[Theoretical] Astrophysics (765649S)

VITALY NEUSTROEV

SPACE PHYSICS AND ASTRONOMY RESEARCH UNIT
UNIVERSITY OF OULU

2026

Contact details

- **Lecturer:** Vitaly Neustroev
- **Location:** MA 308
- **Email:** vitaly@neustroev.net; vitaly.neustroev@oulu.fi
- **Assistent:** Paula Kvist

  paula.kvist@oulu.fi

- **Web-site:** https://vitaly.neustroev.net/teach/spring-2026/

Aim of the Course

Develop physical understanding of:

- How astronomical objects produce radiation, radiation transport
- Formation, structure, evolution and death of stars
- Stellar atmospheres
- Spectral line formation
- Interstellar medium

This course is a "descendant" of previously taught courses "Stellar structure and evolution", "Interstellar matter", and "Stellar atmospheres".

Syllabus

1. **Introduction:** What is astrophysics and theoretical astrophysics? Astronomical units.
2. **Radiation processes:** fluxes and magnitudes; bolometric flux and bolometric correction; spectral types; luminosity classes; effective temperature; specific intensity; optical depth; source function; equation of radiative transfer; optical depth; blackbody radiation; radiation from atoms; spectral lines; bremsstrahlung; synchrotron radiation.
3. **Stars:** basic assumptions and observations; measuring masses; hydrostatic equilibrium; virial theorem; characteristic timescales; gas and radiation pressure; degeneracy pressure; Eddington limit; energy transport by radiation; nuclear reactions; neutrino oscillations; convection.
4. **Stellar evolution:** star formation; Young Stellar Objects; binary formation; low mass stars; white dwarfs; mass transfer binaries; Type II supernovae; neutron stars; black holes.
5. **Stellar photospheres:** Stellar types, spectra, temperatures. Continuous and line spectra. Spectral analysis. Theory of line formation.
6. **Interstellar Medium:** Cooling and heating of the gas and dust. Multiphase interstellar medium. Basics of gas dynamics. Physics of HII regions. Shock waves. Evolution of photoionized nebulae. Stellar winds. Supernovae explosions.

Schedule

1. Officially, lectures should take place on Wednesday, and Thursday, while exercise sessions on Monday, in one of the lecture halls M203 or M204.
2. However, I will **usually** give lectures on **Monday** and **Wednesday**, and exercise and practical sessions sessions on **Thursday**.
3. **Important!** Classes on **Thursday** will only occur when I announce them!
4. Also, a few lectures will be skipped due to classes overscheduling.

Check the course web-page for announcements!

https://vitaly.neustroev.net/teach/spring-2026/

Recommended Textbooks

Textbook choice for this course is largely a matter of personal taste. Here is a list of recommended books (check the course web-page!). Study them in parallel with the lectures:

- D. Prialnik: An introduction to the theory of stellar structure and evolution*
- R. Kippenhahn, A. Weigert: Stellar structure and evolution
- J. E. Dyson, D. A. Williams: The physics of the interstellar medium, 2nd ed., Institute of Physics Publishing, 2003
- E. Böhm-Vitense: Stellar astrophysics, vol. 2 & 3, Cambridge Univ. Press, 1992*
- David F. Gray, The Observation and Analysis of Stellar Photospheres, 3rd Edition, 2005, Cambridge University Press, ISBN: 9780521066815**
- Lecture notes (**not enough!**)

* Available in the Pegasus Library

** eBook (through the Pegasus Library)

Assessment

Astrophysics is a difficult course.

To pass it, students must attend class on a regular basis, complete homework assignments, present an essay, and to pass written intermediate exams and at the end of the course.

Your grade will be based on:

- 50% Exams: an intermediate and the final
- 30% Homeworks: at least 5 sets of compulsory problems (return by the deadline)
- 20% Essay: 5 pages + 15 min presentation (compulsory)
- Active participation will be taken into account

Introduction

WHAT IS ASTROPHYSICS?
THEORETICAL ASTROPHYSICS
ASTRONOMICAL UNITS

Astrophysics

Application of the laws of physics to understand the nature and behaviour of astronomical objects, and to predict new phenomena that could be observed.

Observational Astrophysics

deals with collecting useful data through observations of astronomical objects using different scientific instruments.

Observational astronomy (765640S, 5 ECTS)

Theoretical Astrophysics

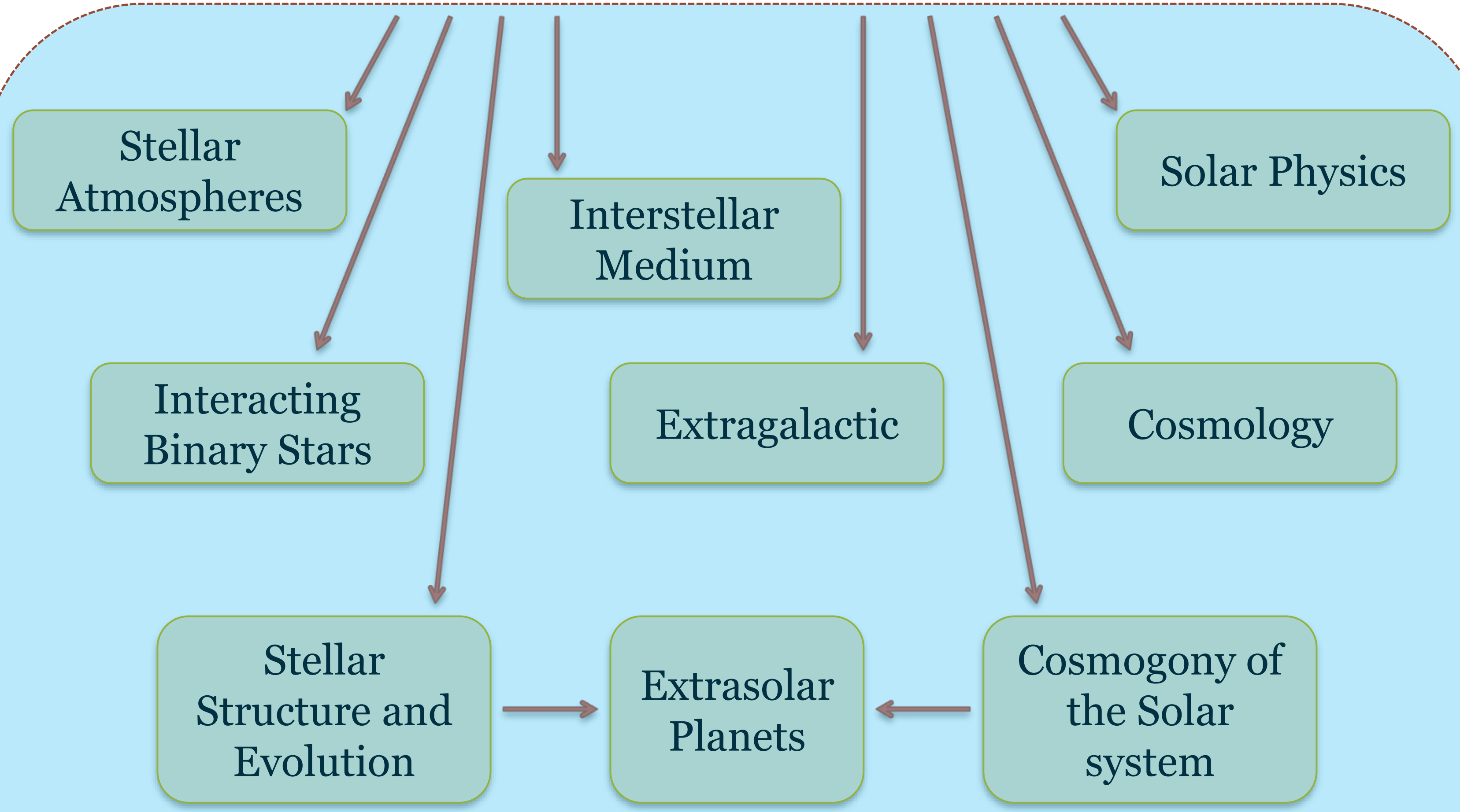
uses physics to interpret observational data and construct physical models. Theory connects all the data together into a full understanding and makes predictions about phenomena we haven't observed yet.

This course

Astrophysics

- Most branches of physics find some application in astronomy.
- Main difference between astrophysics and other branches of physics: controlled experiments are (almost) never possible.
- This means:
  - If many different physical effects are operating at the same time in a complex system, we can't isolate them one by one.
  - Knowledge of rare events is limited - nearest examples will be distant. For example, no supernova has exploded within the Milky Way since telescopes were invented.
  - Need to make best use of all the information available - many advances have come from opening up new regions of the electromagnetic spectrum.
  - Statistical arguments play a greater role than in many areas of lab physics.

Theoretical Astrophysics



Most of astronomical objects are detected via electromagnetic radiation

Physical conditions

Physical conditions in astronomical objects are very diverse:

- Temperatures:
  - 3 K (microwave background radiation);
  - 10 K (molecular gas in star forming region);
  - 10^{12} K (gas near a black hole).
- Densities as high as 10^{15} g cm^{-3} in neutron stars
- Velocities above 0.99 c (speed of light)

Examples: The Sun

Physical conditions in the center of the Sun are:

- Temperature 1.5×10^7 K
- Density 150 g cm^{-3}

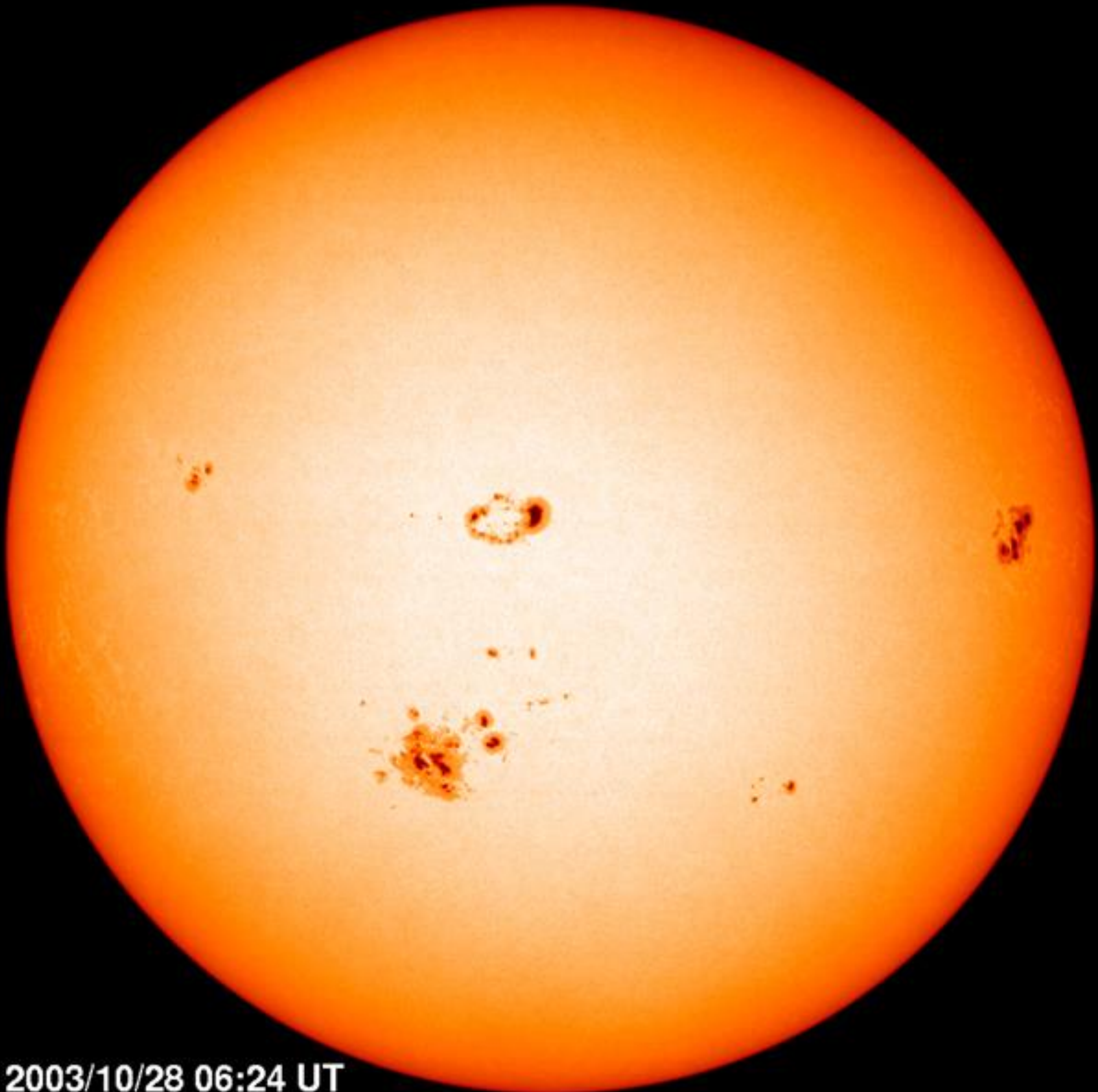
Temperature (and to a lesser extent density) is well within range accessible to lab experiments.

→ High confidence that we understand most of the basic physics (i.e. what are the laws) pretty well.

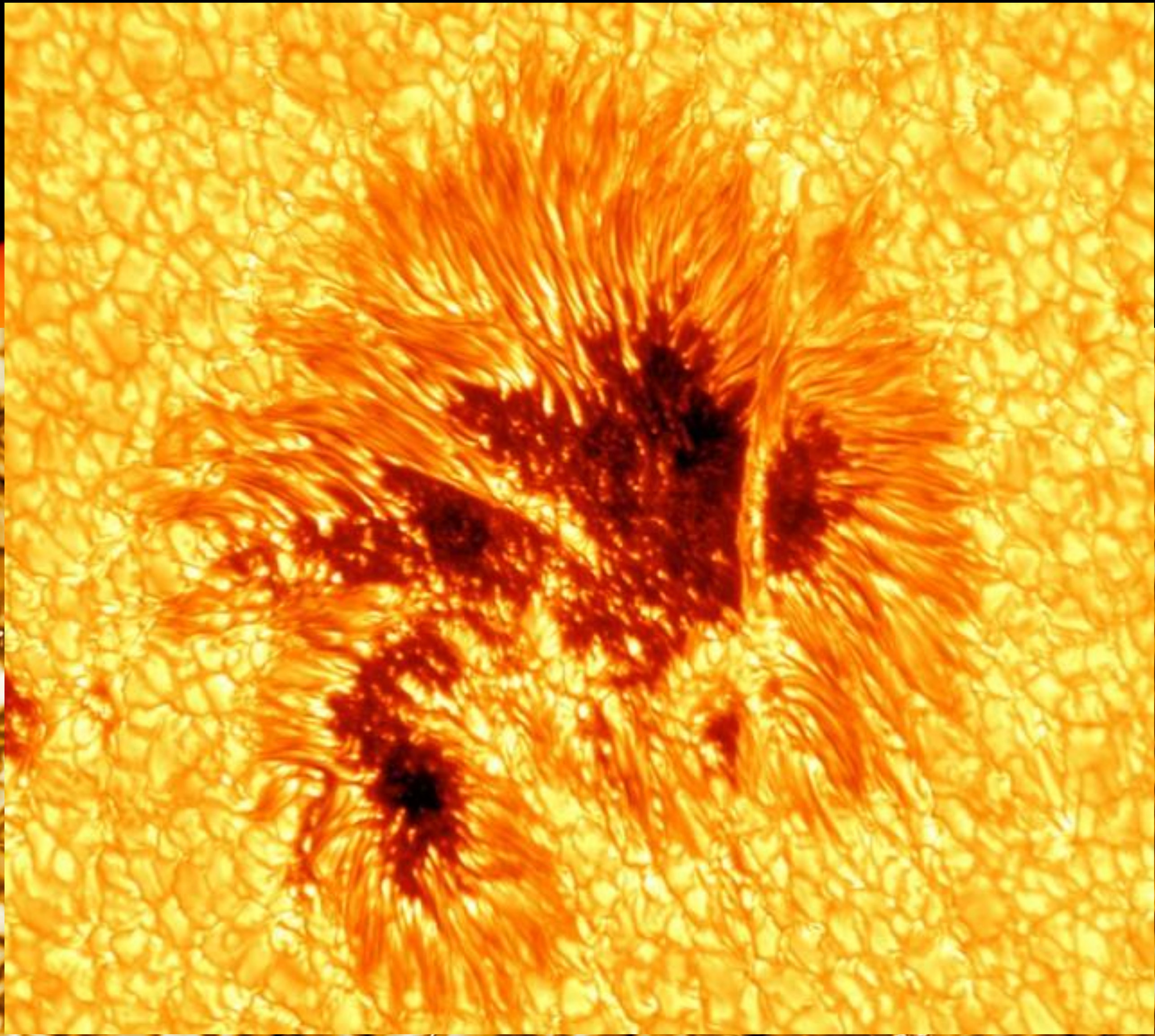
Numerous excellent observations also available.

Detailed comparison between theory and observations is possible.

The Sun



The Sun



Examples: Stellar remnants

Neutron stars can have magnetic fields >> lab conditions:

- Earth's magnetic field ~10^{-4} Tesla (1 Gauss)
- Strongest magnets ~40 T (4 x 10^{5} G)
- Magnetar ~10^{11} T (10^{15} G)

Black holes produce gravitational fields enormously stronger than any found in the Solar System.

In both cases we think we know the physics needed to understand these objects:

- matter in superstrong magnetic fields (Quantum electro-dynamics)
- Black Holes (General Relativity)

But untested in the lab - ideally would hope observations could test theory in new regimes.

First-ever Image of a Black Hole

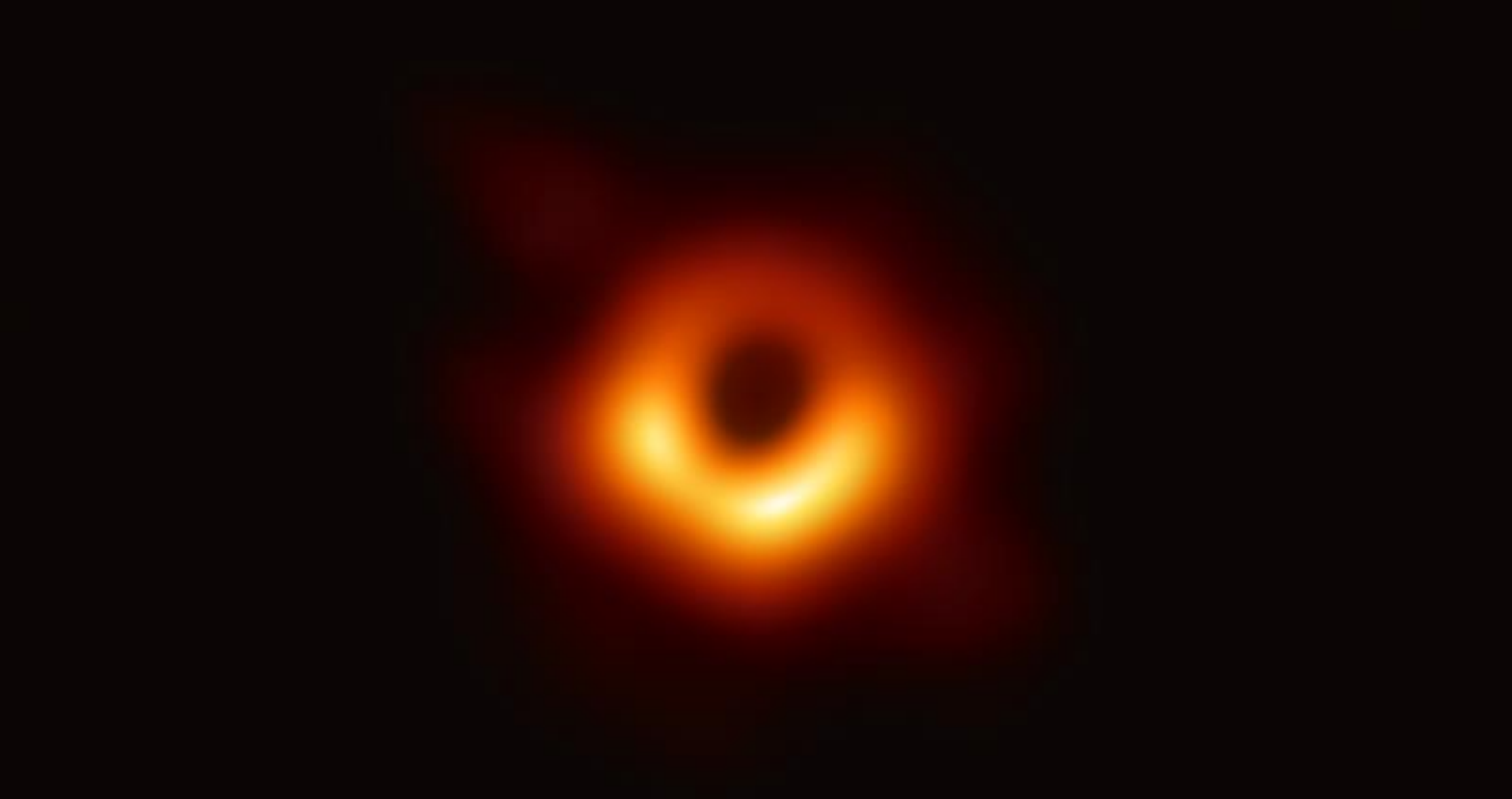


Image credit: the Event Horizon Telescope Collaboration

Black Hole

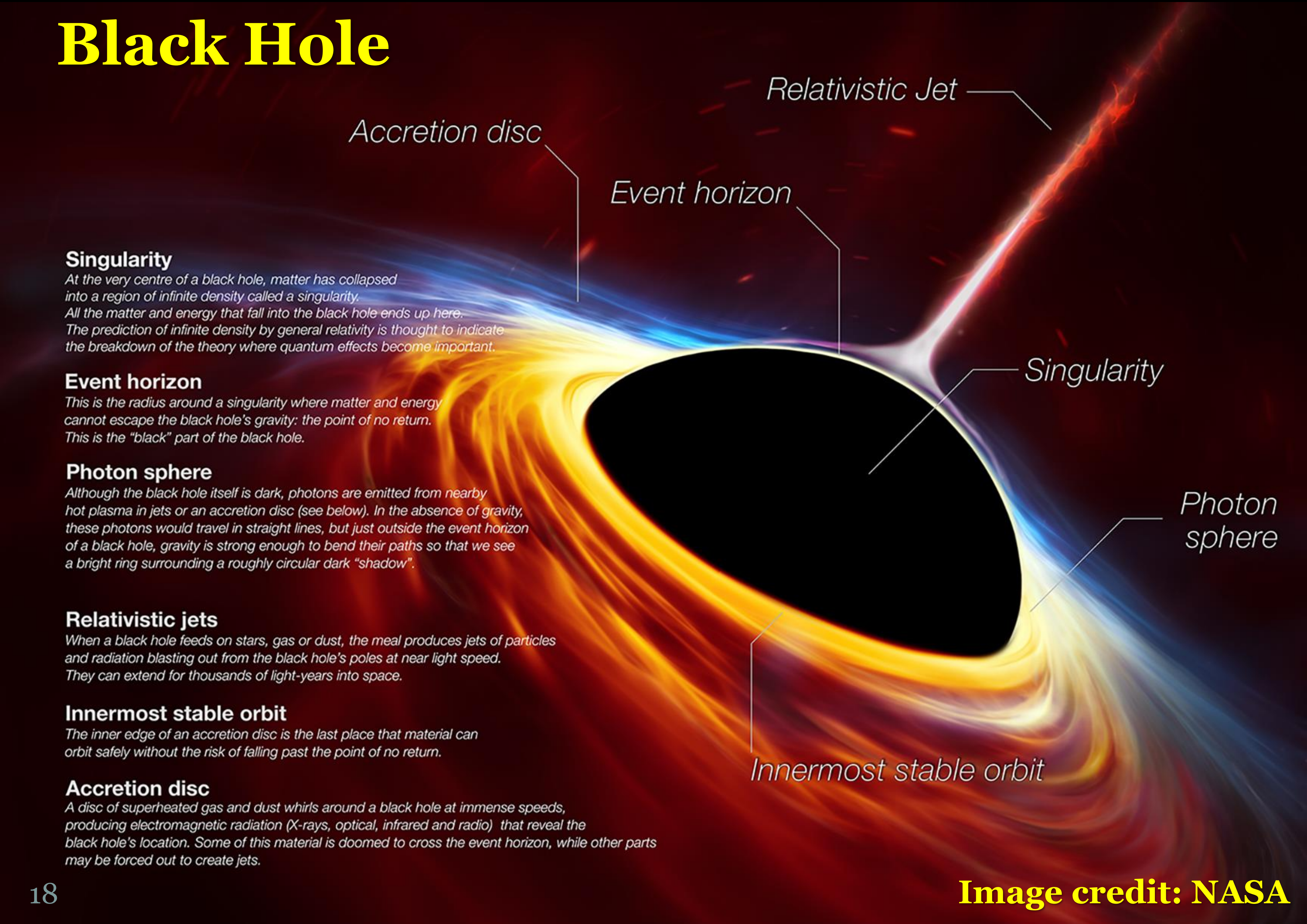


Image credit: NASA

Examples: Cosmology

Observations of the rotation curves of spiral galaxies suggest presence of **dark matter** - probably in the form of an unknown elementary particle.

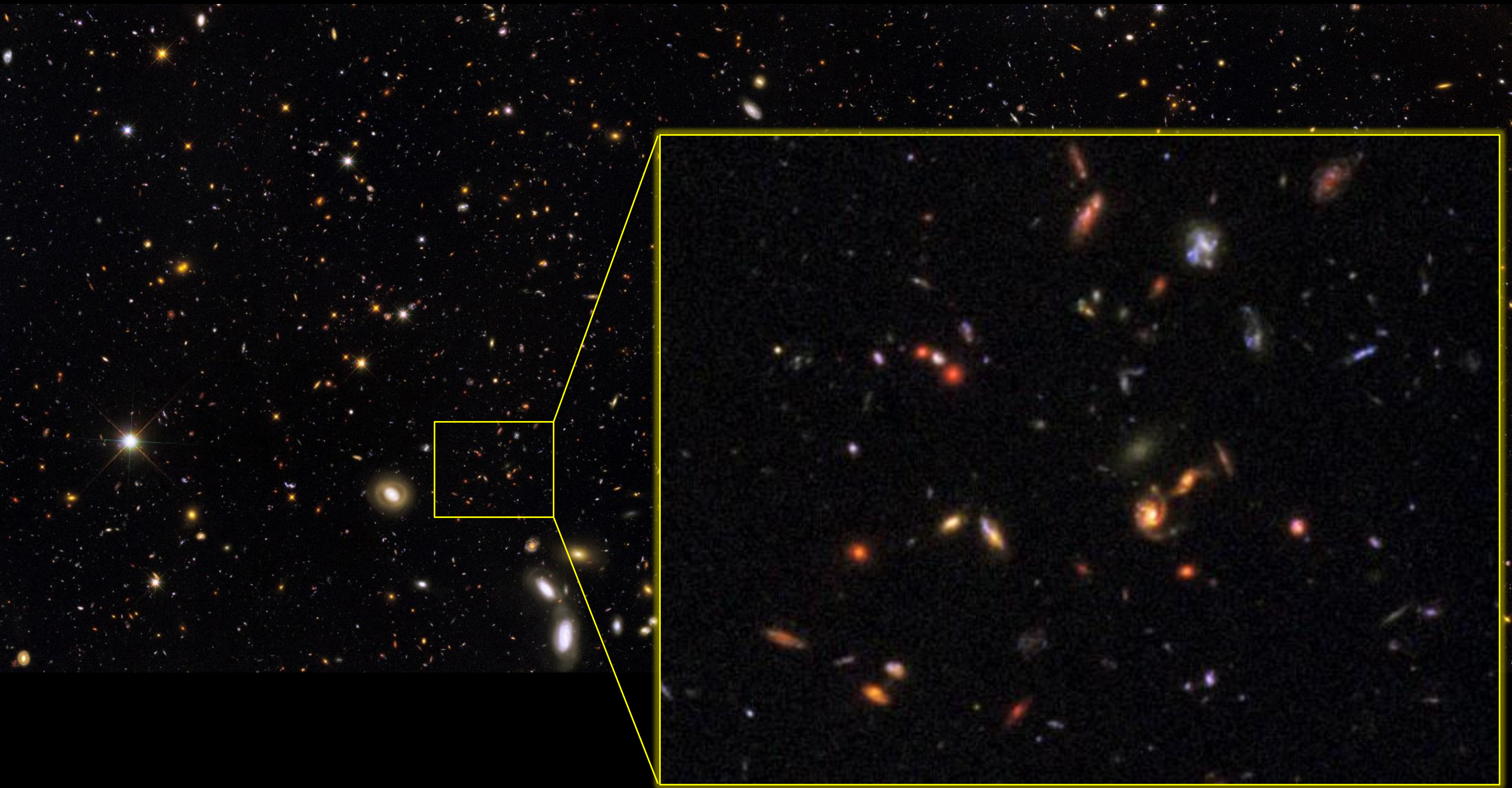
Observations of the brightness of distant supernovae suggest presence of **dark energy** - not understood at all.

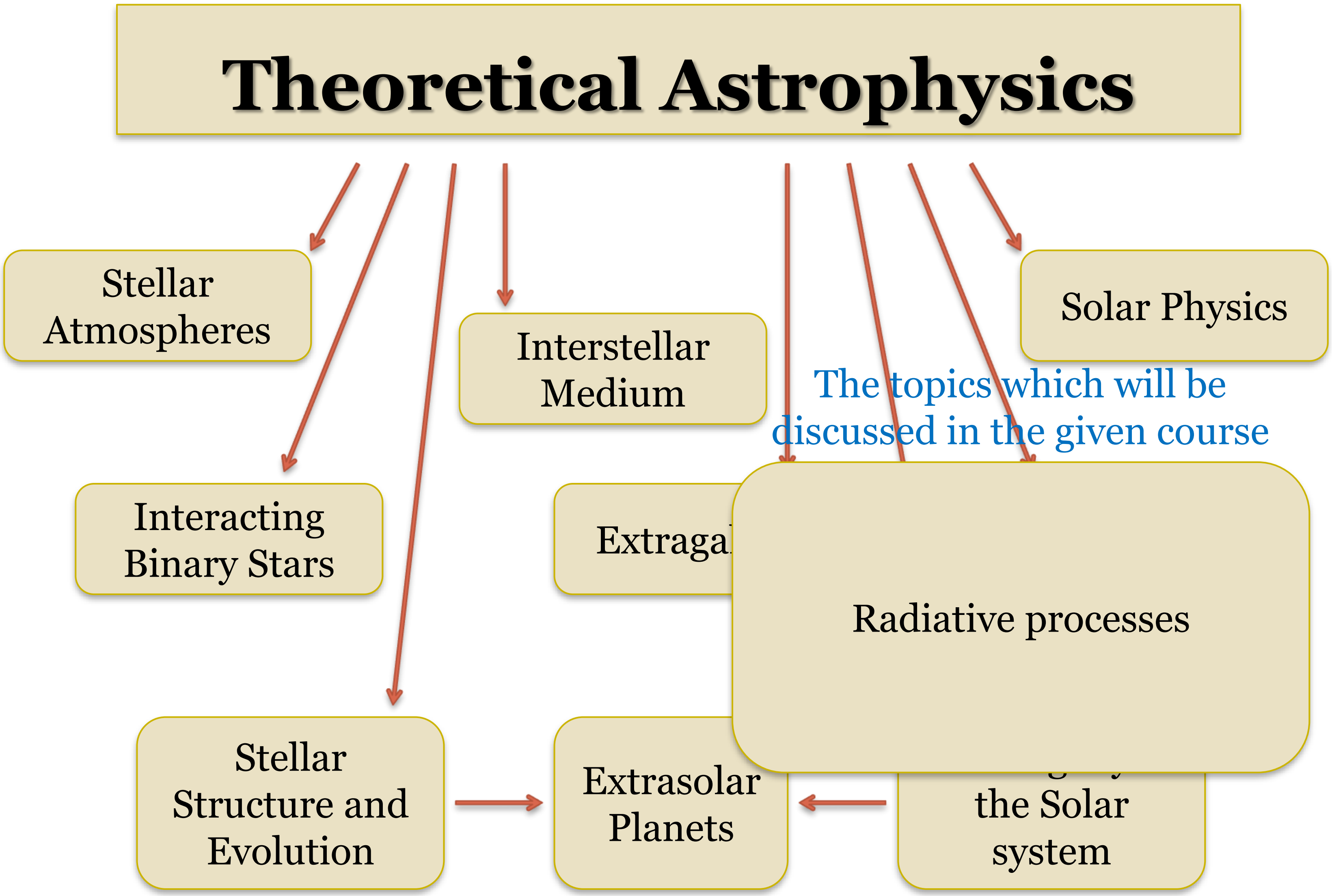
Astronomical observations hint at presence of new physics, which may be testable in the lab in the future.

One of the deepest views of the Universe

Great Observatories Origins Deep survey data

One of the deepest views of the Universe





Most of astronomical objects are detected via electromagnetic radiation

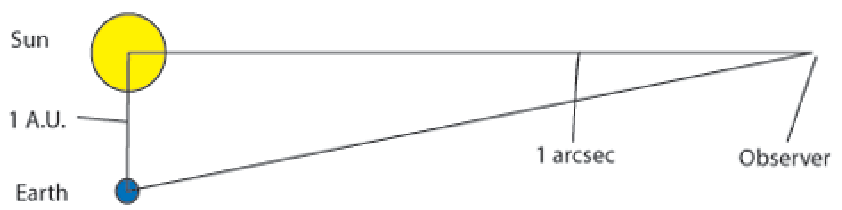
Astronomical units (1)

- Distance: an astronomical unit (AU or au) is the mean distance between the Earth and the Sun (technically the radius of a circular orbit with same period as the Earth).

$$1 \text{ au} = 1.496 \times 10^{13} \text{ cm}$$

- A parsec (pc) is defined as the distance at which 1 au subtends an angle of 1 arcsecond.

$1 \text{ arcsec} = 4.85\times10^{-6}$ radians



Astronomical units (2)

$$1'' = \frac{1\ \text{au}}{1\ \text{pc}} \qquad 1\ \text{pc} = \frac{1.496\times10^{13}\text{cm}}{4.85\times10^{-6}} = 3.086\times10^{18}\ \text{cm}$$

1 pc = 3.26 light years - roughly the distance to the nearest stars. Convenient unit for stellar astronomy.

Sizes of galaxies usually measured in kpc (galaxy scales are 10-100 kpc).

Cosmological distances are hundreds of Mpc to Gpc.

Observable Universe is a few Gpc across.

Astronomical units (3)

- Wavelengths in the optical range are usually measured in Angstroms, but may show plots in nm:

$$1\ \text{Å} = 10^{-8}\ \text{cm} = 10^{-10}\ \text{m} = 0.1\ \text{nm}$$

- Other common units are the Solar mass, Solar radius, and Solar luminosity:

  $R_{\odot}=6.955\text{x}10^{10}$ cm,
  $L_{\odot}= 3.845\text{x}10^{33}$ erg/s,
  $M_{\odot}=1.989\text{x}10^{33}$ g

cgs (cm/gram/second) units

Fundamental:

Gravitational constant, $G=6.679x10^{-8}$ $cm^3/g/s^2$
Stefan-Boltzmann: $\sigma=5.6705x10^{-5}$ $erg/cm^2/s/K^4$
Speed of light, $c=2.99792x10^{10}cm$,
Electron mass: $m_e=9.109x10^{-28}$ g
Planck constant $h=6.626x10^{-27}$ erg s
Electron charge: $4.803x10^{-10}$ e.s.u.
Boltzmann const: $k=1.380x10^{-16}$ erg/s or $8.617x10^{-5}$ eV/K
Gas constant $R=8.314x10^{7}$ erg/mol K

Solar:

Radius $R_{\odot}=6.955x10^{10}$ cm,
Luminosity $L_{\odot}= 3.845x10^{33}$ erg/s,
Mass $M_{\odot}=1.989x10^{33}$ g

Astronomical:

Parsec, pc: $3.086x10^{18}cm$
Astronomical Unit, AU: $1.496x10^{13}$ cm
Angstrom, 1 Å = $10^{-8}cm$

Miscellaneous

Energy of 1 eV=$1.602x10^{-26}$ erg

Stars

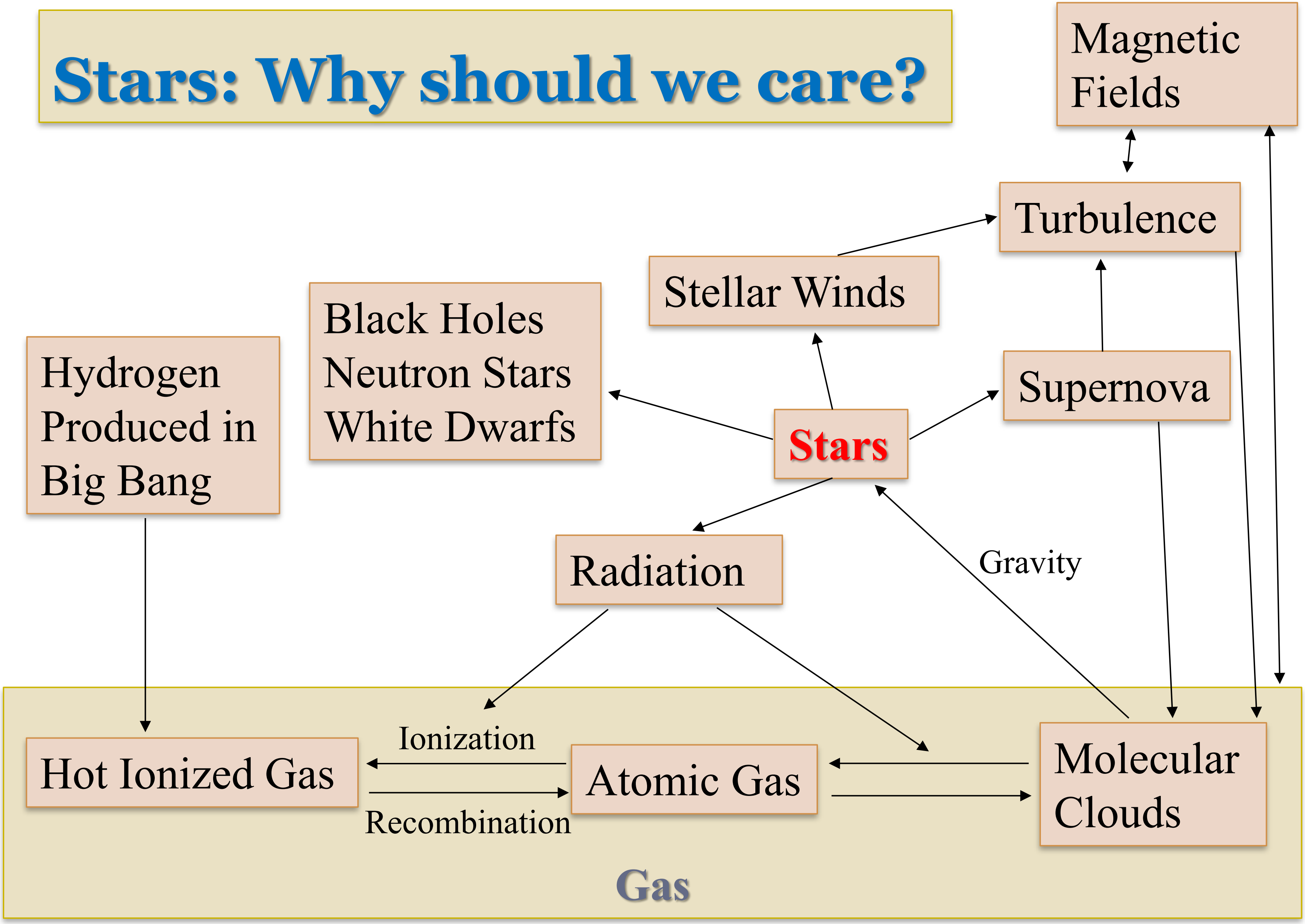
ROLE OF STARS
DEFINITION
WHAT CAN WE LEARN FROM OBSERVATIONS?
PROPERTIES OF STARS
STELLAR TIMELINE

Star Field as seen through the Hubble Space Telescope

Role of stars

- Astronomy (Greek :
  αστρονομία = ἄστρον + νόμος,
  astronomia = astron + nomos,
  literally, “law of the stars”).
- Most of the visible **matter** in the Universe (97% in our Galaxy) is contained within stars.
- Stars produce most of the **energy** in the Universe in the present time.
- The creation of the **chemical elements** (nucleosynthesis) mostly occurs in stars at present.
- In the Milky Way about 400 billion ($4x10^{11}$) stars.

Stars: Why should we care?



What is a star?

Elementary definition:

- Star is a huge glowing self-luminous gaseous sphere

Size

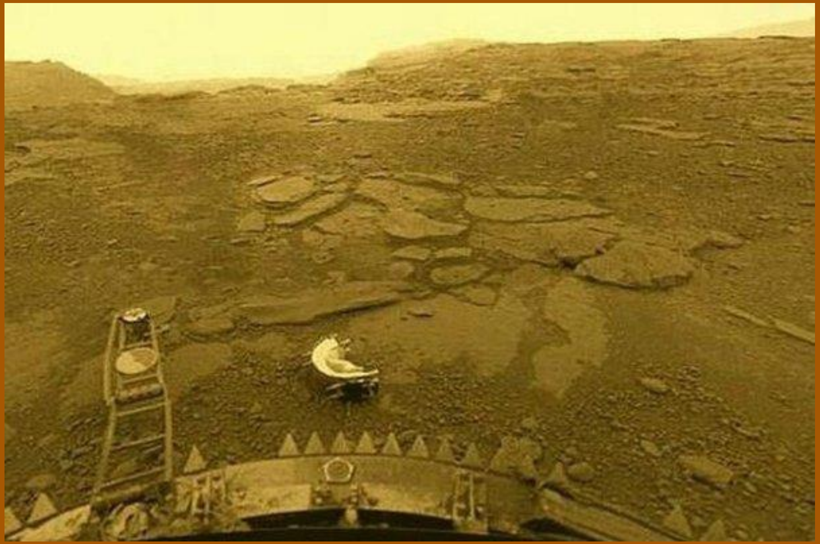
Star is a **huge** glowing self-luminous gaseous sphere

- Sun 700 000 km= 7×10^{10} cm
- Earth 6500 km = 6.5×10^{8} cm
- Compact stars:
  - White dwarfs ~ 10^{4} km ~ 10^{9} cm
  - Neutron stars ~10 km ~ 10^{6} cm

Temperature

Star is a huge **glowing** self-luminous gaseous sphere

- By temperature, the temperature of the surface is usually meant.
- However, normal stars have no solid or liquid surface. Therefore, the photosphere (a star's outer shell from which light is radiated) is typically used to describe the star's visual surface.
  - Sun T = 5777 K
  - Very low-mass stars T = 800-1000 K
  - Compare with Venus surface T = 700 K



Energy production

Star is a huge glowing **self-luminous** gaseous sphere

- Jupiter (a planet, not a star) radiates about twice as much energy as it receives from the Sun, so it produces energy and can also be treated as self-luminous object

State of matter

Star is a huge glowing self-luminous **gaseous** sphere

- Sun:
  - Average density: 1.4 g/cm^3
  - Centre density: 162 g/cm^3
  - Photosphere density: 2×10^{-7} g/cm^3

- Densities of compact stars are extremely high
  - White dwarfs: 10^6 g/cm^3
  - Neutron stars: 10^{15} g/cm^3
  - Neutron stars have solid surface (crust) with cracks and starquakes

Form

Star is a huge glowing self-luminous gaseous **sphere**

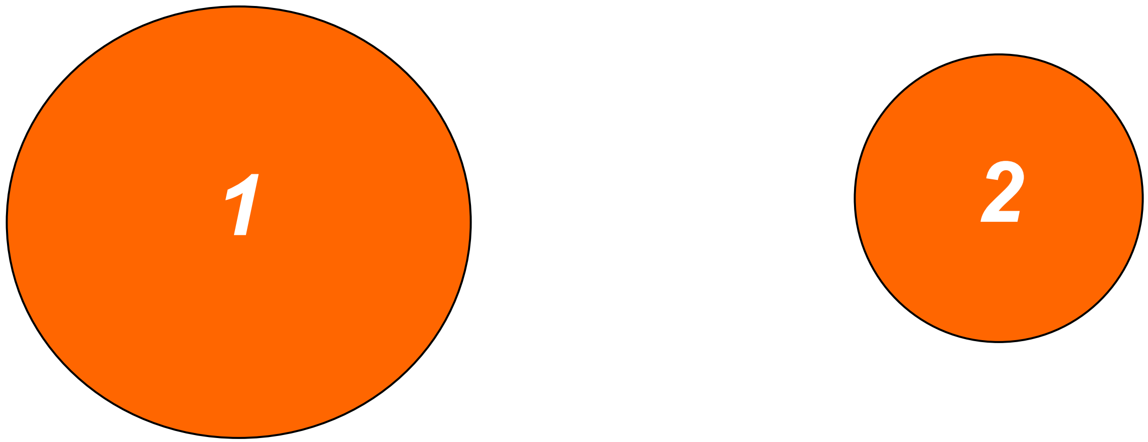
- Rotating stars are oblate due to centrifugal forces.
  - Example: α Eri (Achernar) V=0.5 mag
    - Rotational velocity at equator is 225 km/s
    - Equatorial radius is 11.8 $R_{\odot}$
    - Polar radius is 7.6 $R_{\odot}$
    - Flatness is 2:3
  - Sun:
    - Flatness is 9×10^{-6}
- Stars in double systems are elongated due to gravitational attraction

What is a star?

Definition:

- Stars are self-gravitating objects where thermonuclear reactions, which convert hydrogen into helium, operate or occurred in the past.

L vs R and T_{eff}

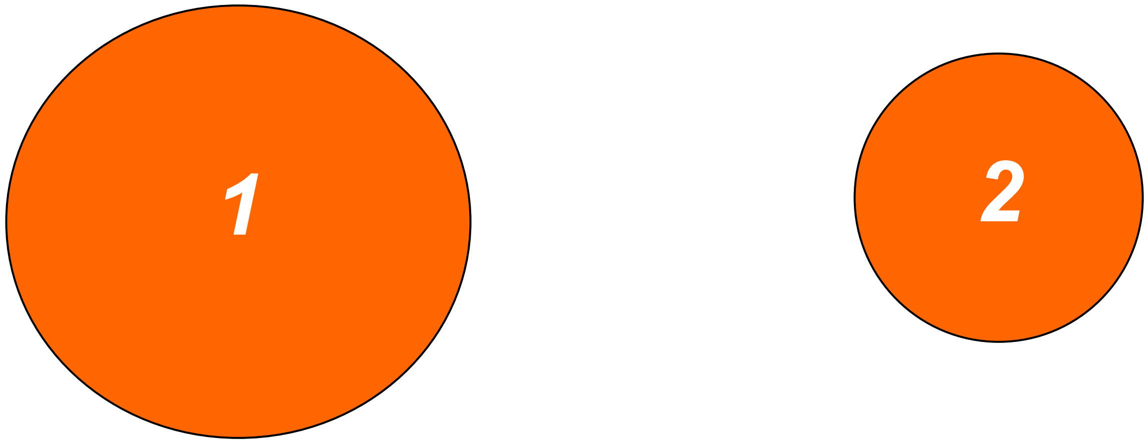


$R = 2R_{\odot}$ $R = R_{\odot}$

$T = T_{\odot}$ $T = T_{\odot}$

Which star is more luminous?

L vs R and T_{eff}



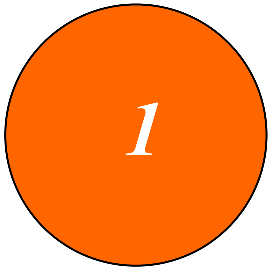
$R = 2R_{\odot}$ $\qquad$ $R = R_{\odot}$

$T = T_{\odot}$ $\qquad$ $T = T_{\odot}$

Each cm^2 of each surface emits the same amount of radiation.

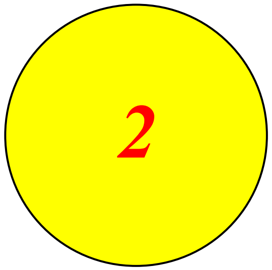
The larger stars emits more radiation because it has a larger surface.
It emits 4 times as much radiation.

L vs R and T_{eff}



$R = R_{\odot}$

$T = T_{\odot}$



$R = R_{\odot}$

$T = 2\,T_{\odot}$

Which star is more luminous?

L vs R and T_{eff}

$R = R_\odot$ $R = R_\odot$

$T = T_\odot$ $T = 2\,T_\odot$

The hotter star is more luminous.

Luminosity varies as T^4 (Stefan-Boltzmann Law)

Luminosity Law

$$L \propto R^2\ T^4$$

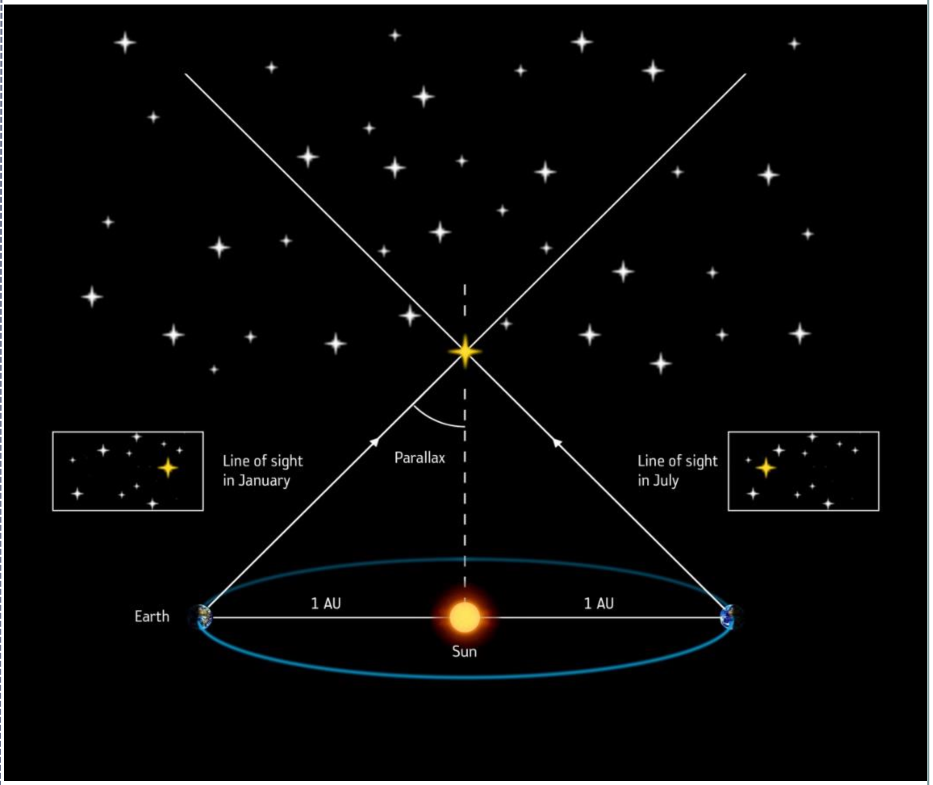
$$\text{Luminosity} \propto \text{Surface Area} \propto (\text{Radius})^2$$

$$\text{Luminosity} \propto (\text{Temperature})^4$$

If star 1 is 2 times as hot as star 2, and the same radius, then it will be $2^4 = 16$ times as luminous.

What can we learn from observations?

- Stellar Luminosities come from distance measurements. The best way to perform such measurements is through parallax:
  - Ground-based measurements (difficult)
  - Hipparcos (1989-1993, >100 000 stars measured)
  - Gaia (launched in 2013, goal – to measure one billion sources, 1% of the Galaxy's population).



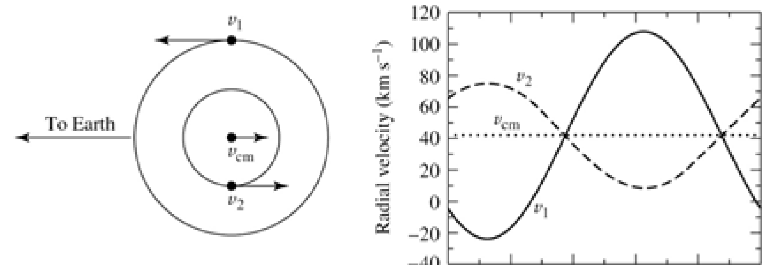
What can we learn from observations?

- Stellar Sizes and Masses primarily come from Binary Stars:

Spectroscopic Binaries (4)

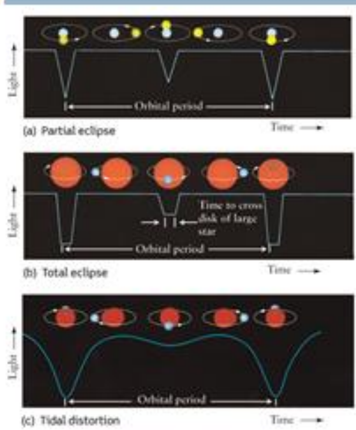
21

- Radial Velocity curve for Double-lined SB in **a Circular Orbit**:



Eclipsing (Photometric) Binaries

24



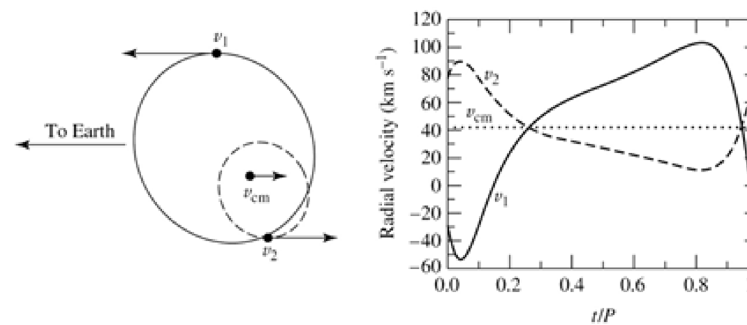
- By studying the shape of the eclipses, in conjunction with a knowledge of their radial velocity curves, it is possible to determine the masses and radii of the stars in the binary.
- Eclipsing binaries are hence extremely useful systems.

Interacting Binary Stars

Spectroscopic Binaries (5)

22

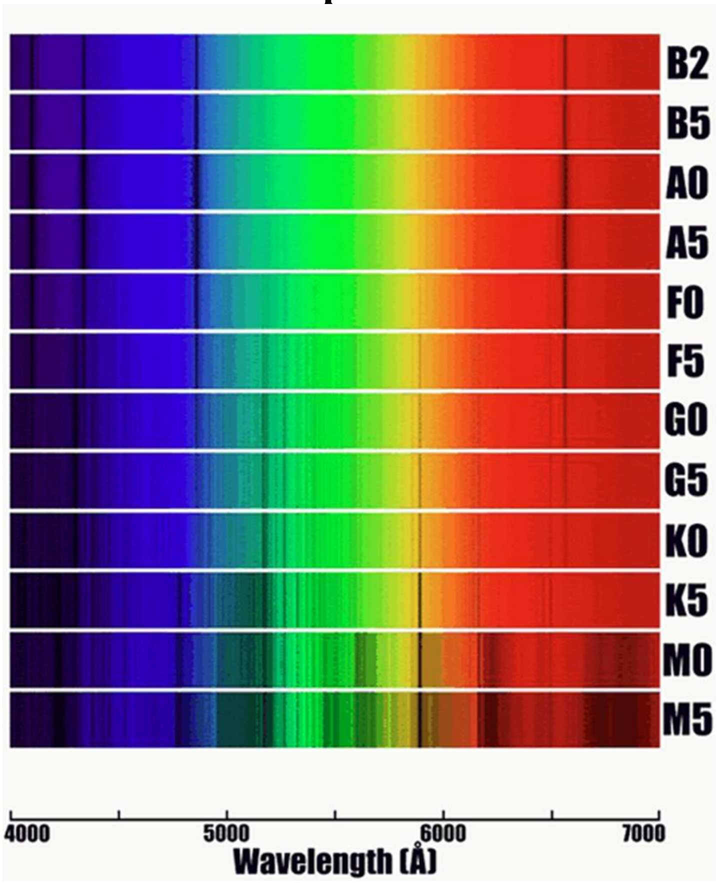
- Radial Velocity curve for Double-lined SB in **an Elliptical Orbit (e=0.4)**:

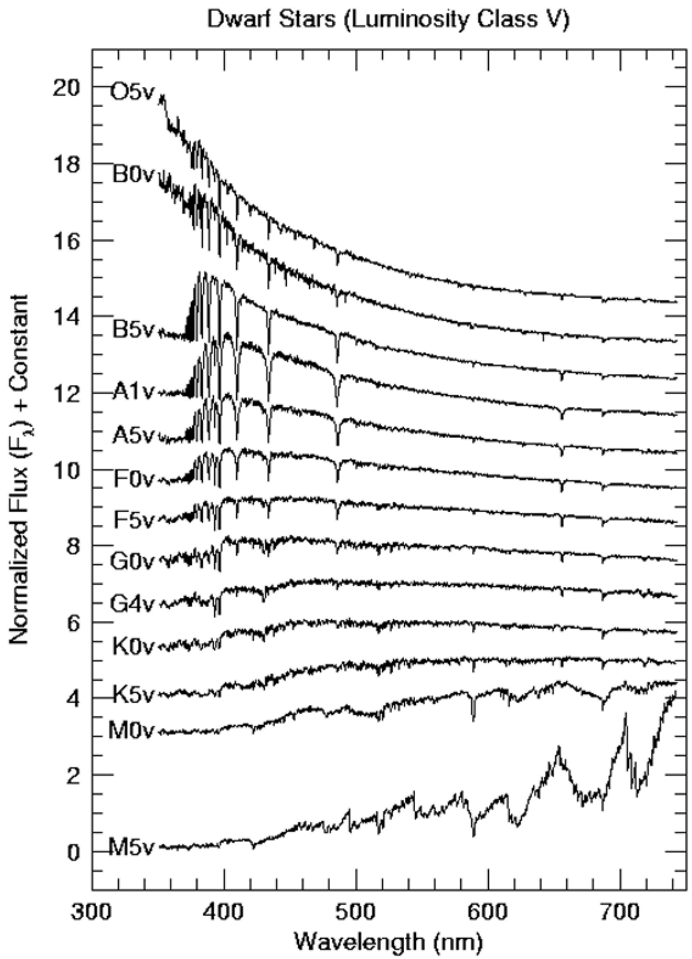


Interacting Binary Stars

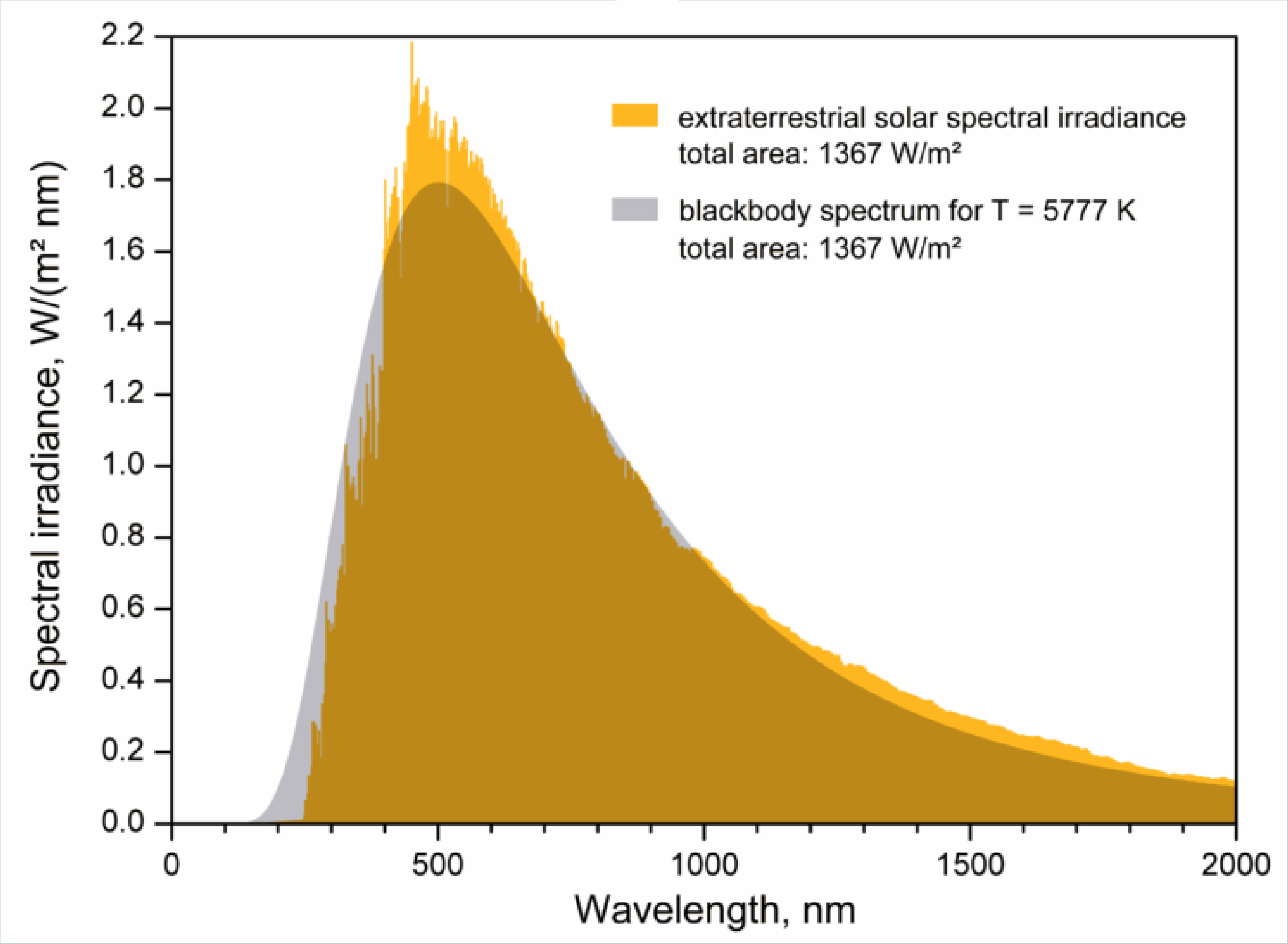
What can we learn from observations?

- Stellar Temperatures come from spectra:





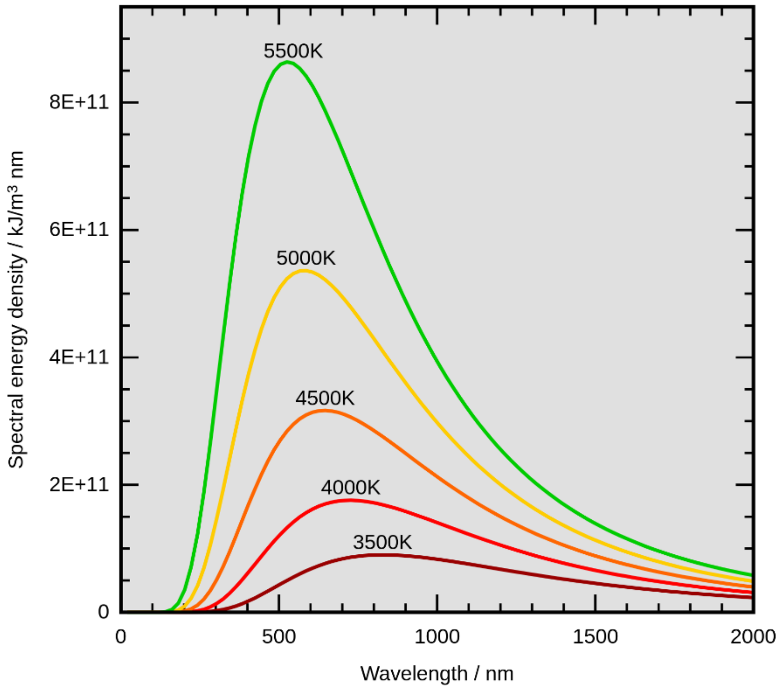
Stars share properties of black-bodies



Properties of the Planck law

- For increasing temperatures, the black body intensity increases for all wavelengths. The maximum in the energy distribution shifts to shorter λ (longer ν) for higher temperatures.
- **λ_{max} T = 2.98978 x10^{7}** Å K

  is Wien's displacement law for the maximum I_λ providing an estimate of the peak emission (λ_{max} =5175 Å for the Sun).



Stefan – Boltzmann Law

Blackbody radiation is continuous and isotropic whose intensity varies only with wavelength and temperature.

Following empirical (Josef Stefan in 1879) and theoretical (Ludwig Boltzmann in 1884) studies of black bodies, there is a well known relation between Flux and Temperature known as Stefan-Boltzmann law:

$$F=\sigma T^4$$

with $\sigma=5.6705 \times 10^{-5}$ erg cm^{-2} s^{-1} K^{-4}

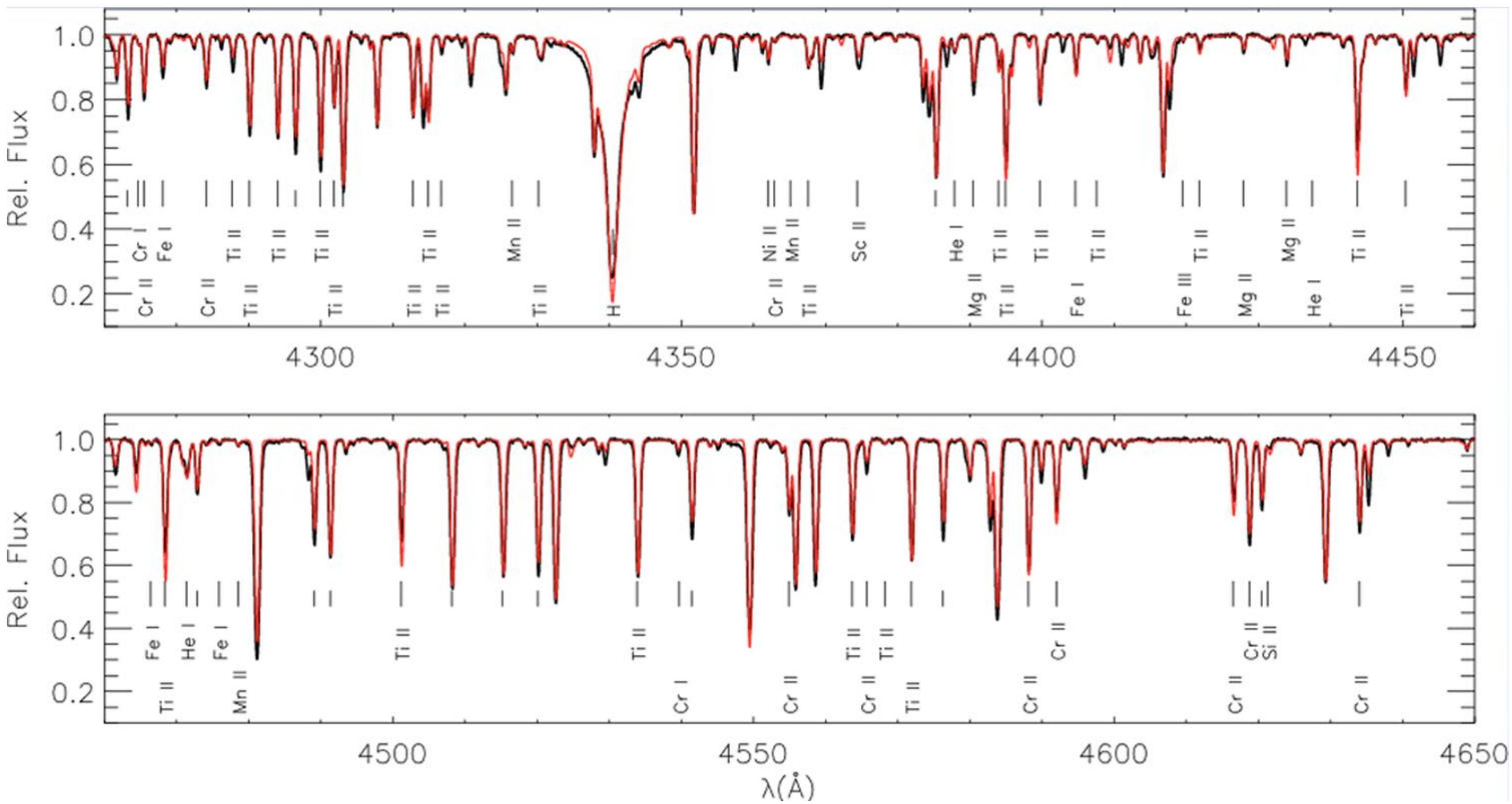
Effective temperatures of stars

- The Stefan-Boltzmann law, $F = \sigma T^4$, or alternatively $\frac{L}{4\pi R^2} = \sigma T_{\text{eff}}^4$ defines the "effective temperature" of a star, i.e. the temperature which a black body would need to radiate the same amount of energy as the star.

- T_{eff} is 5777K for the Sun.

What can we learn from observations?

Stellar Abundances also come from spectra:



Primary star parameters (T_{eff}, log g)

- **Effective temperature** (in K) is defined by $L=4\pi R^2 \sigma T_{eff}^4$

  (here L - luminosity, R - stellar radius), related to *ionization*.

- **Surface gravity** (cm/s^2), $g = GM/R^2$, related to *pressure*.

- The Sun has T_{eff}=5777K, log g=4.44 – its atmosphere is only a few hundred km deep, <0.1% of the stellar radius.
- A red giant has log g~1 (extended atmosphere), whilst a white dwarf has log g~8 (effectively zero atmosphere), and neutron stars have log g~14-15

Our Star, the Sun

A very ordinary star!

table 18-1 Sun Data

Distance from the Earth:	Mean: 1 AU = 149,598,000 km
	Maximum: 152,000,000 km
	Minimum: 147,000,000 km
Light travel time to the Earth:	8.32 min
Mean angular diameter:	32 arcmin
Radius:	696,000 km = 109 Earth radii
Mass:	1.9891×10^{30} kg = 3.33×10^{5} Earth masses
Composition (by mass):	74% hydrogen, 25% helium,
	1% other elements
Composition (by number of atoms):	92.1% hydrogen, 7.8% helium,
	0.1% other elements
Mean density:	1410 kg/m^3
Mean temperatures:	Surface: 5800 K; Center: 1.55×10^{7} K
Luminosity:	3.86×10^{26} W
Distance from center of Galaxy:	8000 pc = 26,000 ly
Orbital period around center of Galaxy:	220 million years
Orbital speed around center of Galaxy:	220 km/s