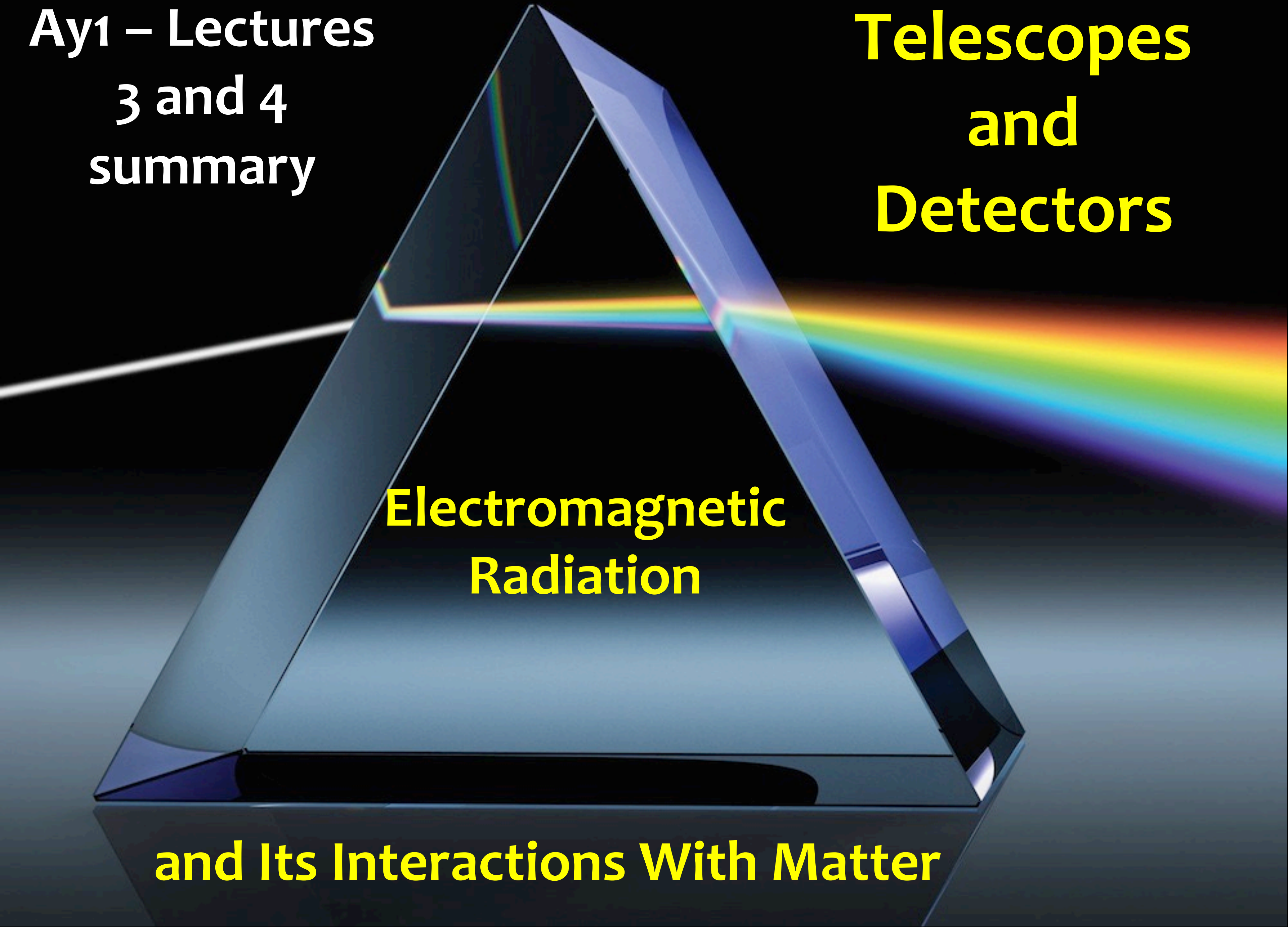
Ay1 – Lectures 3 and 4 summary

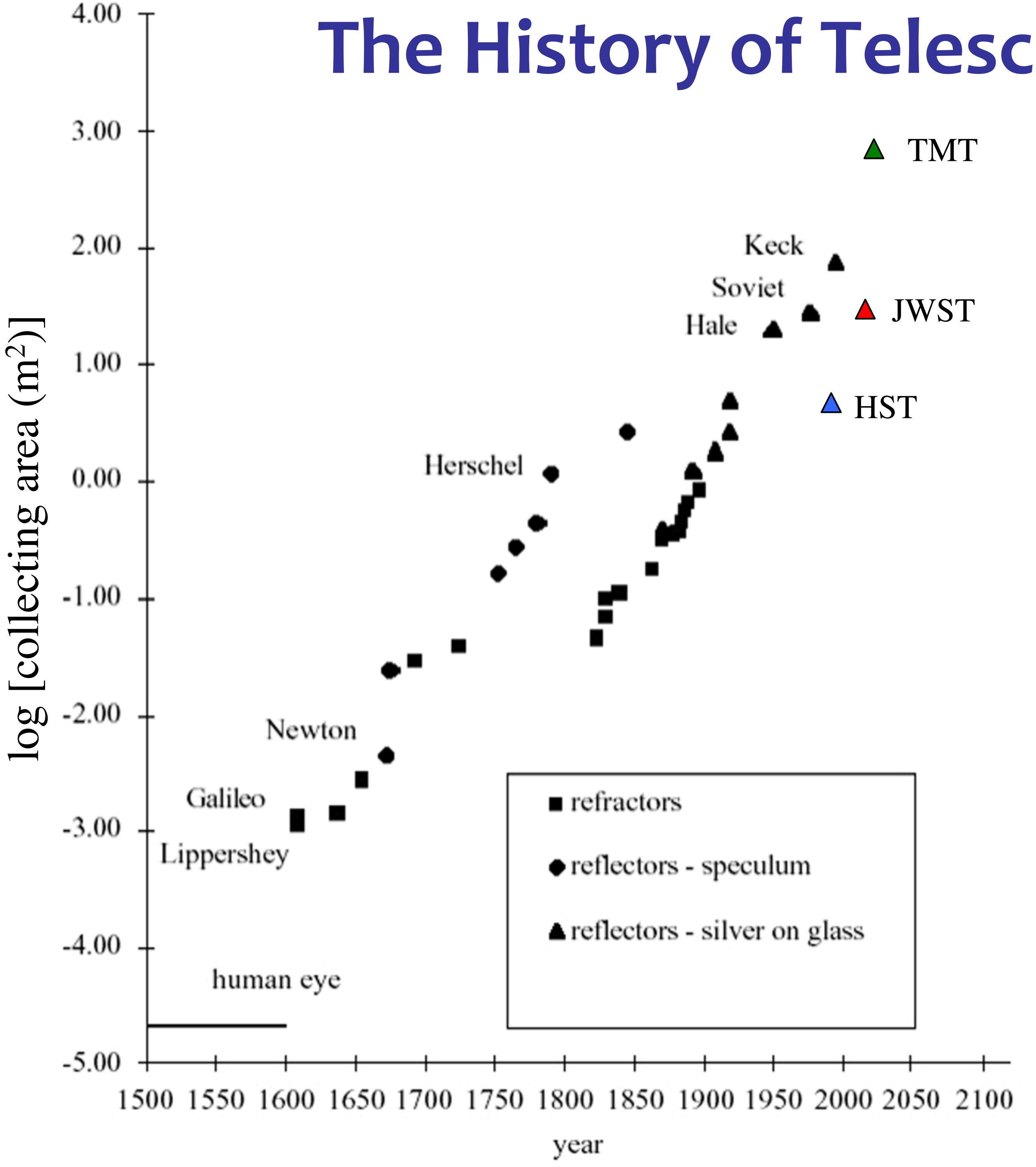
Telescopes and Detectors

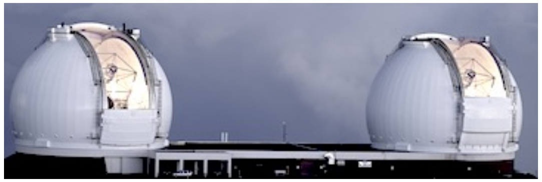


Electromagnetic Radiation

and Its Interactions With Matter

The History of Telescopes





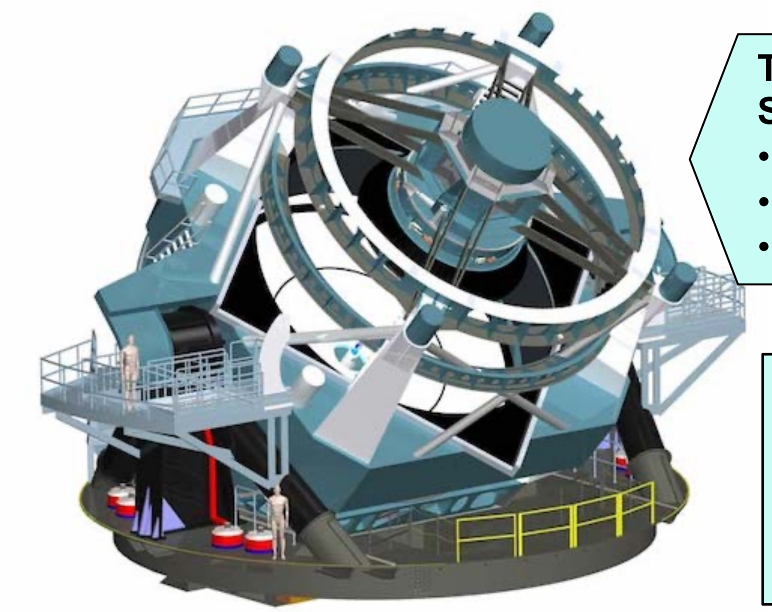
Modern Telescope Mirror Designs

- Lightweight honeycomb structures
- Thin meniscus (+ active optics)
- Segmented (all segments parts of the same conic surface); e.g., the Kecks, TMT
- Multiple (each mirror/segment a separate telescope, sharing the focus); e.g., HET, SALT
- Liquid, spinning

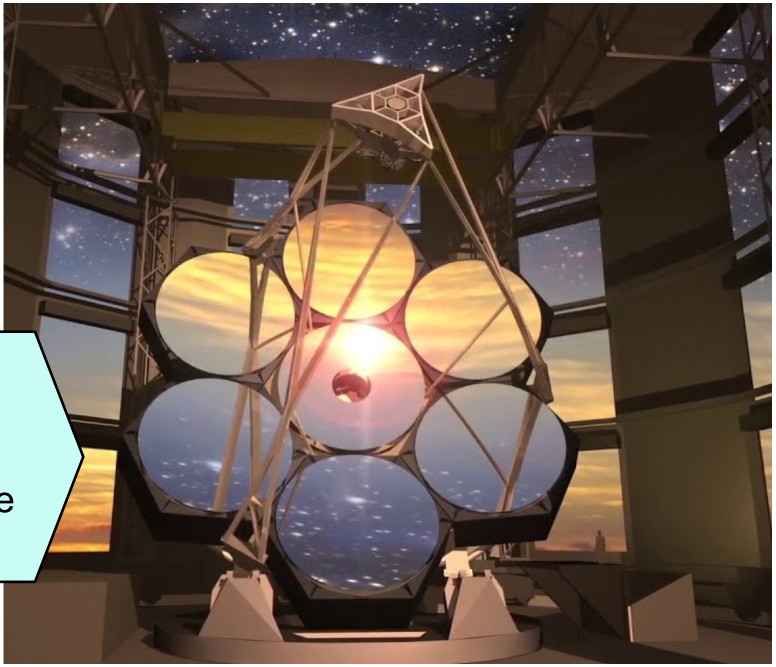
The critical issues:

  - Surface errors (should be $< \lambda/10$)
  - Active figure support (weight, thermal)
  - Thermal equilibrium (figure, seeing)

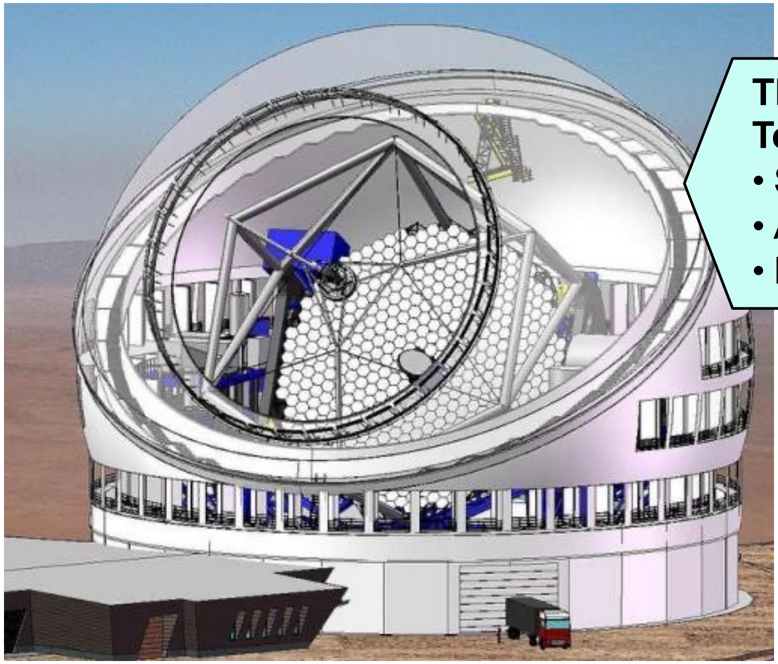
The Next Generation of Telescopes



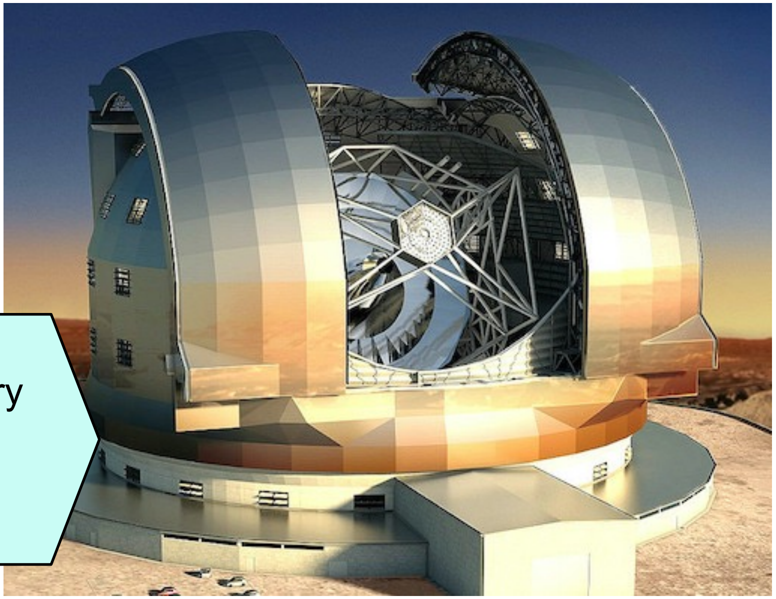
The Large Synoptic Survey Telescope
- Wide field design
- 8.4(6.4) m primary
- First light ~ 2022



The Giant Magellan Telescope (GMT)
- Multiple mirror design, 24m aperture
- First light ~ 2029?



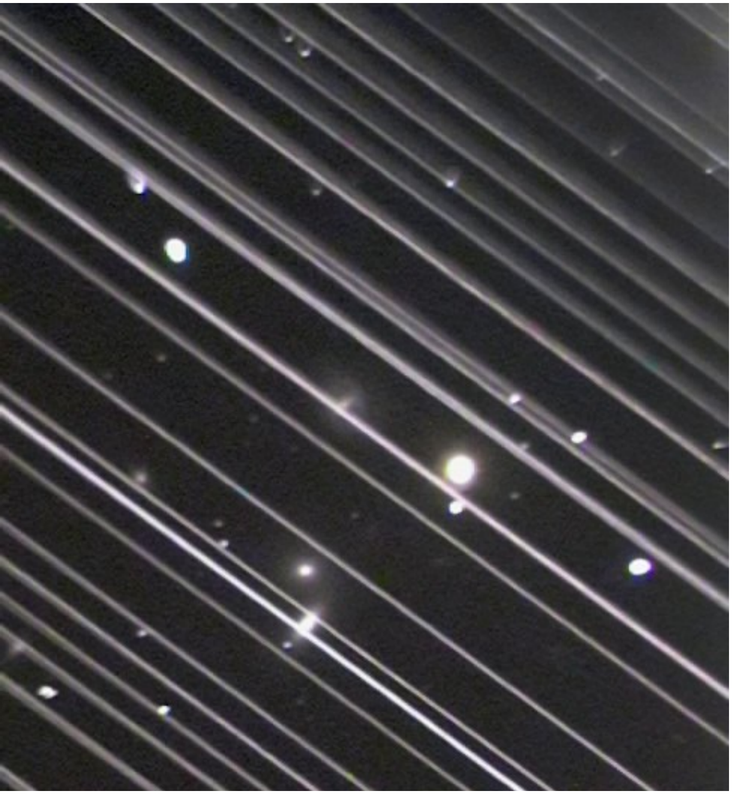
The Thirty Meter Telescope (TMT)
- Segmented primary
- Adaptive Optics
- First light ~ 2027?



The ESO 42m ELT
- Segmented primary
- Adaptive Optics
- First light ~ 2026?

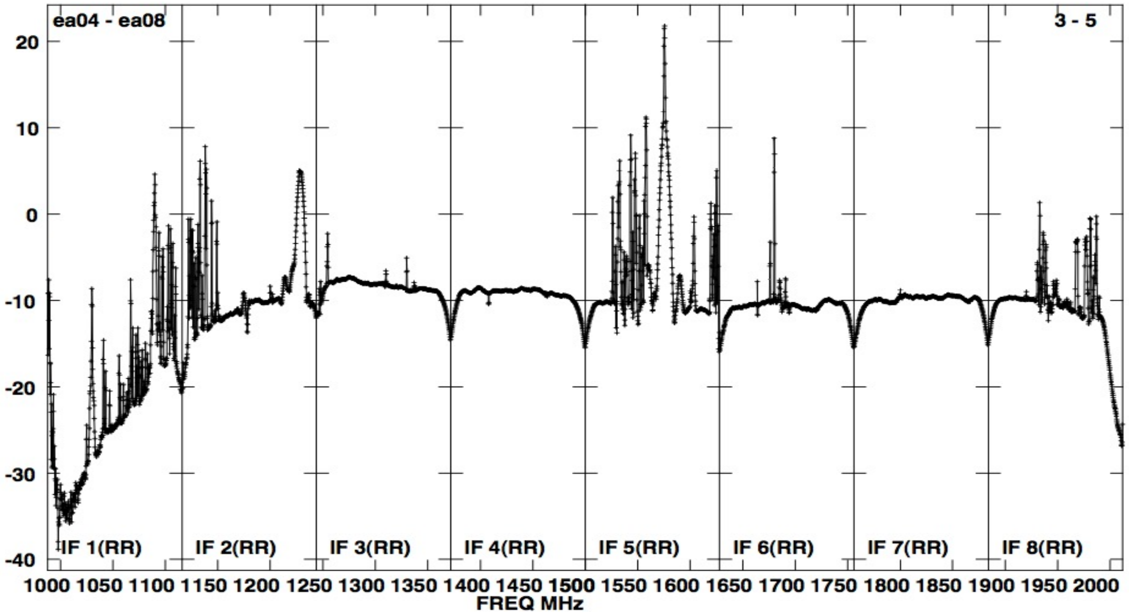
Light Pollution

Starlink satellites



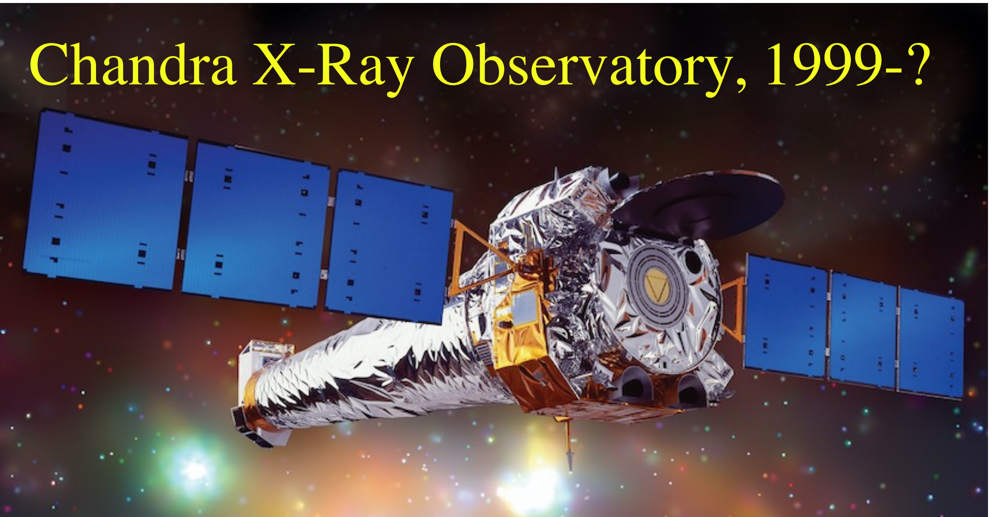
Night in America

Radio interference



Telescopes in Space

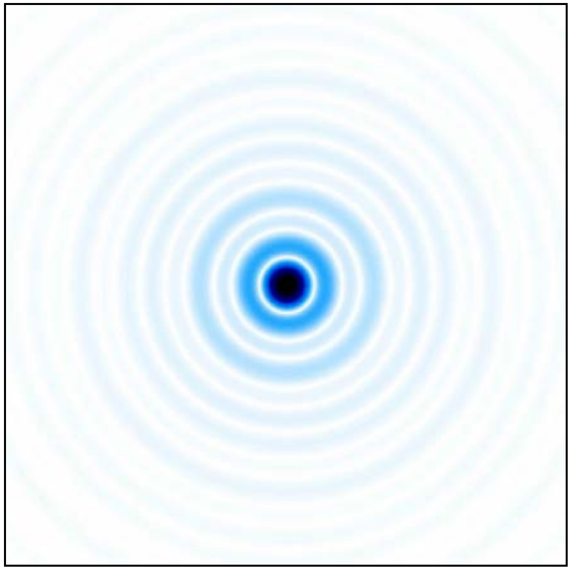

James Webb Space Telescope (JWST), 6.5 m, 2021-?


Chandra X-Ray Observatory, 1999-?


Hubble Space Telescope (HST) 2.4 m, 1990-?

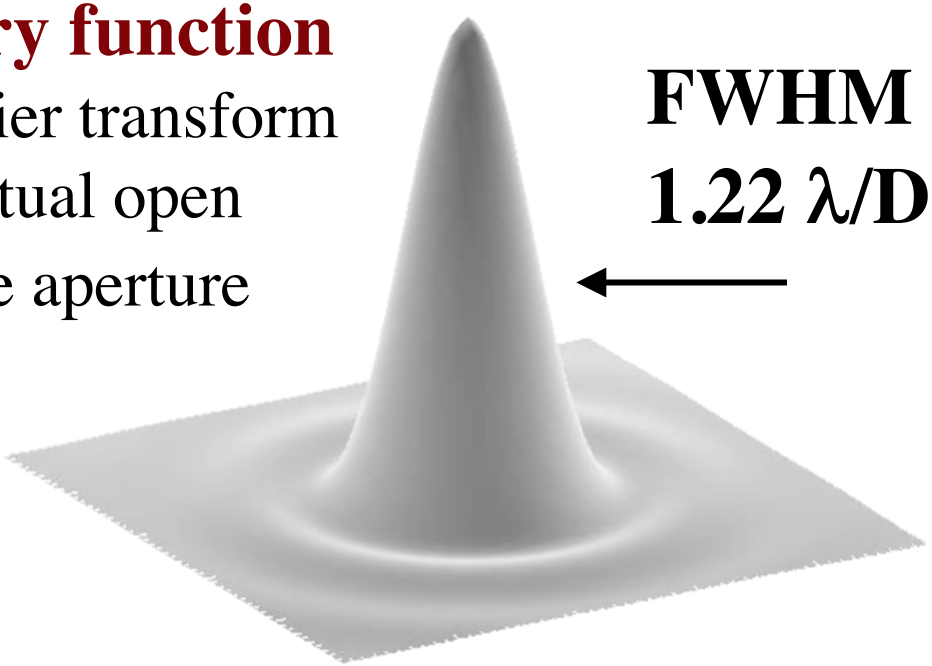

Nancy G. Roman Space Telscope 2.4 m, 2025-?

Diffraction-Limited Imaging (an ideal telescope)



The Airy function

~ a Fourier transform of the actual open telescope aperture

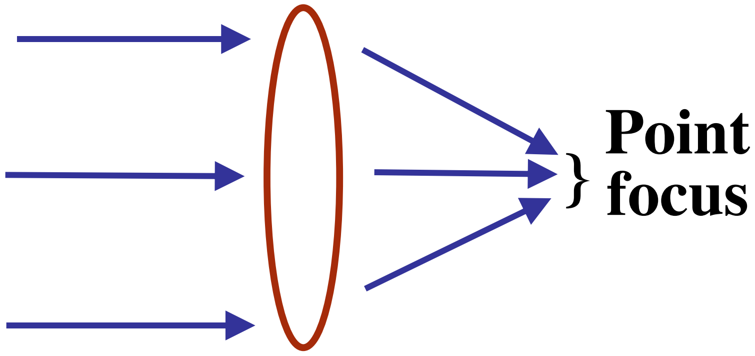


FWHM = 1.22 λ/D

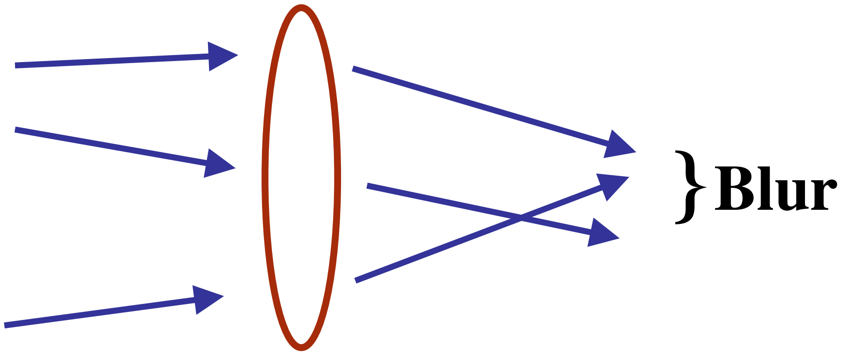
In reality, it tends to be more complex, due to the mirror geometry, etc. Also, from the ground, the resolution is generally limited by the seeing, plus the instrument optics, etc.

Optical Consequences of Turbulence

- Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
- Light rays are refracted many times (by small amounts)
- When they reach telescope they are no longer parallel
- Hence rays can’t be focused to a point:



Parallel light rays

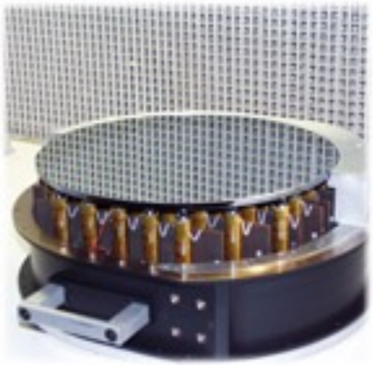


Light rays affected by turbulence

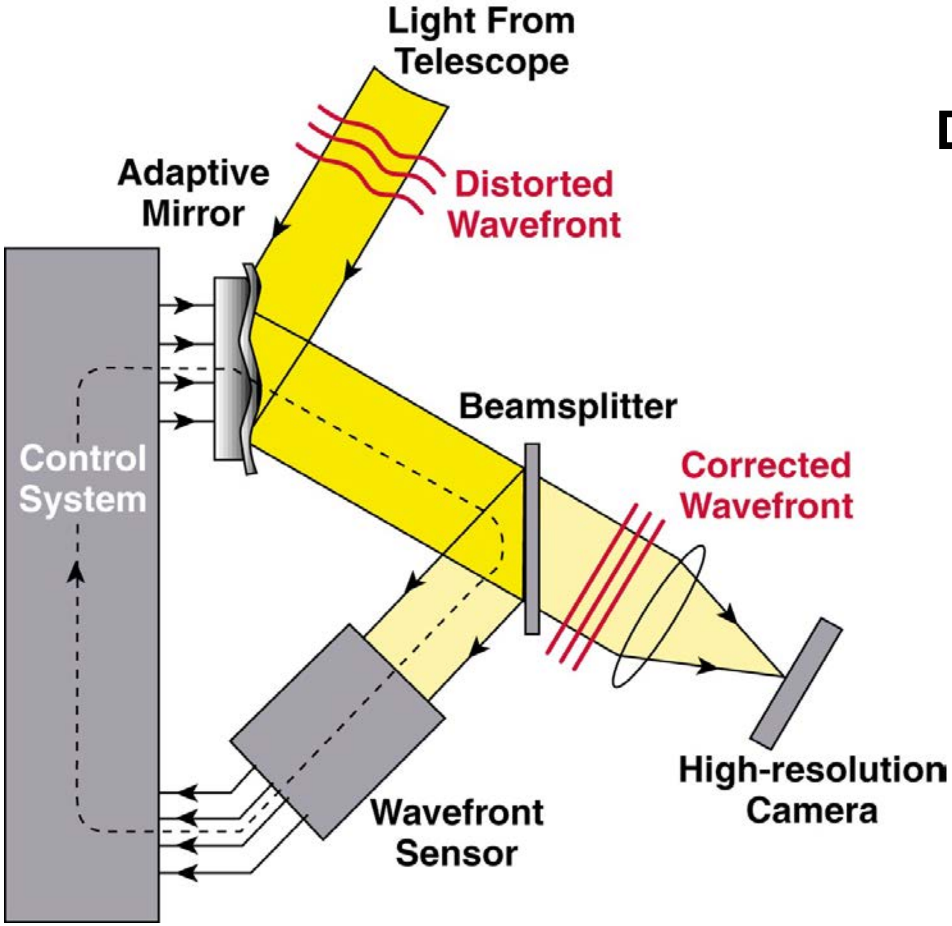
Can we compensate for this? Yes, with **Adaptive Optics**

Schematic of Adaptive Optics System

Atmospheric turbulence



Deformable mirror

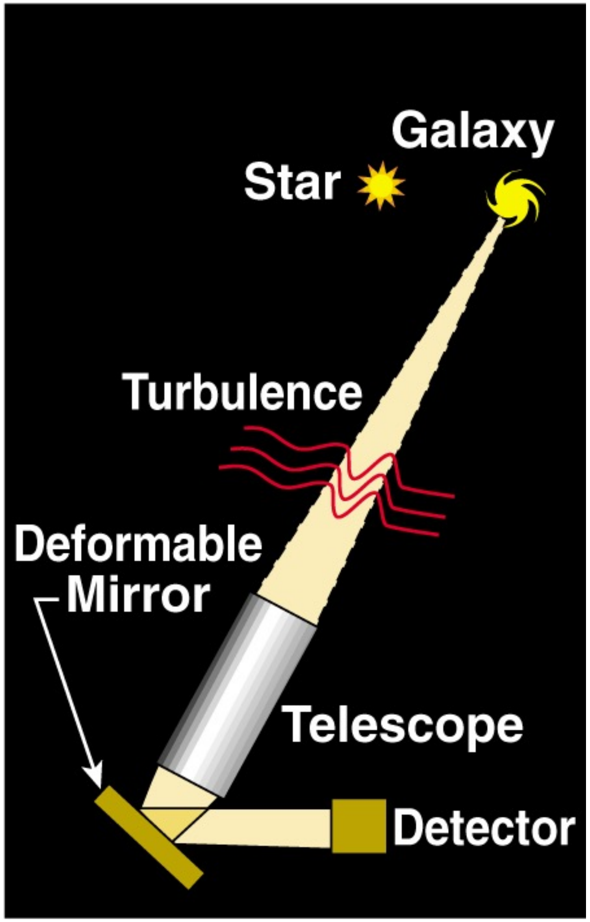


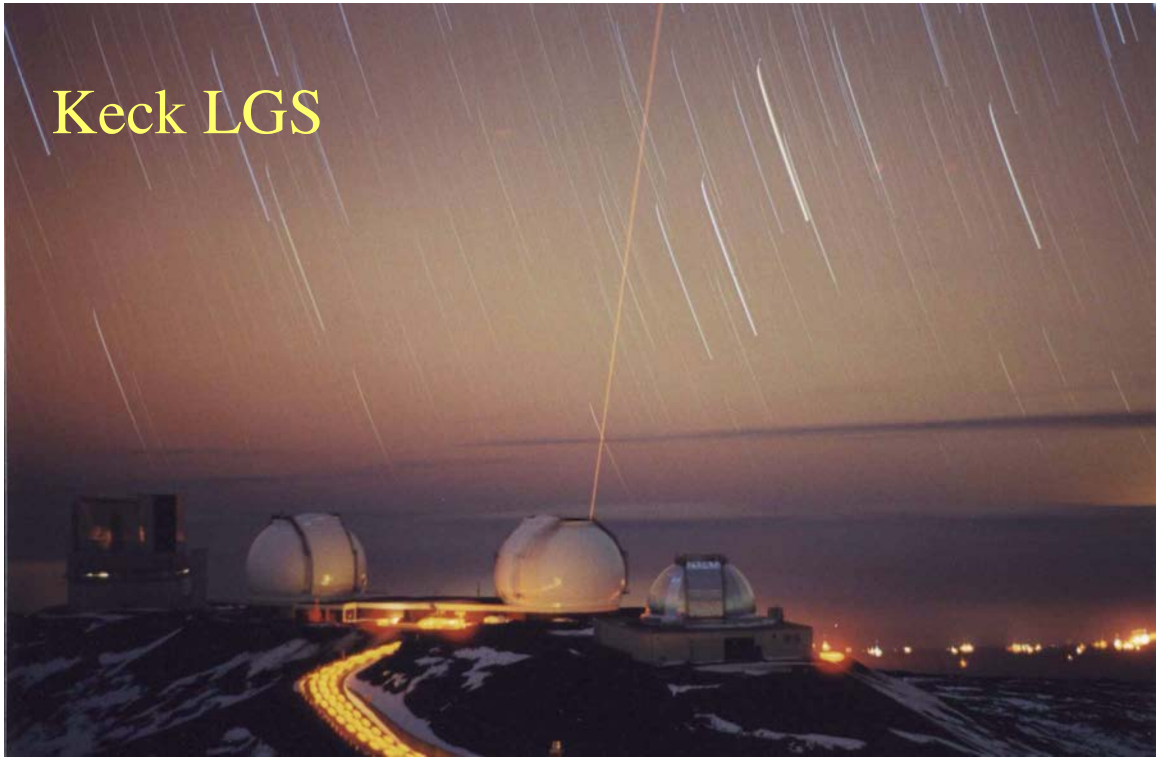
Feedback loop: next cycle corrects the (small) errors of the last cycle

But you need a bright star very close to your target (a few arcsec) in order to compute the correction

If there's no close-by bright star, create one with a laser!

Use a laser beam to create an artificial "star" at altitude of ~ 100 km (Na layer, Na D doublet)

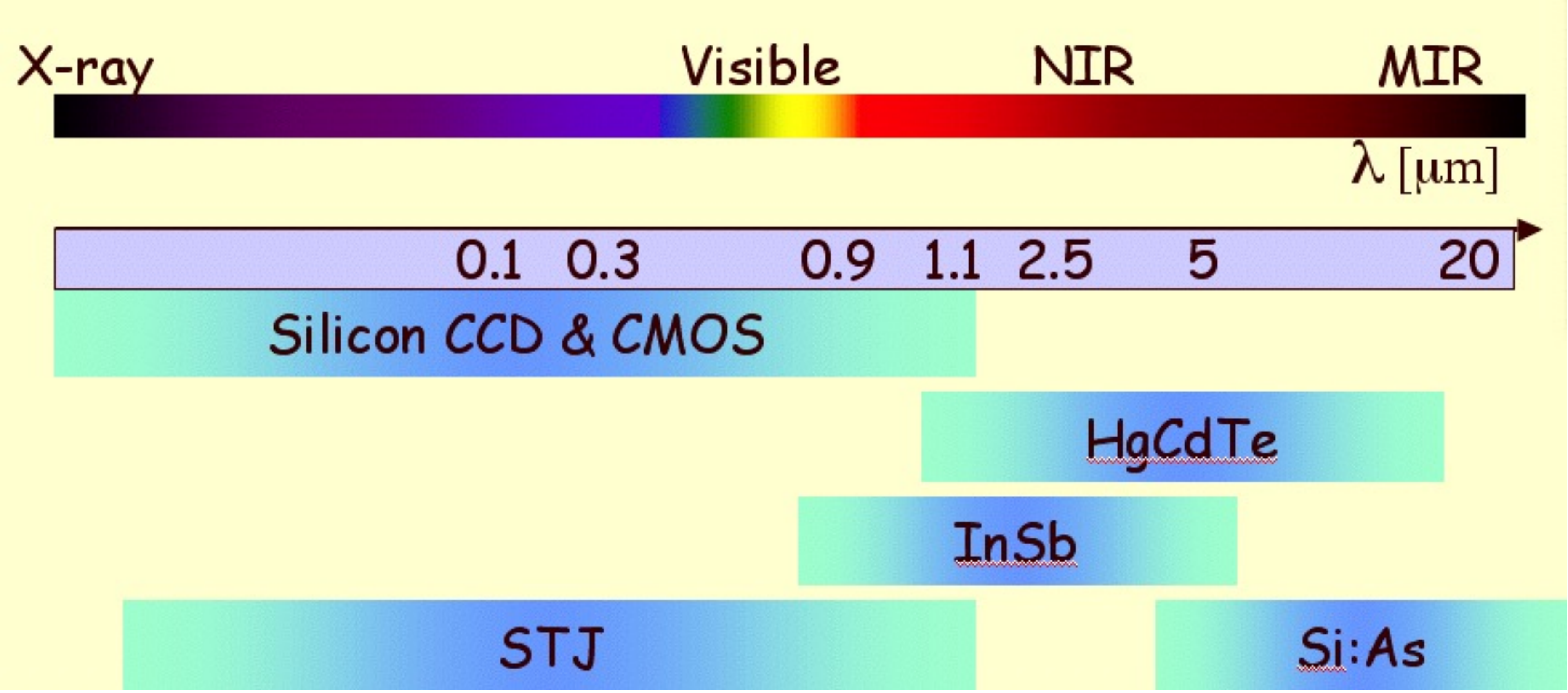




Evolution of Astronomical Detectors

- **Historical evolution:** Eye → Photography → Photoelectic (single-channel) devices → Plate scanners → TV-type imagers → Semiconductor-based devices (CCDs, IR arrays, APDs, bolometers, …) → Energy-resolution arrays (STJ, ETS)
- *Astronomical detectors today are applications of solid state physics*
- **Detector characteristics:** Sensitivity as a f(λ), size, number of pixels, noise characteristics, stability, cost
- **Types of noise:** Poissonian (quantum), thermal (dark current, readout), sensitivity pattern
- **Quantum efficiency:** QE = N(detected photons)/N(input photons)
- **Detective Quantum Efficiency:** DQE = $(S/N)_{out}/(S/N)_{in}$

Solid-State Detector Technologies



2-D focal plane arrays :

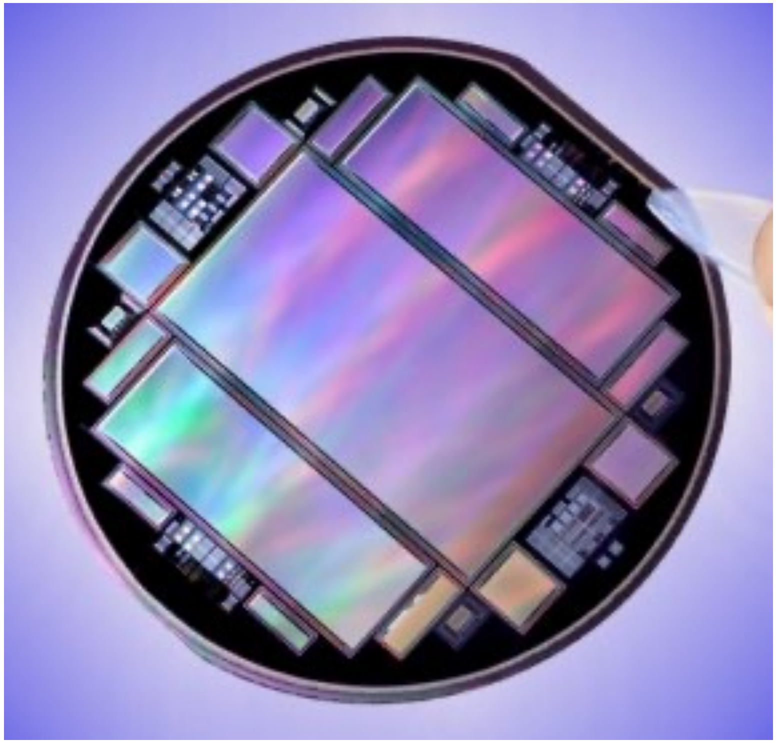
- Optical – silicon-based (CCD, CMOS)
- Infrared – IR material + silicon CMOS multiplexer

Five Basic Steps of Optical/IR Photon Detection

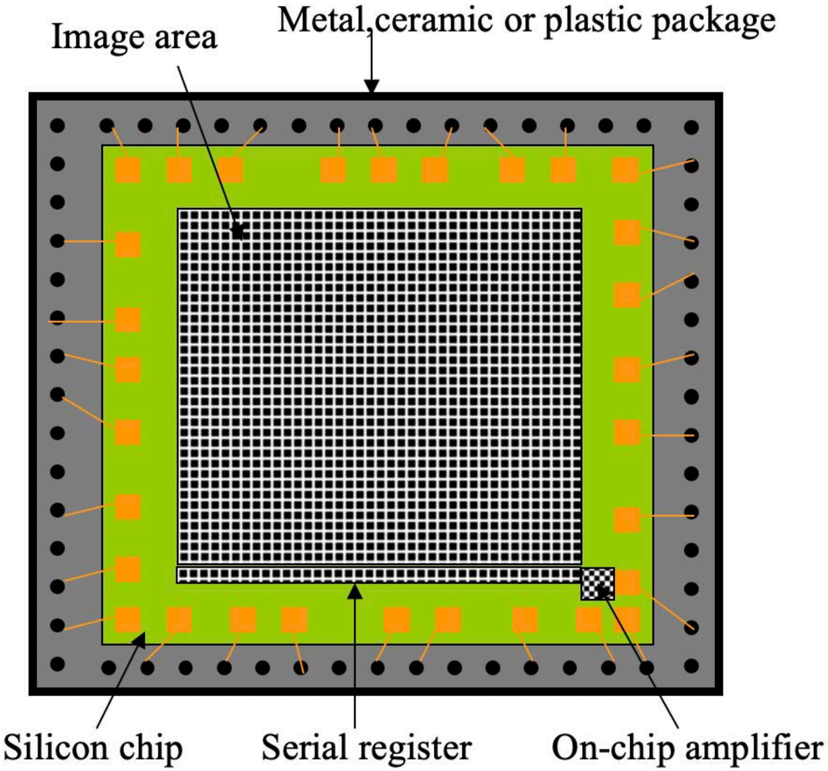
1. **Get light into the detector :** need anti-reflection coatings
2. **Charge generation :** popular materials include Si, HgCdTe, InSb
3. **Charge collection :** electrical fields within the material collect photoelectrons into pixels.
4. **Charge transfer :** in IR, no charge transfer required. For CCD, move photoelectrons to the edge where amplifiers are located.
5. **Charge amplification & digitization :** This process is noisy. In general, CCDs have lowest noise, CMOS and IR detectors have higher noise.

Charge Coupled Devices (CCDs) are now the detectors of choice (in visible, UV, and X-ray)

Nearly ideal detectors in terms of the quantum efficiency, wavelength response, noise, etc. Counting photons in a pixel array



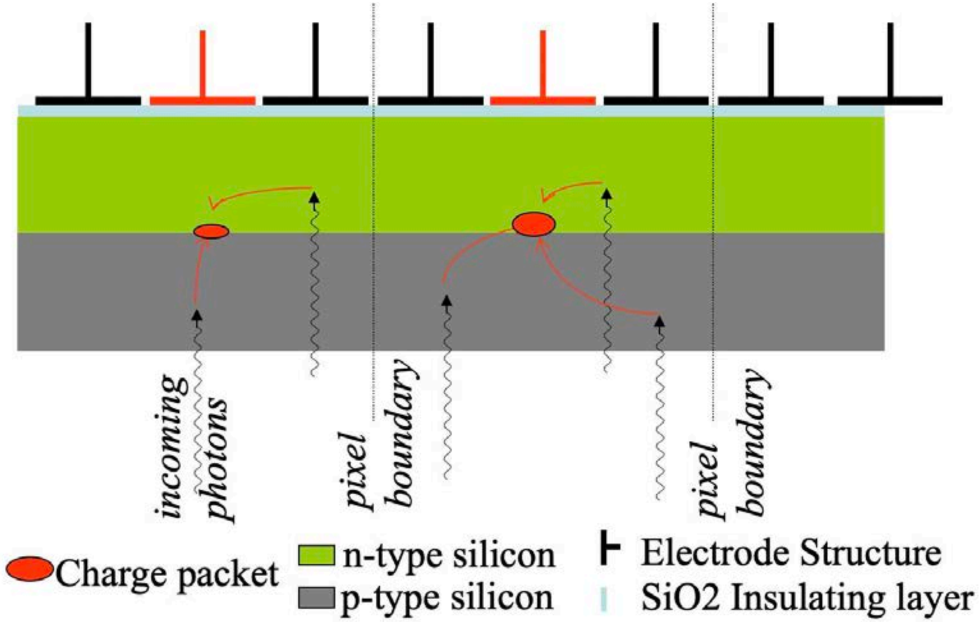
A whole bunch of CCDs on a wafer



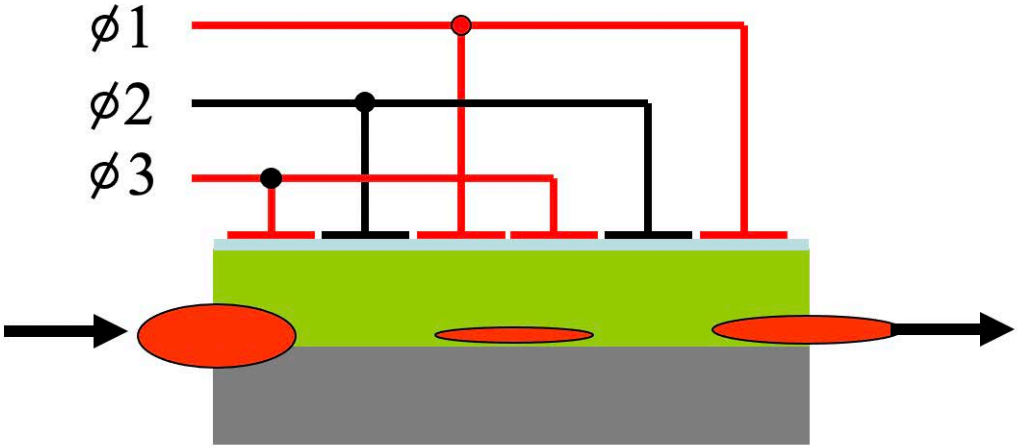
2009 Nobel Prize in Physics Willard Boyle & George Smith

How Does a CCD Work?

A grid of electrodes establishes a pixel grid pattern of potential wells, where photoelectrons are collected in “charge packets”



Typical well (pixel) capacity: a few $\times 10^5 e^-$. Beyond that, the charge “bleeds” along the electrodes.



After the exposure is complete, shift the electric potential pattern by clocking the voltages - pixel positions shift. Pattern of collected electrons (= an image) moves with the voltage pattern, and is read out

IR (Hybrid) Arrays

Not like CCDs!

Each pixel is read out through its own transistor.

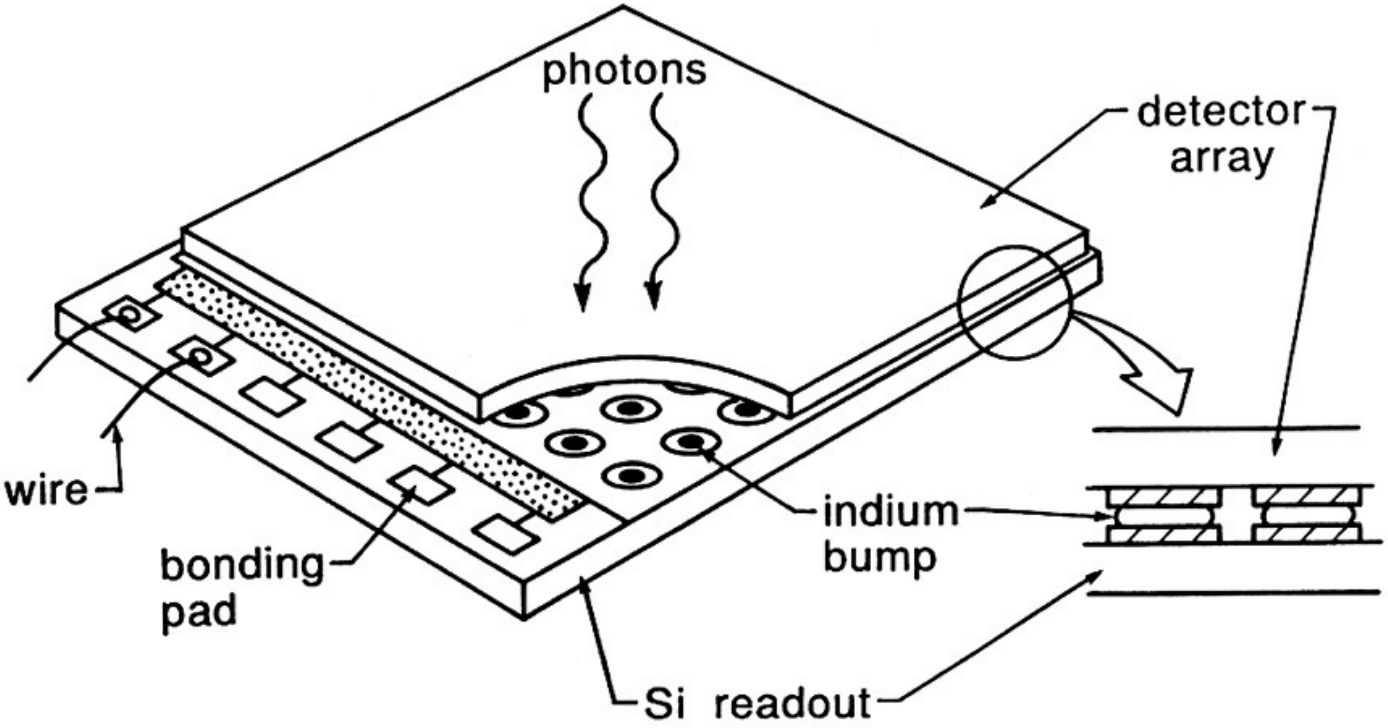
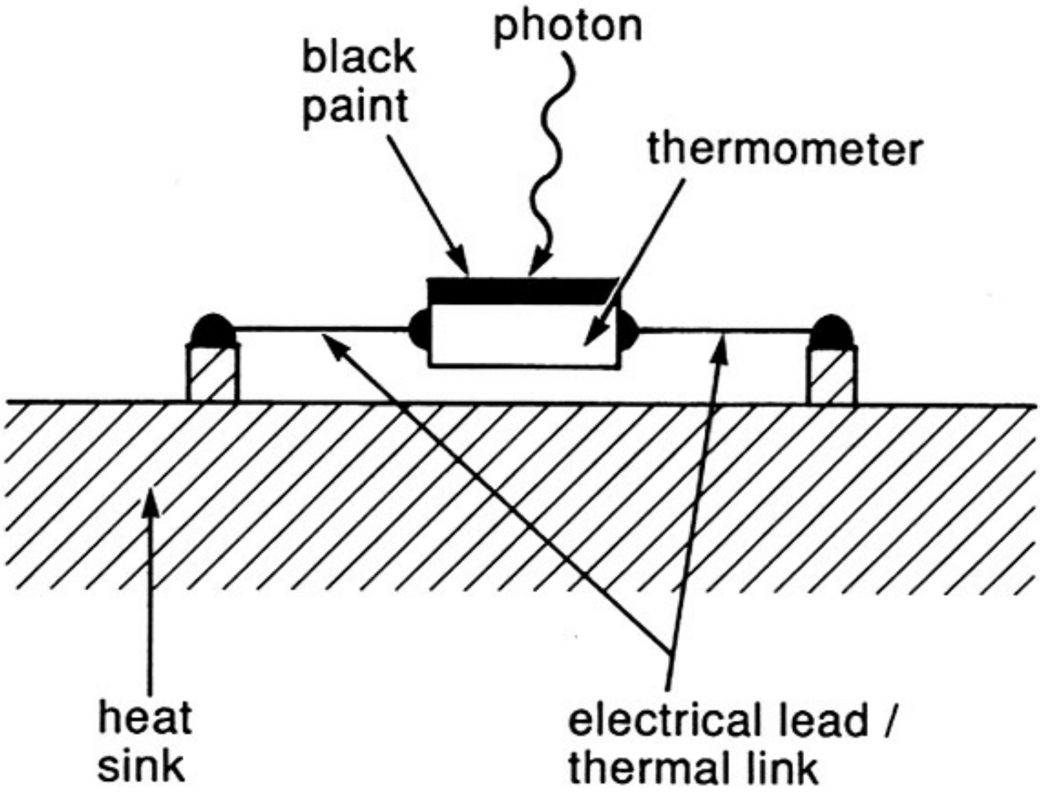


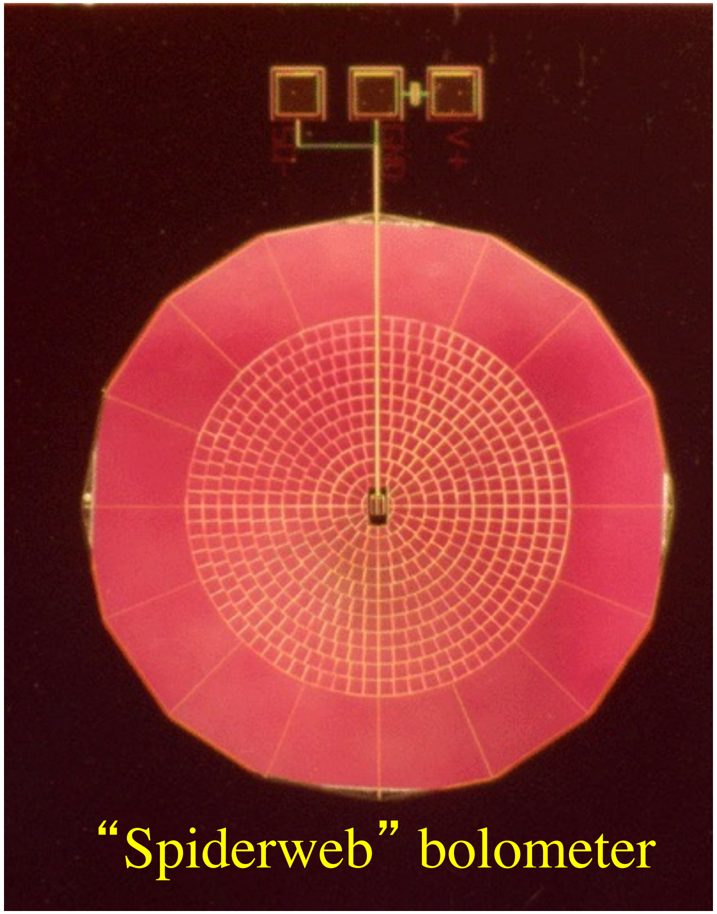
Figure 6.1. Infrared direct hybrid array.

Typical materials:
HgCdTe, InSb, PtSi, InGaAs

Bolometers

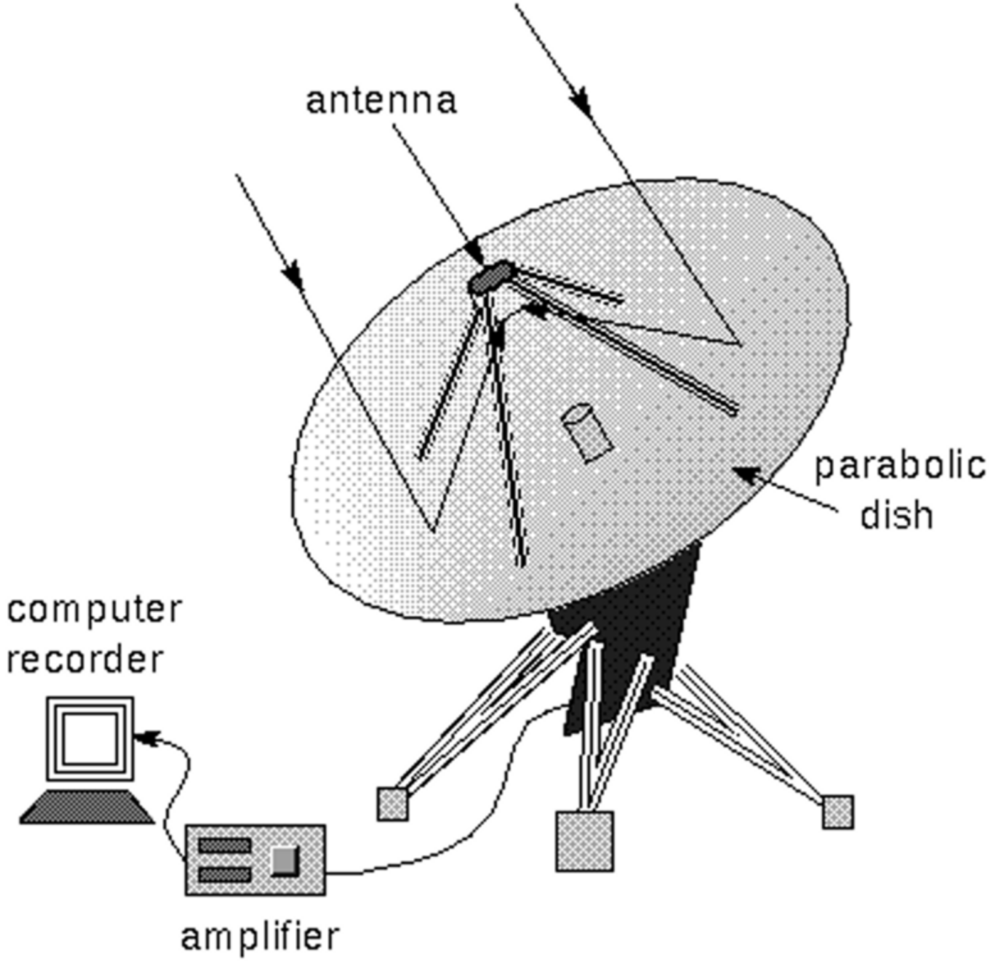
- Measure the energy from a radiation field, usually from a change in resistance of some device as it is heated by the radiation
- Mainly used in FIR/sub-mm/microwave regime





“Spiderweb” bolometer

How a Radio Telescope Works



A radio telescope reflects radio waves to a focus at the antenna. Because radio wavelengths are very large, the radio dish must be very large.

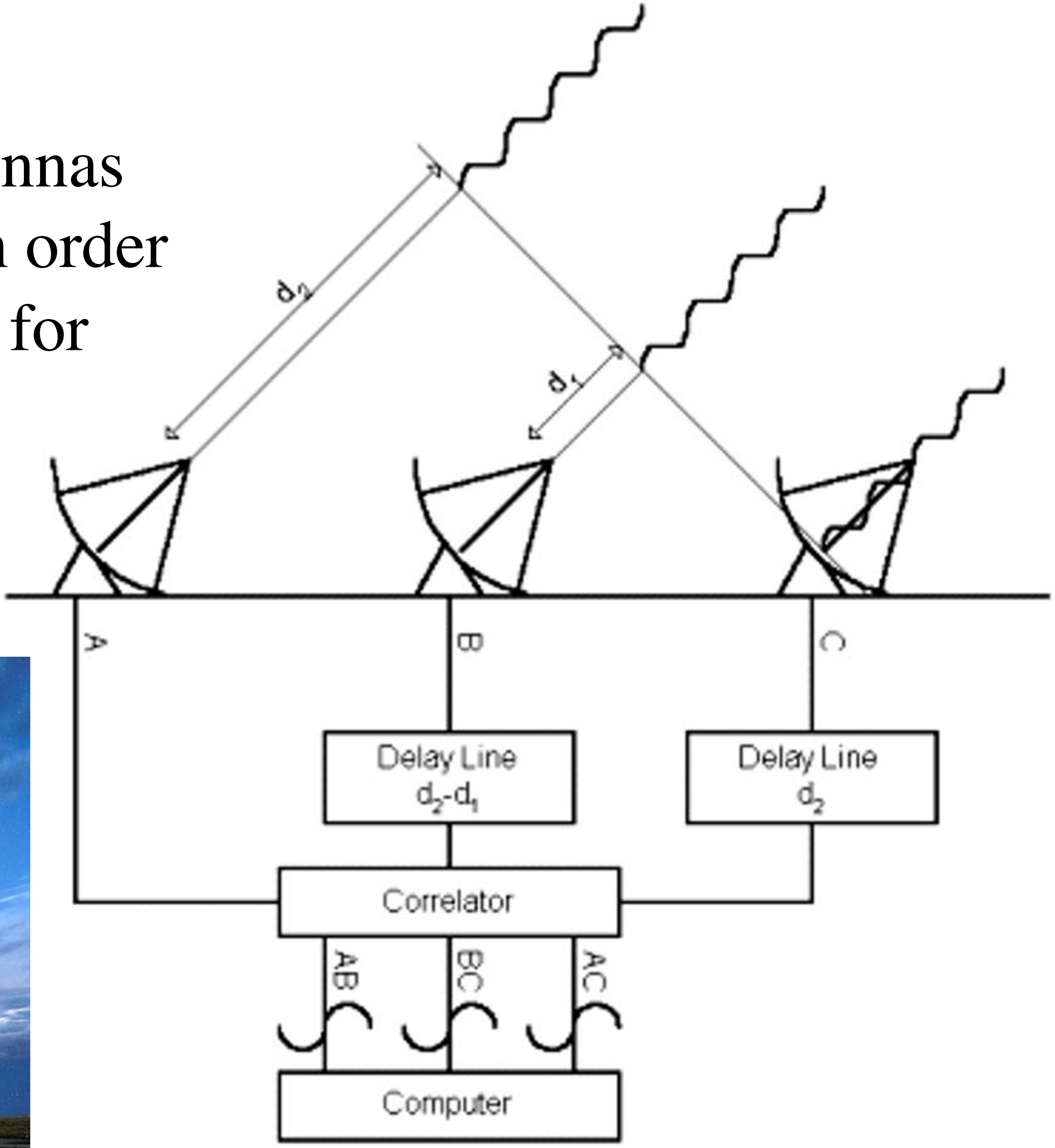
VLA instrument
feed pedestal

How Interferometer Works

Aperture Synthesis:

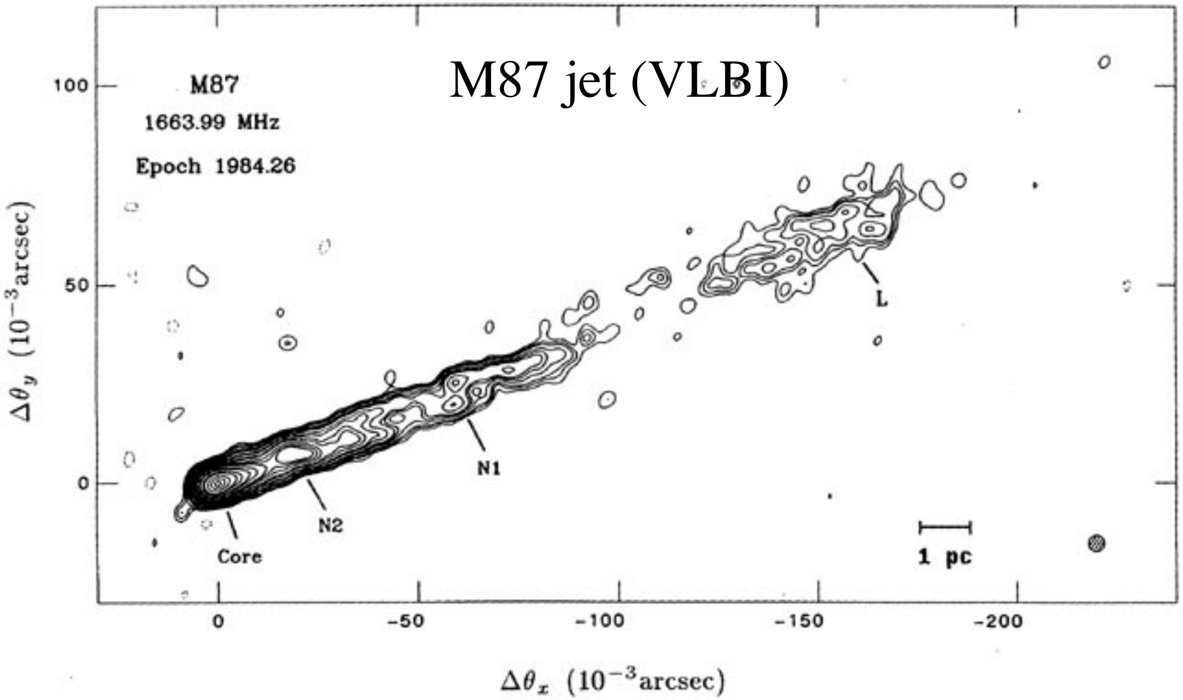
Signals from individual antennas are delayed electronically, in order to simulate a flat wavefront, for slightly different arrival directions, thus mapping a field of view.

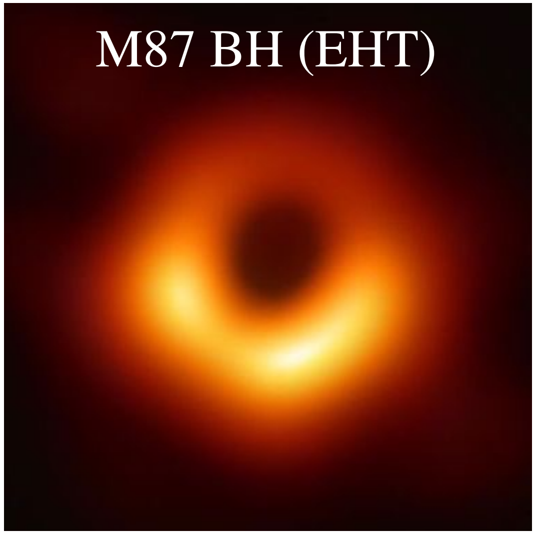
Very Large Array (VLA)



Very Long Baseline Interferometry (VLBI)

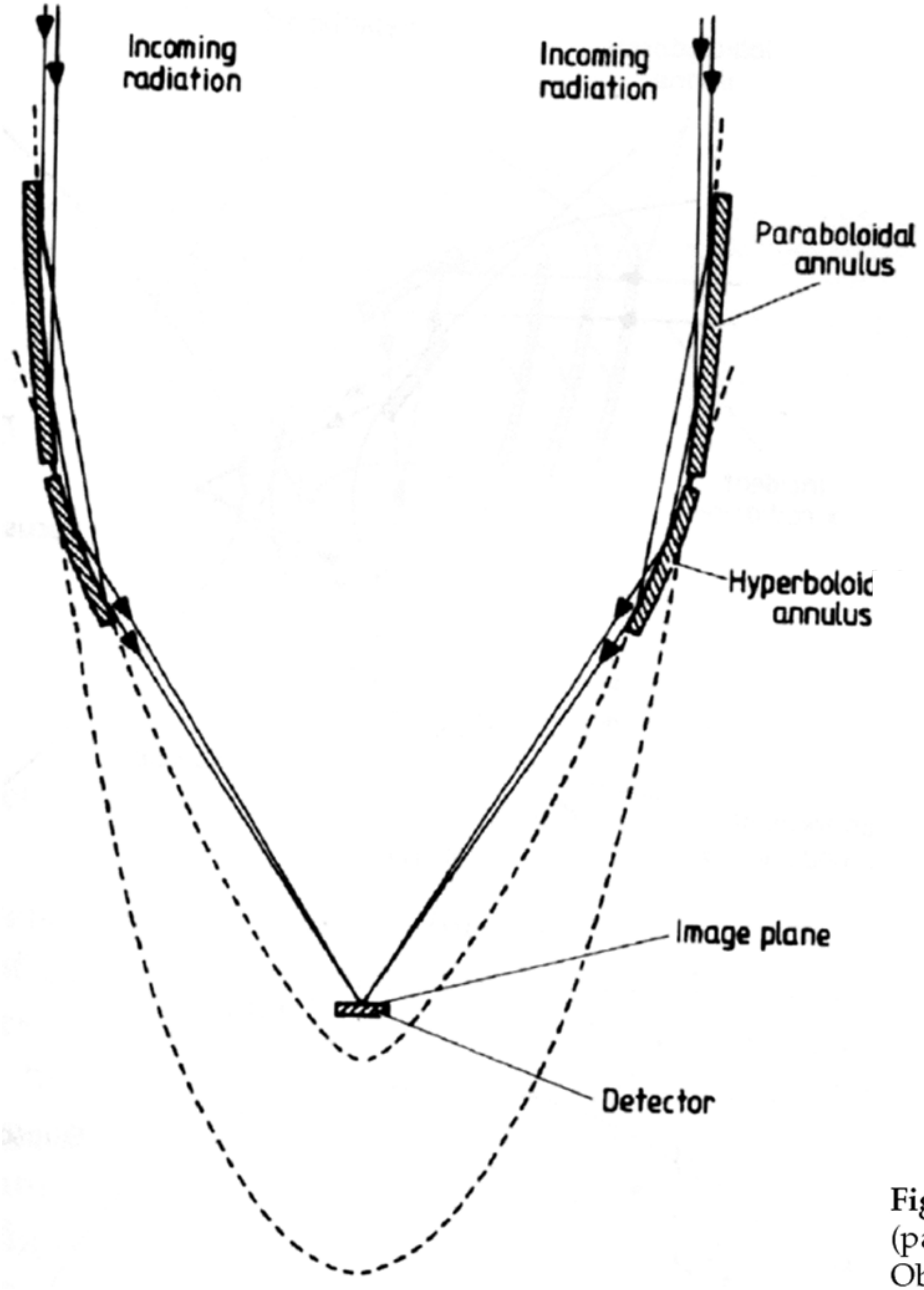
- Antennas very far apart (~ Earth size)
  - Resolution very high: milli-arcsec
  - Remember: beam size ~ λ / D
- Record signals, correlate later
- Examples: VLBA(rray), Event Horizon Telescope


M87 jet (VLBI)


M87 BH (EHT)

X-Ray telescopes:

Grazing incidence mirrors



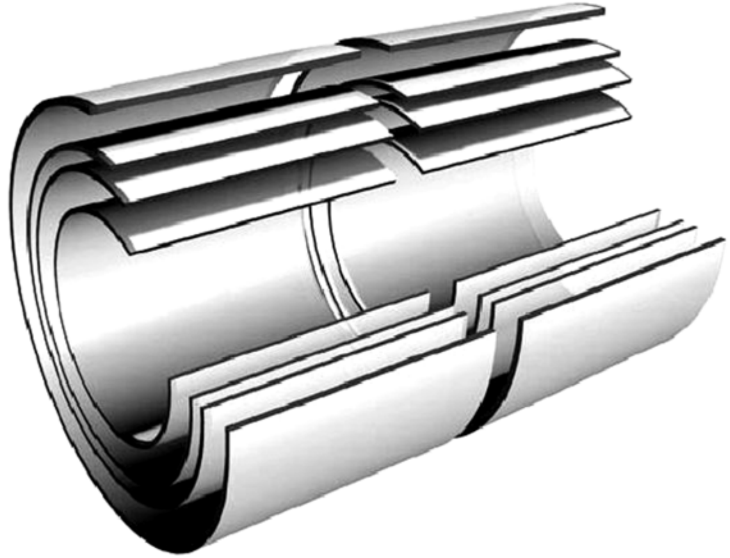
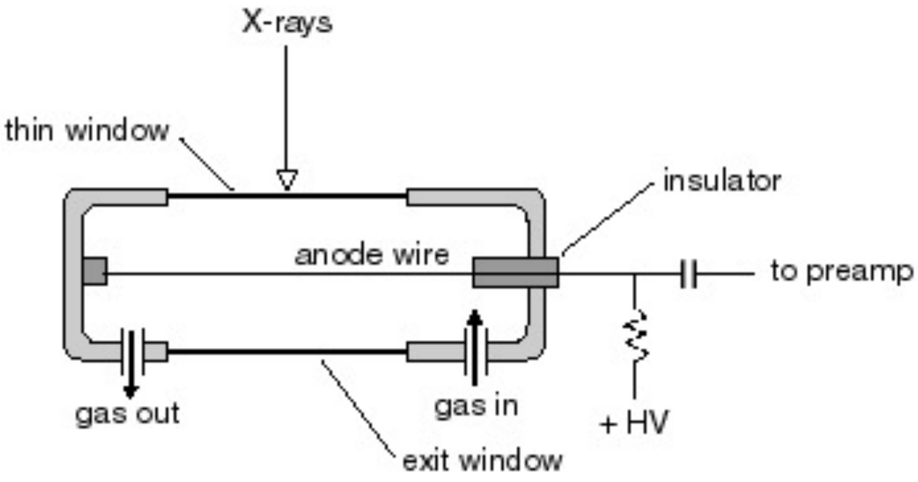
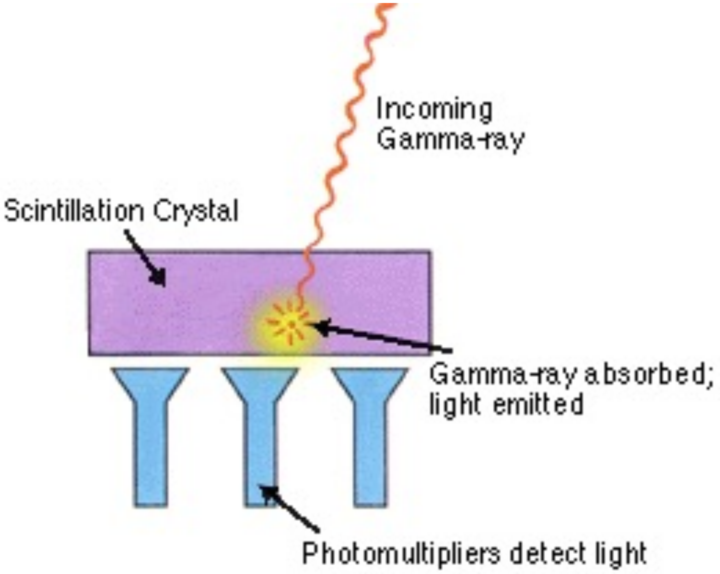


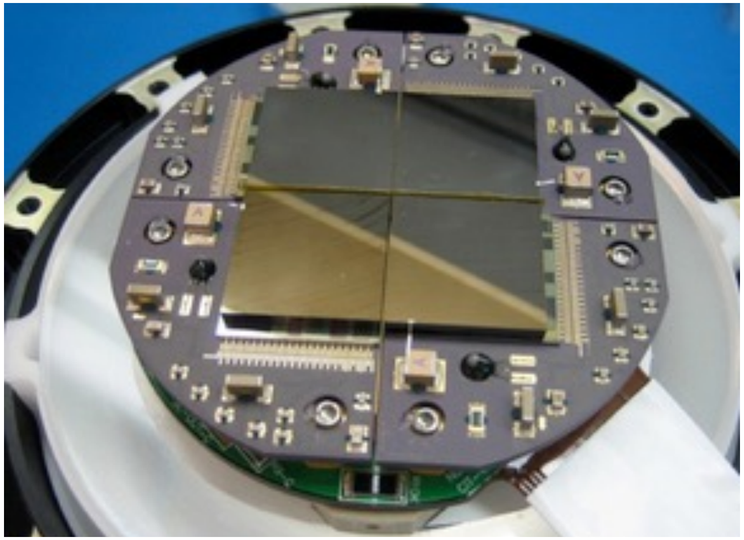
Figure 3. Cutaway schematic drawing of the nested four shells (paraboloid and hyperboloids) of the Chandra X-ray Observatory (courtesy of the Raytheon Co).

X-Ray and Gamma Ray Detectors

- Proportional counters
- Scintillation crystals
- X-ray CCDs
- Solid state CdZnTe arrays
- …



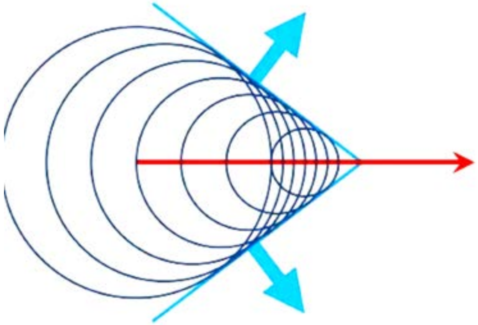


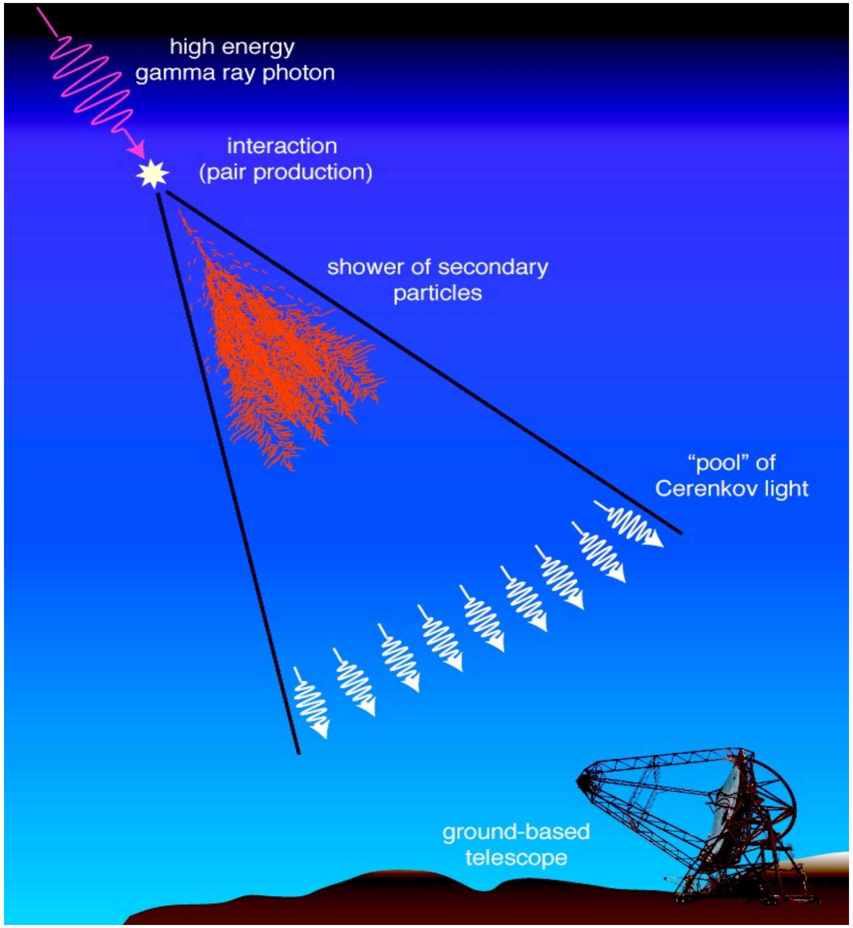


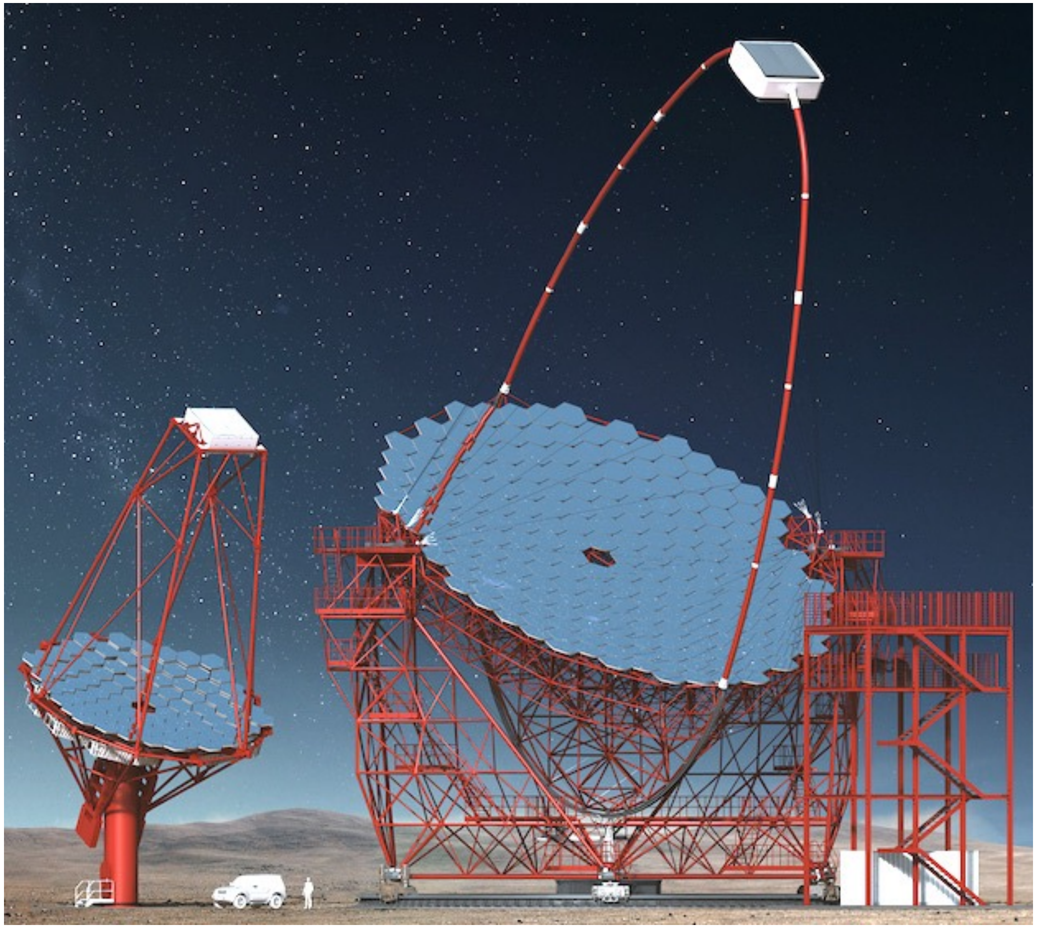
- Air Cerenkov detectors

High-Energy Gamma-Ray (Cherenkov) Telescopes

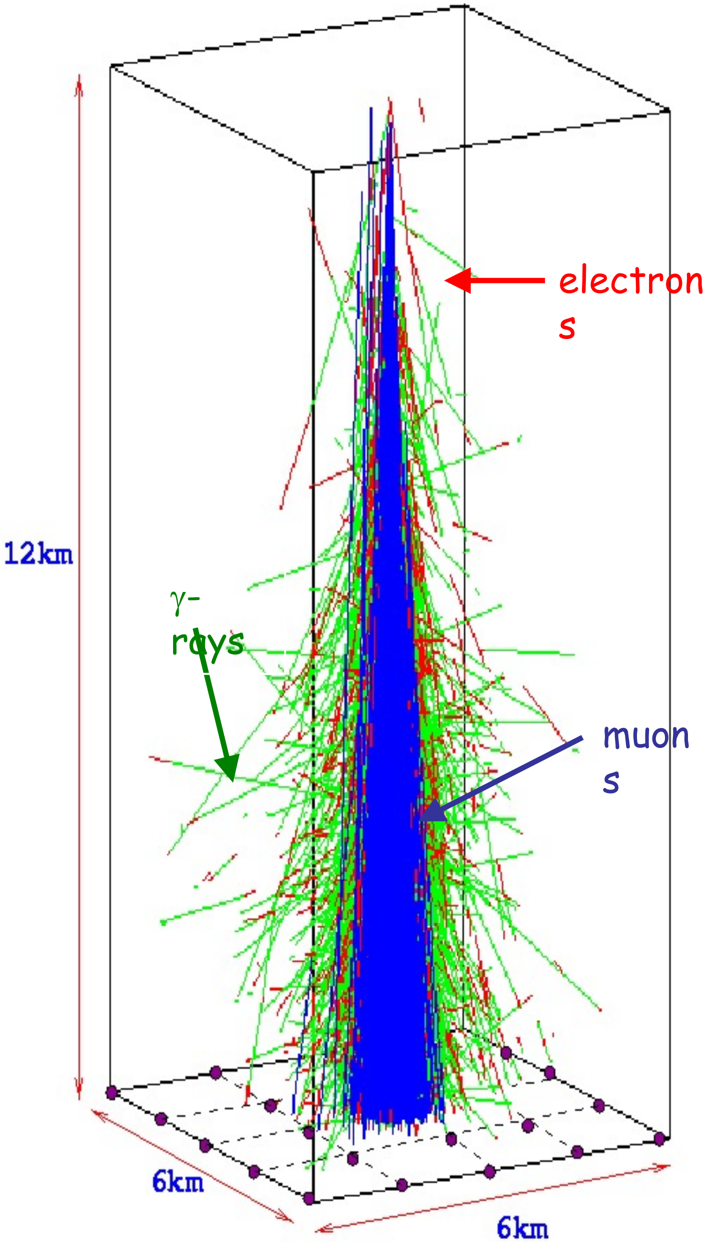
Light emitted by a charged particle moving faster than the speed of light *in that medium* (but $< c$). Similar to the supersonic boom for objects moving faster than the speed of sound

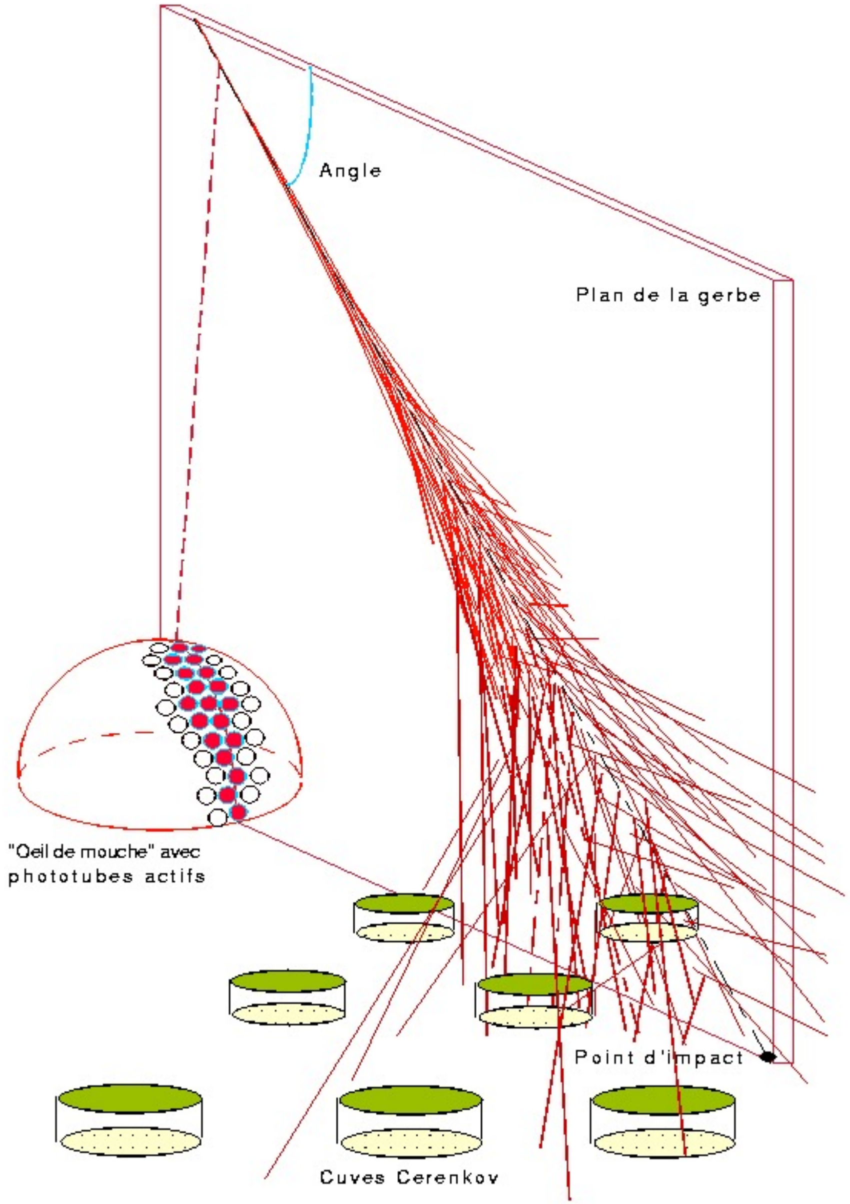






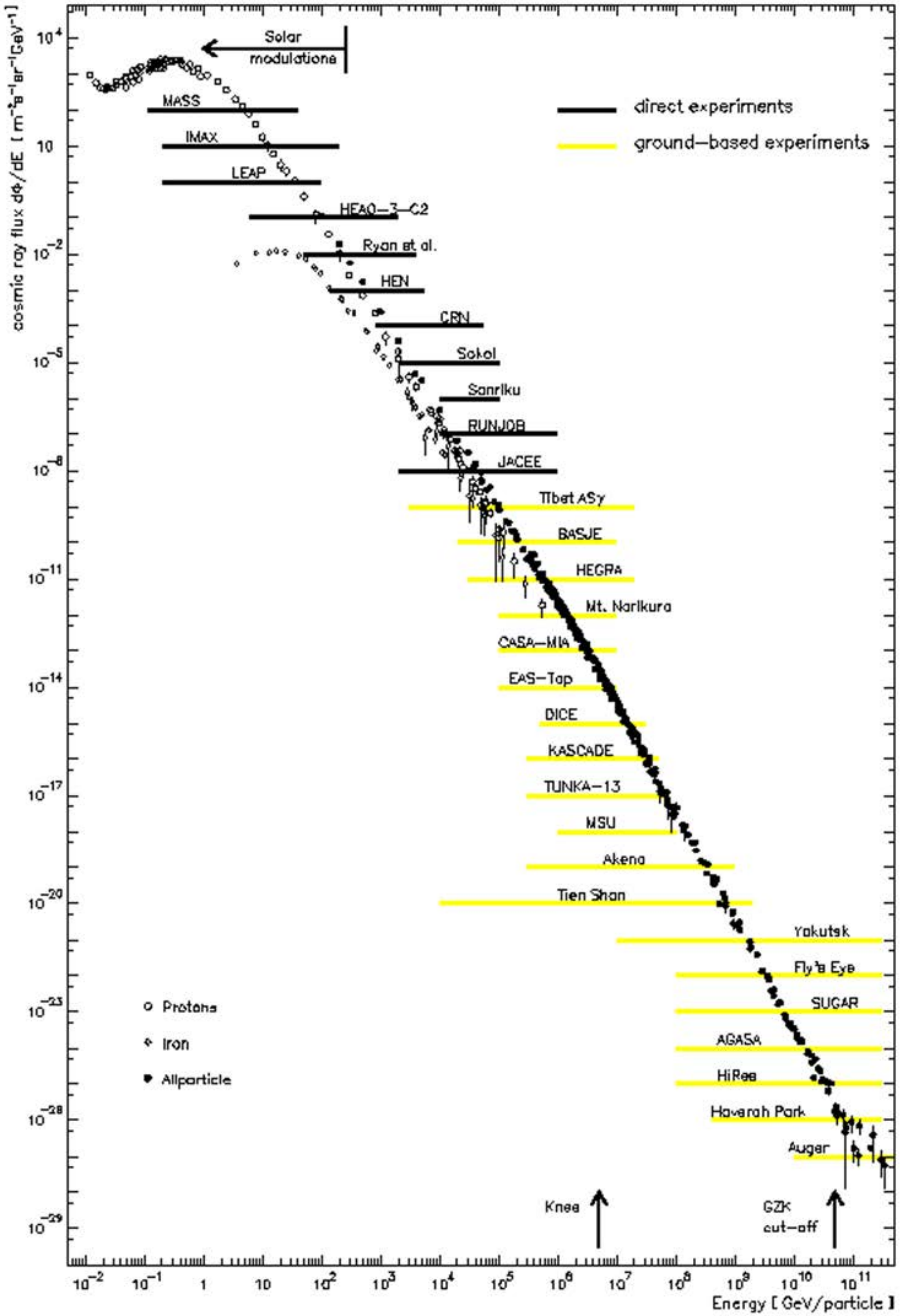
High-Energy Cosmic Rays: Atmospheric Showers



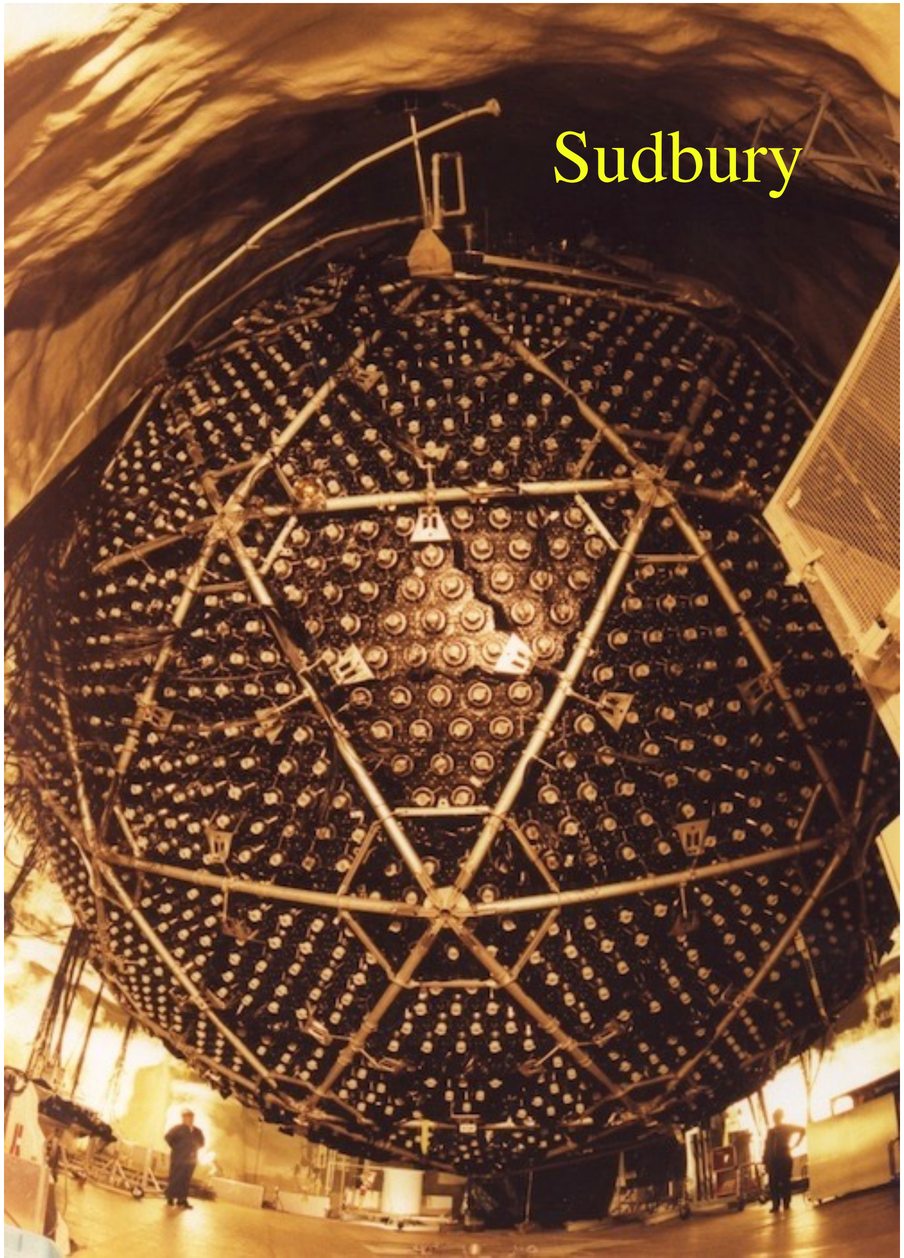


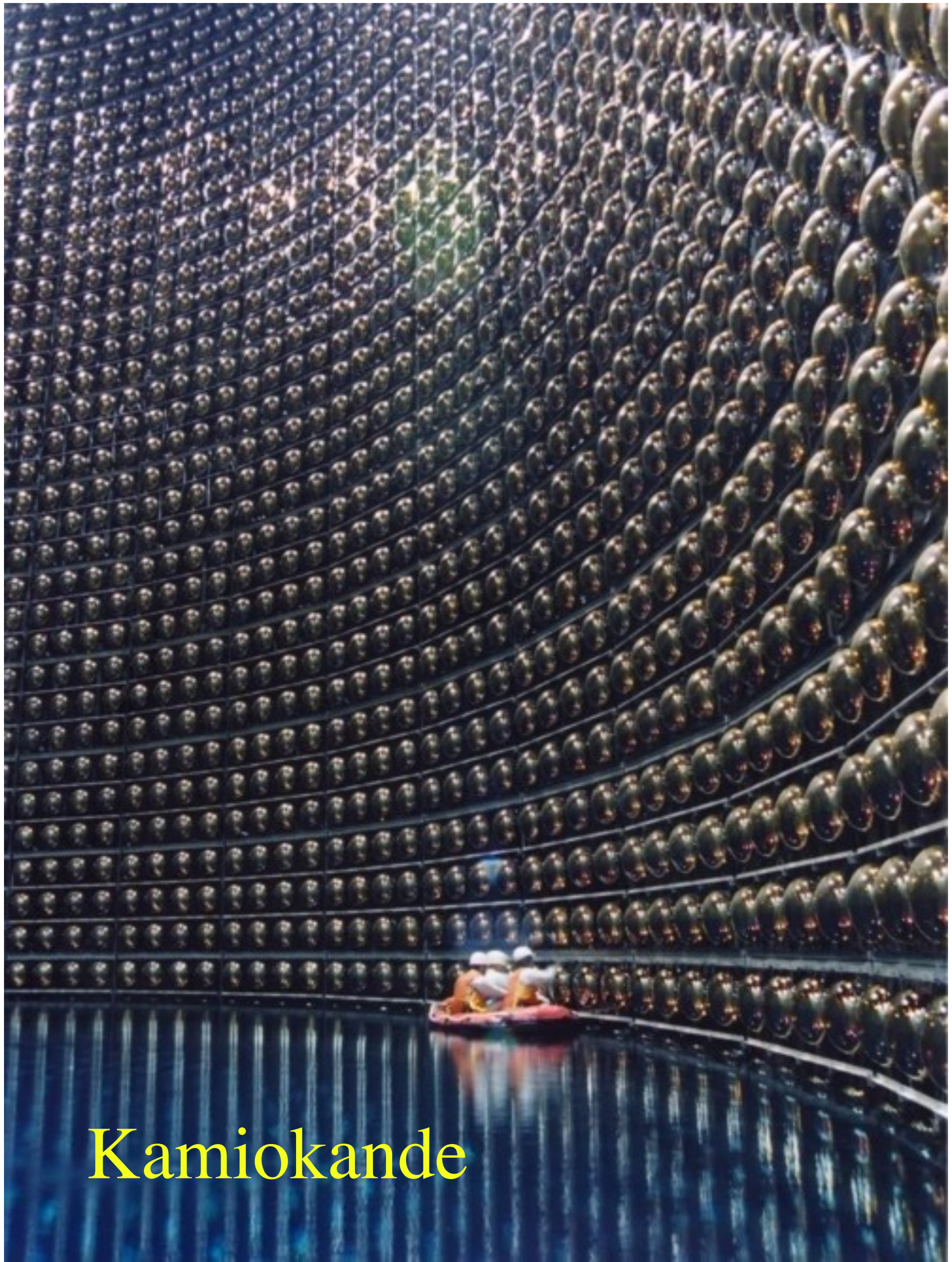
High-Energy Cosmic Rays

The cosmic ray spectrum stretches over some 12 orders of magnitude in energy and some 30 orders of magnitude in differential flux!

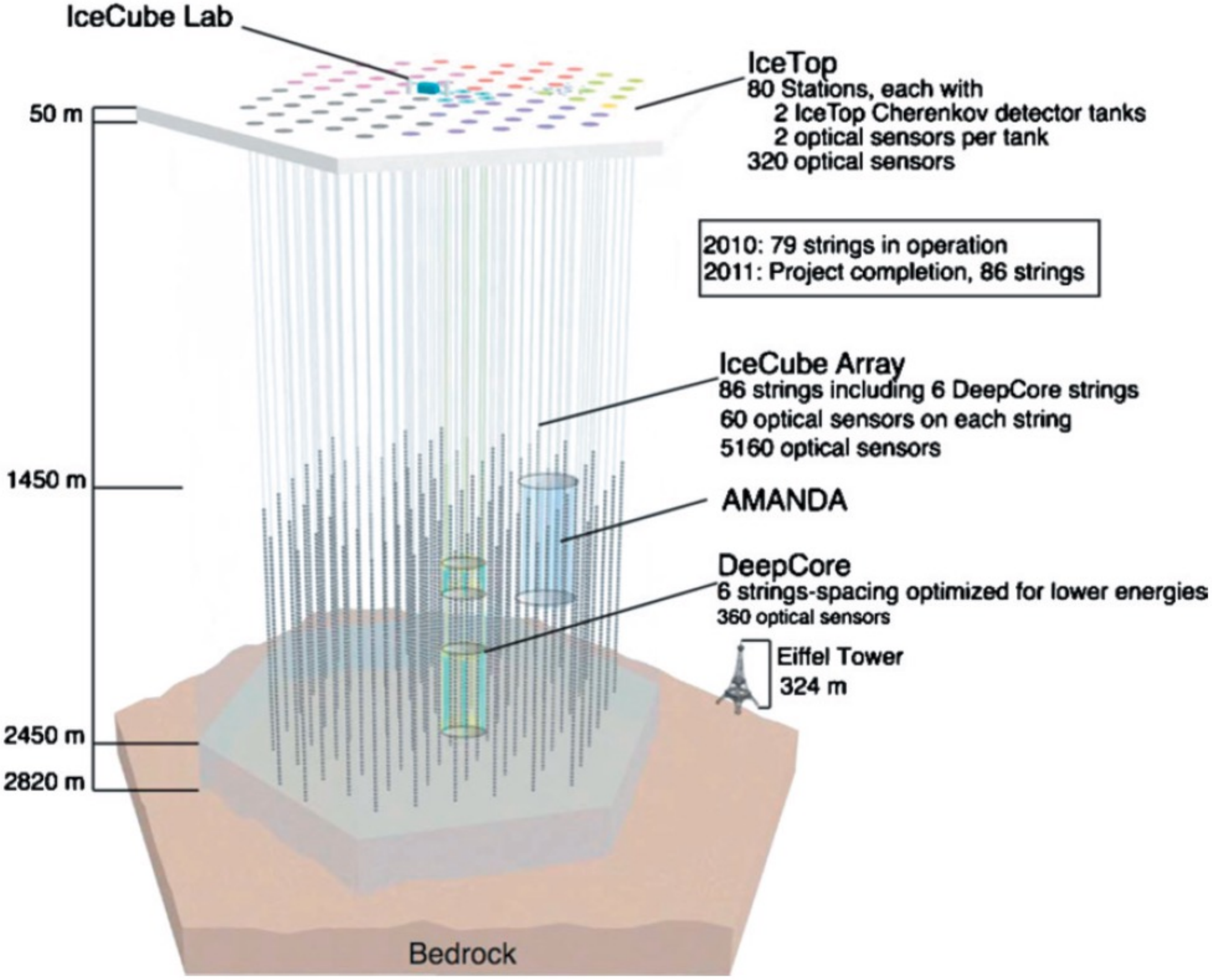


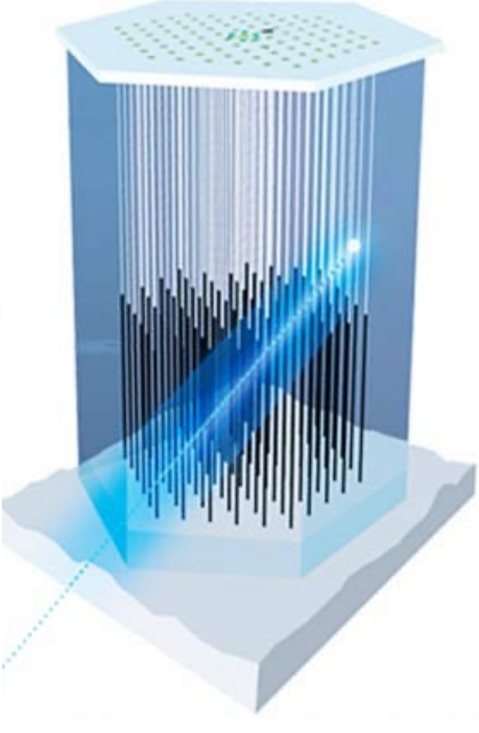
Neutrino Detectors (deep underground)



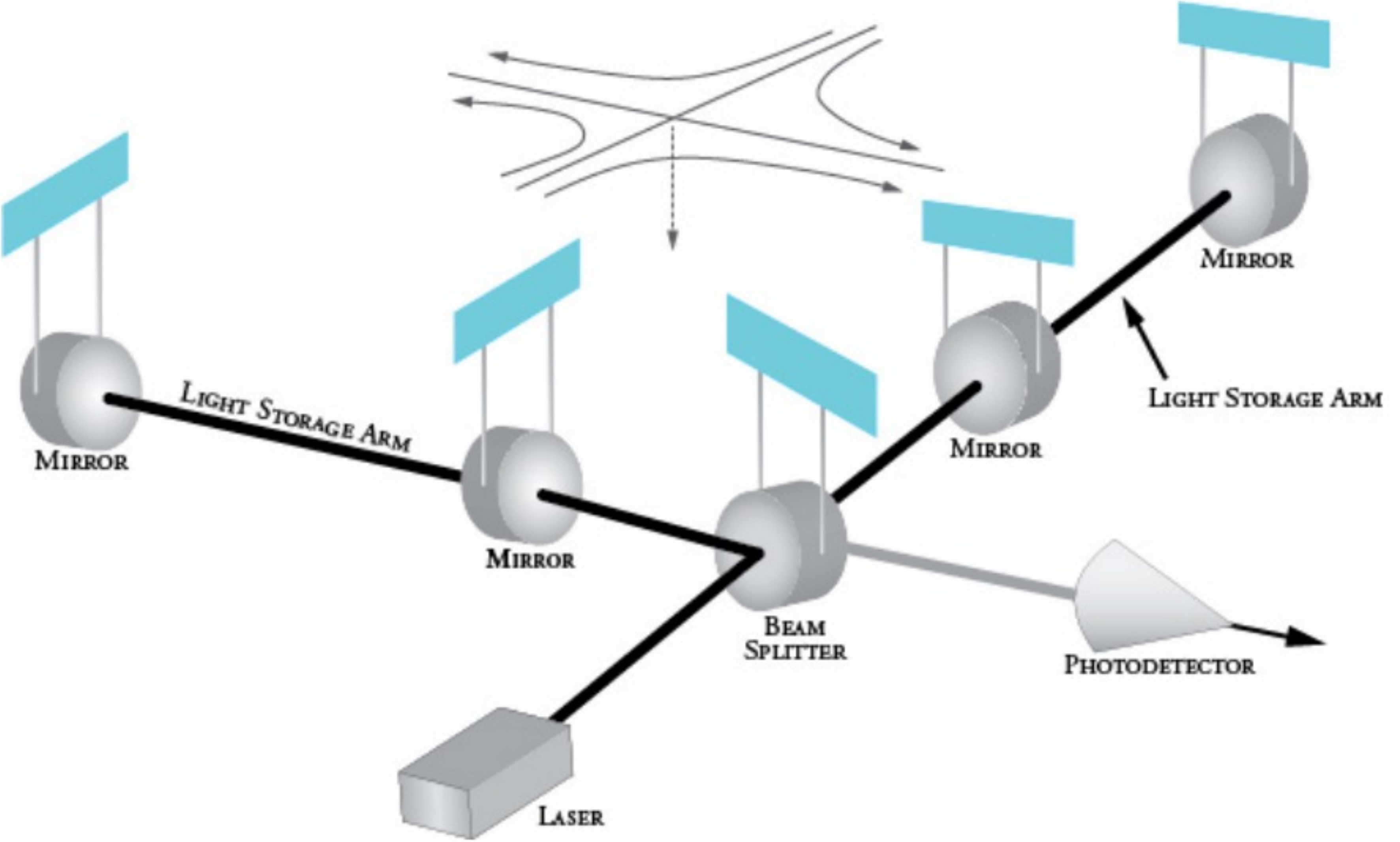


IceCube Neutrino Observatory @ South Pole





How LIGO works: a laser interferometer



Measurement precision: 1 / 1,000,000,000,000,000,000,000

Photon Energies

Electromagnetic radiation of frequency ν, wavelength λ, in free space obeys:

$$\lambda \upsilon = c$$

Individual photons have energy:

$$E = h\nu$$

h = Planck's constant $\quad h = 6.626 \times 10^{-27}$ erg s

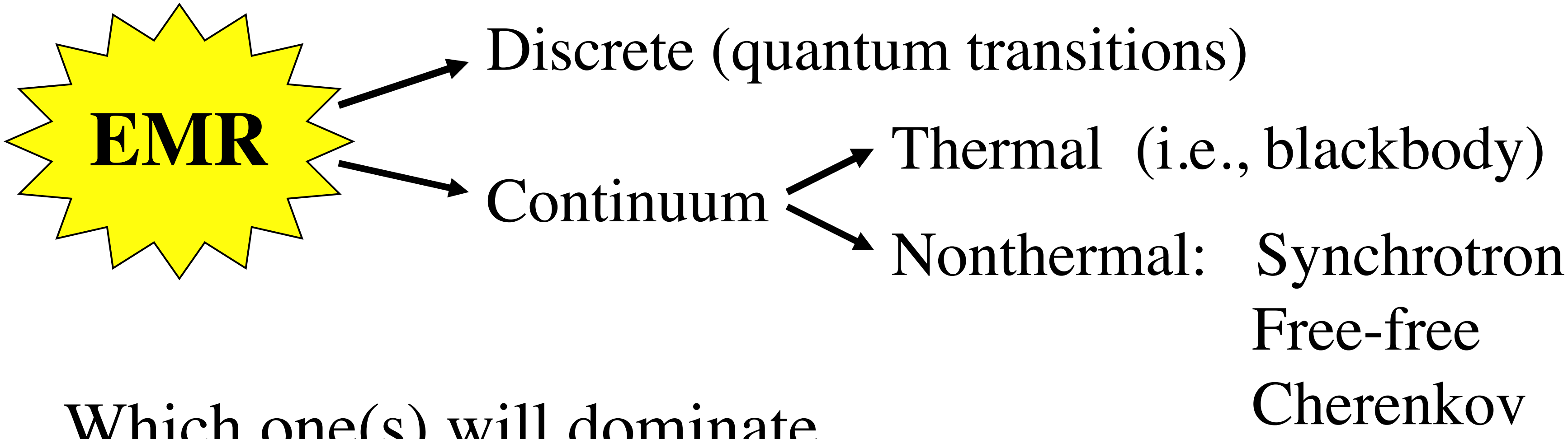
c = speed of light $\quad c = 3.0 \times 10^{10}$ cm s^{-1}

Energies are often given in electron volts, where:

$$1\ \mathrm{eV} = 1.6 \times 10^{-12}\ \mathrm{erg} = 1.6 \times 10^{-19}\ \mathrm{J}$$

Primary Astrophysical Processes Producing Electromagnetic Radiation

- ***When charged particles change direction (i.e., they are accelerated), they emit radiation***
- ***Quantum systems (e.g., atoms) change their energy state by emitting or absorbing photons***



EMR

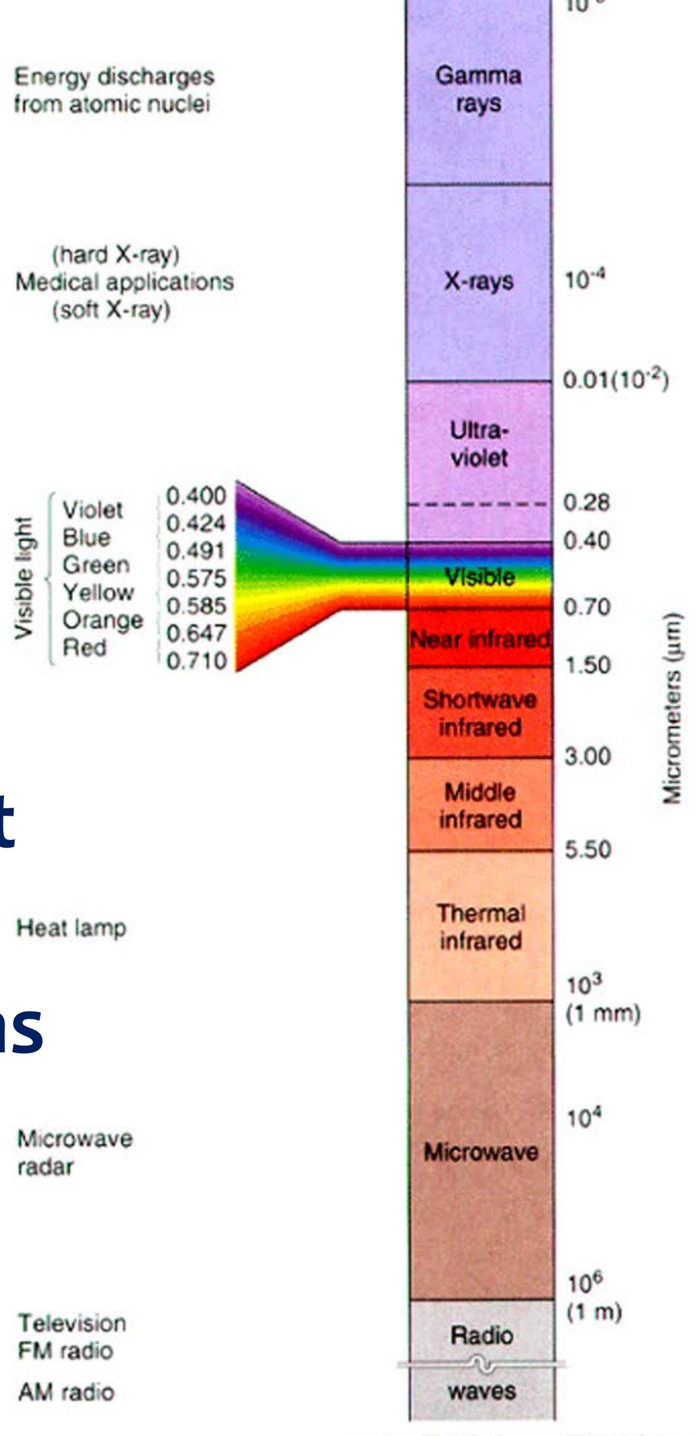
Discrete (quantum transitions)

Continuum

- Thermal (i.e., blackbody)
- Nonthermal: Synchrotron
  Free-free
  Cherenkov

Which one(s) will dominate, depends on the physical conditions of the gas/plasma. Thus, EMR is a *physical diagnostic*.

Different Physical Processes Dominate at Different Wavelengths



Nuclear energy levels

Inner shells of heavier elements

Atomic energy levels
(outer shells)

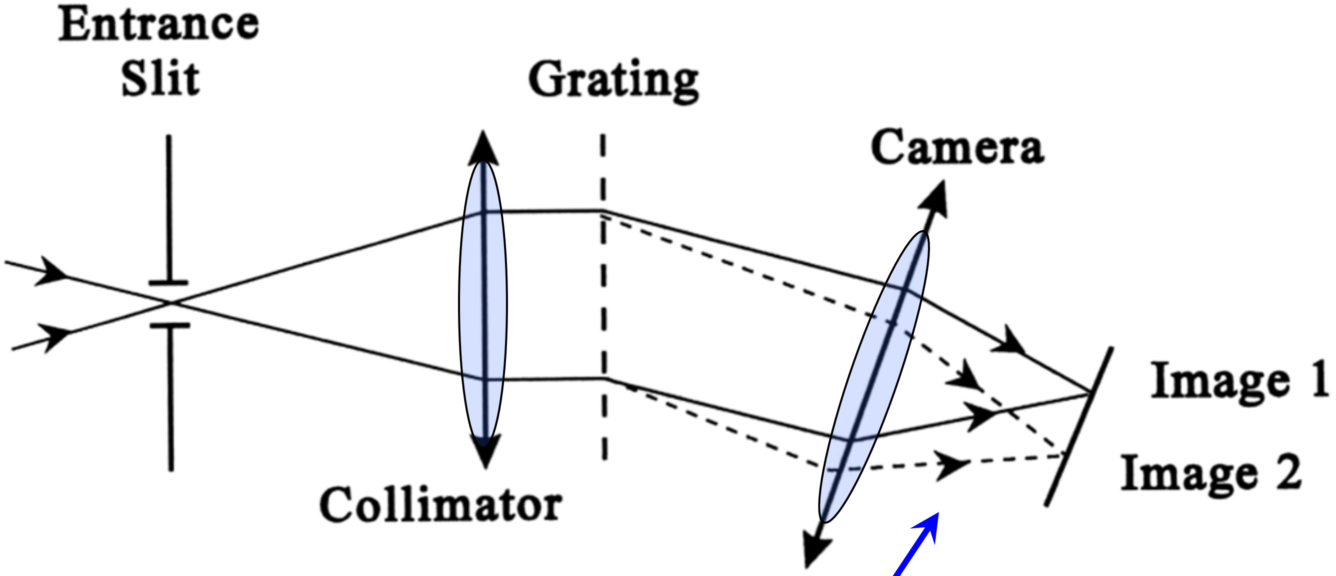
Molecular transitions

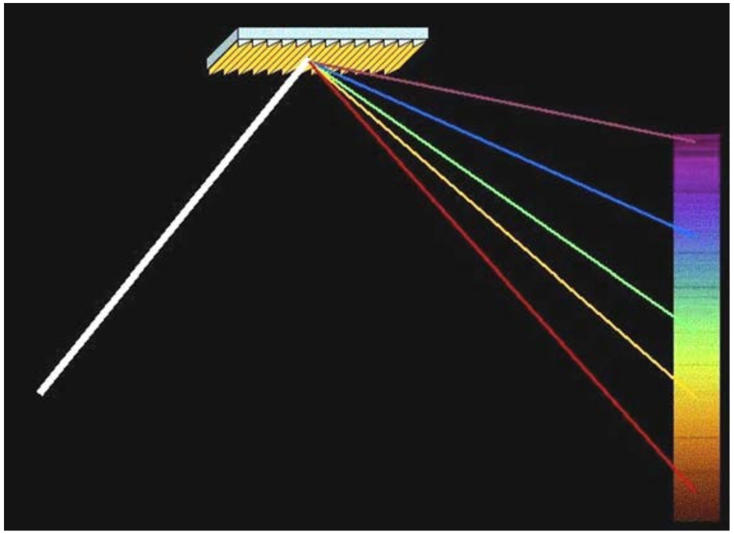
Hyperfine transitions

Plasma in typical magnetic fields

Diffraction Grating Spectrographs

A schematic view of a spectrograph:

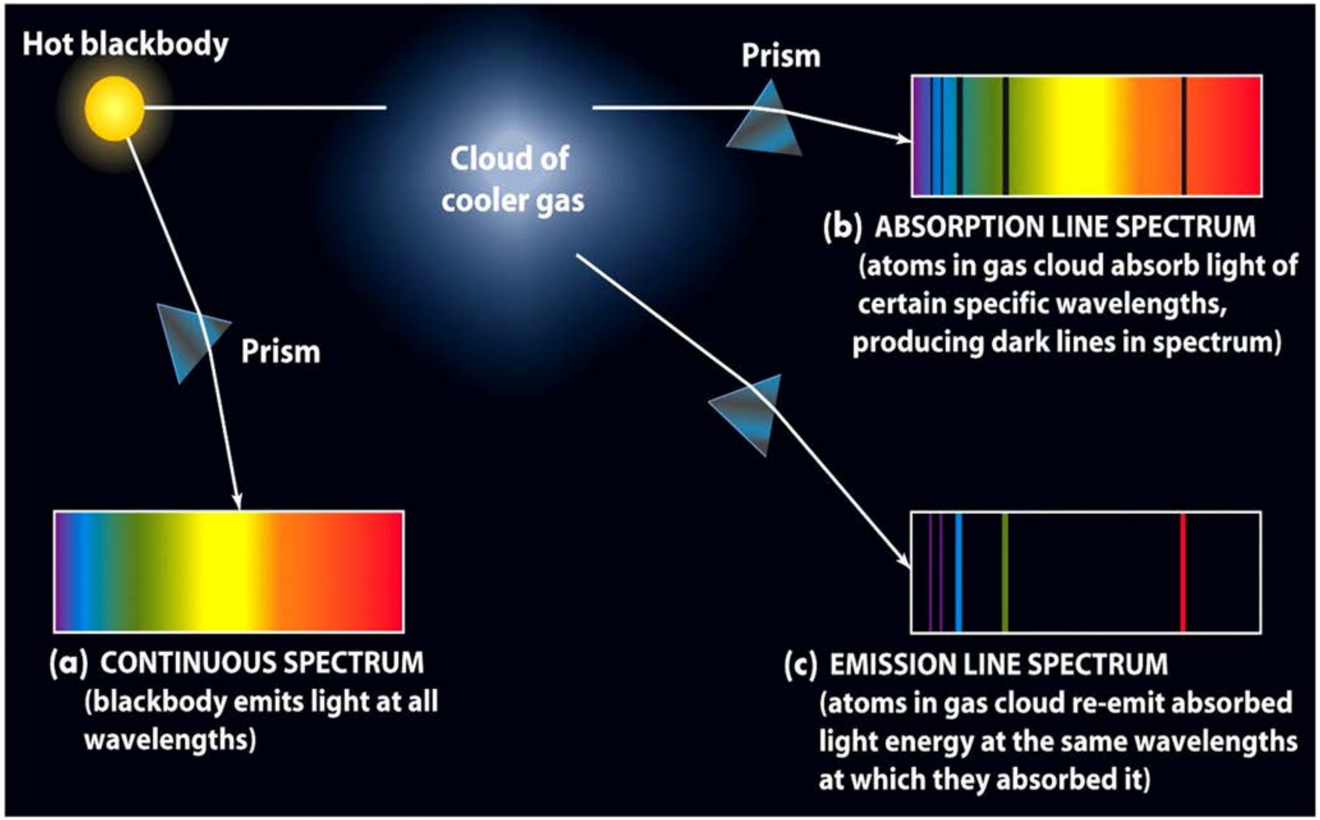




Light of different wavelengths is in phase at different reflection angles from the grating

Detector captures images of the entrance aperture (slit) at different wavelengths

Kirchhoff's Laws



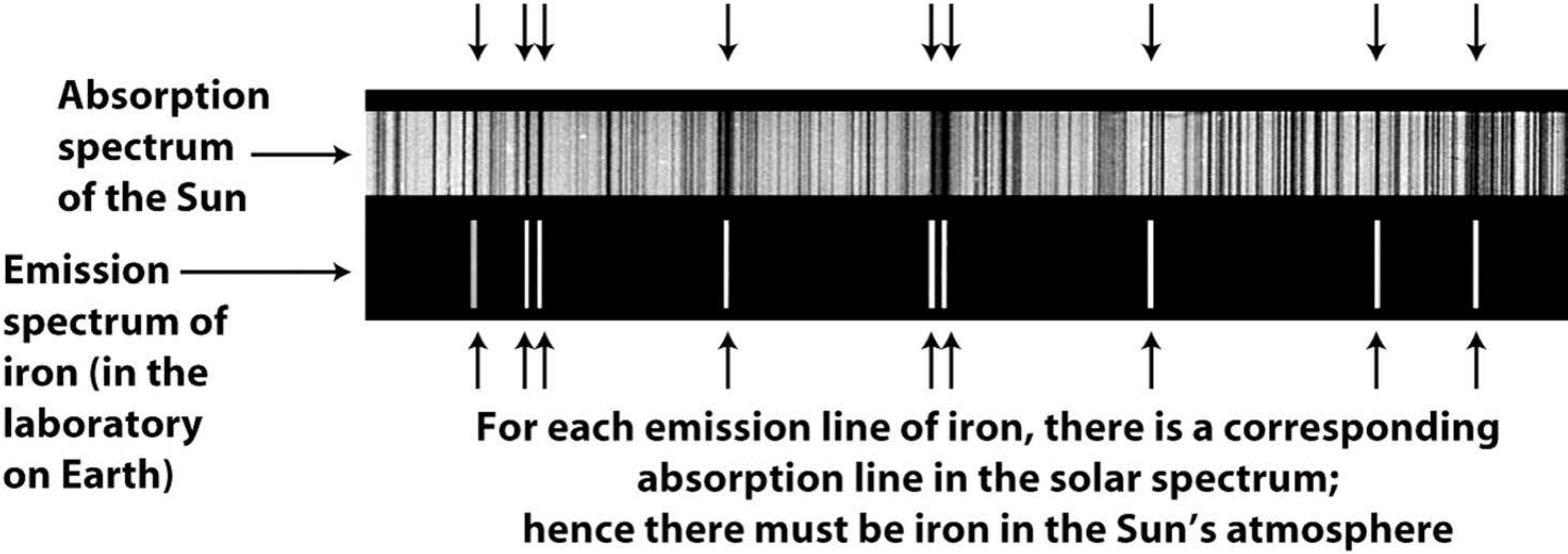
(b) ABSORPTION LINE SPECTRUM (atoms in gas cloud absorb light of certain specific wavelengths, producing dark lines in spectrum)

(a) CONTINUOUS SPECTRUM (blackbody emits light at all wavelengths)

(c) EMISSION LINE SPECTRUM (atoms in gas cloud re-emit absorbed light energy at the same wavelengths at which they absorbed it)

1. **Continuous spectrum**: Any hot opaque body (e.g., hot gas/plasma) produces a continuous spectrum
2. **Emission line spectrum**: A hot transparent gas will produce an emission line spectrum
3. **Absorption line spectrum**: A (relatively) cool transparent gas in front of a source of a continuous spectrum will produce an absorption line spectrum

Astronomical Spectroscopy



For each emission line of iron, there is a corresponding absorption line in the solar spectrum; hence there must be iron in the Sun's atmosphere

Laboratory spectra ➙ Line identifications in astro.sources
Analysis of spectra ➙ Chemical abundances + physical conditions (temperature, pressure, gravity, ionizing flux, magnetic fields, etc.)

+ Velocities

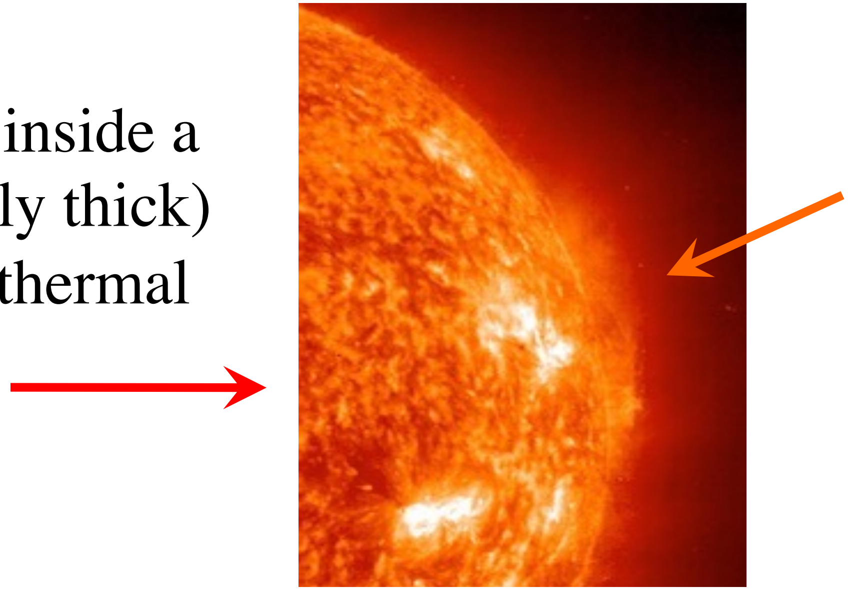
Opaque or Transparent?

It depends on whether the gas (plasma) is

Optically thick: short mean free path of photons, get absorbed and re-emitted many times, only the radiation near the surface escapes; or

Optically thin: most photons escape without being reabsorbed or scattered

(Optical thickness is generally proportional to density)



Hot plasma inside a star (optically thick) generates a thermal continuum

Cooler, optically thin gas near the surface imprints an absorption spectrum

Atomic Radiative Processes

Radiation can be emitted or absorbed when electrons make transitions between different states:

Bound-bound: electron moves between two bound states (orbitals) in an atom or ion. Photon is emitted or absorbed.

Bound-free:

- Bound → unbound: **ionization**
- Unbound → bound: **recombination**

Free-free: free electron gains energy by absorbing a photon as it passes near an ion, or loses energy by emitting a photon. Also called **bremsstrahlung**.

Which transitions happen depends on the temperature and density of the gas → spectroscopy as a physical diagnostic

Energy Levels in a Hydrogen Atom

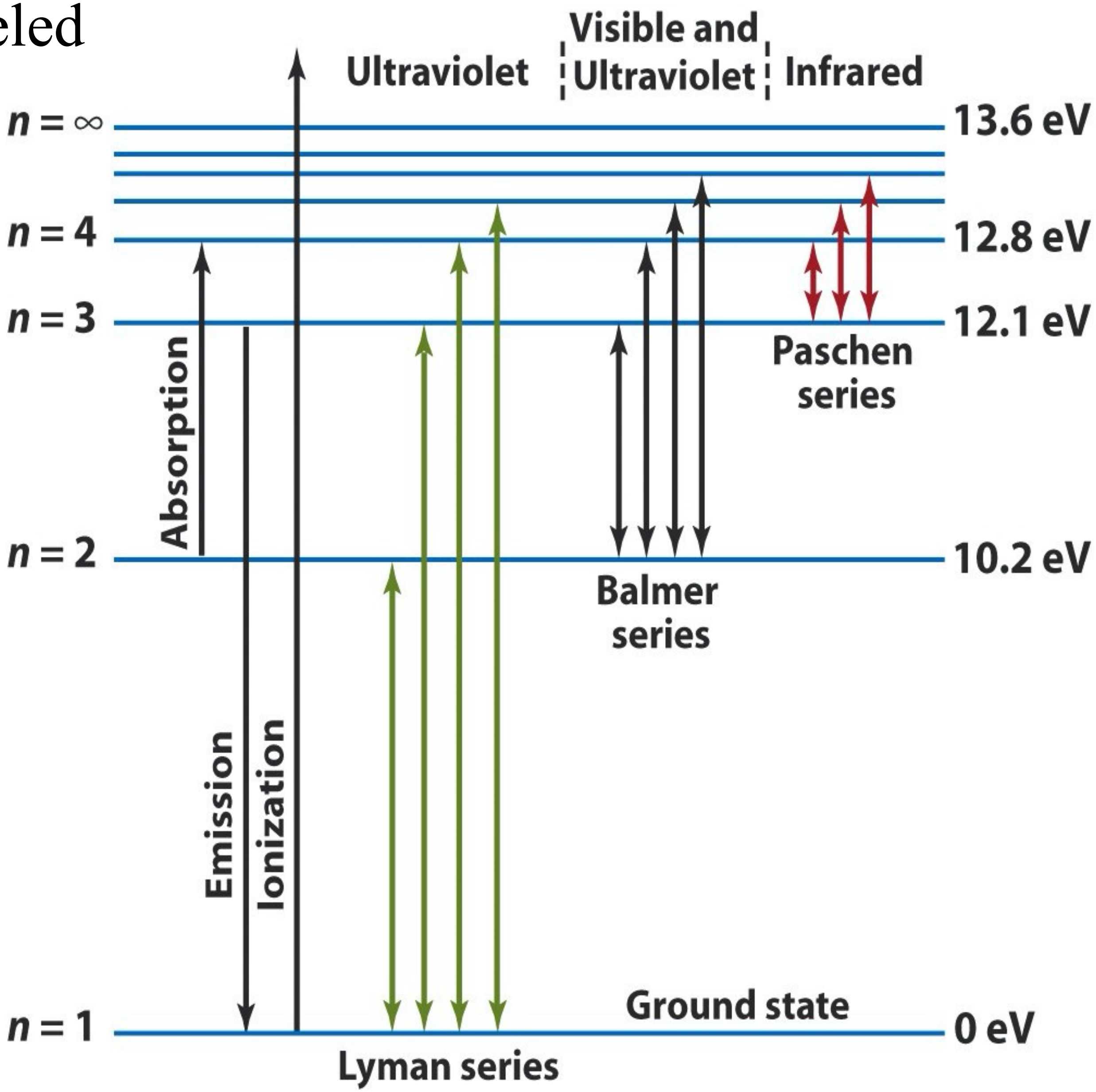
Energy levels are labeled by ***n*** - the *principal quantum number*

Energy of a given level is:

$$E_n = -\frac{R}{n^2}$$

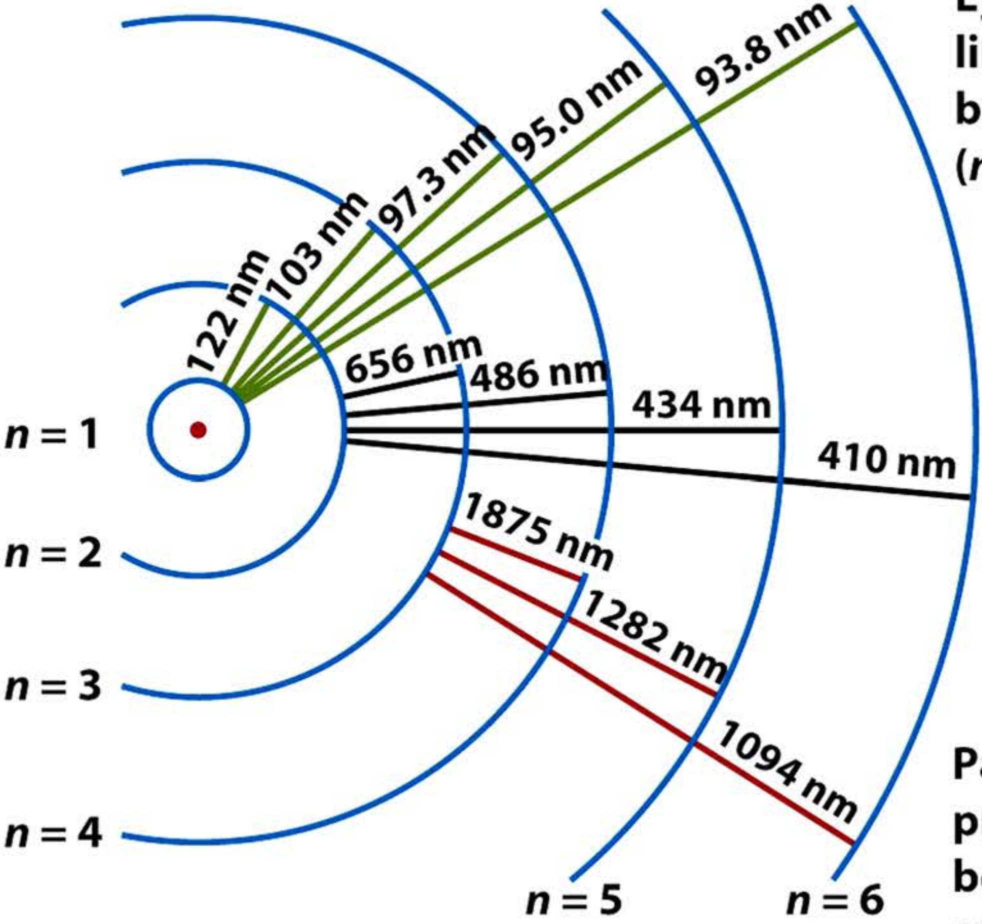
where R = 13.6 eV is a Rydberg' s constant

Lowest level, n=1, is the *ground state*



Families of Energy Level Transitions Correspond to Spectroscopic Line Series

$$\text{Photon energy: } h\nu = \left| E_i - E_j \right|$$

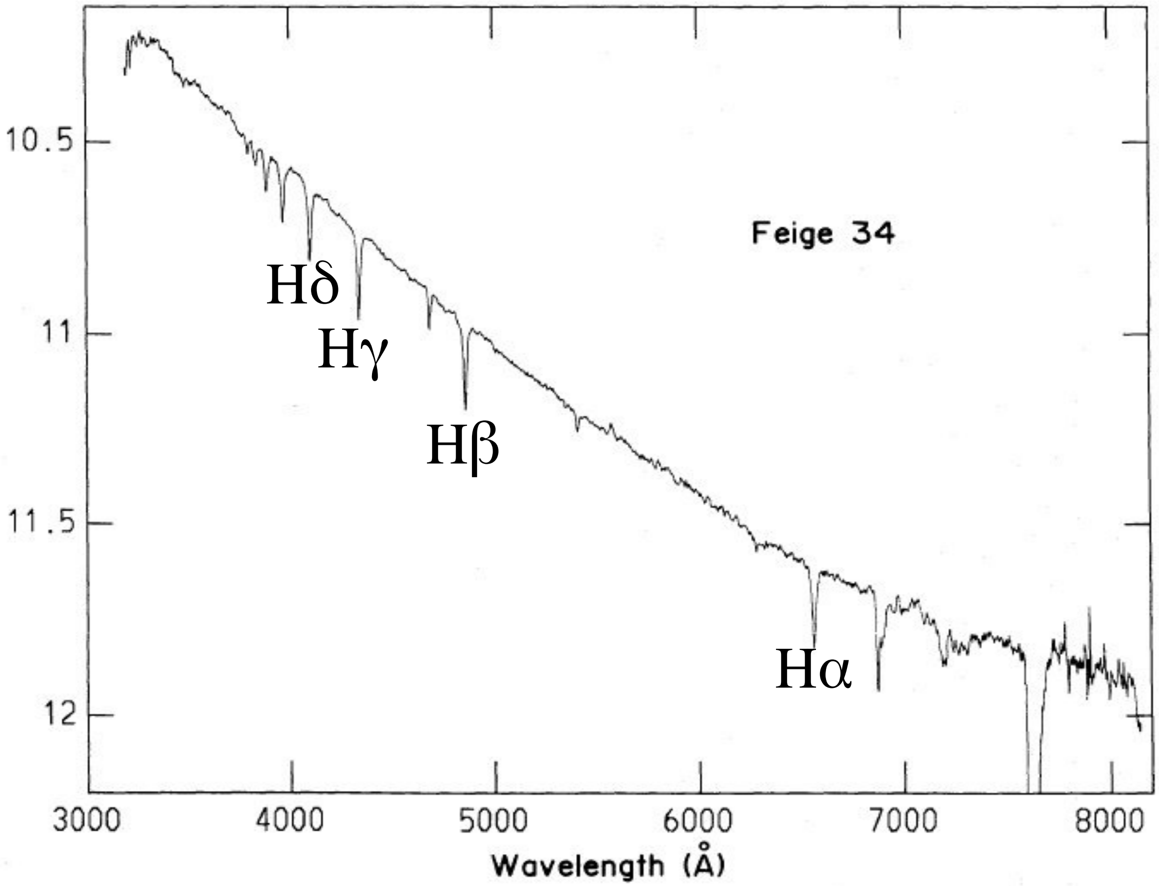


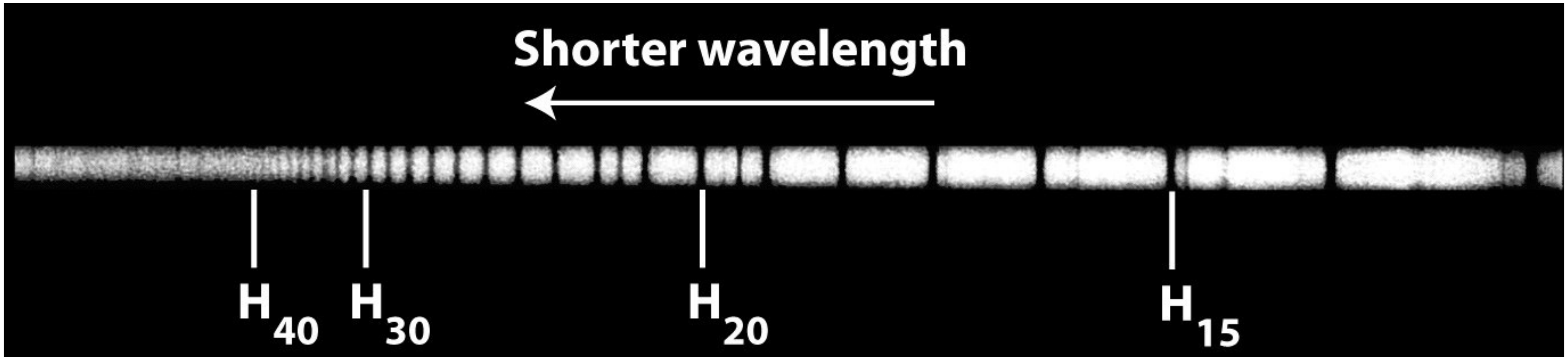
Lyman series (ultraviolet) of spectral lines: produced by electron transitions between the *n* = 1 orbit and higher orbits (*n* = 2, 3, 4, …)

Balmer series (visible and ultraviolet) of spectral lines: produced by electron transitions between the *n* = 2 orbit and higher orbits (*n* = 3, 4, 5, …)

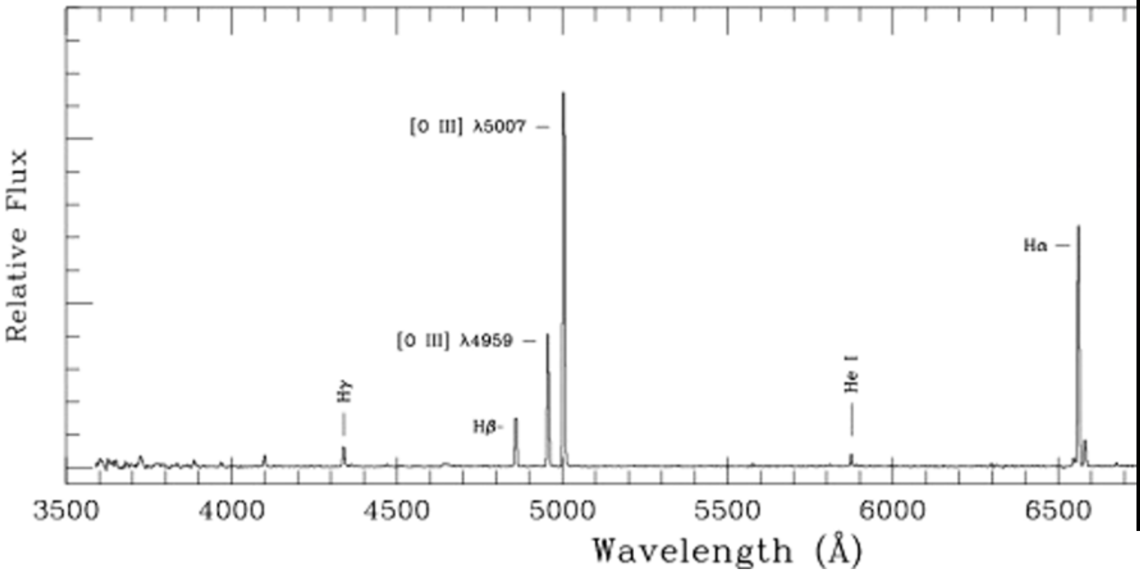
Paschen series (infared) of spectral lines: produced by electron transitions between the *n* = 3 orbit and higher orbits (*n* = 4, 5, 6, …)

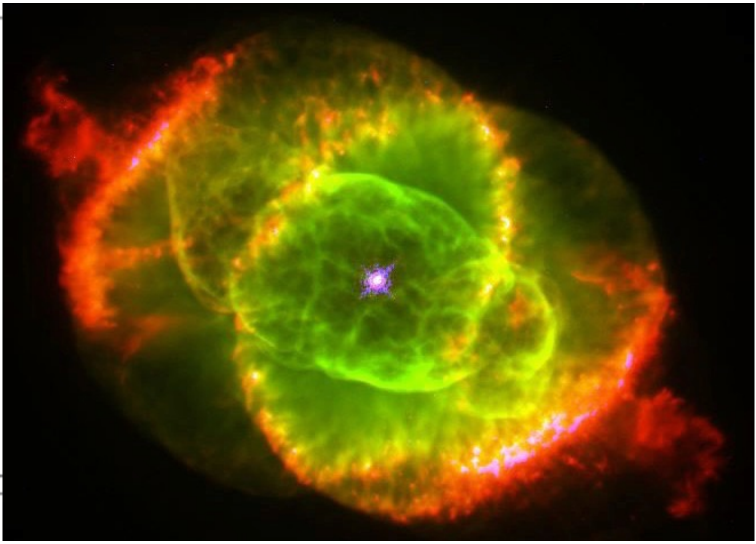
Balmer Series Lines in Stellar Spectra





"Forbidden" Lines and Nebulium





Early spectra of astronomical nebulae have shown strong emission lines of an unknown origin. They were ascribed to a hypothetical new element, "nebulium".

It turns out that they are due to excited energy levels that are hard to reproduce in the lab, but are easily achieved in space, e.g., doubly ionized oxygen. Notation: [O III] 5007 ← Wavelength in Å

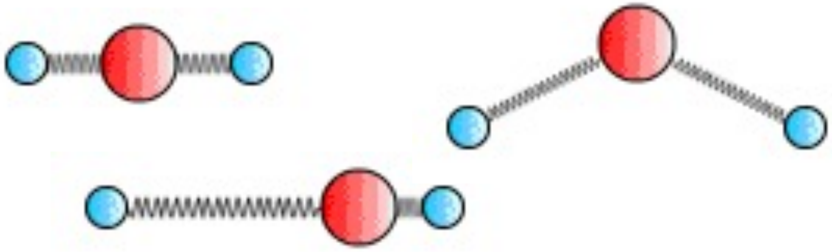
Brackets indicate "forbidden"

Element

Ionization state: III means lost 2 e's

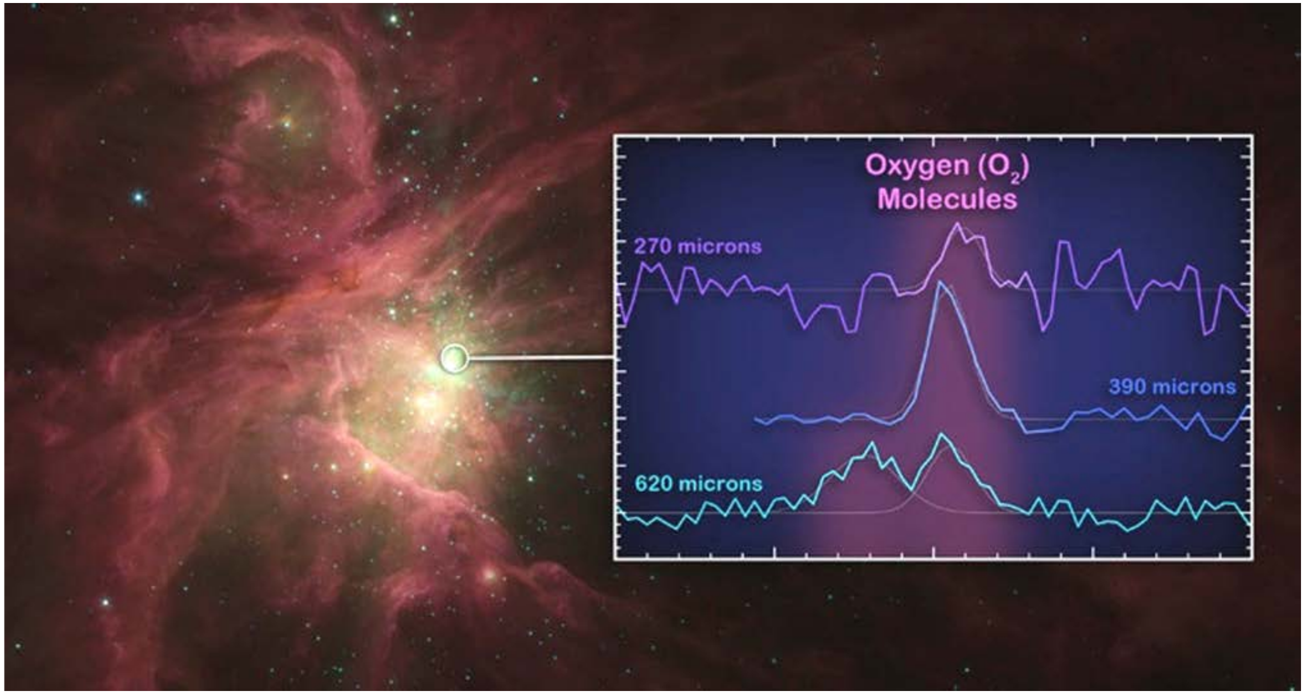
Spectra of Molecules

They have additional energy levels due to vibration or rotation



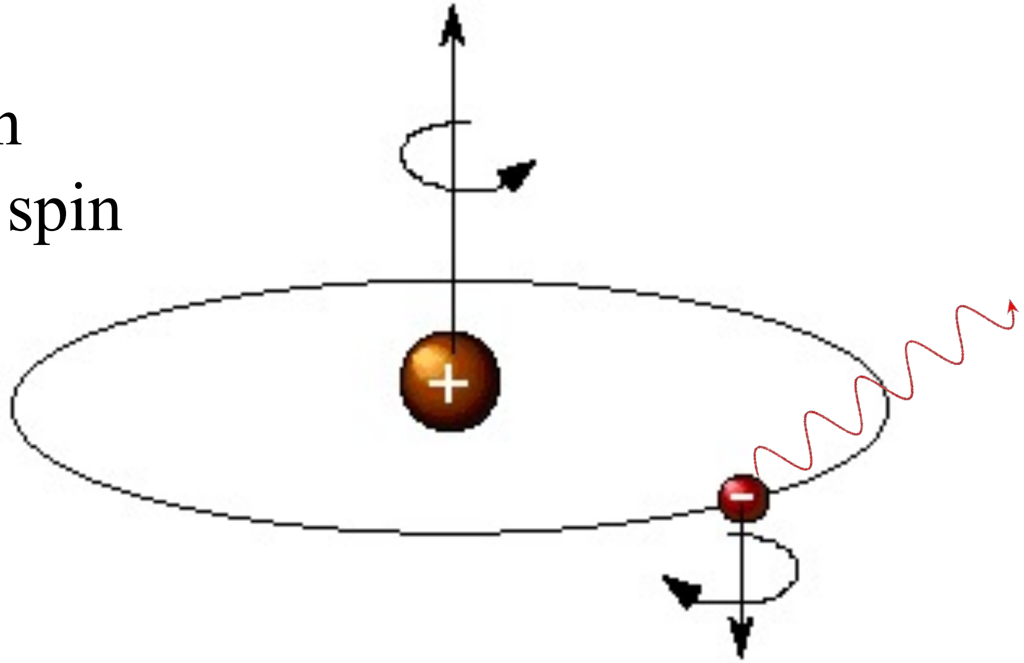
These tend to have a lower energy than the atomic level transitions, and are thus mostly on IR and radio wavelengths

They can thus probe cooler gas, e.g., interstellar or protostellar clouds



Hydrogen 21cm Line

Corresponds to different orientations of the electron spin relative to the proton spin



Lower energy state: Proton and electron have opposite spins.

Transition probability $= 3 \times 10^{-15}\ s^{-1}$ = once in 11 Myr per atom

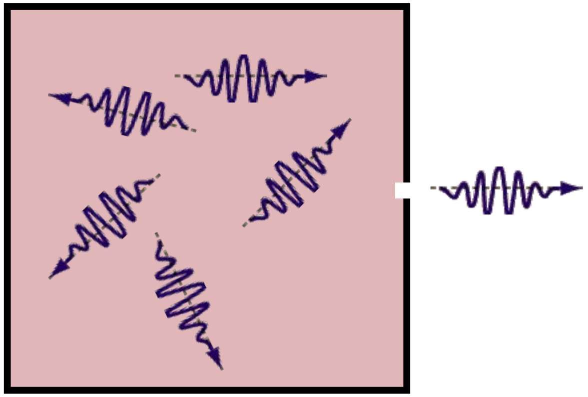
Very important, because neutral hydrogen is so abundant in the universe. This is the principal wavelength for studies of interstellar matter in galaxies, and their disk structure and rotation curves

Blackbody Radiation

This is radiation that is in ***thermal equilibrium*** with matter at some temperature T.

Blackbody is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths

Lab source of blackbody radiation: hot oven with a small hole which does not disturb thermal equilibrium inside:



Blackbody radiation

Important because:

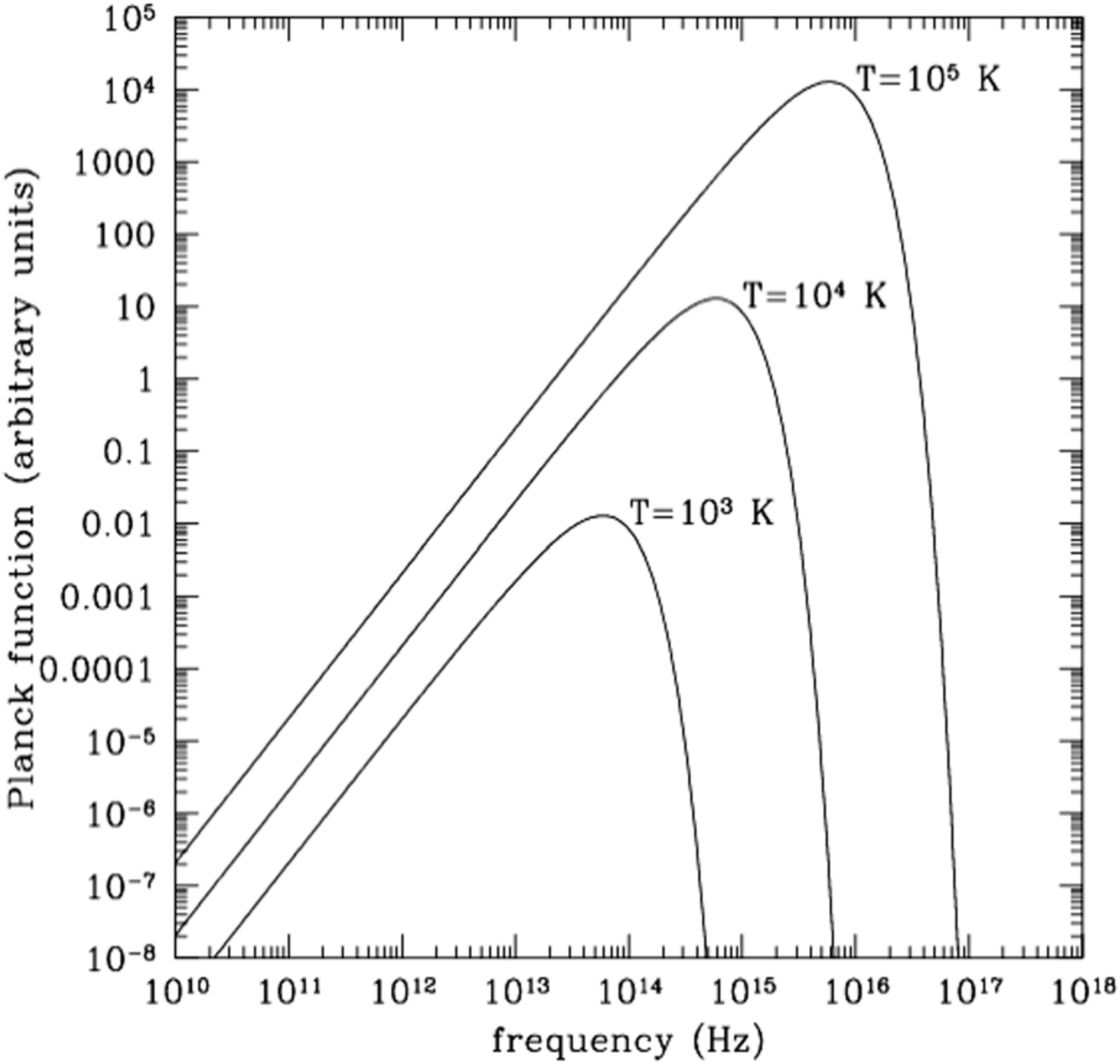
- Interiors of stars (for example) are like this
- Emission from many objects is roughly of this form.

Blackbody Spectrum

The frequency dependence is given by the **Planck function**:

$$B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT)-1}$$

h = Planck's constant
k = Boltzmann's constant



Same units as specific intensity: erg s^{-1} cm^{-2} $sterad^{-1}$ Hz^{-1}

Blackbody Spectrum

The Planck function peaks when $dB_n(T)/d\nu = 0$:

$$h\nu_{\max} = 2.82kT$$

$$\nu_{\max} = 5.88\times10^{10}T \text{ Hz K}^{-1}$$

This is ***Wien displacement law*** - peak shifts linearly with Increasing temperature to higher frequency.

Asymptotically, for low frequencies $h\nu \ll kT$, the ***Rayleigh-Jeans law*** applies:

$$B_\nu^{RJ}(T) = \frac{2\nu^2}{c^2}kT$$

Often valid in the radio part of the spectrum, at freq's far below the peak of the Planck function.

Blackbody Luminosity and Temperature

The **energy density** of blackbody radiation: $u(T) = aT^4$

a = 7.56 x 10^{-15} erg cm^{-3} K^{-4} is the radiation constant.

The **emergent flux** from a blackbody: $F = \sigma T^4$

σ = 5.67 x 10^{-5} erg cm^{-2} K^{-4} s^{-1} = Stefan-Boltzmann const.

A sphere (e.g., a star), with a radius R, temperature T, emitting as a blackbody, has a **luminosity**:

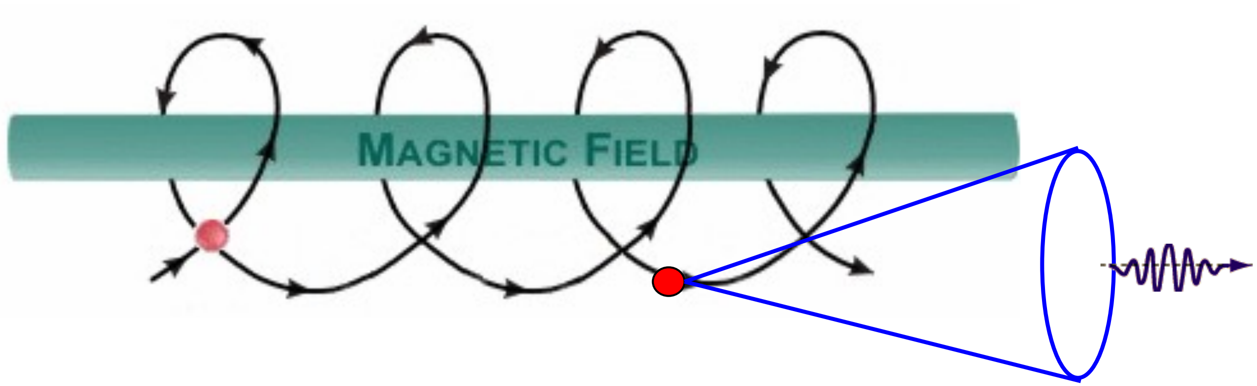
$$L = 4\pi R^2 \sigma T^4$$

For a source with a bolometric flux ***F***, *regardless of whether its spectrum is a blackbody*, define the **effective temperature T_e** :

$$F \equiv \sigma T_e^4$$

e.g., for the Sun: $L_{sun} = 4\pi R_{sun}^2 \sigma T_e^4$ …find T_e = 5770 K.

Synchrotron Emission

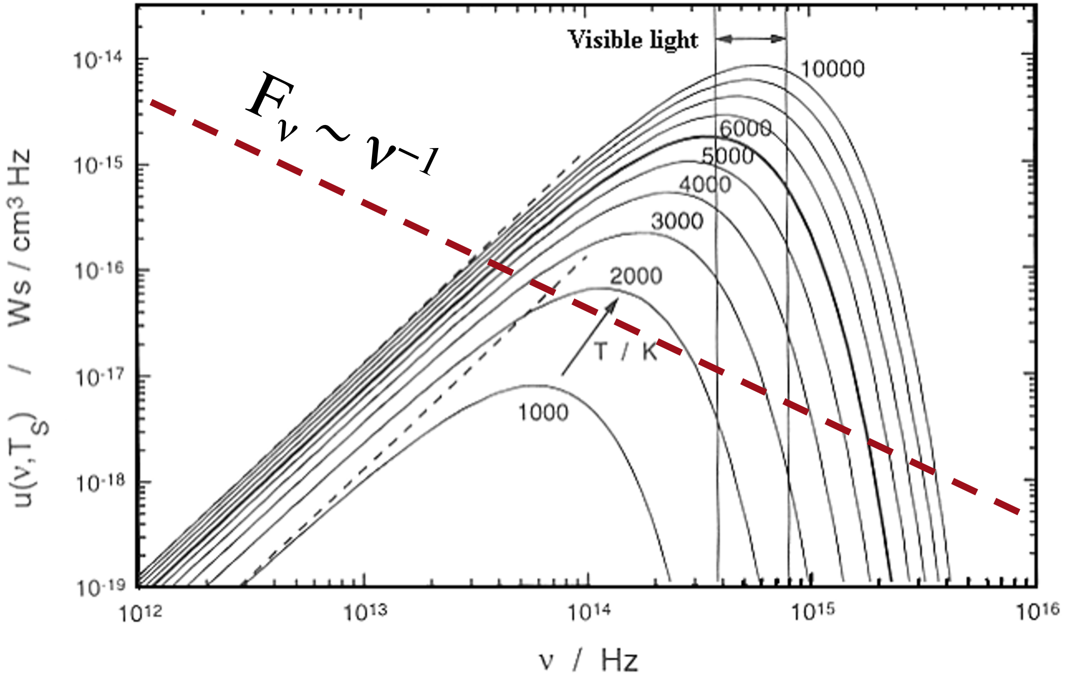


- An electron moving at an angle to the magnetic field feels Lorentz force; therefore it is accelerated, and it radiates in a cone-shaped beam

- The spectrum is for the most part a power law:

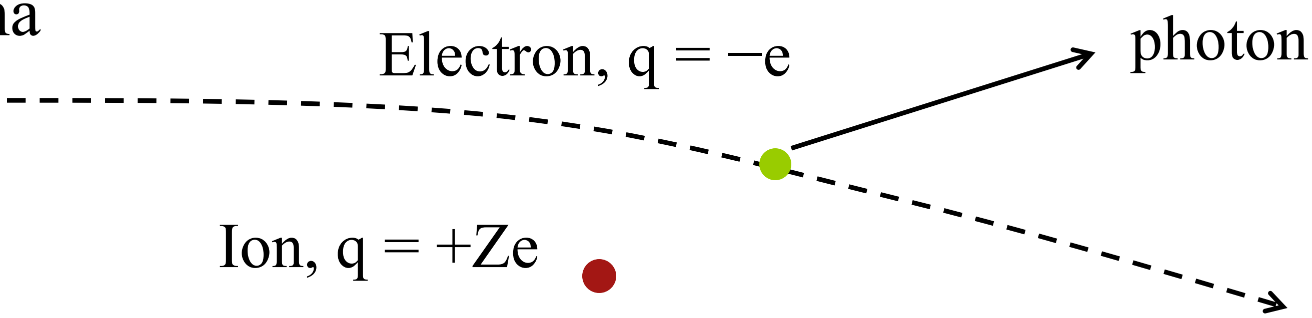
$$F_\nu \sim \nu^\alpha\ , \ \ \alpha \sim -1$$

(*very* different from a blackbody!)



Thermal Bremsstrahlung

A free-free emission from electrons scattering by ions in a very hot plasma



Electron, $q = -e$

photon

Ion, $q = +Ze$

Example: X-ray gas in clusters of galaxies