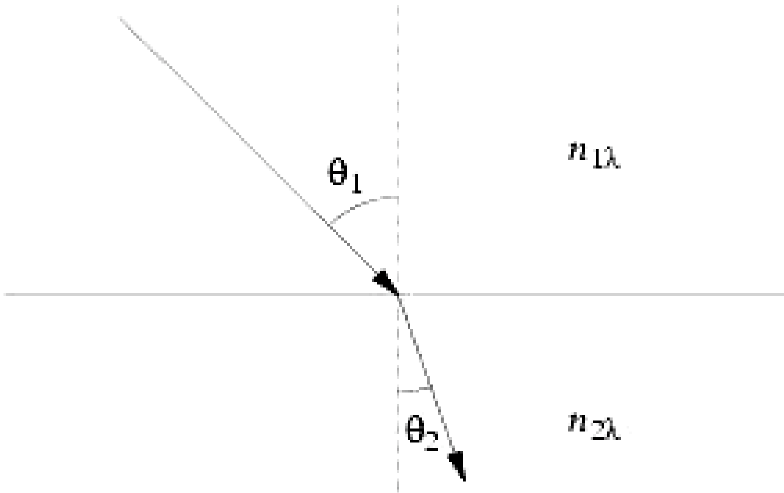
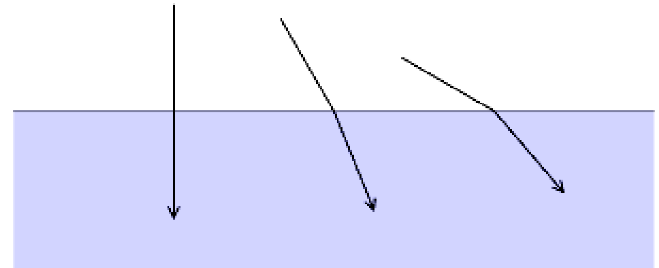
Ay 20 - Fall 2004
Lecture 2

- Telescopes and basic optics
- Atmospheric turbulence and adaptive optics (AO)
- Radio telescopes and interferometry
- Space observatories, high-energy astronomy
- Surveys, archives, data-rich astronomy, and Virtual Observatory (VO)

Note:
This printout is missing many pictures shown in the class, in order to keep the file size reasonably small

Basic Optics: Refraction





Index of refraction:
$n(\lambda) = c / v(\lambda)$

e.g., $n_{air} \approx 1.0003$,
$n_{water} \approx 1.33$,
$n_{glass} \sim 1.5$, etc.

Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

If $\sin \theta_2 = 1$, then we have a total internal reflection for $\theta_1 > \sin^{-1} (n_2/n_1)$; e.g., in optical fibers

Index of Refraction of the Air

Cauchy's approximate formula:

$n_{air} = 1.000287566 + (1.158102 \times 10^{-9}\ \mathrm{m} / \lambda)^{2} + O(\lambda)^{4}$

➥ $\sim 5 \times 10^{-6}$ in visible light

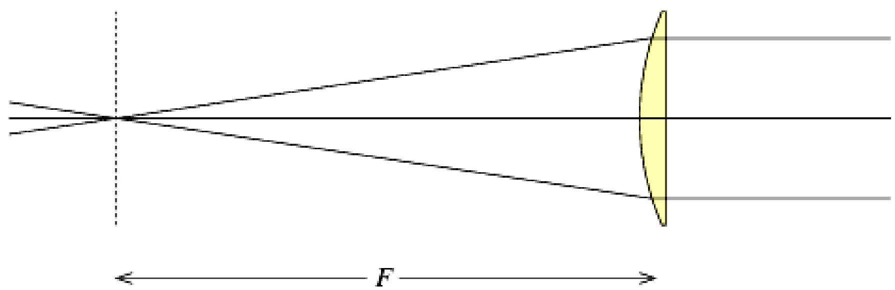
Thus, $\Delta\lambda/\lambda \sim 3 \times 10^{-4}$ in visible light $\sim 1 - 3$ Å

Beware of the air vs. vacuum wavelengths in spectroscopy!

Traditionally, wavelengths ≥ 3000 (2800?) Å are given as air values, and lower than that as vacuum values. Sigh.

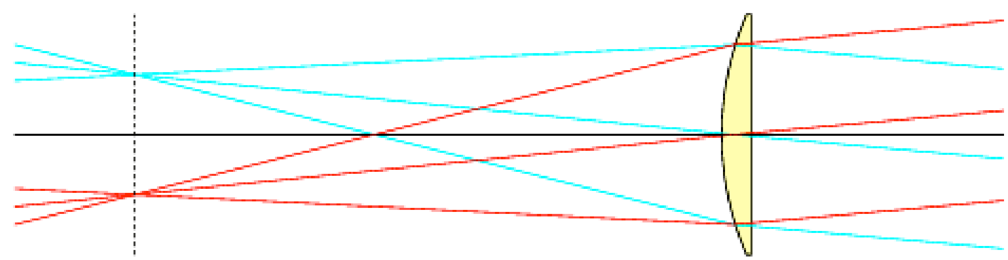
Lenses and Refractive Optics

No longer used for professional telescopes,
but still widely used within instruments

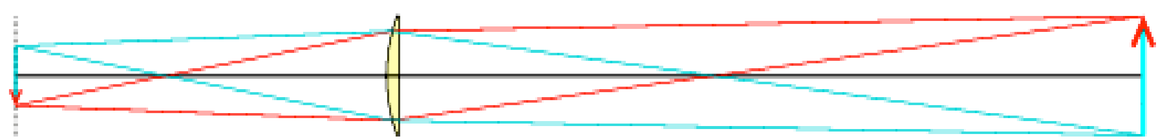


Focal length

Focal plane



Inverted images



Lensmaker's Formula

Using the Snell's law, it can be shown that

$$1/f = (n-1)\,(1/R_1 + 1/R_2)$$

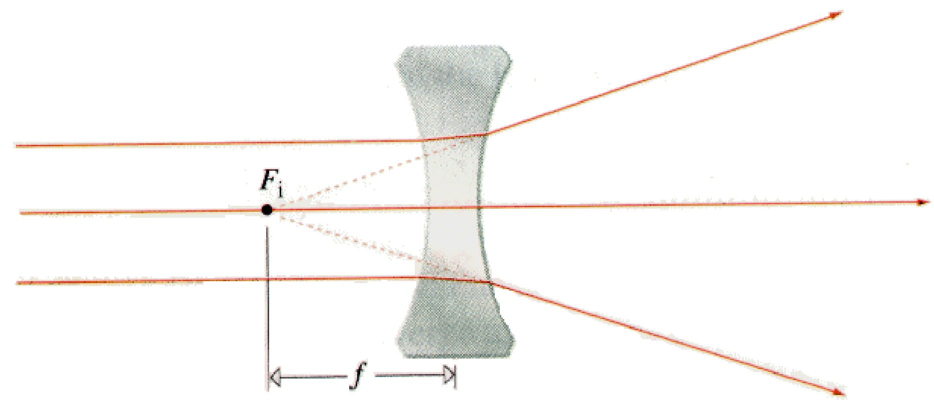
(aka the "lens power")

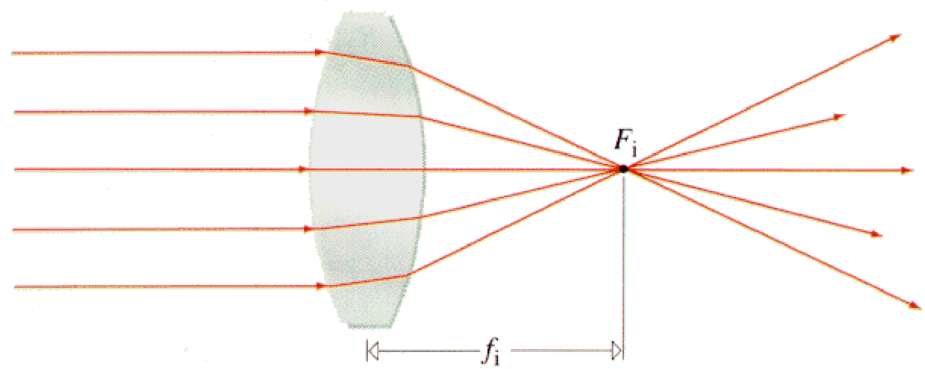
where:

f = focal length

R_1, R_2 = curvature radii of the two lens surfaces

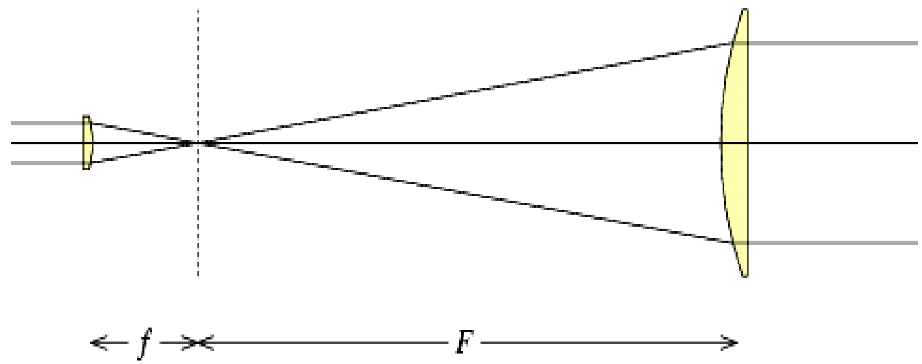
Note that for a spherical mirror, $f = R/2$

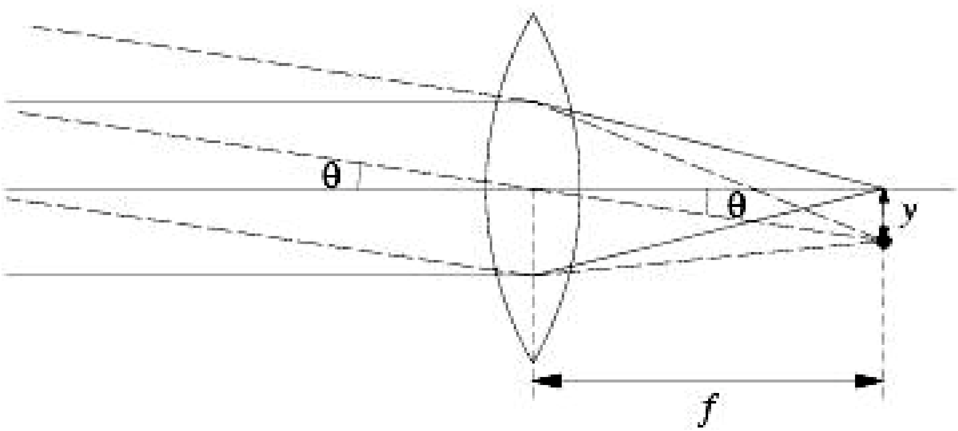




Magnification and Image Scale

$$M = F / f$$



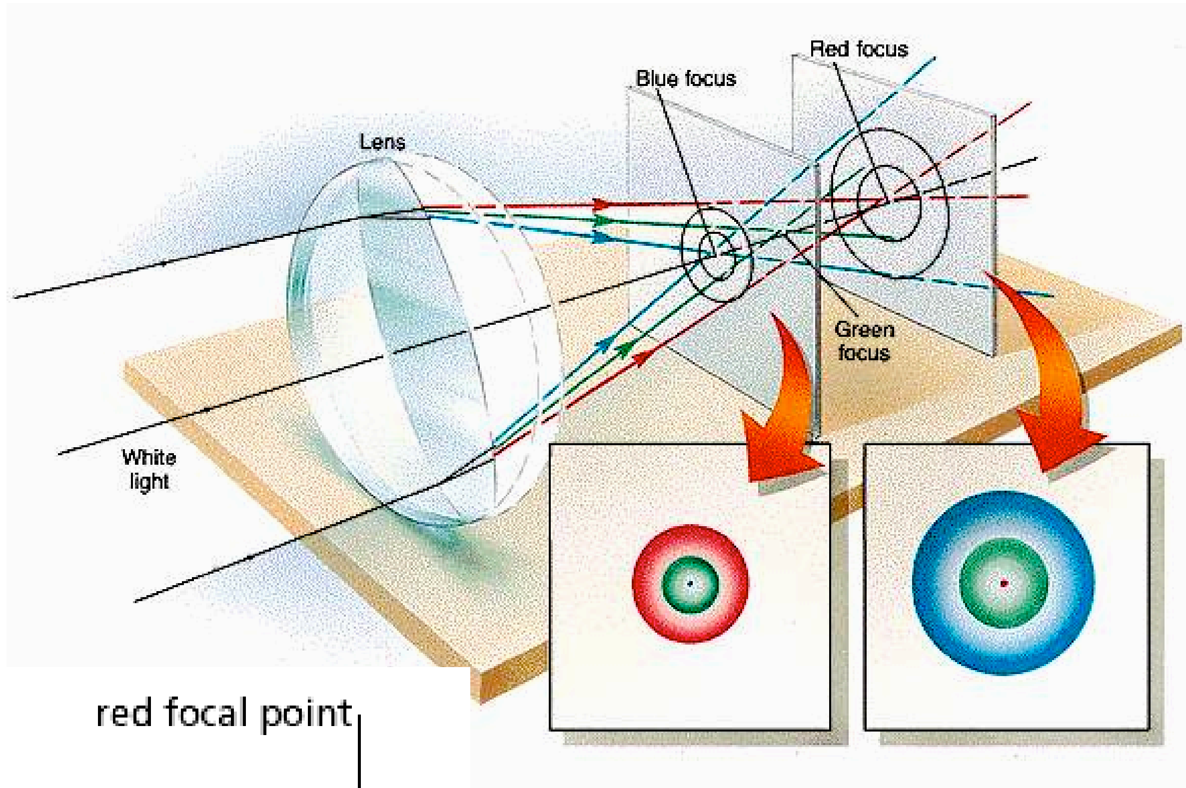


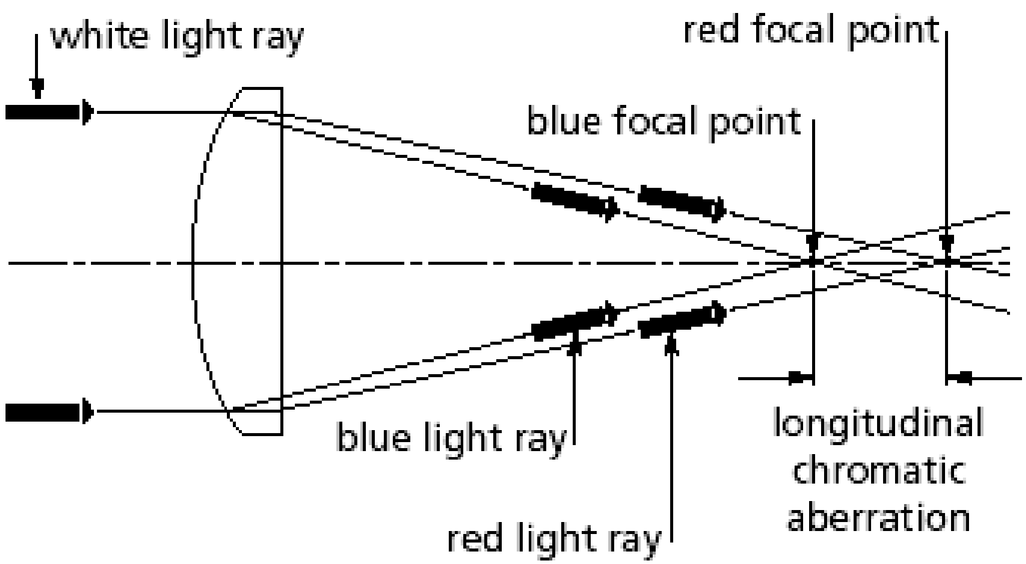
$$y = f \tan \theta \approx f \theta$$

scale: $d\theta / dy = 1 / f$

Chromatic Aberration

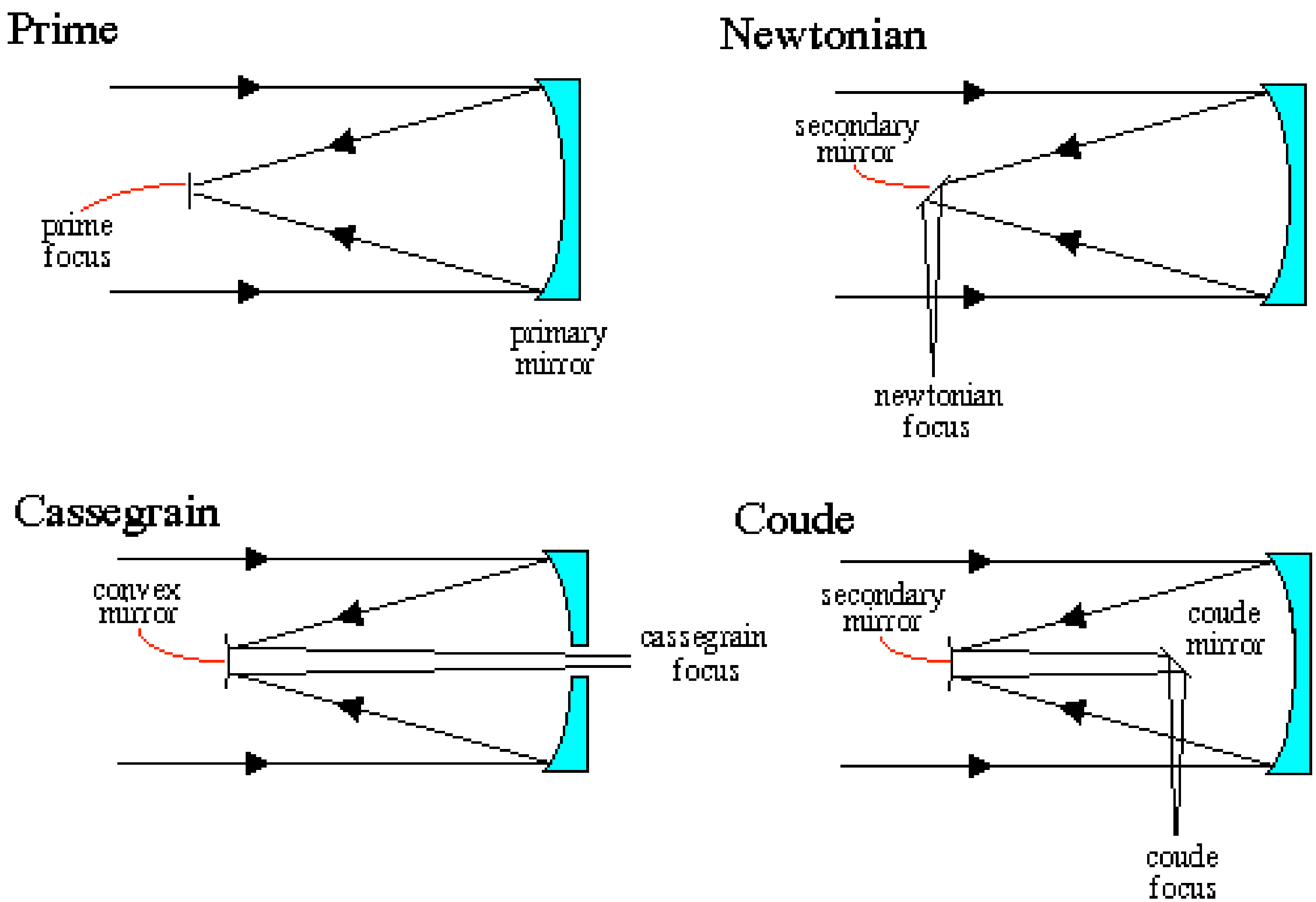
Because the speed of light in any medium is f(□)





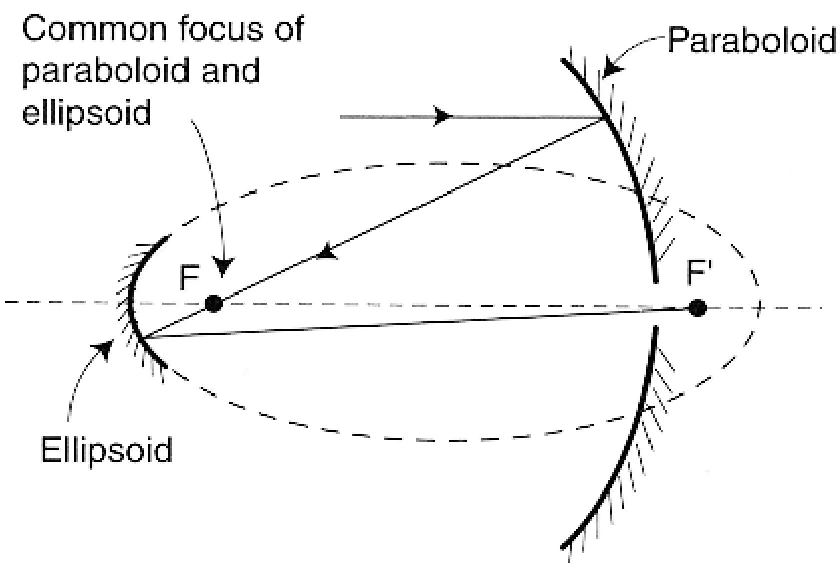
Cured by lens multiplets …
Or by reflective optics!

Reflecting Telescopes

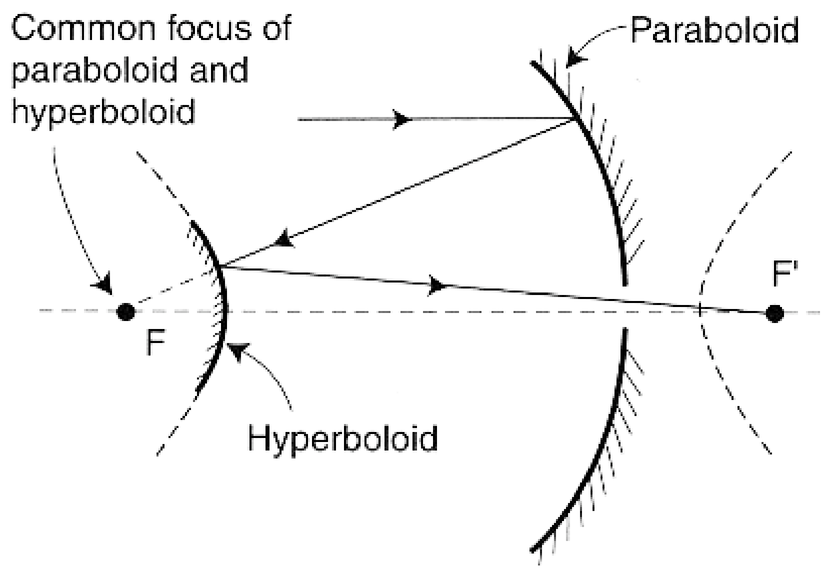


Mirror figures: always conic sections, mostly paraboloid, sometimes hyperboloid (Cassegrain secondary, Ritchie-Chreten both primary and sec.), rarely sphere (Schmidt, Maksutov).

Gregorian vs. Cassegrain

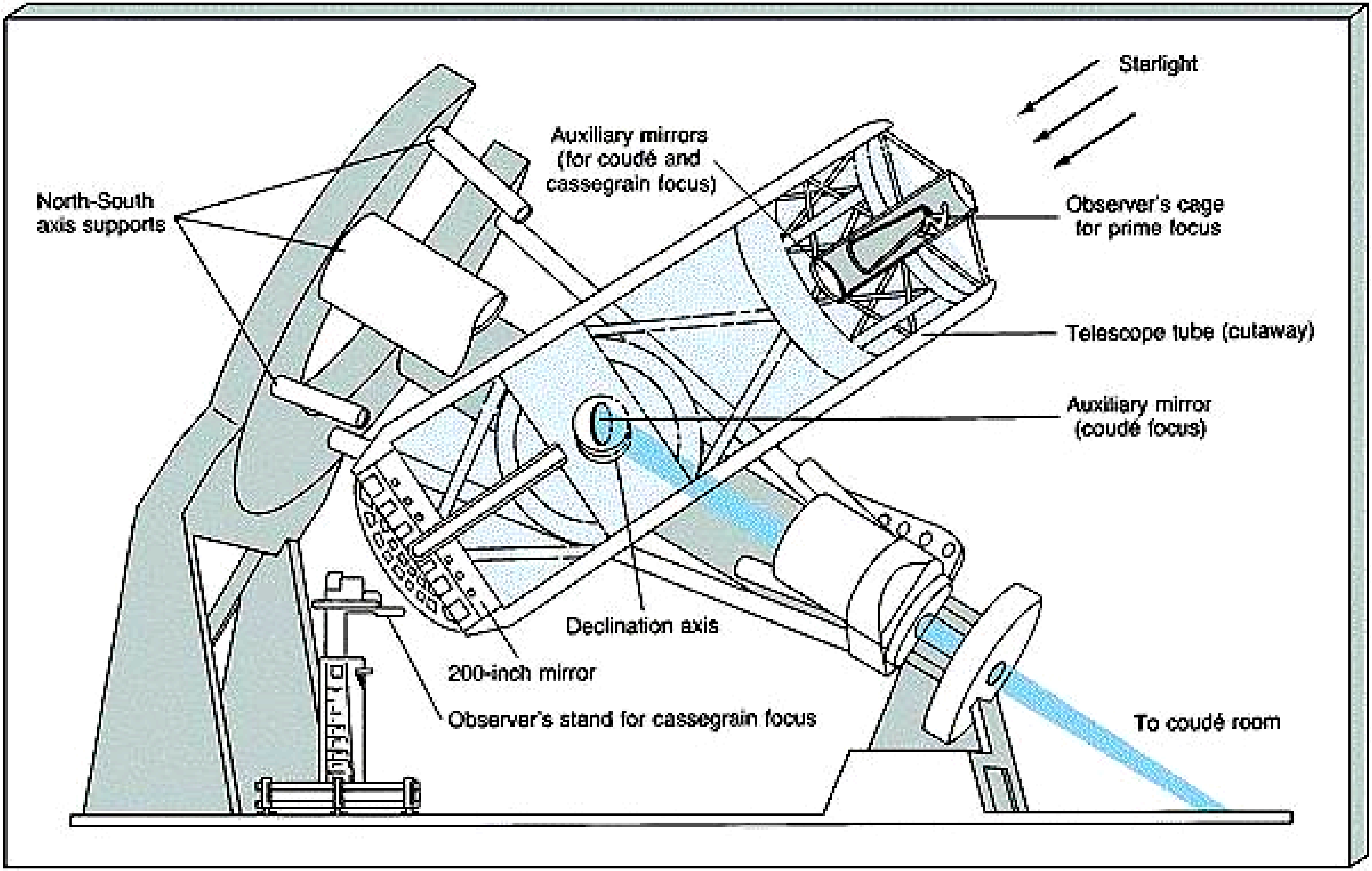


Gregorian telescope

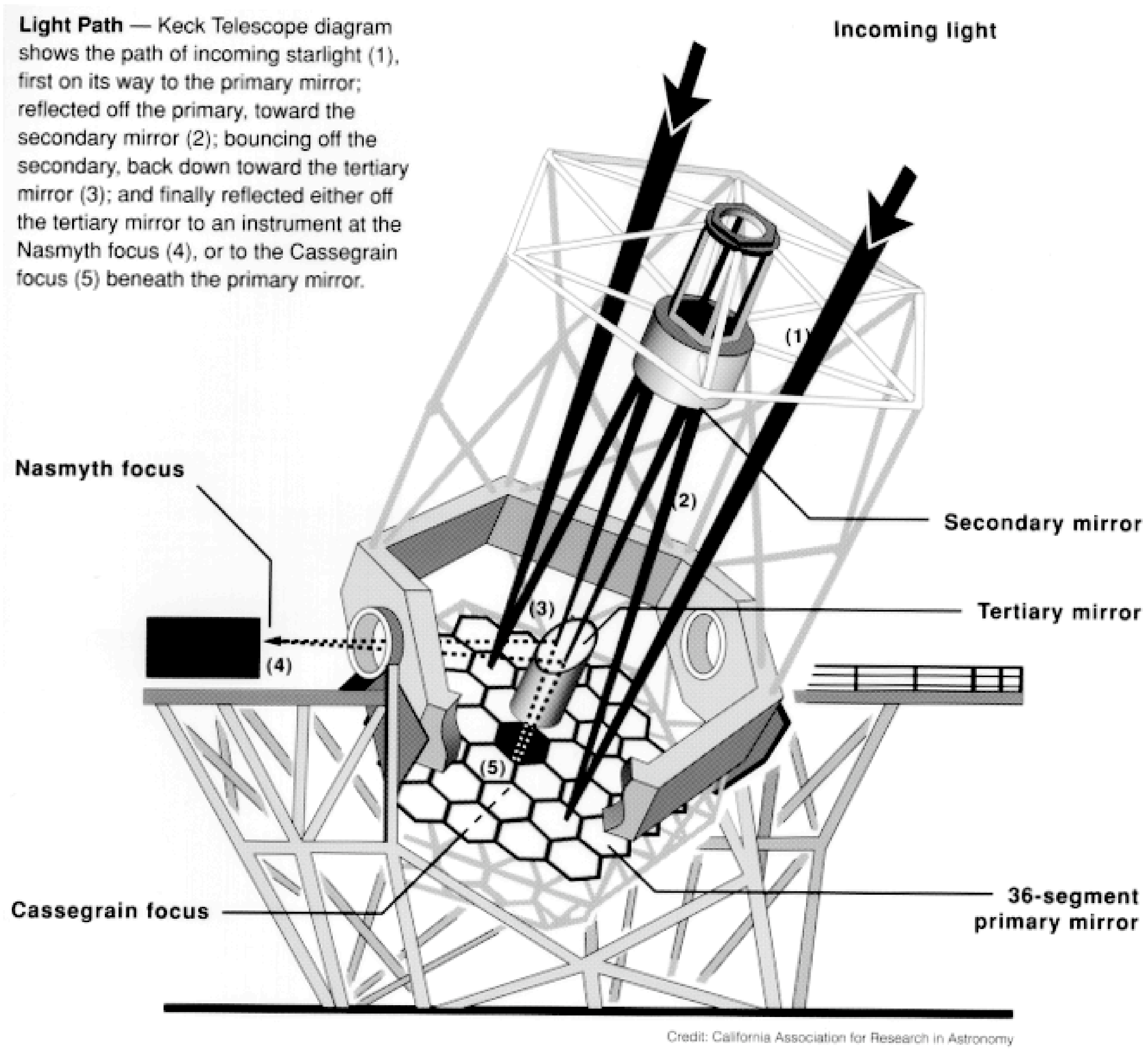


Cassegrain telescope

Palomar Hale 200-inch Telescope

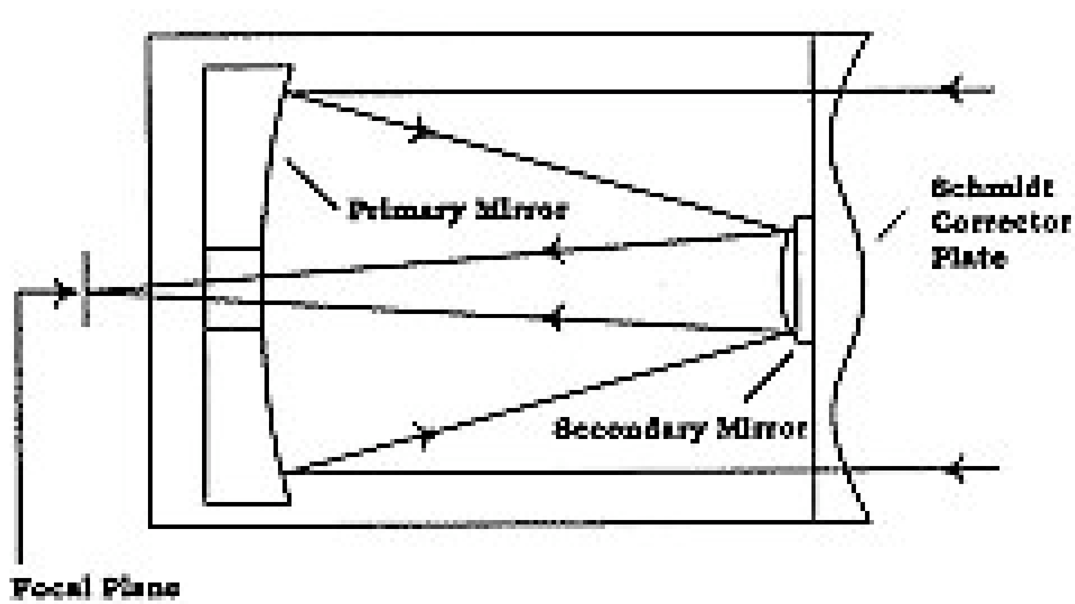


Keck



Light Path — Keck Telescope diagram shows the path of incoming starlight (1), first on its way to the primary mirror; reflected off the primary, toward the secondary mirror (2); bouncing off the secondary, back down toward the tertiary mirror (3); and finally reflected either off the tertiary mirror to an instrument at the Nasmyth focus (4), or to the Cassegrain focus (5) beneath the primary mirror.
Incoming light
(1)
(2)
(3)
(4)
(5)
Nasmyth focus
Secondary mirror
Tertiary mirror
Cassegrain focus
36-segment primary mirror
Credit: California Association for Research in Astronomy

Schmidt Telescopes:
offering a large FOV
(popular for sky surveys)



Aberrations

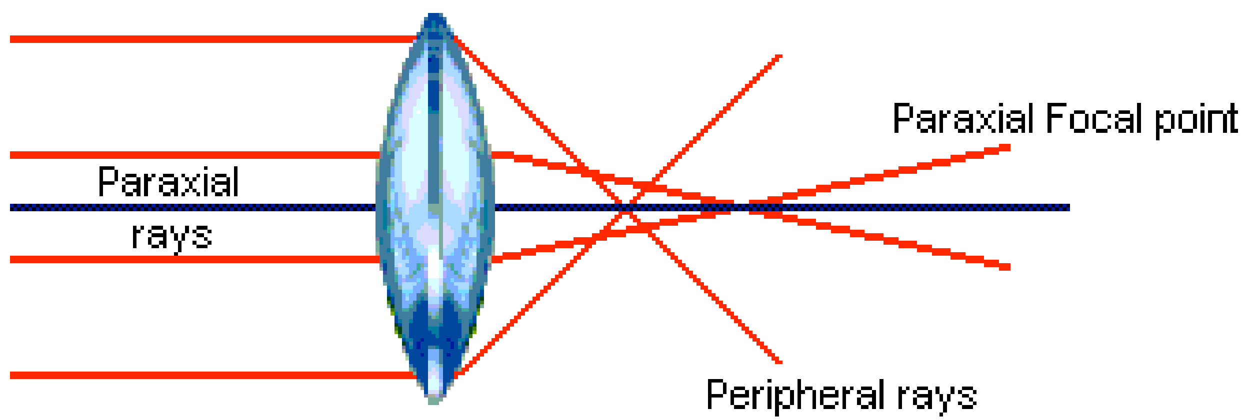
Chromatic

Achromatic

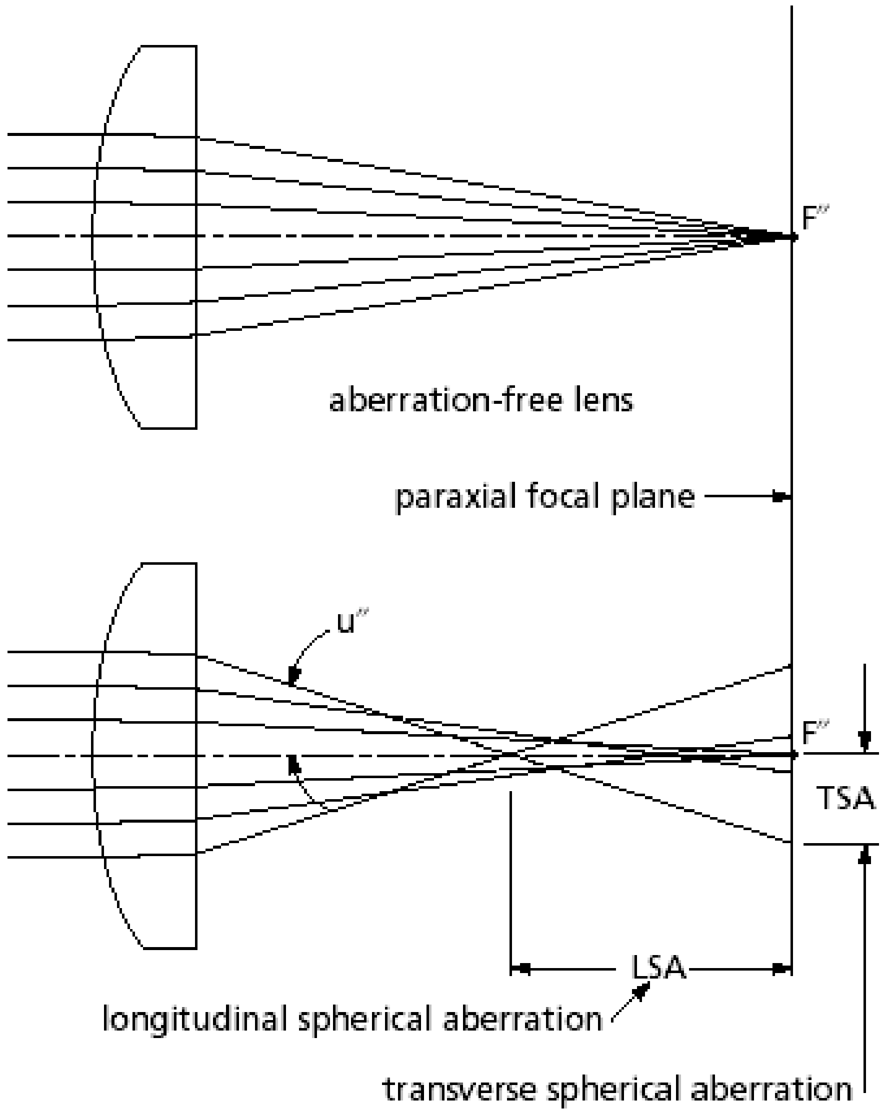
Image Deterioration
(spherical aberration, coma, astigmatism)

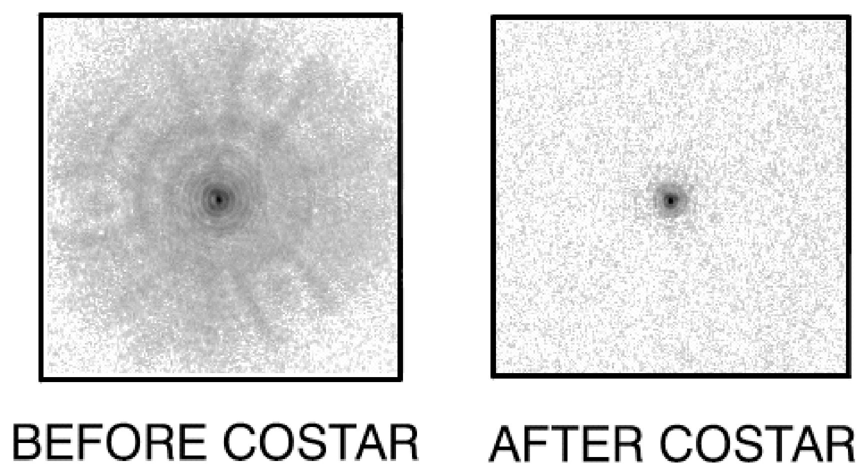
Image Distortion
(Petzval field curvature, pincushion, barrel distortion)

Spherical aberration:

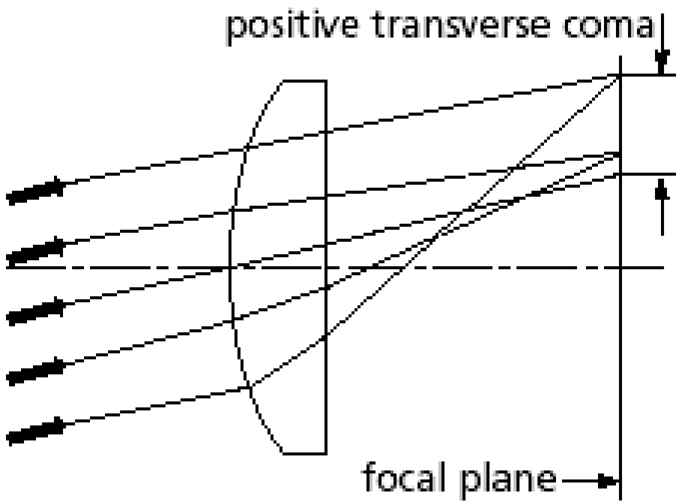


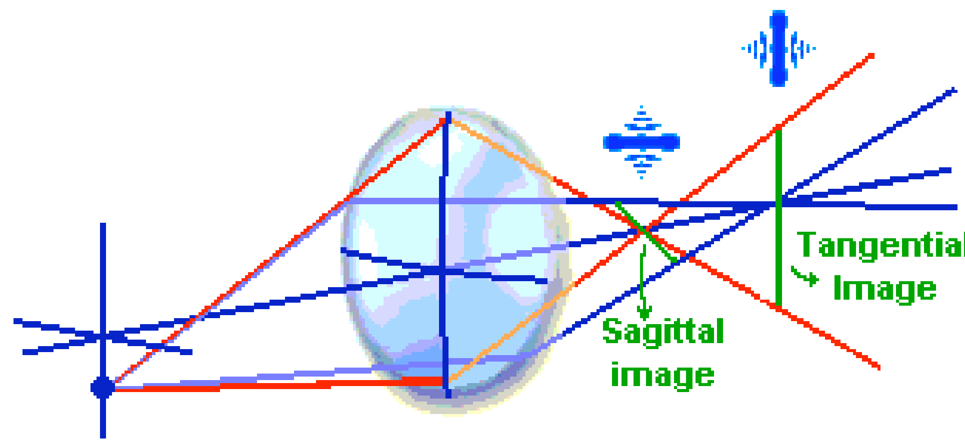
Spherical Aberration: The HST Saga

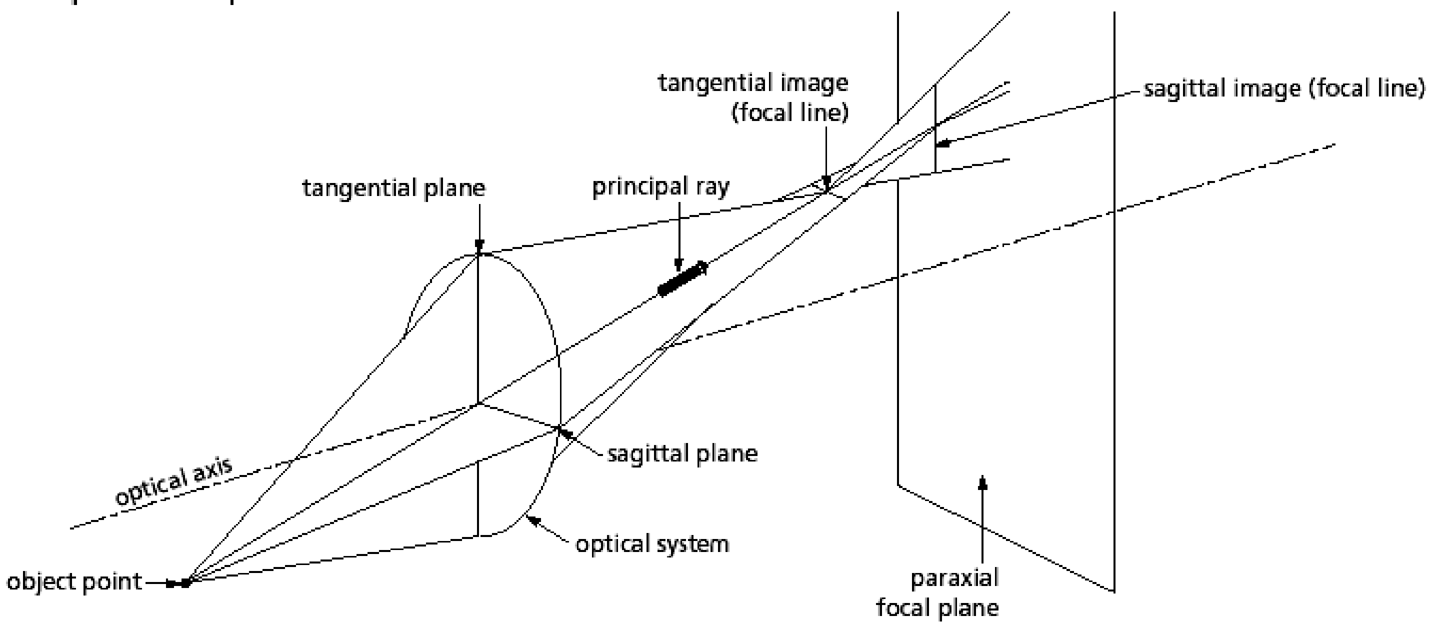




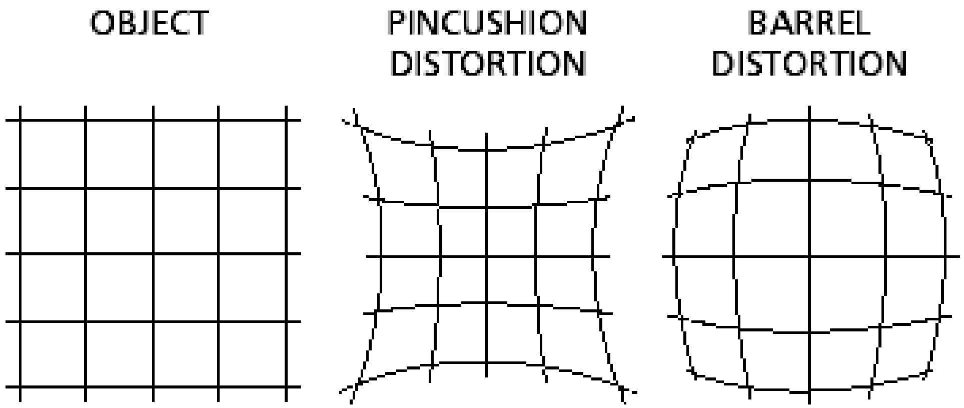
Coma and Astigmatism





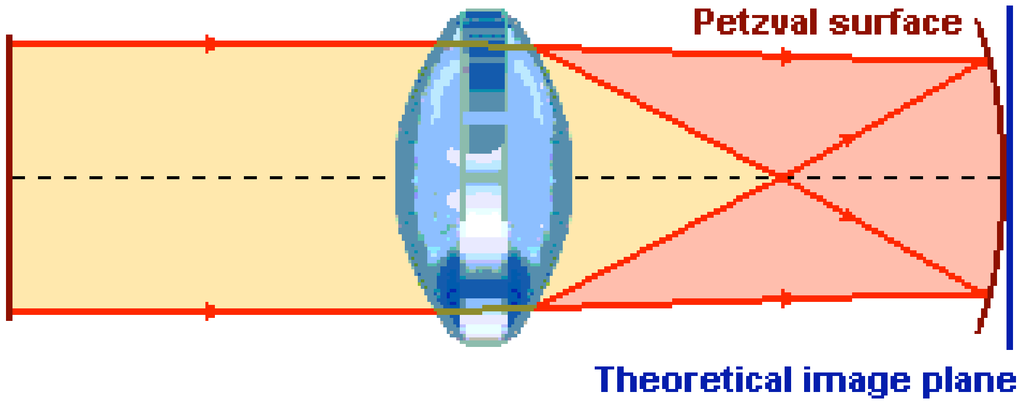


Pincushion and Barrel Distortion



Magnification varies as a function of off-axis distance

Petzval Field Curvature



Focal "plane" is actually spherical

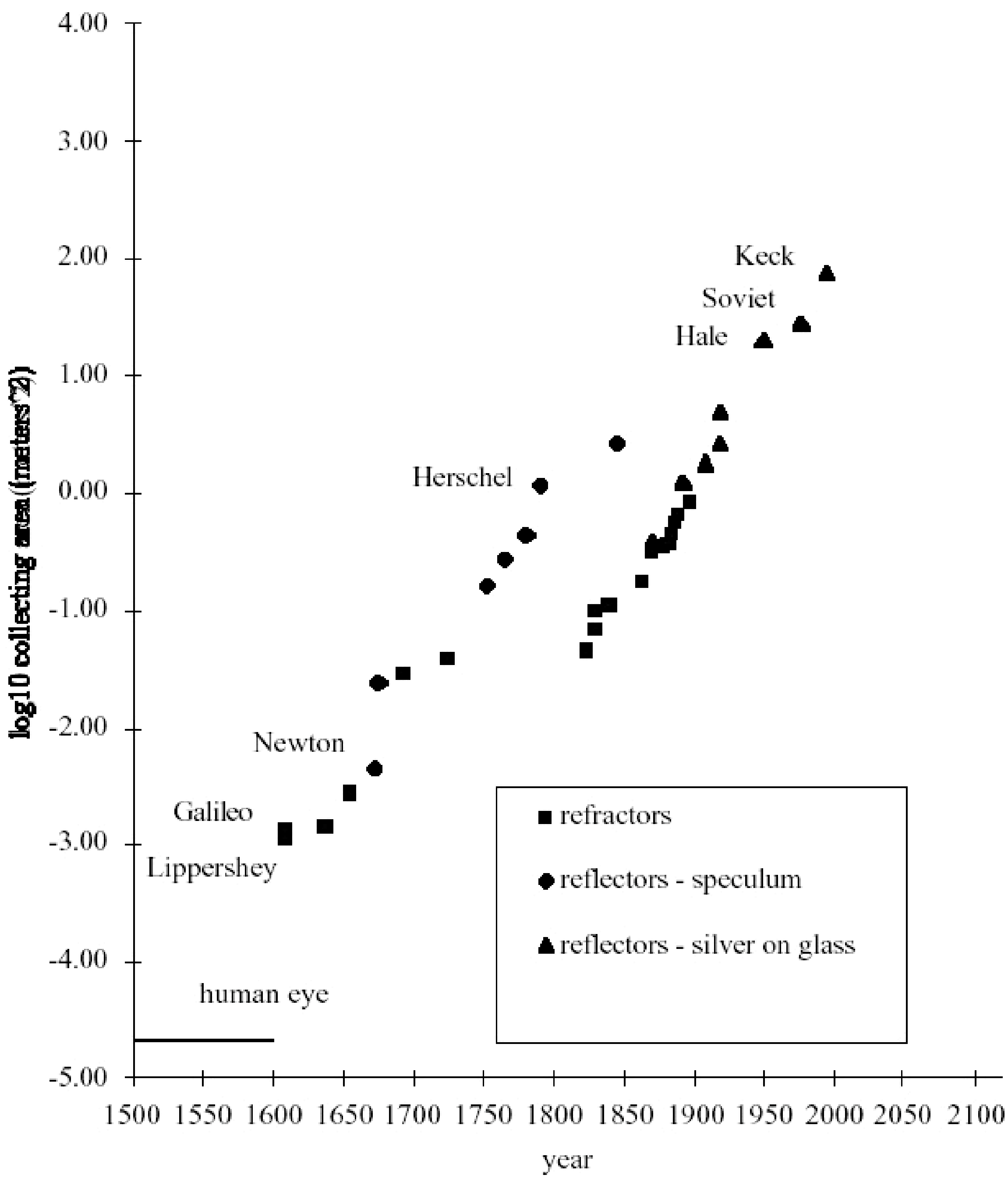
Modern Telescope Mirror Designs

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

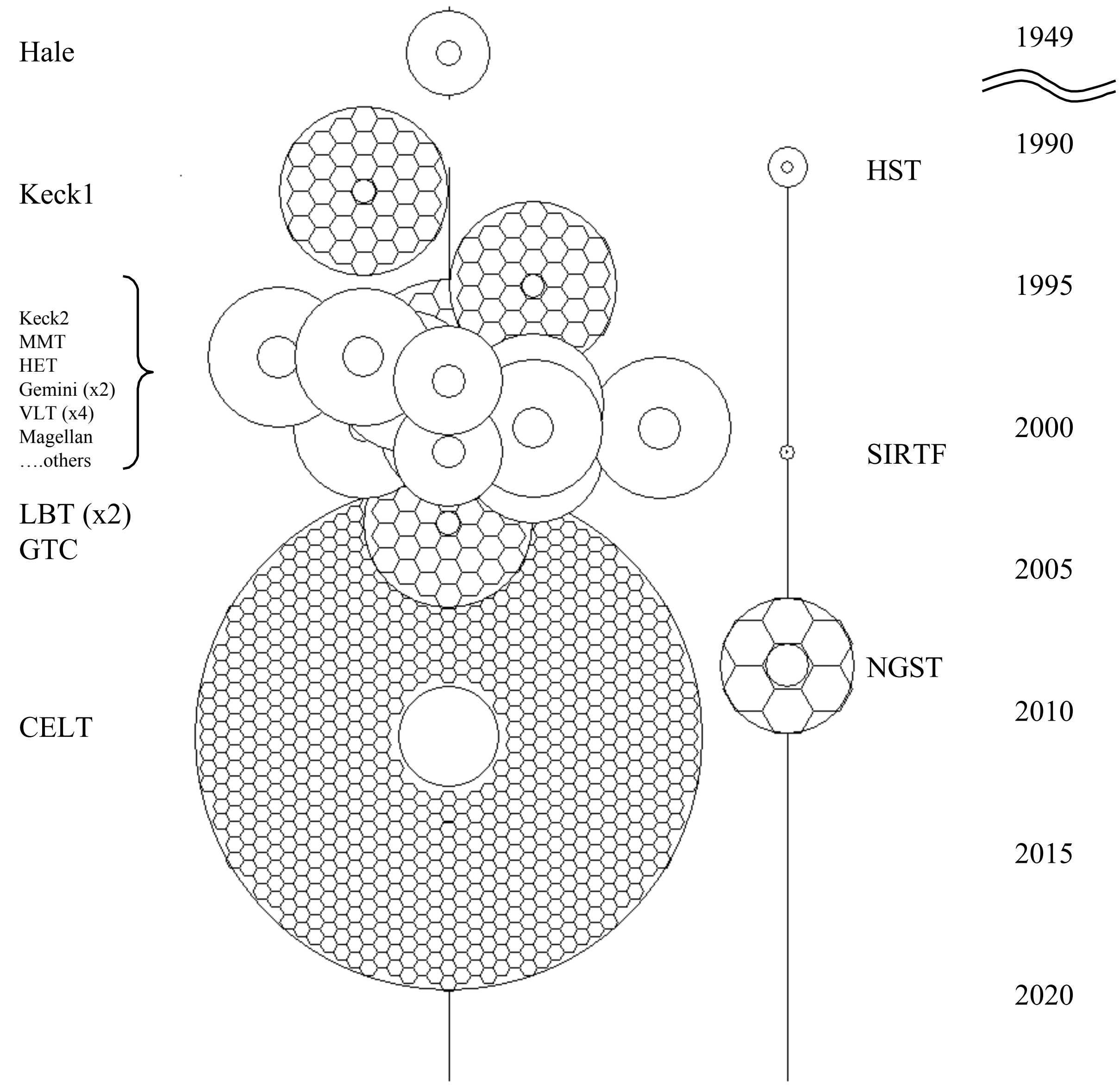
The critical issues:

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

The History of Telescopes



Large telescope projects 1950-2020



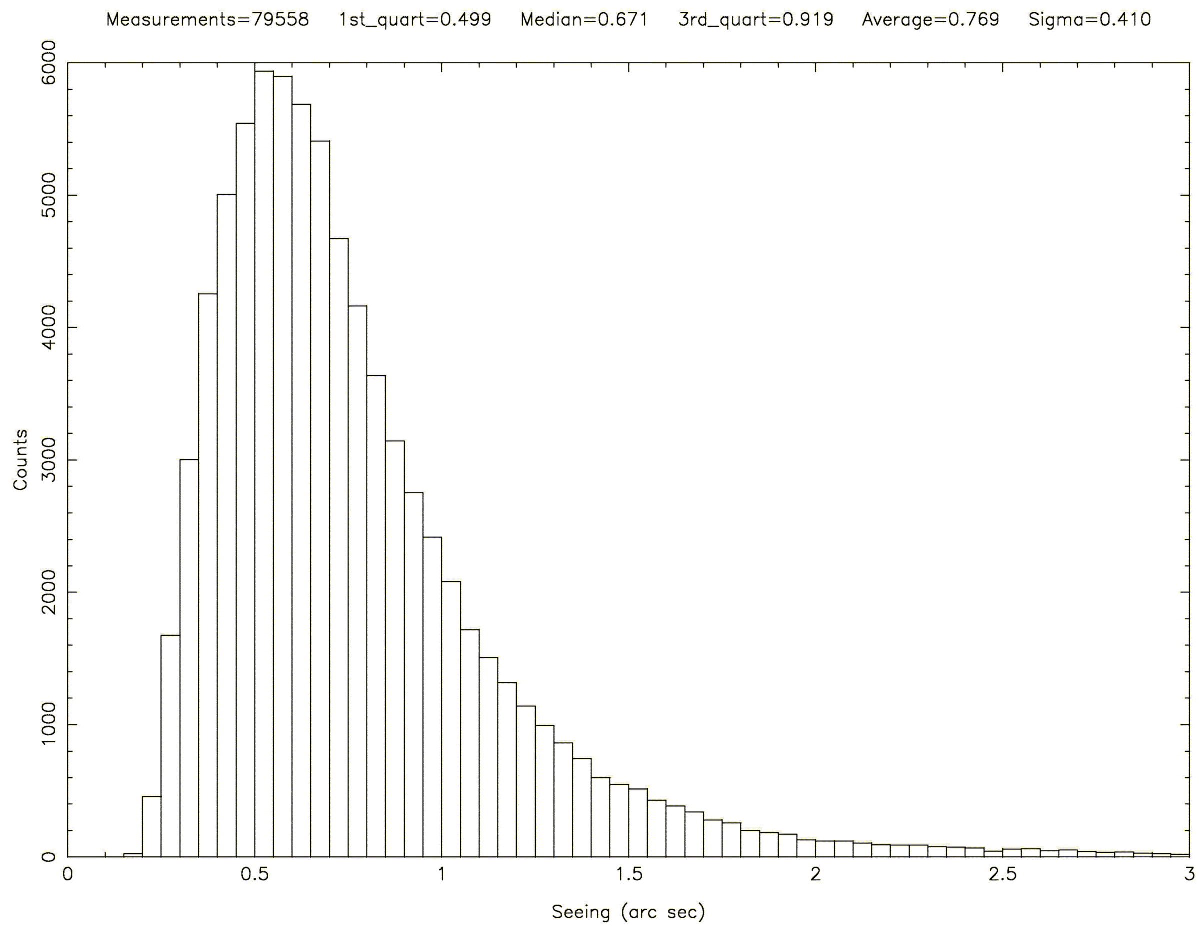
Telescope Site Selection

- Site selection is critically important
  - Number of good nights and atmospheric quality determine the amount and the quality of the science done
- Site selection issues and problems
  - Atmospheric (seeing, transparency, AO issues, wind …)
  - Logistical (ease and cost of construction and operation)
  - Political/sociological (availability, security, staffing, etc.)
  - Geological (earthquakes, volcanos)

Historically, site selection was dominated by the seeing limited visible, conveniece (e.g., within a driving distance), and small or subjective measurements. Nowadays the action is in the IR and AO, and the whole world is a stage.

The Best Known Sites: Mauna Kea, Canarias, Northern Chile, Southern California + Baja, Namibia, Antarctica, + a few …

Seeing measurement telescopes at Cerro Tololo (CTIO) ➔



⬅ Typical seeing distribution

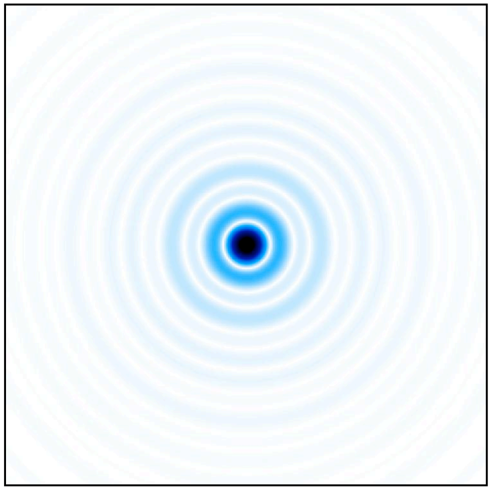
Telescopes in Space

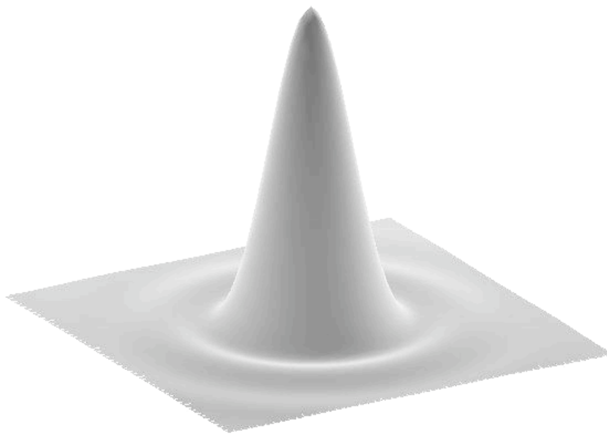
Hubble Space Telescope: only 2.4-m, but location, location, location!

And its successor:

James Webb Space Telescope (JWST)

Diffraction-Limited Imaging (an ideal telescope)

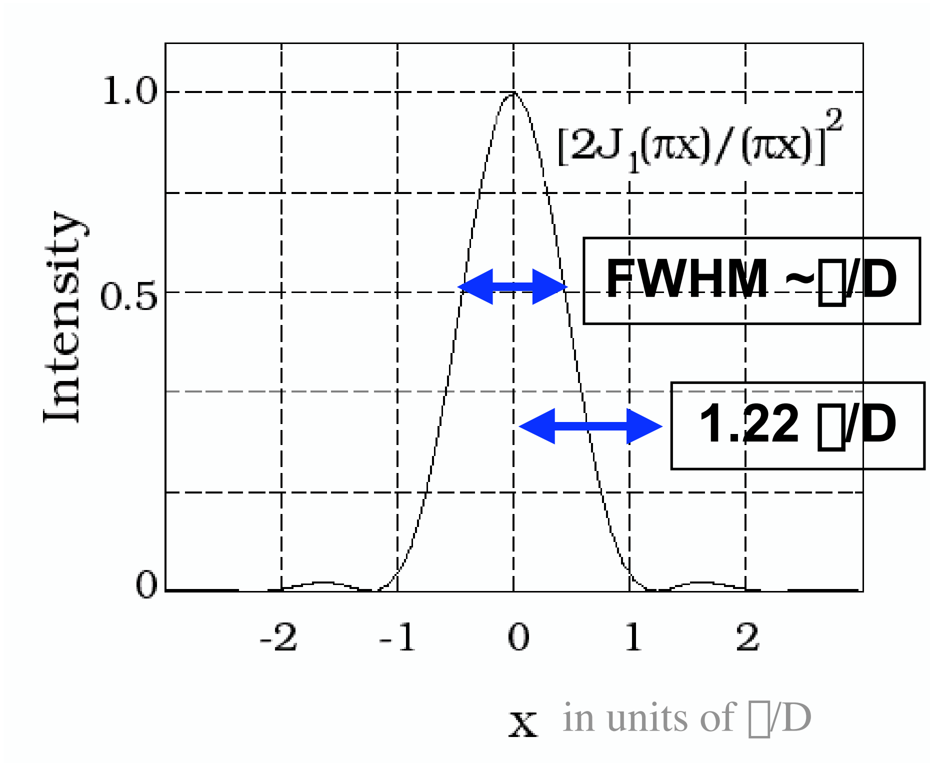




The Airy function
~ a Fourier transform of the actual open telescope aperture

In reality, it tends to be more complex, due to the mirror geometry, etc.

Diffraction-Limited Imaging



With no turbulence, FWHM is diffraction limit of telescope:

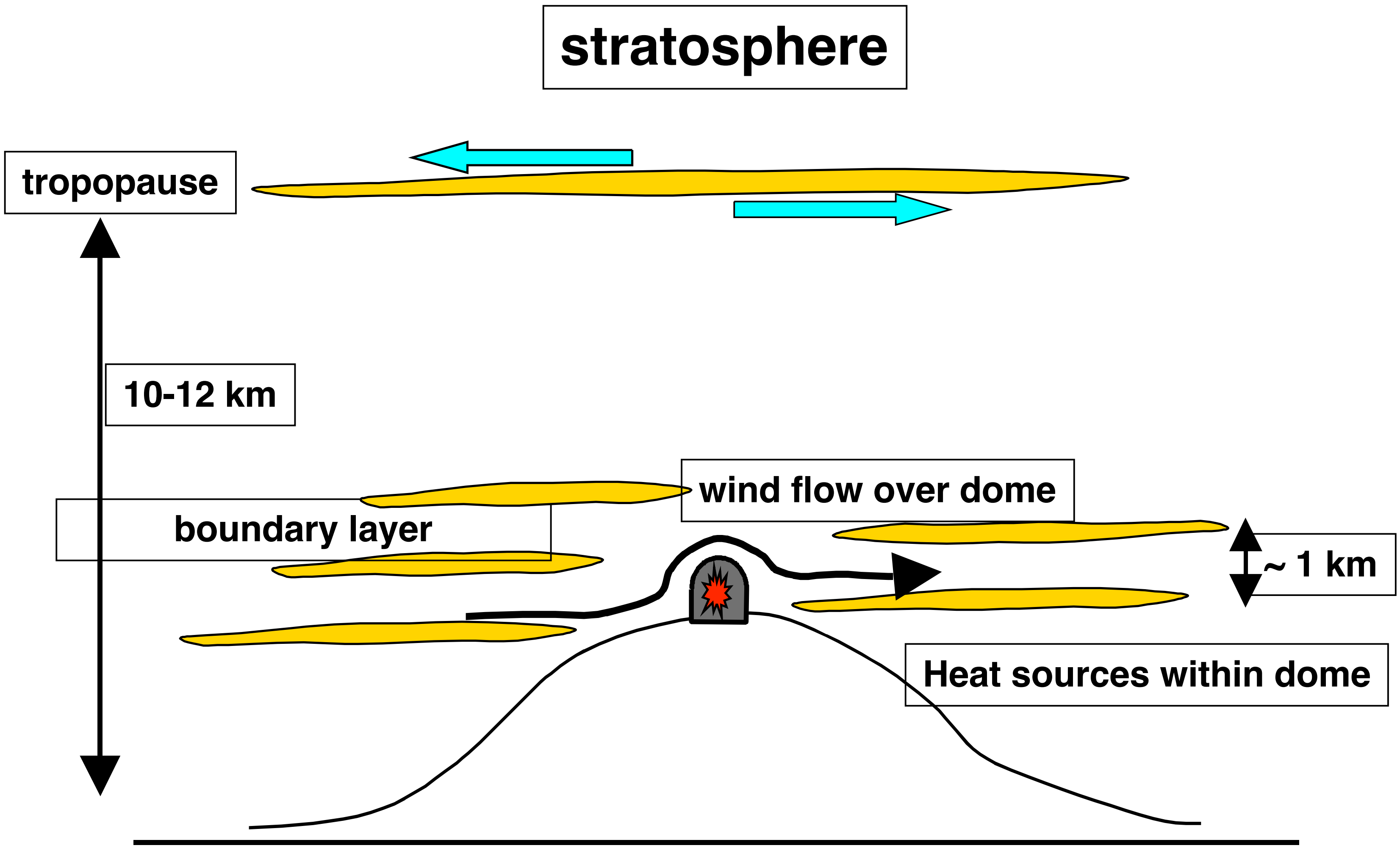
$$\theta \text{ [radians]} \approx \lambda / D$$

Example:

λ/D = 0.02 arc sec for λ = 500 nm, D = 10 m

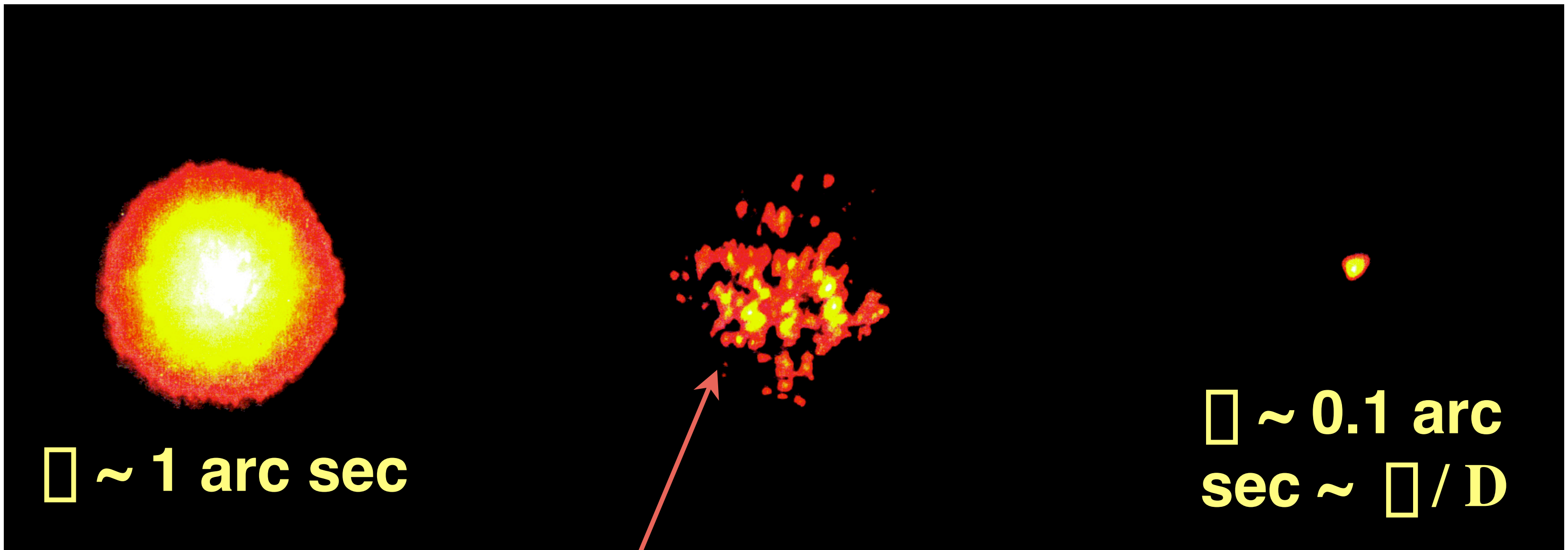
With turbulence, image size (“seeing”) gets much larger, typically ~ 0.5 - 2 arcsec. In order to restore the intrinsic angular resolution, we need **Adaptive Optics (AO)**

Turbulence arises in several places



Images of a bright star

Lick Observatory, 1 m telescope



Long exposure image

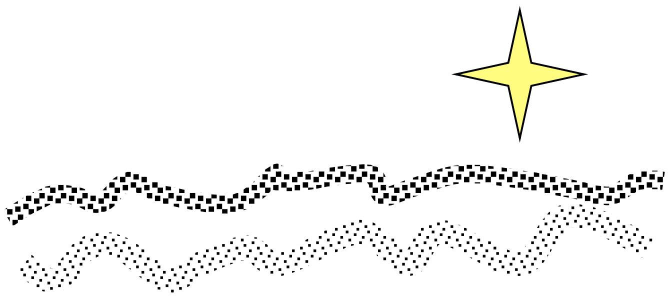
Short exposure image

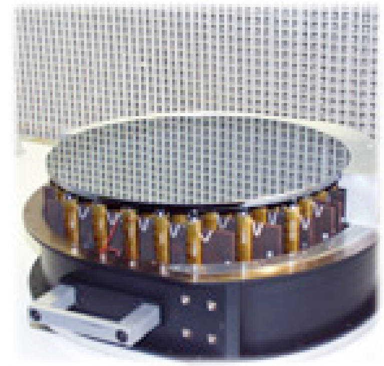
Image with adaptive optics, (nearly) diffraction limited

Speckles (each is at diffraction limit of telescope)

Schematic of adaptive optics system

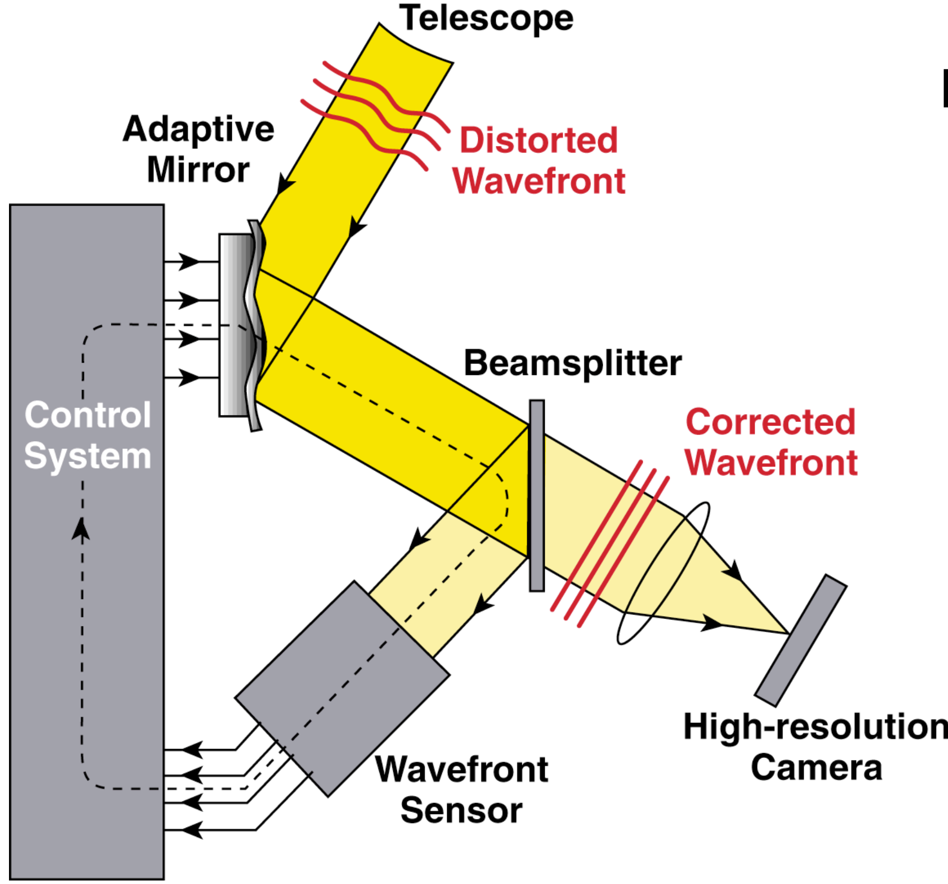
Atmospheric turbulence





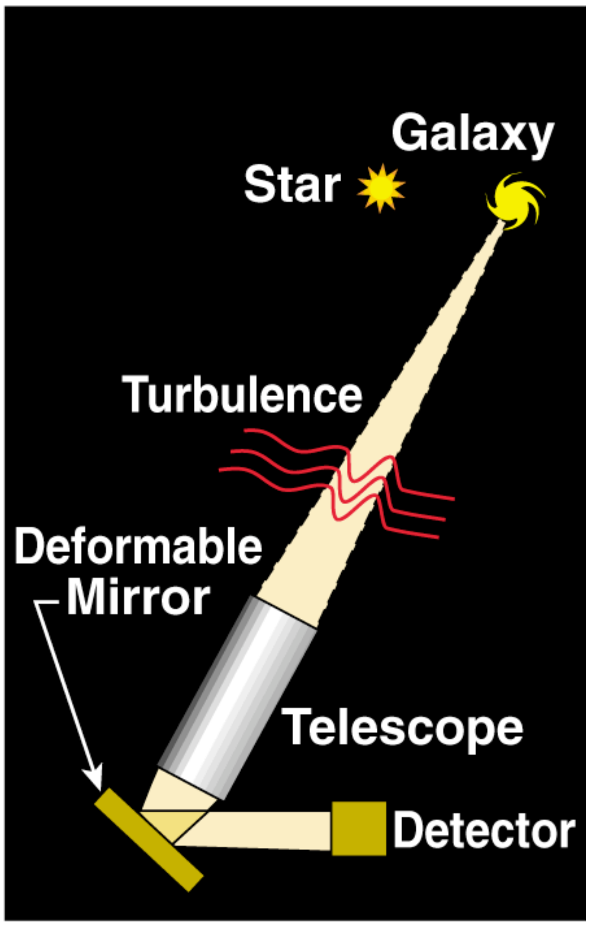
Deformable mirror

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



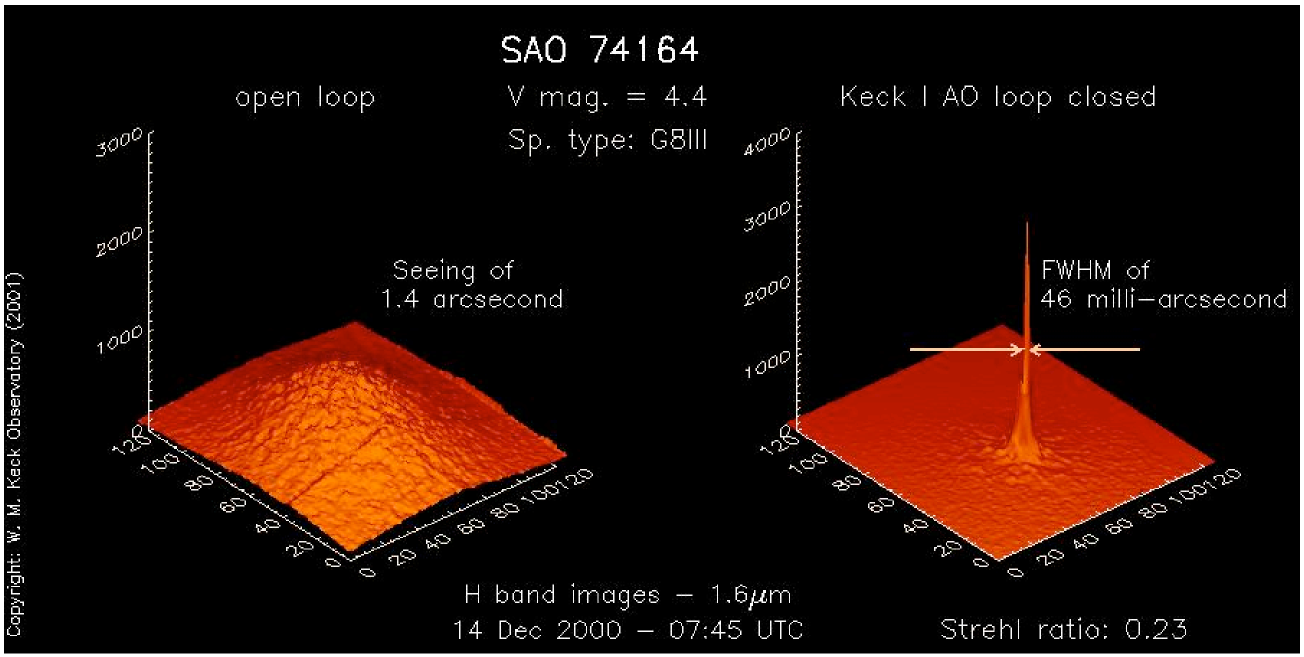
But you need a bright star very close to your target (a few arcsec) in order to compute the correction

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)

Keck AO System Performance



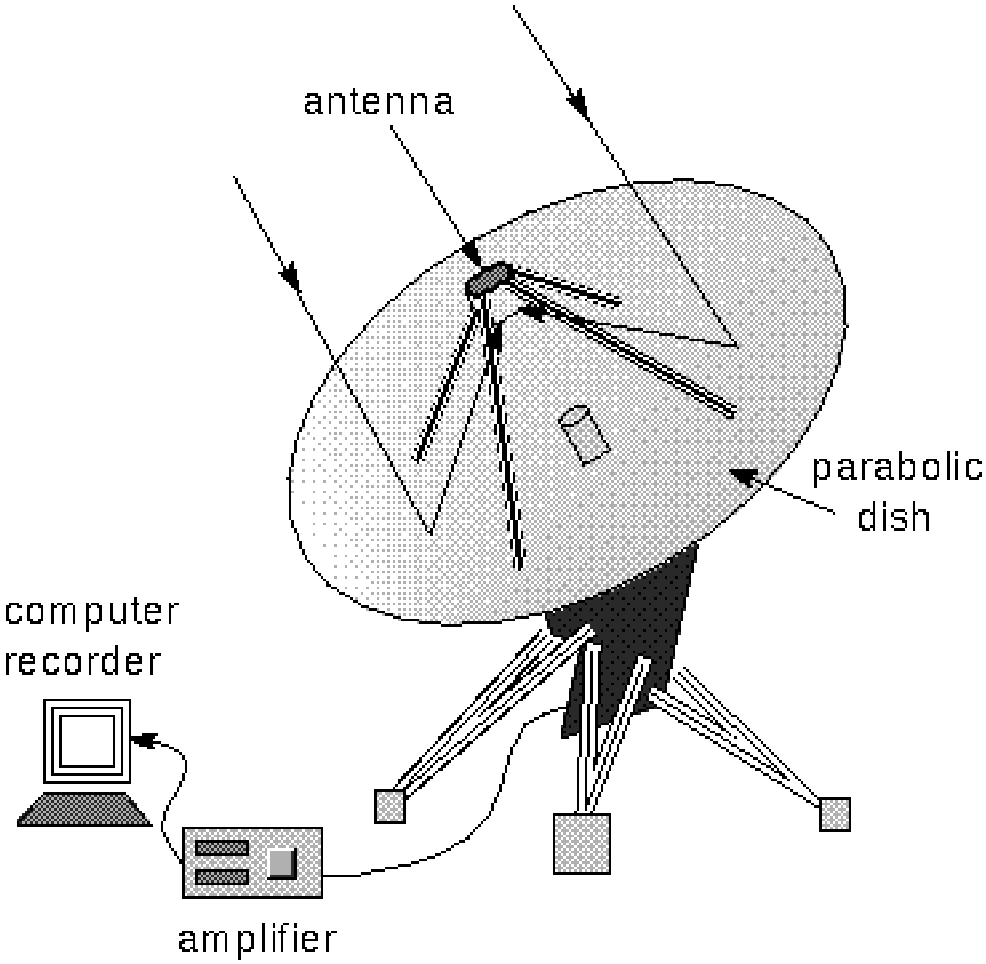
Single Dish (the bigger the better) …

The Green Bank Telescope (GBT), D = 100 m
Arecibo, D = 300 m

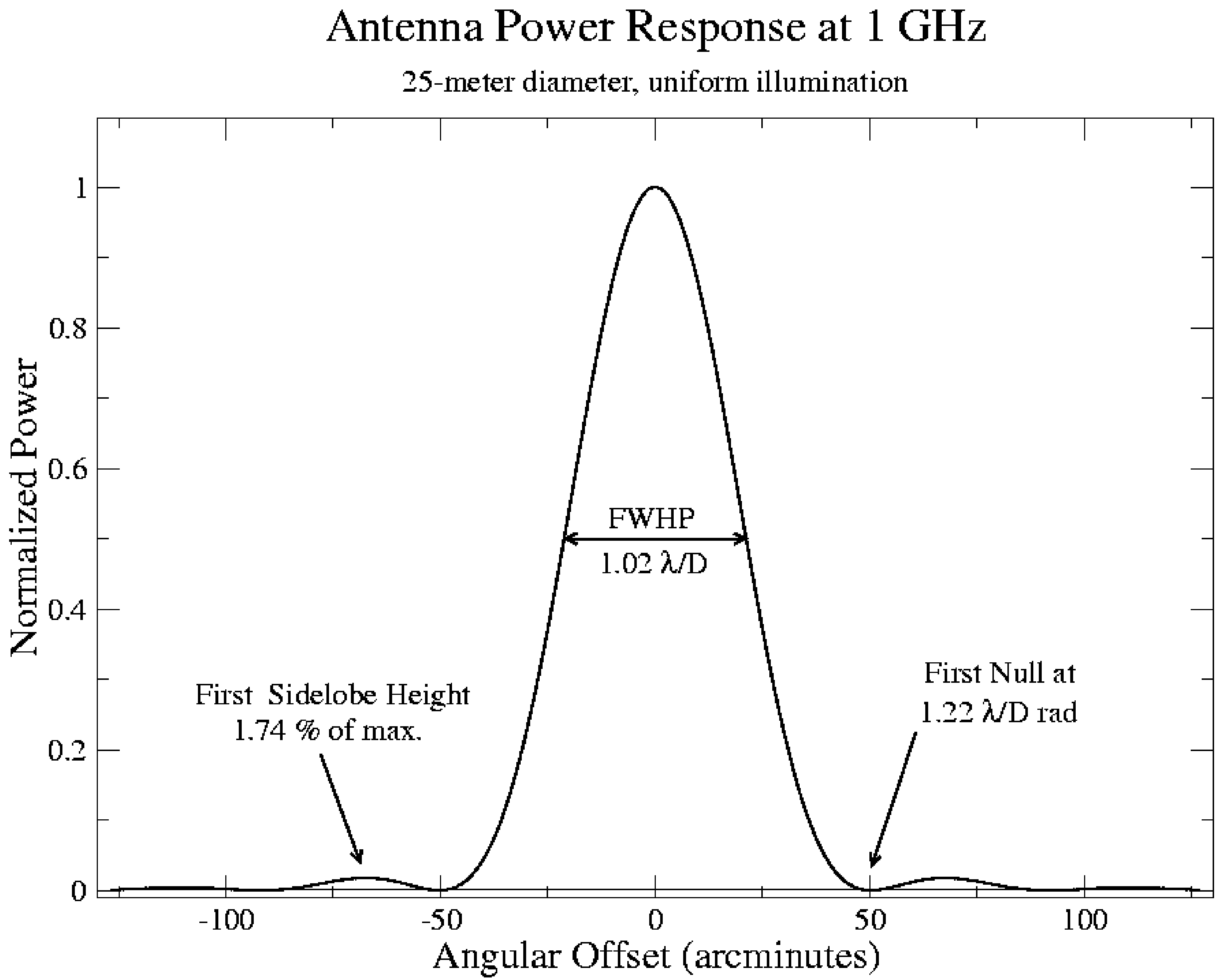
… and Interferometers

They achieve the angular resolution corresponding to the largest baseline between the elements (dishes), but the collecting area is just the sum …

How a Radio Telescope Works



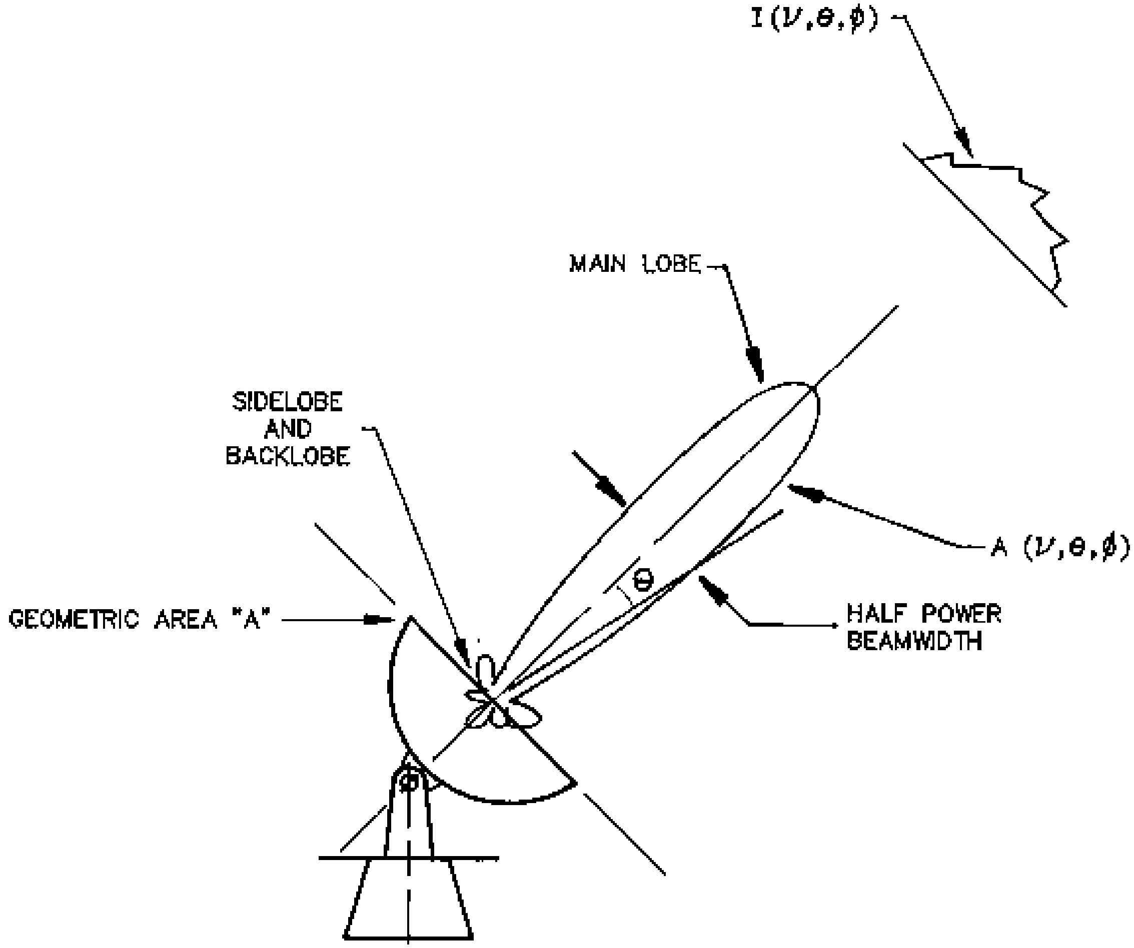
A radio telescope reflects radio waves to a focus at the antenna. Because radio wavelengths are very large, the radio dish must be very large.



Antenna Power Response at 1 GHz
25-meter diameter, uniform illumination
Normalized Power
1
0.8
0.6
0.4
0.2
0
FWHP
1.02 λ/D
First Sidelobe Height
1.74 % of max.
First Null at
1.22 λ/D rad
-100
-50
0
50
100
Angular Offset (arcminutes)

Problems With Single Dishes

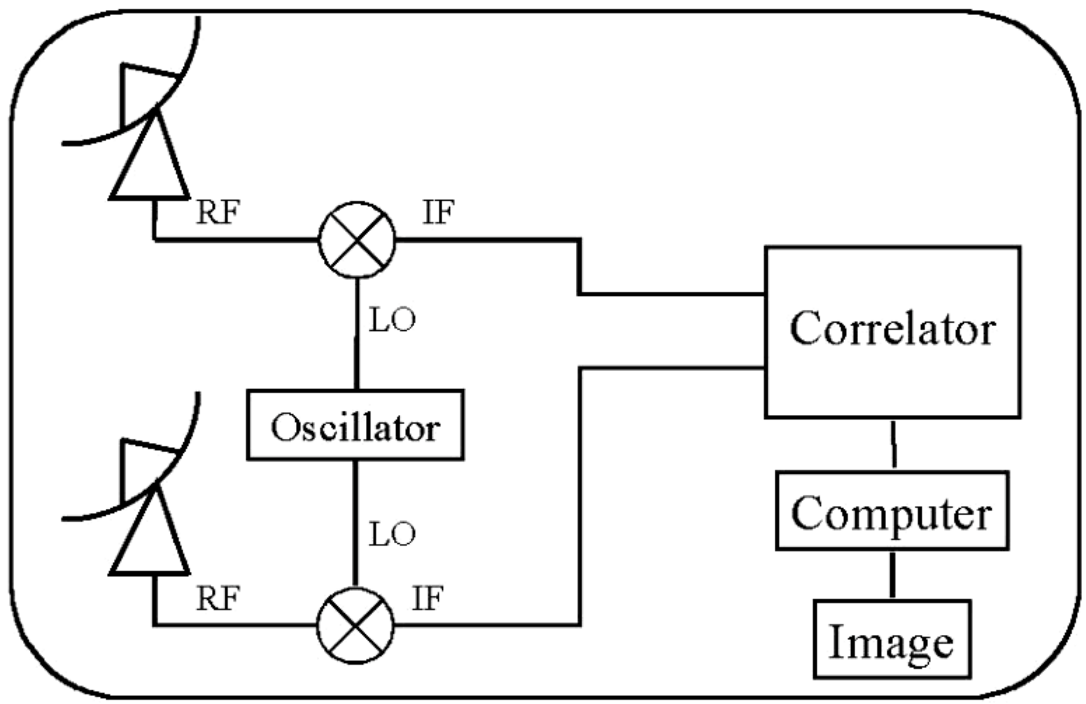
1. Poor resolution!
2. Sidelobes pick up scattered radiation, interference



How Interferometer Works

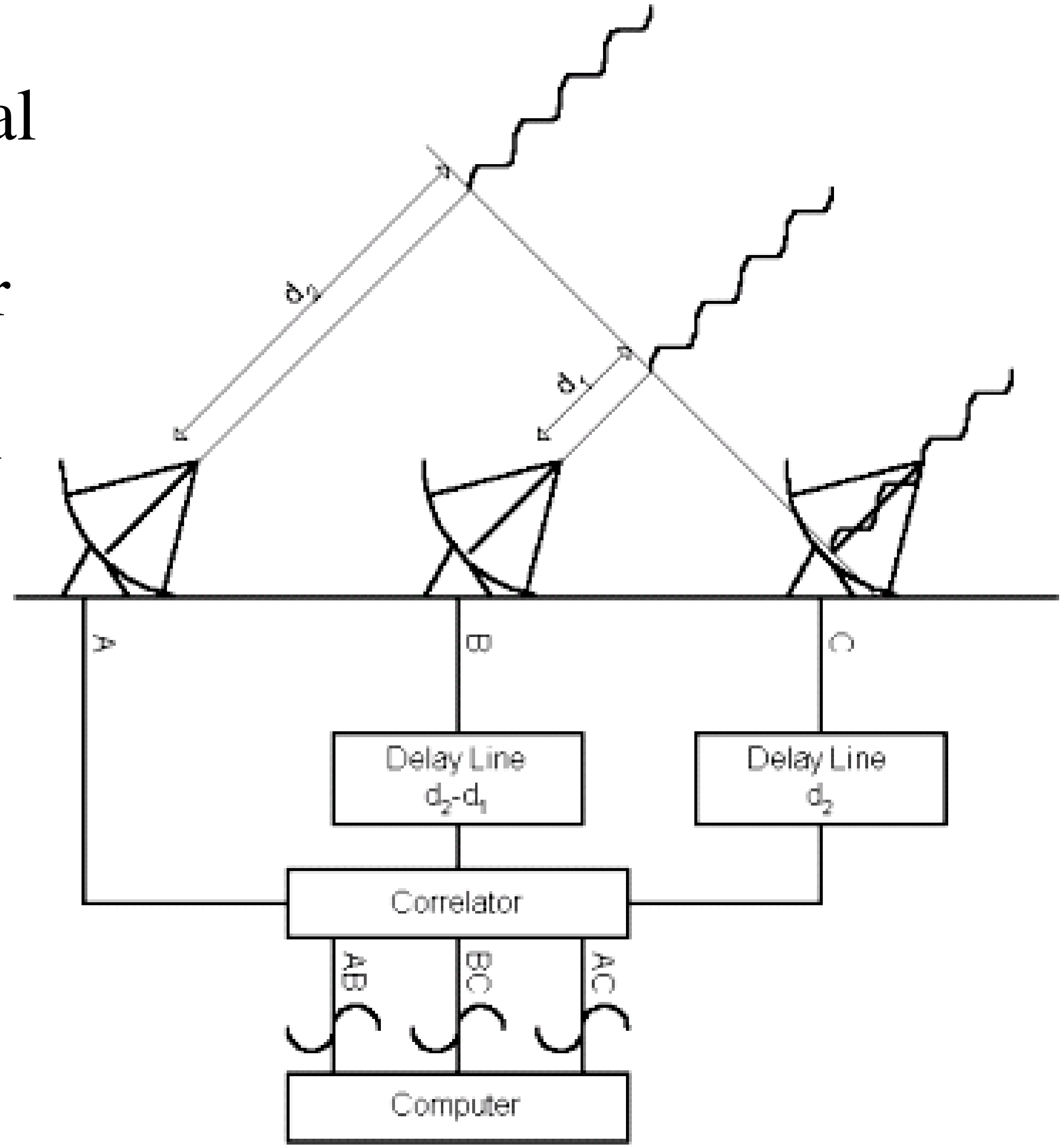
Signals from independent, separated receivers are coherently combined (correlated). What is measured is the amplitude of correlated signal as a function of a spatial baseline, i.e., angular frequency on the sky. This is a Fourier transform of the actual intensity image on the sky.

BASIC LINKED RADIO INTERFEROMETER



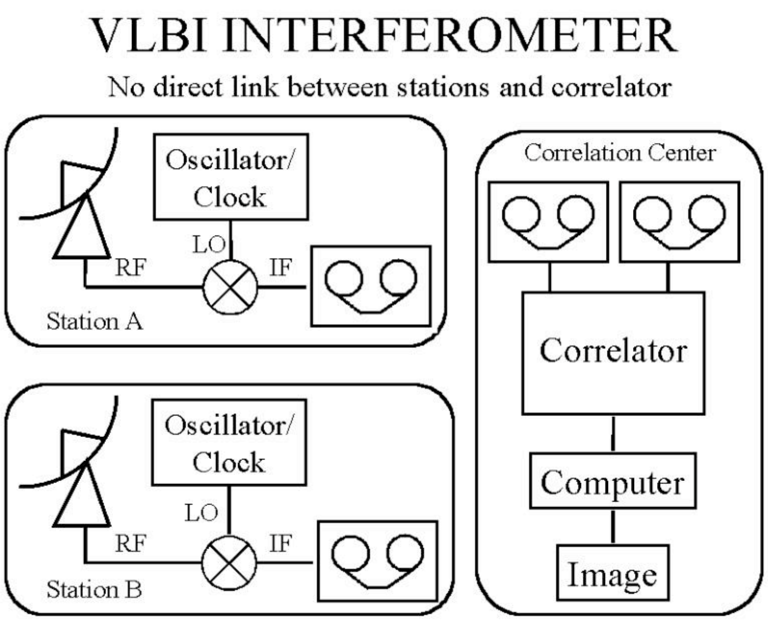
… how interferometer works …

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



Very Long Baseline Interferometry (VLBI)

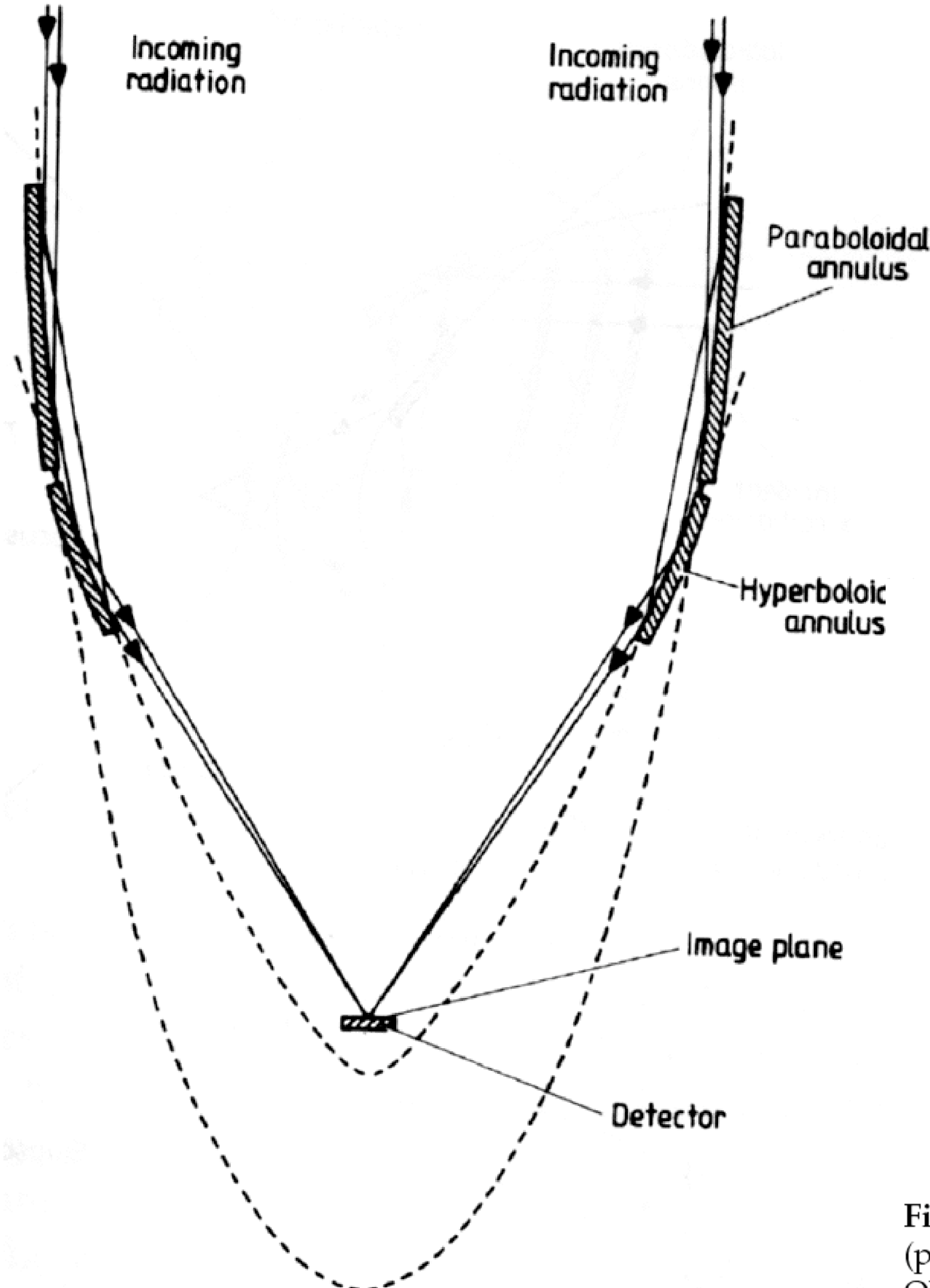
- Antennas very far apart (~ Earth size)
  - ★ Resolution very high: milli-arcsec
- Record signals on tape, correlate later
- Now VLBA(rray)



The Future of Radio Astronomy

Square Kilometer
Array (SKA)

ALMA



X-Ray telescopes:

Grazing incidence mirrors

Why? So that the projected interatomic separations are << □

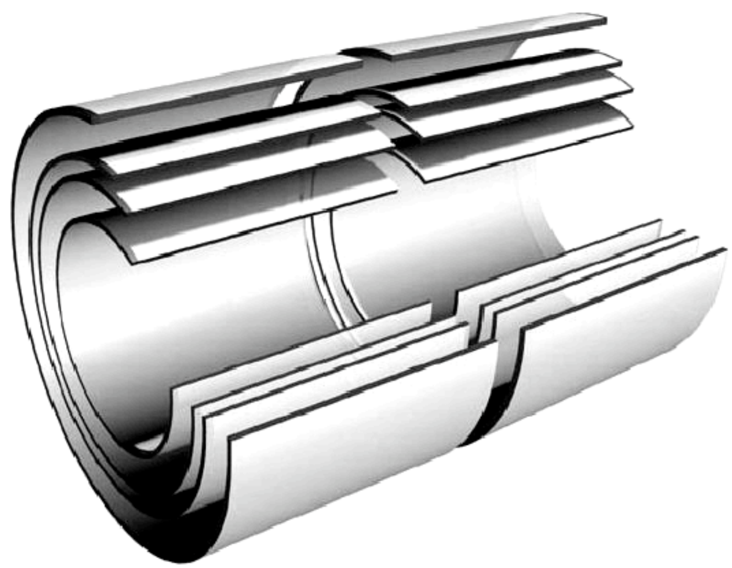
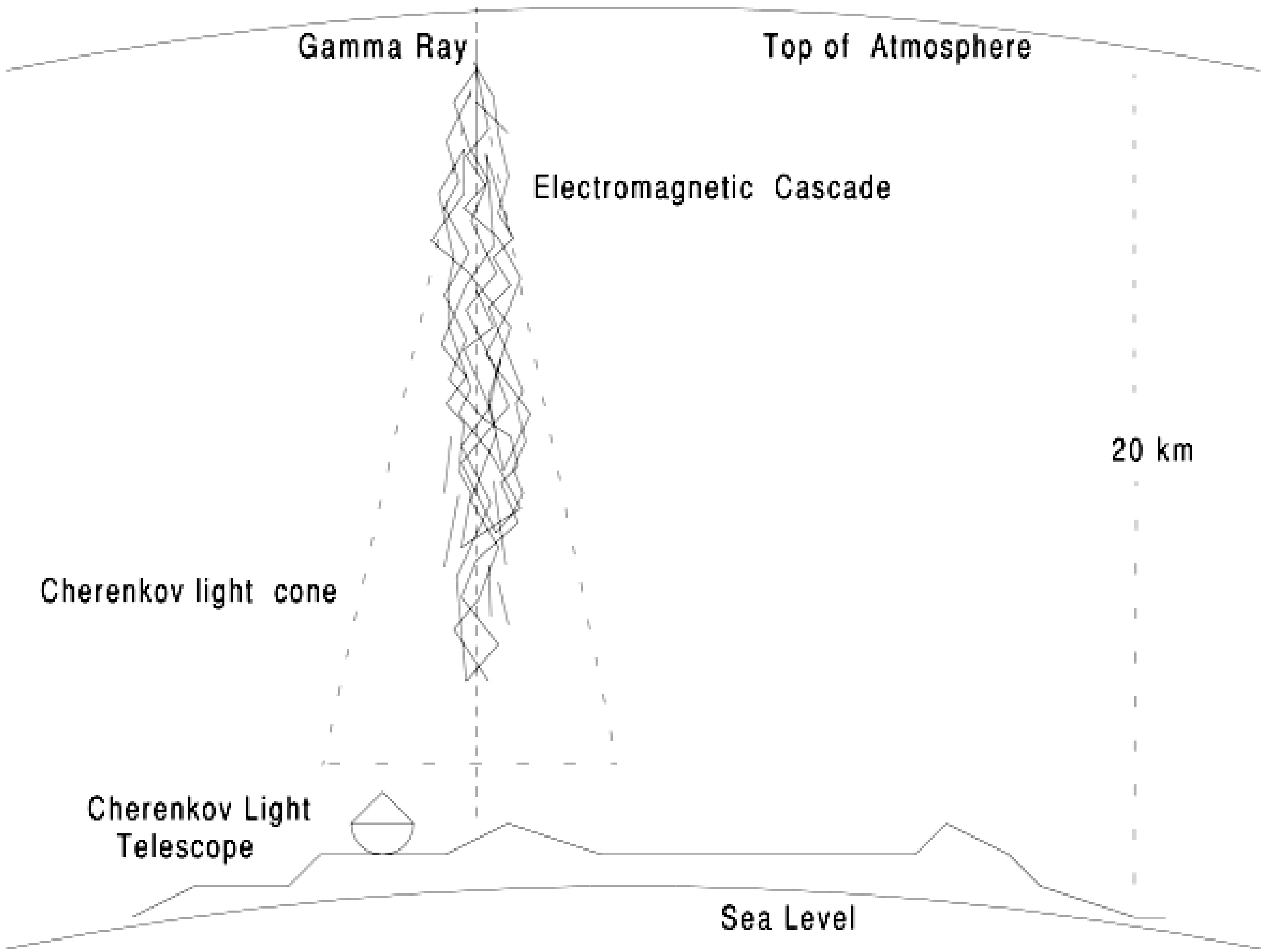
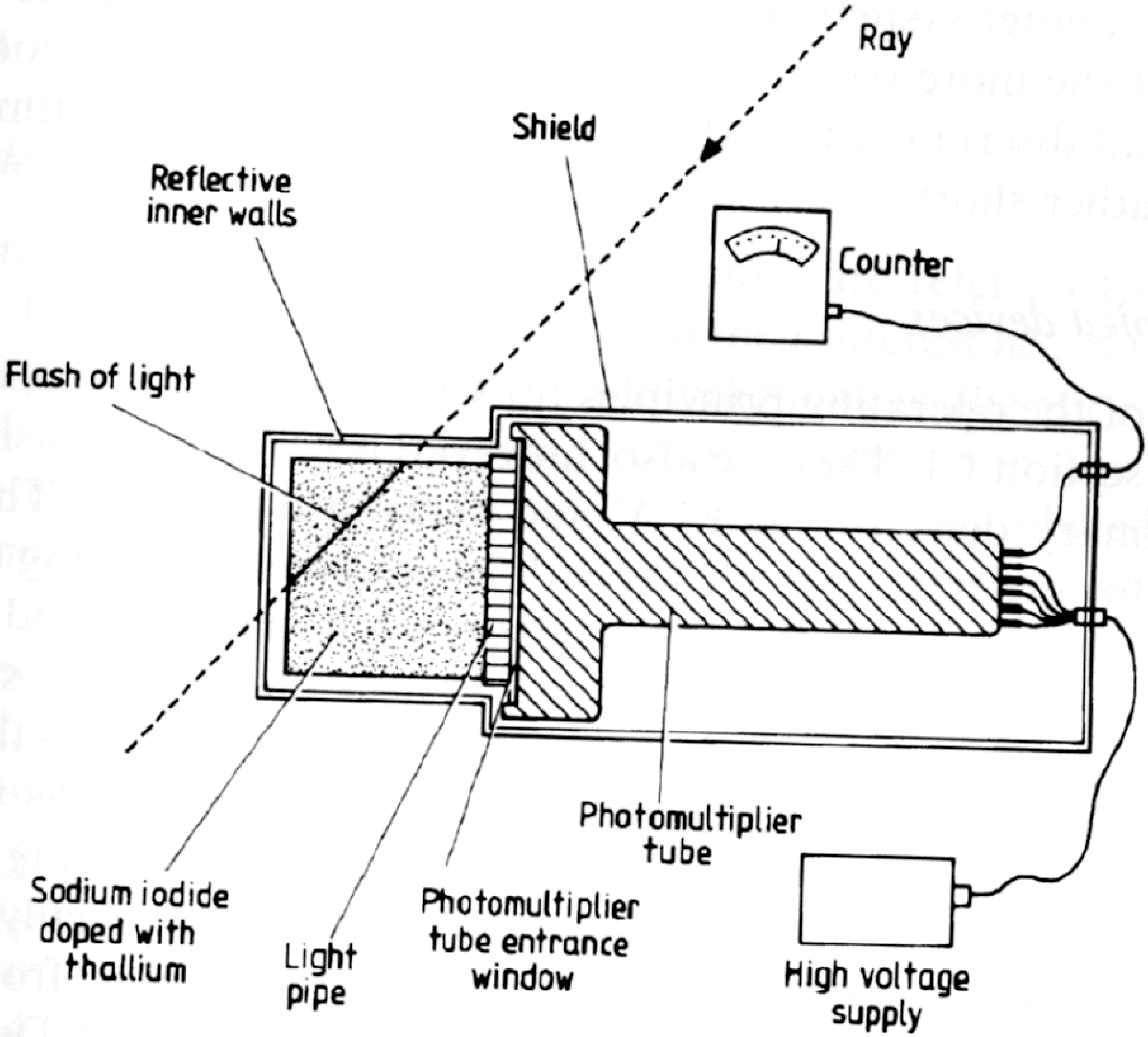


Figure 3. Cutaway schematic drawing of the nested four shells (paraboloid and hyperboloids) of the Chandra X-ray Observatory (courtesy of the Raytheon Co).

Detecting Ultra-High Energy Cosmic Rays




Ray
Shield
Reflective inner walls
Counter
Flash of light
Photomultiplier tube
Sodium iodide doped with thallium
Light pipe
Photomultiplier tube entrance window
High voltage supply

CGRO/COMPTEL

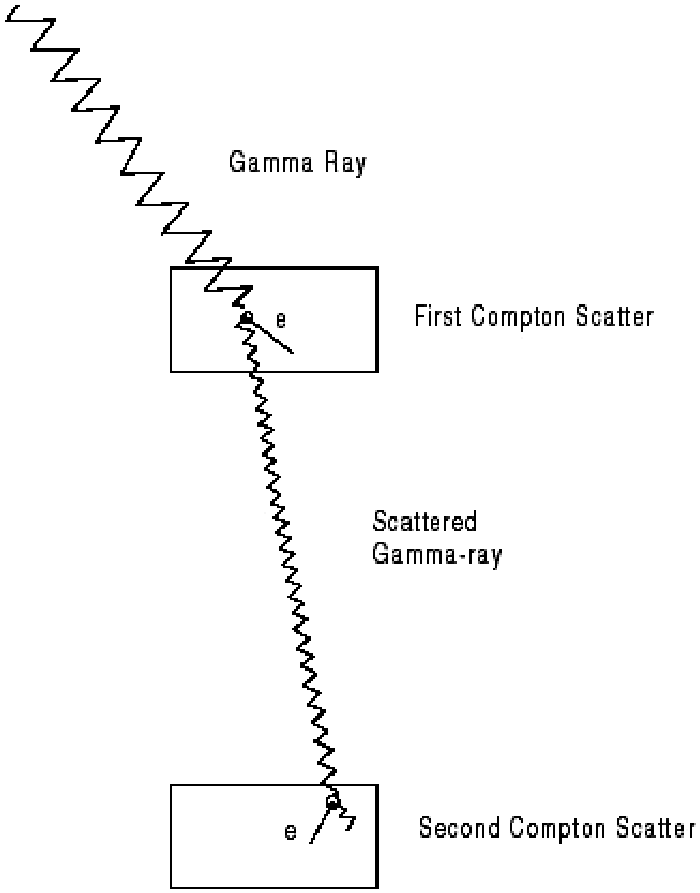
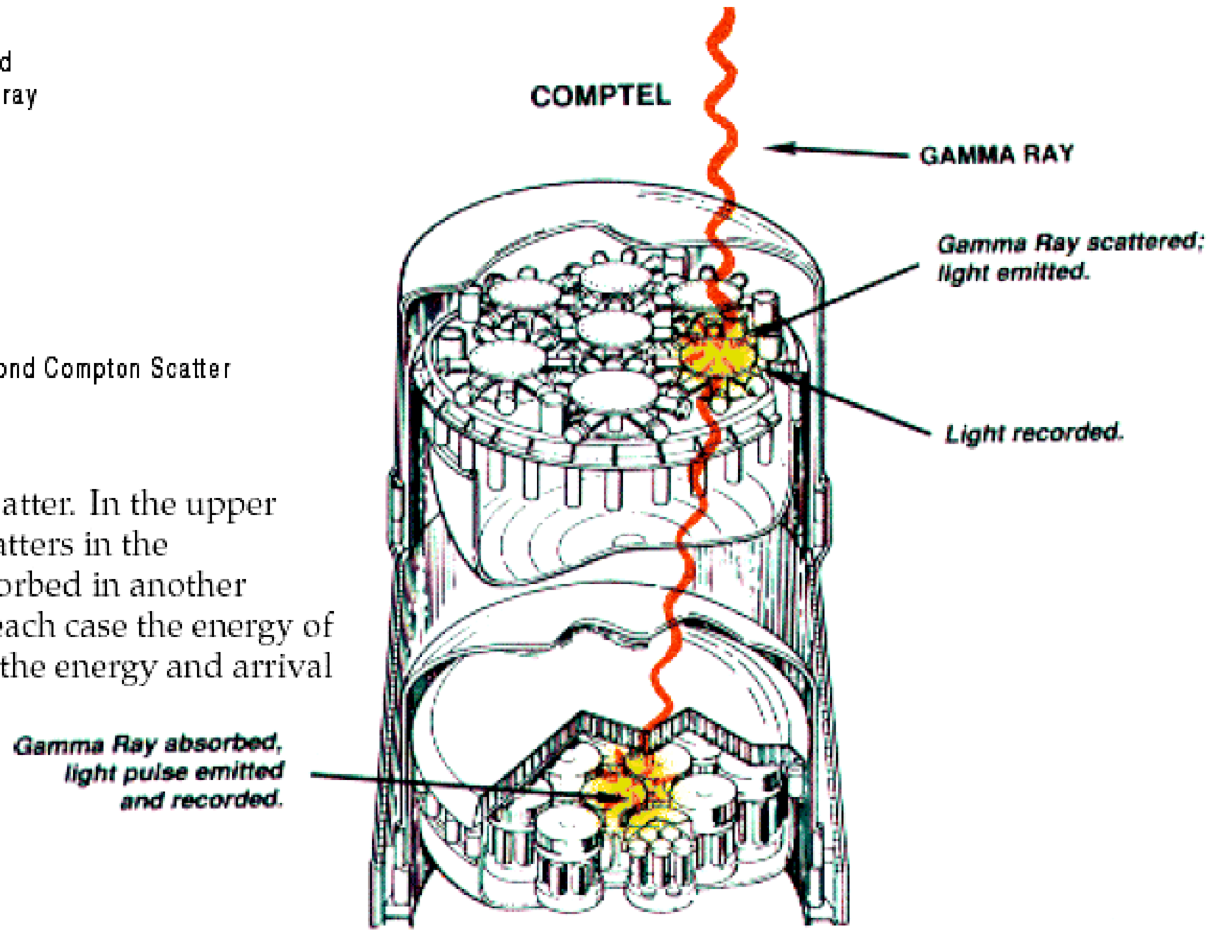


Figure 1. Schematic of double Compton scatter. In the upper scintillator the primary γ-ray Compton scatters in the downward direction; the γ-ray is then absorbed in another Compton scatter in the lower detector. In each case the energy of the recoil electron is measured and thence the energy and arrival direction of the primary are determined.

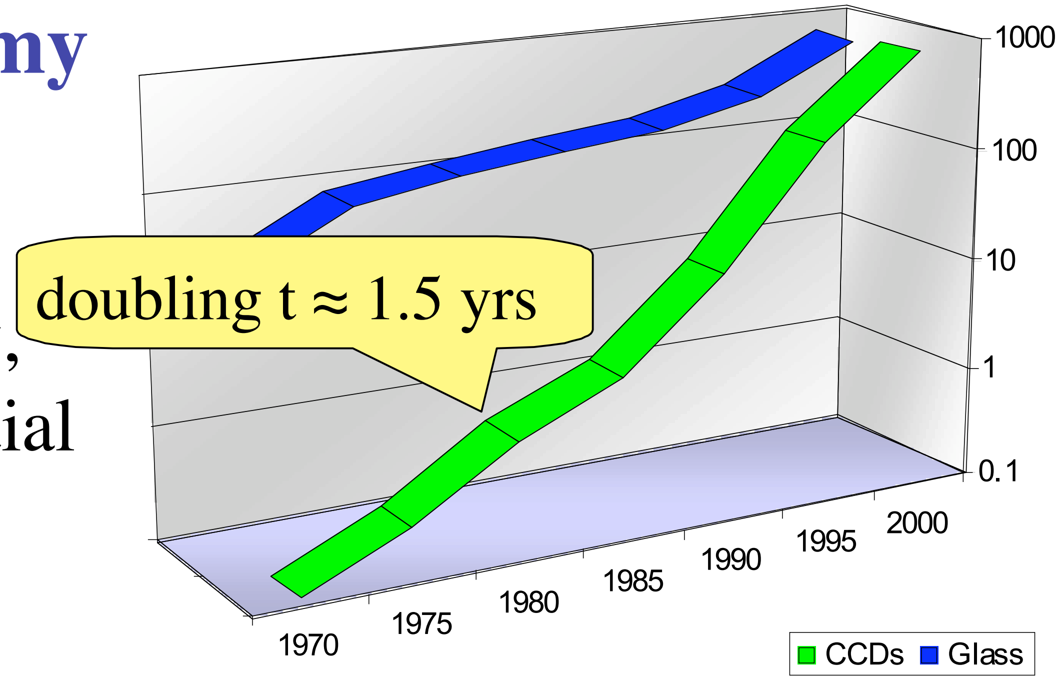


Sky Surveys, Archives, and Virtual Observatory

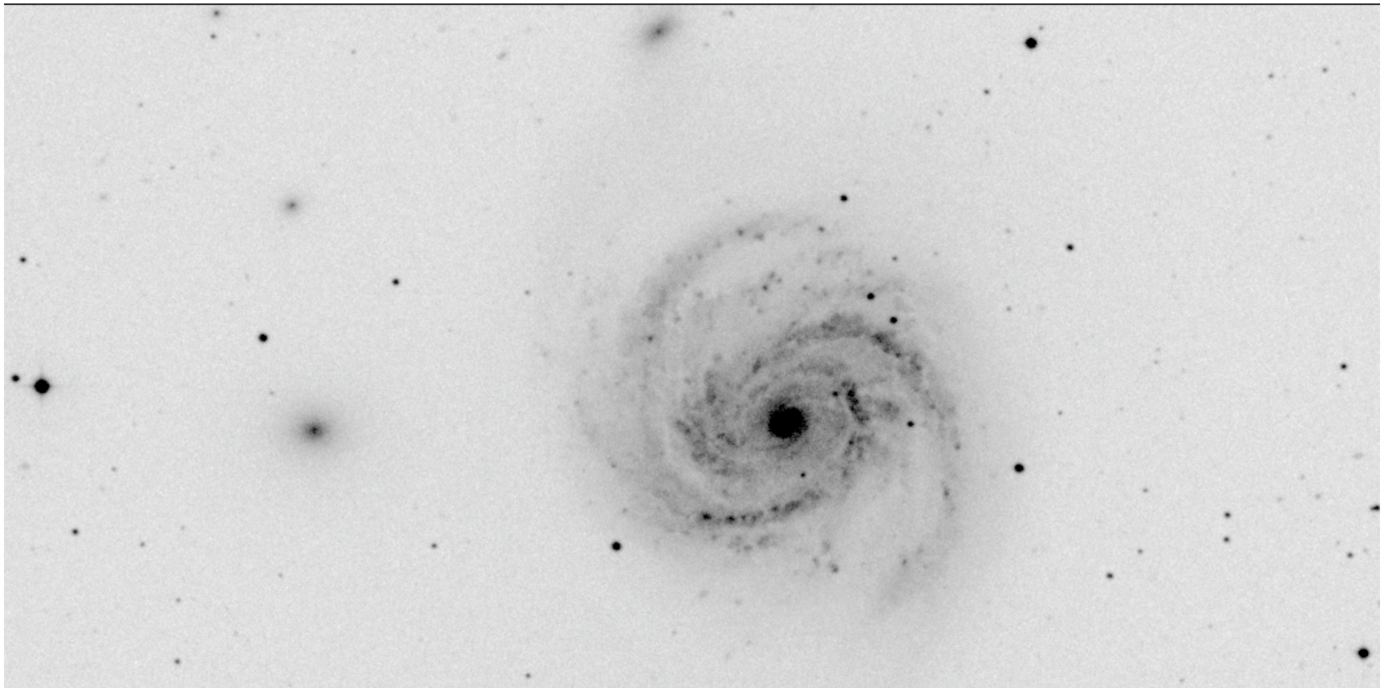
Astronomy is facing a major data avalanche: it has become an immensely data-rich science

The Exponential Growth of Data Volume in Astronomy

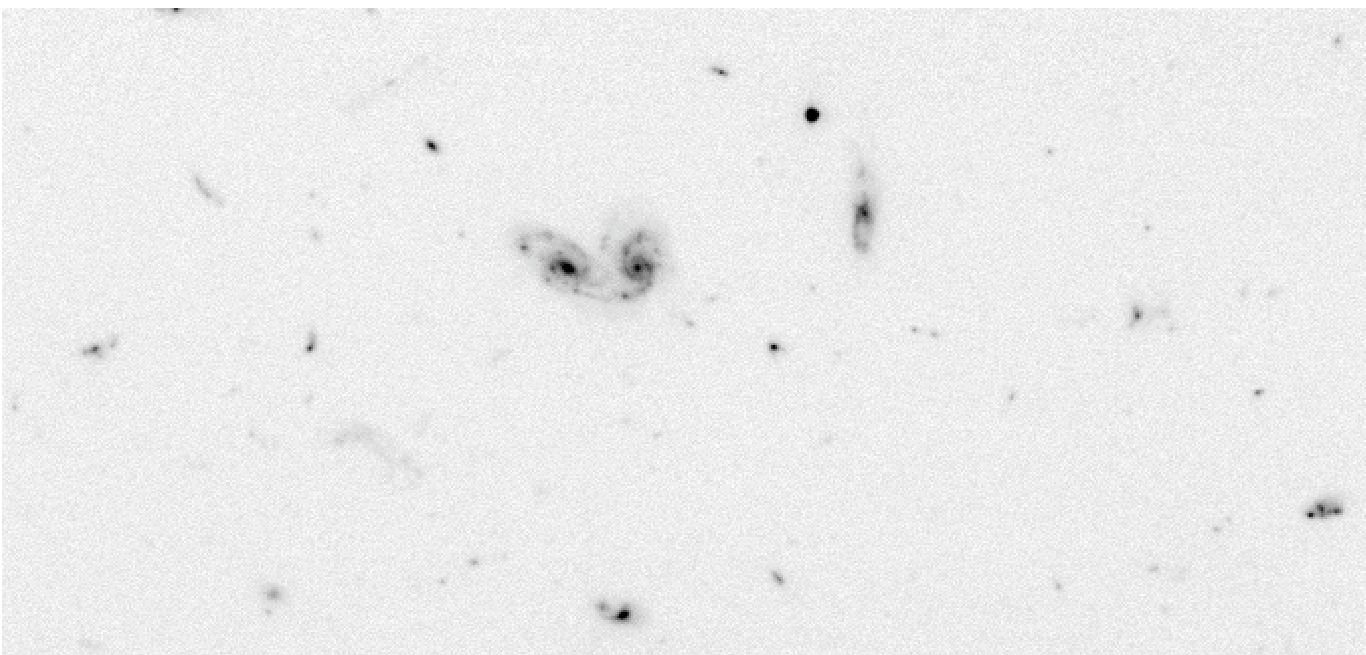
… And also data complexity and quality, driven by the exponential growth in detector and computing technology



- **Large digital sky surveys** are becoming the dominant source of data in astronomy: ~ 10-100 TB/survey (soon PB), ~ 10^6 - 10^9 sources/survey, many wavelengths…
- **Data sets many orders of magnitude larger, more complex, and more homogeneous than in the past**



1 microSky
(DPOSS)



1 nanoSky
(HDF-S)

A Bit of History …

Modern sky surveys were effectively invented at Palomar: Zwicky, POSS-I, POSS-II (DPOSS), now Palomar-Quest…

The Changing Face of Observational Astronomy

- **Large digital sky surveys** are becoming the dominant source of data in astronomy: currently > 200 TB, and growing rapidly
- Spanning a **range of wavelengths**: visible (SDSS, DPOSS, etc.), IR (2MASS, COBE, IRAS, etc.), radio (FIRST, NVSS, etc.), X-ray (RASS, HEAO, etc.) …
- Also: digital libraries, electronic journals, space mission and observatory archives, microlensing experiments, searches for Solar system objects …
- Data sets orders of magnitude **larger, more complex, and more homogeneous** than in the past
- Roughly 1 TB/Sky/band/epoch
  - NB: Human Genome is < 1 GB, Library of Congress ~ 20 TB

The Changing Style of Observational Astronomy

The Old Way:	**Now:**	**Future:**
Pointed, heterogeneous observations (~ MB - GB)	Large, homogeneous sky surveys (multi-TB, ~ 10^6 - 10^9 sources	Multiple, federated sky surveys and archives (~ PB)
Small samples of objects (~ 10^1 - 10^3)	Archives of pointed observations (~ a few TB)	**Virtual Observatory**

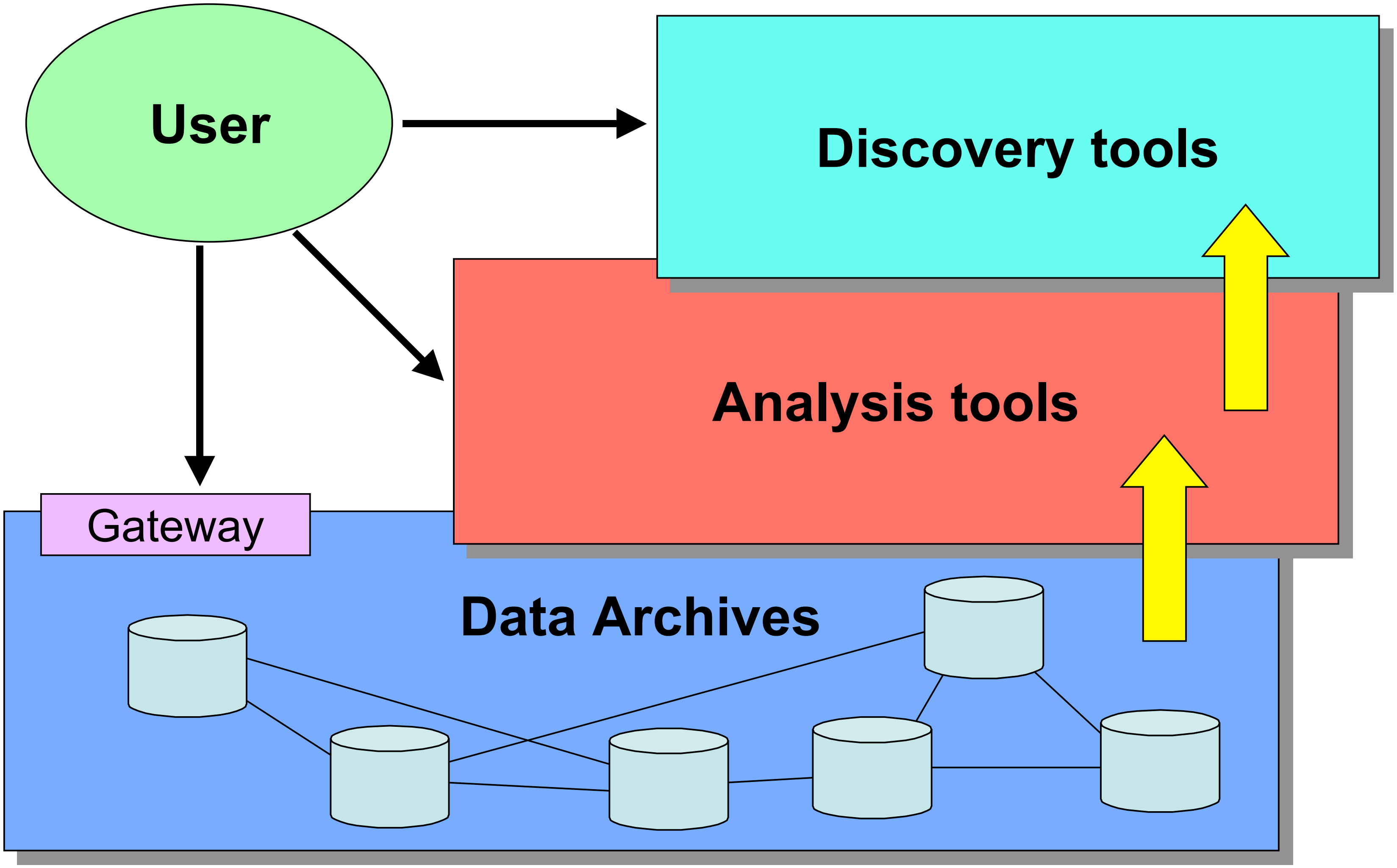
So, What is a Virtual Observatory?

It will be a complete, distributed, web-based ***research environment for astronomy with massive and complex data sets***:

- Federate major data archives, and provide tools for the data exploration
- A framework to harness developments in information technology for the benefit of astronomy

In the US: the National Virtual Observatory (NVO)
(see *http://us-vo.org*)
Globally: International V.O. Alliance (IVOA)

VO: Conceptual Architecture



This quantitative change in the information volume and complexity will enable the

Science of a Qualitatively Different Nature:

- **Statistical astronomy done right**
  - Precision cosmology, Galactic structure, stellar astrophysics …
  - Discovery of significant patterns and multivariate correlations
  - Poissonian errors unimportant
- **Systematic exploration of the observable parameter spaces** (NB: Energy content ≠ Information content)
  - Searches for rare or unknown types of objects and phenomena
  - Low surface brightness universe, the time domain …
- **Confronting massive numerical simulations with massive data sets**

Information Technology → New Science

- The information volume grows exponentially

Most data will never be seen by humans!

➡ The need for data storage, network, database-related technologies, standards, etc.

- Information complexity is also increasing greatly

Most data (and data constructs) cannot be comprehended by humans directly!

➡ The need for data mining and data understanding technologies, hyperdimensional visualization, AI/Machine-assisted discovery …

- These challenges are common to most sciences (and also commerce, industry, security …) - what we develop may find some broad applications (remember WWW!)

In Summary …

- Information technology is revolutionizing all sciences, including astronomy. **VO** is the framework for this change, the astronomy of the 21st century
- We are expecting **a new era of systematic exploration of the universe,** with many new discoveries and surprizes
- The key issues are **methodological:** we have to learn to ask **new kinds of questions,** enabled by the massive data sets and technology