AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Introduction

Course aim

- **Aim:**
  - Gain a broad overview in solar and stellar physics
  - Practical experience with analysing and visualising real data
  - Practical experience with scientific writing

- **Content**
  - Sun's structure and variation on large and small scales.
  - Basic concepts about the physical phenomena that occur in the Sun's atmosphere.
  - How to carry out (theoretically) and interpret observations of the Sun and other stars? (Practical exercises.)
  - Similarities and differences between the Sun and other stars

Introduction

Previous courses / covered topics

AST2210 – Observasjonsastronomi	• Basic understanding of telescopes/instruments • Observation techniques including spectroscopy of stars
AST3310 – Astrofysiske plasma og stjernenes indre	• Stellar interiors (energy production, stratification) • Interior of the Sun
AST4310 – Strålingsprosesser i astrofysikk	• Radiative transfer • Interpretation of stellar spectra

- The most important concepts will be briefly repeated.
- Something missing or unclear? Please let me know!

Assignments

General aim and setup

- **Aim:** Gain experience with writing a **longer scientific report** (similar to what would be published in a scientific journal.

- **Writing process is an essential tool** for developing the scientific analysis, the derived results and conclusions

  ➡ Iterative process with rewriting and improving the different sections repeatedly towards creating a consistent and comprehensive document.

  ➡ The final project assignment is the final scientific report.

  ➡ In order to get started with individual parts:
  Five mandatory assignments to help you getting started and develop the final report.

- The final report will be based on the mandatory assignments.

- You get 2-3 weeks extra to work on the final report after delivery of the last mandatory assignment

Assignments

Setup and submission deadlines

- **IMPORTANT**: The final project assignment can only by submitted and graded **if all five** mandatory assignments have been delivered previously.

- Minor adjustments for the deadlines possible but communicated well in time (if)

Assignment		Submission deadline	Content
Mandatory (not graded)	I	Feb 9	Practical exercises
	II	Mar 3	Tentative science question and project plan, reading list; Introduction and background
	III	Mar 24	Description of data and method(s)
	IV	Apr 21	Analysis and results
	V	May 12	Discussion and conclusion
Final project assignment (graded, 100%)	F	**June 2**	**Complete report**

Assignments

Important advice

- You should working on all mandatory assignments **in parallel** as soon as they become relevant/feasible.
    - Examples:
        - While working on assignment I, start to look at the provided data sets and start reading syllabus/lecture notes and scientific articles
        - While working on the data analysis, review your description (and choice) of data and method
- You can start on the document for the final project assignment already in parallel to mandatory assignment I.

- All templates and a document with more information will be linked on the course webpage

Assignments

Important note

- It is **not expected** that your project assignment contains **novel scientific results.**
- The aim is to learn
  - **HOW to define interesting scientific questions.**
  - **HOW to work with scientific data.**
  - **HOW to present the scientific topic and the performed analysis in a <u>consistent</u> report.**
- **Tip:** It is ok to start from a published paper and do a similar analysis with the data provided for this course (if possible). (But please no copy & paste.)
- You are encouraged to discuss possible topics with me early on.

Technical info

- The assignments are to be prepared with **Latex**
  - Templates for all assignments will be provided.

- Data available for assignments: Observations / simulations for the Sun and other stars
  - Introduced in the group sessions/lecture.
  - Accessible on ITA's disk system: **/mn/stornext/d19/RoCS/svenwe/lecture/AST5770/**
  - **Do you have access?** If not, let us now **immediately**!

- **Data analysis**
  - Recommended: Python / IDL
  - Use ITA machines for working with larger data volumes.
  - Do not store big data files in your ITA home directory.
  - Do not run large jobs on login servers (like tsih2)

Introduction

The AST5770 Allstars - Our favourite examples

Not to scale!

Sun

NASA/SDO

G-type main sequence star

Proxima Centauri

ESA/Hubble & NASA.

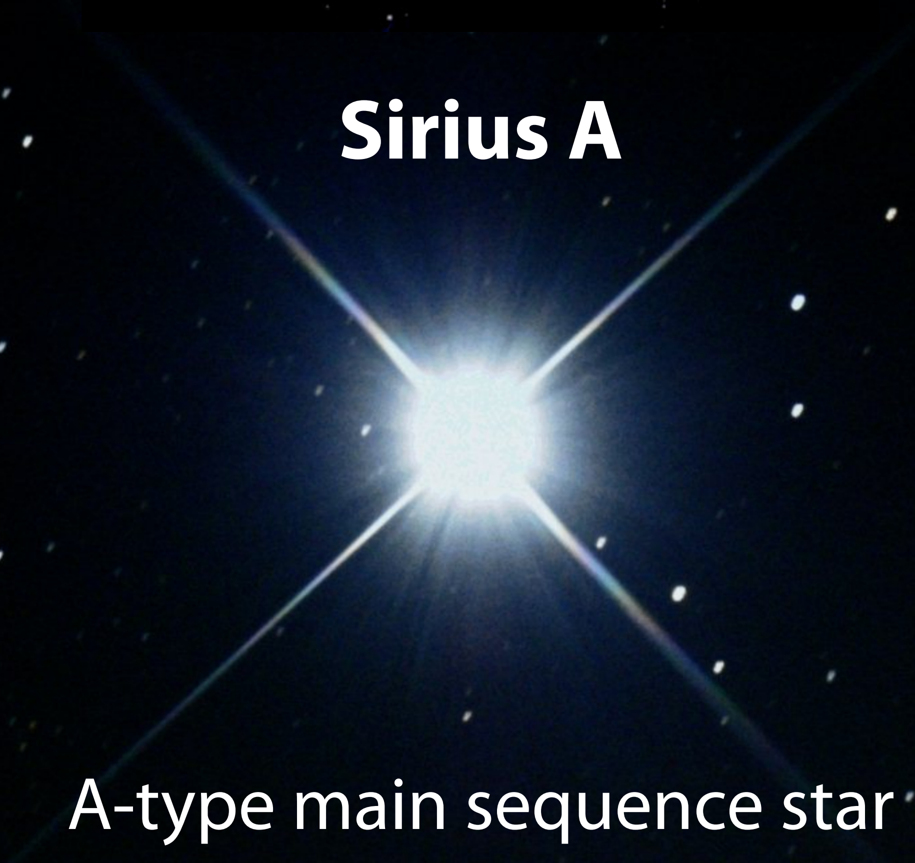
Red dwarf star (M-type, main seq.)

Betelgeuse

ALMA (ESO/NAOJ/NRAO)/
E. O'Gorman/P. Kervella

Red giant star (M-type)

Sirius A



Mellostorm CC-BY-SA-3.0

A-type main sequence star

Introduction

The AST5770 Allstars - Our favourite examples

Not to scale!

Sun

NASA/SDO

Our host star! Close by!
We can observe the Sun in much detail!
➡ **Ultimate reference star!**

Proxima Centauri

ESA/Hubble & NASA.

The **closest star** to us
(after the Sun)

Betelgeuse

ALMA (ESO/NAOJ/NRAO)/
E. O'Gorman/P. Kervella

Giant star. One of the few that can
be observed (somewhat) resolved.

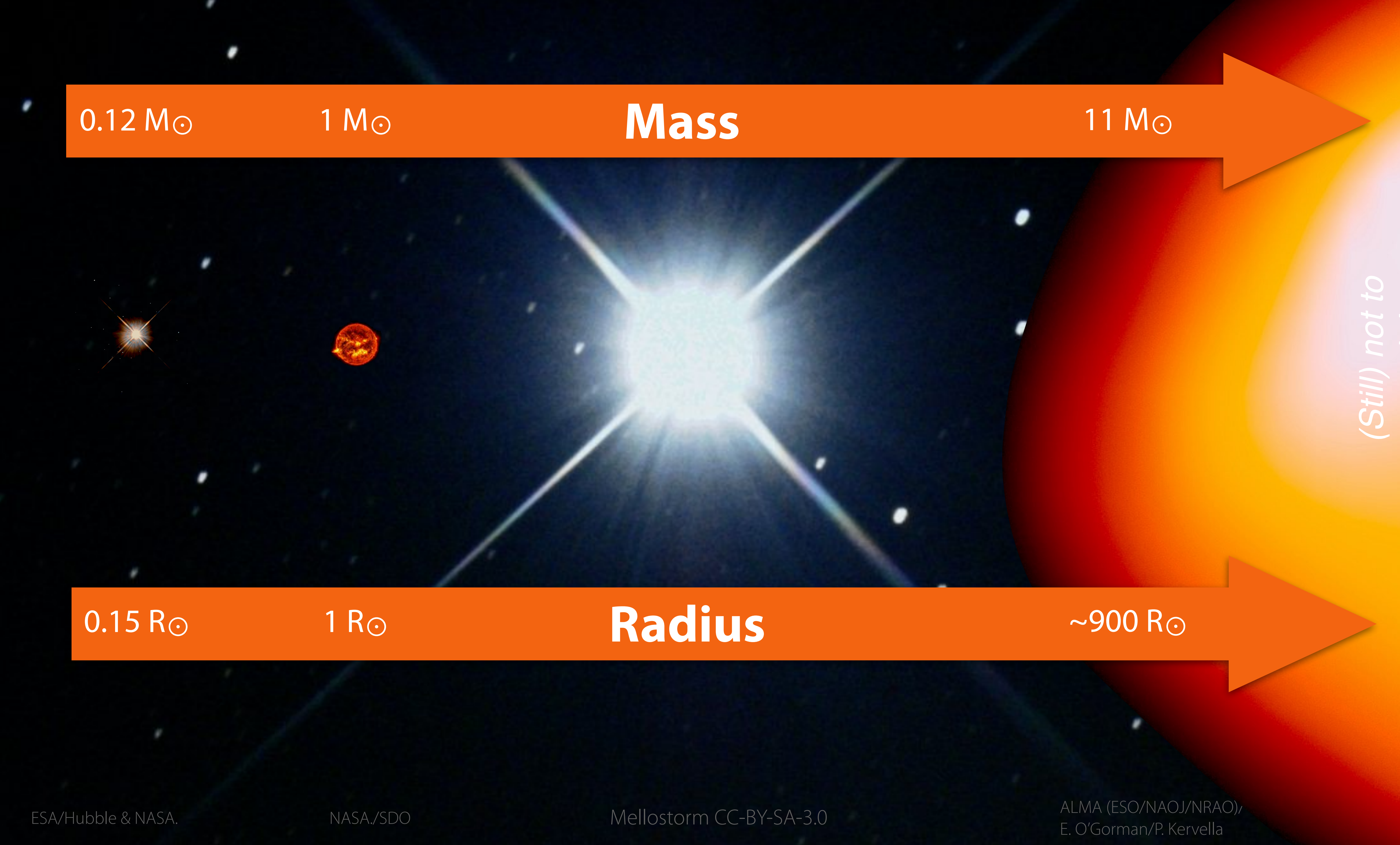
Sirius A

Mellostorm CC-BY-SA-3.0

The **brightest** star in the night sky.

Introduction

The AST5770 Allstars - Our favourite examples



Introduction

What is a star?

- We define a star as an **astronomical object** that

    1. consists of **gas** that is (partially) ionised (plasma) and
    2. is held together and formed into a sphere due to its **own gravity** and
    3. is **luminous** and
    4. releases energy due to **nuclear fusion** in its interior.

- Important: A star is shining by itself!
  ➡ An energy source is required.
  ➡ Brown Dwarfs satisfy the three first criteria but not #4 (no (hydrogen) fusion in their cores)

Introduction

Central questions

- **Dynamos and activity cycles**
  - How are **magnetic fields generated** in stars?
  - How can we explain **activity cycles**?
    (Cycle: large-scale magnetic field is reversed periodically?)
  - How can we explain the differences in **stellar activity** cycles observed for different types of stars as compared to the Sun and other solar-like stars?
  - Prediction of future solar cycles?

Introduction

Central questions

- **Coronal heating**
  - How are the **outer layers** of our Sun (and of other stars) **heated** to extremely high temperatures (Sun: $T > 10^6$ K)?
  - Which **physical mechanisms** are at work and how much do they contribute to the transport of energy upwards and to the heating?
  - How is the available energy **dissipated** into heat in the upper atmosphere?
  - Is this a common phenomenon for **late-type main sequence stars** and what can learn from observable variations?

Introduction

Central questions

- **Stellar activity - Flares, coronal mass ejections, space weather and habitability**
  - What are the exact physical mechanisms at work during **flares and coronal mass ejections (CMEs)** on the Sun?
  - How do they differ from flares on other stars which can even exhibit much stronger **super- and megaflares**?
  - How do these phenomena affect the interplanetary space ("**space weather**") and nearby planets (e.g., geomagnetic storms)?
  - How would understanding these phenomena allow us to **forecast space weather** events to protect our hi-tech infrastructure on Earth and to evaluate the **habitability of exo-planets** orbiting active stars?

Introduction

Central questions

- **Chemical evolution of the universe**
  - Chemical abundances from spectroscopic observations
  - Lithium problem: Observed abundance of Li much lower than expected

- **Plasma physics**
  - Stars serve as astrophysical laboratories that allows for the (remote) observation of plasma under conditions often difficult to obtain under terrestrial laboratory conditions.

- **Other central astrophysical problems**
  - Fast Radio Bursts (FRBs): point source-like millisecond flashes
    — Neutron stars and black holes as final stages in stellar evolution as potential sources?

Stars in the sky – Distances and apparent sizes

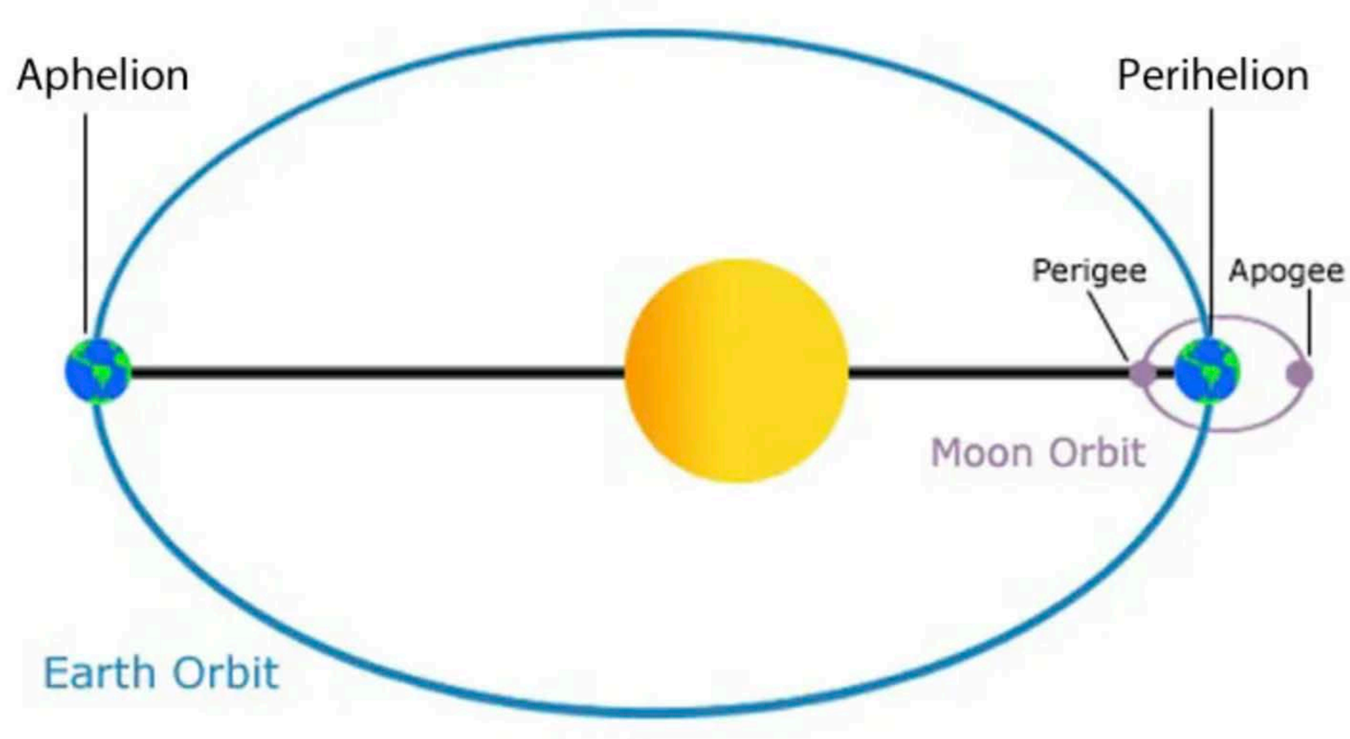
The distance to the Sun

- Average distance to the Sun is defined as **one astronomical unit**

$$1\,\text{AU} = 149597870700\ \text{m}$$

- Easier to remember: **1 AU ≈ 150 × 10⁶ km**.
- Light needs **~ 8 min** from the Sun's surface to Earth's orbit

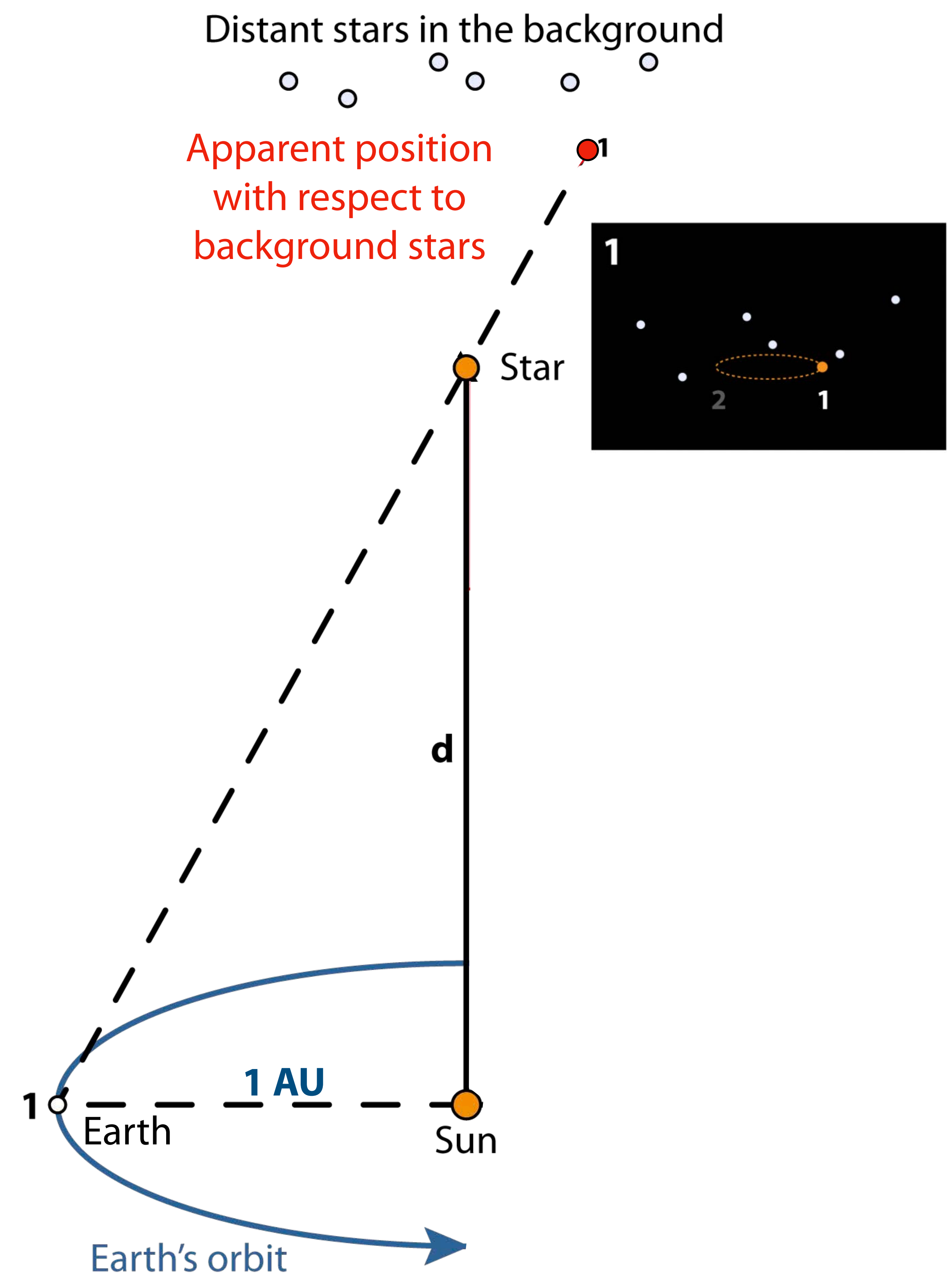
- Earth's orbit is not a perfect circle, varies by about 3% during the year
  - Maximum distance (aphelion): 152.1×10^6 km
  - Minimum distance (perihelion): 147.1×10^6 km



Aphelion versus Perihelion. (Orbits exaggerated). Image credit: NOAA/NASA.

Stars in the sky – Distances and apparent sizes

Parallax



Stars in the sky – Distances and apparent sizes

Parallax

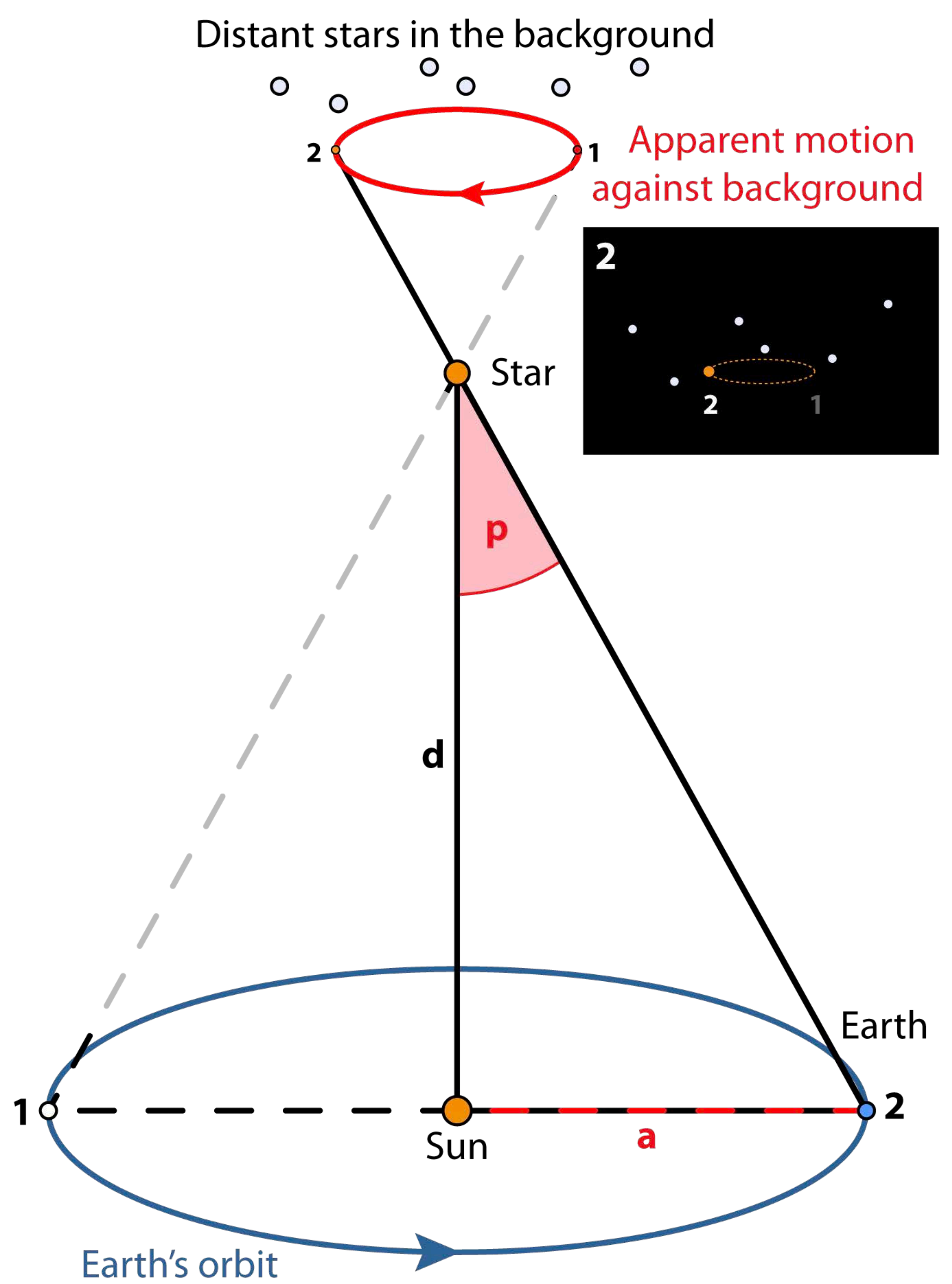
- Star closer to us seen at different angle against more distant stars during the course of a year.

➡ A star seems to be displaced periodically with respect to other stars.

- Caused by motion of the Earth around the Sun.

- Measuring the "displacement angle" accurately allows for **determination of the star's distance d**

$$p = \tan\frac{a}{d} \quad \Rightarrow \quad p \approx \frac{1\,\mathrm{AU}}{d}$$



Stars in the sky – Distances and apparent sizes

Parallax

- The other way around: Earth's orbit seen from a distance d

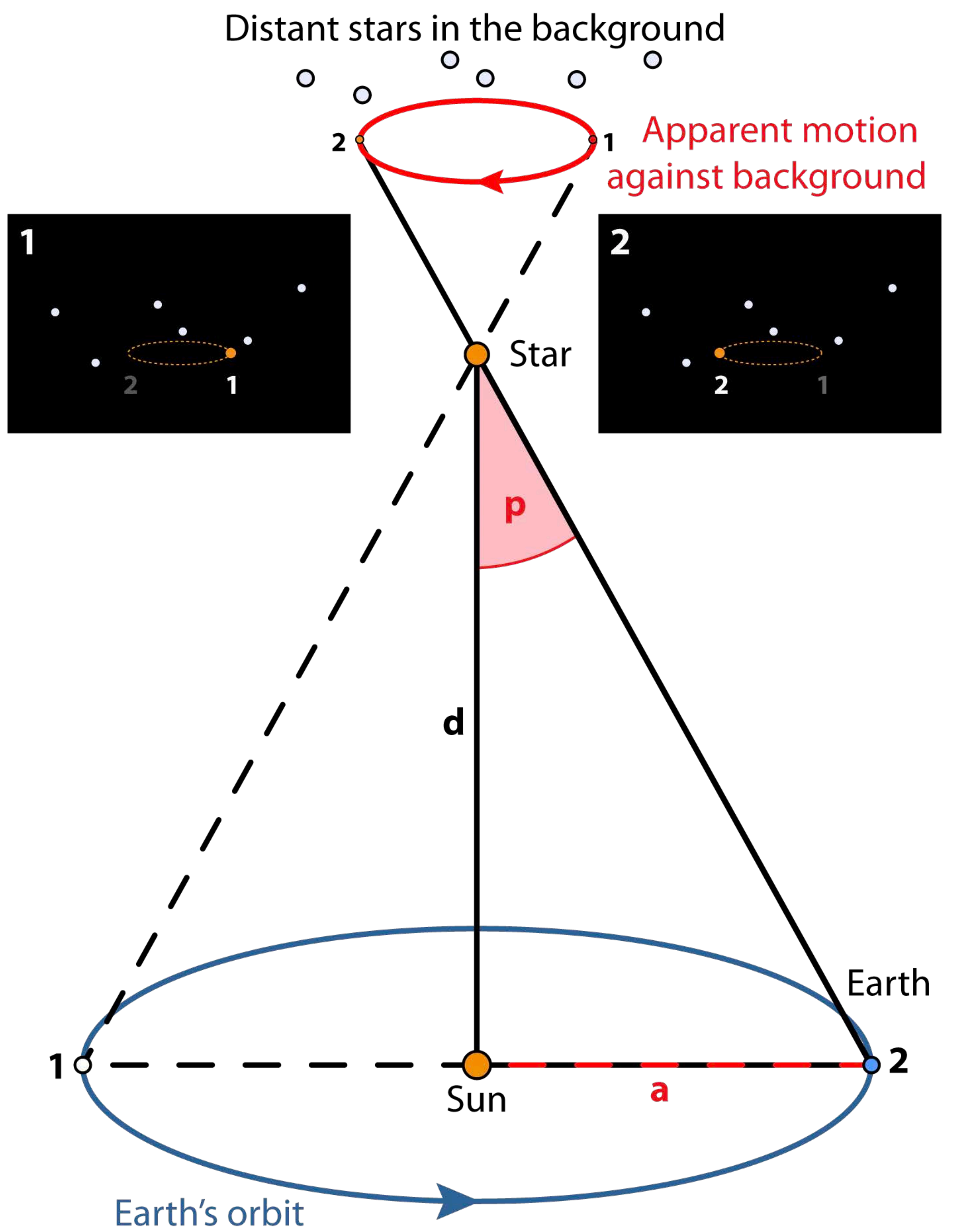
➡ The length **a** appears as **p = 1"** from a distance of d=206265 AU.

➡ This unit is called **parsec** (pc, from parallax and arcsecond).

➡ **1 pc = 206265 AU = 3.26 ly**

(1ly = 9.46×10^{12} km)

➡ **d [pc] = 1/p ["]**



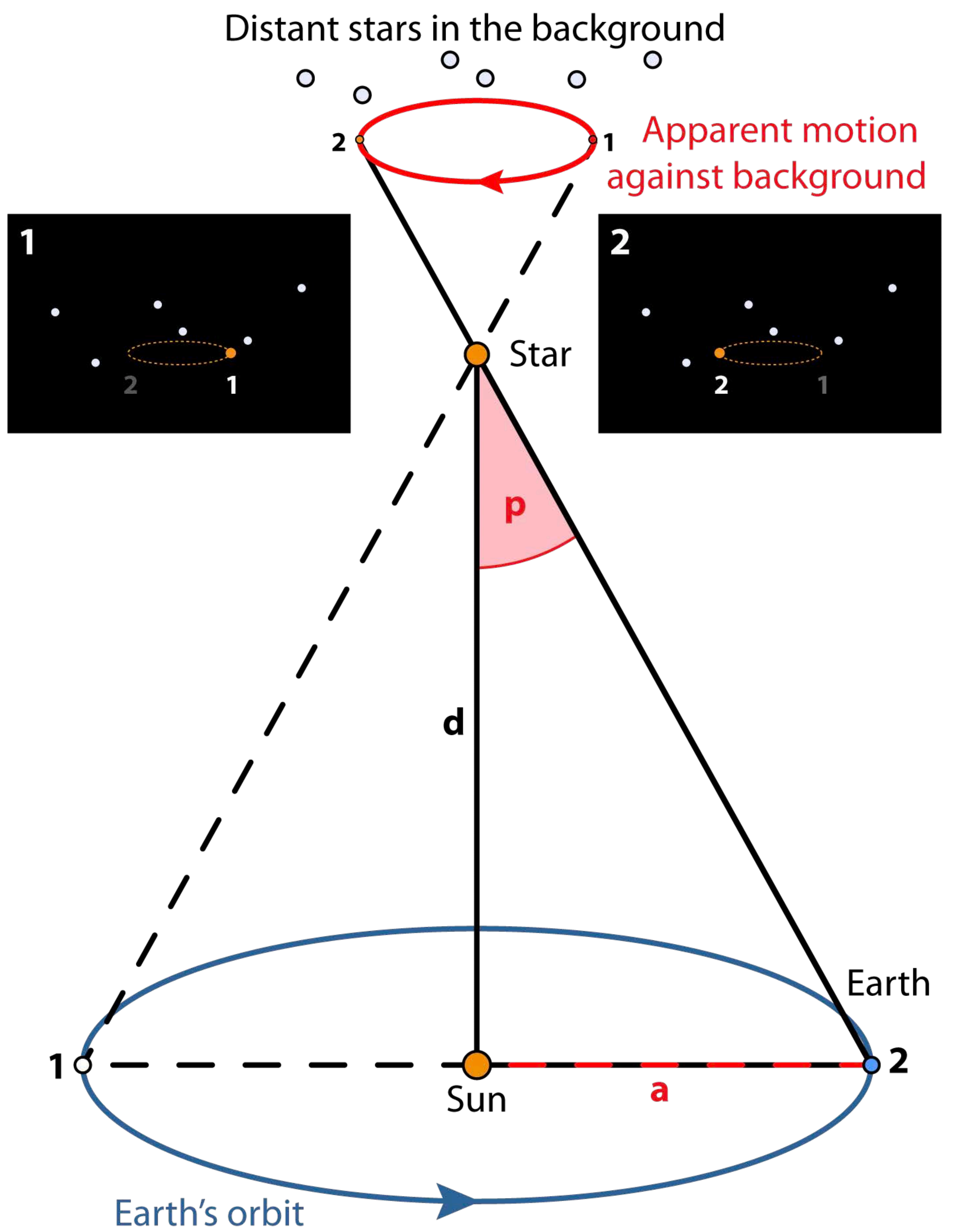
Stars in the sky – Distances and apparent sizes

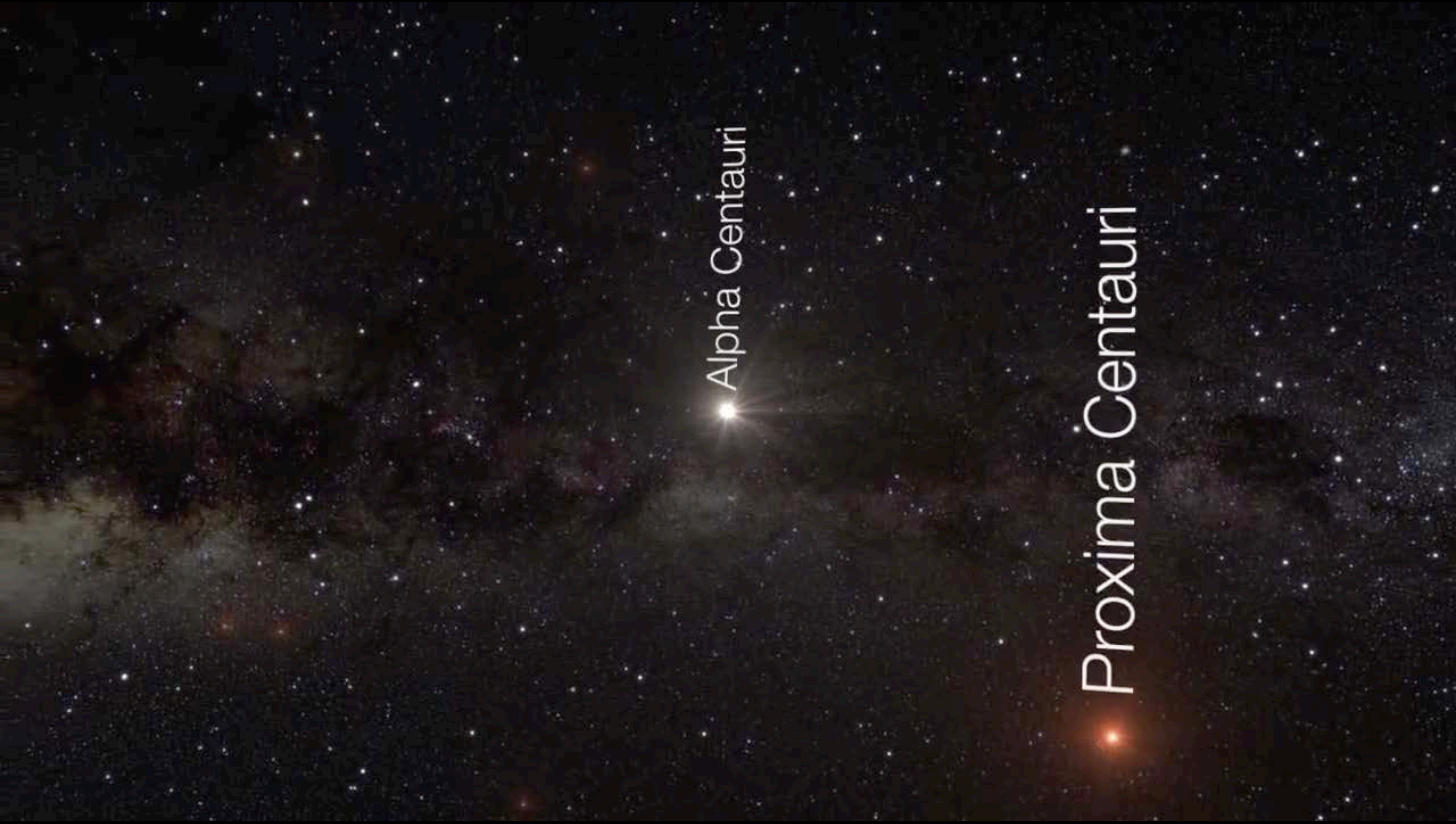
Parallax

- **Example: Proxima Centauri**
- Measured parallax = 0.768″

➡ d [pc] = 1 / 0.768″ = 1.302 pc = **4.243 ly**

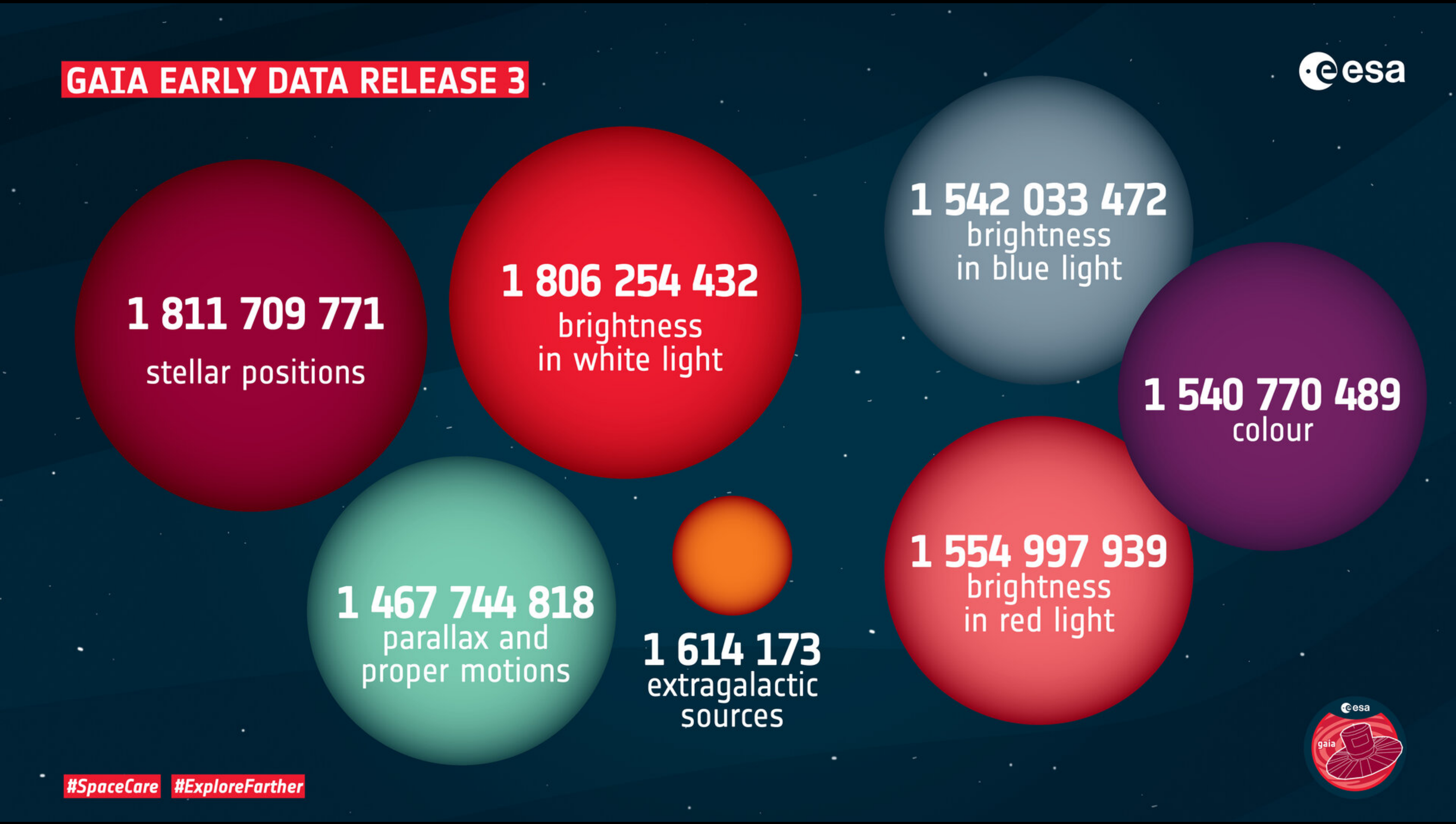
- First parallax measured: Bessel 1838
- **Hipparcos satellite** (1989-1993)
  - Accuracy of 0.001″ for 120,000 stars (+ ~2.5 million stars with lower accuracy.)
- **Gaia mission** (2013-2022)
  - Accuracy of ~ 10^{-4}″
  - Mapping billions of stars in the Milky Way





www.eso.org

GAIA


GAIA EARLY DATA RELEASE 3
esa
1 811 709 771
stellar positions
1 806 254 432
brightness
in white light
1 542 033 472
brightness
in blue light
1 540 770 489
colour
1 467 744 818
parallax and
proper motions
1 614 173
extragalactic
sources
1 554 997 939
brightness
in red light
esa
gaia
#SpaceCare
#ExploreFarther

Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

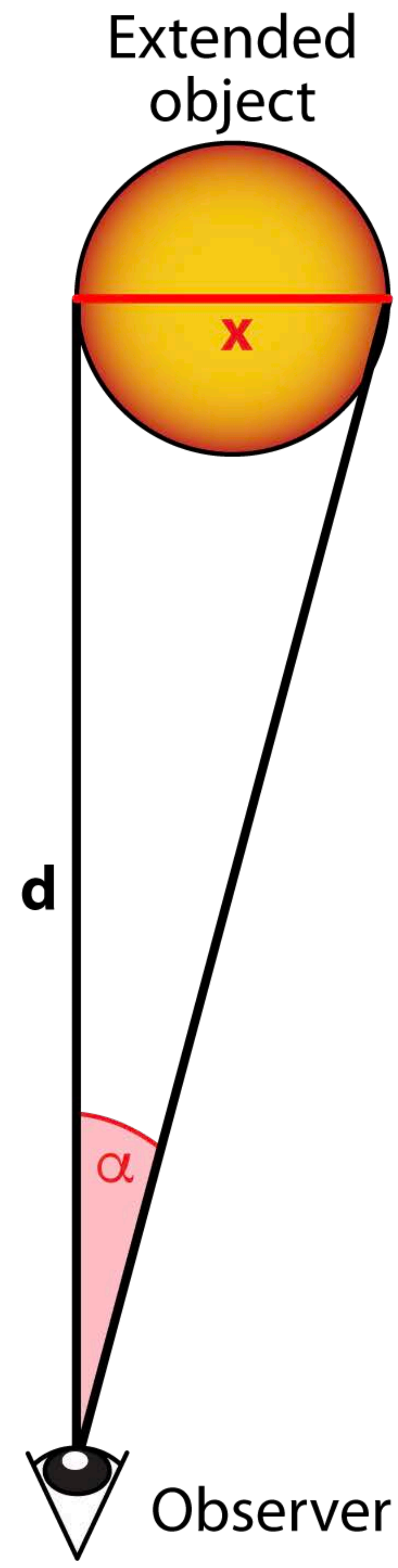
- Object on the sky with diameter x at distance d

➡ Apparent angular extent in the sky

$$\Delta\alpha = \arctan\frac{\Delta x}{d}$$

- **Example 1 - Sun:**
  - $\Delta x = 2\,R_\odot$ with $R_\odot = 696\,342$ km ($\Delta x \approx$ **1.4 10⁶ km**)
  - d = 1AU

  ➡ $\Delta x = 1919''$ (arcsec) $\approx 31'$ (arcmin) $\approx$ **1/2 degree**



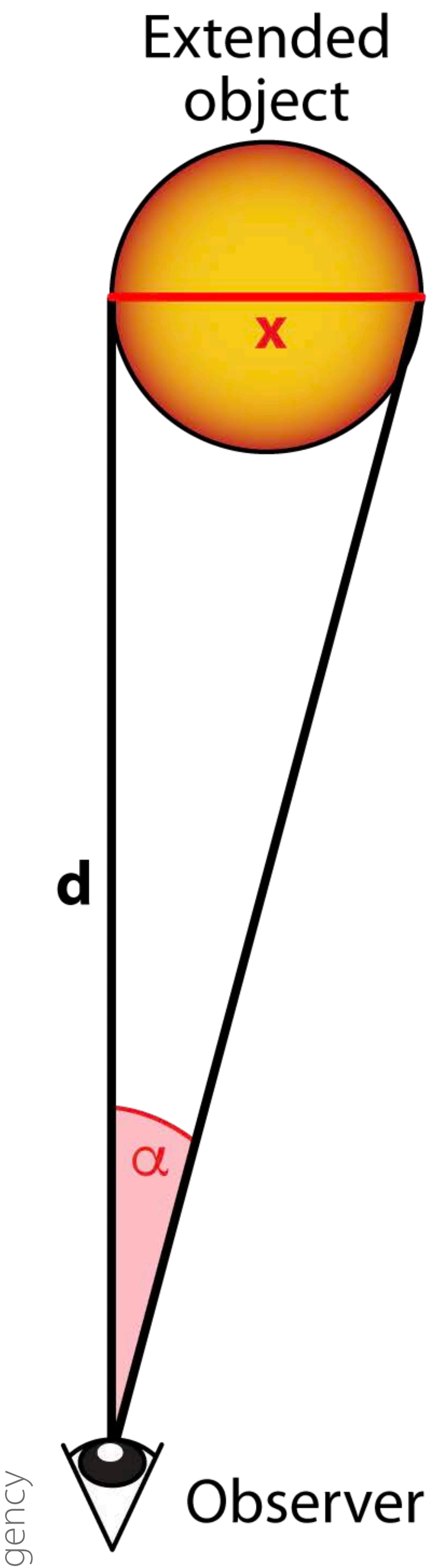
Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

- Object on the sky with diameter x at distance d

➡ Apparent angular extent in the sky

$$\Delta\alpha = \arctan\frac{\Delta x}{d}$$

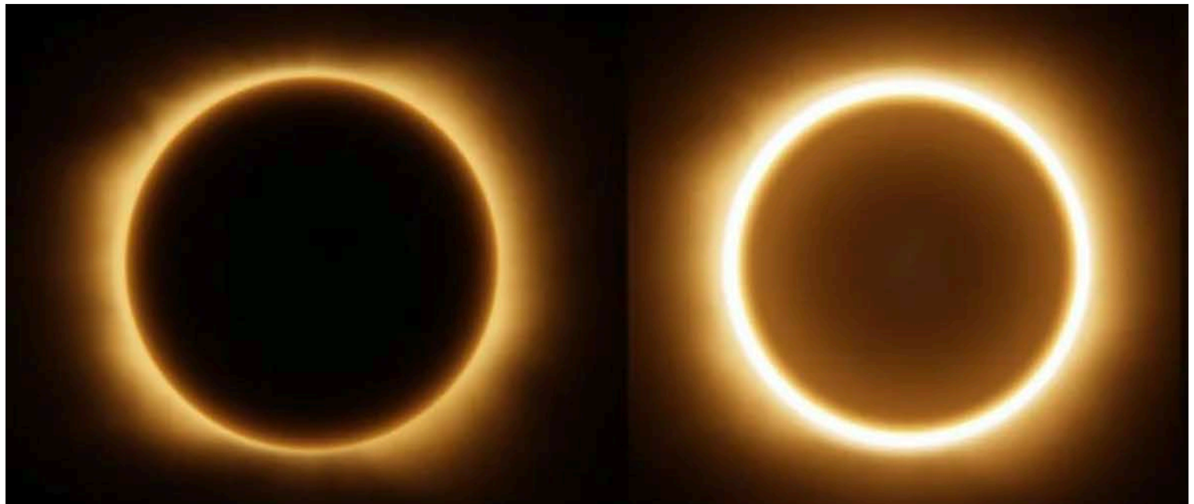


- **Example 1 - Sun:**
  - $\Delta x = 2\,R_\odot$ with $R_\odot = 696\,342$ km ($\Delta x \approx$ **$1.4\ 10^6$ km**)
  - d = 1AU - **Remember: d varies by 3%**

  ➡ Δα varies between 1887" and 1952"

  - Moon's apparent size also varies by a few %

  ➡ Some eclipse are total, others only annular.



Canadian Space Agency

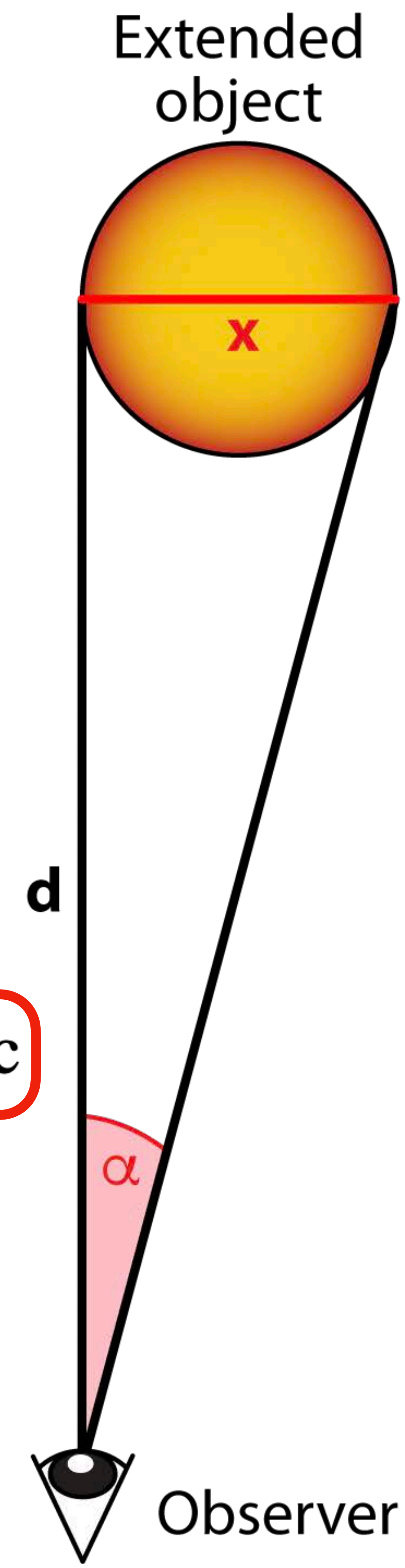
Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

- Object on the sky with diameter x at distance d

➡ Apparent angular extent in the sky

$$\Delta\alpha = \arctan \frac{\Delta x}{d}$$



- **Example 2 - Proxima Cen:**
  - $\Delta x = 2$ R with R = 1.07 10^5 km
  - d = 4.246 ly

$$\Delta\alpha = \arctan \frac{\Delta x}{d} = \arctan \frac{2 \times 1.07 \times 10^5 \text{ km}}{4.246 \times 9.46 \times 10^{12} \text{ km}} = 1.1 \text{ milliarcsec}$$

➡ **Very small!**

➡ Cannot be resolved (decently) with telescopes (yet).

➡ Remains a point source for now.

Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

- Object on the sky with diameter x at distance d

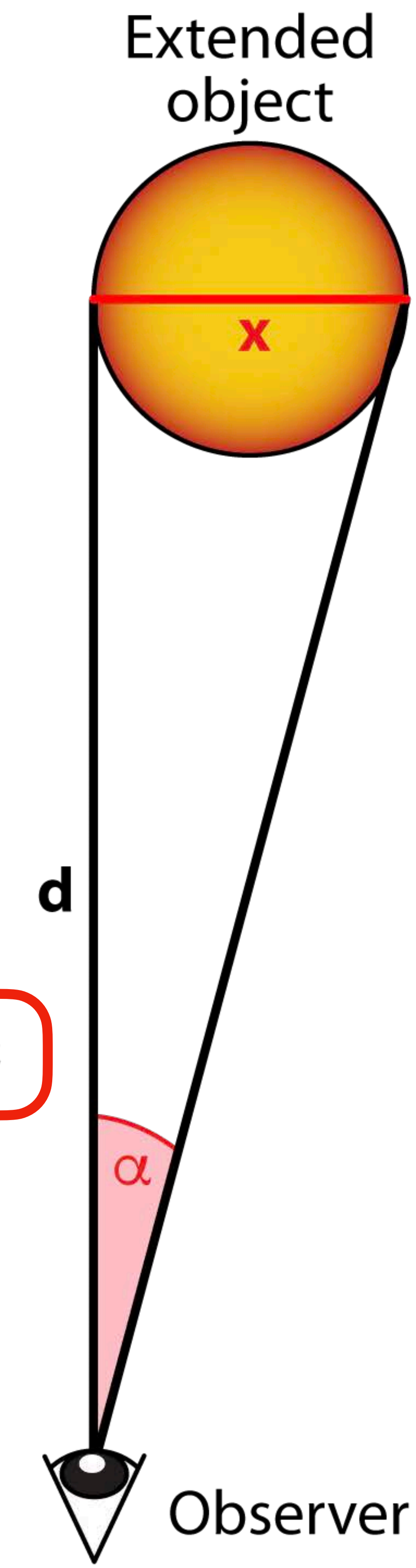
➡ Apparent angular extent in the sky

$$\Delta\alpha = \arctan\frac{\Delta x}{d}$$

- **Example 3 - Betelgeuse:**
  - Δx= 2 R with R = 900 $R_\odot$
  - d = 548 ly

$$\Delta\alpha = \arctan\frac{\Delta x}{d} = \arctan\frac{2 \times 900\, R_\odot}{548 \times 9.46 \times 10^{12}\ \mathrm{km}} = 0.05\,\mathrm{arcsec}$$

➡ **Small but can be (somewhat) resolved with extended interferometric arrays (ALMA!)**

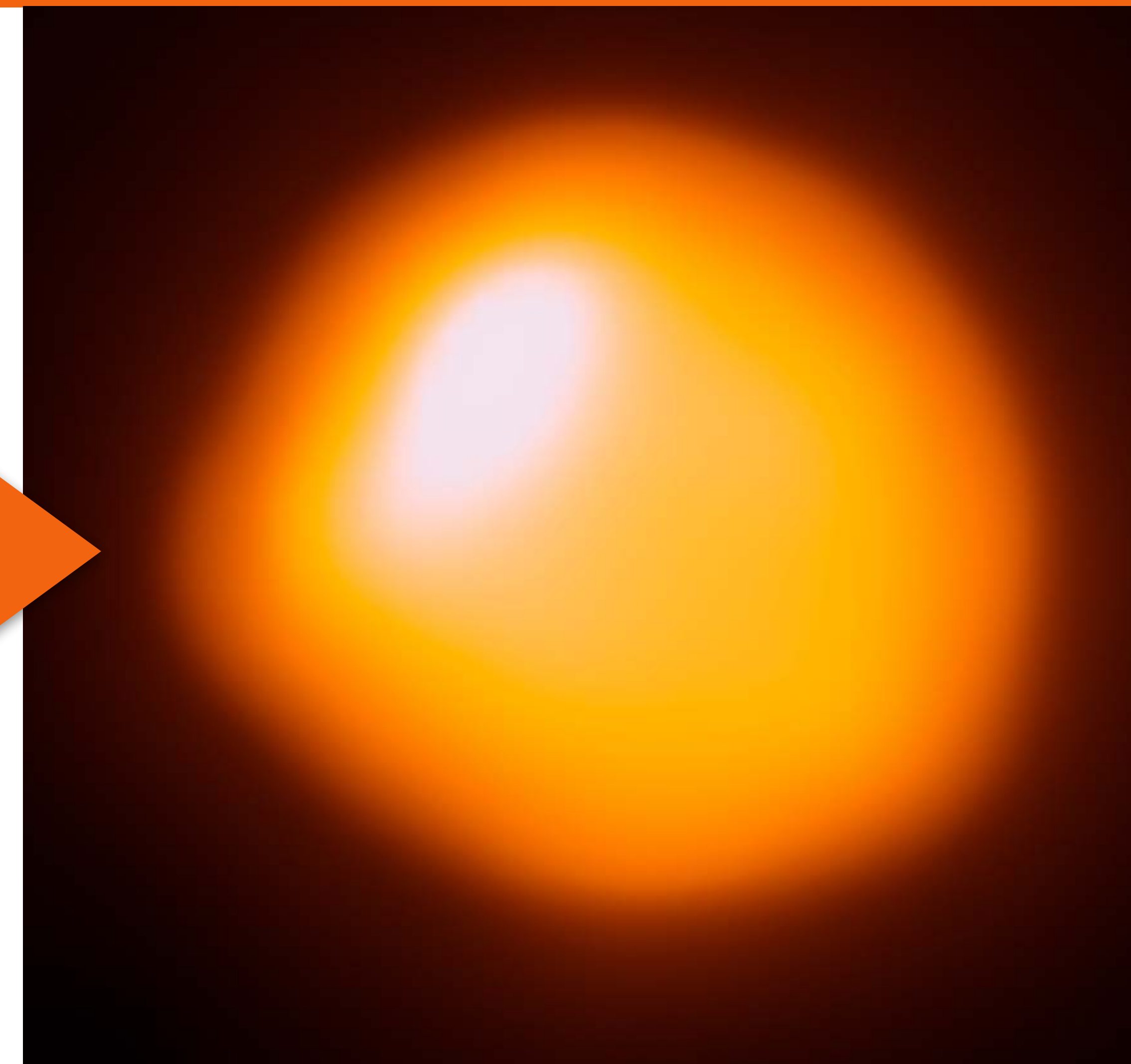


Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

ALMA (ESO/NAOJ/NRAO)/
E. O'Gorman/P. Kervella

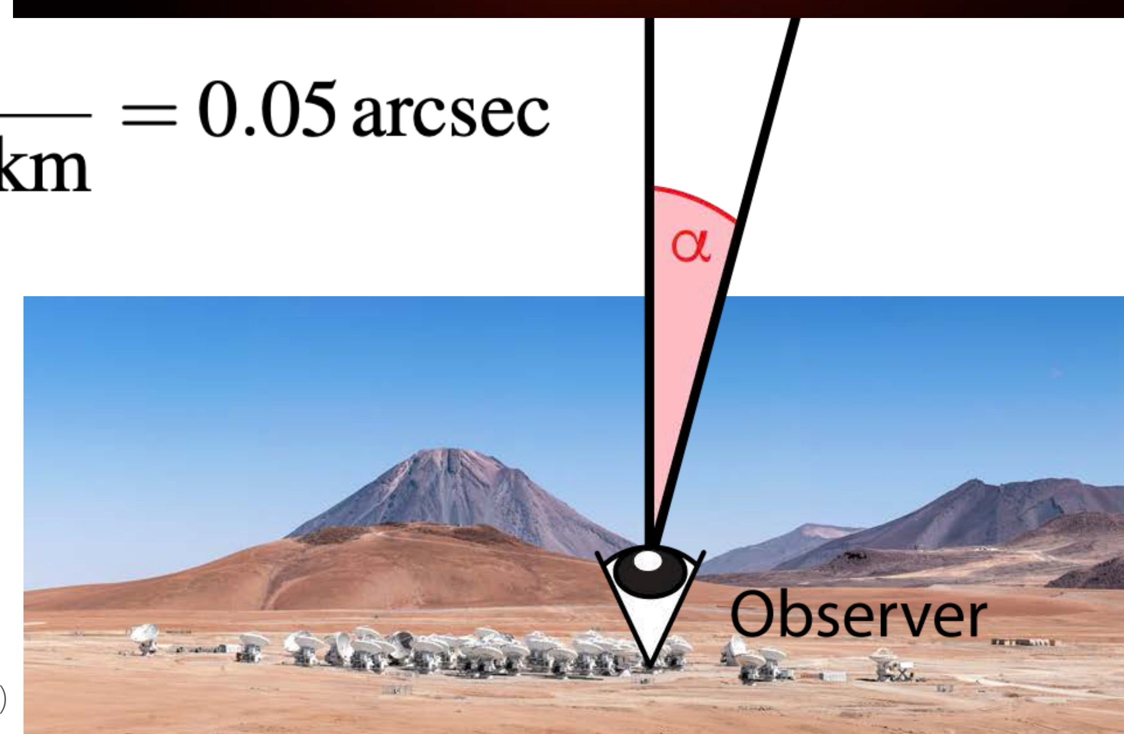
Actual image of Betelgeuse!



- **Example 3 - Betelgeuse:**
  - $\Delta x = 2$ R with R = 900 $R_\odot$
  - d = 548 ly

$$\Delta\alpha = \arctan\frac{\Delta x}{d} = \arctan\frac{2\times 900\, R_\odot}{548\times 9.46\times 10^{12}\ \mathrm{km}} = 0.05\,\mathrm{arcsec}$$

➡ **Small but can be (somewhat) resolved with extended interferometric arrays (ALMA!)**



ALMA (ESO/NAOJ/NRAO)

Stars in the sky – Distances and apparent sizes

Apparent sizes of stars

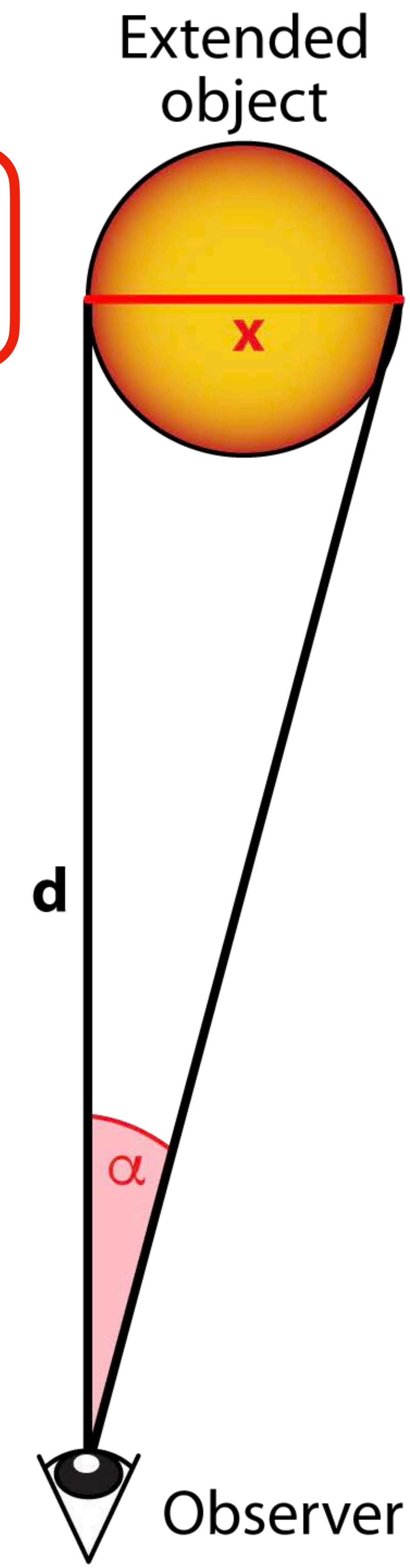
- Object on the sky with diameter x at distance d

➡ Apparent angular extent in the sky

$$\Delta\alpha = \arctan \frac{\Delta x}{d}$$

- **Examples:**

	Sun	**Proxima Cen**	**Betelgeuse**
$\Delta x = 2$ R	$R_\odot = 696\,342$ km $\Delta x \approx 1.4\ 10^6$ km	R = $1.07\ 10^5$ km $\Delta x = 2$ R	R = 900 $R_\odot$ $\Delta x = 2$ R
d	1AU = $1.6\ 10^{-5}$ ly	4.246 ly	548 ly
$\Delta\alpha$	1919″ ≈ 31′ ≈ 1/2 degree	0.0011″ 1.1 milliarcsec	0.05″ 50 milliarcsec
	Can be observed spatially resolved.	➡ Remains a point source for now.	At the limit for the largest interferometric arrays.



Observational stellar parameters

What differences do you see?

- **Apparent brightness**
- **Colours**

Cluster NGC 1783 (NASA/ESA Hubble Space Telescope)

Observational stellar parameters

Recap - radiative flux and radiative flux density

- **Radiative flux** (also called radiation flux) **F**
  energy radiated per time unit through an area
  (over a given wavelength or frequency range)
  - Physical units: J s^{-1} m^{-2} = W m^{-2} (SI), erg s^{-1} cm^{-2} (cgs)

- **Radiative flux density** (also called spectrum)
  energy radiated per time unit through an area per wavelength or frequency unit (**F_λ**, **F_ν**)

$$F_\lambda = \frac{d\nu}{d\lambda} F_\nu = \frac{c}{\lambda^2} F_\nu$$

  - In astrophysics, it is common to use F_ν. The SI unit is W m^{-2} Hz^{-1}.
  - At millimetre and radio wavelengths, common to use the unit Jansky: 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

- Radiative flux through integration over a given wavelength or frequency range

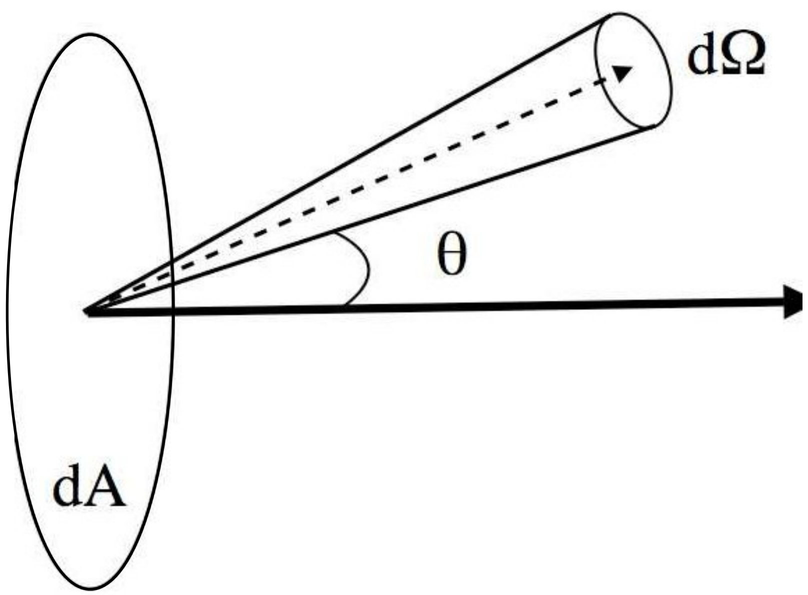
$$F = \int_{\nu_1}^{\nu_2} F_\nu \, d\nu \qquad F = \int_{\lambda_1}^{\lambda_2} F_\lambda \, d\lambda$$

Observational stellar parameters

Recap - irradiance and specific intensity

- **Irradiance** = radiative flux is received by an area (instead of emitted)
- **Total Solar Irradiance (TSI):**
  - measure of the radiation flux from the Sun that is received at the boundary of Earth's atmosphere.
  - Important in the context Sun's impact on Earth's climate.
- **Specific intensity:** I_ν = flux density F_ν emitted per solid angle Ω :

$$F_\nu = \int_\Omega I_\nu \cos\theta d\Omega$$



- Physical units: $\mathrm{J\ s^{-1}\ m^{-2} = W\ m^{-2}\ Hz^{-1}\ sr^{-1}}$ (SI)

Observational stellar parameters

Apparent brightness scale

- Apparent brightness **m** measured on logarithmic scale
- Dimensionless unit magnitudo [mag]
- Defined by Pogson in 1856:
    - star of first magnitude star = 100 times brighter than a 6th magnitude star.
    - $\Delta m = 5$ mag <-> brightness ratio of 100
    - $\Delta m = 1$ mag <-> $100^{1/5} = 2.512$ (Pogson's Ratio)

$$\Delta m = m_1 - m_2 = -2.5 \log(F_1/F_2) \quad \text{[mag]}$$

- Flux ratio F_1/F_2 of the two stars.

- Origin of the scale defined by bright star α Lyrae, ($m = 0$ mag at all wavelengths)

Observational stellar parameters

Apparent brightness scale

bright	-26.7	Sun ($m_\odot$)
	-12.6	Full moon
	-4.4	Venus (max.)
	-1.4	Sirius (brightest star in the sky)
	0.5	Betelgeuse (visual band, variable)
	6.5	Limit for naked eye
	10.0	Limit for binoculars
	11.1	Proxima Cen (visual band)
	15.1	Pluto
	31.5	Limit of Hubble Space Telescope
faint	~ 34	Limit of James Webb Space Telescope (infrared)

$\Delta m = 1$ mag = factor 2.512

- Individual stars
  - Different distances to us
  - Different "energy output"

Observational stellar parameters

Absolute brightness

- Apparent brightness depends on properties of the star but also on distance!

➡ Distance dependence to be removed for direct comparison of stellar properties

- **Absolute brightness** M
  - Also referred to as absolute magnitude
  - Definition: brightness that a star has at a (fictive) **standard distance of 10 parsec** from the observer

  ➡ (independent of the distance!)

Observational stellar parameters

Distance modulus

- Definition:
  Distance modulus = difference between apparent and absolute brightness **m – M**

- Additional astronomical **extinction A** (here in magnitudes) due to the interstellar medium along line of sight (LOS) between star and observer
  ➡ further reduces the apparent brightness.

- Derivation: same star at its real distance $r = r_1$ and at the standard distance $r_2 = 10$ pc

➡ $$\Delta m = m_1 - m_2 = -2.5 \log(F_1/F_2) \,,$$ $F \propto r^{-2}$, $F_1/F_2 \propto r_2^2/r_1^2$

➡ $m - M = 5 \log r\,[\mathrm{pc}] - 5 + A$.

- Note m-M=0 for a star at a distance of 10 pc (with A=0)
  (definition of the absolute brightness).

Observational stellar parameters

Absolute brightness

➡ brightness at standard distance of 10 parsec

	Apparent brightness m_V*	**Absolute brightness M_V***	**Distance modulus $(m - M)_V$***	**Distance**
Sun	-26.74	4,83	-31,57	1 AU
α Cen A Solar-like star	0,01	4,38	-4,37	4.4 ly
Sirius A brightest star (after Sun)	-1,47	1,42	-2,89	8.7 ly
Proxima Cen closest star (after Sun)	11,13	15,6	-4,47	4.2 ly
Betelgeuse	0,5	-5,85	6,35	550 ly

* All brightness at visible wavelengths, astronomical extinction ignored (A=0)

- Sun would be among the fainter stars observable with the naked eye when observed from a distance of 10 pc.

Observational stellar parameters

Bolometric brightness

- **Bolometric = all wavelengths**

- Integration of the wavelength-dependent radiation flux F_λ over **all wavelengths,** or equivalently F_ν over **all frequencies**

$$F = \int_0^\infty F_\lambda d\lambda = \int_0^\infty F_\nu d\nu$$

➡ **Apparent bolometric brightness** m_{bol} is a measure for the **total radiative flux F** of a star

Observational stellar parameters

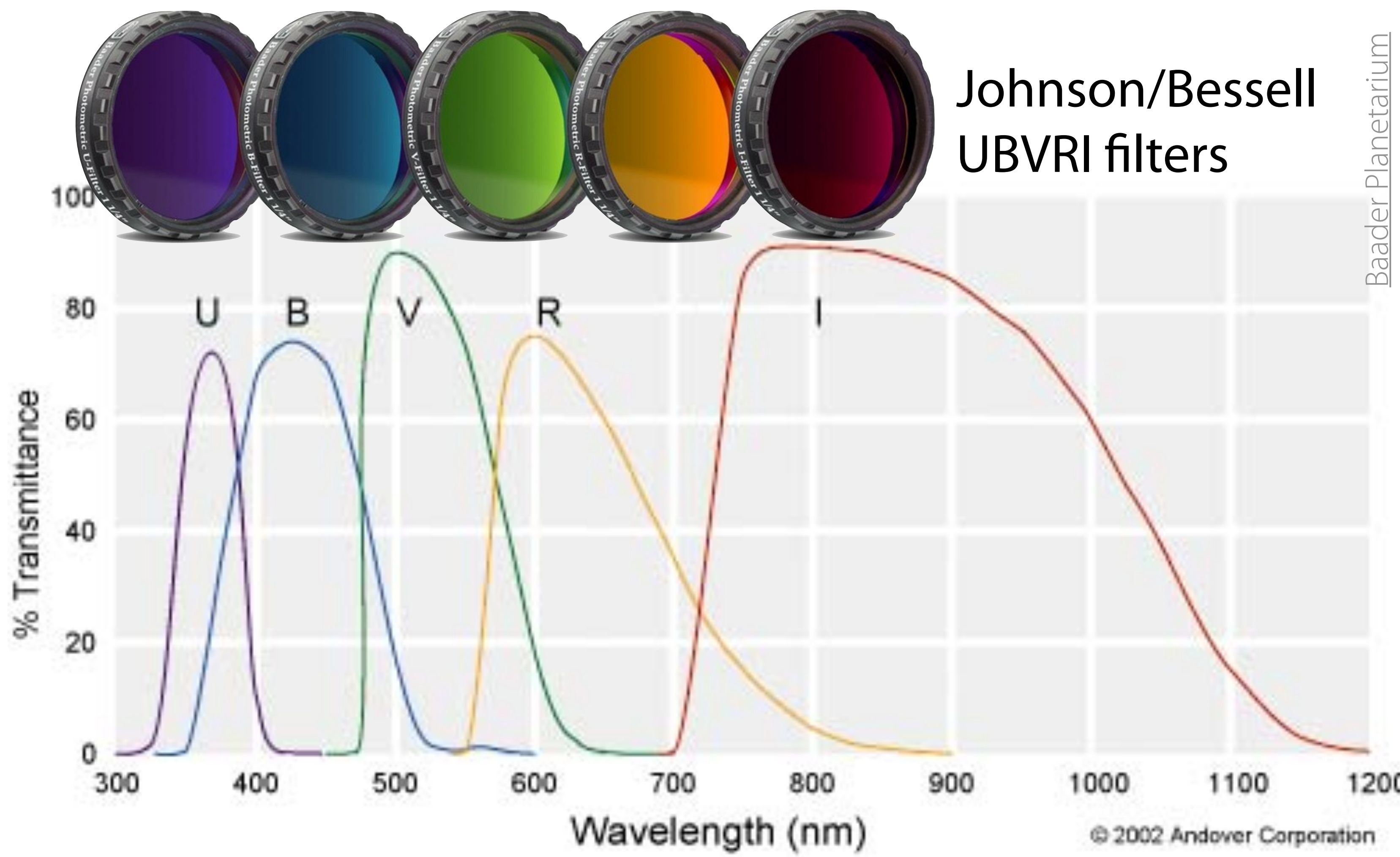
Photometry and colours

- Use of different filters in an observation
- Transmission of only limited wavelength ranges
- Standardised filter system(s)
  - Most common: UBVRI(+)
  - Originally **UBV** (ultraviolet — blue — visual)
  - Extended into the infrared (IR)

- Brightness measured in a selected filter marked with corresponding index
- Example: Visual (**V**)
  - Apparent brightness: $m_V = V$
    (Often only the filter ID is used!)
  - Absolute brightness: M_V

UBVRI filter system + extension

Filter	descript.	λ [nm]	FWHM [nm]
U	UV	365	66
B	blue	440	94
V	visual	548	88
R	red	658	138
I	IR	806	149
J	IR	1220	213
H	IR	1630	307
K	IR	2190	490
L	IR	3450	473
M	IR	4750	460



Johnson/Bessell UBVRI filters

Baader Planetarium

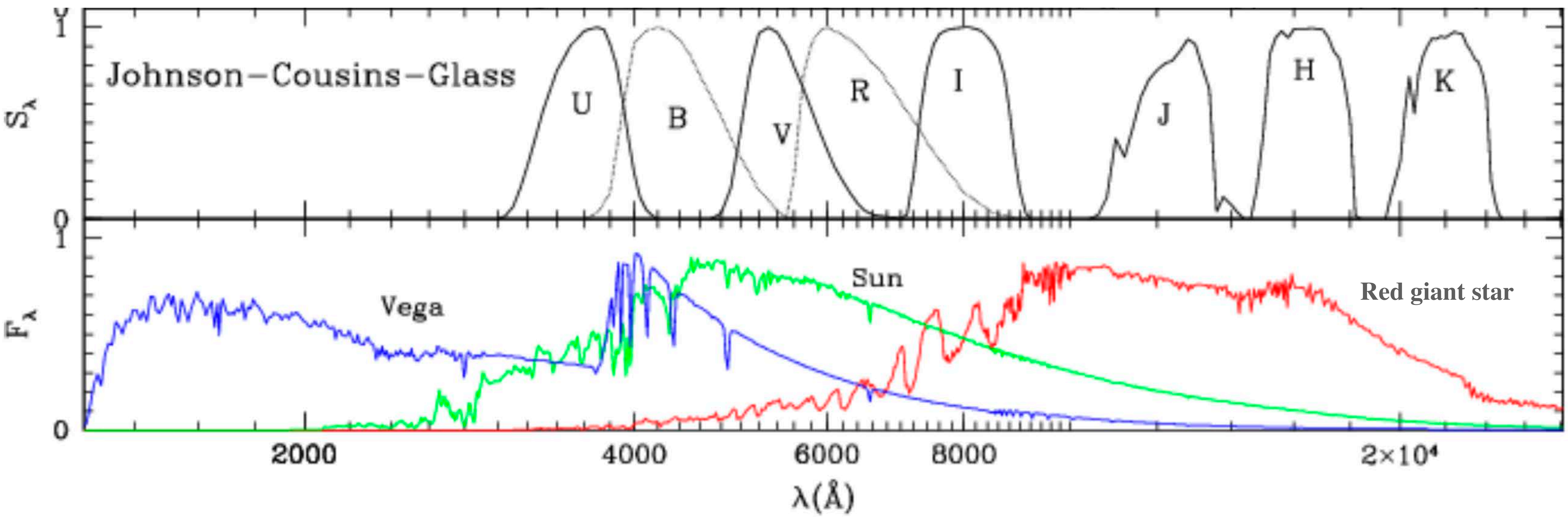
Observational stellar parameters

Photometry and colours, color index

- Measuring brightness with different filters captures **variation of flux density as function of wavelength** (spectrum)
  ➡ Reveals difference between stars

- **Colour index:** difference of two brightness measured in different bands, $m_X - m_Y$.

- Example: m_B - m_V = B - V



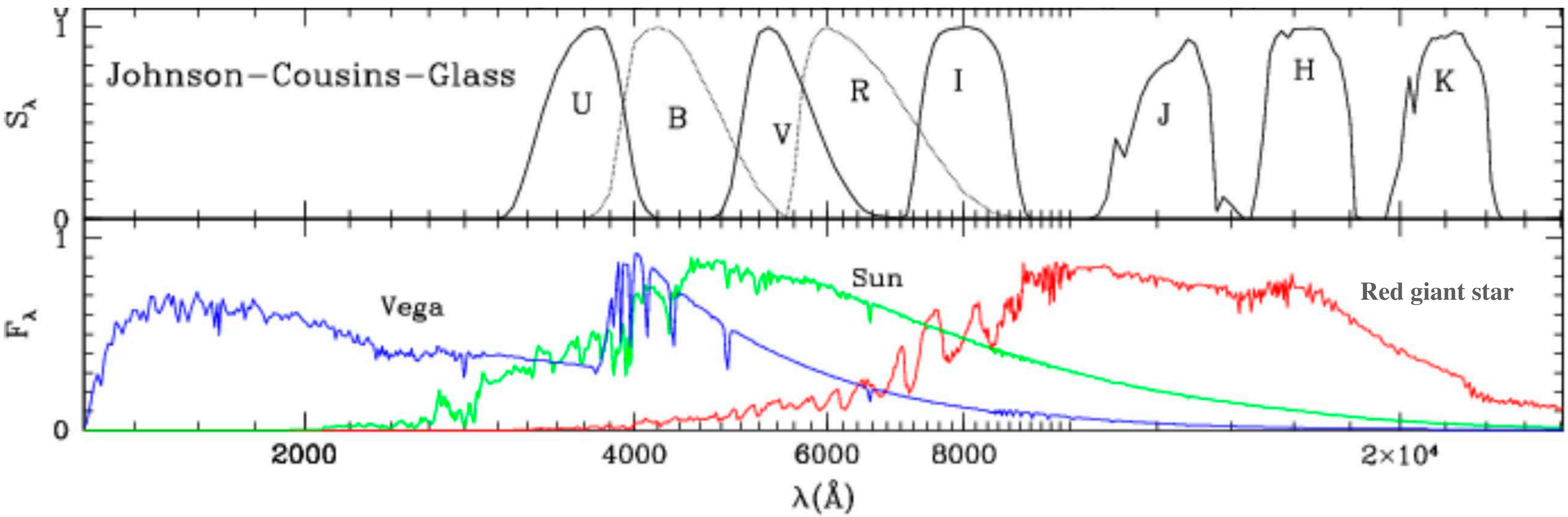
Observational stellar parameters

Photometry and colours, color index

- Measuring brightness with different filters captures **variation of flux density as function of wavelength** (spectrum)
  ➡ Reveals difference between stars

- **Colour index:**
  - **Examples**

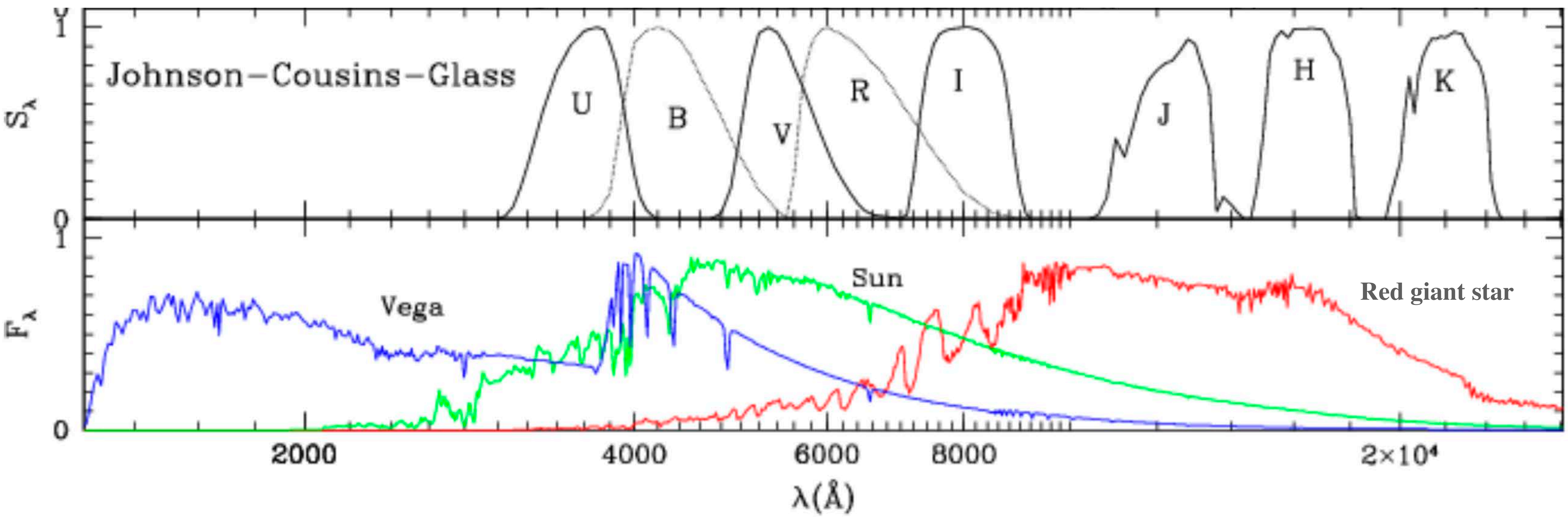
Star	U = m_U	B = m_B	V = m_V	$(U-B)$	$(B-V)$
Sun	−25.85	−26.03	−26.70	0.18	0.67
Proxima Cen	14.21	12.95	11.13	1.26	1.82
Betelgeuse	∼ 0.50	∼ −1.6	∼ −3.4	+2.06	+1.85



Observational stellar parameters

Bolometric correction

- Filters cover only parts of the spectrum
- Especially measuring with few filters may give incomplete picture
  - ➡ Correction for missing wavelength ranges needed when absolute brightness across all wavelengths is wanted
  - ➡ **Bolometric correction (BC):** $M_{\mathrm{bol}} = M_{\mathrm{V}} + \mathrm{BC}$
- Note: hot stars radiate much in UV, not well captured by the available filter systems; (very) cool stars better covered with IR filters



Observational stellar parameters

Photometry and colours

- Note that different instruments at different telescopes can have other filter systems