Today's Topics

Monday, February 23, 2026 (Week 5, lecture 13) – Chapter 6.

A. Reflecting Telescope
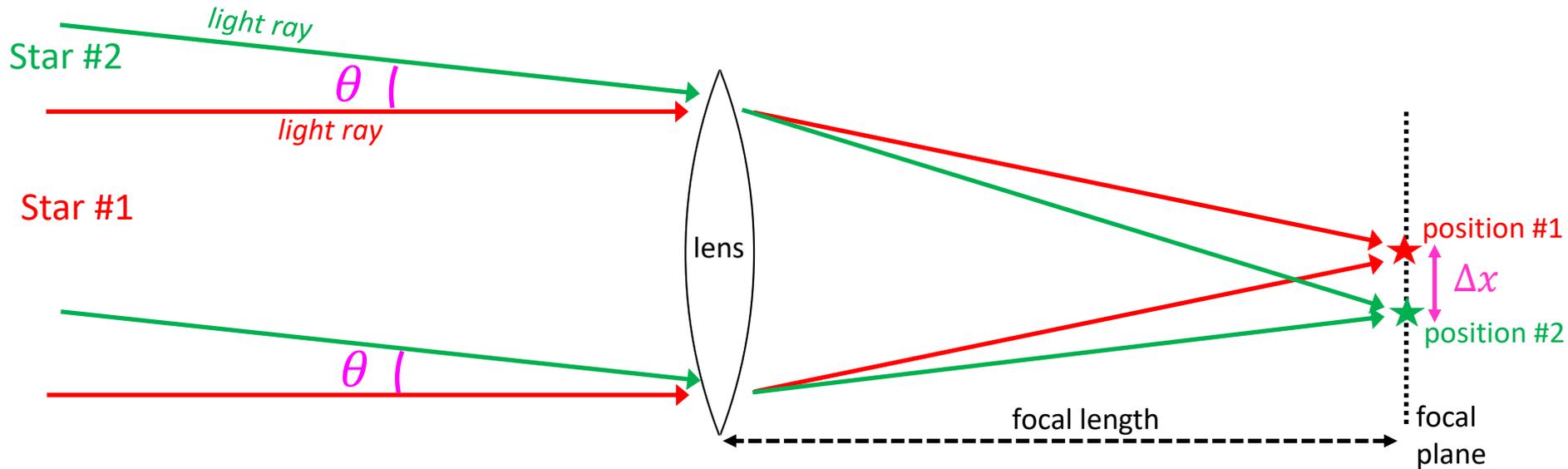
B. Resolving power

C. Adaptive Optics

Problem Set #5 is due on ExpertTA on Friday, March 6, 9:00 AM
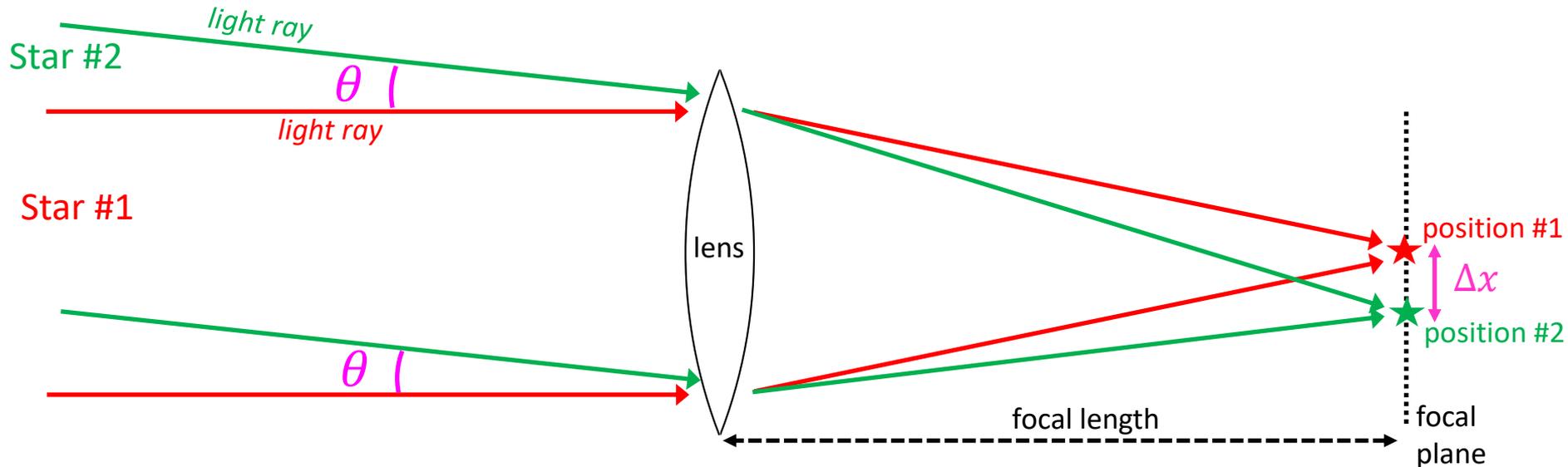
Basic idea: You want to convert a light ray **angle** from a star into a **position**.

Stellar Imaging Basics: Lens

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➢ Bigger lens collects more light.
→ You can see dimmer stars and further away stars.

➢ Magnification = Δx gets bigger (for a given θ).
→ You can distinguish between two very close feature.

➢ Lens subtly distort the image.
→ chromatic aberrations, glass defects, large lens sag.
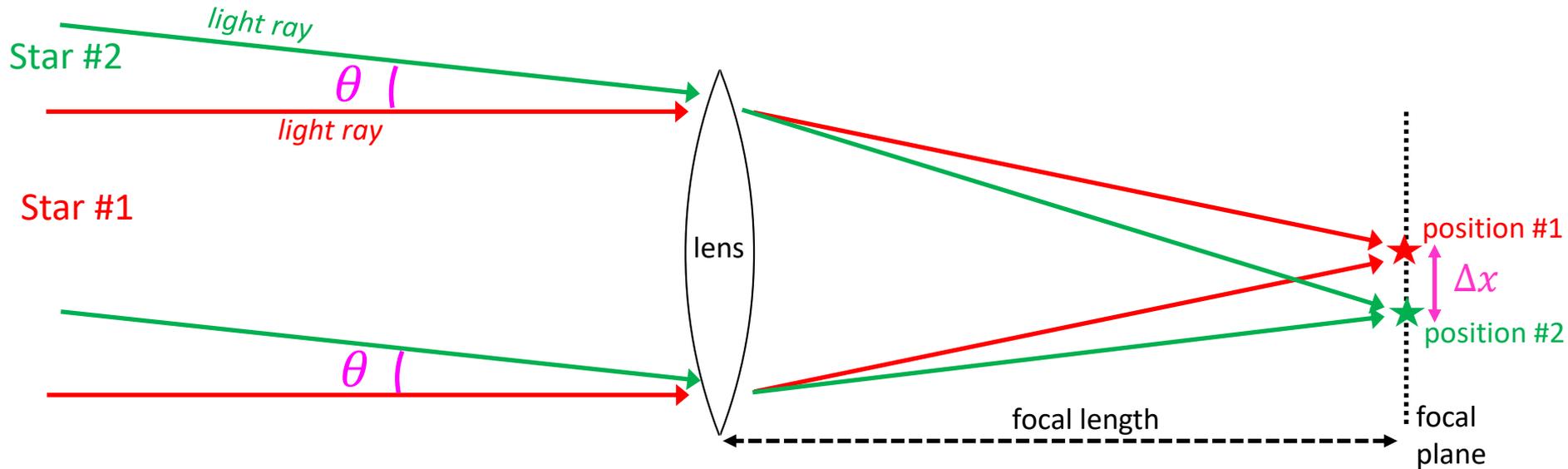
Stellar Imaging Basics: Lens

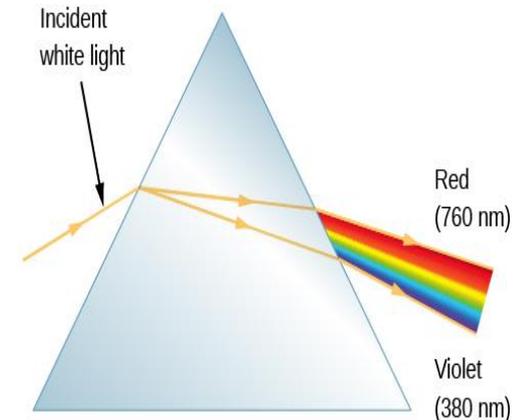**Basic idea:** You want to convert a light ray **angle** from a star into a **position**.

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Stellar Imaging Basics: Mirrors

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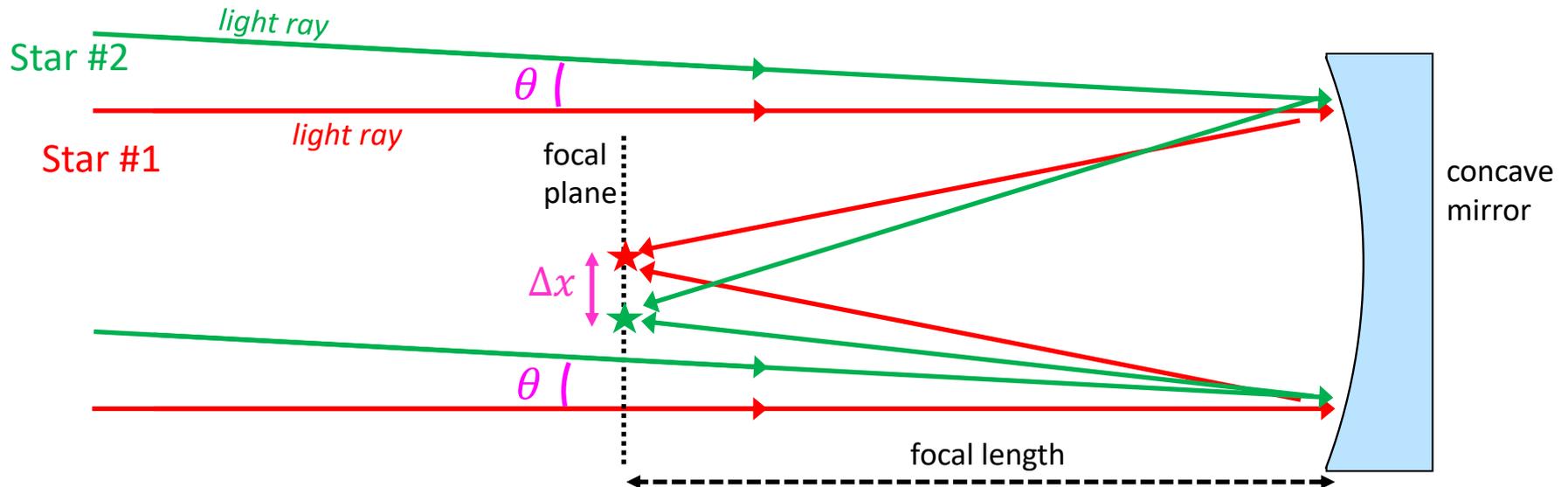

➢ Bigger mirror collects more light.
   → You can see dimmer stars and further away stars.

➢ Magnification = Δx gets bigger (for a given θ).
   → You can distinguish between two very close feature.

➢ Mirrors can provide near zero distortion.
   → no chromatic aberrations, no glass defects, much less large mirror sag.

Reflecting Telescope

A **large curved mirror** collects the light and then focuses it onto a secondary smaller mirror.

→ invented by Isaac Newton.
→ Parabolic curved mirror is ideal.

Newtonian Reflector

Cassegrain Reflector

[OpenStax: Astronomy]

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Benefits

➢ No chromatic aberrations.

➢ Glass defects do not matter.

➢ Large mirror can be supported across its entirety.

→ Sag is less of problem.

Drawbacks

▪ Open to air: more cleaning.

▪ Secondary mirror and support structure introduce diffraction effects from their shadows.

[OpenStax: Astronomy]
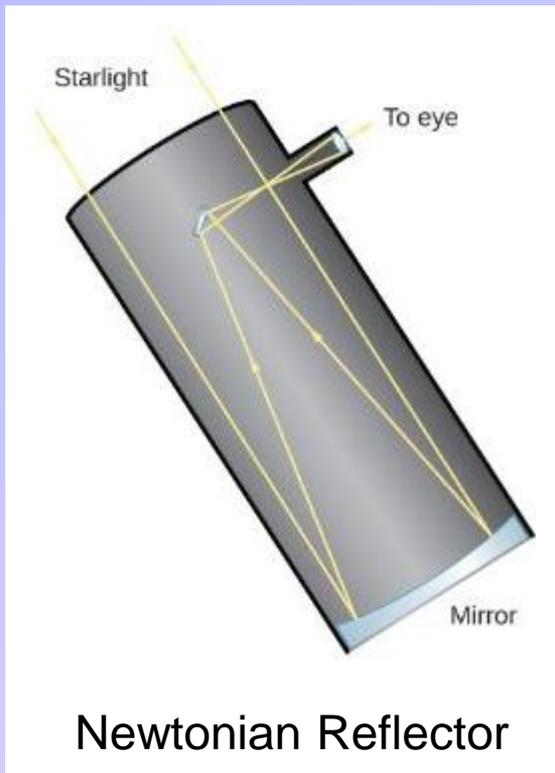
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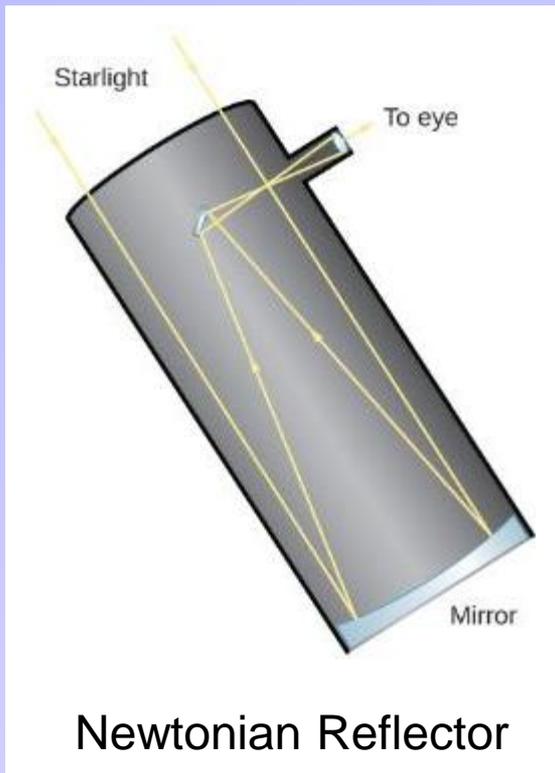→ Parabolic curved mirror is ideal.

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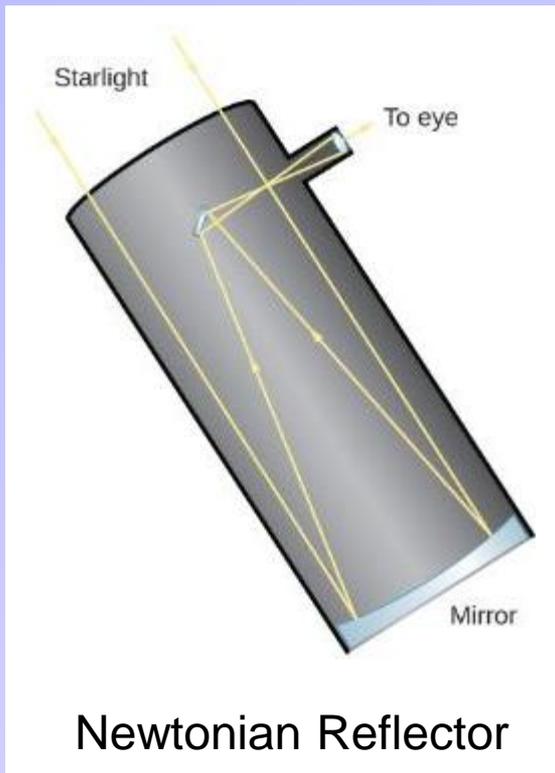**Drawbacks**

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Newtonian Reflector

Cassegrain Reflector

Almost all scientific telescopes are reflectors.

[OpenStax: Astronomy]

Star Spikes

Shadow from support structure for secondary mirror generates "star spikes".

[Cmglee - Own work, CC BY-SA 3.0, Wikipedia]

[ESA/Webb, NASA & CSA, M.Zamani, M. G. Guarcello, and the EWOCS team]
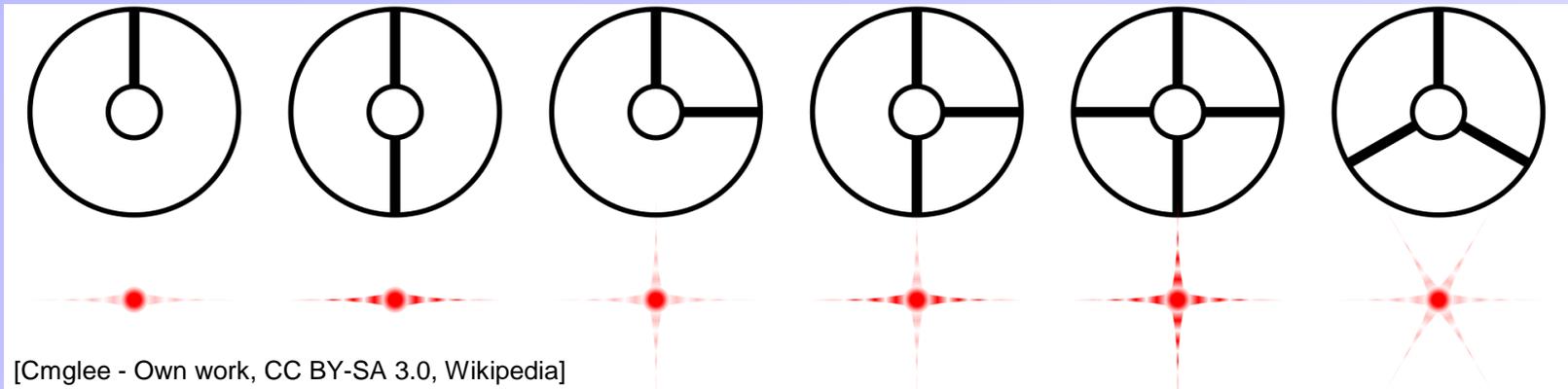
Star Spikes from James Webb Space Telescope image (Westerlund 1 super star cluster).

[NASA, ESA, and H. Richer (University of British Columbia), Wikipedia]

Star Spikes from a Hubble Space Telescope image (NGC 6397).

Single Mirror Telescopes

secondary mirror

primary mirror

camera (inside)

[Gemini North: OpenStax]
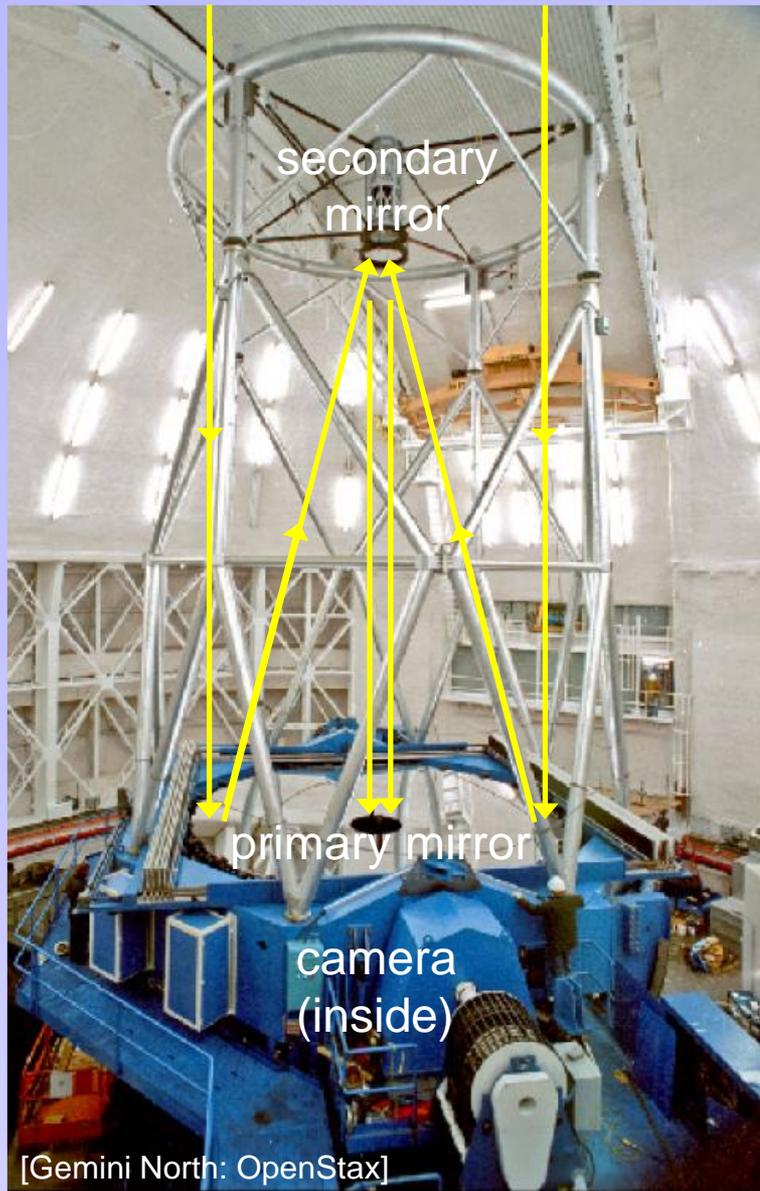
The Gemini telescopes are some of the largest single mirror telescopes.

→ 8.1 m (26 ft) primary mirror.

→ 1 m secondary mirror.

→ Locations: Hawaii & Chile

[Gemini North Primary Mirror: Gemini.edu]
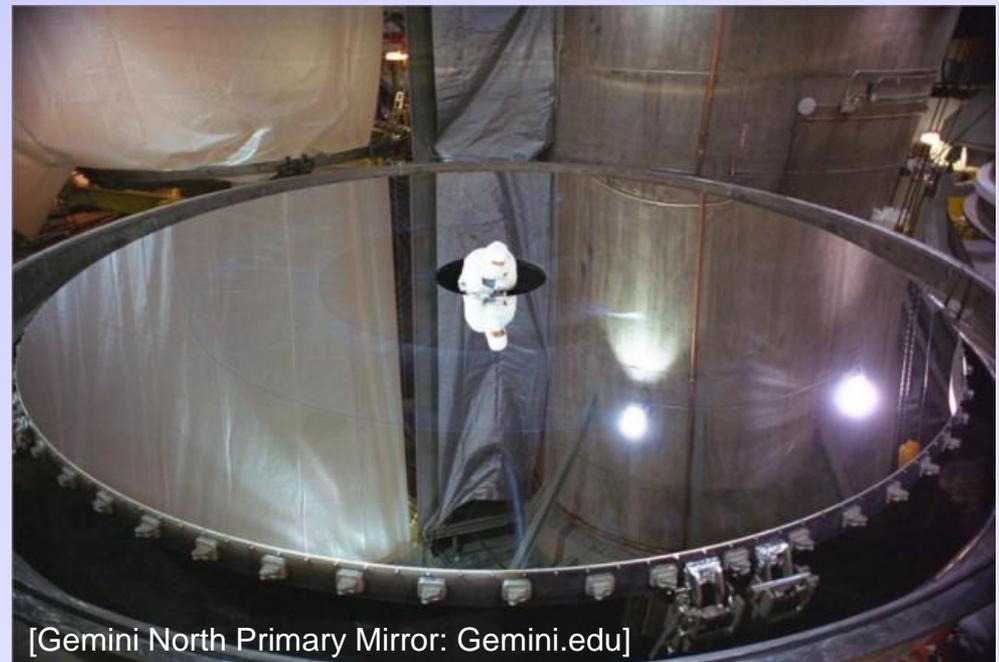
Liquid Mirrors

Fact: A rotating liquid has a parabolic surface (under gravity).

→ exactly the surface needed for a telescope.

→ Rotating liquid mercury makes an excellent mirror.

[Paul Hickson, University of British Columbia]

Large Zenith Telescope: 6 m diameter.

Benefits:

- About 1/10th the cost of a solid mirror.
- Much lighter than a solid mirror.
- Good for star surveys.

Downsides

➢ Telescope must be pointed vertically upwards.

➢ Limited star tracking.

➢ Mercury is toxic.

Segmented Telescopes

Problem: A single mirror larger than 8 m will experience significant sag issues.

Solution: Segment the mirror into smaller sections for easier support.

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36-segment mirror of the Keck telescope (Hawaii)
[by SiOwl - Own work, CC BY 3.0, Wikipedia]

[NASA, Wikipedia]

*18-segment mirror of the future
James Webb Space Telescope.*

Comparison of Big Telescopes
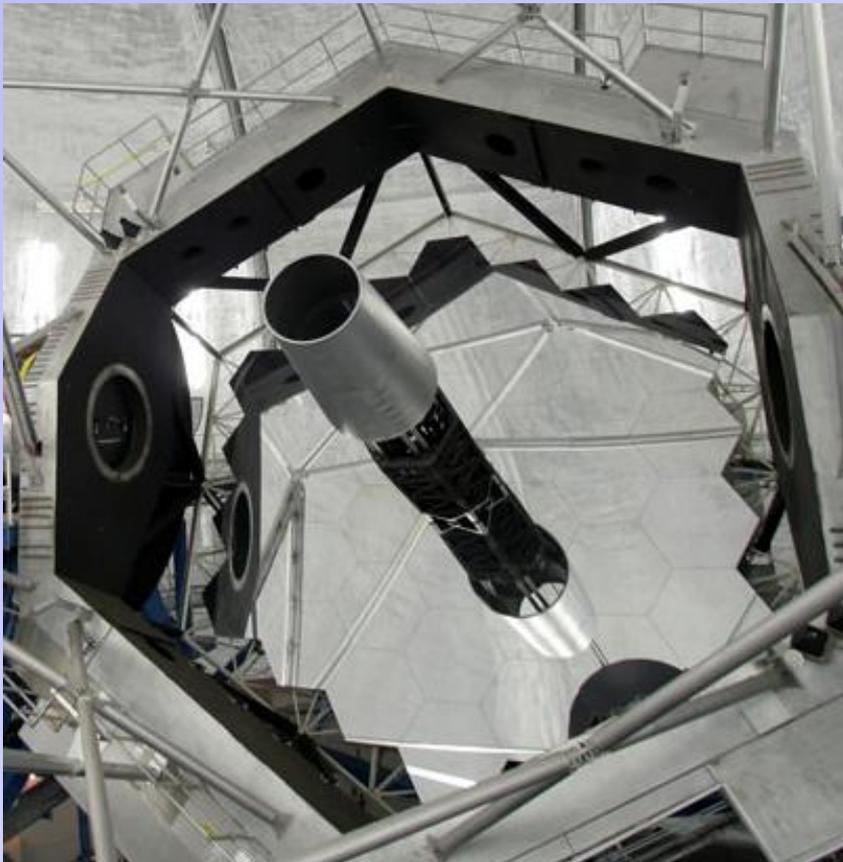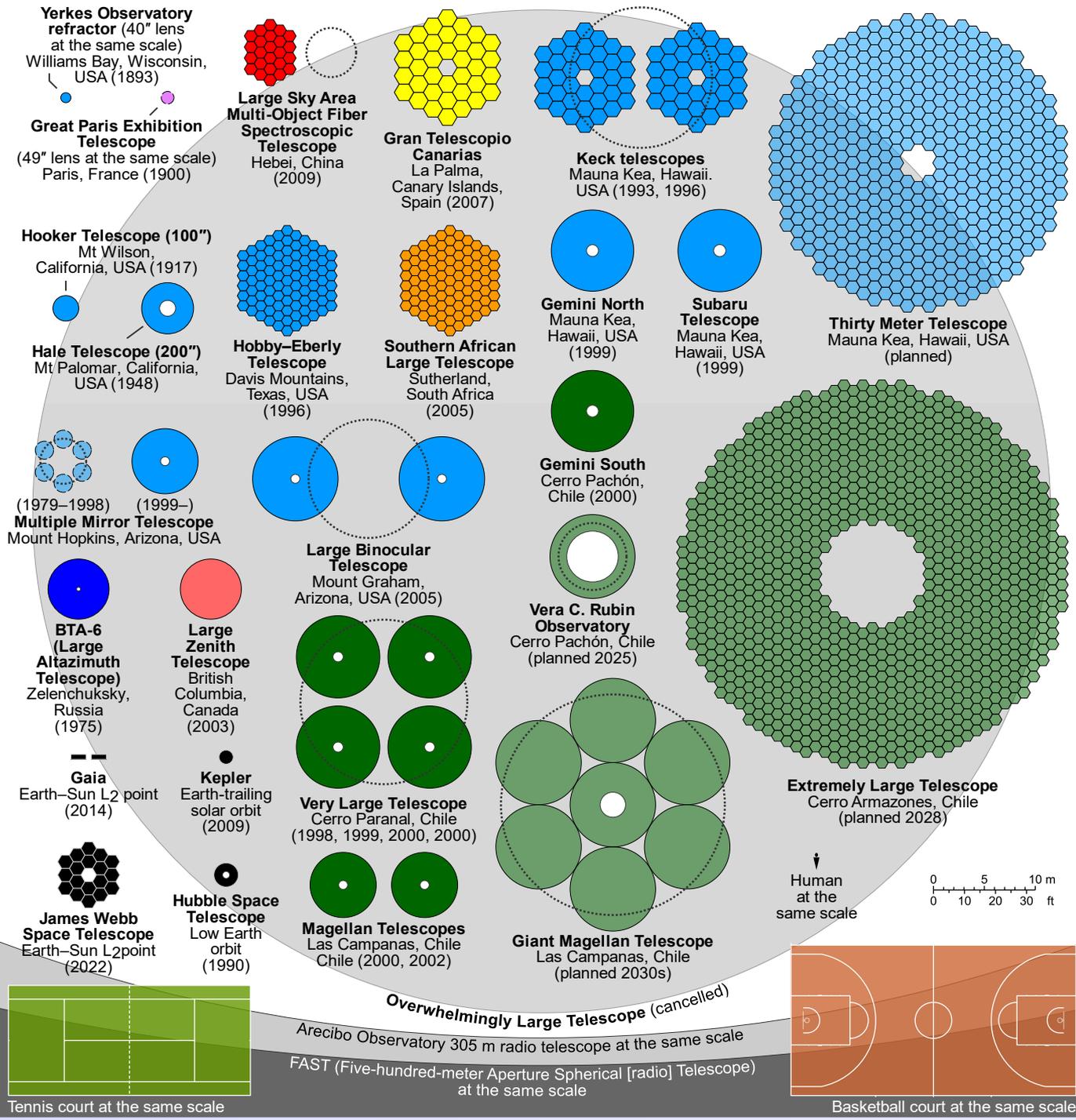
Yerkes Observatory refractor (40″ lens at the same scale) Williams Bay, Wisconsin, USA (1893)

Great Paris Exhibition Telescope (49″ lens at the same scale) Paris, France (1900)

Large Sky Area Multi-Object Fiber Spectroscopic Telescope Hebei, China (2009)

Gran Telescopio Canarias La Palma, Canary Islands, Spain (2007)

Keck telescopes Mauna Kea, Hawaii. USA (1993, 1996)

Hooker Telescope (100″) Mt Wilson, California, USA (1917)

Hale Telescope (200″) Mt Palomar, California, USA (1948)

Hobby–Eberly Telescope Davis Mountains, Texas, USA (1996)

Southern African Large Telescope Sutherland, South Africa (2005)

Gemini North Mauna Kea, Hawaii, USA (1999)

Subaru Telescope Mauna Kea, Hawaii, USA (1999)

Thirty Meter Telescope Mauna Kea, Hawaii, USA (planned)

Gemini South Cerro Pachón, Chile (2000)

(1979–1998)   (1999–)
Multiple Mirror Telescope Mount Hopkins, Arizona, USA

Large Binocular Telescope Mount Graham, Arizona, USA (2005)

Vera C. Rubin Observatory Cerro Pachón, Chile (planned 2025)

BTA-6 (Large Altazimuth Telescope) Zelenchuksky, Russia (1975)

Large Zenith Telescope British Columbia, Canada (2003)

Gaia Earth–Sun L$_2$ point (2014)

Kepler Earth-trailing solar orbit (2009)

Very Large Telescope Cerro Paranal, Chile (1998, 1999, 2000, 2000)

Extremely Large Telescope Cerro Armazones, Chile (planned 2028)

Human at the same scale

0   5   10 m
0 10 20 30 ft

James Webb Space Telescope Earth–Sun L$_2$ point (2022)

Hubble Space Telescope Low Earth orbit (1990)

Magellan Telescopes Las Campanas, Chile Chile (2000, 2002)

Giant Magellan Telescope Las Campanas, Chile (planned 2030s)

Overwhelmingly Large Telescope (cancelled)

Arecibo Observatory 305 m radio telescope at the same scale

FAST (Five-hundred-meter Aperture Spherical [radio] Telescope) at the same scale

Tennis court at the same scale

Basketball court at the same scale

Angular Resolution

of a Telescope

(i.e. what's the smallest angular separation a telescope can measure)

Diffraction

wavelength
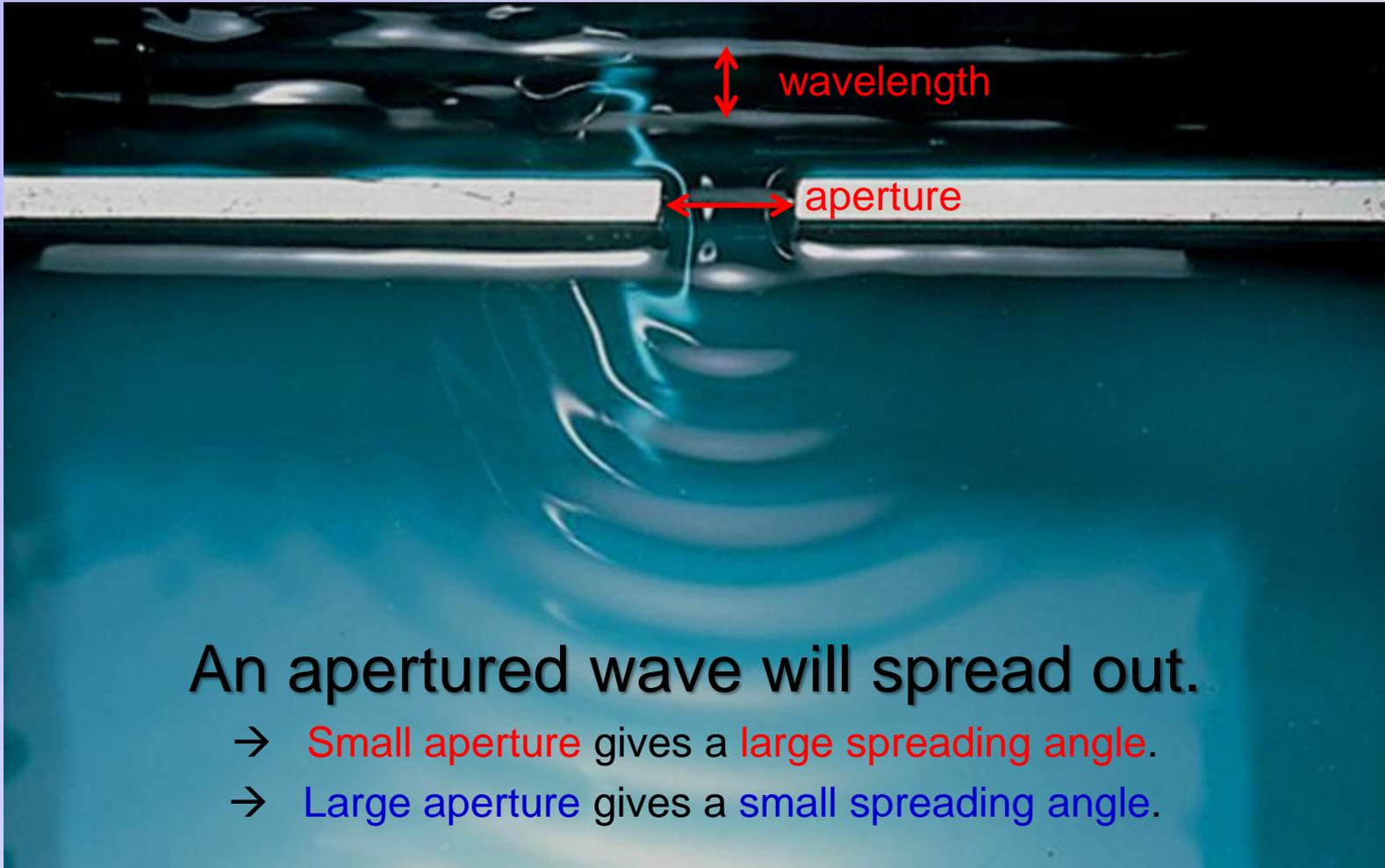
aperture

An apertured wave will spread out.

→ Small aperture gives a large spreading angle.
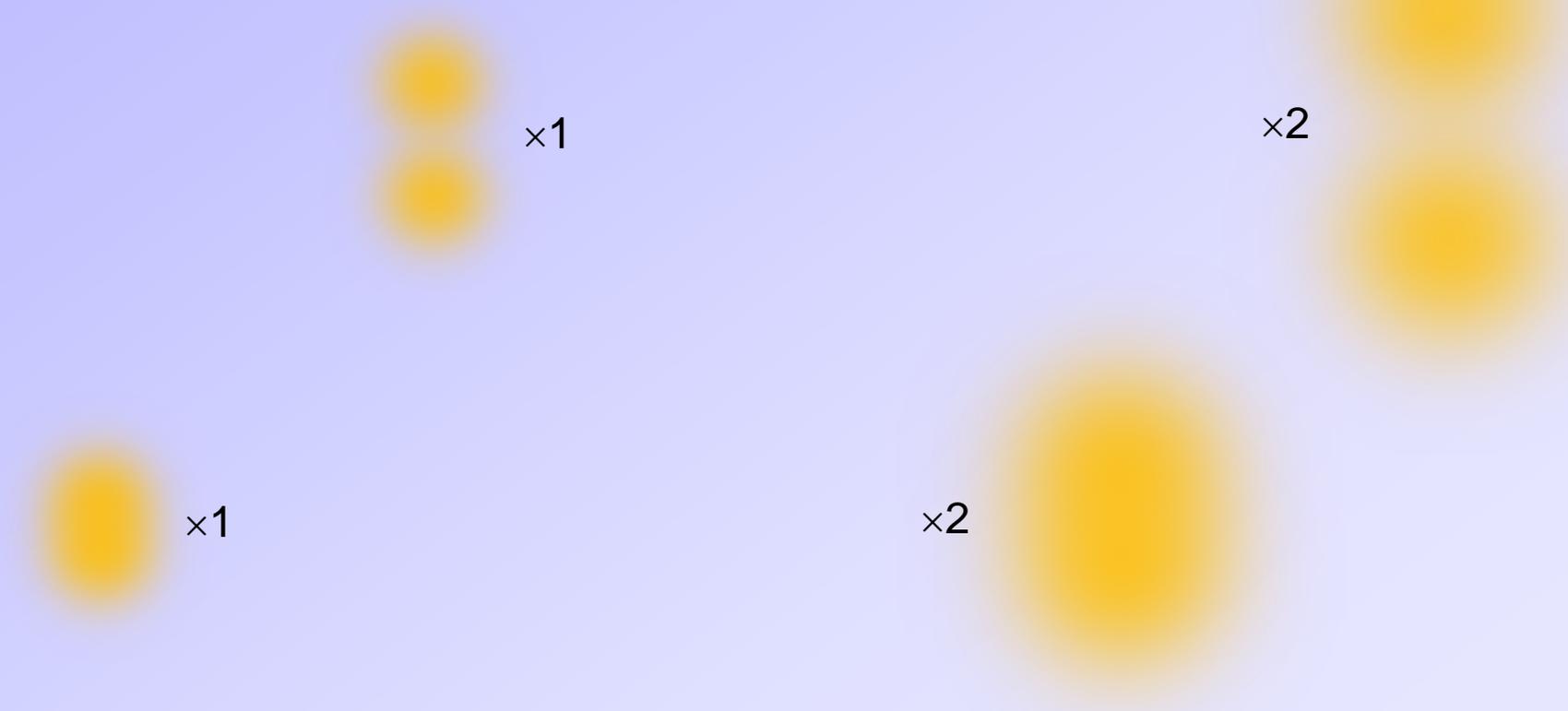
→ Large aperture gives a small spreading angle.

Resolving Power

The minimum resolvable angle is fixed by the aperture of the telescope, i.e. the mirror size.
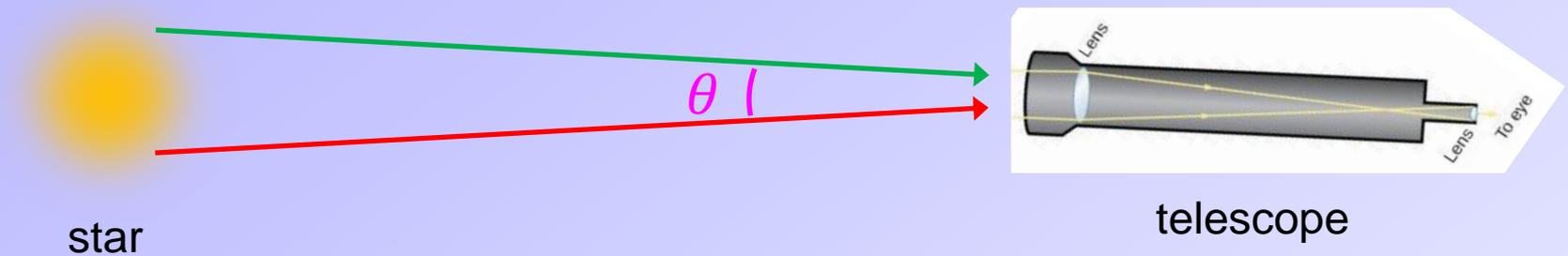
For objects that are really close together, magnifying the image cannot help resolve two objects right next to each other.
→ The spot size is magnified the same as the separations.

×1

×2

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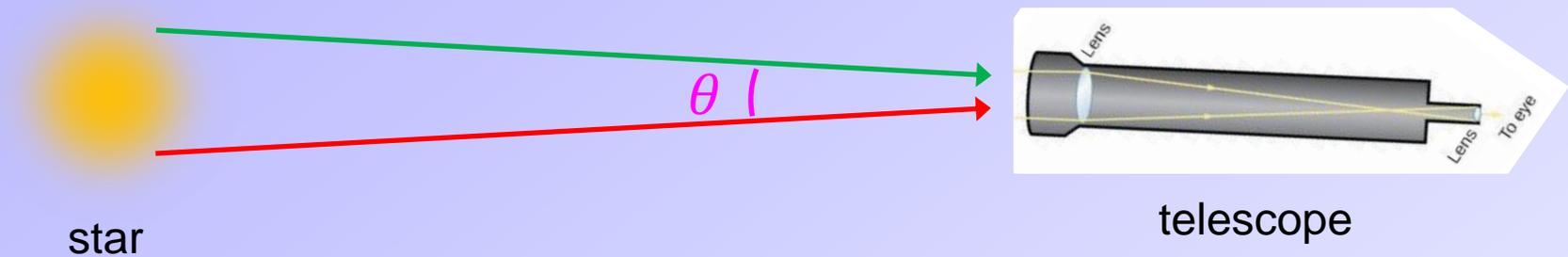→ The spot size is magnified the same as the separations.

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Resolving Power: Rayleigh Criterion

The minimum resolvable angle is fixed by the aperture of the telescope, i.e. the diameter of the primary mirror or lens size.

star

telescope

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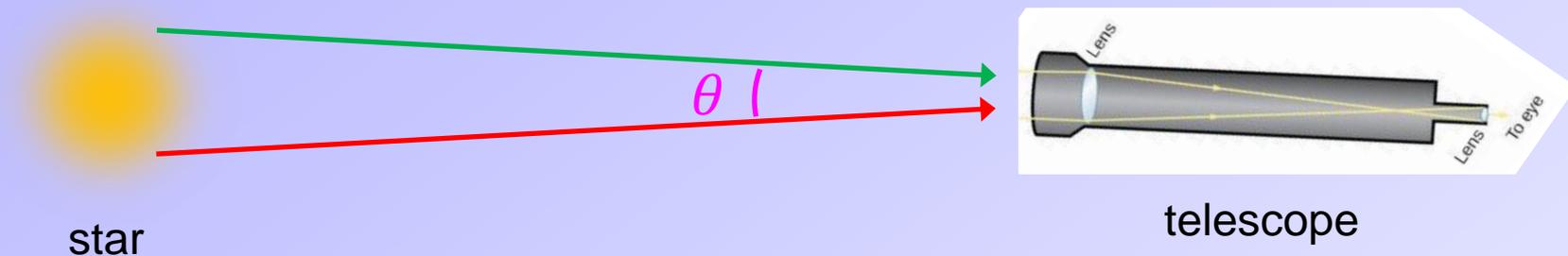

star   telescope

The **angular resolution** of a telescope, i.e. <u>resolving power</u>, is given by:

radians

wavelength in meters

SI units: $\theta_{min} = 1.22 \dfrac{\lambda}{D}$

Resolving Power: Rayleigh Criterion

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SI units: $\theta_{min} = 1.22 \dfrac{\lambda}{D}$

wavelength in nanometers

More useful units: $\theta_{min,\,arcsecond} = 0.000252 \dfrac{\lambda_{nm}}{D_m}$

diameter in meters

angular resolution in arcseconds

What's an arcsecond ?

There are "2π" radians in a circle

1 degree = 1/360th of a circle = $1 \times \frac{2\pi}{360} = 0.017453$ rads

1 arcminute = 1/60th of a degree

1 arcsecond = 1/60th of 1 arcminute = 1/3600th of a degree

1 milli-arcsecond = 1 mas = 1/1000th of 1 arcsecond

1 micro-arcsecond = 1 µas = $1/10^6$ of 1 arcsecond

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Examples

Angular size of **Moon** $= 31$ arcminutes $= 31' \sim 0.5°$

Angular size of **Jupiter** $= 30 - 50$ arcseconds $= 30'' - 50''$

Angular size of **Proxima Centauri** $= 0.001'' = 1$ mas (nearest star: 4.2 ly)

Angular size of **Betelgeuse** $\simeq 0.05'' = 50$ mas (very large star: 640 ly)

Adaptive Optics

(i.e. the benefits of deformable mirrors)

Atmospheric Turbulence

Problem

Atmospheric turbulence limits optical angular resolution to $0.5''$
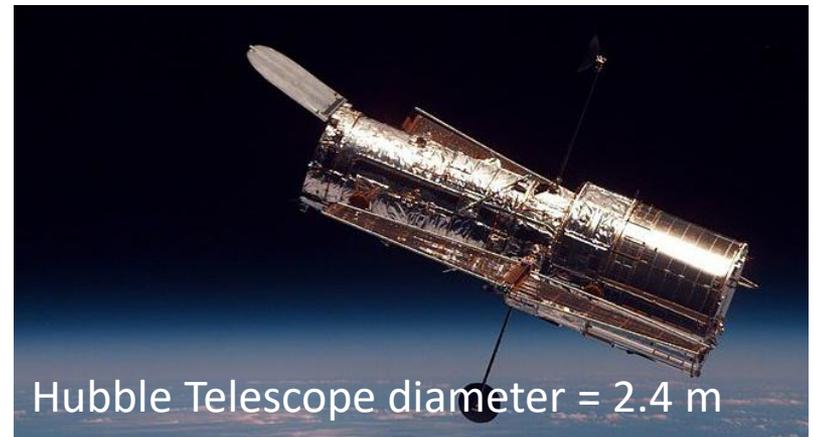
(0.5 arcseconds)

Atmospheric Turbulence

Problem [Recall: Gemini Telescope should have an angular resolution of $\theta_{min} \simeq 0.016''$]

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(0.5 arcseconds)

Solution #1

➢ Get rid of atmosphere (mountain tops help).

➢ Put telescope in space … very expensive, difficult.

Hubble Telescope diameter = 2.4 m

[OpenStax, NASA]

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Solution #2

➢ Adaptive optics

→ Account for atmospheric fluctuations and remove effect from image.

➢ Keep telescope on ground … less expensive, but challenging.
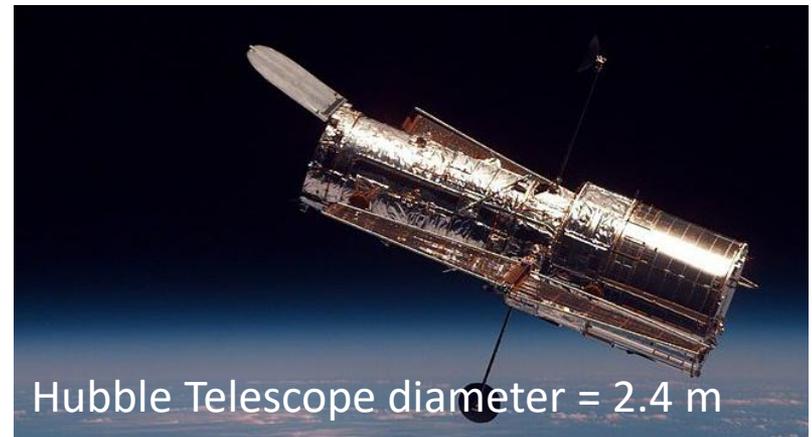
Adaptive Optics

Basic Idea

- Take a point-like star (very far away) but close to the object you want to image.

- The shape of the "guide star" fluctuates / "twinkles" due to atmospheric turbulence.

- **Actively deform your mirror** (slightly) to eliminate shape fluctuations.
    - → Guide star becomes a point star now (due to mirror deformation feedback).
    - → Often deform the secondary mirror.
    - → Feedback deformation rate: 100-1000 Hz.

- The main object becomes undistorted.

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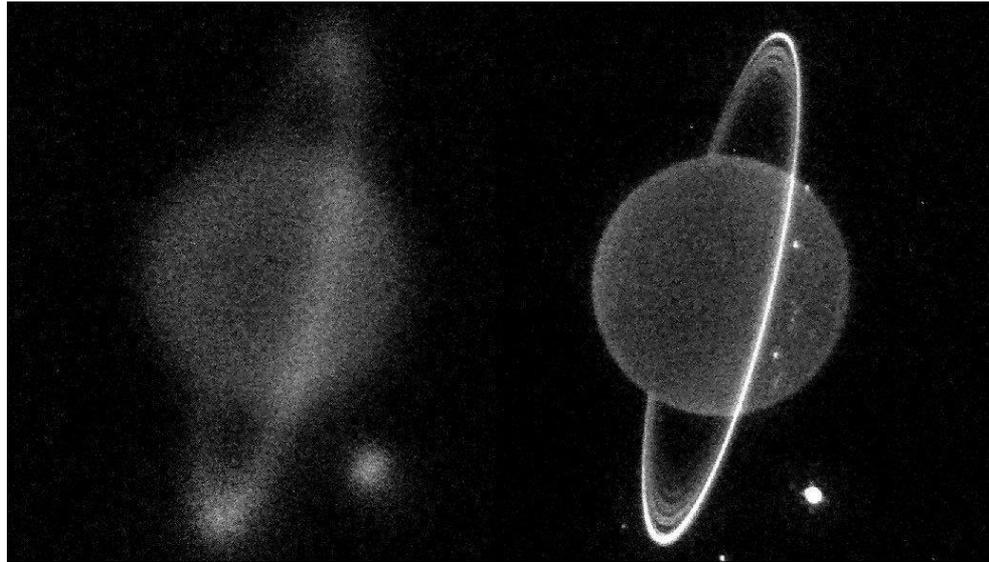- The main object becomes undistorted.

Laser Guide Star

- If there is no nearby point-like star, then a laser can create an **artificial guide star**.

- The laser excites **sodium** atoms in the upper atmosphere (altitude >50 km) to create artificial "star."
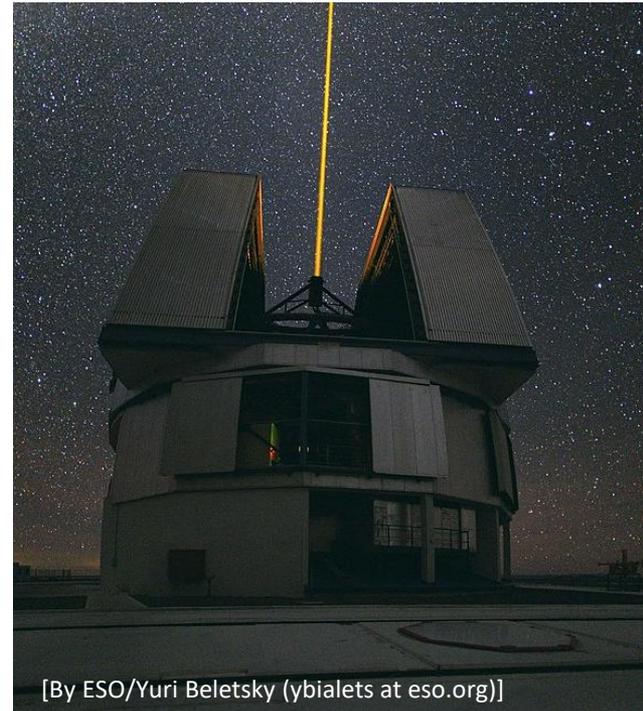
[By ESO/Yuri Beletsky (ybialets at eso.org)]

Adaptive Optics Images

Planet: Uranus
(it has rings!)

[by Heidi B. Hammel and Imke de Pater]

without AO   with AO

Milky Way center

Adaptive Optics: Past & Present

History

- Developed by astronomy & military communities.

- First proposed in 1953 by Horace Babcock (astronomer).

- Robert Leighton (CalTech) implemented the first system in 1957.

- 1970s: first wave of large scale use in astronomy.

- **Present:** Adaptive optics are standard equipment at large observatories

[Wikipedia: ioerror - Flickr, CC BY-SA 2.0]

Freeman Dyson, IAS Princeton (JASON: developed theory)

[UCSC website]

Claire Max, UC Santa Cruz (JASON: laser guide stars)

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[Wikipedia: ioerror - Flickr, CC BY-SA 2.0]

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Present

[In theory: $\theta_{min} \simeq 0.016''$]

- Gemini telescopes have an angular resolution of $\theta_{min} \simeq 0.05''$ in the near-IR (1.6 μm).

- Gemini telescopes uses **5 laser guide stars** and 3 deformable mirrors !!!

- Adaptive optics work best in the infrared (competitive with space-based telescopes).

- For visible light, space-based telescopes have better angular resolution.