Optical Astronomy

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)

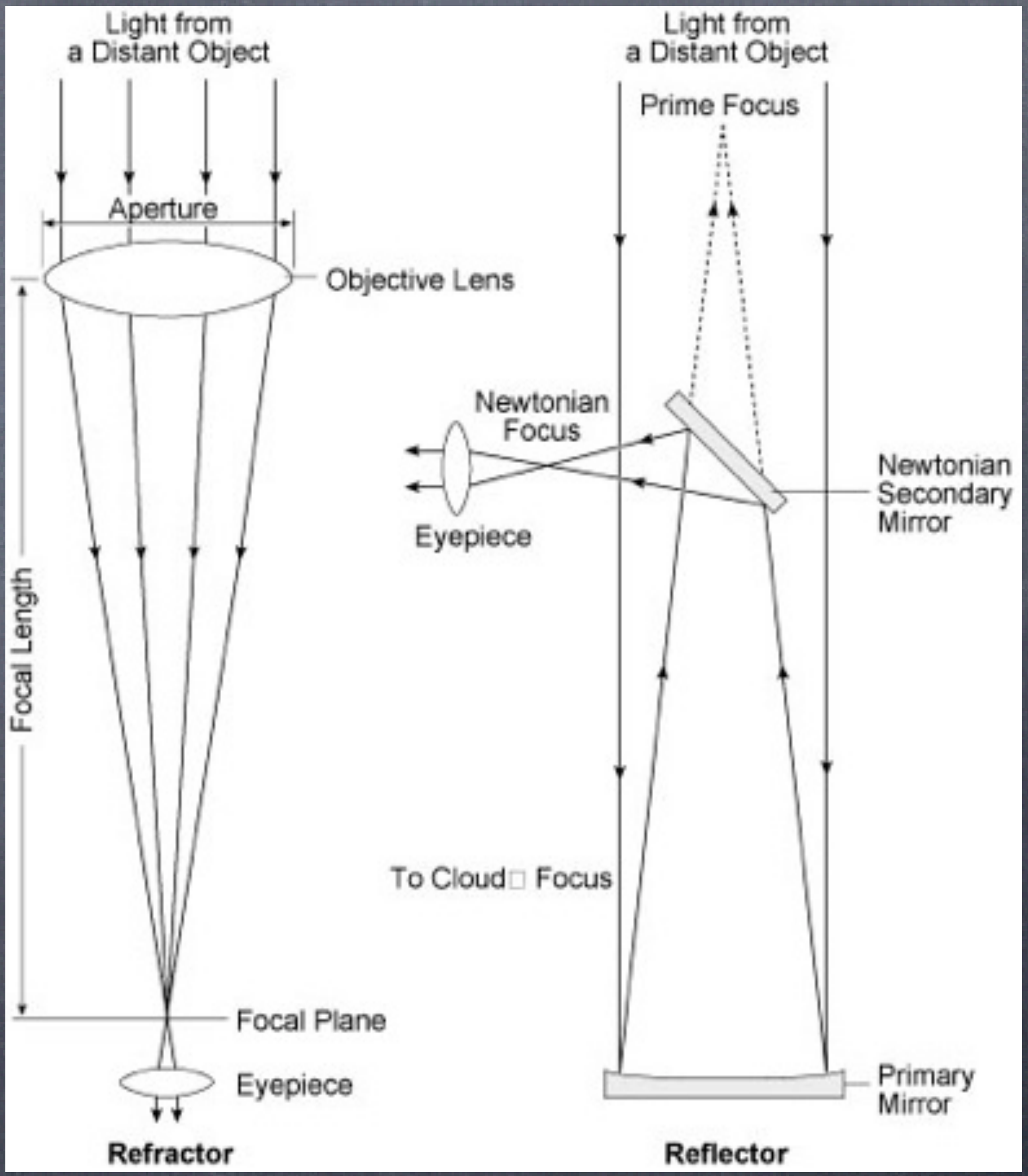
Space-Based: Hubble Space Telescope 2.4-m

Telescope Basics

Selenographia, 1647

First recorded optical telescopes appeared in the Netherlands in the early 1600s

Refracting Reflecting

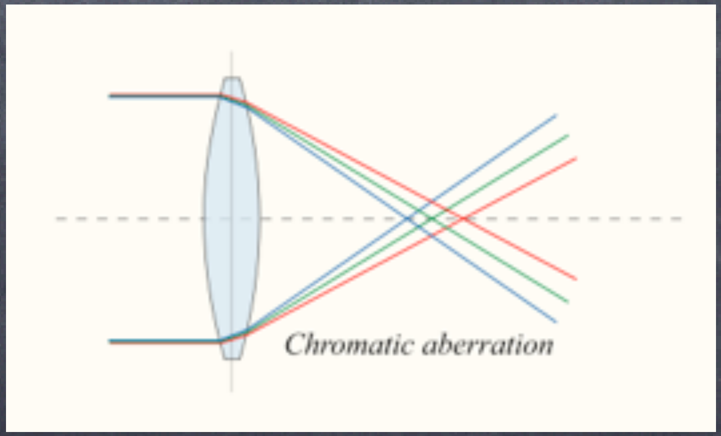


Refracting Telescopes

Early telescopes were primarily refracting telescopes. The metal mirrors of early reflecting telescopes were of poor quality and the design of refracting telescopes is relatively simple.

Downsides of refracting telescopes:

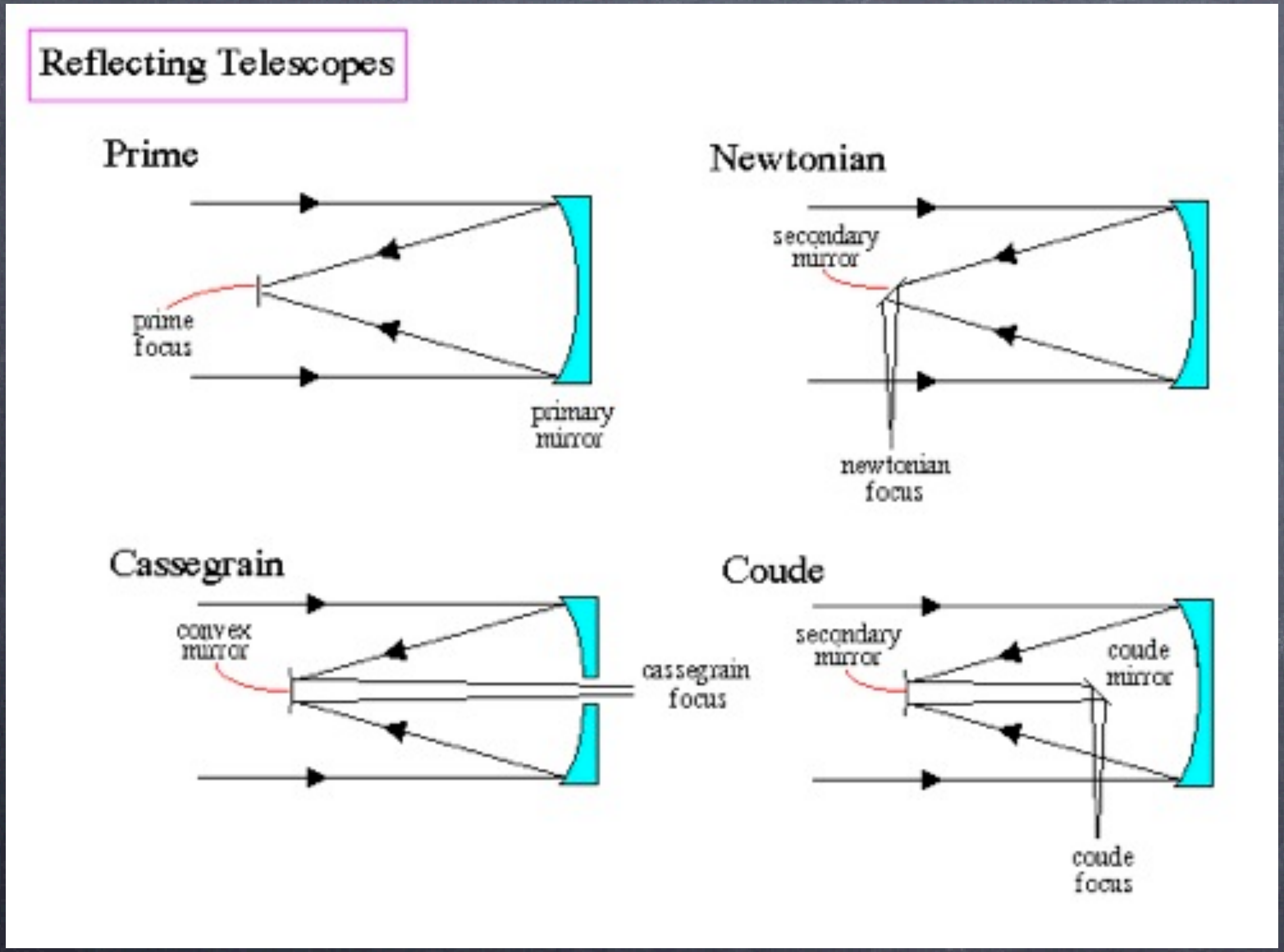
- lens must be supported on the edges and at the top of telescope tube and tend to sag if too large
- lens must be free of defects throughout (no air bubbles) and both surfaces precisely polished
- chromatic aberration



Lick 36-inch refractor, 1888
second only to Yerkes 40-inch

Reflecting Telescopes

Large modern telescopes are reflectors. Reflectors became competitive with refractors with the development of thin metal coatings (like silver) applied to glass mirrors in the 19th century.



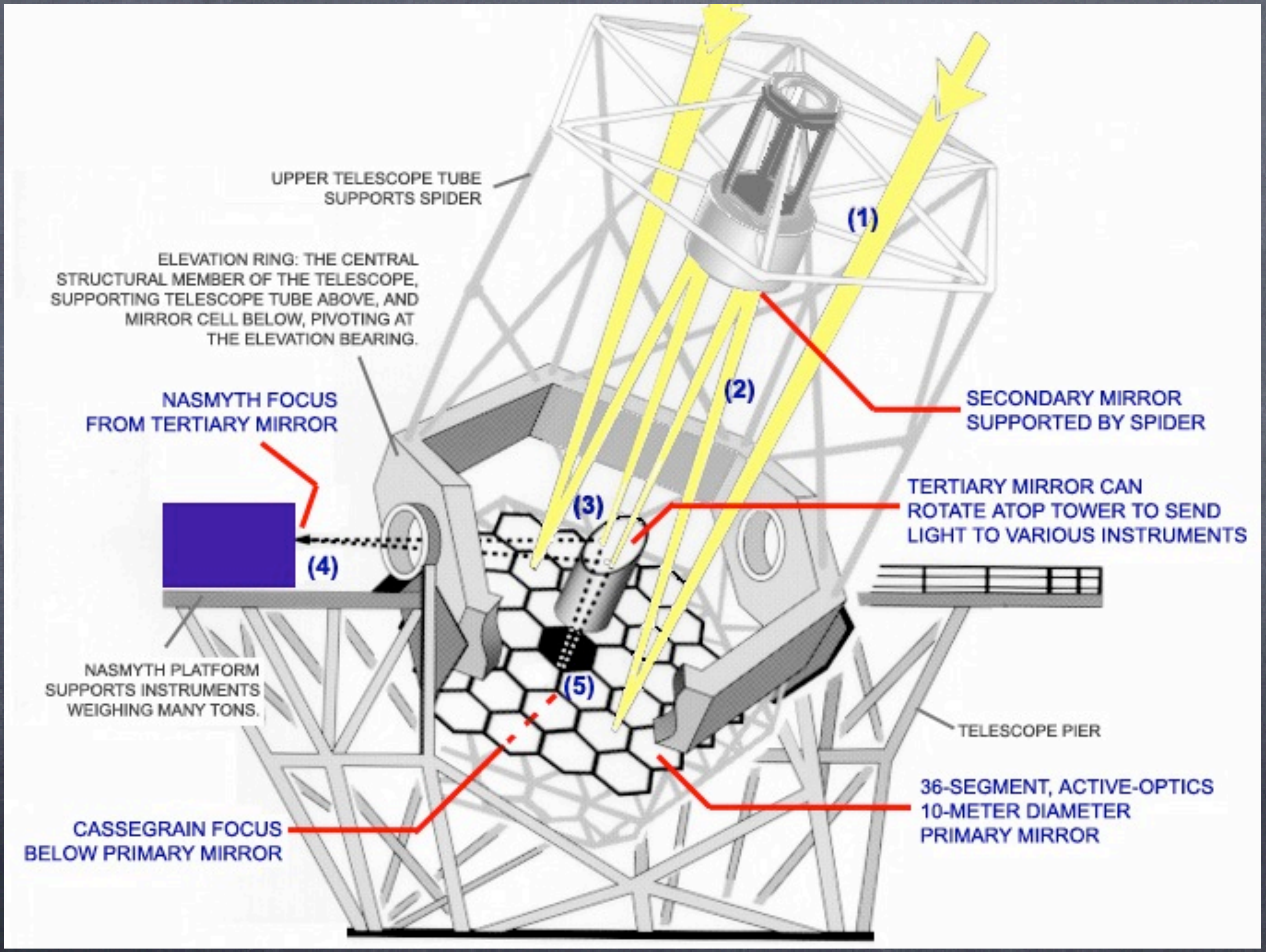
Prime: light blocked by observer/instruments

Newtonian: massive detectors exert torque

Cassegrain: focus behind telescope, long focal length

Coude: sends light to a special room for massive, stationary instruments (high-resolution spectroscopy)

Keck Light Path

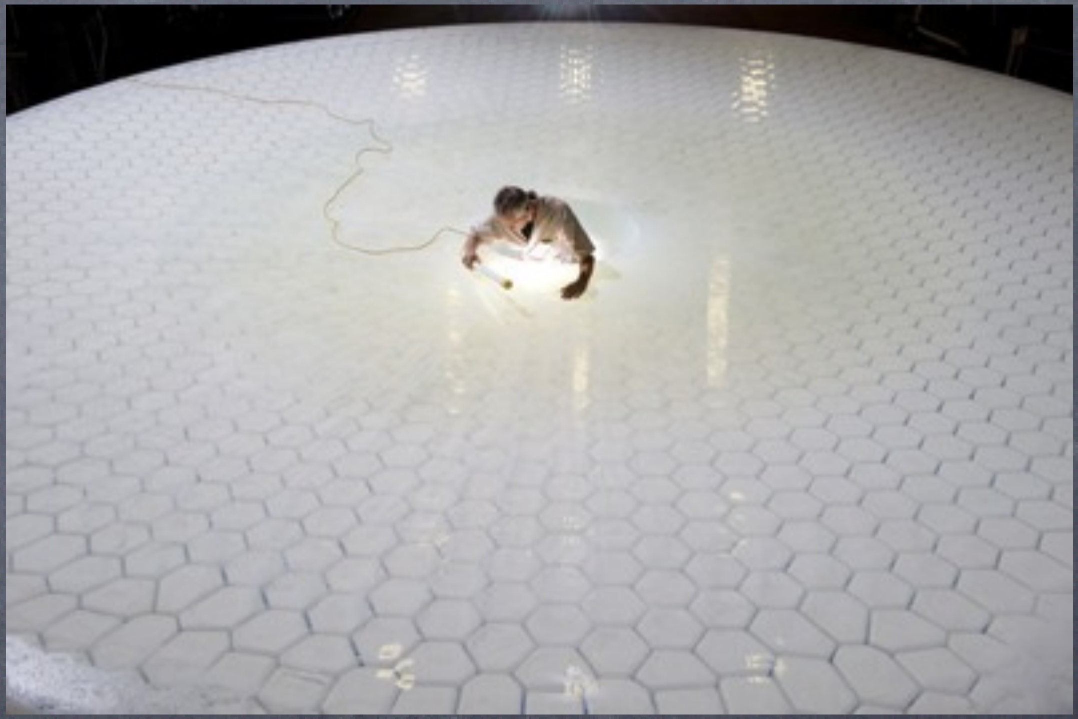


How to Make Them Big

Segmented (e.g. Keck)

Laurie Hatch 2007

Honeycomb (e.g. LBT, Magellan)

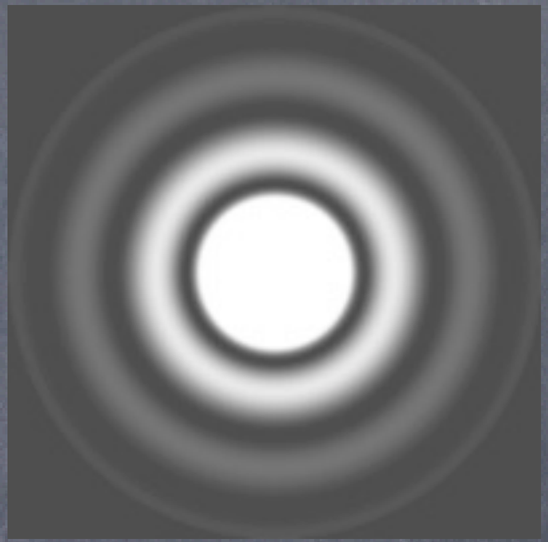


Joe McNally 2010

Basic Properties

angular resolution: Rayleigh criterion $\theta = 1.22\ \lambda/D$

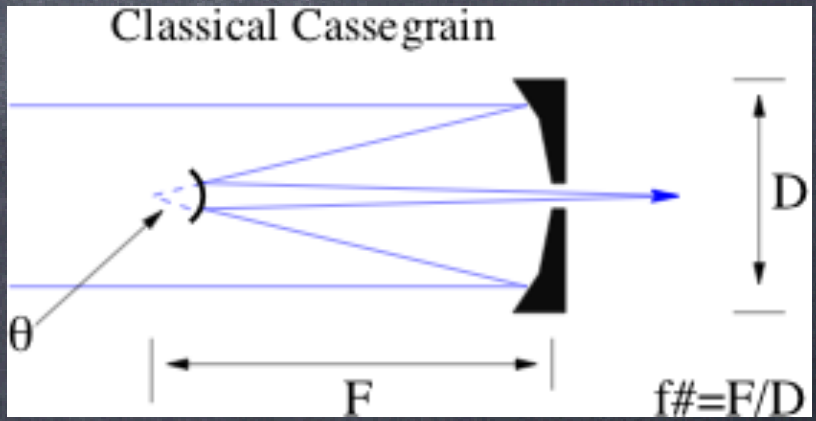
(ground based telescopes limited by seeing of at best 0.4"-0.5")



Airy Disk: circular aperture diffraction pattern

f ratio: ratio of the focal length to the aperture diameter (f/4 means F/D = 4)

plate scale: scale of the image is determined by the focal length S = 206265/F arcsec/mm (with F in mm). Low F gives larger field of view.



LSST - A Case Study

Most of the design details of the telescope and camera flow from the constraints on the optical design

- Median delivered seeing at the site is ~ 0.6 arcsec.
  - Assuming 3X oversampling -> a plate scale of 0.2 arcsec per pixel.
- Keep camera size as small as possible. Minimum pixel size is ~ 10 μm.
  - Driven by charge diffusion in the CCD and full well capacity, given the 100 μm depletion depth necessary to achieve the desired spectral range.
- Plate scale -> a focal length of 10.3 m.
- Single visit depth requirements -> Minimum aperture diameter of 6.5 m.
  - Assumes nominal throughput losses in the atmosphere, mirrors, lenses, and CCD detectors.
- Implied focal ratio is < 1.5.
- No. of required visits -> FOV > 3.5 degs.
  - Implies 3.2 Gigapixels. → 189 4kx4k CCDs
- Implied focal plane diameter is 63 cm.
- Fast slew and settling -> Keep telescope mount as compact as possible.

Slide from Steve Kahn

Seidel Aberrations

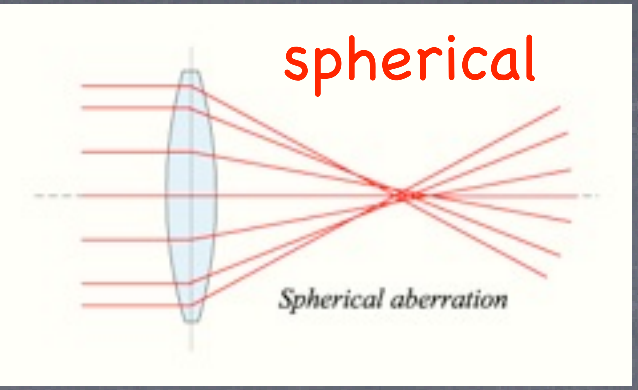
Spherical aberration: light rays are not all bent to a single point (spherical mirrors have this aberration)

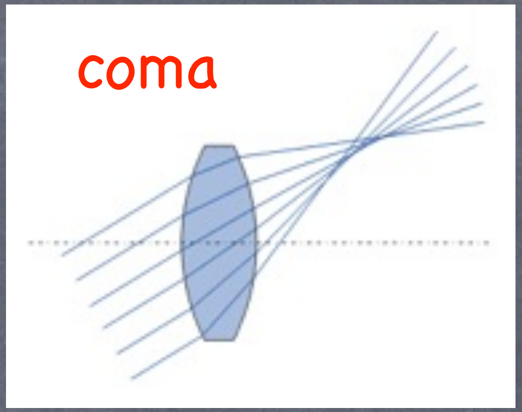
Coma: off-axis sources are elongated (comet-like) because the focal length of depends on off-axis angle

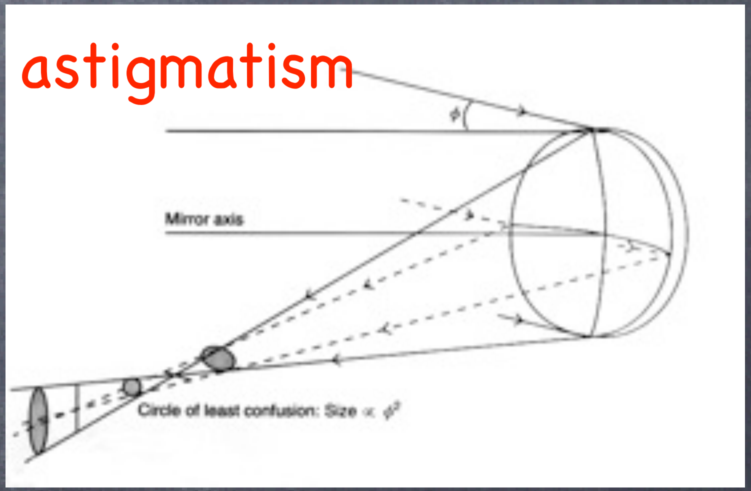
Astigmatism: off-axis, symmetric aberration due to light rays being focused differently in different planes

Field curvature: when the focal plane is curved rather than flat

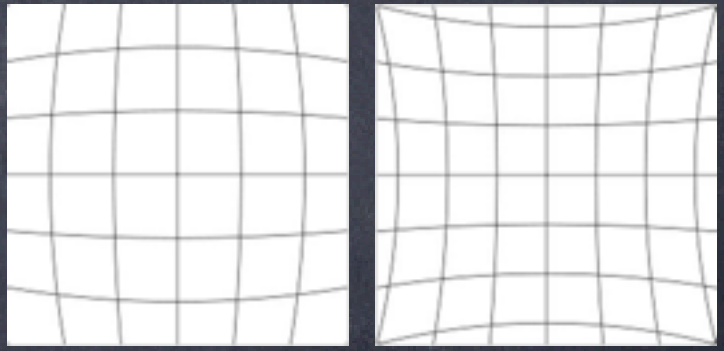
Distortion: plate scale depends on off-axis angle



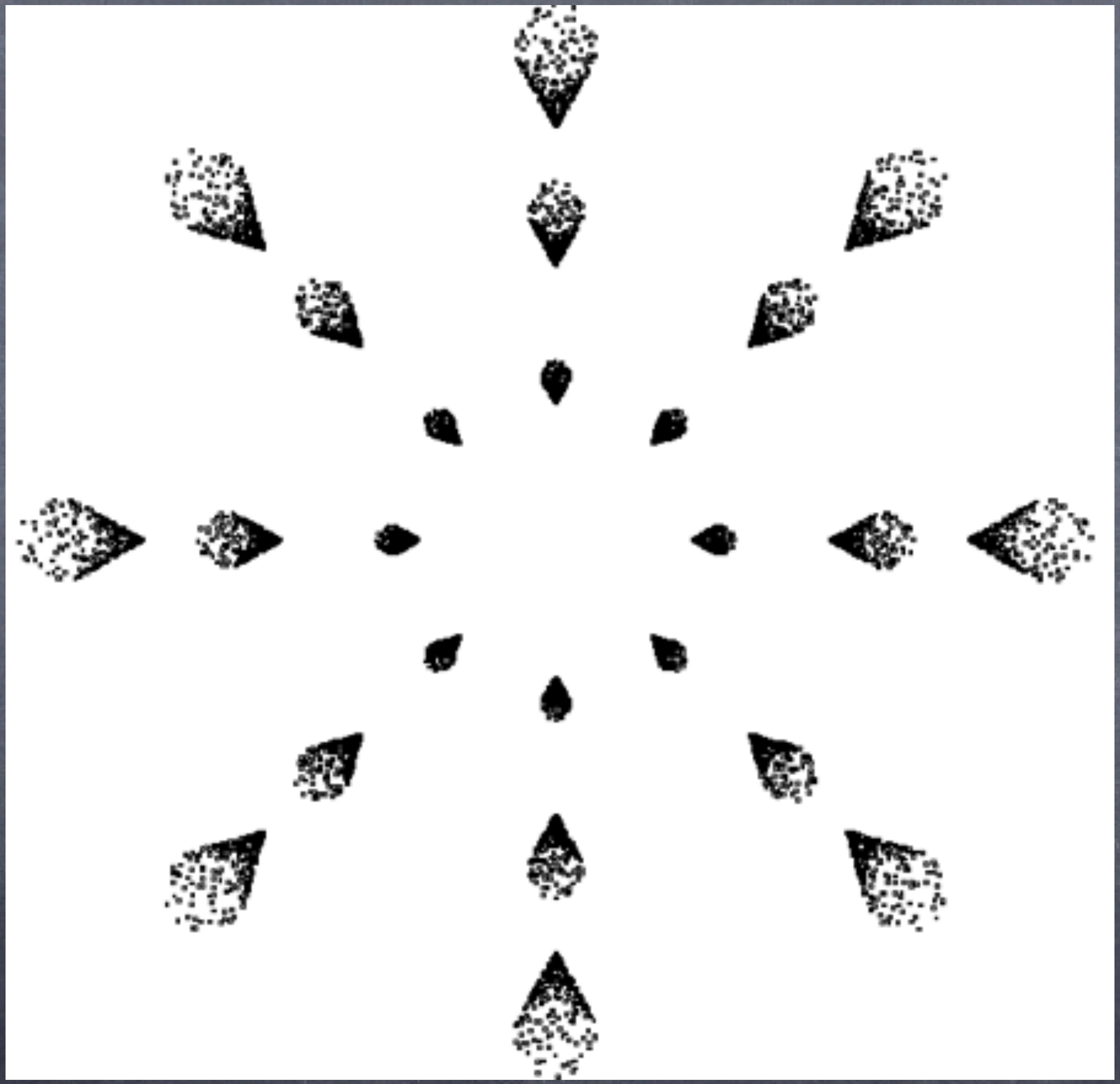




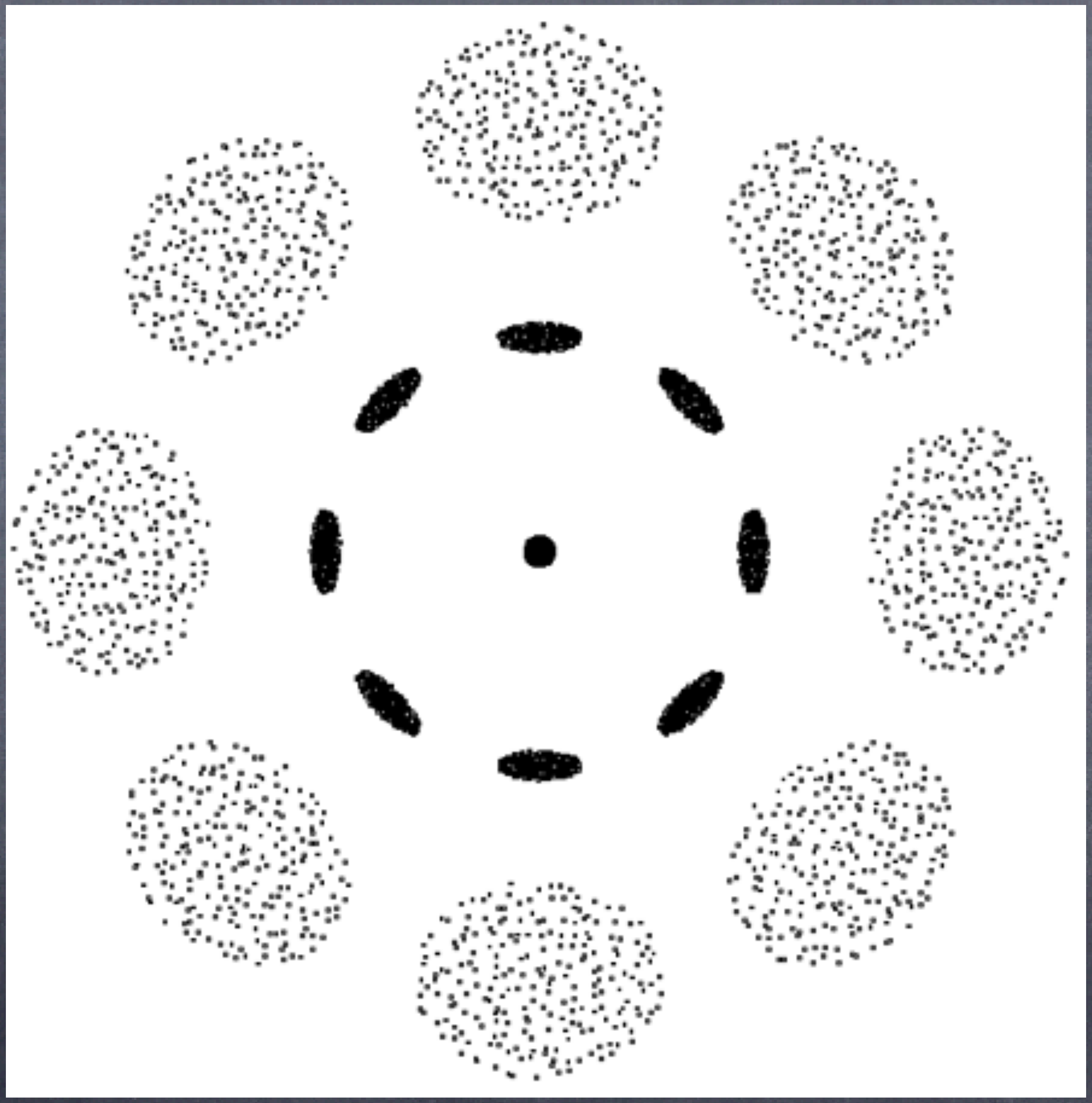
Distortion



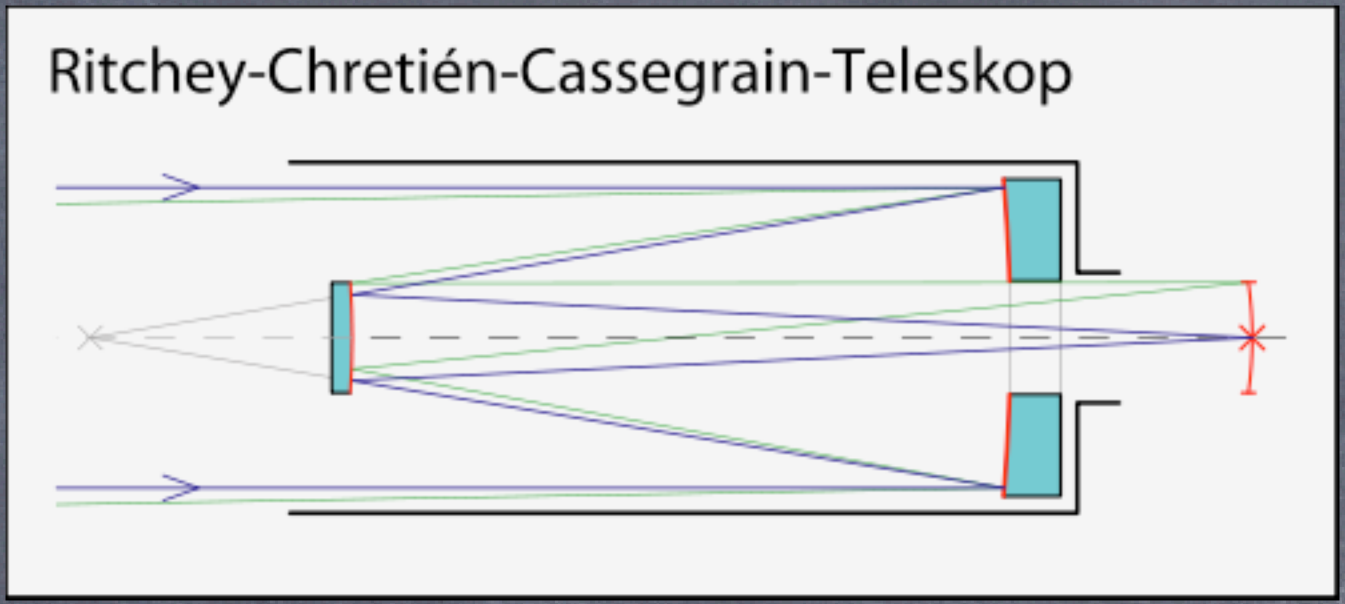
Coma



Astigmatism



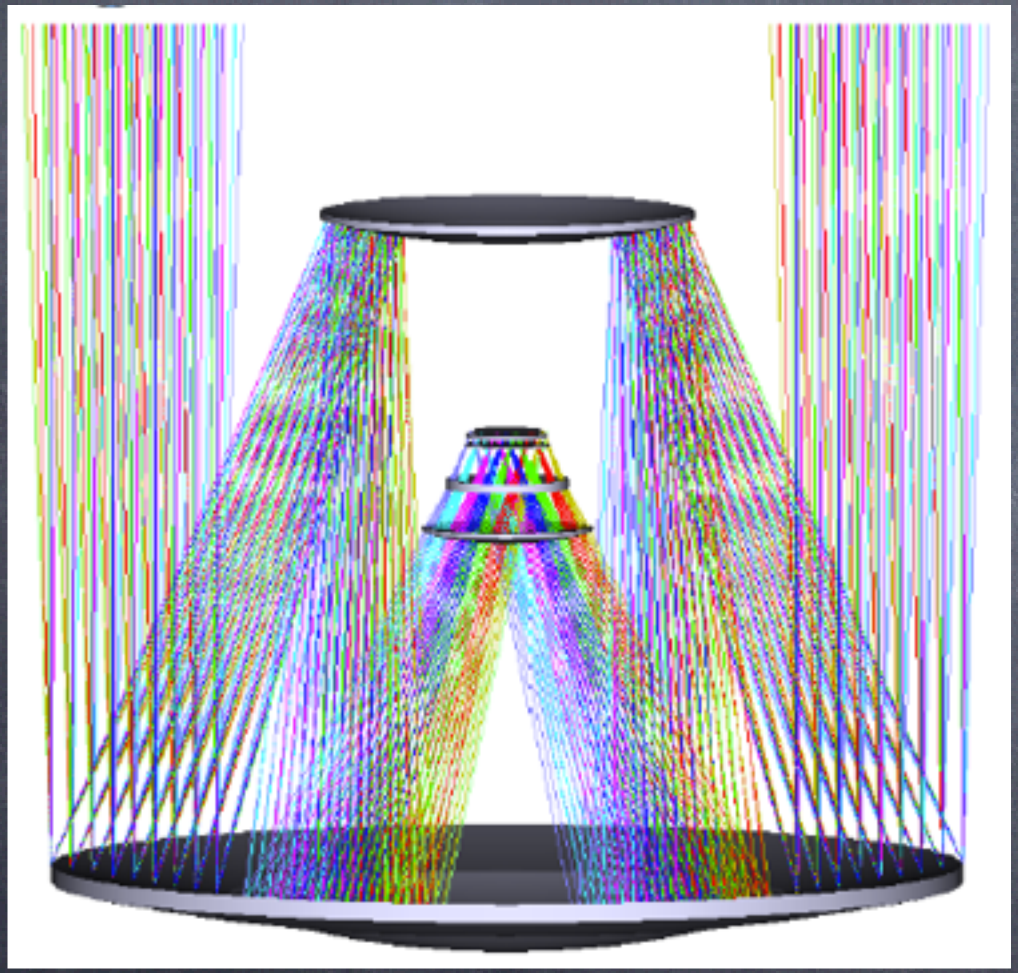
Reducing Aberrations



Richey-Chretién: special type of Cassegrain telescope designed to eliminate coma. Both the primary and secondary mirrors are hyperbolic. Gives a larger field of view free of aberration appropriate for large area surveys.

LSST - A Case Study

LSST will use a three mirror design (called a modified Paul-Baker) to get small aberrations over a large field with small f ratio.



Aerodynamic facility design

The Hubble Space Telescope
1990-present

Hubble is a 2.4 m Cassegrain telescope in low-Earth orbit with instruments which cover the near-UV to the near-IR.

Science Drivers

In 1946, Lyman Spitzer wrote a paper advocating for a space telescope, highlighting the improved angular resolution and possibility for IR and UV observations. He then spent much of his career pushing for its development.

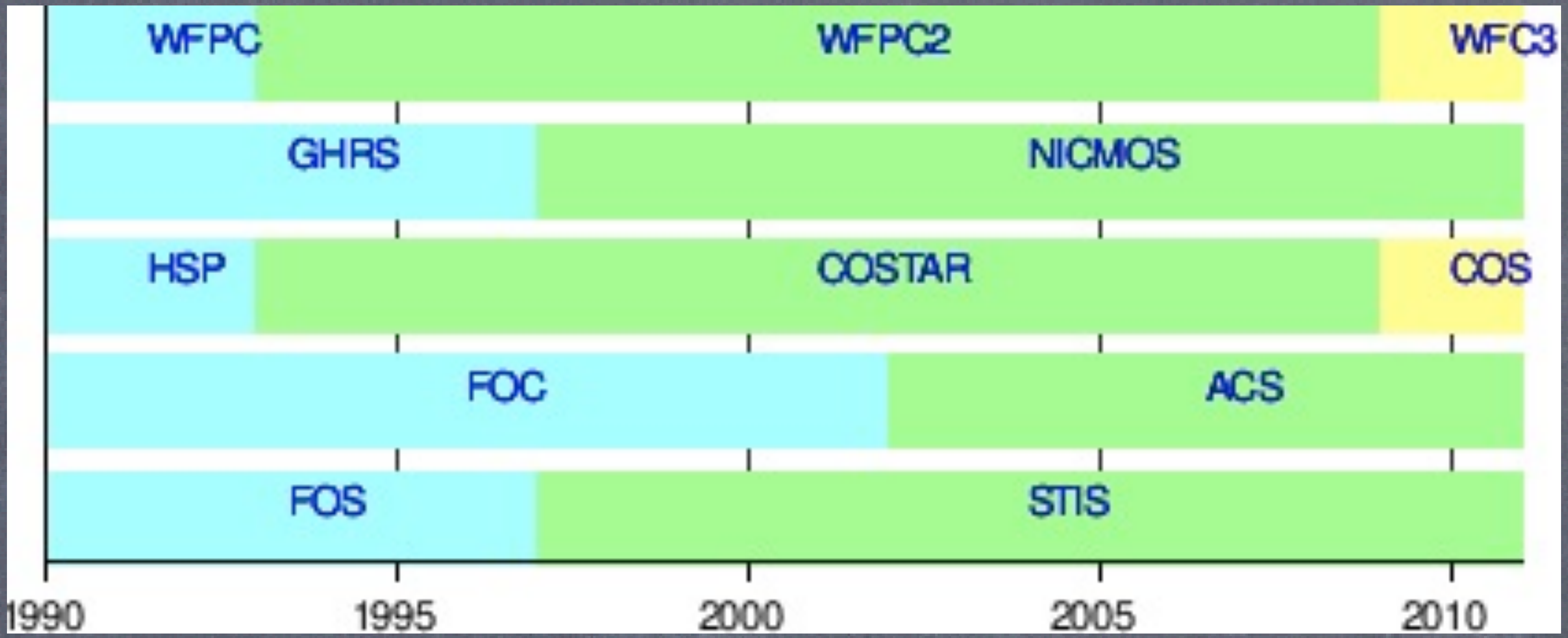
Hubble Key Projects (circa 1990):

(1) Determine the properties of the intergalactic medium using quasar absorption lines

(2) Medium deep survey using the Wide Field Camera

(3) Determine the Hubble constant to within ten percent

Hubble Over Time



Hubble is unique among space telescopes in that it can be serviced. The expense of servicing means that no NASA satellite since has adopted this model, but servicing has given Hubble a very long lifetime and increased capabilities. Hubble is on its third generation of instruments and has been serviced 5 times.

Initial Instruments

Wide Field and Planetary Camera (WF/PC): high resolution CCD imager. Combined a wide-field camera with 0.1"/pixel (f/12.9) and the planetary camera with 0.043"/pixel (f/30).

Goddard High Resolution Spectrograph (GHRS): high resolution UV spectrograph.

High Speed Photometer (HSP): fast timing visible and UV instrument to measure variable stars. Removed for COSTAR.

Faint Object Camera (FOC): high spatial resolution UV and optical imaging (0.014"/pixel)

Faint Object Spectrograph (FOS): near-UV to near-IR spectroscopy

The Flawed Mirror

(an example of spherical aberration)

The Hubble primary mirror was polished to an incorrect shape meaning it is slightly too flat on the edges and light was not all focused to the same point.

Hubble was then given eyeglasses in the form of COSTAR (Corrective Optics Space Telescope Axial Replacement) which used an additional mirror to add the inverse spherical aberration. New instruments have included their own corrective optics.

WF/PC image showing spreading of light from a star

before and after COSTAR

Current Instruments

Advanced Camera for Surveys (ACS):

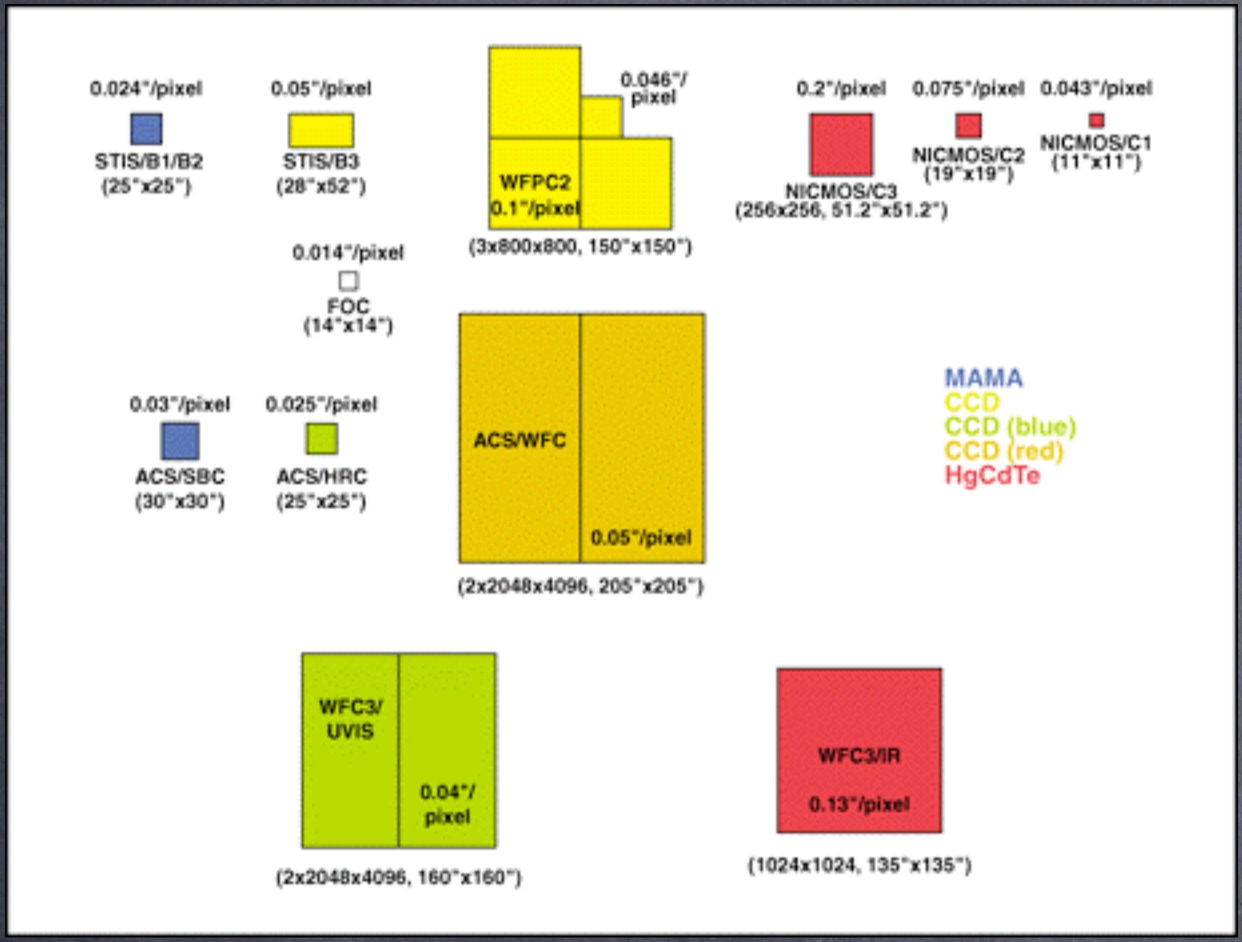
Wide-field CCD imager with near-UV to near-IR capabilities. High QE gave jump in sensitivity. Wide field channel has 3.4′ FOV and plate scale of 0.05″

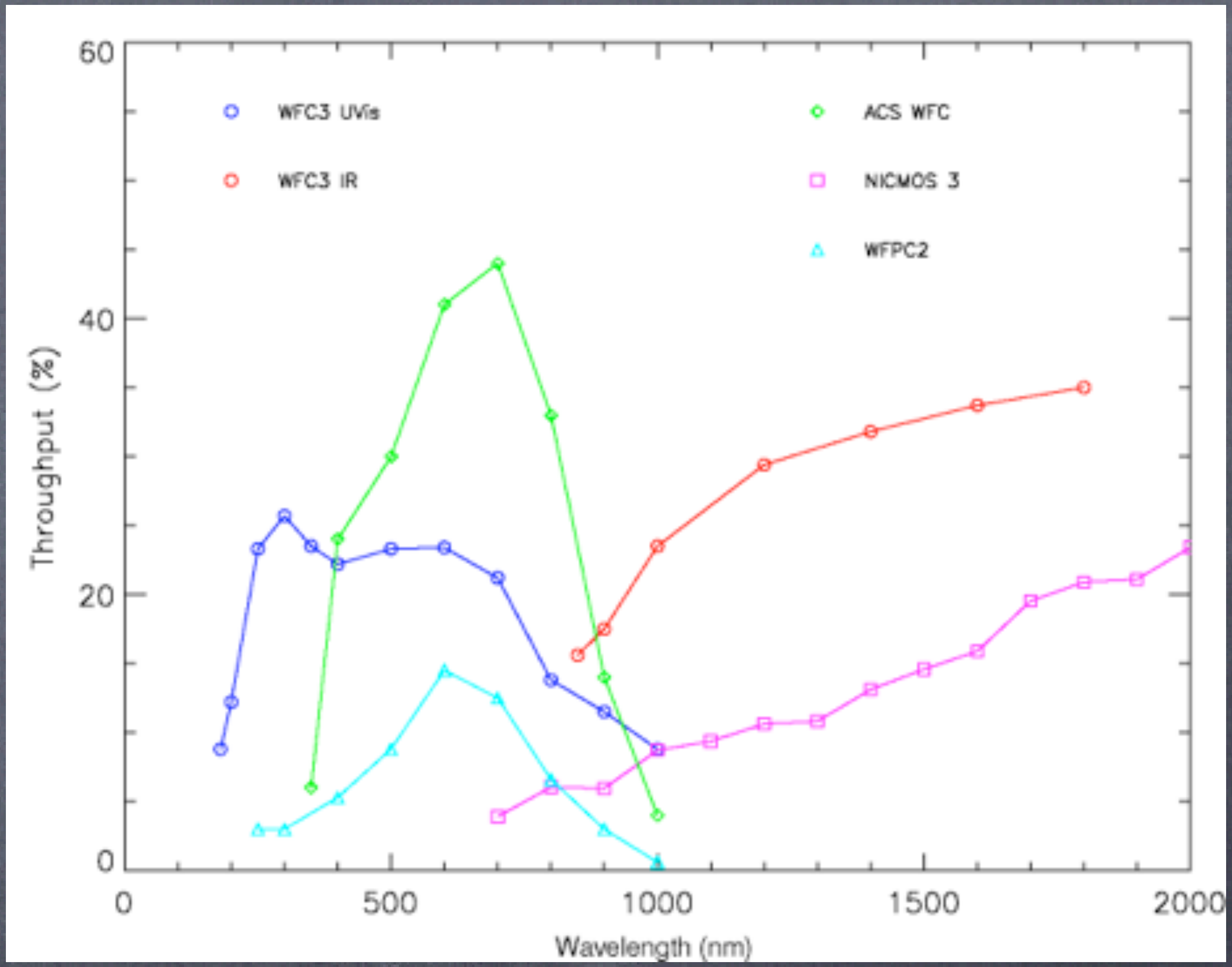
Wide Field Camera 3 (WFC3):

WFC3 has two CCD arrays, one for UV/optical imaging (200-1000nm) with 2.7′ FOV and 0.04″ pixels, and one for IR (800-1700nm) with ~2.2′ FOV and 0.13″ pixels.

Both instruments are very versatile with a large range of filters and low-resolution grisms.

Current Instruments





WFC3 offers much improved UV and IR sensitivity, while ACS is better for visible. Both have similar FOV and pixel scale.

Current Instruments

Cosmic Origins Spectrograph (COS):
ultraviolet spectrograph with high sensitivity and low to moderate spectral resolution (R~3000 and 20,000)* with a small FOV of 2.5". Two channels FUV (115-205nm) and NUV (170-320nm) using microchannel plate and Multi-Anode Multichannel Array detectors**.

Space Telescope Imaging Spectrograph (STIS):
imaging spectrograph with three detector arrays covering the optical/near-IR (CCDs, 52" FOV), near-UV, and far-UV (MAMA, 25" FOV) with a broad range of spectral and imaging options

The two spectrographs are clearly complimentary.

* $R = \lambda/\Delta\lambda$

** more on UV detectors later

Major Results/Discoveries

- Measurement of the distances of Cepheid variable stars to pin down the Hubble constant
- Observations of high-z supernovae contributing to measurements of the accelerating expansion of the universe
- Deep Field and Ultra Deep Field, studies of high-z galaxies and galaxy evolution in general
- Proto-planetary disks around young stars
- Optical counterparts to gamma-ray bursts
- Extrasolar planets imaging and spectra

Hubble Images as Art

Ground Based Telescopes: Keck Example

Twin 10-m telescopes on Mauna Kea in Hawaii. Primary mirrors composed of 36 hexagonal segments controlled by active optics.

Keck Instruments

Visible Light (300 - 1000 nm):

DEIMOS: faint-object, multi-slit imaging spectrograph, moderate spectral resolution, relatively large FOV (16.7'x5')

HIRES: high-resolution spectrograph

LRIS: faint object, low resolution, multi-object spectrograph

ESI: spectrograph and imager, blue to the infrared in a single exposure, ability to switch between 3 modes during a night.

Near-IR (1000 - 5000 nm):

NIRC2: near-IR camera and spectrograph working with AO, plate scale 0.01"-0.04", max FOV 40"

NIRSPEC: moderate to high resolution near-IR spectrograph

OSIRIS: near-IR integral field spectrograph working with AO, resolution near the diffraction limit, small FOV

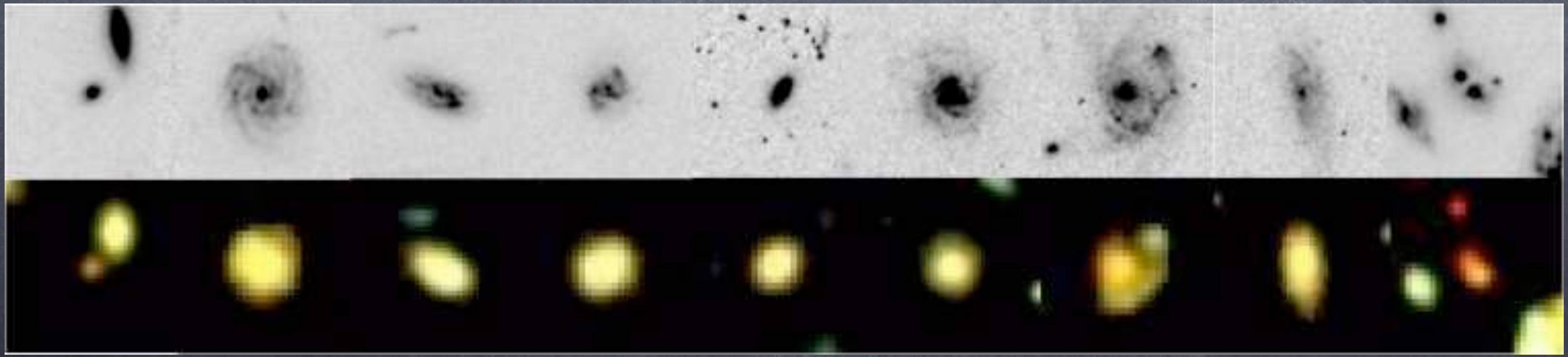
Major Science Results

- Discovery of extra-solar planets through radial velocity measurements
- Tracing the orbit of stars around the Galactic Center
- Redshifts of high-z supernovae to measure cosmic expansion
- Galaxy evolution, galaxy redshifts surveys (DEEP, DEEP2)
- Studies of the intergalactic medium, measurement of light element abundances to probe baryon fraction

Ground vs. Space: Spatial Resolution

Hubble: diffraction limit $\theta = 1.22\ \lambda/2.4\text{m} = 0.04''$ at 4000 Å

Keck: Even very good seeing is on the order of 0.4-0.5″ for ground based telescopes (depends a bit on wavelength)



VLT and HST comparison, MPIA 2003

Adaptive Optics

The shape of the incoming wavefront is measured, a computer calculates the optimal mirror shape and a deformable mirror is used to correct for the distortion.

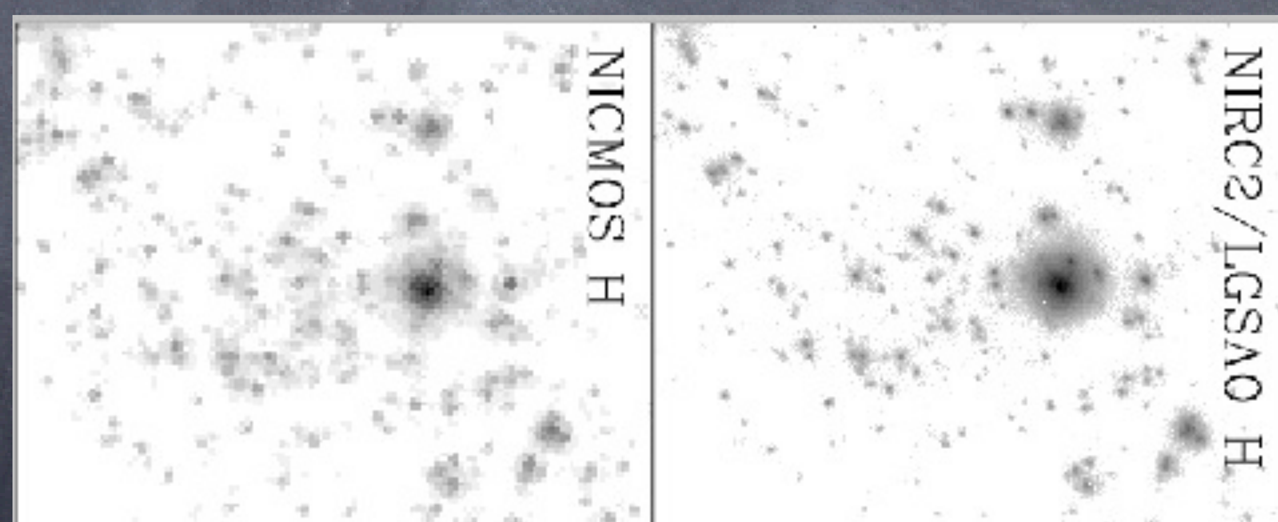
This must be done very quickly since the atmosphere is always changing (on the order of milliseconds).

The wavefront is measured using either a natural guide star (must be bright, which limits sky area) or using a laser.

Spatial Resolution - AO

Can be as good as 0.05" depending on conditions, guide star magnitude, i.e. somewhat better than HST diffraction limit in near-IR (trade-off limited FOV).

Strehl ratio: ratio of peak intensity of a point source compared to theoretical maximum. S = 0.5-0.6 at best for Keck AO.



Keck Observatory/James Graham & and Nate McCrady

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FWHM for Keck Adaptive Optics and NICMOS Images, from Two Pointlike Sources

Parameter	*J* Band		*H* Band		*K* Band	
	Point Source 1	Point Source 2	Point Source 1	Point Source 2	Point Source 1	Point Source 2
Keck FWHM (arcsec)........................	0.13	0.16	0.13	0.13	0.10	0.12
NICMOS FWHM (arcsec)..................	0.12	0.11	0.17	0.13	0.19	0.17

Max et al. 2005

Ground vs. Space: Sensitivity

What effects this?

- telescope diameter
- background (Keck has background from the sky, etc.)
- spatial resolution
- QE of the instruments

SIGNAL-TO-BACKGROUND RATIOS FOR KECK AO AND NICMOS IMAGES OF TWO POINTLIKE SOURCES

	Point Source 1		Point Source 2	
Band/Filter	Keck AO	NICMOS	Keck AO	NICMOS
J/F110W	1.1	3.4	1.6	2.5
H/F160W	1.3	2.4	1.6	2.3
K'/F222M	2.6	0.7	3.6	0.9

Max et al. 2005

** WFC3 is more sensitive than NICMOS

Wavelength Coverage

HST: roughly 0.1 - 1.7 μm
Keck: roughly 0.3 - 5 μm
JWST: roughly 0.6 - 27 μm

Ground vs. Space: Cost

HST: cost at launch $1.5 billion and $6-10 billion total including operations and 5 servicing missions

Keck: something like $230 million plus $10-25 million per year

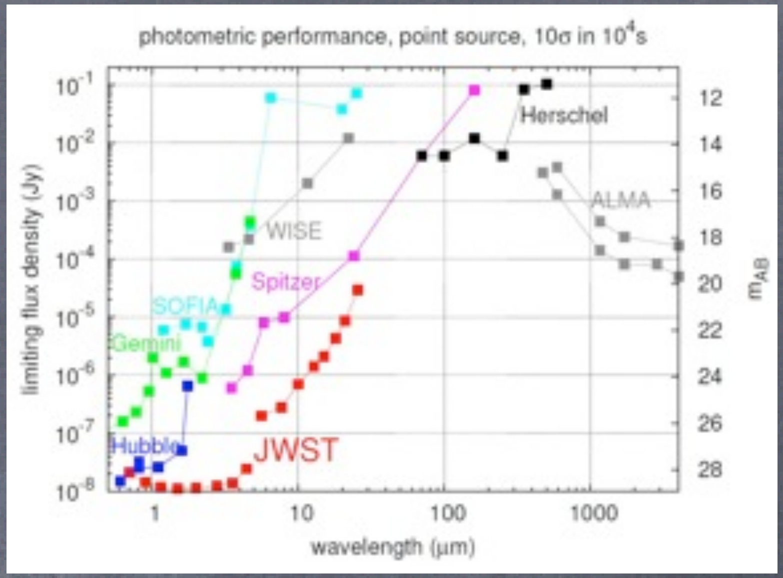
JWST: something like $8-9 billion to launch

TMT: something like $1 billion

Future Telescopes

James Webb Space Telescope:

6.5 m telescope, near-IR to mid-IR
launch planned for 2018
instruments NIR camera, NIR spectrograph, MIR imager/spectrograph



Thirty meter class telescopes (TMT, GMT, ELT):

- Thirty Meter Telescope: 30-m made of 492 smaller 1.4 m hexagonal segments, 0.3–28 μm, will go on Mauna Kea
- Giant Magellan Telescope: 25-m, consisting of seven 8.4-m telescopes, 0.3-25 μm, will go at Las Campanas in Chile
- Extremely Large Telescope: 39-m at Cerro Armazones, Chile

Science with Thirty Meter Telescopes

Nine times the collecting area of Keck, and (if they get diffraction-limited resolution with AO) a factor of ten better resolution than Hubble.

- Study high-redshift galaxies in the epoch of reionization, when did the first galaxies form?
- When did first supermassive black holes form and relationship of black hole growth to galaxy evolution
- Study Earth-mass extrasolar planets and planetary atmospheres

Large Area Optical Surveys (some)

2dF Galaxy Redshift Survey: spectroscopic survey of around 250,000 objects using the 3.9-m Anglo-Australian Telescope between 1997 and 2002 covering 1500 deg^2

Sloan Digital Sky Survey: 2.5-meter at Apache Point, NM
imaging: 14,555 deg^2 (35% of the sky) in 5 filters
spectroscopy: over 1 million spectra

Dark Energy Survey: 5000 deg^2 survey in 5 bands using a new camera on the Blanco 4-m telescope

LSST: 6-band (0.3-1.1 μm) 20,000 deg^2 survey
8.4-m telescope with a 3.5 deg diameter FOV, will image the entire survey area every 3 days

Ultraviolet Astronomy

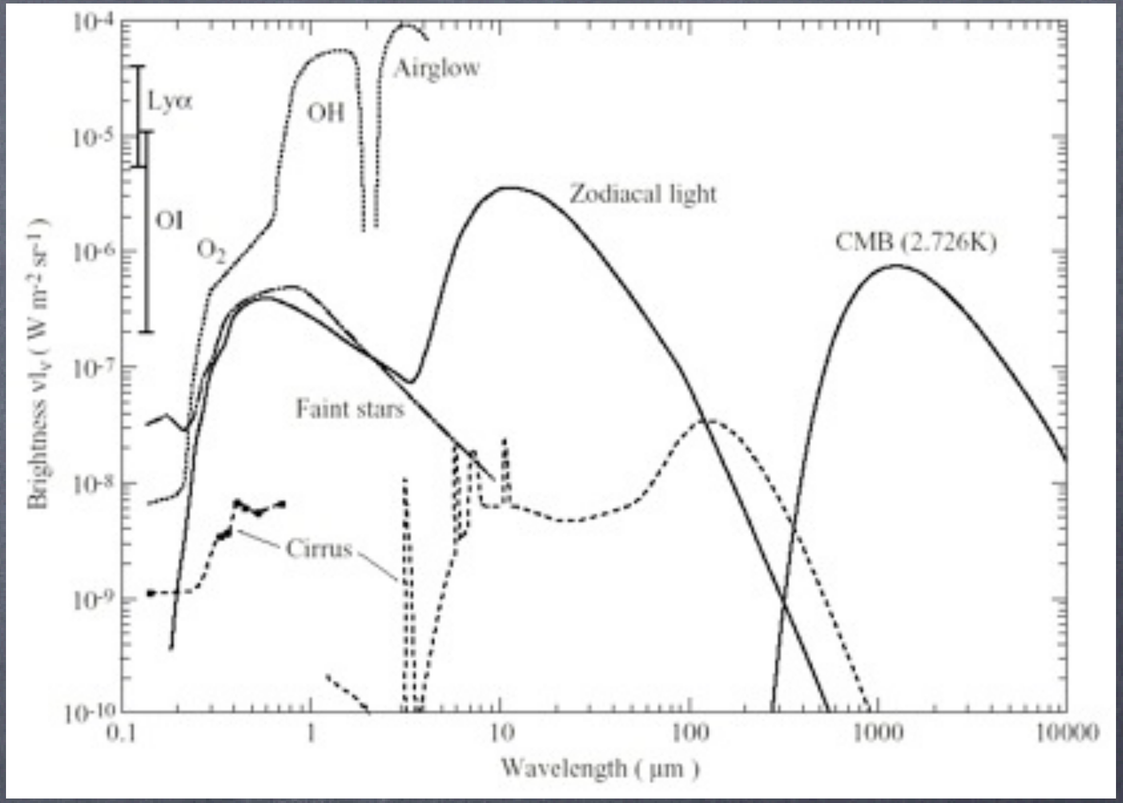
Sources of Emission

- Young, hot stars
- AGN, “big blue bump” from inner accretion disk
- Many important line features probing ISM, IGM
  - Lyman alpha
  - O VI, C IV, N V --> warm gas, WHIM
  - deuterium --> probe of primordial nucleosynthesis

UV Background and Extinction

Pros: low cosmic background

Cons: strong extinction by dust



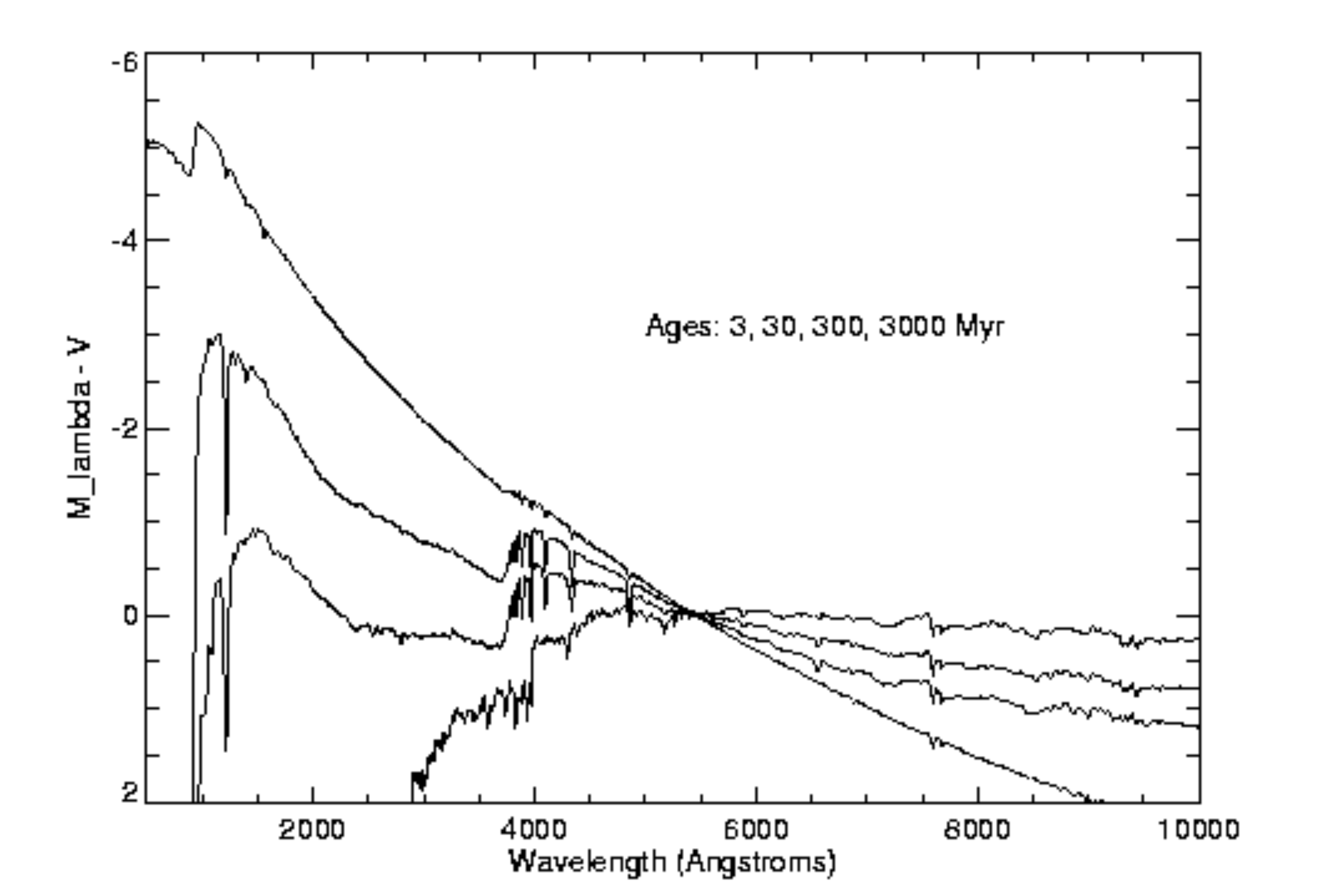
Leinert et al. 1998

Stellar Populations in Different Bands

A GALEX Instrument Overview and Lessons Learned, Morrissey, SPIE

UV probes sites of active star formation

Stellar Populations in Different Bands



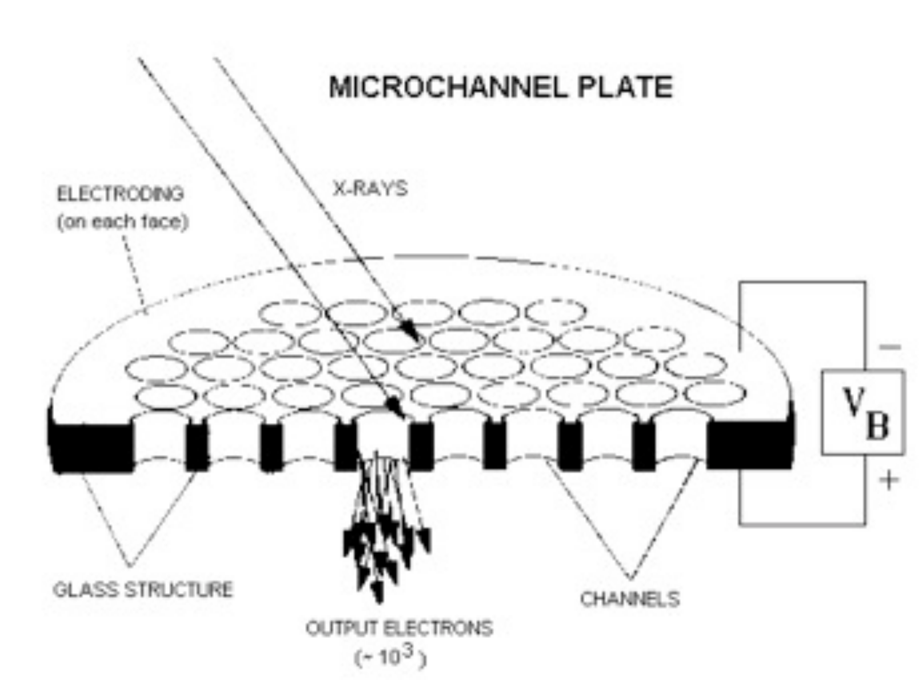
WFC3 White Paper Stiavelli and O'Connell

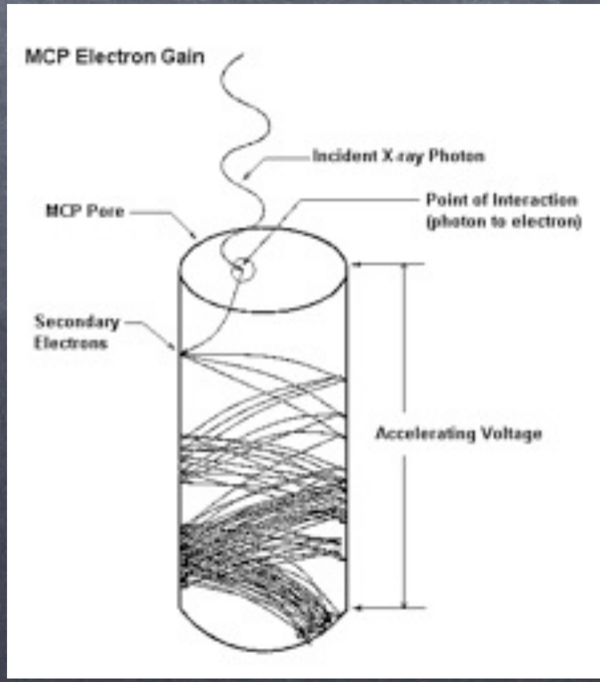
UV gives sensitive probe of stellar population age.

UV Detectors

UV detectors need to be "solar blind" (not sensitive to visible photons). UV detectors are often based on UV sensitive photocathodes amplified by stacks of microchannel plates (also used in X-ray).

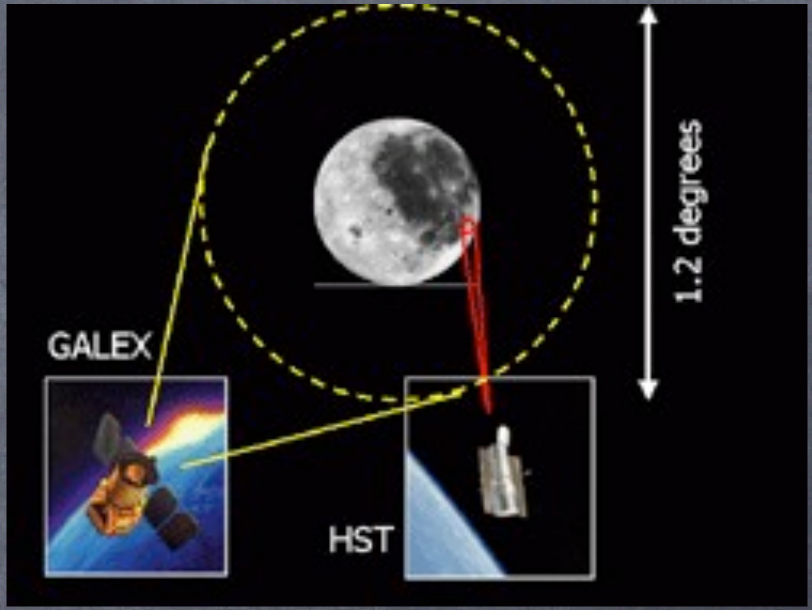
Microchannel plate: electron multiplier made of a thin disk of lead-oxide glass with a large array of parallel tubes. A photon knocks an electron out of the resistive material. Electrons then accelerated down the tube by an applied voltage, creating a cascade of events which are then detected.





GALEX
(April 2003-December 2011)

50 cm Ritchey-Chretien telescope with a large field of view (1.2 deg) and moderate spatial resolution (4-5"), optimized for large UV surveys. GALEX has conducted a shallow survey over 2/3 of the sky plus some smaller deeper surveys.



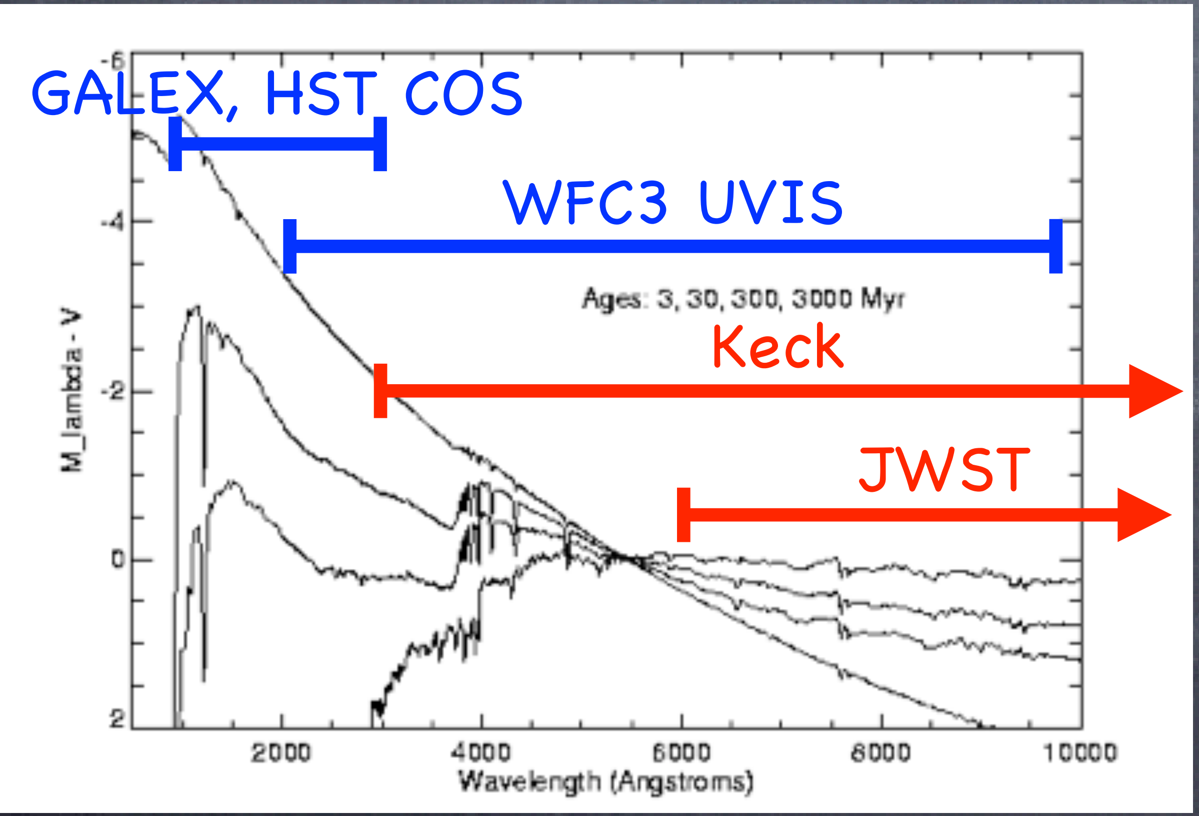
Two instruments: NUV (177-283 nm) and FUV (134-178 nm, not operational since 2009) for imaging and low-resolution grism spectroscopy.

HST

Several of the current instruments on HST have UV sensitivity. The UVIS CCD array which is part of WFC3 is sensitive down to 200 nm while COS and STIS allow both near-UV and far-UV spectroscopy.

Future

?



UV probes active star formation, stellar population age, the intergalactic medium (including "missing baryons", the gas which feeds and is expelled from galaxies, metal enrichment) among many other science topics.