THE PAST 100 YEARS

ASTRONOMICAL VIEW OF THE WORLD – LECTURE 7

JONI TAMMI

EXCURSION TONIGHT:

OBSERVATORY MUSEUM:

DIVIDE INTO GROUPS AT 18:00, BE THERE A BIT BEFORE

TODAY

Astronomy in the 1900s

- Focus on stars, and their role in the Universe

Next weeks:

- Astronomy in the 2000s (L8)
- Astronomy in art and popular culture (L9)
- Astrobiology and Life in the Universe (L10)
- Big Bang theory & modern cosmology (L11)

PRELIMINARY WORK

Sun & Stars
[23 min]

- What physical processes are involved in stars that keep them shining?
- What is the H-R diagram and what is it good for?
- What kind of a star is our own Sun?
- What is solar wind?
- What is a star's spectrum?
- What do spectral lines tell us about the star?

Expanding Universe
[23 min]

- What observational evidence we have for expanding Universe?
- What is cosmological redshift?
- Why it is different from the Doppler effect?
- Why it’s the Universe expanding rather than things flying away from us?
- How is “Einstein’s gravity” different from “Newton’s gravity”?

IN THE BEGINNING OF THE 20TH CENTURY

New concepts:

- Statistical physics (understanding gas)
- Atoms (but no internal structure yet)
- Radioactivity (but no fusion or fission)
- Quantum mechanics being born
- Electromagnetism

Astronomical view of the World:

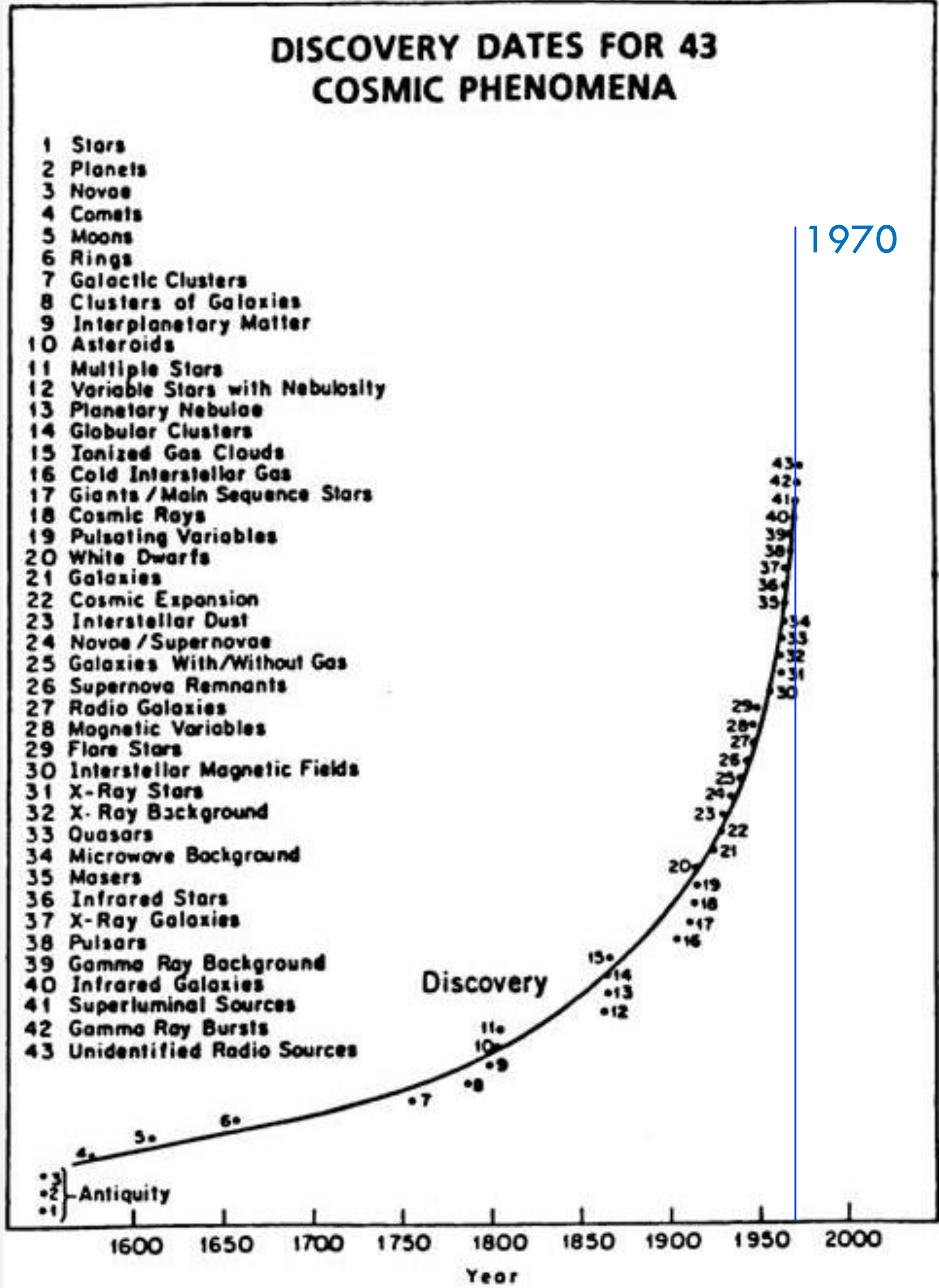
- Not sure how the stars work. Probably made of the same stuff than the Earth.
- Light may not propagate in ”aether” (Michelson-Morley experiment in 1887)
- Universe is eternal and unchanging.
- Sun is just a star; Earth still unique?
- Hypothesis: maybe other galaxies?

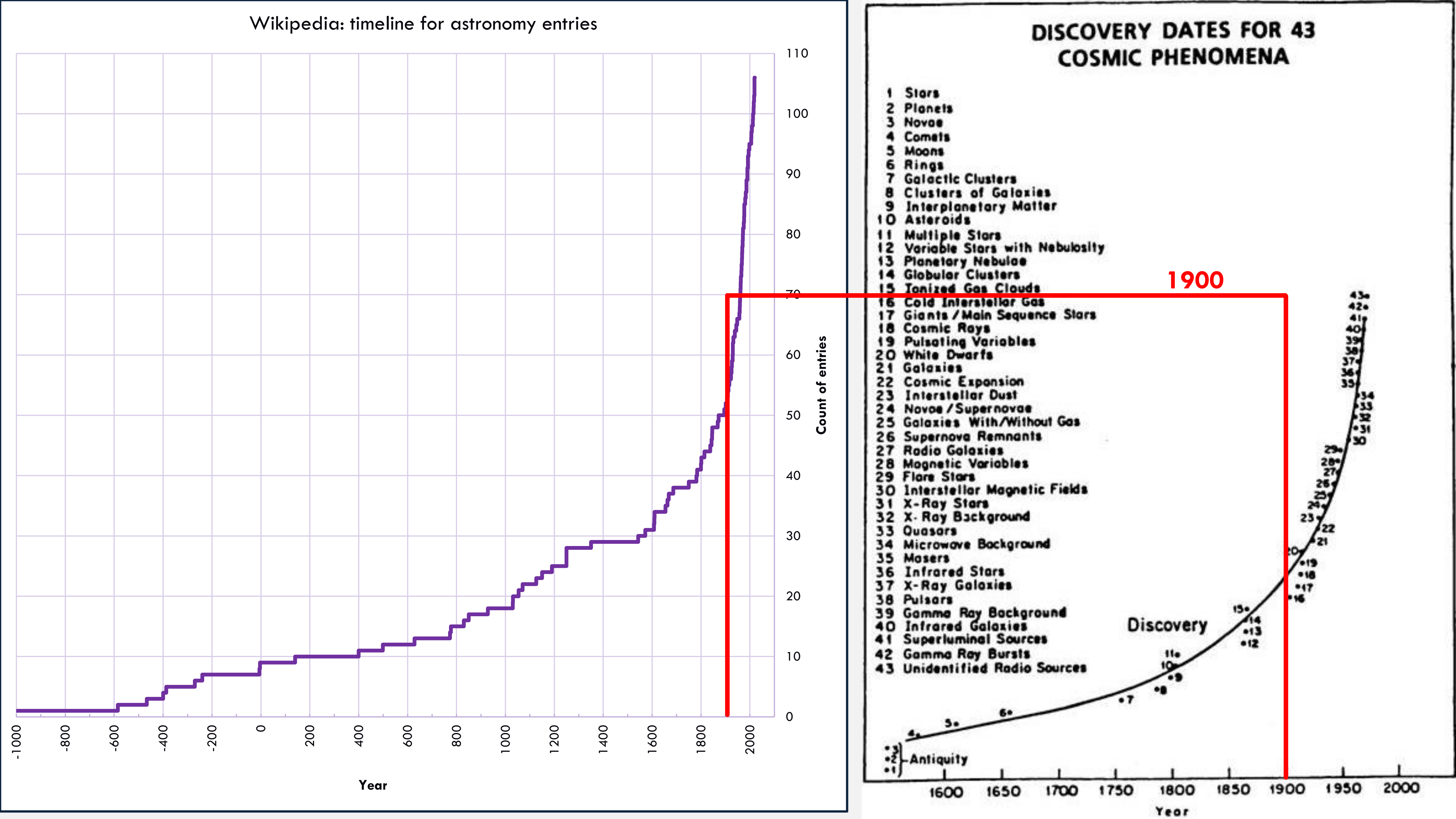
RECENT PARADIGM SHIFTS

Late 19th century

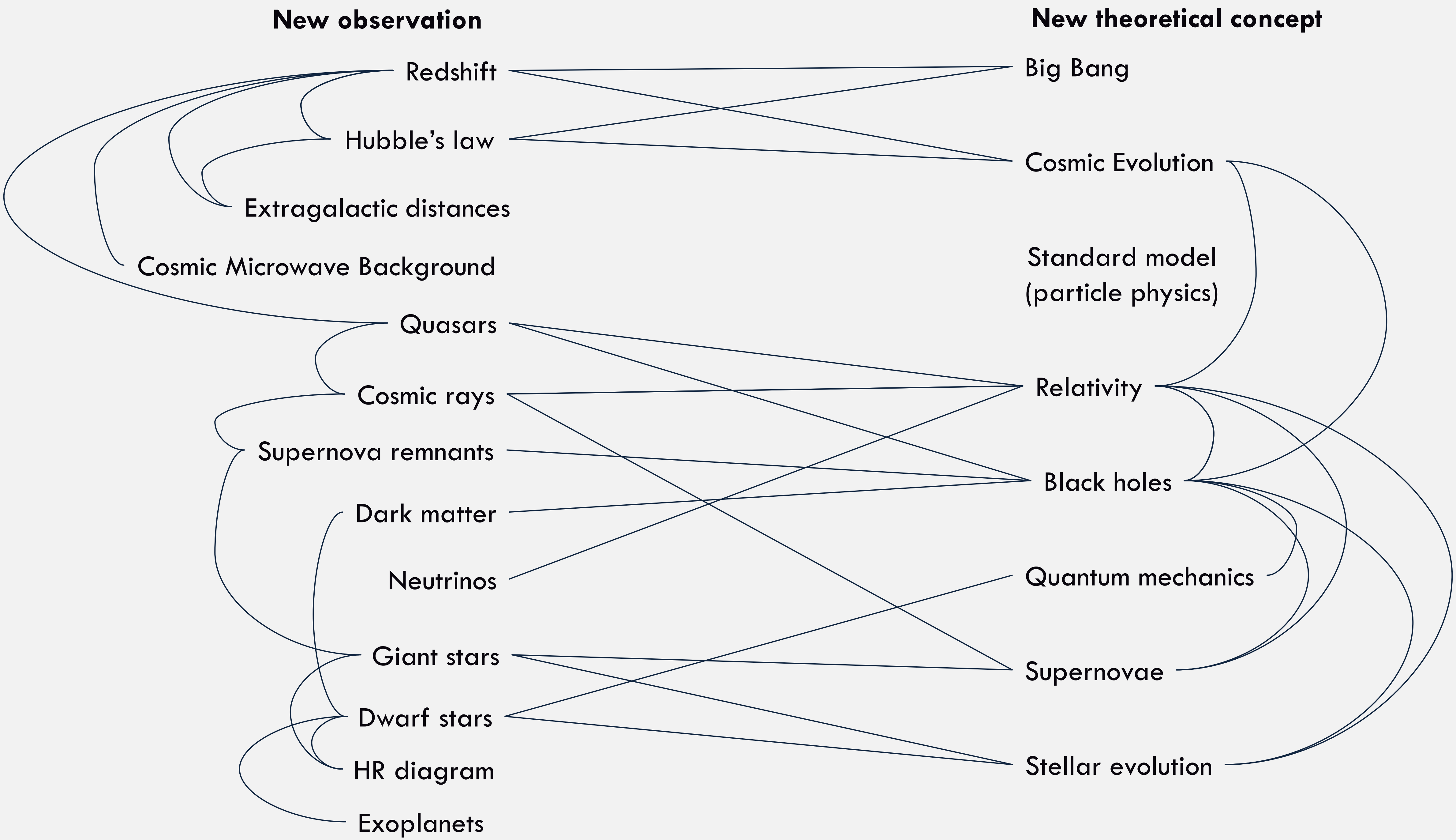
- Humans are related to animals
- (Genetic) traits can be inherited
- The Earth is millions of years old
- There are different kinds of stars

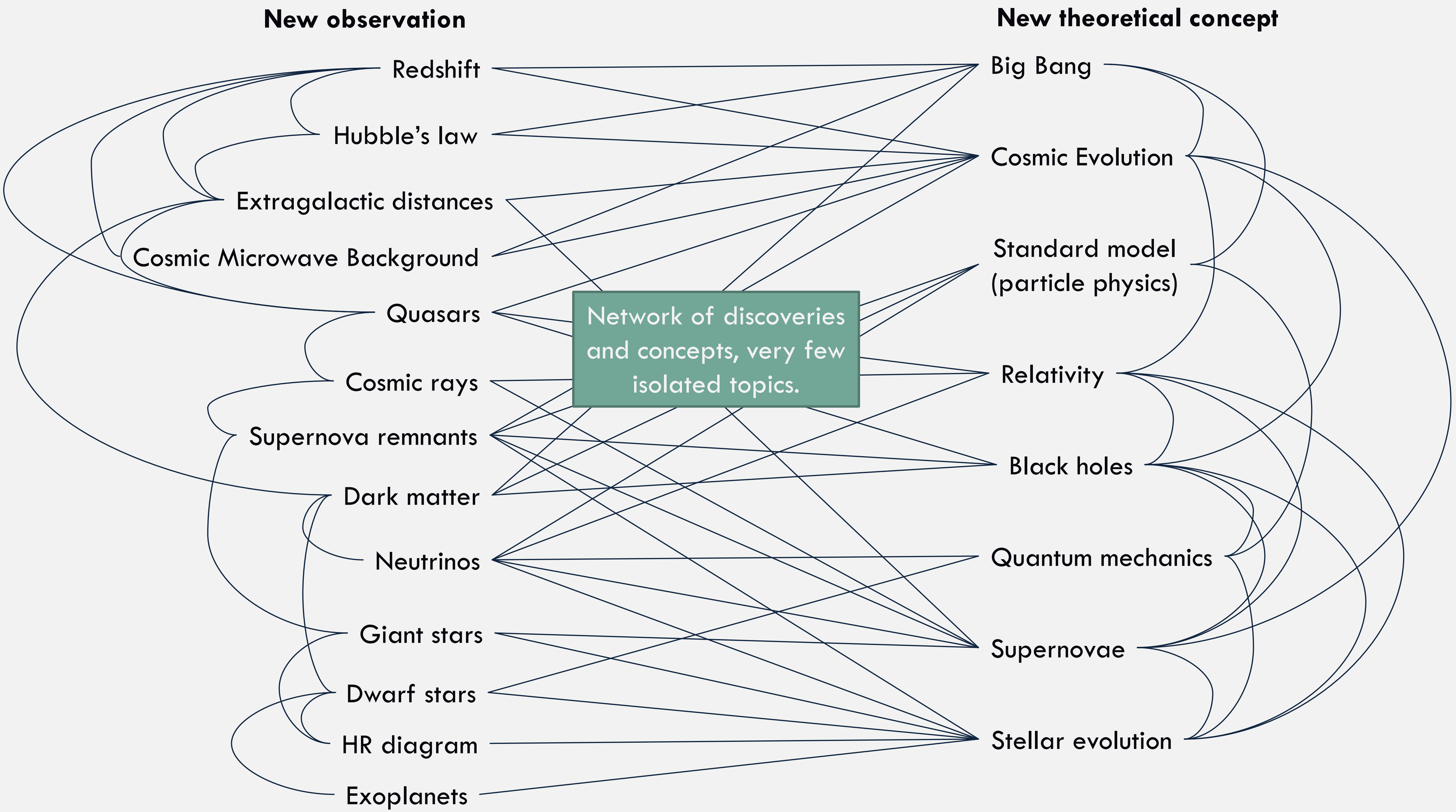
- The Scientific method





Wikipedia: timeline for astronomy entries
Count of entries
Year
DISCOVERY DATES FOR 43 COSMIC PHENOMENA
1 Stars
2 Planets
3 Novae
4 Comets
5 Moons
6 Rings
7 Galactic Clusters
8 Clusters of Galaxies
9 Interplanetary Matter
10 Asteroids
11 Multiple Stars
12 Variable Stars with Nebulosity
13 Planetary Nebulae
14 Globular Clusters
15 Ionized Gas Clouds
16 Cold Interstellar Gas
17 Giants / Main Sequence Stars
18 Cosmic Rays
19 Pulsating Variables
20 White Dwarfs
21 Galaxies
22 Cosmic Expansion
23 Interstellar Dust
24 Novae / Supernovae
25 Galaxies With/Without Gas
26 Supernova Remnants
27 Radio Galaxies
28 Magnetic Variables
29 Flare Stars
30 Interstellar Magnetic Fields
31 X-Ray Stars
32 X-Ray Background
33 Quasars
34 Microwave Background
35 Masers
36 Infrared Stars
37 X-Ray Galaxies
38 Pulsars
39 Gamma Ray Background
40 Infrared Galaxies
41 Superluminal Sources
42 Gamma Ray Bursts
43 Unidentified Radio Sources
1900
Discovery
Antiquity
Year


New observation
New theoretical concept
Redshift
Hubble's law
Extragalactic distances
Cosmic Microwave Background
Quasars
Cosmic rays
Supernova remnants
Dark matter
Neutrinos
Giant stars
Dwarf stars
HR diagram
Exoplanets
Big Bang
Cosmic Evolution
Standard model (particle physics)
Relativity
Black holes
Quantum mechanics
Supernovae
Stellar evolution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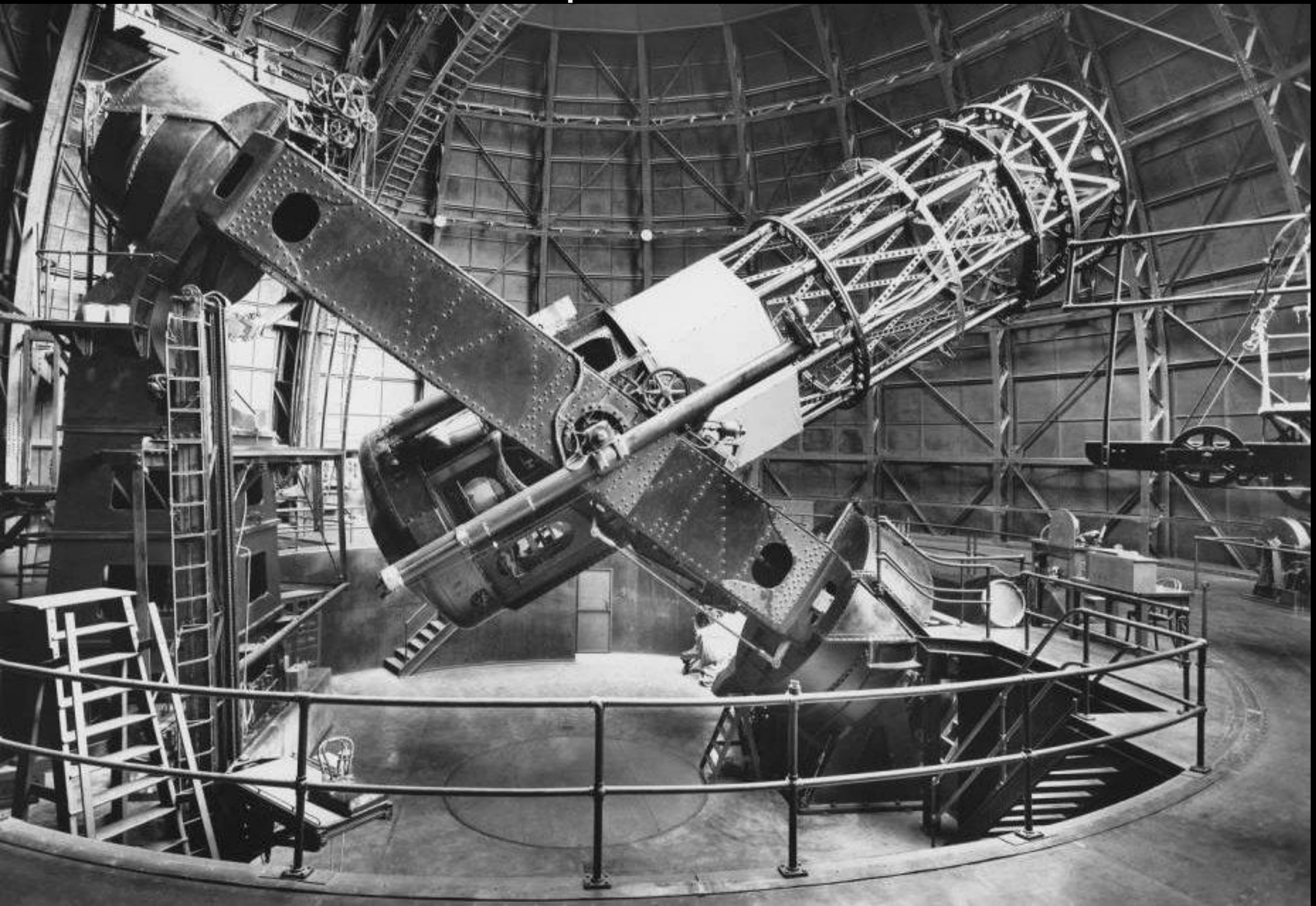
New theoretical concept
Big Bang
Cosmic Evolution
Standard model
(particle physics)
Relativity
Black holes
Quantum mechanics
Supernovae
Stellar evolution
Network of discoveries and concepts, very few isolated topics.

Samuel Oschin telescope, 1.22m, 1948

TECHNOLOGICAL IMPROVEMENTS IN THE 20TH CENTURY

- Telescopes / optics
  - See smaller details
  - See fainter objects

Hooker telescope, 2.54m, 1917



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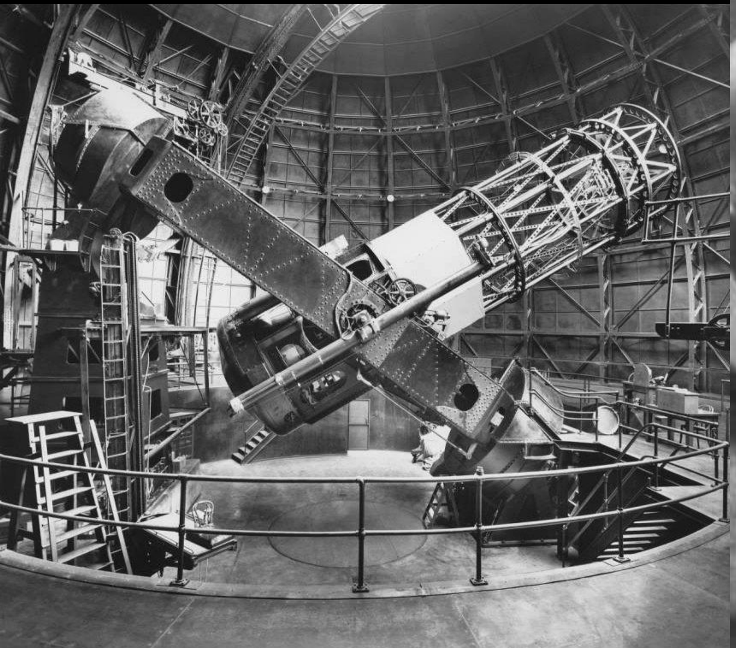


Hubble space telescope, 2.4m, 1990

TECHNOLOGICAL IMPROVEMENTS IN THE 20TH CENTURY

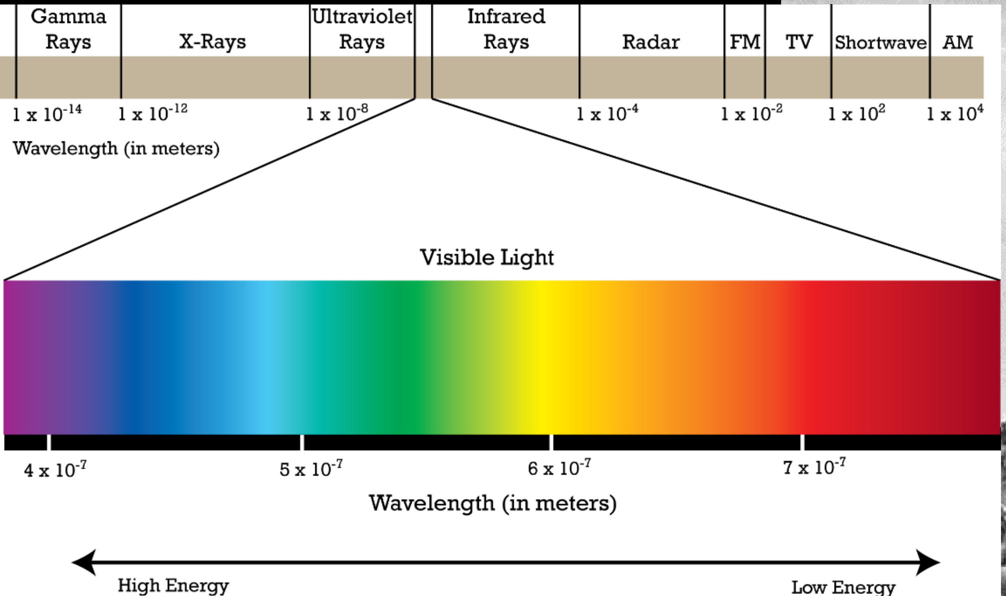
- Telescopes / optics
  - See smaller details
  - See fainter objects

Led to, for example:
different types of galaxies

TECHNOLOGICAL IMPROVEMENTS

- Telescopes / optics
  - See smaller details
  - See fainter objects
- New wavelengths
  - See different energies
  - See “invisible” objects

The Parkes radio telescope, 64 m, 1961



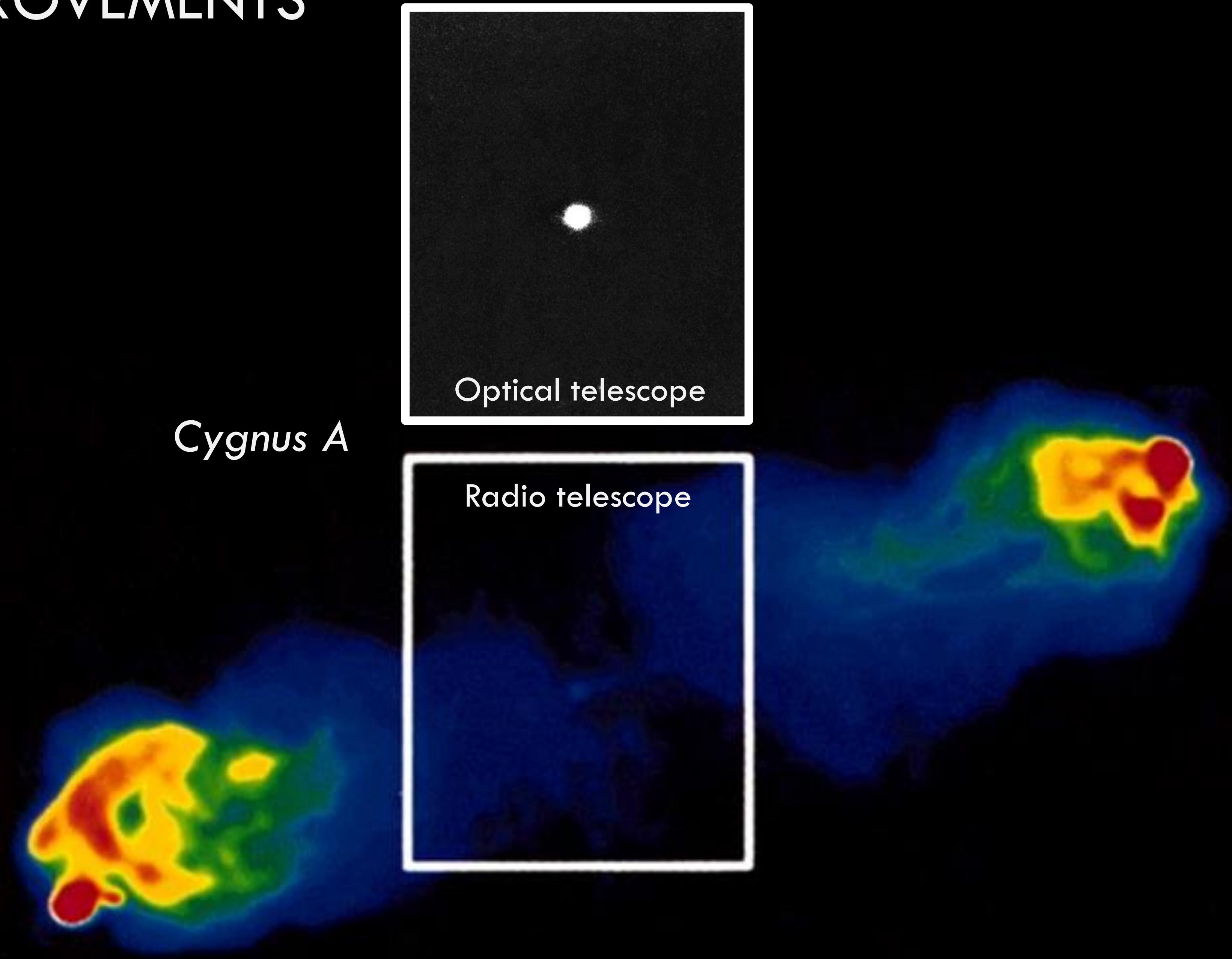
TECHNOLOGICAL IMPROVEMENTS

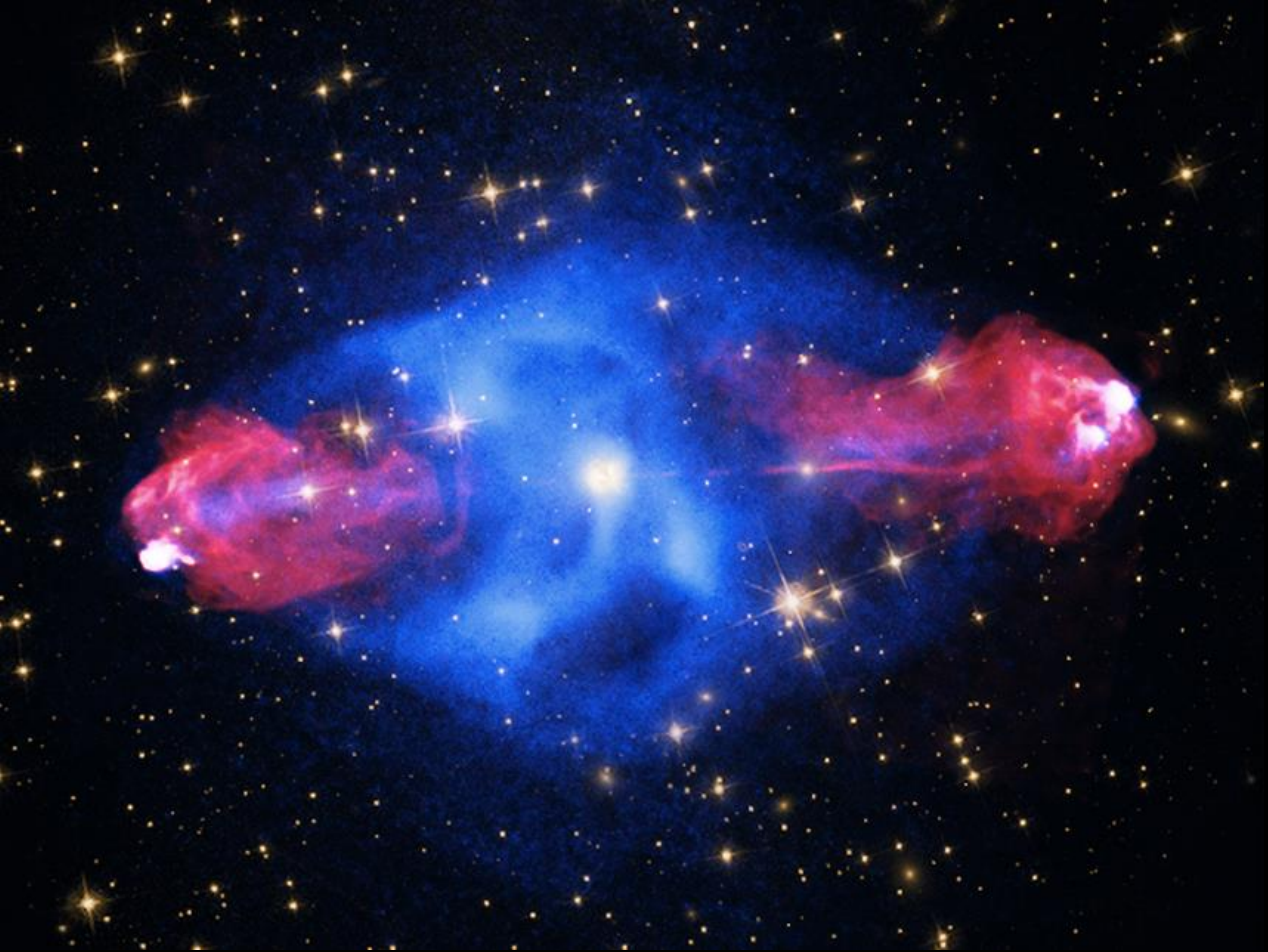
- Telescopes / optics
  - See smaller details
  - See fainter objects
- New wavelengths
  - See different energies
  - See “invisible” objects

Led to, for example: completely new objects;

Radio galaxies and

”Quasi stars” / Quasars





X-rays

Optical

Radio

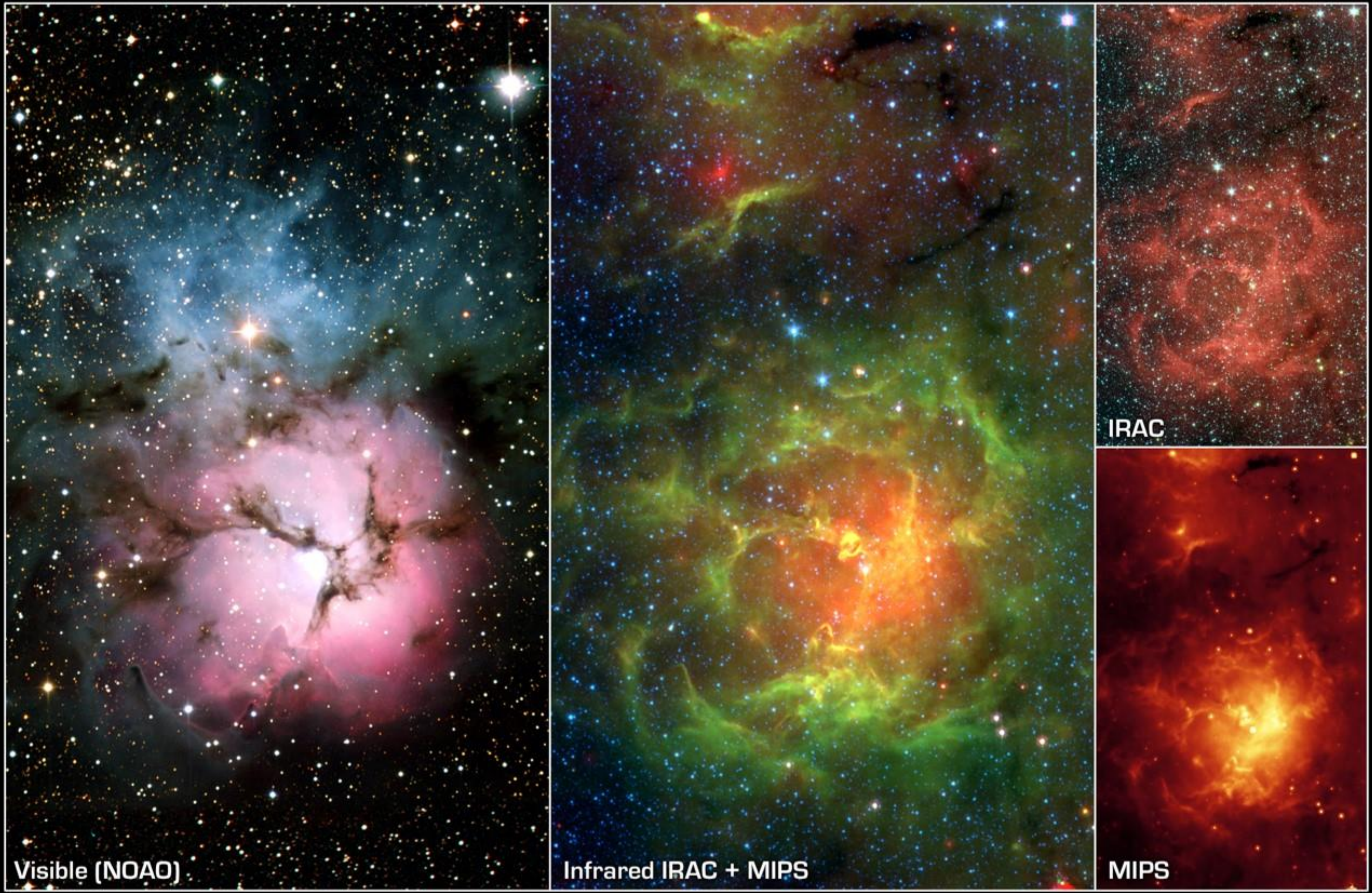
M20

Reflection nebula

Dark/ absorption nebula

Emission nebula

Open cluster



Trifid Nebula/Messier 20

NASA / JPL-Caltech / J. Rho (SSC/Caltech)

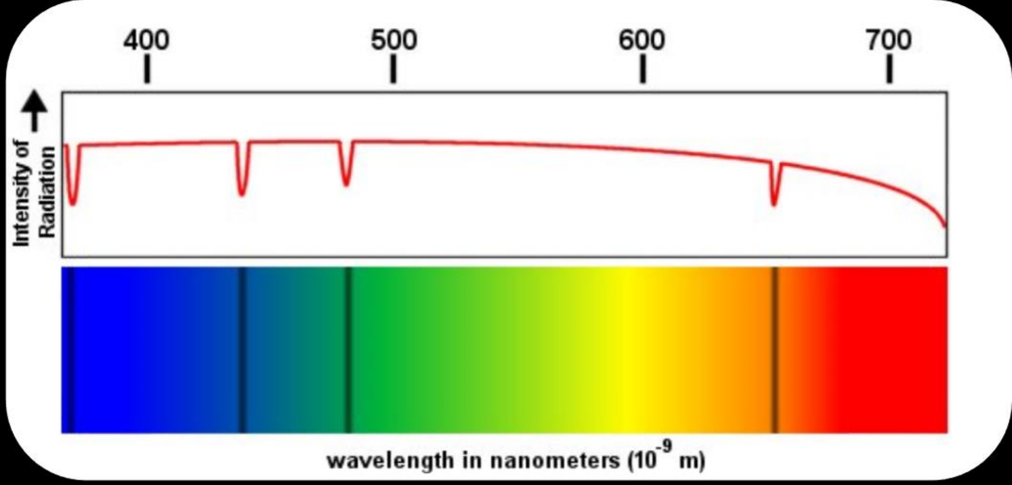
Spitzer Space Telescope • IRAC + MIPS

ssc2005-02a

TECHNOLOGICAL IMPROVEMENTS

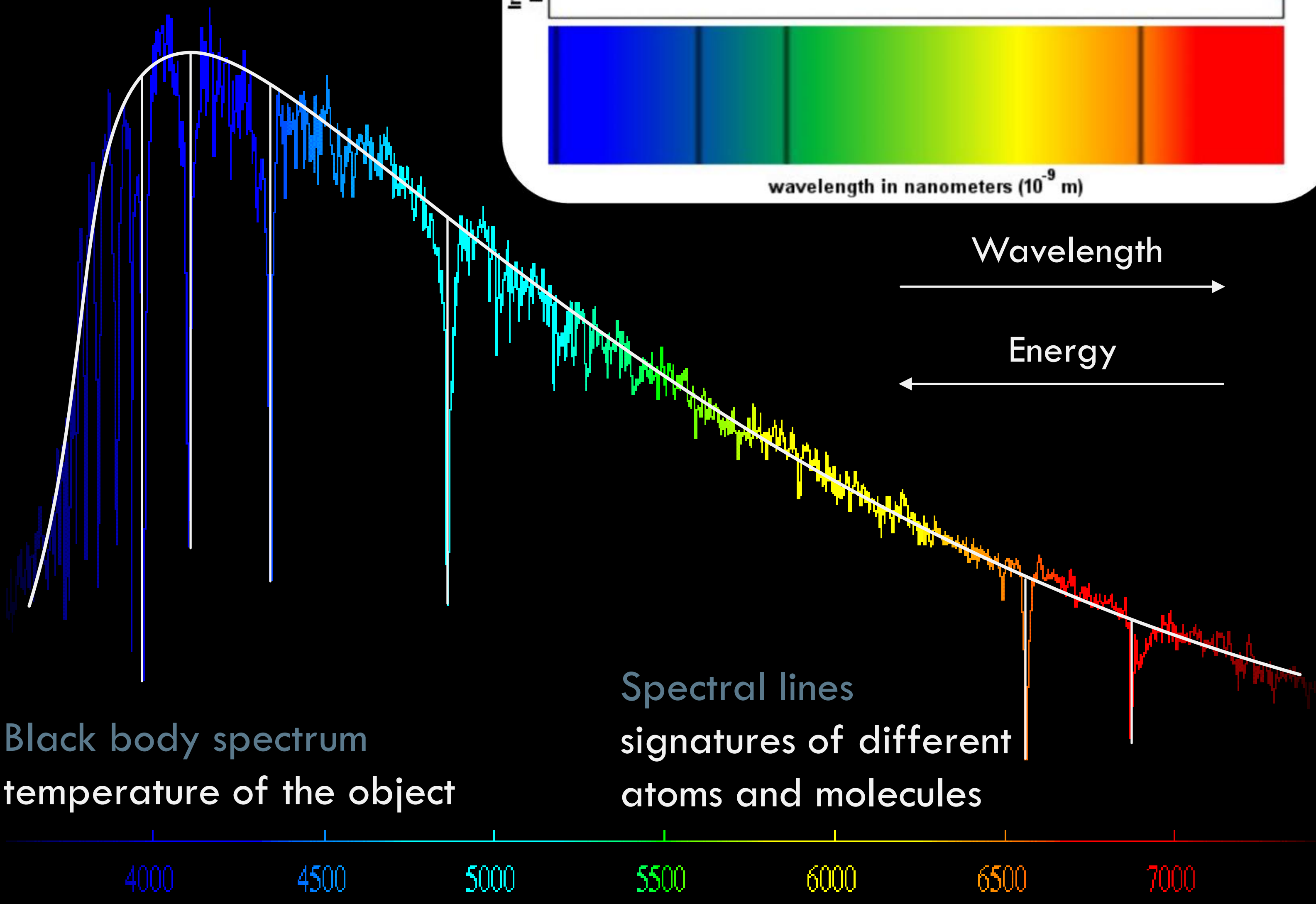
- Telescopes / optics
  - See smaller details
  - See fainter objects
- New wavelengths
  - See different energies
  - See “invisible” objects
- Understanding spectroscopy
  - What the object is made of

Led to, for example: Stellar composition and evolution.



Wavelength

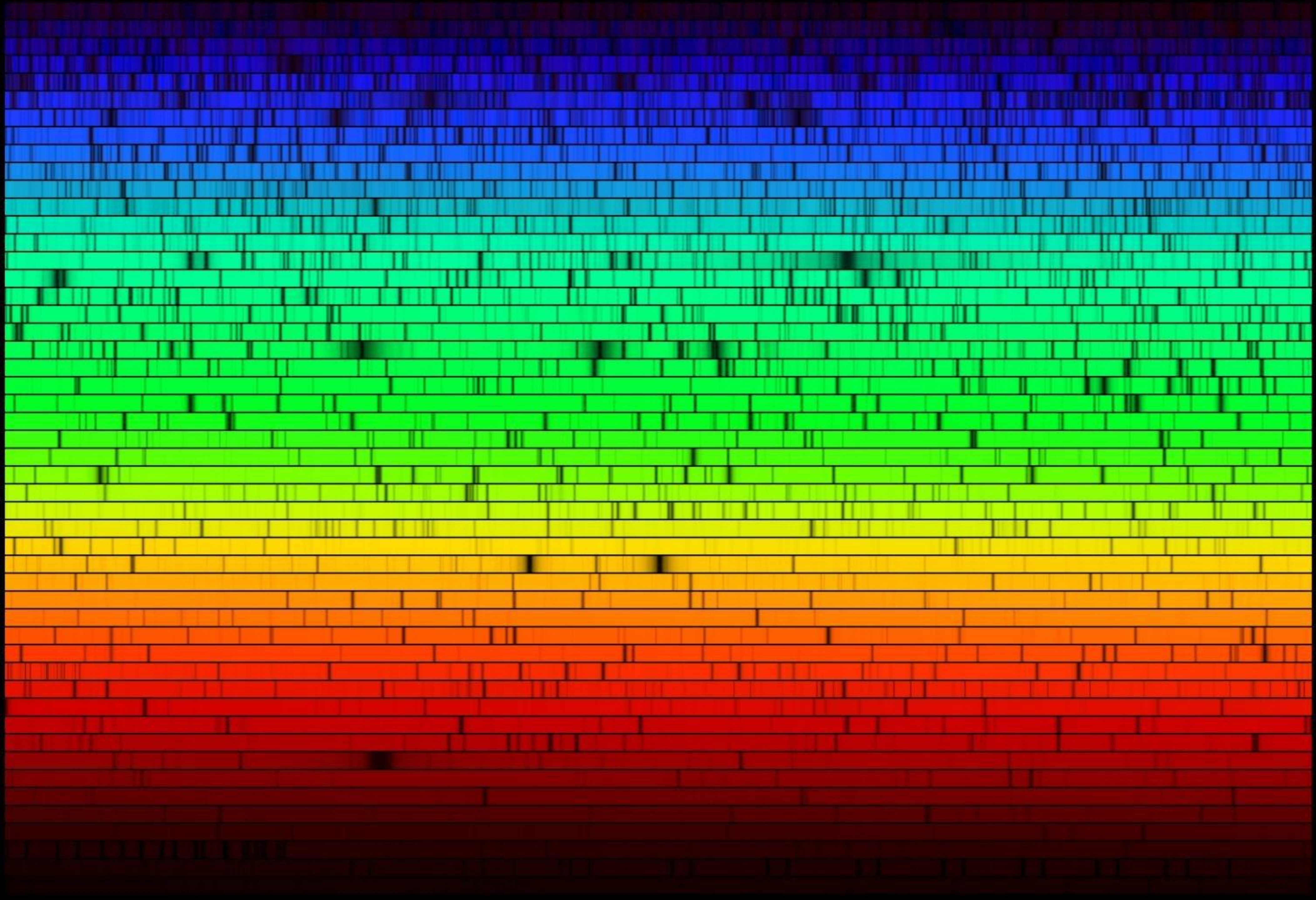
Energy



Black body spectrum
temperature of the object

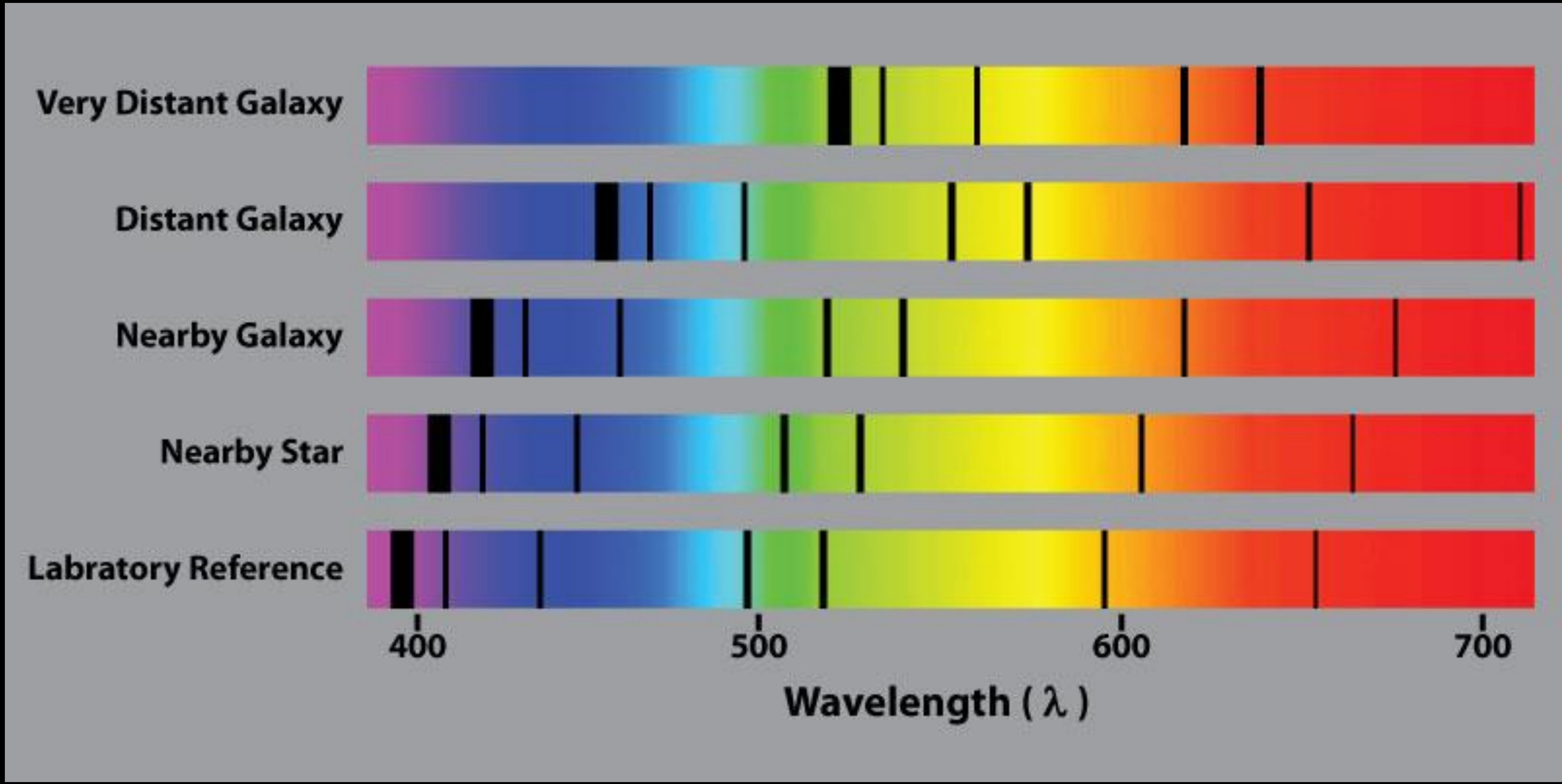
Spectral lines
signatures of different atoms and molecules

THE SUN



TECHNOLOGICAL IMPROVEMENTS

- Telescopes / optics
  - See smaller details
  - See fainter objects
- New wavelengths
  - See different energies
  - See "invisible" objects
- Understanding spectroscopy
  - What the object is made of
  - Red/blueshift



Preliminary work: Hubble's law, expansion of the Universe

Doppler effect: Object moves → wavelength changes.

TECHNOLOGICAL IMPROVEMENTS

Hubble's law: the farther it is, the faster the distance grows (= the larger the redshift)

- Telescopes / optics
  - See smaller details
  - See fainter objects
- New wavelengths
  - See different energies
  - See "invisible" objects
- Understanding spectroscopy
  - What the object is made of
  - Red/blueshift

Galaxies far, far away.
Expansion of the universe.

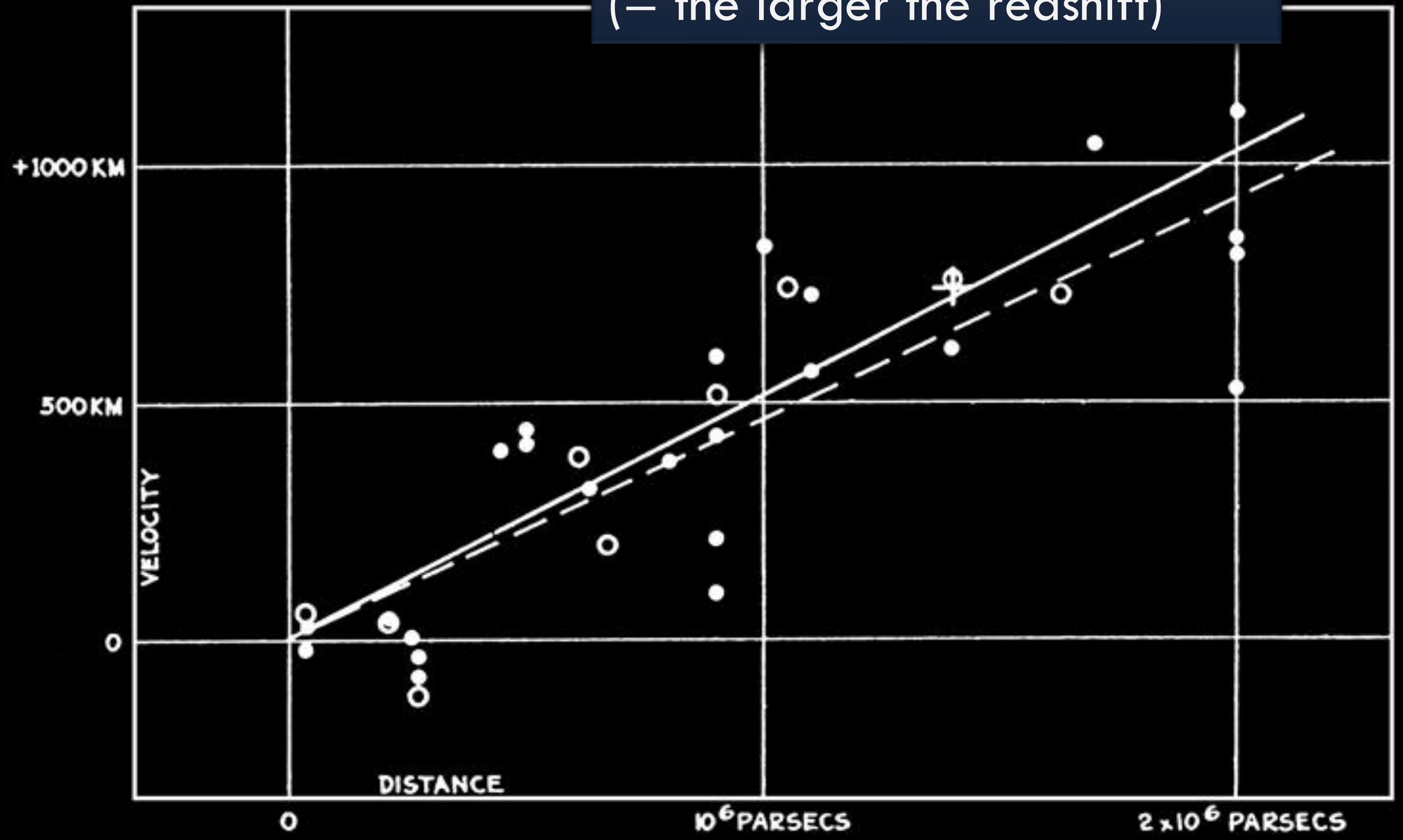


Figure 1, from the article *A relation between distance and radial velocity among extra-galactic nebulae* by Hubble, E. P. (1929), in Proc. Natl. Acad. Sci. USA 15, 168–173 (link)

STORY SO FAR

Expansion of the Universe

- ~~Galaxies are moving away from each others~~
- The distance between galaxies is growing
- Hubble's law: $v = H_0 D$
- Universe is expanding

Hubble constant tells us how fast the Universe expands.

- The expansion speed v between two points is simply their distance D times the Hubble constants H_0.
- Hubble constant $H_0 \approx 70$ (km / s) / Mpc
- Mpc = mega-parsec ≈ 3 million ly
- The distance between two galaxies grows at the speed of 70 (km / s) / Mpc.
- Each second, space "grows" 70 km / Mpc.

$D = 1$ Mpc → $v = 70$ km/s

$D = 2$ Mpc → $v = 140$ km/s

$D = 10$ Mpc → $v = 700$ km/s

$D = 100$ Mpc → $v = 7000$ km/s

STORY SO FAR

Expansion of the Universe

- ~~Galaxies are moving away from each others~~
- The distance between galaxies is growing
- Hubble's law: $v = H_0 D$
- Universe is expanding
- Universe has a finite lifetime

> Hubble constant tells us how fast the Universe expands, and how old it is.

Today bigger than yesterday
= yesterday smaller than today.

Hubble's law: $v = D\, H_0$

High-school physics: $v = \frac{D}{t} = D\, \frac{1}{t}$

$$H_0 = \frac{1}{t} \quad \Leftrightarrow \quad t = \frac{1}{H_0}$$

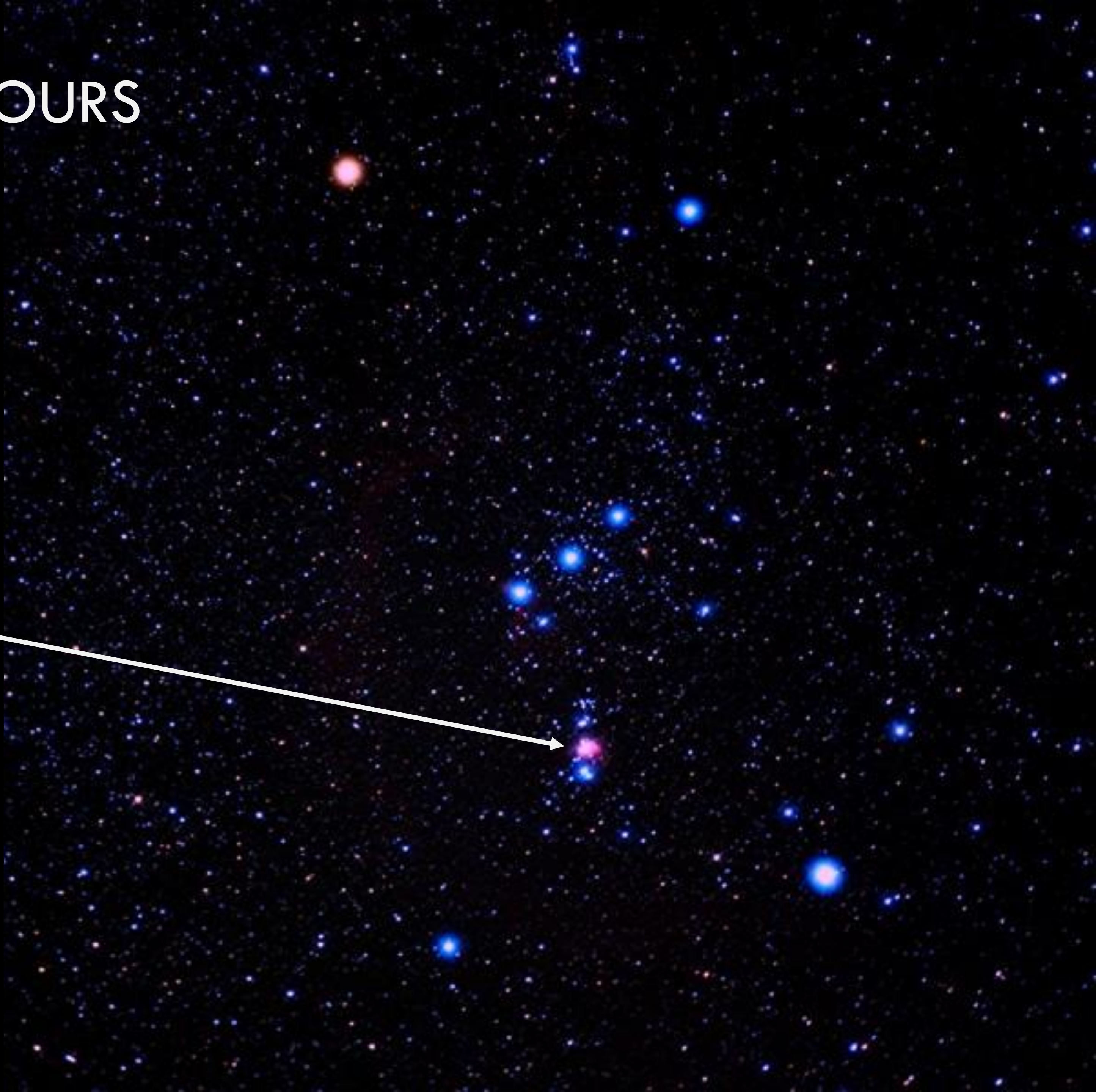
What time?

Hubble time, Universe's lifetime

$H_0 = 68$ km/s/Mpc → $t = 13.8$ Gy

STARS & STELLAR EVOLUTION

STARS HAVE DIFFERENT COLOURS



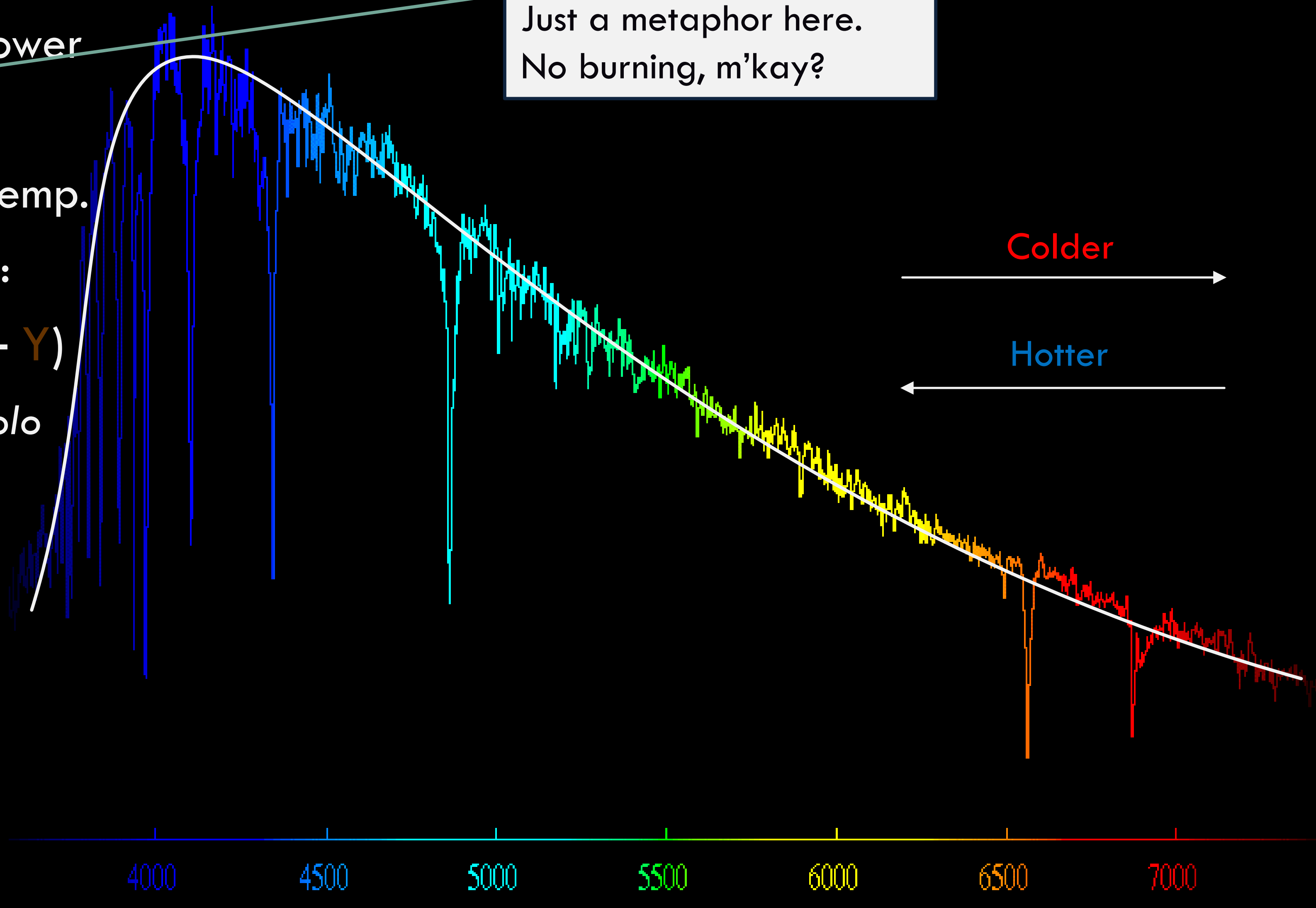
STARS HAVE DIFFERENT COLOURS

- All run by fusion, but with different power
- More massive → "burns" hotter
- Stars are "black bodies" → color = temp.
- Classification by colour (temperature):

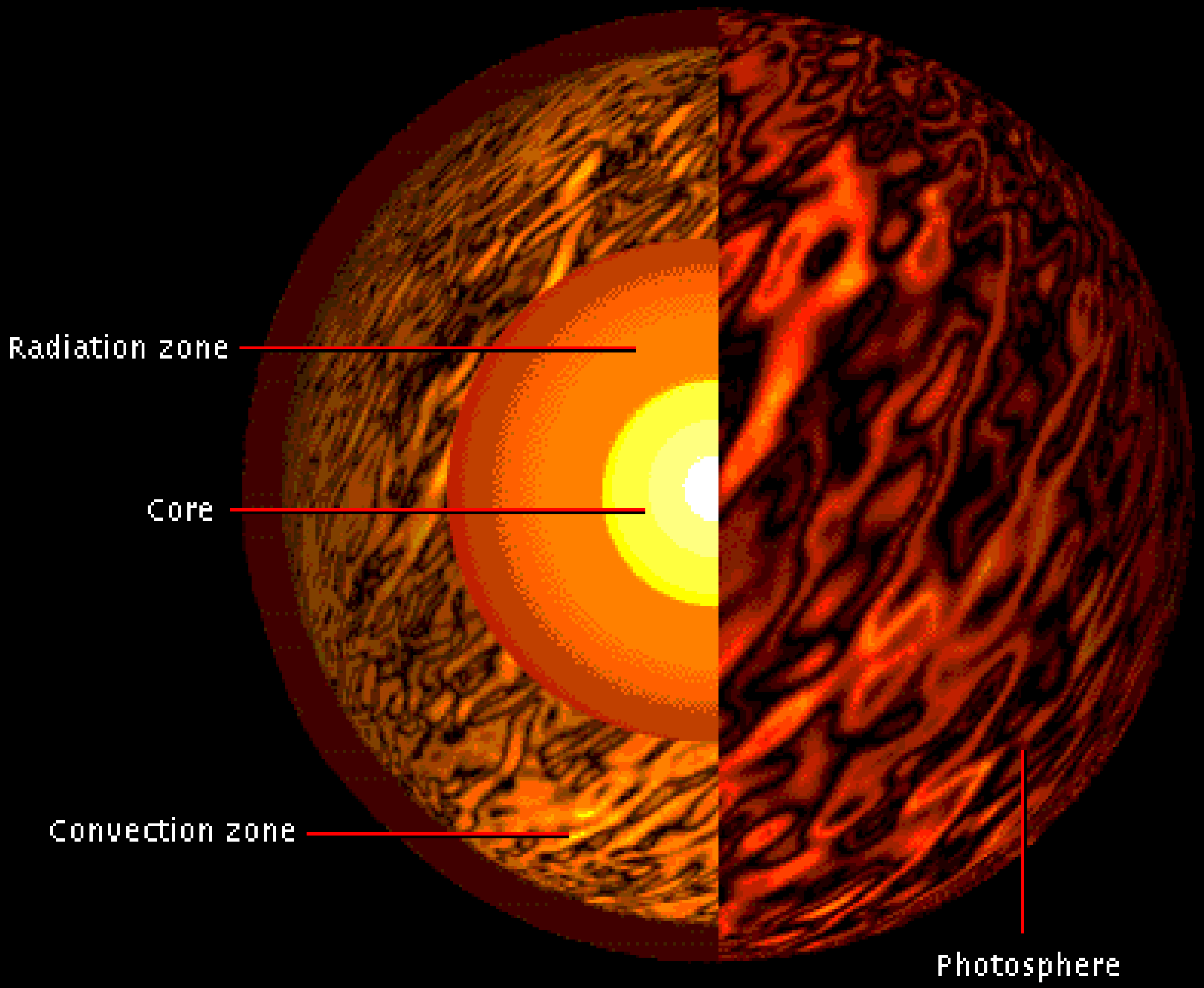
O – B – A – F – G – K – M (– L – T – Y)

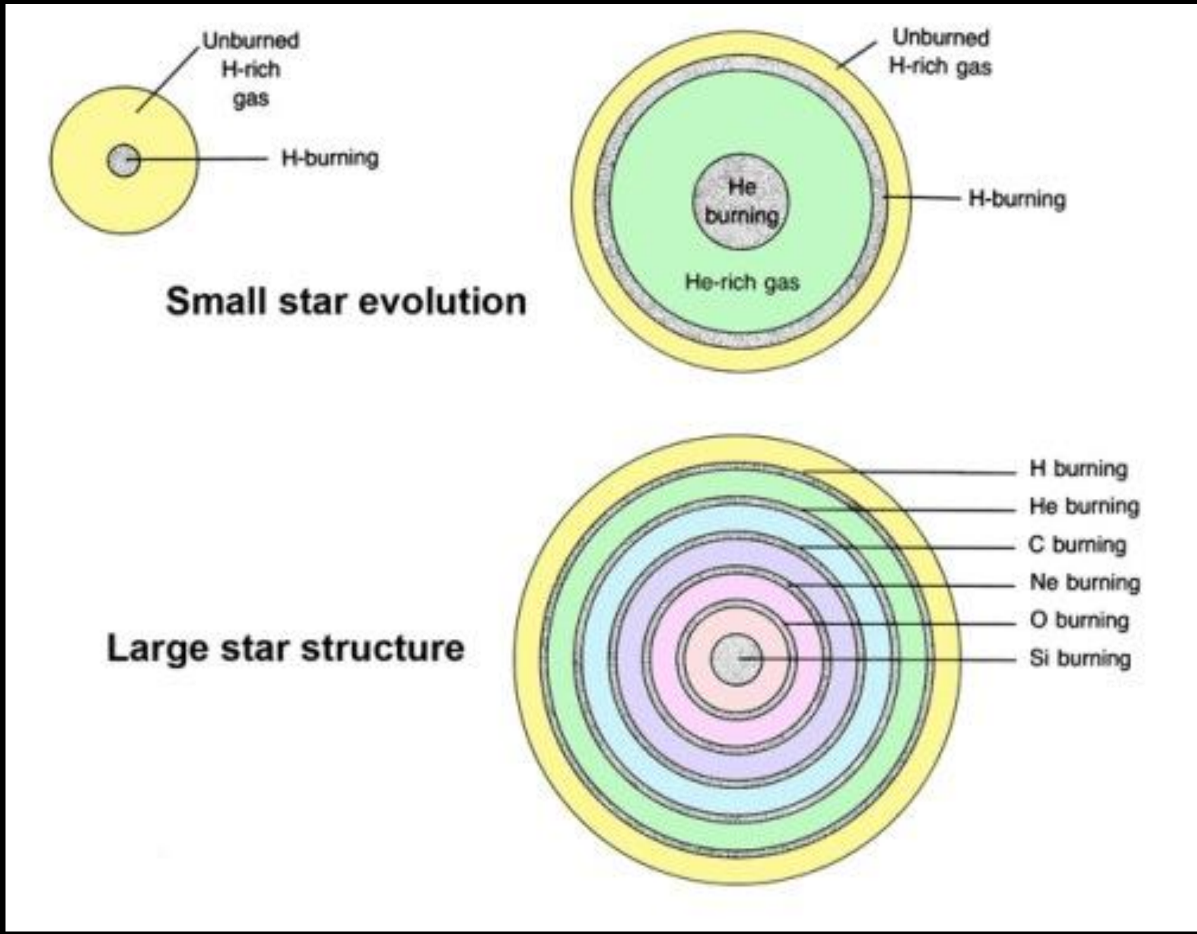
Oh Be A Fine Girl, Kiss Me Later Today #Yolo
Guy
Genderless person

N.B.: Stars *do not* burn.
No burning gas balls etc.
Just a metaphor here.
No burning, m'kay?



X-axis: Wavelength (Å), not temperature


Radiation zone
Core
Convection zone
Photosphere


Unburned
H-rich
gas
H-burning
Small star evolution
Unburned
H-rich gas
He
burning
H-burning
He-rich gas
Large star structure
H burning
He burning
C burning
Ne burning
O burning
Si burning

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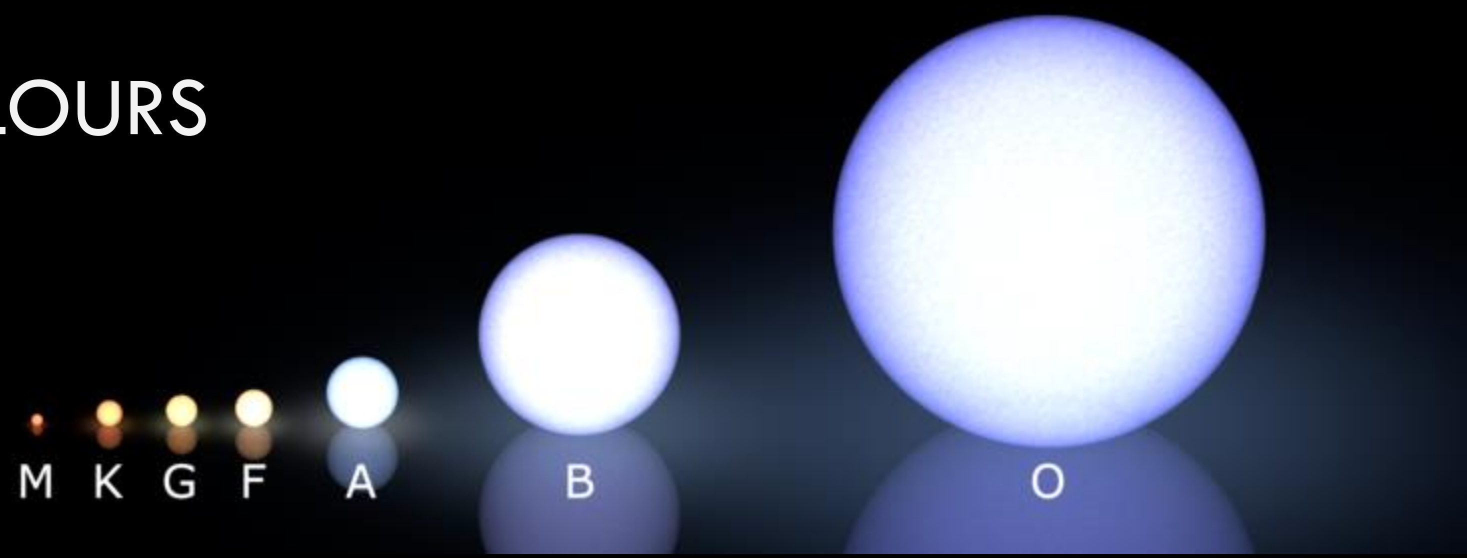
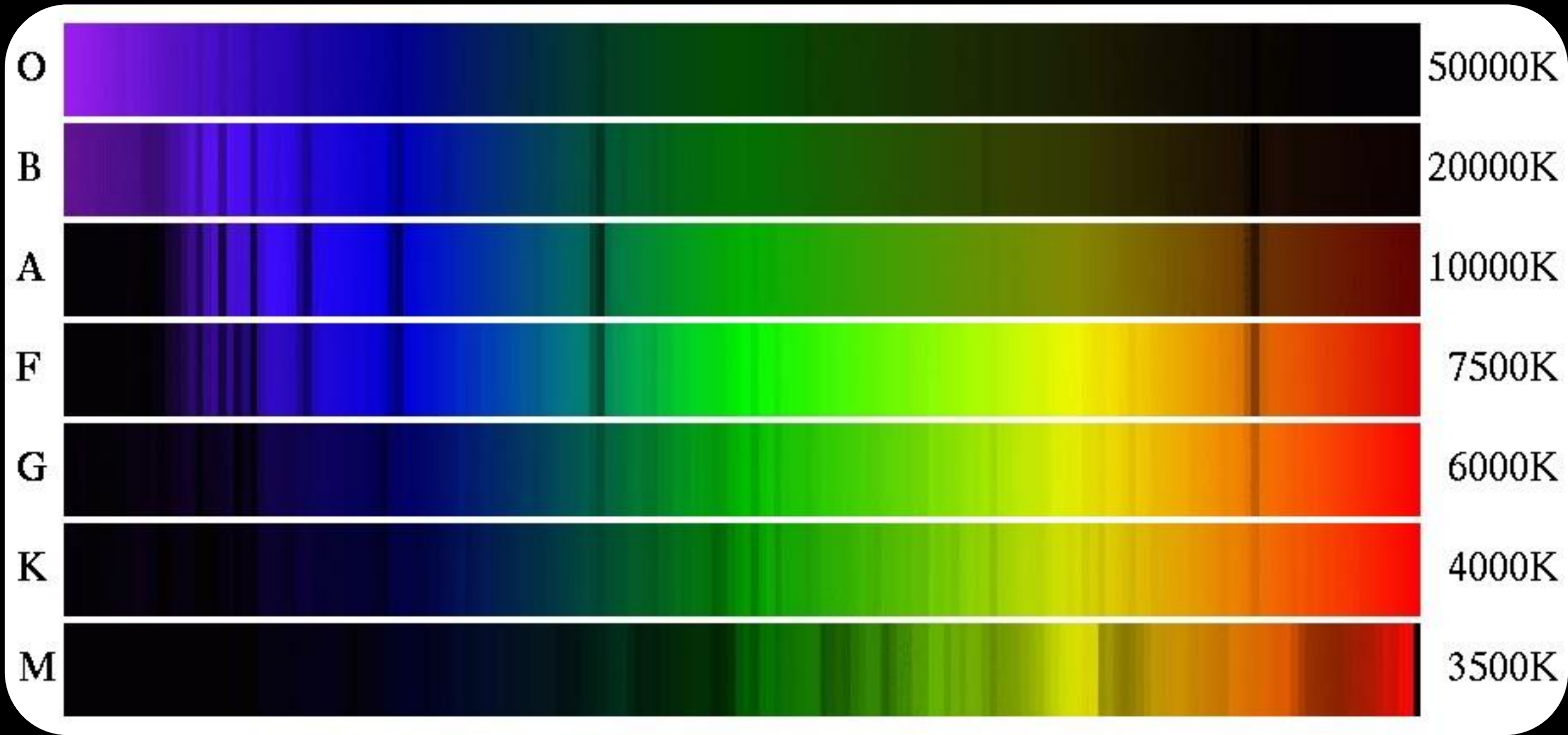


N.B. No red/blueshift; spectral lines in the same place.

O: Very massive (> 16 Msun)
Very hot (> 30 000 K)
Live a short time (millions of years)

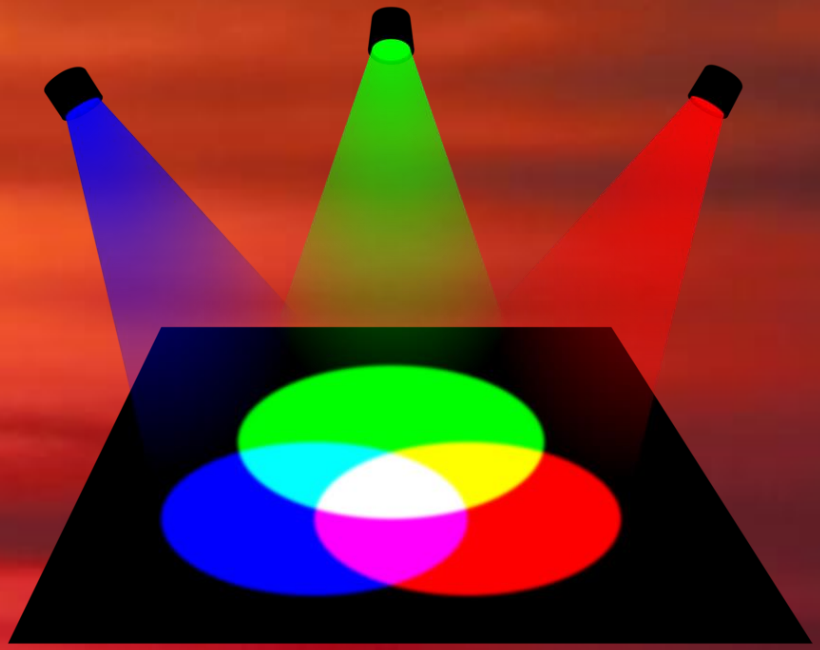
G: Average mass (~ 1 Msun)
Average temp. (~ 5 500 K)
Live billions of years (~10 Gy for Sun)

T: Low mass (~ 0.01 Msun)
Low temp. (~ 1 000 K)
Live "forever"



SO WHAT COLOUR IS THE SUN?

- Yellow? Orange? Red?
  - Only when seen through a “blue lense” (the atmosphere).
- White.
  - *“But you just said it’s yellow dwarf?!”*
  - Yes, its a *white* yellow dwarf.



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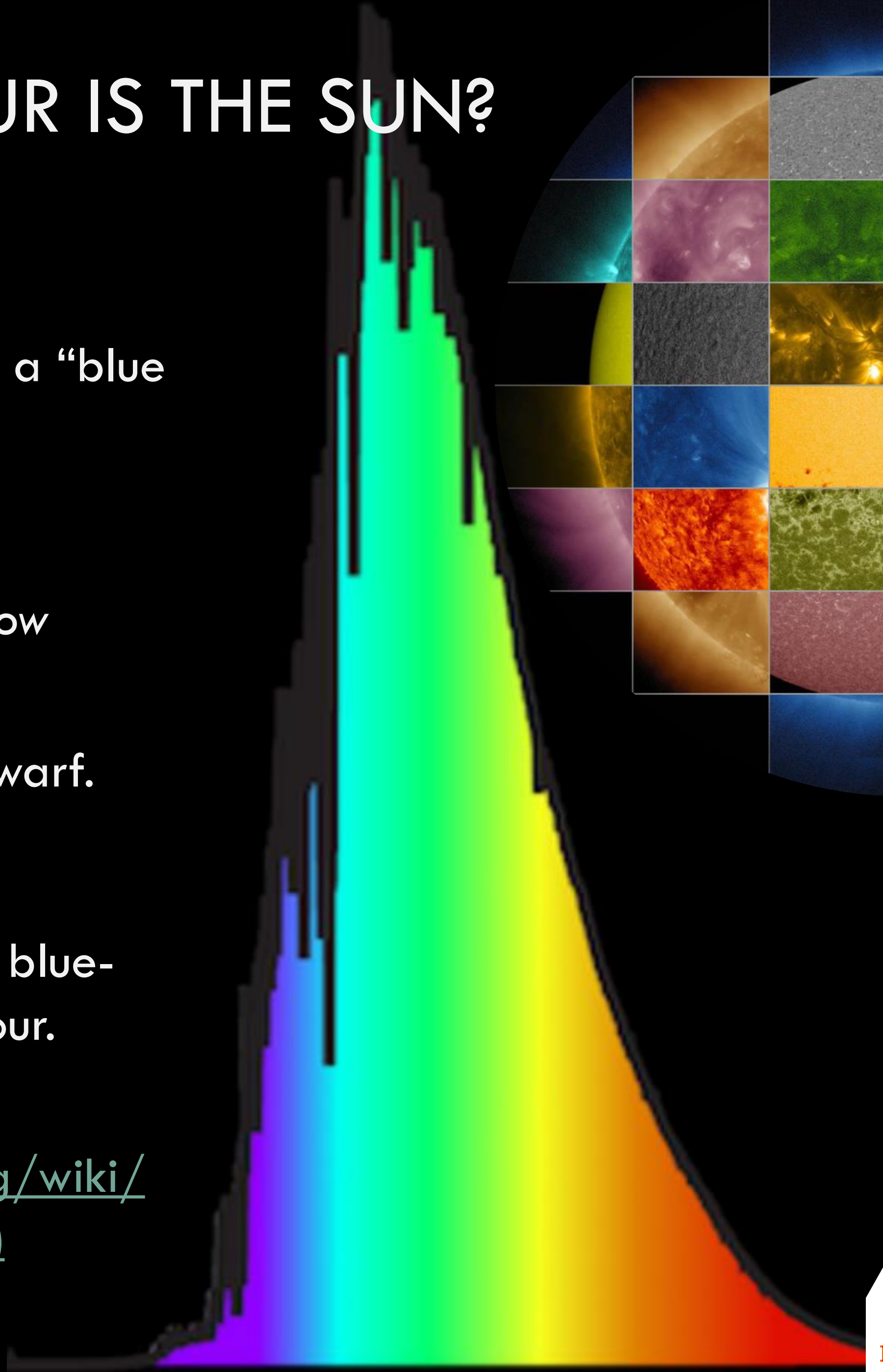
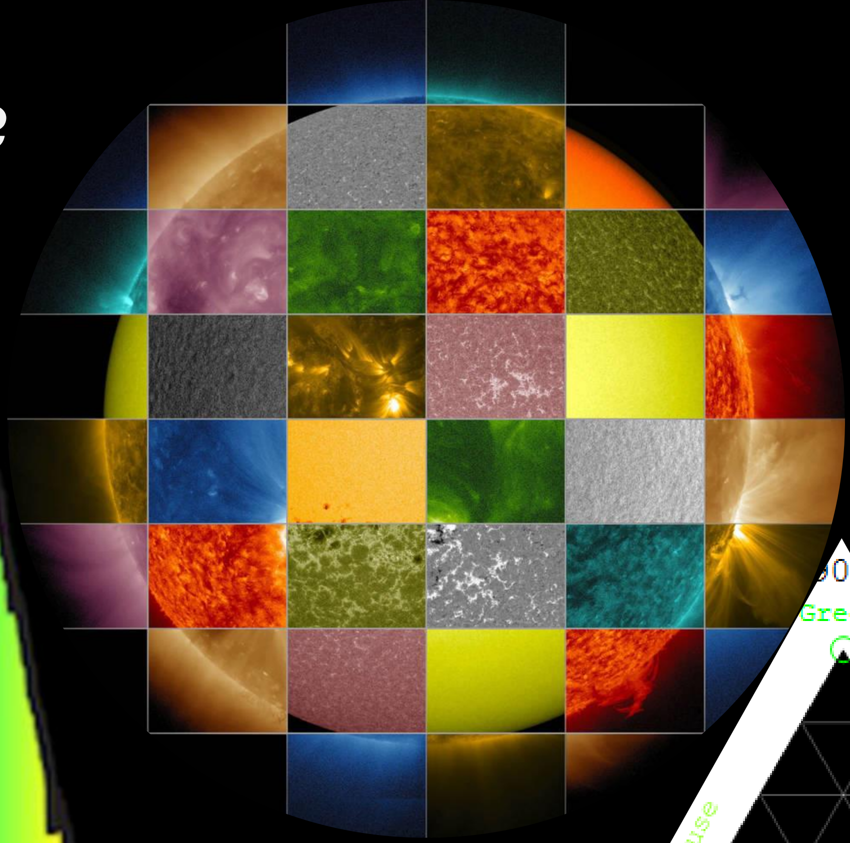
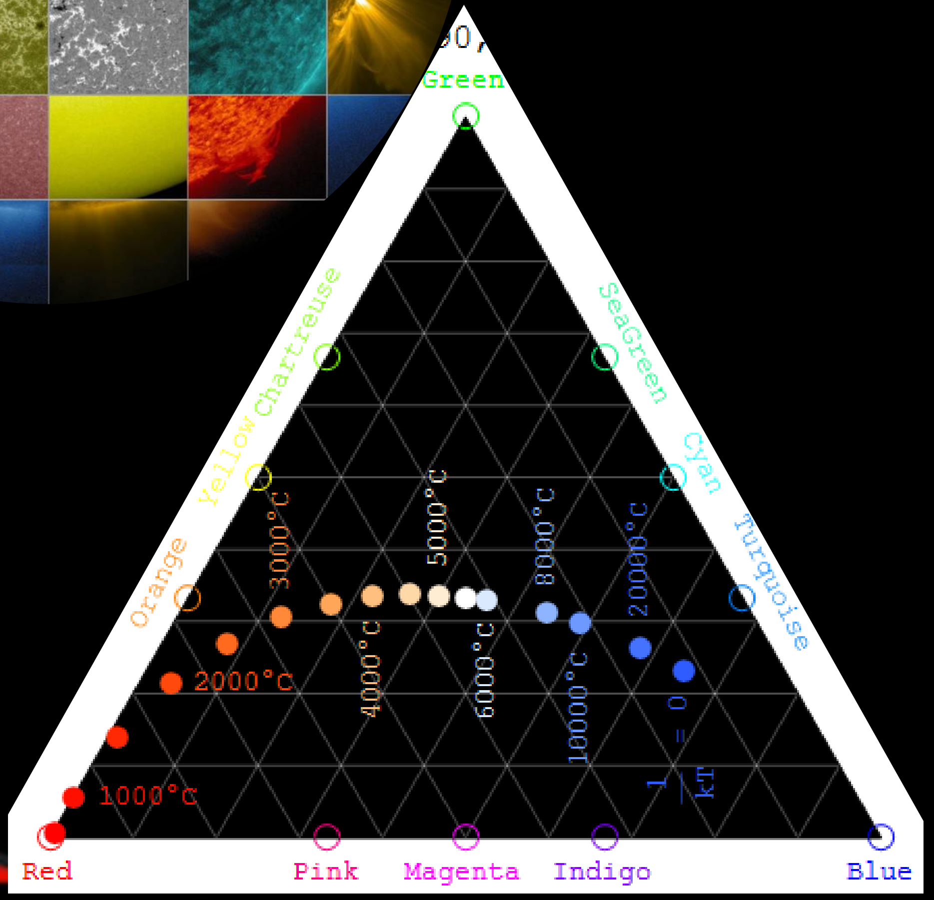
- Green?
  - Peak of the spectrum at blue-green; the brightest colour.
  - Green stars? https://en.wikipedia.org/wiki/Green_star_(astronomy)



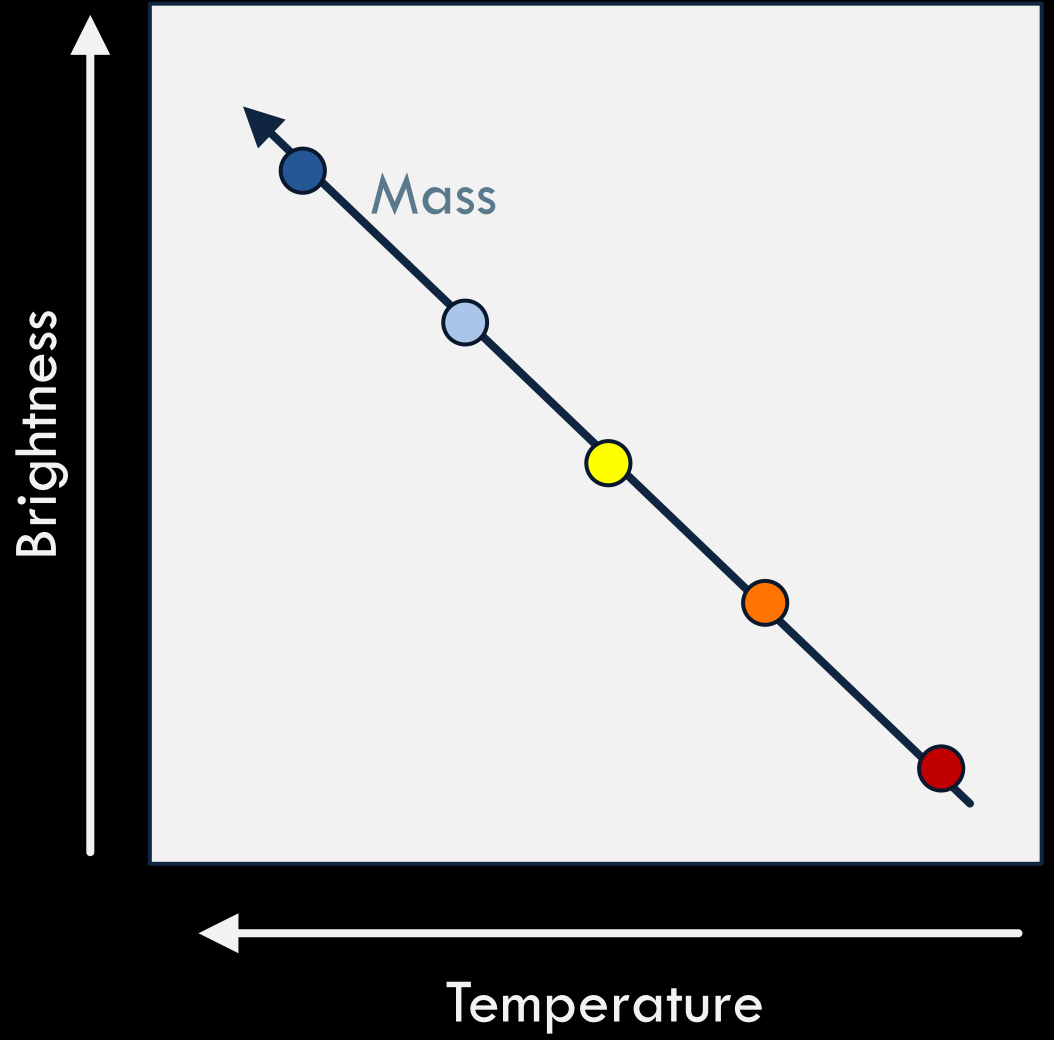




NOT ALL STARS LOOK THE SAME

http://youtu.be/855LIxE0qP0

HERTZSPRUNG-RUSSELL DIAGRAM



Preliminary work:
"The single-most important graph in all of astronomy."

Nice line from cool and faint low-mass stars to bright and hot high-mass stars.

A general rule:

More massive → hotter → brighter

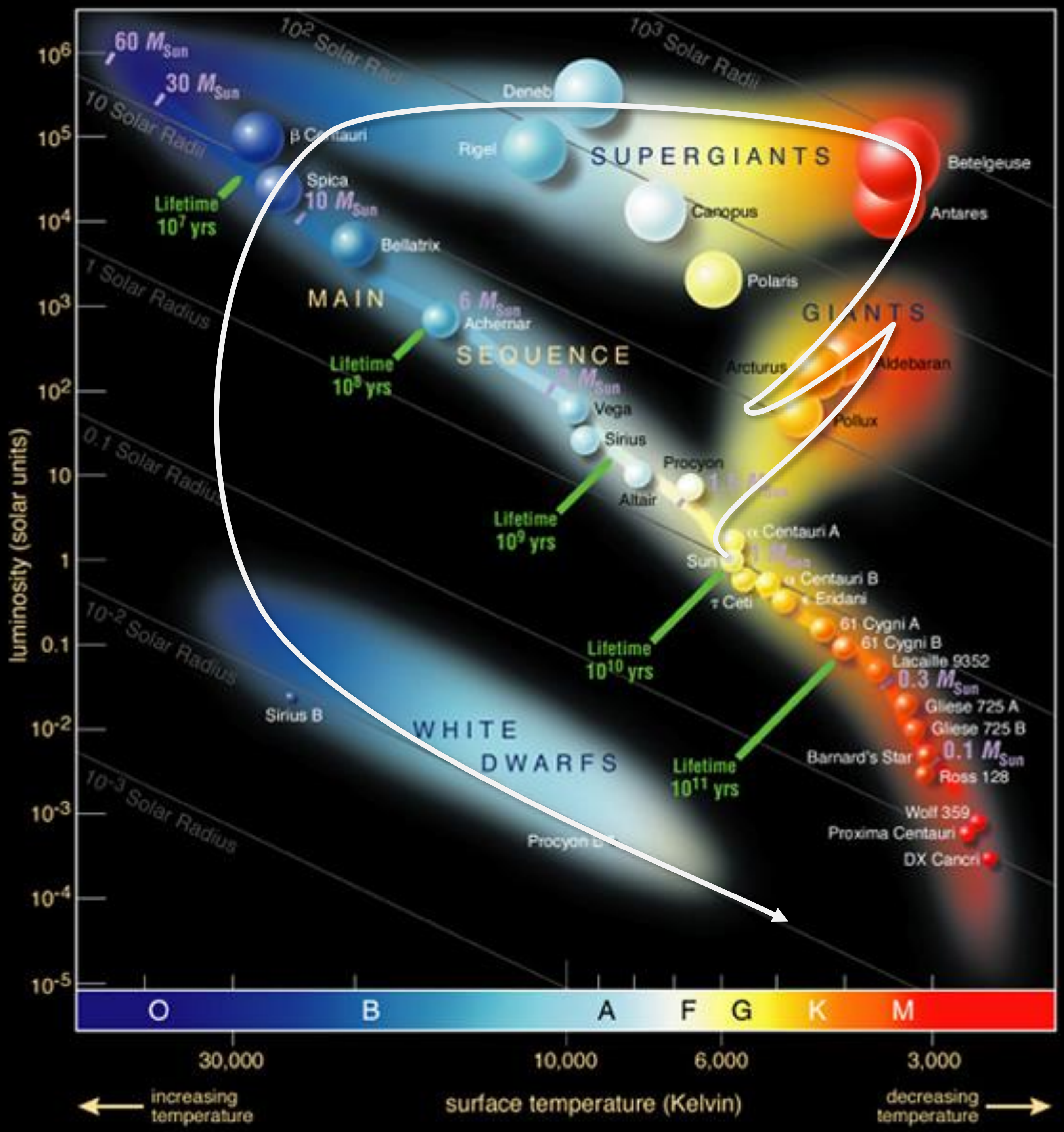
Recap from preliminary work

HERTZSPRUNG-RUSSELL DIAGRAM

"Normal stars" live in the Main Sequence

- Mass (0.1 to ~60 M_{Sun})
- Lifetime (3 million years to "eternal")

During stellar evolution, star moves in the diagram (e.g. becomes a Red Giant and later a White Dwarf)



DIFFERENT LIFES AND FATES

Sun-like stars:
Main seq. → Red giant → White dwarf
+ planetary nebula

Light-weight Red Dwarfs (< 0.5 Msun):
Main seq. (long time) → White Dwarf

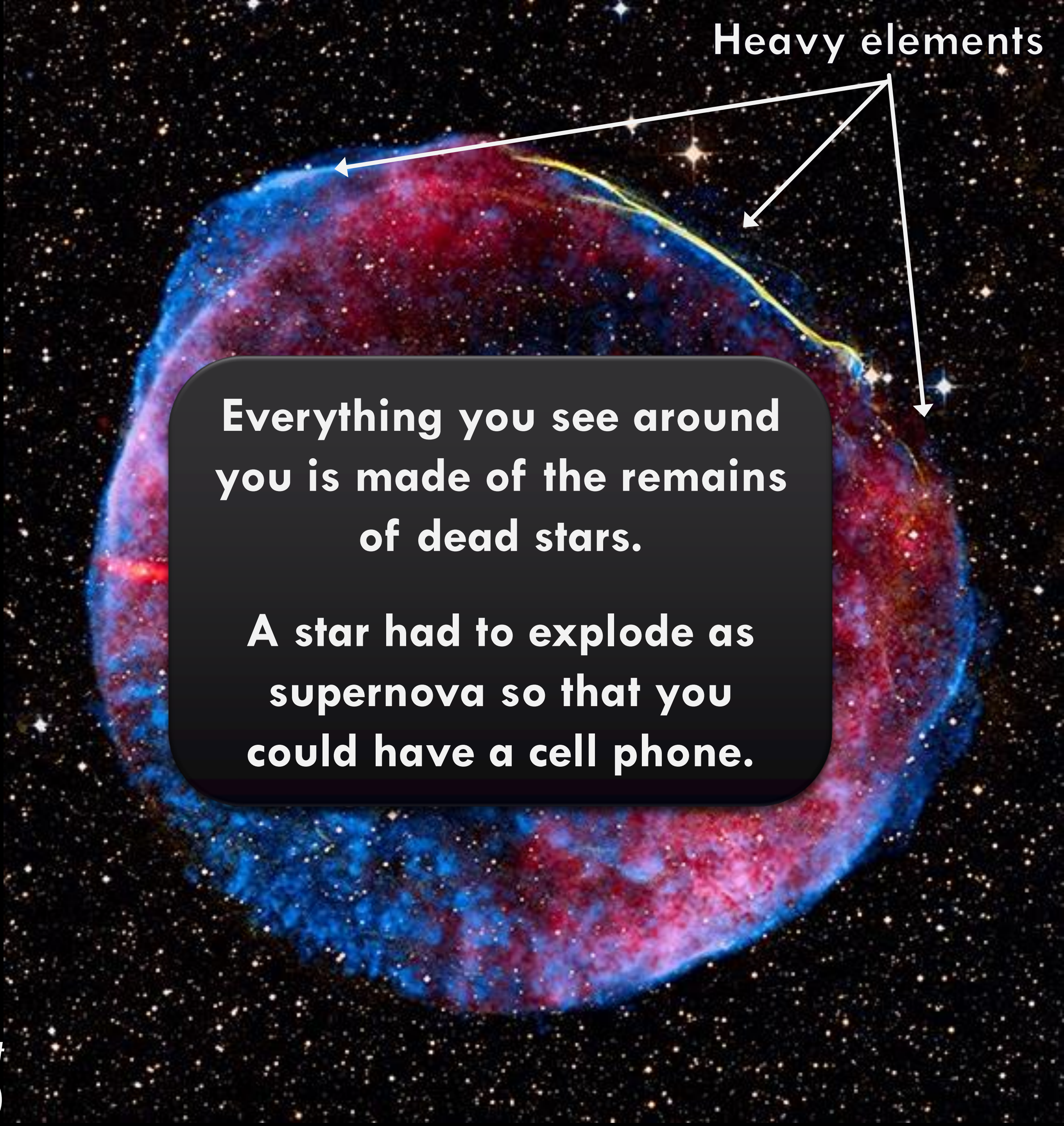
Planetary nebula
(outer layer of a red giant blown out by the stellar wind)

DIFFERENT LIFES AND FATES

Sun-like stars:
Main seq. → Red giant → White dwarf
+ planetary nebula

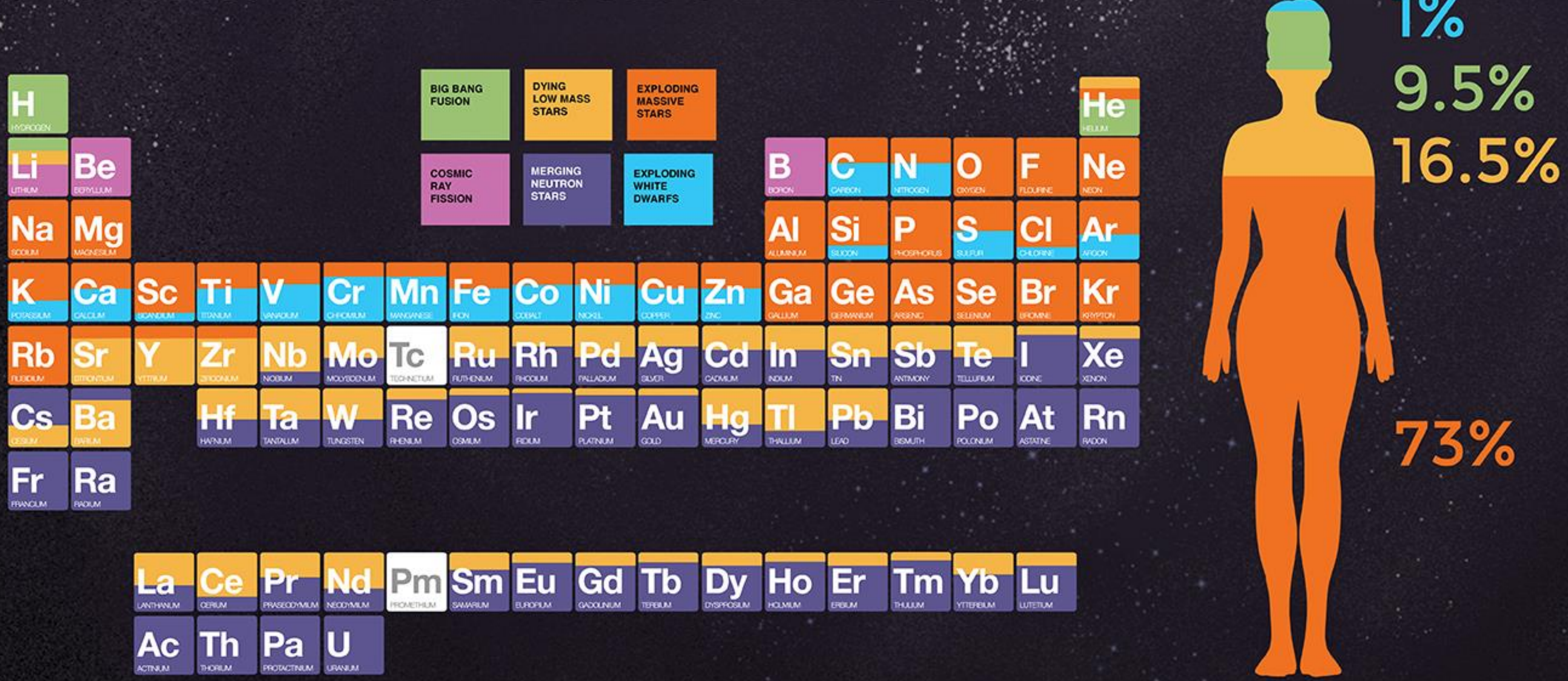
Light-weight Red Dwarfs (< 0.5 Msun):
Main seq. (long time) → White Dwarf

Massive stars:
Main seq. → Red giant →
Supernova + neutron star / black hole



Supernova remnant
(expanding explosion of the star)

ORIGINS: SOLAR SYSTEM ELEMENTS



http://chandra.harvard.edu/photo/2017/casa_life/

STAR'S FINAL STATE

- Small mass: White dwarf
  - Mass of the Sun ($M \lesssim 1.4 M_{\odot}$)
  - Size of the Earth

(Solar Mass: $1\ M_{\odot} \approx 2 \times 10^{30}$ kg)

Chandrasekhar limit: $M \approx 1.4 M_{\odot}$
If more massive than this, then gravity will be too strong to prevent collapse.

- No fusion anymore, just cooling down slowly (over billions of years)
- Gravity balanced by "electron degeneracy pressure"

STAR’S FINAL STATE

- Small mass: White dwarf
  - Mass of the Sun ($M \lesssim 1.4 M_\odot$)
  - Size of the Earth
- Medium mass: Neutron star
  - Mass: $1.4\ M_\odot \lesssim M \lesssim 3\ M_\odot$
  - Size: Tens of kilometres

- Gravity overcomes the electron deg. pressure
- Collapse and structural change of the matter
  - Electron capture: $p^+ + e^- \leftrightarrow n + \nu_e$
- Mostly neutrons
- Gravity now balanced by ”neutron degeneracy pressure”
- Very hot (~million Kelvin)
- Often extreme magnetic fields
- Spin rapidly (up to thousand times *a second*)
- Spin → radio pulses → pulsars


Crab Nebula • M1
HST ACS/WFC
F606W+POL60V
Sept. 6, 2005
2008
© 2017 Detlef Hartmann

STAR'S FINAL STATE

- Small mass: White dwarf
  - Mass of the Sun ($M \lesssim 1.4 M_{\odot}$)
  - Size of the Earth
- Medium mass: Neutron star
  - Mass: $1.4\ M_{\odot} \lesssim M \lesssim 3\ M_{\odot}$
  - Size: Tens of kilometres
- High mass: Black hole
  - Mass: $M \gtrsim 3\ M_{\odot}$
  - Size: Kilometres (3 km per 1 $M_{\odot}$)

- Gravity overcomes every balancing force
  - Collapses even further
  - Gravity increases → even light can't escape
- Details (matter, internal structure) unknown
- "Region of spacetime" rather than an object
- Properties:
  - Mass – of the collapsing object
  - Charge – of the collapsing object (neutral)
  - Angular momentum – from the collapsing object
    - Can rotate almost "at the speed of light"

TODAY

Astronomy in the 1900s

- Focus on stars, and their role in the Universe

Next weeks:

- Astronomy in the 2000s (L8)
- Astronomy in popular culture (L9)
- Astrobiology and Life in the Universe (L10)
- Big Bang theory & modern cosmology (L11)