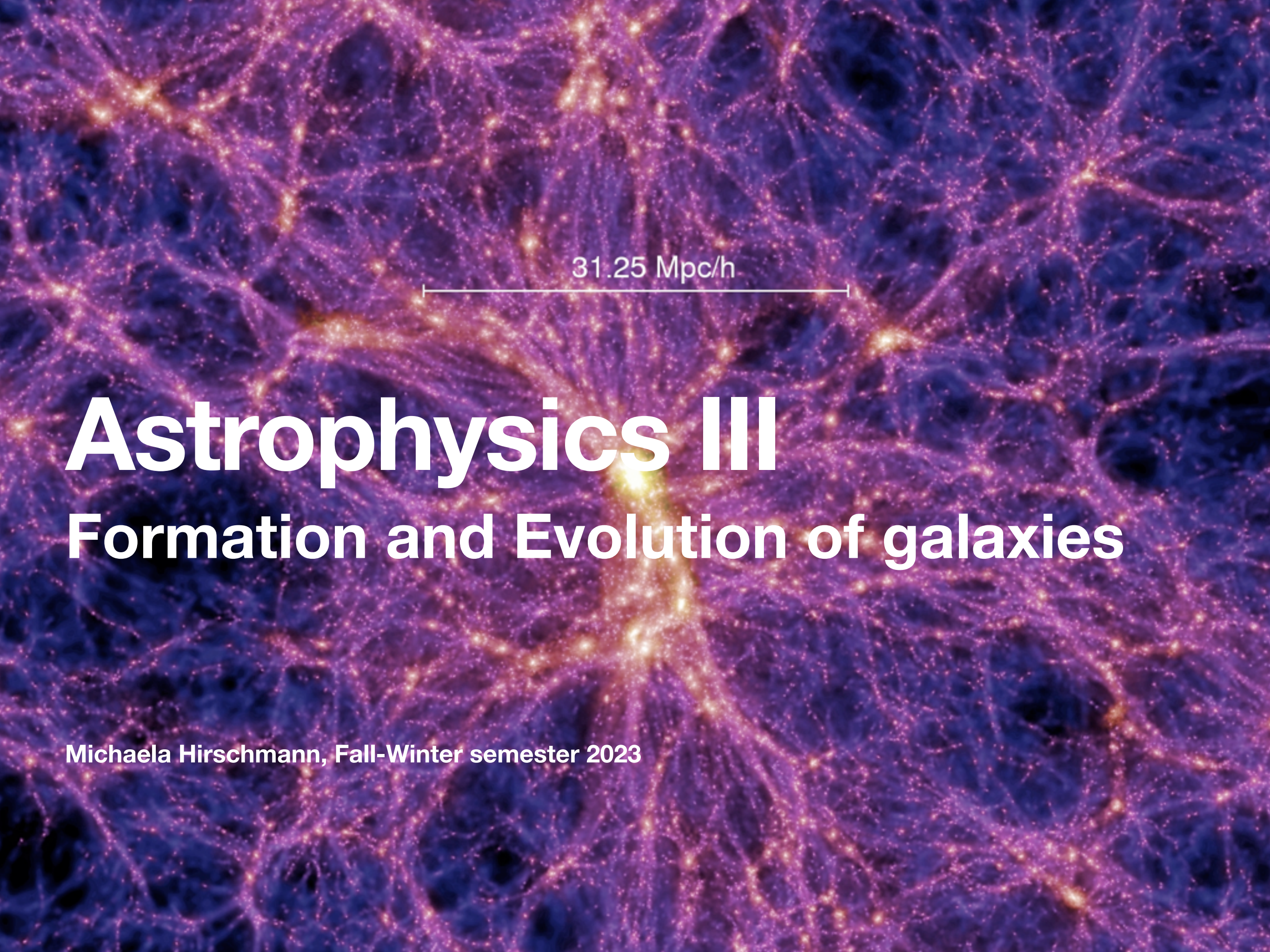


A visualization of the cosmic web, showing a complex network of filaments and clusters of galaxies. The filaments are represented by thin, glowing purple lines, while the clusters are denser regions of orange and yellow light. The background is a deep blue.

31.25 Mpc/h

Astrophysics III

Formation and Evolution of galaxies

Michaela Hirschmann, Fall-Winter semester 2023

A bit about me...

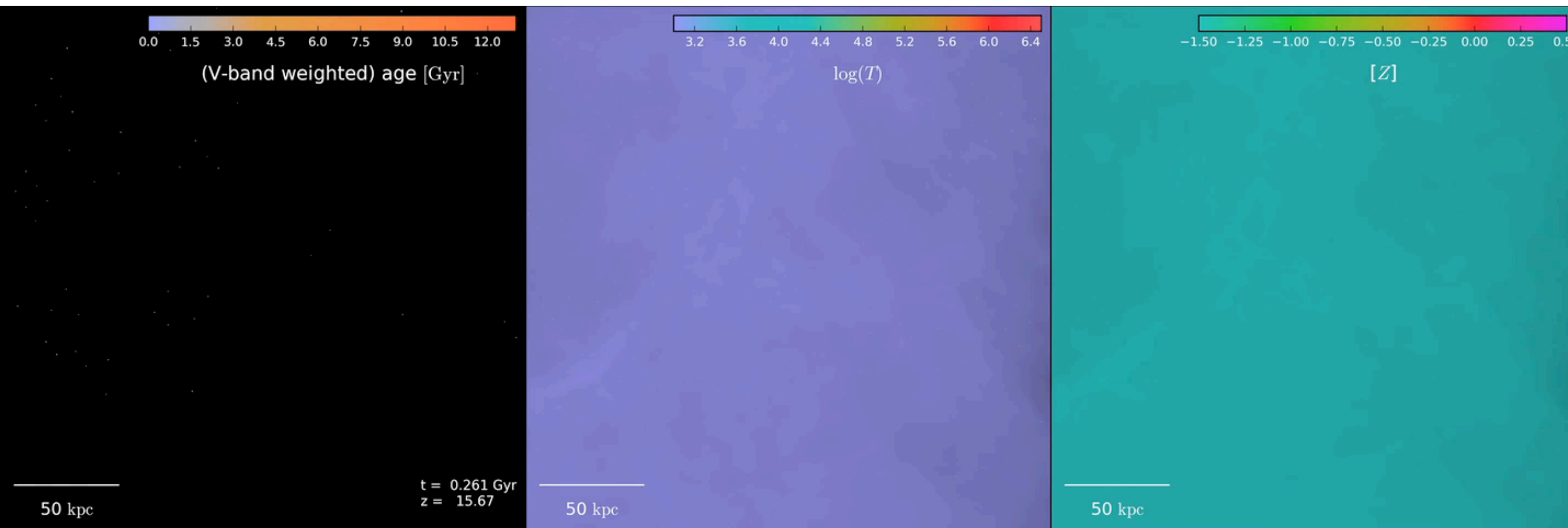
- Assistant Professor at EPFL, leading the GALSPEC laboratory and a PRIMA research group (4PD, 3PhD, several master students)
- Before: Assistant Professor and Visiting Professor at U. Copenhagen and Vienna
- Postdocs at INAF—Trieste Observatory, CNRS—Astrophysical institute of Paris
- PhD at Max Planck Institute for Extraterrestrial Physics and University Observatory Munich, LMU

GALSPEC Team



A bit about me...

- Our main research interests:
 - Different unsolved questions of galaxy formation and evolution
 - Theoretical/numerical modelling (in a cosmological context)
 - Supermassive black holes and active galactic nuclei
 - High-redshift galaxies
 - Interface between simulations and observations to closely link them to enable a meaningful comparison of obs.
- <https://www.epfl.ch/labs/galspec/prof-michaela-hirschmann/>



Your turn...



Your name?

Year, MAI/MA3?

Major subject(s)?

Pre-knowledge in Astrophysics astro-I/astro-II?

Your motivation, why are you here?

What do you expect from this course?

Why this Astro course?

- One introductory course at the bachelor level
 - Astro-I (Basics, Solar system, star formation and stellar evolution, the interstellar medium, galaxy classification, and the basics of cosmology) — F Courbin — now JP Kneib
- Four courses at the master level
 - Astro-II (electromagnetic radiation, energetic processes, basic concepts for stellar astrophysics) — P Jablonka — **not this term!**
 - Astro-III (Formation and evolution of galaxies, observational and theoretical facts) — M Hirschmann
 - Astro-IV (Galactic Dynamics, stellar orbit theory and collision-less systems) Y Revaz
 - Astro-V (Observational cosmology and gravitational lensing) JP Kneib

Big questions in the field

- ✳ How do galaxies come into existence, and how do they evolve?
 - ✳ Which physical mechanisms affect/drive the evolution of galaxies, what leads to the observed diversity of galaxies?
 - ✳ What can we learn from observations and numerical simulations about galaxies and their properties at different cosmic epochs?
-
- ➡ Applying different physical disciplines (e.g., atomic & particle physics, thermodynamics, electrodynamics, mechanics, fluid dynamics, etc.)
 - ➡ First extragalactic “nebulae” conclusively discovered only a century ago, since then tremendous progress: “golden age of galaxy-evolution research”
 - ➡ Comprehensive, complex & rapidly expanding field within astrophysics

Lecture details

Cursus	Sem.	Type	Language of teaching	Credits	Session	Semester	Exam	Workload	Weeks	Hours
Ing.-phys	MA1, MA3	Opt.	English	4	Winter	Fall	Oral	120h	14	4 weekly
Physicien	MA1, MA3	Opt.								
Space technologies minor	H	Opt.								
			Lecture	2 weekly						
			Exercises	2 weekly						

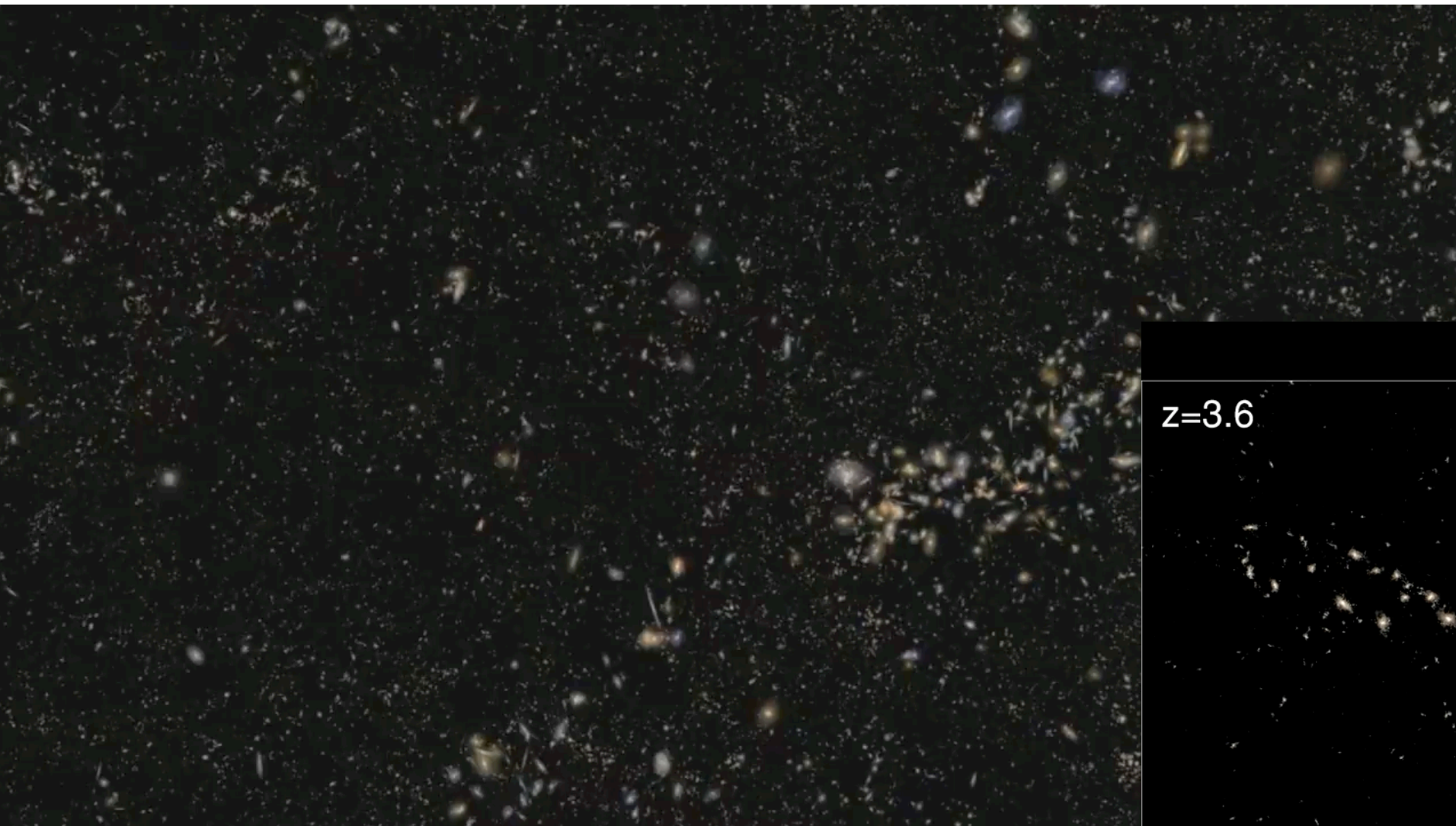
- When? Fridays 10-12am, 1-3pm (actual start: 10.15am and 1.15am), **zoom line will be provided**

NO exercise today!

- Where? **CE1104**
- Learning Pre-requisites: Bachelor in physics or mathematics, Astrol, Astroll, basic python knowledge
- Assessment methods: oral exam (100%) at the end of the course
- Learning Outcomes:
 - Acquire basic knowledge of observational facts of galaxies near & far
 - Theorise basic principles leading to the formation of a galaxy and affect its continued evolution

At the end of the course...

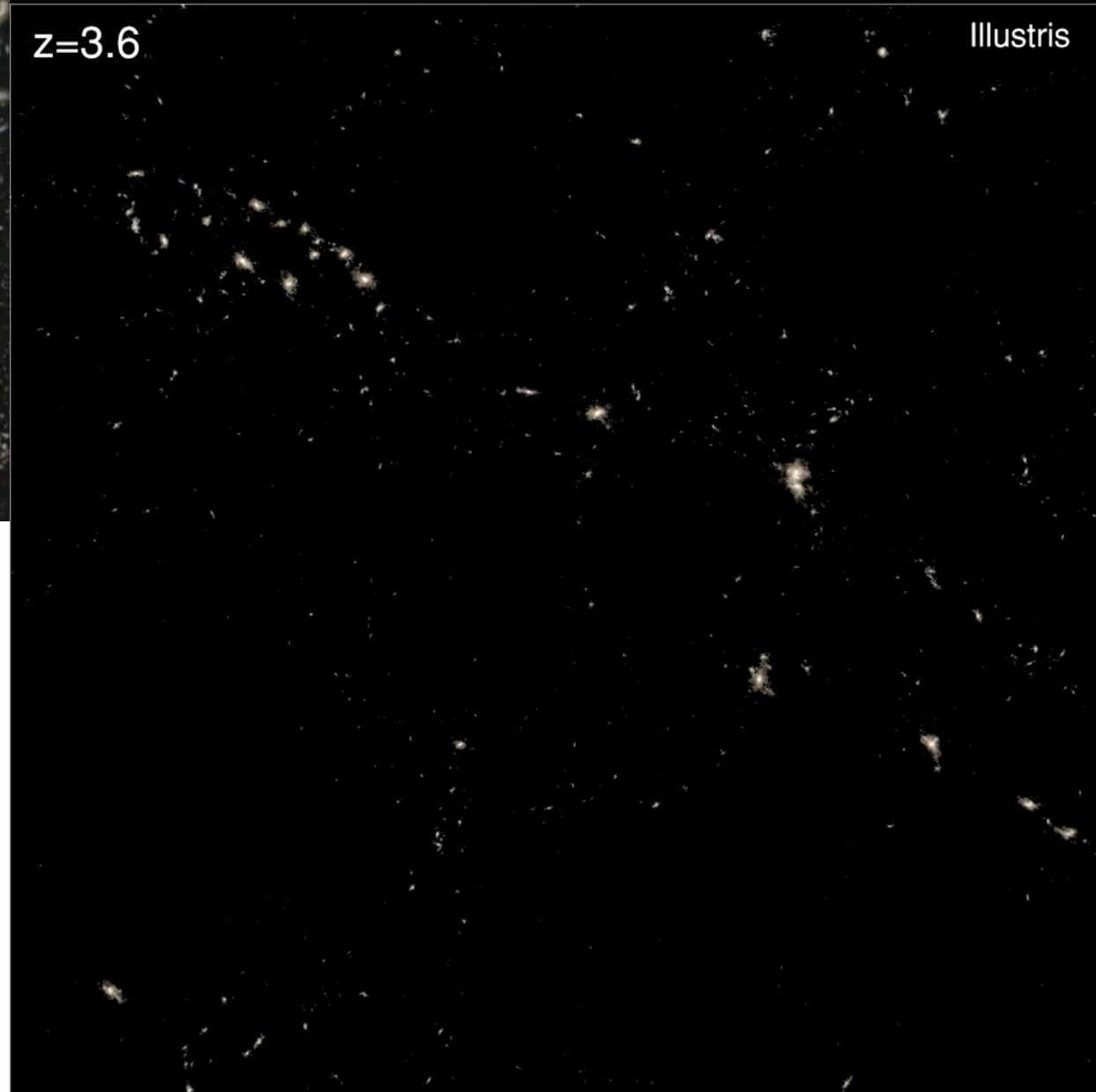
... you will understand
what you see here



galaxies are at the nexus
between the large scales
of the cosmic web and the 'small'
scales of stars and planets

$z=3.6$

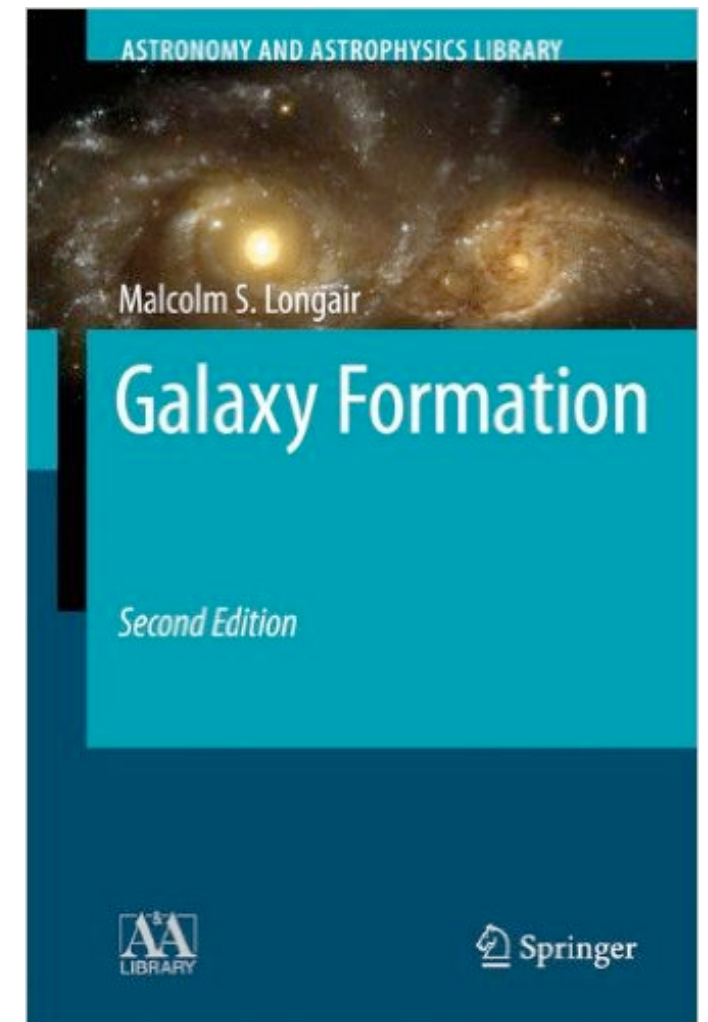
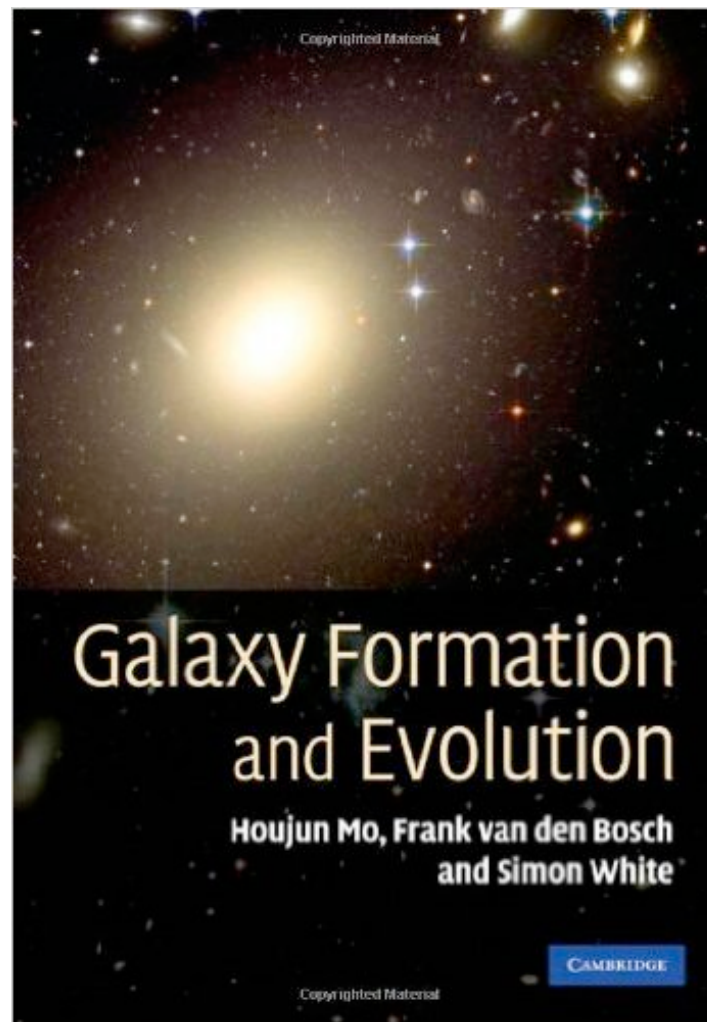
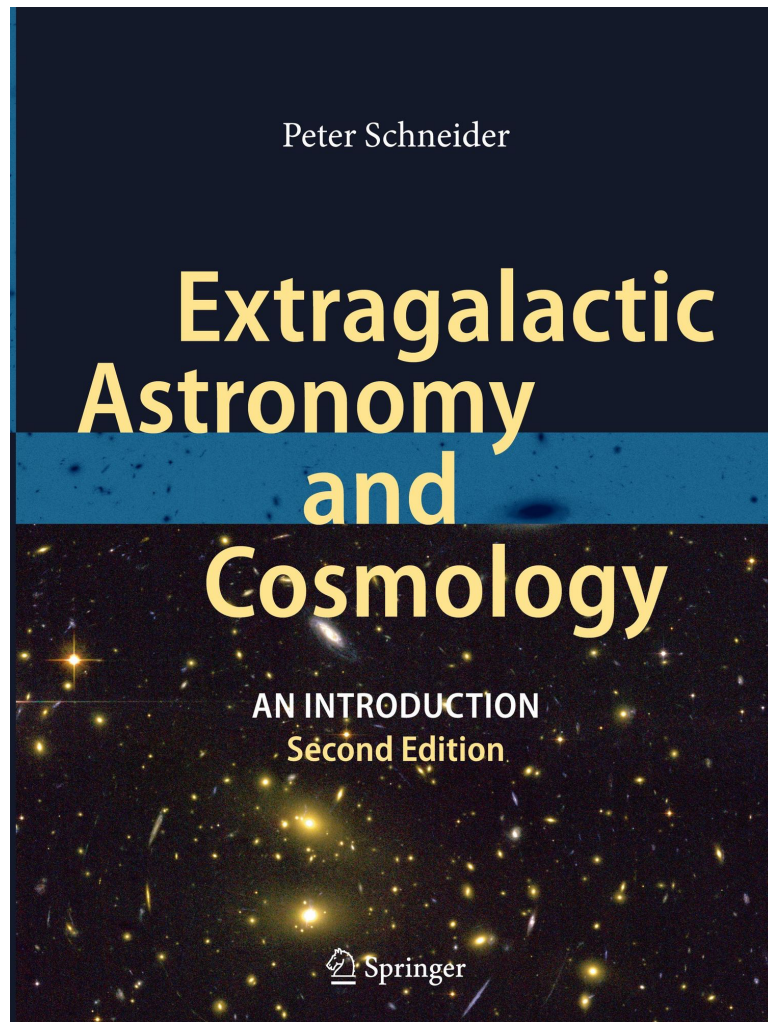
Illustris



What to expect from this course?

- Introduce you to the basics for galaxy formation, including both observations and models
- Give you an overview about the current state of the art in galaxy formation, which are the main successes, challenges, failures, and future directions
- Prepare you for scientific working (master/semester thesis) by (i) reading and understanding scientific journals and (ii) learning how to analyse and interpret data sets from real observations/simulations
- Maybe motivate you for a semester/master thesis in this field?
—> TALK TO ME! <https://www.epfl.ch/labs/galspec/practical-works-and-master-projects/>

Literature for this course



Literature:

- Schneider: Extragalactic astronomy and cosmology (sec. edition), 2015
- Mo, van den Bosch & White: Galaxy formation and evolution, 2010
- Longair: Galaxy formation (Third edition), 2023

Exercise sessions...

- Exercises will deepen your understanding of the lecture content and will allow you to get experience with observational and simulation data.
- Analytic calculations & analysis of observational data and numerical simulations (requires some literature search and reading)
- Exercise tasks provided each week (moodle) to discuss and work on at home.
- Solutions to the exercises (in your notebooks) will be discussed in the exercise sessions. The first 10min of each exercise session solutions will be explained.
- If interested, reading suggestions of scientific articles are provided for each lecture topic (no subject of the oral exam)

I strongly suggest to attend and work through the exercise sessions, as their content will be part of the final oral exam!!



Lucie Scharre



Jonathan Petersson

Any questions to the course?

Lecture content and schedule

- *Chapter 1:* Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2:* Brief review on stars
- *Chapter 3:* Radiation processes in galaxies and telescopes;
- *Chapter 4:* The Milky Way
- *Chapter 5:* The world of galaxies I
- *Chapter 6:* The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies
- *Chapter 10:*
 - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11:*
 - Dark matter and the large-scale structure
 - Cosmological N-body simulations of dark matter
- *Chapter 12:* Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14:* Gas cooling/heating and star formation
- *Chapter 15:* Stellar feedback processes
- *Chapter 16:* Black hole growth & AGN feedback processes
- *Chapter 17:* Modern simulations & future prospects

Part I:
Observational
basics & facts of
galaxies
first 7 lectures

Part II:
Theory & models
of
galaxy evolution
processes
second 7 lectures

Outline of Chapter I — Introduction



- What is a galaxy?
- Astrophysical scales
- Basic Observable quantities

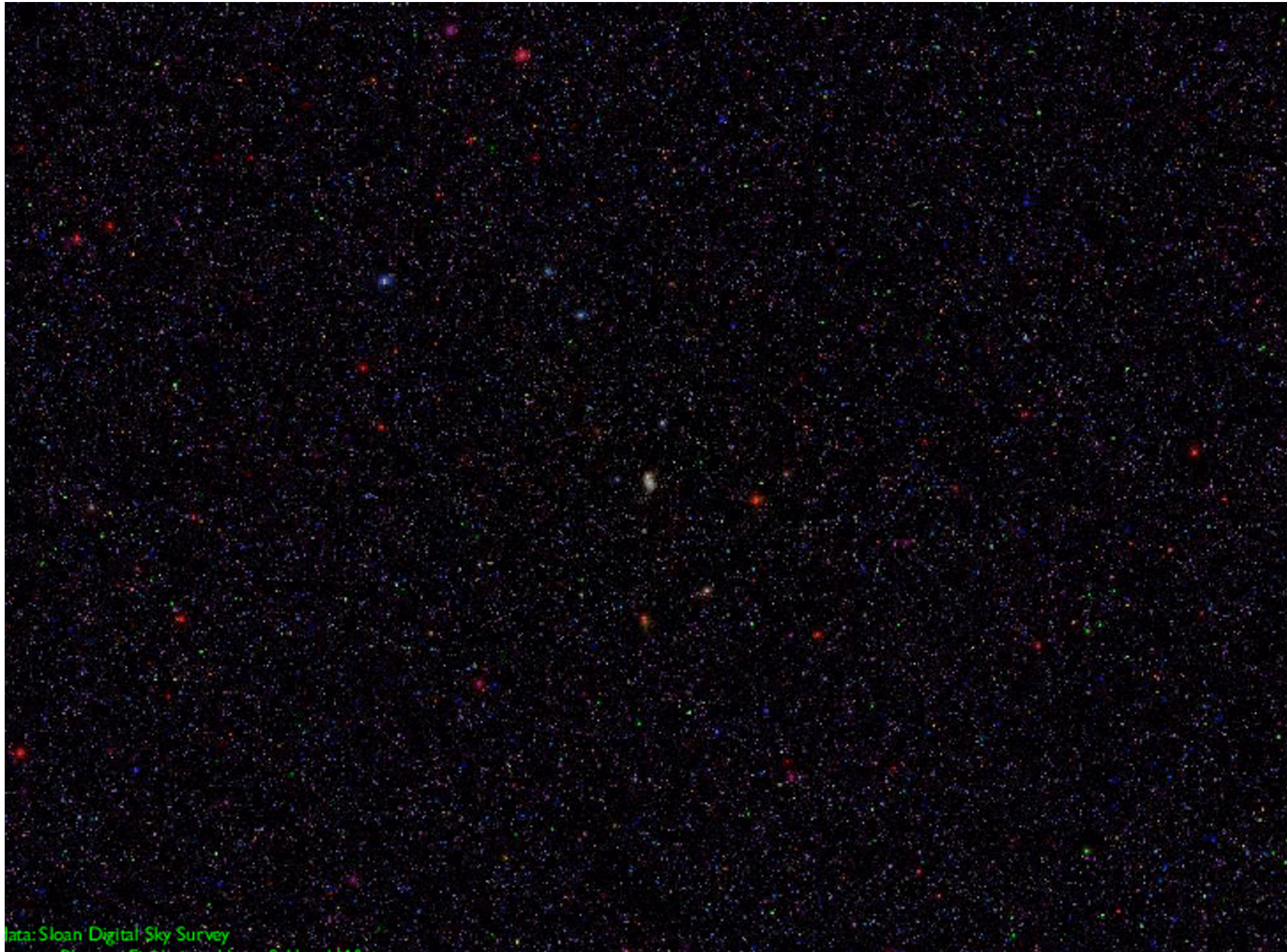
What is a galaxy?

How do observers tell the difference between a planet, a star, and a galaxy?

- Planets:
 - reflect light (similar phases as the moon);
 - specific motion on the sky wrt fixed background stars;
 - bright, steady apparent disks, no twinkling
- Stars:
 - luminous spheres of plasma, produce own light;
 - relatively constant positions relative to each other;
 - point-sources and “twinkle” due to atmospheric effects
- Galaxies:
 - NO noticeable motion over short timescales,
 - NO point-sources, extended structure, faint, fuzzy patches of light

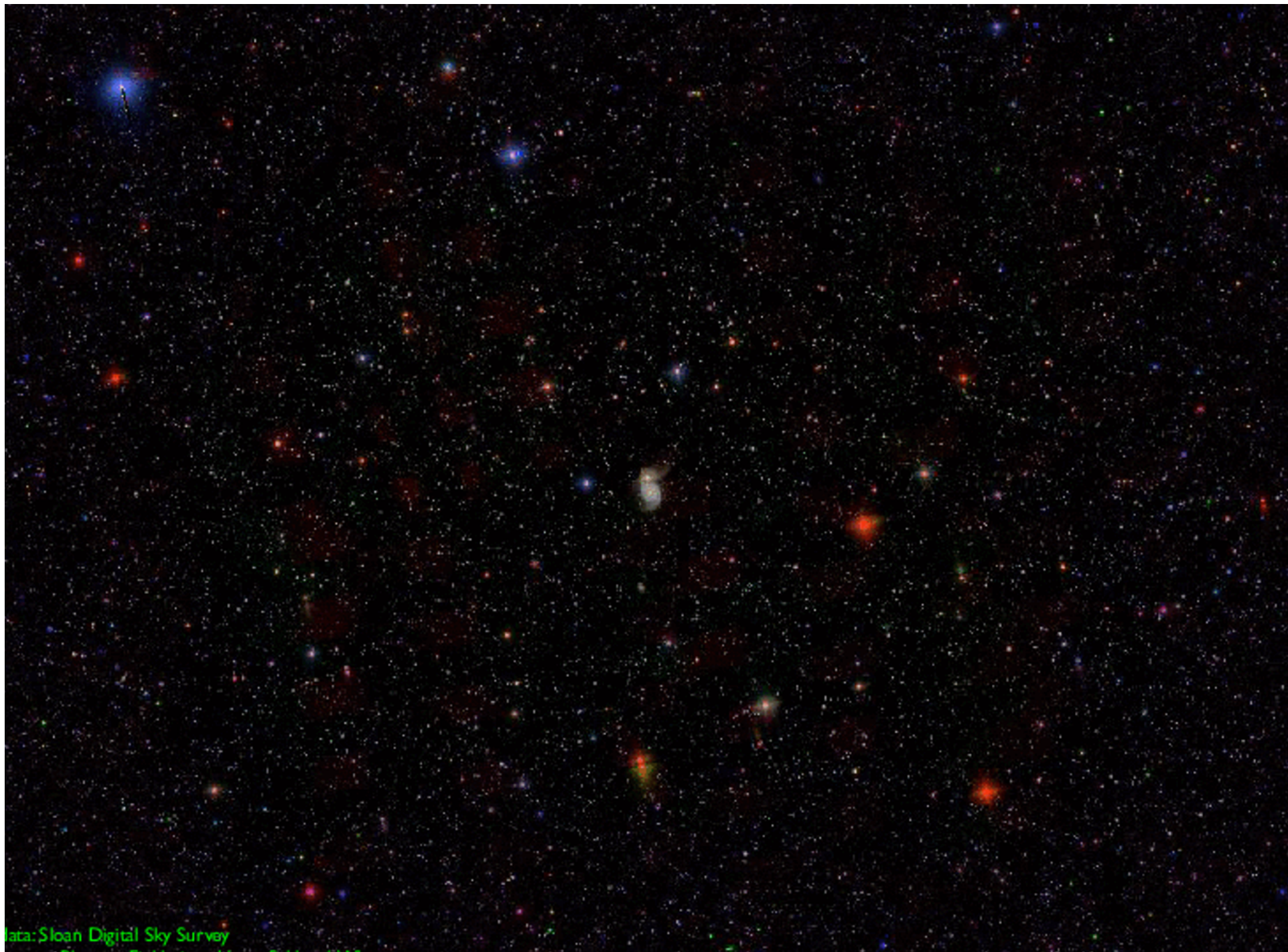
What is a galaxy?

- how do observers tell the difference between a planet, a star, and a galaxy?



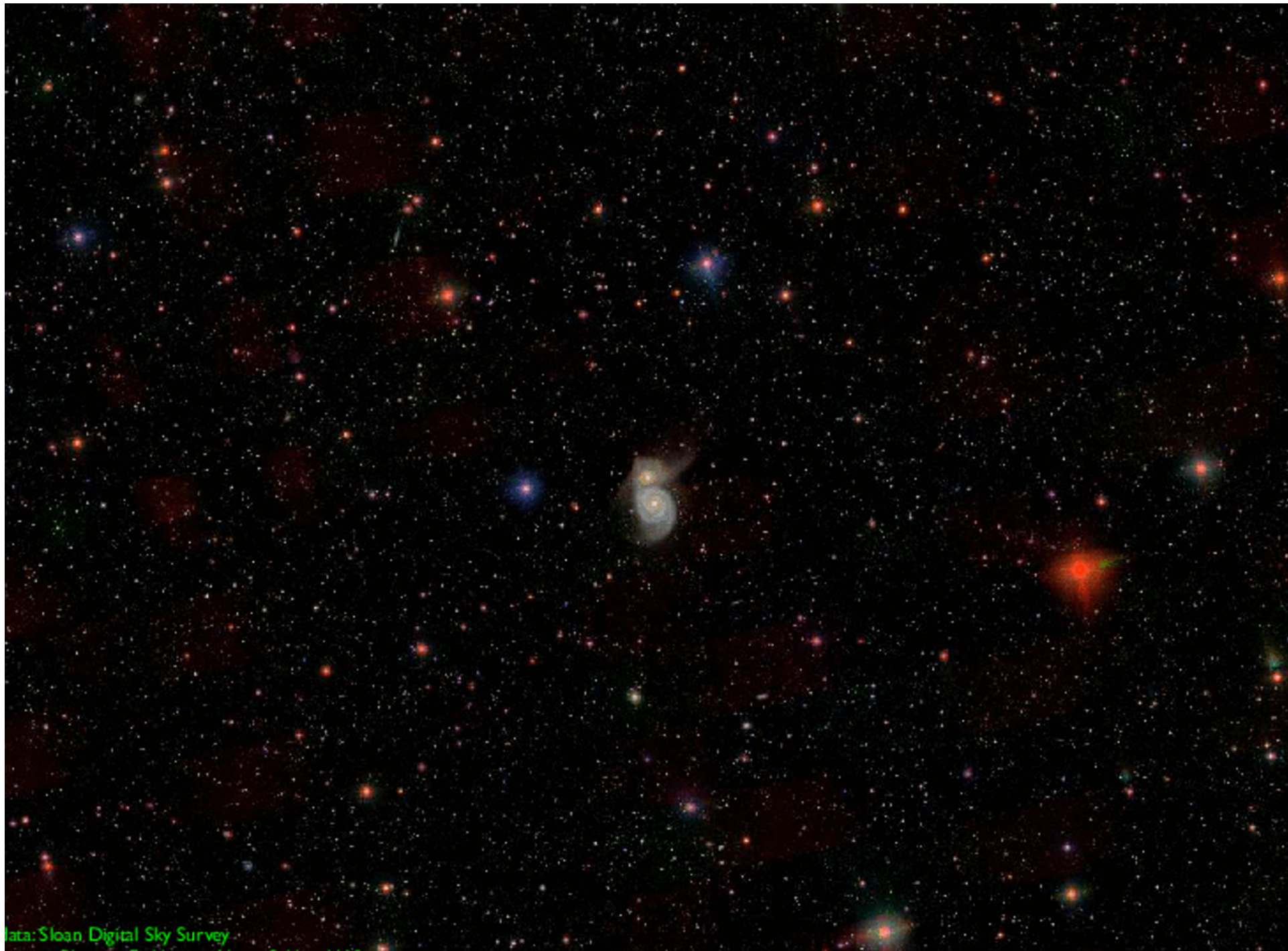
What is a galaxy?

- how do observers tell the difference between a planet, a star, and a galaxy?



What is a galaxy?

- how do observers tell the difference between a planet, a star, and a galaxy?



What is a galaxy?

- how do observers tell the difference between a planet, a star, and a galaxy?



What is a galaxy?

- how do observers tell the difference between a planet, a star, and a galaxy?



What is a galaxy?



- what is our modern conceptual definition of a galaxy?

What is a galaxy?

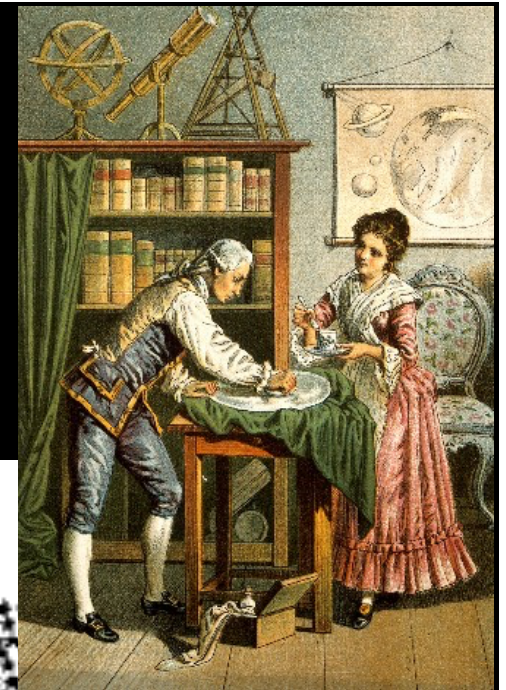
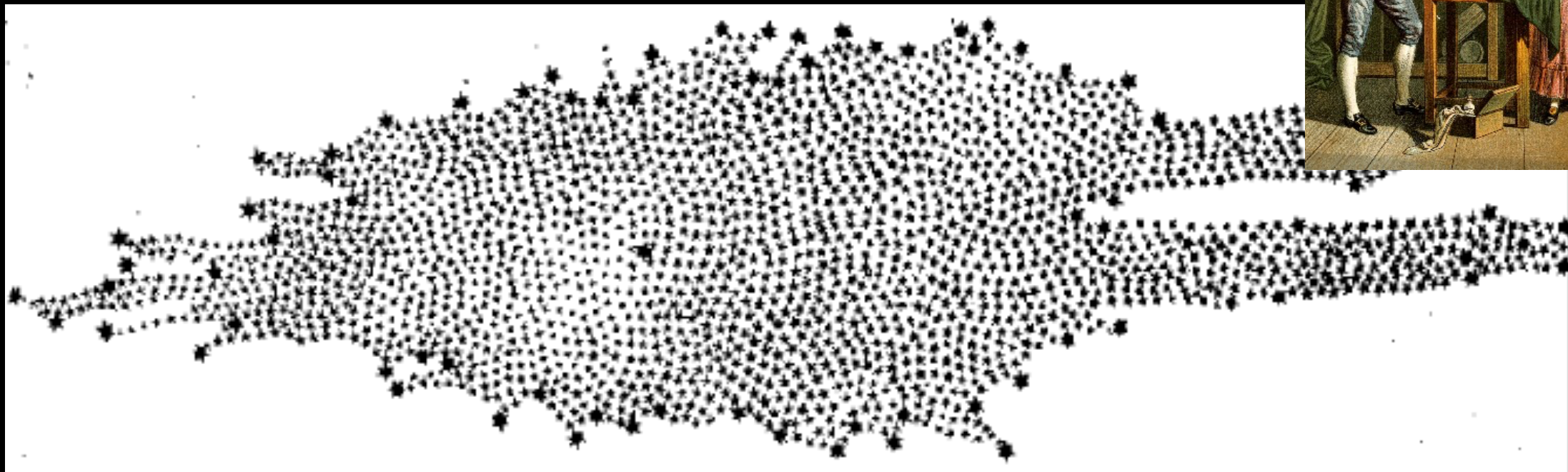


- what is our modern conceptual definition of a galaxy?
 - ➡ **A gravitationally bound collection of stars, gas, dust and dark matter**

Our Milky Way galaxy



Our Milky Way galaxy



The shape of our Galaxy as deduced from star counts by William Herschel in 1785; the solar system was assumed near center.

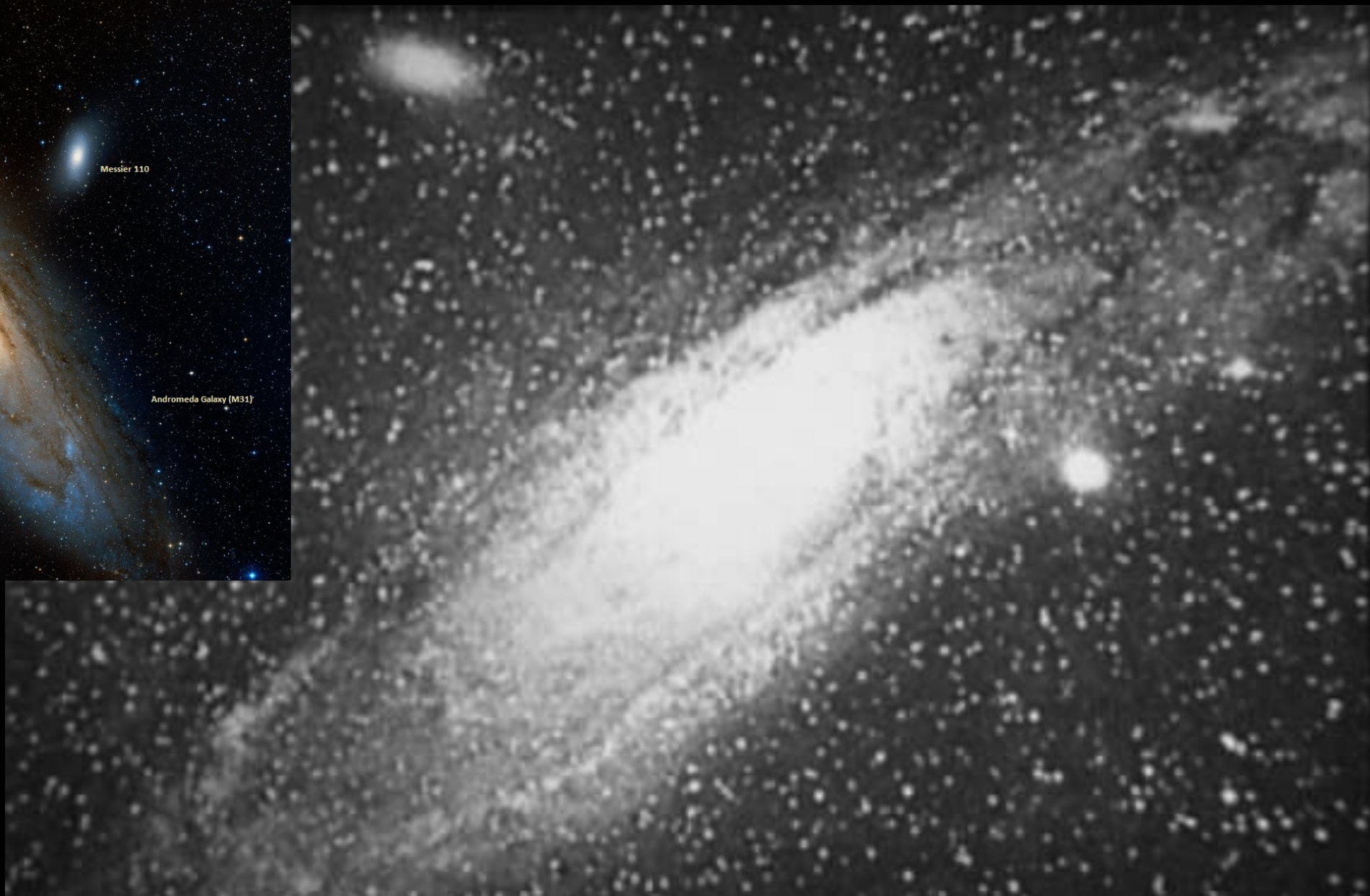
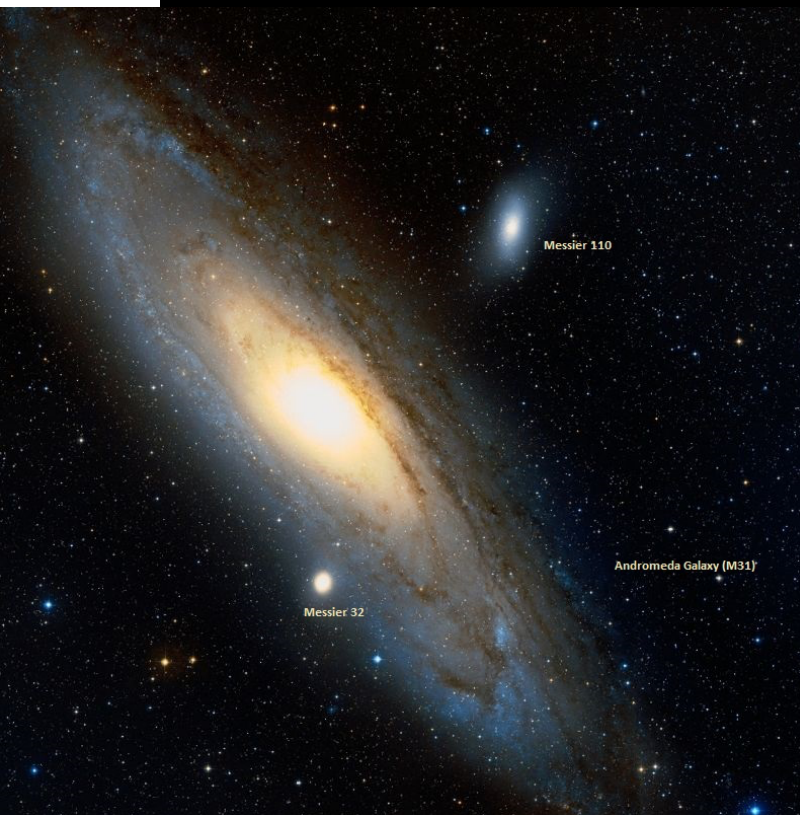
Nearby galaxies



sketch of M51 by Lord Rosse, 1845

Nearby galaxies

- The very first non-MW, “galaxy” nebulae, Andromeda galaxy, was already observed around 900 by Abd al-Rahman al-Sufi
- Observed over and over again, but true shape not realised until...



photograph of the “Great Andromeda Nebula” from 1899

Foundation of extra-galactic Astrophysics

- Since 900: Repeated observations of “galaxy” nebulae
- 19th century: drawings/images of nebulae
- 1915: General relativity by Einstein
- 1916: Vesto Slipher showed that local “nebulae” are receding from us
- 1920: The “great debate” between Harlow Shapley and Heber Curtis at Museum of Natural History in Washington: Galactic or extragalactic nature of “spiral nebulae”?
- 1922: GR combined with cosmological principle, Friedmann equations are derived (different scenarios for the evolution of the Universe)
- 1925: Hubble showed that some of observed “nebulae” are extragalactic (using distances from Cepheid variables),

➡ **Start of extra-galactic astrophysics**

Outline of Chapter I — Introduction



- What is a galaxy?
- Astrophysical scales and units
- Basic Observable quantities

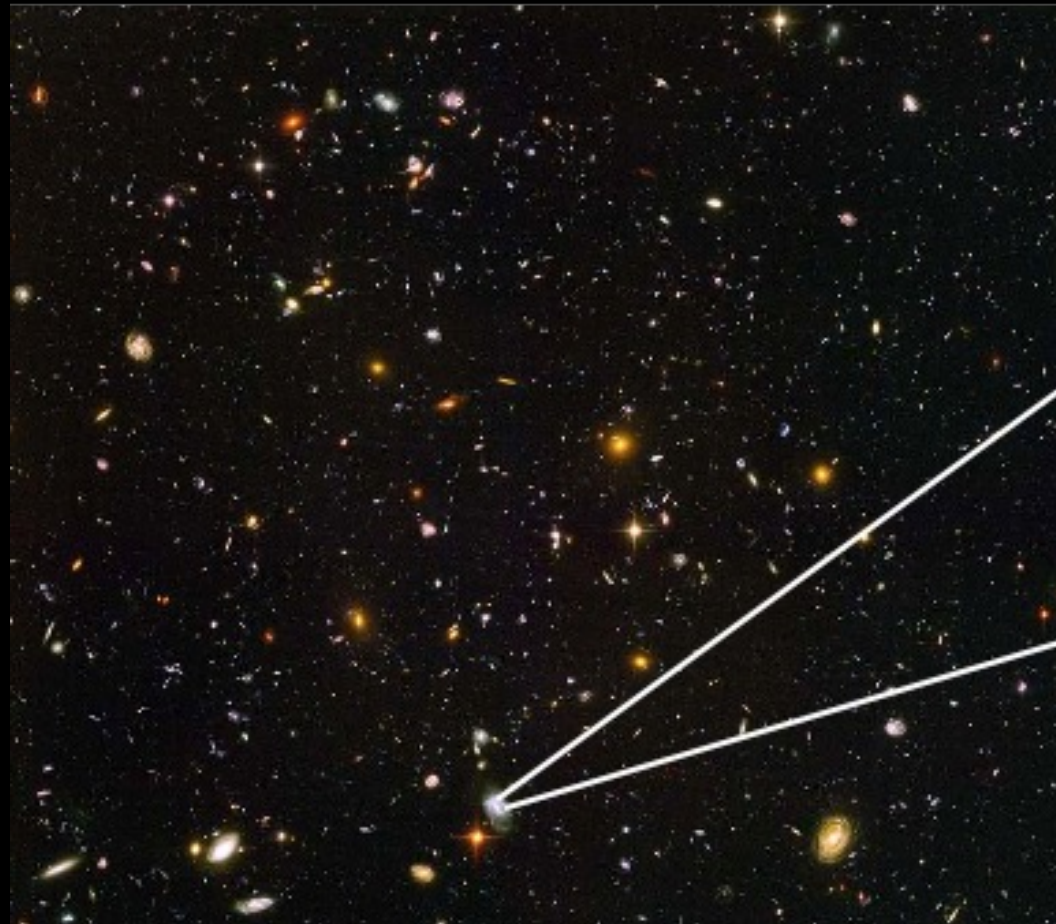
Astrophysical scales

A sense of scale...

$\sim 10^9$ m



How many stars are there in our Galaxy?



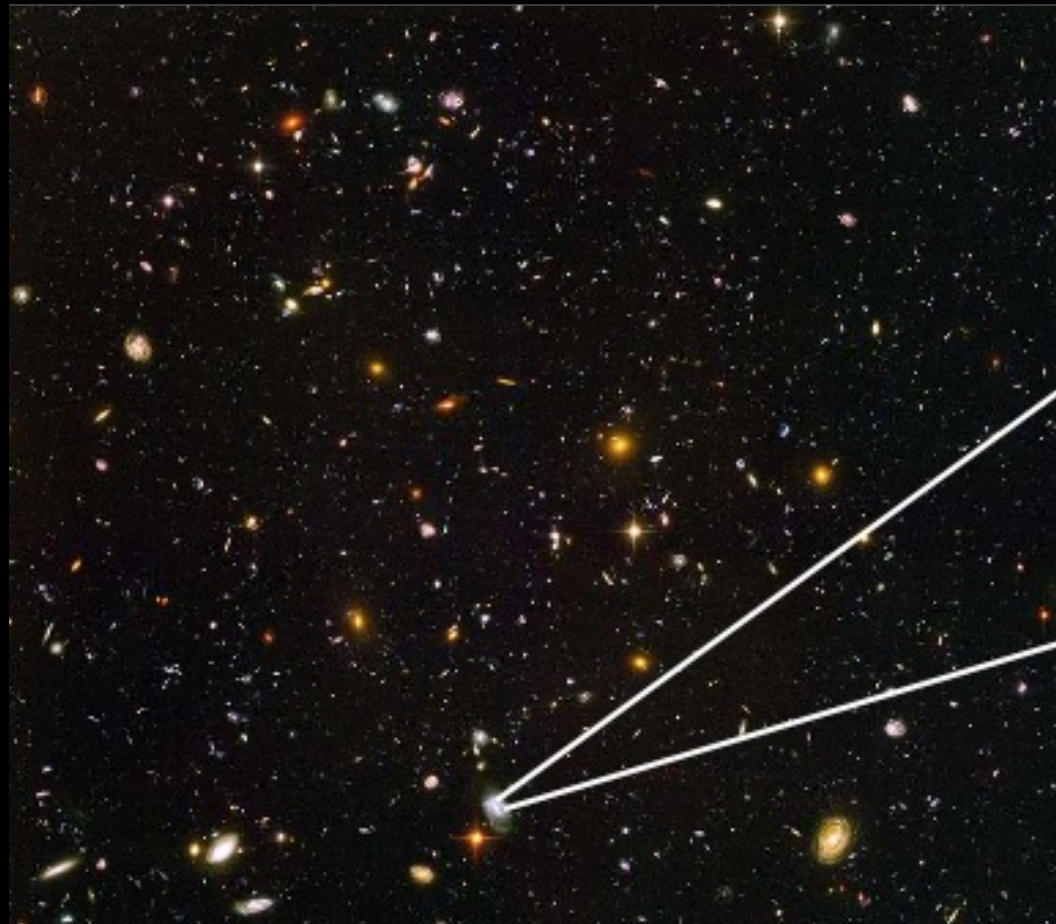
Astrophysical scales

A sense of scale...

$\sim 10^9$ m



100 billion stars in our galaxy.....

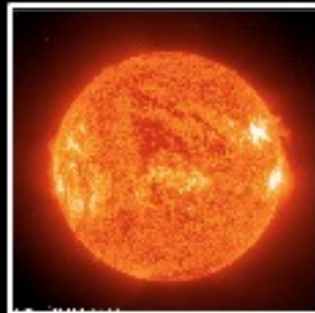


How many galaxies are there in the observable Universe?

Astrophysical scales

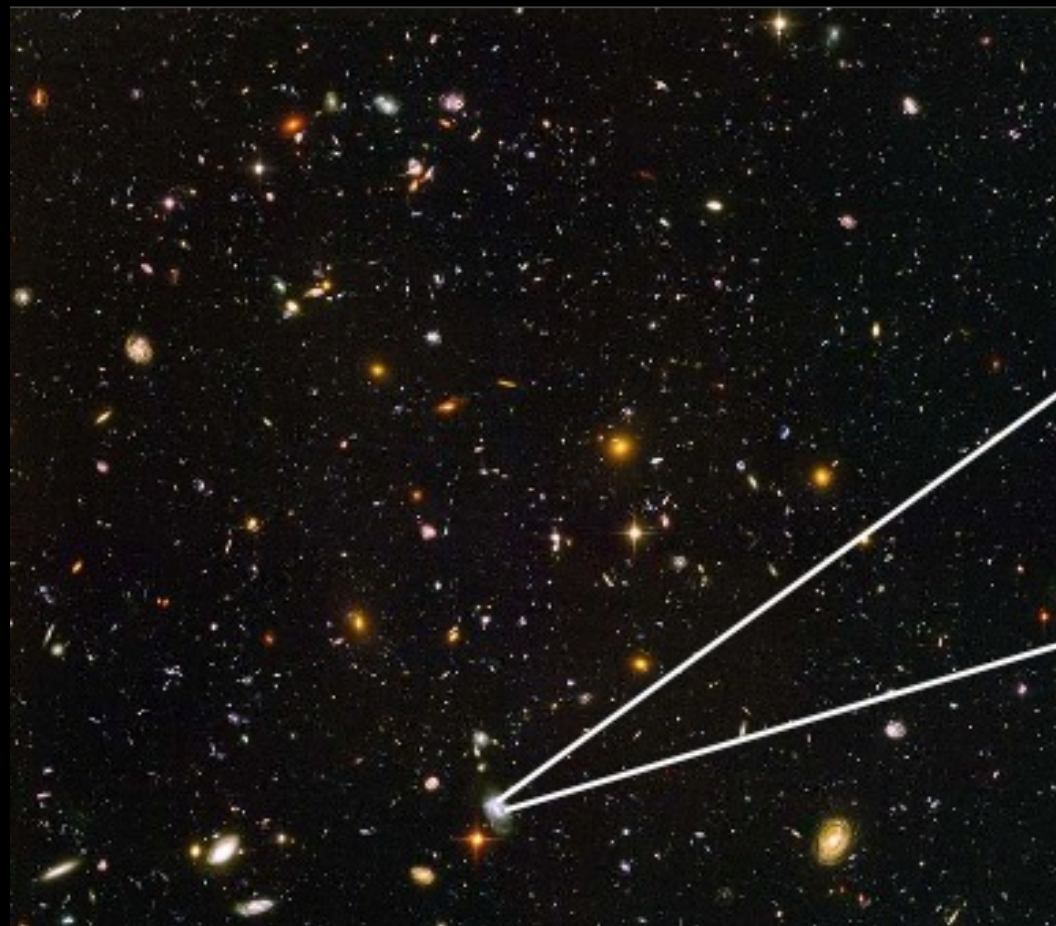
A sense of scale...

$\sim 10^9$ m



100 billion stars in our galaxy.....

$\sim 10^{21}$ m



$\sim 10^{26}$ m

100 billion galaxies in the observable Universe

Useful astrophysical units — Masses

Scales → Useful units

- Masses: Solar Masses ($M_{\odot} \sim 2 \times 10^{30} \text{ kg}$)
 - mass of all stars in Milky Way?
 - mass of all stars in smallest galaxies?
 - largest bound structures (clusters)?

Useful astrophysical units — Masses

Scales → Useful units

- Masses: Solar Masses ($M_{\odot} \sim 2 \times 10^{30} \text{ kg}$)
 - mass of all stars in Milky Way $\sim \text{few } 10^{10} M_{\odot}$
 - mass of all stars in smallest galaxies $\sim \text{few } 10^6 M_{\odot}$
 - largest bound structures (clusters) $\sim 10^{15} M_{\odot}$

Useful astrophysical units — Lengths

Scales → Useful units

- Lengths: Parsecs (pc, kpc, Mpc)
 - distance to nearest stars?
 - distance of Sun from MW center?
 - MW-disk radius?
 - distance to nearest galaxy?
 - distance to nearest cluster?
 - size of largest structures today?
 - observable Universe?

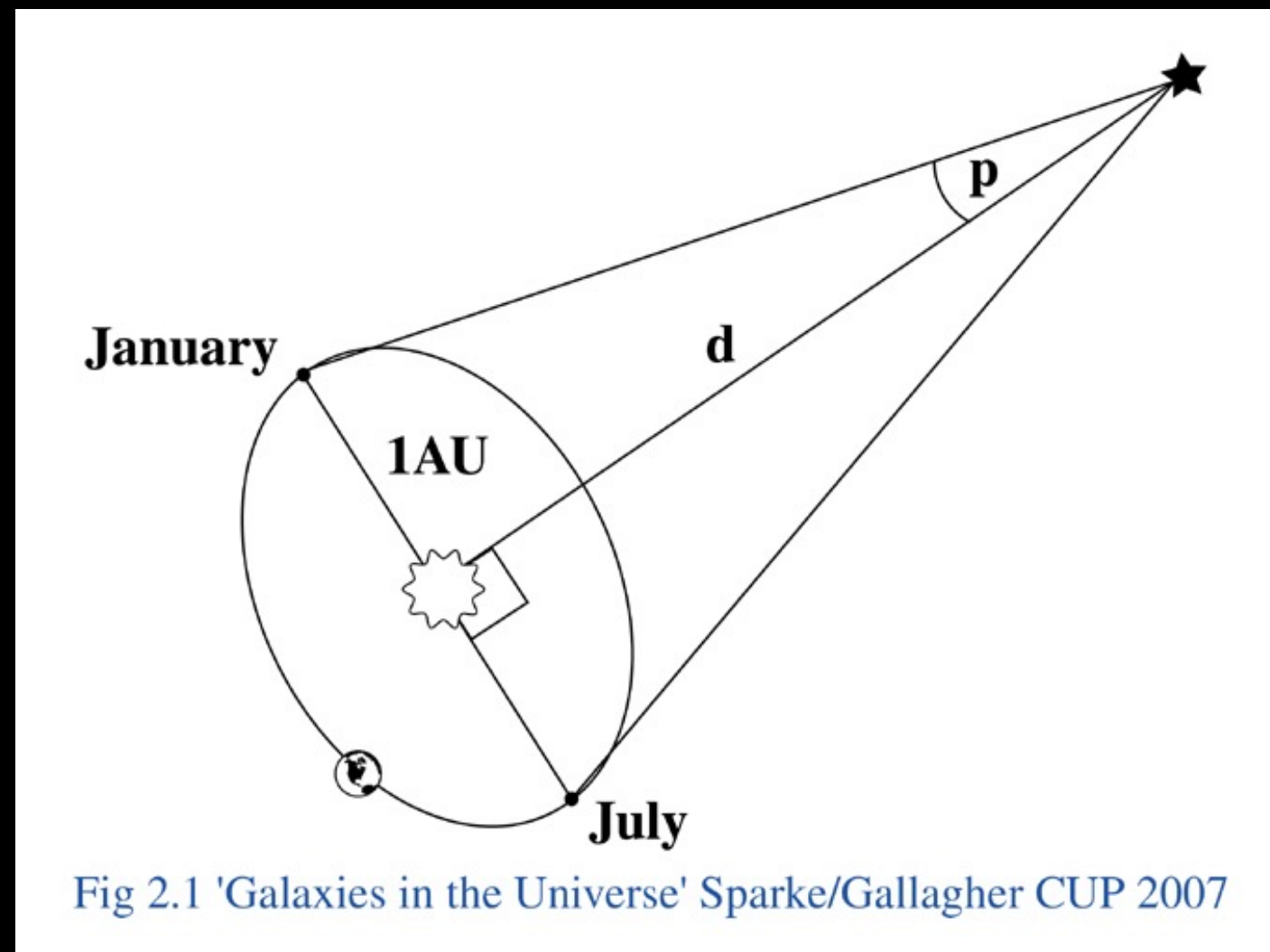
Useful astrophysical units — Lengths

definition of a parsec

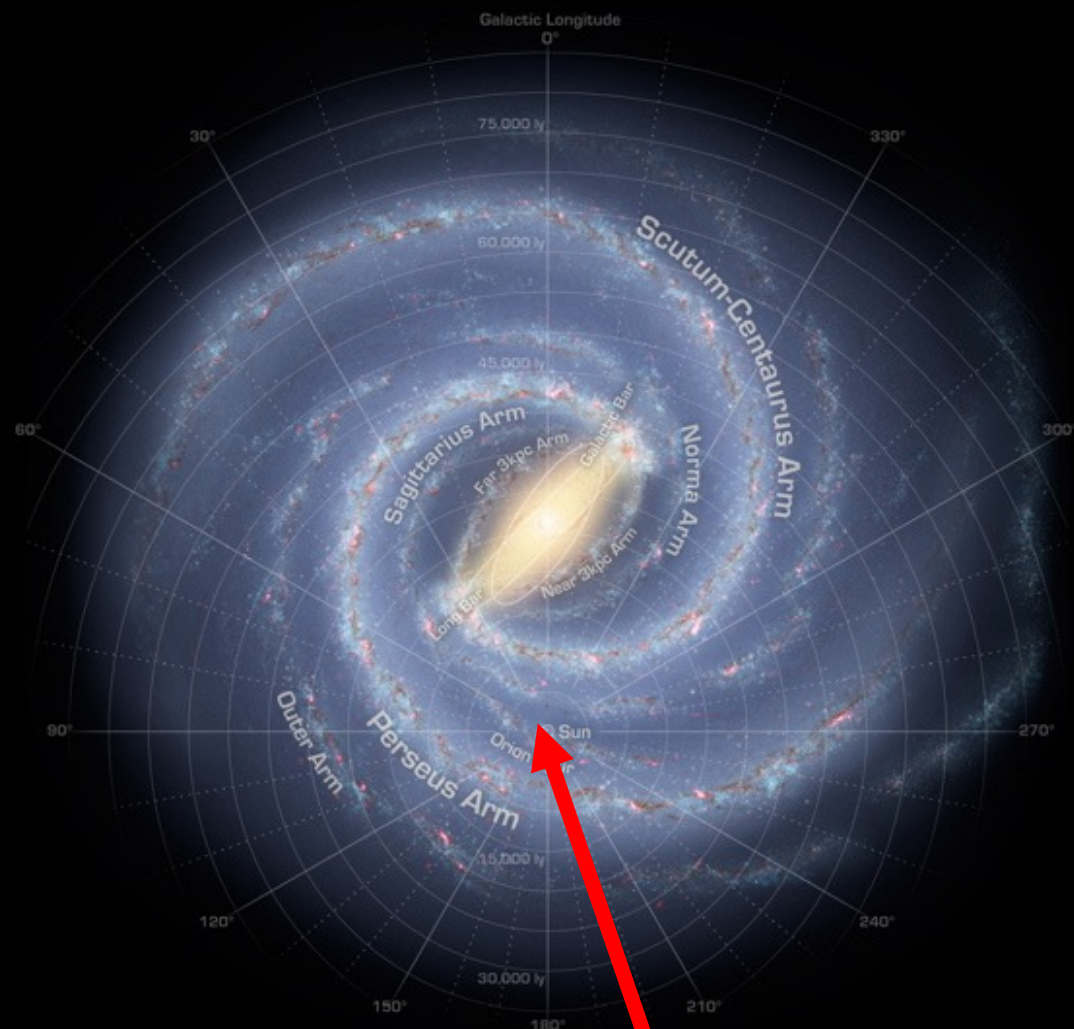
1pc = distance to star with a parallax of 1
arcsecond

$\sim 3 \times 10^{16}$ m

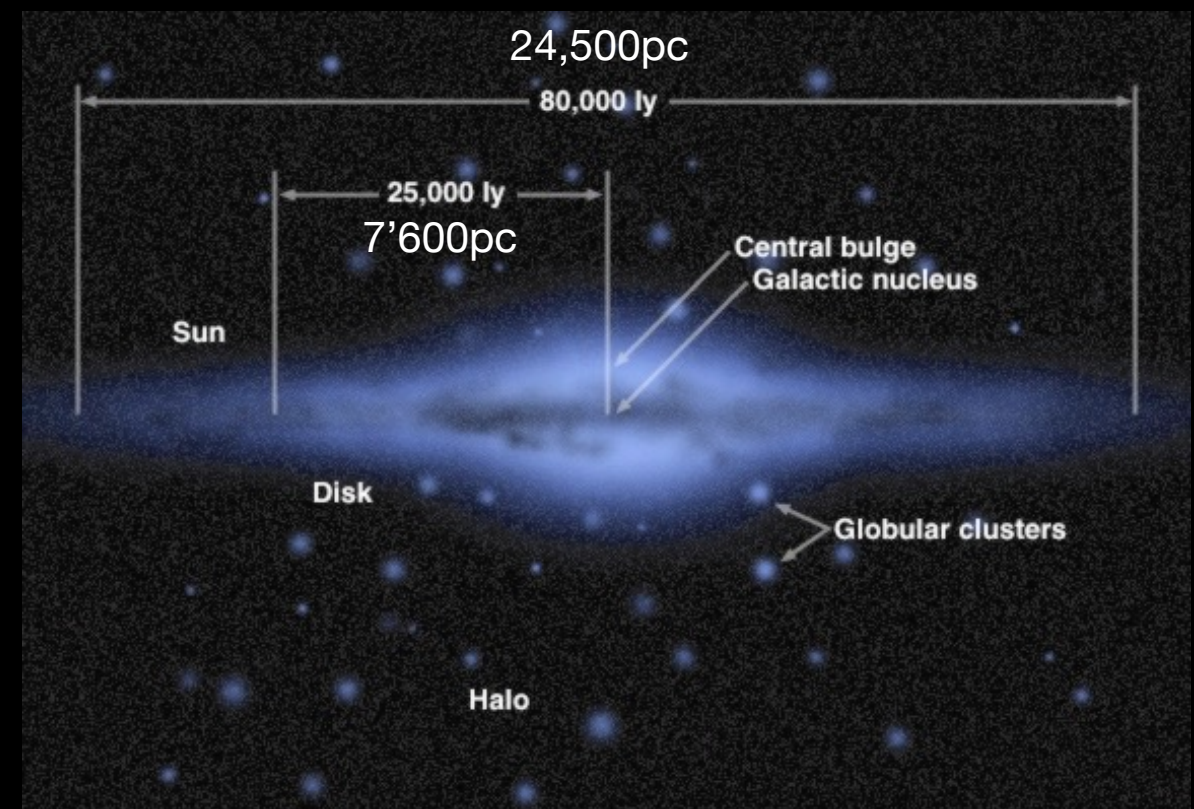
~ 3.26 ly



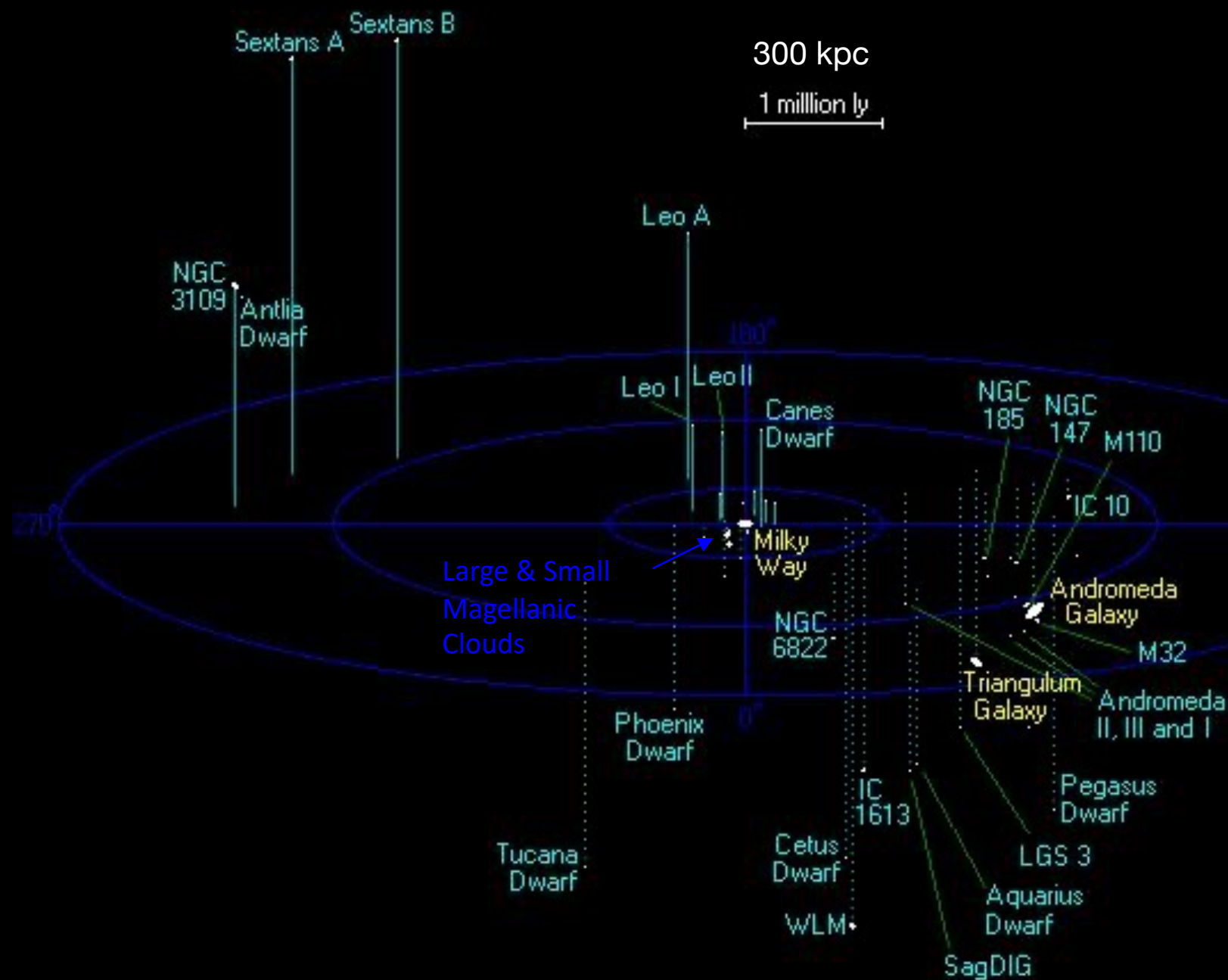
Useful astrophysical units — Lengths



you are here



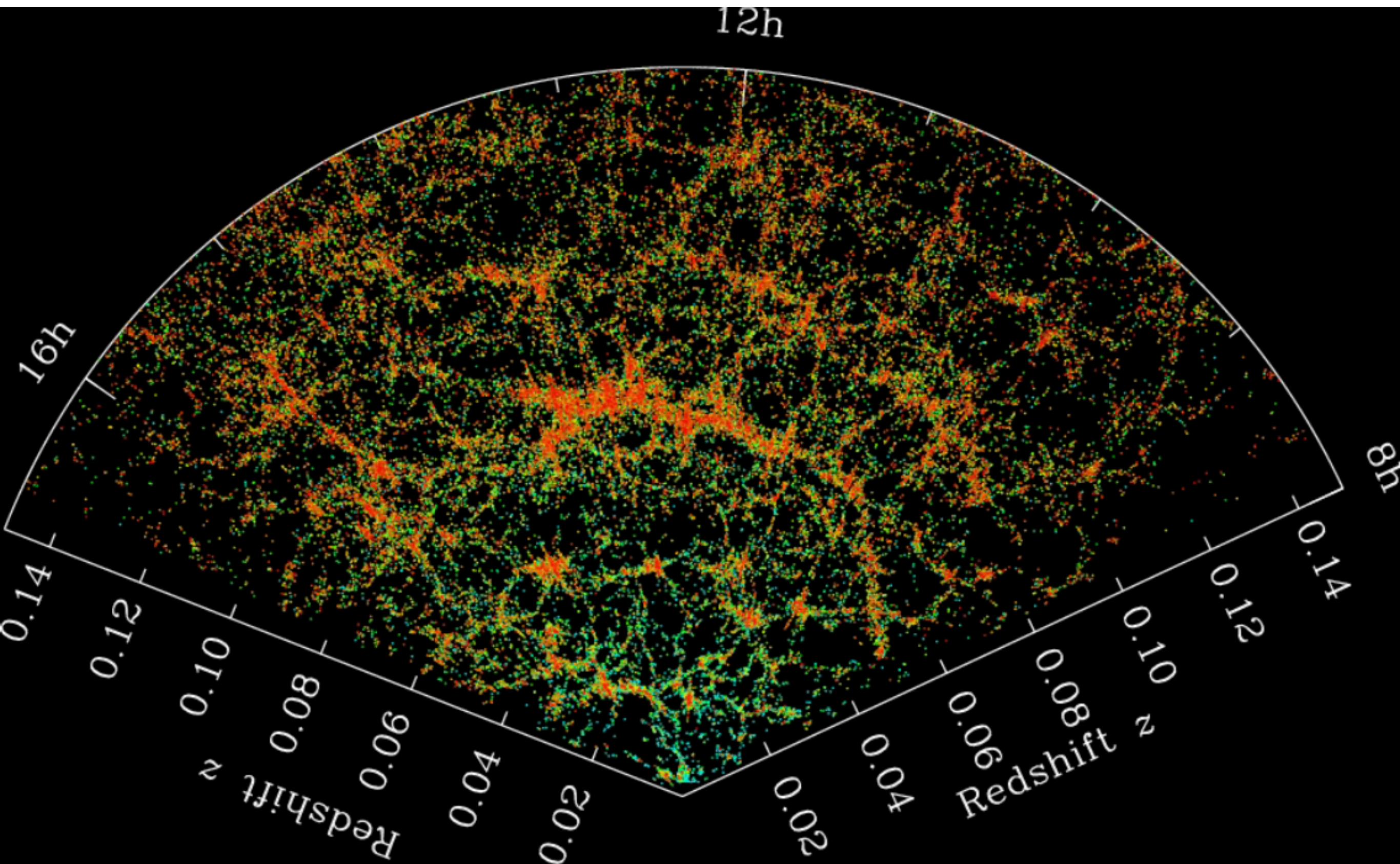
Useful astrophysical units — Lengths



Andromeda+M32



Useful astrophysical units — Lengths



Useful astrophysical units — Lengths

Scales → Useful units

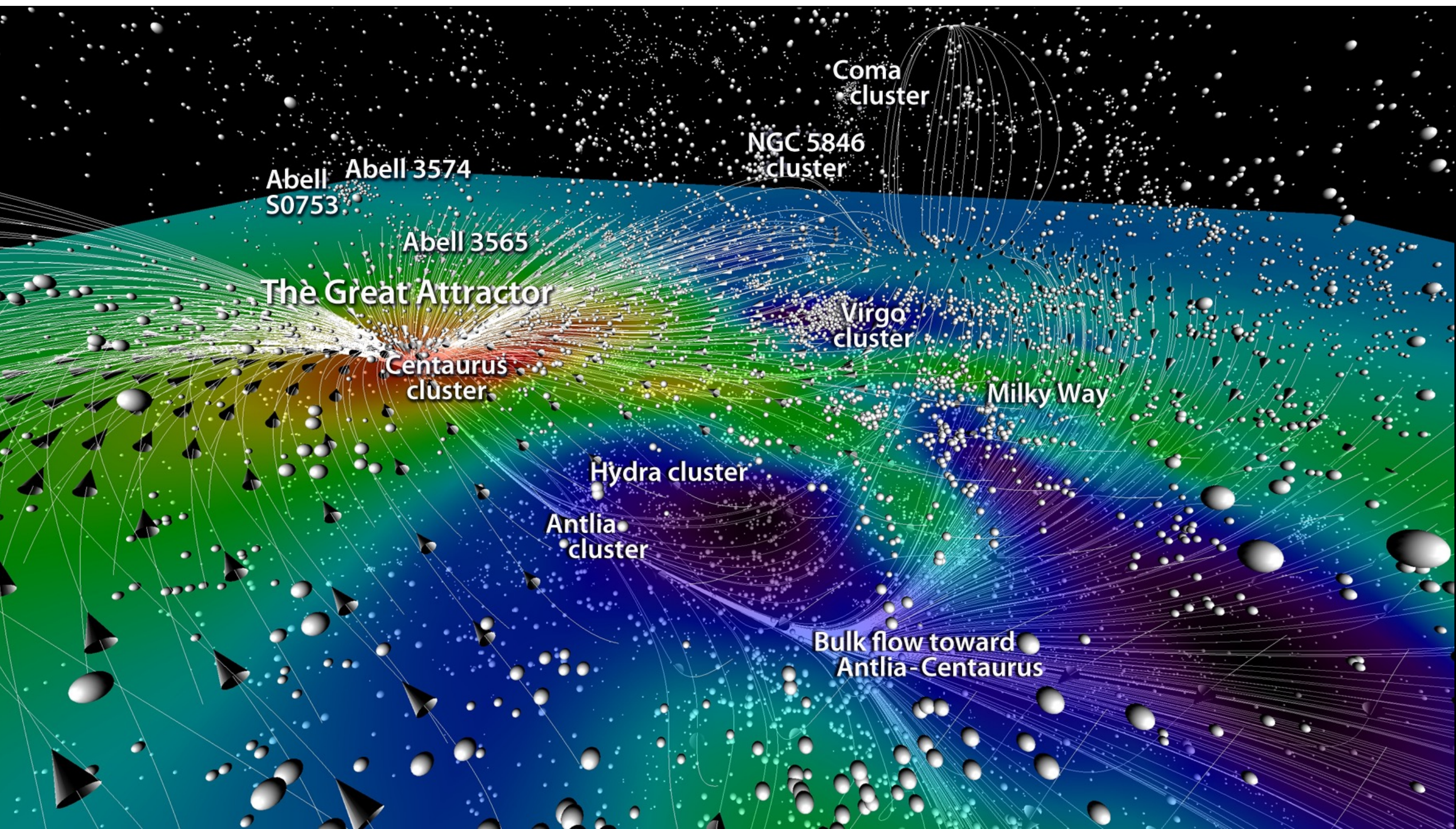
- Lengths: Parsecs (pc, kpc, Mpc)
 - distance to nearest stars $\sim \text{pc}$ (~ 4 ly)
 - distance of Sun from MW center: ~ 8 kpc
 - MW-disk radius ~ 20 kpc
 - distance to nearest galaxy $\sim 10\text{-}50$ kpc. M31 is about 1 Mpc away.
 - distance to nearest cluster 16.5 Mpc (~ 50 million ly)
 - size of largest structures today $\sim 50\text{-}100$ Mpc
 - observable Universe ~ 28 billion pc

Useful astrophysical units — Speeds

Scales → Useful units

- Speeds: km/s
 - typical rotation speeds of stars in MW?
 - motion of our Galaxy relative to the “local standard of rest”?

Useful astrophysical units — Speeds



Useful astrophysical units — Speeds

Scales → Useful units

- Speeds: km/s
 - typical rotation speeds of stars in MW ~ 200 km/s
 - motion of our Galaxy relative to the “local standard of rest”: ~ 600 km/s (1.3 million miles/hr)

Useful astrophysical units — Times

Scales → Useful units

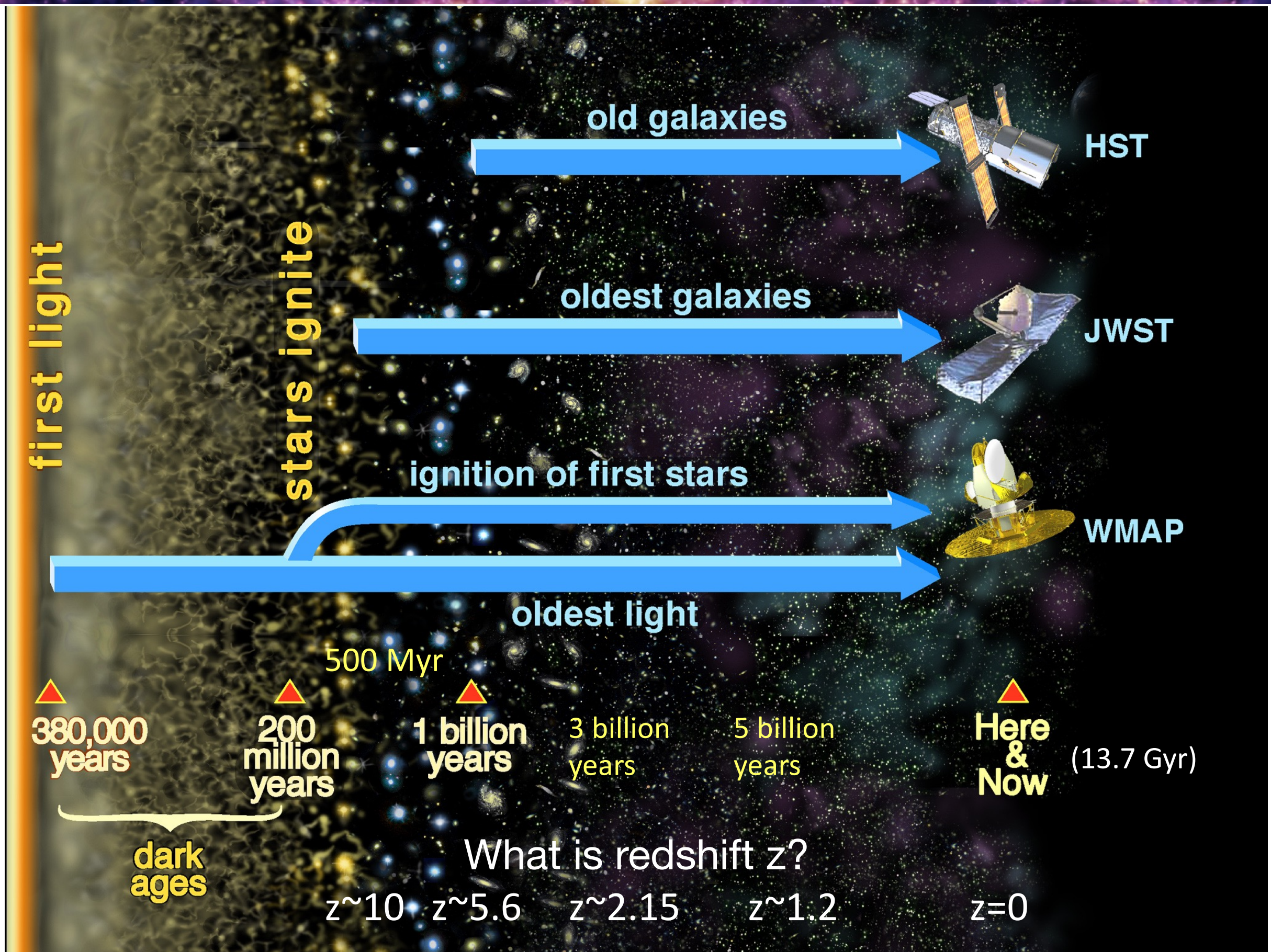
- time: Myr, Gyr
 - lifetime of star?
 - rotation time at radius of Sun?
 - age of the Universe?

Useful astrophysical units — Times

Scales → Useful units

- time: Myr, Gyr
 - lifetime of star: few Myr to 10^{12} yr
 - rotation time at radius of Sun: ~ 200 Myr
 - age of the Universe: 13.8 Gyr

Useful astrophysical units — Times



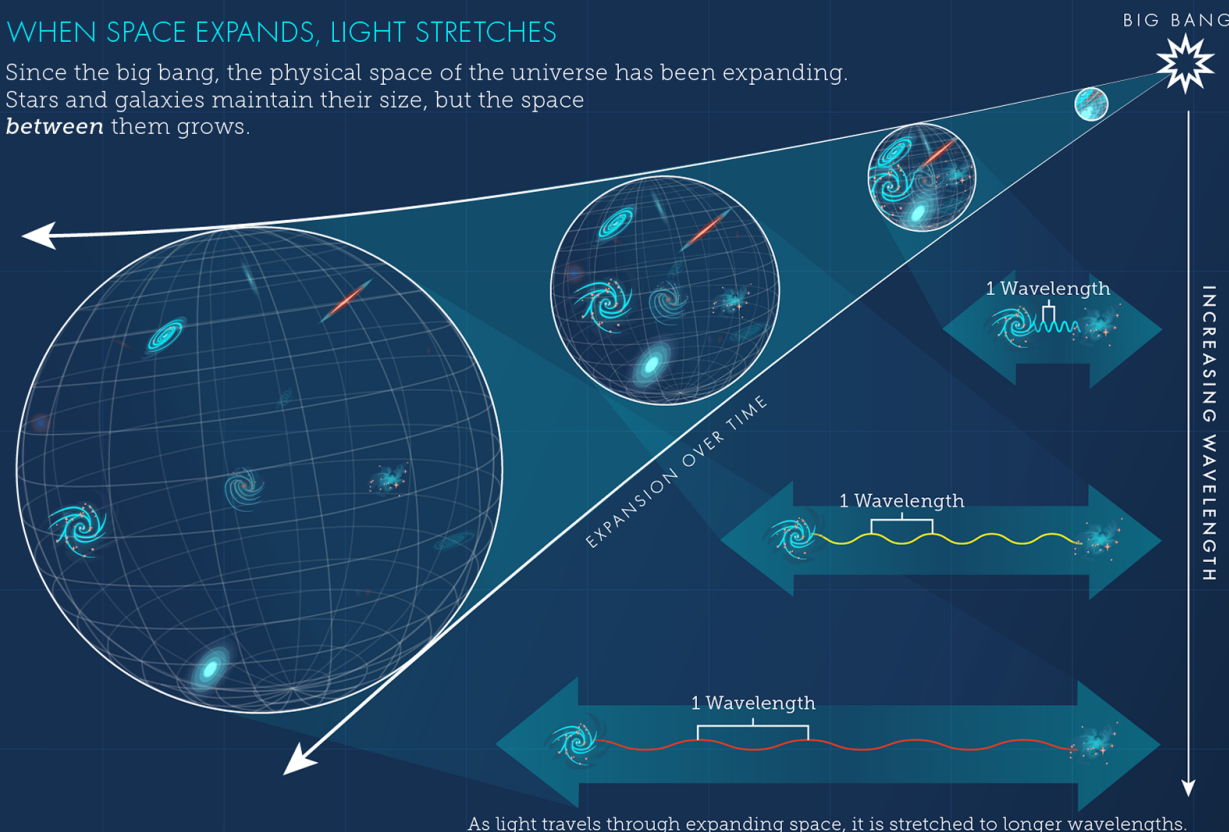
Useful astrophysical units — Redshift

- **1927**: Lemaitre: Expanding Universe as a natural consequence of GR
- **1929**: Hubble confirmed Lemaitre's prediction, and discovered the velocity-distance relation $v_r \sim H_0 d$, thus, demonstrating that the Universe is expanding (BB?):
- Because of expansion of space, wavelength of radiation emitted from a object is stretched: the more distant it is, the more the wavelength is stretched, and the more time has passed until photons are reaching us → redshifted wavelength measure for time (and distance)!

WHAT IS COSMOLOGICAL REDSHIFT?

WHEN SPACE EXPANDS, LIGHT STRETCHES

Since the big bang, the physical space of the universe has been expanding. Stars and galaxies maintain their size, but the space *between* them grows.



$$z = \frac{\lambda_{\text{obsv}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$$

	z=0	z=1	z=2	z=6
Time after BB	~13.8 Gyr	~5.9 Gyr	~3.3 Gyr	~0.9 Gyr

Outline of Chapter I — Introduction



- What is a galaxy?
- Astrophysical scales and units
- Basic Observable quantities

how do astronomers study astronomical objects?

- everything we know about astronomy* has been learned by studying electromagnetic radiation

*With several notable exceptions thanks to Gravitational wave detectors

describing the radiation field

- what do we actually measure?

Observing galaxies

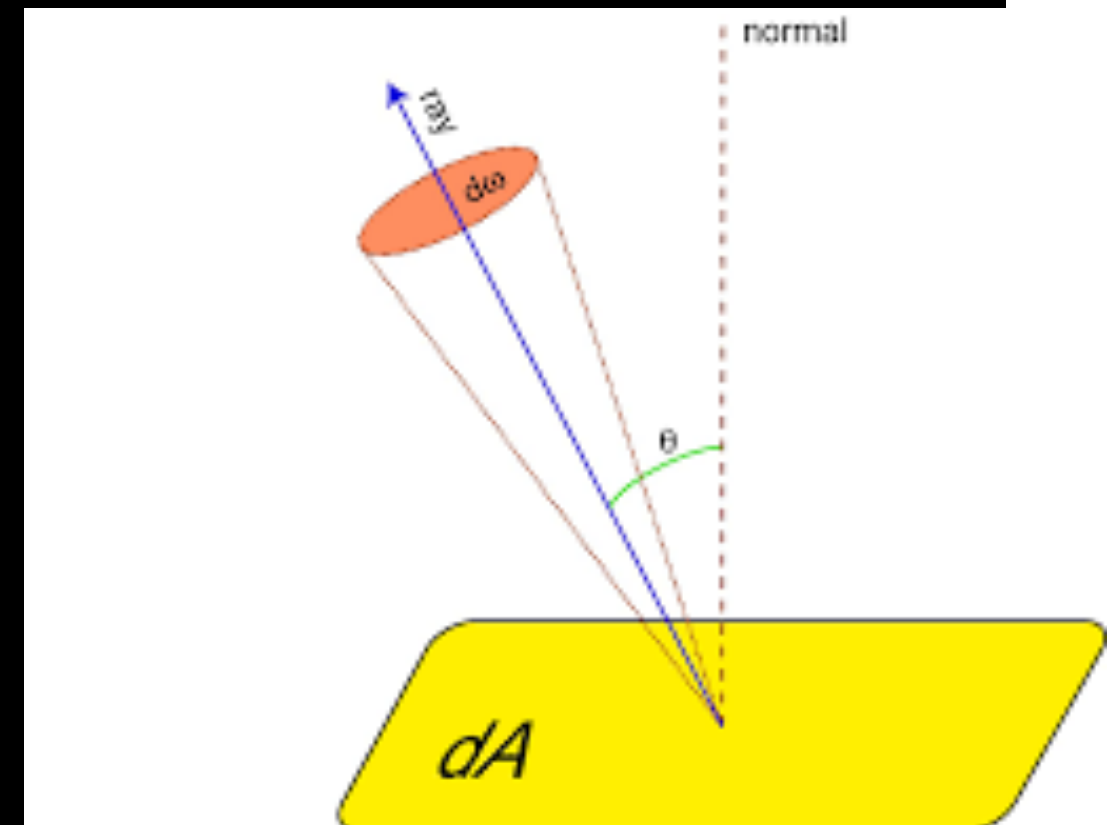
describing the radiation field

- specific intensity:

$$dE = I_\nu dA \cos \theta dt d\omega d\nu$$

energy per unit area, time, solid angle,
frequency

units: $\text{erg cm}^{-2} \text{s}^{-1} \text{ster}^{-1} \text{Hz}^{-1}$



describing the radiation field

- specific intensity: I_ν

units: $\text{erg cm}^{-2} \text{s}^{-1} \text{ster}^{-1} \text{Hz}^{-1}$

how do we get the specific net flux (F_ν)? what are its units?

describing the radiation field

- specific intensity I_ν
- specific net flux – integrate I_ν over all solid angle. units: $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$
- Total flux in frequency range/ bolometric flux [$\text{erg/cm}^2/\text{s}$]:

$$F = \int_{\nu_1}^{\nu_2} f_\nu d\nu;$$

describing the radiation field

- specific intensity I_ν
- specific net flux – integrate I_ν over all solid angle. units: $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$
- Total flux in frequency range/ bolometric flux [$\text{erg/cm}^2/\text{s}$]:

$$F = \int_{\nu_1}^{\nu_2} f_\nu d\nu;$$

- Total/bolometric Luminosity: total radiation energy per unit time [erg/s], related to flux via distance d

$$L = 4\pi d^2 f;$$

describing the radiation field

- specific intensity I_ν
- specific net flux – integrate I_ν over all solid angle. units: $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$
- apparent magnitude

describing the radiation field

- specific intensity I_ν
- specific net flux – integrate I_ν over all solid angle. units: $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$
- apparent magnitude:

$$m_1 - m_2 = -2.5 \log \left(\frac{f_1}{f_2} \right) ; \quad \frac{f_1}{f_2} = 10^{-0.4(m_1 - m_2)}$$

Measure for brightness of an astrophysical object. Dependent on intrinsic luminosity, distance from earth, (and dust extinction)

the magnitude system

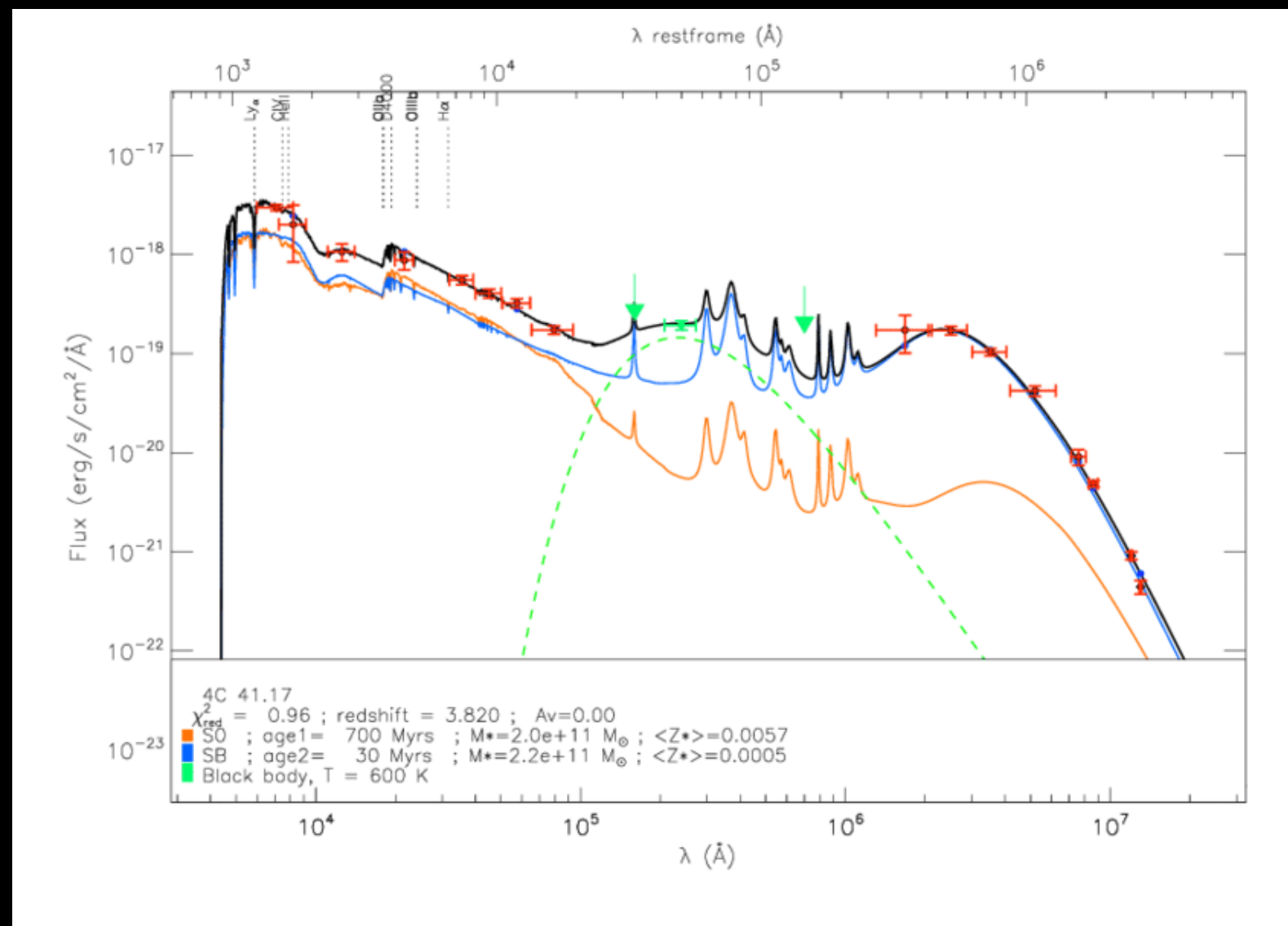
- galaxy 1 has an apparent magnitude of 18
- galaxy 2 has an apparent magnitude of 20
 - which galaxy is brighter?

A lower apparent magnitude indicates a brighter object!

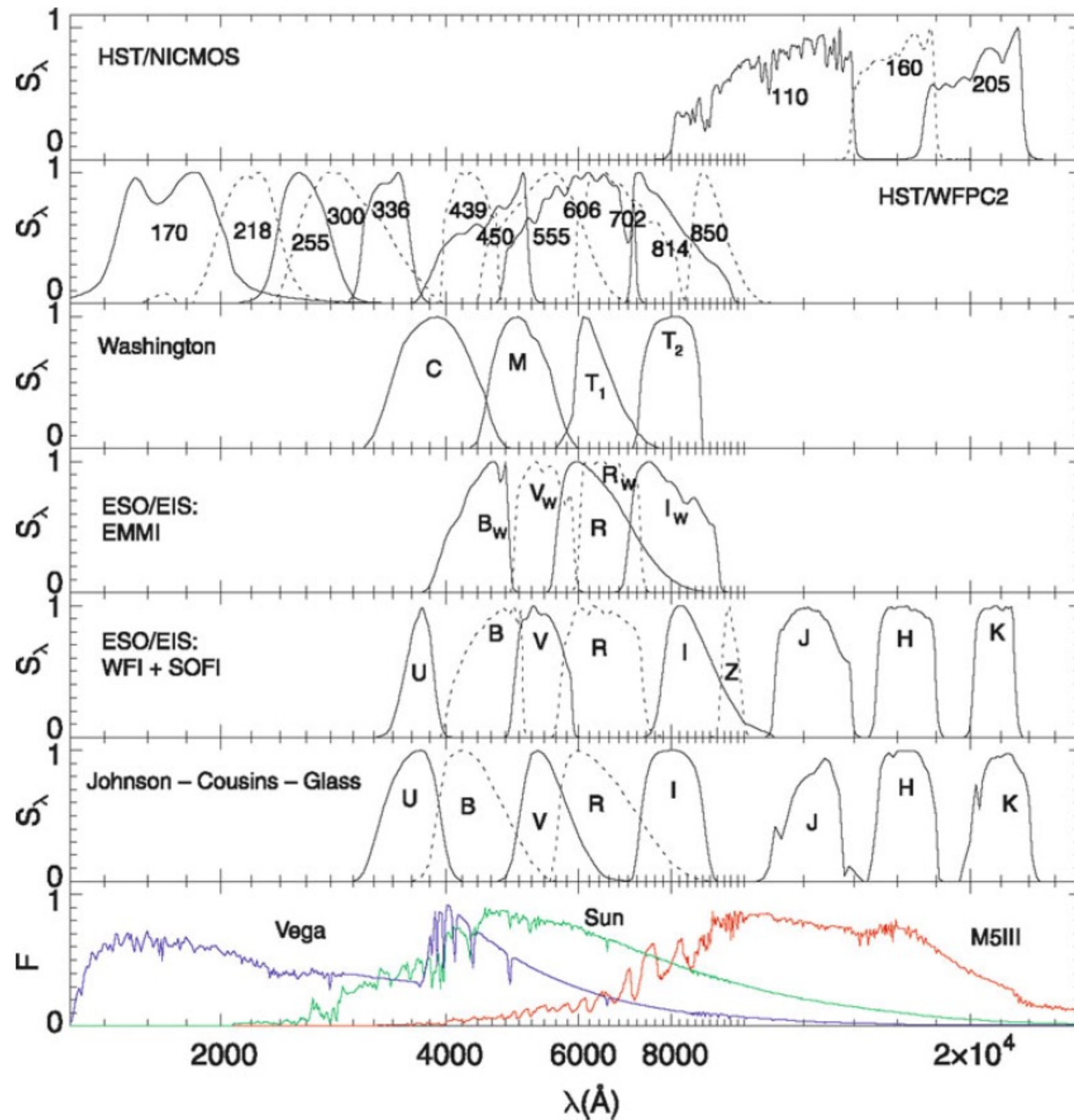
Observing galaxies

spectral energy distribution (SED)

- [integrated] flux as a function of wavelength



Observing galaxies



Observing galaxies

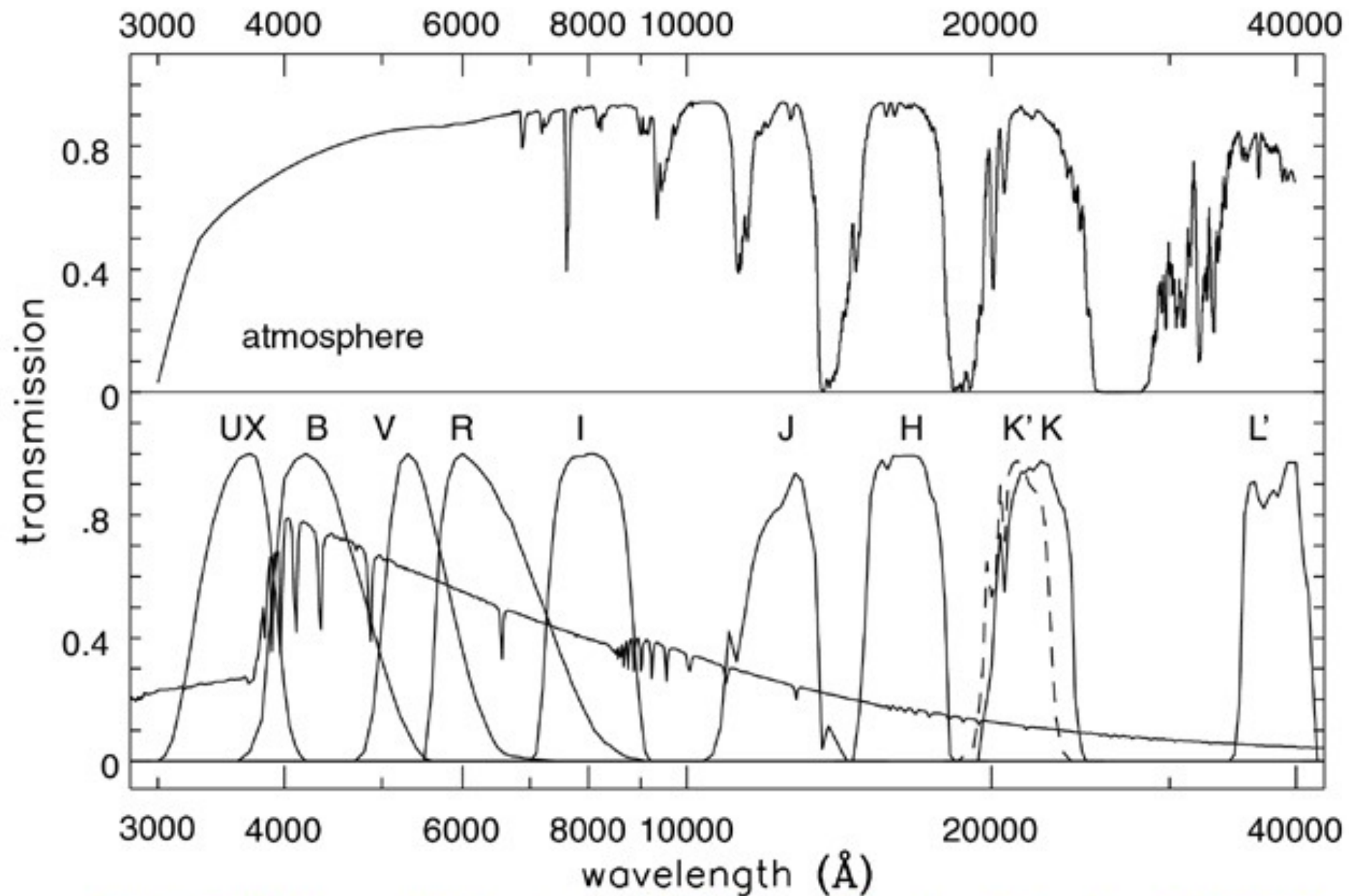


Fig 1.7 (M. Bessell) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

describing the radiation field

- specific intensity I_ν
- specific net flux – integrate I_ν over all solid angle. units: $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$
- apparent magnitude in a filter band:

$$m_X = -2.5 \log \left(\frac{\int d\nu T_X(\nu) f_\nu}{\int d\nu T_X(\nu)} \right) + \text{const.} , \quad (\text{A.25})$$

how would you compute

- absolute magnitude?
- bolometric magnitude?

Observing galaxies

how would you compute

- absolute magnitude $M = -2.5 \log (F \text{ at } 10\text{pc}) + \text{constant}$

$$m-M = 5 \log (D/1 \text{ pc}) - 5$$

m-M	-5	0	5	10
D/pc	1	10	100	1000

Observing galaxies

how would you compute

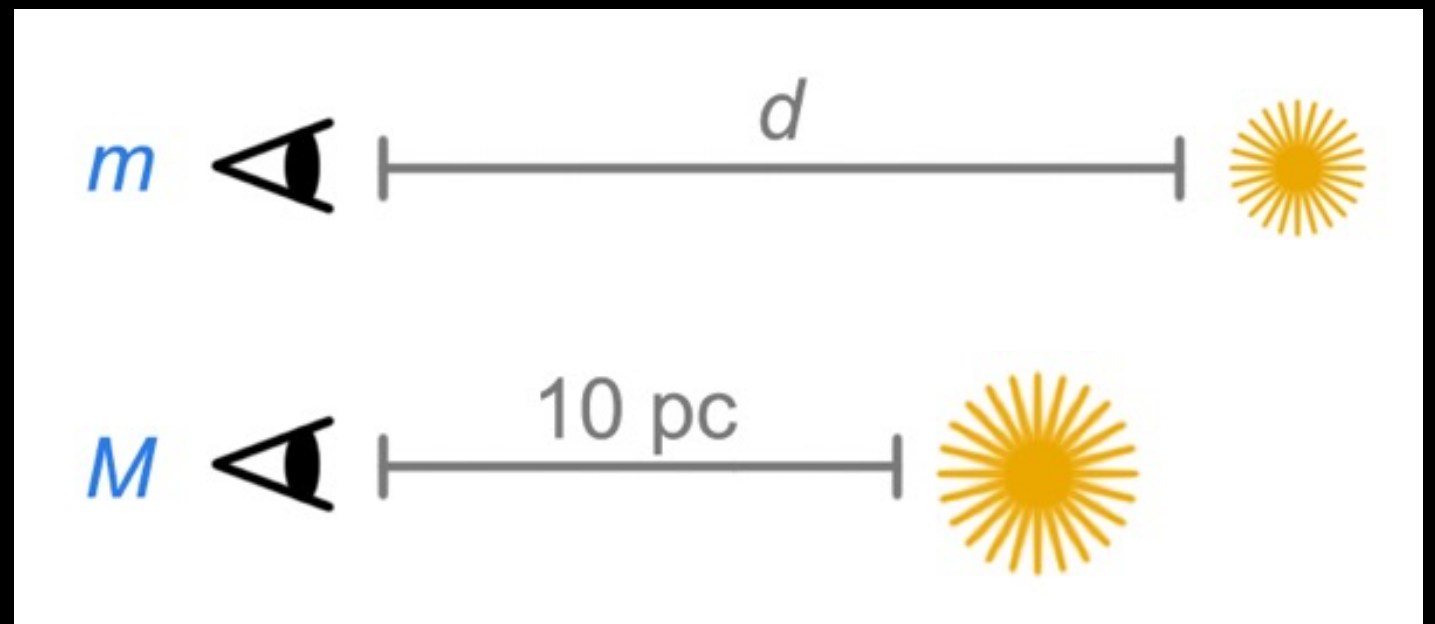
- absolute magnitude $M = -2.5 \log (F \text{ at } 10\text{pc}) + \text{constant}$

$$m-M = 5 \log (D/1 \text{ pc}) - 5$$

m-M	-5	0	5	10
D/pc	1	10	100	1000

- bolometric magnitude

$$M_{\text{bol}} = 4.74 - 2.5 \log(L/L_{\text{sun}})$$



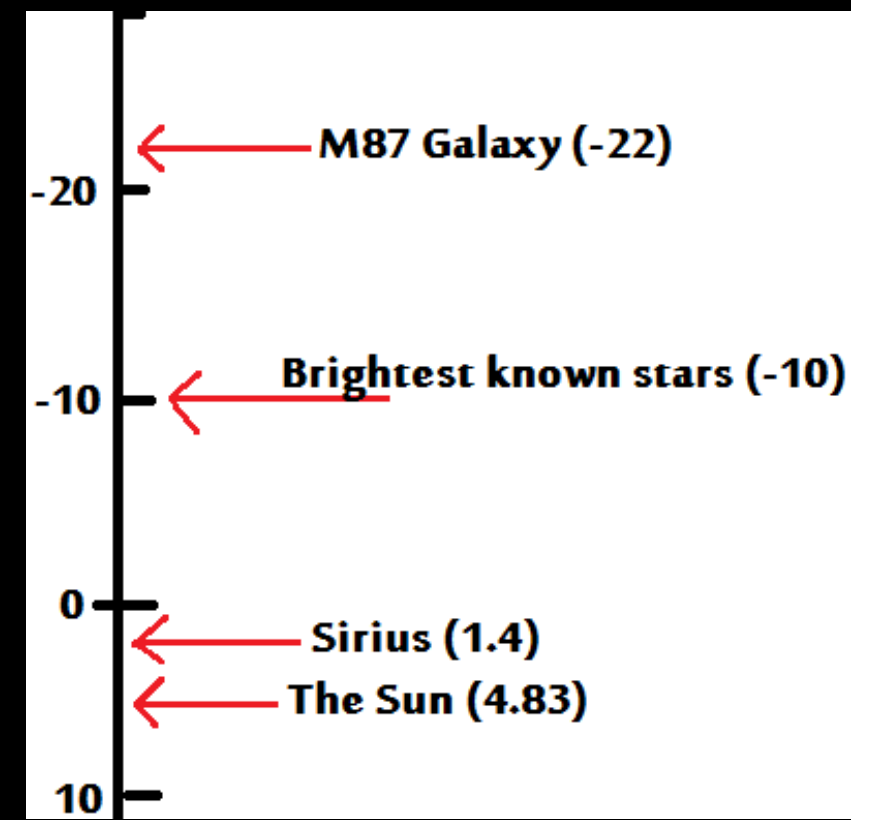
Observing galaxies

fun with the magnitude system

- galaxy 1 has absolute magnitude -16
- galaxy 2 has absolute magnitude -20
 - which galaxy is more luminous?

$$M \sim -2.5 \log(L) + \text{const}$$

The general rule is that a smaller absolute magnitude corresponds to a more luminous object



Observing galaxies

what do astronomers mean by color?

what do astronomers mean by color?

- the difference of the apparent magnitude in one filter band and that in another $m_x - m_y$
 - equivalent to the (log of the) ratio of the fluxes at two wavelengths
- U-V ($= m_U - m_V$), B-V, B-K, etc.

m_U = magnitude in UV

m_V = magnitude in visible

Observing galaxies

color

- galaxy 1 has $U-V=1$
- galaxy 2 has $U-V=5$
 - which galaxy is redder?

large $U-V$ implies large m_U , i.e. low UV contribution and/or low m_V , i.e. large red contribution $\rightarrow$ redder colors)

a more positive $(U-V)$ value indicates that the object is "redder," meaning it emits relatively more light in the longer wavelength (redder) part of the spectrum compared to the shorter wavelength (bluer) part

Review Chapter I — Introduction

- Definition of a galaxy — A gravitationally bound collection of stars, gas, dust and dark matter
- Start of extragalactic astronomy: ~1925, when Hubble showed that distances of nebulae go beyond the MW (via Cepheids)...
- Astronomical scales and units — pc (3×10^{16} m), M_{sun} ($\sim 2 \times 10^{30}$ kg), redshift, Myr-Gyr, km/s
 - Observable size and age of Universe: ~28 Gpc, 13.8 Gyr
- Observable quantities for electromagnetic radiation:
 - Flux at a given wavelength (SED) [erg/s/cm^2]
 - Apparent magnitude m $m_1 - m_2 = -2.5 \log \left(\frac{S_1}{S_2} \right)$; $\frac{S_1}{S_2} = 10^{-0.4(m_1 - m_2)}$
 - Absolute magnitude M : $m - M = 5 \log (D / 1 \text{ pc}) - 5$
 - Bolometric magnitude: $M_{\text{bol}} = 4.74 - 2.5 \log (L / L_{\text{sun}})$
 - Colors: e.g. U-V ($= m_U - m_V$)

Outline of Chapter 2 — Review on stars



- Observables
- Stellar spectra
- Stellar evolution

Review on stars — observables

stars: what properties can we measure?

- Apparent and absolute magnitudes
- Luminosity L dependent on flux+distance: $f=L/4\pi d^2$, L often given in $L_{\text{sun}} = 3.8 \times 10^{33} \text{ erg/s}$
- Masses (e.g., orbital motions in binary star systems) between 0.075 and $\sim 100 M_{\text{sun}}$
- Radii (e.g. via photometry: change in brightness during passages with other stars/planets provides information about the size of the star), range from 0.1 — 1000 R_{sun}
- Spectra ($\rightarrow$ stars are approx. blackbodies, $3000 < T < 100000 \text{ K}$, with absorption and emission features from atoms & molecules in the stars atmosphere)

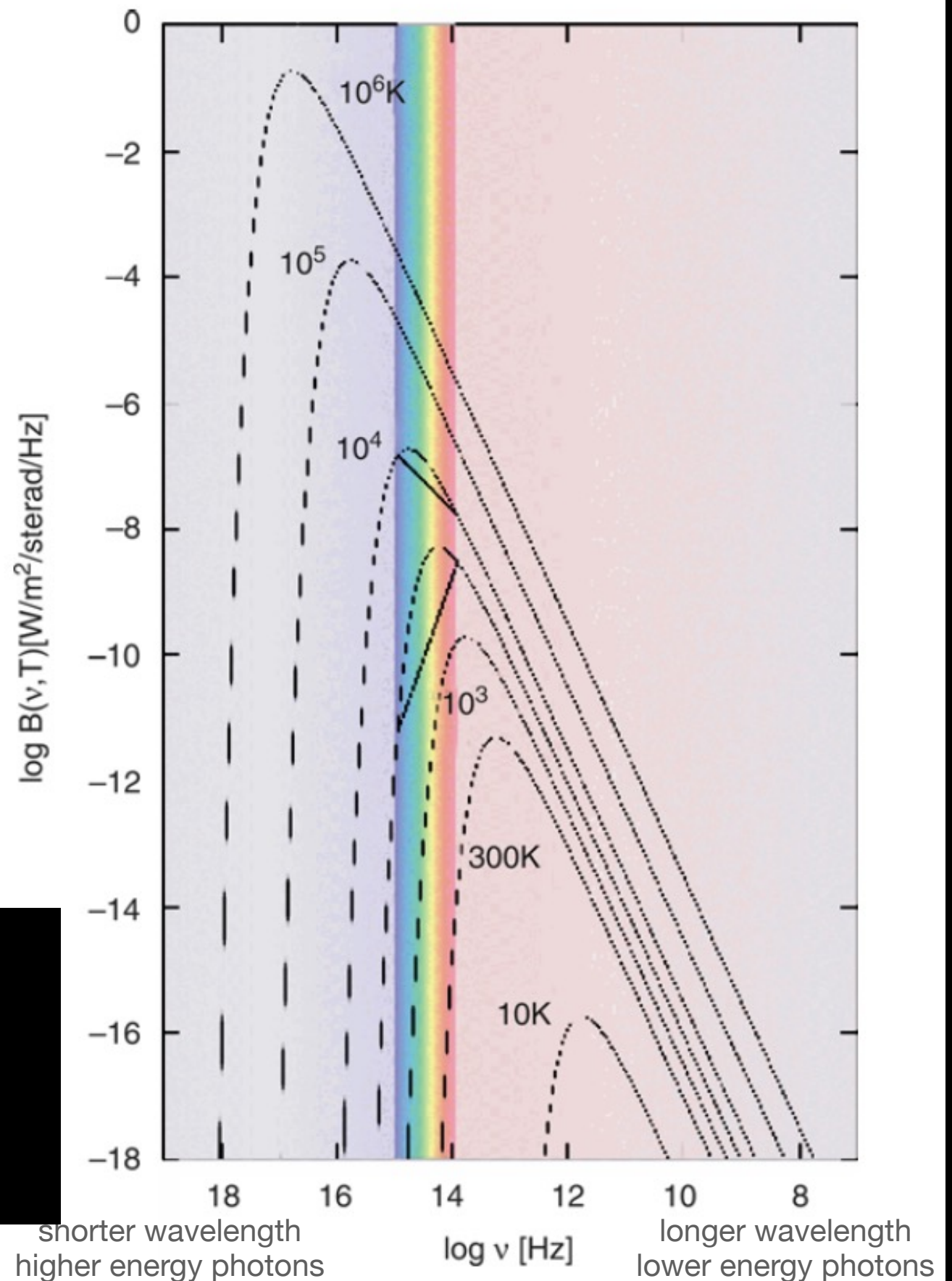
Review on stars —stellar spectra

stars are, to very good approximation,
blackbody radiators

$$B_\nu(T) = \frac{2h_P\nu^3}{c^2} \frac{1}{e^{h_P\nu/k_B T} - 1},$$

$$\nu_{\max} = 5.88 \times 10^{10} \text{ Hz} \frac{T}{1 \text{ K}}.$$

$$F = \int_0^\infty d\nu F_\nu = \pi \int_0^\infty d\nu B_\nu(T) = \pi B(T) = \sigma_{\text{SB}} T^4, \quad (\text{A.22})$$



Review on stars —stellar spectra

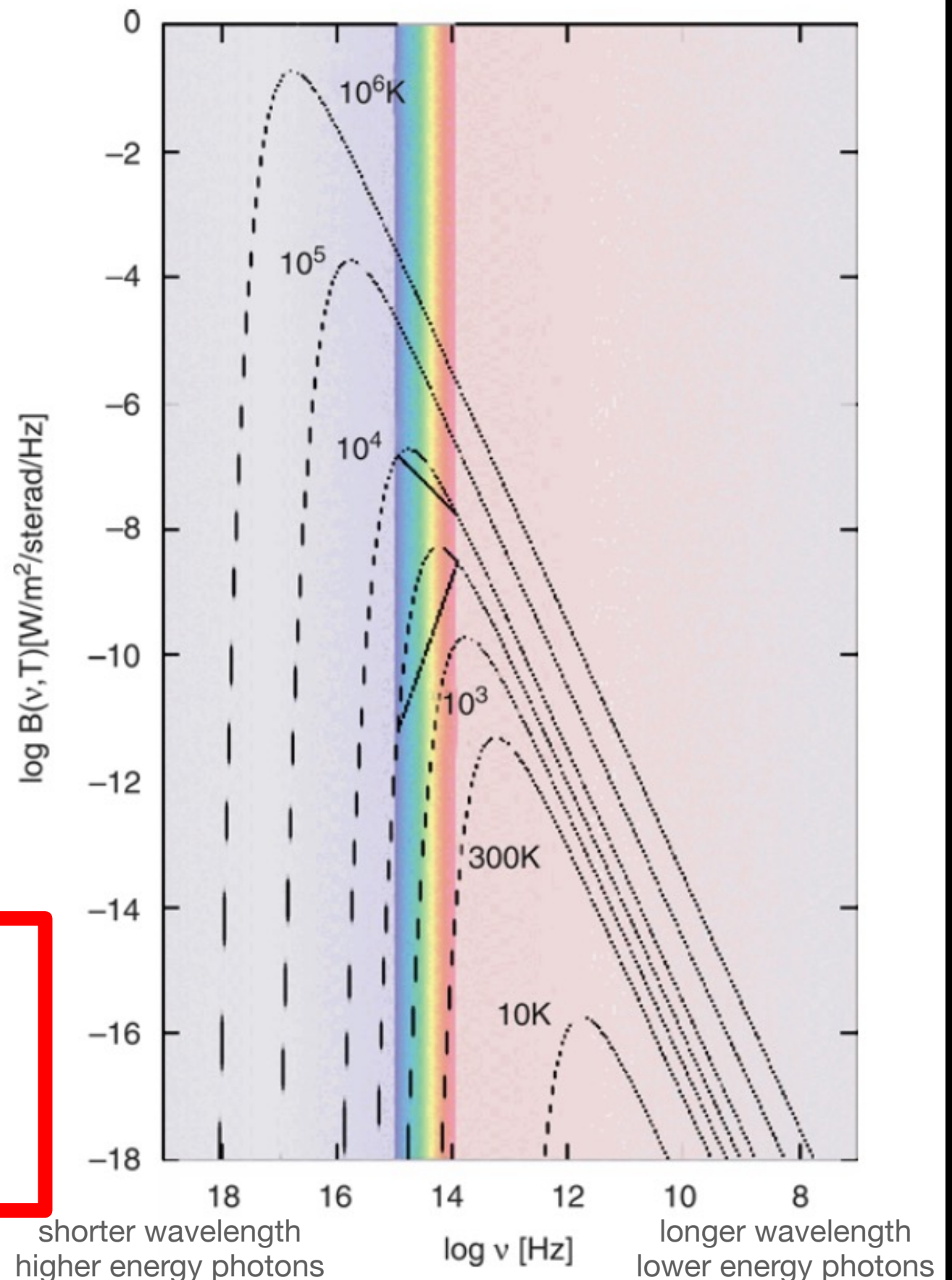
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$$L = 4\pi R^2 \sigma_{\text{SB}} T^4,$$



Review on stars —stellar spectra

Stellar spectra:

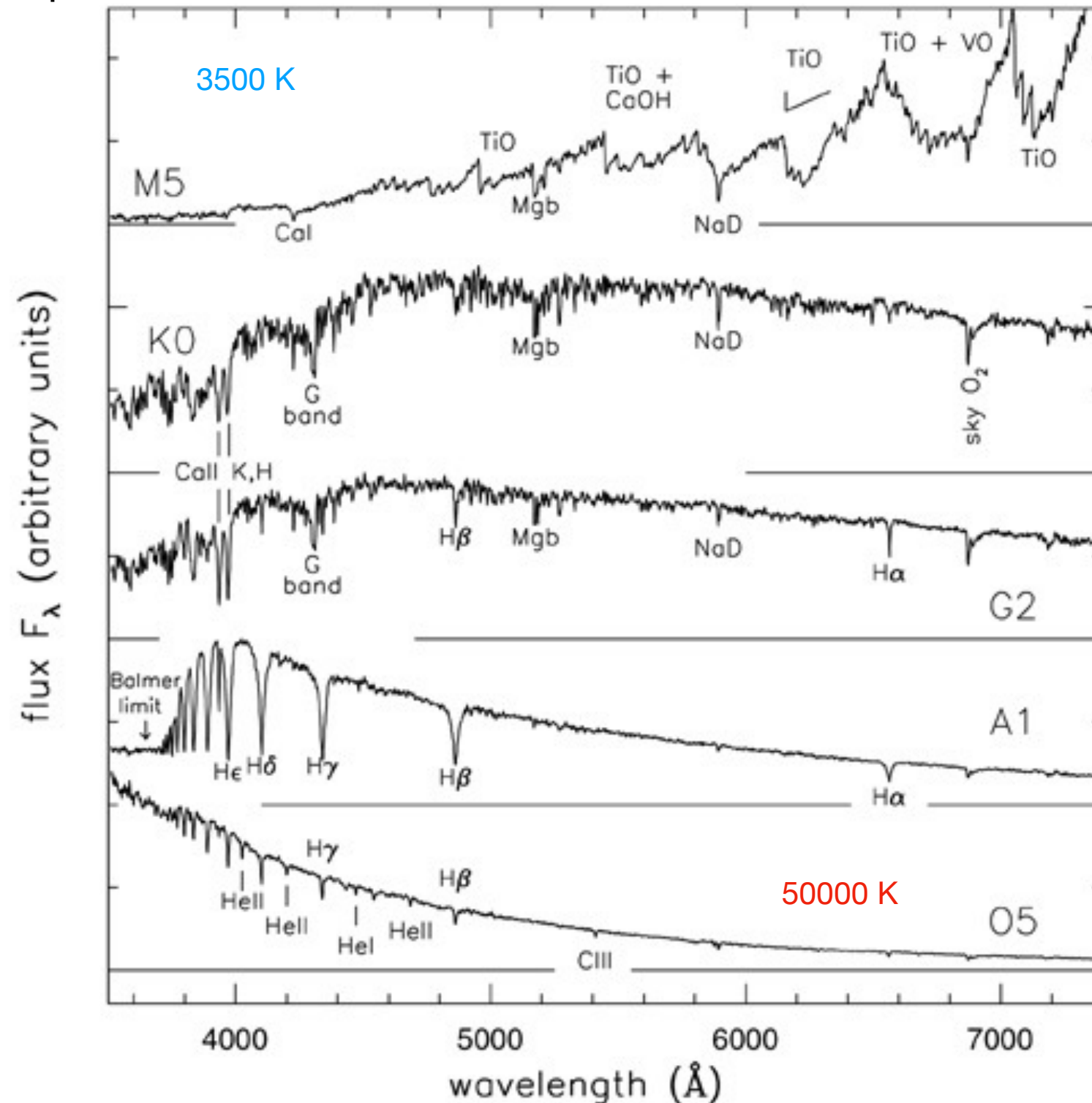


Fig 1.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

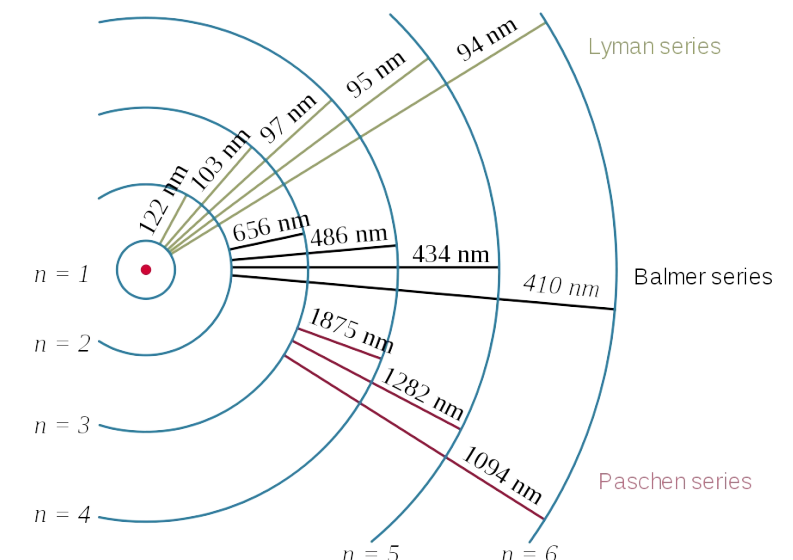


Annie Jump Cannon

Oh Be A Fine Girl Kiss Me
Oh Be A Fine Guy Kiss Me

stellar spectral class:
OBAFGKM

each class divided into 0
(hottest)--9 (coolest) –
we are a G2 star



Review on stars —stellar spectra

Stellar spectra:

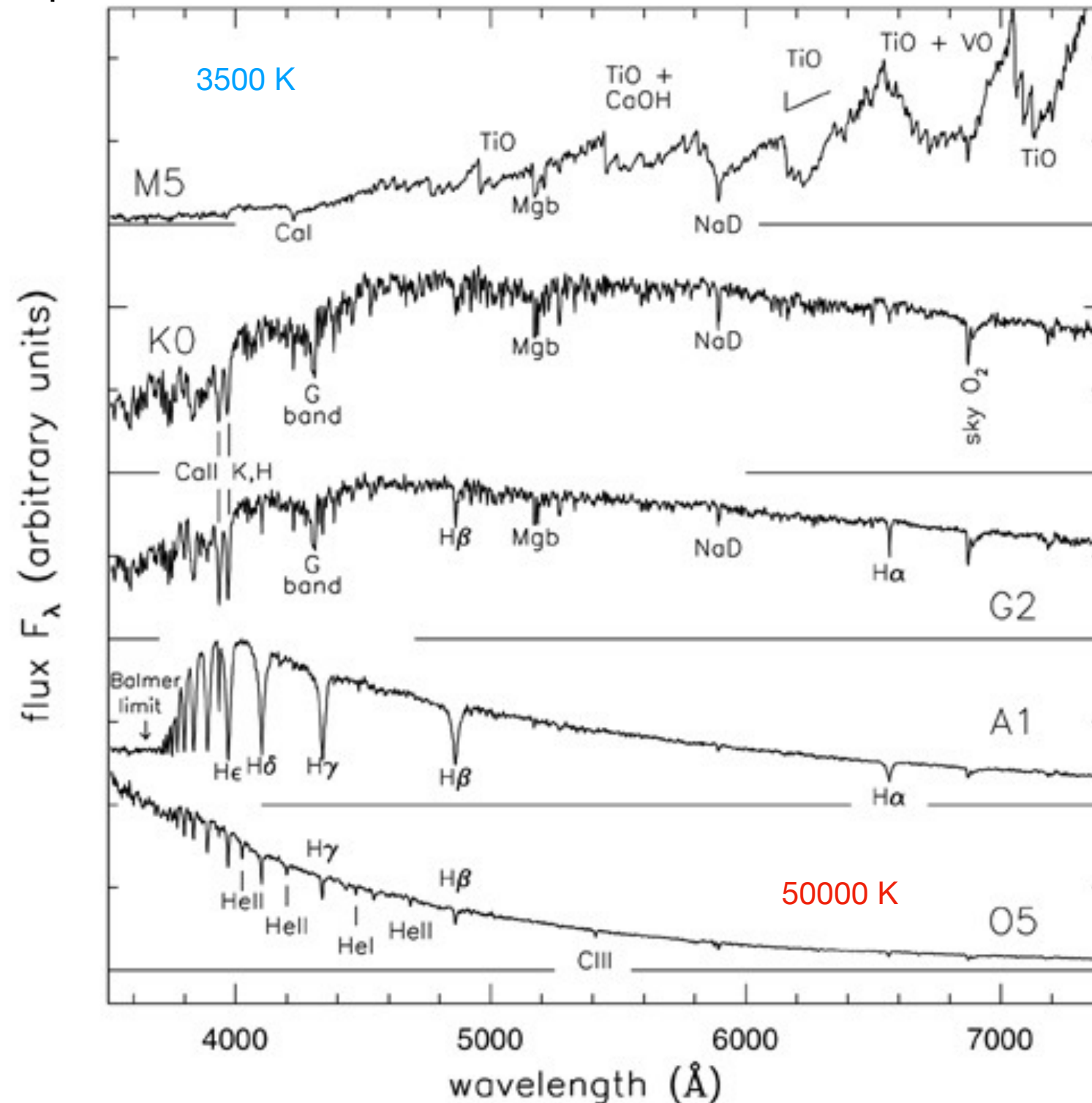


Fig 1.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

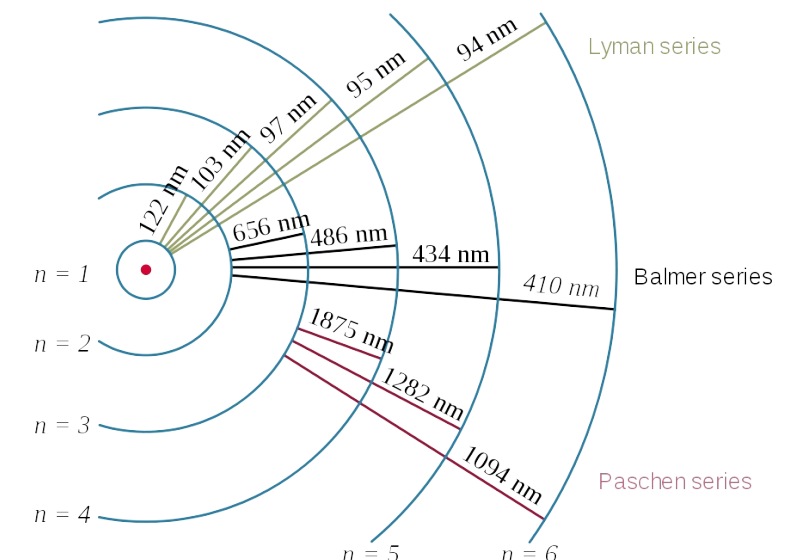


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Review on stars —Metals in stars

Some notes on metals in stars

- Different elements were produced in different ways, their relative fractions can tell us about the formation history of the stars in a galaxy
- All elements heavier than H and He referred to as metals
- Notation for ‘metallicity’ (relative to the Sun)
- Abundance ratios: $[A/B] = \log \left(\frac{\text{number of A atoms}}{\text{number of B atoms}} / \frac{\text{number A}}{\text{number B}}_{\text{sun}} \right)$ — — —
e.g., [O/H], [Fe/H], [O/Fe], etc.
- Total metallicity Z: mass of metals/total mass; $Z_{\text{sun}} \sim 0.02$
- Sun’s composition (photosphere): H=72%, He=26%, ~2% everything else.

Review on stars —stellar spectra

Strength and type of absorption lines in stellar spectra depends on

- Temperature:
 - The hotter the stars, the higher ionisation absorption lines
 - The cooler the stars, more molecule absorption lines
 - A stars have most prominent Balmer absorption lines
- Chemical composition: H, He, trace amounts of Li were formed in the Big Bang – all other elements (up to Fe) — called METALS — were synthesized in stars and SNaE.

Review on stars — stellar evolution

what keeps the Sun stable?

- why doesn't our Sun collapse due to its own gravity?

Review on stars — stellar evolution

what keeps the Sun stable?

- why doesn't our Sun collapse due to its own gravity?
- the plasma in our Sun is in hydrostatic equilibrium self-gravity = internal pressure
- pressure and density in the core of our Sun is sufficient for hydrogen to be fused into helium

Review on stars — stellar evolution

stellar structure & evolution

- think of stars as balls of ideal gas
- continuous battle between gravity & radiation pressure
- what are the essential physical parameters needed to model stellar evolution?

Review on stars — stellar evolution

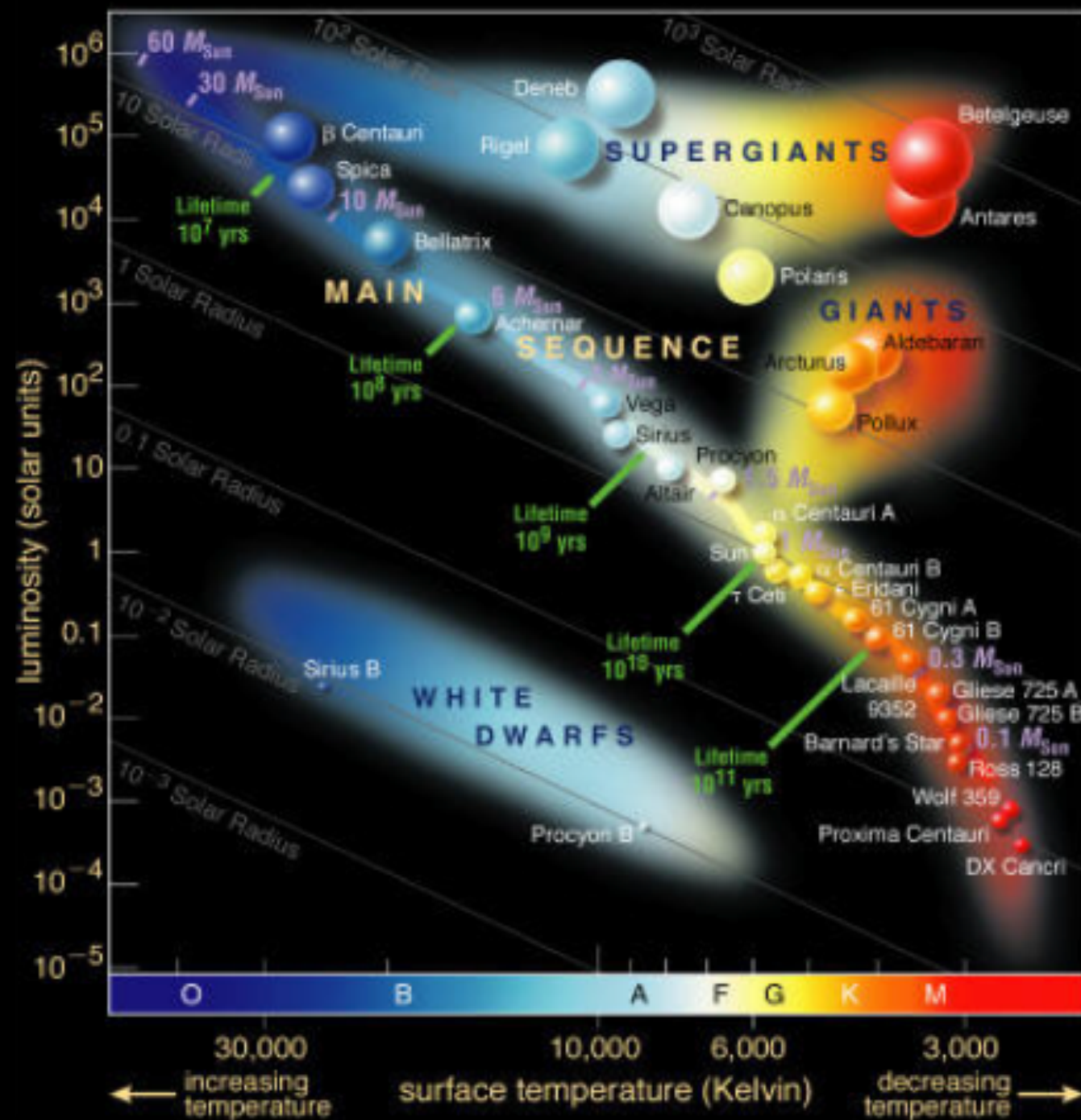
stellar structure & evolution

- think of stars as balls of ideal gas
- continuous battle between gravity & radiation pressure
- what are the essential physical parameters needed to model stellar evolution? →
density, pressure, temperature, and chemical composition

Review on stars — stellar evolution

what is a Hertzsprung-Russell diagram?

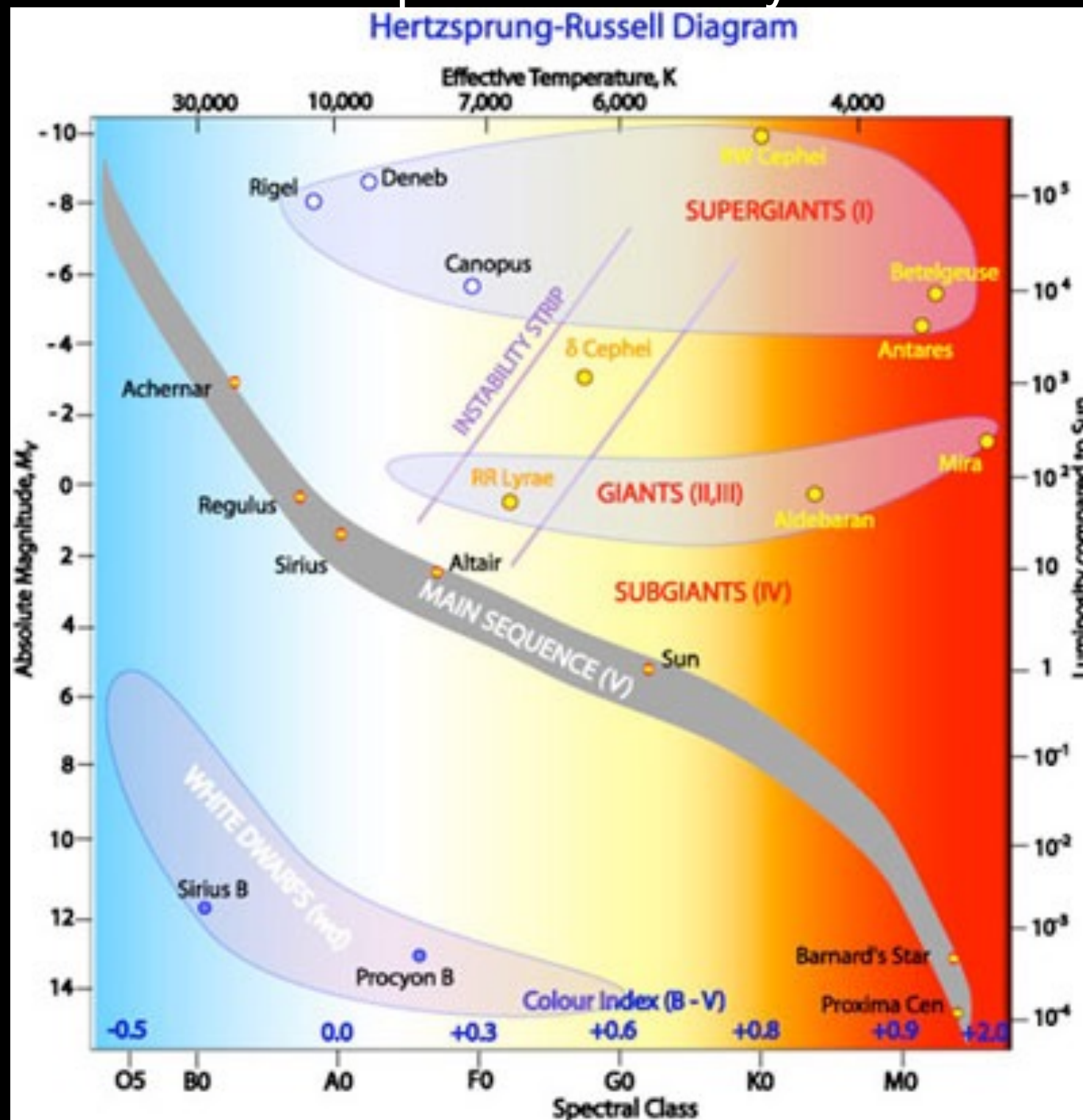
Absolute magnitude/Lum versus spectral class, color, T



stars' occupy only specific regions depending on their evolutionary state (in which they spend some time)

Review on stars — stellar evolution

Stars' paths in this diagram are almost entirely determined by their initial mass and chemical composition ("stellar tracks") — can be modeled quite accurately for most stars



Review on stars

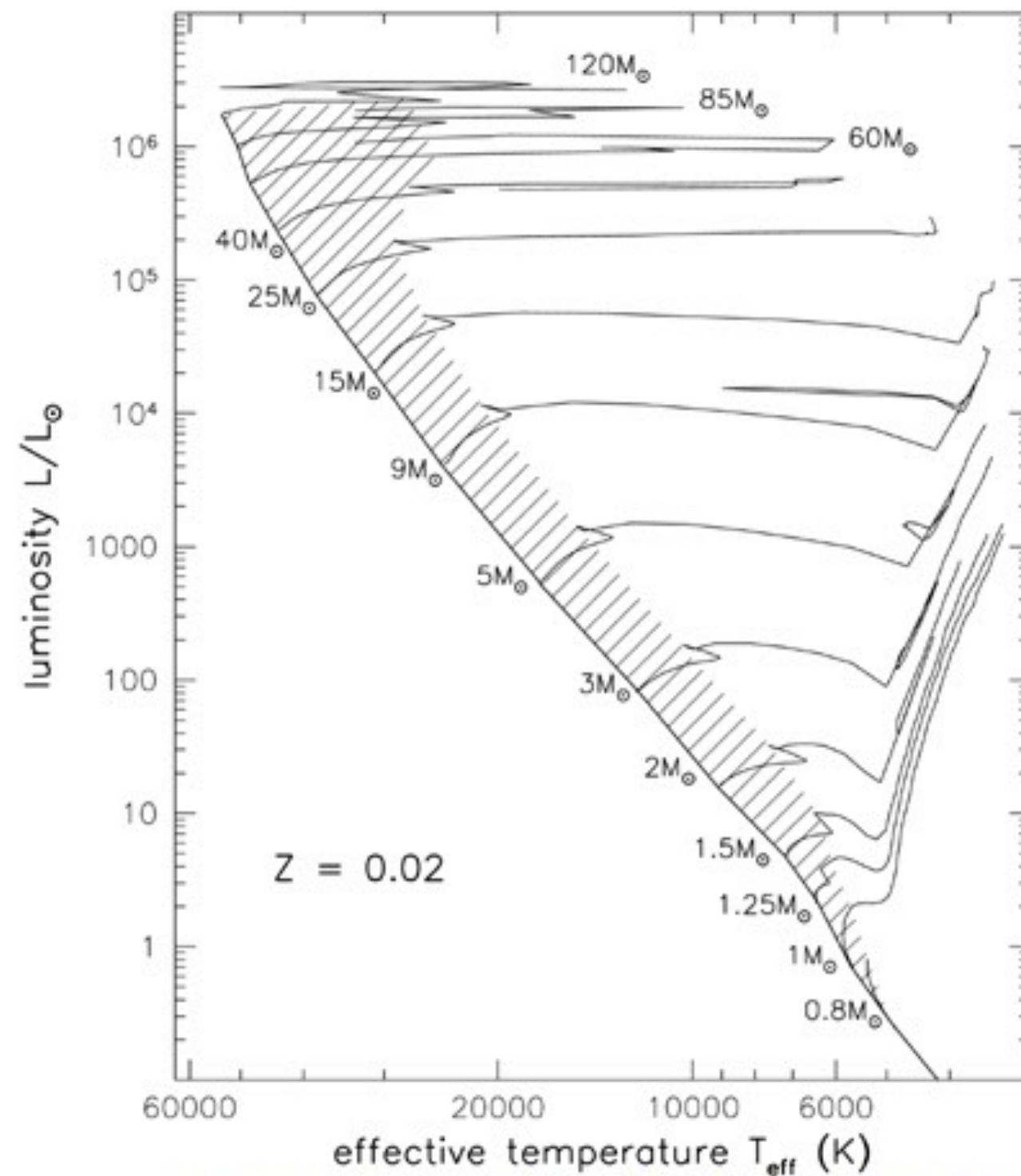
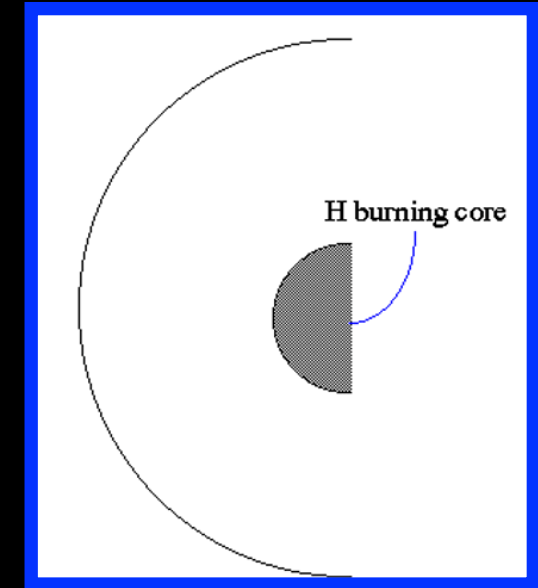


Fig 1.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Review on stars — stellar evolution

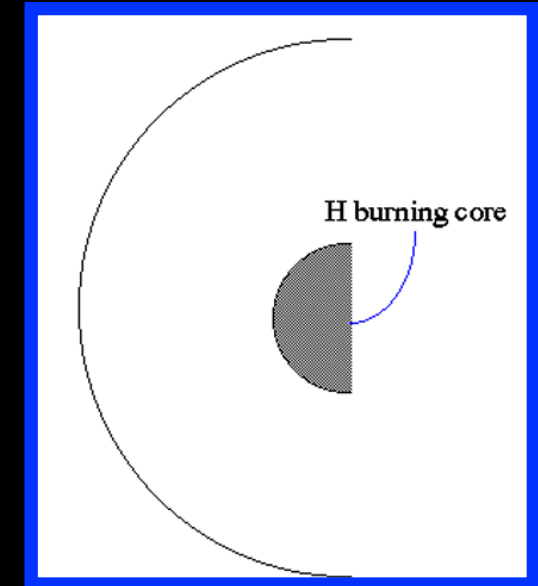
Main sequence:



- hydrogen burns in the core ($\rightarrow$ He).
- for any particular spectral type/color/T, MS stars have nearly the same mass & luminosity – the hottest stars are the most massive, most luminous, and the largest in R.
- $R \sim M^{0.7}$
- $L \sim M^{\alpha}$ where $\alpha \sim 5$ for $M < M_{\text{sun}}$ and $\alpha \sim 3.9$ for $M_{\text{sun}} < M < 10 M_{\text{sun}}$

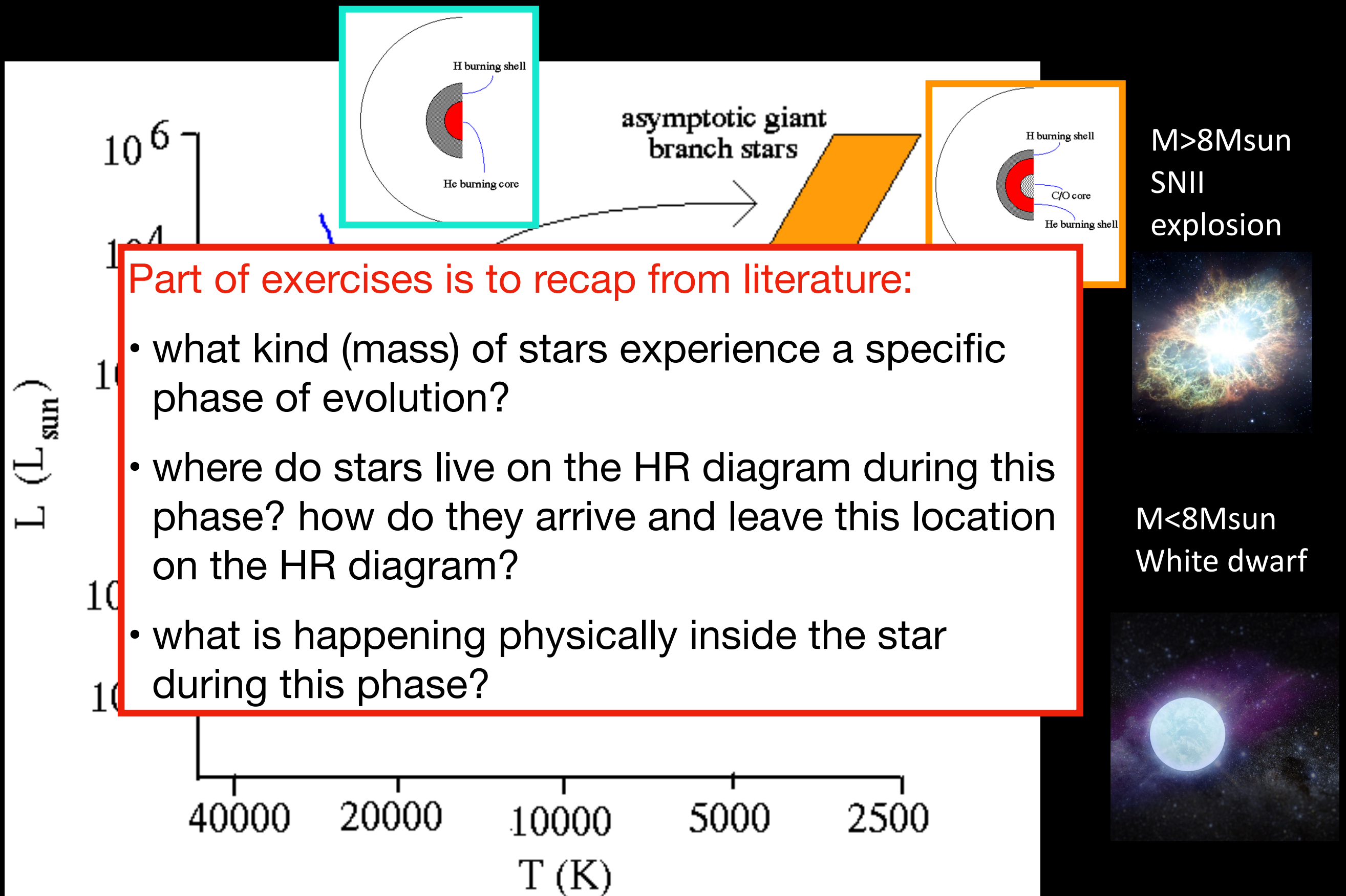
Review on stars — stellar evolution

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- how does the lifetime on the main sequence depend on the stars mass? why?
 - ➔ more massive stars are hotter and burn through their fuel faster.

Review on stars —stellar evolution



effect of chemical composition on stellar structure and evolution

- metals provide a source of *opacity* – for a given [core] luminosity, there is stronger radiation pressure in a metal-rich star
- implies a metal-poor star of the same mass will be more denser, more compact, and burn hotter in its core.
- what does this imply about the location on the HR diagram?

Review on stars

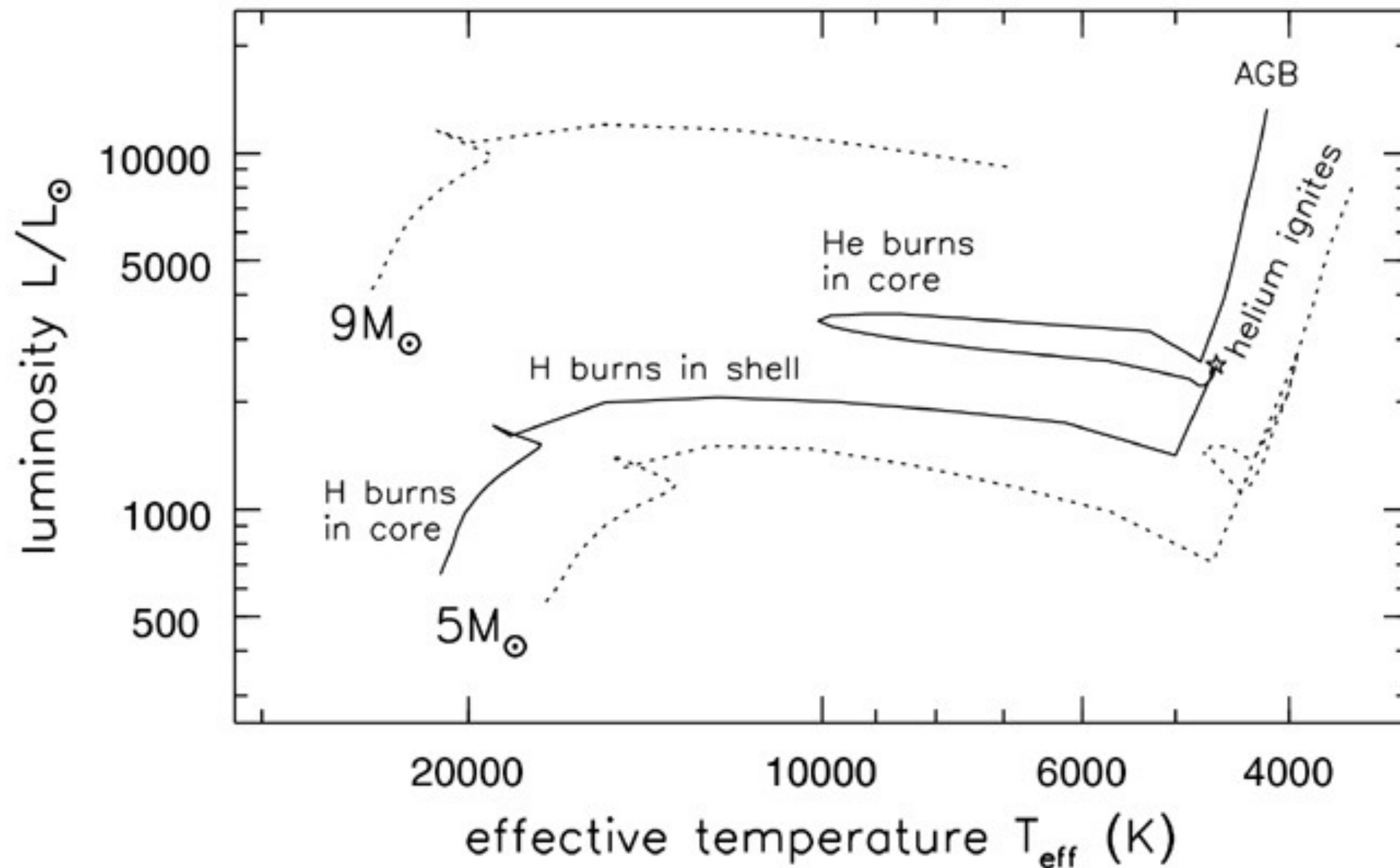


Fig 1.5 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

dotted curves: star with solar composition; solid curve:
 $5 M_{\text{sun}}$ star with $Z = 0.001$ ($1/20^{\text{th}}$ solar)

Summary Chapter 2

Review on stars:

- Luminosity of a star linked to Radius and Temperature

$$L = 4\pi R^2 \sigma_{\text{SB}} T^4$$

- Different spectral classes depending on spectral shape and absorption line features, Massive O & B stars are the bluest, low-mass M stars redder
- Stability of a star is given by the hydrostatic equilibrium
- Hertzsprung Russel (color-magnitude $\sim$ T-L) Diagram contains information about the evolutionary phase of a star
- The luminosity, size, color, location on MS, lifetime, evolution (and death/end product) of a star is mainly dependent on its mass and metallicity at birth (<https://sites.uni.edu/morgans/astro/course/Notes/section2/spectralmasses.html>)

Up next...

- *Chapter 1*: Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2*: Brief review on stars
- *Chapter 3*: Radiation processes in galaxies and telescopes;
- *Chapter 4*: The Milky Way
- *Chapter 5*: The world of galaxies I
- *Chapter 6*: The world of galaxies II
- *Chapter 7*: Black holes and active galactic nuclei
- *Chapter 8*: Galaxies and their environment;
- *Chapter 9*: High-redshift galaxies
- *Chapter 10*:
 - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
 - Dark matter and the large-scale structure
 - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13*: Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *Chapter 17*: Modern simulations & future prospects

Part I:
Observational
basics & facts of
galaxies
first 7 lectures

Part II:
Theory & models
of
galaxy evolution
processes
second 7 lectures