AY257: Modern Observational Techniques

- This class is mostly about astronomical data and data reduction techniques.
- Working through the homework problems is the best way to learn the material
- We will work in the IRAF environment. Not necessarily the best, but it is widely available and free.

Data Reduction Tools

- IRAF developed at NOAO soon after digital detectors became widespread
  - Lots of packages, well documented, good control of details, good statistical basis, all-in-one package except for publication-quality plots
  - http://ssb.stsci.edu/ureka/ easy install: recommend doing so!
- IDL has many well-developed astro-related routines ⇩
- Python has many well-developed astro-related routines ⇧
- Many observatories maintain data reduction pipelines

Data Reduction Literature

- Measuring the Universe (Rieke)
- Observational Astrophysics (Lena, Lebrun, Mignard)
- CCDs in Astronomy, ASP Conf Series 8
- Astronomical CCD Observing and Reduction Techniques, ASP Conf Series 23
- Electronic Imaging in Astronomy, Ian McLean

Outline

- I. Telescope history
- II. S/N calculations
- III. Planning an observing run
  - a) Proposal Writing
  - b) Aircharts
  - c) Calibration Frames
  - d) Checks during the run
- IV. Data Reduction
  - i. Preliminary processing: overscan, bias, flat-fielding
  - ii. Photometry
    - a. Imaging cameras
    - b. Point Sources
    - c. Surface Photometry
    - d. Star-galaxy separation
    - e. calibration

Outline cont.

iii. Spectral data
  a. Spectrometer design
  b. Formats
  c. Extraction
  d. Radial velocity measurements
  e. Equivalent width measurements
  f. Indices
iv. IR (to 10μ)
v. Radio
vi. X-ray/gamma-ray astronomy
vii. Database astronomy

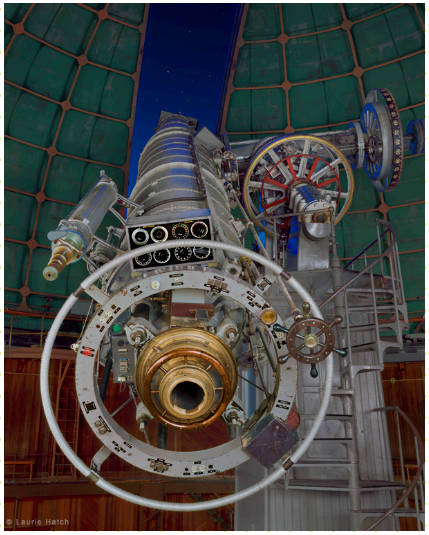
Homeworks

- Homework should be written up carefully using Latex/WORD with embedded figures. Purpose, ``howto'', results.
- Fine to work together, but everyone should do their writeups independently.
- Will need access to a computer with IRAF or IDL, Latex or Word, plotting package (e.g. SM, Python) to do the homeworks and writeups.
- Learning to use these packages is a great side benefit of the class.

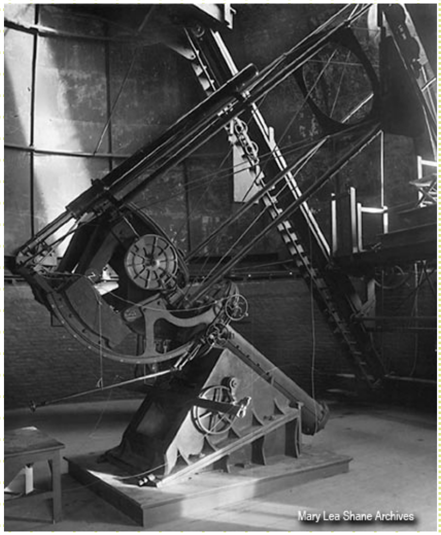
Bolte Schedule

- Not optimum
  - Sept 29/31: no class
  - Oct 15: guest lecture

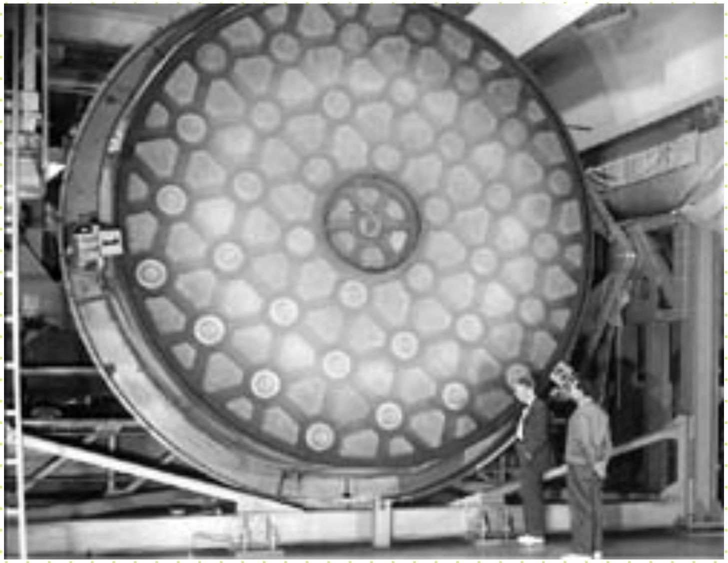
Telescopes in the last 400 years



© Laurie Hatch



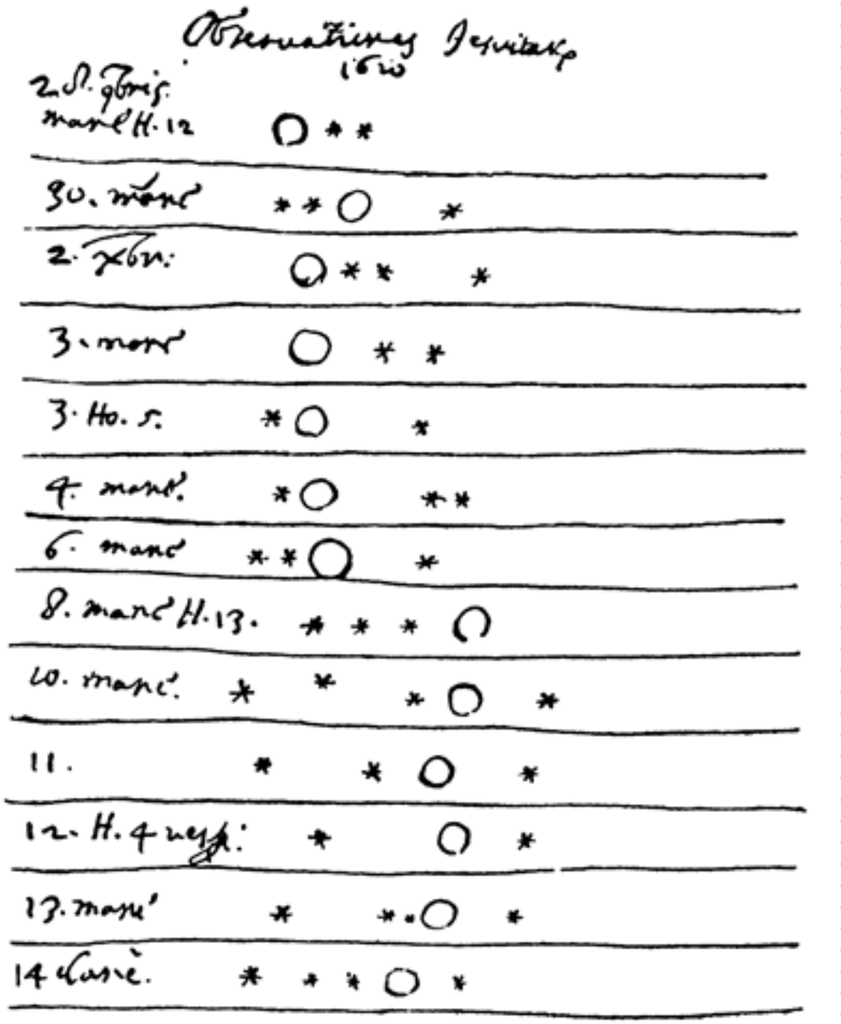
Mary Lea Shane Archives



The Start: Galileo

- 1608 Hans Lippershey applied for a patent for "*seeing things far away as if they were nearby*"
- 1609 Galileo built a 1.5cm diameter refracting telescope with 33x magnification and made observations of celestial objects

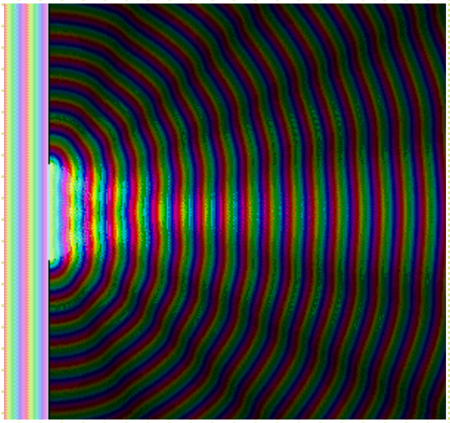
Galileo's Observations



With his telescope he:

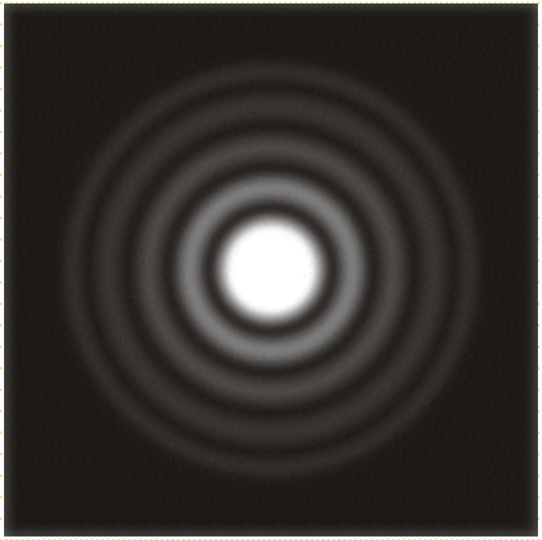
- Had more light-gathering capability and could see fainter objects
- Had higher spatial resolution because of magnification *and smaller diffraction limit than the unaided eye*

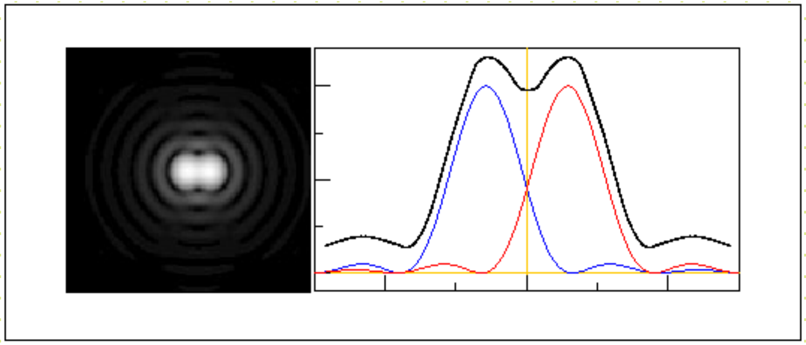
Diffraction Limit for circular aperture



- Rayleigh Criterion when first Airy minimum coincides with second source maximum
- $\theta_R = 1.22\lambda/D$ where:

θ_R is separation of sources in radians, λ is the wavelength of light and D is the diameter of the aperture

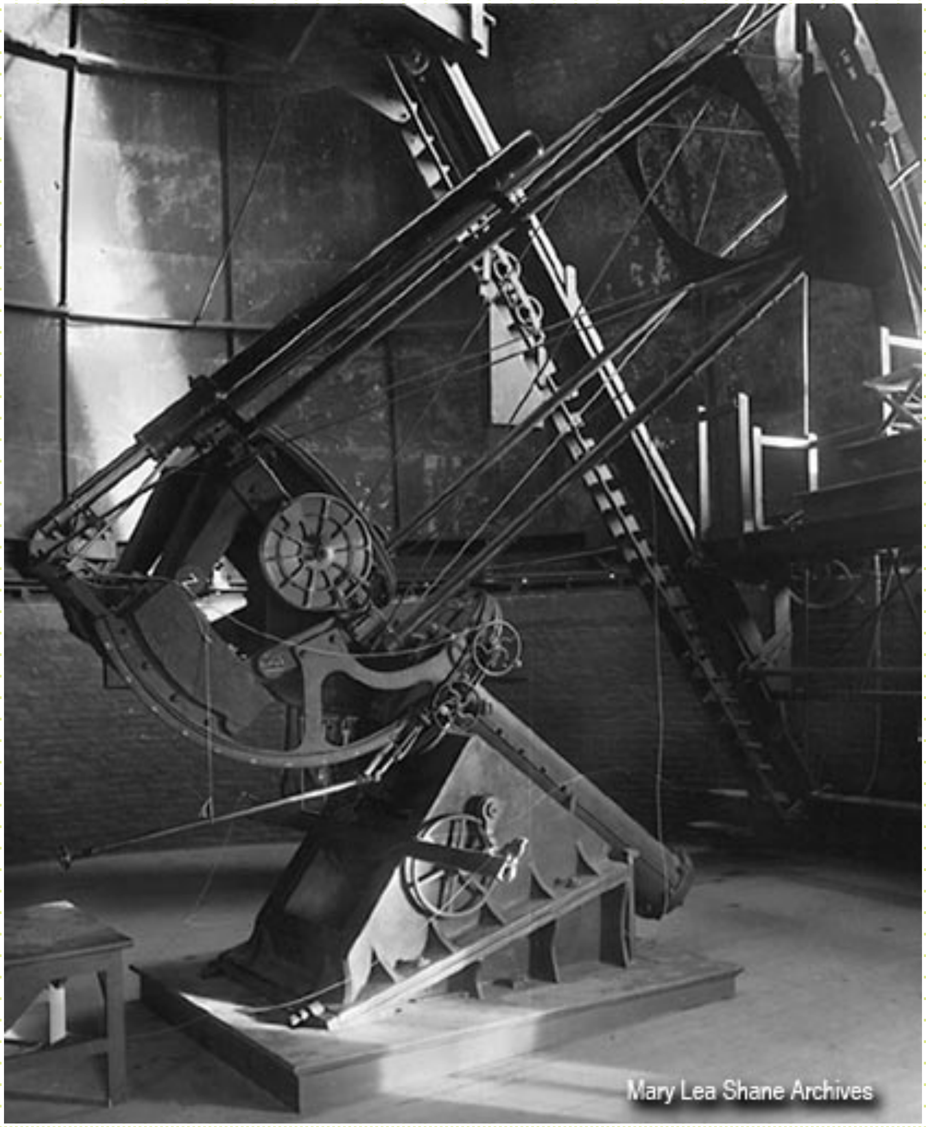




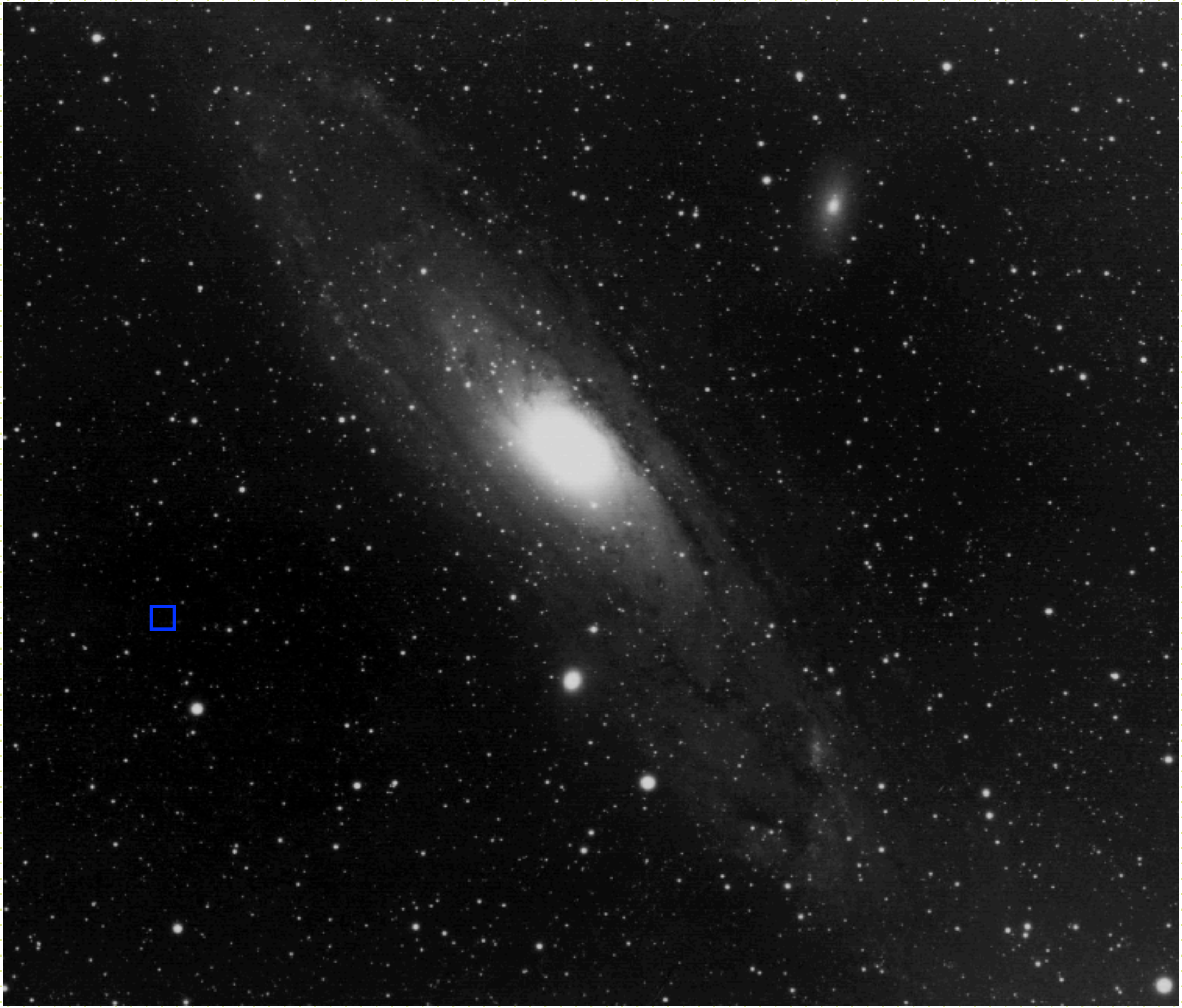
- Human eye: D~5mm
  - θ_R~25 arcsec @550nm
- Galileo 1.5 inch = 38mm telescope:
  - θ_R~3.2 arcsec @550nm
- 5-inch telescope: θ_R~1 arcsec @550nm
- 10m Keck telescope:
  - θ_R~0.012 arcsec@550nm
- Moon is 30 arcmin in diameter, unaided eye can resolve big craters

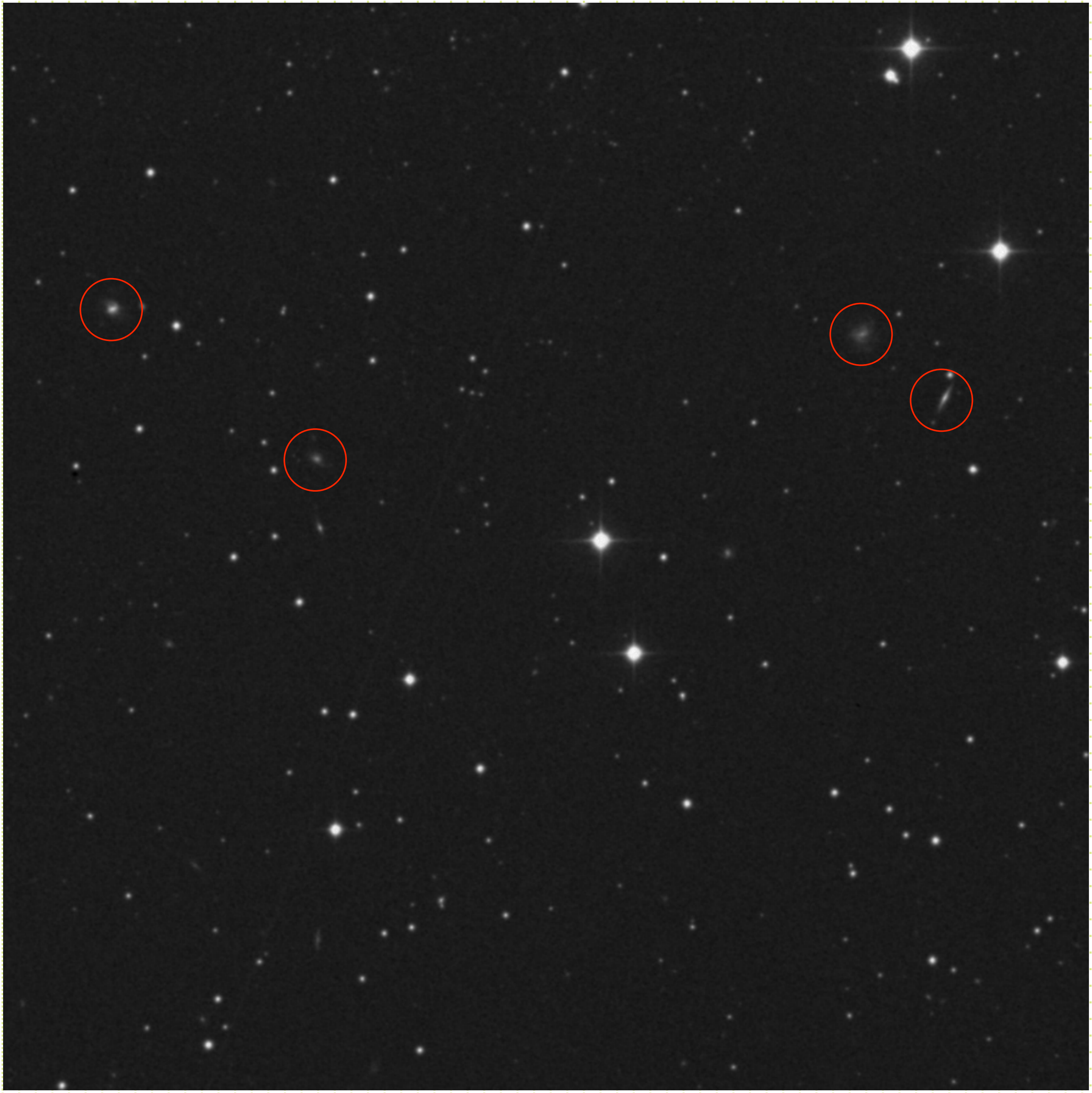
- Galileo observed imperfections on the surface of the moon and the Sun
- Perhaps most importantly, with the improved spatial resolution of his telescopes, Galileo observed that Venus showed different phases

Photographic Plates and the Universe

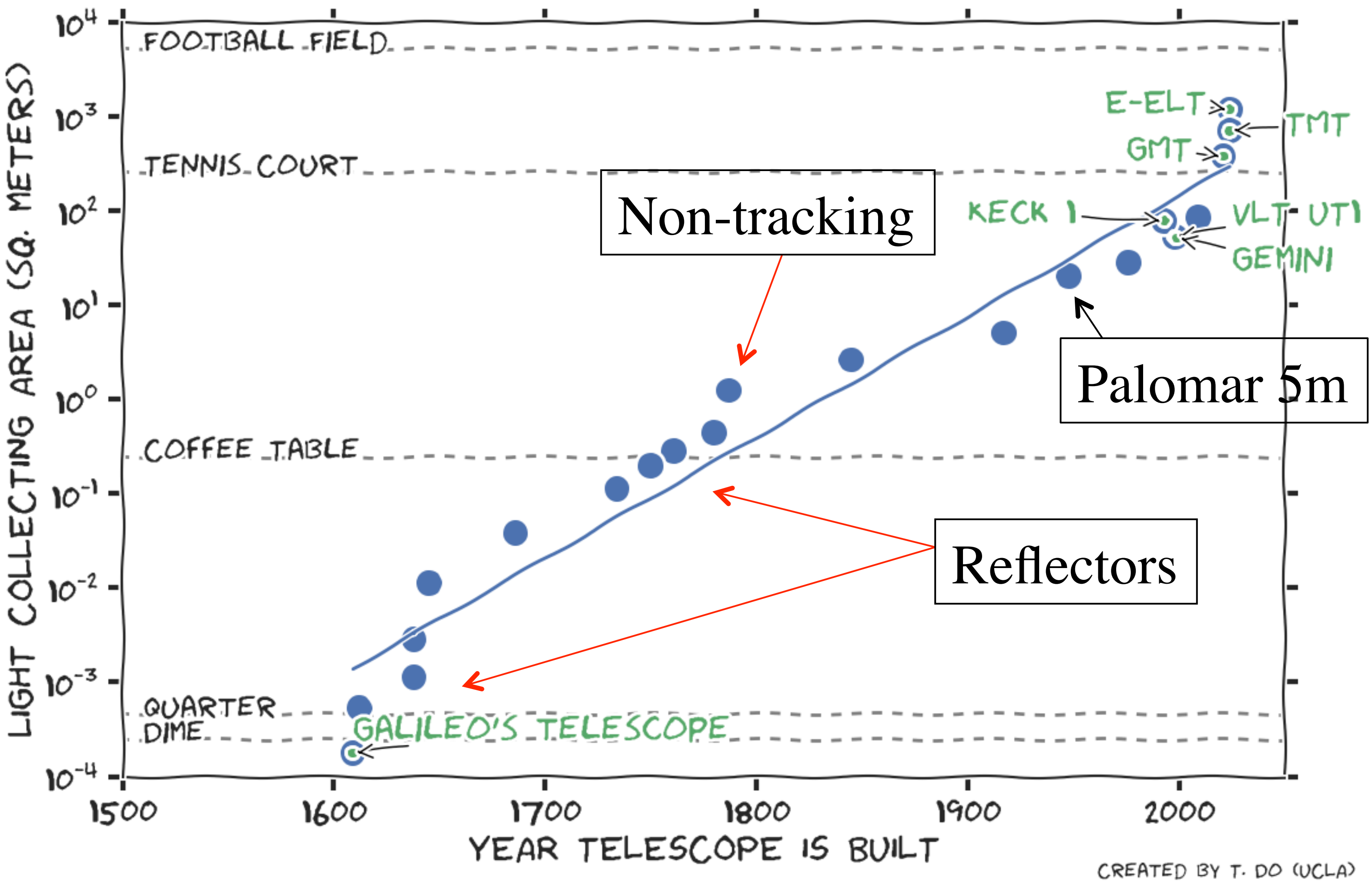

Mary Lea Shane Archives

- 1896 the 36″ Crossley Reflecting Telescope arrived at Lick Observatory
- “faster” optics and possibilities of building larger and larger mirrors (can support mirrors from behind)
- Photographic plates allowed long exposures





- Lick Observatory 36-inch Great Refractor and Yerkes 40-inch Refractor were the largest built along with a slew of 30-inch telescopes, all in the late 1800s early 1900s
- Crossley 36-inch Reflector started the trend to reflectors. 60-inch at Mt Wilson (1908), 72-inch DAO telescope (1918), 100-inch Mt Wilson (1919)…



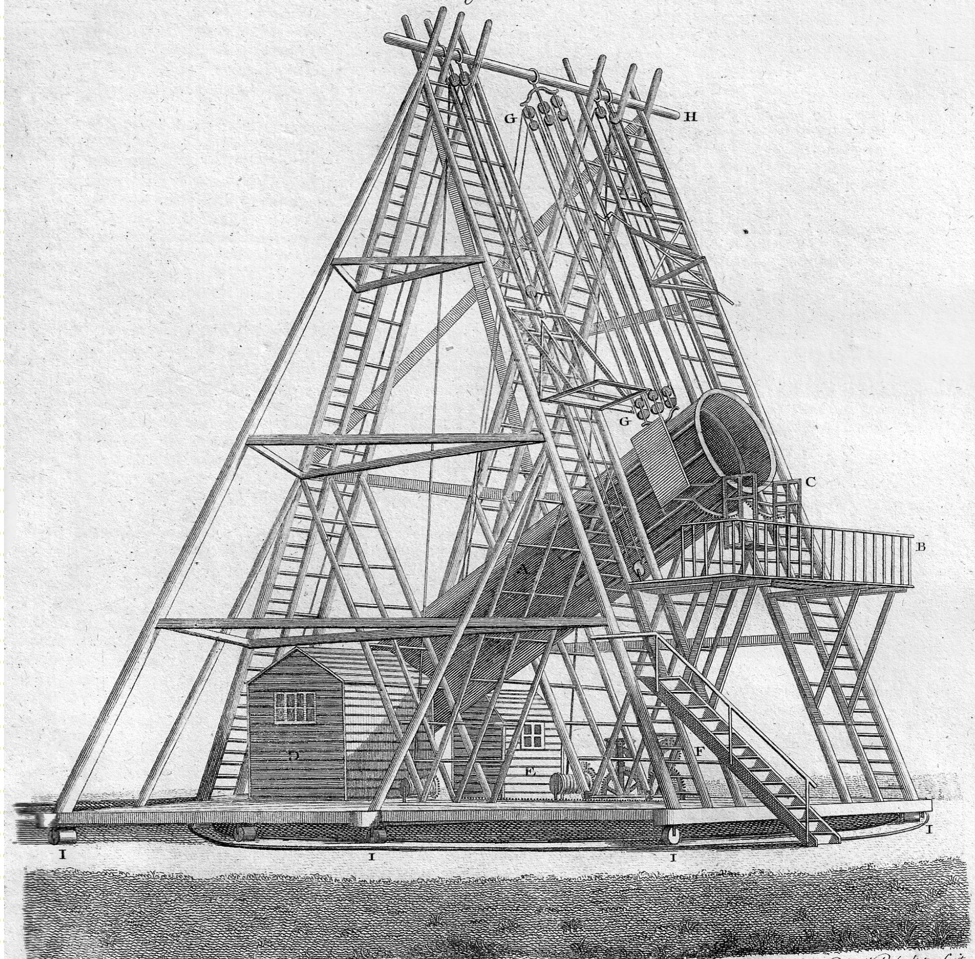
Non-tracking

Reflectors

Palomar 5m

Herschels Grand
TELESCOPE,
Fig. 24.

Plate DV.

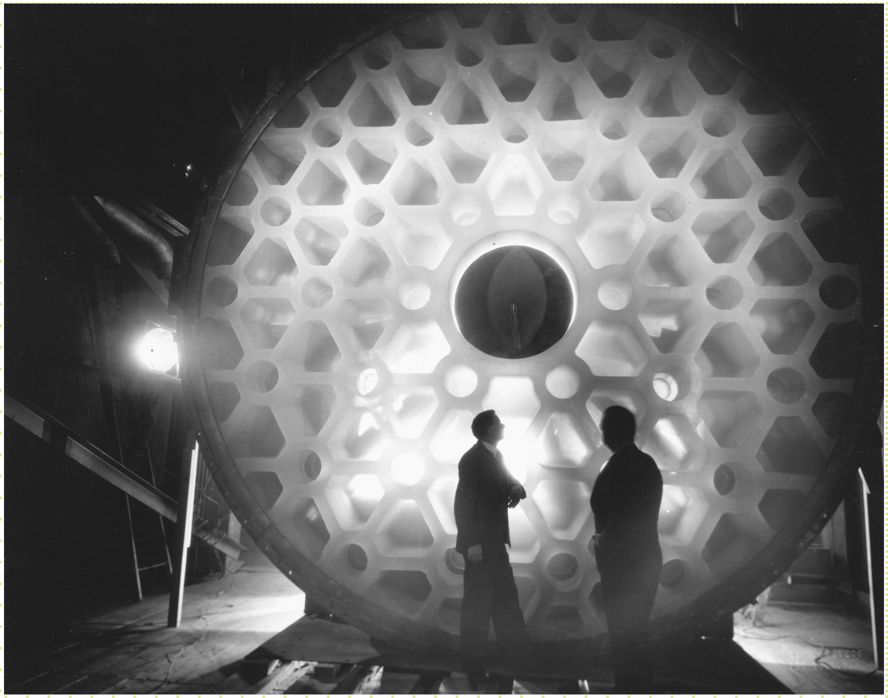


A. Bell Prin. Wal. Sculptor fecit.

What makes telescopes hard to build

- The optics need to be accurate on all spatial scales and stable (gravity vector, temperature, wind) to <10% of the wavelength of light:
  - 0.5μm is the center of the visible-light spectrum. Human hair has a typical diameter of 50μm
- The telescope structure needs to be very stiff and rigid to preserve the alignment of the optics and to point the telescope
  - Pointing accuracies and motion smoothness need to be <1´´
  - A highly-optimized 10m steel structure deforms ~ 1mm due to gravity forces, or 20,000 x larger than the optical tolerances
  - A 10m steel structure will deform 120μm for every °C change in temperature

The Trouble with Big Mirrors



- Palomar 5m Pyrex Mirror weighs 14.5 tons and the support structure almost the same
- Surface is polished to ~ 50nm precision over 11 years of grinding
- Very difficult to maintain that exquisite figure for different orientations

For glass, deflection δ scales with radius (r) and thickness (h) as:

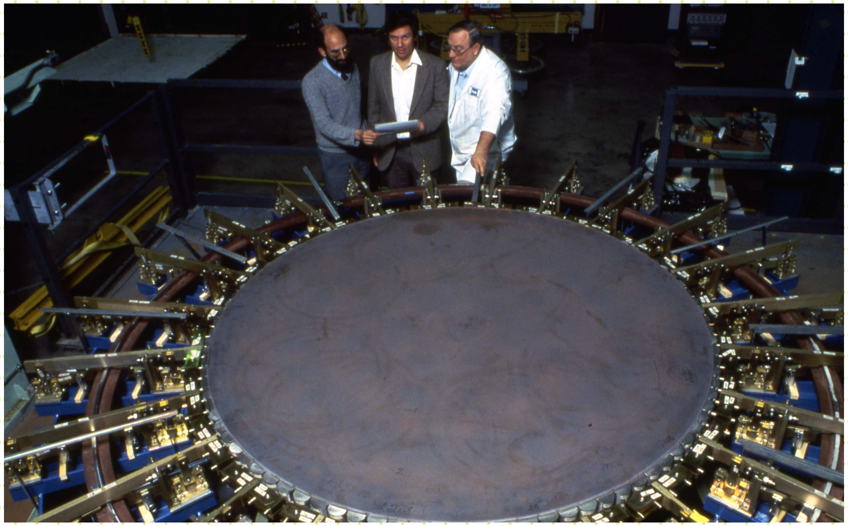
$$\delta \propto \frac{r^4}{h^2}$$

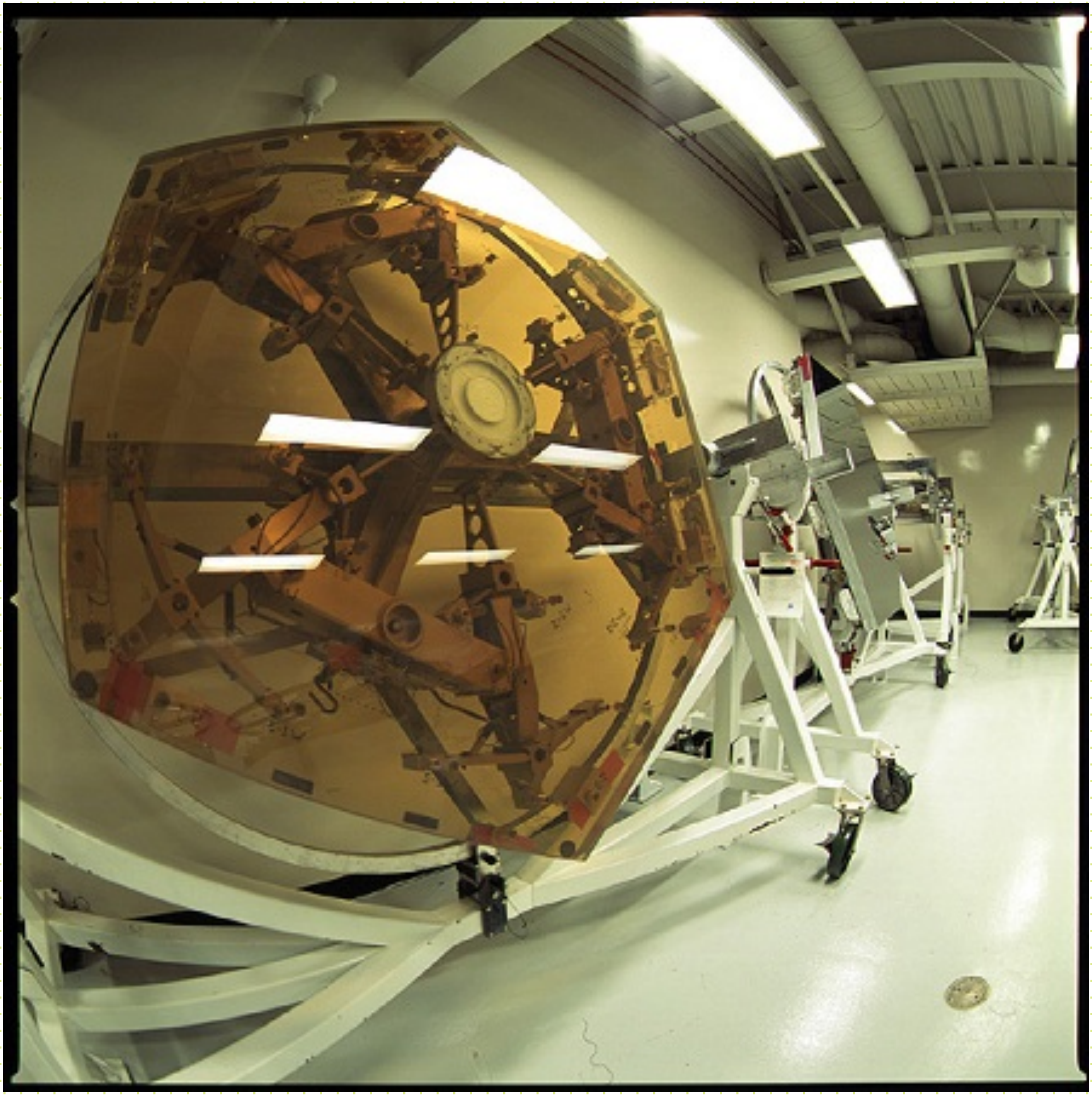
Moving beyond the 5-m limit

- Palomar 5m was completed in 1949, reigned for 40 years
- In the 1980s, two University of California physicists, Jerry Nelson and Terry Mast, proposed a new approach to building giant mirrors using hexagonal segments that fit together and are controlled very precisely

Stressed Mirror Polishing

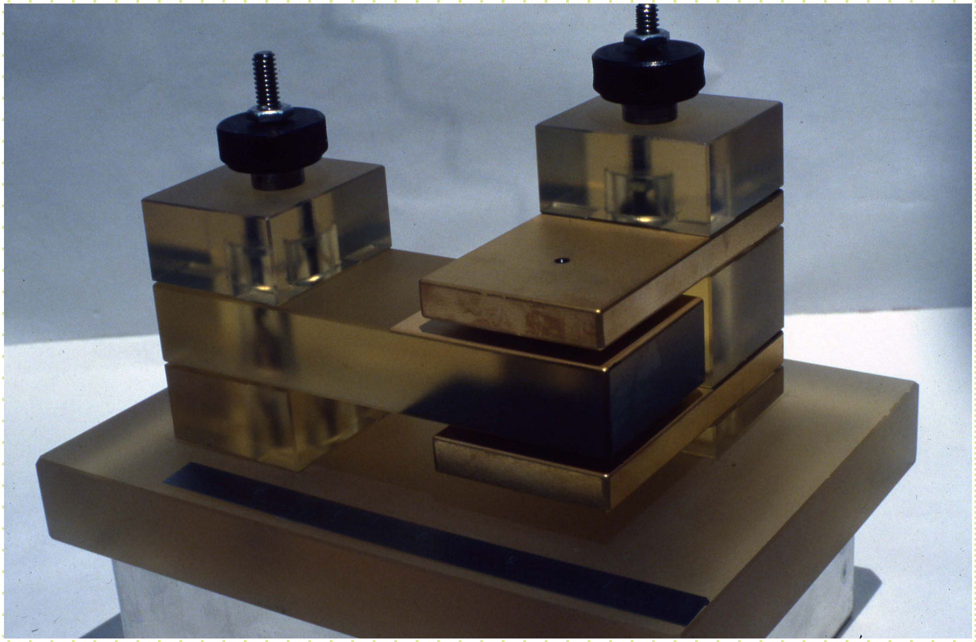
- Developed by Nelson
  - Tension perimeter of a round blank
  - Polish a sphere
  - Release tension and the mirror is close to right figure
  - Cut to hexagon and improve figure
  - Ion-figure for small scale smoothness
  - Add Whiffle-tree passive support and warping harnesses adjusted at telescope
  - For Keck, 36 1.8m segments
  - 1% light loss from gaps, sharp edges





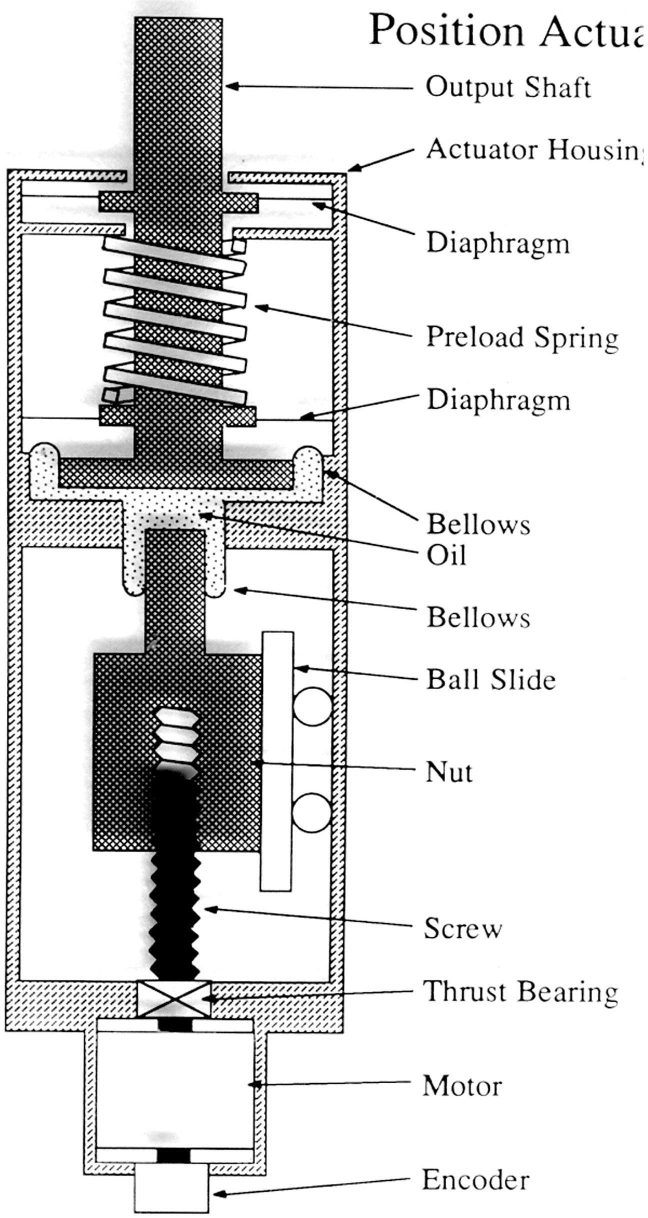
Edge sensors

- 2 edge sensors per segment edge
- Differential capacitive sensors
- Measures height difference between adjacent segments
- Extreme stability needed (drift rates of ~20nm/ week)
- Noise level ~ 1 nm



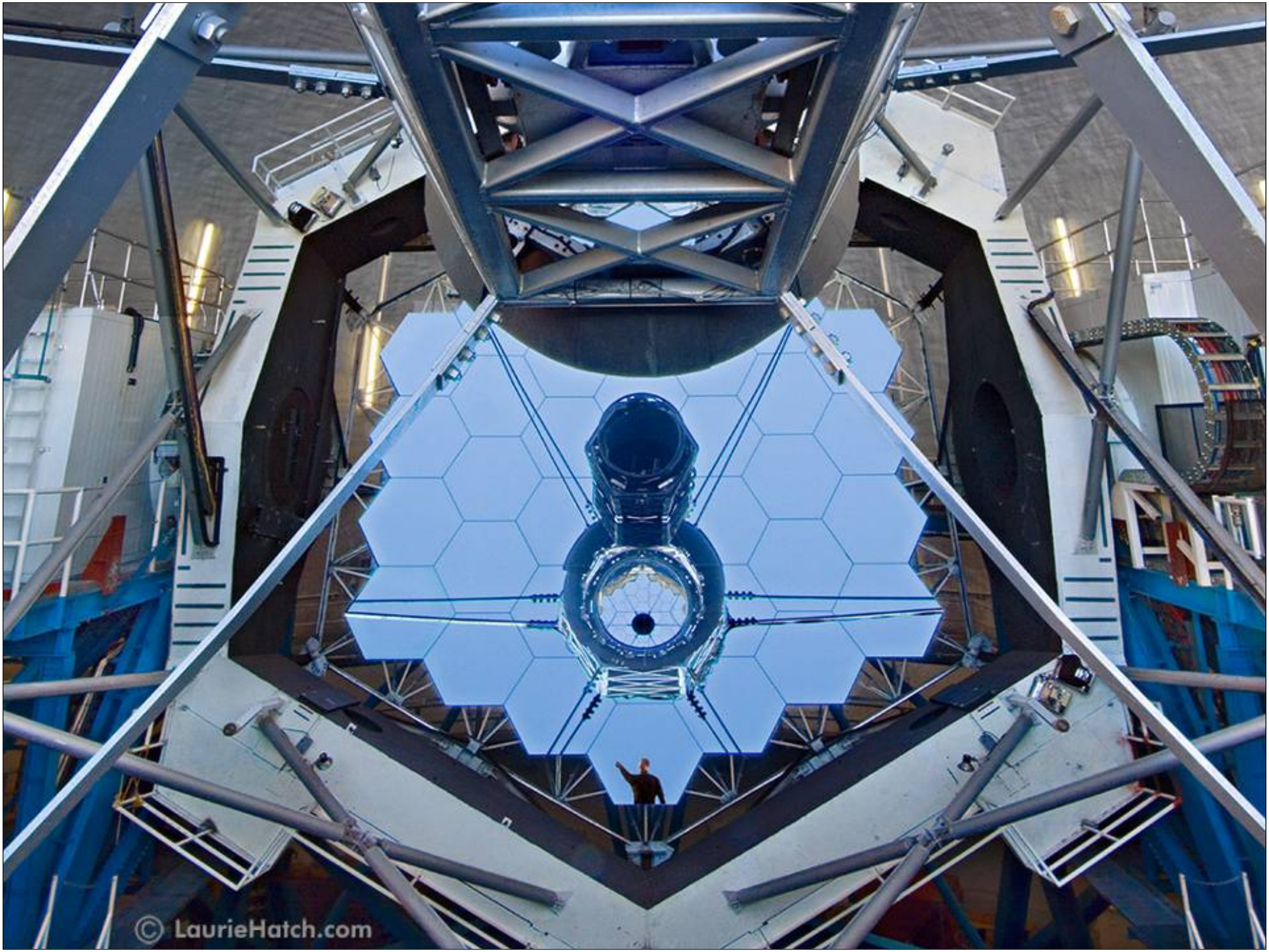
Displacement actuators

- 3 actuators per segment control piston tip/tilt
- Actuator range is 1.2 mm
- Motor driven roller screw and hydraulic reducer
- Since there is closed loop control, smoothness is needed but not high level of accuracy
- Actuator smoothness is ~ 4 nm

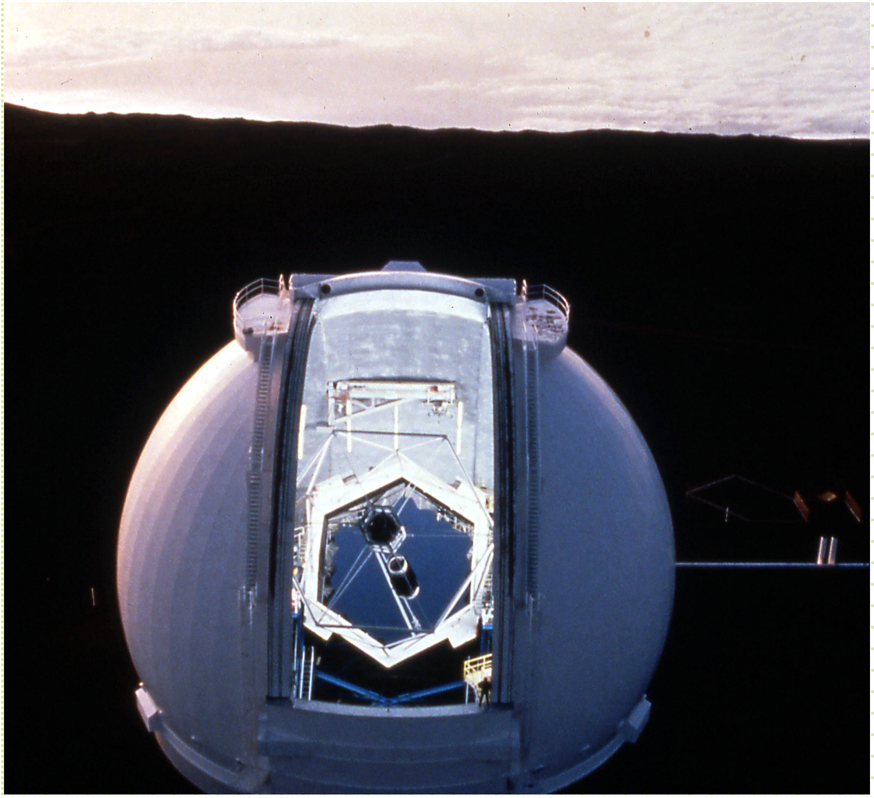


W.M. Keck Observatory

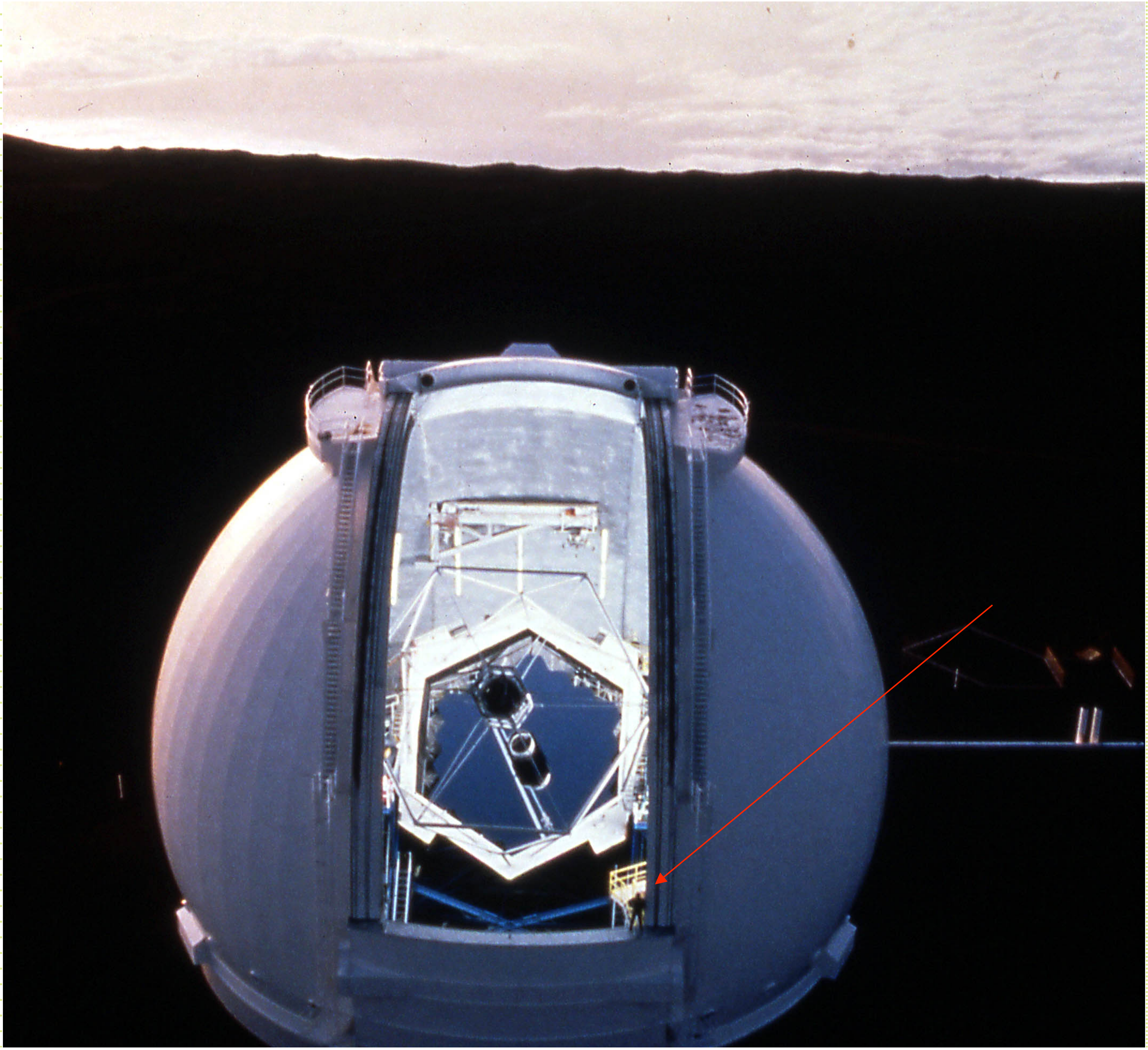
- Nelson/Mast concept became an observatory via gift from the Keck Foundation to Caltech and partnership between Caltech and the University of California
- “prototype” Keck 1 was a spectacular success
- One attractive aspect to segmented approach was scalability of the concept to even larger primary mirrors


© LaurieHatch.com

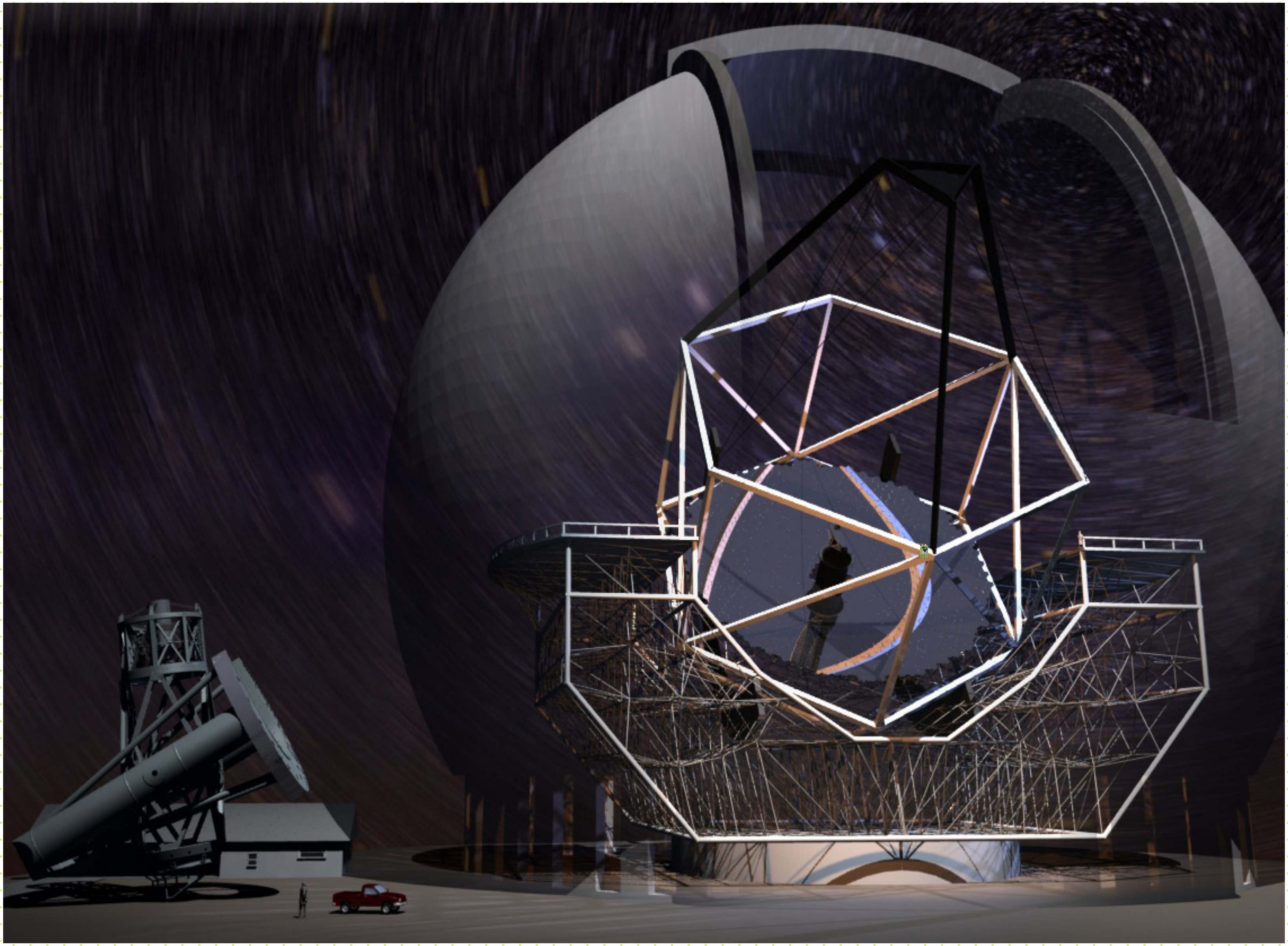
W.M. Keck Observatory

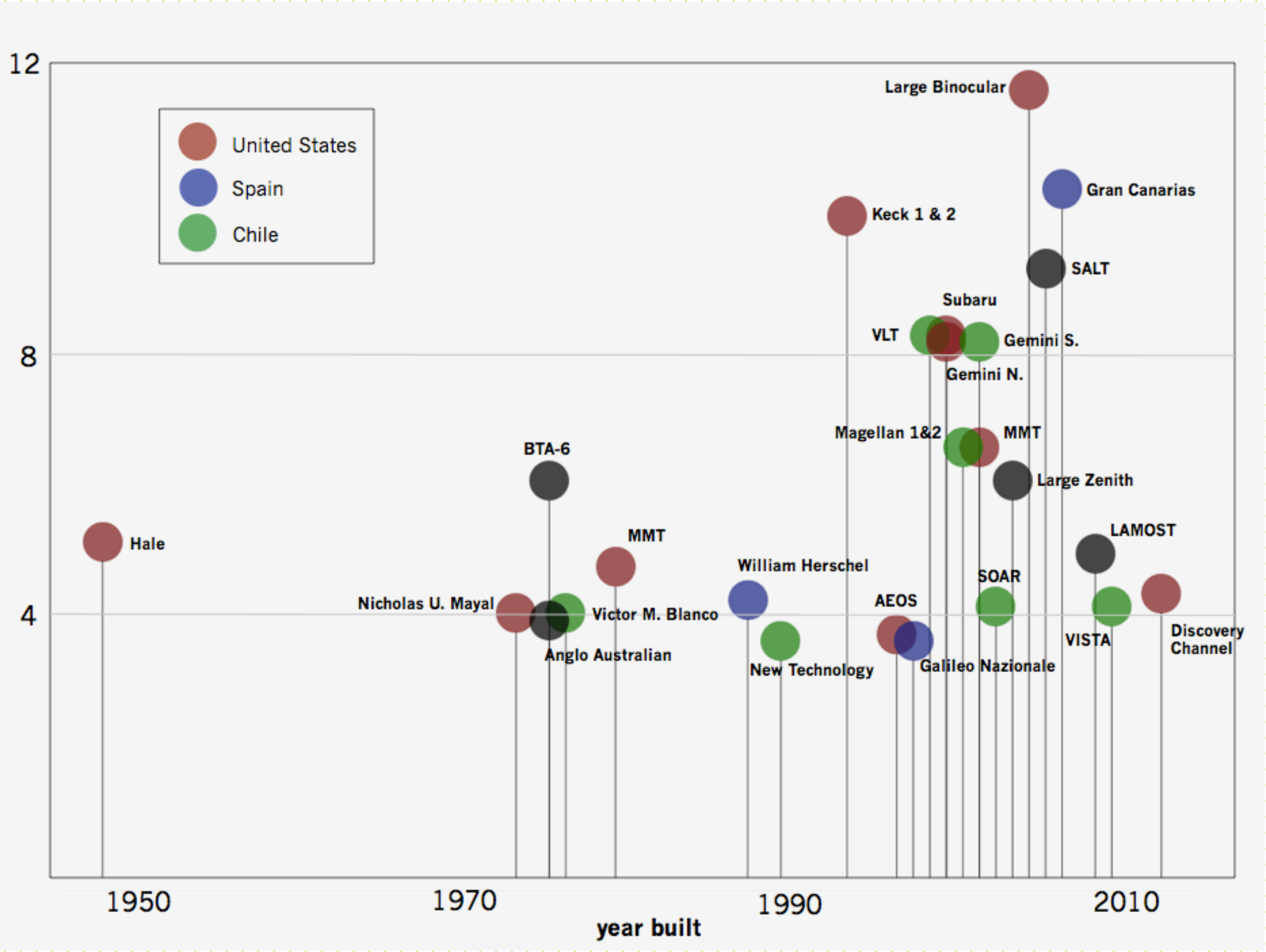


- Twin 10m telescopes designed by UC astronomers in the 1980s.
- Capital funding from the Keck Foundation via a gift to Caltech ($180M)
- UC contributes ~$10M/year operations for equal-share partnership with CIT
- NASA came in as 1/6th partner as part of the funding of the second telescope

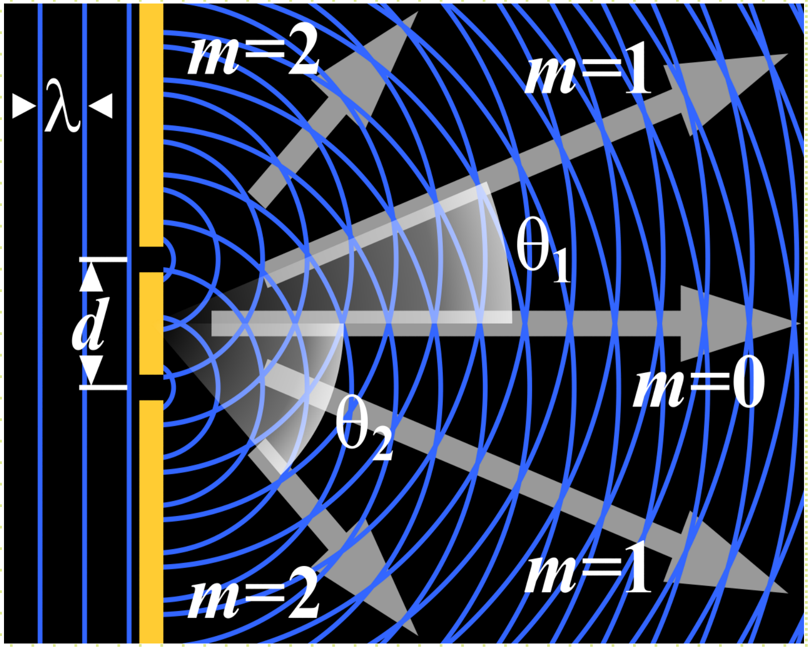


The Future: Thirty-Meter Telescope

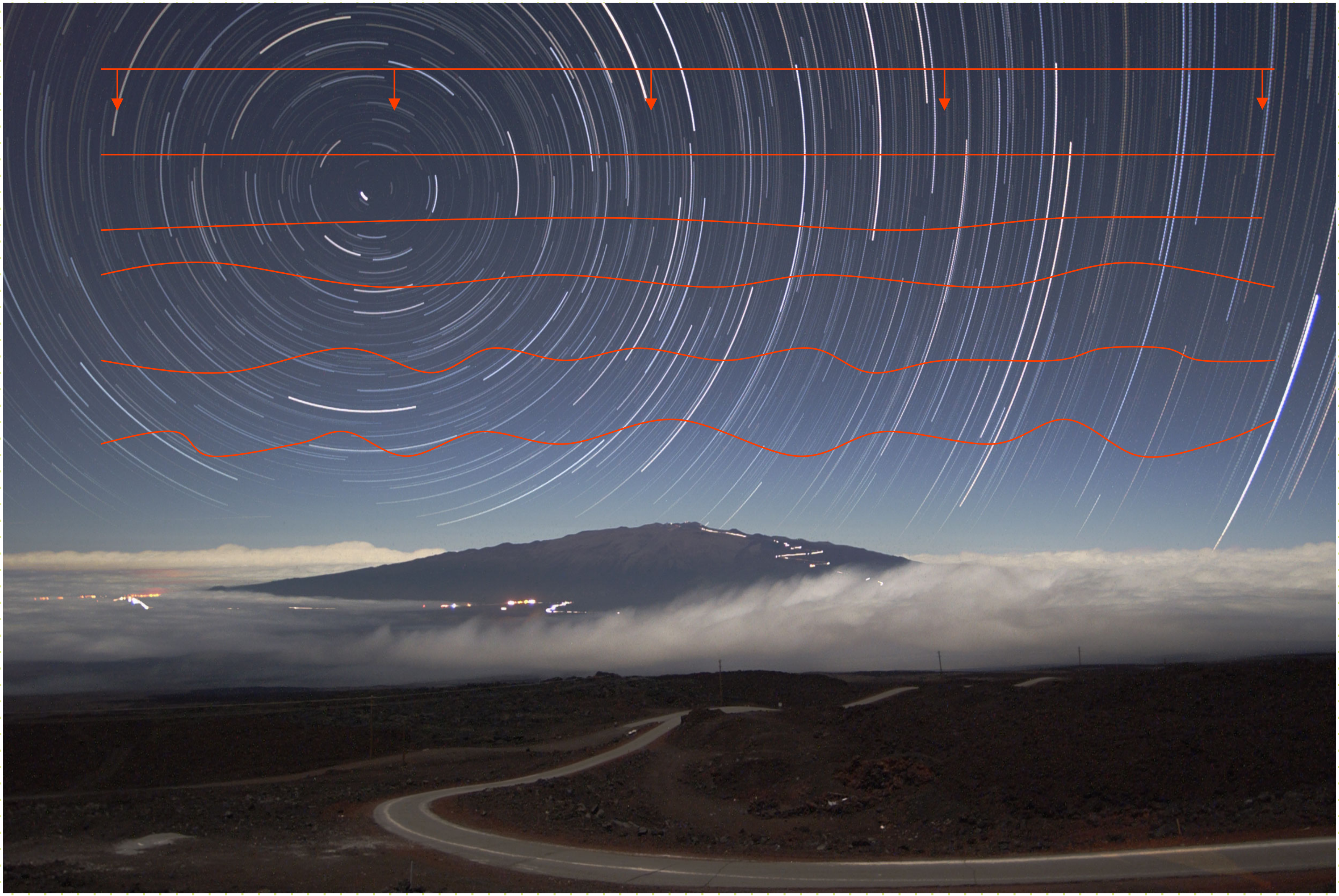



12
8
4
United States
Spain
Chile
Large Binocular
Gran Canarias
Keck 1 & 2
SALT
Subaru
VLT
Gemini S.
Gemini N.
Magellan 1&2
MMT
Large Zenith
BTA-6
Hale
MMT
LAMOST
William Herschel
SOAR
AEOS
Nicholas U. Mayal
Victor M. Blanco
Anglo Australian
New Technology
Galileo Nazionale
VISTA
Discovery Channel
1950
1970
1990
2010
year built

The 3rd Revolution in Astronomy: Adaptive Optics

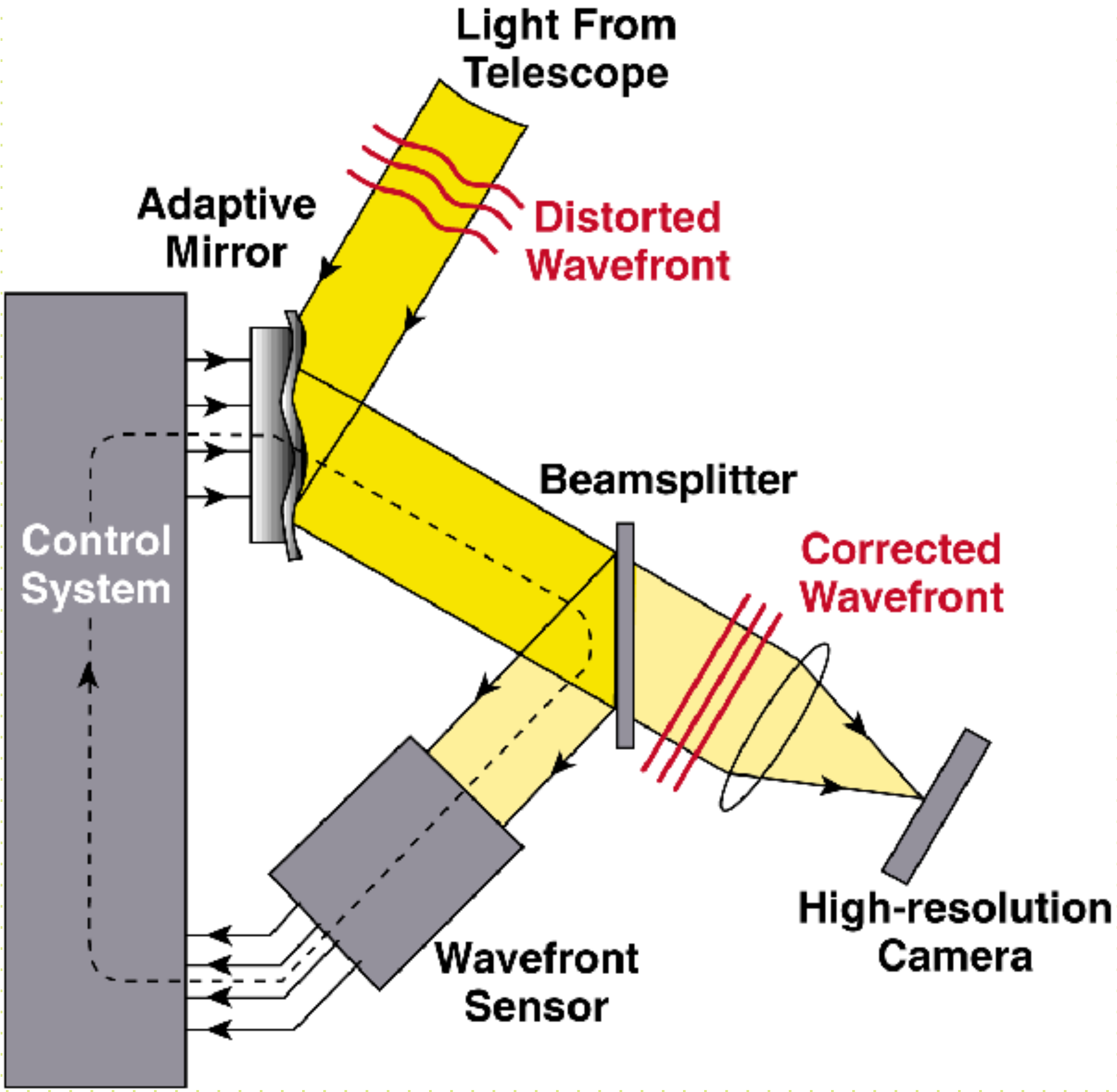


- Theoretical resolution is set by primary mirror diameter and diffraction properties of light
- For telescopes at the surface of the Earth, resolution is set by blurring of the atmosphere to ~1´´, equivalent to a 6-inch telescope



Adaptive Optics

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



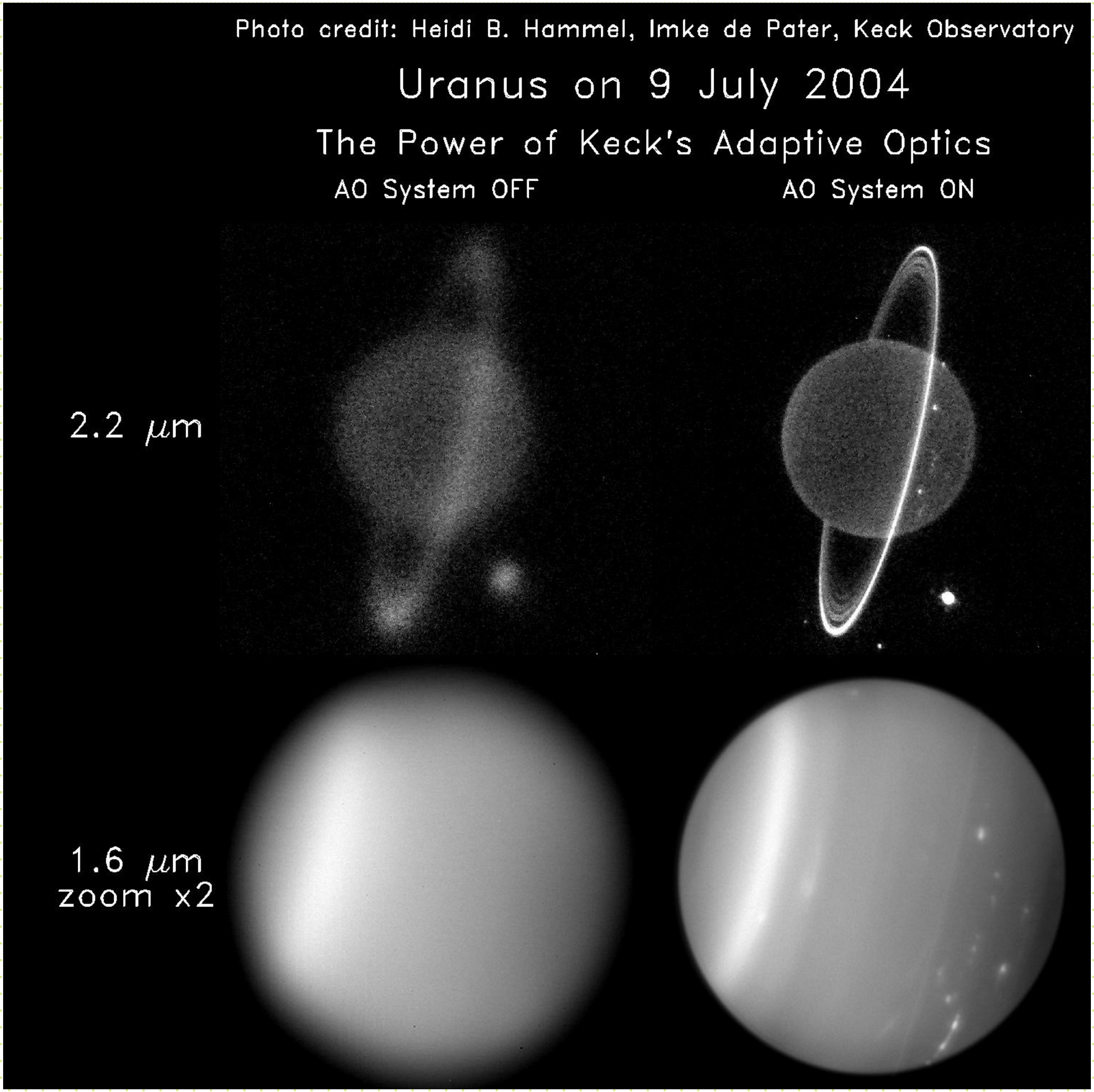
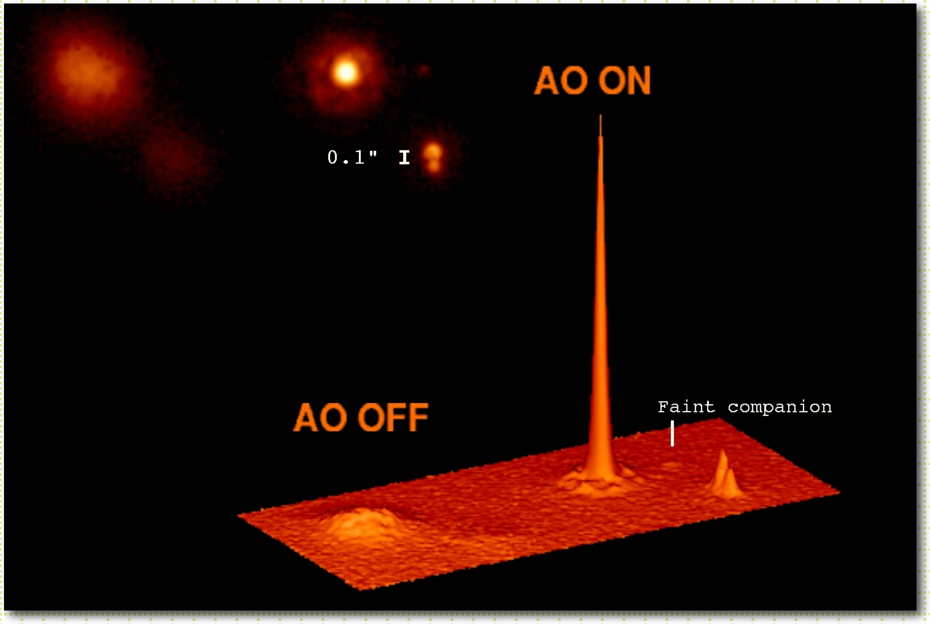


Photo credit: Heidi B. Hammel, Imke de Pater, Keck Observatory

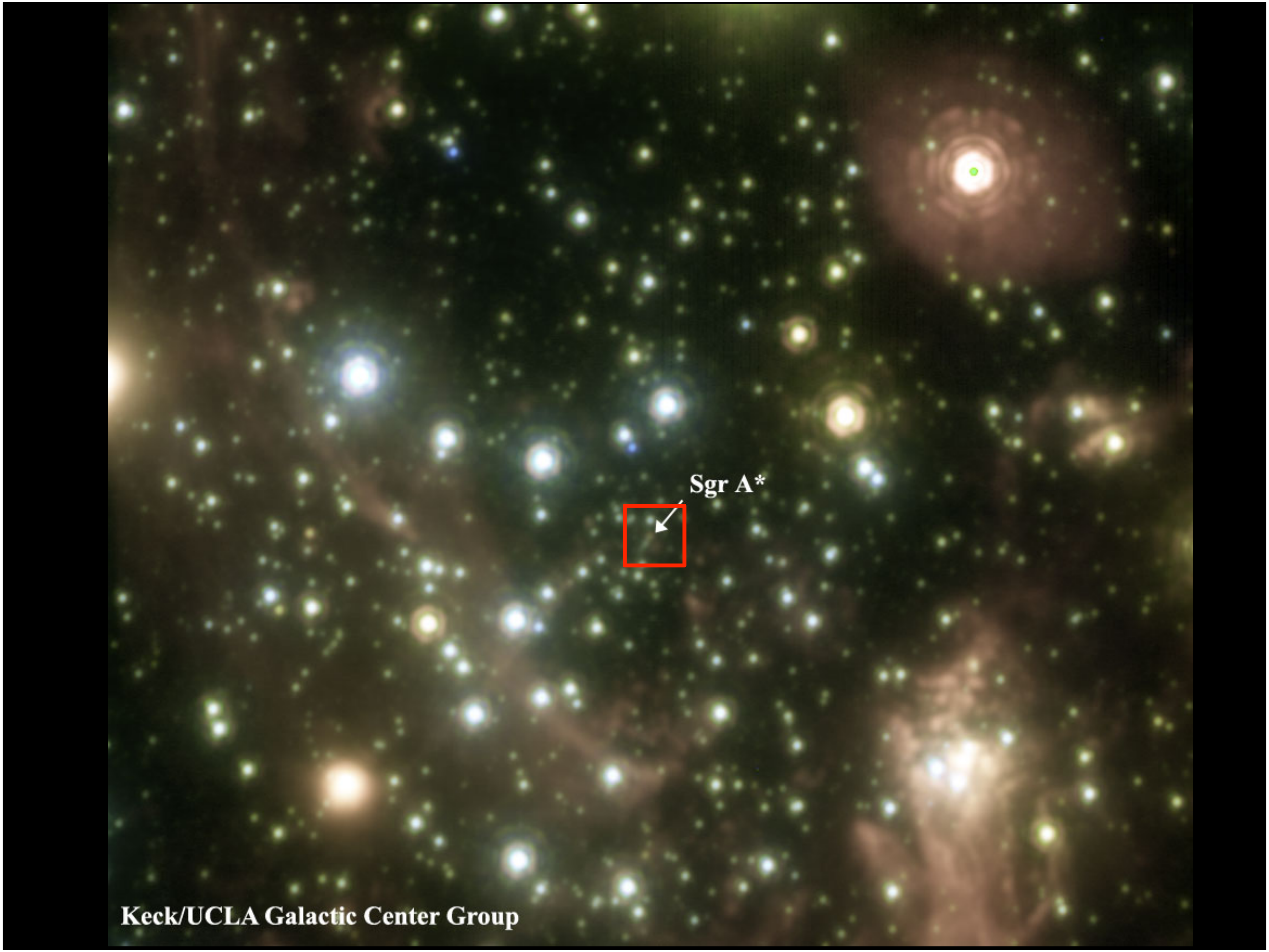
Uranus on 9 July 2004

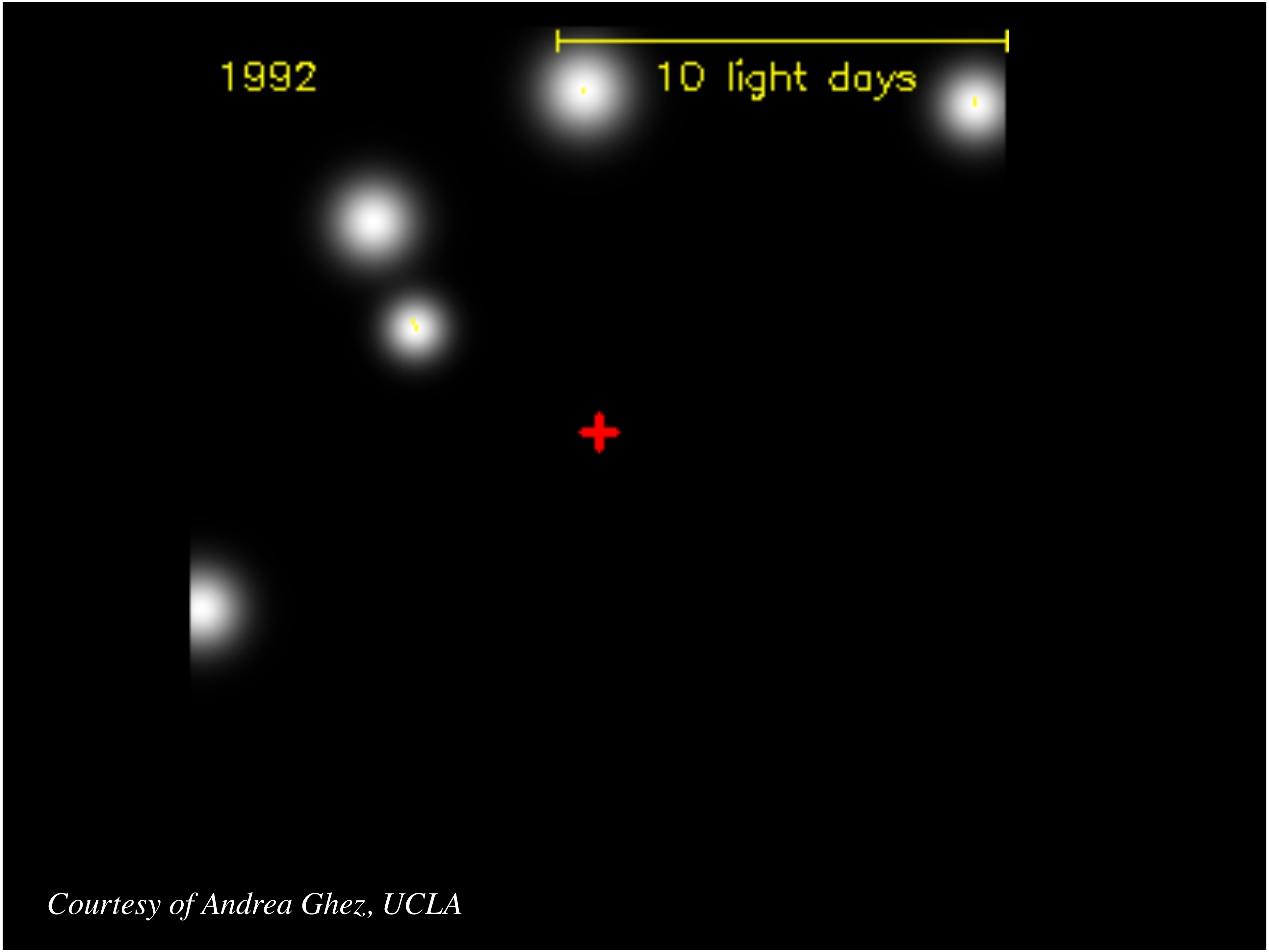
The Power of Keck's Adaptive Optics

AO works

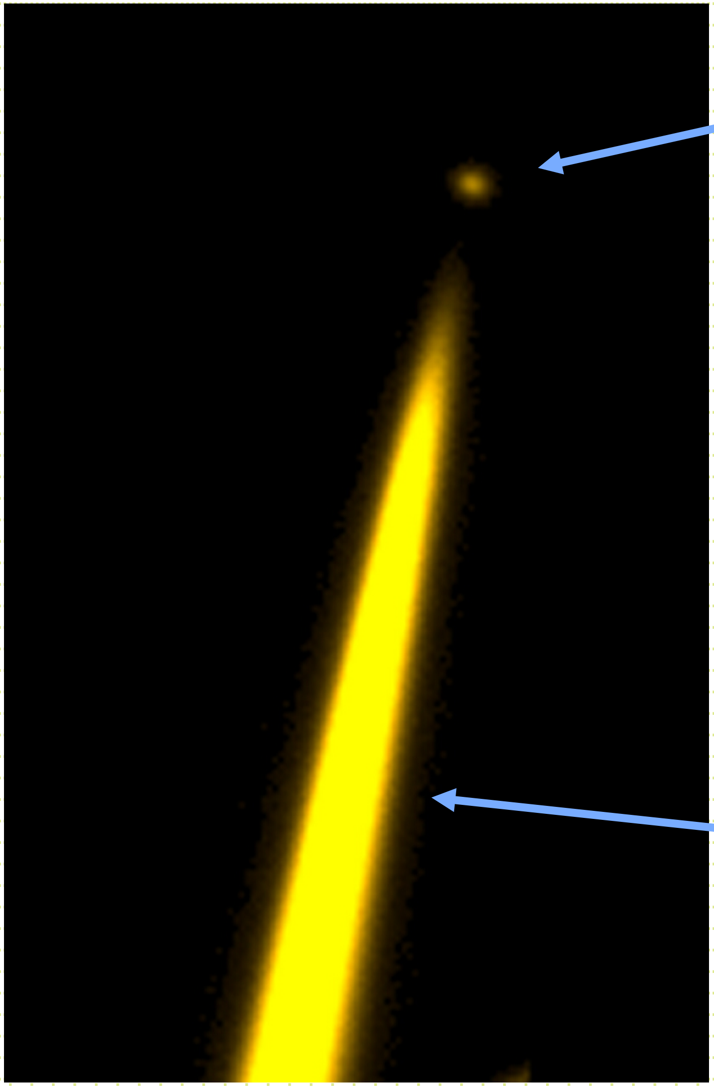


- Correction is easier and better for wavelengths > 1μ
- Need to correct at 50Hz or faster
- For 10m, diffraction limit is 0.02″ @ 1μ, for 30m it is 0.007″
- For many observations the sensitivity gain scales as D^4


Sgr A*
Keck/UCLA Galactic Center Group



Courtesy of Andrea Ghez, UCLA

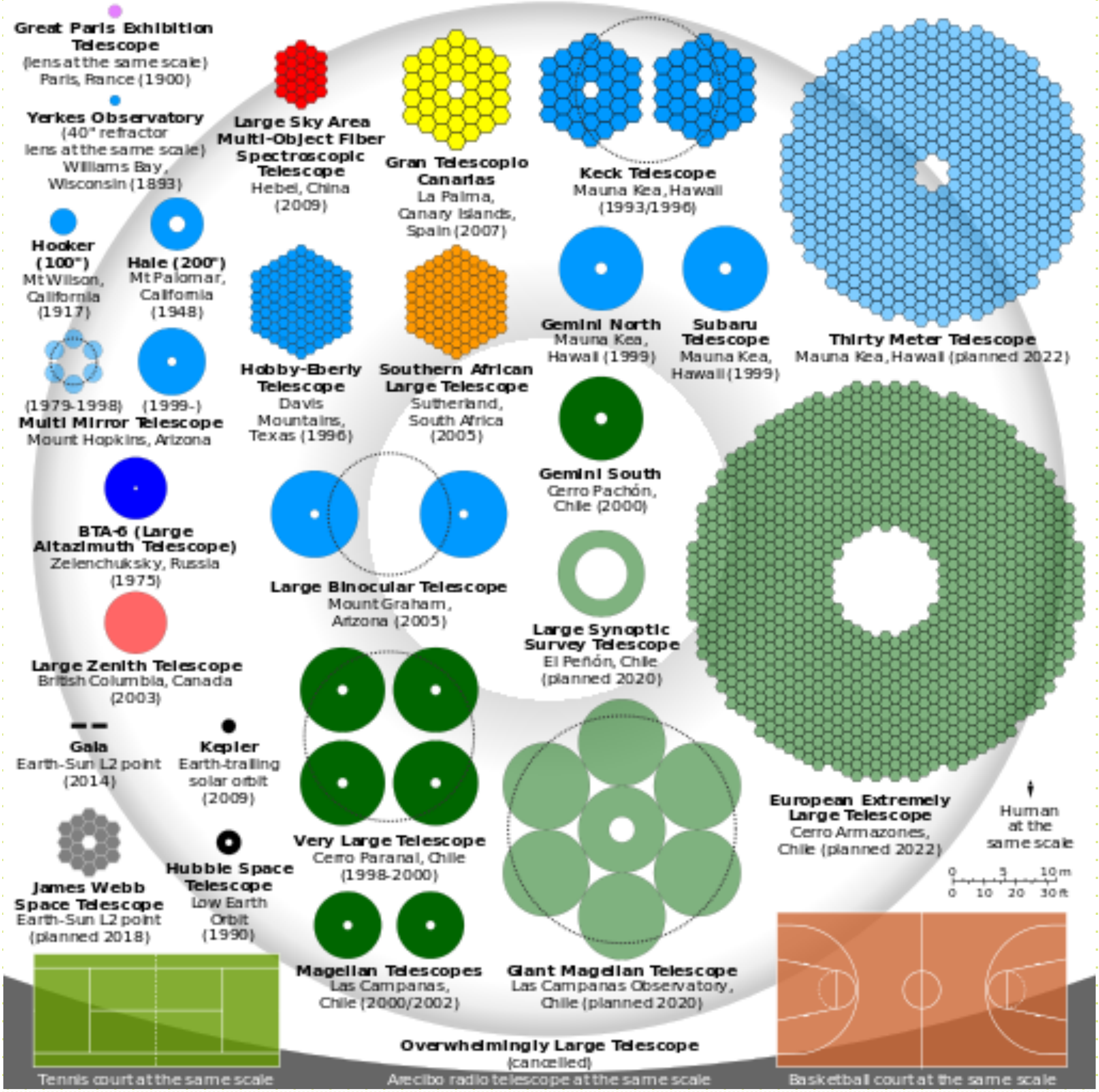


Guide star in sodium layer at ~ 90 km

Scattered light from low in atmosphere

The Adaptive Optics Era is here

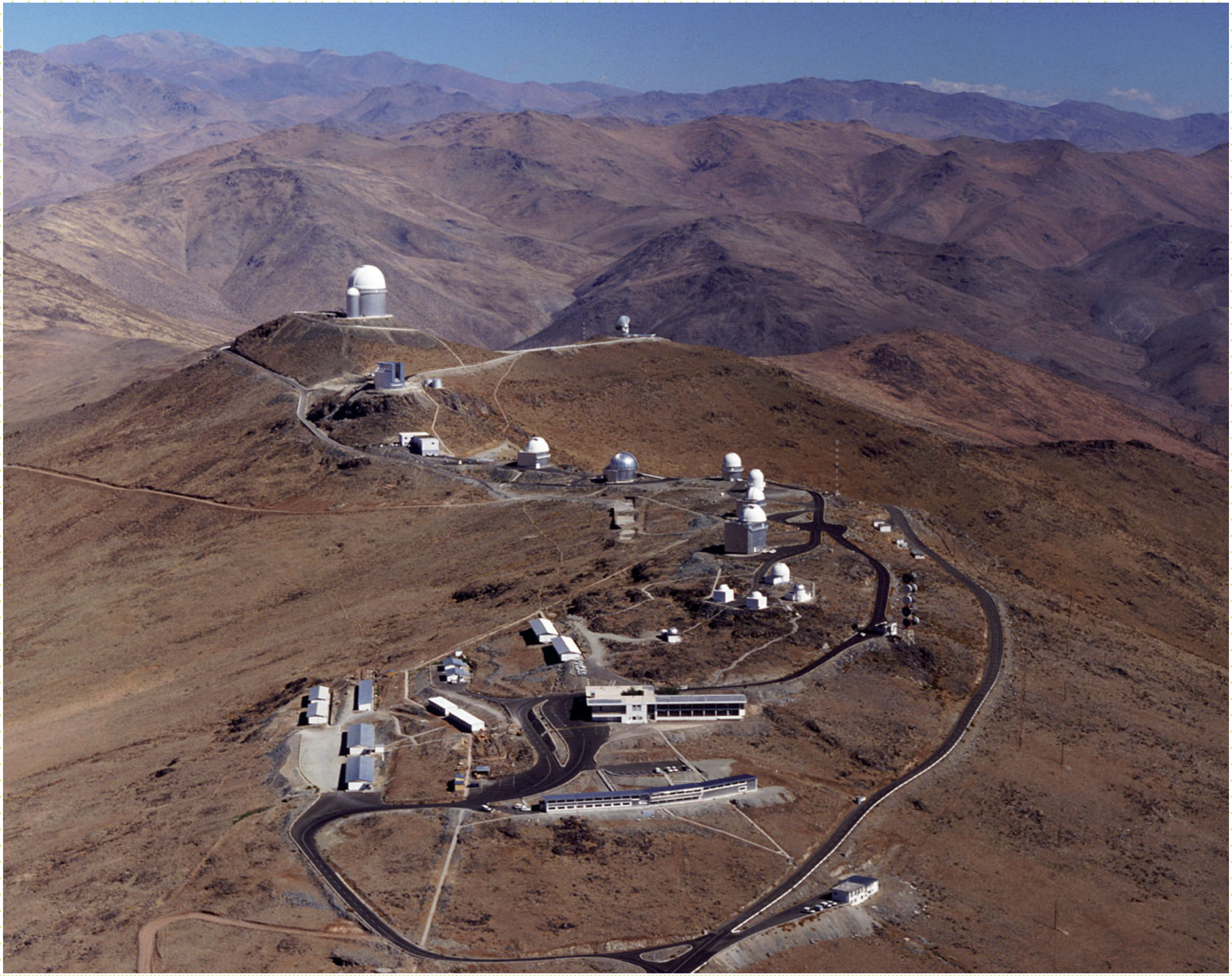
Keck 1 and 2, Subaru at Mauna Kea (photo credit: Dan Birchall)

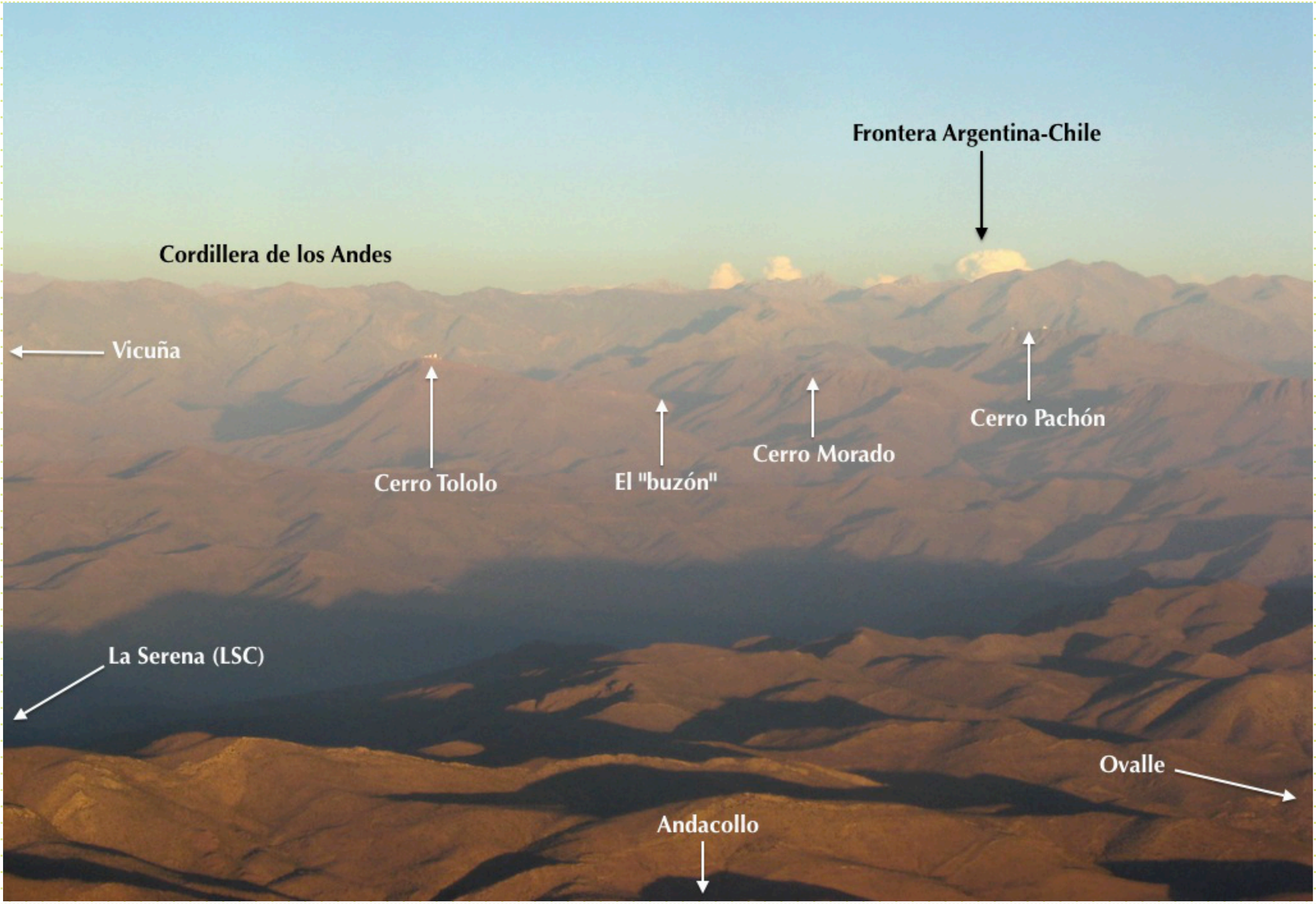

Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998) (1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
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)
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)
Gemini South
Cerro Pachón, Chile (2000)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

Telescopes

- Lots of ground-based telescopes around the world.
  - Some have open access, some are limited
  - Some have open access archives, some don’t
- Lots of options for use
  - Travel to telescope for “PI-based” nights
  - Remotely access in PI mode
  - Robotic or queue mode
  - Survey mode with access to data or data products


CSO
Subaru
Keck 10m
JCMT
UHH
UKIRT
UH 2.2m
IRTF
CFHT
Gemini N




Frontera Argentina-Chile
Cordillera de los Andes
Vicuña
Cerro Pachón
Cerro Morado
Cerro Tololo
El "buzón"
La Serena (LSC)
Ovalle
Andacollo

W.M. Keck Obs control room, Waimea, HI

What makes a good optical/IR site?

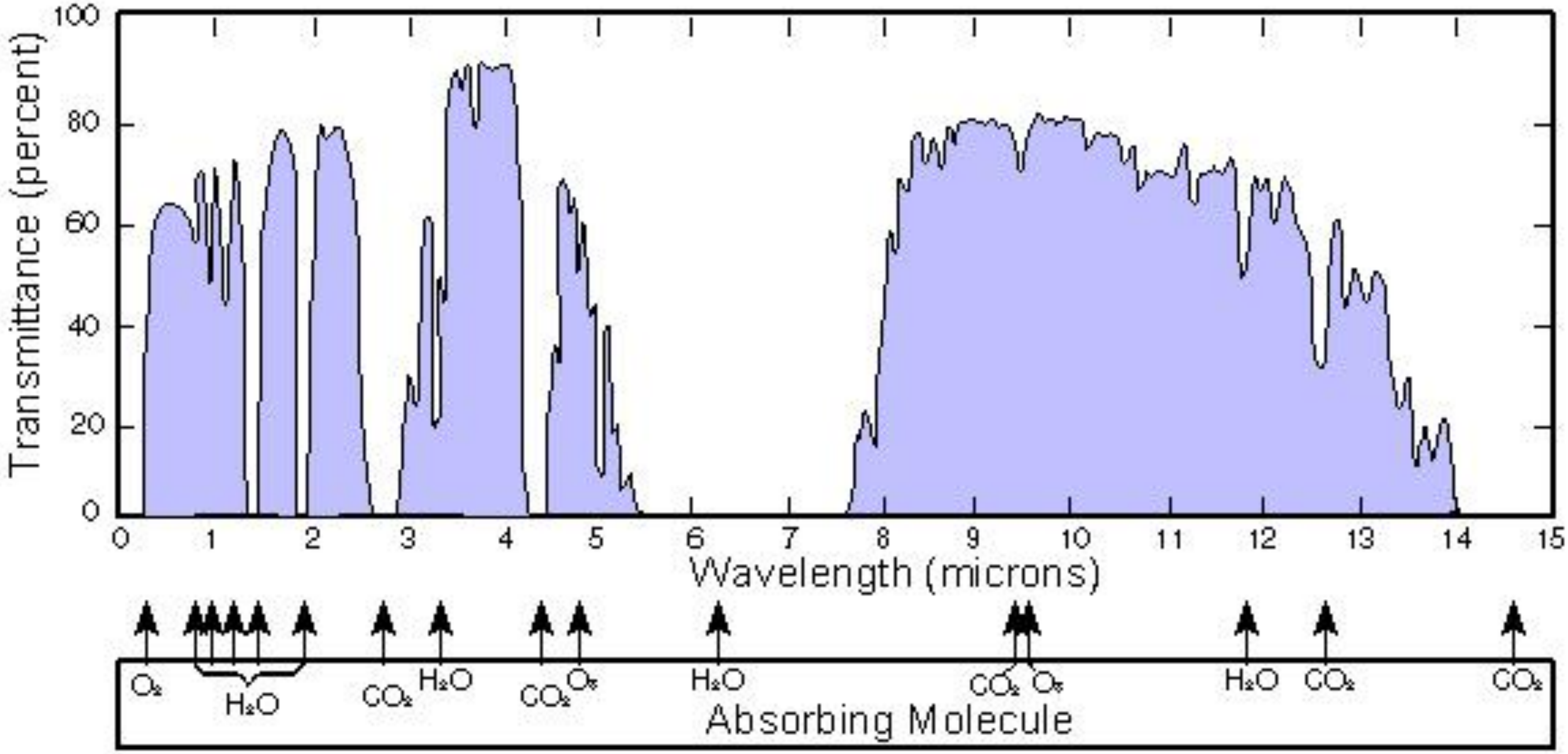
- Dark skies
  - Increasingly difficult!
- Clear (no clouds) weather
- High altitude
- Low precipitable water vapor
- Laminar wind flows
- Hawaii, northern Chile, islands off Europe

Radio Telescopes

- As we will talk about later, there are many different types of signals from the Universe.
- Radio telescopes are sensitive to long wavelength electro-magnetic radiation

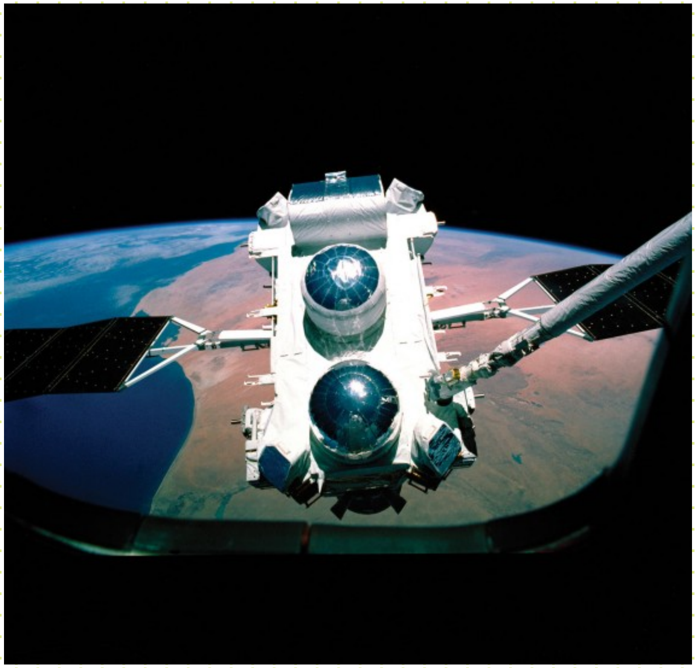
Space Telescopes

- No distortion from the atmosphere (can do wide-field high-quality imaging)
- No absorption or emission background from the atmosphere:
  - X-ray telescopes
  - far infrared telescopes
  - gamma-ray telescopes have to be in orbit
- A little pricey, can't always do upgrades


Transmittance (percent)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Wavelength (microns)
O_2
H_2O
CO_2
H_2O
CO_2
O_3
H_2O
CO_2
O_3
H_2O
CO_2
CO_2
Absorbing Molecule

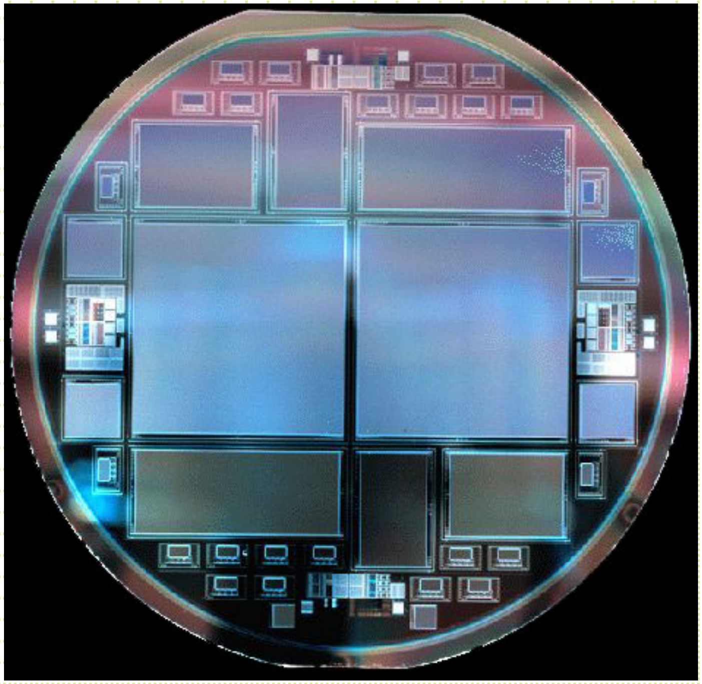

Optical "window"
Radio "window"

The Space Age



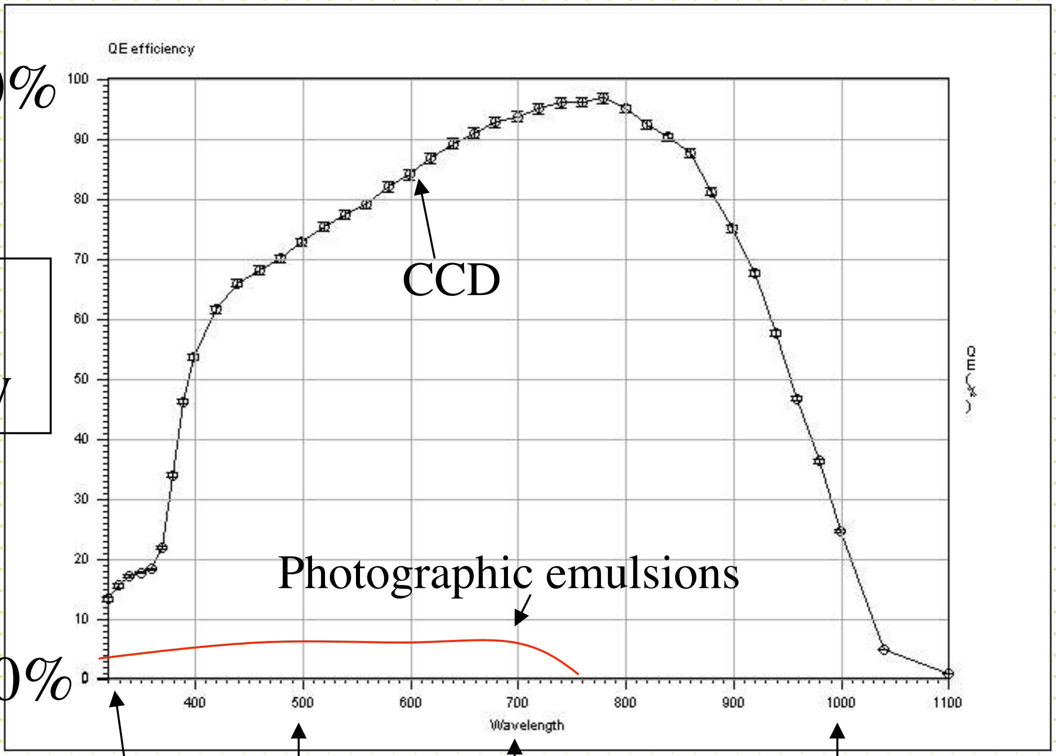
Digital Detectors

- By far the most common detector for wavelengths 300nm$<\lambda<$1000nm is the CCD.



CCDs

1. Quantum efficiency is more than an order of magnitude better than photographic plates.



100%

0%

Quantum Efficiency

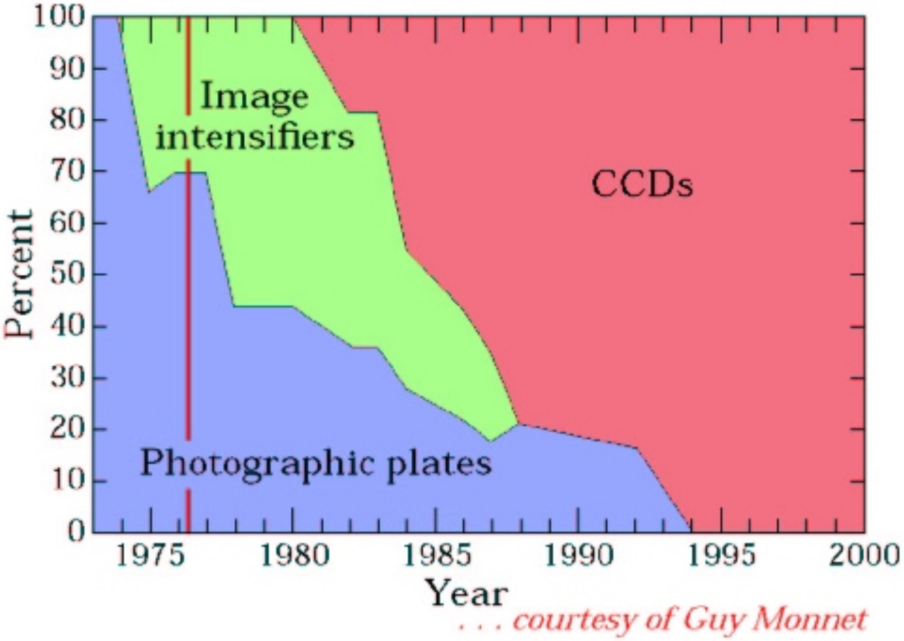
CCD

Photographic emulsions

300nm 500nm 700nm 1000nm

These are silicon fab-line devices and complicated to produce

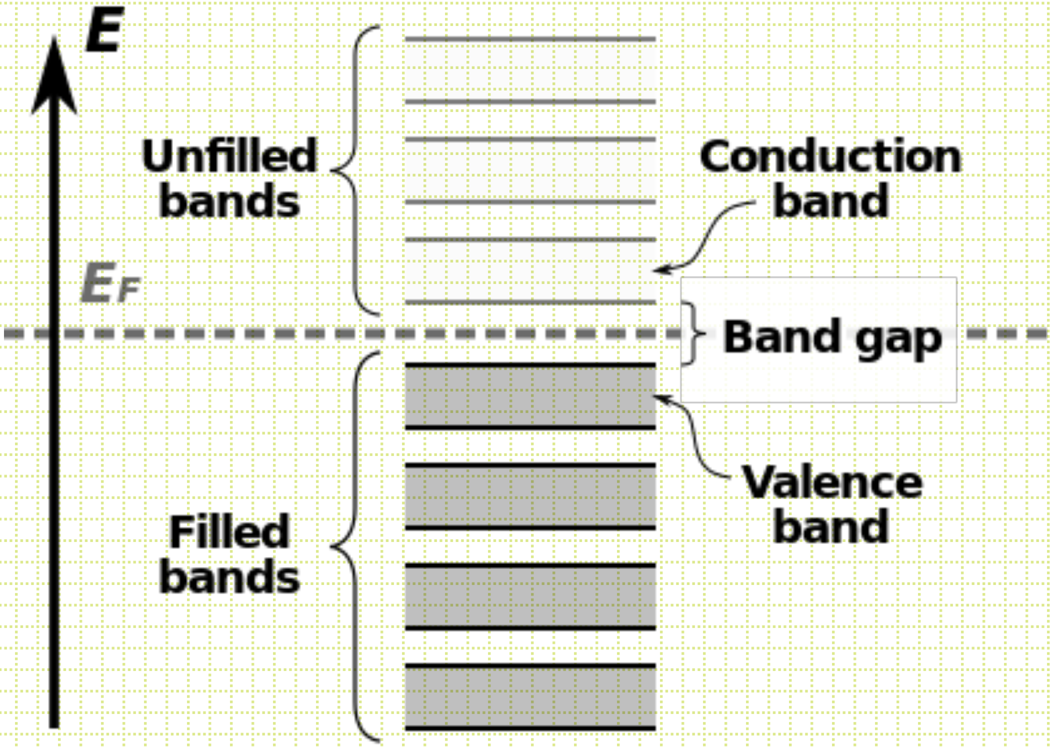
Invented 1969 Boyle and Smith at AT&T Bell Labs



. . . courtesy of Guy Monnet

CCDs remain physically small compared to photographic plates, but they took over rapidly anyway.

CCDs: How do they work?



Photon with energy greater than the band gap can be absorbed and bump an e- into the conduction band

λ_{max}= 1.24 μm/E_{gap}(eV)

For Si:
E_{gap}=1.11eV
λ_{max}=1.12μm

To catch Infrared photons, need a material with a smaller band gap

CCDs: How do they work?

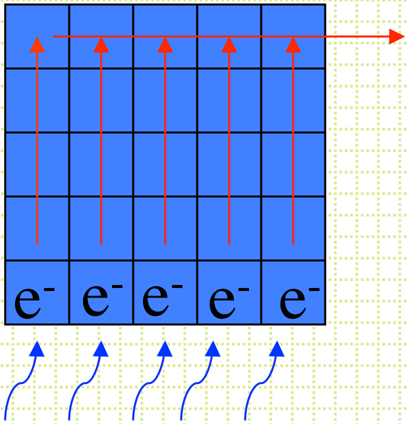
- Silicon semiconductors with ``gate’’ structure to produce little potential corrals.

Photons

Electrons bumped into conduction band

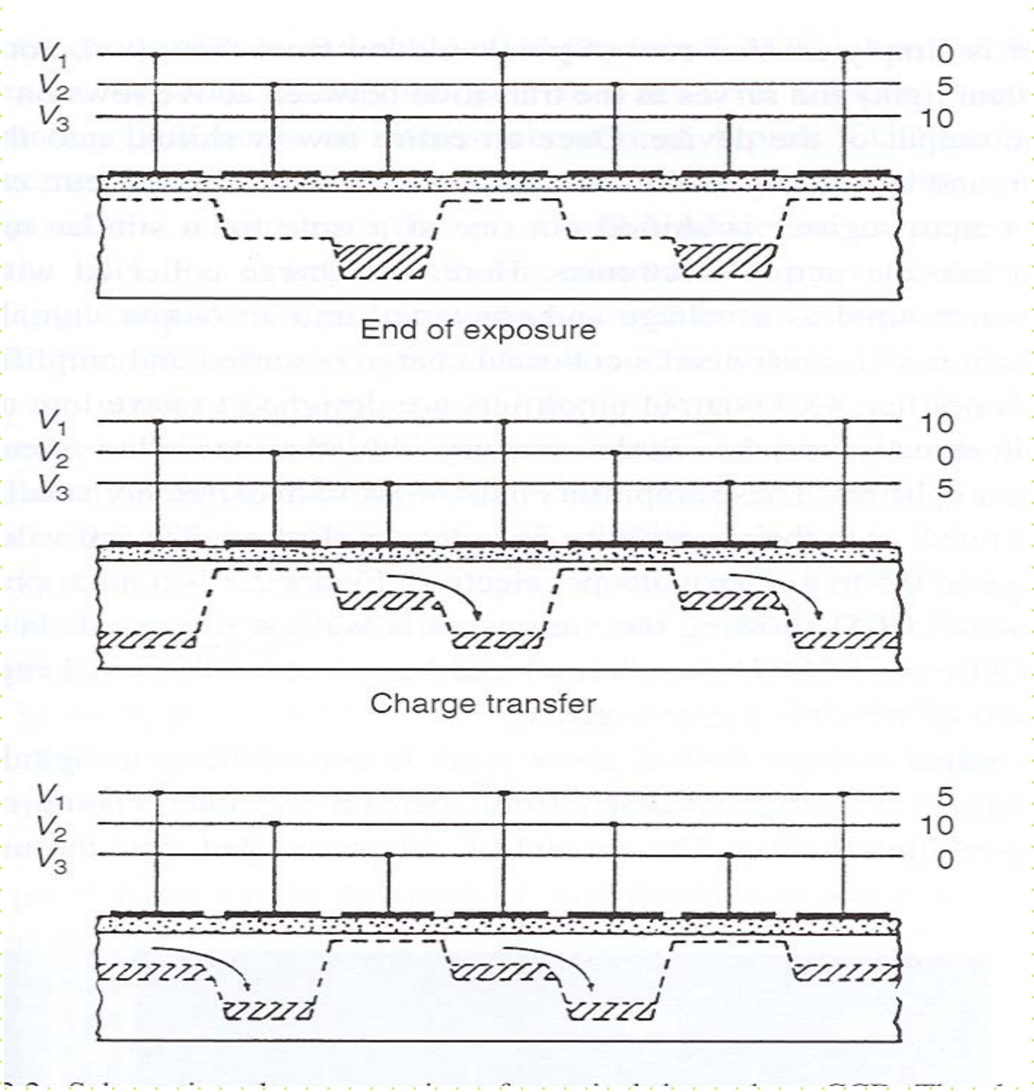
Read out and amplify current

A/D convert to DN



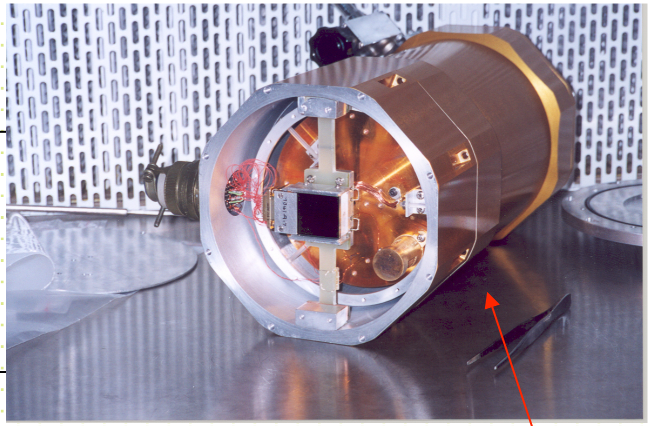
`clock’ parallel and serial registers

``CTE’’ > 0.99999



- Example three-phase readout to create bucket brigade and move accumulated charge into readout amplifier

CCD operation



- At room temperature, electrons in high-energy tail of the silicon spontaneously pop up into the conduction band: “dark current”. Cooling the detectors reduced the dark current although at about -120C the quantum efficiency starts to decrease.
- Therefore, CCDs usually are put into dewars with liquid nitrogen cold baths and heaters and the temperature is actively controlled to ~1C.
- Readout speed is typically adjustable--faster readout gives higher readout noise per pixel.

CCDs cont.

- The potential corrals that define the pixels of the CCD start to flatten as e^- collect. This leads first to saturation, then to e^- spilling out along columns.
- The "inverse gain" is the number of e^- per final "count" post the A/D converter.
- One *very* important possibility for CCDs is to tune the response to be linear.

- ``Counts’’ = ADU = DN

Analogue-to-digital unit

Digital Number

- DN is not the fundamental unit, the # of detected electrons is. The ``Gain’’ is set by the electronics.
- Most A/D converters use 16 bits.

DN from: $\boxed{0 \text{ to } (2^{16} - 1) = 65535}$

for unsigned, long integers

- Signed integers are dumb: -32735 to +32735

$+/-(2^{15} - 1)$

What gain do you want?

Example: LRIS-R had a SITe 24μ-pixel CCD with pixel ``wells'' that hold ~350,000 e-

- 16-bit unsigned integer A/D saturates at 65535DN
- Would efficiently maximize dynamic range by matching these saturation levels:

$$\boxed{\frac{350{,}000}{65{,}535} = 5.3\frac{e-}{DN}}$$

- Note, this undersamples the readout noise and leads to "digitization" noise.

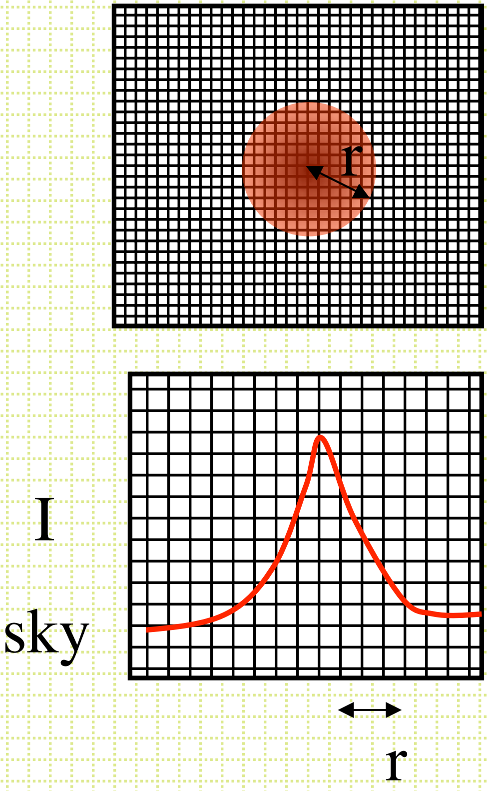
Signal-to-Noise (S/N)

- Signal=$R_{*} \bullet t$

time

detected e-/second

- Consider the case where we count all the detected e- in a circular aperture with radius r.



- Noise Sources:

$\sqrt{R_* \cdot t}$ ⇒ shot noise from source

$\sqrt{R_{sky} \cdot t \cdot \pi r^2}$ ⇒ shot noise from sky in aperture

$\sqrt{RN^2 \cdot \pi r^2}$ ⇒ readout noise in aperture

$\sqrt{\left[RN^2 + (0.5 \times \mathrm{gain})^2\right]} \cdot \sqrt{\pi r^2}$ ⇒ more general RN

$\sqrt{\mathrm{Dark} \cdot t \cdot \pi r^2}$ ⇒ shot noise in dark current in aperture

$R_* = \mathrm{e}^-/\mathrm{sec}$ from the source

$R_{sky} = \mathrm{e}^-/\mathrm{sec/pixel}$ from the sky

RN = read noise (as if RN^2 e^- had been detected)

Dark = e^- /second/pixel

- Note that each arriving photon is independent of previous or subsequent photons so the noise is “statistical” or “shot” or “Poisson”. For Poisson distribution the standard deviation is:

$$\boxed{\sigma=\sqrt{N}}$$

- Need to apply this to detected e–, not counts

S/N for object measured in aperture with radius r: n_{pix}=# of pixels in the aperture= πr^2

$$\begin{matrix}\text{Signal} \longleftrightarrow \\[2em] \text{Noise} \longleftrightarrow\end{matrix} \quad \frac{R_* t}{\left[\underbrace{R_* \cdot t}_{\sqrt{(R_* \cdot t)^2}} + \underbrace{R_{\text{sky}} \cdot t \cdot n_{\text{pix}}}_{\text{Noise from sky } e\text{- in aperture}} + \underbrace{\left(RN + \frac{\text{gain}}{2}\right)^2 \cdot n_{pix}}_{\text{Readnoise in aperture}} + \overbrace{\text{Dark} \cdot t \cdot n_{\text{pix}}}^{\text{Noise from the dark current in aperture}}\right]^{\frac{1}{2}}}$$

All the noise terms added in quadrature
Note: always calculate in *e*-

S/N Calculations

- So, what do you do with this?
  - Demonstrate feasibility
  - Justify observing time requests
  - Get your observations right

Side Issue: S/N ⇔ δmag

$$m \pm \delta(m) = c_o - 2.5\log(S \pm N)$$

$$= c_o - 2.5\log\left[S\left(1 \pm \tfrac{N}{S}\right)\right]$$

$$= \underbrace{c_o - 2.5\log(S)}_{\text{m}} - \underbrace{2.5\log(1 \pm \tfrac{N}{S})}_{\delta\text{m}}$$

$$\delta(m) \approx 2.5\log(1 + \tfrac{1}{S/N})$$

Note:in log +/- not symmetric

$$= \frac{2.5}{2.3}\left[\tfrac{N}{S} - \tfrac{1}{2}(\tfrac{N}{S})^2 + \tfrac{1}{3}(\tfrac{N}{S})^3 - \ldots\right]$$

$$\approx 1.087(\tfrac{N}{S})$$

Fractional error

This is the basis of people referring to +/- 0.02mag error as “2%”

S/N ⟺ δmag

S/N	δmag
2	0.44
10	0.10
100	0.01

How do you get values for some of these parameters?

- Dark Current: CCD@-120˚C < 2*e*-/pix/hour

  Insb: ~2*e*-/pix/sec
- RN: CCD: 2 - 6 *e*-/pix

  Insb: 10 - 25 *e*-/pix
- R_*: for a given source brightness, this can be calculated for any telescope and total system efficiency.
- In practice: *Go to the facility WWW site for everything!*

Source Count Rates

Example: LRIS on Keck 1

for a B=V=R=I=20mag object @ airmass=1

B	1470 e-/sec
V	1521 e-/sec
R	1890 e-/sec
I	1367 e-/sec

To calculate R_* for a source of arbitrary brightness only requires this table and a bit of magnitude math.

Source Count Rates

$$\mathrm{m}_1 = c_o - 2.5\log(\mathrm{I}_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\mathrm{m}_2 = c_o - 2.5\log(\mathrm{I}_2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\mathrm{m}_1 - \mathrm{m}_2 = -2.5\left[\log(\mathrm{I}_1) - \log(\mathrm{I}_2)\right] \ldots\ldots\ldots (1) - (2)$$

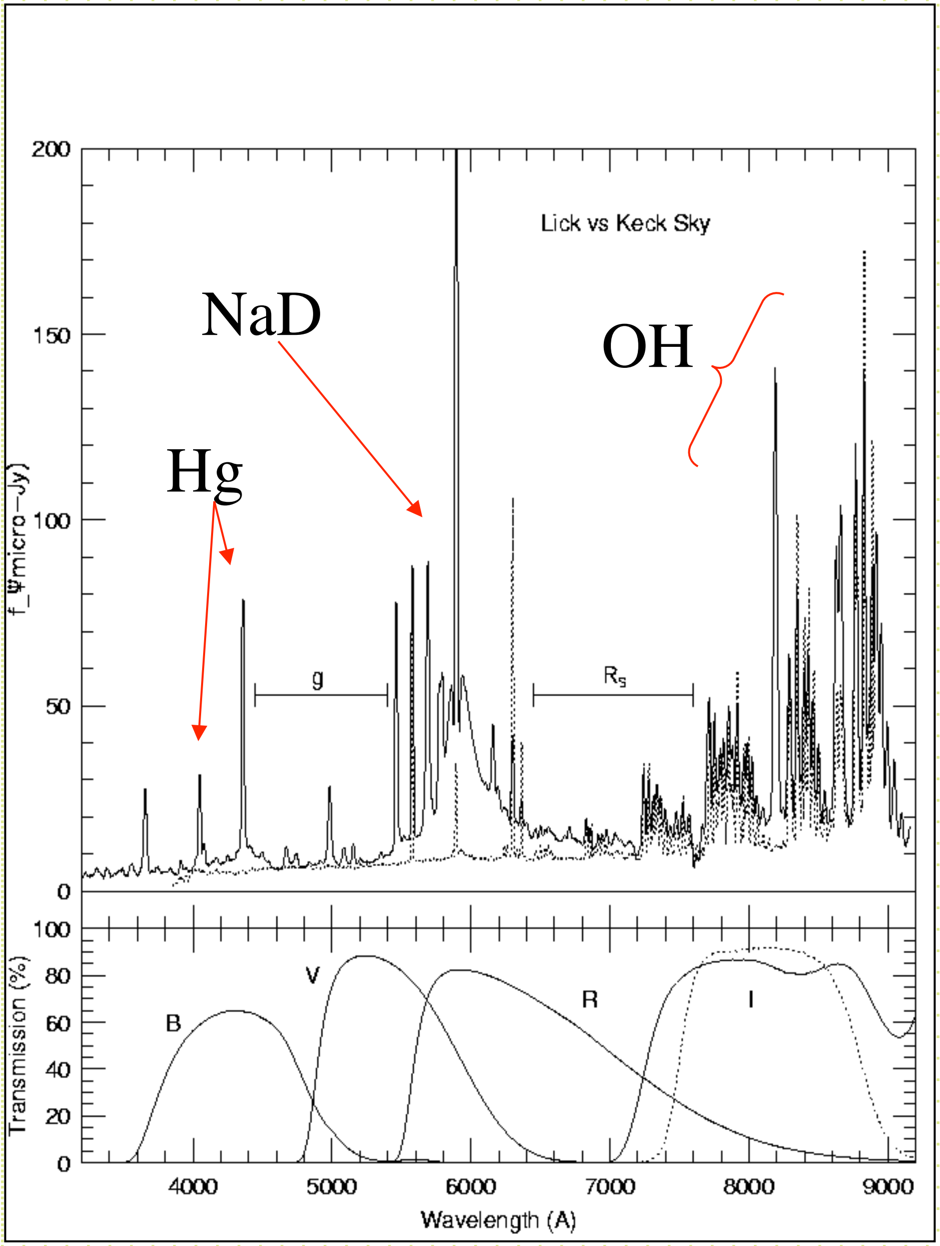
$$\mathrm{m}_1 - \mathrm{m}_2 = -2.5\log\left(\frac{\mathrm{I}_1}{\mathrm{I}_2}\right)$$

$$\frac{\mathrm{I}_1}{\mathrm{I}_2} = 10^{-\left(\frac{\mathrm{m}_1 - \mathrm{m}_2}{2.5}\right)}$$

Let I_2 be the intensity for the fiducial m=20 object

$$\mathrm{I}_1 = R_*(\mathrm{m}_1) = \mathrm{I}_{20} \cdot 10^{-\left(\frac{\mathrm{m}_1 - 20}{2.5}\right)}$$

R_{sky}



Signal from the sky background is present in every pixel of the aperture. Because each instrument generally has a different pixel scale, the sky brightness is usually tabulated for a site in units of mag/ arcsecond^2.

(mag/□″)

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

Scale ⇒"/pix (LRIS - R : 0.218"/pix)

Area of 1 pixel = (Scale)^2 (LRIS – R : 0.0475"^{2}

this is the ratio of flux/pix to flux/"

In magnitudes:

$$I_{pix} = I_{''}\text{Scale}^2 \qquad I \Rightarrow \text{Intensity } (e^-/\text{sec})$$

$$-2.5\log(I_{pix}) = -2.5[\log(I_{''}) + \log(\text{Scale}^2)]$$

$$m_{pix} = m_{''} - 2.5\log(\text{Scale}^2) \qquad \text{(for LRIS - R: add 3.303mag)}$$

and

$$R_{sky}(m_{pix}) = R(m = 20) \times 10^{(0.4 - m_{pix})}$$

Example, LRIS in the R - band:

$$R_{sky} = 1890 \times 10^{0.4(20-24.21)} = 39.1 \ e^- /\text{pix}/\text{sec}$$

$$\sqrt{R}_{sky} = 6.35e^- /\text{pix}/\text{sec} \approx \text{RN in just 1 second}$$

S/N - some limiting cases. Let's assume CCD with Dark=0, well sampled read noise.

$$\frac{R_* t}{\left[R_* \cdot t + R_{\text{sky}} \cdot t \cdot n_{\text{pix}} + (RN)^2 \cdot n_{pix}\right]^{\frac{1}{2}}}$$

Bright Sources: $(R_* t)^{1/2}$ dominates noise term

$$\text{S/N} \approx \frac{R_* t}{\sqrt{R_* t}} = \sqrt{R_* t} \propto t^{\frac{1}{2}}$$

Sky Limited $(\sqrt{R_{\text{sky}} t} > 3 \times \text{RN})$: $\text{S/N} \propto \dfrac{R_* t}{\sqrt{n_{\text{pix}} R_{\text{sky}} t}} \propto \sqrt{t}$

Note: seeing comes in with n_{pix} term

What is ignored in this S/N eqn?

- Bias level/structure correction
- Flat-fielding errors
- Charge Transfer Efficiency (CTE) 0.99999/ pixel transfer
- Non-linearity when approaching full well
- Scale changes in focal plane
- A zillion other potential problems