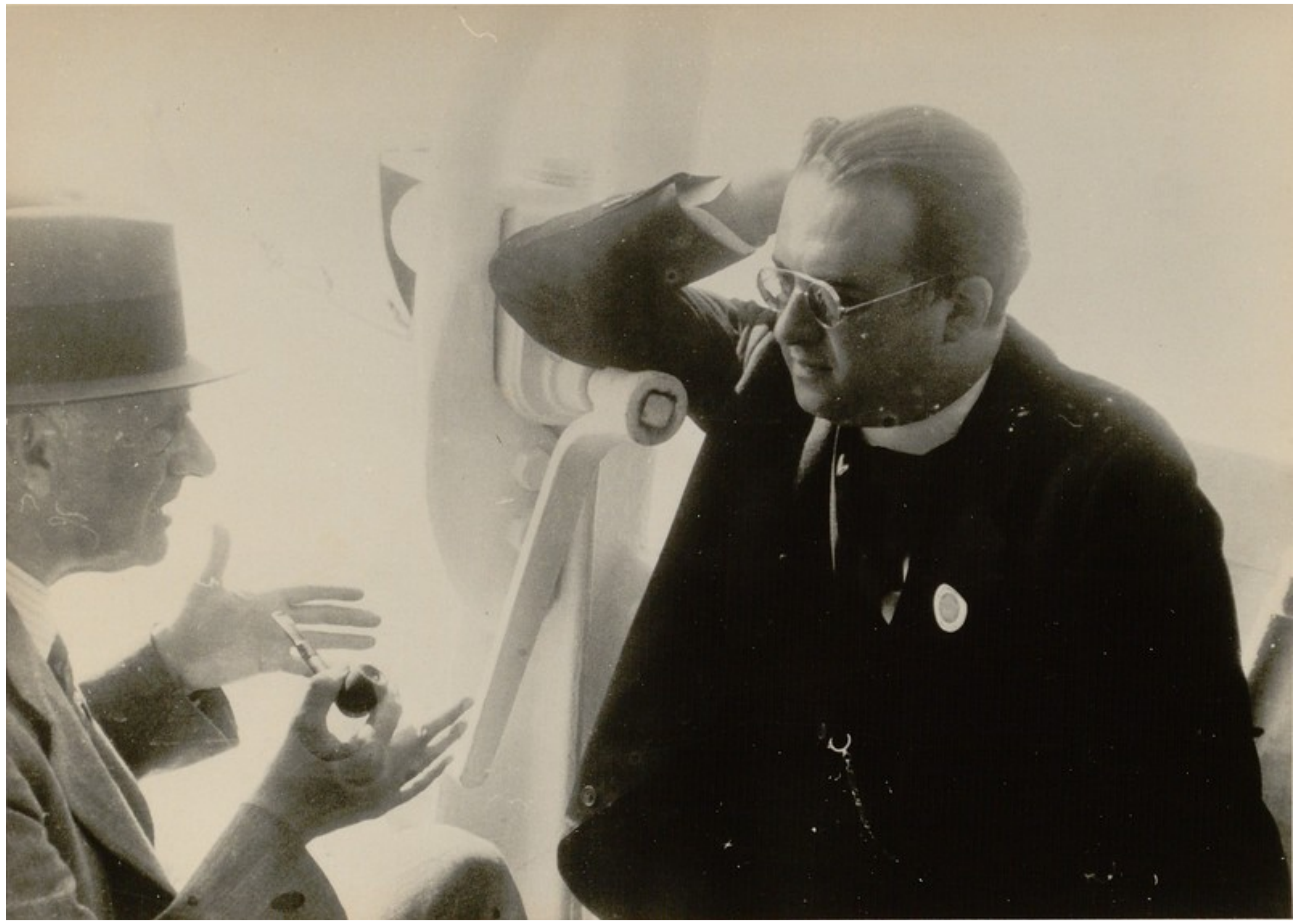
When pretending that a redshift is velocities due to a Doppler shift, the convention is to use units of $\mathrm{km\,s^{-1}}$*, as we will see in the next lecture.*

The beginnings of modern cosmology

Measurements of the **line-of-sight** velocities of galaxies in the 1910-20s (most famously those by Vesto Slipher) turned out to be a vital breakthrough that kick-started modern cosmology.

All the galaxies we can see (except Andromeda and handful of others very nearby) are moving very fast **away** from the Milky Way. Their light is **systematically redshifted**.

This was recognised as a cosmologically important fact, and explained essentially correctly as a consequence of General Relativity, by Georges Lemaître in 1927.



UCLArchives

The beginnings of modern cosmology

In the late 19th Century, it was assumed that the Universe:

- Consisted of many **stars**, …
- … which have a more or less random distribution on large scales, ….
- … over an infinite volume …
- … that does not change with time.

All of these ideas were doubted to some extent, but there was not much direct observational evidence to contradict them.

One of the main reasons for doubt was an idea associated with H. Olbers (1820s), based on the distance-independence of surface brightness: the above assumptions imply the night sky should have the same surface brightness as the Sun, which is obviously not true. Something must be wrong (or missing).

The beginnings of modern cosmology

There are many ways that Olbers' puzzle could be solved; in the end, the real solution is that **the Universe is not infinitely old**.

The physical explanation for this is that **space itself** is **expanding**: points that are close together now will be further apart in future, even if they have no local acceleration (e.g. due to gravity).

The possibility that space can expand was very quickly recognised as a consequence of GR.

When Lemaître proposed that galactic redshifts were evidence of this expansion, he also estimated the **expansion rate** from average redshift and average distance of nearby galaxies. Soon after **Edwin Hubble** carried out similar work with more data (specifically, more distances).

Lemaître also stressed ($\sim$ 1930) that an expanding universe must have some sort of an **origin of time**, at which the distance between nearby points in space was "zero".

We will discuss these ideas in the next lecture.

Summary

Conventional units of cosmology: Mpc, Gyr, $M_\odot$

Light signals traverse the distance between source and observer at a **finite speed**, so they take a **finite time** to arrive; the signal provides **information about the source in the observer's past**, when the signal was emitted.

Angular size and apparent brightness **decrease as distance increases**; this can be used to infer the distance of a source if its **intrinsic** size or luminosity is known (standard rulers and standard candles).

Physical *(peculiar)* motions of stars and galaxies arise from **gravitational accelerations**.

Redshift: $z = \dfrac{\lambda_o - \lambda_e}{\lambda_e}$

For next time: Ch. 3 in Ryden; 2.2–2.5 in Huterer.