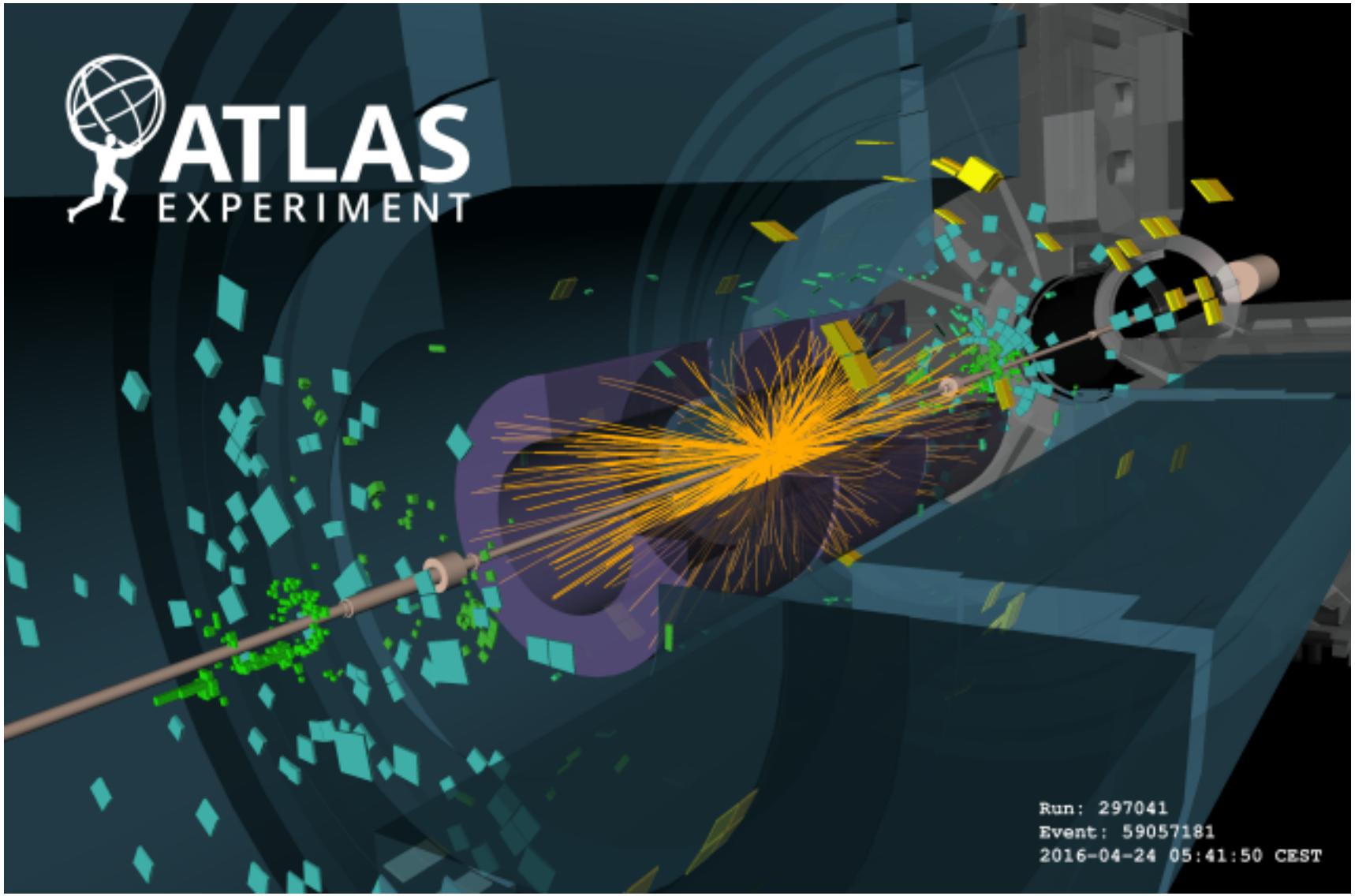
Physics 294H

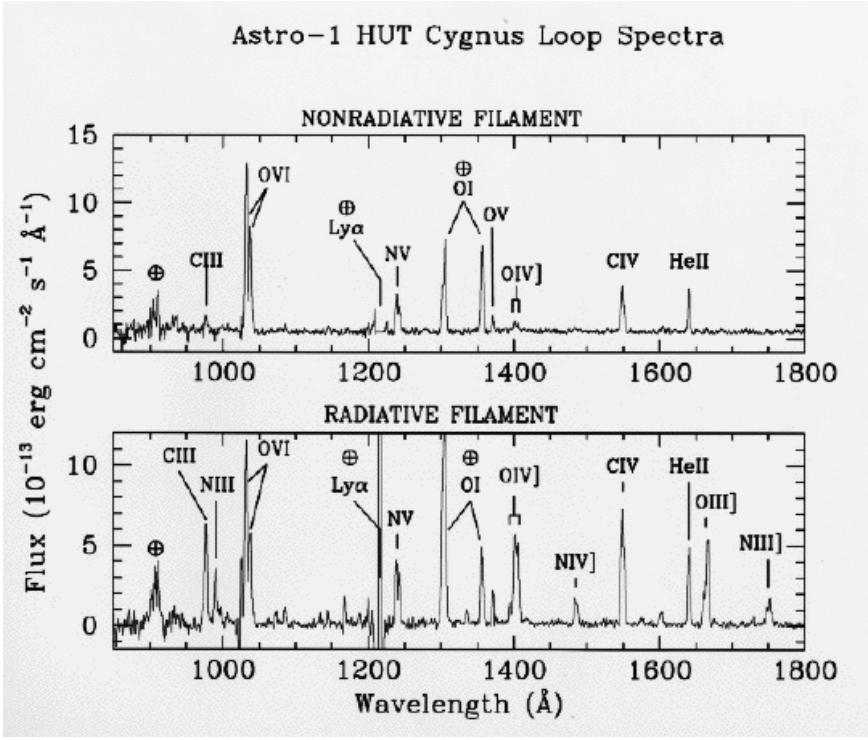
- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Help-room hours: 12:40-2:40 Monday (note change); 3:00-4:00 PM Friday**
  - **36.73 hand-in problem for next Wed**
- Average on 3rd exam =77/120
- **Final exam Thursday May 5 10:00 AM – 12:00 PM 1420 BPS**
  - **Are there any conflicts?**
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

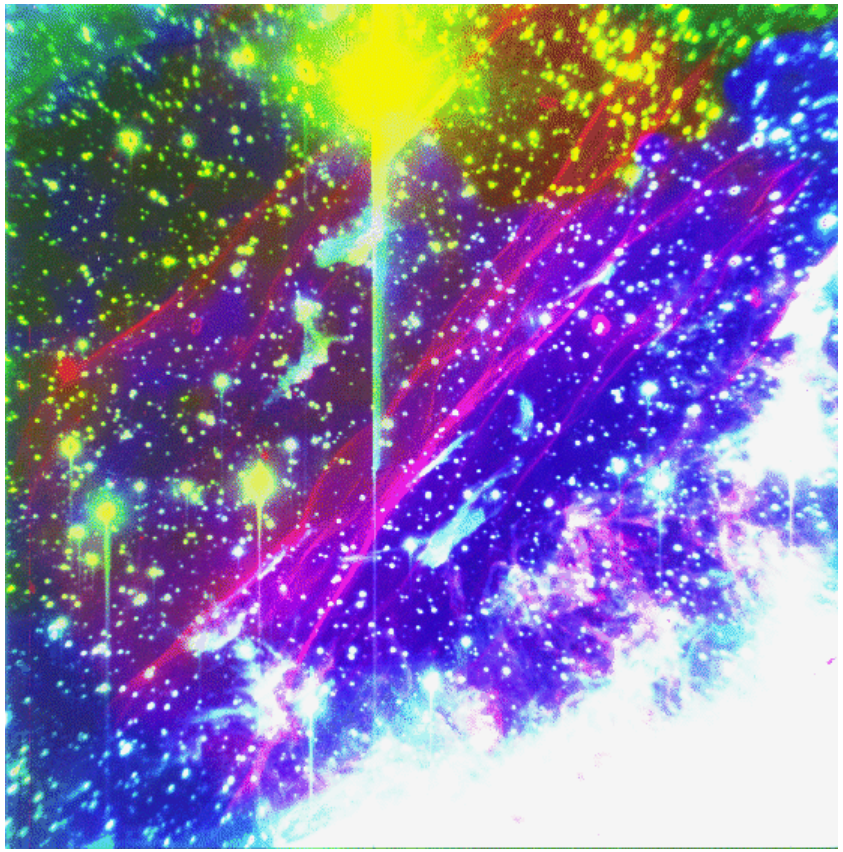
The LHC has started up again



Spectrum from an active galactic nucleus

- emission lines are observed at specific wavelengths using diffraction gratings

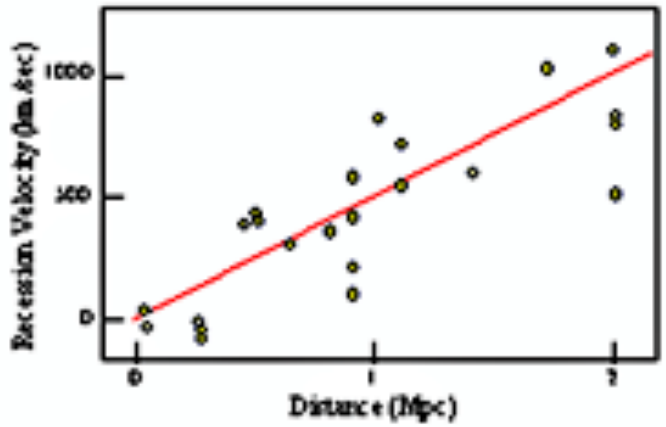




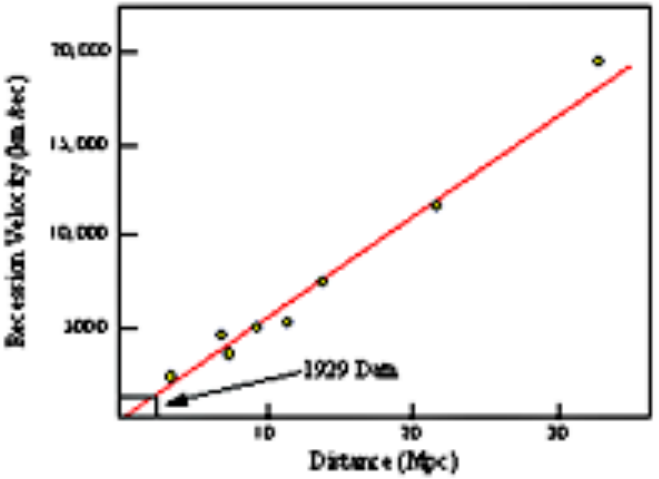
Redshifts and the expansion of the universe

- The universe is expanding
- This was first discovered by examining spectral lines in other galaxies
- The further away the galaxies were, the larger the shift of the spectral lines towards the red end of the spectrum
- It's just like Doppler shift for sound

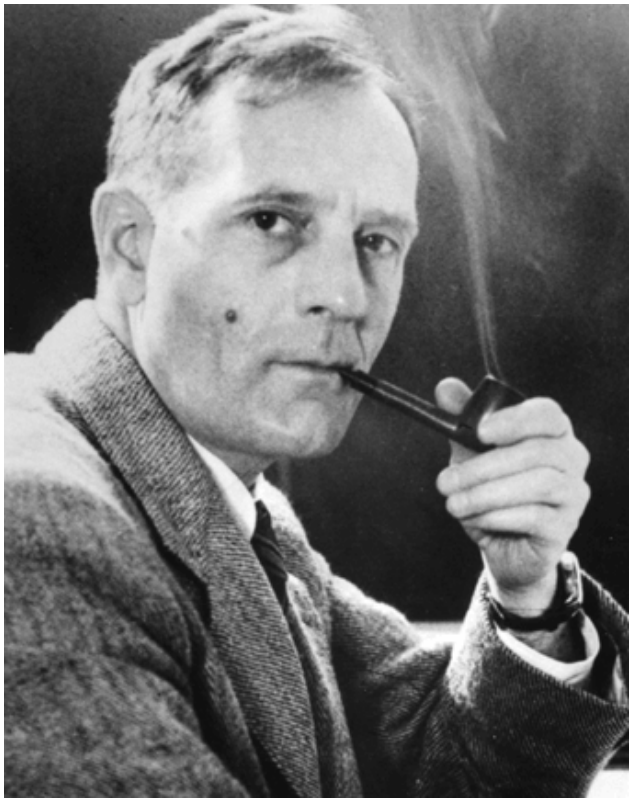
Hubble's Data (1929)



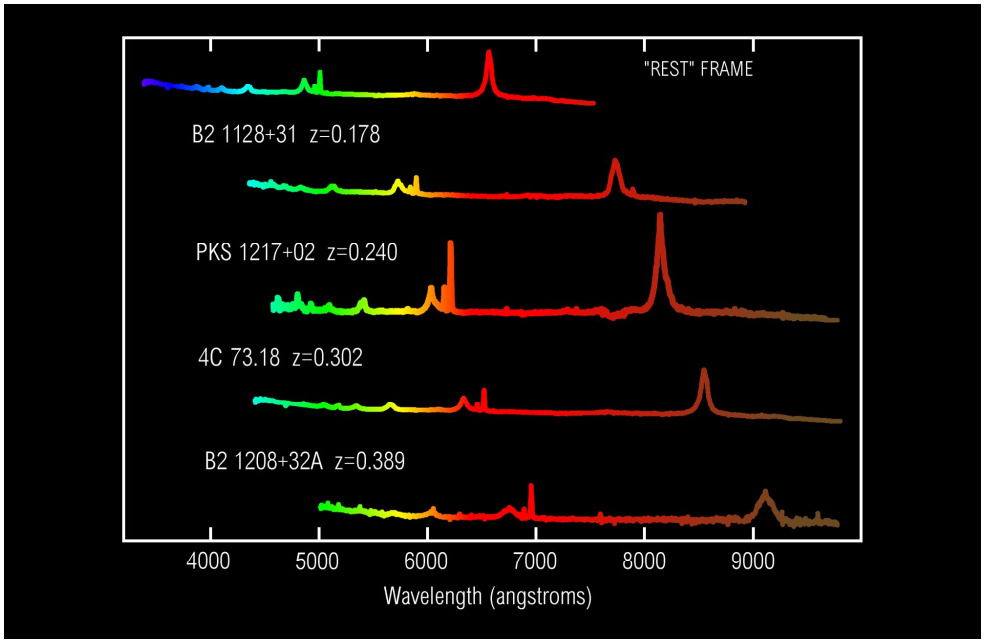
Hubble & Humason (1931)

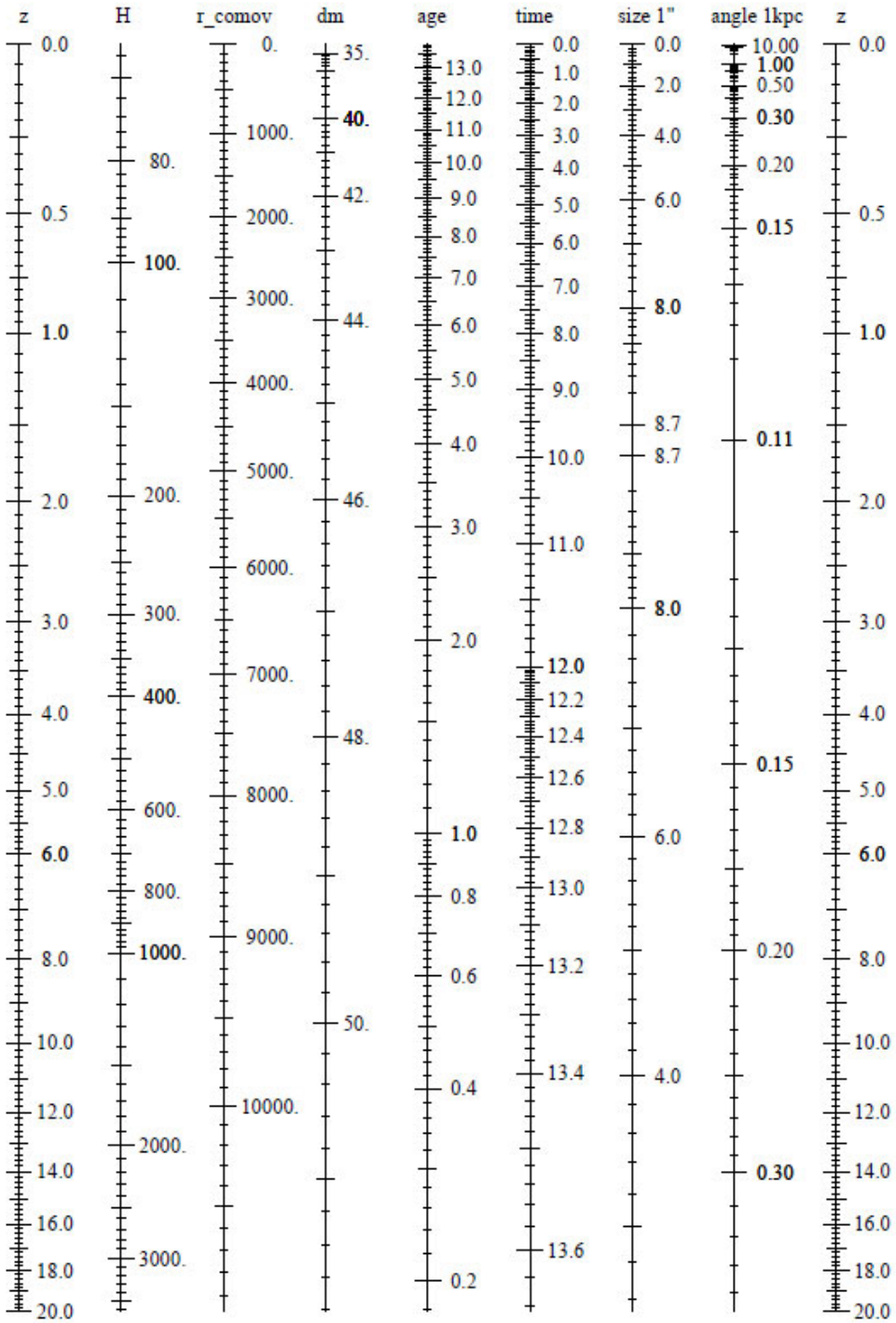


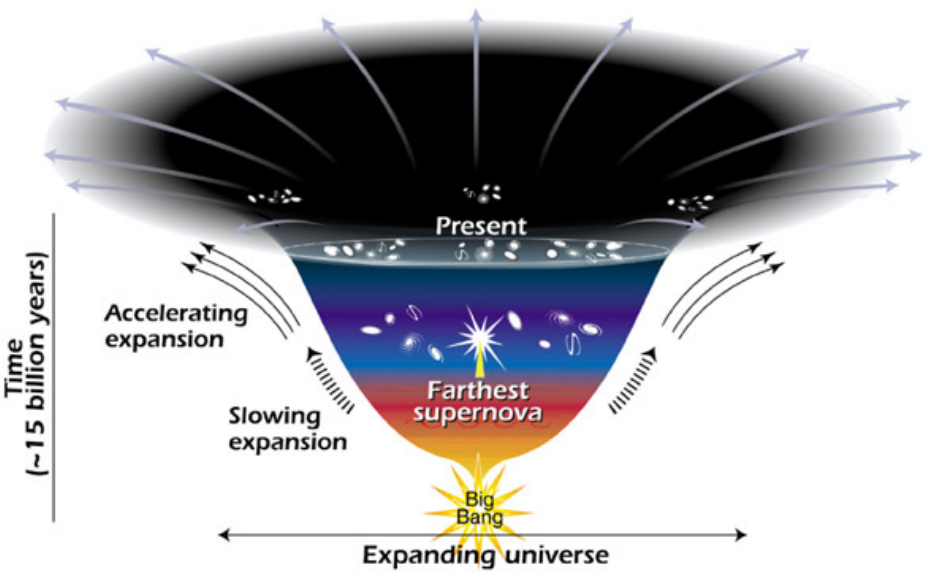
Redshifts and the expansion of the universe



redshifts from 4 quasars





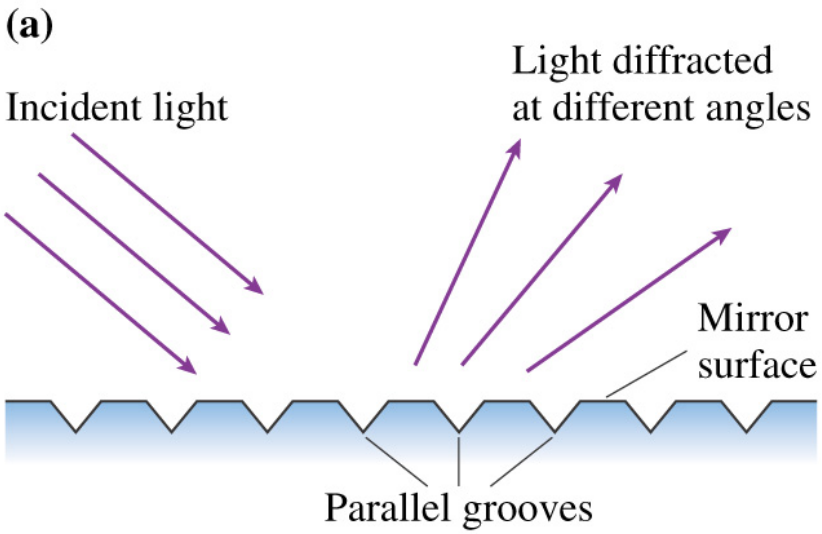


Notable candidates for most distant astronomical objects, based on photometric redshift estimates

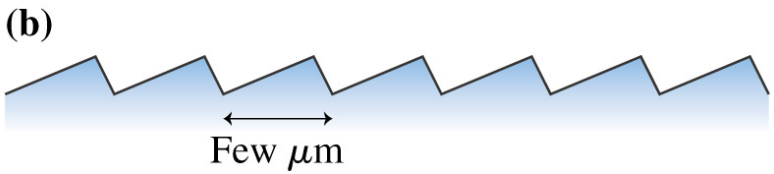
Name	Redshift (z)	Light travel distance§ (Gly)	Type	Notes
UDFj-39546284	$z_p \approx 11.9$?	13.37	Protogalaxy	This is a candidate protogalaxy,[20][21][22][23] although recent analyses have suggested it is likely to be a lower redshift source.[24][25]
MACS0647-JD	$z_p \approx 10.7$	13.3	Galaxy	Candidate most distant galaxy, which benefits by being magnified by the gravitational lensing effect of an intervening cluster of galaxies.[26][27]
A2744-JD	$z_p \approx 9.8$	13.2	Galaxy	Galaxy is being magnified and lensed into three multiple images, geometrically supporting its redshift. Faintest known galaxy at z~10.[28][29]
MACS1149-JD	$z_p \approx 9.6$	13.2[30]	Candidate galaxy or protogalaxy	[31]
GRB 090429B	$z_p \approx 9.4$	13.14[32]	Gamma-ray burst	[33] The photometric redshift in this instance has quite large uncertainty, with the lower limit for the redshift being z>7.
UDFy-33436598	$z_p \approx 8.6$	13.1	Candidate galaxy or protogalaxy	[34]
UDFy-38135539	$z_p \approx 8.6$	13.1	Candidate galaxy or protogalaxy	A spectroscopic redshift of z=8.55 was claimed for this source in 2010,[35] but has subsequently been shown to be mistaken.[36]
BoRG-58	$z_p \approx 8$	13	Cluster or protocluster	Protocluster candidate[37]

§ The tabulated distance is the light travel distance, which has no direct physical significance. See discussion at distance measures and Observable Universe

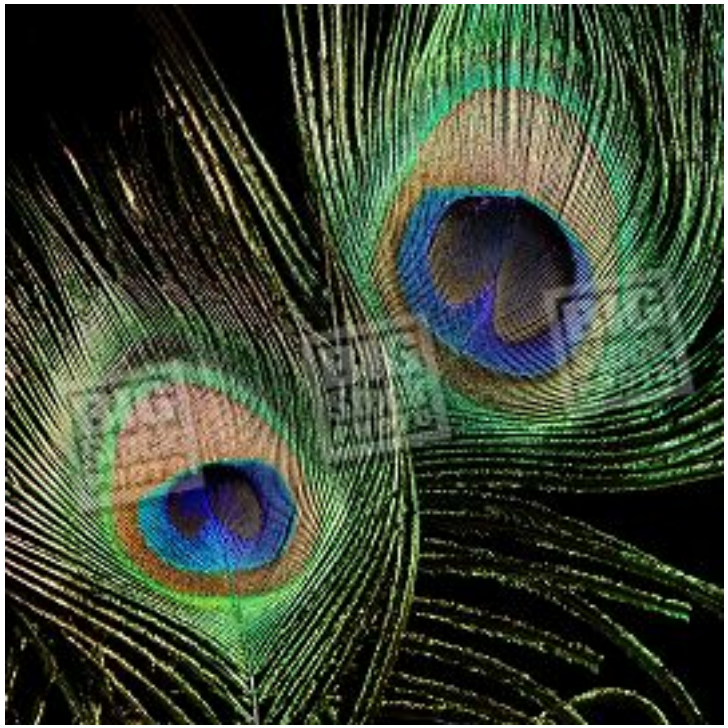
Reflection grating



A reflection grating can be made by cutting parallel grooves in a mirror surface. These can be very precise, for scientific use, or mass produced in plastic.

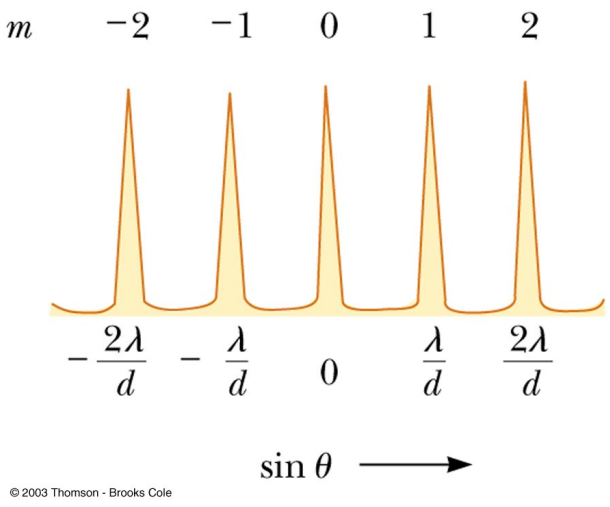


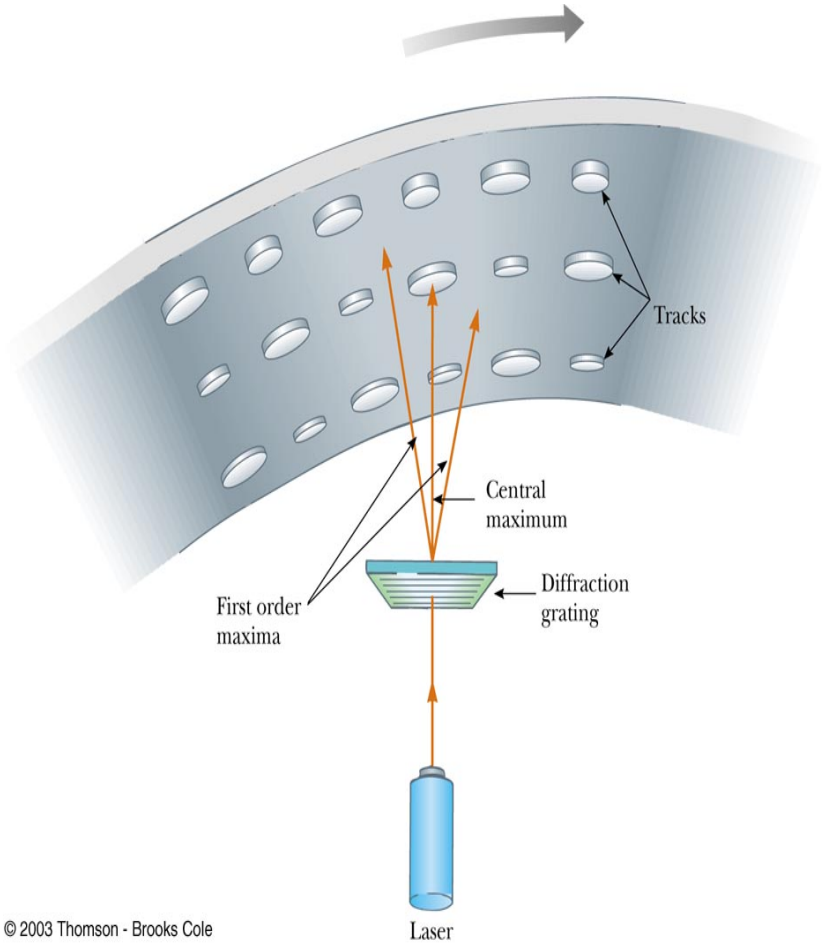
Naturally occurring microscopic ridges are present in some bird feathers and insect shells. These cause iridescence when white light reflects off them.



Diffraction gratings in CD players

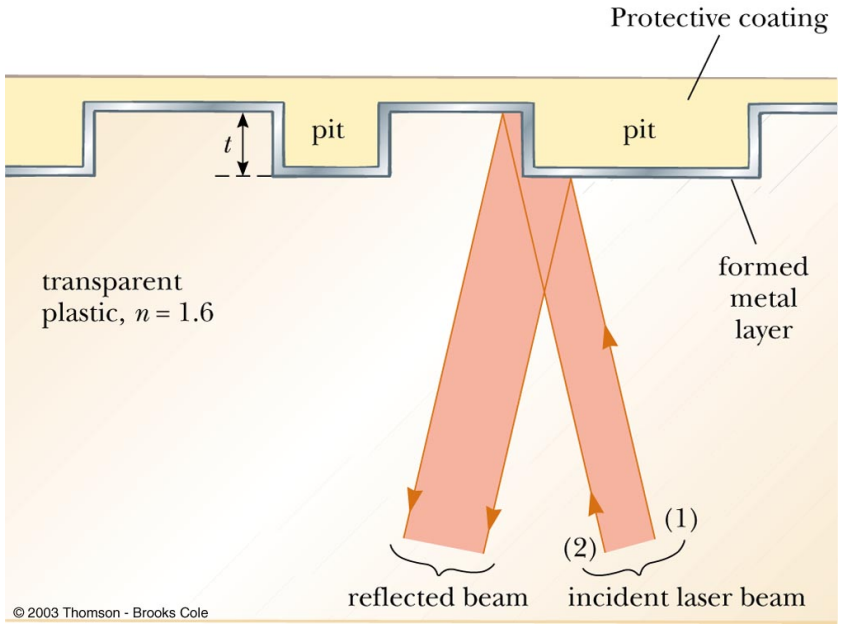
- Diffraction gratings are also involved in CD players
- Laser must follow the spiral track correctly
- Laser light fed through a diffraction grating
  - central maximum is used to read info
  - maxima on either sided are used for steering





Application of interference

- Laser is set up to reflect off of CD surface
- Surface has a series of bumps and pits encoding information (i.e. the music)
  - depth of depression is equal to 1/4 of the wavelength of the laser light
- So when the laser light comes to an edge (leading or trailing), part of the light reflects from the top of the bump and part from the depression (with a path length difference then of 1/2 of a wavelength)
  - this insures destructive interference
- Bump edges interpreted as one's and depressions as 0's



DVD player uses a shorter wavelength laser and smaller track separation, pit depth and length

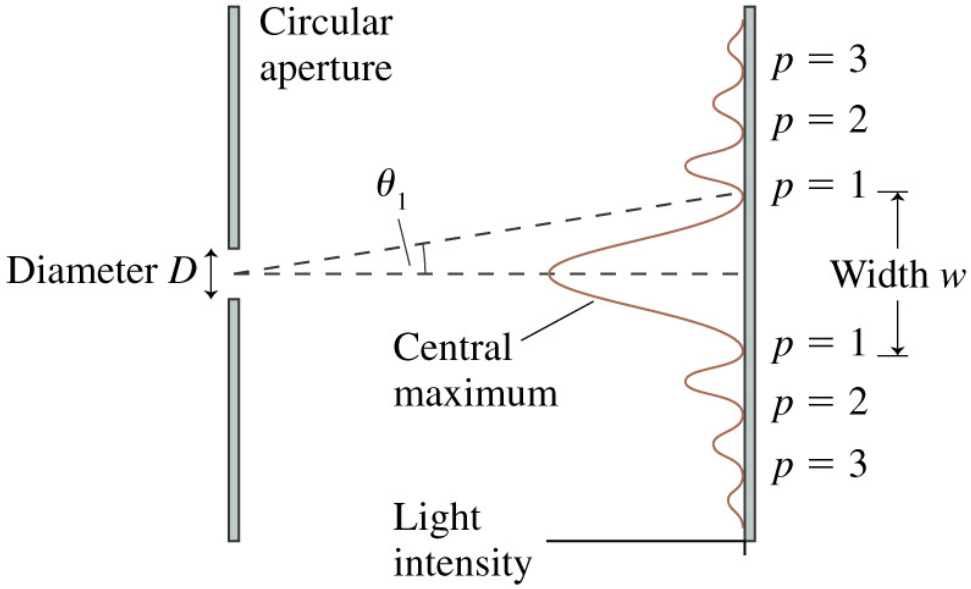
DVD can store 30X as much info

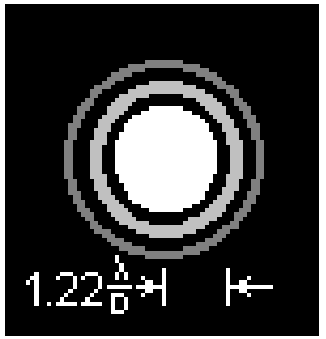
Circular openings

- Thus far, we've been considering rectangular slits, but of course diffraction also occurs when a light wave passes through a circular opening
- In fact, this is a very common occurrence in optical instruments since telescopes and microscopes and other optical instruments have circular openings and diffraction will occur
- The pattern is more complex since now it's in 2-D
- The angle of the first diffractive minimum is given by

$$\theta_1 = \frac{1.22\lambda}{D}$$

  - where D is the diameter of the slit



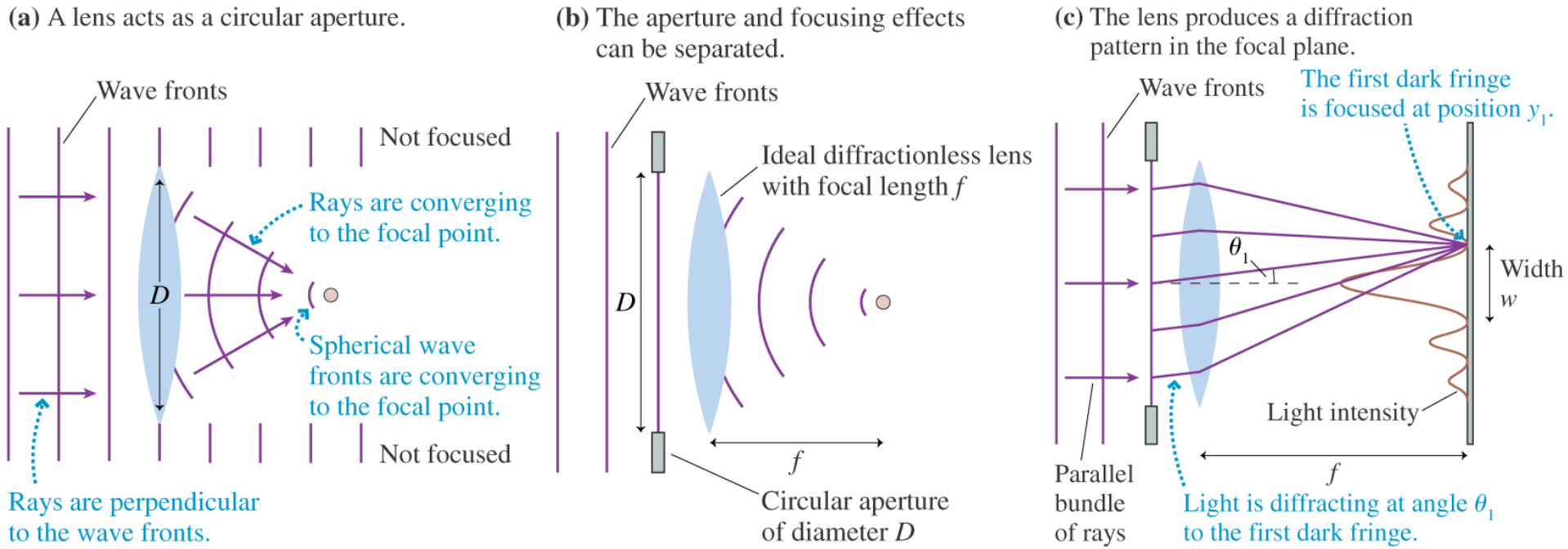


Airy Disc

Resolution of optical instruments

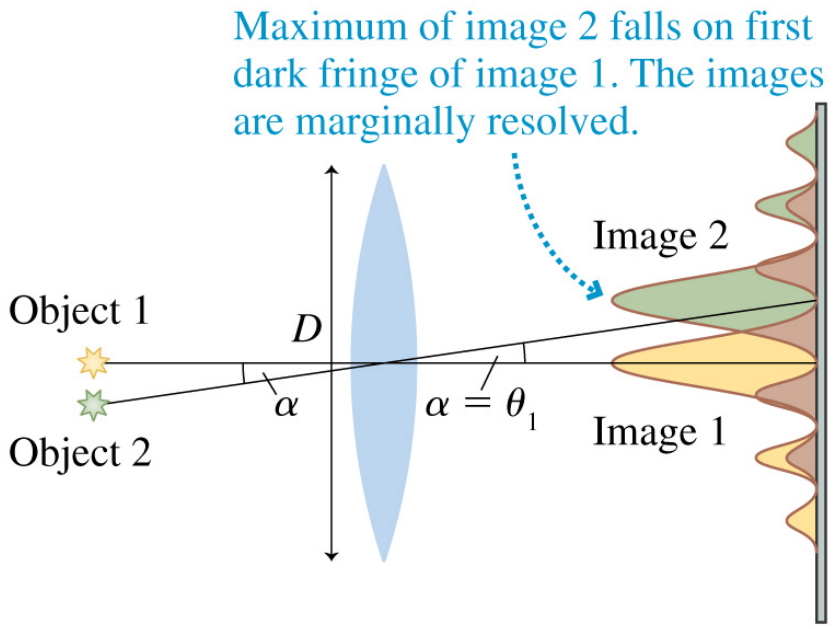
- According to the ray model of light, a perfect lens (one with no aberrations) should be able to form a perfect image
- But in fact the performance of optical instruments is limited by diffraction
- The lens both focuses and diffracts light waves
- The minimum spot size that the lens can focus to is

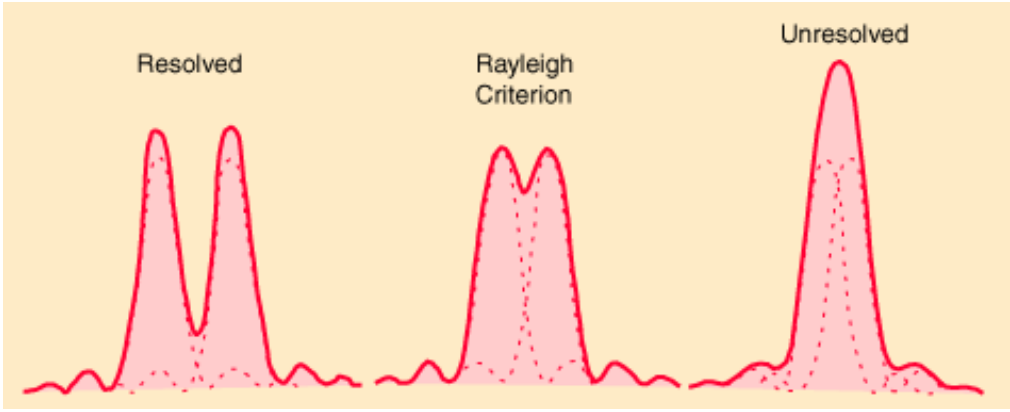
$$w = 2f\theta_1 = \frac{2.44\lambda f}{D}$$



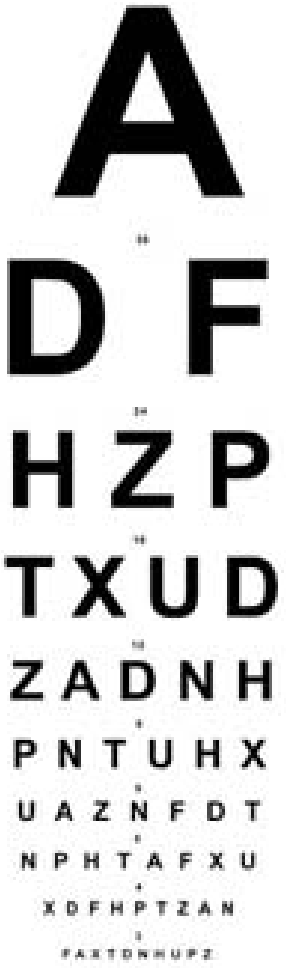
Rayleigh criterion

- When can you resolve two images as separate images?
- Lord Rayleigh (of Rayleigh scattering) studied this, so the Rayleigh criterion is named after him
- Two objects can be resolved if their angular separation α is greater than θ_1
- If α is less than θ_1, the two diffraction patterns are too overlapped to be separated





20/20 vision and the diffraction limit



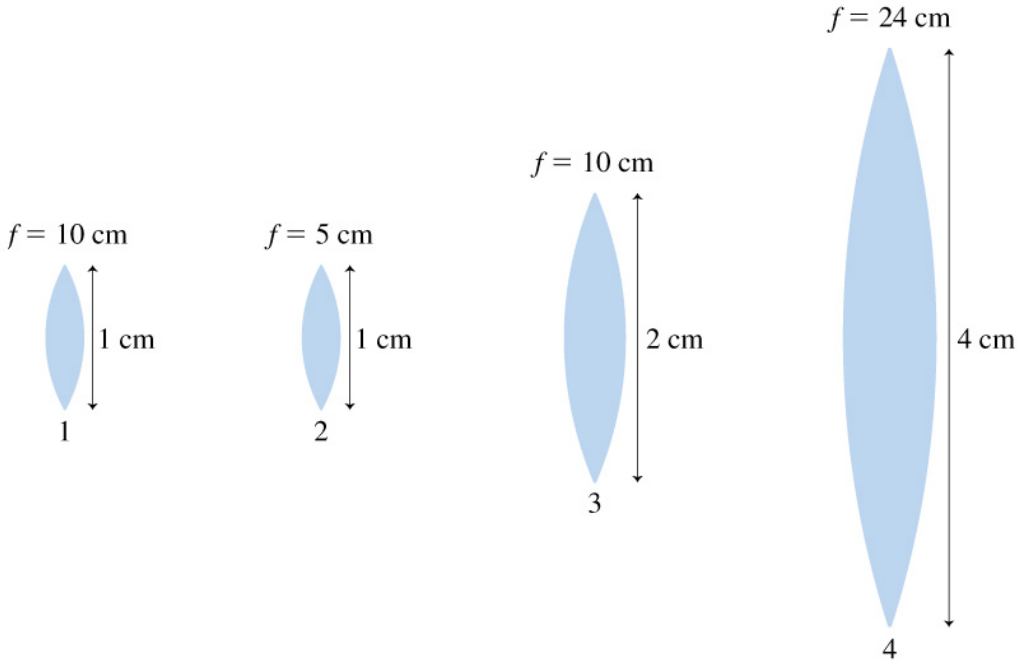
- Visual acuity measured with a chart developed by Hermann Snellen in 1862
- If you can distinguish the letters on the 4th row at 20 feet, you have 20/20 vision
  - 2 rows up, 20/40
  - 2 rows down 20/10
- What is diffraction limit for vision?
  - for a iris diameter of 5 mm and a wavelength of 500 nm, the Rayleigh limit is

$$\theta_R = 1.22\frac{\lambda}{d} = \frac{1.22X5X10^{-5}\,cm}{0.5cm} = 1.22X10^{-4}\,rad$$

  - 20/20 vision corresponds to about 8X the Rayleigh limit
  - most acute vision, under optimum circumstances corresponds to 2X10-5 rad, or ~twice the Rayleigh limit

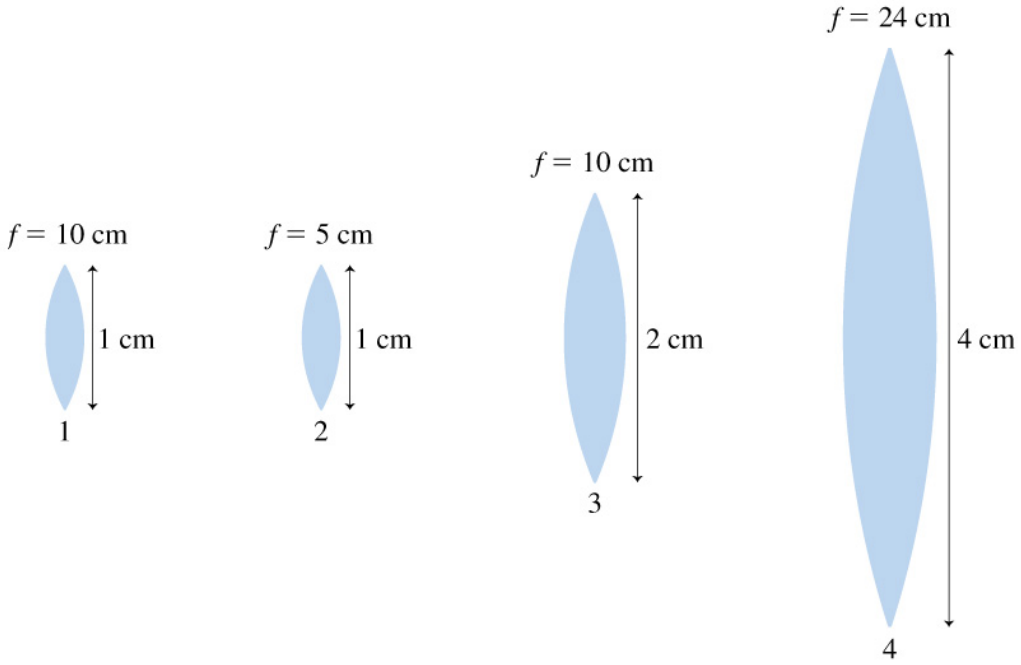
iclicker

- Four diffraction-limited lenses focus plane waves of light with the same wavelength λ.
- Which lens has the smallest spot size?
- 1=A
- 2=B
- 3=C
- 4=D



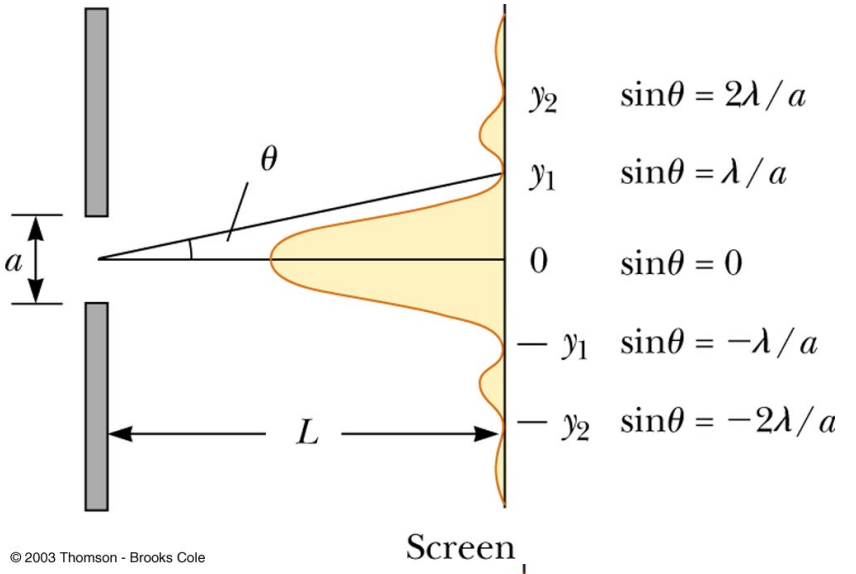
iclicker

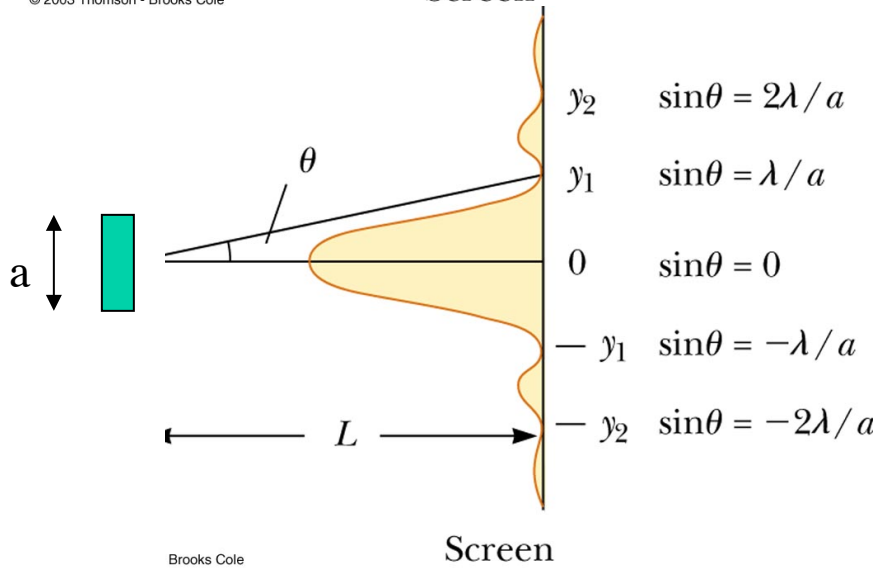
- Four diffraction-limited lenses focus plane waves of light with the same wavelength λ.
- What color of light will give the smallest spot size?
- A=red
- B=orange
- C=yellow
- D=green
- E=blue



Babinet's principle

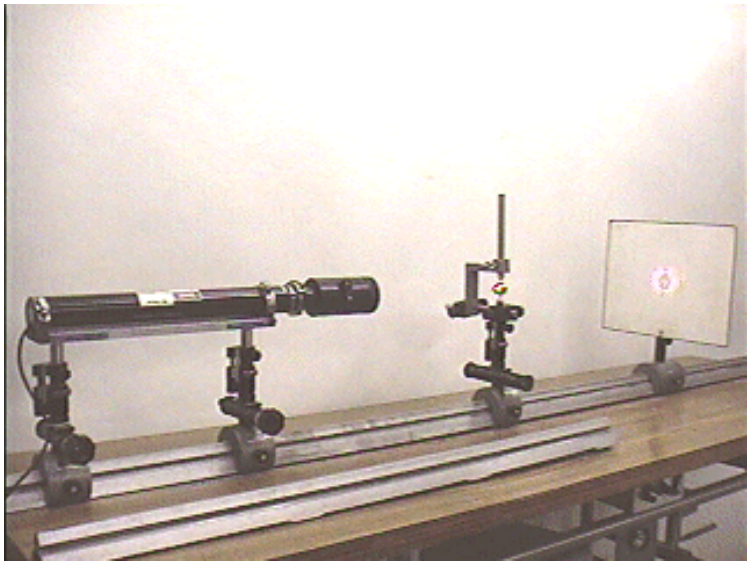
- Diffraction pattern from a thin object is the same as diffraction pattern from a thin slit of the same size
  - minima at $a\sin\theta = m\lambda$
- Can use to measure diameter of an object, for example students' hair

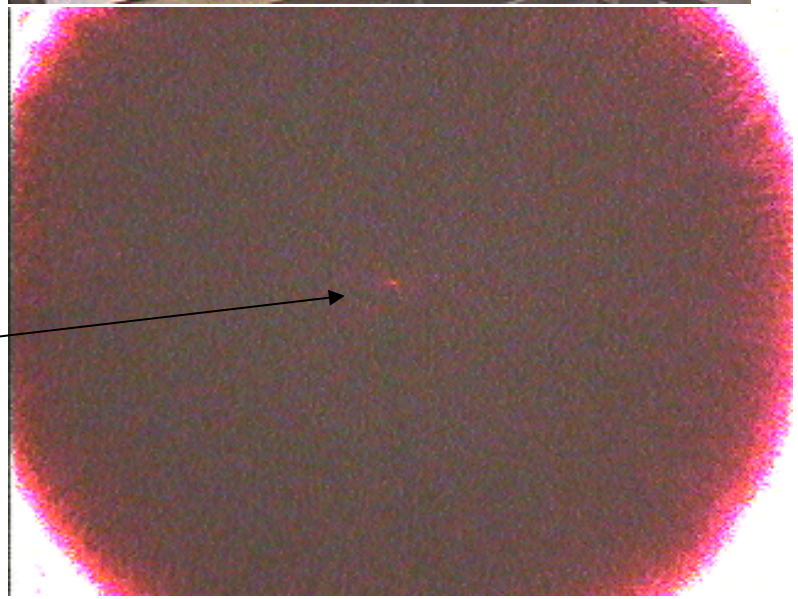




Poisson's (or Arago's bright spot)

- Some history:In 1818, Augustin Fresnel submitted a paper on the theory of diffraction for a competition sponsored by the French Academy. His theory represented light as a wave, as opposed to a bombardment of hard little particles, which was the subject of a debate that lasted since Newton's day. Siméon Poisson, a member of the judging committee for the competition, was very critical of the wave theory of light. Using Fresnel's theory, Poisson deduced the seemingly absurd prediction that a bright spot should appear behind a circular obstruction, a prediction he felt was the last nail in the coffin for Fresnel's theory. However, Dominique Arago, another member of the judging committee, almost immediately verified the spot experimentally. Fresnel won the competition, and, although it may be more appropriate to call it "the Spot of Arago," the spot goes down in history with the name "Poisson's bright spot" like a curse.





A (partial) optics timeline

1000 to 1599 - Arab and Chinese scholars experiment with light, lenses, and mirrors for several hundred years, but interest wanes. In Medieval Europe, Copernicus launches the scientific revolution with his shocking theory that the Earth revolves around the sun.

1600 to 1699 - Microscopes and telescopes broaden the worldview of early scientists and the scientific revolution culminates with the publication of Isaac Newton's ***Principia***.

1700 to 1799 - Newton publishes ***Opticks***, discussing the corpuscular theory of light, scientists establish procedures for the scientific method, Herschel discovers Uranus, and a few scientists begin to study electricity.

1800 to 1833 - Newton's corpuscular theory of light is overturned by the wave theory of light, scientists discover "invisible" infrared and ultraviolet light, and the first photographic image is recorded.

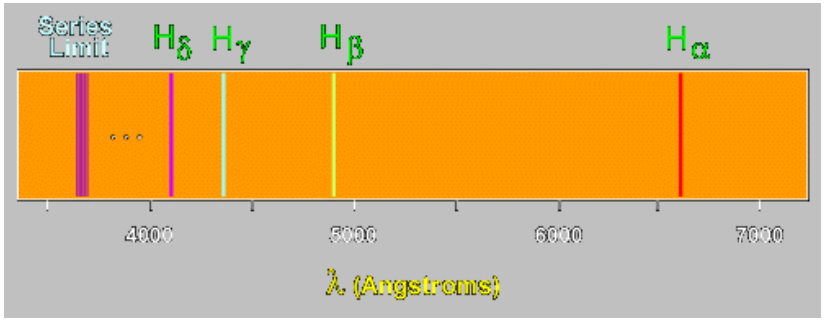
1834 to 1866 - Photography undergoes major developments, the speed of light is measured accurately for the first time, the new field of spectroscopy is introduced, and Maxwell theorizes that light is a type of electromagnetic wave.

1867 to 1899 - Hertz proves that light is an electromagnetic wave, Michelson and Morley show that there is no ether permeating space, Tesla and Marconi invent radio, and Eastman invents photographic film.

1900 to 1933 - Einstein and Planck revolutionize physics, and physicists now regard light as both a wave and a particle. In addition, radio becomes a popular broadcast communications medium, television is invented.

Johann Balmer and the hydrogen spectrum

- Hydrogen is the simplest atom with one proton and one electron
- The visible part of the spectrum has 4 spectral lines
  - 656.46 nm
  - 486.27 nm
  - 434.17 nm
  - 410.29 nm



- Balmer felt that there must be some simplifying relation among those wavelengths

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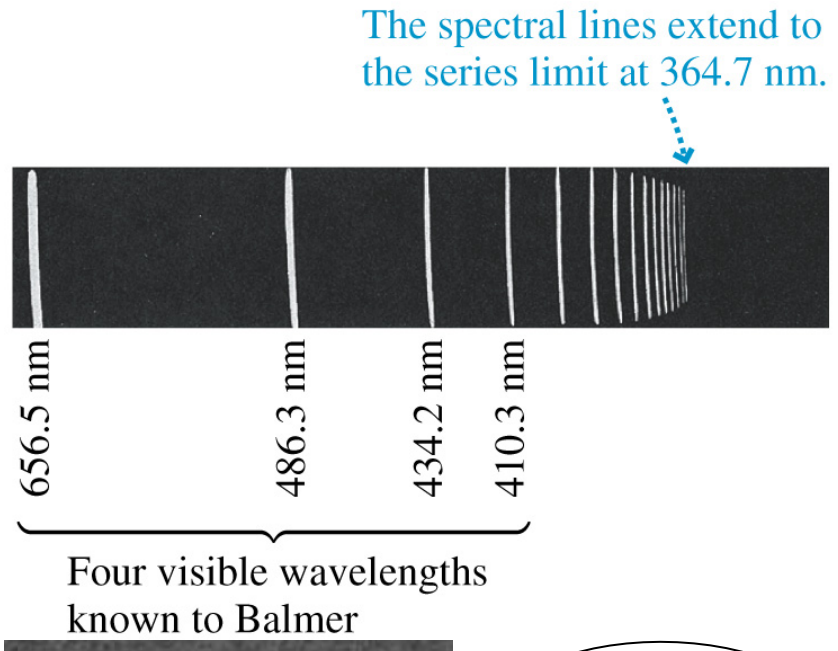
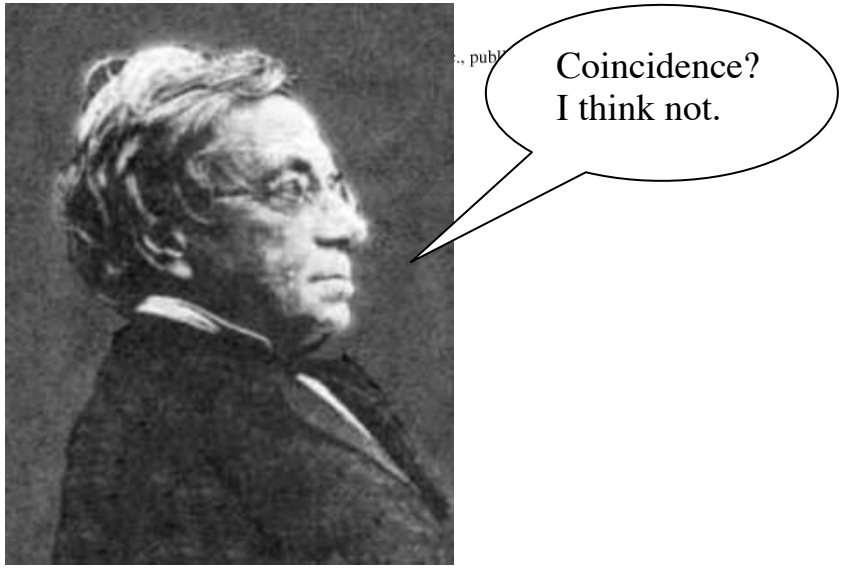
…and he was right

- By trial and error, he discovered that the 4 wavelengths in the visible spectrum of hydrogen could be represented by the simple formula

$$\lambda = \frac{91.18nm}{\left(\frac{1}{2^2} - \frac{1}{n^2}\right)} \quad n = 3,4,5,6$$

- What's more, they also describe wavelengths emitted by hydrogen in the UV corresponding to n=7,8,9,…
  - to better than a fraction of a %



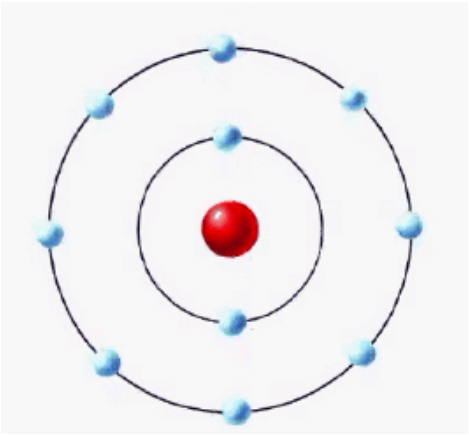


More generally

- Hydrogen spectrum can be described by a more general formula, where both m and n are integers
  - m=1 Lyman series (UV)
  - m=2 Balmer series (visible)
  - m=3 Paschen series (IR)
- Why? Balmer didn't have any explanation; this was just an empirical fit to the data
- It does imply that there is something discrete about the hydrogen atom; m and n are always integers

$$\lambda = \frac{91.18nm}{\left(\frac{1}{m^2} - \frac{1}{n^2}\right)}$$

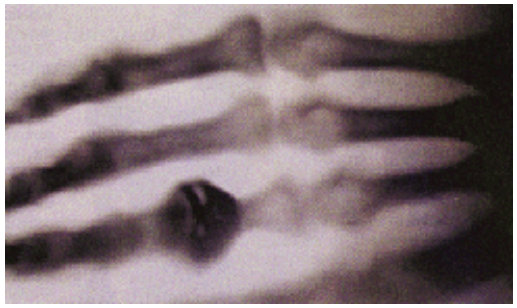
Later we'll talk about the Bohr model for the atom, inspired by this finding of Balmer's

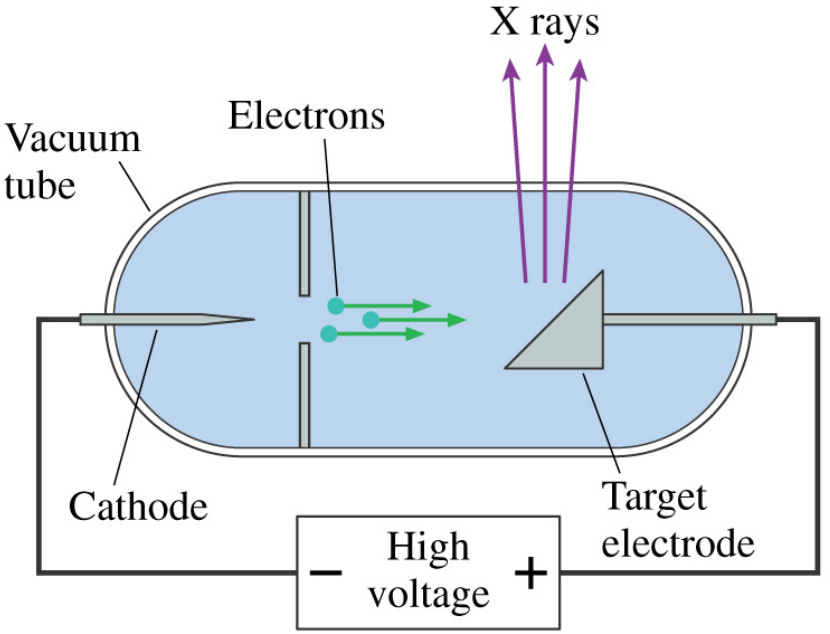


Meanwhile, back at the lab

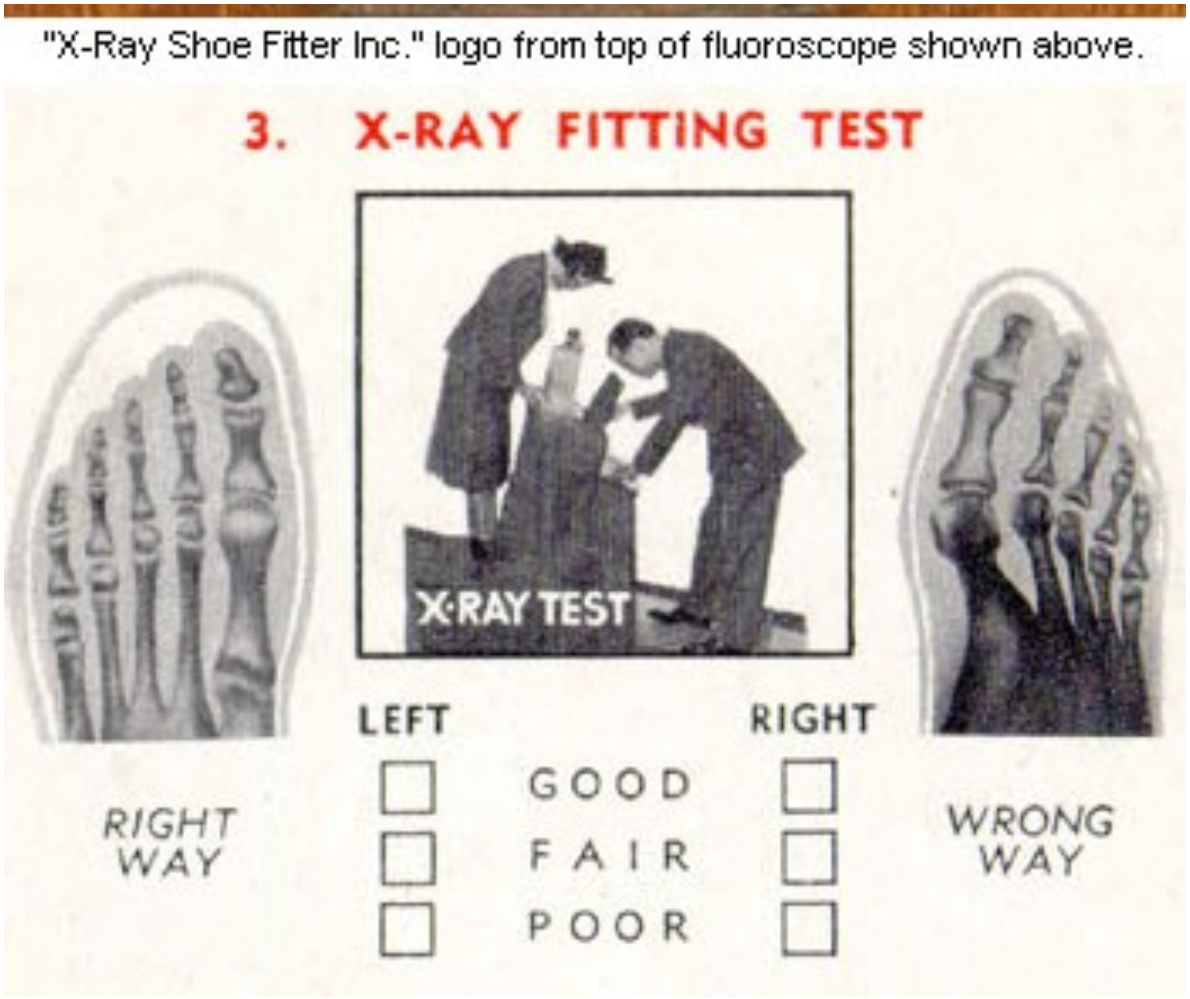
- Wilhelm Roentgen accelerated electrons in an evacuated glass tube and found that x-rays were produced
  - X because they were unknown
  - caused undeveloped photographic film to be exposed
  - suspicion was that they were some sort of EM radiation, of very short wavelength

Mrs. Roentgen, the first test subject





…amazingly enough

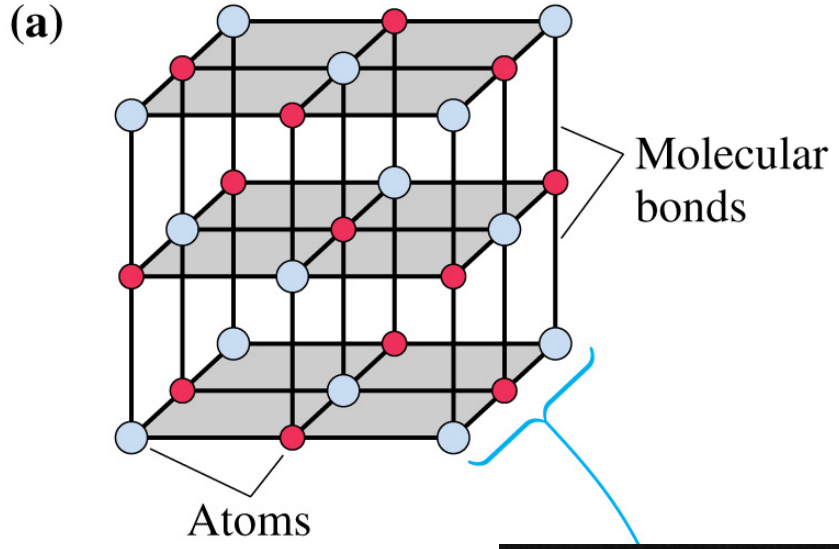


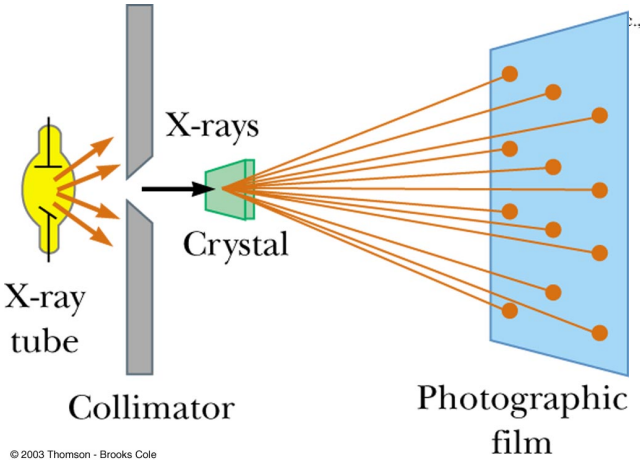
…not such a good way of fitting shoes

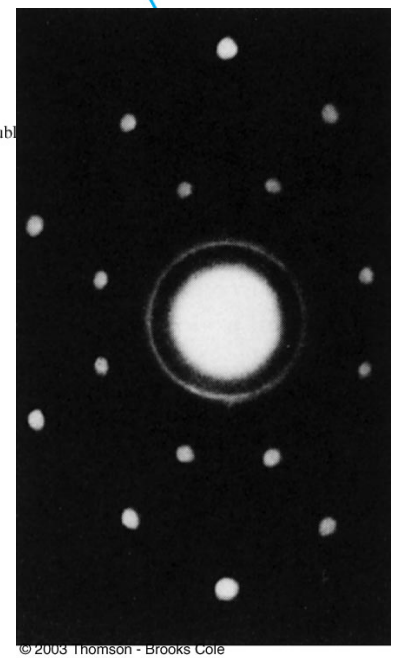
…and of course there's that foot cancer thing

X-ray diffraction

- It was suggested about this time that solids may consist of atoms arranged in a crystalline structure with spacing ~0.1 nm
- Max van Laue realized that x-rays passing through a crystalline solid should diffract, if they really were a short wavelength EM radiation

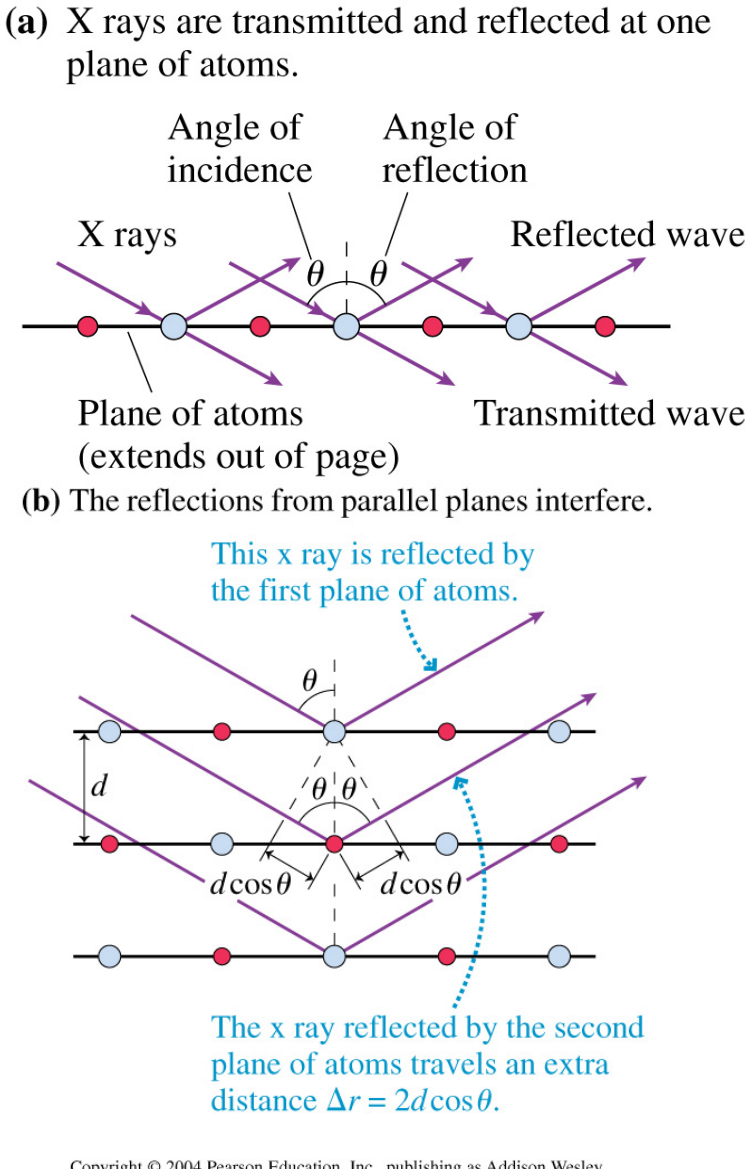






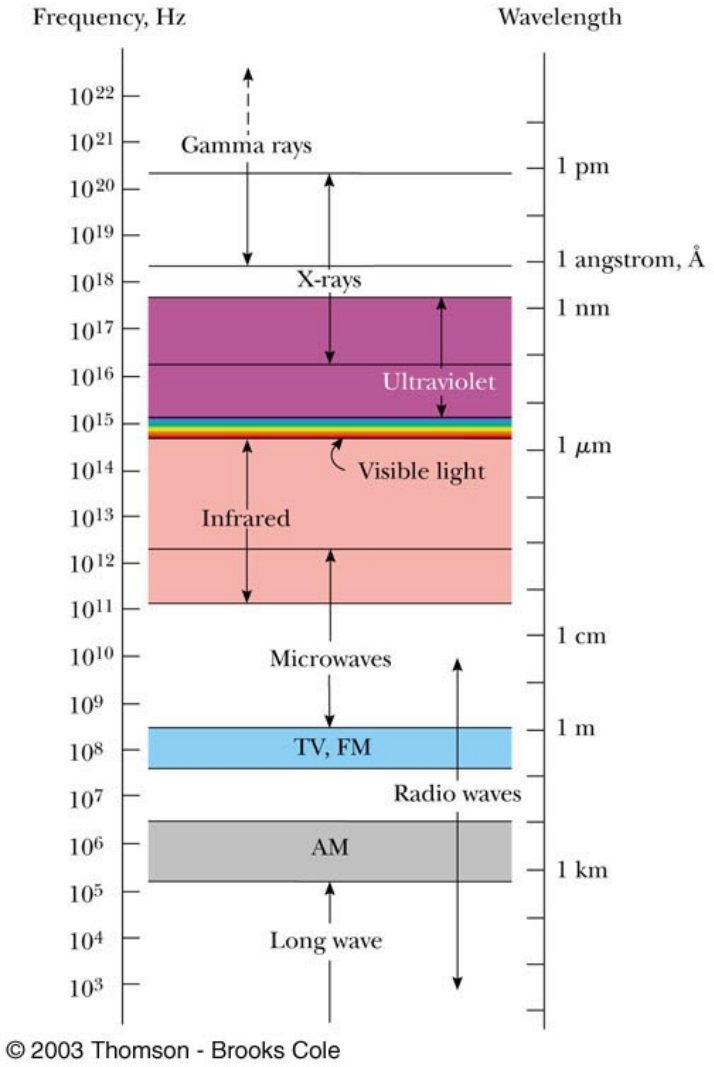
Indeed they did

- As the x-rays pass through the planes of atoms in a crystalline solid, most penetrate but some reflect off of each layer
- X-rays reflecting from each plane interfere with each other
- If path length difference $2d\cos\theta$ is a multiple of the wavelength of the x-rays, then have constructive interference
  - $2d\cos\theta = m\lambda$ is called the Bragg condition



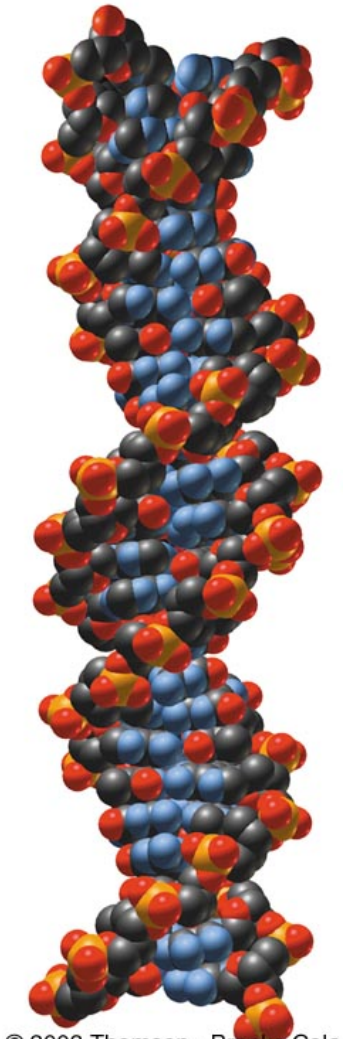
X-rays

- This indicated that x-rays were EM radiation of wavelengths of order of 1nm or less



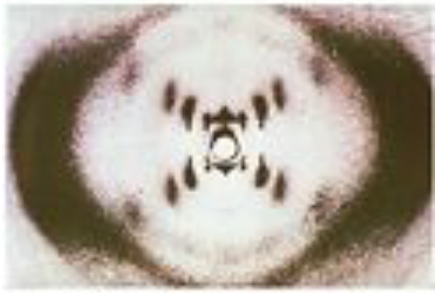
DNA

- For example, how was the structure of DNA determined?
- Since the atoms are spaced by about 1 Angstrom apart, then use X-rays of wavelength 1 Angstrom (0.1 nm)



Rosalind Franklin

- "As a scientist Miss Franklin was distinguished by extreme clarity and perfection in everything she undertook. Her photographs are among the most beautiful X-ray photographs of any substance ever taken. Their excellence was the fruit of extreme care in preparation and mounting of the specimens as well as in the taking of the photographs. "



cross pattern of X-ray diffraction picture was a clue that DNA had a helical structure…a clue picked up by Watson and Crick for their Nobel prize winning work 50 years ago…which did not include Franklin