Astro 426/526

Fall 2019

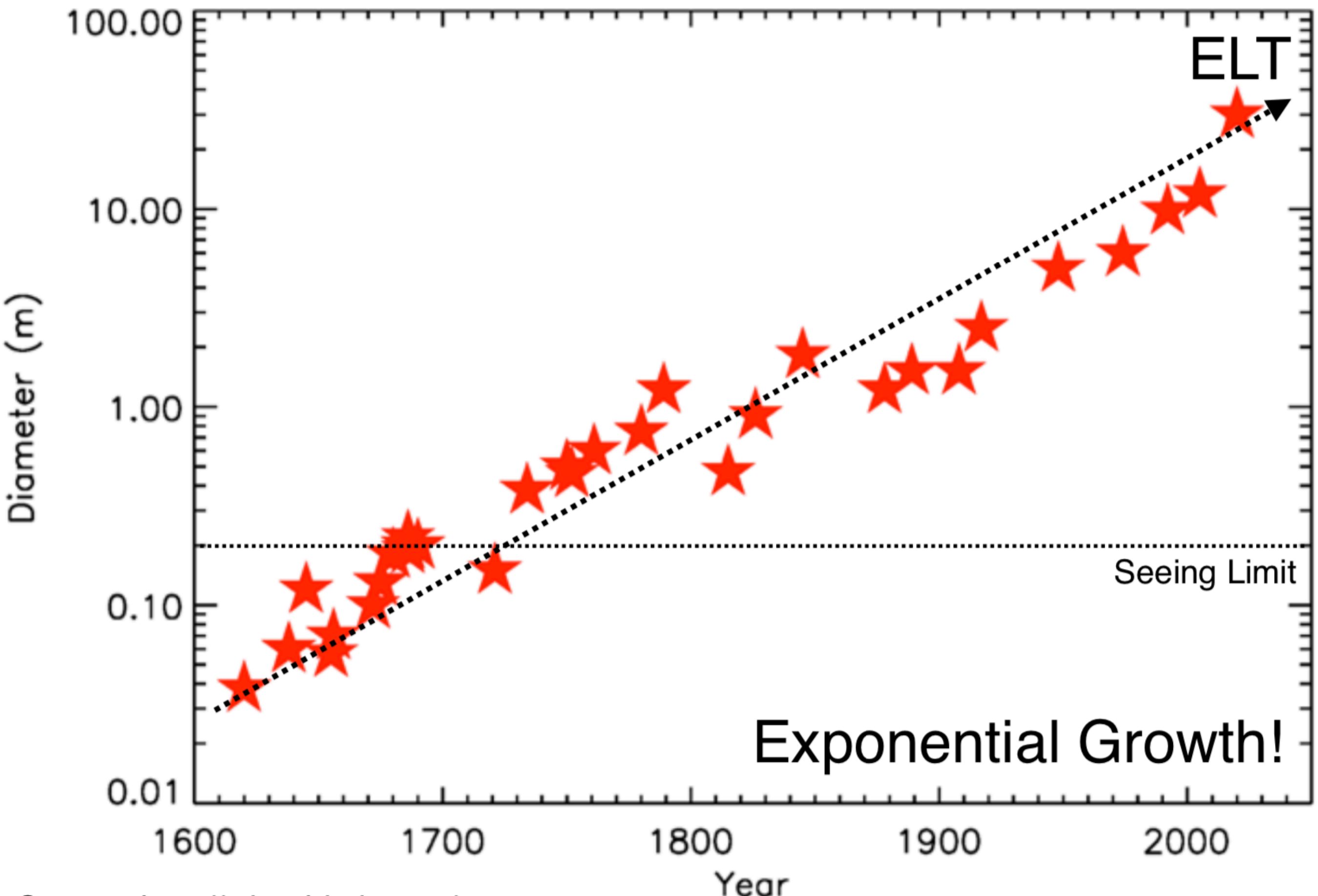
Prof. Darcy Barron

Lecture 8: Detection principles across wavelengths

Reminders

- HW 2 due Friday Sept 25 at 5pm
- Mid-term exam Wed Oct 2
- For next two weeks: detectors, statistics, and noise
  - Summarized in Section 1.4.2 (Detectors: Basic Principles) and Section 1.5 (Statistics and noise) of *Measuring the Universe*
  - For this week: read chapter 3 of Measuring the Universe (Detectors for the ultraviolet through infrared)
  - For the week after (Sept 23): read chapter 3 of *Practical Statistics for Astronomers*
  - If you have a limited background in statistics, may also need to reference or skim Chapter 2 of *Practical Statistics for Astronomers*

Explosive Growth in Ground-Based Optical/Infrared Telescopes



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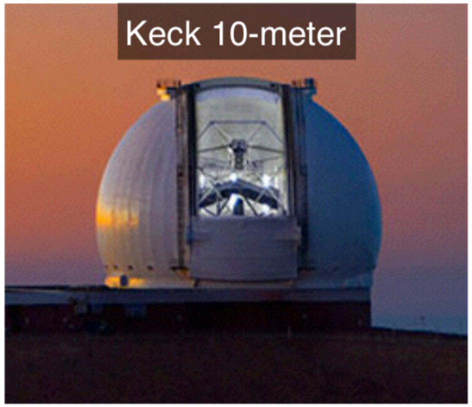
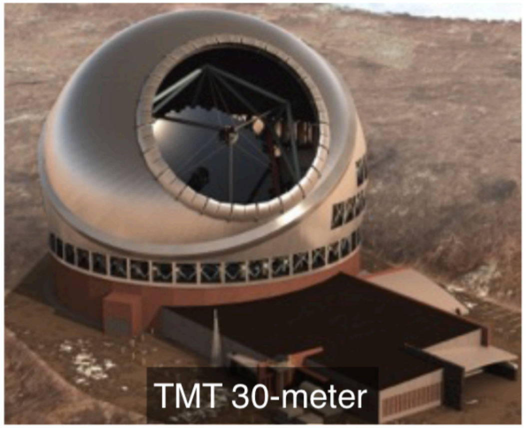
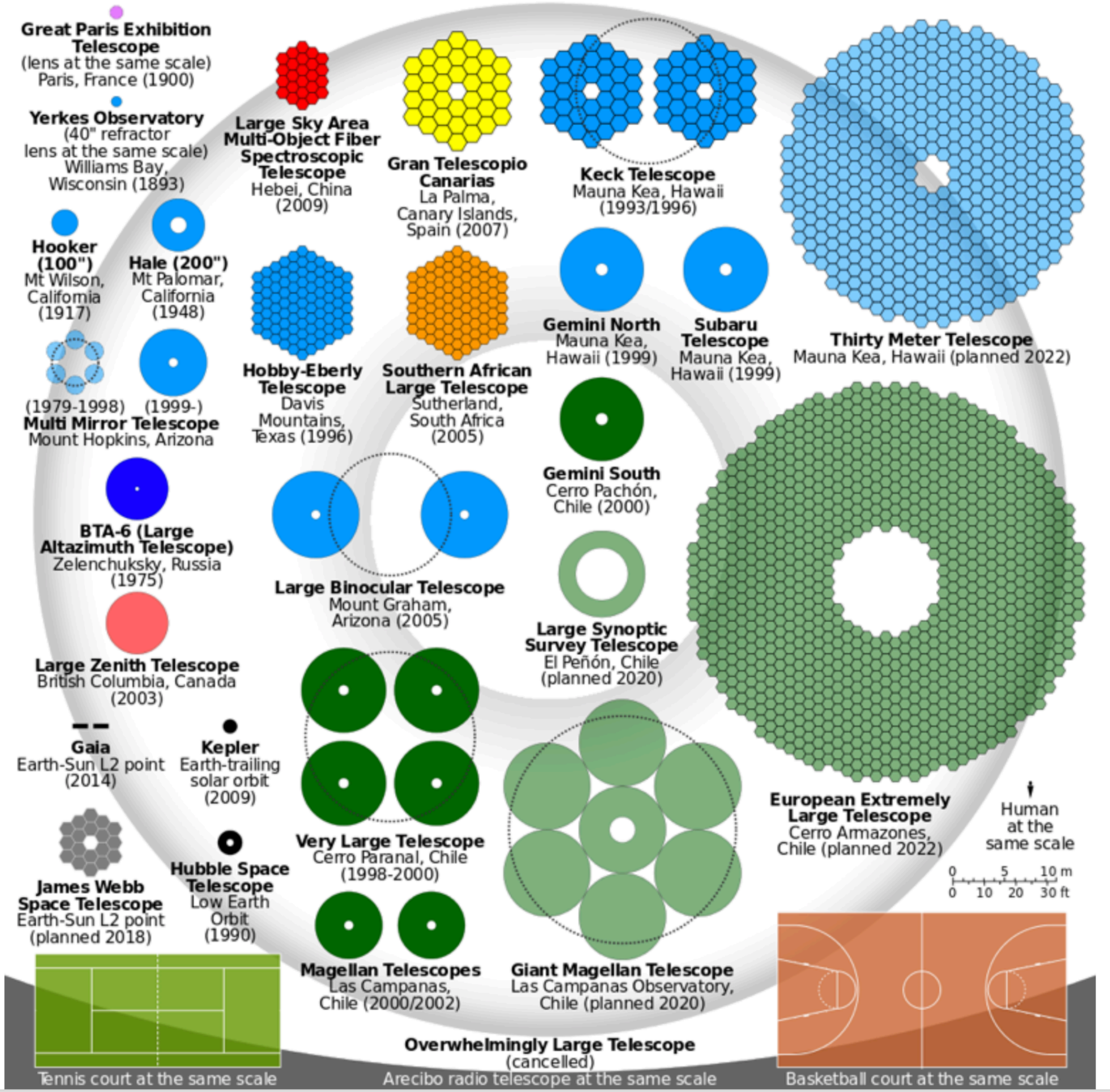
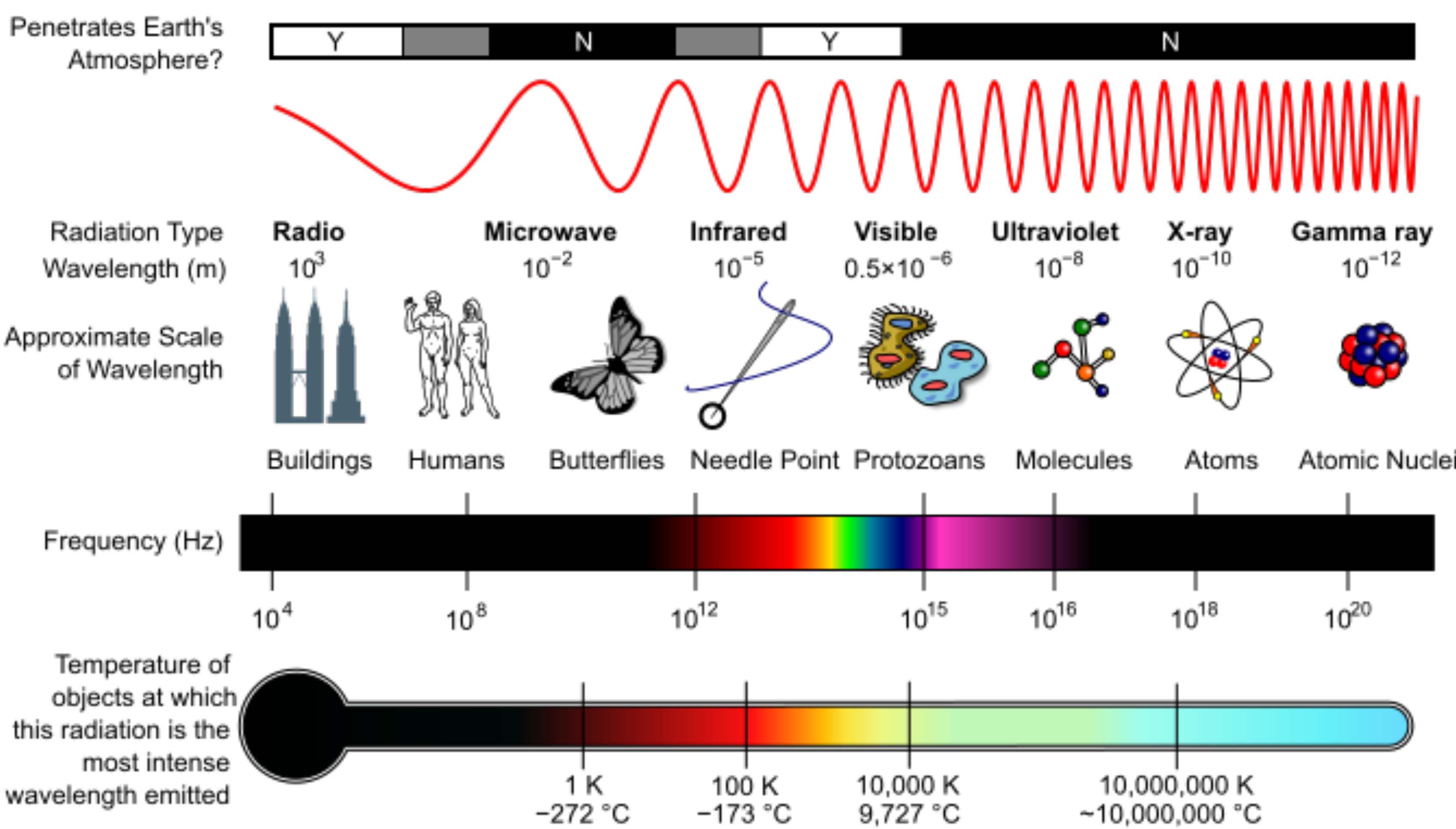


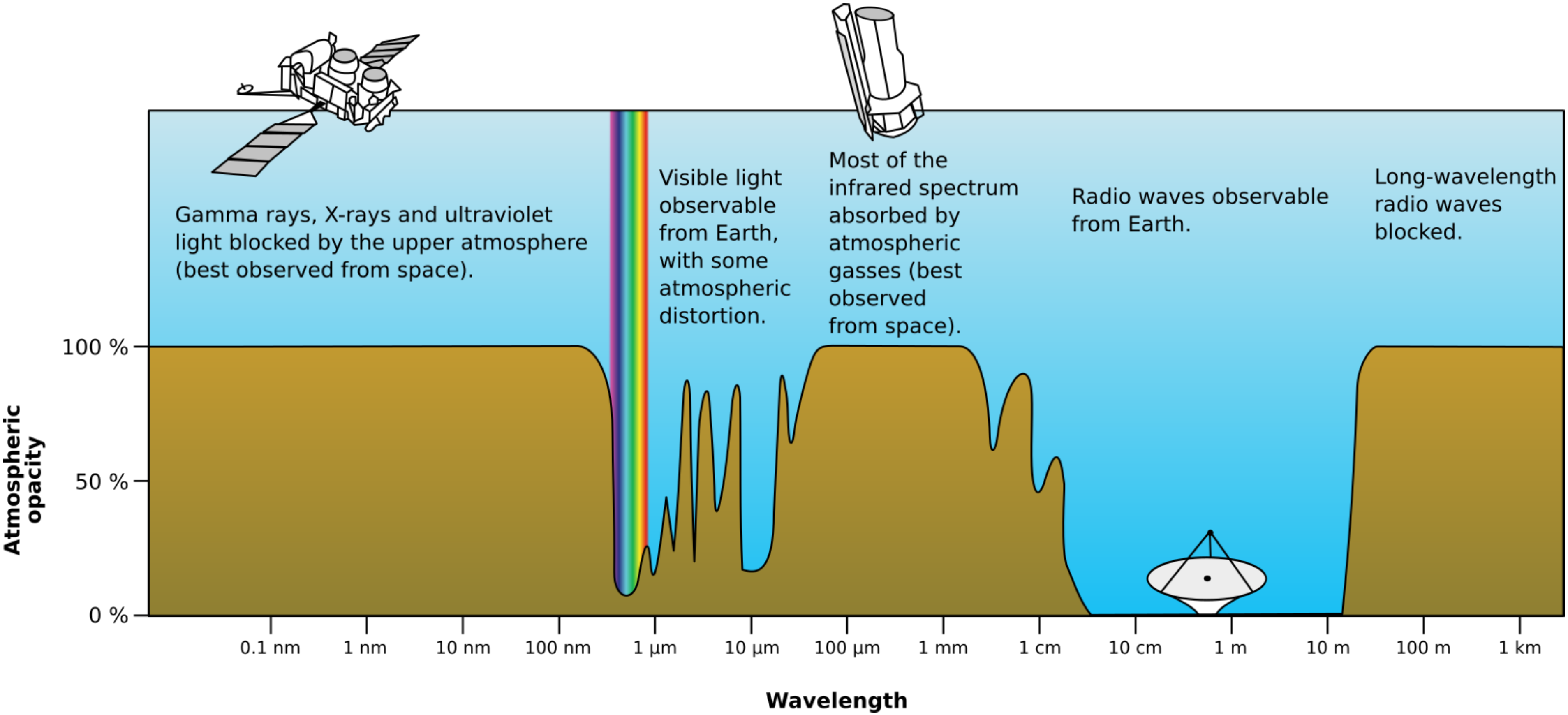




Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón, Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale


Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Radio
10^3
Microwave
10^-2
Infrared
10^-5
Visible
0.5×10^-6
Ultraviolet
10^-8
X-ray
10^-10
Gamma ray
10^-12
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

Electromagnetic spectrum and our atmosphere

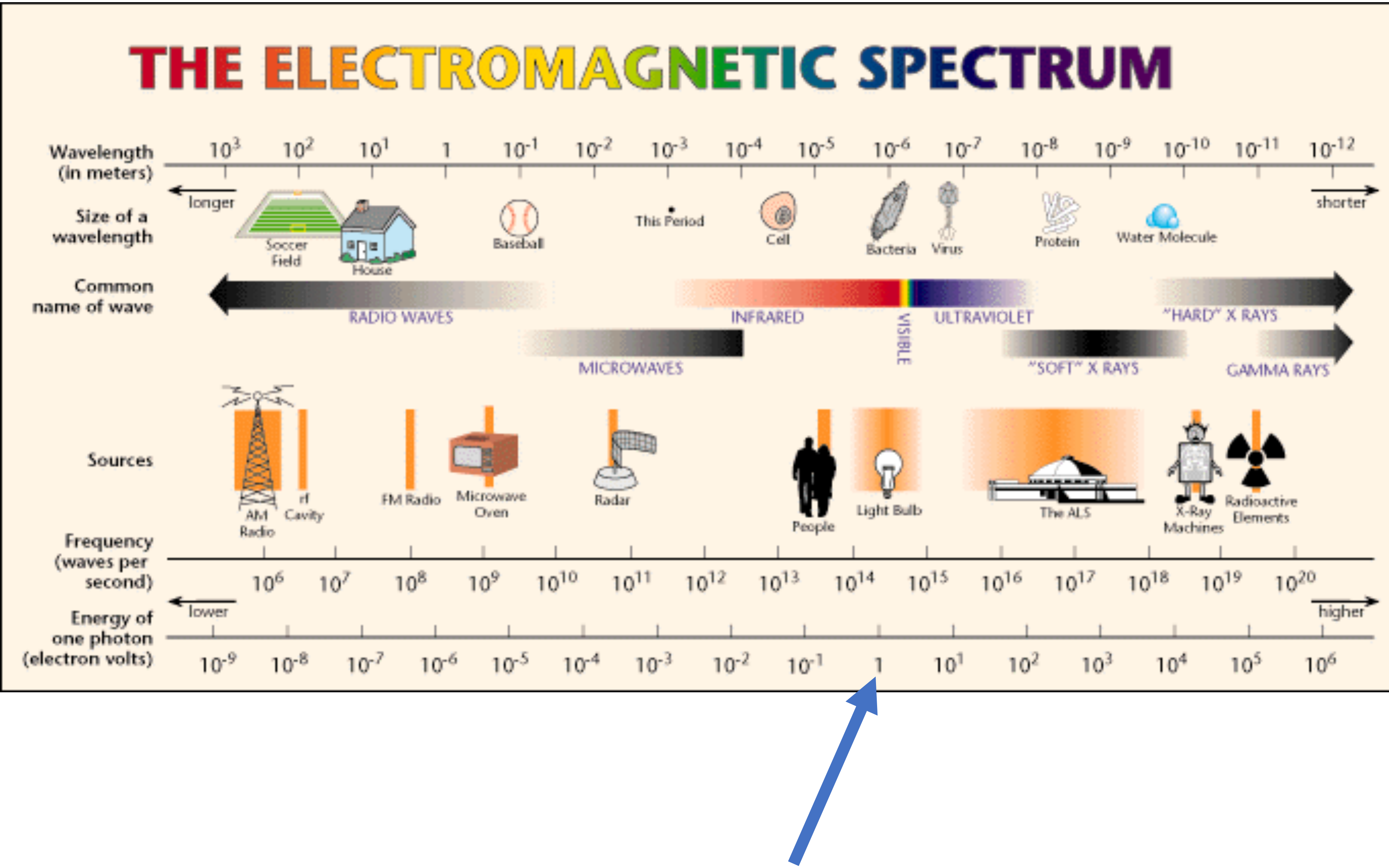


Telescope location vs wavelength

- Must be in space (totally blocked by atmosphere)
  - Wavelengths shorter than 0.3 microns
    - Ultraviolet, x-ray, gamma ray
  - Wavelengths between 40 to 300 microns
- Must be at a special site to reduce atmospheric absorption
  - 40 microns to ~ 1 cm
    - Submillimeter and millimeter/microwave
- Can be anywhere (but interference from man-made sources or local weather will help determine site)
  - Wavelengths longer than 1 cm but less than 100 m
    - Radio
  - Wavelengths ~ 0.3 microns to 40 microns
    - Optical and some infrared

Choosing telescope sites

- Some sites are chosen just to avoid interference (communication, street lights, clouds, etc)
  - VLA, Kitt Peak, Karoo desert, western Australia
- Some sites are chosen for atmospheric stability
  - Want **laminar** (not turbulent) airflow over your site
  - Mountaintops facing into prevailing winds coming from ocean
- Some sites are chosen for amount of atmosphere
  - Scale height of atmosphere is 8km
  - Scale height of water is 2km
- The best are good at all 3, and still relatively easy to access
  - Mauna Kea, South Pole, Chajnantor Plateau


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

Three methods of detection

- Coherent detectors
  - Interact local electric field with electrical field of incoming photons and measure interference
- Thermal detectors
  - Absorb energy of incoming photons and measure change in temperature
- Photon detectors
  - Absorb energy of incoming photons and release free charge carriers

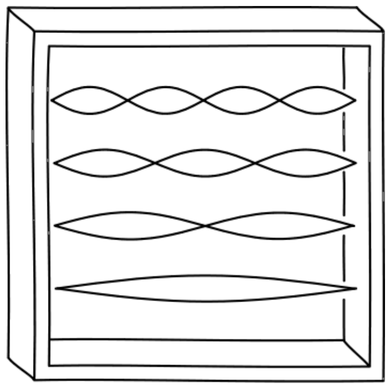
Attributes of Detector System

- Responsivity
- Spectral Response
- Frequency Response (or Bandwidth)
- Efficiency
- Electrical bandwidth
- Read noise (or readout noise)
- Photon noise

Photon statistics

- Photons are bosons, and they follow Bose-Einstein statistics
  - Arrivals are **not independent**
  - Noise is not just proportional to number of photons received
  - Two noise terms: **shot noise** and **photon bunching/wave noise**
- Boltzmann occupation number n_s
  - number of photons in standing-wave mode in box at temperature T
  - number of photons/s/Hz in (diffraction limited) beam in free space (Richards 1994, J.Appl.Phys)

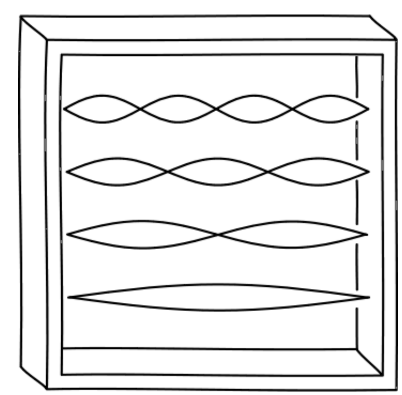
$$\langle n_s \rangle = \left(e^{h\nu_s/kT} - 1\right)^{-1}$$

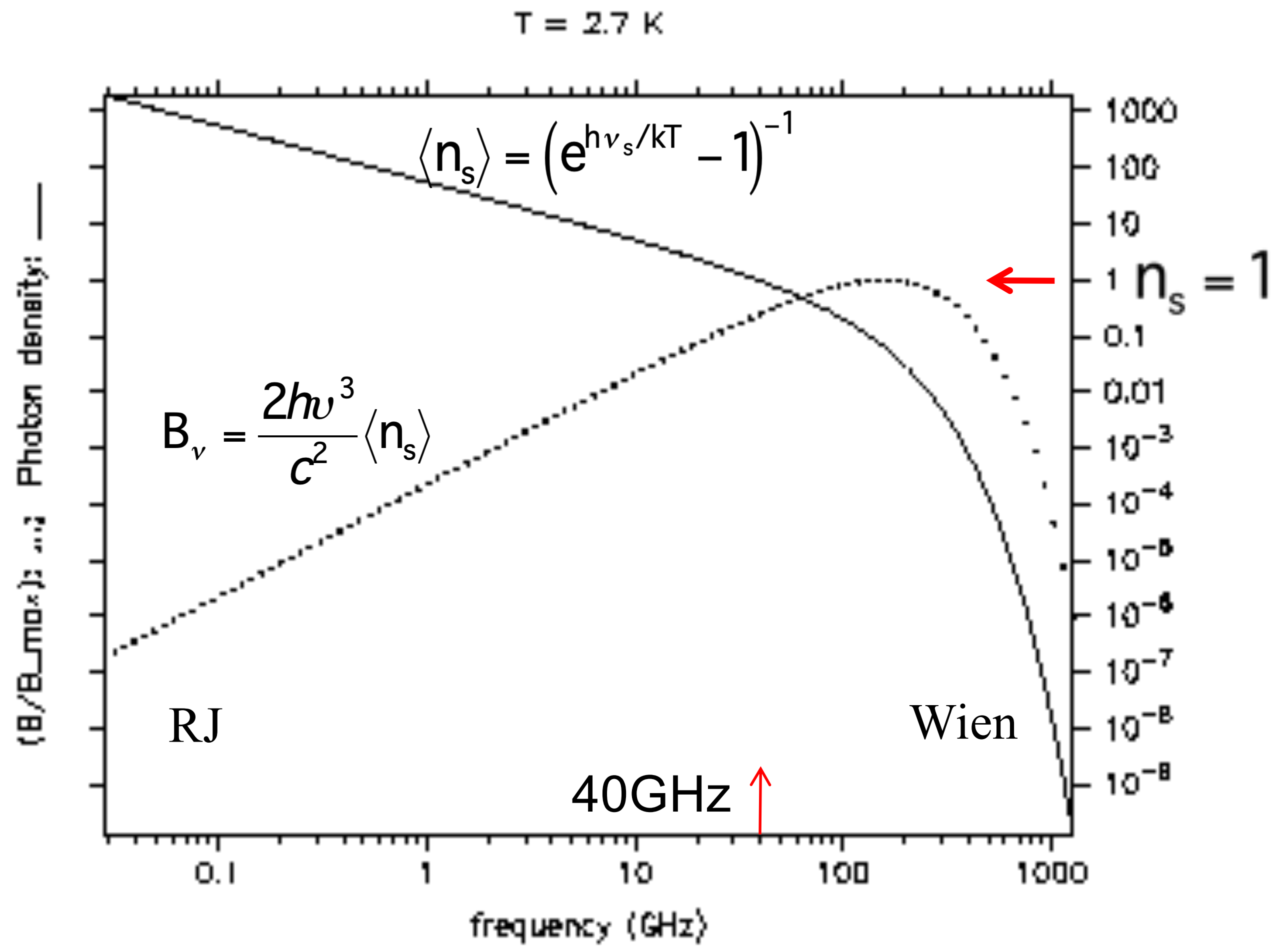


Photon statistics

- Three regimes
  - $n_s >> 1$
    - $h\nu << kT$
    - Radio wavelengths
    - Photon "bunching" is significant
  - $n_s \sim 1$
    - $h\nu \sim kT$
    - ~ Millimeter wavelengths
    - Both noise terms must be considered
  - $n_s << 1$
    - $h\nu >> kT$
    - Shot noise is significant
    - **Noise follows Poisson statistics**

$$\langle n_s \rangle = \left(e^{h\nu_s/kT} - 1\right)^{-1}$$





Wien: $n_s < 1 \Rightarrow$ noise $\propto \sqrt{n_s}$ (counting stats)

RJ: $n_s > 1 \Rightarrow$ noise $\propto n_s$ (wave noise)

Shot noise on an ideal detector

- Let P be the power falling onto the detector
  - With an efficiency η in a small bandwidth Δν
- Only considering shot noise as a noise source
- Average rate of photon emission events is given by r
  - $r = \frac{\eta P}{h\nu}$
- The average number of photon events occurring in a time T is given by $\overline{N} = rT$
  - (Actual number of events will fluctuate around N for any one particular interval of length T)
- Probability P(N) that in any one such interval, exactly N photoevents occur, is given by the Poisson probability distribution:
  - $P(N) = \frac{\overline{N}^N}{N!} e^{-N}$

Poisson distribution

- A specific kind of binomial distribution
- For very rare, independent events with a large number of trials
- “Poisson clumping”
- (pages 38-39 of Practical Statistics for Astronomers)