Lecture 1 – Organization of the course

Introducing the lecturer: **Pawel Artymowicz**

[guide to Polish pronunciation: substitute w → v, z → h,
neglect some diacritical marks & things become readable.]

Milestones, for those of you who want a scientific career in academia:

- 5 years undergraduate Physics + Astronomy, Univ. of Warsaw, Poland
- 4 years graduate study at the Space Telescope Science Institute, Baltimore, MD.
- PhD from Polish Acad of Sci. in 1990

- 3 years: postdoctoral NASA Hubble Fellow at Univ. of California, Santa Cruz (UCSC), USA
- 11 years: Senior Researcher, asst. and assoc. prof. in Stockholm University, Sweden
- last 17 years: full tenured prof. of Physics and Astrophysics at UofT.

My areas of expertise:

- Planetary systems, origins:
  - Dusty disks like Beta Pictoris, dust avalanches, dust disk instabilities
  - Migration of protoplanets in disks, flow of gas around them
  - Numerical hydrodynamics, CPU & GPU supercomputing
- Young binary stars
- Galactic dynamics, black holes and active galactic nuclei

- Aerodynamics and aviation (FAA & TC pilot, investigator of an airliner crash)

Organization of the course

Where to look for course information:

syllabus, home assignments, lecturer's contact information etc.

- Quercus for announcements, exam files during exam, and for submission of your work (assignments) and viewing the marked term work.
- Web page of ASTB03 - assignment texts, contact information, grading scheme, lecture notes, extra books and links & other materials
- https://planets.utsc.utoronto.ca/~pawel/ASTB03/ or just google ASTB03
- Your TA (marker) is Aravind Shaj (aravind.shaj@mail.utor...)
- Please ask questions during the lecture, or during the
- Office 'hour': walk with me to SW astro (5^{th}) floor after lecture
- Send email about individual matters to me at either pawel@utsc.utoronto.ca or pawel.artymowicz@utoronto.ca

Lecture 1 & 2 – A tour of your Universe

- Before we start talking about the major steps humanity took to explore and understand the cosmos
- we will define it by taking a brief voyage to the limits of the known universe.

What are astronomy and astrophysics ?

- It is more than the study of planets, stars, and galaxies.

  It is the study of the whole universe in which you live.

  It is the most ancient science once thought to be very different from Physics. Today astronomy is practically a part of physics.

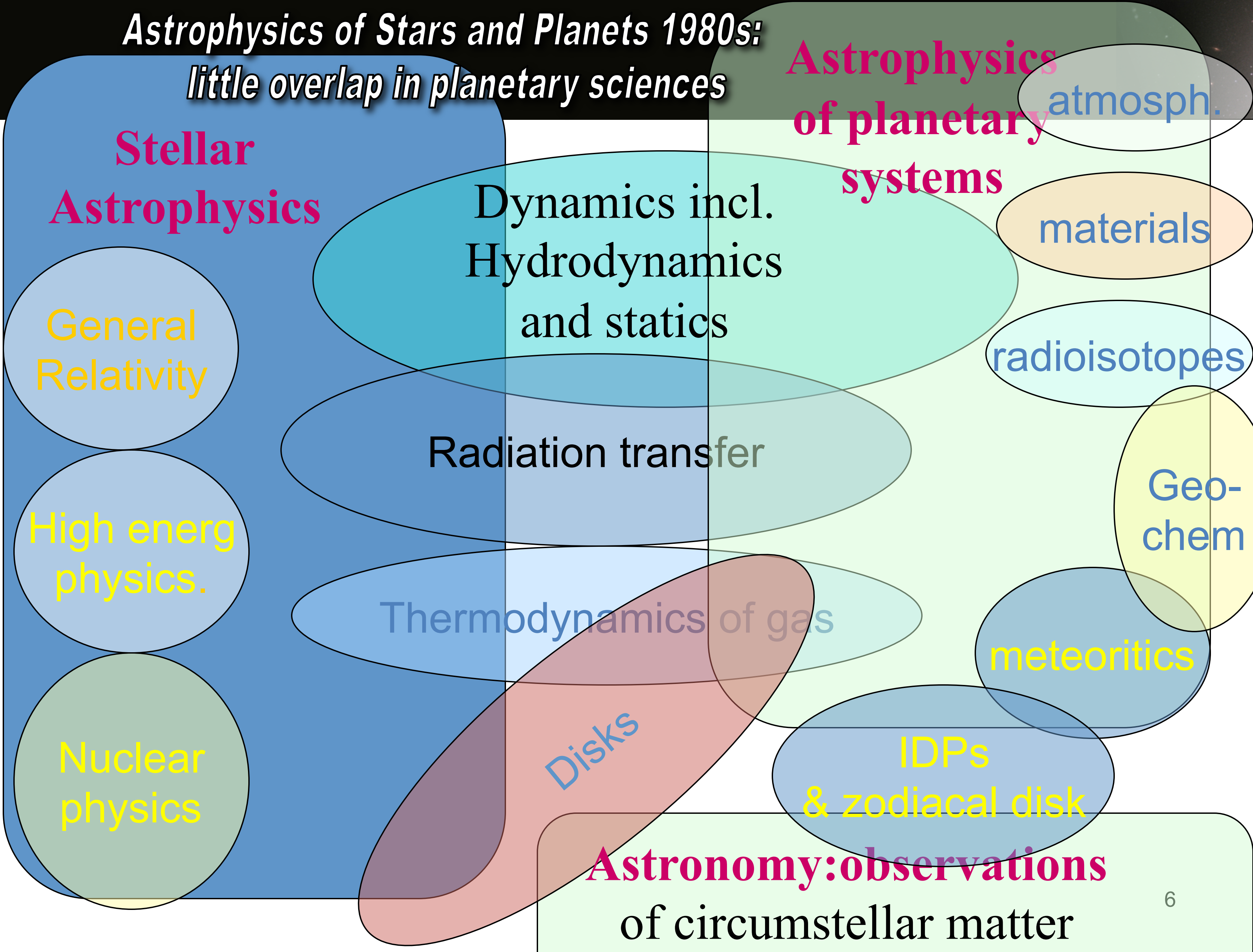
  It is also connected with *astronautics* (space exploration, literally: stellar navigation) and so on…

  Astronomy ≠ astrology. The connection between astrology and astronomy was lost about 500 years ago. Astrology is about horoscopes etc.

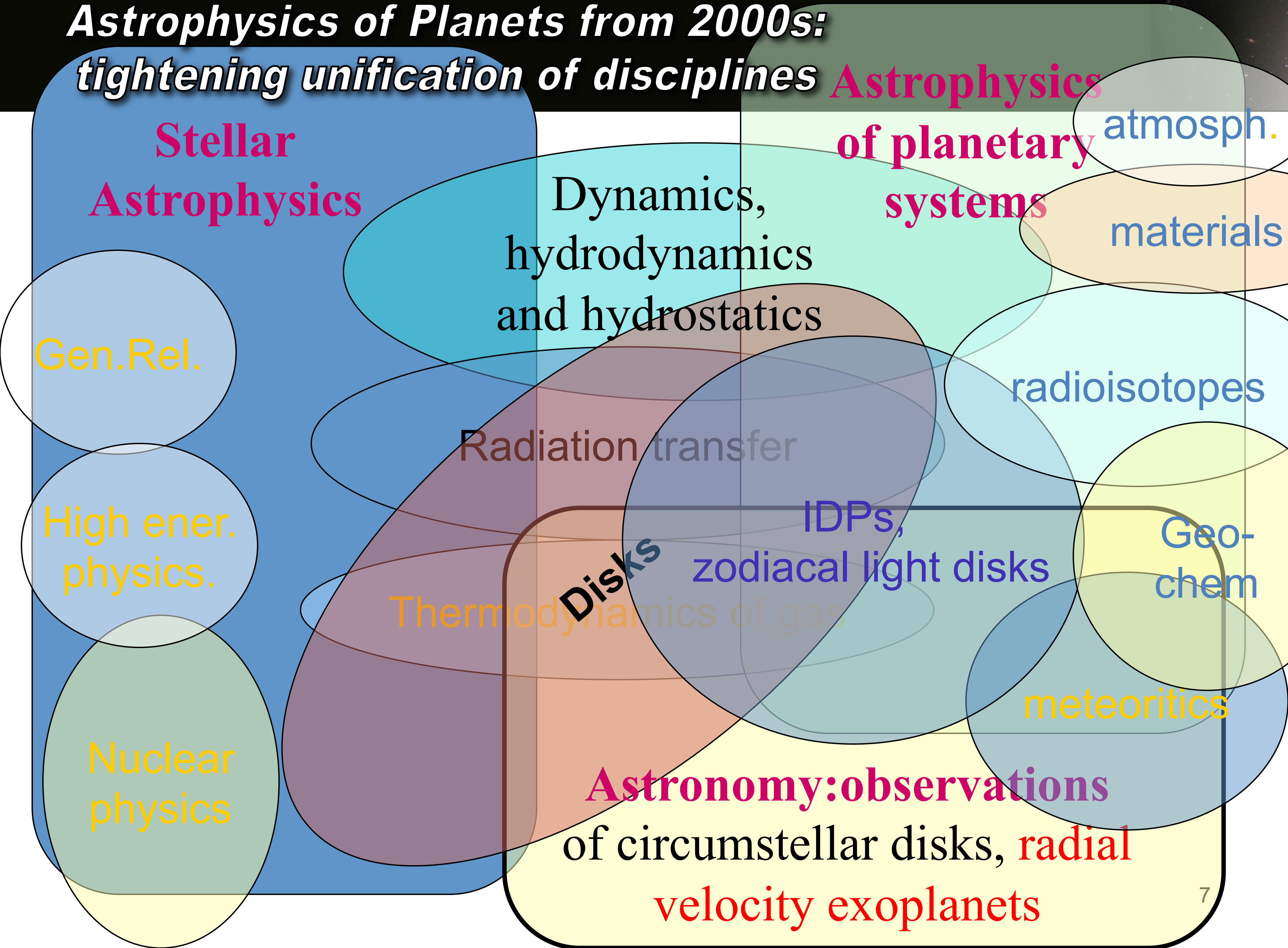
  Many people (esp. in North America) distinguish between astronomy (observational science) and astrophysics (theoretical science).

  But for example in England, people tend to divide astronomy into observational and theoretical, and call practitioners of those branches correspondingly.

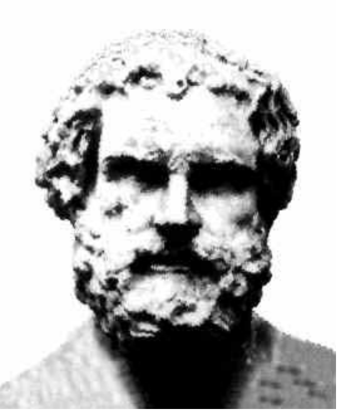
Astrophysics of Stars and Planets 1980s: little overlap in planetary sciences



Astrophysics of Planets from 2000s: tightening unification of disciplines

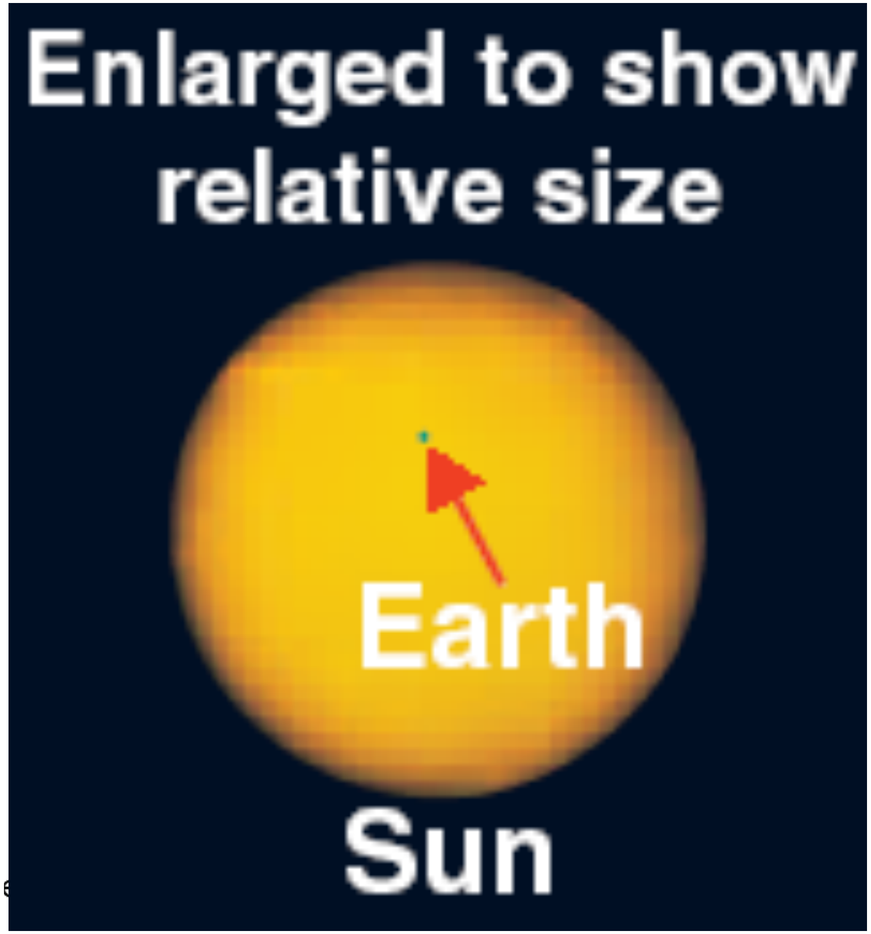


- Humanity is confined to a small planet circling an average star.
- The study of astronomy can take you beyond these boundaries and help you not only see where you are in the universe, but understand what you are.
- You will see how science works and how it solves the oldest questions asked by humankind, such as the existence of other planets like our own, and other solar systems.



Journey from Solar System to Galaxy to Universe

- Let us compare objects of different sizes in order to comprehend the scale of the universe
- for example, you can see
- ASTRO by Seeds, Backman et al., (2013)



Our imaginary journey

- Every time you move 10 times away, your field of view encompasses an area 10 x 10 larger than the previous square, while volume grows like 3rd power of scale (10x10x10 times). Distances are first expressed as 1, 10, or 100 meters, until we come to such large distances that a meter becomes too small as a unit.
- We start using either prefixes (e.g., "kilo," which means "one thousand") or scientific notation (i.e., using powers of 10).
- Prefixes — the inverse is called:
  - $10^1 = 10$ (deca, d) — deci 10^{-1}
  - $10^2 = 10 * 10 = 100$ (hecta, h) — cento 10^{-2}
  - $10^3 = 10 * 10 * 10 = 1000$ (kilo, k) — milli 10^{-3}
  - $10^6 = 1,000,000$ (mega, M) — micro(μ) 10^{-6}
  - $10^9 = 1,000,000,000$ (giga, G — nano 10^{-9}
  - $10^{12}= 1,000,000,000,000$ (tera, T) — pico 10^{-12}
  - $10^{15}= 1,000,000,000,000,000$ (peta, P) — femto 10^{-15}
  - $10^{18}= 1,000,000,000,000,000,000$ (exa, E) — atto 10^{-18}

(you may recognize these prefixes from the world of computers)

A tour of the universe

Journey from Solar System to Galaxy to Universe

At a distance scale of of 10 km you could see a city, or the Large Hardon Collider (10+ km radius) near Geneva

Journey from Solar System to Galaxy to Universe

- Mountains and valleys, all geological features on Earth, are only temporary features on Earth that are slowly but constantly changing.
  - As you explore the Universe, you will come to see that it, too, is always evolving
  - An interesting fact: our Sun and Earth are not that much younger than the whole Universe, only about 3 times (4567 Myr vs. 14300 Myr = 14.3 Gyr)
  - Our Milky Way, a spiral Galaxy, a giant star city around which center the sun travels, is almost as old as the Universe (10 Gyr)

Time lapse movie of the rotating sky showing Earth's rotation via apparent sky rotation

- In the next step of the journey, you see the entire planet Earth, which is about 13000 kilometers in diameter.
  - This picture shows part of the daylight and part of the night side of planet Earth. Scale of the picture is several x 1000 km
  - The thin blue streak is our atmosphere – let's not pollute it!

The rotation of Earth on its axis each 24 hours carries you eastward, and as you cross the sunset line into darkness you say that the Sun has set.

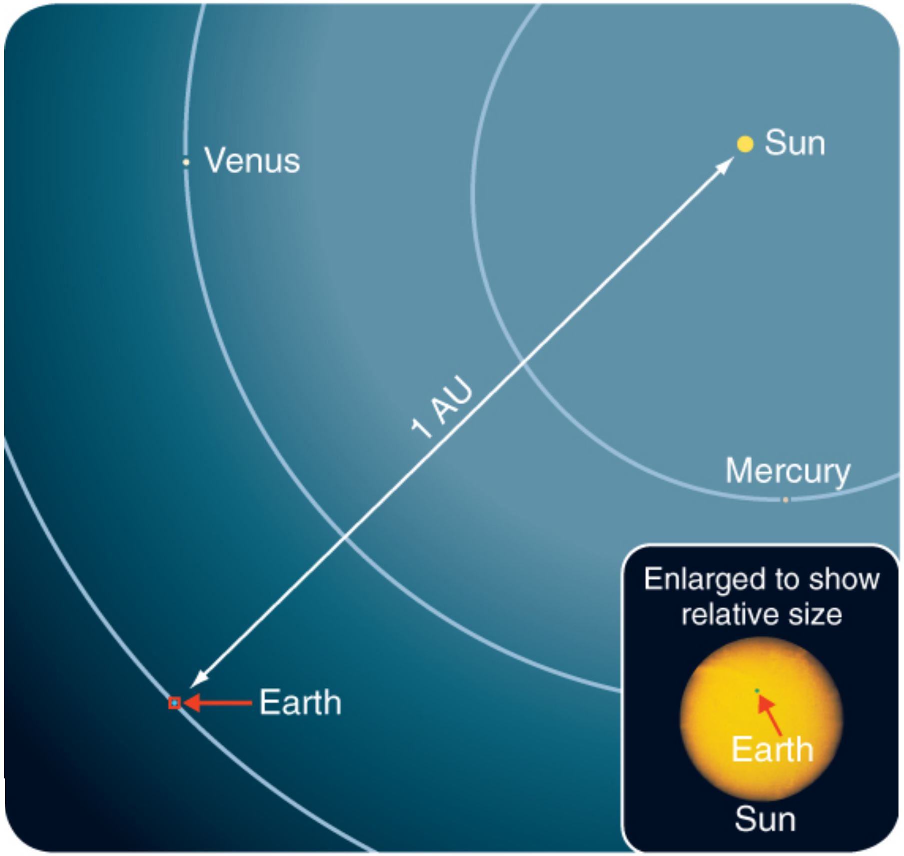
Earth from International Space Station (real time):
https://www.youtube.com/watch?v=86YLFOog4GM&t=0s

scale ~10^4 km

Journey from Solar System to Galaxy to Universe

- Enlarge your field of view by a factor of 100, and you see a region 10^6 km wide (1 mln km)
  - Earth is the small dot shown by red arrow, and **the Moon** – with a diameter only about 1/4 that of Earth, is an even smaller dot somewhere inside the small red area

Figure 1.9



The Moon

- Some high-mileage cars may have travelled the equivalent of a trip to the Moon. They would never reach Venus.
- The average distance of the Moon from Earth is 384000 km. (Soon, we will jump to another measuring unit...)
- The Moon shows phases, because it revolves around Earth and thus is illuminated from a changing direction. The Moon spins as fast as it orbits the Earth on average, but not precisely so all the time, since it is on a slightly elliptic orbit and so moves non-uniformly around the Earth (speeds up and slows down). Hence we see over time > 55% of its surface, instead of exactly 50%.
- See the Moon changing from hour to hour throughout 2012
    - https://www.youtube.com/watch?v=7JqVqvIlrwA (animation over one full year)

From Solar System to the Galaxy

- You may have noticed in the previous picture a new distance unit which is more convenient than kilometer.
- (Almost) 150 million km is the average Sun-Earth distance, the so-called semi-major axis of Earth's orbit. This distance is called the Astronomical Unit (AU).
- It is 1 AU = $1.496 * 10^8$ km = 149.6 mln km = $1.496 * 10^{11}$ m.
- Introducing new units is another way astronomers deal with large numbers. Using the Astronomical Unit, you can then say, for example, that the average distance from Venus to the Sun is about 0.72 AU

Figure 1.9

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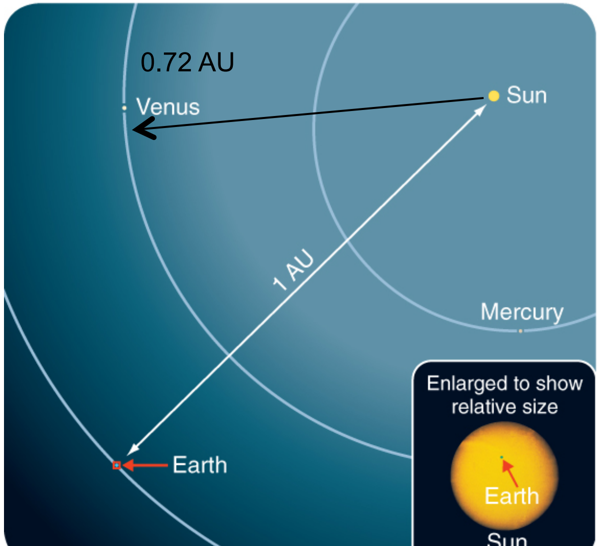
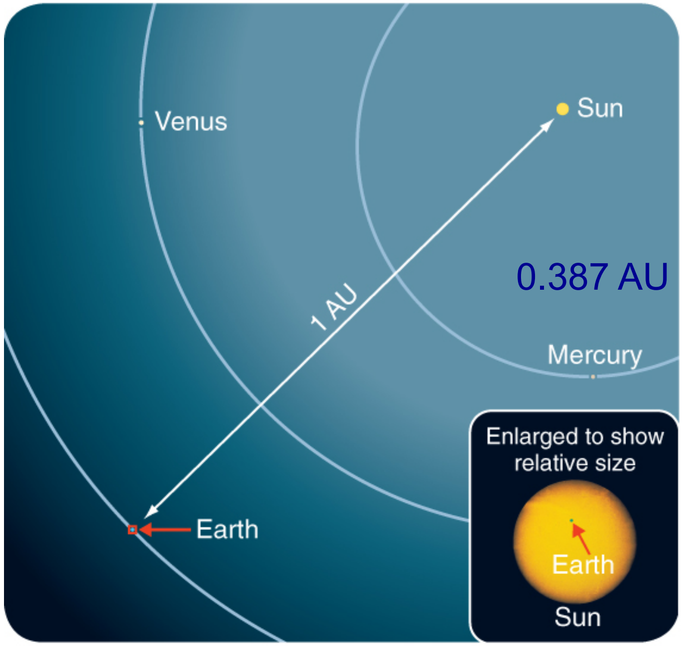


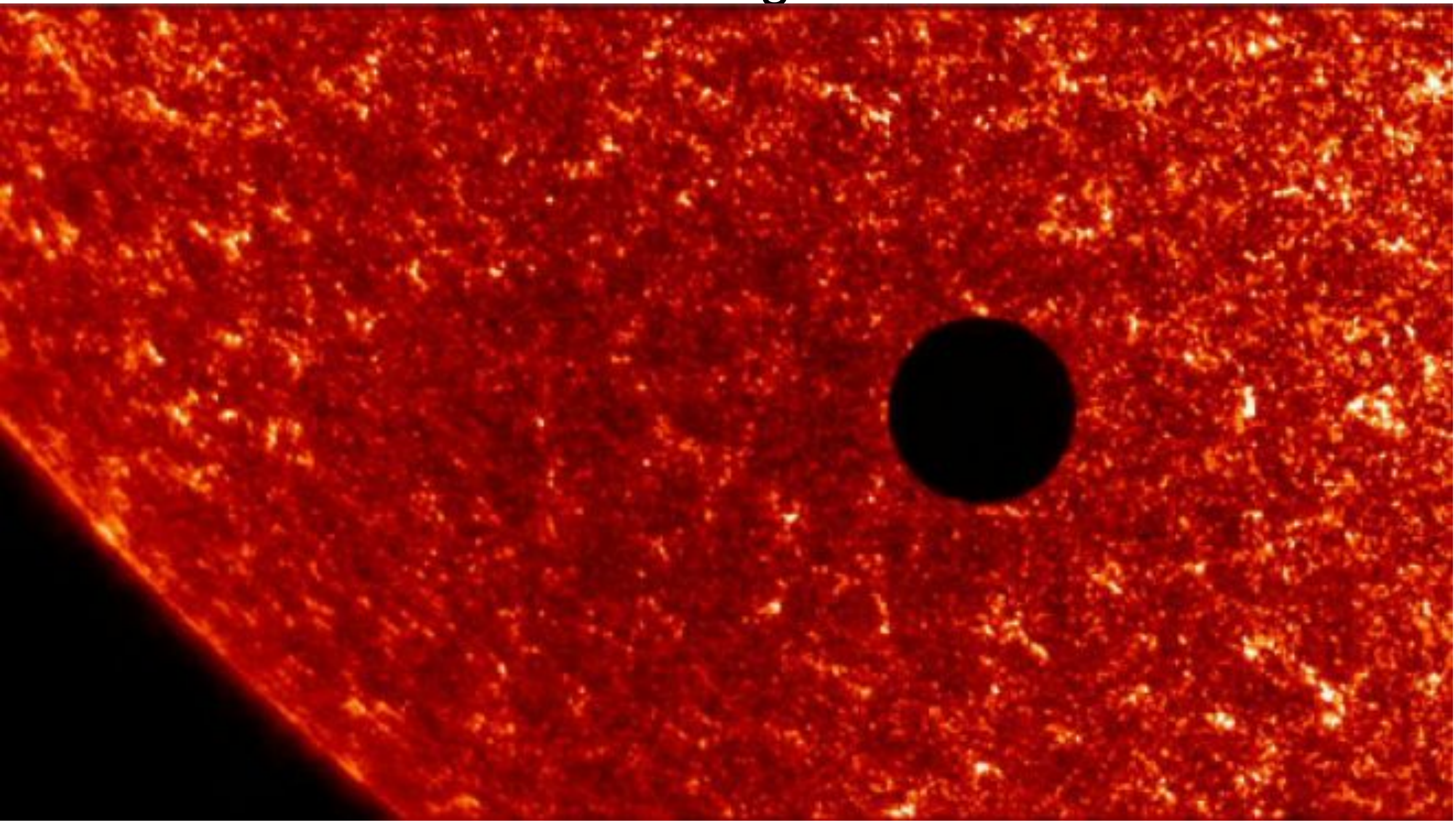
- The solar system consists of the Sun, its family of planets, and some smaller bodies, such as moons, asteroids, and comets
  - Like Earth, Venus and Mercury are planets – small, nonluminous bodies that shine by reflecting sunlight
- Venus size = Earth
- Mercury > ~ Moon
  - In this figure they are both too small to be seen as anything but tiny dots.

Figure 1.9



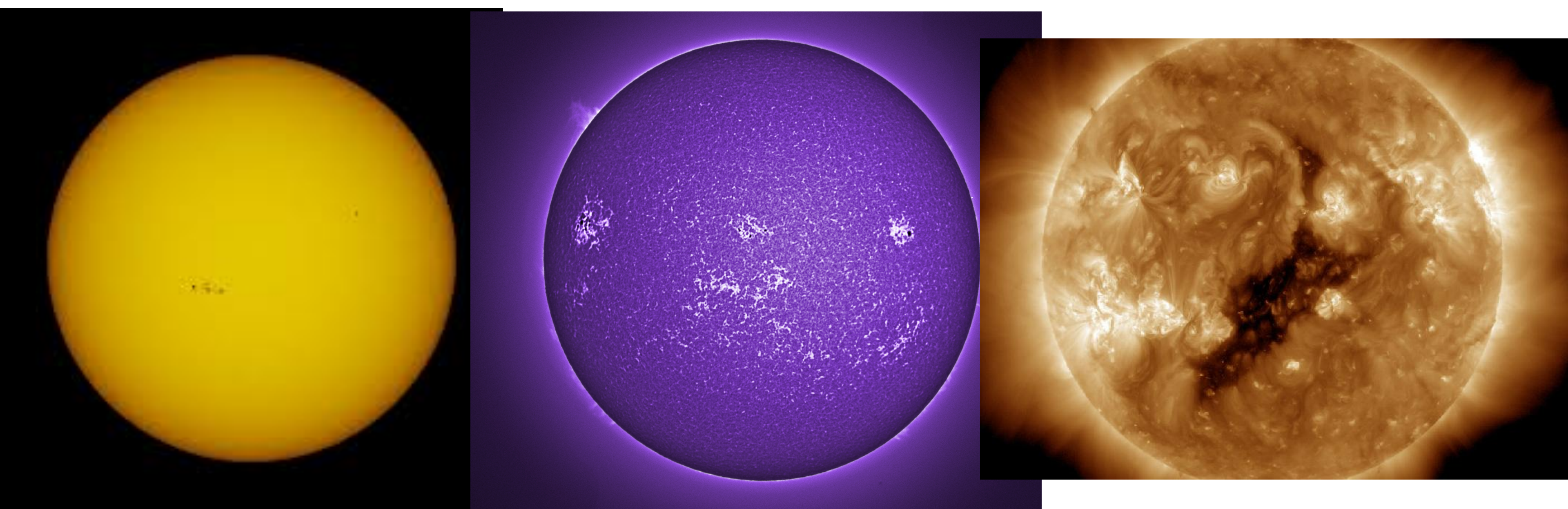
Solar dynamics Observatory – a spacecraft (robot)

- Picture of Venus transiting in front of an active sun



Our nearest star

- The Sun is a star, a self-luminous ball of hot gas that generates its own energy.
  - The Sun is about 110 times larger in diameter than Earth, its diameter is ~1.4 million km, i.e. radius ~$0.7 \cdot 10^6$ km
  - but it, too, is nothing more than a dot in the previous view of the inner solar system

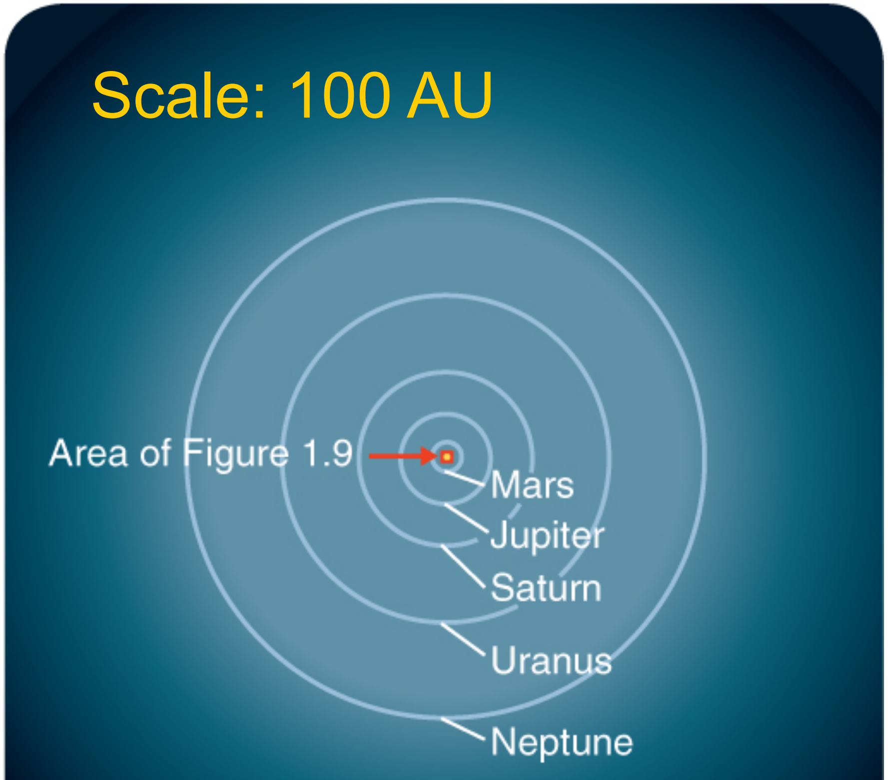


- Solar Dynamics Observatory, a spacecraft observatory of the sun, i.e. robotic observatory in space, watched our star continuously for years in multiple bandpasses (wavelengths, most UV and EUV – extreme UV)

https://www.youtube.com/watch?v=cgcyJxk017M

- Now we are jumping 100 times farther away than the previous view, from about 1 AU to 100 AU.
  - Here you see the entire solar system, which like other known solar systems is of order 100 AU across
  - All 8 major planets' orbits
  - The details of the Earth's & Venus' orbit are lost in the red square at the centre

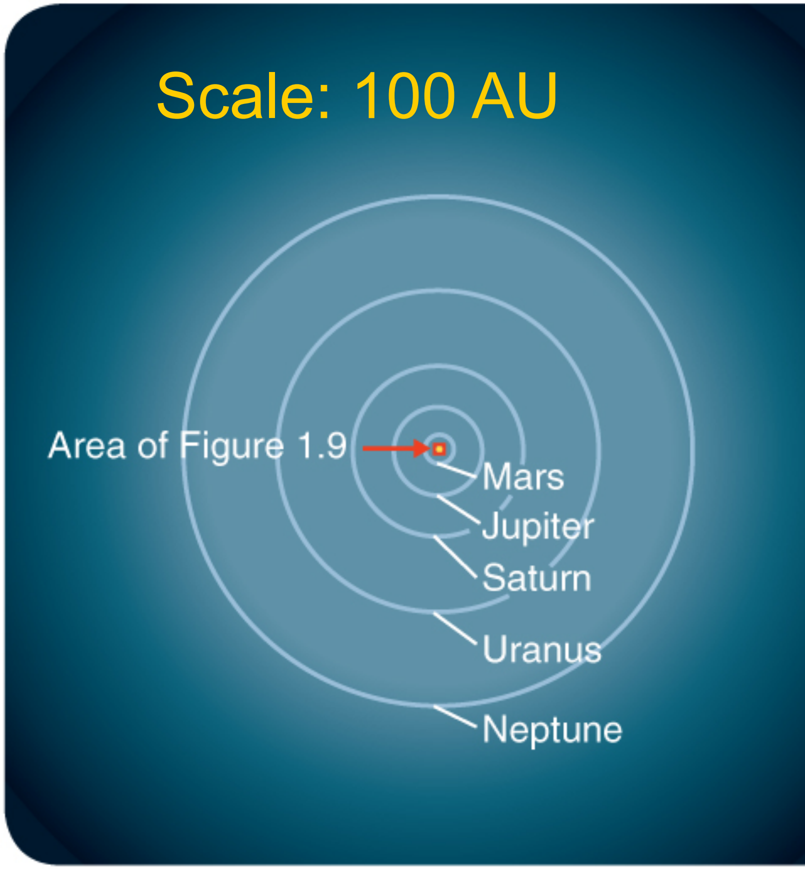
Figure 1.10



- Light from the Sun reaches Earth in only 8 minutes, but it takes over 4 hours to reach Neptune.

Figure 1.10

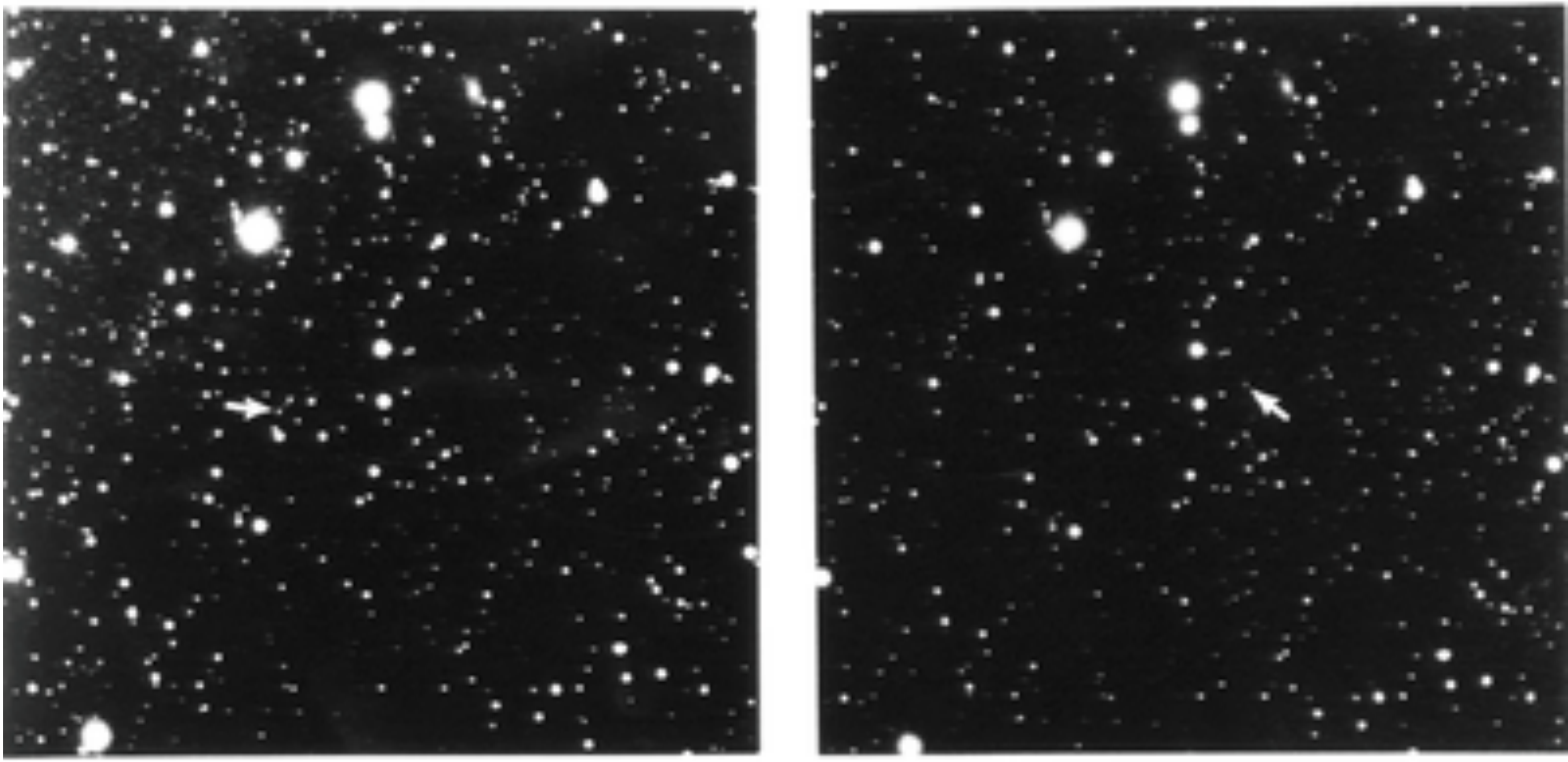
You can't skype or talk to an astronaut on the Moon on anybody much outside the Earth in *real time*.
You need to say/text & then wait a bit.
Hope you don't mind!



BTW: Pluto, once a planet,
orbits mostly outside Neptune's orbit,
but it is no longer considered a
major planet so it is not shown.

Pluto indeed is rather small (< Moon) and faint

DISCOVERY OF THE PLANET PLUTO

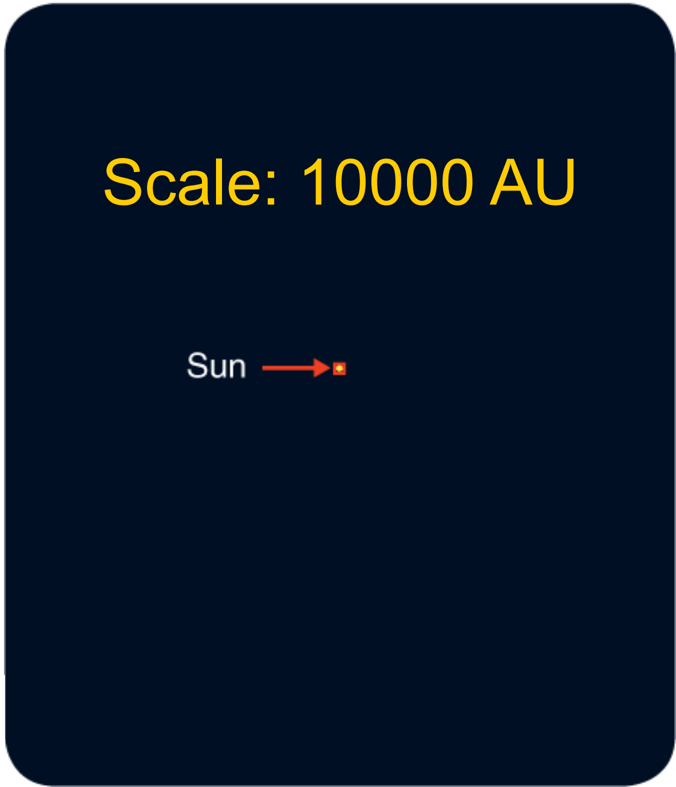


January 23, 1930 January 29, 1930

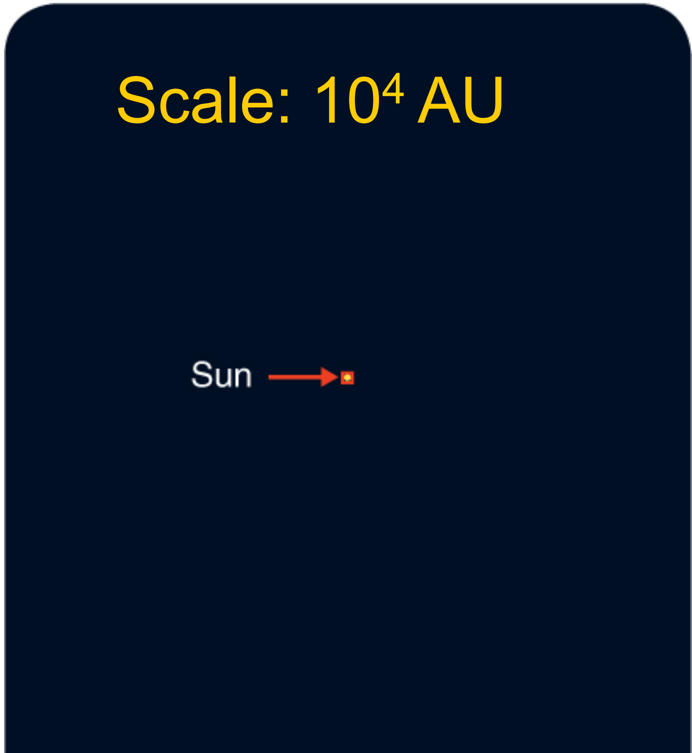
When you again move away 100 times farther, the solar system becomes invisibly small.

Figure 1.11

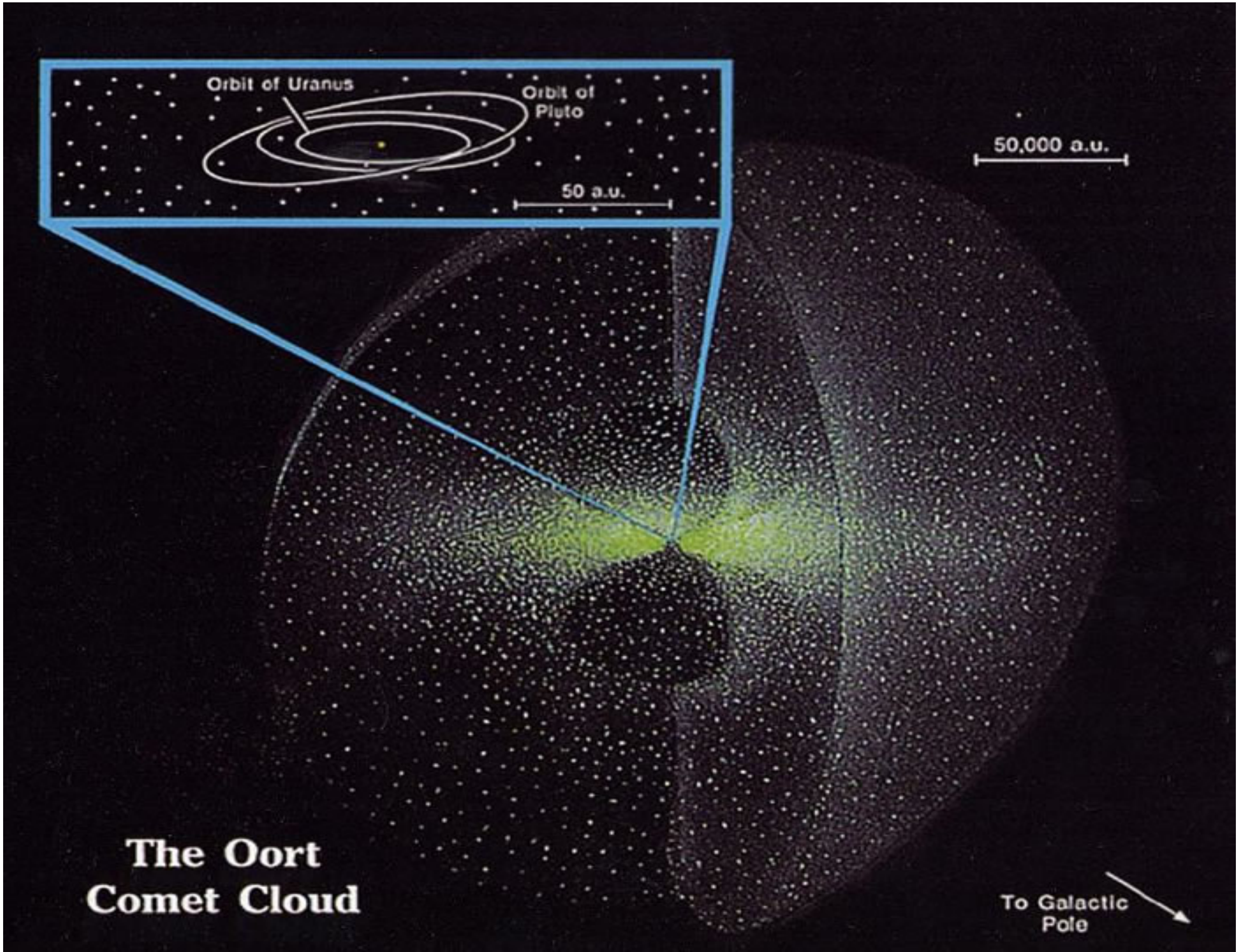
- The Sun is only a point of light, and all the planets and their slightly elliptical orbits are now crowded into the small red square at the centre.



- In this picture, the planets and the comets are too small and reflect too little light to be visible so near the brilliance of the Sun. Figure 1.11
  - Nor are any stars in the range, except for the Sun
  - but if you could see comets... you'd see billions of them



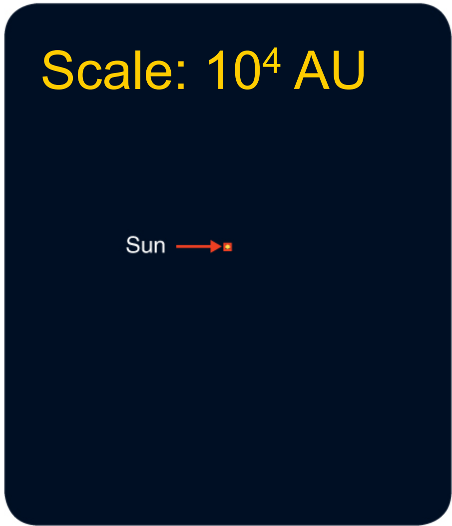
Oort cloud of comets around our Solar System



From Solar System to Galaxy to Universe

- The Sun is a fairly typical star, a bit larger than average, and it is located in a fairly normal neighborhood of a somewhat biggish galaxy.
  - Although there are many billions of stars like the Sun, none is close enough to fit in a frame of this diagram, which is just 100 times larger than the planetary region.
- The stars are separated by aver. distances ~30 times larger than this view. This calls for a larger unit of distance

Figure 1.11

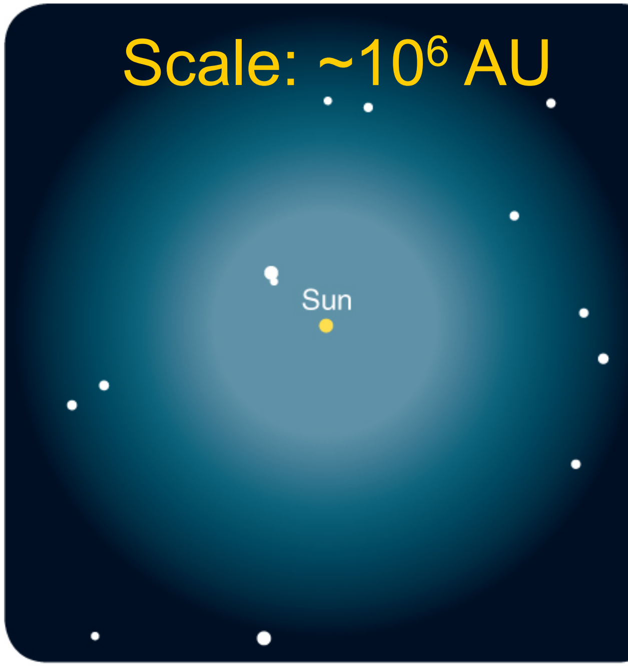


From Solar System to Galaxy to Universe

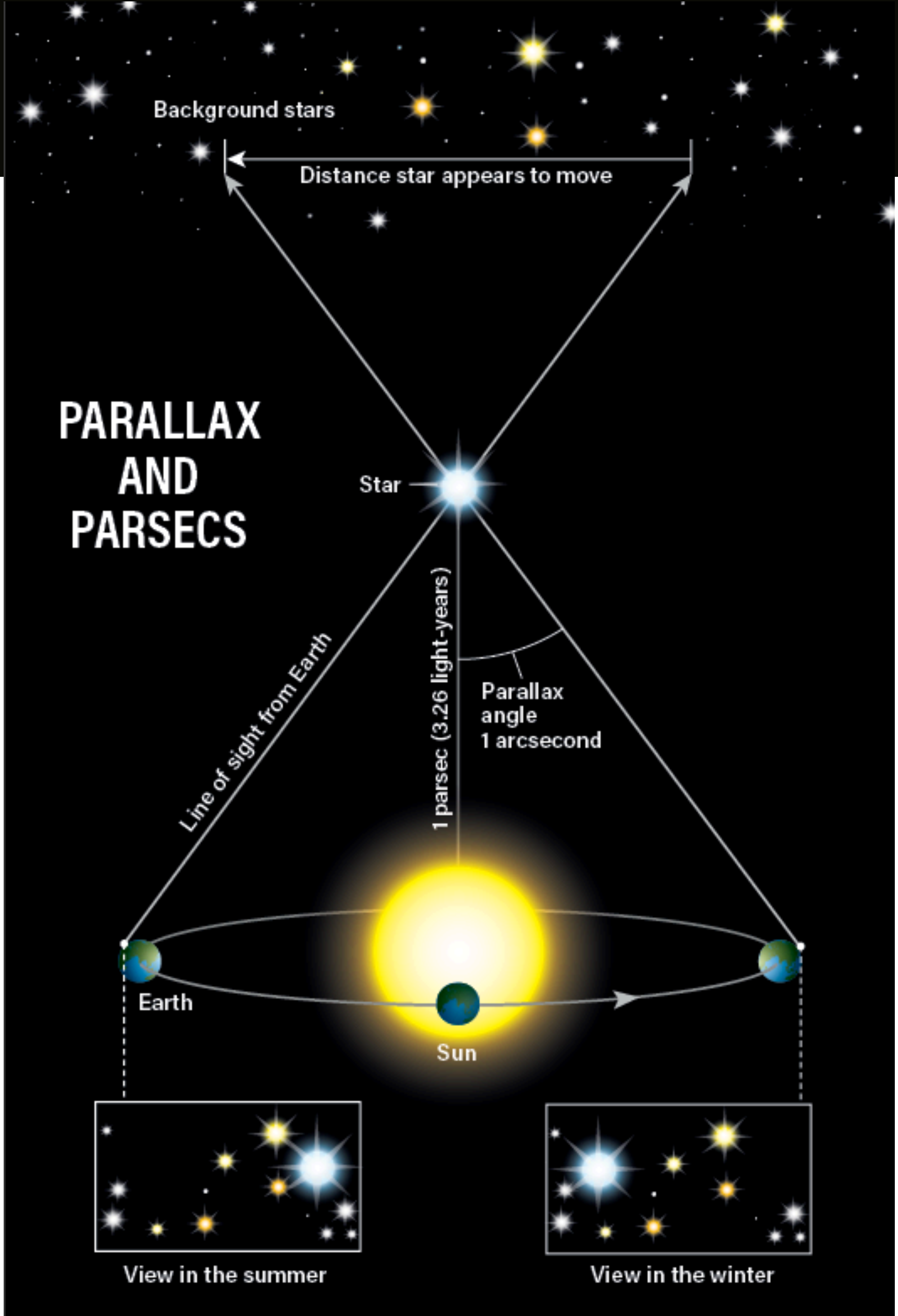
- In this figure, your view has expanded to a diameter a bit over one million AU. The Sun is at the center, and you now see a few of the nearest stars.
- Symbol ~ here means 'of order' or 'order of magnitude' or 'very roughly equal to', usually rounded to the nearest power of 10)

[In math, ~ may mean something very different: proportionality]

Figure 1.12



Parsec & light year



1 pc = 206265 AU

nearest stars are at ~1 pc

Definition: 1 AU at 1 pc spans 1” (arcsecond)

1” = 1’/60 = 1/60 of arcminute = $1^{o}/3600$

parsec is named so because:

parallax = arc**sec**ond at 1pc

Another unit of *distance* is 3.26 times smaller than 1pc: light year

1 ly ~ 10^{13} km = 63000 AU is covered by light in vacuum in 1yr time.

space ←→ time (conversion factor is 1 ly / 1 yr)

From Solar System to Galaxy to Universe

- It is difficult to grasp the great isolation of the stars.
  - If the Sun were represented by a golf ball in Toronto, the nearest star would be another golf ball in Quebec City or in Chicago.
  - Mathematically, the average star-star distance in a galaxy is $\sim 10^{13}$ km, whereas a star has diameter $\sim 10^{6}$ km. The difference is a factor of $\sim 10^{7}$ (10 million).
  - The cube of this factor tells you the ratio of average empty volume surrounding a star to its volume: $\sim 10^{21}$!
  - BTW, the universe is filled much more tightly with galaxies than a galaxy with stars, on average

- One of the nearest stars to the Sun, Proxima Centauri, is 4.2 ly from Earth.
  - In other words, light from Proxima Centauri takes 4.2 years to reach us.

Figure 1.12

At 4.3 ly from us is a companion, Alpha Cen B. An Earth-mass planet was recently discovered around it!

From the Solar System to Universe

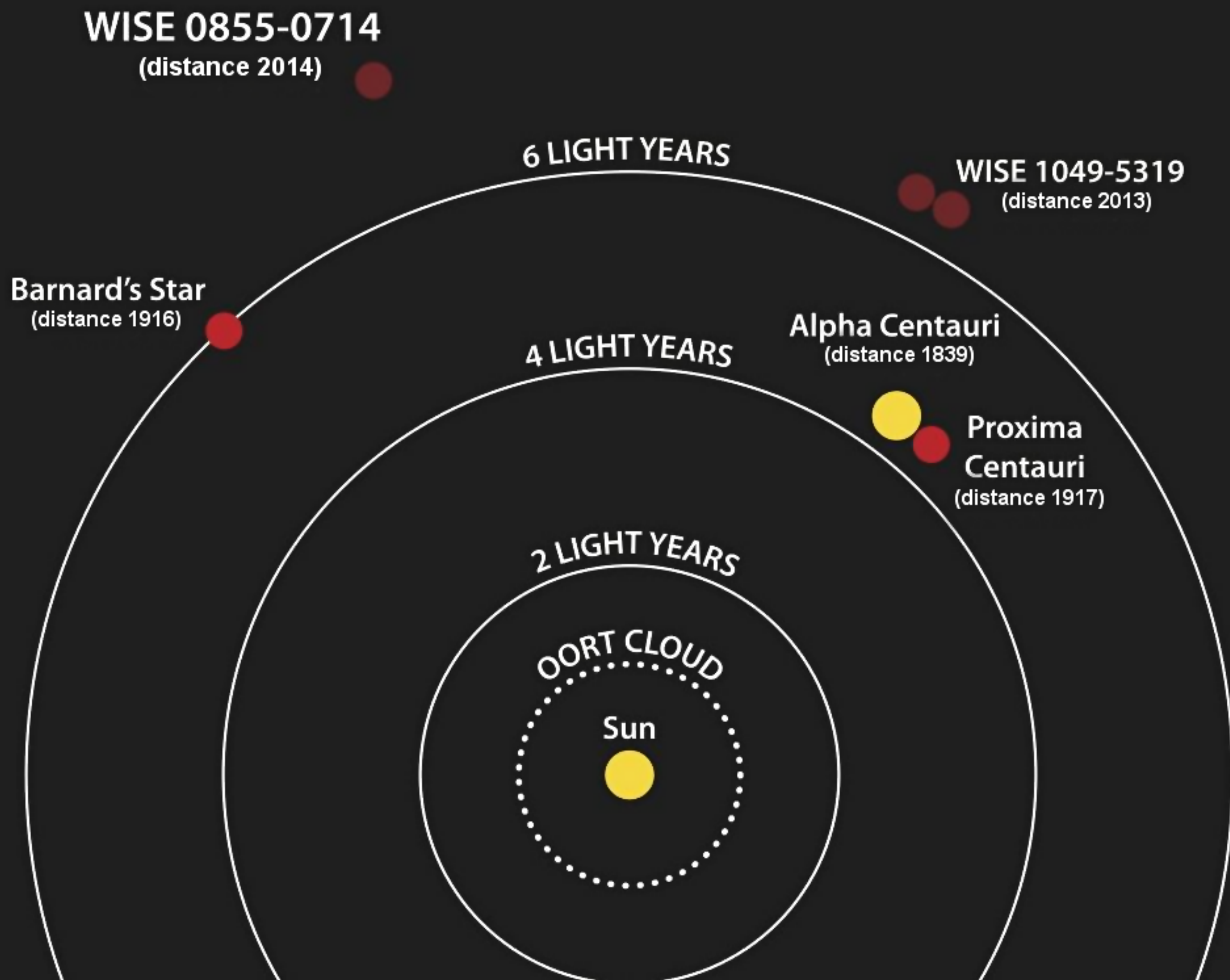
- In sky pictures the sizes of the dots represent not the sizes of the stars but their brightness.
  - This is the custom in astronomical diagrams, and it is also how starlight is recorded.
  - Bright stars make larger spots than faint stars in a photograph or electronic picture.
    - The size of a star image in a photograph tells you not how big the star really is but only how bright it looks.

From Solar System to Galaxy to Universe

Although these stars are roughly the same size as the Sun, they are so far away that you cannot see them as anything but points of light.

Even with large single telescopes on Earth, you still see only points of light when you look at stars, and any planets that might circle those stars are usually much too small and faint to be visible [but there are exceptions…]

THE SUN'S CLOSEST NEIGHBORS



Solar neighborhood

- When you zoom out by another factor of 100, the Sun and its neighboring stars vanish into the background of thousands of stars.
  - This figure has scale of 1700 ly in diameter.

Figure 1.13

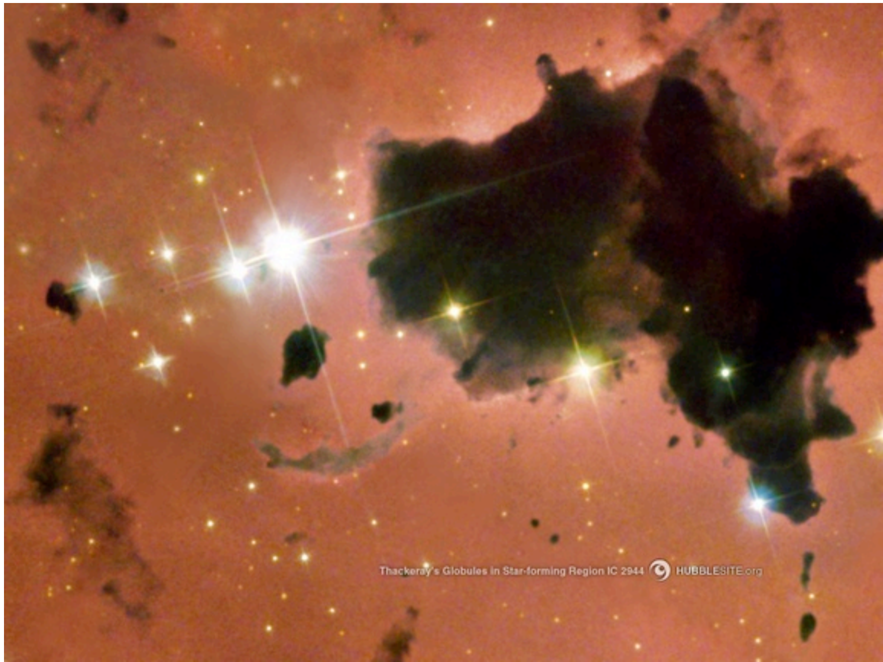
Of course, no one has ever journeyed thousands of light-years from Earth to look back and photograph the Sun's neighborhood, so this is a representative picture from Earth of a part of the sky.

The Sun is faint enough that it would not be easily located in a picture at this scale.

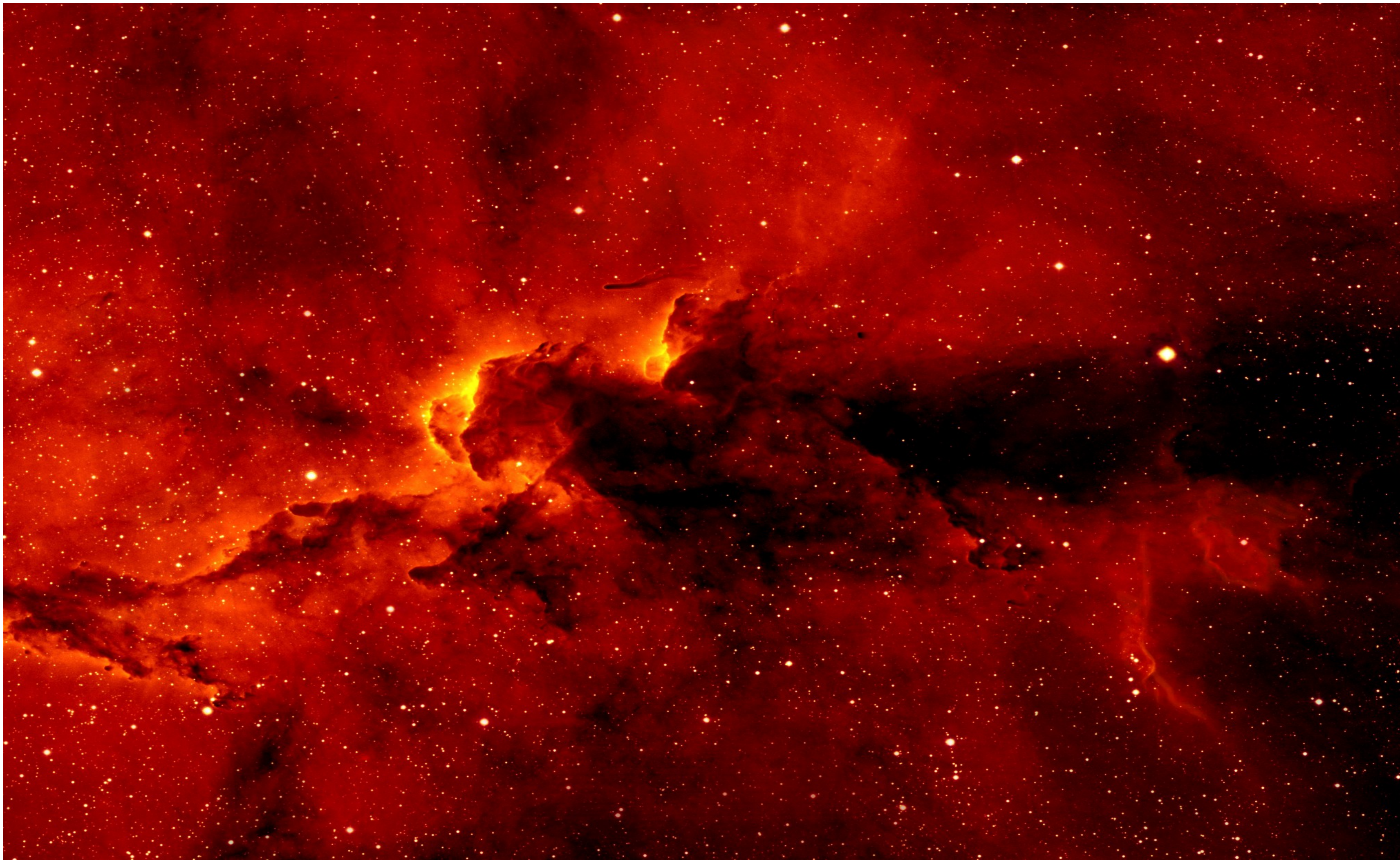
–

Some things that are invisible in this figure are actually critically important.

- You do not see the thin gas that fills the spaces between the stars.
- Although these clouds of gas are thinner than the best vacuum produced in laboratories on Earth, it is these clouds that give birth to new stars.



The Sun formed from such a cloud about 4.56 billion years ago (4.56 Gy ago)



- If you expand your view again, you see our galaxy. It has a **scale of 10^5 pc.**
  - A galaxy is a great cloud or disk of stars, gas, and some dust bound together by the combined gravity of all the matter
  - In fact, some of it is "dark matter", currently unknown type of invisible particles, which interact only through gravitation. (Lots of them are passing through you every second… but it's safe!)

This actually isn't our Galaxy, but a similar one (NGC1232) seen from the top.

Spiral Galaxy NGC 1232 - VLT UT 1 + FORS1

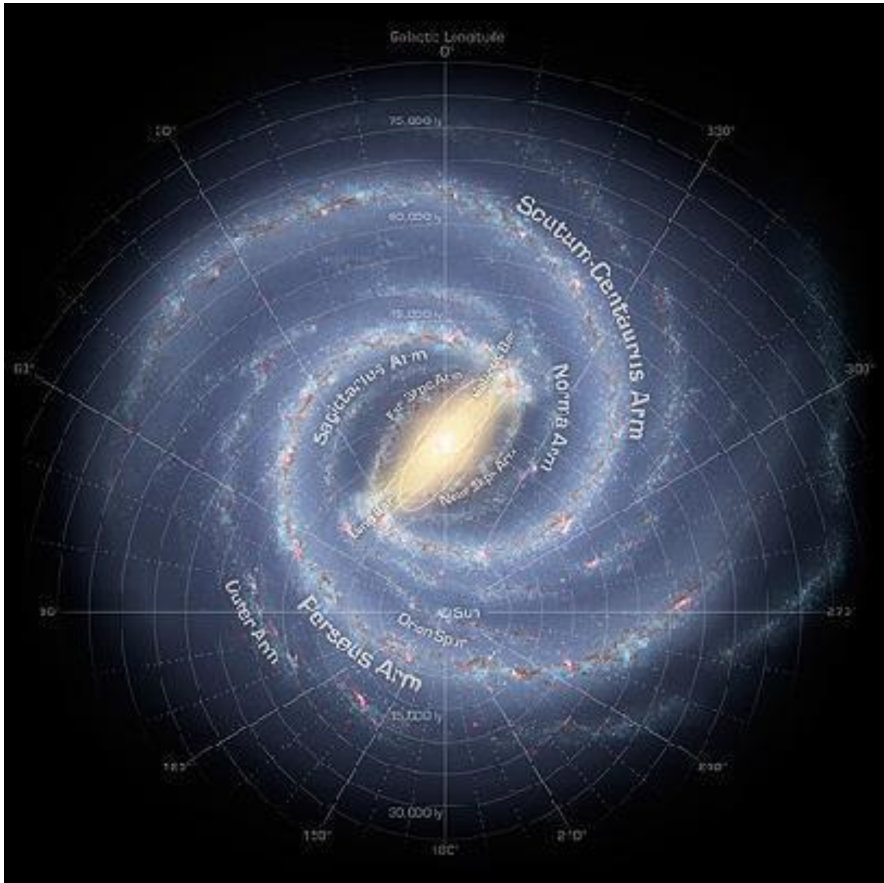
ESO PR Photo 37d/98 (23 September 1998)

From Solar System to Galaxy to Universe

- In the night sky, you see our galaxy from the inside as a great, cloudy band of stars ringing the sky as the Milky Way.
  - Our galaxy is called the Milky Way, Milky Way galaxy, or the Galaxy.

It has a small spindle-like structure in the center called a galactic bar.

Our Sun would be invisible in such a picture, using today's telescopes You would find it about two thirds of the way from the center to the edge.



- Our Galaxy contains over 100 billion stars, (10^{11} stars or 100G stars)
- like many others, it has a set of graceful spiral arms winding outward through the disk.

- NGC7331, similar to MW

From Solar System to Galaxy to Universe

- Each year, a few stars are born in great clouds of gas and dust as they pass through the spiral arms.
  - The disk of our galaxy is roughly 80 000 ly in diameter. We use infrared light to see the center through the dark, dusty clouds

From Solar System to Galaxy to Universe

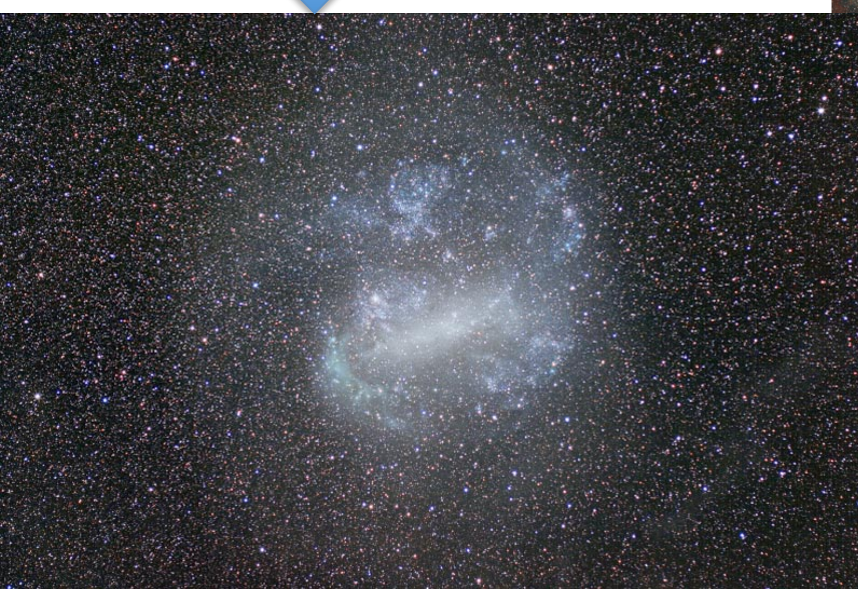
- Only a century ago, astronomers thought that our Galaxy was the entire universe – an *island universe* of stars in an otherwise empty vastness.
  - Now we know that the Milky Way (a.k.a. Galaxy) is not unique; it is a typical galaxy in many respects, although larger than most
  - In fact, ours is only one of a hundred billions (10^{11} or 100G) galaxies scattered throughout the **observable universe**.

From Solar System to Galaxy to Universe

- Other galaxies, for instance the nearby Large Magellanic Cloud galaxy (LMC) also have star formation regions.

Tarantula Nebula

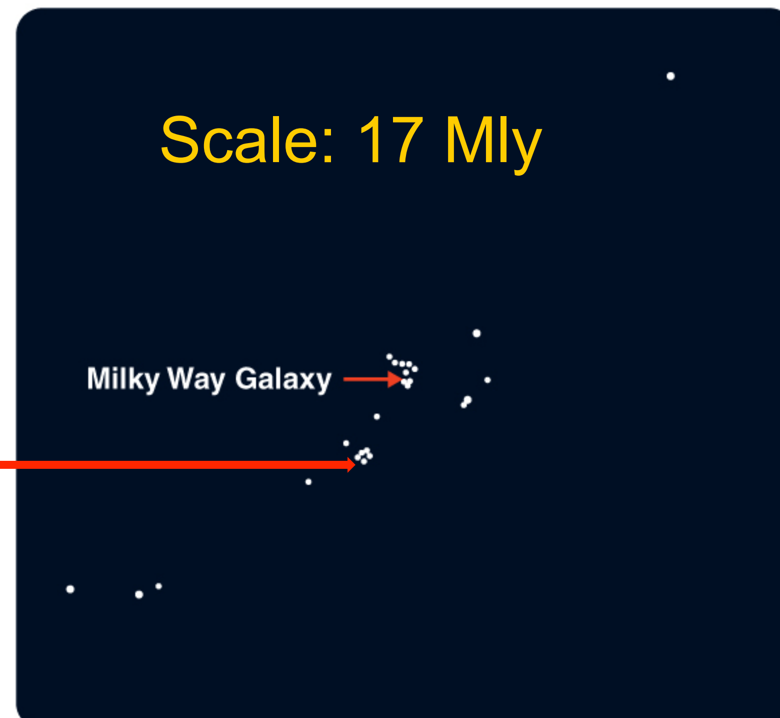
in LMC



Zooming out 100x to the Local Group

- This figure includes a region called Local Group, 17 million ly in diameter. Each of the dots represents a galaxy.
  - Our Galaxy is part of a Local Group of a few dozen galaxies, including the most massive Andromeda (M31)

Figure 1.15



– Some of the galaxies have beautiful spiral patterns like our own galaxy, but others do not

– The general classification scheme of galaxies by Edwin Hubble (who in 1920s observed the fact that galaxies tend to move away from each other):

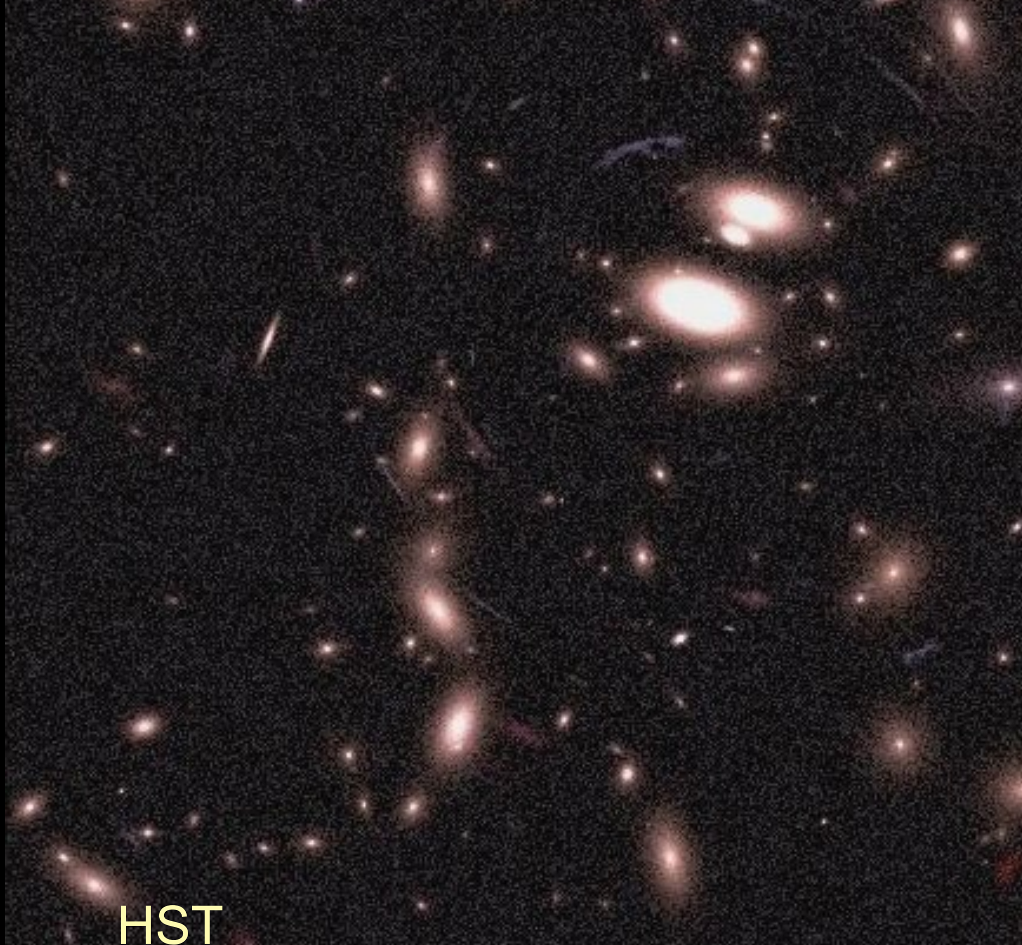
spiral, elliptical (smooth and without arms), or irregular.

A galaxy cluster held together by gravitation.

Galaxies are often found in clusters. We name them after constellations they are in on the sky: Virgo Cluster, Hercules cluster, Coma cluster and so on.

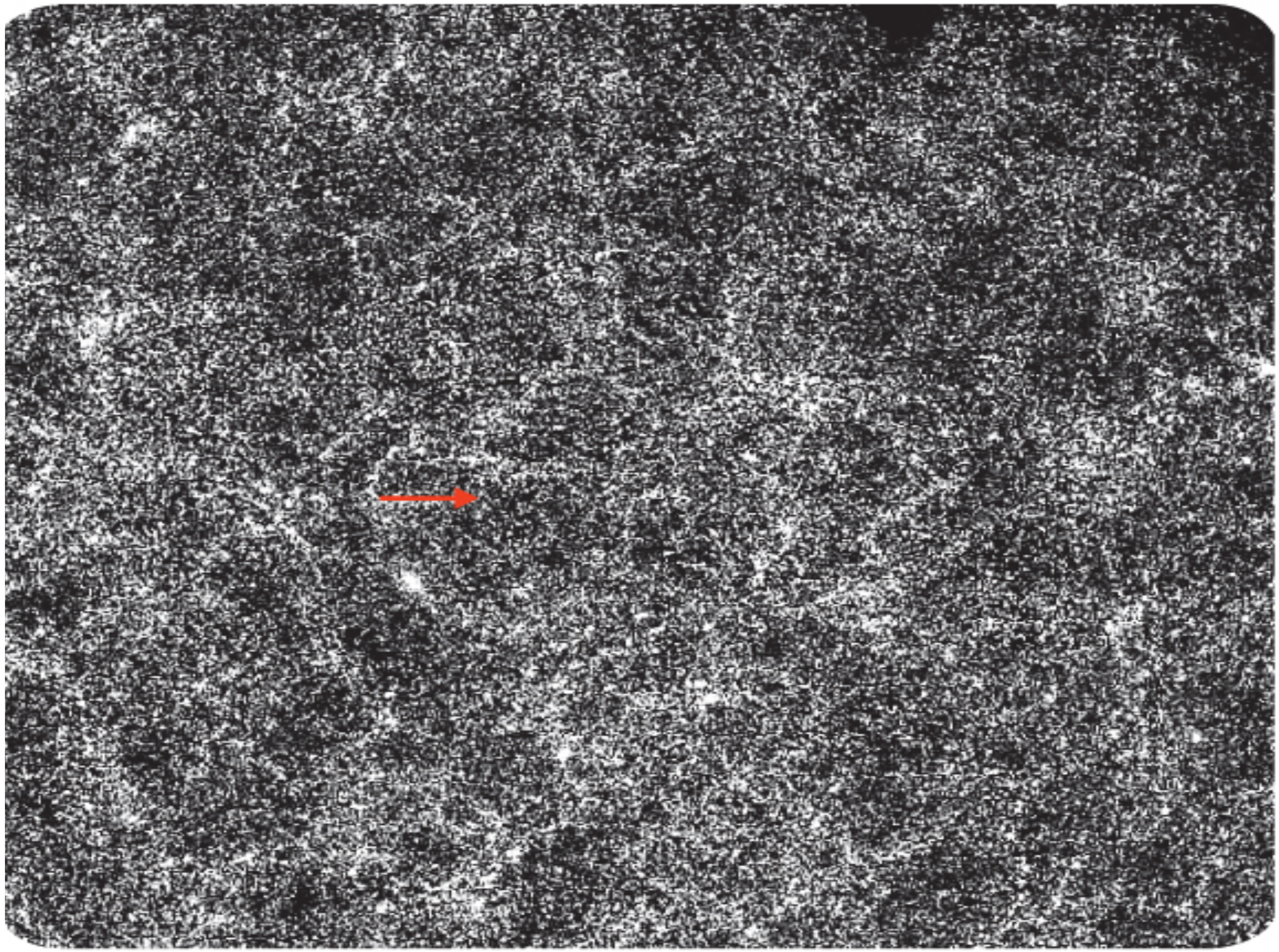
There are also superclusters containing hundreds of cluster, such as Abel supercluster, The Great Attractor etc.

BTW, these pictures show gravitational lensing (arcs) due to dark matter.



From Galaxies to the Universe

This picture represents a view with a diameter of 1.7 Gly (giga light-years, 100 x scale of Local Group of galaxies)

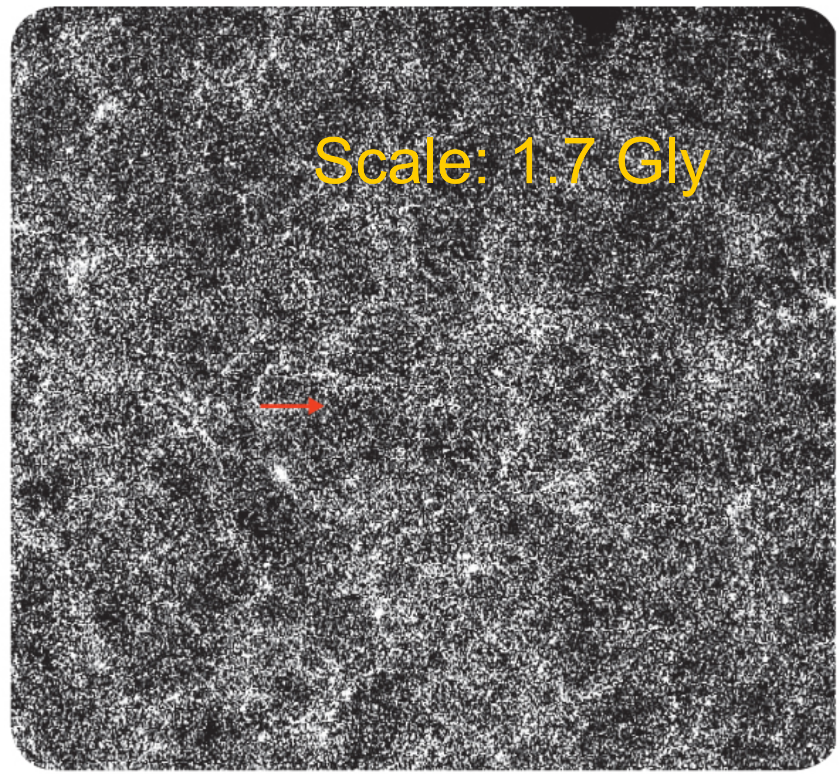


Detail from galaxy map from M. Seldner, B. L. Siebers, E. J. Groth and

Galaxy to Universe

- Clusters of galaxies are connected in a vast network. They are grouped into superclusters – clusters of clusters – and the superclusters are linked to form long filaments and walls outlining voids that seem nearly empty of galaxies.

Figure 1.16

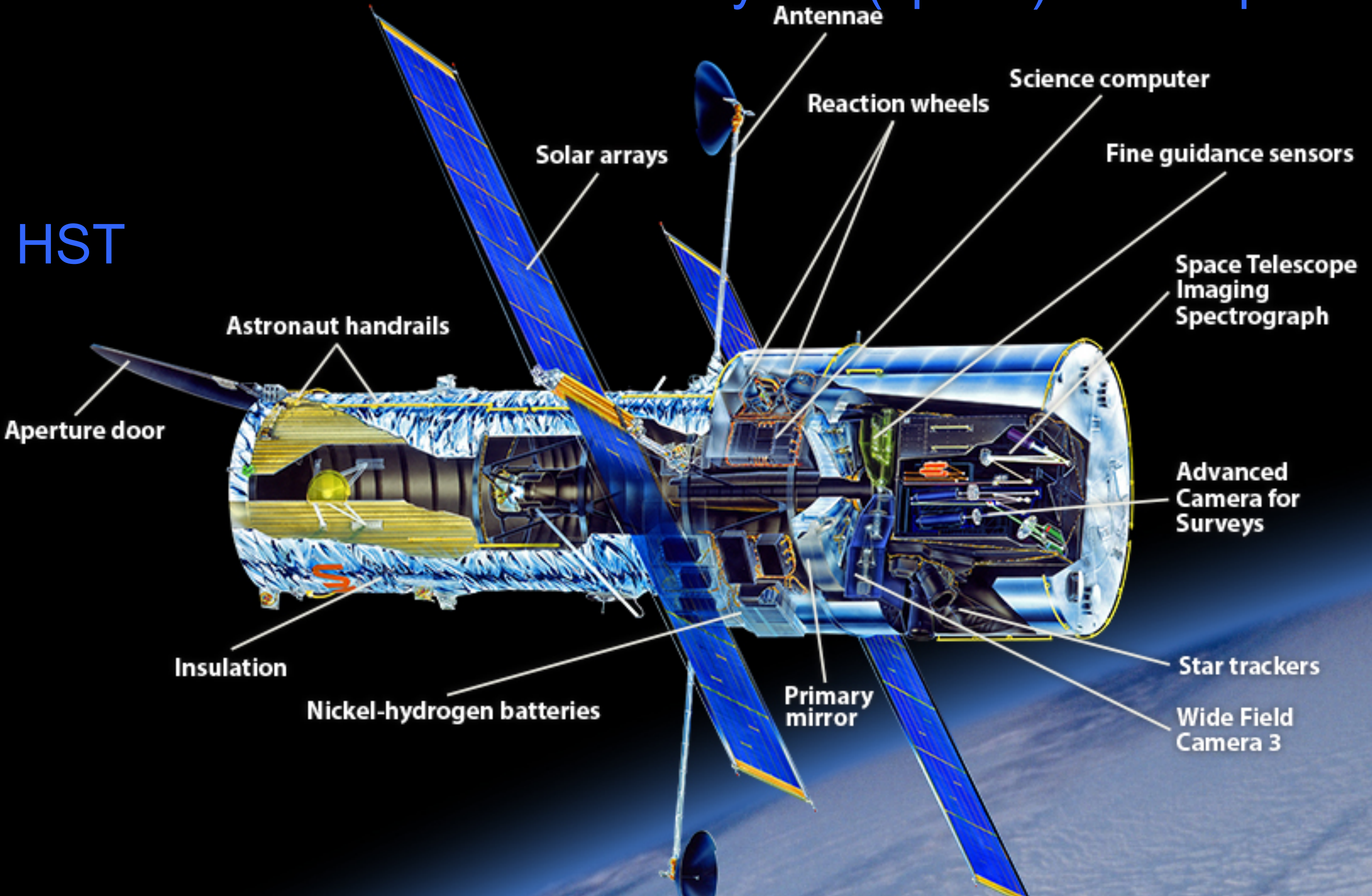


Detail from galaxy map from M. Seldner, B. L. Siebers, E. J. Groth, and

These filaments, walls and voids appear to be some of the largest structures in the universe

INSTRUMENTS for today's Great Moments in Astronomy: (space) telescopes

HST



HST = Hubble Space Telescope & JWST = J.Webb Space Tel.

- https://www.youtube.com/watch?v=--X9zfgZtS0

a 15-min video on the 20th anniversary if Hubble (now is the 32nd !)

- https://www.youtube.com/watch?v=IUDtKcvGcOo

see the HUBBLE ULTRA DEEP FIELD image

Hubble deep field – when HST stared at nothing for 100 hours

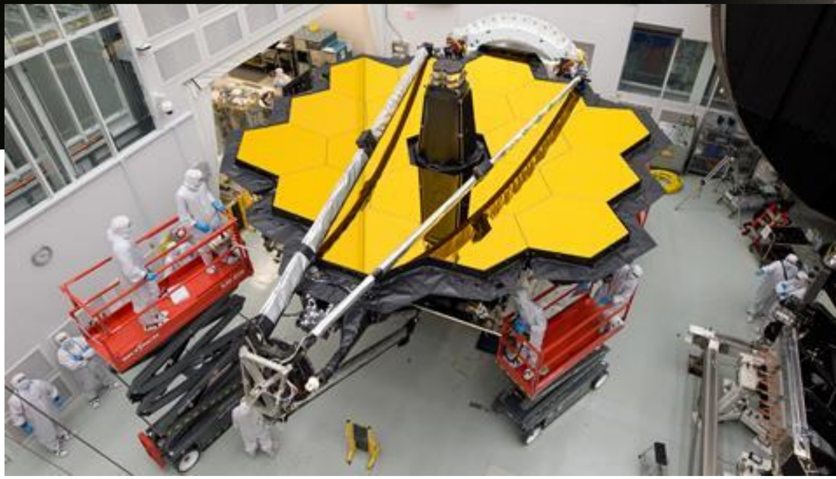
The next great telescope in space: J. Webb Space Telescope, Launched in December 2021; resides far from Earth.

Compare their image quality:

https://www.youtube.com/watch?v=VvDqxFLcZKk

From galaxies to the limits of the observable Universe

J. Webb Space Telescope
(Dec 2021-)



- A mistake found, amog others, in *the*
- *ASTRO textbook (cf.* the list of literature on our course page)

- ~~"The sequence of figures ends here because it has reached the limits of the best telescopes."~~

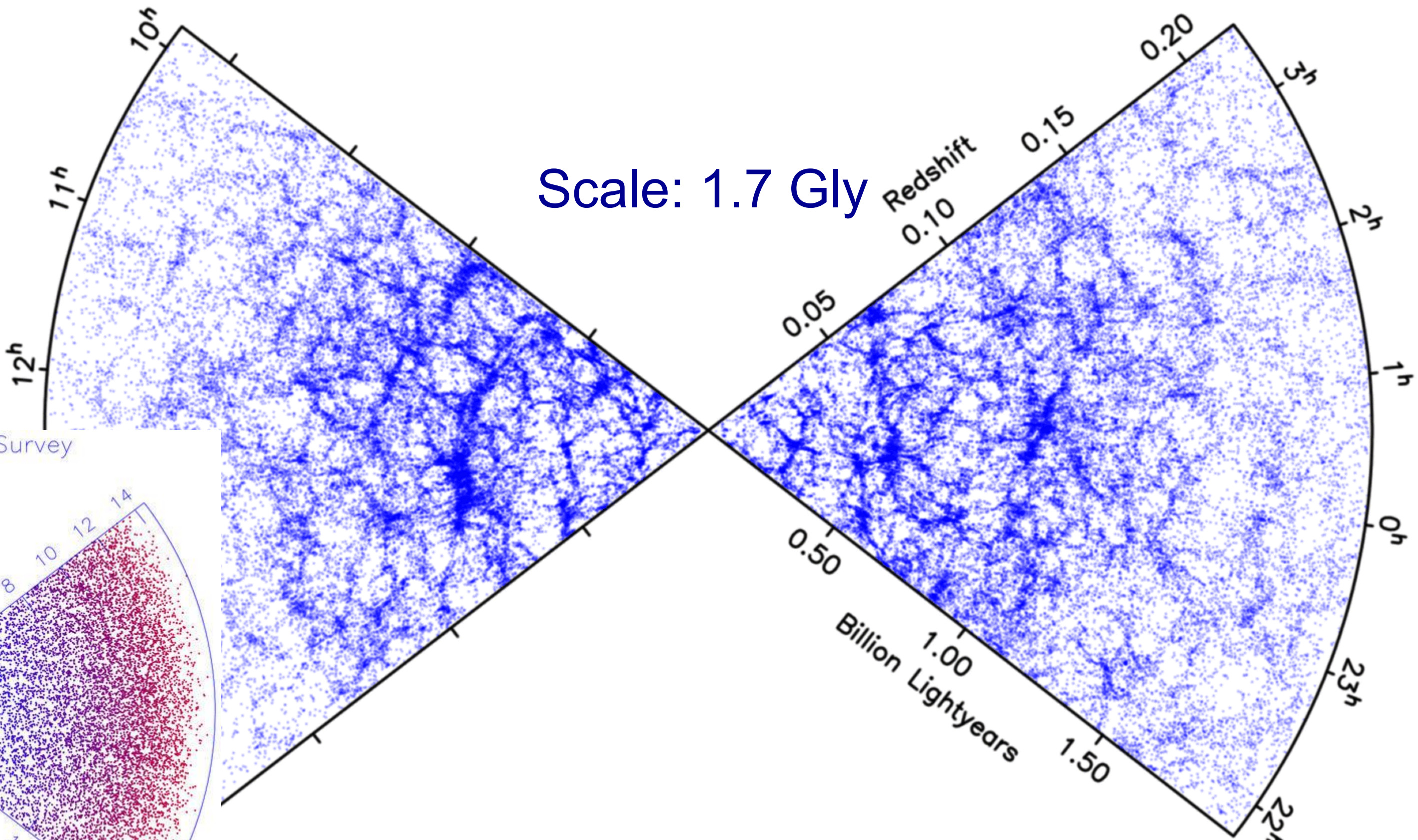
- Better said:
- We have reached the cosmic horizon, at about

  ~ (time since Big Bang) x (speed of light) = 14.3 Gyr * 1 ly/yr = 14.3 Gly
- Light travels only so far in the age of universe… it actually moves pretty
- slowly...
- The actual size ('diameter') of the universe is larger than indicated above, because the universe (vacuum) expands faster than light in its distant parts. Very distant parts are not able to communicate. When we see the furthest objects, they have already moved away from us and will never hear from us.

Limit of observable universe: dozens of billion light years across

- We are not (and will never be) able to look at pictures 10x larger than those below. This the largest "Google Map" there is, because of the finite speed of light. This is the end of our journey through distance scales. Beyond those scales lies much of the Cosmos, which however cannot be seen.

Scale: 1.7 Gly



Scale: 14 Gly