



**Stars:
The Building Blocks
of the Universe**

Homeworks and lectures

- Homework 1 (introductions) due now
- slides and homework at <https://gherczeg.github.io/modernastronomy/>
 - (can follow along and scroll back and forth)
- Zoom link also there:
 - <https://us06web.zoom.us/j/81758755807?pwd=JXAbeWyFviXBR8wvGZdCeW2oIF3dmc.1>
- Homework 2: due Monday, March 23 at 3:00pm
 - Some files to be circulated by wechat and at github
 - <https://gherczeg.github.io/modernastronomy/>
 - No late homework accepted
 - Submission at a PKU website, to be circulated by wechat
 - For some questions, if more than 5 people have the same answer, they will get a 0 for the question
- Ask questions during lecture!
 - Personal questions, ask during break
 - I leave at 5pm and will not stay to answer questions
- Projects:
 - First project: oral report related to astronomy
 - Second project: citizen science project and summary (oral and written)

openstax “textbook”

<https://openstax.org/details/books/astronomy>

Astronomy

Preface

Chapter 1. Science and the Universe: A Brief Tour

[Introduction](#)

- 1.1. [The Nature of Astronomy](#)
 - 1.2. [The Nature of Science](#)
 - 1.3. [The Laws of Nature](#)
 - 1.4. [Numbers in Astronomy](#)
 - 1.5. [Consequences of Light Travel Time](#)
 - 1.6. [A Tour of the Universe](#)
 - 1.7. [The Universe on the Large Scale](#)
 - 1.8. [The Universe of the Very Small](#)
 - 1.9. [A Conclusion and a Beginning](#)
- [For Further Exploration](#)

Chapter 2. Observing the Sky: The Birth of Astronomy

[Thinking Ahead](#)

- 2.1. [The Sky Above](#)
- 2.2. [Ancient Astronomy](#)
- 2.3. [Astrology and Astronomy](#)
- 2.4. [The Birth of Modern Astronomy](#)

[Key Terms](#)

[Summary](#)

[For Further Exploration](#)

[Collaborative Group Activities](#)

[Exercises](#)

[Review Questions](#)

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Student resources

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Summary

Astronomy is designed to meet the scope and sequence requirements of one- or two-semester introductory astronomy courses. The book begins with relevant scientific fundamentals and progresses through an exploration of the solar system, stars, galaxies, and cosmology. The *Astronomy* textbook builds student understanding through the use of relevant analogies, clear and non-technical explanations, and rich illustrations. Mathematics is included in a flexible manner to meet the needs of individual instructors.

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Optional reading

Chapter 5. Radiation and Spectra

[Thinking Ahead](#)

5.1. [The Behavior of Light](#)

5.2. [The Electromagnetic Spectrum](#)

5.3. [Spectroscopy in Astronomy](#)

5.4. [The Structure of the Atom](#)

5.5. [Formation of Spectral Lines](#)

5.6. [The Doppler Effect](#)

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[Summary](#)

Chapter 19. Celestial Distances

[Thinking Ahead](#)

19.1. [Fundamental Units of Distance](#)

19.2. [Surveying the Stars](#)

19.3. [Variable Stars: One Key to Cosmic Distances](#)

19.4. [The H-R Diagram and Cosmic Distances](#)

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Chapter 17. Analyzing Starlight

[Thinking Ahead](#)

17.1. [The Brightness of Stars](#)

17.2. [Colors of Stars](#)

17.3. [The Spectra of Stars \(and Brown Dwarfs\)](#)

17.4. [Using Spectra to Measure Stellar Radius, Composition, and Motion](#)

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[Figuring for Yourself](#)

Chapter 18. The Stars: A Celestial Census

[Thinking Ahead](#)

18.1. [A Stellar Census](#)

18.2. [Measuring Stellar Masses](#)

18.3. [Diameters of Stars](#)

18.4. [The H-R Diagram](#)

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Exercises

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Homework

- Question 1: Space is big!
 - part b: calculate the distance, then convert to something (for example, Shanghai)
 - part d: remember scientific notation!
- Question 2: star clusters
 - Look up “HR diagrams”
- Question 3: Gaia and star clusters
 - Hard! Not everyone will be able to get through all the steps
 - Clusters: stars born at the same time, should have similar motions through space
 - Real data!
- Question 4: Kepler’s laws
 - Sort-of real data (processed, but real)
 - Exoplanets!

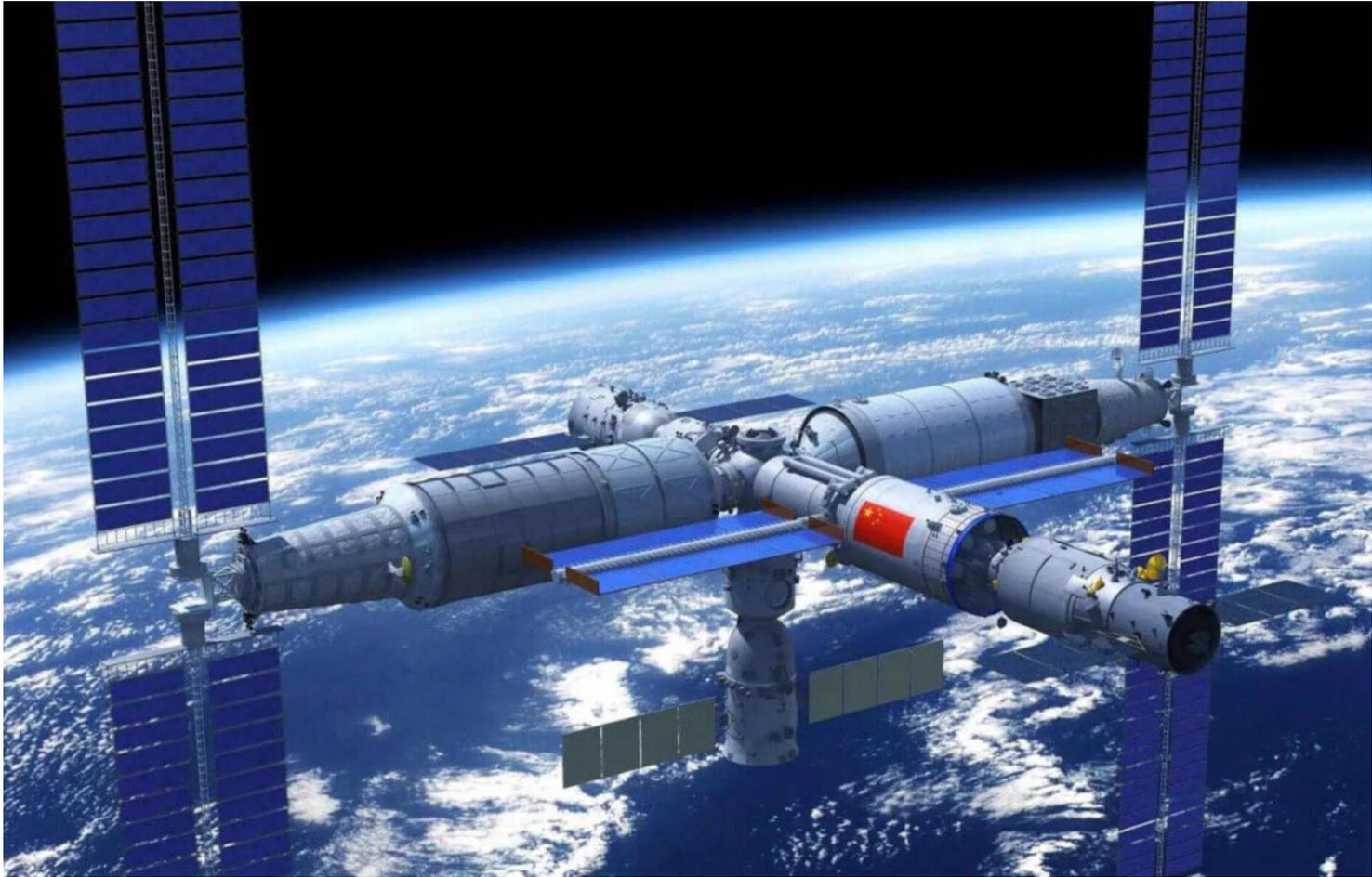
General tip: Use resources combined with your own brain! The homework is intended to provide a path to learning about astronomy in a way that is separate from class. **It’s ok to not finish every part of every question. There is no final exam, so some homework questions are hard. I do not expect all of you to finish all of the homework!**

SHOW ALL WORK!!!

For questions 1, 2, and 4,

Bring questions to class next week!

Tiangong Space Station



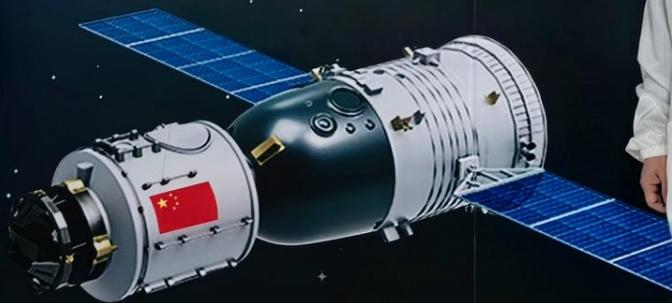
Chinese Space Station Telescope



- 2-m optical/UV telescope
- Wide field of view (300 times Hubble Space Telescope)

博大楼

成测试区



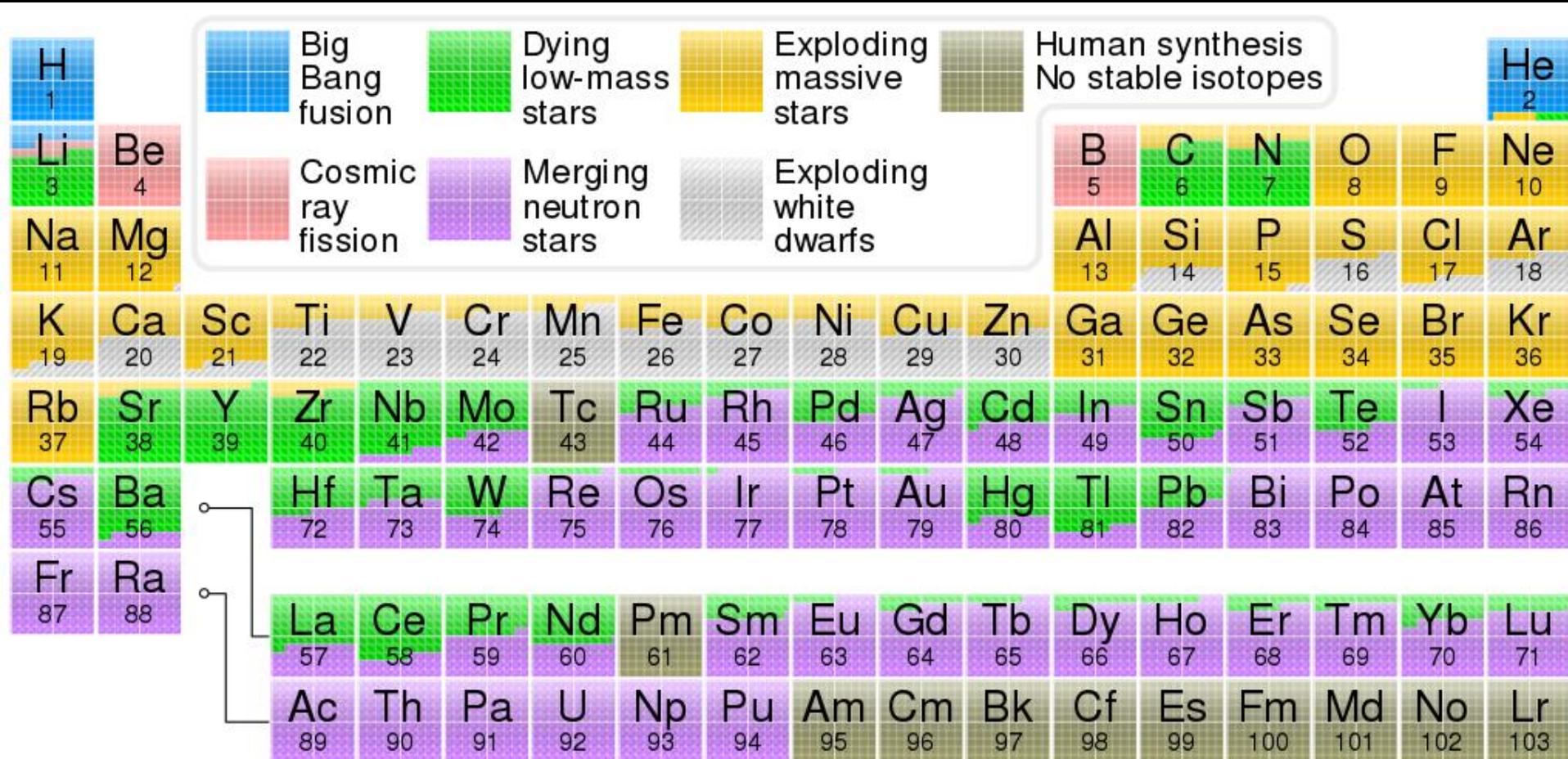




Replica of CSST size
(no photos of CSST allowed)

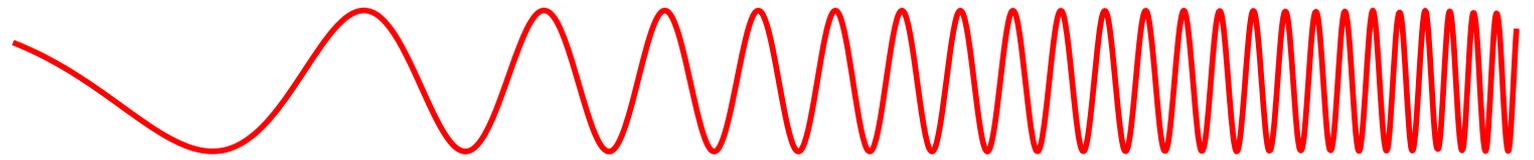
The Cosmically Abundant Elements

Element ^[1]	Symbol	Number of Atoms per Million Hydrogen Atoms
Hydrogen	H	1,000,000
Helium	He	80,000
Carbon	C	450
Nitrogen	N	92
Oxygen	O	740
Neon	Ne	130
Magnesium	Mg	40
Silicon	Si	37
Sulfur	S	19
Iron	Fe	32



Electromagnetic spectrum (energy of light)

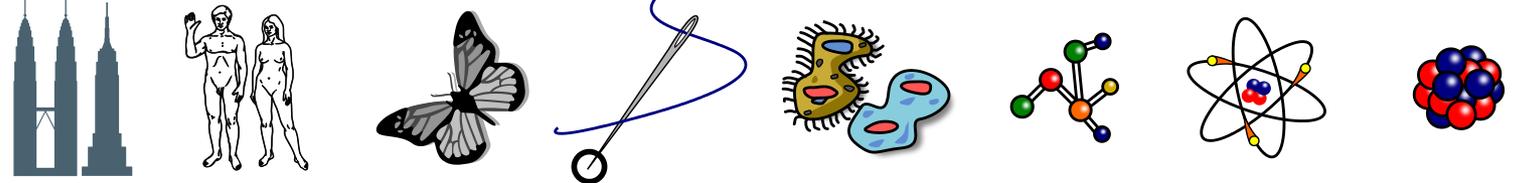
Penetrates Earth's Atmosphere?



Radiation Type
Wavelength (m)

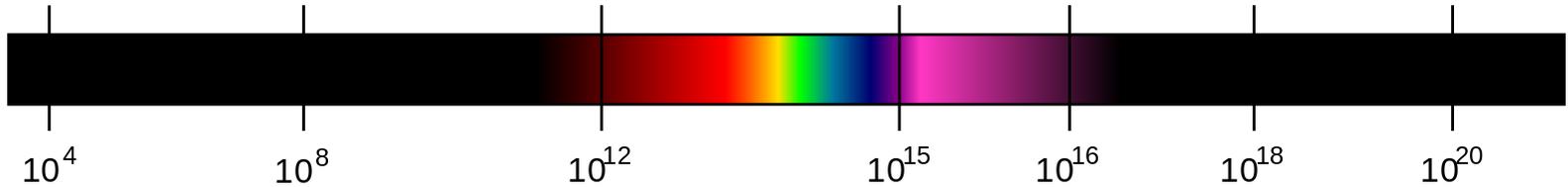


Approximate Scale of Wavelength

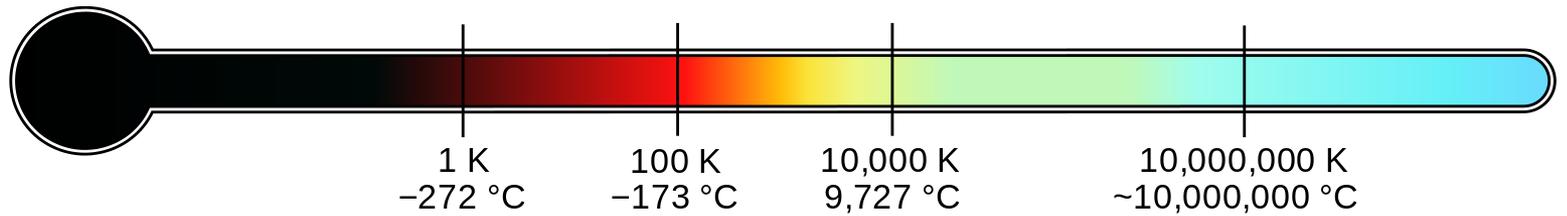


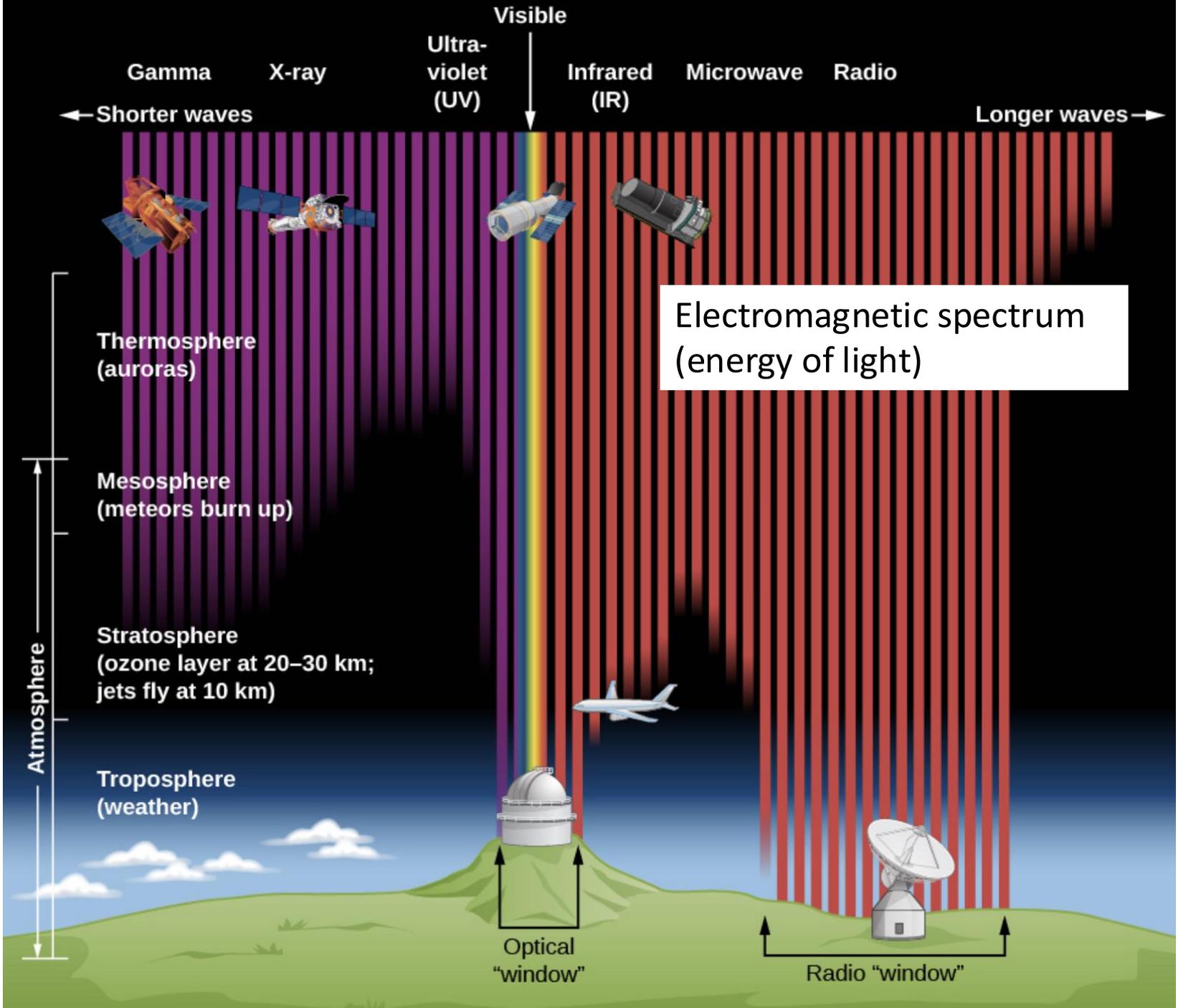
Buildings Humans Butterflies Needle Point Protozoans Molecules Atoms Atomic Nuclei

Frequency (Hz)



Temperature of objects at which this radiation is the most intense wavelength emitted





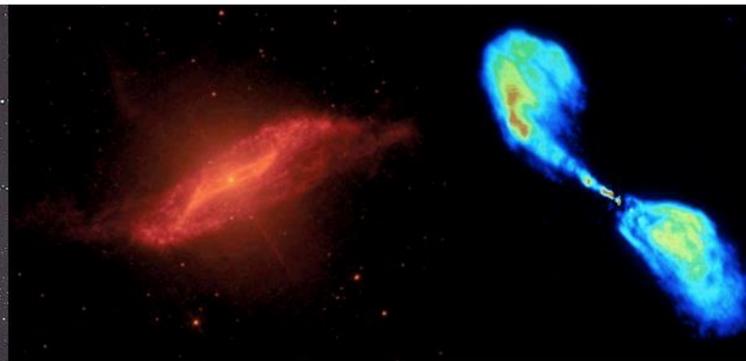
X-ray

ultraviolet

optical

infrared

radio



short wavelength

long wavelength



X ray

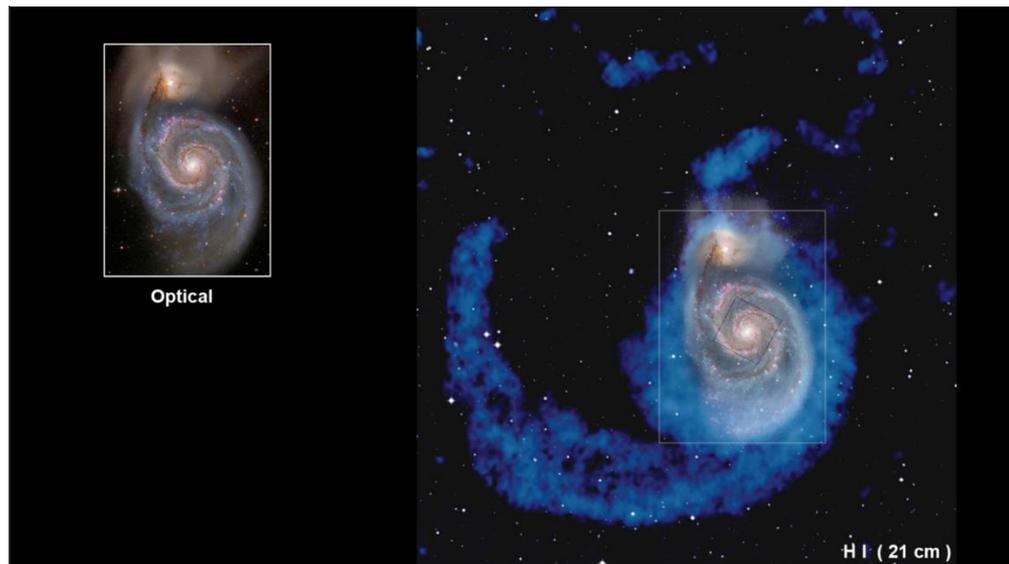
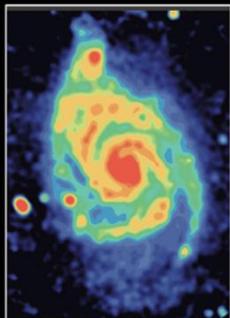
UV

Optical

NIR

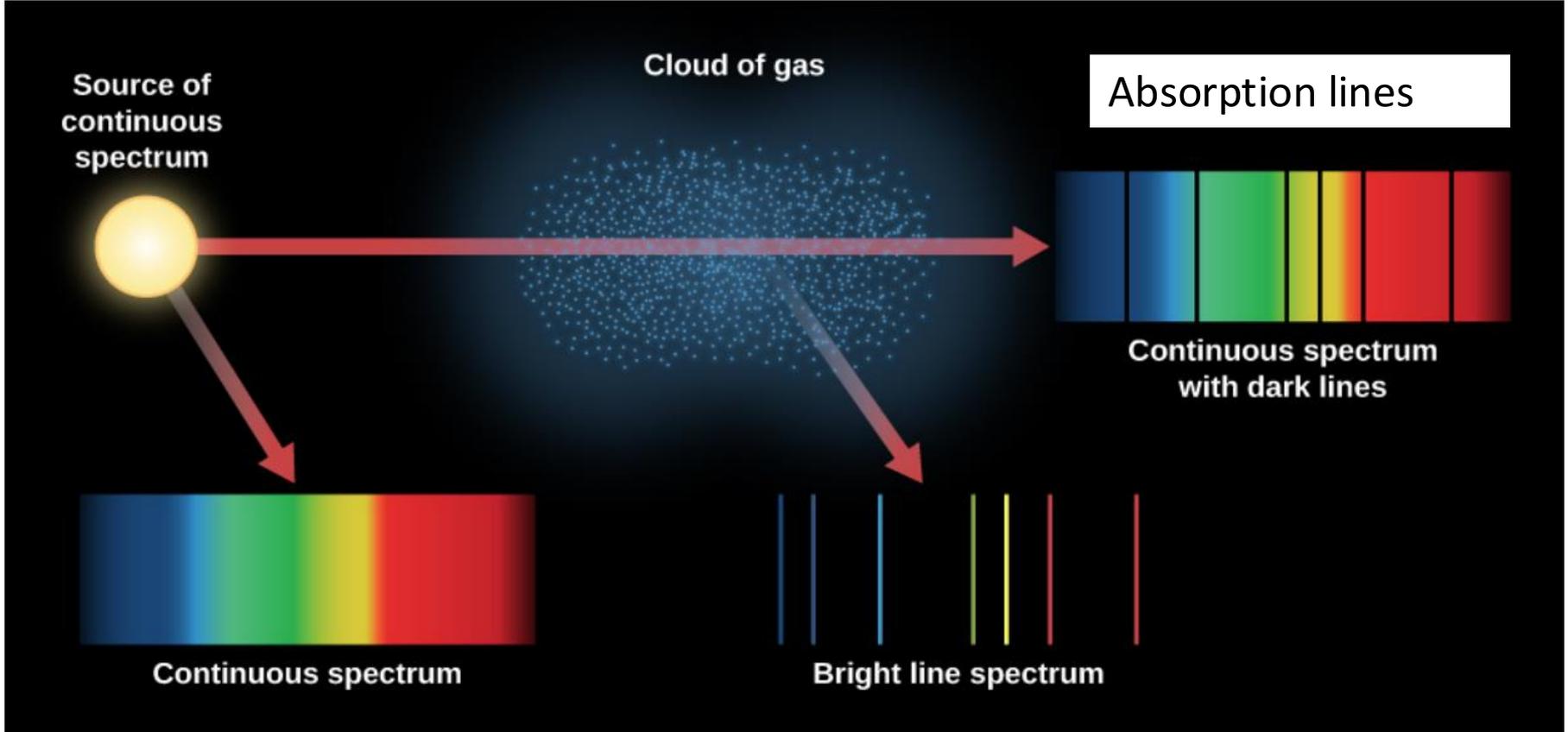
MIR

Radiocontinuum



Optical

HI (21 cm)



Emission lines



The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.



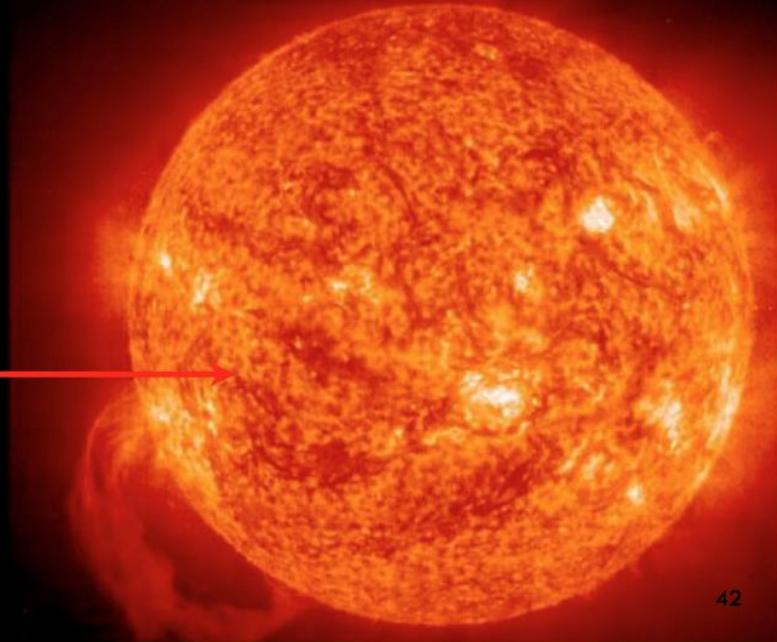
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150,000,000 km

8 m

The Sun



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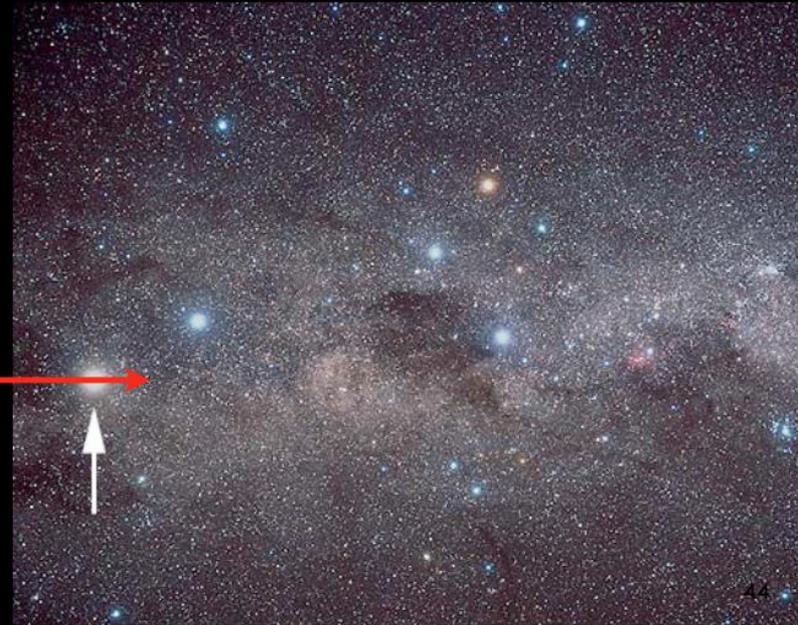
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40 trillion km

4.3 y

The nearest star, alpha Centauri

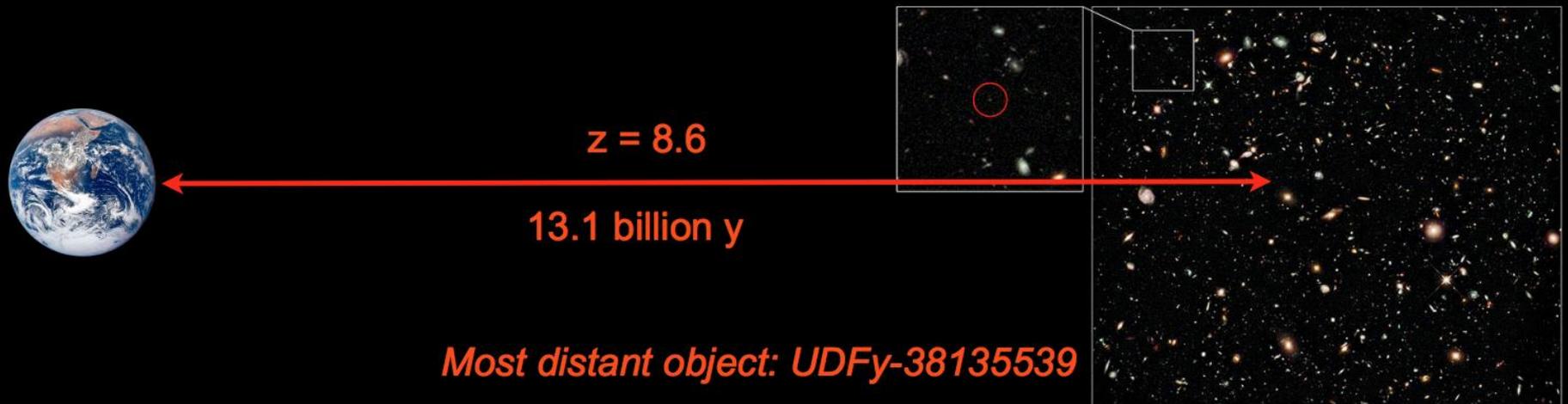


The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.



The Andromeda galaxy

The finite speed of light, combined with these enormous distances, means that when we look out into the universe, the light we see was emitted some time ago – a *long* time ago, if the object is very distant. When we look out into the Universe, we are looking back in time.

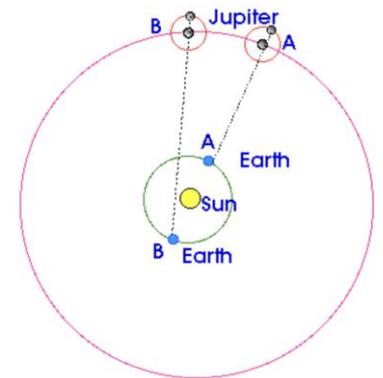


How was the speed of light measured? (ask random questions of LLM!)

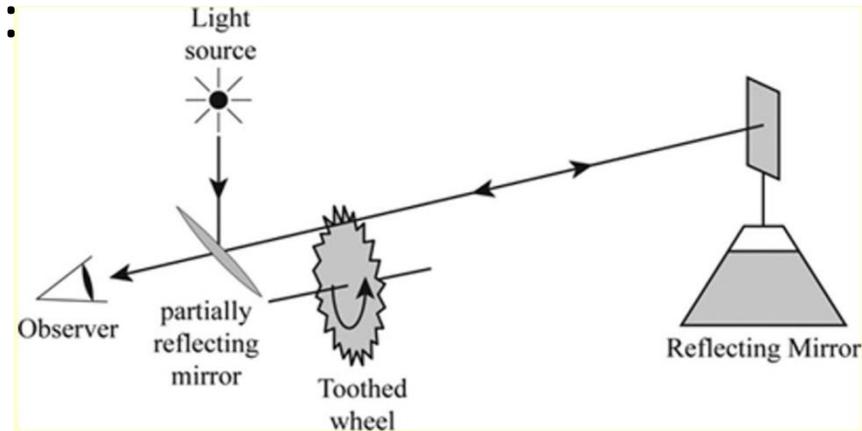
- Speed of light: 2.9979×10^{10} cm/s (fixed)
 - Meter is now defined based on the speed of light!
- Ole Romer (1676): Io eclipses of Jupiter depend on orbits of Jupiter and Earth!
 - Occurs later when Jupiter-Earth distance is larger
 - 2.2×10^{10} cm/s

How was the speed of light measured? (ask random questions of LLM!)

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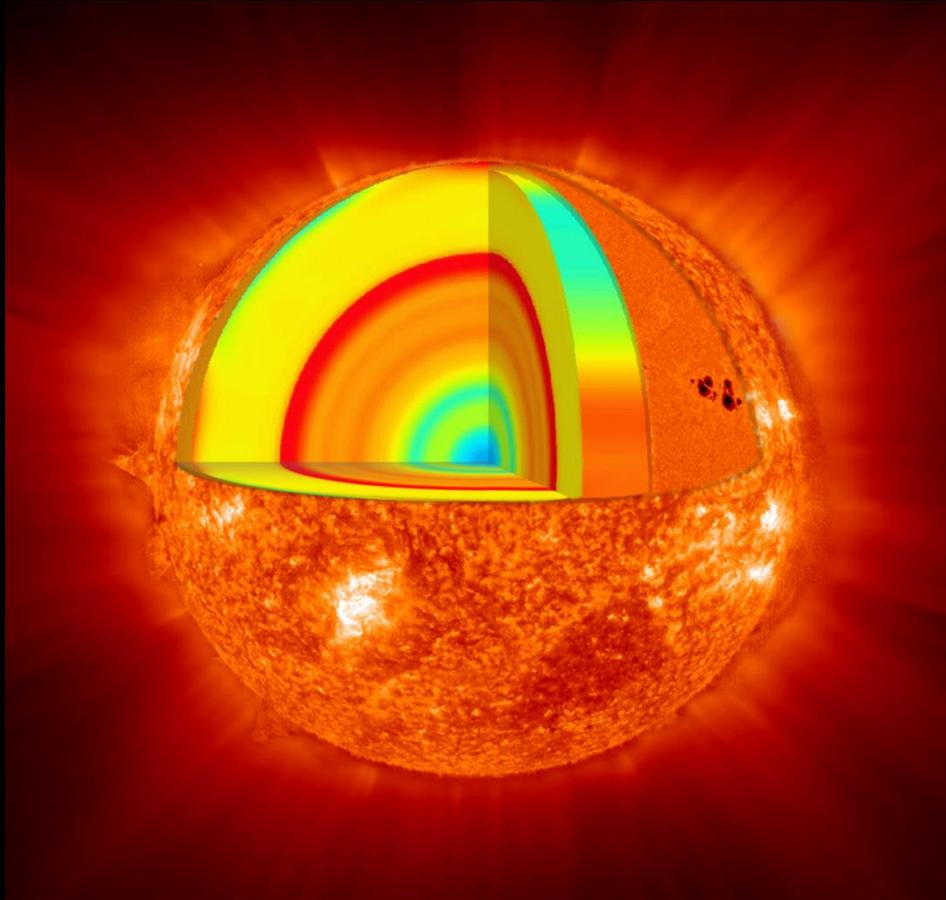


- James Bradley (1728): stellar aberration, 3.01×10^{-10}
- First experiment: Fizeau (1849): 3.13×10^8
 - Shine a light source+rotating wheel/mirror
 - Teeth of wheel blocks out light



- Physics theory: speed of light= c

Stars: the Building Blocks of the Universe



Important concepts for Lecture 2

- HR Diagram: how we understand stars and stellar evolution
 - Apparent magnitude: the magnitude we see
 - Absolute magnitude (luminosity): corrected for distance
 - x-axis: temperature (measured from spectra or colors)
- Main sequence: where stars spend most of their life
 - H burning
- After H burning: stars become giants
 - Core shrinks until He burning
- Fusion: lighter elements => heavier elements
 - Difference in mass converted to energy
 - Occurs in very hot core
- Sun: we see the cool photosphere in optical light
 - Hot corona in X-rays

A large, bright, spiral galaxy with a prominent central bulge, surrounded by numerous smaller stars and distant galaxies in a dark cosmic field. The galaxy's light is concentrated in the center and along its spiral arms, with a bright, multi-pointed starburst pattern at the very center. The surrounding field is filled with many smaller, distant galaxies and individual stars, some of which also exhibit starburst patterns.

Galaxy:
Almost all light from stars

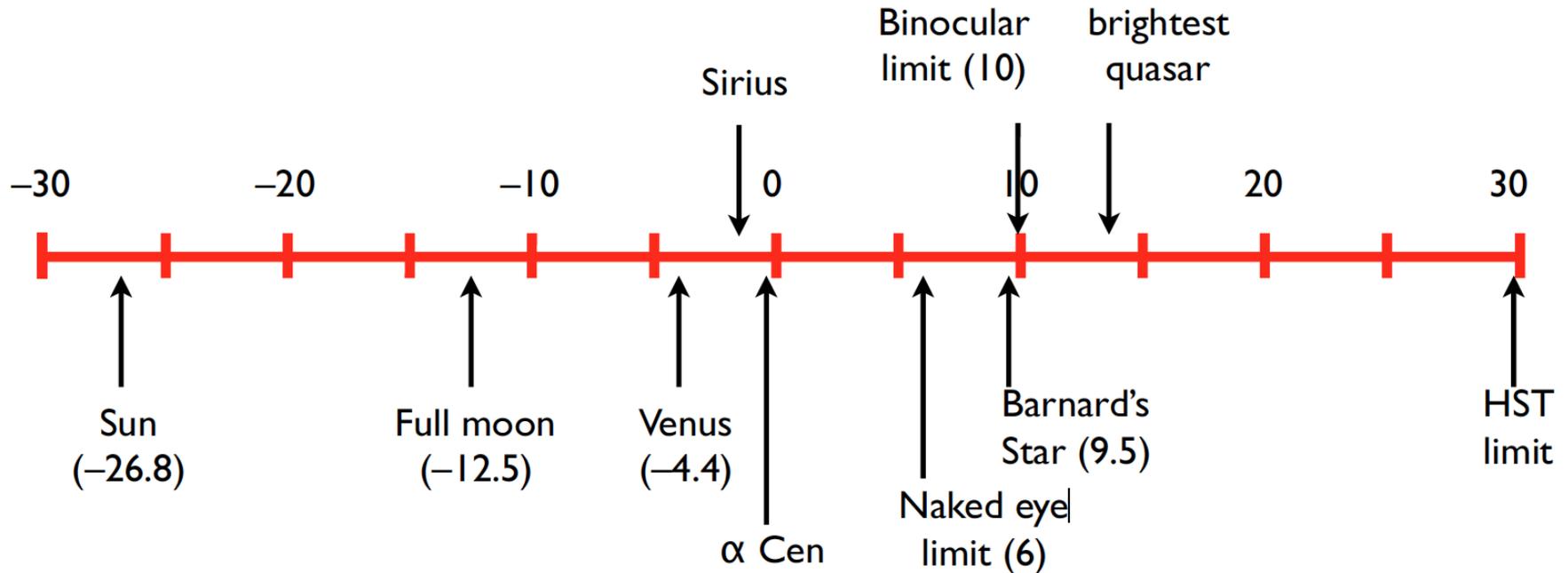
How to describe a star?

Easy or hard to measure? Raise your hands

- Temperature: Easy!
- Radius: very hard
- Composition: easy
- Rotation: not too hard
- Mass: hard
- Age: very hard
- Density: hard to measure, easy to estimate
- Does it have planets?: very hard, but a focus
- Brightness: ancient people could do it!
- Luminosity: hard, but Gaia

Magnitudes (how bright are stars)

Reverse system: negative magnitude brighter



- Brightness: how bright are they at Earth
- Luminosity: how much energy are they emitting?

star	apparent mag
Sirius	-1.50
Canopus	-0.73
Alpha Centauri	+0.10
Vega	+0.04
Arcturus	0
Capella	+0.05
Rigel	+0.08
Procyon	+0.34
Betelgeuse	+0.41
Achernar	+0.47

Sky is 2D!

Distance is usually
uncertain

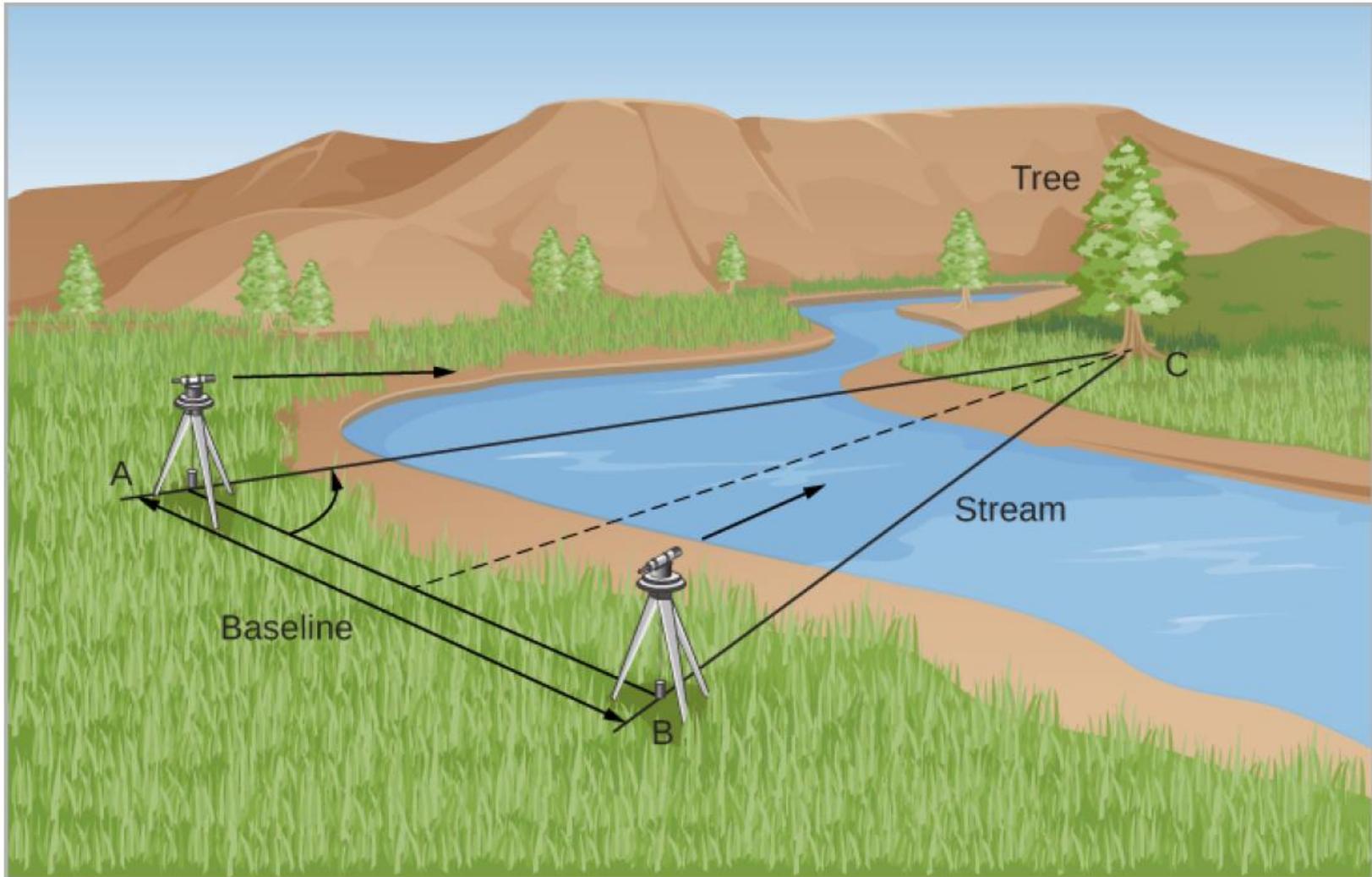
Reverse sytem: negative
magnitude brighter



Other galaxies: all stars at same distance!
[challenge is distance to each galaxy]

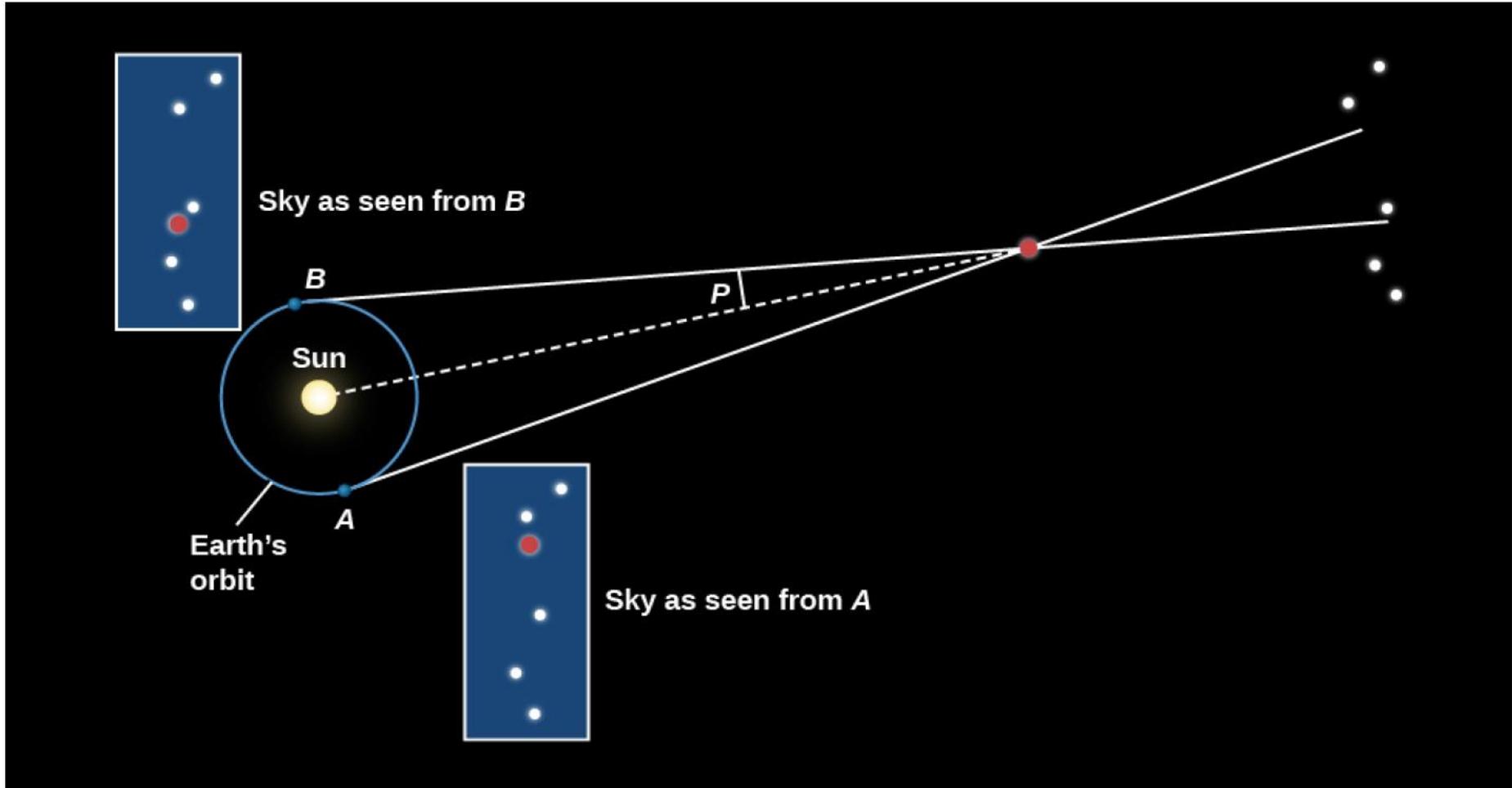
Our own galaxy (Milky Way):
3D, must have distances!

Distance: parallax



Distance: parallax

Very hard to measure



Gaia satellite: parallax distances to ~1 billion stars!



Accuracy of positions:
Human hair at distance of 1000 km!
(or a coin on the moon)

Ordered by brightness

star	apparent mag	distance (pc)
Sirius	-1.50	2.6
Canopus	-0.73	96
Alpha Centauri	+0.10	1.3
Vega	+0.04	7.9
Arcturus	0	11.6
Capella	+0.05	13.1
Rigel	+0.08	184
Procyon	+0.34	3.5
Betelgeuse	+0.41	131
Achernar	+0.47	45

Ordered by distance

star	apparent mag	distance (pc)
Proxima Centauri	11.5	1.3
Alpha Centauri	0.1	1.3
Barnard's Star	9.5	1.8
Wolf 359	13.5	2.3
Lalande 21185	7.5	2.5
Sirius	-1.5	2.6
Luyten 726-8	12.5	2.7
Ross 154	10.6	2.9
Ross 248	12.2	3.2
Epsilon Eridani	3.7	3.3

Known star systems within 5.0 parsecs (16.3 light-years)

Designation		Distance ^[6] (light-years (±err))	Stellar class	Apparent magnitude (m _V ^[5] or m _J)	Absolute magnitude (M _V ^[5] or M _J)	Epoch J2000.	
System	Star					Right ascension ^[5]	Declination ^[5]
Solar System	Sun	0.000 0158	G2V ^[5]	−26.74 #	4.85	N/A	
Alpha Centauri (Rigil Kentaurus)	Proxima Centauri (V645 Centauri)	4.2441 ±0.0011	M5.5Ve	11.09	15.53	14 ^h 29 ^m 43.0 ^s	−62° 56′ 00″
	α Centauri A (HD 128620)	4.3650 ±0.0068	G2V ^[5]	0.01 #	4.38	14 ^h 39 ^m 36.5 ^s	−60° 55′ 00″
	α Centauri B (HD 128621)		K1V ^[5]	1.34 #	5.71	14 ^h 39 ^m 35.1 ^s	−60° 55′ 00″
Barnard's Star (BD+04°3561a)		5.9577 ±0.0032	M4.0Ve	9.53	13.22	17 ^h 57 ^m 48.5 ^s	+04° 35′ 10″
Luhman 16 (WISE 1049–5319) §	Luhman 16A §	6.5029 ±0.0011	L8±1 ^[12]	10.7 J	14.2 J	10 ^h 49 ^m 15.57 ^s	−53° 47′ 00″
	Luhman 16B §		T1±2 ^[12]				
WISE 0855–0714 §		7.26 ±0.13 ^[16]	Y2	25.0 J		08 ^h 55 ^m 10.83 ^s	−07° 14′ 00″
Wolf 359 (CN Leonis)		7.856 ±0.031	M6.0V ^[5]	13.44	16.55	10 ^h 56 ^m 29.2 ^s	+07° 44′ 00″
Lalande 21185 (BD+36°2147)		8.307 ±0.014	M2.0V ^[5]	7.47	10.44	11 ^h 03 ^m 20.2 ^s	+35° 51′ 00″

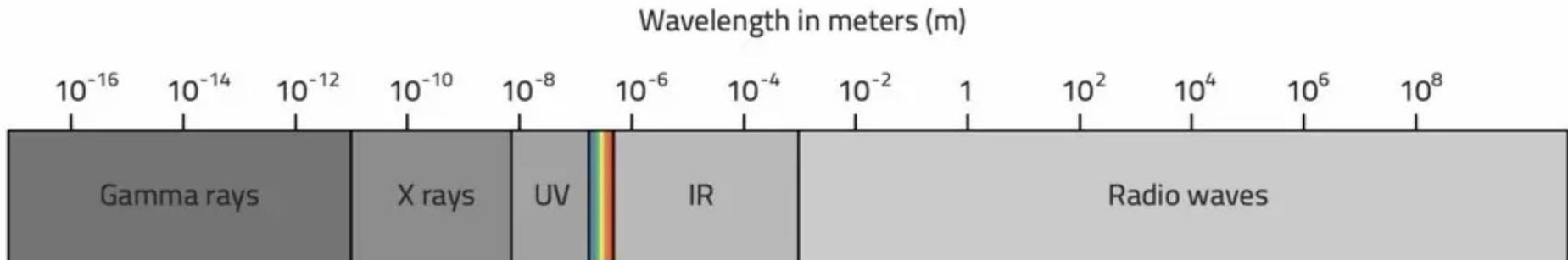
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	α Centauri B (HD 128621)		K1V ^[5]	1.34 #	5.71	14 ^h 39 ^m 35.1 ^s	-60°
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Luhman 16 (WISE 1049–5319) §	Luhman 16A §	6.5029 ±0.0011	L	13.44	16.55	10 ^h 56 ^m 29.2 ^s	+07°
	Luhman 16B §						
WISE 0855–0714 §		7.26 ±0.13 ^[16]	T	13.44	16.55	10 ^h 56 ^m 29.2 ^s	+07°
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Lalande 21185 (BD+36°2147)		8.307 ±0.014	M2.0V ^[5]	7.47	10.44	11 ^h 03 ^m 20.2 ^s	+35°

Brown dwarfs:
don't burn hydrogen!

Stars within 21 Light-Years of the Sun

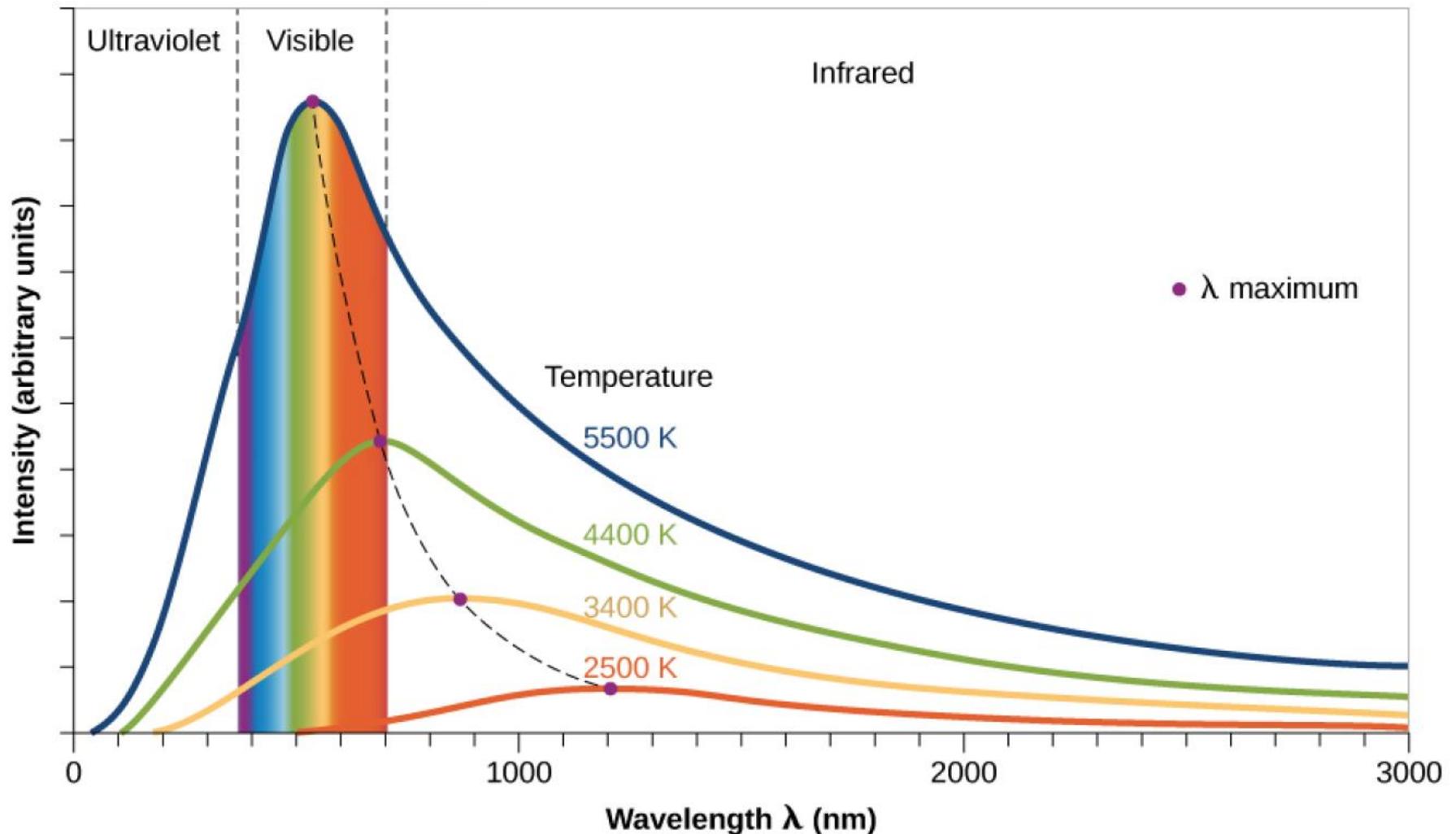
Spectral Type	Number of Stars
A	2
F	1
G	7
K	17
M	94
White dwarfs	8
Brown dwarfs	33



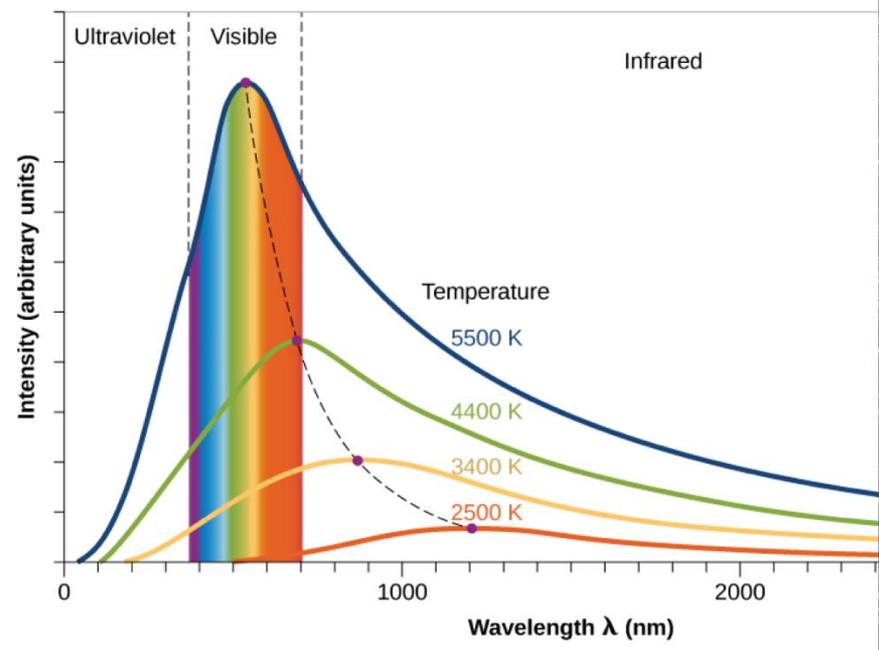
Type of Radiation	Wavelength Range (nm)	Radiated by Objects at This Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10 ⁸ K	Produced in nuclear reactions; require very high-energy processes
X-rays	0.01–20	10 ⁶ –10 ⁸ K	Gas in clusters of galaxies, supernova remnants, solar corona
Ultraviolet	20–400	10 ⁴ –10 ⁶ K	Supernova remnants, very hot stars
Visible	400–700	10 ³ –10 ⁴ K	Stars
Infrared	10 ³ –10 ⁶	10–10 ³ K	Cool clouds of dust and gas, planets, moons
Microwave	10 ⁶ –10 ⁹	Less than 10 K	Active galaxies, pulsars, cosmic background radiation
Radio	More than 10 ⁹	Less than 10 K	Supernova remnants, pulsars, cold gas

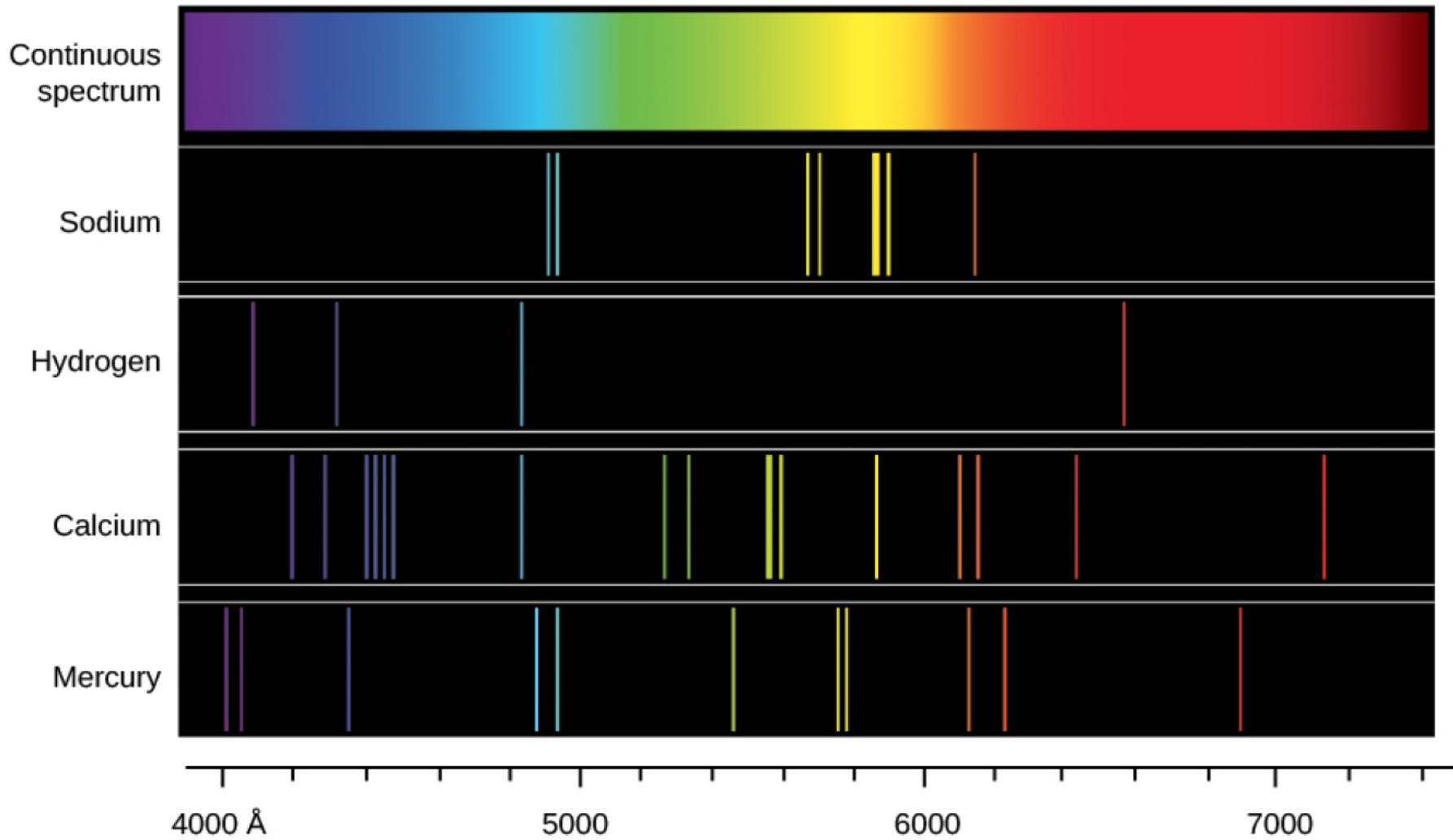
Blackbody emission: hotter things emit at higher energies
(=shorter wavelengths)

Peak of blackbody: $\lambda_{\max} \cdot T = 0.288 \text{ cm} \cdot \text{K}$



Star Color	Approximate Temperature		Example
Blue	25,000 K	Blue	Spica
White	10,000 K		Vega
Yellow	6000 K		Sun
Orange	4000 K	Red	Aldebaran





Spectral Type (temperature) from dark absorption lines

O



B



A



F



G



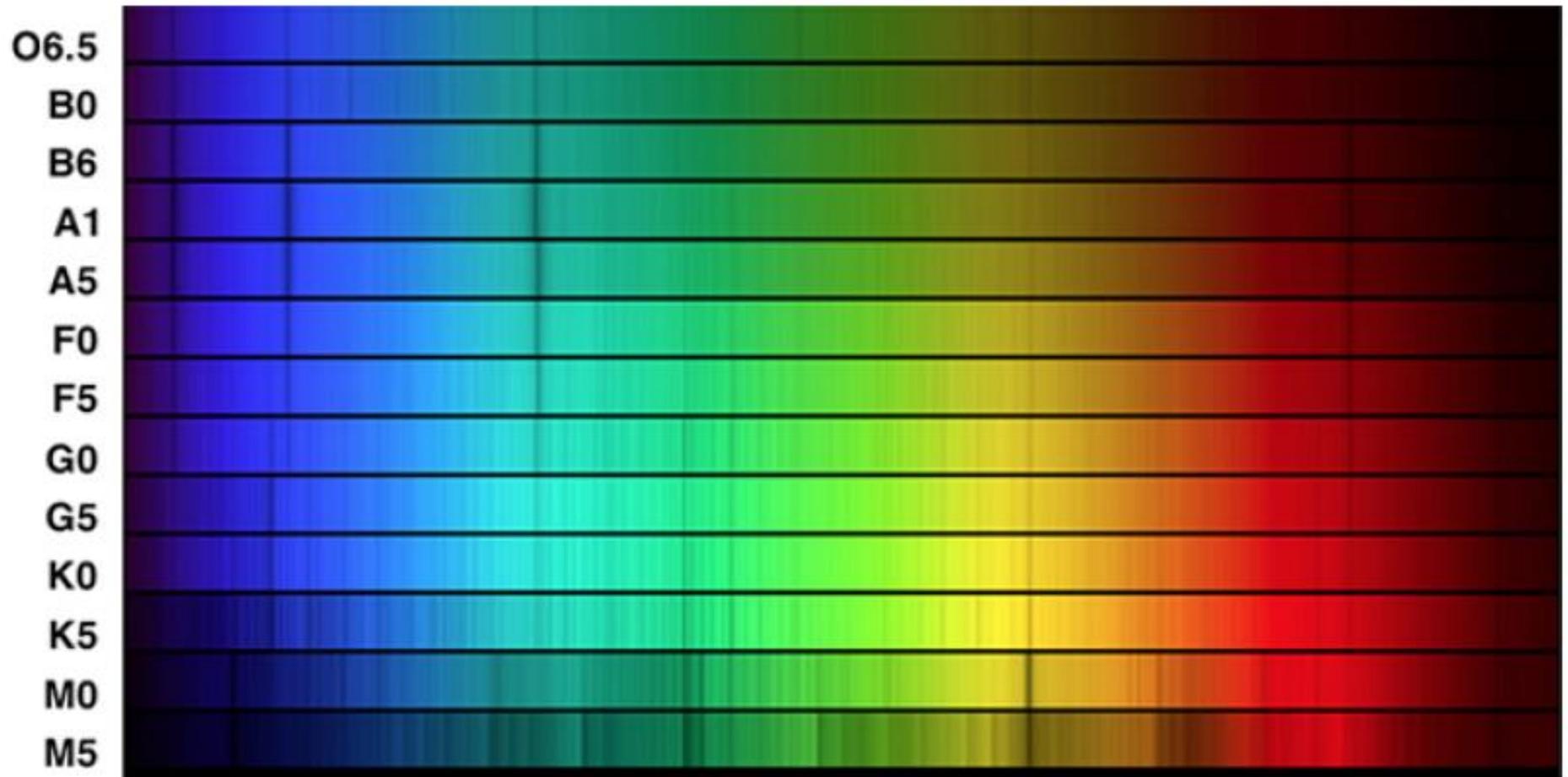
K

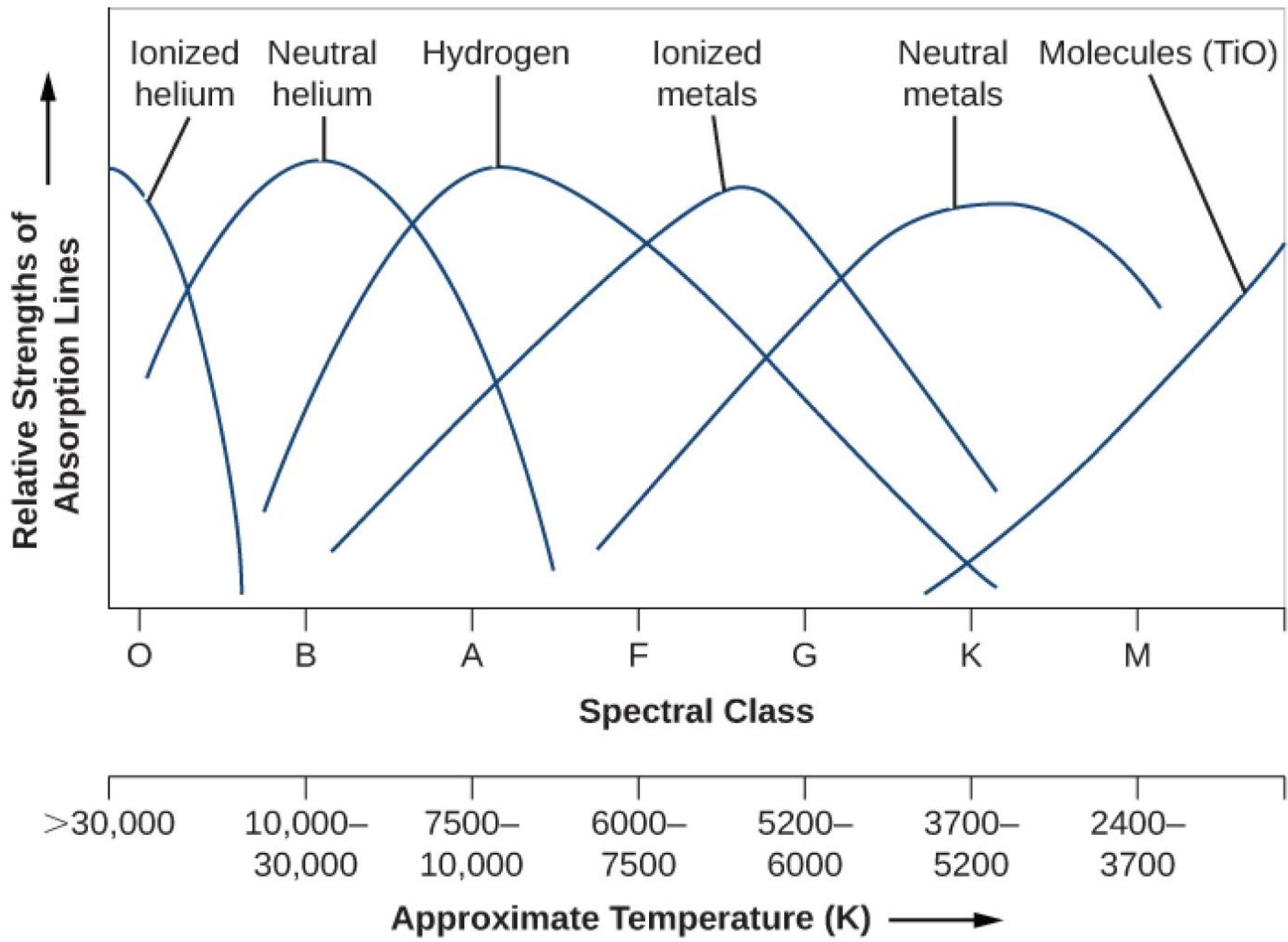


M



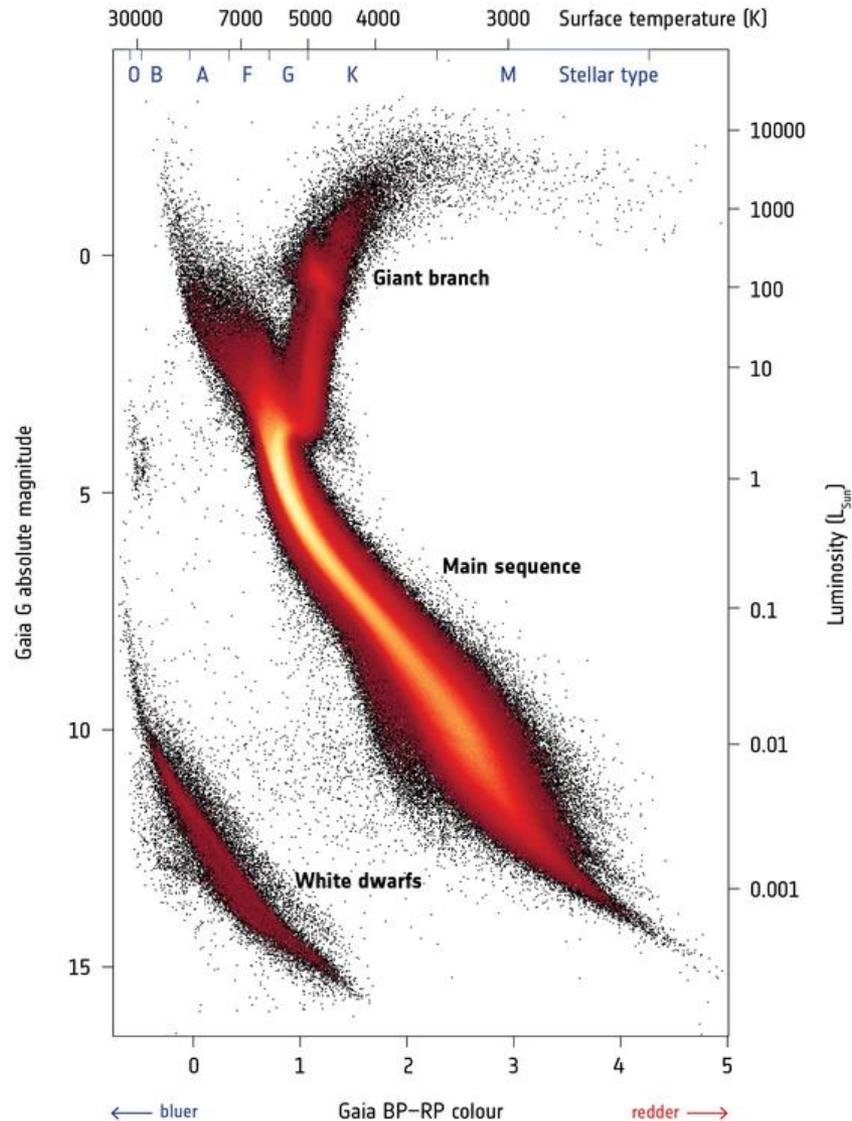
Spectral Type (temperature) from dark absorption lines





Type	Colour	Main characteristics
O	Blue	Ionised helium and metals; weak hydrogen
B	Blue	Neutral helium, ionised metals, stronger hydrogen
A	Blue	Hydrogen dominant, singly-ionised metals
F	Blue to white	Hydrogen weaker, neutral and singly-ionised metals
G	White to yellow	Singly-ionised calcium, hydrogen weaker, neutral metals
K	Orange to red	Neutral metals, molecular lines begin to appear
M	Red	Titanium oxide molecular lines dominate, neutral metals

→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM



HR diagram (Hertzsprung-Russell)

Main sequence:

- most stars on main sequence
- Defined by hydrogen burning

Stars in other locations:

- Stellar evolution! (age)

Women of Harvard University



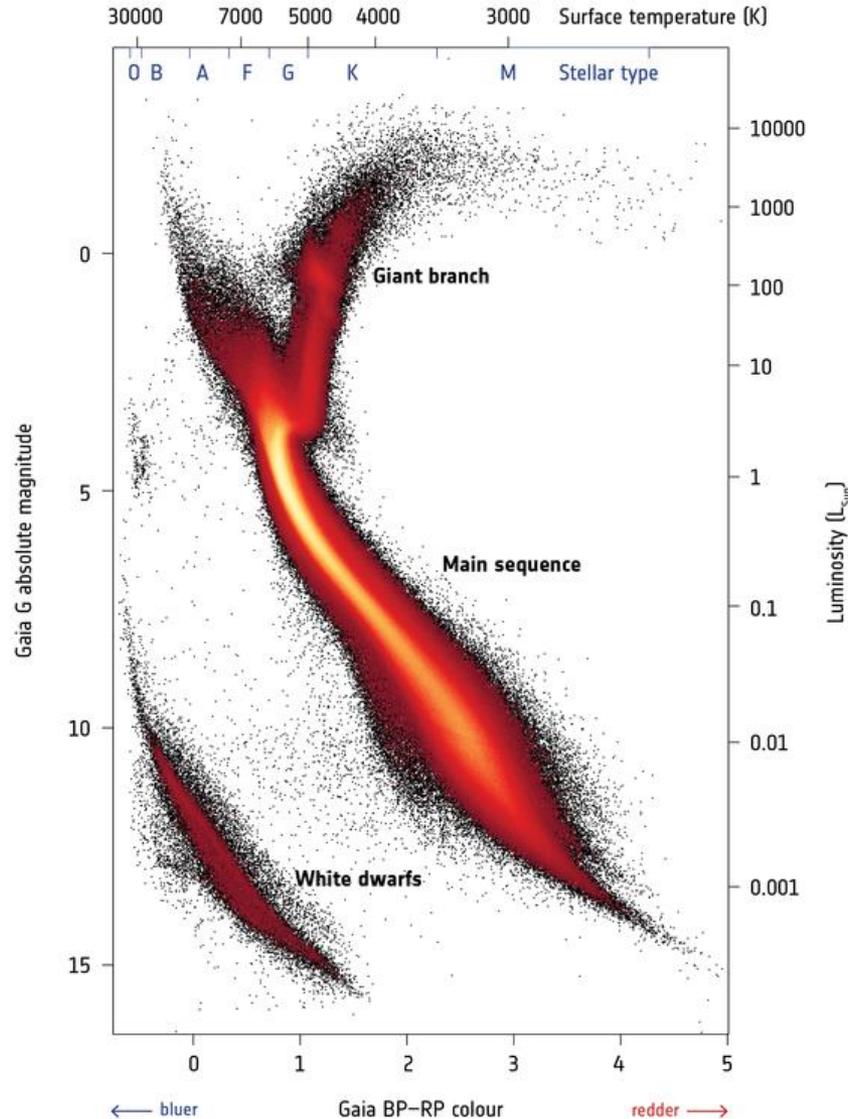


Annie Jump-Cannon



Cecilia Payne: “most brilliant PhD thesis” ever

→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM



HR diagram (Hertzsprung-Russell)

Main sequence:

- most stars on main sequence
- Defined by hydrogen burning

Stars in other locations:

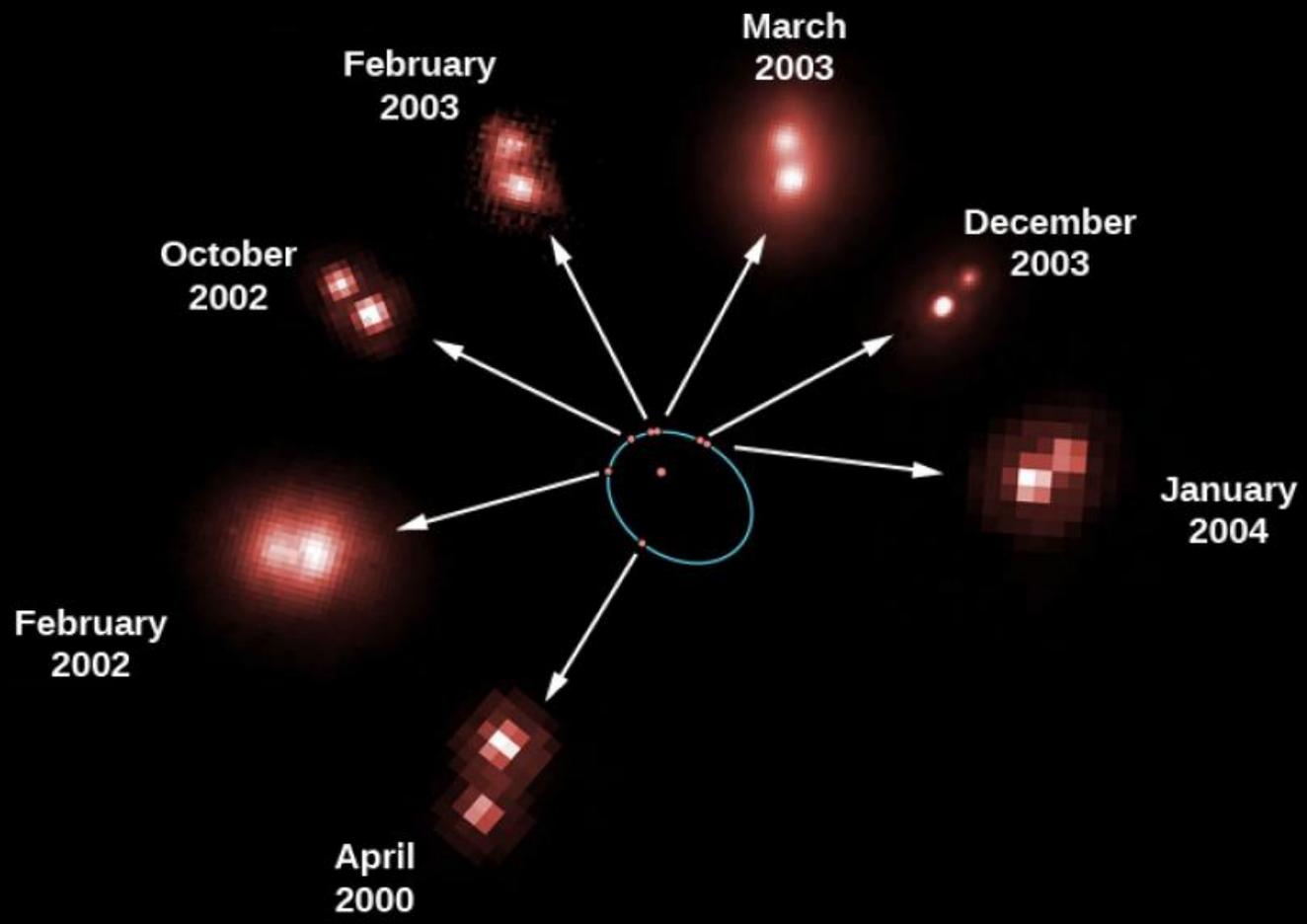
- Stellar evolution! (age)

The Abundance of Elements in the Sun

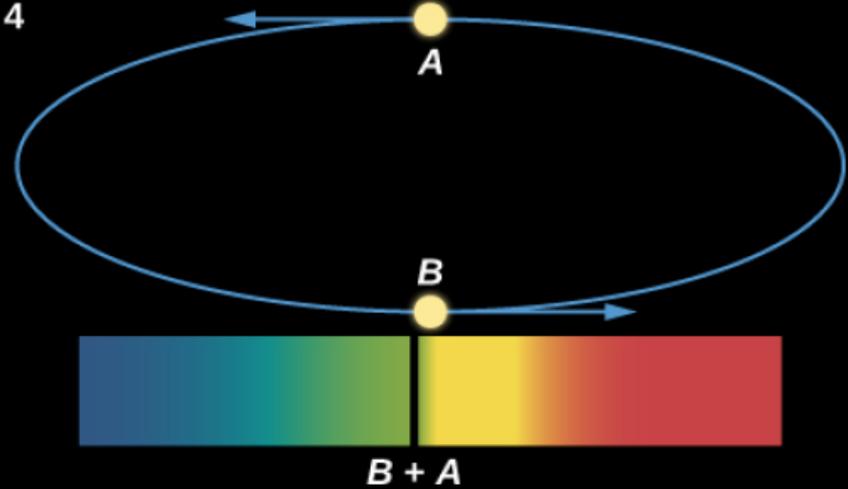
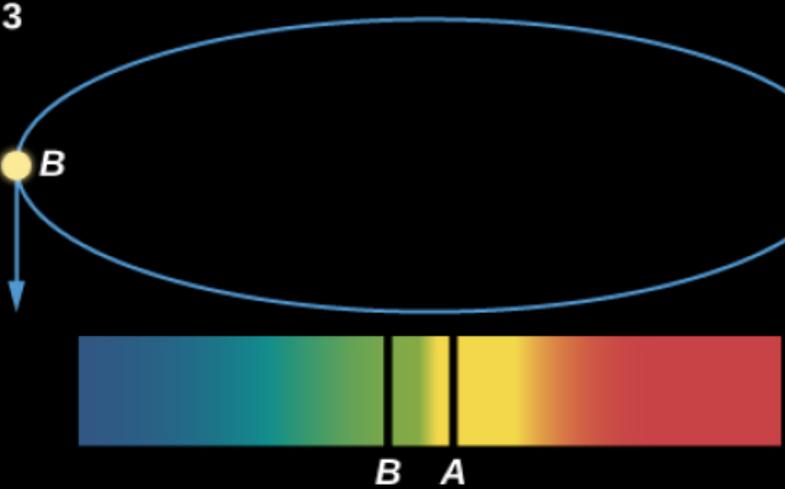
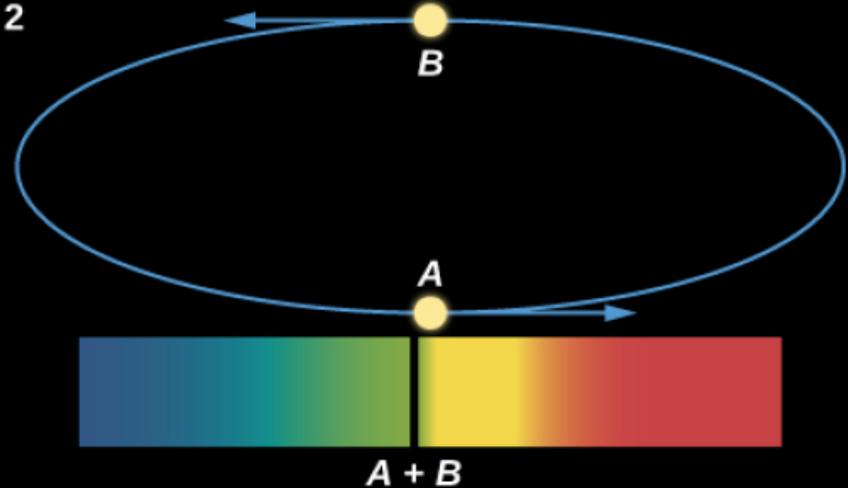
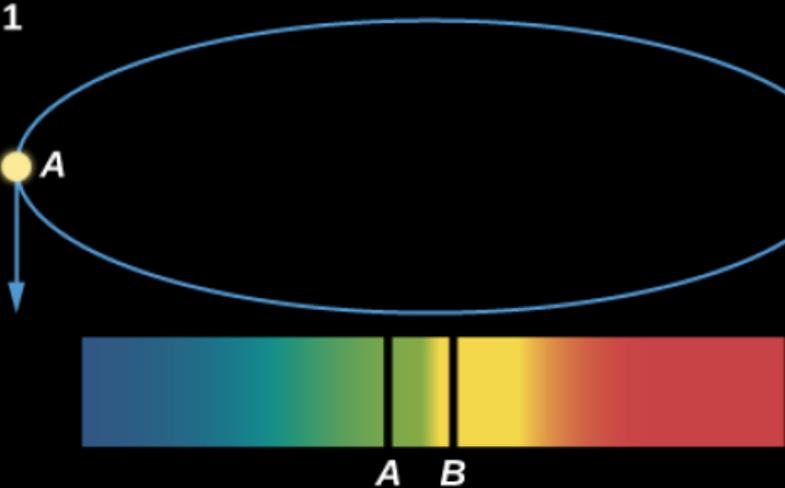
Element	Percentage by Number of Atoms	Percentage By Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.80
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

Measuring the Characteristics of Stars

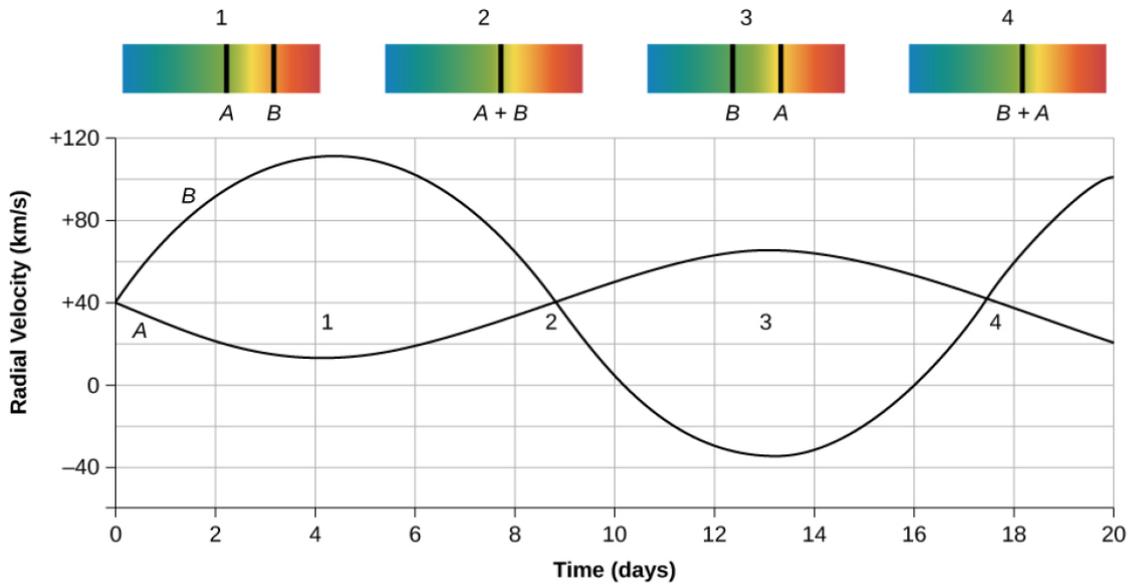
Characteristic	Technique
Surface temperature	<ol style="list-style-type: none">1. Determine the color (very rough).2. Measure the spectrum and get the spectral type.
Chemical composition	Determine which lines are present in the spectrum.
Luminosity	Measure the apparent brightness and compensate for distance.
Radial velocity	Measure the Doppler shift in the spectrum.
Rotation	Measure the width of spectral lines.
Mass	Measure the period and radial velocity curves of spectroscopic binary stars.
Diameter	<ol style="list-style-type: none">1. Measure the way a star's light is blocked by the Moon.2. Measure the light curves and Doppler shifts for eclipsing binary stars.



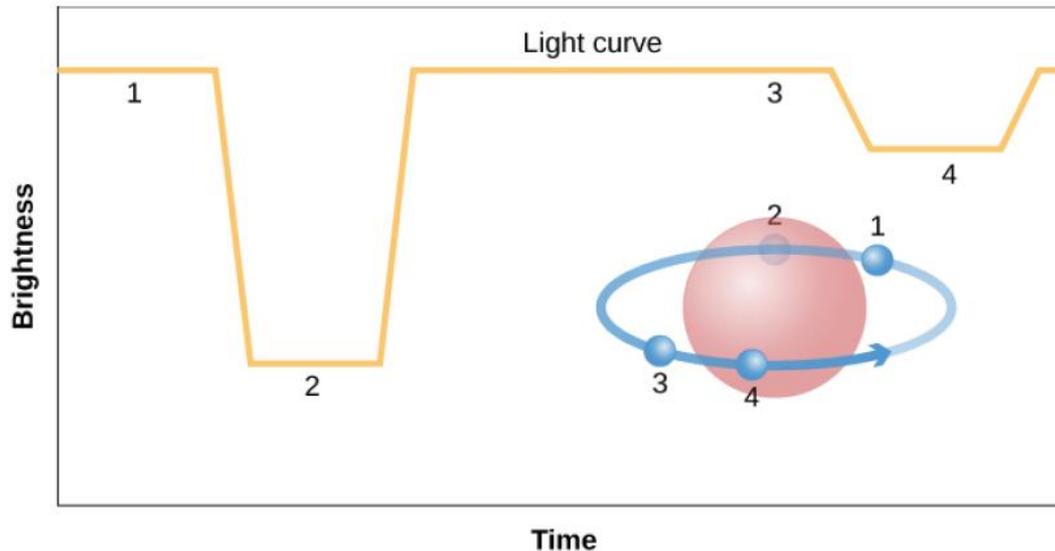
Keplerian motion and Doppler shifts

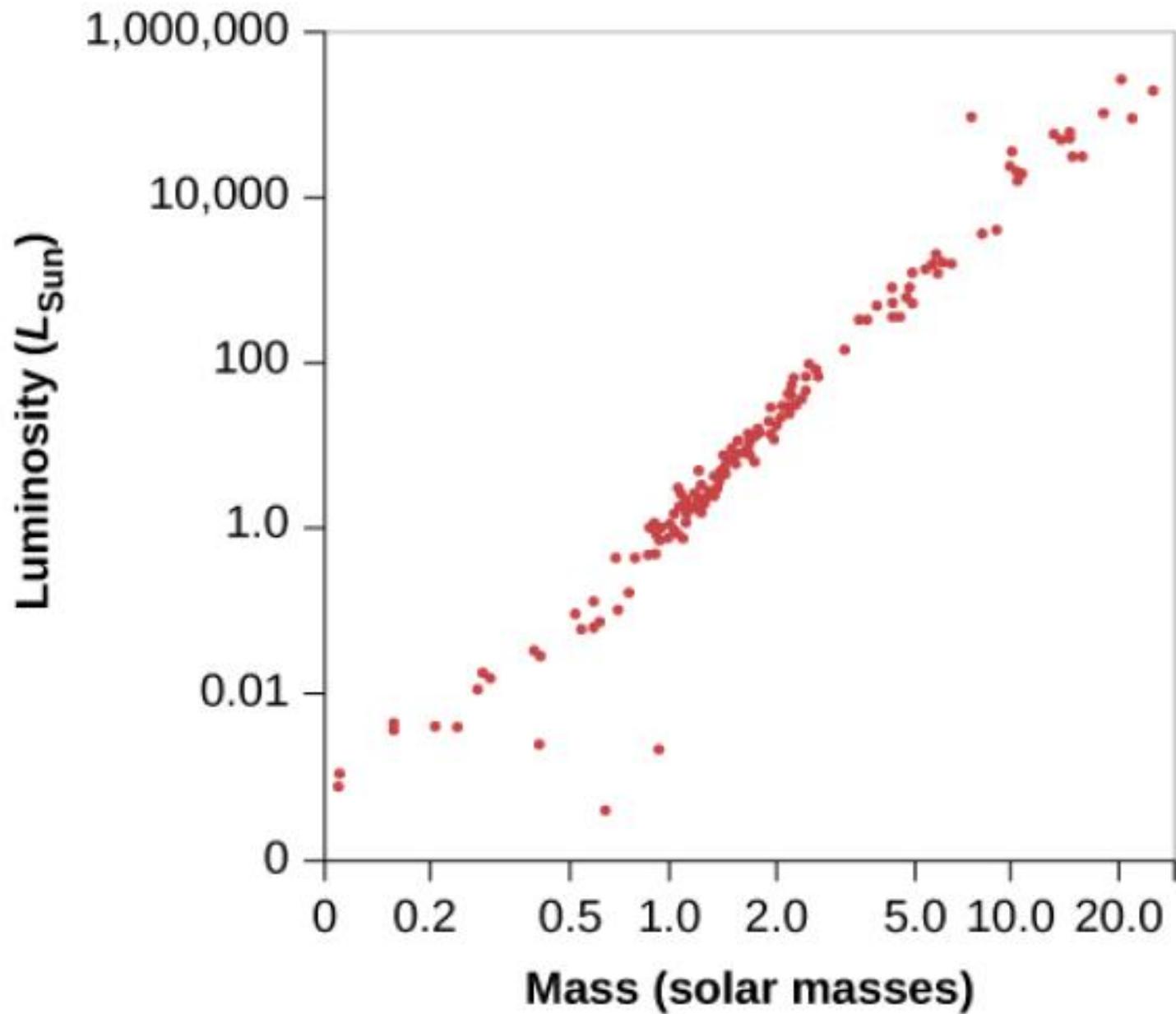


Stellar masses from radial velocity and gravity

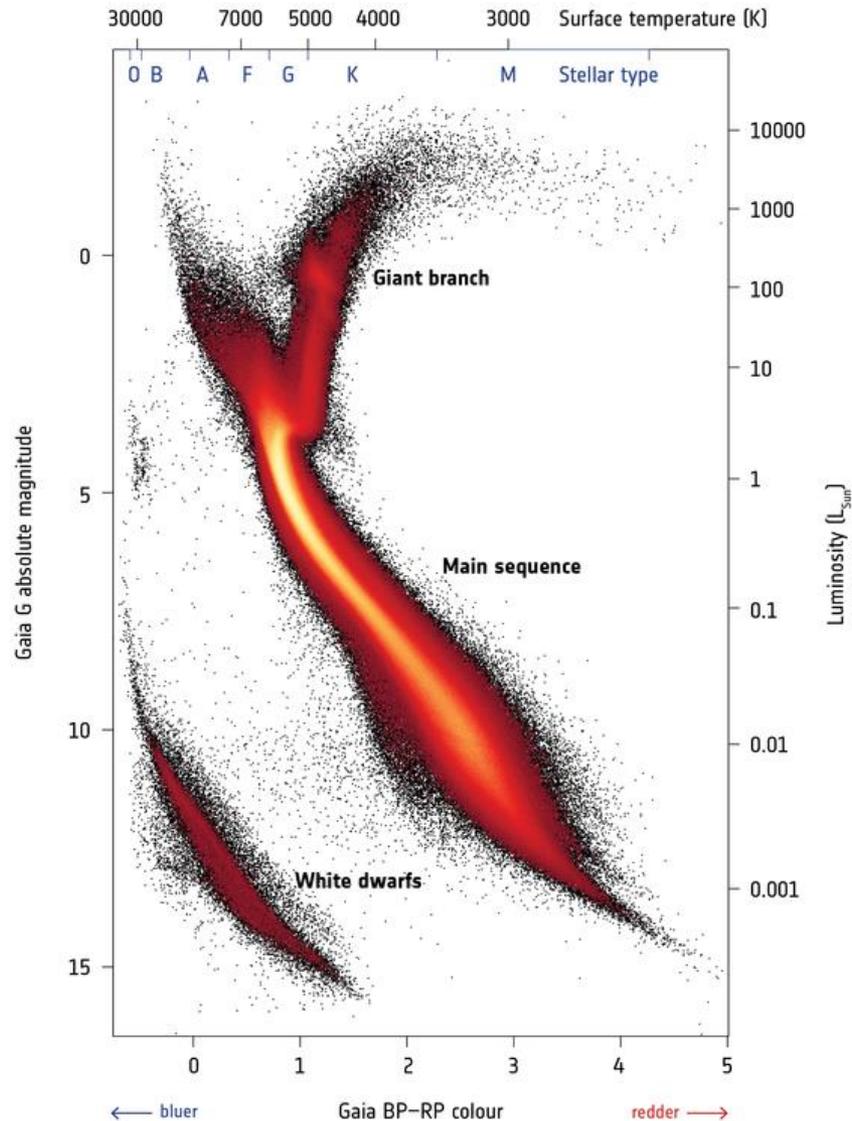


Eclipsing binary systems:
Benchmarks for stellar masses





→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM



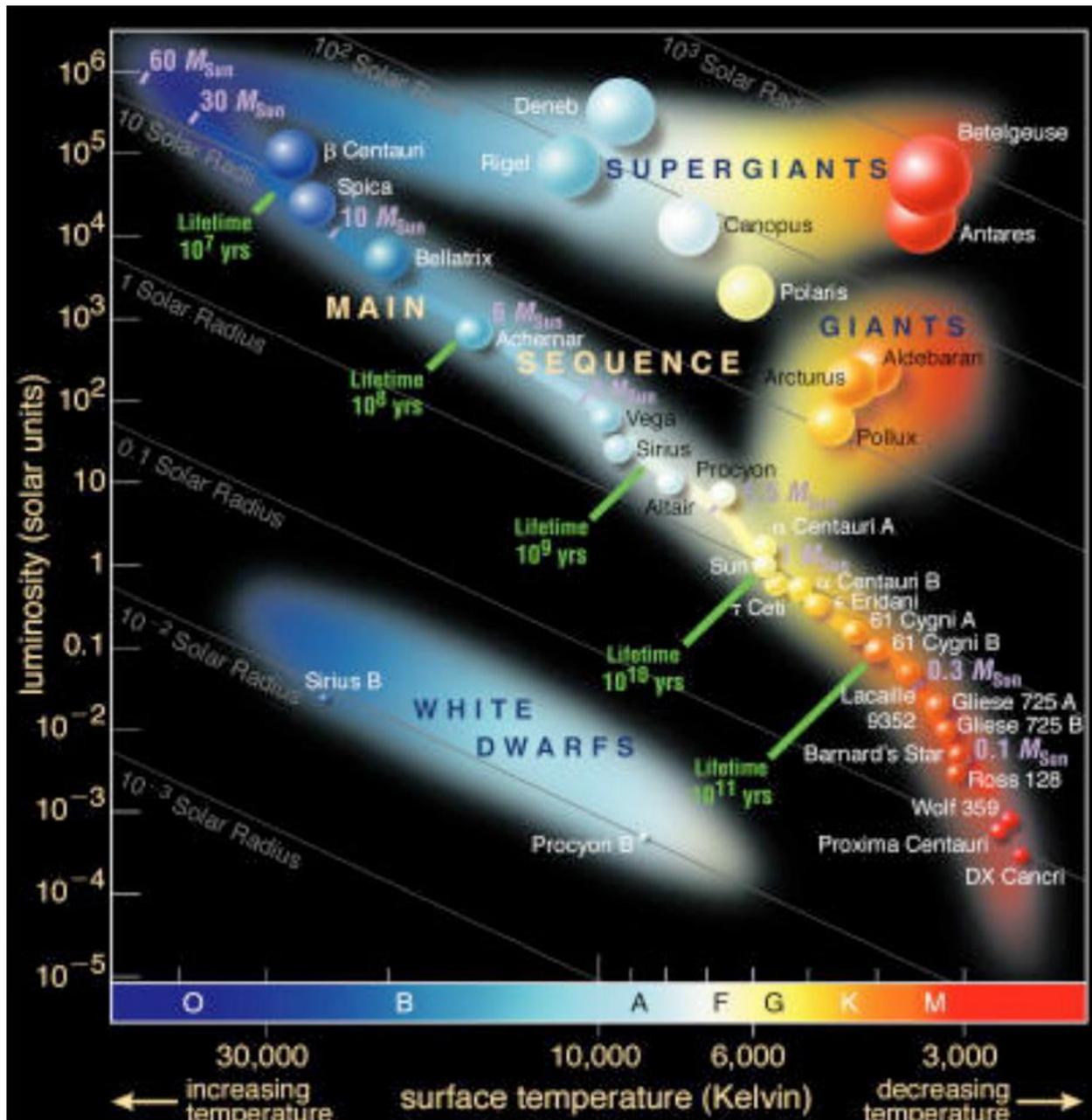
HR diagram (Hertzsprung-Russell)

Main sequence:

- most stars on main sequence
- Defined by hydrogen burning

Stars in other locations:

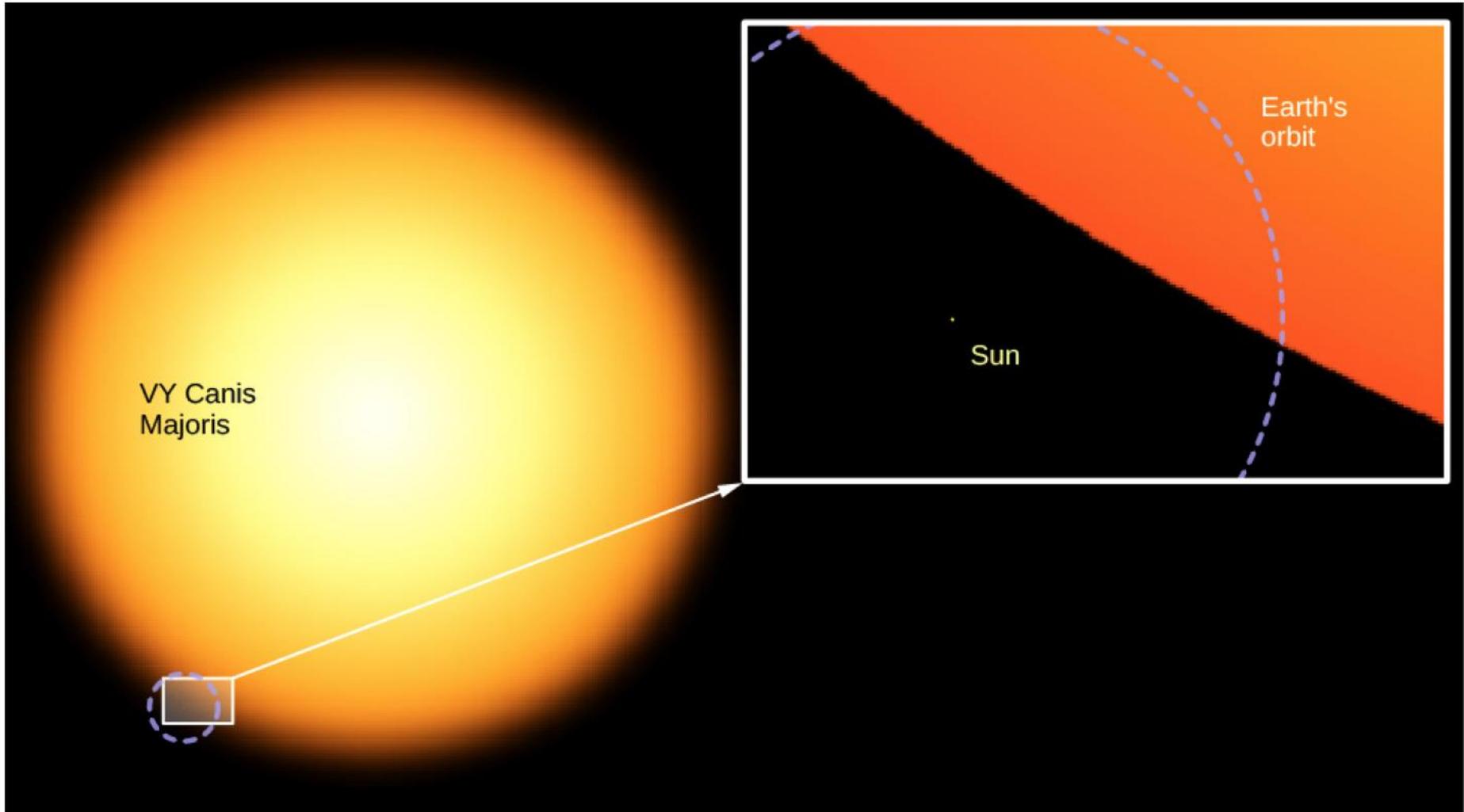
- Stellar evolution! (age)



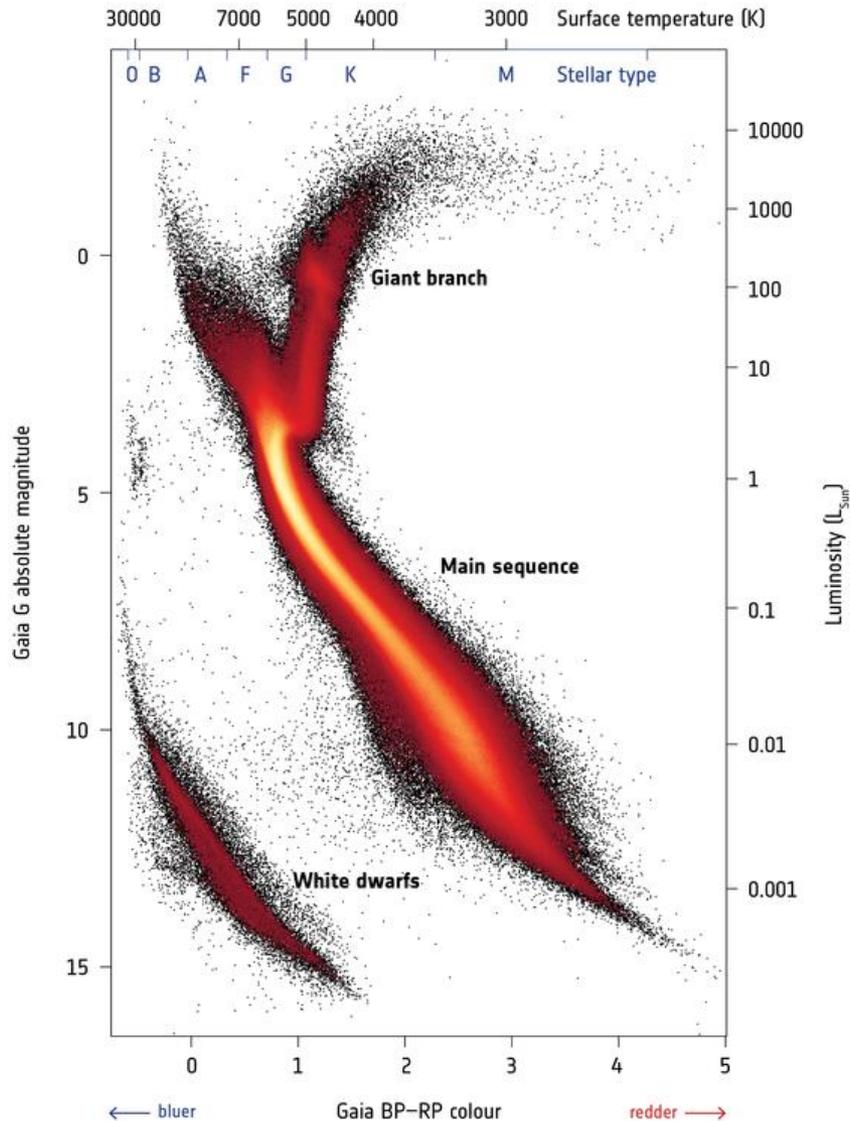
Characteristics of Main-Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Temperature	Radius (Sun = 1)
O5	40	7×10^5	40,000 K	18
B0	16	2.7×10^5	28,000 K	7
A0	3.3	55	10,000 K	2.5
F0	1.7	5	7500 K	1.4
G0	1.1	1.4	6000 K	1.1
K0	0.8	0.35	5000 K	0.8
M0	0.4	0.05	3500 K	0.6

Evolved stars: red giants, can be huge!



→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM

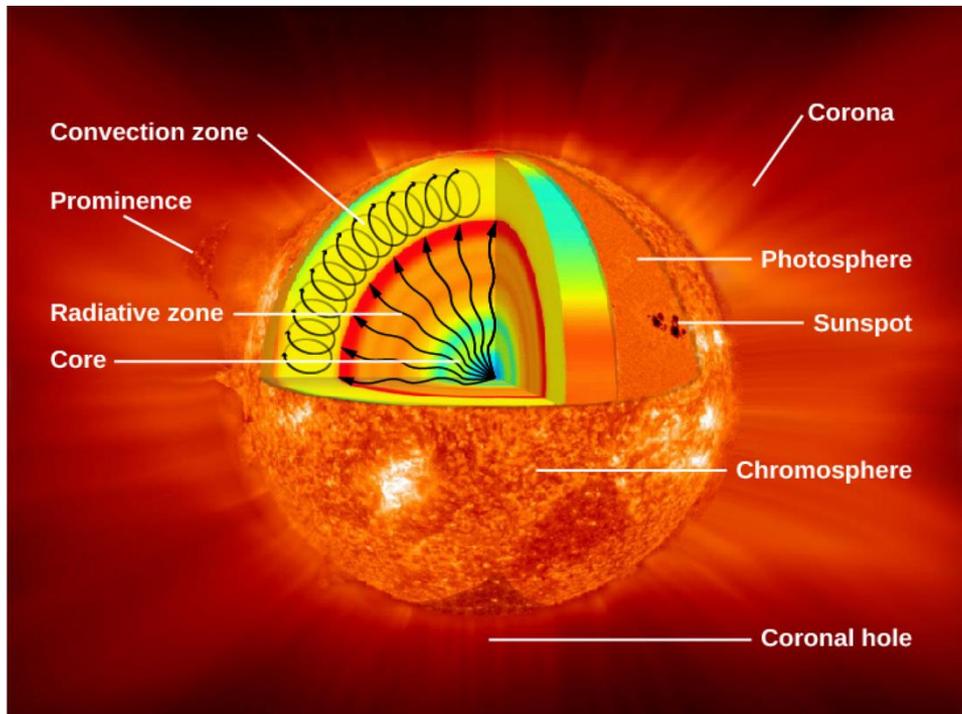


What is the Main Sequence?

- 90% of a star's life
- Defined by hydrogen burning core
- Evolves once hydrogen is gone

- What does hydrogen burning mean?

Where does the sun's energy come from? Hydrogen burning and the interior of the sun



▼ 15 The Sun: A Garden-Variety Star

Thinking Ahead

15.1 The Structure and Composition of the Sun

15.2 The Solar Cycle

15.3 Solar Activity above the Photosphere

15.4 Space Weather

Key Terms

Summary

For Further Exploration

Collaborative Group Activities

► Exercises

▼ 16 The Sun: A Nuclear Powerhouse

Thinking Ahead

16.1 Sources of Sunshine: Thermal and Gravitational Energy

16.2 Mass, Energy, and the Theory of Relativity

16.3 The Solar Interior: Theory

16.4 The Solar Interior: Observations

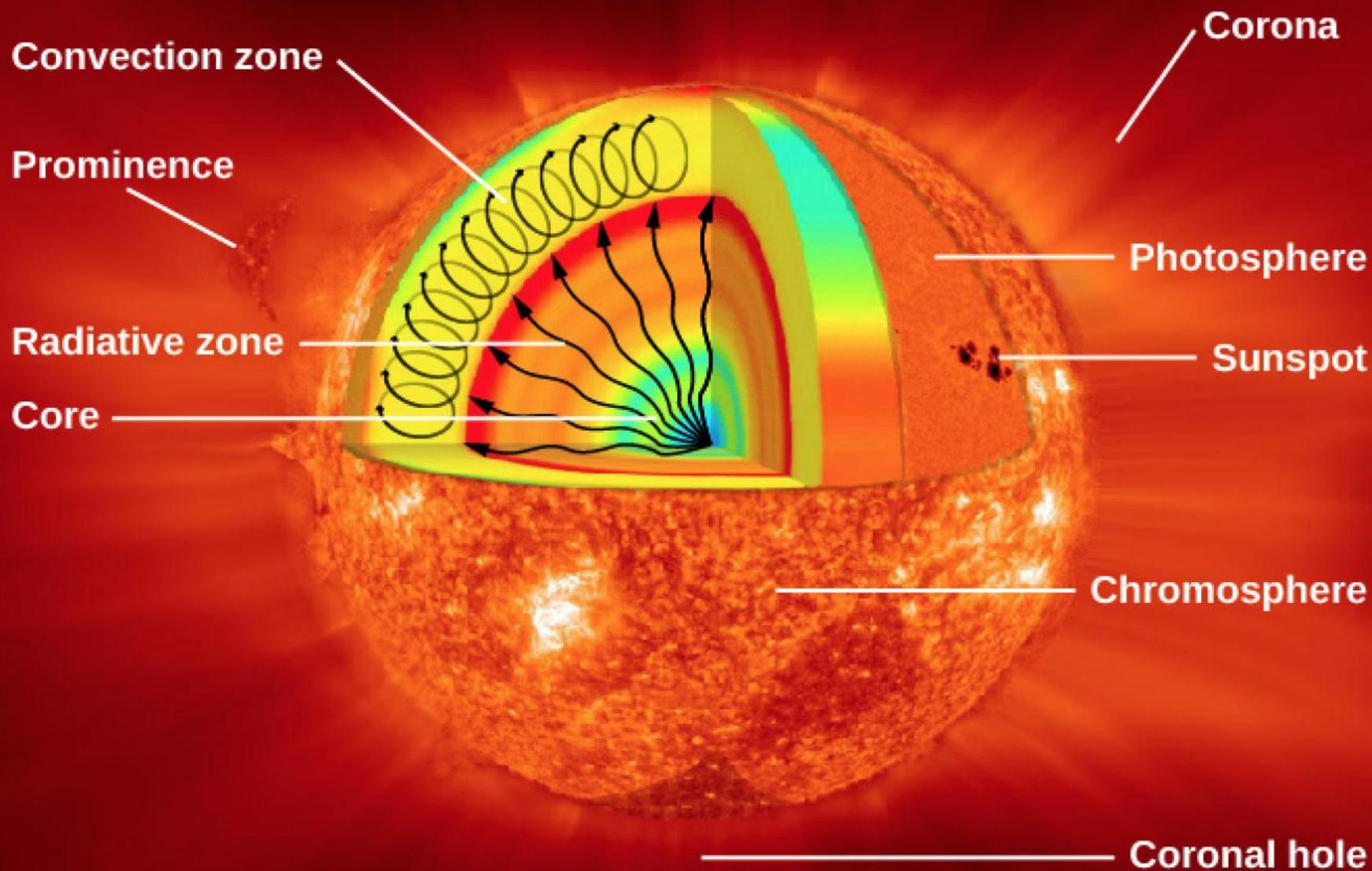
Key Terms

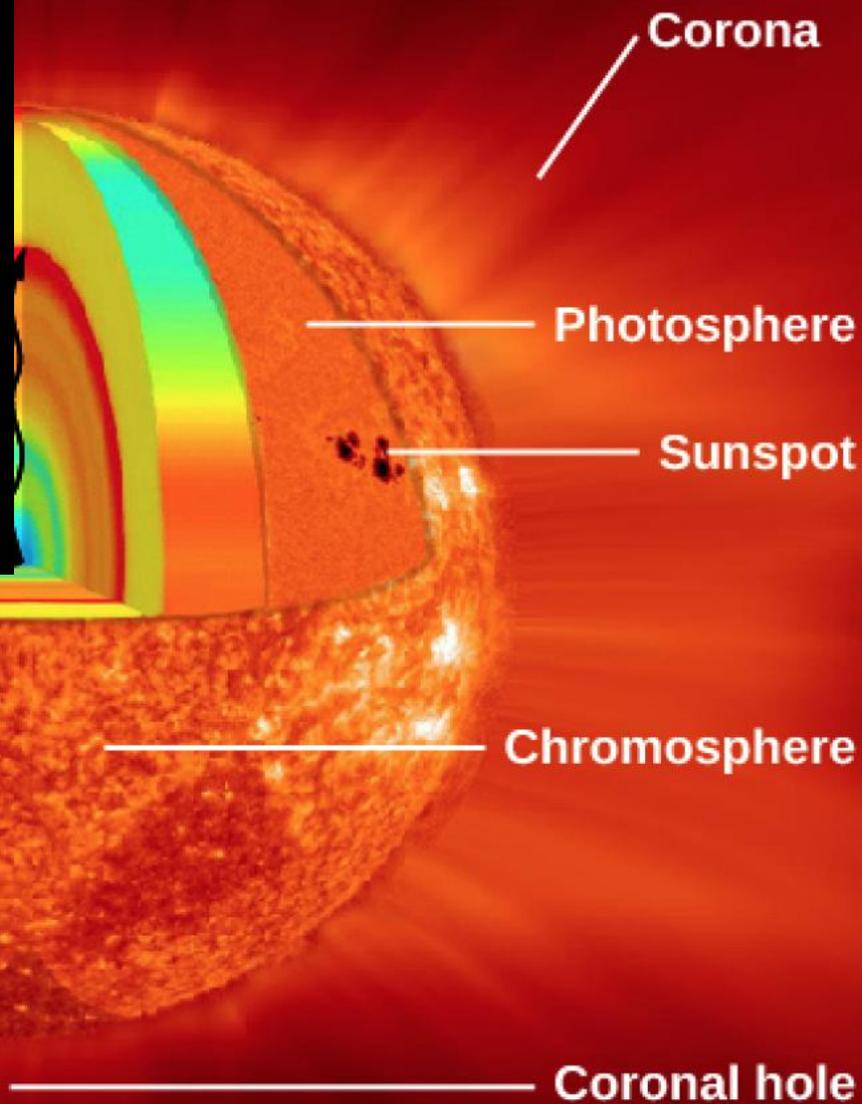
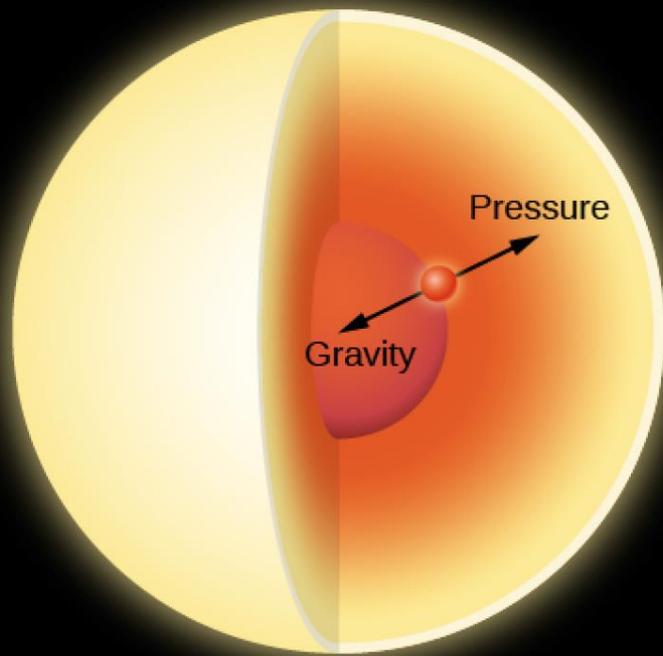
Summary

For Further Exploration

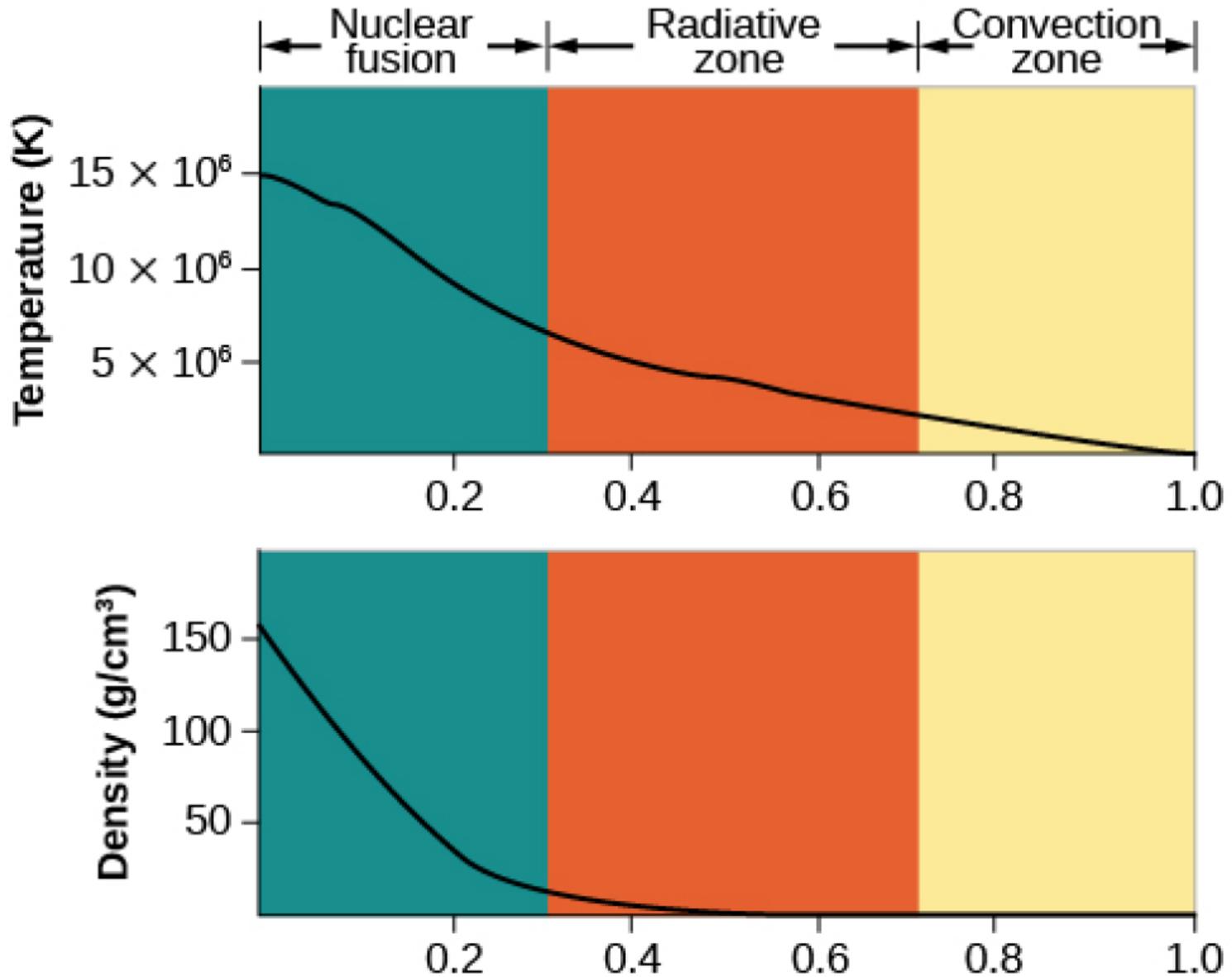
Collaborative Group Activities

► Exercises



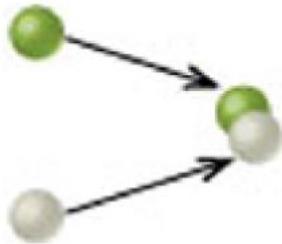


Core: very dense, 15 million K



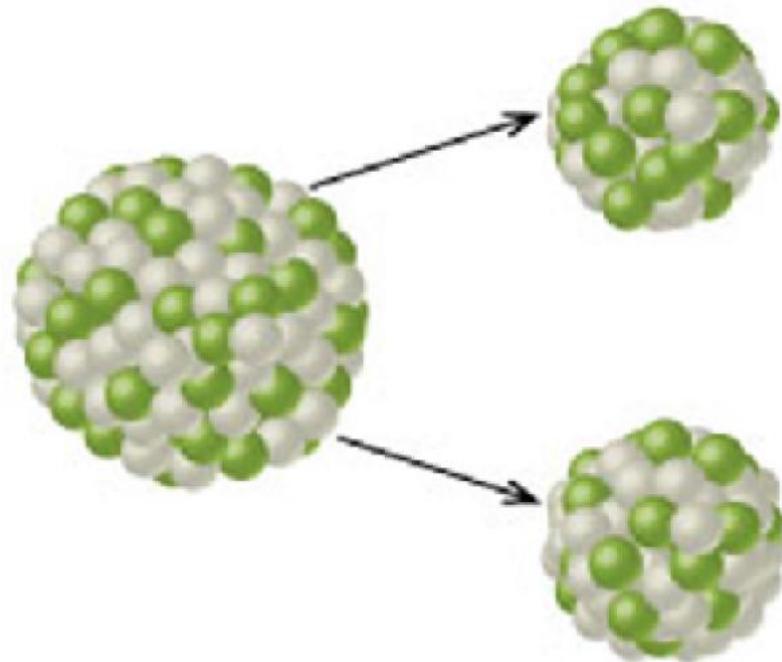
Fusion

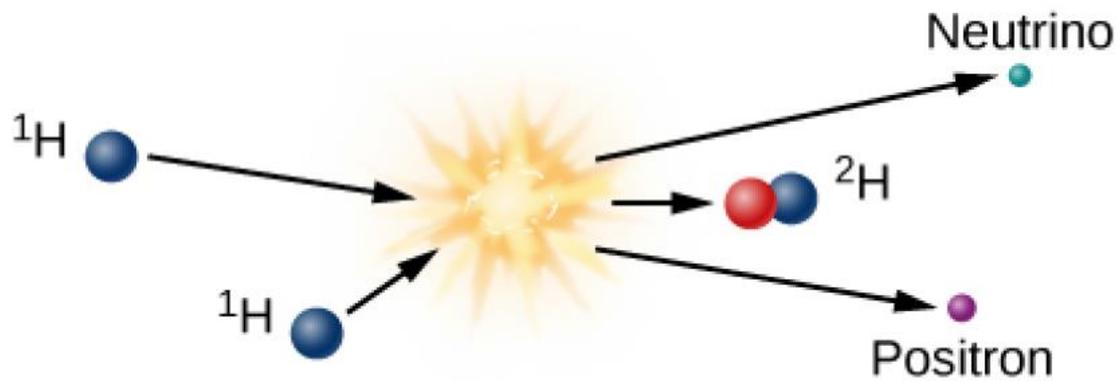
2 light => 1 heavy



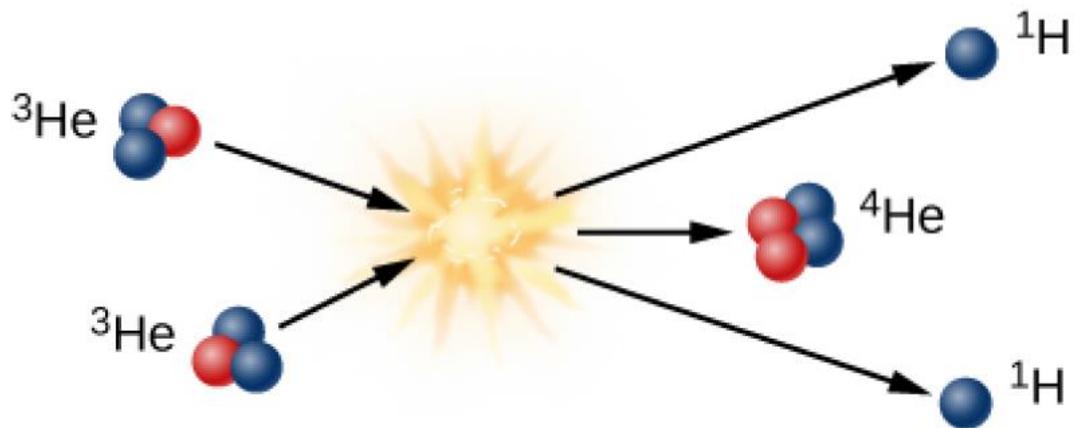
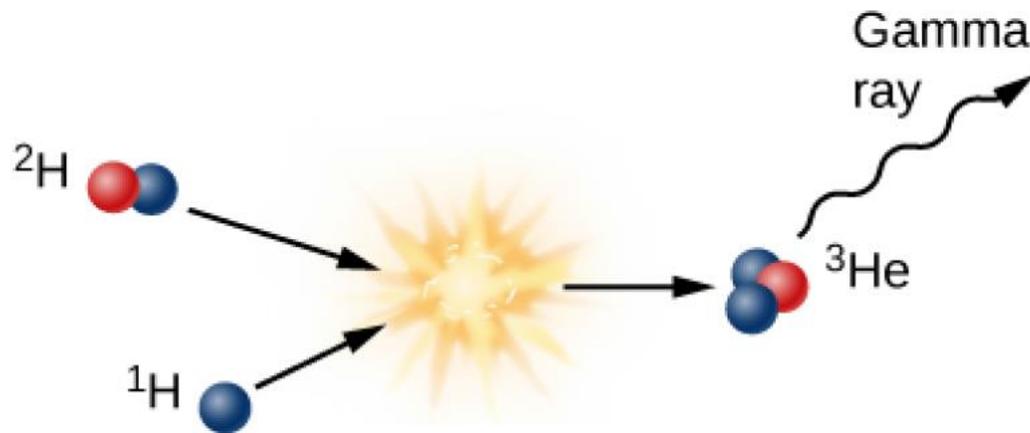
Fission

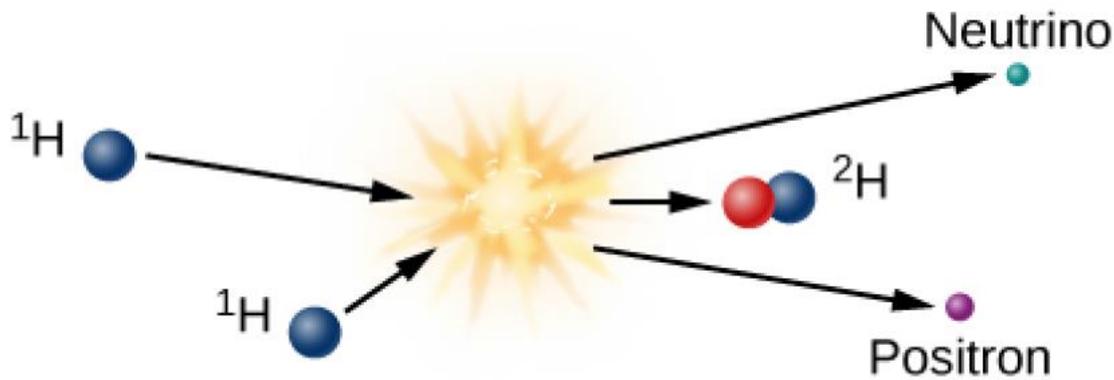
1 heavy => 2 light





Fusion at core
4 Hydrogen atoms
turns into 1 He atom





Fusion at core
 4 Hydrogen atoms
 turns into 1 He atom

Atomic weights

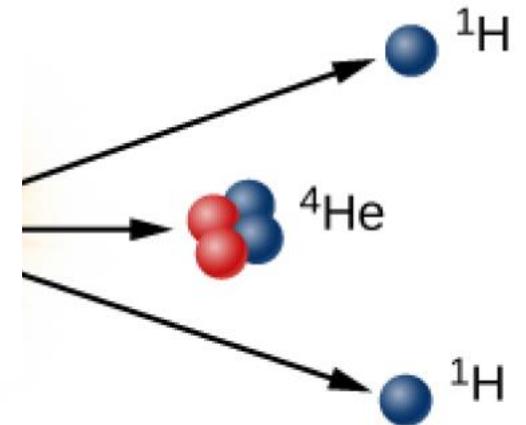
4 H: 4.032
 1 He: 4.003

Lose 0.7% of the mass:
 it turns into energy!

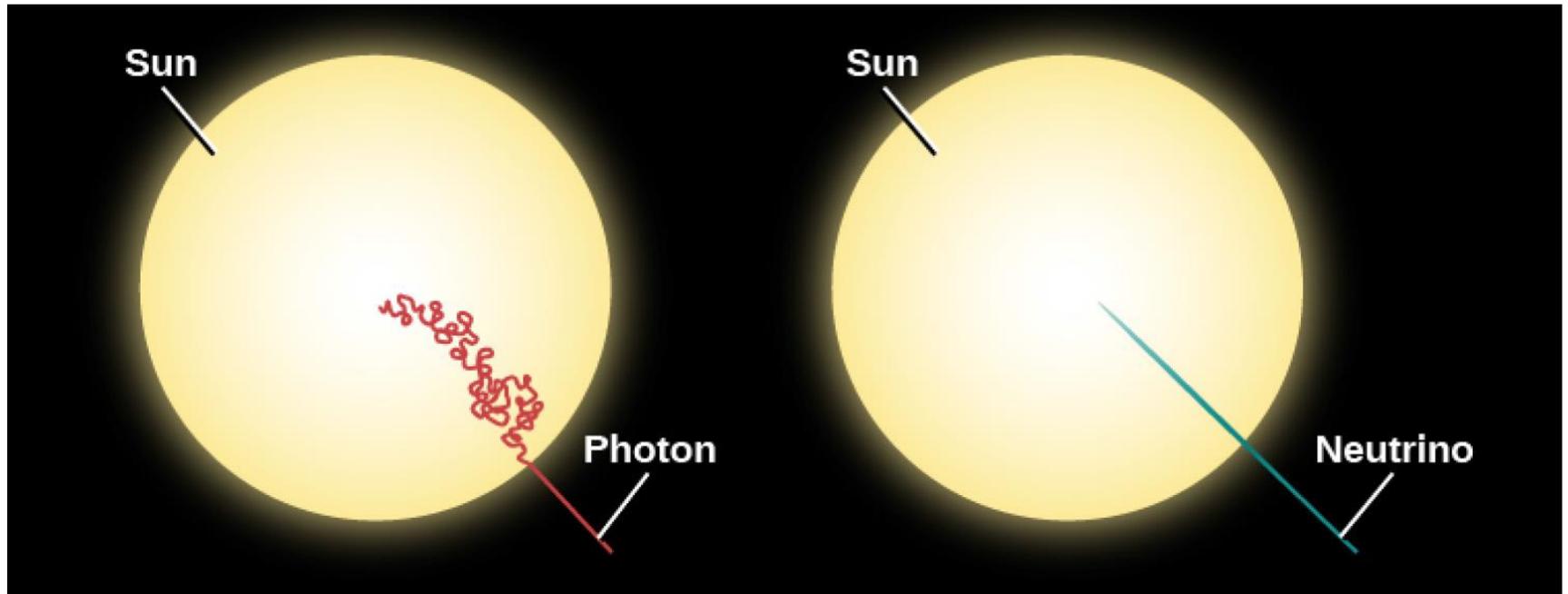
$$E=mc^2$$

(c=speed of light, E=energy,
 m=mass)

na



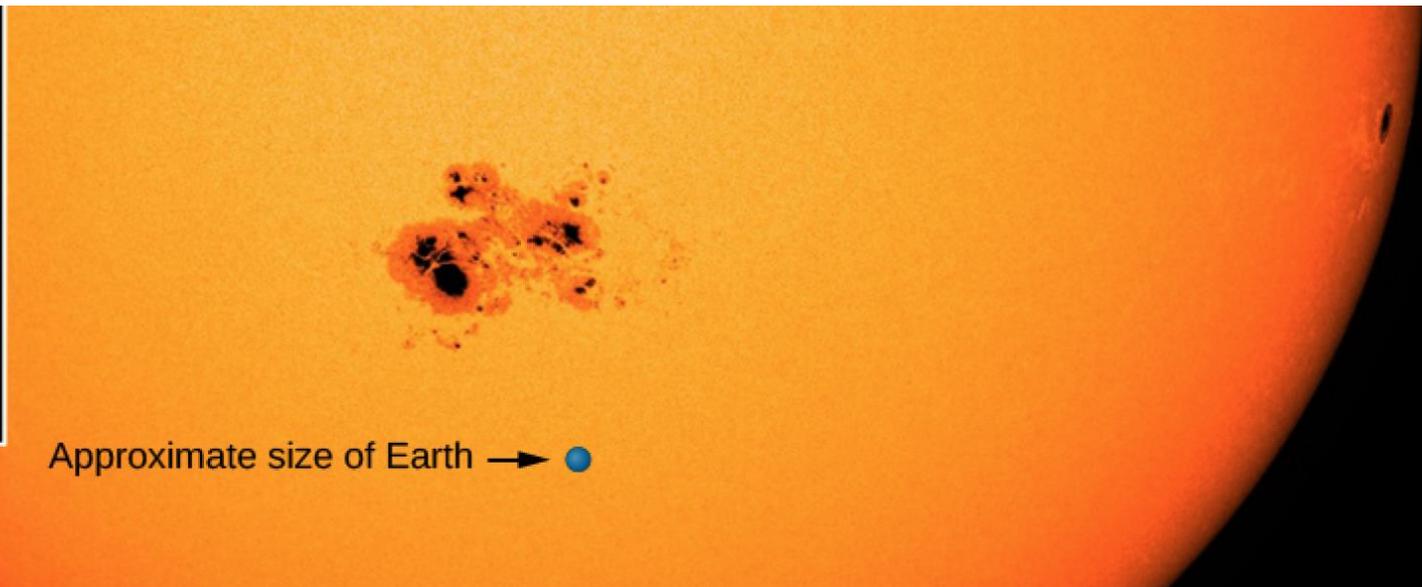
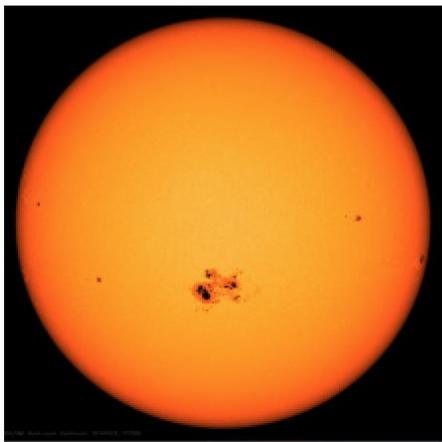
How long does it take energy to escape from the sun's core?



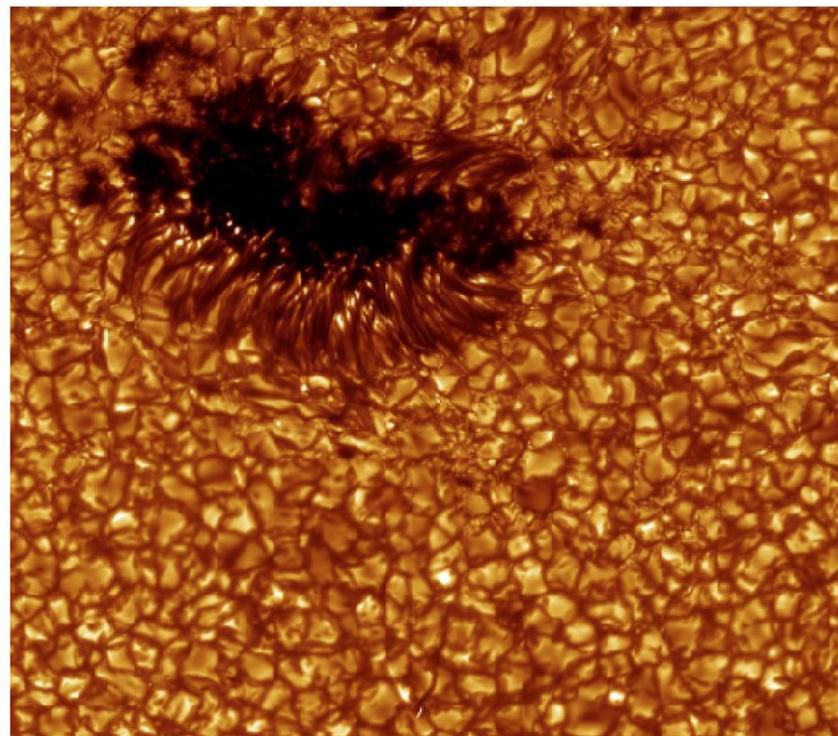
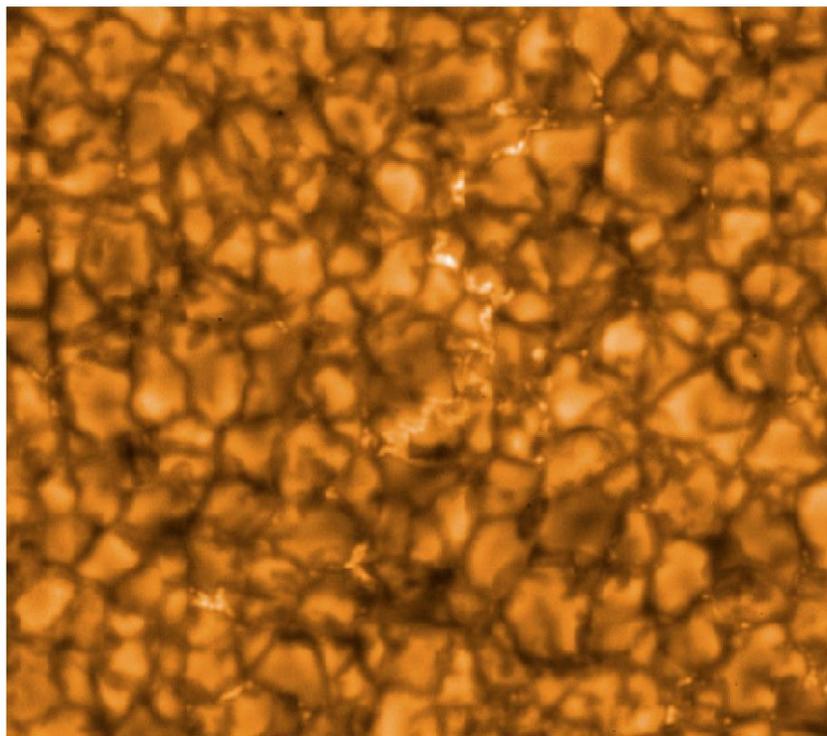
Most energy: 1 million years!

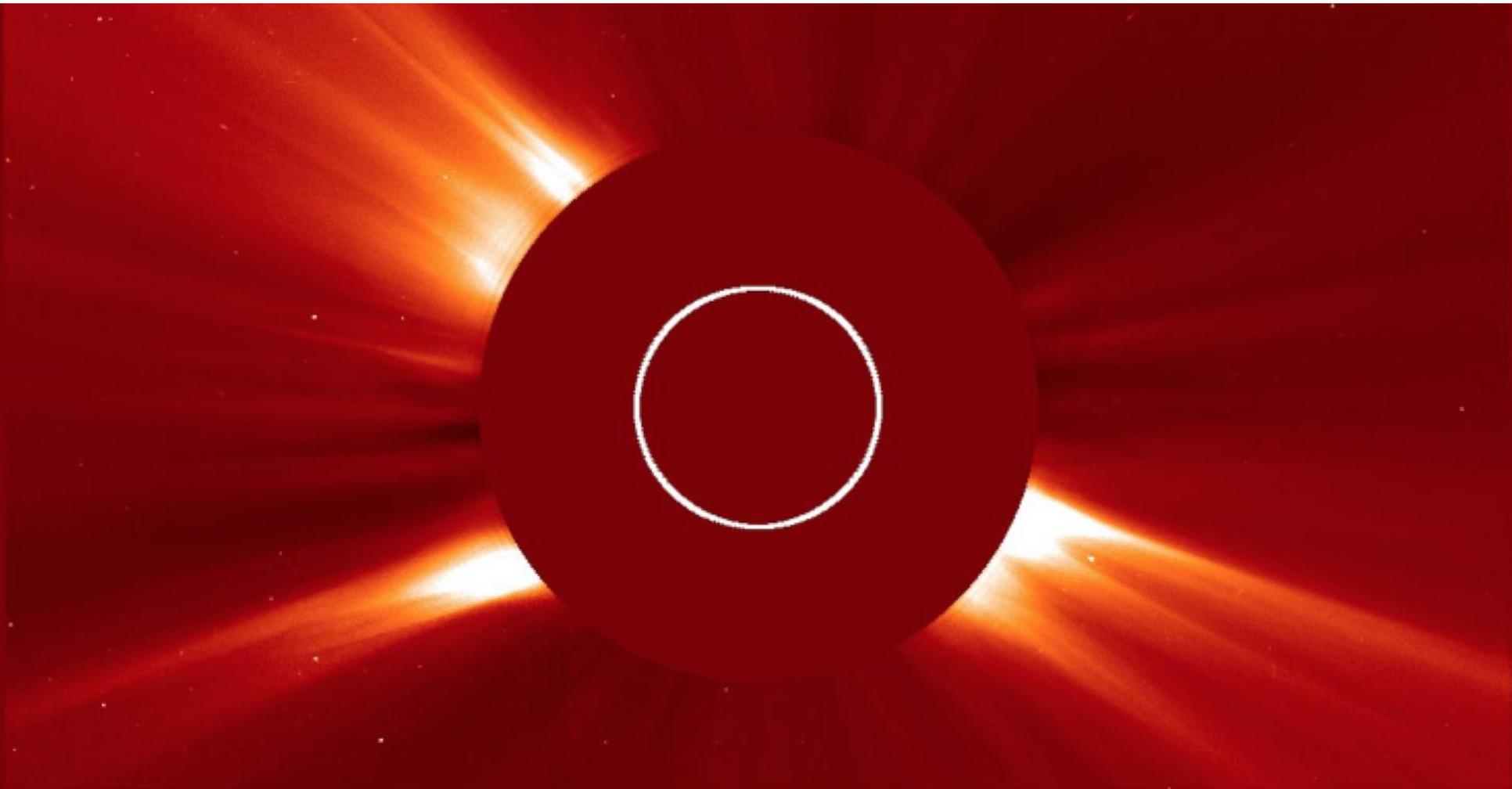
Neutrinos: do not interact with matter, so escapes immediately

Solar neutrino problem: recent Nobel Prize



Approximate size of Earth → ●

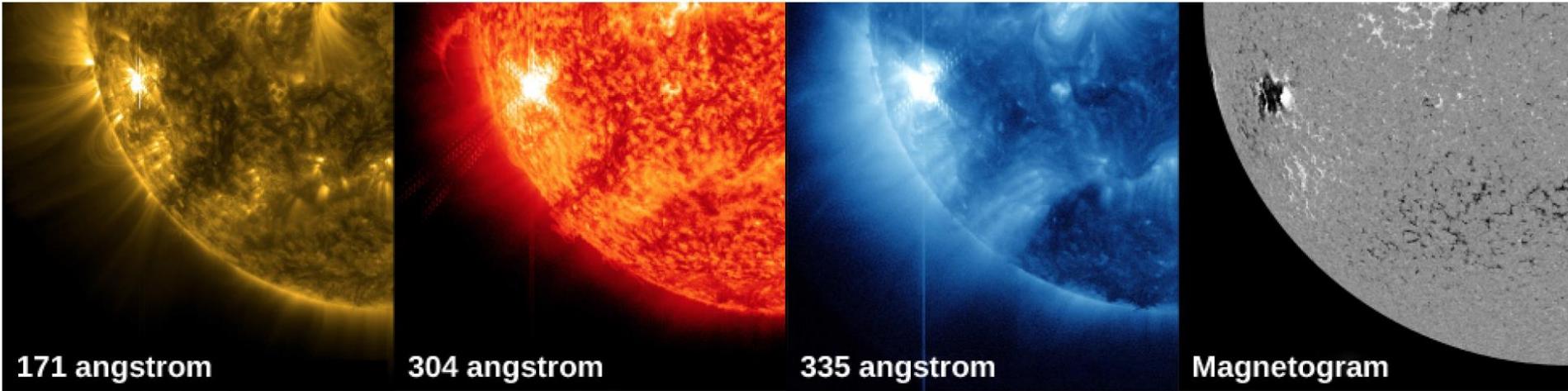






“WHITE SATIN”

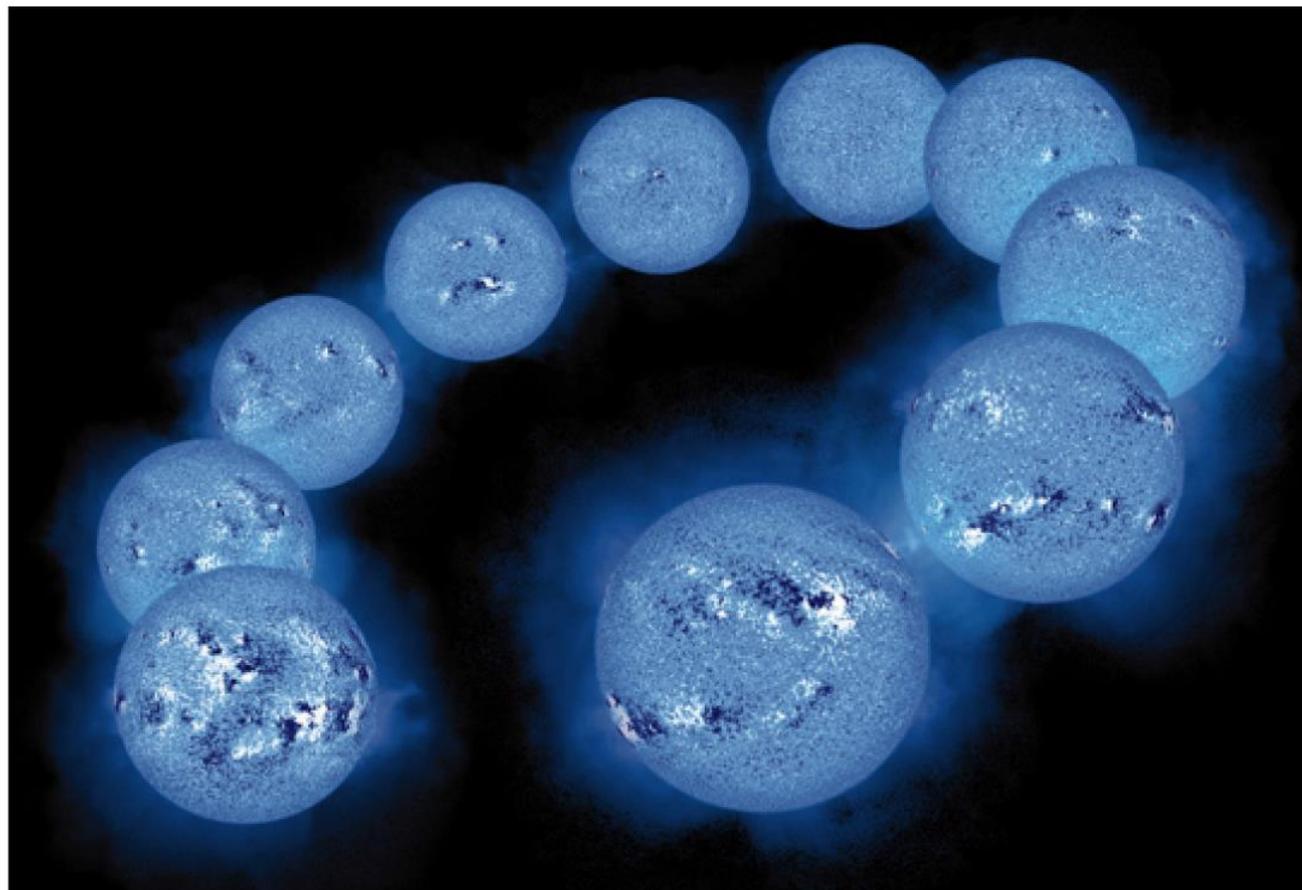
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AURORAHUNTER.COM



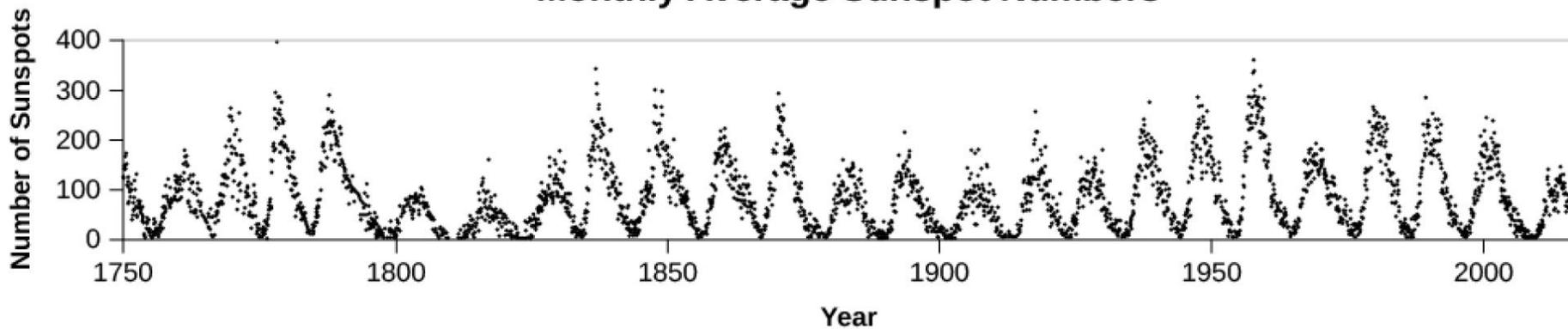
Sun: looks different at different wavelengths:
magnetic activity!

Flares, coronal mass ejections, corona

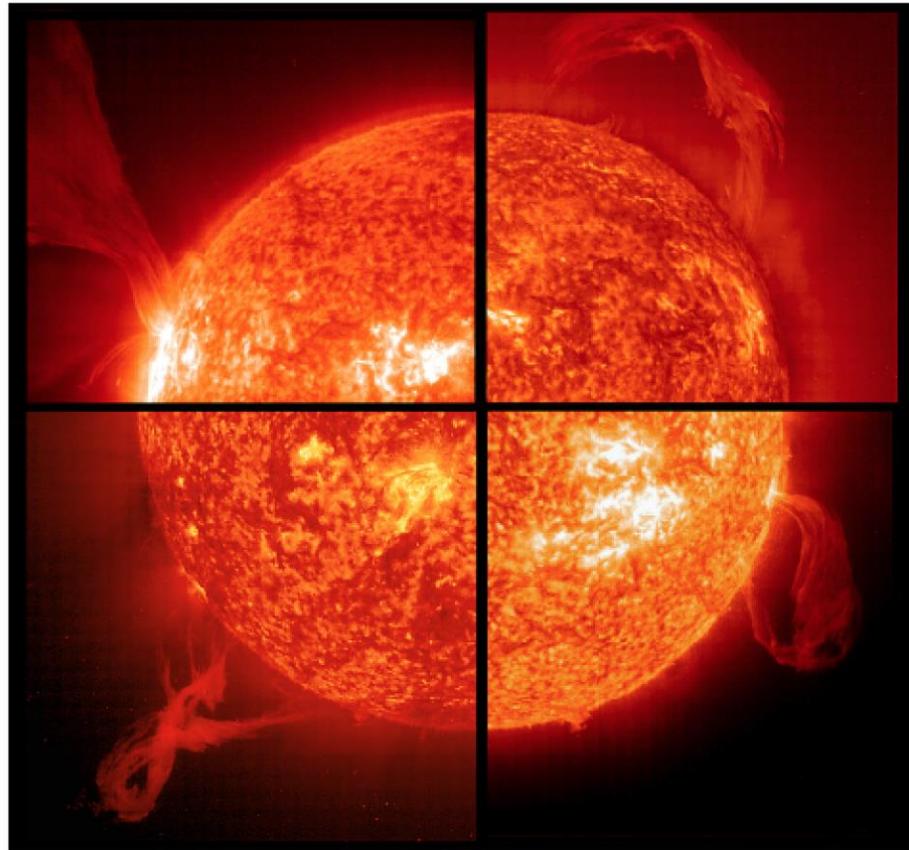
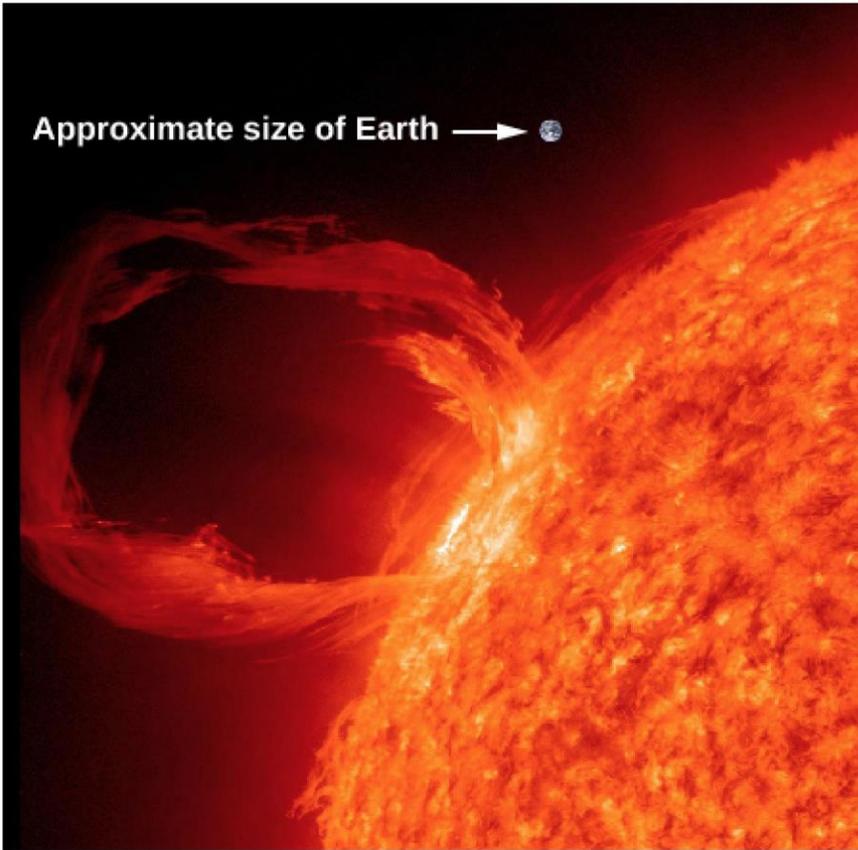
11 year
magnetic cycles



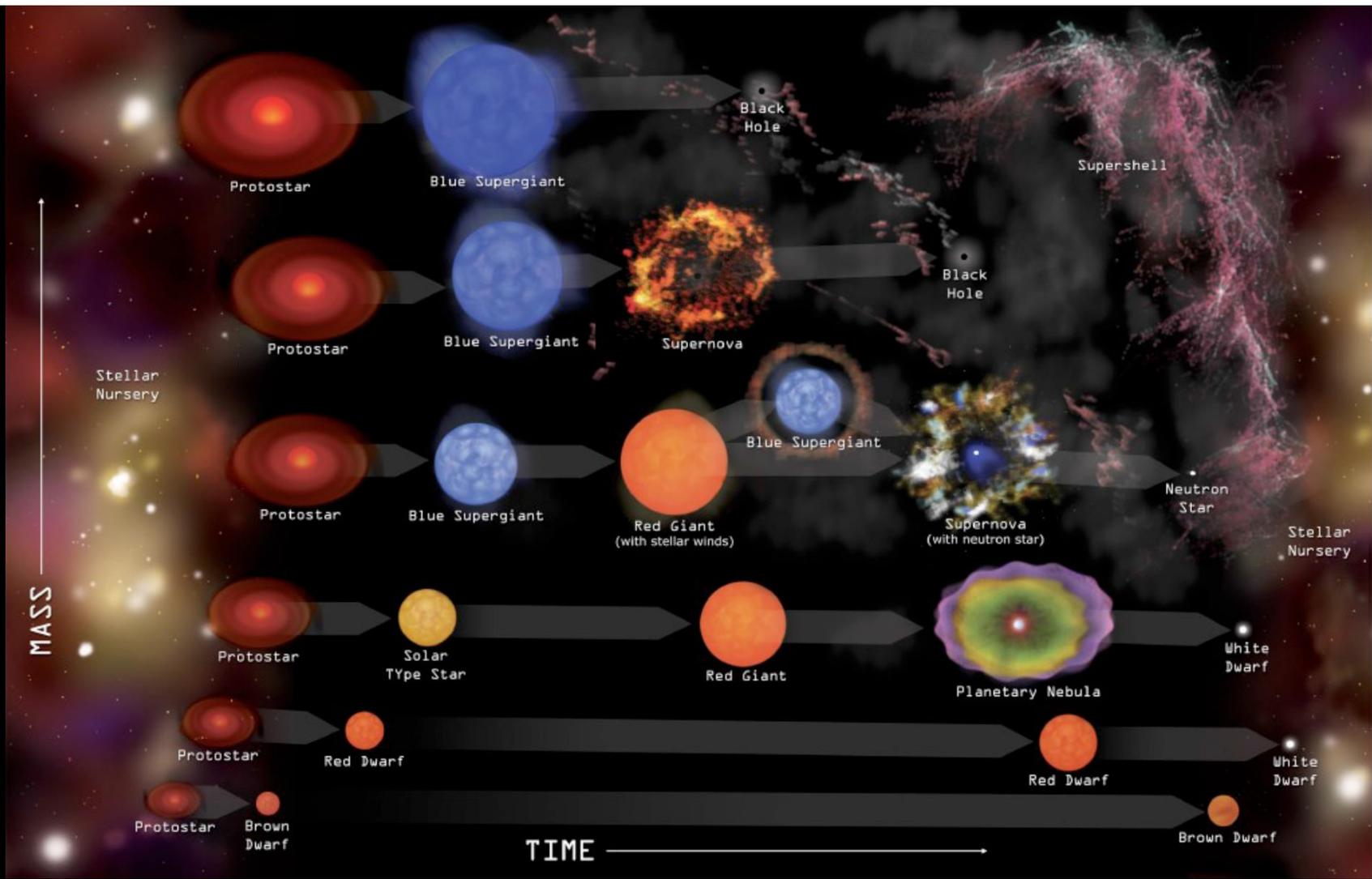
Monthly Average Sunspot Numbers



Approximate size of Earth →







Important concepts for Lecture 2

- HR Diagram: how we understand stars and stellar evolution
 - Apparent magnitude: the magnitude we see
 - Absolute magnitude (luminosity): corrected for distance
 - x-axis: temperature (measured from spectra or colors)
- Main sequence: where stars spend most of their life
 - H burning
- After H burning: stars become giants
 - Core shrinks until He burning
- Fusion: lighter elements => heavier elements
 - Difference in mass converted to energy
 - Occurs in very hot core
- Sun: we see the cool photosphere in optical light
 - Hot corona in X-rays