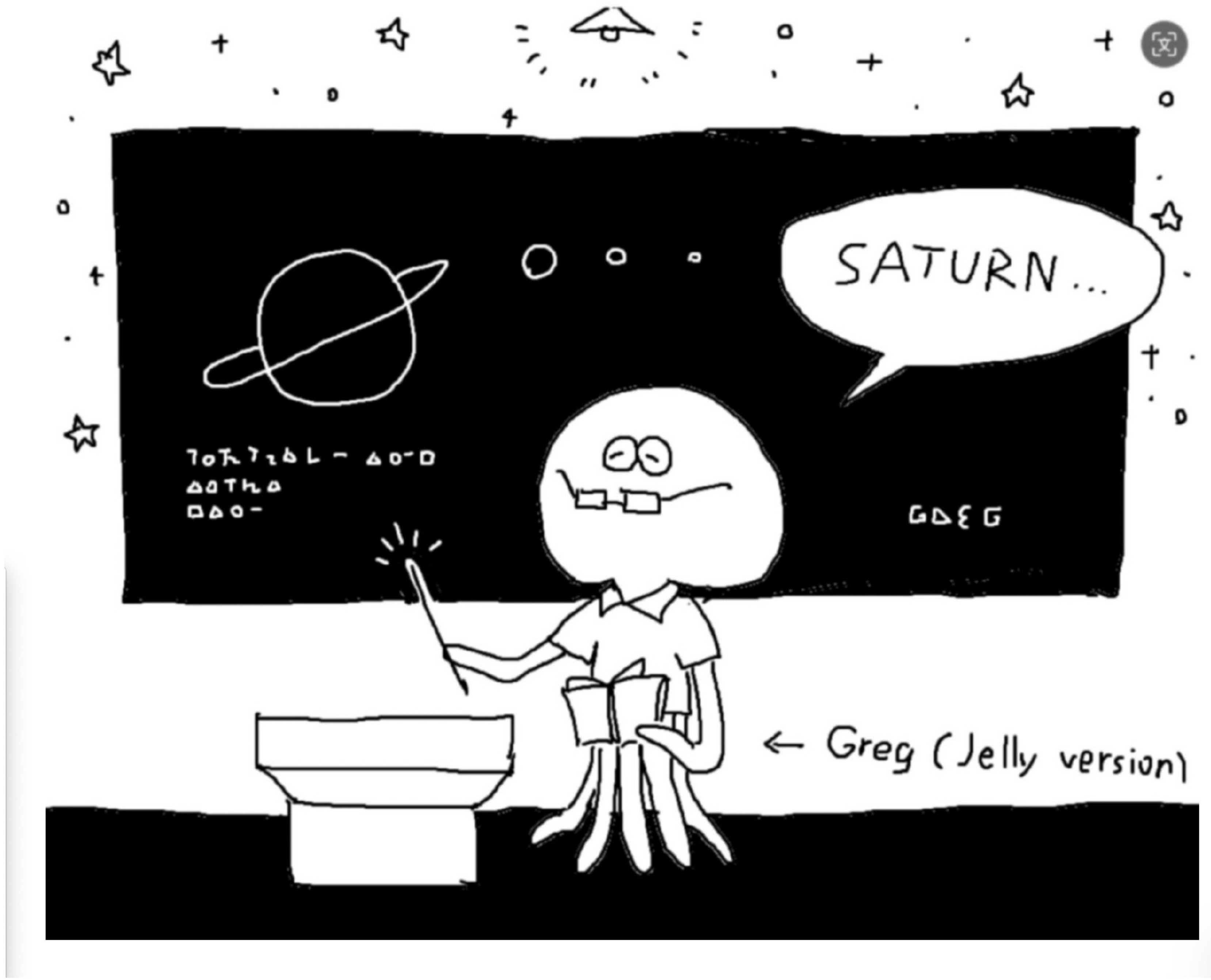
Stars:
The Building Blocks of the Universe

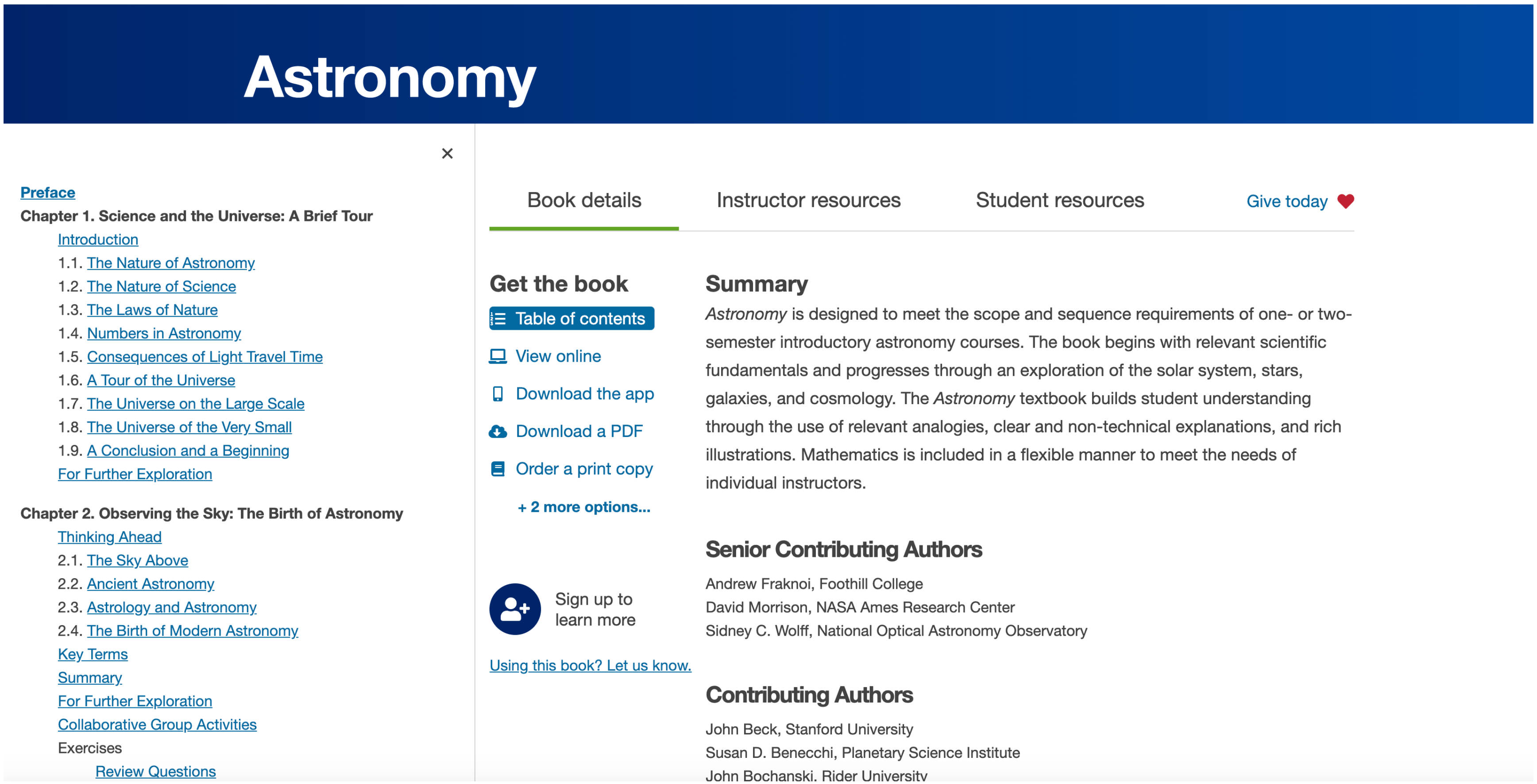
Homeworks and lectures

- wechat: circulating vidos of lectures, slides, homework
- Introduction: grades mailed back to most of you
  - ”boring” things about you are usually more interesting!
  - 30% of you said that you are shy/introverts!
  - Grades not yet returned if submitted after 9.18 at 1pm
  - If you did not receive a grade, email me: gjh1@pku.edu.cn
- Homework 1: due Thurs, Oct. 10, 1:00pm
  - Some files to be circulated by wechat and at github
  - https://gherczeg.github.io/modernastronomy/


SATURN...
← Greg (Jelly version)

openstax “textbook”

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



Optional reading

Chapter 5. Radiation and Spectra

Chapter 19. Celestial Distances

Chapter 17. Analyzing Starlight

ter 18. The Stars: A Celestial Census

Homework

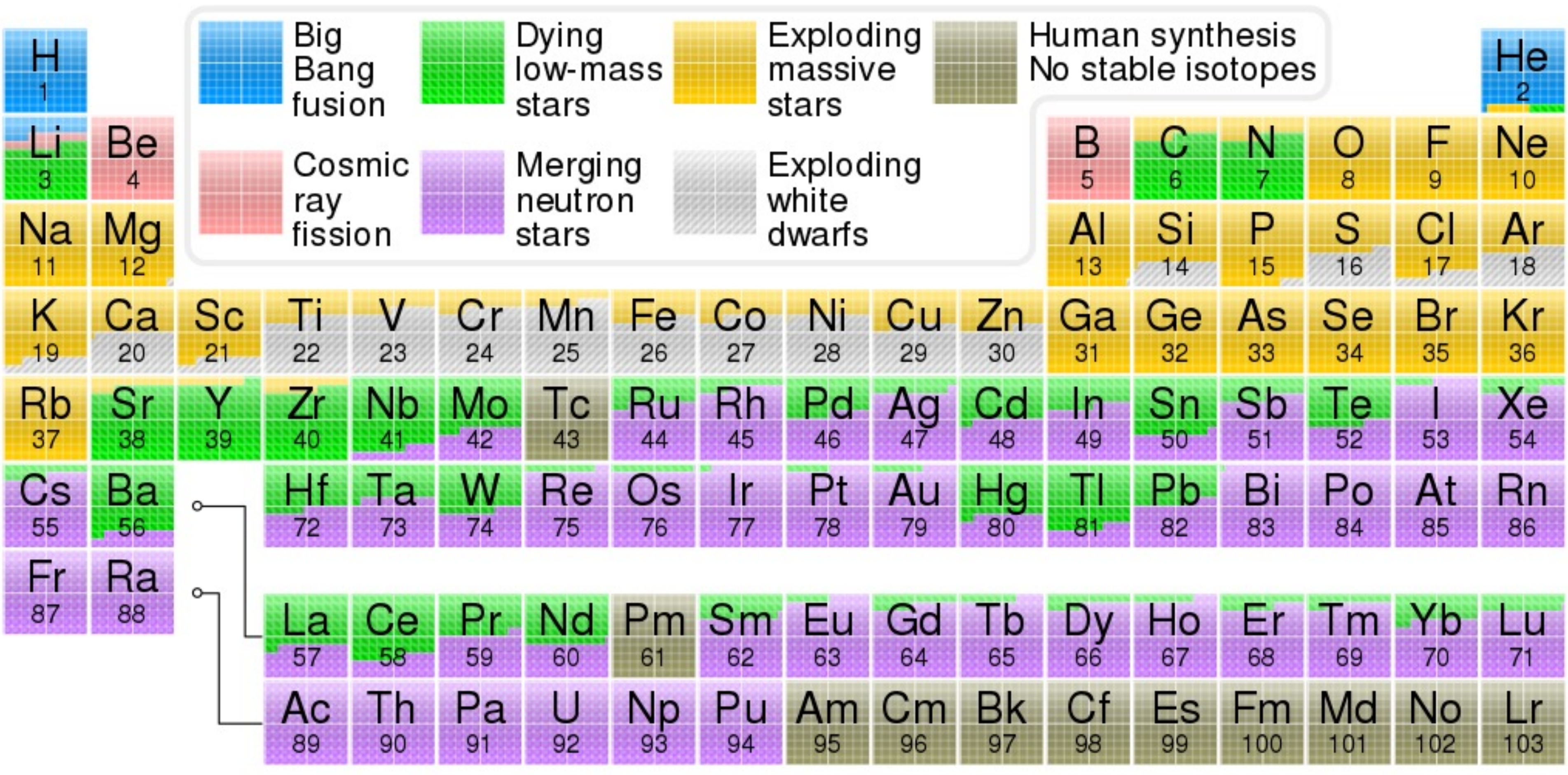
- Question 1: Space is big!
  - part b: calculate the distance, then convert to something (for example, Shanghai)
  - part d: remember scientific notation!
- Question 2: star clusters
  - Look up "HR diagrams"
- Question 3: Gaia and star clusters
  - Hard! Not everyone will be able to get through all 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!**

Bring questions to class next week!

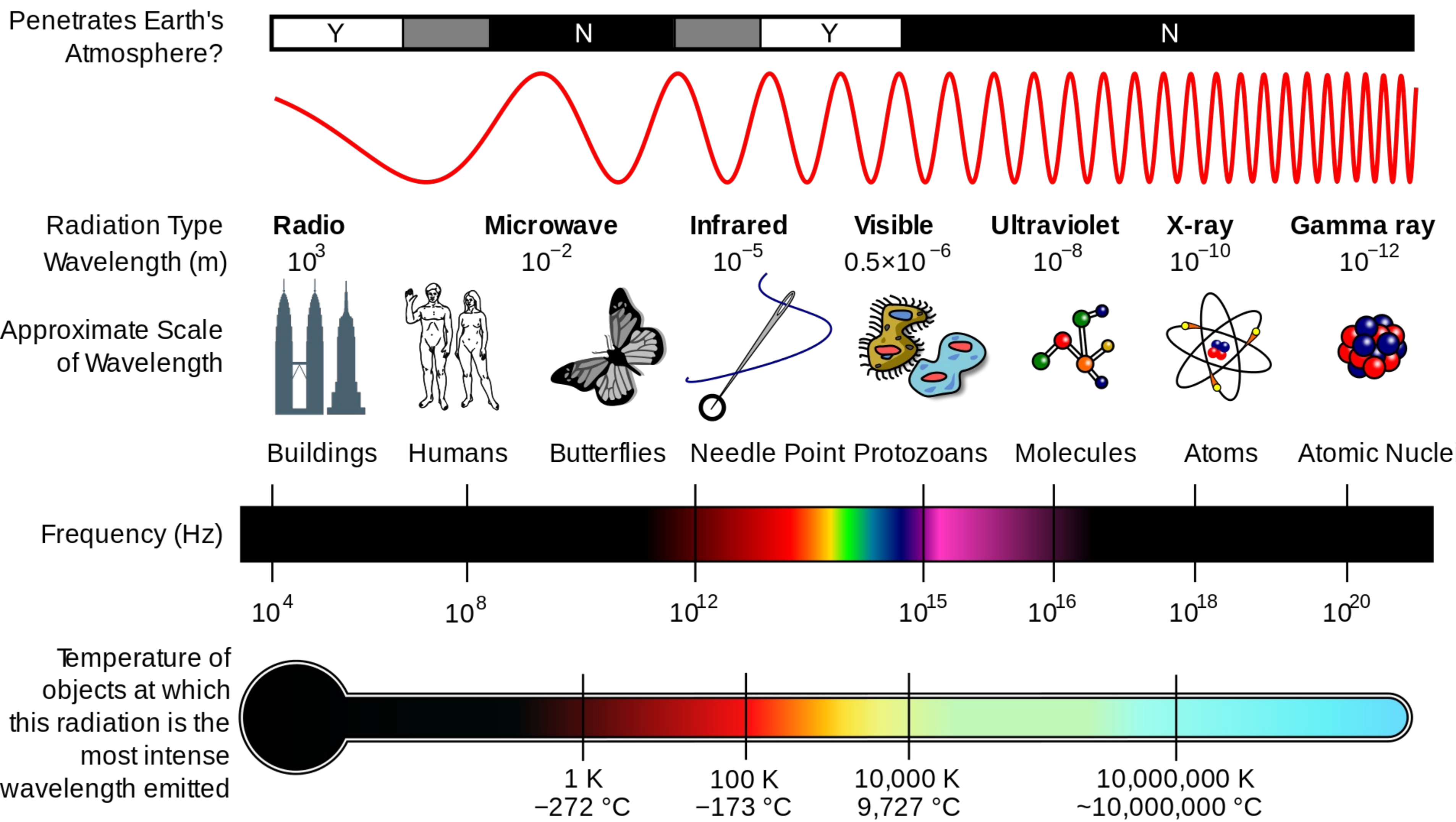
The Cosmically Abundant Elements

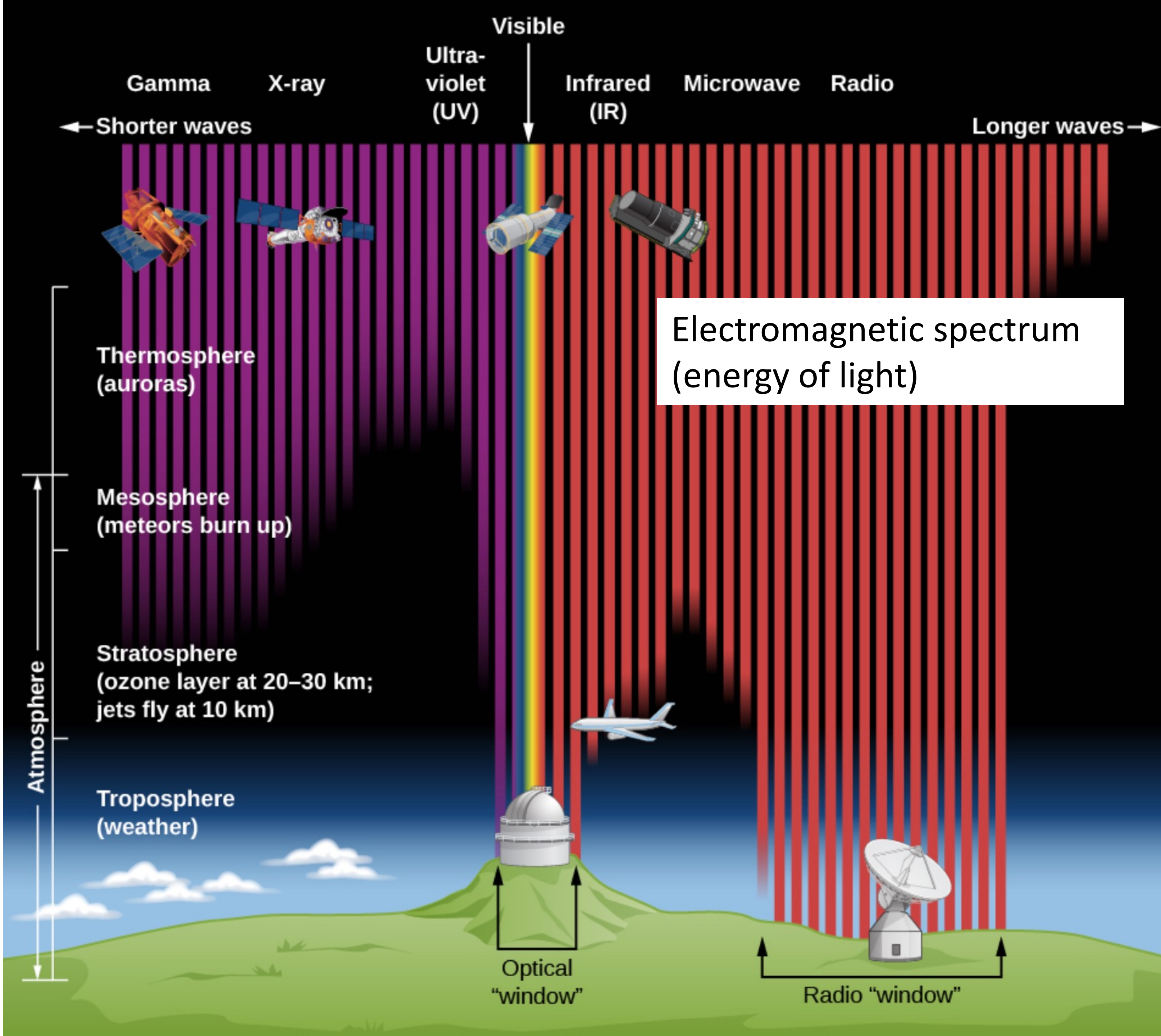
Element[1]	Symbol	Number of Atoms per Million Hydrogen Atoms
Hydrogen	H	1,000,000
Helium	He	80,000
Carbon	C	450
Nitrogen	N	92
Oxygen	O	740
Neon	Ne	130
Magnesium	Mg	40
Silicon	Si	37
Sulfur	S	19
Iron	Fe	32



Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

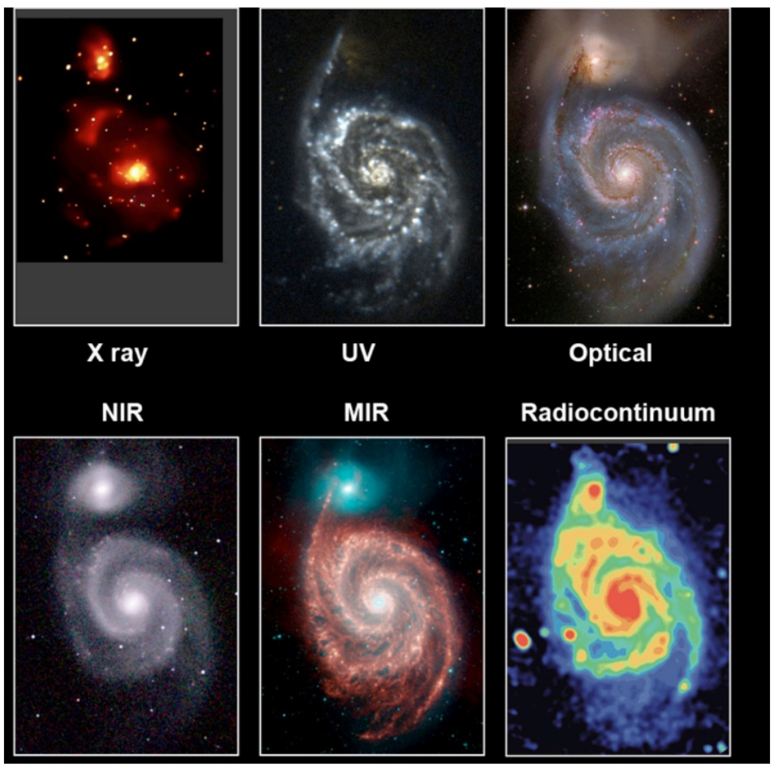
Electromagnetic spectrum (energy of light)

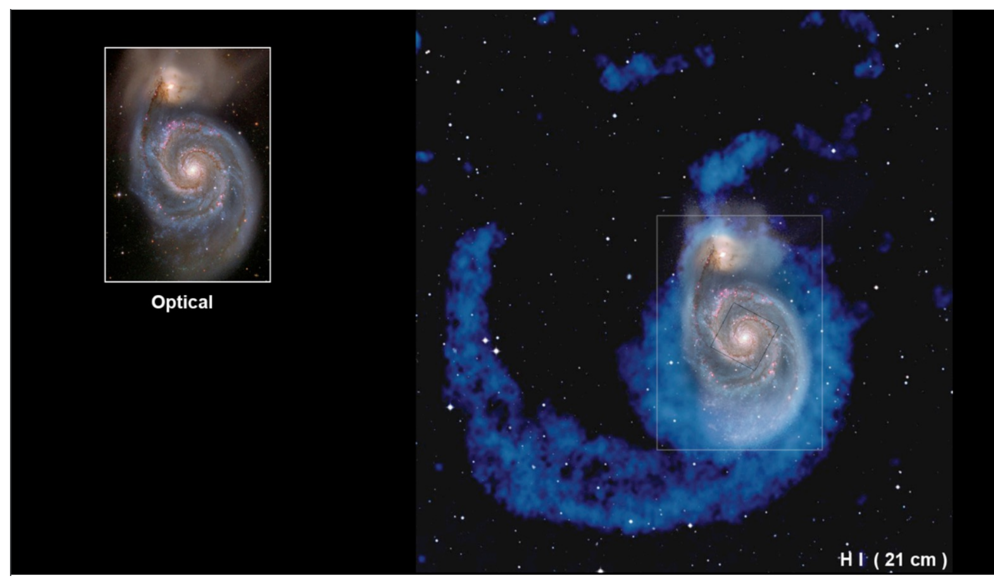


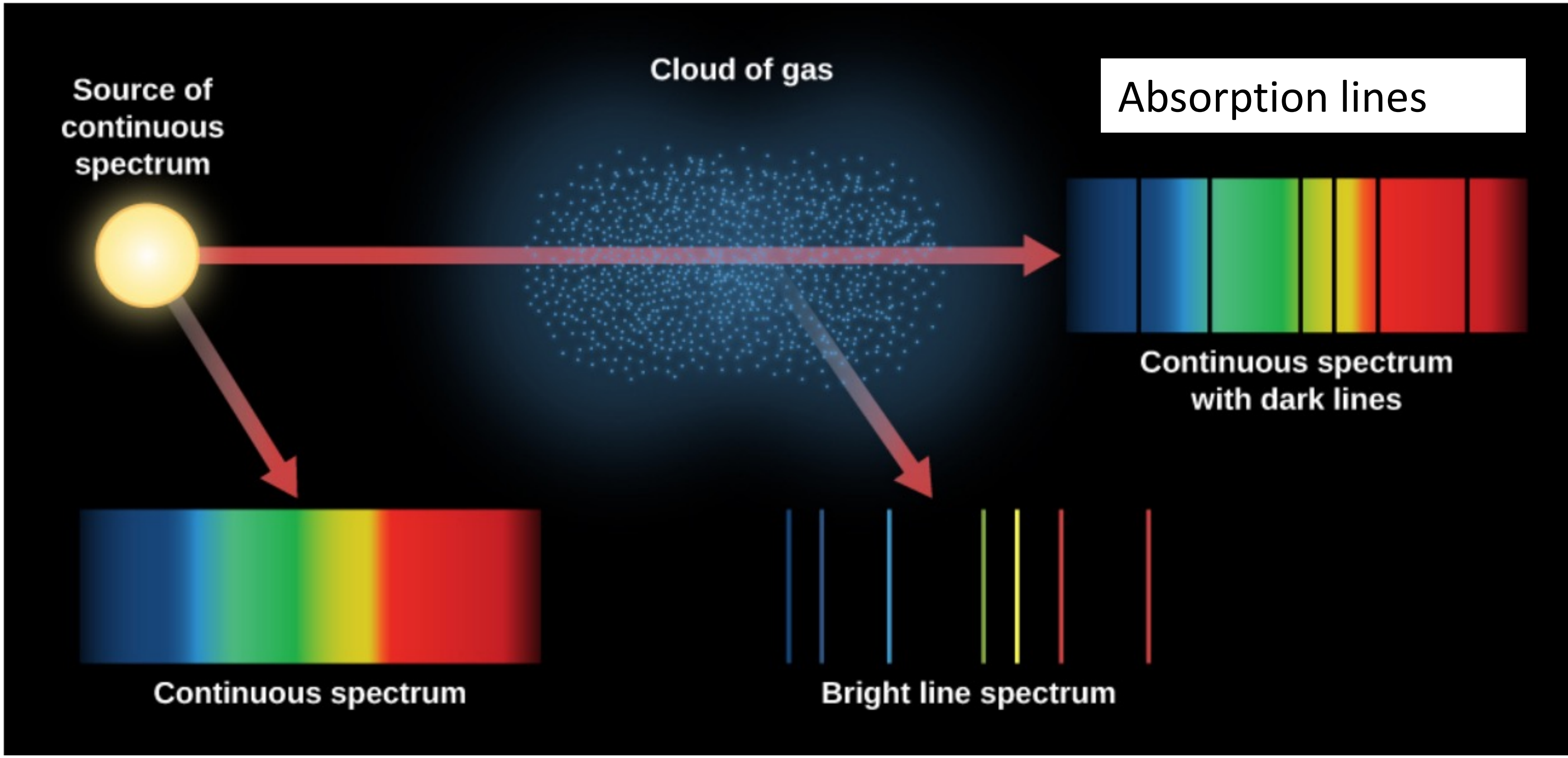

Visible
Gamma
X-ray
Ultra-
violet
(UV)
Infrared
(IR)
Microwave
Radio
Shorter waves
Longer waves
Electromagnetic spectrum
(energy of light)
Thermosphere
(auroras)
Mesosphere
(meteors burn up)
Stratosphere
(ozone layer at 20–30 km;
jets fly at 10 km)
Troposphere
(weather)
Atmosphere
Optical
“window”
Radio “window”

X-ray ultraviolet optical infrared radio

short wavelength —— long wavelength







Emission lines


WWW.NEWS.CN


天河
天河高性能计算机系统
WWW.NEWS.CN

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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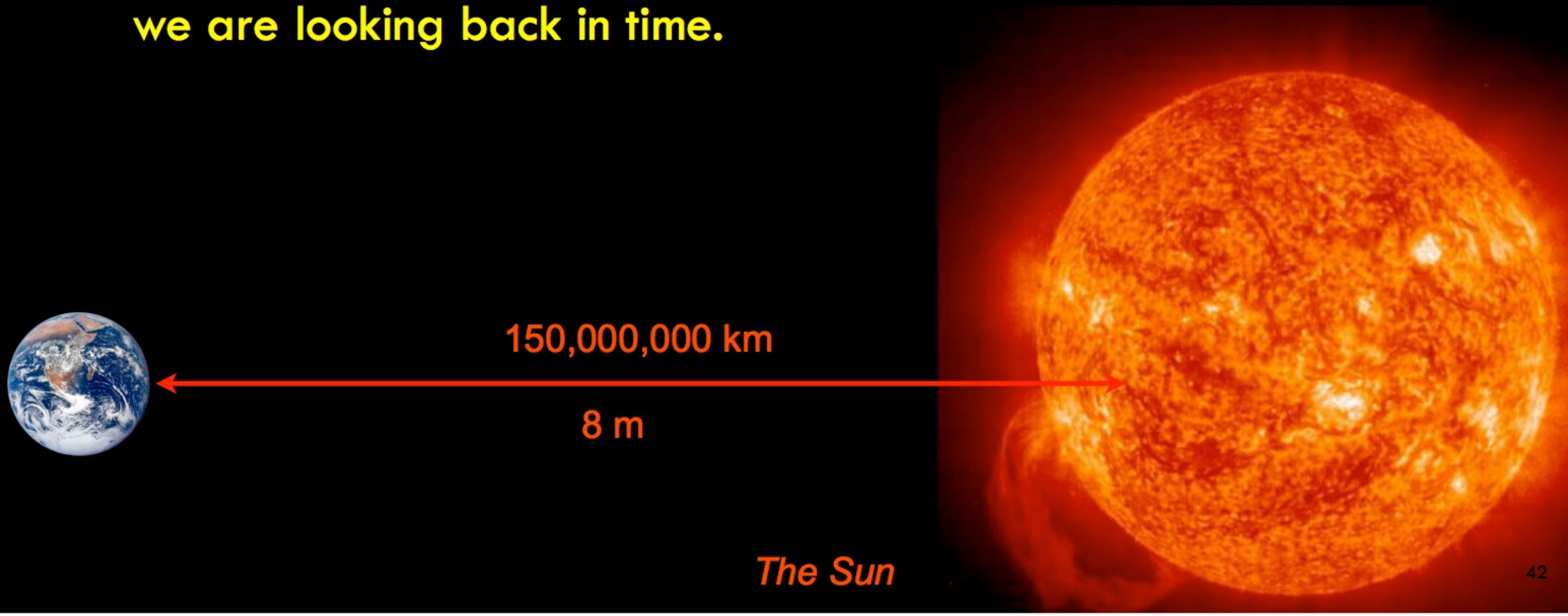

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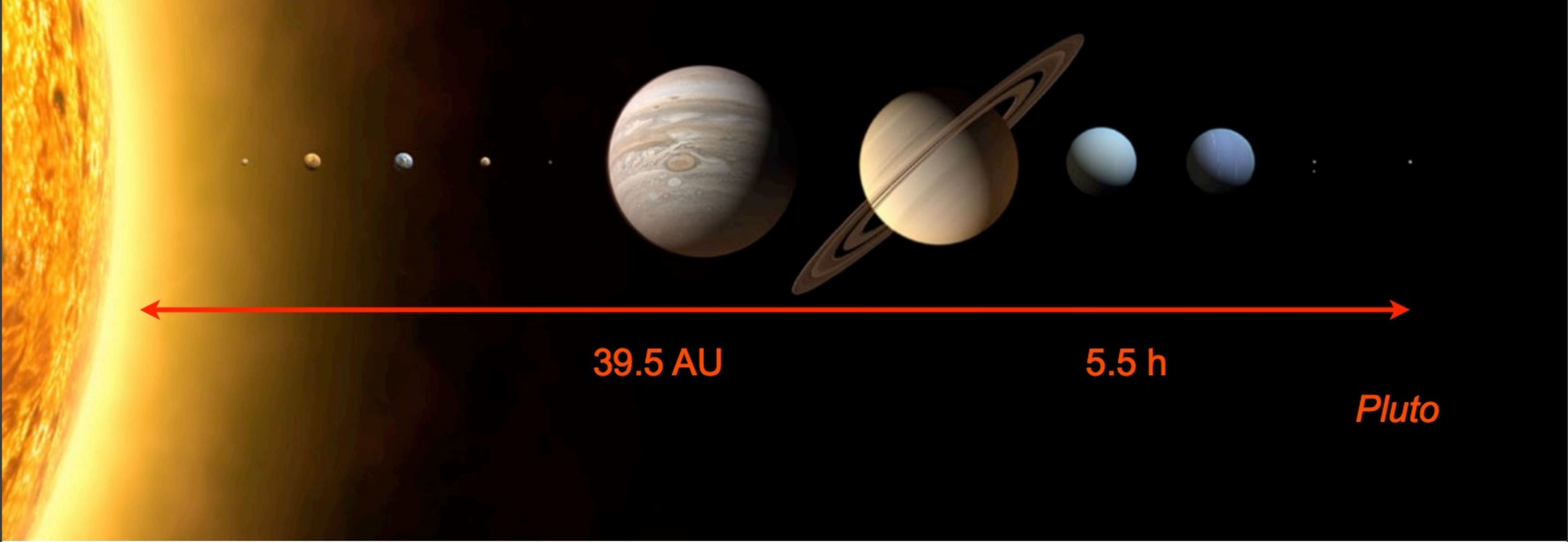

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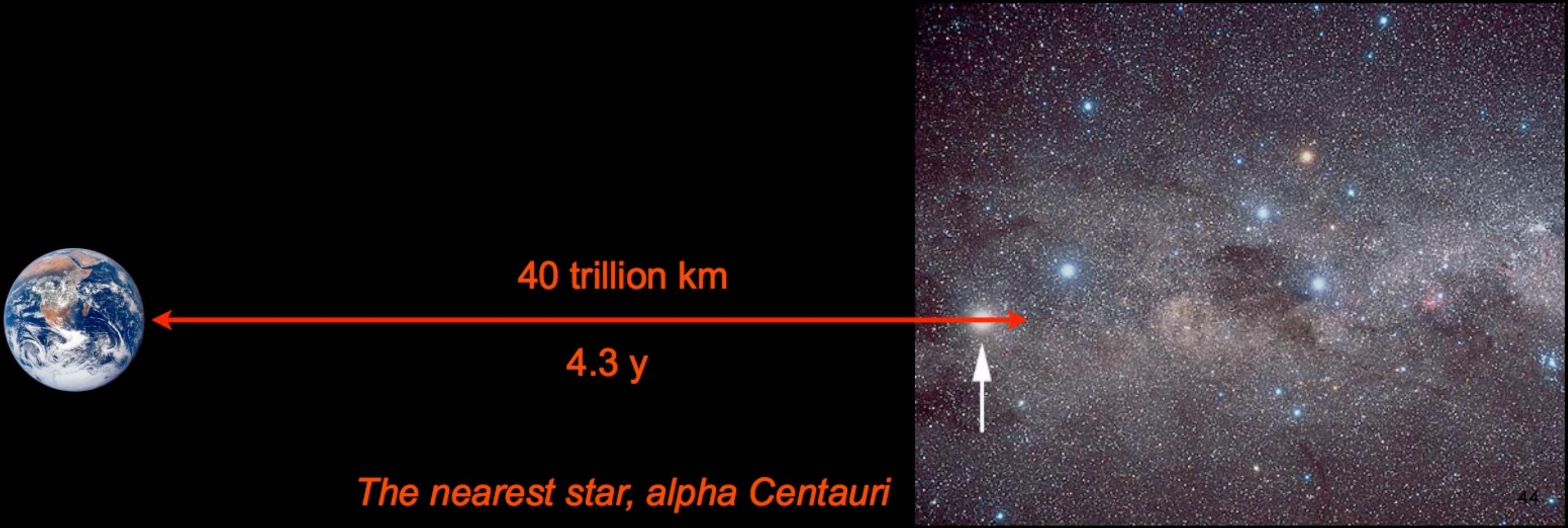

The nearest star, alpha Centauri

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

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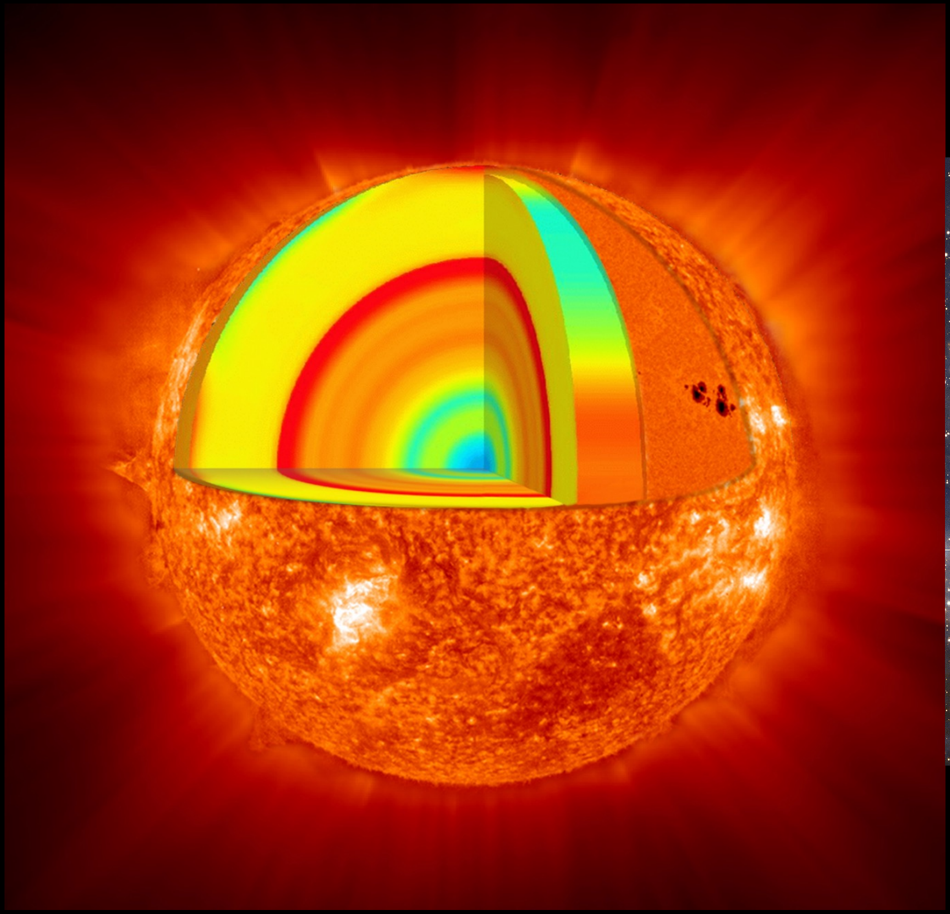
Important numbers

- Astronomical Unit (AU): 1.5×10^{13} cm
  - Sun to Earth
- Speed of light: 3×10^{5} km/s
- Light year: 10^{18} cm

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

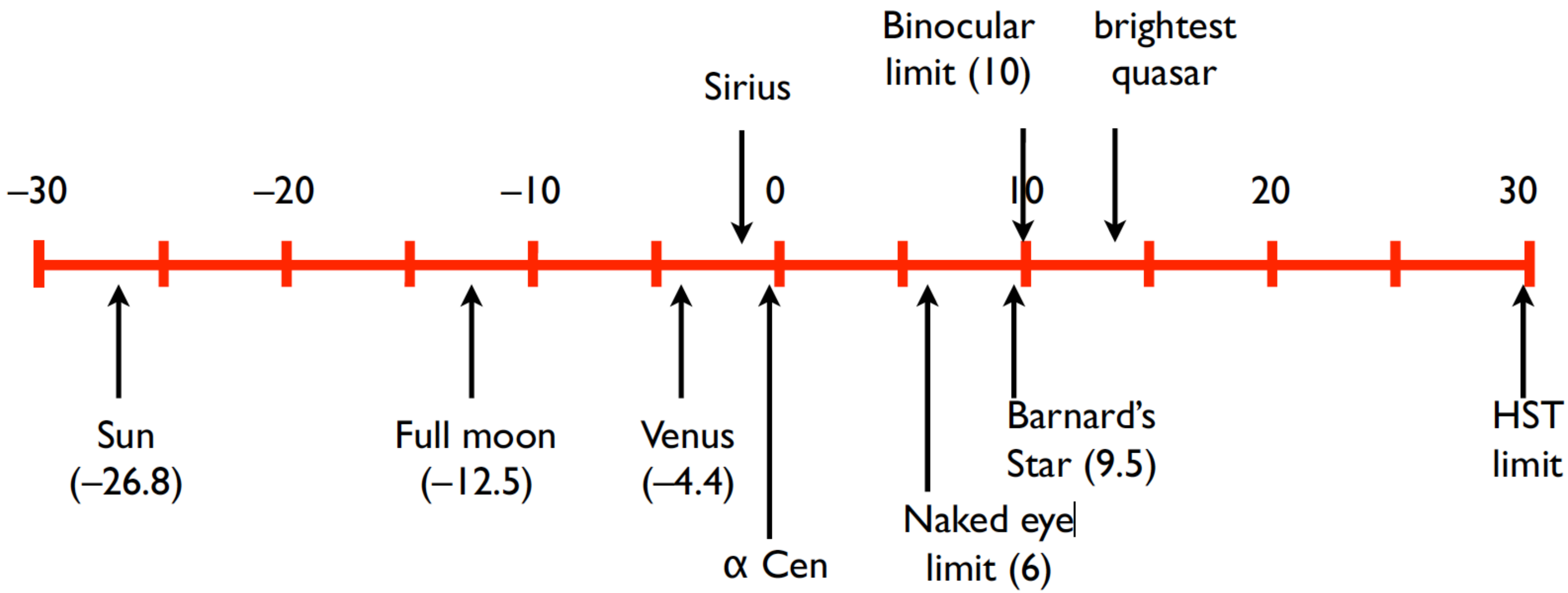

Galaxy:
Almost all light from stars

How to describe a star?
Easy or hard to measure? Raise your hands

- Temperature:
- Radius:
- Composition:
- Rotation:
- Mass:
- Age:
- Density:
- Does it have planets?:
- Brightness:
- Luminosity:

Magnitudes (how bright are stars)

Reverse sytem: 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!

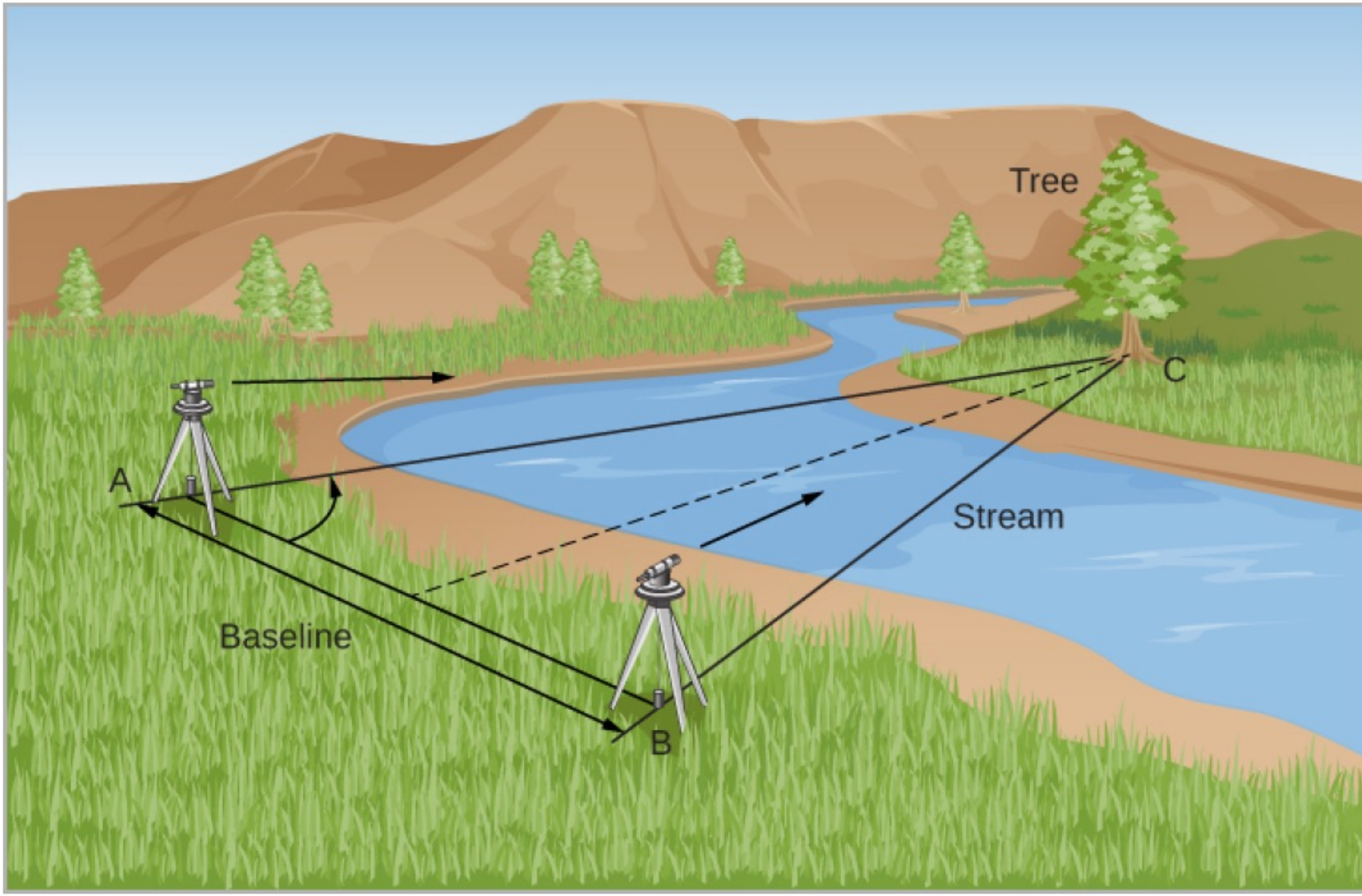
Distance is usually uncertain

Reverse sytem: negative magnitude brighter

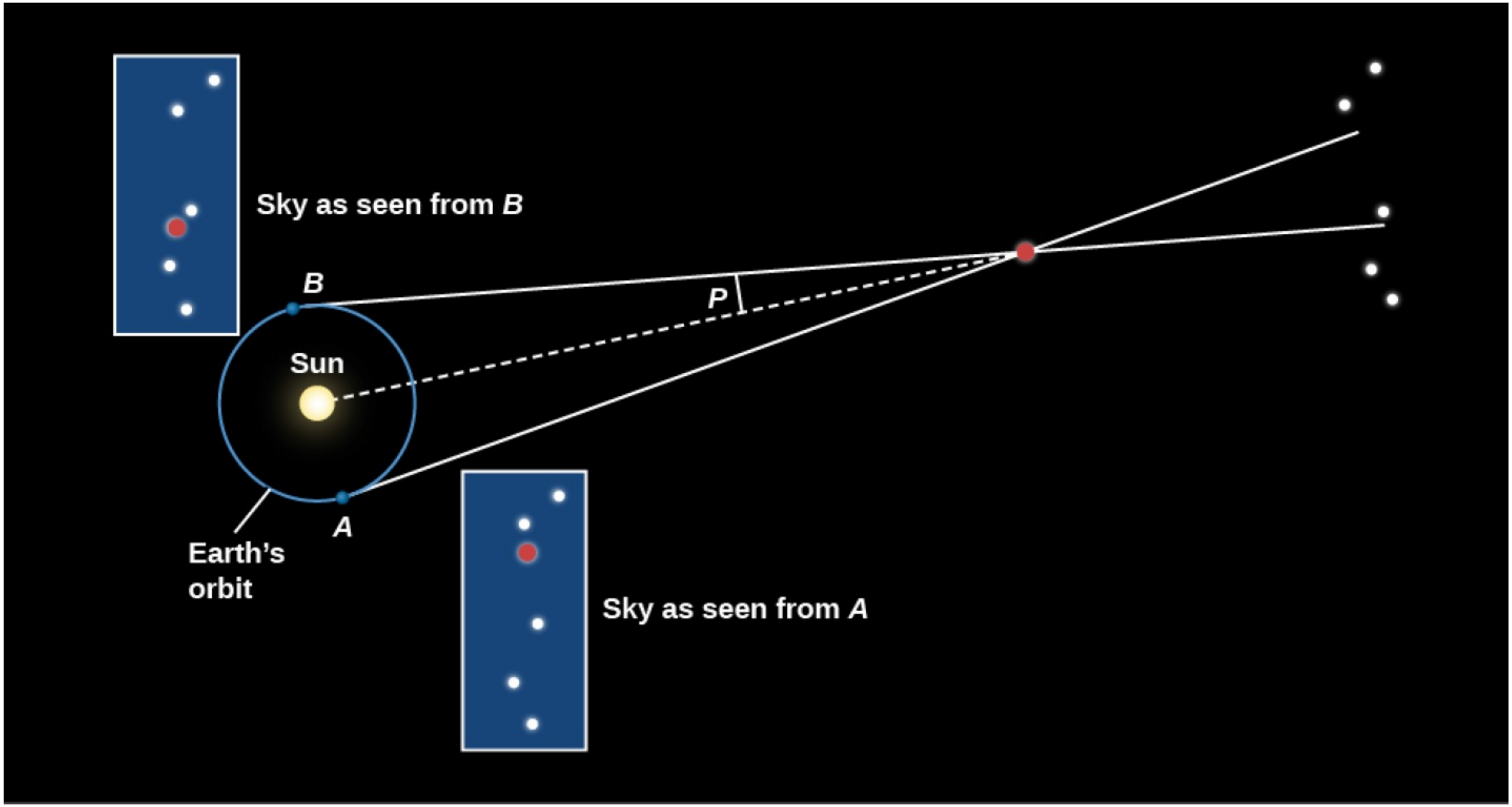
Other galaxies: all stars at same distance!
[challenge is distance to each galaxy]

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

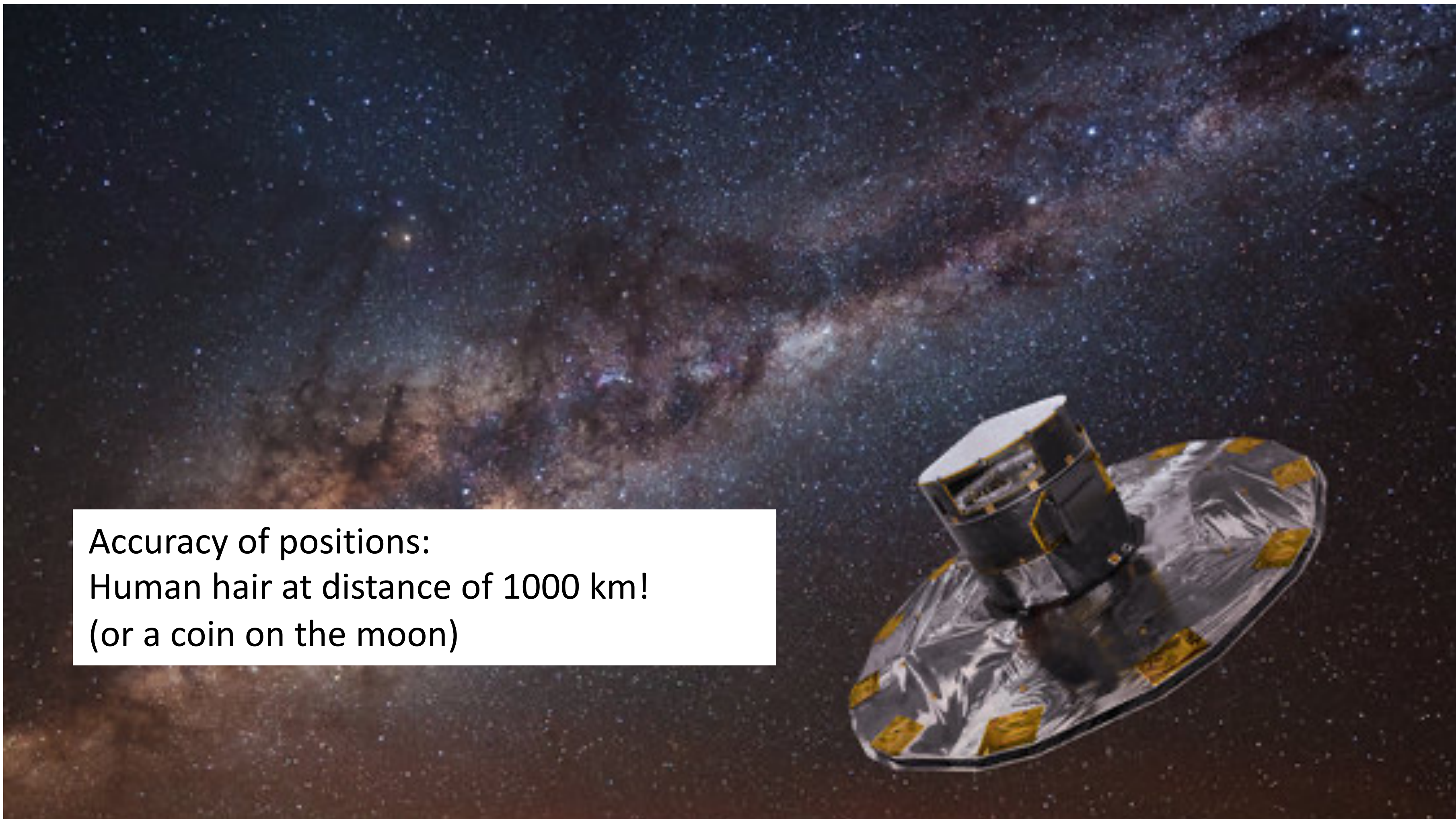
Distance: parallax



Distance: parallax
Very hard to measure



Gaia satellite:
parallax distances to ~1 billion stars!



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]	Decli
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
	α Centauri A (HD 128620)	4.3650 ±0.0068	G2V[5]	0.01 #	4.38	$14^h 39^m 36.5^s$	−60
	α Centauri B (HD 128621)		K1V[5]	1.34 #	5.71	$14^h 39^m 35.1^s$	−60
Barnard's Star (BD+04°3561a)		5.9577 ±0.0032	M4.0Ve	9.53	13.22	$17^h 57^m 48.5^s$	+04
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
	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°
Wolf 359 (CN Leonis)		7.856 ±0.031	M6.0V[5]	13.44	16.55	$10^h 56^m 29.2^s$	+07
Lalande 21185 (BD+36°2147)		8.307 ±0.014	M2.0V[5]	7.47	10.44	$11^h 03^m 20.2^s$	+35

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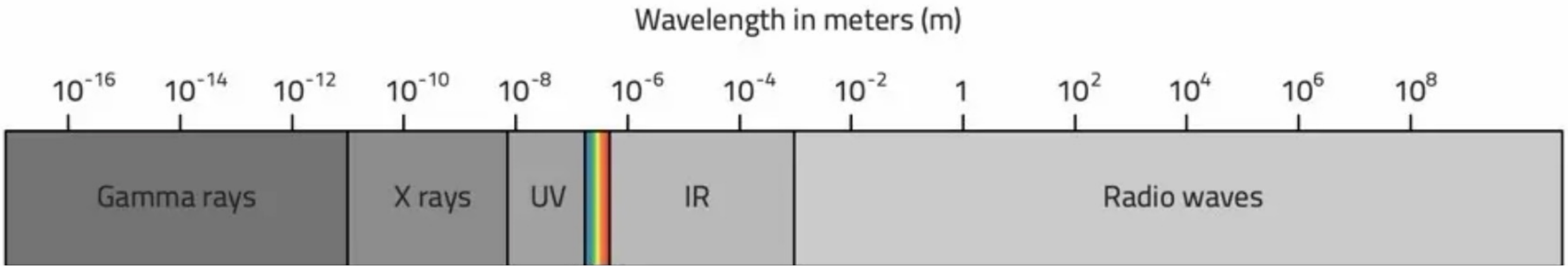
Brown dwarfs:
don't burn hydrogen!

Stars within 21 Light-Years of the Sun

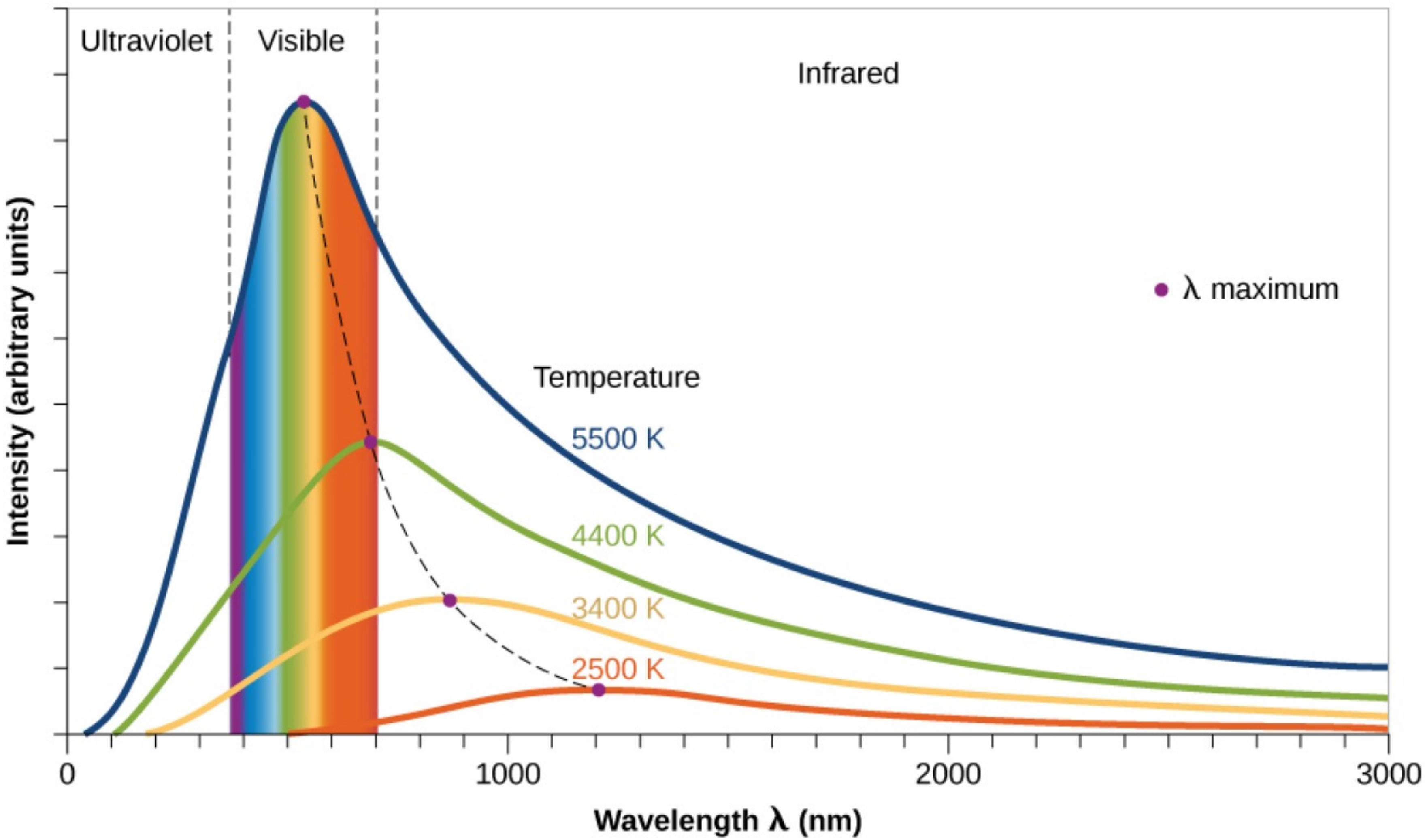
Spectral Type	Number of Stars
A	2
F	1
G	7
K	17
M	94
White dwarfs	8
Brown dwarfs	33



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)

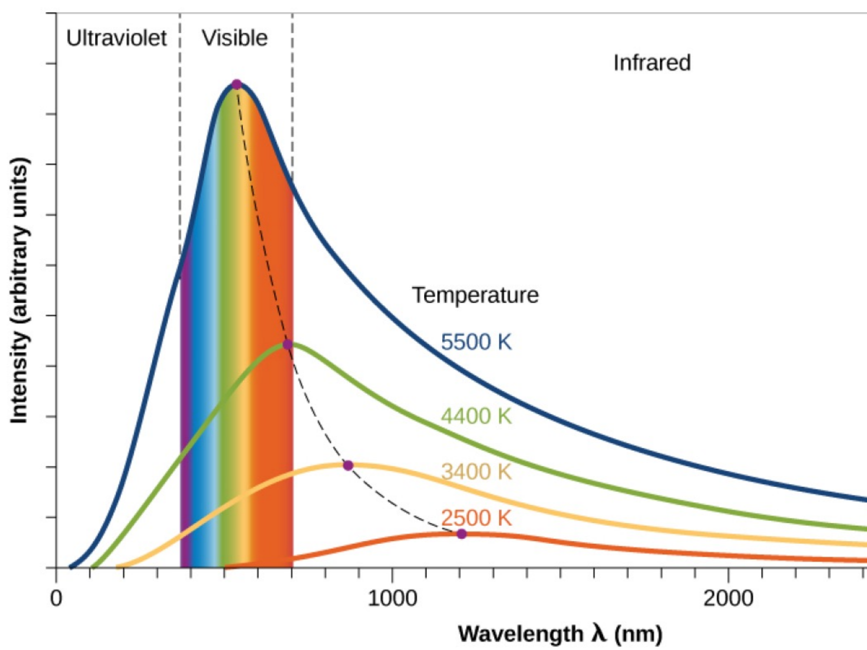
Peak of blackbody: $$\lambda_{\mathrm{max}} \cdot T = 0.288\ \mathrm{cm} \cdot \mathrm{K}$$

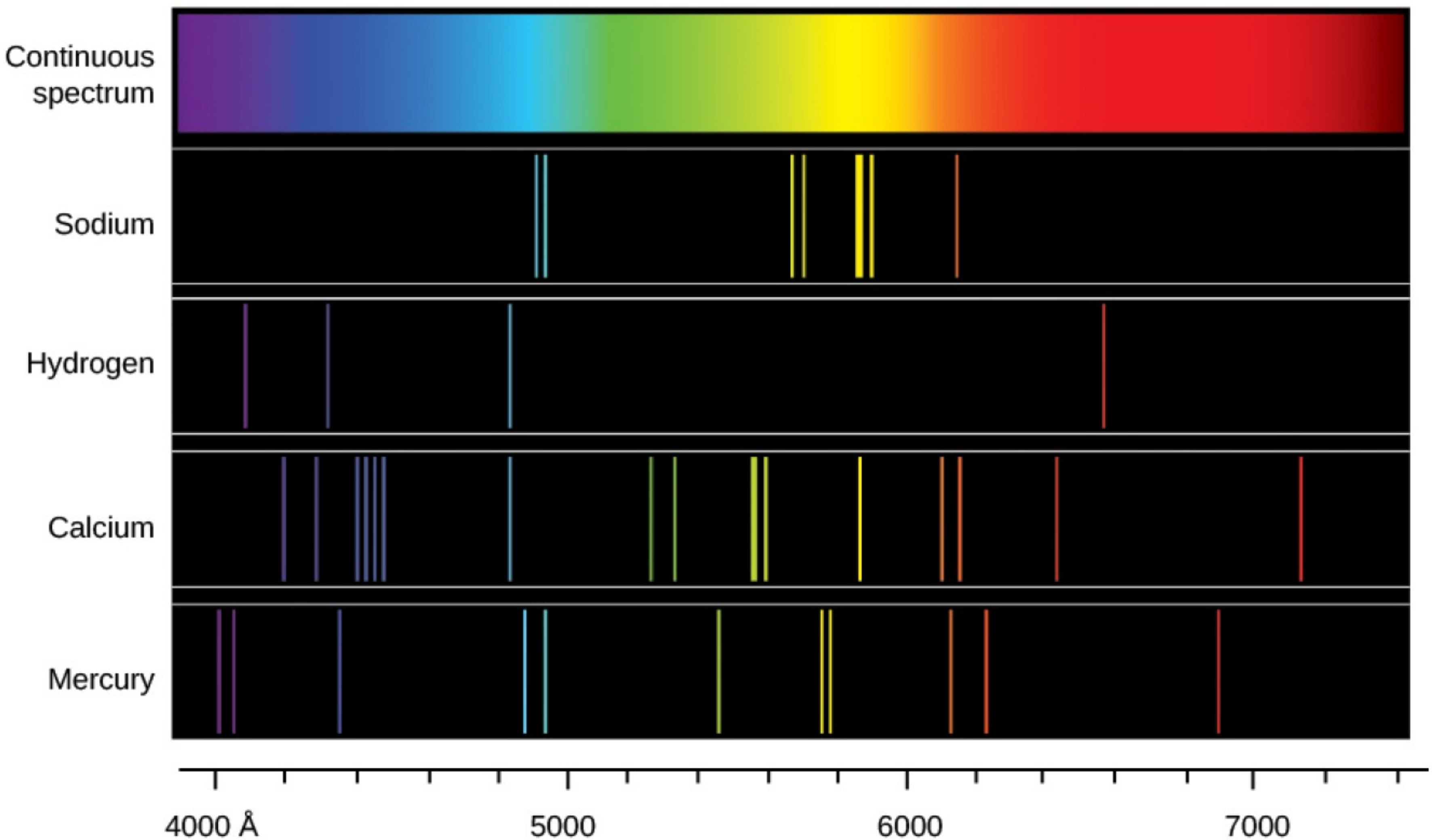


Star Color	Approximate Temperature	Example
Blue	25,000 K	Spica
White	10,000 K	Vega
Yellow	6000 K	Sun
Orange	4000 K	Aldebaran

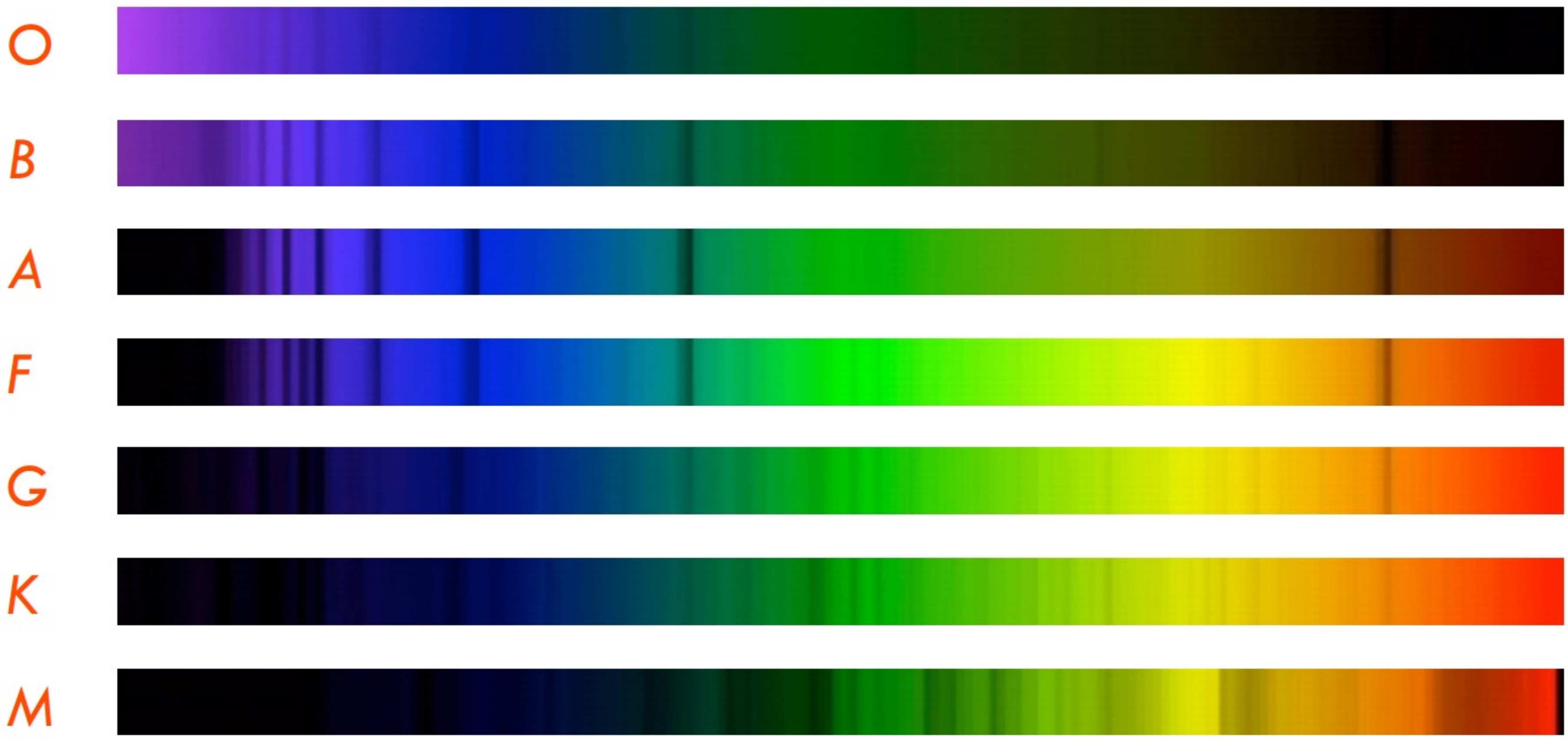
Blue

Red




Continuous spectrum
Sodium
Hydrogen
Calcium
Mercury
4000 Å
5000
6000
7000

Spectral Type (temperature) from dark absorption lines



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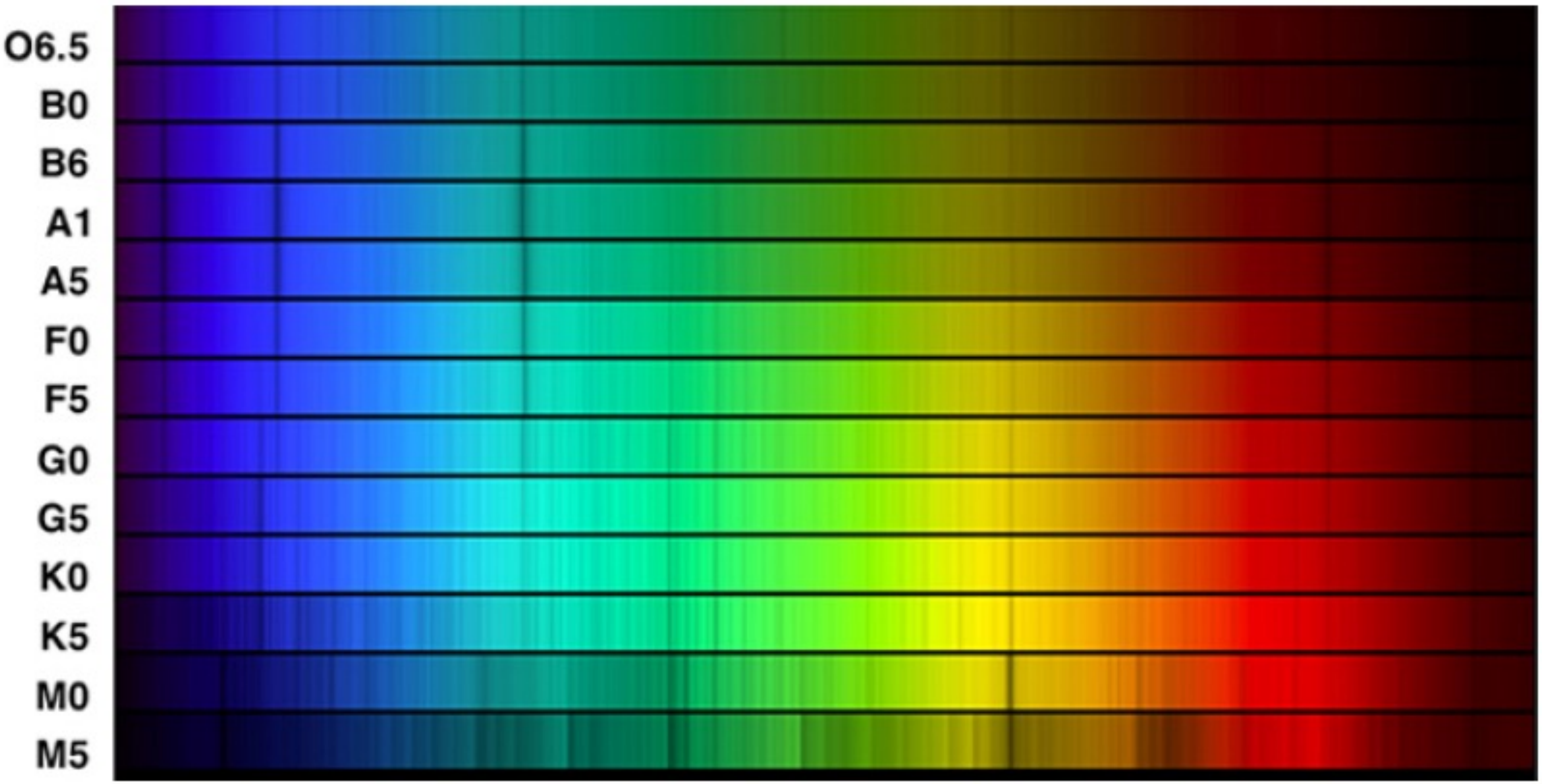
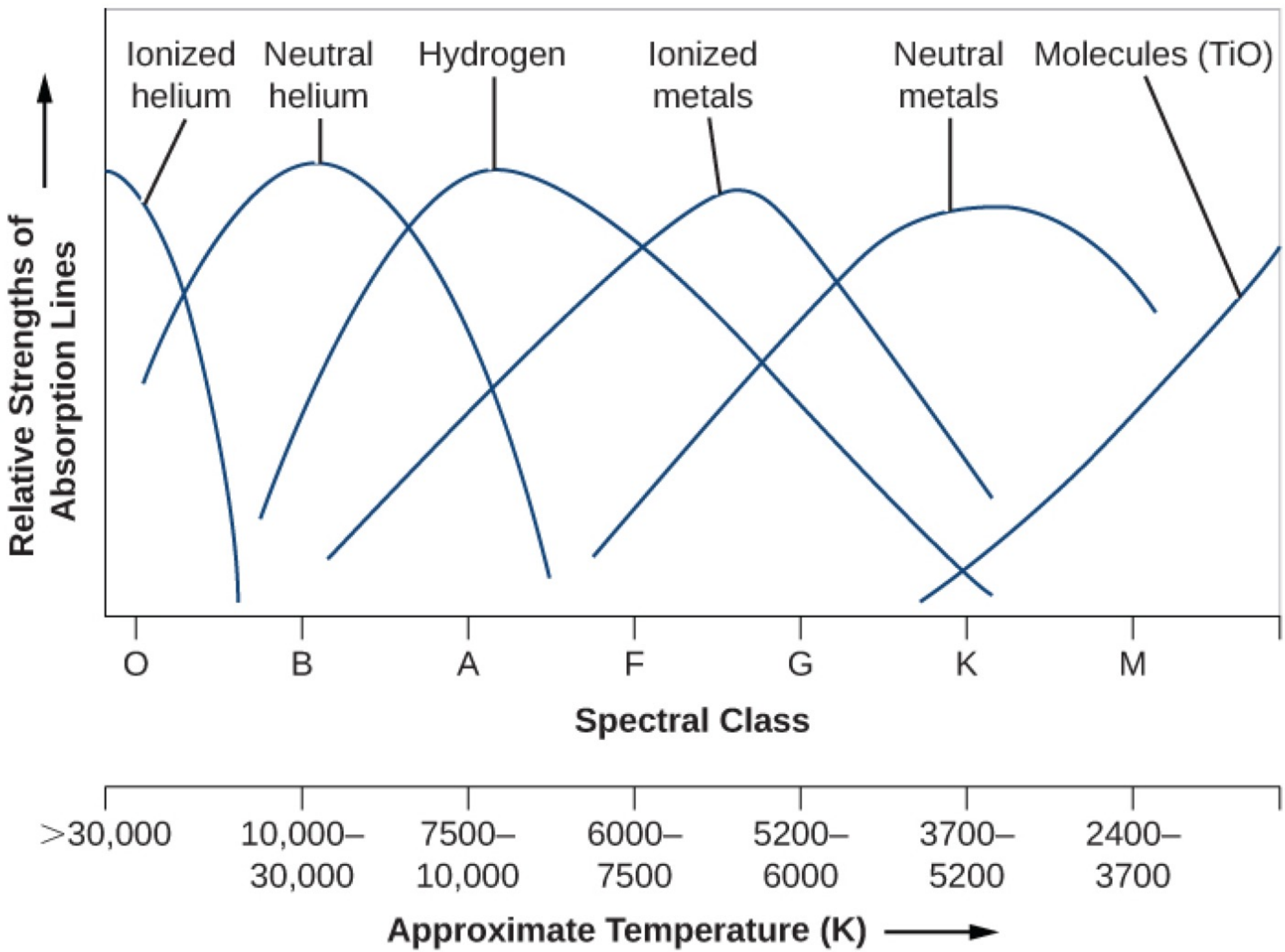
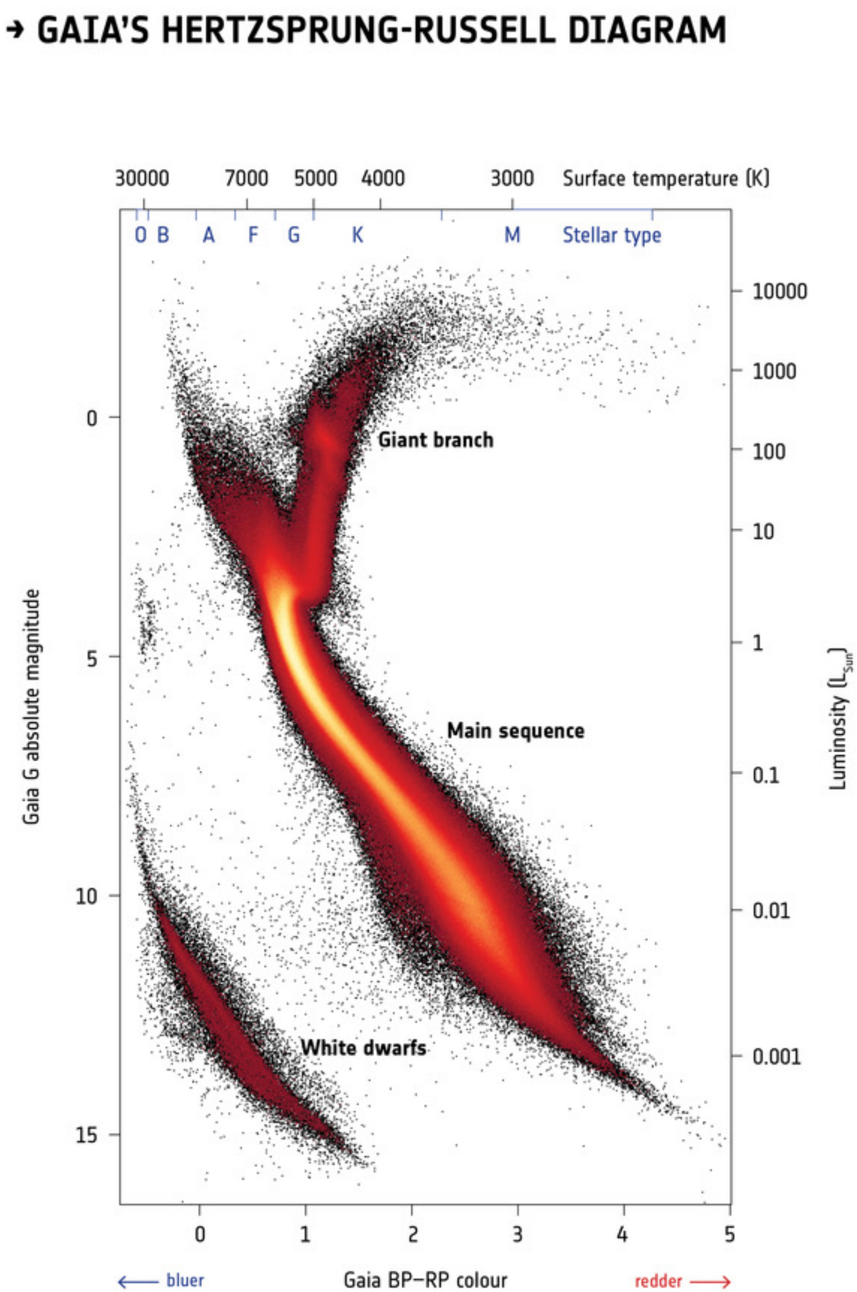




Ionized helium
Neutral helium
Hydrogen
Ionized metals
Neutral metals
Molecules (TiO)
Relative Strengths of Absorption Lines
O
B
A
F
G
K
M
Spectral Class
>30,000
10,000–30,000
7500–10,000
6000–7500
5200–6000
3700–5200
2400–3700
Approximate Temperature (K)

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



HR diagram (Hertsprung-Russell)

Main sequence:

- most stars on main sequence
- Defined by hydrogen burning

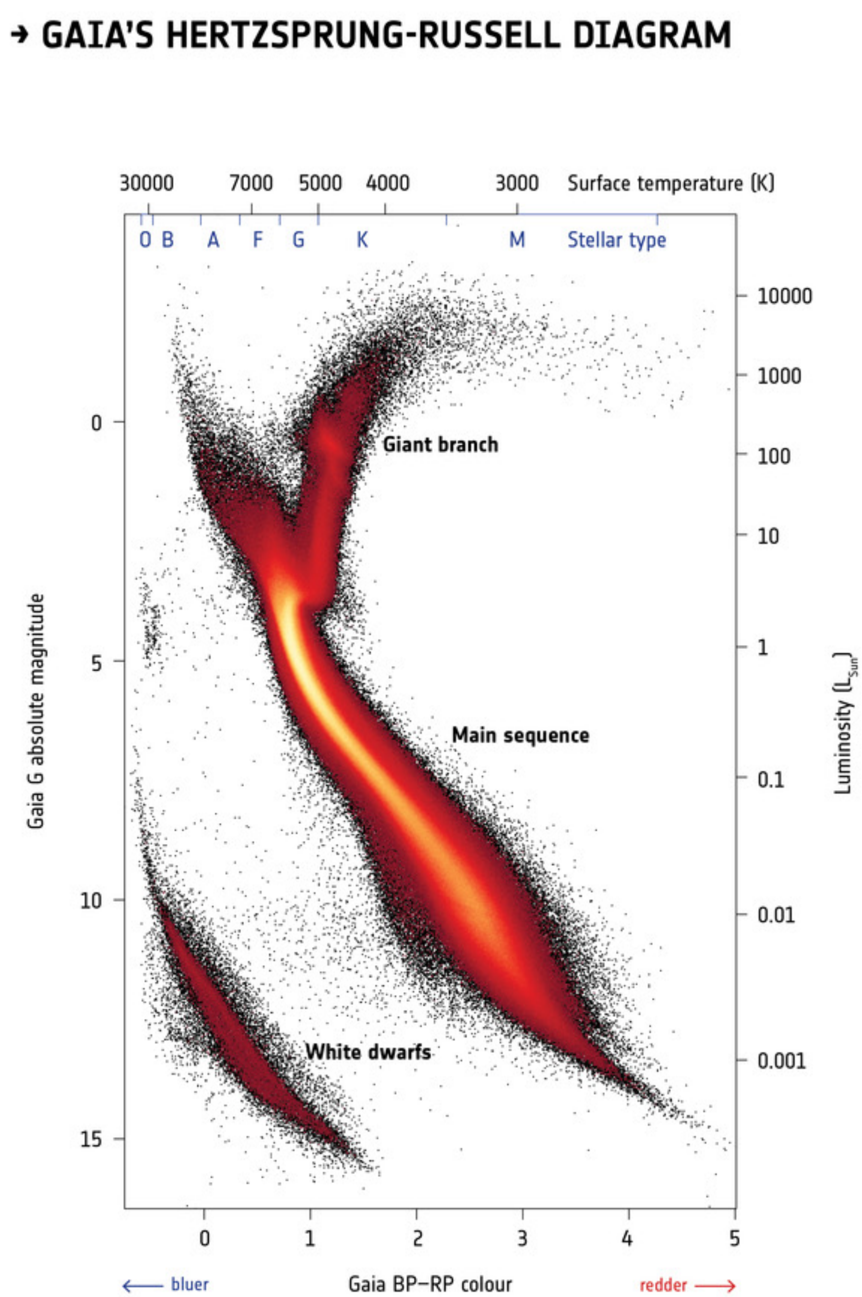
Stars in other locations:

- Stellar evolution! (age)

Women of Harvard University

Annie Jump-Cannon

Cecilia Payne: “most brilliant PhD thesis” ever



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Main sequence:

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Stars in other locations:

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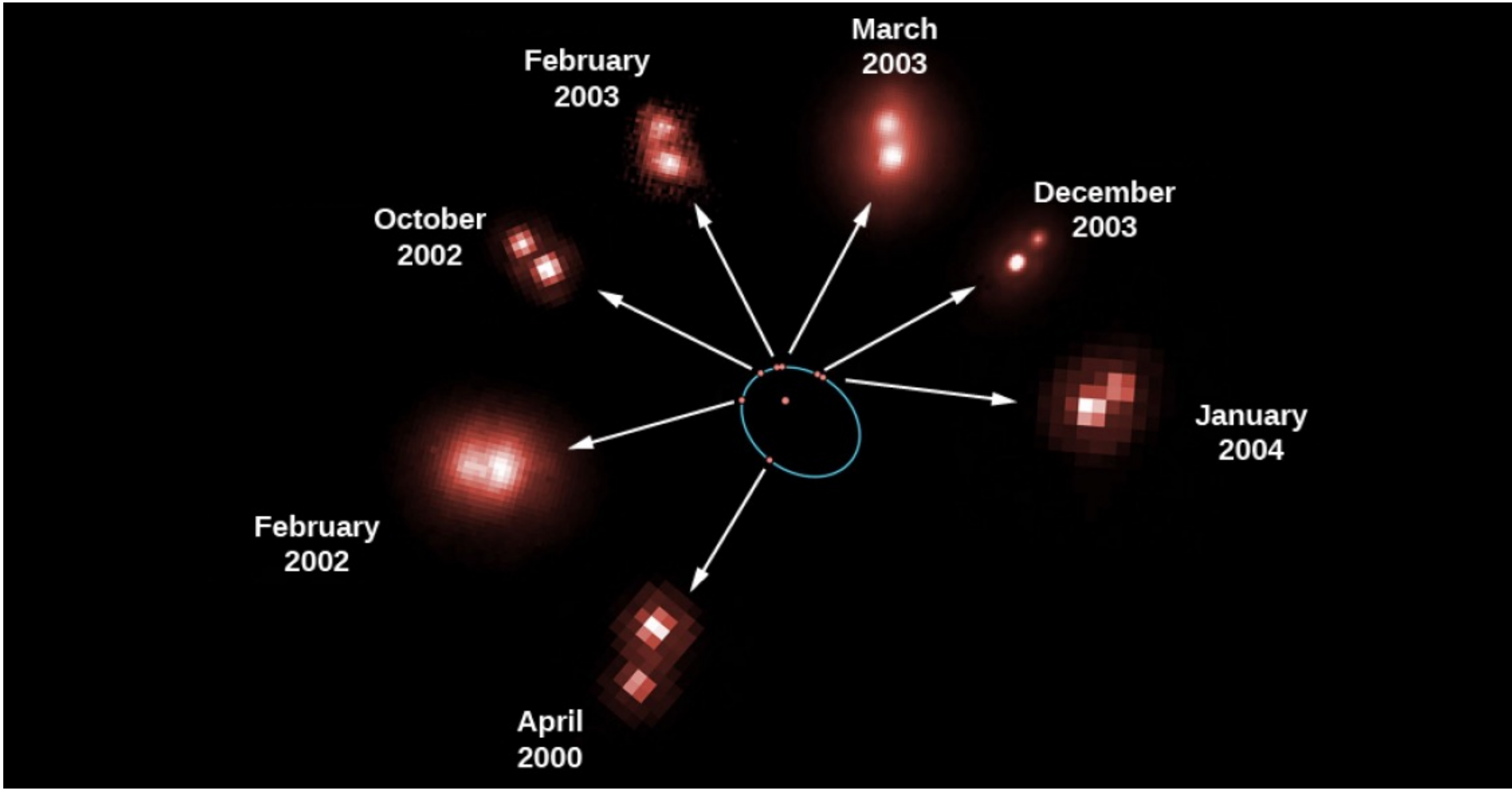
The Abundance of Elements in the Sun

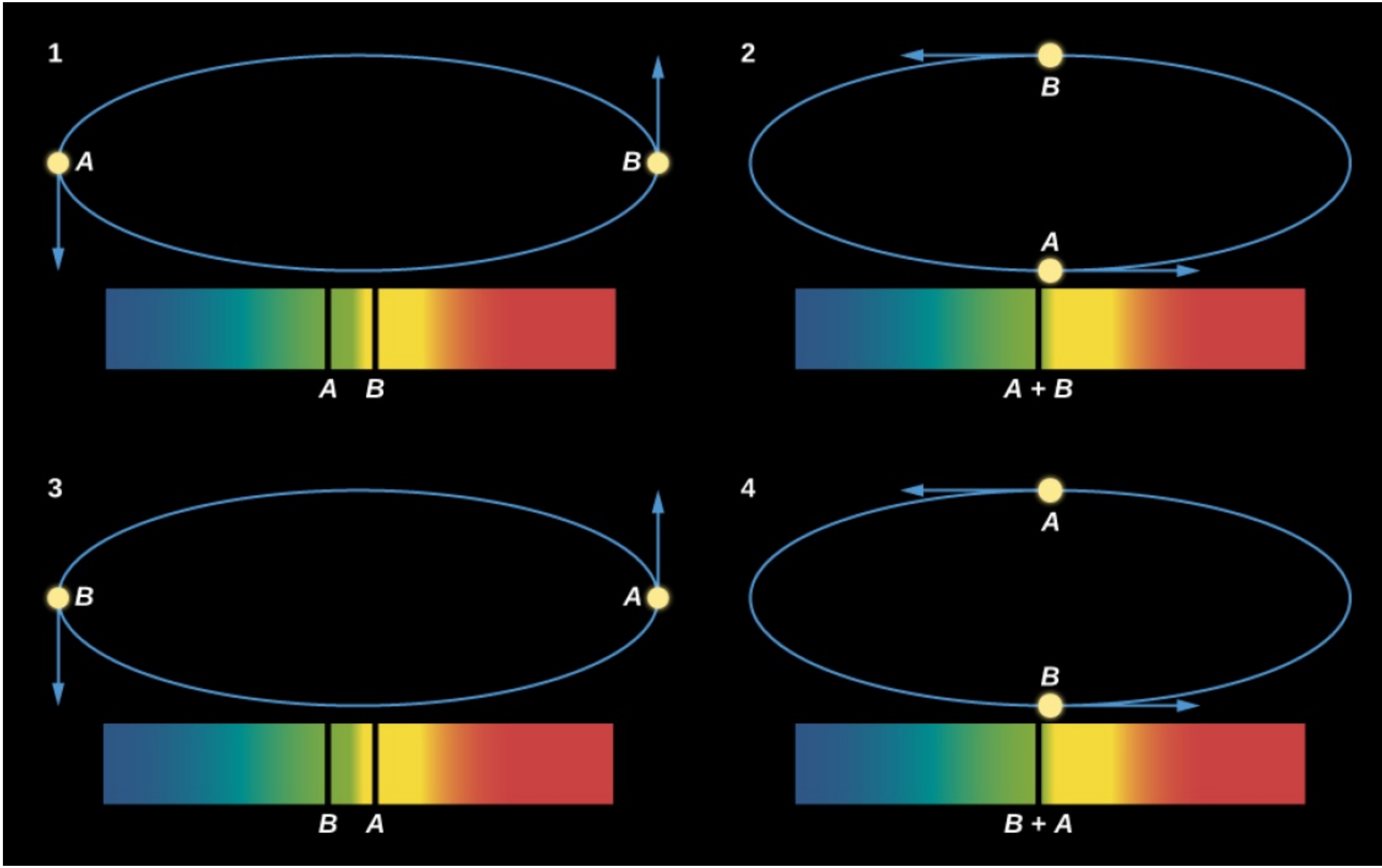
Element	Percentage by Number of Atoms	Percentage By Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.80
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

Measuring the Characteristics of Stars

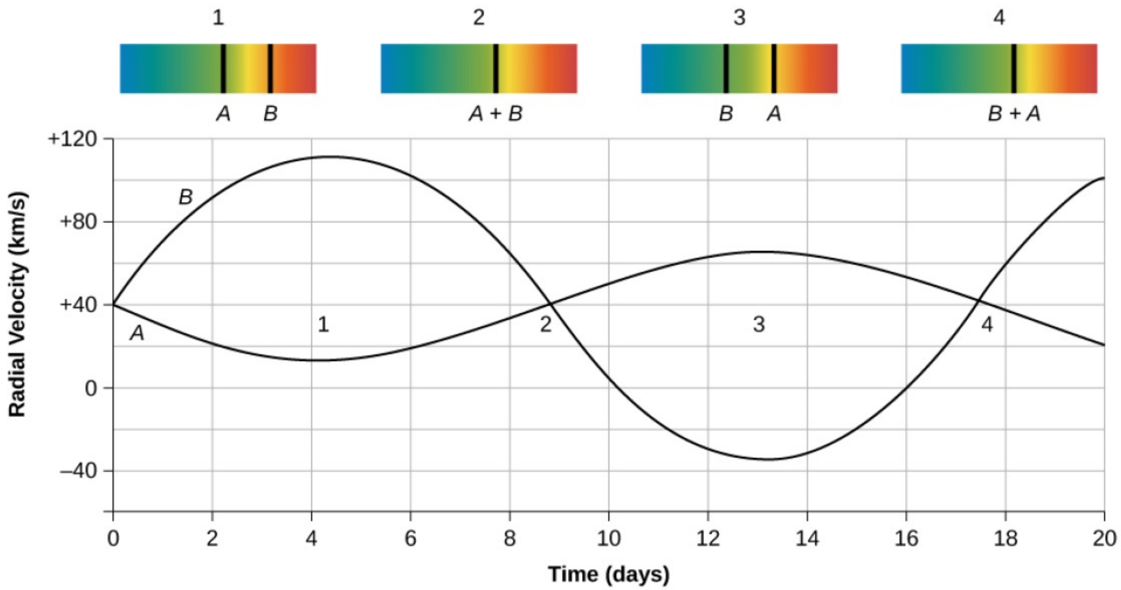
Characteristic	Technique
Surface temperature	1. Determine the color (very rough). 2. Measure the spectrum and get the spectral type.
Chemical composition	Determine which lines are present in the spectrum.
Luminosity	Measure the apparent brightness and compensate for distance.
Radial velocity	Measure 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	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.

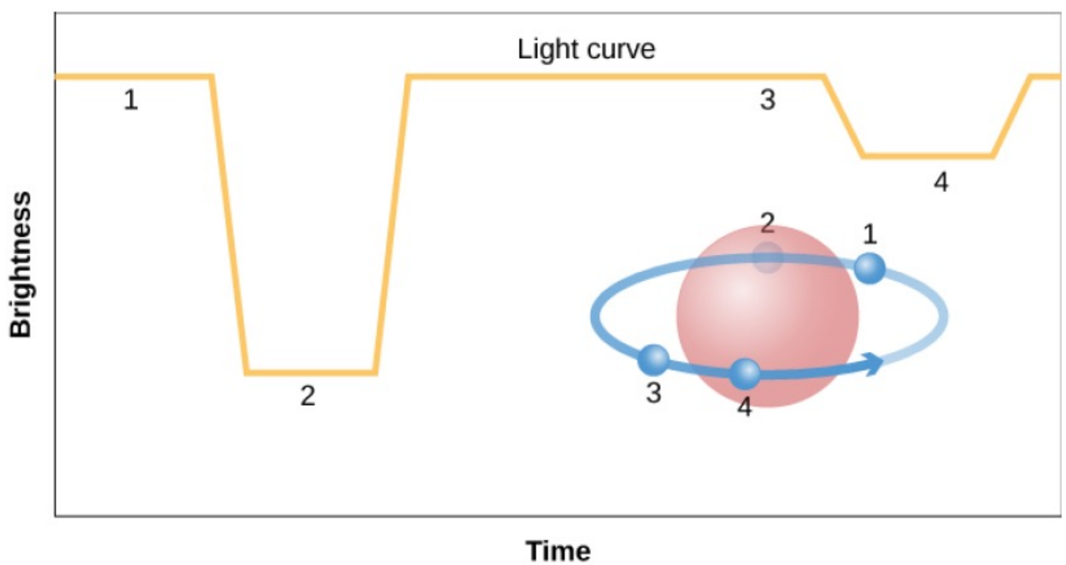

March
2003
February
2003
October
2002
December
2003
January
2004
February
2002
April
2000

Keplerian motion and Doppler shifts

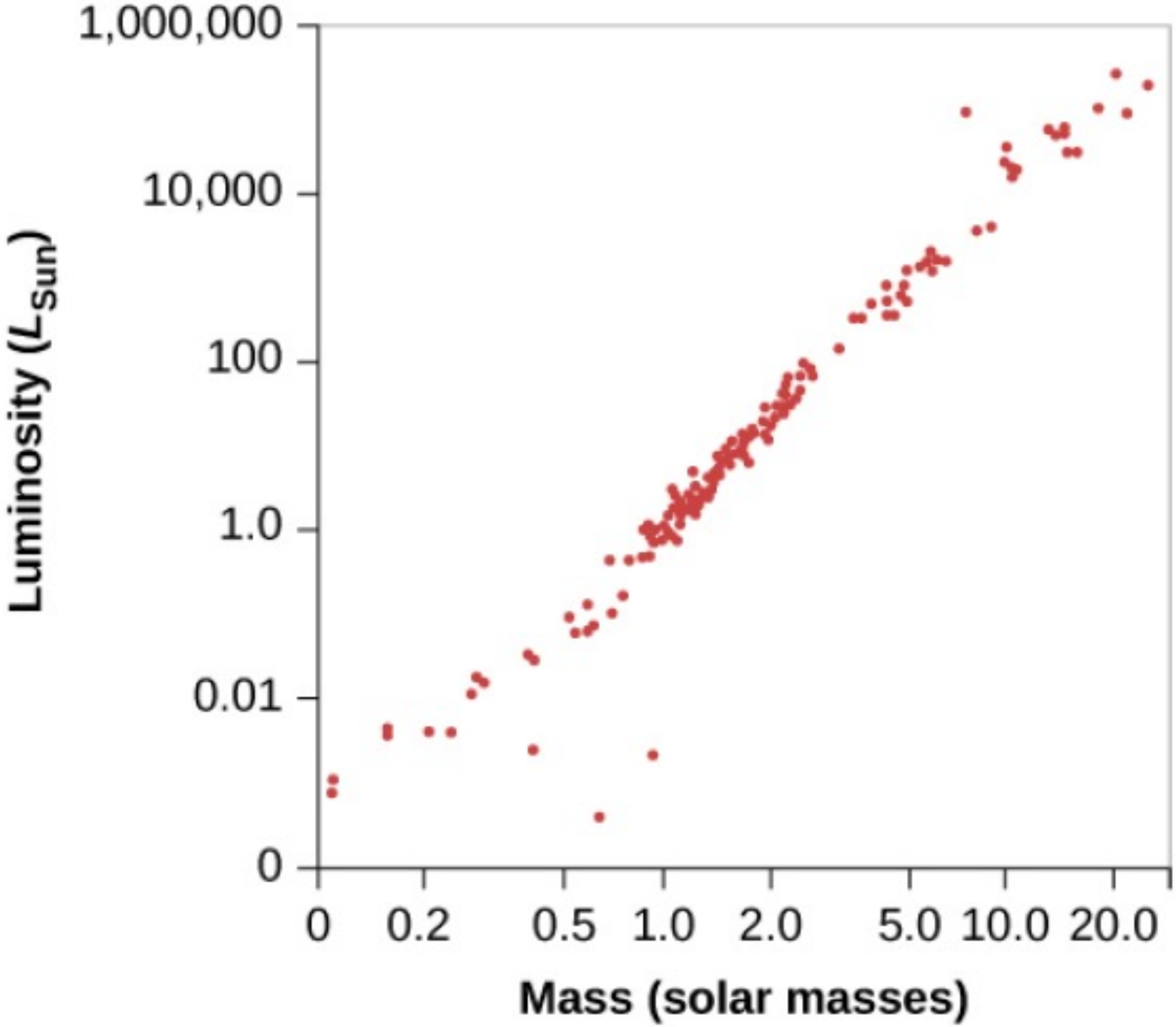


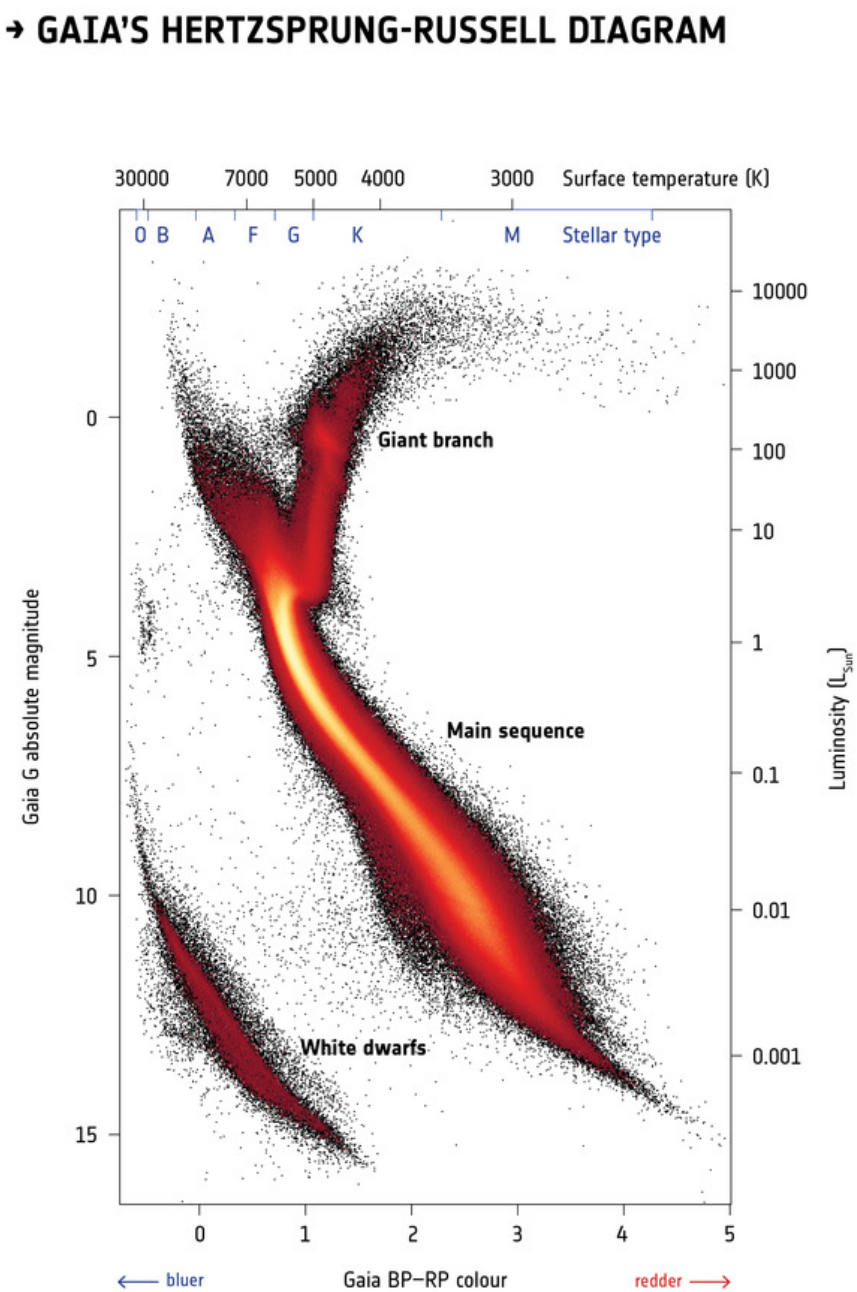
Stellar masses from radial velocity and gravity





Eclipsing binary systems: Benchmarks for stellar masses


1,000,000
10,000
100
1.0
0.01
0
Luminosity (L_{Sun})
0
0.2
0.5
1.0
2.0
5.0
10.0
20.0
Mass (solar masses)



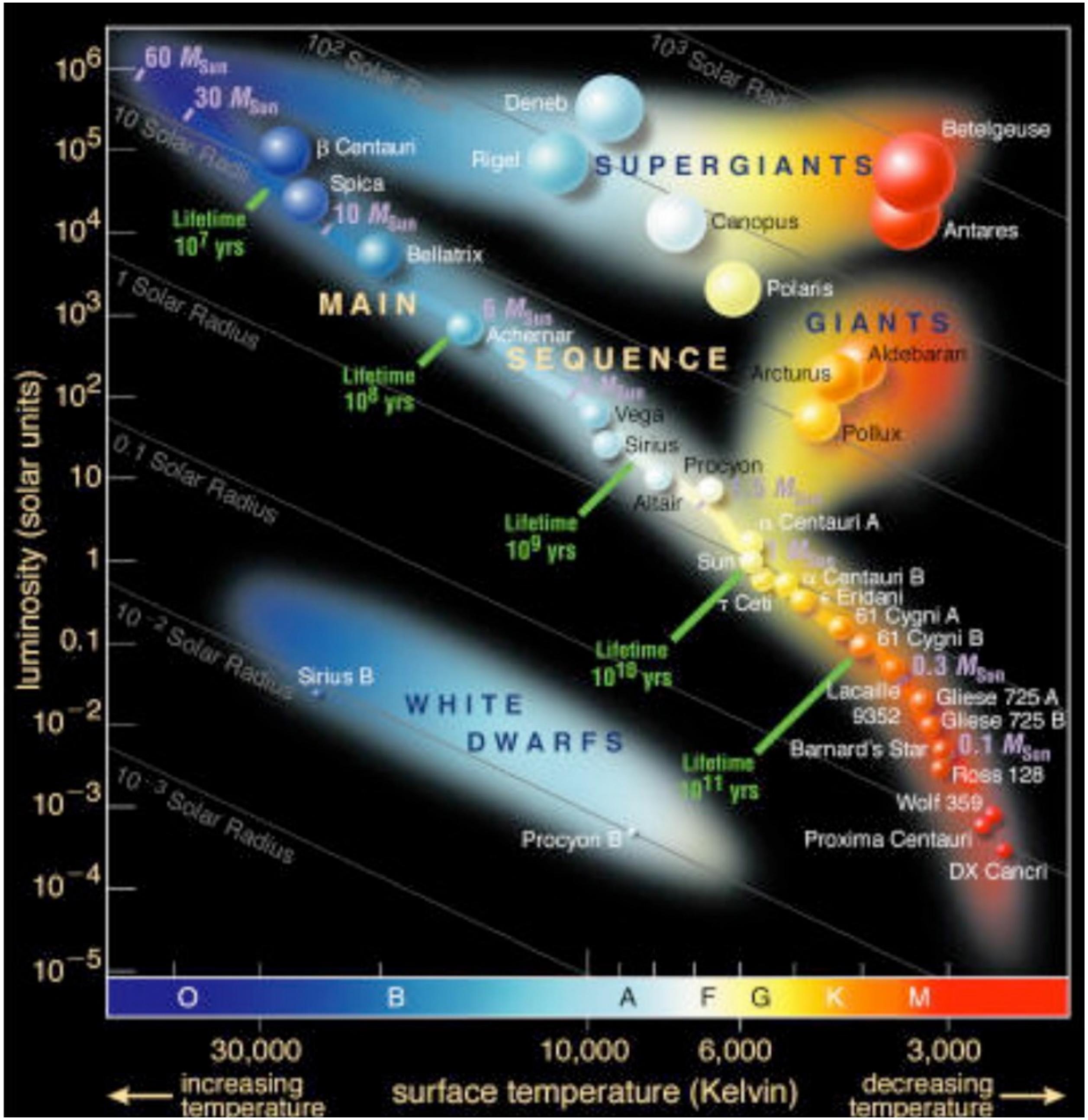
HR diagram (Hertsprung-Russell)

Main sequence:

- most stars on main sequence
- Defined by hydrogen burning

Stars in other locations:

- Stellar evolution! (age)

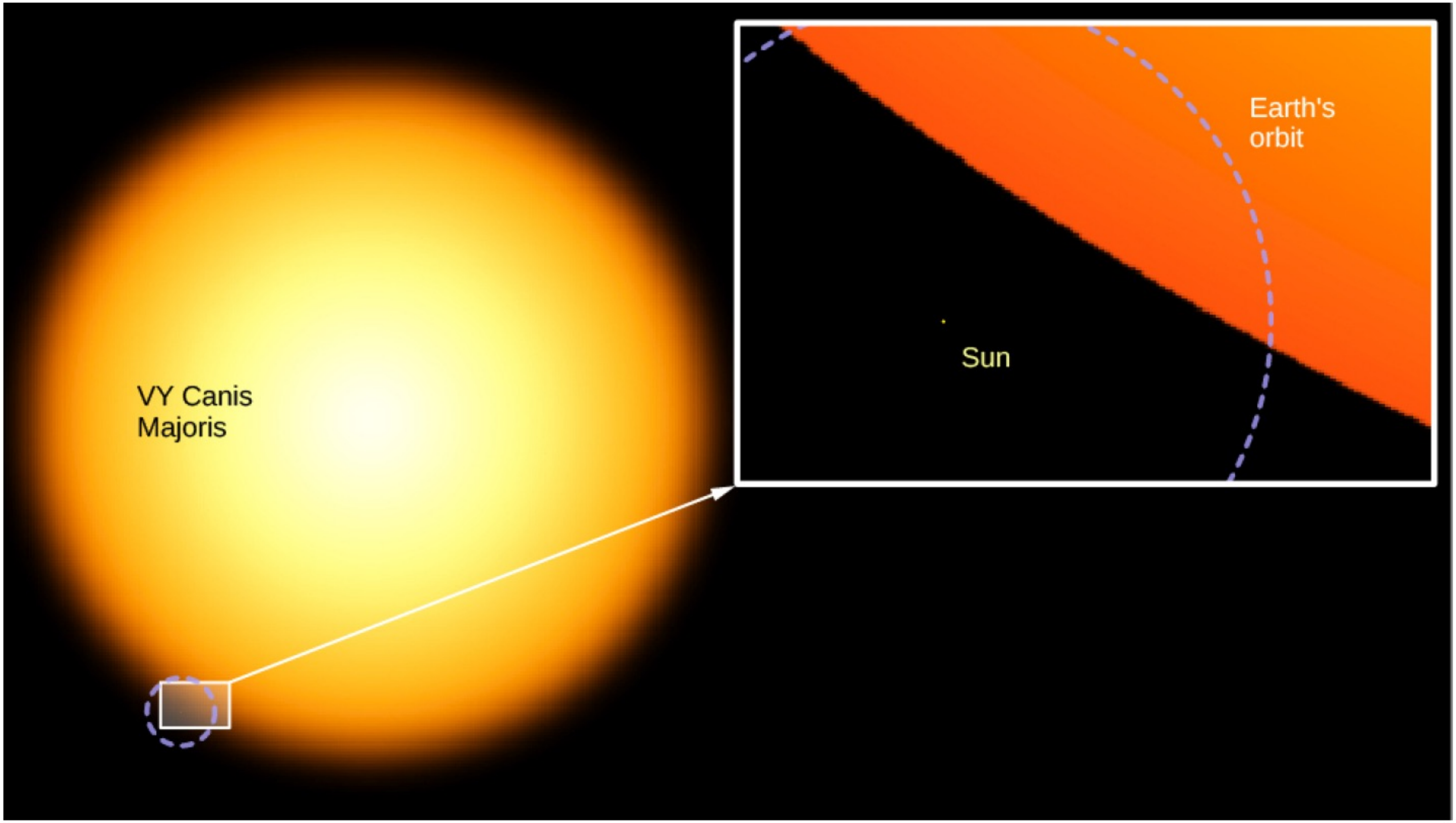


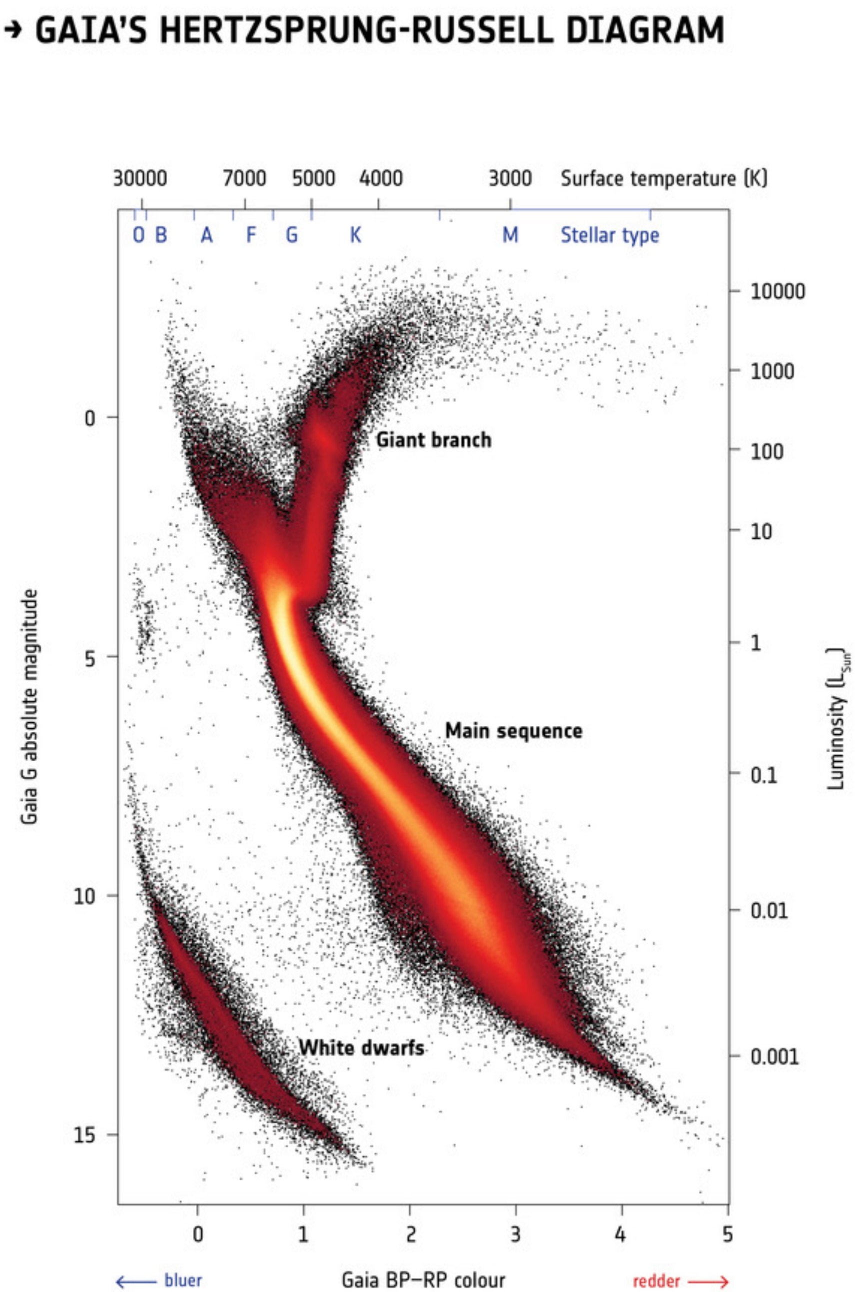
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
luminosity (solar units)
60 M_Sun
30 M_Sun
10 Solar Radii
β Centauri
Spica
10 M_Sun
Lifetime 10^7 yrs
Bellatrix
MAIN
SEQUENCE
6 M_Sun
Achernar
Lifetime 10^8 yrs
1 Solar Radius
Deneb
Rigel
SUPERGIANTS
Betelgeuse
Canopus
Antares
Polaris
GIANTS
Aldebaran
Arcturus
Pollux
Vega
Sirius
Procyon
Altair
0.1 Solar Radius
Lifetime 10^9 yrs
α Centauri A
Sun
1 M_Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lifetime 10^10 yrs
0.3 M_Sun
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
0.1 M_Sun
Ross 128
Lifetime 10^11 yrs
Wolf 359
Proxima Centauri
DX Cancri
10^-2 Solar Radius
Sirius B
WHITE DWARFS
10^-3 Solar Radius
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

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!



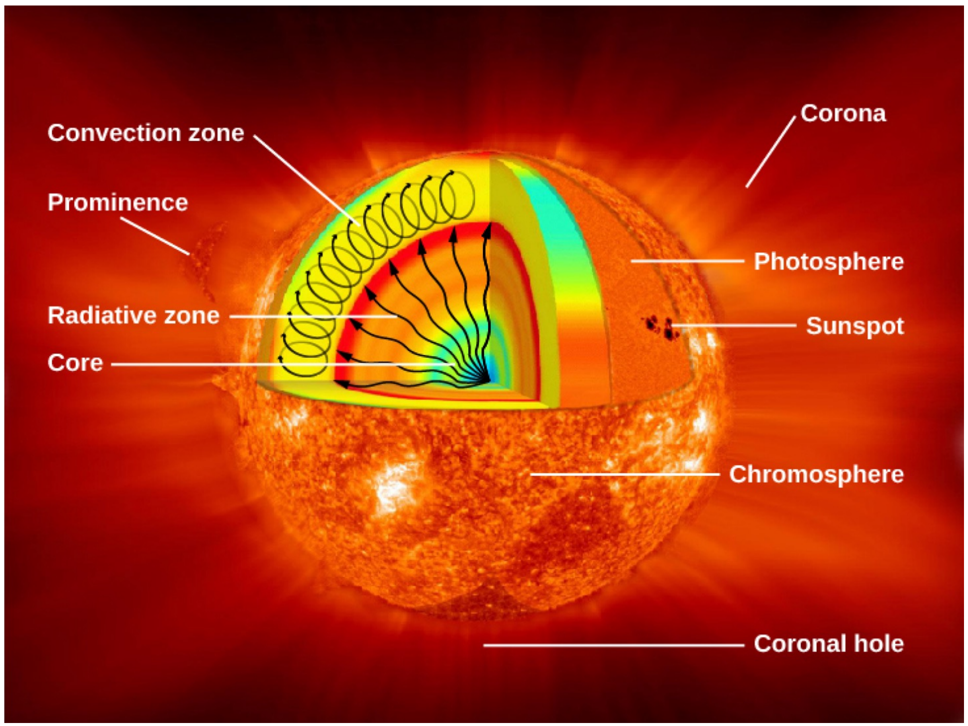


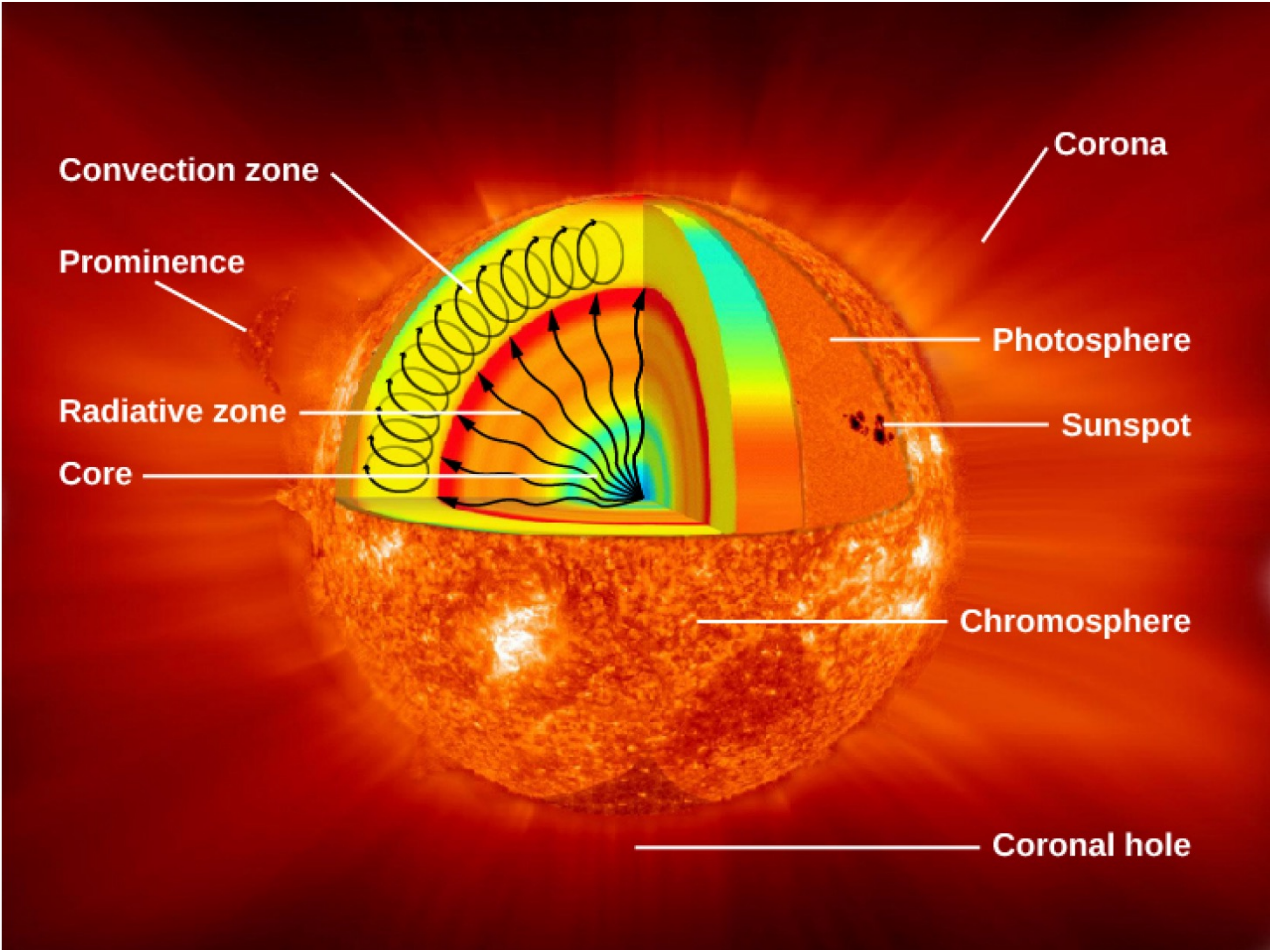
What is the Main Sequence?

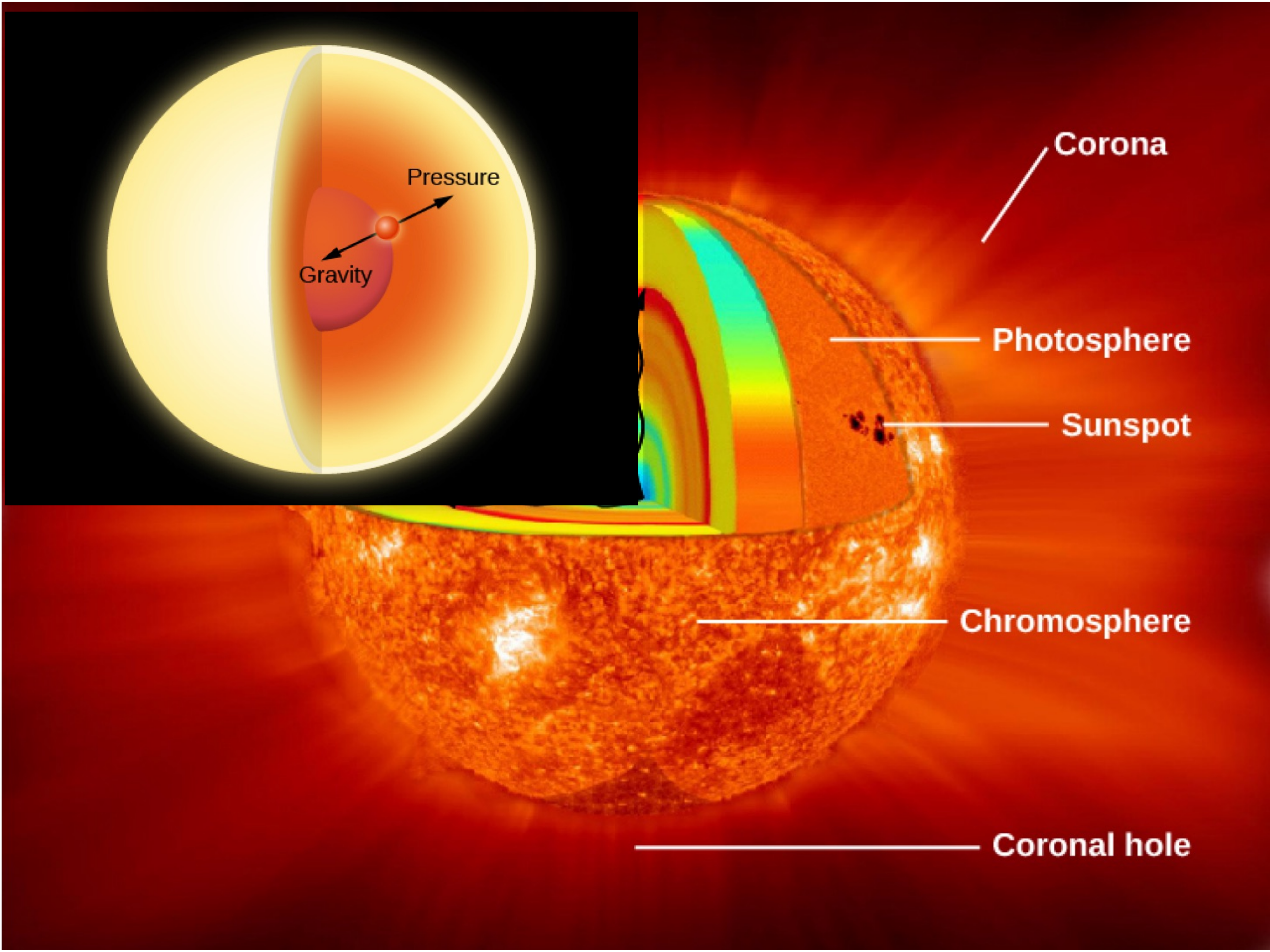
- 90% of a star's life
- Defined by hydrogen burning core
- Evolves once hydrogen is gone

- What does hydrogen burning mean?

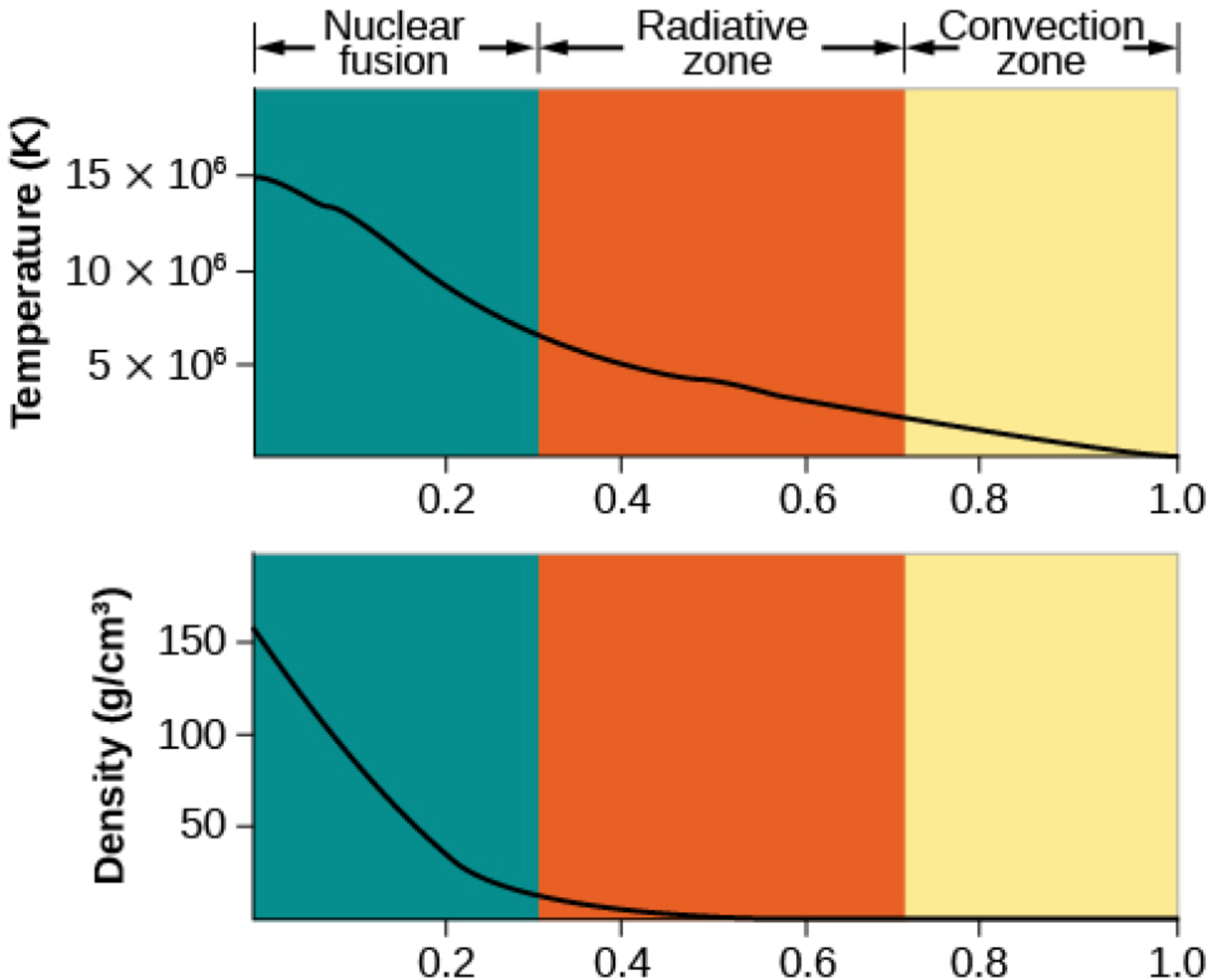
Where does the sun's energy come from? Hydrogen burning and the interior of the sun




Corona
Convection zone
Prominence
Photosphere
Radiative zone
Sunspot
Core
Chromosphere
Coronal hole

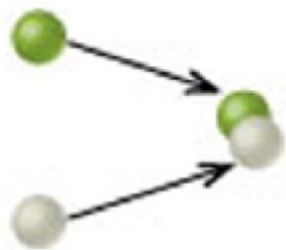

Pressure
Gravity
Corona
Photosphere
Sunspot
Chromosphere
Coronal hole

Core: very dense, 15 million K



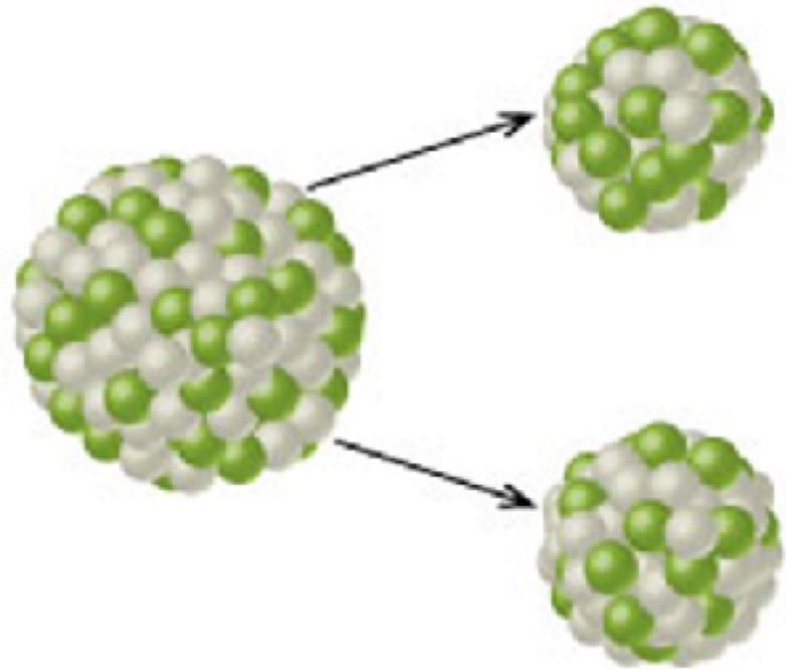
Fusion

2 light => 1 heavy



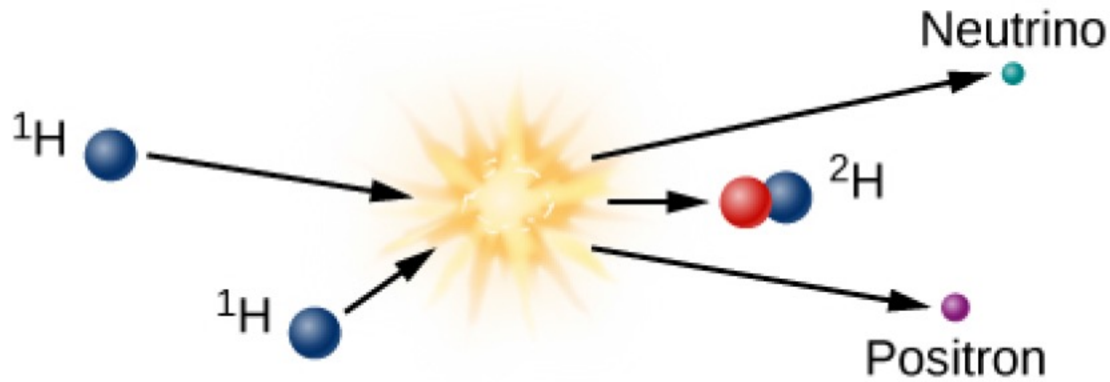
Fission

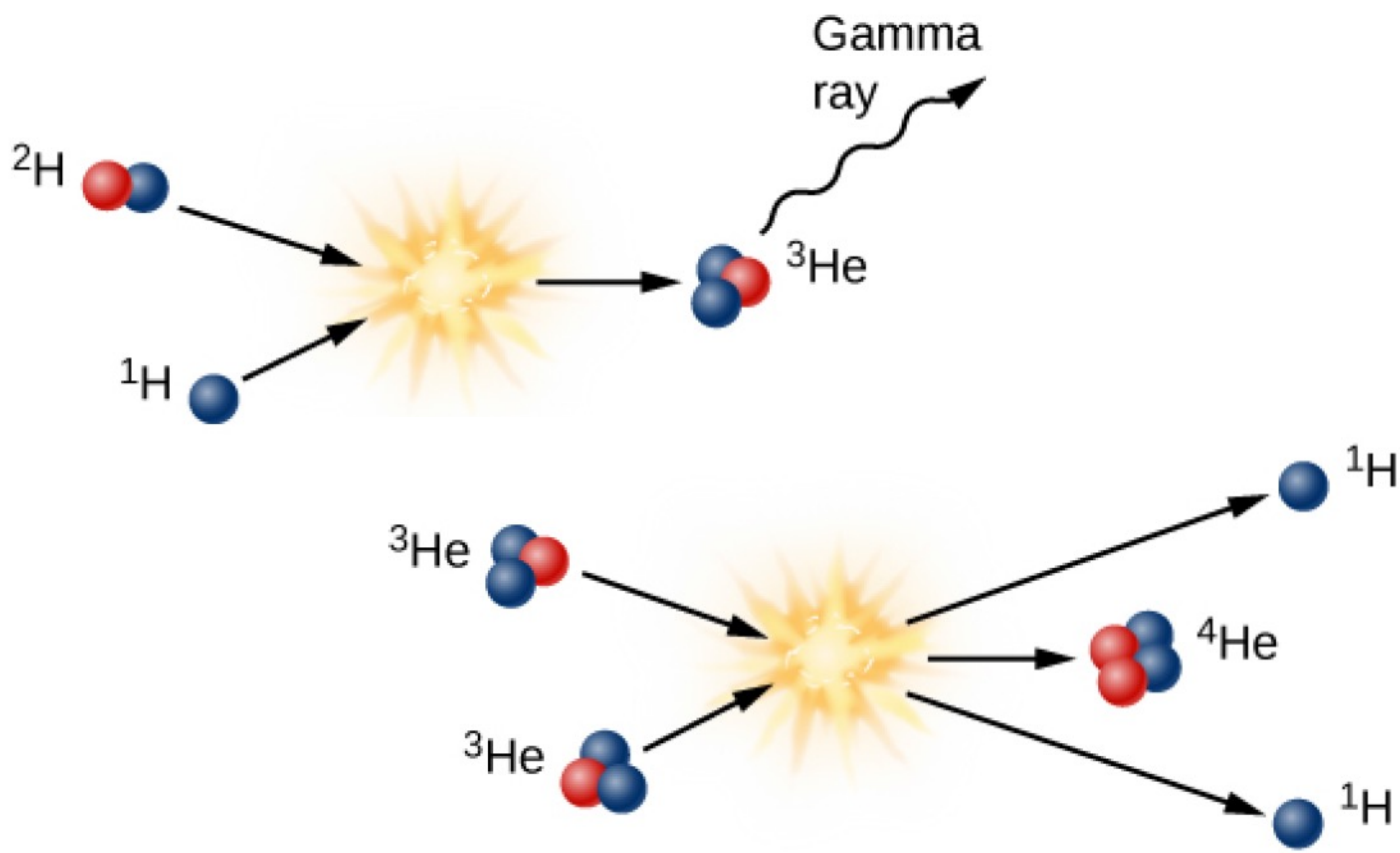
1 heavy => 2 light

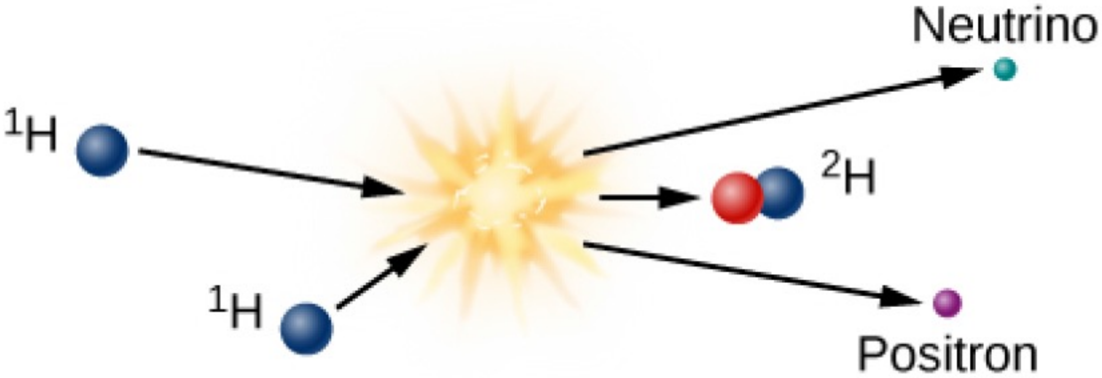


Fusion at core

4 Hydrogen atoms turns into 1 He atom







Fusion at core

4 Hydrogen atoms turns into 1 He atom

Atomic weights

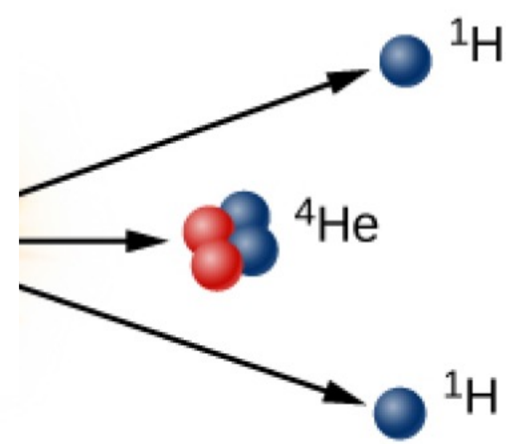
4 H: 4.032

1 He: 4.003

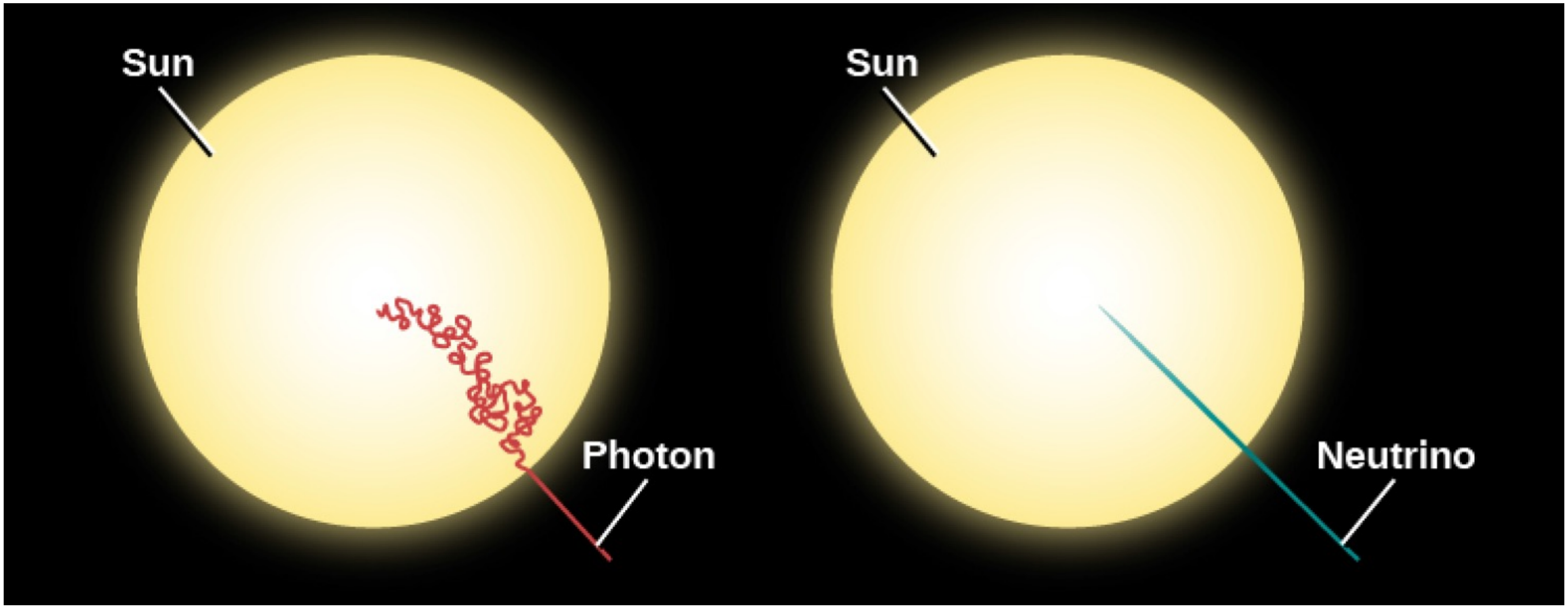
Lose 0.7% of the mass: it turns into energy!

$$E=mc^2$$

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



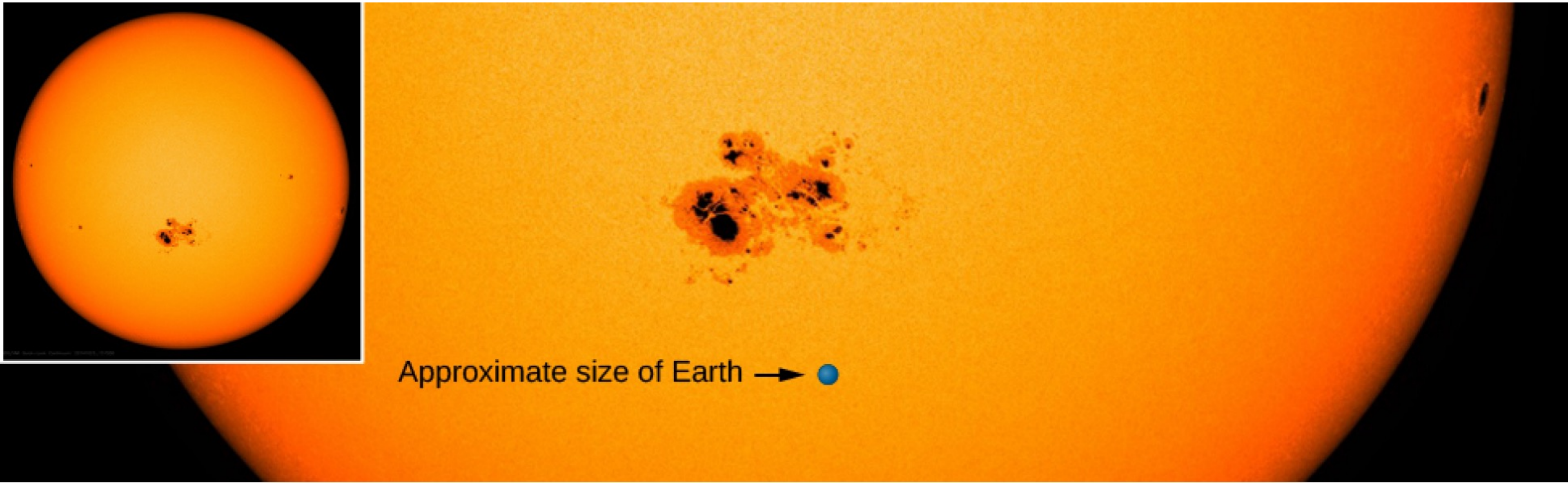
How long does it take energy to escape from the sun's core?

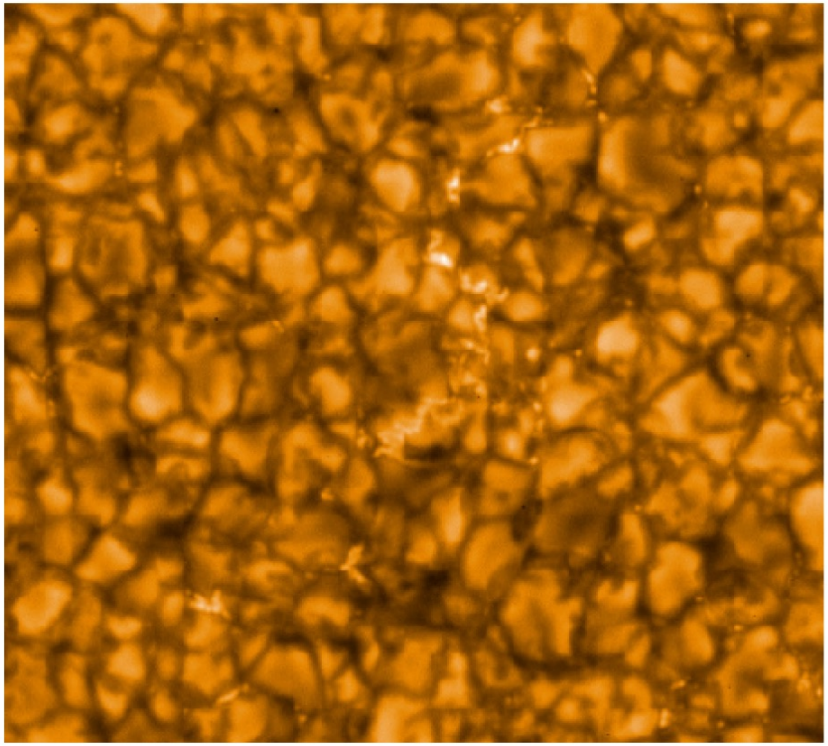


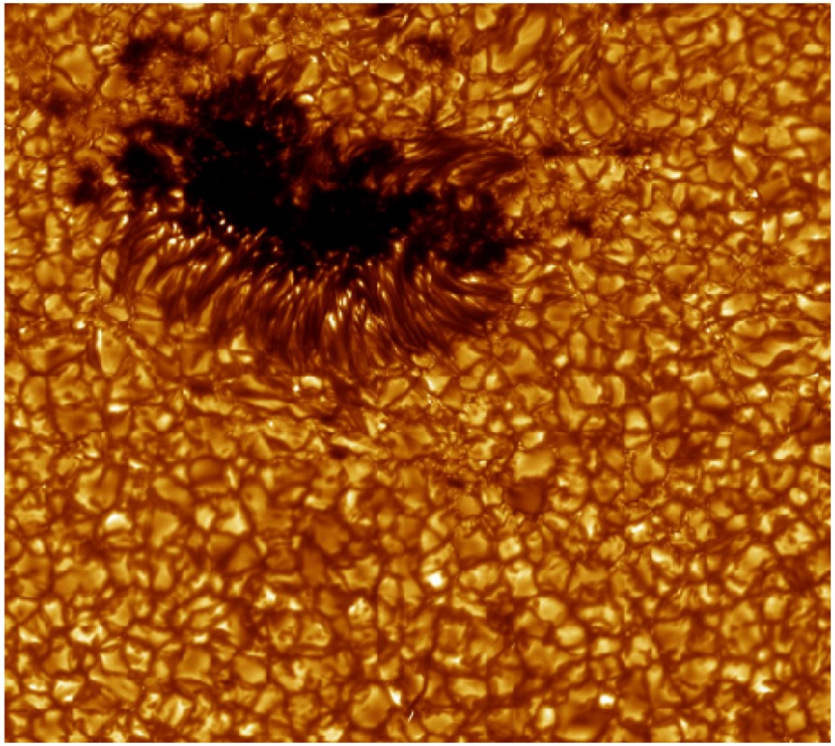
Most energy: 1 million years!

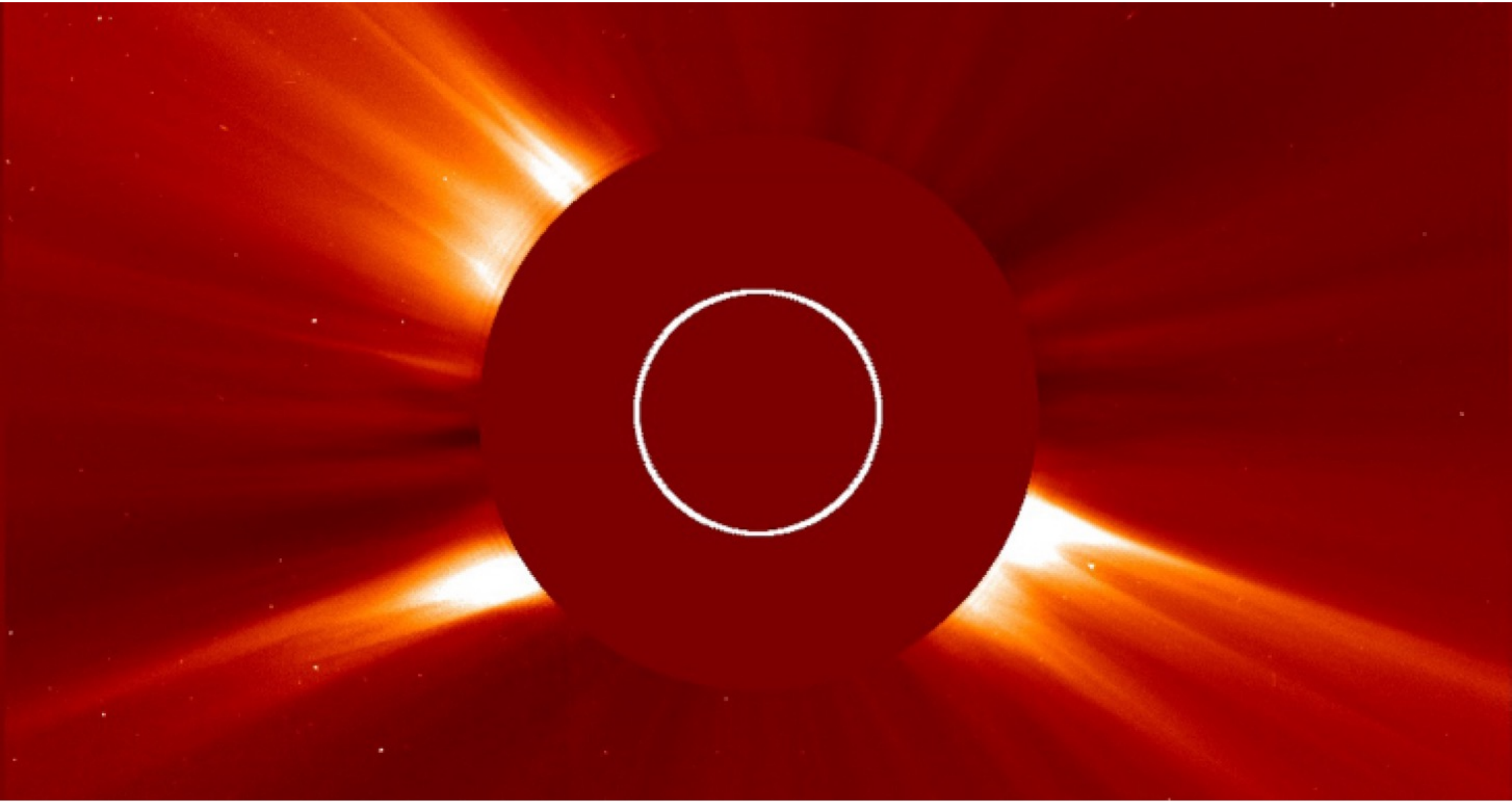
Neutrinos: do not interact with matter, so escapes immediately

Solar neutrino problem: recent Nobel Prize

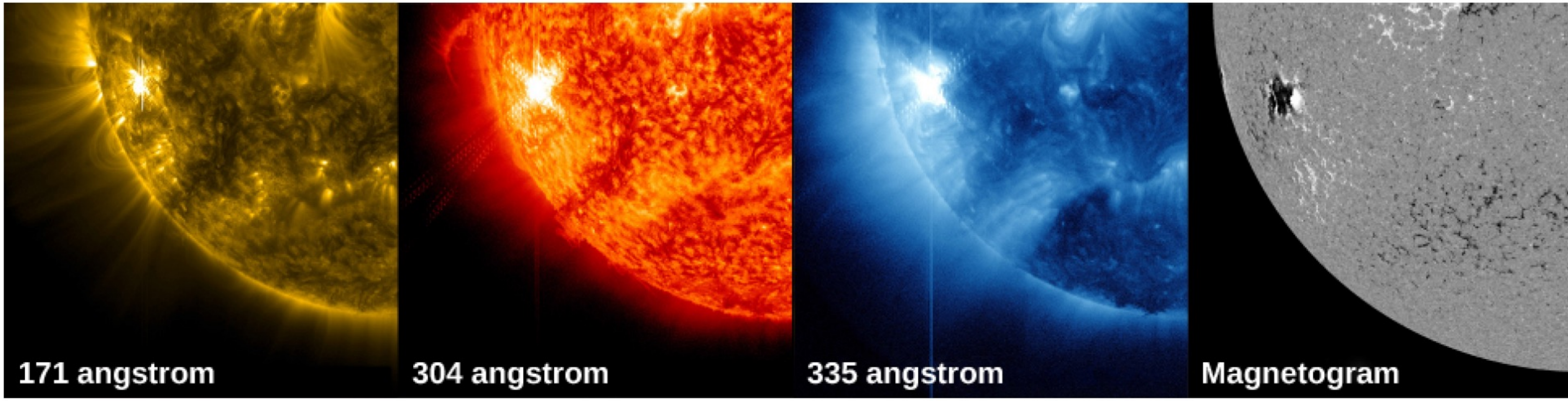

Approximate size of Earth







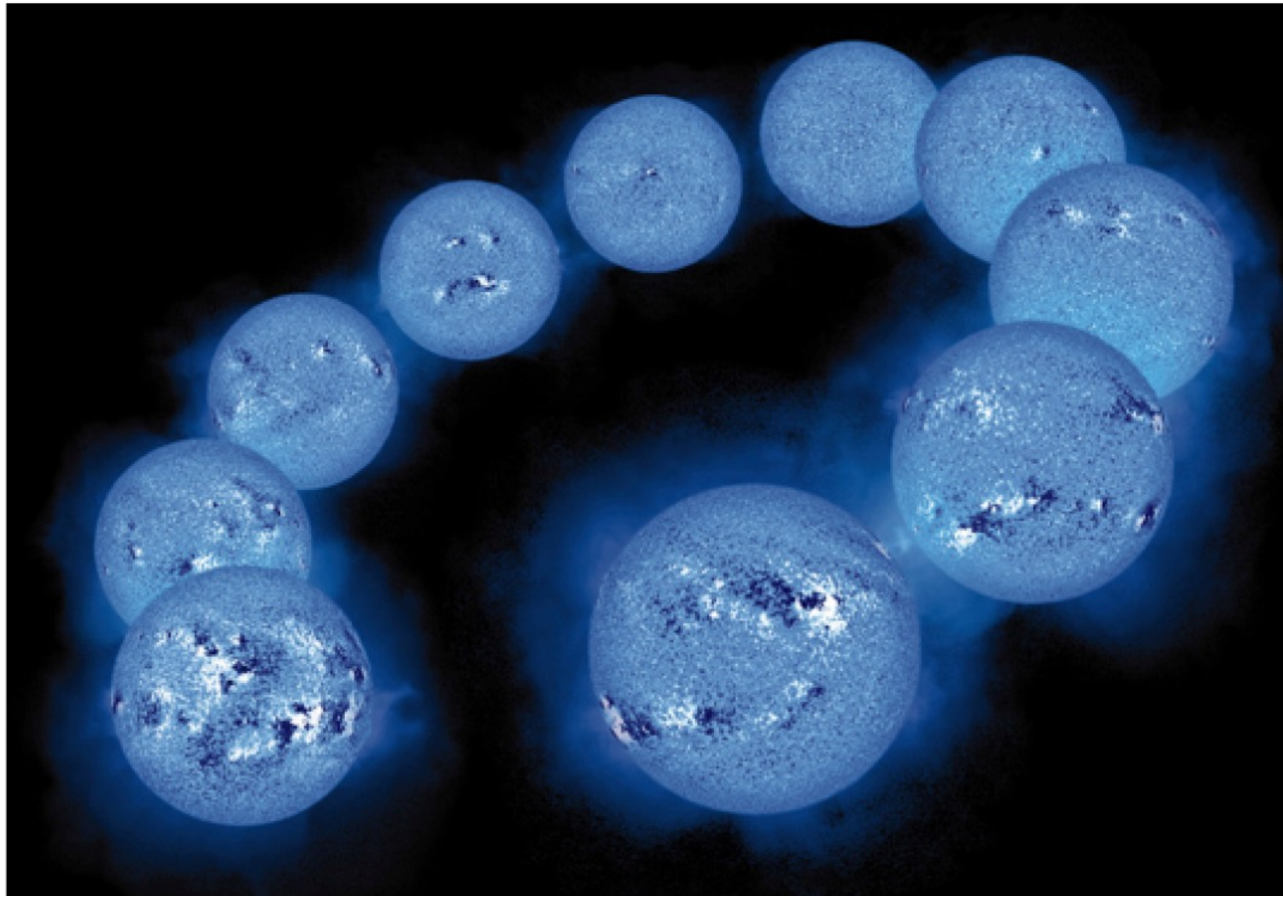

"White Satin"
© Todd Salat
AuroraHunter.com

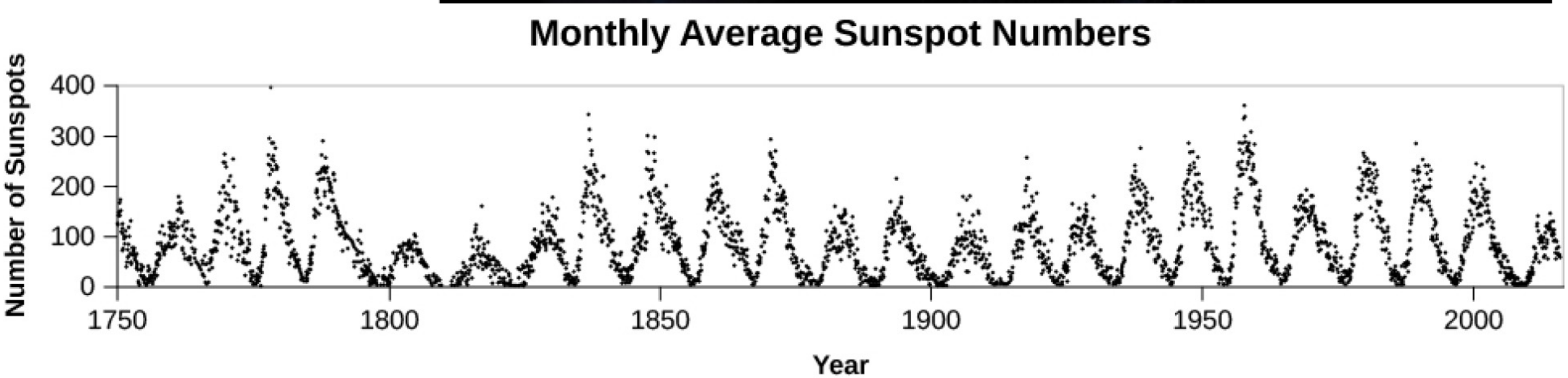


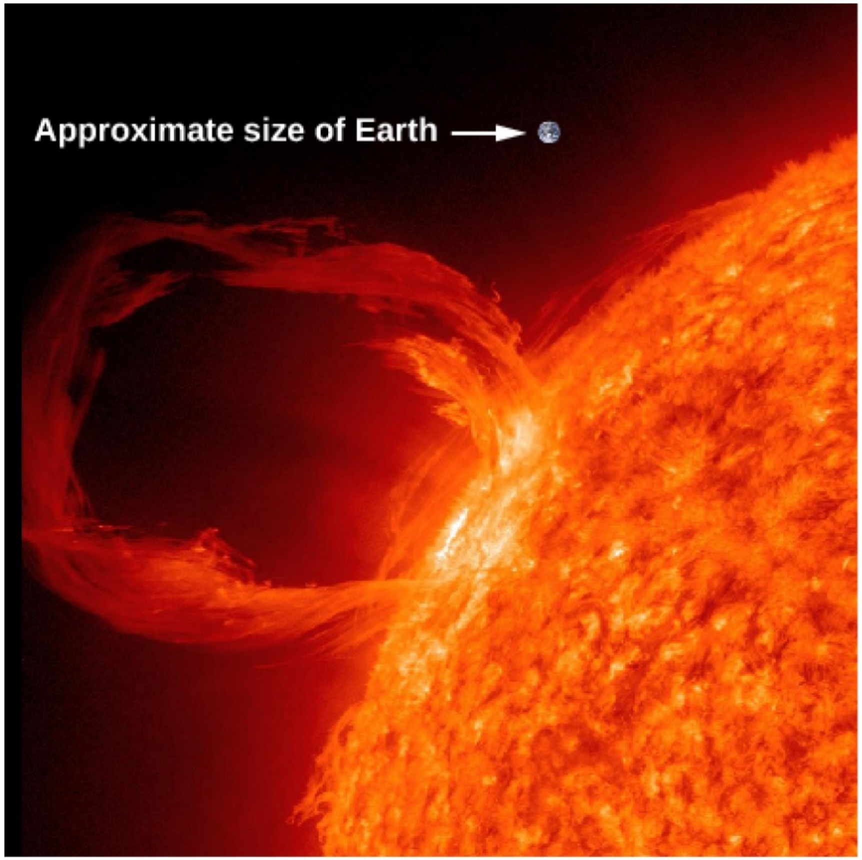
Sun: looks different at different wavelengths: magnetic activity!

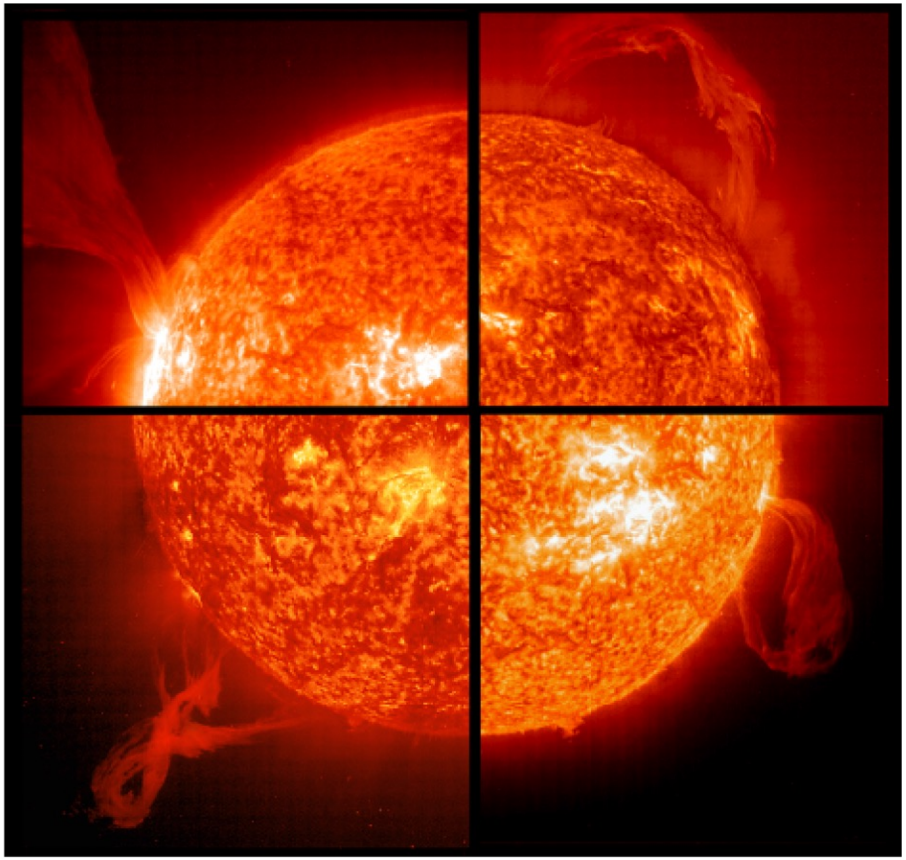
Flares, coronal mass ejections, corona

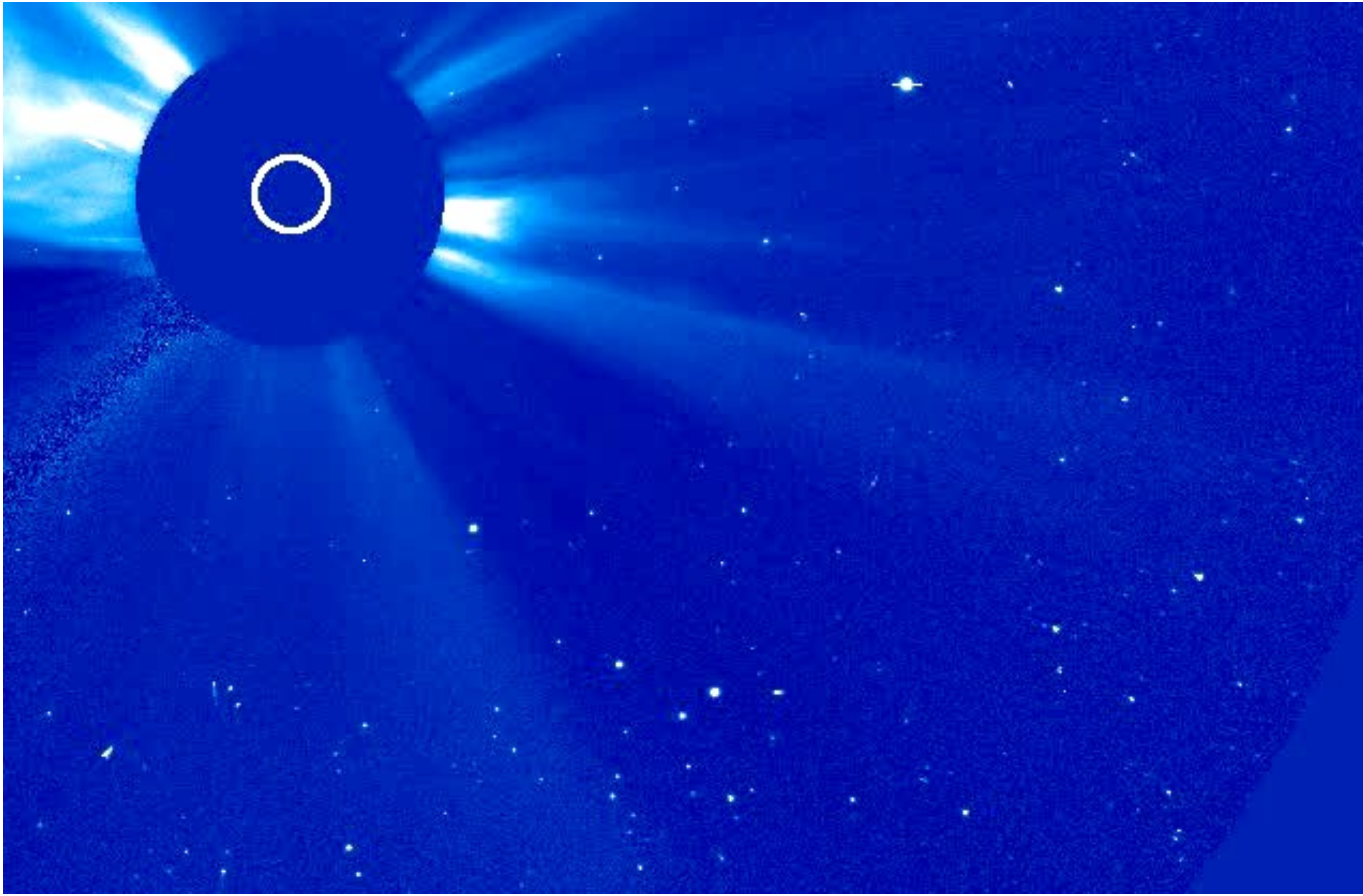
11 year magnetic cycles

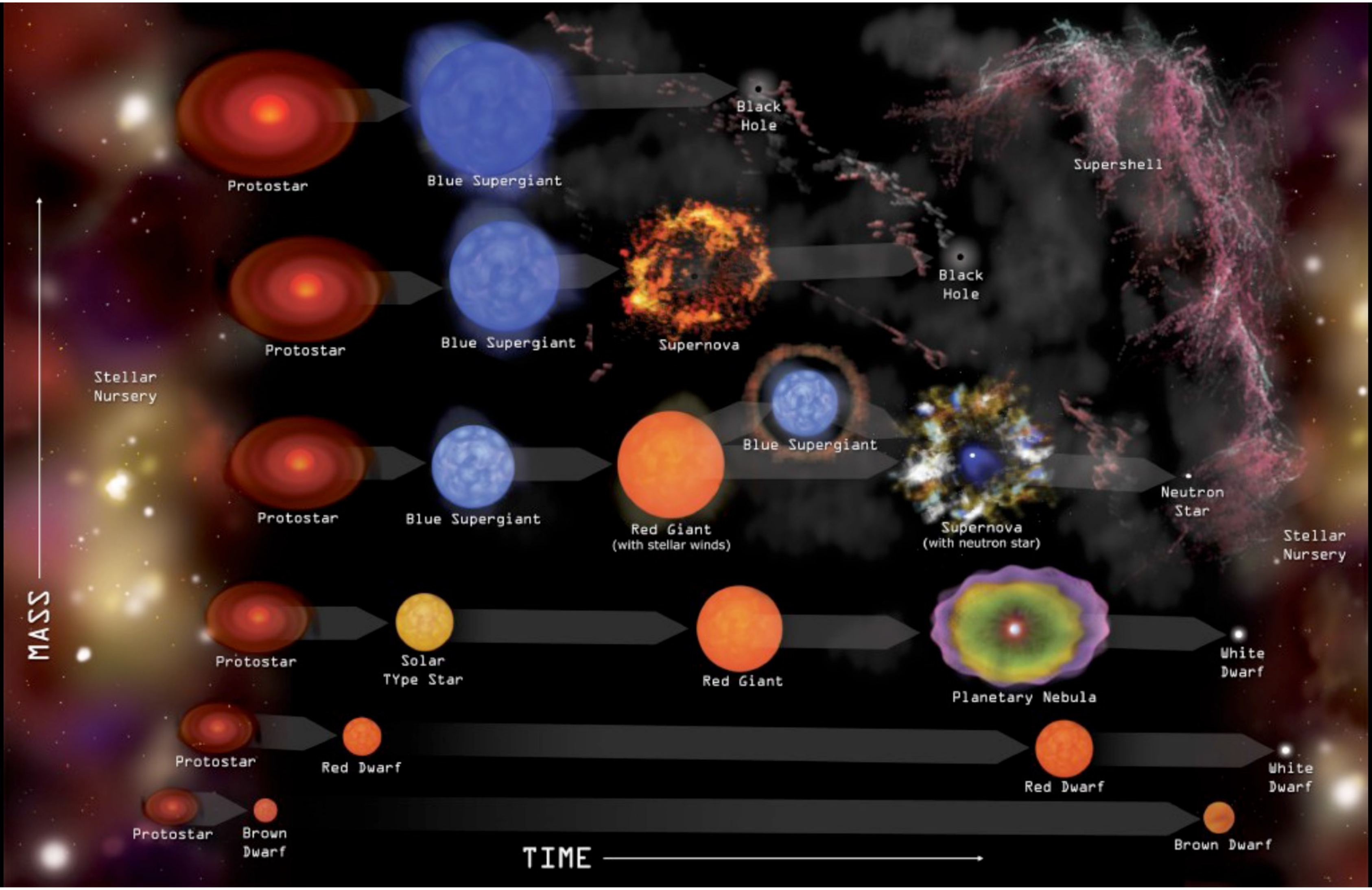





Approximate size of Earth






Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
TIME
Brown Dwarf

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