

Modern Astronomical Techniques - ASTR 257

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Office: ISB 305


Office Hours: Wed 11-12:30

Overview

This class will survey current observational capabilities across the electromagnetic spectrum. For each wavelength, we will consider the basics of the instruments used, the capabilities of current and next generation instruments, the major sources of emission, and science highlights.

In addition, we will cover some basic statistics, data analysis, and work with data archives and online catalogs.

Outline

1. The atmosphere, overview of current telescopes, basic concepts
 2. CCDs
 3. Proposal writing
 4. Optical and UV
 - telescopes and instruments
 - intro to FITS data and optical data reduction
 5. Infrared
 6. X-ray
 - telescopes and instruments
 - data analysis examples in the photon counting regime
 7. Data archives, object catalogs/databases
 8. Statistics and regression analysis
 9. Hard X-ray and Gamma-ray (space and ground)
 10. Radio
 - telescopes and instruments, interferometry basics
 - data analysis examples
 11. Non-photon signals: neutrinos, cosmic rays, gravity waves
- 

Some Useful Texts

“Measuring the Universe: A Multiwavelength Perspective”
– George Rieke

“Observational Astrophysics” – Lena, Lebrun, Mignard

Cambridge Observing Handbooks for Research Astronomers:

“Handbook of CCD Astronomy” – Howell

“Handbook of X-ray Astronomy” – Arnaud, Smith, Siemingowska

“Handbook of Infrared Astronomy” – Glass

“Practical Statistics for Astronomers” – Wall and Jenkins

“Data Reduction and Error Analysis for the Physical Sciences” –
Bevington and Robinson

Grading

Homework Assignments: 6 assignments (1-1.5 weeks to complete). These will include some data analysis and use of concepts from class.

Mock Observing Proposal: Everyone will prepare a mock observing proposal for either:

- Chandra X-ray Observatory (ACIS)
- Hubble Space Telescope (ACS or WFC3 imaging)

Proposals will be peer-reviewed by the class near the end of the quarter. Grading will be based on both the proposal and participation in the review.

No Final Exam, but the last homework will be due during finals week.

Some Schedule Notes

April 9: Prof. Profumo, astronomical signals of dark matter

May 28 (?): Emma Storm, radio data analysis tutorial

Proposal Dates:

April 30 – discuss proposal topic ideas

May 9 – pick topic, initial feasibility study due

May 23 – draft of introduction due

May 30 – full proposal due

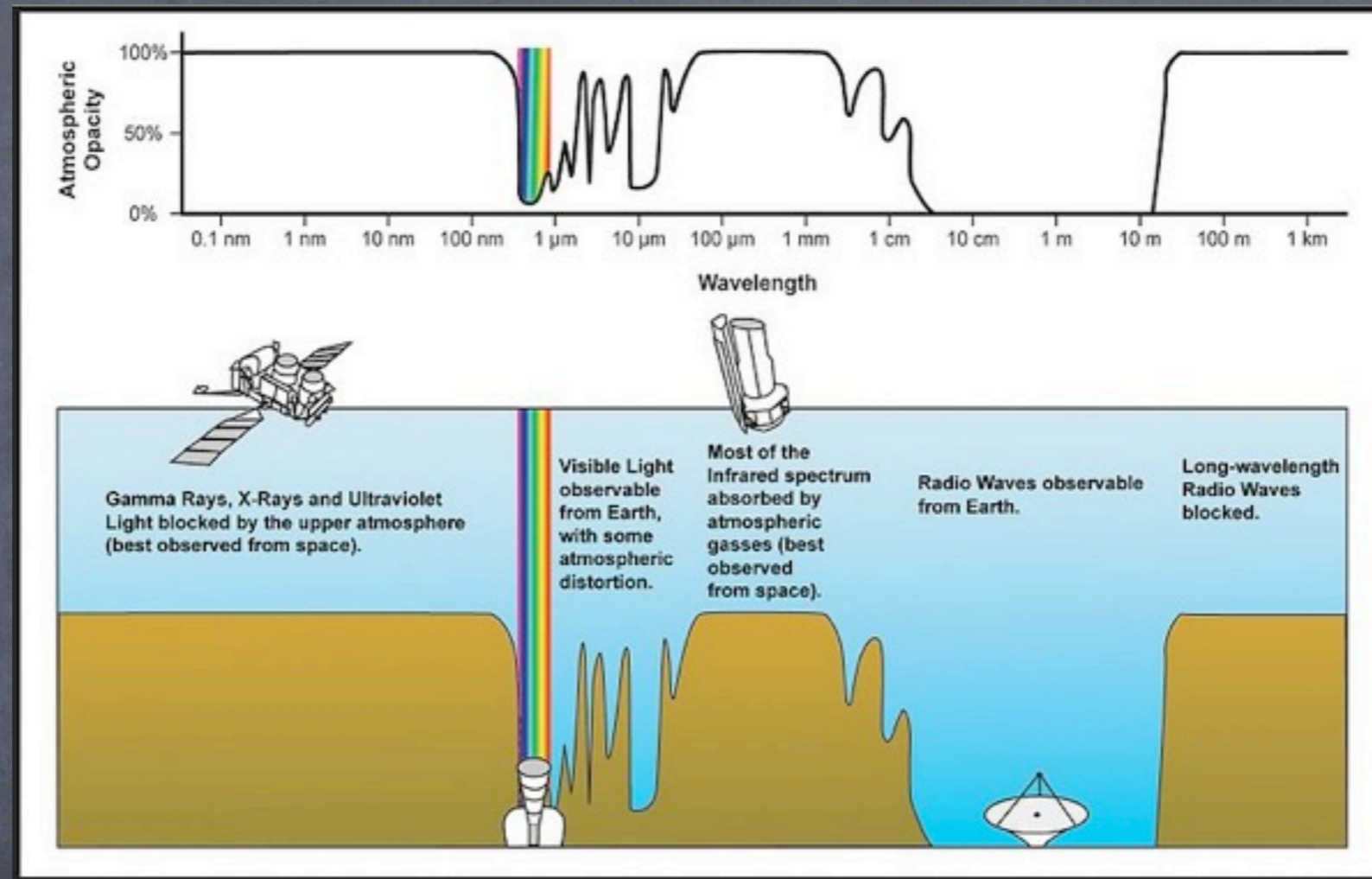
June 6 – proposal review ****attendance important**

Class Webpage

http://scipp.ucsc.edu/~tesla/ay257_2013.html

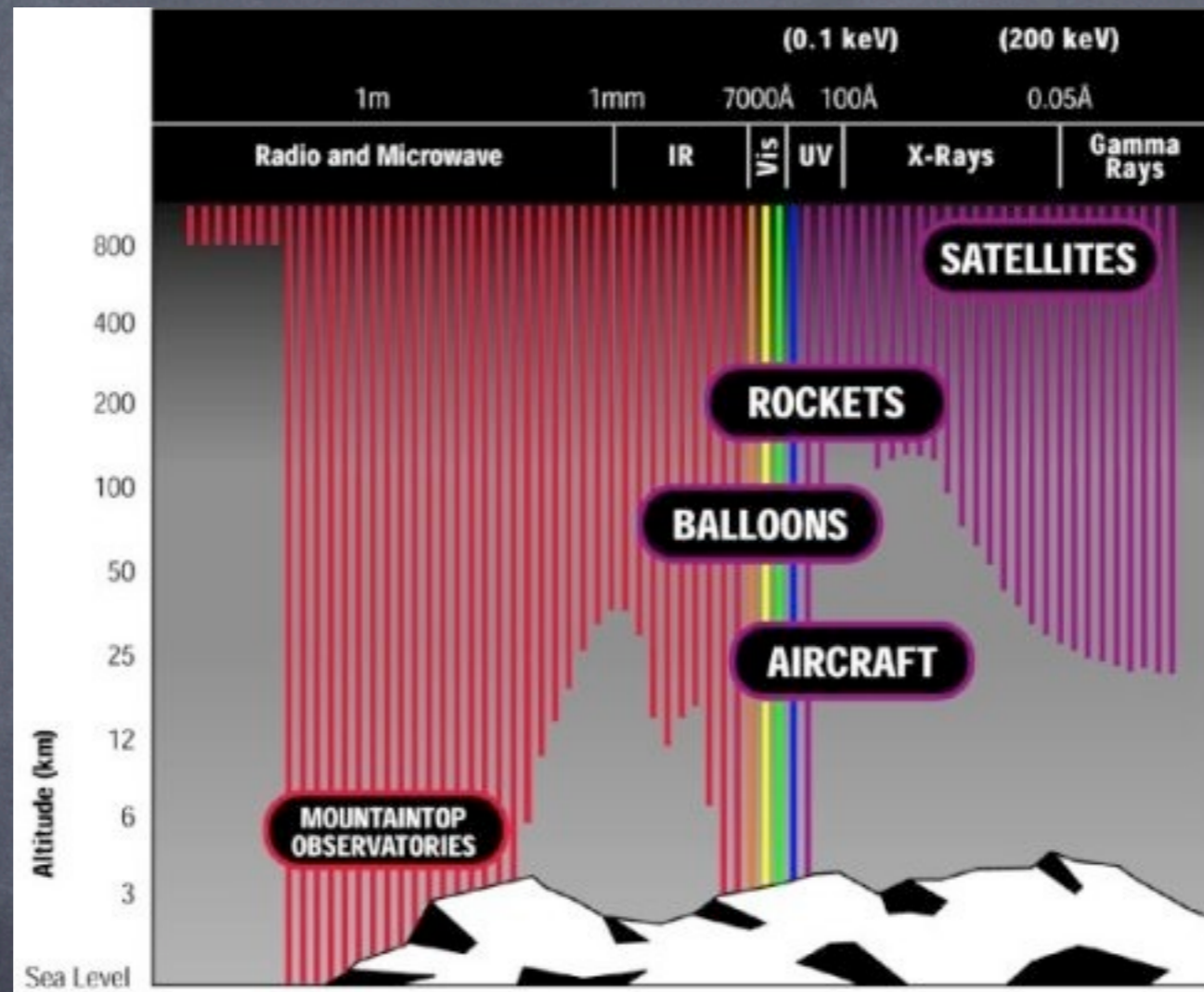
The Atmosphere and Telescopes Across the Electromagnetic Spectrum

The Pesky Atmosphere



The optical and radio wavebands are the two major windows for ground based observing with other wavelengths suffering severe attenuation by the Earth's atmosphere.

The Pesky Atmosphere



Seen in a different way, here is the depth to which different frequencies of light penetrate. Some observations can be done with balloons, aircraft, and rockets.

The Radio Window

The atmosphere is transparent to radio waves between roughly 5 MHz and 300 GHz, limited at the low end by reflection by the ionosphere (>50 km) and at the high end by absorption by water and CO₂. Also, daylight is not a problem!

Interference:

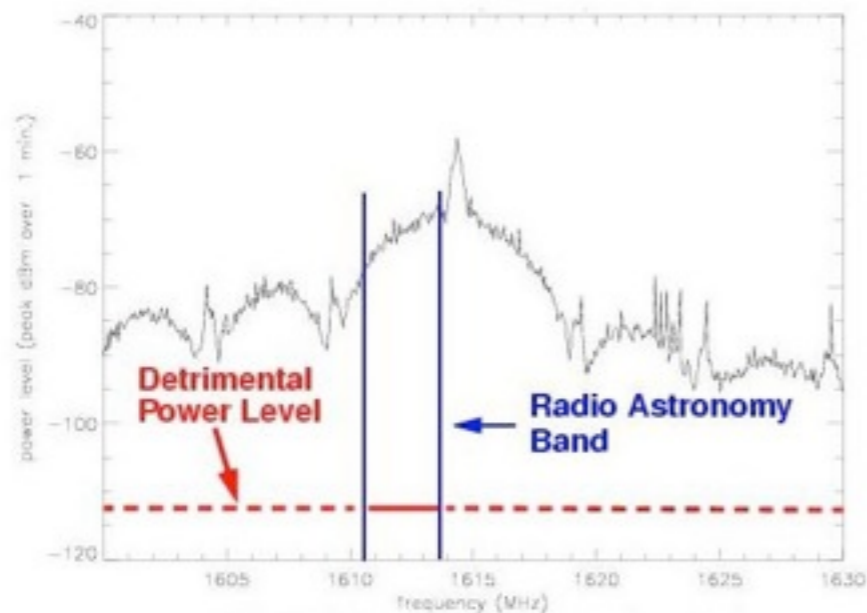
Man-made interference is a big problem. A cell phone on the Moon would be a strong radio source!!

Certain narrow bands are reserved for radio astronomy, and radio telescopes are located in radio quiet areas (sometimes in valleys), but this is an increasing problem.

National Radio Quiet Zone established around NRAO in Green Bank, WV.

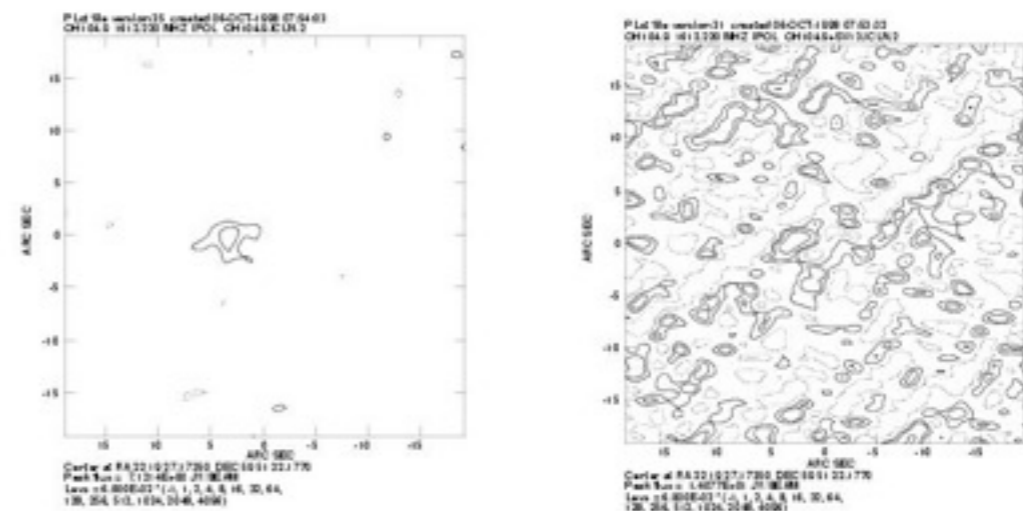
Radio Interference

"Spillover" Into a Radio Astronomy Band by a Too-Broad Transmitter



This graph illustrates interference to radio astronomy from a satellite transmitter whose signal is so broad that it spills into the band of frequencies allocated to radio astronomy by international agreement. The radio astronomy band lies between the two vertical blue lines. The horizontal red line indicates the power level defined by the International Telecommunications Union (ITU) as detrimental to radio astronomy; any signal above the red line is above this detrimental level. Instead of being designed and built to eliminate signals outside of its authorized range, this transmitter spreads radio emissions over a very wide range of frequencies, far beyond its ITU-authorized range.

Effect of Radio Interference On Astronomical Observations



VLA Images of OH/IR Star at 1612 MHz: No satellite present (left) and satellite -22 degrees from star (right)

(From G.B. Taylor, NRAO)

NRAO website

Poor engineering can cause transmitters to emit outside their proscribed range. Satellites particularly a problem, but also cell phones, microprocessors in everything, flying squirrels (with tags) ...

Radio Telescopes

Single Dish:

- Green Bank Telescope, West Virginia (100-m steerable dish)
- Effelsberg Telescope, Germany (100-m steerable dish)
- Arecibo Telescope, Puerto Rico (305-m fixed dish)



Arrays:

- Very Large Array (VLA/JVLA), New Mexico (27 25-m dishes, max 36 km baseline)
- Very Long Baseline Array (VLBA) (10 25-m dishes, Hawaii to the Virgin Islands)
- Low Frequency Array for radio astronomy (LOFAR) (~20,000 small antennas over 100 km in Netherlands)

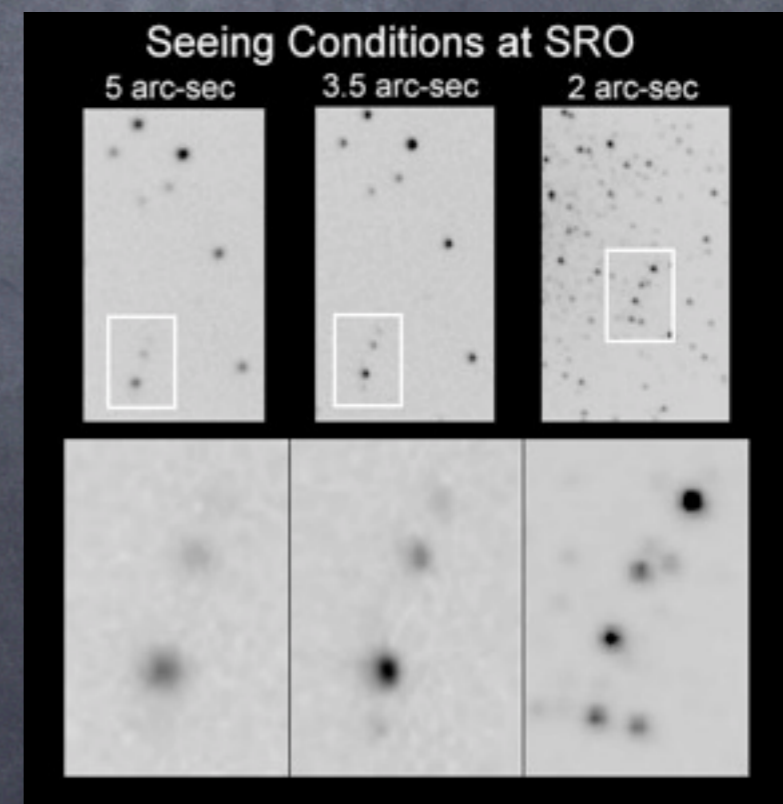


The Optical Window

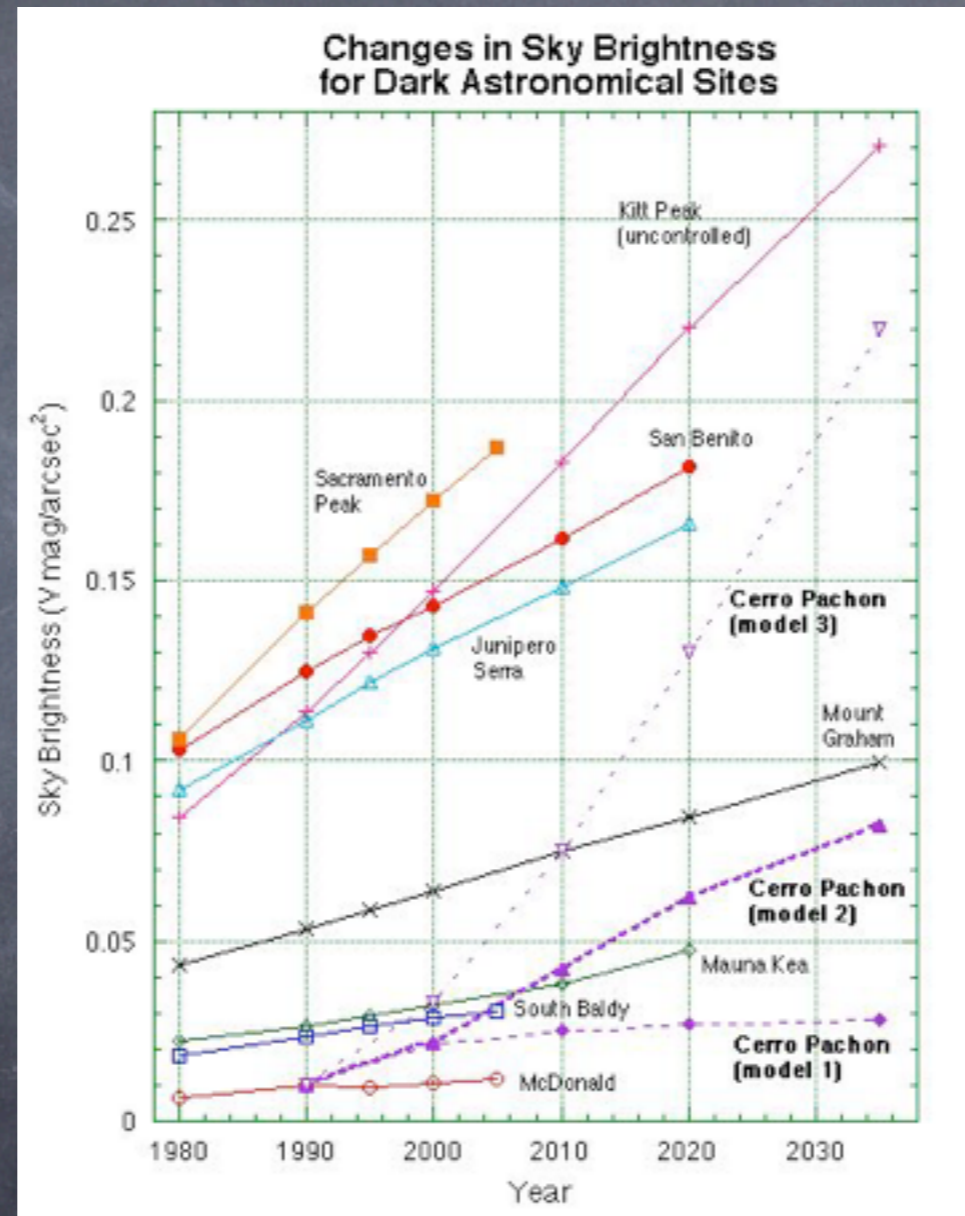
Light from the near UV to the near IR (~300–1100 nm) also passes through the atmosphere (not coincidentally this includes the wavelength range our eye detects).

Obviously, atmospheric extinction and turbulence play a large role in ground-based optical observing (need good weather and good seeing!) --- to be discussed.

Also major light sources like the Sun, the Moon, and light pollution...



Light Pollution



A. Walker

Optical Telescopes

Ground Based Telescopes



Astronomy Magazine, November 2010

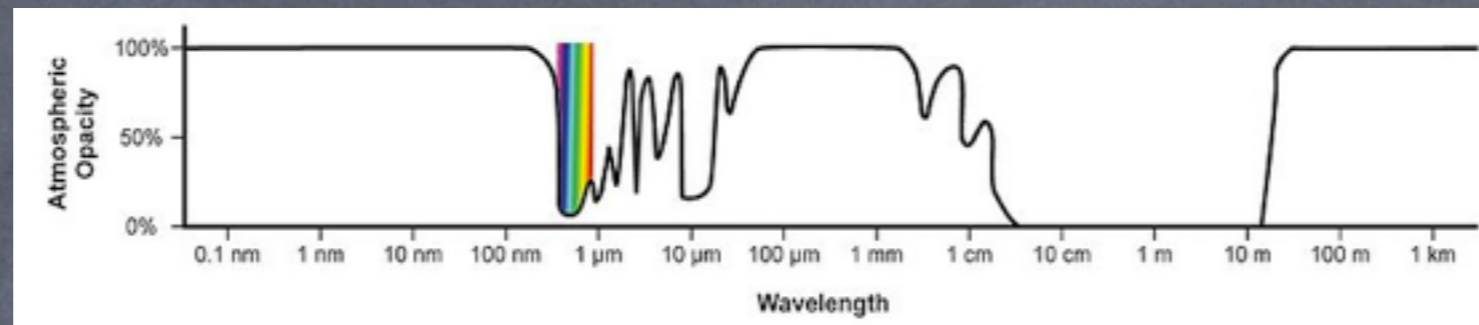
Optical Telescopes

Major Ground Based:

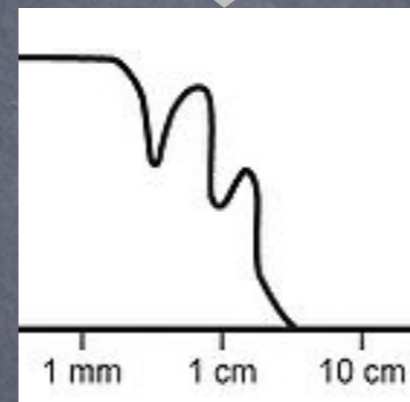
- 10-m: Gran Telescopio CANARIAS (Canary Islands)
2 Keck Telescopes (Hawaii)
- 8-m: Large Binocular Telescope (2) (Arizona)
Subaru (Hawaii)
4 VLT telescopes (Chile)
Gemini North (Hawaii) and South (Chile)
- 6.5-m: 2 Magellan Telescopes (Chile)
MMT (Arizona)
- also fixed ~ 9.2-m telescopes SALT (South Africa) and Hobby-Eberly (Texas)

Space-Based: Hubble Space Telescope 2.4-m

Microwave/Submm

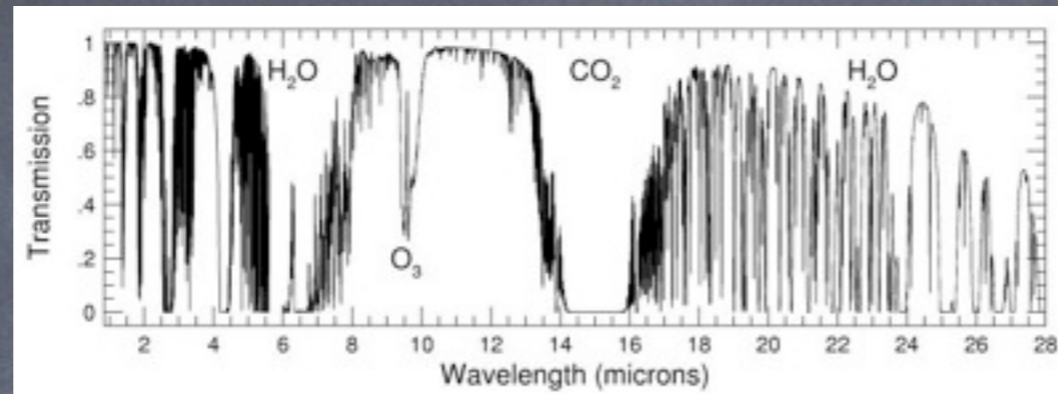


At shorter wavelengths, atmospheric absorption by water is an issue and telescopes must be located in high, dry places.



Observations using a ground-based (e.g. ALMA, SPT, ACT, CARMA), space-based (e.g. WMAP, Planck), and balloon-borne (e.g. BOOMERanG) instruments.

Infrared Astronomy



Most of the infrared band is absorbed by water or CO₂. The atmosphere also emits in infrared peaking around 10 μm . **Only a few, mostly near-IR bands are observable from the ground.**

Infrared Windows in the Atmosphere

| Wavelength Range | Band | Sky Transparency | Sky Brightness |
|--------------------|--|--|----------------|
| 1.1 - 1.4 microns | J | high | low at night |
| 1.5 - 1.8 microns | H | high | very low |
| 2.0 - 2.4 microns | K | high | very low |
| 3.0 - 4.0 microns | L | 3.0 - 3.5 microns: fair 3.5 - 4.0 microns: high | low |
| 4.6 - 5.0 microns | M | low | high |
| 7.5 - 14.5 microns | N | 8 - 9 microns and 10 - 12 microns: fair others: low | very high |
| 17 - 40 microns | 17 - 25 microns: Q 28 - 40 microns: Z | very low | very high |
| 330 - 370 microns | | very low | low |

Infrared Telescopes

Ground: various instruments on the major telescopes, typically in high, dry places and mostly near IR

Plane:

- SOFIA (2010-)
- 0.3–1600 μm , 2.7-m on a Boeing 747



Space:

- Spitzer (2003, warm mission 5/2009-), 3–180 μm , 0.85-m
- WISE (12/2009–2/2011), all-sky survey at 3, 5, 12, 22 μm
- AKARI, 2–180 μm , (2006, warm mission)
- Herschel (2009–2013), 55–671 μm , 3.5-m
- JWST (2018?), 0.6–28 μm , 6.5-m

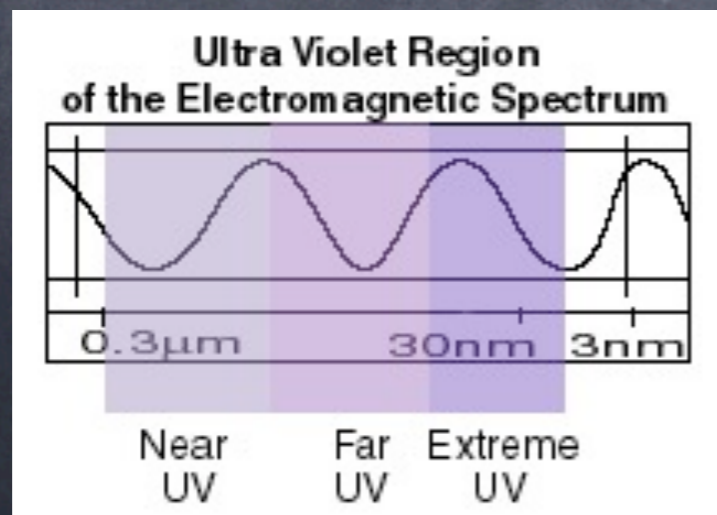


Ultraviolet Telescopes

UV radiation is absorbed by ozone in the upper atmosphere (20–30 km). Thank you ozone! Consequently, observations are done from space.

UV Telescopes:

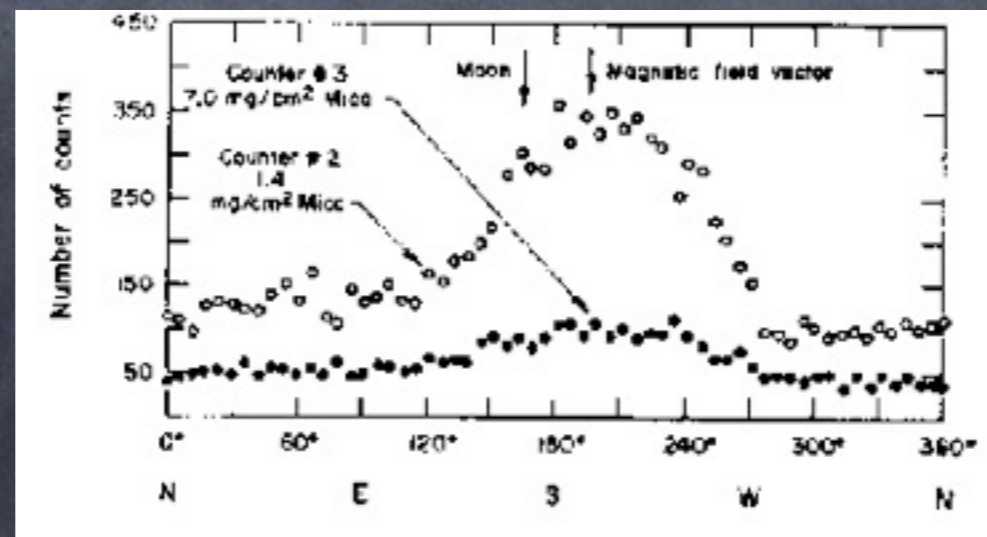
- HST, UV imaging and spectroscopic capabilities
- FUSE (1999–2007), high-res spectroscopy, 90–120 nm
- GALEX (2003–2011), UV surveys, imaging and spectroscopic observations in two bands: Far UV 1350–1780Å and Near UV 1770–2730Å



X-ray Astronomy

X-rays are absorbed by individual atoms in the Earth's atmosphere. The atmosphere is thick enough that X-rays have a negligible chance of reaching the ground and observations must be done with balloons or satellites.

Early X-ray observations were made with sounding rockets and balloons. The first cosmic X-ray source, the neutron star X-ray binary Scorpius X-1, was discovered by a rocket flight in 1962. For this and his contribution to the development of X-ray instruments Riccardo Giacconi won the nobel prize in 2002.



X-ray Telescopes

Soft X-ray:

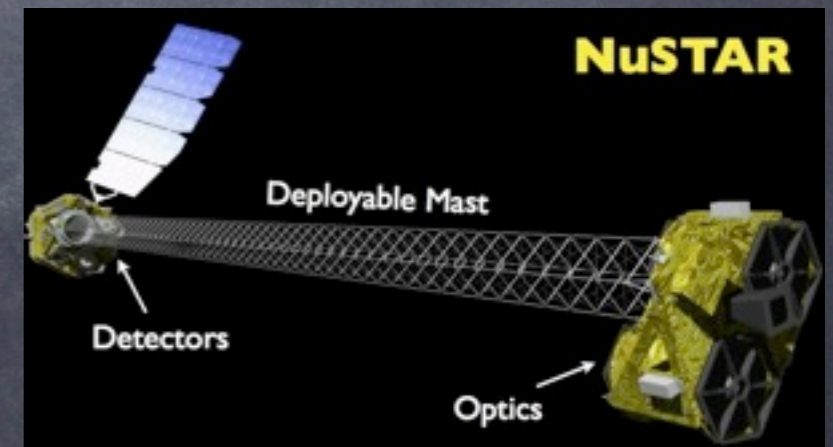
- Chandra (1999-), 0.2-10 keV
- XMM (2000-), 0.2-10 keV
- Suzaku (2005-), 0.2-600 keV

Hard X-ray:

- Integral (2002-), 3 keV-10 MeV
- Swift (2004-), 15-150 keV, GRB monitor with large FoV

Future:

- NuSTAR (2012-), hard X-ray imaging
- eROSITA (2014), all-sky survey
- ASTRO-H (2014), high-res spectra
- ATHENA (formerly IXO, formerly Con-X and XEUS)??

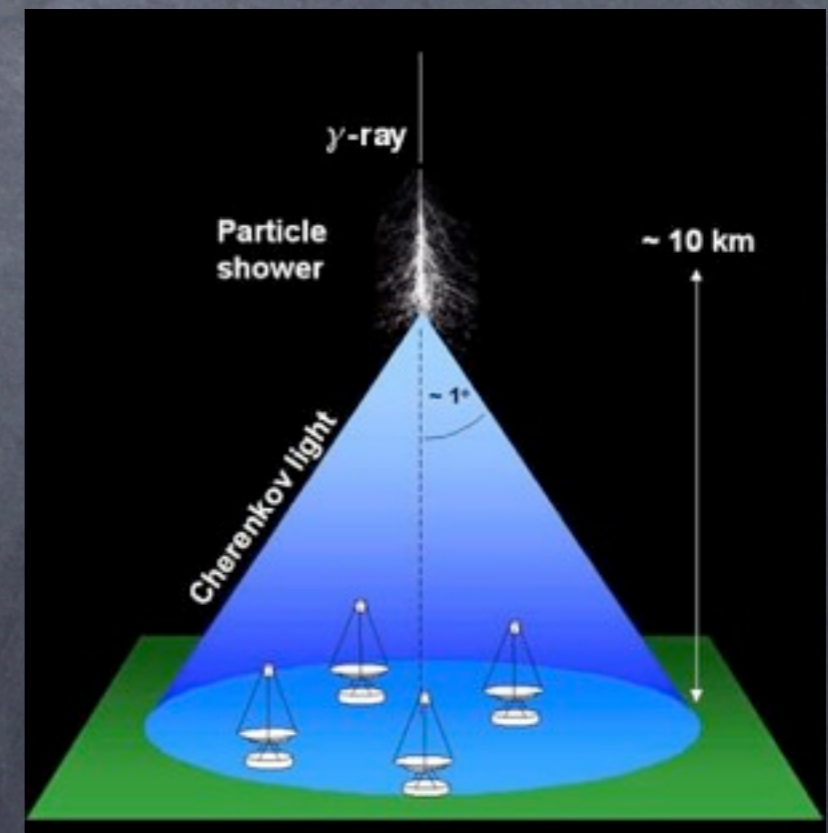


Gamma-Ray Astronomy

Gamma-ray radiation with energies below about 50 GeV are similarly absorbed by the atmosphere. The first gamma-ray satellite Explorer 11 launched in 1961 detected < 100 cosmic photons coming from all directions (Galactic background).

Very high energy gamma-rays can be detected from the ground. Here the atmosphere helps us!

They produce showers of secondary particles in the atmosphere (10–20 km) which lead to Cherenkov radiation (produced by fast moving charged particles which displace electrons in atoms of the surrounding medium).



Gamma-Ray Telescopes

Space:

- Fermi-LAT (2008-), 30 MeV-300 GeV
- AGILE (2007-), 30 MeV-50 GeV

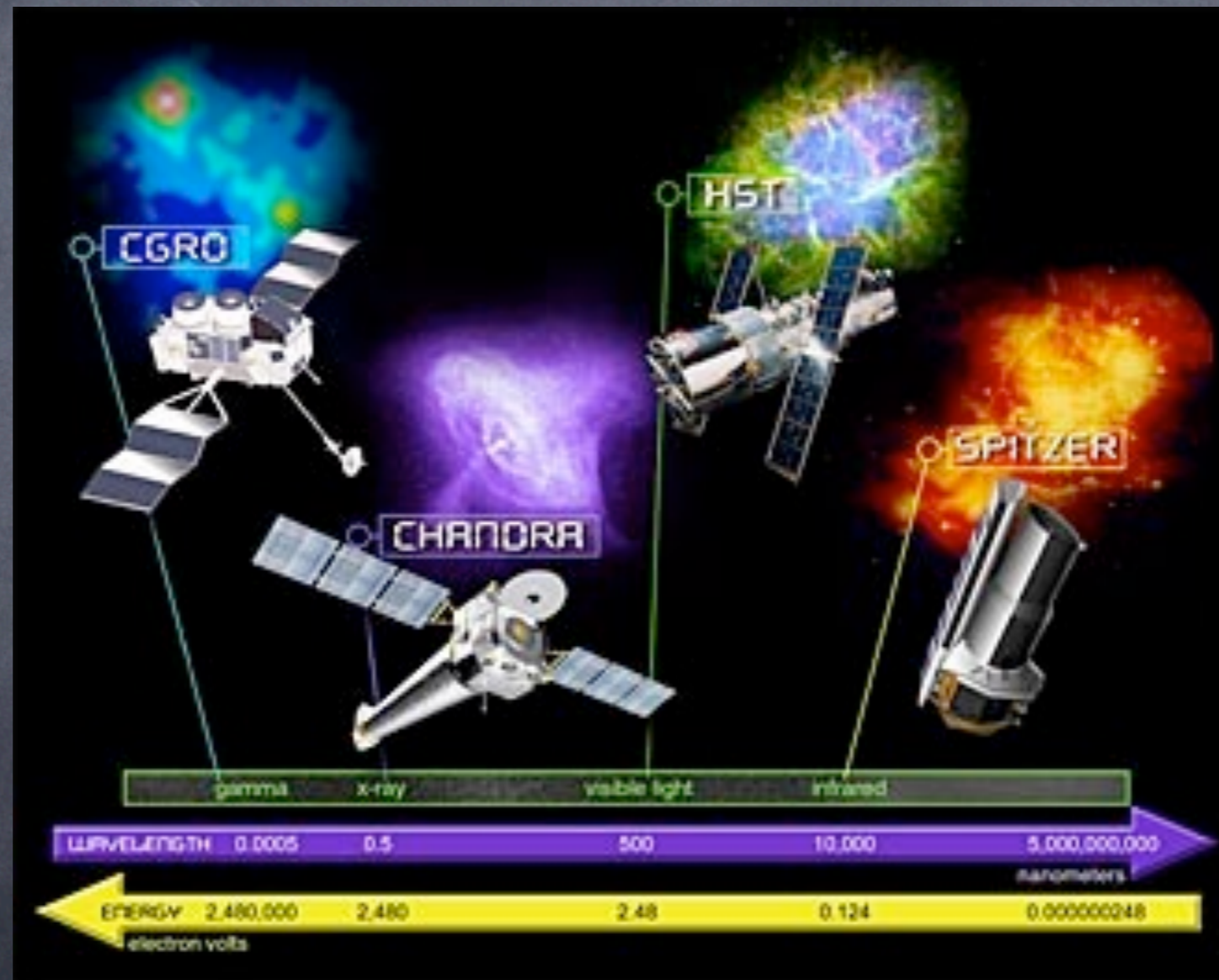


Ground: Atmospheric Cherenkov Telescopes (50 GeV-100 TeV)

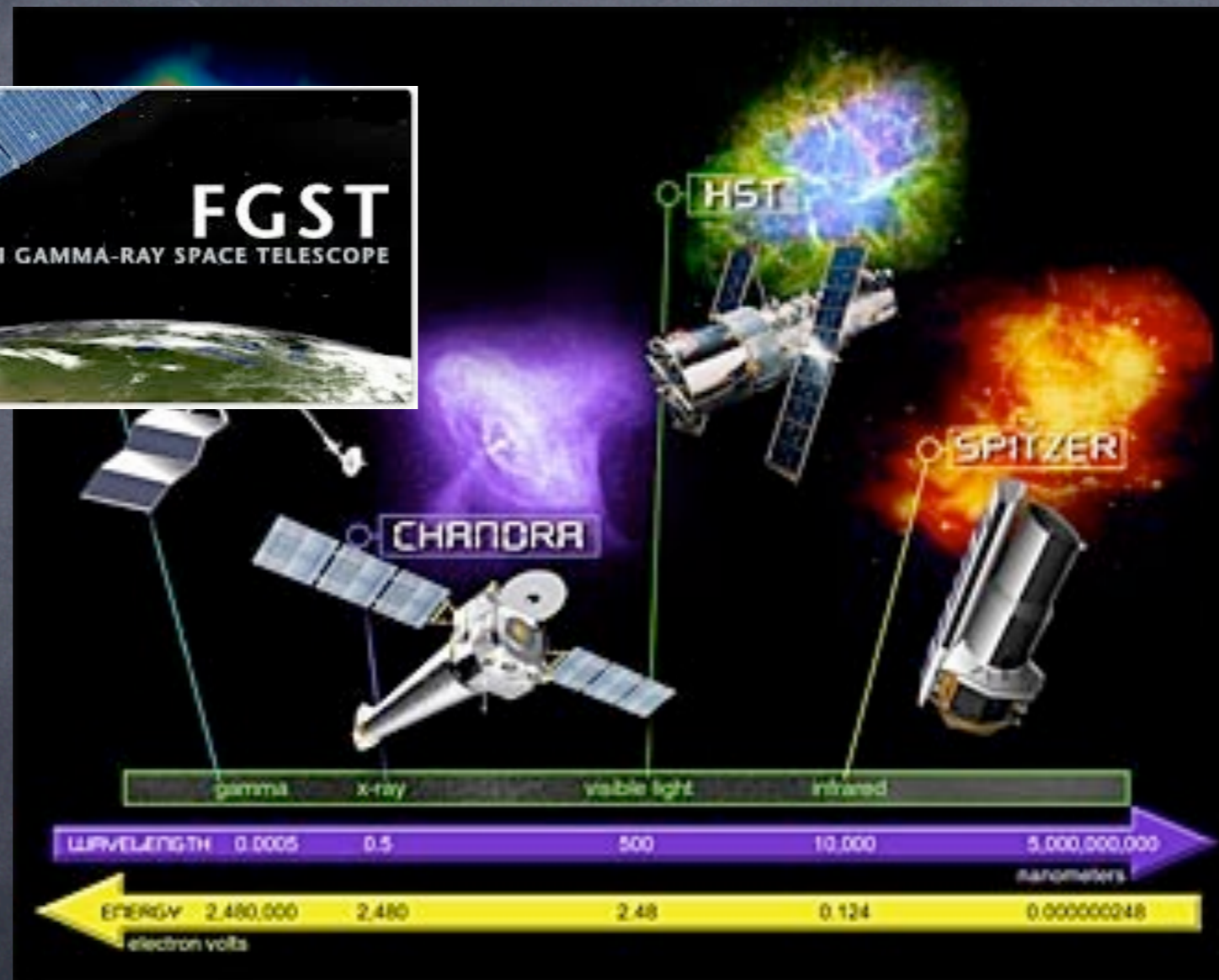
- HESS II (2002-, Namibia, 5 telescopes)
- MAGIC (2004-, Canary Islands, 2 telescopes)
- VERITAS (2007-, Arizona, 4 telescopes)
- CANGAROO III (2004, Australia, 4 telescopes)



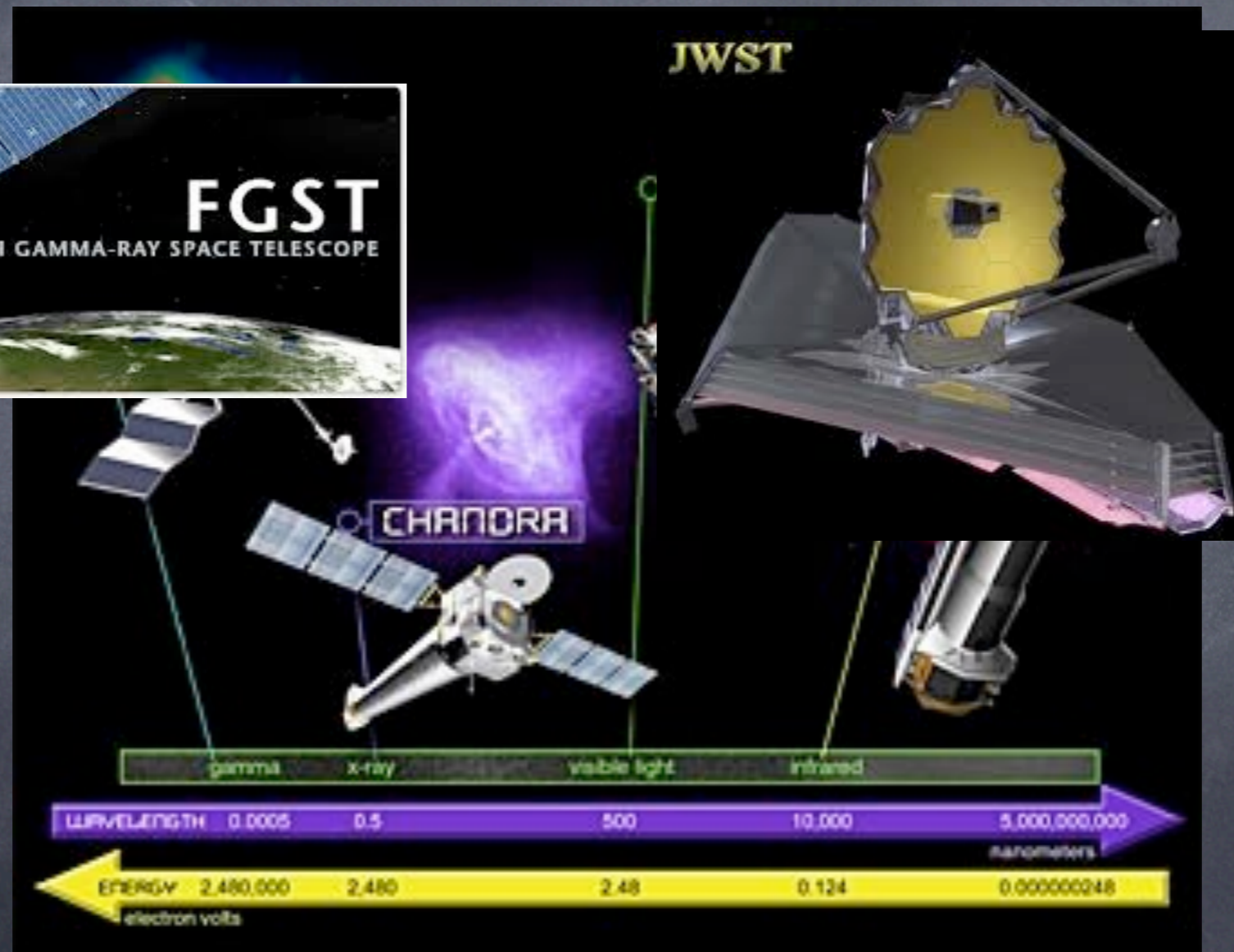
NASA Missions: Great Observatories



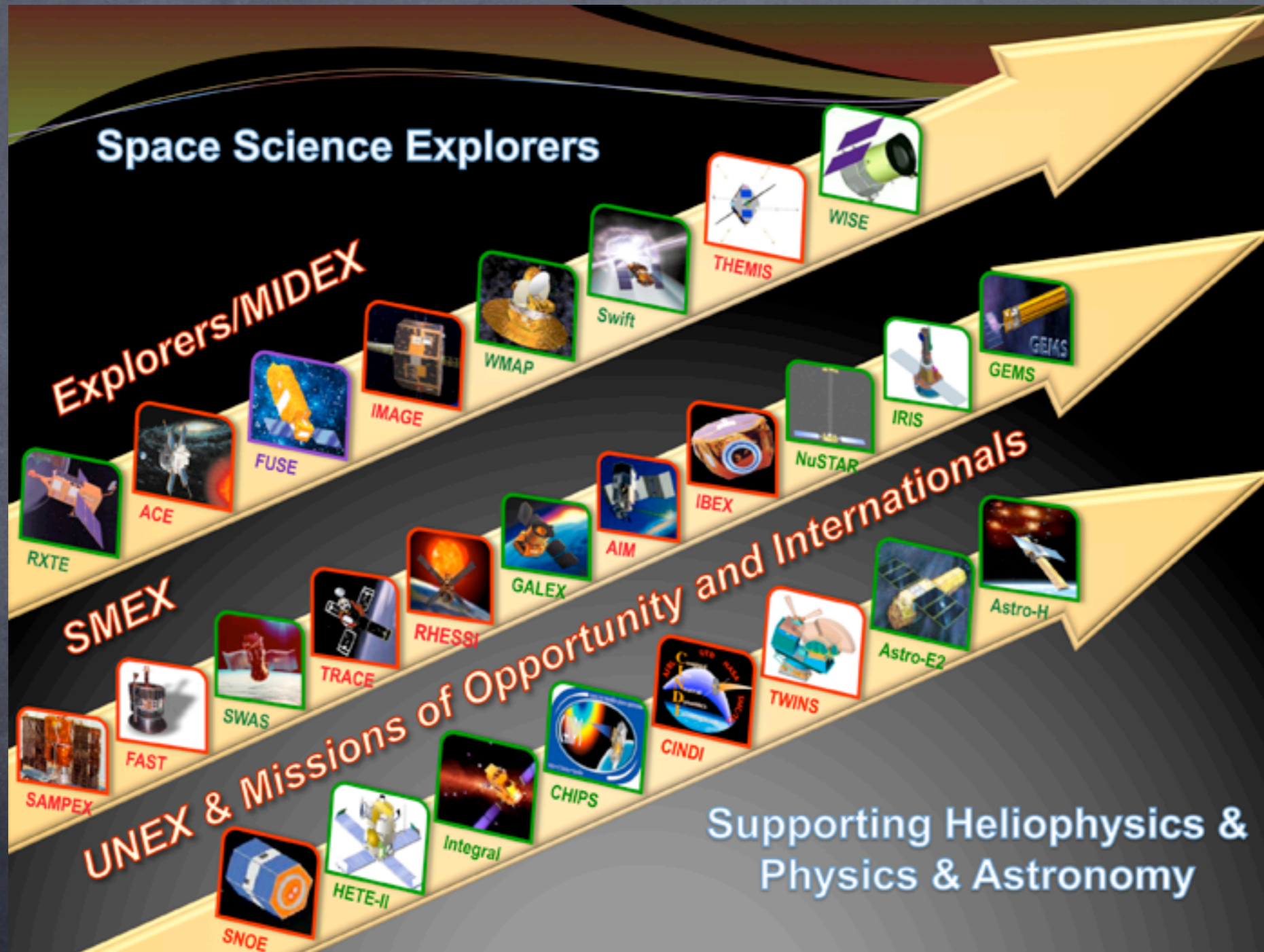
NASA Missions: Great Observatories



NASA Missions: Great Observatories



NASA Missions



Not Just Photons!

Neutrino detectors:

underwater, under ice, and underground

- IceCube (South Pole)
- Baikal (Lake Baikal)
- ANTARES (Mediterranean Sea)



Cosmic-Ray Detectors:

- ground (Pierre Auger, HiRes)
- space (PAMELA, AMS-2)



Gravity Wave Detectors:

- LIGO (advanced LIGO 2014)



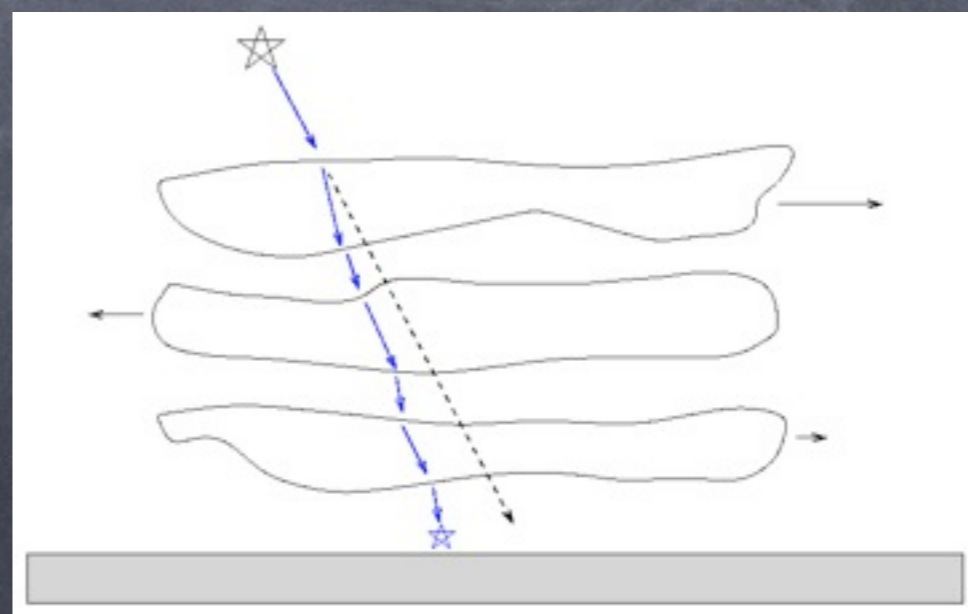
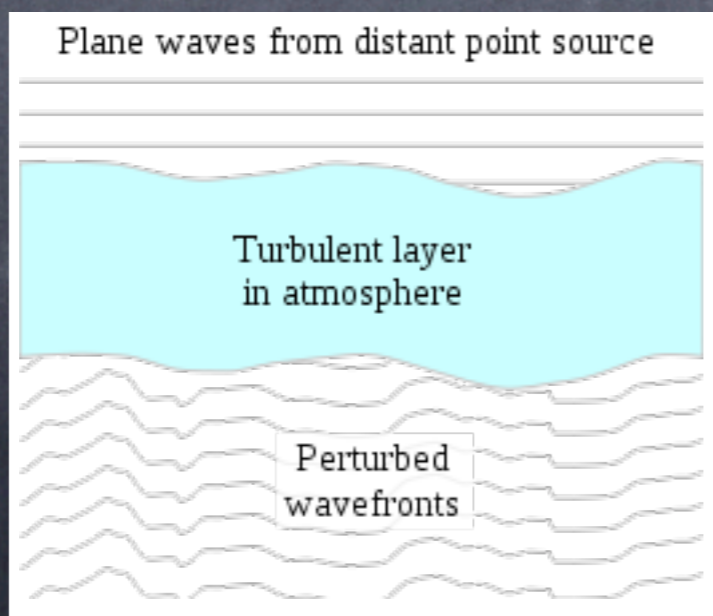
Some Basic Concepts:

Observing through the Atmosphere:
Seeing, Airmass, Sky Brightness

Seeing

Seeing is an all-encompassing term for the distortion of astronomical sources due to the atmosphere, including variations in intensity, position, and sharpness of an image.

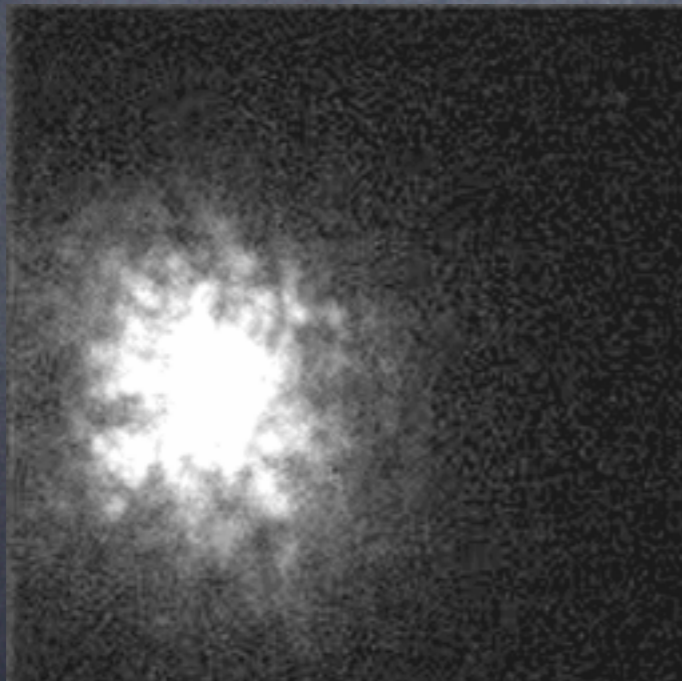
Different layers of the atmosphere have different indices of refraction (different temperature and pressure) which light must pass through. Differential motion of layers and mixing due to turbulence lead to a constantly changing atmospheric refraction causing stars to "twinkle" and blurring images in long exposures.



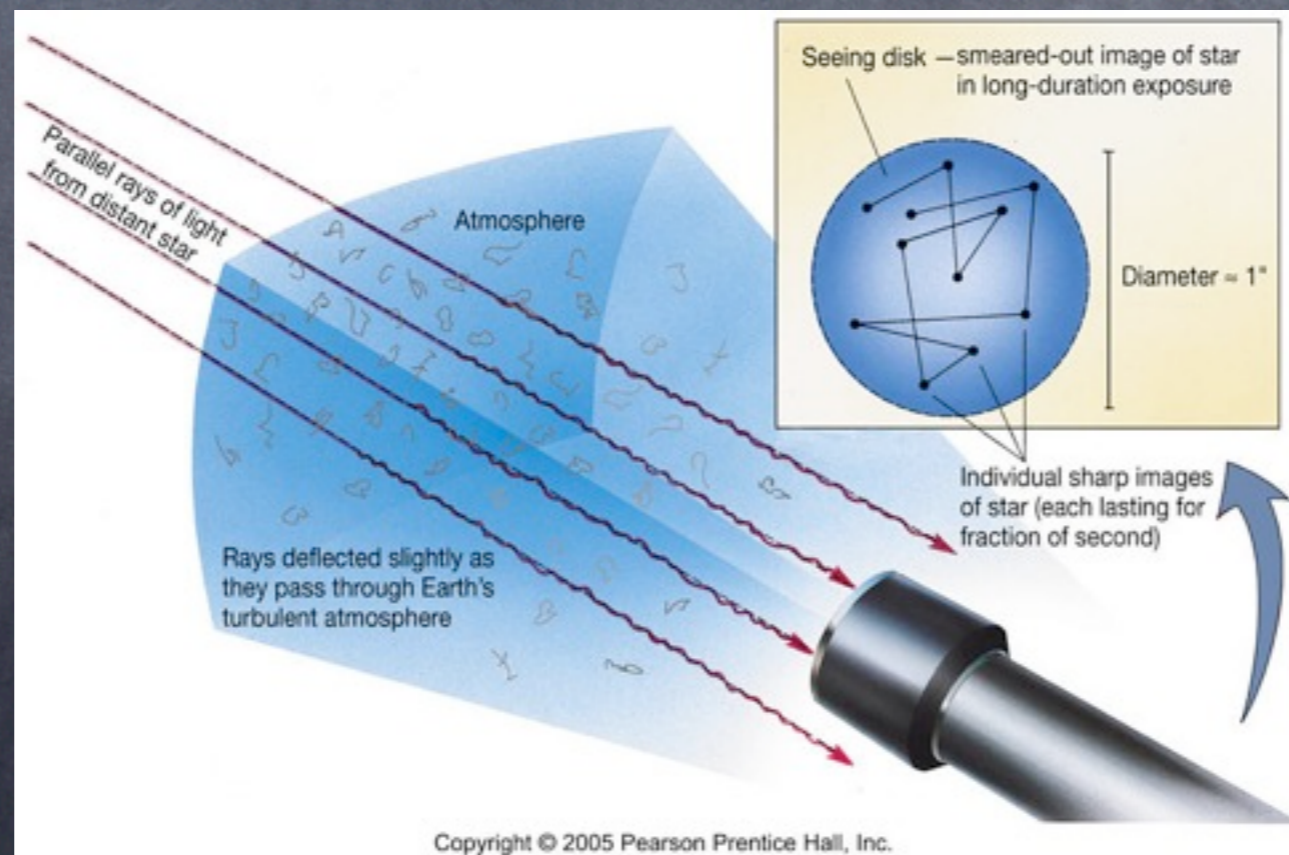
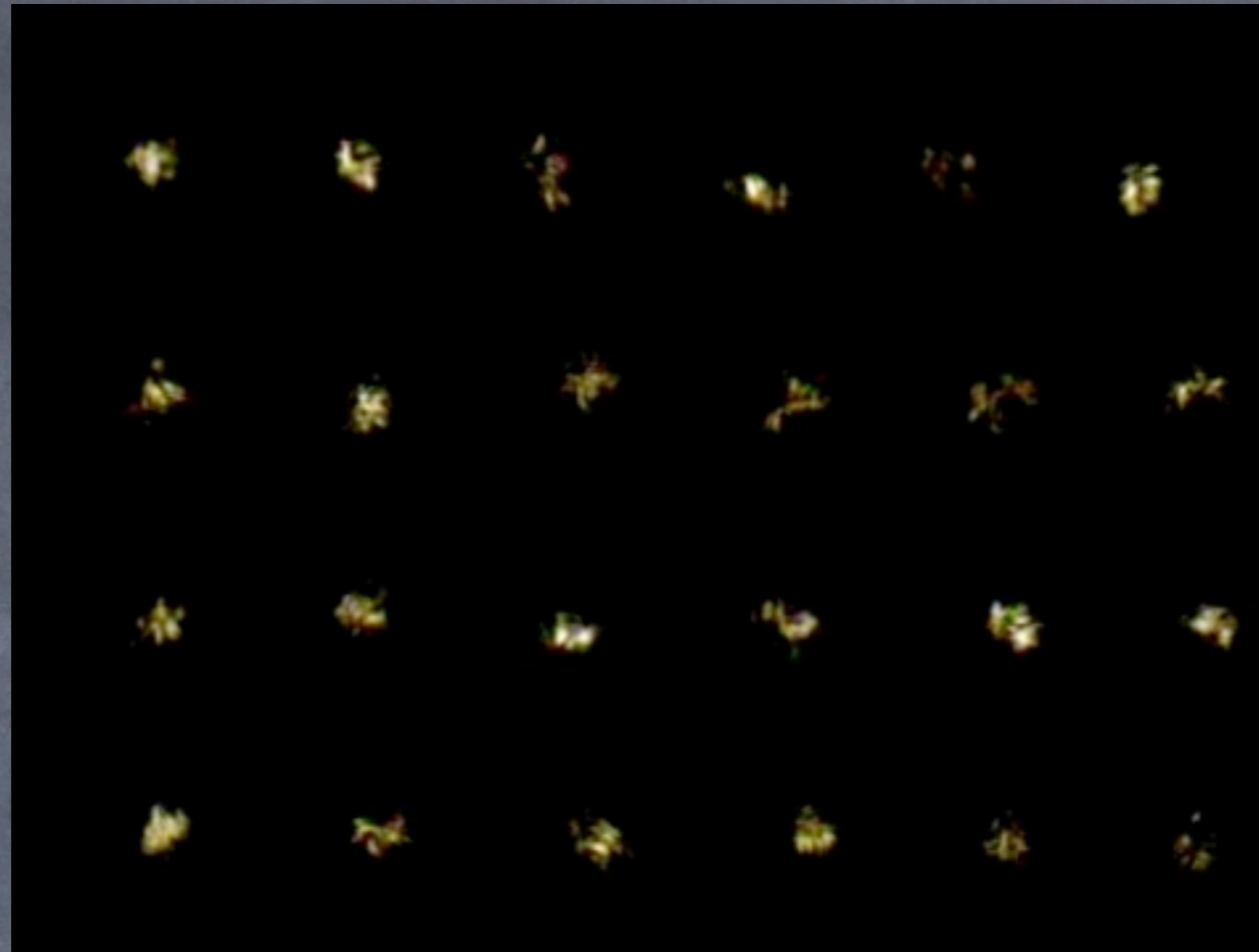
Seeing

In short exposures, the effects of the atmosphere are “frozen” in. The image of a star dances, changes shape, breaks up in to speckles.

In long exposures you get an average, blurred image characterized by the “seeing disk”.



Series of short images of a star



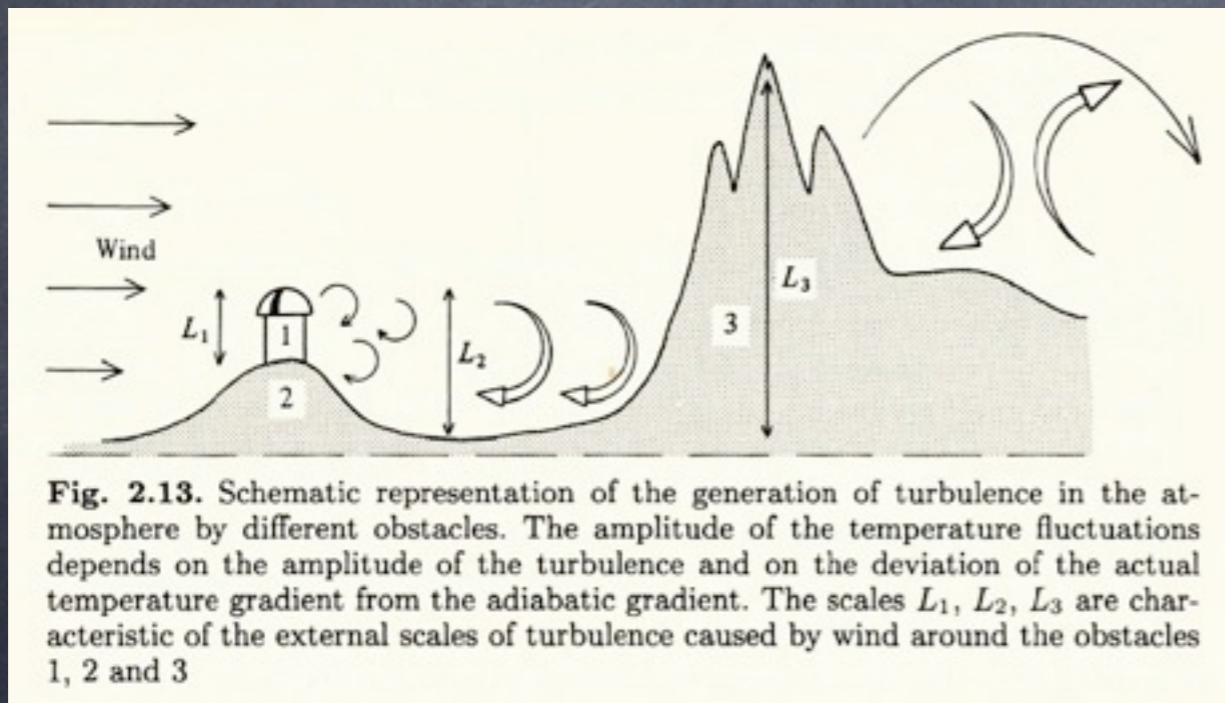
Average smearing in long exposure gives "seeing disk"

Components of Seeing

Upper atmosphere – turbulence in the atmosphere at around 5–10 km

Local atmosphere – air flow around the observatory site, ground layer seeing

Dome seeing – the way air flows around the dome, temperature differences between inside and out, thermal turbulence created convection inside the dome



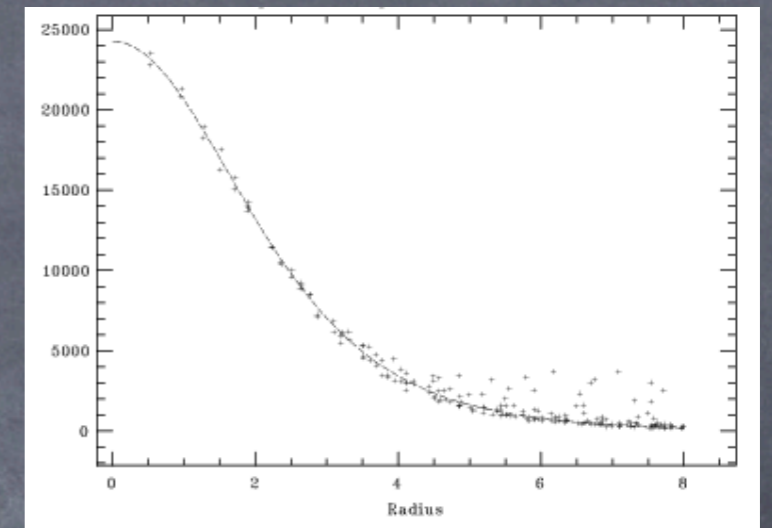
Typically you want to put your telescope on a mountain ridge, near the coast with winds from the ocean ...

From Observational Astrophysics, Lena, Leburn, Mignard

Seeing cont.

Measuring seeing:

Seeing is typically quoted as the FWHM of the seeing disk (typically fit a Gaussian profile to the radial profile of bright stars in the field).



Improving seeing:

Speckle Imaging: take a series of short exposures with the atmosphere effectively frozen, shift-and-add on brightest speckle or use lucky imaging (only add best images)

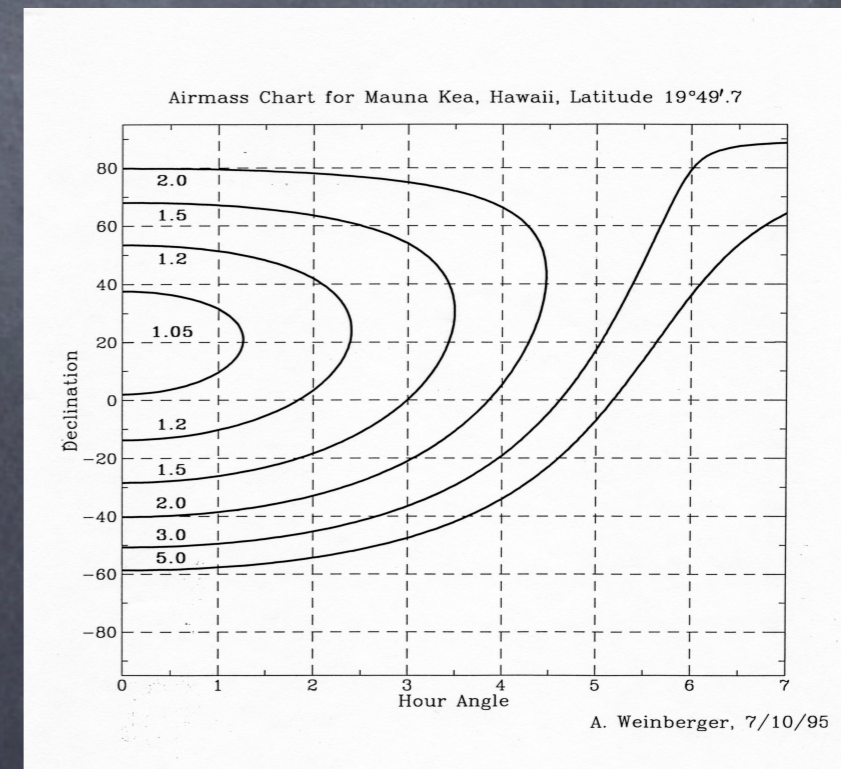
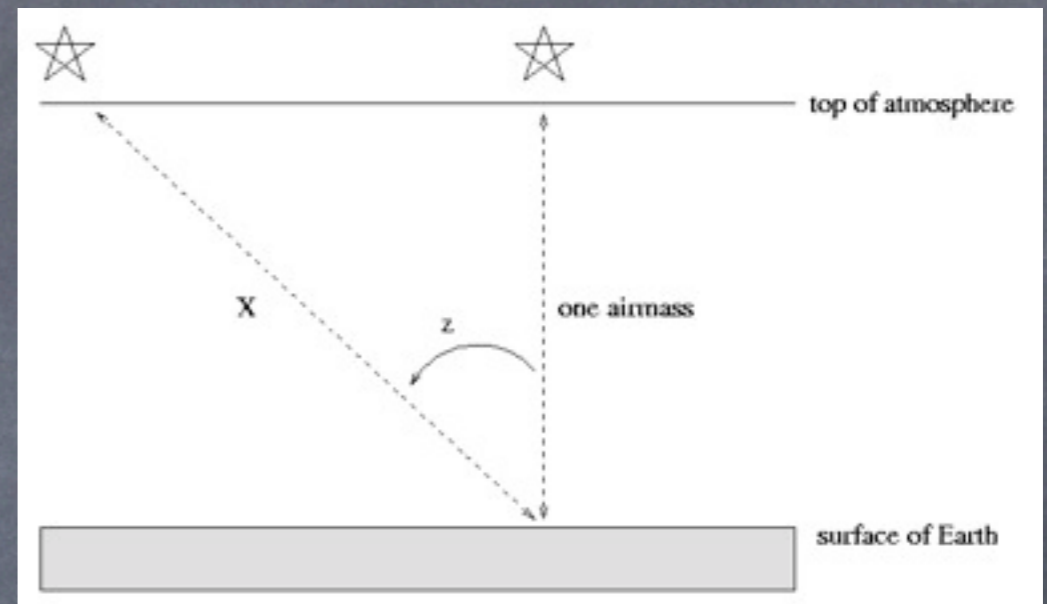
Adaptive optics: measure and correct for wavefront distortion using laser or bright guide star

Airmass

The path length of light through the atmosphere depends on the location of an object in the sky. The level of extinction of the star's light depends on its zenith angle.

Air mass refers to the thickness of the atmosphere for a given source position, and is defined to be one for a star at zenith.

Air mass = $\sec(z)$ (roughly)



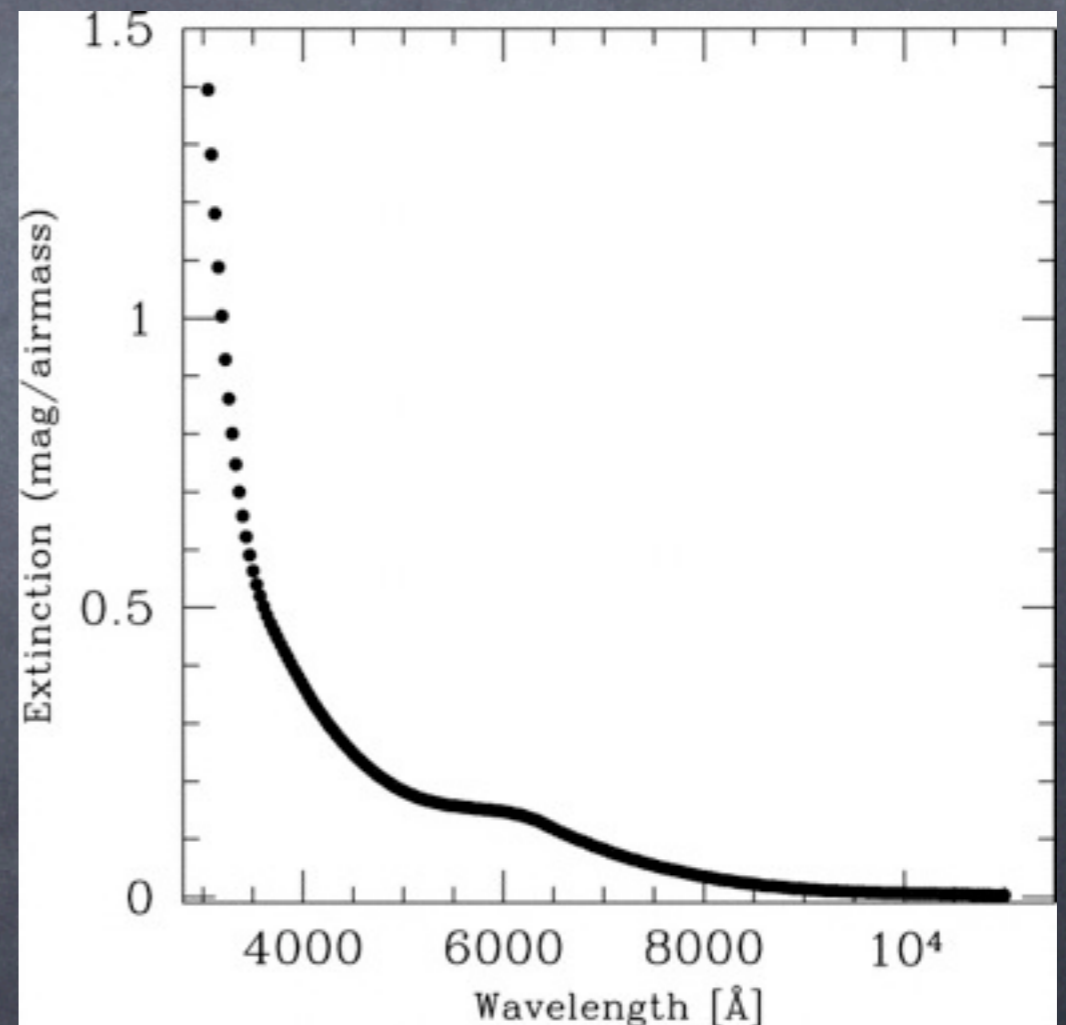
Extinction due to the Atmosphere

Extinction due to scattering and absorption by the atmosphere for a given airmass depends on the wavelength of light.

$$m(A) = m + k \cdot A$$

where A is the airmass and k is the extinction coefficient for a given wavelength. For example, Rayleigh scattering cross-section scales as λ^{-4} .

(Also depends on location, time ...)



Stritzinger et al, PASP, 117, 810, 2005

Sky Brightness

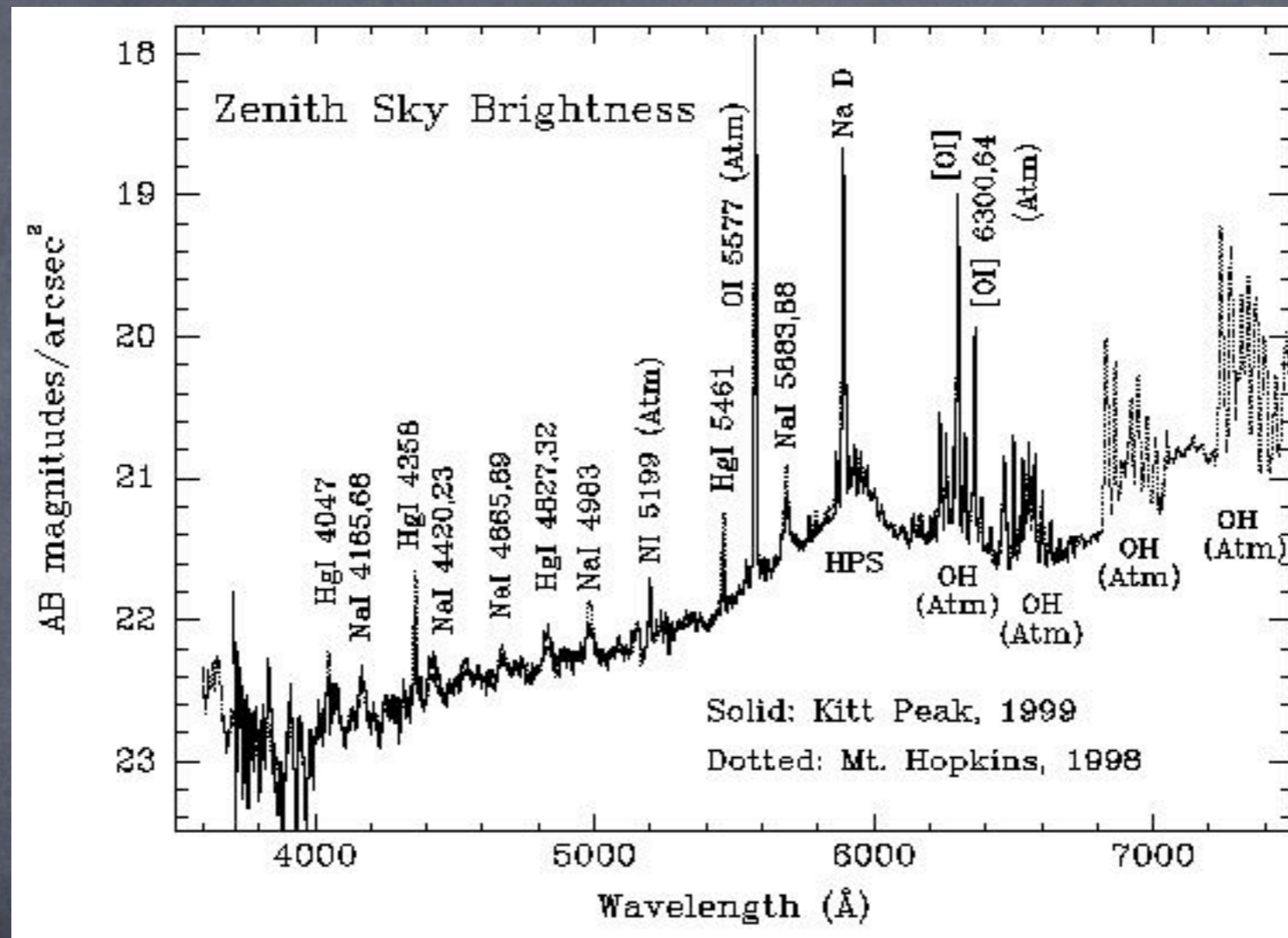
Depends on telescope site, moon phase, filter,

For Cerro Tololo, from Alistair Walker, NOAO Newsletter #10

| Sky Brightness (mag/arcsec ²) | | | | | |
|---|------|------|------|------|------|
| lunar age (days) | U | B | V | R | I |
| 0 | 22.0 | 22.7 | 21.8 | 20.9 | 19.9 |
| 3 | 21.5 | 22.4 | 21.7 | 20.8 | 19.9 |
| 7 | 19.9 | 21.6 | 21.4 | 20.6 | 19.7 |
| 10 | 18.5 | 20.7 | 20.7 | 20.3 | 19.5 |
| 14 | 17.0 | 19.5 | 20.0 | 19.9 | 19.2 |

Some notes: moon light is pretty blue, giving a 5 mag (100x) dependence on phase for U band but less than 1 mag for I band. At new moon, the sky is faint in the blue, but bright in the red.

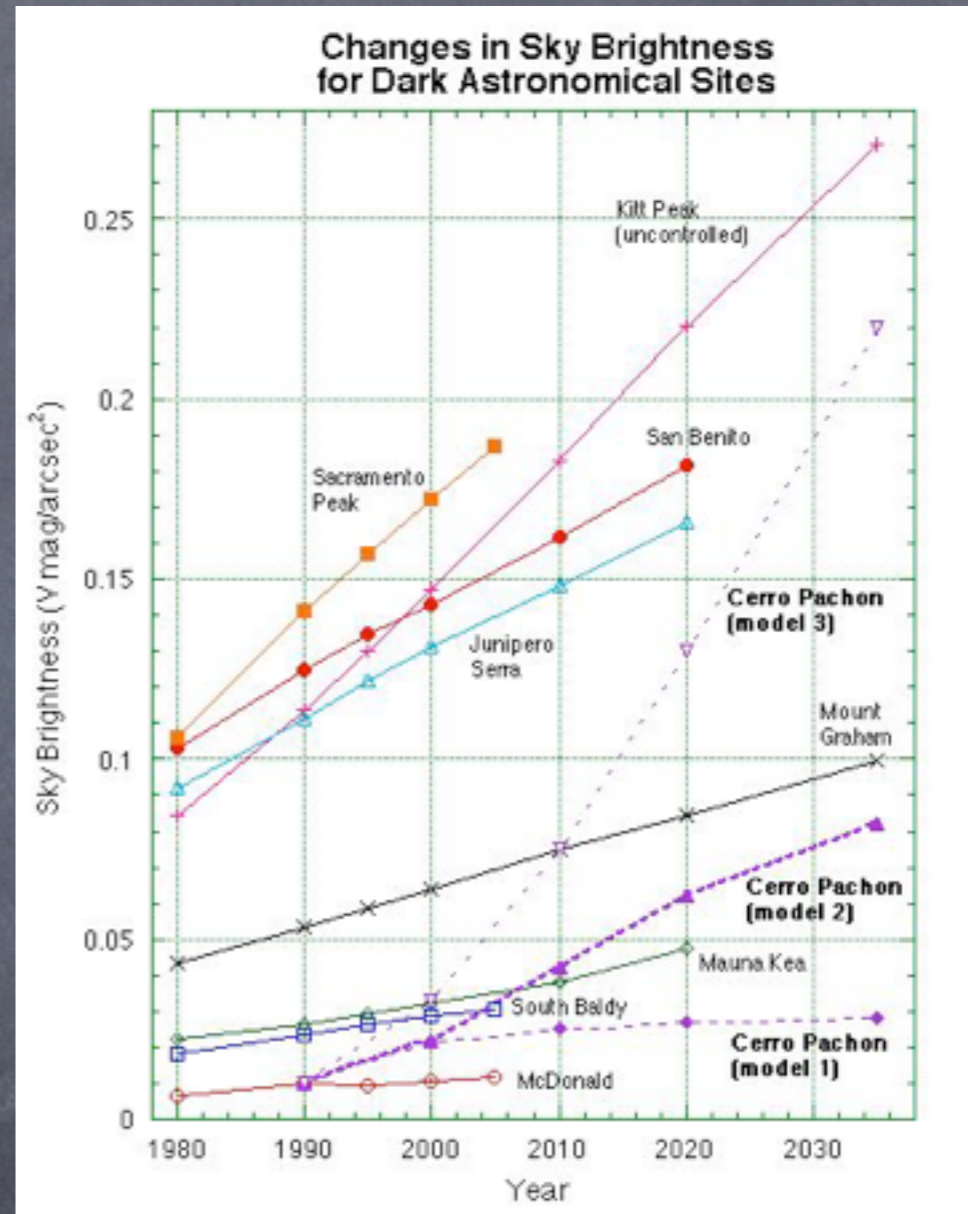
Atmospheric Lines



Massey & Foltz 2000

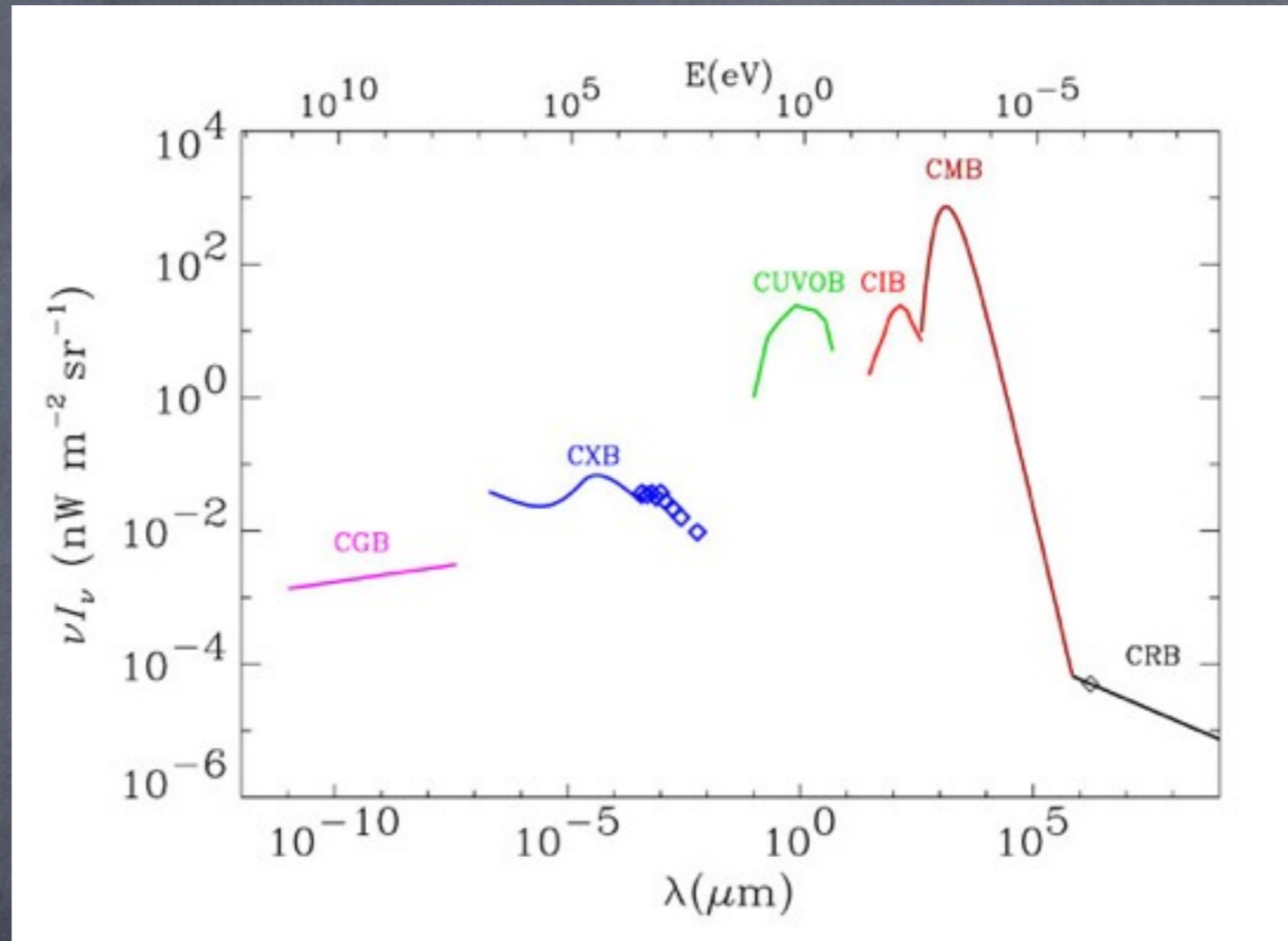
Absorption and emission features from the sky give extinction or background in narrow bands. Strong line emission shows up in ground based spectroscopic observations, particularly in the red.

Sky brightness depends strongly on site.



A. Walker

Cosmic Backgrounds



Hauser & Dwek 2001

Even in space there are backgrounds from faint, unresolved sources, our own Galaxy, dust in the Solar System, ...

Some Basic Concepts:

Magnitudes and Photometric Systems

Magnitudes

$$m = -2.5 \log(F/F_0)$$

Apparent magnitude for a given band defined relative to the reference flux for that band. An increase of 1 mag means a lower flux by about 2.5.

$$M = m - 5 (\log(D_L) - 1)$$

Absolute magnitude is the magnitude it would have at 10 parsecs.

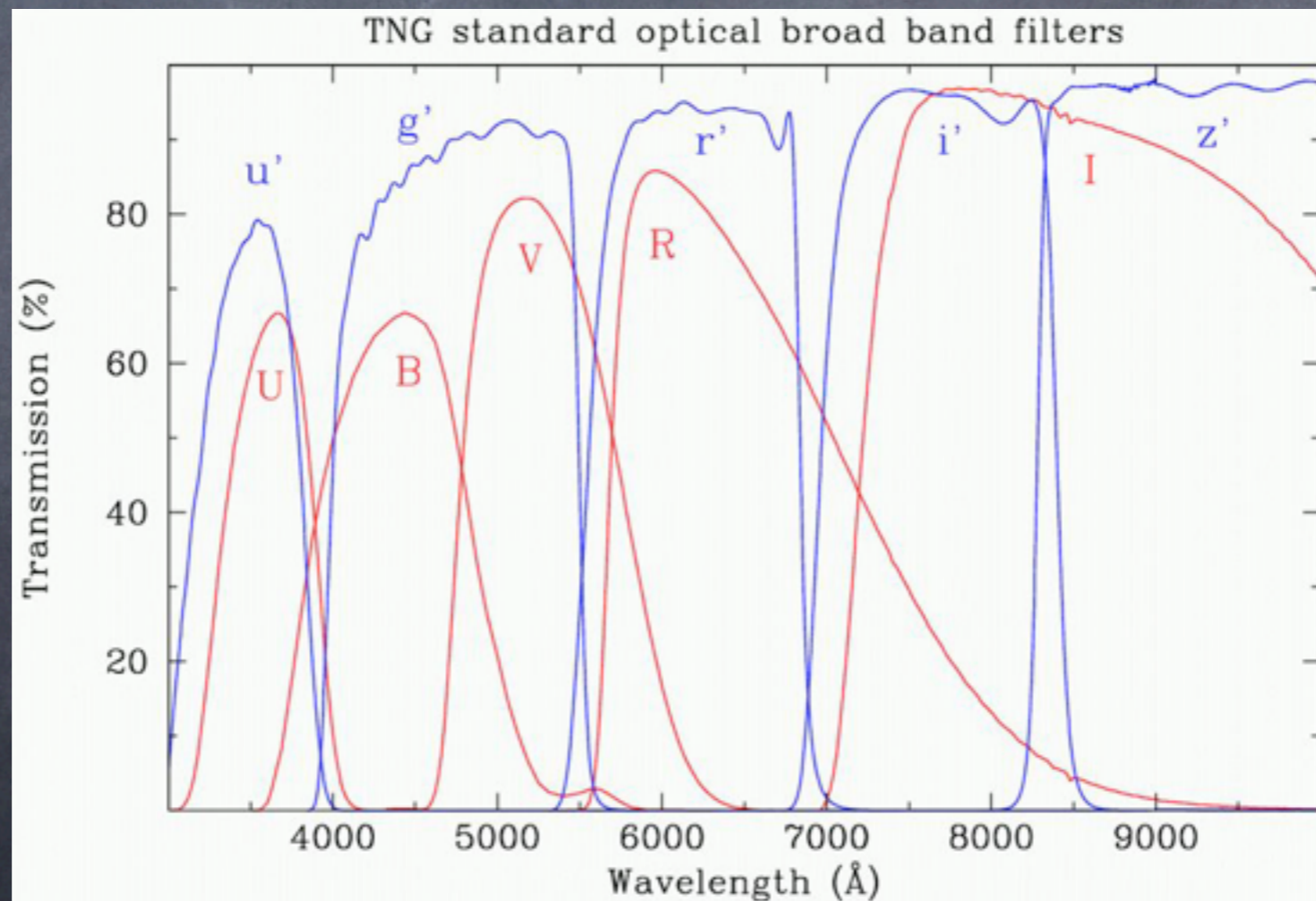
Other wavelengths use more logical flux units:

Radio: Jy = 10^{-26} W/m²/Hz

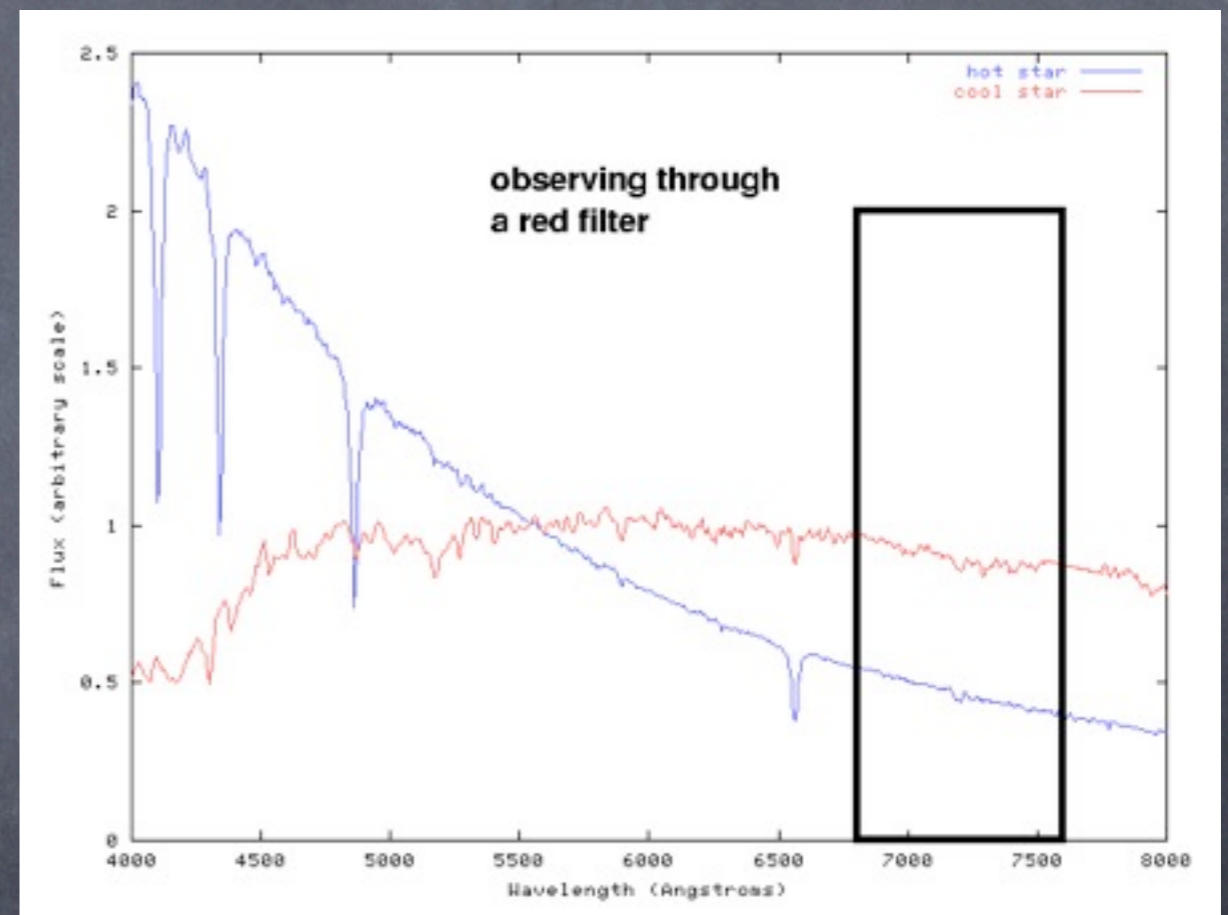
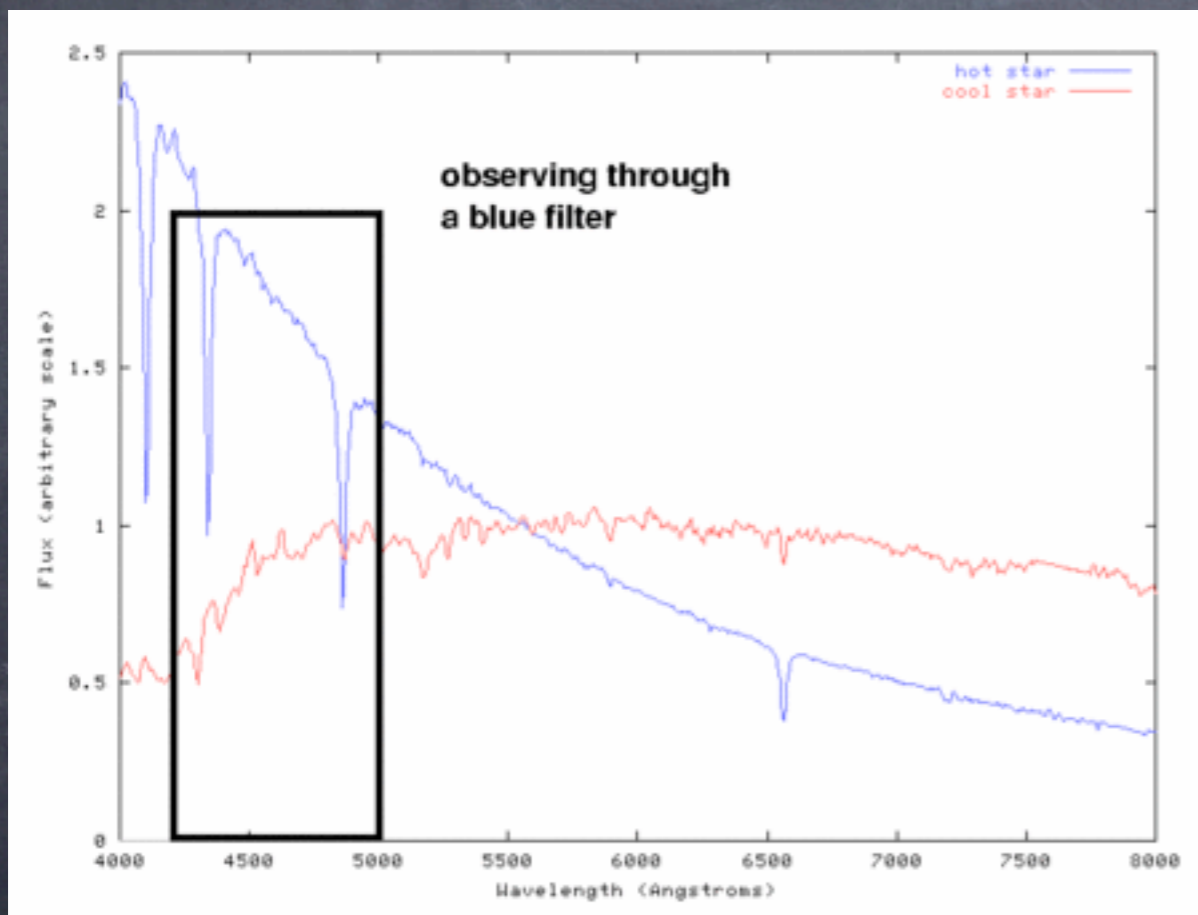
X-ray, gamma-ray: ergs/cm²/s

Filters

Optical/UV/IR imaging is done through filters with varying width and wavelength response. While this may seem obvious, the choice of filter(s) can dramatically effect what you observe, and things like flux and color depend on the specific filter system.

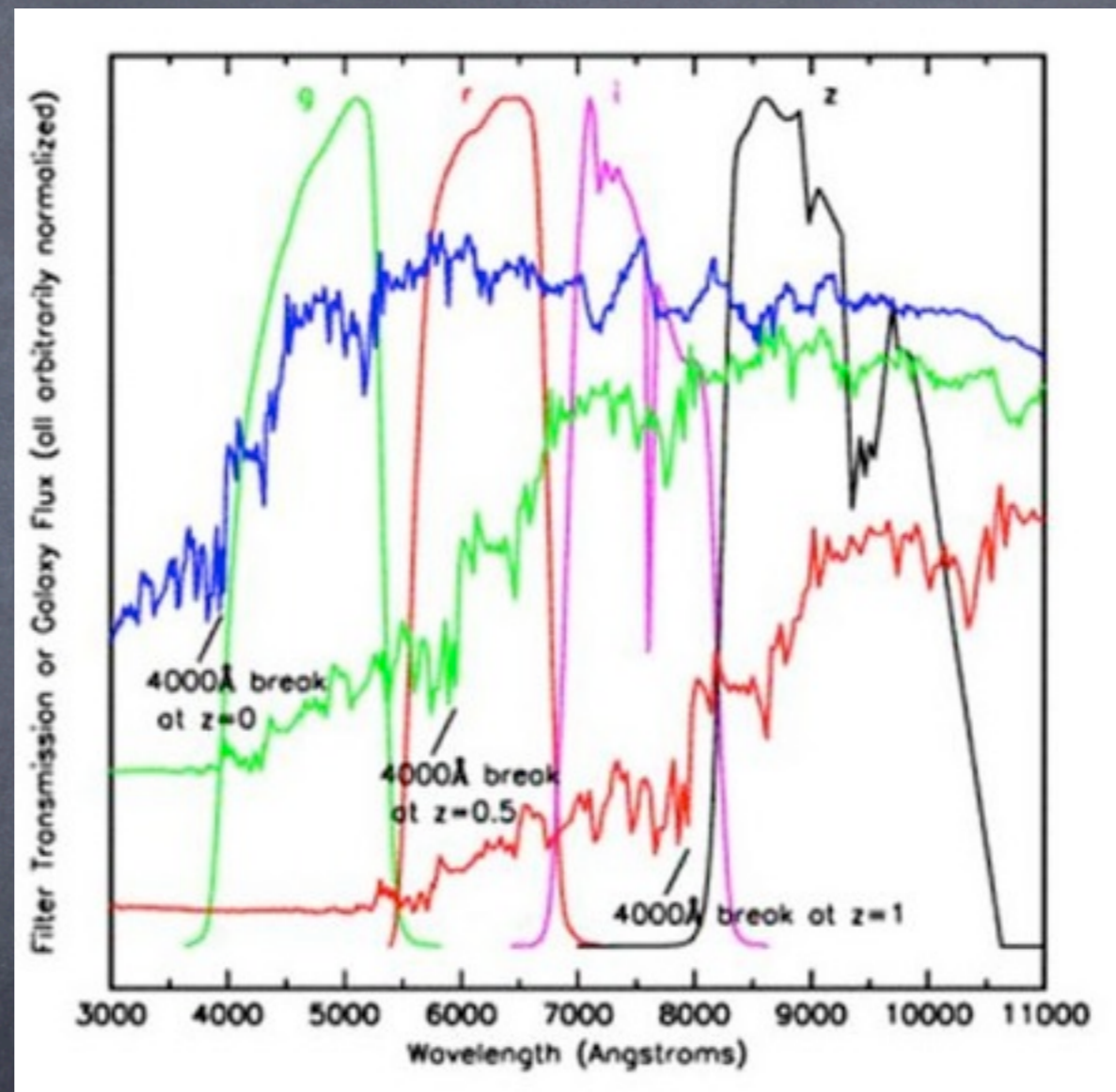


Observing Through Filters



Which object is brightest depends on the filter you use.

Observing Through Filters

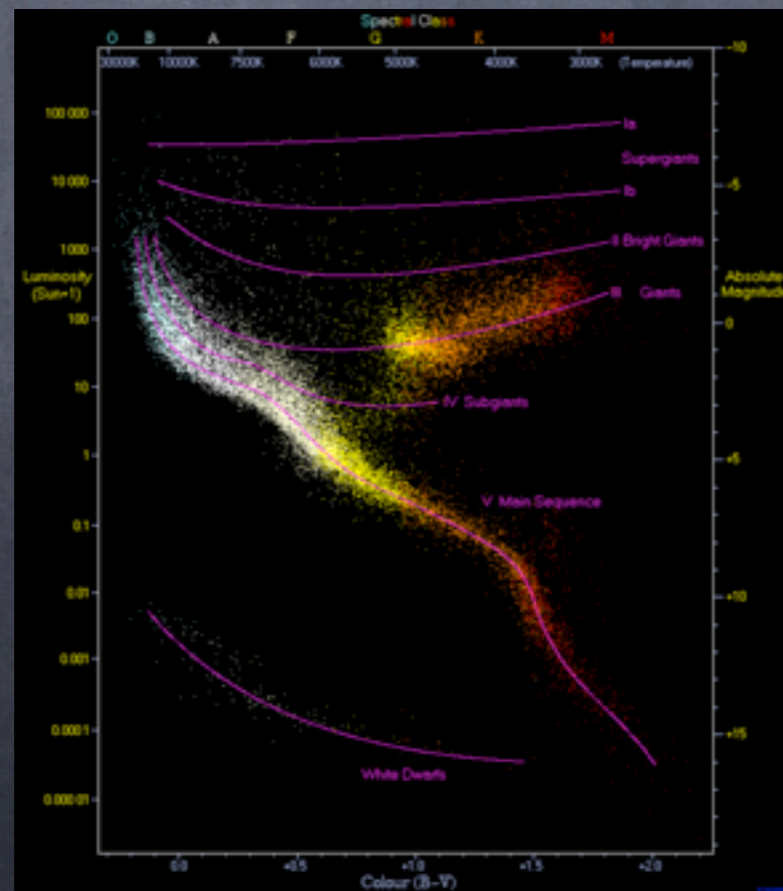


Example of using photometry to measure redshift from the Dark Energy Survey website.

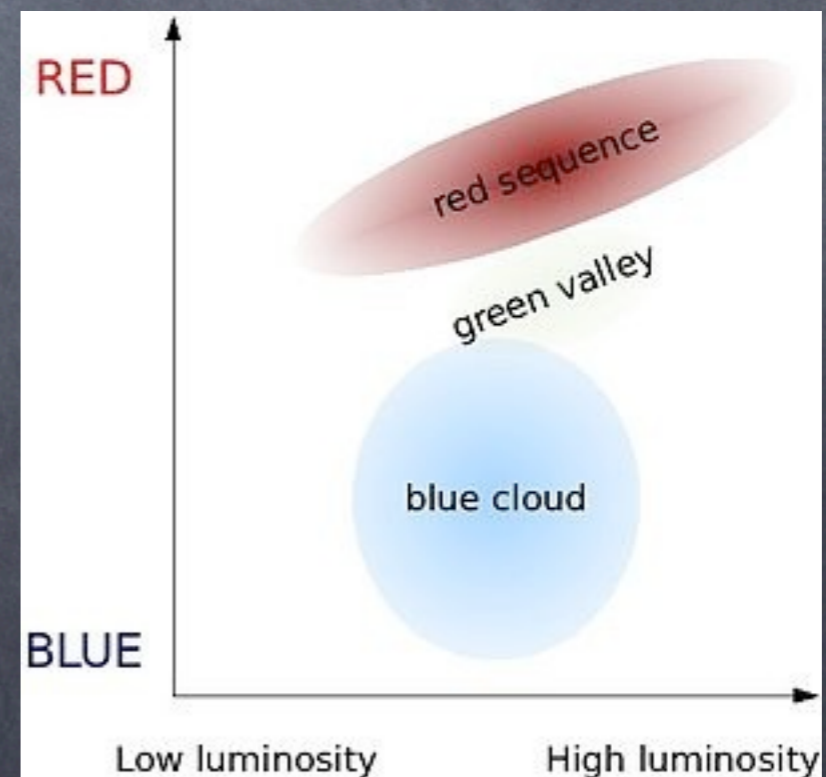
Colors

The color of an object simply refers to the difference in its magnitude in different bands (e.g. B-V, r-i).

Colors or sets of colors can be used estimate galaxy redshift and to determine galaxy/stellar type (e.g. "blue" means young stars).



Richard Powell



Bell et al. 2004, ApJ, 608, 752

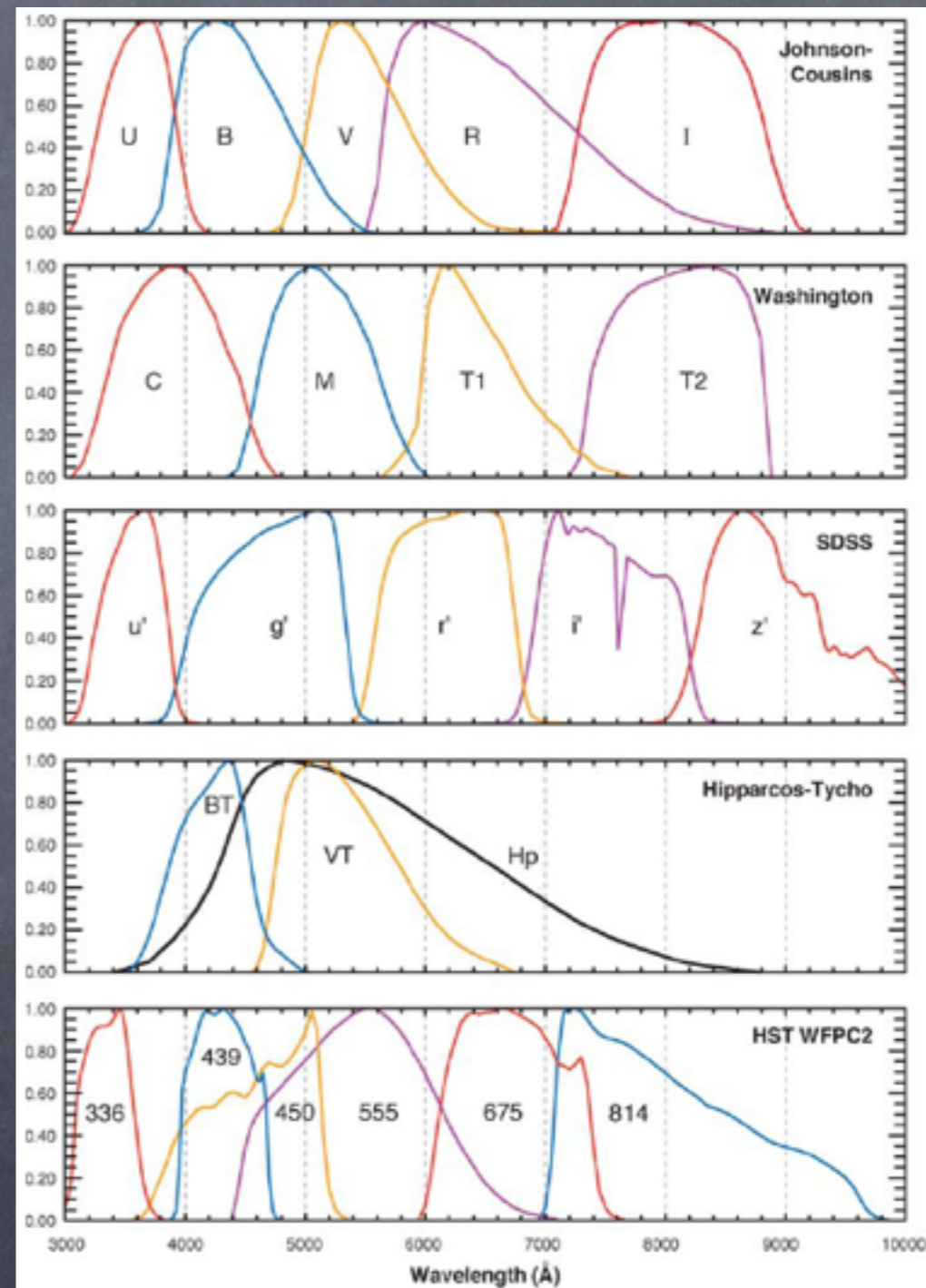
Photometric Systems

There are many and even for the same system filters are slightly different for different telescopes.

Commonly used broad band:
Johnson-Cousins (UBVRI)
SDSS (u,g,r,i,z)

and intermediate band:
Strömgen (uvby)
DDO five color

There are also narrow band filters to focus on emission lines



Photometric Zero Points

Vega magnitude system:

Defined such that the star Vega has $V=0.03$ and zero colors (originally $V=0$, but measurements changed slightly). In this system, the zero point flux is different for different bands, since it is based on the SED of Vega (an A0 V star). Johnson UVBRI uses this system.

AB magnitude systems:

Defined such that a source with a constant flux per unit frequency has zero colors. Here $m_{AB} = -2.5 \log(f) - 48.60$ with f in $\text{ergs/cm}^2/\text{s/Hz}$ and the magnitude zero-point corresponds to a flux density of 3631 Jy. SDSS uses this system.