Lecture 1: Overview and the Night Sky at a Glance

Learning Objectives and Overview

By the end of this course, students will be able to:

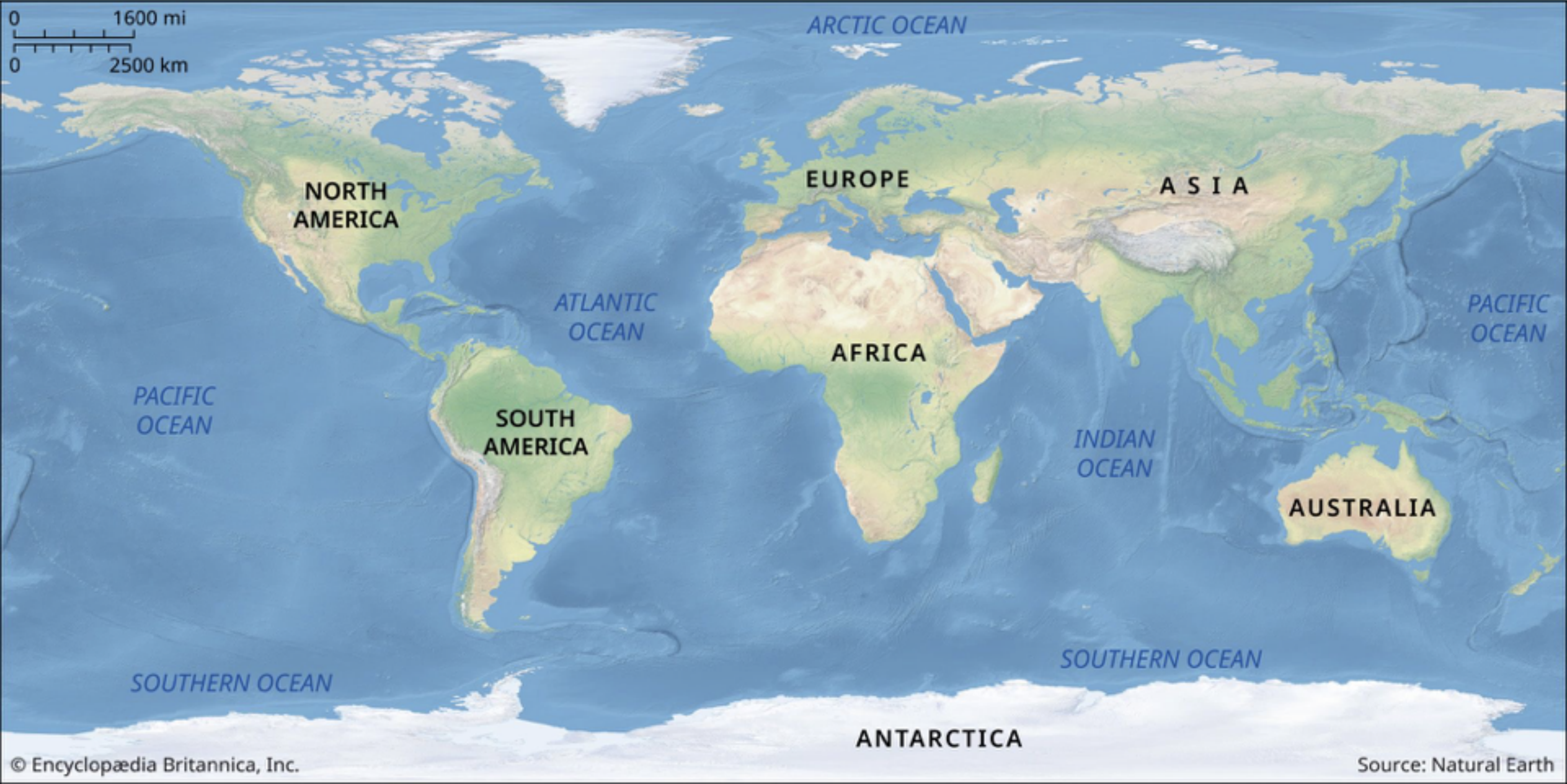
…identify major stars and constellations in the night sky, recount the life-cycle of a star form the Main Sequence to supernova, and distinguish between White Dwarfs, Neutron Stars, and Black Holes.

…describe the basic components of an optical telescope,explain the major differences between optical, infrared, and UV astronomy, describe why X-ray and gamma ray telescopes operate differently from OIR and UV telescopes.

…describe the basic components of a radio antenna, explain how radio interferometers work, and list the astrophysical sources of radio waves.

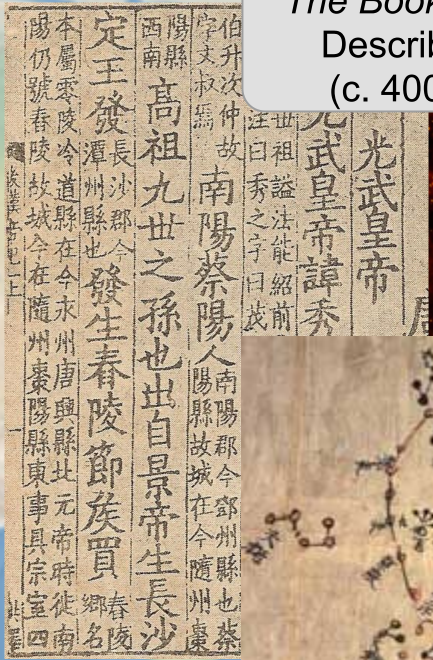
…describe the components of a galaxy (disk, bulge, ISM, halo, CGM), define cosmology, how it is studied (redshift, CMB, 21 cm cosmology, simulations, FRBs), explain how distance, redshift, and time are related within general relativity, and understand how the presence of dark matter and dark energy affect our picture of the Universe.

…list some of the major questions in astronomy today and refer to resources to continue exploring astronomy within and around Pasadena.


0
1600 mi
0
2500 km
ARCTIC OCEAN
NORTH AMERICA
EUROPE
ASIA
ATLANTIC OCEAN
PACIFIC OCEAN
AFRICA
PACIFIC OCEAN
SOUTH AMERICA
INDIAN OCEAN
AUSTRALIA
SOUTHERN OCEAN
SOUTHERN OCEAN
ANTARCTICA
© Encyclopædia Britannica, Inc.
Source: Natural Earth

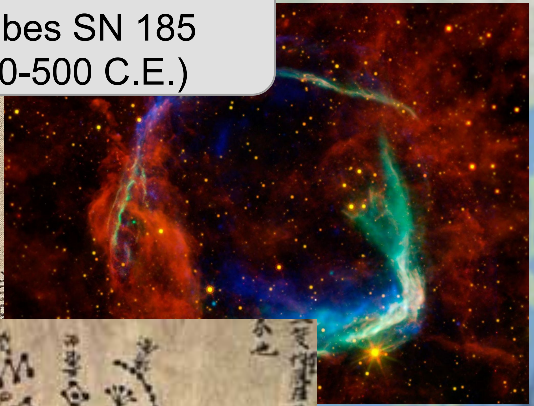

Aristotle's "Heavenly Spheres" model (c. 384-322 B.C.E.)
Night of the 8th, first part of the night, the Moon stood 2 ½ cubits below β Librae.
-567 III 8
Babylonian Astronomical Diaries c. 652-262 B.C.E.)
Antithykera Mechanism (c. 150-100 B.C.E)
Nebra Sky Disc (c. 1600 B.C.E.)
SOL ET LVNAE
Aristarchus Uses Lunar Eclipse easure Moon's Size . 300-200 B.C.E.)
Nabta Playa (9000-3500 B.C.E.)
Astrolabe Developed in Greece spread to Western World by Ara Astronomers (c. 600 C.E.)
ATLANTIC OCEAN
AFRICA
A S
SOUTH MERICA
INDIAN


Mayan Calendar: the *Haab, Tzolk'in,* and the Long Count)
(c. 500 B.C.E)
Dresden Codex
(c. 1000-1100 C.E.)
PACIFIC
OCEAN
AMERICA



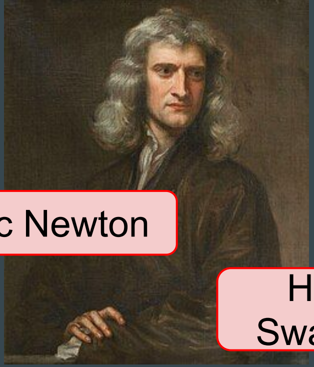
光武皇帝
光武皇帝諱秀
世祖謚法能紹前
注曰秀之字曰茂
伯升次仲故
字文叔焉
南陽蔡陽人
南陽郡今鄧州縣也蔡
陽縣故城在今隨州棗
陽縣
西南
高祖九世之孫也出自景帝生長沙
定王發
長沙郡今
潭州縣也
發生舂陵節侯買
舂陵
鄉名
本屬零陵今道縣在今永州唐興縣北元帝時徙南
陽仍號舂陵故城今在隨州棗陽縣東事具宗室四

The Book of Later Han Describes SN 185 (c. 400-500 C.E.)



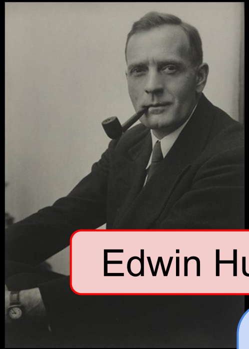
Chinese Star Maps (c. 1200 B.C.E.; copies from Tang Dynasty c. 800-900 C.E.)

Milestones in Modern Astronomy

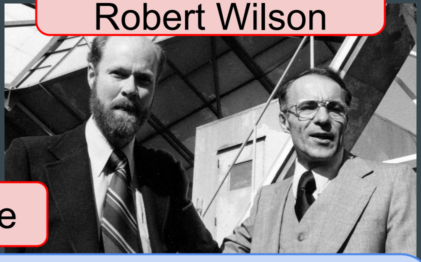


Isaac Newton

Henrietta Swan Leavitt



Edwin Hubble



Arno Penzias and Robert Wilson

1608 – Invention of the Telescope

1687 – Newton's Laws of Gravity

1918 - Galaxy Center

1920s - Hubble's Law of Universal Expansion & Einstein's Theory of General Relativity

1543 – Heliocentric Solar System

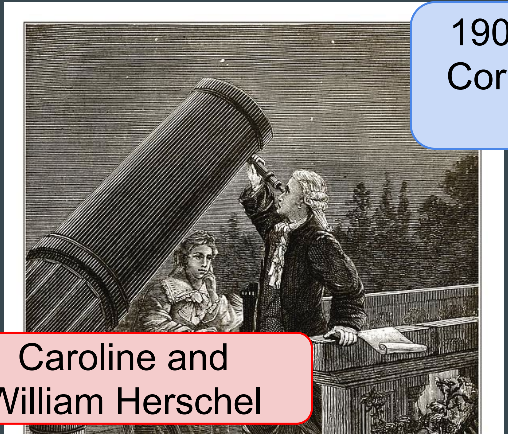
1609 – Kepler's Laws of Elliptical Motion

1800 - Discovery of IR Radiation

1964 - Cosmic Microwave Background

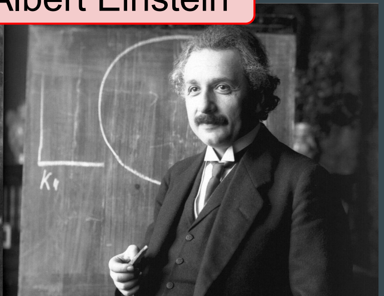
1908 - Distance/Period Correlation for Cepheid Variable Stars

Galileo Galilei



Caroline and William Herschel

Alexander Friedmann



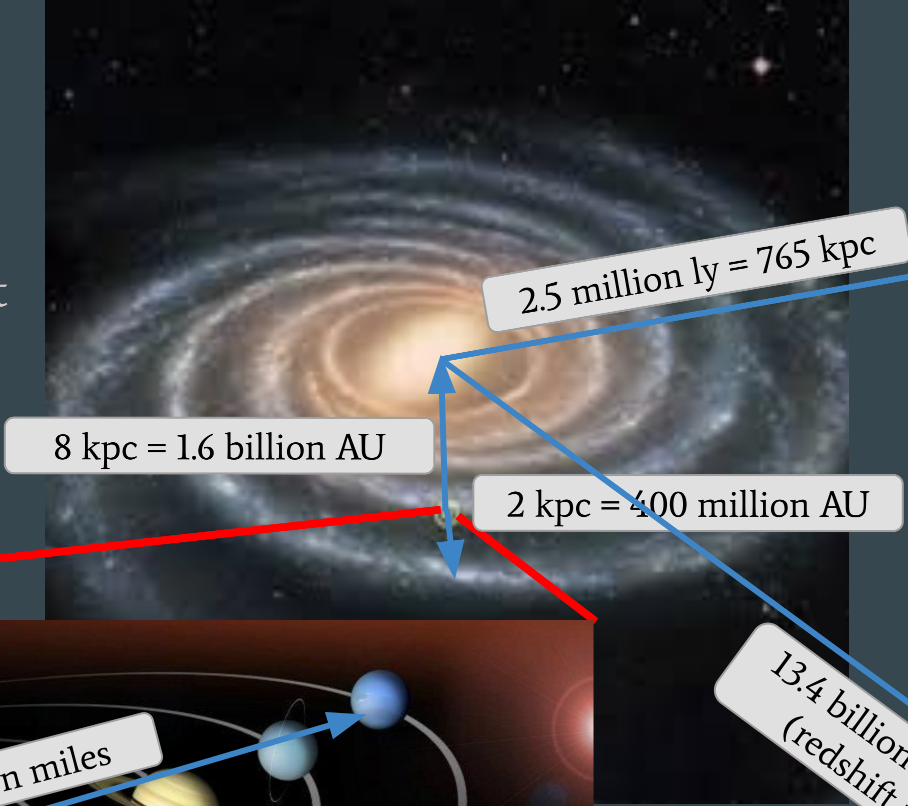
Albert Einstein

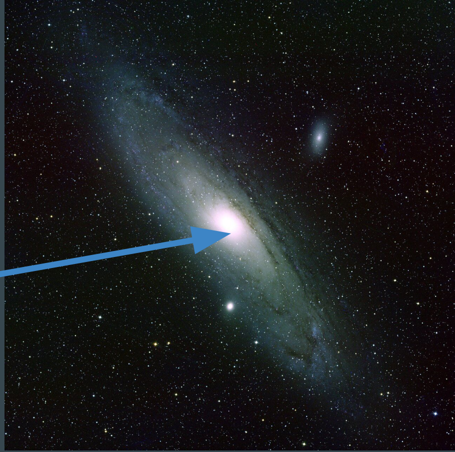
Distance Scales

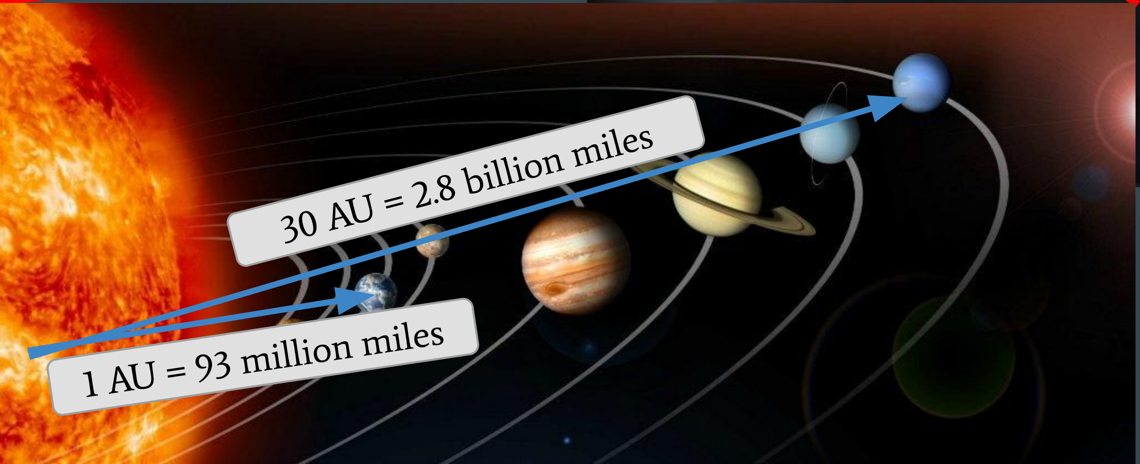
AU=Astronomical Unit

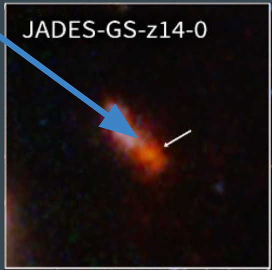
ly=light-year

pc=parsec

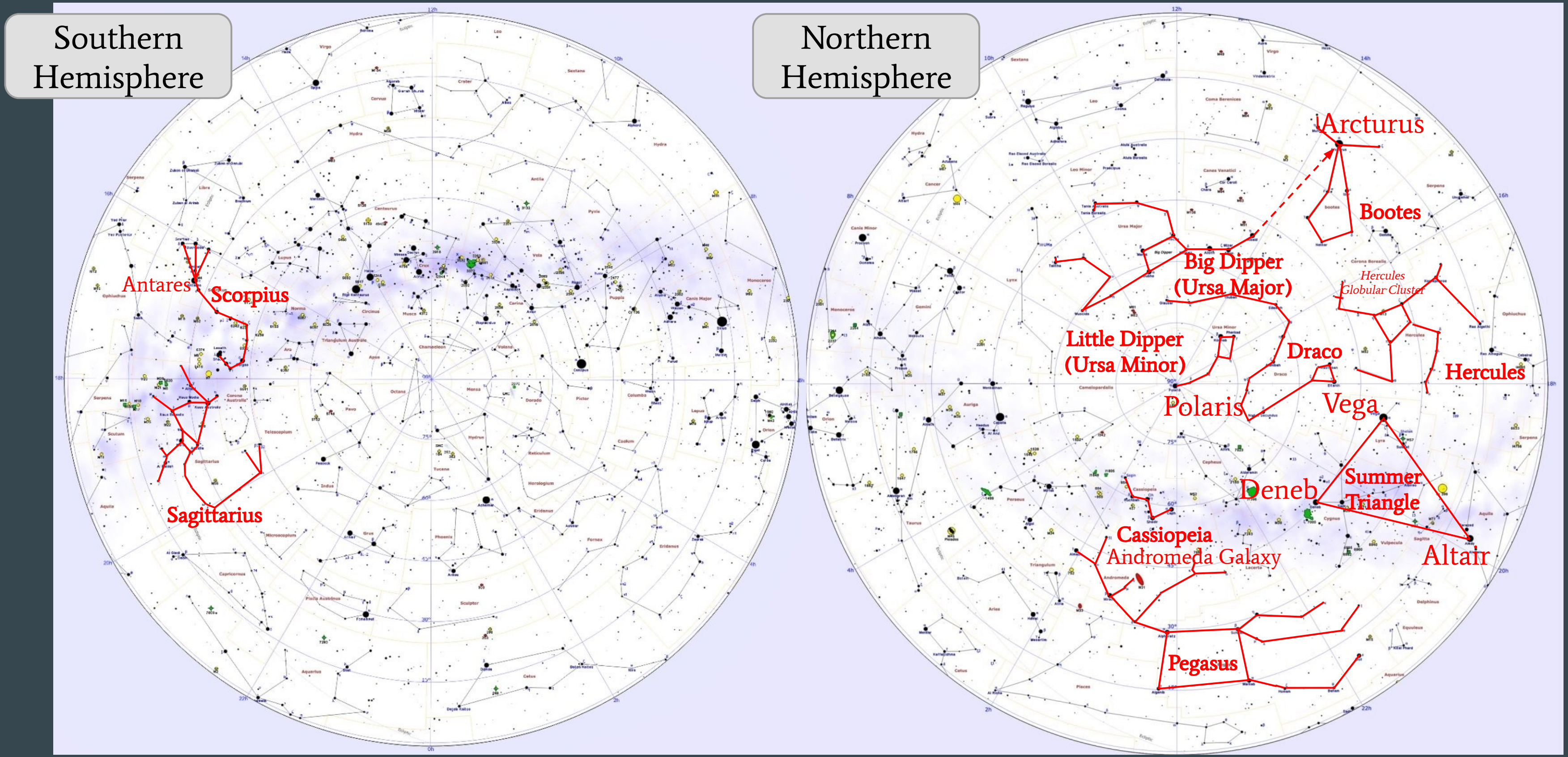




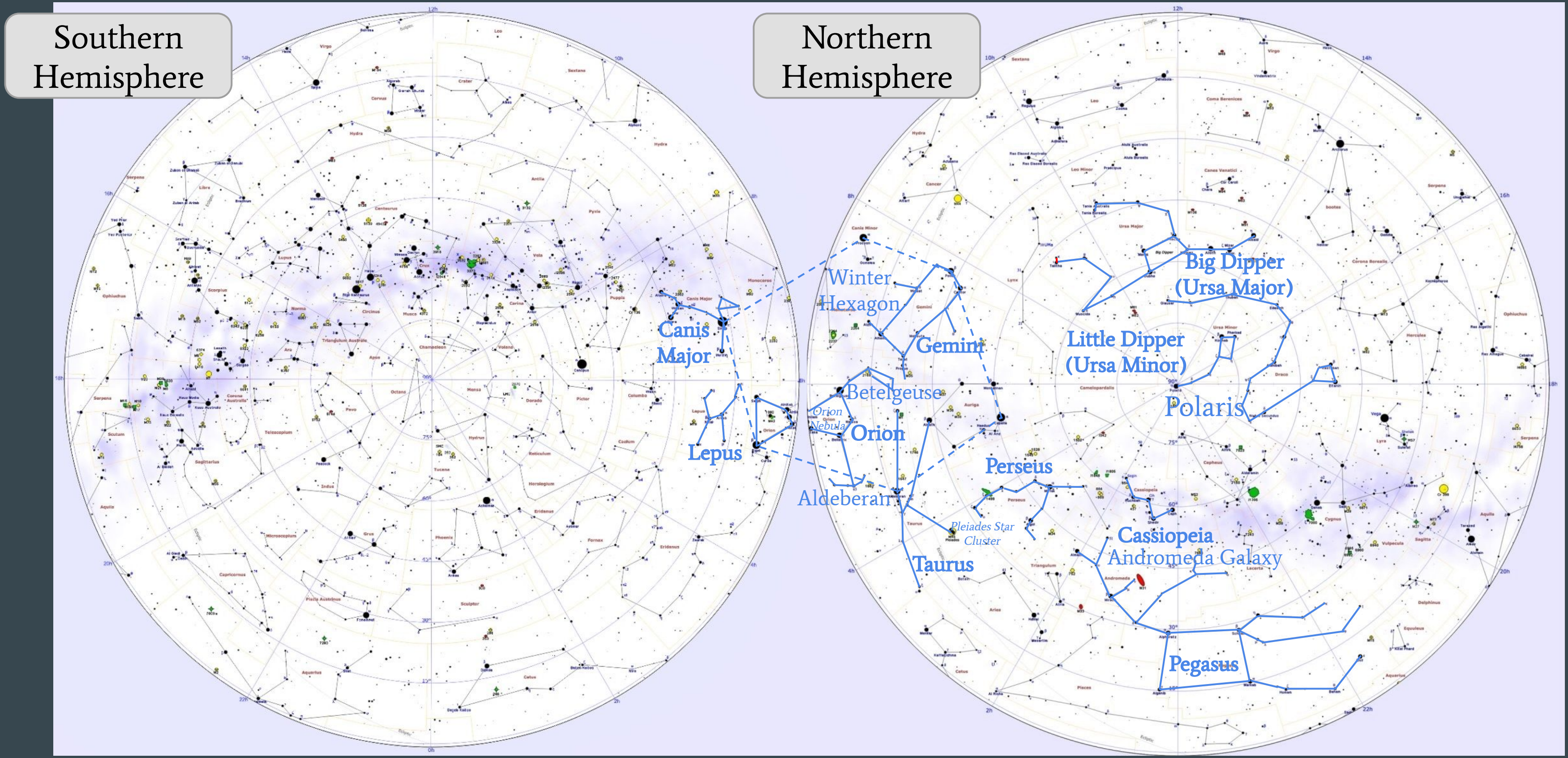




Navigating with Constellations and Asterisms: Summer in Pasadena



Navigating with Constellations and Asterisms: Winter in Pasadena



Celestial Coordinates

Sidereal Time: time measured relative to field stars instead of the Sun

1 Sidereal Day = 23 hours 56 minutes

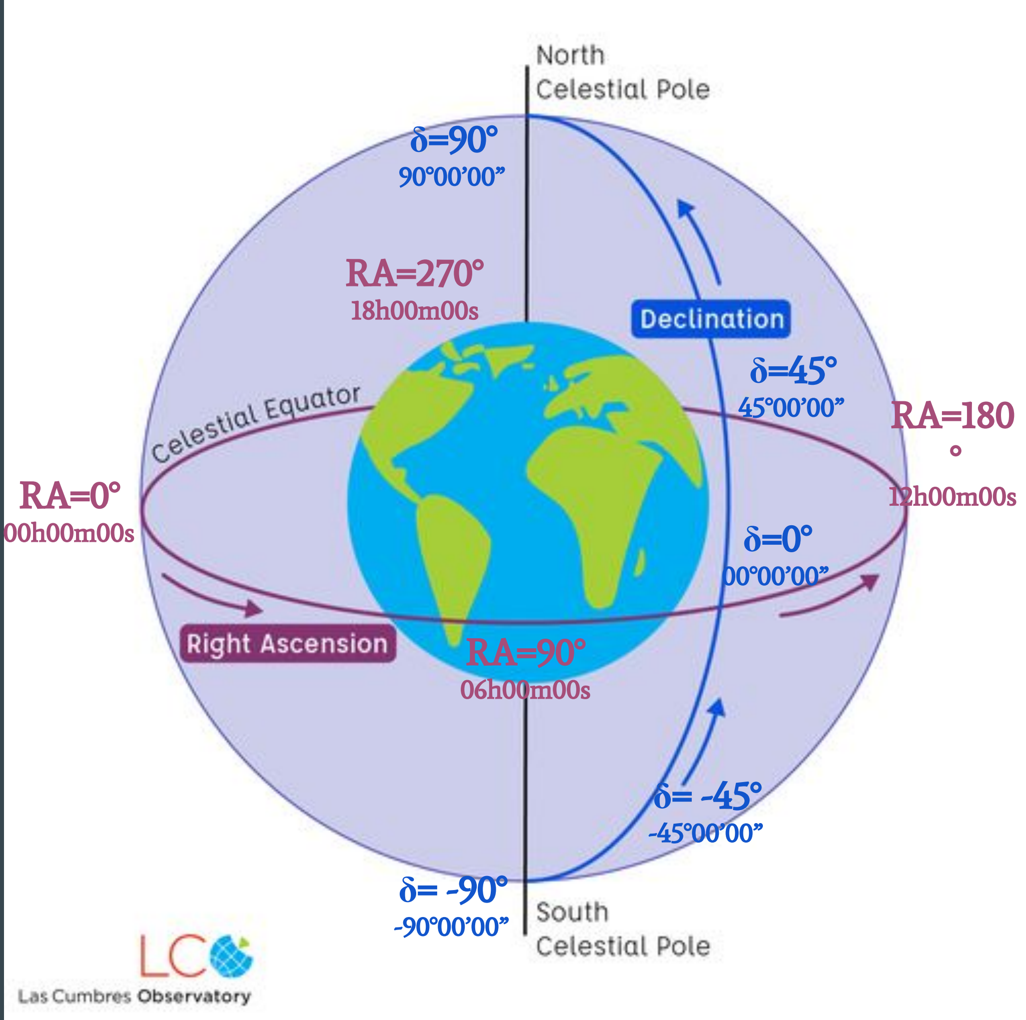
Centered on Earth and aligned with Equator and Poles:

- **Right Ascension** (**RA;** Celestial Longitude)
- **Declination** (Celestial Latitude)

RA can be specified in **degrees (0 - 360) or hours (0 - 24)**

RA[degrees] = 15 ×RA[hours]

Local Sidereal Time (LST): current RA overhead at the observer's location



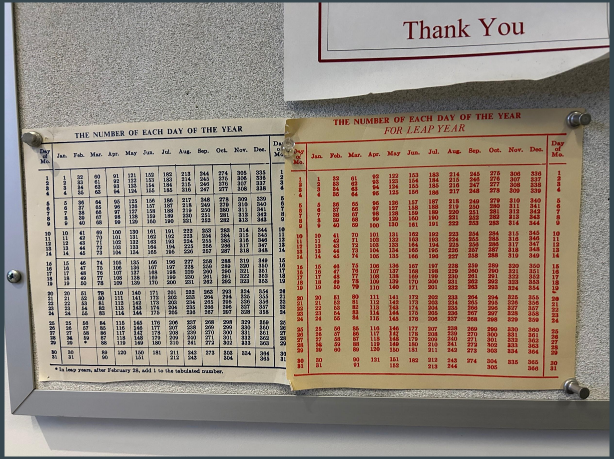
Celestial Coordinates

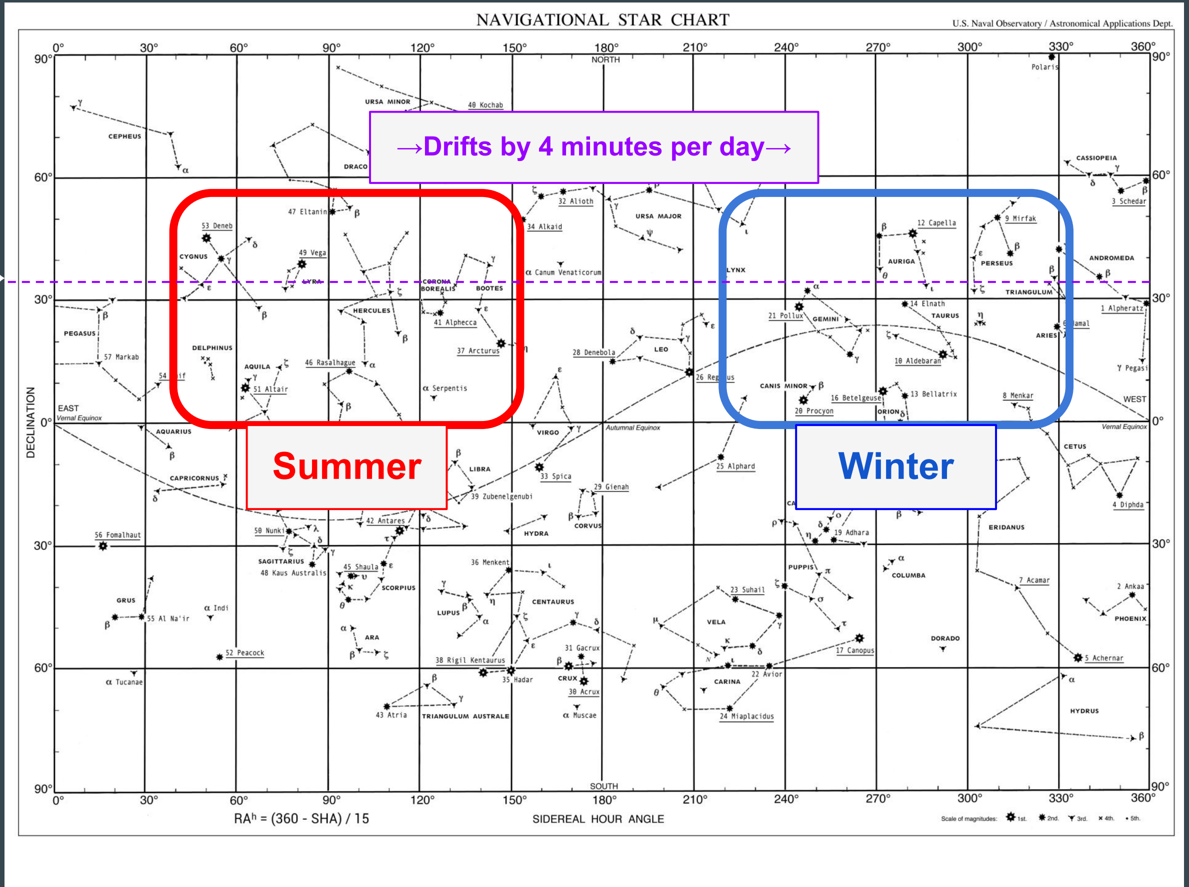
Pasadena is at longitude 118.1°

Note: PST = UTC + 8 hours

Pasadena is at latitude 34.15° →

Lookup LST here: https://aa.usno.navy.mil/data/siderealtime





At-Home Astronomy: Online Star Maps

Stellarium: https://stellarium-web.org/

Make Your Own Star Wheel (*Sky & Telescope*): https://stellarium-web.org/

Aladin: https://aladin.cds.unistra.fr/AladinLite/

Pan-Starrs (Northern Sky Survey): https://ps1images.stsci.edu/cgi-bin/ps1cutouts

SkyMapper (Southern Sky Survey): https://skymapper.anu.edu.au/image-cutout/

1.1

Interstellar Medium (ISM) – gas & dust between stars in the Galaxy

~70% of ISM is Hydrogen

Neutral Hydrogen (HI)

$q = 1.6 \times 10^{-19}$ C

A=1
Z=1

⊕ proton, ⊖ electron

Total charge: $+q - q = 0$

Ionized Hydrogen (HII, H^+) → HII region

A=1
Z=1

⊕ proton

Total charge: $+q$

*also have free electrons

$n_{ISM} \sim 1$–1000 particles per cubic cm (cm^{-3})

Molecular Hydrogen (H_2) → molecular clouds

Deuterium (^2H) [isotope]

A=2
Z=1

neutron, q=0

~28% of ISM is Helium

Neutral Helium (He)

A=2
Z=2

Singly-Ionized Helium (He^+)

A=2
Z=2

Total charge: $+q$

Doubly-Ionized Helium (He^{2+})

A=2
Z=2

Total charge: $+2q$

~1.5% of ISM are Metals – any element with Z>2 (heavier than Helium)

~0.5% of ISM is Dust – silicates, carbon molecules, hydrocarbons, graphite

↳ Carbon (C): A=6

M_λ ↑ absolute magnitude

A_λ ↑ extinction – dimming of light from scattering and absorption by dust particles

m_λ ↑ apparent magnitude

$$m_\lambda = M_\lambda + 5\log_{10}(d) - 5 + A_\lambda$$

1.21

Energy - "ability to move or change matter in some way"

- energy is always conserved: $E_{initial} = E_{final}$

Kinetic Energy

m = mass, $\vec{v}$ = velocity

$$E_{kinetic} = \frac{1}{2} m |\vec{v}|^2 > 0$$

↳ Thermal Energy

Ideal gas law: $PV = NkT$

N = # particles
$k = 1.38 \times 10^{-23}$ J/K
T = temperature (K)

$$E_{thermal} = \frac{3}{2} NkT > 0$$

Boltzmann Dist.

$$f(v) = \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 e^{-\frac{mv^2}{2kT}}$$

Potential Energy - stored energy that can change to another form

↳ Gravitational Potential Energy

F_g = force due to gravity ($g = 9.81$ m/s²)

$$E_{grav} = mgr < 0 \quad \text{for } r \ll R_E$$

Newton's Gravitational Constant

$$G = 6.67 \times 10^{-11} \frac{m^3}{kg\, s^2}$$

$$E_{grav} = \frac{-GMm}{r} < 0$$

for 2 masses

$$E_{grav} = -\frac{3}{5} \frac{GM^2}{R} < 0$$

for extended object

free-fall timescale

$$t_{ff} = \sqrt{\frac{3\pi}{32 G \rho_0}}$$

Total Energy

$$E_{tot} = E_{kinetic} + E_{grav} \begin{cases} < 0 \rightarrow \text{bound} \\ > 0 \rightarrow \text{unbound} \end{cases}$$

Virial Theorem: equilibrium

$$2E_{kinetic} + E_{grav} \approx 0$$

How does a cloud of gas collapse into a star?

initial density: $\rho_0 = \frac{M}{\frac{4}{3}\pi R^3}$

$R = \left(\frac{M}{\frac{4}{3}\pi}\right)^{1/3} \frac{1}{\rho_0}$

System will collapse if $2E_{kinetic} + E_{grav} < 0$

$$2\left(\frac{3MkT}{4m}\right) < \frac{3GM^2}{5R}$$

$$\frac{10R}{G}\left(\frac{kT}{4m}\right) < M \Rightarrow \frac{10}{G}\left(\frac{4}{3}\pi\right)^{-1/3}\left(\frac{kT}{4m}\right) < M^{2/3}$$

Jeans criteria

$$M_J = \sqrt{\left(\frac{1}{\frac{4}{3}\pi}\right)\left(\frac{10kT}{\rho_0 G 4m}\right)^3} < M$$

$$R_J = \sqrt{\frac{15kT}{4\pi G \rho_0 4m}} < R$$

1.3

Equations of Stellar Structure:

M(r) - mass enclosed within radius r

$$\rho(r) = \frac{M(r)}{V_{olume}} = \frac{M(r)}{\frac{4}{3}\pi r^3}$$

① Hydrostatic Equilibrium

balance of gravity and pressure:

$$\frac{dP}{dr} = -\frac{GM(r)\rho}{r^2}$$

→ star is only supported if pressure is higher at center of the star

② Mass Conservation

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

for constant density:

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\int dM = M = \int_0^{R_*} 4\pi r^2 \rho \, dr$$

$$M = \frac{4}{3}\pi R_*^3 \rho$$

③ Pressure Equation of state - tells us how gas is composed and behaves

- Ideal gas - gas w/ negligible volume, similarly sized particles & no interaction between particles.

$$P = \frac{N}{V}kT = \frac{\rho kT}{\mu m_H}$$

for any other gas: $P = \frac{1}{3}\int_0^\infty n_p p v \, dp$ (v = velocity, n_p = density, p = momentum)

radiation pressure - pressure exerted by photons in thermal equilibrium

$$P = \frac{1}{3} a T^4$$ where $a = 7.56 \times 10^{-16}\ J/m^3K^4$

④ Luminosity Gradient -

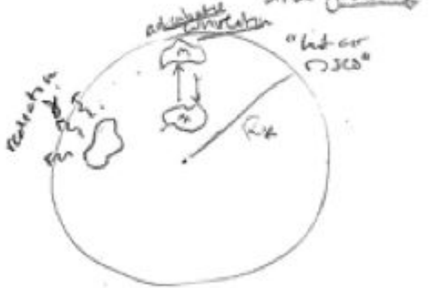
- luminosity - power (energy produced per unit time)

$$\frac{dL}{dr} = 4\pi r^2 \rho(r)\,\epsilon(r)$$

↳ total power released per unit mass by nuclear reactions and gravity

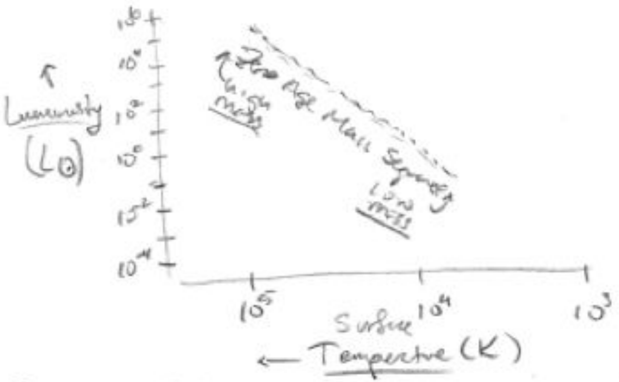
⑤ Radiative Transport - describes how energy is transported within the star

$$\frac{dT}{dr} = \begin{cases} \frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L}{4\pi r^2} & \text{radiation} \\ \left(\frac{1}{\gamma}-1\right)\frac{\mu m}{k}\frac{GM}{r^2} & \text{adiabatic convection} \end{cases}$$



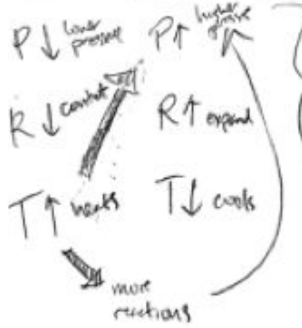
Stellar Evolution

The Hertzsprung Russel Diagram



Feedback Stability

$\mu\uparrow$ = net mean molecular weight → $\mu = 1$ for Hydrogen, $\mu = 2$ for He core



radiated energy

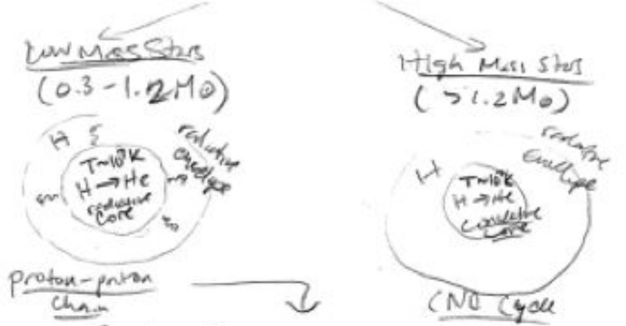
$E_{output} \approx 25\,MeV$

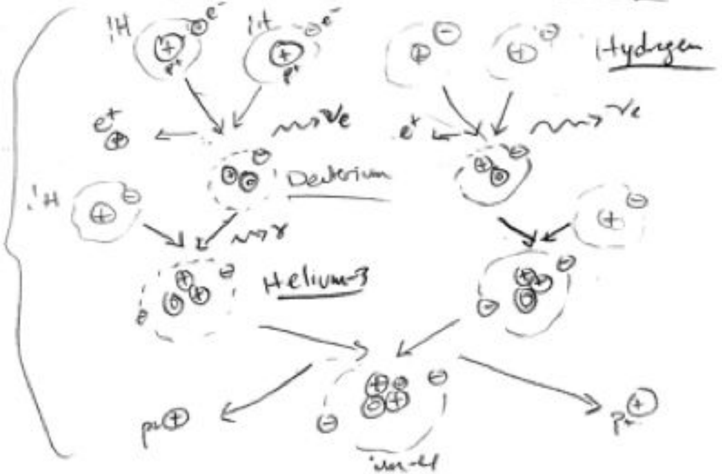
$(\gamma, \nu_e, e^+, p^+)$

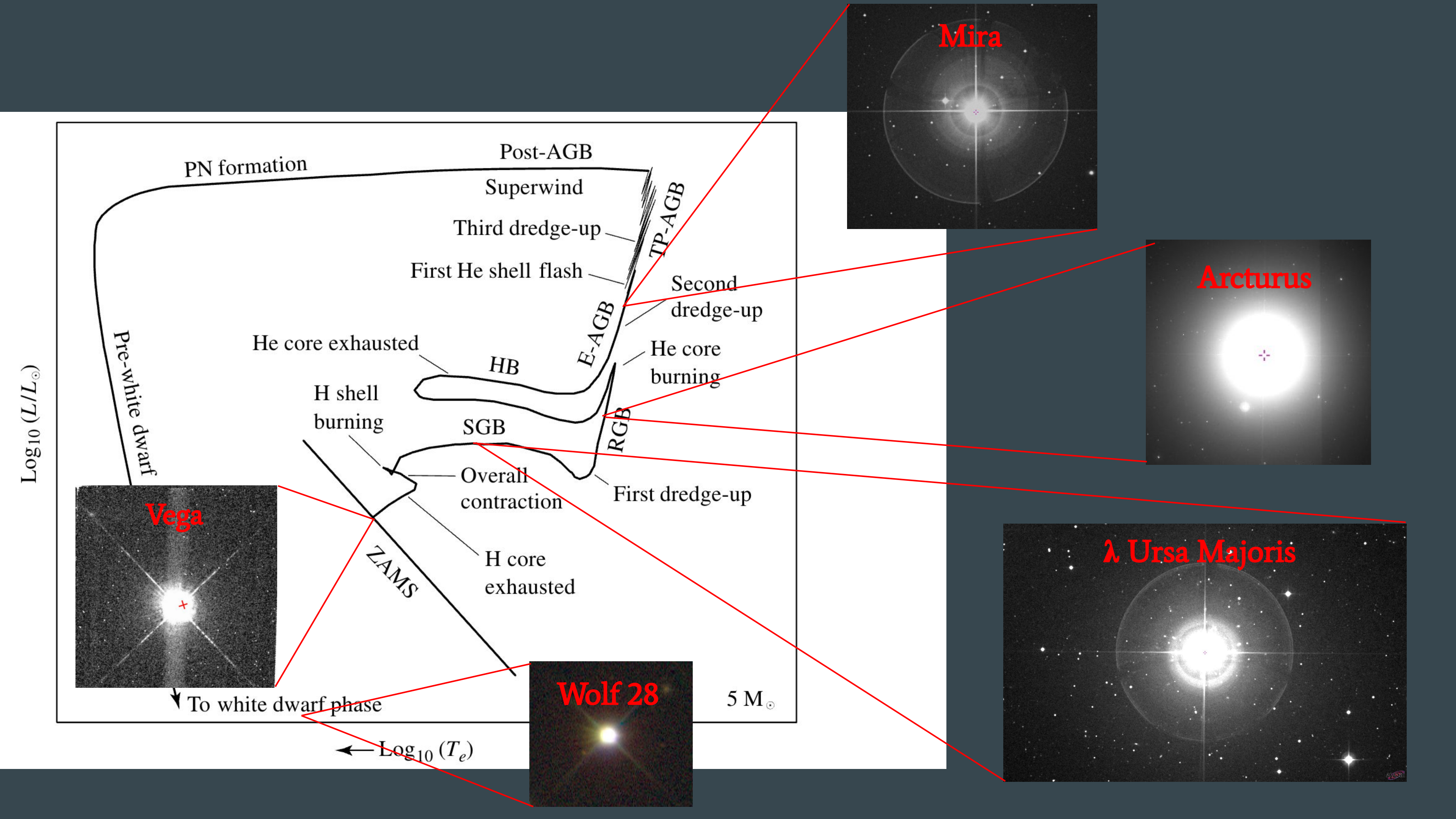
$PV = NkT$

Main Sequence – hydrogen being to fuse into helium:

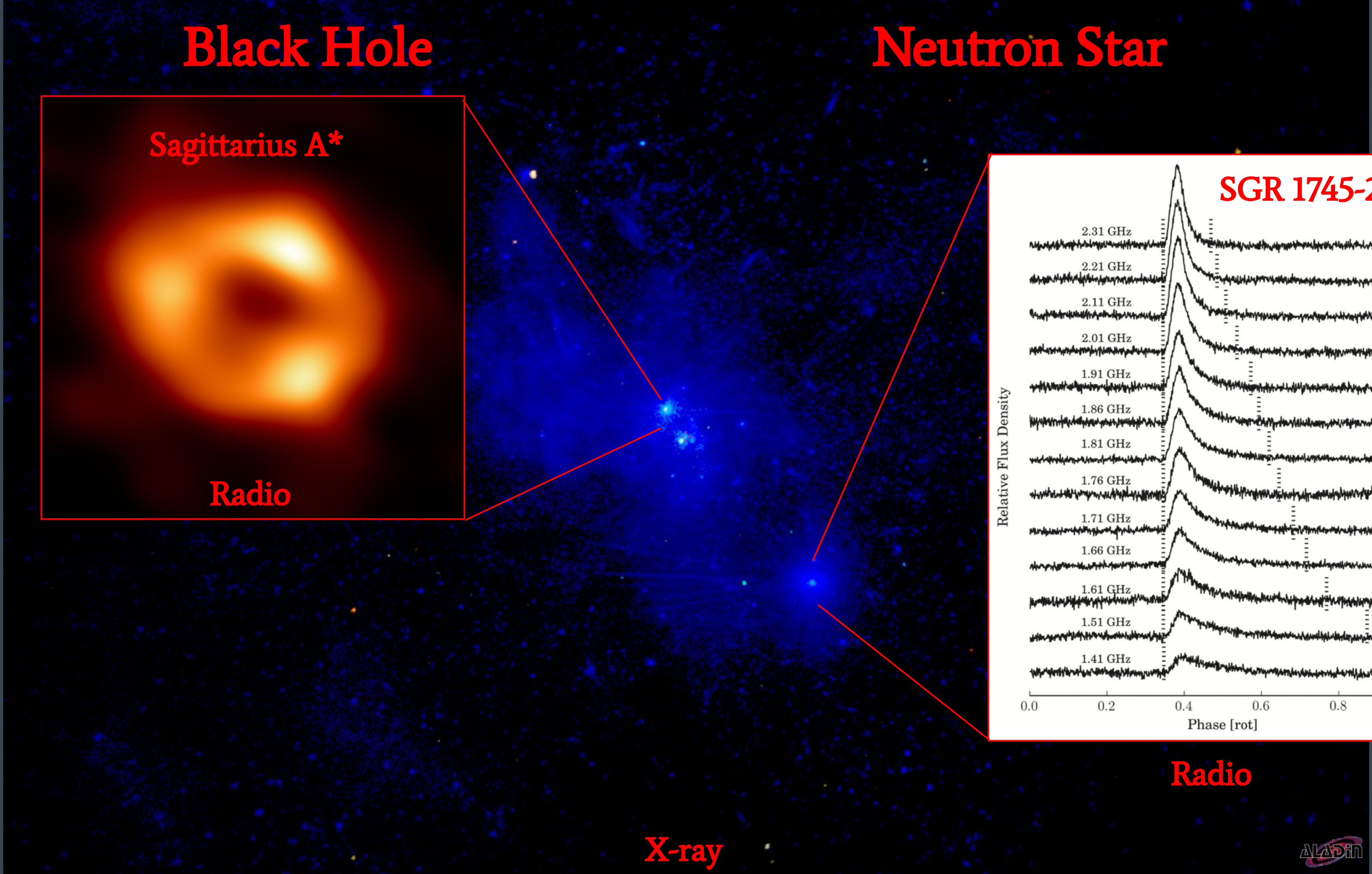
$$6\,{}^1_1H \longrightarrow {}^4_2He + 2\,{}^1_1H$$







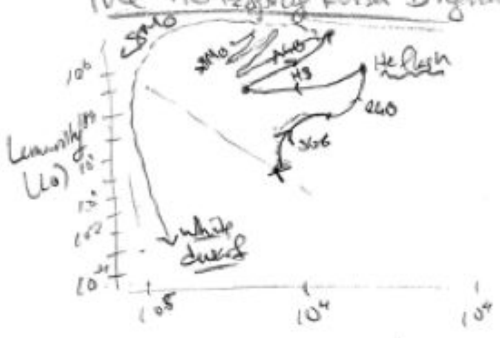
Mira
Arcturus
λ Ursa Majoris
Vega
Wolf 28
PN formation
Post-AGB
Superwind
Third dredge-up
TP-AGB
First He shell flash
Second dredge-up
E-AGB
He core exhausted
HB
He core burning
H shell burning
SGB
RGB
Pre-white dwarf
Overall contraction
First dredge-up
H core exhausted
ZAMS
To white dwarf phase
5 M☉
$\log_{10}(L/L_\odot)$
$\leftarrow \log_{10}(T_e)$


Black Hole
Neutron Star
Sagittarius A*
Radio
SGR 1745-29
2.31 GHz
2.21 GHz
2.11 GHz
2.01 GHz
1.91 GHz
1.86 GHz
1.81 GHz
1.76 GHz
1.71 GHz
1.66 GHz
1.61 GHz
1.51 GHz
1.41 GHz
Relative Flux Density
0.0
0.2
0.4
0.6
0.8
1.0
Phase [rot]
Radio
X-ray
ALADIN

1.5

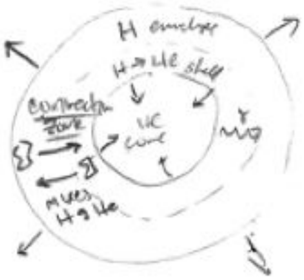
Stellar Evolution

The Hertzsprung Russell Diagram



Red Giant Branch
↓
Convective Mixing
↳ L↑ faster

Sub-Giant Branch – after hydrogen finishes burning, needs to get to T~10⁸ K to begin He fusion



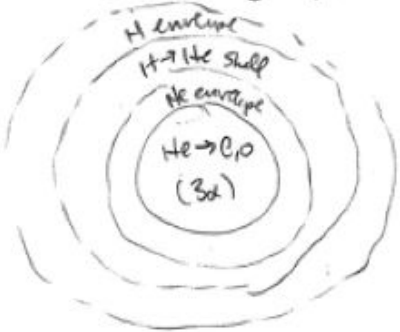
core: contracts (R↓)
heats (T↑)
releases gravitational energy via radiation

shell – continues Hydrogen burning, deposits mass onto core

envelope – radiation pressure from core (P↑)
Luminosity increases (L↑)
expands (R↑) &
cools (T_eff↓)

Horizontal Branch – Helium burning, fusing to Carbon
↳ triple alpha process

$$3\,{}^{4}_{2}He \rightarrow {}^{12}_{6}C + \gamma$$ } $E_{gained} \approx 7.367$ MeV



Asymptotic Giant Branch

Same as Sub-Giant/Red Giant

outer layers expand away
↓
core contracts
↓
e⁻ degeneracy pressure
↓
white dwarf star

continues burning cycle until Fe core
↓
neutronization
core collapse → neutron star / black holes

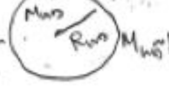
1.6

White Dwarf Stars (for $M_* < 8M_\odot$)

- Central star exposed gradually as envelope expands ($T_{eff}\uparrow \rightarrow$ blue)

supported by e⁻ degeneracy pressure – quantum mechanical pressure
↳ Pauli exclusion principle – 2 electrons can't occupy the same energy state
↳ forces free electrons in core into higher energy states → higher velocities → "pressure"

$$P_e \propto \rho^{5/3}$$



↳ Chandrasekhar mass limit – maximum mass before e⁻ degeneracy pressure fails ⇒ $M_{WD} \sim 1.44 M_\odot$

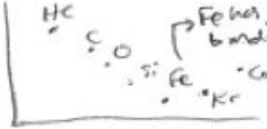
- for $M_* < 4M_\odot \rightarrow$ C, O White Dwarf
  $4M_\odot < M < 8M_\odot \rightarrow$ O, Ne, Mg White Dwarf
- mass loss accelerates (expanding envelope → wind)

$$\dot{M} = dM/dt = 10^{-4} M_\odot/yr$$

Neutron Stars & Black Holes (for $M_* > 8M_\odot$)

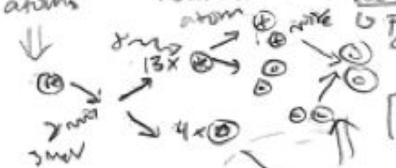
- (Supergiant) continues burning until fuses iron (Fe) in core
- photodissociation
  ↳ $T > 10^{10}$K
  ↳ energetic photons (~3MeV) break down Fe atoms

binding energy ↓ energy required to bind protons, neutrons, e⁻ into atom



→ Fe has lowest binding energy

A = atomic mass #



- neutronization
  ↳ protons capture e⁻ and decay to neutrons

$$p + e^- \rightarrow n + \nu_e$$

- core collapse
  ↳ outer layers infall under gravity
  ↳ "bounce" off central star

$M_{core} > 1.4 M_\odot$ ↓ collapses further into Black Hole

$M_{core} \lesssim 1.4 M_\odot$ ↓ neutron star

↳ core supported by neutron degeneracy pressure
↳ forces neutrons into higher energy states

$$P_n \propto \rho^{4/3}$$

↳ Chandrasekhar limit = $M_{CH} = 1.4 M_\odot$

Think-Pair-Share

How would you classify a new star given it's apparent magnitude?

Think-Pair-Share

How would you classify a new star given it's apparent apparent magnitude?

How might a binary companion star impact a star's evolution?

1.7 Binary Stars

	Single	Binary	Triple+
Sun-like Stars:	60%	30%	10%
O-type stars:	6%	21%	73%

} Most high mass stars are in orbit with other stars

Types of Binaries:

- cataclysmic variables (CVs)

↳ Type Ia SNe - accretes mass until it exceeds Chandrasekhar limit

- X-ray Binaries:

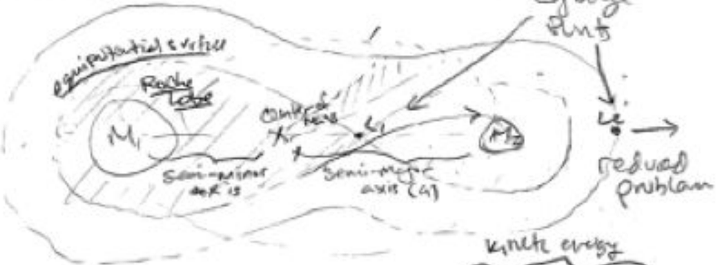
millisecond pulsar

$M_{tot} = M_1 + M_2$

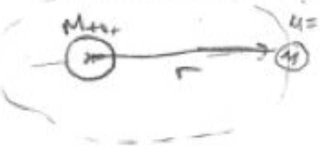
$\mu = \frac{M_1 M_2}{M_1 + M_2}$

Center of Mass:

$r_{CM} = \frac{M_1 r_1 + M_2 r_2}{M_1 + M_2}$

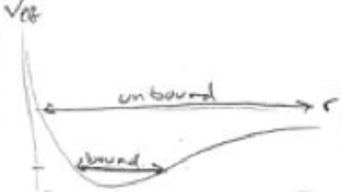


reduced problem



total energy: $E = E_{kin} + E_{grav} = \underbrace{\frac{1}{2}\mu\dot{r}^2 + \frac{1}{2}\mu\omega^2 r^2}_{\text{kinetic energy}} - \overbrace{\frac{GM_1M_2}{r}}^{\text{potential energy}}$

$= \underbrace{\frac{1}{2}\mu\dot{r}^2 + \mu\omega^2 r^2}_{\text{effective kinetic energy } K_{eff}} \underbrace{- \frac{1}{2}\mu\omega^2 r^2 - \frac{GM_1M_2}{r}}_{\text{effective potential energy } U_{eff}}$



effective potential: $V_{eff} = \frac{U_{eff}}{\mu} = -\frac{1}{2}\omega^2 r^2 - \frac{G(M_1+M_2)}{r}$

Kepler's Laws

1. Stars & Planets in bound systems move in elliptical orbits around the center of mass
2. Area swept out by a radius vector is constant: $dA/dt = \text{constant}$
3. Orbital period squared is proportional to the semimajor axis cubed: $T_{orb}^2 = \frac{4\pi^2}{G(M_1+M_2)} a^3$

Questions, Comments, or Concerns?

https://forms.gle/ywP1THADKCq1nDPy9

Lecture 2: Electromagnetic Radiation from Infrared to Gamma Rays

Learning Objectives and Overview

By the end of this course, students will be able to:

…identify major stars and constellations in the night sky, recount the life-cycle of a star form the Main Sequence to supernova, and distinguish between White Dwarfs, Neutron Stars, and Black Holes.

…describe the basic components of an optical telescope,explain the major differences between optical, infrared, and UV astronomy, describe why X-ray and gamma ray telescopes operate differently from OIR and UV telescopes.

…describe the basic components of a radio antenna, explain how radio interferometers work, and list the astrophysical sources of radio waves.

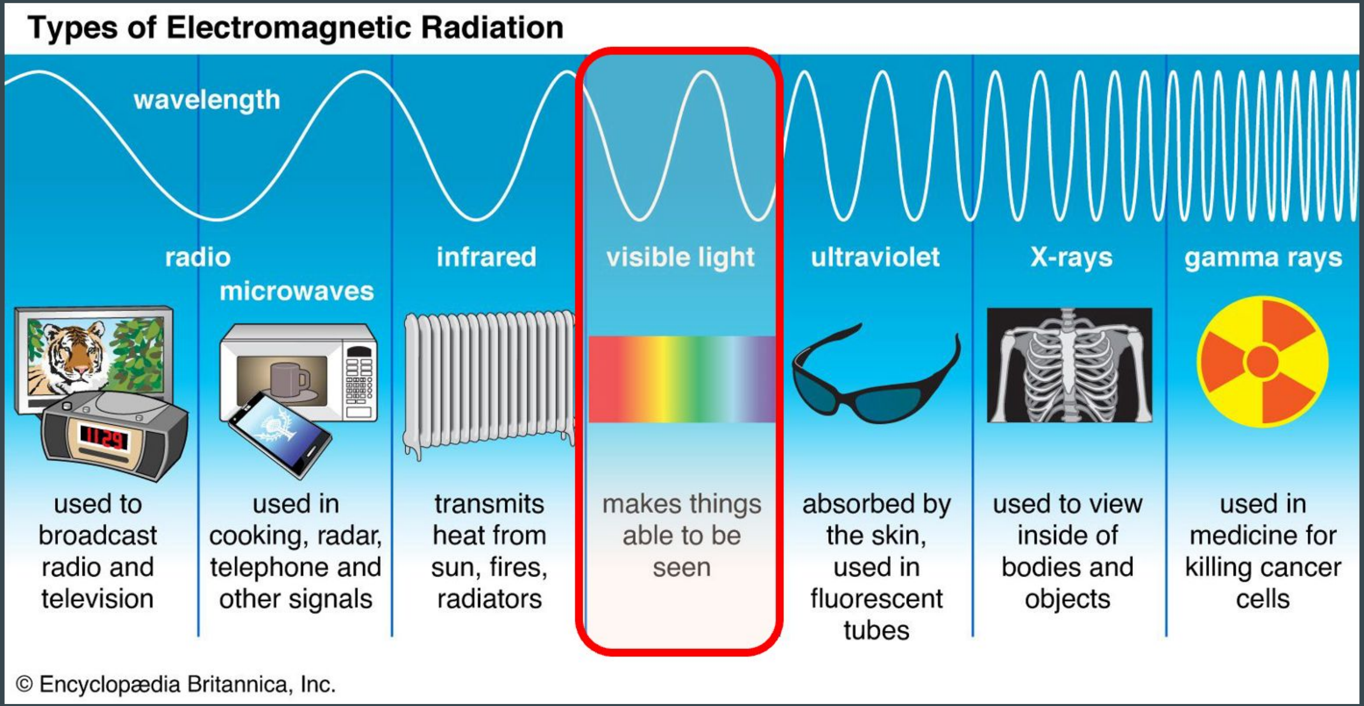
…describe the components of a galaxy (disk, bulge, ISM, halo, CGM), define cosmology, how it is studied (redshift, CMB, 21 cm cosmology, simulations, FRBs), explain how distance, redshift, and time are related within general relativity, and understand how the presence of dark matter and dark energy affect our picture of the Universe.

…list some of the major questions in astronomy today and refer to resources to continue exploring astronomy within and around Pasadena.

What is Light?

Light is **energy** that travels in **waves** carried by **electric and magnetic fields**

All waves have a wavelength and speed *c*=**671 million miles per hour = 299 million meters per second**

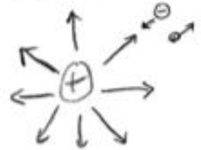


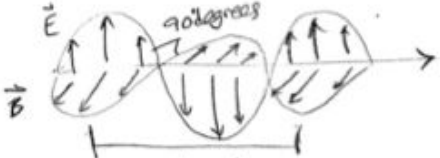
Light can also be defined as particles, **photons** , which are discrete **quanta** of electromagnetic fields

2.1|

Electromagnetic Radiation (Light) –

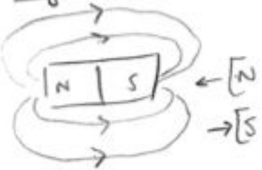
Electric field





wavelength (λ) – distance between wave crests

Magnetic field



frequency (ν): $\nu = c/\lambda$

Energy: $E = h\nu = pc$
↑ Planck's constant

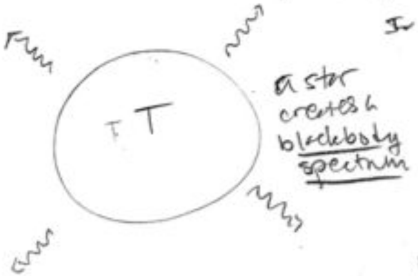
speed of light –
$c = 300$ million meters / second

Photon – packet of light energy that behaves like a massless particle
γ
$E = h\nu$

absorption
$E = E_2 - E_1$
$\lambda = \frac{hc}{E}$

⇒ each chemical has unique absorption & emission lines

Blackbody Radiation – radiation from an object with temperature T



lower frequency ← longer wavelength (redder)

→ higher frequency shorter wavelengths (bluer)

e.g. Hydrogen Balmer Lines

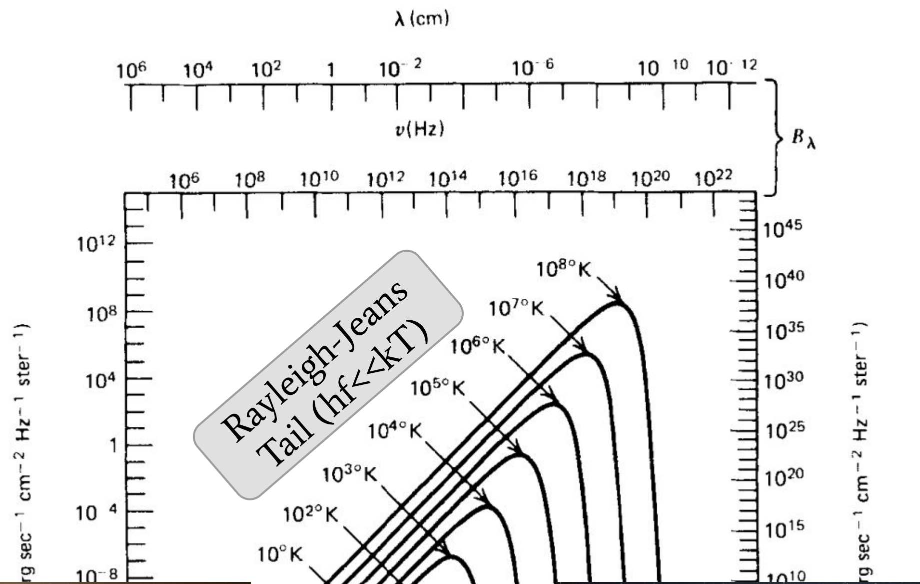
$n=3 \to 2$: 626.279 nm → red
$n=4 \to 2$: 486.176 nm → green
$n=5 \to 2$: 434.5472 nm → blue

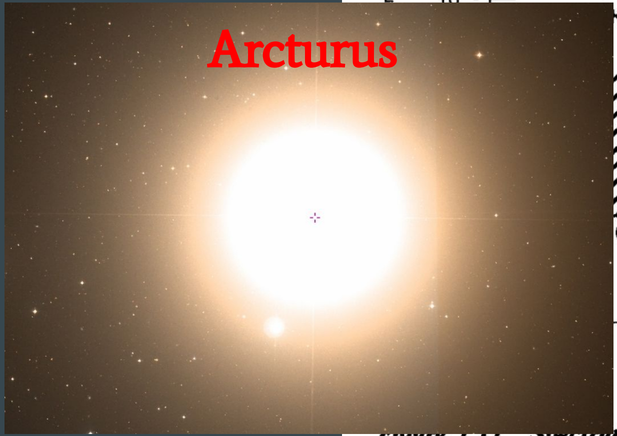
Blackbody Radiation

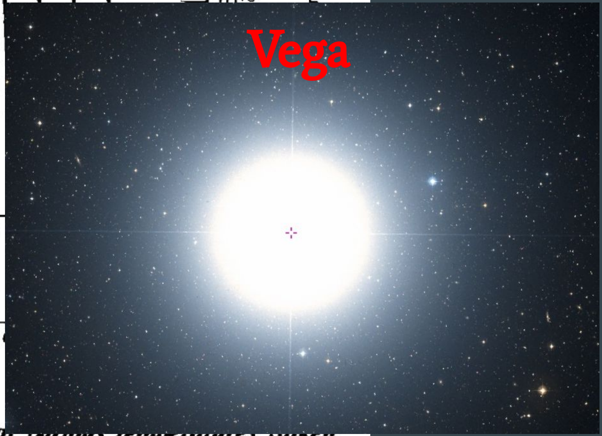
Radiation that is in thermal equilibrium (all photons at the same temperature)

Hotter = BLUE

Colder = RED







... Spectrum of blackbody radiation ...
from Kraus, J. D. 1966, Radio Astronomy, McGraw-Hill Book Company)

Stellar Spectra

Stars' spectra tell us about their chemical content, environment, age, and speed!

Kirchoff's Laws:

1. perfect blackbody has continuous spectrum with no spectral lines
2. **hot diffuse gas** produces bright **emission** lines
3. **cool dense gas** in front of continuous spectrum source produces dark **absorption** lines

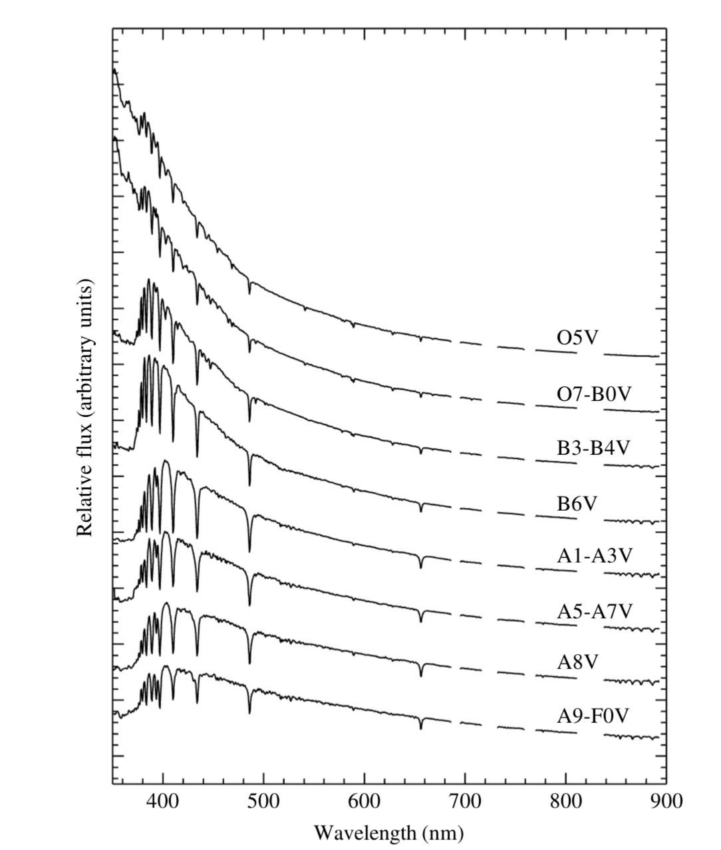
Spectra can be used to measure **radial velocities** of stars and **cosmological redshifts (distances)** of galaxies using the **doppler effect:**

Radial velocity: v = (λc)Δλ

Cosmological redshift: z = Δ λ/Δλ - 1

Luminosity distance: D = cz/H0 (Hubble's constant H0 ≅70 km/s/Mpc)

Demo:
https://phys.libretexts.org/Courses/HACC_Central_Pennsylvania's_Community_College/Astronomy_103%3A_Introduction_to_Planetary_Astronomy/04%3A_Electromagnetic_Radiation/4.04%3A_Kirchhoffs_Laws

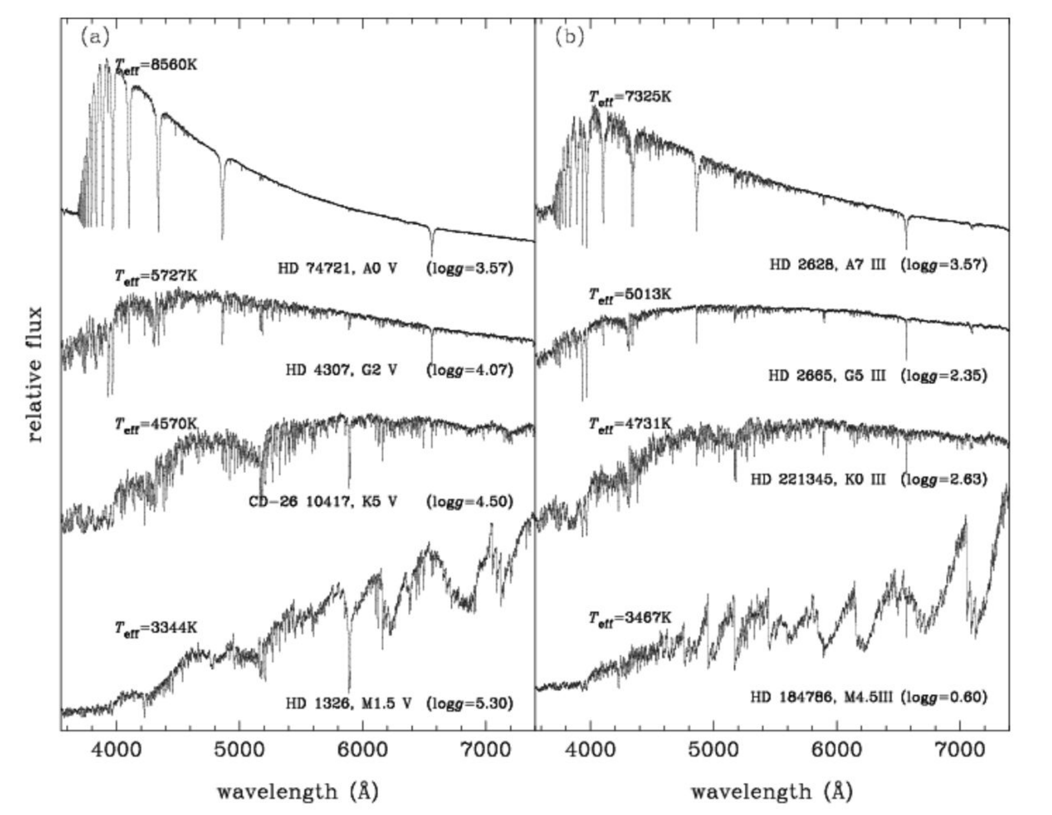


Sub-Giant Star Spectra
(Silva & Cornell 1992)

Think-Pair-Share

How would you distinguish which spectral lines come from the star and which ones come from gas in the Interstellar Medium?

Stellar Spectra Examples

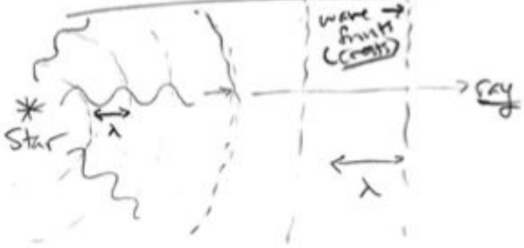


MILES Stellar Spectra Library (Falcón-Barroso+2011) https://research.iac.es/proyecto/miles/pages/stellar-libraries/miles-library.php

Spectral Class	Color	Approximate Temperature (K)	Principal Features	Examples
O	Blue	> 30,000	Neutral and ionized helium lines, weak hydrogen lines	10 Lacertae
B	Blue-white	10,000–30,000	Neutral helium lines, strong hydrogen lines	Rigel, Spica
A	White	7500–10,000	Strongest hydrogen lines, weak ionized calcium lines, weak ionized metal (e.g., iron, magnesium) lines	Sirius, Vega
F	Yellow-white	6000–7500	Strong hydrogen lines, strong ionized calcium lines, weak sodium lines, many ionized metal lines	Canopus, Procyon
G	Yellow	5200–6000	Weaker hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of ionized and neutral metals	Sun, Capella
K	Orange	3700–5200	Very weak hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of neutral metals	Arcturus, Aldebaran
M	Red	2400–3700	Strong lines of neutral metals and molecular bands of titanium oxide dominate	Betelgeuse, Antares
L	Red	1300–2400	Metal hydride lines, alkali metal lines (e.g., sodium, potassium, rubidium)	Teide 1
T	Magenta	700–1300	Methane lines	Gliese 229B
Y	Infrared[1]	< 700	Ammonia lines	WISE 1828+2650

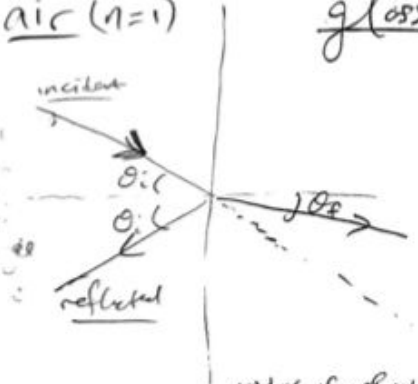
2.2

Geometric Optics



Stars emit light in all directions (isotropic)

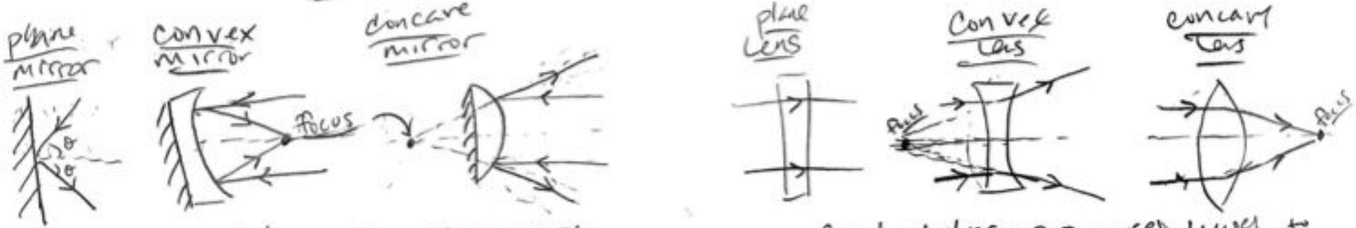
Law of reflection: light is reflected at the angle of incidence



Snell's law of refraction: transmitted light bends toward the normal in medium where $v < c$

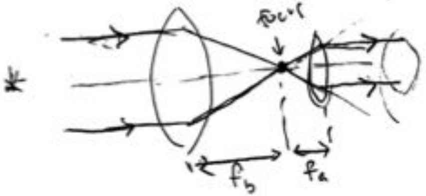
index of refraction: $n = \frac{c}{v}$

lens – uses refraction to ...



reflective telescope – uses mirrors to focus & magnify light

refractive telescope – uses lenses to focus & magnify light



magnification

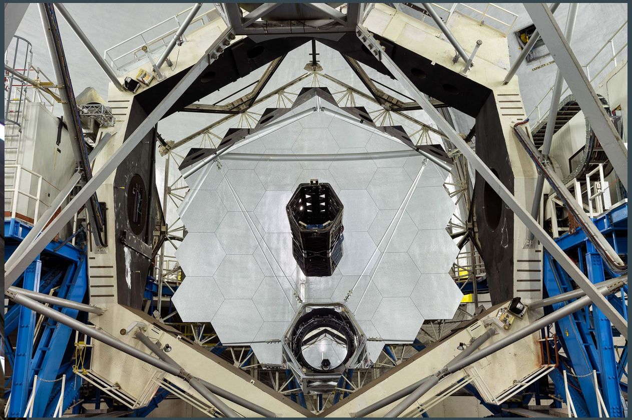
$$M = \left(\frac{f_b}{f_a}\right)^2$$

Telescope Design Examples

Las Cumbres Observatories - 1 meter Ritchey-Chretién reflecting telescopes

Palomar Hale Telescope - 200 inch Cassegrain telescope

Keck I & II telescopes - 10 meter Ritchey-Chretién reflecting telescopes with adaptive optics



Think-Pair-Share

Why are modern telescopes almost exclusively *reflective* telescopes?

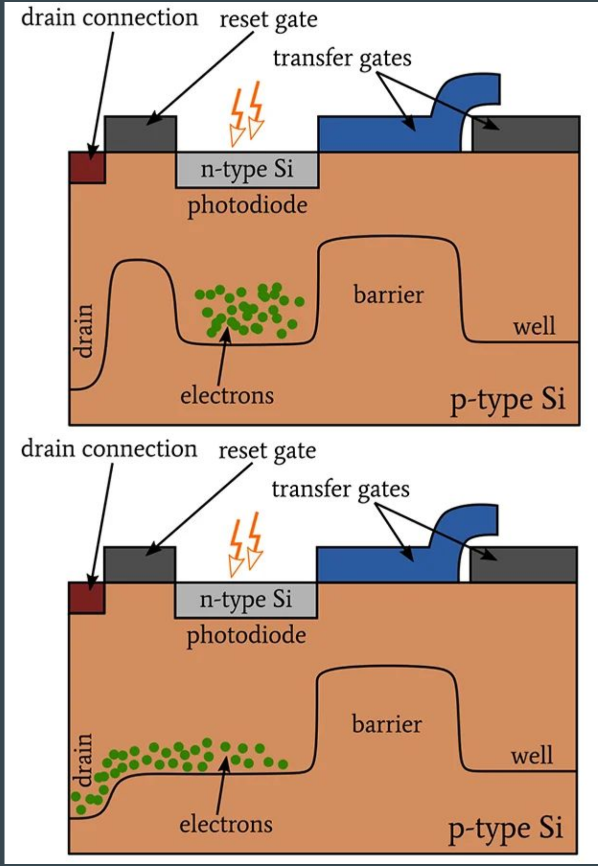
Demo: **Let’s go through the components of refractive binoculars and a reflective Gskyer telescope!**

Detectors: Photographic Film/Plates

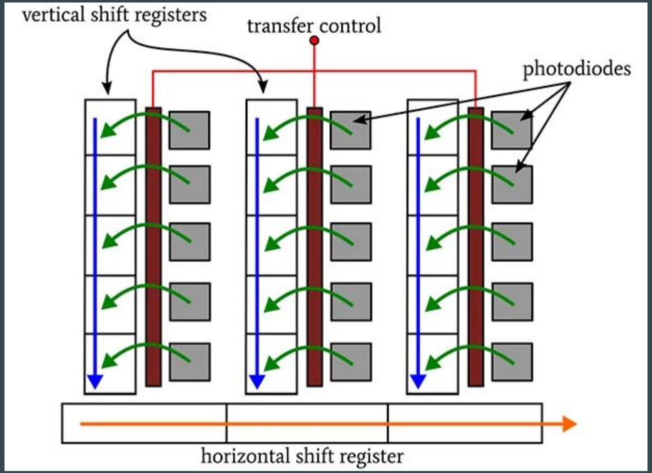
Detectors: Charge-Coupled Devices (CCD) & CMOS Detectors

Detection

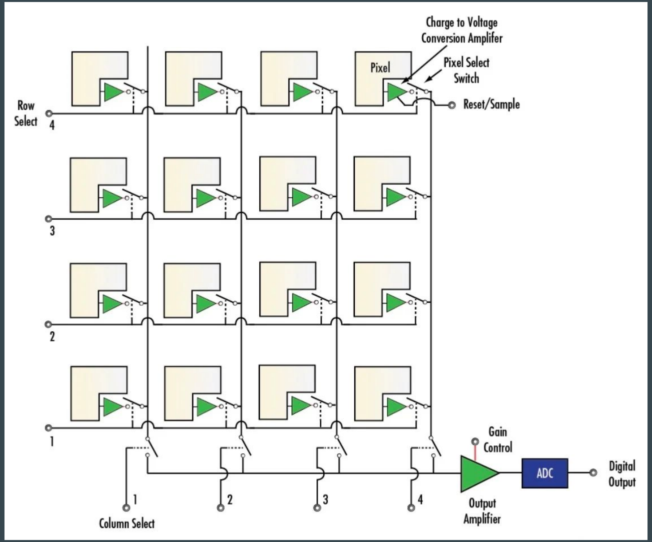
Readout



CCD

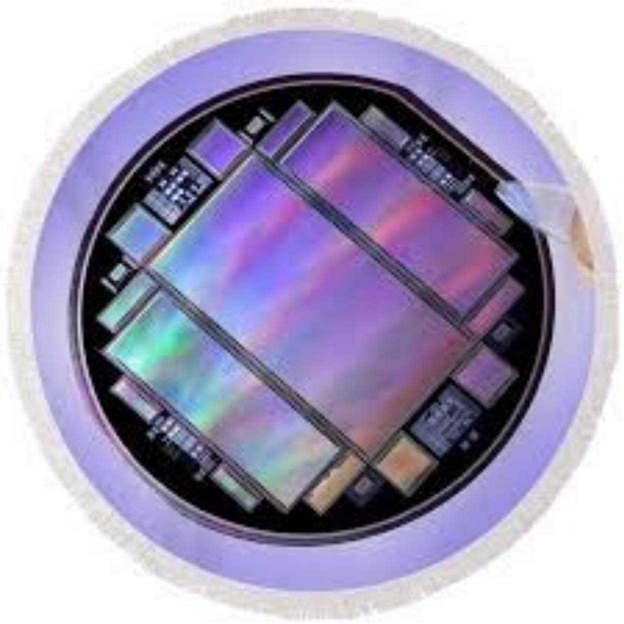


CMOS



Detectors: Charge-Coupled Devices (CCD) & CMOS Detectors

Keck Echellete Spectrograph Imager (ESI) 2048 x 4096 CCD (15 μm pixels)

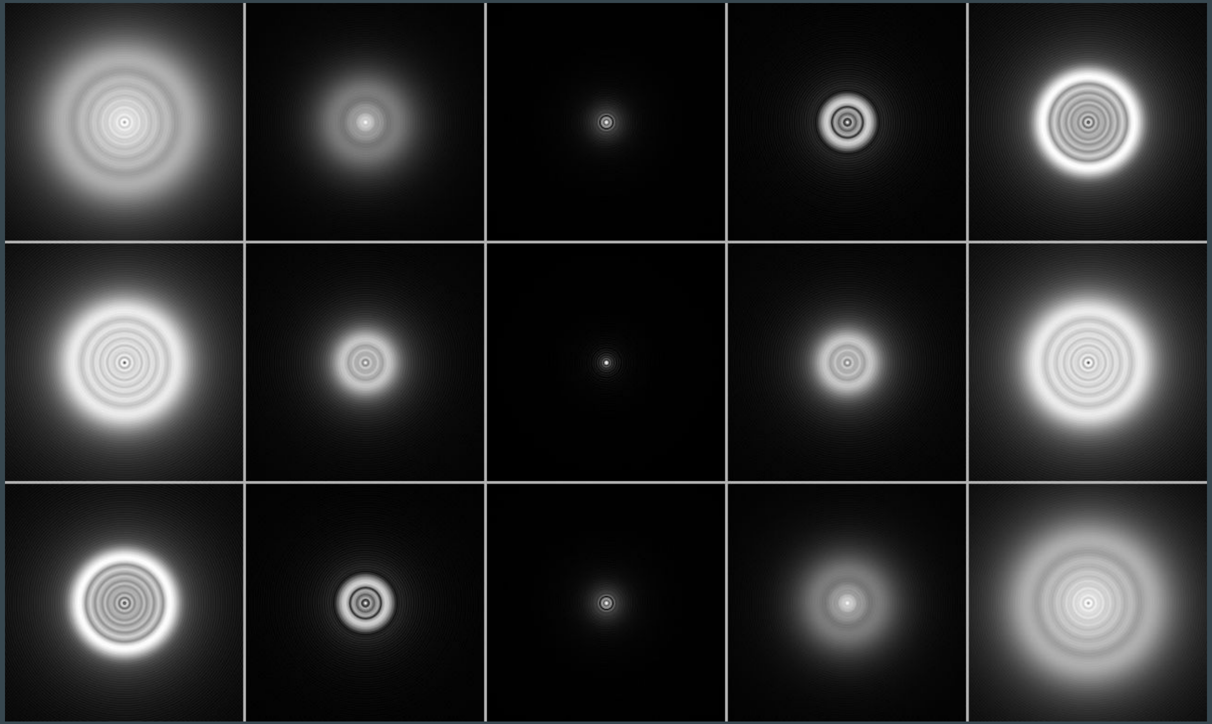


ESI CCD Characteristics	
Full-well depth	105,000e-
Read noise	2.7e-
Dark current (-120C)	2 e-/pix/hour
Gain (low)	1.29 e-/DN
Gain (high)	0.5 e-/DN
Serial CTE (fast readout)	0.99998
Serial CTE (normal readout)	0.99998
Serial CTE (slow readout)	0.99999
Readout time (fast)	39 sec
Readout time (normal)	57 sec
Readout time (slow)	120 sec

ESI CCD Q.E.	
3200 Å	10.2%
3500 Å	12.1%
4000 Å	60.8%
4500 Å	75.5%
5000 Å	82.4%
6000 Å	80.3%
6500 Å	79.7%
7000 Å	77.1%
8000 Å	68.9%
9000 Å	45.0%
10000 Å	11.3%

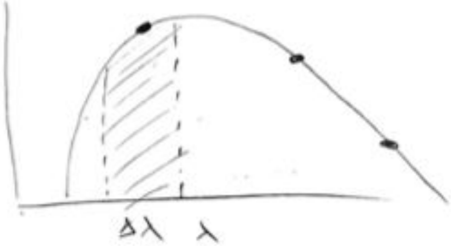
Point Spread Function

Spatial response of the detector due to the aperture size ; single lens makes an Airy function PSF ("spherical aberration")



2.31

Photometry - measuring brightness (flux) of a star in particular wavelength range using filters



↳ Ultraviolet $100\text{ nm} < \lambda < 400\text{ nm}$

Optical $380\text{ nm} < \lambda < 750\text{ nm}$

Infrared $700\text{ nm} < \lambda < 1\text{ mm}$

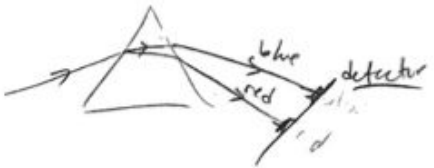
} Photometric Systems — standard ranges based on telescope filters, e.g. UBVRI JHK

↳ magnitude - brightness in wavelength range (m_V)

color - difference in magnitude between different filters ($m_V - m_B$)

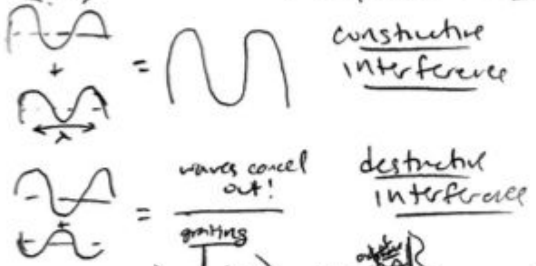
Spectroscopy - breaking light into its component wavelengths (dispersion) to measure high resolution spectrum

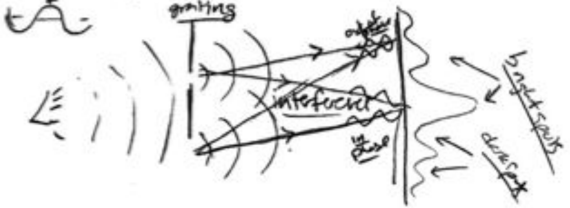
- Prism - uses wavelength dependence of index of refraction for dispersion



- Diffraction Grating - uses interference to disperse light

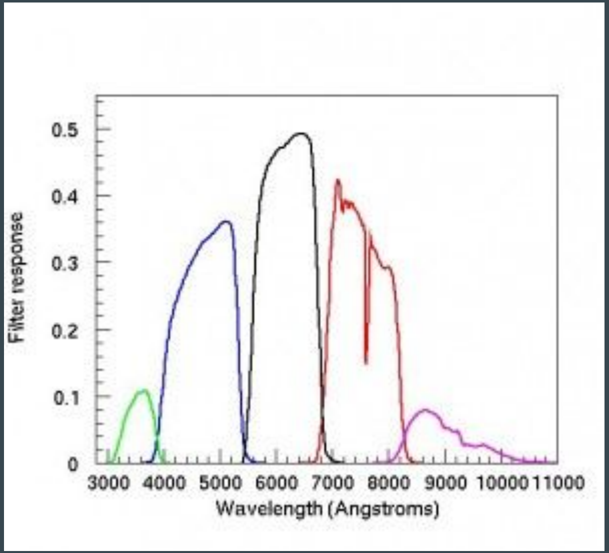
Superposition Principle - when 2 light waves add together, they interfere to produce a resultant



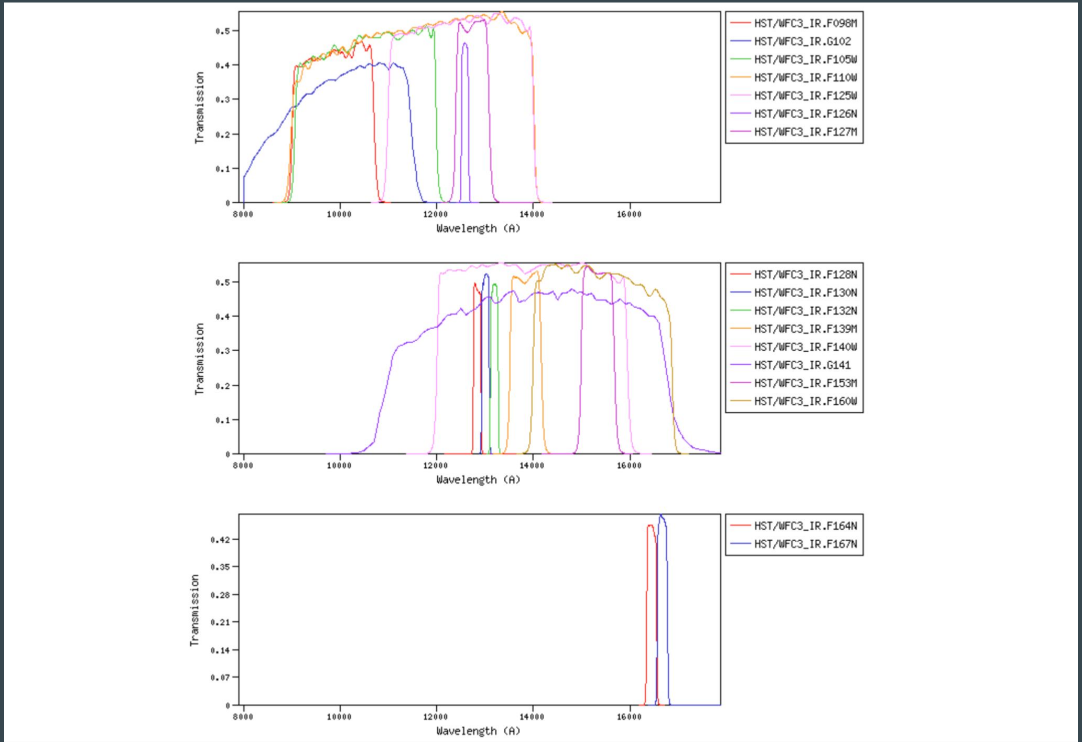


Photometric System Examples

SDSS

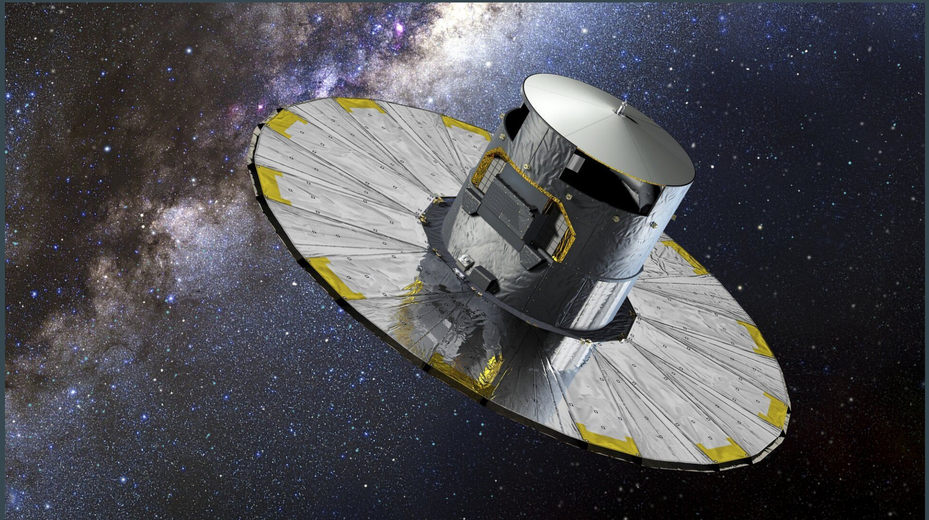


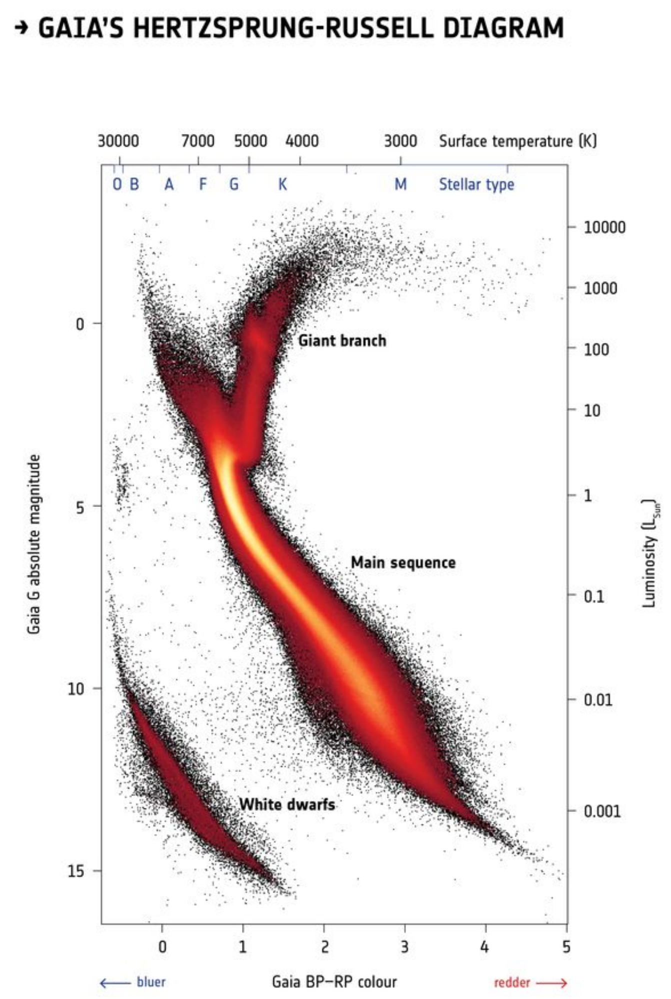
HST WideField IR Camera



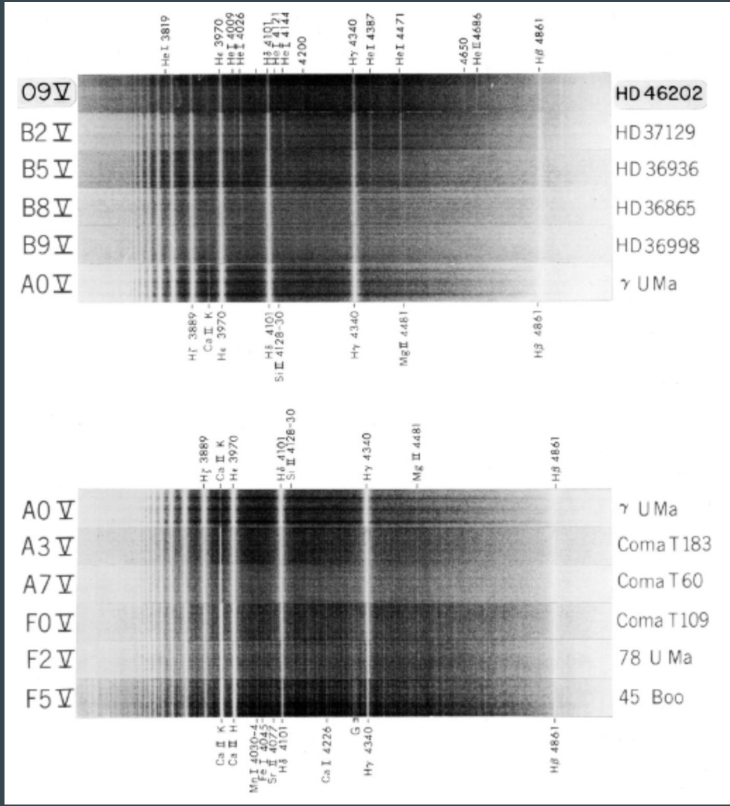
The Hertzsprung-Russell Diagram

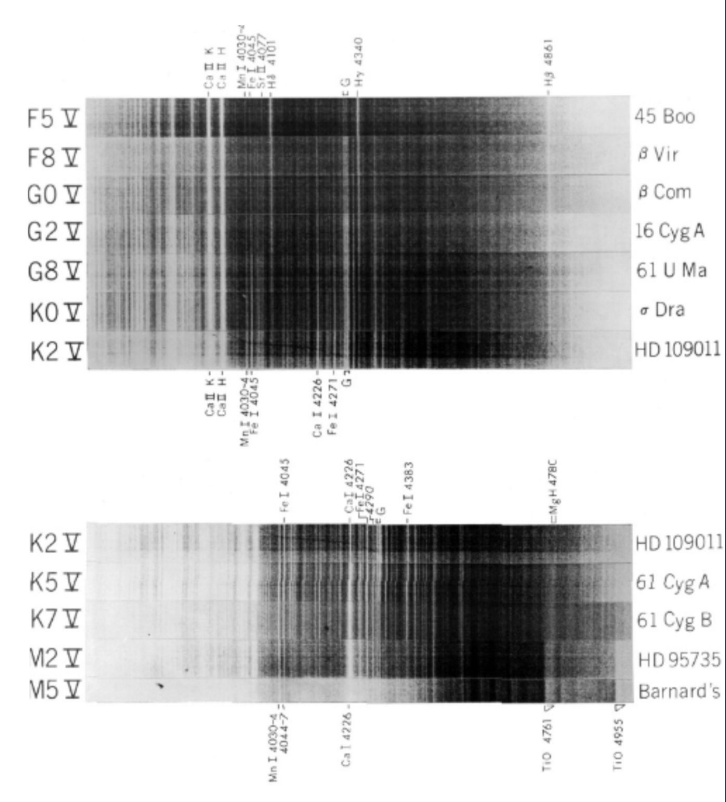
- **Color-Index** (B-V or BP-RP) closely relates to **stellar type (O-M)** and **effective surface temperature**
- European Space Agency's *Gaia* telescope has mapped over 2 billion stars to the H-R diagram!





Stellar Spectra Examples - How do we measure stars' spectra?





From 1968 Atlas of Stellar Spectra

Diffraction Gratings

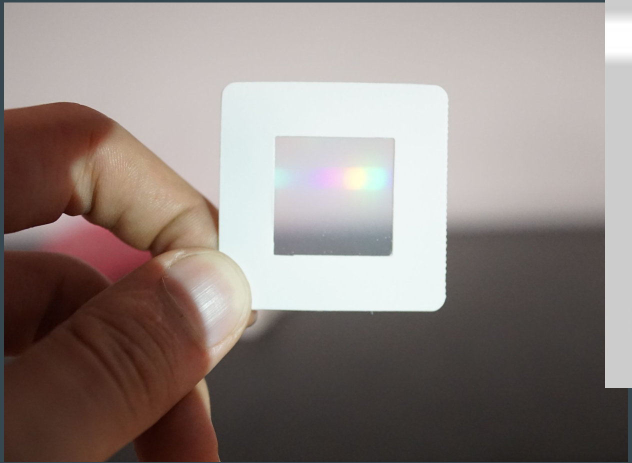
Series of N slits creates **interference** , **or diffraction** between light passing through

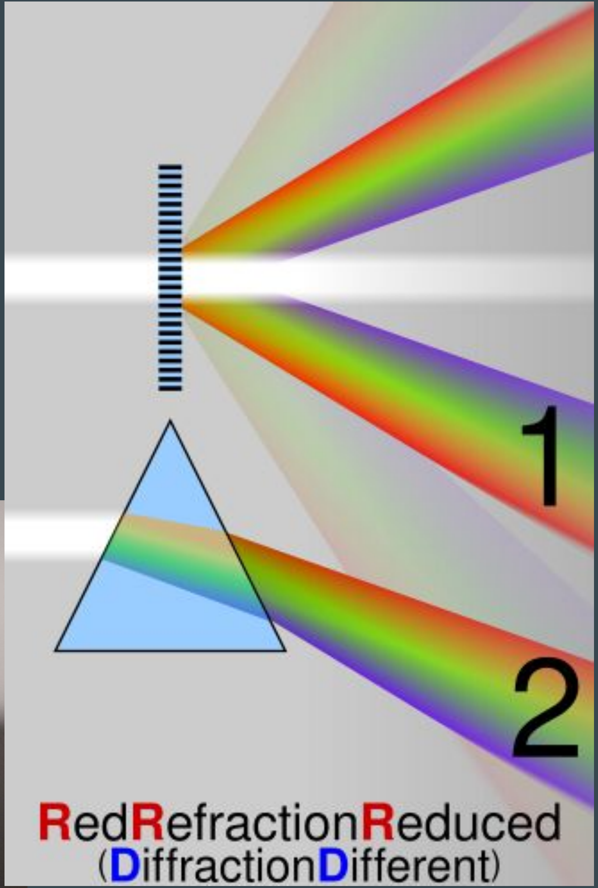
constructive interference : $d\sin\theta = m\lambda$

destructive interference: $d\sin\theta = (m+½)\lambda$

Resolution:

$$R = \Delta\lambda/\lambda = Nm$$





$d\sin\theta=2\lambda$

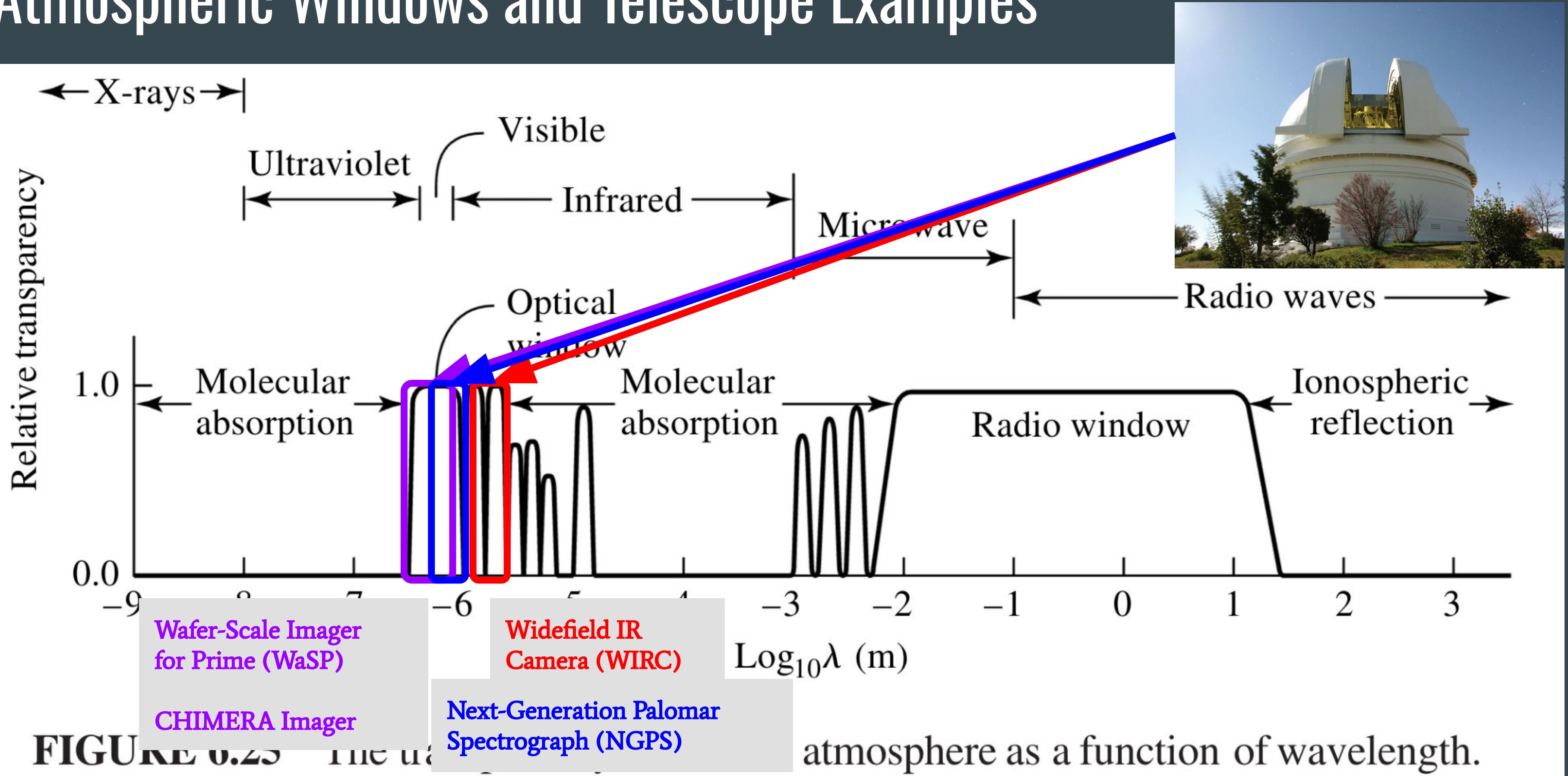
$d\sin\theta=\lambda$

$d\sin\theta=0$

$d\sin\theta=-\lambda$

Atmospheric Windows and Telescope Examples

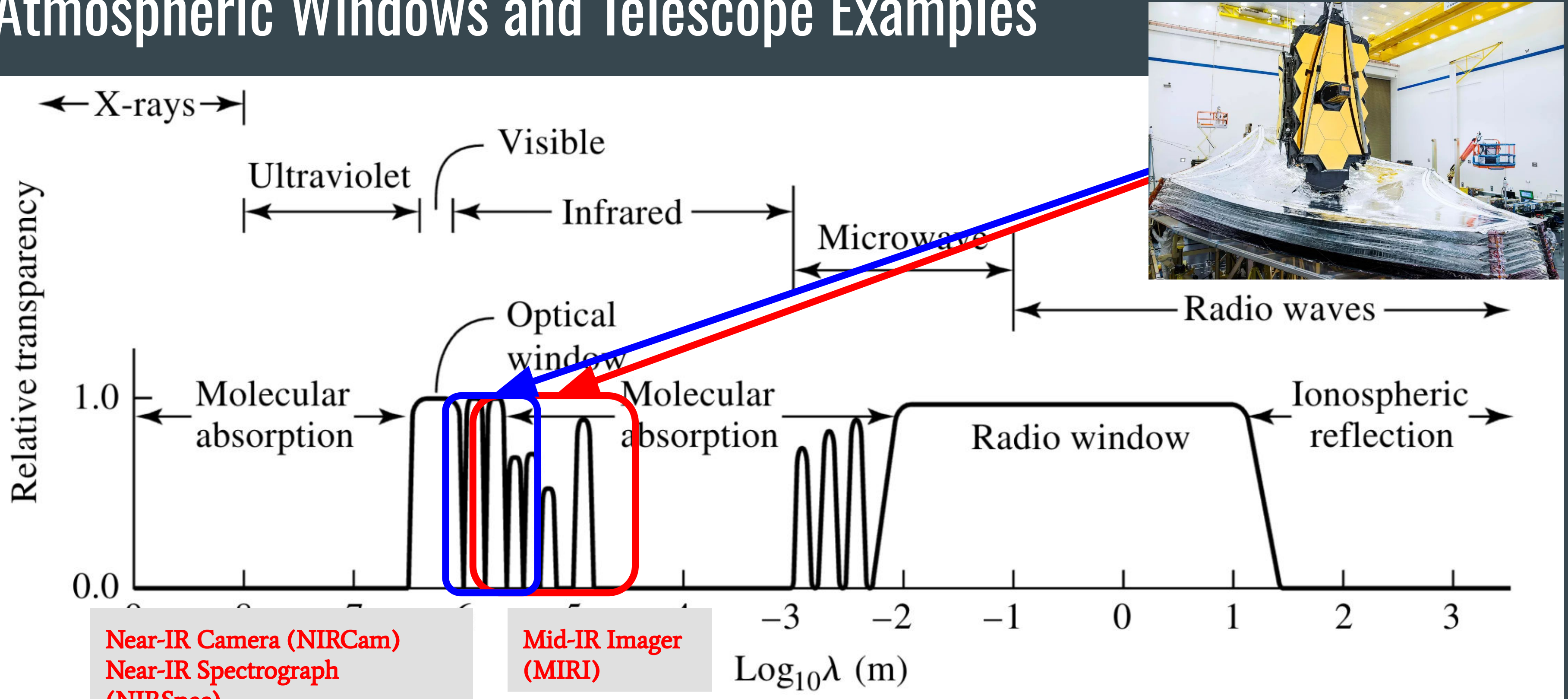
Palomar 200-inch
Hale Telescope



atmosphere as a function of wavelength.

Atmospheric Windows and Telescope Examples

James Webb Space Telescope (JWST)



Near-IR Camera (NIRCam)
Near-IR Spectrograph (NIRSpec)
Near-Infrared Imager and Slitless Spectrograph (NIRISS)

Mid-IR Imager (MIRI)

FI[...]sparency of Earth's atmosphere as a function of wavelength.

Atmospheric Windows and Telescope Examples

GALactic EXplorer (GALEX)

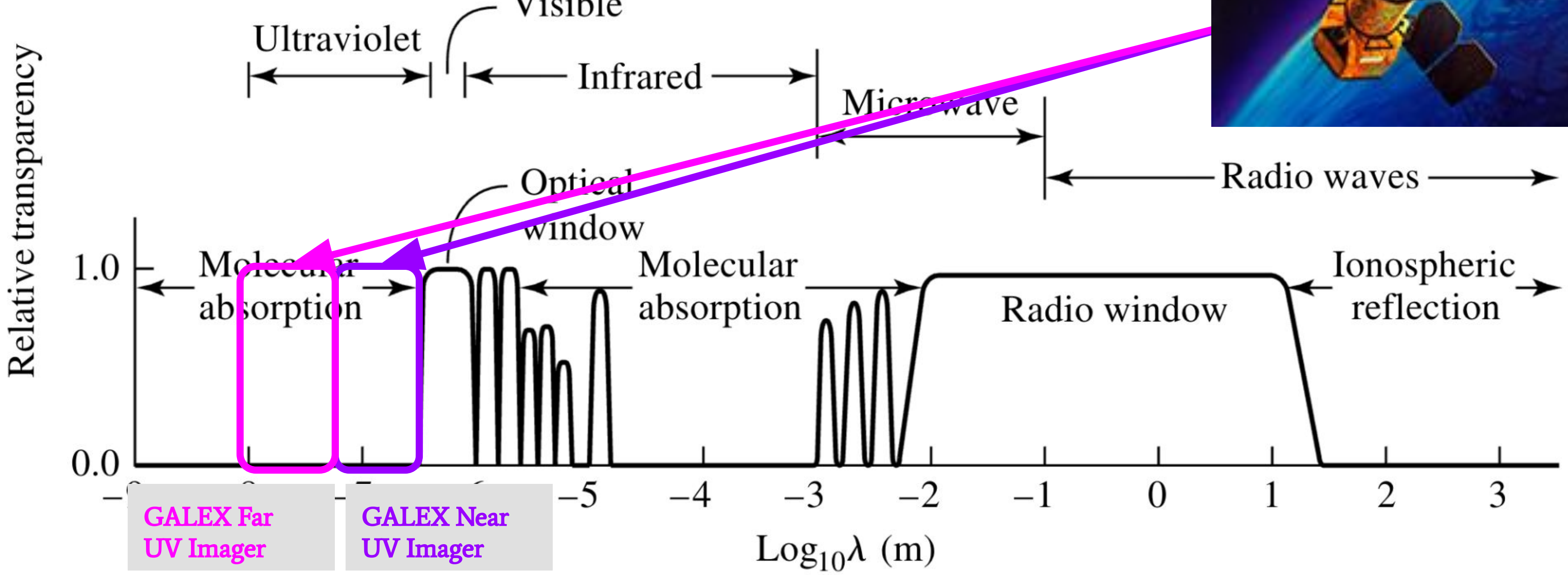


FIGURE 6.25 The transparency of Earth's atmosphere as a function of wavelength.

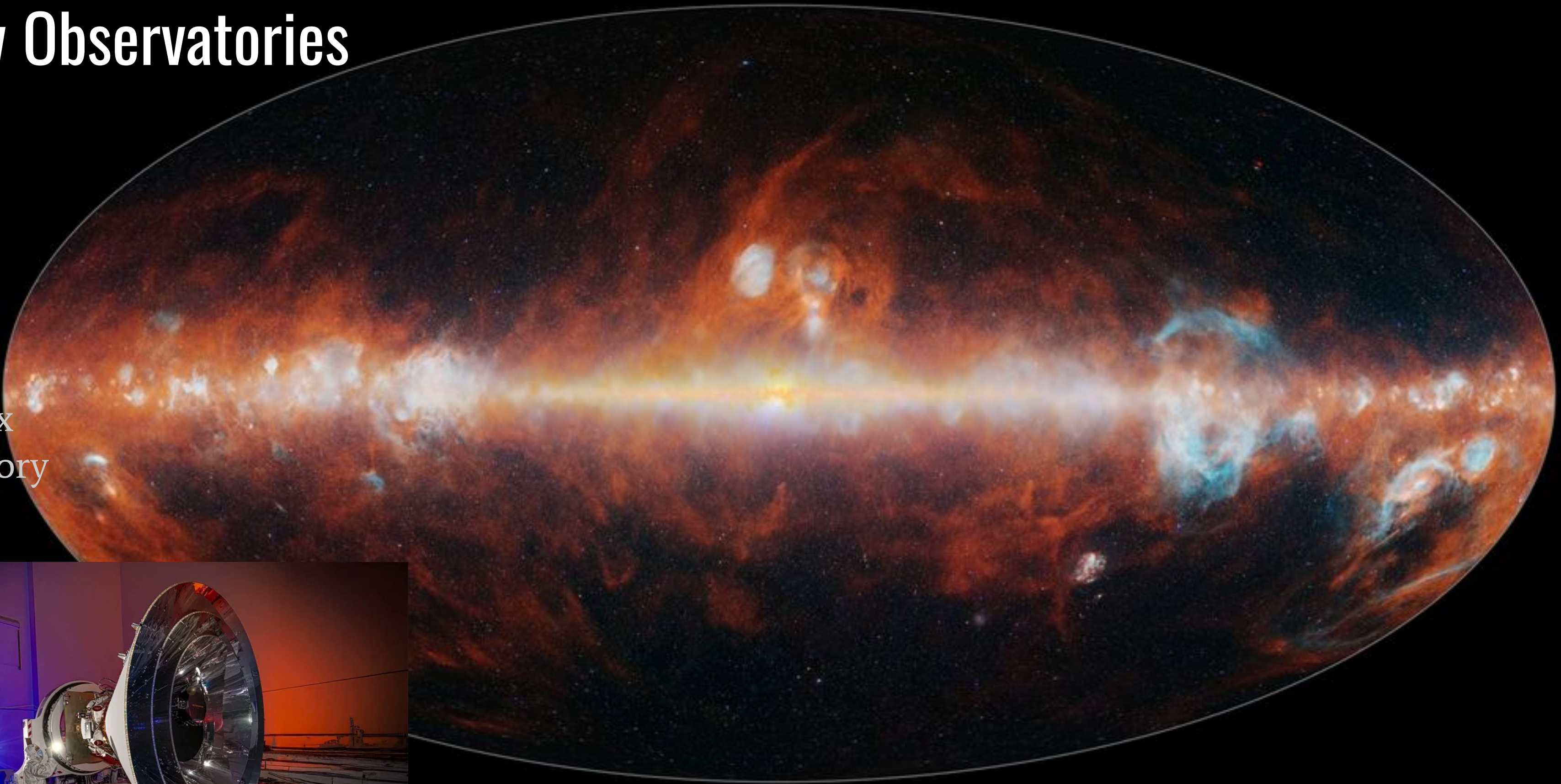
New Observatories

James Webb Space Telescope (JWST)

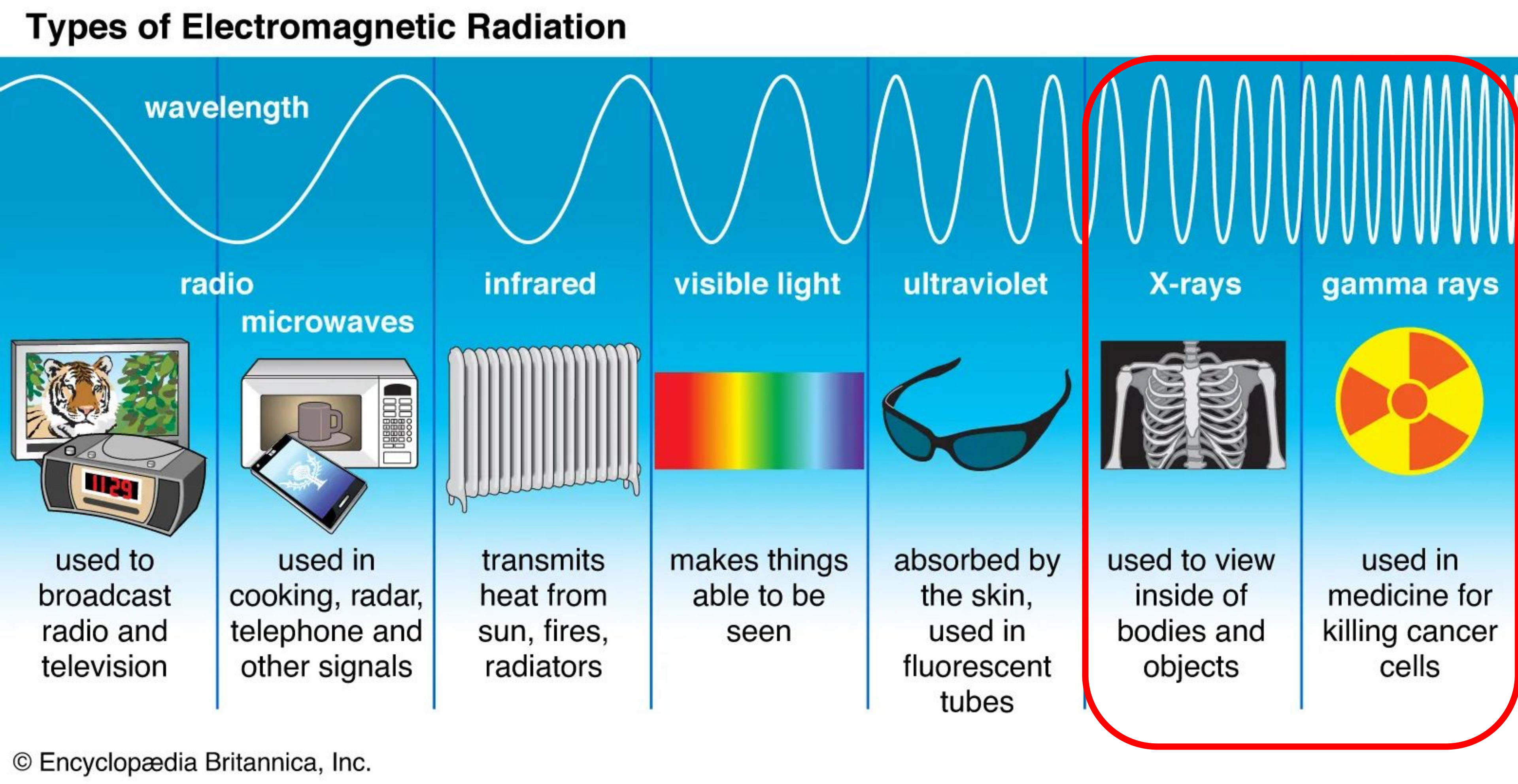
New Observatories

Vera Rubin Observatory

New Observatories



SPHEREx
Observatory



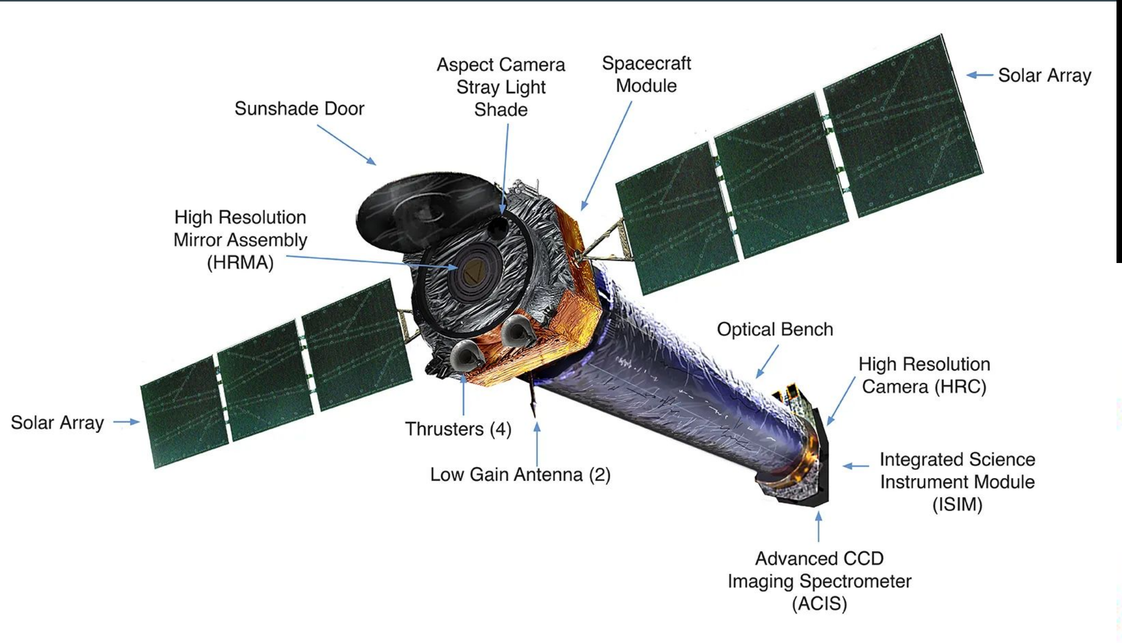
Types of Electromagnetic Radiation
wavelength
radio
microwaves
infrared
visible light
ultraviolet
X-rays
gamma rays
used to broadcast radio and television
used in cooking, radar, telephone and other signals
transmits heat from sun, fires, radiators
makes things able to be seen
absorbed by the skin, used in fluorescent tubes
used to view inside of bodies and objects
used in medicine for killing cancer cells
© Encyclopædia Britannica, Inc.

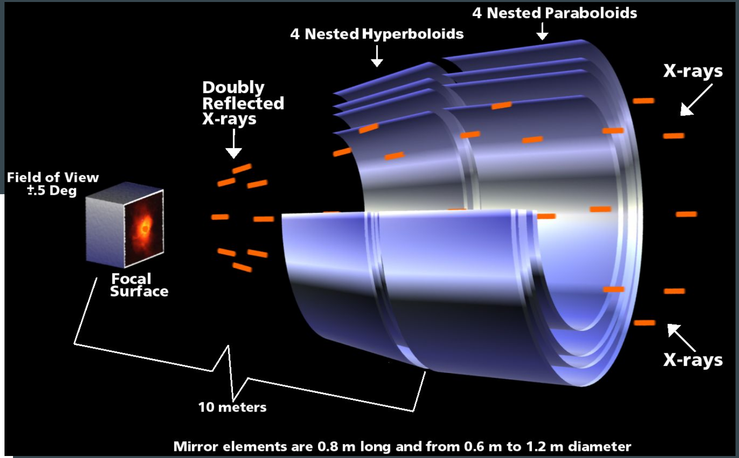
**Remember: energy E[eV] = hc/λ[m]

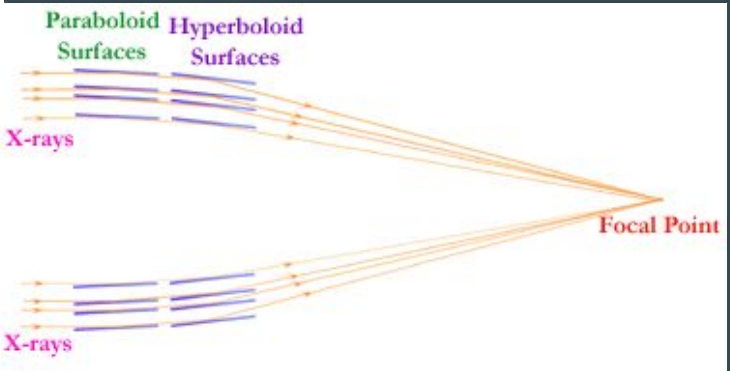
Chandra X-Ray Telescope - grazing incidence

Soft X-rays: 100 electronVolts (eV) - 500 eV

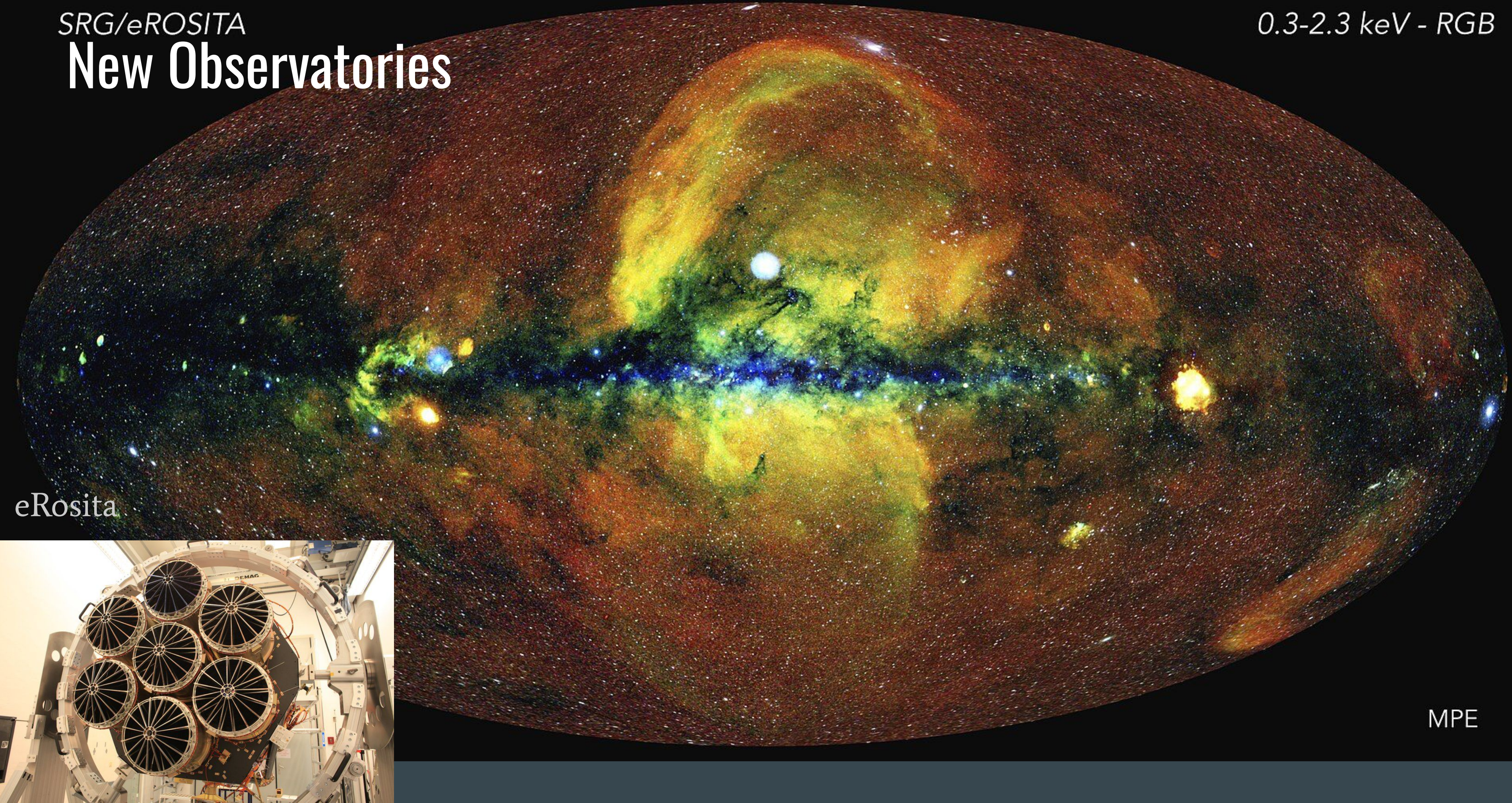
Hard X-rays: 500 eV - 100 keV







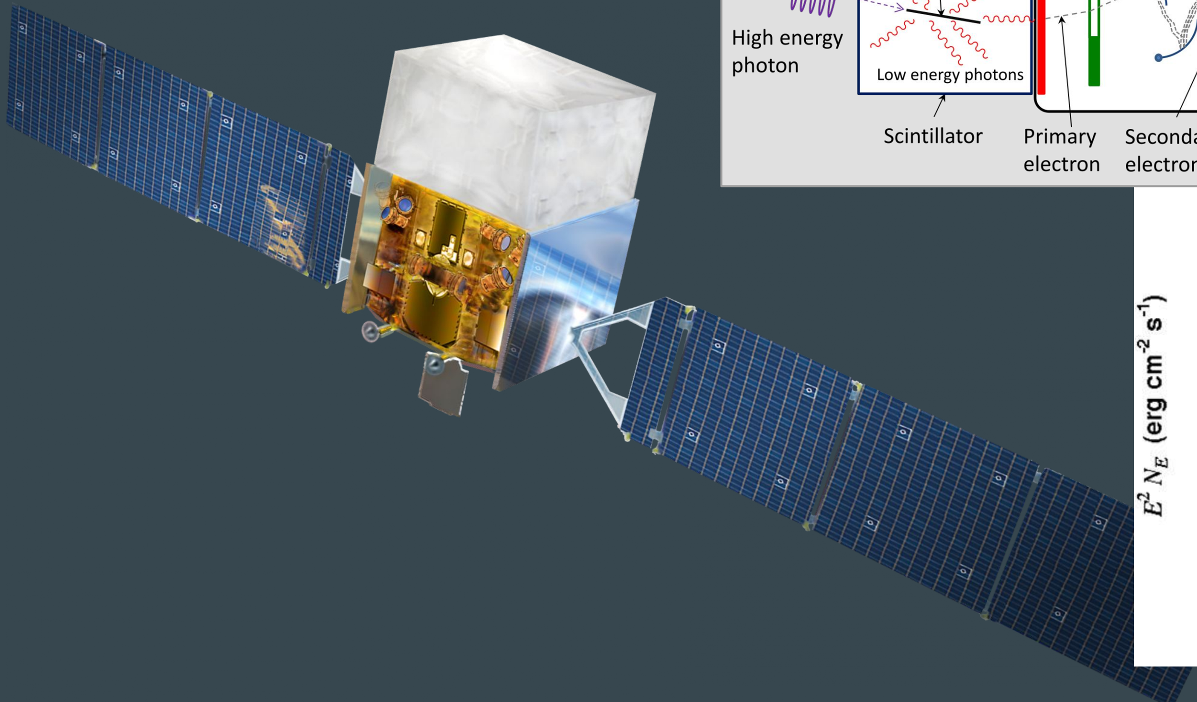
New Observatories

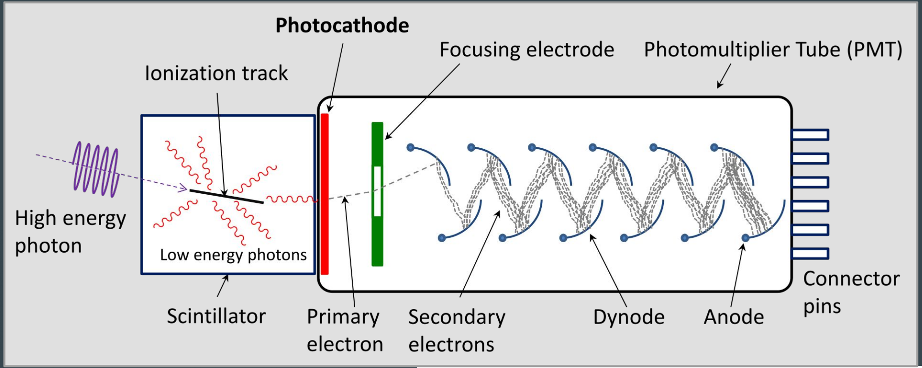


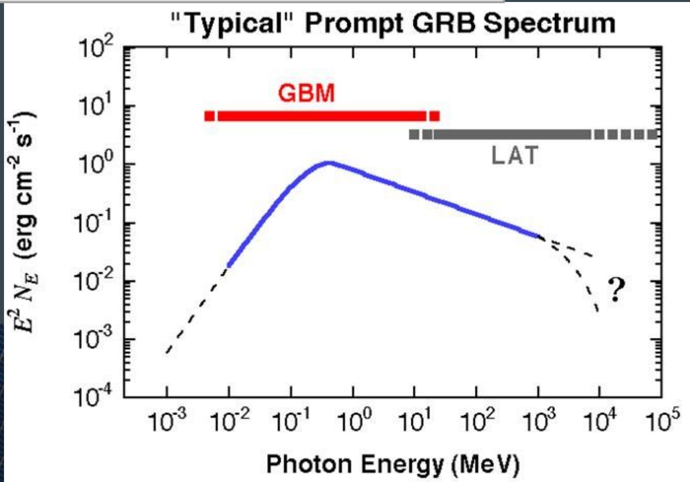
eRosita

Fermi Gamma-Ray Burst Monitor - scintillometry

Gamma Rays: 100 keV - 1000 TeV





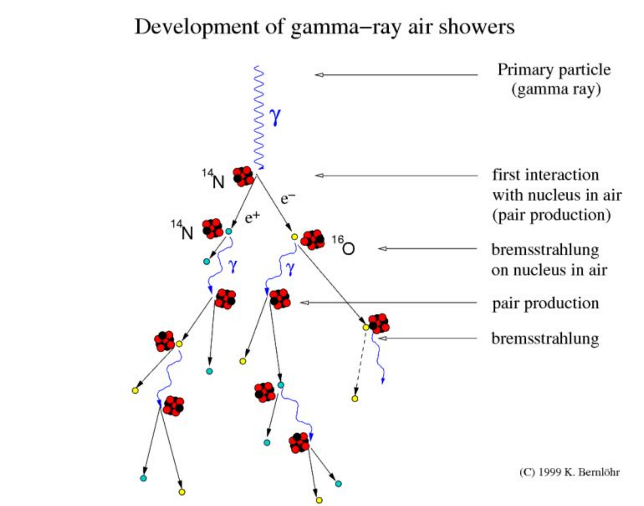


VERITAS - atmospheric Cherenkov detection

**Remember: energy E[eV] = hc/λ[m]

Gamma Rays: 100 keV - 1000 TeV

VERITAS uses the **atmosphere itself** as a scintillator!




Atacama Large
Millimeter Array
(ALMA)

At-Home Astronomy: Stellar Spectra and X-ray Images

Stargazing Nights are a Great Way to learn to use telescopes!

- LA Astronomical Society - https://www.laas.org/
  - Every Wednesday at Garvey Ranch 7:30-10pm
  - Monthly Star Parties at Griffith Park 2pm-9:45pm (next one is Feb 21) https://griffithobservatory.org/event/public-star-party-february-21-2026/
- Caltech Stargazing Lectures - https://www.astro.caltech.edu/outreach/stargazing-lecture-series

Tools for Stellar Spectra:

- SVO Filter Profile Service: https://svo2.cab.inta-csic.es/theory/fps
- MILES Library of Stellar Spectra: https://research.iac.es/proyecto/miles/pages/stellar-libraries/miles-library.php
- NIST Atomic Spectra Database: https://physics.nist.gov/PhysRefData/ASD/lines_form.html

Tools for X-ray Data:

- eRosita X-ray Image Skyview: https://erosita.mpe.mpg.de/dr1/erodat/skyview/sky/
- Chandra video of Kepler's Supernova Remnant: https://chandra.harvard.edu/photo/2026/kepler/

Questions, Comments, or Concerns?

https://forms.gle/ywP1THADKCq1nDPy9

Lecture 3: Radio Astronomy and Compact Stellar Remnants

•••

Learning Objectives and Overview

By the end of this course, students will be able to:

…identify major stars and constellations in the night sky, recount the life-cycle of a star form the Main Sequence to supernova, and distinguish between White Dwarfs, Neutron Stars, and Black Holes.

…describe the basic components of an optical telescope,explain the major differences between optical, infrared, and UV astronomy, describe why X-ray and gamma ray telescopes operate differently from OIR and UV telescopes.

…describe the basic components of a radio antenna, explain how radio interferometers work, and list the astrophysical sources of radio waves.

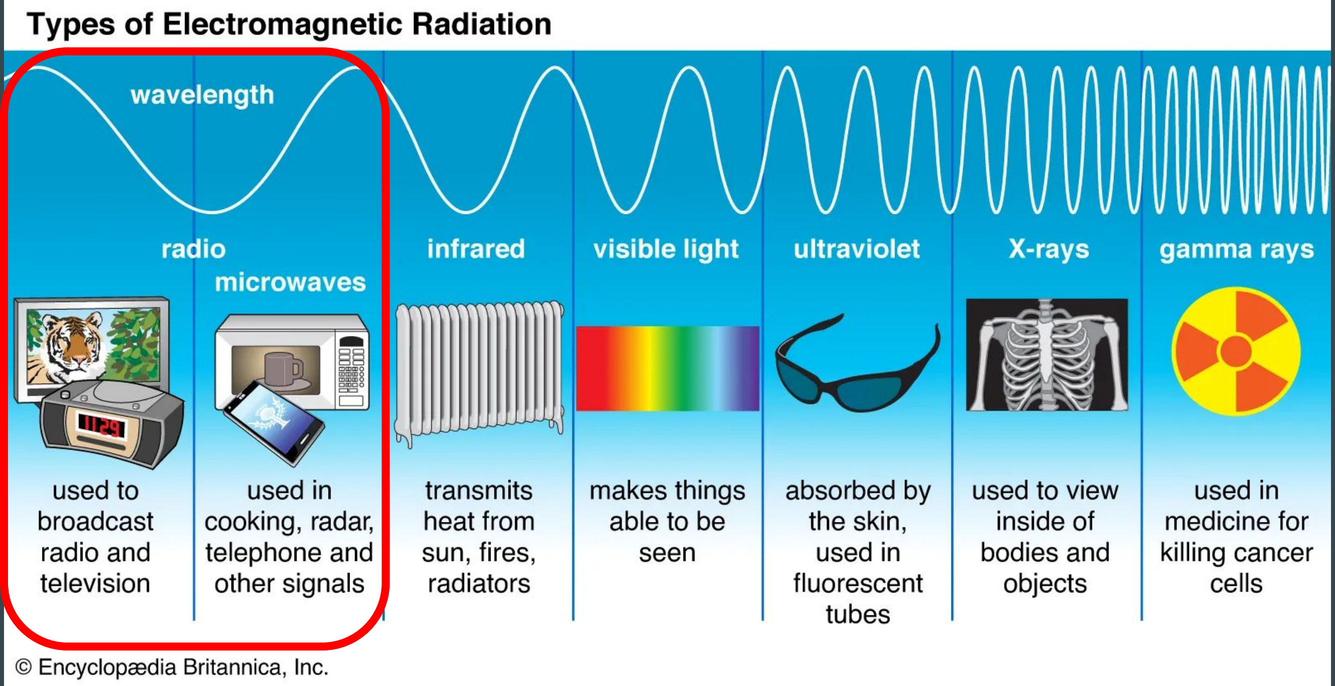
…describe the components of a galaxy (disk, bulge, ISM, halo, CGM), define cosmology, how it is studied (redshift, CMB, 21 cm cosmology, simulations, FRBs), explain how distance, redshift, and time are related within general relativity, and understand how the presence of dark matter and dark energy affect our picture of the Universe.

…list some of the major questions in astronomy today and refer to resources to continue exploring astronomy within and around Pasadena.

Recap: What is Light?

Light is **energy** that travels in **waves** carried by **electric and magnetic fields**

All waves have a wavelength and speed *c*=**671 million miles per hour = 299 million meters per second**



Light can also be defined as particles, **photons** , which are discrete **quanta** of electromagnetic fields

Recall: Atmospheric Windows

Radio light has wavelengths from 1 mm - 10 m

frequencies from 10 kHz - 3 THz

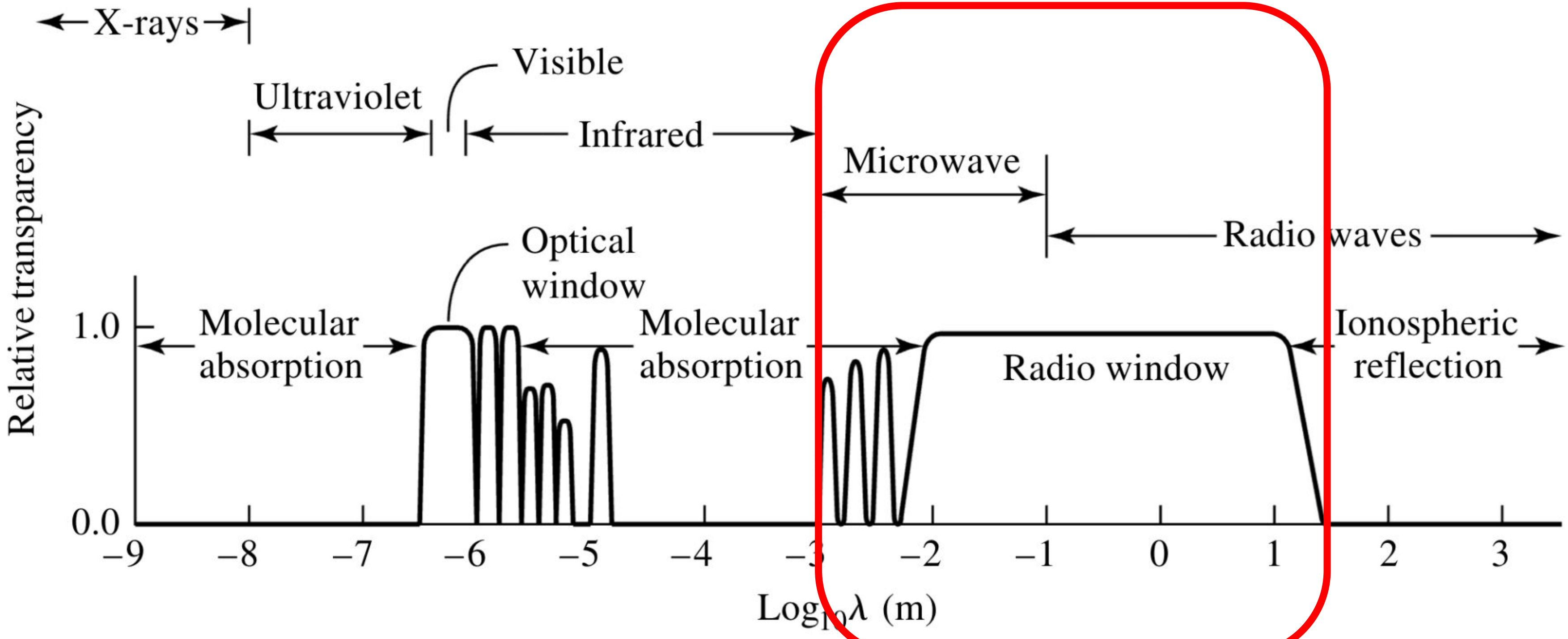
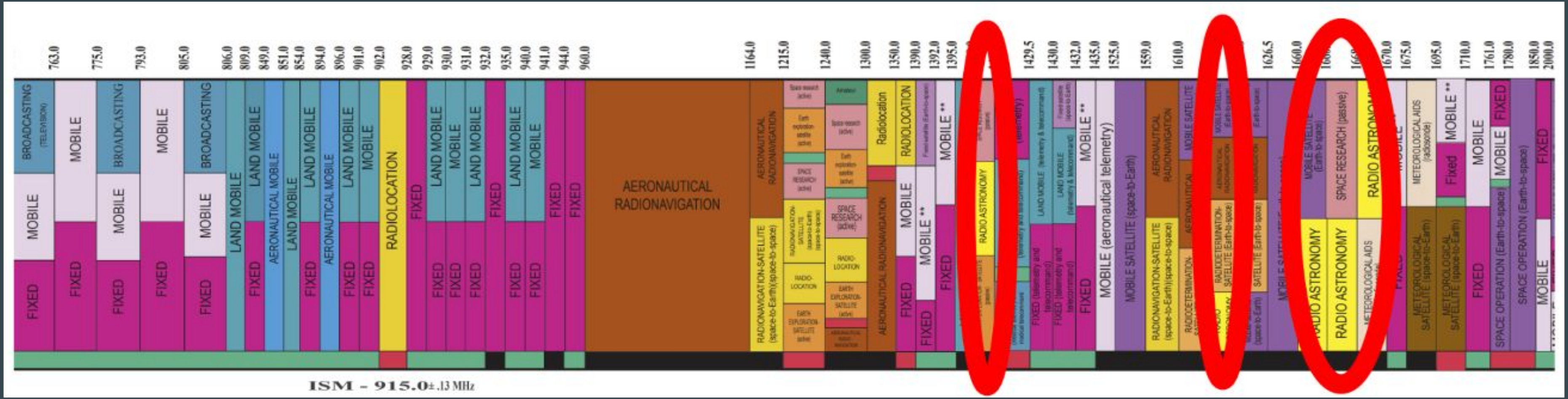


FIGURE 6.25 The transparency of Earth's atmosphere as a function of wavelength.

Radio Spectrum Allocations



The Federal Communications Commission (FCC) and International Telecommunications Union (ITU) regulate the frequency spectrum and reserve specific “bands” (frequency/wavelength ranges) for communications, television, GPS, satellites, HAM radio, radio astronomy, and more.

For example, FM radio uses 88-108 MHz while radio astronomy often uses 400-800 MHz various sub-bands between 1-2 GHz

IEEE Standard Radio Bands

Band Designation	Nominal Frequency Range
HF	3-30 MHz
VHF	30-300 MHz
UHF	300-1000 MHz (Note 5)
L	1-2 GHz
S	2-4 GHz
C	4-8 GHz
X	8-12 GHz
Ku	12-18 GHz
K	18-27 GHz
Ka	27-40 GHz
V	40-75 GHz
W	75-110 GHz
mm (Note 9)	110-300 GHz
Sub-mm	>300 GHz

Recall: Blackbody Radiation

Radiation that is in thermal equilibrium (all photons at the same temperature)

Rayleigh-Jeans Law:

$I_\nu = 2\nu^2 kT/c^2$

Brightness Temperature:

$T_b = c^2 I_\nu / 2k\nu^2$

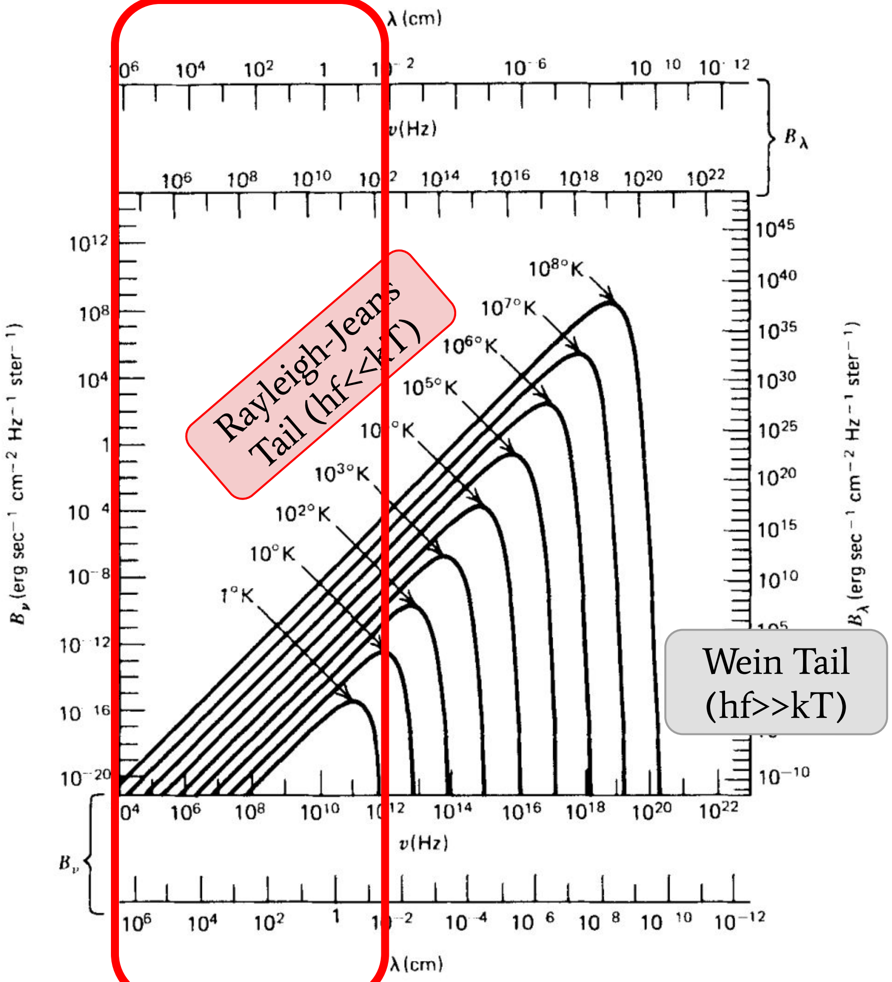
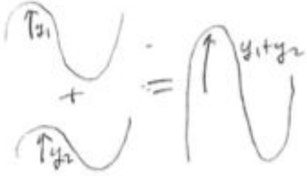


Figure 1.11 Spectrum of blackbody radiation at various temperatures (taken from Kraus, J. D. 1966, Radio Astronomy, McGraw-Hill Book Company)

3.3 |

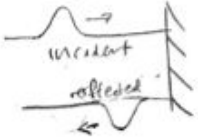
Antenna - converts radiation in space into electrical current or vice versa

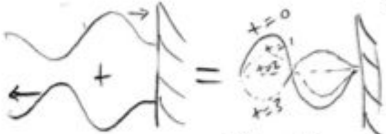
superposition / interference



constructive interference

destructive interference





Standing wave

Incident and reflected wave interfere to produce a wave that appears stationary

Standing wave modes - only certain wavelengths are allowed to create standing waves!

$$\lambda_n = \frac{2L}{n}$$ ← length of string (L); ← any number (n)

Circuit - allows electrons to flow from high potential energy to low potential energy

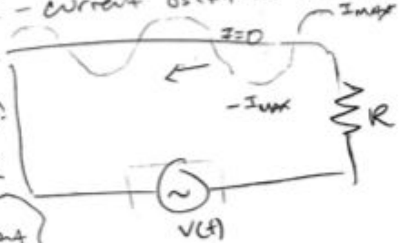
Ohm's law

$$V = IR$$

V - voltage - potential energy per unit charge

I - current - rate that charges flow

alternating current - current oscillates with time



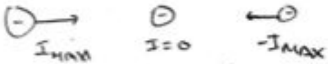
↳ current on wire behaves like waves on a string!

↳ charges accelerate

↓

wire with alternating current radiates (transmission)

EM waves that hit a wire induce a current (receiving)

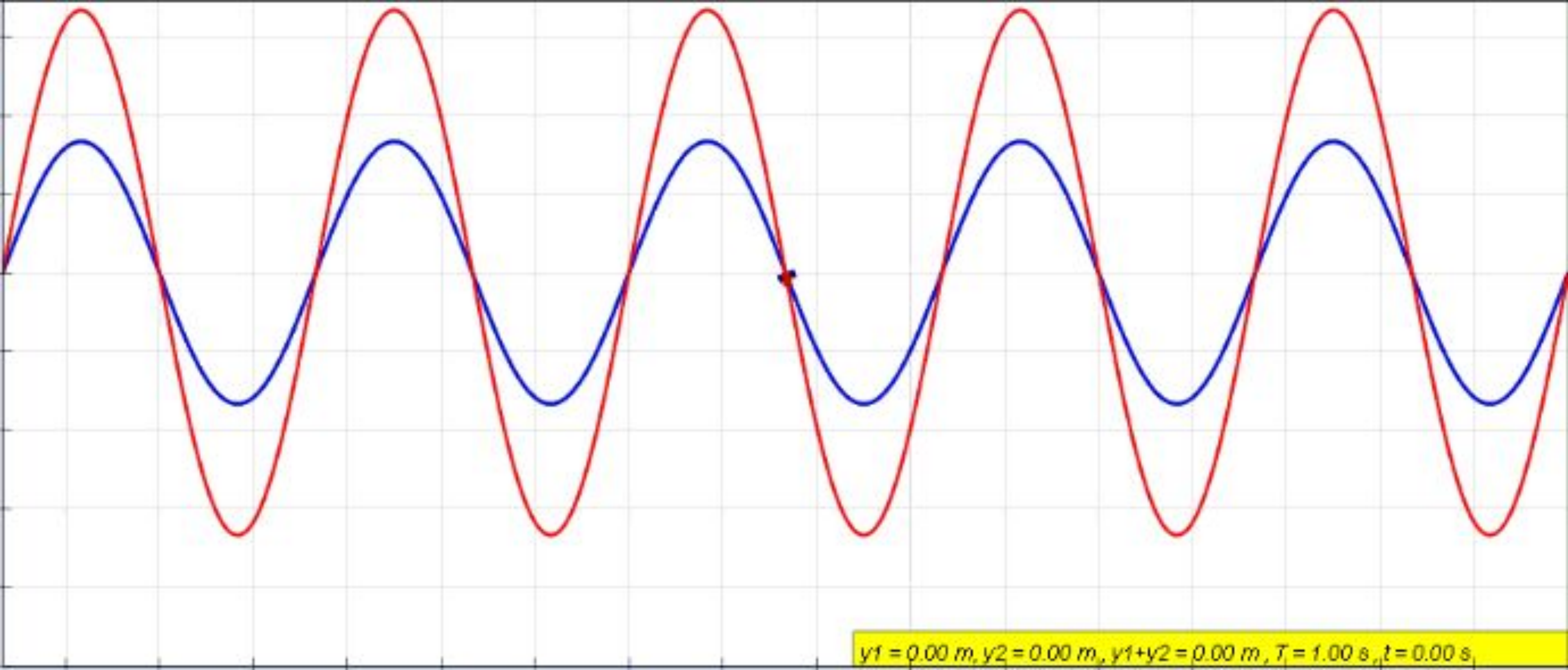


- Terminated wire ⇒ standing wave

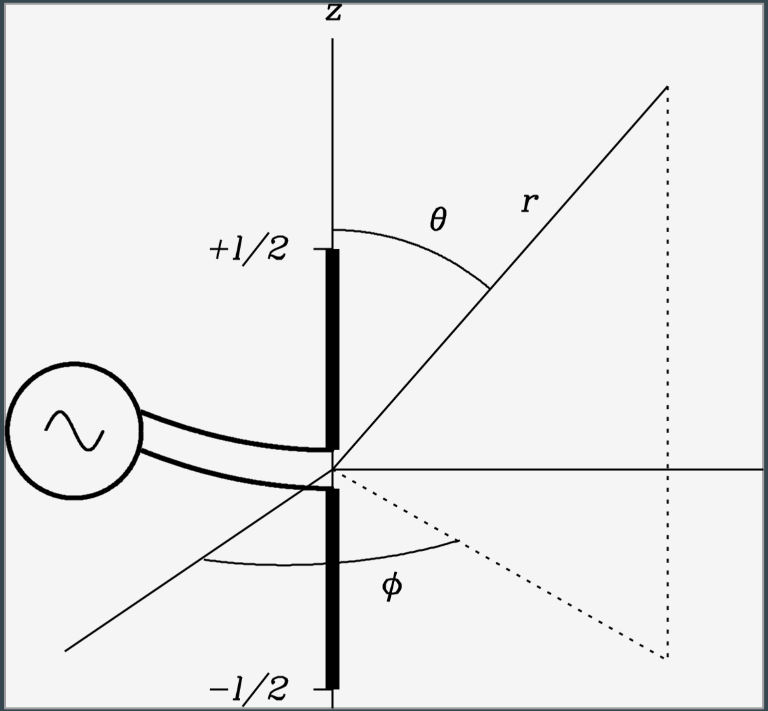
$$\lambda_n = \frac{2L}{n}$$

half-wave dipole: $L = \frac{\lambda_1}{2}$

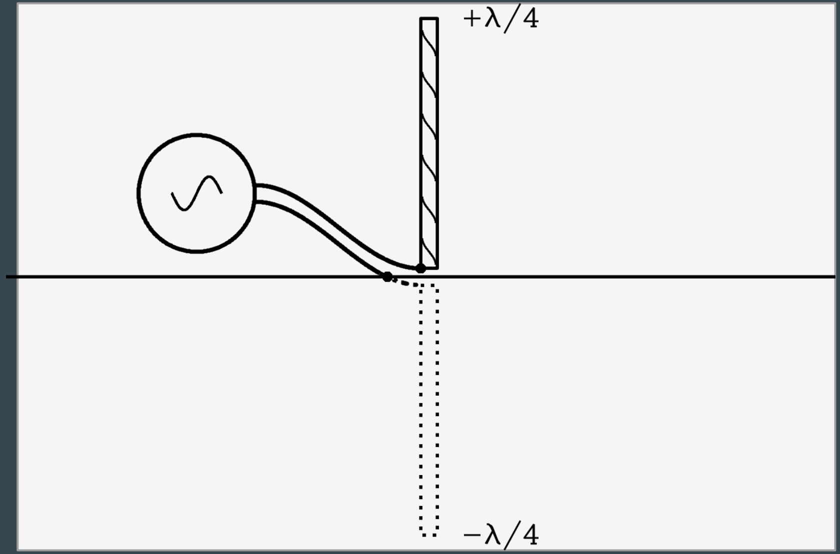
Standing Waves



Half-Wave Dipole Antenna



Ground-Plane Dipole Antenna



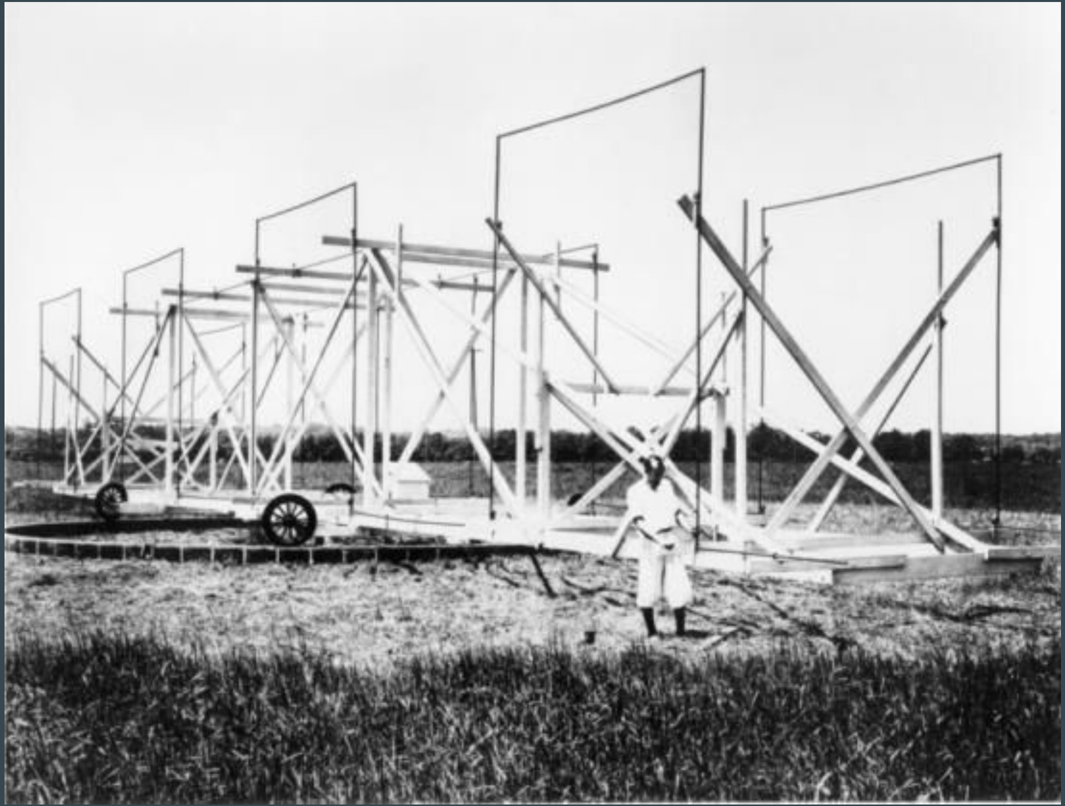
"Essential Radio Astronomy" James Condon & Scott Ransom: https://www.cv.nrao.edu/~sransom/web/xxx.html

Karl Jansky’s Radio Telescope (1932)

Bell Telephone Laboratories

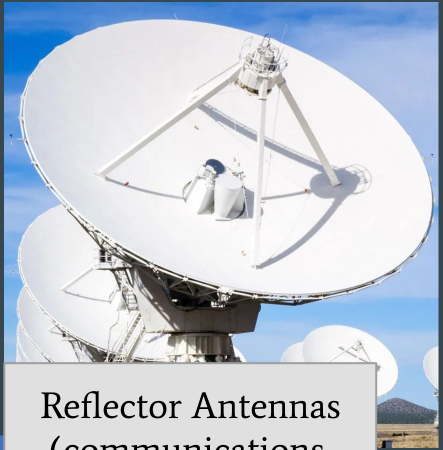
Karl Jansky discovered “Electrical disturbances of apparently extraterrestrial origin” at 20 MHz – first evidence of astrophysical radio waves!

Unit of flux density: **Jansky (Jy)**



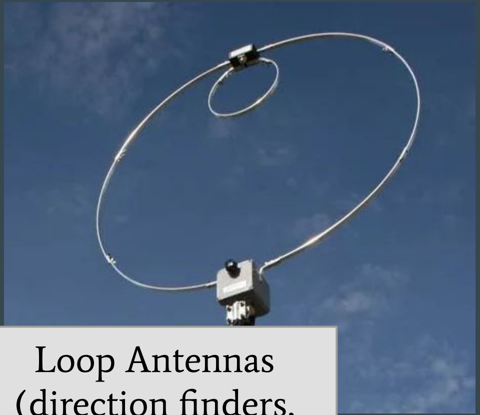
The Antenna Family

Horn Antennas
(radar)

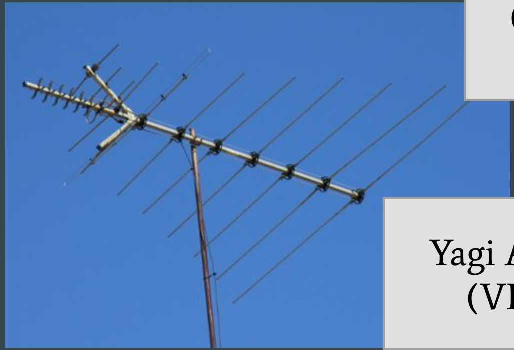


Reflector Antennas
(communications,
astronomy)

Wide Band Antennas
(adjustable
wavelength range)



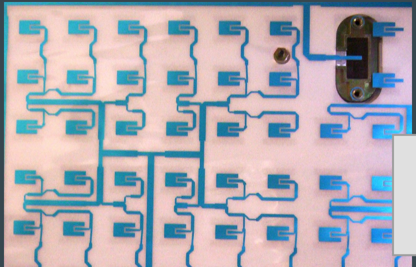
Loop Antennas
(direction finders,
radio receivers)



Yagi Antennas
(VLF, LF)

Helical antennas
(weather, GPS,
astronomy)

Lens antennas
(mm-wavelengths)



Patch, Microstrip Antennas
(cell phones)

3.4

Dish - reflects & focuses radio waves towards the antenna

↳ Bigger dish = higher sensitivity
= higher resolution

↳ Antenna temperature - temperature of resistor dissipating same power output by antenna

Radiometer Equation: $\sigma_T \approx \frac{T_{cmb} + T_{sky} + T_{sys}}{\sqrt{2 \times BW \times t_s}}$ → minimum signal we can detect

σ_T ↑ noise temperature; BW ↑ range of frequency; t_s ↑ sampling time

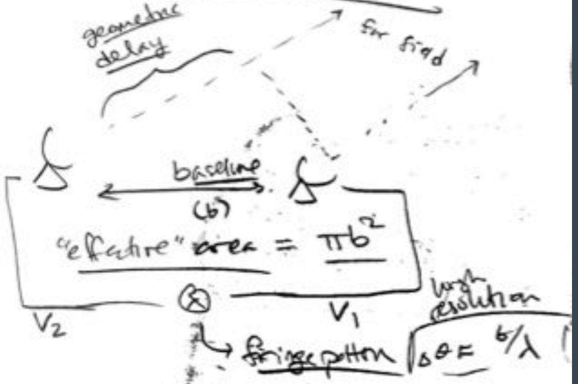
Interferometer - 2 or more radio antennas combined to increase the area

↳ cross correlation - multiply and average signals from 2 antennas

↳ interferometer sensitivity for N antennas:

$$\sigma_T = \frac{T_{cmb} + T_{sky} + T_{sys}}{\sqrt{N(N-1)}\, \Delta\nu\, t_s}$$

large N = low σ_T = high sensitivity



Single-Dish Telescopes

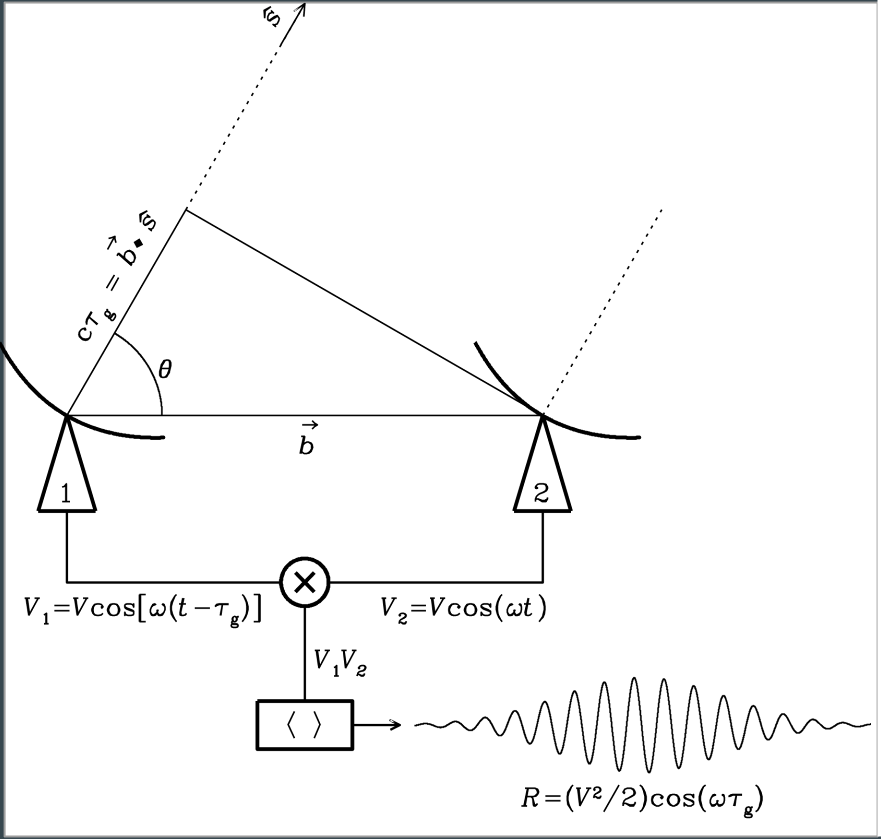
305 Meter Arecibo Telescope
(Arecibo, Puerto Rico)

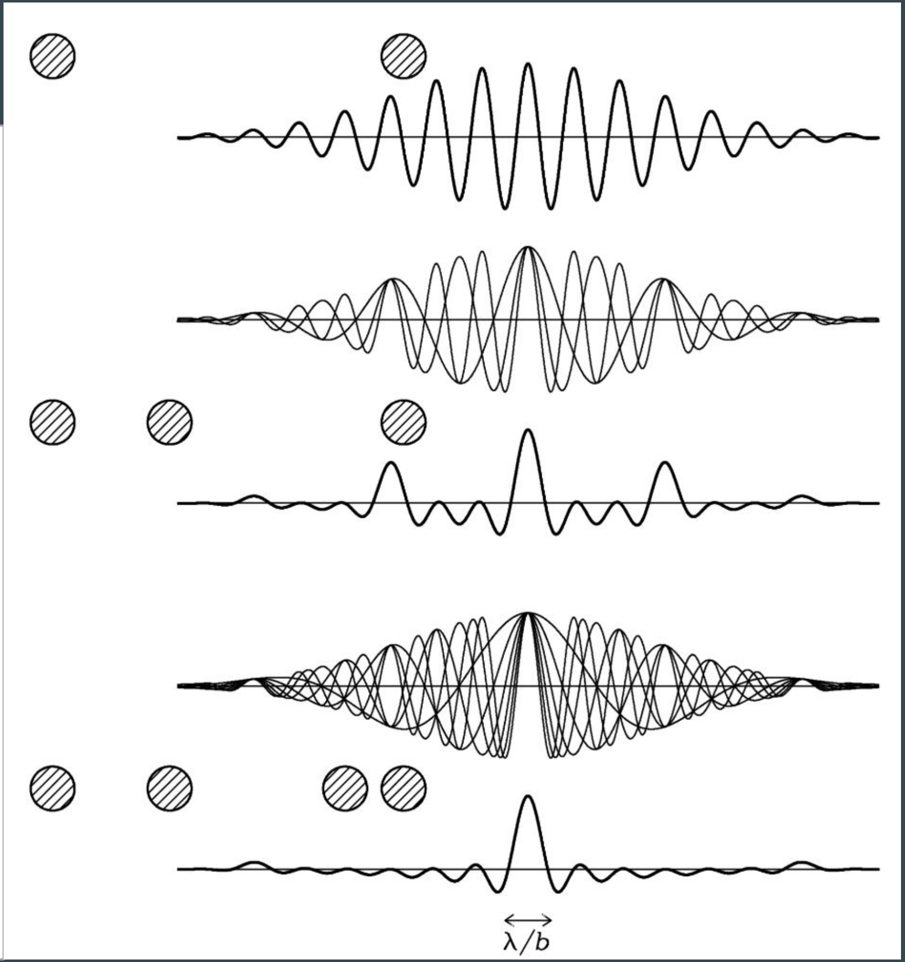
Five-Hundred-Meter Aperture Spherical Telescope (FAST; Guizhou, China)

Parkes Murriyang 64 Meter Telescope (Parkes Australia)

Green Bank 100 Meter Telescope
(Green Bank, West Virginia)

Interferometry

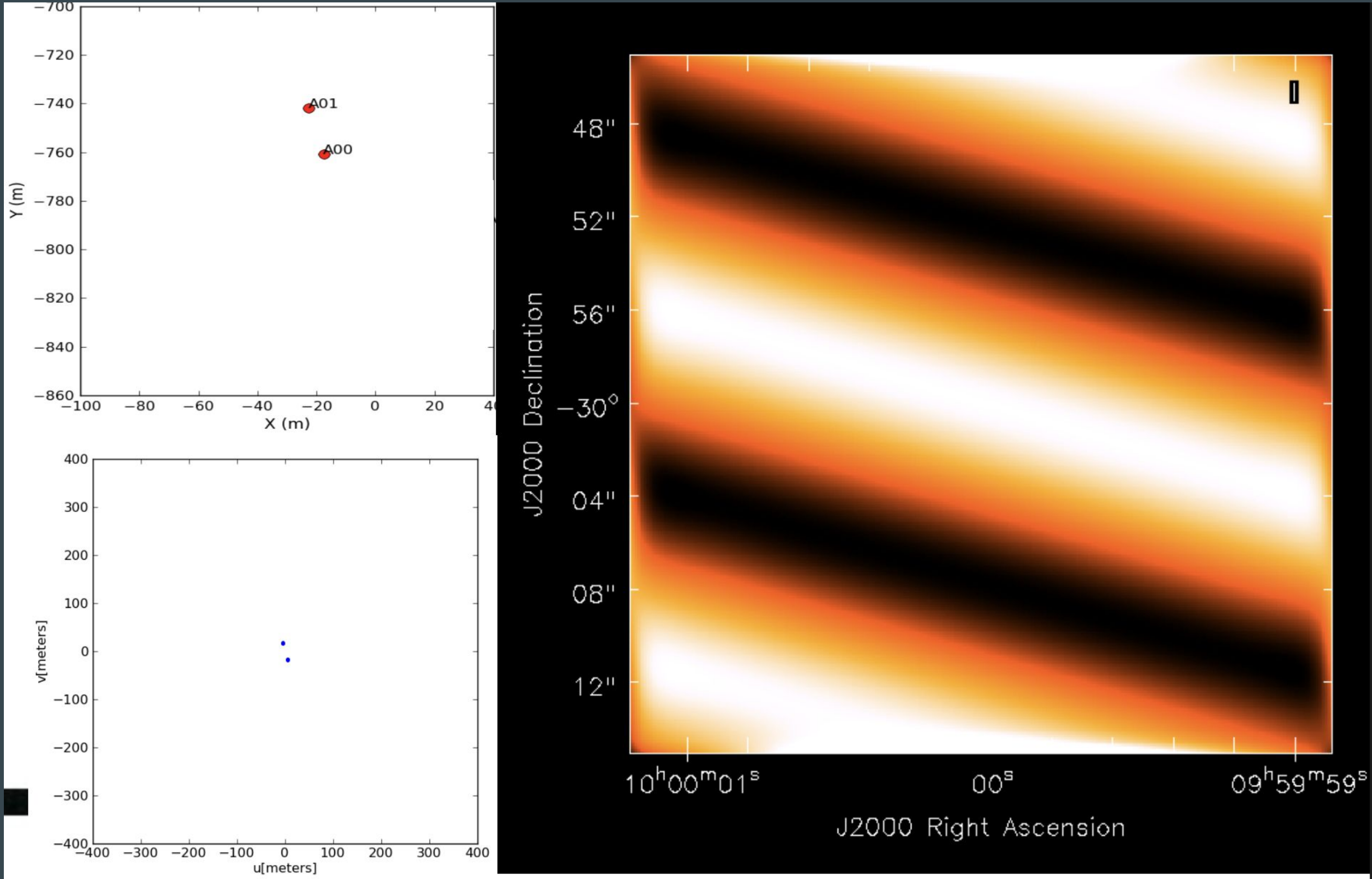




"Essential Radio Astronomy" James Condon & Scott Ransom: https://www.cv.nrao.edu/~sransom/web/xxx.html

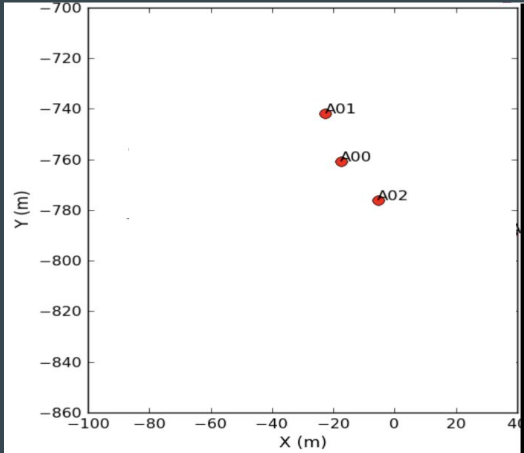
Fringe patterns

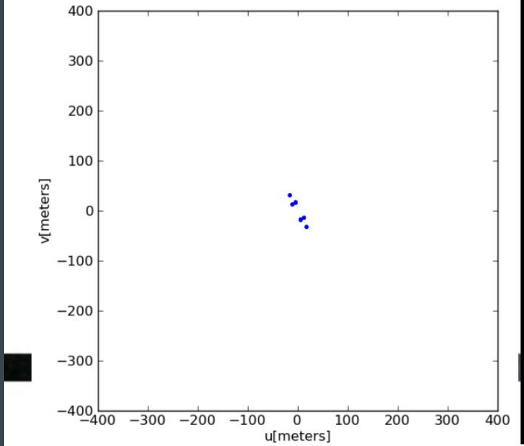
NRAO Introduction to Radio Astronomy – Cassie Reuter: https://science.nrao.edu/facilities/alma/naasc-workshops/nrao-cd-northwestern19/Interferometry_Basics.pdf

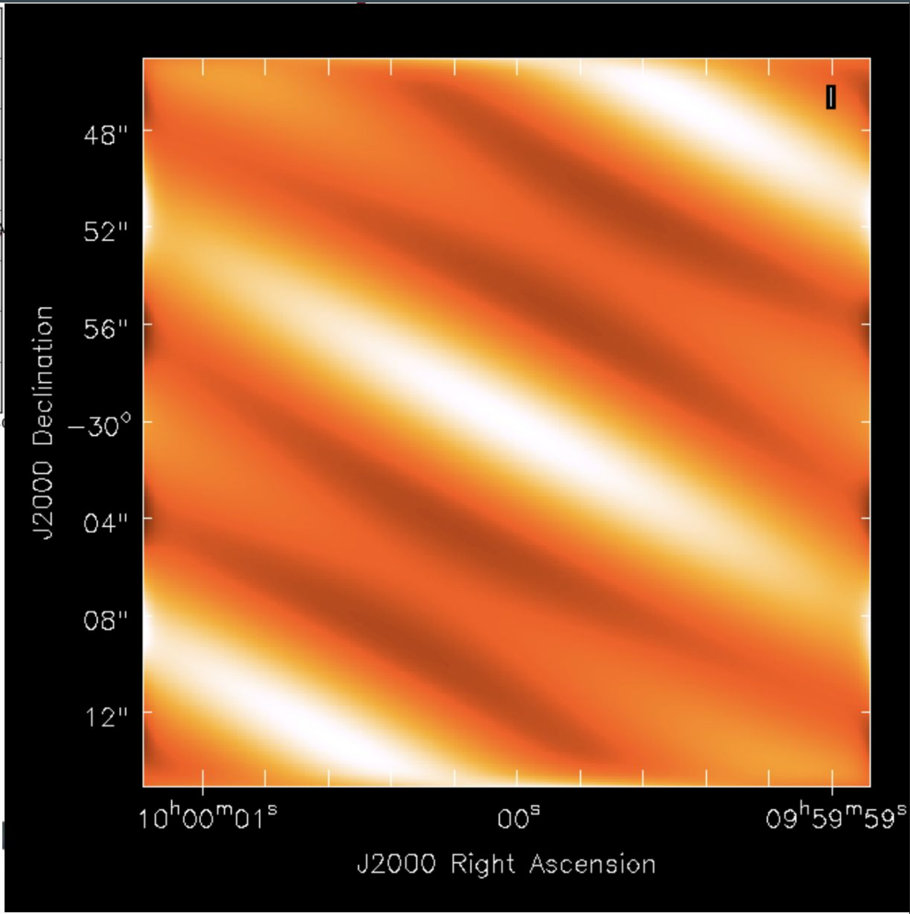


Fringe patterns

NRAO Introduction to Radio Astronomy – Cassie Reuter: https://science.nrao.edu/facilities/alma/naasc-workshops/nrao-cd-northwestern19/Interferometry_Basics.pdf

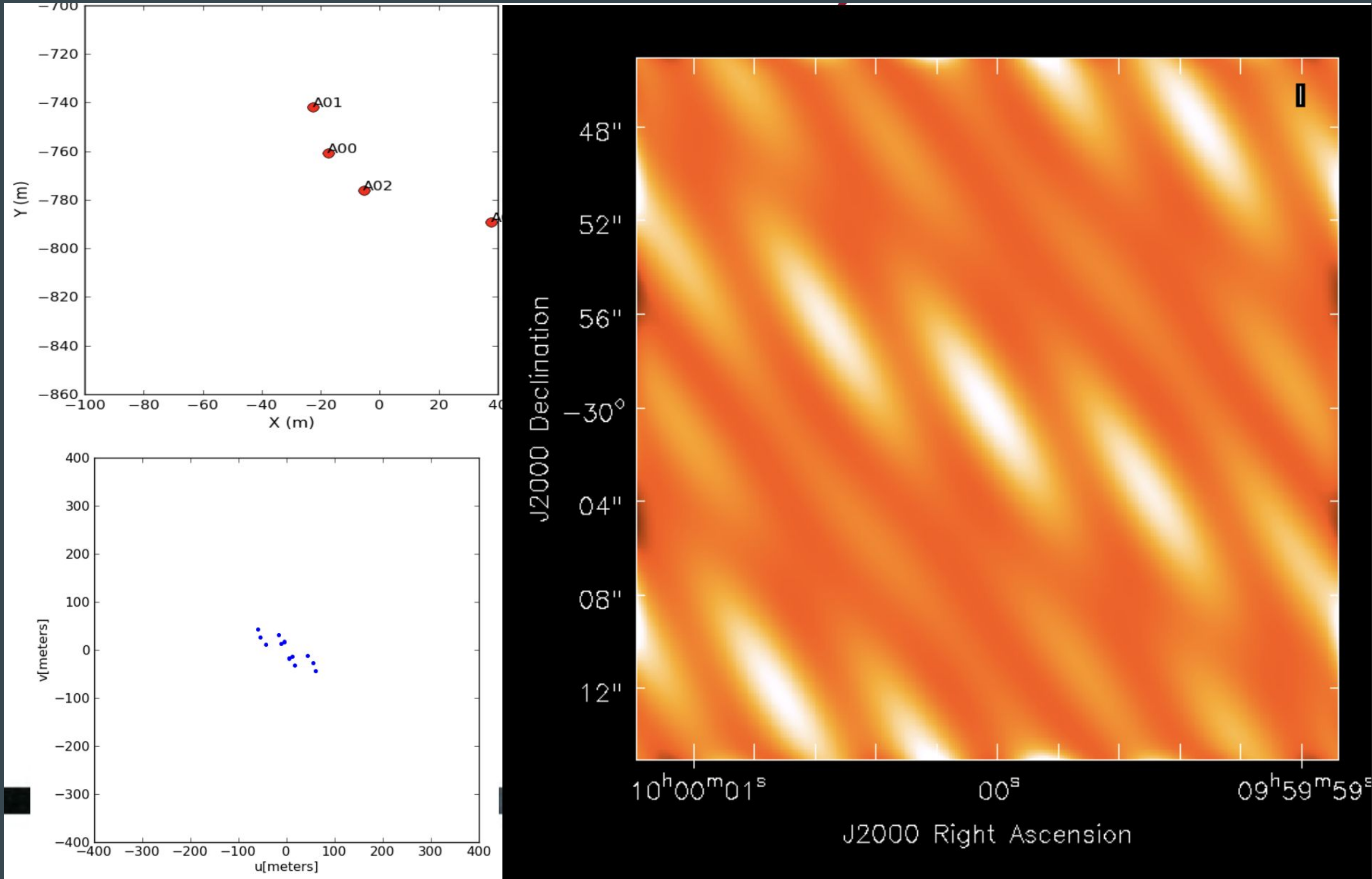






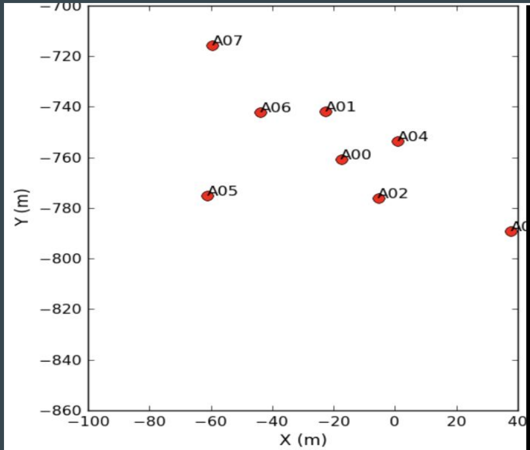
Fringe patterns

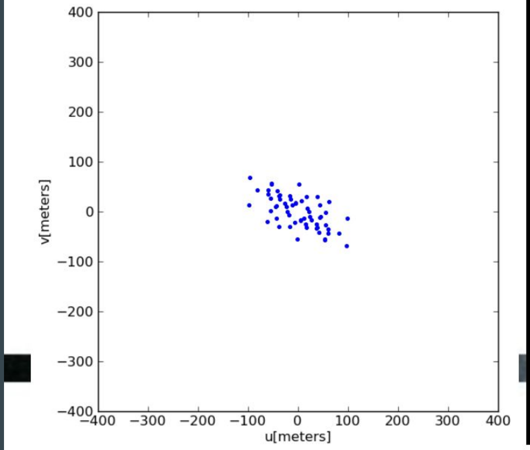
NRAO Introduction to Radio Astronomy – Cassie Reuter: https://science.nrao.edu/facilities/alma/naasc-workshops/nrao-cd-northwestern19/Interferometry_Basics.pdf

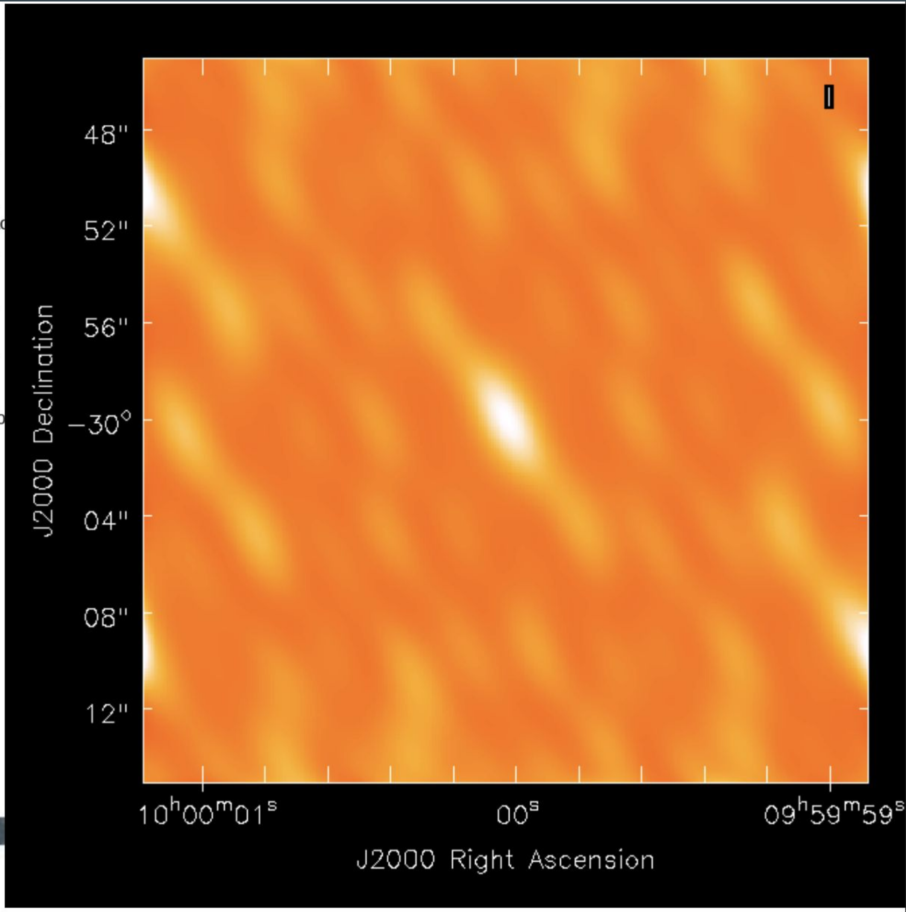


Fringe patterns

NRAO Introduction to Radio Astronomy – Cassie Reuter: https://science.nrao.edu/facilities/alma/naasc-workshops/nrao-cd-northwestern19/Interferometry_Basics.pdf

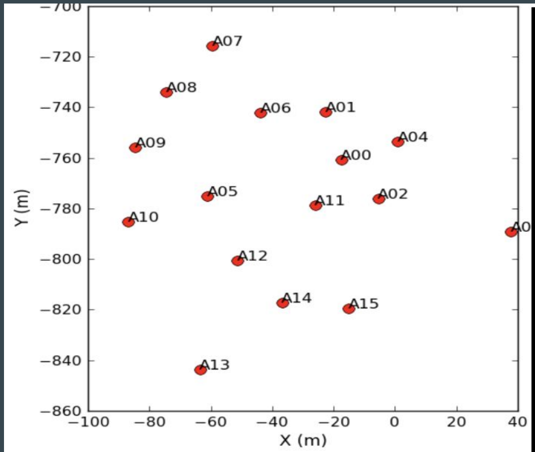


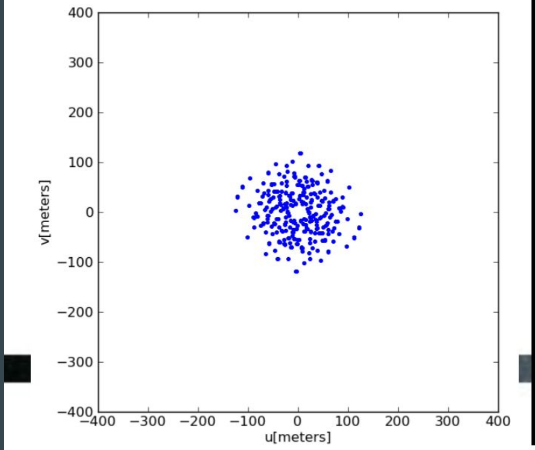


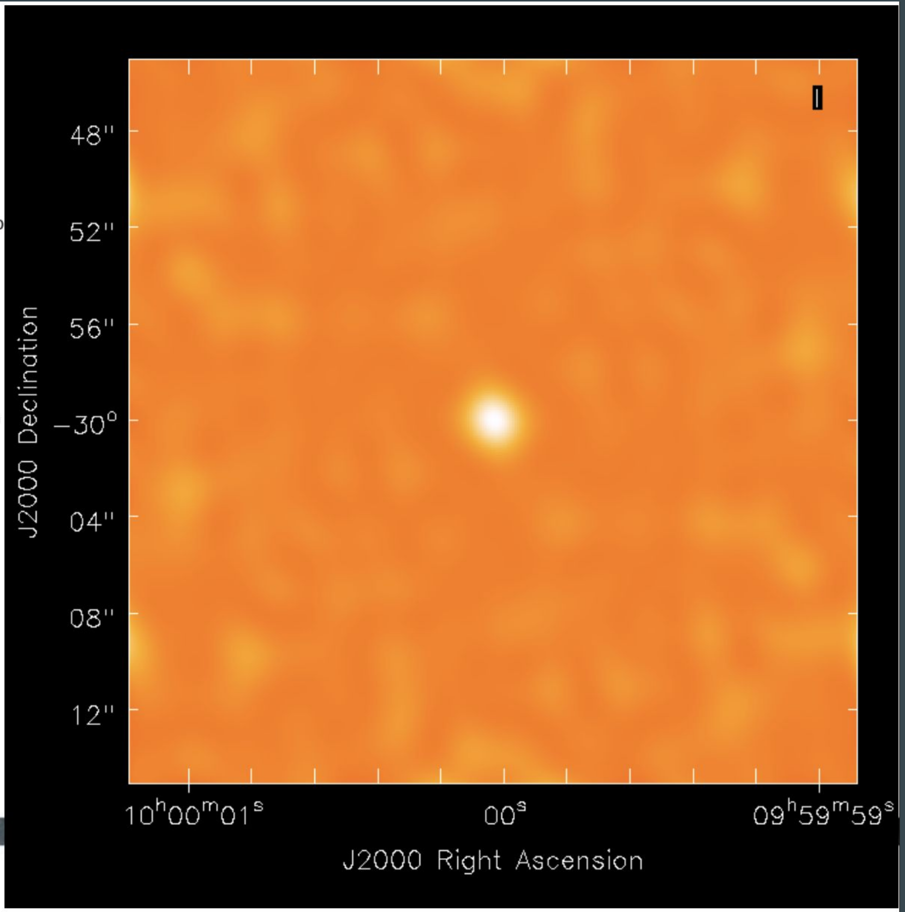


Fringe patterns

NRAO Introduction to Radio Astronomy – Cassie Reuter: https://science.nrao.edu/facilities/alma/naasc-workshops/nrao-cd-northwestern19/Interferometry_Basics.pdf

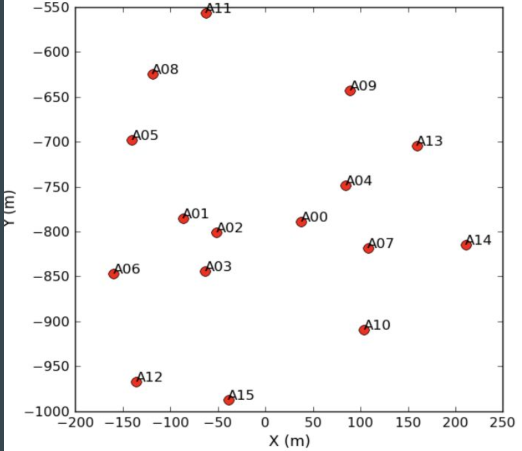


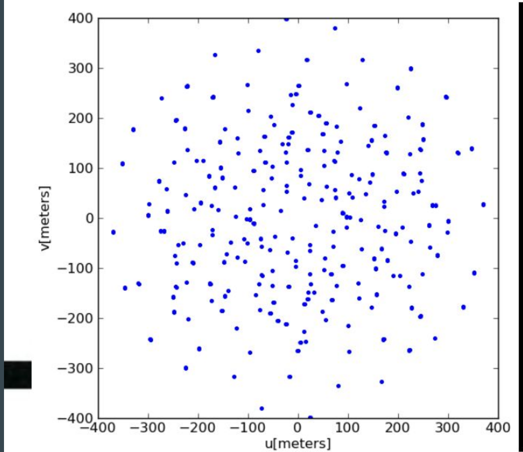


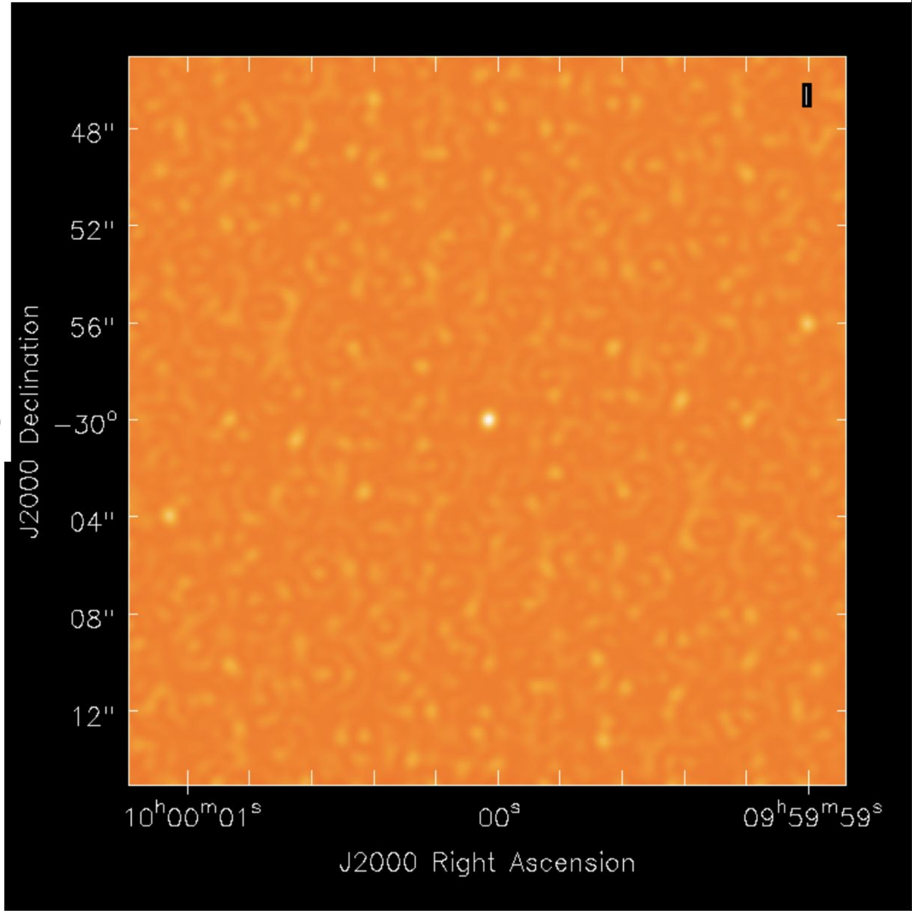


Fringe patterns

NRAO Introduction to Radio Astronomy – Cassie Reuter: https://science.nrao.edu/facilities/alma/naasc-workshops/nrao-cd-northwestern19/Interferometry_Basics.pdf







Demo: **Let's experiment with our own miniature interferometer!**

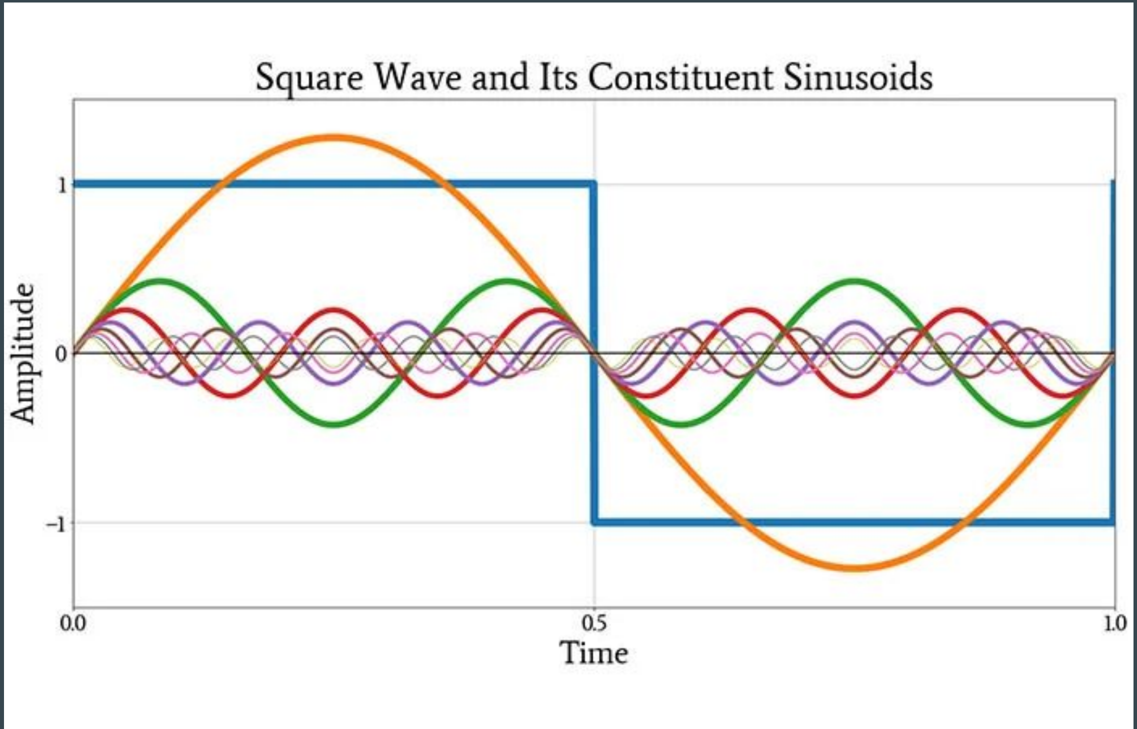
What happens when we add/remove components of the interferometer?

What allows us to build such a small optical interferometer, while radio interferometers can span hundreds of miles?

Fourier Representation of Signals

Any real signal can be represented by a sum of sinusoids with **fourier amplitudes** →

Any **complex** signal can be represented by a sum of complex exponentials with **fourier amplitudes**



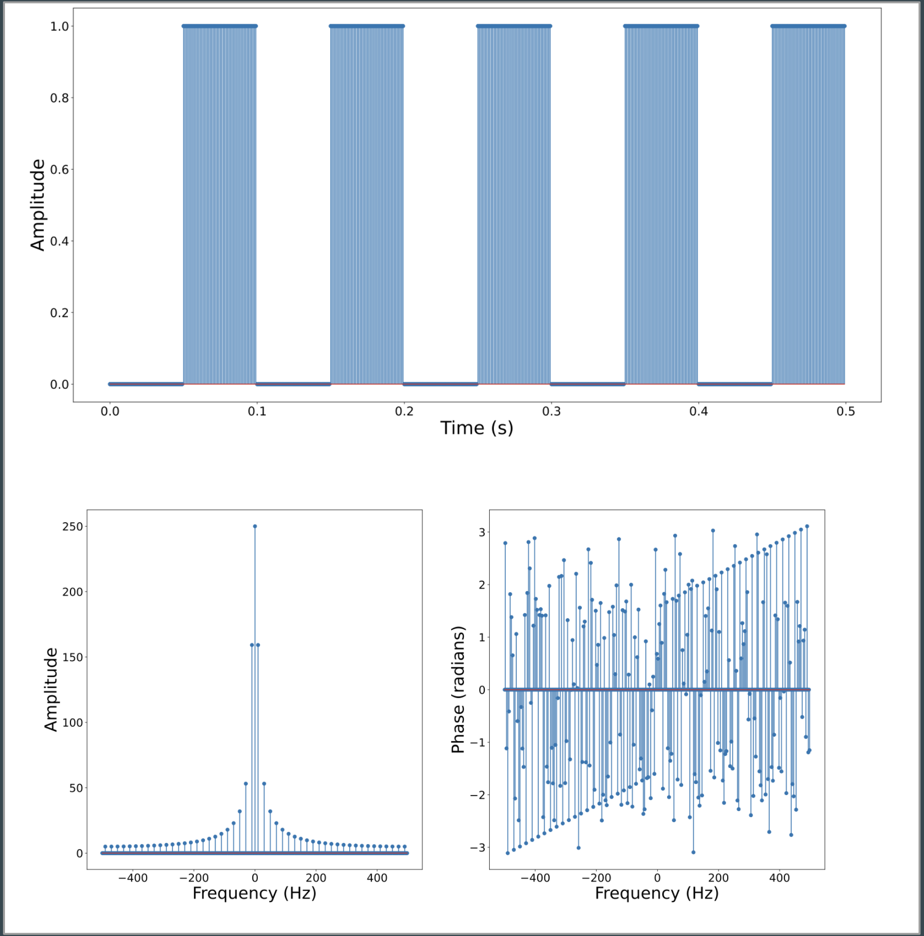
Fourier Representation of Signals

Discrete Fourier Transform converts time domain signal to **fourier domain (** frequency) representation:

DFT: $F[k]=\sum f[x]e^{-2\pi ikx/N}$

iDFT: $f[x]=(1/N)\sum F[k]e^{2\pi ikx/N}$

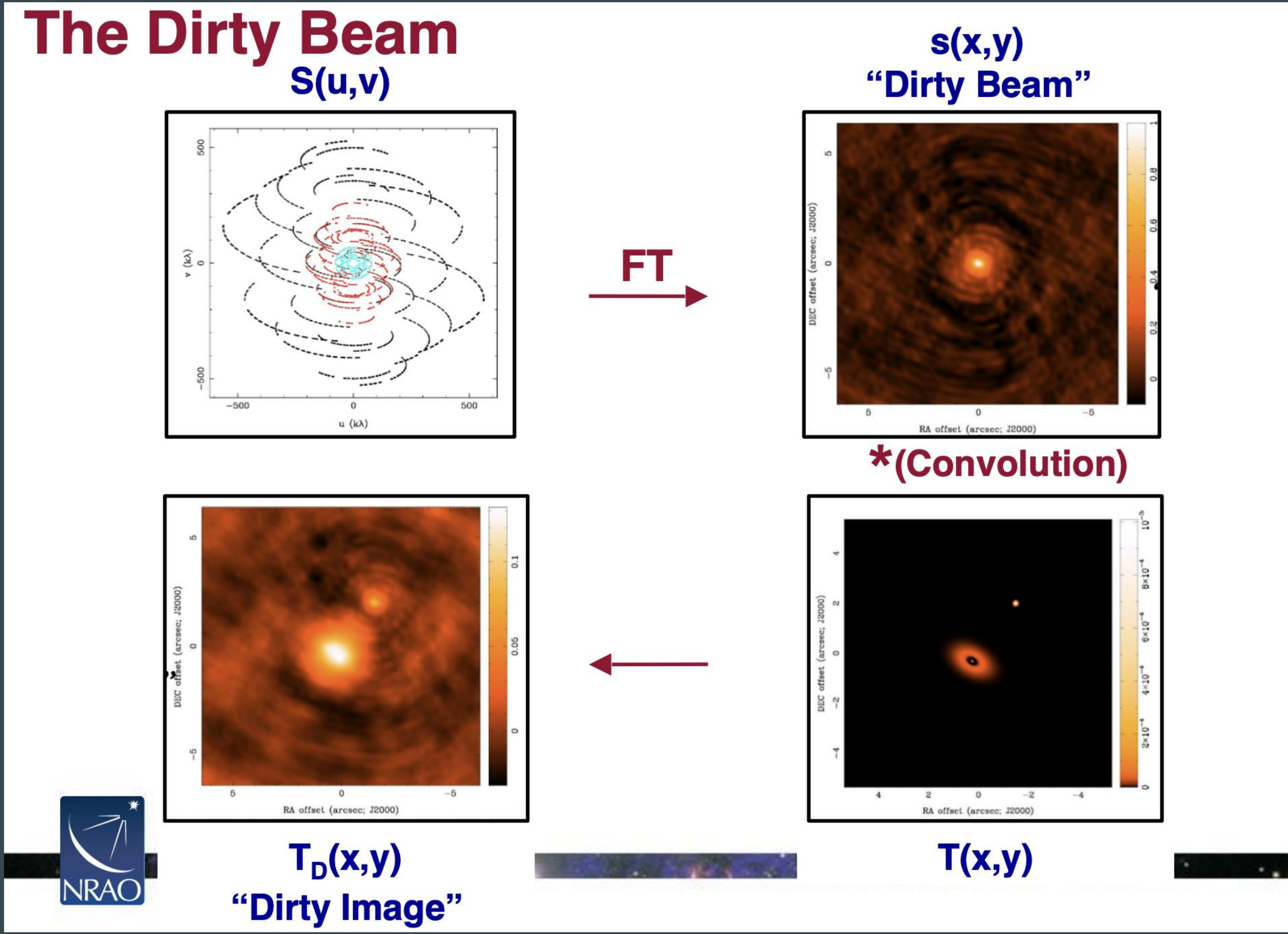
Fast Fourier transform is an algorithm to compute the DTFT quickly and efficiently



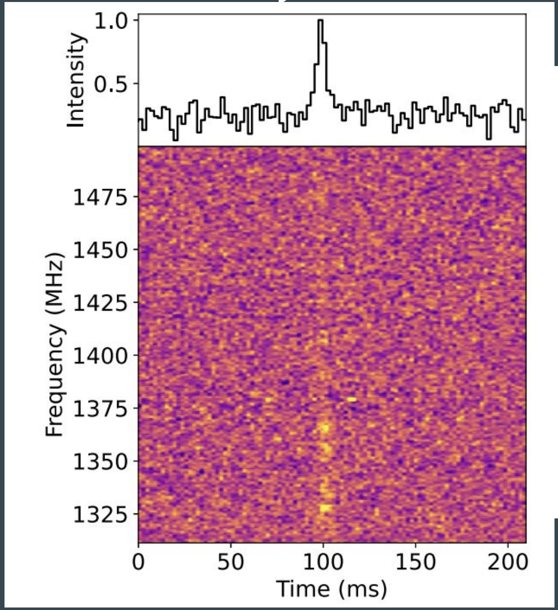
Radio Imaging

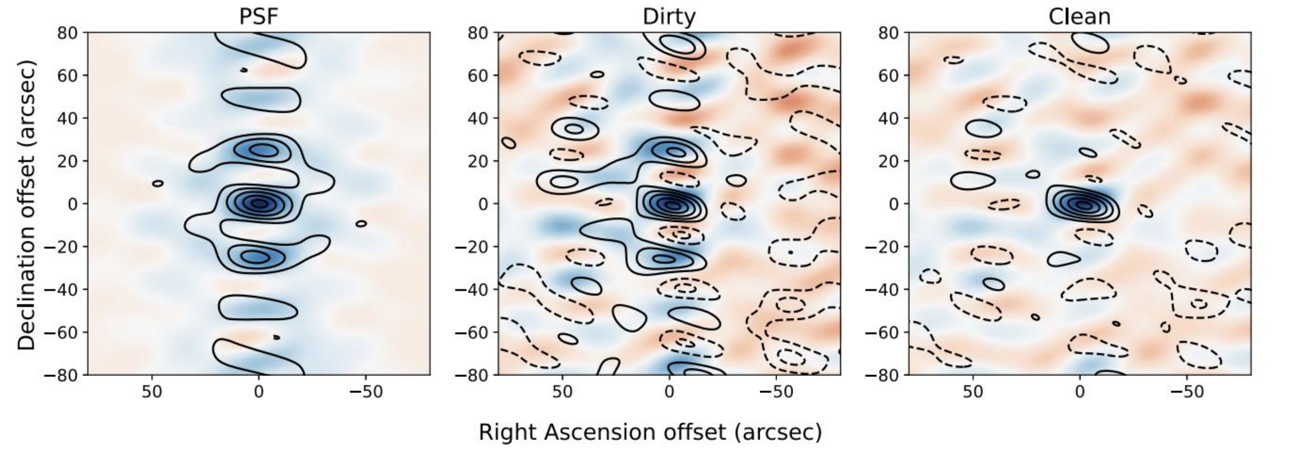
Stages of Imaging:

1. Grid to UV plane
2. FFT
3. "Clean" (convolve with PSF)



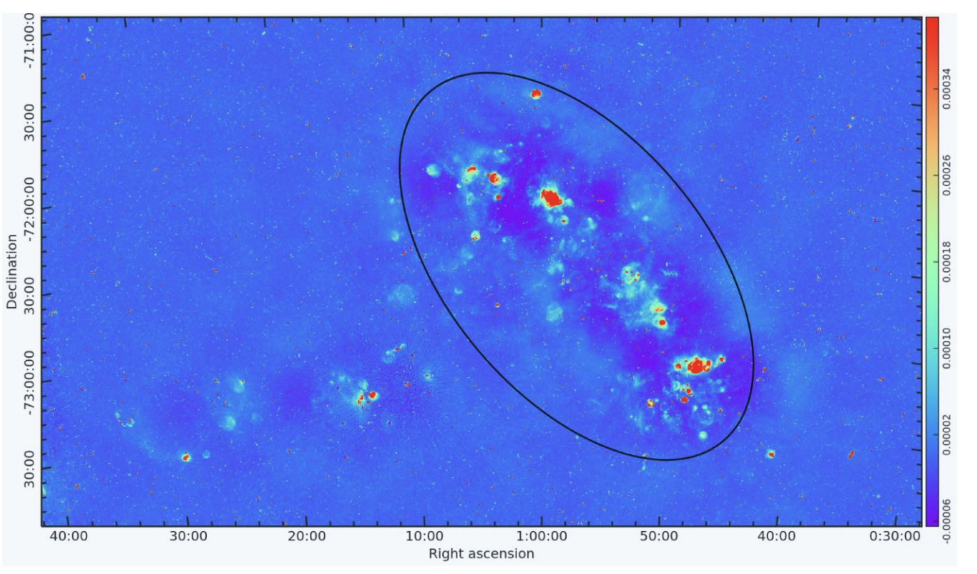
Examples: DSA-110 (97x10 meter antennas, Owens Valley, CA)



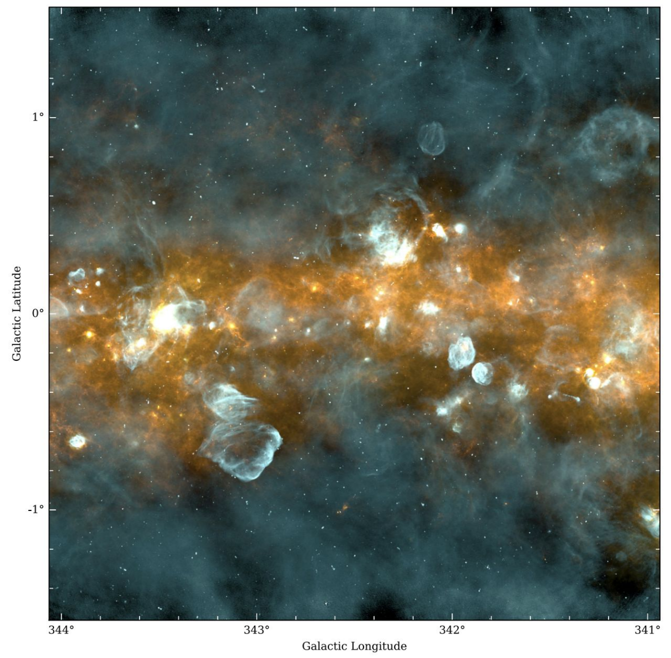


Fast Radio Burst (FRB) detected and localized by the DSA-110 (Ravi et al., 2023)

Examples: MeerKAT (64x13.5 meter antennas, South Africa)



Radio Image of the Small Magellanic Cloud (Cotton et al., 2024)



IR + Radio Image of Galactic Plane (Goedhart et al., 2024)

3.7

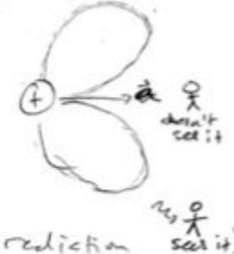
Radiation – electromagnetic waves from accelerating charged particles detectable in the far field

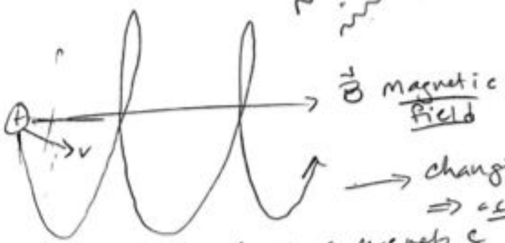
Cyclotron radiation

↳ charged particle in $\vec{B}$ field moves non-relativistically ($v << c$, $\gamma \sim 1$)

$$\nu_c = \frac{qB}{2\pi m}$$

$$P = \frac{2q^2a^2}{3c^3}$$





→ changing direction ⇒ acceleration ⇒ radiation

a charged particle in a magnetic field moves in a helix

Synchrotron radiation

↳ charged particle in $\vec{B}$ field moves relativistically ($v \sim c$, $\gamma >> 1$)

$$\nu_s = \frac{qB}{2\pi \gamma m}$$

↳ $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ Lorentz factor

incoherent radiation – N particles radiate separately

$$P_{total} = N \times P$$

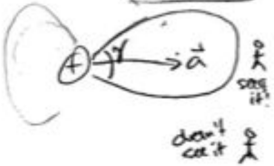
coherent radiation – N particles radiate together

$$P_{total} = N^2 \times P$$

← coherent boost

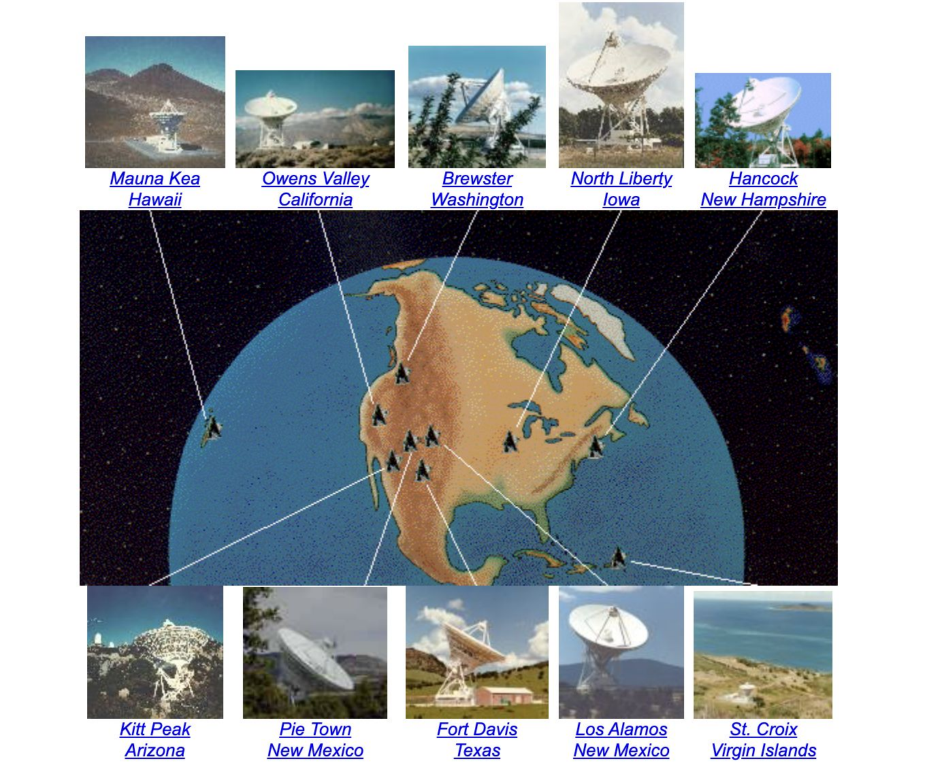
relativistic boost → $P = \frac{2q^2a^2}{3c^3}\gamma^2$

observe radiation on astrophysical scales!



Very-Long Baseline Interferometry (VLBI)

Combines data from antennas around the world (maximum baselines ~1000 km) to achieve high angular resolution (~milliarcseconds)



Very Long Baseline Array (VLBA)

Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry (TANAMI) Array

Example: Event Horizon Telescope (EHT)

1.3 mm Images of the Black Hole M87 in the Andromeda Galaxy (EHT Collab. 2017)

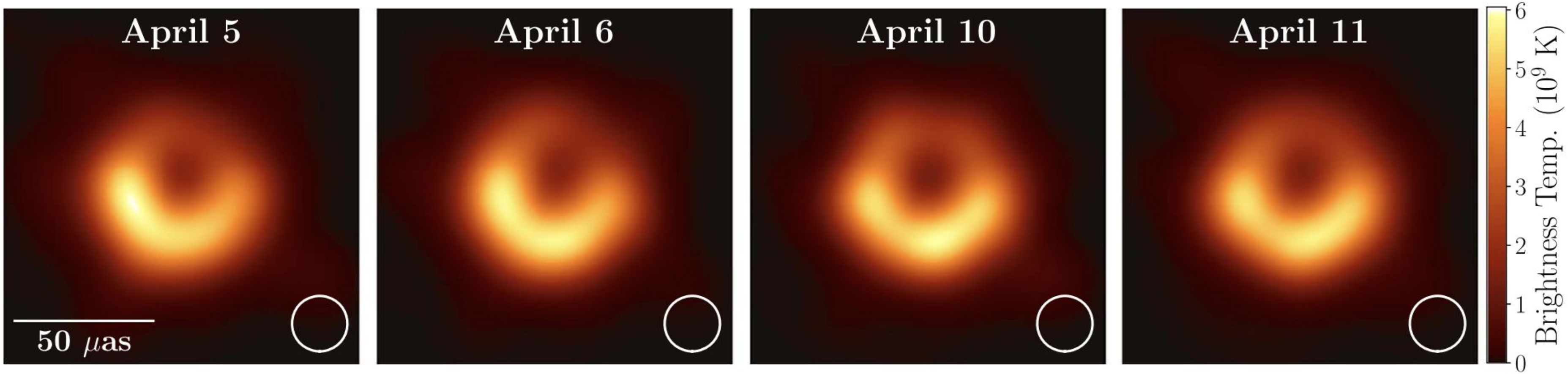


Figure 15. Averages of the three fiducial images of M87 for each of the four observed days after restoring each to an equivalent resolution, as in Figure 14. The indicated beam is 20 μas (i.e., that of DIFMAP, which is always the largest of the three individual beams).

Think-Pair-Share

Compare and contrast the properties of single-dish antennas and interferometers.

Why don't we use interferometry in other areas of astronomy? E.g. why don't we have optical or x-ray interferometers?

ISM Cyclotron and Synchrotron Radiation

Free electrons moving in the magnetized, ionized ISM produce radiation emission in dense regions

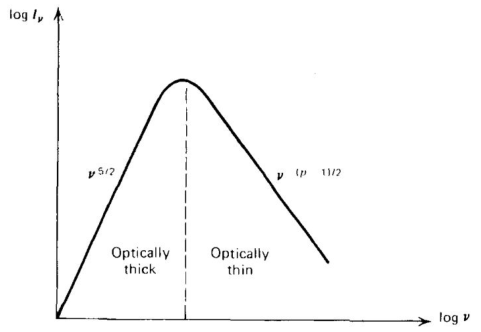


Figure 6.12 Synchrotron spectrum from a power-law distribution of electrons.

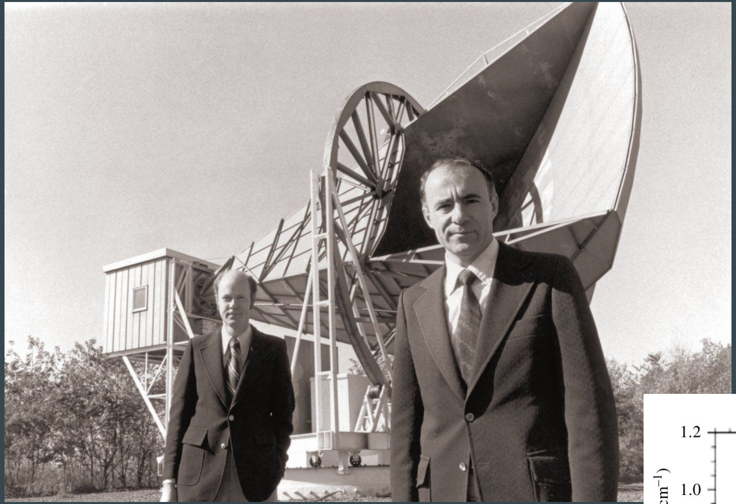
Synchrotron radiation comes from **charges moving relativistically**

Cyclotron radiation comes from **charges moving non-relativistically**

IR + Radio Image of Galactic Plane (Goedhart et al., 2024)

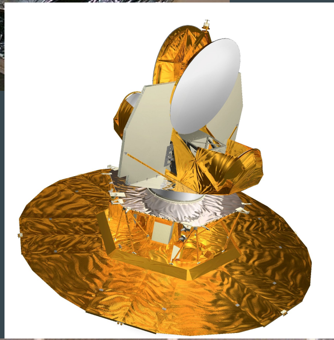
Cosmic Microwave Background (CMB)

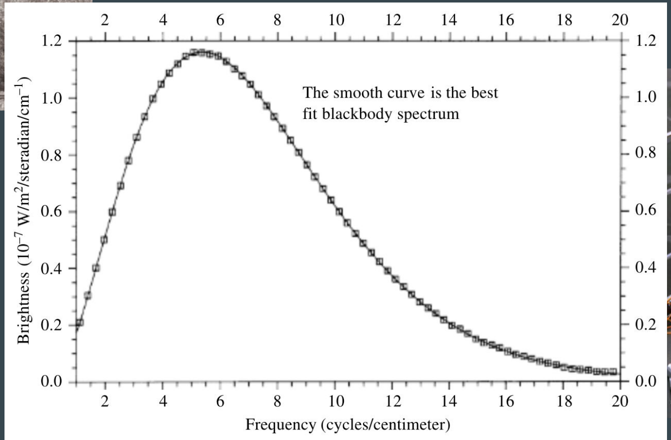
2.725 K Blackbody radiation from dense, early universe in thermal equilibrium

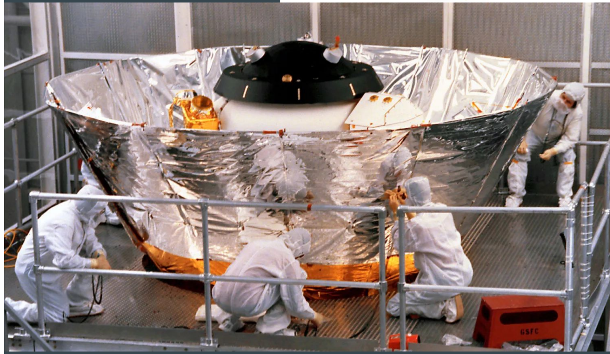


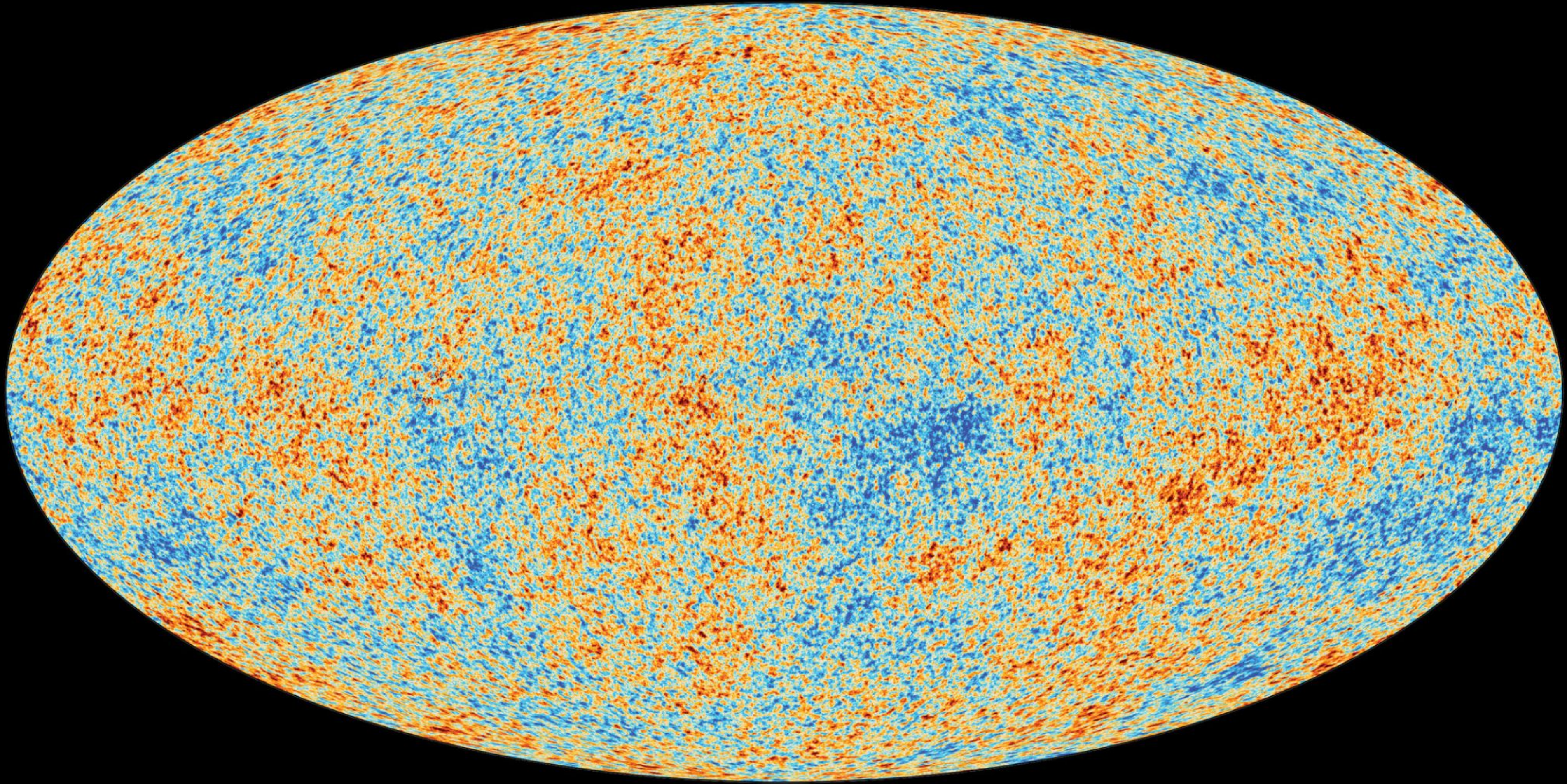
Arno Penzias and Robert Wilson at the Holmdel Horn Antenna used to detect the noise temperature of the CMB (Penzias & Wilson 1967)

The COsmic Background Explorer (COBE), Wilkinson Microwave Anisotropy Probe (WMAP) and the Max Planck Telescope characterized the CMB with Microwave and IR detectors







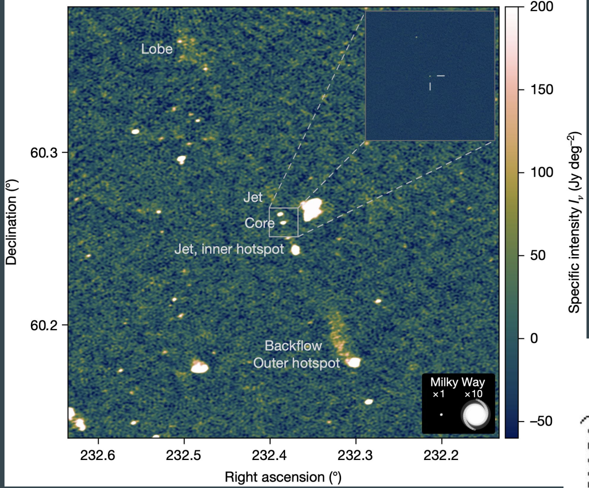


Supermassive Black Hole (SMBH) Jets

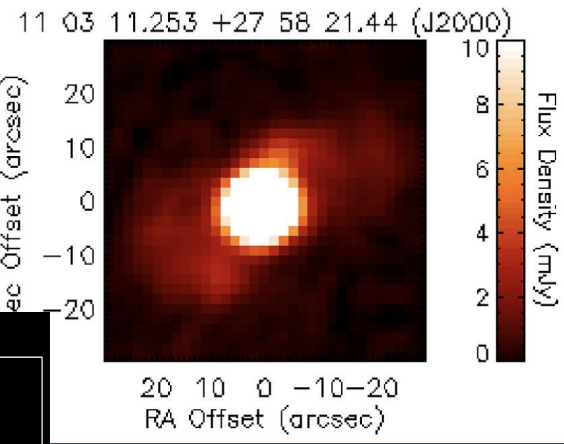
Active Galactic Nuclei - Matter falling gravitationally into SMBH at center of galaxy creates a radio-loud **accretion disk**

Magnetic field of the black hole can collimate matter into a powerful **jet** of relativistic charges radiating coherently in **radio, X-rays and gamma rays**

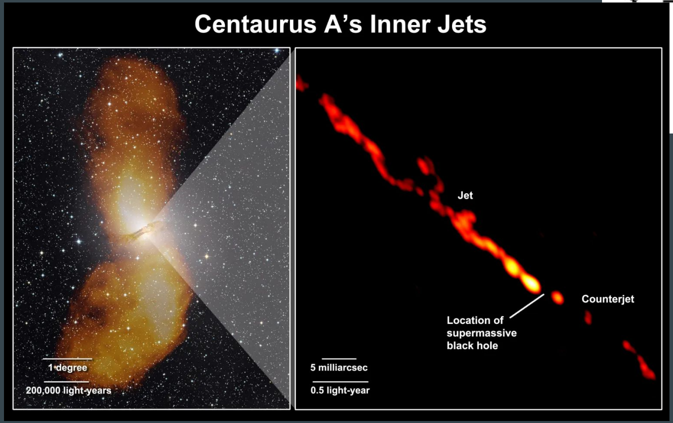
Jet can also form turbulent **shocks** with surrounding matter that generates synchrotron emission



Largest Known (7 Mpc) Radio Jet at λ=1.02 m from the Porphyrion SMBH Detected by the International LOw Frequency ARray (LOFAR) Telescope (ILT; Oei et al., 2024)



VLBA image of an AGN at the center of a spiral galaxy at λ=20 cm (Kaviraj et al., 2015)



Radio shock fronts (left) and radio jet (right) from SMBH at center of Centaurus A galaxy at 8.4 GHz (Müller et al., 2014)

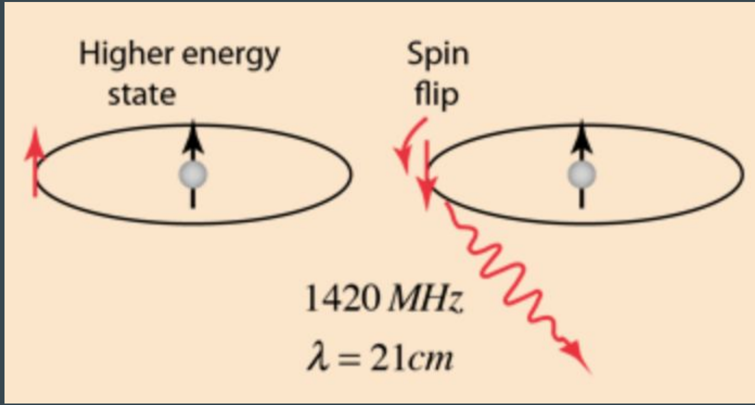
21 cm Hyperfine Hydrogen Spin-Flip Emission Line

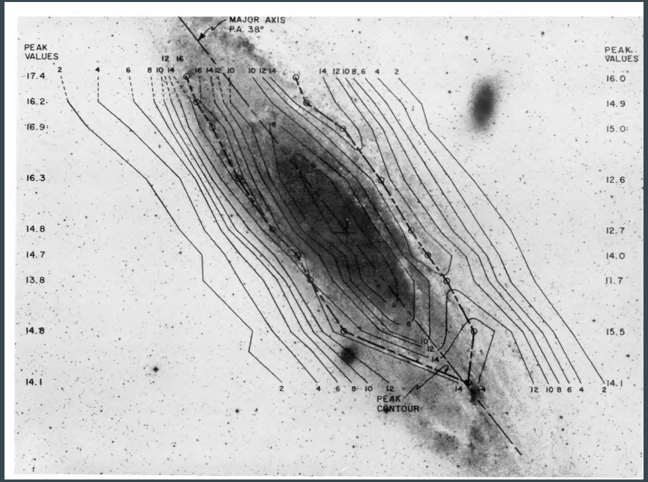
Spin: quantum mechanical property of particles

- **fermions** (e.g. electrons, positrons) - spin-½ particles which can have s=±½
- **bosons** (e.g. protons, neutrons) - spin-1 particles which can have s=0,±1

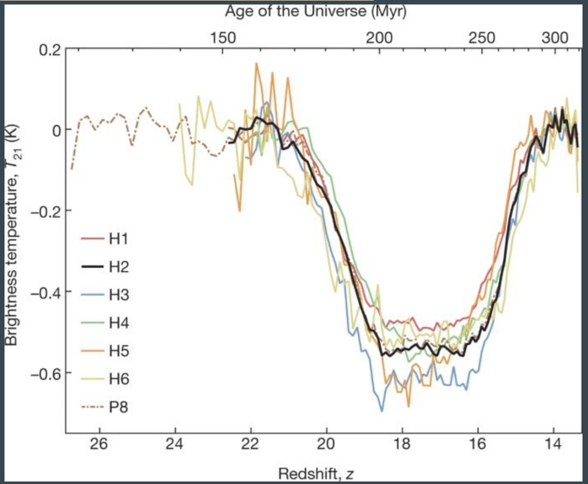
21-cm transition - “hyperfine” transition of Hydrogen electron from **s=+½ to s=-½**

- **Primary tracer of star formation in galaxies**





High-resolution H-I absorption map of the Andromeda Galaxy from the GBT 100-m telescope (Roberts et al., 1966)



Possible detection of 21 cm Hydrogen line from early universe by EDGES Experiment (Bowman et al., 2018)

Think-Pair-Share

We mentioned that white dwarfs, neutron stars, and black holes have ‘radio emission’; what do you think that means? Why do we not detect them on our car radios?

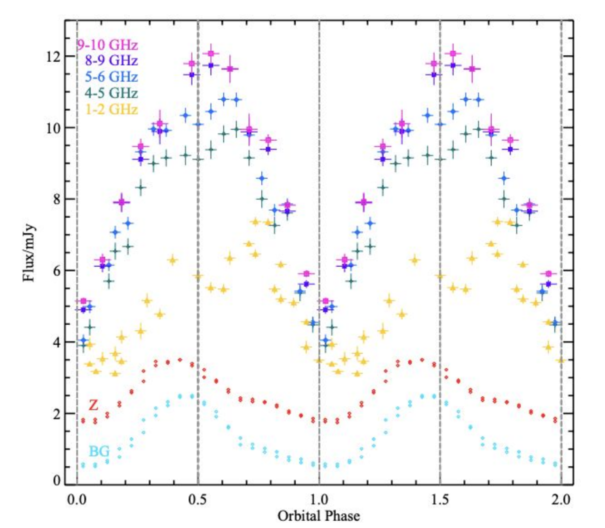
Demo: **Let's explore the radio sky!**

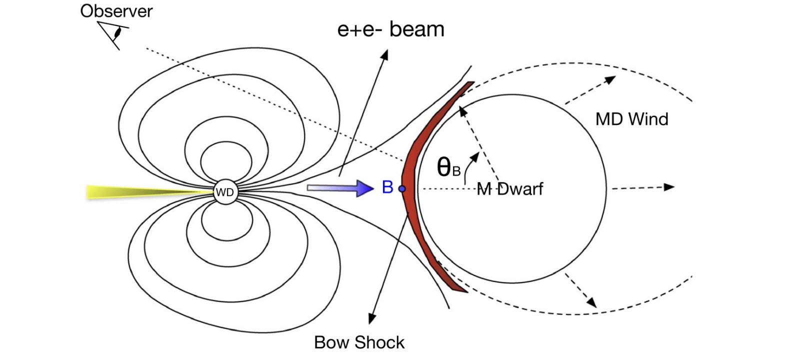
What sounds different between the signals we play? Do pulsars sound different than FRBs? From magnetars?

Polars (White Dwarf-M Dwarf Binaries)

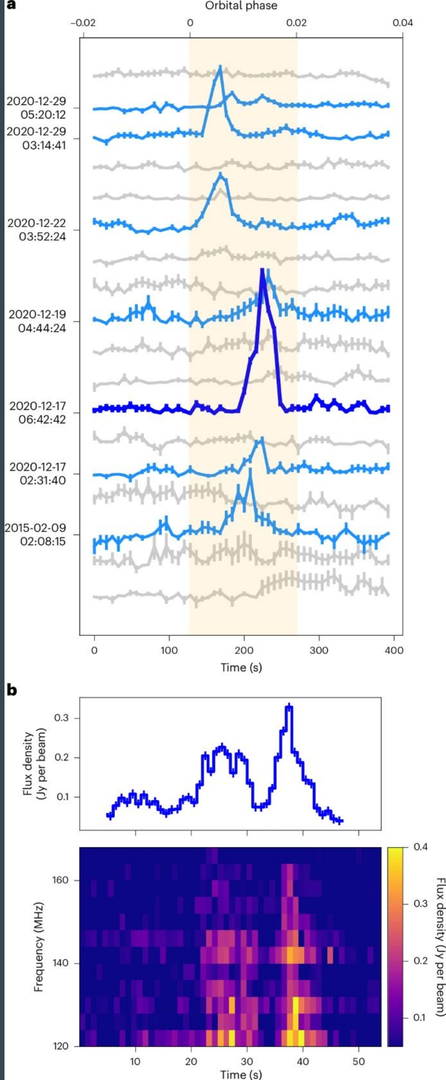
Polars are White Dwarf - M Dwarf binaries which produce coherent, periodic radio emission by streaming charged particles between the stars' magnetic poles.

E.g. AR Scorpii produces radio emission at beat frequencies between the 3.6 hour orbital period and 1.95 rotation period (Geng et al., 2016; Stanway et al., 2018)

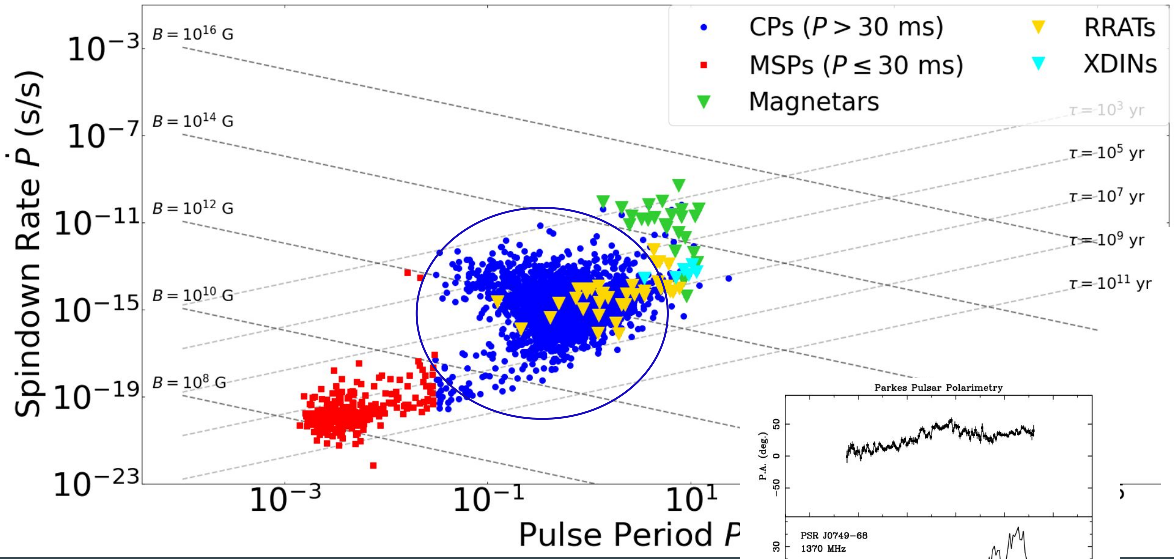


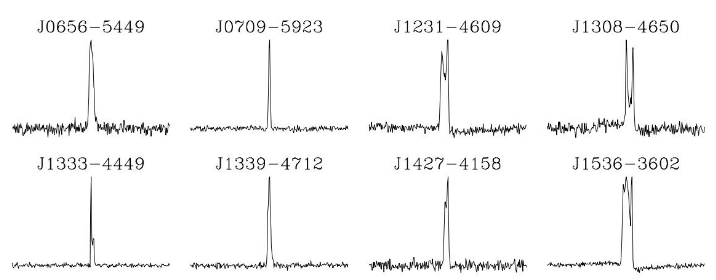


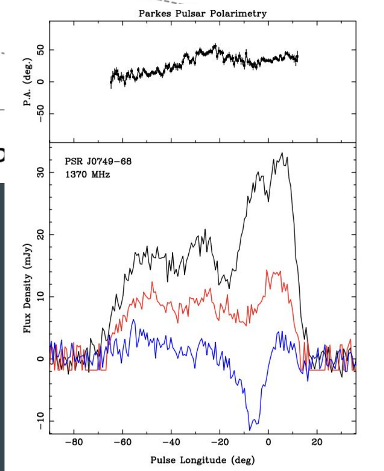
Long Period Radio Transients (LPTs or LPRTs) were discovered in 2022; at least 2 are intermediate polars with hour-scale periods, but are **magnetically locked** . E.g. ILT 1101+5521 has a 2-hour period suspected to be the orbital period (de Ruiter et al., 2025)



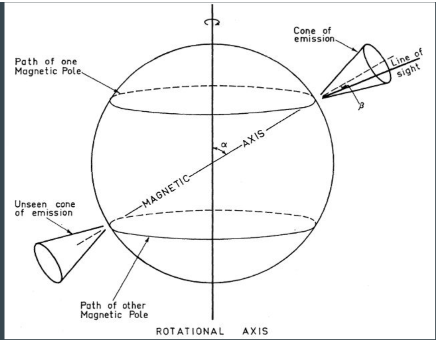
Neutron Stars: Pulsars, Radio Magnetars, RRATs, magnetars



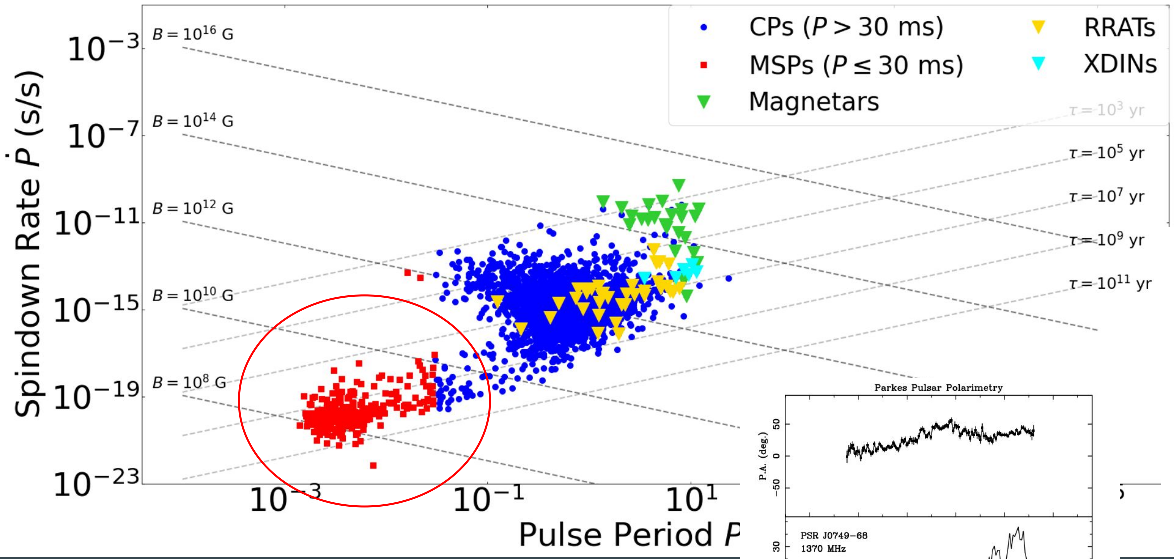


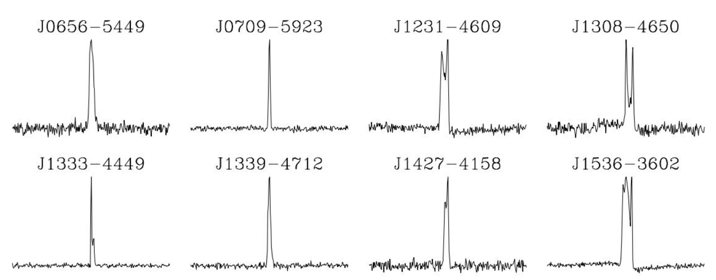


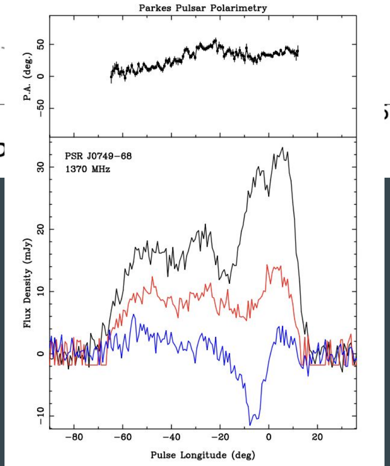
Slow Pulsars (0.3-10 s): produce coherent radio emission from magnetic poles via charged particle 'avalanche'



Neutron Stars: Pulsars, Radio Magnetars, RRATs, magnetars

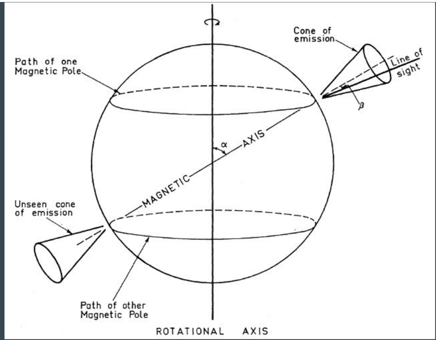




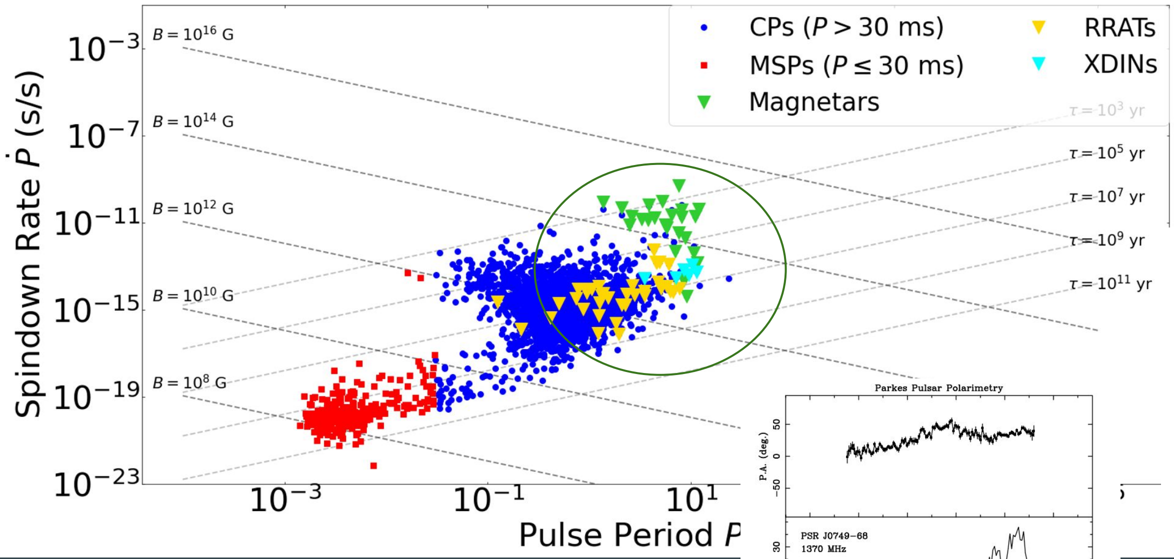


Millisecond Pulsars (<0.3 s): initially lost their rotational energy, then accreted from companion to spin up to millisecond periods

Slow Pulsars (0.3-10 s): produce coherent radio emission from magnetic poles via charged particle 'avalanche'

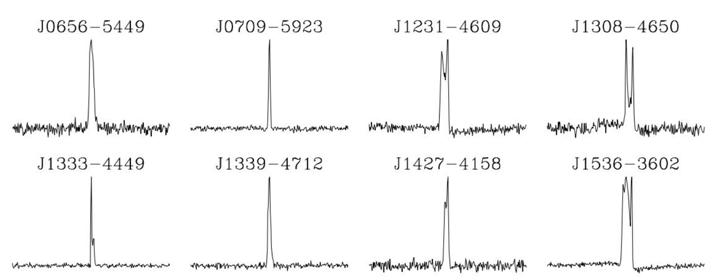


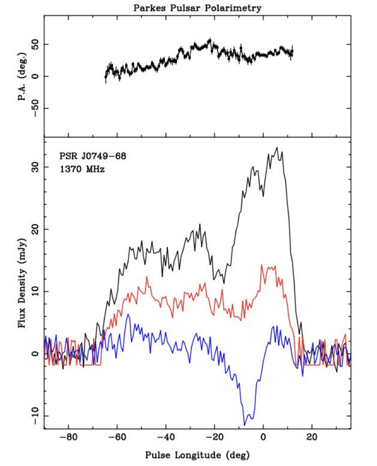
Neutron Stars: Pulsars, Radio Magnetars, RRATs, magnetars



Rotating Radio Transients (RRATs): only detectable through single pulses because of irregular nulling

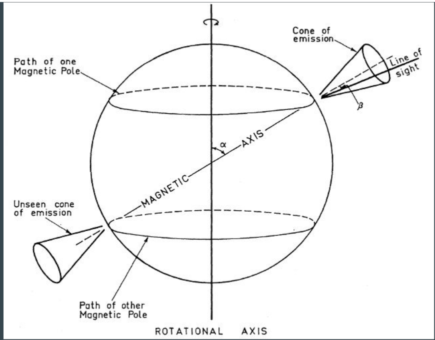
Magnetars (>2s): largest magnetic fields, produce giant flares and pulses that exceed rotational energy





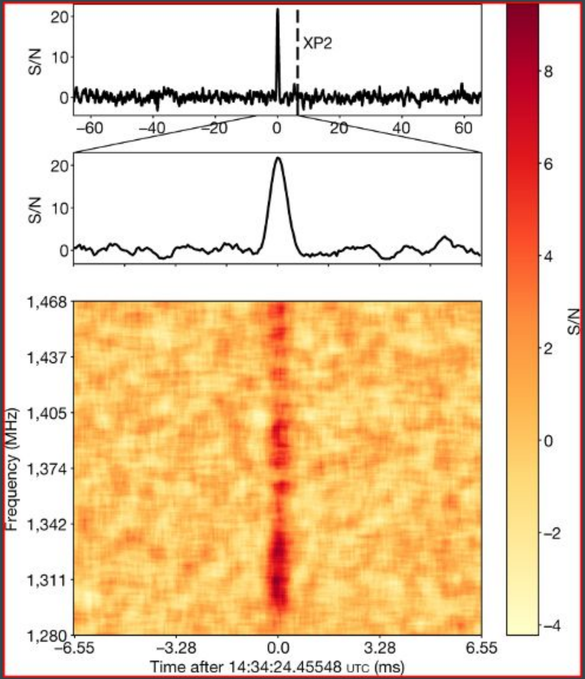
Millisecond Pulsars (<0.3 s): initially lost their rotational energy, then accreted from companion to spin up to millisecond periods

Slow Pulsars (0.3-10 s): produce coherent radio emission from magnetic poles via charged particle 'avalanche'

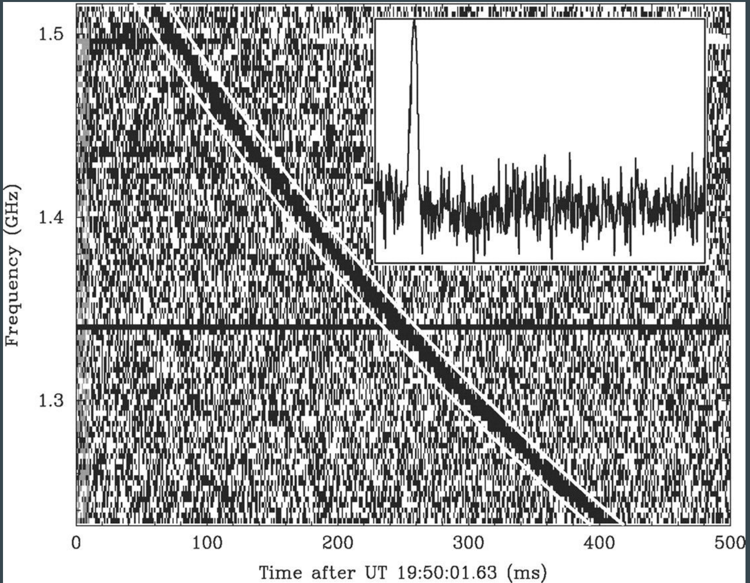


Fast Radio Bursts (FRBs)

Extragalactic radio bursts lasting <1ms with unknown source mechanism; leading candidates are magnetars



In 2020, an FRB-like burst was detected from a Galactic magnetar, **SGR J1935+54,** making magnetars the primary candidates (e.g. Bochenek et al., 2020)



First FRB (The Lorimer Burst), detected by the Parkes telescope, was determined extragalactic due to the large frequency-dependent **dispersive delay**

$$I\left(t + \frac{e^2 DM}{2\pi m_e c}(\nu_0^{-2} + \nu^{-2}), \nu\right)$$

At-Home Astronomy: Quick-look Radio Images

Images from the Very Large Array (VLA) and Australia Square Kilometre Array Pathfinder (ASKAP) interferometers:

- VLASS, RACS, NVSS Quick-look images: https://cutouts.cirada.ca/
- MeerKAT SAO Survey: https://archive-gw-1.kat.ac.za/public/repository/10.48479/3wfd-e270/index.html

Owens Valley Radio Observatory: https://www.ovro.caltech.edu/

Questions, Comments, or Concerns?

https://forms.gle/ywP1THADKCq1nDPy9

Lecture 4: Large-Scale Structure and Cosmology

Learning Objectives and Overview

By the end of this course, students will be able to:

…identify major stars and constellations in the night sky, recount the life-cycle of a star form the Main Sequence to supernova, and distinguish between White Dwarfs, Neutron Stars, and Black Holes.

…describe the basic components of an optical telescope,explain the major differences between optical, infrared, and UV astronomy, describe why X-ray and gamma ray telescopes operate differently from OIR and UV telescopes.

…describe the basic components of a radio antenna, explain how radio interferometers work, and list the astrophysical sources of radio waves.

…describe the components of a galaxy (disk, bulge, ISM, halo, CGM), define cosmology, how it is studied (redshift, CMB, 21 cm cosmology, simulations, FRBs), explain how distance, redshift, and time are related within general relativity, and understand how the presence of dark matter and dark energy affect our picture of the Universe.

…list some of the major questions in astronomy today and refer to resources to continue exploring astronomy within and around Pasadena.

Galaxy Morphology

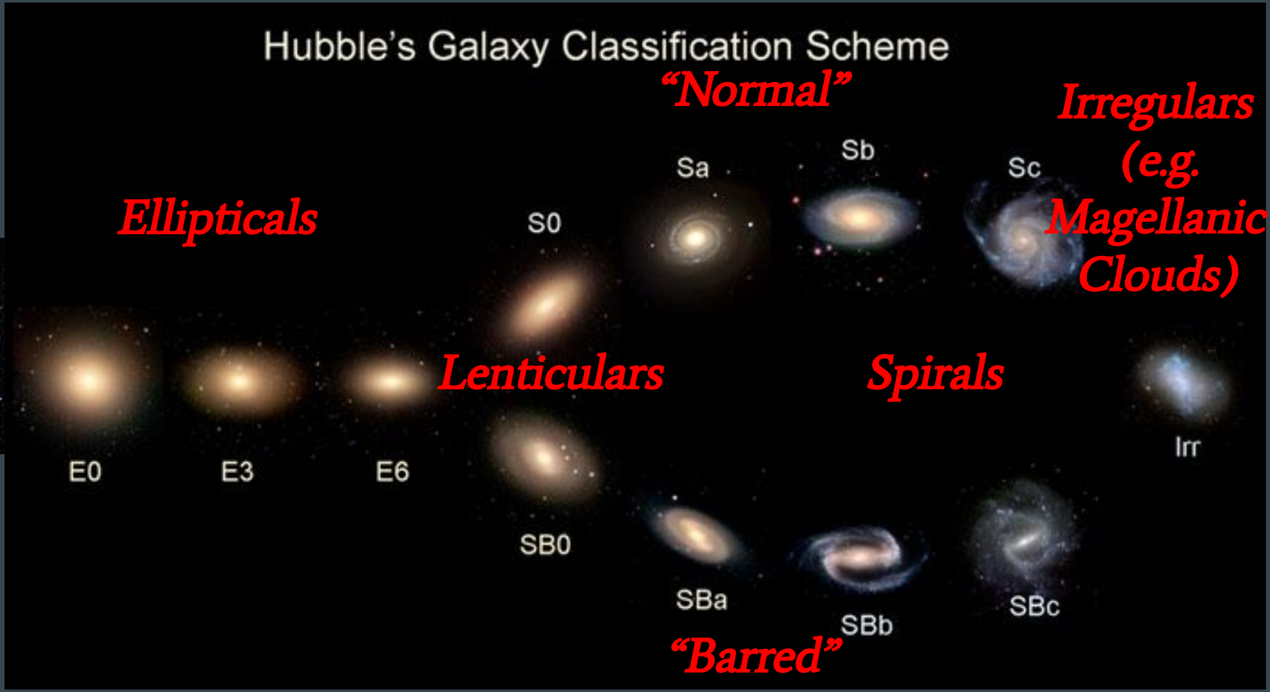
A **Galaxy** is a gravitationally-bound collection of stars, gas, and dust, like our galaxy, the **Milky Way**

Globular Clusters

Dwarf Galaxies

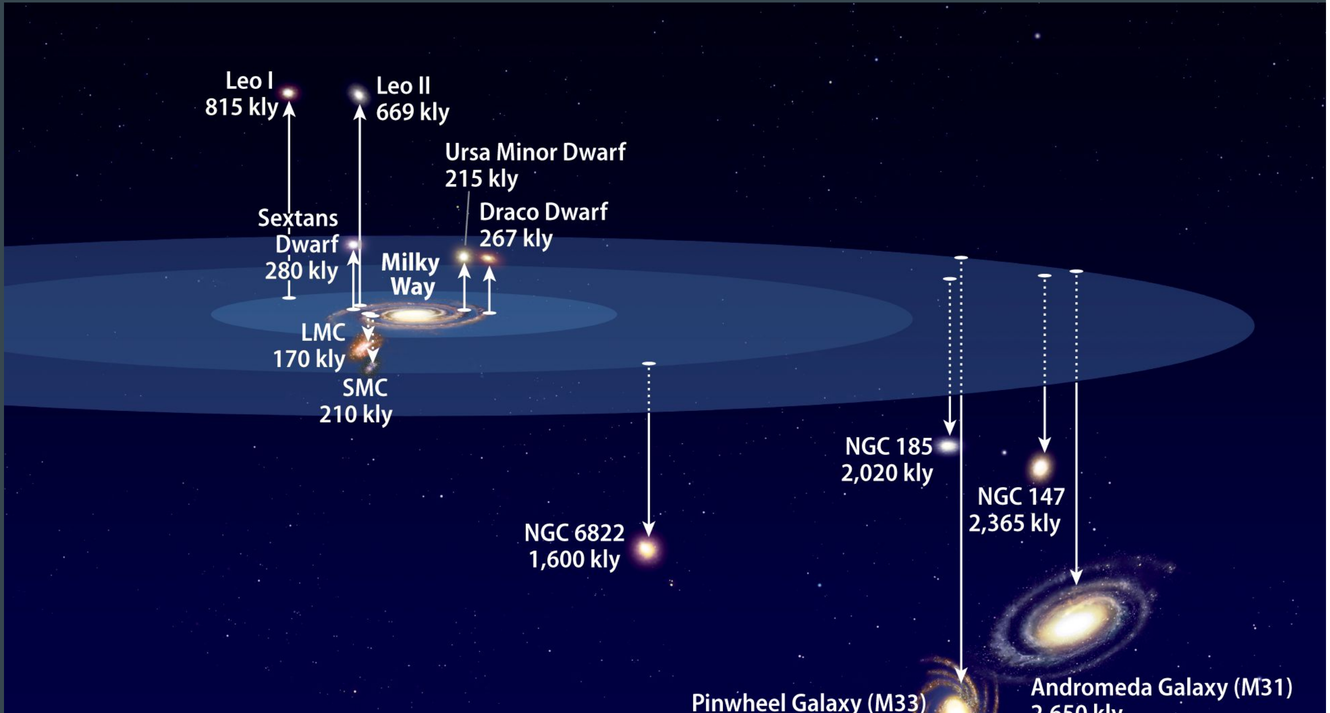
dSph

dE



The Local Group

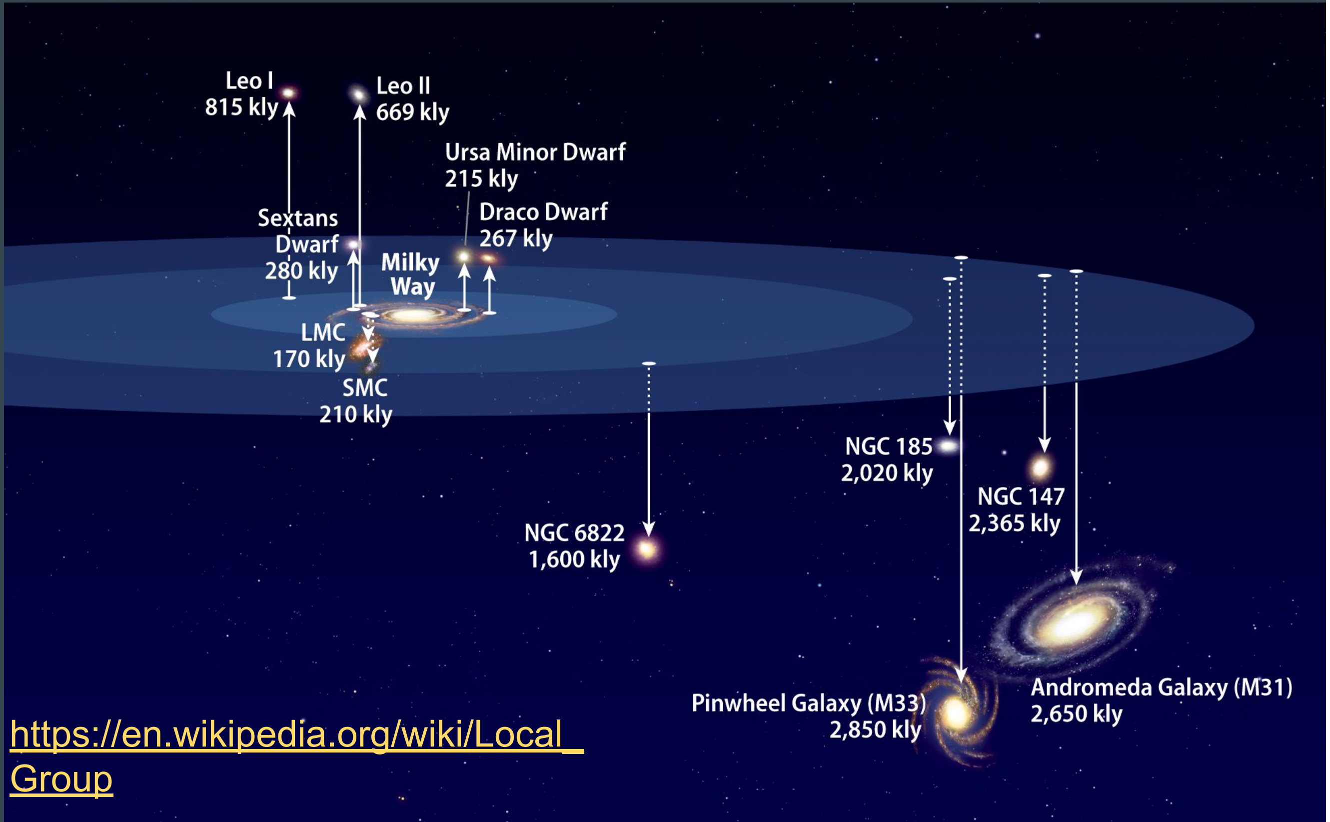
Local Group Galaxies and Classifications (McConnachie 2012)



https://en.wikipedia.org/wiki/Local_Group

(1) Galaxy	(2) Other Names	(3)	(4)
The Galaxy	The MW	G	S(B)bc
Canis Major		G	????
Sagittarius dSph		G	dSph
Segue (I)		G	dSph
Ursa Major II		G	dSph
Bootes II		G	dSph
Segue II		G	dSph
Willman 1	SDSS J1049+5103	G	dSph
Coma Berenices		G	dSph
Bootes III		G	dSph?
LMC	Nubecula Major	G	Irr
SMC	Nubecula Minor	G	dIrr
	NGC 292		
Bootes (I)		G	dSph
Draco	UGC 10822	G	dSph
	DDO 208		
Ursa Minor	UGC 9749	G	dSph
	DDO 199		
Sculptor		G	dSph
Sextans (I)		G	dSph
Ursa Major (I)		G	dSph
Carina		G	dSph
Hercules		G	dSph
Fornax		G	dSph
Leo IV		G	dSph
Canes Venatici II	SDSS J1257+3419	G	dSph
Leo V		G	dSph
Pisces II		G	dSph
Canes Venatici (I)		G	dSph
Leo II	Leo B	G	dSph
	UGC 6253		
	DDO 93		
Leo I	UGC 5470	G/L	dSph
	DDO 74		
	Regulus Dwarf		
Andromeda	M31	A	Sb
	NGC 224		
	UGC 454		
M32	NGC 221	A	cE
	UGC 452		
Andromeda IX		A	dSph

The Local Group



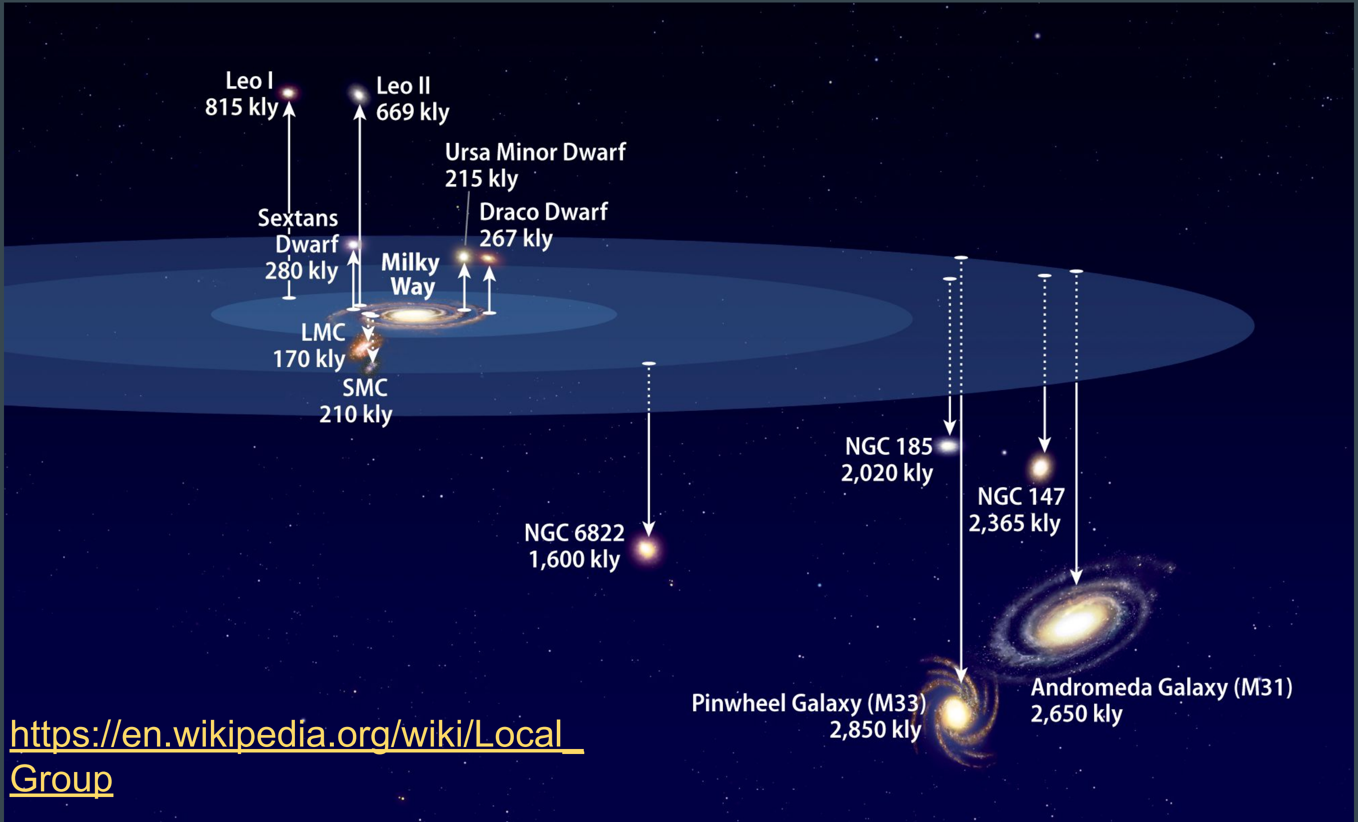
https://en.wikipedia.org/wiki/Local_Group

Local Group Galaxies and Classifications (McConnachie 2012)

(1) Galaxy	(2) Other Names	(3)	(4)
NGC 205	M110 UGC 426	A	dE/dSph
Andromeda XVII		A	dSph
Andromeda I		A	dSph
Andromeda XXVII		A	dSph
Andromeda III		A	dSph
Andromeda XXV		A	dSph
Andromeda XXVI		A	dSph
Andromeda XI		A	dSph
Andromeda V		A	dSph
Andromeda X		A	dSph
Andromeda XXIII		A	dSph
Andromeda XX		A	dSph
Andromeda XII		A/L	dSph
NGC 147	UGC 326 DDO 3	A	dE/dSph
Andromeda XXI		A	dSph
Andromeda XIV		A/L	dSph
Andromeda XV		A	dSph
Andromeda XIII		A	dSph
Andromeda II		A	dSph
NGC 185	UGC 396	A	dE/dSph
Andromeda XXIX		A	dSph
Andromeda XIX		A	dSph
Triangulum	M33 NGC 598 UGC 1117	A	Sc
Andromeda XXIV		A	dSph
Andromeda VII	Casseopia dSph	A	dSph
Andromeda XXII		A	dSph
IC 10	UGC 192	A	dIrr
LGS 3 (Local Group Suspect 3)	Pisces (I)	A	dIrr/dSph
Andromeda VI	Pegasus dSph	A	dSph
Andromeda XVI		A/L	dSph
The rest of the Local Grou			
Andromeda XXVIII		A/L	dSph?
IC 1613	DDO 8 UGC 668	L	dIrr
Phoenix		L/G	dIrr/dSph
NGC 6822	IC 4895 DDO 209 Barnard's Galaxy	L/G	dIrr

The Local Group

Local Group Galaxies and Classifications (McConnachie 2012)

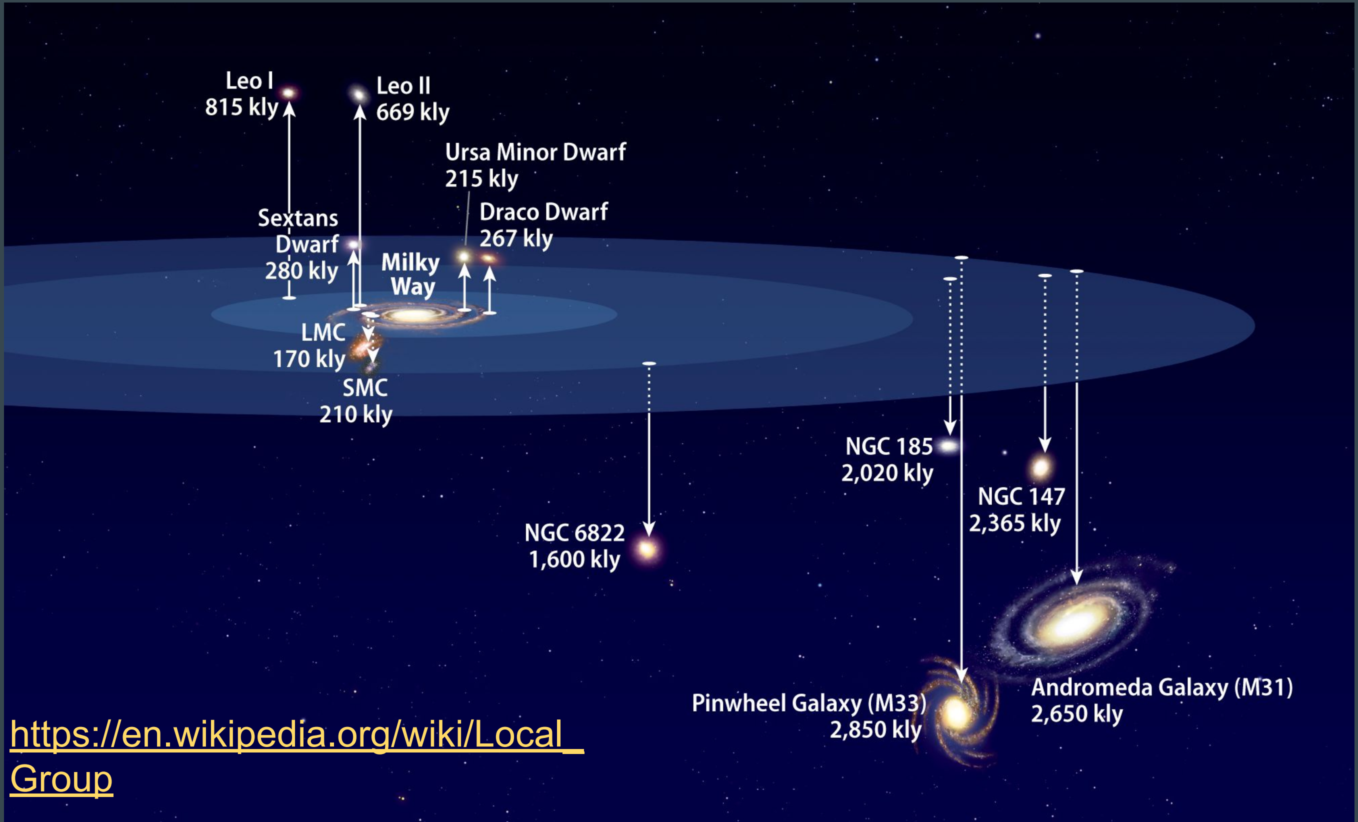


https://en.wikipedia.org/wiki/Local_Group

(1) Galaxy	(2) Other Names	(3)	(4)
Cetus		L	dSph
Pegasus dIrr	UGC 12613 DDO 216	L/A	dIrr/dSph
Leo T		L/G	dIrr/dSph
WLM (Wolf-Lundmark--Melotte)	UGCA 444 DDO 221	L	dIrr
Leo A	Leo III UGC 5364 DDO 69	L	dIrr
Andromeda XVIII		L	dSph
Aquarius	DDO 210	L	dIrr/dSph
Tucana		L	dSph
Sagittarius dIrr	UKS 1927-177	L	dIrr
UGC 4879	VV 124	L	dIrr/dSph
NGC 3109	DDO 236 UGCA 194	N	dIrr
Sextans B	UGC 5373 DDO 70	N	dIrr
Antlia		N	dIrr
Sextans A	UGCA 205 DDO 75	N	dIrr
HIZSS 3(A)		N	(d)Irr?
HIZSS 3B		N	(d)Irr?
KKR 25		N	dIrr/dSph
ESO 410- G 005	UKS 0013-324	N	dIrr/dSph
NGC 55		N	Irr
ESO 294- G 010		N	dIrr/dSph
NGC 300		N	Sc
IC 5152		N	dIrr
KKH 98		N	dIrr
UKS 2323-326	UGCA 438	N	dIrr
KKR 3	KK 230	N	dIrr
GR 8	UGC 8091 VV 558 DDO 155	N	dIrr
UGC 9128	DDO 187	N	dIrr
UGC 8508		N	dIrr
IC 3104	ESO 020- G 004 UKS 1215-794	N	dIrr
DDO 125	UGC 7577	N	dIrr
UGCA 86		N	dIrr
DDO 99	UGC 6817	N	dIrr
IC 4662	ESO 102- G 014	N	dIrr

The Local Group

Local Group Galaxies and Classifications (McConnachie 2012)



https://en.wikipedia.org/wiki/Local_Group

(1) Galaxy	(2) Other Names	(3)	(4)
DDO 190	UGC 9240	N	dIrr
KKH 86		N	dIrr
NGC 4163	UGC 7199 NGC 4167[k]	N	dIrr
DDO 113	UGCA 276 KDG 90	N	dIrr

Galaxy Luminosity Function

Luminosity Function - number of galaxies with luminosity between L→L+dL (distribution)

Schecter Function - originally proposed to be a universal Galaxy Luminosity Function, but now we see it varies with:

- Morphology
- Galaxy density (**void**, **cluster**, **supercluster**)

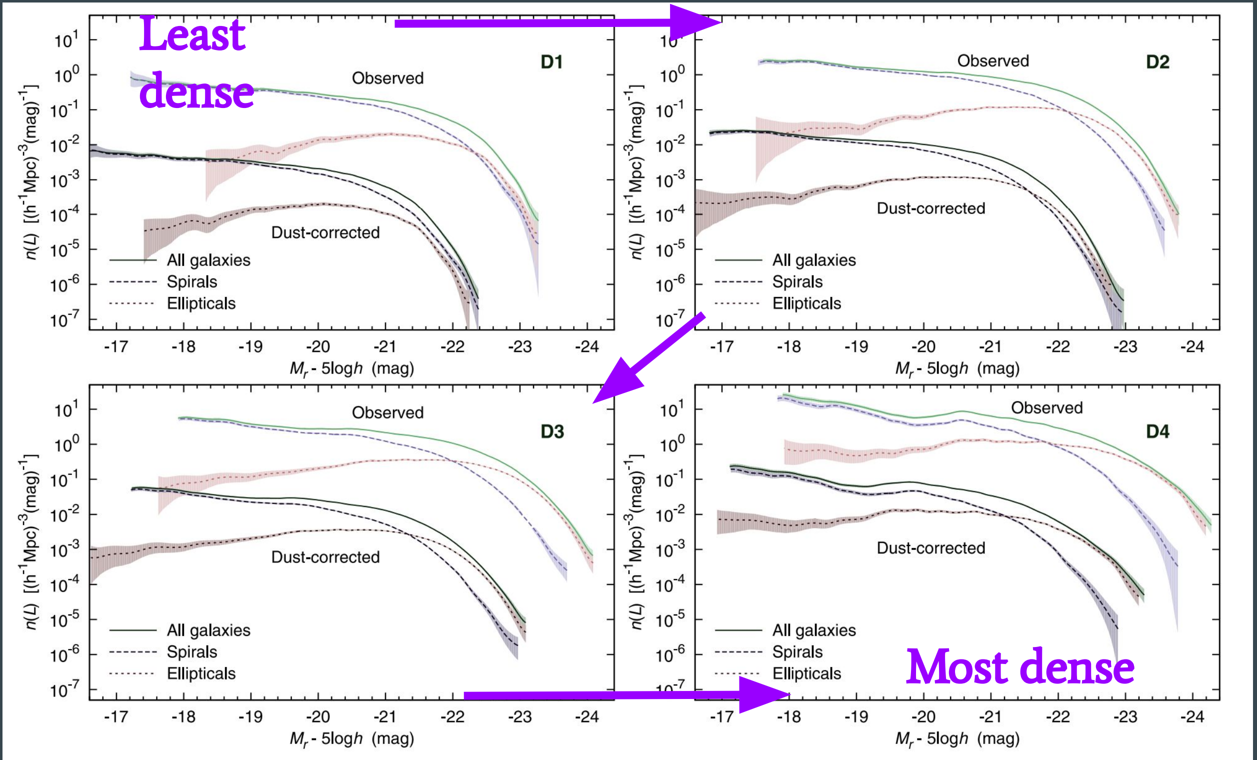
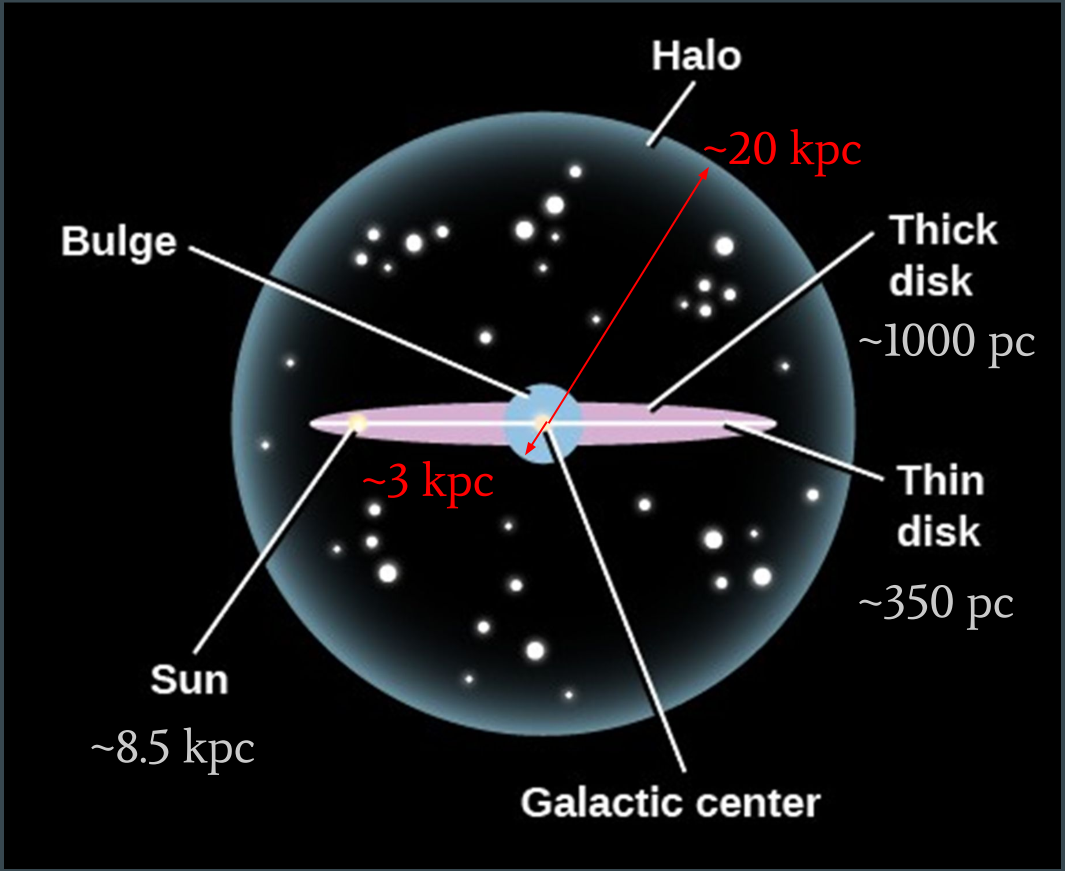


Fig. 13. LFs for different types of galaxies in different environments: *upper left* panel shows the least dense environment (D1) and *bottom right* panel shows the most dense environment (D4). Green solid lines show the LFs for all galaxies; blue dashed lines show the LFs for spiral galaxies; red dotted lines show the LFs for elliptical galaxies. The *upper* LFs in each panel are the observed LFs that are shifted up two units in logarithmic scale and right by one mag. The *lower* LFs in each panel are the attenuation-corrected LFs. Filled areas show the 95% confidence regions. The panels D1 to D4 show different global environmental regions: D1 are void regions and D4 are supercluster regions. The LFs have been normalised to the volume of each sample.

Luminosity functions from Sloan Digital Sky Survey Data Release 7 (Tempel et al., 2011)

Milky Way Structure



Milky Way Star Formation and Stellar Populations

Population I Stars

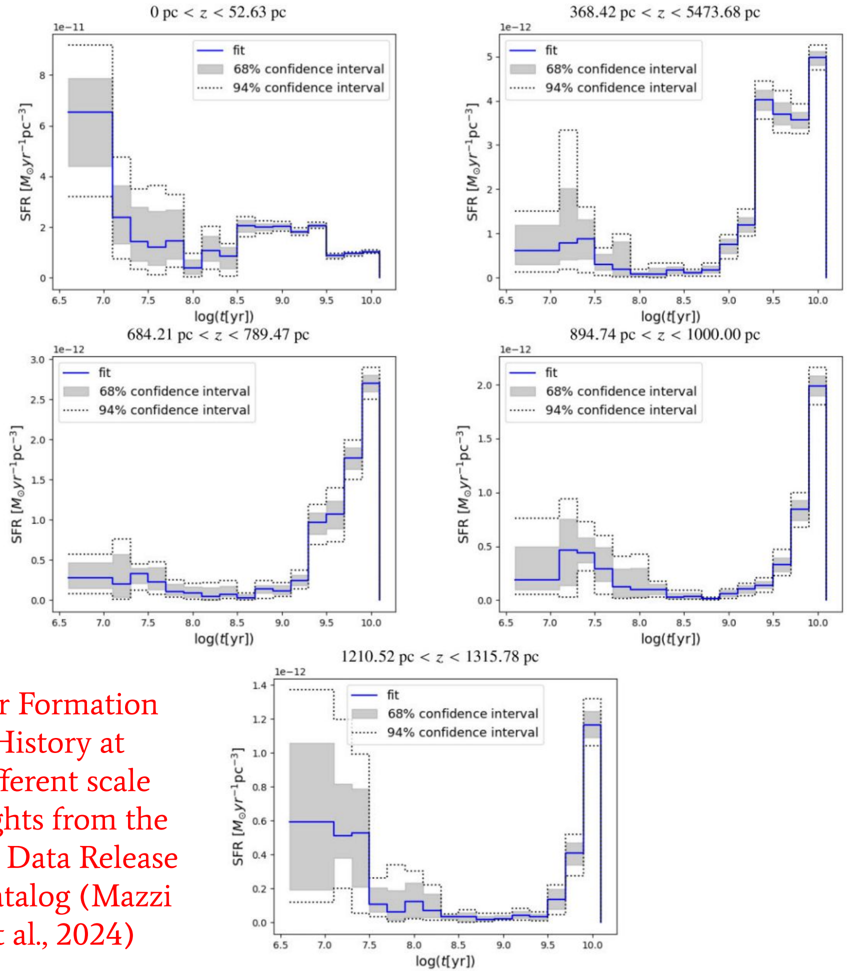
- Metal rich, formed after the explosions of the first stars
- Most in **thin disk** , high fraction of heavy metals (Fe, Si, Ti) → Type 1a SNe, younger
- Some in **bulge,** mostly oxygen, carbon → Type II Sne, older

Population II Stars

- Metal poor, formed from earliest gas in the Galaxy
- Bulge and halo

Population III (?) – theorized to form from primordial gas before galaxies formed

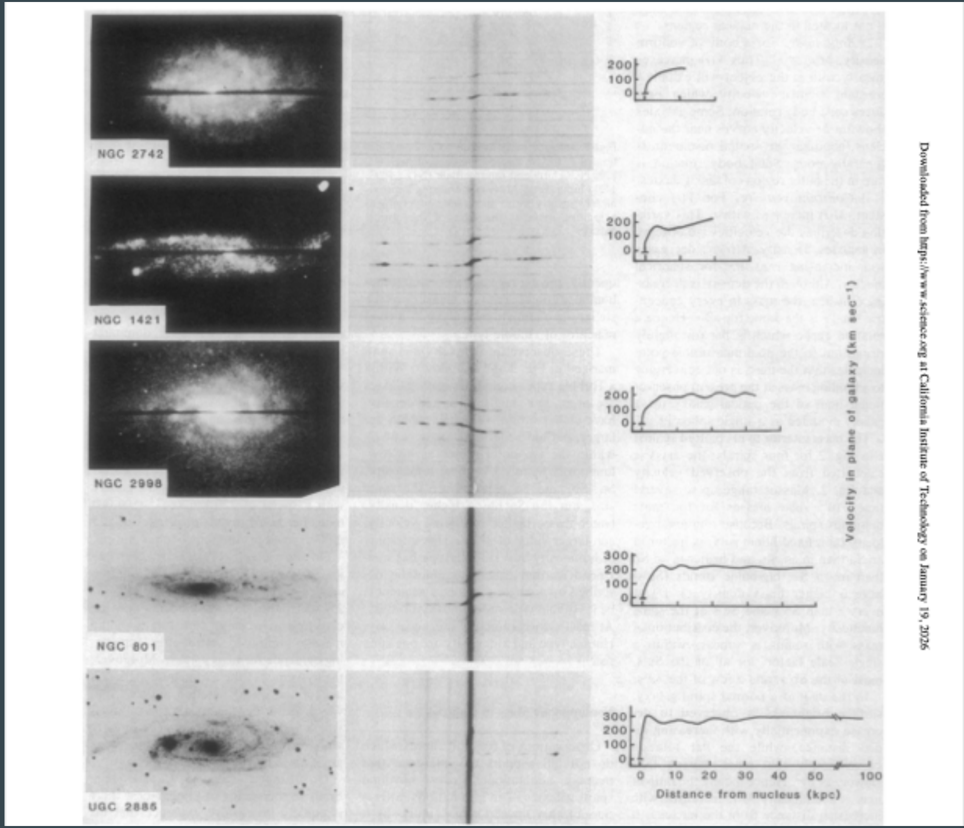
Star Formation History - star formation rate as a function of Galaxy age; remains complex, population model insufficient



Star Formation History at different scale heights from the Gaia Data Release 2 Catalog (Mazzi et al., 2024)

Figure 6. The SFR per unit volume as a function of age determined for the same slices of the sample shown in Fig. 4, also indicated on top of each panel. The blue lines represent the best fitting SFR values, while the grey-shaded areas and the dashed lines mark the 68 and 94 per cent confidence intervals, respectively. We note that the SFR at young ages (log (t[yr]) ≲ 7.5) is non-zero even at large z, although it is very uncertain.

Missing Matter?



Images, spectra, and rotation curves for a sample of galaxies showing flat rotation curves (Rubin et al. 1962, 1983)

Mounting evidence for large amount of 'non-luminous' matter:

- 1933: Fritz Zwicky identified stellar mass of Coma cluster much lower than dynamical mass based on galaxy velocities
- 1940: Jan Oort studies of NGC 3115 dynamics imply mass distribution different than light distribution
- 1945: Martin Schwarzschild finds inconsistent rotation curve of M31
- **1962: Vera Rubin measures flat Milky Way rotation curve from 888 stars, first confirmation of a "Dark Matter Halo"**

Think-Pair-Share

How do you think galaxies formed?

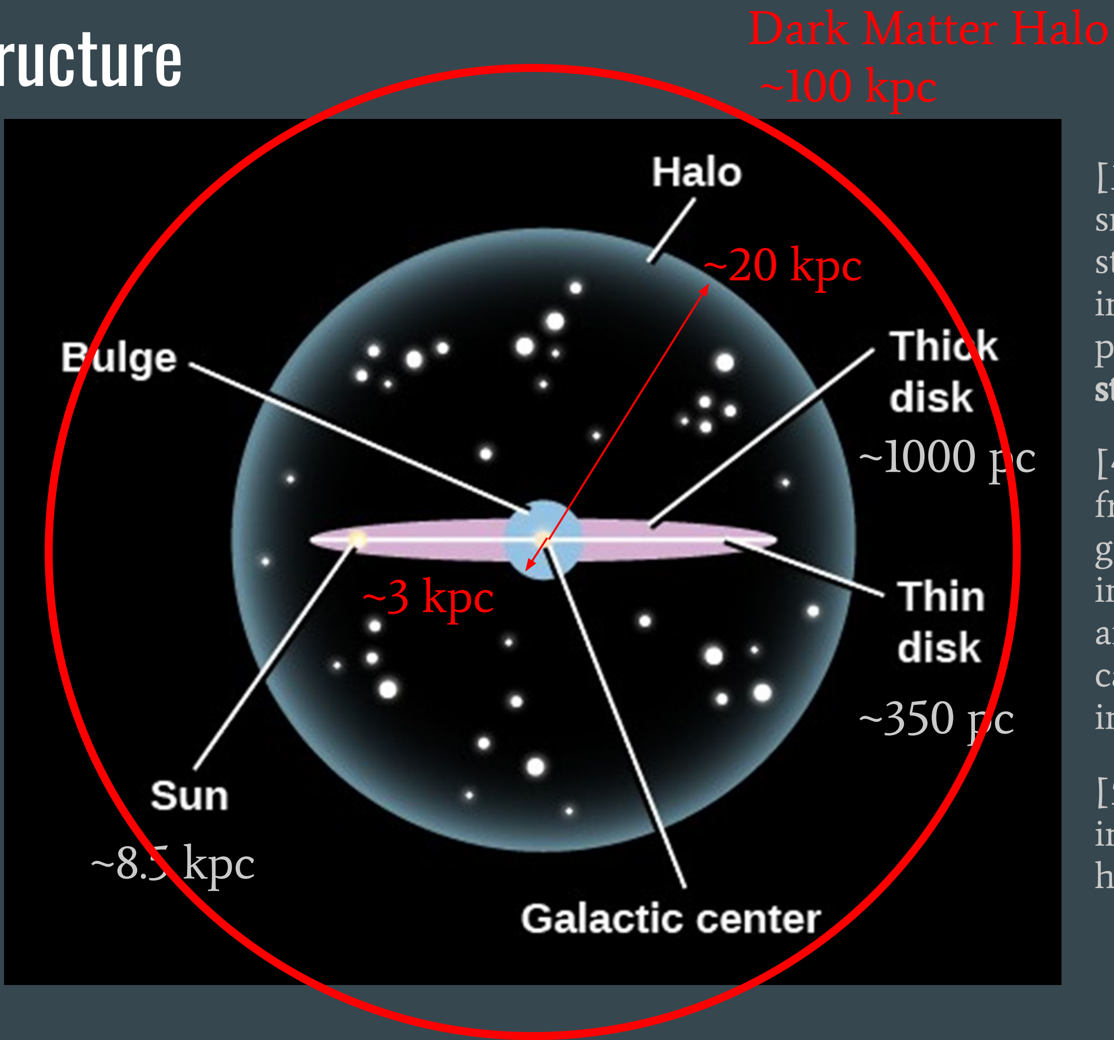
What role do you think dark matter plays in galaxy formation?

Milky Way Structure

Hierarchical (bottom-up) galaxy formation:

[1] Dark matter perturbations (10^{12}Msun) define where galaxies will form → **cosmic web**

[2] Within DM perturbations, first small clusters (10^{6}Msun) collapse, begin forming stars and globular clusters → **bulge**



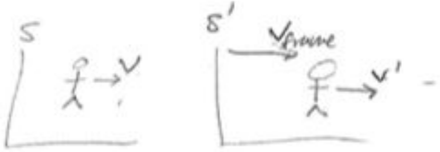
[3] Collisions between small clusters disrupt star formation, collide into larger (10^{10}Msun) proto-galaxies → **stellar halo**

[4] Residual torque from collisions and gravitational interactions induce angular momentum, causes matter to settle into disk → **thick disk**

[5] Cool gas settles into smaller scale height → **thin disk**

4.1) Special Relativity

Newtonian relativity →



$$v' = v - v_{frame}$$

↳ but what happens if $v = c$, the speed of light?

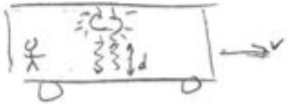
↳ Newtonian physics breaks down when $v \to c$

Einstein's Postulates

1) Principle of Relativity – laws of physics apply in all inertial reference frames

2) Speed of Light in a vacuum is $c = 3\times10^8$ m/s in all inertial reference frames

Ex:



frame S: if you're on the train, how long for light to reach the ground?

$$\Delta t = 2d/c$$

Frame S': if you observe at rest, how long for light to reach the ground?

$$d' = \sqrt{d^2 + \left(\frac{v\Delta t'}{2}\right)^2}$$

$$\Delta t' = \frac{2d'}{c} = \frac{2\sqrt{d^2 + \left(\frac{v\Delta t'}{2}\right)^2}}{c}$$

$$\frac{c^2\Delta t'^2}{4} = d^2 + \frac{v^2}{4}\Delta t'^2$$

$$(c^2 - v^2)\Delta t'^2 = 4d^2$$

$$\Delta t' = \frac{2d}{c\sqrt{1 - v^2/c^2}} = \frac{\Delta t}{\sqrt{1 - v^2/c^2}}$$

Lorentz Factor:

$$\gamma \equiv \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

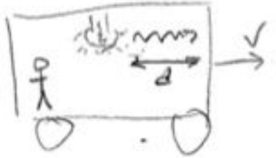
Time Dilation

$$\Delta t' = \gamma \Delta t$$

"moving clocks run slow"

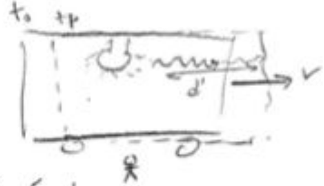
4.2

Ex.



frame S: how long does it take for light to reach end of the train?

$$\Delta t = \frac{d}{c}$$



frame S': how long does it take if we observe from the platform?

$$\Delta t' = \frac{d'}{c}$$

$$\frac{d'}{\Delta t'} = \frac{d}{\Delta t} \quad \text{since } c \text{ is the same in both frames}$$

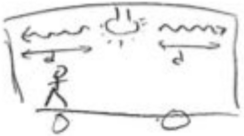
$$d' = d\left(\frac{\Delta t'}{\Delta t}\right) = \gamma d$$

Length contraction

$$\boxed{d' = \gamma d}$$

"Length of moving objects are shorter"

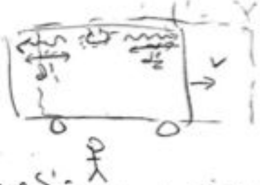
Ex.



frame S: When does the light hit each side of the train?

$t_1 = d/c \qquad t_2 = d/c$

$t = t_1 = t_2 = d/c$



frame S': When does the light hit each side of the train?

$t_1' = \frac{d_1'}{c} = \frac{d' - vt_1'}{c} \qquad t_2' = \frac{d_2'}{c} = \frac{d' + vt_2'}{c}$

$t_1'\left(1 + \frac{v}{c}\right) = \frac{\gamma d}{c} \qquad t_2'\left(1 - \frac{v}{c}\right) = \frac{\gamma d}{c}$

$t_1' = \frac{\gamma}{1 + \frac{v}{c}} t \qquad t_2' = \frac{\gamma}{1 - \frac{v}{c}} t$

$\Rightarrow t_1' = \frac{1 - \frac{v}{c}}{1 + \frac{v}{c}} t_2'$

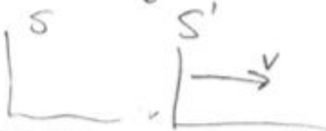
relativity of simultaneity

"events that are simultaneous in one frame are not simultaneous in another"

4.3

Lorentz transformations

- to convert from frame S to frame S' moving at velocity v relative to S in x direction



$S \to S'$

$$ct' = \gamma(ct - \beta x)$$
$$x' = \gamma(x - \beta ct)$$
$$y' = y$$
$$z' = z$$

$S' \to S$

$$ct = \gamma(ct' + \beta x')$$
$$x = \gamma(x' + \beta ct')$$
$$y = y'$$
$$z = z'$$

Momentum: measure of an object's inertia ($p = mv$)

- relativistic ⇒ use proper velocity measured in rest frame:

$$p = \gamma m v$$

Energy: $E = \gamma mc^2 = (pc)^2 + (mc^2)^2$

- rest energy: for $\gamma = 1$

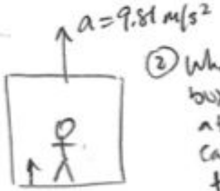
$$E_{rest} = mc^2$$

What if frame S' is accelerating?

① inside box of no windows on the ground

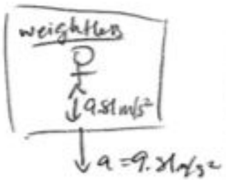
gravity and acceleration are equivalent

... (equivalence principle)

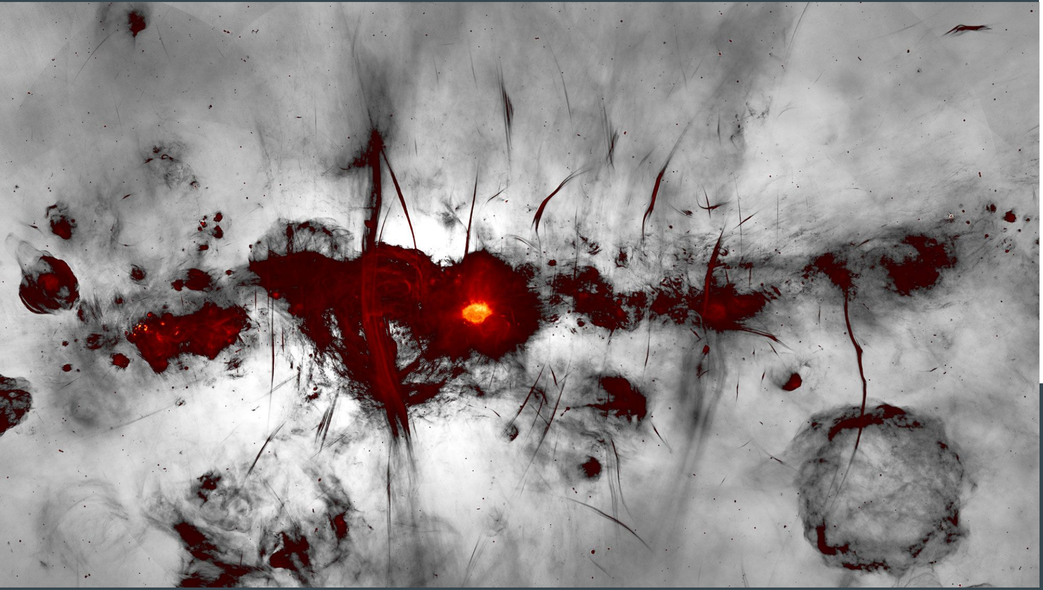


② What if the box is pulled at 9.81 m/s²? Can you tell the difference?

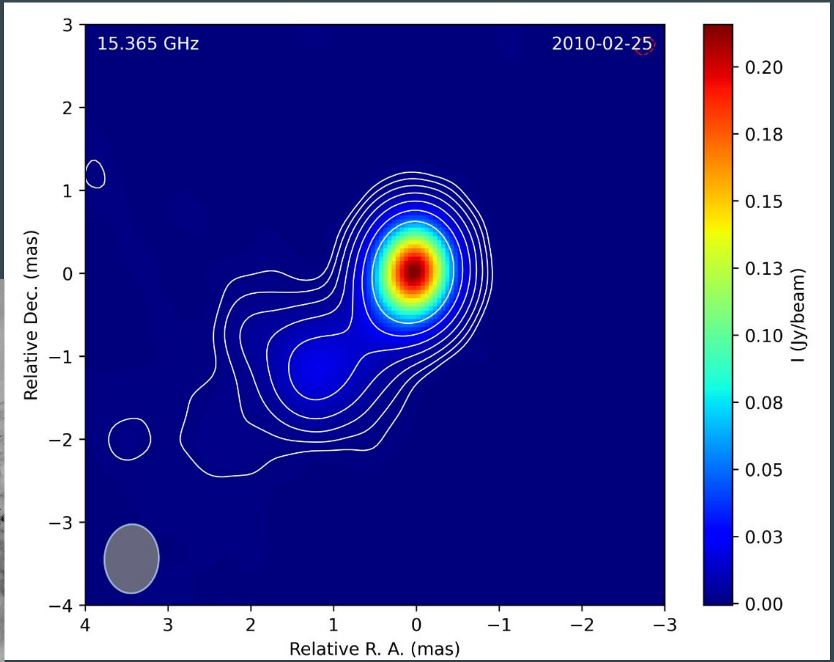
③ What if the box is falling under gravity?



Special Relativity in Astronomy



Synchrotron Radiation (MeerKAT 1.3 GHz; Heywood+2024)



Superluminal Motion (Blazar J1429+5406; Koller & Frey 2025)

Think-Pair-Share

Let's do a thought experiment: say there are two twins who start on earth. If one twin starts travelling very fast, he experiences time passing more slowly than the one on earth. After a long time, he turns around and comes back at the same speed. When he arrives, will he be older, younger, or the same age as his twin? Why?

The Twin Paradox

It's not really a paradox!

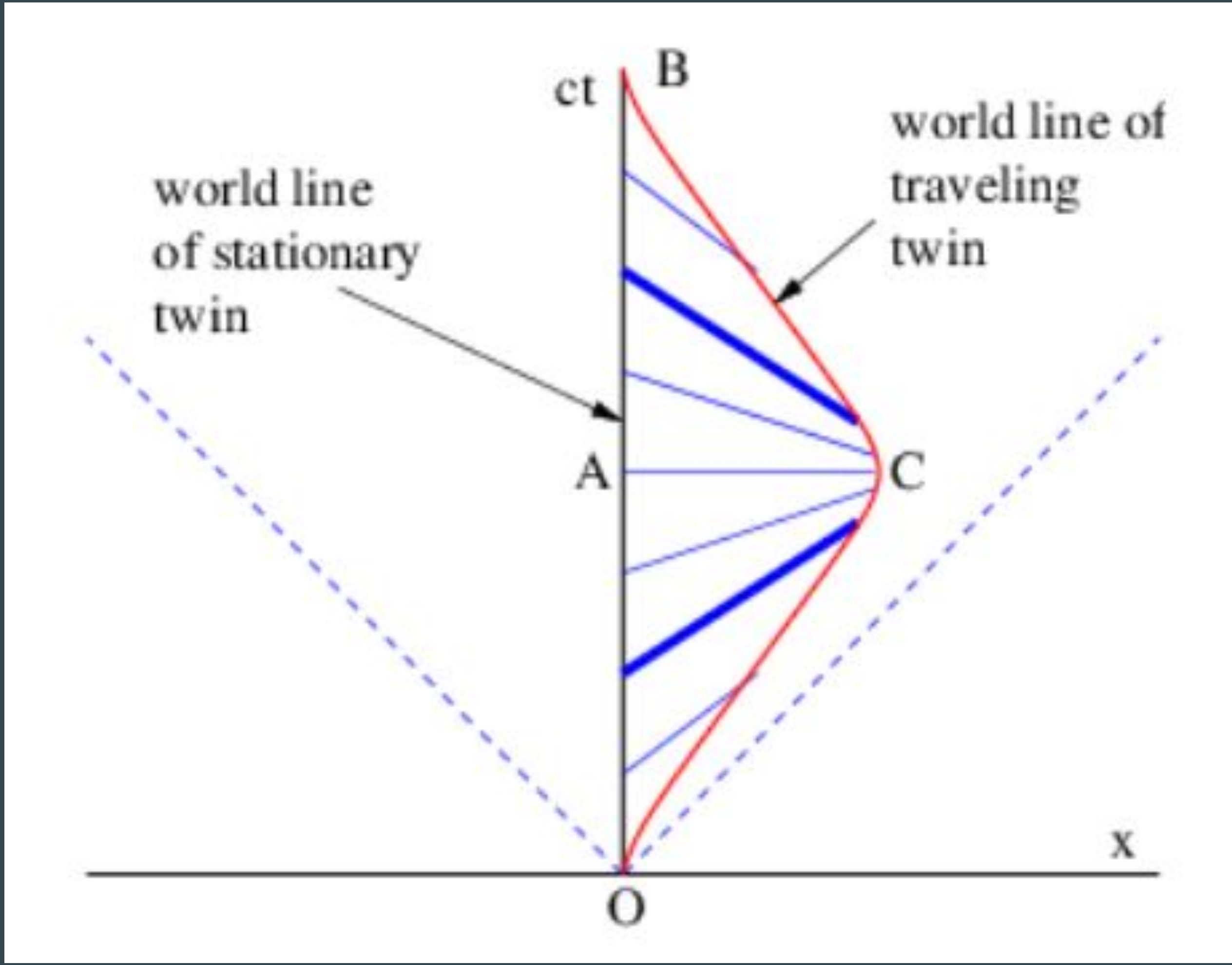
While the twin is traveling, his clock runs **slower** than the stationary twin → traveling twin is younger

But to the traveling twin, the stationary twin is moving → stationary twin is younger

How can both be true?

When the moving twin turns around, they're **accelerating**, so their reference frame changes → the stationary twin is correct!

https://www.sciencealert.com/in-space-scott-kelly-aged-more-slowly-than-his-brother-on-earth-and-here-s-why



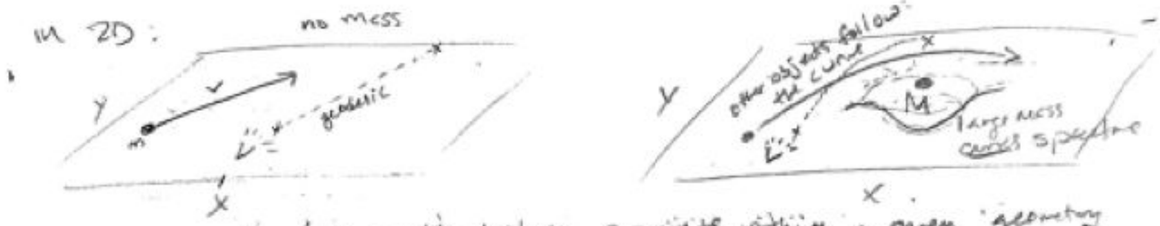
4.4

General Relativity – geometric description of spacetime including gravity

- spacetime: x, y, z, ct

① Mass tells spacetime how to curve,
Spacetime tells mass how to move

in 2D:



- geodesic – shortest path between 2 points within a given geometry
- light always follows geodesic, which is curved in curved spacetime

② Equivalence Principle – gravitational & inertial mass are the same, i.e. gravity is indistinguishable from acceleration

- gravitational redshift

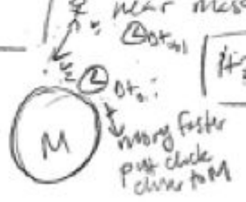
$$1+z = \frac{\lambda_{obs}}{\lambda_0} = \frac{\nu_0}{\nu_{obs}} = \sqrt{1-\frac{2GM}{r_0c^2}}$$

wavelength increases when light travels away from a massive object
wavelength decreases when light travels towards massive object

- gravitational time dilation

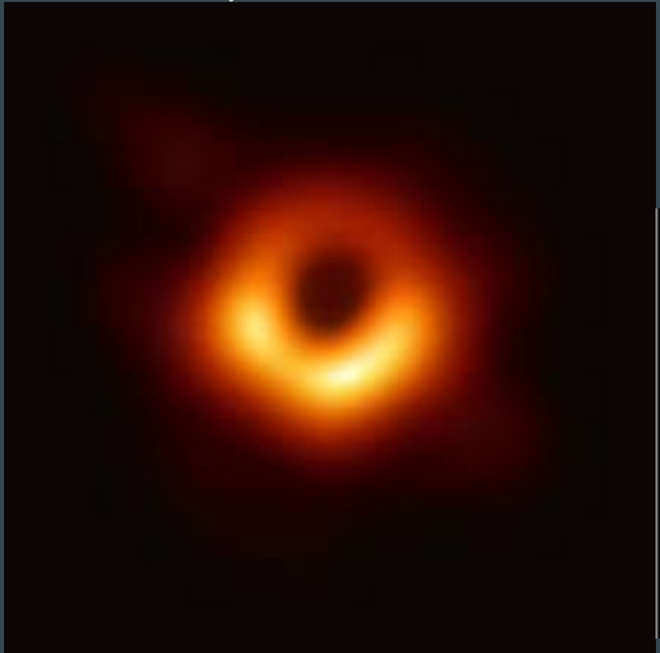
time runs more slowly near massive objects

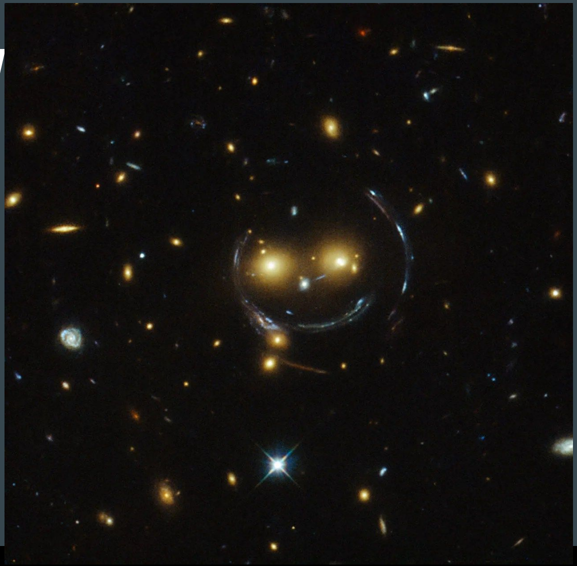
$$1+z = \frac{\Delta t_0}{\Delta t_{obs}} = \sqrt{1-\frac{2GM}{r_0c^2}}$$



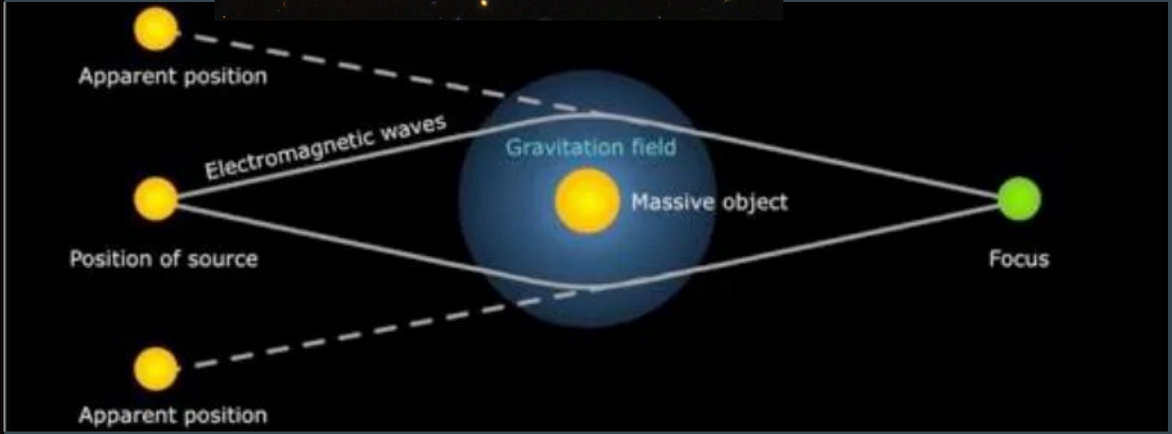
General Relativity in Astronomy

1.3 mm Image of the Black Hole M87 in the Andromeda Galaxy (EHT Collab. 2017)



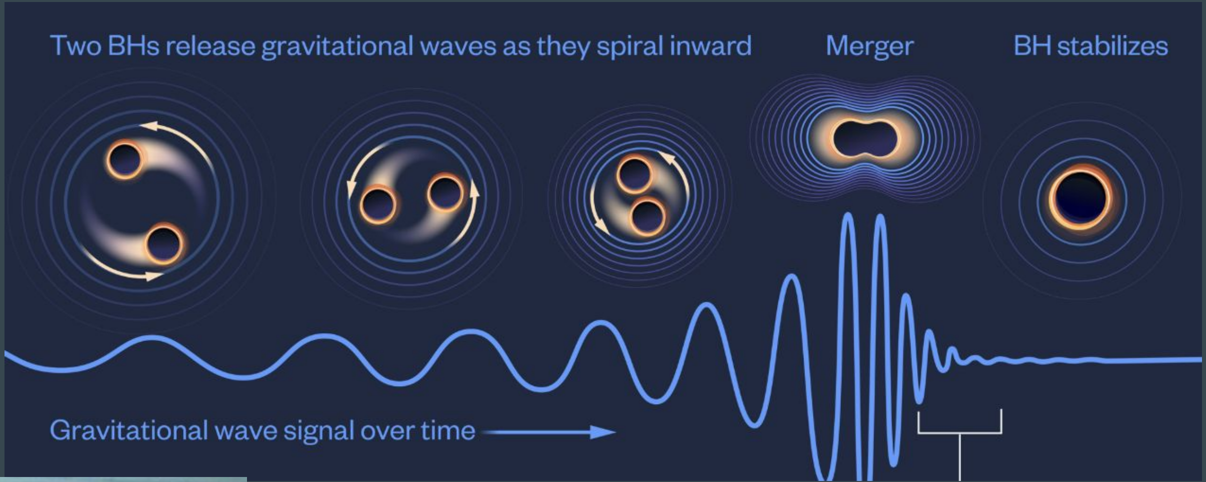


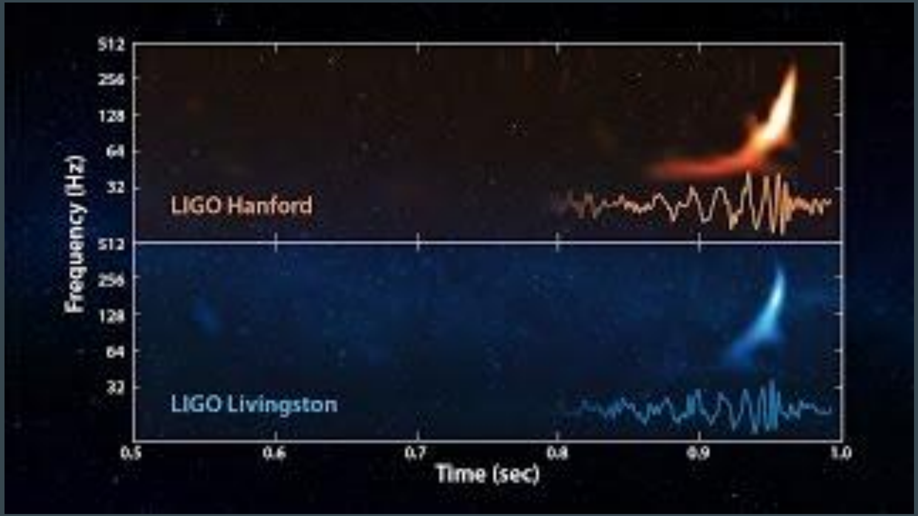
Gravitational Lensing Observed by the Hubble Telescope



Gravitational Waves

Laser Interferometer Gravitational-Wave Observatory (LIGO)





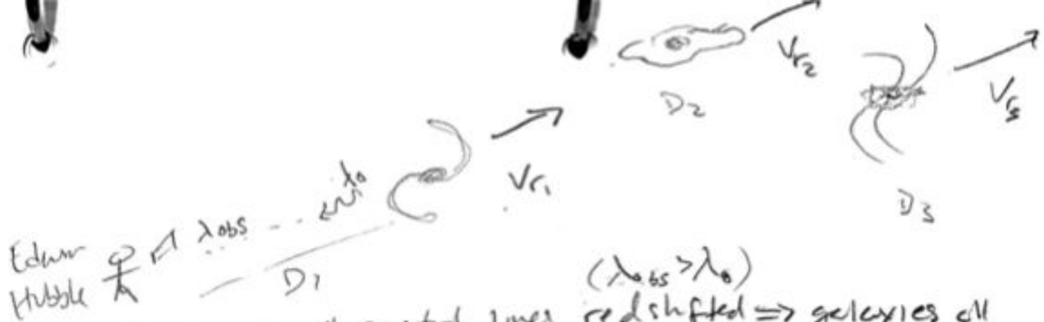
At-Home Astronomy: Gravitational Lensing and Gravitational Waves

Hubble Gravitational Lensing Image Archives:
https://esahubble.org/images/archive/category/cosmology/

Gravitational Waves:

- Open Source Catalog and Tutorials on Accessing LIGO/VIRGO/KAGRA data: https://gwosc.org/tutorials/
- Gravitational Wave alerts on your phone: https://www.ligo.caltech.edu/page/GWPhoneAlerts

4.5



↳ observed all spectral lines **redshifted** ($\lambda_{obs} > \lambda_0$) ⇒ galaxies all moving **away** from us

↳ more distant galaxies moving away **faster**: $D_3 > D_2 > D_1$
$V_{r_3} > V_{r_2} > V_{r_1}$

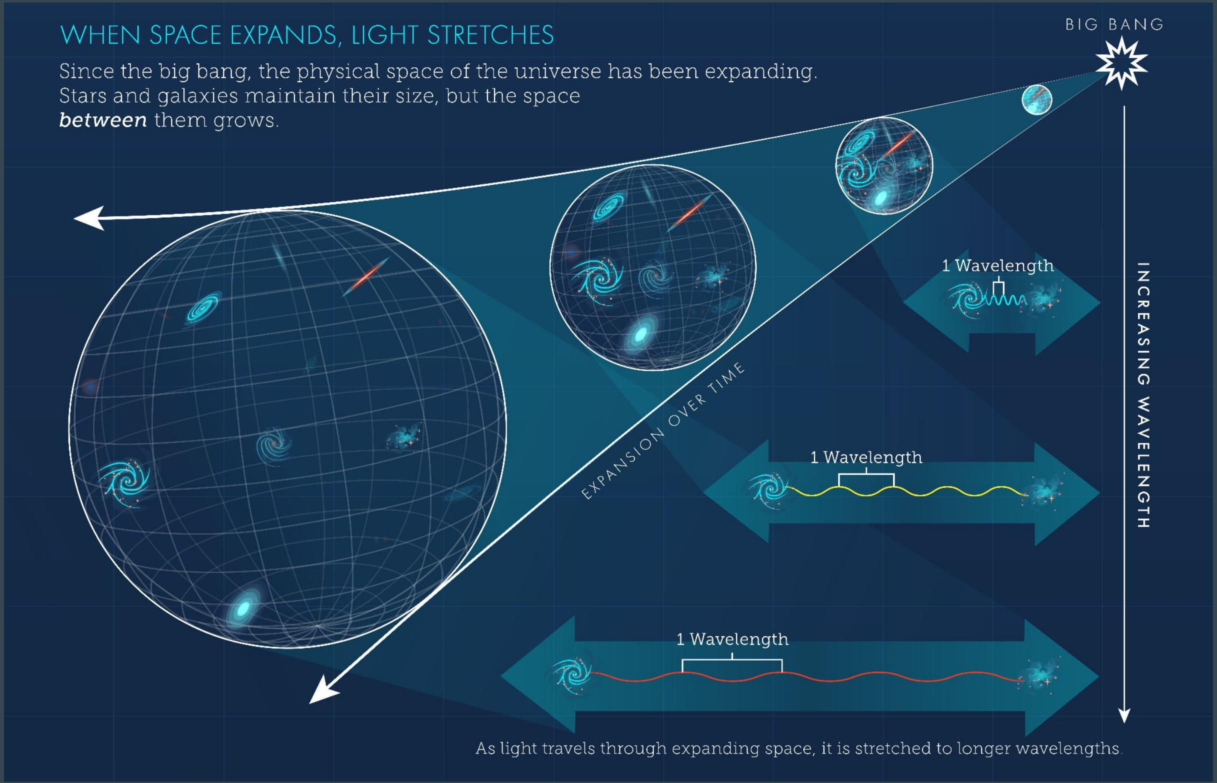
Hubble's law
cosmological redshift: $V_r \approx cz \approx \frac{H_0}{c} D$ ← Hubble's constant $H_0 \sim 70$ km/s/Mpc

- **isotropic** – universe has no preferred center or direction
  ⇒ galaxies are all moving away from each other

} spacetime itself, **the universe is expanding**

- expansion is **accelerating** → driven by **dark energy**

The Expanding Universe



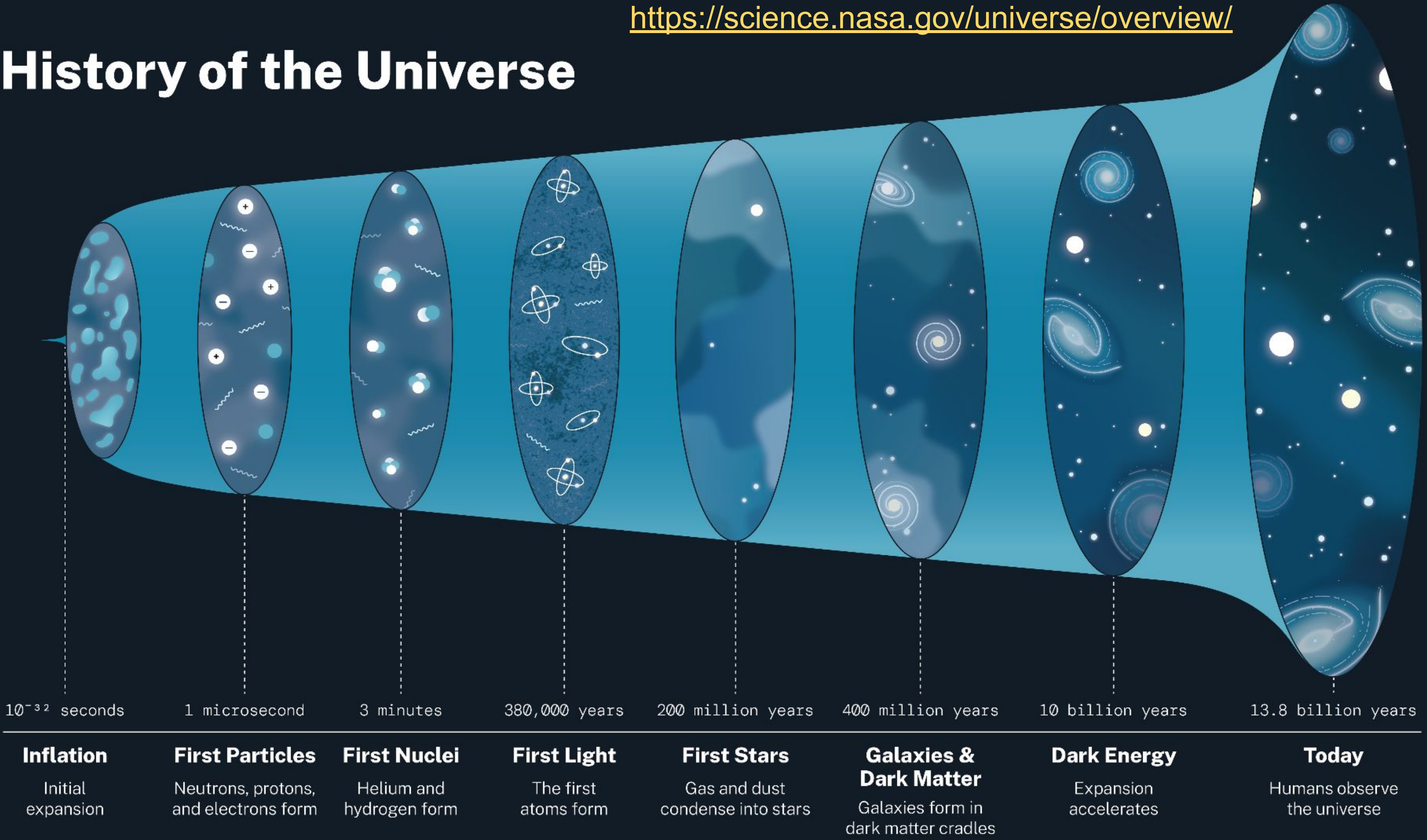
https://science.nasa.gov/mission/hubble/science/science-behind-the-discoveries/hubble-cosmological-redshift/

Think-Pair-Share

If the Universe is expanding, why don't we see evidence of it on Earth?

https://science.nasa.gov/universe/overview/

History of the Universe



Questions, Comments, or Concerns?

https://forms.gle/ywP1THADKCq1nDPy9